## TEQ Review Meeting preparation and SC Meeting Brussels – list of participants

| Name and Surname | Institution | Signature |
|---|---|---|
| Angelo Bassi | UniTs | |
| Irene Spagnul | UniTs | |
| Catalina Curceanu | INFN | |
| Peter Barker | UCL | |
| Mauro Paternostro | QUB | |
| Michael Drewsen | AU | |
| Liberato Manna | TUD | |
| Hendrik Ulbricht | UoS | |
| Caslav Brukner | OEAW | |
| Stefan Olsonrobbie | M2 | |

Brussels, February 25th 2019

# TEQ Review Meeting agenda

**February 26, 2019**

**EU Executive Research Agency, Brussels**

**Place Charles Rogier 16, 1210 Brussels (room COV2 17-SDR1)**

| | | |
|---|---|---|
| 9:00 – 9:15 | R. Borissov | Introduction, tour du table |
| 9:15 – 9:45 | A. Bassi | Overview by the coordinator |
| 9:45 – 10:30 | L. Manna – M. Drewsen | WP1: Trapping |
| Coffee (10:30 – 11:00) | | |
| 11:00 - 11:45 | P. Barker | WP2: Cooling |
| 11:45 – 12:30 | H. Ulbricht | WP3: Testing |
| Lunch (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, L. Manna, M. Paternostro, H. Ulbricht
- **TEQ members**
- **Administrative Officer:** Irene Spagnul
- **PO:** Roumen Borissov
- **Reviewers:** R. Filip, R. Quidant, W. Struyve

# The Network

## UniTs - University of Trieste

Angelo Bassi
PI
Website

Luca Ferialdi

Lorenzo Asprea

Matteo Carlesso
Website Manager

Caitlin Jones
Social Media Manager

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

## M2 - M Squared Lasers Limited

Nils Hempler
Local PI
Website

Joseph Thom

James Bain

Stefan Olsonrobbie

## INFN - Istituto Italiano Fisica Nucleare

Catalina Curceanu
Local PI & Press Officer

Kristian Piscicchia

Alberto Clozza

Massimiliano Bazzi

## AU - Aarhus University

Michael Drewsen
Local PI
Website

Cyrille Solaro

Aurelién Dantan
Website

Vincent Jarlaud

## TUD - Delft University of Technology

Liberato Manna
Local PI
Website

Luca De Trizio

Arjan Houtepen
Website

Jence Mulder

## UoS - University of Southampton

Hendrik Ulbricht
Local PI
Website

Giulio Gasbarri

Christopher Timberlake

Andrea Vinante

Ashley Setter

## OEAW - Austrian Academy of Sciences

Caslav Brukner
Local PI
Website

Esteban Castro Ruiz

Ilya Kull

## UCL - University College London

Peter Barker
Local PI
Website

Antonio Pontin

Thomas Penny

Anishur Rahman

Jonathan Gosling

Marco Toroš

TEQ

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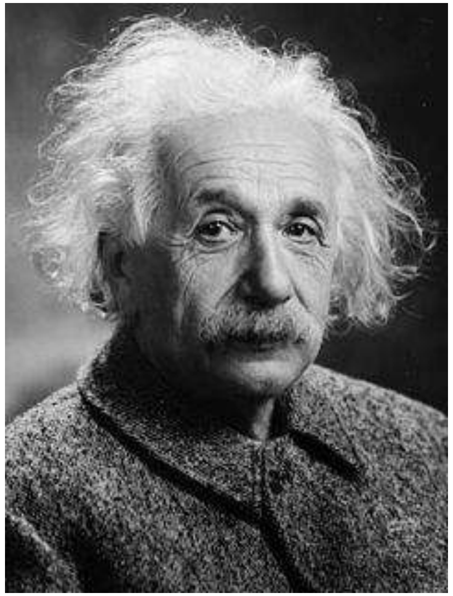
# Long-term vision and targeted breakthrough

*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*



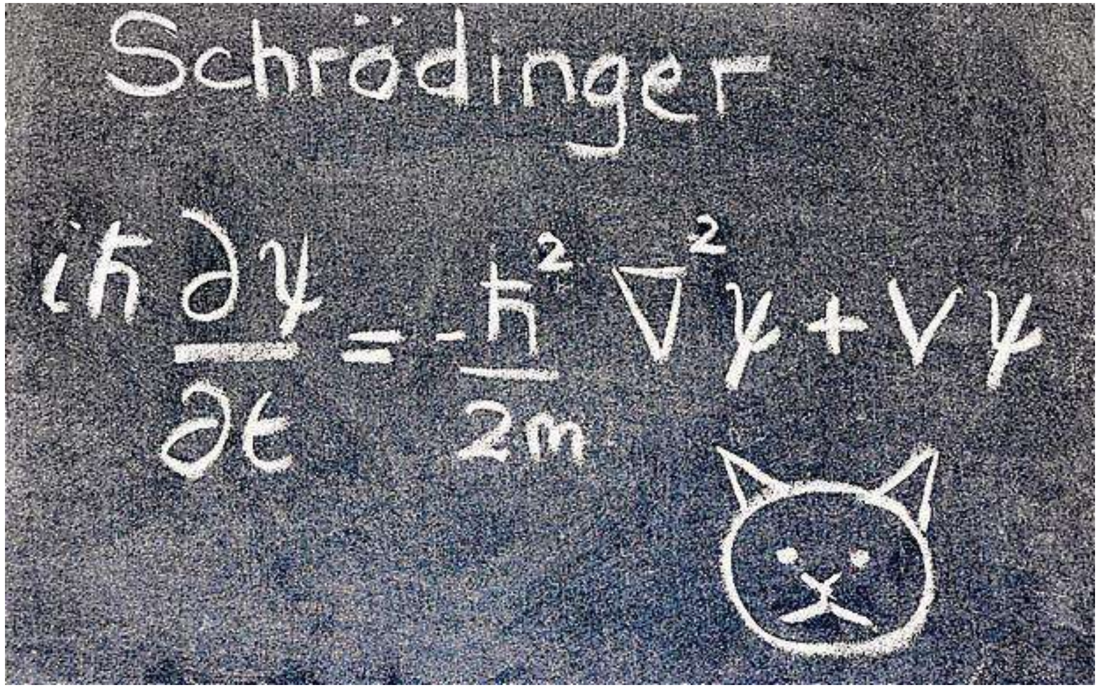
*Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing.*
**Albert Einstein**

*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.

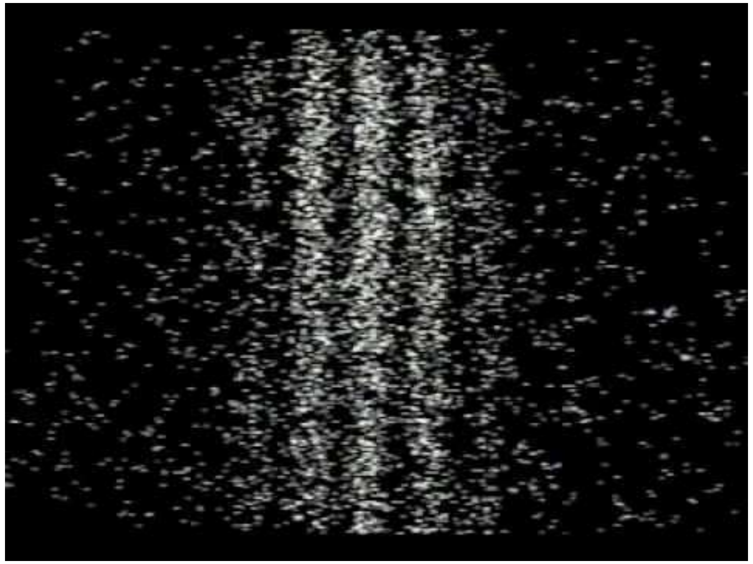
Why is it so? How is quantumness lost when moving from the micro- to the macro-world?

# The core of TEQ

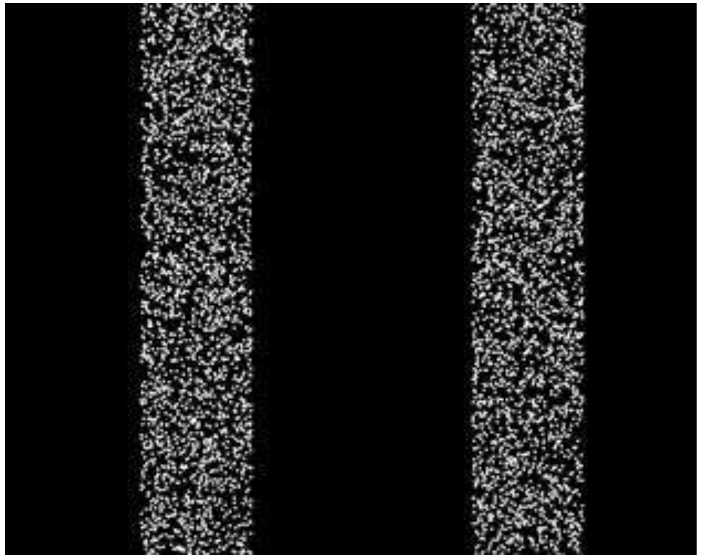
Is the lack of observation of quantum effects at the macroscopic level a manifestation of a breakdown of quantum linearity, or simply the consequence of the fact that no one so far was able to create a macroscopic quantum superposition?

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

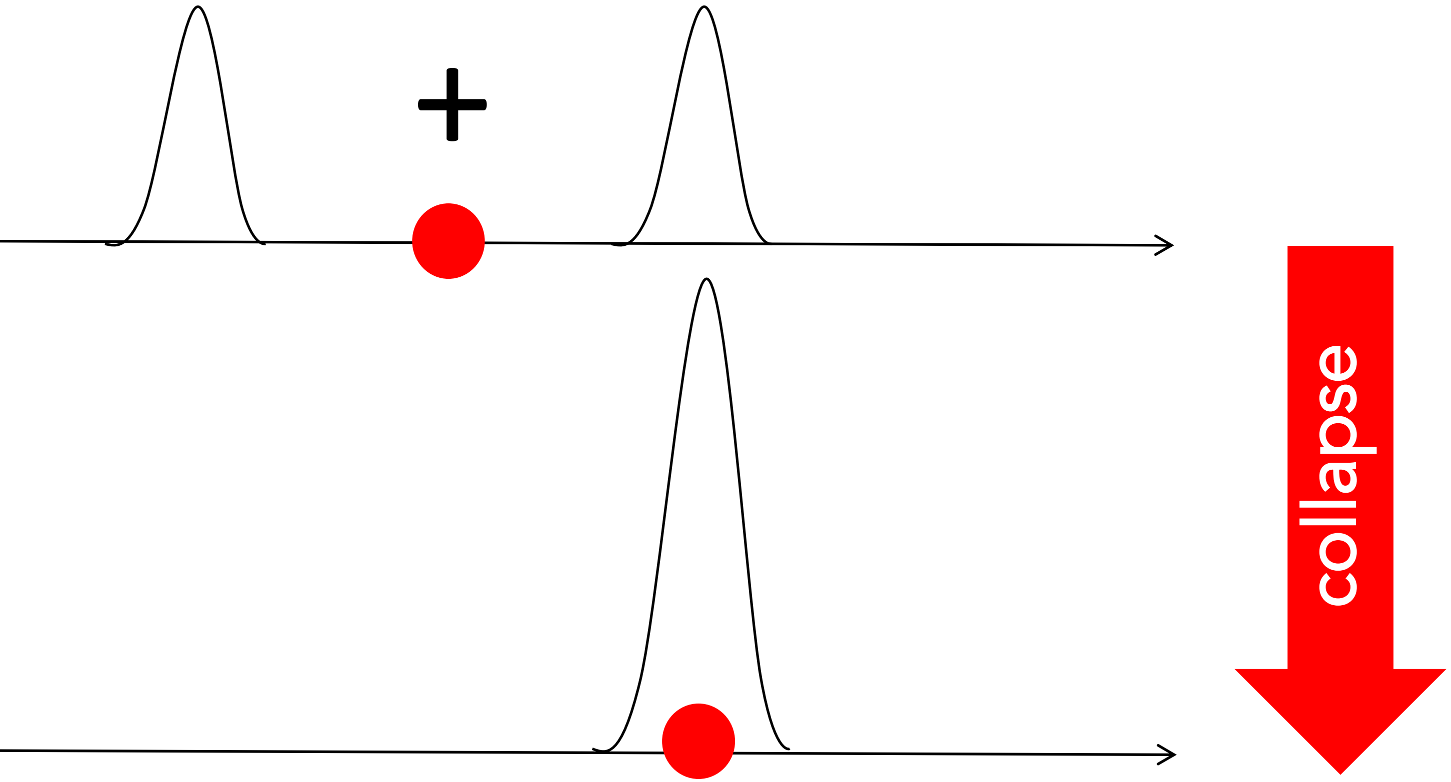


Quantum Mechanics ok!



Quantum Mechanics wrong!

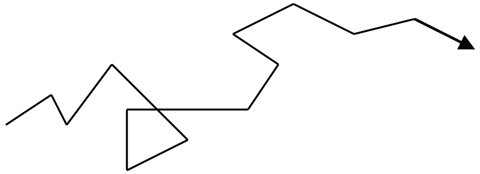
# A novel route: non-interferometric experiments




= 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

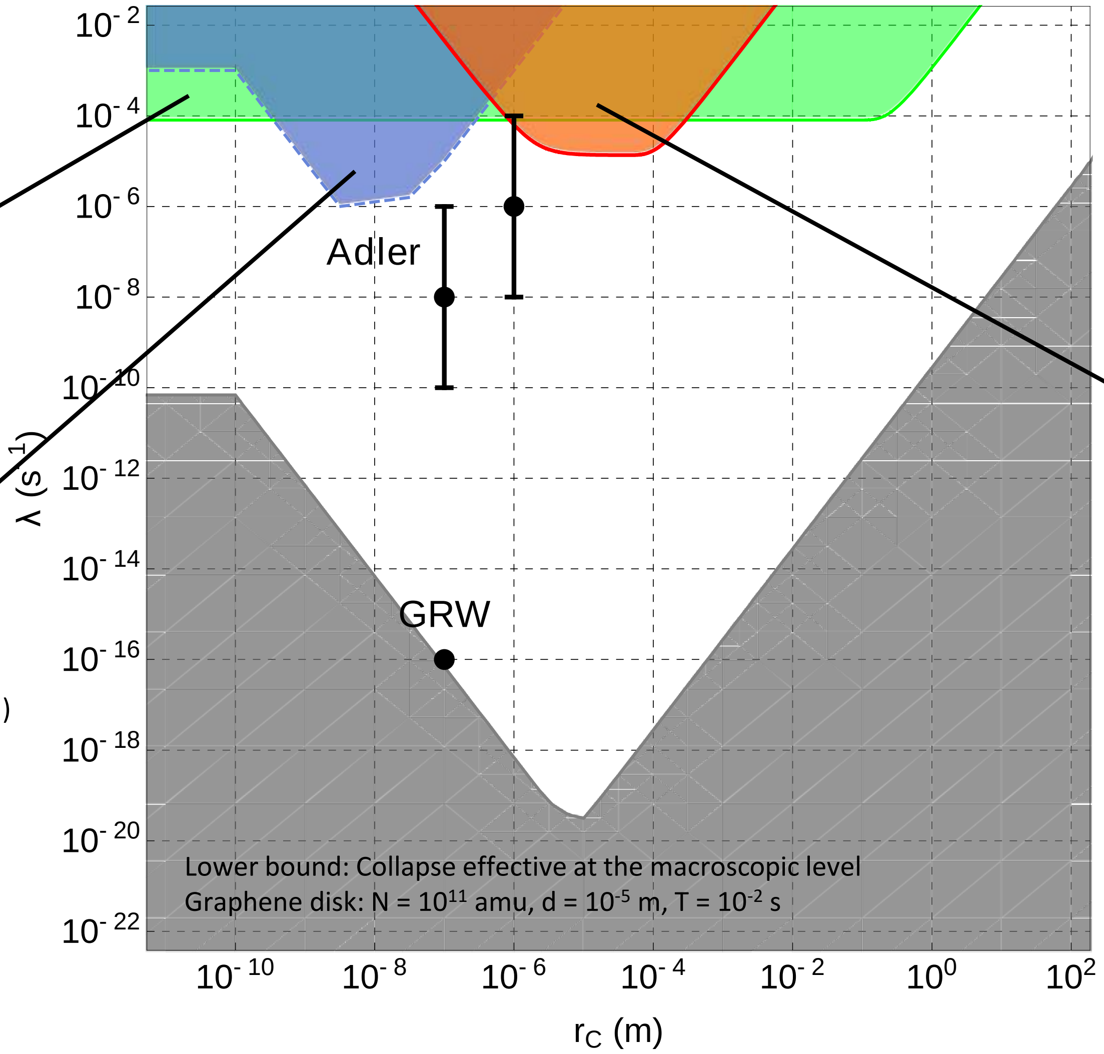
T. Kovachy *et al.*, Nature 528, 530 (2015)

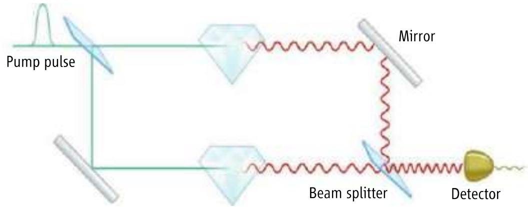
M = 87 amu
d = 0.54 m
T = 1 s

## Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)
M. Toros *et al.*, ArXiv 1601.03672

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

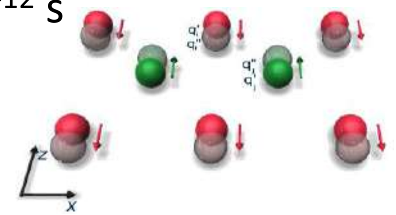



## Entangling Diamonds

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

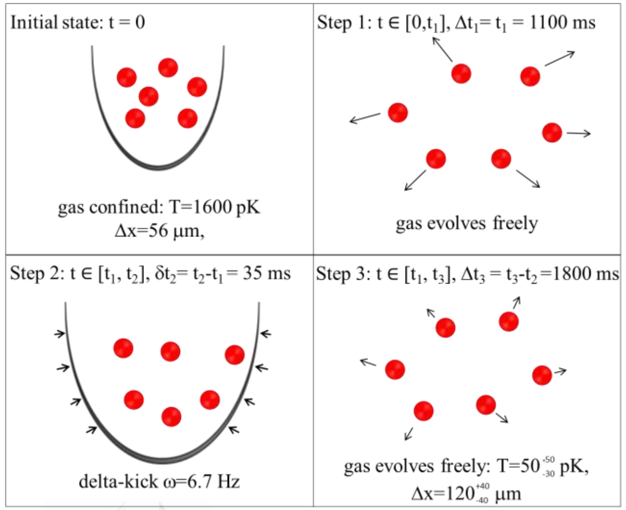
M = $10^{16}$ amu
d = $10^{-11}$ m
T = $10^{-12}$ s

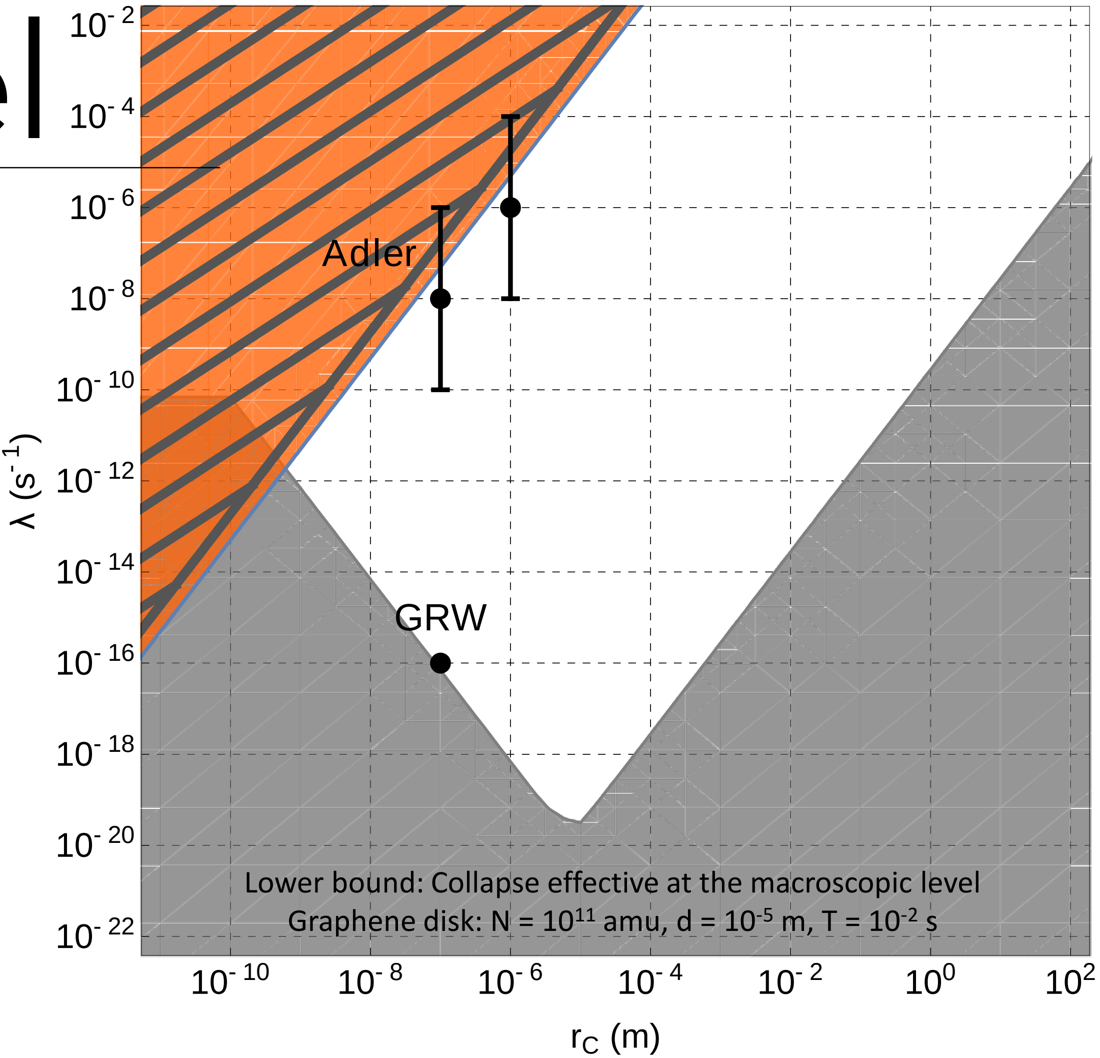


# A comparison: non-interferometric bounds on the CSL model

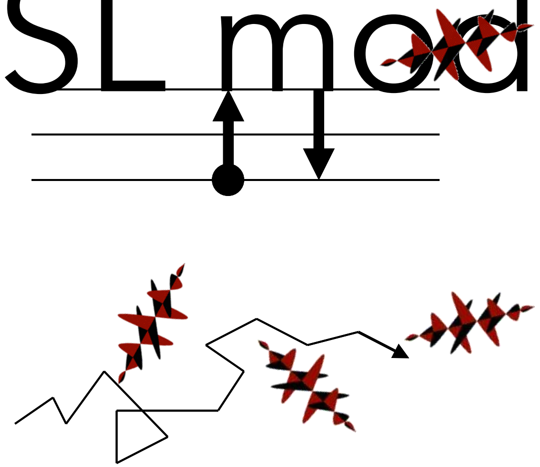
**Cold atom gas**

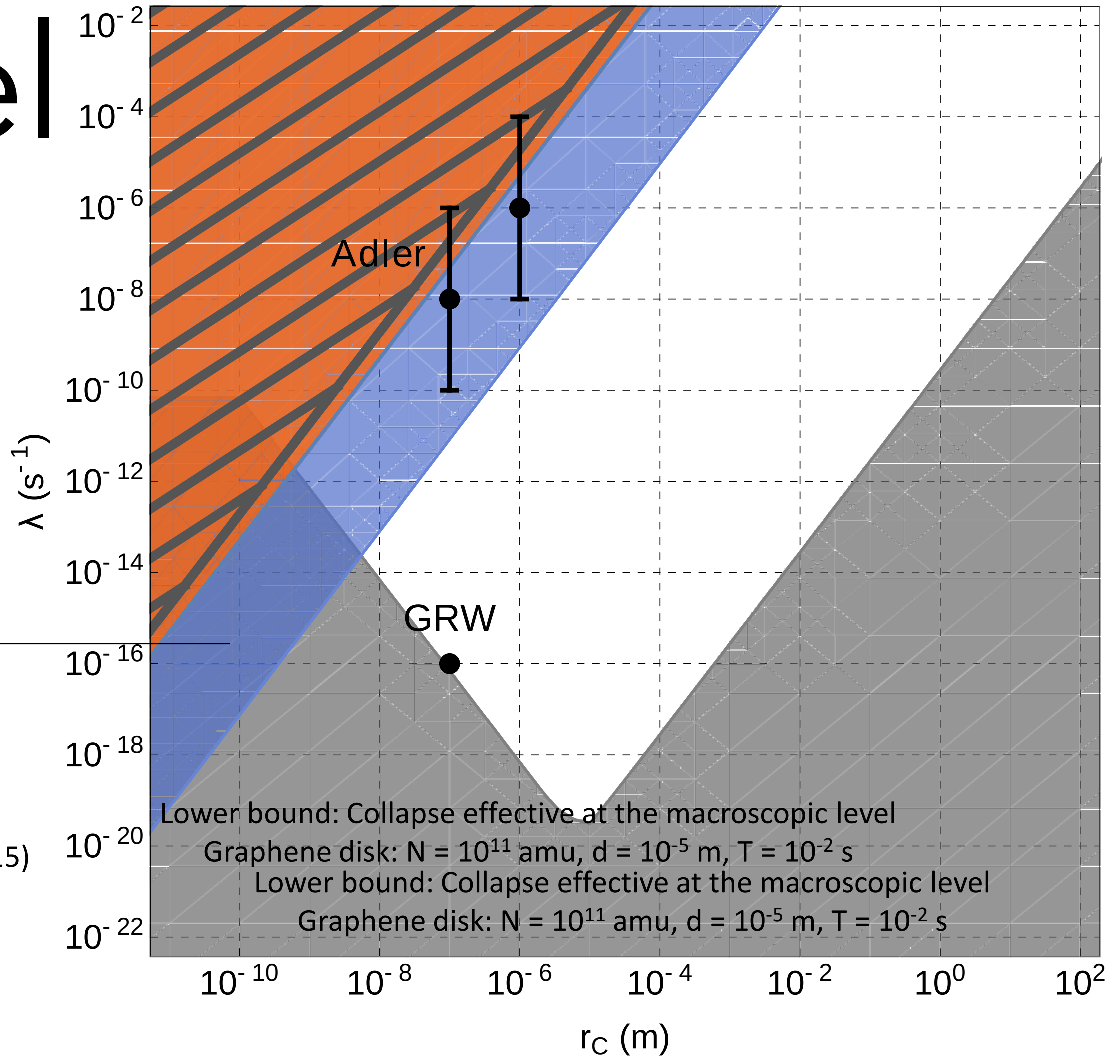
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.,* Physica A 462, 764 (2016)



# A comparison: non-interferometric bounds on the CSL model

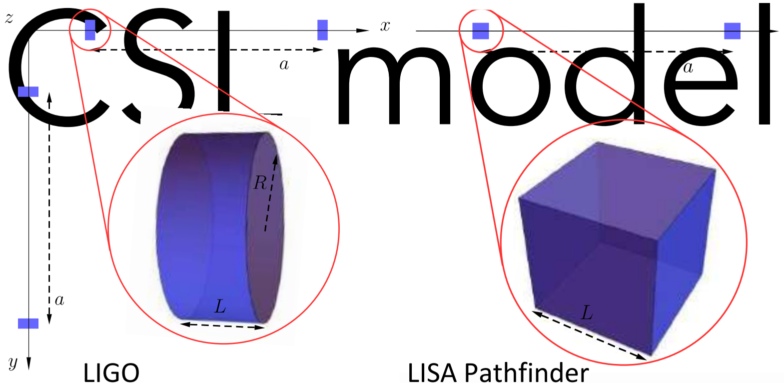


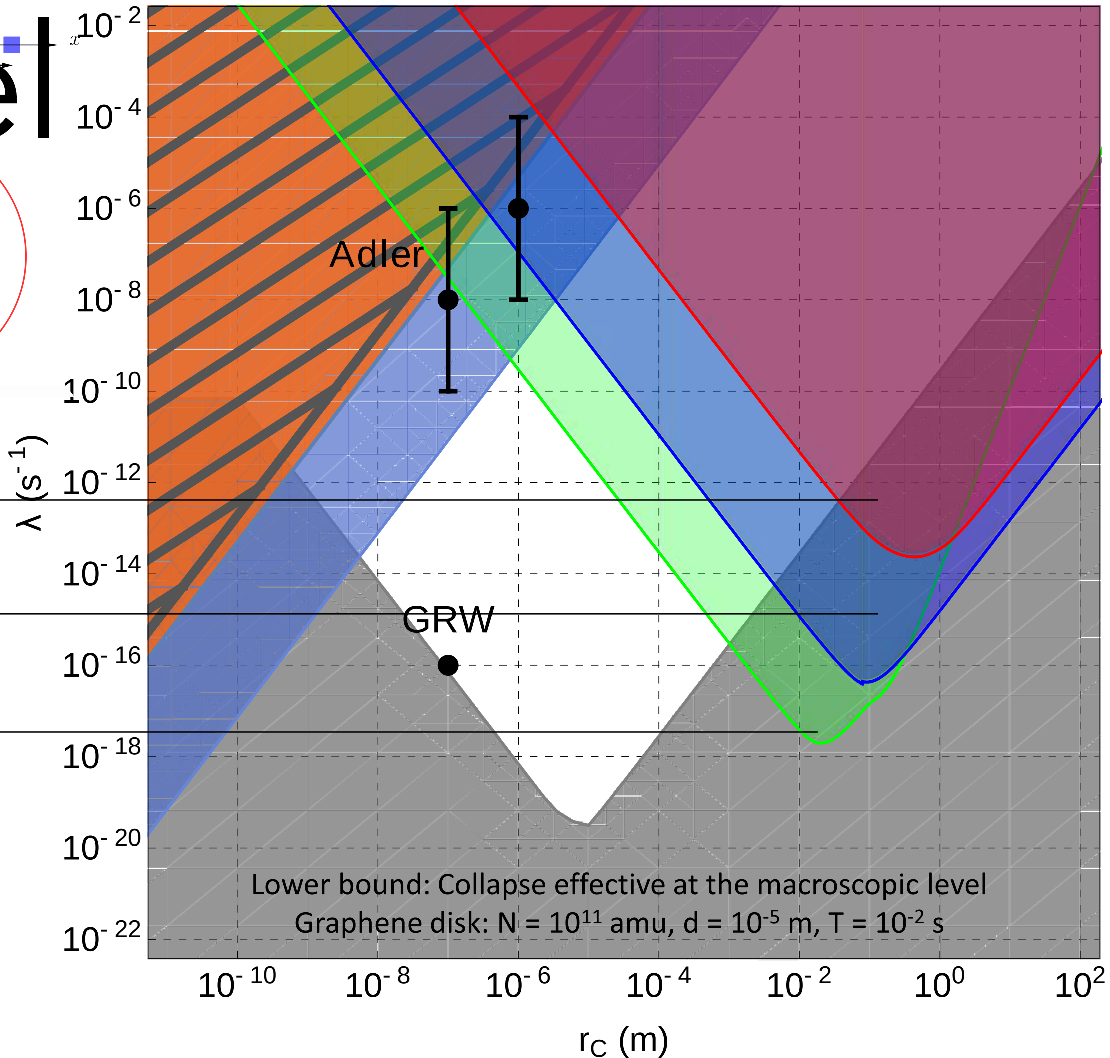



**X rays**


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

# A comparison: non-interferometric bounds on the CSL model



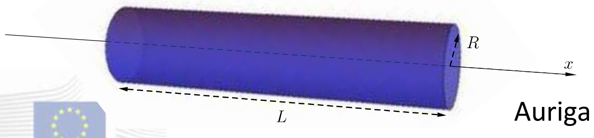




**Auriga**

**Ligo**

**Lisa Pathfinder**

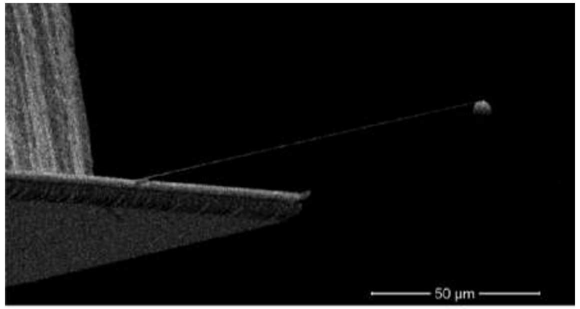
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

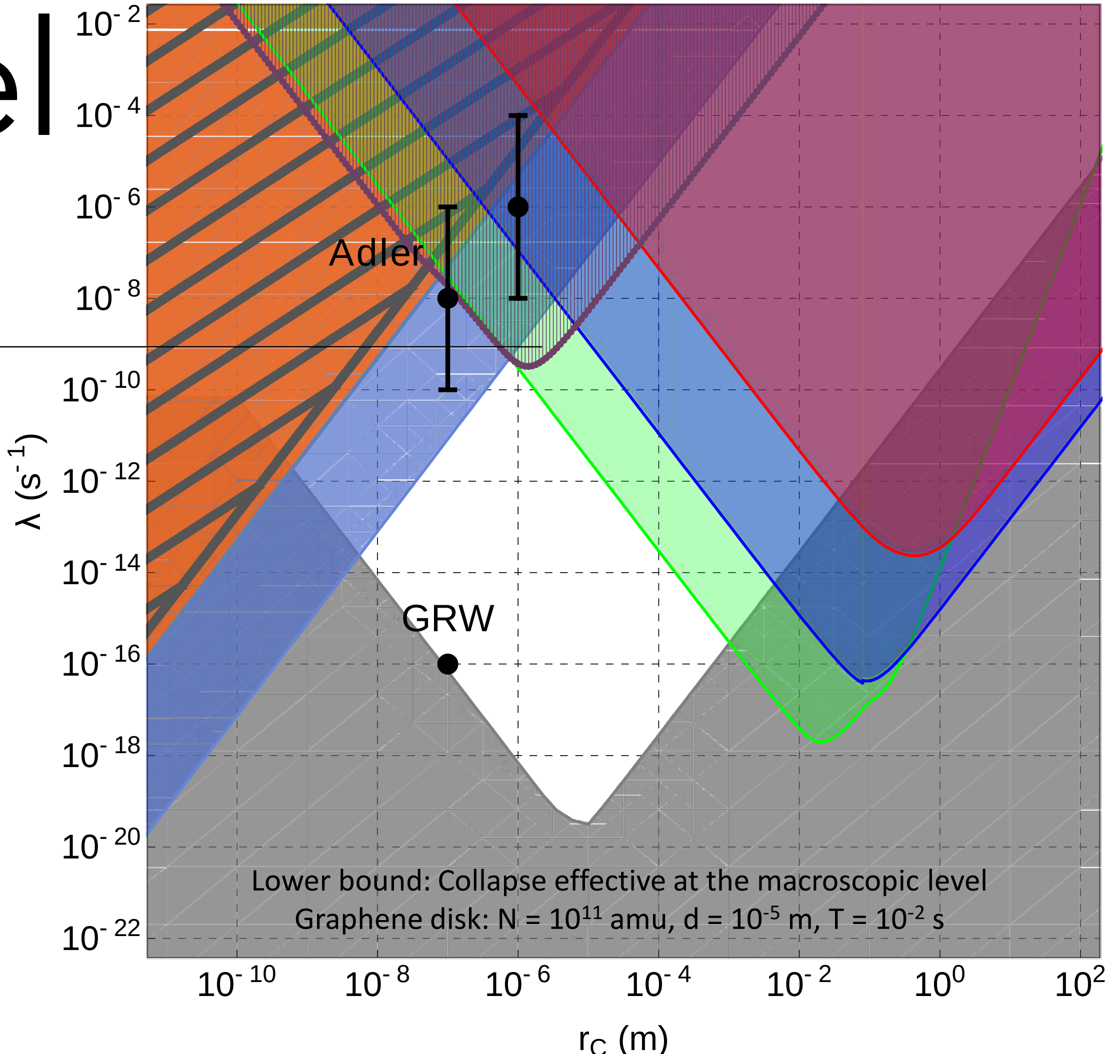


# A comparison: non-interferometric bounds on the CSL model

**Cantilever**

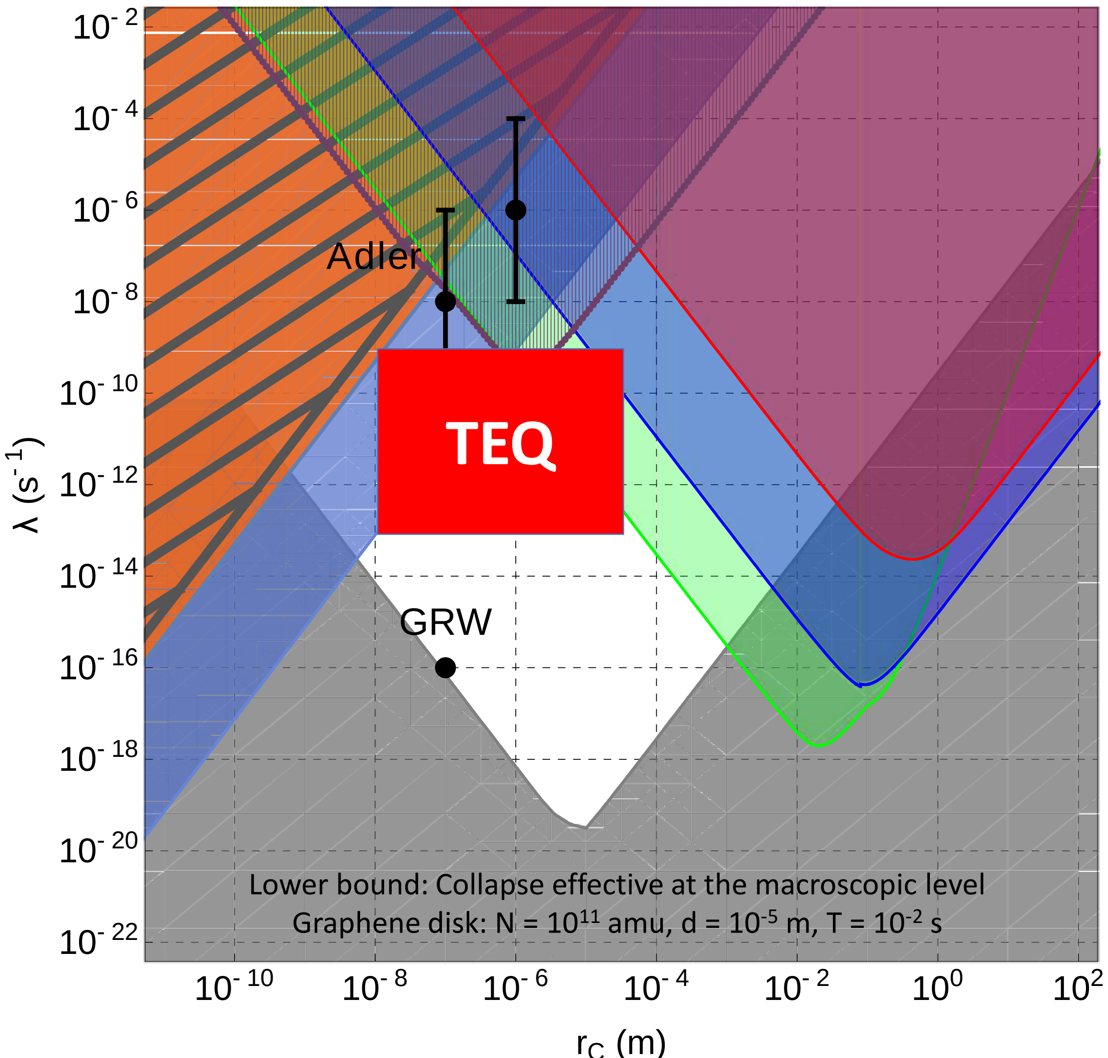
A. Vinante *et al.,* Phys. Rev. Lett. 116, 090402 (2016)



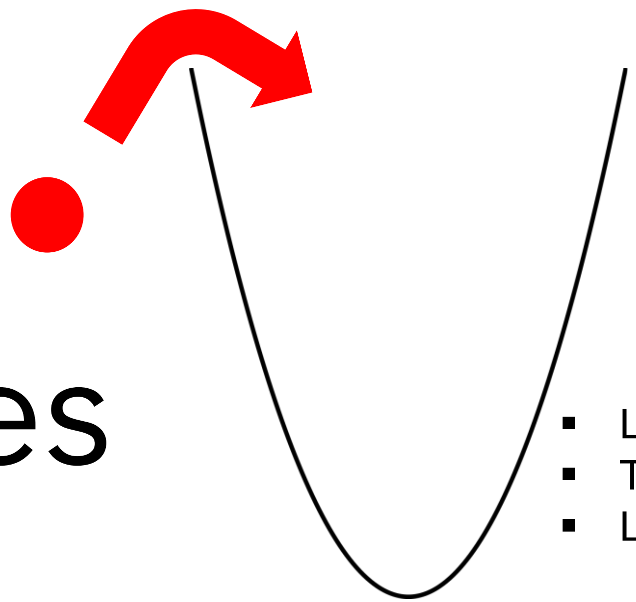



# The overarching goal of the project…

…is to test CSL in a parameter range which is two orders of magnitude beyond any other test performed so far

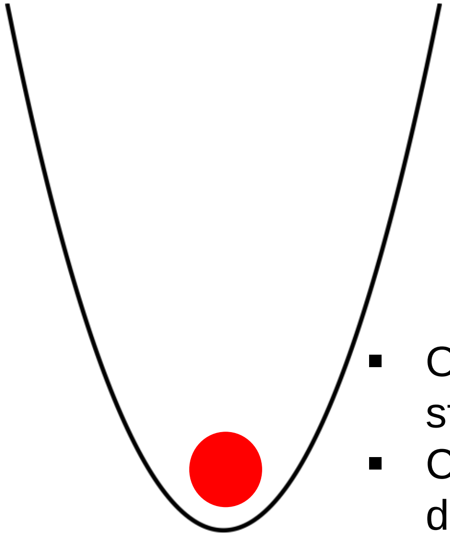


# TEQ's Objectives



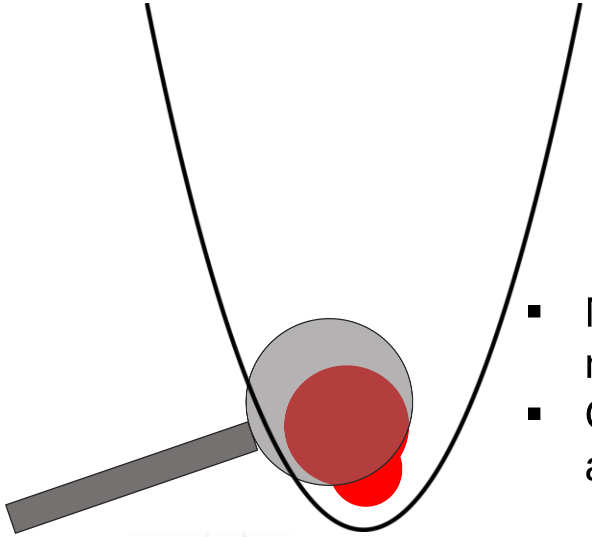
- Low-noise trap
- Tailored NCs
- Loading mechanics

## 1. Trapping



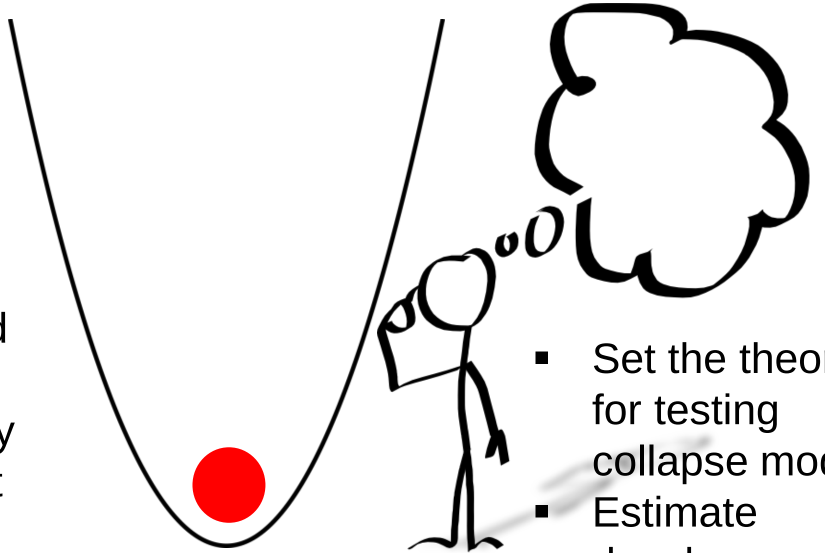
- Optimal cooling strategies
- Control decoherence

## 2. Cooling



- Monitor trapped motion
- Compare theory and experiment

## 3. Testing



- Set the theory for testing collapse models
- Estimate decoherence

## 4. Enabling

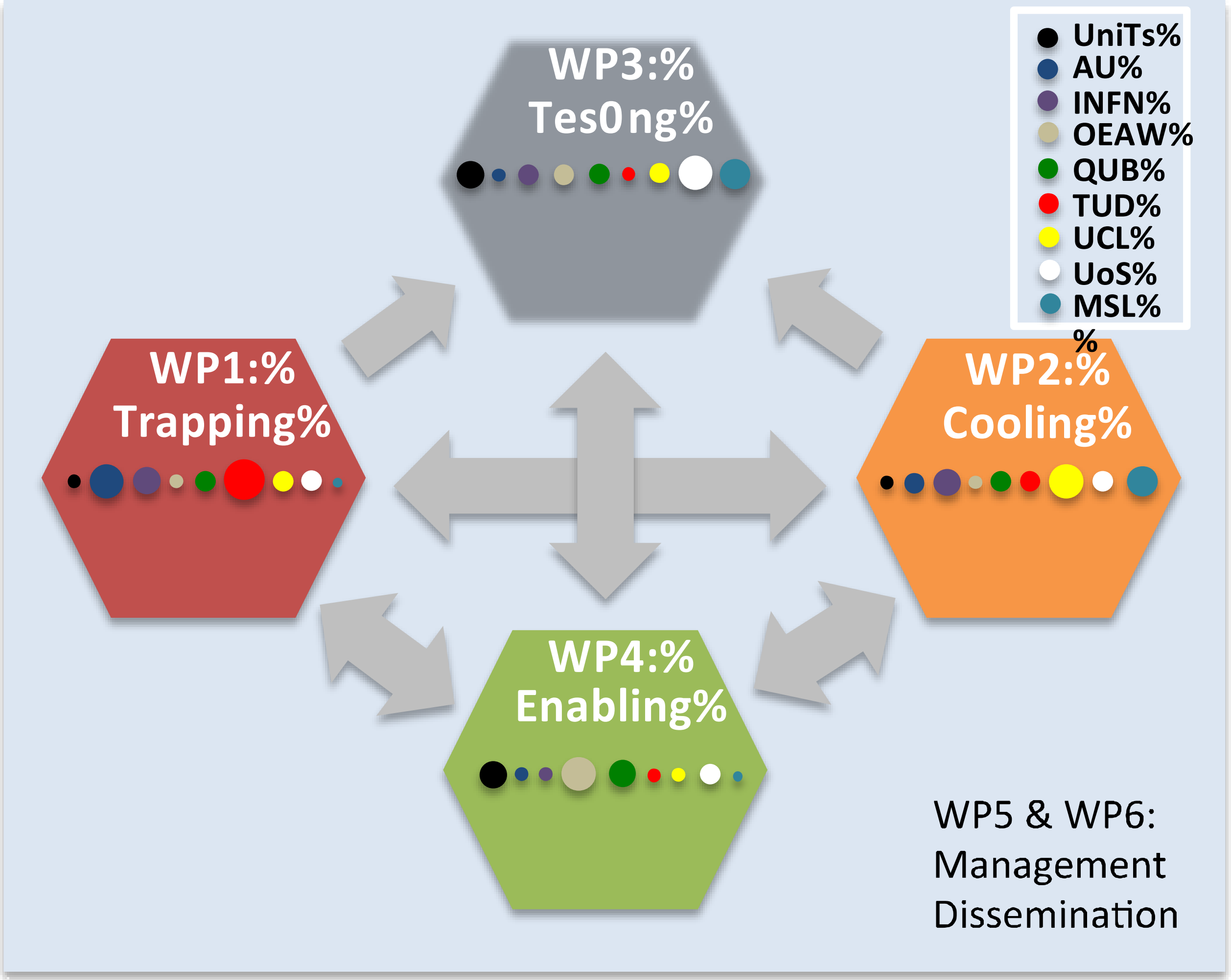
- Visionary perspectives on the study of the foundations of quantum mechanics

## 5. Ruling out

# 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
L. Manna

| 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

| 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

TEQ European Commission

# WP Breakdown

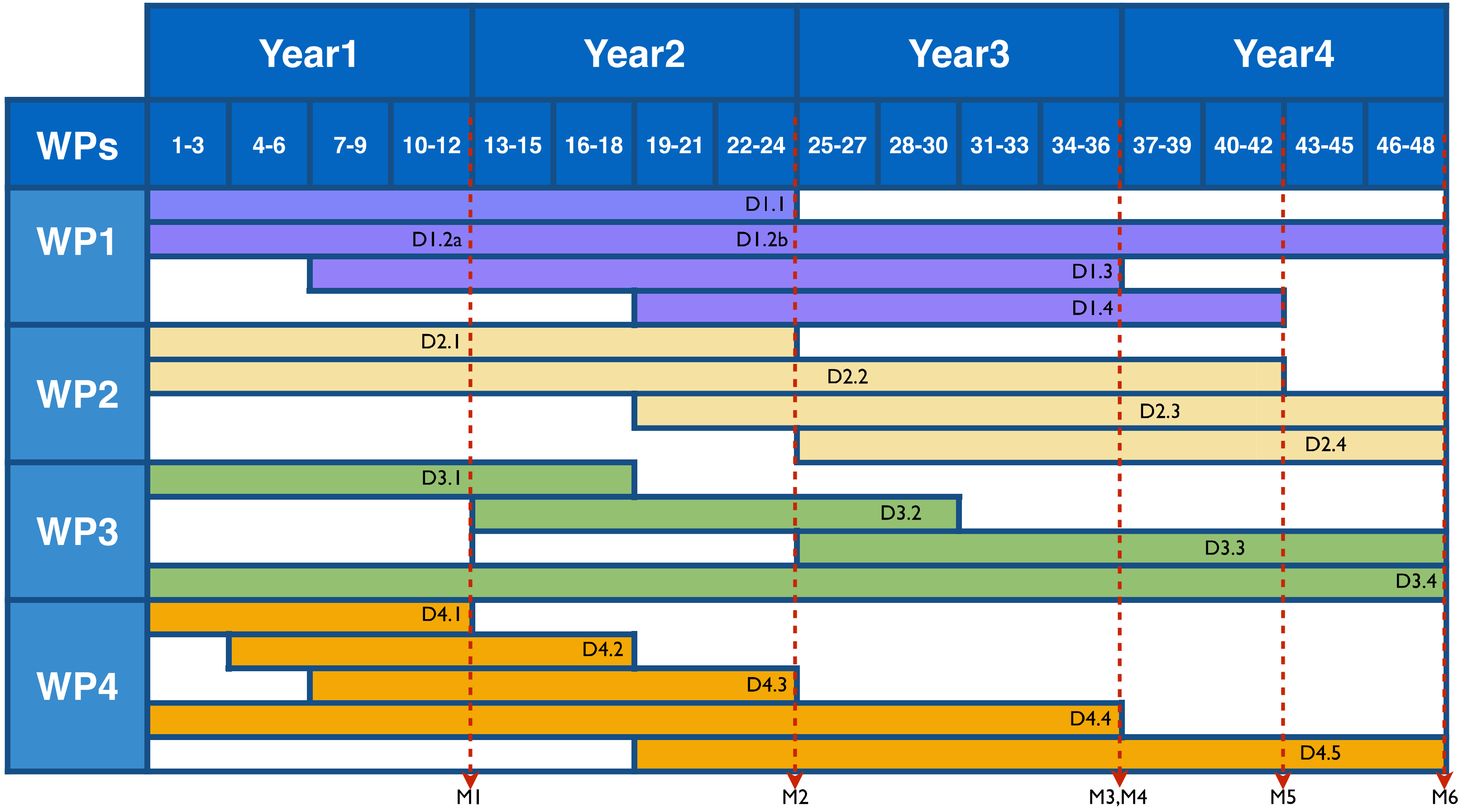
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Work package number** | 5 | **Start Date or Starting Event** | | | | Mth 1 | | | |
| **Work package title** | **Management** | | | | | | | | |
| **Participant number** | **1** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| **Short name of participant**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

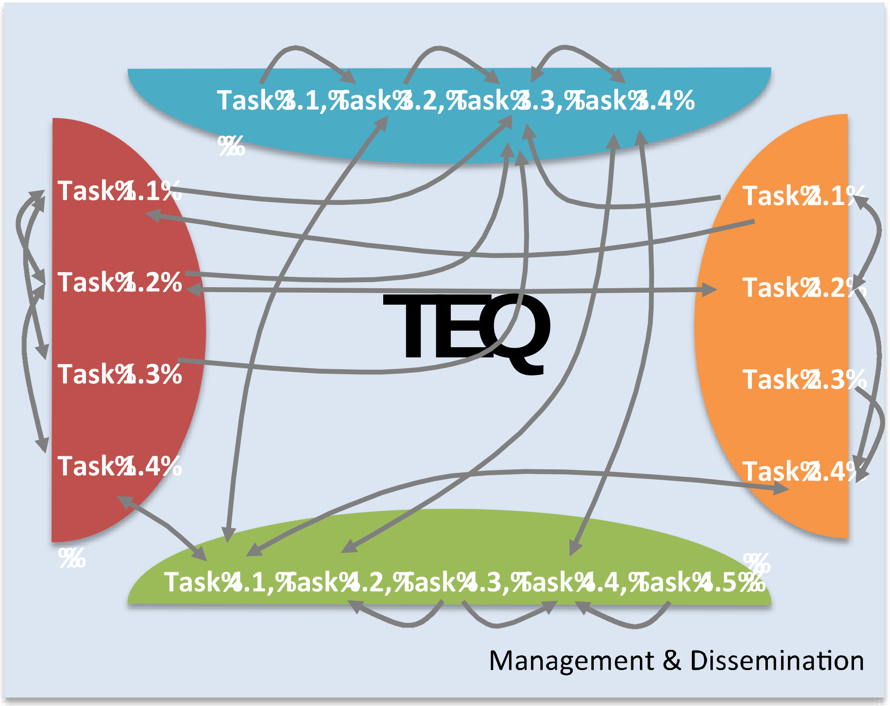
A. Bassi

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **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 | Title | Lead Beneficiary | Nature | Dissemination Level | Est. Del. Date (annex I) | Receipt Date | Approval Date | Status |
| WP5 | D5.1 | Website | UNITS | Websites, patents filling, etc. | Public | 28 Feb 2018 | 15 Mar 2018 | 23 Aug 2018 | Approved |
| WP6 | D6.1 | Press releases | UNITS | Websites, patents filling, etc. | Public | 31 Mar 2018 | 28 Mar 2018 | 23 Aug 2018 | Approved |
| WP5 | D5.2 | Data Management Plan | UNITS | ORDP: Open Research Data Pilot | Public | 30 Jun 2018 | 28 Jun 2018 | | Submitted |
| WP1 | D1.2 | 1-Colloidal NCs | TU Delft | Report | Public | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP2 | D2.1 | Low noise electronics | INFN | Report | Public | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP3 | D3.1 | Low noise environment | SOUTHAMPTON | Report | Public | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP4 | D4.1 | Calibration of decoherence | QUB | Report | Public | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP6 | D6.2 | Popular press articles | UNITS | Websites, patents filling, etc. | Public | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP6 | D6.5 | Dissemination and Exploitation Plan | UNITS | Report | Confidential, | 31 Dec 2018 | 19 Dec 2018 | | Submitted |
| WP5 | D5.3 | Project Review meeting documents M12 | UNITS | Report | Confidential, | 28 Feb 2019 | 08 Feb 2019 | | Submitted |
| WP4 | D4.2 | Bounds to CSL & SN models | QUB | Report | Public | 30 Jun 2019 | | | Pending |
| WP6 | D6.3 | Videos | UNITS | Websites, patents filling, etc. | Public | 31 Aug 2019 | | | Pending |
| WP1 | D1.1 | Rf trap for NCs | AU | Report | Public | 31 Dec 2019 | | | Pending |
| WP1 | D1.3 | 2-Colloidal NCs | TU Delft | Report | Public | 31 Dec 2019 | | | Pending |
| WP4 | D4.3 | Size of superposition | QUB | Report | Public | 31 Dec 2019 | | | Pending |
| WP6 | D6.4 | Workshop | UNITS | Websites, patents filling, etc. | Public | 31 Dec 2019 | | | Pending |
| WP2 | D2.2 | Optimal cooling strategies | SOUTHAMPTON | Report | Public | 31 Mar 2020 | | | Pending |
| WP3 | D3.2 | Systematic effects investigated | SOUTHAMPTON | Report | Public | 30 Apr 2020 | | | Pending |
| WP5 | D5.4 | Project Review meeting documents M30 | UNITS | Report | Confidential, | 31 Aug 2020 | | | Pending |
| WP1 | D1.4 | Loading and control device | UCL | Report | Public | 31 Dec 2020 | | | Pending |
| WP1 | D1.5 | Quantification of heating | QUB | Report | Public | 31 Dec 2020 | | | Pending |
| WP4 | D4.4 | Bounds to the ecCSL model | UNITS | Report | Public | 31 Dec 2020 | | | Pending |
| WP2 | D2.3 | Internal state cooling | UCL | Report | Public | 28 Feb 2021 | | | Pending |
| WP3 | D3.3 | Ultimate experiment | SOUTHAMPTON | Report | Public | 30 Apr 2021 | | | Pending |
| WP2 | D2.4 | Quantify decoherence | QUB | Report | Public | 31 Aug 2021 | | | Pending |
| WP4 | D4.5 | Time-dilation/gravity collapse | OEAW | Report | Public | 31 Aug 2021 | | | Pending |
| WP3 | D3.4 | General bound | QUB | Report | Public | 31 Dec 2021 | | | Pending |
| WP5 | D5.5 | Project Review meeting documents M48 | UNITS | Report | Confidential, | 31 Dec 2021 | | | Pending |

# 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*]. |

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# 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. |

# 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 |

# Thank you

Testing the large-scale
limit of
quantum mechanics

# WP1: TRAPPING

L. Manna – TUD
M. Drewsen - AU

# 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].

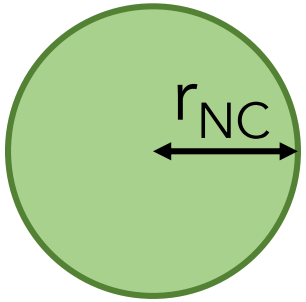
Testing the large-scale limit of quantum mechanics

# Status of TEQ-trap and low-noise electronics

M. Drewsen - AU

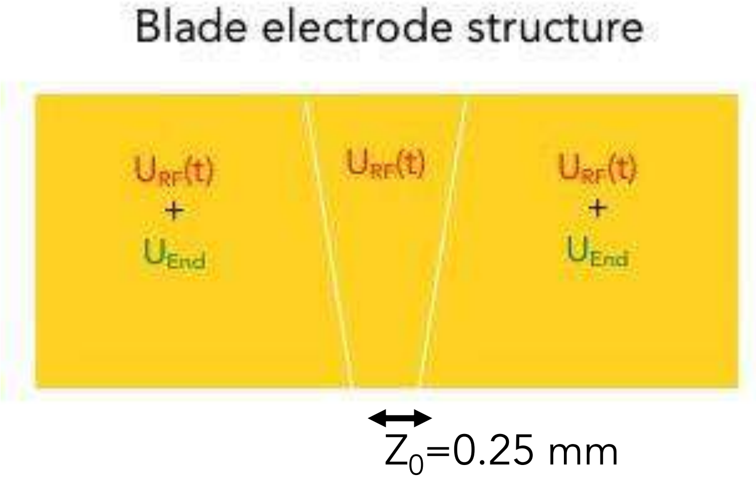
# The TEQ-trap design parameters

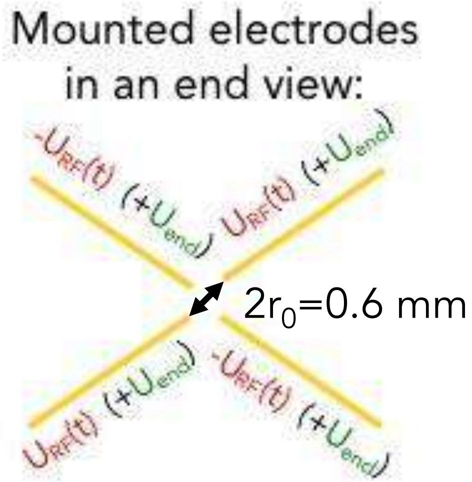
## The nano-crystal




$r_{NC}$=50 nm
$\rho_{NC}$=5 g/cm$^3$
$m_{NC}$=2.6x10$^{-18}$kg
$Q_{NC}$=10 e

## The TEQ-trap




$U_{RF}(t)=U_{RF}\sin(\Omega_{RF}t)$

## Requirements to trapping frequencies

$\omega_z=2\pi$ x (100-1000) Hz

$$\omega_z = \sqrt{\frac{2\kappa U_{End}}{z_0^2} \times \frac{Q_{NC}}{m_{NC}}}$$

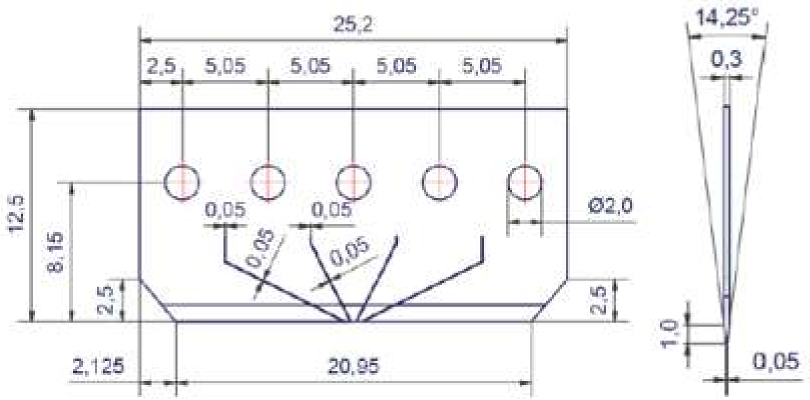
=> $U_{End}$= 0.3-30 V for $\kappa$=0.25

$\omega_r > \omega_z$

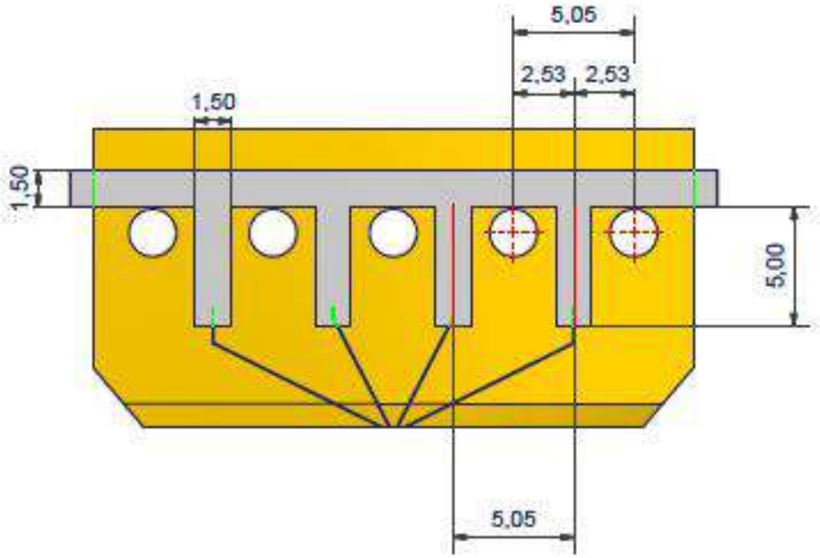
$\omega_r = 2\omega_z$ , $\Omega_{RF}$= 15$\omega_z$ => $U_{RF}$= 15-1500 V

# The TEQ-trap

## The blade design

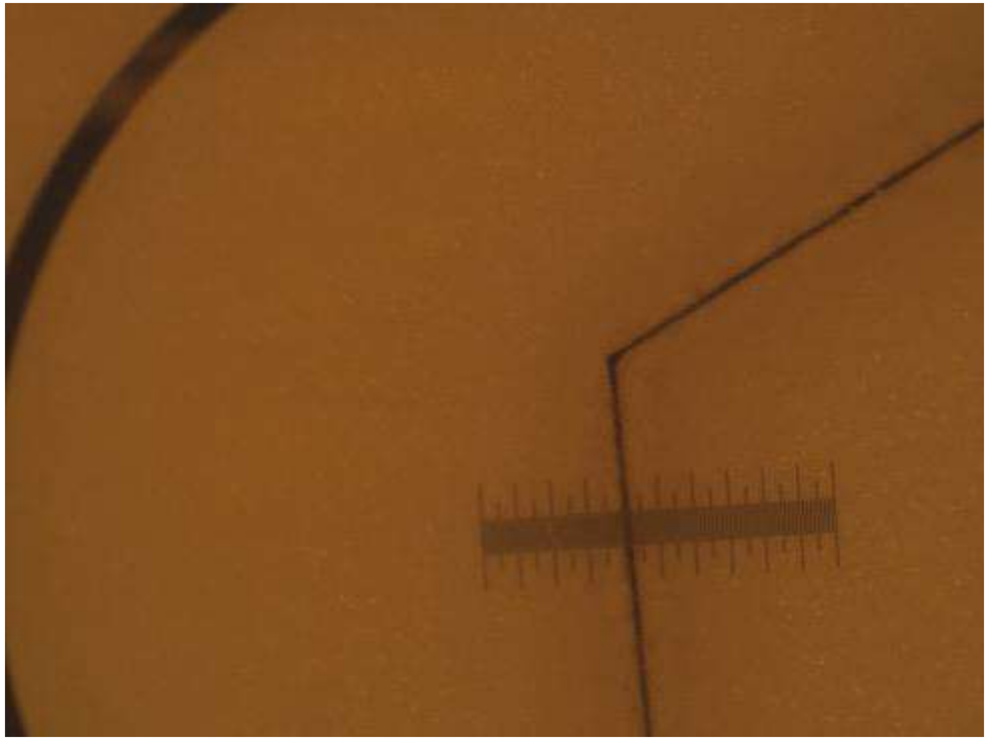


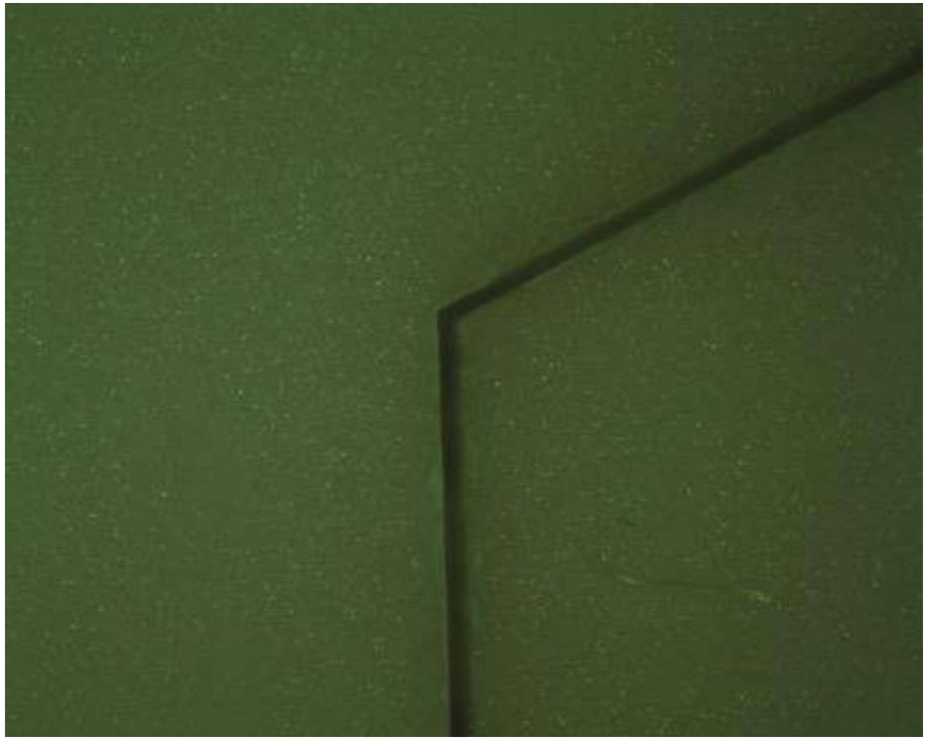

Laser Micromachining Limited
OpTIC Technium
St. Asaph Business Park
Denbighshire
LL17 0JD, UK
Tel: +44 (0)1745 535165
Fax: +44 (0)1745 535101



