TEQ Review Meeting II agenda

September 15, 2020

Remote meeting Via Webex

9:30 – 9:45	R. Borissov	Introduction, tour du table
9:45 – 10:15	A. Bassi	Overview by the coordinator
10:15 – 11:00	M. Drewsen – A. Houtepen	WP1: Trapping
11:00 - 11:45	P. Barker	WP2: Cooling
11:45 – 12:30	H. Ulbricht	WP3: Testing
Lunch break (12:30 – 13:30)		
13:30 – 14:15	M. Paternostro	WP4: Enabling
14:15 – 14:30	A. Bassi	WP5: Management
14:30 – 14:45	C. Curceanu	WP6: Dissemination
14:45 – 15:15	I. Spagnul	Financial data
15:15 – 15:45		Innovation potential discussion
15:45 – 16:15	*General discussion*	
16:15 – 16:45	*Assessment preparation by monitors and PO*	
16.45 – 17:00	R. Borissov	Closing

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

TEQ : Testing the large-scale limit of Quantum Mechanics

Overview

Angelo Bassi, UniTs - PI

Acknowledgements

It all started back in 2015…

- **The local PIs:** P. Barker, C. Brukner, C. Curceanu, M. Drewsen, N. Hempler, A. Houtepen, M. Paternostro, H. Ulbricht
- **TEQ members**
- **Administrative Officer:** Irene Spagnul
- **PO:** Roumen Borissov
- **Reviewers:** R. Filip, T.E. Northup, W. Struyve

The Network

UniTs - University of Trieste

- Angelo Bassi
  PI
  Website
- Luca Ferialdi
- Lorenzo Asprea
- Anirudh Gundhi
- Matteo Carlesso
  Website Manager
- Caitlin Jones
  Social Media Manager
- José Luis Gaona Reyes
- Irene Spagnul
  Administrative Officer

QUB - Queen's University of Belfast

- Mauro Paternostro
  Local PI
  Website
- Gabriele De Chiara
- Alessio Belenchia
- Alessandro Ferraro
- Marta Maria Marchese
  Publications & Dissemination Manager

INFN - Istituto Italiano Fisica Nucleare

- Catalina Curceanu
  Local PI & Press Officer
- Kristian Piscicchia
- Alessandro Scordo
- Fabrizio Napolitano
- Alberto Clozza
- Massimiliano Bazzi
- Elisabetta Pace

UCL - University College London

- Peter Barker
  Local PI
  Website
- Antonio Pontin
- Thomas Penny
- Markus Rademacher
- Anishur Rahman
- Jonathan Gosling
- Marco Toroš

OEAW - Austrian Academy of Sciences

- Caslav Brukner
  Local PI
  Website
- Esteban Castro Ruiz
- Ilya Kull
- Luis Cortés Barbado

AU - Aarhus University

- Michael Drewsen
  Local PI
  Website
- Cyrille Solaro
- Aurelién Dantan
  Website
- Vincent Jarlaud

UoS - University of Southampton

- Hendrik Ulbricht
  Local PI
  Website
- Christopher Timberlake
- Andrea Vinante
- James Bain
- Stefan Olsonrobbie

M2 - M Squared Lasers Limited

- Nils Hempler
  Local PI
  Website
- Joseph Thom

TUD - Delft University of Technology

- Liberato Manna
  Local PI
  Website
- Luca De Trizio
- Arjan Houtepen
  Website
- Jence Mulder

THANKS TO PAST MEMBERS

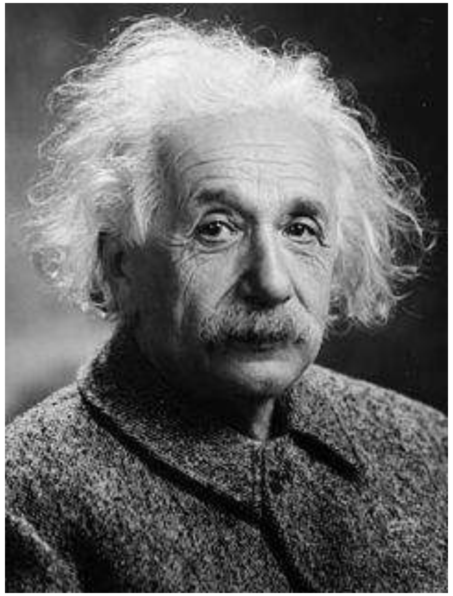
- Ousama Houhou (QUB)
- Ashley Setter (Soton)
- Giulio Gasbarri (UniTS, Soton)
- Flaminia Giacomini (OEAW)

Long-term vision and targeted breakthrough

The long-term vision of TEQ is the identification of the ***fundamental limitations*** *to the applicability of* ***quantum mechanics*** *towards the establishment of a novel paradigm for quantum-enhanced technology that makes use of large-scale devices*

TEQ

European Commission



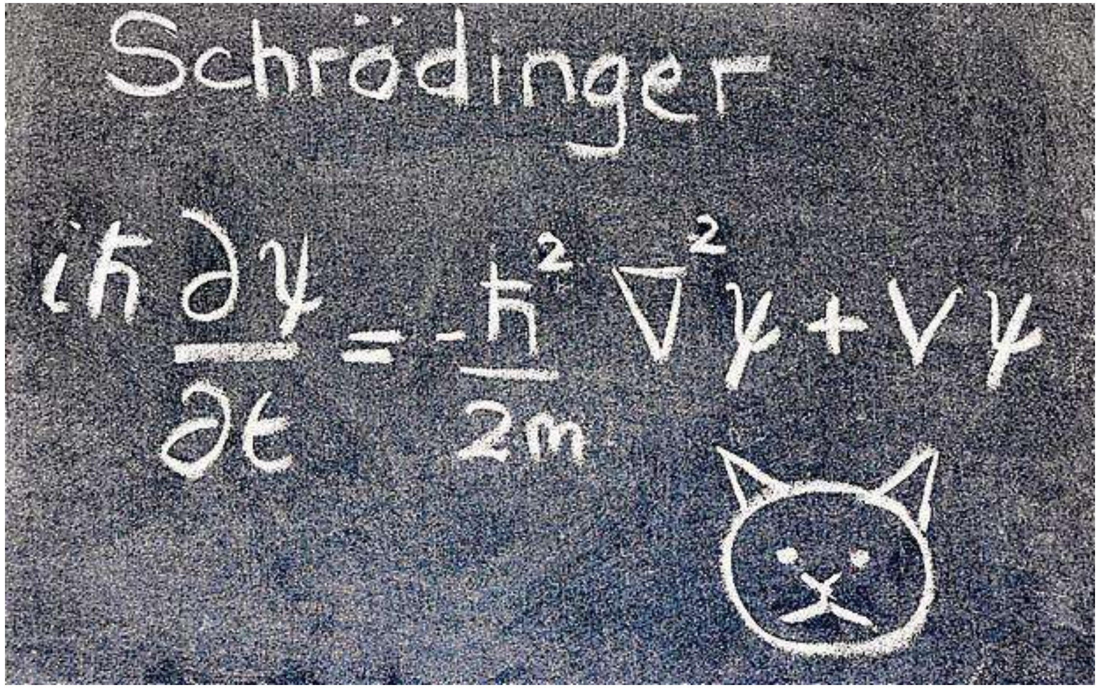
Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing.
Albert Einstein

I think I can safely say that no one understands quantum mechanics
Richard Feynman

I'm not as sure as I once was about the future of quantum mechanics.
Steven Weinberg

I am inclined to put my money on the idea that if you push quantum mechanics hard enough it will break down and something else will take over – something we can't envisage at the moment.
Anthony J. Leggett

The trouble with Quantum Mechanics



Microscopic systems can be in a **quantum superposition**; macroscopic systems no… at least so far.

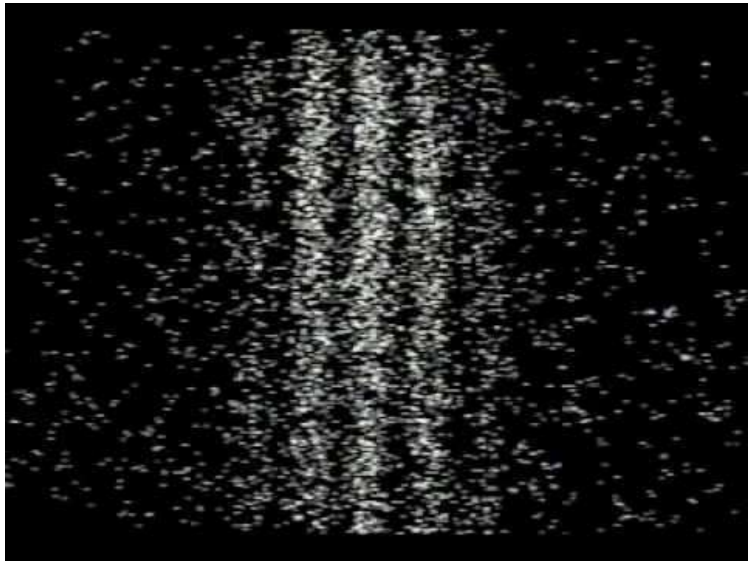
Why is it so? How is quantumness lost when moving from the micro- to the macro-world?

The core of TEQ

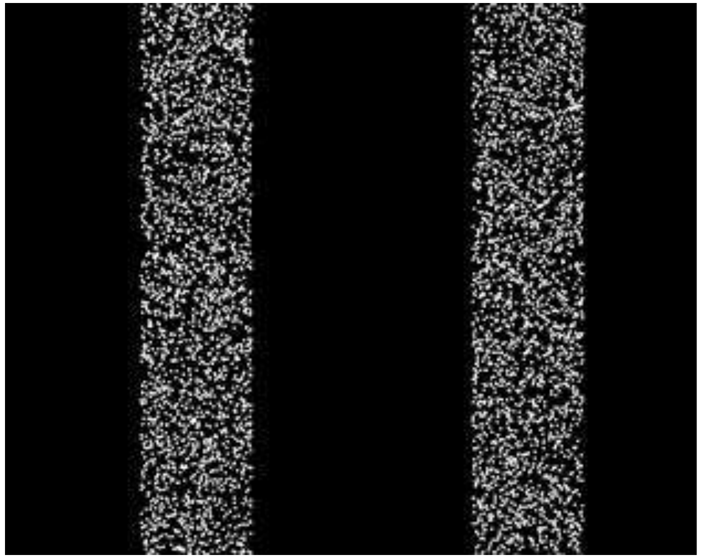
Is the lack of observation of quantum effects at the macroscopic level a manifestation of a breakdown of quantum linearity, or simply the consequence of the fact that no one so far was able to create a macroscopic quantum superposition?

We are presented with a compelling case for the **exploration of quantum effects at the large scale** and open up a new route for fundamental and technologically relevant investigations.

The standard route: large-mass matter-wave interferometry

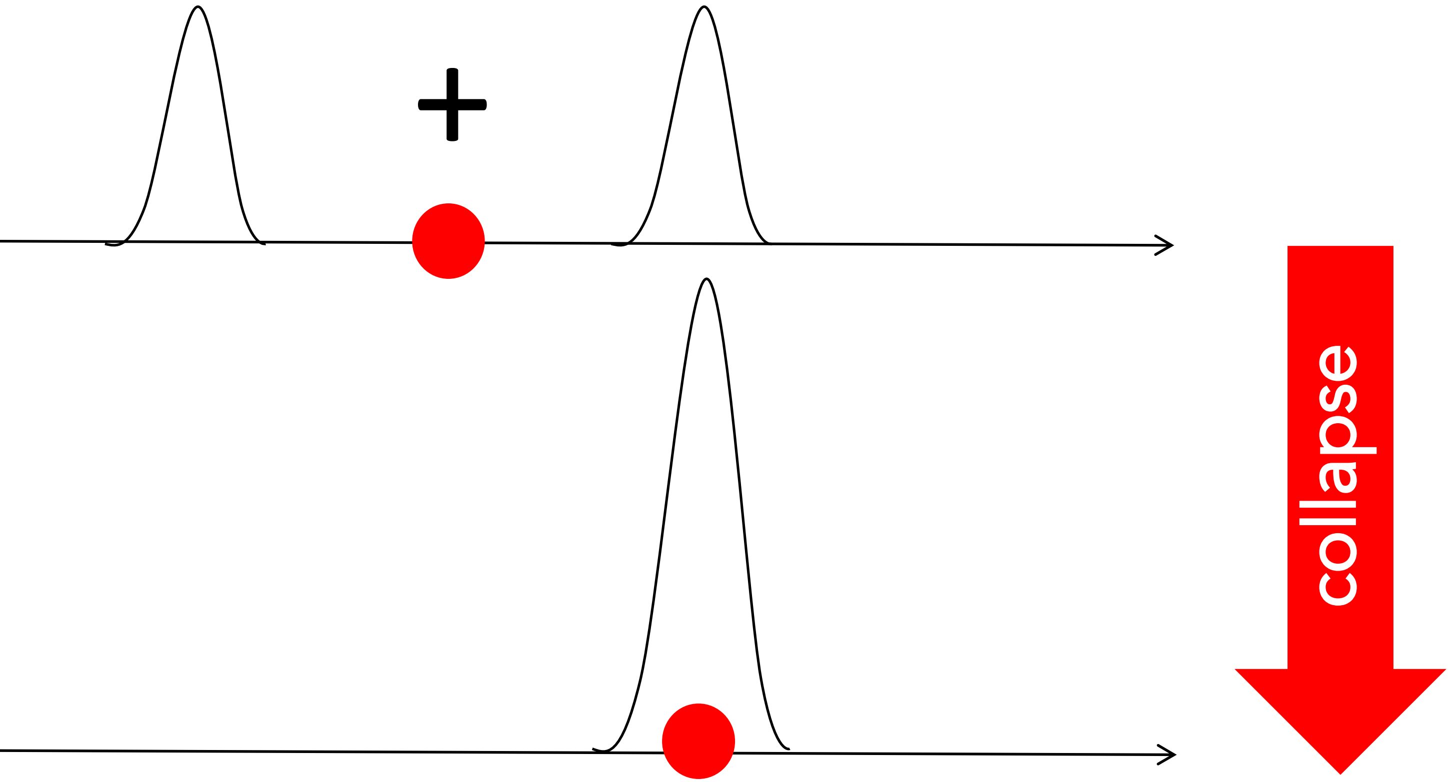


Quantum Mechanics ok!



Quantum Mechanics wrong!

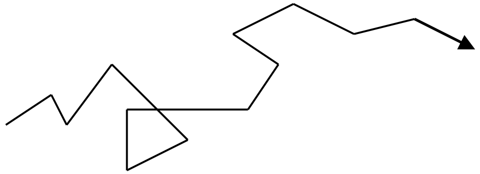
A novel route: non-interferometric experiments



= center of mass

A localization of the wave function changes the position of the center of mass

Collapse-induced Brownian motion



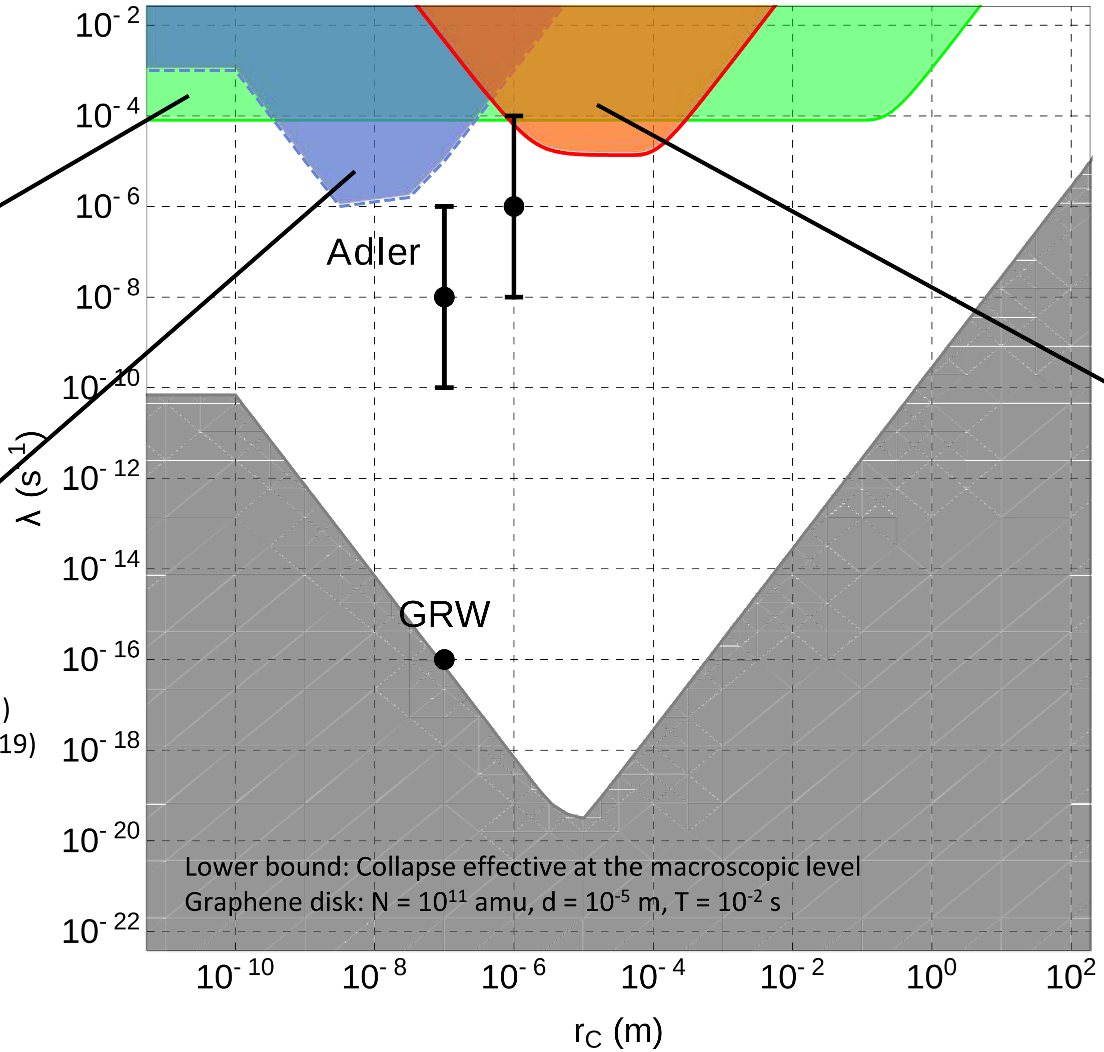
Also theoretical reasons for that

A comparison: interferometric bounds on the CSL model

Atom Interferometry

T. Kovachy *et al.*, Nature 528, 530 (2015)

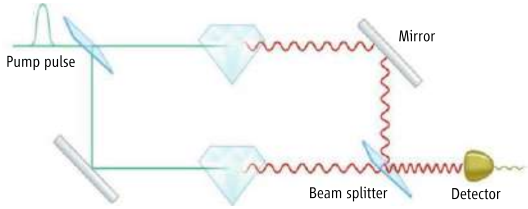
M = 87 amu
d = 0.54 m
T = 1 s



Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)
Y.Y. Fein *et al.* Nature Physics 15, 1242 (2019)

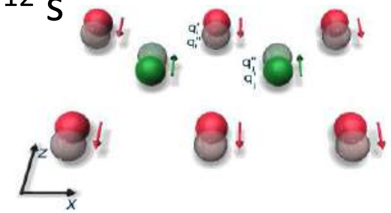
M = 10^4 amu
d = 10^{-7} m
T = 10^{-3} s



Entangling Diamonds

K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al.*, PRA 94, 012108 (2016)

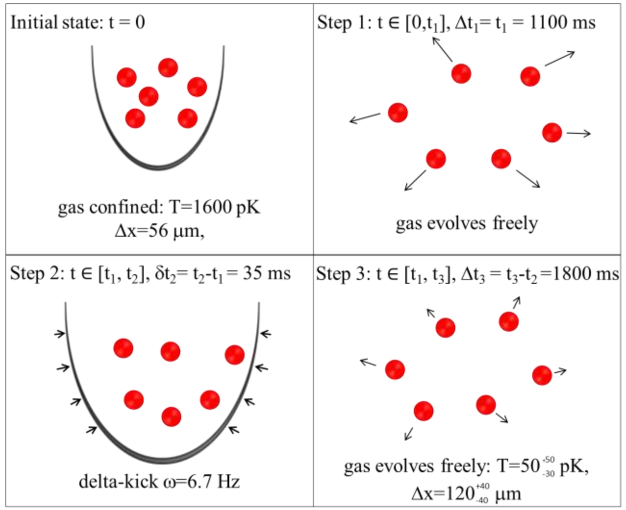
M = 10^{16} amu
d = 10^{-11} m
T = 10^{-12} s

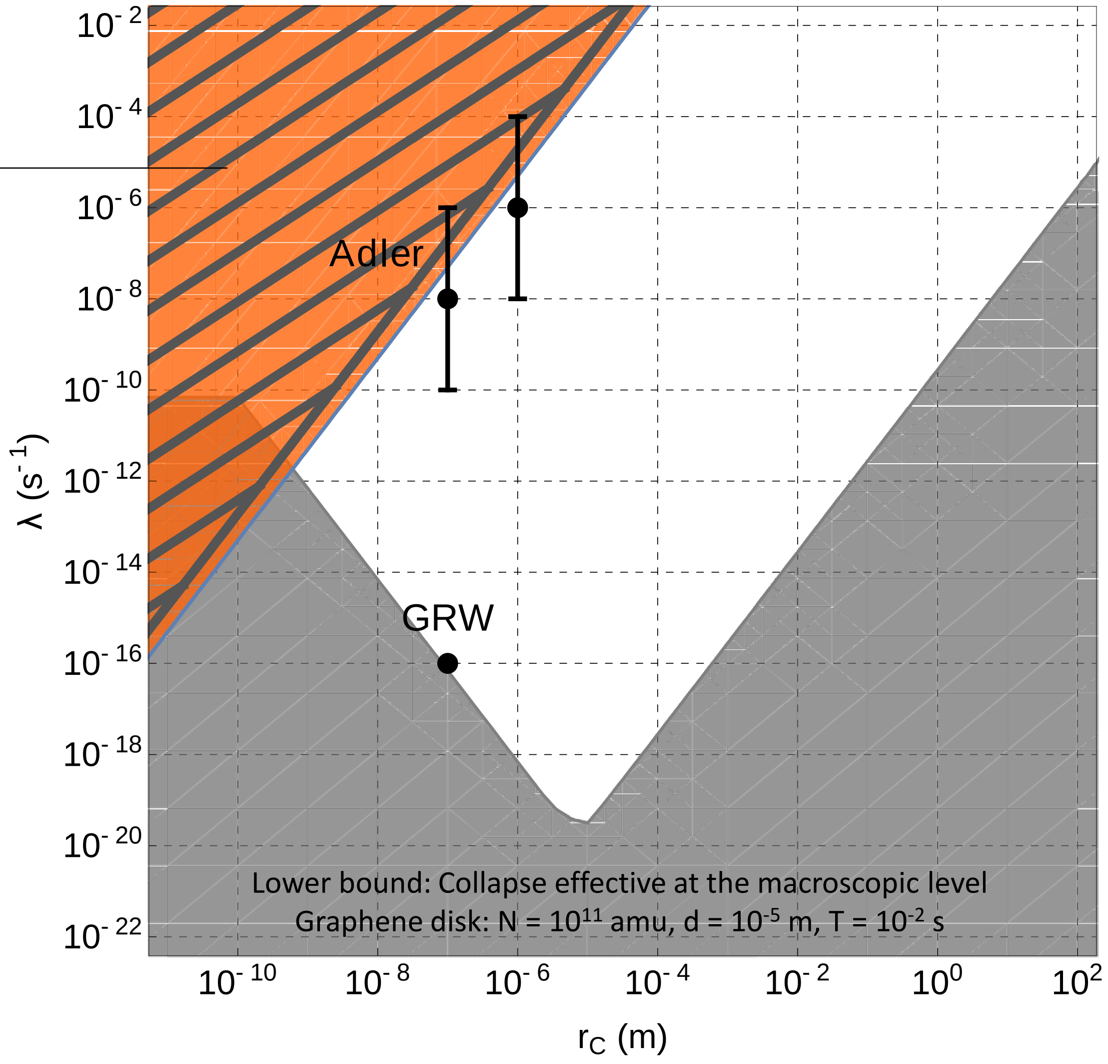


Non - Interferometric Experiments

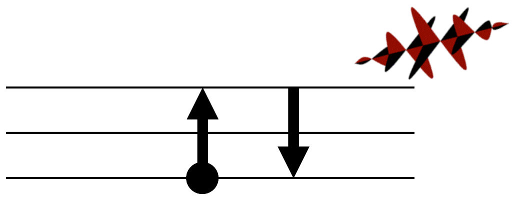
Cold atom gas

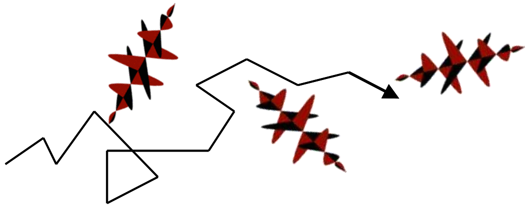
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.*, Physica A 462, 764 (2016)



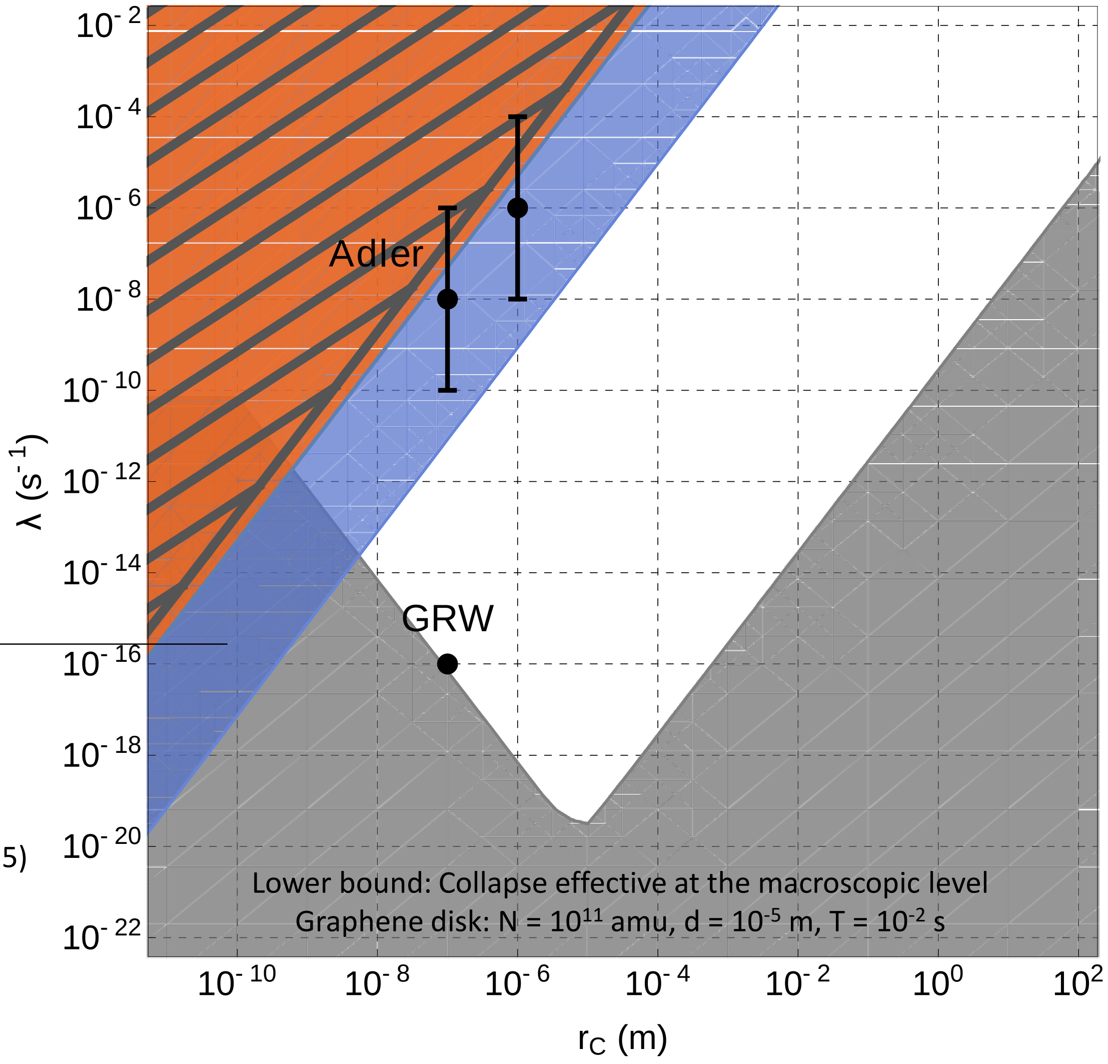


Non - Interferometric Experiments



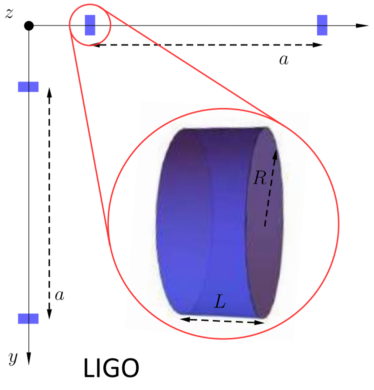


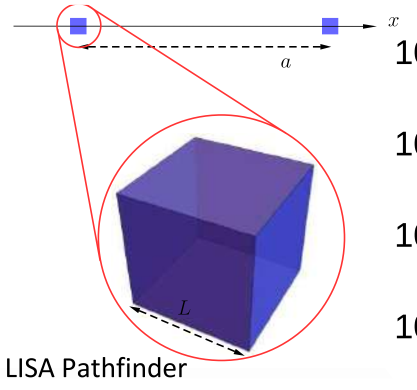
X rays



S.L. Adler *et al.,* Jour. Phys. A 40, 13395 (2009)
S.L. Adler *et al.*, Journ. Phys. A 46, 245304 (2013)
A. Bassi & S. Donadi, Annals of Phys. 340, 70 (2014)
S. Donadi & A. Bassi, Jounr. Phys. A 48, 035305 (2015)
C. Curceanu *et al.,* J. Adv. Phys. 4, 263 (2015)
+ several more

Non - Interferometric Experiments

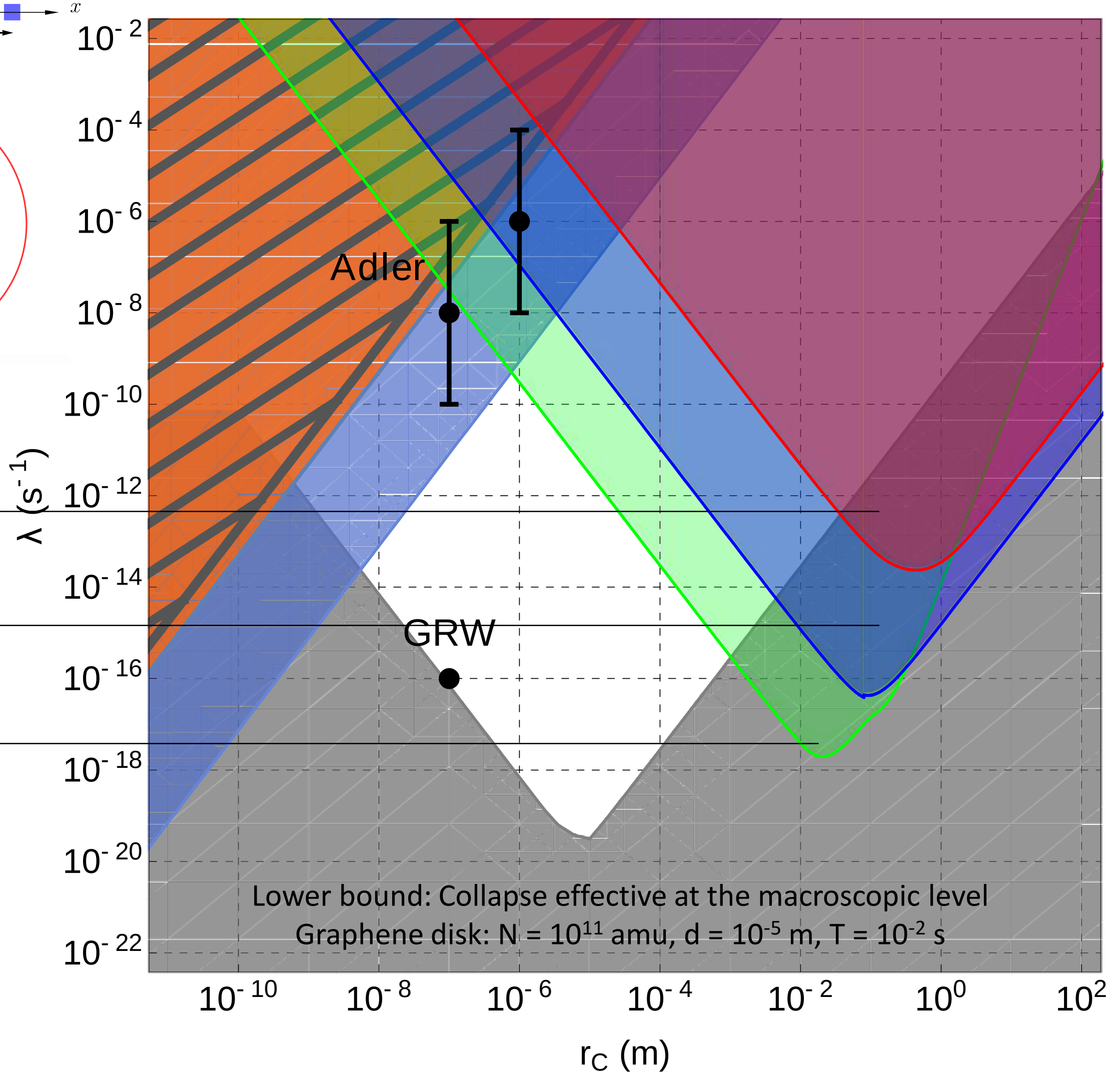




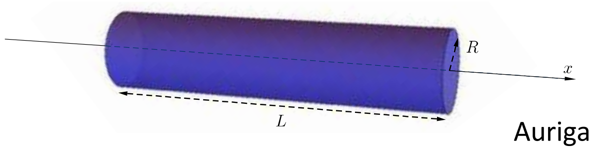
Auriga

Ligo

Lisa Pathfinder



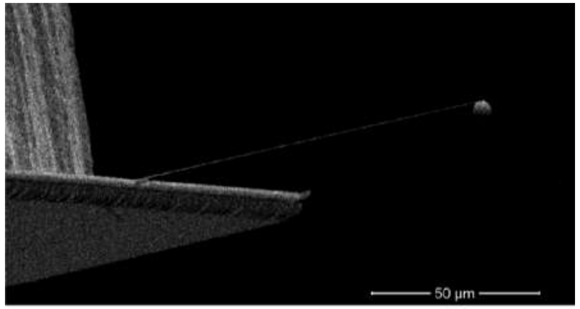
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

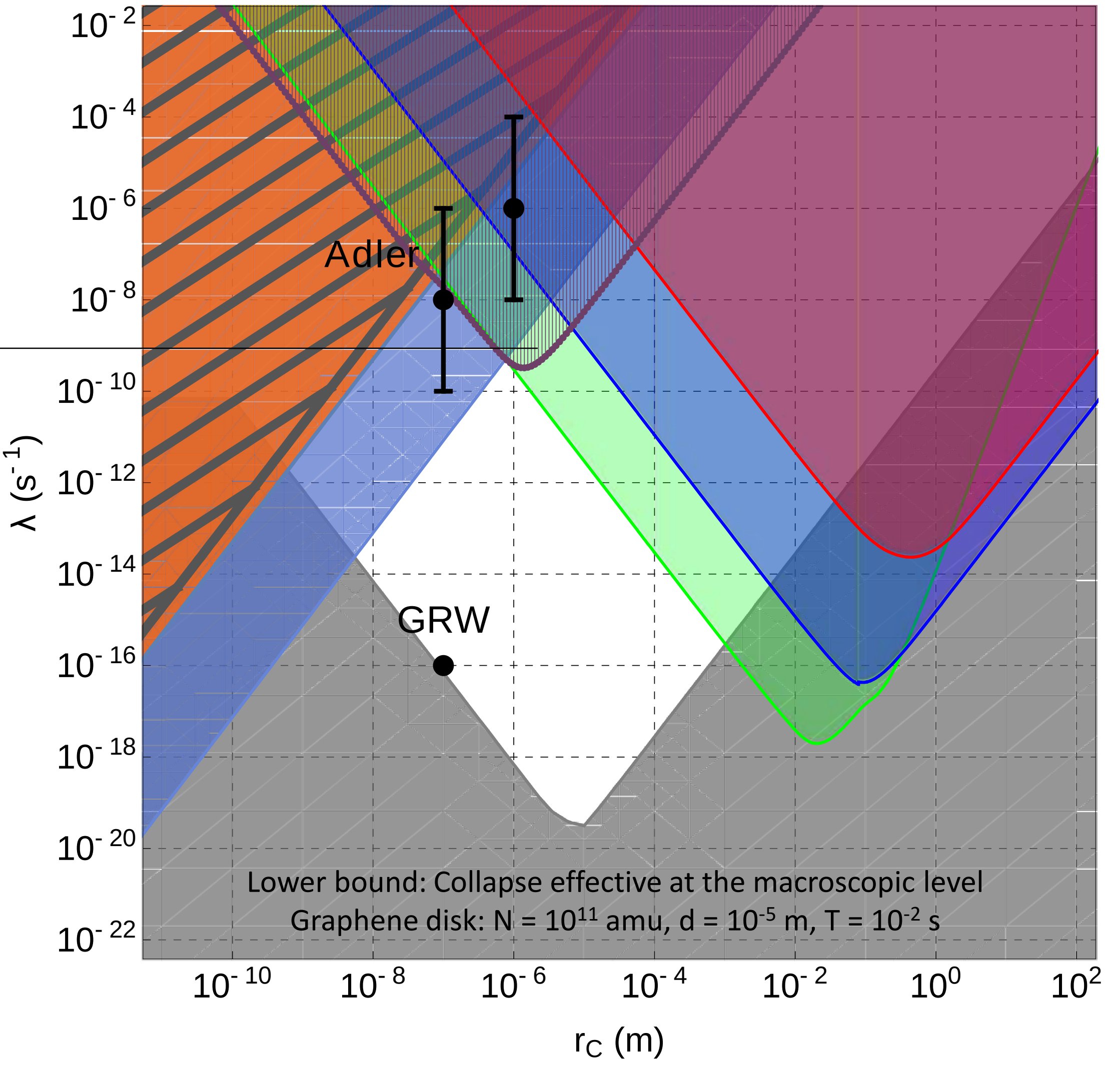


Non - Interferometric Experiments

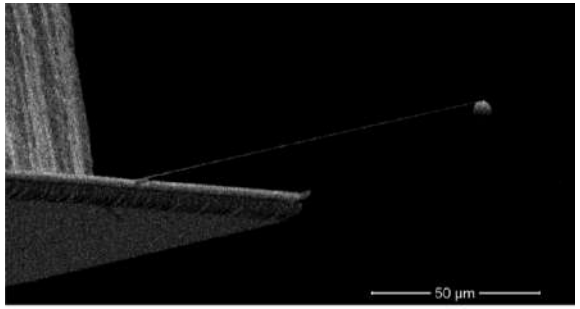
Cantilever

A. Vinante *et al.*, Phys. Rev. Lett. 116, 090402 (2016)



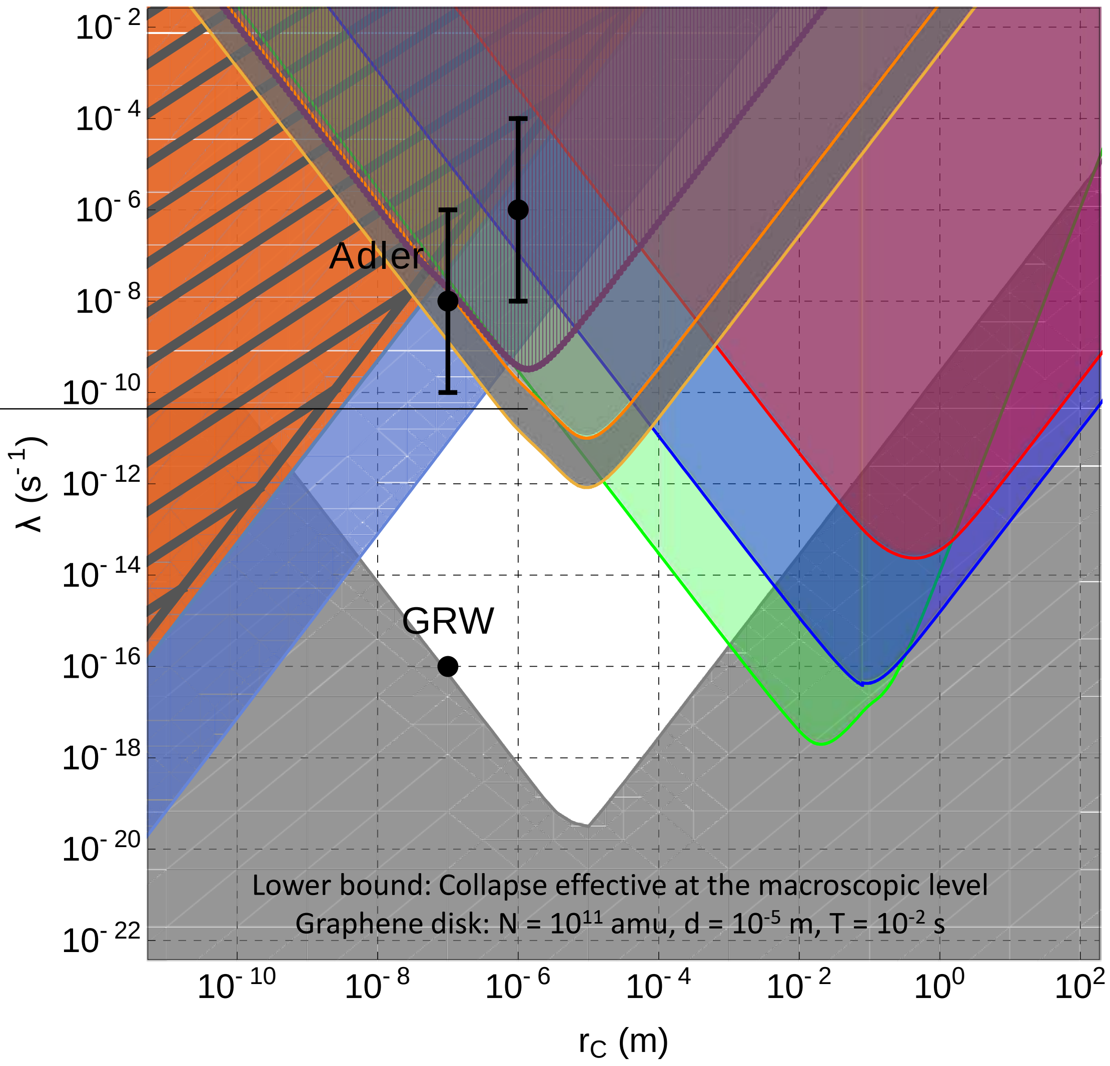


Non - Interferometric Experiments



Cantilever – update

A. Vinante *et al., Phys. Rev. Lett. 119, 110401 (2017).*



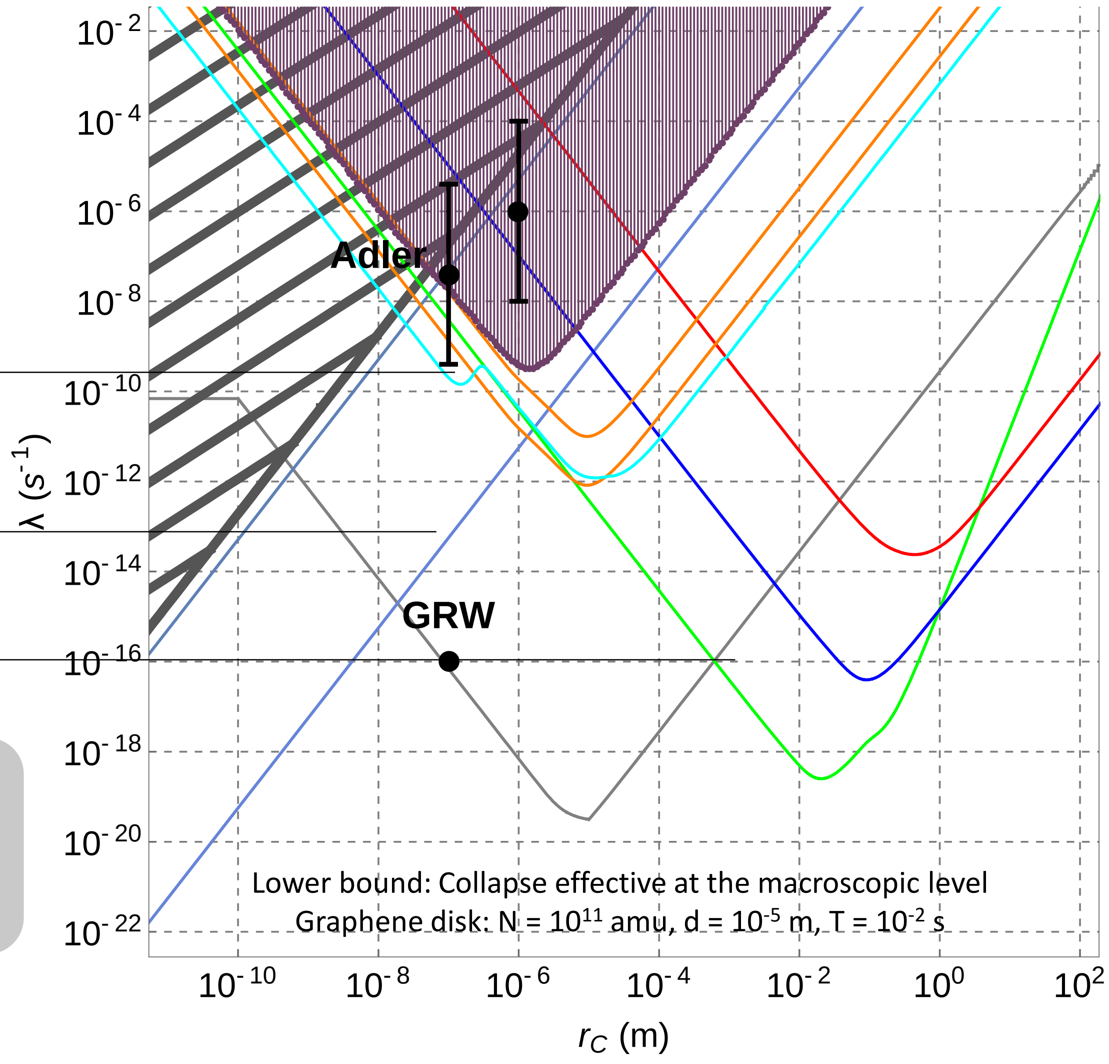
Non - Interferometric Experiments

Update 2

A. Vinante *et al., Phys. Rev. Lett. (2020), to appear.*

K. Pisicchia *et al., Entropy 19, 319 (2017)*

M. Carlesso *et al., N. Journ. Phys 20, 083022 (2018)*



TEQ

H2020 FET project
www.tequantum.eu

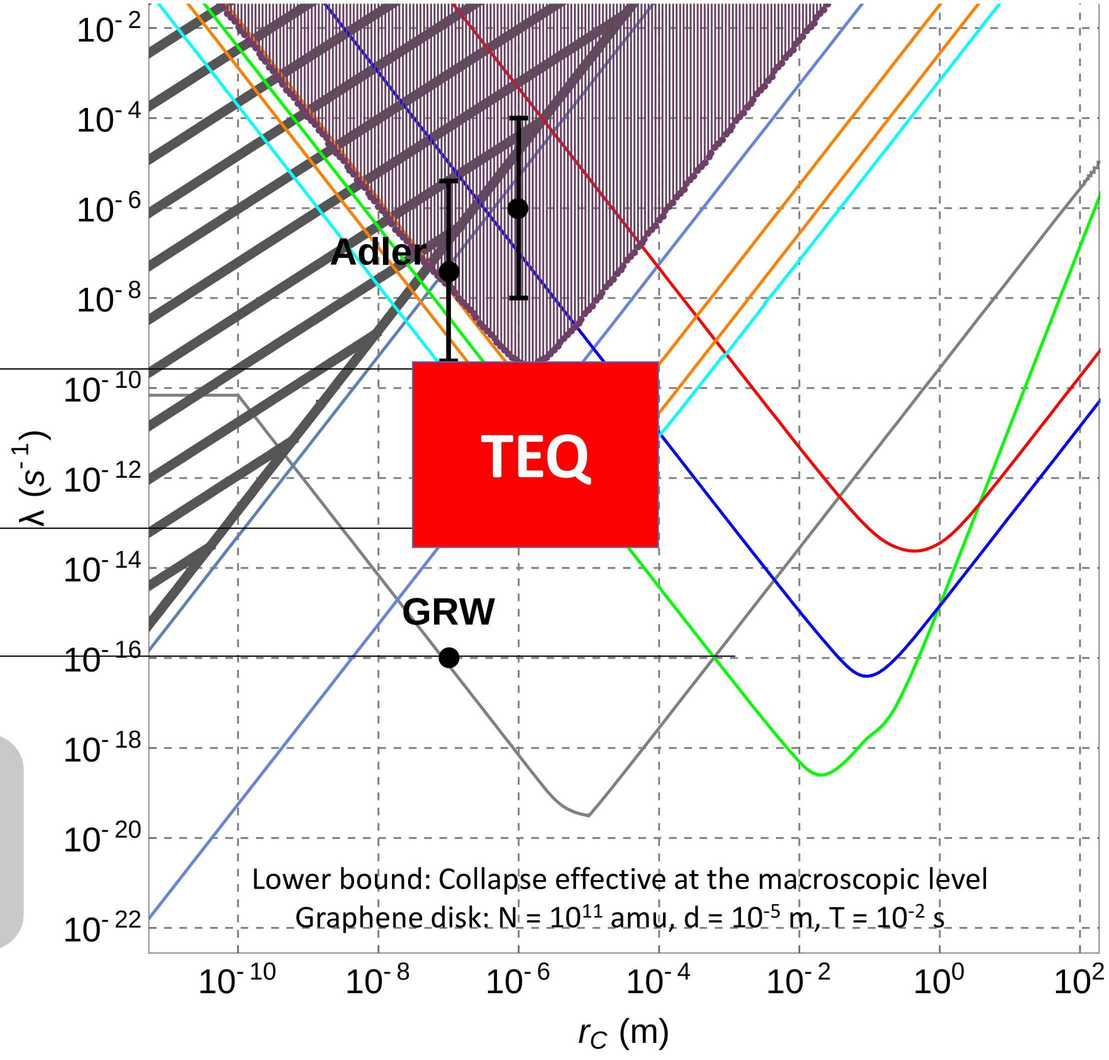
Non - Interferometric Experiments

Update 2

A. Vinante *et al.*, *Phys. Rev. Lett. (2020), to appear.*

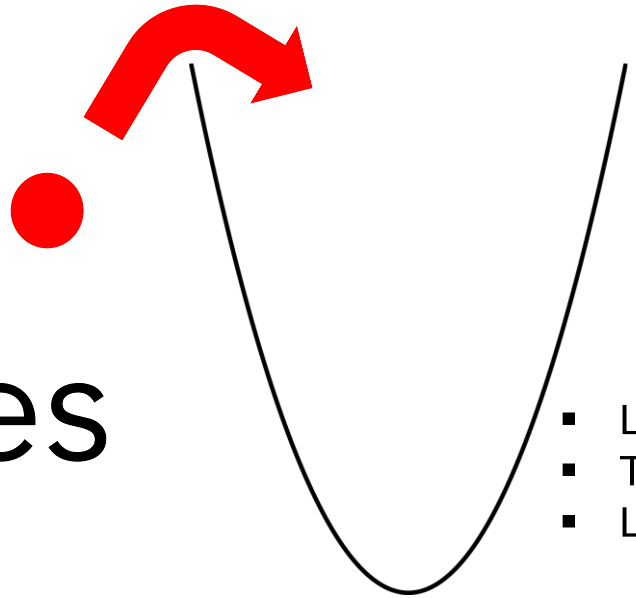
K. Pisicchia *et al.*, *Entropy 19, 319 (2017)*

M. Carlesso *et al.*, *N. Journ. Phys 20, 083022 (2018)*



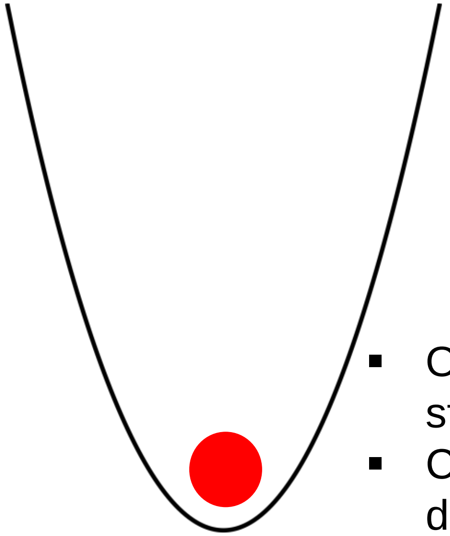
H2020 FET project
www.tequantum.eu

TEQ's Objectives



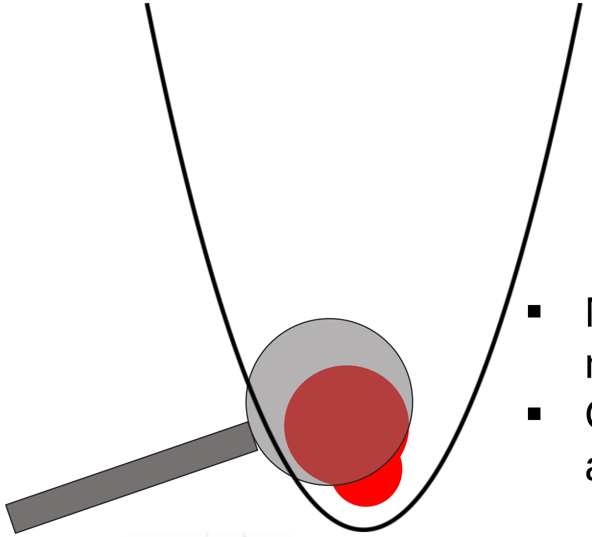
1. Trapping

- Low-noise trap
- Tailored NCs
- Loading mechanics



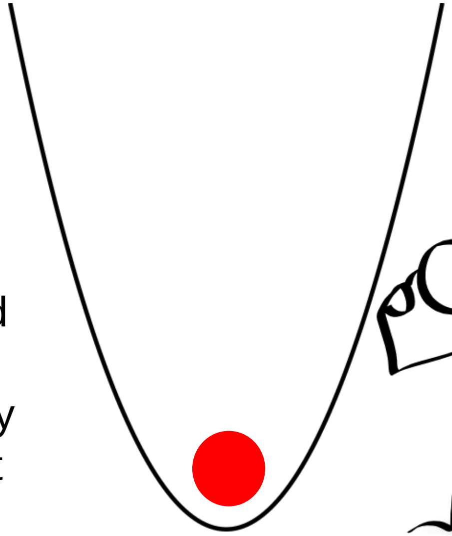
2. Cooling

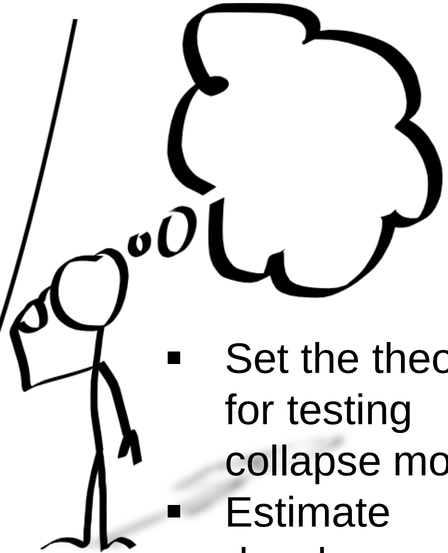
- Optimal cooling strategies
- Control decoherence



3. Testing

- Monitor trapped motion
- Compare theory and experiment





4. Enabling

- Set the theory for testing collapse models
- Estimate decoherence

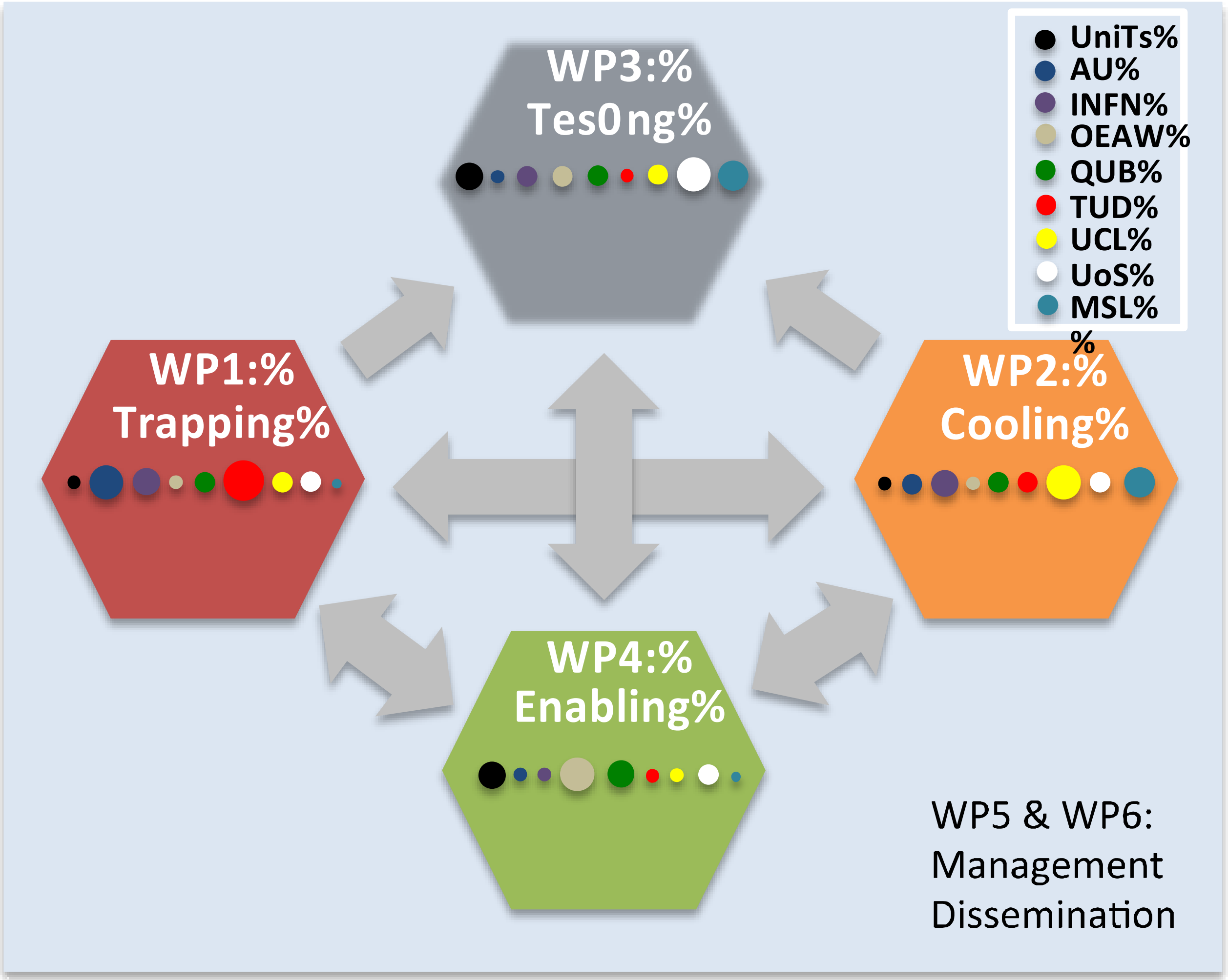
5. Ruling out

- Visionary perspectives on the study of the foundations of quantum mechanics

TEQ's scientific Structure

H. Ulbricht (UoS)

M. Drewsen (AU)



P. Barker (UCL)

M. Paternostro (QUB)

WP Breakdown

Work package number	1	Start Date or Starting Event				Mth 1		
Work package title	**Trapping**							
Participant number	1	**2**	3	4	5	6	7	8	9
Short name of participant	UniTs	**AU**	INFN	OEAW	QUB	TUD	UCL	UoS	MSL
PM per participant:	8	**30**	19	8	16	38	5	5	0

→ M. Drewsen
A. Houtepen

Work package number	2	Start Date or Starting Event				Mth 1		
Work package title	**Cooling**							
Participant number	1	2	3	4	5	6	**7**	8	9
Short name of participant	UniTs	AU	INFN	OEAW	QUB	TUD	**UCL**	UoS	MSL
PMs per participant:	8	15	20	12	16	9	**40**	10	22

→ P. Barker
C. Curceanu

Work package number	3	Start Date or Starting Event				Mth 1		
Work package title	**Testing**							
Participant number	1	2	3	4	5	6	7	**8**	9
Short name of participant	UniTs	AU	INFN	OEAW	QUB	TUD	UCL	**UoS**	MSL
PMs per participant:	11	6	10	16	16	3	5.6	**36**	22

→ H. Ulbricht

Work package number	4	Start Date or Starting Event				Mth 1		
Work package title	**Enabling**							
Participant number	1	2	3	4	**5**	6	7	8	9
Short name of participant	UniTs	AU	INFN	OEAW	**QUB**	TUD	UCL	UoS	M2
PMs per participant:	30	2	4	33	**27.2**	3	2	2	0

→ M. Paternostro
C. Brukner

European Commission

WP Breakdown

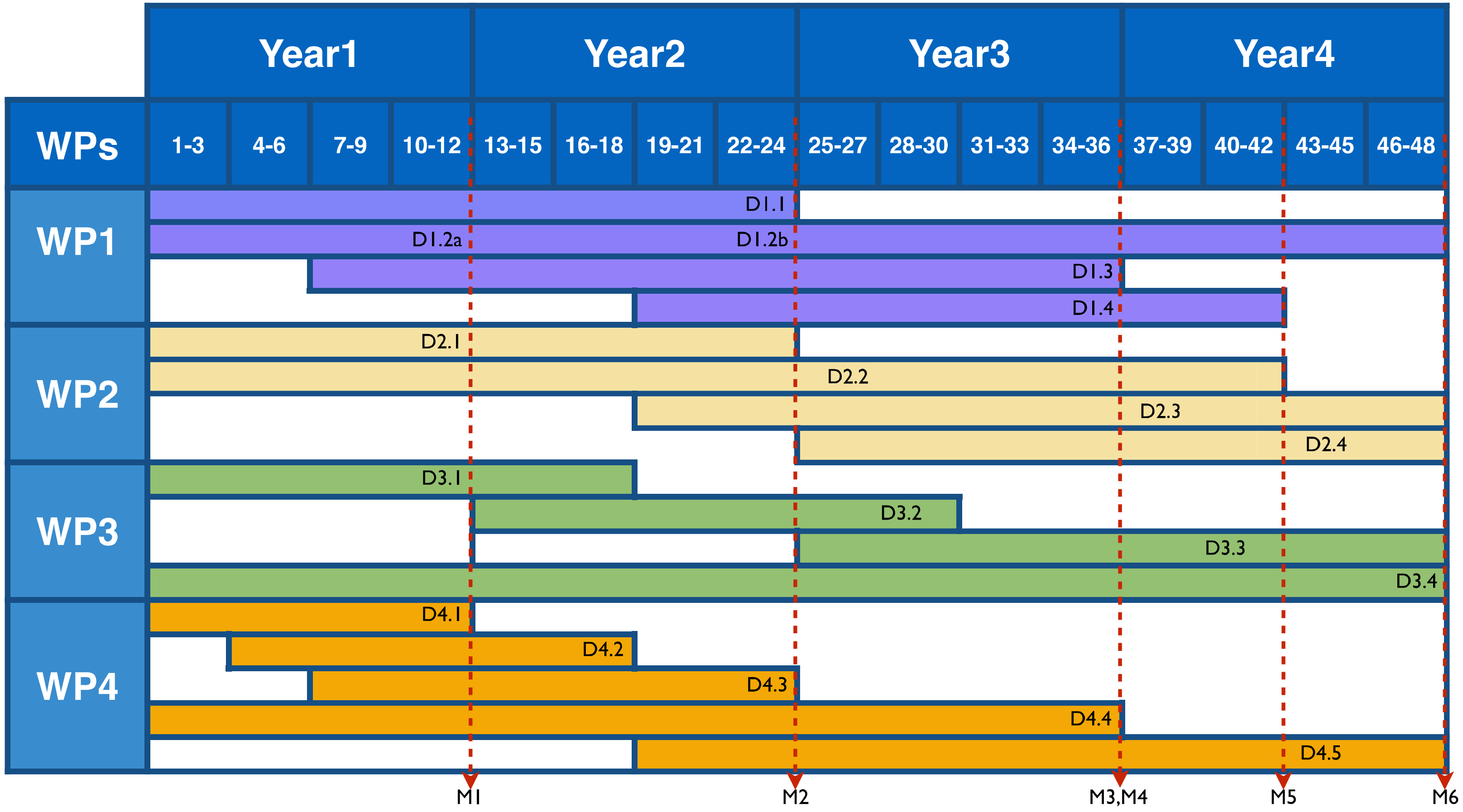
Work package number	5	**Start Date or Starting Event**				Mth 1			
Work package title	**Management**								
Participant number	**1**	2	3	4	5	6	7	8	9
Short name of participant	**UniTs**	AU	INFN	OEAW	QUB	TUD	UCL	UoS	MSL
PMs per participant:	**40**	2	4	2	2	2	2	2	2

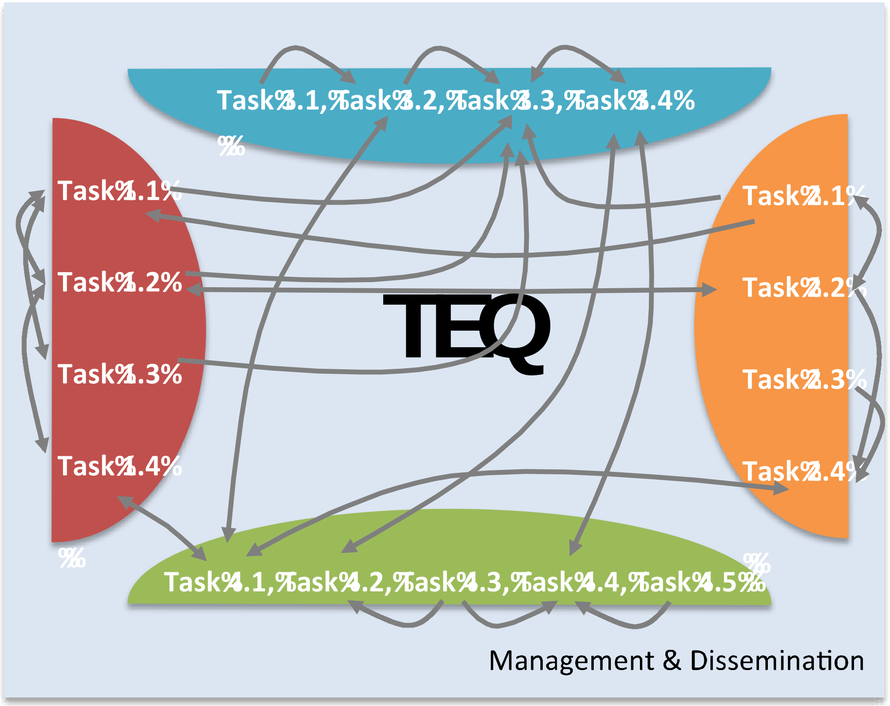
A. Bassi

Work package number	6	**Start Date or Starting Event**				Mth 1			
Work package title	**Dissemination**								
Participant number	**1**	2	3	4	5	6	7	8	9
Short name of participant	**UniTs**	AU	INFN	OEAW	QUB	TUD	UCL	UoS	MSL
PMs per participant:	**18**	2	4	2	2	2	2	2	2

C. Curceanu

WP Breakdown - tasks





List of Deliverables

Deliverables, Ethics, DMP, Other Reports									
WP No	Del Rel. No	Del No	Title	Description	Lead Beneficiary	Nature	Dissemination Level	Est. Del. Date (annex I)	Status
WP5	D5.1	D19	Website	Website and logo	UNITS	Websites, patents	Public	28 Feb 2018	Approved
WP6	D6.1	D24	Press releases	Press releases on the aims and context o	UNITS	Websites, patents	Public	31 Mar 2018	Approved
WP5	D5.2	D20	Data Management Plan	We will demonstrate the compliance with	UNITS	ORDP: Open Rese	Public	30 Jun 2018	Approved
WP1	D1.2	D2	1-Colloidal NCs	NCs of controlled size/shape/composition	TU Delft	Report	Public	31 Dec 2018	Approved
WP2	D2.1	D6	Low noise electronics	Creation of low noise electronics for state	INFN	Report	Public	31 Dec 2018	Approved
WP3	D3.1	D10	Low noise environment	Low noise environment for the ultimate ex	SOUTHAMPTON	Report	Public	31 Dec 2018	Approved
WP4	D4.1	D14	Calibration of decoherence	Quantification of environmental decoherer	QUB	Report	Public	31 Dec 2018	Approved
WP6	D6.2	D25	Popular press articles	Articles on popular press	UNITS	Websites, patents	Public	31 Dec 2018	Approved
WP6	D6.5	D28	Dissemination and Exploitation Pla	Dissemination and Exploitation Plan of TE	UNITS	Report	Confidential, only f	31 Dec 2018	Approved
WP5	D5.3	D21	Project Review meeting documents	Technical/scientific report, outcome of the	UNITS	Report	Confidential, only f	28 Feb 2019	Approved
WP4	D4.2	D15	Bounds to CSL & SN models	Provision of bounds on the effects of CSL,	QUB	Report	Public	30 Jun 2019	Submitted
WP6	D6.3	D26	Videos	Video-abstracts of relevant publications, vi	UNITS	Websites, patents	Public	31 Aug 2019	Submitted
WP1	D1.1	D1	Rf trap for NCs	Commission of an rf trap for NCs with ele	AU	Report	Public	31 Dec 2019	Submitted
WP1	D1.3	D3	2-Colloidal NCs	NCs of controlled size/shape/composition	TU Delft	Report	Public	31 Dec 2019	Submitted
WP4	D4.3	D16	Size of superposition	Design of experimental schemes for the c	QUB	Report	Public	31 Dec 2019	Submitted
WP6	D6.4	D27	Workshop	Workshop "Redefining the foundations of	UNITS	Websites, patents	Public	31 Dec 2019	Submitted
WP2	D2.2	D7	Optimal cooling strategies	Identification of optimal cooling strategies	SOUTHAMPTON	Report	Public	31 Mar 2020	Submitted
WP3	D3.2	D11	Systematic effects investigated	Systematic effects are investigated	SOUTHAMPTON	Report	Public	30 Apr 2020	Submitted
WP5	D5.4	D22	Project Review meeting documents	Technical/scientific report, outcome of the	UNITS	Report	Confidential, only f	31 Aug 2020	Pending
WP1	D1.4	D4	Loading and control device	Construct particle loading and charge con	UCL	Report	Public	31 Dec 2020	Pending
WP1	D1.5	D5	Quantification of heating	Quantification of relevant heating mechani	QUB	Report	Public	31 Dec 2020	Pending
WP4	D4.4	D17	Bounds to the ecCSL model	Provision of bounds on the effects of ener	UNITS	Report	Public	31 Dec 2020	Pending
WP2	D2.3	D8	Internal state cooling	Demonstration of internal state cooling an	UCL	Report	Public	28 Feb 2021	Pending
WP3	D3.3	D12	Ultimate experiment	The ultimate experiment assembled and	SOUTHAMPTON	Report	Public	30 Apr 2021	Pending
WP2	D2.4	D9	Quantify decoherence	Quantitative understanding of decoherenc	QUB	Report	Public	31 Aug 2021	Pending
WP4	D4.5	D18	Time-dilation/gravity collapse	Quantitative comparison between time-dil	OEAW	Report	Public	31 Aug 2021	Pending
WP3	D3.4	D13	General bound	General bound on macroscopicity of quan	QUB	Report	Public	31 Dec 2021	Pending
WP5	D5.5	D23	Project Review meeting documents	Technical/scientific report, outcome of the	UNITS	Report	Confidential, only f	31 Dec 2021	Pending

TEQ

List of Milestones

Milestone number. Name [Related WP]	Date	Means of verification
M1. Preparation of NCs with minimum absorption & stable against aggregation [WP1]	12	Combination of optical, electron microscopy, and surface analysis methods [*TR*].
M2. NC-Trapping in low-noise environment [WP1]	24	Measurement of temperature of NCs [*TR*].
M3. Cooling of internal and centre-of-mass (CoM) degrees of freedom of a charged NC [WP2]	36	Changes in the line shape of the mechanical CoM and cooling transition [*preprint*].
M4. New tests for ecCSL and SN. [WP4]	36	Rigorous modelling of non-interferometric tests for ecCSL and SN [*preprint*].
M5. Experimental test of the quantum superposition principle [WP3]	42	Observation of broadening of mechanical spectral line [*preprint*].
M6. Time dilation decoherence & gravity-induced collapse. [WP4]	48	Connection between time dilation decoherence and gravity-induced collapse [*preprint*].

Critical risks

Description of WPs risk [*risk level*]	Proposed risk-mitigation measures
WP1: No nebulisation of NCs in the trap via standard techniques [***medium***]	Use of laser desorption and/or large (10^{-7}-10^{-6}m) solvothermally prepared particles stabilized with inorganic ligands.
WP2&3: Strong environmental & technical noise within target range of mechanical frequency [***low***]	Modify total charge on NCs and tune trap properties for trapping/cooling in noise-free region. Modify environment to reduce low frequency noise sources.
WP3: Noises in the ultimate experiment cannot be supressed [***medium***]	Systematic effects will be separated in frequency and studied. Detection noise can be averaged out in longer measurement runs.
WP4: Difficulties in the management of the ecCSL [***medium***]	Use of quantum unravelling techniques and application of methods for open-system quantum Monte-Carlo.
WP5: Violation of CA by a partner [***very low***]	Rescheduling of deliverables, interruption of payments, removal/substitution of partner.

Unforeseen risk: COVID-19 PANDEMIC

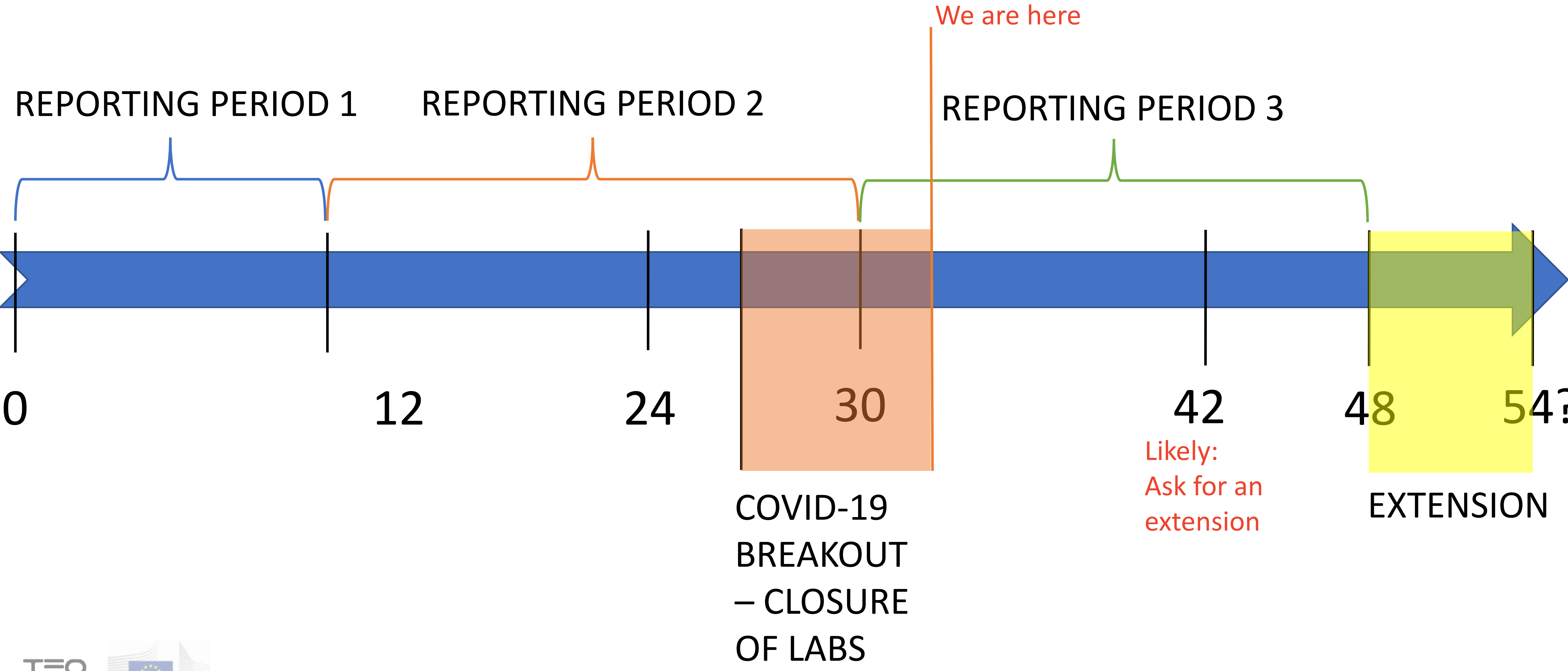
The COVID-19 outbreak caused the temporary closure (3-4 months) of labs at INFN (Frascati, Italy), Aarhus University (Denmark), TUDelft (Delft, the Netherlands), University of Southampton (UK), UCL (London, UK) and caused delays in the project development during spring/summer of 2020. The closure can impact the development of the project during the third reporting period.

Summary of effort

	WP1	WP2	WP3	WP4	WP5	WP6	Total
1 – UniTs	8	8	11	30	**40**	**18**	115
2 – AU	**30**	15	6	2	2	2	57
3 – INFN	19	20	10	4	4	4	61
4 – OEAW	8	12	16	33	2	2	73
5 – QUB	16	16	16	**27.2**	2	2	79.2
6 – TUD	38	9	3	3	2	2	57
7 – UCL	5	**40**	5.6	2	2	2	56.6
8 – UoS	5	10	**36**	2	2	2	57
9 – MSL	0	22	22	0	2	2	48
Total PMs	129	152	125.6	103.2	58	36	603.8

	Personnel	Other Direct	Indirect	Total	%	Requested
UniTs	417008	80000	124252,00	621260,00	100	621260,00
AU	275000	137500	103125,00	515625,00	100	515625,00
INFN	200000	107500	76875,00	384375,00	100	384375,00
OEAW	265000	32900	74475,00	372375,00	100	372375,00
QuB	309259	44500	88439,75	442198,75	100	442198,75
TUD	251572	63500	78768,00	393840,00	100	393840,00
UCL	222703	192494	103799,25	518996,25	100	518996,25
UoS	239997	342396	145598,25	727991,25	100	727991,25
M2	175000	140850	78962,50	394812,50	100	394812,50
TOTAL	2355539	1141640	874294,75	4371473,75		4371473,75

TEQ development timeline



Thank you

Testing the large-scale
limit of
quantum mechanics

European
Commission

WP1: TRAPPING

A. Houtepen – TUD
M. Drewsen - AU

Role TU Delft in TEQ

- Synthesizing nanoparticles to TEst the large scale limit of Quantum mechanics

- TU Delft & IIT Genova

Prof. L. Manna - IIT

Dr. L. De Trizio - IIT

F. De Donato - IIT

Jence Mulder - TUD

Jasper van Blaaderen - TUD

Arjan Houtepen - TUD

Summary of WP1

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
8	30	19	8	16	38	5	5	0

Objectives

O1.1 Construction of a low noise trap for NCs suitable for a cryogenic environment.
O1.2 Synthesis of NCs with tailored properties.
O1.3 Loading of multiply charged NCs into the trap.
O1.4 Quantification of heating sources and their effects on the trapped NCs.

Tasks

T1.1 Construction of a low-noise rf trap.
T1.2 Synthesis of colloidal NCs with specific properties.
T1.3 Methods for loading charged NCs into rf traps.
T1.4 Theoretical identification of heating mechanisms and their effects.

Deliverables

D1.1 Rf trap for NCs [M 24].
D1.2 1-Colloidal NCs [M 12].
D1.3 2-Colloidal NCs [M 24].
D1.4 Loading and control device [M 36].
D1.5 Quantification of heating [M 36].

