Testing the Large-Scale Limit of Quantum Mechanics
(TEQ)

Liberato Manna
Luca De Trizio
Francesco De Donato

Trieste – 2nd of February

The best particles for non-interferometric test of quantum superposition principle

Shape:

Spherical particles (for tests with translational motion)

Size:

In the range of **50 nm – 1 μm** for the diameter of a sphere

Optical properties:

- *V*ery **low absorption** at the optical wavelength of the detection/cooling laser [**1064nm** (UCL) or **1550nm** (Southampton)]

- **High refractive index and/or polarizability**

- **Resonant transitions** for optical [Raman type/ Anti-stokes fluorescence cooling] refrigeration – active internal state cooling.

Required Materials:

RE: $\boldsymbol{SiO_2}$ colloidal **nanocrystals**
having a diameter of **50 - 300 nm**

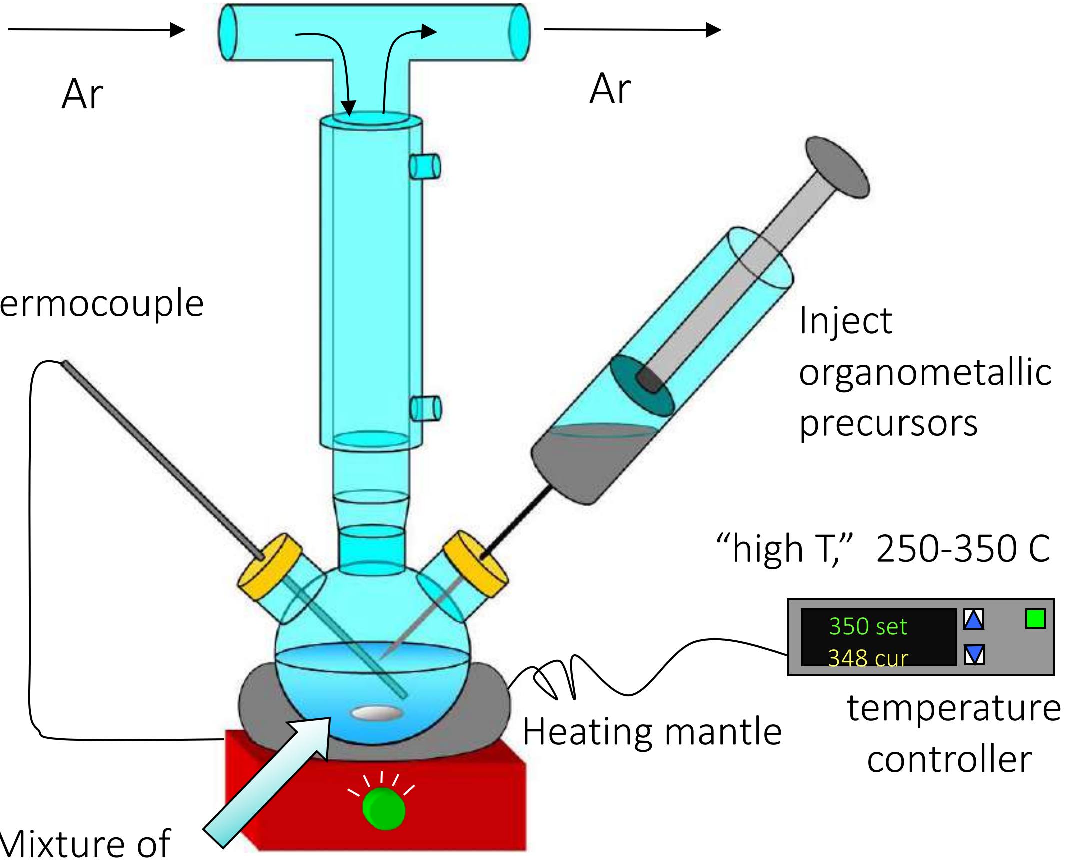
Optical refrigeration: **YLiF**$_4$ **doped with Yb or Yb/Er**
(doping level should reach 50 % Yb)

or alternatively ***Yb***$^{3+}$**doped β-NaYF**$_4$

Best *solvent* for colloidal solutions for use in sprays are water and organic solvents [methanol, ethanol]
→ **Polar solvents**

How do we fabricate nanostructures at IIT/Delft?

Synthesis of colloidal nanocrystals



Ar

Ar

thermocouple

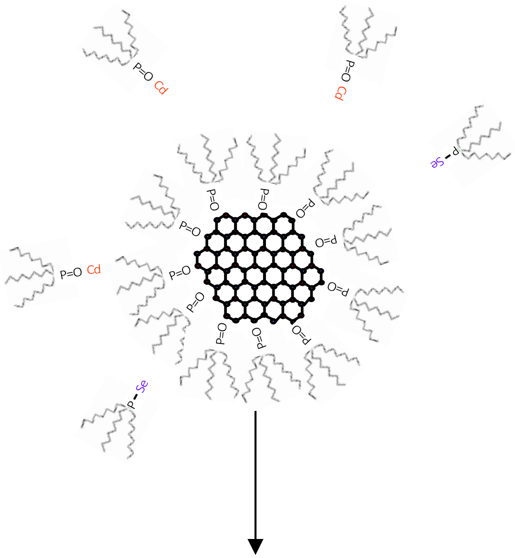
Inject
organometallic
precursors

“high T,” 250-350 C

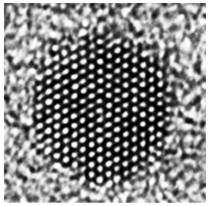
Heating mantle

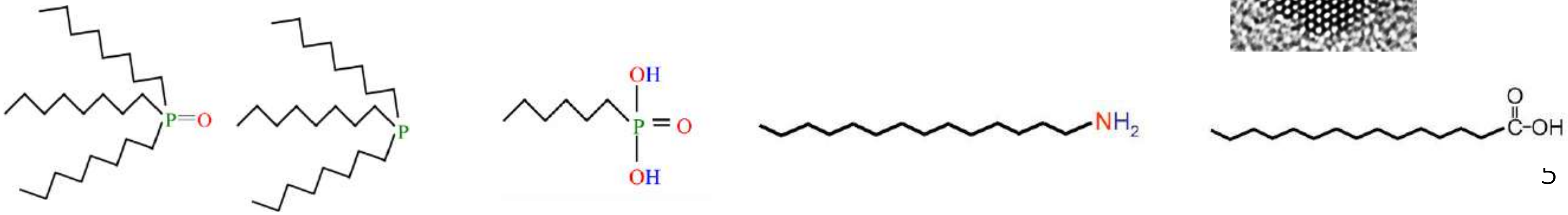
temperature
controller

Mixture of
surfactants

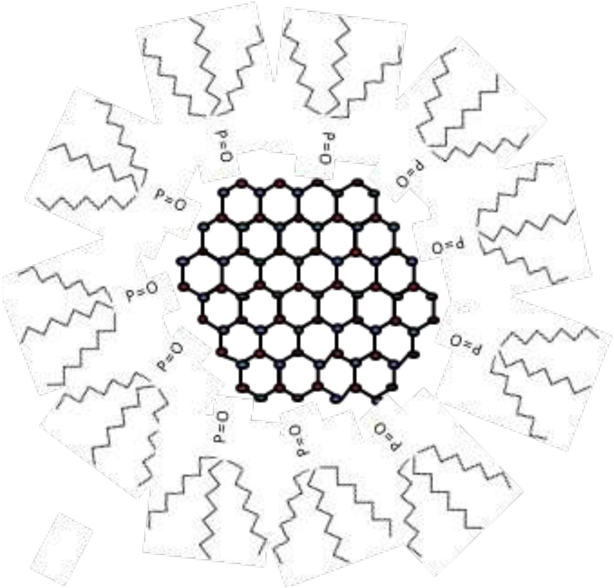


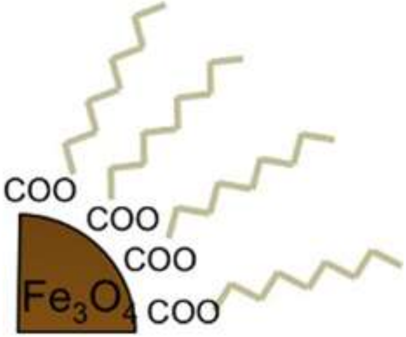
Highly crystalline
Narrow size
distribution





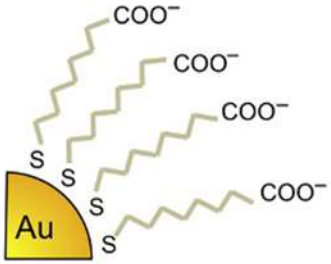
Ligand Exchange in Colloidal nanocrystals

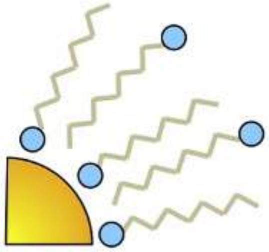




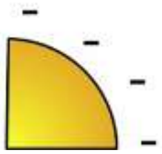
lipophilic

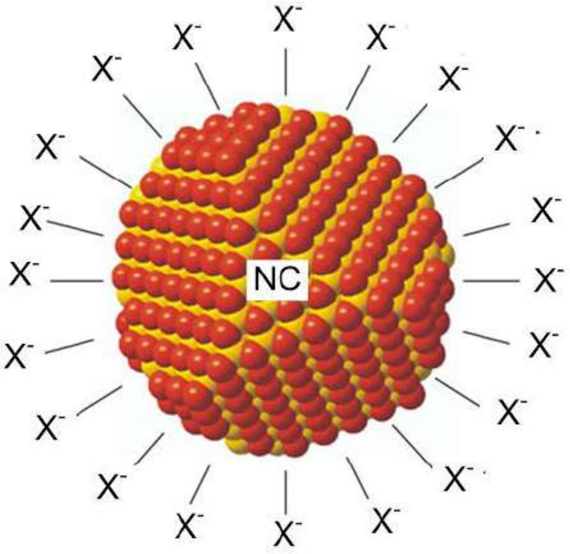
hydrophilic





or





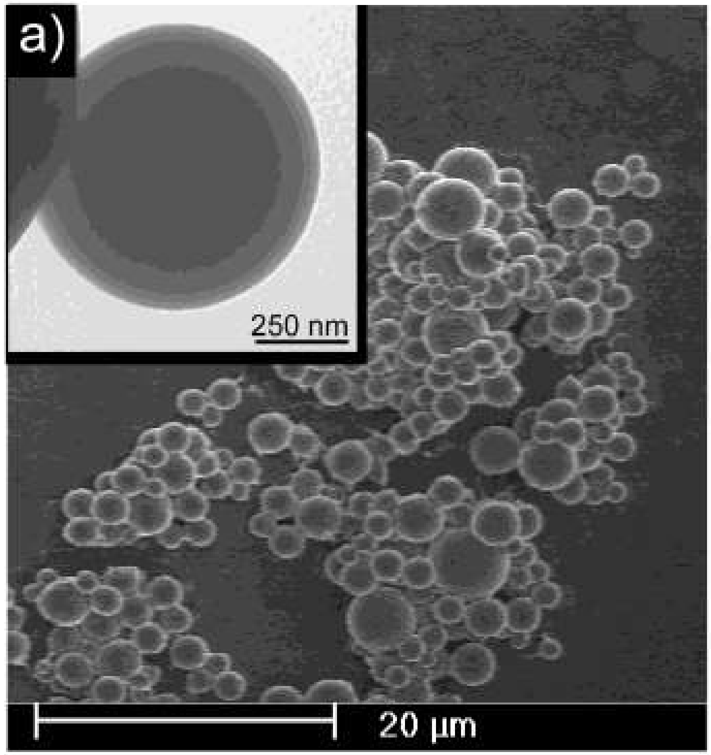
Colloidal SiO_2 Nanocrystals

Reference paper: **Rare-Earth-Doped Colloidal SiO_2Spheres**
de Dood et al. *Chem. Mater.*, **2002,** 14 (7), pp 2849–2853

Acid-catalyzed procedure:

Addition of **Tetraethoxysilane** (TEOS) to a mixture of **acetic acid** and water under stirring for 30 min at room temperature → followed by annealing at 900°C for 30min

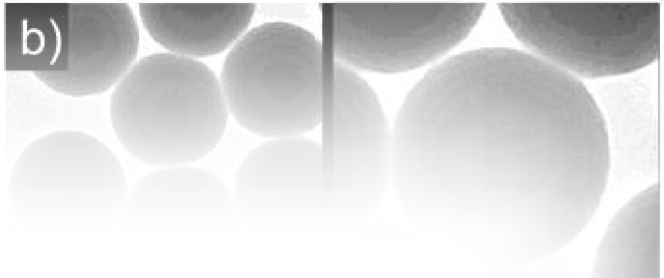
Why acid-catalyzed procedure? → **No doping can be achieved in base-catalyzed procedures**



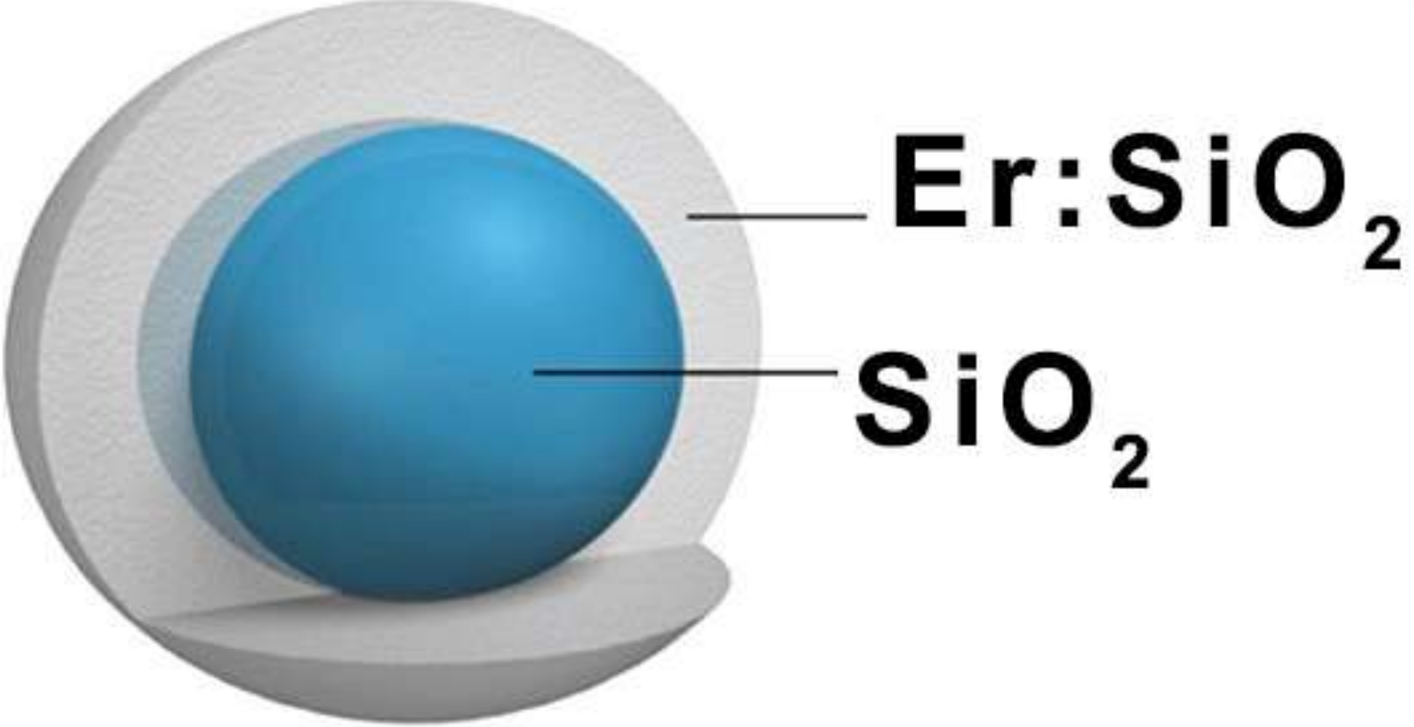
Mean diameter of 2.2 μm
Size polydispersity of 40%

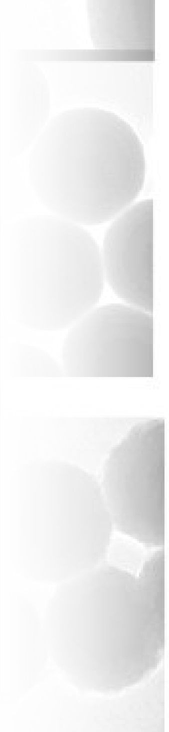
*Possible **doping** with*
Eu^{3+}** and **Tb^{3+}
using the corresponding chloride salts

Alternative Procedure: doped SiO_2



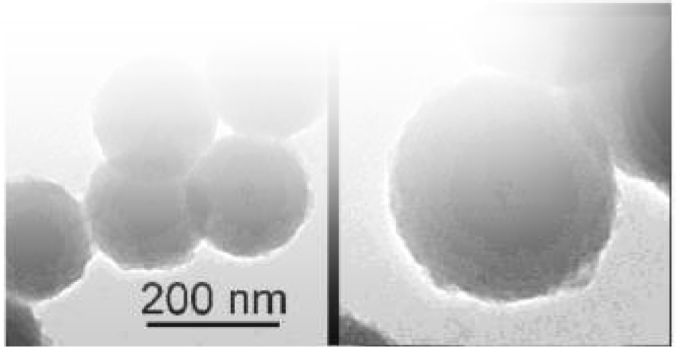
FIRST STEP: base-catalyzed synthesis of SiO2 spheres
(185nm in siz





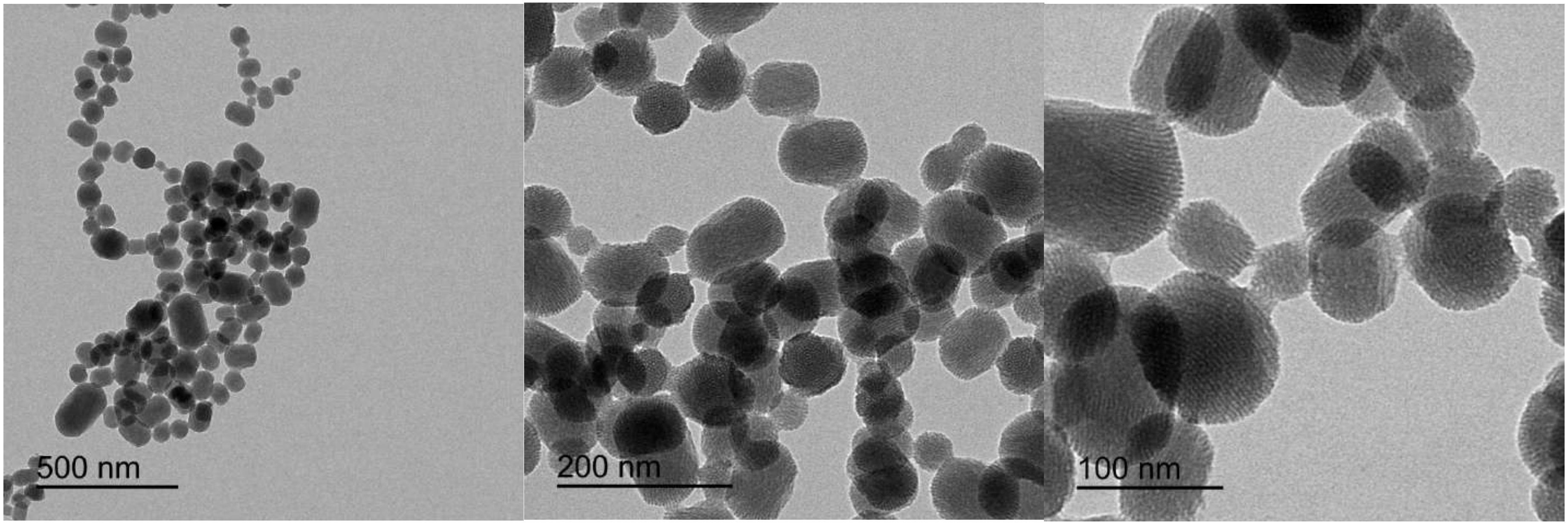
SECON
shell

Tetraethoxysilane (TEOS) to a mixture of **acetic acid** and aqueous solution of $ErCl_3$ under stirring for 45 min at room temperature
(194 nm in size)



Our Results

1st step-> Synthesis of the SiO_2 undoped "core"



Synthesis

0.2 g of CTAB (Cetyl trimethylammonium bromide), 0.6 mL of NaOH 2M and 116 mL of H_2O mixed at 80°C.

After the dissolution of CTAB, 1 mL of TEOS was added dropwise.

Reaction time 2h at 80°C.

Questions

1) Is the SiO_2@Er:SiO_2 core-shell system desirable for the project?

2) If yes which size would be the best ?

TO DO LIST :

1) Find a suitable acid- or base- catalyzed synthesis of SiO_2 to get a «monodisperse» sample with the desired size (CORE)

2) Test if the acid-catalyzed synthesis repoted by de Dood et al. can be used to achieve SiO2@Yb/Er doped SiO2 spherical nano heterostructures

YLF Systems

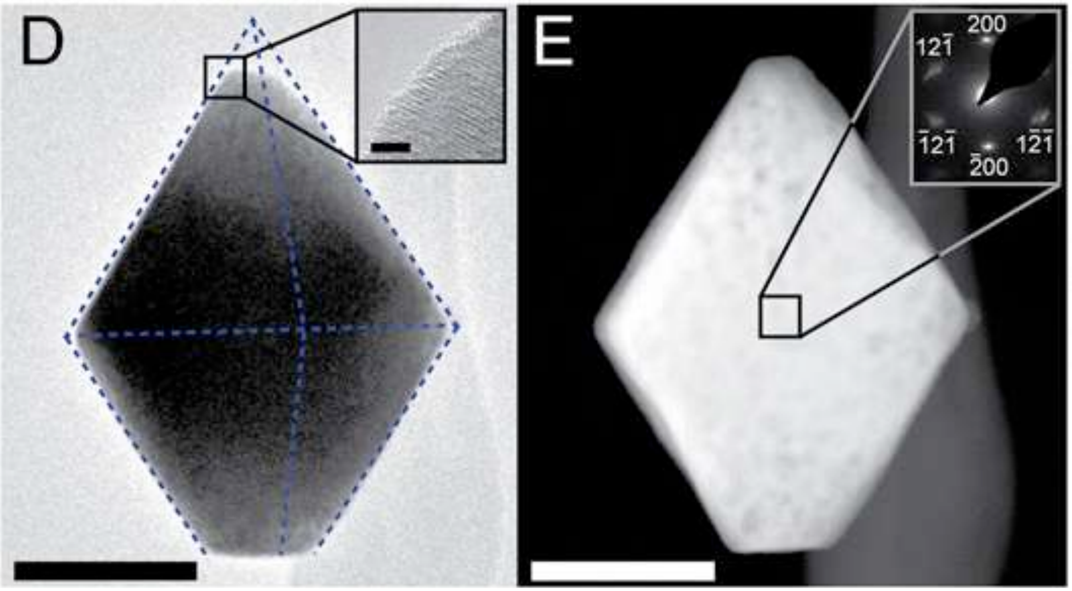
Reference paper: **Laser refrigeration of hydrothermal nanocrystals in physiological media** Roder et al. *PNAS* **2015**, 112 (49) 15024-15029.

Solvothermal Approach

1) **Y** nitrate, **Yb** nitrate and **Er** nitrate + Lithium fluoride (LiF), nitric acid (HNO3), ammonium bifluoride (NH4HF2), and EDTA are analytical grade.

23-mL Teflon-lined autoclave and heated to 220 °C for 72 h. Washing with ethanol and DI water

The final white powder is obtained by calcining at 300 °C for 2 h.