# The TEQ-trap

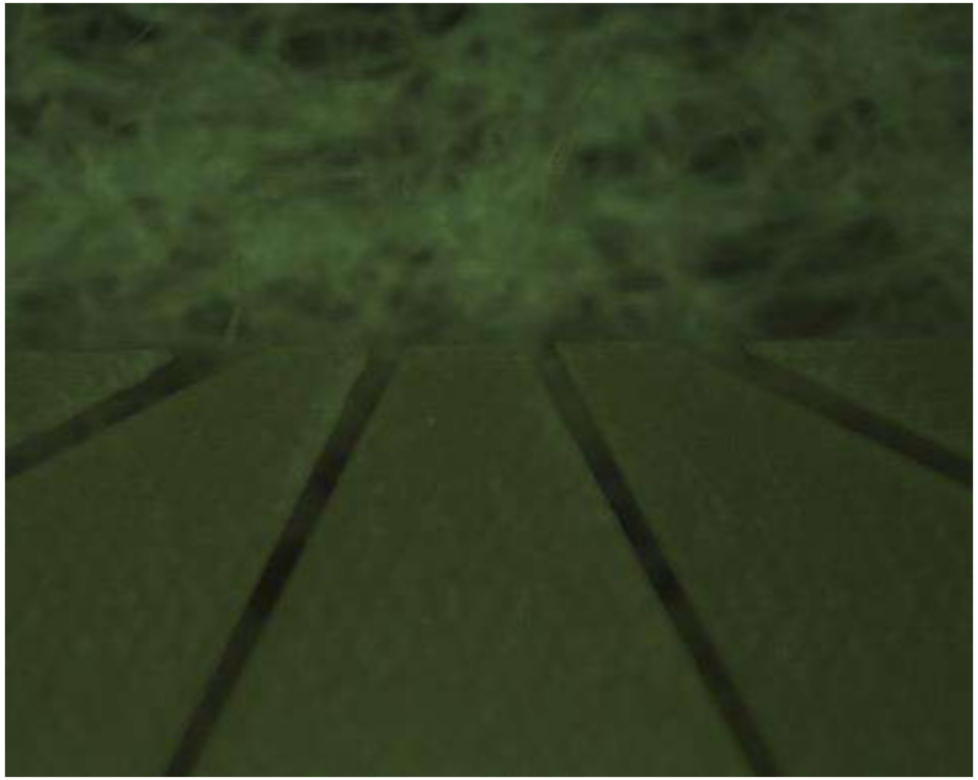
## Details of the blades





# The TEQ-trap

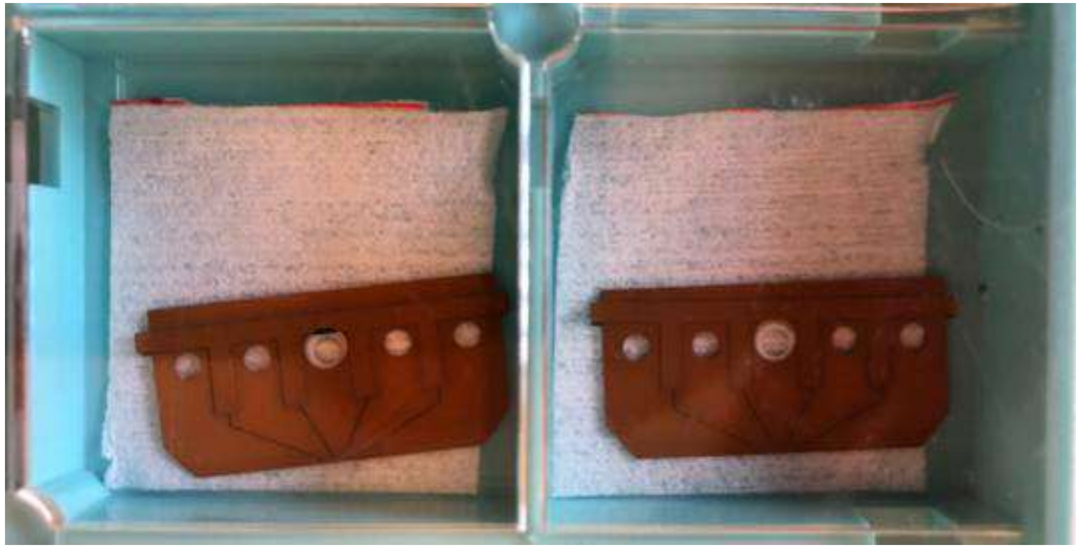
## Details of the blades



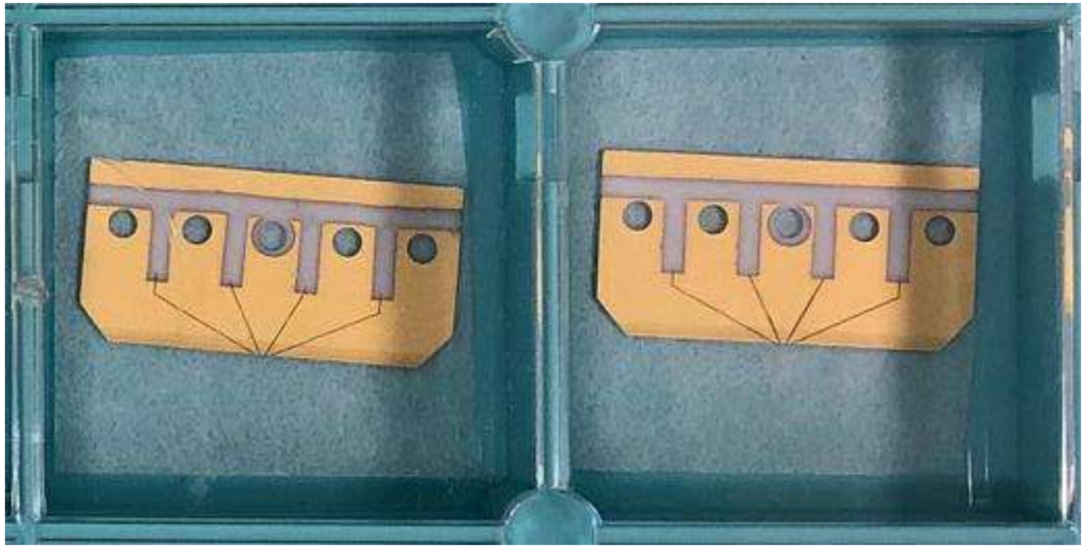
# The TEQ-trap

## The blade design

Blades after gold coating

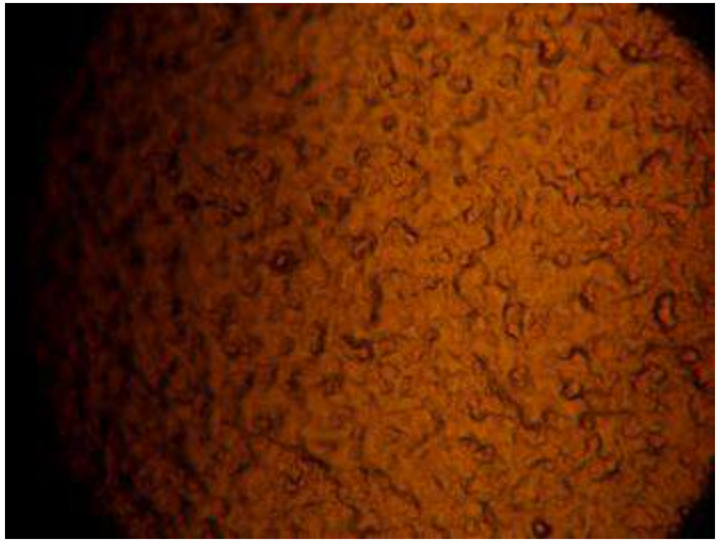


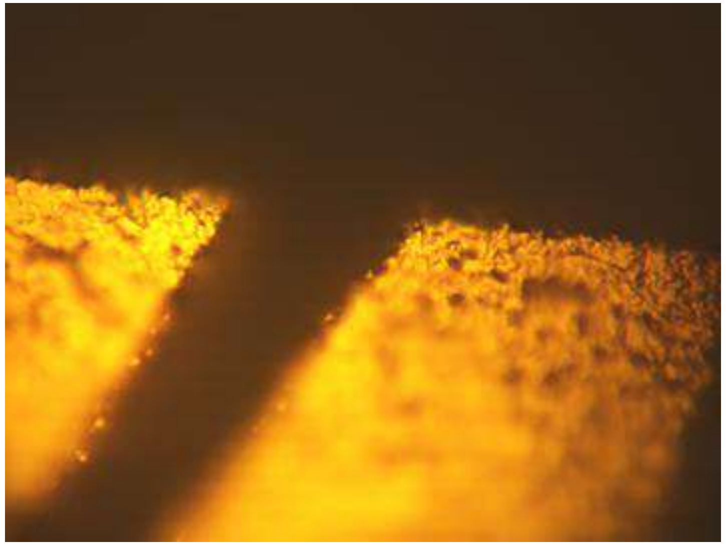
Blades after anealing

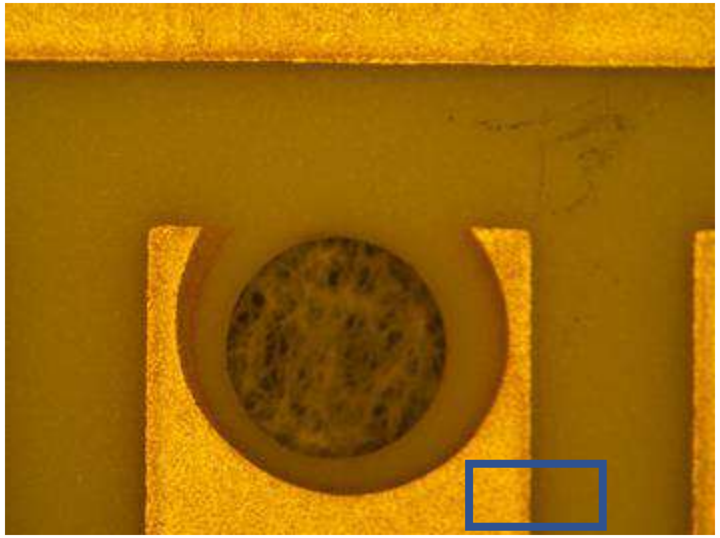


# The TEQ-trap

## The blade after anealing

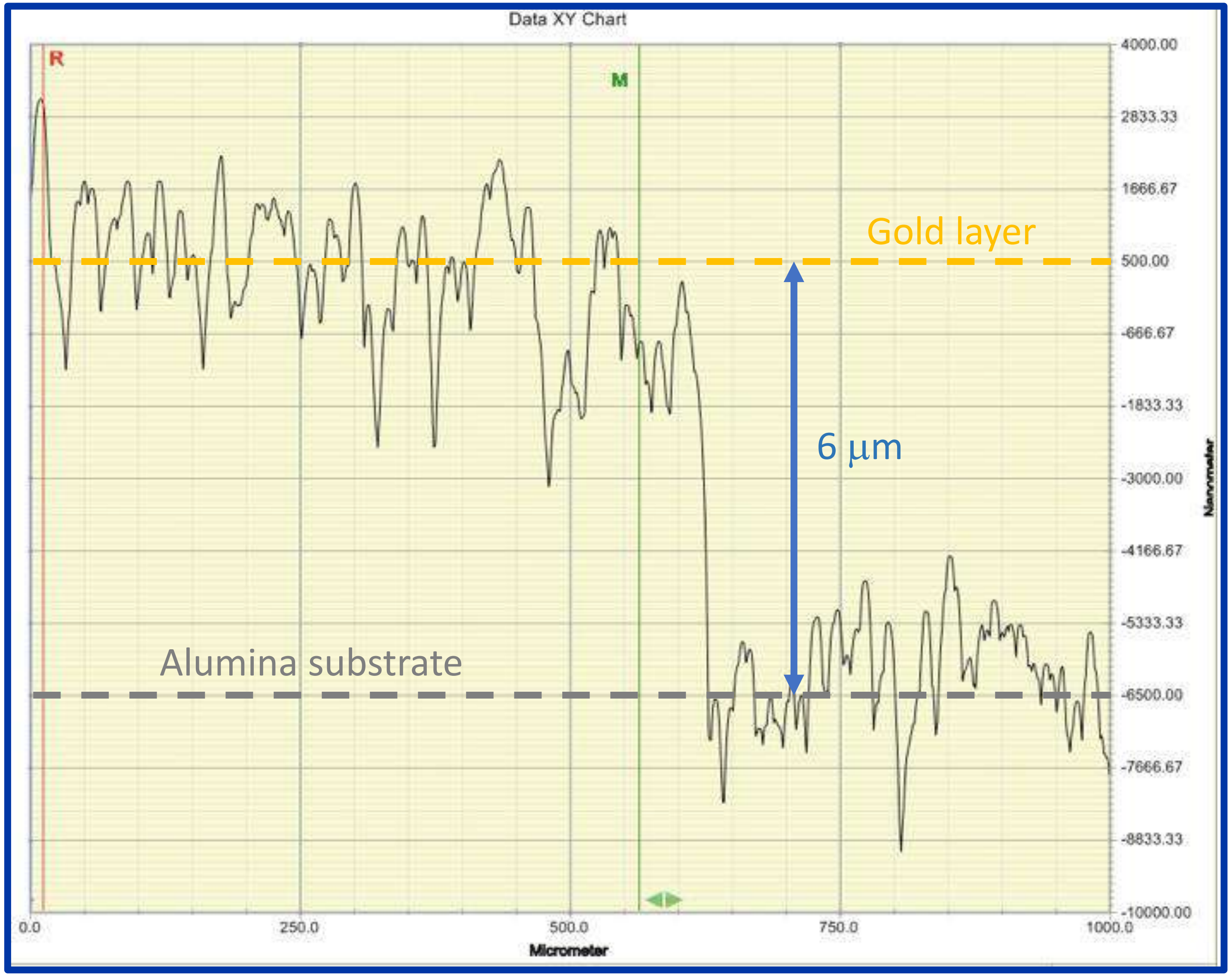






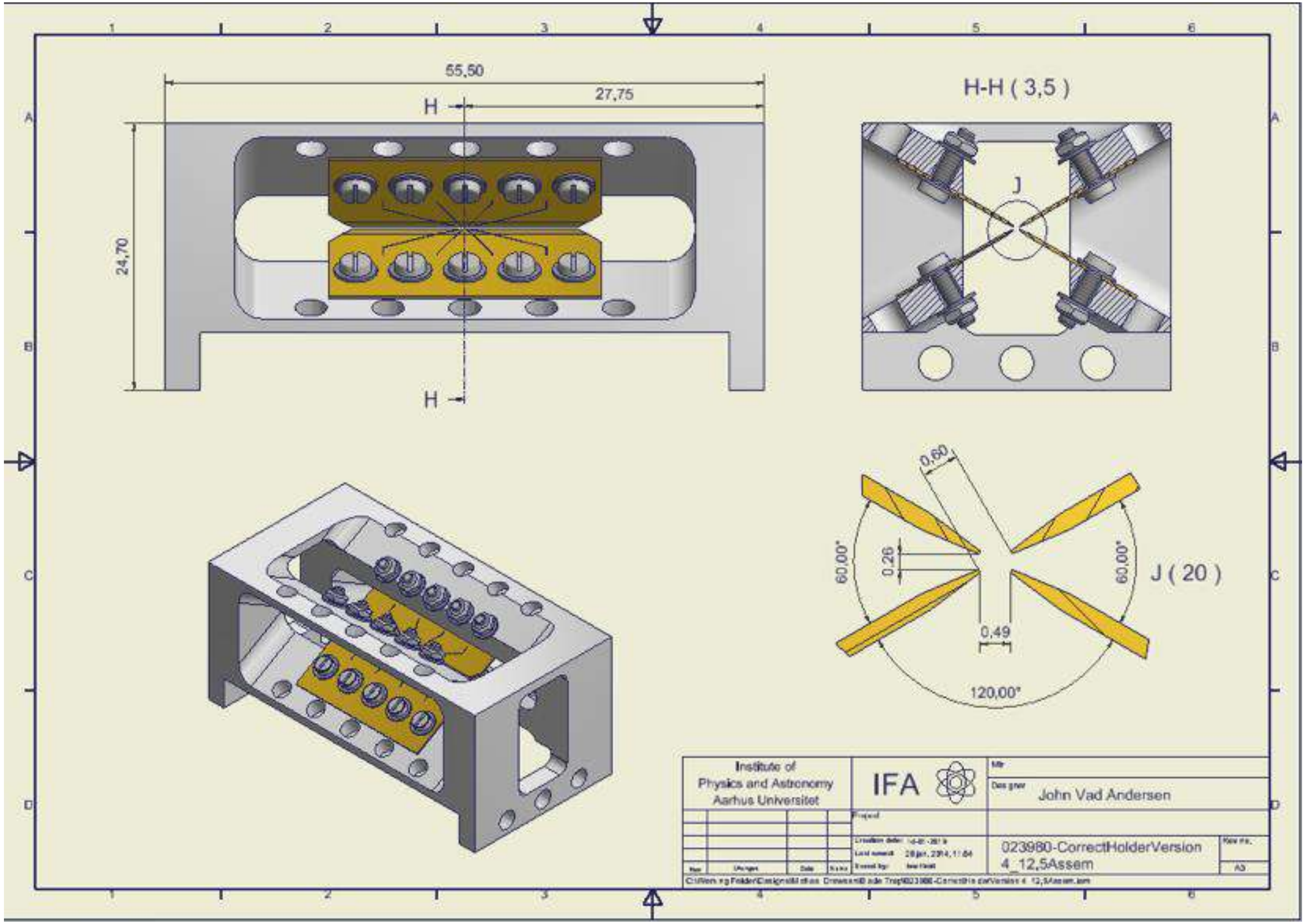
# The TEQ-trap

## The blade after anealing



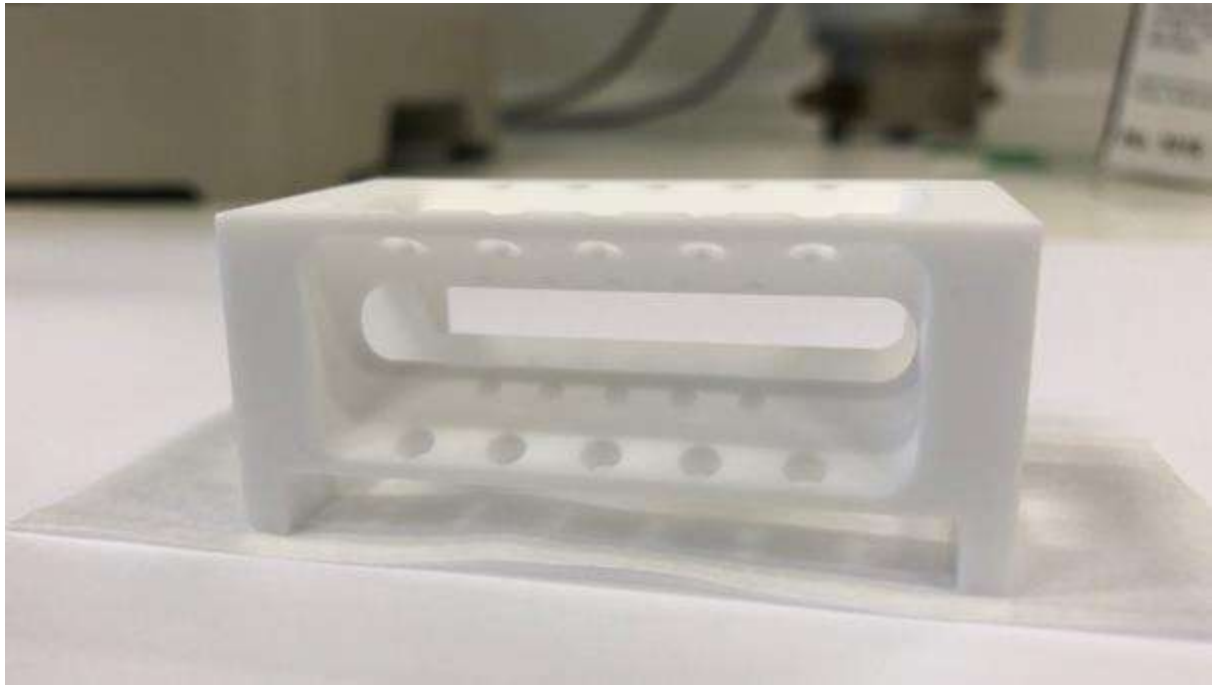

Thick gold layer needed for low ressistance and good heat con-duction

# The TEQ-trap


55,50
27,75
H
24,70
H
H-H ( 3,5 )
J
0,60
0,26
60,00°
60,00°
J ( 20 )
0,49
120,00°
Institute of
Physics and Astronomy
Aarhus Universitet
IFA
John Vad Andersen
023980-CorrectHolderVersion
4_12,5Assem

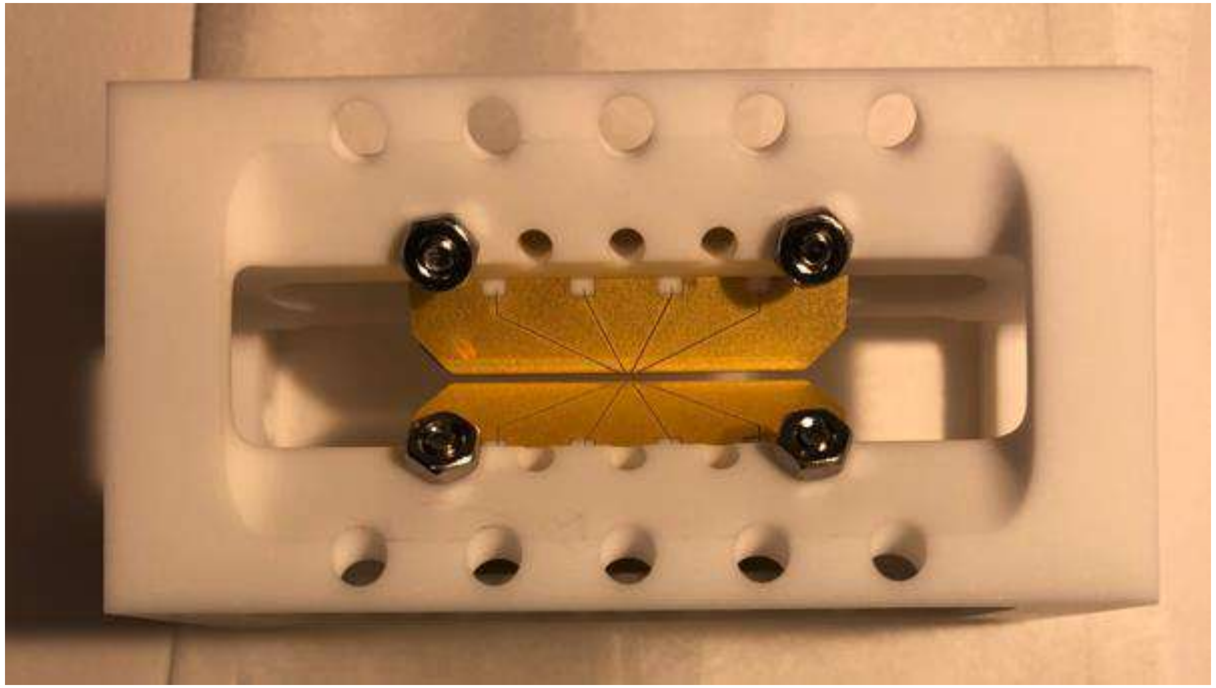
# The TEQ-trap

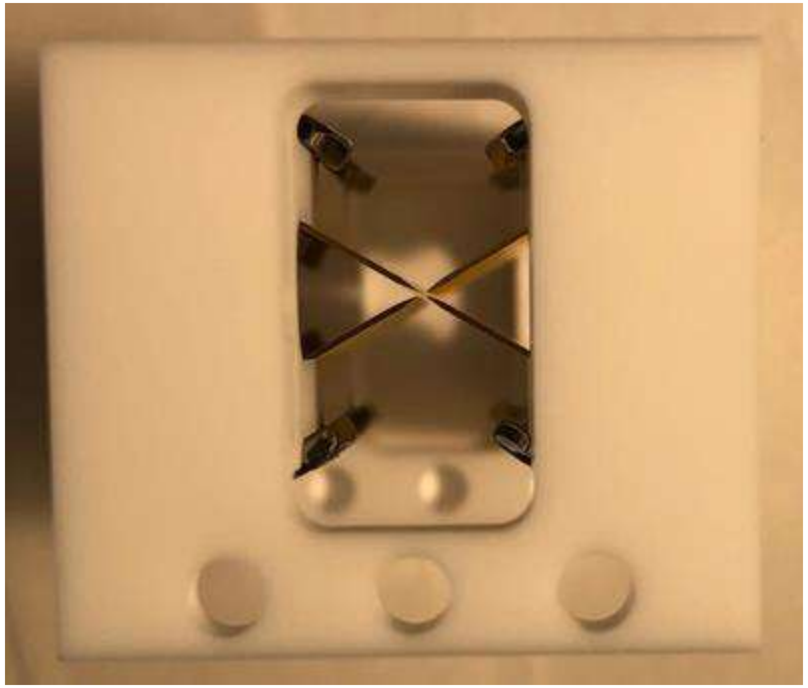
The blade support made in Macor®



# The TEQ-trap

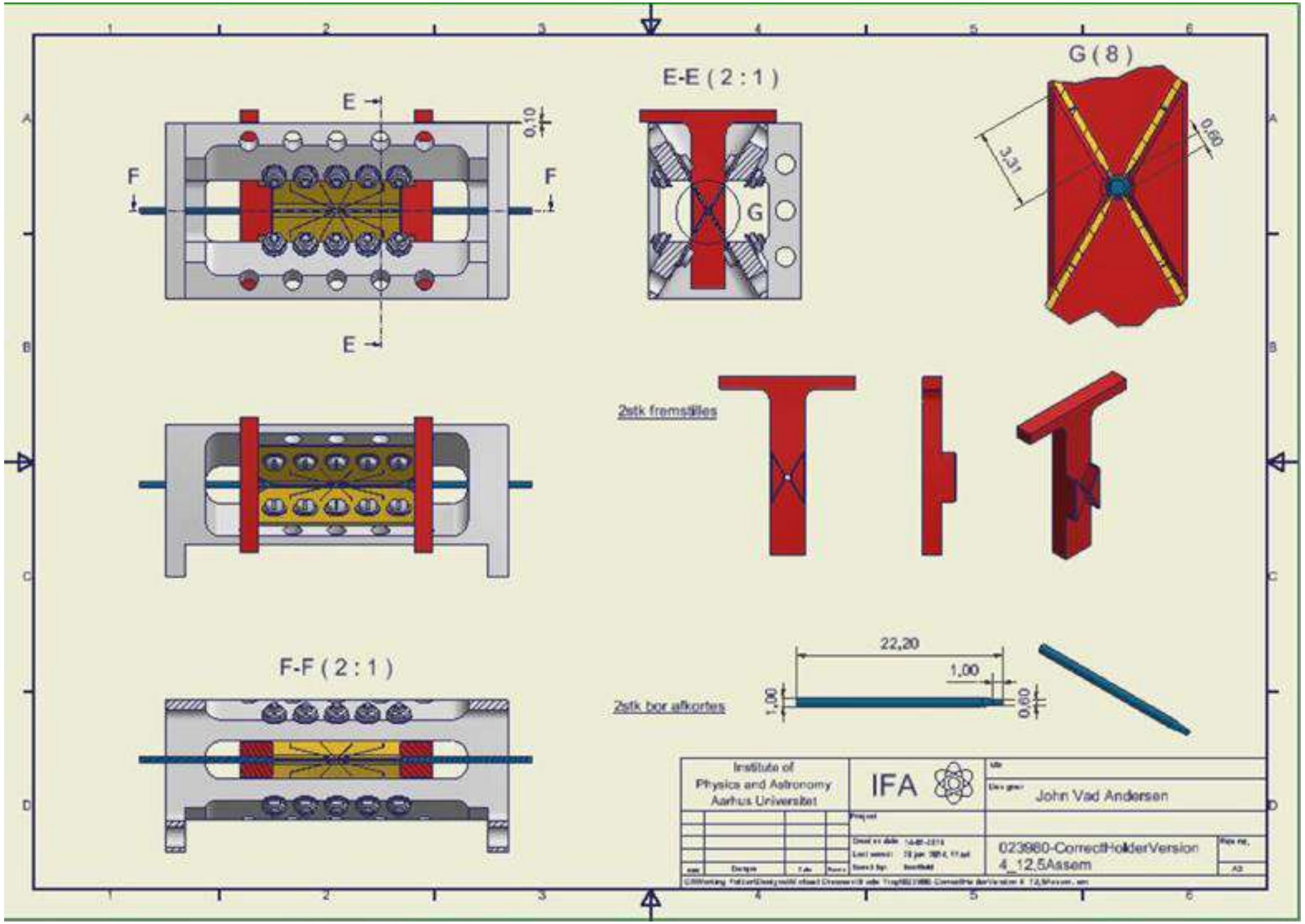
The blades mounted on support





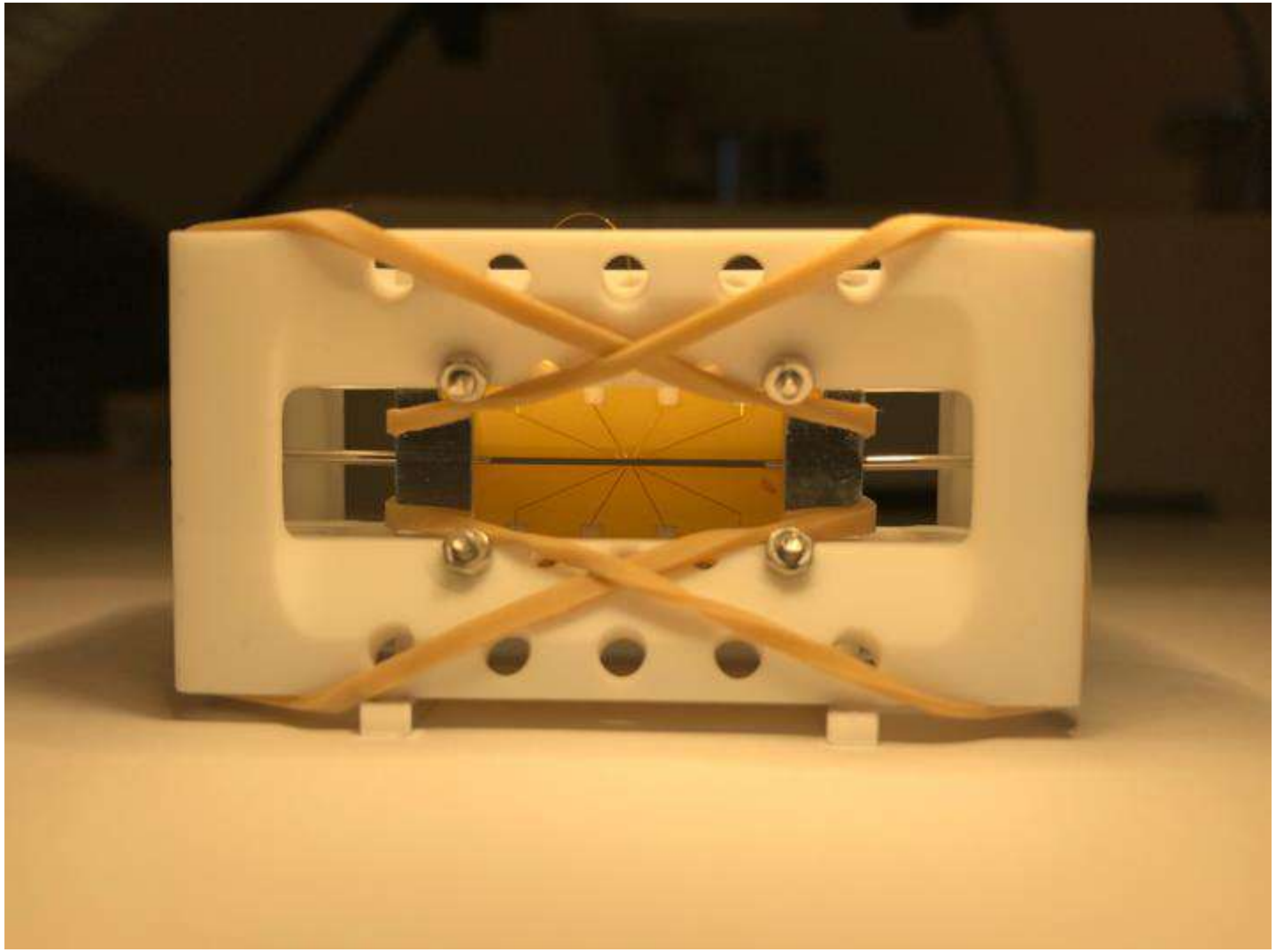
# The TEQ-trap

Blade alignment tools



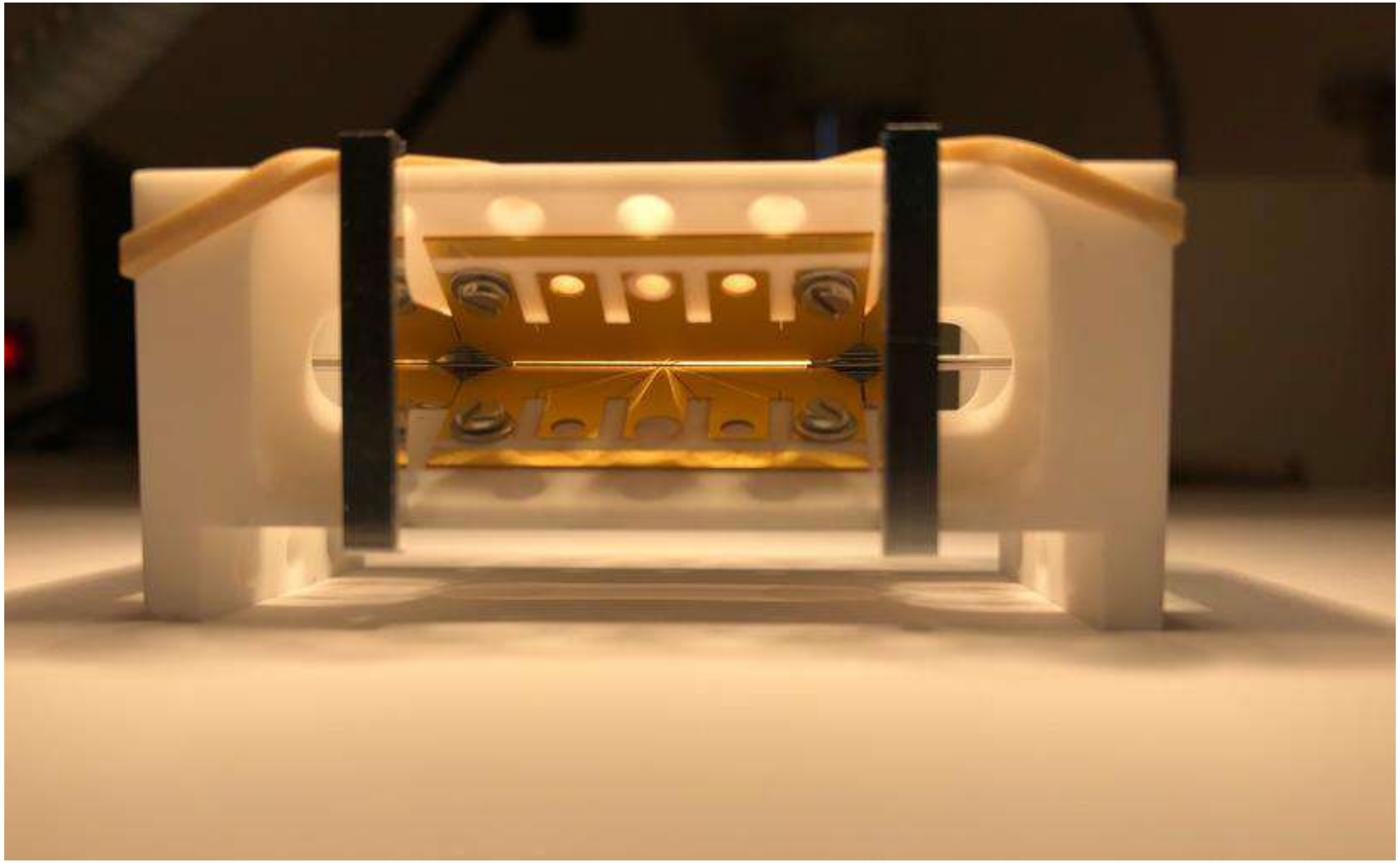
# The TEQ-trap

## Blade alignment tools



# The TEQ-trap

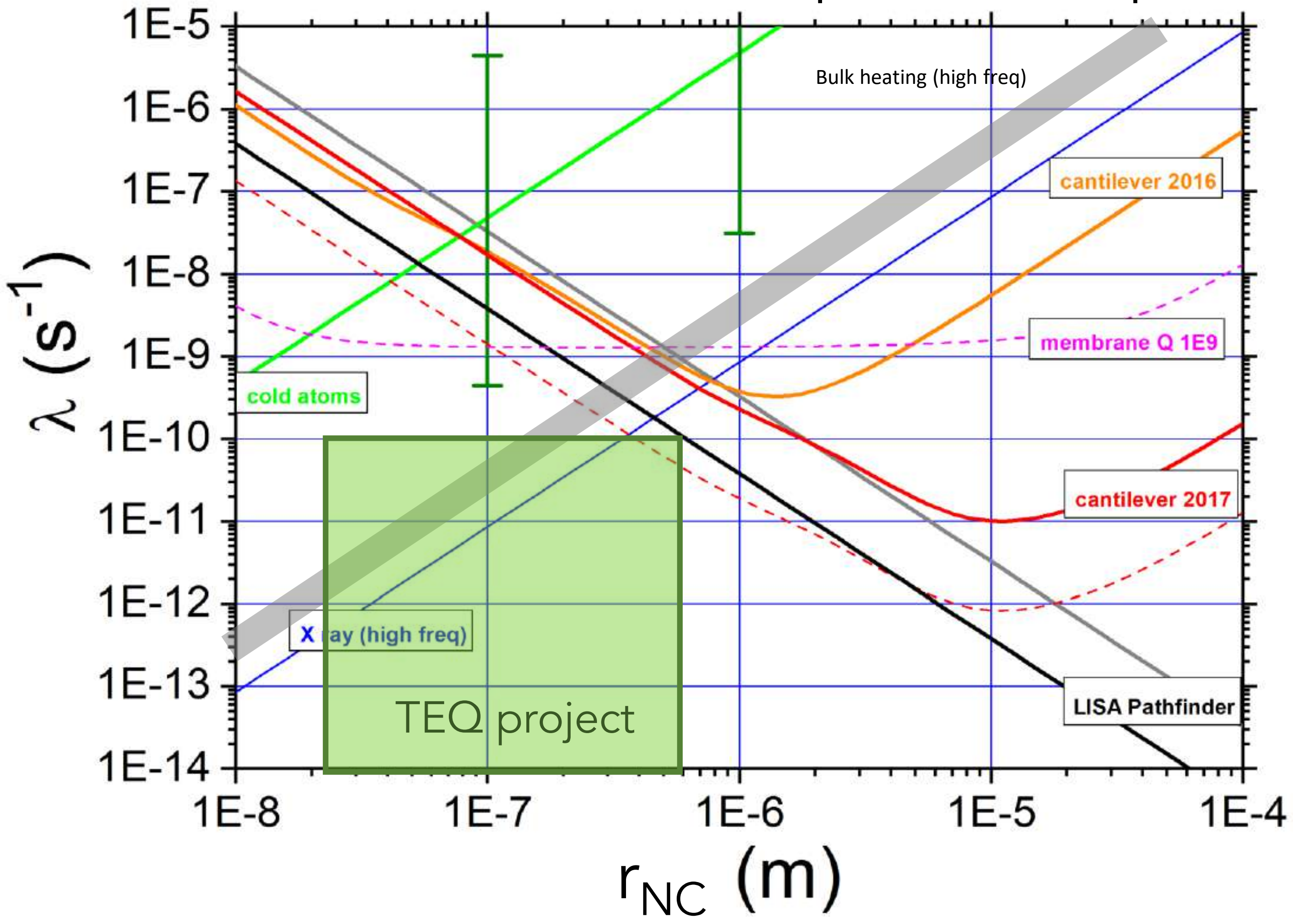
## Blade alignment tools

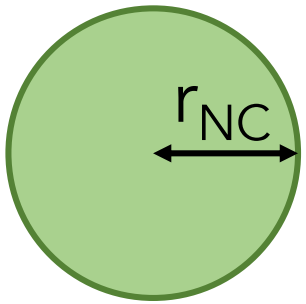


All trap parts send to the UCL partner for first test at room temperature

# What noise level can be accept in the TEQ experiments?

Current bounds on CSL parameter space



# What noise level can be accept in the TEQ experiments?

In terms of forces:

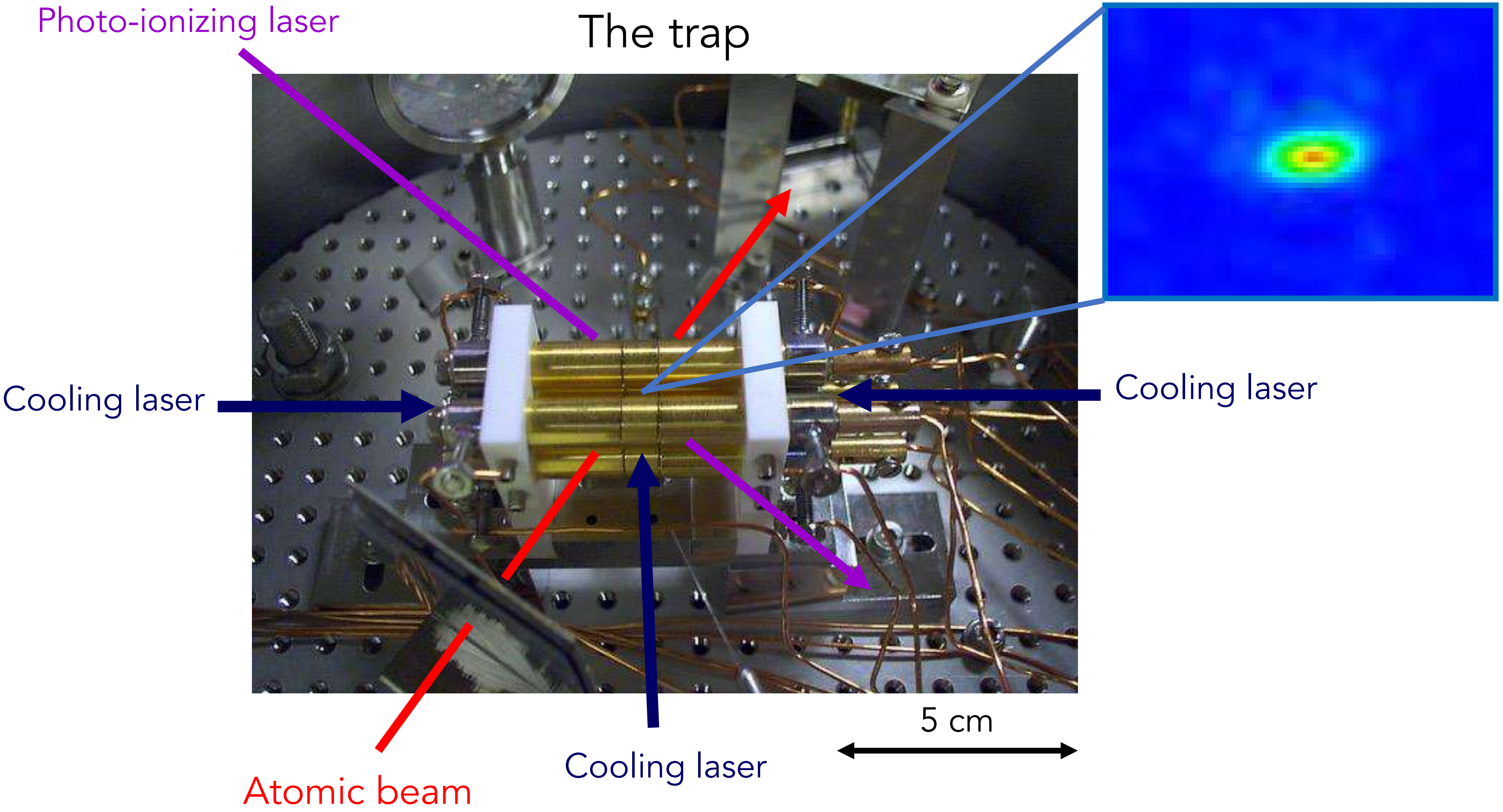
$$\sqrt{S_F(\omega)} \leq 3 \cdot 10^{-22} N / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100 - 1000) Hz$$

In terms of electrode voltages:

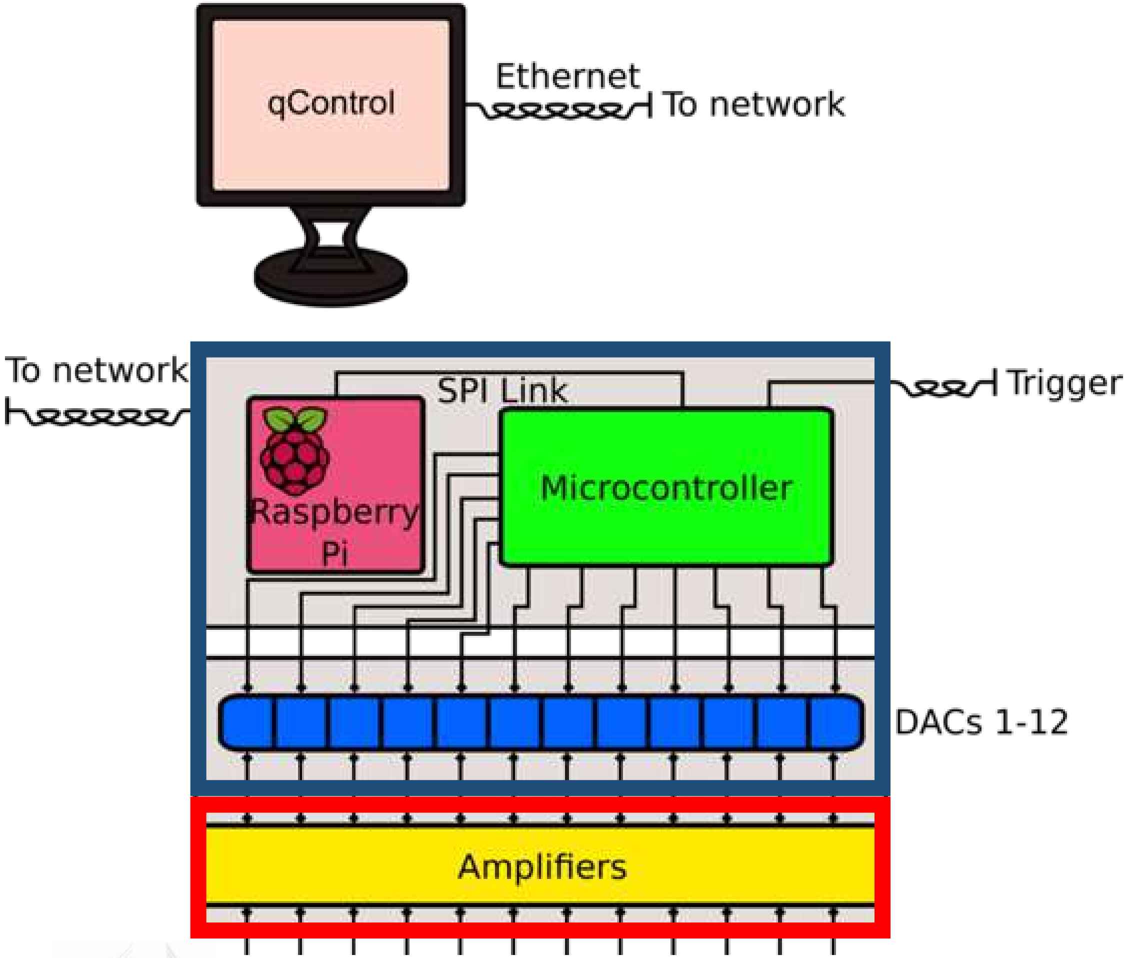
$$\sqrt{S_V^{DC}(\omega)} \leq 25 nV / \sqrt{Hz} \quad , \quad \omega_z \approx 2\pi \times (100 - 1000) Hz$$

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

# The Aarhus linear Paul trap setup



# The DC voltage supplies





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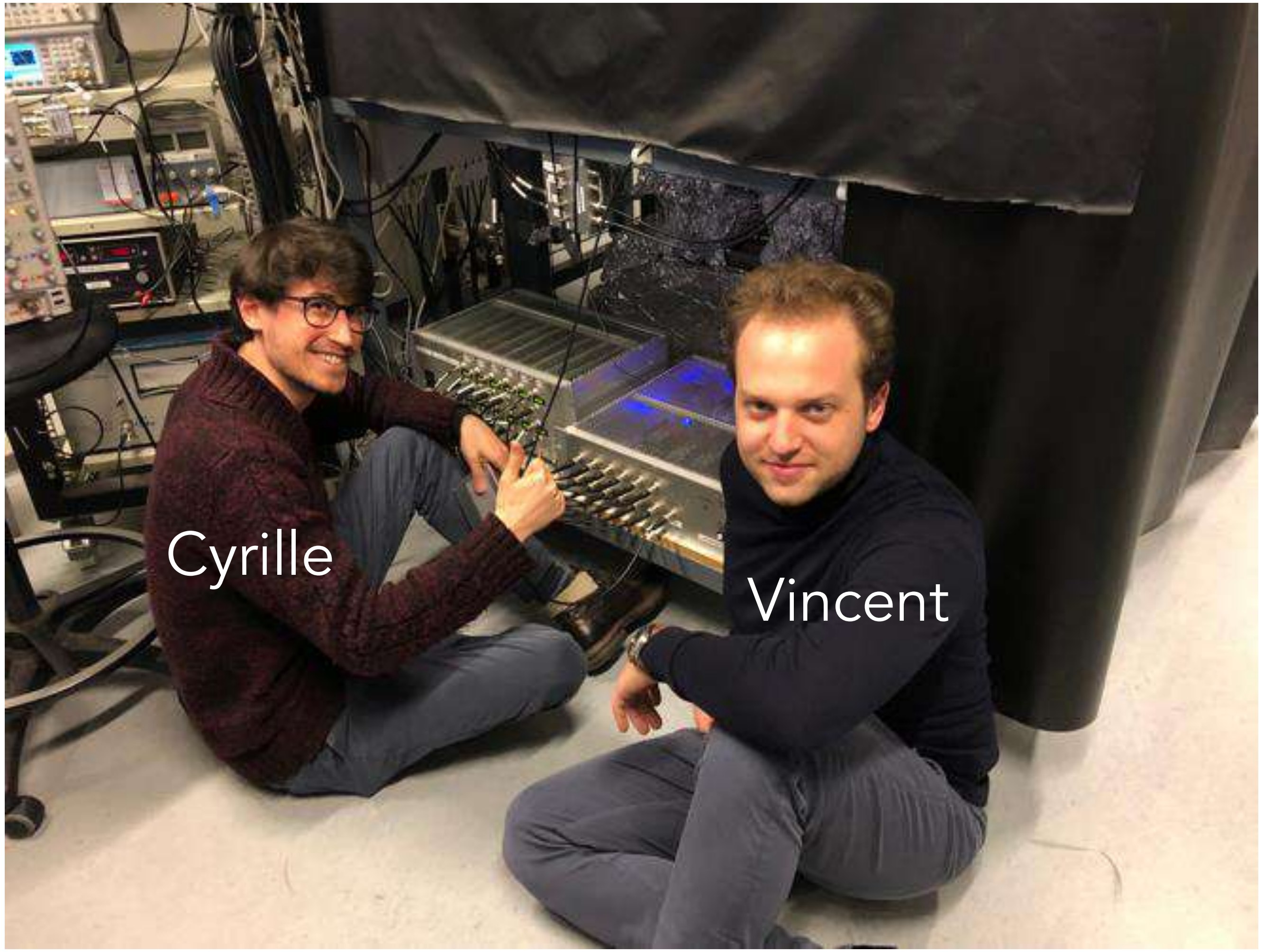
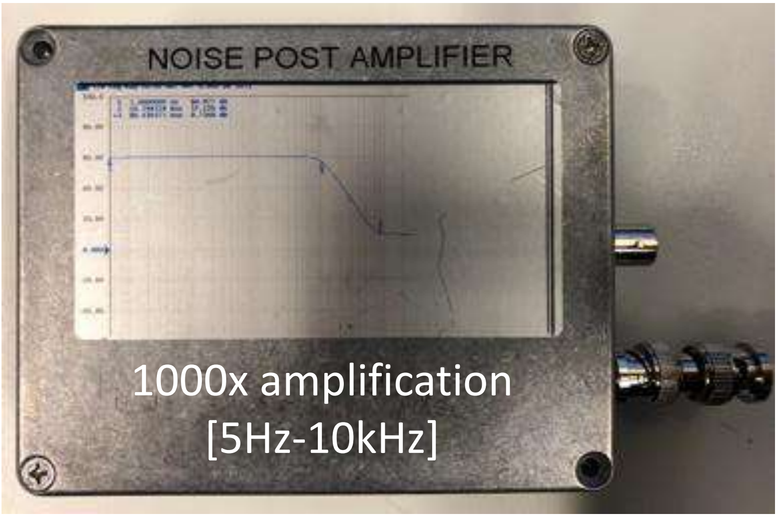
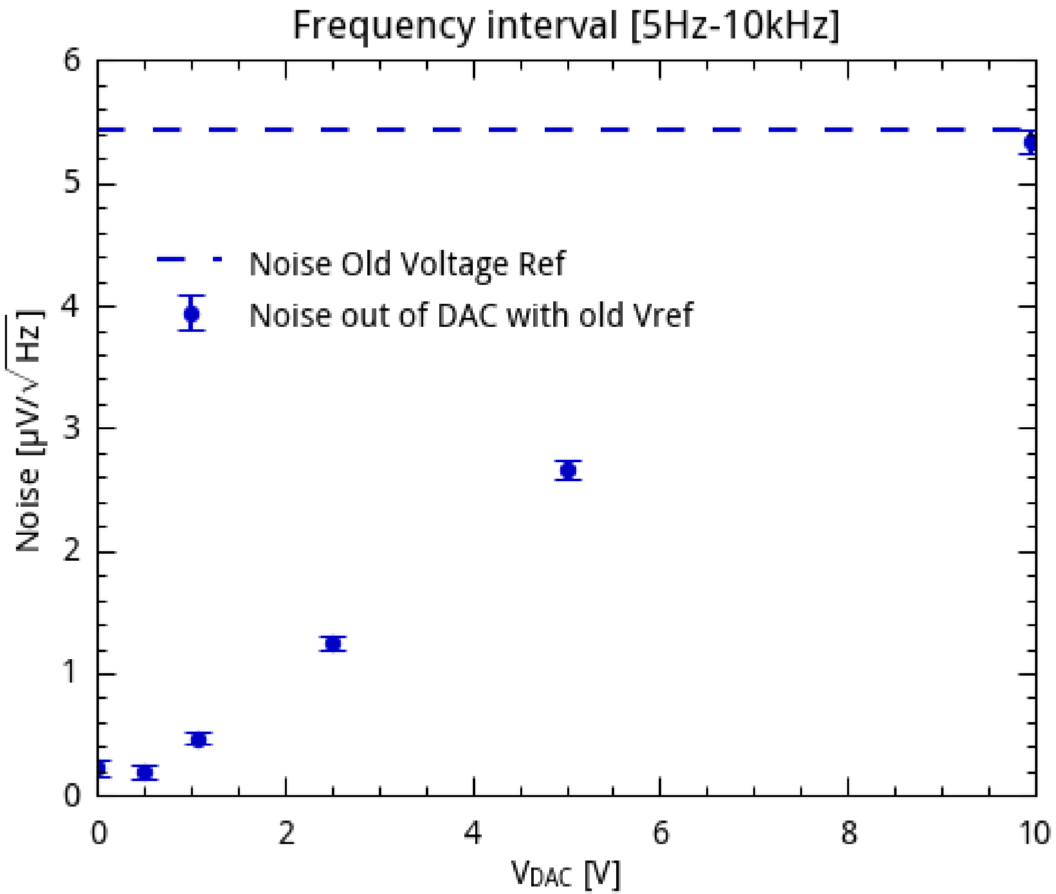


# The DC voltage supplies

## The noise of the DACs voltages

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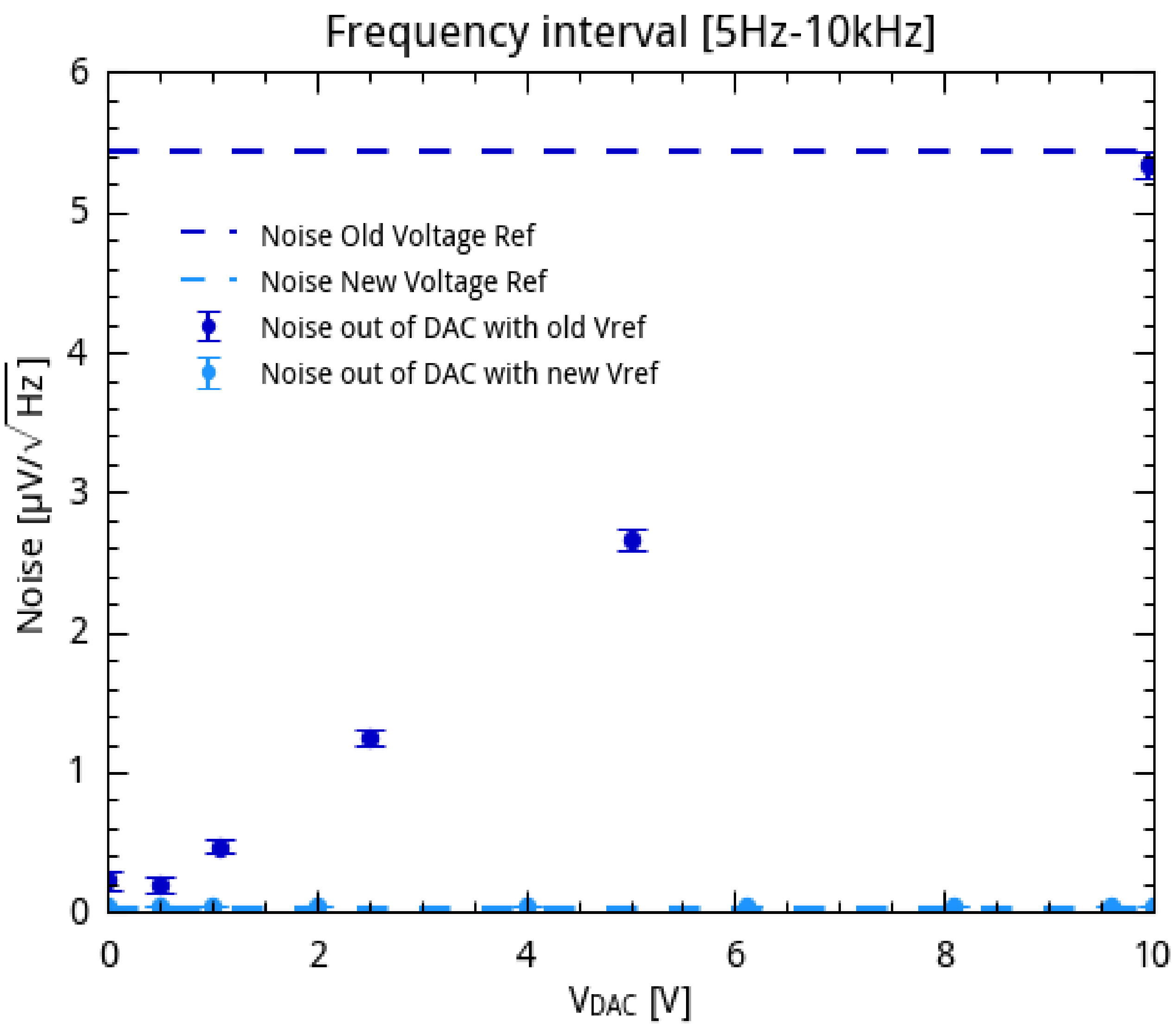

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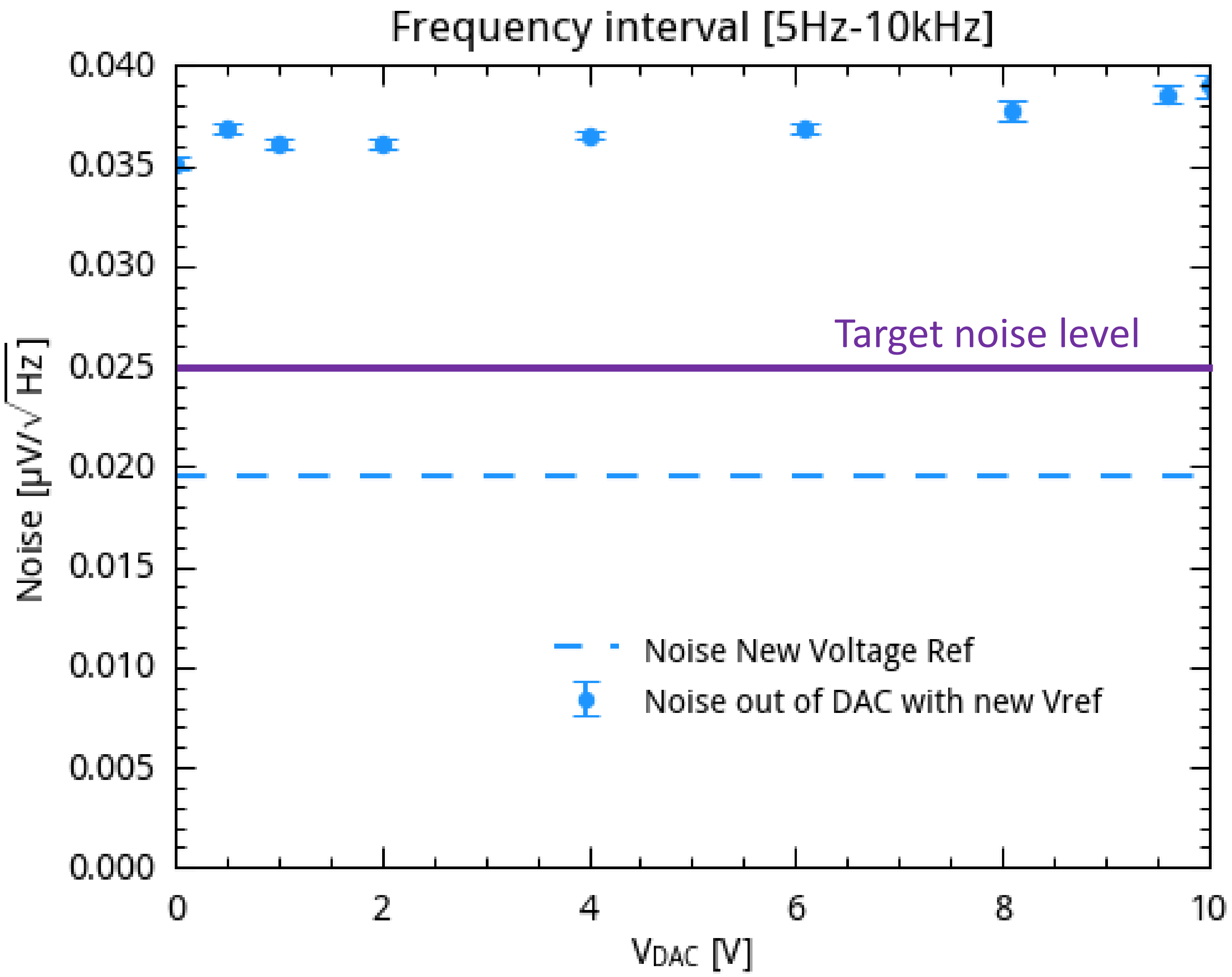
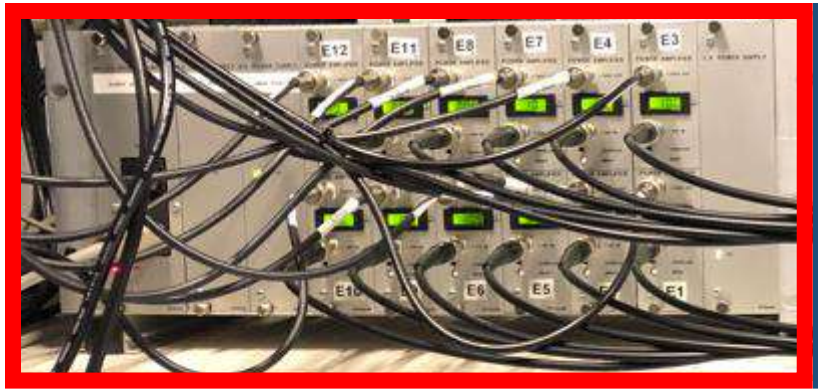
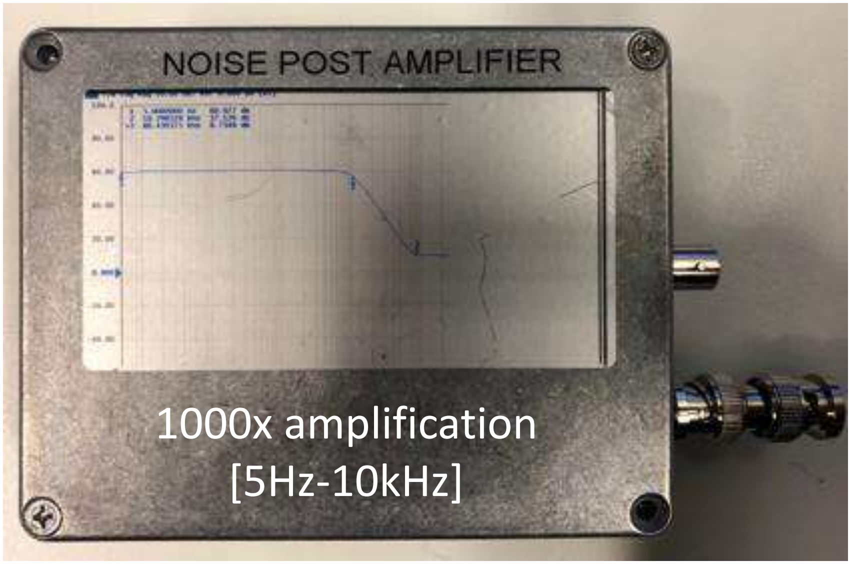


# The DC voltage supplies

## The noise of the DAC + 10x amplifier voltages



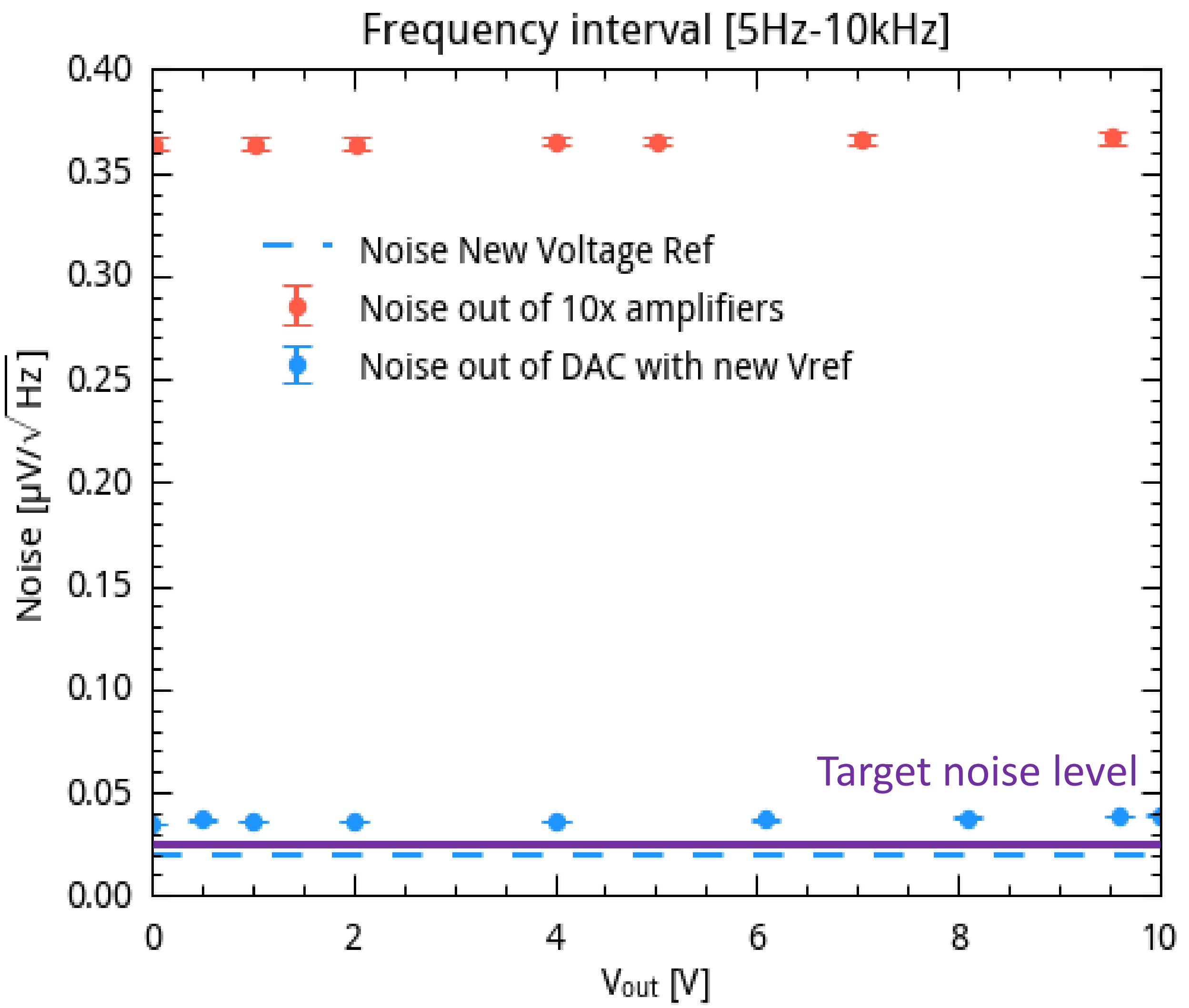





1000x amplification
[5Hz-10kHz]

# The DC voltage supplies

The noise of the DAC + 10x amplifier voltages




Amplifier noise

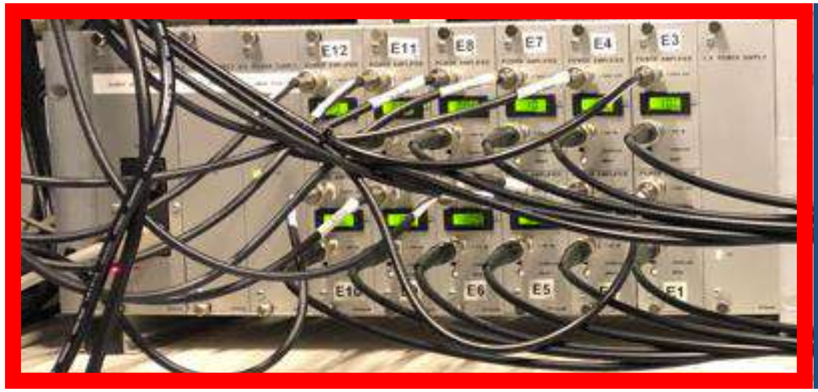
=

9.9x DAC output !

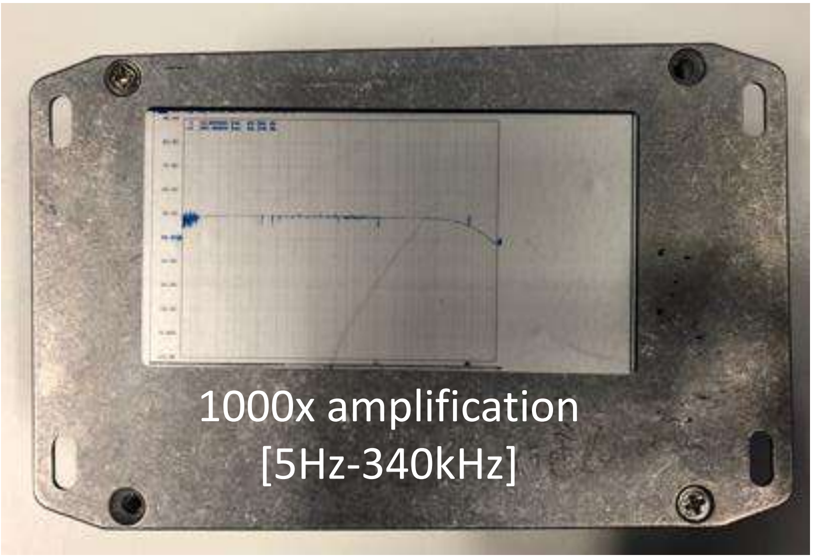
Very noiseless amplifier !!