Outline

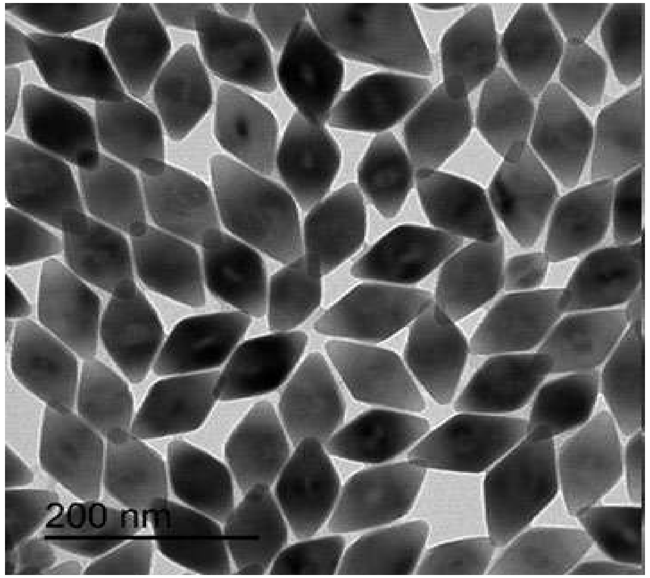
- Nanocrystal requirements
- Choice of nanocrystal system
- Synthesis
- Ligand exchange/removal
- Improving crystallinity, controlling size
- Improving the photoluminescence quantum yield: core-shell NCs

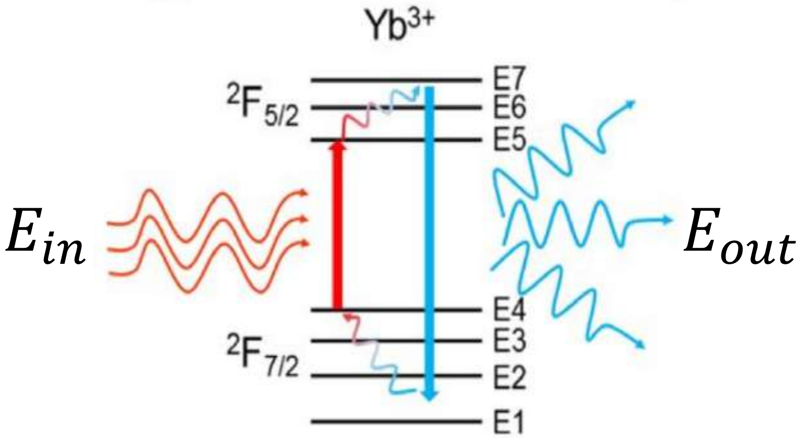
Material requirements

The optimal NC:

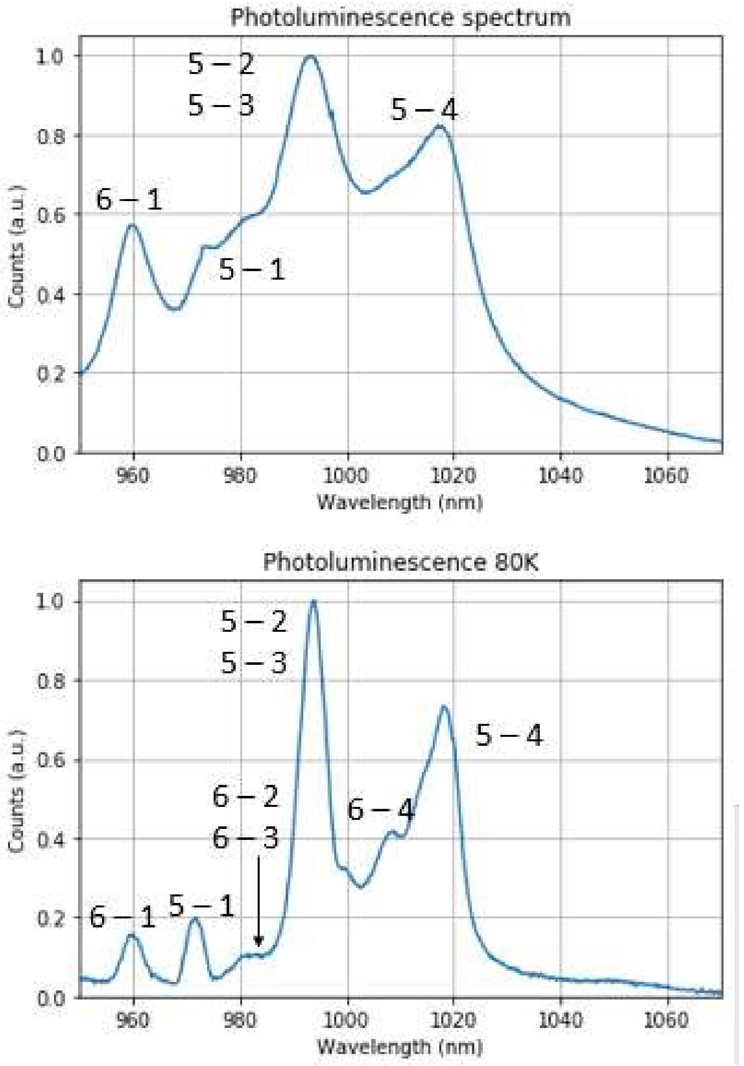
- Regular, non-spherical shape
- Size from 50 nm - 1µm, monodisperse
- Very low absorption at 1064 and 1550 nm
- Dispersed in polar solvent (e.g. methanol), suitable for electrospray
- Surface should be charged (controlled charge/mass ratio)
- Cooling of the lattice temperature via optical refrigeration

Yb:YLiF$_3$ NCs





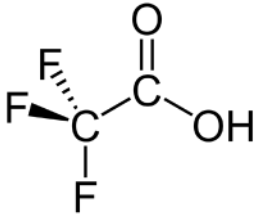
Internal cooling via phonon
assisted Anti-Stokes Fluorescence



Synthesis

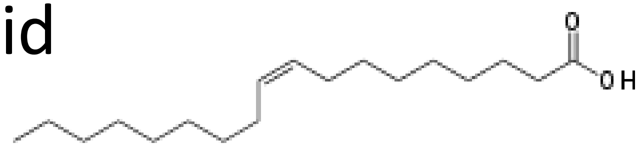
- Li_2CO_3, Y_2O_3, trifluoroacetate → LiTFA and $YbTFA_3$
- Yb_2O_3 can be added to dope the particles
- Solvent octadecene (ODE), surfactants oleic acid
- Cracking of the TFA salts at 300°C → Nucleation and growth of oleate stabilized YLF nanocrystals (or Yb:YLF)
- Purifying and concentrating the particles

TFA

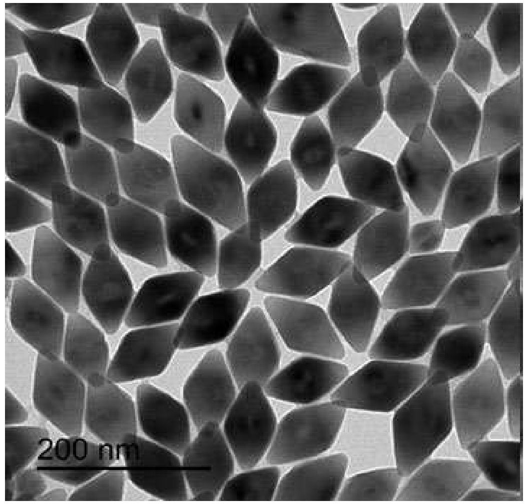


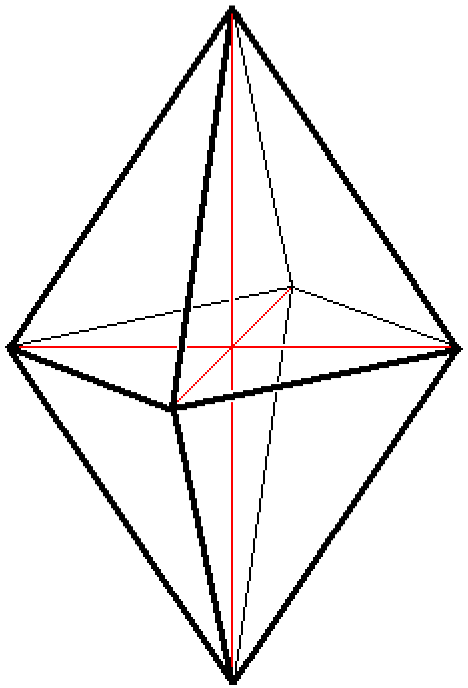
ODE

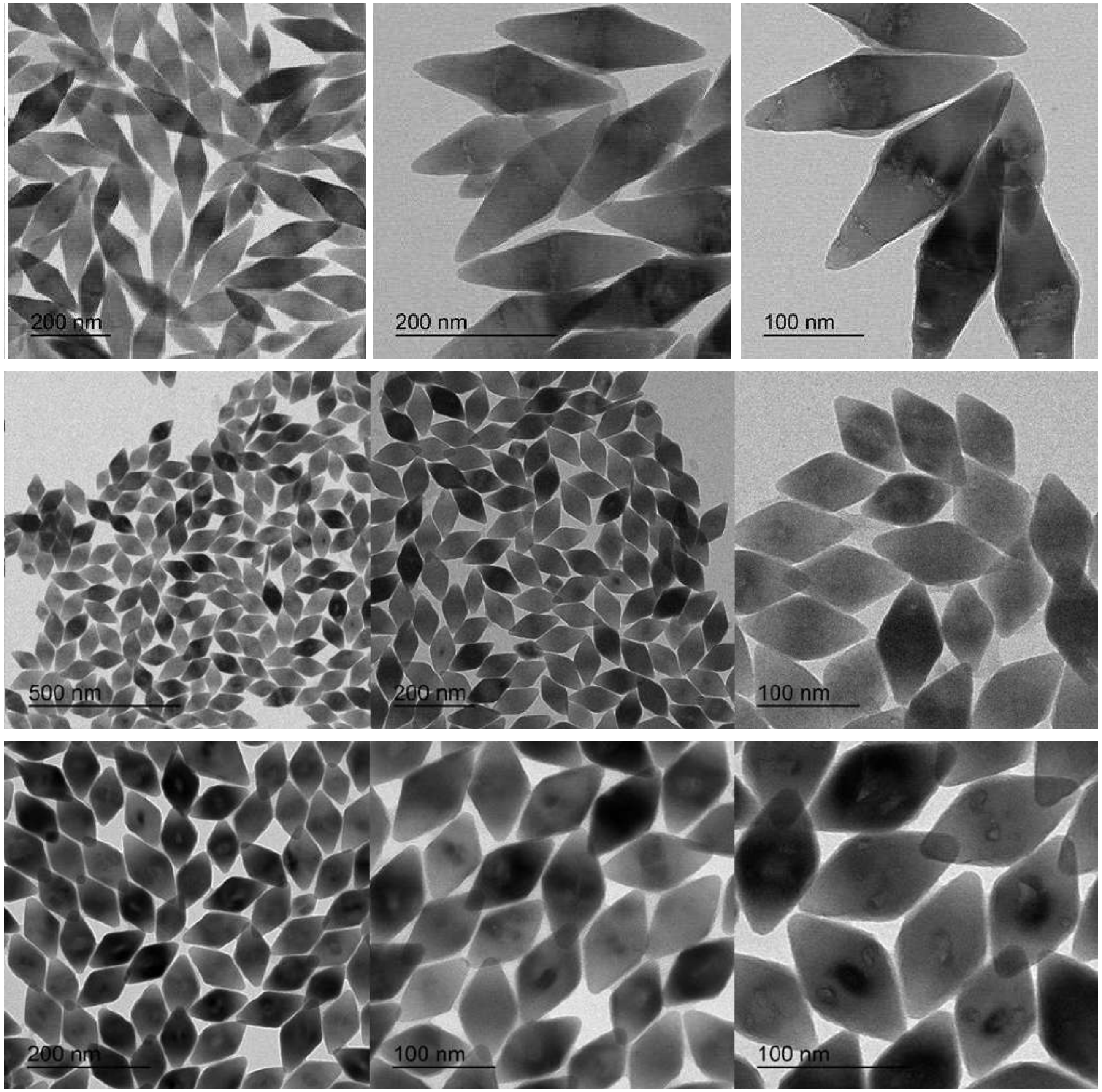
Oleic acid



NCs in hexane







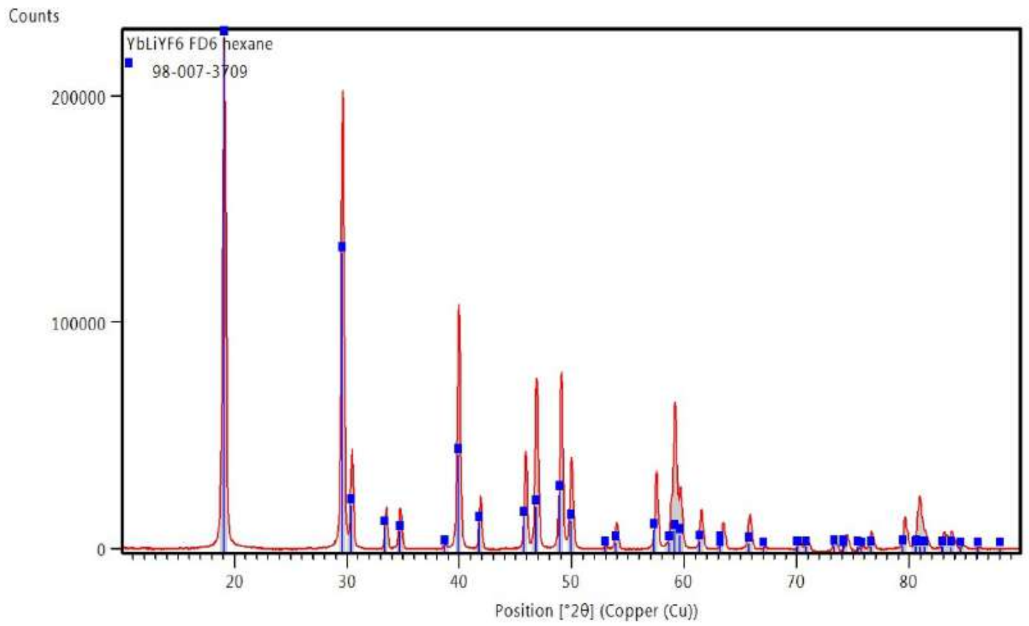
Pure YLF

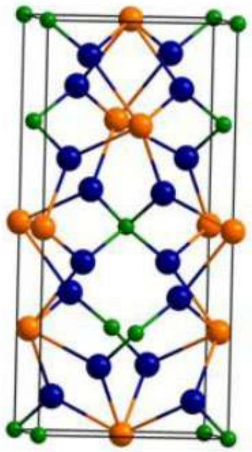
Yb:YLF (0.3:1)

Yb:YLF (1.27:1)

Structural analysis

- XRD pattern fits perfectly to known YLF pattern (Scheelite crystal structure)
- Identical for Yb:YLF and YLF
- No secondary phases
- Elemental anaylsis (ICP-AES) confirms composition and inclusion of Yb for doped samples.

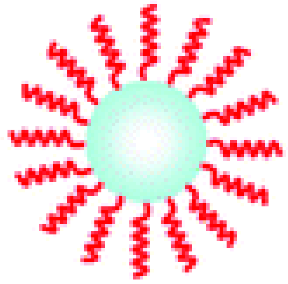


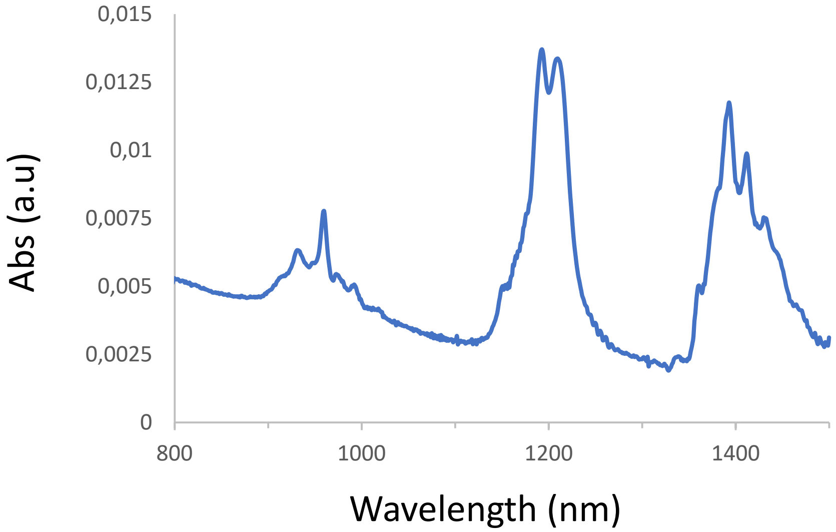


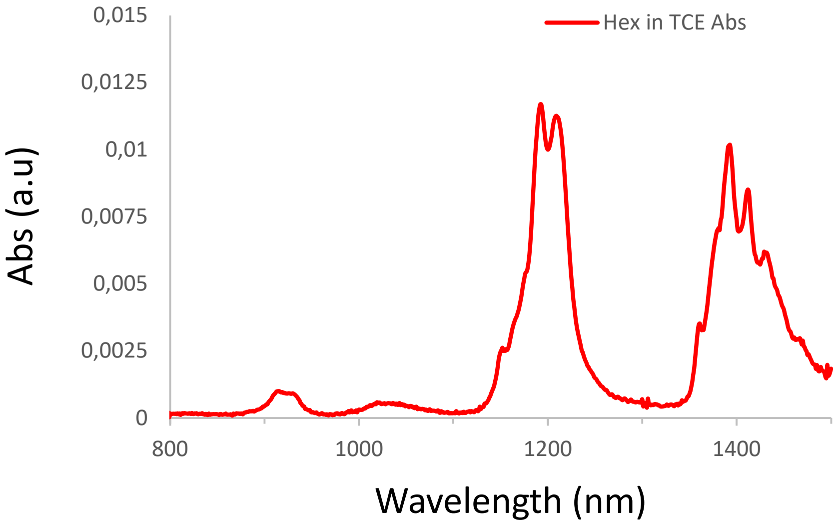
Scheelite

*ISBN: 978-1-62618-097-0 (**227**)*

Absorption Spectroscopy

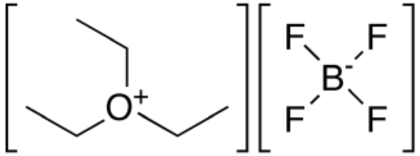




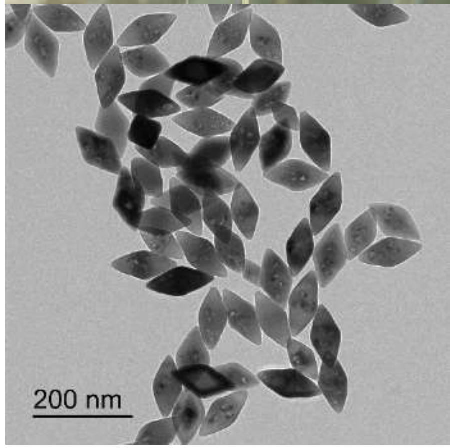


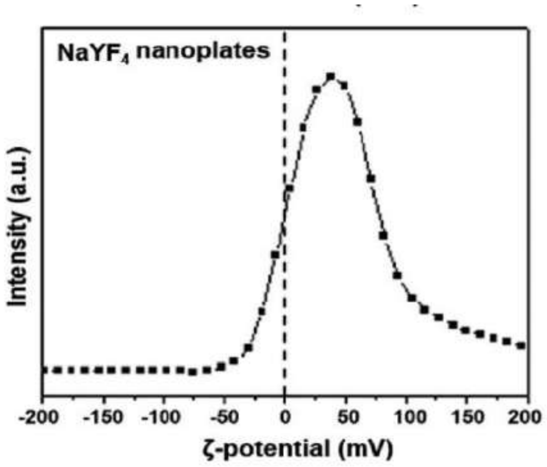
- Absorption 1100 – 1500 nm related to solvents and organic surfactants:
  - → Remove solvent
  - → Change ligands for short, non-absorbing ligands

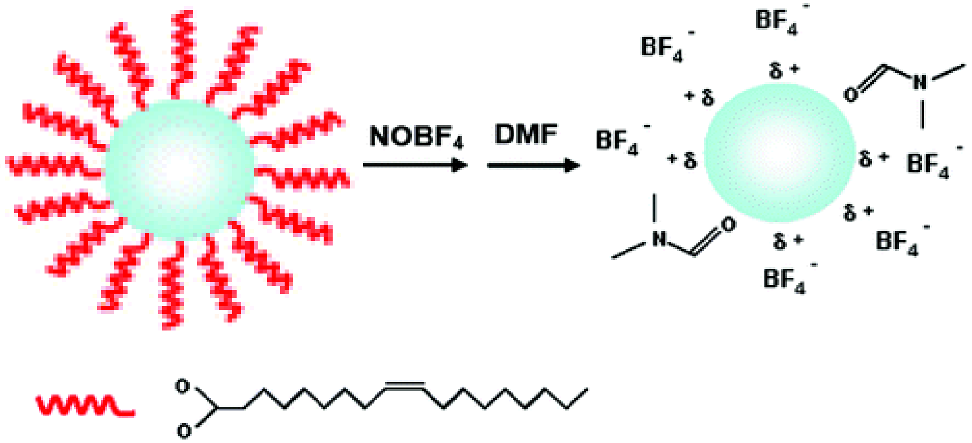
Ligand exchange



- Removing absorbing ligands (oleate)
- Ligand exchange with triethyloxonium (Et_3OBF_4) for oleate → MeOH dispersible
- Positively charged surfaces

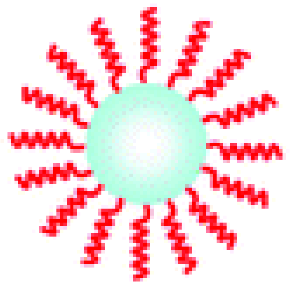


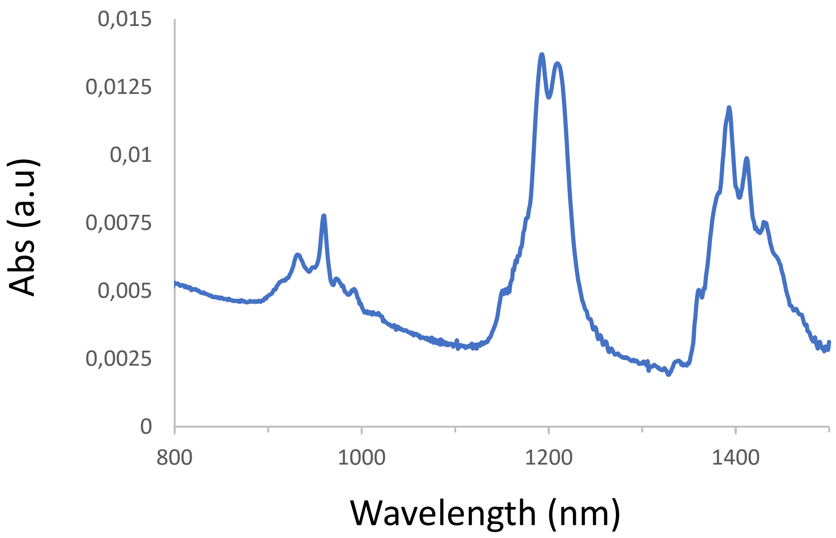


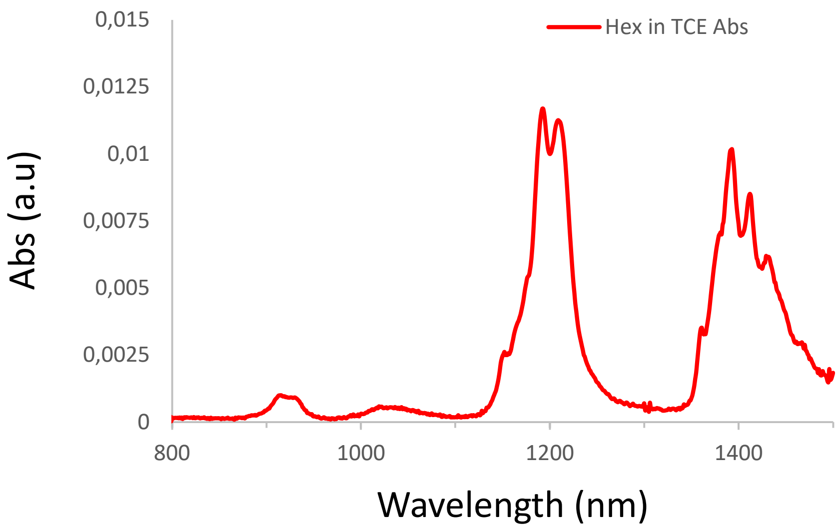


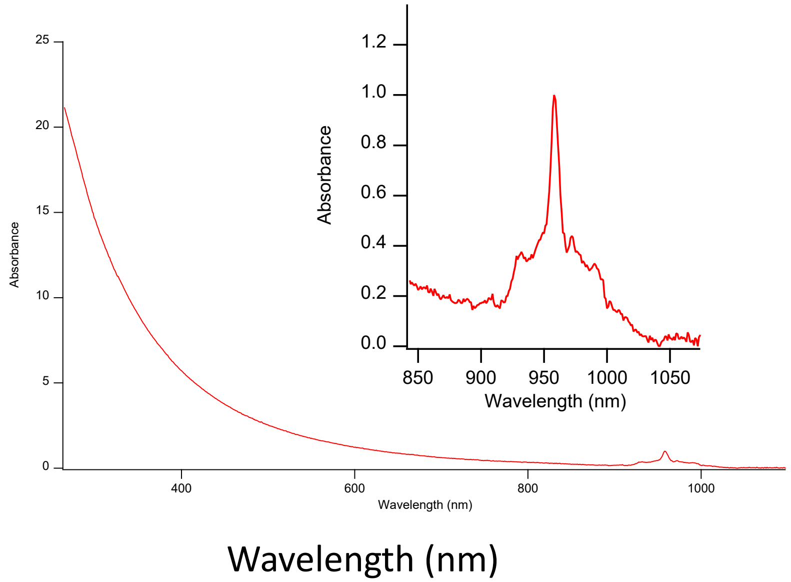
J. Am. Chem. Soc. 2011, 133, 998–1006

Absorption Spectroscopy





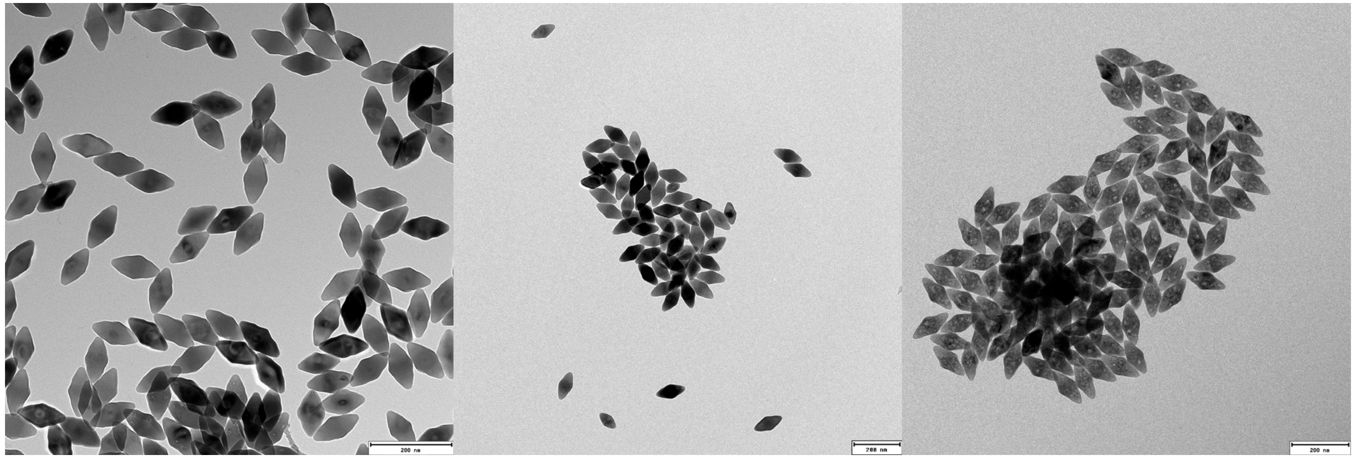




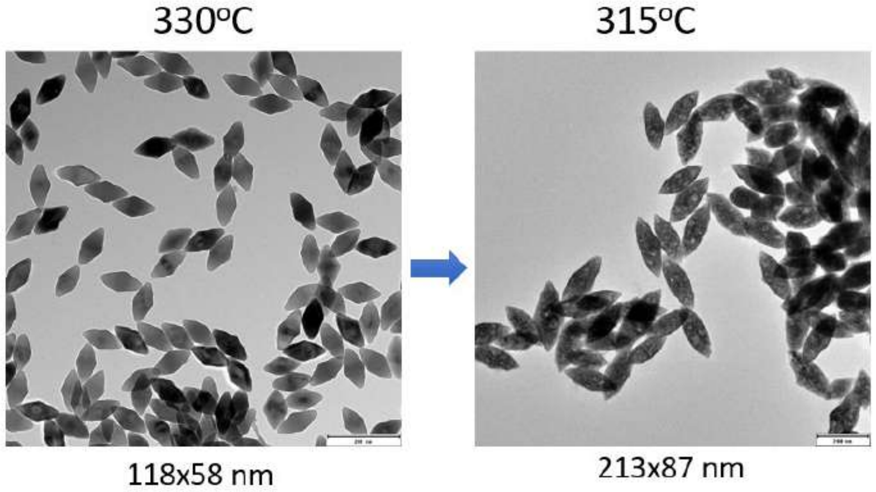
- Absorption 1100 – 1500 nm related to solvents and organic surfactants:
  - → Remove solvent
  - → Change ligands for short, non-absorbing ligands

Results past year

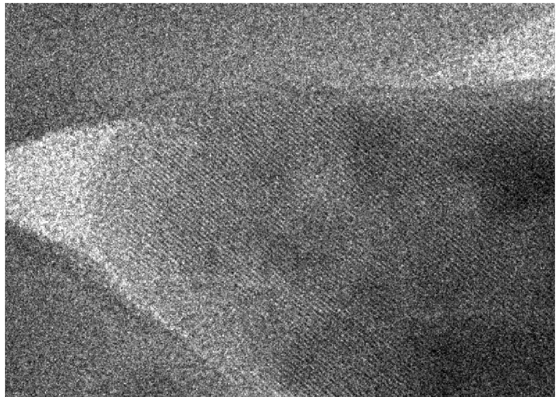
- Improved reproducibility



- Improved control over particle size (between 100 nm and 350 nm)



- Improved crystallinity

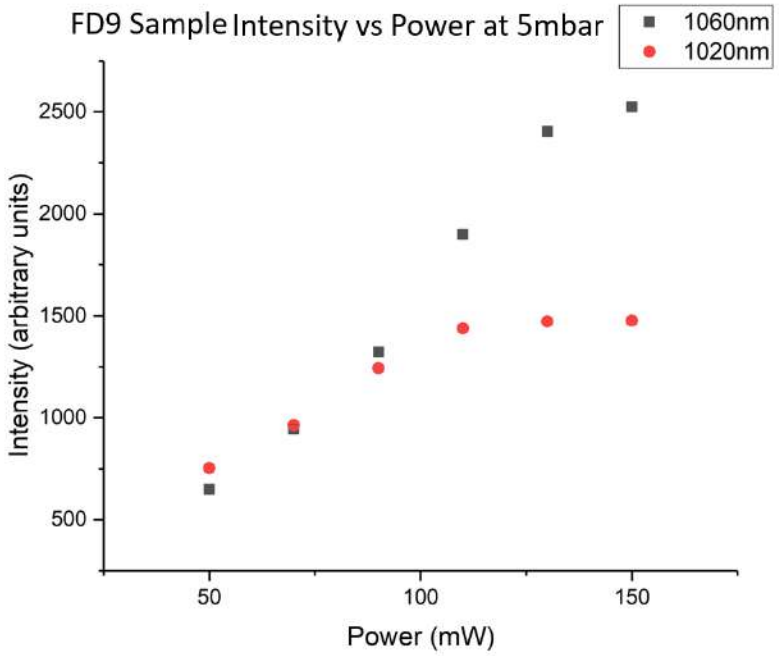


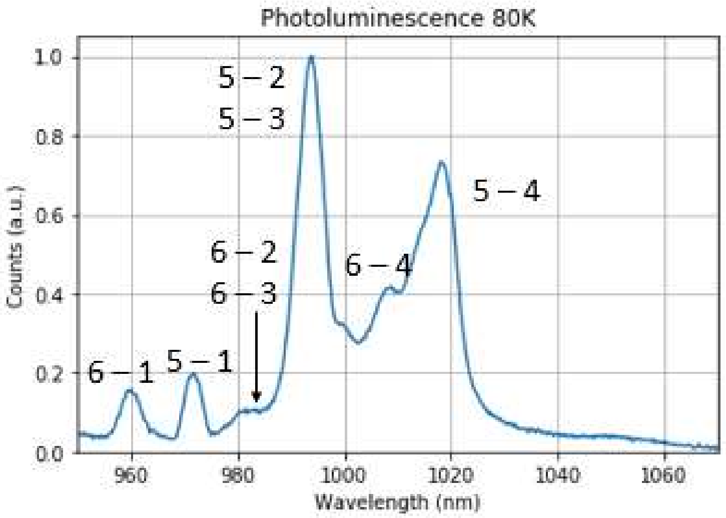
What happens when these NCs are trapped?

Measurements at UCL:

Scattered light intensity of trapping beam proportional to nanocrystal volume.

Constant intensity as a function of trapping power indicates volume reduction in nanocrystal at 1020 nm.

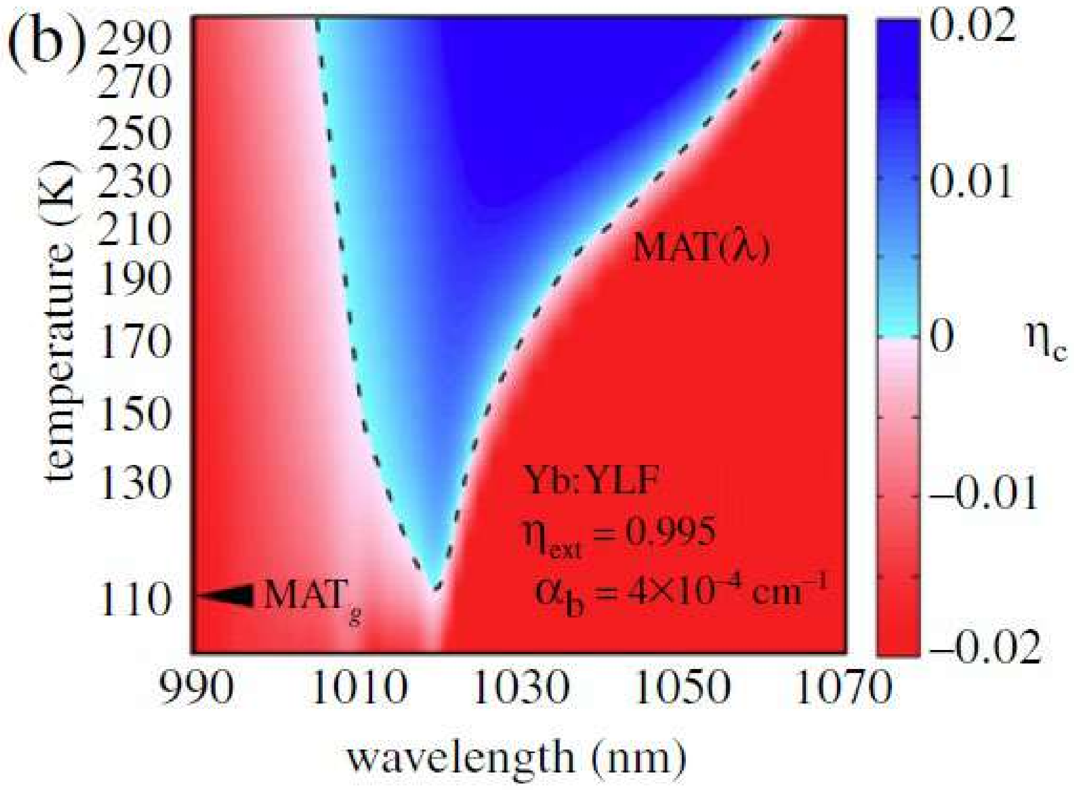




Exciting Yb^{3+} results in heating, not cooling!

The PLQY is not high enough for cooling

So what do we need?



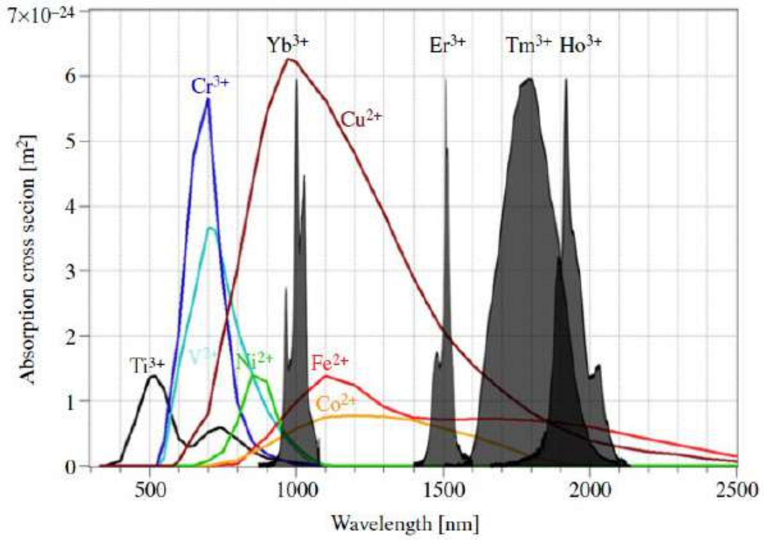
Advances in Optics and Photonics **4**, 78–107 (2012)

- At RT a PLQY of 97.4% balances heating due to non-radiative recombination and cooling due to Anti-Stokes fluorescence
- A PLQY of 99.5% allows cooling to 110K.
- But the PLQY of the initial samples turned out to be ~30%...

Why is the PLQY so low?

- Impurities in the crystal, e.g. Fe^{2+}, Cu^{2+}, Ni^{2+}, may act as traps or cause background absorption.
- Impurity concentrations of <100 bbp are desired…
- Energy transfer to high energy vibrations (ligands, solvent, OH^-).

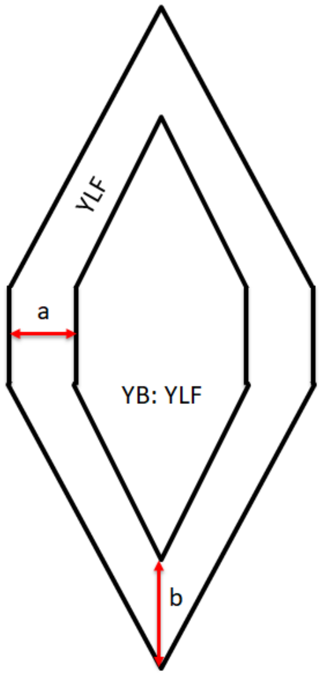
- **We need to remove the surface and the impurities**…

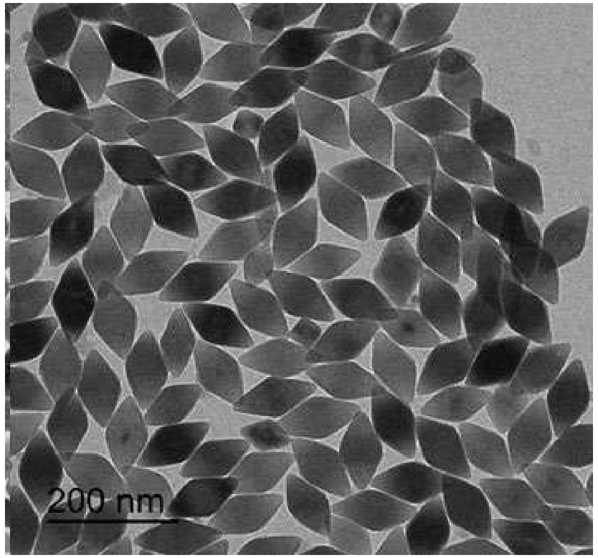


Advances in Optics and Photonics **4**, 78–107 (2012)

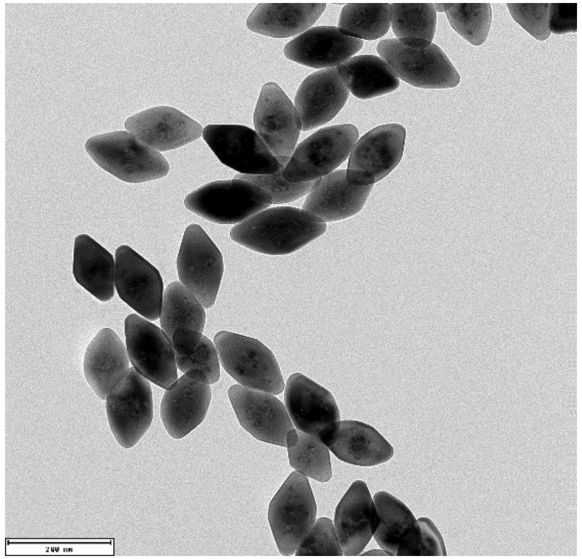
Core shell particles

- Shell of pure YLF: no Yb ions near the surface
- Reduces PL quenching at the surface (e.g. energy transfer to surfactants or solvent vibrations)





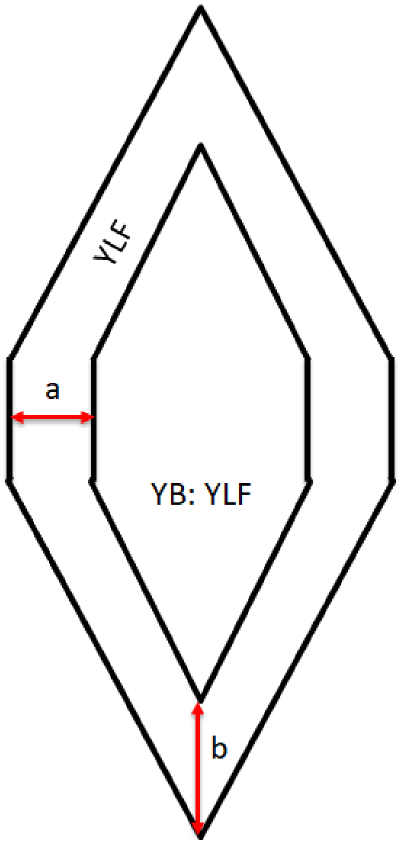
Yb:YLF (0.2:1)

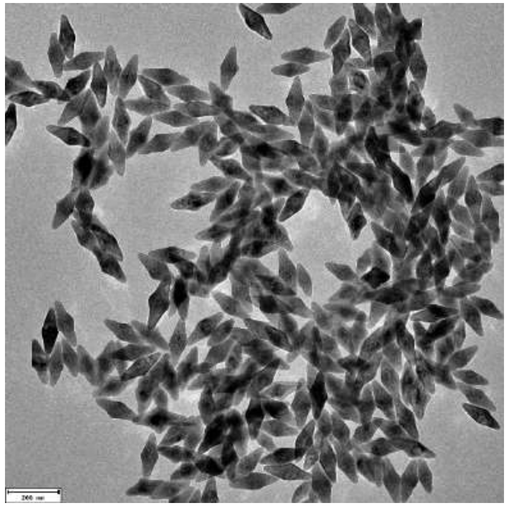


YLF@Yb:YLF (0.2:1)

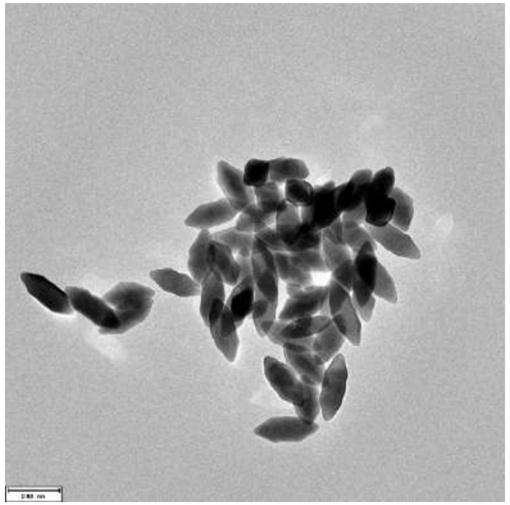
Increasing the shell thickness

adding more shell precursors; 10% Yb for all cores





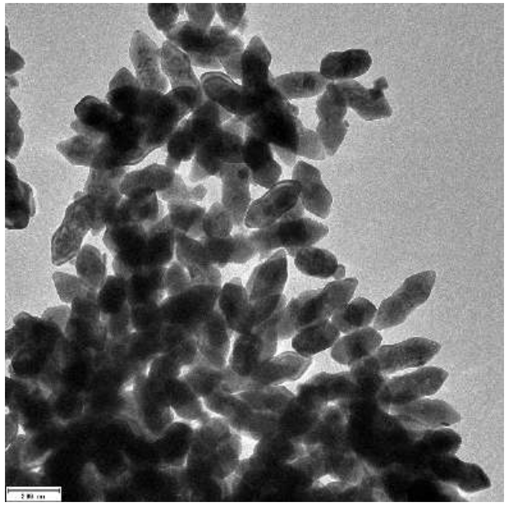
Core 031



Core/Shell 033

b : 30 nm

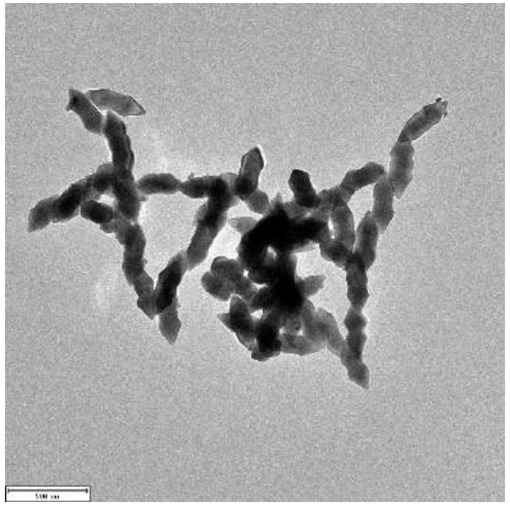
a : 12.5 nm



Core/Shell 053

b : 104 nm

a : 18,6 nm

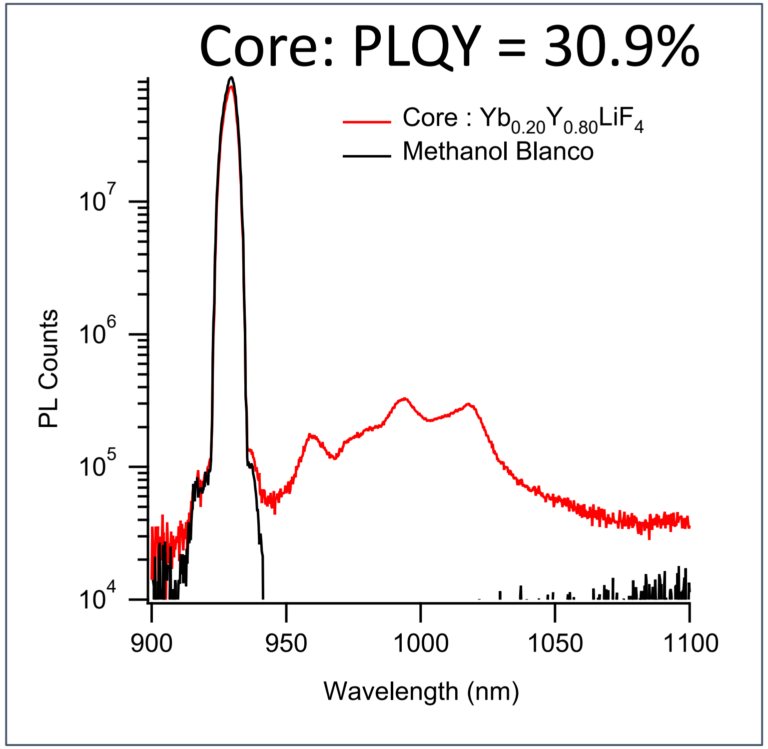


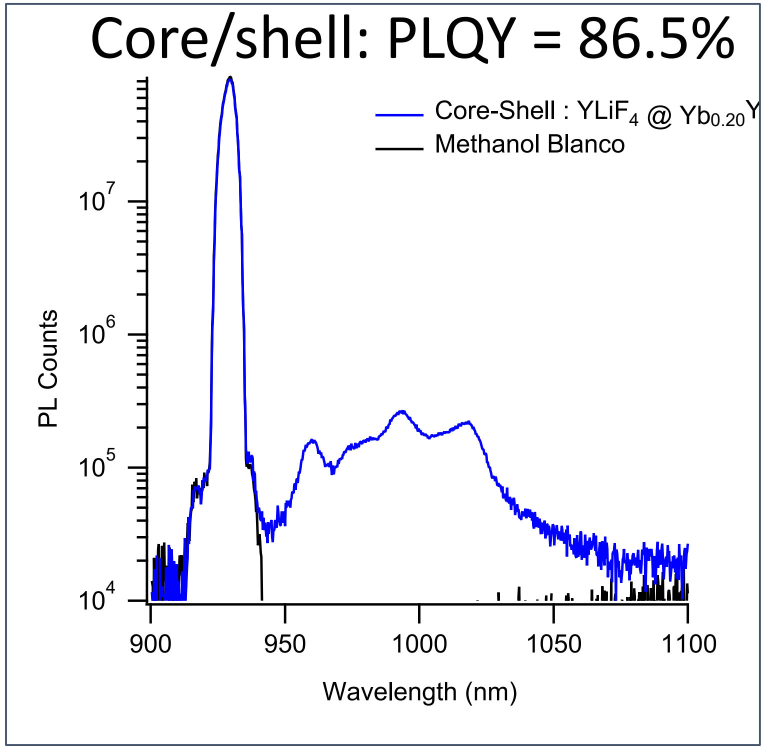
Core/Shell 054

b : 138 nm

a : 47 nm

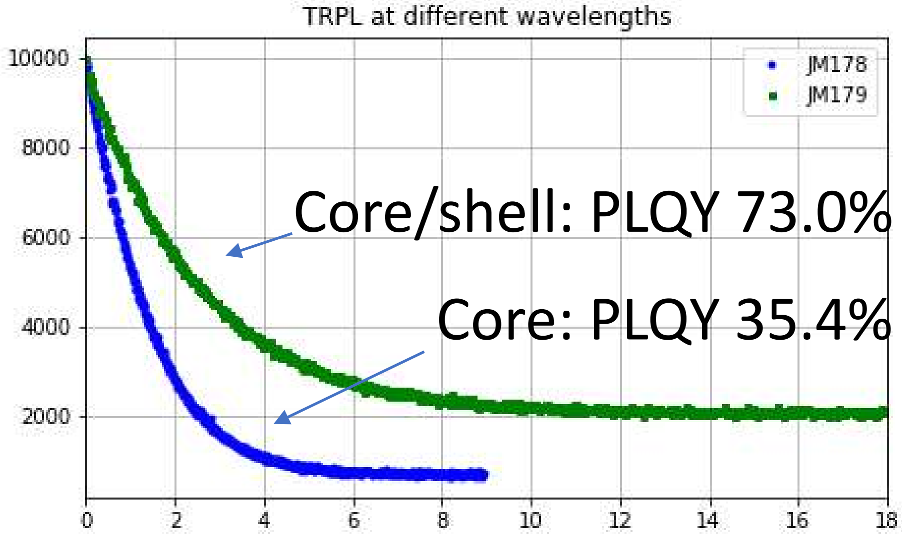
Improving PLQY by shell growth



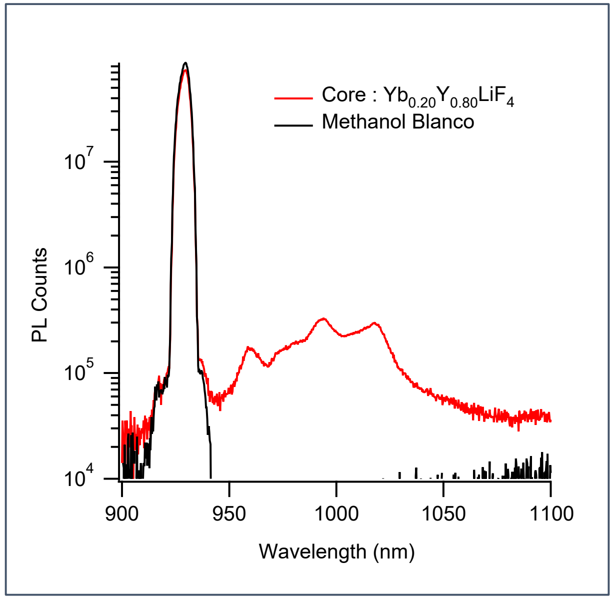


- YLF-shell growth increases from ~30% to~86%
- This is still too low…
- Plus, the PLQY is hard to measure accurately due to the low absorption by the Yb.

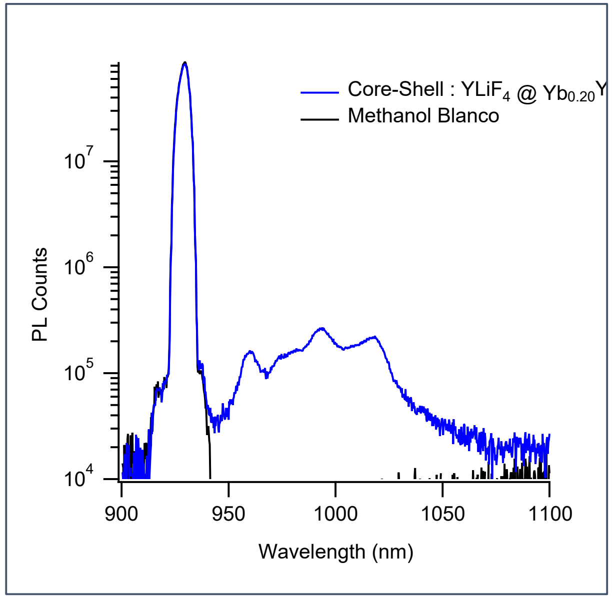
Determining PLQY from TRPL



Core: PLQY = 30.9%



Core/shell: PLQY = 86.5%



$$\Gamma_{rad}(n) = \frac{\Gamma_{rad}^{bulk}}{n}\left(\frac{3n^2}{2n^2 + n_{NC}^2}\right)^2 \qquad \eta = \frac{\Gamma_{rad}(n)}{\Gamma_{total}(n)}$$

$\Gamma_{total}(n)$ From the fit of the TRPL spectra

Current status

- **YLF particles without Yb can be trapped. No significant heating due to background absorption.**
- Clean NCs with low impurity content.

- Yb:YLF NCs not stable in trap: PLQY of the Yb emission is too low → heating
- Maximum achieved PLQY ~80%

- Cause of remaining PL quenching is not clear
  - crystal defects
  - energy transfer to OH^- impurities in the YLF lattice
  - Energy transfer to surface moieties/solvent
- The target, 97.4%, is challenging…

Next steps

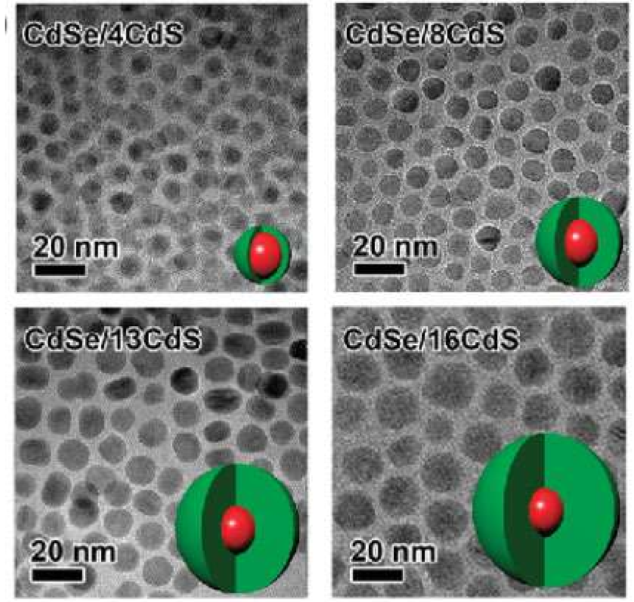
- Investigate the cause of <100% PLQY in core-shell NCs
- Improve PLQY further:
  - ➢Optimize Yb concentration (high absorption vs concentration quenching)
  - ➢Remove all traces of water from the synthesis
  - ➢Lower T shell growth (avoid Yb^{3+} diffusion)
- Determine (and control) the surface charge density using dynamic light scattering (DLS)

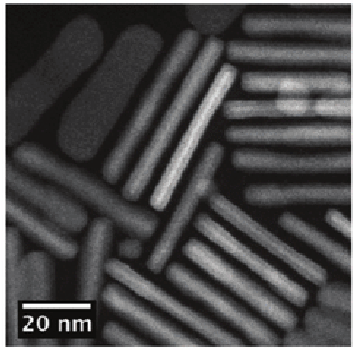
- Optical refrigeration experiments at UCL.

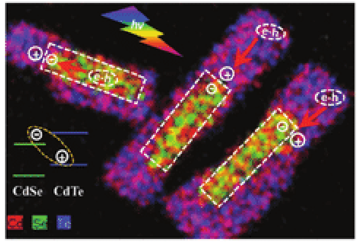
Other materials

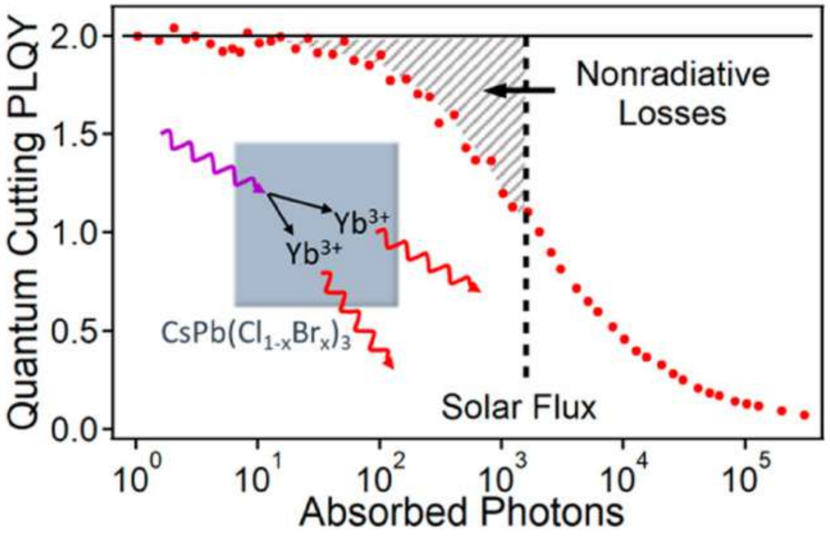
- CdSe/CdS/ZnS colloidal Quantum Dots, record PLQY 99.7% or 2D Nanoplatelets

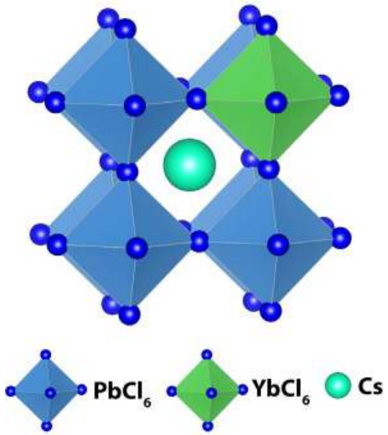
- Yb^{3+} doped $CsPbCl_3$ Nanocrystals

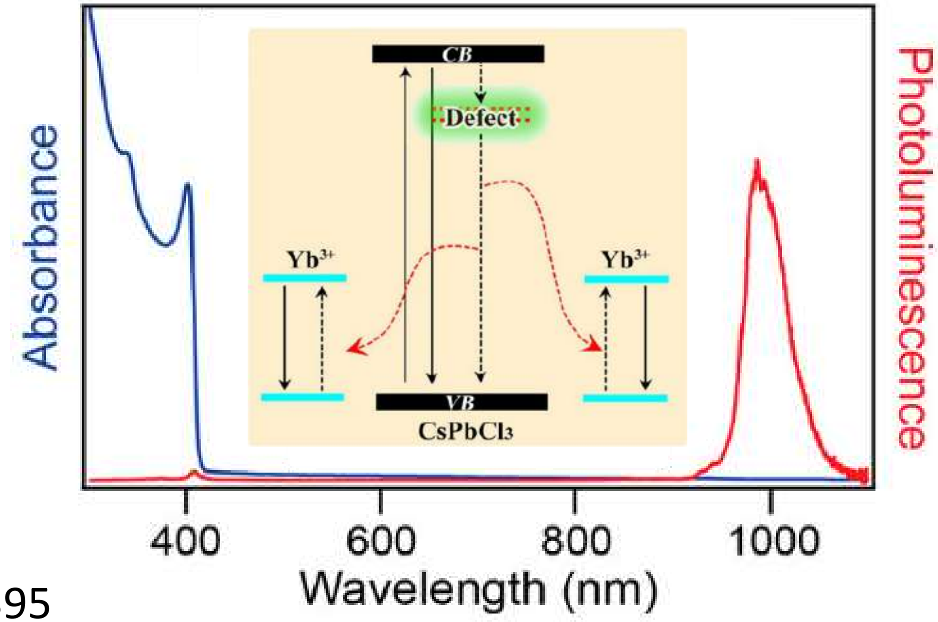












J. Phys. Chem. C 2019, 123, 12474−12484; ACS Energy Lett. 2018, 3, 2390−2395

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

WP1: TRAPPING

M. Drewsen – AU
A. Houtepen – TUD

Summary of WP1

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
8	30	19	8	16	38	5	5	0

Objectives

O1.1 Construction of a low noise trap for NCs suitable for a cryogenic environment.
O1.2 Synthesis of NCs with tailored properties.
O1.3 Loading of multiply charged NCs into the trap.
O1.4 Quantification of heating sources and their effects on the trapped NCs.

Tasks

T1.1 Construction of a low-noise rf trap.
T1.2 Synthesis of colloidal NCs with specific properties.
T1.3 Methods for loading charged NCs into rf traps.
T1.4 Theoretical identification of heating mechanisms and their effects.

Deliverables

D1.1 Rf trap for NCs [M 24].
D1.2 1-Colloidal NCs [M 12].
D1.3 2-Colloidal NCs [M 24].
D1.4 Loading and control device [M 36].
D1.5 Quantification of heating [M 36].

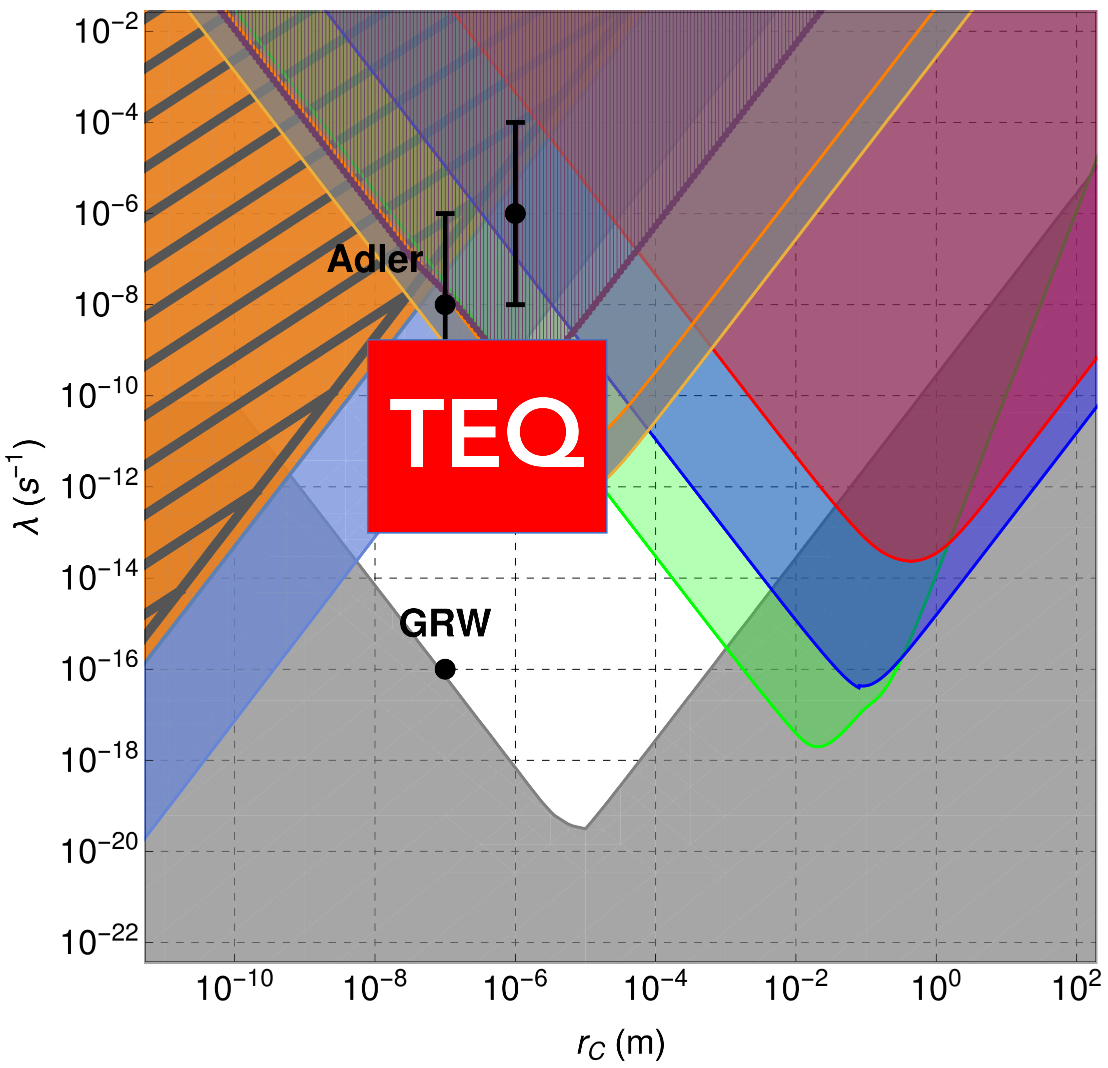
Testing the large-scale limit of quantum mechanics

Status of TEQ-trap and low-noise electronics

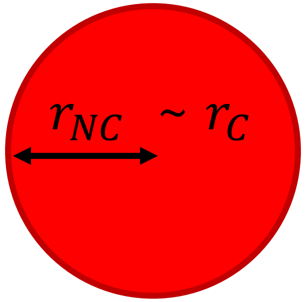
M. Drewsen - AU

CSL exclusion plot

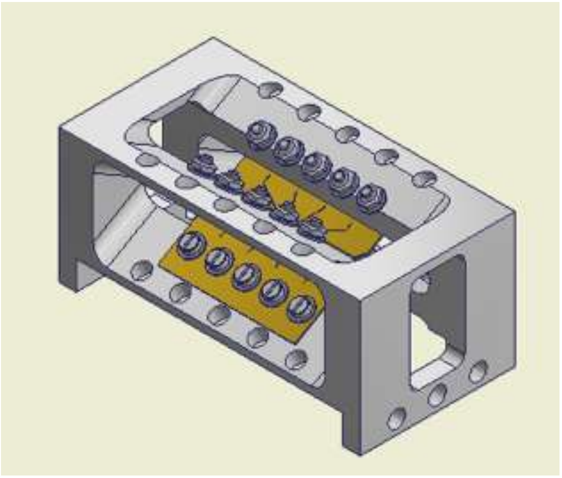
Current bounds in CSL parameter space



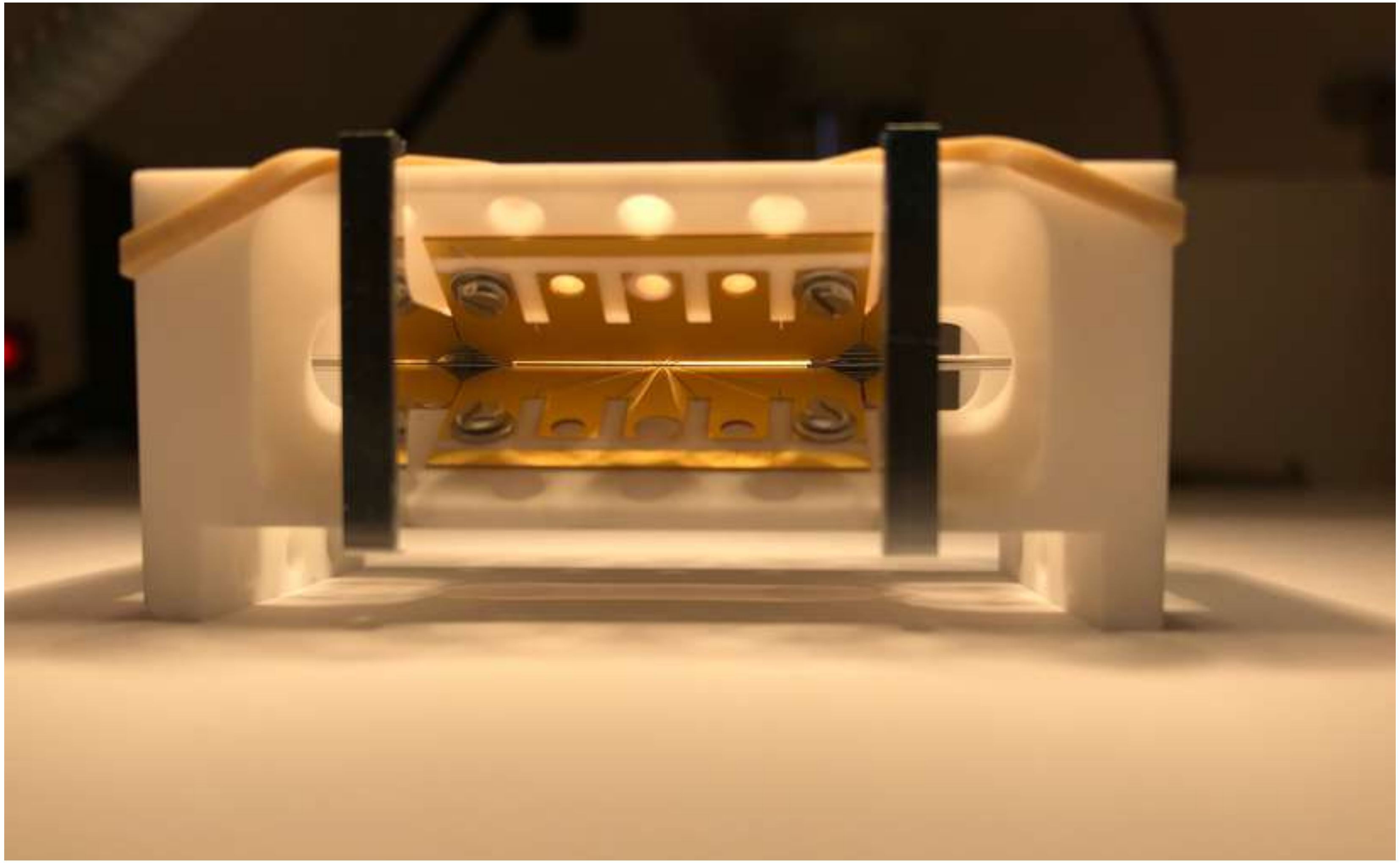
Nano-Crystal



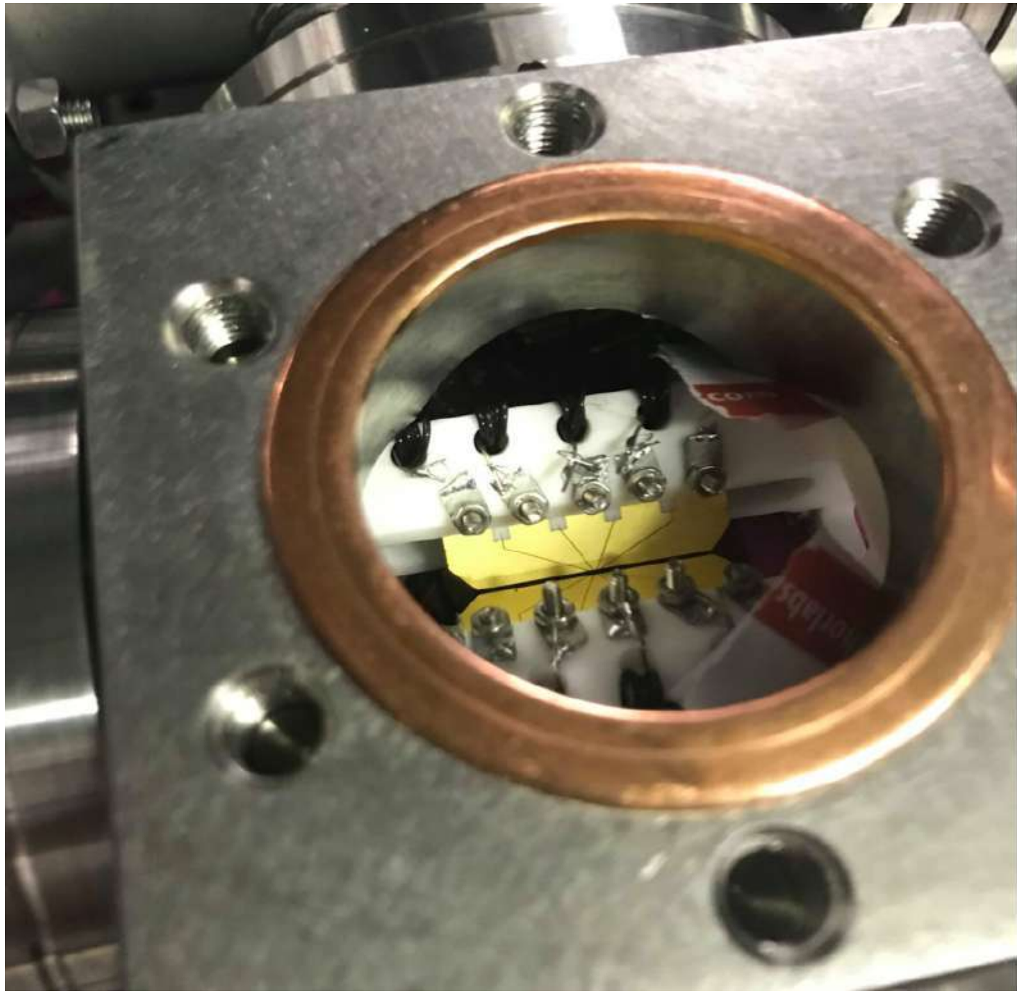
Charged particle trap



The TEQ-trap at AU

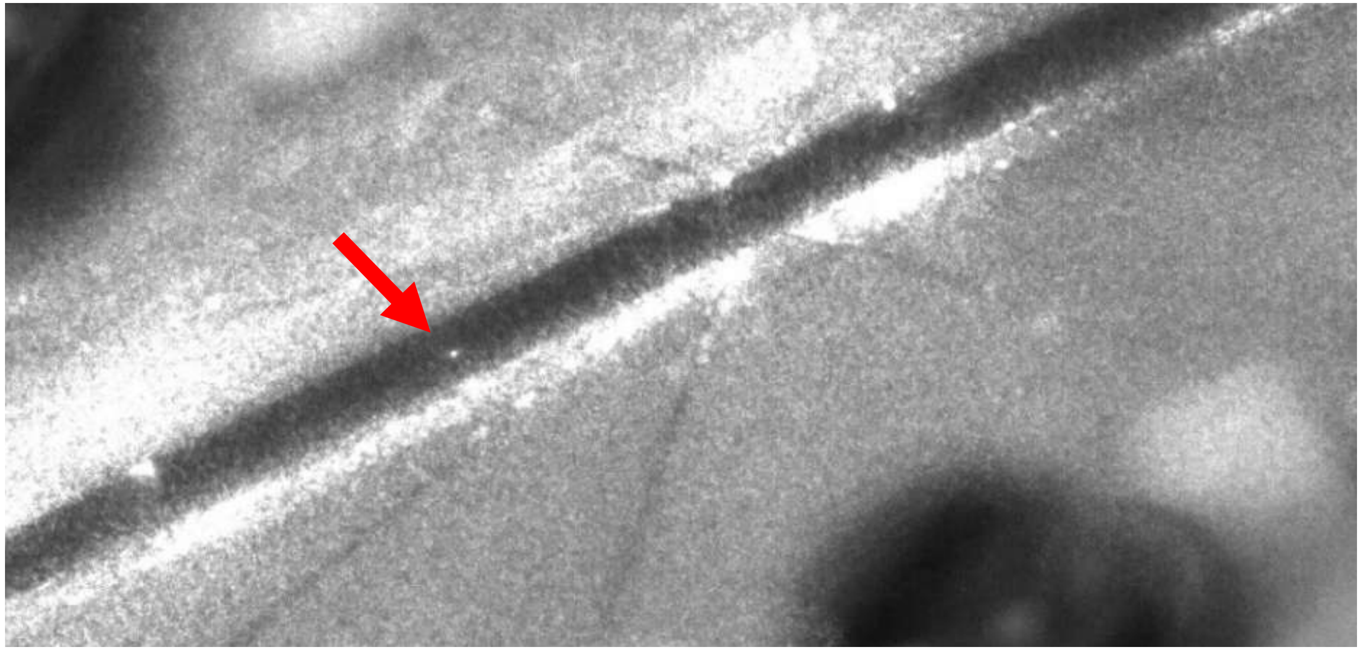


The TEQ-trap at UCL



The TEQ-trap at UCL

First silica nano-particle trapped in the TEQ-trap (Dec. 2019)!



7,5 mm

The DC voltage supplies

What noise level can be accepted in the TEQ experiments?