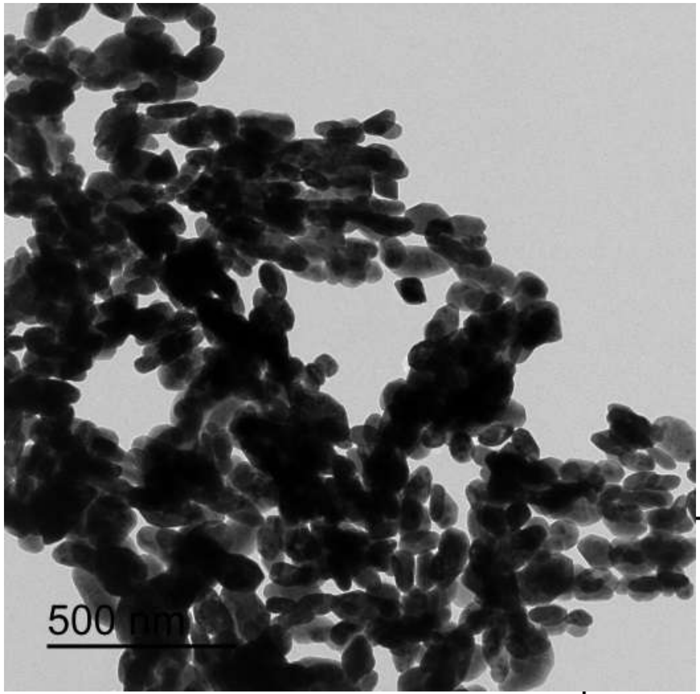
200nm

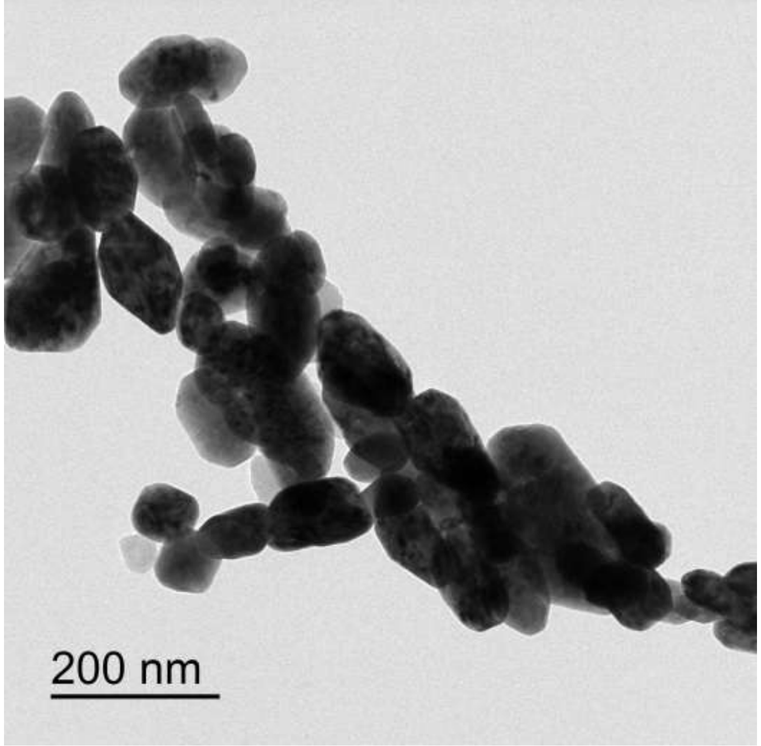
2% Er^{3+},10%Yb^{3+}:$LiYF_4$

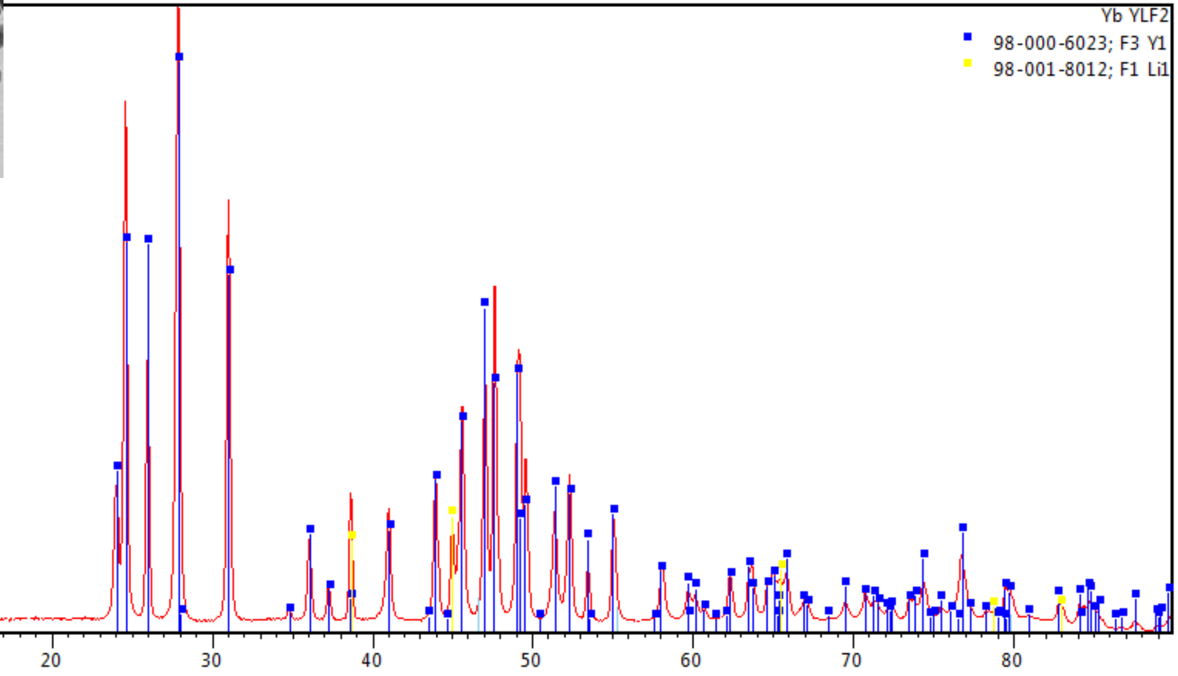
10% Yb^{3+}:$LiYF_4$

Our Results: Solvothermal Approach

Yb:YLF Sample 2

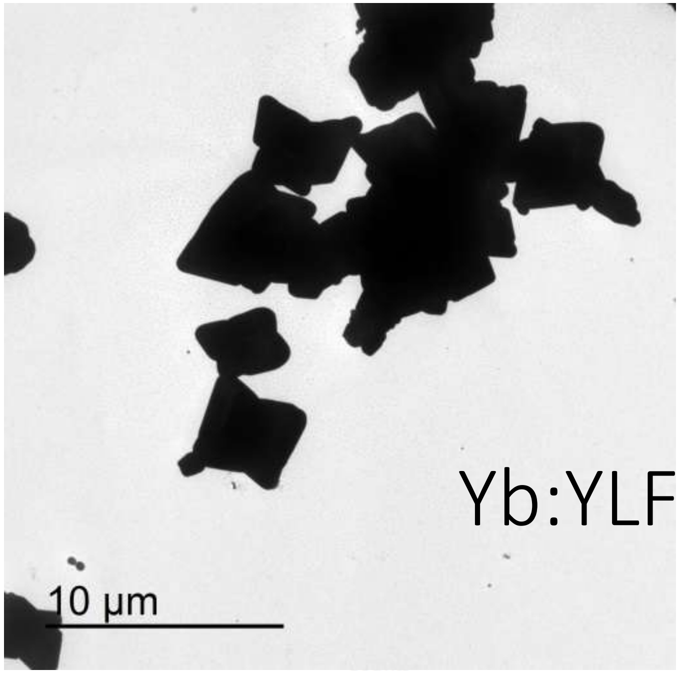




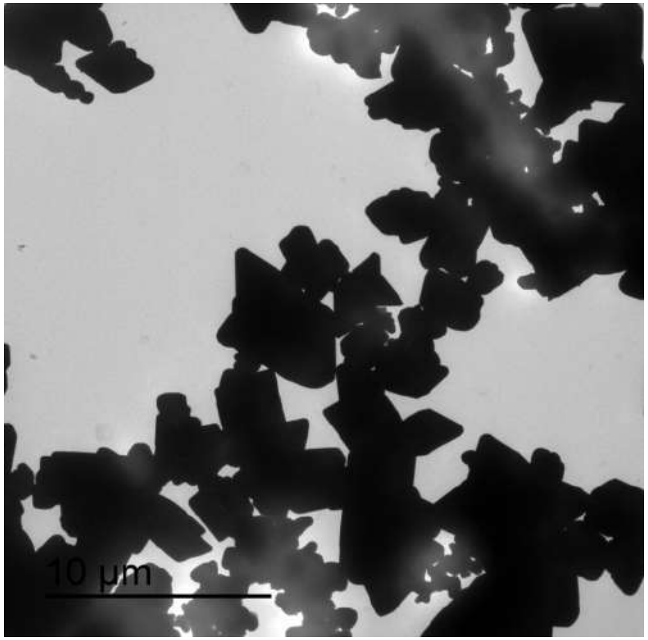


Our Results

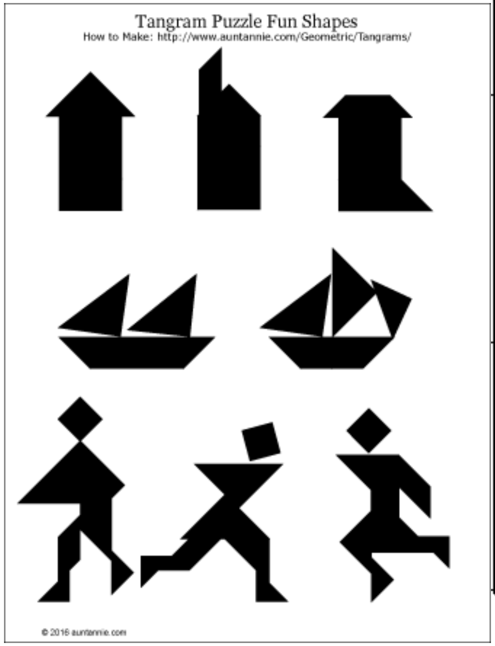
Solvothermal Approach

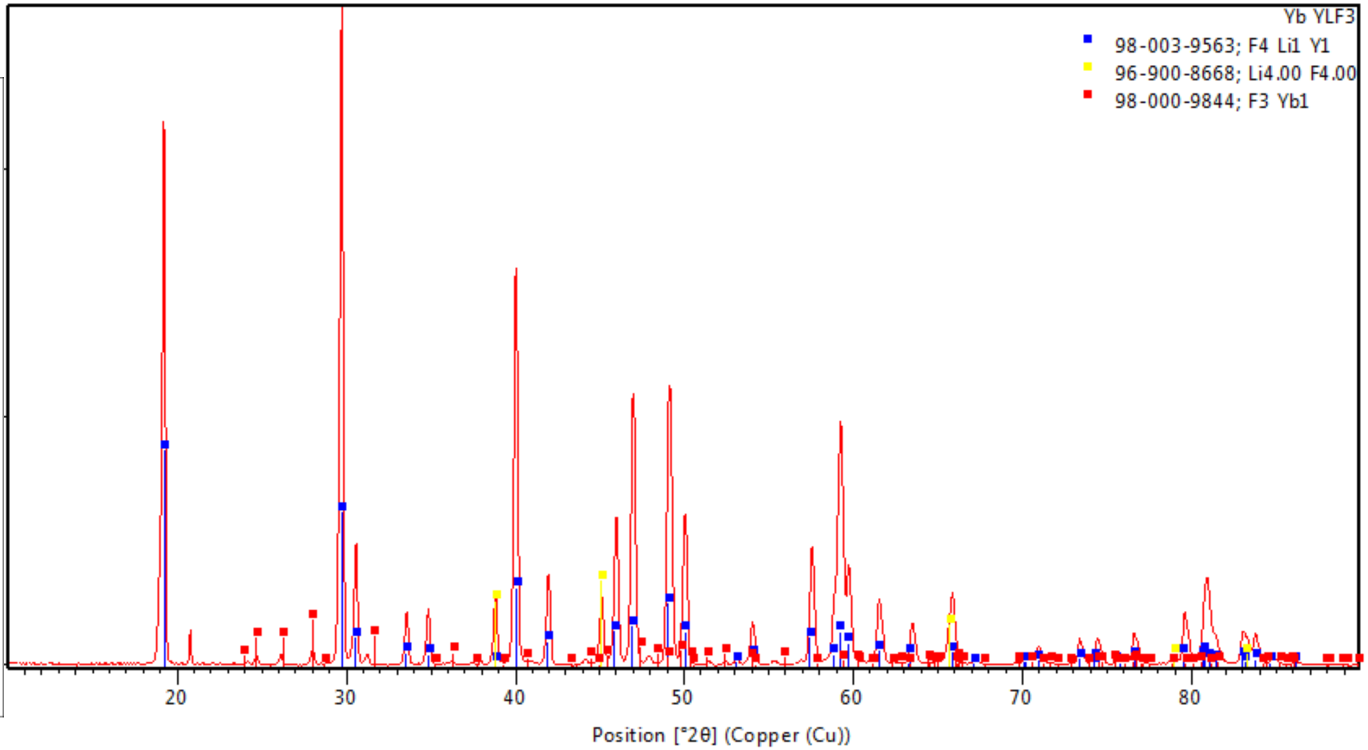


Yb:YLF Sample 3

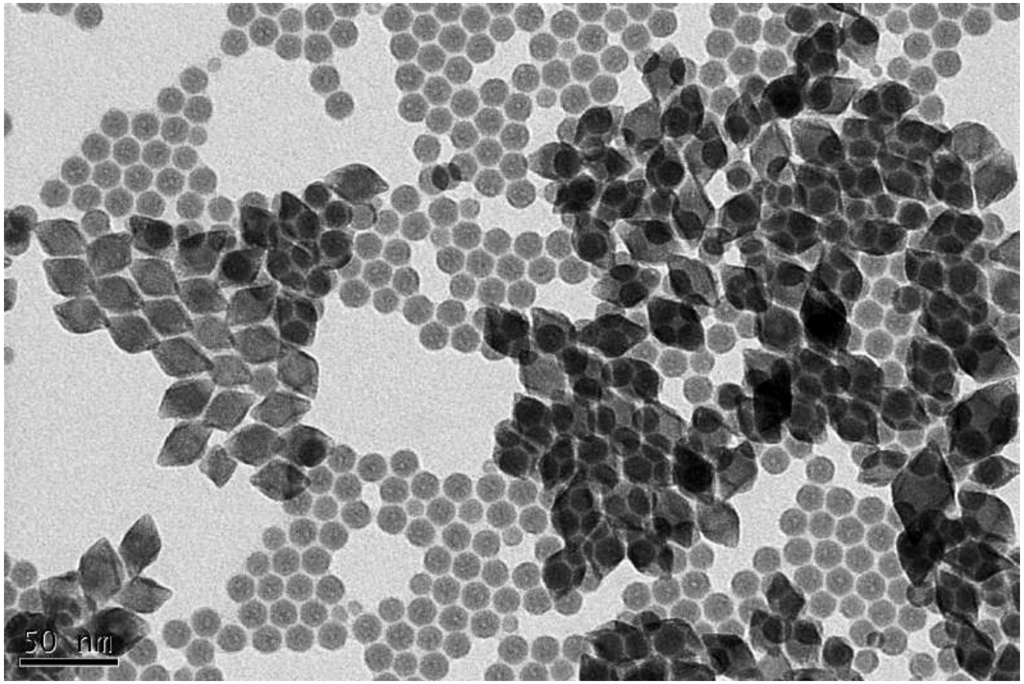


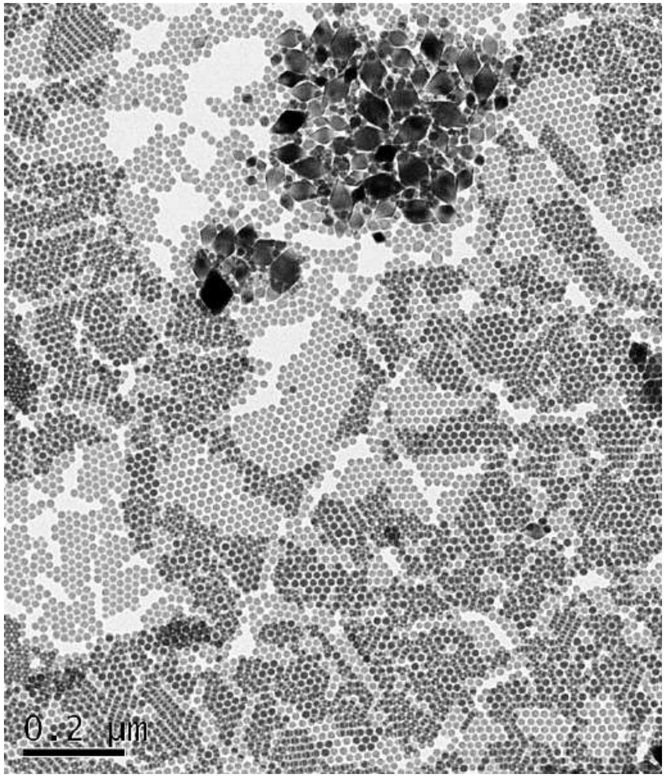
Tangram-like NCs





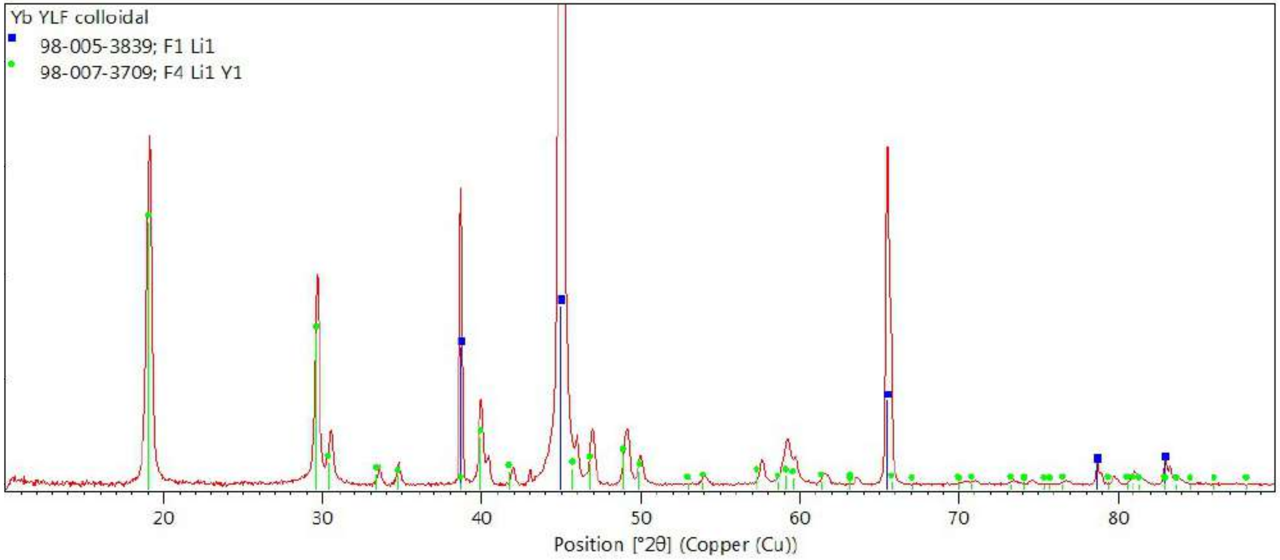
Colloidal Approach





Yb:$YLiF_4$

\+ LiF



Thanks for Your Attention

TEQ kick off meeting
Trieste, 2nd February 2018
UniTs – Via Filzi 14

09:45 Welcome and presentation of the plan for the meeting (Angelo Bassi)
Presentation of the participants
10:00 Roadmap over the four years and focus on the first year: theory (Mauro Paternostro)
10:30 Roadmap over the four years and focus on the first year: experiment (Hendrik Ulbricht)
11:00 Coffee Break
11:30 Scientific discussion on theory part + presentations from participants (moderated by Mauro Paternostro)

- Matteo Carlesso
- Alessio Belenchia

13:30 Lunch
15:00 Scientific discussion on experimental part + presentations from participants (moderated by Hendrik Ulbricht)

- Michael Drewsen
- Luca De Trizio
- Antonio Pontin
- Anis Rahman
- Catalina Curceanu
- James Bain

17.00 Coffee break
17:30 Steering Committee meeting (Chaired by Angelo Bassi)
20:30 Dinner

Agenda of the First Steering Committee meeting

1. Welcome to the SC members and adoption of agenda
2. Presentation of the Management Structure
3. Website
4. Consortium Agreement
5. Budget
6. Milestones and Deliverables
7. Dissemination and Exploitation Plan
8. Data Management Plan
9. Open Access
10. Recruitment Plan
11. Distribution of Tasks
12. Plan for Review
13. Next SC meeting
14. AOB
15. Closing

TEQ - Kick off Meeting

Name and Surname	Institution	Signature
Angelo Bassi	UniTs	
Matteo Carlesso	UniTs	Matteo Carlesso
Giulio Gasbarri	UniTs	Giulio Gasbarri
Catalina Curceanu	INFN	
Antonio Pontin	UCL	
Anis Rahman	UCL	Anis
Mauro Paternostro	QUB	
Michael Drewsen	AU	
Liberato Manna	TUD	
Arjan Houtepen	TUD	

Luca De Trizio	TUD	
Francesco De Donato	TUD	
Hendrik Ulbricht	UoS	
Andrea Vinante	UoS	
Alessio Belenchia	OEAW	
James Bain	M2	

Trieste, February 2nd 2018

Testing the large-scale limit of quantum mechanics

Kick off Meeting

Trieste 2nd February 2018

(Angelo Bassi – University of Trieste & INFN)

Schedule

09:45	Welcome and presentation of the plan for the meeting (AB)
	Presentation of the participants
10:00	Roadmap over the four years and focus on the first year: theory (MP)
10:30	Roadmap over the four years and focus on the first year: experiment (HU)
11:00	Coffee Break
11:30	Scientific discussion on exp. part + presentations from participants
13:30	Lunch
15:00	Scientific discussion on theory part + presentations from participants
17.00	Coffee break
17:30	Steering Committee meeting
20:30	Dinner

Participants to the KO Meeting

UniTs	Angelo Bassi, Matteo Carlesso, Giulio Gasbarri
INFN	Catalina Curceanu
UCL	Antonio Pontin, Anis Rahman
QUB	Mauro Paternostro
AU	Michael Drewsen
TUD	Liberato Manna, Arjan Houtepen, Luca De Trizio, Francesco De Donato
UoS	Hendrik Ulbricht, Andrea Vinante
OEAW	Alessio Belenchia
M2	James Bain

TEQ in Brief

Start date: 1st January 2018
Duration: 48 months
Budget: 4.371.473,75 Eur
Total PMs: 603,80
Project Officer: Dr. Roumen Borissov

Website: www.tequantum.eu

For acknowledgements: “This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 766900”

Steering Committee Meeting

AGENDA (UPDATED)

1. Welcome to the SC members and adoption of agenda
2. Presentation of the Management Structure
3. Website
4. Consortium Agreement
5. Budget
6. Milestones and Deliverables
7. Dissemination and Exploitation Plan
8. Data Management Plan
9. Open Access

9. Open Access

10. Recruitment Plan
11. Distribution of Tasks
12. Plan for Review
13. Next SC meeting
14. AOB
15. Closing

2. Management Structure

From the proposal (now GA)

Project
Coordinator: A. Bassi
Deputy coordinator: C. Curceanu

Steering Committee
Chair: A. Bassi
Vice Chair: C. Curceanu
Members: A. Bassi, C. Curceanu, H. Ulbricht, M. Paternostro, P. Barker, A. Dantan, L. Manna, C. Brukner, N. Hempler
Meetings: twice per year, in person every 12 months.

Duties of the SC
1)The management of resources in order to meet schedules /goals;
2) The resolution of any conflicts arising within the Consortium;
3) The creation of a technological/scientific roadmap and its updating;
4) The compliance with legal obligations as specified in the CA

2. Management Structure

Voting Procedure for the SC
One vote per person. In case of stalemate, the vote of the Chair prevails.

Vote via email (eVote): 5 working days for discussing/deciding.

Minutes will be sent via email to the SC and uploaded on the private part of the website

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Amendments to the structure of SC
Members:
A. Dantan → M. Drewsen

Press Officer (chosen among members of the consortium. Will be in charge of the dissemination plan). Together with other potential figures to help in managing the project, will be identified by the Chair, who will the write to the SC for approval.

3. Website

Finalized and functioning

4. Consortium Agreement

Finalized and signed

5. Budget

2.112.878,98 Eur received by UniTs on 31.12.2017. Distributed proportionally to partners on 29.01.2018 (within one month's time)

Distribution of first instalment

BENEFICIARIES	%	TOTAL FINANCED	PRE-FINANCING	Pre-financing SUBDIVISION	RESIDUE to be paid
UNIVERSITA' DEGLI STUDI DI TRIESTE	0,142116832	621.260,00	2.112.878,98	300.275,67	320.984,33
AARHUS UNIVERSITET	0,117952212	515.625,00		249.218,75	266.406,25
ISTITUTO NAZIONALE DI FISICA NUCLEARE	0,087928013	384.375,00		185.781,25	198.593,75
OESTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN	0,085182943	372.375,00		179.981,25	192.393,75
THE QUEENS UNIVERSITY OF BELFAST	0,101155531	442.198,75		213.729,40	228.469,35
TECHNISCHE UNIVERSITEIT DELFT	0,090093187	393.840,00		190.356,00	203.484,00
UNIVERSITY COLLEGE LONDON	0,118723405	518.996,25		250.848,19	268.148,06
UNIVERSITY OF SOUTHAMPTON	0,166532225	727.991,25		351.862,44	376.128,81
M-SQUARED LASERS LIMITED	0,090315652	394.812,50		190.826,04	203.986,46
	1	**4.371.473,75**	2.112.878,98	**2.112.878,98**	2.258.594,77

6. Milestones

Milestone number[18]	Milestone title	WP number[9]	Lead beneficiary	Due Date (in months)[17]	Means of verification
MS1	Preparation of NCs	WP1	2 - AU	12	Preparation of NCs with minimum absorption & stable against aggregation. Means of verification: Combination of optical, electron microscopy, and surface analysis methods
MS2	NC-Trapping	WP1	2 - AU	24	NC-Trapping in low-noise environment. Means of verification: Measurement of temperature of NCs
MS3	Cooling	WP2	7 - UCL	36	Cooling of internal and centre-of-mass (CoM) degrees of freedom of a charged NC Means of verification: Changes in the line shape of the mechanical CoM and cooling transition
MS4	New tests for collapse models	WP4	5 - QUB	36	New tests for the energy-conserving CSL model (ecCSL) and for the Schrödinger-Newton equation (SN). Means of verification: Rigorous modelling of non-interferometric tests for ecCSL and SN
MS5	The final experiment	WP3	8 - SOUTHAMPTON	42	Experimental test of the quantum superposition principle. Means of verification: Observation of broadening of mechanical spectral line.
MS6	Quantum & Gravity	WP4	5 - QUB	48	Time dilation decoherence & gravity-induced collapse. Means of verification: Connection between time dilation decoherence and gravity-induced collapse

6. Deliverables

Deliverable Number[14]	Deliverable Title	WP number[9]	Lead beneficiary	Type[15]	Dissemination level[16]	Due Date (in months)[17]
D1.1	Rf trap for NCs	WP1	2 - AU	Report	Public	24
D1.2	1-Colloidal NCs	WP1	6 - TU Delft	Report	Public	12
D1.3	2-Colloidal NCs	WP1	6 - TU Delft	Report	Public	24
D1.4	Loading and control device	WP1	7 - UCL	Report	Public	36
D1.5	Quantification of heating	WP1	5 - QUB	Report	Public	36
D2.1	Low noise electronics	WP2	3 - INFN	Report	Public	12
D2.2	Optimal cooling strategies	WP2	8 - SOUTHAMPTON	Report	Public	27
D2.3	Internal state cooling	WP2	7 - UCL	Report	Public	38
D2.4	Quantify decoherence	WP2	5 - QUB	Report	Public	44
D3.1	Low noise environment	WP3	8 - SOUTHAMPTON	Report	Public	12
D3.2	Systematic effects investigated	WP3	8 - SOUTHAMPTON	Report	Public	28
D3.3	Ultimate experiment	WP3	8 - SOUTHAMPTON	Report	Public	40
D3.4	General bound	WP3	5 - QUB	Report	Public	48
D4.1	Calibration of decoherence	WP4	5 - QUB	Report	Public	12
D4.2	Bounds to CSL & SN models	WP4	5 - QUB	Report	Public	18
D4.3	Size of superposition	WP4	5 - QUB	Report	Public	24
D4.4	Bounds to the ecCSL model	WP4	1 - UNITS	Report	Public	36
D4.5	Time-dilation/gravity collapse	WP4	4 - OEAW	Report	Public	44
D5.1	Website	WP5	1 - UNITS	Websites, patents filling, etc.	Public	2
D5.2	Data Management Plan	WP5	1 - UNITS	ORDP: Open Research Data Pilot	Public	6
D5.3	Project Review meeting documents M12	WP5	1 - UNITS	Report	Confidential, only for members of the consortium (including the Commission Services)	14
D5.4	Project Review meeting documents M30	WP5	1 - UNITS	Report	Confidential, only for members of the consortium (including the Commission Services)	32
D5.5	Project Review meeting documents M48	WP5	1 - UNITS	Report	Confidential, only for members of the consortium (including the Commission Services)	48
D6.1	Press releases	WP6	1 - UNITS	Websites, patents filling, etc.	Public	3
D6.2	Popular press articles	WP6	1 - UNITS	Websites, patents filling, etc.	Public	12
D6.3	Videos	WP6	1 - UNITS	Websites, patents filling, etc.	Public	20
D6.4	Workshop	WP6	1 - UNITS	Websites, patents filling, etc.	Public	24
D6.5	Dissemination and Exploitation Plan	WP6	1 - UNITS	Report	Confidential, only for members of the consortium (including the Commission Services)	12

7. Dissemination & Exploitation Plan

The Chair will prepare a draft plan, based on the TEQ project (as in the GA) and will be circulated for discussion and approval.

8. Data Management Plan

Unit leaders will inquire with their institutions on regulations and constraints. Deadline: 1 month.
A round of emails will follow, to discuss how to proceed.
The Chair will prepare a draft of plan for discussion and approval.

9. Open Access

Scientific papers will be uploaded on the public TEQ website (or on the ArXiv, with a link on to it on the TEQ website).
For Journals with a 6-month embargo policy, papers will be uploaded on the ArXiv or the TEQ website at the end on month 6.

10. Recruitment plan

Discussion of the recruitment plan and of potential issues.

Gender balance policies should be duly taken care of, during recruitment procedures.

11. Distribution of tasks

Management and scientific development of the **first quarter** of the first year of TEQ: H. Ulbricht will coordinate the experimental part, M. Paternostro will coordinate the theory part.

Date of the first ‘check-point’: June 2018

12. Plan for Review

Review number [19]	Tentative timing	Planned venue of review	Comments, if any
RV1	14	Brussels	
RV2	32	Brussels (to be confirmed)	
RV3	48	Brussels (to be confirmed)	

Identification of strategy for the review meeting.

Inquire with the PO what he expects from the meeting. Discussion will take place during the next SC meeting.

Rehearsal day before the Review meeting.

13. Next SC meeting

Where: Delft
When: Early December 2018. A doodle will be sent to define the date
Structure: Two-day meeting, internal to the consortium.

14. AOB

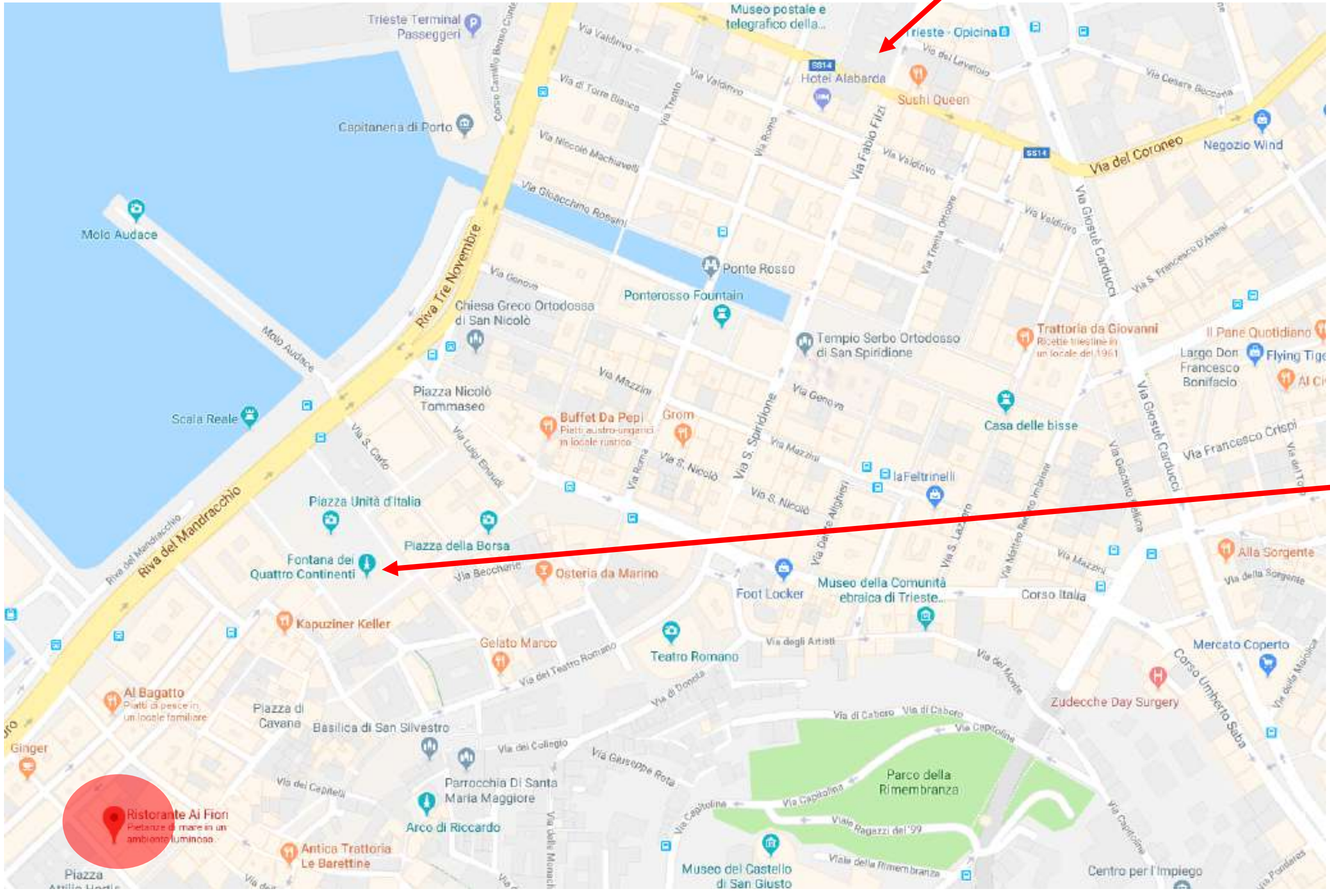
15. Closing

Many thanks for the collaboration!

Dinner

Restaurant “Ai Fiori”
Piazza Attilio Hortis 7
At: 20:30

We are here



We meet at 20:20 in Piazza Unità near the fountain

TEQ: Roadmap over the 4 years and focus on the 1st year: theory

TEQ

Testing the large-scale limit of quantum mechanics

HORIZON 2020

Kick-off Meeting

Trieste 2 February 2018

Scope of my role

Coordinate the theoretical efforts

Oversee the development of the workplan (theory only)

Identify possible roadblocks and corresponding mitigation measures (theory only)

In synergy with theory partners
and Angelo

TEQ

Theory part of the Consortium

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

Angelo Bassi
Matteo Carlesso (PhD)
Giulio Gasbarri (PDRA)

Alessio Belenchia
(currently OEAW, soon QUB)
+
Andre' Grossardt
(QUB)

QUEEN'S
UNIVERSITY
BELFAST

Mauro Paternostro
PhD (Marta Marchese)
PDRA

ÖAW AUSTRIAN ACADEMY OF SCIENCES

Caslav Brukner

?? cf. Alessio's talk

Marko Toros
(formerly UNITS, now UoS)

Our broad theoretical goal

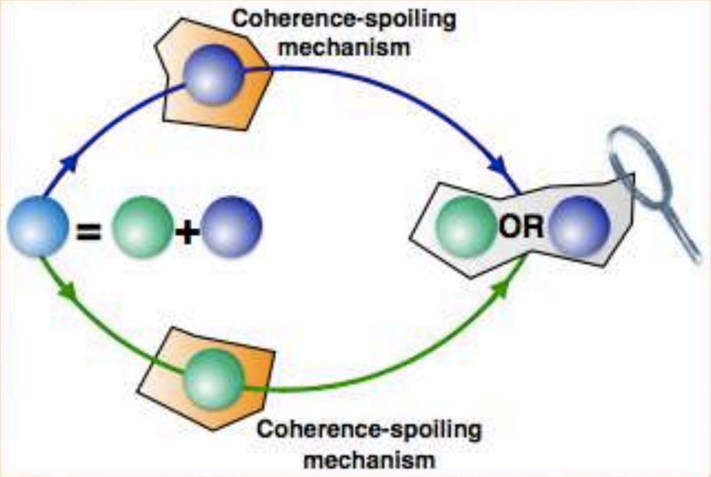
The long-term vision of TEQ is the identification of the fundamental limitations to the applicability of quantum mechanics towards the establishment of a novel paradigm for quantum-enhanced technology that makes use of large-scale devices.

Targeted breakthroughs

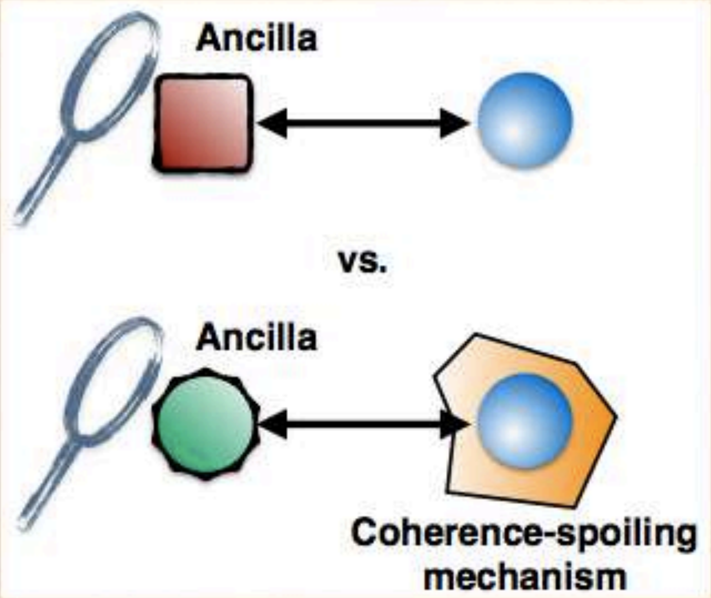
2) We will identify the core sources of environmental decoherence affecting the system, and characterize them experimentally.

3) We will devise and implement suitable diagnostic strategies able to infer possible effects arising from non- standard decoherence mechanisms.