# The DC voltage supplies

## The noise of the DAC + 10x amplifier voltages







# The DC voltage supplies

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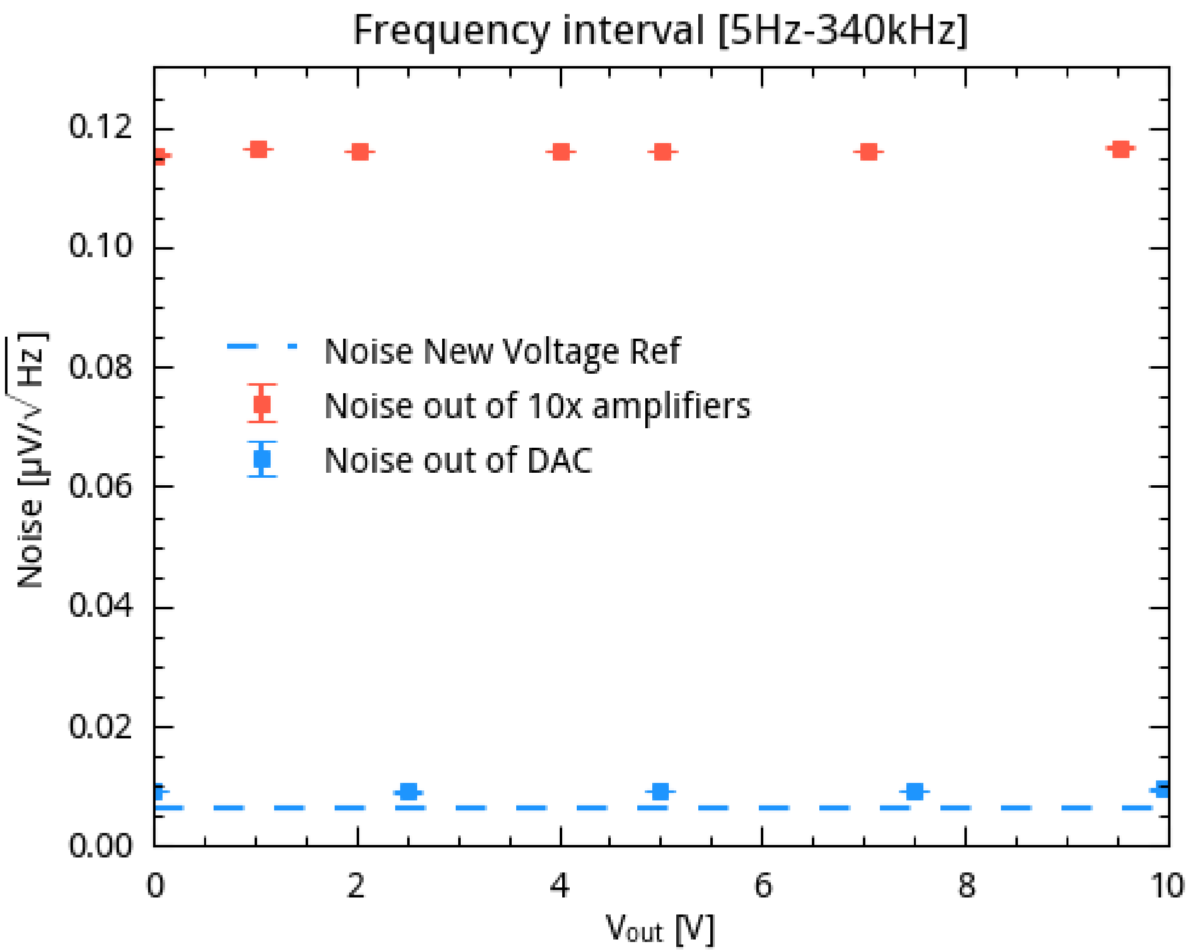



Amplifier noise

=

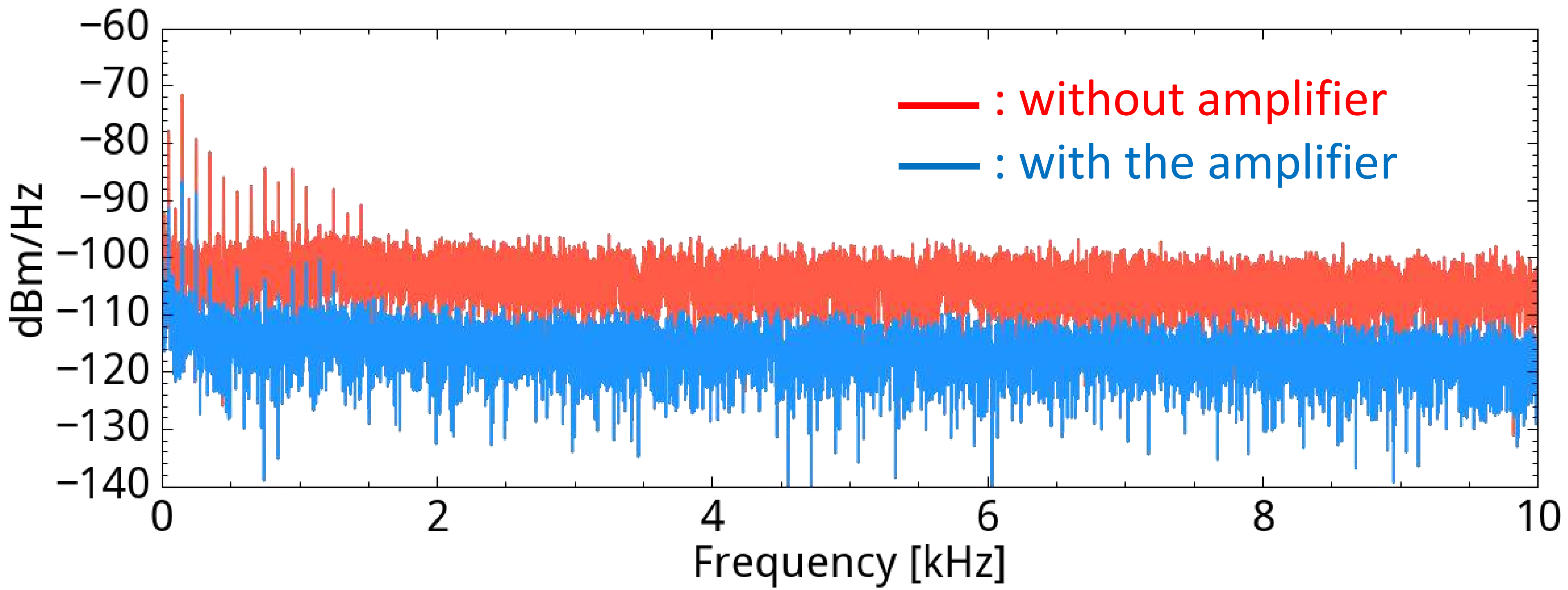
12.5x DAC output !

Still very noiseless amplifier !!

# The DC voltage supplies

## The noise of the DAC + 10x amplifier voltages

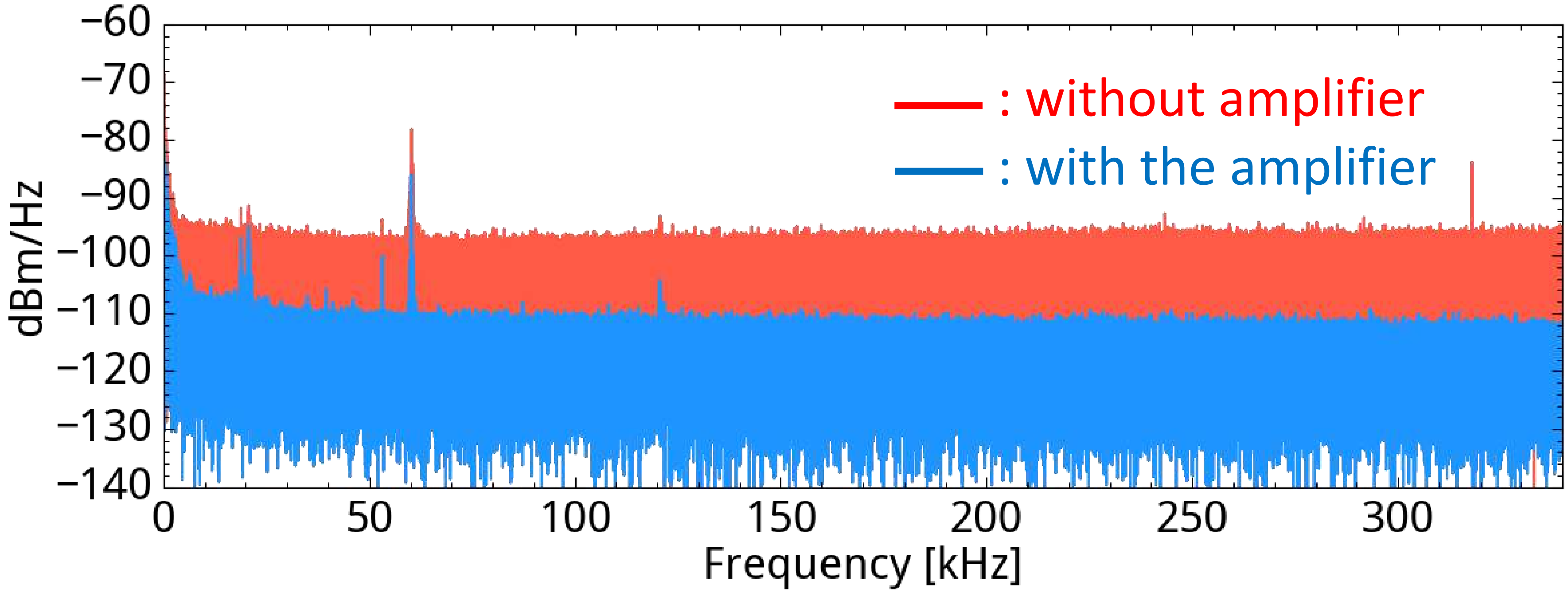
Spectrum analyser noise power spectrum in the 5Hz to 10kHz range



# The DC voltage supplies

The noise of the DAC + 10x amplifier voltages

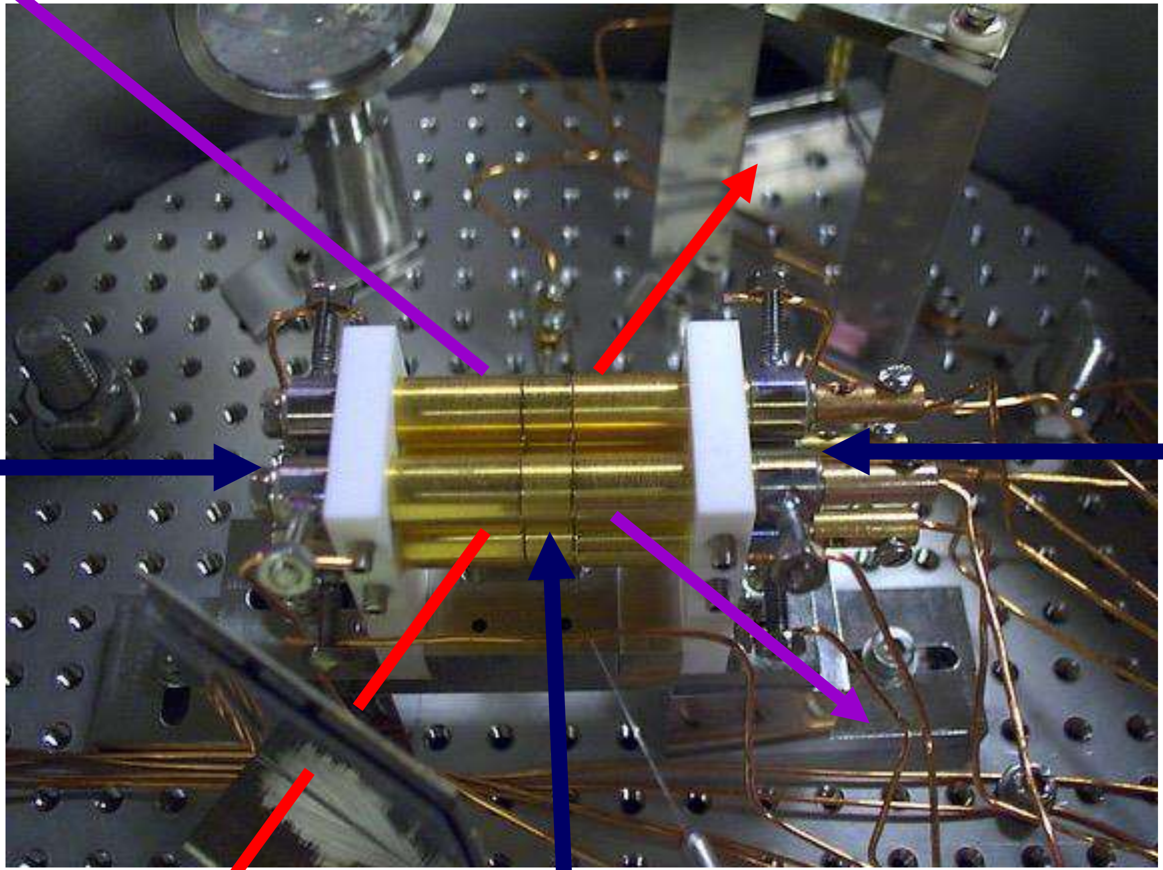
Spectrum analyser noise power spectrum in 5Hz to 340kHz range




In the [5Hz to 340kHz] range

# Noise measurements with the Aarhus linear Paul trap setup

The trap



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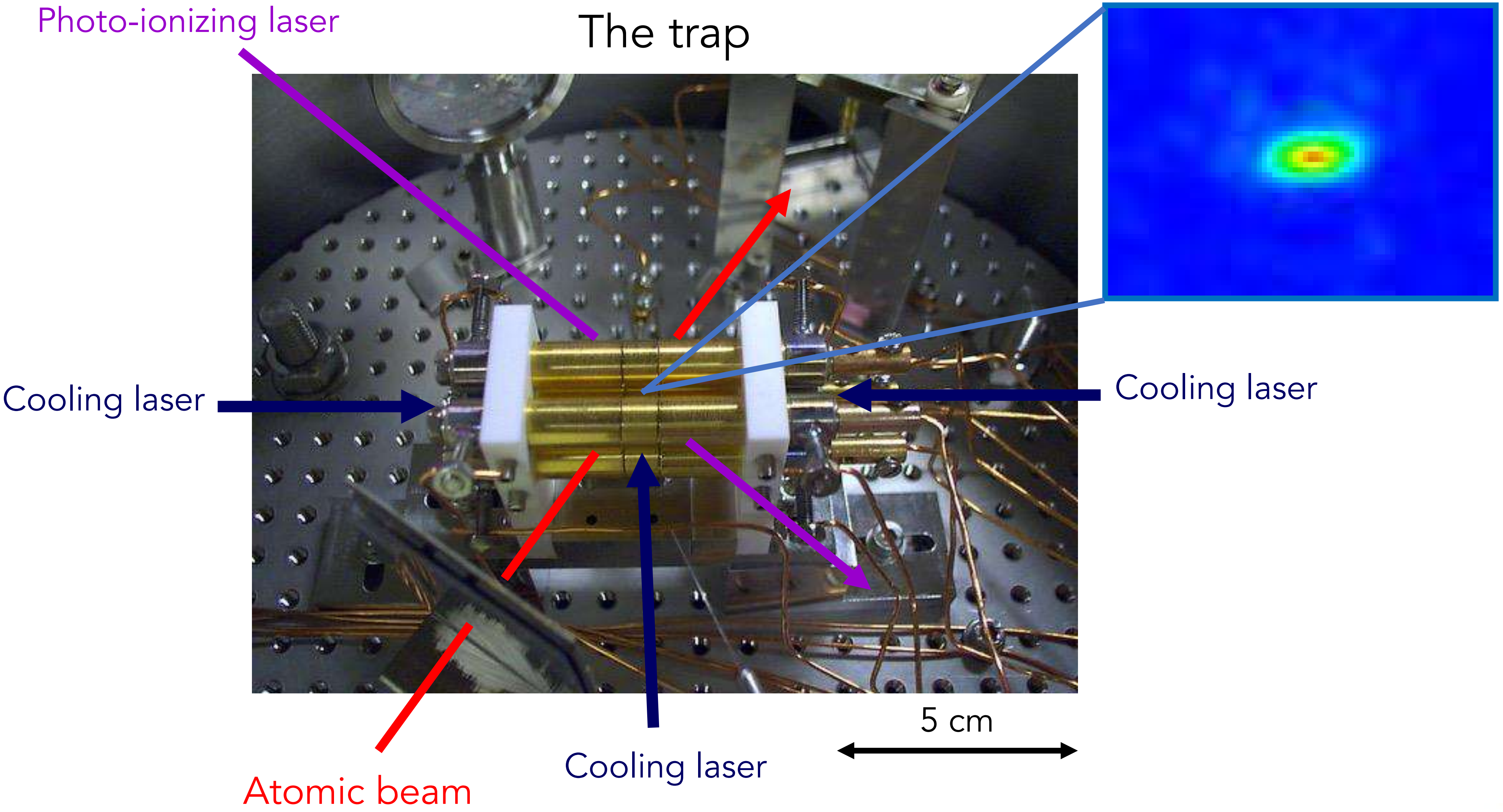
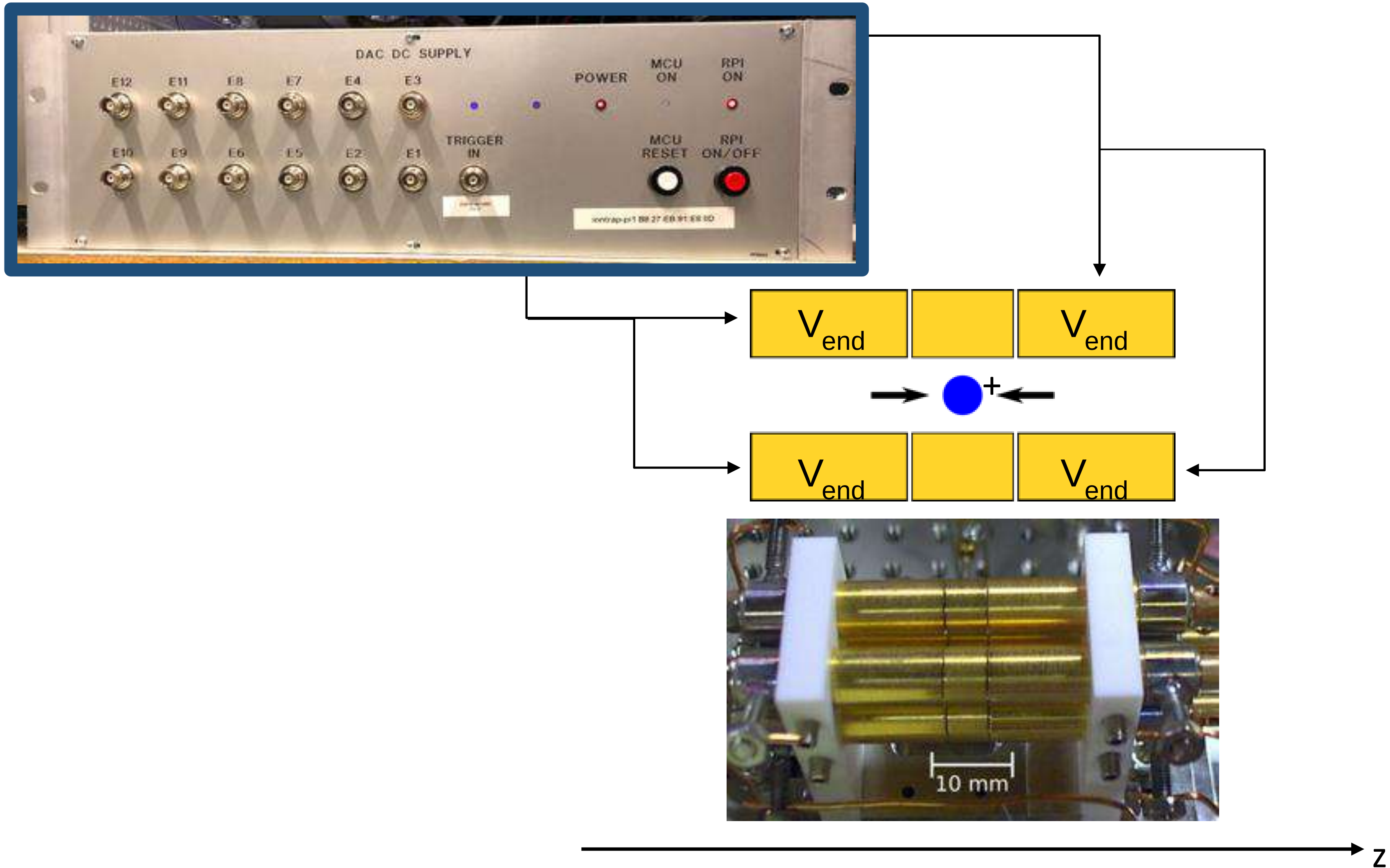


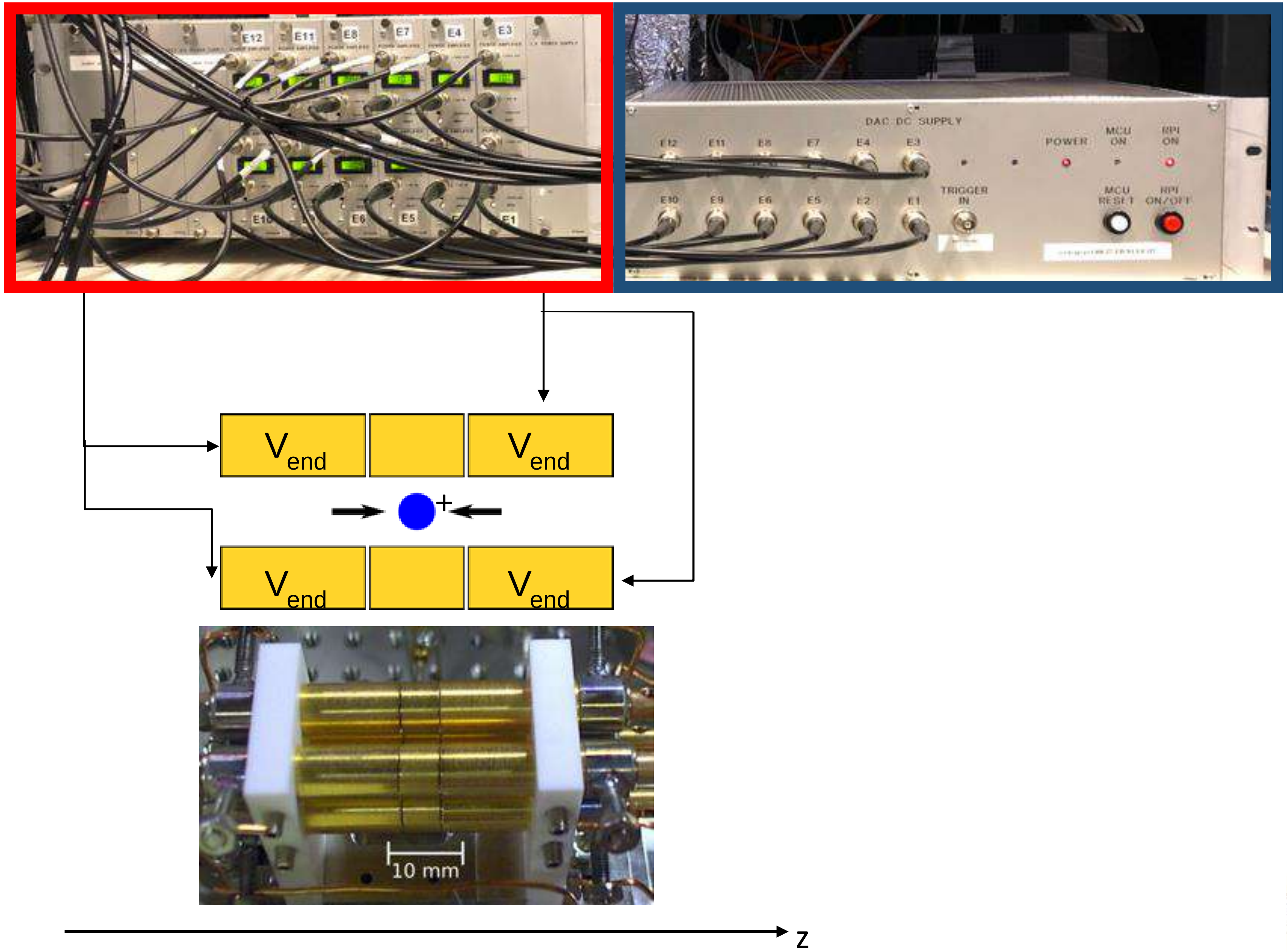
# Noise measurements with the Aarhus linear Paul trap setup

The DC voltage setup



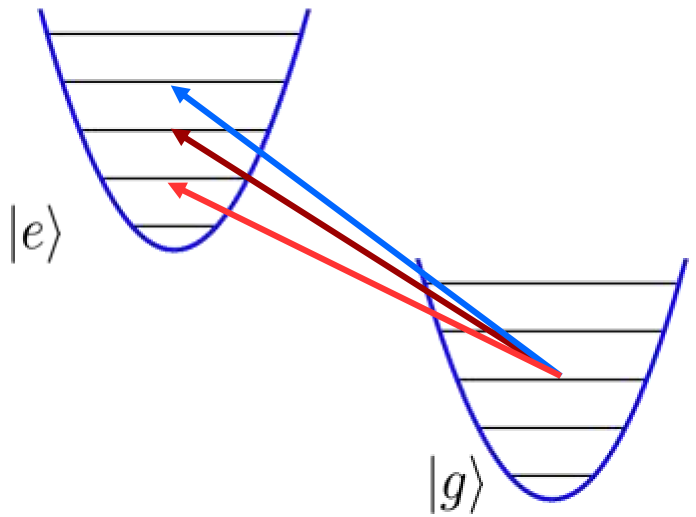
# Noise measurements with the Aarhus linear Paul trap setup

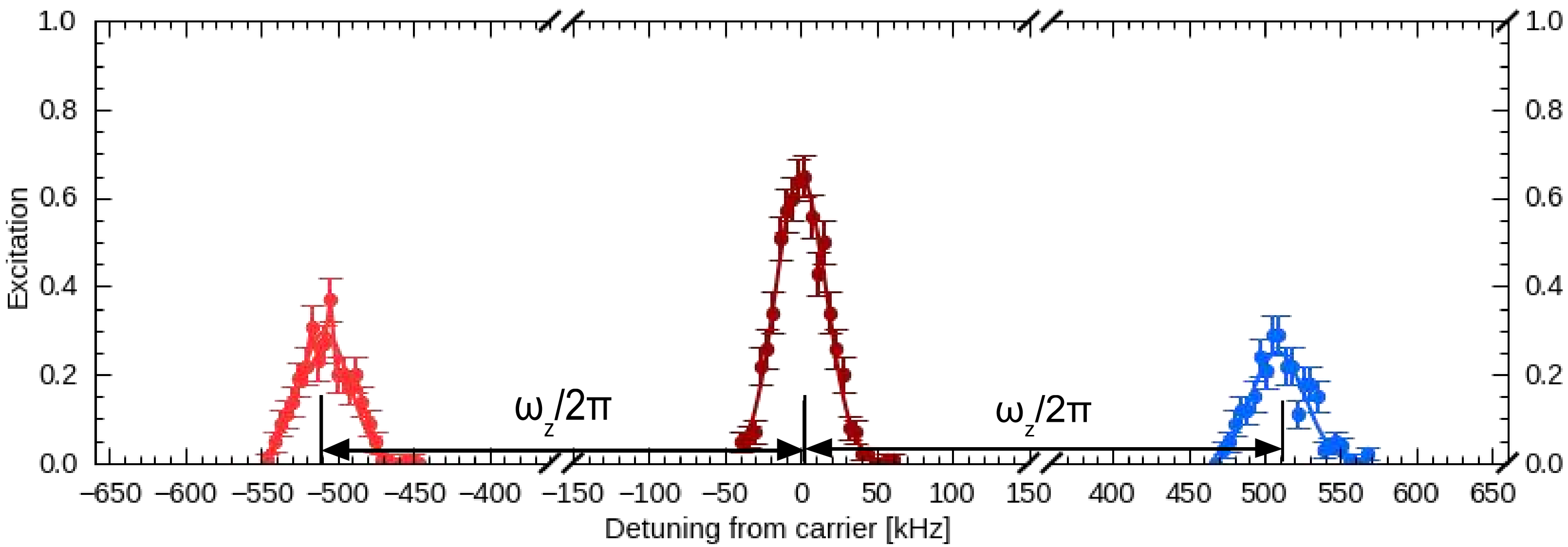
DC Supply



# Noise measurements with the Aarhus linear Paul trap setup

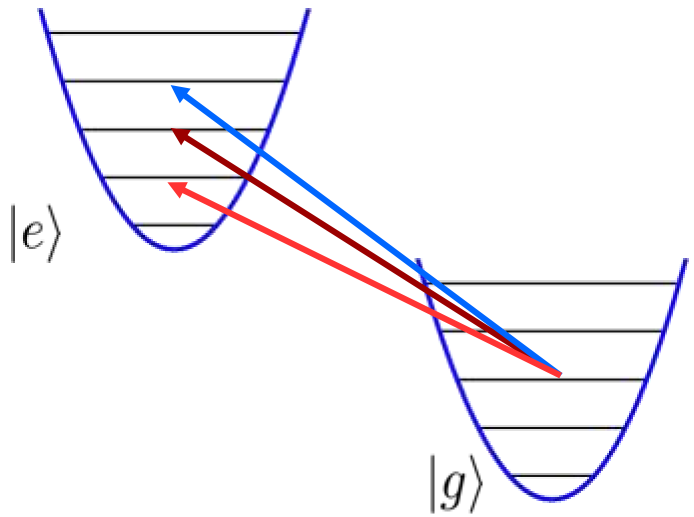
Motional sideband spectroscopy of a single $^{40}Ca^{+}$ ion

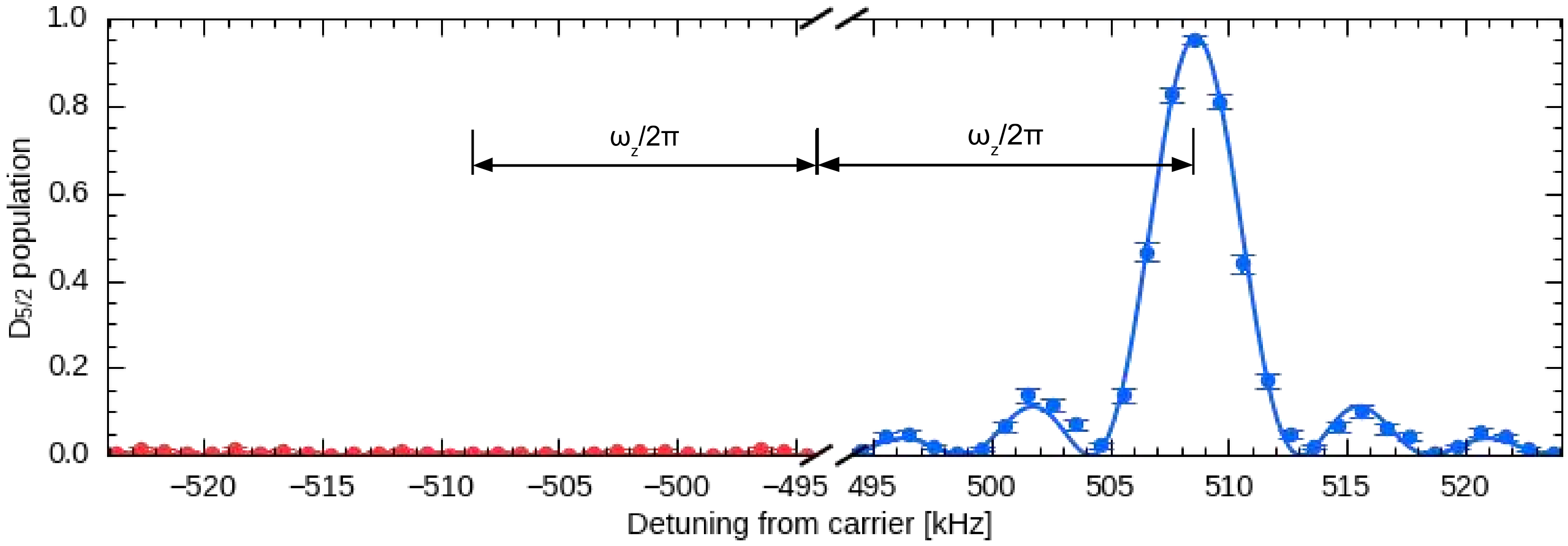


# Noise measurements with the Aarhus linear Paul trap setup

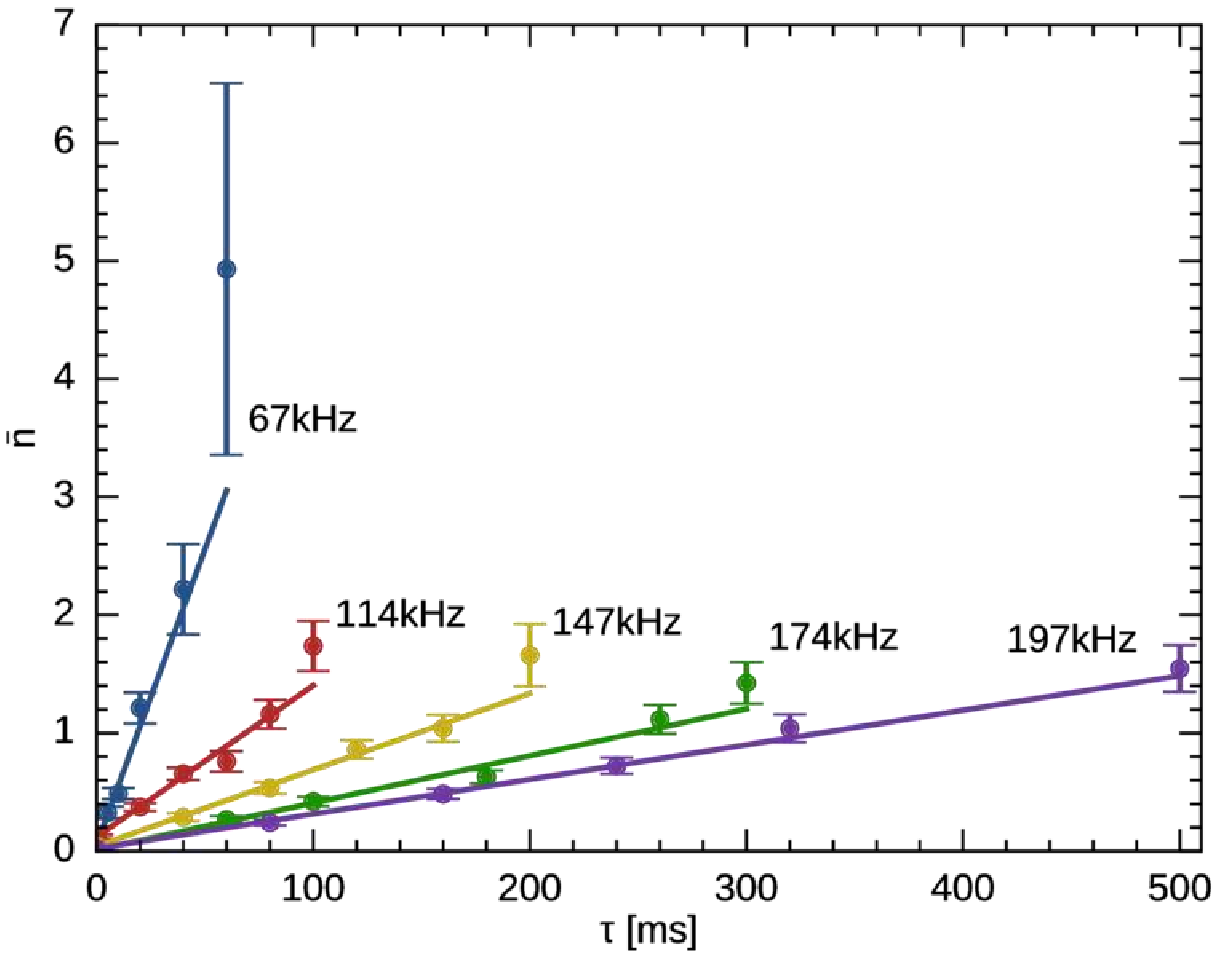
Laser cooling of a single $^{40}Ca^{+}$ ion to the motional ground state



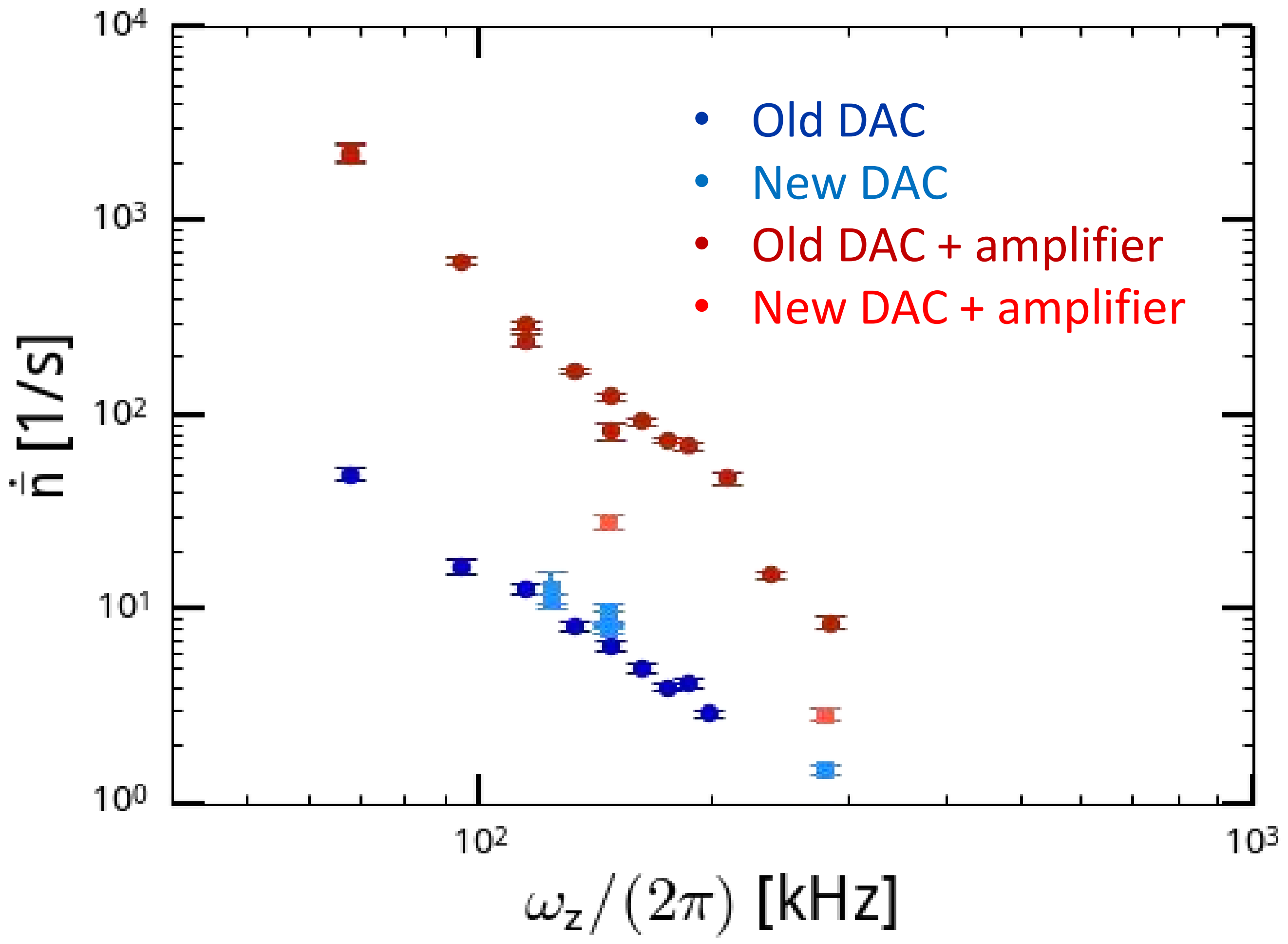
# Noise measurements with the Aarhus linear Paul trap setup

Motional heating of a single $^{40}Ca^{+}$ ion due to noise



# Noise measurements with the Aarhus linear Paul trap setup

Motional heating of a single $^{40}Ca^{+}$ ion due to electrical noise



# Status of the TEQ-trap setup

So far:

- First complete trap for room-temperature experiments finalized
- Low-noise digitally controllable DC voltage supplies have constructed
- Test with trapped ions have been performed in the 100 kHz-range

Next step:

- Final design for cryogenic-temperature experiments
- Improve low-noise DC voltage supplies further (probably using filters)
- Decide on RF/AC voltage supplies

Testing the large-scale
limit of
quantum mechanics

European
Commission

# WP1: TRAPPING

L. Manna – TUD
M. Drewsen - AU

# 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

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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].

# The synthesis and characterization of photon upconverting $Yb:YLiF_4$

Delft University of Technology
Department of Chemical Engineering
Opto-Electronic Materials Group

# Material requirements

The optimal NC:

- Shape → regular, non-spherical
- Size → 50 nm - 1µm, monodisperse
- Absorption → very low at 1064 and 1550 nm
- Solvent → polar, suitable for electrospray
- Charge → defined for surface
- Optical refrigeration → photon upconversion

# Proposed materials

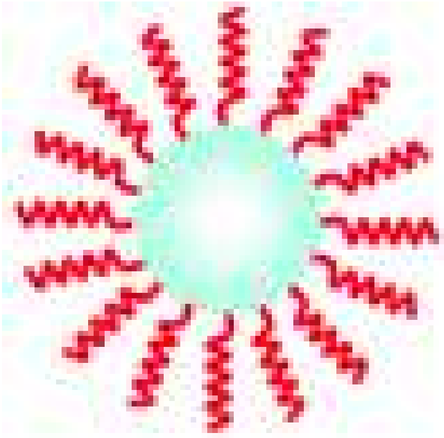
- CdS
- CdSe
- CdTe
- CdSe@CdS
- ZnSe
- $SiO_2$
- Yb:$YLiF_4$

Size difficulties (CdS, CdSe, CdTe, CdSe@CdS)

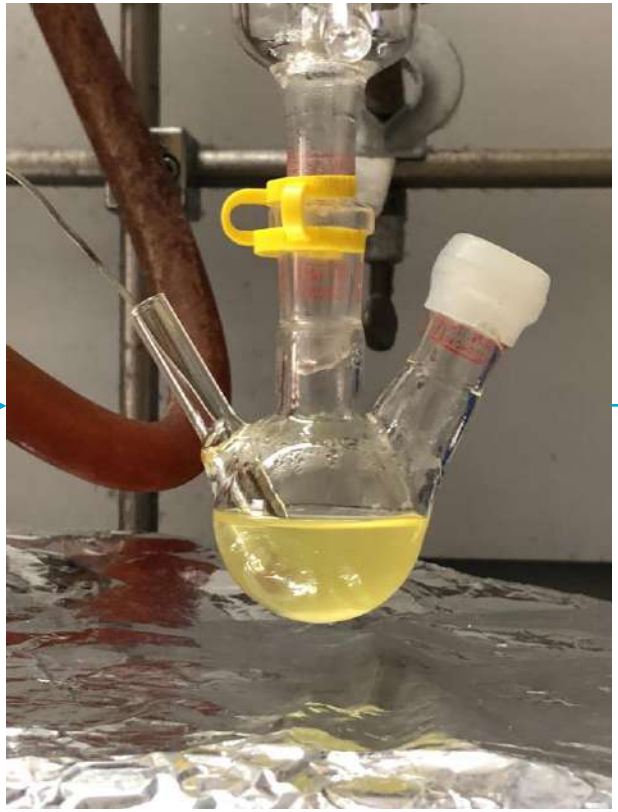
Spherical (ZnSe, $SiO_2$, Yb:$YLiF_4$)

→ Size and shape fulfil requirements in theory

# Synthesis

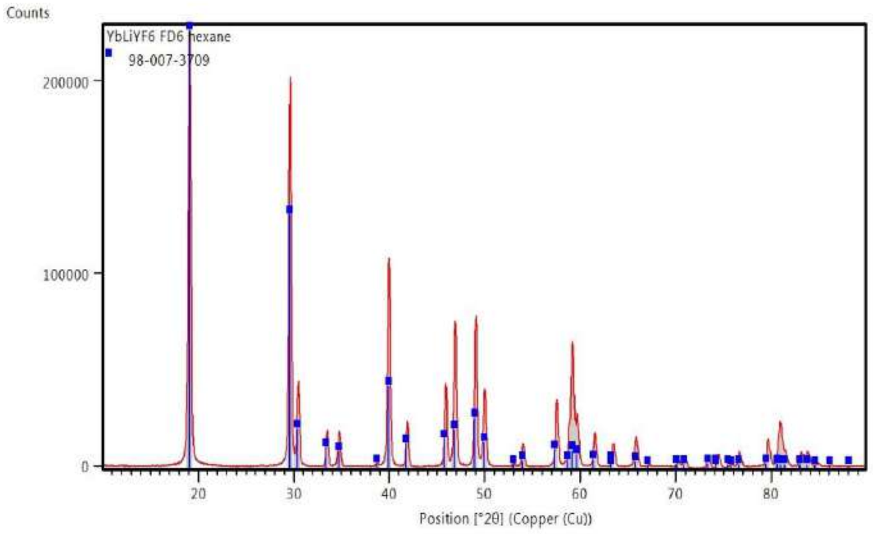


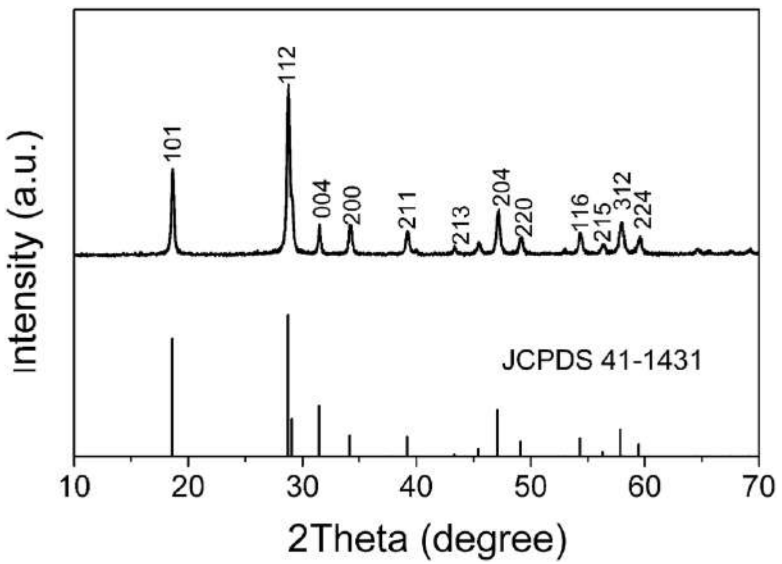
- Synthesis of trifluoroacetate (TFA) salts
- Cracking of the TFA salts
- Purifying and concentrating the particles

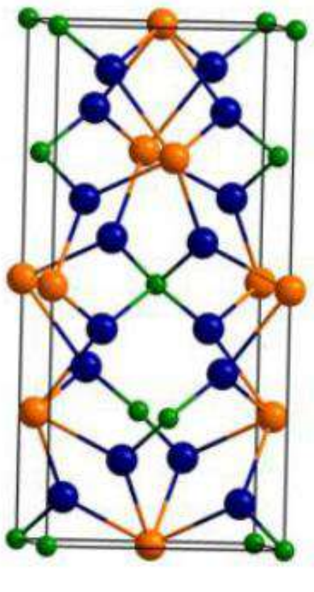


# XRD Analysis

- XRD pattern fits perfectly
- Planes correspond with $CaWO_4$ structure



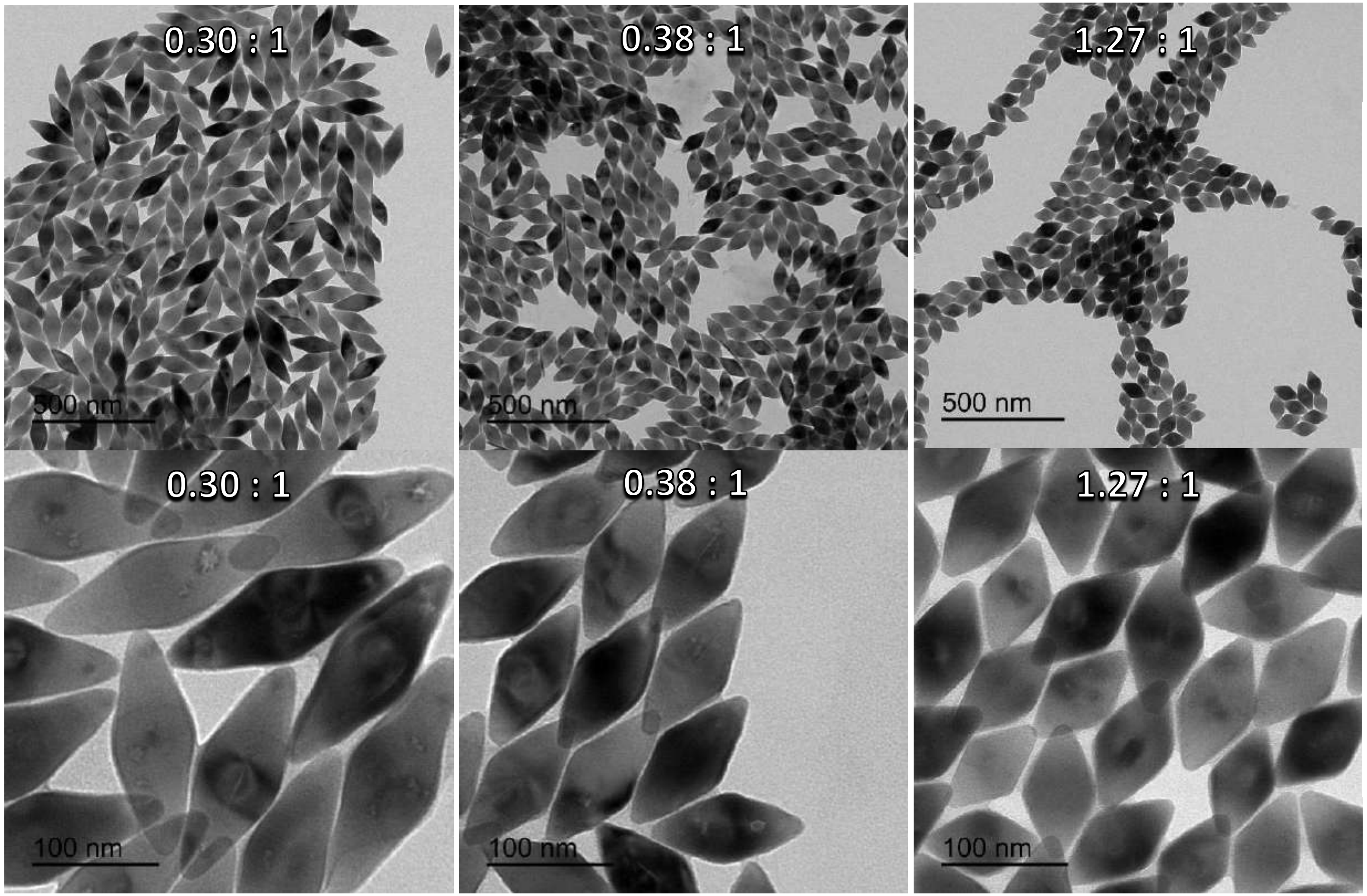



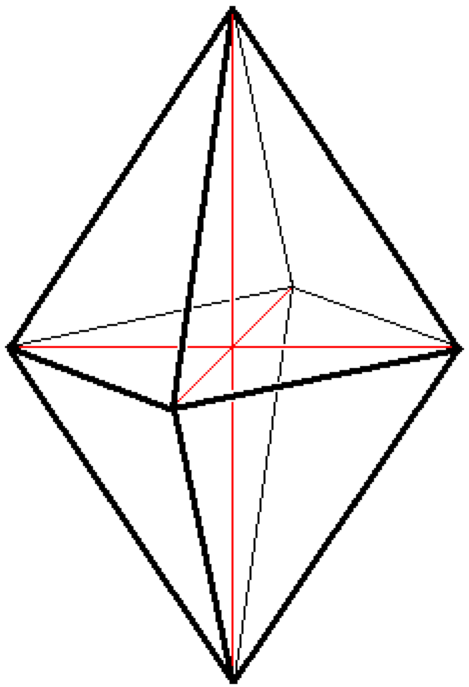
*Scheelite*

*DOI: 10.1039/C5RA20633B*

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

# TEM Imaging samples (Yb : Y)



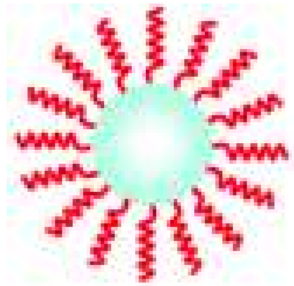



# Material requirements

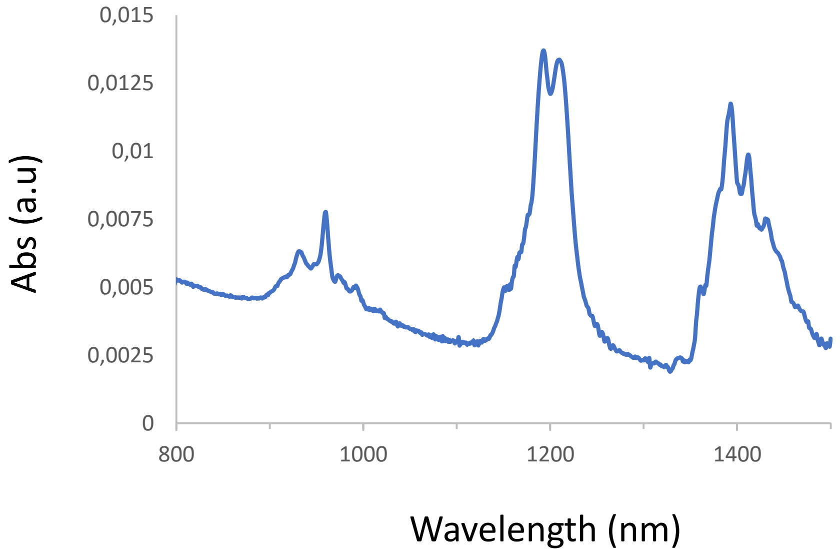
The optimal NC:

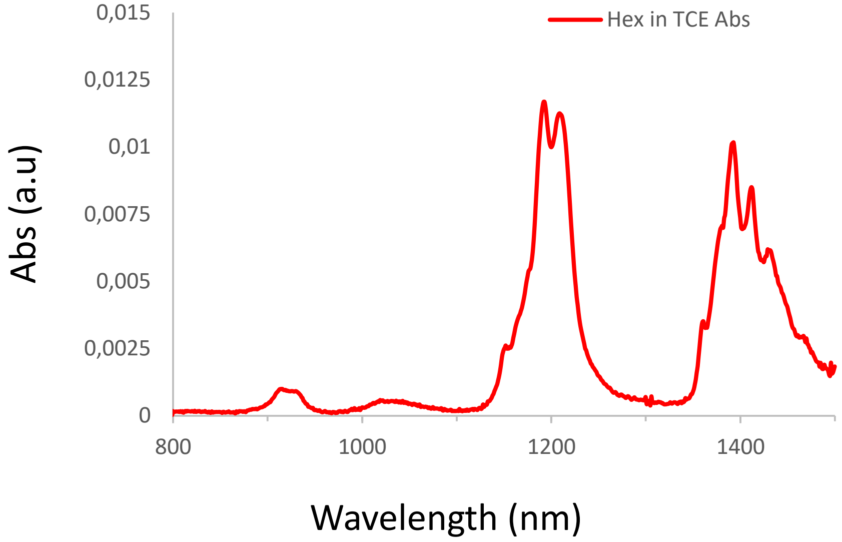
- Shape → regular, non-spherical
- Size → 50 nm - 1µm, monodisperse
- Absorption → very low at 1064 and 1550 nm
- Solvent → polar, suitable for electrospray
- Charge → defined for surface
- Optical refrigeration → photon upconversion

# Absorption Spectroscopy



- Requirement: very low absorption at 1064 nm and 1550 nm




- Absorption 1100 – 1500 nm related to solvents and organic surfactants:

→ Removing solvent
→ Changing ligands for shot, non-absorbing ligands

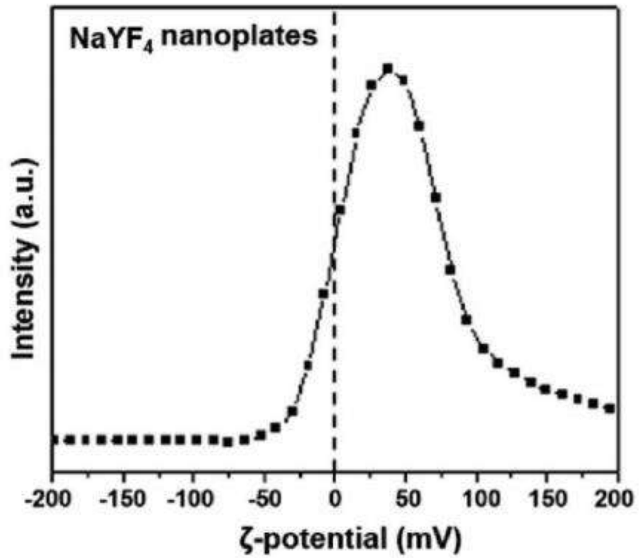
# Material requirements

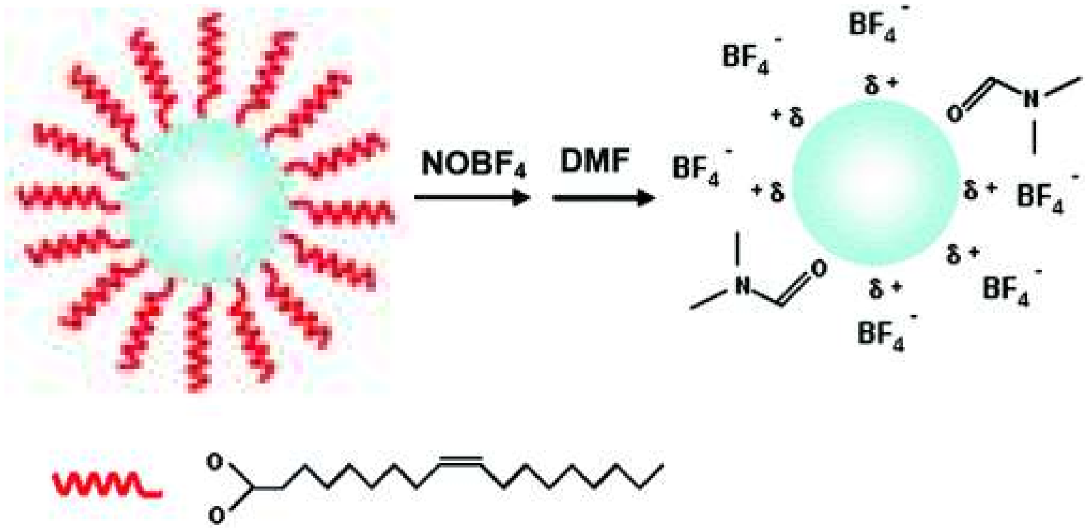
The optimal NC:

- Shape → reg✓ar, non-spherical
- Size → 50✓ - 1µm, monodisperse
- Absorption → very low ~ 1064 and 1550 nm
- Solvent → pc ✗ suitable for electrospray
- Charge → defined for surface
- Optical refrigeration → photon upconversion

# Ligand exchange

- Requirement: defined surface charge
- Removing absorbing ligands (oleate)
- Ligand stripping with $Et_3OBF_4$ or $NOBF_4$

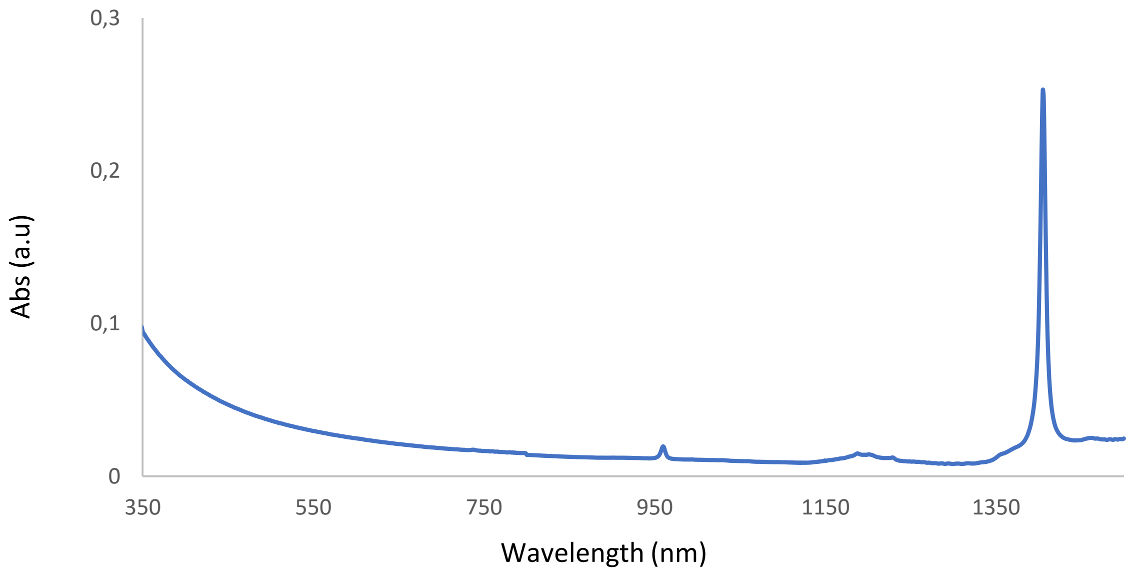


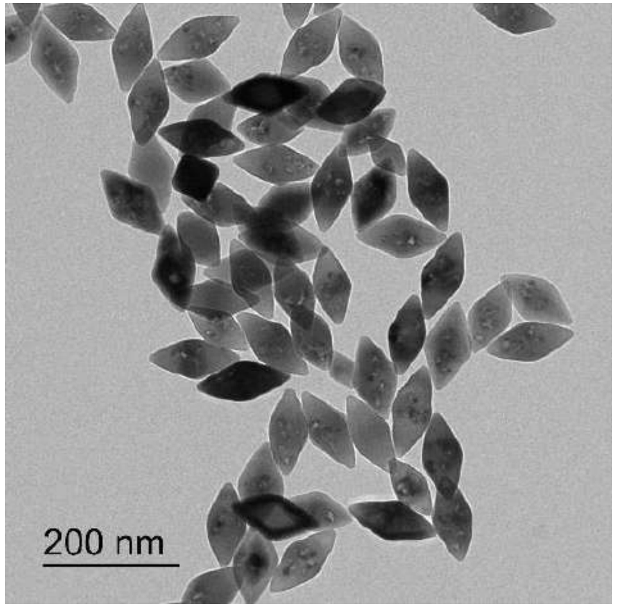




*DOI: 10.1021/ja108948z*

# Absorbance change

- Phase transfer: hexane → methanol
- Very low absorbance at 1064 and 1550 nm
- Charge-stabilized in MeOH



# Ligand exchange

- After a ligand exchange with $Et_3OBF_4$, the particles can be better dispersed than the sample prepared in hexane

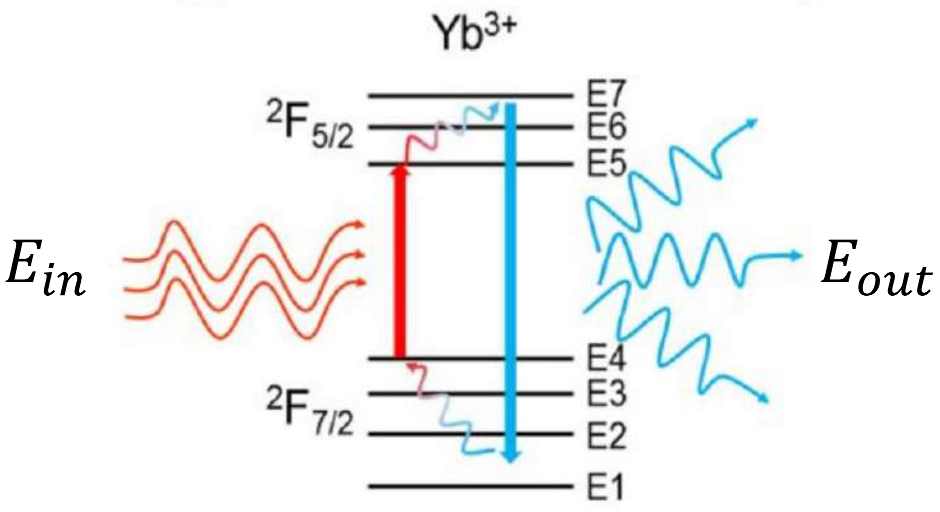
# Material requirements

The optimal NC:

- Shape → reg✓ar, non-spherical
- Size → 50✓ - 1µm, monodisperse
- Absorption → very low ✓ 1064 and 1550 nm
- Solvent → po✓ suitable for electrospray
- Charge → defined ~ surface
- Optical refrigeration → photon upconversion

# Optical refrigeration principle

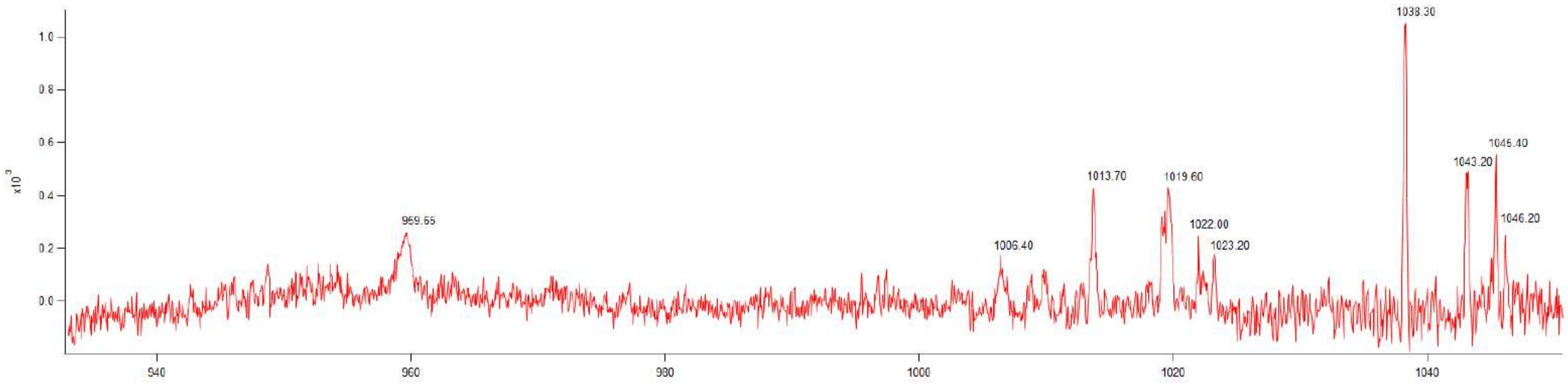
- Phonon-assisted anti-Stokes photoluminescence
- High quantum yield required for cooling




*DOI: 10.1117/12.2080343*

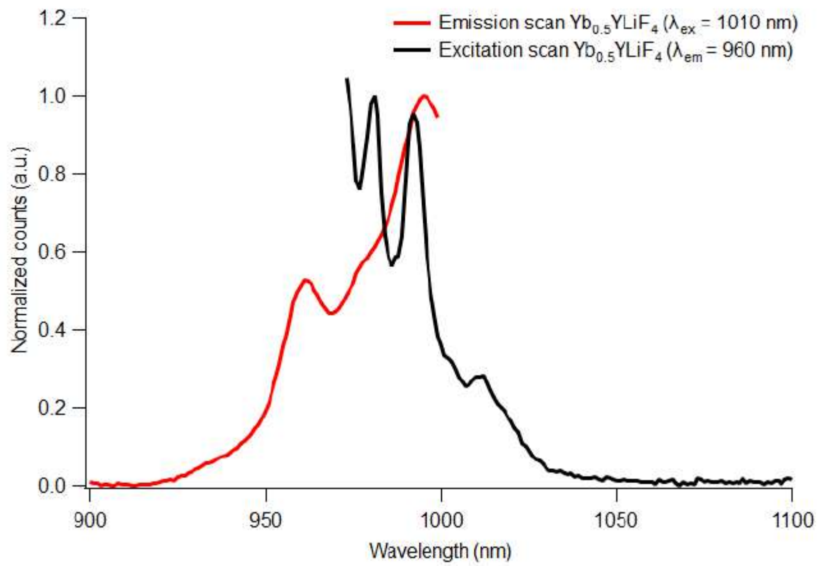
# Absorbance of $Yb^{3+}$ ion

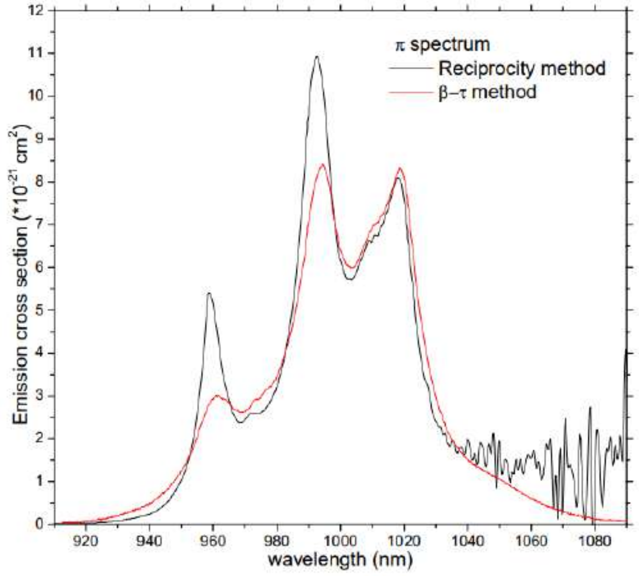
- After subtracting the absorbance features related to solvents and Rayleigh scattering, different absorption peaks of the $Yb^{3+}$ ion can clearly be distinguished from the background



# Emission and excitation spectroscopy

- **Excitation at 1010nm, emission peaks at 960nm and 995nm**
- Photon upconversion of 64meV (960nm) and 19 meV (995nm)



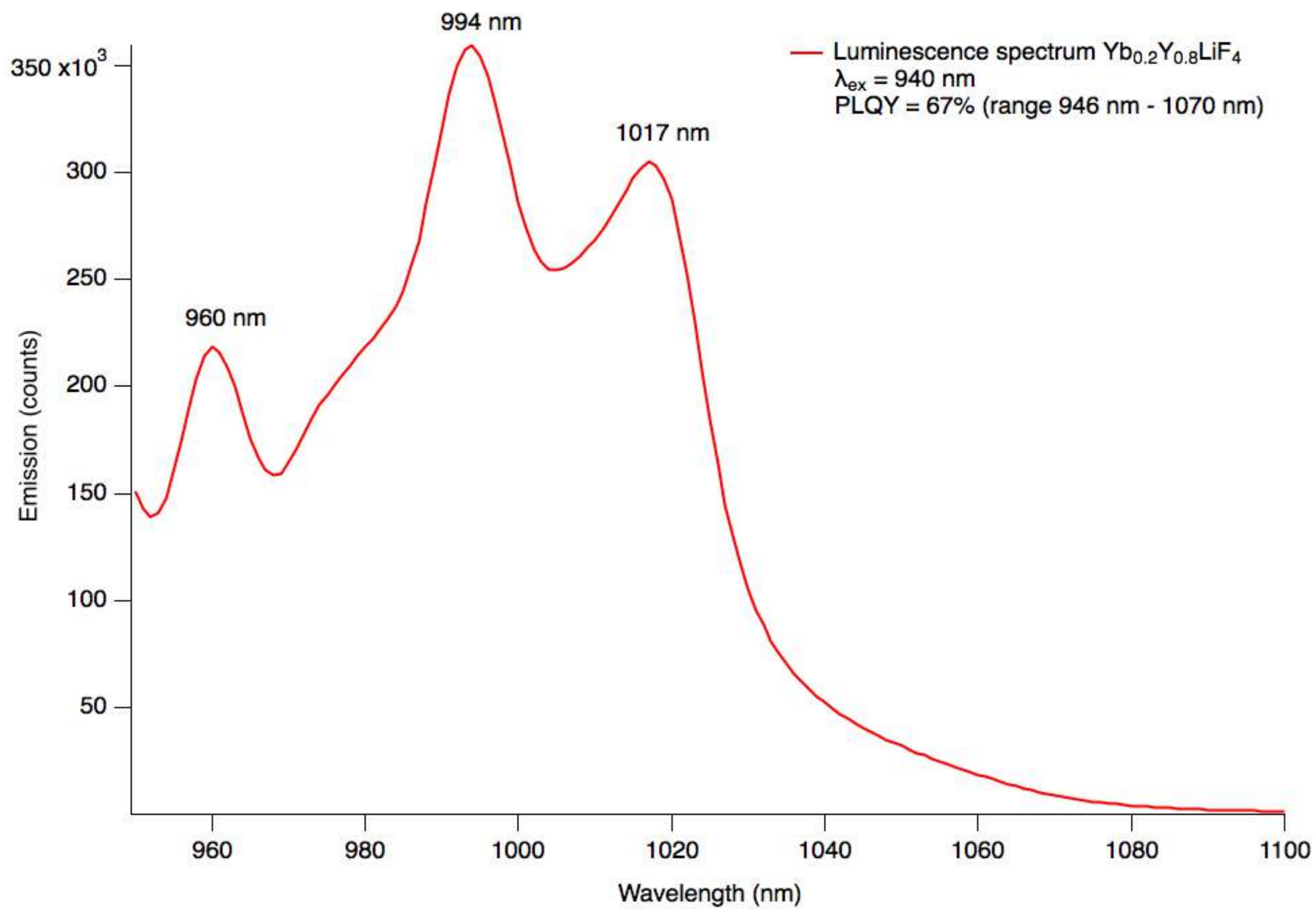



# Material requirements

The optimal NC:

- Shape → reg✓ar, non-spherical
- Size → 50✓ - 1µm, monodisperse
- Absorption → very low✓ 1064 and 1550 nm
- Solvent → po✓ suitable for electrospray
- Charge → defined ~ surface
- Optical refrigeration → photon u~nversion