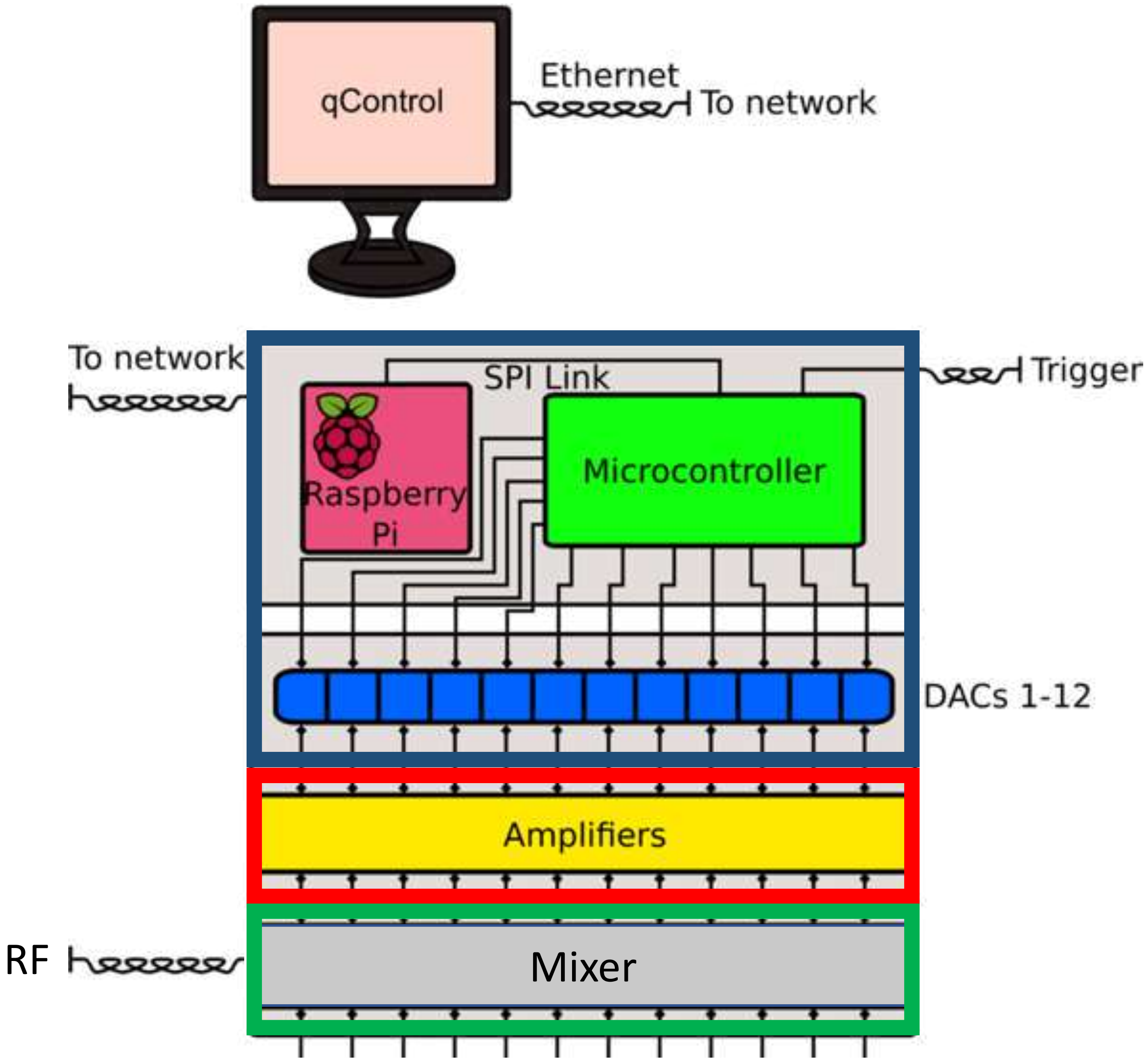
In terms of forces:

$$\sqrt{S_F(\nu)} \leq 3 \cdot 10^{-22}\, N / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100 - 1000)\, Hz$$

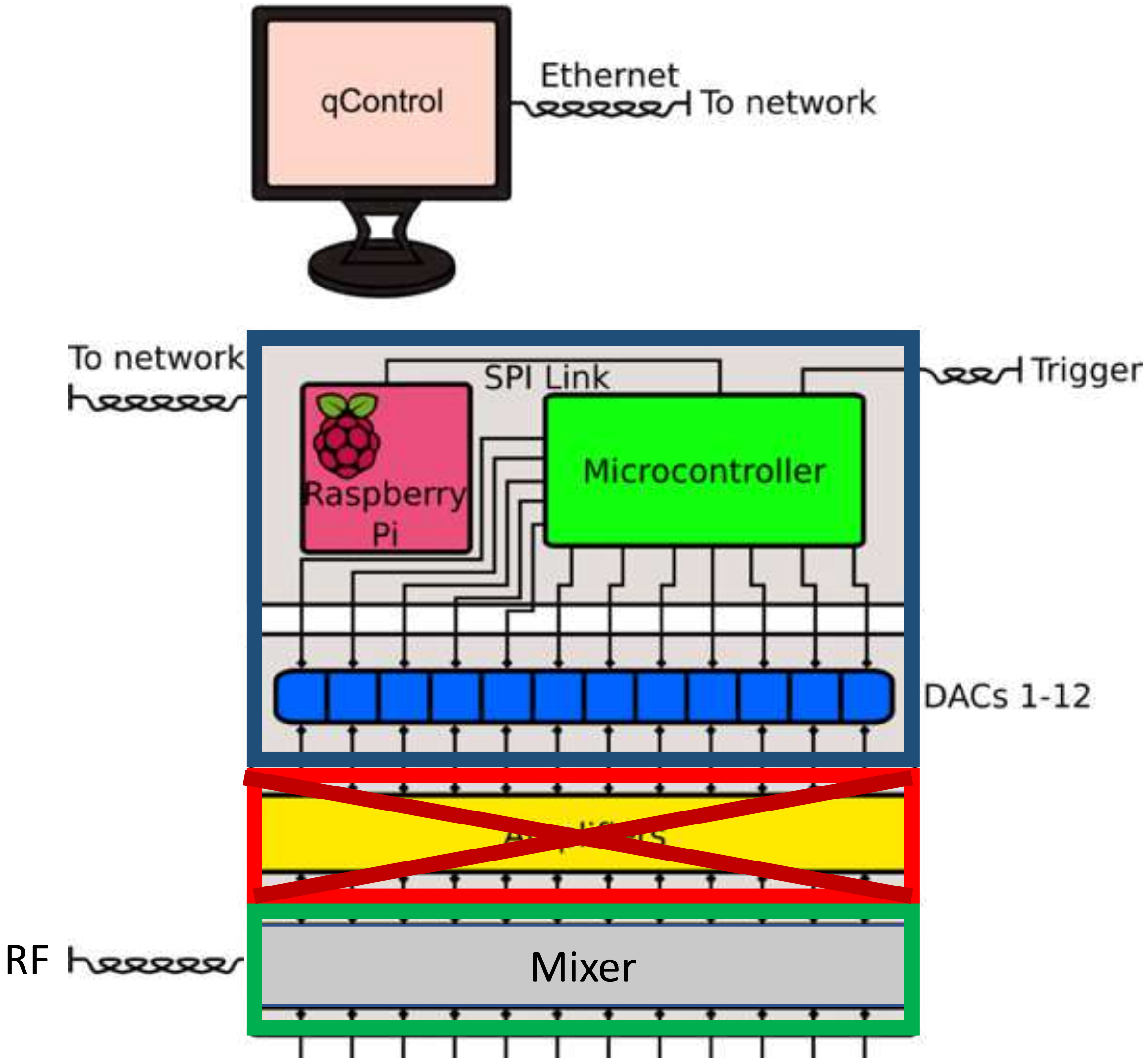
In terms of electrode voltages:

$$\sqrt{S_V^{DC}(\nu)} \leq 25 nV / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100 - 1000)\, Hz$$

The DC voltage supplies

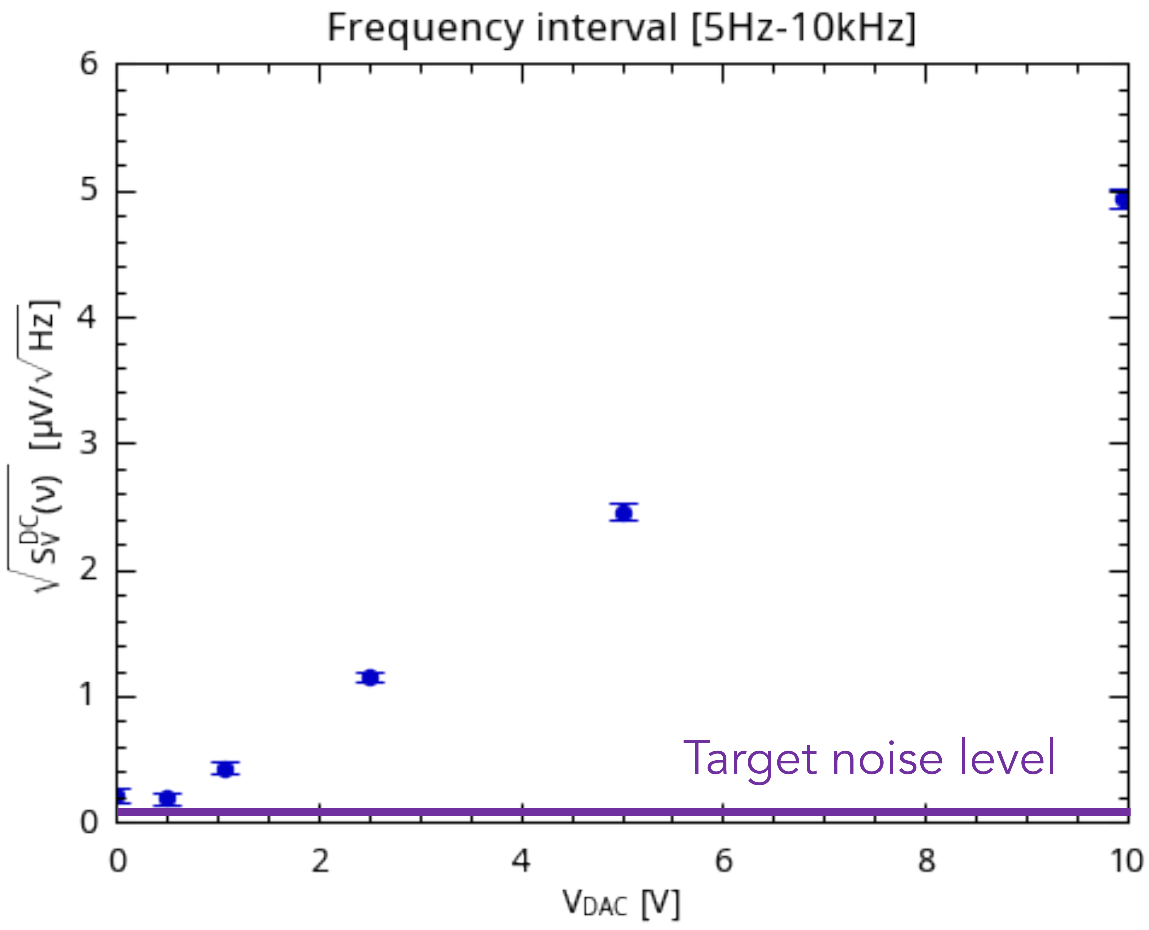


The DC voltage supplies



The DC voltage supplies

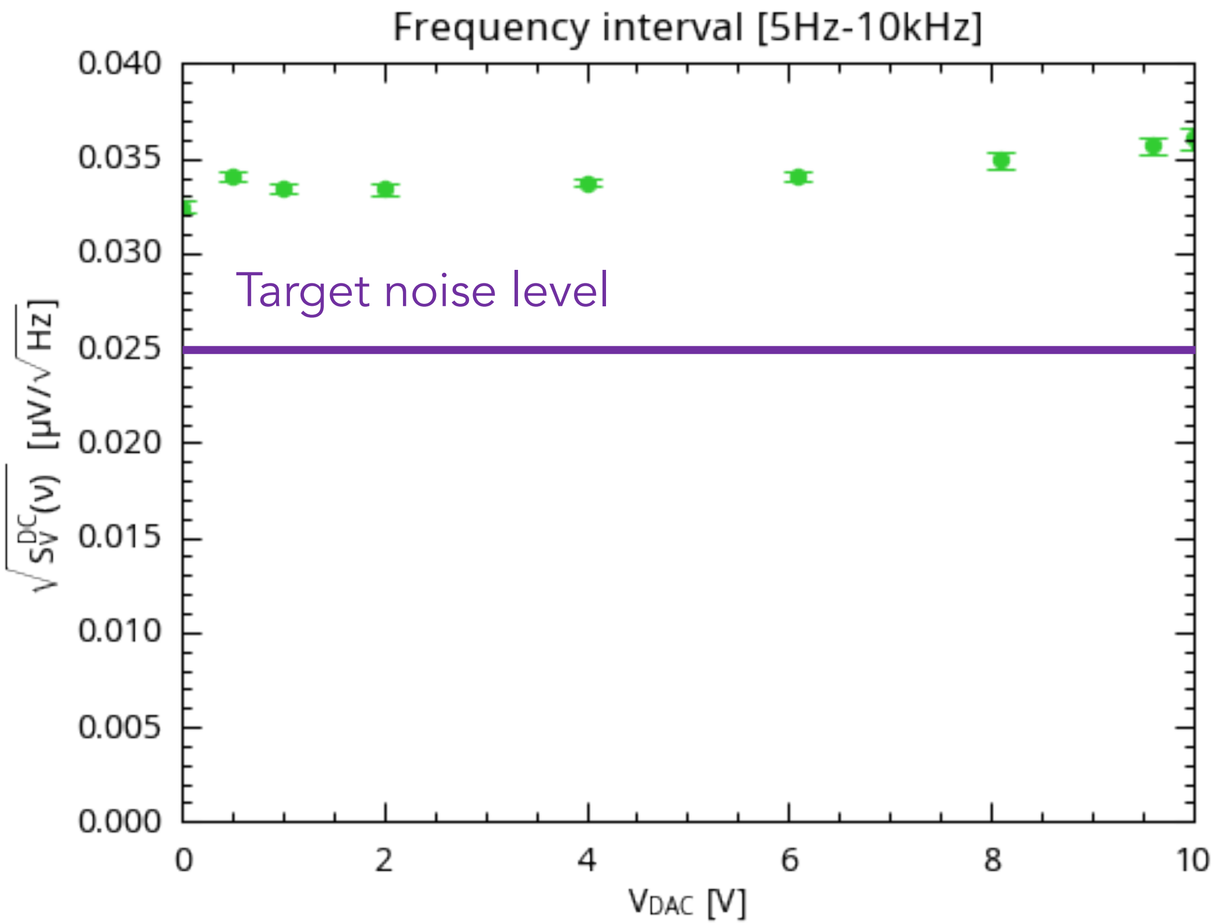
The noise of the DACs voltages ***prior to TEQ***



The DC voltage supplies

Last review meeting…

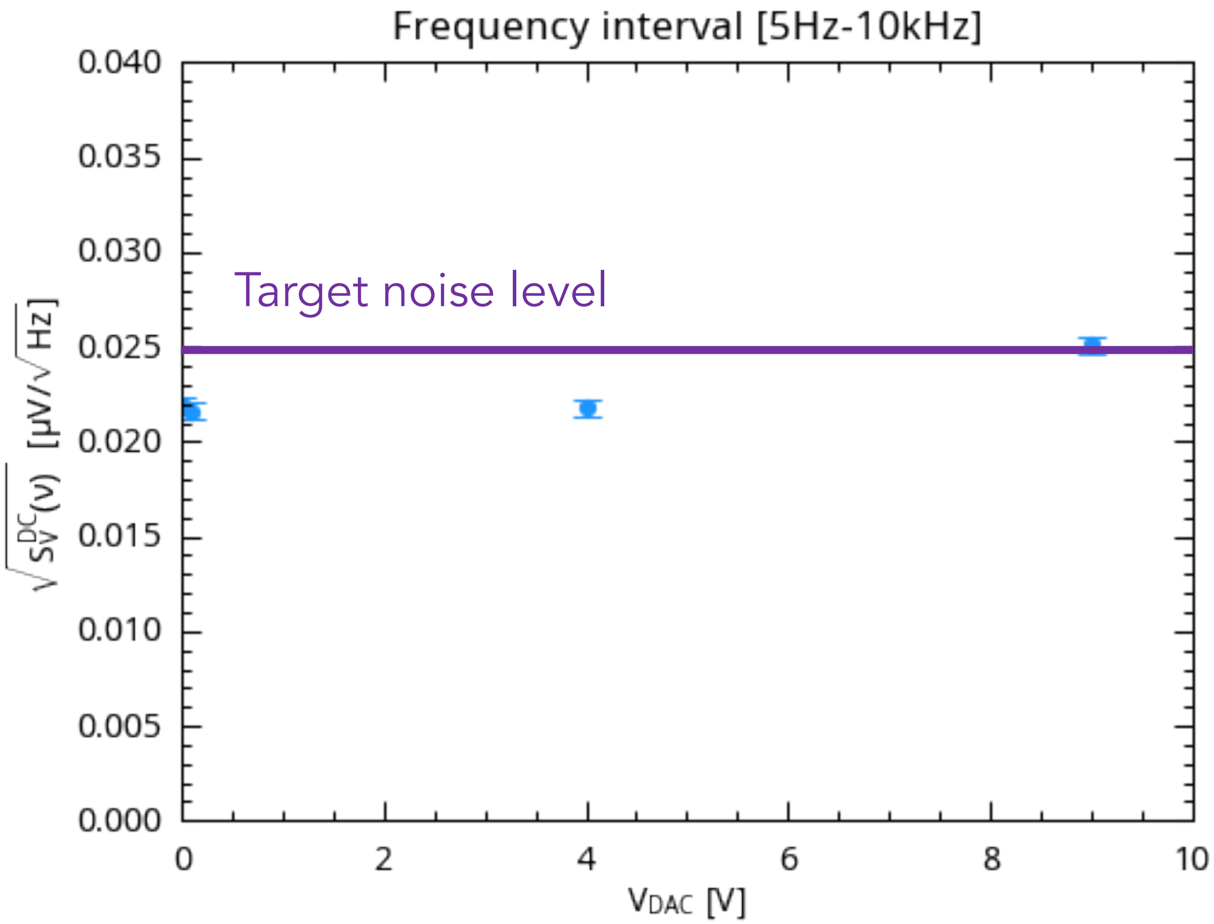
The noise of the DACs voltages: first developments



The DC voltage supplies

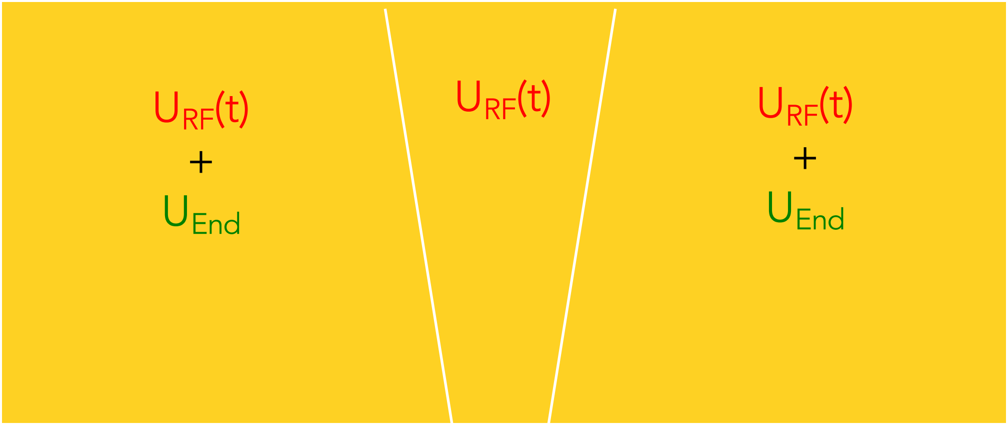
Since last review meeting…

The noise of the DACs voltages: without the Mixer

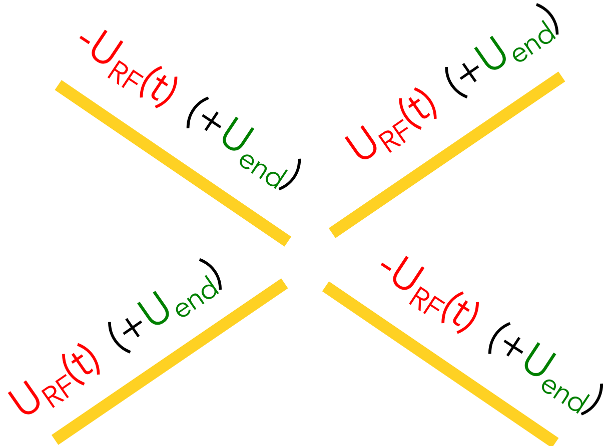


Blade electrode wiring I

Blade electrode structure



Mounted electrodes
in an end view:

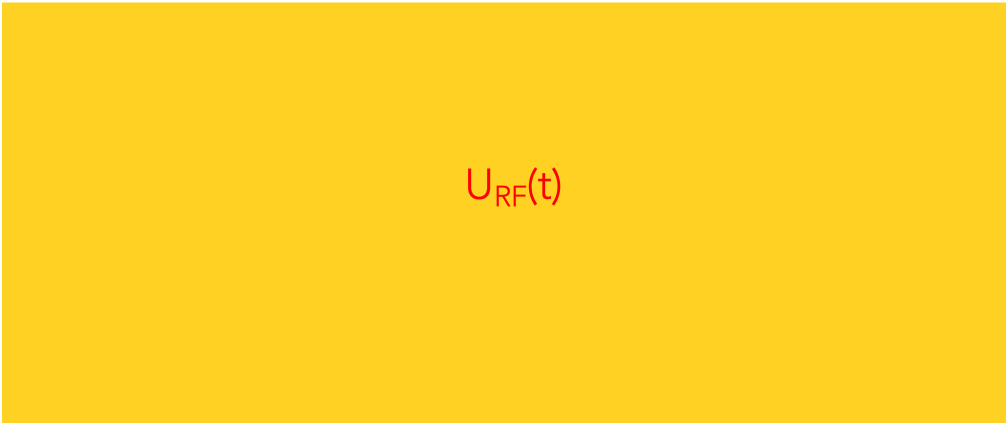


<u>Note:</u>

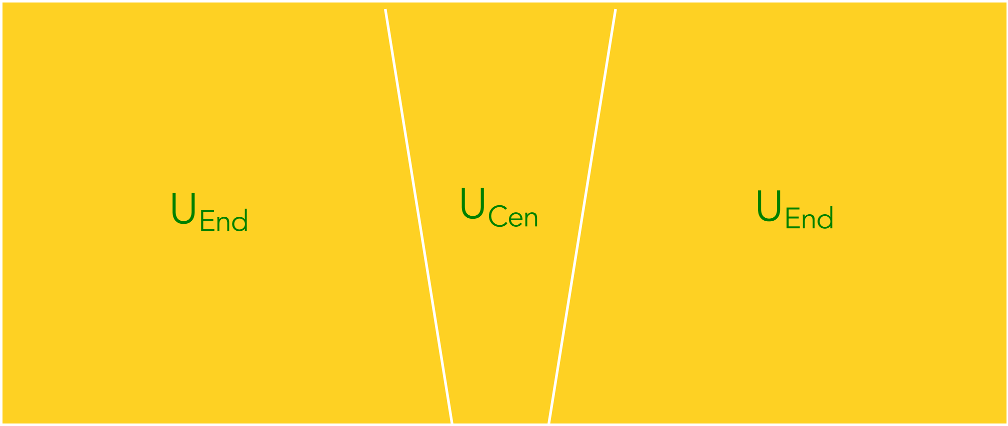
$U_{RF}(t)$ and U_{end} ***has to be mixed*** together.

Blade electrode wiring II

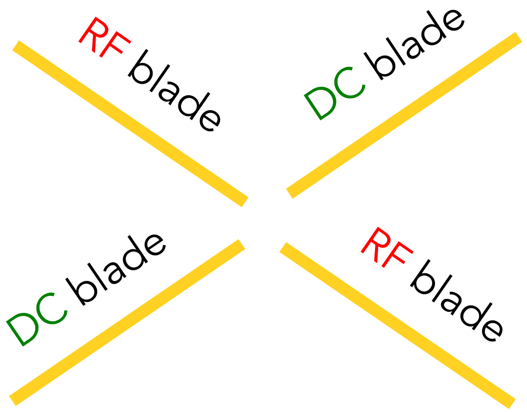
RF blade electrode



DC blade electrode



Mounted electrodes
in an end view:

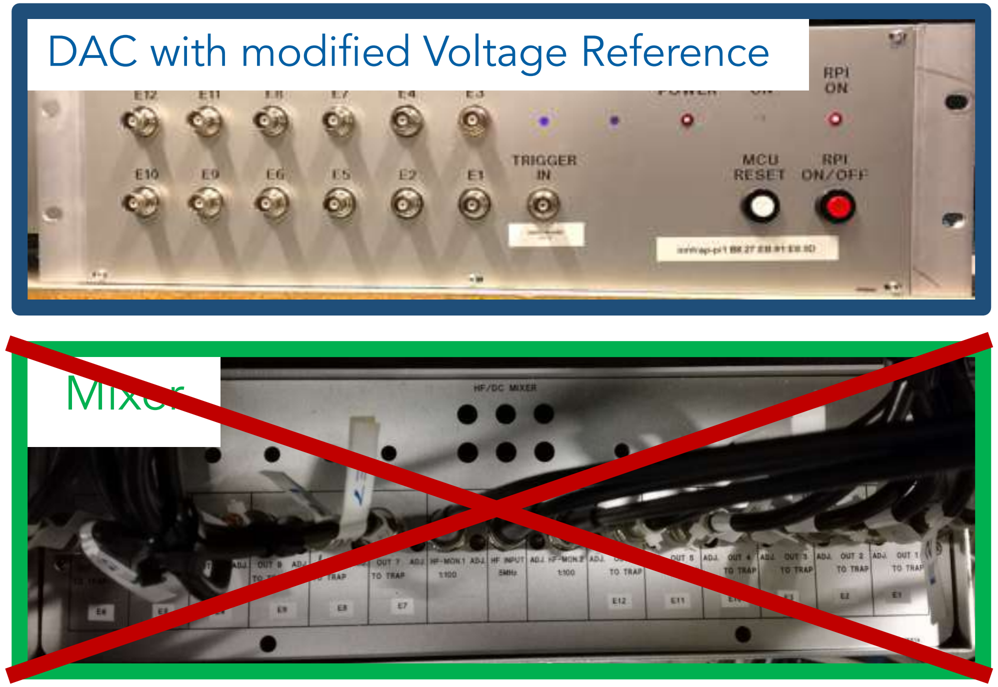


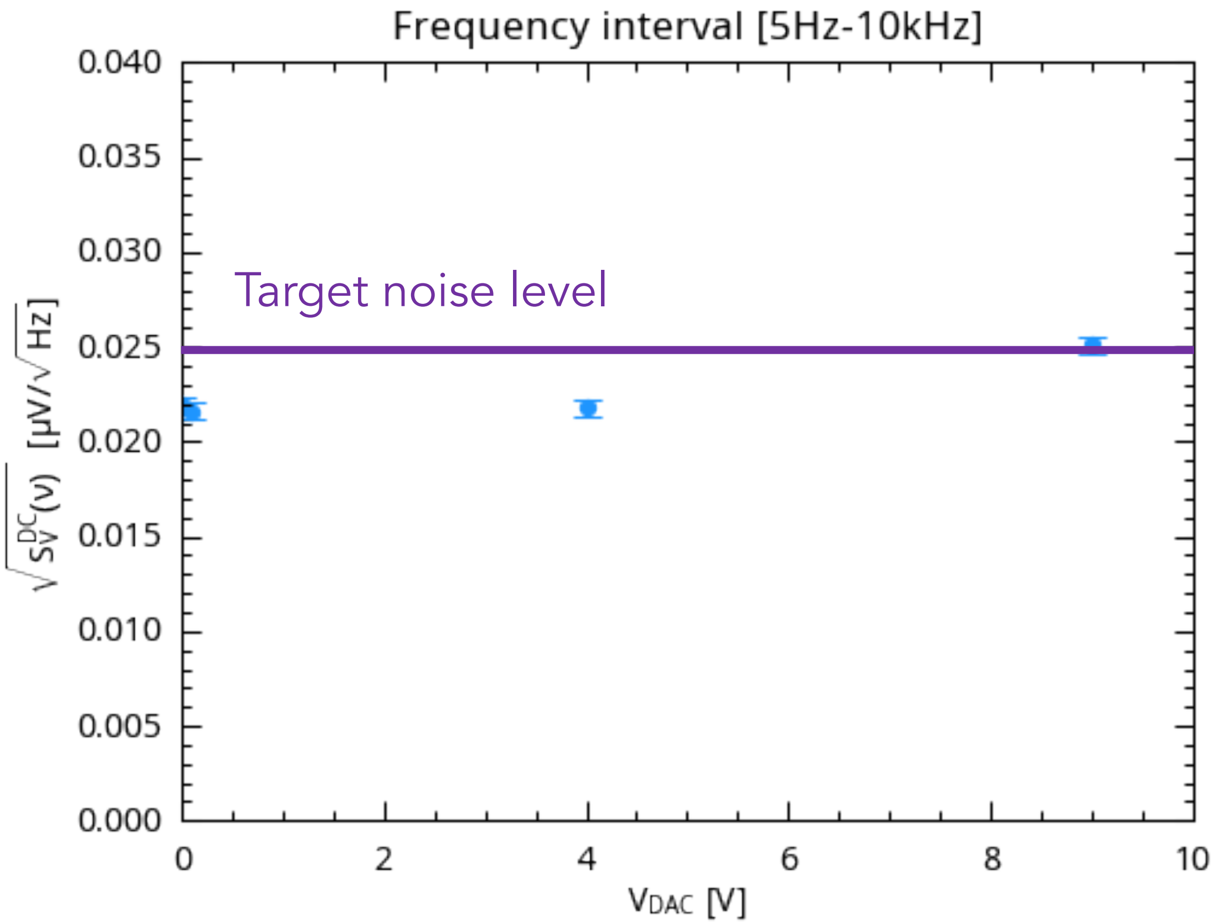
No mixing of $U_{RF}(t)$
and U_{end} needed!

The DC voltage supplies

Since last review meeting…

The noise of the DACs voltages: without the Mixer





DC noise requirements reached, but only at 10V.

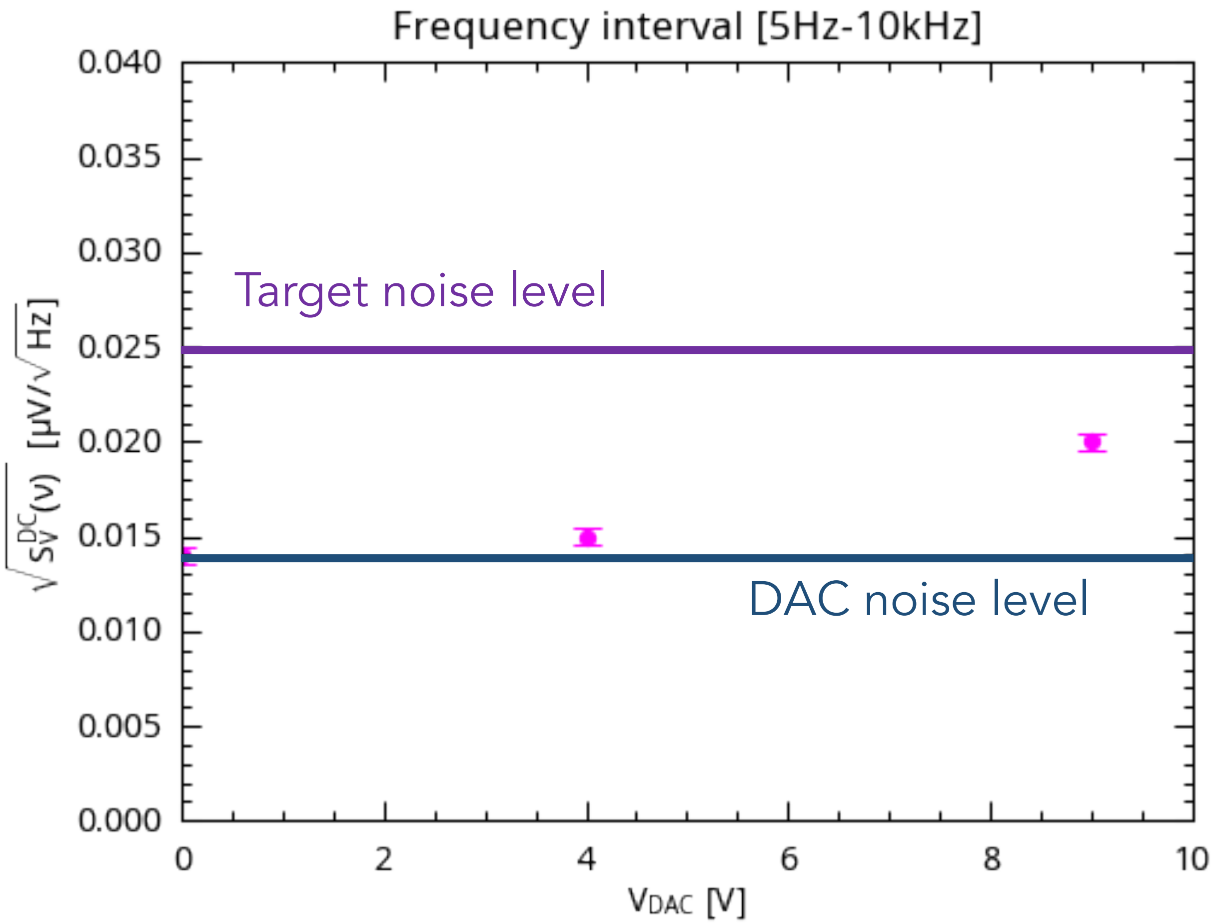
The DC voltage supplies

The noise of the DACs voltages: further improvements

15V Supply	Voltage Regulator	Voltage Reference	DACs

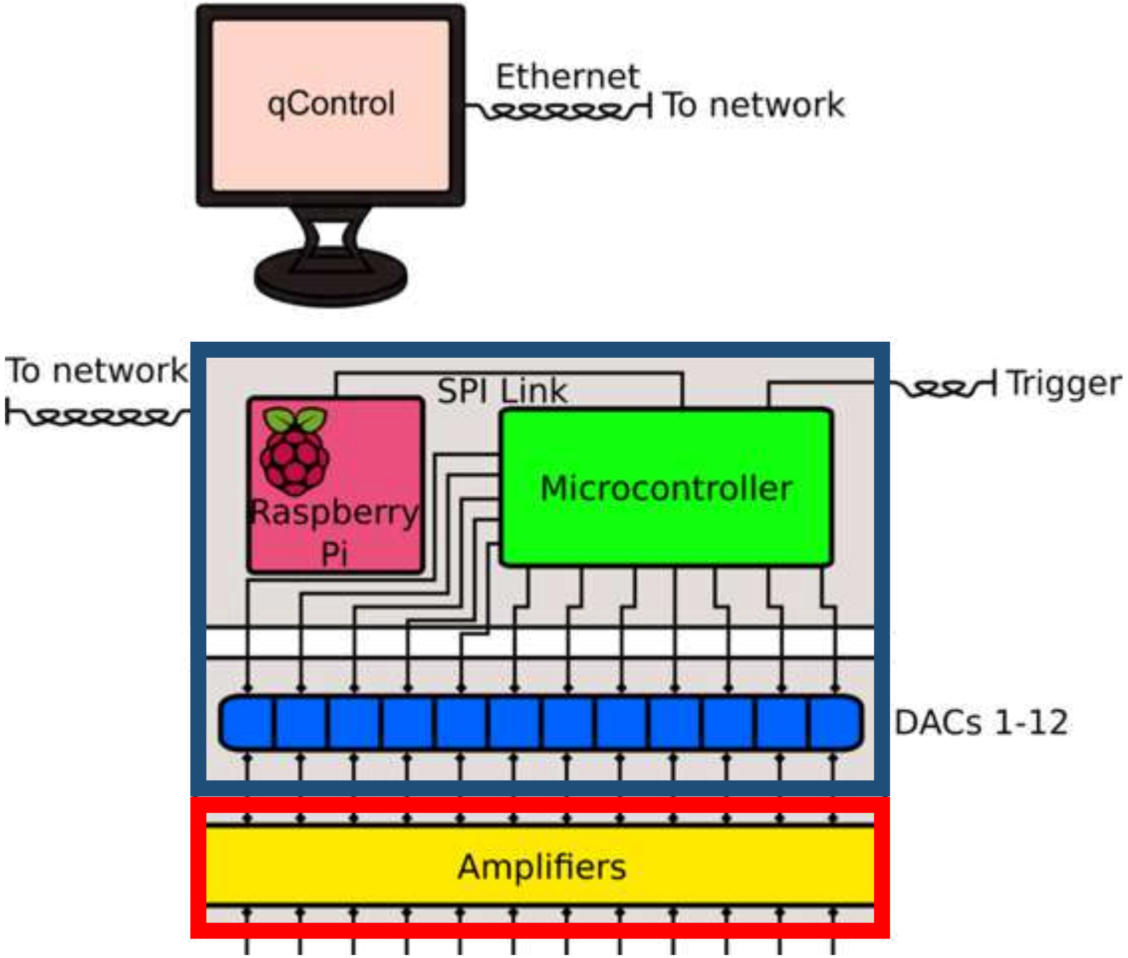
Improvements:

- 15V supply placed outside box
- Voltage regulator modified
- Voltage reference modified



By appropriate filtering + different voltage reference in parallel, noise properties as good as batteries can be achieved!

The DC voltage supplies



Reducing the amplifier gain to 2x and running the DAC at ± 10 V, we should at least be able to have difference of 40 V and a noise of 30 nV/sqrt(Hz) @ > 500 Hz

The DC voltage supplies

An analog alternative:

WP2 by Catalina Curceanu

The RF voltage supply

What noise level can be accepted in the TEQ experiments?

In terms of forces:

$$\sqrt{S_F(\nu)} \le 3\cdot 10^{-22}\, N / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

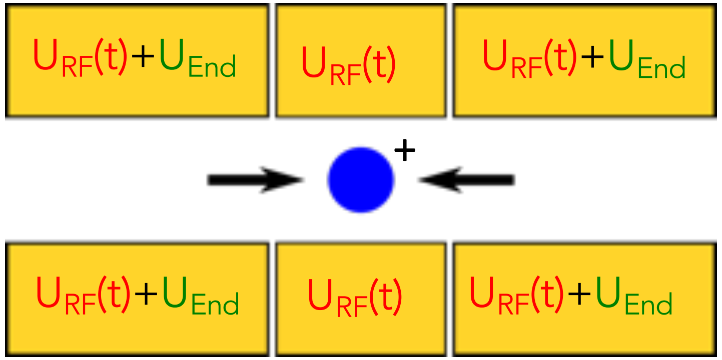
In terms of electrode voltages:

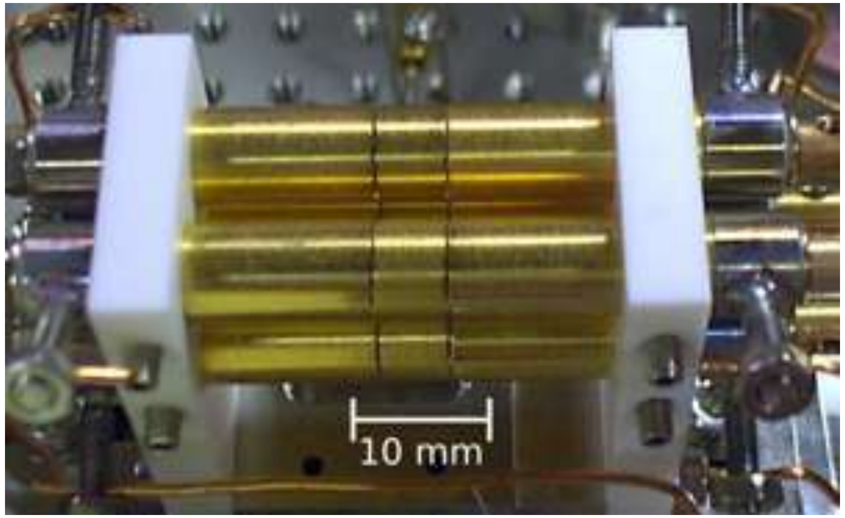
$$\sqrt{S_V^{DC}(\nu)} \le 25 nV / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

Initial guess based on geometry of the TEQ trap

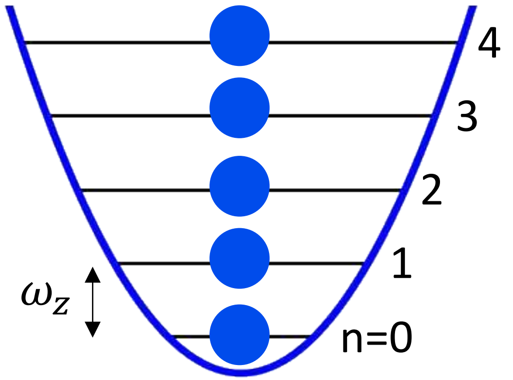
$$\sqrt{S_V^{AC}(\nu)} \le 70 nV / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

Noise measurements with the Aarhus linear Paul trap setup





z



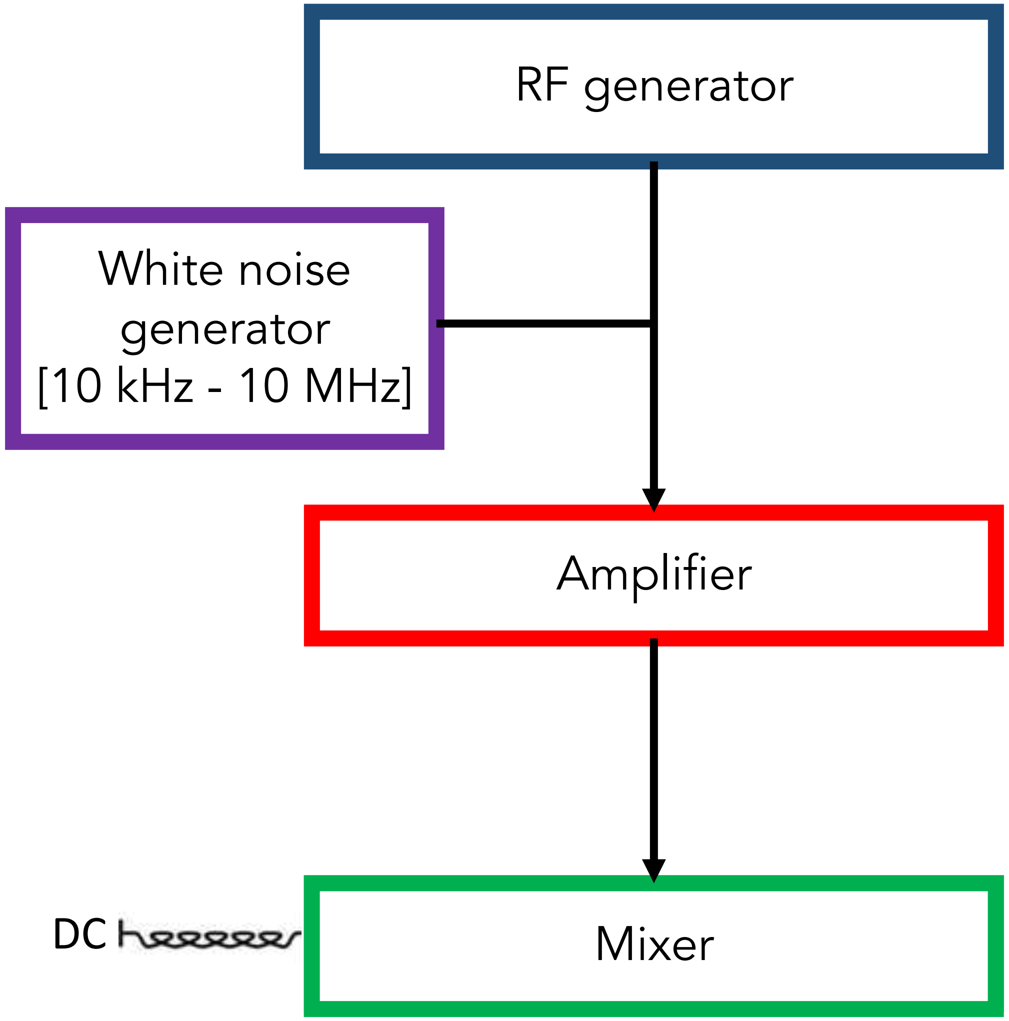
z

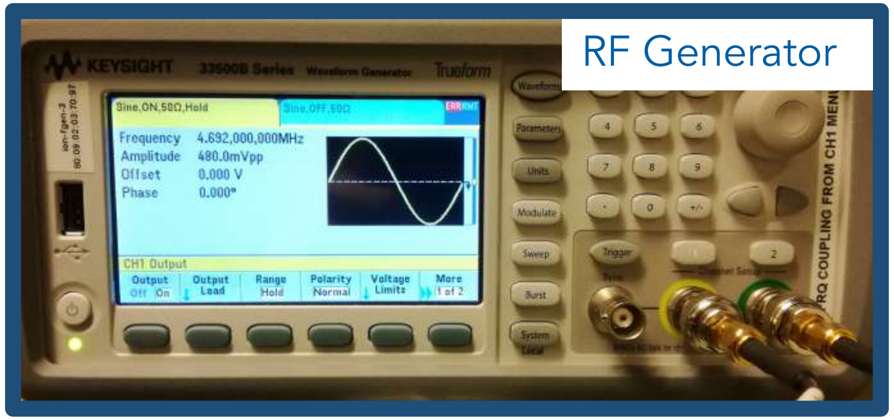
Model for heating from electronic noise:

$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4m\hbar\omega_z} F(\omega_z)^2 \frac{S_{V_{DC}}(\omega_z)}{D^2}$$

Based on our experiments on the DC supply we found A=0.88

The RF voltage supply

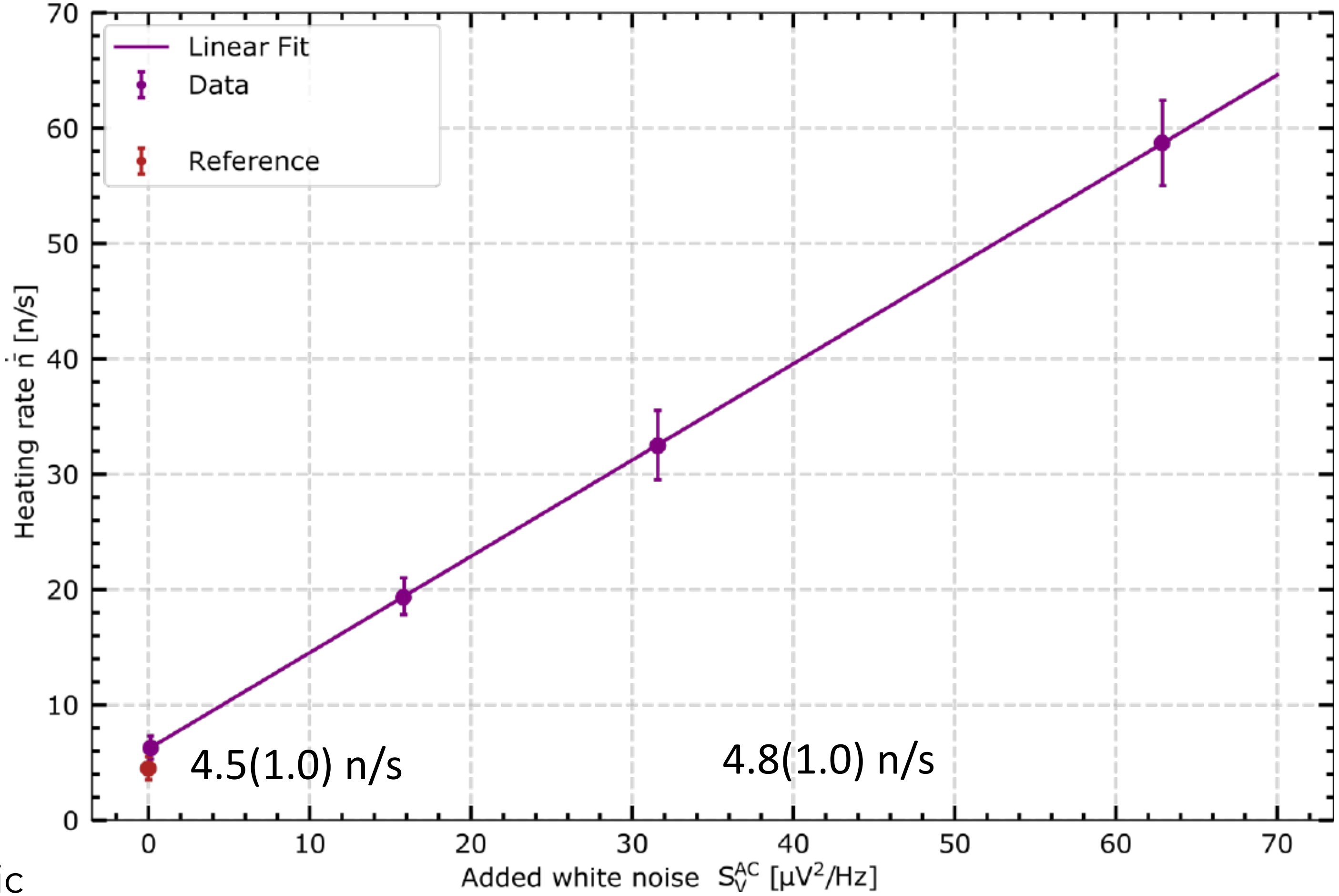




The RF voltage supply

The heating rates

Low frequency filtering in the [0, 600 kHz] range: $S^{AC}_{V,ion} < 1000$ nV²/Hz



Model for heating from electronic noise:

$$\dot{\bar{n}} \sim A \times 8 \frac{e^2}{4m\hbar\omega_z D^2} S^{AC}_{V,ion}(\omega)$$

$S^{AC}_{V,ion}(\omega = \omega_z = 150\ kHz) \longrightarrow$ $\boxed{A < 0.0002}$

What noise level can be accepted in the TEQ experiments?

In terms of forces:

$$\sqrt{S_F(\nu)} \leq 3\cdot 10^{-22}\, N/\sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

In terms of electrode voltages:

$$\sqrt{S_V^{DC}(\nu)} \leq 25 nV/\sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

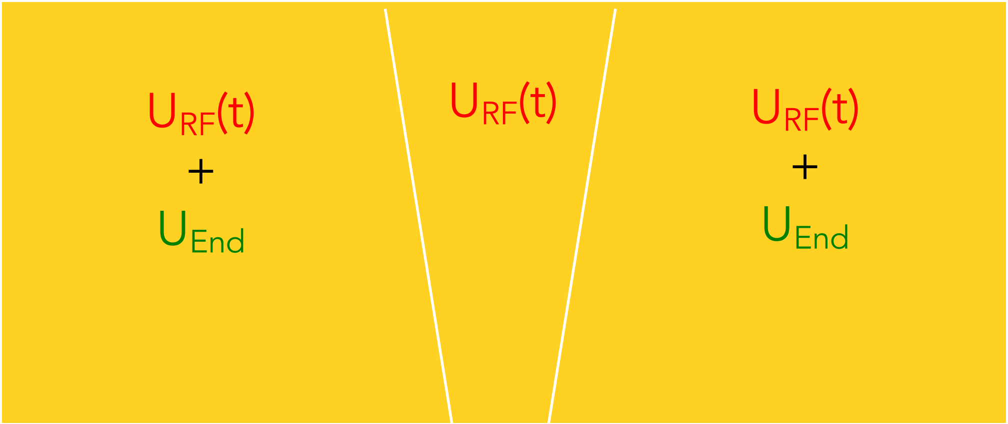
$$\sqrt{S_V^{AC}(\nu)} \leq 70 nV/\sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100-1000)\, Hz$$

We can work with 500 times larger spectral density noise of the AC supply than initially guessed, or equivalent 5000 times larger than DC noise!

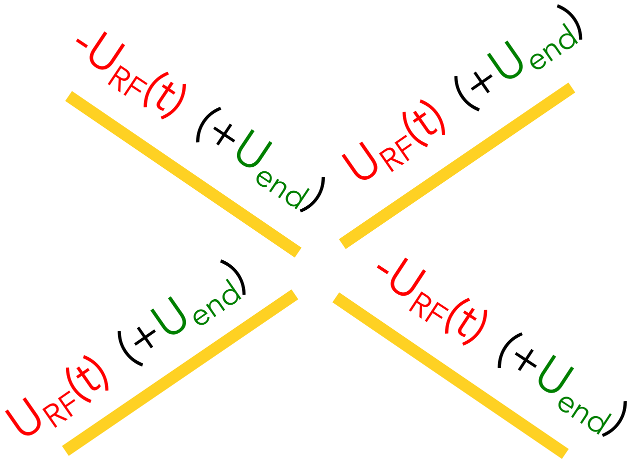
Discussion of blade electrode wiring

Blade electrode wiring I

Blade electrode structure



Mounted electrodes in an end view:

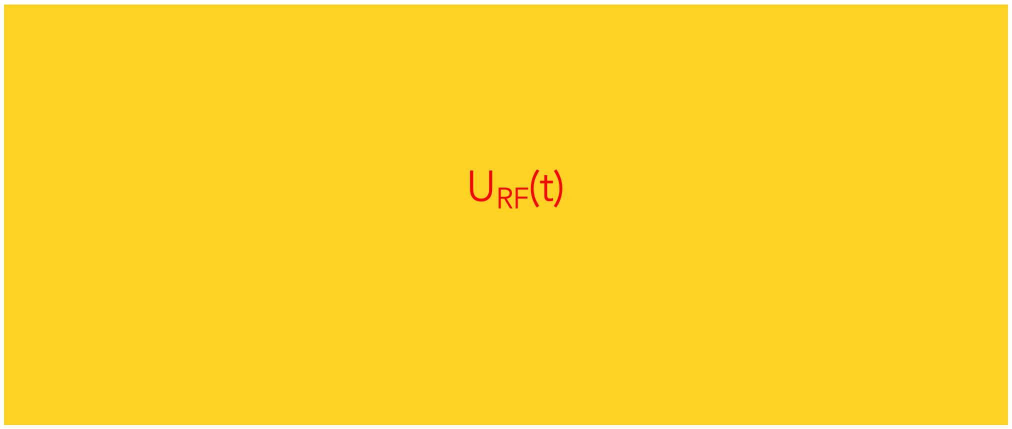


<u>Note:</u>

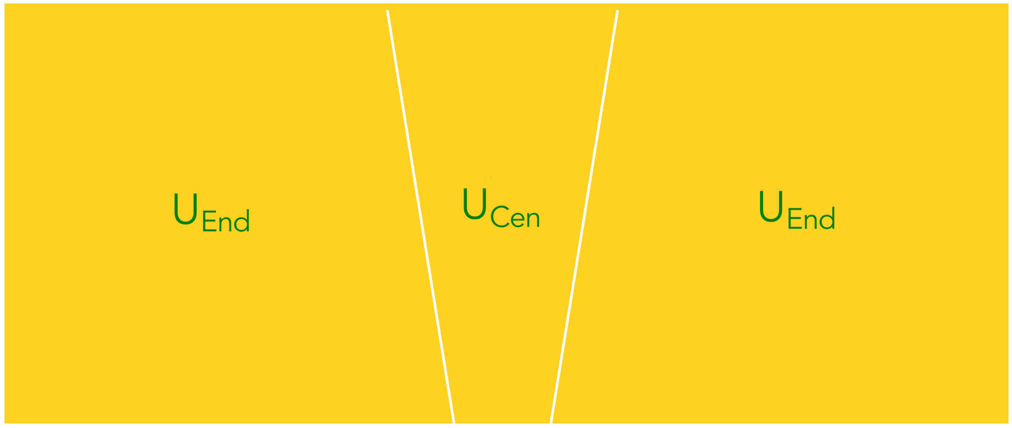
$U_{RF}(t)$ and U_{end} ***has to be mixed*** together.

Blade electrode wiring II

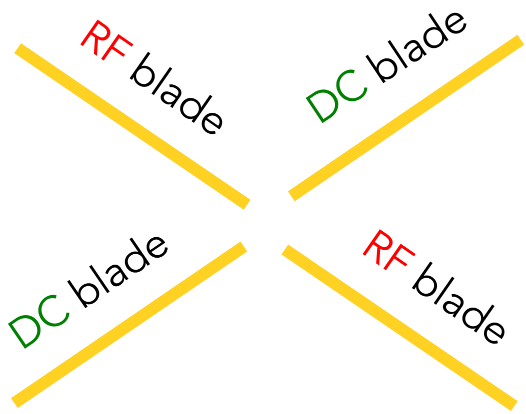
RF blade electrode



DC blade electrode



Mounted electrodes
in an end view:

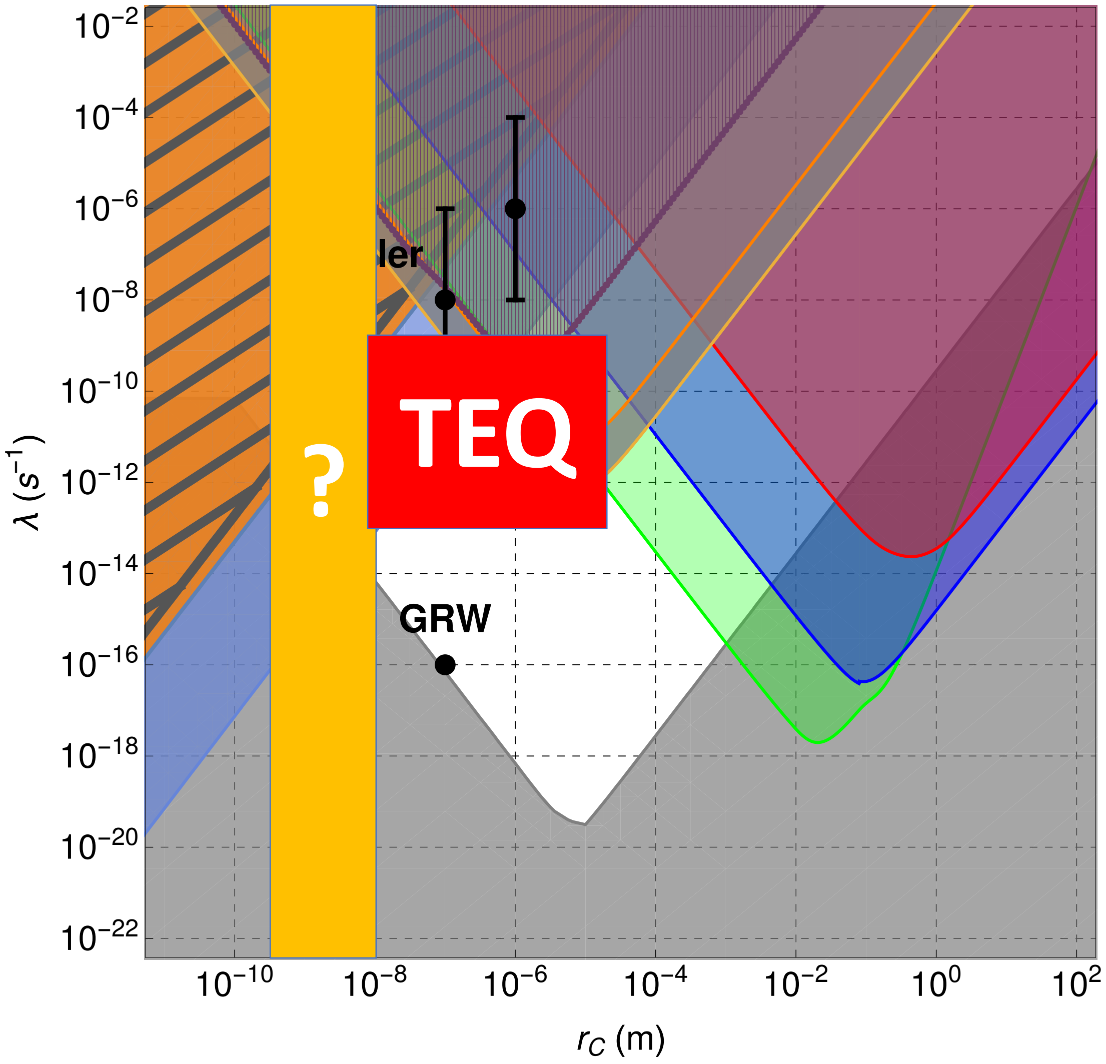


No mixing of $U_{RF}(t)$
and U_{end} needed!

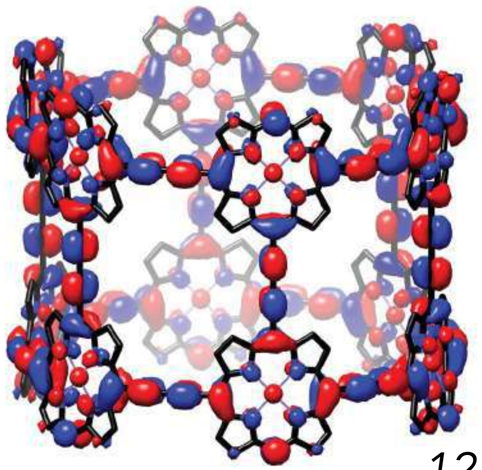
+ Enables high pass filtering of the AC voltages at the same time as low pass filtering of DCs at the trap!

CSL exclusion plot, Aarhus cryogenic trap?

Current bounds in CSL parameter space

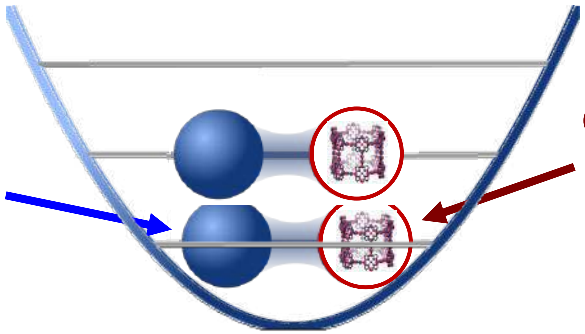


Complex molecular ions



12-porphyrin

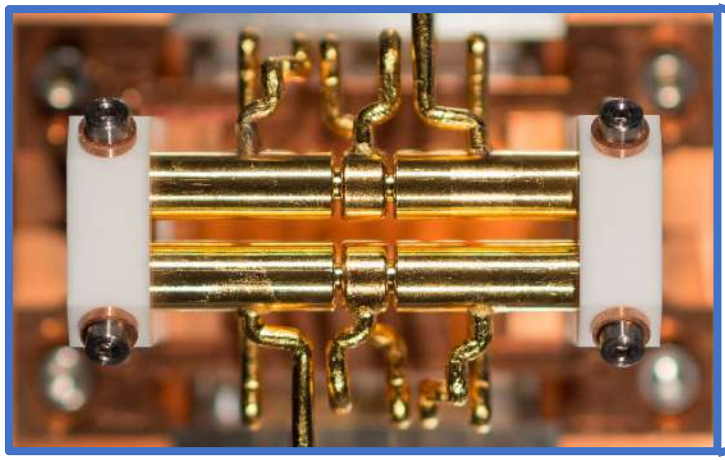
CSL heating

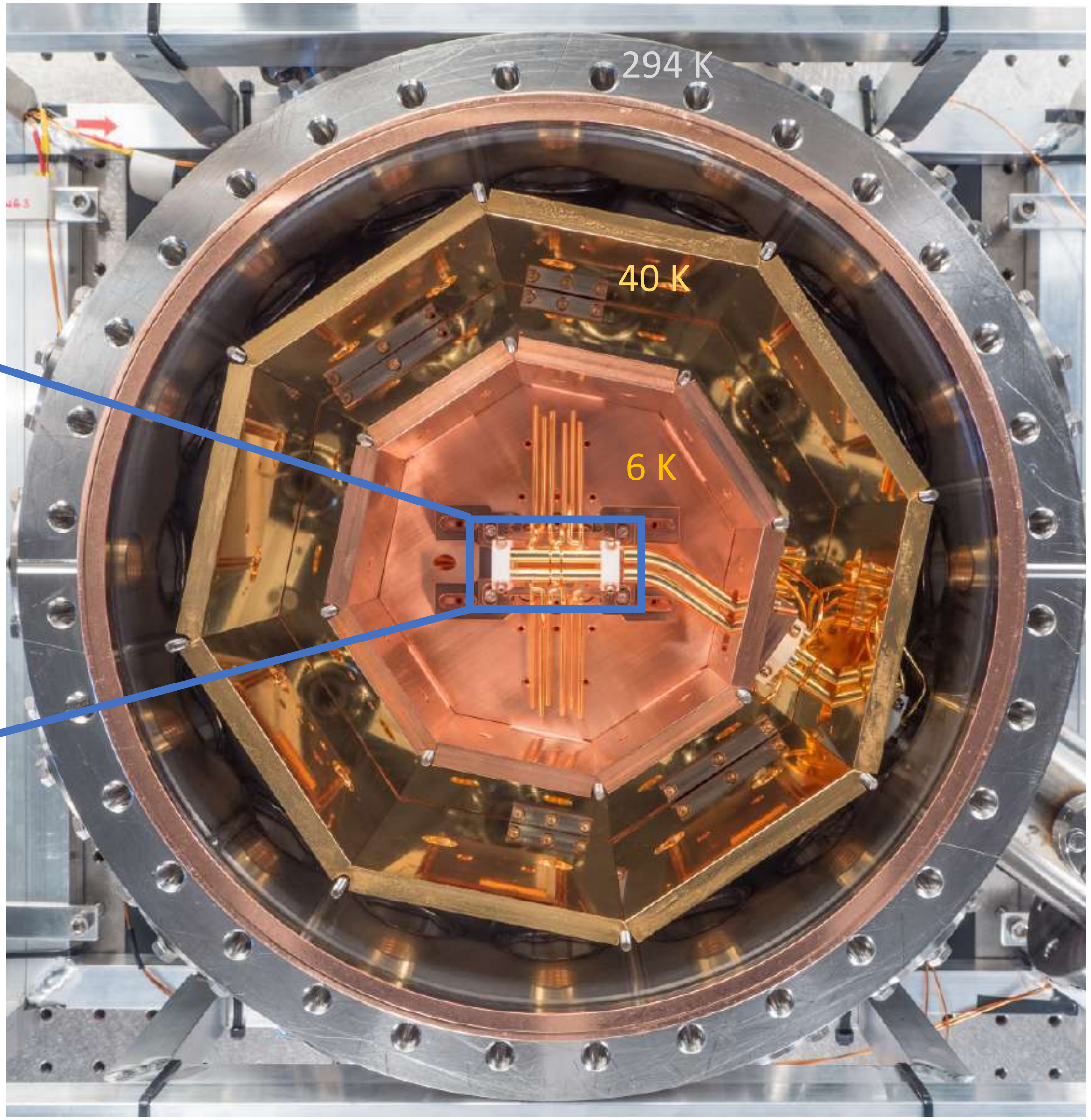


???

Cryogenic trap for sympathetic cooling of complex molecular ions via laser-cooled Ba^+ ions

The linear Paul trap

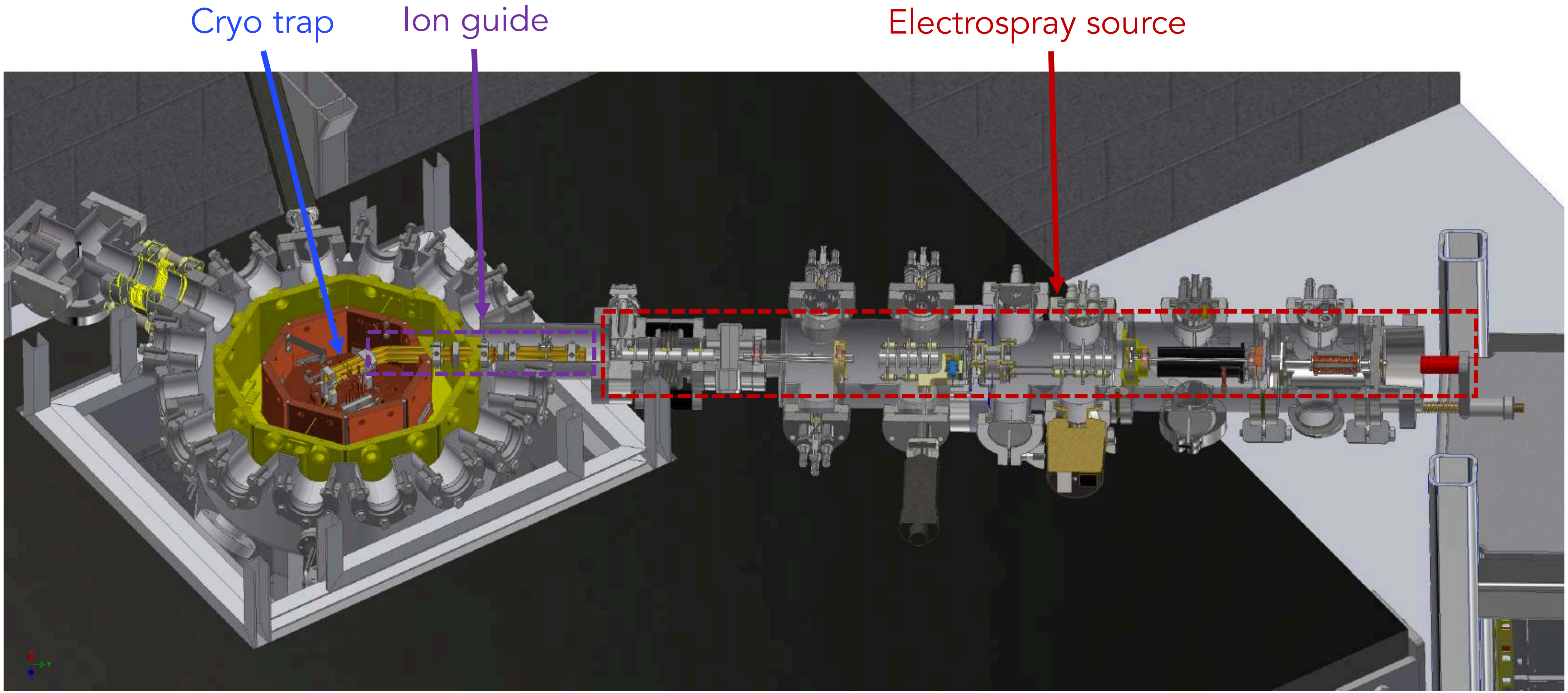




Vacuum @ trapped ions:

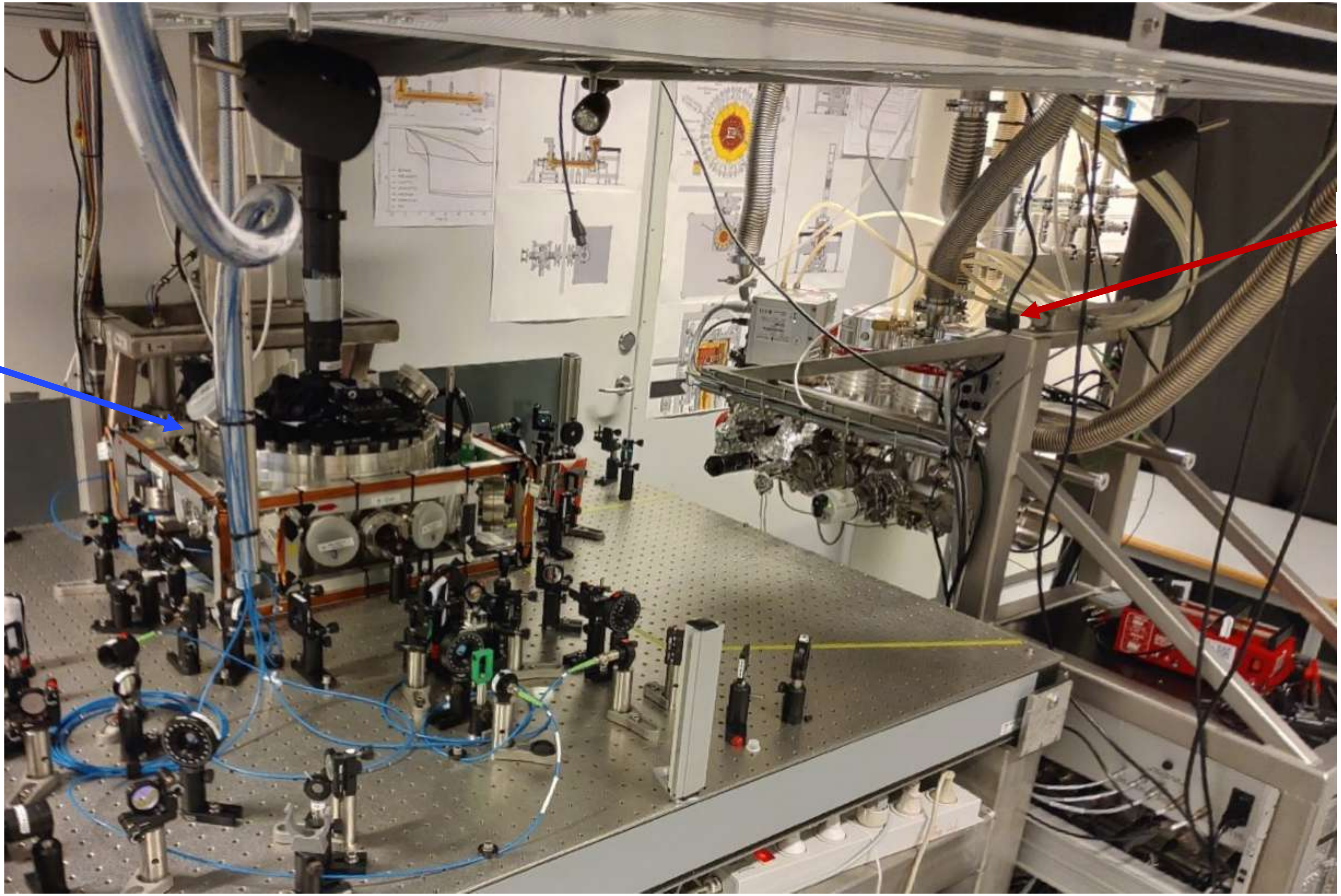
~ 10^{-13} mbar !!

Cryogenic trap for sympathetic cooling of complex molecular ions via laser-cooled Ba$^+$ ions



Cryogenic trap for sympathetic cooling of complex molecular ions via laser-cooled Ba^+ ions

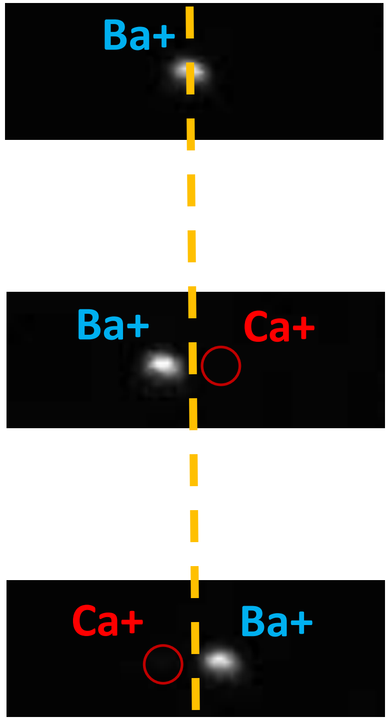
Cryo trap



Electrospray source

Cryogenic trap for sympathetic cooling of complex molecular ions via laser-cooled Ba^+ ions

Sympathetic cooling of a single $^{40}Ca^+$ ion



Summary of WP1

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
8	30	19	8	16	38	5	5	0

Objectives

O1.1 Construction of a low noise trap for NCs suitable for a cryogenic environment.
O1.2 Synthesis of NCs with tailored properties.
O1.3 Loading of multiply charged NCs into the trap.
O1.4 Quantification of heating sources and their effects on the trapped NCs.

Tasks

T1.1 Construction of a low-noise rf trap.
T1.2 Synthesis of colloidal NCs with specific properties.
T1.3 Methods for loading charged NCs into rf traps.
T1.4 Theoretical identification of heating mechanisms and their effects.

Deliverables

D1.1 Rf trap for NCs [M 24].
D1.2 1-Colloidal NCs [M 12].
D1.3 2-Colloidal NCs [M 24].
D1.4 Loading and control device [M 36].
D1.5 Quantification of heating [M 36].

Status of the TEQ-trap setup

So far:

- First complete trap for room-temperature experiments finalized, and silica-nanoparticle trapped at UCL
- Low-noise digitally controllable DC voltage supplies have been constructed + analog alternative
- Test with trapped ions have been performed in the 100 kHz-range
- Influence of noise from RF source has been studied with trapped ions

Next step:

- Final trap-design for cryogenic-temperature experiments
- Decide on RF/AC voltage supplies
- Loading protocol: Electrospray + guide

TEQ

Testing the large-scale
limit of
quantum mechanics

European Commission

WP2: COOLING

P. Barker - UCL
C. Curceanu - INFN

Summary of WP2

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
8	15	20	12	16	9	40	10	22

Objectives

O2.1 To develop low noise trap, detection and feedback electronics.
O2.2 To determine optimal detection and cooling strategies for trapped NCs.
O2.3 To cool internal states of trapped NCs.
O2.4 To understand and control sources of decoherence.

Tasks

T2.1 Design, construct and test low noise electronics.
T2.2 Implement optical, resistive and cavity cooling.
T2.3 Identify materials and perform internal cooling of NCs.
T2.4 Study and measure non-equilibrium dynamics for all systems.

Deliverables

D2.1 Low noise electronics [M 12].
D2.2 Optimal cooling strategies [M 27].
D2.3 Internal state cooling [M 38].
D2.4 Quantify decoherence [M 44].

TEQ

European Commission

Outline

Low noise electronics (2.1)
- Paul trap electronics
- Implementation on Paul Trap

Centre-of-mass cooling (2.2)
- Optimal cooling strategies using feedback methods
- Cavity cooling in the Paul trap

Internal state cooling (2.3)
- Characterisation of trapped Yb:YLF nanocrystals
- Inducing and controlling rotation

Understanding and controlling sources of decoherence (2.4)
- measurements of linewidth and noise
- application to dissipative collapse models

Low noise electronics (2.1)

Activities in low noise electronics since last review (2.1)

From last meeting at UCL in July, LNF activities are:

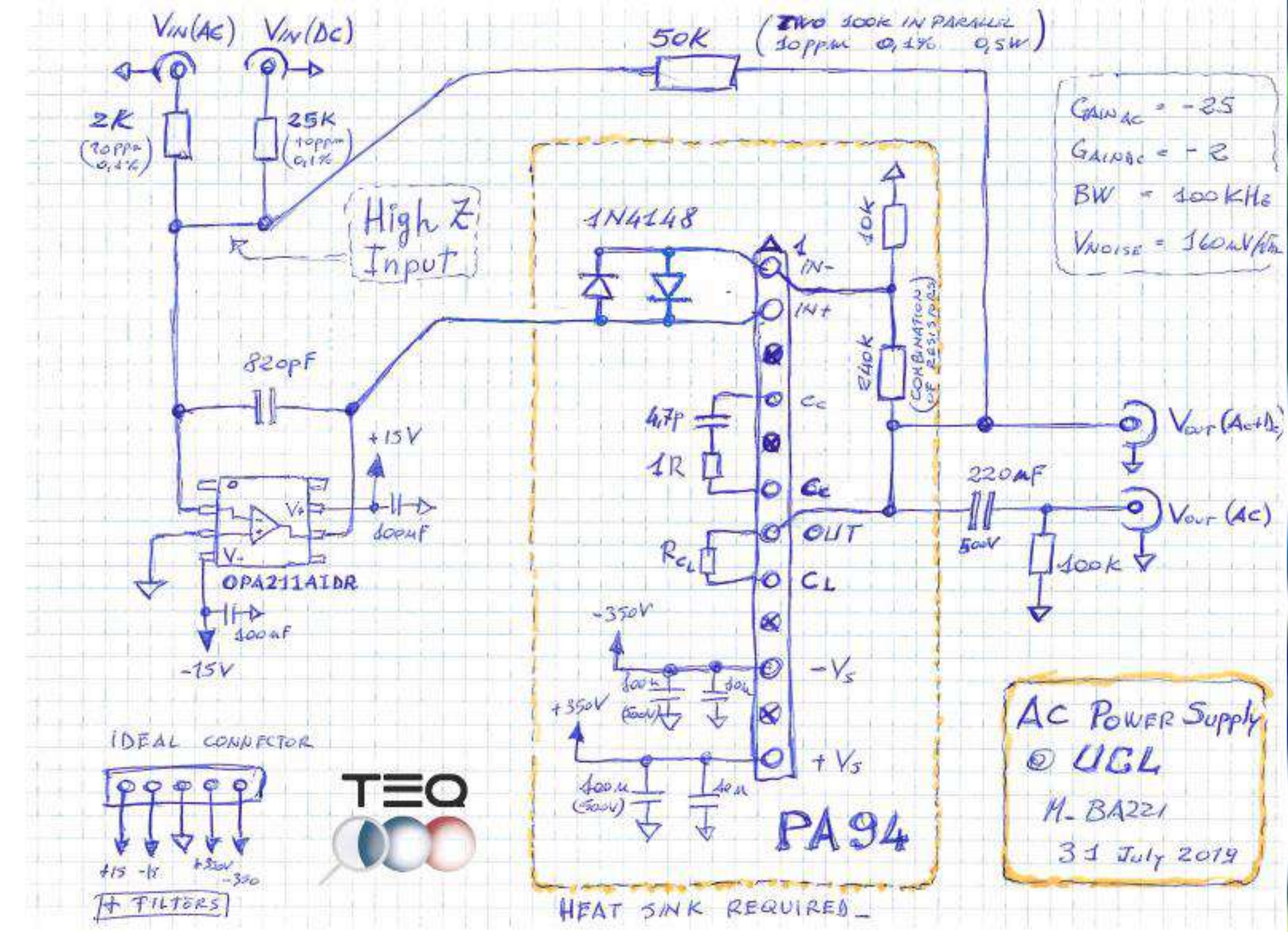
UCL system

- Design of a low noise AC amplifier
- Design of HV power supplies
- PCB design and production
- Mounting and test
- Further assistance

Aarhus system

- Developed low noise amplifier for DAC's – reported at last review
- Added low noise reference voltage

Preliminary Design



Specifics

AC GAIN = -25

DC GAIN = -2

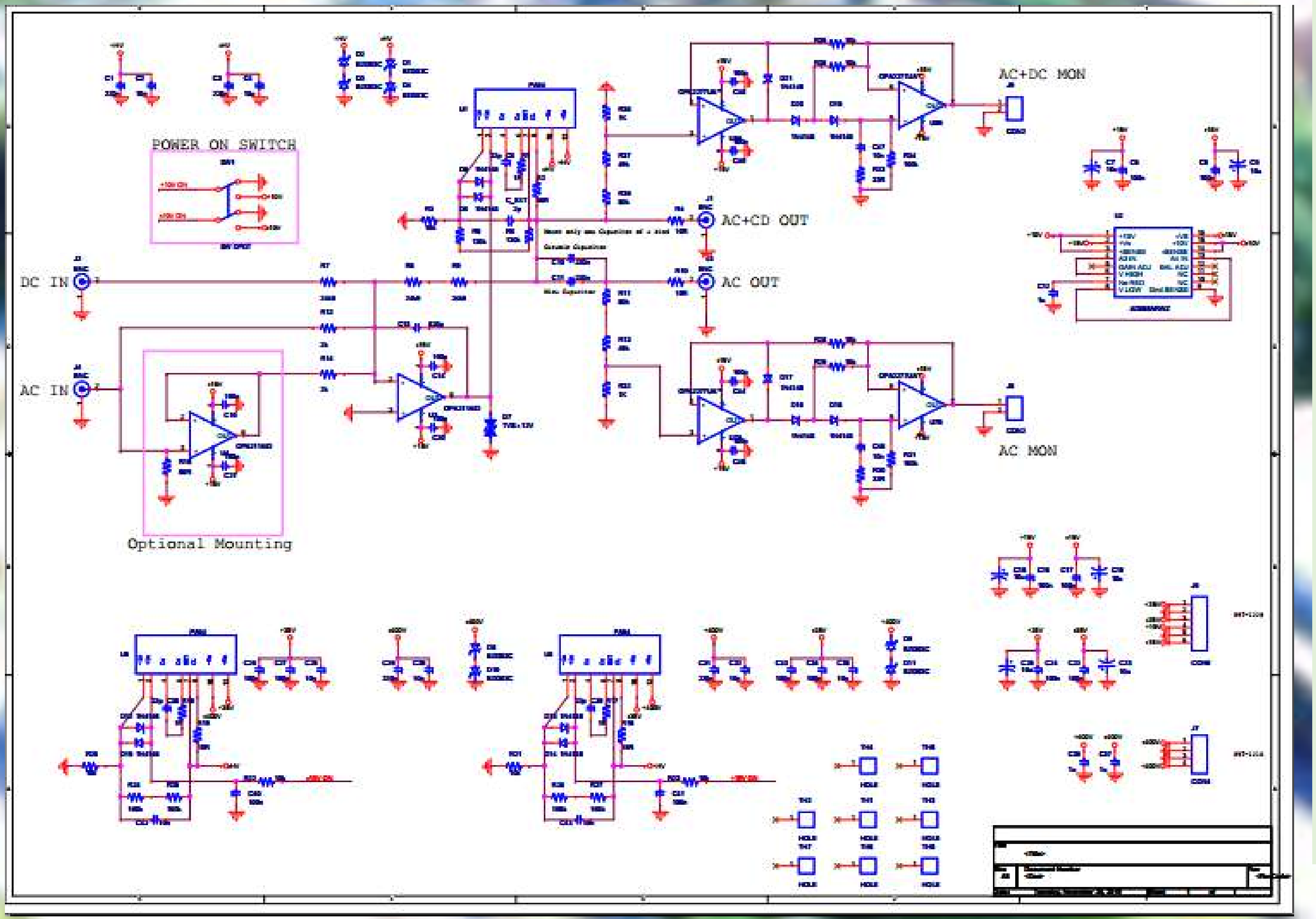
BW = 100kHz

Estim. Noise= 160nV

Power Supply= ±350V (included)

(discussed with Antonio Pontin @UCL)

Amplifier Design



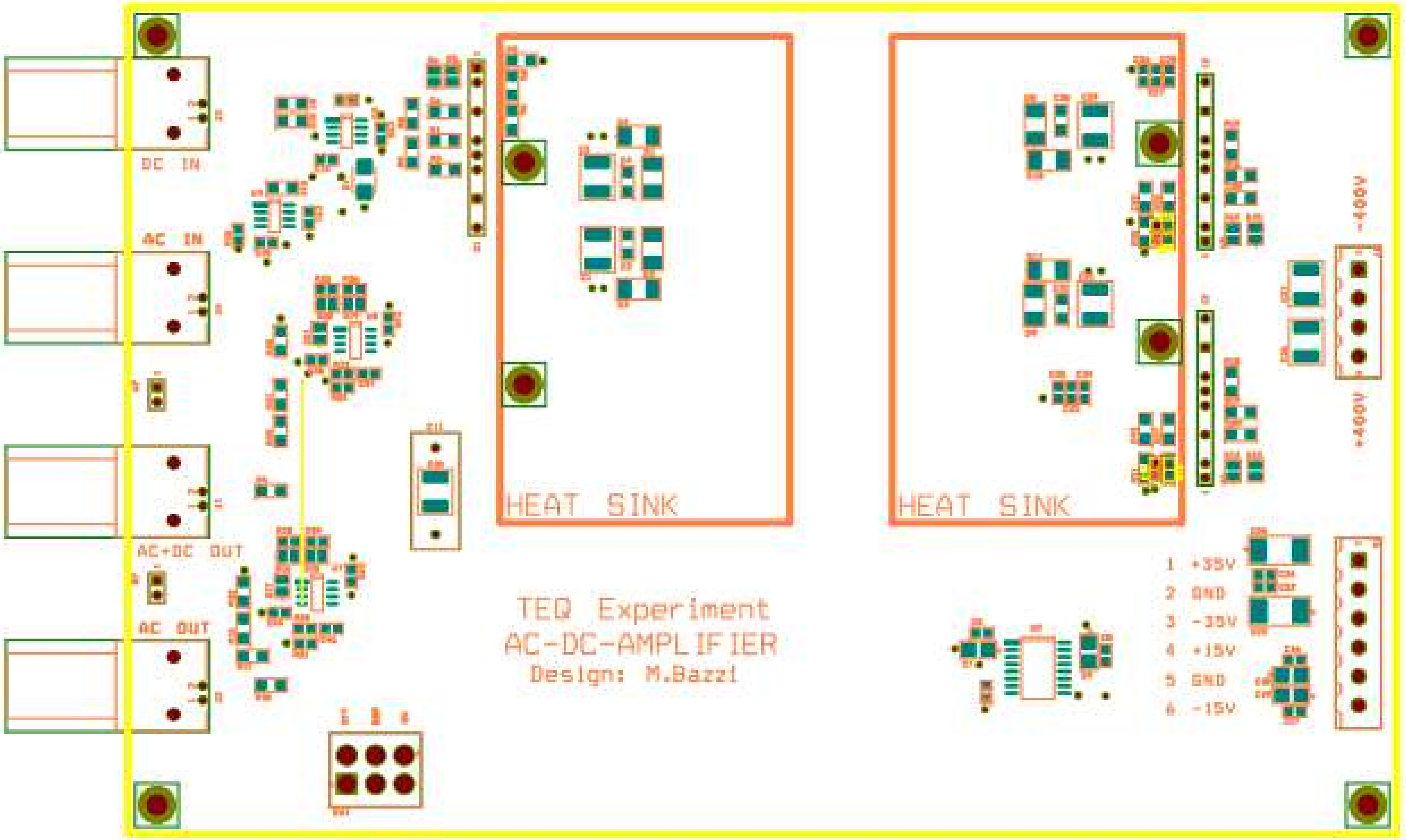
The circuit provides AC and DC amplification, an AC output and a mixed output (AC+DC).