The foundational approach



Before TEQ



With TEQ

TEQ

The theoretical "basket" within the Consortium

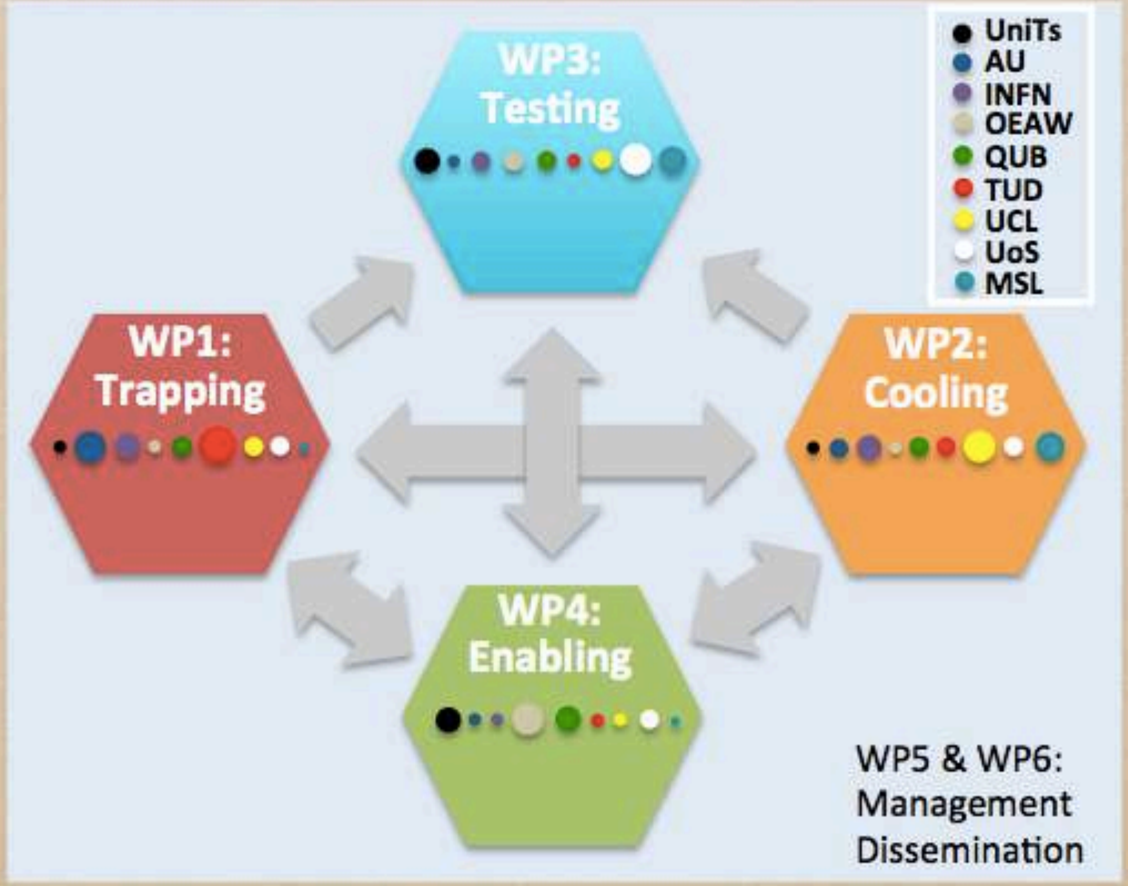
1) Expertise in theoretical quantum optics, optomechanics, many-body theory, open-system dynamics, foundations of quantum mechanics, collapse models

2) Some of the leading experts in the theoretical modelling of non-standard decoherence

3) Theorists with long-standing tradition of interactions with experimentalists

4) Pioneers of the non-interferometric approach

The scientific work-packages



● UniTs
● AU
● INFN
● OEAW
● QUB
● TUD
● UCL
● UoS
● MSL

WP3: Testing

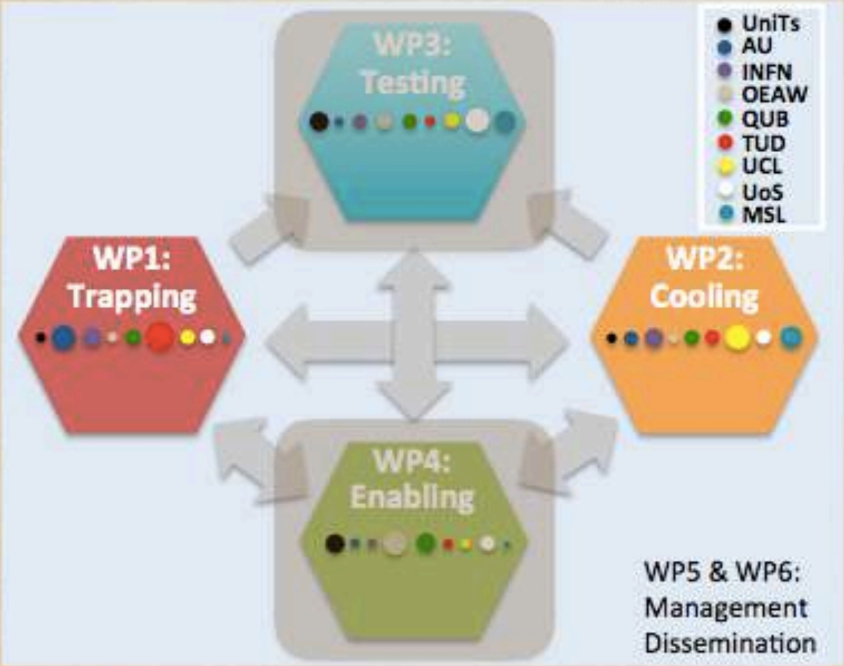
WP1: Trapping

WP2: Cooling

WP4: Enabling

WP5 & WP6:
Management
Dissemination

The scientific work-packages (focus on theory)



Testing

1) Assessment of fundamental mechanisms
2) Validation of the non-interferometric approach

Enabling

1) Theoretical platform for the study of macroscopic quantum effects
2) A roadmap towards the construction of high-sensitivity metrological devices for frequency and displacements

The scientific work-packages (focus on theory)

WP3: Testing

UoS

O3.2 To perform tests of CSL noise effects on motion of trapped NC

O3.3 To adapt theory to experimental parameters to optimise the test of quantum superposition.

Task 3.4: Characterisation of mass-dependent CSL-based heating effect affecting the dynamics of a mechanical oscillator [QUB, UniTS, OEAW, UoS, UCL].

Study of noise or its effect on the motion of the oscillator

M. Bahrami et al., Phys. Rev. Lett. 112, 012023 (2014), S. Nimmrichter et al., ibid. 113, 020405 (2014)
D. Goldwater et al., Phys. Rev. A 94, 010104(R) (2016); J. Vovrosh, et al. arXiv:1603.02917 (2016).

Partners involved: QUB, UniTS, OEAW, UoS, UCL

The scientific work-packages

WP4: Enabling

QUB

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.

Task 4.1 Assess decoherence on the experimental setup at the core of WP3 [QUB, UoS, OEAW].

Task 4.2 Determine experiment-specific bounds to CSL and SN mechanisms [UniTs, QUB].

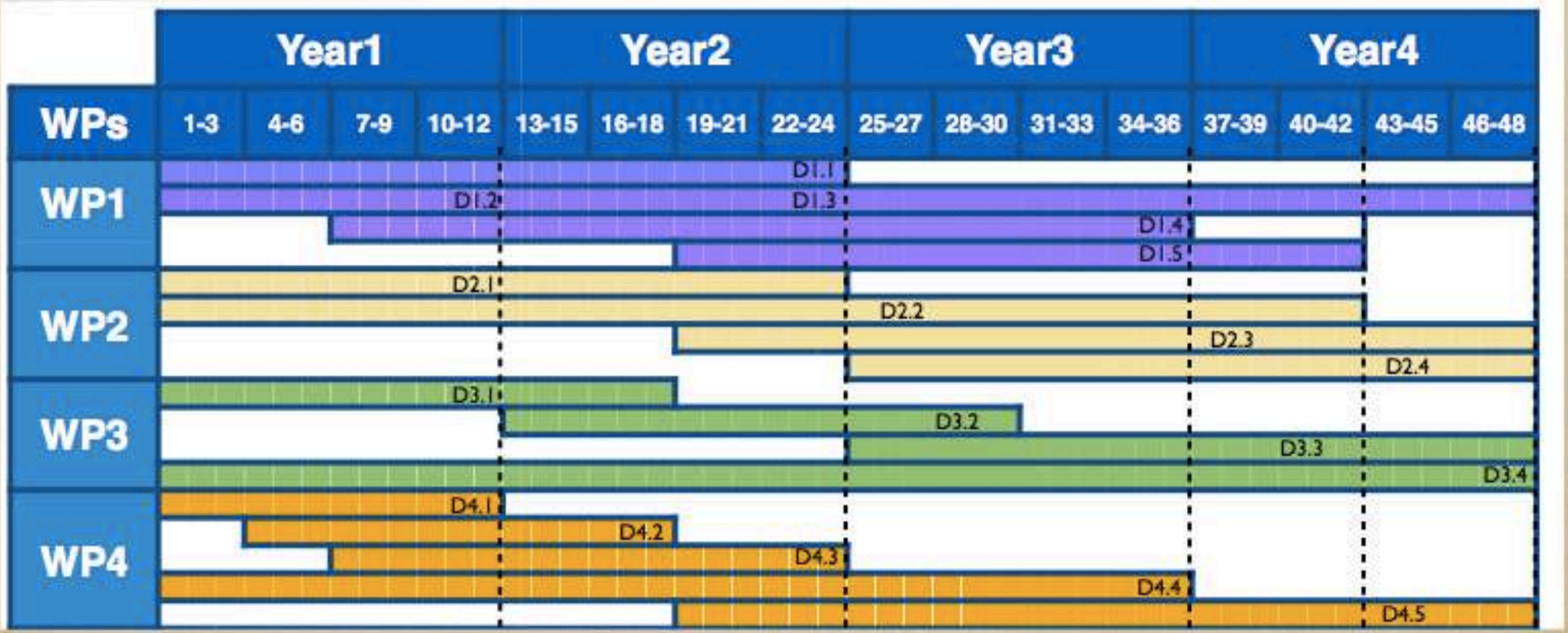
Task 4.3 Develop schemes to quantify the macroscopicity of superposition states [QUB, UniTs].

Task 4.4 Design setting for the test of energy–conserving CSL and SN model [UniTs, QUB].

Task 4.5 Compare time dilation decoherence and gravity induced collapse [OEAW, UniTs, QUB].

Work already in development

Plan for the first year: Timetable



	Year1				Year2				Year3				Year4			
WPs	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48
WP1	🟪	🟪	🟪	🟪	🟪	🟪	🟪	D1.1								
	🟪	🟪	🟪	D1.2	🟪	🟪	🟪	D1.3	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
			🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	D1.4				
							🟪	🟪	🟪	🟪	🟪	D1.5	🟪	🟪		
WP2	🟨	🟨	🟨	D2.1	🟨	🟨	🟨	🟨								
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	D2.2	🟨	🟨	🟨	🟨	🟨		
							🟨	🟨	🟨	🟨	🟨	🟨	D2.3	🟨	🟨	🟨
									🟨	🟨	🟨	🟨	🟨	🟨	D2.4	🟨
WP3	🟩	🟩	🟩	D3.1	🟩	🟩										
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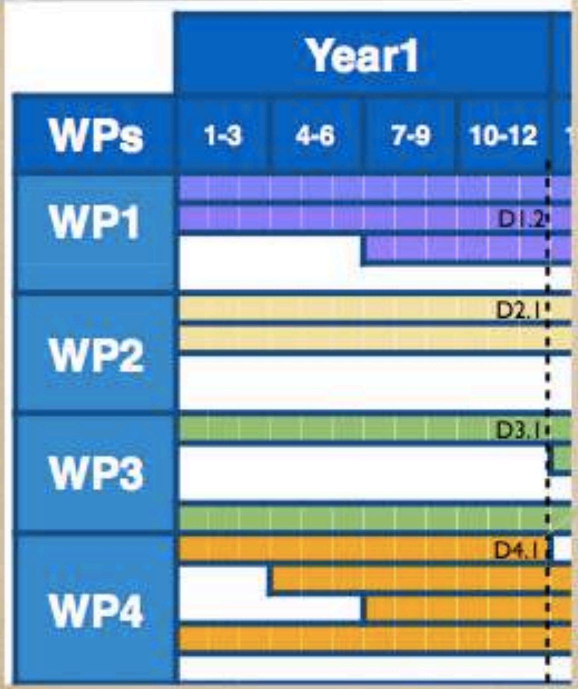
									🟩	🟩	🟩	🟩	🟩	D3.3	🟩	🟩
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	D3.4
WP4	🟧	🟧	🟧	D4.1												
		🟧	🟧	🟧	🟧	D4.2										
			🟧	🟧	🟧	🟧	🟧	D4.3								
	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	D4.4				
							🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	D4.5	🟧

Plan for the first year: Timetable



D4.1: Calibration of decoherence (QUB)

Only one possible strategy

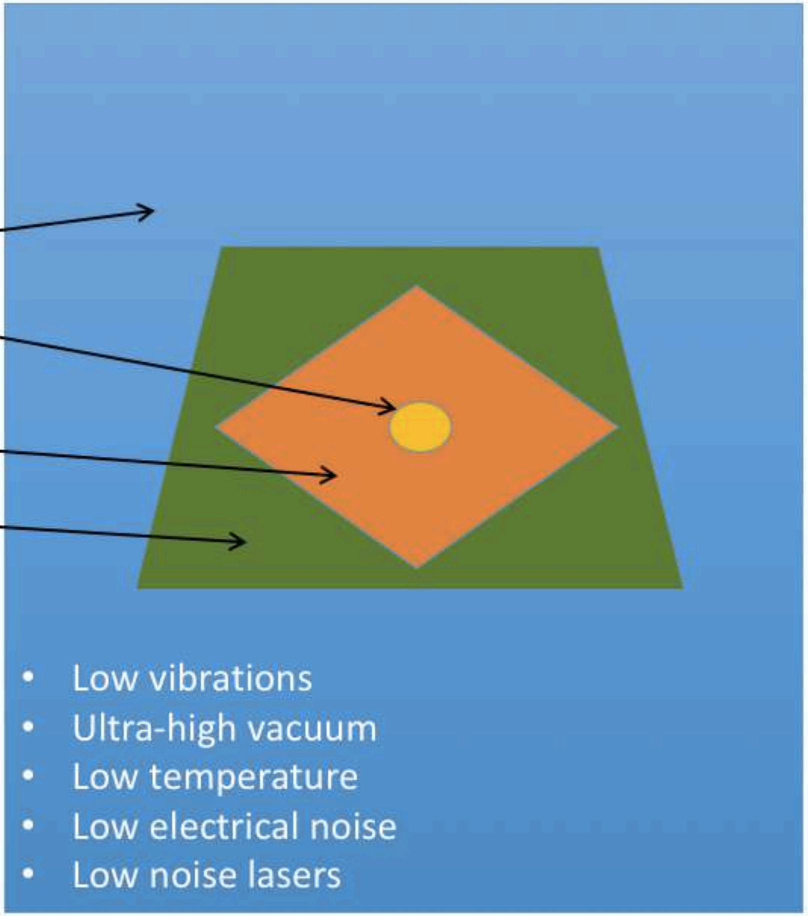
1) Interact as much as possible

2) Do the best science we can: we have the resources and the expertise

3) Enjoy our work (a "childish" enthusiasm never hurts)

TEQ - experiments

- Particles
- Environment
- Trapping
- Detection



- Low vibrations
- Ultra-high vacuum
- Low temperature
- Low electrical noise
- Low noise lasers

Particle ….

Has to meet month 12 deliverable (D1.2)

- Synthesis for UCL: particles for internal cooling [has started]
- Synthesis for UoS: Rare-earth doped Silica, Lithium Niobate, Barium borate [has started]
- Synthesis for AU: do we need some particles to be tested at AU?

- -> UCL, UoS and possibly AU need to test the particles and feedback information for improvements of properties for trapping and detection and cooling and possible next batch of synthesis.

- Are targets for particles clear? (type, size, quality, quantity)
- Do we need more guidance from theory: What particles are the best for CSL test? (would need involvement of UnTri)

Environment ….

has to meet **month 12** deliverable (D3.1)

- He-3 sorption refrigerator,
  - Janis [much probably]
  - 300mK, (50uW @ 350mK), [heat load for Paul trap estimated]
  - UHV,
  - Direct optical access, and fibre optical access
  - ‘no-vibration’ as no mechanical parts or pumps or cryo-coolers.
  - Electrical wires for Paul trap
  - Tender is out: deadline 13/2/2018 to decide and place order.
  - Alternative trap: magnetic trapping of permanent magnet above superconductor (no heating, neutral particle, fits to low T)
  - Low noise laser(s): one at UCL and one at UoS (M2)

Trapping ……

next deliverable in month 12 (D2.1)

- Paul trap for ~100 Hz oscillation/motion of particle (delivery at month 24)
- Gold coated ceramics based design (discuss with AU, UCL)
- Low noise electronics for Paul trap, based on AU existing design (INFN)
- Heating of operating trap has been estimated and (should) work in cryostat
- Design of electrodes has to be discussed together with optical detection (AU and UCL): cavity vs high NA optics
- Particle loading mechanism, based on piezo shaking (UCL)
- Next step: decide the design and plan the building of the trap
- Discussion of alternative trapping with magnetic trap.

Detection

- Optical detection and cooling for trapped nanoparticle ion (UCL)
- Cooling of internal temperature of particle (UCL)
- Low noise electronics for optical detectors (photodiode amplifier) (INFN) -> deliverable month 12 (D2.1)
- Low noise lasers (M2)

- Alternative: if magnetic trap, then should be SQUIDs for particle detection

TEQ

Testing the large-scale limit of quantum mechanics

Kick off Meeting

Matteo Carlesso - UniTs

2nd February 2018

UniTs – QMTS group.

Bassi Group
University of Trieste
QUANTUM MECHANICS

Angelo Bassi	PI
Giulio Gasbarri	Postdoc
Matteo Carlesso	Postdoc
Caitlin Jones	PhD student
TBA	Administrative Officer

Directly involved in TEQ

Lorenzo Asprea	PhD student
Luca Curcuraci	PhD student
José Luis Gaona Reyes	PhD student

Indirectly involved in TEQ
as part of the research group

UniTs – Core Tasks.

Angelo Bassi	• Management of the project. • Leadership of WP5 and WP6. • Co-leadership of WP3. • Preparation, implementation and update of the DMP. • Coordination for dissemination and communication.
Giulio Gasbarri **Matteo Carlesso** **Caitlin Jones**	• Theory for testing energy-conserving CSL model. • Theory for testing non-Markovian CSL model. • Assessment of decoherence in experiments. • Development gravity-induced collapse models.

WP1: Trapping | WP2: Cooling | WP3: Testing | WP4: Enabling | WP5: Management | WP6: Dissemination

WP1: Trapping

Theoretical study for the quantification of the heating effects, which

- Affect the trapping mechanism
- Enhance the loss of particles
- Limits the trapping time

Working together with QUB and OEAW.
Collaboration with AU and UoS.

WP1: Trapping
WP2: Cooling
WP3: Testing
WP4: Enabling
WP5: Management
WP6: Dissemination

WP2: Cooling

Theoretical study for the characterization the relevant sources of decoherence:

- Study the non-equilibrium dynamics of the trapped NC
- Quantify the decoherence action and effects on NC
- Understand how it affects CSL experiments

Working together with QUB, OEAW and UCL.

WP1: Trapping

WP2: Cooling

WP3: Testing

WP4: Enabling

WP5: Management

WP6: Dissemination

WP3: Testing

Adapt theory to experiments

- Optimization of tests of quantum superposition
- Theoretical prediction of experimental outcomes
- Infer bounds on collapse models

Working together with QUB, OEAW, UoS and UCL.

WP1: Trapping

WP2: Cooling

WP3: Testing

WP4: Enabling

WP5: Management

WP6: Dissemination

WP4: Enabling

Theoretical development and investigation non-standard models of QM

- Energy-conserving CSL model
- Time-dilation decoherence
- Gravity-induced collapse models
- Assessing quantumness of gravity
- Measure of macroscopicity

Working together with QUB, OEAW and UCL.

UniTs in TEQ.

WP1: Trapping

WP2: Cooling

WP3: Testing

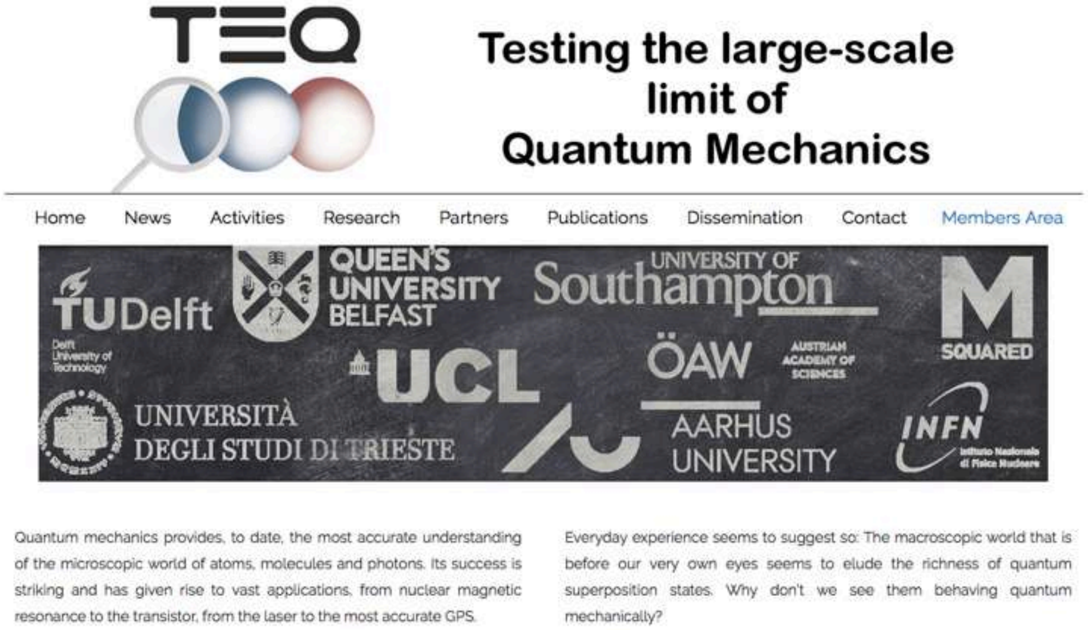
WP4: Enabling

WP5: Management

WP6: Dissemination

WP5: Management
WP6: Dissemination

Website
www.tequantum.eu



Testing the large-scale limit of Quantum Mechanics

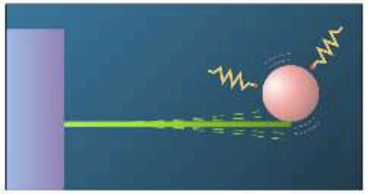
Quantum mechanics provides, to date, the most accurate understanding of the microscopic world of atoms, molecules and photons. Its success is striking and has given rise to vast applications, from nuclear magnetic resonance to the transistor, from the laser to the most accurate GPS.

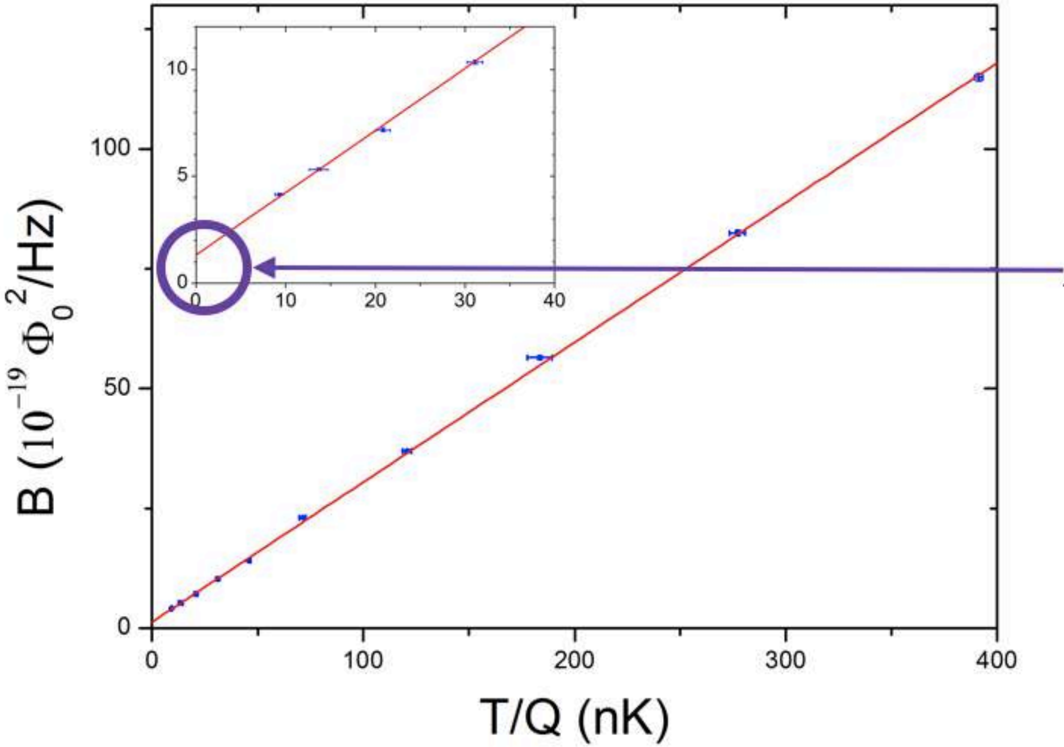
Everyday experience seems to suggest so: The macroscopic world that is before our very own eyes seems to elude the richness of quantum superposition states. Why don't we see them behaving quantum mechanically?

Multilayer test masses to enhance collapse noise effects

$$\mathcal{S}(\omega) = \frac{2M\gamma_{\mathrm{m}}k_{\mathrm{B}}T + \mathcal{S}_{\mathrm{CSL}}}{M^2[(\omega_0^2 - \omega^2)^2 + \gamma_{\mathrm{m}}^2\omega^2]},$$

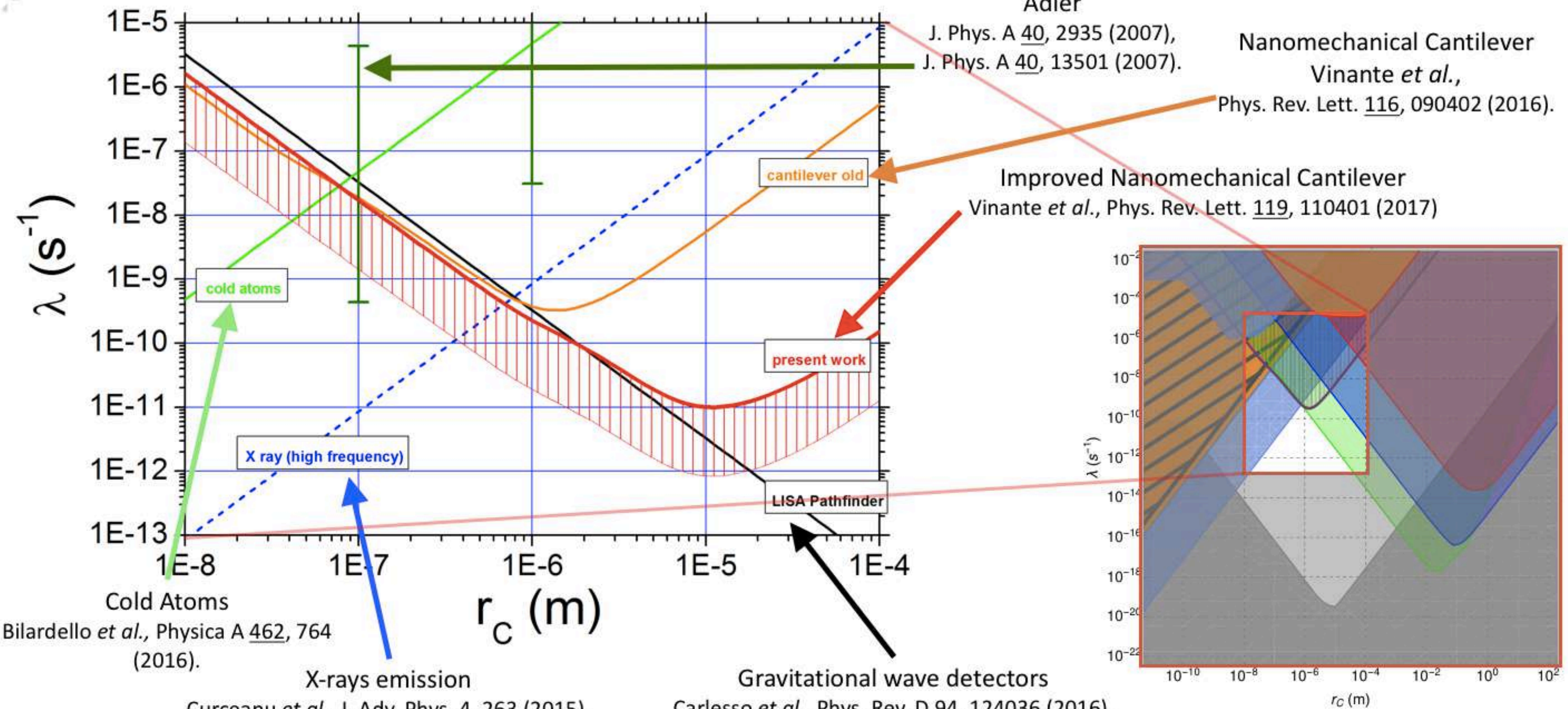
$$\mathcal{S}_{\mathrm{CSL}} = \mathcal{S}_{\mathrm{CSL}}(\lambda, r_C)$$





$$\Delta T^{\mathrm{V}}_{\mathrm{CSL}} = \frac{\mathcal{S}_{\mathrm{CSL}}}{2k_{\mathrm{B}}M\gamma_{\mathrm{m}}}$$

Multilayer test masses to enhance collapse noise effects



Adler
J. Phys. A 40, 2935 (2007),
J. Phys. A 40, 13501 (2007).

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

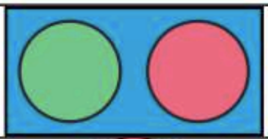
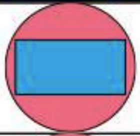
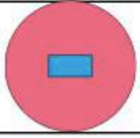
Improved Nanomechanical Cantilever
Vinante *et al.*, Phys. Rev. Lett. 119, 110401 (2017)

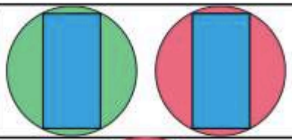
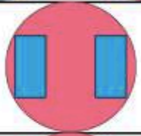
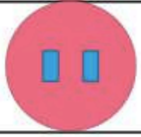
Cold Atoms
Bilardello *et al.*, Physica A 462, 764 (2016).

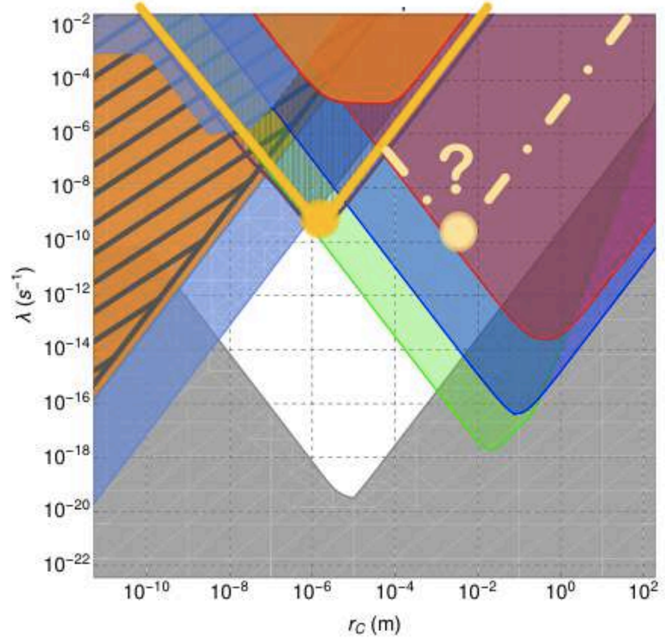
X-rays emission
Curceanu *et al.*, J. Adv. Phys. 4, 263 (2015).

Gravitational wave detectors
Carlesso *et al.*, Phys. Rev. D 94, 124036 (2016).