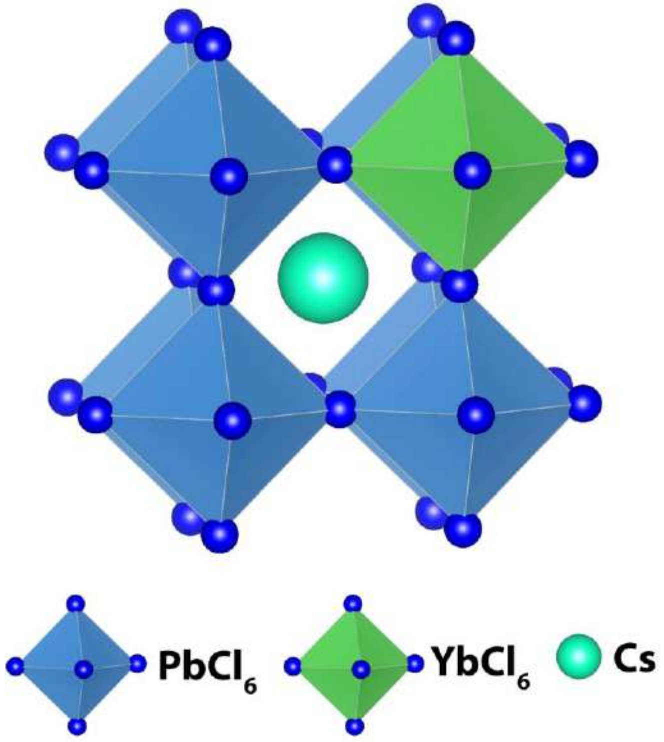
# Latest results on YLF NCs containing 20% Yb



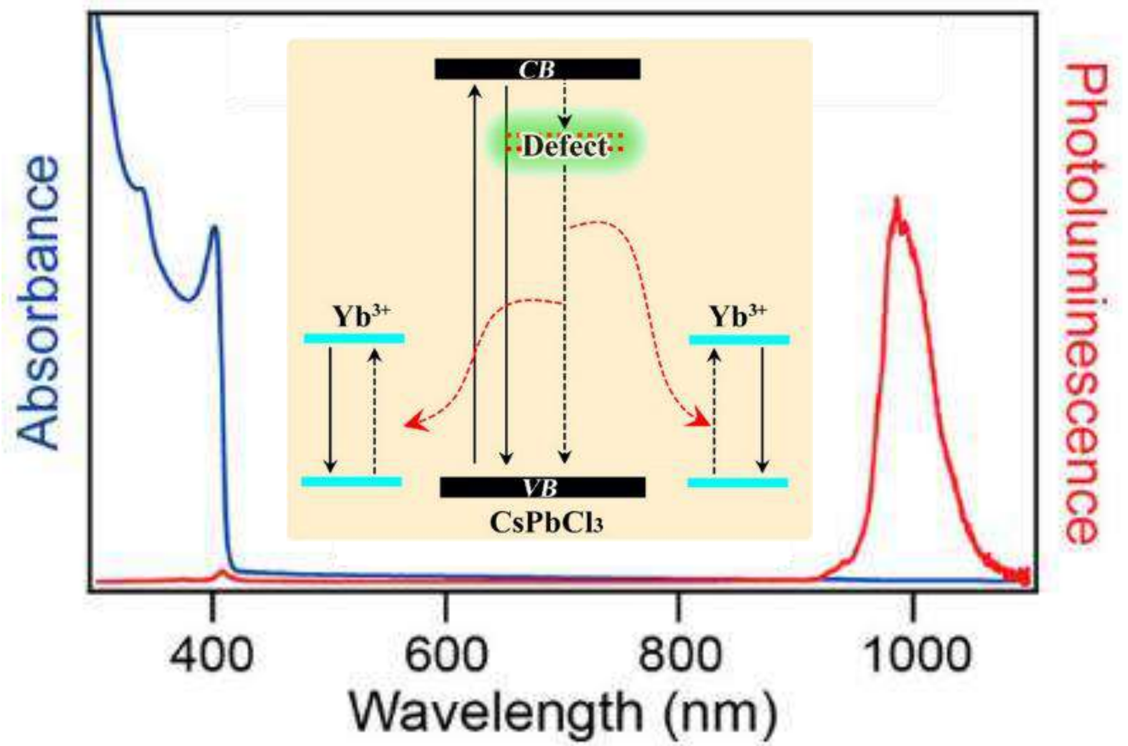
# Outlook

- Size, shape, solvent and absorption parameters meet the requirements
- Charging surface is possible
- More analysis needed for a defined charge
- Nanoparticles show upconversion, but phonon-emission is far larger, hence the particles are heating up instead of cooling down
- Growing a shell of undoped $YLiF_4$ on top of $Yb:YLiF_4$ might improve PLQY
- Alternative materials will be tested, for example rare earth doped halide perovskites

# A possible alternative: Yb doped $CsPbCl_3$ Nanocrystals



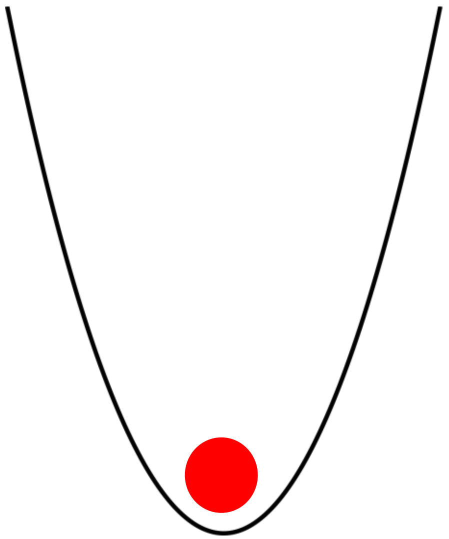

PLQY as high as 170% - Quantum Cutting




References

https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.8b05104
https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.8b03966?src=recsys QY 150%
https://pubs.acs.org/doi/10.1021/acs.nanolett.8b01066 QY 170%
https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201704149 QY 146%
https://pubs.acs.org/doi/full/10.1021/acs.jpclett.8b03406

Testing the large-scale limit of quantum mechanics



# WP2: COOLING

P. Barker – UCL

# 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].

# Outline

Low noise electronics (2.1)

Paul trap electronics (INFN) (T2.1)– see also WP1

Homodyne detection (UCL)

Centre-of-mass cooling (2.2)

Opto-electrical feedback cooling (UCL)

Internal state cooling (2.3)

Loading, trapping and characterisation of Yb:YLF nanoparticles (UCL, TUD)

Understanding and controlling sources of decoherence (2.4)

First measurements of Paul trap stability and noise characterisation (UCL)

# Low noise electronics for Paul trap (INFN)

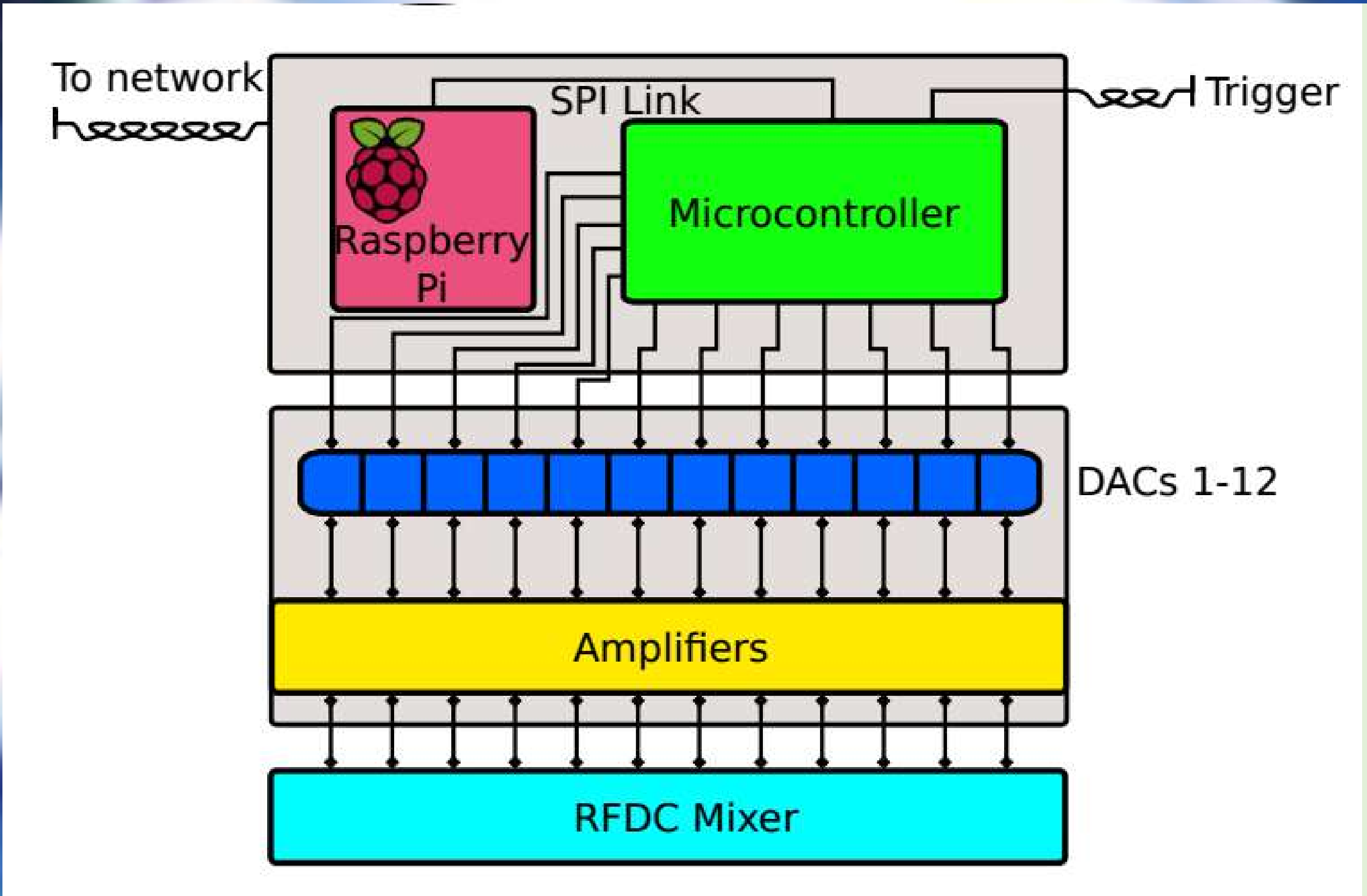
# Power Supply Requirements

Due to its ambitious finality, the Particle Trap Power Supply must respond to the following specifics:

- Max amplitude 50V
- Typical Bandwidth 10kHz
- Maximum output Noise 22nV/√Hz

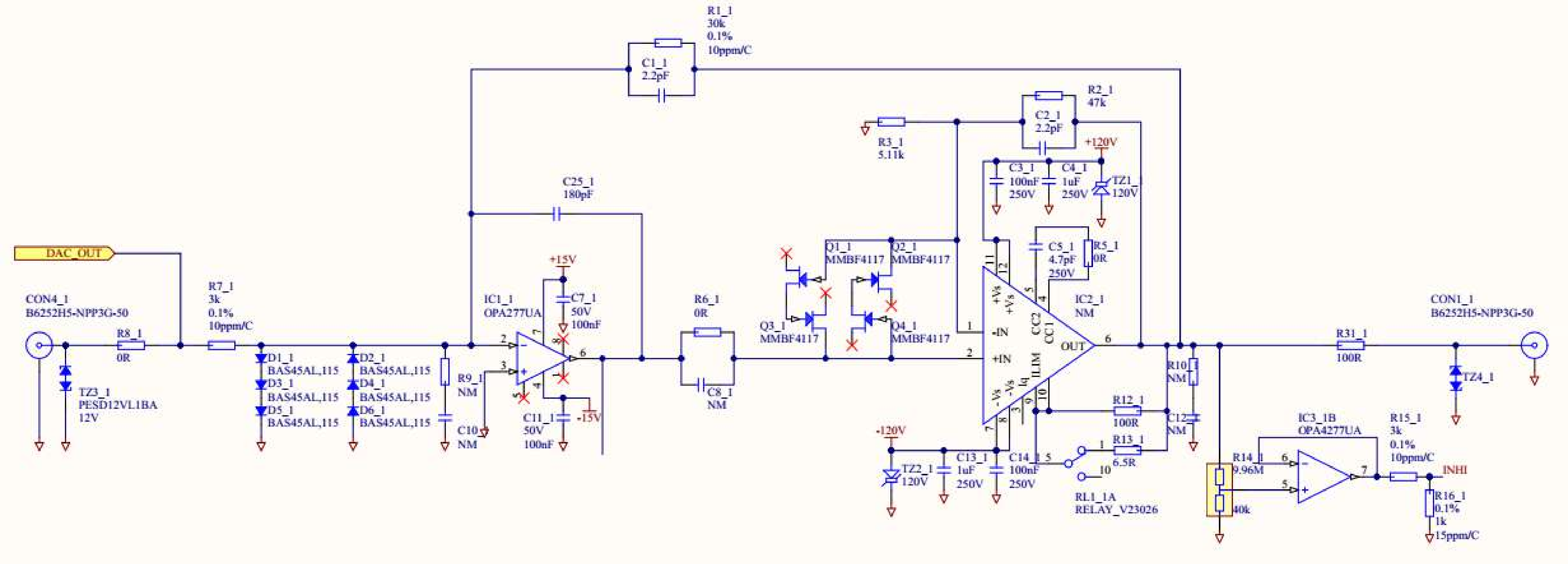
(V) $S_V^{DC}(\omega) \leq 5 \cdot 10^{-16}\ V^2/Hz$ @ $\omega = 100 - 1000\,Hz$ AND $V_{DC} = 50\,V$

# Current Power Supply Apparatus




- Raspberry $\pi$ *microcontroller*
- AD5791 DAC
- Custom HV amplifier
- RF DC Mixer

# Amplifier Schematic



# Power Supply Requirements

Current design has been thoroughly reviewed to check if specifics were respected.

DC GAIN = 10 OK

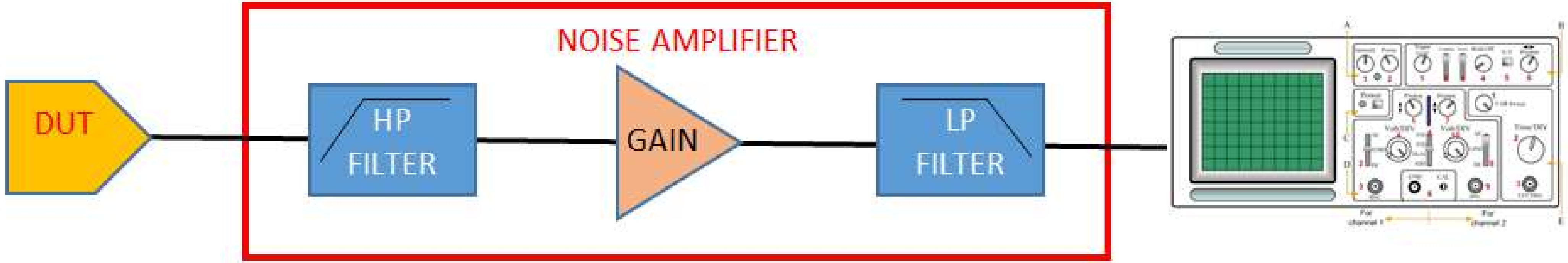
Bandwidth = 300kHz OK

NOISE…

Among all specifics, noise is indeed the most critical.

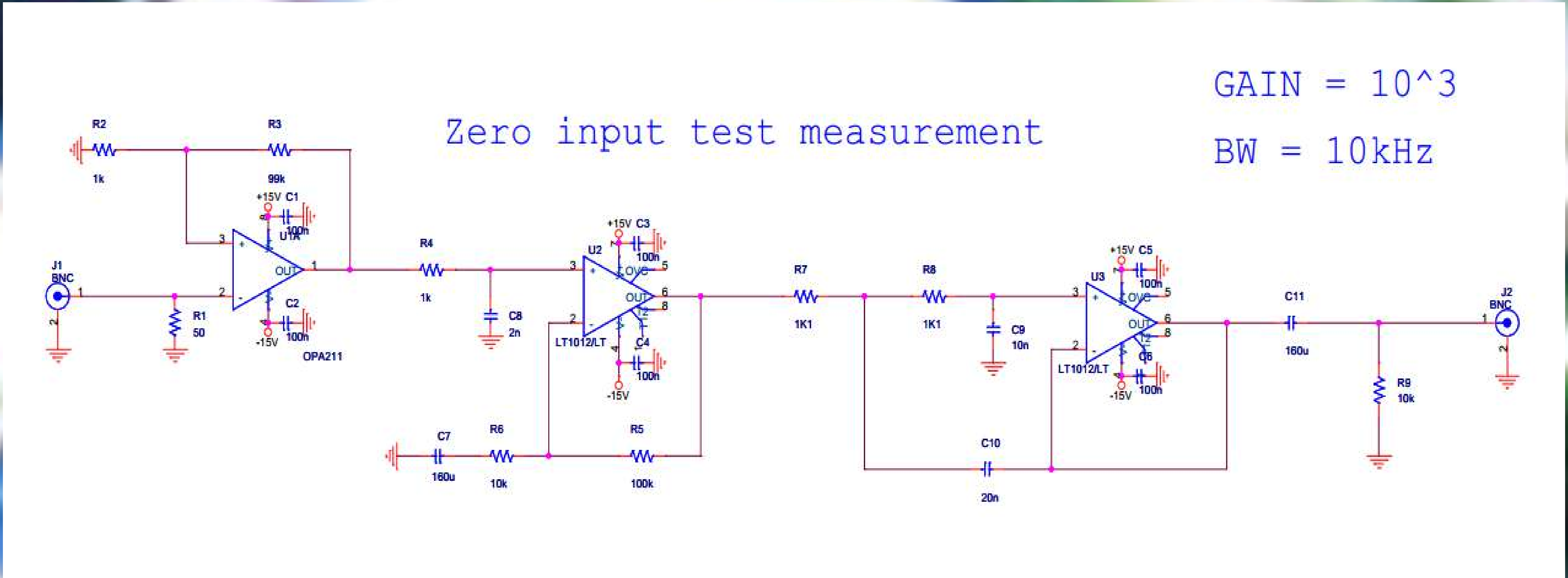
# Amplifier NOISE measurement

Block diagram of a noise amplifier

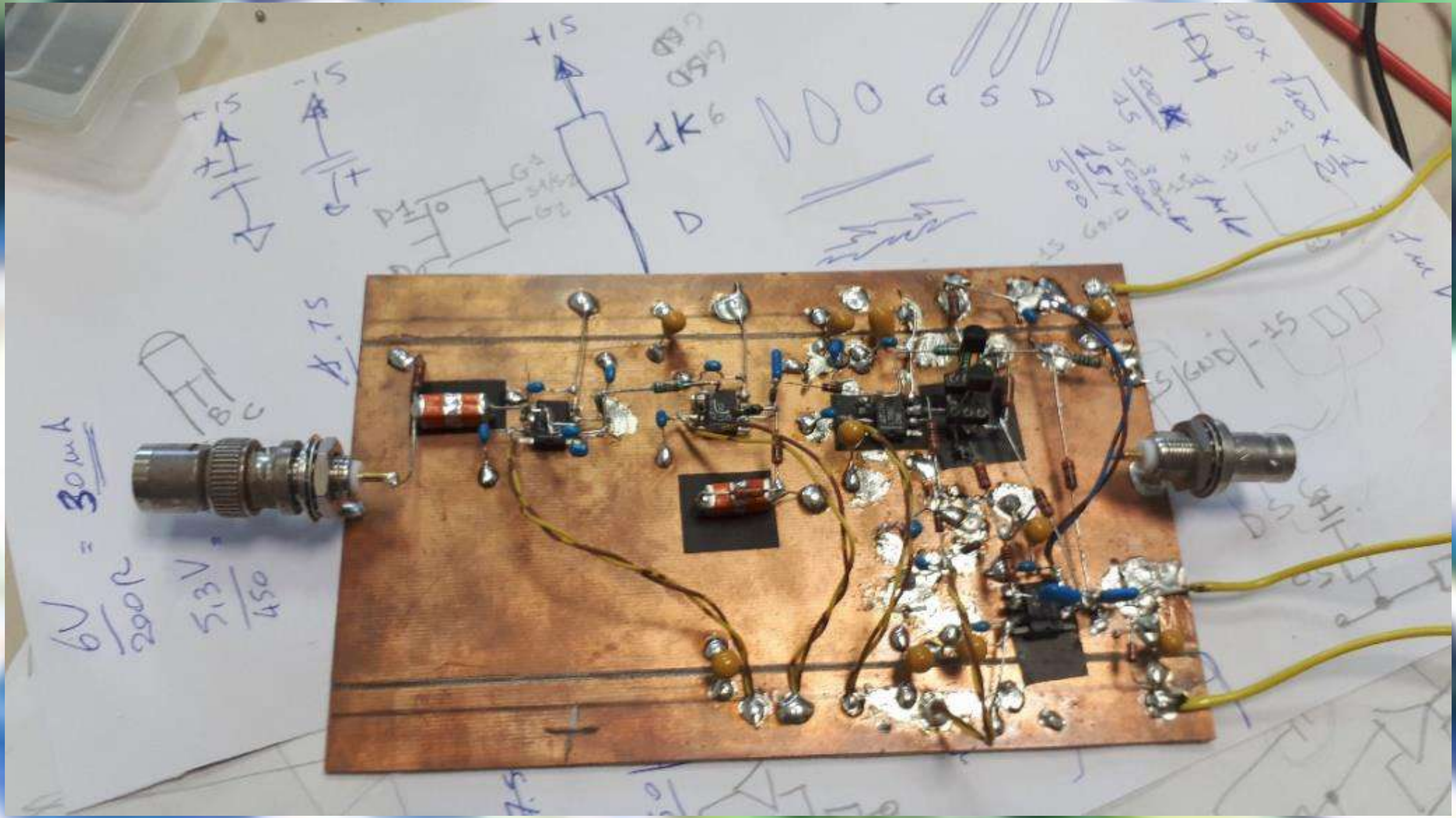



Gain x √BW must be in the order of $10^5 \div 10^6$

# Amplifier NOISE measurement



# Amplifier NOISE measurement

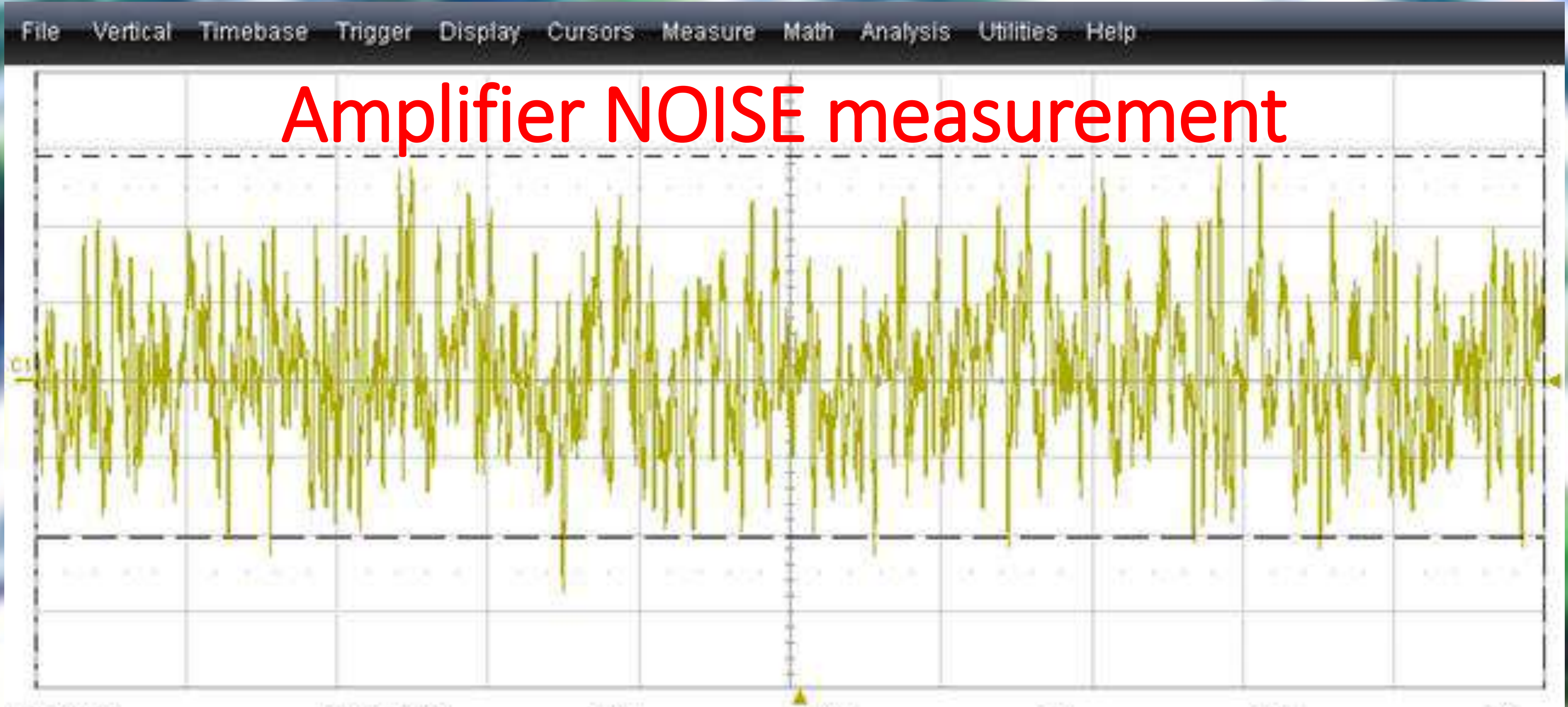



Gain $10^6$

BW 10Hz

Special features like Utra Low Noise, OFFSET and DRIFT compensation…

# Amplifier NOISE measurement




| Measure | P1:rms(C1) | P2:- - - | P3:- - - | P4:- - - | P5:- - - | P6:- - - |
|---|---|---|---|---|---|---|
| value | 17.97 mV | | | | | |
| mean | 17.8859 mV | | | | | |
| min | 16.02 mV | | | | | |
| max | 19.78 mV | | | | | |
| sdev | 552.0 µV | | | | | |
| num | 5.064e+3 | | | | | |
| status | ✔ | | | | | |

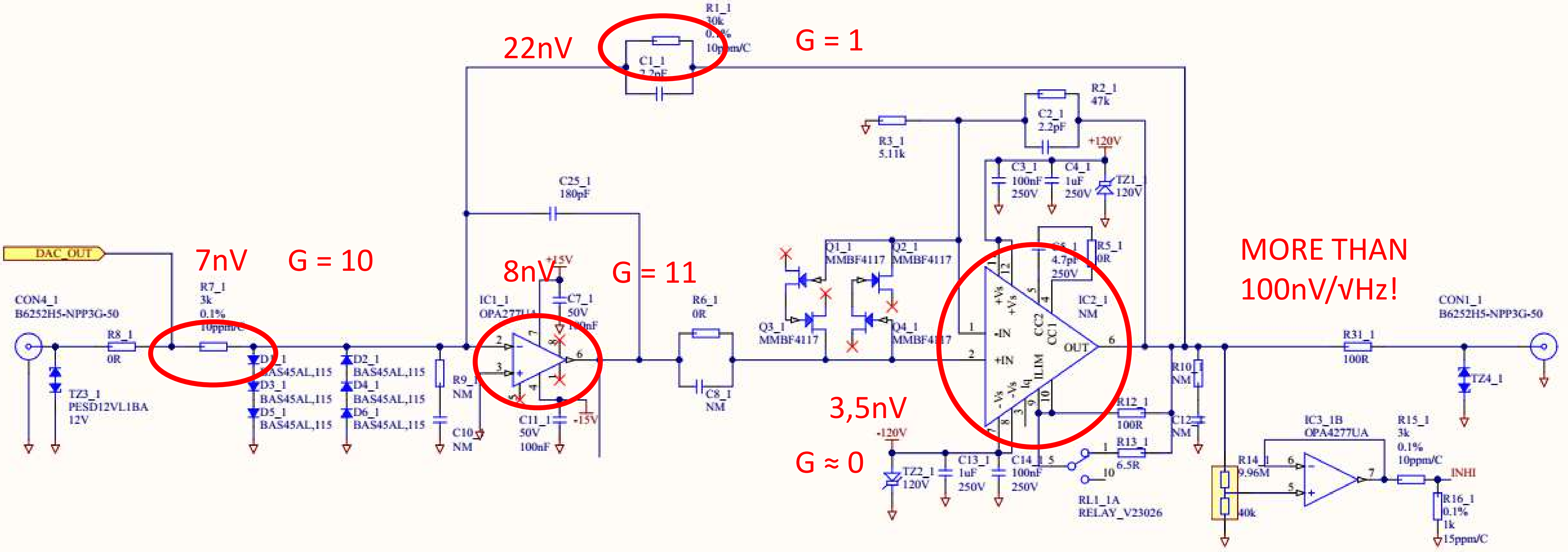
178nv/√HZ

# Amplifier NOISE analysis

NOISE analysis include:

- Identify the main noise sources
- Calculate Noise GAIN for each source
- Output Noise Estimation for each source
- Quadratic Sum of all Noise contibution

# Amplifier NOISE analysis

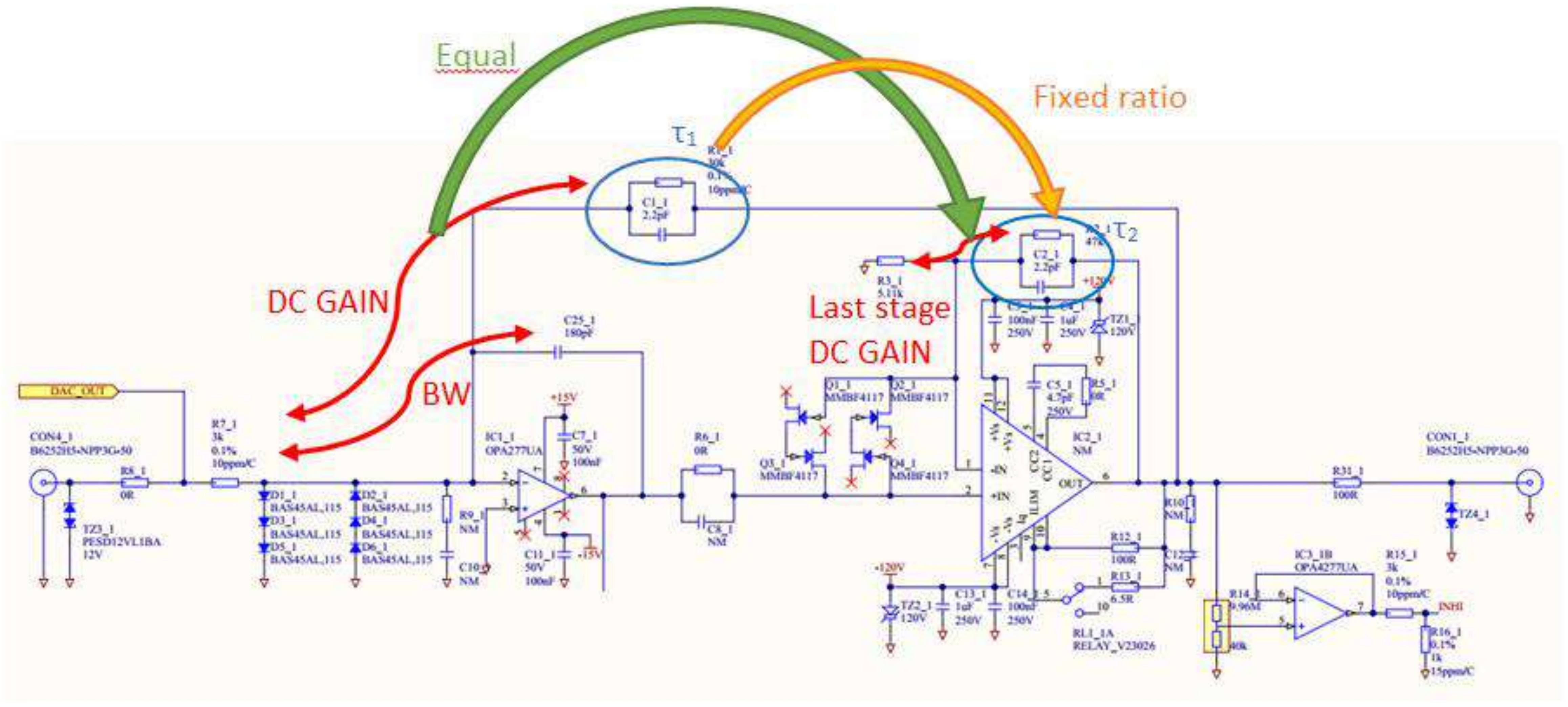


# Power Supply Adjustements

## Current design can be salvaged with a few expedients:

- Reduce resistor values, maintaining DC Gain
- Increase capacitor values, maintaining time constants
- Replace OPA277 with a low noise amplifier
- AND… Keep track of all relations to guarantee stability!

# Power Supply Adjustements



# Power Supply Adjustements

Possible solution is to replace:

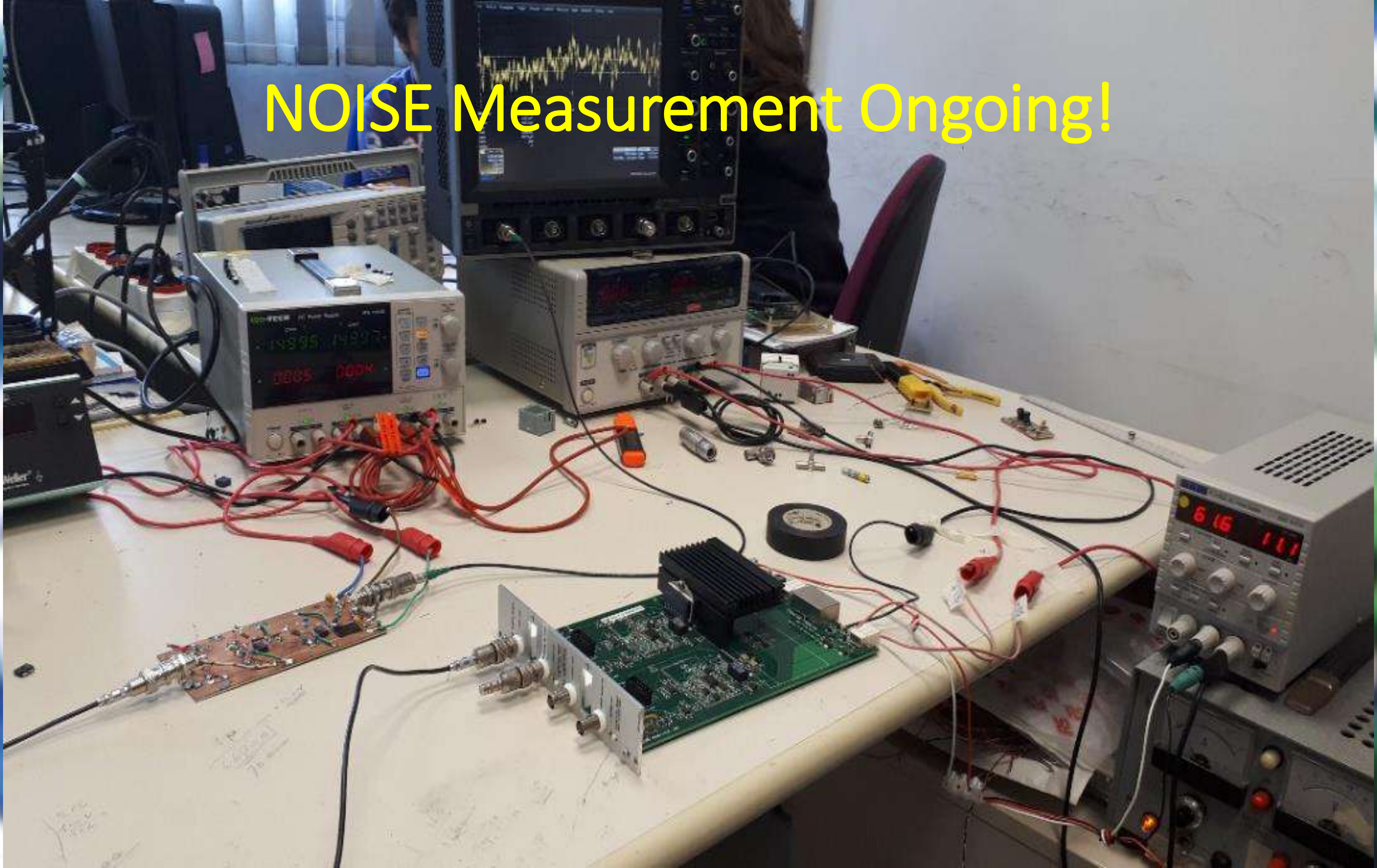
- $R_1$=2K5 $R_7$=250R $C_1$=27pF $C_{25}$=2,2nF
- OPA277 replaced with OPA211 (same package, 1nV of noise)

Result is…

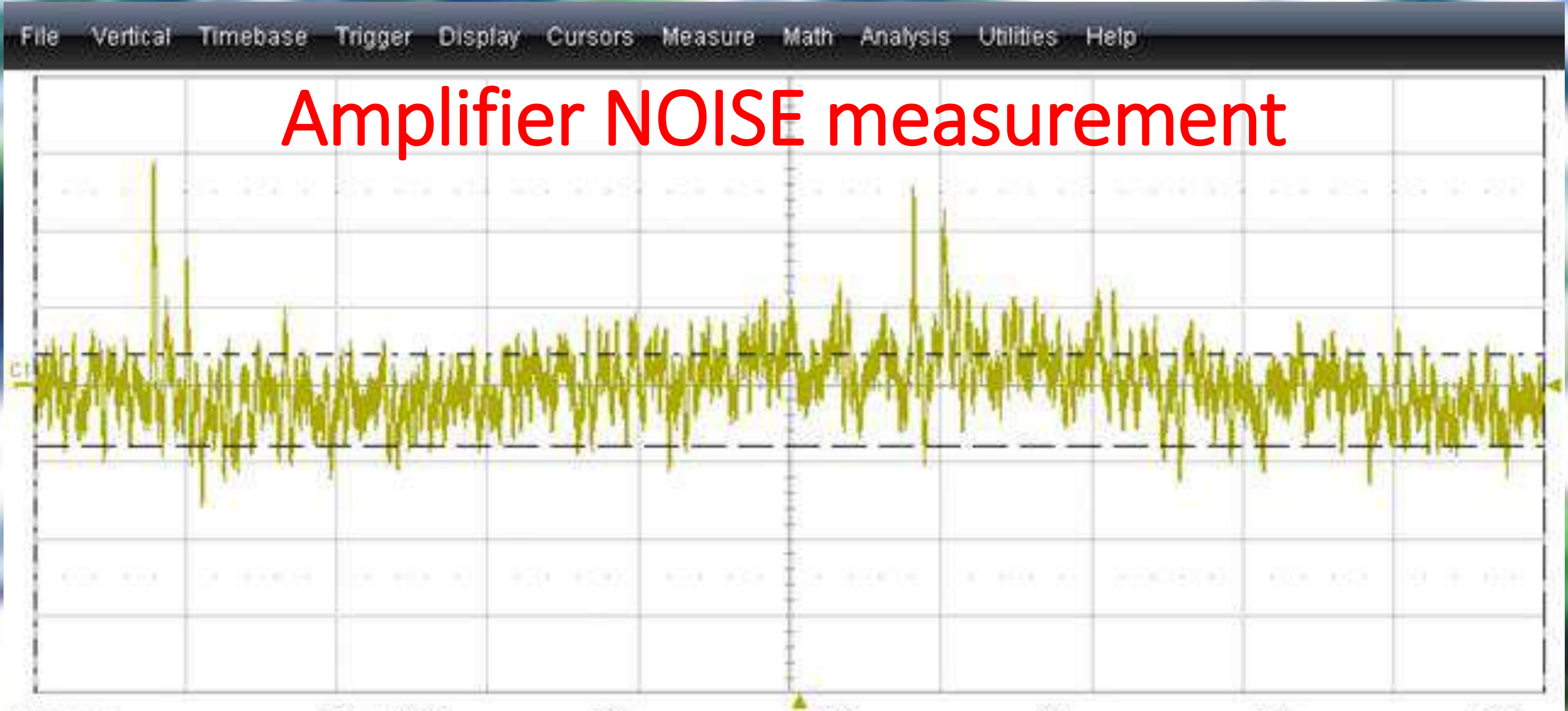
## 20nV/√Hz of noise!

## This is the first deliverable

# NOISE Measurement Ongoing!



# Amplifier NOISE measurement



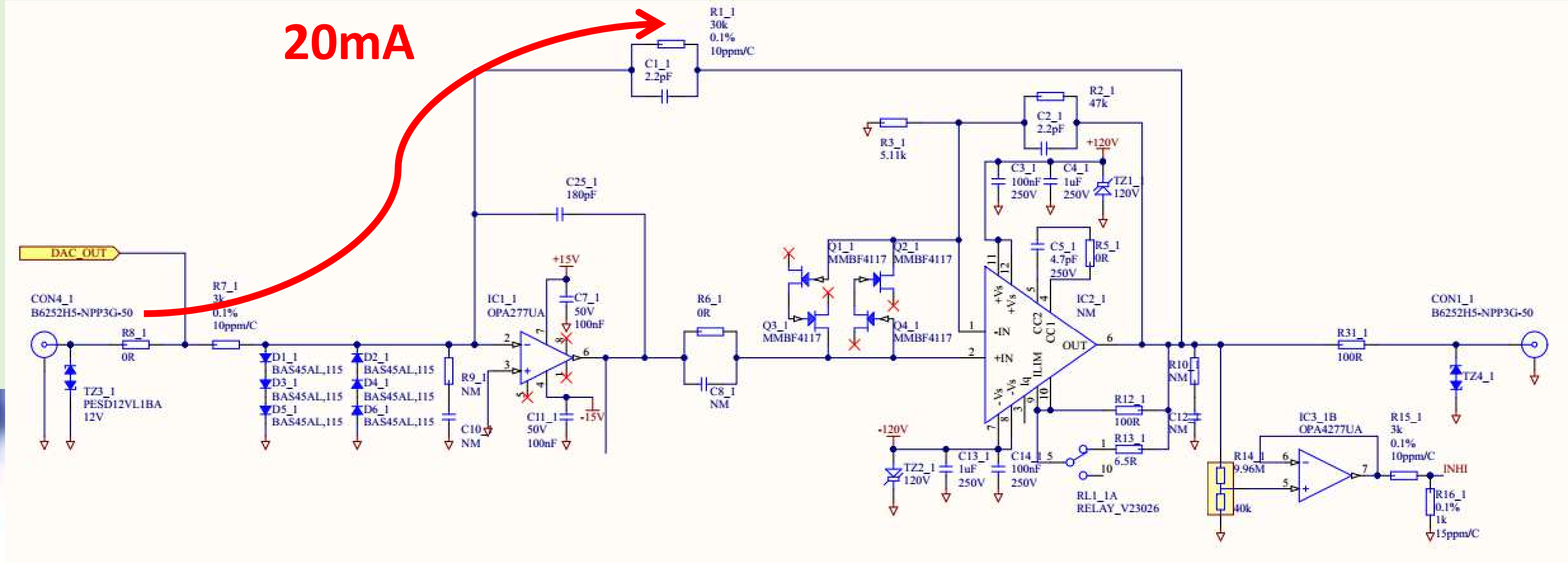

| Measure | P1:rms(C1) | P2:- - - | P3:- - - | P4:- - - | P5:- - - | P6:- - - |
|---|---|---|---|---|---|---|
| value | 2.14 mV | | | | | |
| mean | 2.0545 mV | | | | | |
| min | 1.84 mV | | | | | |
| max | 2.52 mV | | | | | |
| sdev | 62.7 µV | | | | | |
| num | 11.155e+3 | | | | | |
| status | ✔ | | | | | |

20nv/√HZ

# Drawbacks

Advantages always comes with disadvantages:

- Smaller resistors correspond to higher currents
- With a 5V input, driving current becomes 20mA!
- Feedback current is 20mA as well



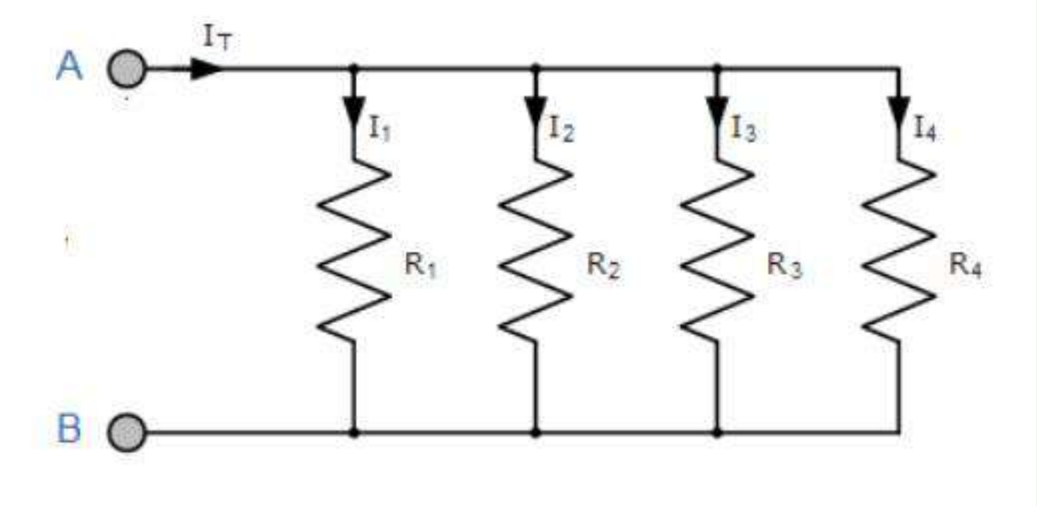
# Drawbacks

Advantages always comes with disadvantages:

- A 20mA current is too much for a driving stage
- The heat generated by a single resistor can be too high

  (i.e.: the heat genereted by $R_1$ is 1W!)

# Solutions




R1 can be replaced with 4 resistors in parallel of 10k each.

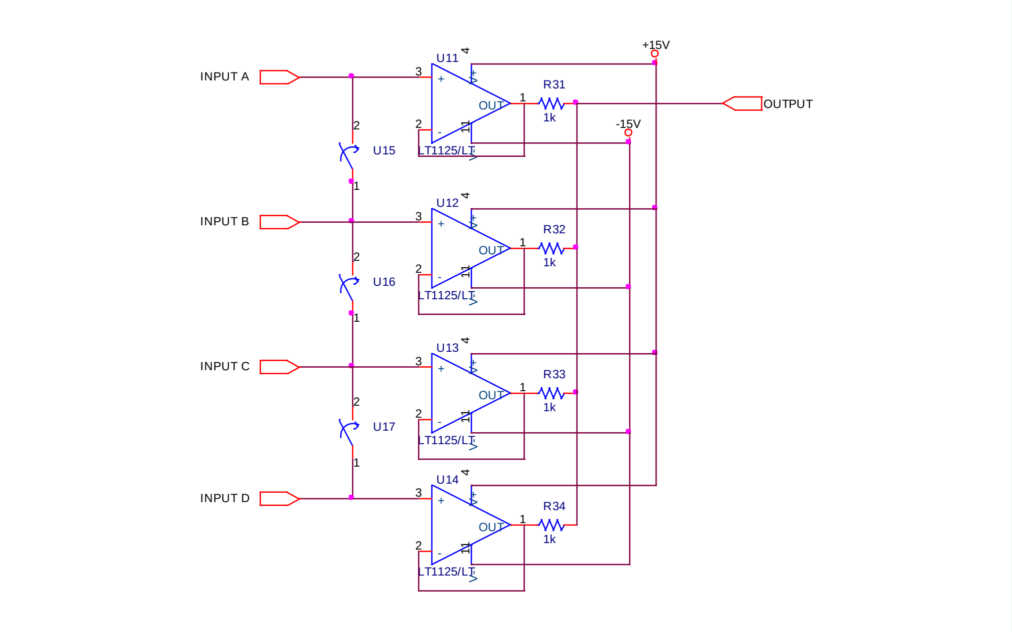
The heat generation is equally split.

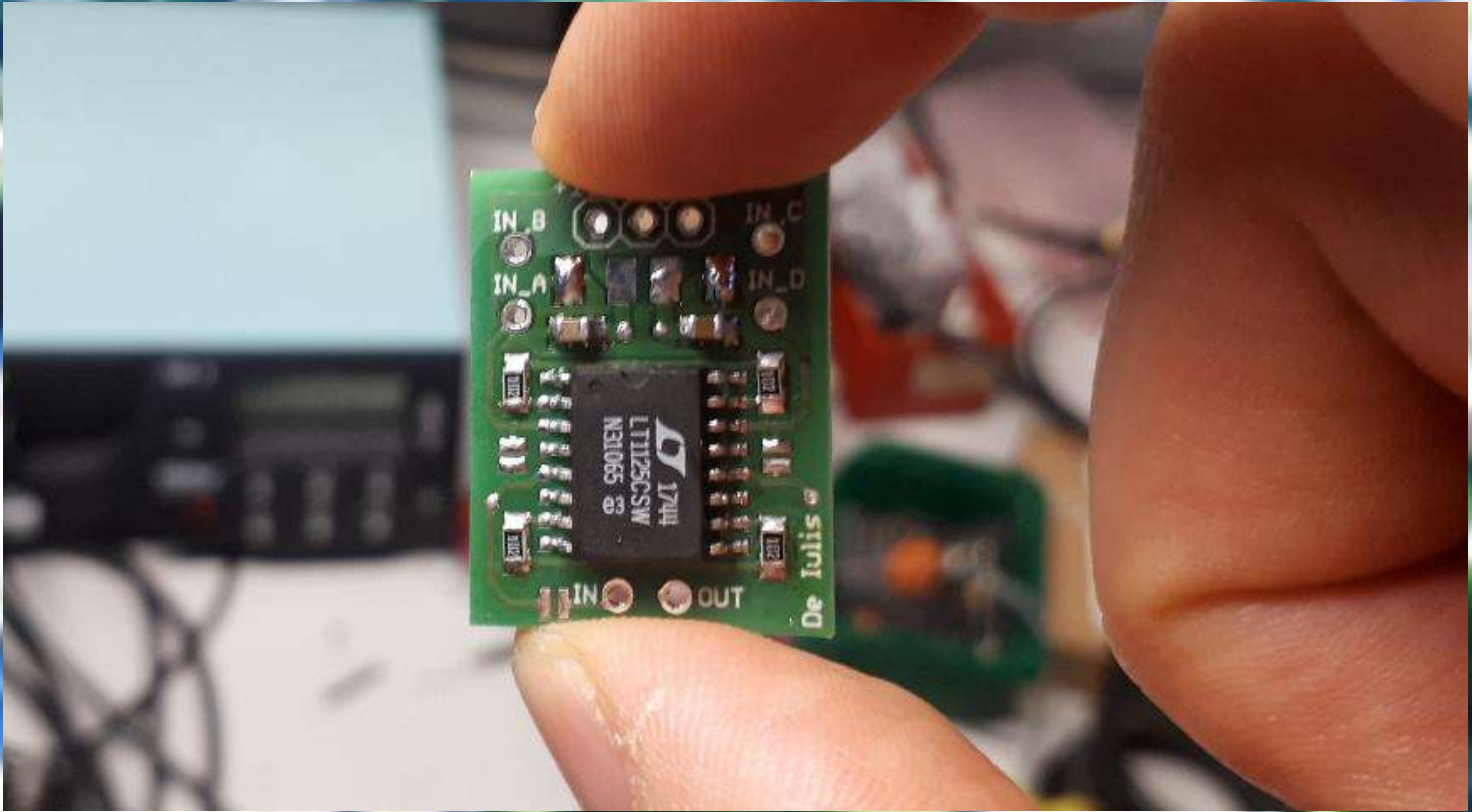
0.1% tolerance, 10ppm thermal drift, 250mW resistors can be easily found.

Axial resistor recommended

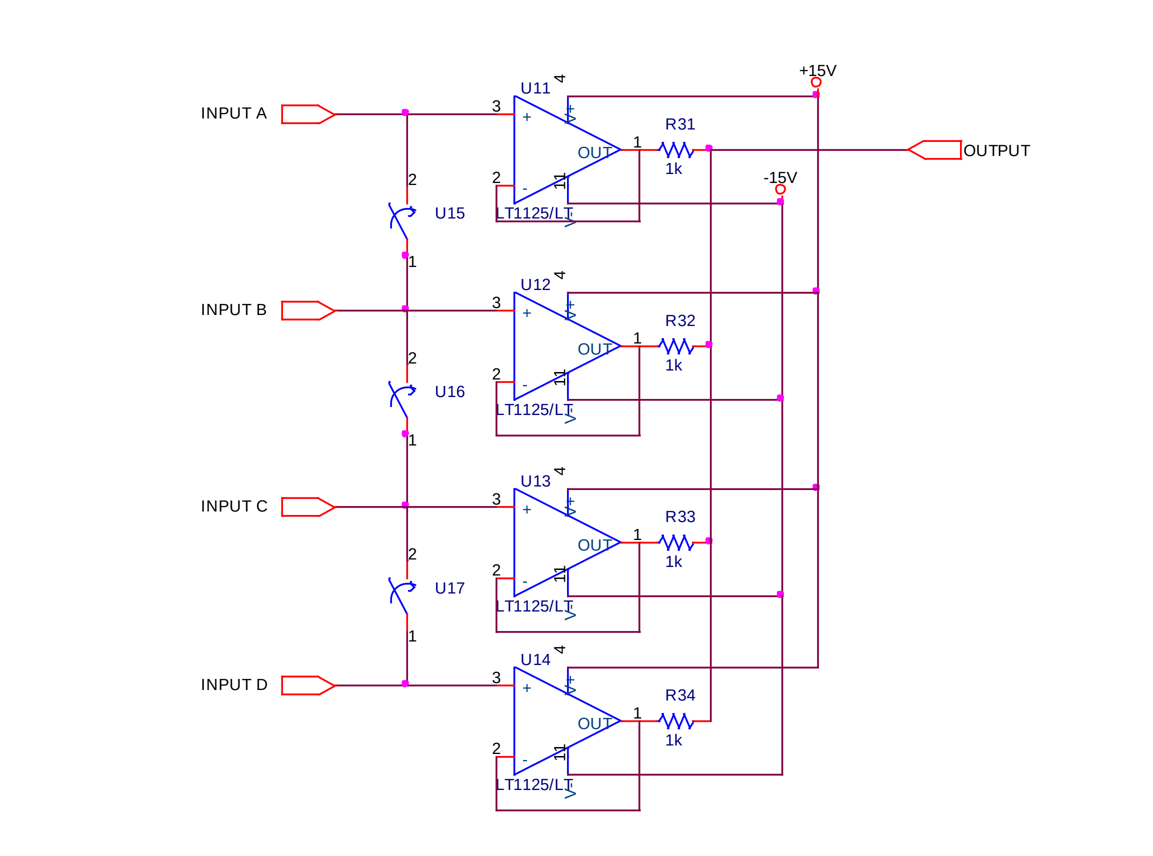
# Solutions

For the driving stage it is necessary to add a block that provides all the current required




IN_B
IN_C
IN_A
IN_D
LT1125CSW
1744
N31065 e3
IN
OUT
De Iulis

# Solutions




This block replaces $R_7$.

Low noise stage (≈2nV).

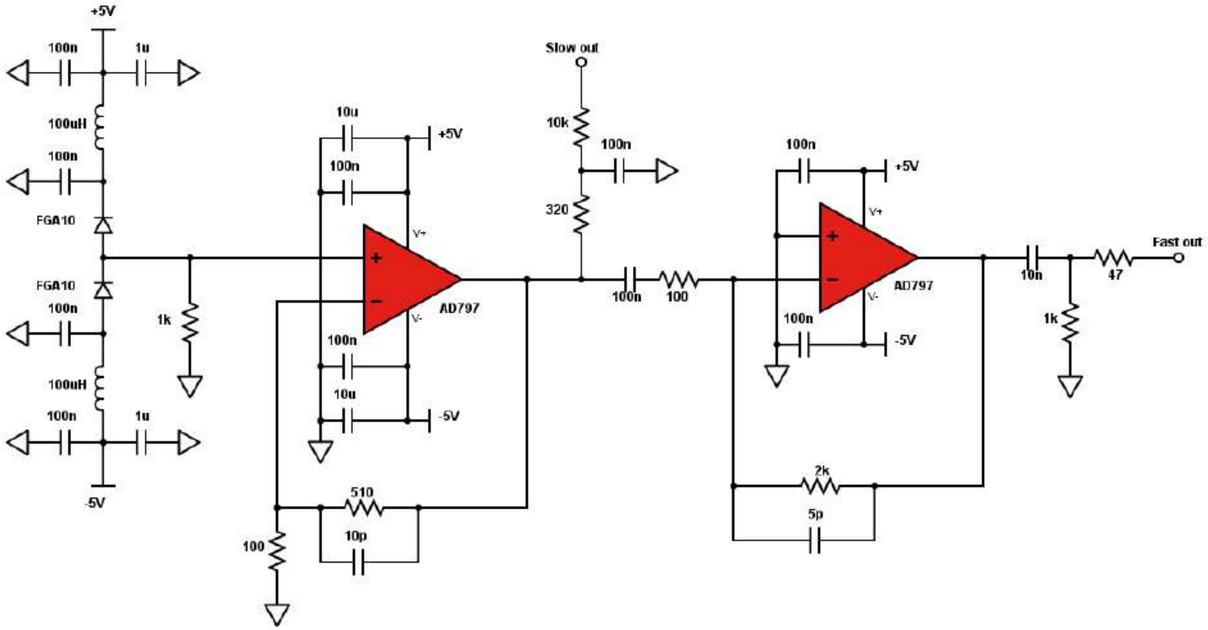
Can give up to 80mA of current.

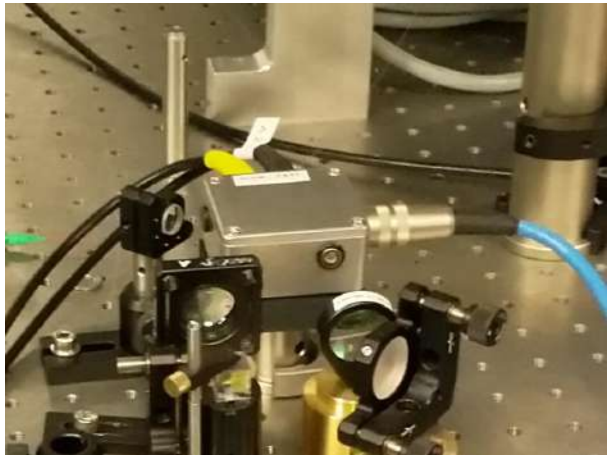
This buffer can also accept four independent inputs.

The combination of four uncorrelated identical sources can reduce noise of a factor 2 compared to the single source.

# Electronics developed for a general homodyne applications.

- Simple pre-Amp configuration
- High dynamic range, necessary to explore all quadratures
- More than 50dB of extinction ratio for intensity noise



Dark noise dominated by Jonhson noise of the shut resistance.

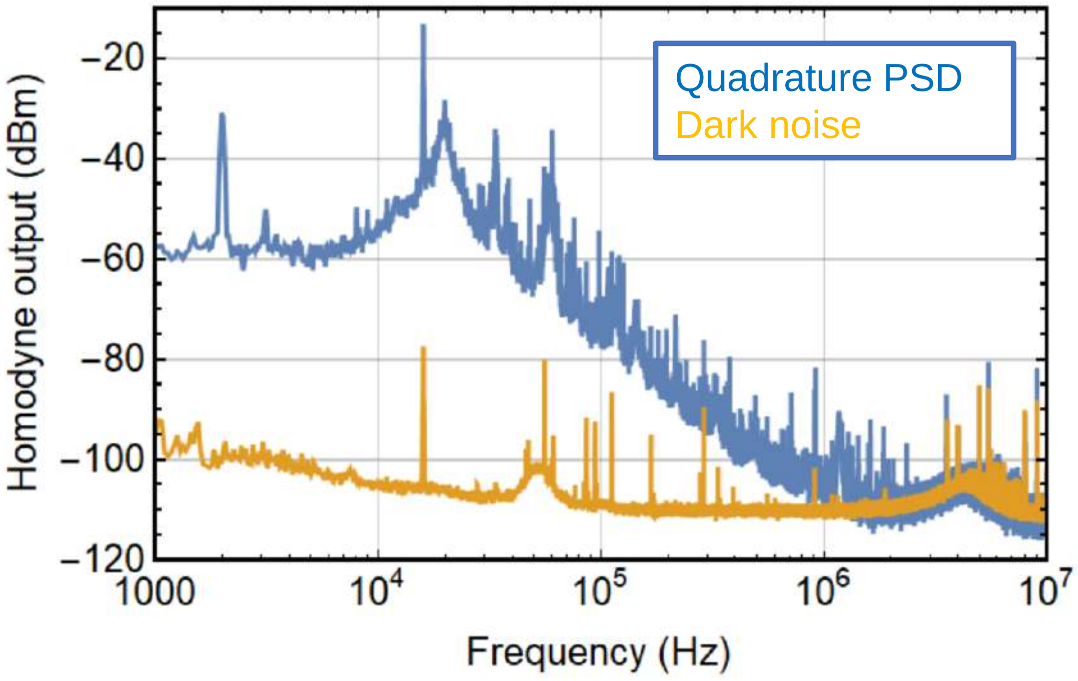
For low powers (big $R_{shunt}$) dark noise can be significantly worst than in typical commercial photodiodes

For high powers (small $R_{shunt}$) the differences reduces.

There's a lot of room to improve and this is something that could be improved by TEQ

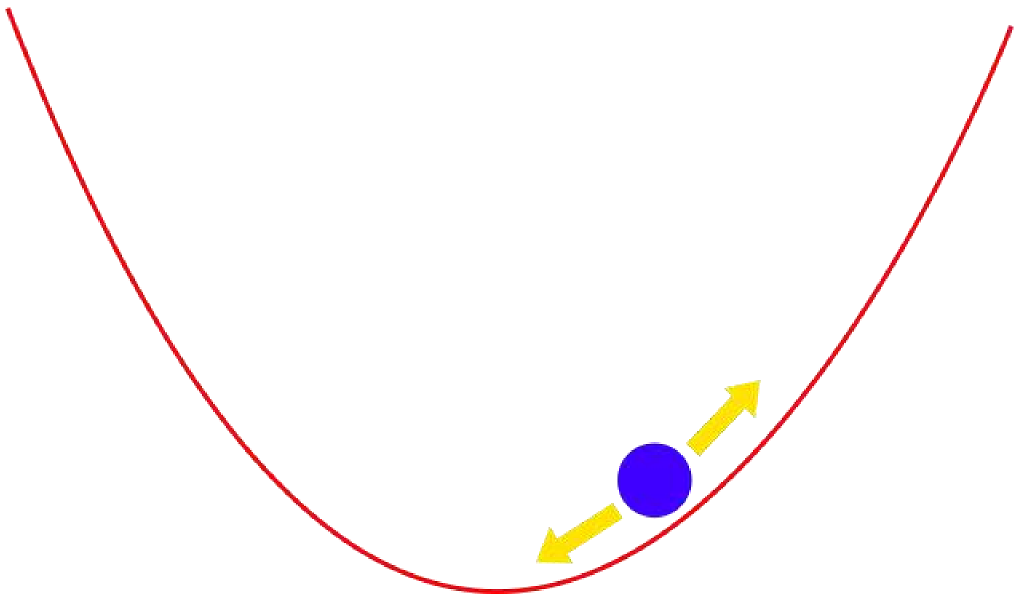
# Phase quadrature of cavity transmitted beam

- Cavity half linewidth ≈ 9 kHz
- Output power ≈ 2 μW

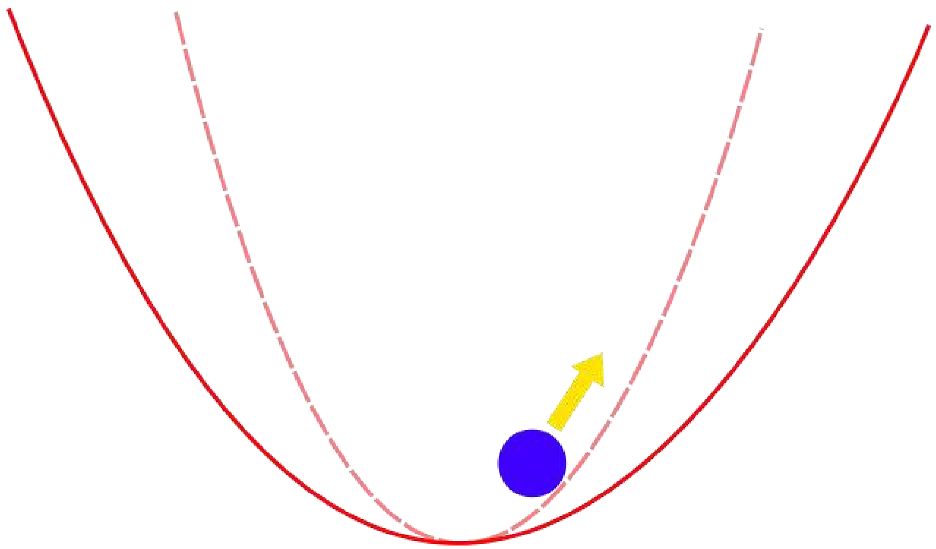



In our typical configuration dark noise becomes relevant only at high frequency and only due to cavity cut-off

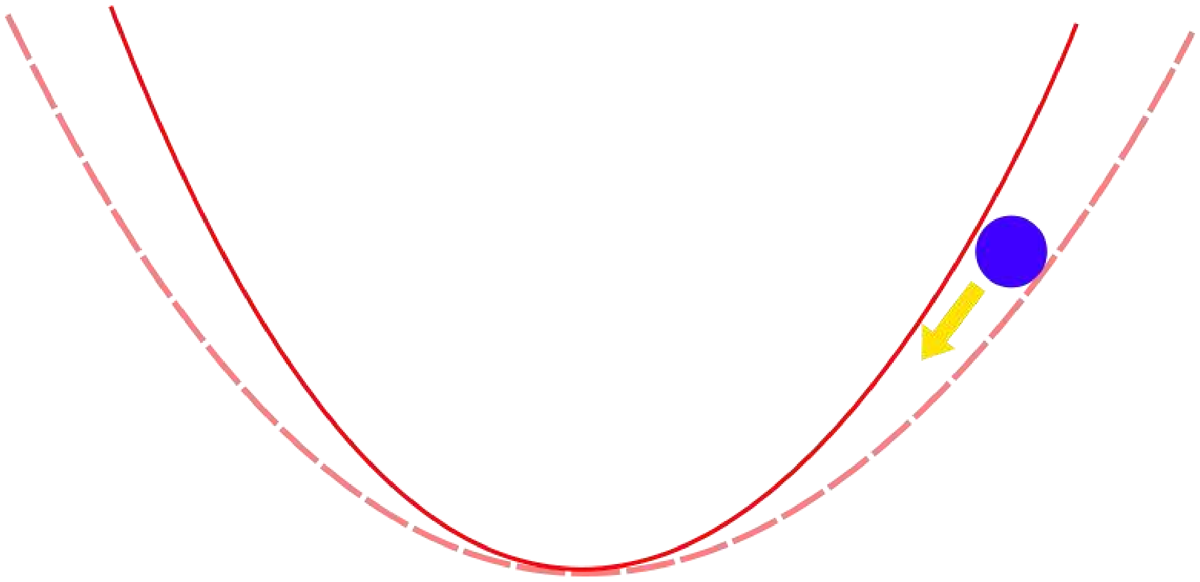
# Optical Electrical - Feedback cooling



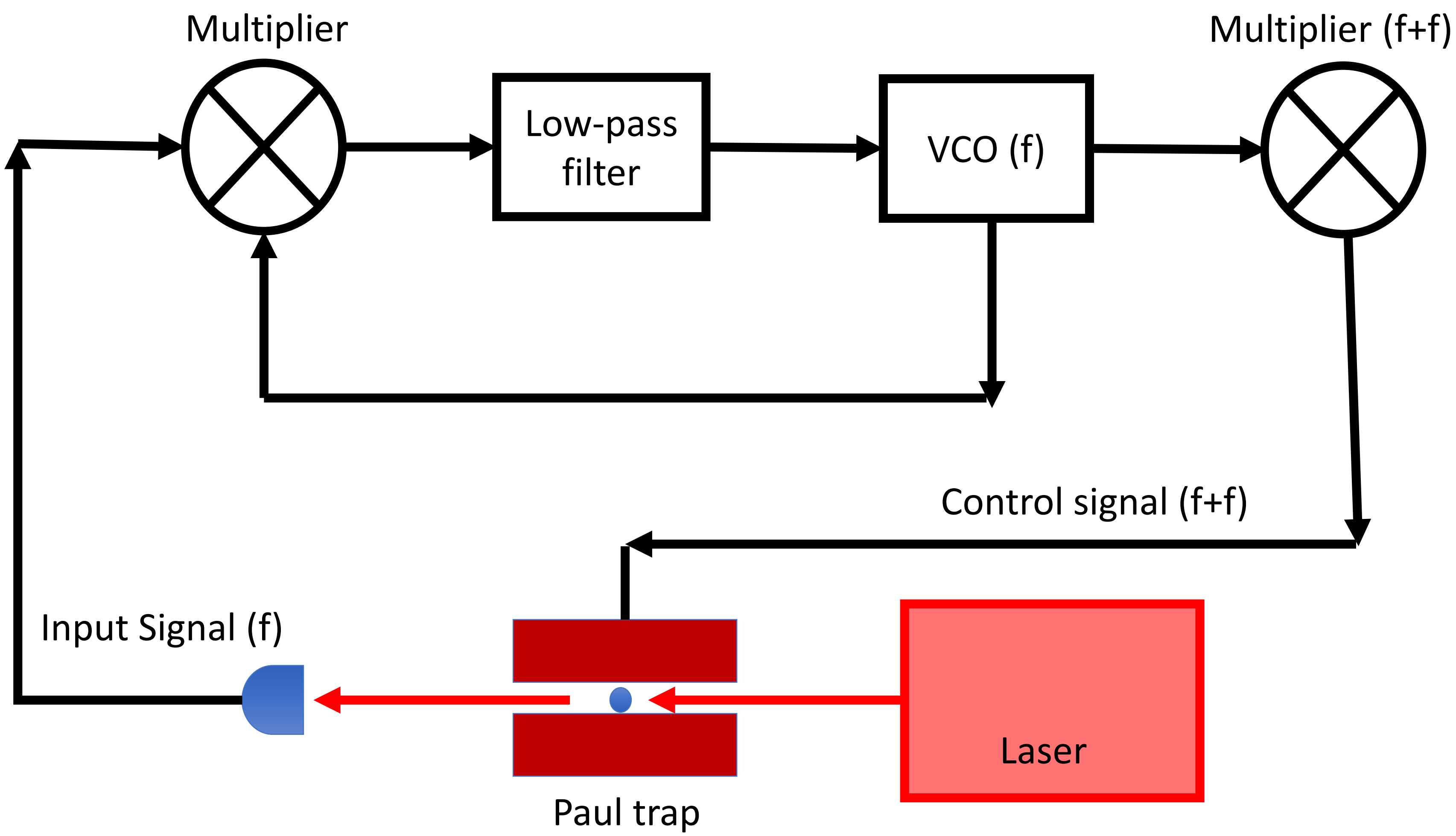
# Increase trap stiffness and slow particle



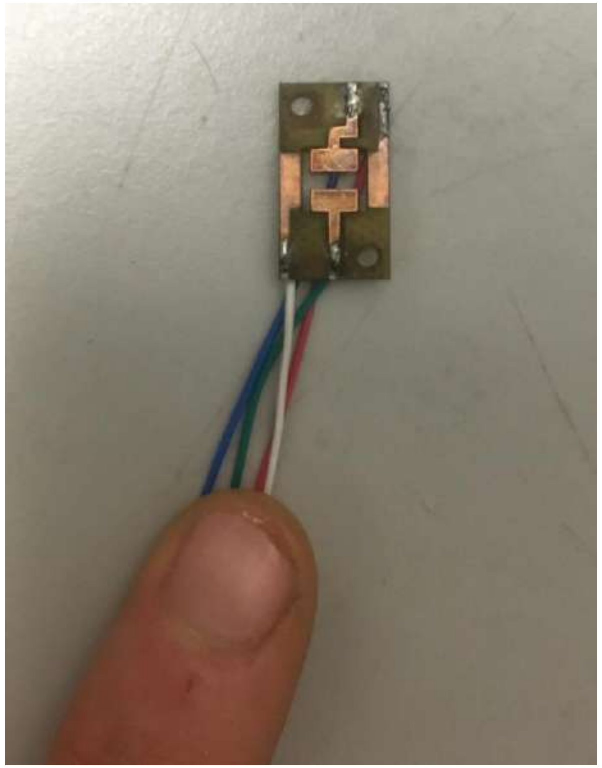
Reduce stiffness so that particle does not gain lost kinetic energy