Output Noise is coherent between both outputs.

Amplifier HV supply is produced by a dedicated circuitry on board.

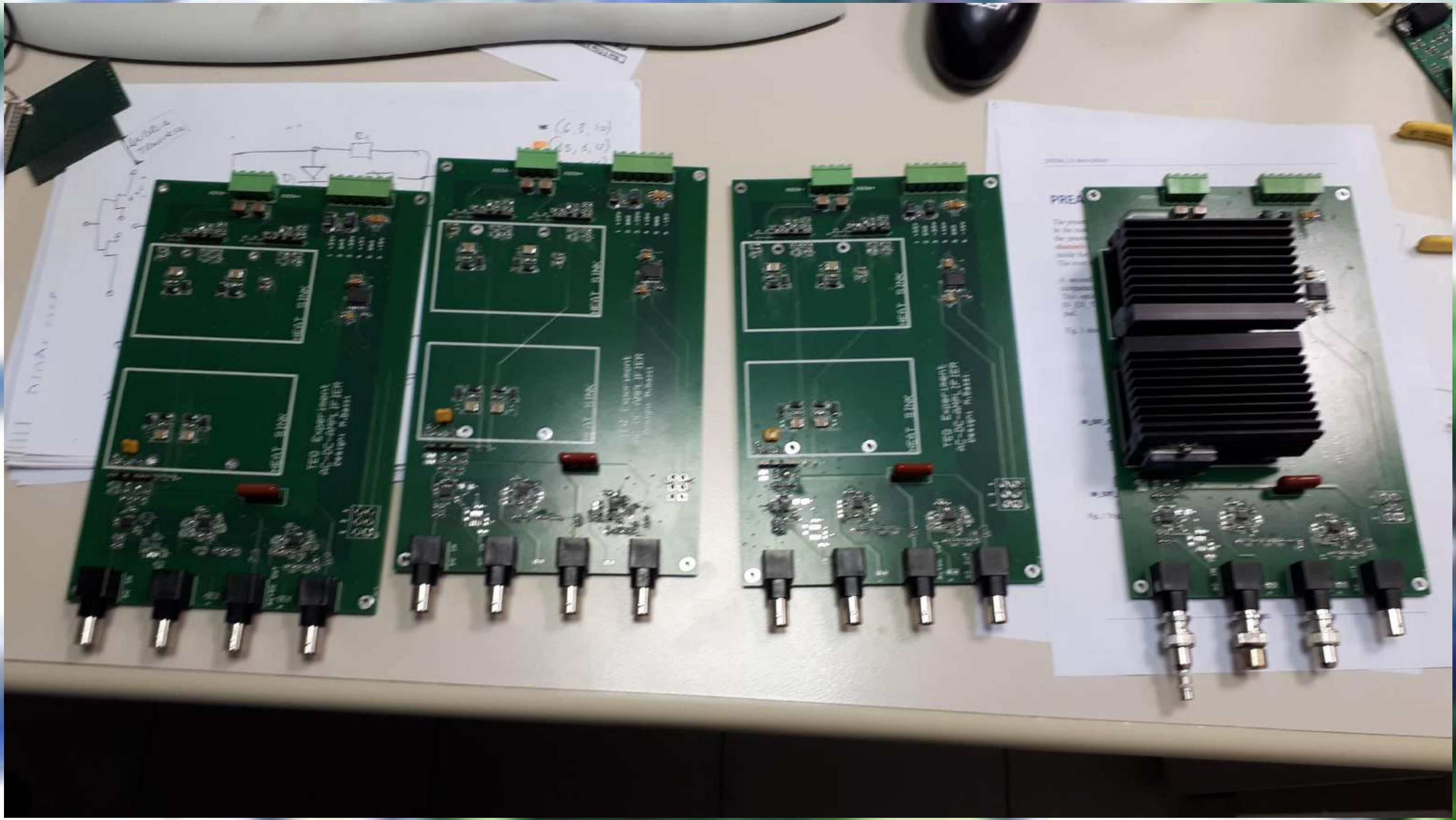
Two output monitors have been included.

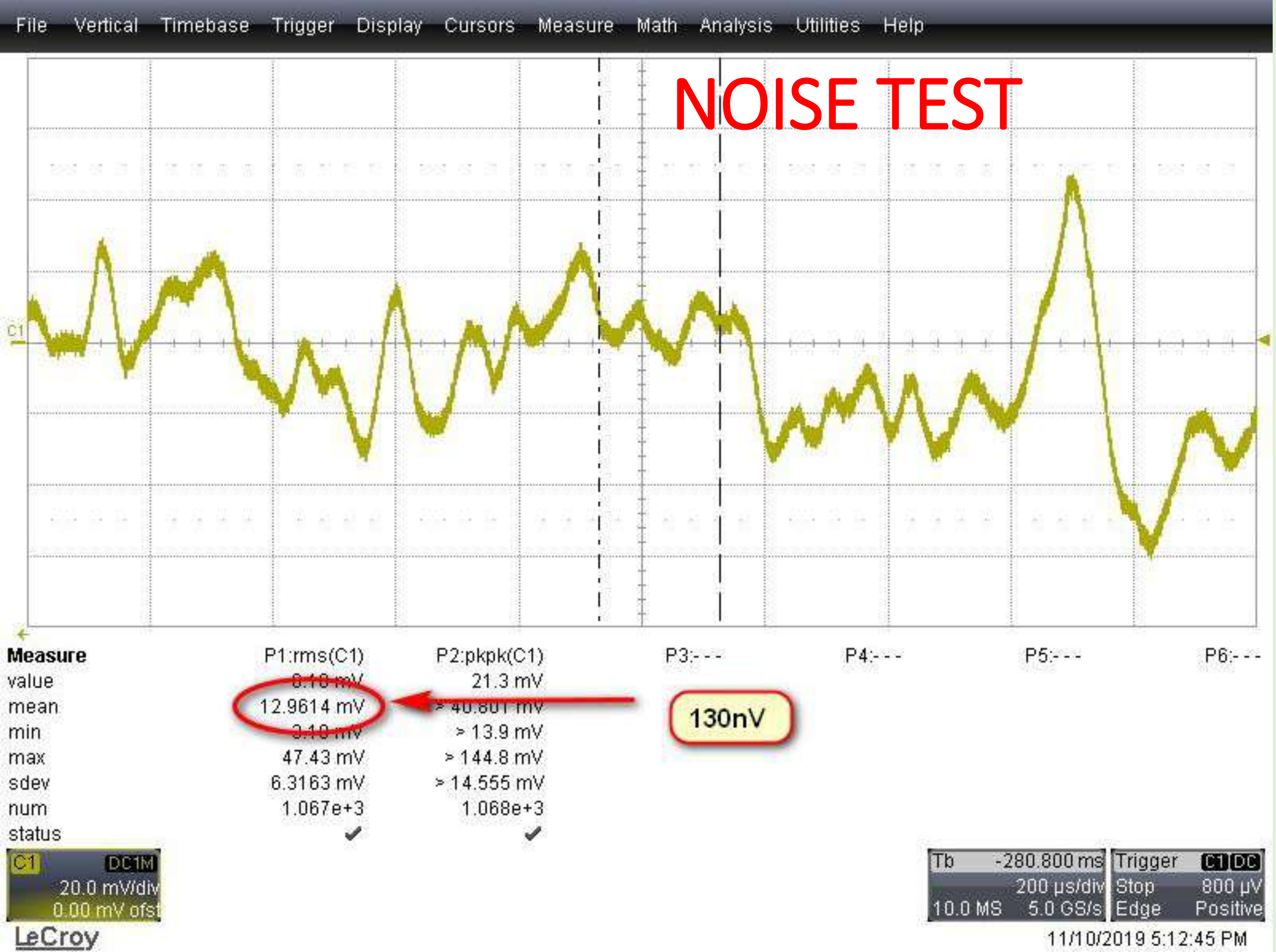
PCB Design



DC IN
AC IN
AC+DC OUT
AC OUT
HEAT SINK
HEAT SINK
TEQ Experiment
AC-DC-AMPLIFIER
Design: M.Bazzi
1 +35V
2 GND
3 -35V
4 +15V
5 GND
6 -15V
-400V
+400V

PCB Design





Noise tests confirmed noise behavior predicted during design.

By modifying some internal parameters, the minimum reacheable noise is 130nV/√Hz.

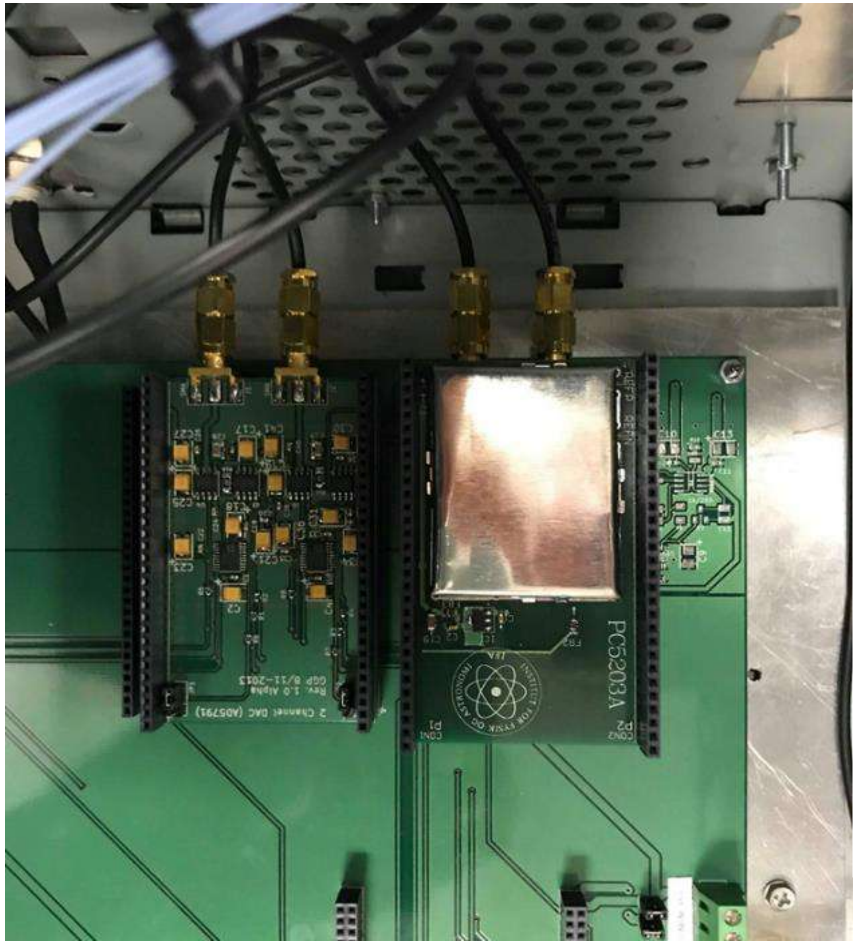
By lowering the noise, power consuption increases (and heat!).

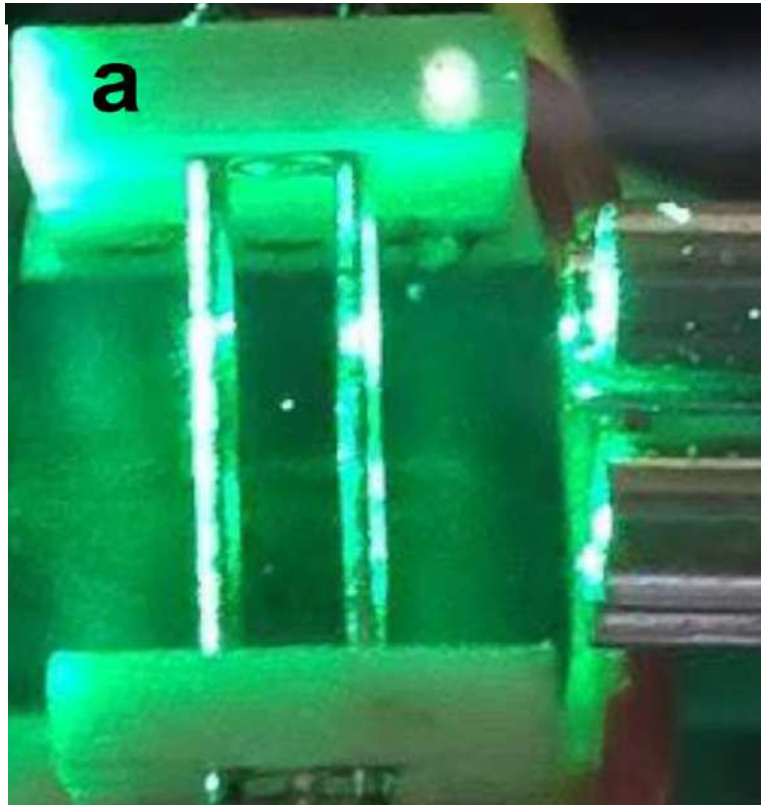
Noise limit is set by safety constraints.

Amplifier Design

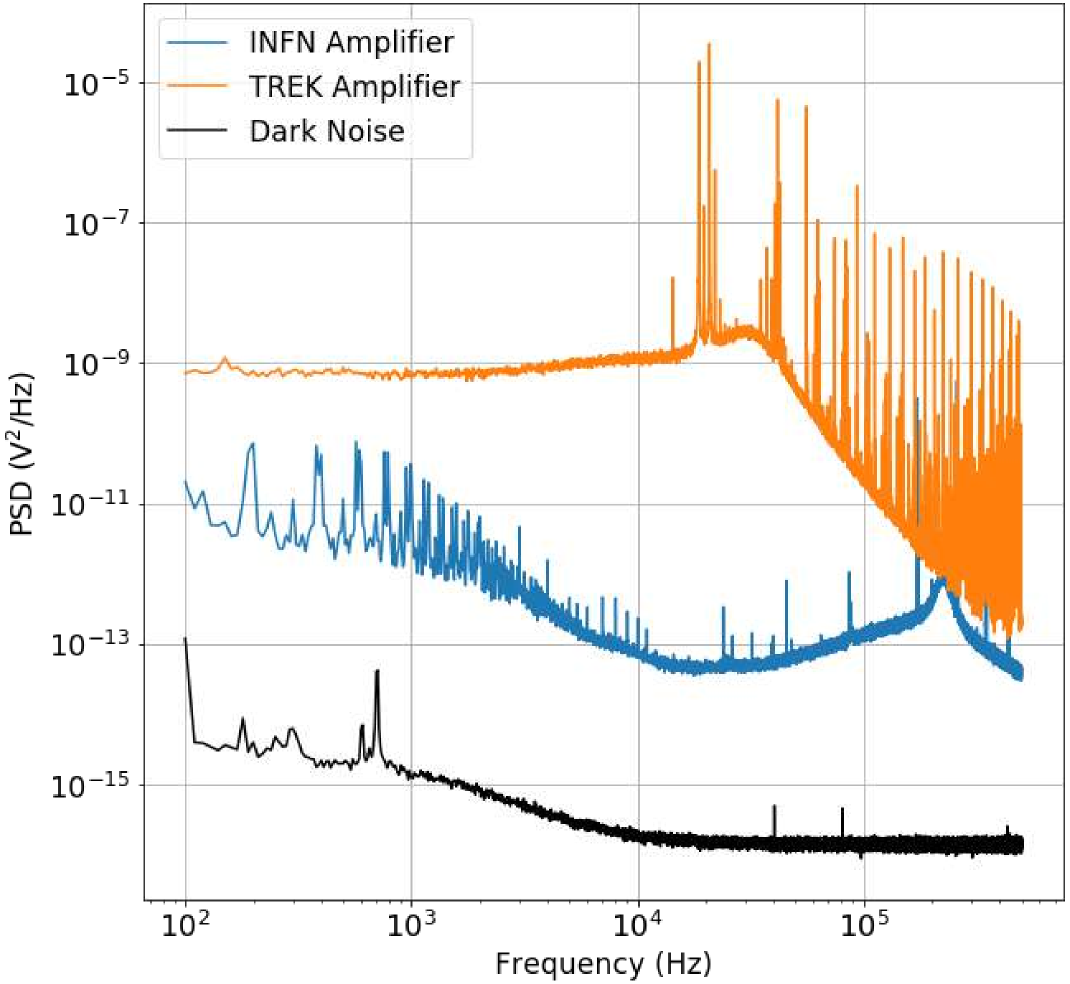
- Preliminary schematic was promptly produced and shared within collaboration (LNF, UCL, Southhampton) (July 2019).
- Mechanical details and constraints (dimensions, connectors, holes) defined in accordance with UCL (August/September 2019).
- PCB produced, mounted and tested (November 25 2019).
- 4 complete and fully operative modules have been sent to UCL. Two versions have been developed and sent with different noise (135nV – 195nV).
- LNF will also provide all the necessary adsistance for final installation.

Electronics implementation on Paul trap



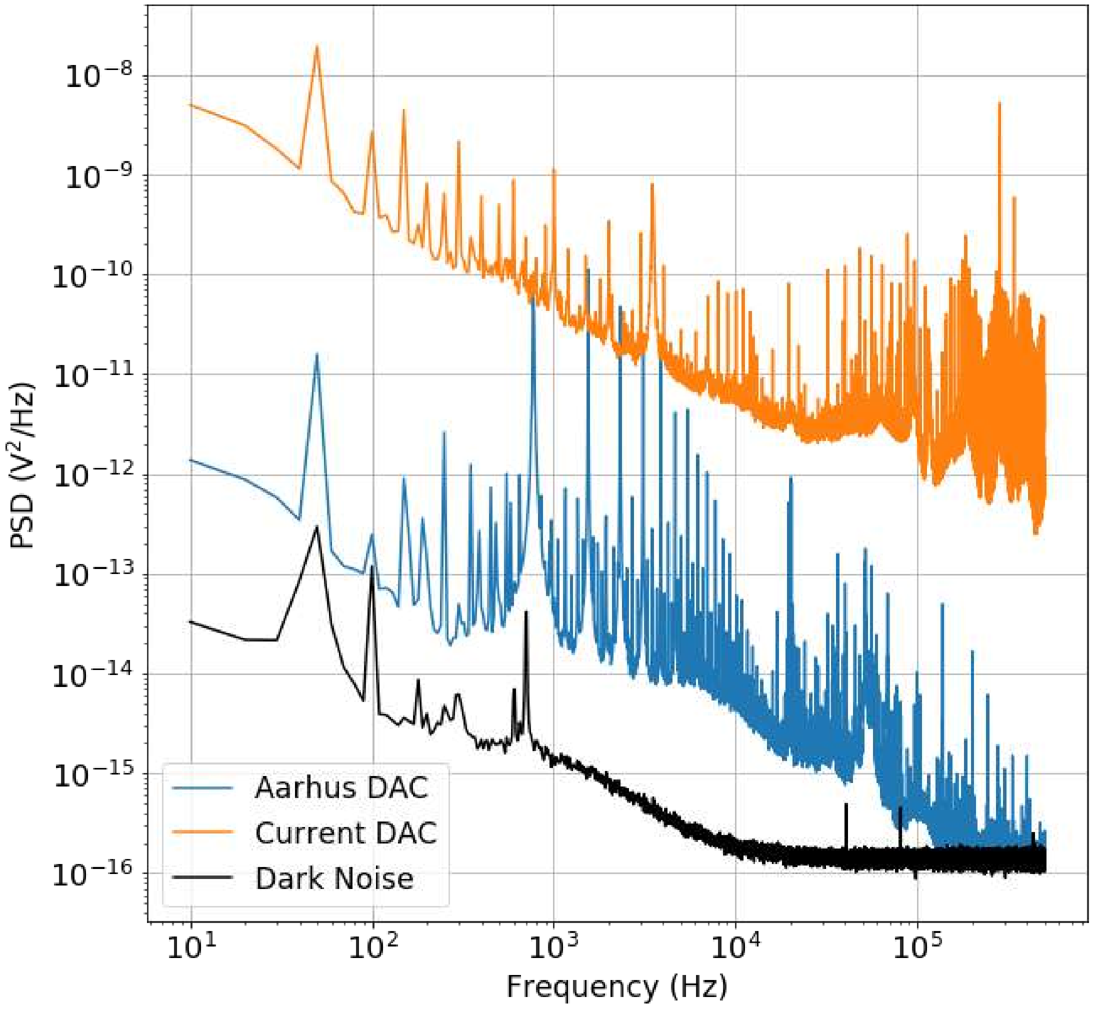


Amplifier noise measurements



2-4 orders of magnitude improved noise in the 1-10kHz range

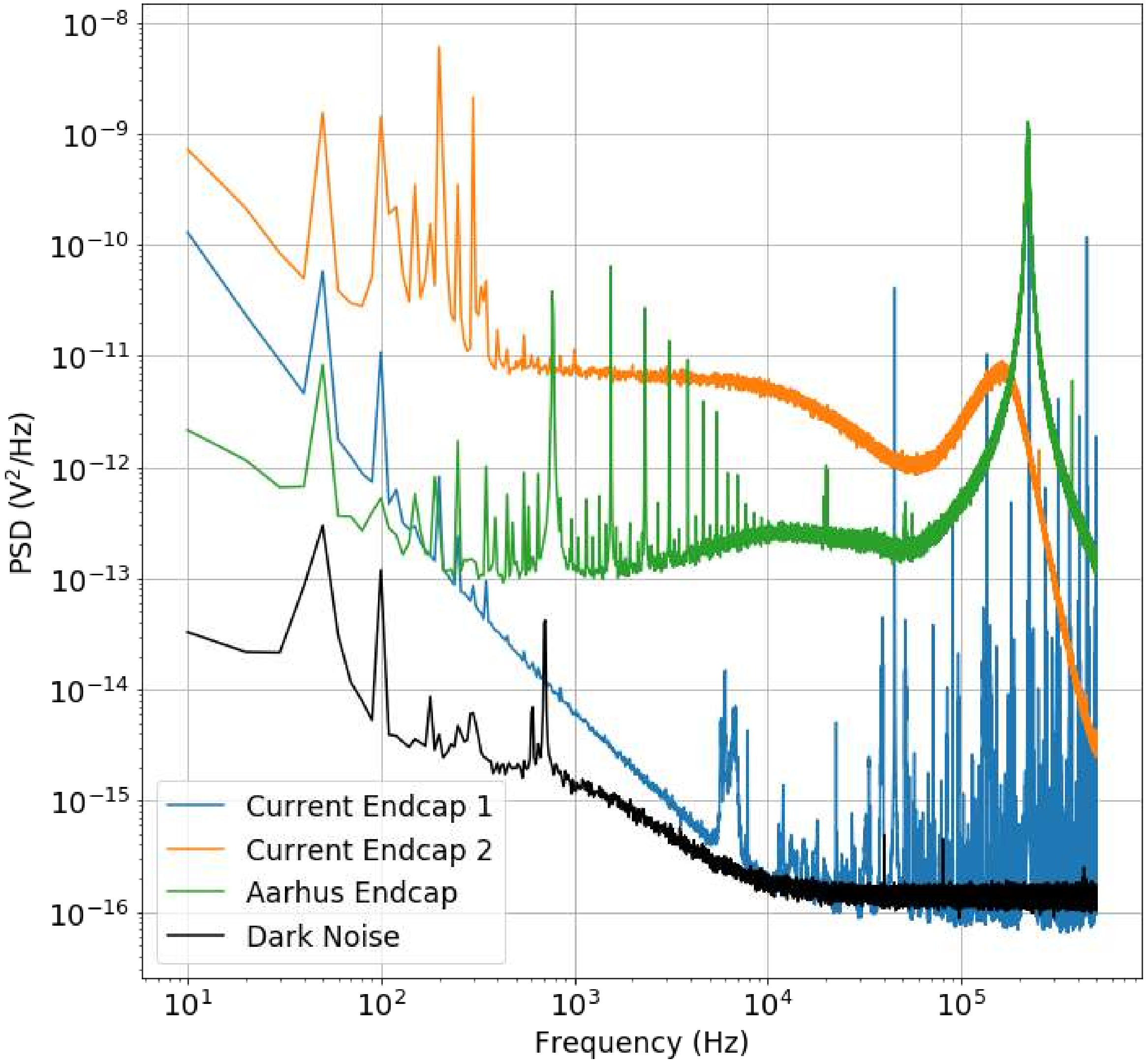
DAC noise measurements



4 orders of magnitude improved noise in the 10-10000Hz range

Noise spikes every 700Hz that reach the previous noise level

Noise measured on end caps



2 orders of magnitude improve noise in the 100-1000Hz region (over one endcap)

Symmetric noise properties allow for cancellation of noise on particle

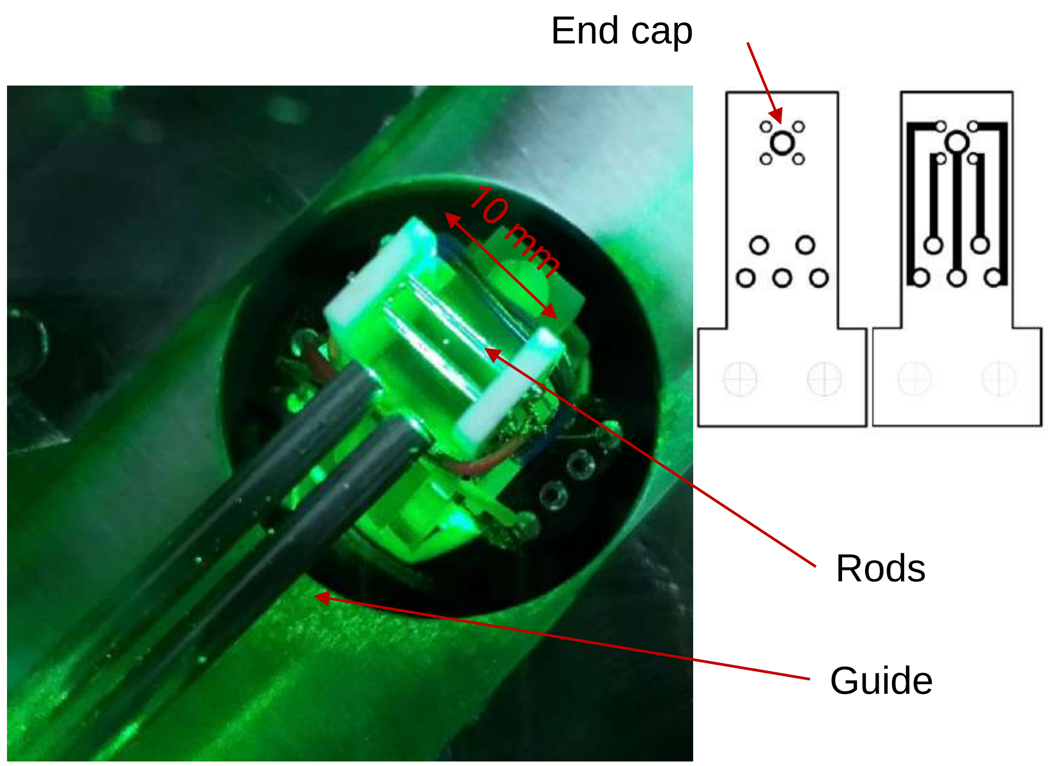
Noise spikes every 700Hz above level of previous noise

Current trap

Linear trap

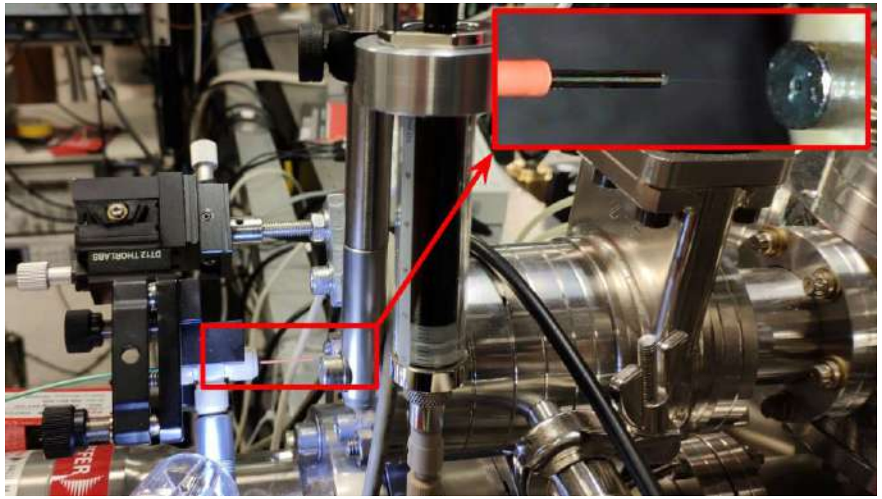
- AC distance: r_o = 1.1 mm
- DC distance: d_o = 3.5 mm

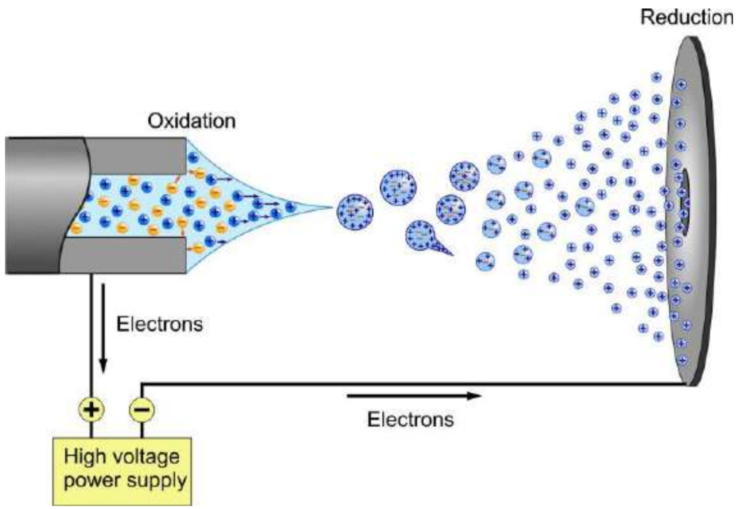
Efficiencies: η = 0.82
κ = 0.086



Trap loading

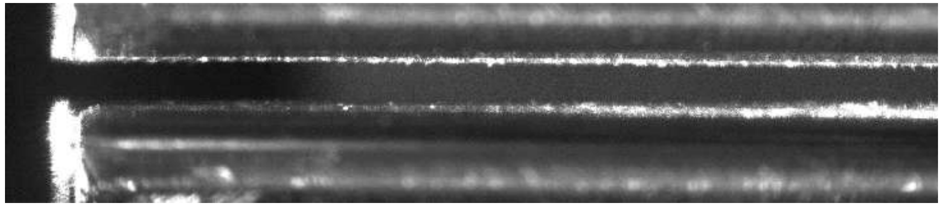
- Trapping at low pressure ~ 10^{-1} mbar
- Q/m ~ 0.1 – 2 roughly 10 – 1000 charges





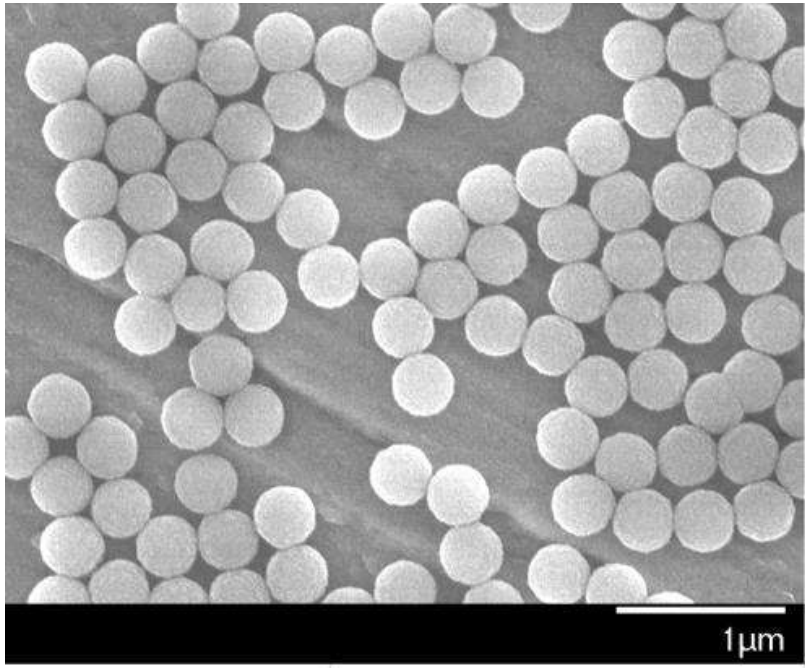
Guide is necessary

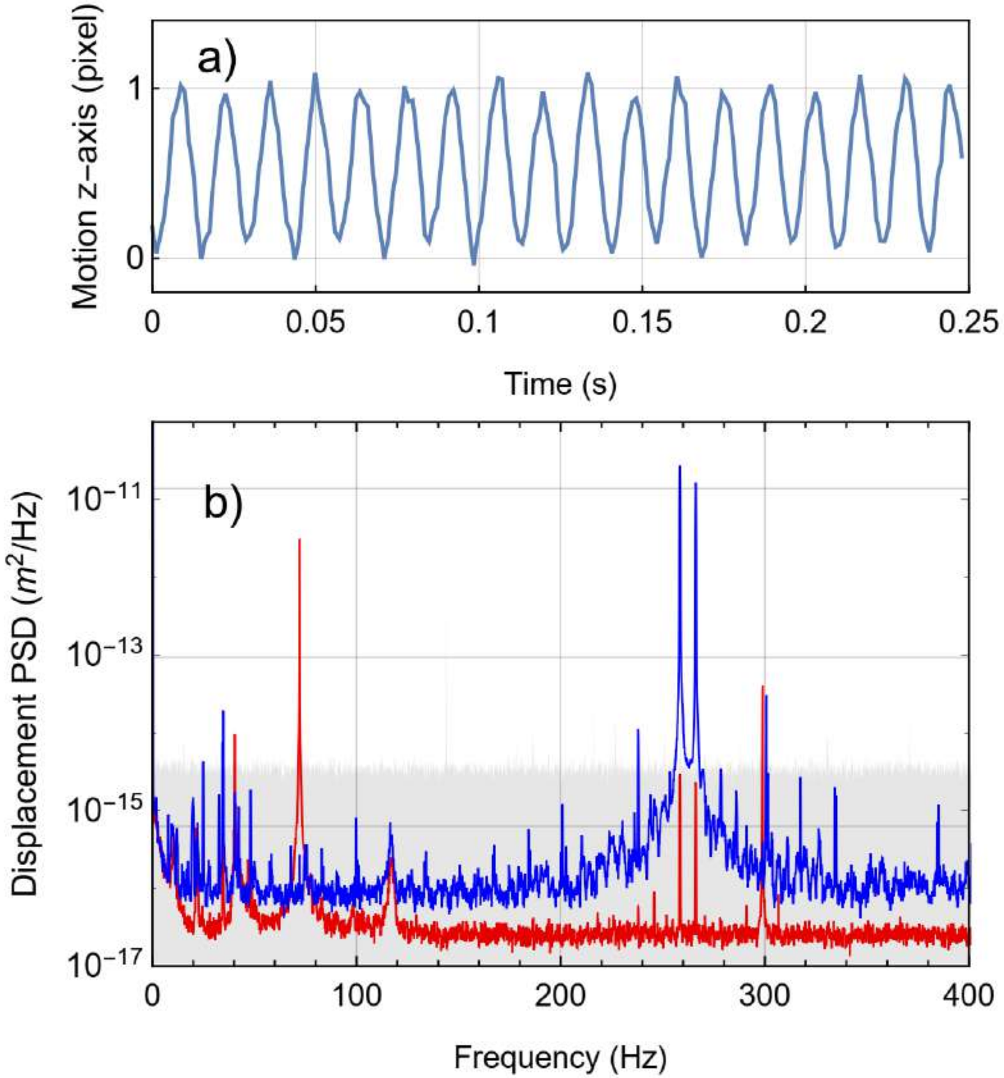
Quite easy to trap droplets!!



Vacuum
10^{-1} mbar

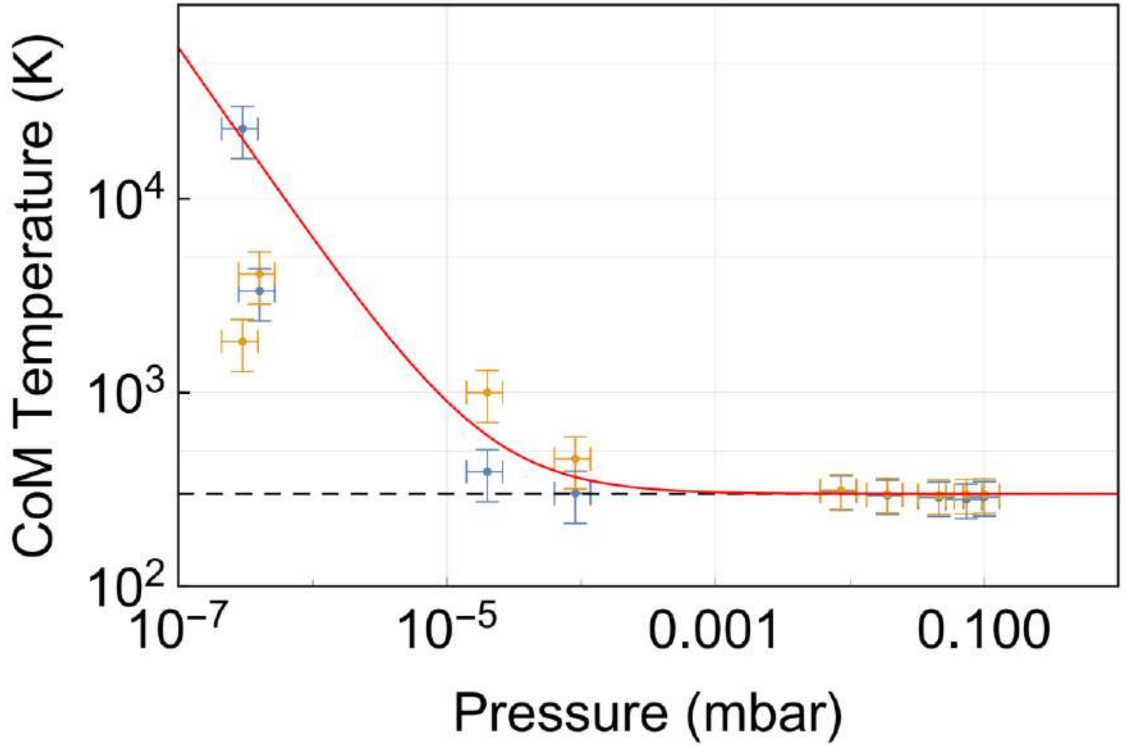
Detection

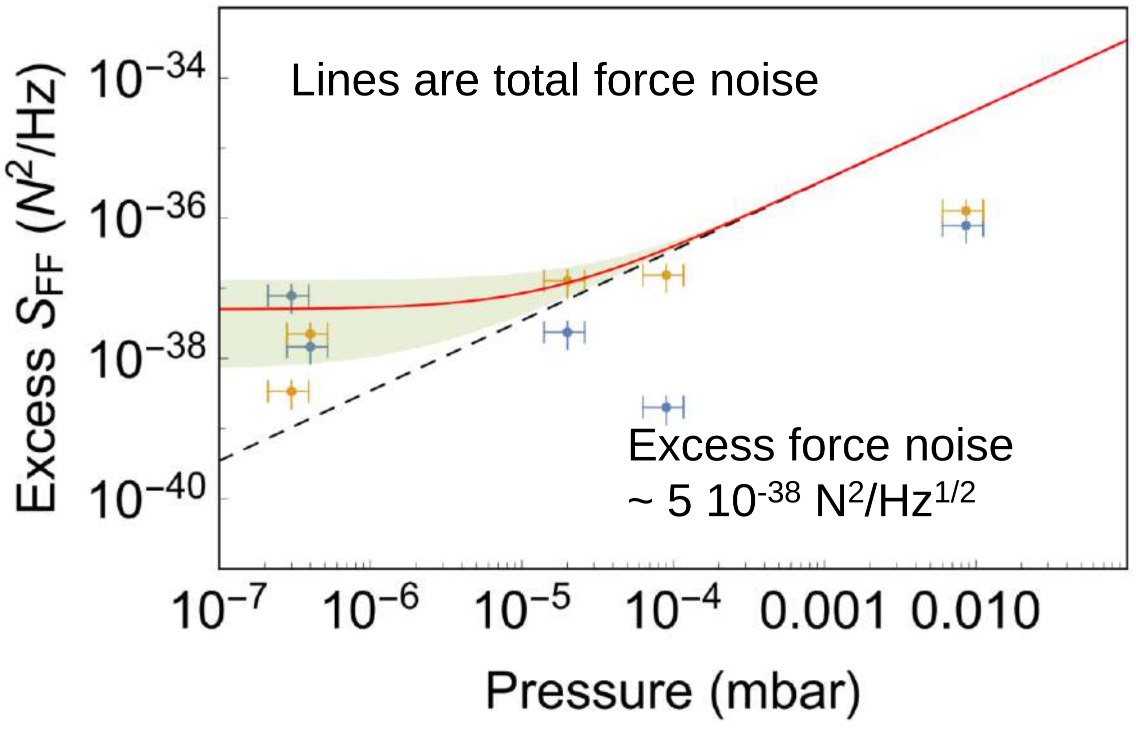




- Simple
- Absolute calibration
- Easy to extend to 3 DoF

Heating by excess noise





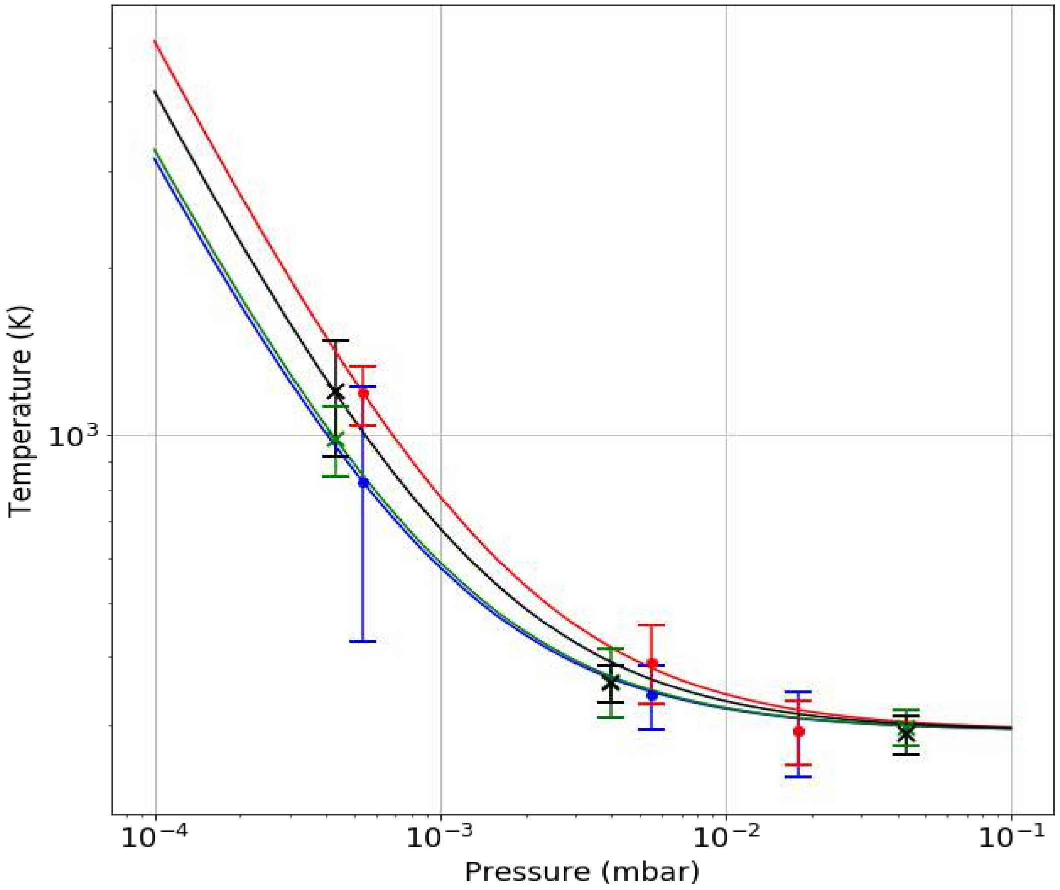
Measured noise sources

Compensation: $S_v \simeq 3\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$

Endcaps: $S_v \simeq 3\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$

AC (broadband): $S_v \simeq 220\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$

Recent tests to measure heating due to voltage noise



Increase effects of excess voltage noise by displacing particle from trap centre

$$T = T_0 + \frac{q^2}{2\gamma_0 m}(S_{AC}\left(\frac{\langle x\rangle}{D1}\right)^2 + S_{comp}(\frac{1}{D} + \frac{\langle x\rangle}{D1})^2)$$

New Electronics: $S_{ac} = 5\text{x}10^{-10}$, $S_{comp}=3\text{x}10^{-11}$ V^2/Hz

Old Electronics: $S_{ac}= 4\text{x}10^{-9}$, $S_{comp} = 3\text{x}10^{-10}$ V^2/Hz

Electronics

- All electronics developed delivered to UCL for testing (D2.1)
- All electronics implemented on UCL Paul traps
- Need further tests to confirm lower motional noise on particles – ongoing (delayed by Covid)
- Test on Blade trap from Aarhus (delayed by Covid)

Centre-of-mass cooling(2.2)

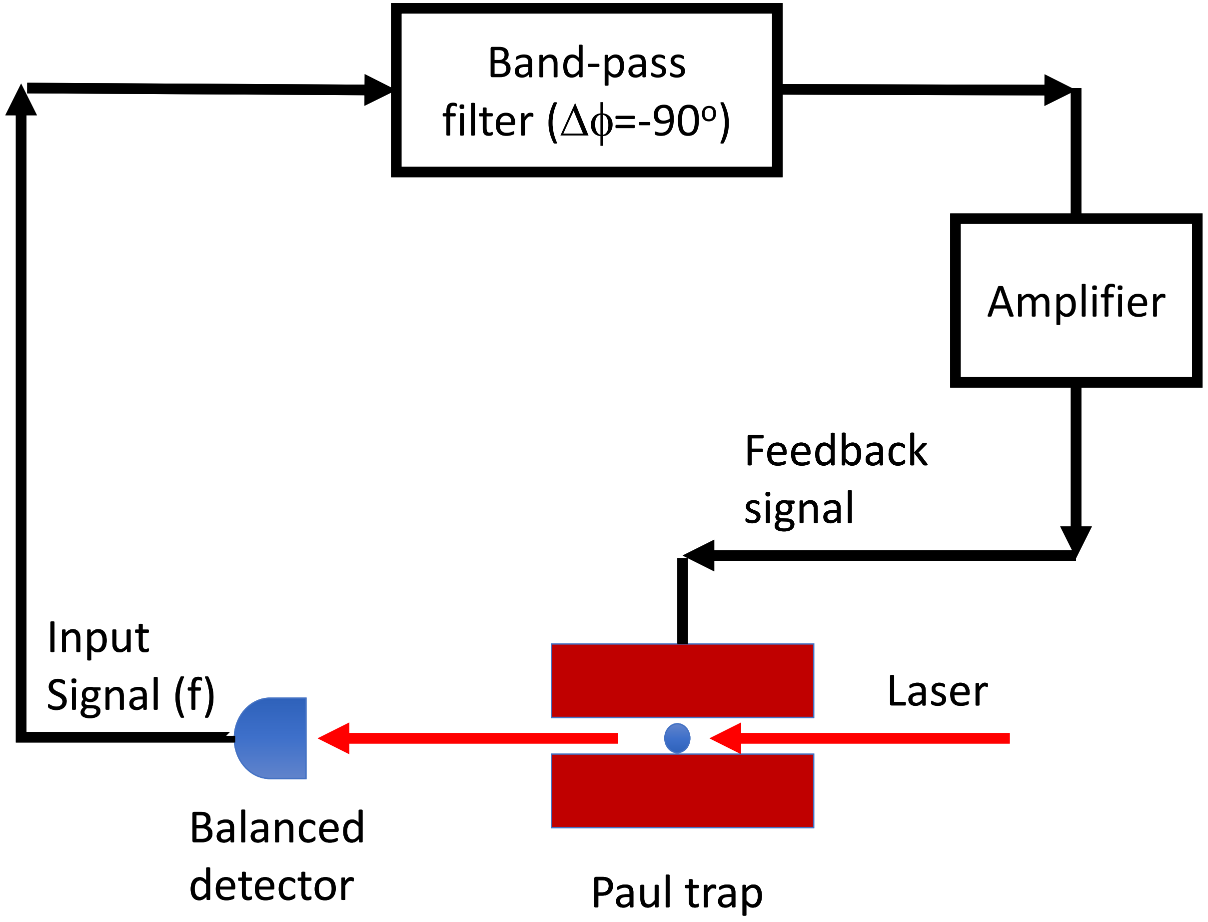
Comparison between active feedback methods

Two common ways to use feedback for cooling

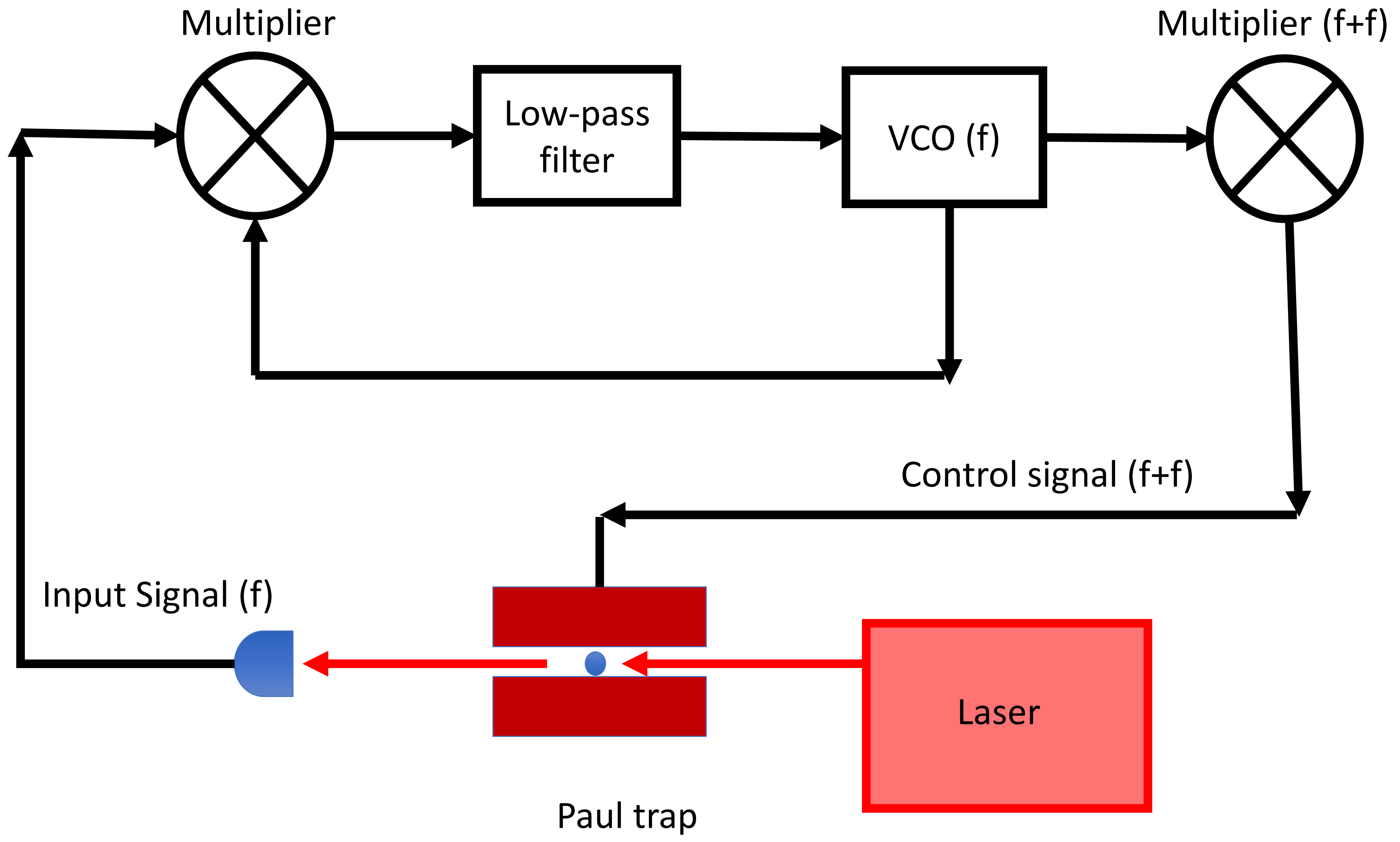
- Velocity damping
- Parametric

We have <u>previously</u> demonstrated parametric feedback cooling and recently velocity damping

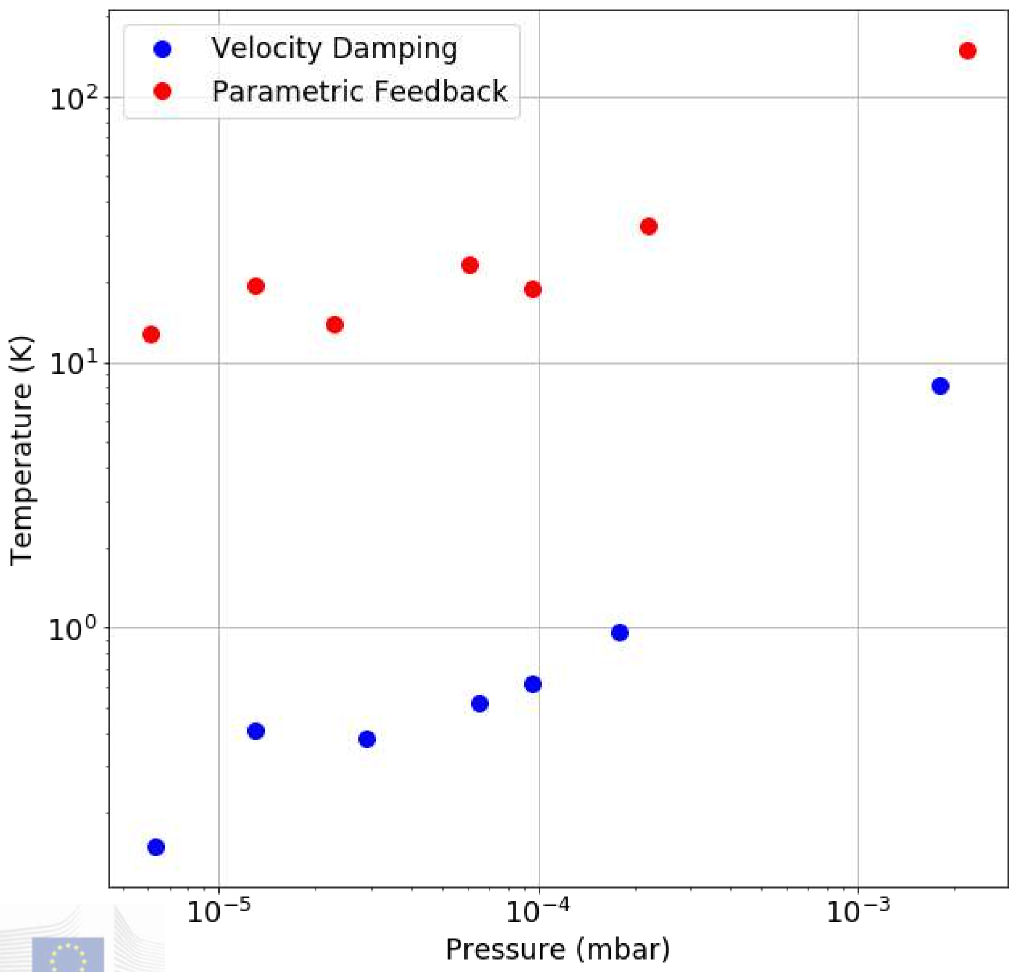
Wanted to compare these two as part of determining optimal strategy

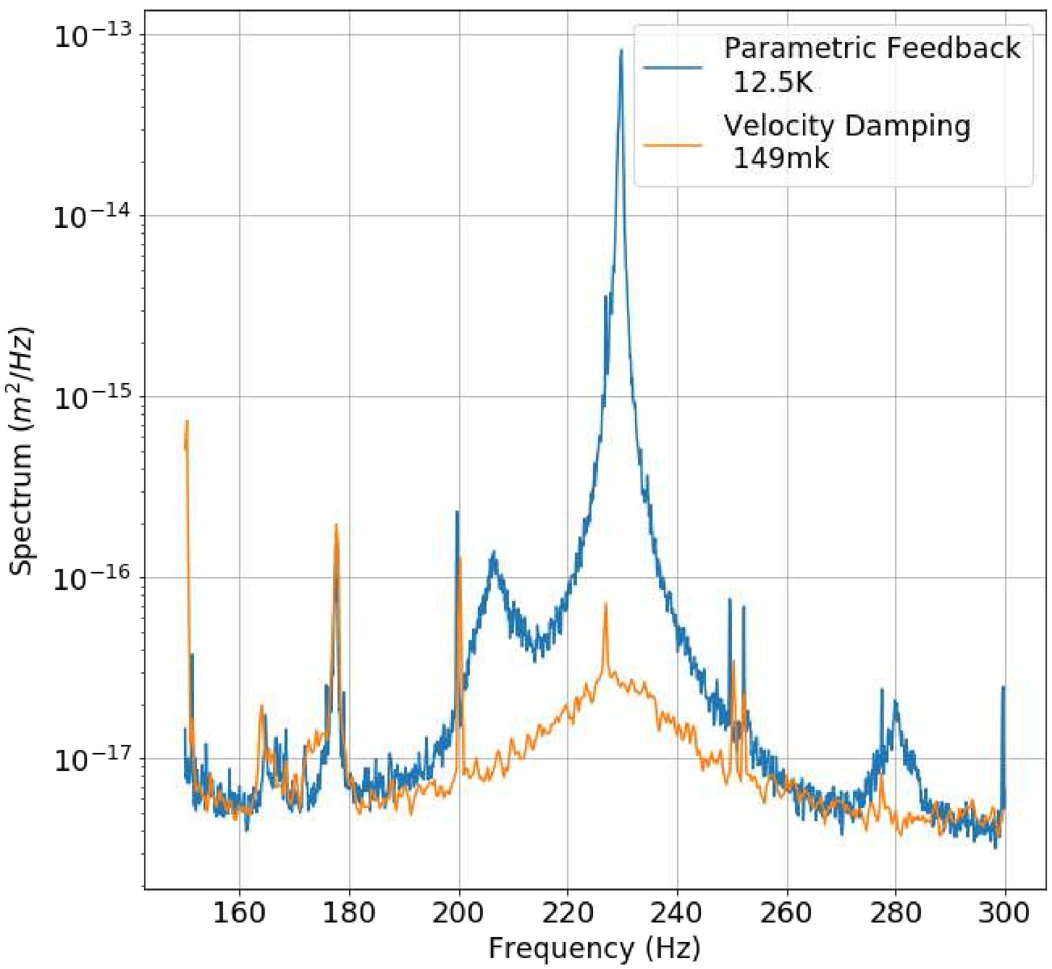


Recent tests to measure heating due to voltage noise - Parametric

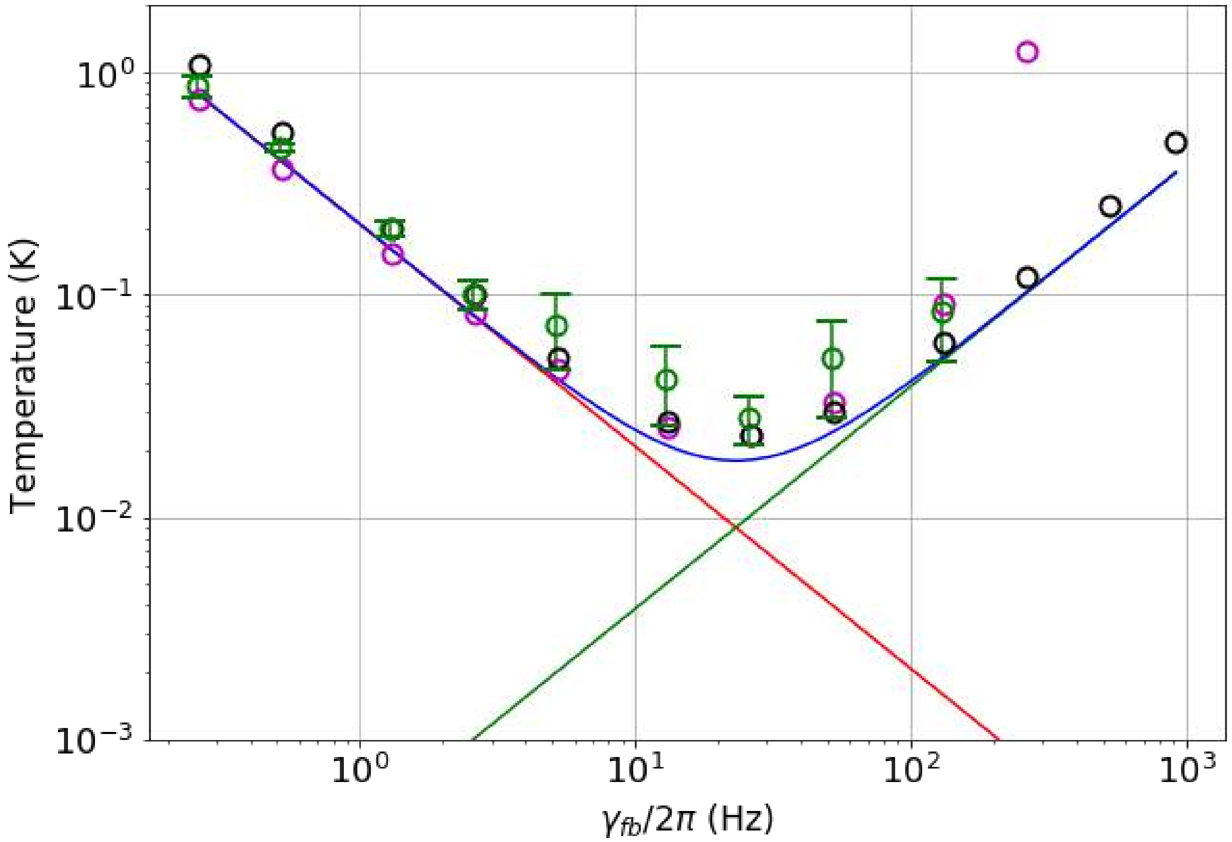


Feedback cooling





Velocity damping (10^{-6} mbar)



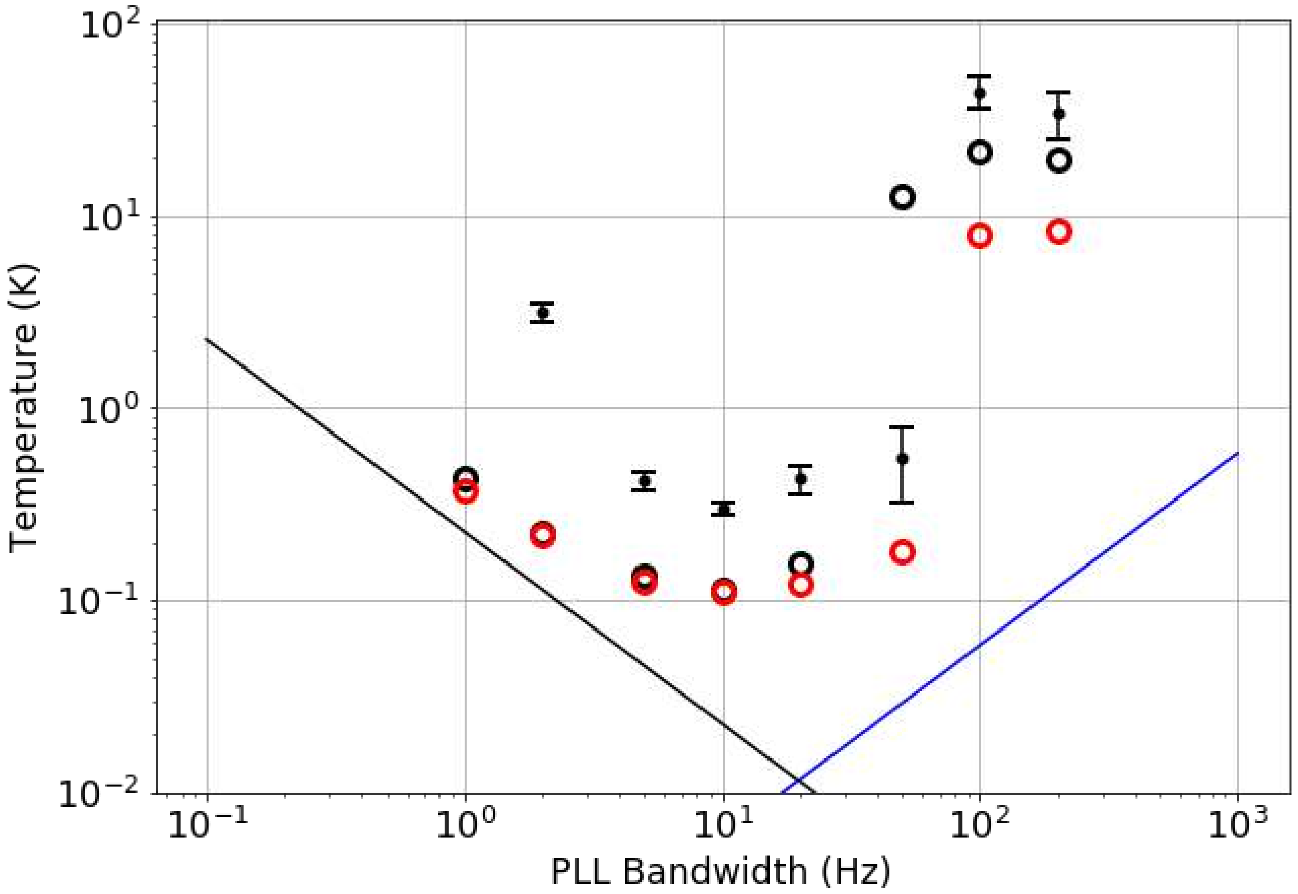
Blue line – analytical model

Black circles - simulation with ideal filter

Purple circles simulation - deviates rapidly at high gain. Shifted position becomes a worse prediction of the velocity.

Green circles - experimental results for velocity damping. Measured with out-of-loop detector.

Parametric cooling (10^{-6}mbar)



Black line - limit of PLL bandwidth on the oscillator linewidth (Temp). Oscillator linewidth > PLL bandwidth - PLL no longer tracks frequency.

Blue line - detection noise floor. As the bandwidth increases more noise is included with the loop decreasing the SNR in PLL.

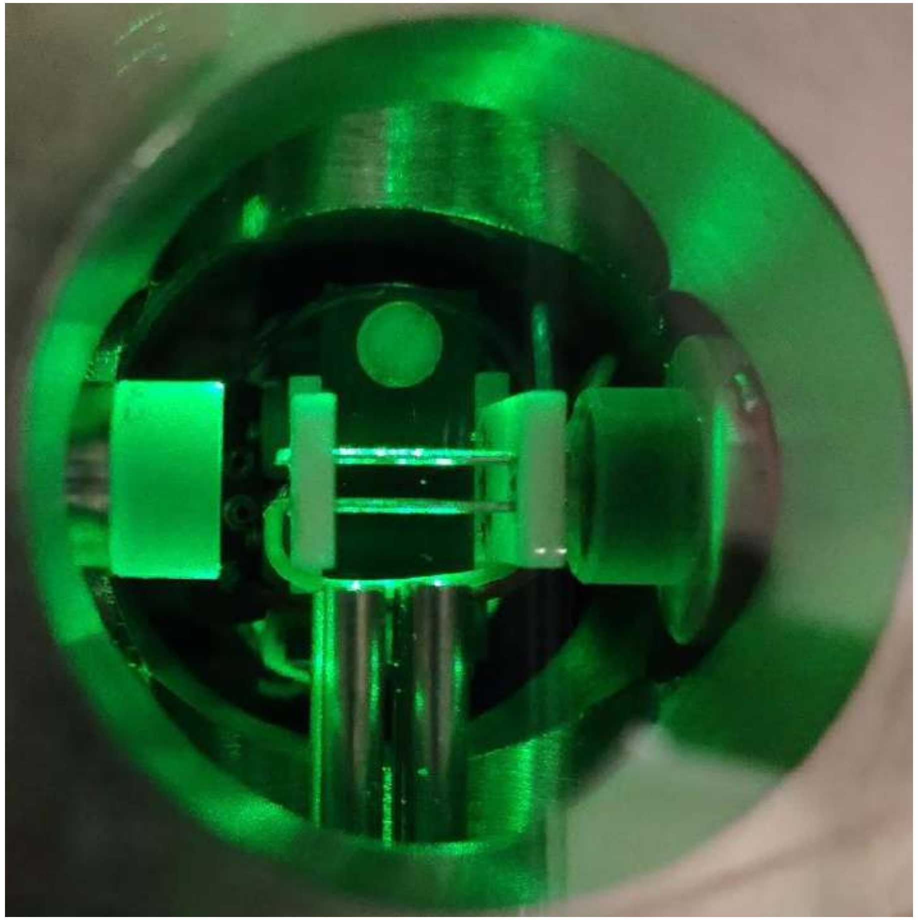
Red circles – simulation. Temperature above bounds but minimum where both bounds are equal.

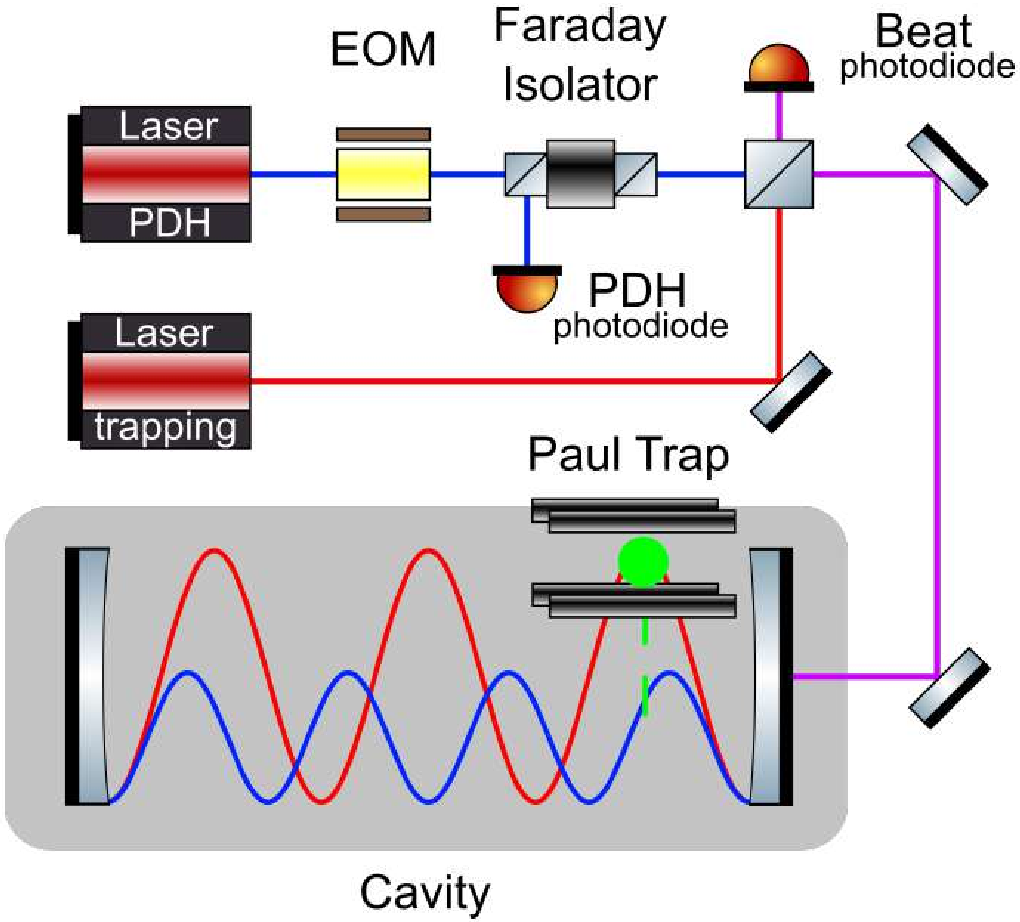
Black dots - experimental data.