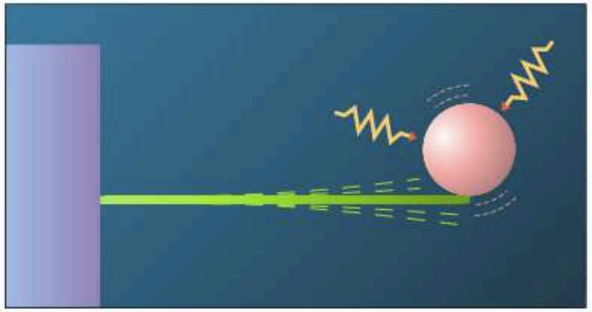
Multilayer test masses to enhance collapse noise effects

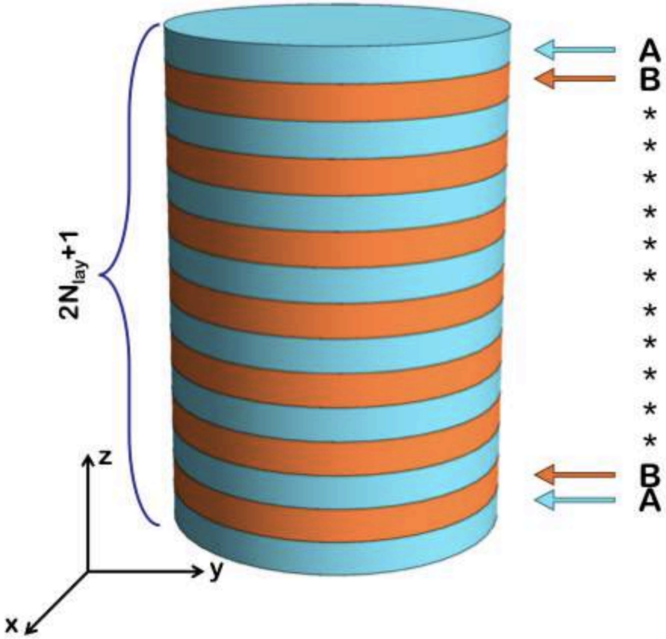
$r_C \ll L$		Incoherent action Weak effect
$r_C \sim L$		Coherent action Strong effect
$r_C \gg L$		Coherent unfocused action Weak effect

$r_C \sim L$ $r_C < d$		Incoherent action Weak effect
$r_C \gg L$ $r_C \gtrsim d$		Coherent action Strong effect
$r_C \gg L$ $r_C \gg d$		Coherent unfocused action Weak effect



Multilayer test masses to enhance collapse noise effects





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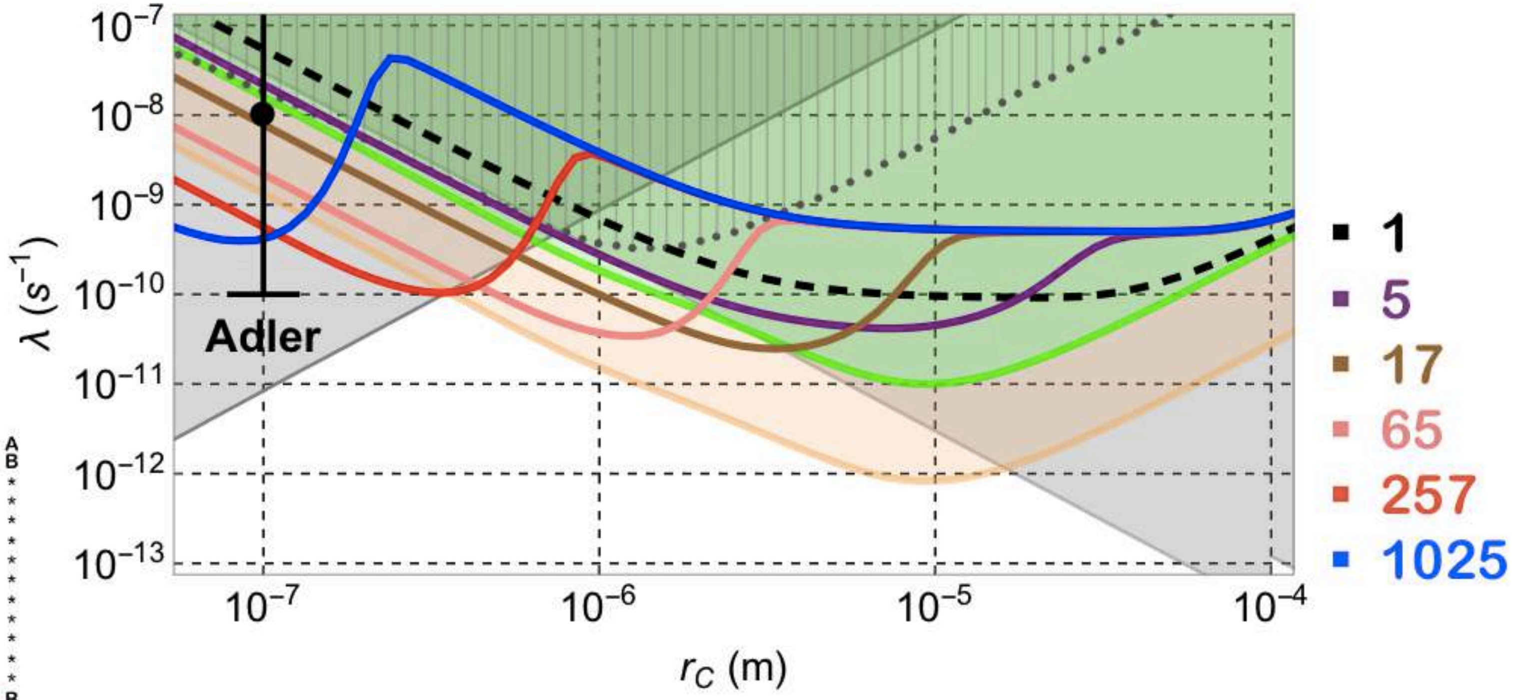
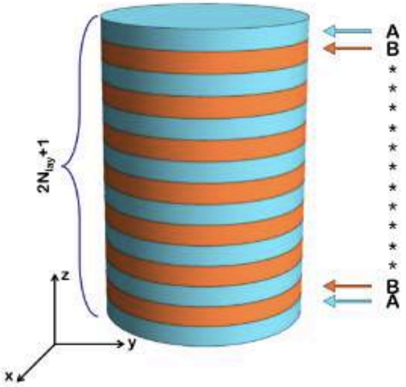
$$\mathcal{S}_{\mathrm{CSL}} = \frac{\hbar^2\lambda r_C^3}{\pi^{3/2}m_0^2}\int d\mathbf{k}\,|\tilde{\mu}(\mathbf{k})|^2 e^{-\mathbf{k}^2 r_C^2} k_z^2,$$

$$\mathcal{S}_{\mathrm{CSL}} = \frac{\hbar^2\lambda r_C^3}{\pi^{3/2}m_0^2}\int d\mathbf{k}\sum_{\alpha,\beta}\left(\tilde{\mu}_\alpha(\mathbf{k})\tilde{\mu}_\beta^*(\mathbf{k})\right) e^{-\mathbf{k}^2 r_C^2} k_z^2,$$

- N single layer contributions from self-correlation
- N(N-1) cross-correlated terms

Multilayer test masses to enhance collapse noise effects





UniTs – Contributions to deliverables.

WP1

Quantify heating [Mth 36]

WP2

Quantify decoherence [Mth 44]

WP3

Bounds on macroscopicity [Mth 48]

WP4

Bounds on ecCSL model [Mth 36]
Bounds on CSL and SN model [Mth 18]
Size of superposition [Mth 24]
Time dilation and gravity collapse [Mth 44]

WP5

Website and logo [Mth 2]
Data Management Plan [Mth 6]
Project Review meeting doc. [Mth 14, 32, 48]

WP6

Press releases [Mth 3]
Popular press articles [Mth 12]
Videos [Mth 20]
Workshop [Mth 24]
Dissemination and Exploitation Plan [Mth 12]

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

European Commission

TEQ

Testing the Large-Scale Limit for Future Quantum Technologies

KICK-OFF MEETING

Alessio Belenchia, IQOQI Vienna

Trieste, 02.02.2018

Outline of the talk

1. TEQ workplan
2. The Vienna TEQ-Node
3. Deliverables outline
4. A puzzle in-between gravity and quantum

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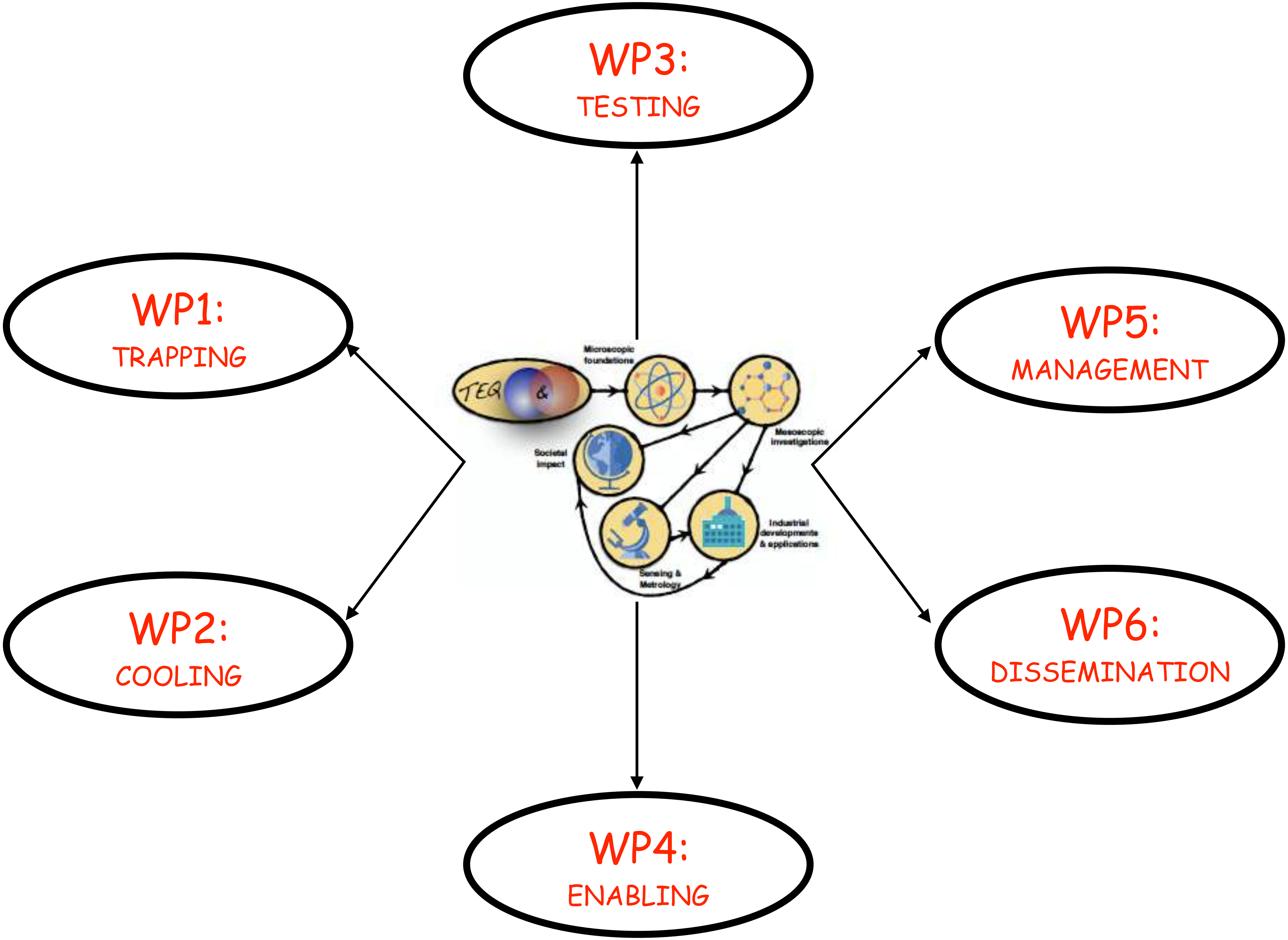


WP3:
TESTING

WP1:
TRAPPING

WP5:
MANAGEMENT

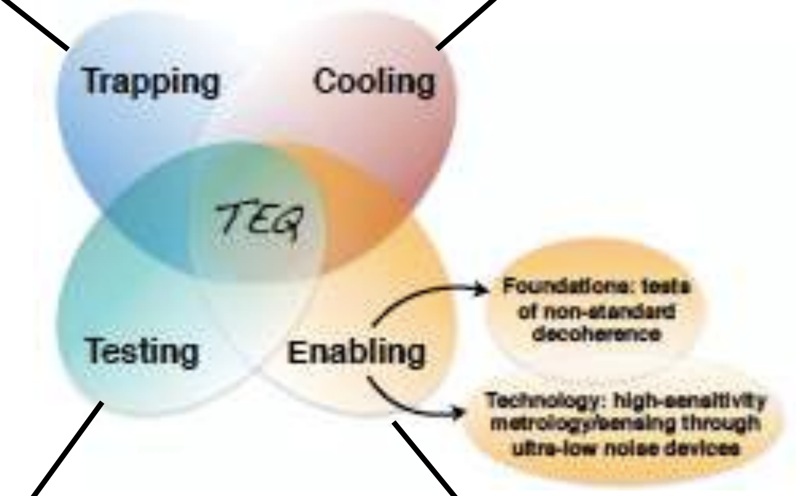
WP2:
COOLING

WP6:
DISSEMINATION

WP4:
ENABLING

WP1:
TRAPPING

WP2:
COOLING



WP3:
TESTING

WP4:
ENABLING

WP3:
TESTING

Task 3.4 Adapt theory and predict experimental outcomes [QUB, UniTS, OEAW, UoS, UCL]

Non-interferometric testing: QUB, OEAW and UniTs will develop the theoretical prediction put forward in [2] which embodies the basic building block of our inference strategy. Such calculations will be reformulated for the needs of the experimental setting discussed here. The CSL mechanism results in the introduction of a mass-dependent non-linear term, which induces an additional heating affecting the dynamics of a mechanical oscillator. The effect is observed from the study of the noise properties of the system. This approach will allow us to bound theoretically the entity of such effects and falsify/confirm them.

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Task 4.5 To compare time dilation decoherence and gravity induced collapse [OEAW, UniTs, QUB]

WP4:
ENABLING

Testing non-standard models of quantum mechanics: QUB, OEAW and UniTs will assess the energy-non-conserving nature of the CSL mechanism. The latter is characterised by an unbound increase of the mean energy of the system it affects. Attempts at ‘curing’ such syndrome have been made [1]. However, some difficulties remain, in that the collapse operator of the energy-conserving CSL (ecCSL) mechanism is not self-adjoint [1]. WP4 will identify an ecCSL-equivalent stochastic potential to be used in the equations describing the motion of the system at the core of TEQ. QUB, OEAW, and UniTs will use the quadratic coupling of light to the position of a mechanical system to magnify small effects, such as those entailed by the Schrödinger-Newton (SN) model [2].

Time-dilation decoherence and gravity-induced collapse models: The predictions of time-dilation decoherence will be compared to those arising from gravitationally-induced collapse models. While such mechanisms are different, the latter can be obtained from quantum theory due to entanglement between the degree of freedom (DoF) we are interested in and unknown ones. OEAW, QUB and UniTs will investigate whether gravitationally-induced collapse can be understood as stemming from entanglement between the position of the system used in TEQ and a “sea of clocks” embodied by uncontrollable internal DOF.

Measuring the size of a coherent superposition state: QUB, OEAW and UniTs will quantify the ‘size’ of a quantum superposition by means of recent measures of macroscopicity [3]. They will design non-tomographic strategies for the assessment of such figures of merit, studying the effect of decoherence and gravity-induced influences.

Outline of the talk

1. TEQ workplan
2. The Vienna TEQ-Node
3. Deliverables outline
4. A puzzle in-between gravity and quantum

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4. A puzzle in-between gravity and quantum

Caslav Brukner:
Prof. of Quantum Foundations and Quantum Information in Vienna.

Relevant contributions:

1. *I. Pikovski, M. Zych. F. Costa, C. Brukner, "Universal decoherence due to gravitational time dilation", Nature Physics 11, 668–672 (2015).*
2. *O. Oreshkov, F. Costa, Č. Brukner, "Quantum correlations with no causal order", Nature Communications 3, 1092 (2012).*
3. *M. Zych, F. Costa, I. Pikovski, T. C. Ralph and Č. Brukner, "General relativistic effects in quantum interference of photons", Class. Quantum Grav. 29, 224010 (2012).*
4. *Pikovski, M. R. Vanner, M. Aspelmeyer, M. S. Kim and Č. Brukner, "Probing Planck-scale physics with quantum optics", Nature Physics 8, 393 (2012).*
5. *M. Zych, F. Costa, I. Pikovski, and Č. Brukner, "Quantum interferometric visibility as a witness of general relativistic proper time", Nature Communication 2, 505 (2011).*

Ilya Kull:
Newly appointed PhD student in Brukner's group working on:

- Indefinite causal structure
- MPS

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SCIENCES

Esteban Castro Ruiz:
PhD student in Brukner's group working on:

- Indefinite causal structure
- Quantum reference frames
- Entanglement of quantum clocks due to gravity

Relevant works:

1. *arxiv1712.07207 Quantum mechanics and the covariance of physical laws in quantum reference frames*
2. *Entanglement of quantum clocks through gravity, PNAS 114, E2303 (2017)*

Alessio Belenchia:
PostDoc in Brukner's group with expertise/interested in

- QG phenomenology
- Analogue Gravity
- Gravitational physics
- Gravity/Quantum interface
- Foundations of QT

Relevant works:

1. *Phys.Rev.Lett. 116, 161303 (2016)*
2. *Phys. Rev. D 95, 026012 (2017)*
3. *arxiv18XX.XXX (see in a minute)*

Universal time dilation “decoherence”

$$\hat{H} = mc^2 + \frac{\hat{p}^2}{2m} + m\Phi(\hat{x}) + \hat{H}_{int} - \boxed{\hat{H}_{int}\frac{\hat{p}^2}{2m^2c^2}} + \boxed{\hat{H}_{int}\frac{\Phi(\hat{x})}{c^2}}$$

SR time dilation

Grav. time dilation

The “speed“of proper time $\dot{\tau} = 1 - \boxed{\frac{v^2}{2c^2}} + \boxed{\frac{\Phi(x)}{c^2}}$

Internal energy gravitates: this makes possible to entangle internal and external d.o.f.s.

Universal time-dilation due to (special and general) relativistic effects gives rise to decoherence of the center-of mass state

$$\dot{\rho}_{cm}(t) = -\frac{i}{\hbar}\left[H_{cm} + \frac{\bar{E}_0}{c^2}\Gamma(x,p), \rho_{cm}(t)\right] - \left(\frac{\Delta E_0}{\hbar c^2}\right)^2 \int_0^t ds \left[\Gamma(x,p), e^{-iH_{cm}s/\hbar}\left[\Gamma(x,p), \rho_{cm}(t-s)\right] e^{iH_{cm}s/\hbar}\right]$$

Quantum reference frames

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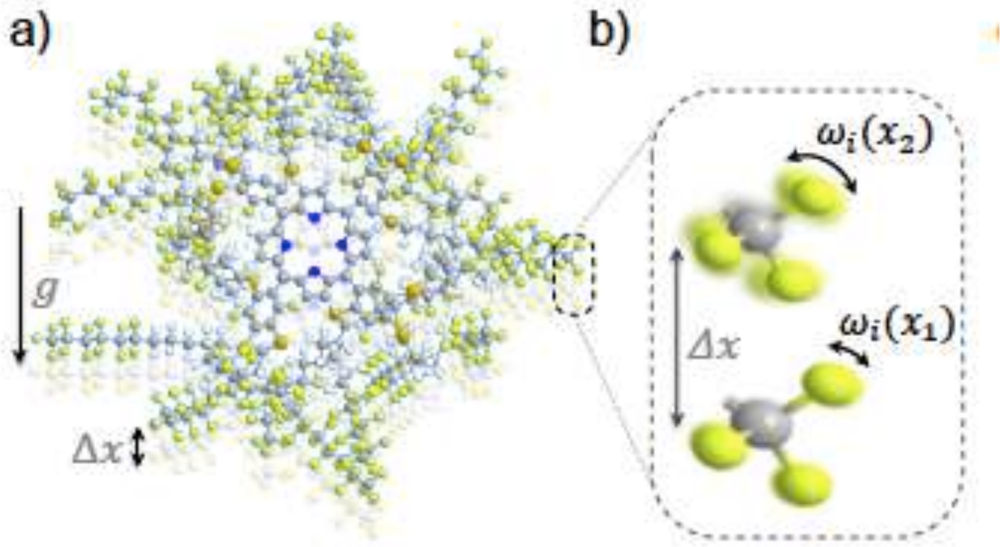

$$\mathcal{V} = \left|\langle e^{-iH_{int}\Delta\tau/\hbar}\rangle\right|$$

$$\tau_{dec} = \frac{\sqrt{2}\hbar c^2}{g|\Delta x|\Delta E_0}$$

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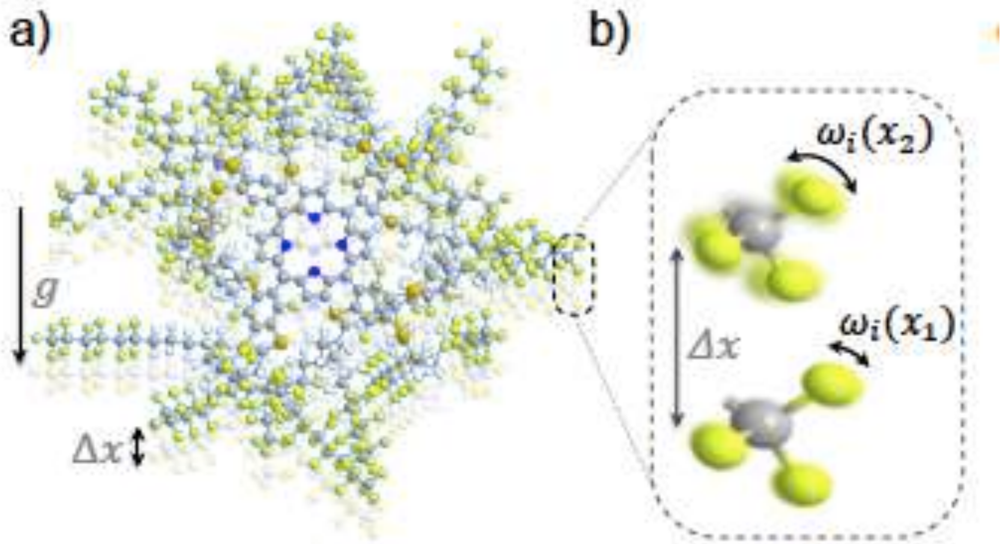

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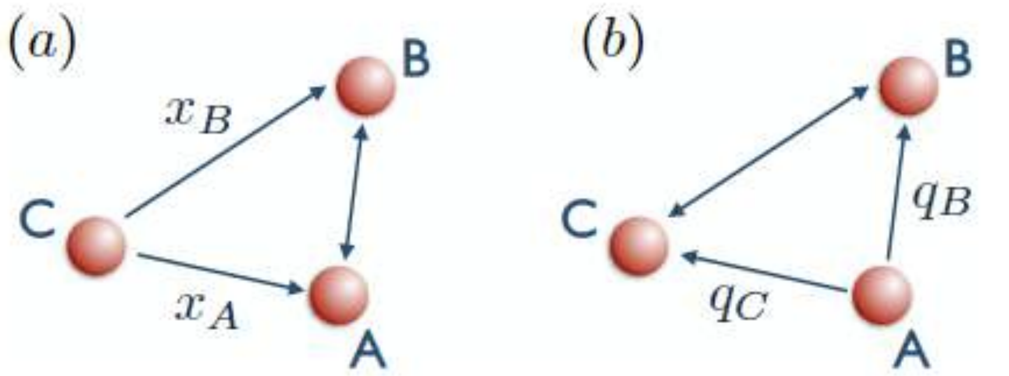
Quantum reference frames

- Reference frames are/could be associated to physical systems
- What if the system in question is in a quantum state?
- How physics is described from the point of view of a quantum “particle”?



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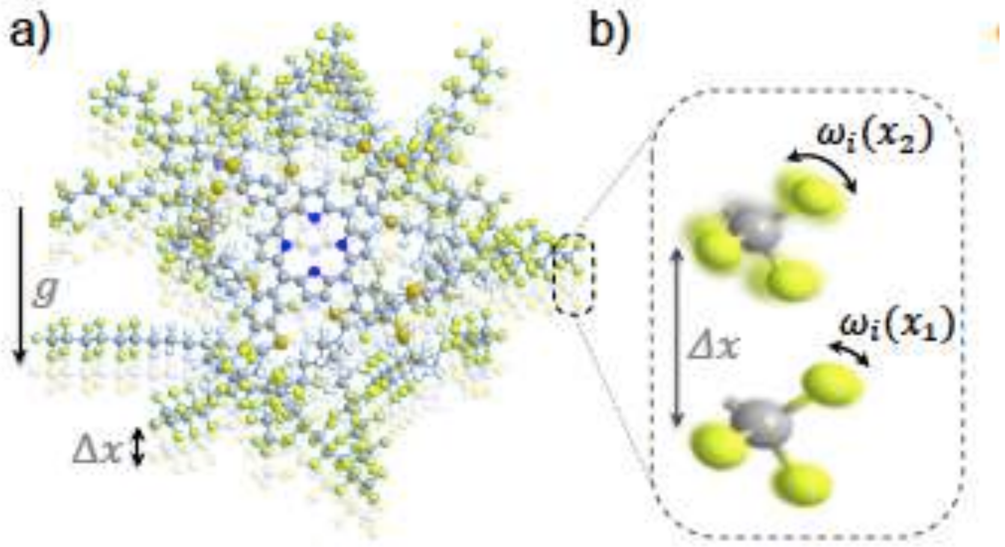

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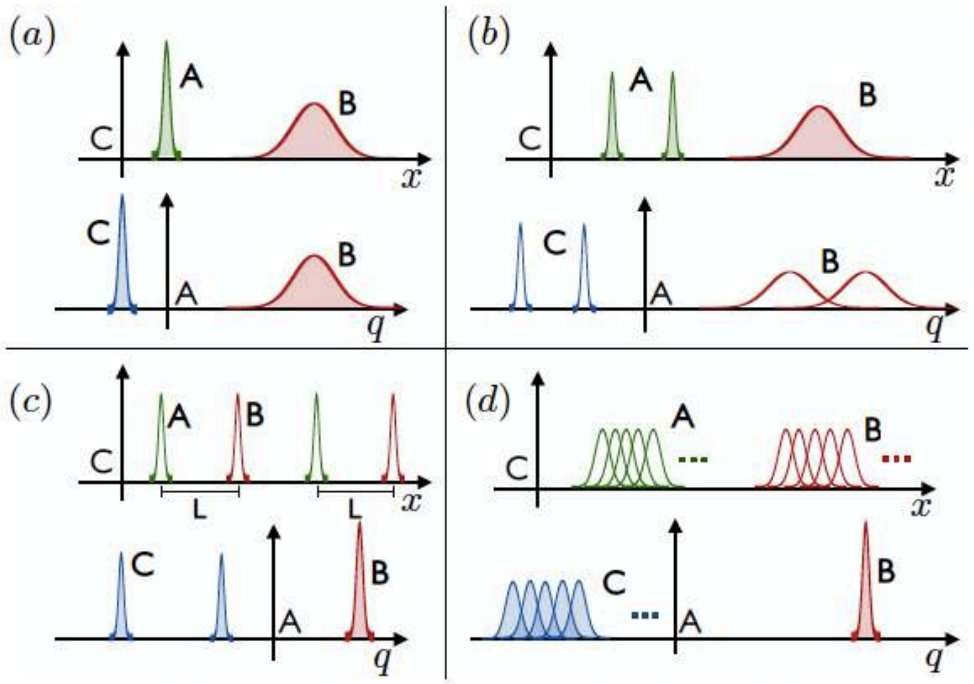
Quantum reference frames

- Reference frames are/could be associated to physical systems
- What if the system in question is in a quantum state?
- How physics is described from the point of view of a quantum “particle”
- No need for any external reference, full relational description is possible
- Extended Galilean transformations were considered
- Insight for situation in which a rest frame cannot be readily defined



Quantum Equivalence Principle

The internal energy in QM contributes to the total mass-energy

$$\hat{M}_\alpha = m_\alpha \hat{\mathbb{I}} + \frac{\hat{H}_\alpha}{c^2}$$

$$\hat{M}_g \hat{M}_i^{-1} \approx \begin{pmatrix} r_1 & r \\ r^* & r_2 \end{pmatrix}$$

WEP:

$$M_i = M_g$$

Q-WEP:

$$\hat{M}_i = \hat{M}_g$$

Quantum gravity phenomenology with table-top experiments

Quantum Equivalence Principle

Violation of the classical WEP if different

$$\hat{M}_g \hat{M}_i^{-1} \approx \begin{pmatrix} r_1 & r \\ r^* & r_2 \end{pmatrix}$$

Violation of the Q-WEP if non-vanishing

$$a_1 = g\langle 1|\hat{M}_g\hat{M}_i^{-1}|1\rangle = gr_1,$$

$$a_2 = g\langle 2|\hat{M}_g\hat{M}_i^{-1}|2\rangle = gr_2,$$

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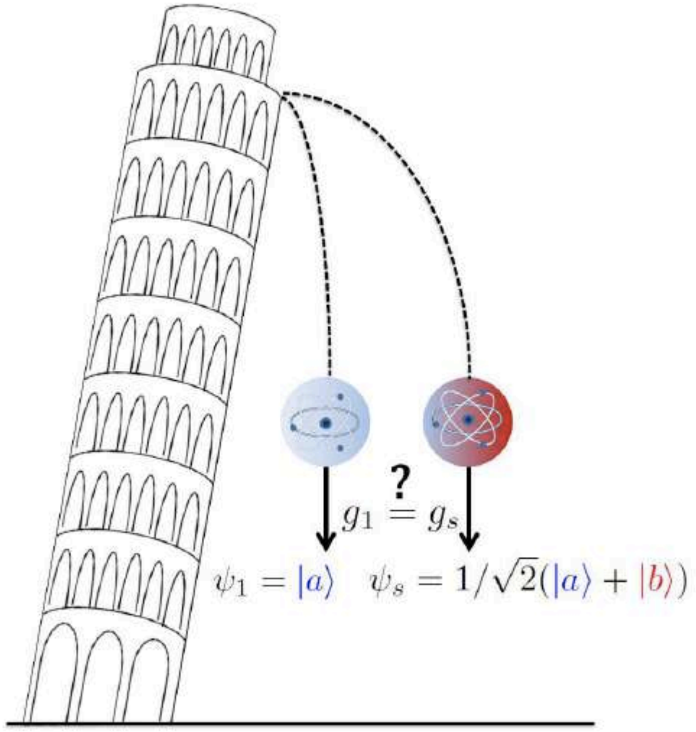

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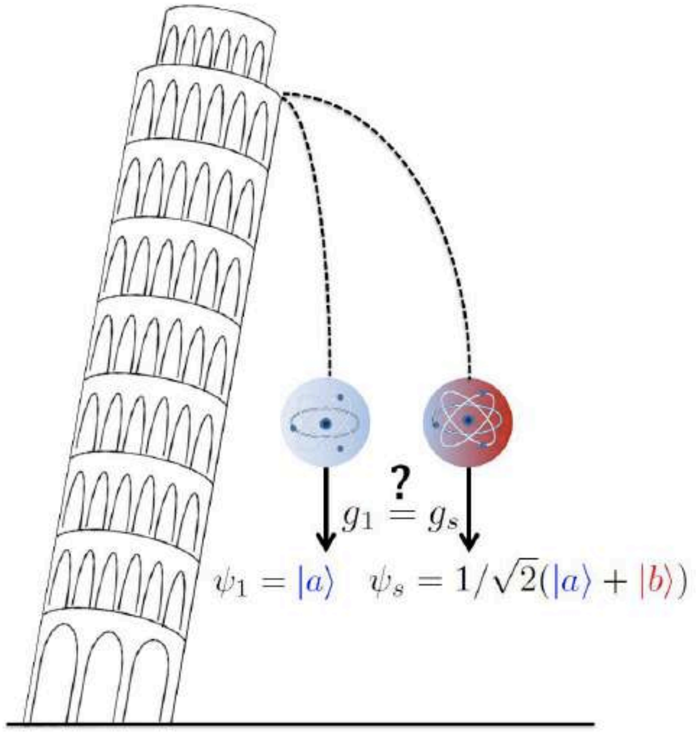