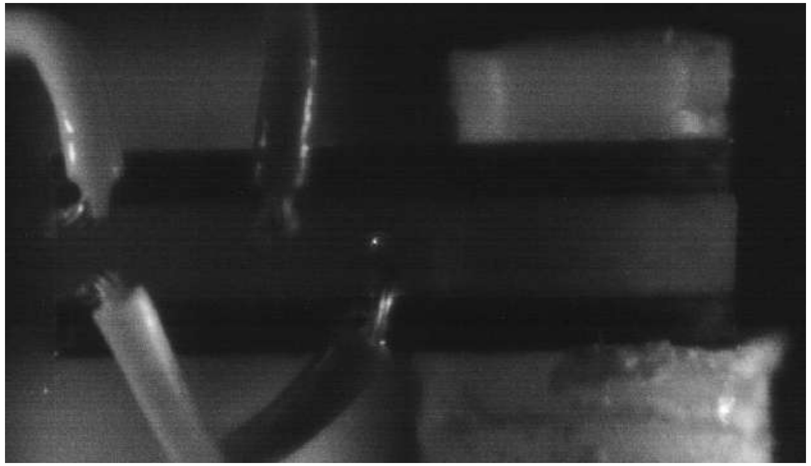
# Optical-electric feedback cooling

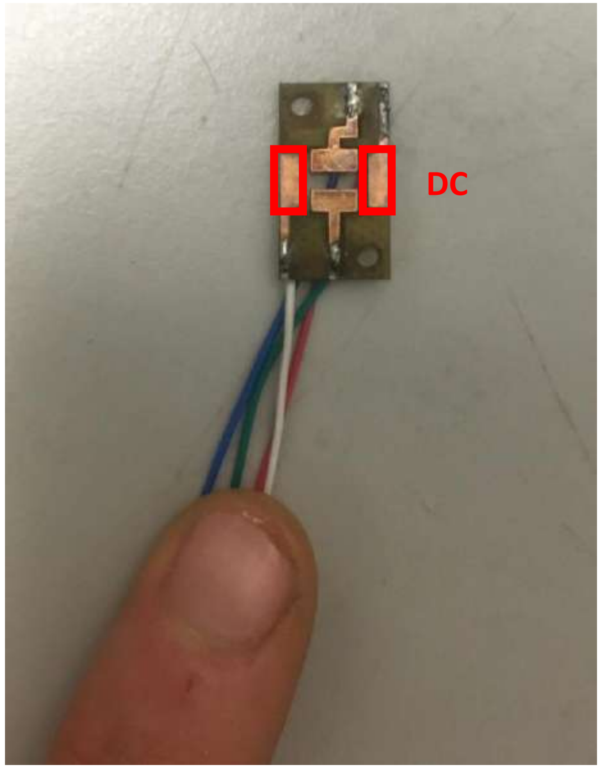


# Demonstration on simple trap

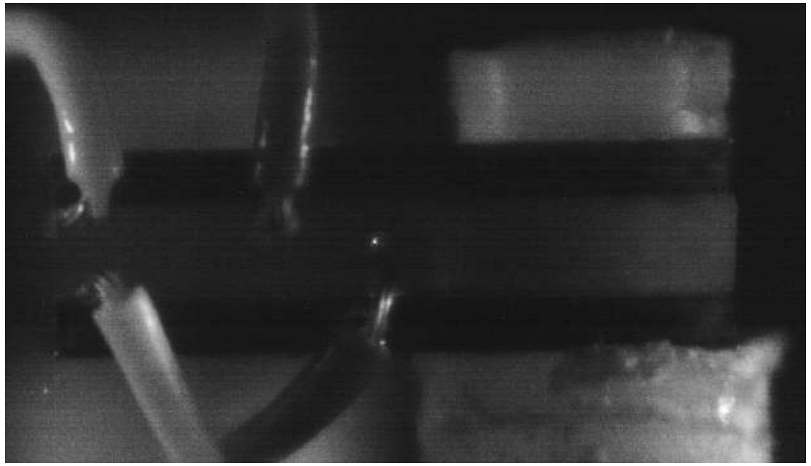


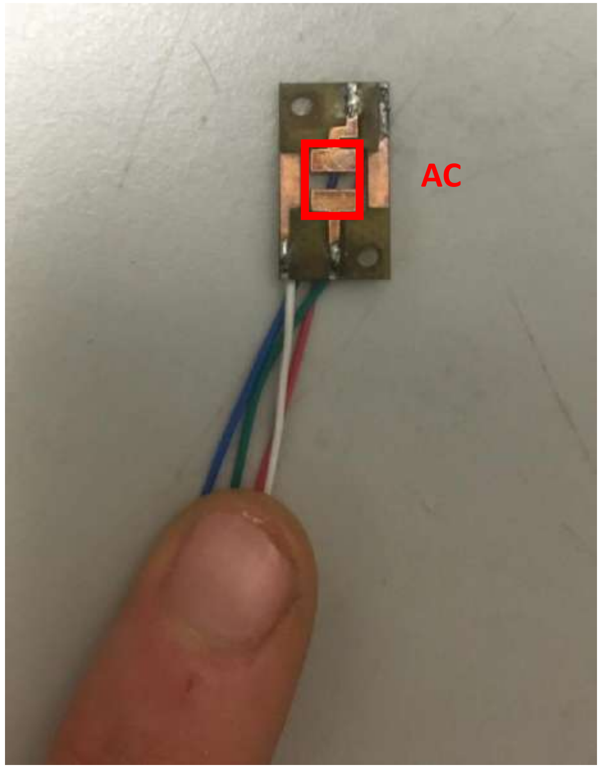
$V_0 = 100V - 450V$
$U_0 = 1V - 30V$
$\omega_d = 2kHz - 8kHz$



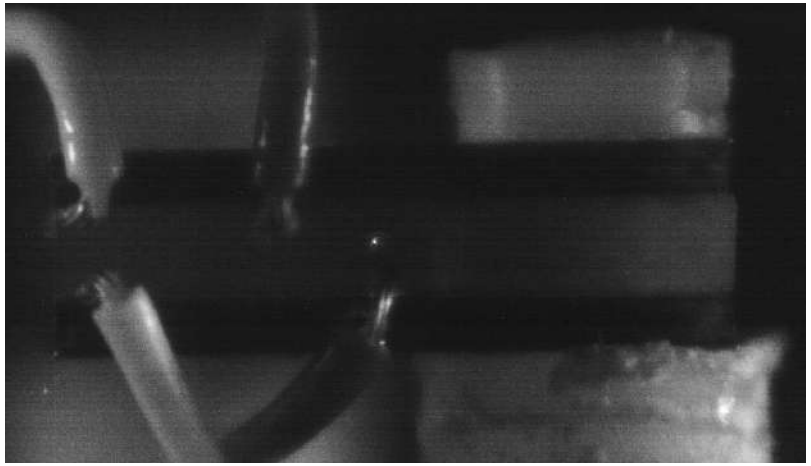


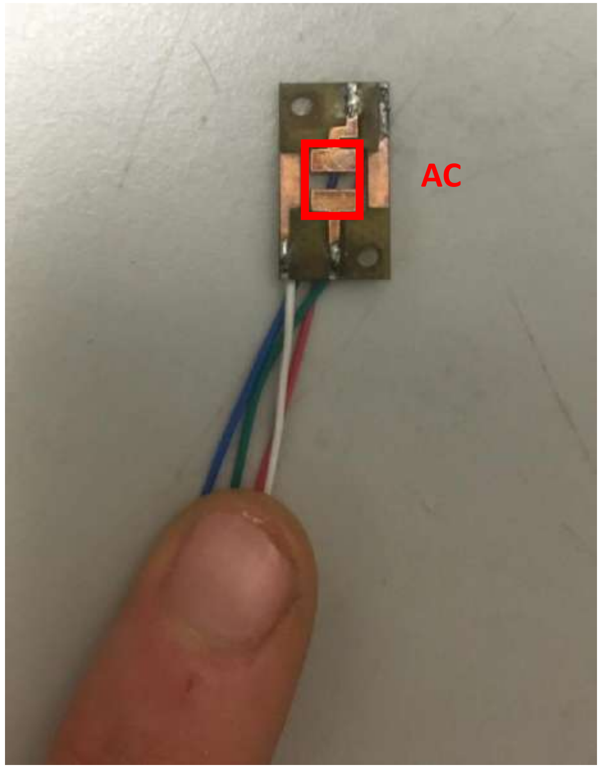

$$V_0 = 100\text{V} - 450\text{V}$$
$$U_0 = 1\text{V} - 30\text{V}$$
$$\omega_d = 2\text{kHz} - 8\text{kHz}$$



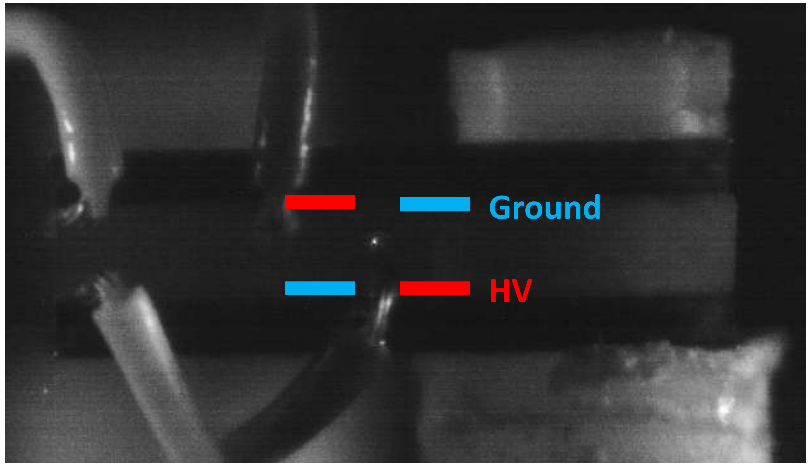



$$V_0 = 100V - 450V$$
$$U_0 = 1V - 30V$$
$$\omega_d = 2kHz - 8kHz$$

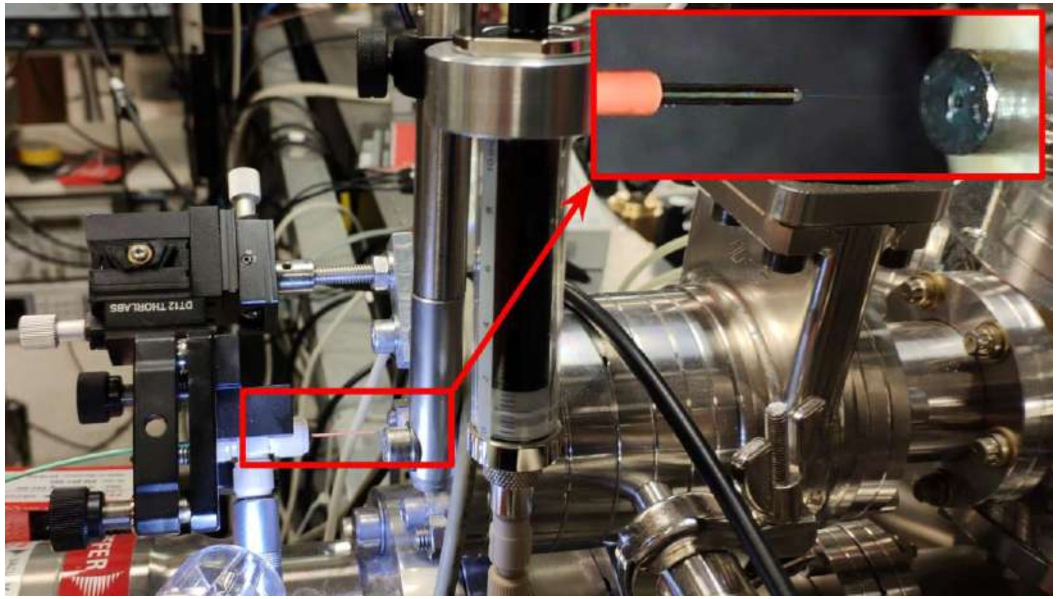


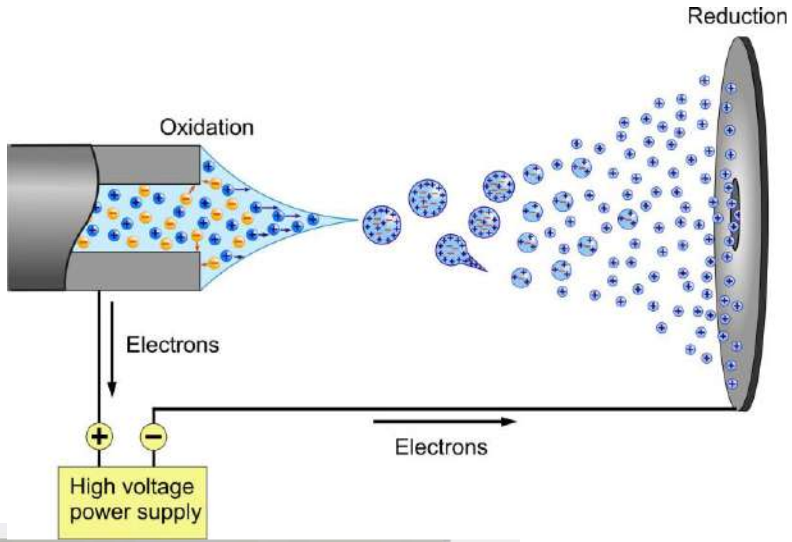


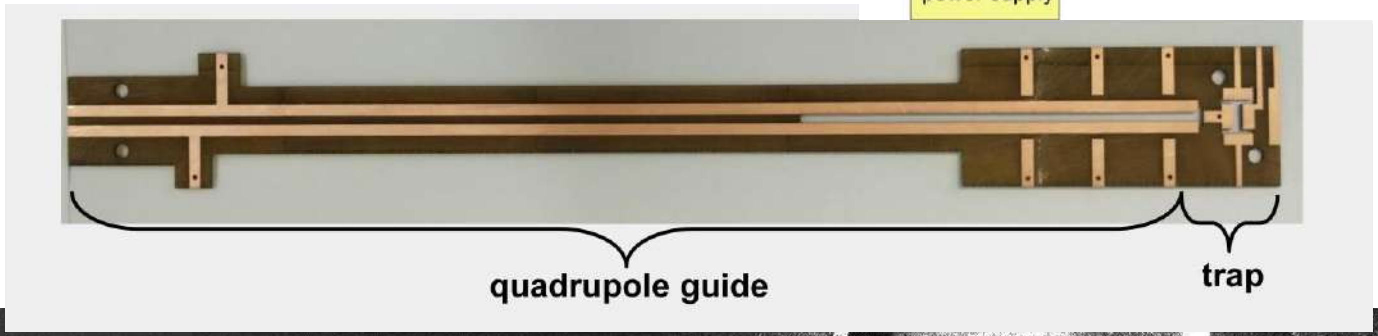

$$V_0 = 100V - 450V$$
$$U_0 = 1V - 30V$$
$$\omega_d = 2kHz - 8kHz$$

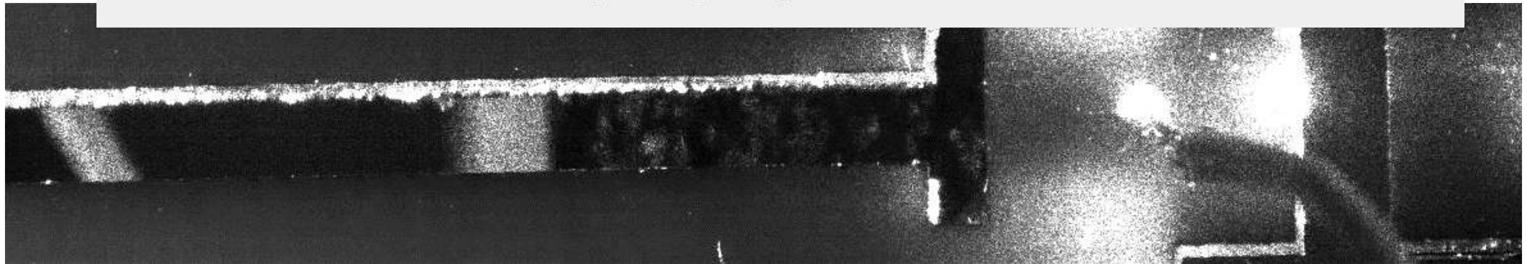


# Trap loading with Electrospray

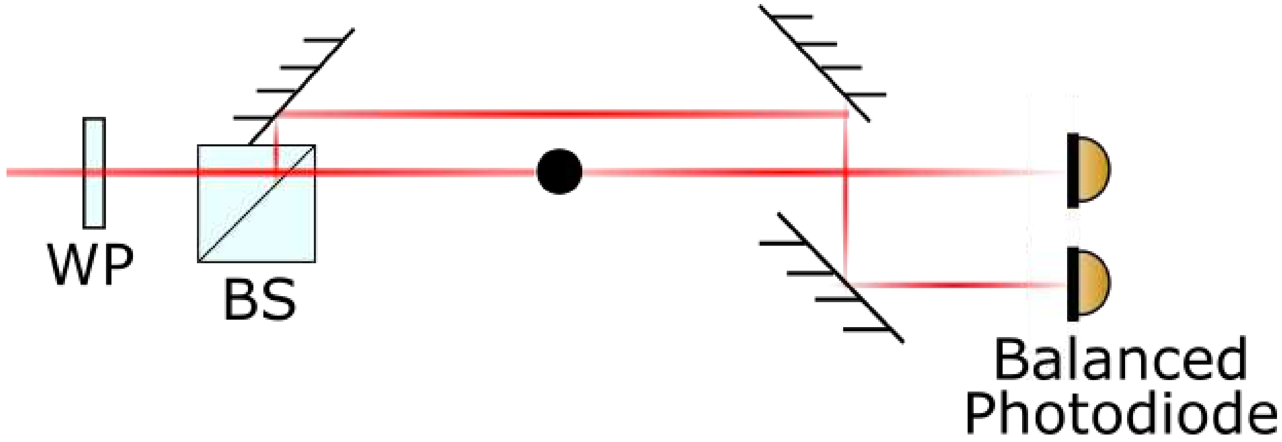




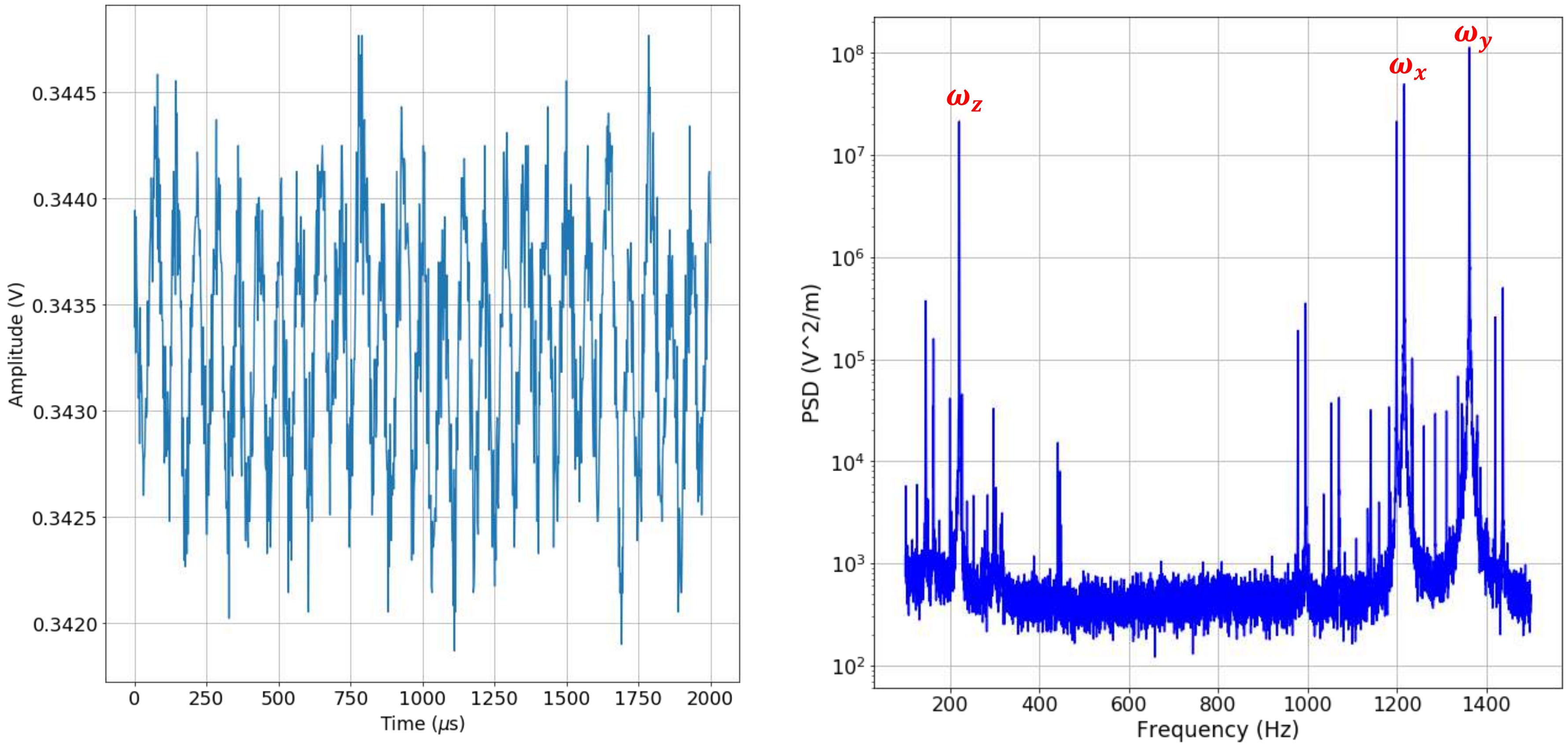



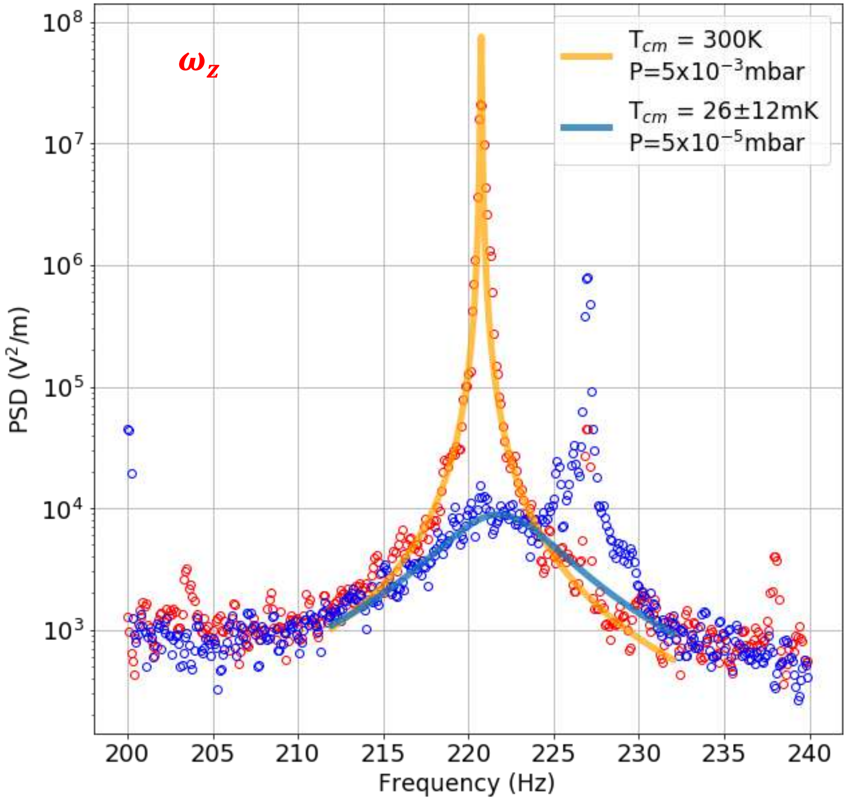
# Homodyne detection of motion




# Recorded Spectra



# Cooled spectra




$$S_x(x) = \frac{\Gamma_0 k_B T/(\pi m)}{([\Omega_0{}^2 + \delta\Omega^2]^2)^2 + \Omega^2[\Gamma_0 + \delta\Gamma]^2}$$

$$T_{cm} = T_0 \frac{\Gamma_0}{\Gamma_0 + \delta\Gamma}$$

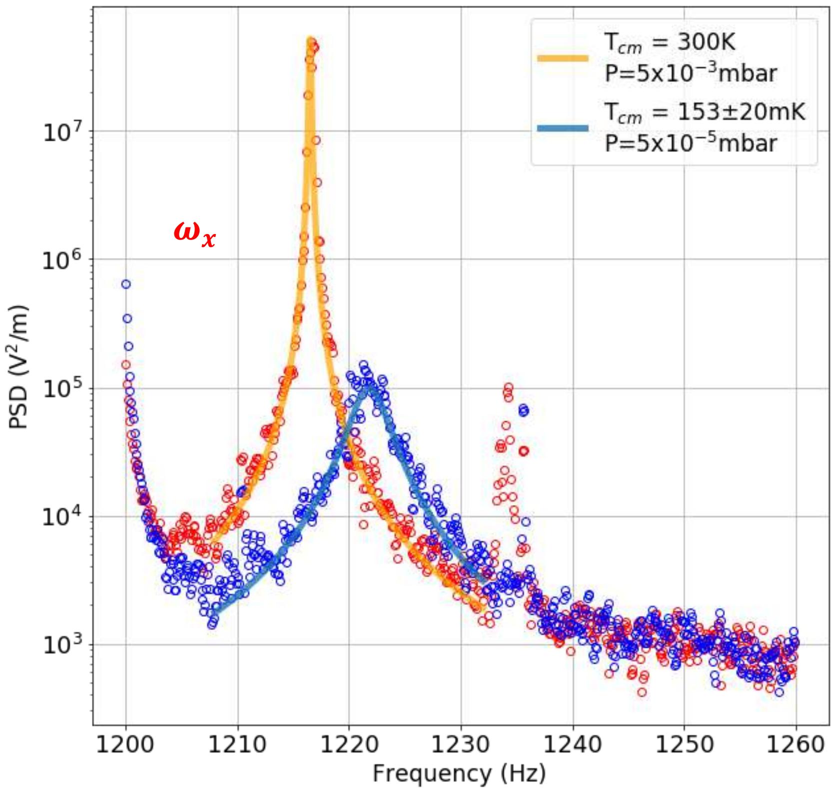
$\Gamma_0$ Environmental Damping

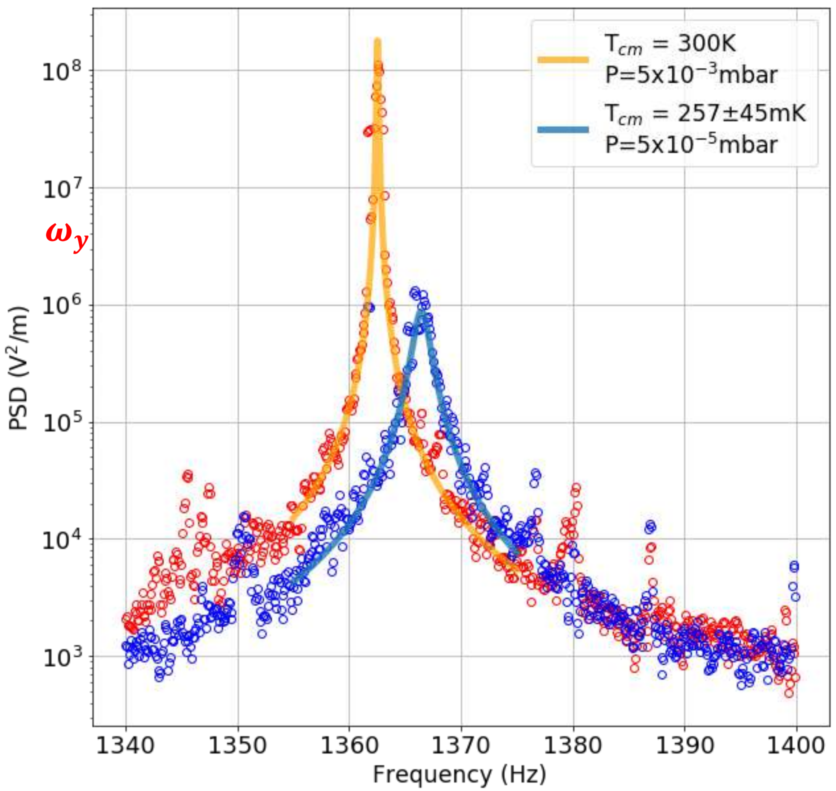
$\delta\Gamma$ Additional Feedback Damping

$\Omega_0$ Natural Frequency

$\delta\Omega$ Frequency Shift from Feedback

# Cooled spectra

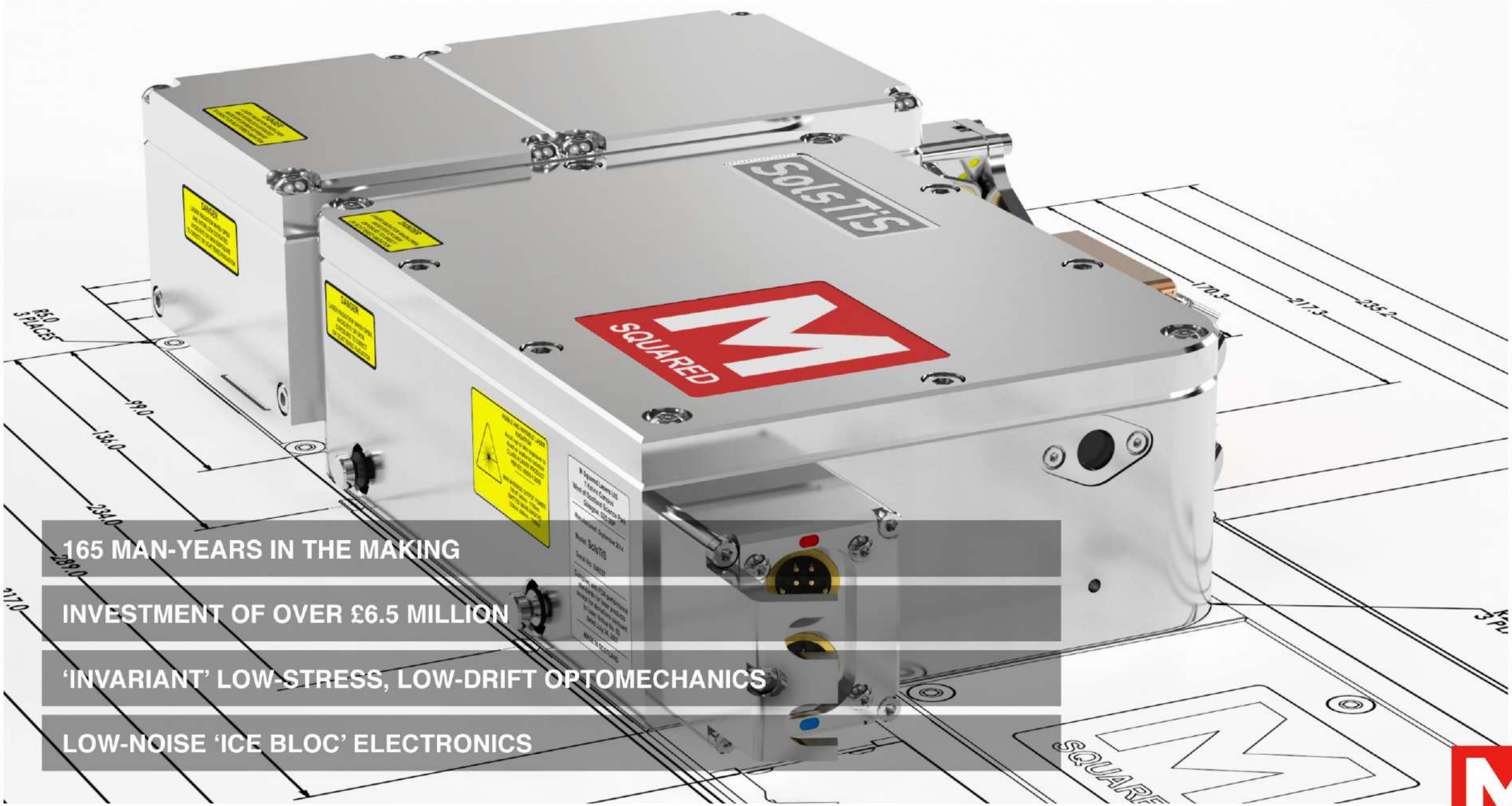



Temperatures down to mK suitable to begin experiments
Requirements of $10^{-13}$ mbar to reduce effects of particle heating
Better detection – via cavity required for lower temperatures (discussion WP3)
Careful reduction of stray fields

# TEQ Period 1 Review

26th February 2019
Stefan Olsson Robbie - Project Manager Innovation




165 MAN-YEARS IN THE MAKING

INVESTMENT OF OVER £6.5 MILLION

‘INVARIANT’ LOW-STRESS, LOW-DRIFT OPTOMECHANICS

LOW-NOISE ‘ICE BLOC’ ELECTRONICS

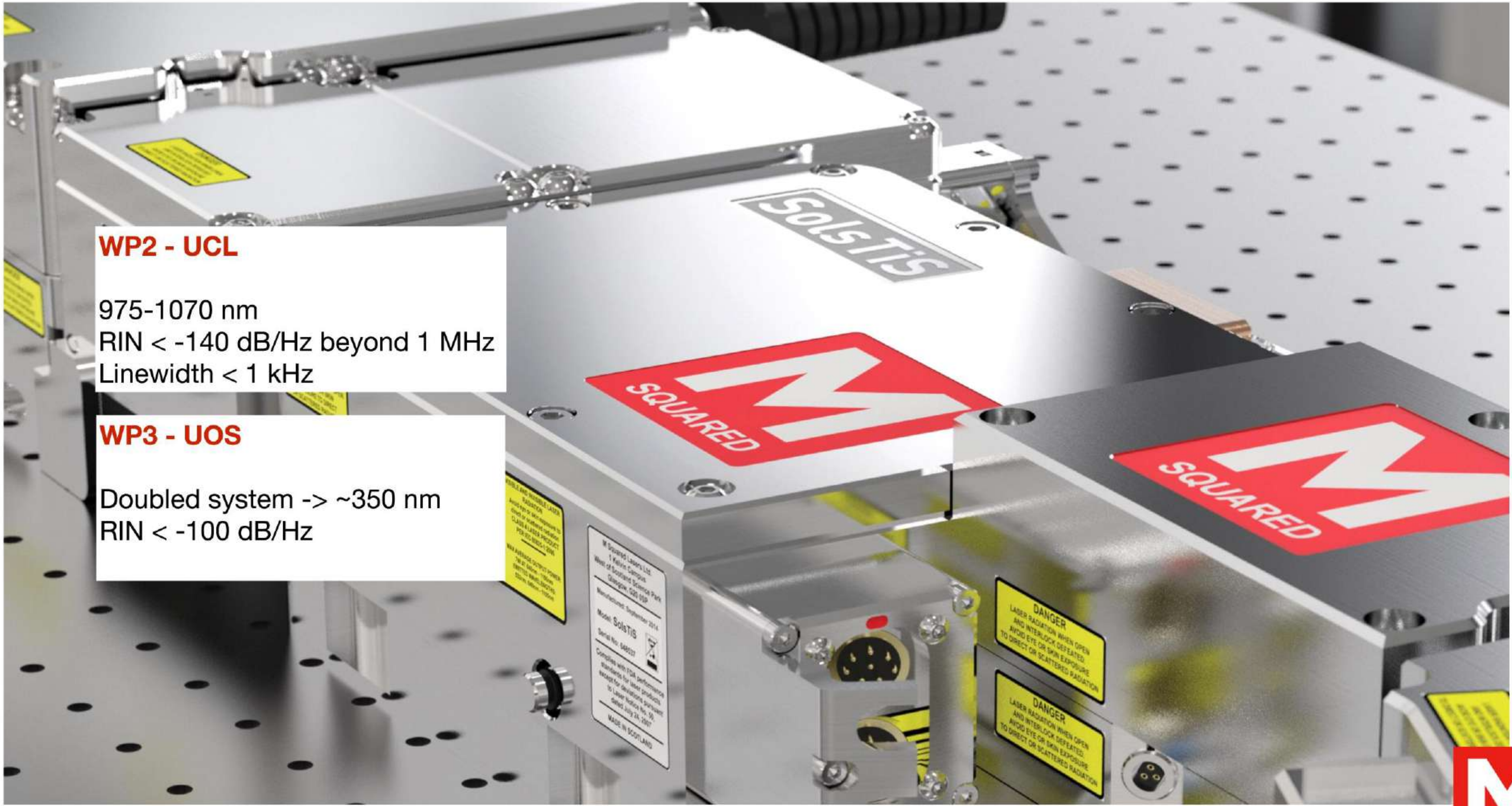
M SQUARED

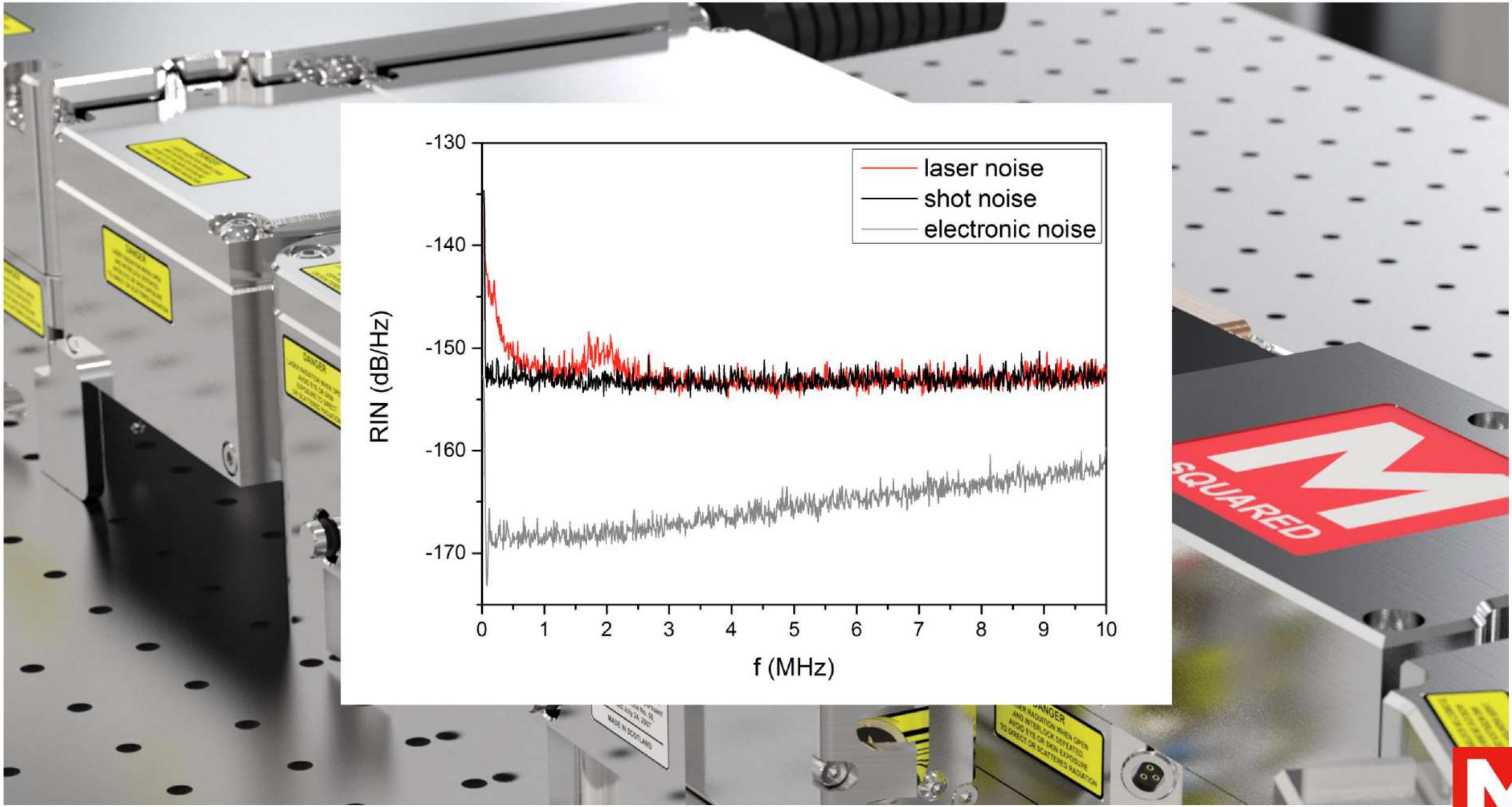
**WP2 - UCL**

975-1070 nm
RIN < -140 dB/Hz beyond 1 MHz
Linewidth < 1 kHz

**WP3 - UOS**

Doubled system -> ~350 nm
RIN < -100 dB/Hz




SQUARED
laser noise
shot noise
electronic noise
RIN (dB/Hz)
f (MHz)
-130
-140
-150
-160
-170
0
1
2
3
4
5
6
7
8
9
10

M SQUARED

## Linewidth Narrowing


**Laser**

- Intracavity EOM
- External AOM

**Stable Reference**

- SLS cavity
  - Ion pump
  - Vibration isolation
  - Temp control- Tolerable drift rate: Hz/s?
  - Acoustic housing

**Stable Light Transfer**

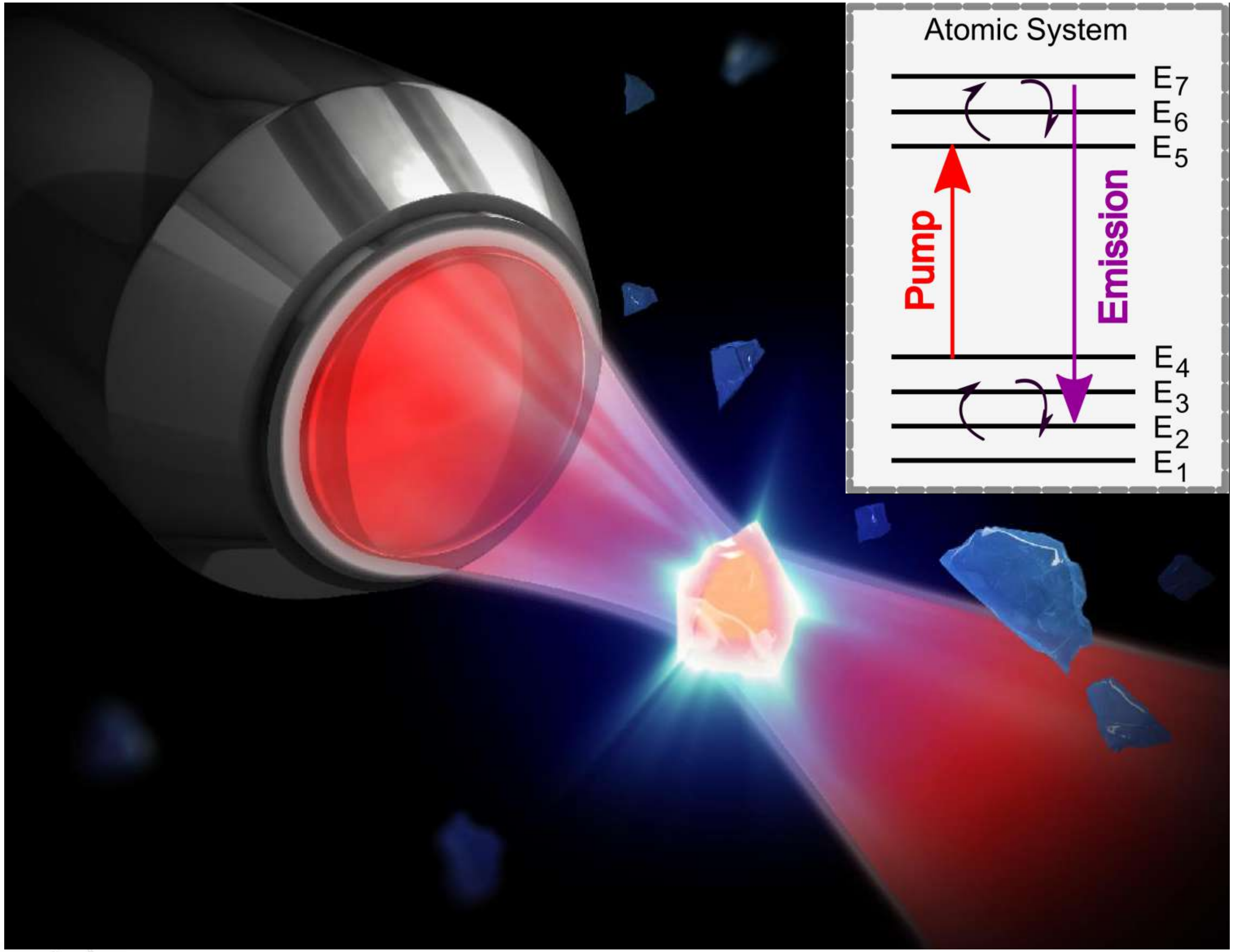
- Fibre phase noise cancellation ?

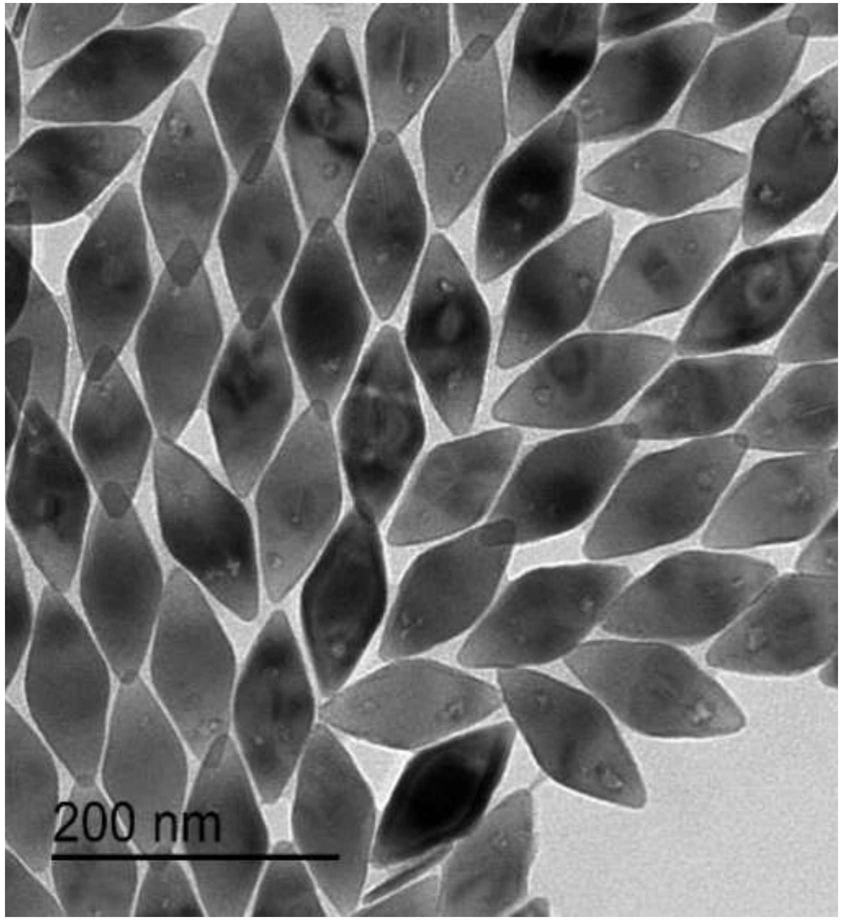
**Error Signal Generation**

- M Squared developing proprietary locking technology

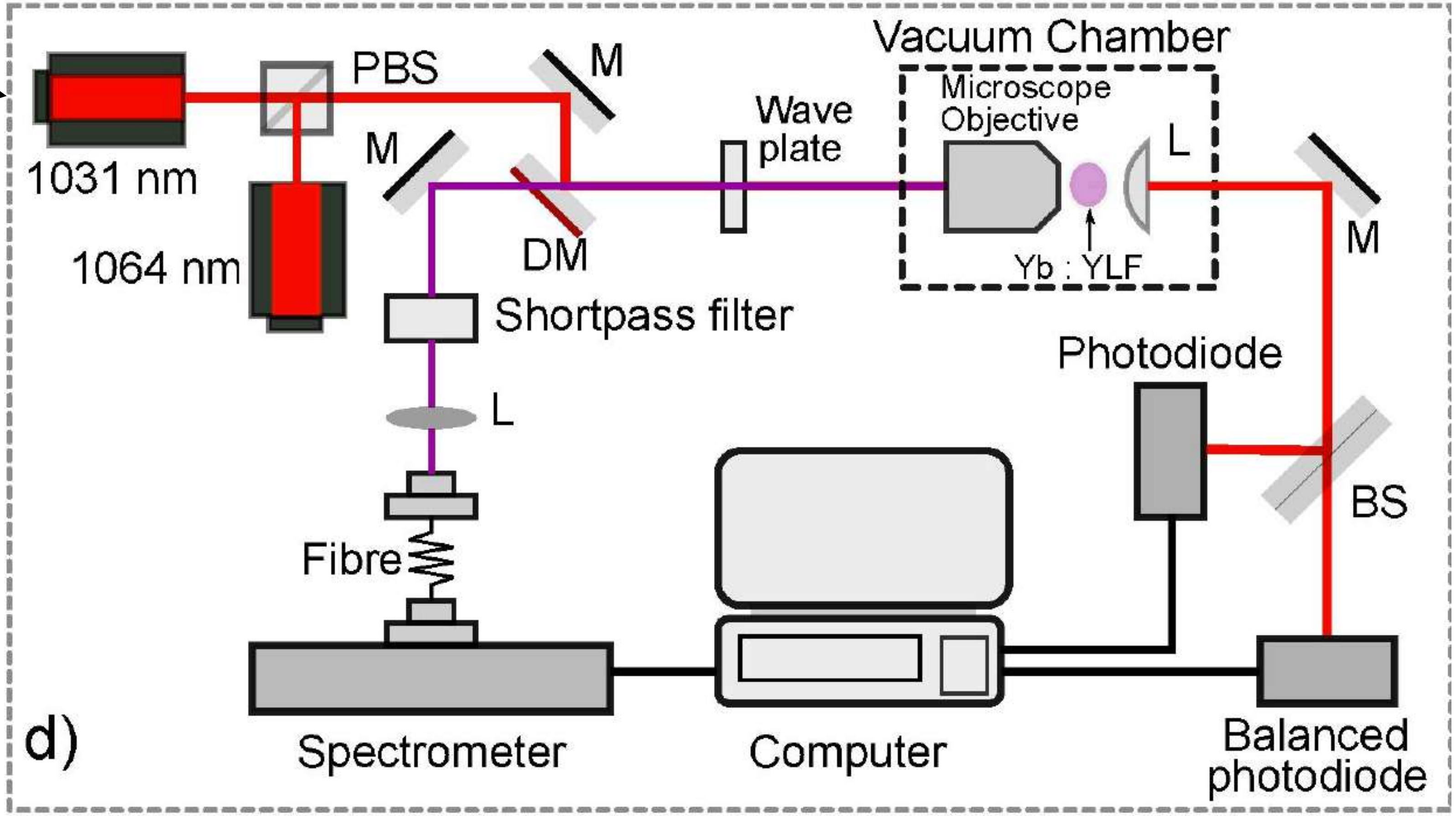
M SQUARED

# Internal cooling

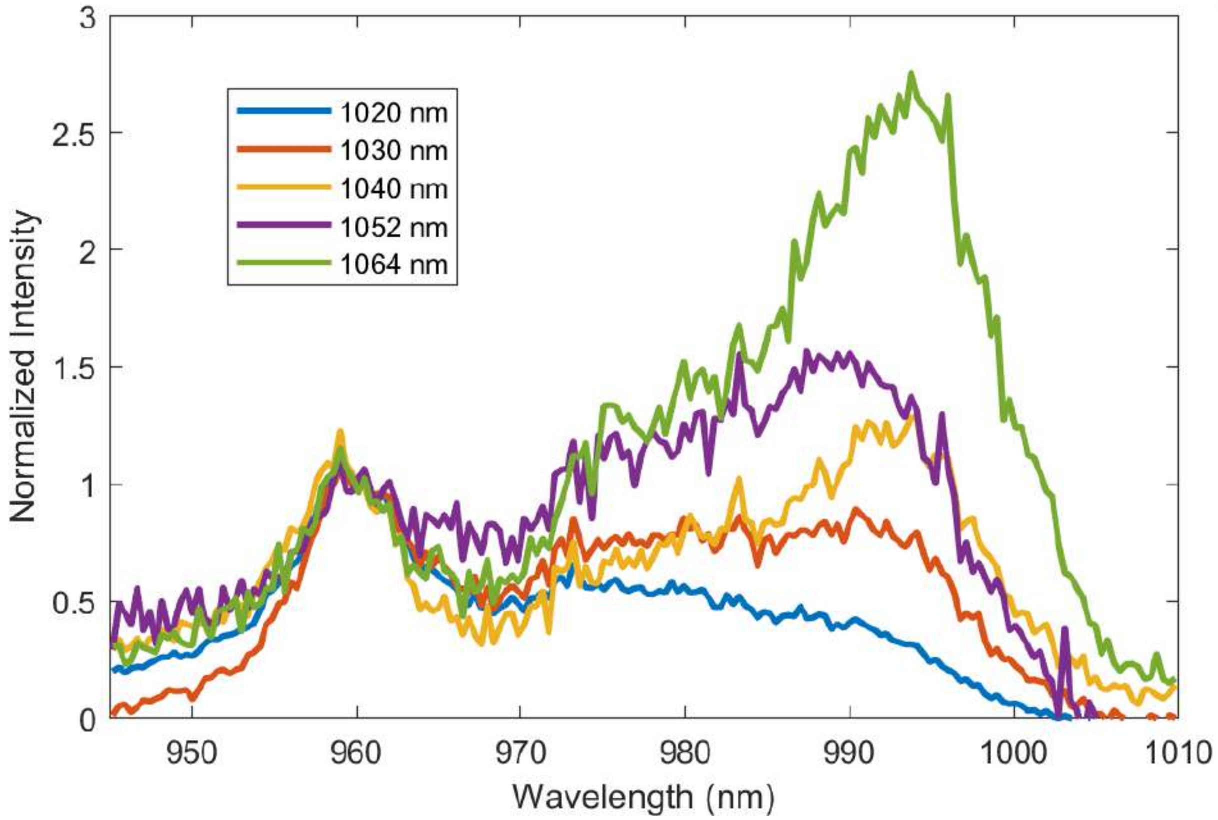


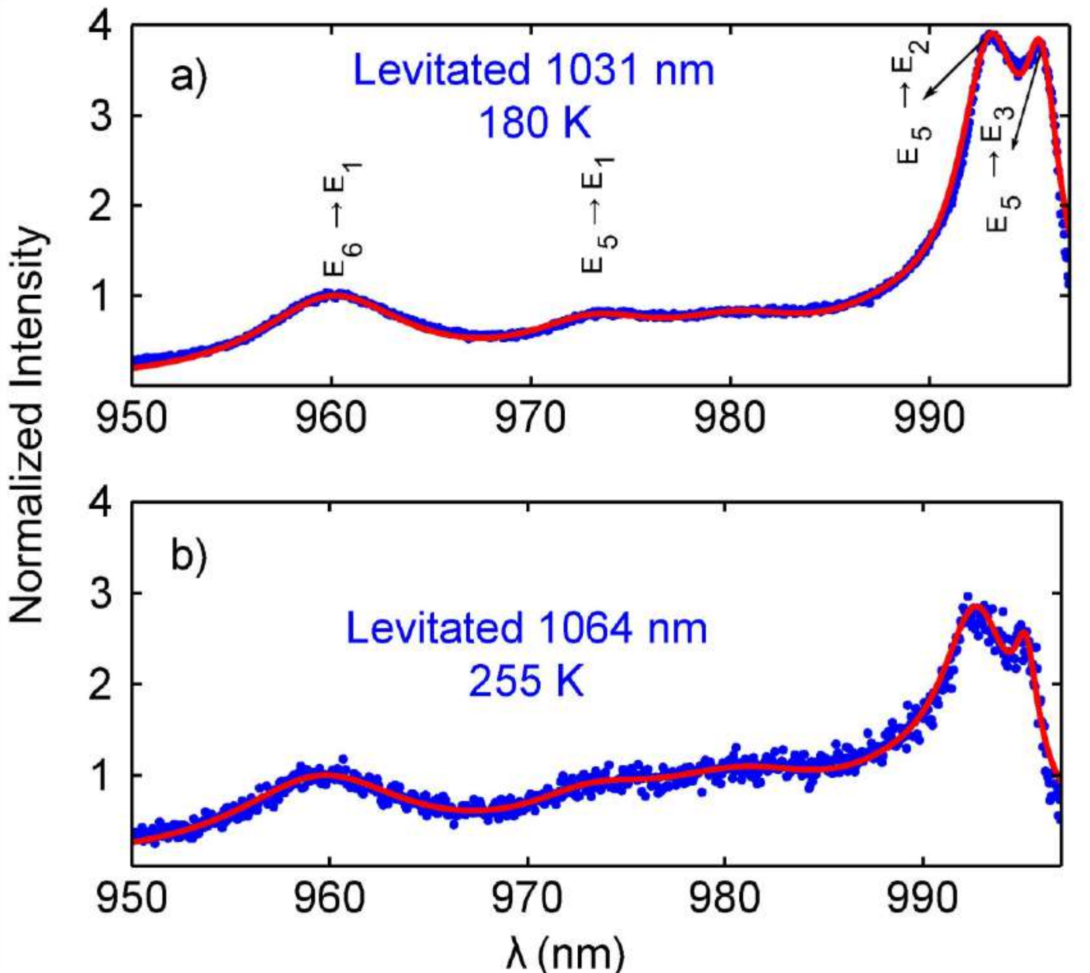
# New laser system from M2 allows us to tune from 975 -1075 nm



# Spectra recorded of new Yb:YLF nanocrystals



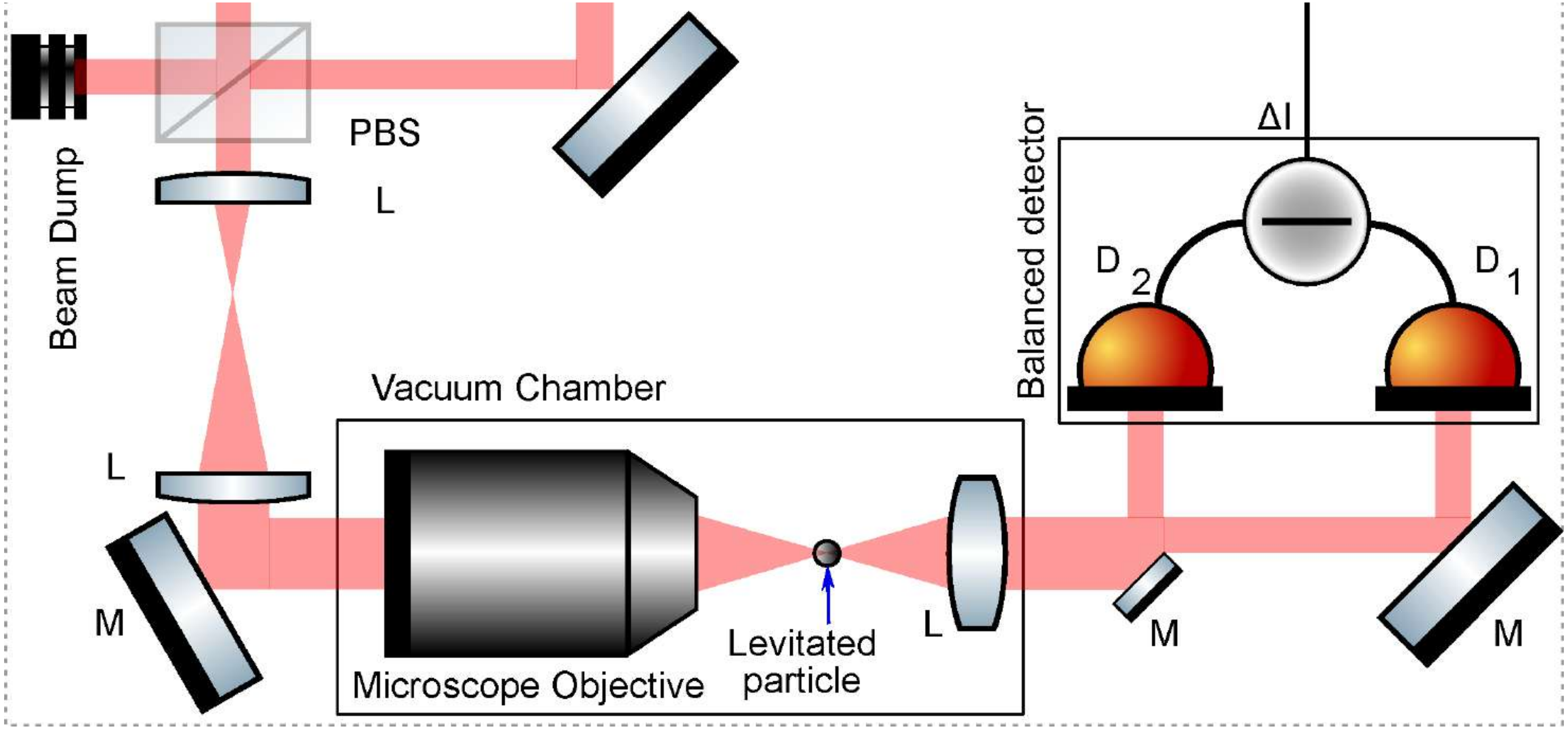

Can compare with previous results –
Appear to have low temperatures 200 K




Temp. from Boltzmann distr. - $\frac{1}{T} = \frac{1}{T_0} + \frac{k_B}{\Delta E_{65}} \ln \frac{R}{R_0}$

where $R = \frac{I(E_6 \rightarrow E_1)}{I(E_5 \rightarrow E_2)}$ at T and $R_0 = \frac{I(E_6 \rightarrow E_1)}{I(E_5 \rightarrow E_2)}$ at $T_0$

# Single beam homodyne detection



# Trap frequencies at 5 mBar

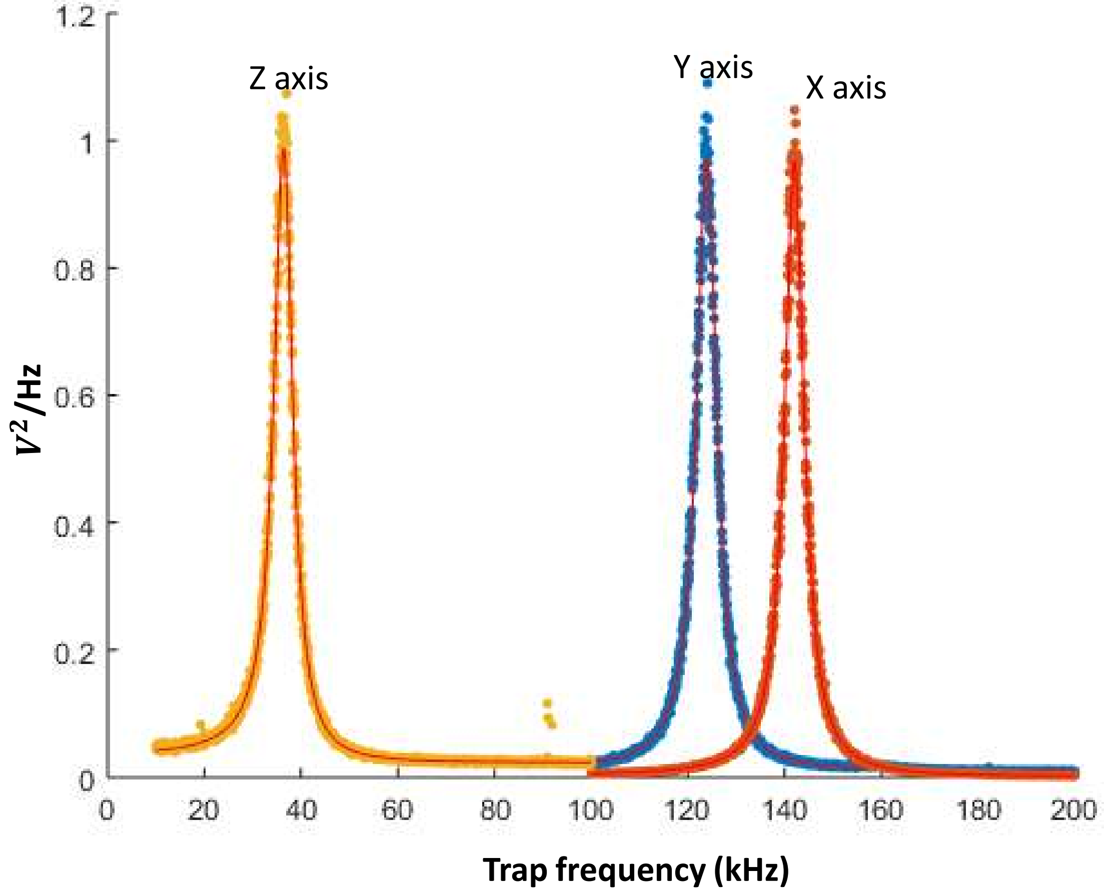
- Power spectral density

$$S_x(\omega) = \frac{2k_BT}{M}\frac{\gamma}{(\omega^2-{\omega_0}^2)^2+\gamma^2\omega^2}$$

- Temperature and damping are related as - $T \propto \gamma^2$

- Assume

$$T = T_{cal}\frac{\gamma^2}{\gamma_{cal}^2}$$

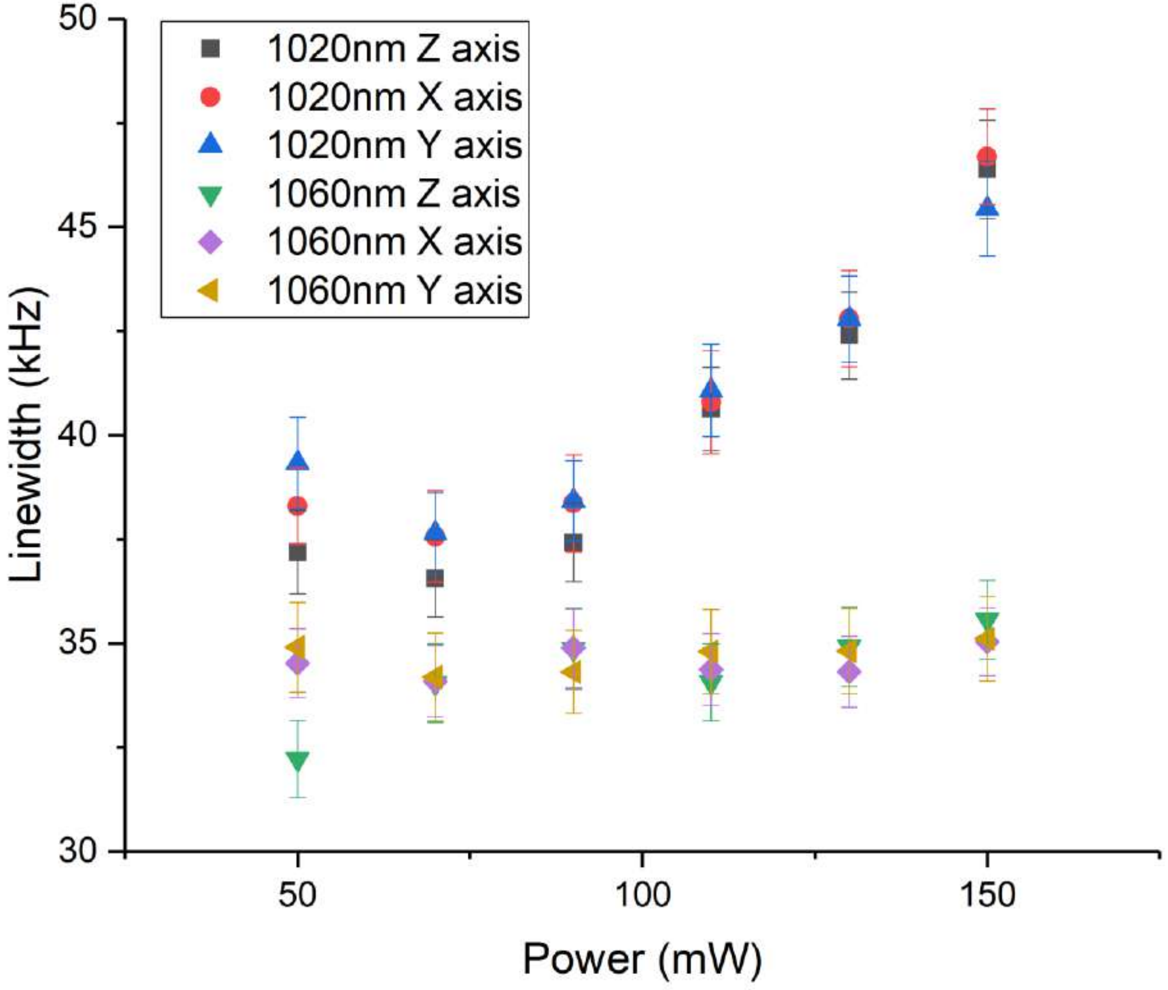


# Linewidth with power (5mbar)

Collisions -> Internal T leads to centre of mass temperature.

Assuming initial temperature of 1020 nm at 50 mW was $T_{CM}$=300 K .

Highest temperature was $T_{CM}$=(440±10) K.

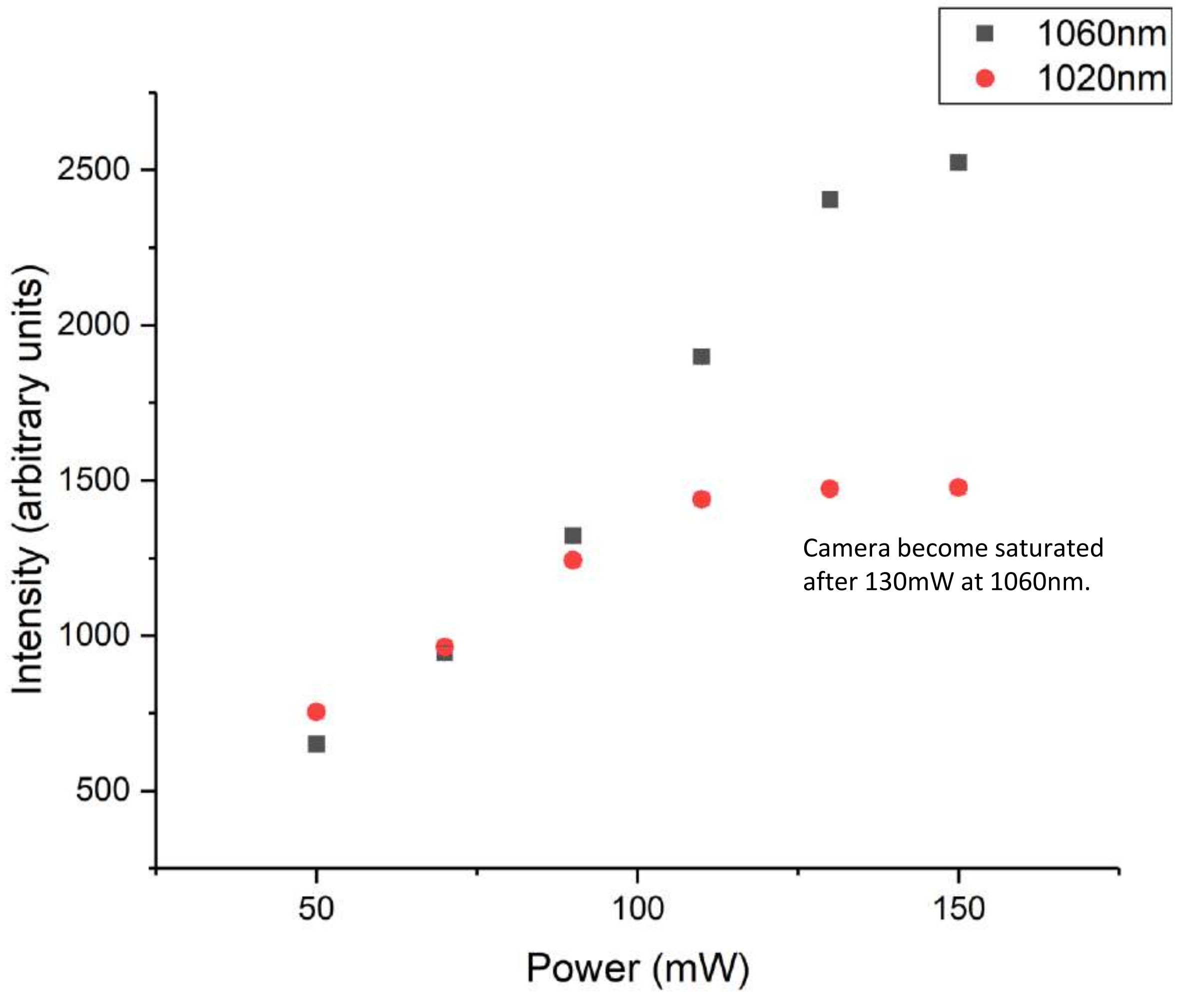


# Intensity vs Power at 5mbar

Scattered intensity ~ particle volume

1020 nm light intensity reduces at higher power - reducing in size.