Velocity damping - easier and achieves temperature 1 order of magnitude lower than parametric method

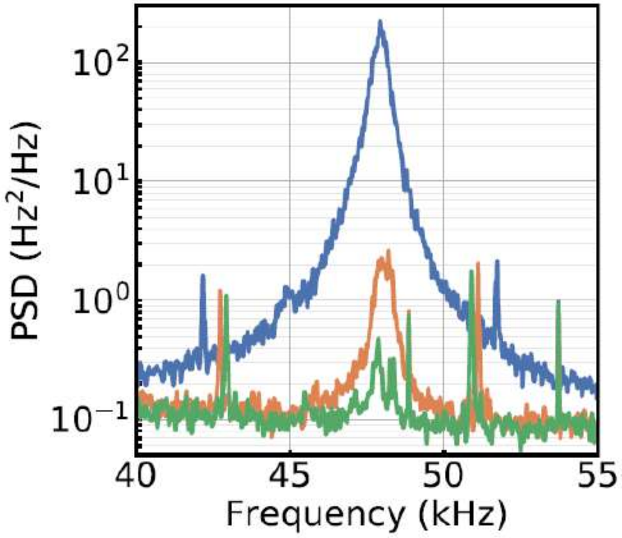
Cavity cooling in the Paul trap

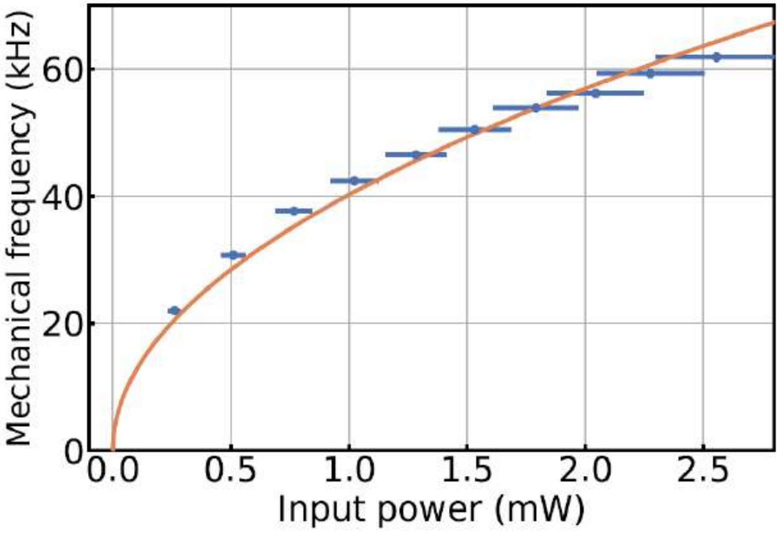
Only suitable for where displacement of particle << $\lambda/2$





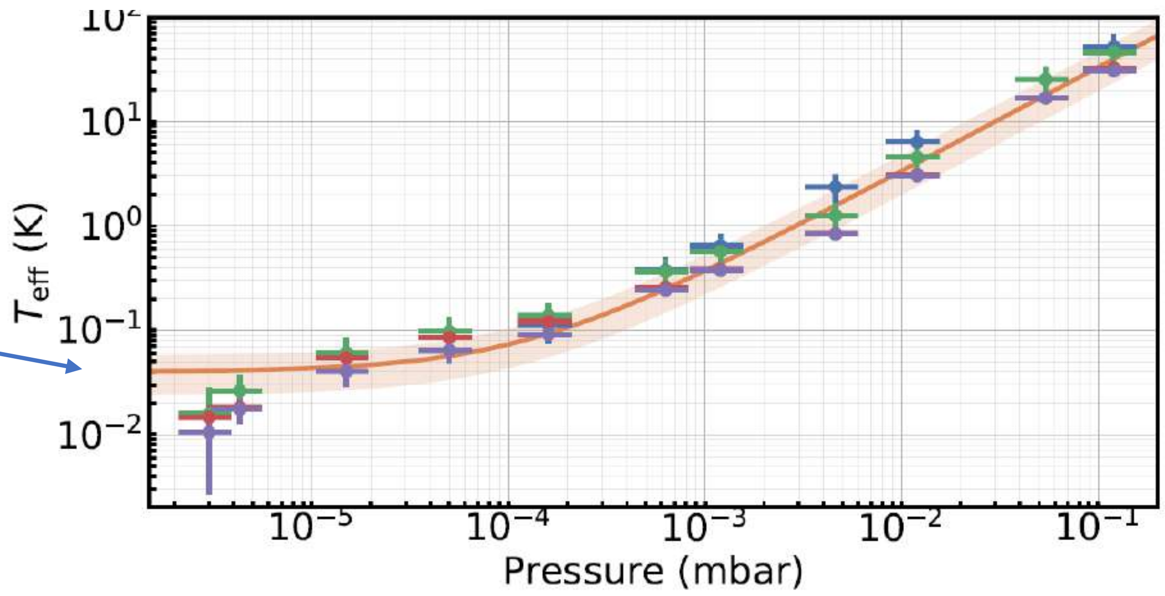
Linear coupling



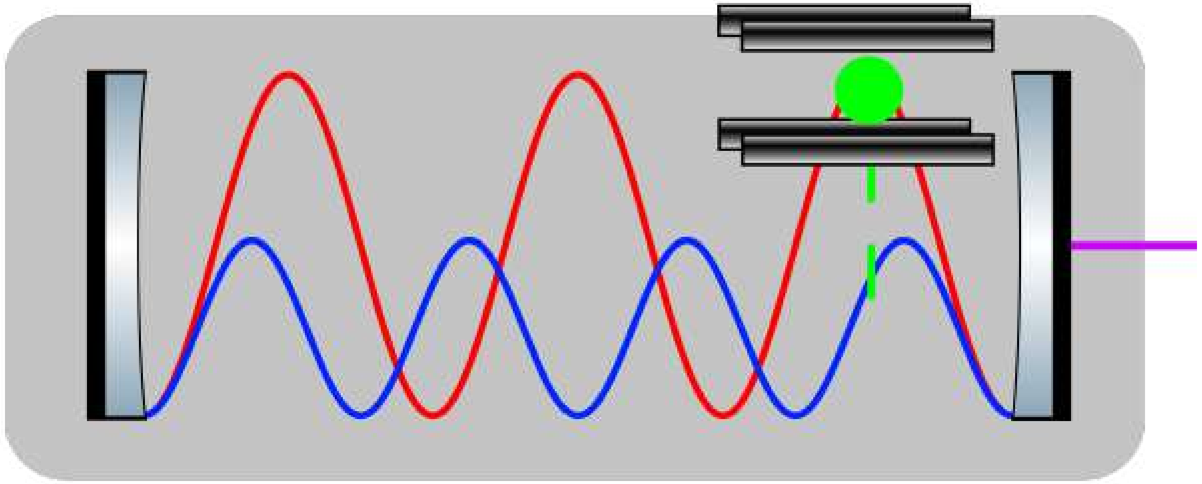


Temperature limit of 20 mK at 10^{-6} mbar

- currently limited by voltage noise induced by misalignment between cavity and Paul trap
- eventually limited by frequency noise in the laser



Non-linear coupling



Of interest for phonon shot noise measurements, protocols for generating non-classical states

Dynamics – same as parametric feedback cooling but is passive

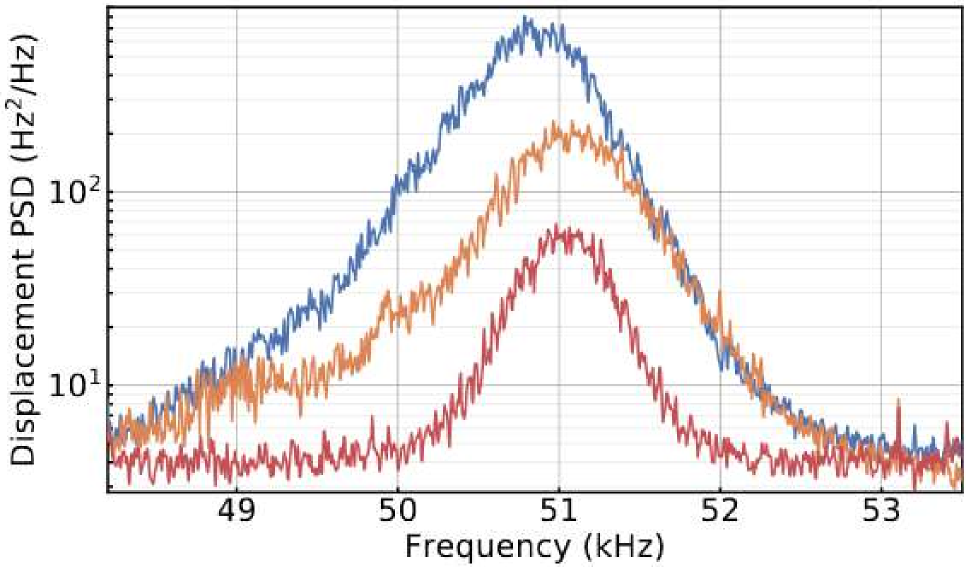
$$\dot{R} = -\frac{\gamma_m}{2}R + \frac{\omega_m^2\gamma_{nl}}{8}R^3 + \frac{S_{F_{th}}}{4m^2\omega_m^2 R} + \xi = -\frac{d\mathcal{V}(R)}{dR} + \xi\,,$$

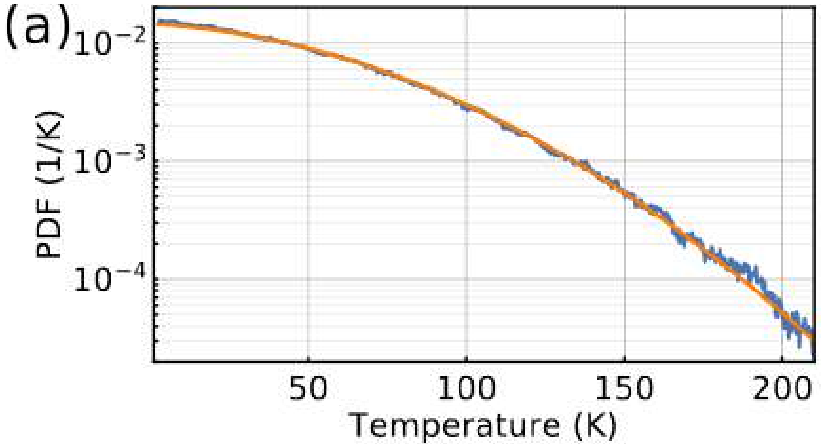
$$\dot{\varphi} = \frac{3\omega_m}{8}\epsilon_D R^2 + \frac{1}{R}\chi.$$

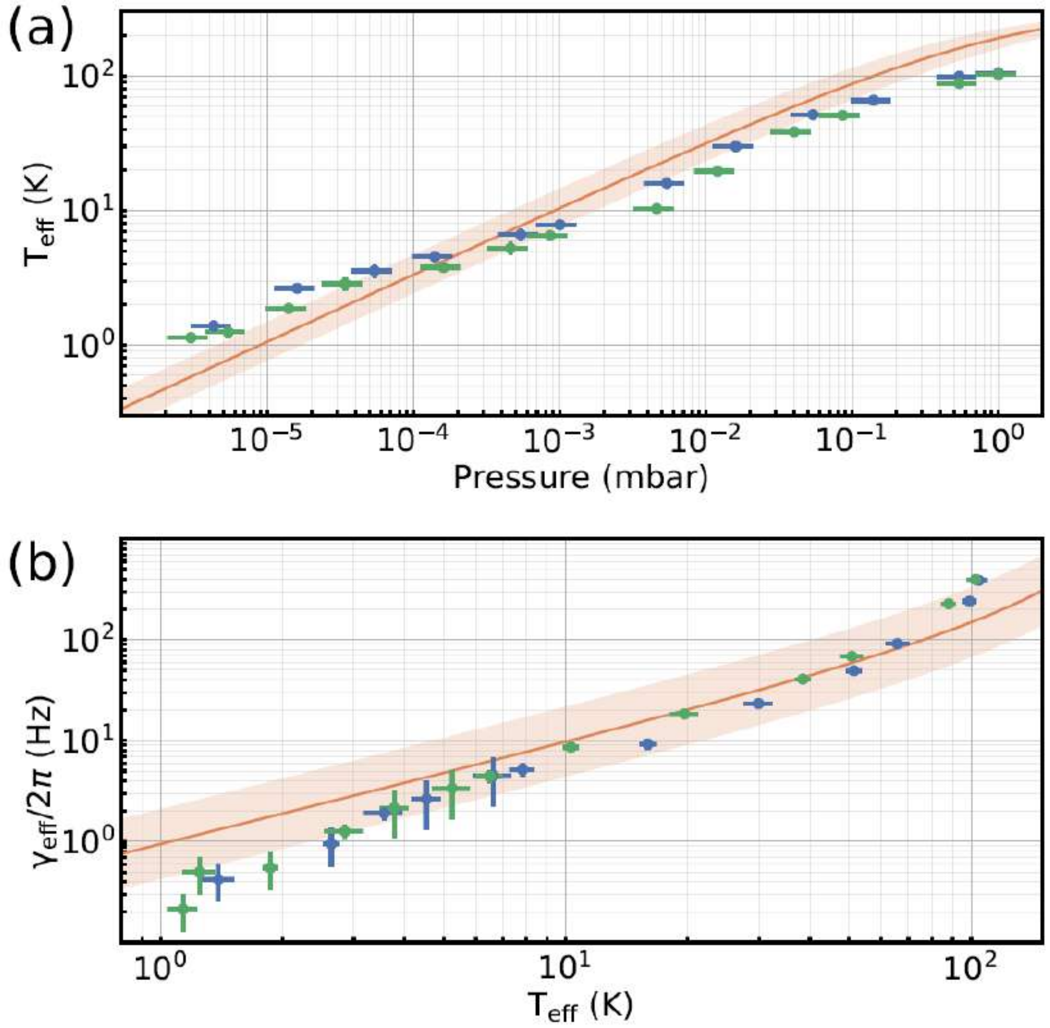
$$P_\infty(E) = \frac{\mathcal{N}}{m\omega_m^2}\exp\left[-\frac{E}{k_B T_b}\left(1 + \frac{\gamma_{nl}}{4m\gamma_m}E\right)\right]$$

Non-linear coupling

See arXiv:2006.16103 for more details

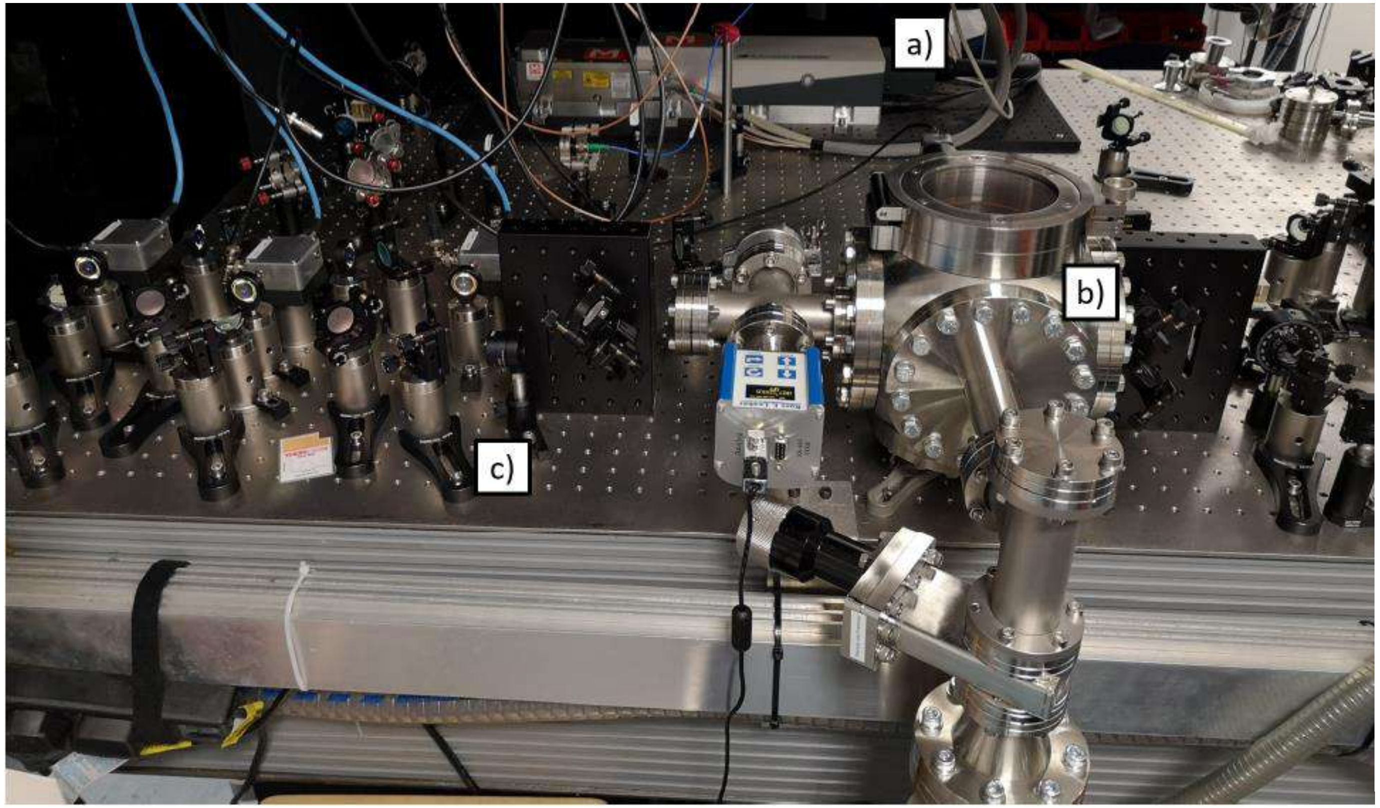


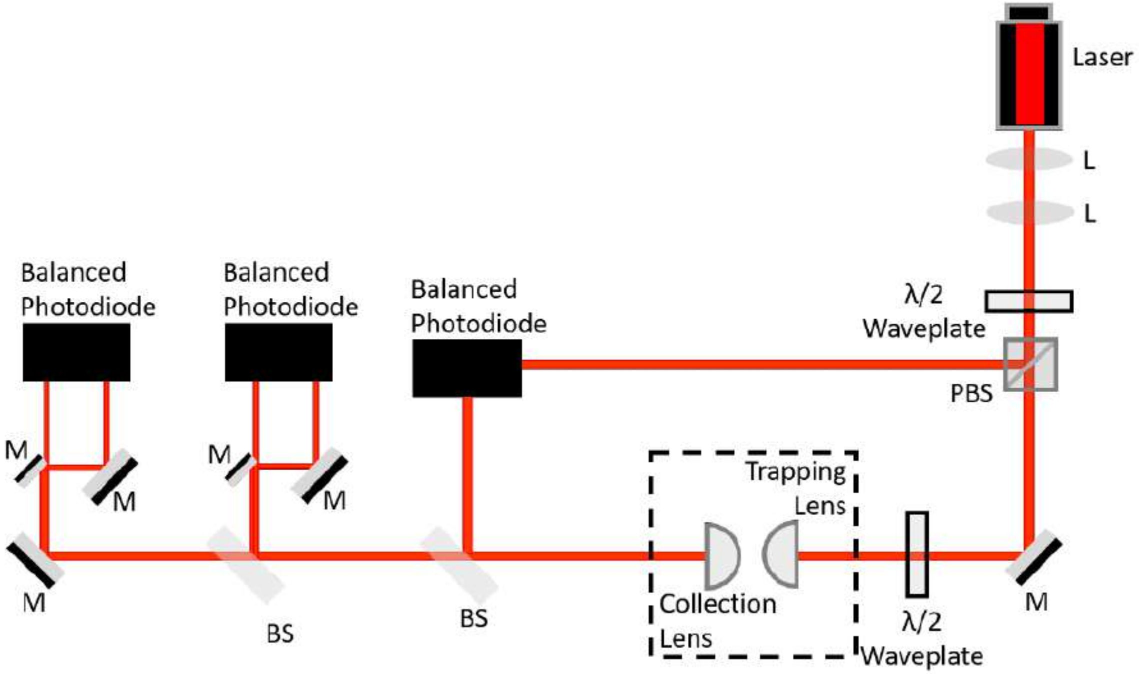




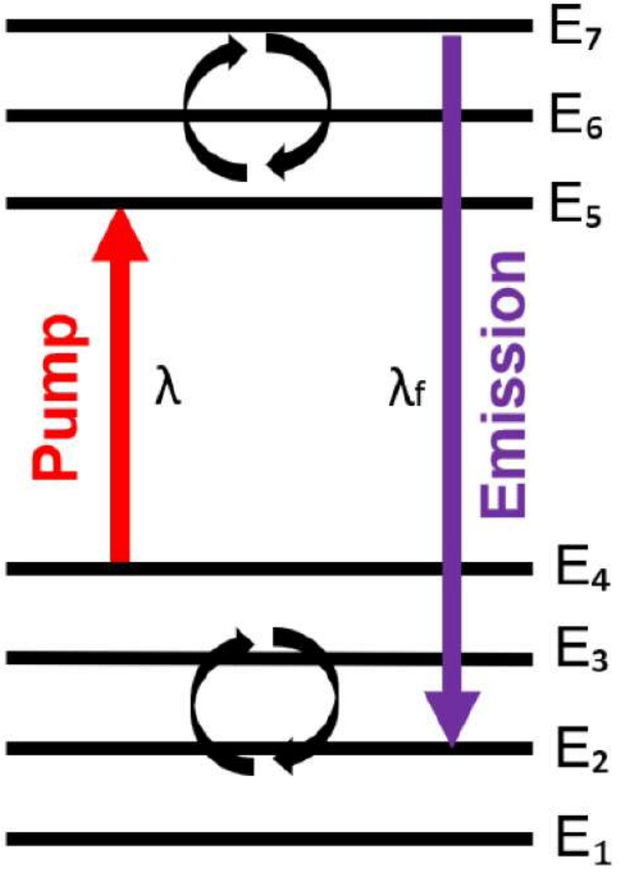
Internal state cooling (2.3)

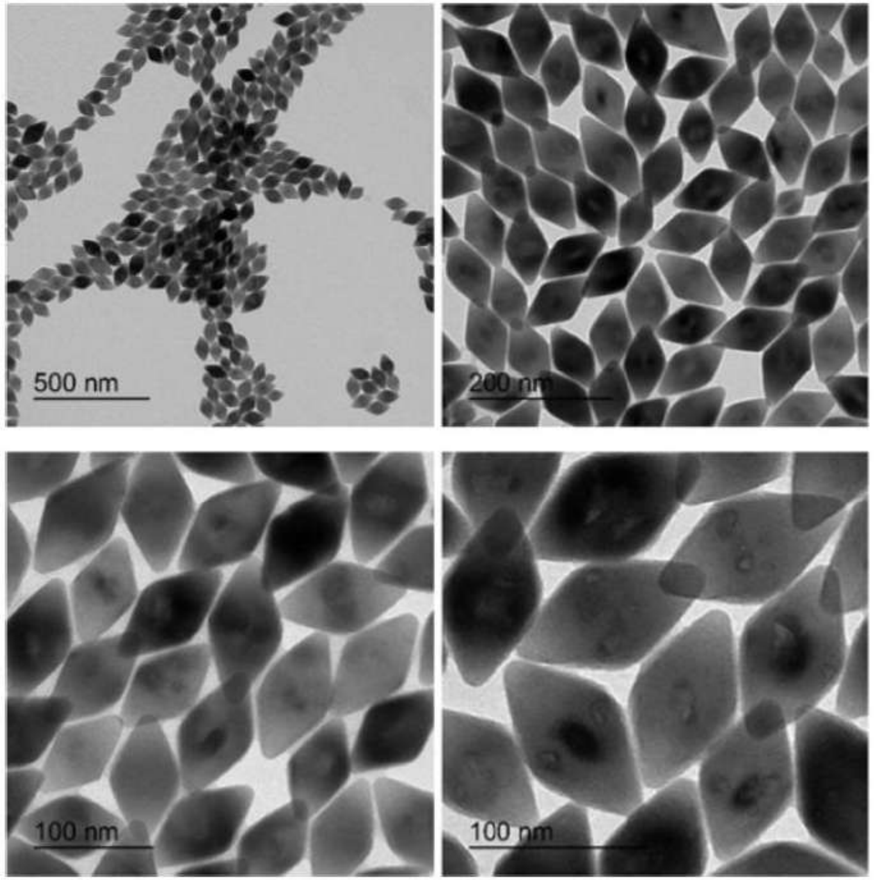
Optical trapping experiment





Laser refrigeration





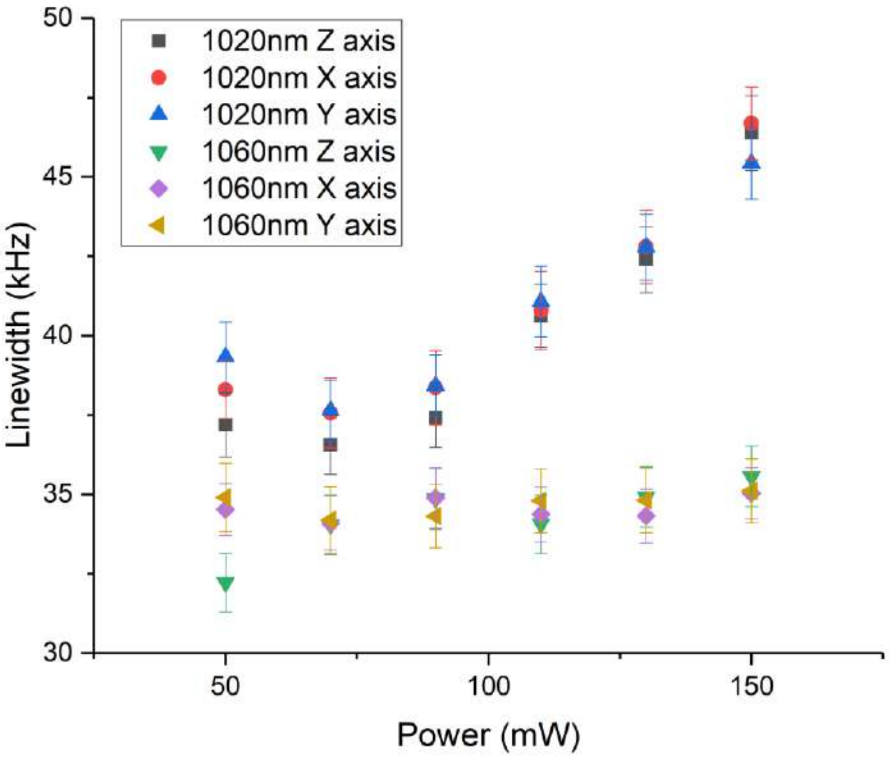
Previously– loss in particle size in trap by heating

Trapped particle is an oscillator undergoing Brownian motion. The linewidth, γ, of the power spectral density of its displacement is proportional to its temperature as T.

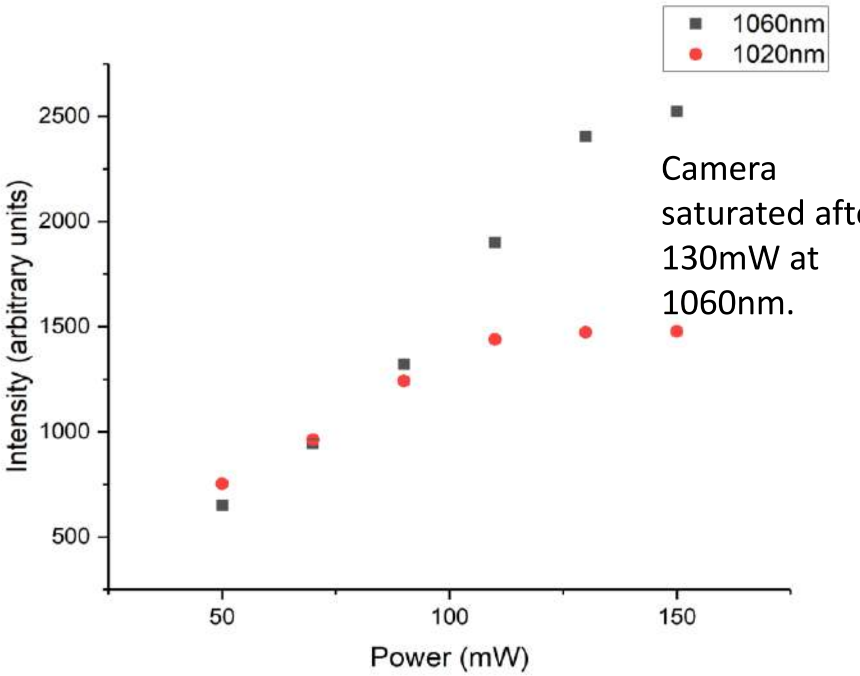
$$T_{hot} = \frac{(T^{imp})^{3/2} + \frac{\pi}{8}(T^{em})^{3/2}}{(T^{imp})^{1/2} + \frac{\pi}{8}(T^{em})^{1/2}}$$

For doped YLF nanocrystals at a trapped wavelength of 1020 nm, the linewidth increases with trapping power indicating heating up to 420 K when compared to 1064 nm where little to no heating occurs.

Linewidth vs Power at 5mbar

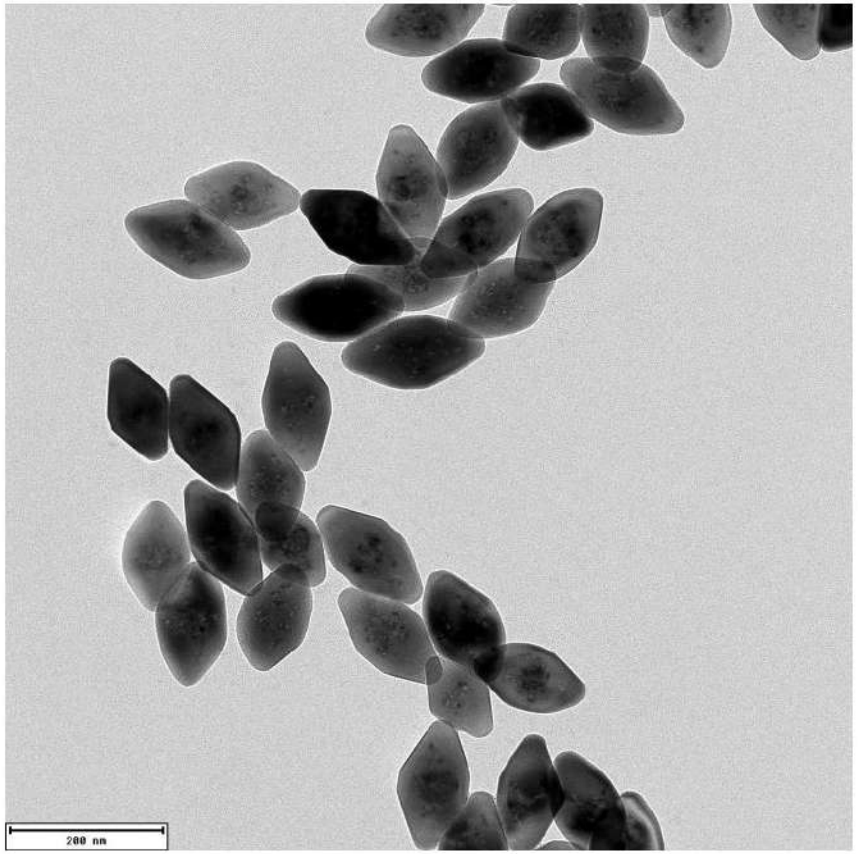


Intensity vs Power at 5mbar

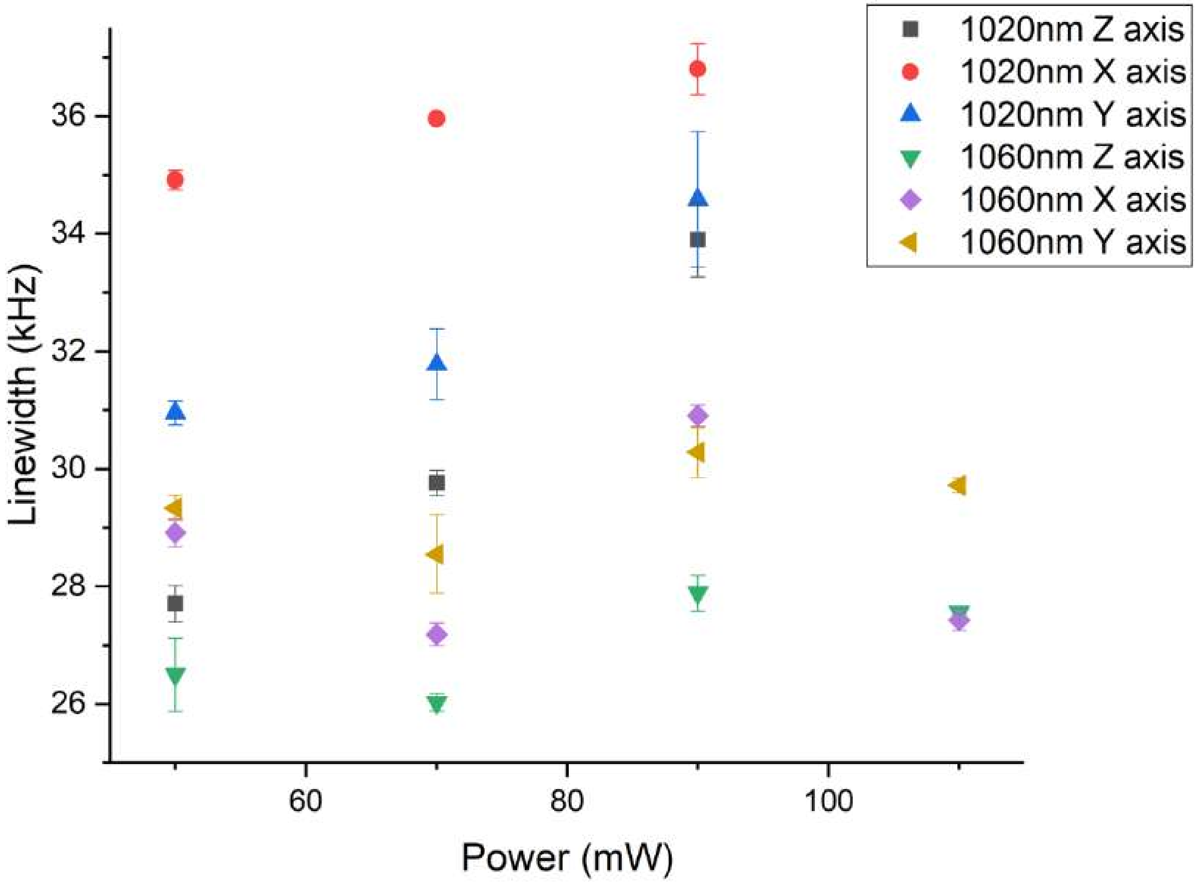


Camera saturated after 130mW at 1060nm.

Core and core shell nanocrystals

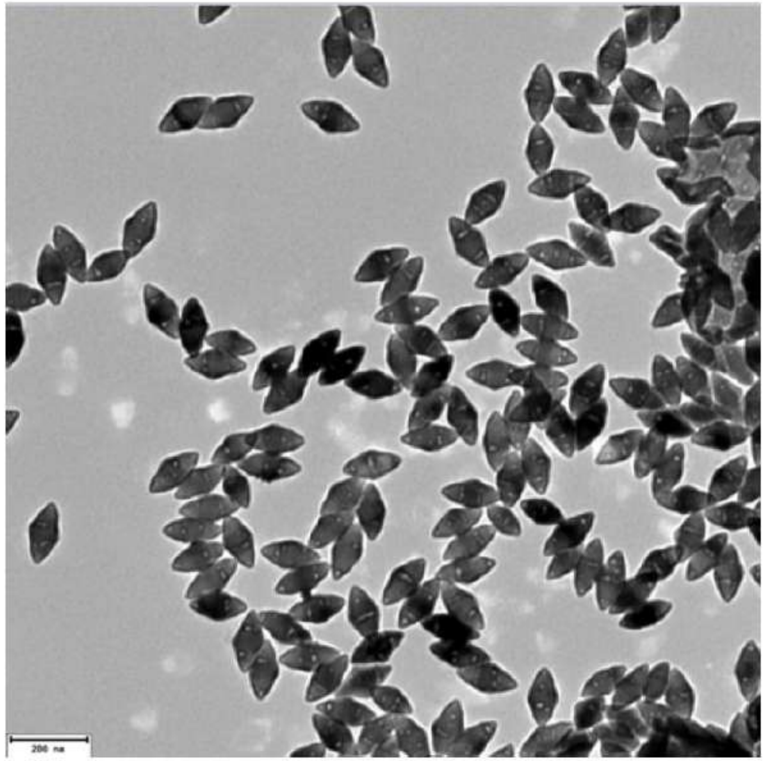


TEM image of the colloidally grown bipyramidal core-shell Yb^{3+}:YLF nanocrystal, JM179 sample. Credit: Jence Mulder.

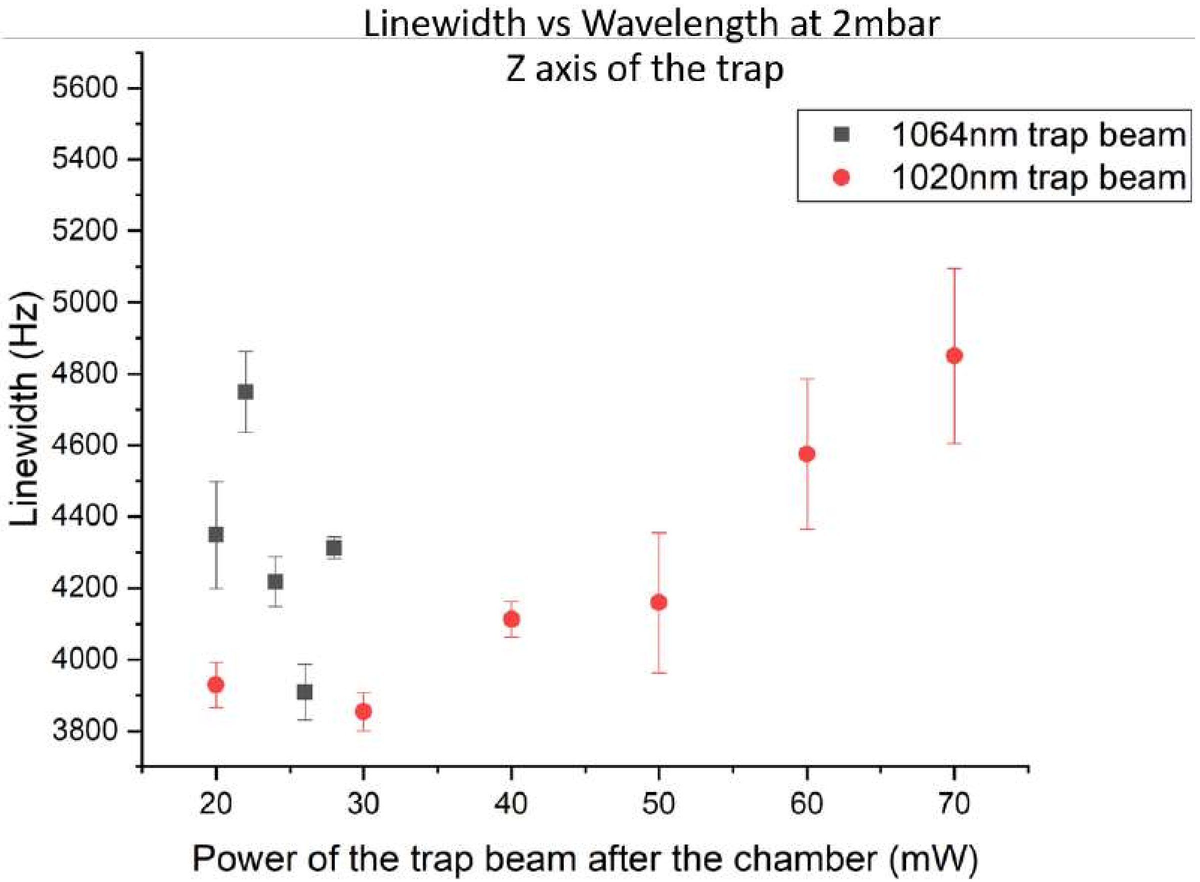


Both JM178 and 179 tested. JM179 melted before 178

Undoped YLF nanocrystals

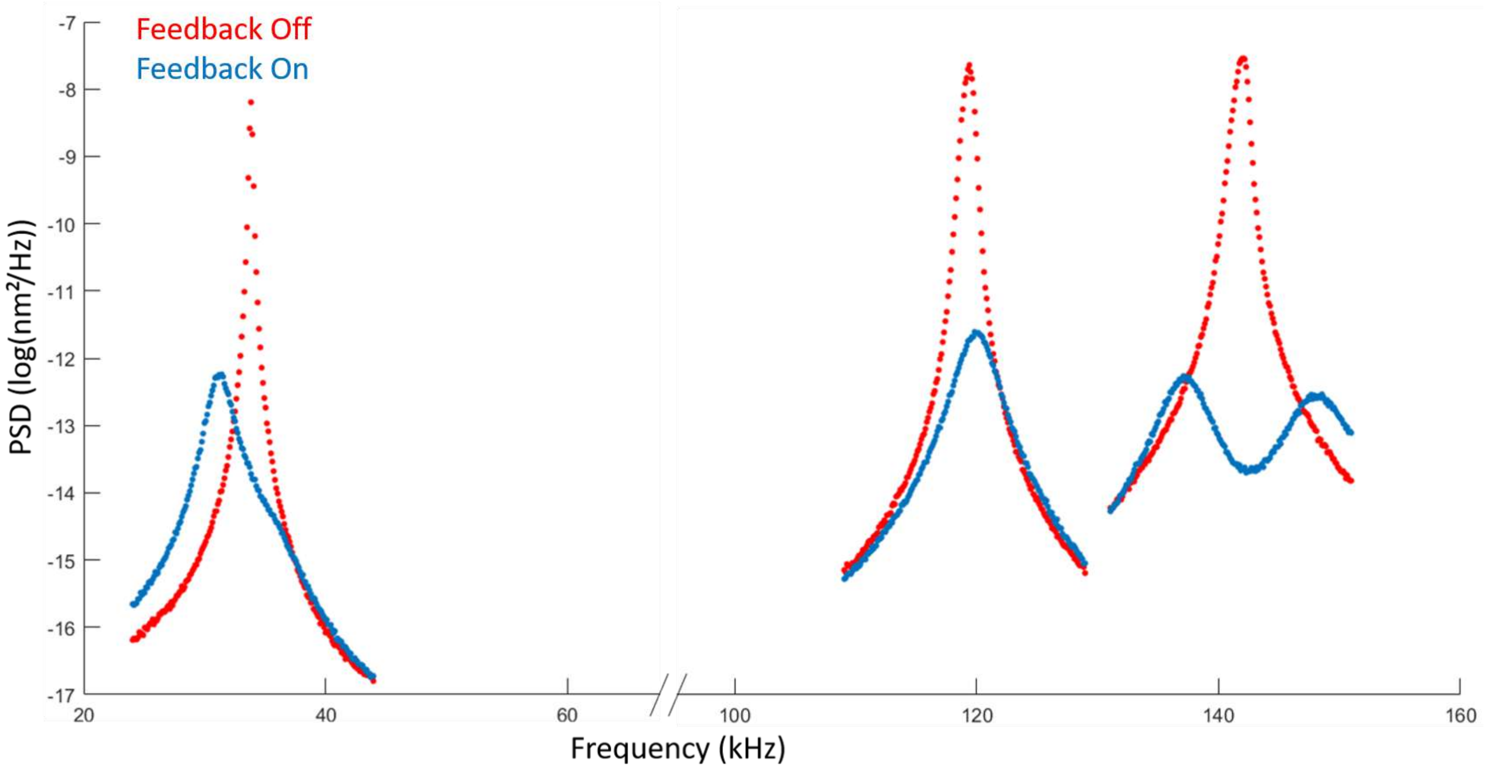


SEM image of the colloidally grown bipyramidal undoped YLF nanocr
JJB26 sample. Credit: Jence Mulder and Jasper van Blaaderen.

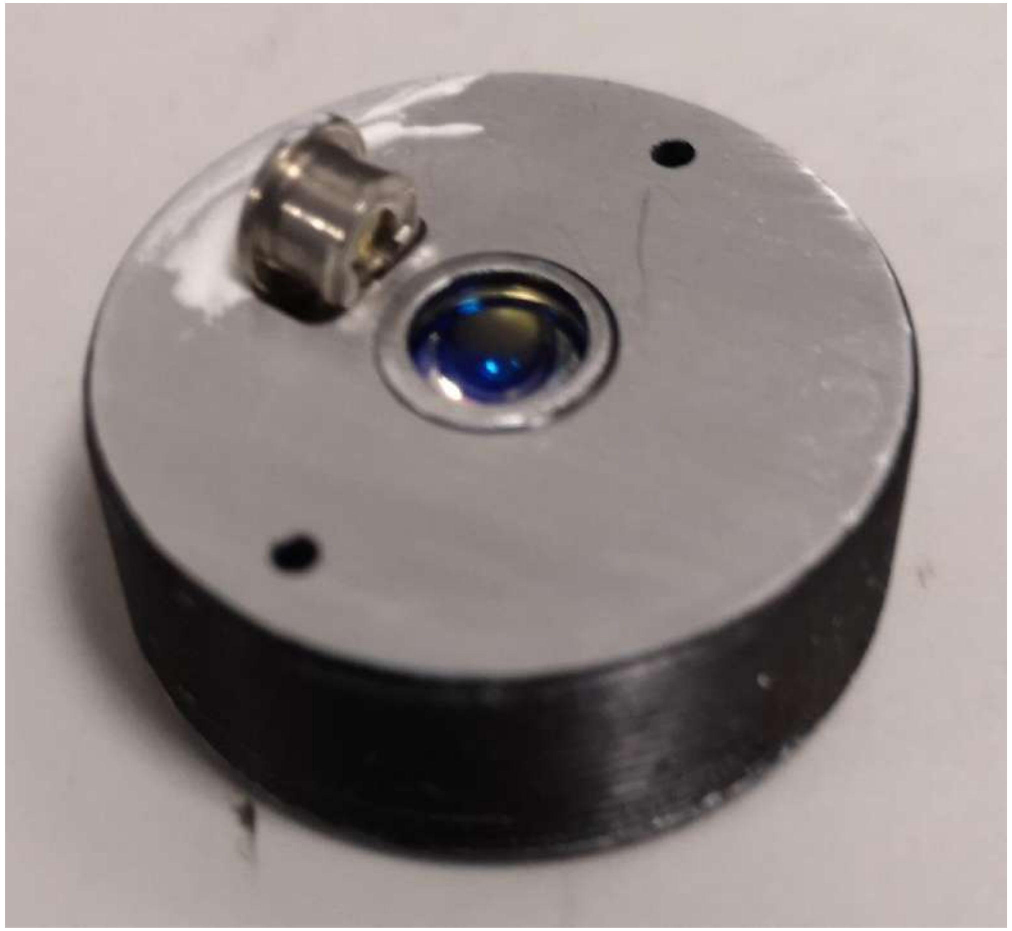


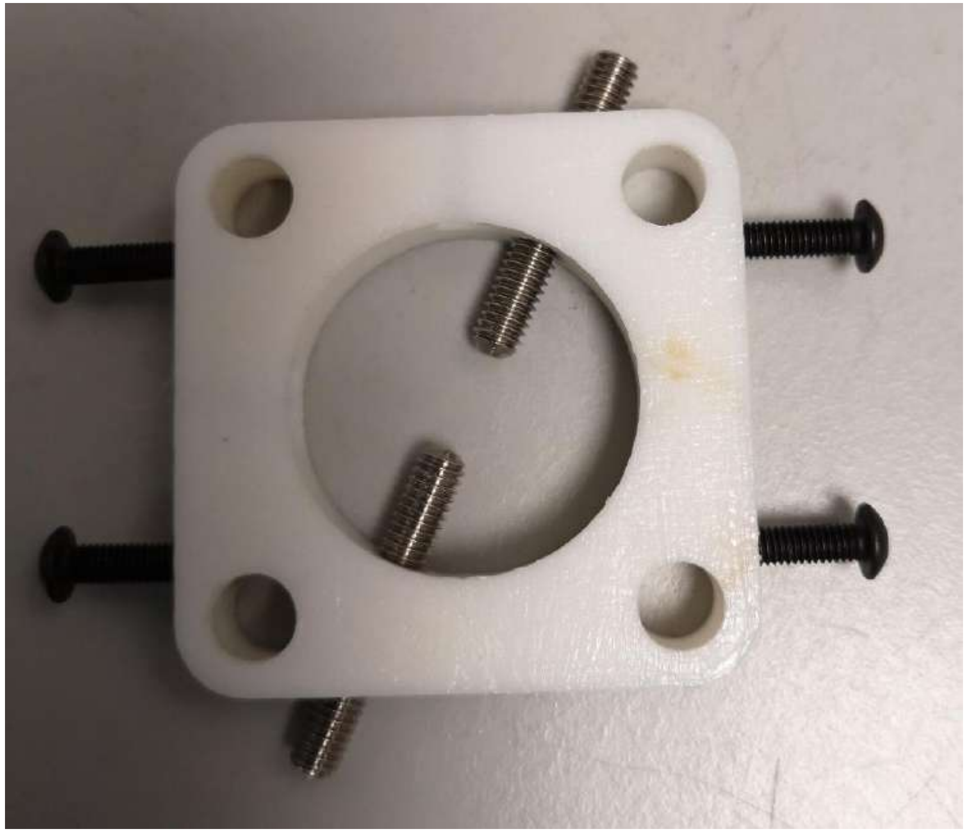
Trapping and COM cooling of undoped YLF

- No significant heating of the undoped YLF nanocrystals
- Samples JJB26 & JJB57 only lost below 10^{-2}mbar (0.57 mbar below)



Alpha particle charging of particles



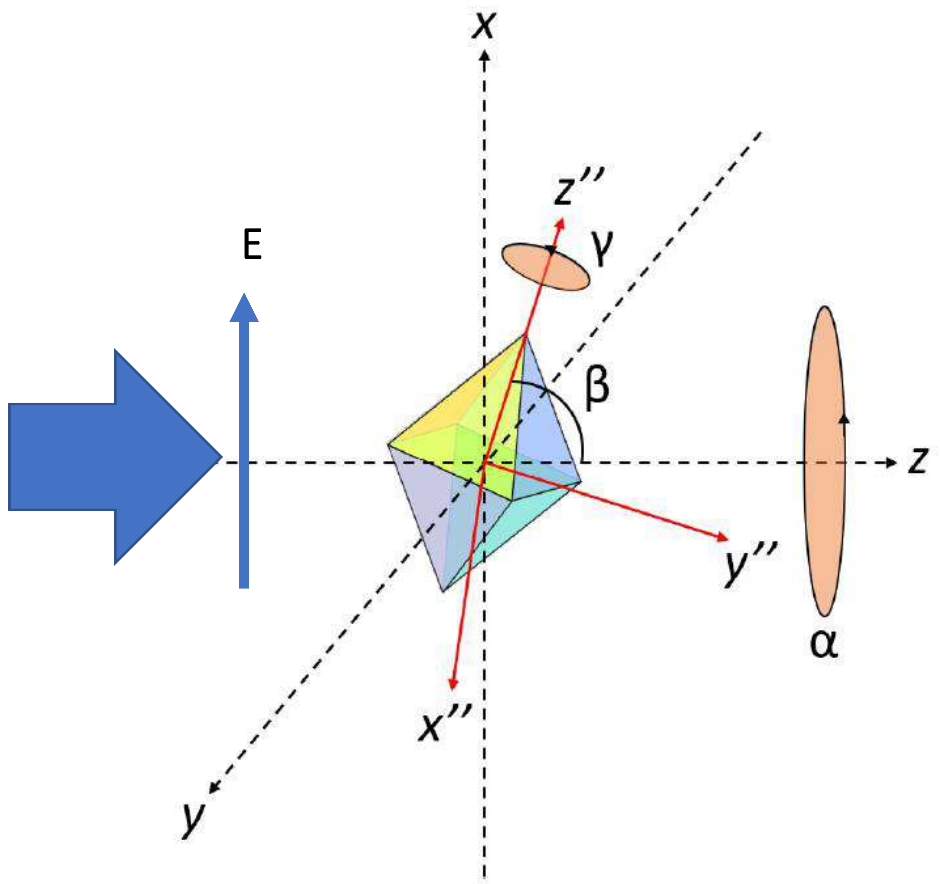


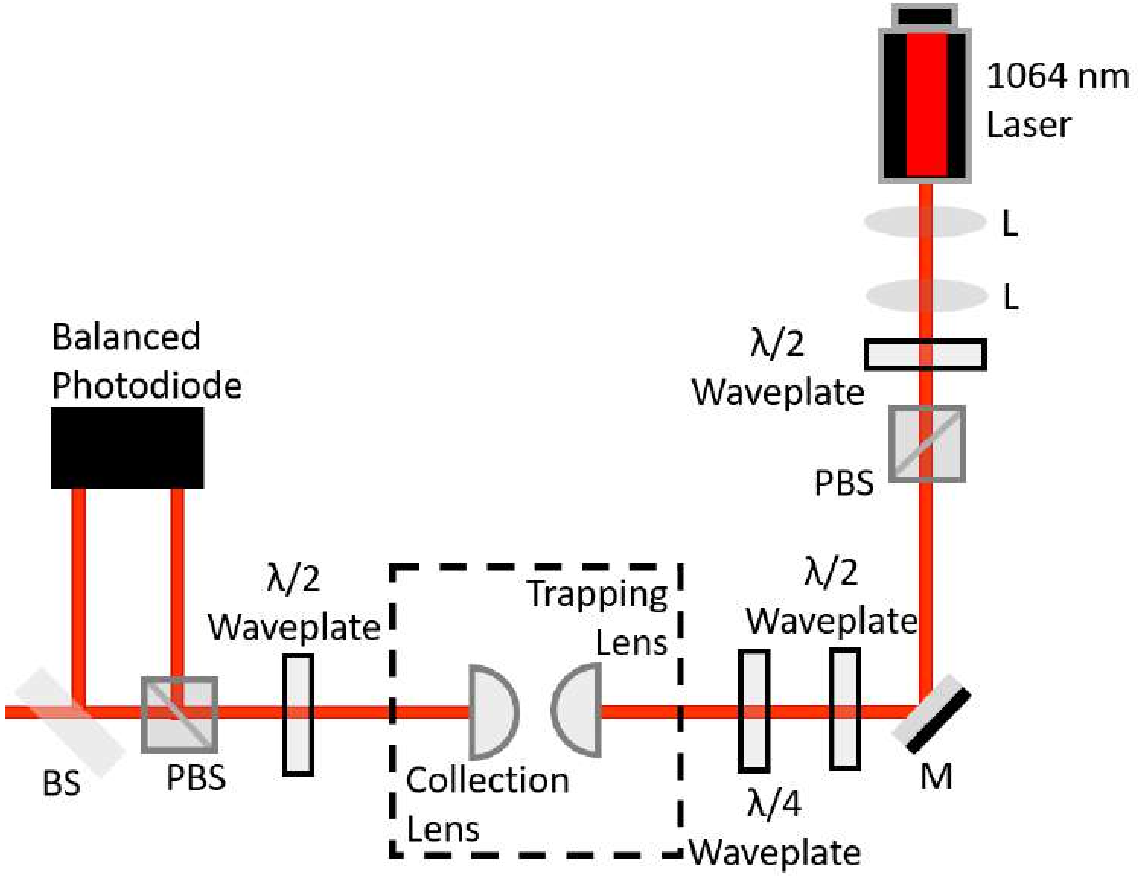
Laser problems – focus on undoped YLF

- Unstable Ti:Sa pump laser since 11/19
- Unable to use for measurements
- Recently resumed YLF nanocrystal testing with new pump laser in 09/20 manufactured by M2
- Focused on undoped YLF measurements

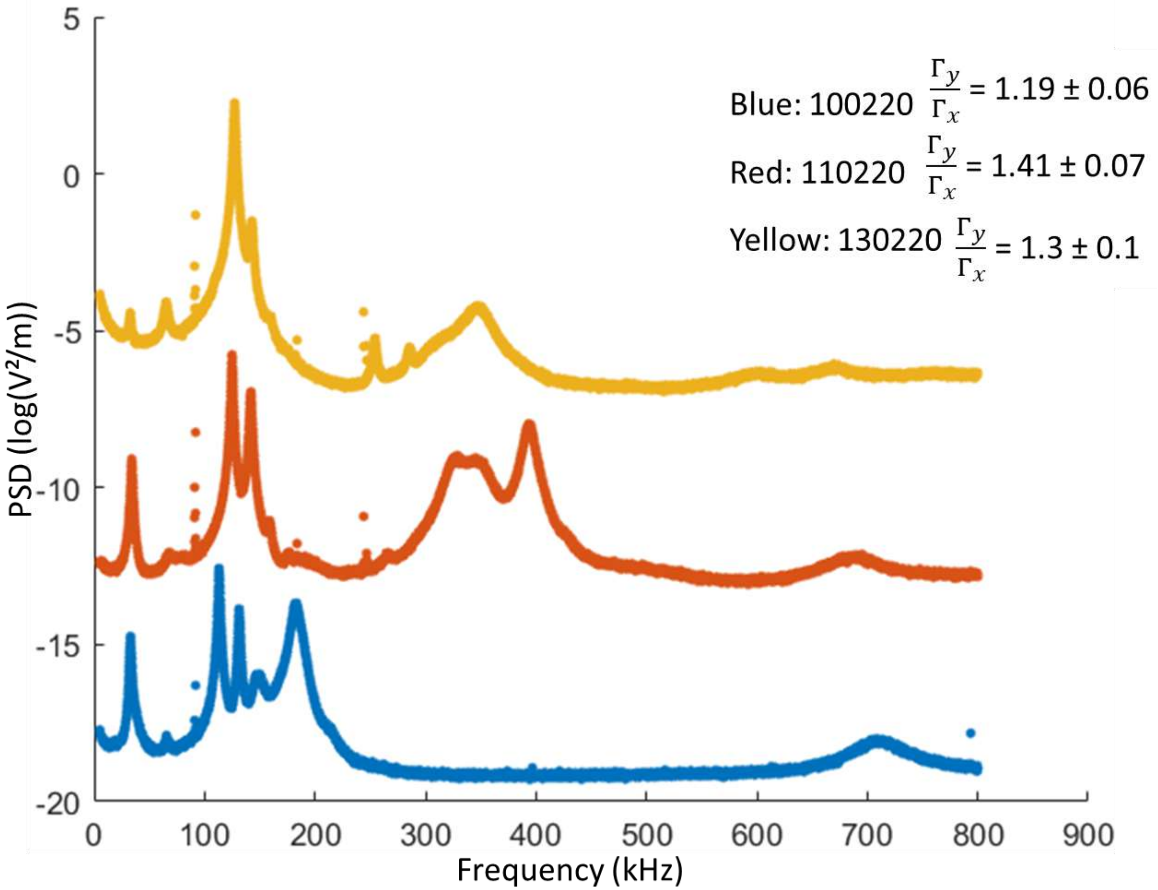
Rotation of nanocrystals

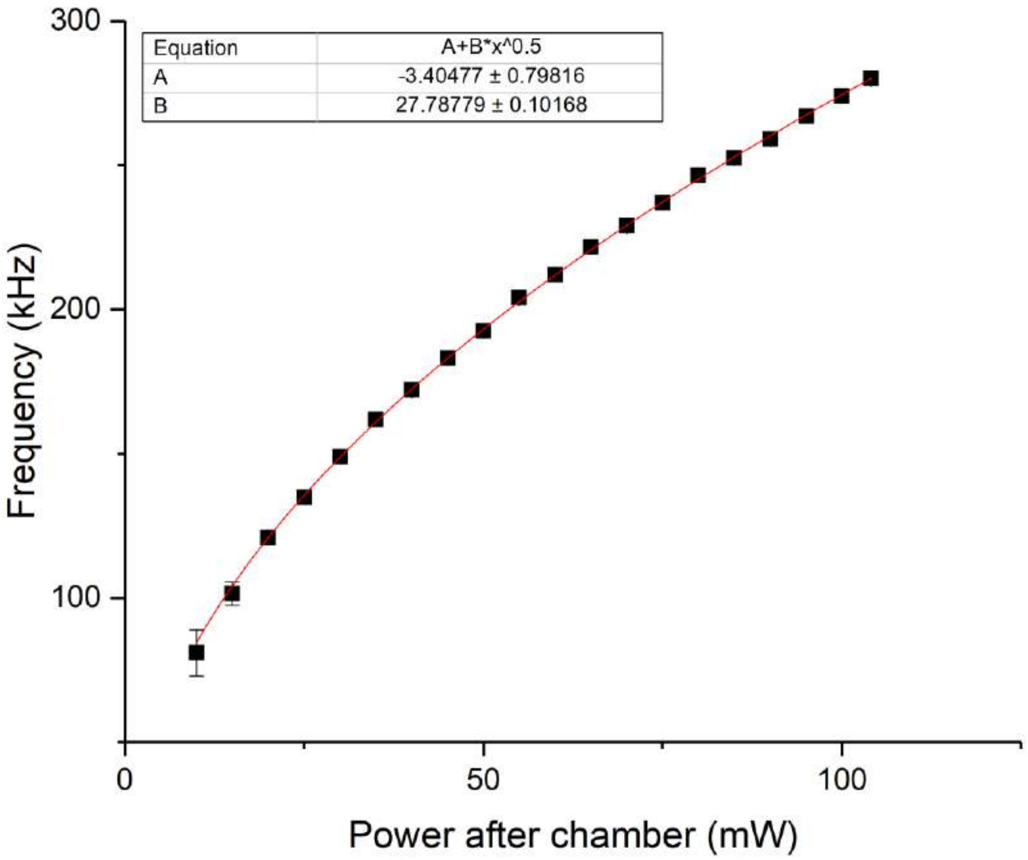
Shape asymmetry and intrinsic birefringence – transfer angular momentum of light to particle



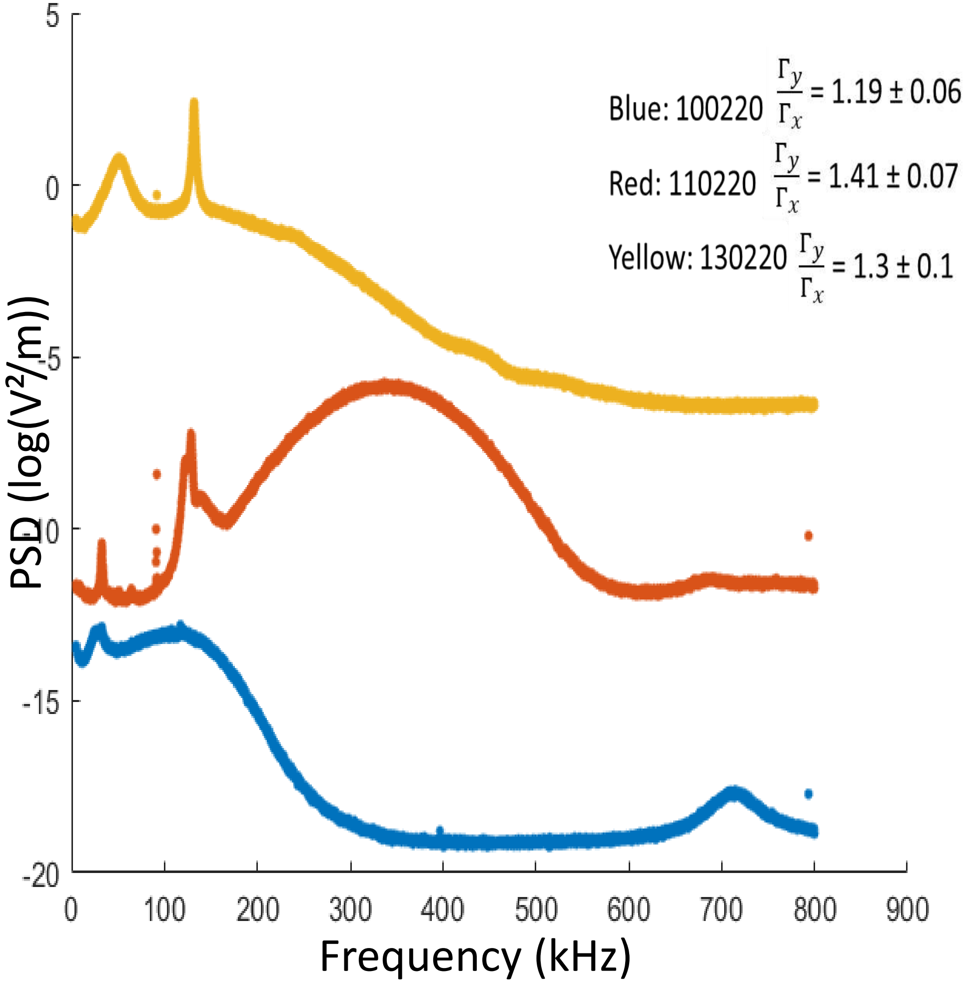


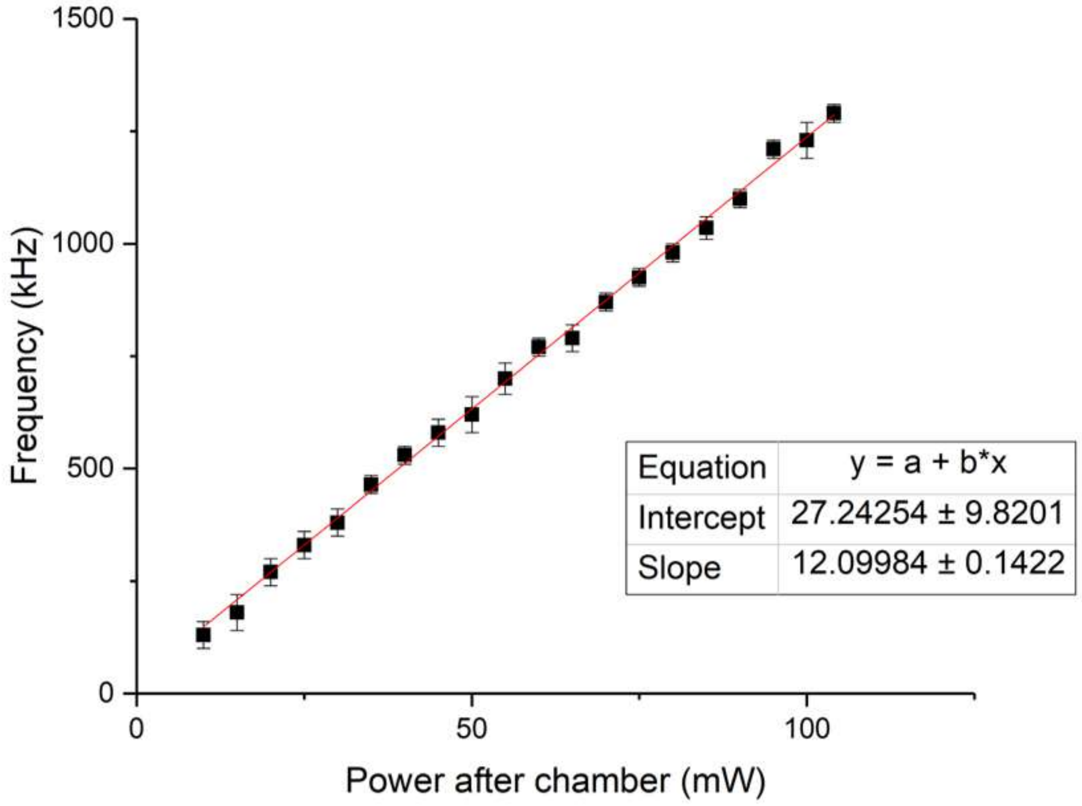
Librational frequency frequency, 5mbar, linear polarisation



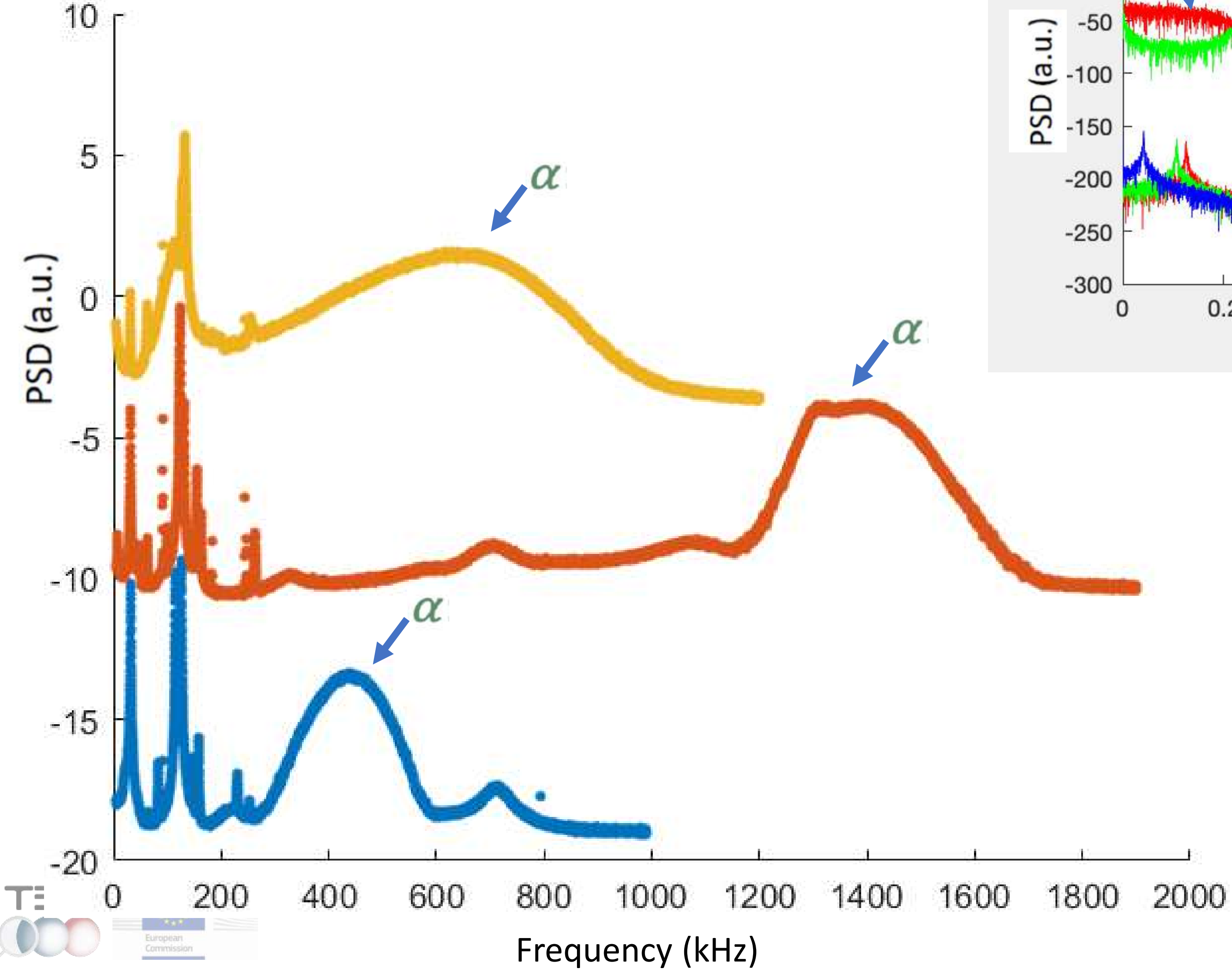


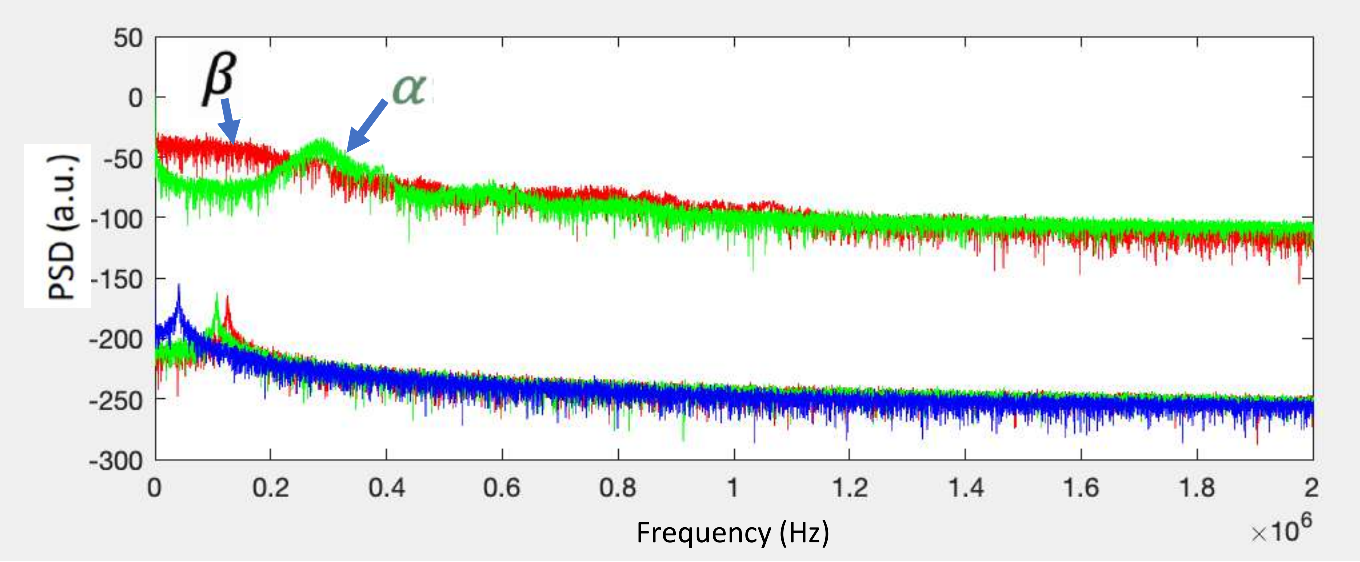
Rotational frequency, 5mbar circular polarisation

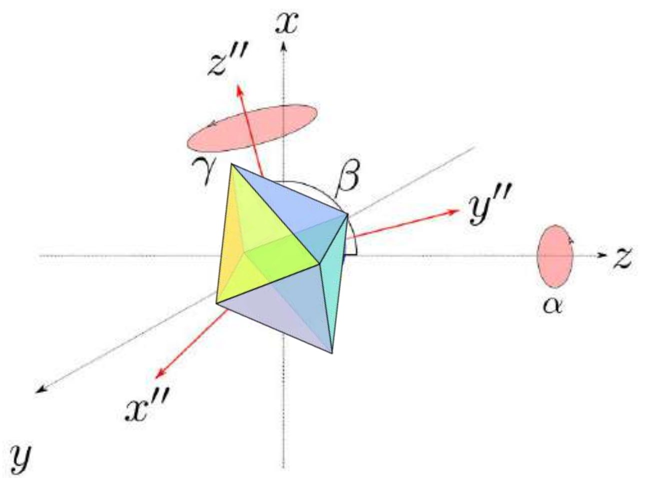




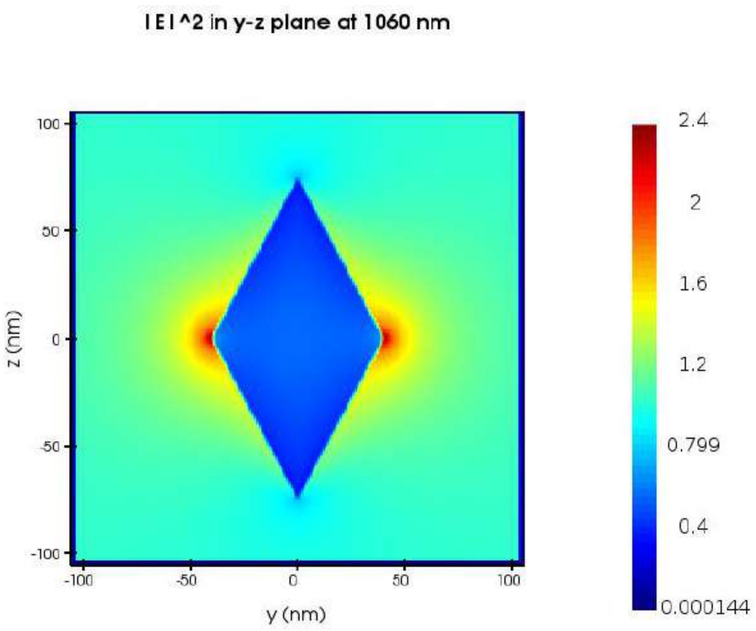
Comparison with data

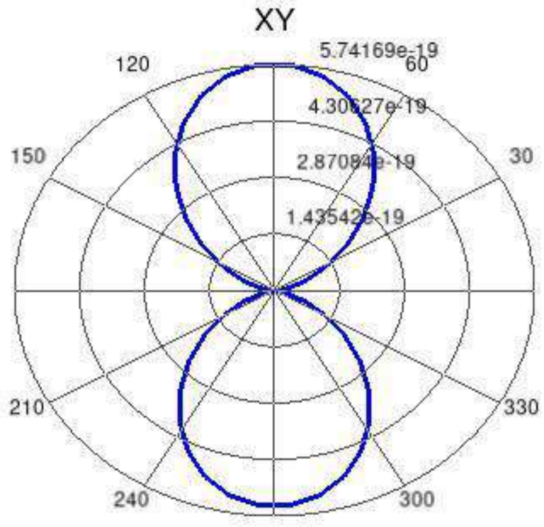


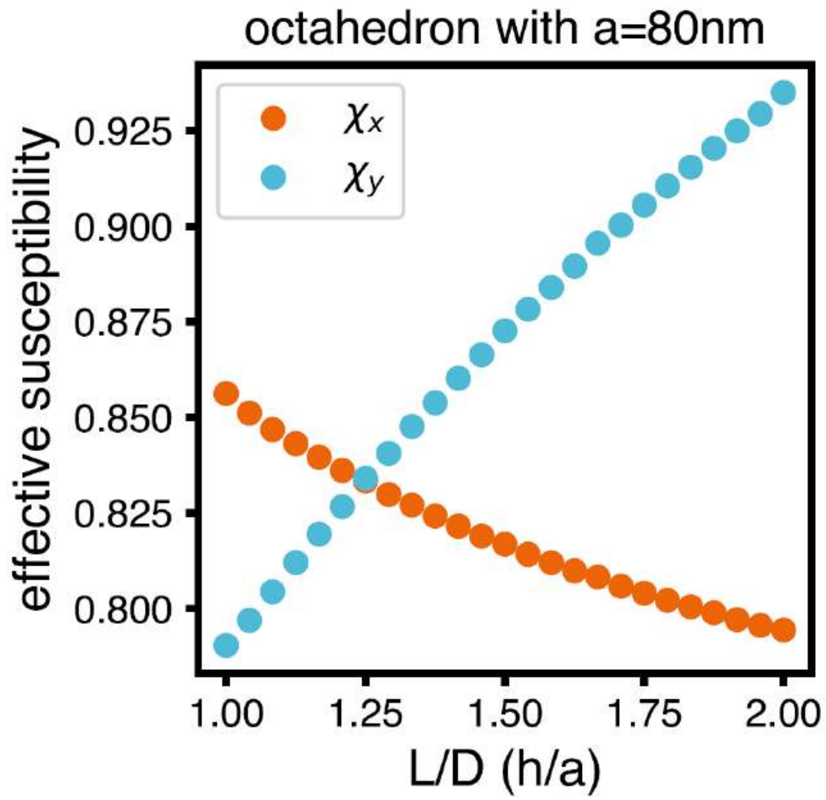


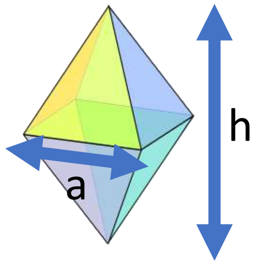


FTDT calculations of scattered light and susceptibility in near-field and far-field







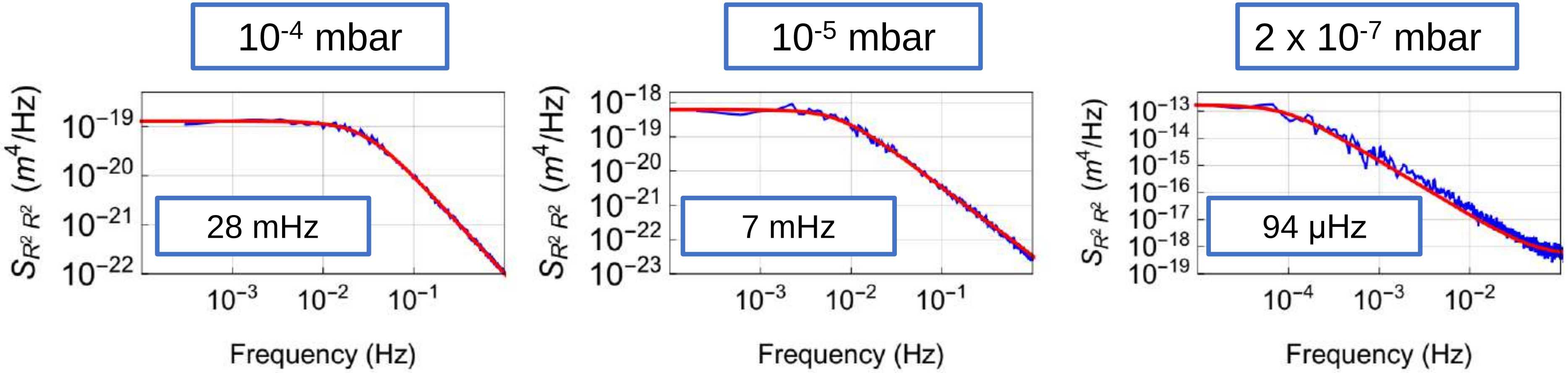


Future work

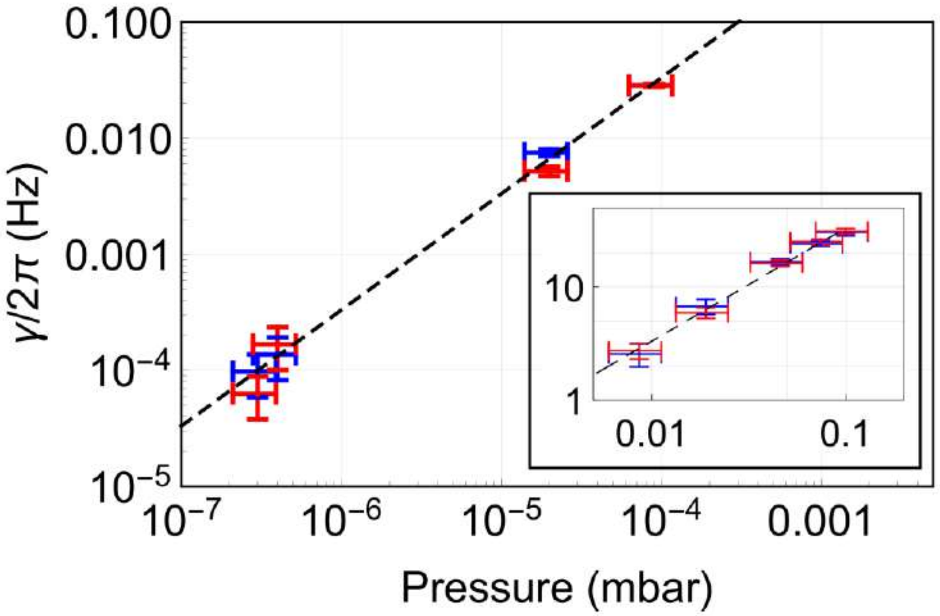
- With arrival of new pump laser we are again testing heating from Delft samples
- Redo rotation measurements and compare with calculations done during lock down
- Study nanocrystal cooling and dynamics in Paul trap

Understanding and controlling sources of decoherence (2.4)

Linewidth measurements



Radius 231 nm

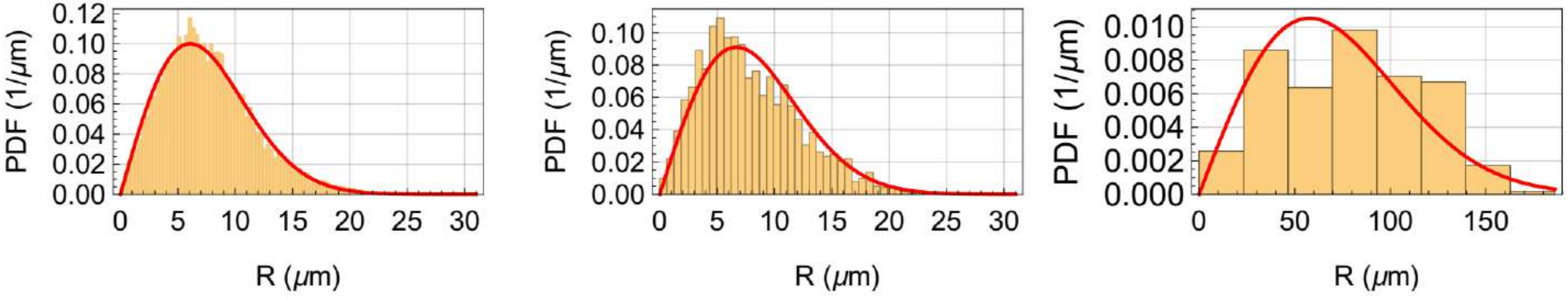


COM temperature

Rayleigh distributions directly related
to the variance of the oscillator

10^{-5} mbar

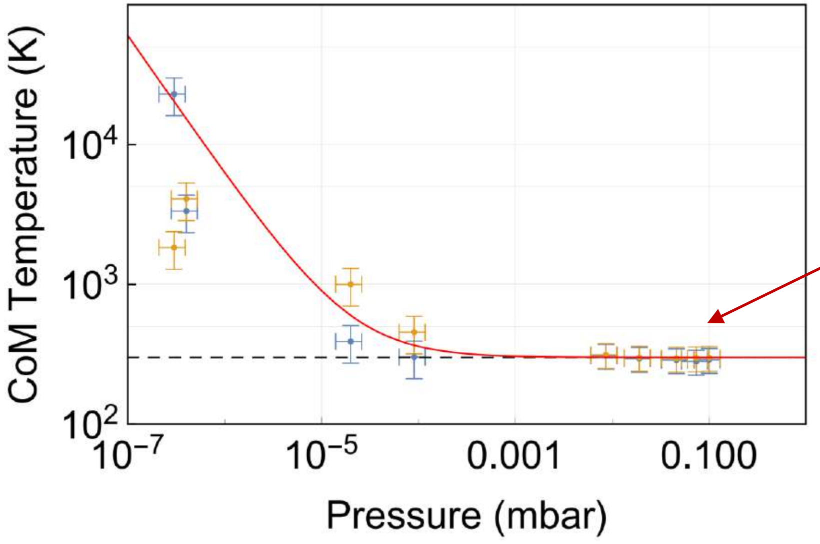
10^{-7} mbar



If thermal

$$RD(\sigma) = x\,e^{-\frac{x^2}{2\sigma^2}}$$

$$\sigma = \left(\frac{4-\pi}{2}\frac{k_B T}{m\omega_o^2}\right)^{\frac{1}{2}}$$



Not assumed

Dissipative CSL

Conventional CSL

$$S_{\mathrm{CSL}} = \hbar^2 \eta_{\mathrm{CSL}}$$

J. Nobakht, M. Carlesso, S. Donadi *et al.* Unitary unraveling for the dissipative continuous spontaneous localization model: Application to optomechanical experiments. *Phys. Rev. A*, **98**, 042109 (2018).