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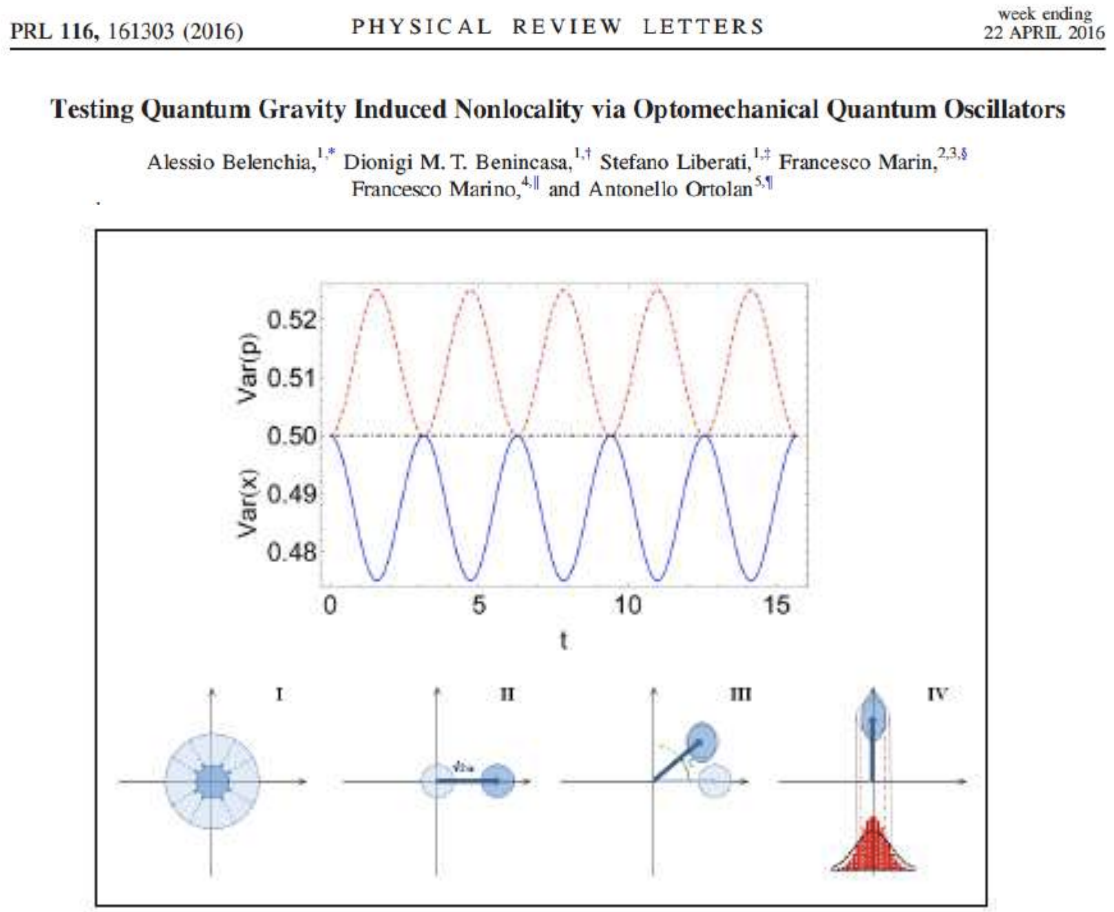


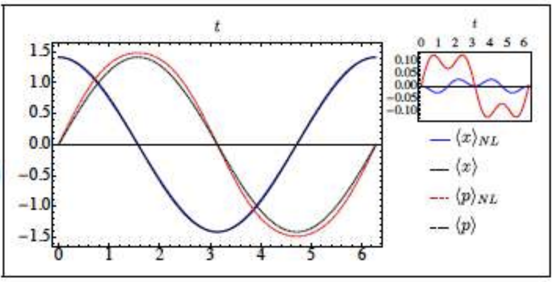
PRL 116, 161303 (2016) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

Testing Quantum Gravity Induced Nonlocality via Optomechanical Quantum Oscillators

Alessio Belenchia,[1,*] Dionigi M. T. Benincasa,[1,†] Stefano Liberati,[1,‡] Francesco Marin,[2,3,§]
Francesco Marino,[4,∥] and Antonello Ortolan[5,¶]

$$\langle x\rangle = \sqrt{2}\alpha\cos(t)\left(1 + \frac{1}{4}\epsilon\alpha^2 a_2\left[\cos(2t) - 1\right]\right) + \mathcal{O}(\epsilon^2),$$

$$\langle p\rangle = \sqrt{2}\alpha\sin(t)\left(1 + \frac{1}{4}\epsilon a_2\left[\alpha^2(7 + 3\cos(2t)) - 2\right]\right) + \mathcal{O}(\epsilon^2)$$



- Non-local field theories ubiquitous in quantum gravity
- General feature of spacetime discreteness
- Non-relativistic limit gives rise to a non-local Schodinger eq.
- Coherent states modified dynamics: spontaneous, time-periodic squeezing
- Tests with quantum optomechanical oscillators: could cast constraints up to $10^{-26} m$

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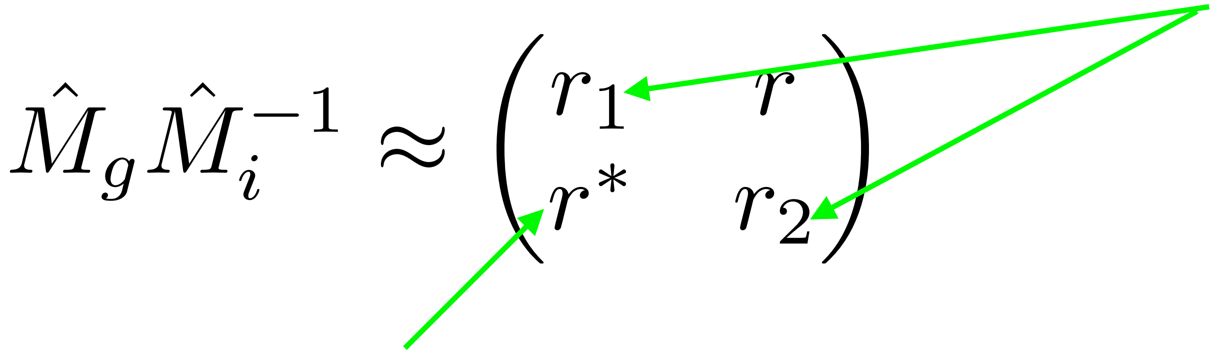

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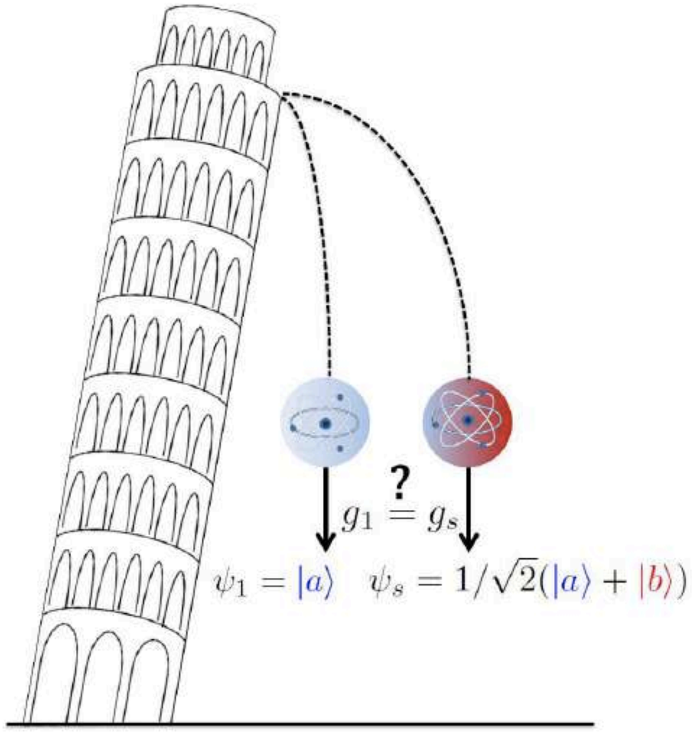

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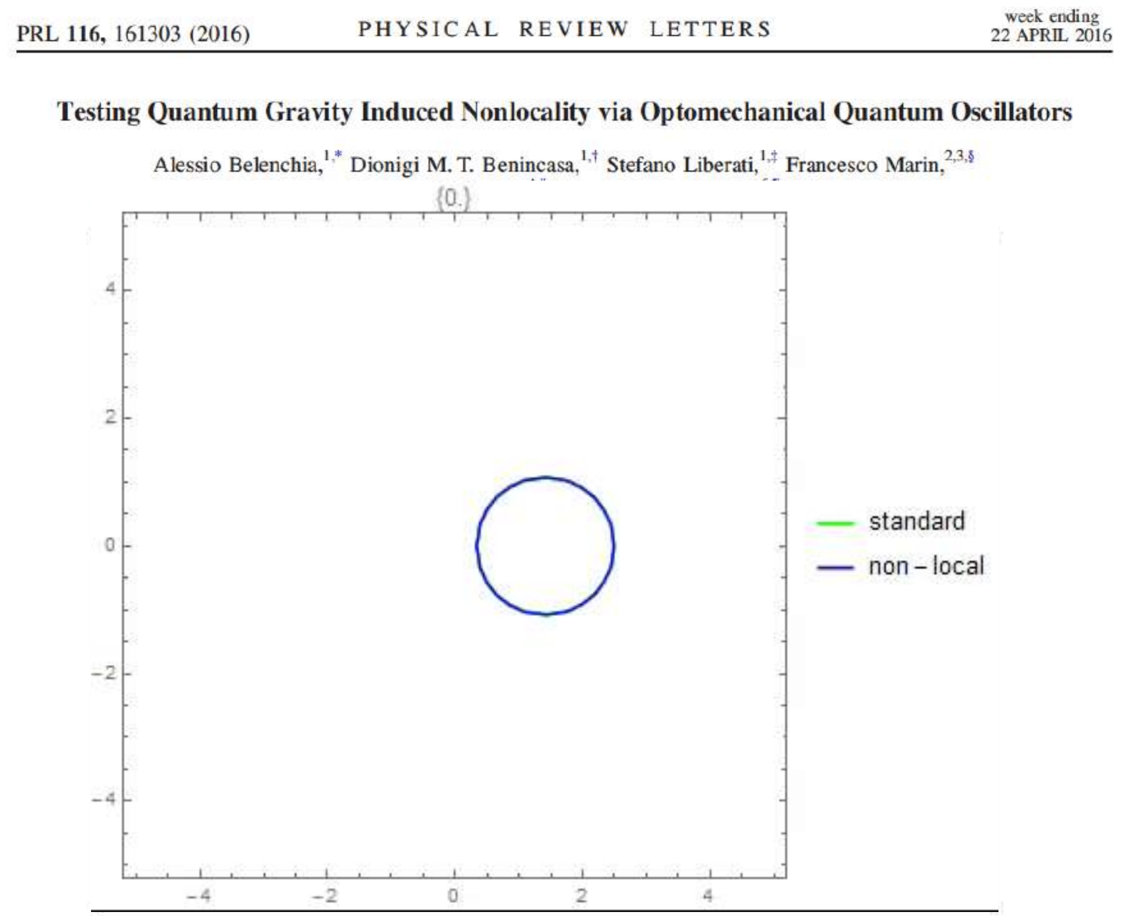

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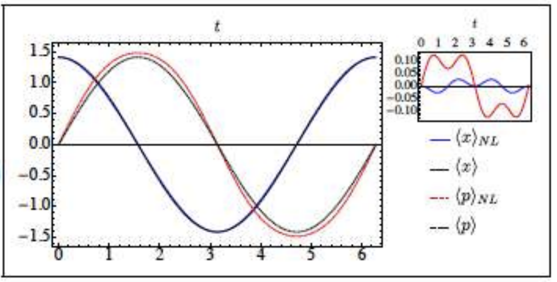

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Outline of the talk

1. TEQ workplan
2. The Vienna TEQ-Node
3. Deliverables outline
4. A puzzle in-between gravity and quantum

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Deliverables WP4

D4.1 Quantification of environmental decoherence effects and experimental calibration [Mth 12].

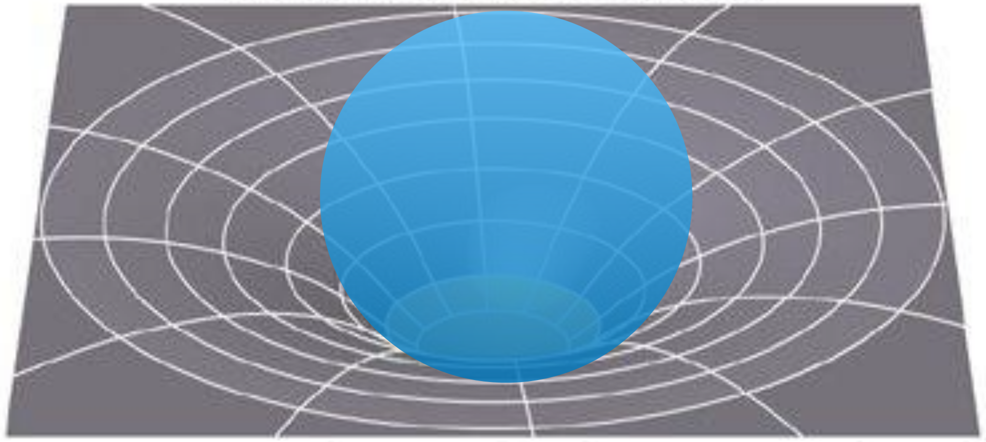
D4.2 Provision of bounds on the effects of CSL, and SN mechanisms [Mth 18].

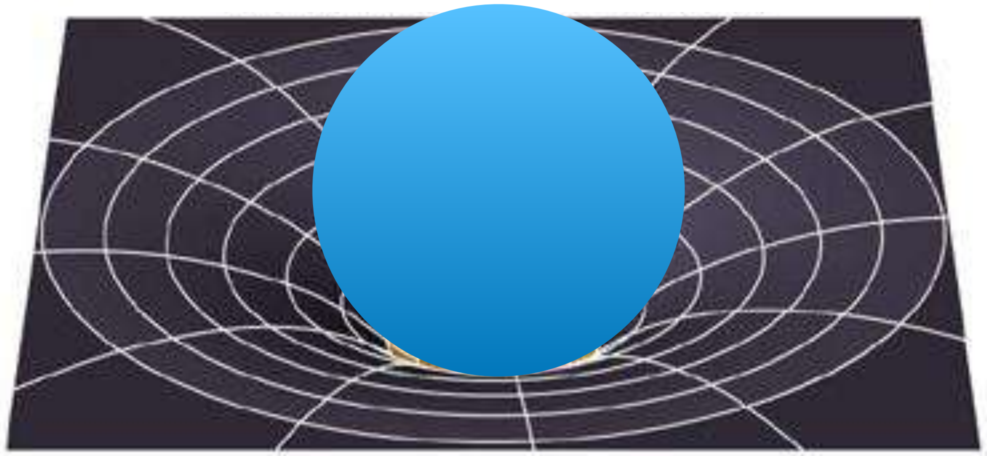
D4.3 Design of experimental schemes for the quantification of the size of quantum superpositions [Mth 24].

D4.4 Provision of bounds on the effects of energy-conserving CSL mechanism [Mth 36].

D4.5 Quantitative comparison between time-dilation decoherence and gravity-induced collapse [Mth 44].

OEAW, QUB and UniTs will investigate whether gravitationally-induced collapse can be understood as stemming from entanglement between the position of the system used in TEQ and a “sea of clocks” embodied by uncontrollable internal DOF.





Could the collapse of a superposition of two massive bodies be caused by entanglement with a “sea of clocks” thanks to the gravitational field generated?

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Setting the Stage

A simple question*

Is gravity quantum as the other fundamental forces?

*to which I don’t know the answer

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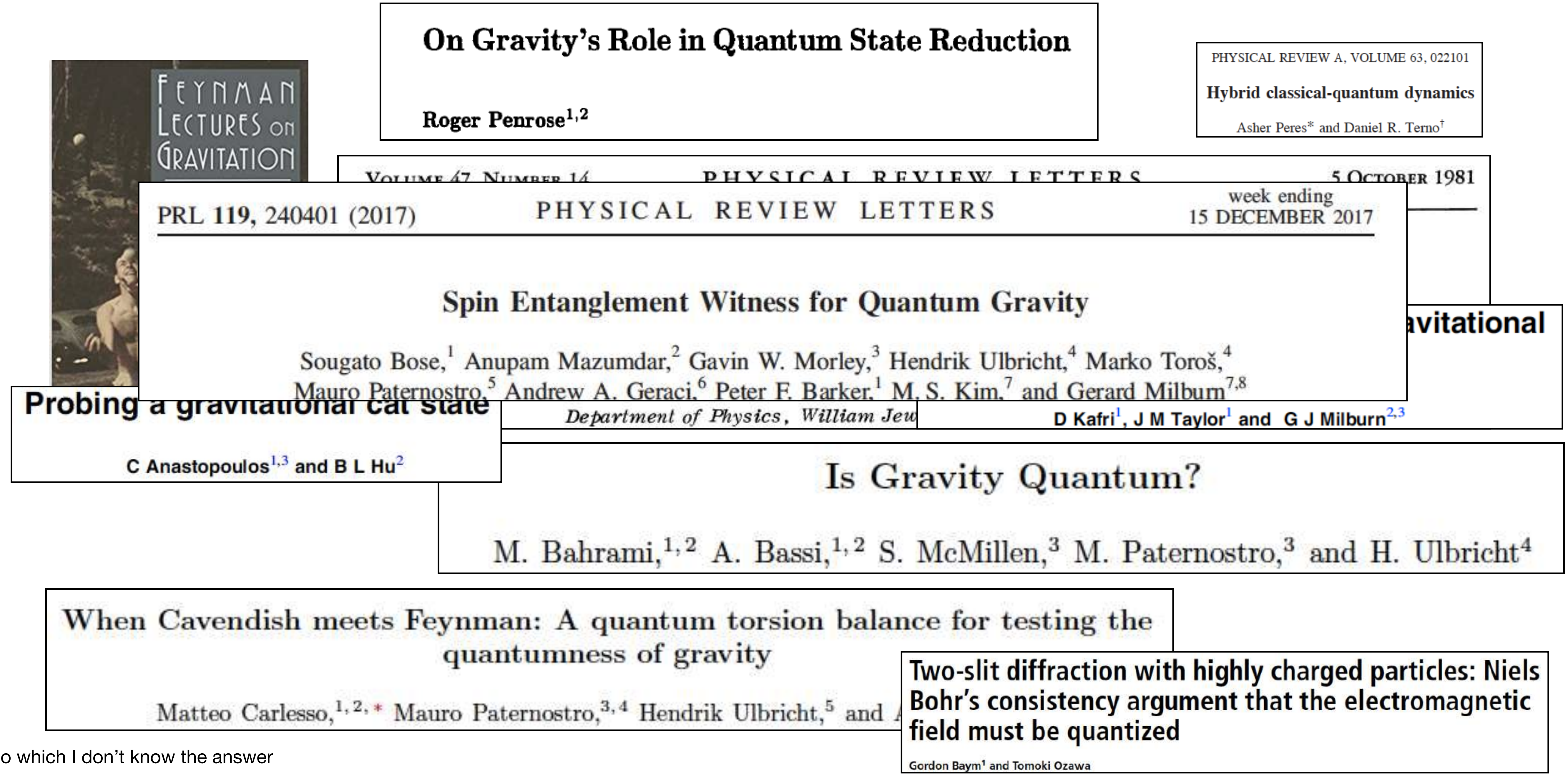

FEYNMAN LECTURES ON GRAVITATION

On Gravity's Role in Quantum State Reduction

Roger Penrose[1,2]

PHYSICAL REVIEW A, VOLUME 63, 022101

Hybrid classical-quantum dynamics

Asher Peres* and Daniel R. Terno†

VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

Department of Physics, William Jew

PRL 119, 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

avitational

D Kafri[1], J M Taylor[1] and G J Milburn[2,3]

Probing a gravitational cat state

C Anastopoulos[1,3] and B L Hu[2]

Is Gravity Quantum?

M. Bahrami,[1,2] A. Bassi,[1,2] S. McMillen,[3] M. Paternostro,[3] and H. Ulbricht[4]

When Cavendish meets Feynman: A quantum torsion balance for testing the quantumness of gravity

Matteo Carlesso,[1,2,*] Mauro Paternostro,[3,4] Hendrik Ulbricht,[5] and

Two-slit diffraction with highly charged particles: Niels Bohr's consistency argument that the electromagnetic field must be quantized

Gordon Baym[1] and Tomoki Ozawa

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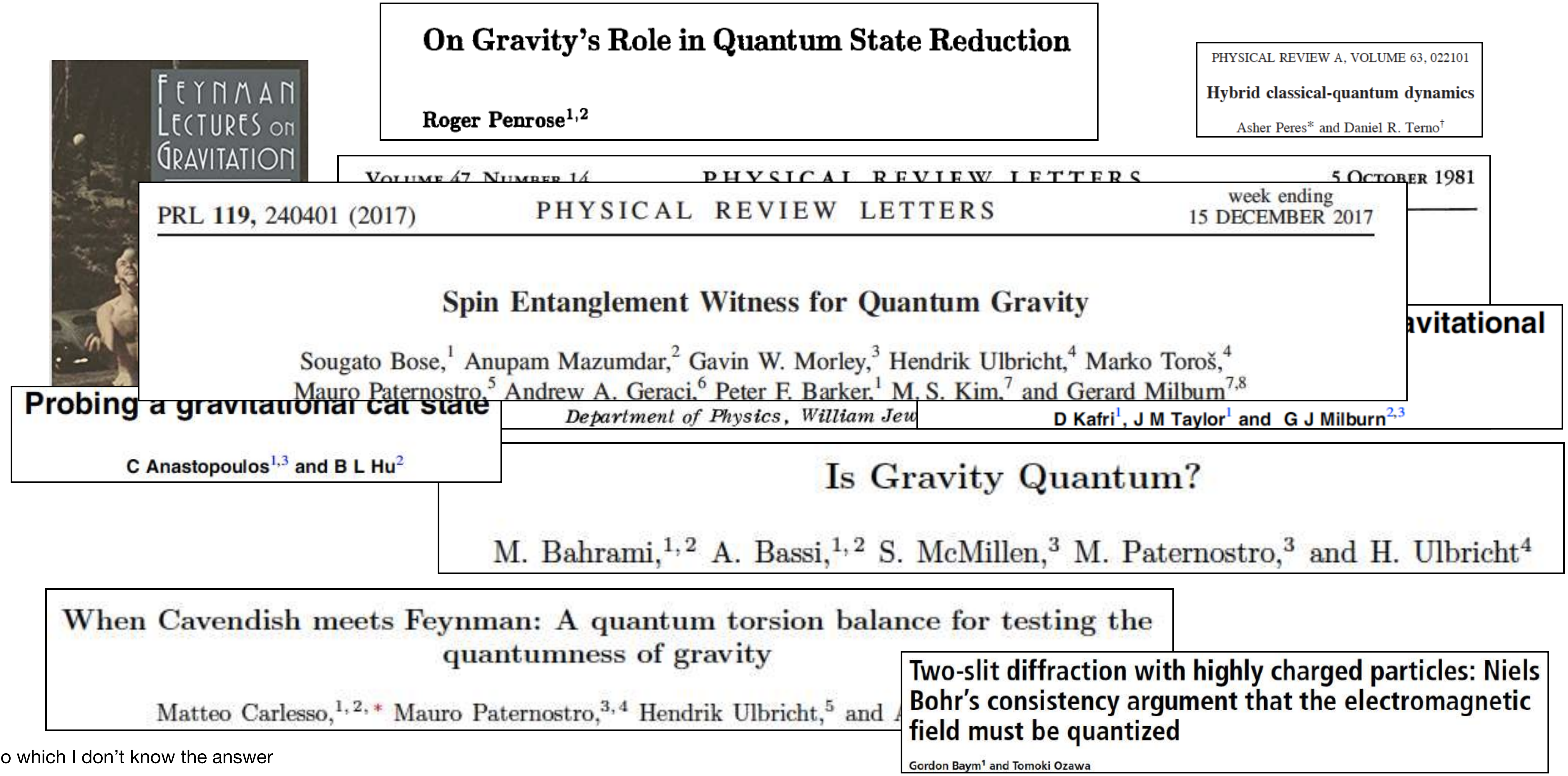

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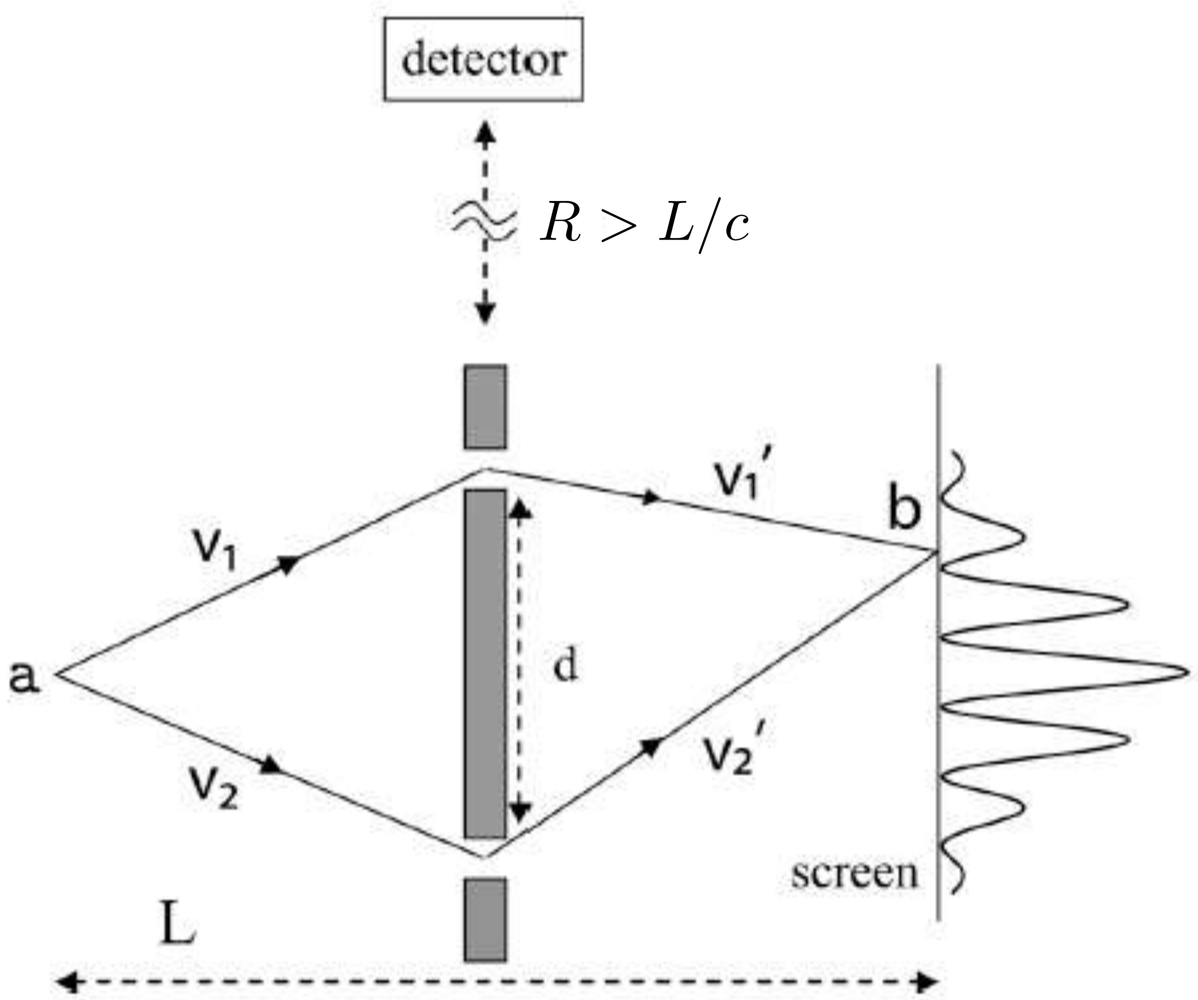
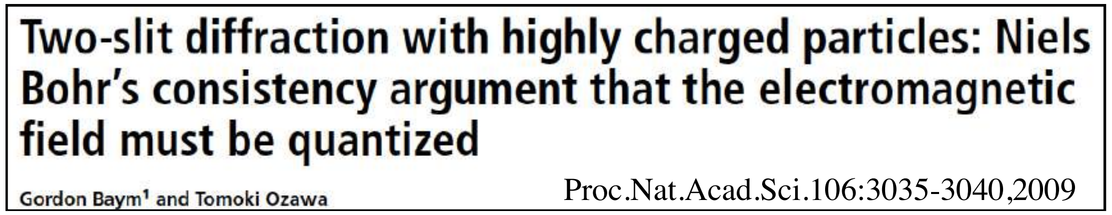
The answer to the previous question rests with experiments (like the one TEQ could enable to make) unless some consistency condition does not enforce it

- **If the gravitational field generated by a mass in superposition of two different locations can entangle two masses, this shows that such a field is not described by semi-classical gravity**
- **This would answer to the important question: which is the gravitational field generated by a superposition of a massive object?**
- **In considering the Newtonian potential we are however considering the non-physical d.o.f.s of the field.**
- **When and how the dynamical d.o.f.s (gravitons) enter the game?**
- **Can we say anything about the quantum nature of these dynamical d.o.f.s? Note that this would close indeed the discussion on the quantum nature of gravity!**

The answer to the previous question rests with experiments (like the one TEQ could enable to make) unless some consistency condition does not enforce it

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Gordon Baym[1] and Tomoki Ozawa