Also agrees with increase in linewidth observed above 90 mW.

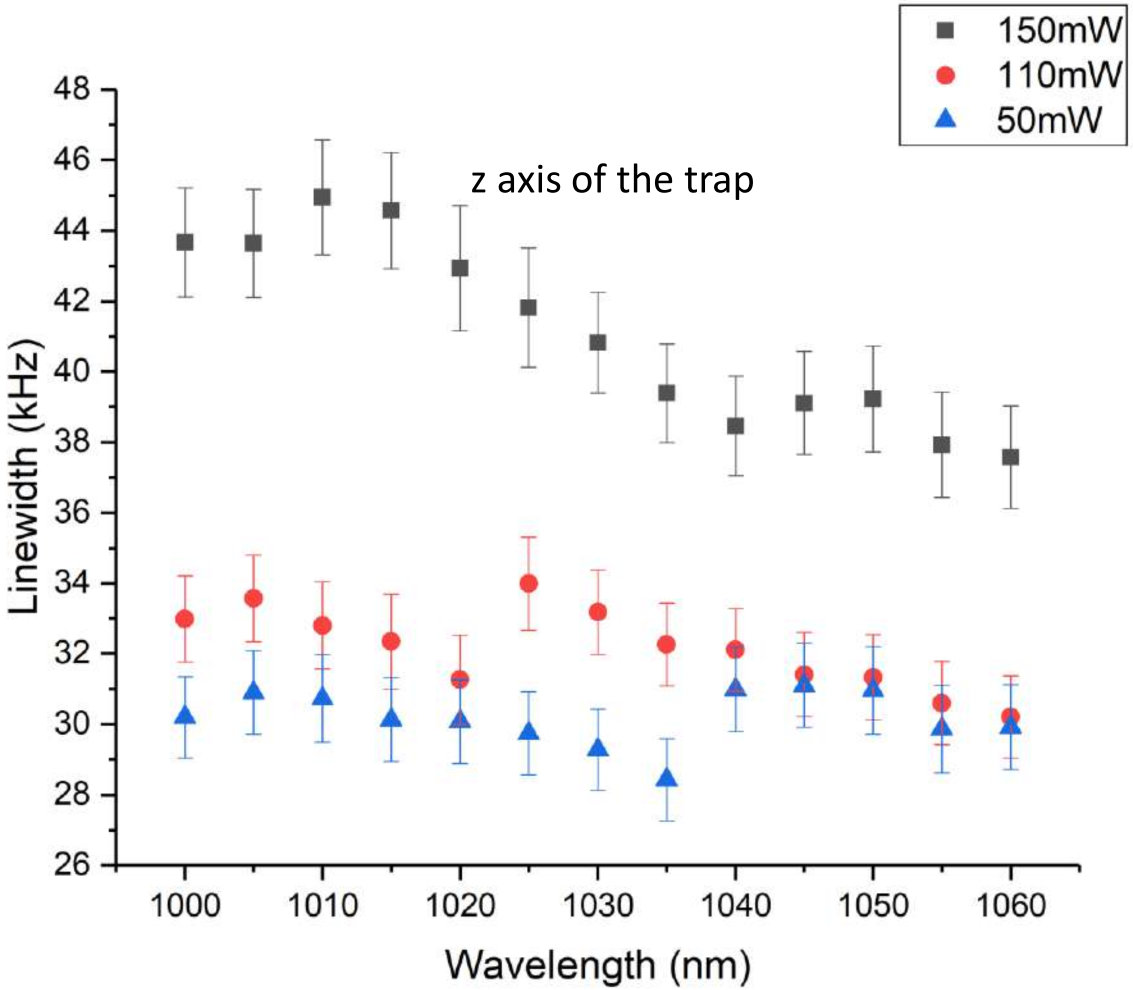



Camera become saturated after 130mW at 1060nm.

# Linewidth with wavelength (5mbar)

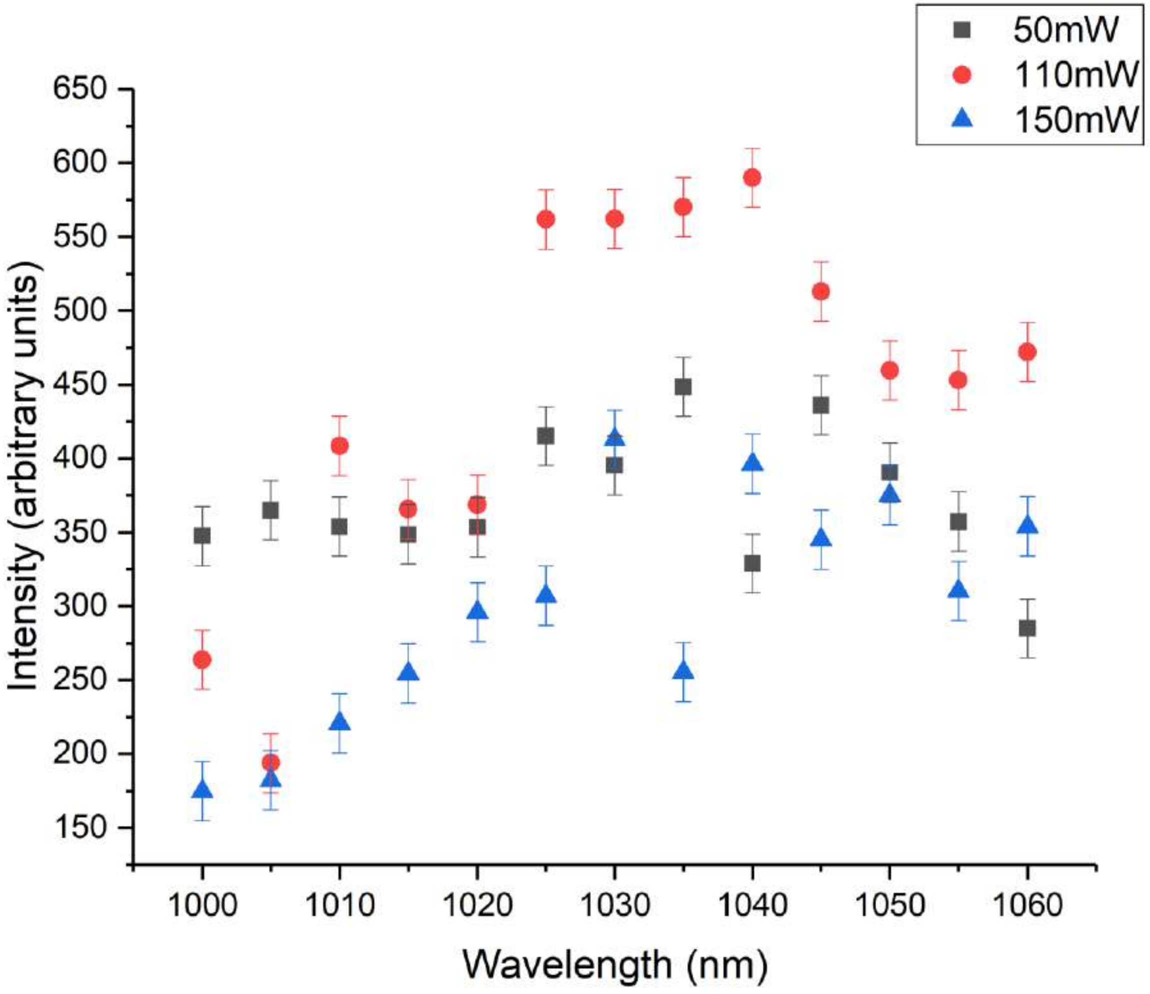
A dramatic increase in the linewidth for 150 mW at 1015 nm.

Assuming temperature for 50 mW was $T_{CM}$=300 K then highest temperature $T_{CM}$=(420±10) K.

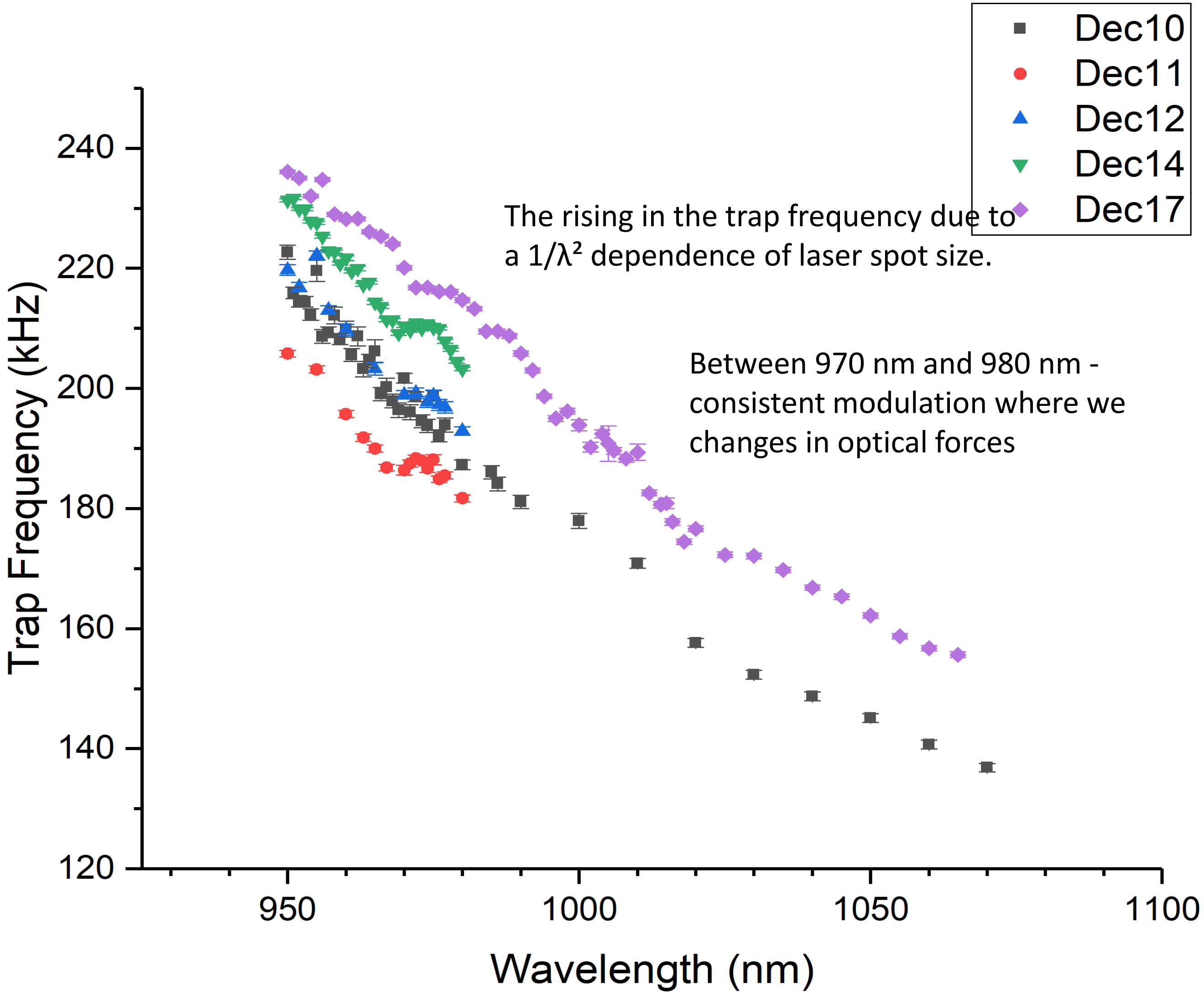


# Scattered light as function of wavelength at 5 mbar

Scattered intensity at 1020 nm
- shows reduced in size.



# Trap frequency vs wavelength at 7mbar



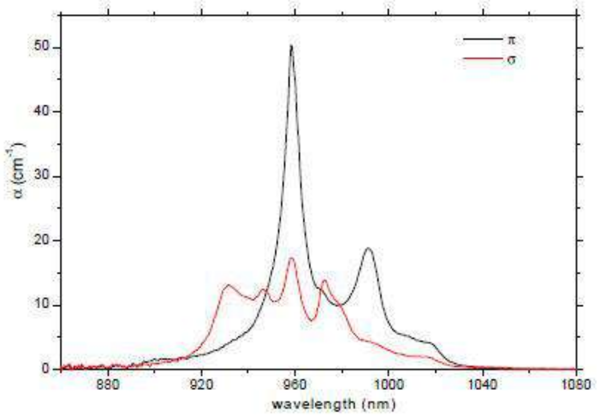



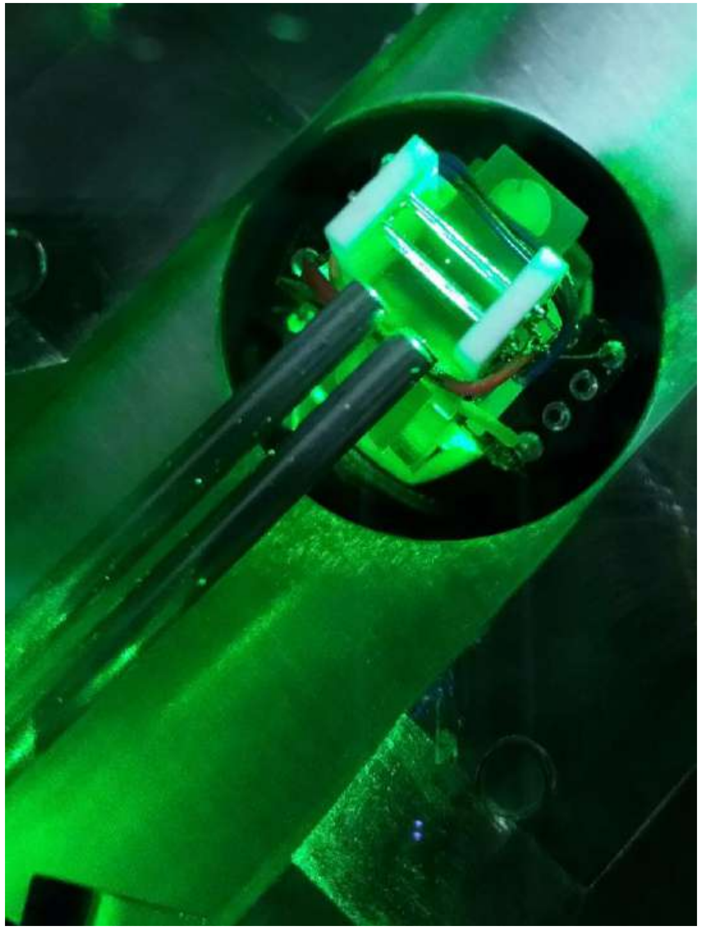

Fig. 2. Room temperature absorption spectra for the YLF: 30% Yb

Vannini, Matteo et al, 2007. *Optics Express* 15 (13): 7994. doi:10.1364/oe.15.007994.

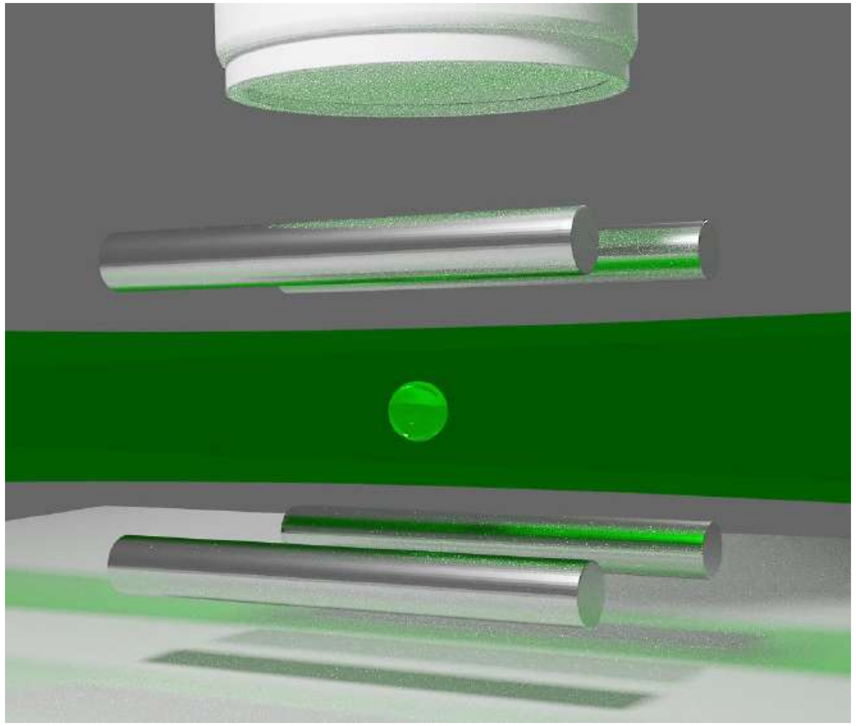
# Future work for internal state cooling

- calibration of motional spectrum as does not require assumption of temperature
- place nanoparticle in Paul trap and measure temperature at lower
- model spectra from strongly pumped NC’s
- explore cooling with lower doping Yb already supplied by Delft

# Characterising the linear Paul trap stability

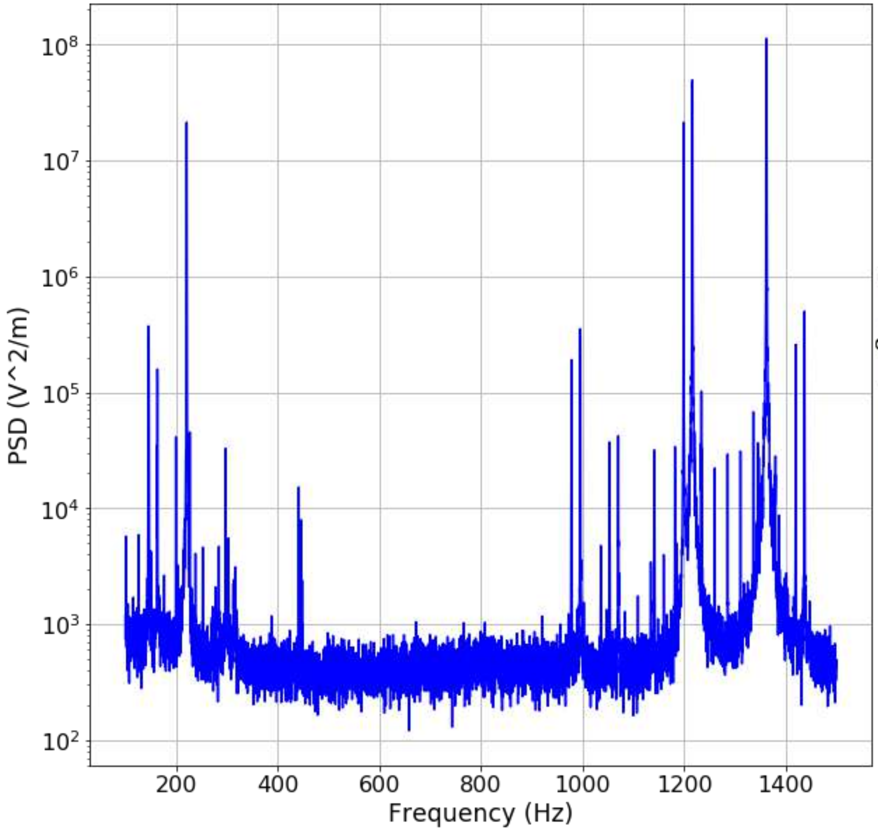


Using a camera for low noise trap characterisation

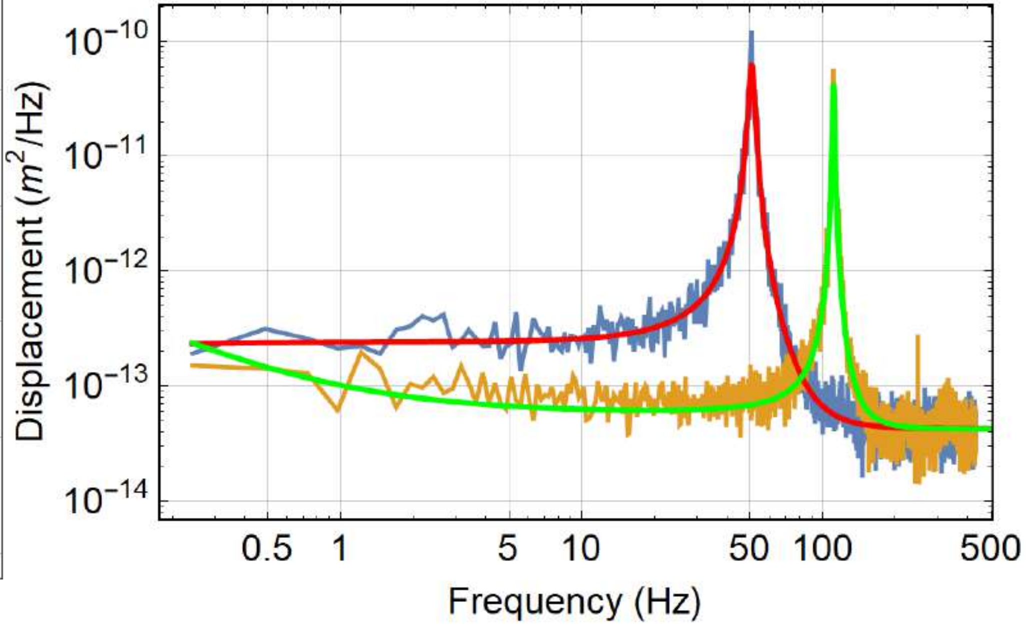


# Characterising the linear Paul trap stability

Detection by photodiode has significant noise in PSD

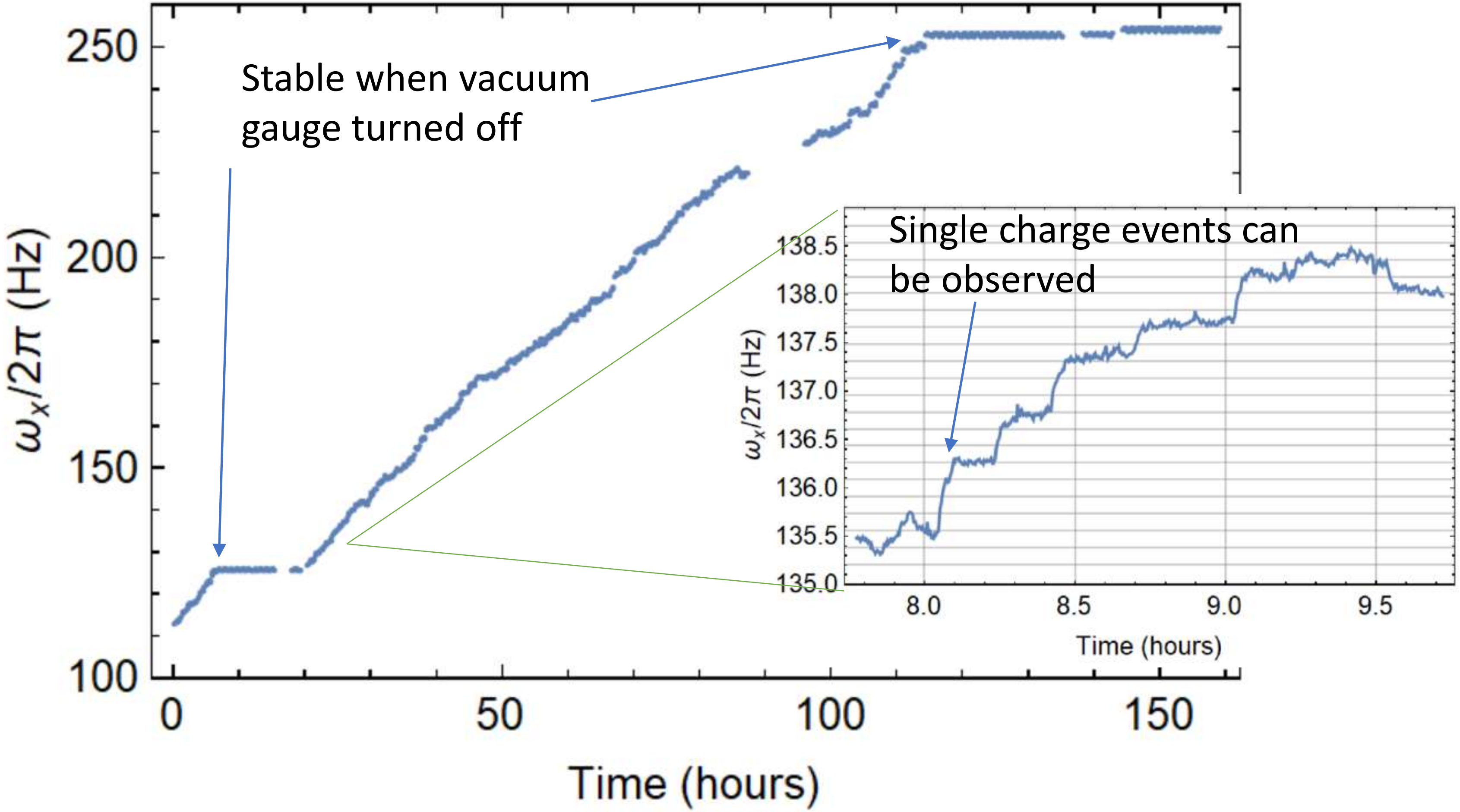



PSD taking from a movie plus Gaussian centroiding yields very low noise

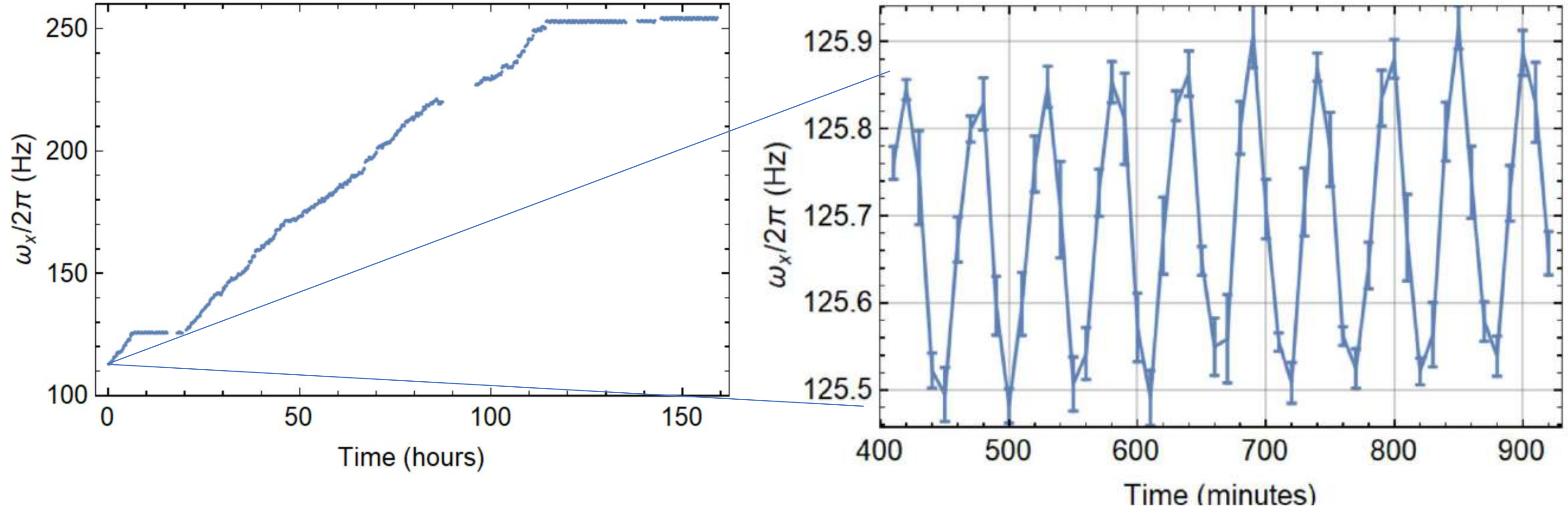


# Characterising the linear Paul trap stability

Frequency changes measured for > 6 days

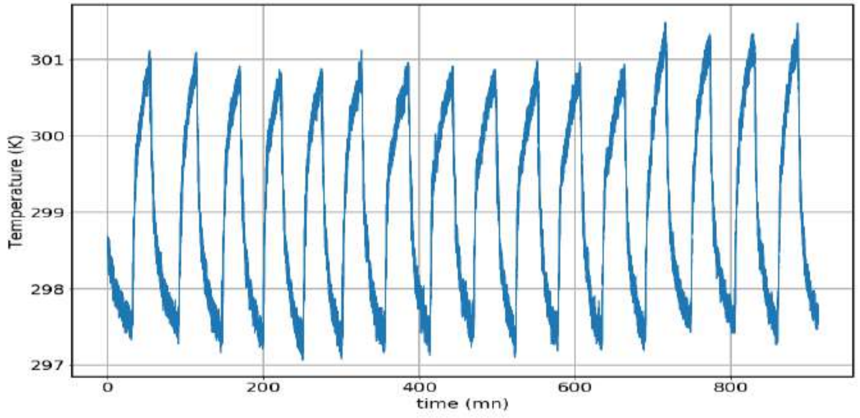


# Characterising the linear Paul trap stability

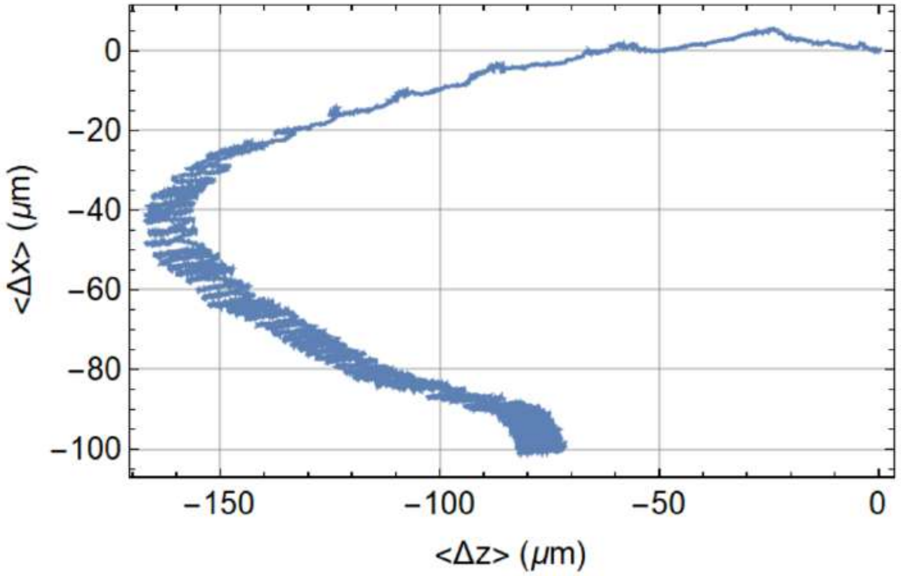



Frequency stability limited by 3 degree C room temperature fluctuation

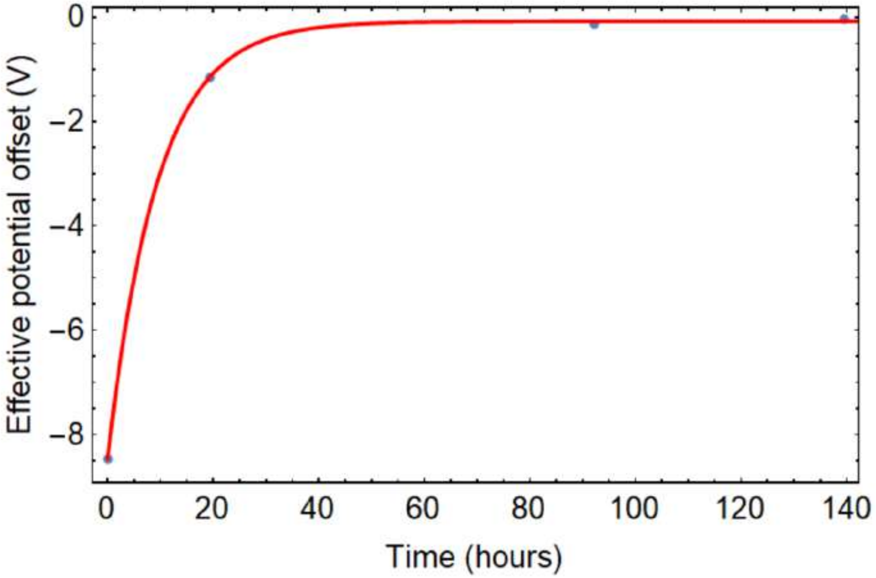
- 200 nm displacement of electrodes in holders
- thermal fluctuations in drive electronics



# Characterising the linear Paul trap stability

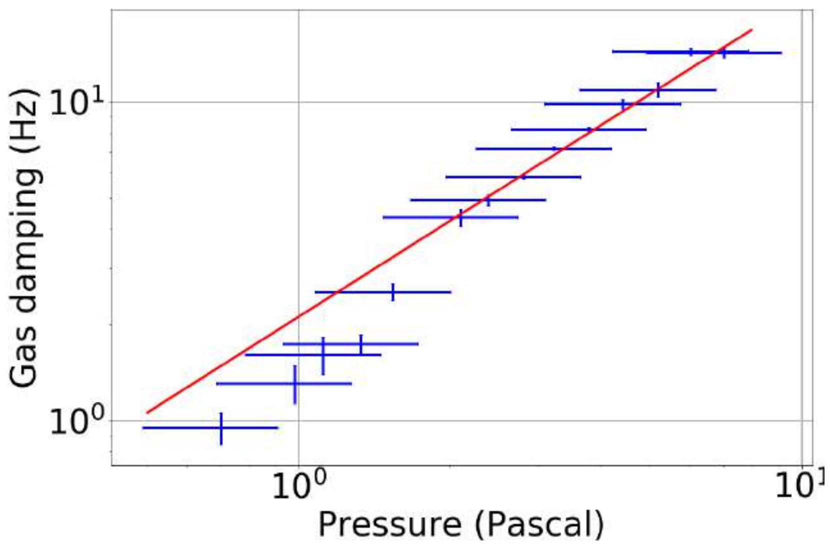



Fluctuation in trap position with time due to build up of charges



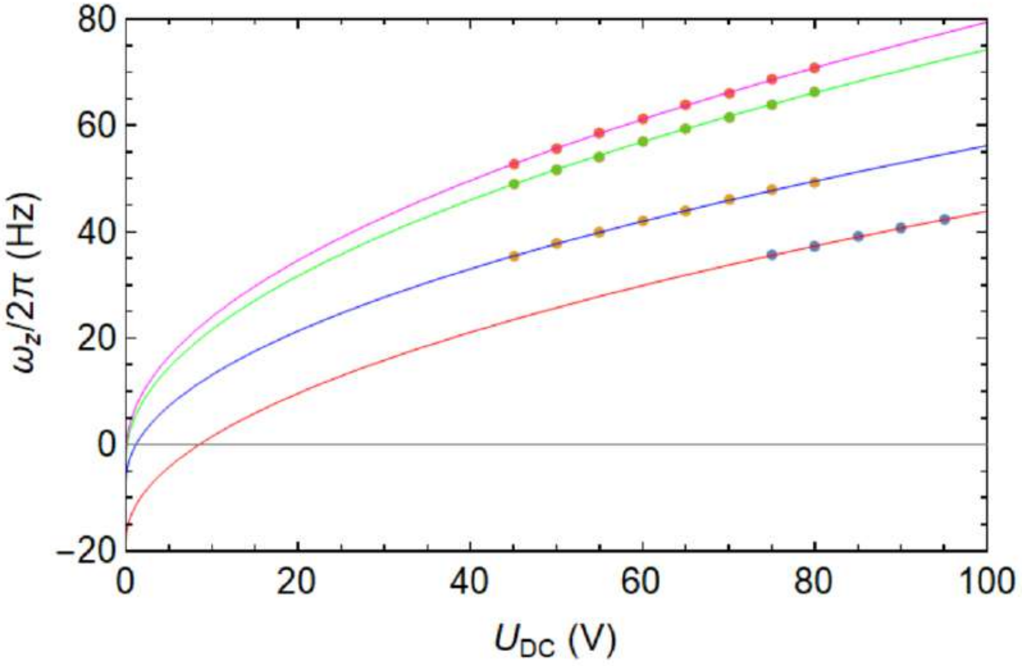

Effective potential change due to charge decay after loading

# Characterising the linear Paul trap stability




Measurement of gas damping

Effects of charging on dielectric end plates



# Characterising the linear Paul trap stability

Issues that need to be addressed/explored

- all dielectrics further away from nanoparticles
  - -> large fixed by new trap from AU
- lower noise electronics from INFN required
  - -> has to be implemented
- all conventional vacuum gauges off during measurement
  - -> this is straightforward
- control of temperature dependence of electronics
  - -> this needs evaluation
- need to keep charged nanoparticles off electrodes
  - -> more precise loading and differential pumping
- mass and size calibration required
- larger the charge the more sensitive to stray fields/fluctuations

# 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

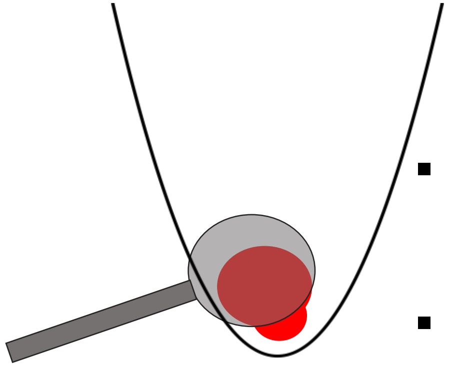
D2.1 Low noise electronics [M 12]. Achieved
D2.2 Optimal cooling strategies [M 27].
D2.3 Internal state cooling [M 38].
D2.4 Quantify decoherence [M 44].

Testing the large-scale limit of quantum mechanics

European Commission

# WP3: TESTING

H. Ulbricht – UoS



3. Testing

- Monitor trapped motion
- Compare theory and experiment

# 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 involved

**Experiments on WP3:**

- **UoS:** Andrea Vinante, Muddassar Rashid, Christopher Timberlake
  Ashley Setter, Hendrik Ulbricht
- **UCL:** Antonio Pontin, Marko Toros, Peter Barker
- **AU:** Michael Drewsen
- **INFN:** Max Bazzi, Catalina Curceanu

## Testing collapse models with levitated nanoparticles: the detection challenge

P. Barker,[1] A. Pontin,[1] M. Rashid,[2] M. Toros,[1] H. Ulbricht,[2] and A. Vinante[2]

[1] *Physics Department, University College London, London, WC1E 6BT, United Kingdom*

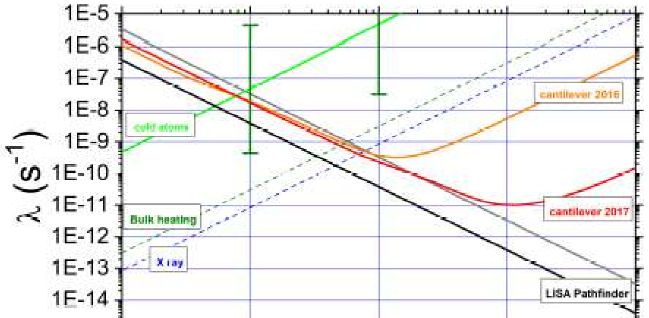
[2] *Department of Physics and Astronomy, University of Southampton, SO17 1BJ, United Kingdom*

(Dated: February 24, 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 a optical cavity, optical tweezer and a electrical readout, and for each one we assess advantages, drawbacks and technical challenges.

### I. INTRODUCTION

Spontaneous wave function collapse (or dynamical reduction) models (CM) [1–5] have been proposed to reconcile the linear and deterministic evolution of quantum mechanics with the nonlinearity and stochasticity of the measurement process. According to CM, random collapses in space (i.e. localizations) of the wave function of any system occur spontaneously, independently of measurement processes, leading to a progressive spatial localization. The collapse rate scales with the size of the



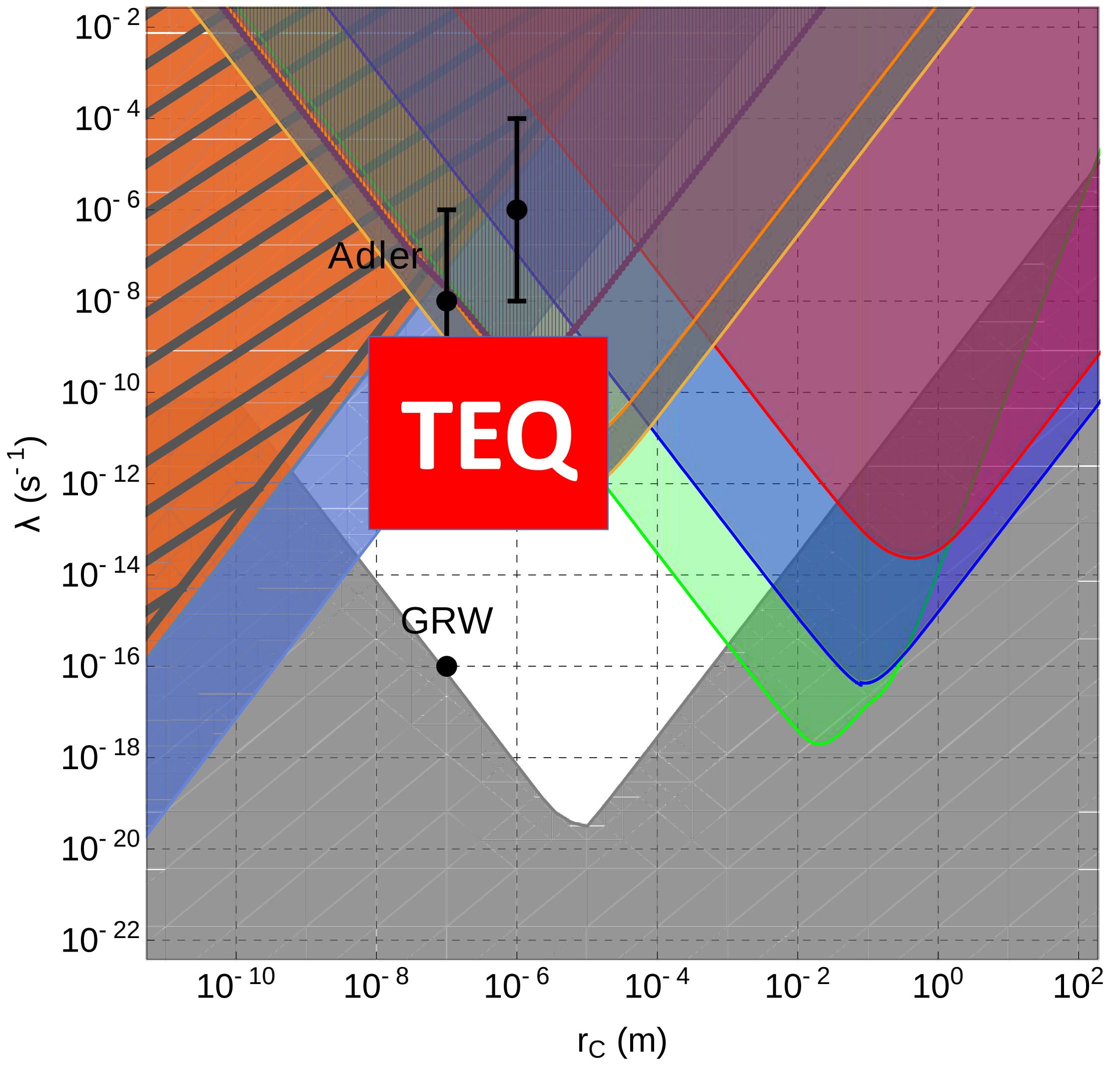
# Outline: WP3 report

① CSL exclusion plot
   i. Force noise measurement approach
   ii. Force measurements in levitated optomechanics

② Comparison of CSL noise to thermal noises
   i. Evaluation of required parameters for TEQ experiment
   ii. Considerations on detection
   iii. Summary of parameters

③ Implementation of low-noise environment at UoS
   i. Low pressure
   ii. Low temperature
   iii. Detection at ultralow power
   iv. Low vibrations

# CSL parameter space: the region TEQ will explore




- **Non-interferometric test**
- **How to convert CSL parameter into experimental ones?**

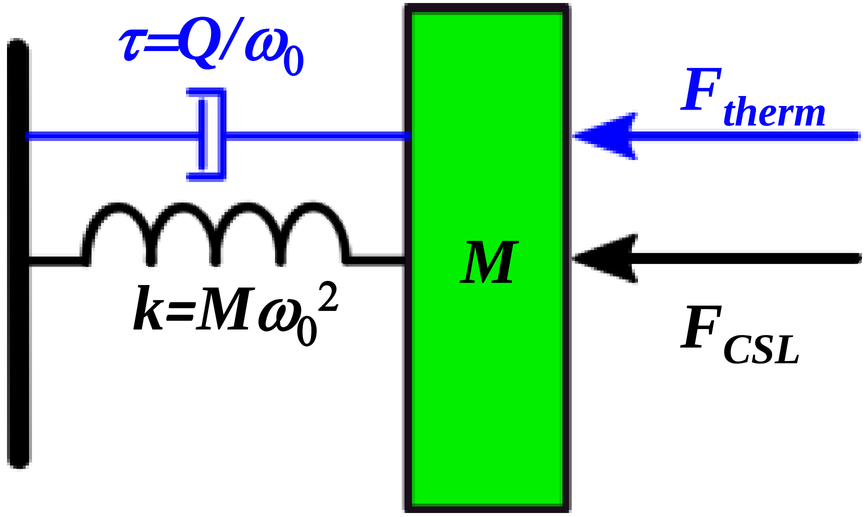
**-> Measure force noise**

# Force (noise) in harmonic oscillator:

- **Earlier CSL tests are based on force noise measurement**
- **New in TEQ is *levitation*, should give higher *Q* and lower frequency, few degrees of freedom**

Thermal bath affect minimum force measured:

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

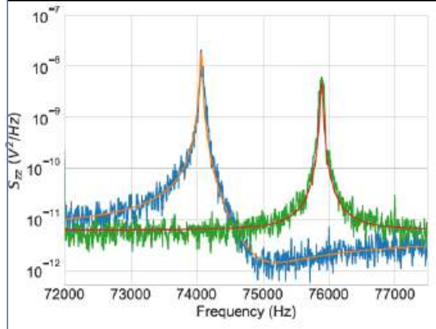




M. Bahrami et al, PRL **112** 210404 (2014)
S. Nimmrichter et al, PRL **113** 020045 (2014)
L. Diosi, PRL **114**, 050403 (2015)
D. Goldwater et al. Phys. Rev. **A 94**, 010104 (2015)
A. Vinante et al, PRL **116**, 090402 (2016)

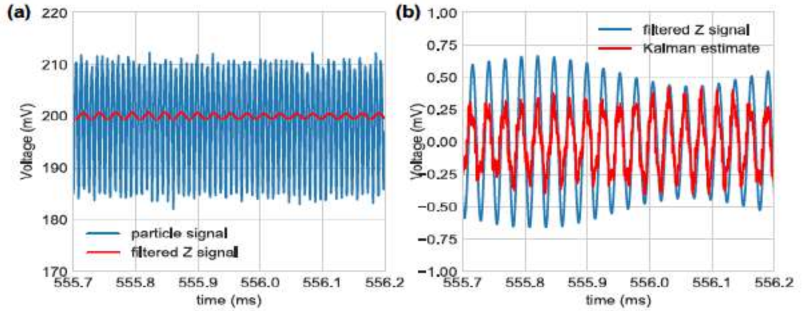
# Force (noise) measurements in levitated opto-mechanics: to get the feel for it ….

**Static force measurement at $10^{-15}$ N level.**



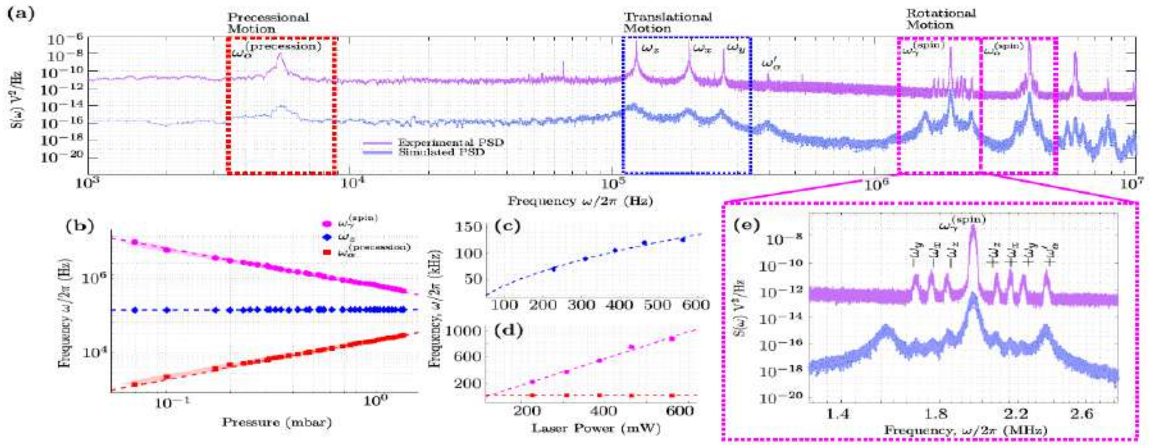

Timberlake, C., M. Toroš, D. Hempston, G. Winstone, M. Rashid, and H. Ulbricht,
**Static force characterization with Fano anti-resonance in levitated optomechanics**,
Appl. Phys. Lett. **114**, 023104 (2019)

**Optical parametric feedback** **cooling** **to 1 mK for x,y,z-motion**




Setter, A., M. Toroš, J. F. Ralph, H. Ulbricht,
**Real-Time Kalman Filter: Cooling of an Optically Levitated Nanoparticle**,
Phys. Rev. **A 97**, 033822 (2018)

**Measured torque:** **1.9 ×$10^{-23}$ Nm @ $10^{-1}$ mbar.**
**Estimated torque sensitivity:** **3.6 × $10^{-31}$ Nm/(Hz)$^{1/2}$ @ $10^{-7}$ mbar.**




Rashid, M., M. Toroš, A. Setter, H. Ulbricht
**Precession Motion in Levitated Optomechanics,**
Phys. Rev. Lett. **121**, 253601 (2018).

# 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 $\lambda$ – CSL parameter
$\varrho$ - 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 [**negligible**]:**

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

**Thermal noise from gas collisions:**

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

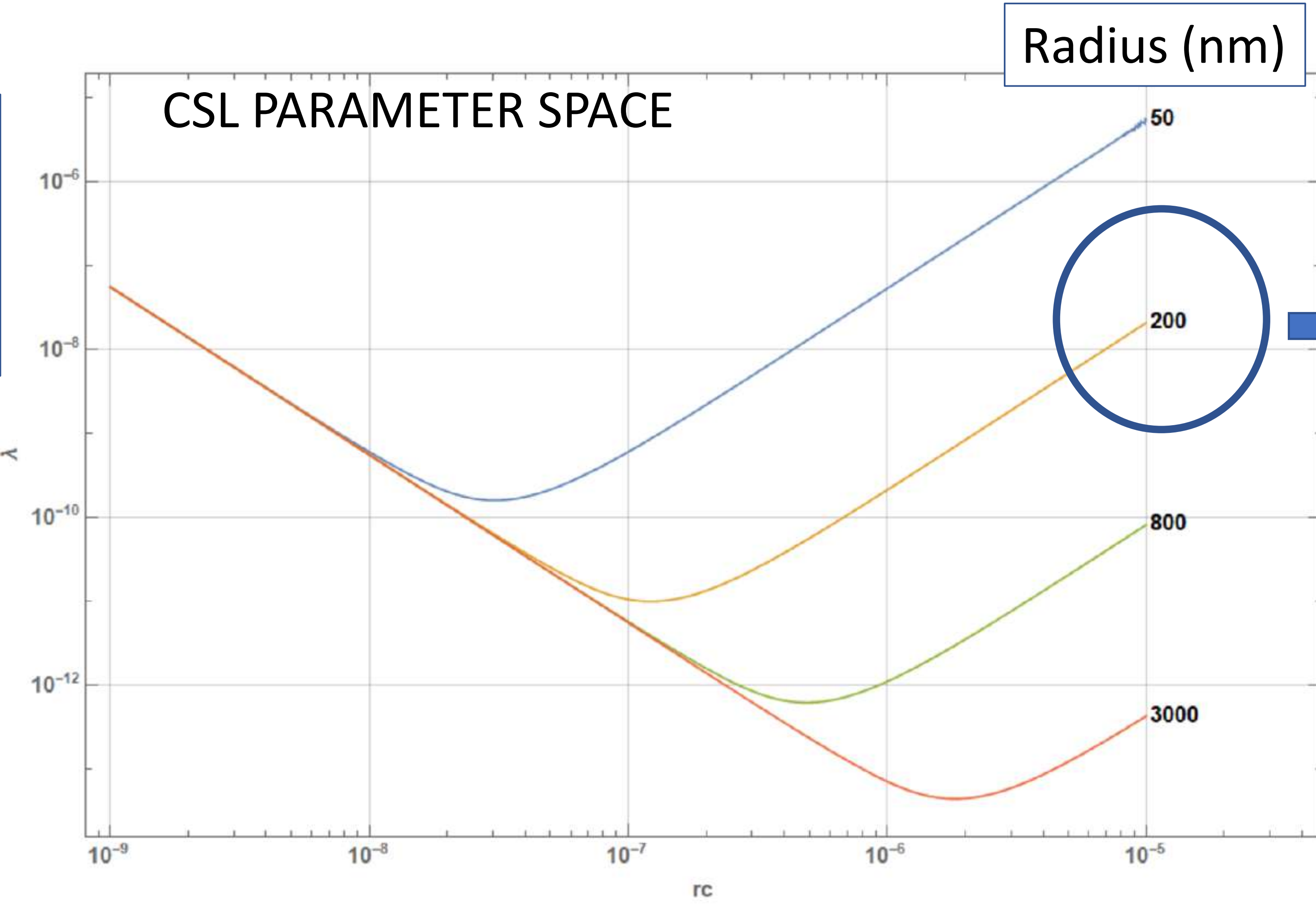
$$\Gamma_{gas} = \sqrt{\frac{8}{\pi}}\left(1 + \frac{8}{\pi}\right)\frac{P_{\mathrm{gas}}}{\rho R\sqrt{\frac{k_B T_{\mathrm{gas}}}{m}}}$$

To maximize SNR:

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

# Dependence on size for fixed gas T, P

$SiO_2$ nanosphere
$P=10^{-10}$ mbar
T=1 K
Helium gas




GOOD TRADE-OFF to probe $r_C = 10^{-7}$ m

HOWEVER: small size → lower vibrational noise & easier Paul trap operation

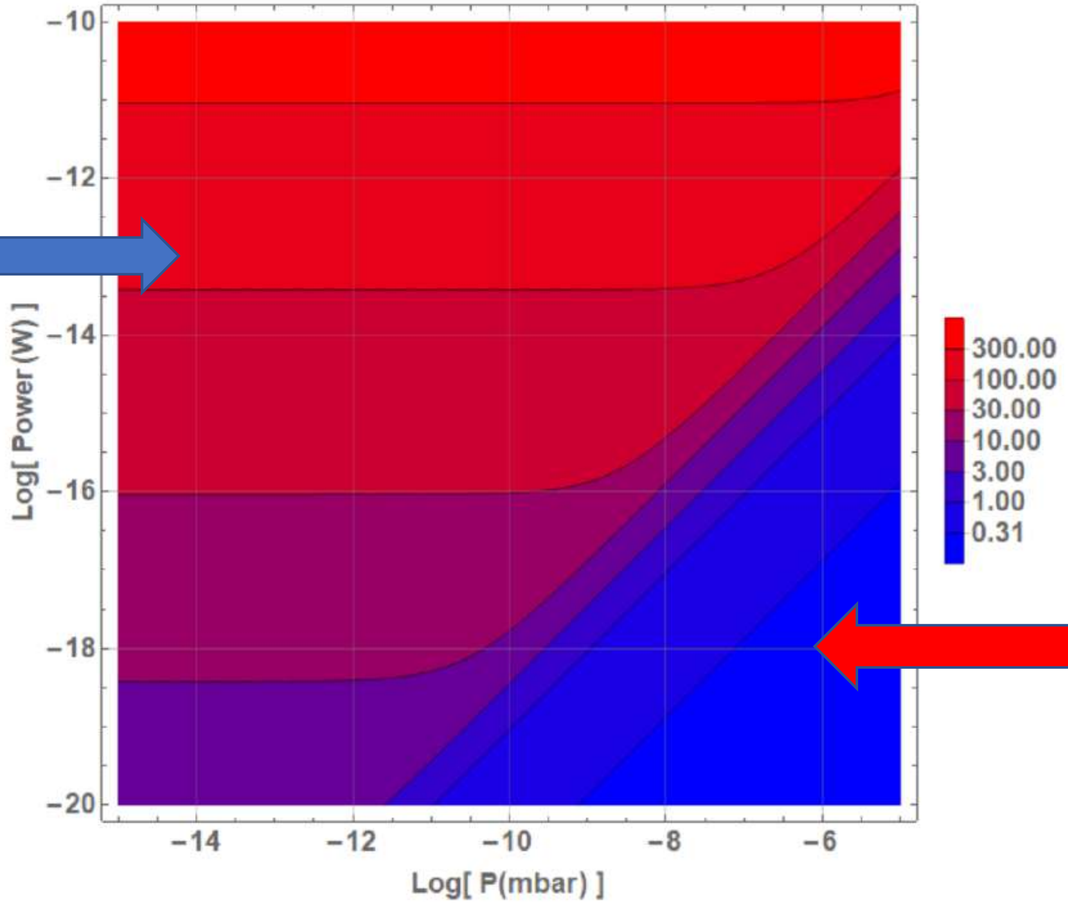
# Challenge: internal heating for optical detection

Internal temperature: determines gas collision effective temperature

Low pressure
High power

Cooling dominated by blackbody emission

NEED TO WORK IN THIS REGIME!



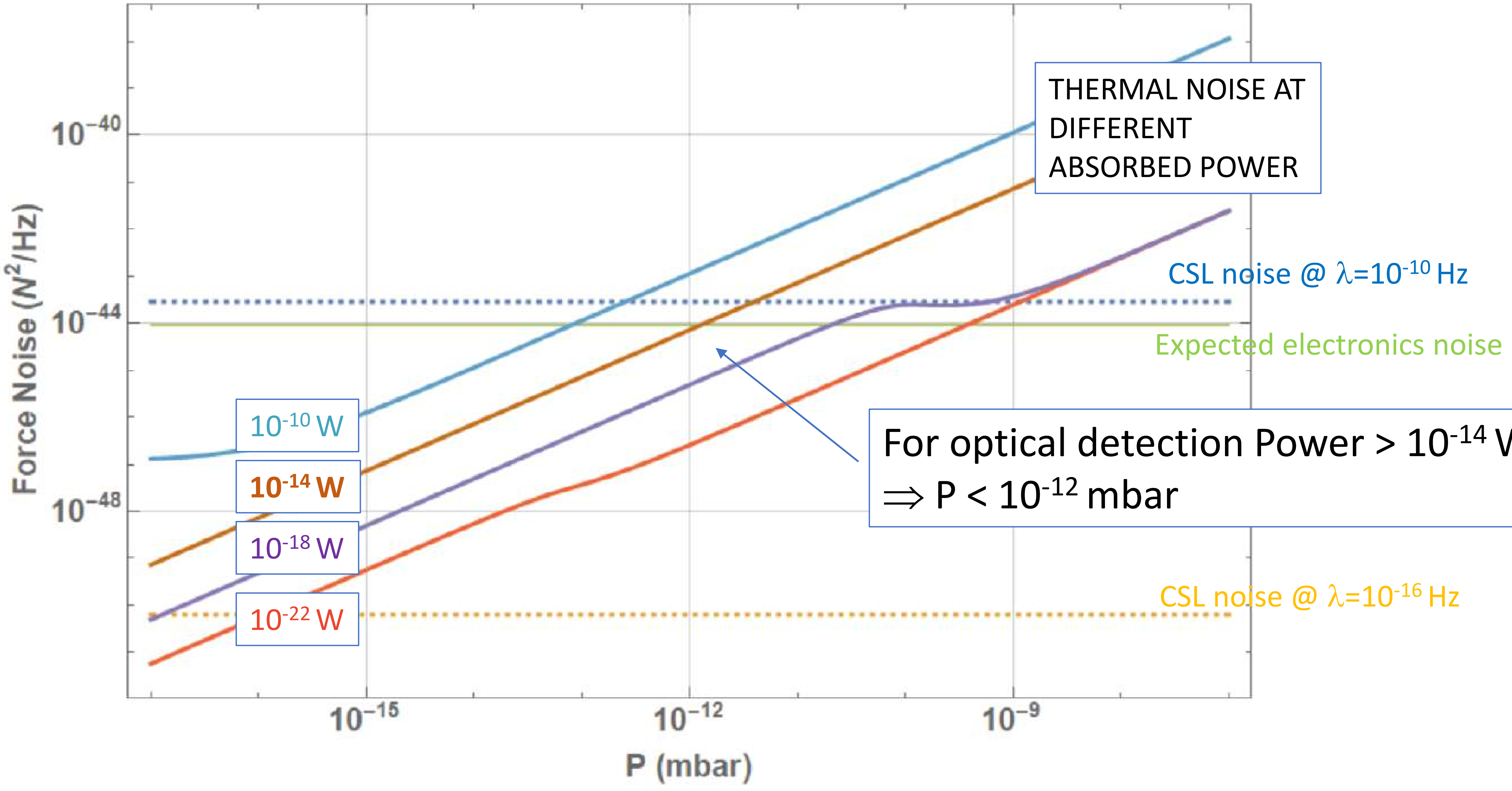

- **Optical trapping is not an option**
- **Noise in Paul trap + electronics needs to be very low (WP1)**

High pressure
Low power

Cooling dominated by Gas collisions

Possible alternative: Electrical Detection (through Paul trap electrodes) + SQUID

# Thermal noise: requirements on gas pressure

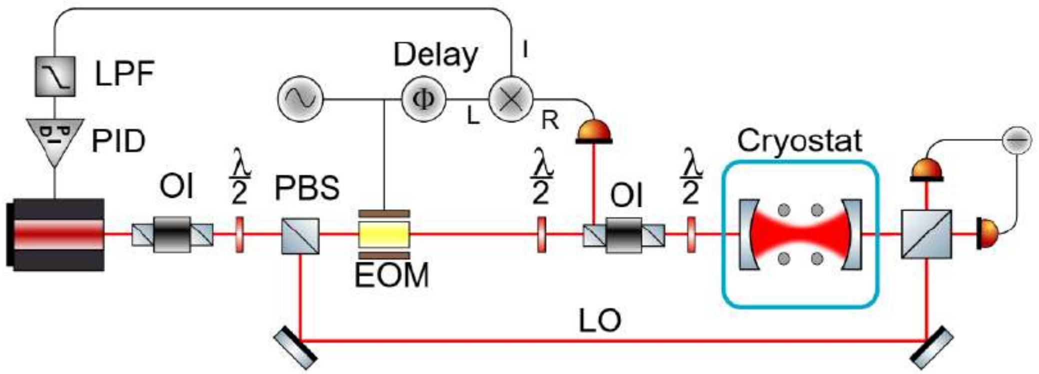



For optical detection Power > $10^{-14}$ W

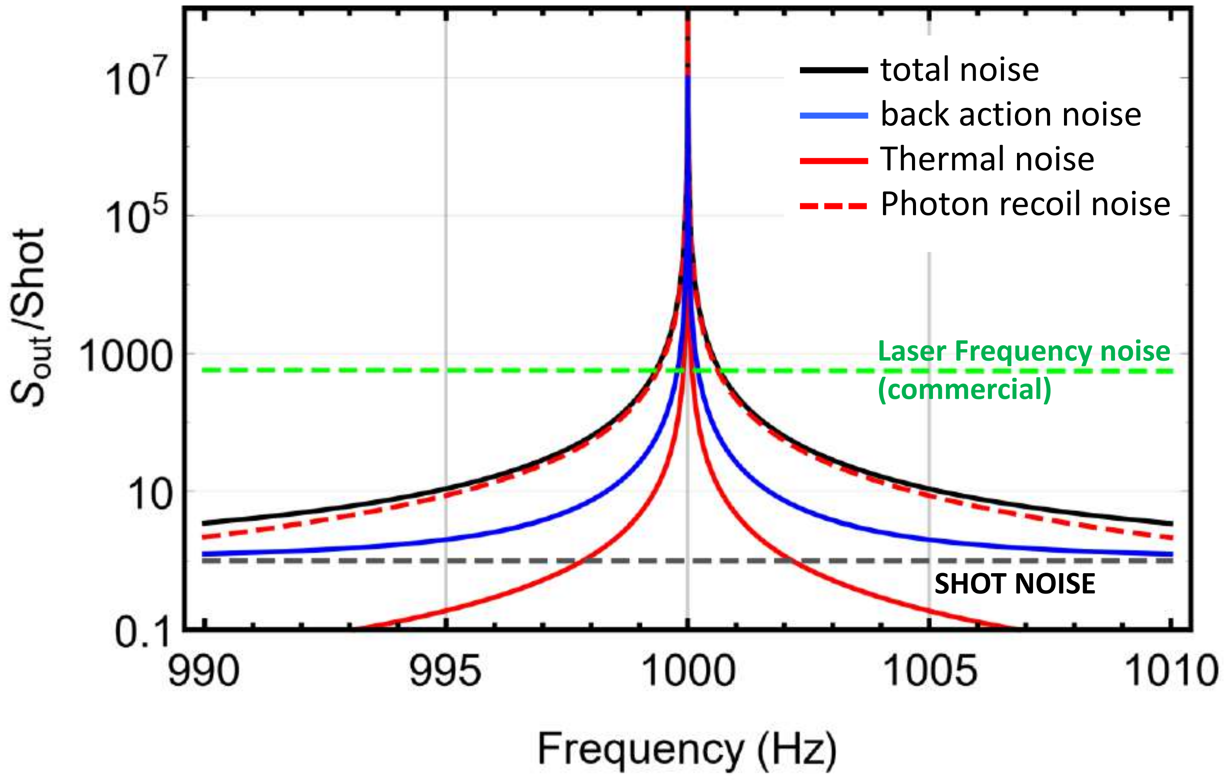
$\Rightarrow$ P < $10^{-12}$ mbar

# Detection at ultralow absorbed power

1) Low-finesse (~1000) OPTICAL CAVITY




NOISE BUDGET @ $P=10^{-13}$ mbar, $10^{-6}$ W cavity input power




Issues:

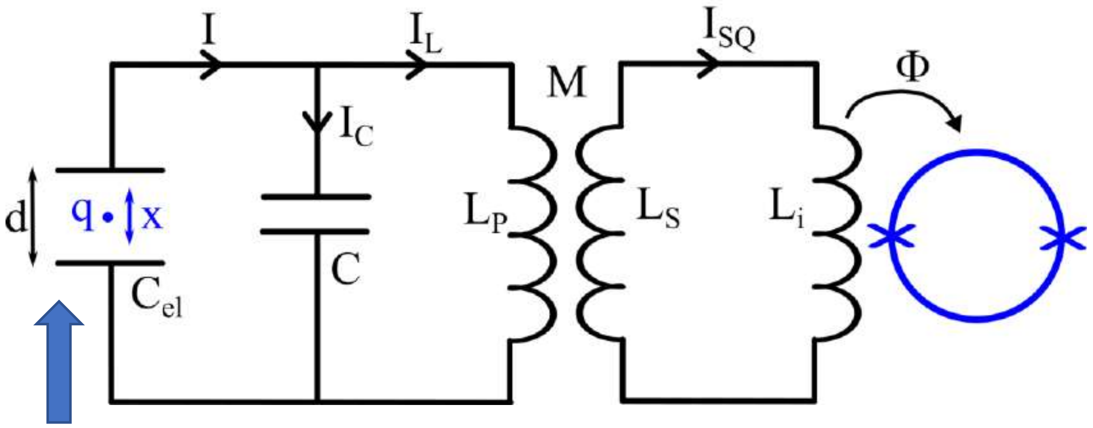
- Locking at low power
- Requires very accurate alignment
- Requires feedback to stabilise particle position

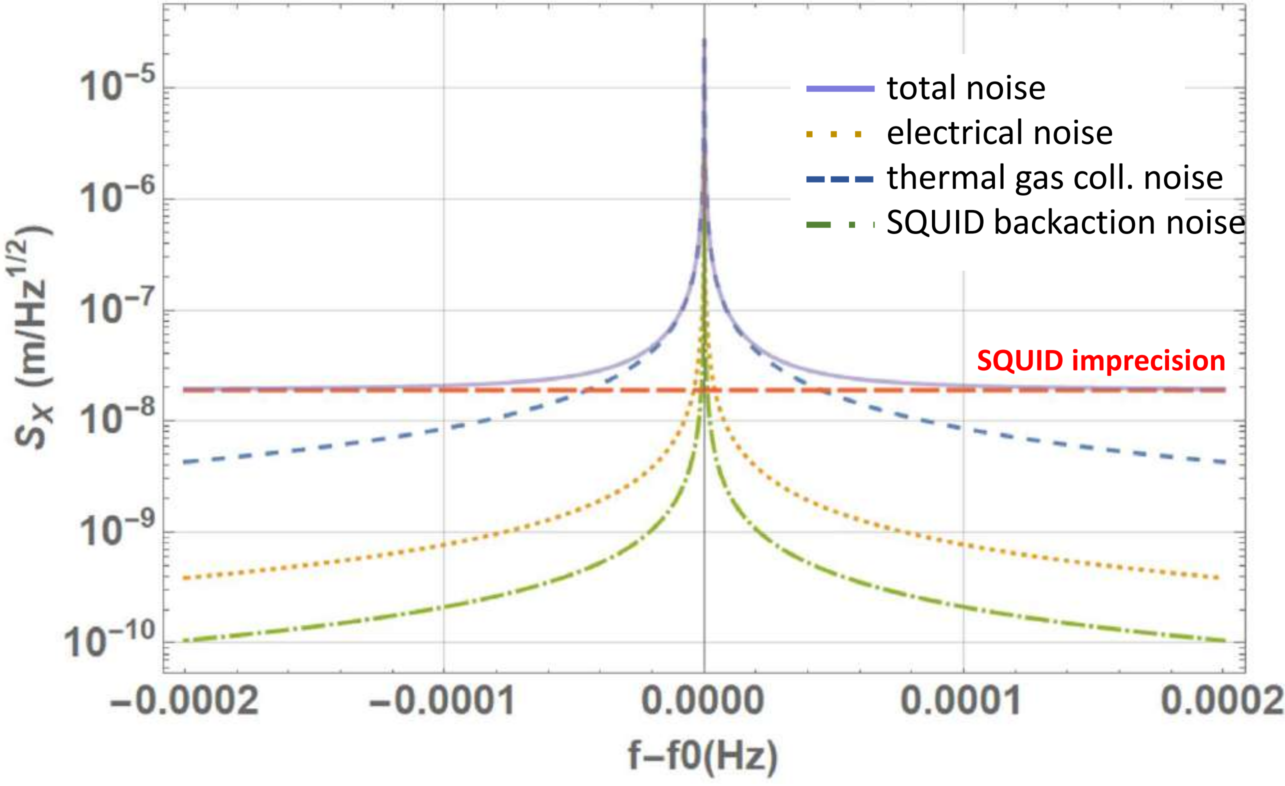
GOOD EFFECTIVE BANDWIDTH ≈ Hz (Photon recoil dominated)

SIMILAR FOR OPTICAL TWEEZER APPROACH (limited by NEP of detector …)

# Detection at ultralow absorbed power

2) Electrical readout + SQUID




Issues:

- Needs a huge superconducting transformer
- Paul trap bias drive could saturate SQUID

Advantages:

- No alignment issues
- No power dissipated in particle
- Lower thermal noise achievable

VERY NARROW BANDWIDTH ≈ mHz
(low coupling, thermal noise dominated)

LOWER FORCE NOISE BUT
NEEDS VERY HIGH FREQUENCY STABILITY!