Dissipative CSL

$$S_{\mathrm{dCSL}}(\omega) = \hbar^2 \eta_{\mathrm{dCSL}}[1 + \kappa^2 m^2 (\gamma_t^2 + \omega^2)]$$

$$\gamma_t = \gamma + \gamma_{\mathrm{dCSL}}$$

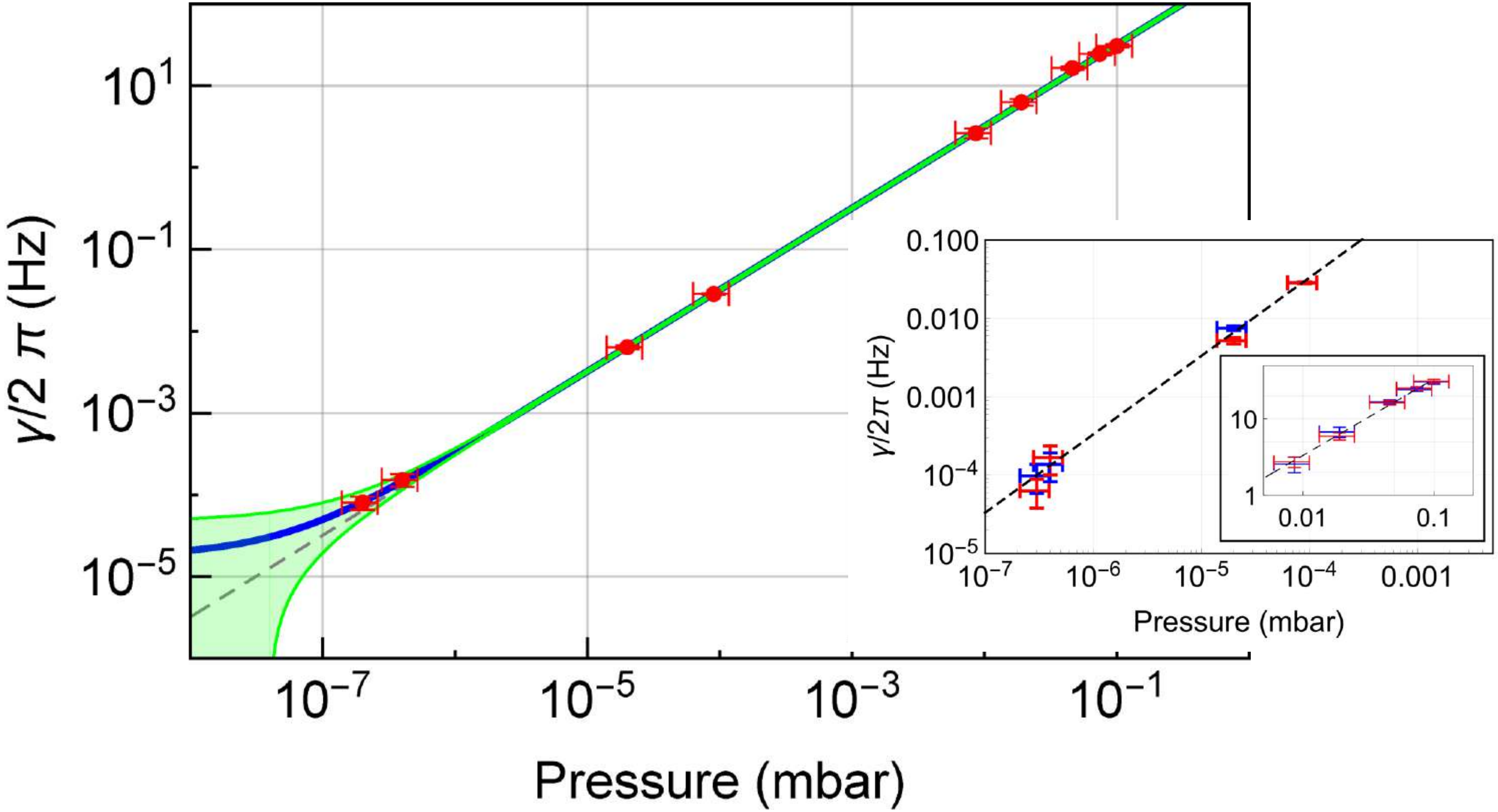
$$\kappa = \gamma_{\mathrm{dCSL}} / 2\hbar\eta_{\mathrm{dCSL}}$$

$$\eta_{\mathrm{dCSL}} = \frac{3\lambda r_C^2 m^2}{(1+\chi_C) r^4 m_0^2}\left[1 - \frac{2r_C^2(1+\chi_C)^2}{r^2} + e^{-\frac{r^2}{r_C^2(1+\chi_C)^2}}\left(1 + \frac{2r_C^2(1+\chi_C)^2}{r^2}\right)\right]$$

$$\chi_C = \hbar^2/(8 m_a k_B T_{\mathrm{dCSL}} r_C^2)$$

Now characterised by linewidth and temperature

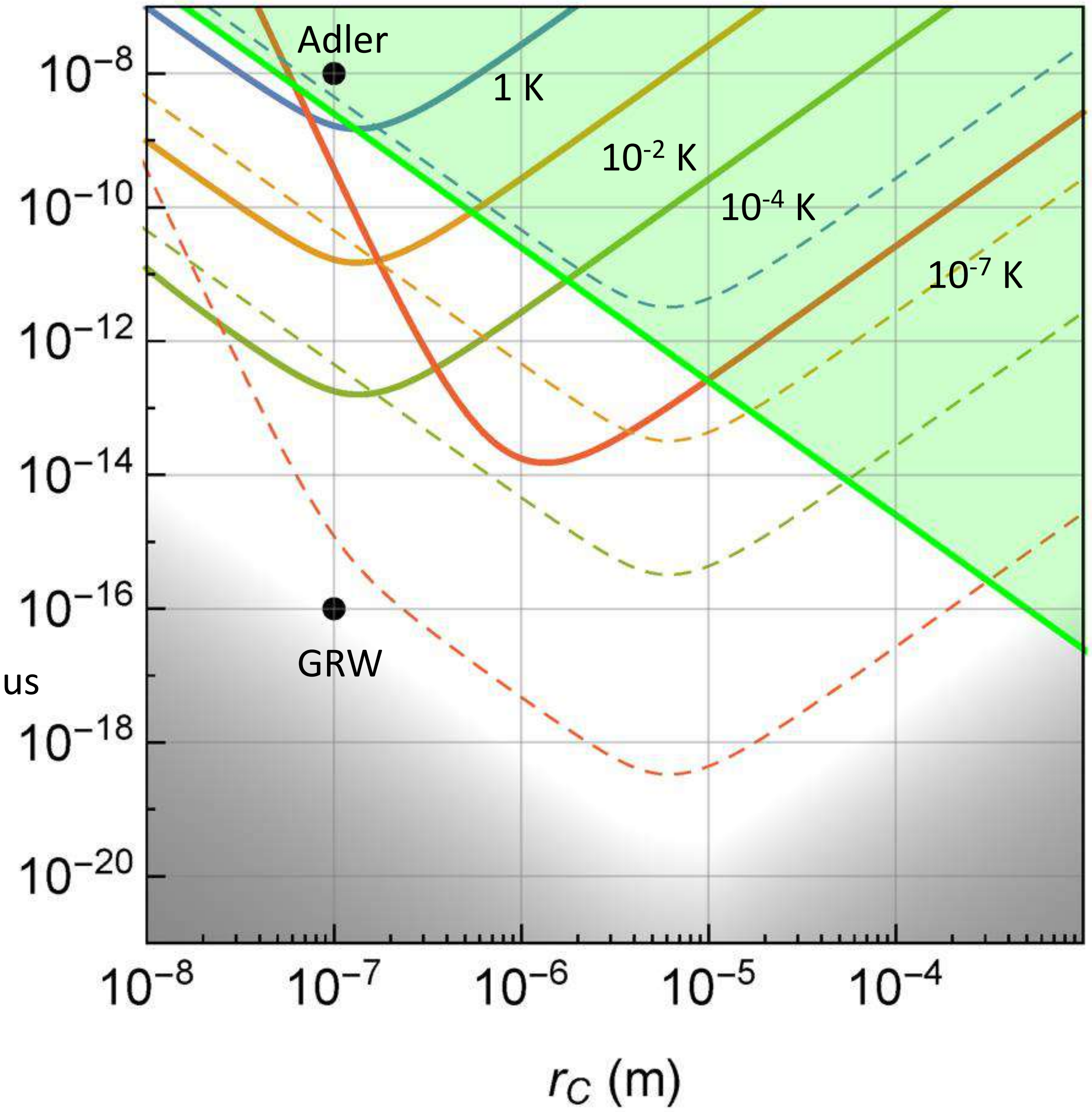
$$\gamma_{\mathrm{cm}}/2\pi \leq 48\mu\mathrm{Hz} \text{ at the 95\% confidence level}$$



Limits on dCSL

Solid lines - 231 nm radius, 10^{-7} mbar

Dashed lines – predicted for 10 000 nm radius



Dissipative Diosi-Penrose

$$\eta_{\mathrm{dDP}} = \frac{Gm_a^2}{\sqrt{\pi} r^6 \hbar} \Bigg[\sqrt{\pi} r^3 \mathrm{Erf}\left(\frac{r}{R_0(1+\chi_0)} \right) + (1+\chi_0) R_0 \Bigg\{ r^2 \left(e^{-\frac{r^2}{(1+\chi_0)^2 R_0^2}} - 3 \right) + 2(1+\chi_0)^2 R_0^2 \left(1 - e^{-\frac{r^2}{(1+\chi_0)^2 R_0^2}} \right) \Bigg\} \Bigg]$$

Collapse rates depends on gravity

$$\chi_0 = \hbar^2 / (8 m_a k_B T_{\mathrm{dDP}} R_0^2)$$

Strength depends on temperature and cut-off distance

$$\gamma_{\mathrm{dDP}} = \eta_{\mathrm{dDP}} 4 R_0^2 \chi_0 (1+\chi_0) m_a / m$$

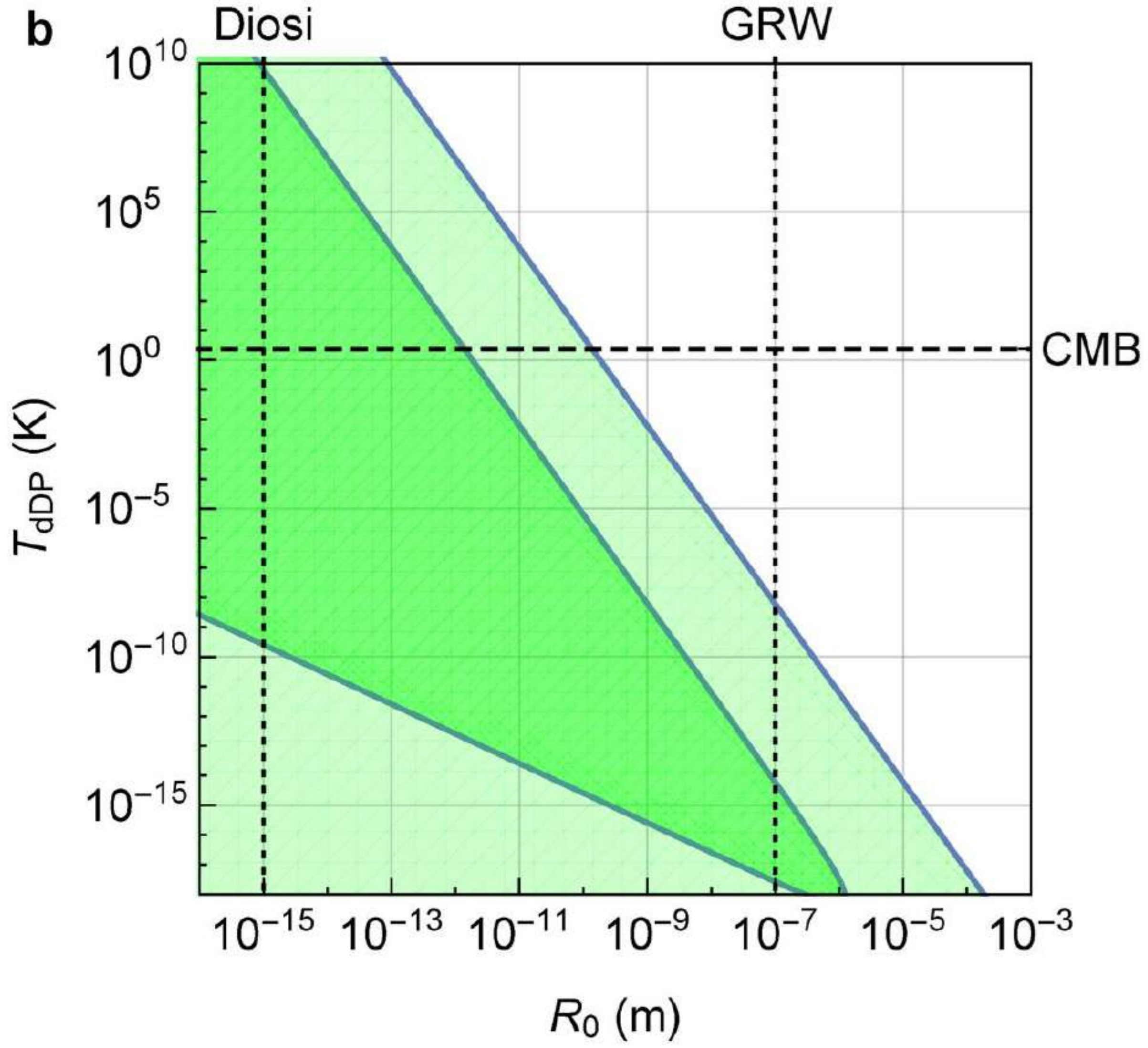
Bounds on dDP

Dark green - current experiment

Light green – 10 000 nm particles

Ultranarrow-linewidth levitated nano-oscillator for testing dissipative wave-function collapse

A. Pontin, N. P. Bullier, M. Toroš, and P. F. Barker
Phys. Rev. Research **2**, 023349 – Published 16 June 2020



Other work that has stemmed from TEQ in this area

- Sympathetic cooling in Paul trap using cold atoms arXiv:2005.11662
- Atom-nanoparticle cat states in Paul traps arXiv:2005.12006
- Levitation with broadband light https://doi.org/10.1364/OPTICA.392210
- Quantum spectrometry from arbitrary noise Phys. Rev. Lett. 123, 230801

Testing the large-scale
limit of
quantum mechanics

WP3: TESTING

H. Ulbricht – UoS

Summary of WP3

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
11	6	10	16	16	3	5.6	36	22

Objectives

O3.1 To develop low noise environment for the low noise trap with optical cooling in dilution fridge.
O3.2 To perform tests of CSL noise effects on motion of trapped NC.
O3.3 To adapt theory to experimental parameters to optimize the test of quantum superposition.

Tasks

T3.1 Set up dilution cryostat and laser for the ultimate experiment.
T3.2 Investigation of systematic effects.
T3.3 Perform the ultimate experiment.
T3.4 Adapt theory and predict experimental outcomes.

Deliverables

D3.1 Low noise environment [M 12].
D3.2 Systematic effects investigated [M 28].
D3.3 Ultimate experiment [M 40].
D3.4 General bound [M 48].

People at WP3: meetings to decide on TEQ ultimate experiment with experimental partners: INFN, AU, UCL + collaboration with theory partners.

- <u>UoS team:</u>
  - Andrea Vinante
  - Giulio Gasbarri
  - Marko Toros (now UCL)
  - Muddassar Rashid
  - Christopher Timberlake
  - Ashley Setter
  - Hendrik Ulbricht

Outline: Report II on WP3 - Testing

① *What we want to test and how* …. CSL exclusion plot

i. Force noise measurement approach
ii. Force measurements in multilayer mass attached to cantilever (CSL tested)

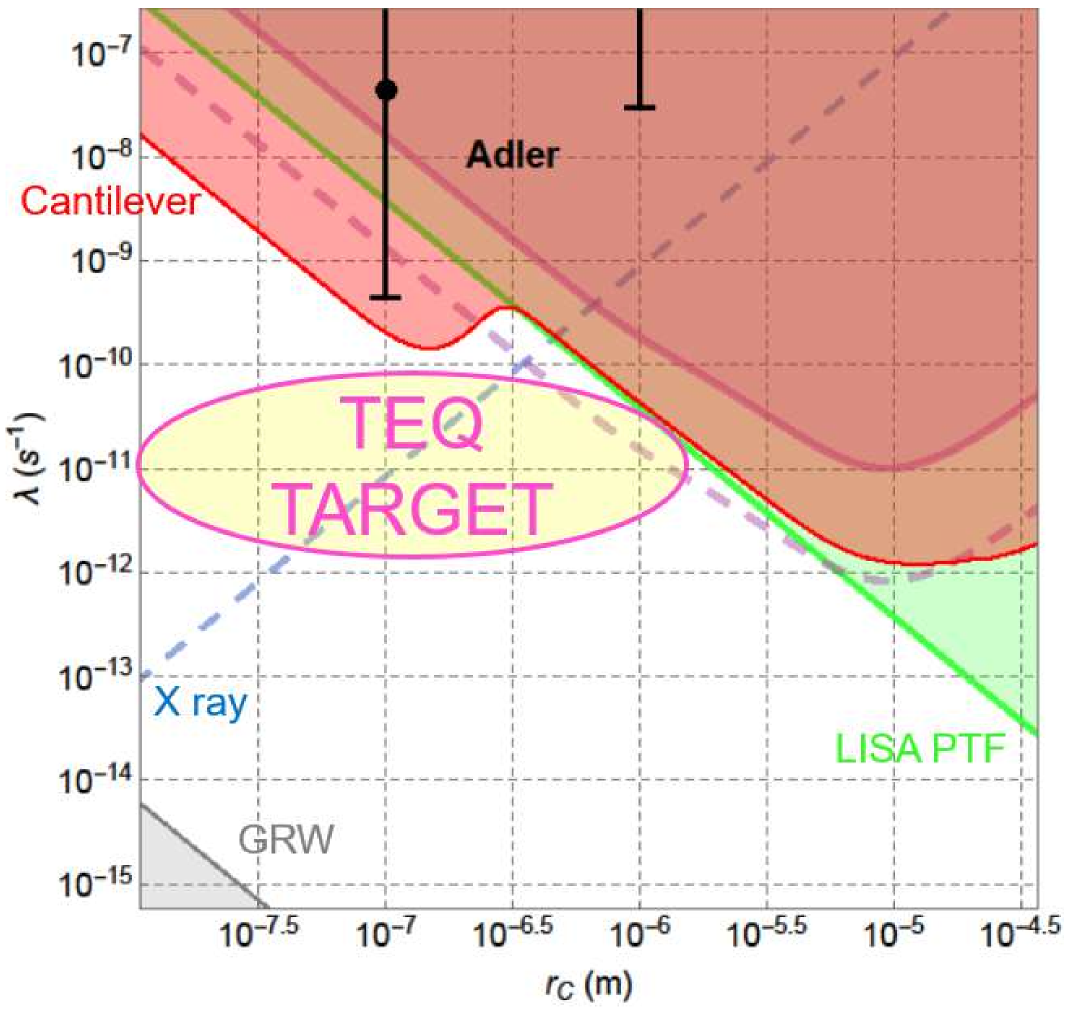
② *Parameters we have to reach* …. Comparison of CSL noise to thermal noises

i. Evaluation of required parameters for TEQ experiment
ii. Considerations on detection
iii. Summary of parameters

③ *What we have achieved with the experiment*… Testing of low-noise environment at UoS (D3.2)

i. Low pressure
ii. Low temperature
iii. Detection at ultralow power
iv. Low vibrations
v. Magnetic levitation tests

CSL parameter space: the region TEQ will explore



- **Non-interferometric test**

-> Measure force noise

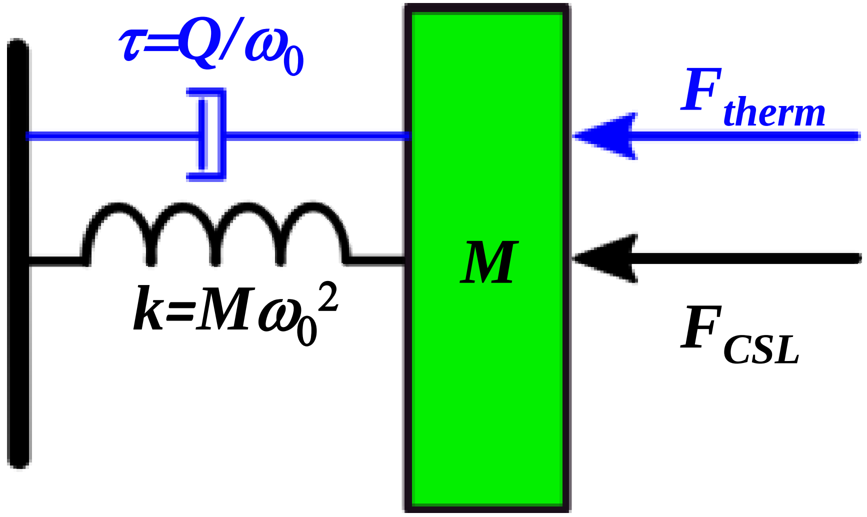
-> Target: $\lambda < 10^{-10}$ Hz

Force (noise) in harmonic oscillator: the TEQ experiment

- **CSL test based on force noise measurement**
  – **non-interferometric**
- **TEQ uses *levitation* for higher *Q* and lower frequency, few degrees of freedom**

Thermal bath affect minimum force measured:

$$F_{min} = \sqrt{\frac{4k_B T_0 m\omega_0}{Q\tau}},$$



M. Bahrami et al, PRL **112** 210404 (2014)
S. Nimmrichter et al, PRL **113** 020045 (2014)
L. Diosi, PRL **114**, 050403 (2015)
D. Goldwater et al. Phys. Rev. **A 94**, 010104 (2015)

A. Vinante et al, PRL **116**, 090402 (2016)
B. …..

Narrowing the Parameter Space of Collapse Models with Ultracold Layered Force Sensors

A. Vinante,[1,2,*] M. Carlesso,[3,4] A. Bassi,[3,4] A. Chiasera,[5] S. Varas,[5] P. Falferi,[2] B. Margesin,[6] R. Mezzena,[7] and H. Ulbricht[1]

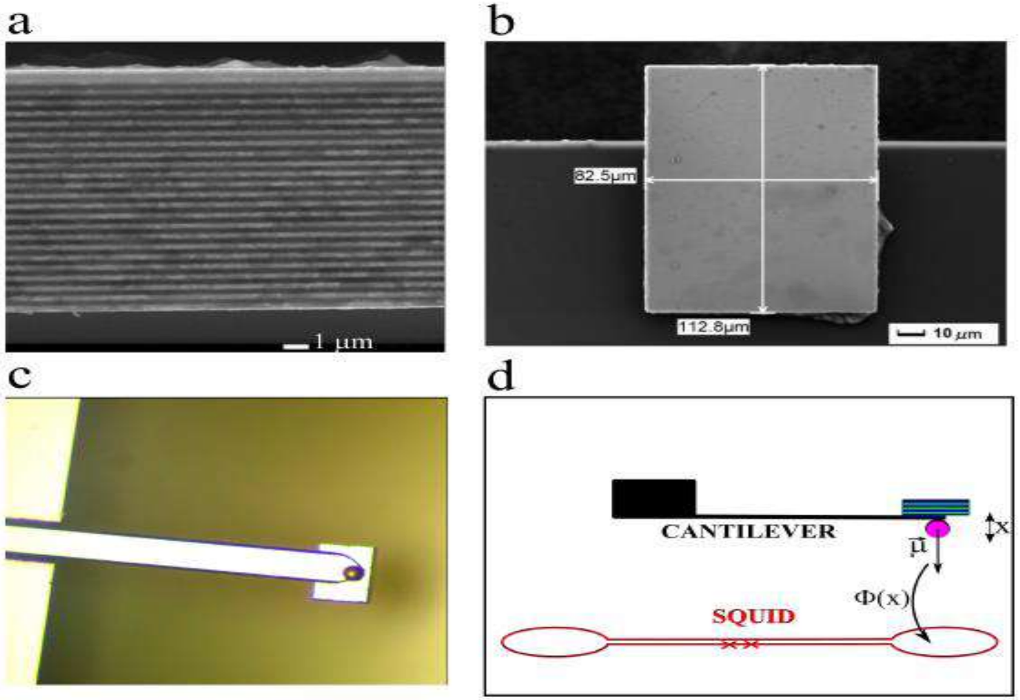
[1]*Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[2]*IFN-CNR and Fondazione Bruno Kessler, I-38123, Trento, Italy*
[3]*Department of Physics, University of Trieste, Strada Costiera 11, 34151 Trieste, Italy*
[4]*Istituto Nazionale di Fisica Nucleare, Trieste Section, Via Valerio 2, 34127 Trieste, Italy*
[5]*IFN-CNR CSMFO Lab and FBK Photonics Unit, I-38123 Trento, Italy*
[6]*Fondazione Bruno Kessler—CMM, I-38123, Trento, Italy*
[7]*Department of Physics, University of Trento, I-38123, Trento, Italy*

(Received 22 February 2020; revised 15 June 2020; accepted 24 July 2020; published 3 September 2020)

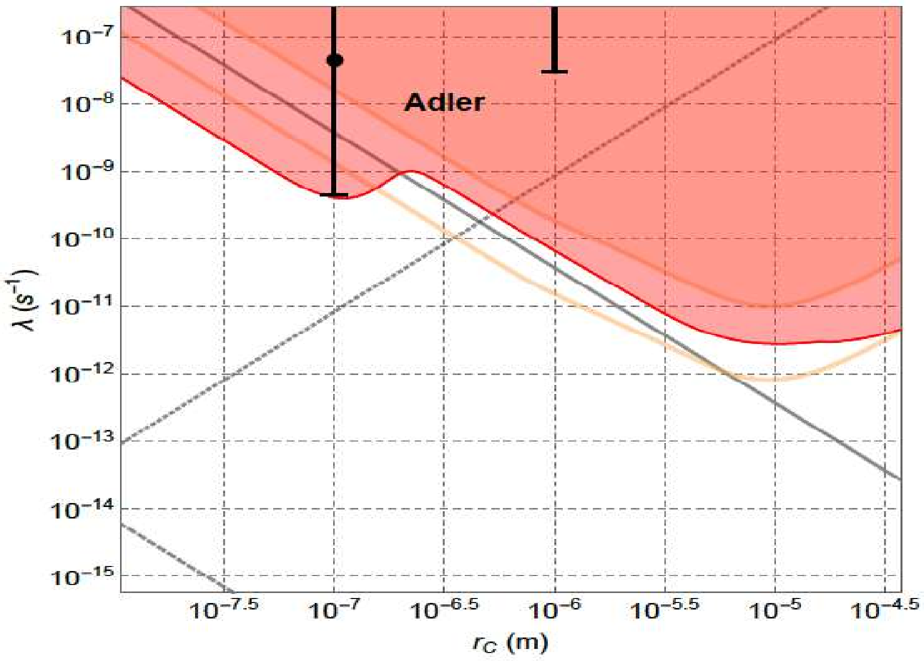
Despite the unquestionable empirical success of quantum theory, witnessed by the recent uprising of quantum technologies, the debate on how to reconcile the theory with the macroscopic classical world is still open. Spontaneous collapse models are one of the few testable solutions so far proposed. In particular, the continuous spontaneous localization (CSL) model has become subject of intense experimental research. Experiments looking for the universal force noise predicted by CSL in ultrasensitive mechanical resonators have recently set the strongest unambiguous bounds on CSL. Further improving these experiments by direct reduction of mechanical noise is technically challenging. Here, we implement a recently proposed alternative strategy that aims at enhancing the CSL noise by exploiting a multilayer test mass attached on a high quality factor microcantilever. The test mass is specifically designed to enhance the effect of CSL noise at the characteristic length $r_c = 10^{-7}$ m. The measurements are in good agreement with pure thermal motion for temperatures down to 100 mK. From the absence of excess noise, we infer a new bound on the collapse rate at the characteristic length $r_c = 10^{-7}$ m, which improves over previous mechanical experiments by more than 1 order of magnitude. Our results explicitly challenge a well-motivated region of the CSL parameter space proposed by Adler.

DOI: 10.1103/PhysRevLett.125.100404

Most recent CSL test result: multi-layered mass



- Sandwich of 40 layers of Tungstenoxid and glass
- Mechanical temperature of cantilever at 10 mK
- Detection of motion by SQUID
- Substantial challenge of Adler's CSL values



Vinante, A., M. Carlesso, A. Bassi, A. Chiasera, S. Varas, P. Falferi, B. Margesin, R. Mezzena, and H. Ulbricht, **Narrowing the parameter space of collapse models with ultracold layered force sensors**, Phys. Rev. Lett. 125, 100404 (2020)

Name of the game: Reduce all noises to be smaller than CSL noise

CSL force noise on a nanosphere:

$$S_{ff,\mathrm{CSL}} = \frac{32\pi^2\hbar^2\lambda r_C^2\rho^2 R^2}{3m_0^2}\left[1 - \frac{2r_C^2}{R^2} + e^{-\frac{R^2}{r_C^2}}\left(1 + \frac{2r_C^2}{R^2}\right)\right]$$

R – radius of sphere
r_c and λ – CSL parameter
ϱ - mass density of sphere
m_0 - mass of sphere
m – mass of background gas
T_{gas} – temperature of background gas
P_{gas} – pressure of background gas

Thermal noise from blackbody photon recoil:

$$S_{ff,\mathrm{bb}} = \frac{160}{\pi}\frac{R^3 k_B^6}{c^5\hbar^4}\mathrm{Im}\frac{\epsilon_{\mathrm{bb}} - 1}{\epsilon_{\mathrm{bb}} + 2}T^6$$

Thermal noise from gas collisions:

$$S_{ff-gas} = 4k_B m T_{\mathrm{gas}}\Gamma_{\mathrm{gas}}$$

$$\Gamma_{gas} = \sqrt{\frac{8}{\pi}}\left(1 + \frac{8}{\pi}\right)\frac{P_{\mathrm{gas}}}{\rho R\sqrt{\frac{k_B T_{\mathrm{gas}}}{m}}}$$

To maximize SNR:

- $R > r_C$ ($> 10^{-7}$ m)
- low T (< 1 K)
- low P ($< 10^{-10}$ mbar)

PHYSICAL REVIEW A **100**, 012119 (2019)

Editors' Suggestion | Featured in Physics

Testing collapse models with levitated nanoparticles: Detection challenge

A. Vinante,[1,*] A. Pontin,[2,†] M. Rashid,[1] M. Toroš,[2] P. F. Barker,[2] and H. Ulbricht[1]

[1]*Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, England, United Kingdom*

[2]*Department of Physics and Astronomy, University College London, London WC1E 6BT, England, United Kingdom*

(Received 20 March 2019; published 16 July 2019)

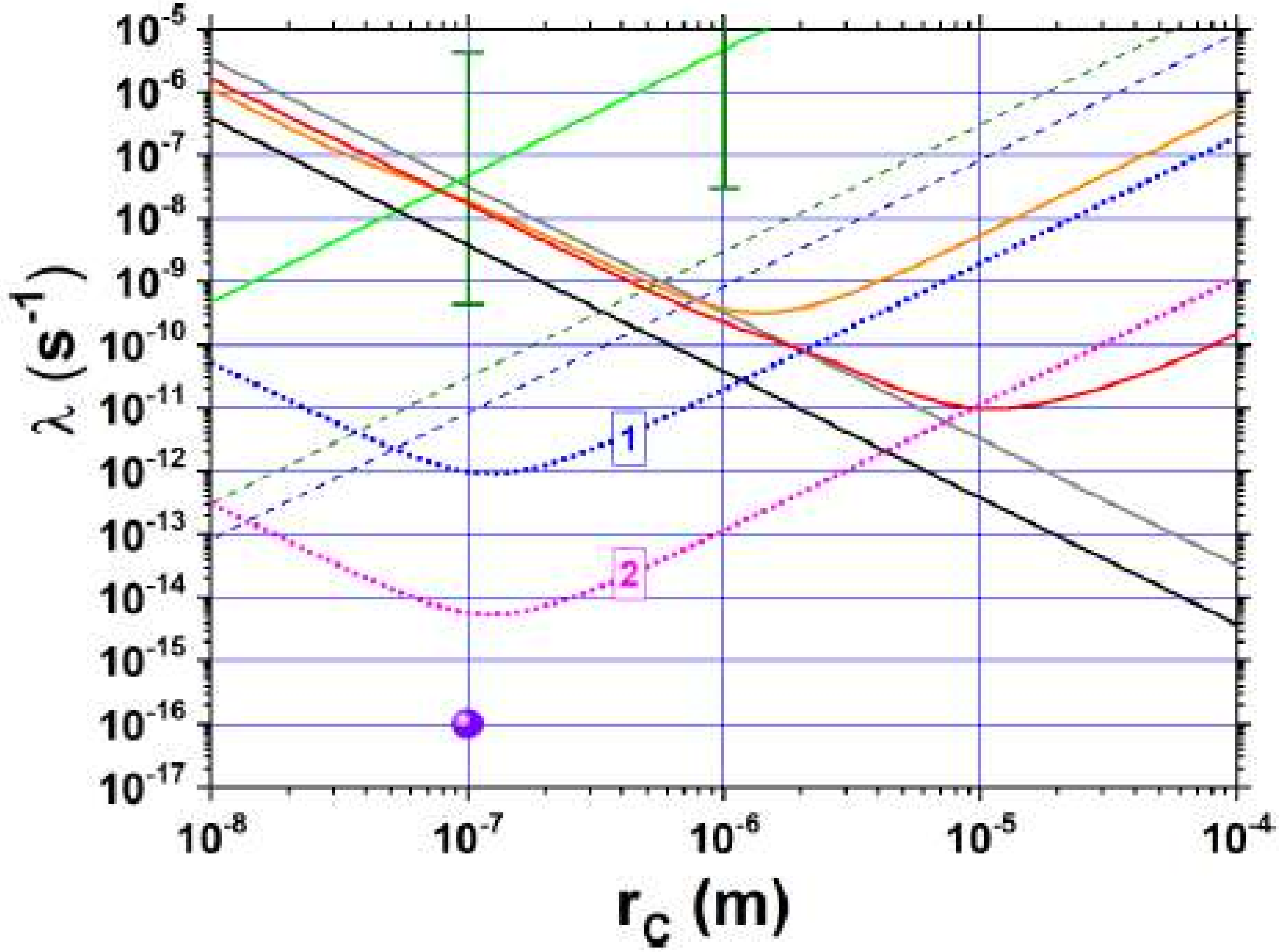
We consider a nanoparticle levitated in a Paul trap in ultrahigh cryogenic vacuum, and look for the conditions which allow for a stringent noninterferometric test of spontaneous collapse models. In particular we compare different possible techniques to detect the particle motion. Key conditions which need to be achieved are extremely low residual pressure and the ability to detect the particle at ultralow power. We compare three different detection approaches based, respectively, on an optical cavity, an optical tweezer, and an electrical readout, and for each one we assess advantages, drawbacks, and technical challenges.

DOI: 10.1103/PhysRevA.100.012119

Summary of requirements to test CSL with Paul trap – ultimate TEQ experiment:

Parameter	Target	Comments
Particle size	R = 200 nm	To probe CSL @ r_c=10^{-7} m
Trapp frequency	100 Hz – 1 kHz	Stable trap and low force noise
Voltage noise (DC)	25 nV/√Hz	Low force noise from Paul trap
Voltage noise (AC)	100 nV/√Hz	Low force noise from Paul trap, relaxed by finding of AU (factor 100?)
Particle material	SiO_2/Yb:YLF	Low absorption, many charges, rotation of non-spherical shapes
Temperature	< 1 K	Reduce thermal noise & gas pressure
Pressure	< 10^{-10} mbar	Reduce thermal noise. Desirable <10^{-12} mbar
Detection power	< 10^{-14} W	Minimize backaction noise and heating
Vibrational attenuation	> 60 dB	Decouple seismic/mechanical noise at trap frequency

Theoretically predicted CSL test by TEQ experiment:



[1] Paul trap with optical readout
[2] Paul trap with SQUID readout

300 mK, 1e-13 mbar

Magnetic levitation: low temperature compatible CSL test platform, alternative approach to Paul trapping at 300 mK

TEQ
European Commission

Applied Physics Letters ARTICLE scitation.org/journal/apl

Acceleration sensing with magnetically levitated oscillators above a superconductor

Cite as: Appl. Phys. Lett. **115**, 224101 (2019); doi: 10.1063/1.5129145
Submitted: 25 September 2019 · Accepted: 16 November 2019 ·
Published Online: 26 November 2019

View Online Export Citation CrossMark

Chris Timberlake,[a] Giulio Gasbarri, Andrea Vinante, Ashley Setter, and Hendrik Ulbricht[b]

AFFILIATIONS

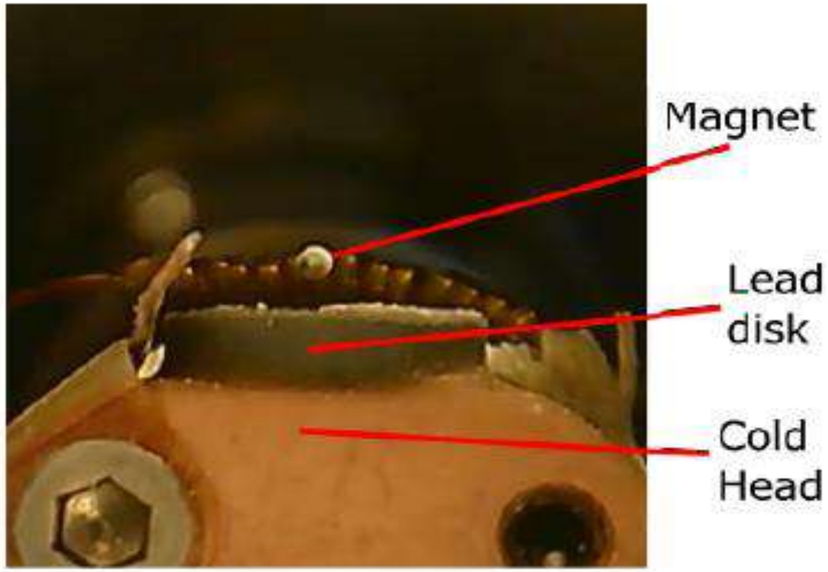
Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom

[a]Electronic mail: ct10g12@soton.ac.uk
[b]Electronic mail: h.ulbricht@soton.ac.uk

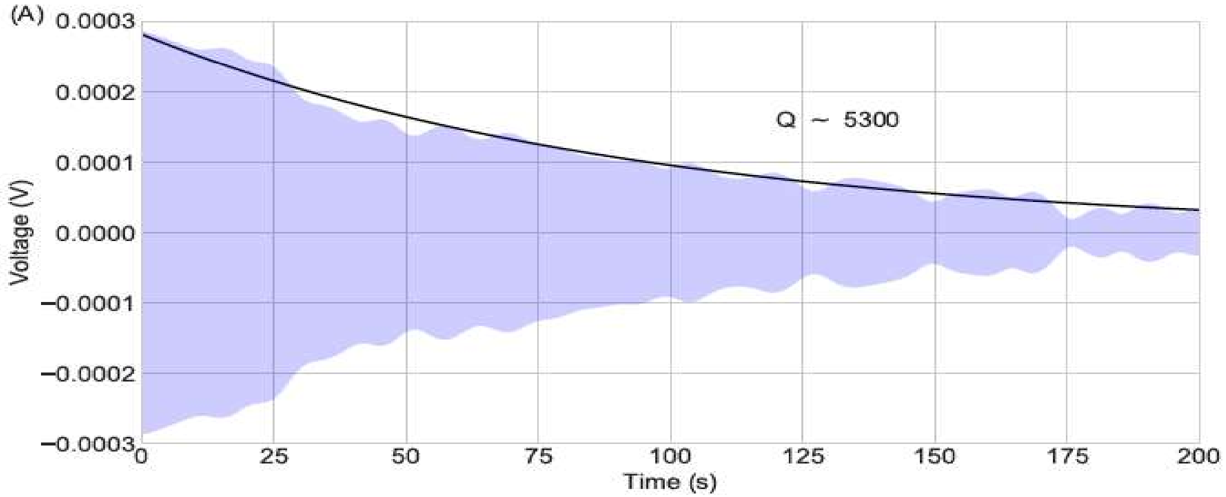
ABSTRACT

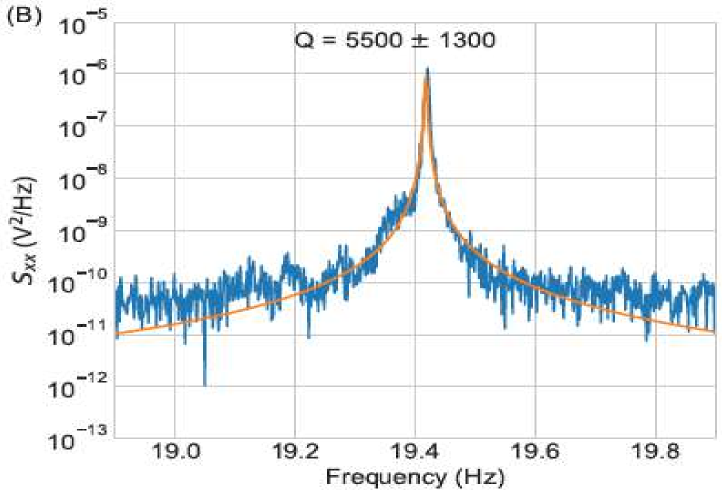
We experimentally demonstrate the stable trapping of a permanent magnet sphere above a lead superconductor, at vacuum pressures of 4×10^{-8} mbar. The levitating magnet behaves as a harmonic oscillator, with frequencies in the 4–31 Hz range detected, and shows promise to be an ultrasensitive acceleration sensor. We directly apply an acceleration to the magnet with a current carrying wire, which we use to measure a background noise of $\sim 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 30.75 Hz frequency. With current experimental parameters, we find an acceleration sensitivity of $S_a^{1/2} = 1.2 \pm 0.2 \times 10^{-10}\,\mathrm{g}/\sqrt{\mathrm{Hz}}$, for a thermal noise limited system. By considering a 300 mK environment, at a background helium pressure of 1×10^{-10} mbar, acceleration sensitivities of $S_a^{1/2} \sim 3 \times 10^{-15}\,\mathrm{g}/\sqrt{\mathrm{Hz}}$ could be possible with ideal conditions and vibration isolation. To feasibly measure with such a sensitivity, feedback cooling must be implemented.

Magnetic levitation: force sensing; g, G measurement; **CSL noise**



- Levitation at < 10^{-8} mbar, 4 K
- Oscillations at 3-21 Hz
- Max. Q-factor measured 10^3
- Limited by Eddy currents
- Detection optically in reflection





Timberlake, C., G. Gasbarri, A. Vinante, A. Setter, and H. Ulbricht, **Acceleration sensing with magnetically levitated oscillators, Appl. Phys. Lett. 115**, 224101 (2019)

PHYSICAL REVIEW APPLIED **13**, 064027 (2020)

Editors' Suggestion

Ultralow Mechanical Damping with Meissner-Levitated Ferromagnetic Microparticles

A. Vinante,[1,2,*] P. Falferi,[2] G. Gasbarri,[1] A. Setter,[1] C. Timberlake,[1] and H. Ulbricht[1,†]

[1] *School of Physics and Astronomy, University of Southampton, SO17 1BJ Southampton, United Kingdom*

[2] *Istituto di Fotonica e Nanotecnologie – CNR and Fondazione Bruno Kessler, I-38123 Povo, Trento, Italy*

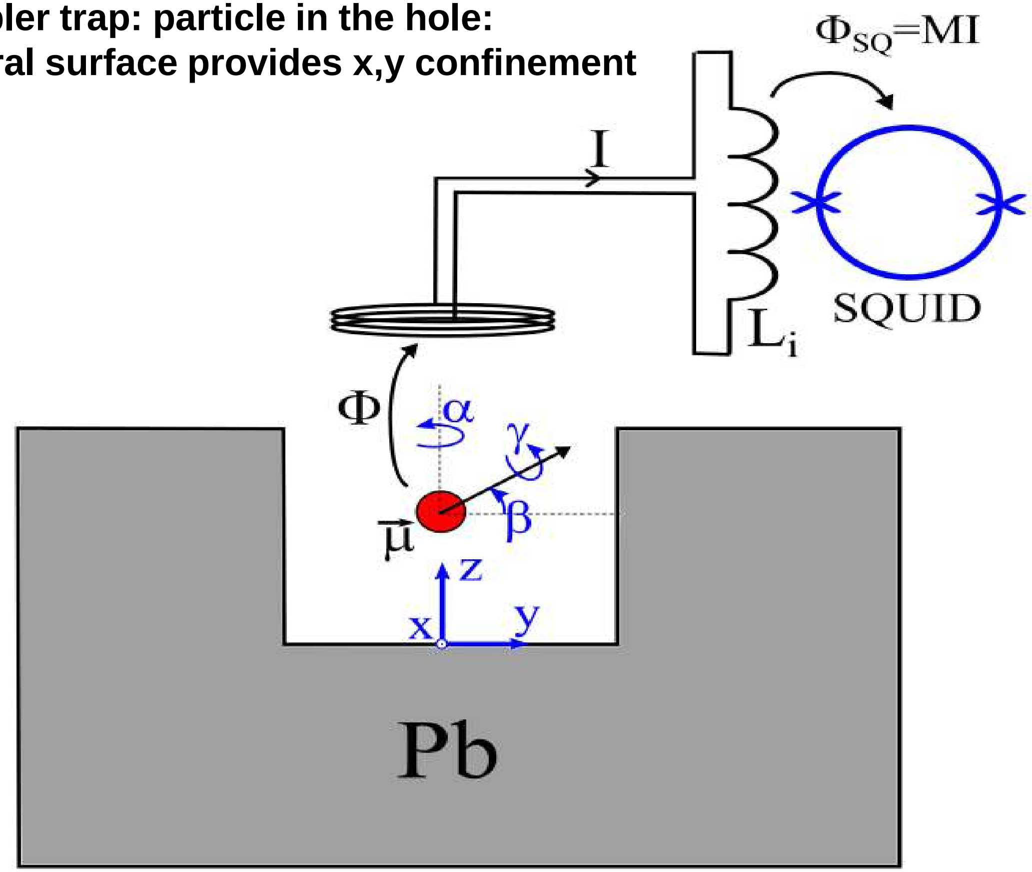
(Received 27 December 2019; revised manuscript received 23 April 2020; accepted 15 May 2020; published 11 June 2020)

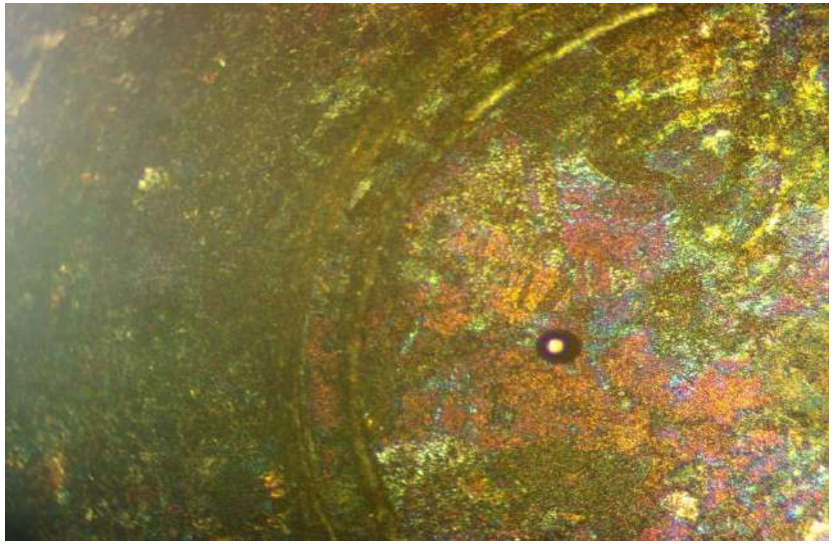
Levitated nanoparticles and microparticles are excellent candidates for the realization of extremely isolated mechanical systems, with a huge potential impact in sensing applications and in quantum physics. Magnetic levitation based on static fields is a particularly interesting approach, owing to the unique property of being completely passive and compatible with low temperatures. Here, we show experimentally that micromagnets levitated above type-I superconductors feature very low damping at low frequency and low temperature. In our experiment, we detect five out of six rigid body mechanical modes of a levitated ferromagnetic microsphere, using a dc superconducting quantum interference device with a single pick-up coil. The measured frequencies are in agreement with a finite-element simulation based on an ideal Meissner effect. For two specific modes, we find further substantial agreement with analytical predictions based on the image method. We measure damping times τ exceeding 10^4 s and quality factors Q beyond 10^7, an improvement of 2–3 orders of magnitude over previous experiments based on the same principle. We investigate the possible residual loss mechanisms besides gas collisions, and argue that a much longer damping time can be achieved with further effort and optimization. Our results open the way towards the development of ultrasensitive magnetomechanical sensors with potential applications to magnetometry and gravimetry, as well as to fundamental and quantum physics.

DOI: 10.1103/PhysRevApplied.13.064027

Meissner levitation with SQUID readout

Simpler trap: particle in the hole:
Lateral surface provides x,y confinement

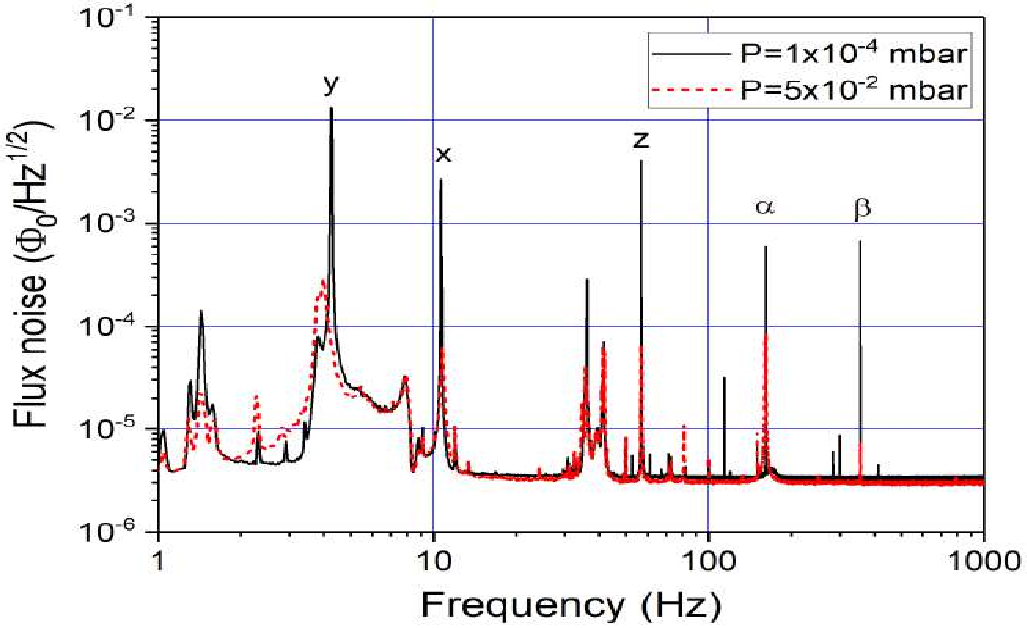


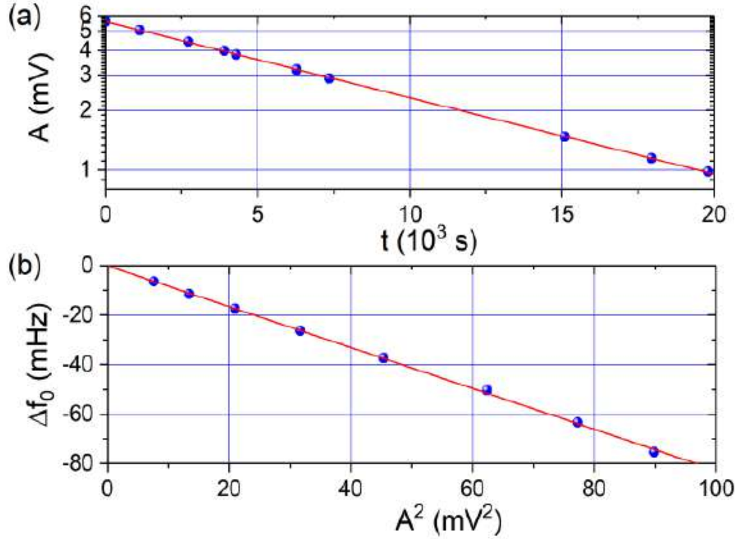


NdFeB microsphere
Radius = 27 um
Trap Radius = 2 mm

Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, **Ultrahigh mechanical quality factor with Meissner-levitated ferromagnetic microparticles,Phys. Rev. Appl. 13**, 064027 (2020)

Some experimental results of Meissner trap:





- **Peaks identified by finite element simulations**
- **z – and beta modes are studied in more detail**
- **All experiments so far a 4 K.**

Beta-mode: libration motion

$$P \sim 10^{-5}\ \mathrm{mbar}$$

$$Q = 1.34 \times 10^{7}.$$

$$\sqrt{S_{\mathcal{T}}} = 1.00 \times 10^{-20}\ \mathrm{Nm}/\sqrt{\mathrm{Hz}}.$$

$$\sqrt{S_B} \approx 1\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$$

$$\sqrt{S_f} \approx 1\ \mathrm{aN}/\sqrt{\mathrm{Hz}} \text{ for the } z \text{ mode}$$

Predicted CSL testing with 300 mK Meissner levitation: depending on particle size…

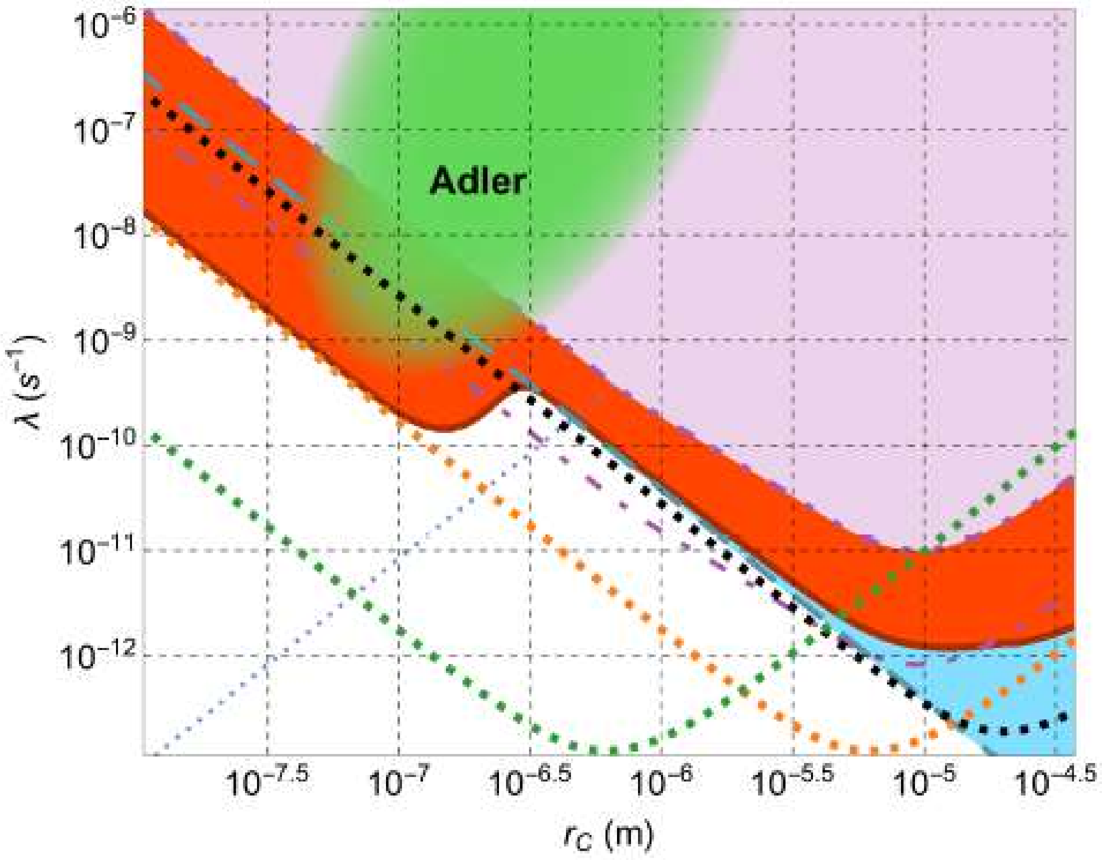
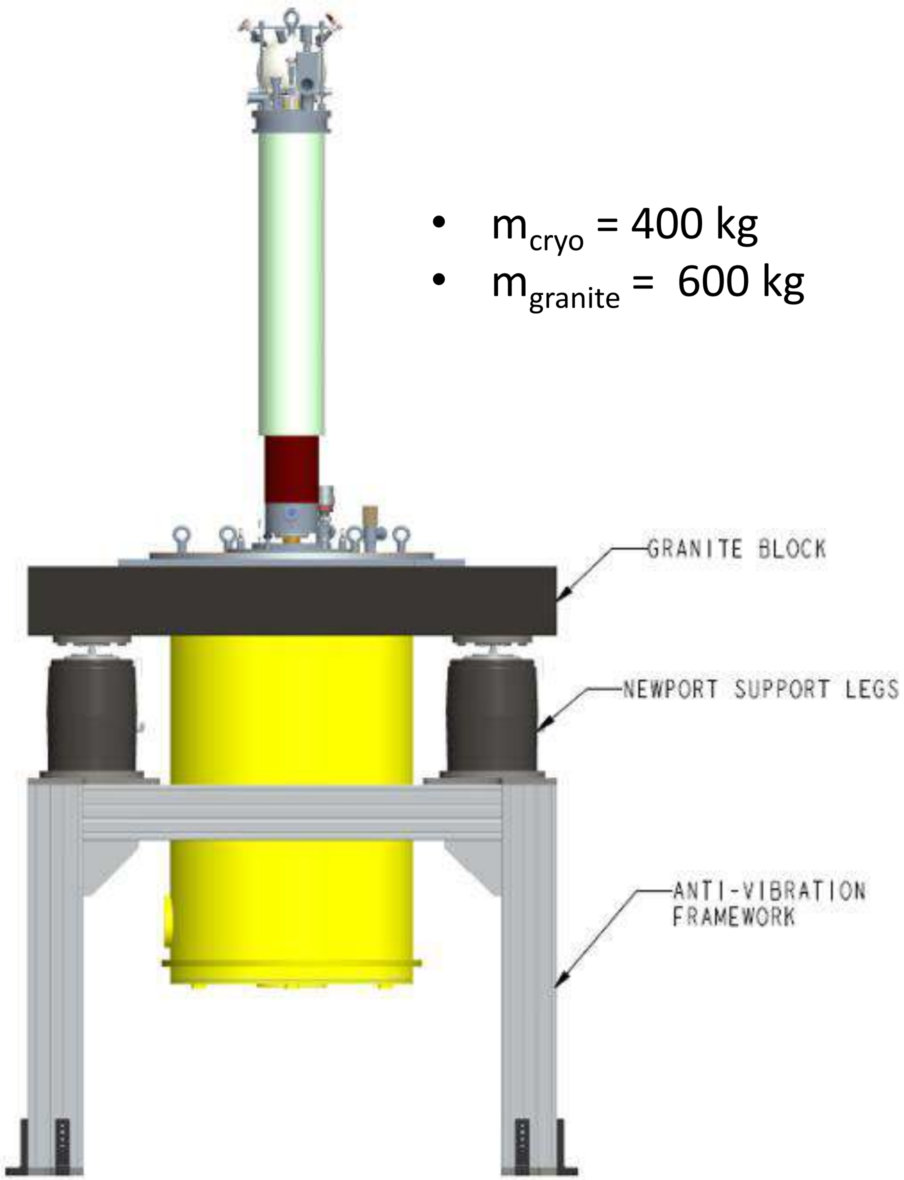


FIGURE 6.16: Exclusion plot for the CSL parameter space. The dotted lines represent the bounds that would be set by our levitating magnet sphere under different experimental conditions. Each bound is predicted for a thermal noise limited system at a temperature of 300 mK. The black dotted line represents the bounds that would be set

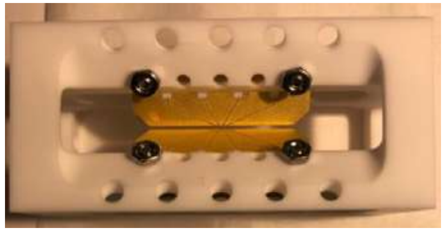
TEQ low-noise environment: at UoS

- Low Temperature: Wet sorption He-3 refrigerator with base temperature 300 mK [for 100 hours, 6 litres of He-3]
- Low Pressure: UHV-compatible cryostat, [CF flanges, beak-out @ 120 ^{o}C, turbo and cryo pump]
- Optical access [wedged windows + 3 fibres, FC-APC, PM, single mode]
- Low vibration mode [no mechanical pumps, no pulsed tube, only He-4 bubbling]
- Low frequency mechanical isolation integrated in cryostat frame (Newport, S-2000A-116, > 30 Hz -> 60 dB attenuation)
- Pre-installed wiring, 20 coaxial + 25 twisted pairs, with superconducting cryogenic section [to avoid resistive heating] for Paul trap voltages.
- Stable laser for detection installed at UoS [SolTis, MSquared].
- Vibration survey at UoS performed [low external vibrations]



- m_{cryo} = 400 kg
- $m_{granite}$ = 600 kg

300 mK fridge



- We had to send cryo back to the manufacturer twice,
- But now works to specs:
  - Temperature: 300 mK
  - Pressure: < 1e-10 mbar
  - Vibrations: see below
  - Hold time: 80 hours (amount of He-3 gas)

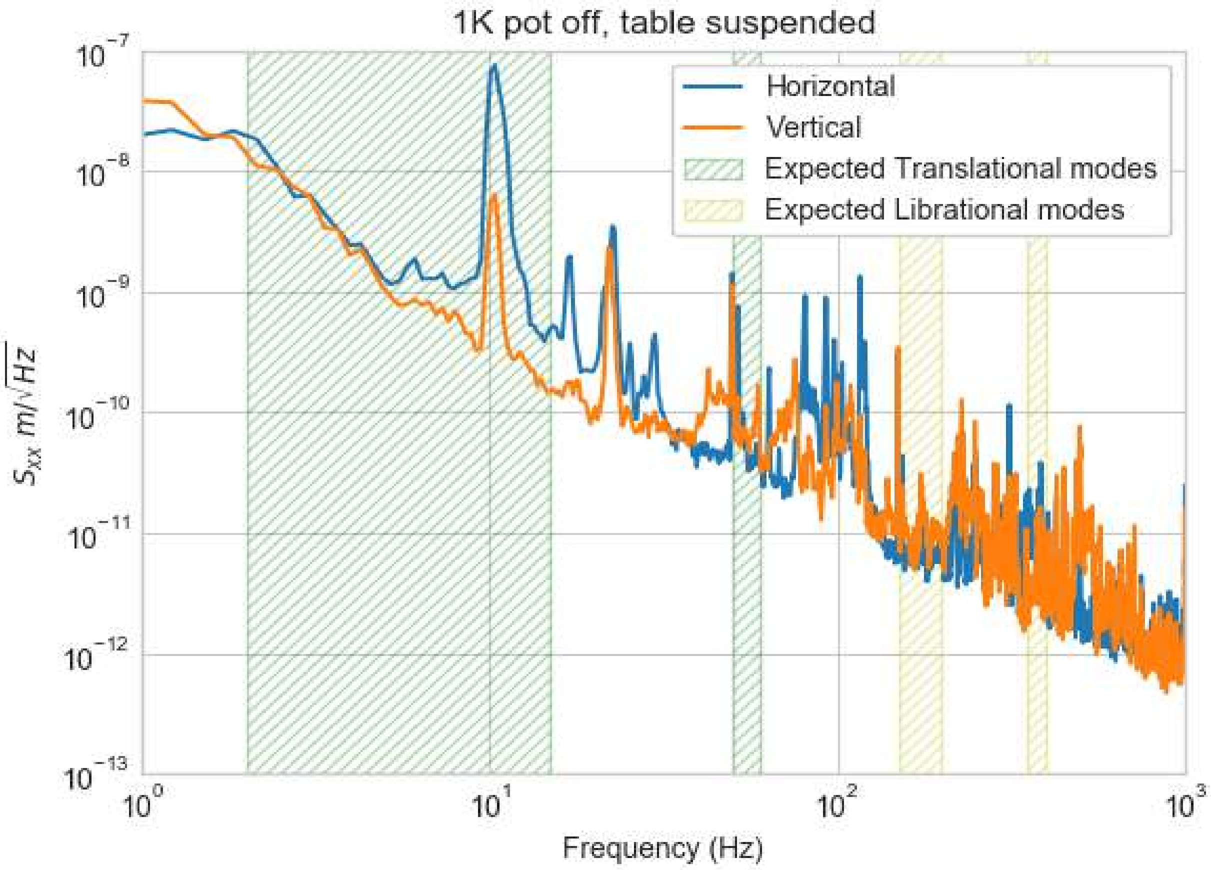
Parameters to be achieved in cryo to test CSL at defined target: with Paul trap and with Meissner trap

	Paul trap, R=200 nm	Magnetic, R=20 μm
Pressure (mbar)	<1e-11 (@T_i=20K)	1e-9 (@T_i=0.3K)
Residual acceleration noise ($m/s^2/\sqrt{Hz}$)	<1e-6	<1e-10
Trap driving voltage noise (V^2/Hz)	<5e-16 DC (<5e-15 AC)	-

TEQ

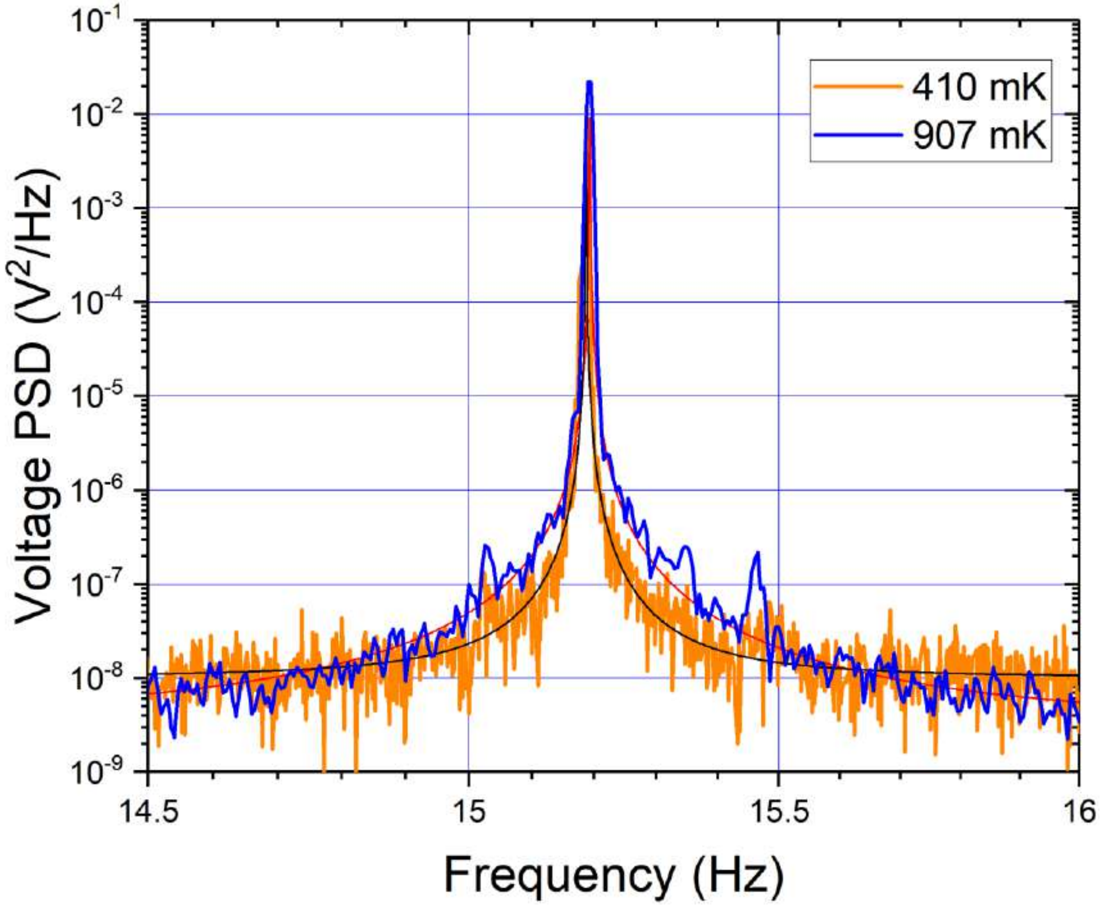
European Commission

Testing conditions at 300 mK: Vibration



- Vibration spectra measured by the **geophones** under different conditions.
- Two geophones (one horizontal and one vertical) are positioned on the 1K pot stage.
- Shaded regions correspond to possible regions for CSL tests.

Testing vibrations by magnetic levitation in cryo:



… For the data at 410 mK we have independently estimated the damping rate g=2e-3 s^{-1} by means of ring down measurements, which implies an acceleration noise S_a=6e-9 m/s^2/√Hz.

-> already sufficient for CSL test by Paul trap,
but Meissner trap needs more Vibration damping.

More tests re-start just now after covid-19 delay!

Summary of WP3

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
11	6	10	16	16	3	5.6	36	22

Objectives

O3.1 To develop low noise environment for the low noise trap with optical cooling in dilution fridge.
O3.2 To perform tests of CSL noise effects on motion of trapped NC.
O3.3 To adapt theory to experimental parameters to optimize the test of quantum superposition.

Tasks

T3.1 Set up dilution cryostat and laser for the ultimate experiment.
T3.2 Investigation of systematic effects.
T3.3 Perform the ultimate experiment.
T3.4 Adapt theory and predict experimental outcomes.

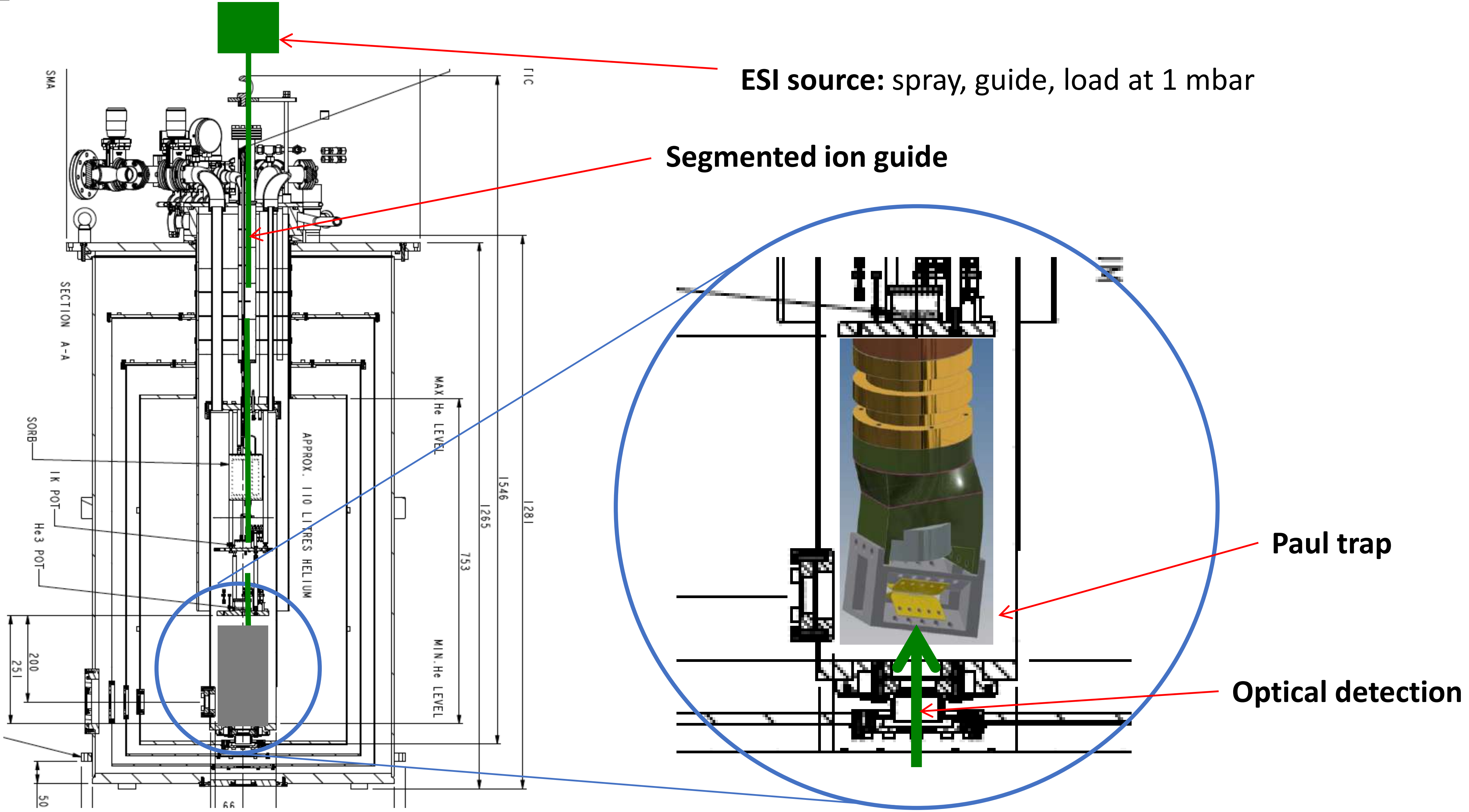
Deliverables

D3.1 Low noise environment [M 12].
D3.2 Systematic effects investigated [M 28].
D3.3 Ultimate experiment [M 40].
D3.4 General bound [M 48].

Next studies:

- Vibration isolation: Spring-mass system to filter mechanical noise.
- Implementation of Paul trap at 300 mK (based on results form TEQ partners).
    - Pick the right trap (blade or rods) depending on UCL results.
    - Pick the right power supplies for the Paul trap (AU or INFN/UCL) after tests at UCL regarding the noise level achieved.
    - Implement particle loading: quadrupole guide after ESI source (UCL/AU designs).
- Tests of mechanical noise and electrical noise with trapped particle.
- CSL tests at 300 mK [D3.3].
    - Meissner or Paul trap decision to achieve scientific goals of TEQ.

Next: Attaching the Paul trap



Testing the large-scale limit of quantum mechanics

European Commission

WP4: ENABLING

M. Paternostro - QUB

&

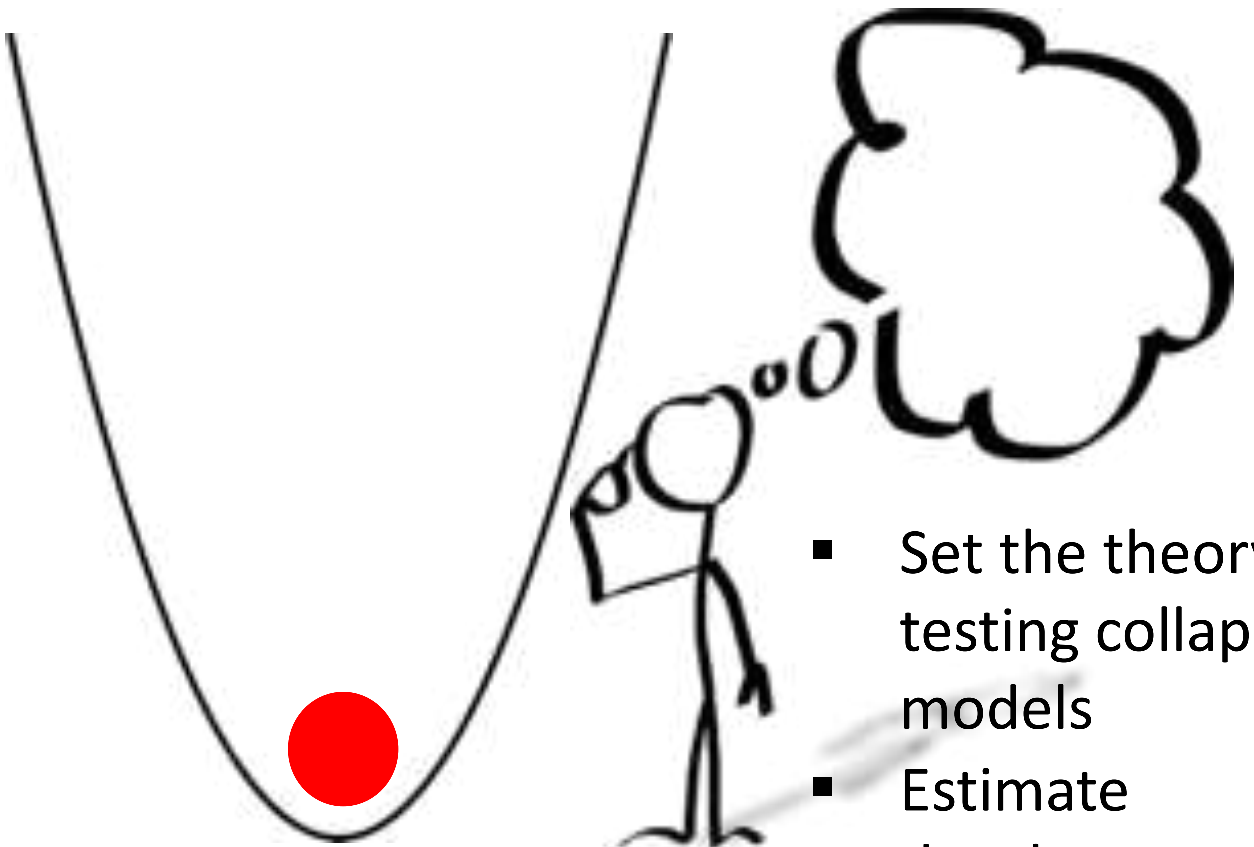
C. Brukner - OEAW

TEQ

Testing the large-scale limit of quantum mechanics

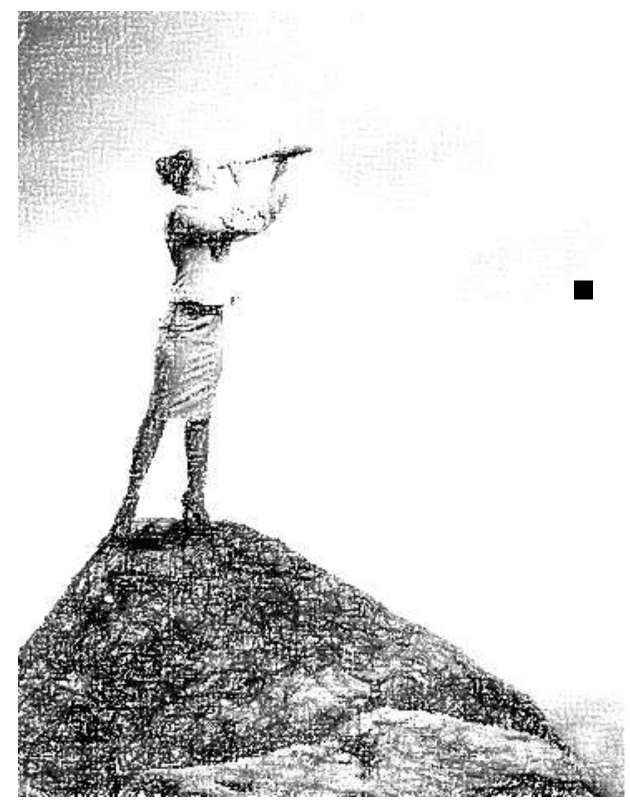
European Commission

What WP4 is about



- Set the theory for testing collapse models
- Estimate decoherence

4. Enabling



- Visionary perspectives on the study of the foundations of quantum mechanics

5. Ruling out

Testing the large-scale limit of quantum mechanics

Summary of WP4

Person-Months

UniTS	AU	INFN	OEAW	**QUB**	TUD	UCL	Soton	M2
30	2	4	33	**27.2**	3	2	2	0

Tasks

T4.1 To assess decoherence on the experimental set up at the core of **WP3**.
T4.2 To determine experiment-specific bounds to CSL and SN mechanisms.
T4.3 To develop schemes to quantify the macroscopicity of quantum superposition states.
T4.4 To design settings for the test of energy-conserving CSL and SN model.
T4.5 To compare time-dilation decoherence and gravity-induced collapse.

Objectives

O4.1 To set up a theoretical framework for the test of quantum mechanics at the mesoscopic level.
O4.2 To design experimental tests able to refine the framework of collapse models.
O4.3 To investigate macro-realism at the mesoscopic level through the experiments at the core of TEQ.

Deliverables

D4.1 Calibration of decoherence [M12]
D4.2 Bounds to CSL & SN models [M18]
D4.3 Size of the superposition [M24]
D4.4 Bounds to the ecCSL model [M36]
D4.5 Time-dilation/gravity collapse [M44]

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

Summary of WP4

Person-Months

UniTS	AU	INFN	OEAW	**QUB**	TUD	UCL	Soton	M2
30	2	4	33	**27.2**	3	2	2	0

Tasks

T4.1 To assess decoherence on the experimental set up at the core of **WP3**.
T4.2 To determine experiment-specific bounds to CSL and SN mechanisms.
T4.3 To develop schemes to quantify the macroscopicity of quantum superposition states.
T4.4 To design settings for the test of energy-conserving CSL and SN model.
T4.5 To compare time-dilation decoherence and gravity-induced collapse.

Objectives

O4.1 To set up a theoretical framework for the test of quantum mechanics at the mesoscopic level.
O4.2 To design experimental tests able to refine the framework of collapse models.
O4.3 To investigate macro-realism at the mesoscopic level through the experiments at the core of TEQ.