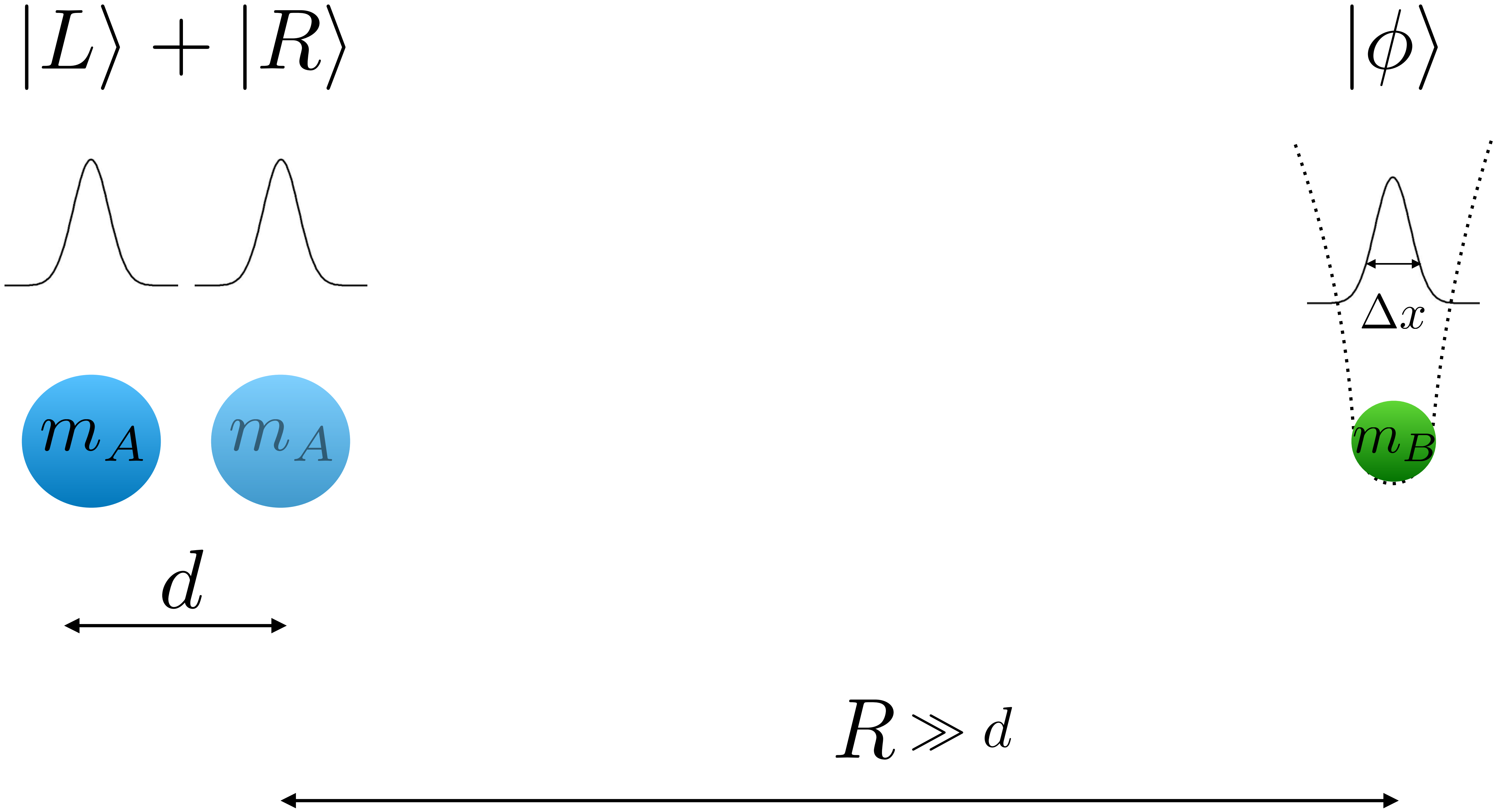
Proc.Nat.Acad.Sci.106:3035-3040,2009

For large enough charges going through the double-slit, the detector far-away will start to collect which-path information

Before reaching that point, the charge undergoing the experiment will start to radiate. It is this radiation then that causes loss of visibility due to the entanglement between photons and the paths

This implies that the electromagnetic field has to be quantized in terms of photons, i.e., the dynamical d.o.f.s are quantum. Electromagnetic field has to be quantized [retro-diction]

A gedankenexperiment:



De Palma, Giovannetti, Mari; Scientific Reports 6, 22777 (2016)

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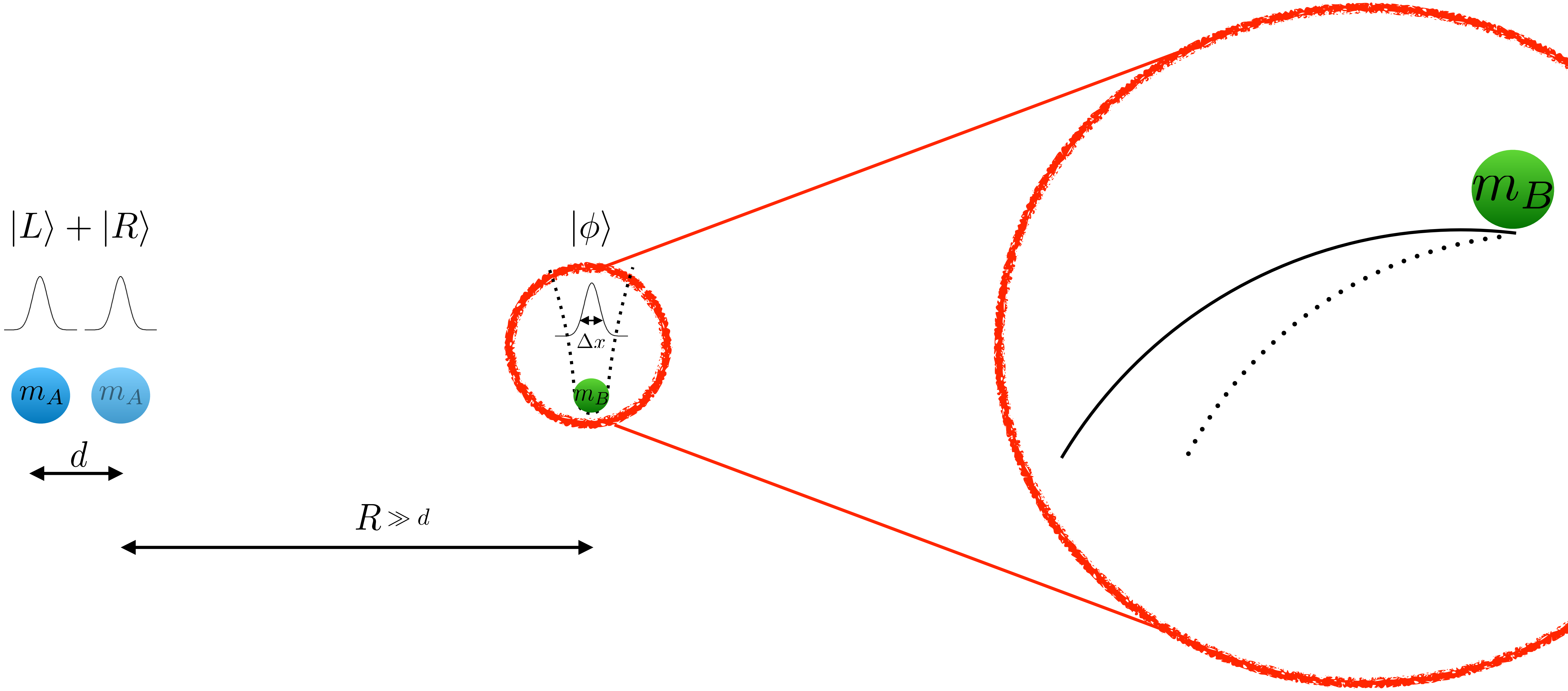

$$(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle) \otimes |\phi_B\rangle$$

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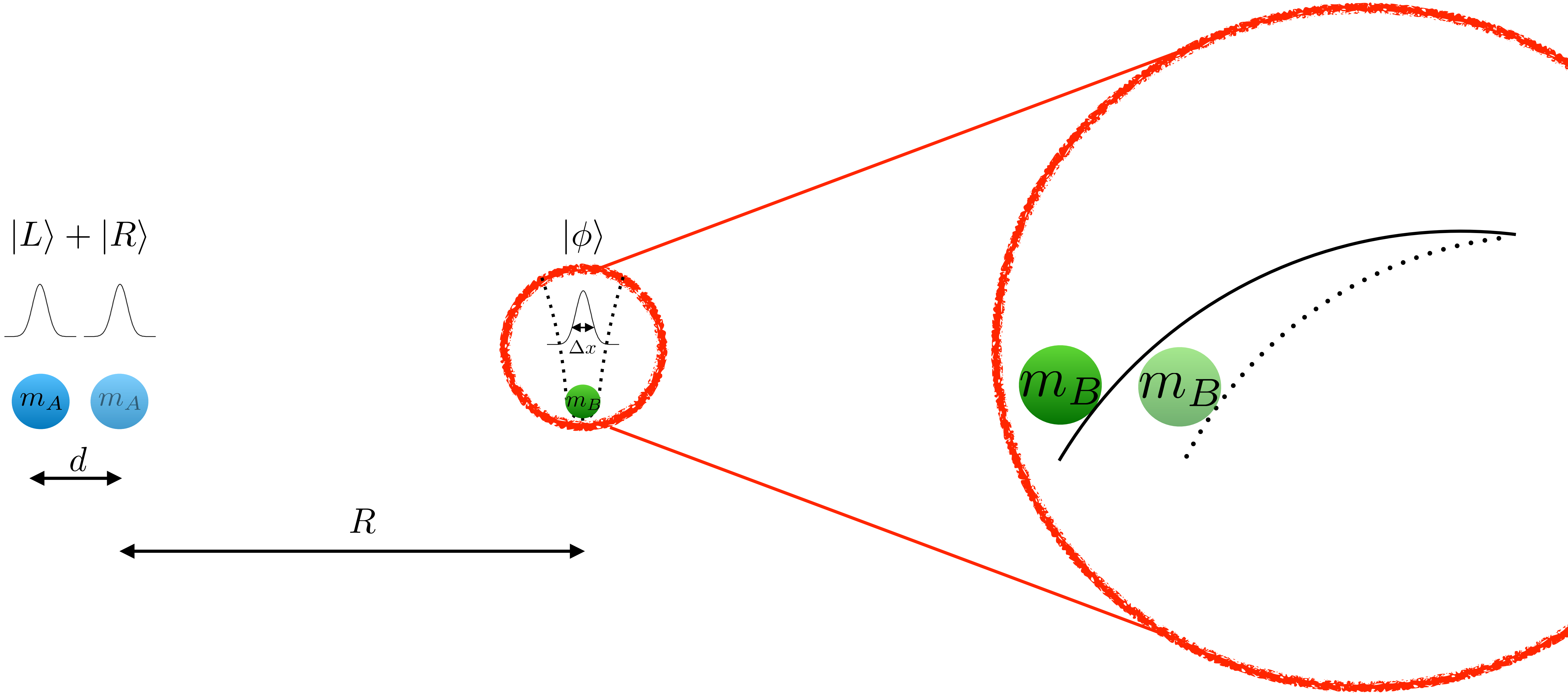

$$(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle) \otimes |\phi_B\rangle \to |L\rangle|\uparrow\rangle|\phi_B^L\rangle + |R\rangle|\downarrow\rangle|\phi_B^R\rangle$$

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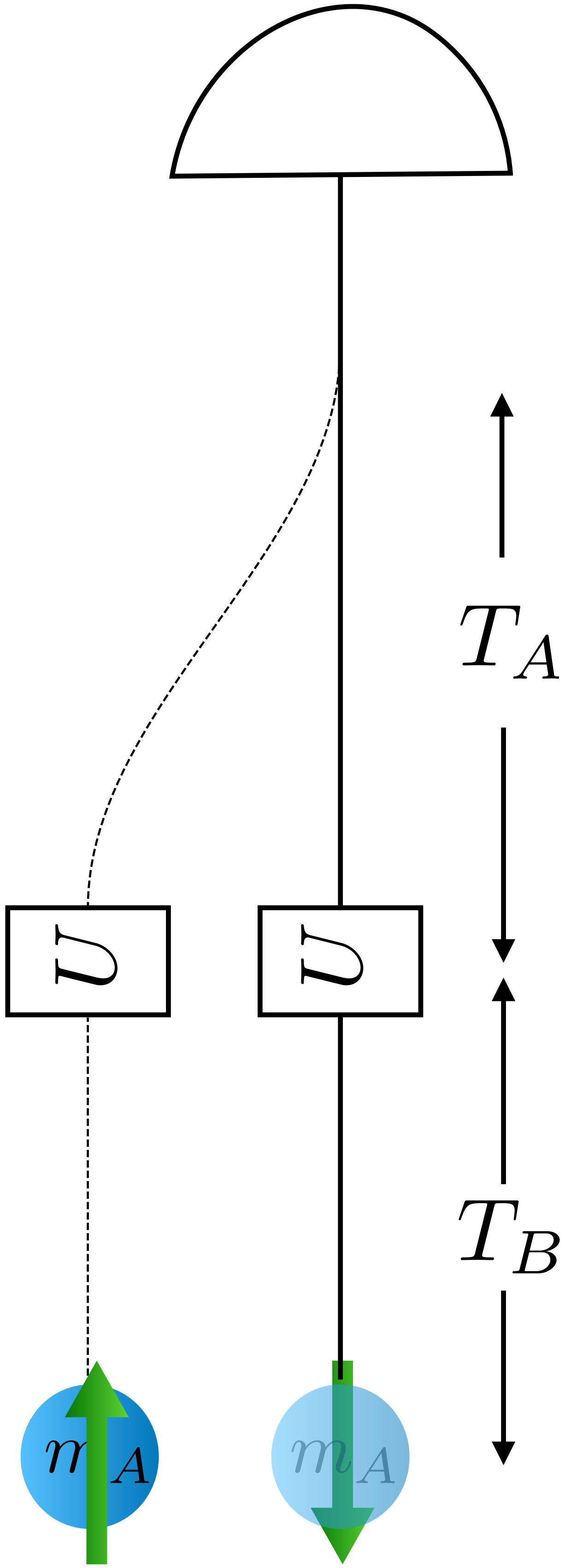


After a pre-established time is elapsed from the start of the protocol

$$|\langle \phi_R(t)|\phi_L(t)\rangle| \ll 1$$

$$|\phi_{L(R)}(t)\rangle = e^{-i\frac{\hat{H}_{L(R)}}{\hbar}t}|\phi\rangle \qquad \hat{H}_{L(R)} = \frac{\hat{P}^2}{2m_B} - F_{L(R)}\hat{X}$$

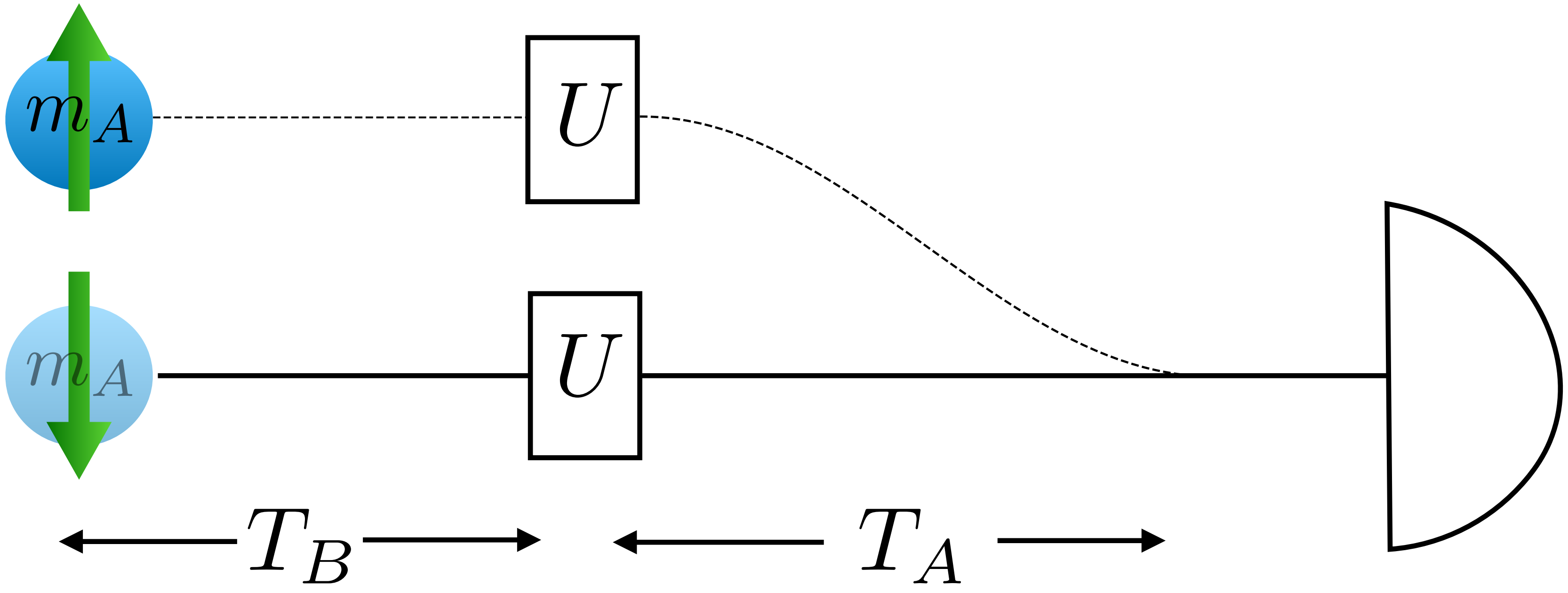
$$T_B^2 \approx \frac{\Delta x R^3}{G m_A d}$$

Alice wants to test the coherence of the state of her spin d.o.f.

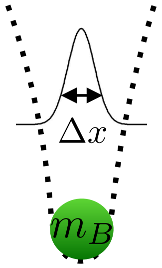
In order to do so, she closed the superposition by way of a spin-controlled unitary in a time T_A

Question: Is Alice able to infer the bit Bob encoded, by switching-off or not his trap, even if Bob is outside of her light-cone?

1st case: Bob does not release the trap

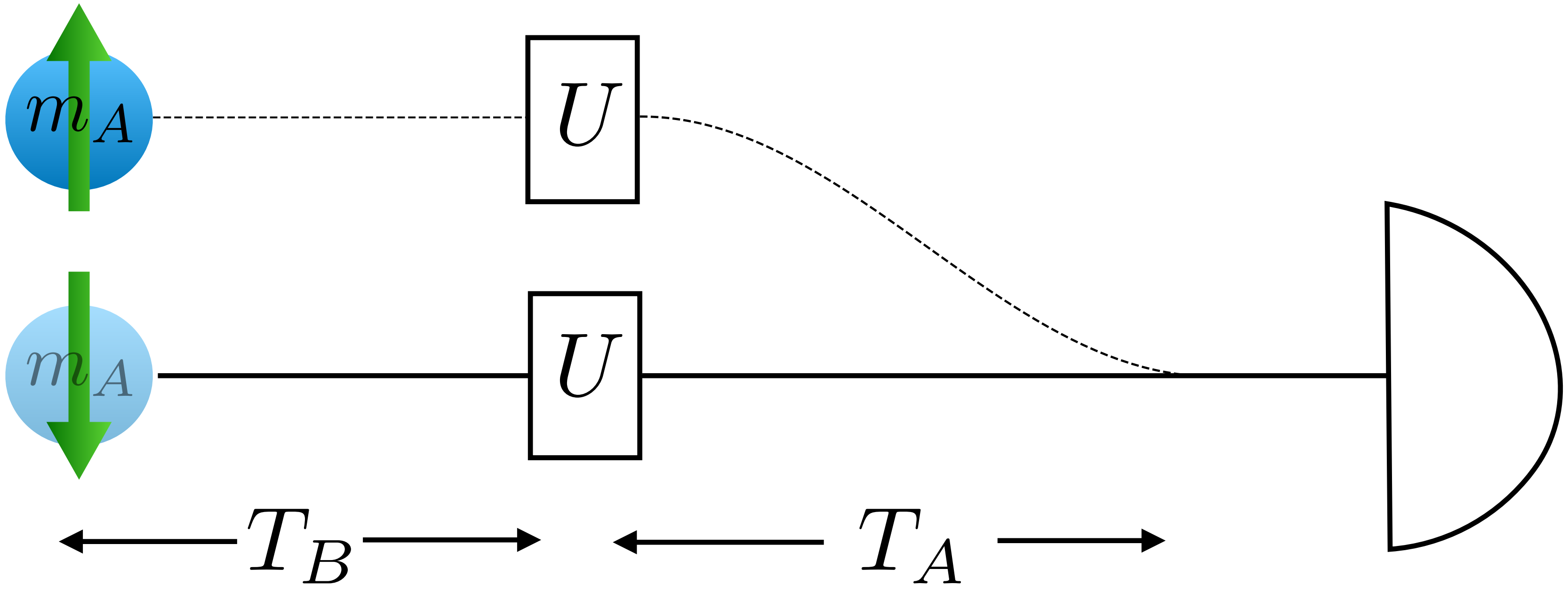


$$\rho_A = \frac{1}{2}|+\rangle\langle+|$$

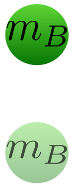


$$\frac{1}{\sqrt{2}}\left(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle\right)_A \otimes |\phi\rangle_B \;\to\; \frac{1}{\sqrt{2}}|R\rangle\left(|\uparrow\rangle + |\downarrow\rangle\right)_A \otimes |\phi\rangle_B$$

2nd case: Bob does release the trap



$$\rho_A = \frac{1}{2}\mathbb{I}$$



$$\frac{1}{\sqrt{2}}\left(|L\rangle|\uparrow\rangle_A|\phi_L\rangle_B + |R\rangle|\downarrow\rangle_A|\phi_R\rangle_B\right) \to \frac{1}{\sqrt{2}}|R\rangle\left(|\uparrow\rangle_A|\phi_L\rangle_B + |\downarrow\rangle_A|\phi_R\rangle_B\right)$$

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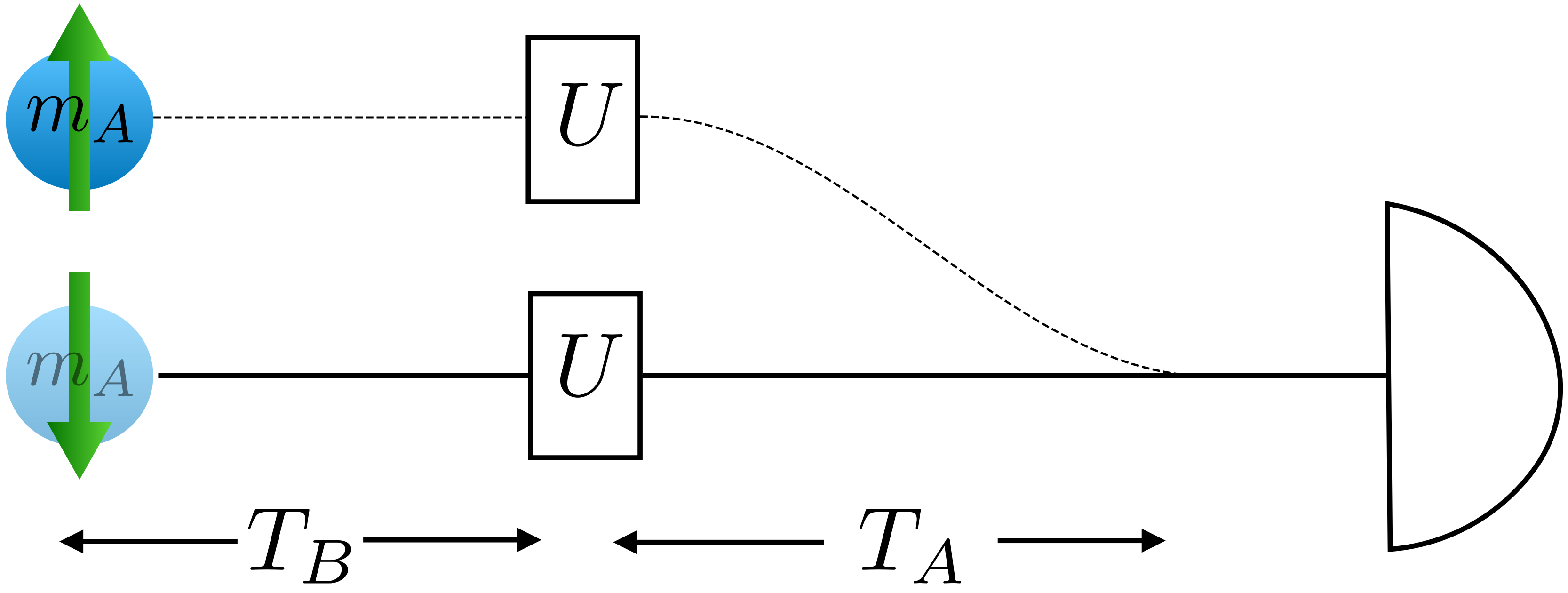
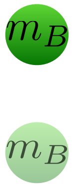


$$\rho_A = \frac{1}{2}\mathbb{I}$$



$$\frac{1}{\sqrt{2}}\left(|L\rangle|\uparrow\rangle_A|\phi_L\rangle_B + |R\rangle|\downarrow\rangle_A|\phi_R\rangle_B\right) \rightarrow \frac{1}{\sqrt{2}}|R\rangle\left(|\uparrow\rangle_A|\phi_L\rangle_B + |\downarrow\rangle_A|\phi_R\rangle_B\right)$$

It seems as if Alice could infer Bob action. However, if

$$T_B + T_A < R/c$$

we clash with causality since we would have superluminal signaling

Resolution in e.m.: photons must exist

Worst case scenario:

Bob's particle is maximally localized at the charge radius $\Longrightarrow$ shorter time needed for entanglement

Further, we optimize the parameters in order to have the maximum T_A consistent with causality, i.e.,

$$T_B + T_A \geq R/c$$

$$T_A \approx \frac{q}{q_P}\frac{d}{c}$$

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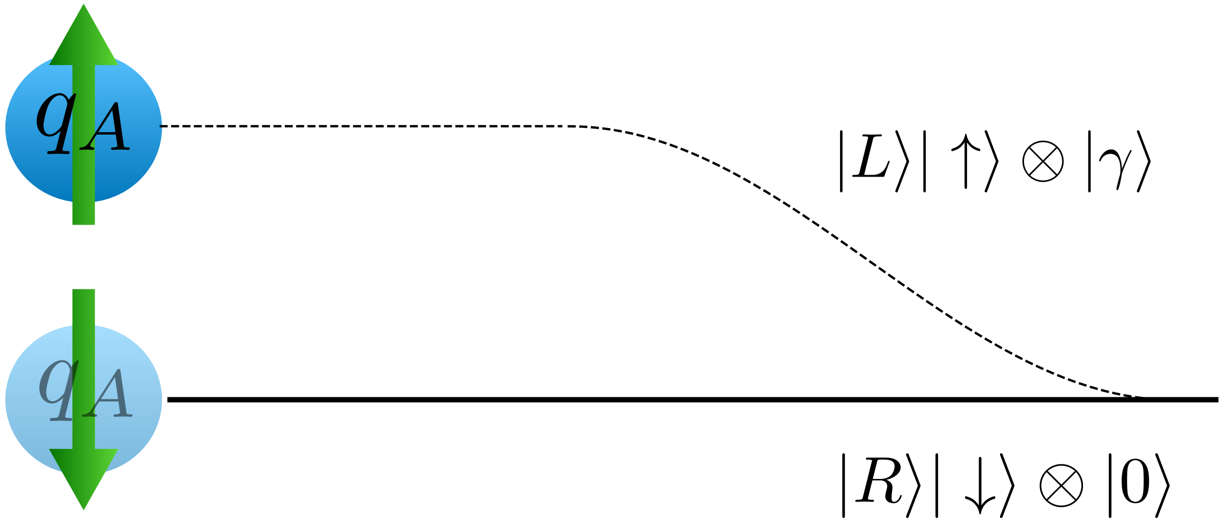
Why cannot we close the superposition faster?

The answer is that you can, but you will radiate and entangled the charge with the radiation emitted which will lead to decoherence of Alice's spin d.o.f. reduced state



$$t^*_{em} \approx \frac{q_A}{q_P}\frac{d}{c}$$

De Palma, Giovannetti, Mari; Scientific Reports 6, 22777 (2016)

What's different about gravity:

Worst case scenario:

Bob's particle is maximally localized at the Planck length $\Rightarrow$ shorter time needed for entanglement

Further, we optimize the parameters in order to have the maximum T_A consistent with causality, i.e.,

$$T_B + T_A \geq R/c$$

$$T_A \approx \frac{m_A}{m_P}\frac{d}{c}$$

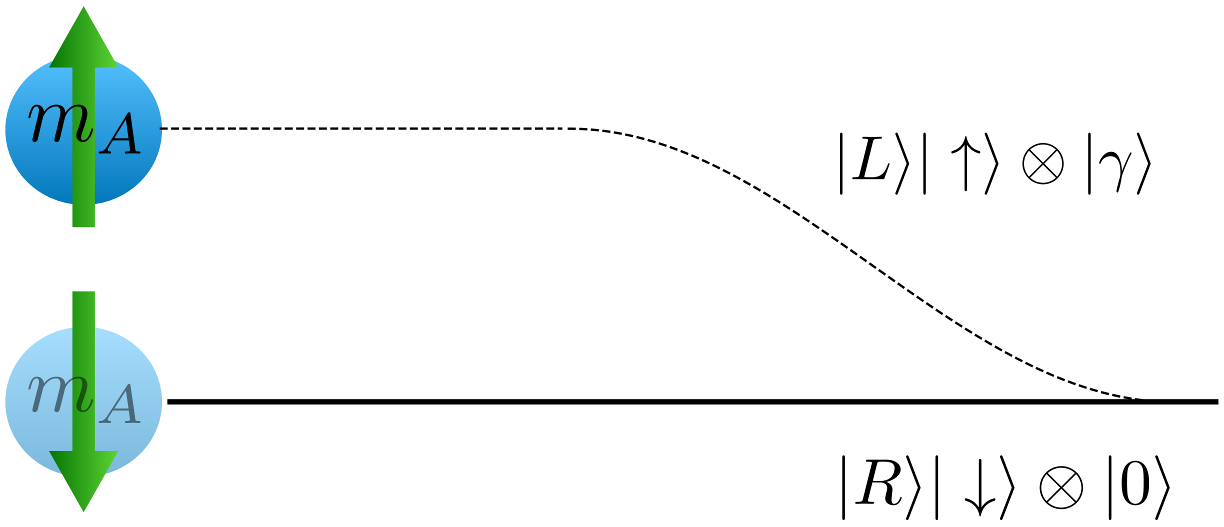
In our set-up, closing Alice's superposition faster than this time leads to superluminal signaling if no other physical effects comes into play in order to prevent it

Why cannot we close the superposition faster?