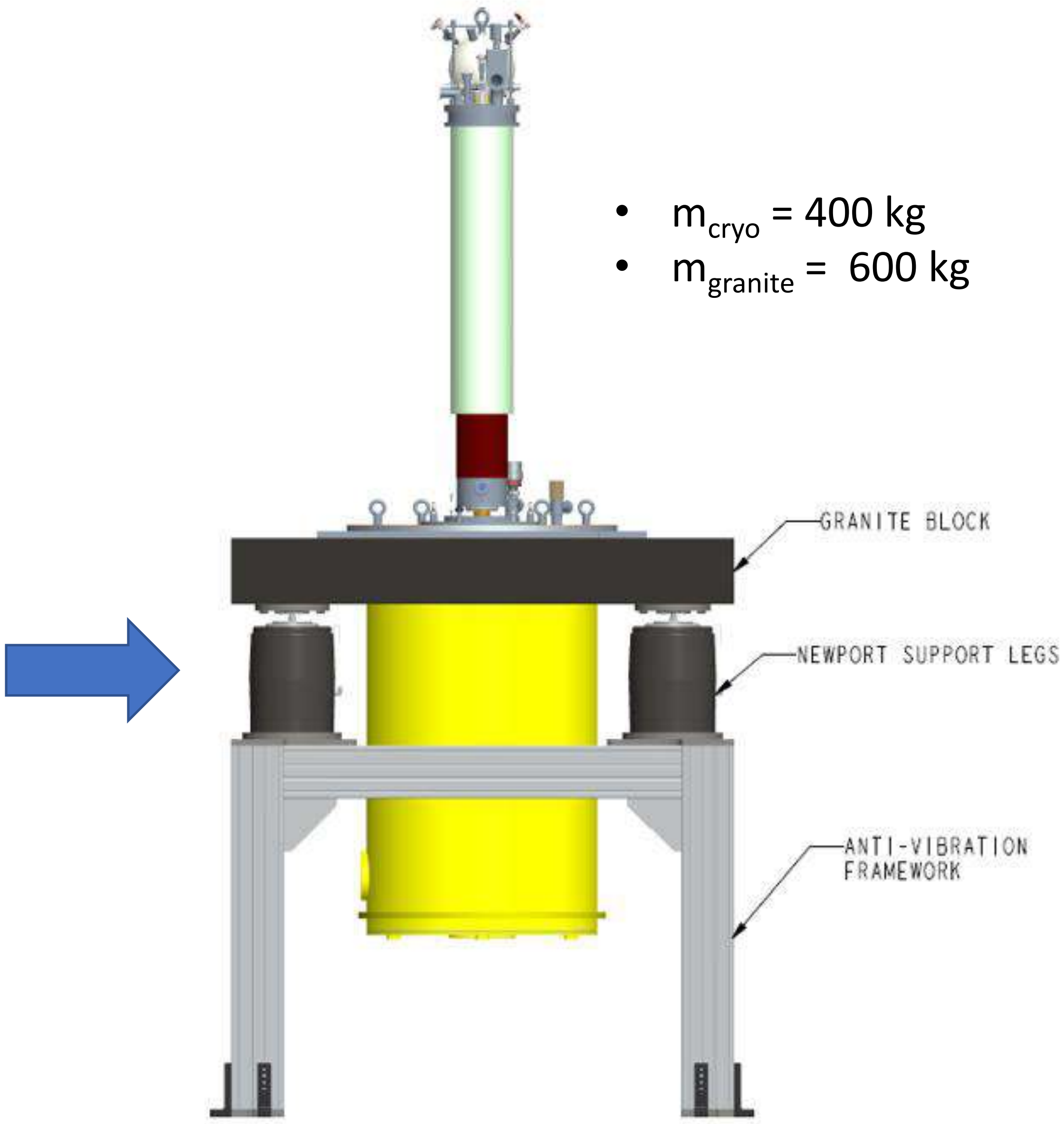
# Summary of requirements to test CSL:

| Parameter | Target | Comments |
|---|---|---|
| Particle size | 200 nm | To probe CSL @ $r_c=10^{-7}$ m |
| Frequency | 100 Hz – 1 kHz | Stable trap and low force noise |
| Particle material | $SiO_2$/Yb:YLiF | Low absorption, many charges, consider effects 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 |
| Optical access | yes | Both wedged windows and fibres for maximum flexibility |
| Vibrational attenuation | > 60 dB | Will ensure seismic/acoustic noise negligible |

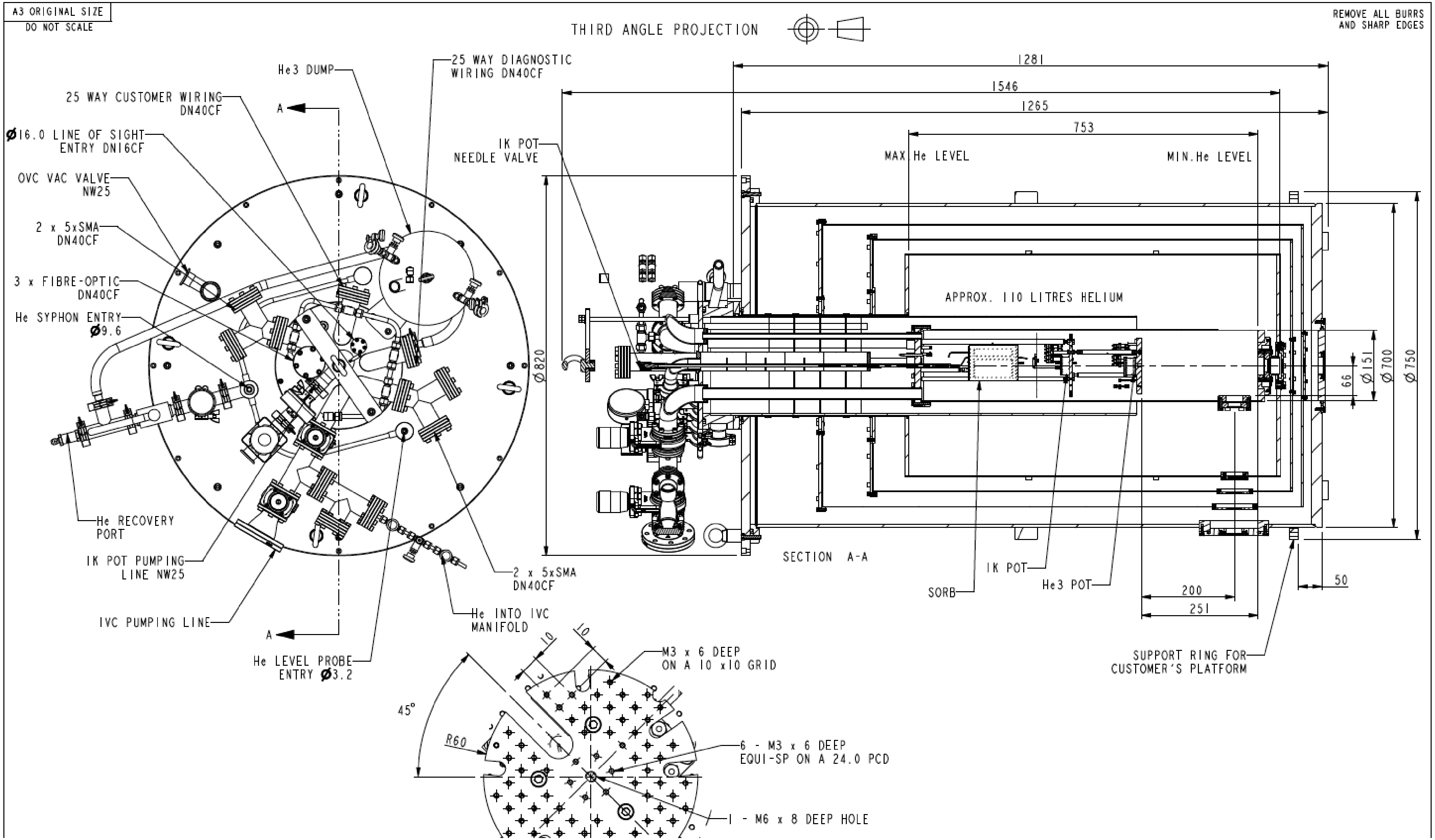
# TEQ low-noise environment: now at UoS!!

- 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]

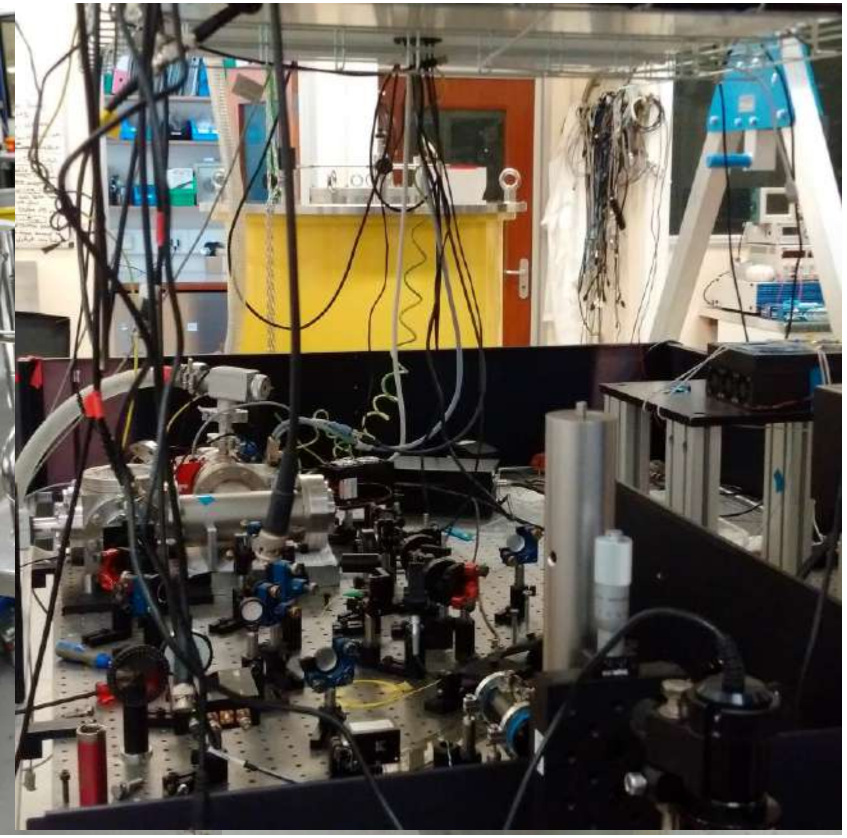
- $m_{cryo}$ = 400 kg
- $m_{granite}$ =  600 kg

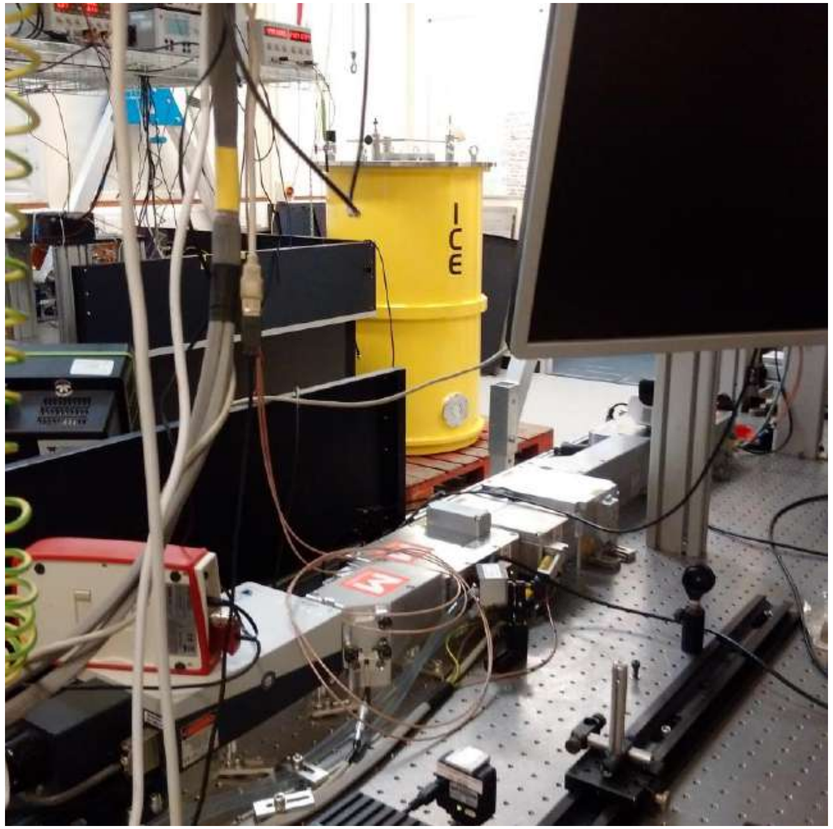


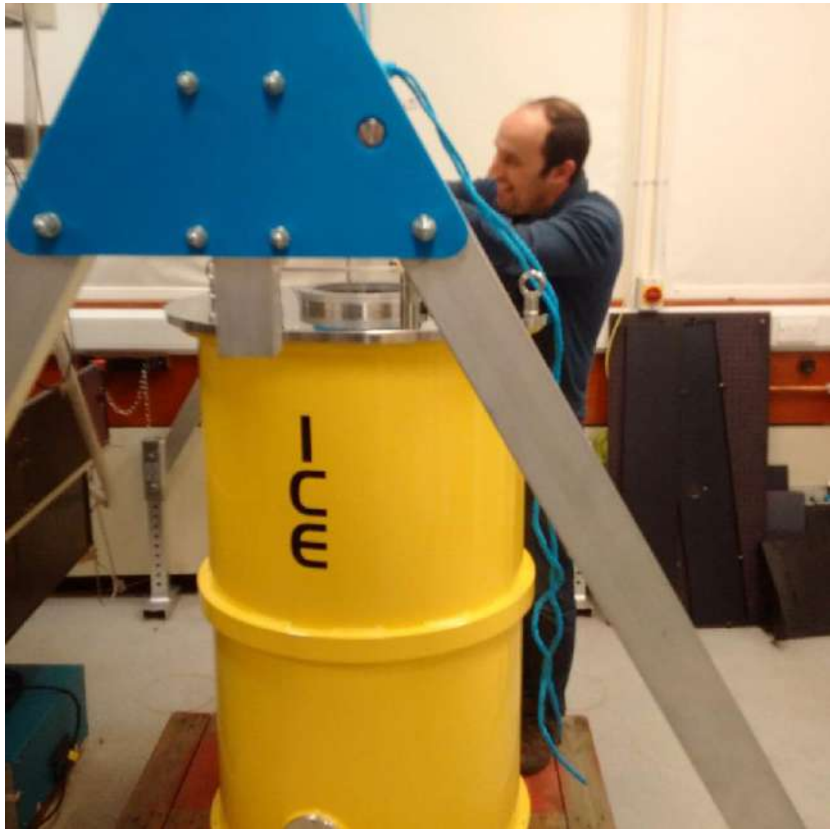
# The He-3 refrigerator: design details



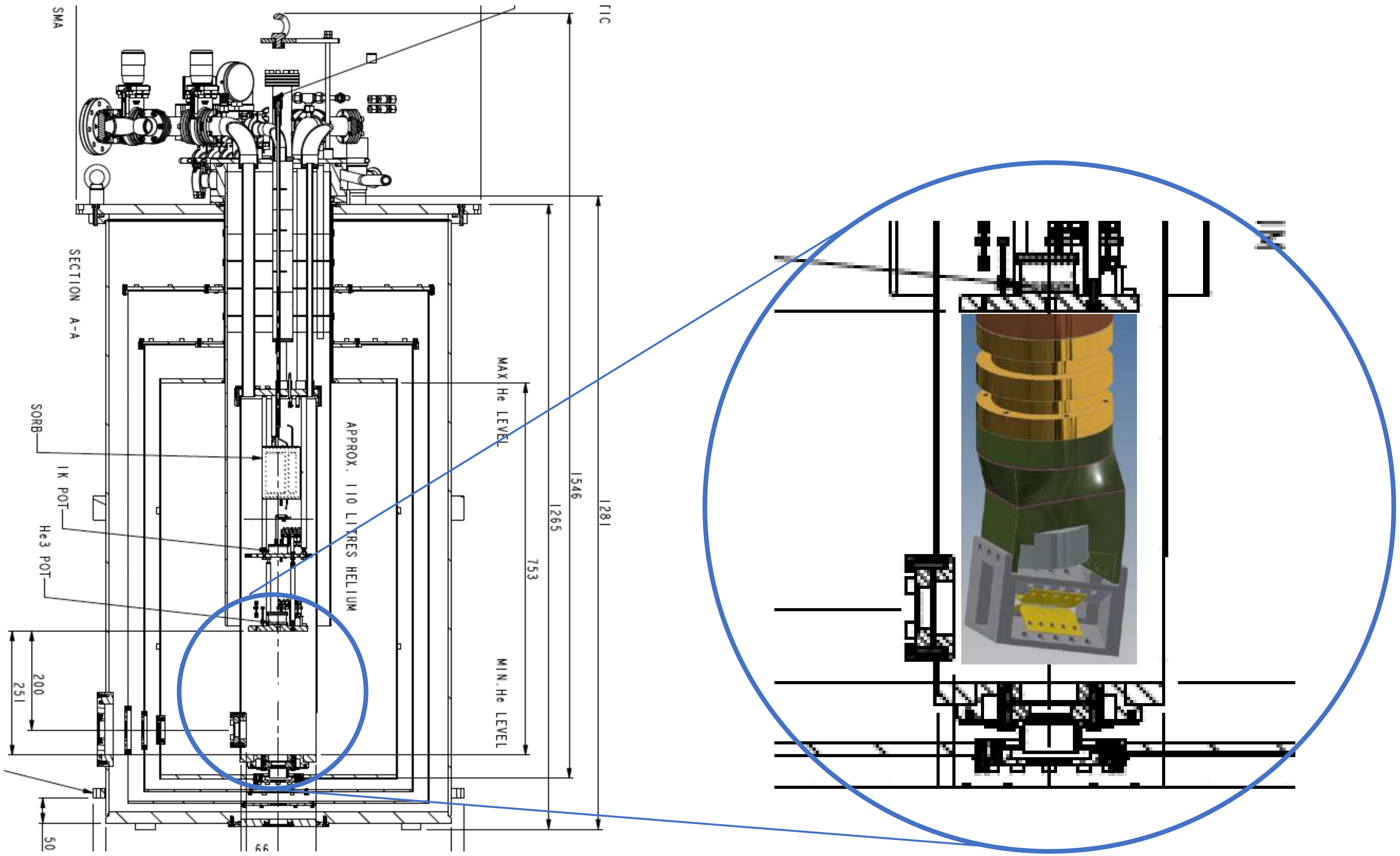
# Some photographs: cryo now in lab in UoS !!





# Next: Testing the cryo and attaching the Paul trap



# Next studies:

- Measure noise in the cryo -> **D.3.2: Investigation of systematic effects. (M28)**
- Different strategies for detection of particle position (together with WP1 and WP2)
- Different strategies for detection of heating (together with all other WP1,2,4)
- Implementation of Paul trap into cryo.
- Particle loading at low T, particle’s charge control at low T

# 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].

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# WP4: ENABLING

M. Paternostro - QUB

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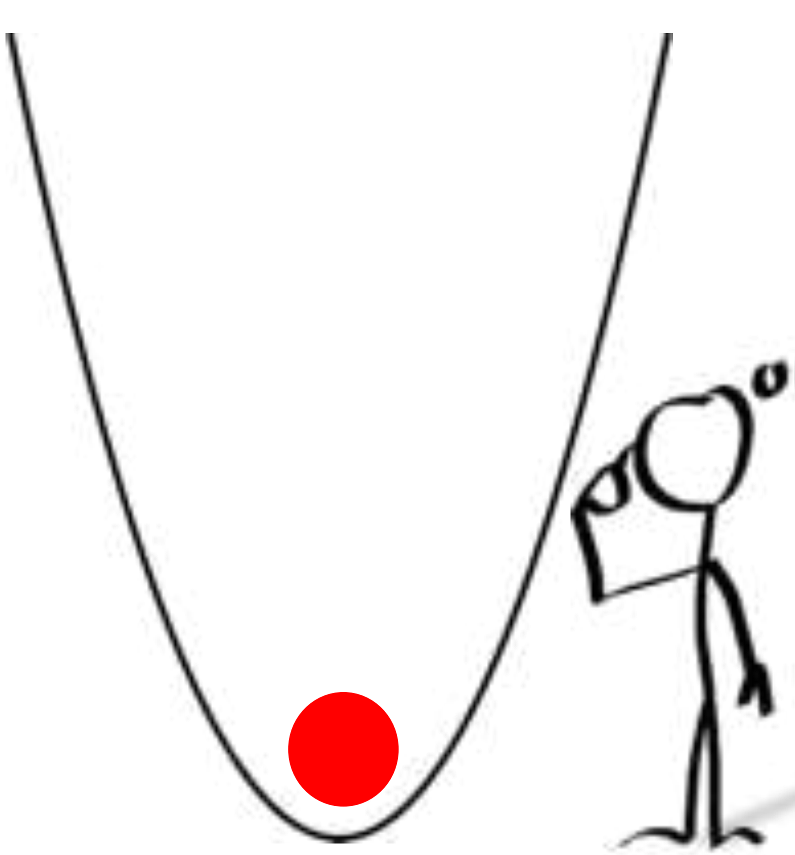
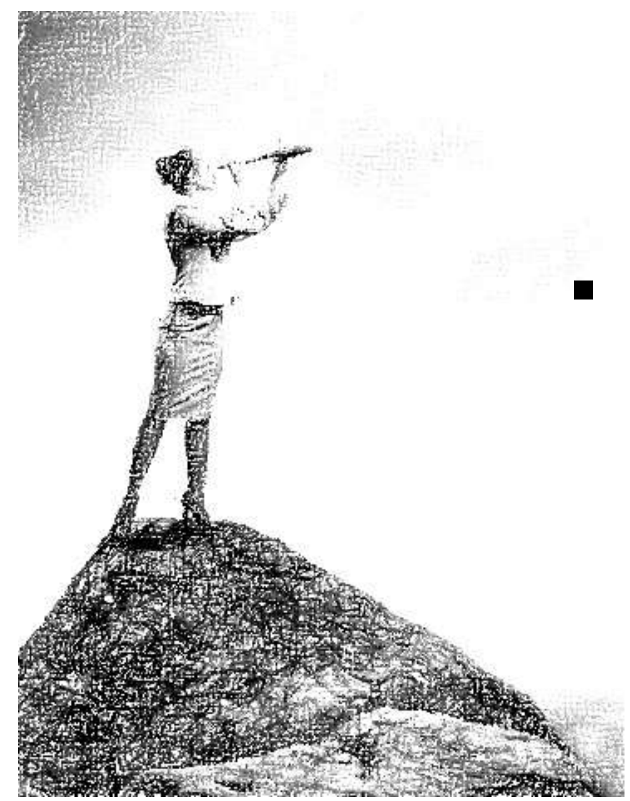
# What WP4 is about




- 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

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# 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]

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# 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.
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**D4.3** Size of the superposition [M24]
**D4.4** Bounds to the ecCSL model [M36]
**D4.5** Time-dilation/gravity collapse [M44]

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# 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


A Belenchia
OEAW/QUB


G Gasbarri
UniTS/SOTON


M Toros
SOTON/UCL


O Houhou
QUB (left)

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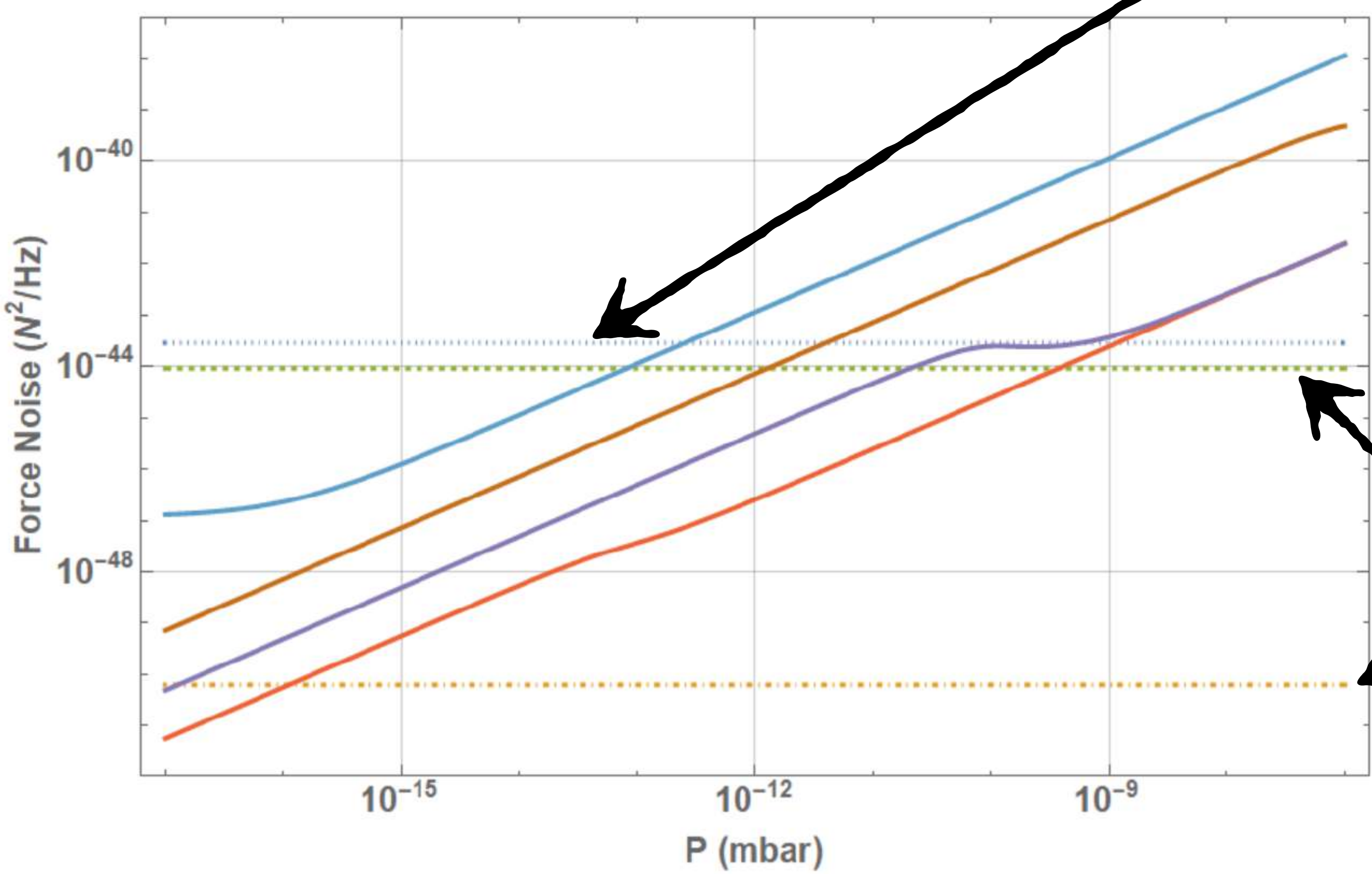
# Calibration of decoherence sources

## Noise related to the trapping mechanisms

- Surface losses in the electrodes of the Paul trap
- Voltage noise in the driving ac and dc biases → Potentially limiting factor due to the fact that the trap potentials have to be kept active all the time




CSL force noise

GRW force noise

**Observation:** A substantive reduction of electronic noise is needed to observe CSL noise.

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# Calibration of decoherence sources

## Noise related to the surrounding environment

- Scattering with gas particles
- Scattering/emission/absorption of blackbody radiation

equilibration of the particle

- Scattering of photons from the driving field
- Possible losses for any electrical detection circuit coupled to the system
- Ambiental vibrational noise

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# Calibration of decoherence sources

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## Noise related to the surrounding environment

- Scattering with gas particles
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equilibration of the particle

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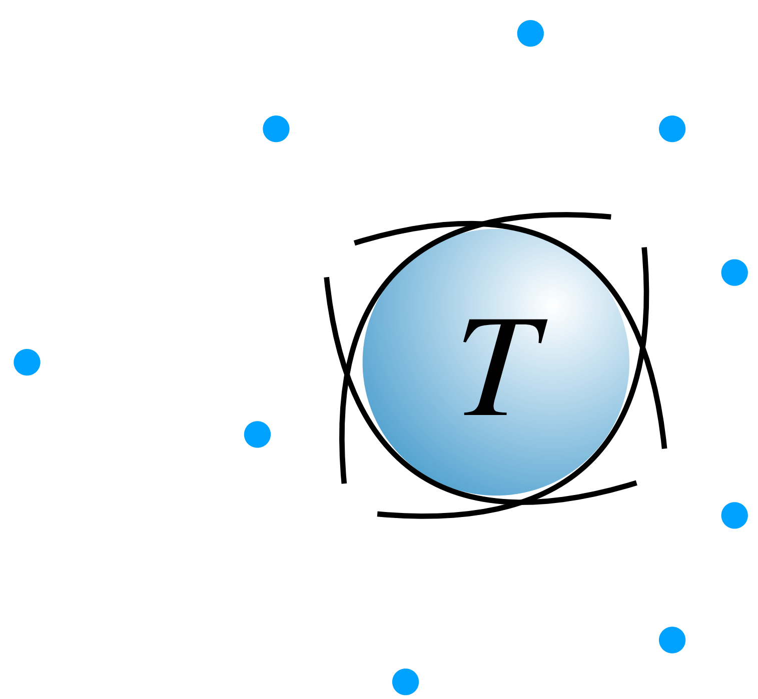


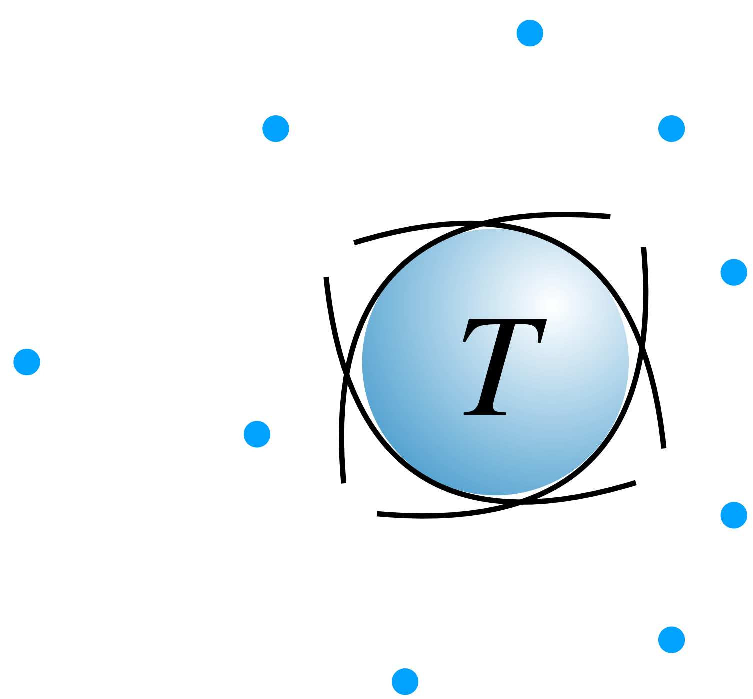

**Observation:** Collisions with gas particles and emission of blackbody radiation determine the bulk temperature of the nanoparticle.

# Calibration of decoherence sources

## Noise related to the surrounding environment

- Scattering with gas particles
- Scattering/emission/absorption of blackbody radiation
- Scattering of photons from the driving field
- Possible losses for any electrical detection circuit coupled to the system
- Ambiental vibrational noise

equilibration of the particle




$$\dot{Q}_{gas} = \frac{\alpha \pi R^2 P_g v_t}{2T_g} \frac{\gamma + 1}{\gamma - 1} (T - T_g)$$

Heat flux from particle to cold environment (classical study)

$$\dot{Q}_{bb} \simeq -\frac{72}{\pi^2} \frac{V k_B^5}{c^3 \hbar^4} \epsilon_{abs} (T^5 - T_g^5)$$

Flux due to blackbody radiation-due

$$\dot{Q}_{bb} + \dot{Q}_{gas} + W_{abs} = 0$$

Power absorbed from light

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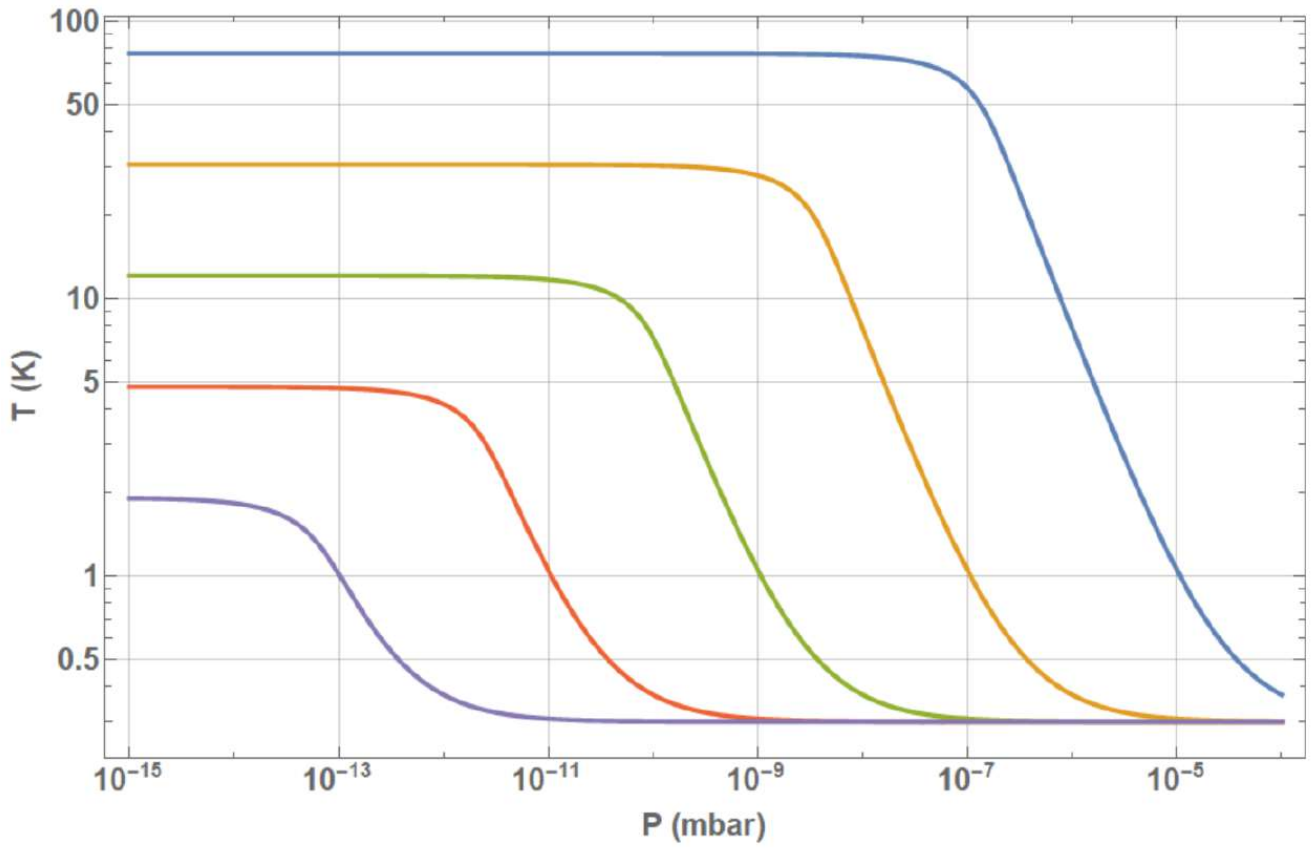
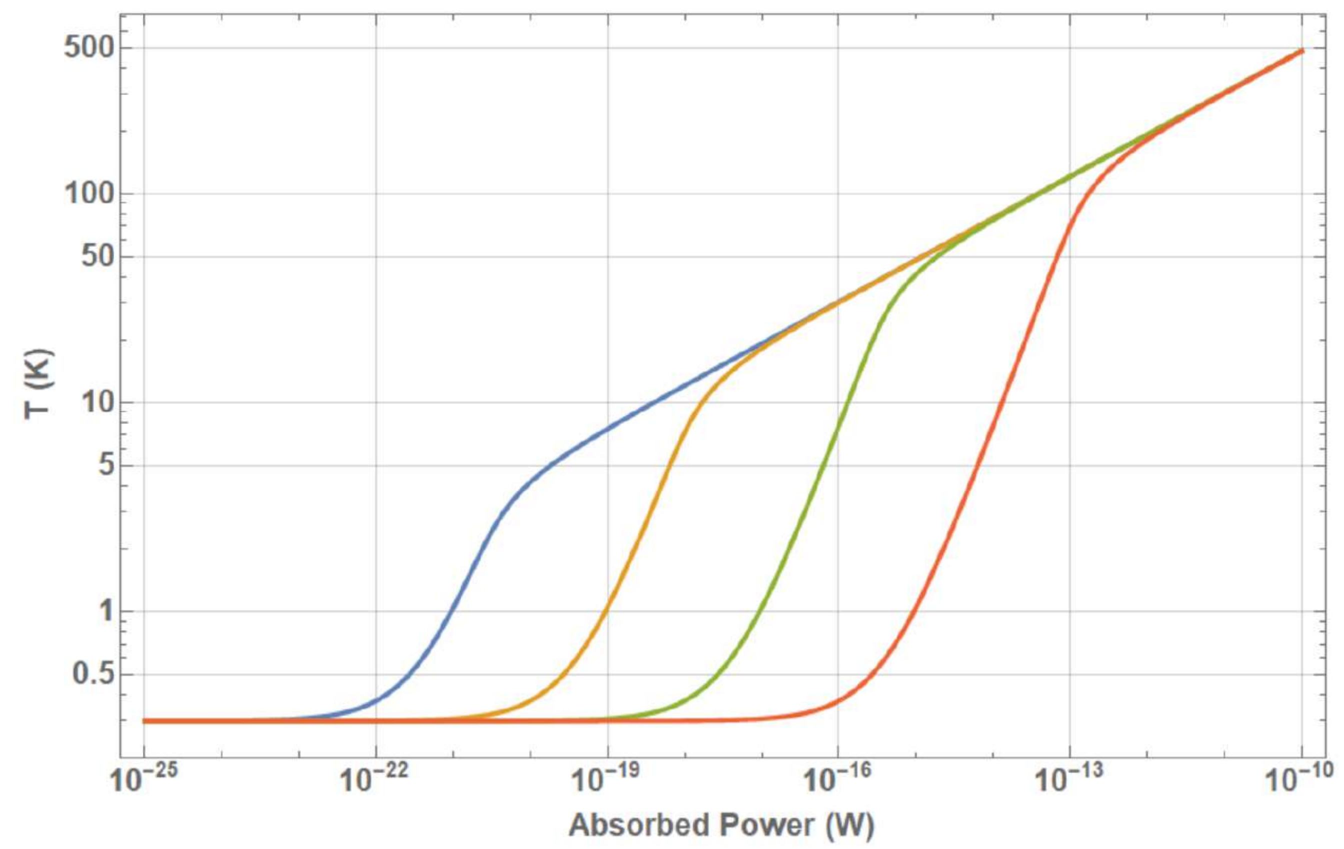
# Calibration of decoherence sources



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# Calibration of decoherence sources

## Noise related to the surrounding environment

- Scattering with gas particles
- Scattering/emission/absorption of blackbody radiation
- Scattering of photons from the driving field — comprehensive approach to scattering
- Possible losses for any electrical detection circuit coupled to the system
- Ambiental vibrational noise

$$\dot{\rho}_S = -i[H_S, \rho_S] + \int d\mathbf{k}\delta(\omega_k - \omega_0)\left(2\mathcal{T}_{\mathbf{k}c}(\hat{r})\hat{a}_0\rho_S\hat{a}_0^\dagger\mathcal{T}^*_{c\mathbf{k}}(\hat{r}) - \left\{|\mathcal{T}_{\mathbf{k}c}(\hat{r})|^2\hat{a}_0^\dagger\hat{a}_0, \rho_S\right\}\right)$$

Cavity field ($\omega_0$, $\hat{a}_0$, $\hat{a}_0^\dagger$) — Scattering amplitude ($\mathcal{T}_{\mathbf{k}c}$)

For $R \ll \lambda$ Rayleigh theory (first-order Born approximation of the scattering amplitude)

$$\Gamma_{sca} = |\alpha|^2 \frac{\epsilon_c k_0^4 V^2}{2V_0}$$

$V$: Volume of nanosphere

$V_0$: Volume of cavity mode

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# Calibration of decoherence sources

## Noise related to the surrounding environment

- Scattering with gas particles
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$$\dot{\rho}_S = -i[H_S,\rho_S] + \int d\mathbf{k}\,\delta(\omega_k-\omega_0)\left(2\mathcal{T}_{\mathbf{k}c}(\hat{r})\hat{a}_0\rho_S\hat{a}_0^\dagger\mathcal{T}^*_{c\mathbf{k}}(\hat{r}) - \left\{|\mathcal{T}_{\mathbf{k}c}(\hat{r})|^2\hat{a}_0^\dagger\hat{a}_0,\rho_S\right\}\right)$$

Cavity field — Scattering amplitude

For $R \geq \lambda$ Mie theory (higher-order expansion of the scattering amplitude)

$$\mathcal{L}[\rho_S] = \frac{|\alpha|^2 c}{2\pi^2 V_0}\int d\Omega |f(\mathbf{k}_0,k_0\mathbf{n})|^2\left[\cos(\mathbf{k}_0\cdot\hat{r})e^{ik_0\mathbf{n}\cdot\hat{r}}\rho_S e^{-ik_0\mathbf{n}\cdot\hat{r}}\cos(\mathbf{k}_0\cdot\hat{r}) - \frac{1}{2}\left\{\cos^2(k_0\cdot\hat{r}),\rho_S\right\}\right]$$

$$= \frac{|\alpha|^2 c V^2\epsilon_c^2 k^4}{12\pi^3 V_0}\int d\Omega\frac{3}{8\pi}\sin^2\theta\left[\cos(\mathbf{k}_0\cdot\hat{r})e^{ik_0\mathbf{n}\cdot\hat{r}}\rho_S e^{-ik_0\mathbf{n}\cdot\hat{r}}\cos(\mathbf{k}_0\cdot\hat{r}) - \frac{1}{2}\left\{\cos^2(k_0\cdot\hat{r}),\rho_S\right\}\right]$$

# Calibration of decoherence sources

## Noise related to the surrounding environment

- Scattering with gas particles
- Scattering/emission/absorption of blackbody radiation
- Scattering of photons from the driving field — comprehensive approach to scattering
- Possible losses for any electrical detection circuit coupled to the system
- Ambiental vibrational noise

$$\dot{\rho}_S = -i[H_S, \rho_S] + \int d\mathbf{k}\,\delta(\omega_k - \omega_0)\left(2\mathcal{T}_{\mathbf{k}c}(\hat{r})\hat{a}_0\rho_S\hat{a}_0^\dagger\mathcal{T}^*_{c\mathbf{k}}(\hat{r}) - \left\{|\mathcal{T}_{\mathbf{k}c}(\hat{r})|^2\hat{a}_0^\dagger\hat{a}_0, \rho_S\right\}\right)$$

Cavity field ($\omega_0$, $\hat{a}_0$, $\hat{a}_0^\dagger$)

Scattering amplitude ($\mathcal{T}_{\mathbf{k}c}$)

Evolution of the cavity field

$$\hat{a}_0(t) = e^{-(\gamma(\hat{r})+i(\omega_{\mathrm{rn}}(\hat{r}))t}a_0 - i\frac{\omega_0\epsilon_c}{2V_0}\int_0^t d\tau\, e^{-(\gamma(\hat{r})+i(\omega_{\mathrm{rn}}(\hat{r}))(t-\tau)}\int_{V(\hat{r})}(f(x)^*)^2\hat{a}_0^\dagger(\tau)$$

$$\gamma_{sca} = 2\frac{\epsilon_c^2 k_0^4 c}{V_0}V^2$$

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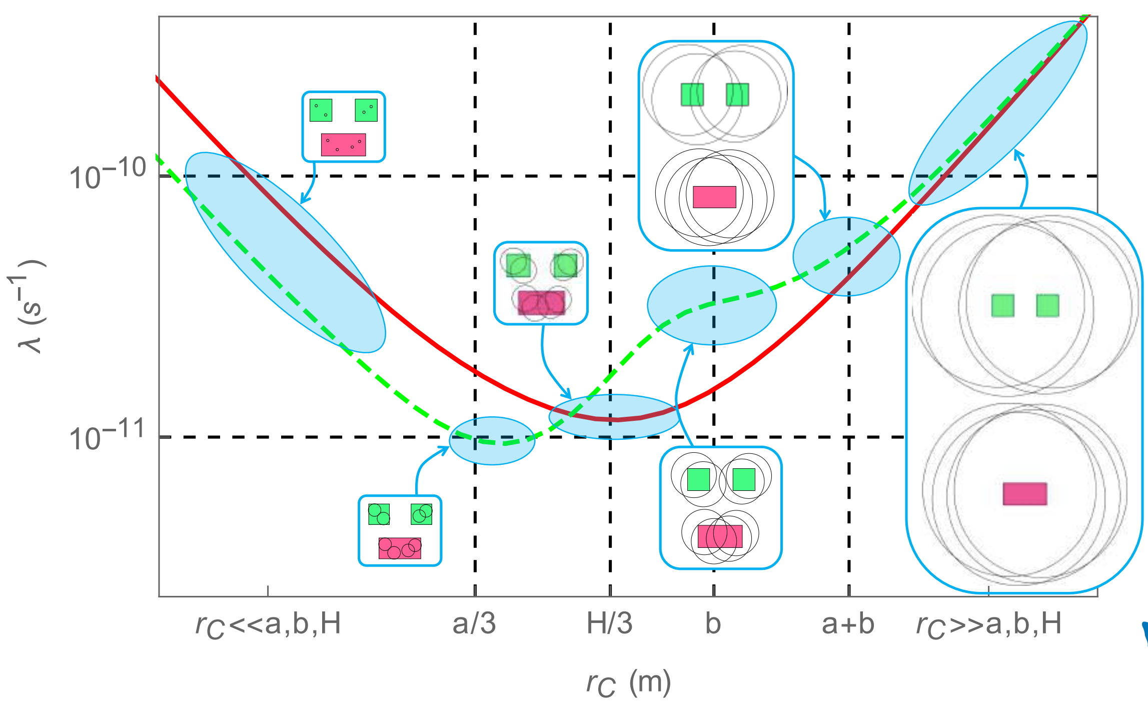
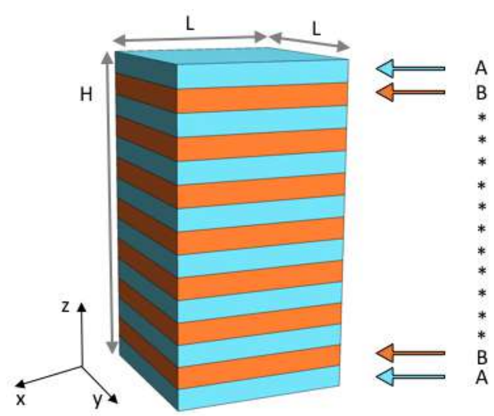
# Going beyond our "dues" for the reporting period

## Amplifying the effects of CSL by smartly designed 'multi-layer' structures




**Intuition:** Thermal forces act on mass as a bulk. CSL force acts on mass "layers".

Two "types" of contributions two CSL force: intra-layer and layer-to-layer.

positive by definition

positive, null, or negative

arranging geometry suitably, can be made to contribute coherently to CSL-due diffusion

M. Carlesso, A. Vinante, and A. Bassi, Phys. Rev. A **98**, 022122 (2018)

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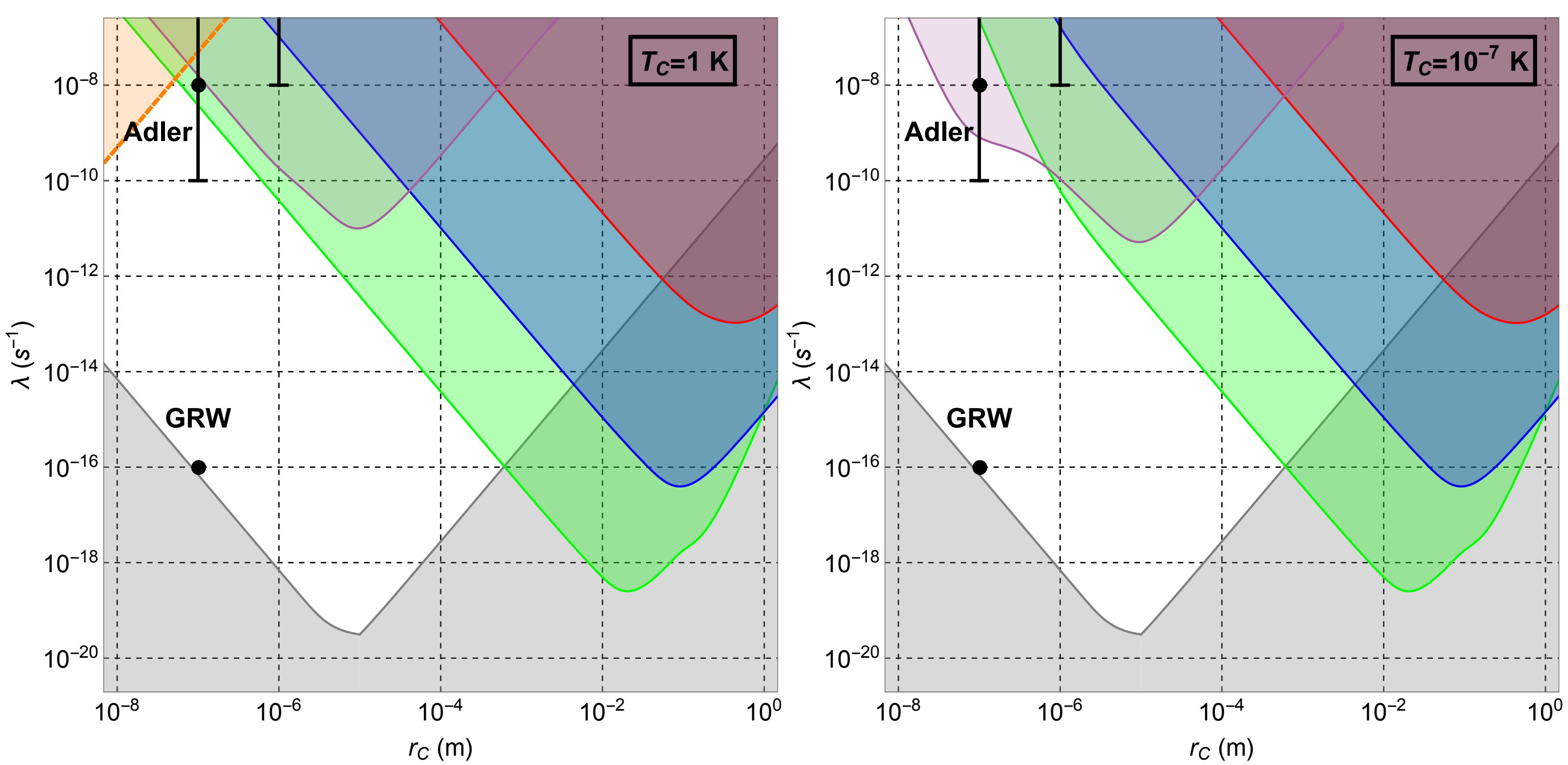
# Going beyond our "dues" for the reporting period

## "Correcting" fallacies in standard CSL: towards a more realistic model




**Problem:** Standard CSL models are not energy-conserving.

We designed a unitary unravelling of energy-conserving CSL to estimate the effects on optomech.

$$\frac{\mathrm{d}\hat{x}}{\mathrm{d}t} = \frac{\hat{p}}{m} - \varkappa\hbar\,\hat{w}_x(t),$$

$$\frac{\mathrm{d}\hat{p}}{\mathrm{d}t} = -m\omega_0^2\hat{x} + \hbar g\hat{a}^\dagger\hat{a} - \gamma\hat{p} + \hat{\xi} - \hbar\hat{w}_p(t),$$

$$\frac{\mathrm{d}\hat{a}}{\mathrm{d}t} = -i\Delta_0\hat{a} + ig\hat{a}\hat{x} - \kappa\hat{a} + \sqrt{2\kappa}\hat{a}_{\mathrm{in}},$$

$$\Delta T_{\mathrm{dCSL}} = \frac{\hbar^2\eta\left[1 + \varkappa^2 m^2\left(\gamma^2 + \omega_0^2\right)\right]}{2k_{\mathrm{B}}m\gamma} - \frac{\gamma_{\mathrm{CSL}}}{\gamma}T$$

J. Nobakht, M. Carlesso, S. Donadi, M. Paternostro and A. Bassi, Phys. Rev. A **98**, 042109 (2018)

TEQ

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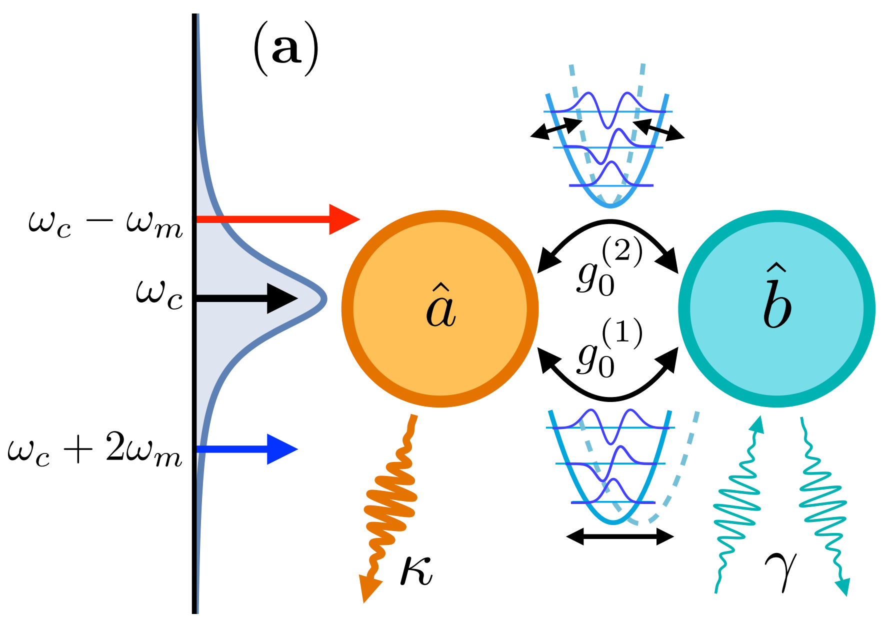
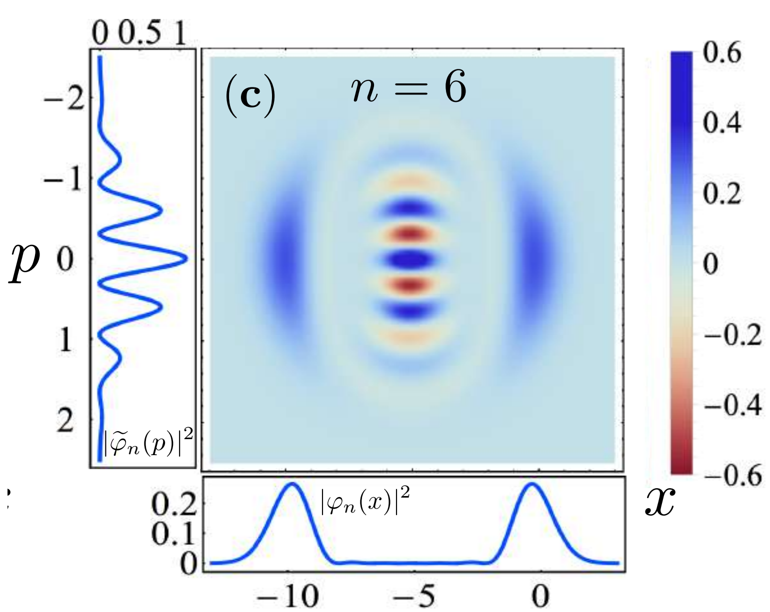
# Going beyond our "dues" for the reporting period

## Looking for smart preparations of non-classical states of massive oscillators




**Problem:** How to efficiently prepare superposition states?

Linear-quadratic model driven by three-tone field

$$\hat{H}_{\mathrm{RWA}} = G_1(\hat{d}^\dagger \hat{f} + \hat{d}\,\hat{f}^\dagger)$$

$$\hat{f} = \hat{b} + \frac{G_2}{G_1}\hat{b}^{\dagger\,2} + \frac{G_3}{G_1}(\hat{b}\hat{b}^\dagger + \hat{b}^\dagger\hat{b})$$

$$|\varphi_n\rangle \propto \hat{D}(\zeta_n)\hat{S}(r)\sum_{j=0}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{2^{2j} j! \sqrt{(n-2j)!}} |n-2j\rangle$$

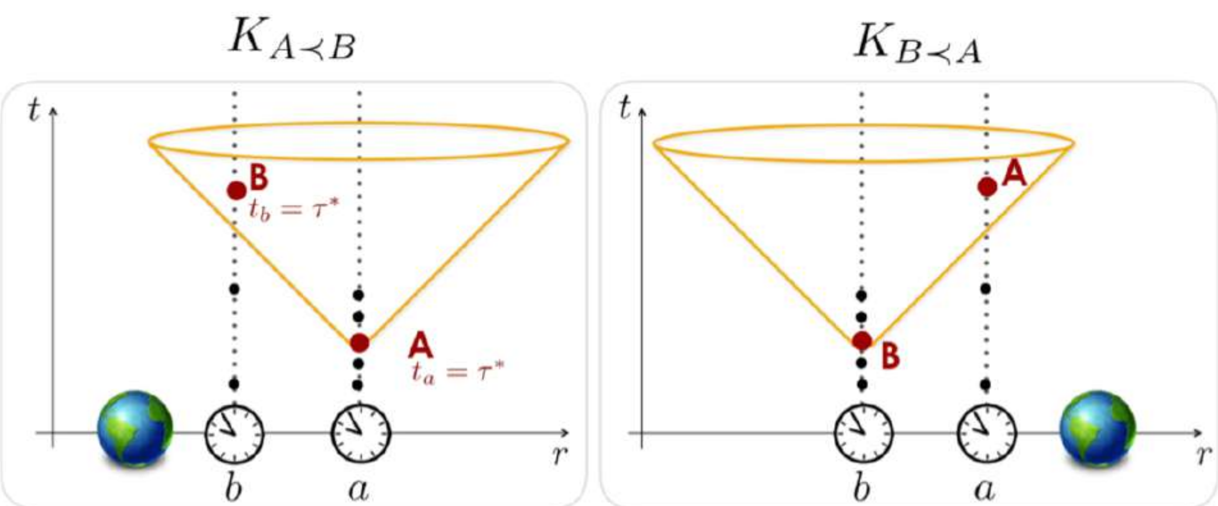
M Brunelli, O Houhou, D W Moore, A Nunnenkamp, M Paternostro, A Ferraro, Phys. Rev. A **98**, 063801 (2018)

Testing the large-scale limit of quantum mechanics

European Commission

# Going beyond our "dues" for the reporting period

**Development of a framework for quantum theory with no fixed causal order** between events (causal loops, "superpositions of casual orders", the quantum switch)



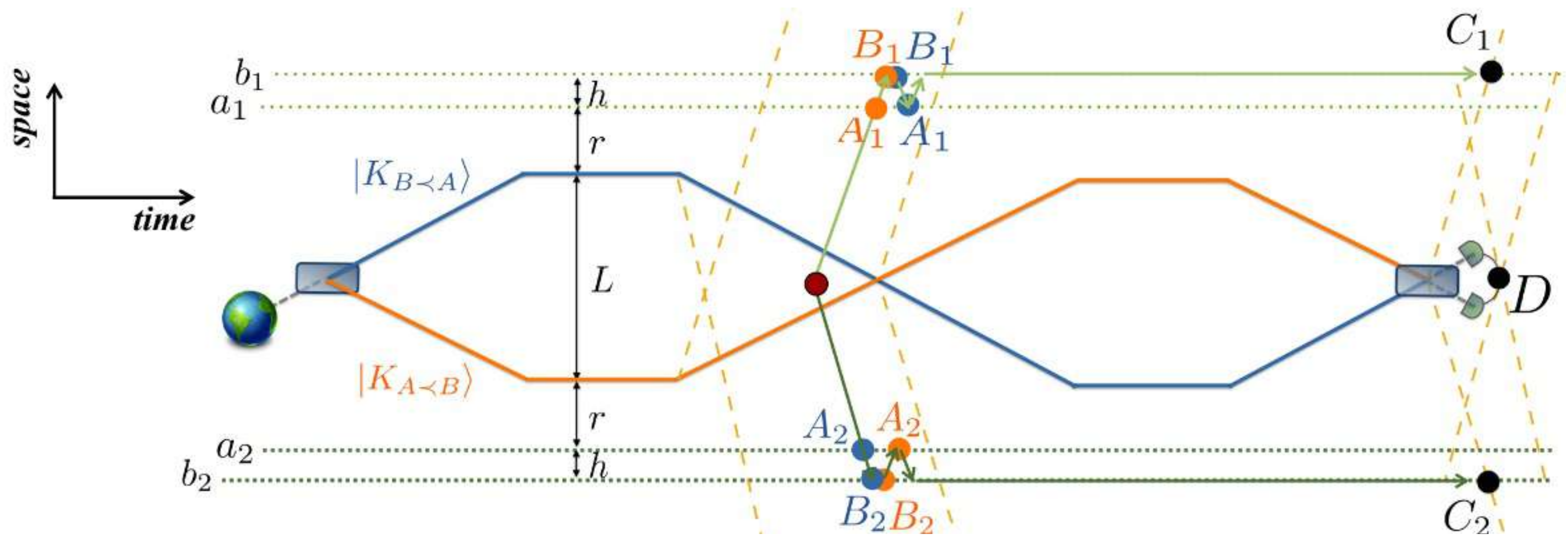

**Problem:** Part of the motivation for gravitationally induced collapse models is the view that a lack of a classical causal structure is purported to prevent a consistent description of physical events and time evolution.

**Even if the modification to quantum theory were true, they do not preclude entangled causal structures for short time scales.**

Testing the large-scale limit of quantum mechanics

# Going beyond our "dues" for the reporting period

A massive body in a spatial superposition leads to "entanglement" of temporal orders between time-like events. This entanglement enables accomplishing a task, violation of a Bell inequality, that is impossible under (local) classical temporal order.




Comparison with **the Diosi-Penrose time:** $T_{DP} = \frac{2\delta^3\hbar}{G(ML)^2}$

$\delta = 10^{-7}s$ $\quad r = 10^{10}R_S,\ L = 5r,\ h = r,\ M = 1g,\ R_S \approx 10^{-30}m,\ T \approx 7\ 10^{-18}s,\ T_{DP} \approx 0.5s$

$\delta = 10^{-15}s$ $\quad r = 10^{7}R_S,\ L = 5\ 10^{5}r,\ h = 10^{5}r,\ M = 10^{-7}kg,\ T \approx 10^{-23}s,\ T_{DP} \approx 10^{-13}s$

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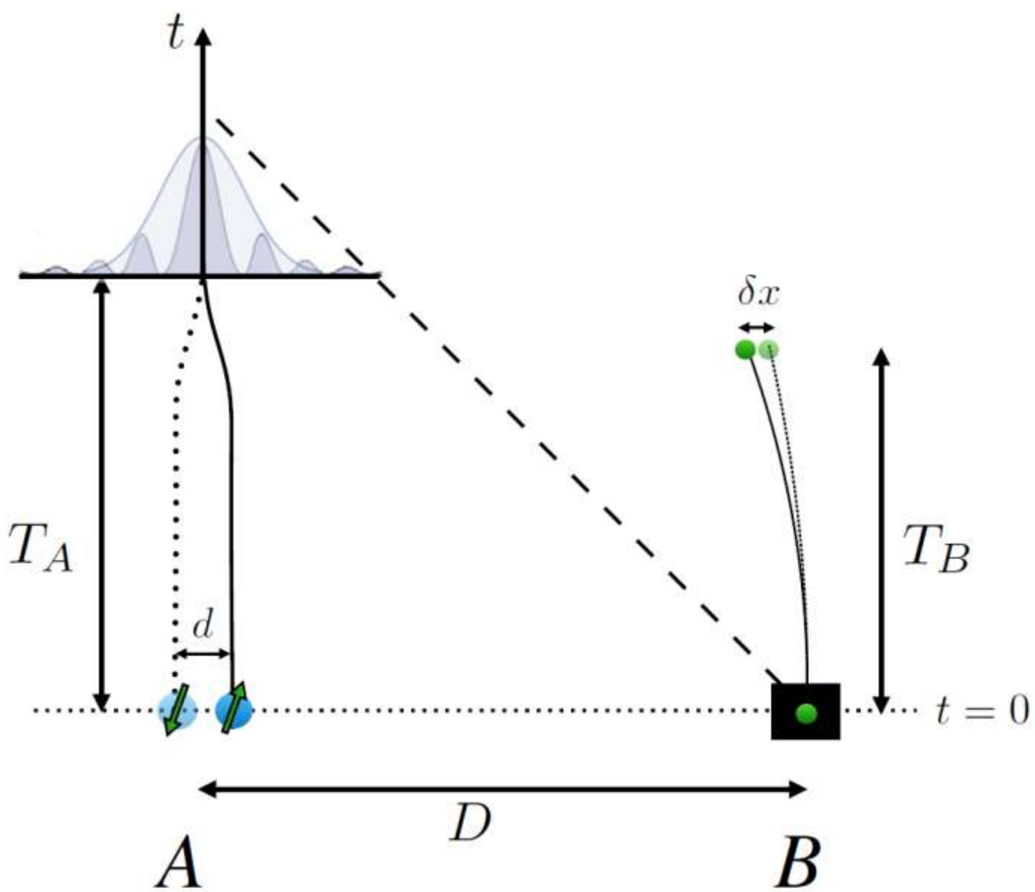
# Going beyond our "dues" for the reporting period

**Reconciling macroscopic superpositions, complementarity and causality**




**Problem:** There have been suggestions that gravity & spacetime could be fundamentally classical. Moreover, it is assumed that macroscopic superpositions of massive objects does not necessitate quantization of gravity

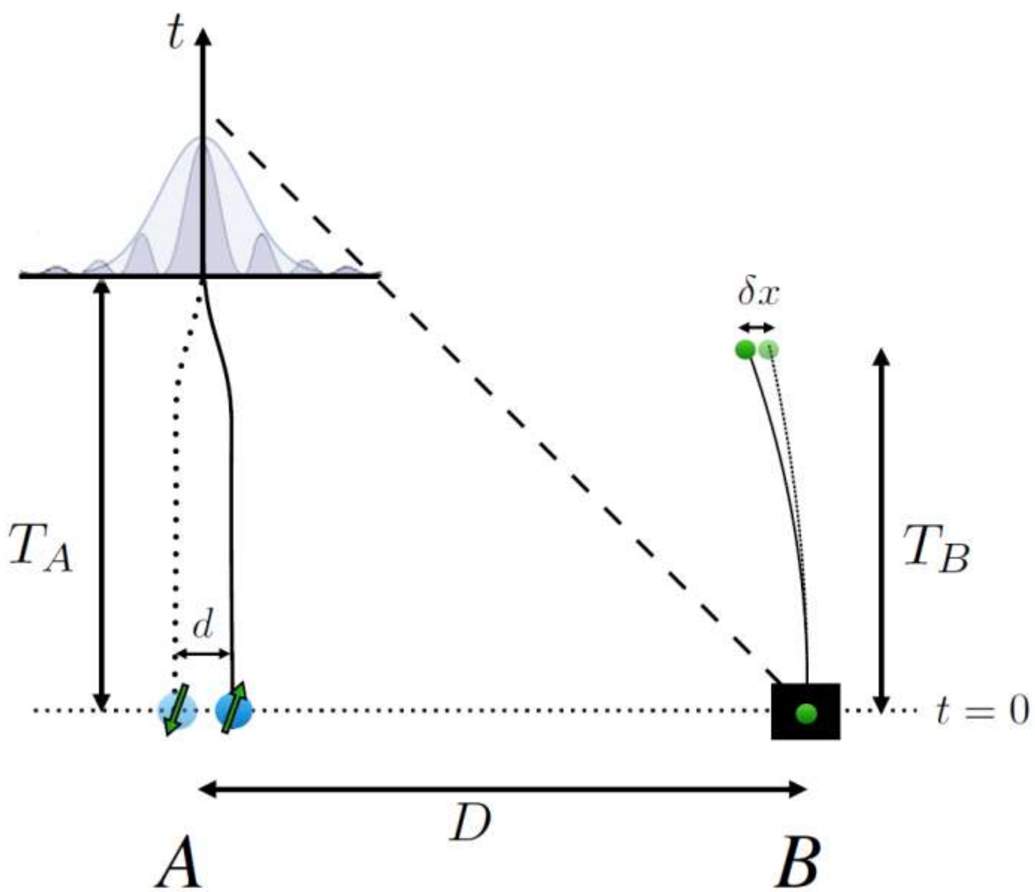
**Suppose** T_A, T_B<D

A. Belenchia, et al. Phys. Rev. D **98**, 126009 (2018)

Testing the large-scale limit of quantum mechanics

# Going beyond our "dues" for the reporting period

## Reconciling macroscopic superpositions, complementarity and causality




**Inconsistencies**?

Assuming complementarity, Alice could determine whether or not Bob opened the trap, in violation of causality. Alternatively, assuming causality, Alice could maintain the coherence while which-path information has been acquired by Bob, in violation of complementarity.