Deliverables

D4.1 Calibration of decoherence [M12]
D4.2 Bounds to CSL & SN models [M18]
D4.3 Size of the superposition [M24]
D4.4 Bounds to the ecCSL model [M36]
D4.5 Time-dilation/gravity collapse [M44]

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

People involved in WP4

UNITS


A Bassi


M Carlesso


C Jones

QUB


M Marchese


L Mancino


MP

OEAW


C Brukner


Ilya Kull


E C Ruiz


L Barbado


F Giacomini


A Belenchia
QUB


G Gasbarri
SOTON


M Toros
SOTON/UCL

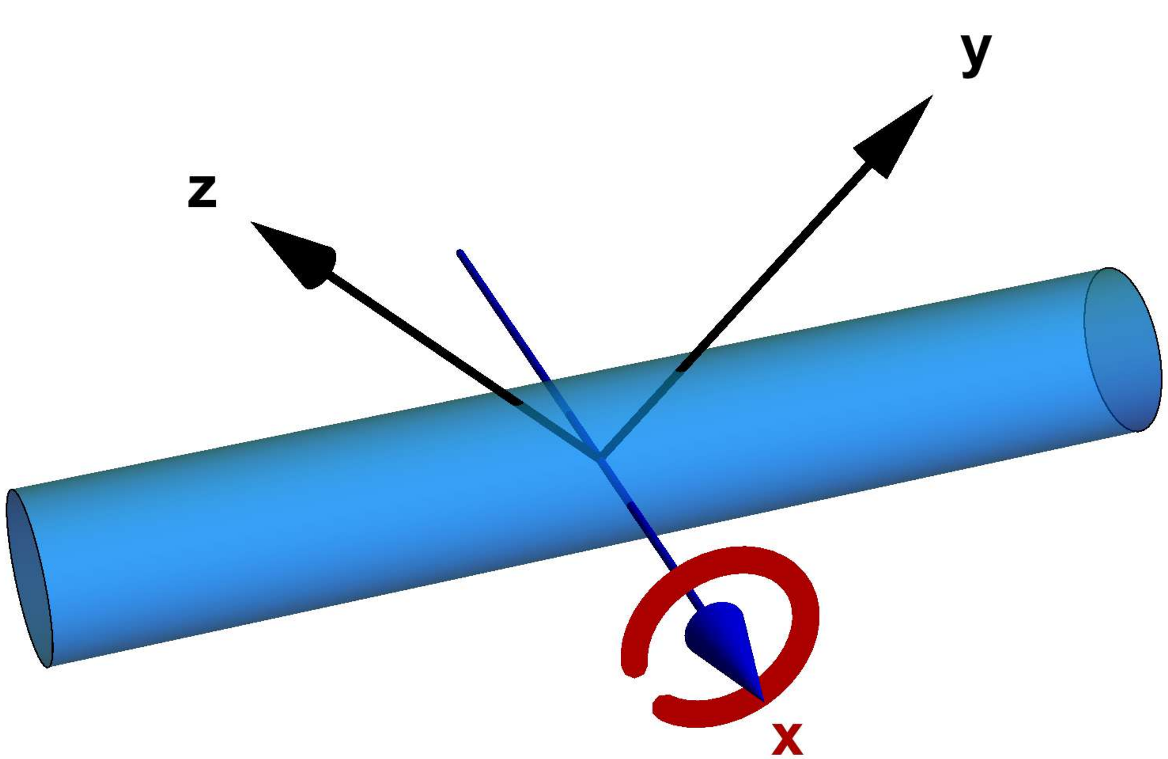
Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models

Bounds on CSL set by roto-vibrational degrees of freedom

- Mechanical system (cylinder) harmonically trapped both in position and rotational degree of freedom
- Monitored motion of (a) CoM vibration along **x**; (b) rotations about **x** axis



$$\hat{H}_{\mathrm{V}} = \hbar\omega_{\mathrm{C}}\hat{a}^\dagger\hat{a} + \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega_{\mathrm{m}}^2\hat{x}^2 - \hbar\chi\hat{a}^\dagger\hat{a}\hat{x}$$

$$\hat{H}_{\mathrm{R}} = \frac{\hat{L}_x^2}{2I} + \frac{1}{2}I\omega_\phi^2\hat{\phi}^2 - \hbar g_\phi\hat{a}^\dagger\hat{a}\hat{\phi}$$

Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models

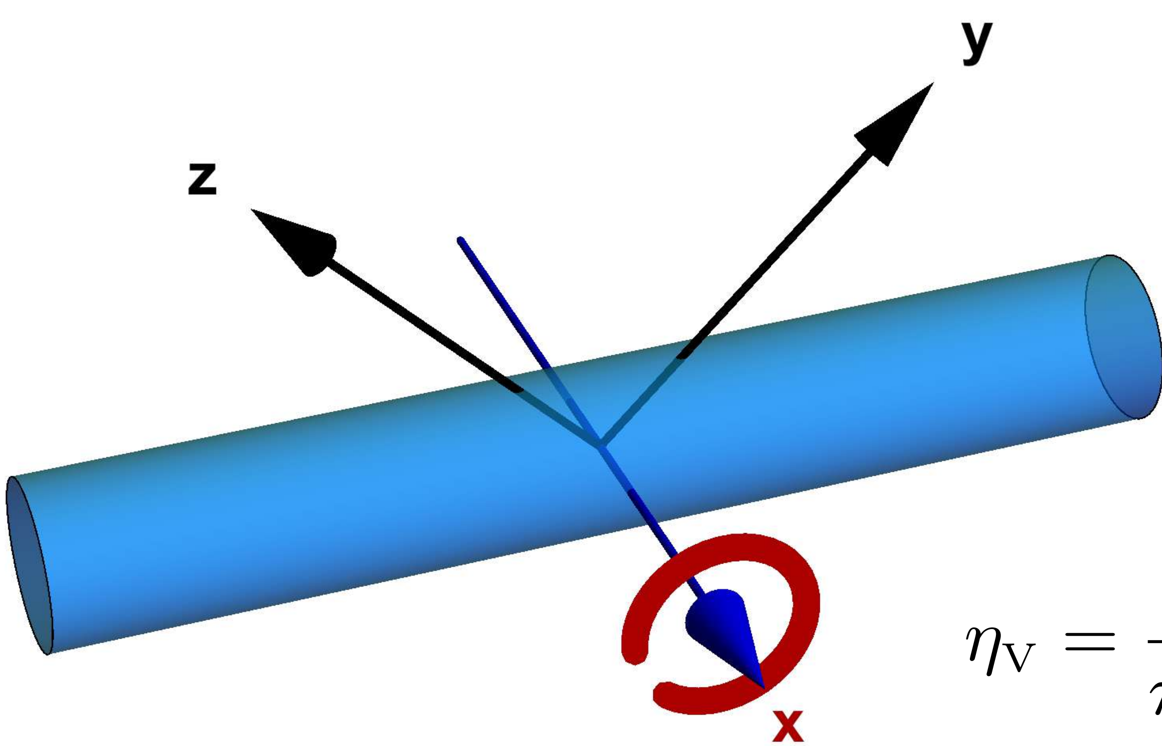
Bounds on CSL set by roto-vibrational degrees of freedom

Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\tfrac{i}{\hbar}[\hat{H}, \hat{\rho}] + \mathcal{L}[\hat{\rho}]$$

$$\mathcal{L}[\hat{\rho}] = -\frac{\lambda}{2r_C^3\pi^{3/2}m_0^2}\int \mathrm{d}^3\mathbf{r}\,[\hat{M}(\mathbf{r}),[\hat{M}(\mathbf{r}),\hat{\rho}]]$$

$$\hat{M}(\mathbf{r}) = \sum_n m_n \exp(-(\mathbf{r}-\hat{\mathbf{r}}_n)^2/2r_C^2)$$



For small-amplitude vibration & rotation

$$\mathcal{L}[\hat{\rho}] \simeq -\frac{\eta_{\mathrm{V}}}{2}[\hat{x},[\hat{x},\hat{\rho}]] - \frac{\eta_{\mathrm{R}}}{2}[\hat{\phi},[\hat{\phi},\hat{\rho}]]$$

$$\eta_{\mathrm{V}} = \frac{\lambda r_C^3}{\pi^{3/2}m_0^2}\int \mathrm{d}^3\mathbf{k}\, e^{-r_C^2k^2}k_x^2|\tilde{\mu}(\mathbf{k})|^2,$$

$$\eta_{\mathrm{R}} = \frac{\lambda r_C^3}{\pi^{3/2}m_0^2}\int \mathrm{d}^3\mathbf{k}\, e^{-r_C^2k^2}|k_y\partial_{k_z}\tilde{\mu}(\mathbf{k}) - k_z\partial_{k_y}\tilde{\mu}(\mathbf{k})|^2$$

Testing the large-scale limit of quantum mechanics

European Commission

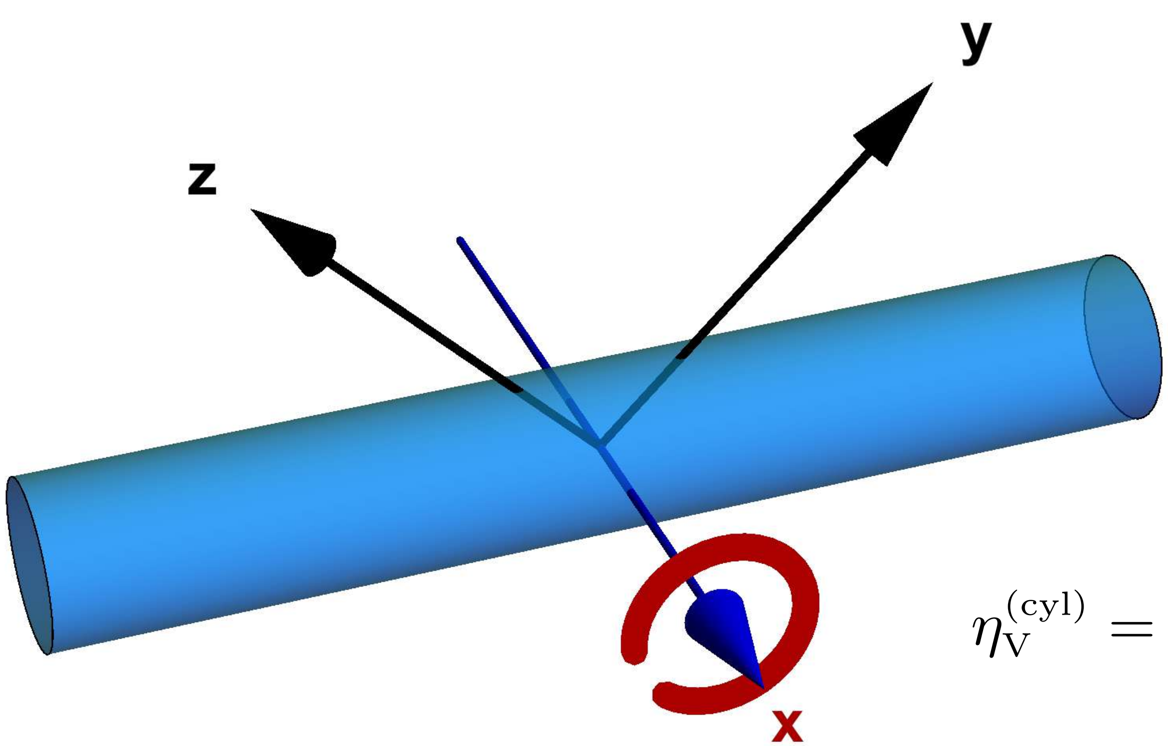
Bounds to collapse models

Bounds on CSL set by roto-vibrational degrees of freedom

Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \mathcal{L}[\hat{\rho}] \qquad \mathcal{L}[\hat{\rho}] = -\frac{\lambda}{2r_C^3\pi^{3/2}m_0^2}\int \mathrm{d}^3\mathbf{r}\,[\hat{M}(\mathbf{r}), [\hat{M}(\mathbf{r}), \hat{\rho}]]$$

$$\hat{M}(\mathbf{r}) = \sum_n m_n \exp(-(\mathbf{r} - \hat{\mathbf{r}}_n)^2/2r_C^2)$$



For small-amplitude vibration & rotation

$$\mathcal{L}[\hat{\rho}] \simeq -\frac{\eta_{\mathrm{V}}}{2}[\hat{x}, [\hat{x}, \hat{\rho}]] - \frac{\eta_{\mathrm{R}}}{2}[\hat{\phi}, [\hat{\phi}, \hat{\rho}]]$$

$$\eta_{\mathrm{V}}^{(\mathrm{cyl})} = \frac{8m^2 r_C^2\lambda}{L^2 m_0^2 R^2}\mathrm{I}_1\left(\frac{R^2}{2r_C^2}\right)e^{-\frac{R^2}{2r_C^2}}\left(\frac{L\sqrt{\pi}}{2r_C}\,\mathrm{erf}\left(\frac{L}{2r_C}\right) - 1 + e^{-\frac{L^2}{4r_C^2}}\right)$$

$$\eta_{\mathrm{R}}^{(\mathrm{cyl})} = \frac{2\lambda r_C^4 m^2}{L^2 R^2 m_0^2}\left\{\left[\left(1 - e^{-\frac{L^2}{4r_C^2}}\right)\left(8 + \frac{R^2}{r_C^2}\right) - \frac{2L\sqrt{\pi}}{r_C}\,\mathrm{erf}\left(\frac{L}{2r_C}\right)\right] + \ldots\ldots\right.$$

TEQ Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models

Bounds on CSL set by roto-vibrational degrees of freedom

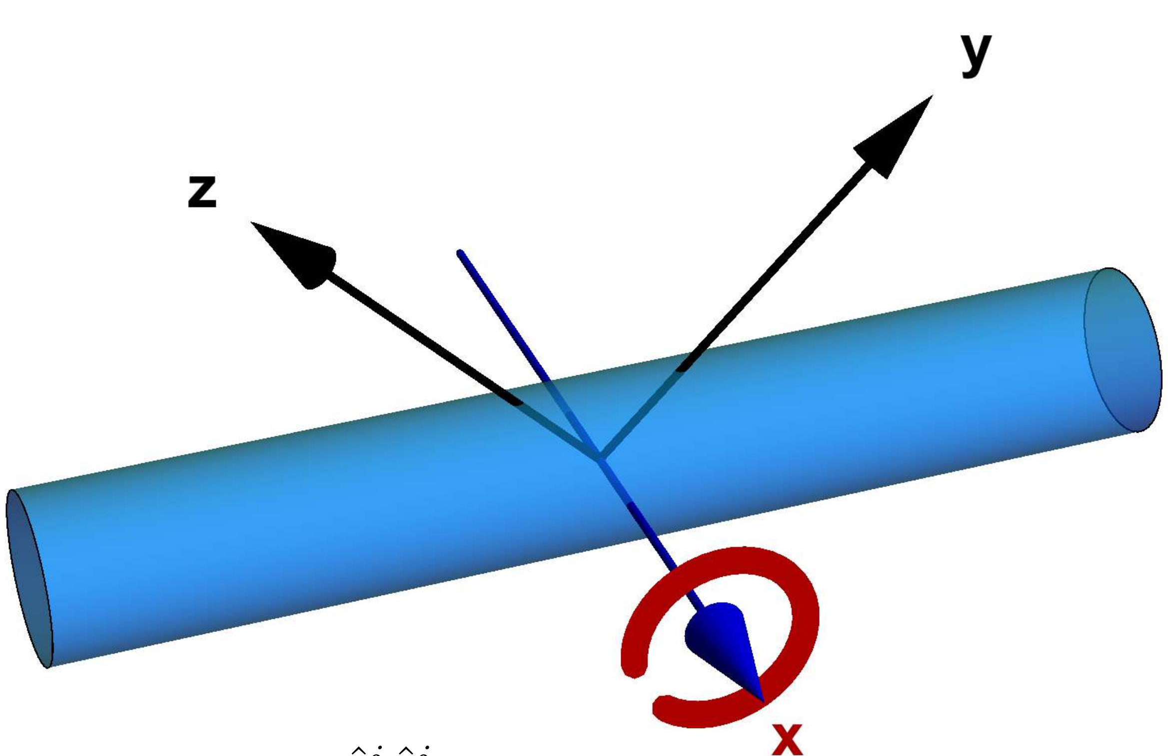
Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \mathcal{L}[\hat{\rho}] \longrightarrow$$

$$\begin{aligned}
\frac{\mathrm{d}\hat{x}}{\mathrm{d}t} &= \hat{p}/m, \\
\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}t} &= \hat{L}_x/I, \\
\frac{\mathrm{d}\hat{a}}{\mathrm{d}t} &= -i(\Delta_0 - g_\phi\hat{\phi} - i\kappa)\hat{a} + i\chi\hat{a}\hat{x} + \sqrt{2\kappa}\hat{a}_{\mathrm{in}}, \\
\frac{\mathrm{d}\hat{p}}{\mathrm{d}t} &= -m\omega_{\mathrm{m}}^2\hat{x} + \hbar\chi\hat{a}^\dagger\hat{a} - \gamma_{\mathrm{m}}\hat{p} + \hat{\xi}^{\mathrm{V}} - \boxed{\hbar\sqrt{\eta_{\mathrm{V}}}w_{\mathrm{V}}}, \\
\frac{\mathrm{d}\hat{L}_x}{\mathrm{d}t} &= -I\omega_\phi^2\hat{\phi} + \hbar g_\phi\hat{a}^\dagger\hat{a} - \frac{D_\phi}{I}\hat{L}_x + \hat{\xi}^{\mathrm{R}} - \boxed{\hbar\sqrt{\eta_{\mathrm{R}}}w_{\mathrm{R}}},
\end{aligned}$$

Quantum Langevin equations

+ noise



CSL force terms

$$\frac{\langle \hat{\xi}_t^j \hat{\xi}_s^j \rangle}{\hbar\epsilon_j} = \int \frac{\mathrm{d}\omega}{2\pi} e^{-i\omega(t-s)}\omega[1 + \coth(\beta\omega)] \qquad (j = \mathrm{R},\mathrm{V})$$

Thermal noise

$$\langle w_i(t) w_j(s) \rangle = \delta_{ij}\delta(t-s)$$

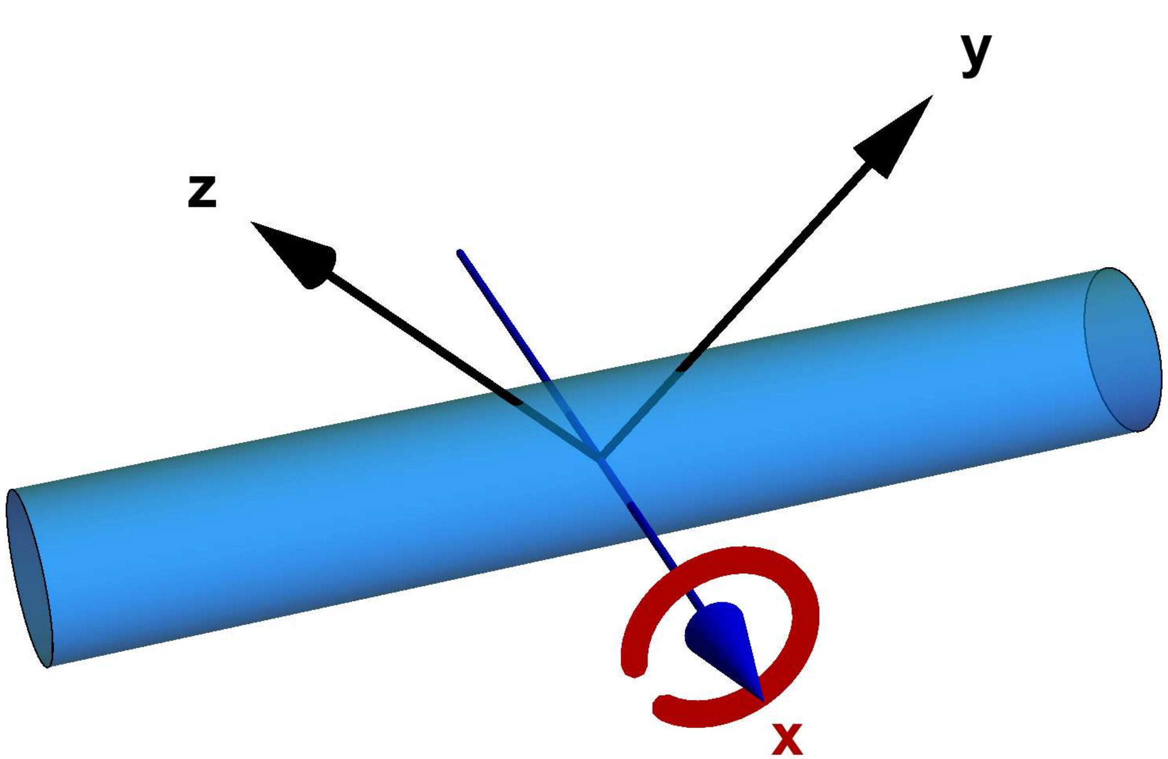
Bounds to collapse models

Bounds on CSL set by roto-vibrational degrees of freedom

Density noise spectrum

$$\mathcal{S}_j(\omega) = \frac{2\hbar^2|\alpha|^2\kappa\mathcal{G}_j^2 + \left[\kappa^2 + (\Delta-\omega)^2\right]\left[\hbar\omega\epsilon_j\coth(\beta\omega) + \hbar^2\eta_j\right]}{\lambda_j^2\left[\kappa^2 + (\Delta-\omega)^2\right]\left[(\omega_{j,\mathrm{eff}}^2-\omega^2)^2 + \Gamma_{j,\mathrm{eff}}^2\omega^2\right]}$$

DNS Parameter	$\mathcal{G}_j$	$\omega_{j,\mathrm{eff}}$	$\Gamma_{j,\mathrm{eff}}$	λ_j
Vibration	χ	$\omega_{\mathrm{m,eff}}$	$\gamma_{\mathrm{m,eff}}$	m
Rotation	g_ϕ	$\omega_{\phi,\mathrm{eff}}$	$D_{\phi,\mathrm{eff}}/I$	I



$$\omega_{\mathrm{m,eff}}^2 = \omega_{\mathrm{m}}^2 - \frac{2\hbar\chi^2|\alpha|^2\Delta(\kappa^2+\Delta^2-\omega^2)}{m\left(\kappa^2+(\Delta-\omega)^2\right)\left(\kappa^2+(\Delta+\omega)^2\right)},$$

$$\omega_{\phi,\mathrm{eff}}^2 = \omega_{\phi}^2 - \frac{2\hbar g_\phi^2|\alpha|^2\Delta(\kappa^2+\Delta^2-\omega^2)}{I\left(\kappa^2+(\Delta-\omega)^2\right)\left(\kappa^2+(\Delta+\omega)^2\right)},$$

$$\gamma_{\mathrm{m,eff}} = \gamma_{\mathrm{m}} + \frac{4\hbar\chi^2|\alpha|^2\kappa\Delta}{m\left(\kappa^2+(\Delta-\omega)^2\right)\left(\kappa^2+(\Delta+\omega)^2\right)},$$

$$D_{\phi,\mathrm{eff}} = D_{\phi} + \frac{4\hbar g_\phi^2|\alpha|^2\kappa\Delta}{\left(\kappa^2+(\Delta-\omega)^2\right)\left(\kappa^2+(\Delta+\omega)^2\right)}.$$

Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models

Bounds on CSL set by roto-vibrational degrees of freedom

Density noise spectrum

$$\mathcal{S}_j(\omega) = \frac{2\hbar^2|\alpha|^2\kappa\mathcal{G}_j^2 + \left[\kappa^2 + (\Delta-\omega)^2\right]\left[\hbar\omega\epsilon_j\coth(\beta\omega) + \hbar^2\eta_j\right]}{\lambda_j^2\left[\kappa^2+(\Delta-\omega)^2\right]\left[(\omega_{j,\mathrm{eff}}^2-\omega^2)^2+\Gamma_{j,\mathrm{eff}}^2\omega^2\right]}$$

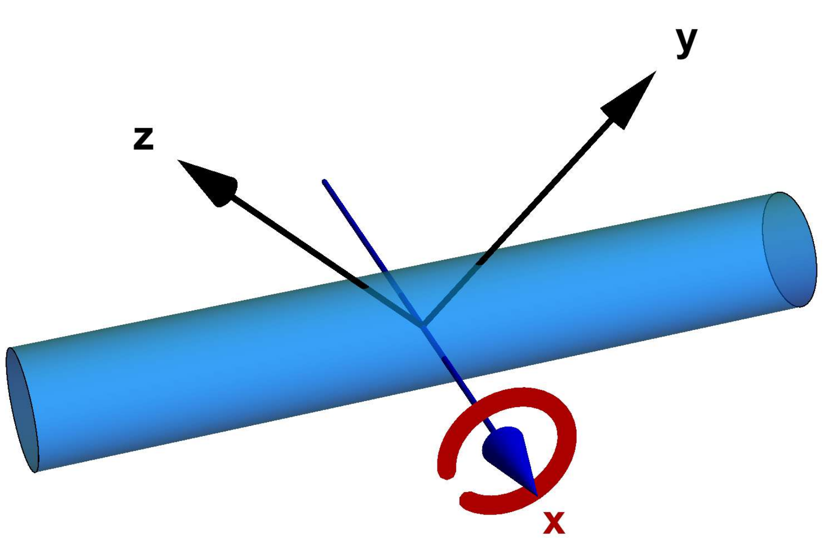
High temperature limit

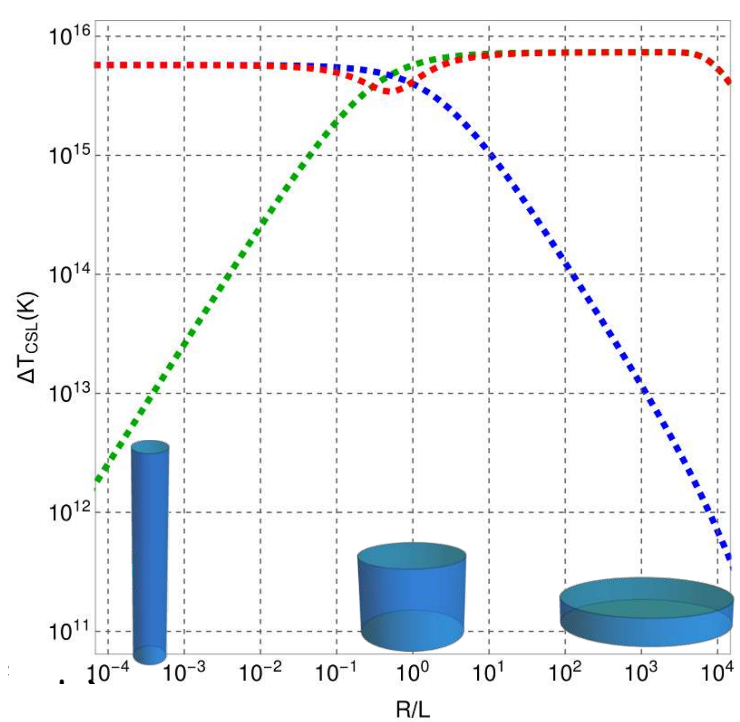
$$\hbar\omega\epsilon_j\coth(\beta\omega) + \hbar^2\eta_j \to \hbar\epsilon_j\left(\frac{1}{\beta} + \frac{\hbar\eta_j}{\epsilon_j}\right) \equiv \frac{\hbar\epsilon_j}{\beta_{j,\mathrm{eff}}}$$

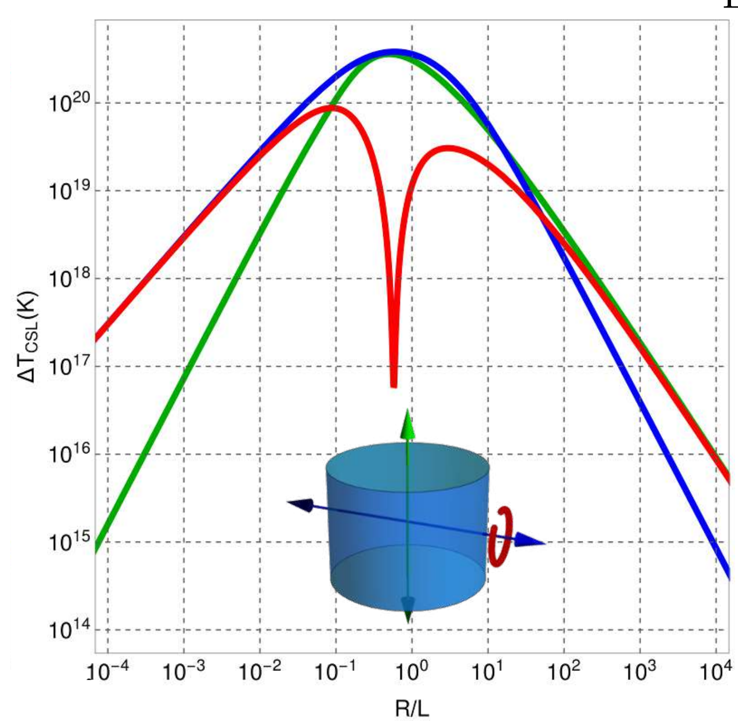
Effective temperatures

$$\Delta T_{\mathrm{CSL}}^{\mathrm{V}} = \frac{\hbar^2\eta_{\mathrm{V}}}{2k_{\mathrm{B}}m\gamma_{\mathrm{m}}}$$

$$\Delta T_{\mathrm{CSL}}^{\mathrm{R}} = \frac{\hbar^2\eta_{\mathrm{R}}}{2k_{\mathrm{B}}D_\phi}$$







$\lambda = 1\,\mathrm{s}^{-1}$

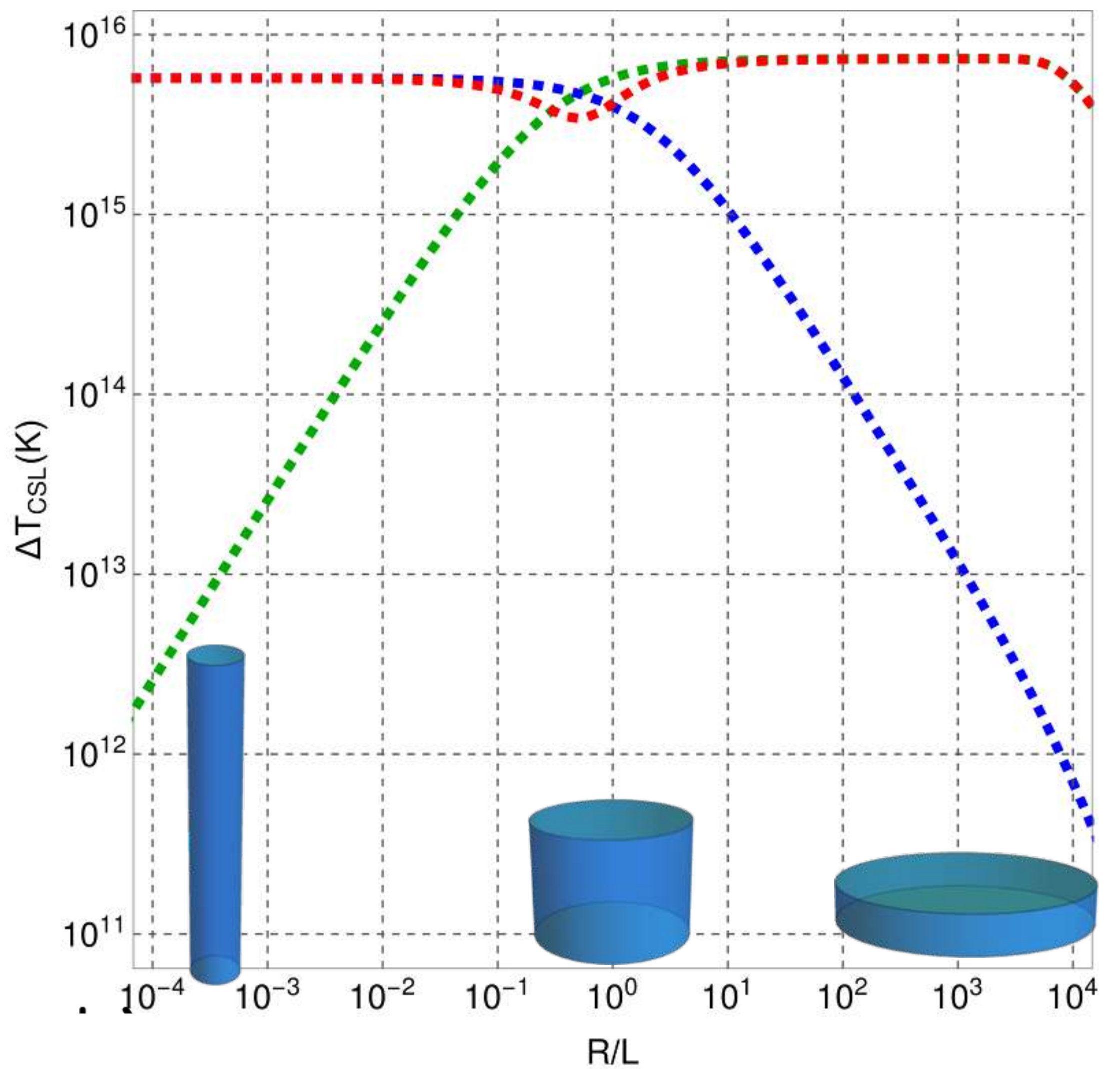
$r_C = 10^{-7}\,\mathrm{m}$

TEQ

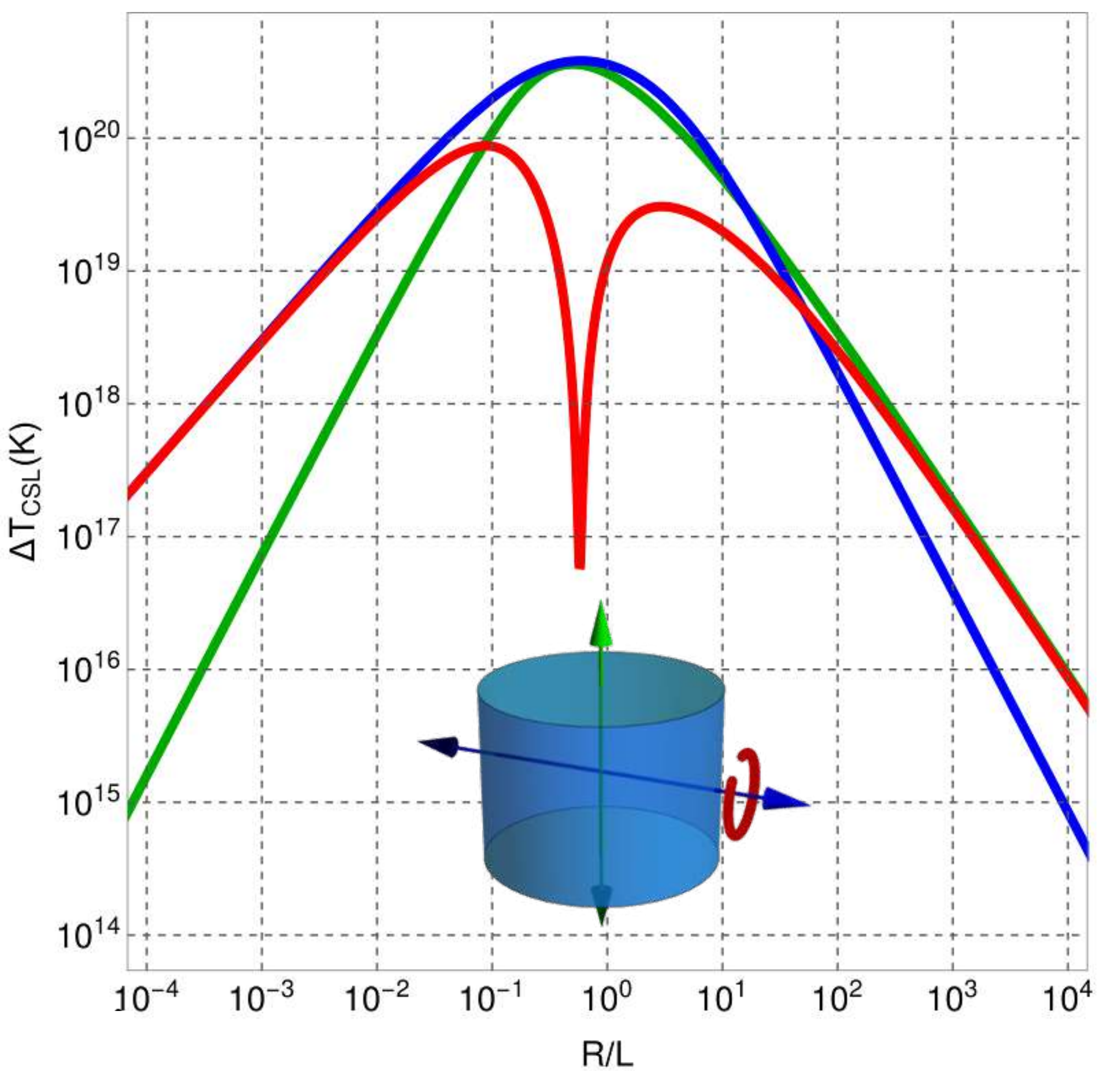
Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models



$$r_C = 10^{-7}\,\mathrm{m}$$



$$r_C = 10^{-4}\,\mathrm{m}$$

Testing the large-scale limit of quantum mechanics

European Commission

Bounds to collapse models

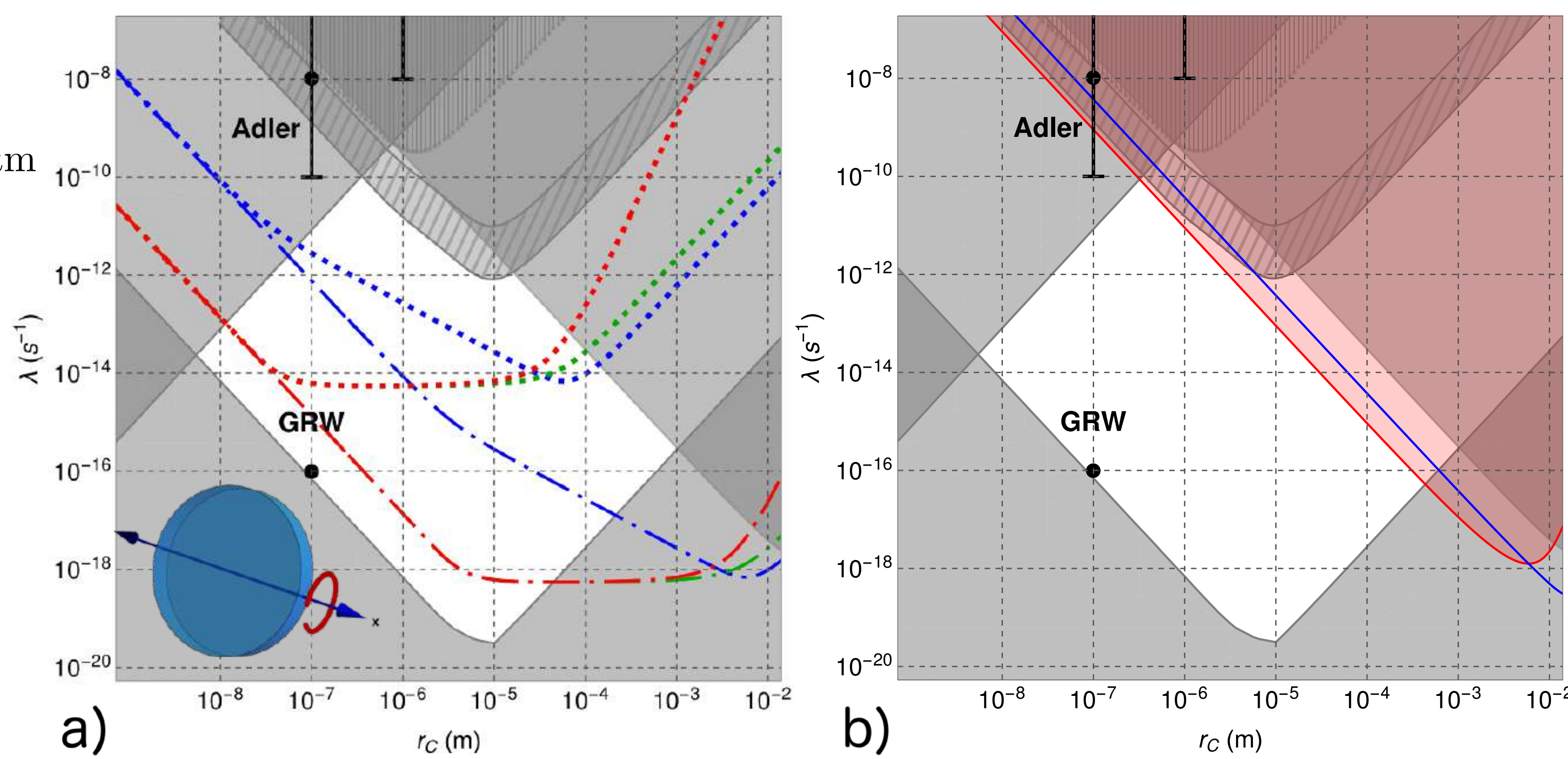
Bounds on CSL set by roto-vibrational degrees of freedom

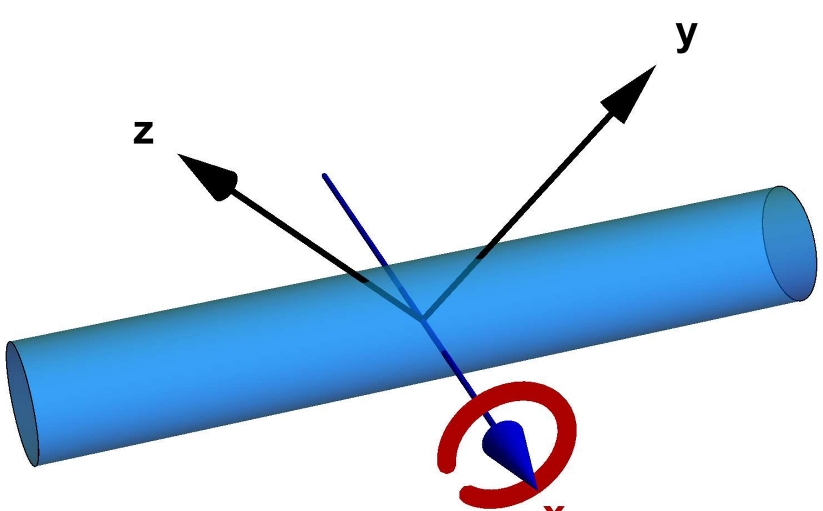
Assessing CSL

Silica ‘coin'

(dotted line) $R = 0.1\text{mm}$ and $L = 0.1\mu\text{m}$

(dash-dot line) $R = 1\text{cm}$ and $L = 10\mu\text{m}$





M Carlesso et al, New J Phys 21, 093052 (2020)

Size of superposition

Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \mathcal{L}[\hat{\rho}] \qquad \hat{H} = \hbar\omega_o a^\dagger a + \hbar\omega_m b^\dagger b - \hbar g a^\dagger a(b + b^\dagger)$$

- What is the capacity of the optomechanical Hamiltonian to generate macroscopic superposition states?
- How do we access such macroscopicity?

Time-evolution operator from optomechanical Hamiltonian

$$U(\tau) = e^{-ira^\dagger a\tau} e^{ik^2(a^\dagger a)^2(\tau - \sin(\tau))} e^{ka^\dagger a(\eta b^\dagger - \eta^* b)} e^{-ib^\dagger b\tau}$$

General form of the time-evolved optomechanical state

$$|\psi(\tau)\rangle = e^{-|\alpha|/2} \sum_{n=0}^{\infty} c_n(\alpha, \tau)\, |n\rangle_c \otimes |\phi_n(\tau)\rangle_m$$

Size of superposition

Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}\boxed{[\hat{H}, \hat{\rho}]} + \mathcal{L}[\hat{\rho}] \qquad \hat{H} = \hbar\omega_o a^\dagger a + \hbar\omega_m b^\dagger b + \hbar g a^\dagger a (b^\dagger + b)^2$$

- What is the capacity of the optomechanical Hamiltonian to generate macroscopic superposition states?
- How do we access such macroscopicity?

Time-evolution operator from optomechanical Hamiltonian

$$U(t) = e^{i\omega_m t/2} e^{\frac{1}{2}(\xi^* b^2 - \xi (b^\dagger)^2)} e^{i\eta(b^\dagger b + \frac{1}{2})}$$

General form of the time-evolved optomechanical state

$$|\psi(\tau)\rangle = \sum_{n=0}^{\infty} z(n,\tau) \, |n\rangle_c \, |\xi(n)\rangle_m$$

Size of superposition

Master equation of mechanical motional state

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}\boxed{[\hat{H},\hat{\rho}]} + \mathcal{L}[\hat{\rho}]$$

Characteristic function of mechanical state

$$\mathcal{I}(\rho) = \frac{1}{2\pi}\int (|\gamma|^2 - 1)\boxed{|\chi(\gamma)|^2} d^2\gamma$$

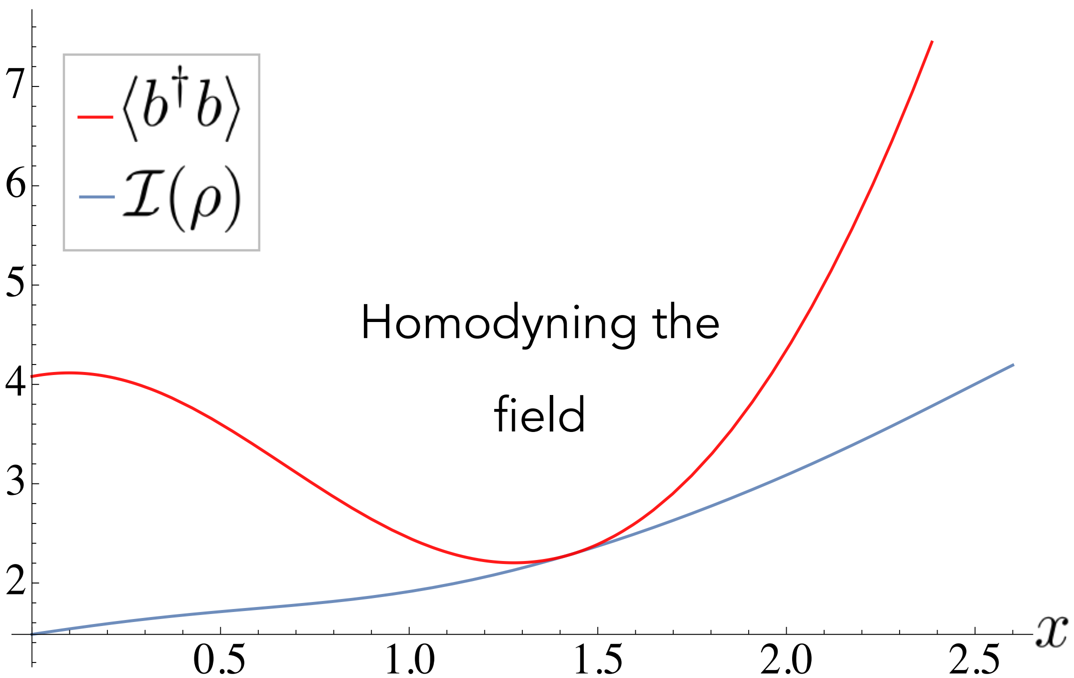
- What is the capacity of the optomechanical Hamiltonian to generate macroscopic superposition states?
- How do we access such macroscopicity?

Result: Reduced state of mechanical system: **Not** macroscopically quantum (incoherent mixture of coherent states)

Question: What if we condition the state of the mechanical system?

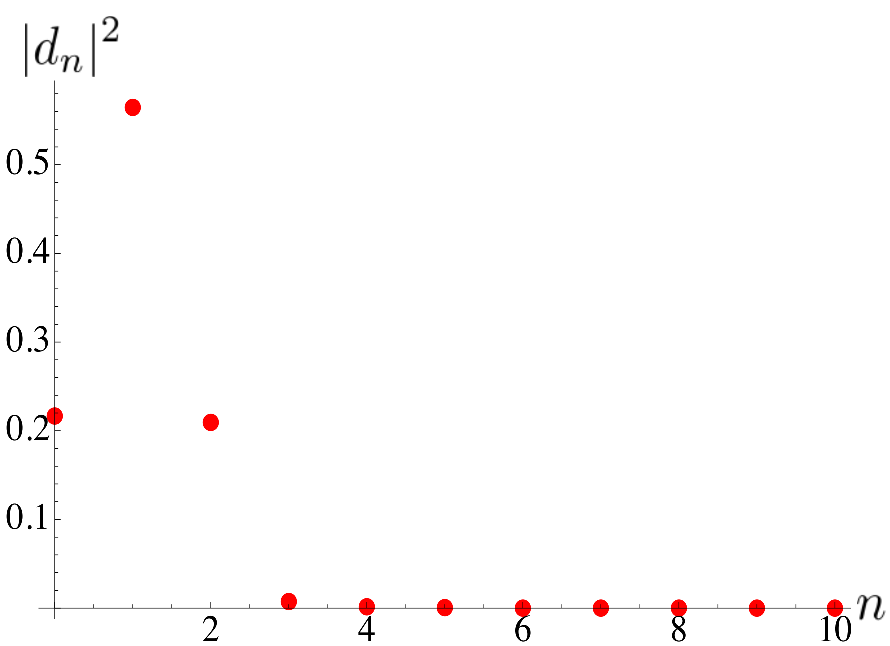
Testing the large-scale limit of quantum mechanics

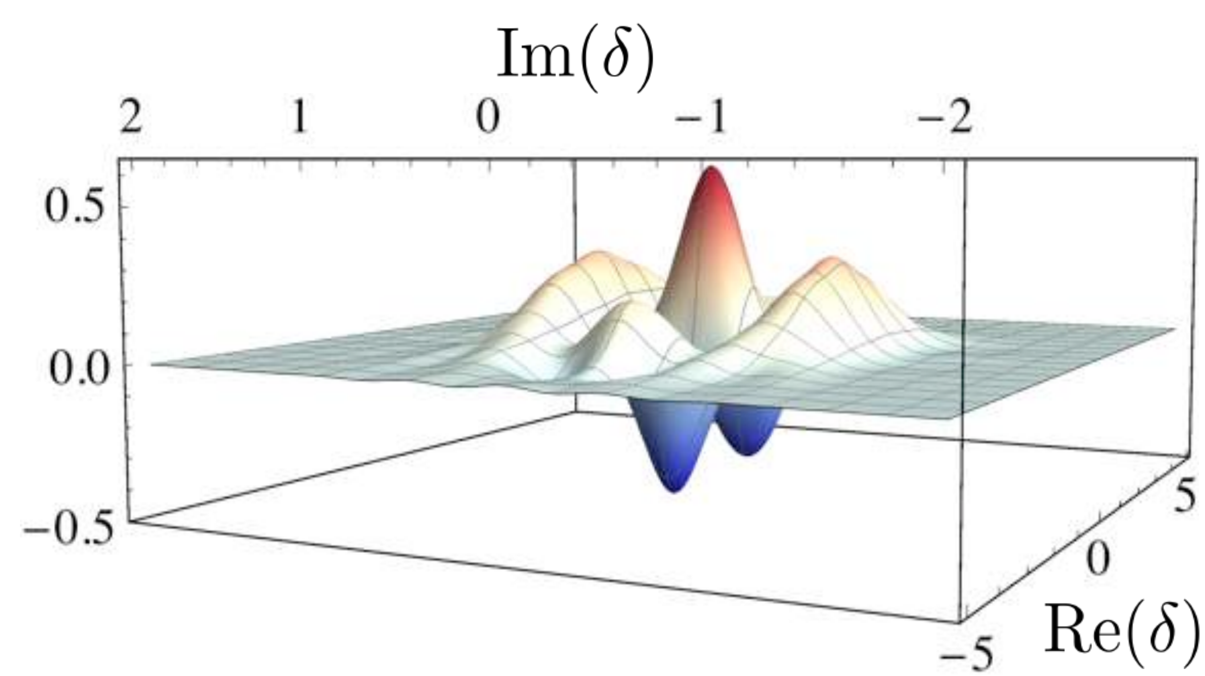
Size of superposition



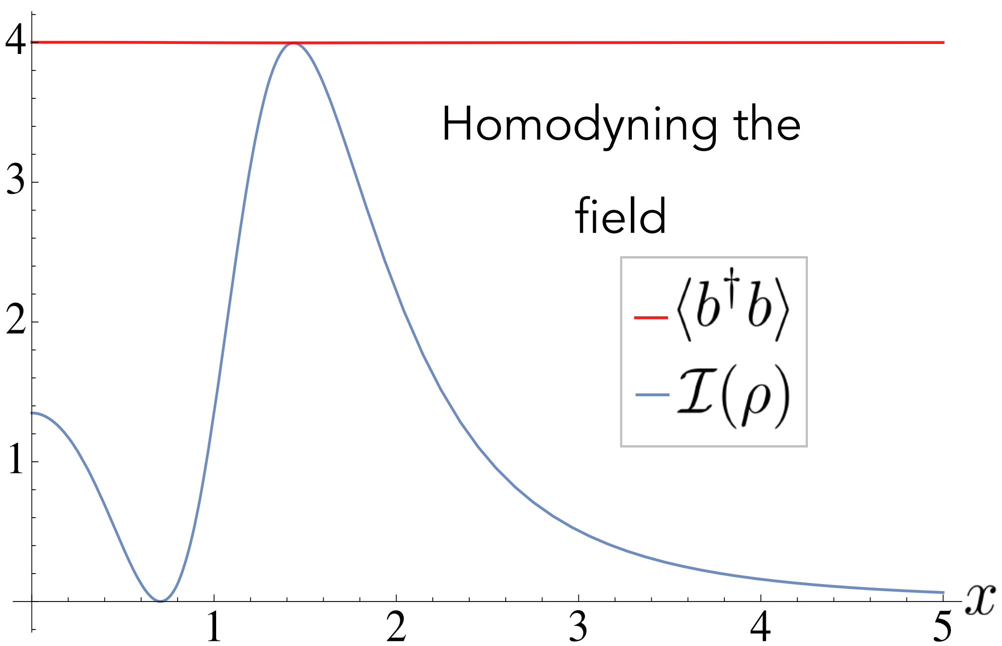
Characteristic function of mechanical state

$$\mathcal{I}(\rho) = \frac{1}{2\pi} \int (|\gamma|^2 - 1)|\boxed{\chi(\gamma)}|^2 d^2\gamma$$



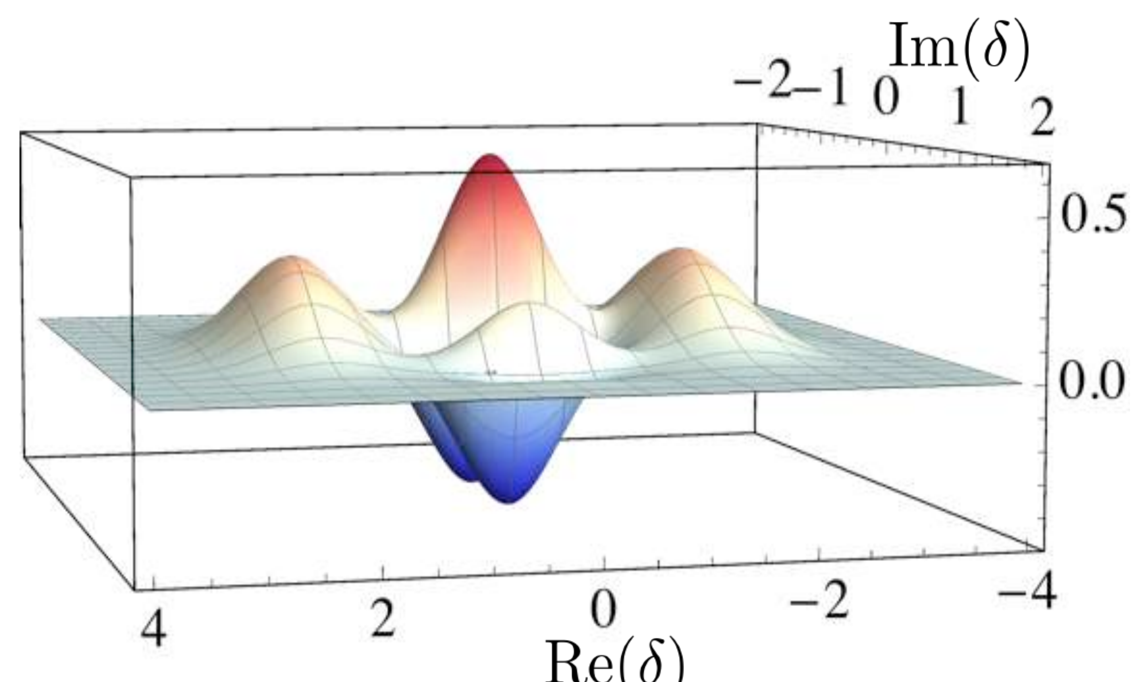


Size of superposition



Characteristic function of mechanical state

$$\mathcal{I}(\rho) = \frac{1}{2\pi}\int (|\gamma|^2 - 1)\boxed{|\chi(\gamma)}|^2 d^2\gamma$$



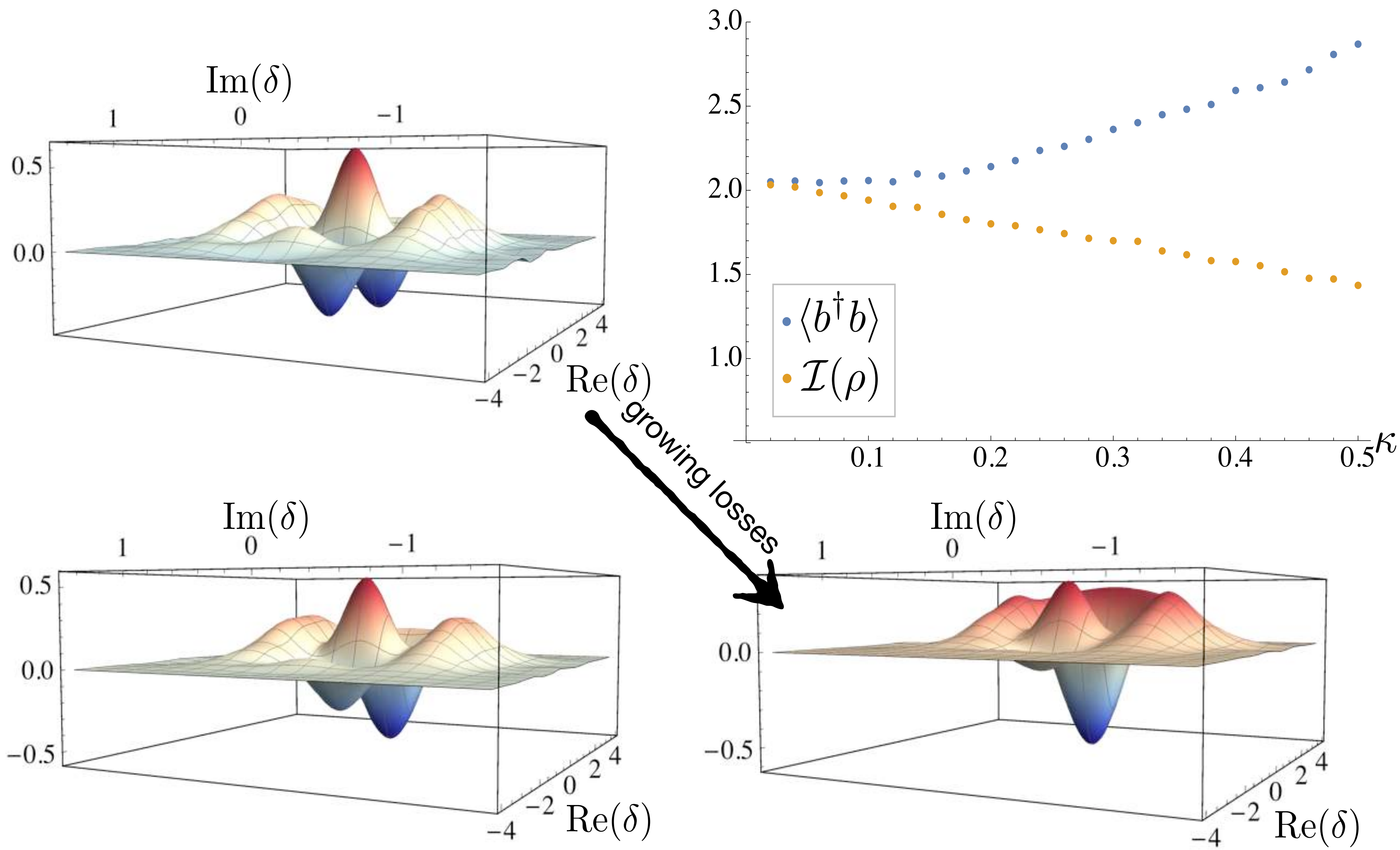
$$|\psi(\tau)\rangle = z(0,\tau)\,|0\rangle_c\,|0\rangle_m + z(1,\tau)\,|1\rangle_c\,|\xi(1)\rangle_m$$

Testing the large-scale limit of quantum mechanics

European Commission

Size of superposition

Adding the effect of optical losses

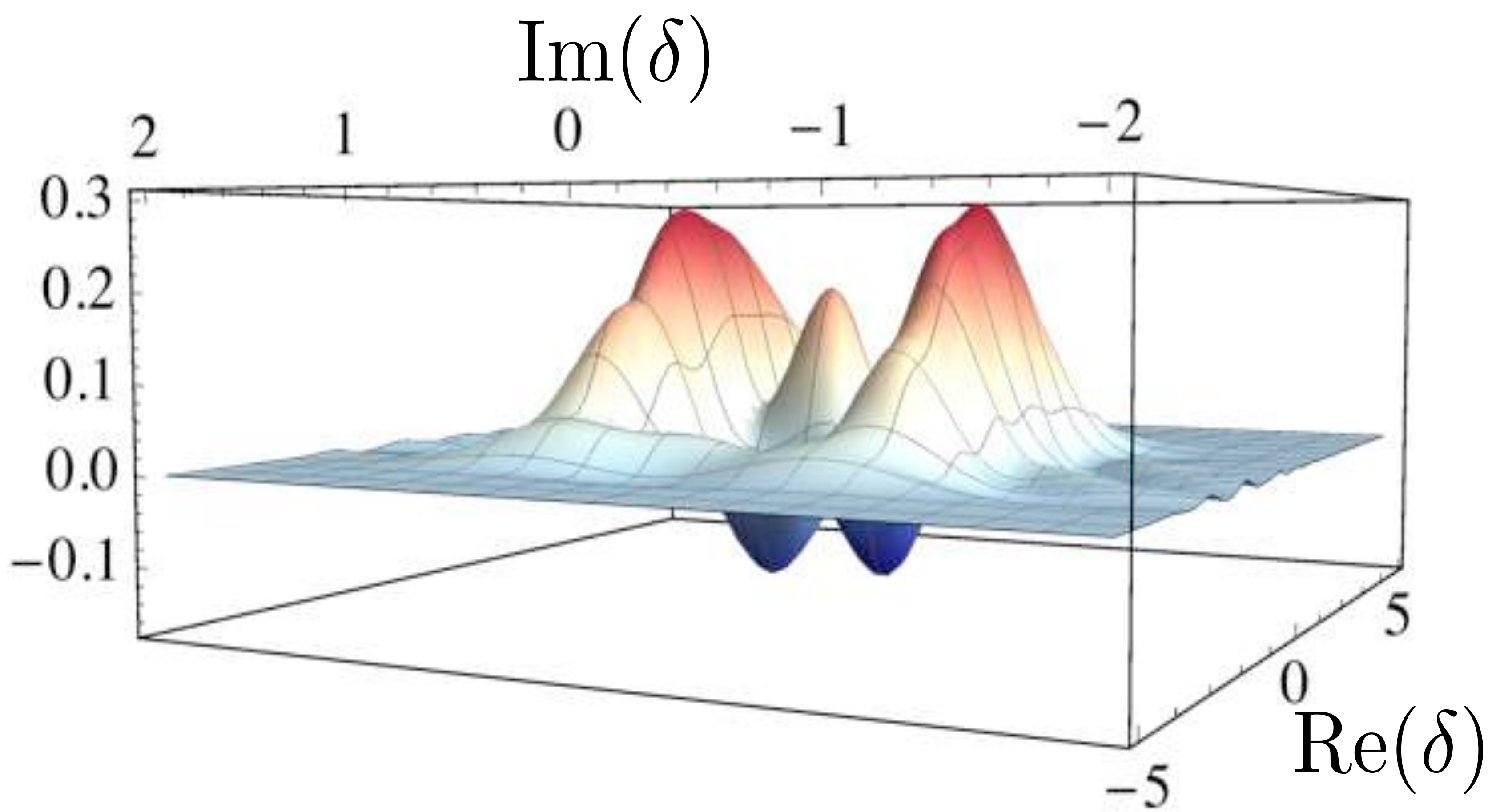


Testing the large-scale limit of quantum mechanics

European Commission

Size of superposition

Adding the effect of thermal nature of the mechanical state



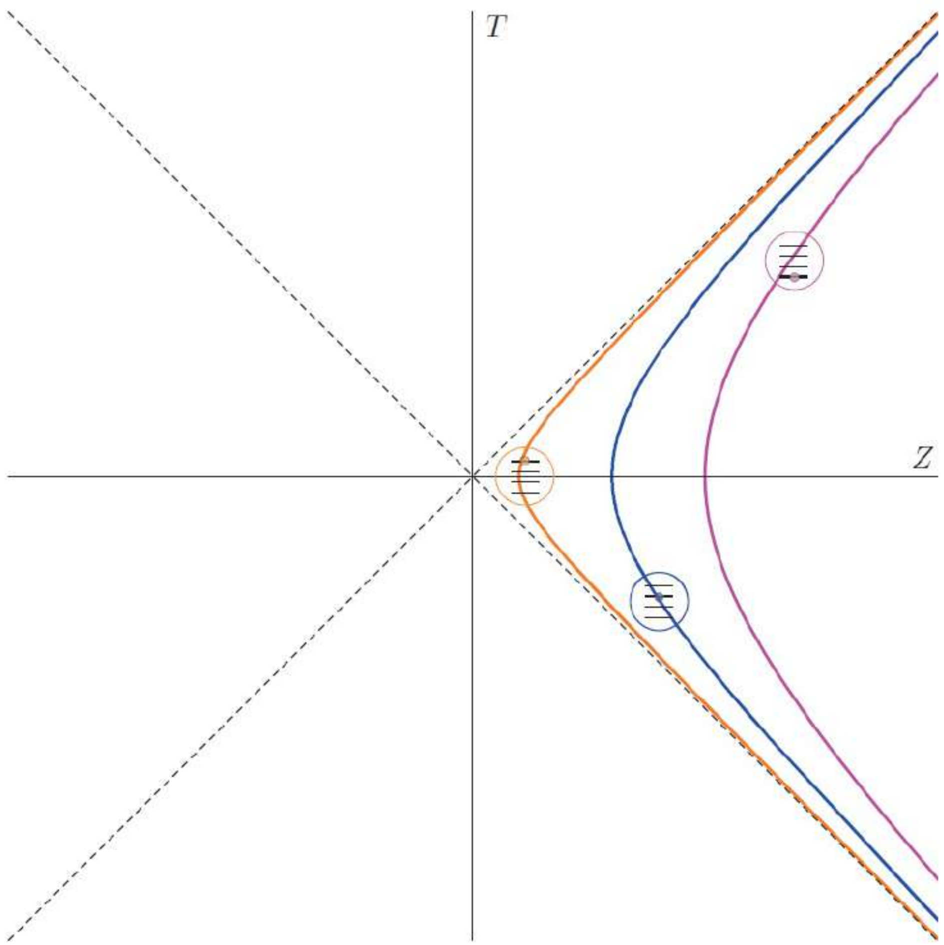
H McAleese & M Paternostro, New J Phys (to appear, 2020)

Testing the large-scale limit of quantum mechanics

European Commission

Going beyond our "dues" for the reporting period

Unruh effect for detectors in superposition of accelerations



Excitations of the detector:

- Incoherent thermal radiation for each trajectory separately (known)
- Coherent contributions that entangle internal and external d.o.f. of the detector (new result)

Physical interpretation:

- First approach to the notion of "superposition of thermal states"
- The detector absorbs a particle of the thermal bath in the surroundings of each trajectory

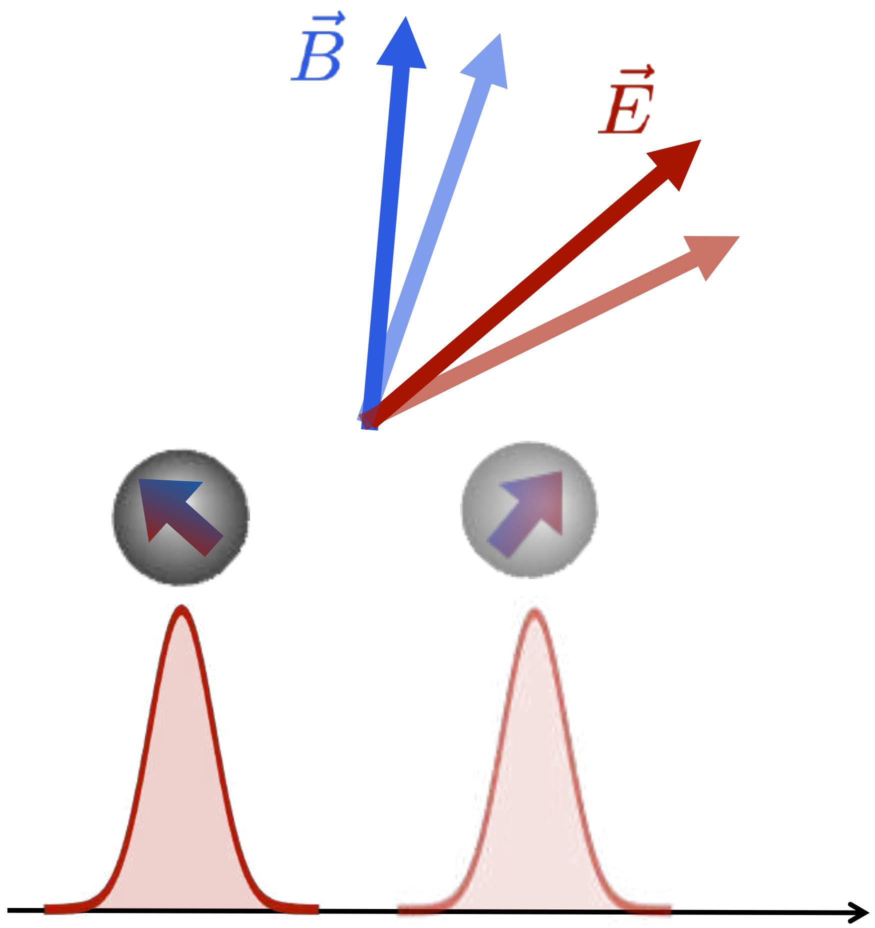
L. C. Barbado, E. Castro-Ruiz, L. Apadula, and Č. Brukner, Phys. Rev. D **102**, 045002 (2020)

Testing the large-scale limit of quantum mechanics

European Commission

Going beyond our “dues” for the reporting period

Relativistic Quantum Reference Frames: The Operational Meaning of Spin



Spin in special relativity:

•Spin is defined as the total angular momentum in the rest frame of the particle

•The rest frame is not (classically) defined for particles in a superposition of momenta

Solution via Quantum Reference Frames:

•Spin is defined as the total angular momentum in the rest frame of the particle

•The rest frame is not (classically) defined for particles in a superposition of momenta

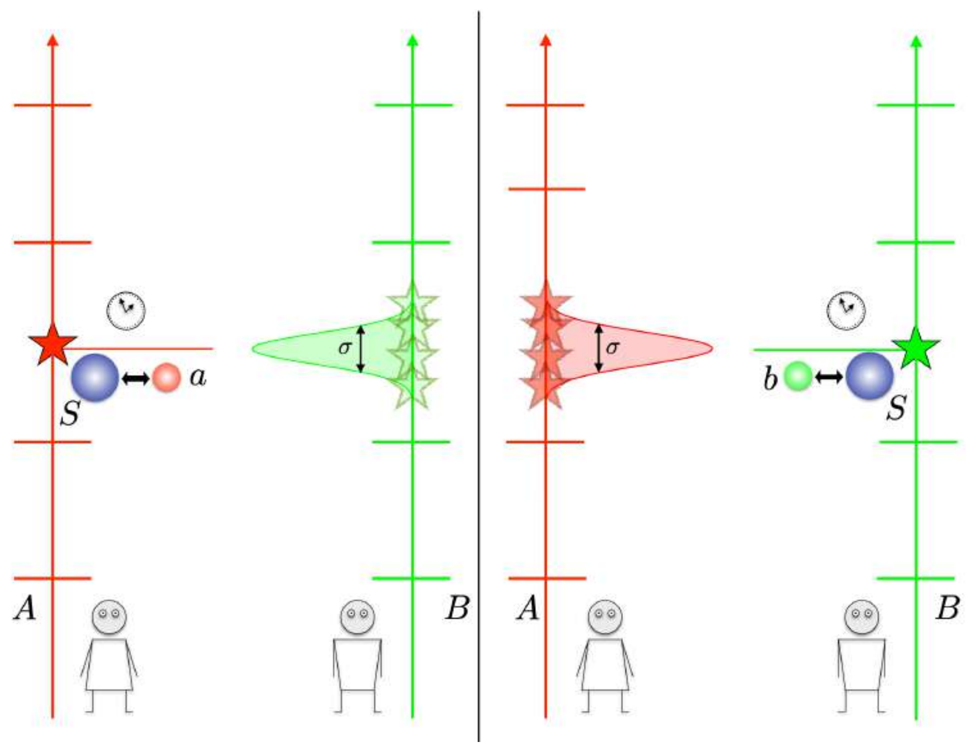
F. Giacomini, E. Castro-Ruiz, and Č. Brukner, Phys. Rev. Lett. 123, 090404 (2019)

Testing the large-scale limit of quantum mechanics

European Commission

Going beyond our “dues” for the reporting period

Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems



Events in quantum mechanics

- The time at which an event happens depends on the reference frame in general relativity
- However, events are always localised in time

Events amid gravitating quantum systems

- Whether an event is localisable in time or not depends on the (quantum) temporal reference frame
- Always possible to find a reference frame for which a given event is localised in time and admits a usual von Neumann description

E. Castro-Ruiz, F. Giacomini, A. Belenchia, and Č. Brukner Nature Commun. **11**, 2672 (2020)

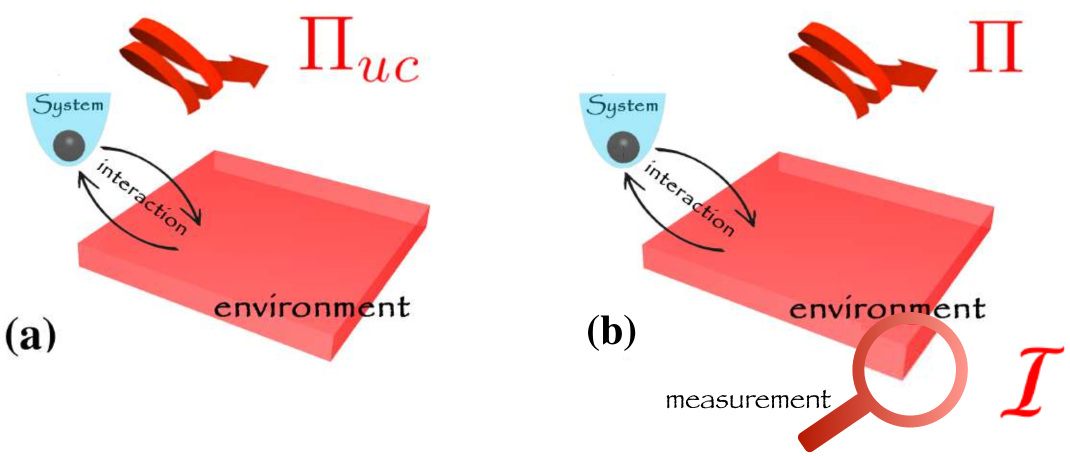
TEQ

Testing the large-scale limit of quantum mechanics

European Commission

Going beyond our "dues" for the reporting period

Heat fluxes in continuously measured systems



$$\boxed{\Pi} = \boxed{\Pi_{uc}} + \boxed{\dot{\mathcal{I}}}$$

Conditional entropy production

Unconditional entropy production

Rate of information gain

Driven-dissipative systems

- Driven-dissipative systems reach non-equilibrium steady states (NESSs) with non-zero heat fluxes to their bath
- NESS are associated with non-zero entropy production

Adding continuous monitoring

- Measuring alters the information we have on the system and thus the amount of entropy flowing to the bath
- this corresponds to an altered heat flux!
- Different measurement straggles achieve different states

A. Belenchia, L. Mancino, G. T. Landi, and M. Paternostro Nature Quant Inf (accepted, 2020)

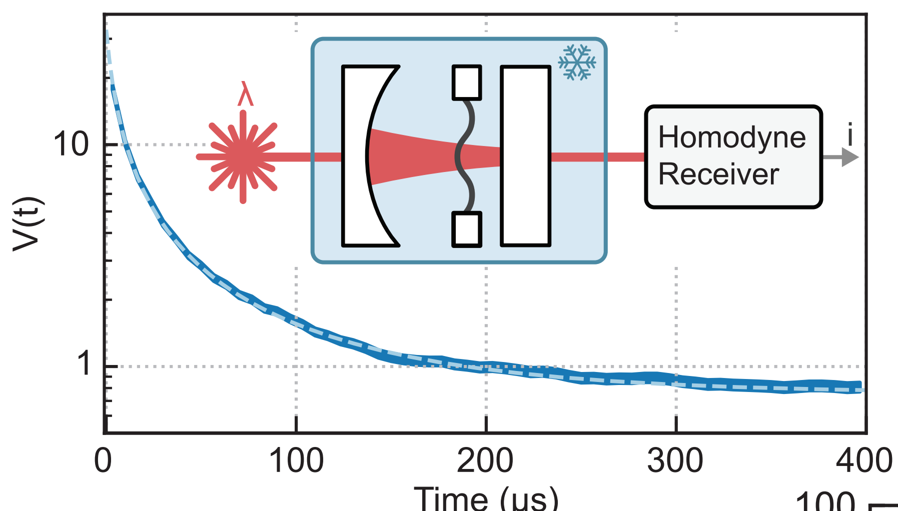
TEQ

Testing the large-scale limit of quantum mechanics

European Commission

Going beyond our "dues" for the reporting period

Heat fluxes in continuously measured systems: experimental test

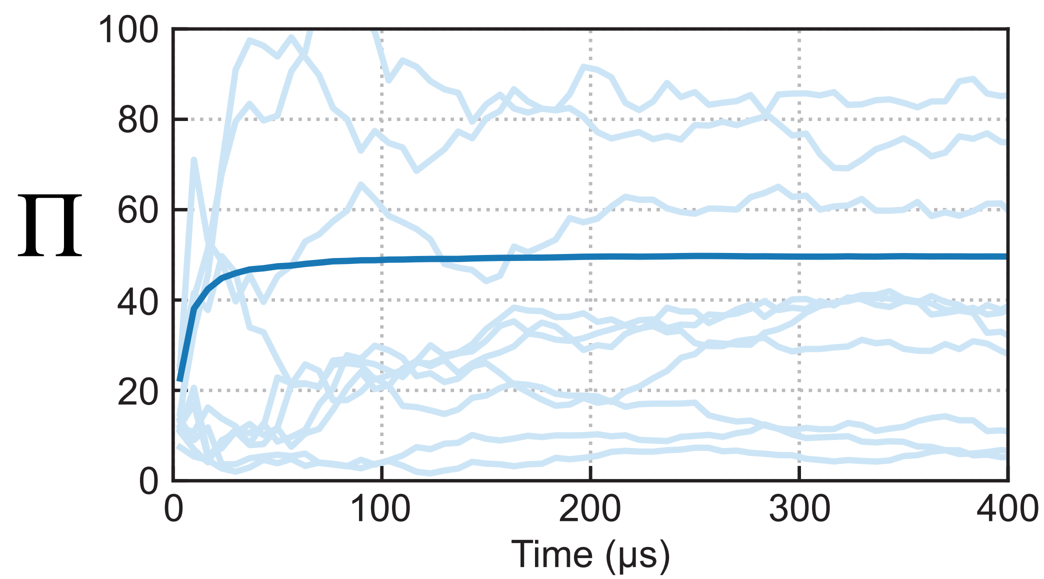


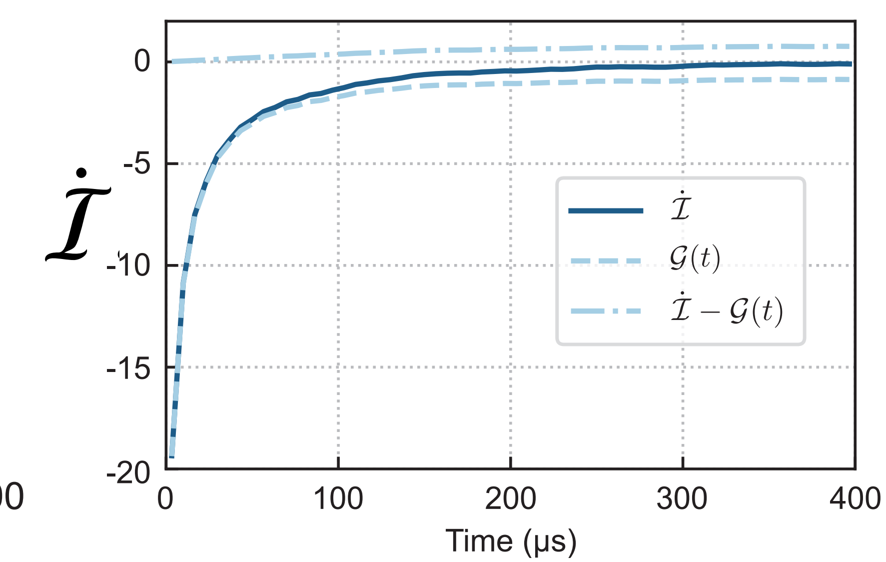
Adding continuous monitoring

$$d\mathbf{r}(t) = -\frac{\Gamma_m}{2}\mathbf{r}dt + \sqrt{4\eta_{\rm det}\Gamma_{\rm qba}}V(t)d\mathbf{W},$$

$$\dot{V}(t) = \Gamma_m(V_{\rm uc} - V(t)) - 4\eta_{\rm det}\Gamma_{qba}V(t)^2$$

$$\Pi = \Pi_{\rm uc} + \dot{\mathcal{I}}$$



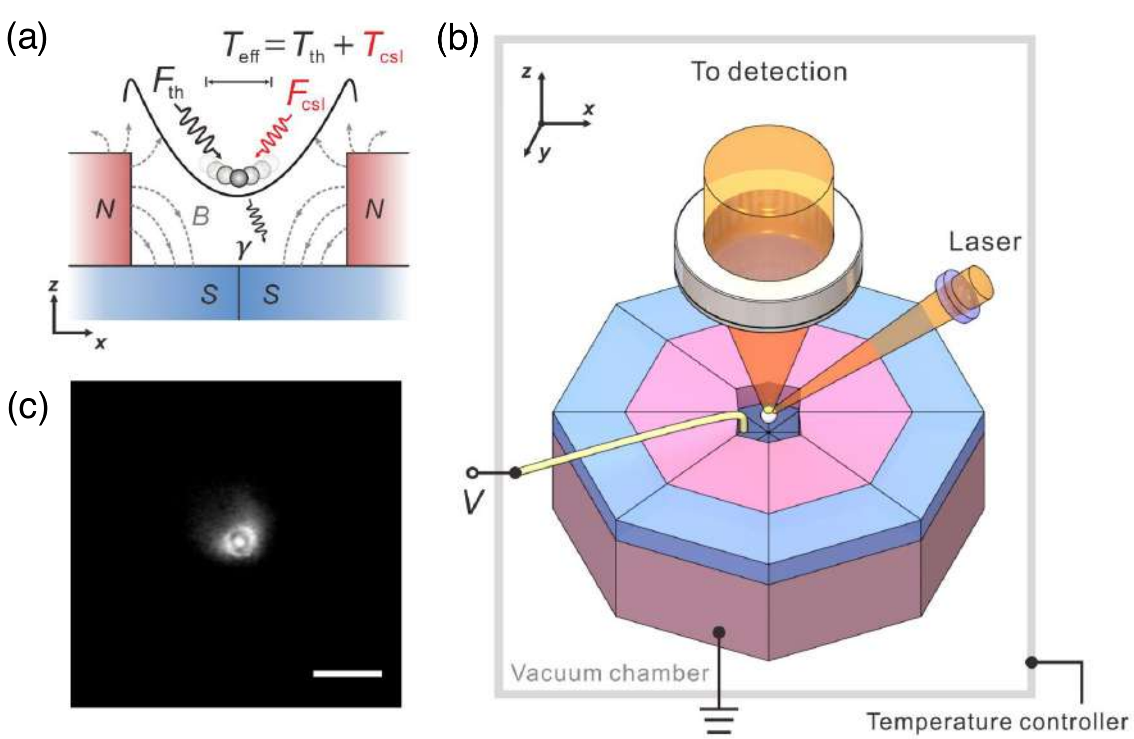


M. Rossi, L. Mancino, G. T. Landi, M. Paternostro, A. Schliesser, A. Belenchia, Phys. Rev. Lett. **125**, 080601 (2020)

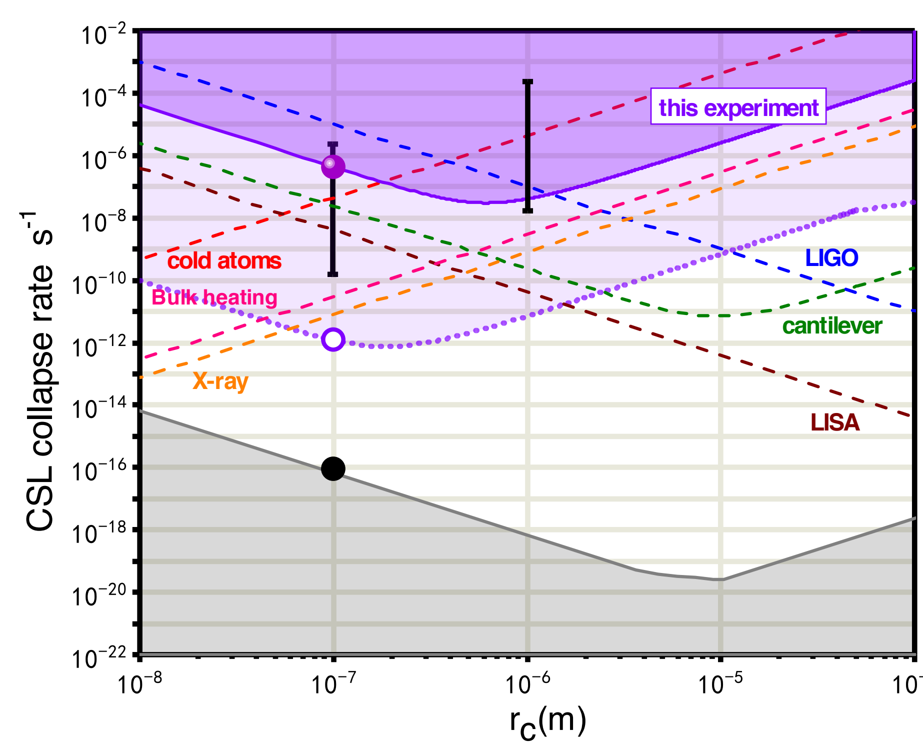
Going beyond our "dues" for the reporting period