The answer is that you can, but you will radiate and entangled the charge with the radiation emitted which will lead to decoherence of Alice's spin d.o.f. reduced state

Still true, however in this case the characteristic time for decoherence is less than

$$t_g^* \approx \sqrt{\frac{m_A}{m_P}\frac{d}{c}}$$



What's different about gravity:

Linearized gravity Hamiltonian

$$H = H_0 + \kappa V + \sum_r \int \frac{d^3k}{(2\pi)^3} \omega_k b_r^\dagger(k) b_r(k)$$
$$- \sqrt{\frac{\kappa\hbar}{2}} \sum_r \int \frac{d^3k}{(2\pi)^3\sqrt{2\omega_k}} \left[b_r^\dagger(k) J_r(k) + b_r(k) J_r^\dagger(k)\right]$$

Source matter current

$$J_r(k) = L_{ij}^r(k) \int d^3x e^{-ikx} T^{ij}(x),$$

TT polarization matrices

$$U(T,0) = \mathcal{D}[\alpha(T)] = \exp\left\{\sum_r \int \frac{d^3k}{(2\pi)^3} \left(f_r(k) b_r^\dagger(k) - f_r^*(k) b_r(k)\right)\right\}$$

Displacement operator

$$f_r(k) = \sqrt{\frac{\kappa\hbar}{2}} \frac{i}{\sqrt{\omega\hbar}} \int_0^T dt' J_r(k,t') e^{-i\omega t'}$$

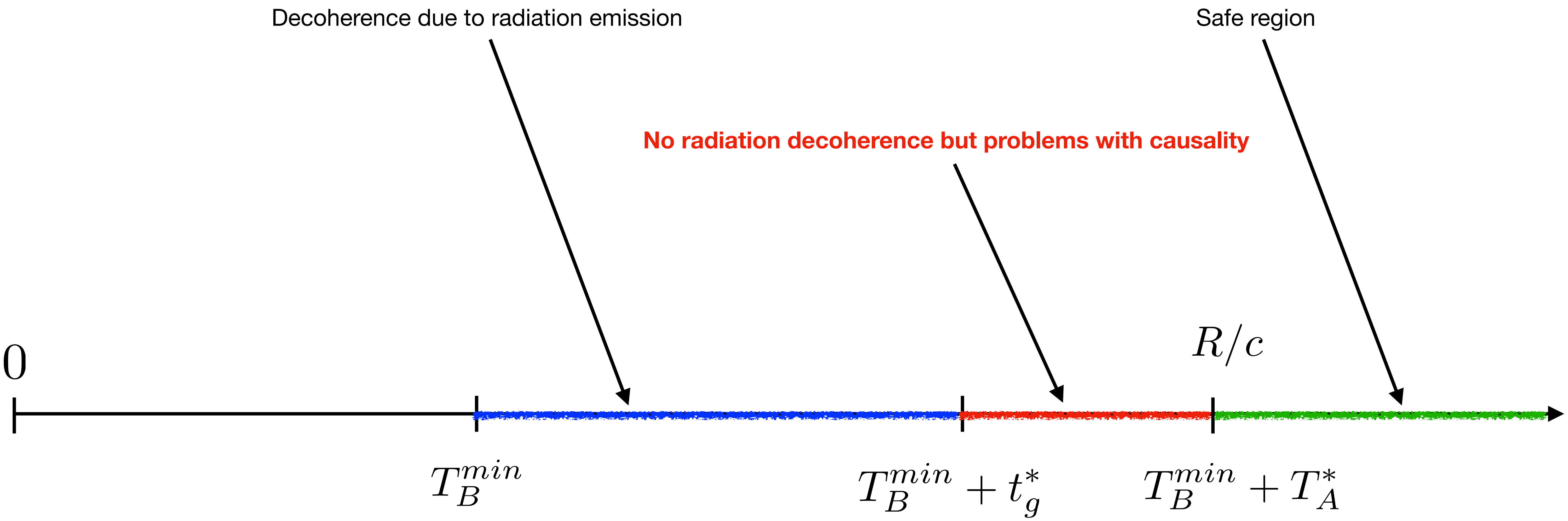
$$|\langle 0|f\rangle|^2 = \exp\left(-\frac{4Gm^2}{c^4\pi^2} \int d^3k \frac{1}{kc} \sum_r |L_{ij}^r g^{ij}(\omega)|^2\right)$$
$$= \exp\left(-\xi/t^4\right) \longleftrightarrow$$

E.m. case:

$$\exp\left(-a\, q^2/t^2\right)$$

$$t_g^* \approx \sqrt{\frac{m_A}{m_P} \frac{d}{c}}$$

What's different about gravity:



Decoherence due to radiation emission

No radiation decoherence but problems with causality

Safe region

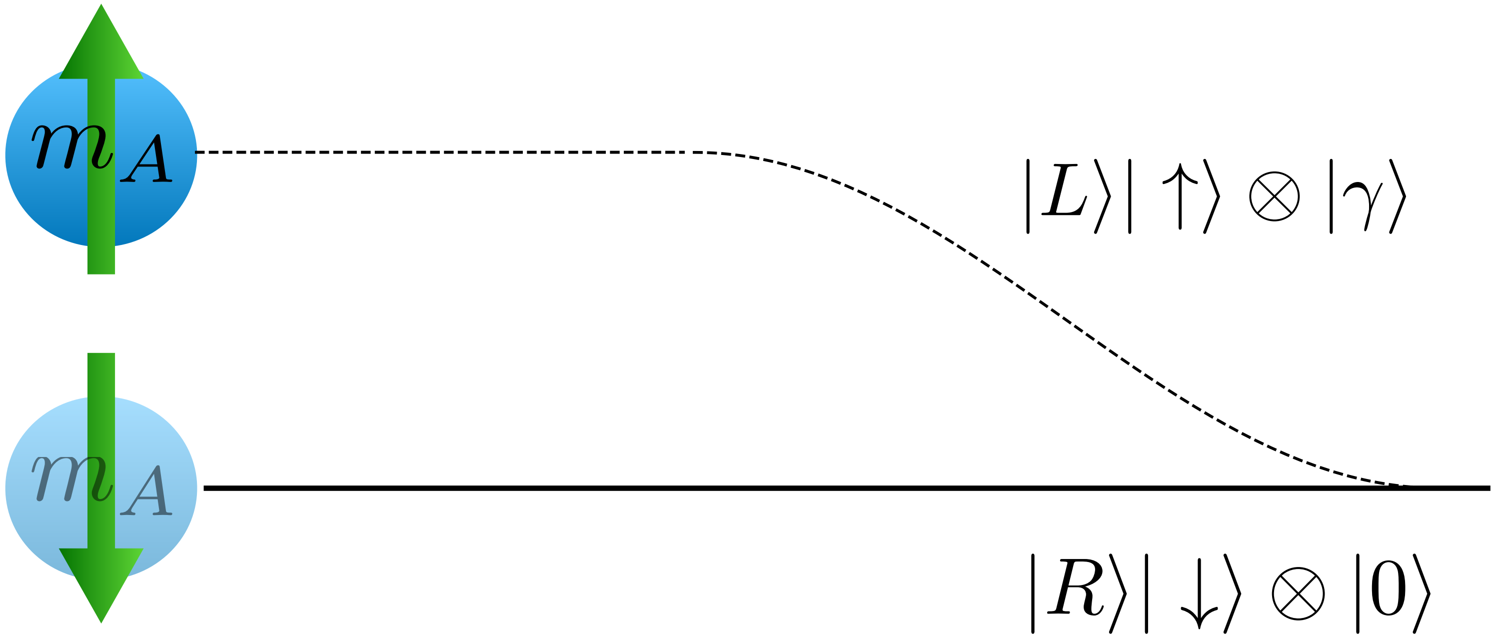
0

R/c

T_B^{min}

$T_B^{min} + t_g^*$

$T_B^{min} + T_A^*$



$|L\rangle|\uparrow\rangle \otimes |\gamma\rangle$

$|R\rangle|\downarrow\rangle \otimes |0\rangle$

$$t_g^* \approx \sqrt{\frac{m_A}{m_P}}\,\frac{d}{c}$$

Discussion:

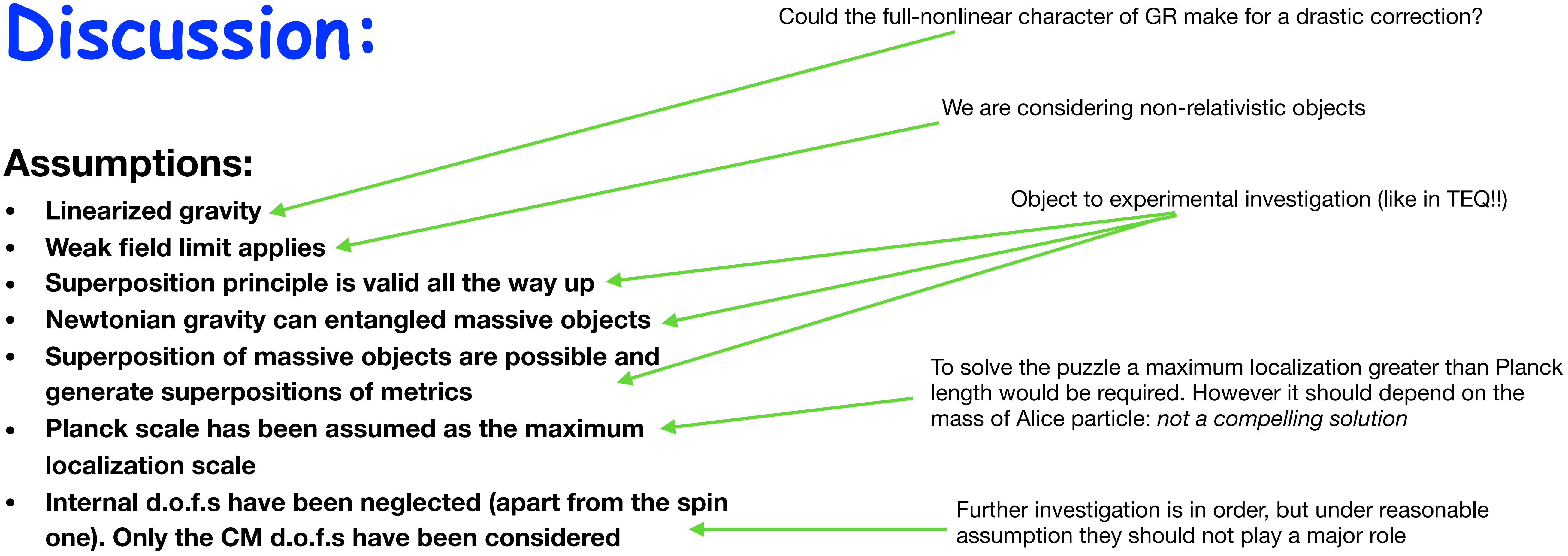
Assumptions:

- Linearized gravity
- Weak field limit applies
- Superposition principle is valid all the way up
- Newtonian gravity can entangled massive objects
- Superposition of massive objects are possible and generate superpositions of metrics
- Planck scale has been assumed as the maximum localization scale
- Internal d.o.f.s have been neglected (apart from the spin one). Only the CM d.o.f.s have been considered

Some possible solutions:

- Gravitational collapse model ? Note that the conundrum arises only for objects of mass greater than Planck mass
- Additional d.o.f.s not considered which can be a further decoherence channel?
- Information capacity of longitudinal d.o.f.s?

Discussion:



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Could the full-nonlinear character of GR make for a drastic correction?

We are considering non-relativistic objects

Object to experimental investigation (like in TEQ!!)

To solve the puzzle a maximum localization greater than Planck length would be required. However it should depend on the mass of Alice particle: *not a compelling solution*

Further investigation is in order, but under reasonable assumption they should not play a major role

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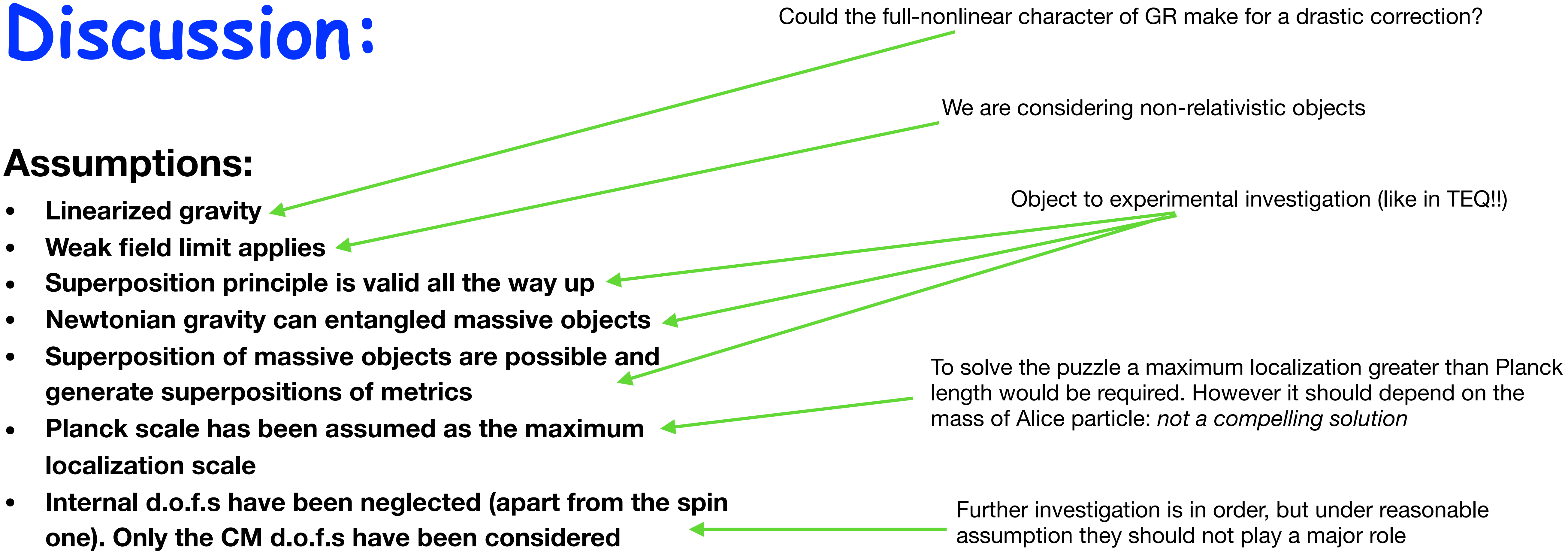

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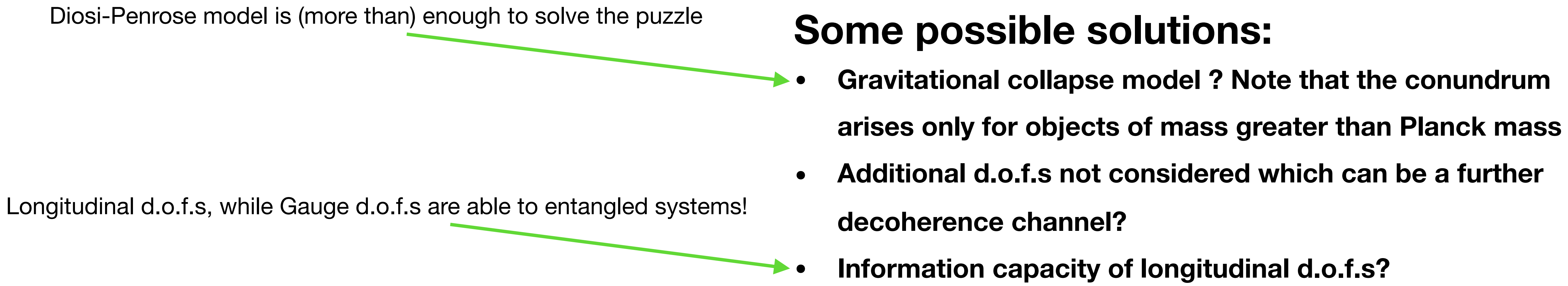

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Diosi-Penrose model is (more than) enough to solve the puzzle

Longitudinal d.o.f.s, while Gauge d.o.f.s are able to entangled systems!


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
spas
mersi
kia ora
barka
welalin
tack
mahalo
tapadh leat
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
thank you
gracias
хвала
kiitos
dankie
nanni
nandri
dhanyavad
mauruuru
köszönöm
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gràcie
hvala
akun
dankon
aciu
djiere dieuf
tau
mochchakkeram
murakoze
enkosi
дякую
mamnun
chokrane
dziękuję
chnorakaloutioun
gratias ago
gràcies
sulpáy
go raibh maith agat
sobodi
dëkuji
obrigado
sagolun
sukriya
kop khun krap
taiku
arigatô
takk
dakujem
trugarez
mèsi
didi madloba
ありがとう
najis tuke
tanemirt
grazie
rahmet
terima kasih
kam sah hamnida
rahmat
diolch
dhanyavadagalu
shukriya
merce
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
ευχαριστώ
merci

TEQ trap design issues

Michael Drewsen
Department of Physics and Astronomy
Aarhus University
Denmark

TEQ Kick-off meeting, February 2, 2018
Trieste, Italy

TEQ trap design issues

I) Potential physical layout

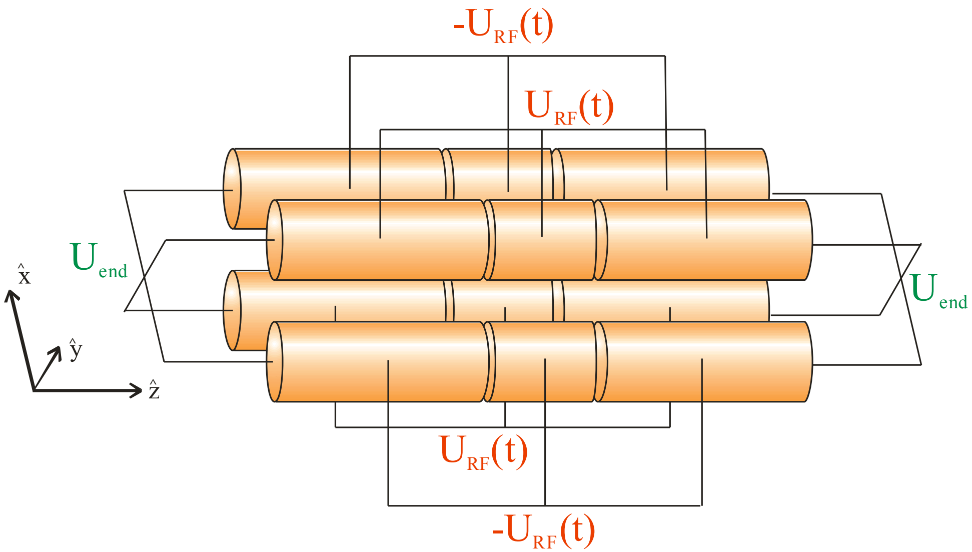
II) Requirements and limitations

III) Existing ion trap as test-bed for low-noise electronics

IV) Unresolved issues

I) Potential physical layout

The linear Paul trap



Sinusoidal RF potential: $U_{RF}(t)=U_{RF}\sin(\Omega t)$

Effective oscillation freq.'s:

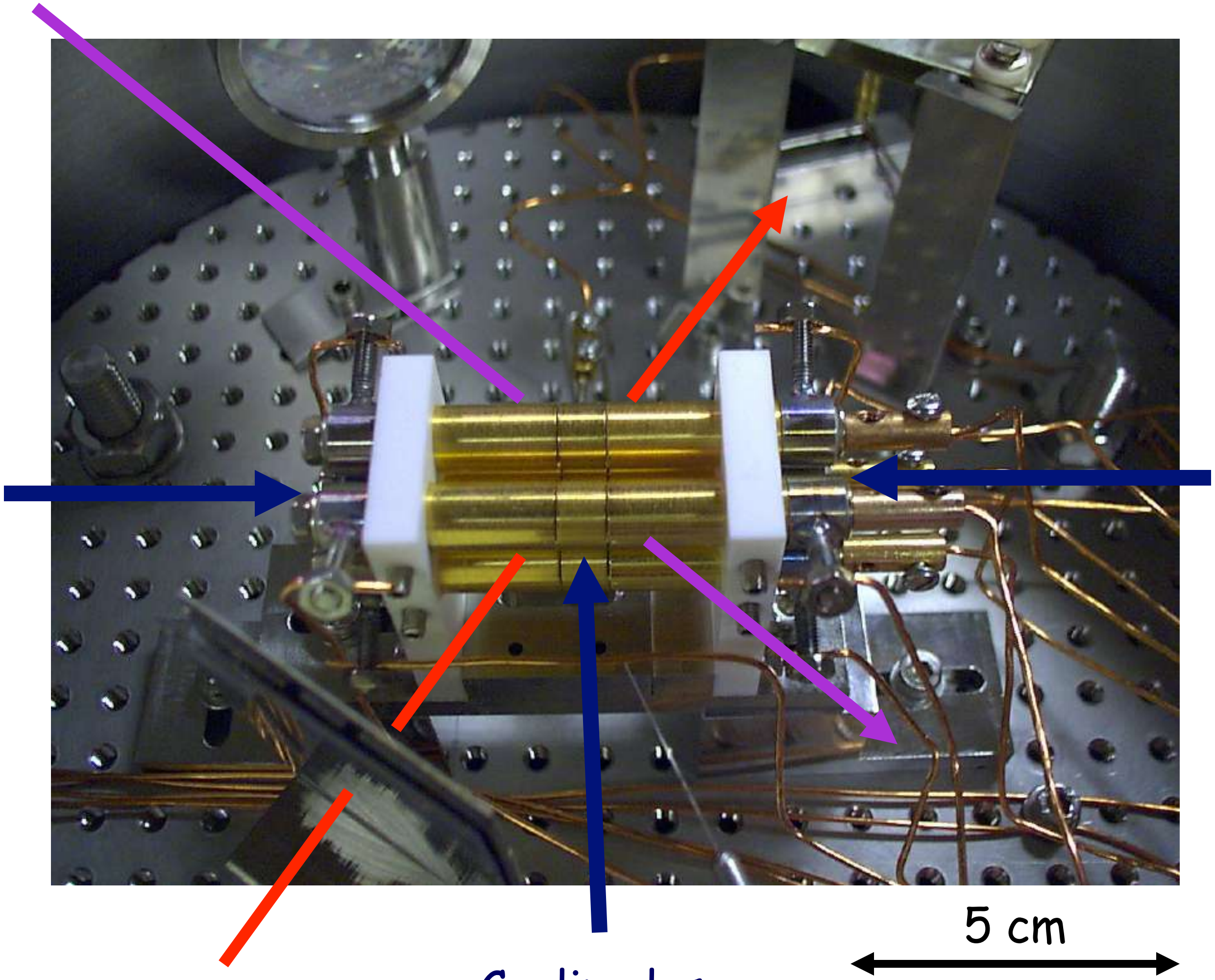
$\omega_r=1/2\,\beta\,\Omega\,,\quad \beta=(1/2\,q^2+a)^{1/2}$

$\omega_z=(-1/2\,a)^{1/2}\Omega$

$$q=\frac{4QU_{RF}}{m\Omega^2 r_0^{\ 2}}\qquad a=-\frac{\alpha Q U_{end}}{m\Omega^2 r_0^{\ 2}}$$

The Aarhus linear Paul trap

Photo-ionizing laser



Cooling laser

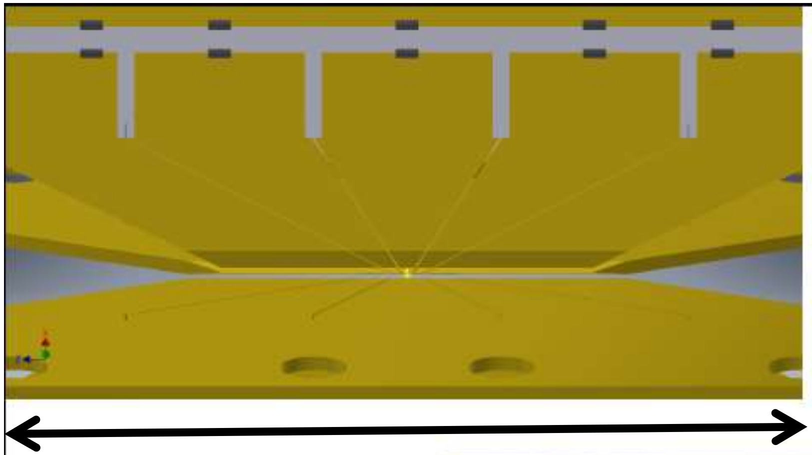
Cooling laser

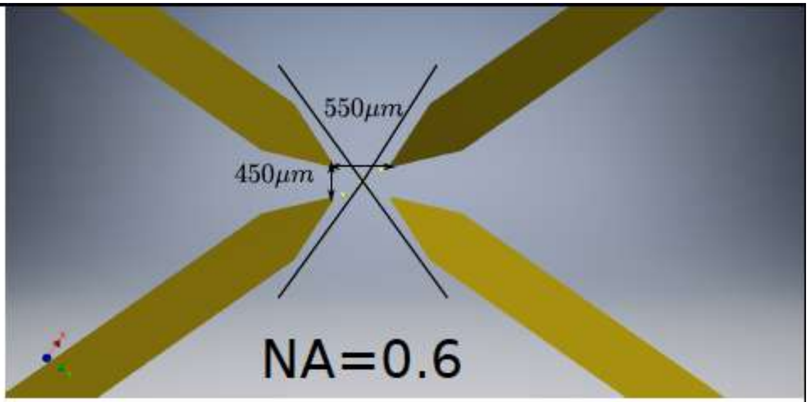
5 cm

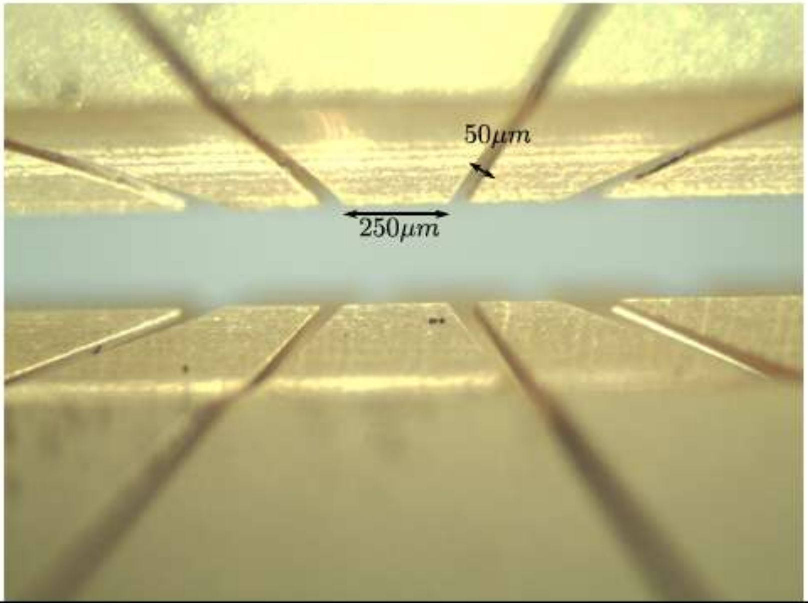
Atomic beam

Cooling laser

Linear rf trap
constructed by Shuoming An, Tsinghua University



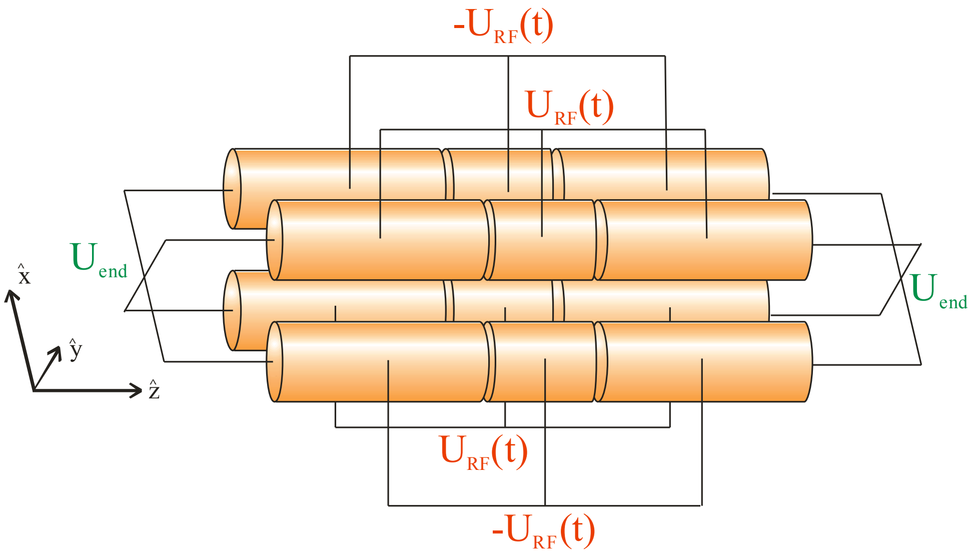




Mat.:
Gold on
Alumina

Design: Chris Monroe’s group

The linear Paul trap



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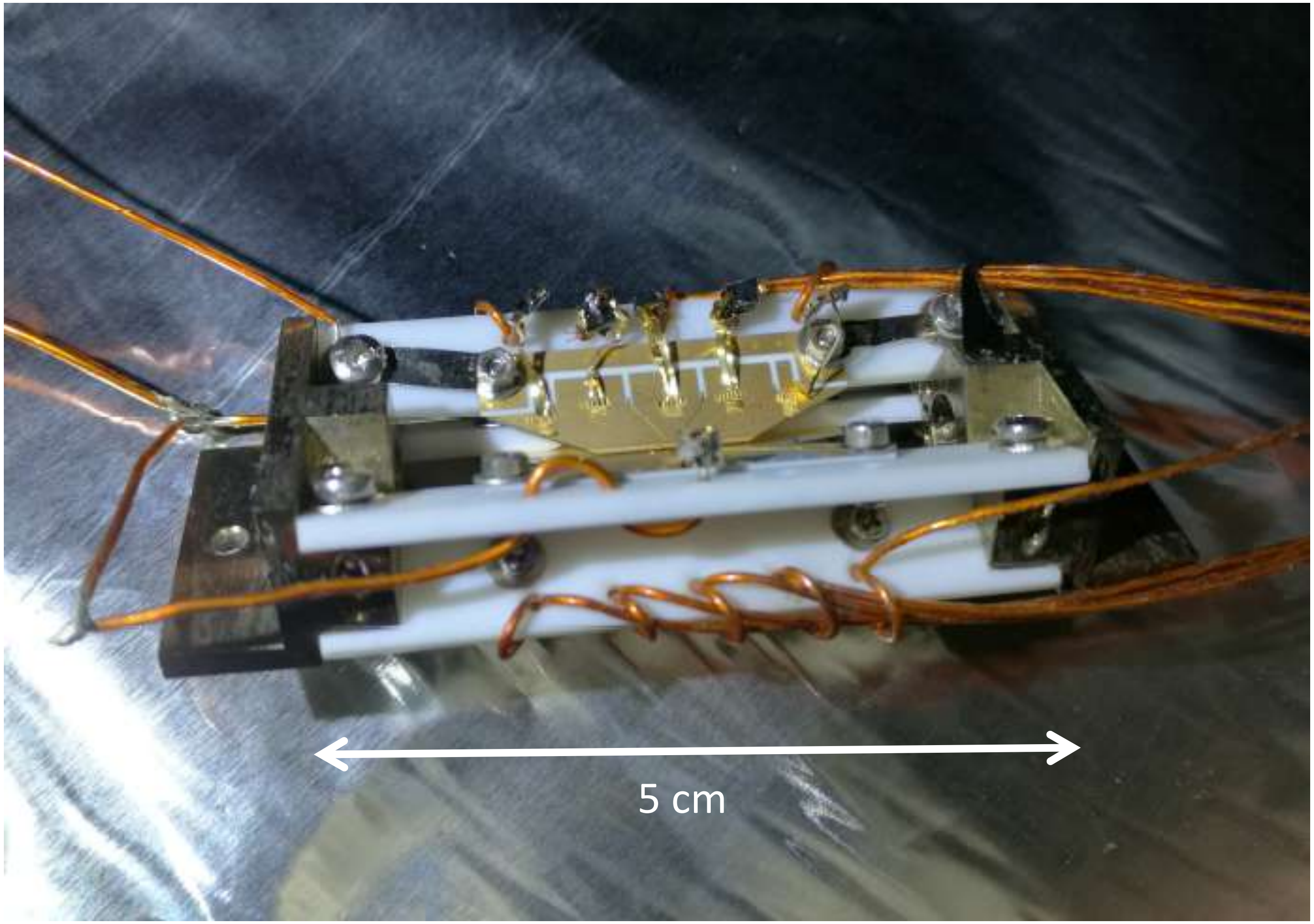
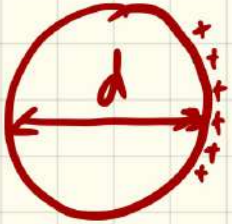
Small-scale linear rf trap
constructed by Shuoming An, Tsinghua Uni.



II) Requirements and limitations

ISSUES REGARDING THE TRAP DESIGN

PARAMETERS RELATED TO PARTICLES:



Q CHARGES

(1)

$$\boxed{\begin{array}{l} Q = 10 - 10^4 e \ (!?) \\ m = 2.6 \cdot 10^{-18}\,\mathrm{kg} \end{array}}$$

$d = 100\,\mathrm{nm}$, $\rho = 5\,\mathrm{g/cm^3}$ $\Rightarrow$ $m = 2.6 \cdot 10^{-18}\,\mathrm{kg}$

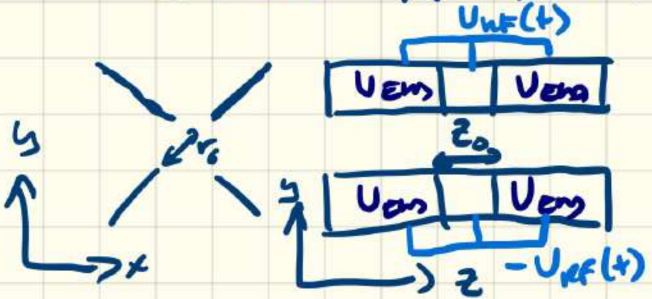
REQUIREMENTS TO EFFECTIVE TRAP FREQUENCIES:

AXIAL: $\omega_z = 2\pi \times (100 - 1000)\,\mathrm{Hz}$

RADIAL: $\omega_r \geq \omega_z$

(2)

LINEAR RF TRAP:



$r_0 \simeq z_0 \simeq 0.5\,\mathrm{mm}$, $\kappa \sim 0.25$

$$\omega_z = \sqrt{\frac{2\kappa U_{END}}{z_0^2} \times \frac{Q}{m}} \xRightarrow{(1+2)} U_{END} = 0.3 - 30\,\mathrm{V}$$

OK!