**Suppose** T_A, T_B<D

A. Belenchia, et al. Phys. Rev. D **98**, 126009 (2018)

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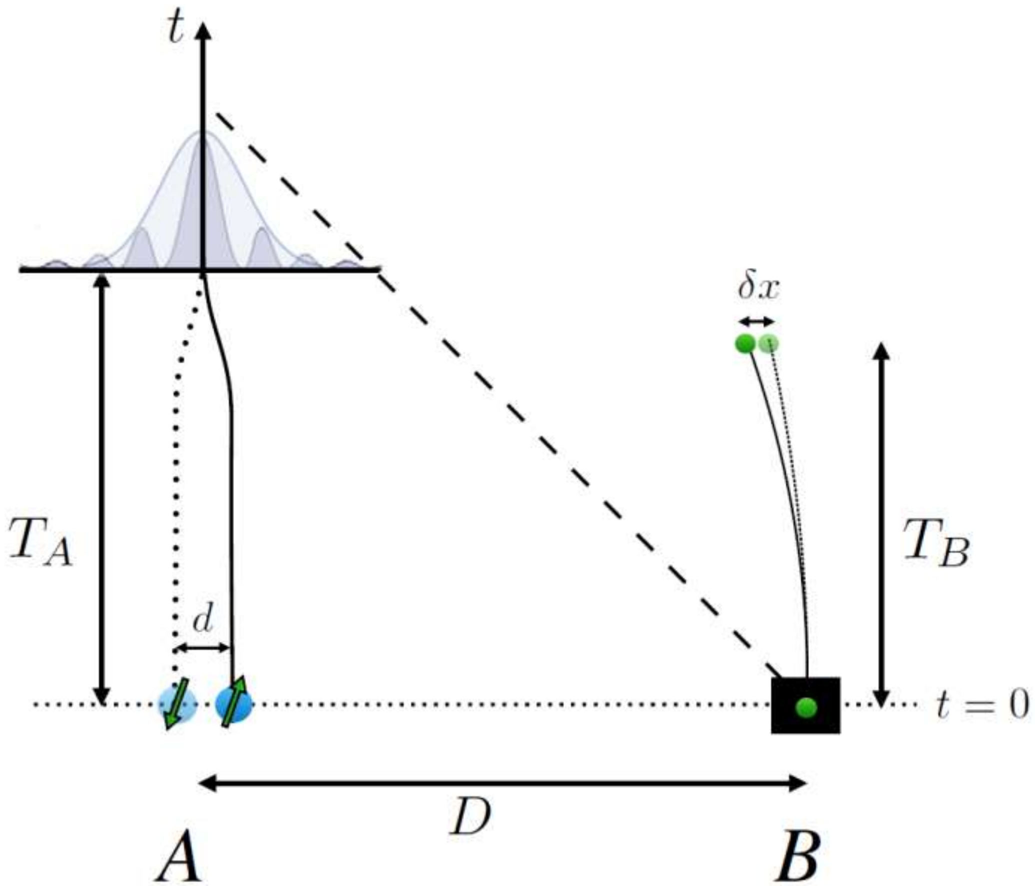
# Going beyond our "dues" for the reporting period

## Reconciling macroscopic superpositions, complementarity and causality




**Suppose** T_A, T_B<D

- **Vacuum fluctuations** limit Bob's ability to acquire which-path information
- **Quantized radiation** decohere Alice's superposition via entanglement with radiation

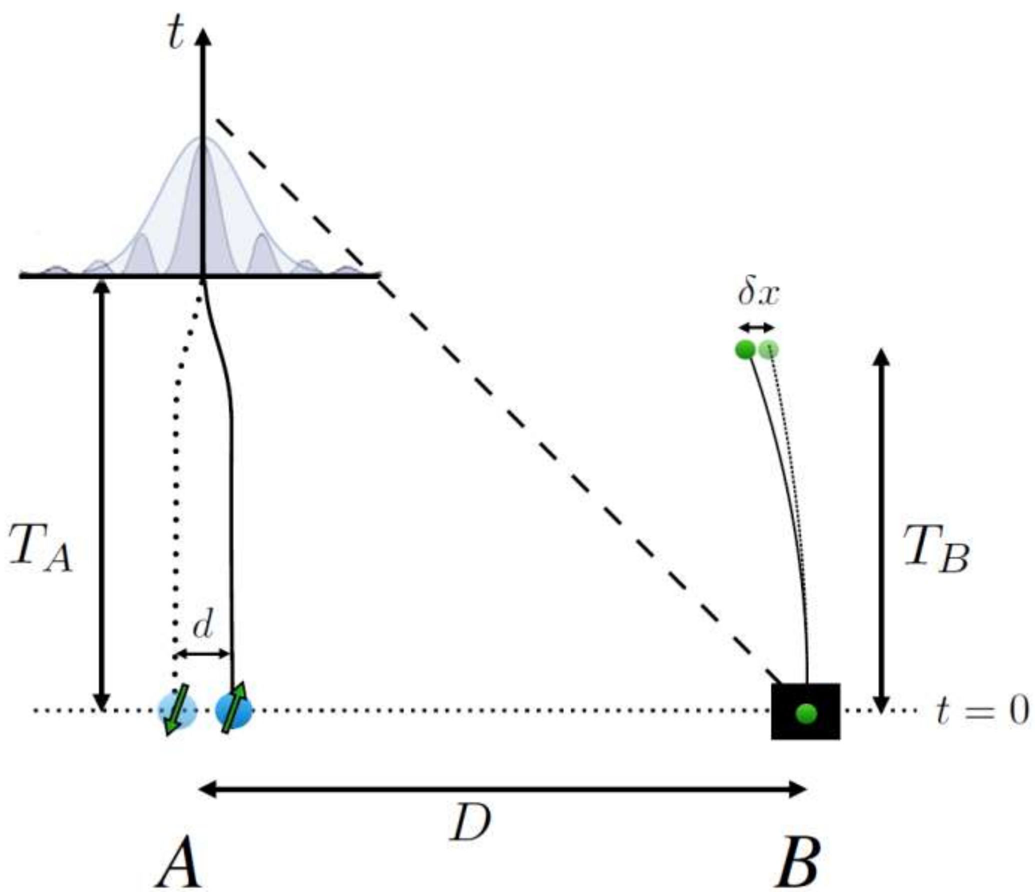
A. Belenchia, et al. Phys. Rev. D **98**, 126009 (2018)

Testing the large-scale limit of quantum mechanics

European Commission

# Going beyond our "dues" for the reporting period

## Reconciling macroscopic superpositions, complementarity and causality

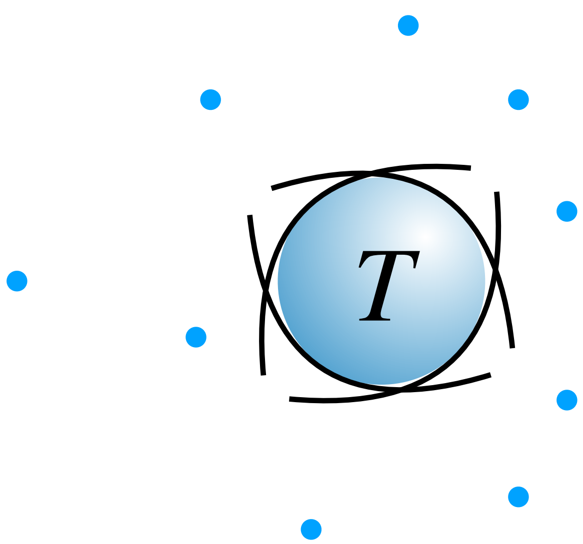



The **quantum nature of the gravitational field**—both with regard to the quantization of gravitational radiation and the impossibility of localization to better than a Planck length—**is essential for avoiding inconsistencies** with "complementarity" and "causality".

**Suppose** T_A, T_B<D

A. Belenchia, et al. Phys. Rev. D **98**, 126009 (2018)

# Current work in progress




**Work being developed:** Quantum description of heat fluxes in a continuously monitored levitated optomechanical system

$$\frac{d\varrho}{dt} = \mathcal{L}\varrho = -i[H,\varrho] + \kappa\,\mathcal{D}[a]\varrho + \Gamma\,\mathcal{D}[b+b^\dagger]\varrho$$

$$d\varrho = \mathcal{L}\varrho\,dt + \sqrt{\eta_1\kappa}\,\mathcal{H}[ae^{i\phi}]\varrho\,dw_1 + \sqrt{\eta_2\Gamma}\,\mathcal{H}[b+b^\dagger]\varrho\,dw_2$$

$$dQ = \mathbf{Tr}[d\varrho H]$$

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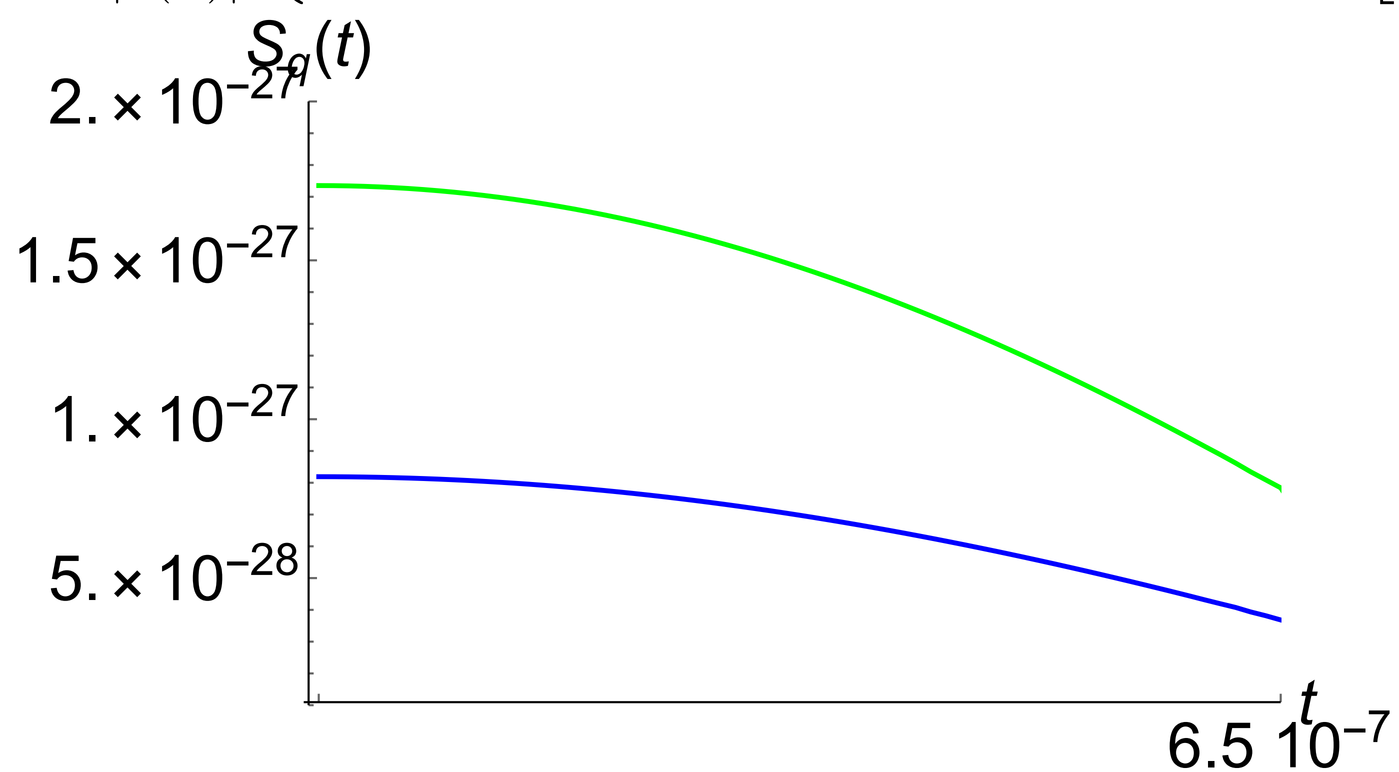
# Current work in progress

**Work being developed:** Develop settings to test energy-conserving CSL. Including rotational degrees of freedom

$$S_q(\omega) = \frac{\hbar}{|d(\omega)|^2}\left\{2\hbar k g^2\alpha^2(\Delta^2+k^2+\omega^2) + m\omega[(\Delta^2+k^2-\omega^2)^2+4k^2\omega^2]\left(\gamma_m \coth\left(\frac{\hbar\omega}{2K_BT}\right)+\frac{\hbar\lambda}{m\omega_m}\right)\right\}$$

$$S_q(\omega) = \frac{\hbar}{|d(\omega)|^2}\left\{2\hbar k g^2\alpha^2(\Delta^2+k^2+\omega^2)+[(\Delta^2+k^2-\omega^2)^2+4k^2\omega^2]\left[m\omega\gamma_m \coth\left(\frac{\hbar\omega}{2K_BT}\right)+\hbar\eta\left(1+x^2m^2(\gamma^2+\omega^2)\right)\right]\right\}$$




QUEEN'S UNIVERSITY BELFAST

UNIVERSITÀ DEGLI STUDI DI TRIESTE

TEQ

Testing the large-scale limit of quantum mechanics

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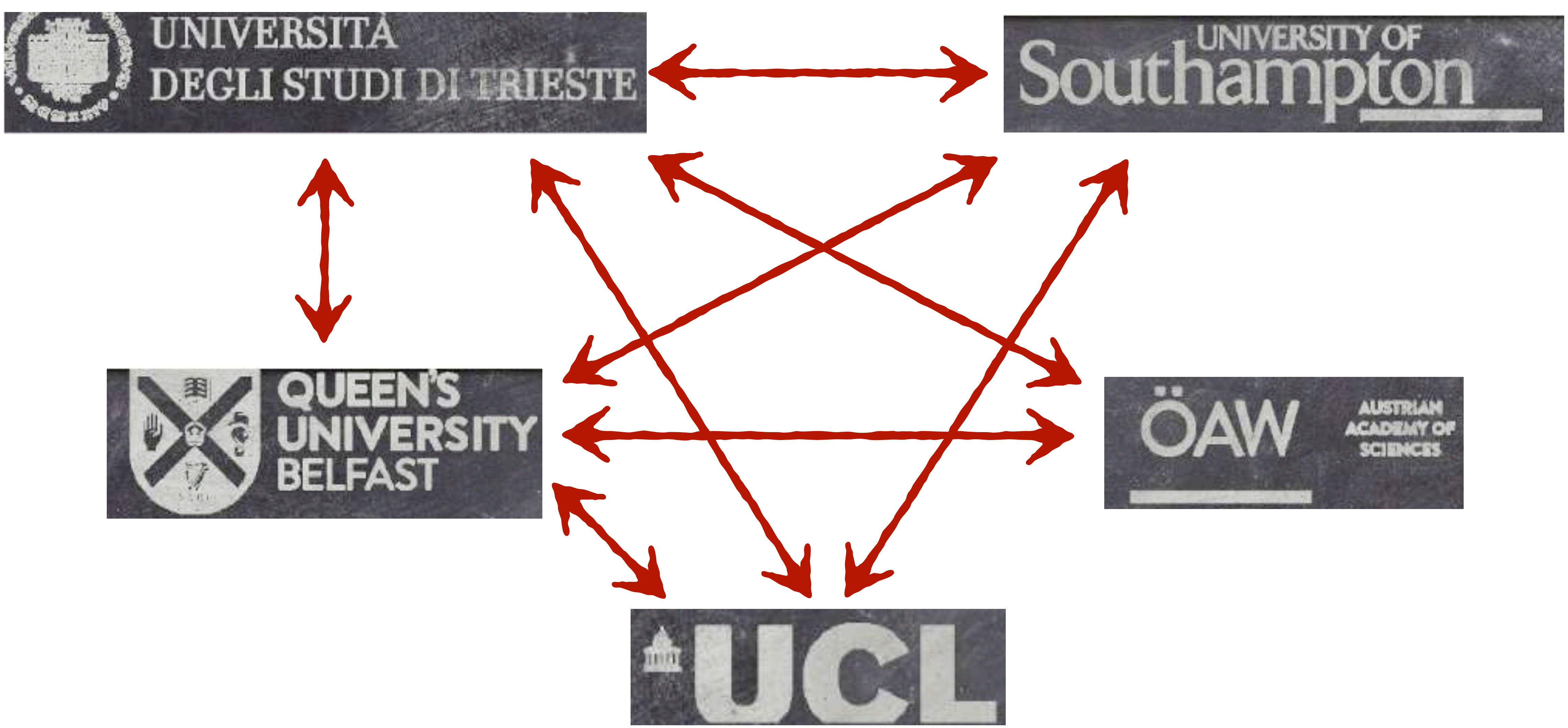
# Intense interactions and collaborations



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# 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]

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# 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].

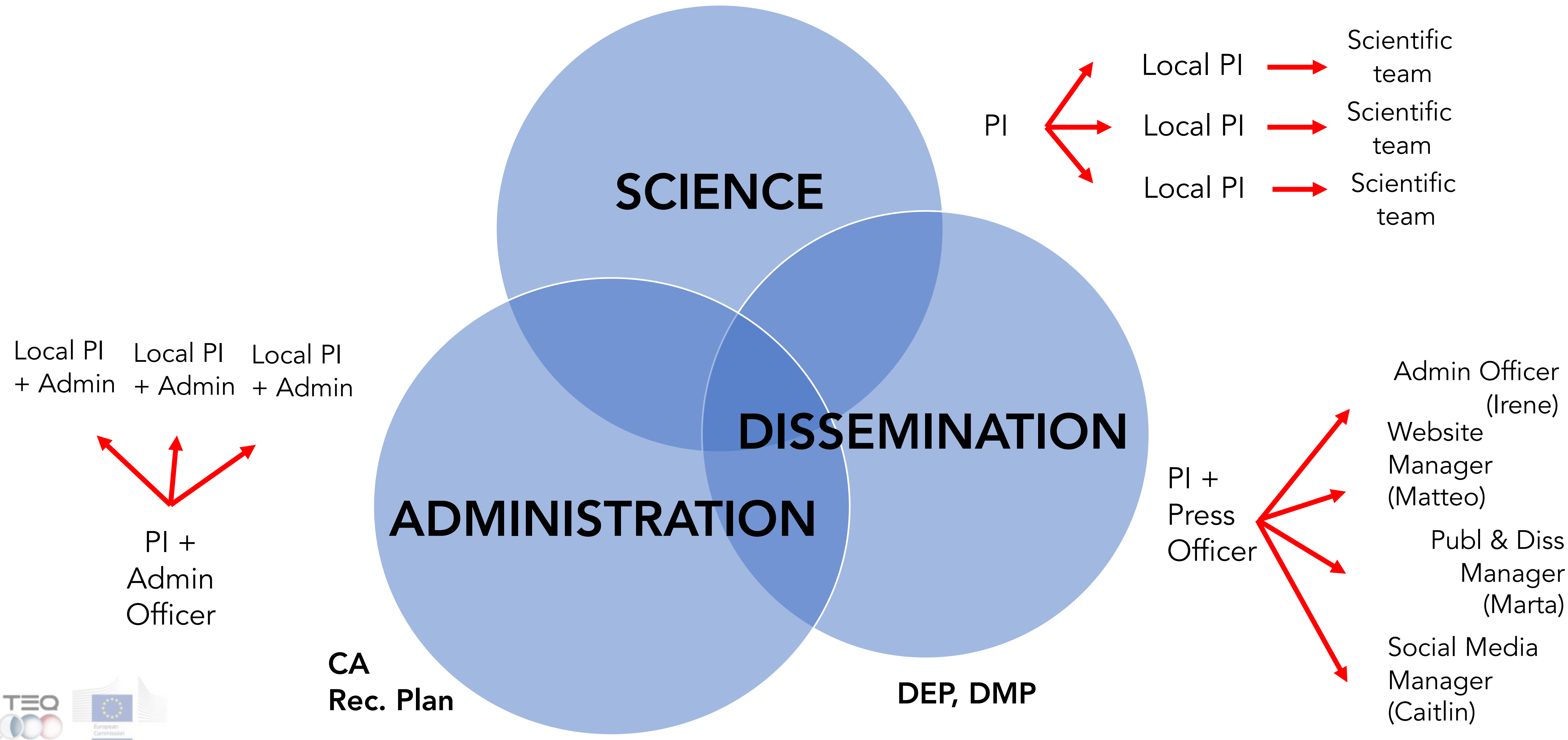
# Organization

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

Matteo Carlesso
Website Manager

Caitlin Jones
Social Media Manager

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

## M2 - M Squared Lasers Limited

Nils Hempler
Local PI
Website

Joseph Thom

James Bain

Stefan Olsonrobbie

## INFN - Istituto Italiano Fisica Nucleare

Catalina Curceanu
Local PI & Press Officer

Kristian Piscicchia

Alberto Clozza

Massimiliano Bazzi

## AU - Aarhus University

Michael Drewsen
Local PI
Website

Cyrille Solaro

Aurelién Dantan
Website

Vincent Jarlaud

## TUD - Delft University of Technology

Liberato Manna
Local PI
Website

Luca De Trizio

Arjan Houtepen
Website

Jence Mulder

## UoS - University of Southampton

Hendrik Ulbricht
Local PI
Website

Giulio Gasbarri

Christopher Timberlake

Andrea Vinante

Ashley Setter

## OEAW - Austrian Academy of Sciences

Caslav Brukner
Local PI
Website

Esteban Castro Ruiz

Ilya Kull

## UCL - University College London

Peter Barker
Local PI
Website

Antonio Pontin

Thomas Penny

Anishur Rahman

Jonathan Gosling

Marco Toroš

European Commission

# ECRs & Gender dimension

| Early Career Researchers | | | | | |
|---|---|---|---|---|---|
| Participating | | | Paid by TEQ | | |
| Postdoc | PhD | Student | Postdoc | PhD | Student |
| 15 | 14 | 1 | 10 | 7 | 1 |

| Beneficiaries | Total number of females in the workforce | Total number of males in the workforce |
|---|---|---|
| 1 - UNIVERSITA DEGLI STUDI DI TRIESTE | 1 | 3 |
| 2 - AARHUS UNIVERSITET | 1 | 4 |
| 3 - ISTITUTO NAZIONALE DI FISICA NUCLEARE | 1 | 1 |
| 4 - OESTERREICHISCHE AKADEMIE DER WISSENSCHAFTEI | 1 | 2 |
| 5 - THE QUEEN'S UNIVERSITY OF BELFAST | 1 | 2 |
| 6 - TECHNISCHE UNIVERSITEIT DELFT | 0 | 2 |
| 7 - UNIVERSITY COLLEGE LONDON | 0 | 4 |
| 8 - UNIVERSITY OF SOUTHAMPTON | 1 | 3 |
| 9 - M-SQUARED LASERS LIMITED | 5 | 16 |

# 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)
- 2 Grants from FQXi (USA)
- 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

- 02.02.2018 (Trieste): Kick off meeting
- 28.03.2018 (London): Scientific meeting
- 22.06.2018 (Southampton): Scientific + SC Meeting
- 8-9.11.2018 (Delft): Scientific + SC Meeting

**Place:** Delft

**Date:** November, 2018

**Schedule**

**November 8th, 2018: TEQ Junior Workshop**

09:30 - 09:50 Welcome and introduction
09:50 - 10:10 J. Mulder (TUD)
10:10 - 10:30 T. Penny (UCL)
10:30 - 11:00 Coffee break
11:00 - 11:20 C. Jones (UniTS)
11:20 - 11:40 M. Marchese (QUB)
11:40 - 12:00 A. Belenchia (OEAW)
12:00 - 13:00 lab tour - theoretical discussion
13:00 - 14:20 Lunch
14:20 - 14:40 M. Toros (UoS)
14:40 - 15:00 M. Bazzi (INFN)
15:00 - 15:30 Coffee break
15:30 - 18:30 Scientific Discussion
19:00 - Social Dinner (see below)

**November 9th, 2018**

09:00 - 10:30 Steering Committee Meeting
10:30 - 11:00 Coffee break
11:00 - 13:00 Steering Committee Meeting
13:00 - 14:00 Lunch

**Participants**

UniTS: A. Bassi, M. Carlesso, C. Jones, G. Gasbarri, L. Asprea, I. Spagnul
INFN: C. Curceanu, M. Bazzi
UCL: P. Barker, J. Gosling, A. Rahman, T. Penney
QUB: M. Paternostro, M.M. Marchese
AU: M. Drewsen
TUD: L. Manna, L. di Trizio, F. de Donato, J. Mulder, A. Houtepen
UoS: A. Vinante, H. Ulbricht, M. Toros
OEAW: A. Belenchia, I. Kull

## WG meeting - TEQ meeting in Delft

View Edit

**Date:**
November, 2018

**Place:**
Delft

**Type Document:**
Activities

**File:**
- Presentation TEQ Delft_Alessio Belenchia OEAW.pdf
- Presentation TEQ Delft_Andrea Vinante UoS.pdf
- Presentation TEQ Delft_Caitlin Jones UniTS.pdf
- Presentation TEQ Delft_Jence Mulder TUD.pdf
- Presentation TEQ Delft_Marko Toros UoS.pdf
- Presentation TEQ Delft_Marta Maria Marchese QUB.pdf
- Presentation TEQ Delft_Massimiliano Bazzi_INFN.pdf
- Presentation TEQ Delft_Tom Penny UCL.pdf
- Presentation TEQ Delft_SC Meeting_Angelo Bassi UniTS.pdf
- TEQ_SC Meeting Minutes_Delft.pdf

TEQ Testing the large-scale limit of quantum mechanics

TEQ Steering Committee Meeting
Delft – 9th November 2018

MINUTES

1. Welcome by the SC Chair and adoption of the agenda

The members present at the Meeting are:

| | |
|---|---|
| UniTS | A. Bassi, M. Carlesso, G. Gasbarri, L. Asprea, C. Jones, I. Spagnul |
| INFN | C. Curceanu, M. Bazzi |
| UCL | P. Barker, A. Rahman, T. Penney |
| QUB | M. Paternostro, M.M. Marchese |
| AU | M. Drewsen |
| TUD | L. Manna, A. Houtepen, J. Mulder, L. De Trizio, F. De Donato |
| UoS | H. Ulbri... |
| OEAW | A. Bele... |

The chair presents the agenda, ...
to the meeting (see attachment ...

2. Review of the first of mo...

The Chair summarizes the mai...
meetings and TEQ official mee...

- ✓ Kick off meeting: 2nd Feb...
- ✓ WG meeting: 28th March...
- ✓ WG meeting: 22nd June...
- ✓ Workshop + SC meeting...

The next TEQ SC meetings will...
will be in Brussels on 26th Febru...

TEQ Testing the large-scale limit of quantum mechanics

The Chair presents the Dissemination and Communication activities so far implemented by the Consortium and described on the TEQ Website. Regarding publications and pre-prints, he gives an overview of the differences in numbers between publications and pre-prints on the Website, on OpenAire and the EU Participant Portal.

Irene Spagnul (TEQ's Administrative Officer) presents the updates of the TEQ's Website (with a focus on Dissemination part and Document part).

Catalina Curceanu (INFN) presents the draft of the TEQ Dissemination and Exploitation Plan (DEP) that has to be delivered by month 12 of the project (December 2018). Discussion followed on changes and additions. The draft is updated and partners agree to review once more the Deliverable draft once it is ready (preparation by UniTS).

3. Mid-term workshop on the topic of the TEQ

From the GA: ...*organization of a workshop on the topic of "Redefining the foundations of physics in the quantum technology era", which will be held in Trieste in the second year of TEQ's lifetime.*

The Chair leads the discussion on the possible dates for the workshop. The Week of September 16th (September 16-19) is agreed among the partners. The Title of the workshop is agreed as written in the GA. The partners agree on the following committees:

Local Committee: Angelo Bassi, Irene Spagnul

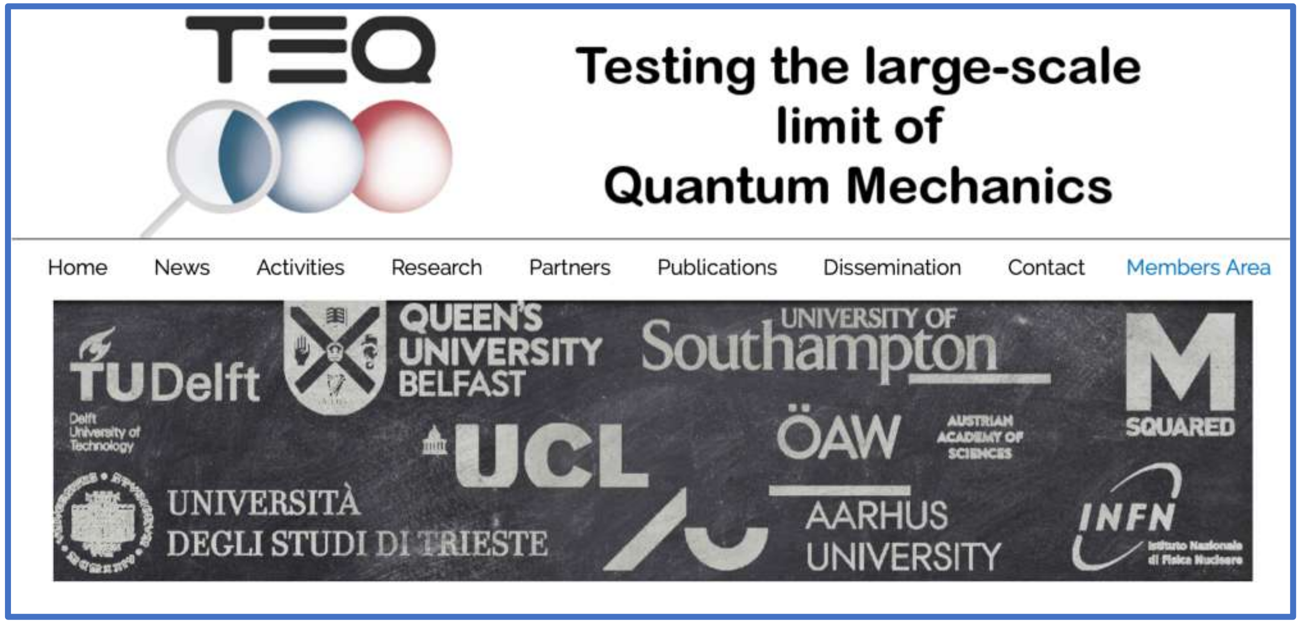
Programme Committee: Angelo Bassi (chair), Catalina Curceanu, Peter Barker, Mauro Paternostro, Michael Drewsen, Liberato Manna, Hendrik Ulbricht, Caslav Brukner, Nils Hempler

The Chair invites the partners to start thinking about the people to invite, being September a busy period.

4. Publications – EU policy on open access

Irene Spagnul (UniTS) presents the EU policy on open access for H2020 FETOPEN publications (obligations and guidelines). The partners are encouraged to use open access publishers or publishers who give less than 6 months' embargo on publications. Moreover, the partners are invited to use the platform Zenodo to deposit and give free access to their research dataset (unless they are allowed to do it on their institutional repositories). Partners discuss on this topic.

# Task 5.2
# Setting up and maintenance of the website




[http://tequantum.eu/](http://tequantum.eu/)

hosted at the servers of INFN in Padriciano (Trieste, ITALY)

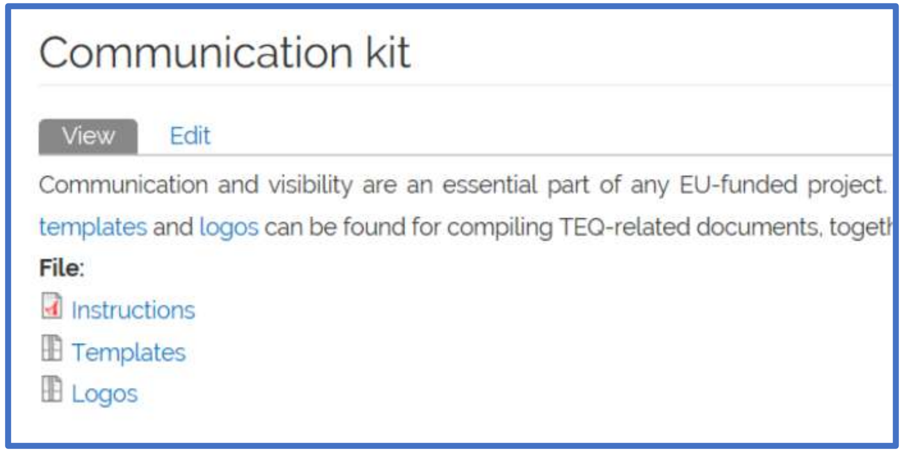
Public area

Private area

The logo represents a superposition, model as a red and a blue
sphere, which is measured by a magnifying glass.
Above, project's acronym.

Based on the same colour palette, fonts and logo, a set of templates have been designed by the TEQ WP6 Leader (UNITS):

- The TEQ letterhead;
- A template for project Deliverables;
- A template for project PowerPoint presentations;
- A template for project Press Releases.



# Administrative Officer

As per GA

- Assists the Chair in **managing** TEQ
- Updates the **public** sections of the website
- Uploads the documents in the **private** area
- Prepares the internal periodic **newsletters**
- Acts as secretary for the planned **workshop**

New administrative roles:
- Proposed on March 2, 2018
- Approved unanimously in e-Vote by the SC on March 11, 2018

## Publications & Dissemination Manager

- Collects list of TEQ related **publications** & checks the acknowledgements
- Collects **dissemination outputs**

## Website Manager

- Controls the **proper functioning** of the website
- Makes **changes** to the structure of the website when needed

## Social Media Manager

- Updates the TEQ **Facebook** account
- Updates the TEQ **Twitter** account
- Responds to questions and moderate comments

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

- Organize scientific and SC meetings
- Ensure respect of deadlines
- Monitor of recruitment plan
- Collecting deliverables and submitting them
- Collecting data, assembling and submitting financial & scientific reports

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

ANNEX I

**Data Management Plan (DMP)**
**TEQ**

Data that will be collected/generated. All digital data and documents that are integral to the research of TEQ, and necessary to validate the results presented in scientific publications, will be collected and stored in the electronic databases. All data and protocols that are the basis for publications will be made publicly available for reuse. Briefly, our data will consist of (but not be limited to)

- Experimental: raw data files from experiments
- Experimental: raw image files
- Experimental: Files with data manually entered
- Theoretical: Numerical simulations
- Software or computational model specifically written for TEQ

In addition, for data that is made publically available, we will document information on how the data were obtained (metadata) to enable others to use these data.

Whom are these data addressed to. Potentially, any theoretical/experimental research group interested in TEQ-related research, in particular in opto-mechanics and quantum foundations.

Collection of data. Data will be collected and catalogued in a standard way. Specific information will be given about:

- Data-set reference and name
- Description of data
- Standards
- Associated metadata

Repositories. Consortium members will deposit their data in online repositories, as listed in Annex I. Information and tools required for mining will be made available so that results can be verified and data re-used.

During the research. It has been verified that for all servers, which the links listed in Annex I point to:

- Have sufficient storage capacity for the duration of the project
- Have sufficient backup capacity for the duration of the project
- Here is no need for extra expertise, other than standard maintenance of the servers provided by their administrators.
- They are free of charge, or alternatively their cots will be paid with the overheads



After the research. Procedures will be put in place for long-term preservation of the data and archiving for three years after the end of the project.

On the TEQ website. Copies of the pre-prints of TEQ-related papers will be made available through the TEQ website in the section *Publications*. In the private part of the TEQ website, a list of all TEQ-related publications will be made available; it will provide detailed information about journal reference and associated preprint on ArXiv. A similar table will be provided for all TEQ-related preprints, whether the related work has been already published or not.

In implementing the above-mentioned, the articles 29.1, 29.2 and 29.3 of the Grant Agreement will be strictly followed.

List of online repositories:

- UniTs: http://www.qmts.it:8080/?q=teq/repository
- INFN: http://www.openaccessrepository.it/
- UCL: http://discovery.ucl.ac.uk/
- QUB: https://pure.qub.ac.uk/portal/en/persons/mauro-paternostro(d10f9f5f-ce96-49f6-bc57-242feb5400e5)/publications.html
- AU: https://www.dropbox.com/sh/8cntnkg5n6vz6i9/AAB3o9wjGoHyEY5sADUhQ0Bla?dl=0
- TUD: data.4tu.nl
- UoS: https://eprints.soton.ac.uk
- OEAW: https://zenodo.org/communities/iqoqi-vienna/
- M2: https://www.dropbox.com/sh/w61iv7iu397rebs/AAAn4JjCpJDdoxV1dXNUL2xKa?dl=0

Further amended

TEQ

Testing the large-scale
limit of
quantum mechanics

European
Commission

# WP6: DISSEMINATION



C. Curceanu - INFN

# 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:

EXTERNAL

Quantum community
Broader scientific community
Industry
Schools, general public…

INTERNAL

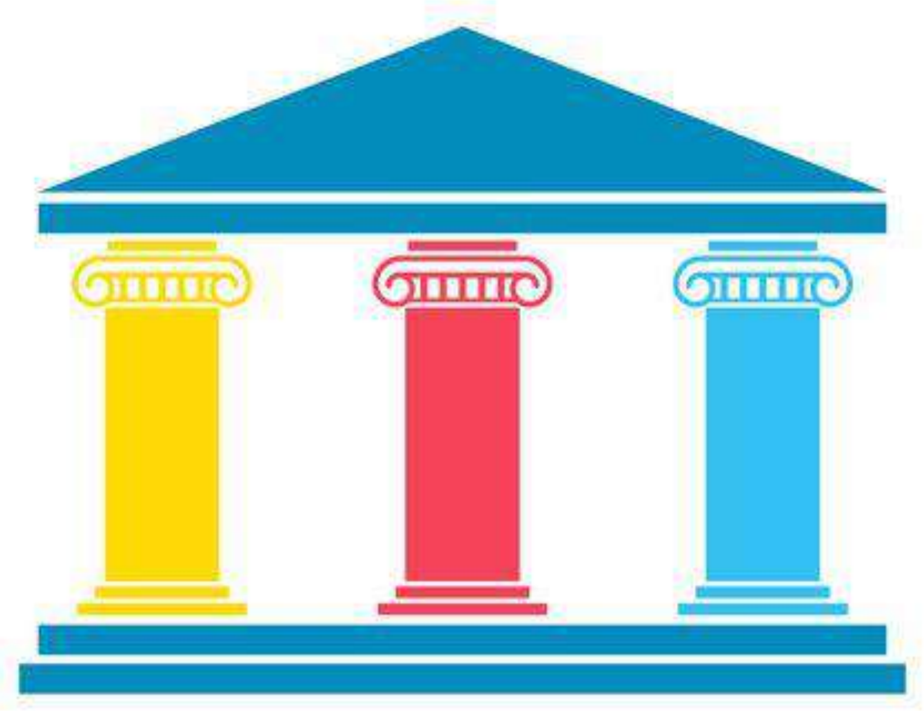
TEQ community

TEQ

# DISSEMINATION Overview

## INTERNAL

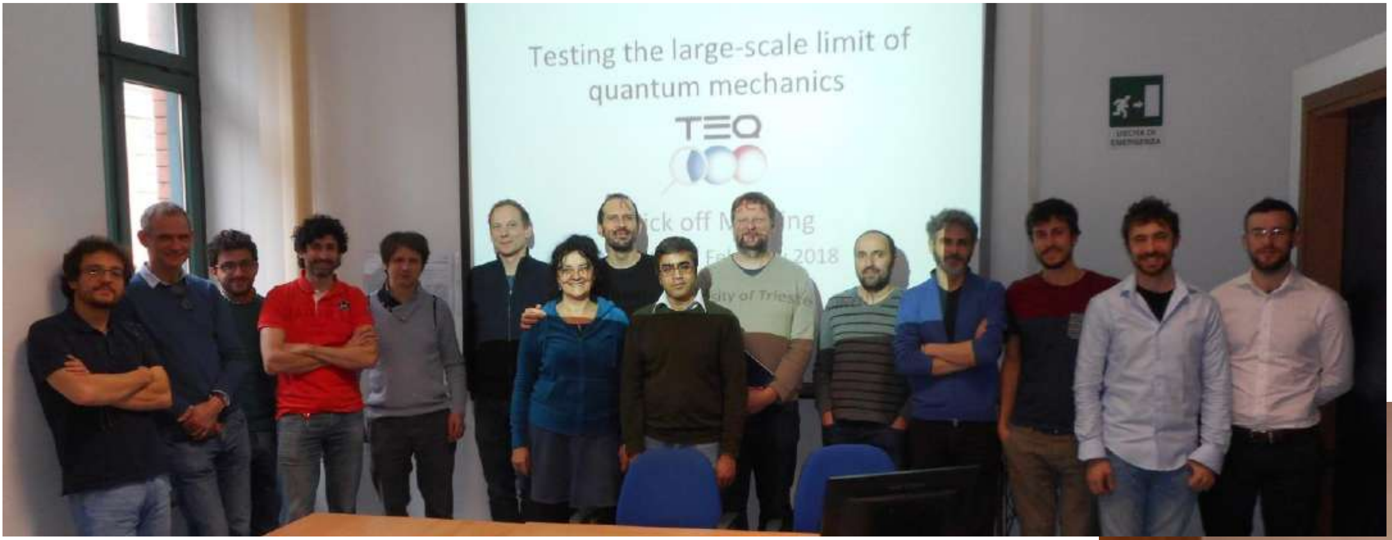
- **Consortium meeting and SC meetings.**
- **TEQ Website .**
- **TEQ Newsletters (4/year).**



# INTERNAL DISSEMINATION

- **Consortium meeting and SC meetings**
  - ✓ 1 Kick-off
  - ✓ 3 Scientific meetings + smaller groups meetings
  - ✓ 3 Steering Committee Meetings

# STEERING COMMITTEE MEETINGS



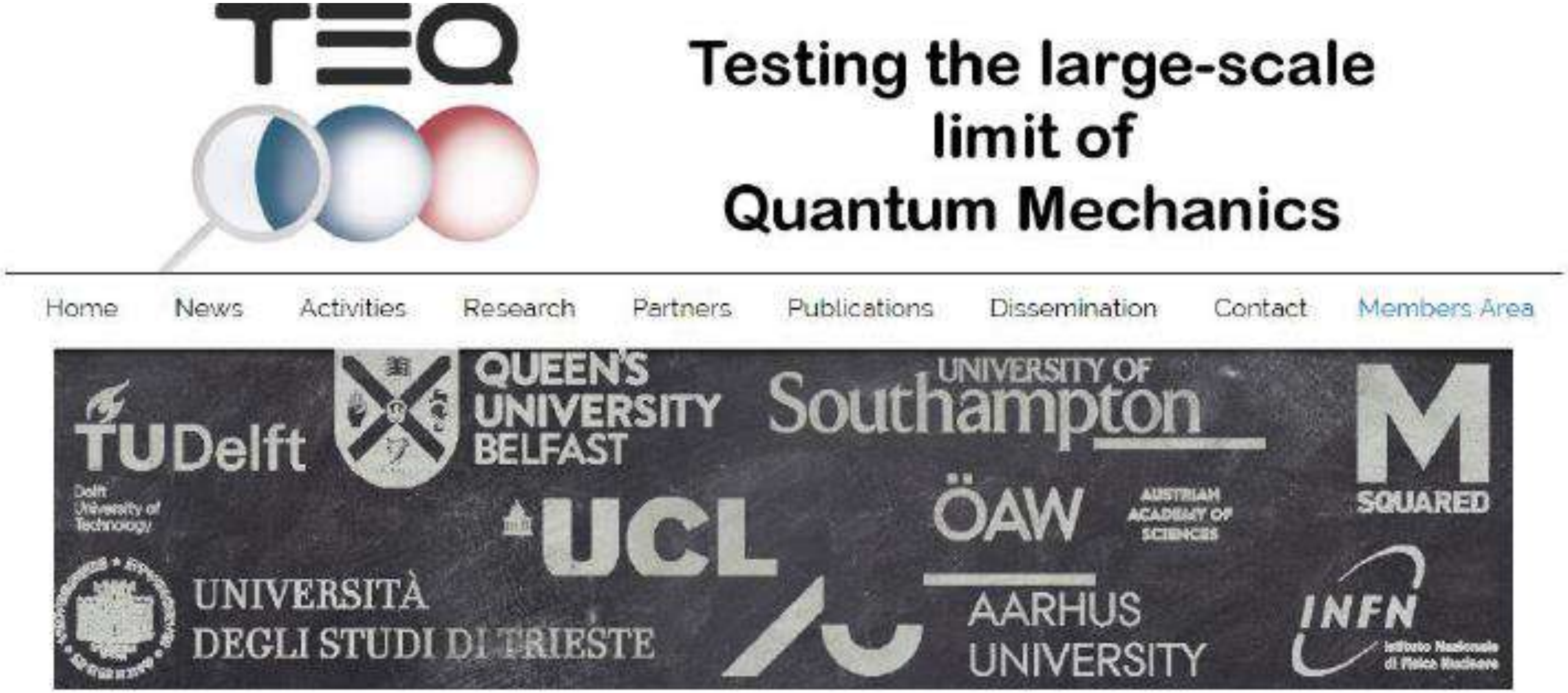

Trieste, 2$^{nd}$ February 2018 – Kick off meeting

Southampton, 22$^{nd}$ February 2018


Delft, 9$^{th}$ November 2018

# INTERNAL DISSEMINATION

- **TEQ Website: tequantum.eu about 900 visits/week (3000 total views)**



# INTERNAL DISSEMINATION

- **TEQ Newsletters**
  - ✓ **June 2018**
  - ✓ **September 2018**
  - ✓ **December 2018**

TABLE OF CONTENTS

Testing the large-scale limit
of quantum mechanics

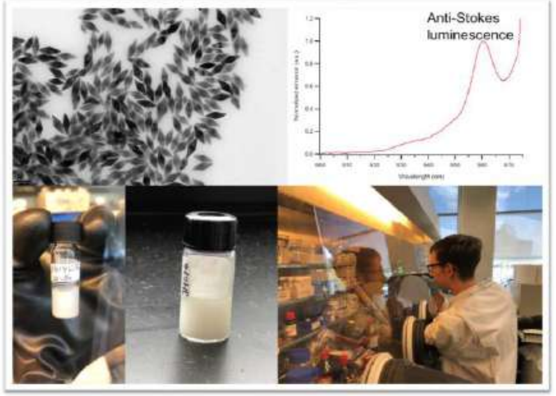
www.tequantum.eu

# NEWSLETTER N.3, December 2018

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.2, September 2018



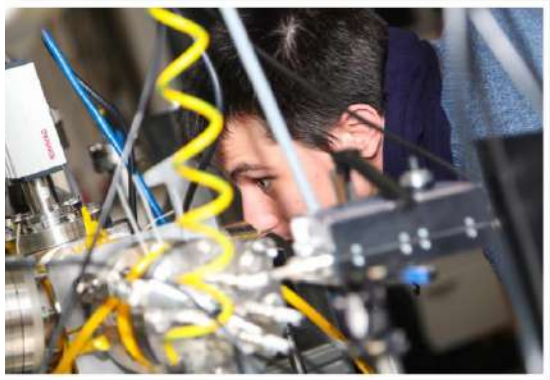

Details and moments of the TEQ experiments at TUDelft. *Credits: Delft University of Technology*


A collection of press articles headings published in 2018 about TEQ.

Testing the large-scale limit
of quantum mechanics

www.tequantum.eu

NEWSLETTER N.1, June 2018



...graduate student working on TEQ experiments at UoS. *Credits: University of Southampton.*

# 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

- (Scientific) Publications: 21, representing 2.63 papers/partner
- Preprints: 30, representing 3 preprints/partner
- Talks: 83, representing 10.3 talks/partner
- Press releases: 3
- Articles in general press: 13
- Facebook and Twitter TEQ accounts
- Radio and TV events
- Event: 1 Quantum Café 400 partecipanti
- Papers in 2019: 3; preprints in 2019: 3

# 21 Scientific Articles - highlights:

- Physical Review Letters (3)
- Physical Review A (12),
- New Journal of Physics (2)
- The European Journal of Physics D (1)
- npj Quantum Information (1)
- Physical Review B (1)
- Nuclear Physics News (1)

- About 100 citations
- More than 120 Tweeters
- 1 Article in Top 5% (Brunelli, M., et al. "Experimental Determination of Irreversible Entropy Production in out-of-Equilibrium Mesoscopic Quantum Systems." Physical Review Letters. 121.16 (2018))) of al research outputs scored by altmetric and other 4 articles in Top 25%
- More than 1000 downloads

# EXTERNAL DISSEMINATION

**83 talks**

61 talks to academics

9 presentations to general public

13 lectures to students

>5000 people

45 cities

20 countries
(8 in EU)

# C. Curceanu at St . Mary College in Hobart (Tasmania, Australia)

# Press Articles

2018 Belfastlive (UK)

University of Southampton (UK)

Before it’s news (UK)

UCL (UK)

Newswise (UK)

Accentmontreal (CA)

New Scientist(UK)

ANSA (IT)

Il Piccolo di Trieste (IT)

Il Piccolo di Trieste (IT)

Il Piccolo di Trieste (IT)

Scientific American(USA)

Le Scienze (IT)

SCIENTIFIC AMERICAN JULY 2018

# How Does the Quantum World Cross Over?

The universe according to quantum mechanics is strange and probabilistic, but our everyday reality seems nailed down. New experiments aim to probe where—and why—one realm passes into the other


**9.5 million print and tablet readers worldwide, 10+ million global online unique visitors monthly**

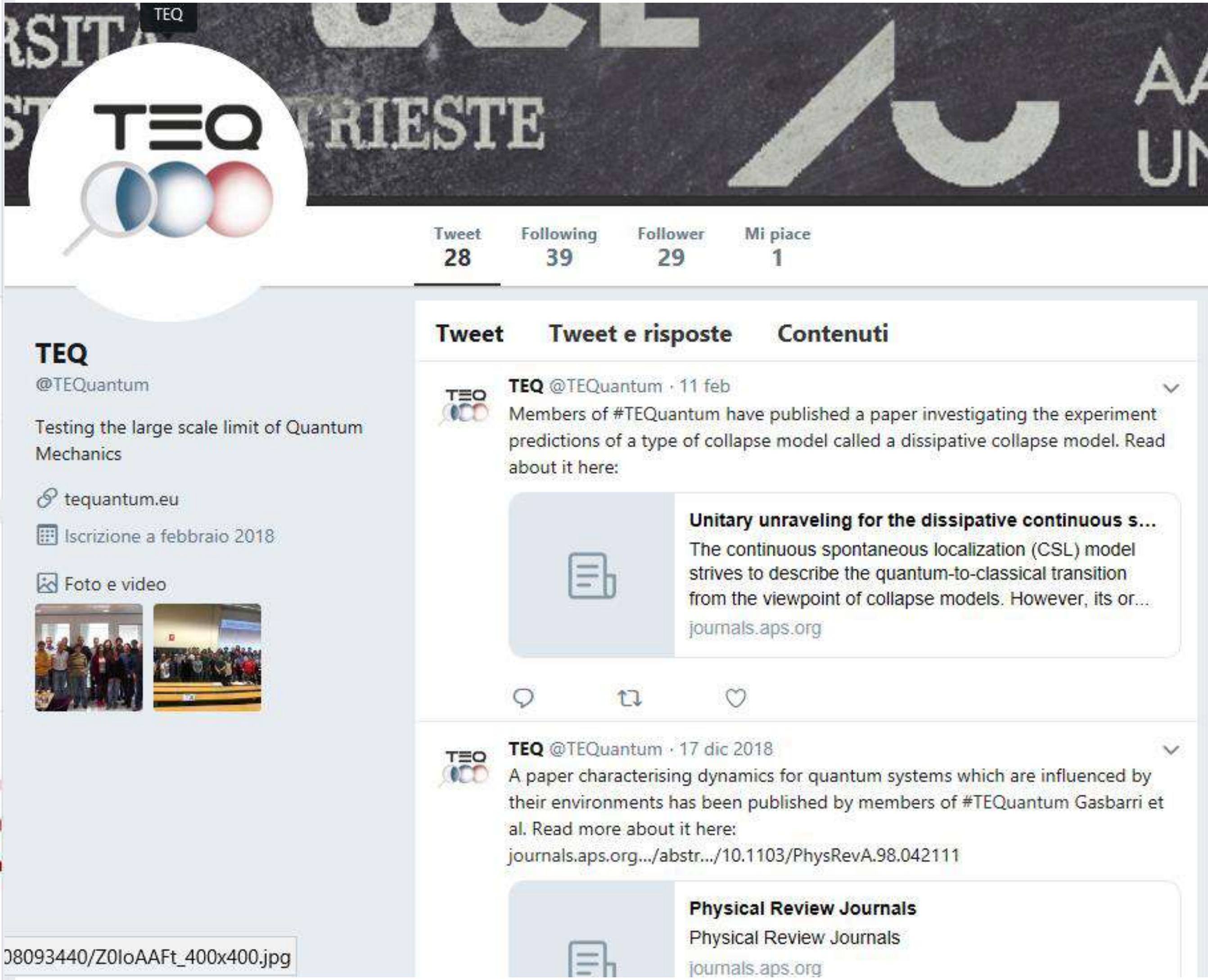

# Is this our first clue to a world beyond quantum theory?

Our best theory of physical reality is exquisite – but inexplicable. A low, unexplained experimental noise could herald a revolution in the making

**1 million worldwide *readers* every week**

**100.000 Paper copies**

# Facebook and Tweeter

# Multimedia

YouTube BE
Cerca
Fondazione
Trieste IN DIRETTA
SMS 3407006567 triesteindiretta@telequattro.it
07/08/2018 - TRIESTE IN DIRETTA
Telequattro

# CAFFÈ DEI QUANTI

Scienza, musica, teatro:
avvicinarsi alla meccanica quantistica

Autunno 2018

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 (12 M) | D.Other direct costs ESTIMATED (48 M) | D.Other direct costs REPORTED (12 M) | Total costs ESTIMATED (48 M) | Total costs REPORTED (12 M) | % Total costs reported |
|---|---|---|---|---|---|---|---|
| **UniTs** | 417 008,00 | 74 016,83 | 80 000,00 | 6 941,18 | 621 260,00 | 100 072,51 | 16,10% |
| **AU** | 275 000,00 | 0,00 | 137 500,00 | 15 213,68 | 515 625,00 | 19 017,10 | 3,68% |
| **INFN** | 200 000,00 | 33 969,69 | 107 500,00 | 3 960,08 | 384 375,00 | 47 412,21 | 12,33% |
| **OEAW** | 265 000,00 | 64 553,46 | 32 900,00 | 0,00 | 372 375,00 | 80 691,83 | 21,66% |
| **QUB** | 309 259,00 | 50 229,24 | 44 500,00 | 7 158,14 | 442 198,75 | 71 734,23 | 16,22% |
| **TUDelft** | 251 572,00 | 38 521,50 | 63 500,00 | 7 943,43 | 393 840,00 | 58 081,16 | 14,74% |
| **UCL** | 222 703,00 | 44 109,68 | 192 494,00 | 117 272,30 | 518 996,25 | 201 727,50 | 38,86% |
| **Southampton** | 239 997,00 | 56 028,96 | 342 396,00 | 63 019,27 | 727 991,25 | 148 810,30 | 20,44% |
| **M2** | 175 000,00 | 186 461,12 | 140 850,00 | 115 700,77 | 394 812,50 | 377 702,40 | 95,66% |
| **Total** | **2 355 539,00** | **547 890,48** | **1 141 640** | **337 208,85** | **4 371 473,75** | **1 105 249,00** | **25,28%** |

# Summary of project effort in Person-Months

| Partner | PMs estimated (48 M) | PMs reported (12 M) | % PMs on total |
|---|---|---|---|
| **UniTs** | 115 | 29.80 | 25,91 % |
| **AU** | 57 | 11.53 | 20,22 % |
| **INFN** | 61 | 4.89 | 8,01 % |
| **OEAW** | 73 | 17.84 | 24,43 % |
| **QUB** | 79.20 | 16.80 | 21,21 % |
| **TUDelft** | 57 | 7.86 | 13,78 % |
| **UCL** | 56.60 | 8.87 | 15,67 % |
| **Southampton** | 57 | 14 | 24,56 % |
| **M2** | 48 | 34.39 | 71,64 % |
| **Total** | **603.80** | **156.54** | **25,92 %** |

# Thank you!

# Assessment of innovation

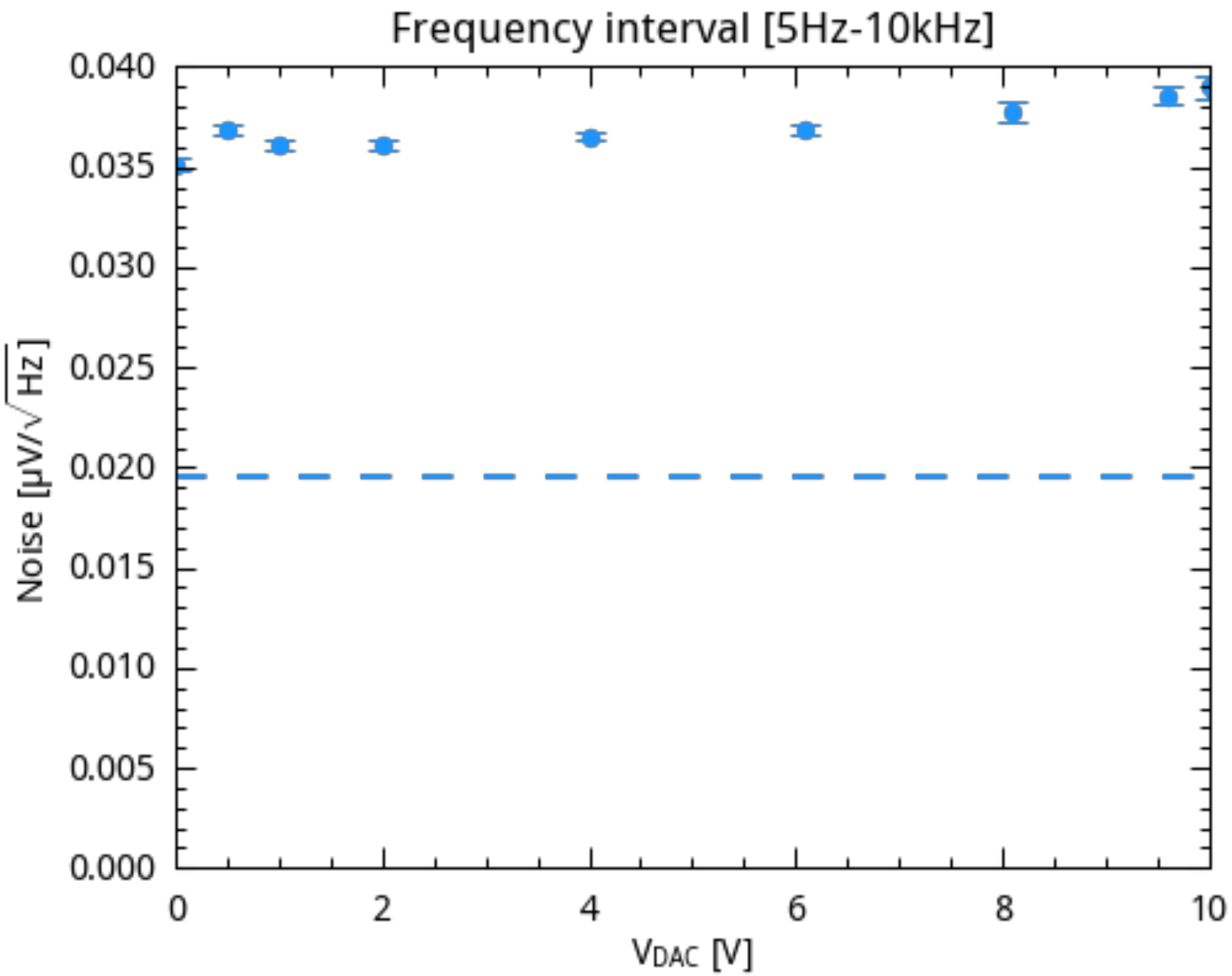
| Innovation<br>Title of innovation | Application/ stakeholders<br>Description of innovation. What is the potential application?<br><br>Who is driving this in the consortium (name specific beneficiary)? | Current status<br>Describe the current status of the innovation (TRL could be used) | Level of Innovation<br>A: Minor, improvements over existing products;<br>B: Innovative but difficult to convert customers;<br>C: Obviously innovative and easily appreciated advantages to customers;<br>D: Very innovative | How will the innovation be exploited?<br>A: Introduced as new to the market<br>B: Only deployed as new to the organization/ company<br>C: No exploitation planned | Market maturity<br>A: The market is not yet existing and it's not clear that the innovation has potential to create a new market<br>B: Market-creating: the market is not yet existing but the innovation has clear potential to create a new market<br>C: Emerging: There is a growing demand and few offerings are available<br>D: Mature | Market competition<br>A: Patchy, no major players<br>B: Established competition but none with a proposition like the one under investigation<br>C: Several major players with strong competencies, infrastructure and offerings | Commercialization horizon<br>A: 1-3 years<br>B: 3-5 years<br>C: 5-10 years | Prospects of realization by end of project<br>What are the expected results by the end of the project?<br>Is spin-off company planned to be established? |
|---|---|---|---|---|---|---|---|---|

# Innovation 1

| Innovation | Application/ stakeholders | Current status | Level of Innovation | How will the innovation be exploited? | Market maturity | Market competition | Commercialization horizon | Prospects of realization by end of project |
|---|---|---|---|---|---|---|---|---|
| ***Low-noise digitally controlled DC-voltage source*** | *The digitally controlled voltage supply developed within the TEQ consortium should find usage in a large range applications where extremely precise and tunable DC-voltages are required, for example ion trap based quantum technology, charged particle optics and, more generally, the emergent market of (quantum) technologies where high-precision is the standard.*<br><br>*Driven by INFN and AU .* | *TRL 3-4* | *C: A final commercial product should potentially have more than a factor of 10 lower noise power spectral density in a broad band range from ~1 KHz to ~1 MHz as compared to current commercial DC-supplies* | *A: The innovation is expected to be introduced at the open market as a much improved product.* | C: *The innovation could immediately be introduced to the emergent market of quantum technologies* | B: *There will be competition by developments in research laboratories focusing on quantum technologies* | B: *~3 years around the end of the TEQ project* | *A product that can be commercialized is the expected result at the end of the project.*<br>*No spin-off company planned to be established, but we consider applying for funds under the FET Innovation Launchpad this year.* |

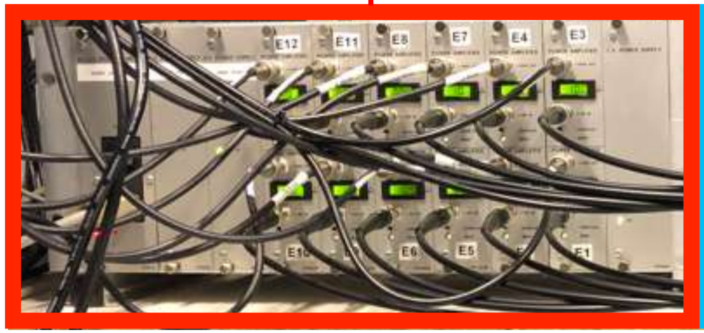
# Low-noise DC voltage supplies

DAC

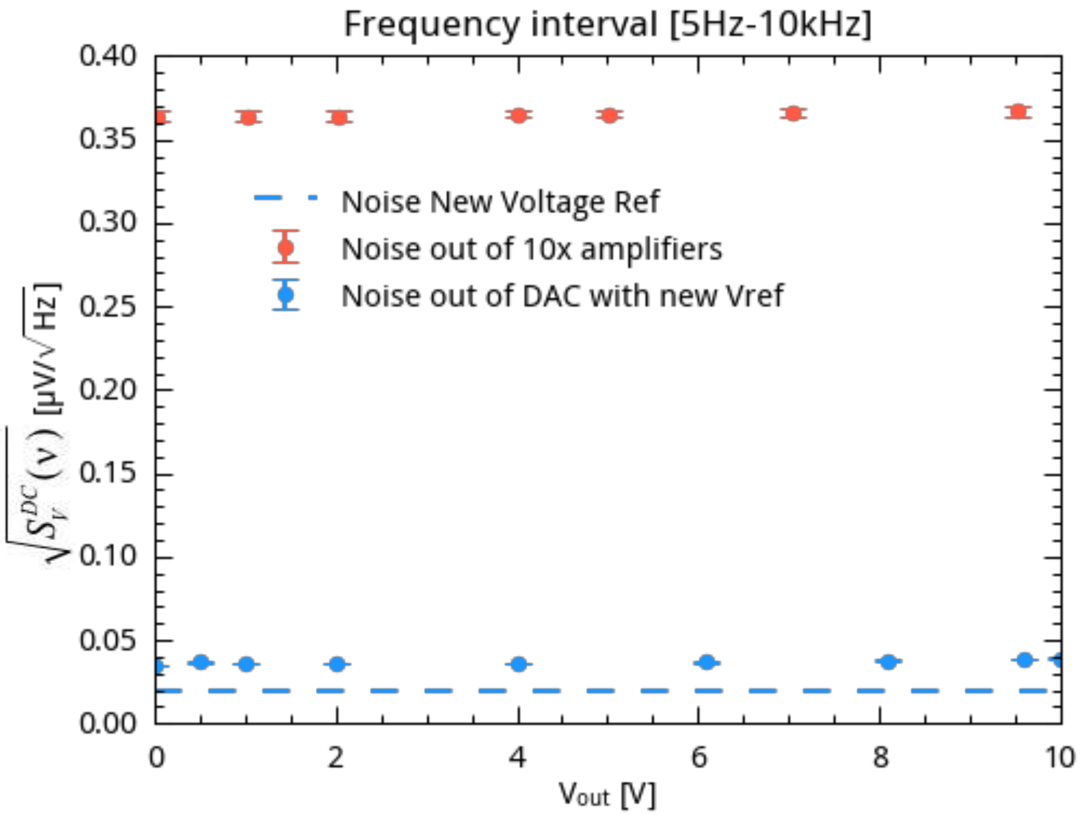



# Low-noise DC voltage supplies

10x amplifier



DAC


Intrinsic amplifier noise

$20\ nV/\sqrt{Hz}$

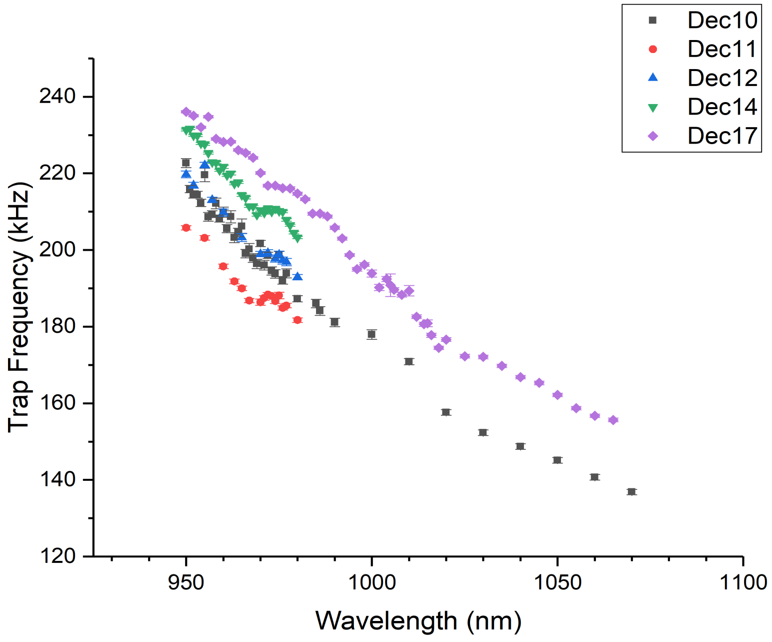
# Innovation 2

| Innovation | Application/ stakeholders | Current status | Level of Innovation | How will the innovation be exploited? | Market maturity | Market competition | Commercialization horizon | Prospects of realization by end of project |
|---|---|---|---|---|---|---|---|---|
| ***Single Nanocrystal characterisation*** | *Measuring properties including the absorption spectrum of a single isolated particle held in vacuum.* | *TRL1* | *B: Innovative but difficult to convert customers* | *A: Introduced as new to the market* | *A: The market is not yet existing and it's not clear that the innovation has potential to create a new market* | *B: Established competition but none with a proposition like the one under investigation* | *C: 5-10 years* | *The expected result is the full evaluation of concept to evaluate utility.* |

# Instrument for single crystal spectroscopy and characterisation

Regular absorption spectroscopy is very difficult for a single crystal and is usually done on a sample containing a large number of crystals. In addition, it must be either on a surface or liquid. As part of TEQ we have developed a type of spectroscopy where the change in absorption from a levitated single crystal can be observed as a change in trap frequency. This is a new method for characterising the absorption properties of isolated single crystals and could be developed into a new type of spectroscopic microscope or as an add-on to existing microscopes.

## Trap frequency of single trapped crystal with wavelength

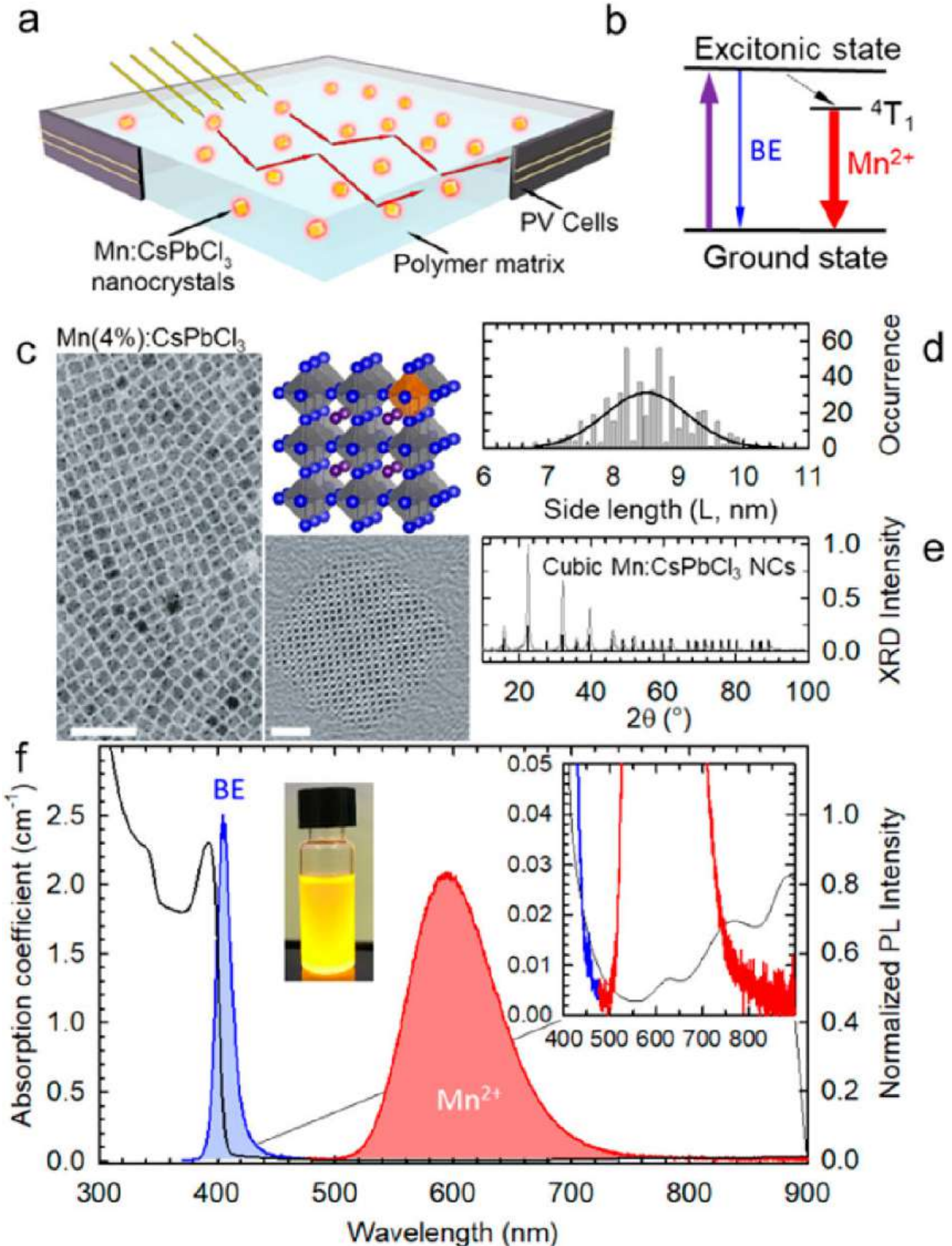


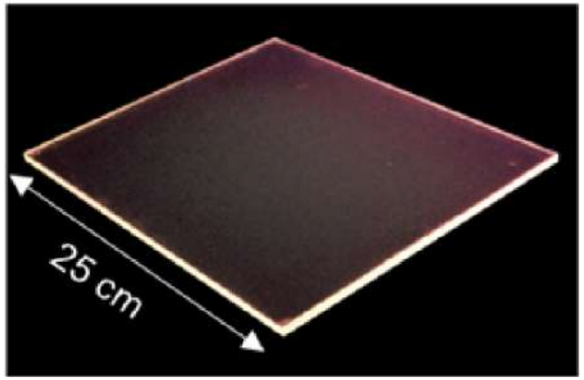

## Commercial Raman microscope from Thermofisher

# Innovation 3

| Innovation | Application/ stakeholders | Current status | Level of Innovation | How will the innovation be exploited? | Market maturity | Market competition | Commercialization horizon | Prospects of realization by end of project |
|---|---|---|---|---|---|---|---|---|
| **Nanoparticles emitting in the near infrared with high quantum yield** | Besides the applications targeted by TEQ, these nanoparticles could find application in luminescent solar concentrators (TU Delft) | At the moment, this is only a proposed idea. The particles need to have absorption in the visible range and Stokes shifted emission in the NIR | B. These particles need to be stable in polymer matrixes and also be non-toxic. At the moment we cannot claim any of these two points. | B. We are in stage of developing this technology. If positive evaluation will be given the Tech transfer office, a patent application will be filed. | C. There are only a few startup companies developing luminescent solar concentrators and looking for these kind of emitters. | A: Patchy, no major players | B: 3-5 years | The most likely scenario is that, if this technology is developed, it will be licensed to an existing company. |

# Near-infrared nanoparticle-based emitters for luminescent solar concentrators




**Idea: to have Yb doped nanoparticles absorbing the solar light and emitting it with QY close to 100% in the NIR**

Meinardi et al. *ACS Energy Lett.*, **2017**, *2* (10), 2368–2377

# Thank you