Testing the large-scale limit of quantum mechanics

Testing CSL in a room-temperature optomechanical platform



- Proof-of- principle experiment with a micro-oscillator generated by a micro-sphere diamagnetically levitated in a magneto-gravitational trap under high vacuum



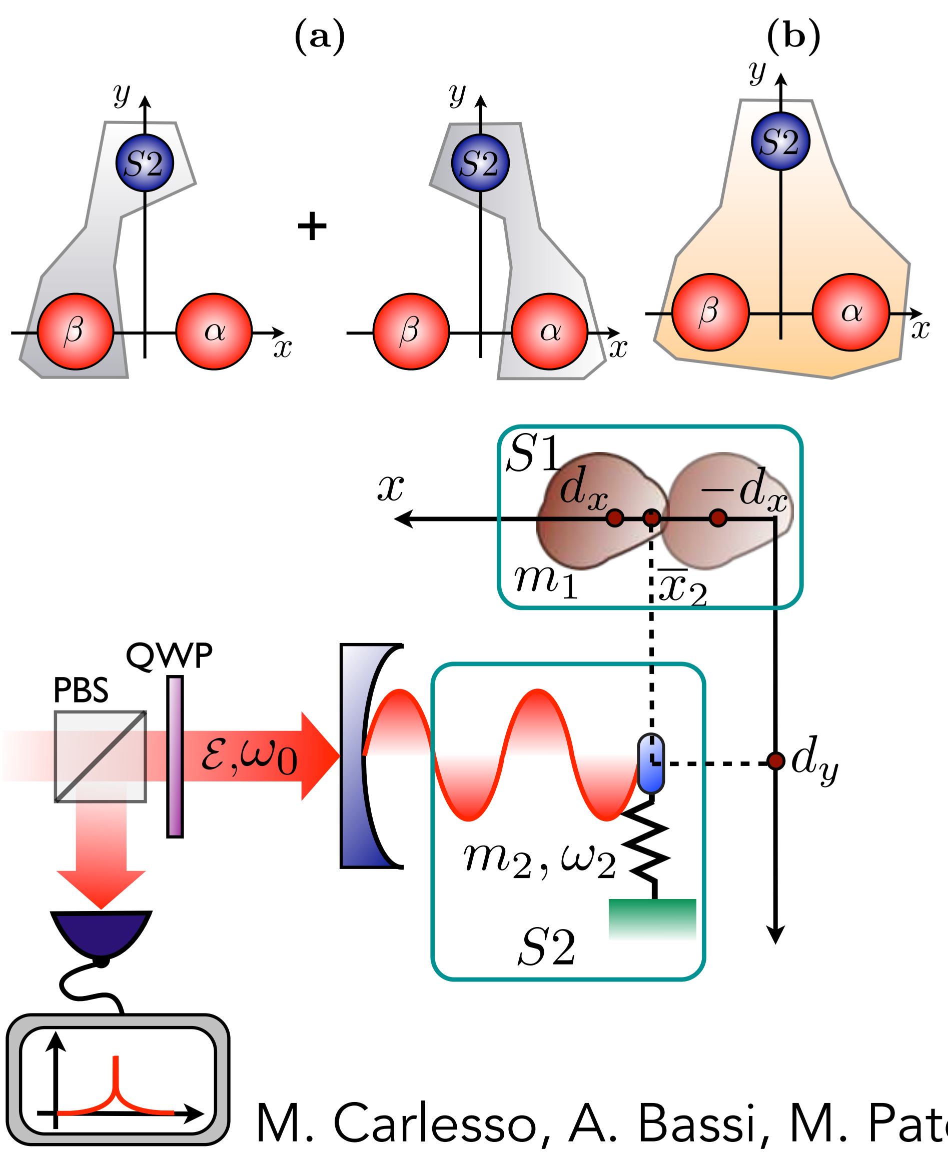
- A new upper bound significantly improving previous results in the same frequency range and partially probing Adler's theoretical proposal

D. Zheng,…., M. Carlesso, and A. Bassi, Phys. Rev. Research **2**, 013057 (2020)

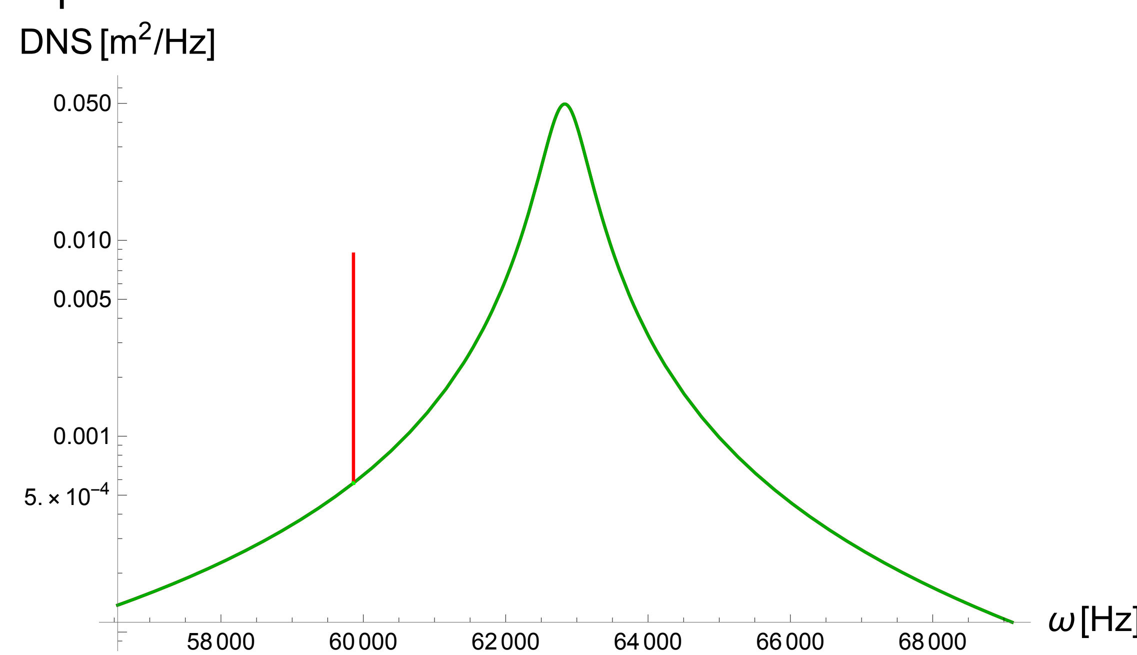
Testing the large-scale limit of quantum mechanics

Going beyond our "dues" for the reporting period

Testing the gravitational field of a quantum superposition



- Classical incoherent admixture of potentials or quantum superposition of gravitational fields?
- Use optomechanics as a transducer and a probe of potential differences



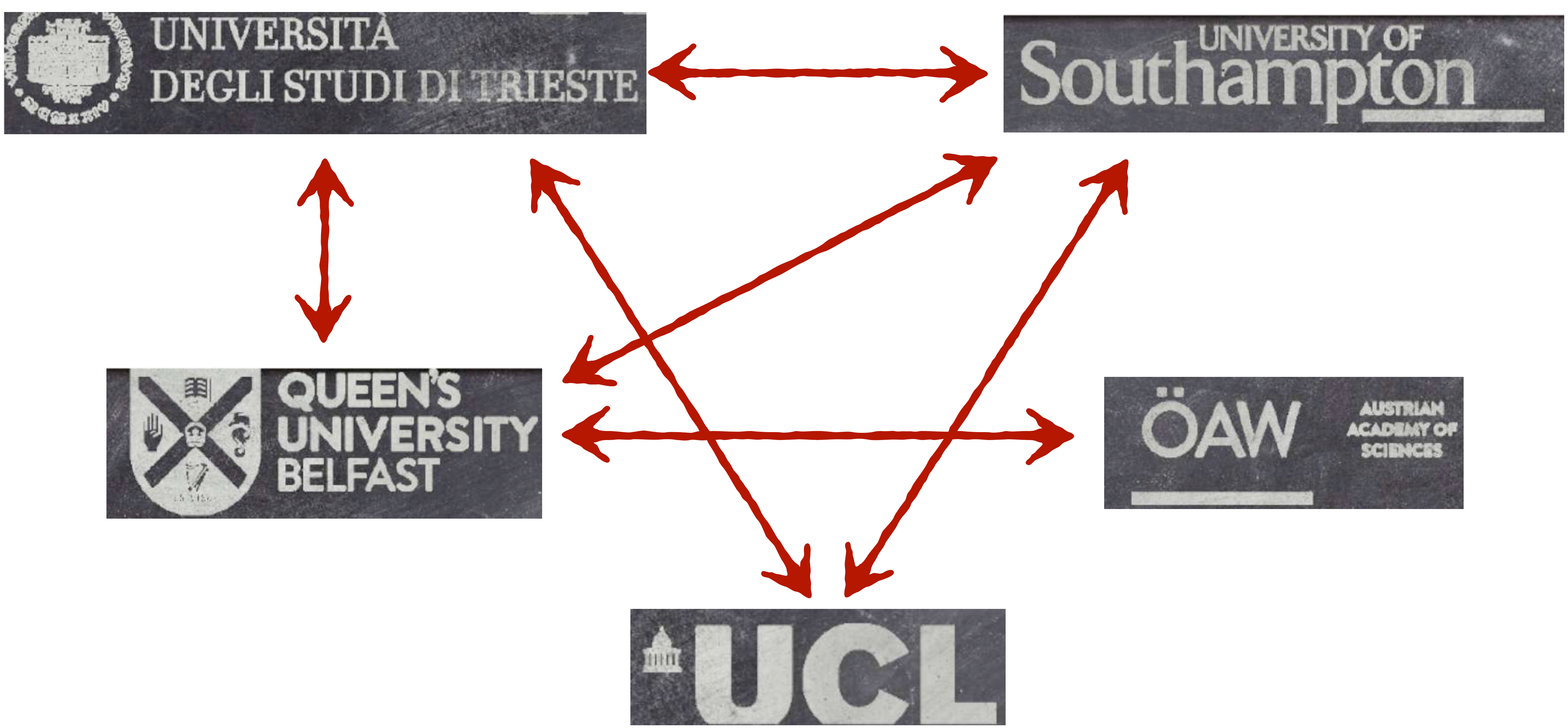
M. Carlesso, A. Bassi, M. Paternostro, and H. Ulbricht, New J. Phys. **2**, 013057 (2020)

TEQ

Testing the large-scale
limit of
quantum mechanics

European
Commission

Intense interactions and collaborations



TEQ

Testing the large-scale limit of quantum mechanics

European Commission

Being ahead of the game

Person-Months

UniTS	AU	INFN	OEAW	**QUB**	TUD	UCL	Soton	M2
30	2	4	33	**27.2**	3	2	2	0

Tasks

T4.1 To assess decoherence on the experimental set up at the core of WP3.

T4.2 To determine experiment-specific bounds to CSL and SN mechanisms.

T4.3 To develop schemes to quantify the macroscopicity of quantum superposition states.

T4.4 To design settings for the test of energy-conserving CSL and SN model.

T4.5 To compare time-dilation decoherence and gravity-induced collapse.

Objectives

O4.1 To set up a theoretical framework for the test of quantum mechanics at the mesoscopic level.

O4.2 To design experimental tests able to refine the framework of collapse models.

O4.3 To investigate macro-realism at the mesoscopic level through the experiments at the core of TEQ.

Deliverables

D4.1 Calibration of decoherence [M12]

D4.2 Bounds to CSL & SN models [M18]

D4.3 Size of the superposition [M24]

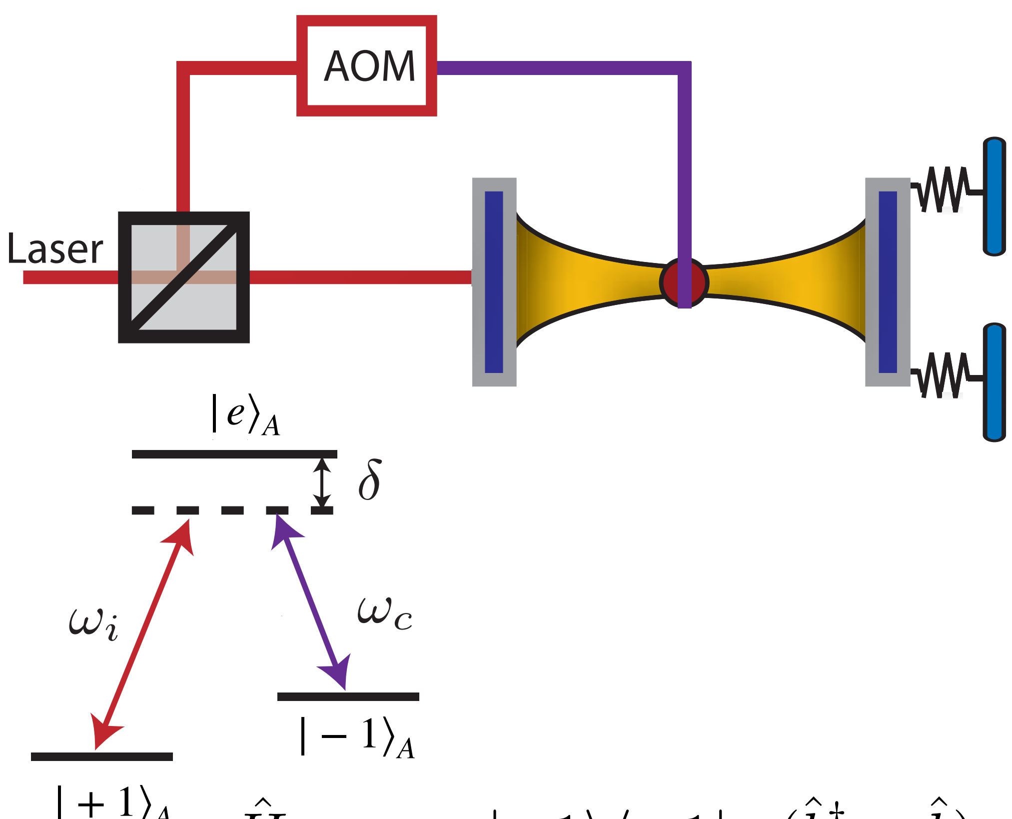
D4.4 Bounds to the ecCSL model [M36]

D4.5 Time-dilation/gravity collapse [M44]

Testing the large-scale limit of quantum mechanics

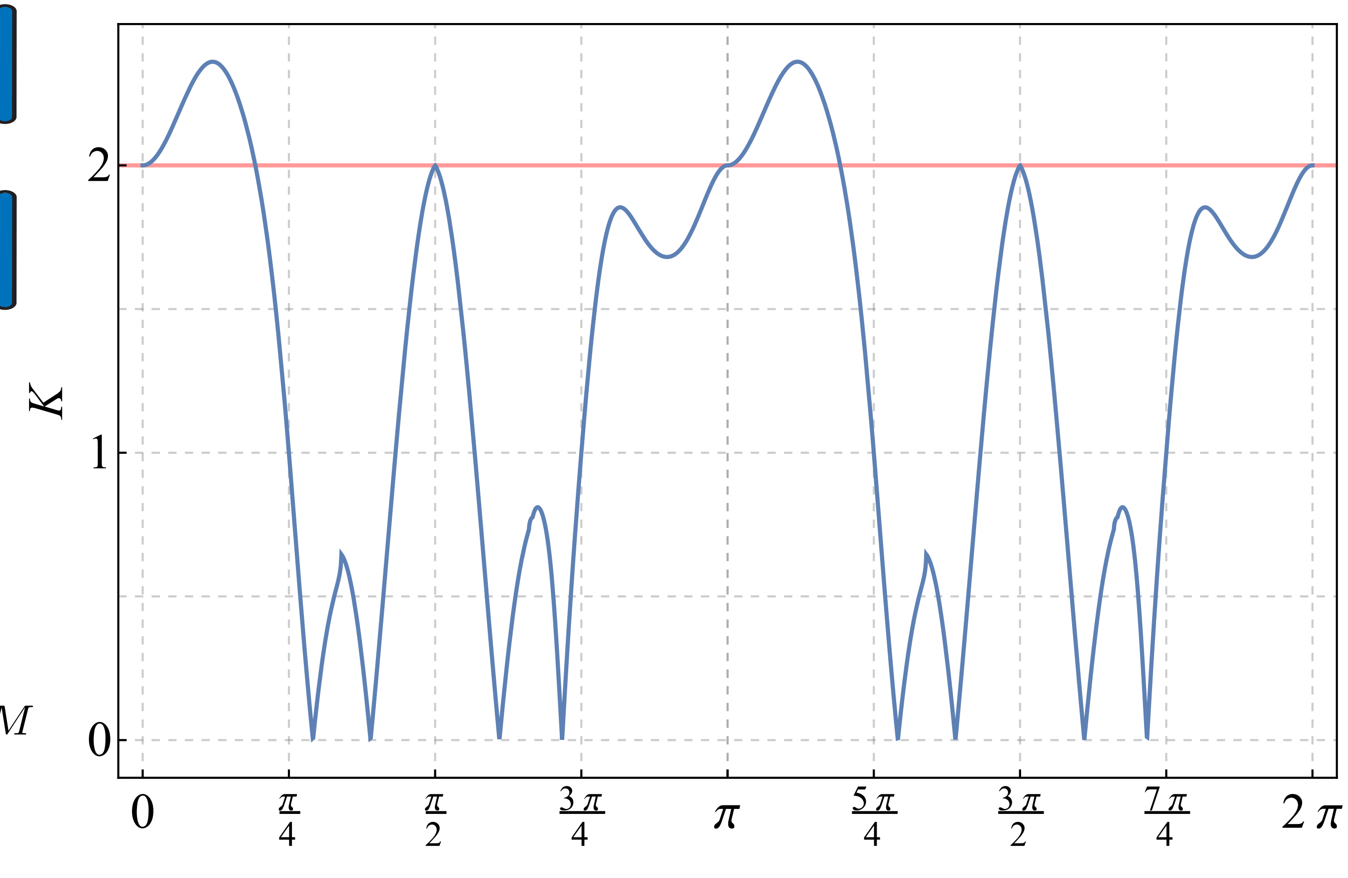
Going beyond our "dues" for the reporting period

Test of macro-realism in hybrid optomechanics



$$\hat{H}_{eff} = \eta\,|{+1}\rangle\langle{+1}|_A(\hat{b}^\dagger + \hat{b})_M$$

- Testing Leggett-Garg inequality via hybrid optomechanics



M. Marchese, H. McAleese, A. Bassi, and M. Paternostro, J. Phys. B **2**, 013057 (2020)

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

WP5: Management

A. Bassi - UniTS

Summary of WP5

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
40	2	4	2	2	2	2	2	2

Objectives

O5.1 Coordination of the project for the achievement of the objectives.

Tasks

T5.1 Organization of the project meetings. Management of unforeseen events.
T5.2 Setting up and maintenance of the website.
T5.3 Monitoring of Work Plan. Preparation of financial & scientific reports.
T5.4 Preparation, implementation and update of the Data Management Plan.

Deliverables

D5.1 Website [M 2].
D5.2 Data Management Plan [M 6].
D5.3 Project Review Meeting documents M12 [M 14].
D5.4 Project Review Meeting documents M30 [M 32].
D5.5 Project Review Meeting documents M48 [M 48].

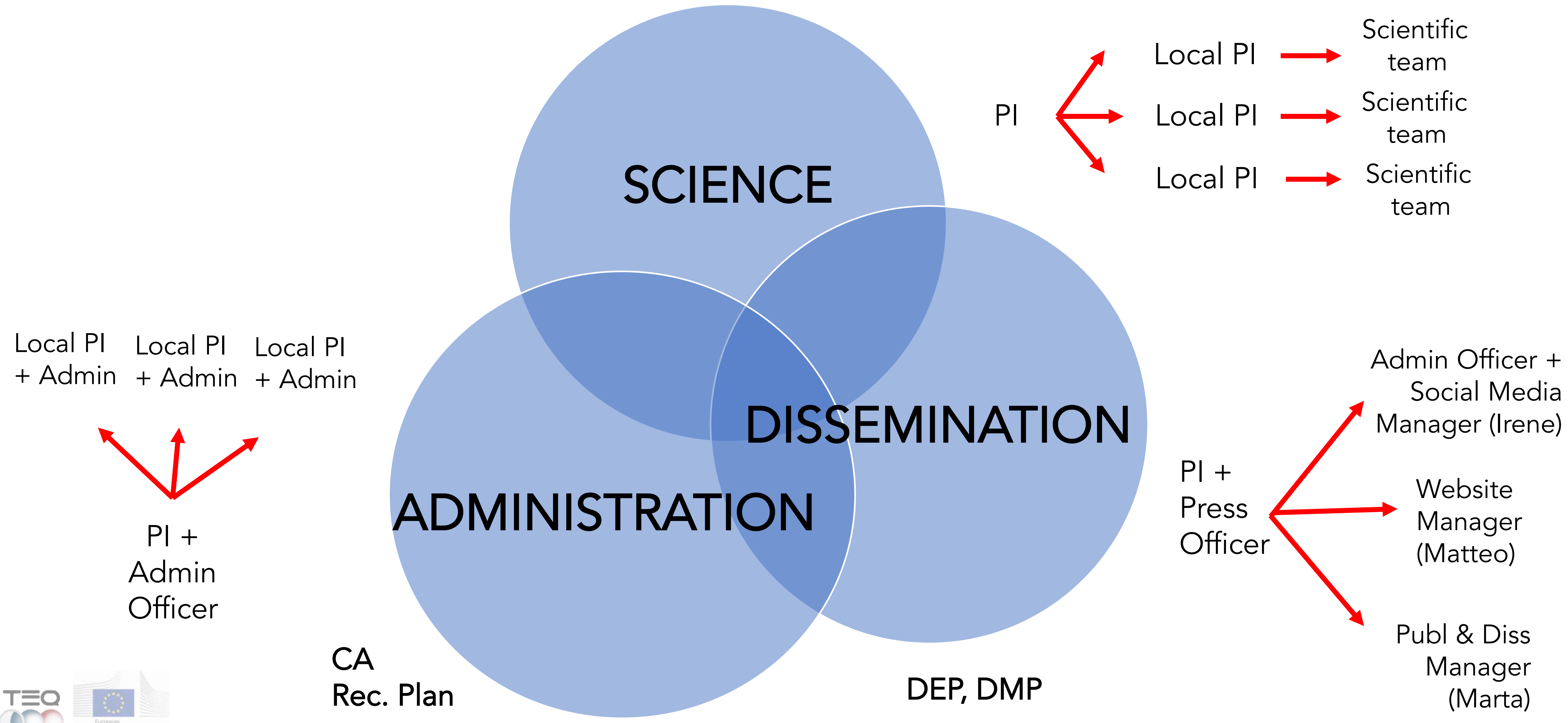
Organization

Project Officer
Grant Agreement

*A **Steering Committee** (SC), chaired by the coordinator (Bassi), will be established as the governance entity for the project. The SC will be formed by [the local PIs]. It will be supported by the **Administrative Officer** appointed to assist with the management of the project and complemented by the **Consortium Press Officer** (CPO), chosen among the members of the Consortium, who will be in charge of the dissemination plan.*
(from the GA – Annex I)

Stakeholders
QT Community
Wider Community
General public
Industry
Press
Policy makers

INTERNAL MANAGEMENT



The Network

UniTs - University of Trieste

Angelo Bassi
PI
Website

Luca Ferialdi

Lorenzo Asprea

Anirudh Gundhi

Matteo Carlesso
Website Manager

Caitlin Jones
Social Media Manager

José Luis Gaona Reyes

Irene Spagnul
Administrative Officer

QUB - Queen's University of Belfast

Mauro Paternostro
Local PI
Website

Gabriele De Chiara

Alessio Belenchia

Alessandro Ferraro

Marta Maria Marchese
Publications & Dissemination Manager

INFN - Istituto Italiano Fisica Nucleare

Catalina Curceanu
Local PI & Press Officer

Kristian Piscicchia

Alessandro Scordo

Fabrizio Napolitano

Alberto Clozza

Massimiliano Bazzi

Elisabetta Pace

UCL - University College London

Peter Barker
Local PI
Website

Antonio Pontin

Thomas Penny

Markus Rademacher

Anishur Rahman

Jonathan Gosling

Marco Toroš

OEAW - Austrian Academy of Sciences

Caslav Brukner
Local PI
Website

Esteban Castro Ruiz

Ilya Kull

Luis Cortés Barbado

AU - Aarhus University

Michael Drewsen
Local PI
Website

Cyrille Solaro

Aurelién Dantan
Website

Vincent Jarlaud

UoS - University of Southampton

Hendrik Ulbricht
Local PI
Website

Christopher Timberlake

James Bain

Stefan Olsonrobbie

Andrea Vinant

TUD - Delft University of Technology

Liberato Manna
Local PI
Website

Luca De Trizio

Arjan Houtepen
Website

Jence Mulder

M2 - M Squared Lasers Limited

Nils Hempler
Local PI
Website

Joseph Thom

THANKS TO PAST MEMBERS

- Ousama Houhou (QUB)
- Ashley Setter (Soton)
- Giulio Gasbarri (UniTS, Soton)
- Flaminia Giacomini (OEAW)

ECRs & Gender dimension

Early Career Researchers		
Postdoc	PhD	Student
11	10	5

Beneficiaries	Total number of females in the workforce	Total number of males in the workforce
1 - UNIVERSITA DEGLI STUDI DI TRIESTE	2	5
2 - AARHUS UNIVERSITET	1	4
3 - ISTITUTO NAZIONALE DI FISICA NUCLEARE	2	4
4 - OESTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN	0	4
5 - THE QUEEN'S UNIVERSITY OF BELFAST	1	3
6 - TECHNISCHE UNIVERSITEIT DELFT	0	5
7 - UNIVERSITY COLLEGE LONDON	0	7
8 - UNIVERSITY OF SOUTHAMPTON	1	8
9 - M-SQUARED LASERS LIMITED	1	5

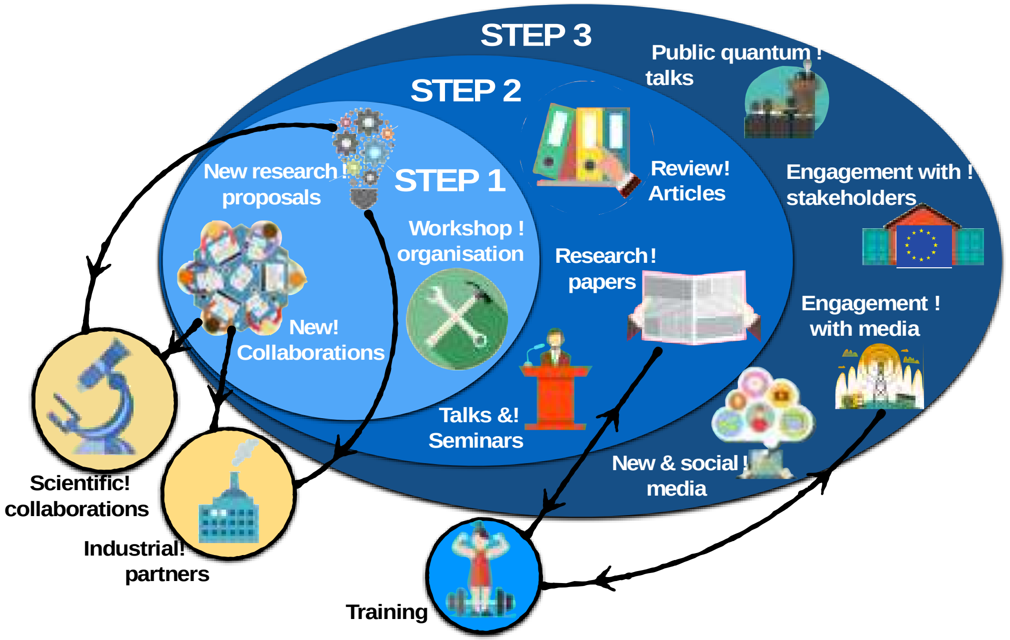
EXTERNAL MANAGEMENT

European Commission

TEQ Testing the large-scale limit of quantum mechanics

Stakeholders

1. QT Community,
2. Wider Community,
3. General public, Industry, Press, Policy makers



Interaction with other EU/(inter-)national projects

- The QT Flagship (EU)
- 2 COST Actions: CA15220 QTSpace + CA17113 on Trapped Ions (EU)
- MAQRO Project ➔ ESA
- 1 Project funded by Centro Fermi (IT)
- 1 Project funded by The John Templeton Foundation (USA)
- 4 Grants from FQXi (USA)
- 3 EPRSC grants (UK)
- 2 MarieCurie Fellowship (EU)
- 1 Fellowship from The Leverhulme Trust (UK)
- 1 Project funded by The Royal Society (UK)
- 1 Newton International Fellowship (UK)

Task 5.1

Organization of the project meetings. Management of unforeseen events

- 31.05.2019 (Frascati): Scientific meeting
- 24.07.2019 (London): Scientific meeting
- 19.09.2019 (Trieste): Scientific + SC Meeting
- 10.12.2019 (Southampton): Scientific meeting
- 13.03.2020 (remote): Scientific meeting
- 19.03.2020 (remote): Beginning of monitoring of the impact of COVID-19 on TEQ
- 23.06.2020 (remote): Scientific meeting
- 17.07.2029 (remote): SC Meeting

TEQ — Testing the large-scale limit of quantum mechanics — www.tequantum.eu

TEQ - Experiment meeting, Trieste 19/9/19

Minutes

Purpose of meeting: To update on developments of setting up the TEQ experiments and its components. This is the follow up meeting from the meeting at UCL in July 2019.

Agenda

14:00	Arrival and start of meeting, general comments, state of play in testing CSL
14:15	Update on blade trap (Michael)
14:45	Update on electronics (Catalina, Max, Peter, Michael)
15:30	Update on particle trapping (Peter, Hendrik)
16:00	Discussion and decision on next steps and timeline for implementation of trap with low noise electronic at Aarhus & UCL, test of blade trap at UCL
16:30	Discussion on detection and particle loading: Options and realisation
17:00	Discussion on next steps with cryo and towards completion of the TEQ experiment at Southampton

Location: Adriatico Guesthouse, Trieste, IT.

Participants: Catalina Curceanu, Michael Drewsen, Peter Barker, Max Bazzi, Antonio Pontin, Andrea Vinante, Matteo Carlesso, Hendrik Ulbricht.

...o UCL for testing for ...tion, to be done in the ...e blade trap and noise ...trap design (decision ...T), pyramid structure. ...lown to level of battery

SC Meeting Trieste

View Edit

Date:
September, 2019

Place:
Trieste

Type Document:
Activities

File:
TEQ_SC Meeting Minutes_Trieste...
TEQ_Trieste_SC_Meeting_Chair.p...

Meeting on TEQ experiment at UCL

Edit

...ondon
...ly, 2019

...al TEQ experiment meeting has been organized to continue the discussion on the techni... held on May 31. This meeting will be held on July 24 at UCL (London) and interested TEQ me...

...rival and start of meeting
...pdate on electronics
...pdate on particle trapping and detection
...pdate on Aarhus electronics, trap blades and parametric heating for detection
...pdate on CSL tests with mechanical resonators, particle launching, cryostat
...pdate on particles
...nch
...scussion and decision on next steps and timeline for development of AC and DC electronics
...scussion on detection: detection requirements, new ideas
...scussion on particle loading: Ideas for loading mechanism (laser induced and Piezo source)
16:00 Conclusion and agreement on next steps, schedule for next meeting

Location: UCL Physics and Astronomy: https://www.ucl.ac.uk/physics-astronomy/about/find-us
The meeting will be held in room E7/E3 which is on the ground floor of the physics building.

giovedì 19/03/2020 18:34
Angelo Bassi <abassi@units.it>
TEQ and the coronavirus outbreak - contingency plan
Messaggio inoltrato in data 27/03/2020 11:40

Dear TEQ Partners,

the coronavirus outbreak is affecting the lives of many people in many different ways. On a much smaller scale, it will affect TEQ as well, since some of the labs have been closed. We need to monitor the situation and be ready, if needed, to take actions, e.g. to ask for an extension.

At the link

https://docs.google.com/document/d/1C0E7n7x9oTOb0wEtLtp1L4Kwkr_d-Fg700ZIXBSqPE8/edit

you can find a google doc. Kindly fill the relevant parts in asap. Remember to keep evidence of all notifications of closure of labs/offices, and any other document related to measures, which will affect the development of TEQ in your unit.

Thank you for the collaboration and kind regards,
Angelo

TEQ — European Commission

Task 5.1
Organization of the project meetings. Management of unforeseen events

The COVID-19 outbreak has affected TEQ since March 2020 with the closure of labs.

The Steering Committee has promptly reacted with the developement of a **CONTINGENCY PLAN.**

Partner	Beginning of shutdown	Expected date of re-opening	Will it impact the TEQ-related activity and how?
UNITS	February 24, 2020	Since May 18 possible for admin and research staff upon written justified request. Smartwork still preferable option.	At the moment, there is no significant impact. Research and management activities can be done remotely.
OEAW	March 13, 2020	Since July 1st, we are fully back in the offices.	We do not experience any significant impact. The theoretical research and management are done remotely via home office and through electronic communication (Skype, Zoom)
QUB	March 16, 2020	As of 6 July 2020, the phased return to labs has started. However, this is only restricted to experimentalists. The QUB unit of TEQ will thus operate remotely, in smart-working mode, for the foreseeable future.	At the moment, there is no significant impact. Research and management activities can be done remotely.
TUD	March 13	April 6, but will likely be extended.	We are unable to perform experiments and hence experience a significant delay.
AU	March 12	June 8, the lab was partially reopened, and since June 29 more or less fully opened	In this period we have not been able to perform any experiments, so this has delayed the work of AU by at least 3 months.
UCL	March 20	July 13 at earliest with only 2 people	No experiments possible at all. This has impacted our work significantly as we cannot carry out any experimental work. Some analysis of data is ongoing. All work is from home.
SOUTHAMPTON	March 17	June 16 partial lab opening, only 1-2 experimentalist per lab	no TEQ experiments since mid March, since then Andrea has started new job at CNR on July 1, and Chris is writing PhD thesis until end of July -> restart TEQ experiments expected at beginning of August 2020, this means a delay on experimental deliverable D3.3 by 4 months (to set up the TEQ experiment and to perform systematic testing of noises).
INFN	March 9th (lab is still opened but only for fundamental services)	Lab was kept open at reduced capacity till 21st June (only fundamental services for lab activities); on 22nd June lab reopened for all users - with special safety procedures in place	Only essential services are undergoing in the lab; It is not possible to work on TEQ electronics development - also because this work should be done in collaboration and following the outcome of tests (of the electronics already delivered) to be done at UCL, which (5 July 2020) are not yet restarted
MSquared	-	-	Core operations still up and running for now. Most staff working from home until further notice.

Assessment (so far)

1. The pandemic is affecting TEQ, both the theory work and even more the experimental one

2. After 6 months from the beginning of the lockdown, only a partial return to a “normal life”

3. We are working hard to stick to the work plan

4. Mitigation measures have been taken: Reporting Period 2 was secured. Period 3 will not - still too early to fully assess the impact.

Actions:

1. Reorganize tasks - no formal action towards the Commission

2. Rescheduling of deliverables - formal action towards the Commission with justification

3. Extension of the Project - formal action towards Commission (still to be assessed)

	Title	Leader	Due date	Effect of 3 months of shutdown and mitigation measures	Effect of 6 months of shutdown and mitigation measures
D1.4	Loading and control device	UCL	31 Dec 2020	Some effect.: Mitigation measure, may need to postpone reporting deadline.	Some effect.: Mitigation measure: may need to postpone reporting deadline.
D1.5	Quantification of heating	QUB	31 Dec 2020	No significant effect.	No significant effect.
D4.4	Bounds to the ecCSL model	UNITS	31 Dec 2020	No effect. Deliverable substantially accomplished. Remaining work can be done remotely. No mitigation measure is needed at the moment.	No effect. Deliverable substantially accomplished. Remaining work can be done remotely. No mitigation measure is needed at the moment.
D2.3	Internal state cooling	UCL	28 Feb 2021	This will cause some delay and this will affect the deliverable but we can working on modelling experiments in context of existing data.	Significant delay as this will have a significant effect on the deliverable. Possible mitigation is to do some experiments at Southampton if their labs are working.
D3.3	Ultimate experiment	UoS	30 Apr 2021	Delay expected as important experimental tests cannot be done in time to assemble the ultimate experiment. Also delays on deliverables of other partners (such as D1.4, D2.3) will affect achievement of D3.3.	Significant delay expected as important experimental tests cannot be done in time to assemble the ultimate experiment. Also knock-on effect from other deliverable delays here.
D2.4	Quantify decoherence	QUB	31 Aug 2021	Too early to assess.	Too early to assess.
D4.5	Time-dilation/gravity collapse	OEAW	31 Aug 2021	Too early to assess.	Too early to assess.
D3.4	General bound	QUB	31 Dec 2021	Too early to assess.	Too early to assess.
D5.5	Project Review meeting documents M48	UNITS	31 Dec 2021	Too early to assess.	Too early to assess.

Task 5.2
Setting up and maintenance of the website

Task 5.3
Monitoring of Work Plan. Preparation of financial & scientific reports.

Task 5.4
Preparation, implementation and update of the Data Management Plan

Testing the large-scale limit of quantum mechanics

European Commission

WP6: DISSEMINATION

C. Curceanu – INFN

15° September 2020

Summary of WP6

Persons-Months

UniTS	AU	INFN	OEAW	QUB	TUD	UCL	Soton	M2
18	2	4	2	2	2	2	2	2

Objectives

O6.1 Implementation of targeted dissemination and communication activities.

Tasks

T6.1 Coordinate and promote dissemination of TEQ and its findings.
T6.2 Manage internal communication.
T6.3 Coordinate and promote external communication to targeted audiences.

Deliverables

D6.1 Press releases [M 3].
D6.2 Popular press articles [M 12].
D6.3 Videos [M 20].
D6.4 Workshop [M 24].
D6.5 Dissemination and exploitation Plan [M 12].

DISSEMINATION towards:

INTERNAL

TEQ community

EXTERNAL

Quantum community

Broader scientific community

Industry

Schools, general public...

DISSEMINATION Overview

INTERNAL

- **Consortium meeting and SC meetings.**
- **TEQ Website .**
- **TEQ Newsletters (4/year).**

INTERNAL DISSEMINATION

Consortium meeting and SC meetings

- 31.05.2019 (Frascati): Scientific meeting
- 24.07.2019 (London): Scientific meeting
- 19.09.2019 (Trieste): Scientific + SC Meeting
- 10.12.2019 (Southampton): Scientific meeting
- 13.03.2020 (remote): Scientific meeting
- 19.03.2020 (remote): Beginning of monitoring of the impact of COVID-19 on TEQ
- 23.06.2020 (remote): Scientific meeting
- 17.07.2029 (remote): SC Meeting

Testing the large-scale limit of Quantum Mechanics

Activities

Frascati - May, 2019

TEQ's low-noise electronics

On May 31, 2019 TEQ partners will meet to discuss the status of the low-noise electronics.

Trieste - May, 2019

Towards a South-East European Quantum Network

An upcoming discussion on the first reliable quantum internet on top of Europe's glass fiber network.

TEQ's low-noise electronics meeting
Frascati, May, 2019

Agenda:

9:30 - 10:15 Update on Aarhus
 electronics status
10:15 - 11:00 Update on UCL trap
11:00 - 11:30 Update on
electronics
development at Frascati
11:30 - 12:00 Coffee Break
12:00 - 13:30 Update on
electronics
development and start discussions
13:30 - 14:30 Lunch
14:30 - 16:00 Discussion about
next steps, concrete plans to
realise different versions (with
decreasing noise) for DC and AC
electronics.
16:00 - 16:30 Coffee break
16:30 - 17:00 Conclusions

TEQ Testing the large-scale limit of Quantum Mechanics

Home News Activities Research Partners Publications Dissemination Contact Members Area

Activities

Trieste - July, 2020

Trieste Junior Quantum Days 2020

The workshop has been cancelled due to the Coronavirus outbreak.

Southampton - June, 2020

Reboot of TEQ experiments after COVID-19 lockdown

TEQ partners will meet to discuss how to restart the experiments after the closure of the labs due to the Coronavirus outbreak.

Aarhus - May, 2020

TEQ meeting in Aarhus

The meeting has been cancelled due to the Coronavirus outbreak.

Southampton - March, 2020

Meeting on TEQ experiment at University of Southampton

On March 13, 2020 experimentalists of TEQ Consortium will hold a meeting hosted by the University of Southampton to discuss updates on the experimental side of the project.

Southampton - December, 2019

Meeting on TEQ experiment at Soton

TEQ experimentalists will meet on December 10 at the labs of the University of Southampton (UK).

Trieste - September, 2019

Redefining the foundations of physics in the quantum technology era

TEQ will explore the macroscopic limit of quantum theory, with the specific goal of answering the question: does quantum coherence survive when the mass/complexity of a system increases, or does it break down as predicted by alternative formulations?

Trieste, Italy - September, 2019

Meeting on TEQ experiment at UNITS

To update on developments of setting up the TEQ experiments and its components, TEQ members will meet in Trieste on September 19.

Trieste - July, 2019

Trieste Junior Quantum Days 2019

A look at the mysteries of quantum theory

The workshop will gather young researchers working in quantum mechanics and its applications. PhD students and PostDocs will be given the opportunity to present their research activity and interact with their colleagues, share motivations, techniques and perspectives, in a friendly and informal environment. In the morning, blackboard lectures by senior experts will provide a perspective on relevant problems in quantum theory.

London - July, 2019

Meeting on TEQ experiment at UCL

TEQ members meet at UCL on July 24 to further discuss the details of the TEQ experiment.

Trieste - June, 2019

School on quantum foundations dedicated to Prof. GianCarlo Ghirardi

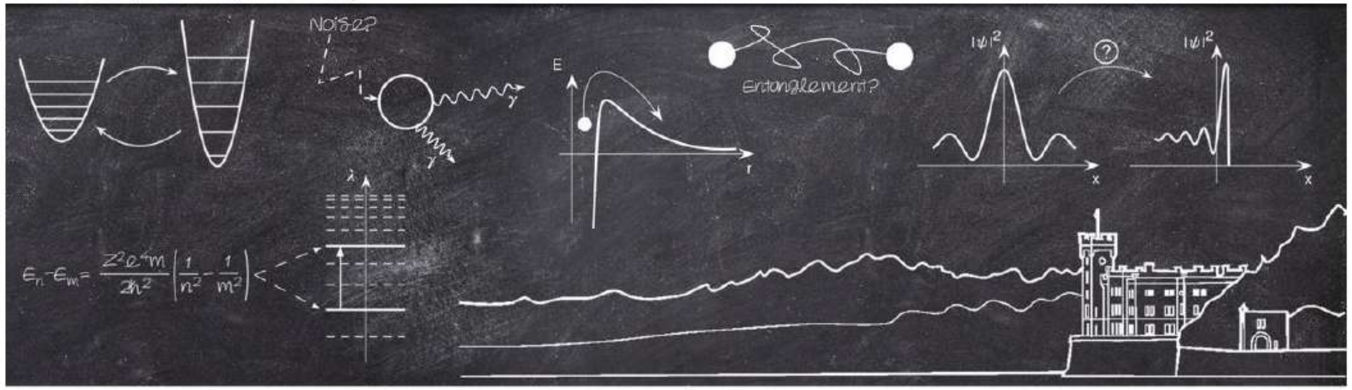
A school on quantum foundations for Master and PhD students to take place in Trieste on June 19-21.

Trieste Junior Quantum Days 2019

Place: Trieste

Date: July, 2019

A look at the mysteries of quantum theory



TEQ

Testing the large-scale limit of Quantum Mechanics

Home News Activities Research Partners Publications Dissemination Contact Members Area

Redefining the foundations of physics in the quantum technology era

Place: Trieste

Date: September, 2019

TEQ - *Testing the Large scale Limit of Quantum Mechanics*, is a EU H2020 FET project, which will explore the macroscopic limit of quantum theory, with the specific goal of answering the question: does quantum coherence survive when the mass/complexity of a system increases, or does it break down as predicted by alternative formulations? Assessing the boundaries of quantum theory is one of the most relevant problems in modern physics, with also a clear technological impact, as the scalability of future quantum technologies depends on the possibly unlimited validity of the quantum paradigm.

Within the framework of TEQ, the workshop *Redefining the foundations of physics in the quantum technology era* will explore the state of the art – both theoretically and experimentally – of our understanding of quantum theory and discuss the new directions of research.

Speakers will include leading senior experts in quantum mechanics as well as junior members of the TEQ consortium.

D6.4 Workshop [M 24]

Redefining the foundations of physics in the quantum technology era

Trieste - 16-19 September, 2019
Adriatico Guesthouse ICTP

TEQ - *Testing the Large scale Limit of Quantum Mechanics*, is a EU H2020 FET project, which will explore the macroscopic limit of quantum theory, with the specific goal of answering the question: does quantum coherence survive when the mass/complexity of a system increases, or does it break down as predicted by alternative formulations? Within the framework of TEQ, the workshop *Redefining the foundations of physics in the quantum technology era* will explore the state of the art – both theoretically and experimentally – of our understanding of quantum theory and discuss the new directions of research.

Speakers

Luis Cortes Barbado (University of Vienna, Austria)
Alessio Belenchia (QUB, Belfast)
Sougato Bose (University College London, UK)
Matteo Carlesso (University of Trieste, Italy)
Tobias Donner (ETH Zurich)
Florian Marquardt (Max-Planck Institute, Germany)
Ron Folman (University of the Negev, Israel)
Stefan Gerlich (University of Vienna, Austria)
Ward Struyve (K.U. Leuven)
Gabriel Hetet (ENS, France)
Cyrille Solaro (Aarhus University, Denmark)
Edward Laird (University of Lancaster, UK)
Luca Mancino (Queen's University Belfast, UK)
Stephan Nimmrichter (Max-Planck Institute, Germany)
Tracy Northup (University of Innsbruck, Austria)
Tjerk Oosterkamp (University of Leiden, NL)
Kristian Piscicchia (INFN, Frascati)
Antonio Pontin (University College London, UK)
Jason Ralph (University of Liverpool, UK)
Andrew Steane (University of Oxford, UK)
Andrea Vinante (University of Southampton, UK)
Magdalena Zych (University of Queensland, Australia)

DELIVERABLE 6.4

Workshop "Redefining the foundations of physics in the quantum technology era"

Grant agreement n°:	766900
Project acronym:	TEQ
Project title:	Testing the Large Scale limit of Quantum Mechanics
Funding scheme:	FET-OPEN
Start date of project:	01 January 2018
Duration:	48 months
Due date of the Deliverable:	31 December 2019
Deliverable issued:	19 September 2019
Dissemination Level:	Public
Version:	1.0

"Redefining the foundation of physics in the quantum technology era"
Trieste, September 16-19, 2019

	Monday, Sept 16	Tuesday, Sept 17	Wednesday, Sept 18	Thursday, Sept 19
09:00 – 09:45		**Andrew Steane** (University of Oxford, UK)	**Stefan Nimmrichter** (Max-Planck Institute for the Science of Light, Erlangen, Germany)	**Ron Folman** (Ben-Gurion University of the Negev, Israel)
09:45 – 10:30		**Luis Cortes Barbado** (University of Vienna, Austria)	**Matteo Carlesso** (University of Trieste, Italy)	**Alessio Belenchia** (Queen's University Belfast, UK)
10:30 – 11:00		**Coffee break**	**Coffee break**	**Coffee break**
11.00 – 11.45		**Gabriel Hetet** (ENS, France)	**Tjerk Oosterkamp** (University of Leiden, The Netherlands)	**Sougato Bose** (University College London, UK)
11:45 – 12:30		**Magdalena Zych** (University of Queensland, Australia)	**Antonio Pontin** (University College London, UK)	**Andrea Vinante** (University of Southampton, UK)
12:30 – 14:00	**Get together lunch**	**Lunch break**	**Lunch break**	
14:00 – 14.45	**Florian Marquardt** (Max-Planck Institute for the Science of Light, Erlangen, Germany)	**Q&A session with Dr. Gaia Donati (Springer Nature)**	**Stephan Gerlich** (University of Vienna, Austria)	
14:45 – 15.30	**Luca Mancino** (Queen's University Belfast, UK)		**Edward Laird** (University of Lancaster, UK)	
15:30 – 16:00	**Coffee break**	**Coffee break**	**Coffee break**	
16.00 – 16:45	**Tobias Donner** (ETH Zurich)	**Ward Struyve** (K.U. Leuven)	**Jason Ralph** (University of Liverpool, UK)	
16:45 – 17:30	**Cyrille Solaro** (Aarhus University, Denmark)	**Tracy Northup** (University of Innsbruck, Austria)	**Kristian Piscicchia** (INFN, Frascati)	
20:00		**Social Dinner**		

The workshop was attended by a total of 44 participants. The speakers were a total of 22, being 8 junior members of the TEQ Consortium and 14 external experts

INTERNAL DISSEMINATION

- **TEQ Website: tequantum.eu 1800 clicks/day; about 90 single visitors/day**

TEQ

Testing the large-scale limit of Quantum Mechanics

Home | News | Activities | Research | Partners | Publications | Dissemination | Contact | Members Area

Testing the large-scale limit of Quantum Mechanics

Quantum mechanics provides, to date, the most accurate understanding of the microscopic world of atoms, molecules and photons allowing them to be in the superposition of two different, perfectly distinguishable configurations at the same time. However, the macroscopic world that is before our very own eyes doesn't seem to respect quantum rules. Why is that so?

TEQ addresses such a fundamental quest from an innovative standpoint, supported by a € 4.4M grant awarded by the European Commission. The TEQ partners will develop new theoretical models and implement a test of the quantum superposition principle on macroscopic objects to establish the ultimate bounds to the validity of the quantum framework, if any.

Quantum mechanics provides, to date, the most accurate understanding of the microscopic world of atoms, molecules and photons allowing them to be in the superposition of two different, perfectly distinguishable configurations at the same time. However, the macroscopic world that is before our very own eyes doesn't seem to respect quantum rules. Why is that so?

TEQ addresses such a fundamental quest from an innovative standpoint, supported by a € 4.4M grant awarded by the European Commission. The TEQ partners will develop new theoretical models and implement a test of the quantum superposition principle on macroscopic objects to establish the ultimate bounds to the validity of the quantum framework, if any.

Facts and Figures

Since January 2018, **68** scientific papers connected with the project have been published. TEQ Consortium members have delivered **252** talks reaching more than **16.400** people in **30** different countries. Moreover, TEQ-related news have been collected in **9** Newsletters and have been published in **31** press articles.

D6.3 Video [M 20]

CONCLUSION

The preparation of the video was fairly shared among the Consortium members and the final result was highly appreciated by the TEQ partners. The video was planned to be a balanced combination of structured explanations of the phases of the project involving the PI and the WP leaders. The rhythm between interviews and lab footages was planned to keep the viewer's attention high till the end of the video. Moreover, the video is divided in chapters recalling the initial illustration of the project's objectives done by the PI: the idea is to offer a structured story that brings the viewer through a path.

The final product is shared with the partners for dissemination through their institutional channels (websites, presentations, talks, etc.) and is posted on TEQ's Youtube channel, on the TEQ Website and on TEQ's social media accounts. The Consortium members are engaged to give maximum dissemination to the video to the scientific community, to the general public and to potential funding agencies.

European Commission | Horizon 2020 European Union funding for Research & Innovation

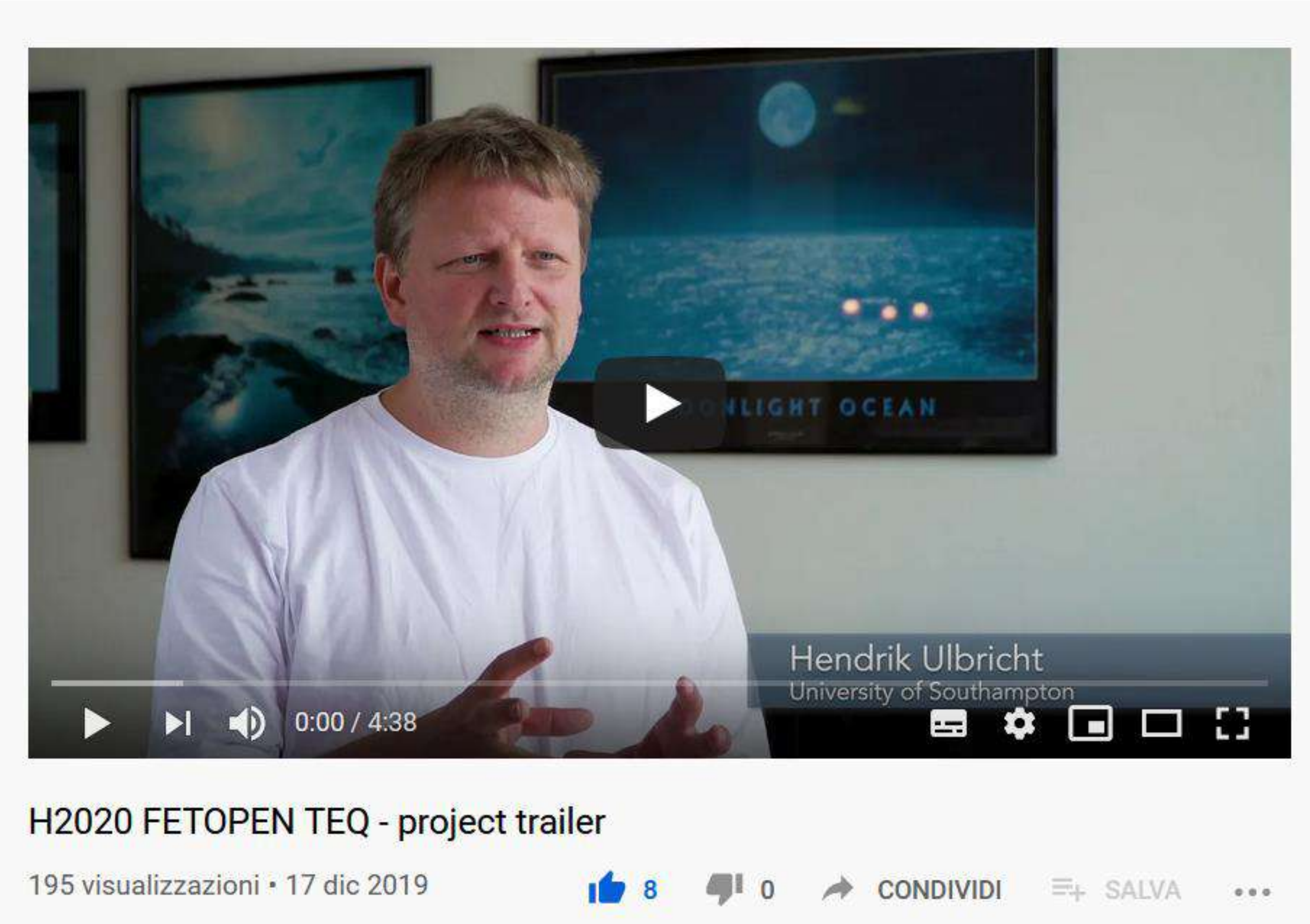
TEQ

DELIVERABLE 6.3

Video

Grant agreement n°:	766900
Project acronym:	TEQ
Project title:	Testing the Large Scale limit of Quantum Mechanics
Funding scheme:	FET-OPEN
Start date of project:	01 January 2018
Duration:	48 months
Due date of the Deliverable:	31 December 2019
Deliverable issued:	26 November 2019
Dissemination Level:	Public
Version:	1.0

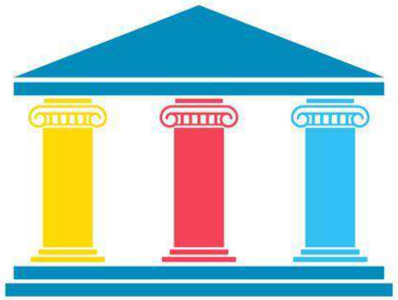
https://youtu.be/-LfxknnVU5Q



INTERNAL DISSEMINATION

- **TEQ Newsletters – 6 since last reporting**
  - ✓ **March, June, September, December 2019**
  - ✓ **March, June 2020**

TABLE OF CONTENTS



TEQ

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.6, September 2019

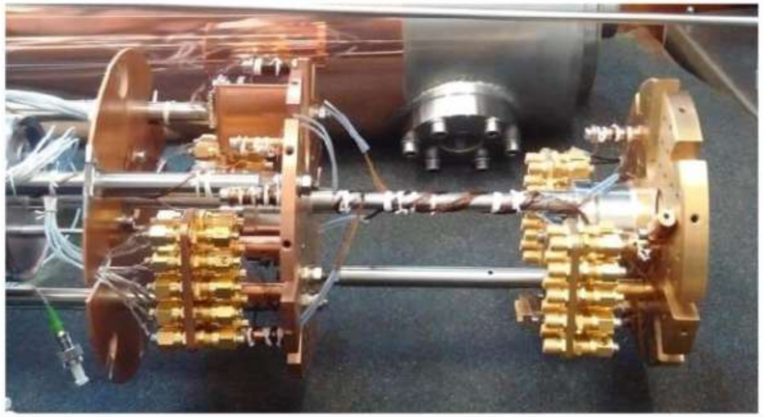
Speaker at the TEQ Workshop "Redefining the foundations of physics in the quantum technology era", Trieste (IT) 16-19 September 2019

TEQ

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.5, June 2019



A detail of the cryostat at the University of Southampton. *Credits: UoS.*

TEQ

Testing the large-scal
of quantum mech

www.tequar

NEWSLETTER N.4, March 2019

The TEQ members and the appointed reviewers at the Research Executive Agency of the European Commission for the TEQ first Review Meeting, Brussels, 26th February 2019.

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.9, June 2020

The Quantum Technology Group of Mauro Paternostro at Queen's University Belfast. *Credits: QUB.*

Testing the large-scal
of quantum mecl

www.tequa

NEWSLETTER N.8, March 2020

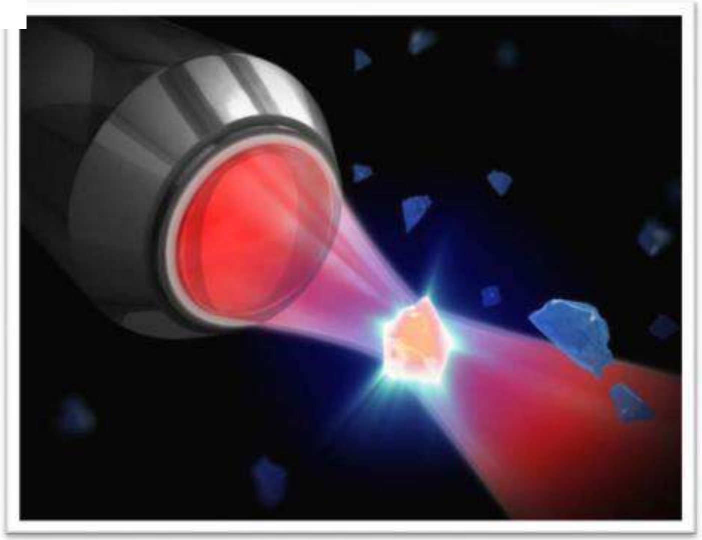


Image of the article on the Smithsonian Magazine (February 5, 2020) describing the TEQ experiment. *Credits: UCL*

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.7, December 2019

A frame of the TEQ video developed as part of the project workplan.

DISSEMINATION

Overview

EXTERNAL

QUANTUM COMMUNITY

- **Publications on specialized journals.**
- **Participation in quantum-related meetings and conferences**

SCIENTIFIC COMMUNITY

- **Publications in broad-readership journals**
- **Participation in broader scientific meetings and conferences**

INDUSTRY

- **Technical reports about TEQ and its findings.**
- **Invitations to visit project groups and labs, and to group meetings.**
- **Presentations and talks to R&D departments in industries.**

GENERAL PUBLIC

- **Publication of popular science articles.**
- **Participation to the yearly Science Café in Trieste, Italy.**
- **Popular-science dissemination colloquia in museums and schools.**
- **Publication on New Scientist and Journals with a similar audience.**
- **Articles and interviews in Newspaper.**
- **Participation to Science-dedicated TV and Radio programs.**
- **Facebook, Twitter and Youtube accounts.**

EXTERNAL DISSEMINATION (Jan. 2019 – June 202

- (Scientific) Publications: 47, representing 5.9 papers/partner
- 1 Chapter in a book
- Preprints: 51, representing 6.38 preprints/partner
- Talks: 161, representing 14.9 talks/partner
- Press releases: 1
- Articles in general press: 11
- Facebook, Twitter and LinkedIn TEQ accounts
- Radio and TV events
- Event: 2 Quantum Café 500 participants

47 Scientific Articles - highlights:

- Physical Review Letters (2)
- Nature Communications (2)
- Physical Review A (10),
- New Journal of Physics (4)
- Physical Review E (2)
- npj Quantum Information (1)
- Applied Physics Letters (3)
- Quantum (1)

- More than 300 citations
- More than 100 Tweeters
- More than 10000 downloads

Article | Open Access | Published: 30 January 2019

Quantum mechanics and the covariance of physical laws in quantum reference frames

Flaminia Giacomini, Esteban Castro-Ruiz & Časlav Brukner

Nature Communications **10**, Article number: 494 (2019) | Cite this article

PAPER • OPEN ACCESS

Testing the gravitational field generated by a quantum superposition

M Carlesso[1,2], A Bassi[1,2], M Paternostro[3] and H Ulbricht[4]

New Journal of Physics, Volume 21, September 2019

View PDF   View ePub

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesells

PAPER • OPEN ACCESS

Ultra-cold single-atom quantum heat engines

Giovanni Barontini[1] and Mauro Paternostro[2]

Published 17 June 2019 •

New Journal of Physics, Volume 21, June 2019

EXTERNAL DISSEMINATION

161 talks

- 80 talks to academics
- 23 presentations to general public
- 58 lectures to students

>10000 people

42 cities

18 countries (12 in EU)

"The rebel physicist". The New York Times dedicates a feature article to the Italian physicist Angelo Bassi

On 25th June 2020 the New York Times published a feature article, written by Bob Henderson, which is professional and personal portrait of Angelo Bassi, professor of Physics at the University of Trieste, as well as leading scientist in the foundations of Quantum Mechanics.

Coming from the renown Trieste school in theoretical physics founded by late Professor GianCarlo Ghirardi, Angelo Bassi has given new drive to the research on the foundations of quantum physics and is currently leading an ambitious international project called *TEQ: Testing the Large Scale of Quantum Mechanics*, having as objective to verify the limits of validity of quantum theory.

The New York Times Magazine

FEATURE

The Rebel Physicist on the Hunt for a Better Story Than Quantum Mechanics

For a century, quantum theory has been scientific orthodoxy. The Italian physicist Angelo Bassi is certain it isn't the full story — and that he can prove it.

C. Curceanu at QCA Theatre
Brisbane
Australia
Public Lecture
9 Aug. 2019

From the Schrödinger cat to quantum computers

Prof Robert Sang and Dr Catalina Curceanu.

Griffith Sciences hosted one of the world's most innovative minds in quantum mechanics at a special evening lecture recently.

'*A Quantum Symphony: From the Schrödinger cat to quantum computers*', featured special guest Dr Caralina Curceanu from the National Laboratory of Frascati in Italy and was held at Griffith's QCA Lecture Theatre South Bank.


TEDxFrascati
x = independently organized TED event
Theme: From an idea to an avalanche
This event occurred on
October 12, 2019
Frascati, Lazio
Italy


Il gatto di Schrödinger
scatena la valanga quantistica
CATALINA
CURCEANU
www.tedxfrascati.com
0:00 / 14:54
12/10/2019 - Frascati, Scuderie Aldobrandini
Il gatto di Schrödinger scatena la valanga quantistica | Catalina Curceanu | TEDxFrascati
3.579 visualizzazioni • 5 nov 2019
81
7
CONDIVIDI
SALVA

Il gatto di Schrödinger scatena la valanga quantistica | Catalina Curceanu | TEDxFrascati

3.579 visualizzazioni • 5 nov 2019

81 7 CONDIVIDI SALVA ...

TEDx

TEDx Talks

26,7 Mln di iscritti

ISCRIVITI

Press Articles

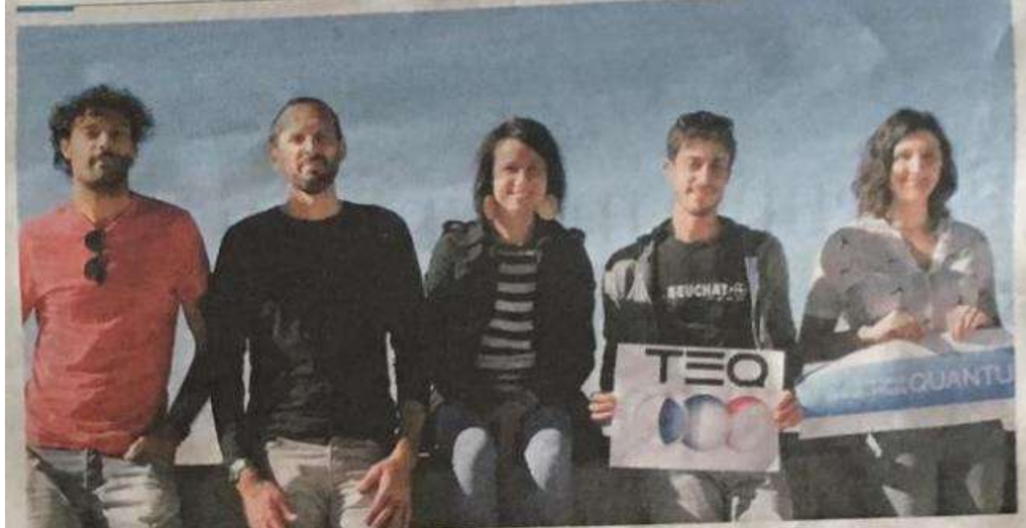
2020

- Smithsonian Magazine (USA)
- New York Times Magazine (USA)
- Il Piccolo (IT)
- Il Piccolo (IT)
- Il Corriere della Sera (IT)

2019

- Il Piccolo di Trieste (IT)
- Medienportal Univie (Austria)
- Hotnews (Romania)
- Il Piccolo di Trieste (IT)
- Techeconomy (IT)
- Il Piccolo di Trieste (IT)

Il Piccolo di Trieste (IT) 2019



Un gruppo di ricercatori e scienziati del progetto Teq dell'Università di Trieste che si occupa di meccanica quantistica

La tesi di Gaia Donati, editor di "Nature" con base a Londra, in questi giorni tiene una serie di conferenze all'Ictp

«Più visibilità all'estero per la ricerca triestina»

IL PERSONAGGIO

«Sono contenta di potermi finalmente fermare per qualche giorno a Trieste, per toccare con mano il tipo di ricerca che viene portata avanti sul territorio, che all'estero è forse ancora poco nota rispetto ad altre realtà». A parlare è Gaia Donati, dal 2017 editor di Nature, con base a Londra. E' una scienziata appassionata di scrittura e di editoria, che in tasca ha un Phd in ottica quantistica sperimentale all'Università di Oxford e una laurea in Fisica alla Sapienza. Si trova a Trieste in questi giorni: ieri ha tenuto un talk all'Ictp e oggi parteciperà a una sessione di domande e risposte sui criteri editoriali e il processo di peer-review della prestigiosa rivista inglese nell'ambito del simposio "Redefining the foundations of physics in the quantum technology era" (Ridefinire le basi della fisica nell'era della tecnologia quantistica), organizzato dall'Università di Trieste all'Ictp per il progetto Teq - Testing the Large scale Limit of Quantum Mechanics. «Trieste è considerato un polo importante per la fisica teorica, anche per la tradizione legata al nome del fisico Gian Carlo Ghirardi - prosegue Donati - e ci sono molti ricercatori e docenti attivi nel campo della meccanica quantistica. Ma, con l'eccezione di Elettra Sincrotrone Trieste, la ricerca triestina potrebbe forse puntare ad una maggiore visibilità all'estero, che nell'ambito della fisica credo potrebbe essere ottenuta con il nuovo centro per la teoria delle tecnologie quantistiche».

Gaia Donati

Inaugurato lo scorso marzo e nato come progetto congiunto di Ictp, Sissa e Università di Trieste, il Trieste Institute for the Theory of Quantum Technologies è per Donati un'idea vincente, perché consentirebbe a Trieste di concentrarsi sugli aspetti fondamentali delle tecnologie quantistiche. Questi temi in Europa sono studiati con grande successo da alcuni gruppi di ricerca, ma l'impressione della scienziata è che questi singoli sforzi siano poco coordinati: iniziative come questa potrebbero aiutare a unificarli e organizzarli in nome di obiettivi comuni. «Buona parte della ricerca portata avanti in questi ultimi anni è stata orientata alle applicazioni pratiche, a dimostrare che la fisica quantistica si può trasportare nel mondo in cui viviamo - evidenzia Donati -. Ma è necessario che ci sia chi invece prosegue con la ricerca di base e sarà interessante vedere che taglio prenderà e come s'inserirà, editorialmente parlando, nella fanfara sul computer quantistico e l'internet quantistico». —

Giulia Basso

Multimedia

2020

- Fisica in una notte di mezza estate - INFN-LNF (IT)
- Rai News 24 - Futuro 24: speciale ESOF2020 Comunicazione Quantistica (IT)

2019

- Radar Rai FVG (IT)

CAFFÈ DEI QUANTI

scienza, musica, teatro: avvicinarsi alla meccanica quantistica

Il grande mondo del piccolo

ottobre_novembre 2019, ore 18.30

Caffè libreria Knulp
via Madonna del Mare 7/a, Trieste

per info e prenotazioni:
T. +39 040 300021

martedì 15 ottobre
L'alfabeto della materia

Il sistema periodico di Primo Levi
Lettura a cura del
Centro Universitario Teatrale CUT Trieste

La materia e i suoi mattoni

Intervento scientifico di
MARIA PERESSI
docente di Fisica della materia
Università di Trieste

Musica
a cura degli studenti
del Conservatorio di Musica "G. Tartini" di Trieste

martedì 29 ottobre
Architetture microscopiche

Il libro dei Mostri di J. Rodolfo Wilcock
Lettura a cura del
Centro Universitario Teatrale CUT Trieste

Materiali nanostrutturati e nanotecnologie

Intervento scientifico di
GIOVANNI COMELLI
docente di Fisica della materia
Università di Trieste

Musica
a cura degli studenti
del Conservatorio di Musica "G. Tartini" di Trieste

martedì 12 novembre
Il futuro in 2D

Flatlandia di Edward Abbot
Lettura a cura del
Centro Universitario Teatrale CUT Trieste

Materiali bidimensionali innovativi

Intervento scientifico di
MARTINA DELL'ANGELA
ricercatrice, Istituto Officina dei Materiali
IOM-CNR, Trieste

Musica
a cura degli studenti
del Conservatorio di Musica "G. Tartini" di Trieste

TEQ · Funded by the Horizon 2020 Framework Programme of the European Union · GENERALI · TS · CUT · AISF · KNULP

Il Caffè dei Quanti è un'iniziativa
sviluppata nell'ambito del progetto di ricerca
TEQ Testing the large-scale limit of quantum mechanics
finanziato dalla **Commissione Europea**
www.tequantum.eu

Ideato e organizzato da
Angelo Bassi
Università di Trieste

Università di Trieste
Dipartimento di Fisica
via Valerio 2, Trieste
T. +39 040 558 3399 / teq@units.it

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

Conservatorio di musica Giuseppe Tartini Trieste · CUT · KNULP · AISF · TEQ · Funded by the Horizon 2020 Framework Programme of the European Union

CAFFÈ DEI QUANTI

scienza, musica, teatro: avvicinarsi alla meccanica quantistica

alla scoperta dell'universo

marzo_aprile 2019, ore 18.30

Caffè libreria Knulp
via Madonna del Mare 7/a, Trieste

per info e prenotazioni:
T. +39 040 300021

mercoledì 20 marzo
Il buio nell'universo

Le Cosmicomiche
di Italo Calvino
Lettura a cura degli studenti
del Centro Universitario Teatrale – CUT Trieste

Il lato oscuro dell'Universo

Intervento scientifico di
STEFANO BORGANI
Dipartimento di Fisica, Università di Trieste

Musica
MATTEO CHIODINI chitarra
Conservatorio "G. Tartini" di Trieste

mercoledì 3 aprile
Imparare a guardare

La Ginestra
di Giacomo Leopardi
Lettura a cura degli studenti
del Centro Universitario Teatrale – CUT Trieste

Come osservare l'Universo. Dal cannocchiale di Galileo ai telescopi giganti del futuro

Intervento scientifico di
STEFANO CRISTIANI
Istituto Nazionale di Astrofisica – INAF Trieste

Musica
SIMONE LANZI contrabbasso
PIERCARLO FAVRO chitarra
KRISTINA IVANOVIĆ voce
Conservatorio "G. Tartini" di Trieste

mercoledì 17 aprile
In principio la luce

La Biblioteca di Babele
di Jorge Luis Borges
Lettura a cura degli studenti
del Centro Universitario Teatrale – CUT Trieste

Prima del Big Bang: l'universo inflazionario

Intervento scientifico di
PAOLO CREMINELLI
International Centre for Theoretical Physics – ICTP Trieste

Musica
ANDREA CORAZZA clarinetto
FEDERICO FORTI pianoforte
Conservatorio "G. Tartini" di Trieste


musica
cinema

TEQ

Testing the large-scale limit of quantum mechanics

European Commission

FINANCIAL DATA

I. Spagnul - UniTS

Estimated budget for the action

Partner	A.Direct personnel costs	D.Other direct costs	E.Indirect costs	Total costs	Reimboursement rate	Requested EU contribution
UniTs	417 008,00	80 000,00	124 252,00	621 260,00	100%	**621 260,00**
AU	275 000,00	137 500,00	103 125,00	515 625,00	100%	**515 625,00**
INFN	200 000,00	107 500,00	76 875,00	384 375,00	100%	**384 375,00**
OEAW	265 000,00	32 900,00	74 745,00	372 375,00	100%	**372 375,00**
QUB	309 259,00	44 500,00	88 439,75	442 198,75	100%	**442 198,75**
TUDelft	251 572,00	63 500,00	78 768,00	393 840,00	100%	**393 840,00**
UCL	222 703,00	192 494,00	103 799,25	518 996,25	100%	**518 996,25**
Southampton	239 997,00	342 396,00	145 598,25	727 991,25	100%	**727 991,25**
M2	175 000,00	140 850,00	78 962,50	394 812,50	100%	**394 812,50**
Total	**2 355 539,00**	**1 141 640**	**874 294,75**	**4 371 473,75**		**4 371 473,75**

Summary of estimated project effort in Person-Months

	WP1	WP2	WP3	WP4	WP5	WP6	Total Person/Months per Participant
1 - UNITS	8	8	11	30	40	18	115
2 - AU	30	15	6	2	2	2	57
3 - INFN	19	20	10	4	4	4	61
4 - OEAW	8	12	16	33	2	2	73
5 - QUB	16	16	16	27.20	2	2	79.20
6 - TU Delft	38	9	3	3	2	2	57
7 - UCL	5	40	5.60	2	2	2	56.60
8 - SOUTHAMPTON	5	10	36	2	2	2	57
9 - M2	0	22	22	0	2	2	48
Total Person/Months	129	152	125.60	103.20	58	36	603.80

Summary of financial situation

Partner	A.Direct personnel costs ESTIMATED (48 M)	A.Direct personnel costs REPORTED (30 M)	D.Other direct costs ESTIMATED (48 M)	D.Other direct costs REPORTED (30 M)	Total costs (incl. Indirect costs) ESTIMATED (48 M)	Total costs (incl. Indirect costs) REPORTED (30 M)	% Total costs reported (Jan 2018-Jun 2020)
UniTs	417 008,00	247 670,28	80 000,00	41 470,98	621 260,00	360 301,57	57,99%
AU	275 000,00	113 521,68	137 500,00	60 776,33	515 625,00	217 872,51	42,25%
INFN	200 000,00	153 703,95	107 500,00	18 618,08	384 375,00	215 402,54	56,03%
OEAW	265 000,00	218 934,64	32 900,00	960,00	372 375,00	274 868,31	73,81%
QUB	309 259,00	170 592,68	44 500,00	17 328,73	442 198,75	234 901,77	53,12%
TUDelft	251 572,00	158 669,80	63 500,00	23 716,17	393 840,00	227 982,46	57,88%
UCL	222 703,00	106 557,38	192 494,00	153 336,43	518 996,25	324 867,29	62,59%
Southampton	239 997,00	136 199,91	342 396,00	195 052,78	727 991,25	414 065,87	56,87%
M2	175 000,00	188 081,23	140 850,00	137 934,52	394 812,50	407 519,73	103,21%
Total	**2 355 539,00**	**1 493 931,55**	**1 141 640,00**	**649 194,02**	**4 371 473,75**	**2 677 781,81**	**61,25%**

Summary of project effort in Person-Months

Partner	PMs estimated (48 M)	PMs reported (30 M) Incl. adjs	% PMs on total
UniTs	115	103.55	90,04 %
AU	57	31.92	56,00 %
INFN	61	30.79	50,47 %
OEAW	73	50.65	69,38 %
QUB	79.20	54.51	68,82 %
TUDelft	57	31.64	55,50 %
UCL	56.60	30.87	54,54 %
Southampton	57	36.54	64,10 %
M2	48	34.70	72,29 %
Total	**603.80**	**415.73**	**68,85 %**

Thank you!