RADIAL FREQUENCY:

$$(*) \quad \omega_r^2 = \frac{q^2}{8}\Omega^2 - \frac{1}{2}\omega_z^2 \quad , \quad U_{RF}(t) = U_{RF}\cos(\Omega t)$$

$$(**) \quad q = \frac{2U_{RF}}{r_0^2\,\Omega^2} \times \frac{Q}{m}$$

STABLE MOTION: $q \in [0; 0.9]$

SAY $\omega_r = 2\omega_z$

$$(*) \Rightarrow \quad 4\tfrac{1}{2}\,\omega_z^2 = \frac{q^2}{8}\Omega^2$$

$$q = 0.1 \Rightarrow \quad \Omega = 60\,\omega_z$$

$Q = 10$:

$$\omega_z = 2\pi \times 100\,\text{Hz} \Rightarrow \Omega = 2\pi \times 6\,\text{kHz} \overset{(**)}{\Longrightarrow} U_{RF} = 29\,\text{V} \quad \text{OK!}$$

$$\omega_z = 2\pi \times 1000\,\text{Hz} \Rightarrow \Omega = 2\pi \times 60\,\text{kHz} \overset{(**)}{\Longrightarrow} U_{RF} = 2.9\,\text{kV} \quad ↯$$

BUT IF $Q \gtrsim 100$ OK!

WHAT ABOUT HEAT LOAD?

AT THE LOWEST TEMPERATURE (~20mK) THE CRYOSTATE HAS A COOLING POWER OF ONLY ~50 μW!

POWER DISSIPATED BY DRIVING THE TRAP

RESISTIVITY OF LEAD AND ELECTRODE MATERIAL

$$\text{Cu}: \quad \rho_{Cu} = 10^{-11}\,\Omega\text{m}$$

$$\text{Au}: \quad \rho_{Au} = 10^{-10}\,\Omega\text{m} \qquad @\ T \sim 1\,\text{K}$$

CROSS-SECTION OF WIRES + ELECTRODES

$$A_{wire} \simeq \pi \times (100\,\mu\text{m})^2 \approx A_{elec.} \simeq 10\,\mu\text{m} \times 3000\,\mu\text{m} \simeq 3 \times 10^{-8}\,\text{m}^2$$

IF LEAD WIRES HAS A LENGTH OF $l = 20\text{ cm} = 0.2$

$\Rightarrow$
CALCULATING
$$R_{WIRE} = 6.7 \cdot 10^{-5}\ \Omega$$

$$R_{ELECTRODE} = 3 \cdot 10^{-5}\ \Omega$$

$l \sim 0.01\text{ m}$

$$\Rightarrow \quad \boxed{R_{TOT} = 20 \times (R_{WIRE} + R_{ELE.}) \simeq 2\text{ m}\Omega.} \quad (4)$$

ASSUME CAPACITANCE OF ALL ELECTRODES + WIRE TO BE $C_{TOT} = 200\text{ pF}$

INSTANT CURRENT TO A ELECTRODE:

$$U_{RF}(t) = \frac{q(t)}{C_{TOT}} \Rightarrow \frac{dU_{RF}}{dt} = \Omega U_{RF}(t) = \frac{i(t)}{C_{TOT}}$$

$$\Rightarrow \quad i(t) = C_{TOT}\Omega U_{RF}(t)$$

THEN THE TOTAL MEAN ELECTRICAL POWER DISSIPATED IS

$$\overline{P_{TOT}} = R_{TOT} \cdot \overline{i^2(t)}$$

$$= \frac{1}{2} R_{TOT} \cdot C_{TOT}^2 \cdot \Omega^2 \cdot U_{RF}^2$$

FOR $\Omega = 2\pi \times 30\,kHz$ AND $U_{RF} \hat{=} 300\,V$, ONE GETS

$$\boxed{\overline{P_{TOT}} = 1.3 \cdot 10^{-7}\,W = 0.1\,\mu W \ll P_{CRYO} \approx 50\,\mu W} \tag{5}$$

GREAT!

ANY PROBLEM WITH FINITE HEAT TRANSPORT FROM TRAP/WIRES TO CRYO-HEAD?

ESTIMATE OF TEMPERATURE DIFF. ΔT BETWEEN TRAP AND CRYO-HEAD:

LET'S ASSUME $l = 5\,\mathrm{cm}$ AS THE DISTANCE FROM THE TRAP TO CRYO_HEAD, AND AN AVERAGED CROSS-SECTION BE $A = 0{,}2\,\mathrm{cm} \times 0.5\,\mathrm{cm} = 0.1\,\mathrm{cm}^2$

USING SHAPAL™ AS INSULATOR AND COPPER AS MAIN SUPPORT, A CONSERVATIVE ESTIMATE OF THE HEAT CONDUCTIVITY IS: $\rho_{\mathrm{heat}} = 1\,\mathrm{W \cdot cm^{-1} \cdot K^{-1}}$

SINCE $P_{\mathrm{cryo}} \gg \overline{P}_{\mathrm{tot}}$ WE GET

(C) $$\boxed{\frac{A}{l}\rho_{\mathrm{heat}}\,\Delta T = \overline{P}_{\mathrm{tot}} \Rightarrow \Delta T \simeq 6.5\,\mu\mathrm{K}.}$$

GREAT JOB!

ESTIMATE OF HEAT LOAD FROM WIRES
GOING FROM 4K → 20 mK

USING $\rho_{HEAT} = 10\ W\,cm^{-1}\,K^{-1}$ FOR COPPER

A WIRE LENGTH OF $\ell = 0.2\,m$ AND $A_{WIRE} = 3\cdot 10^{-8}\,m^{2}$

AS EARLIER, WE GET

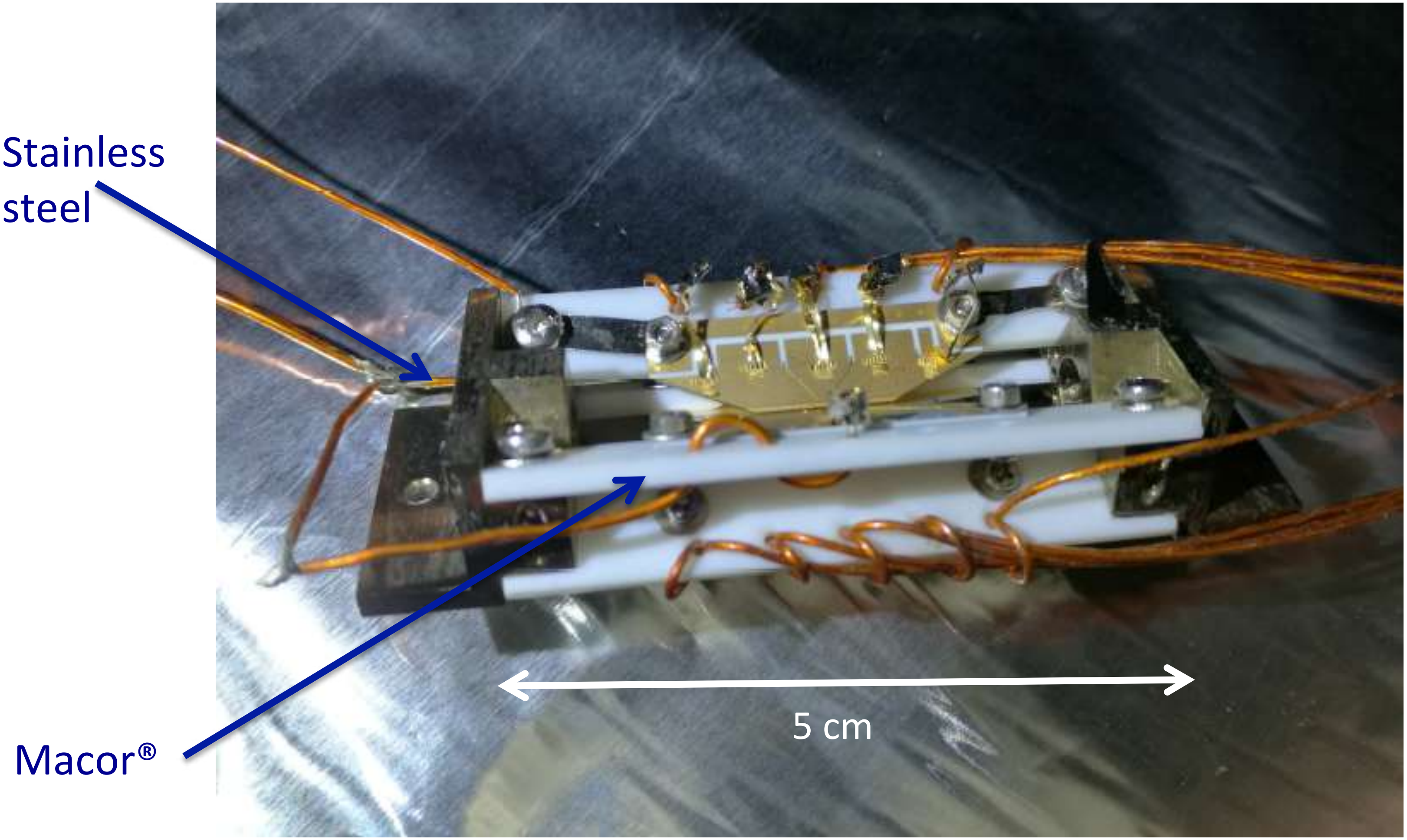
$$P_{4K,WIRE} = \frac{A}{\ell}\,\rho_{HEAT}\cdot\Delta T \quad , \Delta T = 4K$$

$$\Downarrow$$

$$P_{4K,WIRE} = 6\,\mu W \Rightarrow \boxed{P^{TOT}_{4K,WIRE} \simeq 100\,\mu W \sim P_{CRYO}}$$

HOWEVER, WE CAN EASILY DECREASE $\frac{A}{\ell}$ BY A FACTOR OF 10, WITHOUT PROBLEMS WITH ELECTRICAL HEATING, SO THIS IS FINE TOO

Small-scale linear rf trap
constructed by Shuoming An, Tsinghua Uni.



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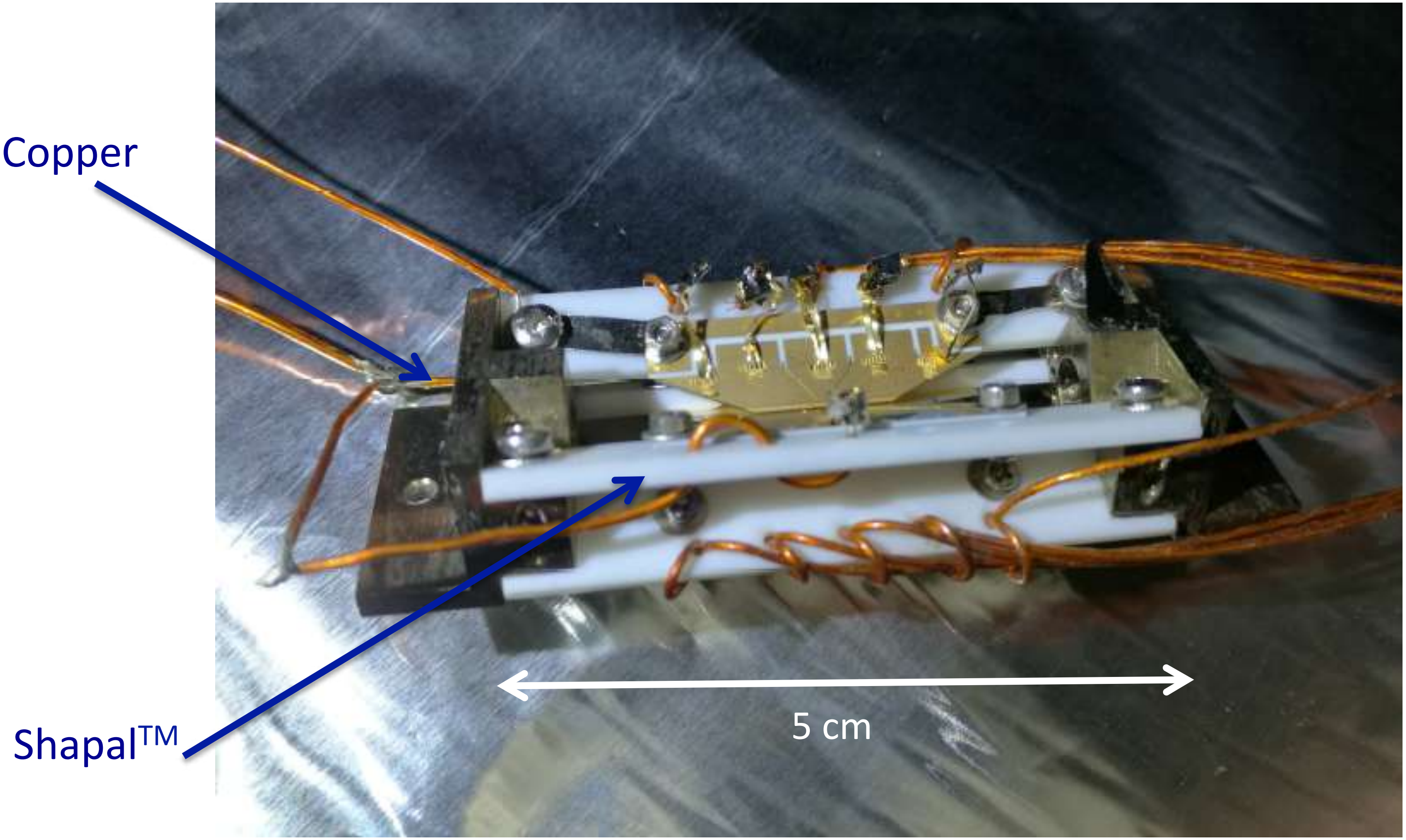
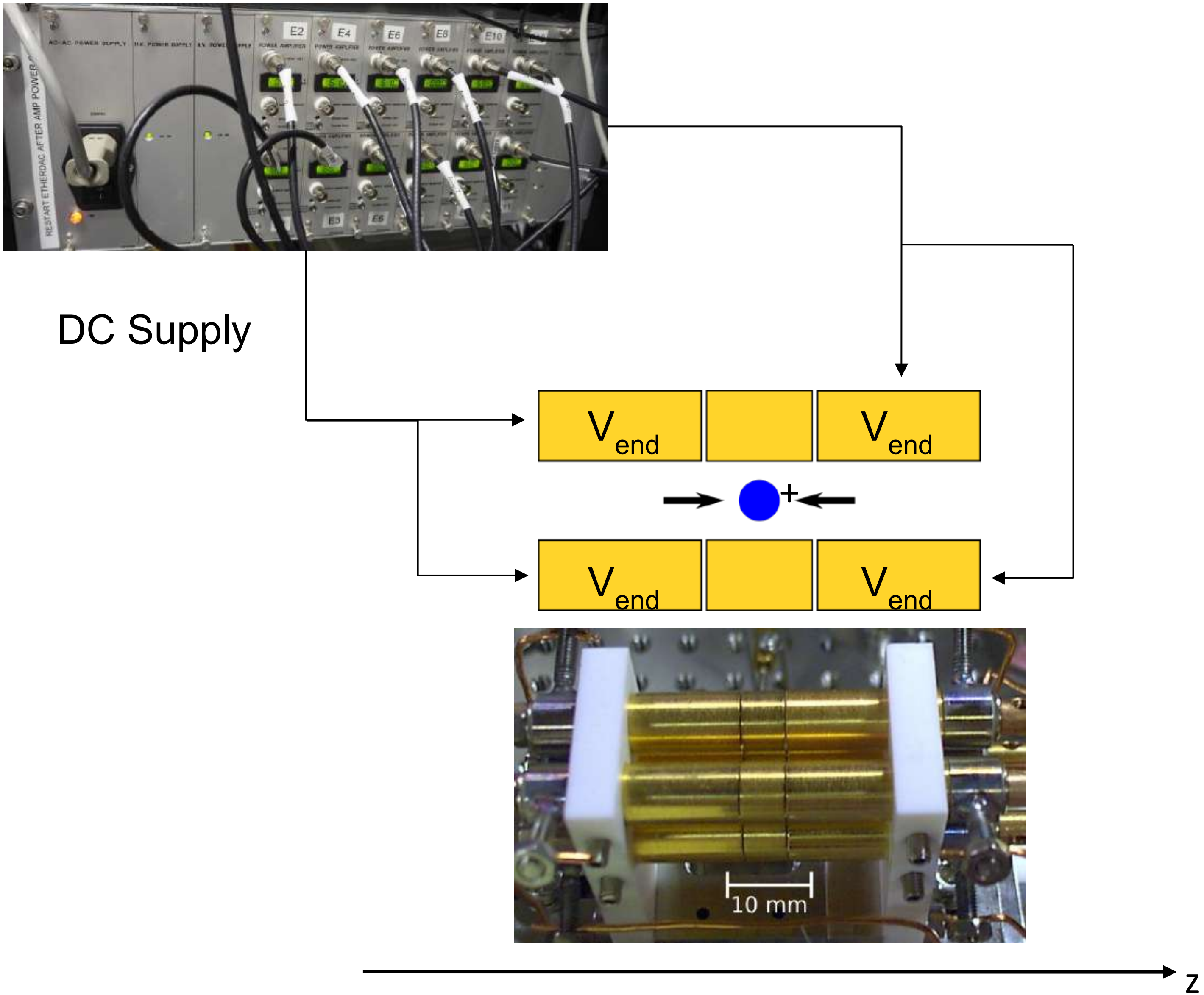


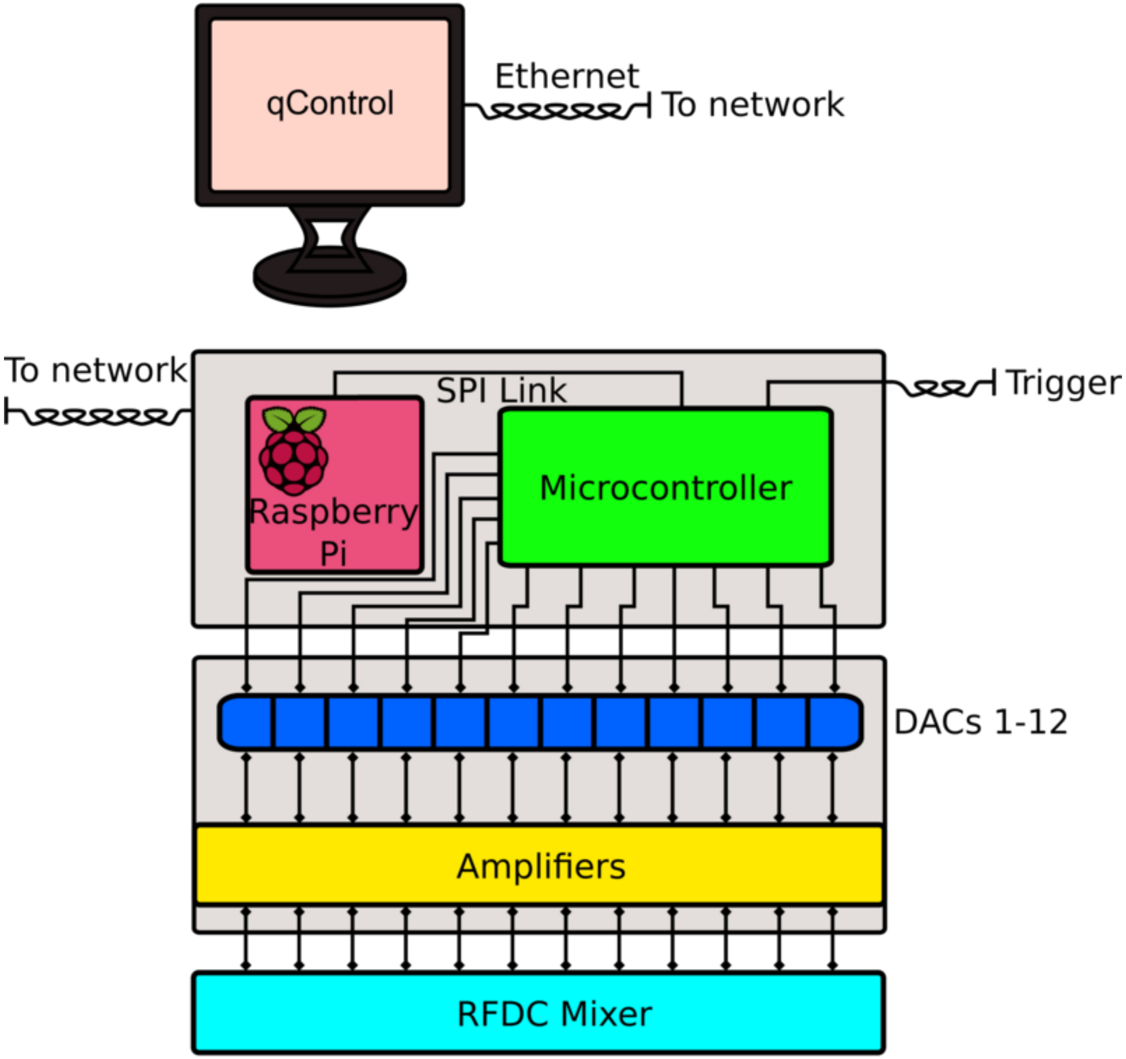
III) Existing ion trap as test-bed for low-noise electronics

Past DC supply noise-tests



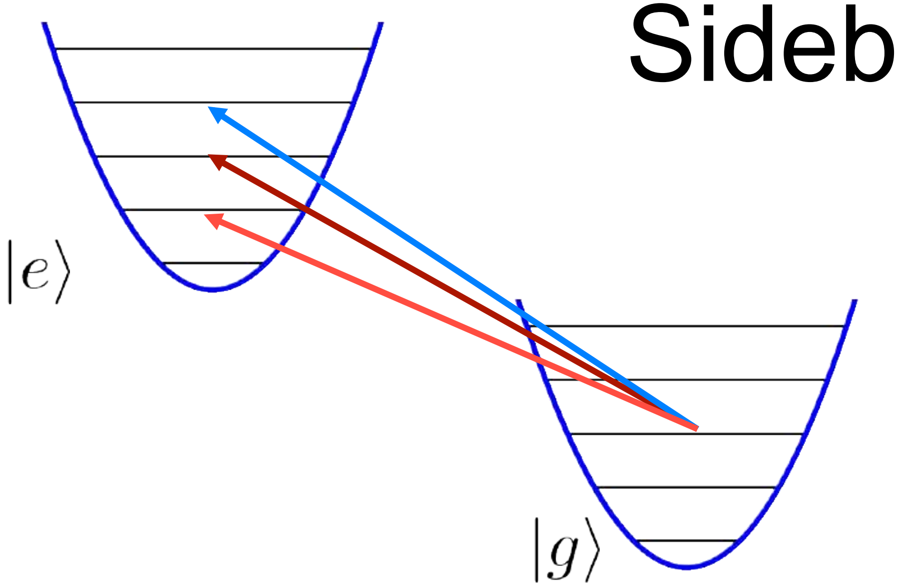
DC Supply

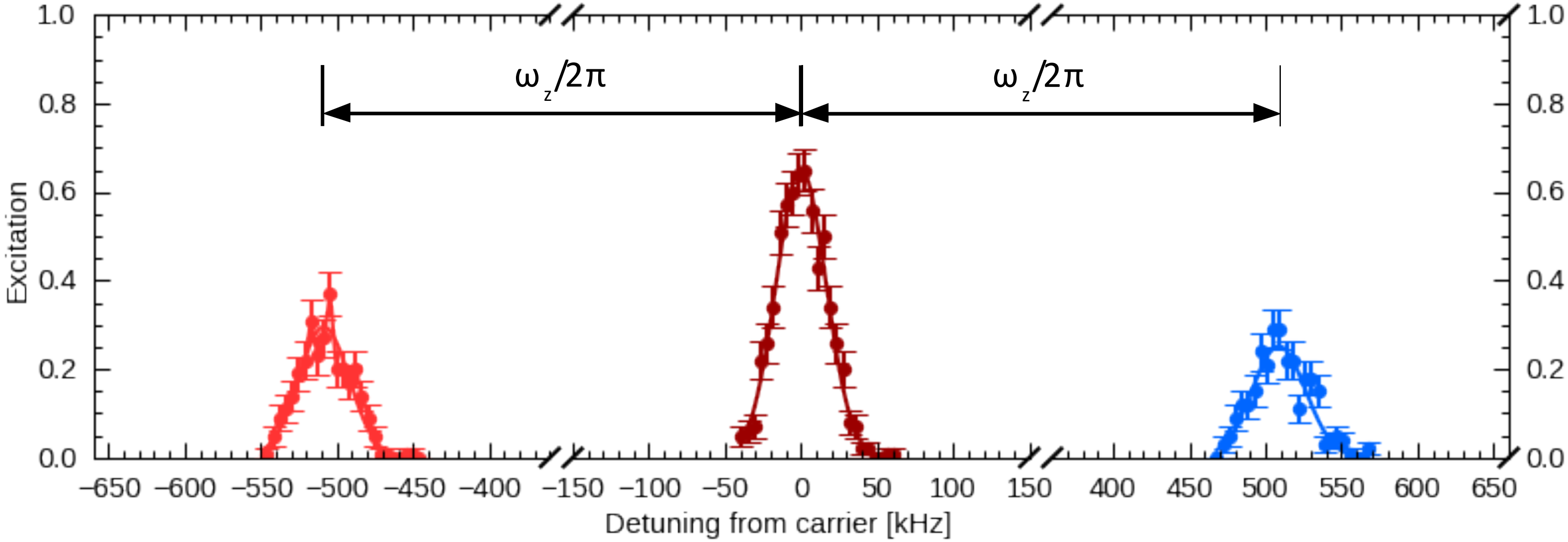
DC supply



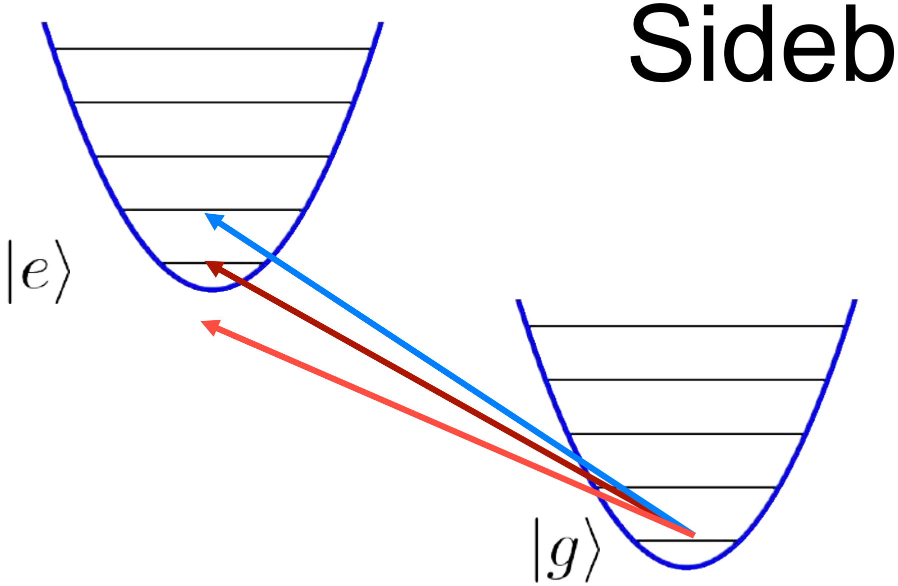
EtherDAC 2.1

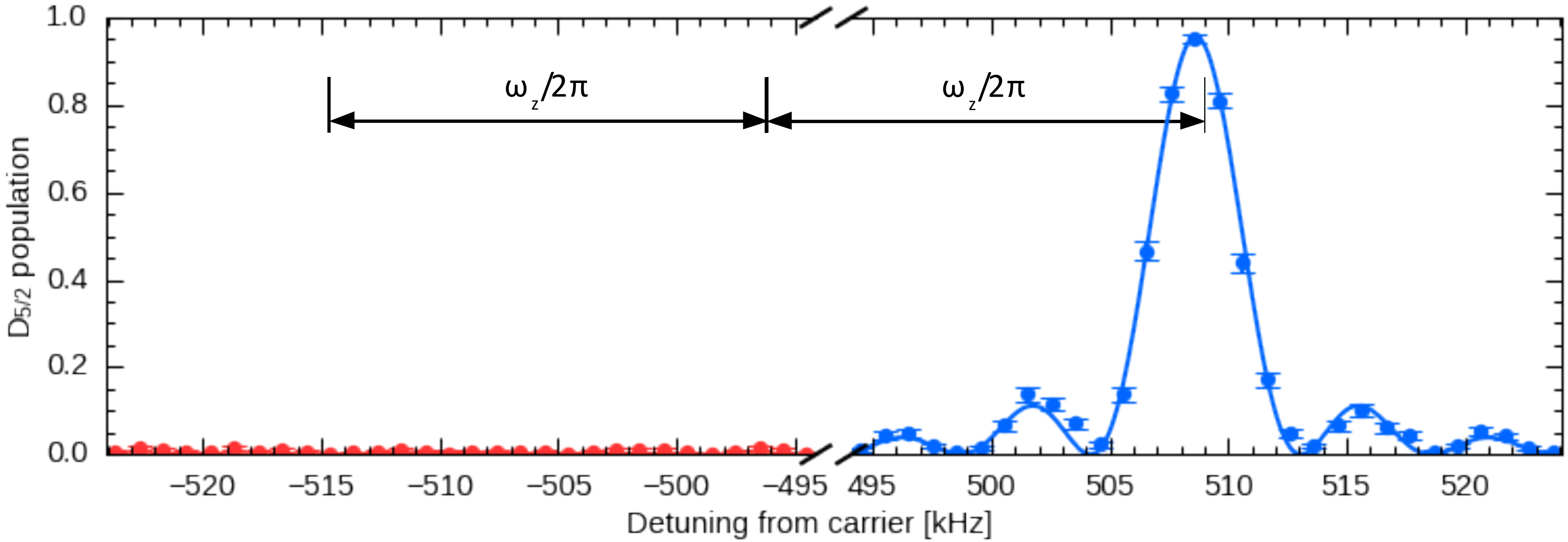
Sidebands


$|e\rangle$
$|g\rangle$

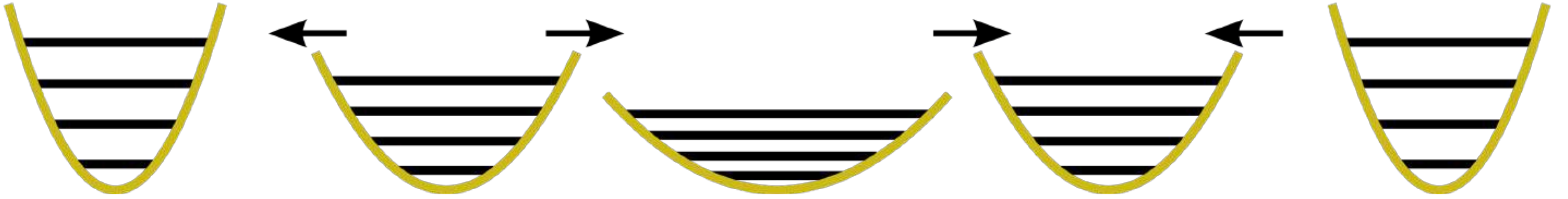

$\omega_z/2\pi$
$\omega_z/2\pi$
Excitation
0.0
0.2
0.4
0.6
0.8
1.0
−650 −600 −550 −500 −450 −400 −150 −100 −50 0 50 100 150 400 450 500 550 600 650
Detuning from carrier [kHz]

Sidebands


$|e\rangle$
$|g\rangle$


$\omega_z/2\pi$
$\omega_z/2\pi$
$D_{5/2}$ population
1.0
0.8
0.6
0.4
0.2
0.0
−520
−515
−510
−505
−500
−495
495
500
505
510
515
520
Detuning from carrier [kHz]

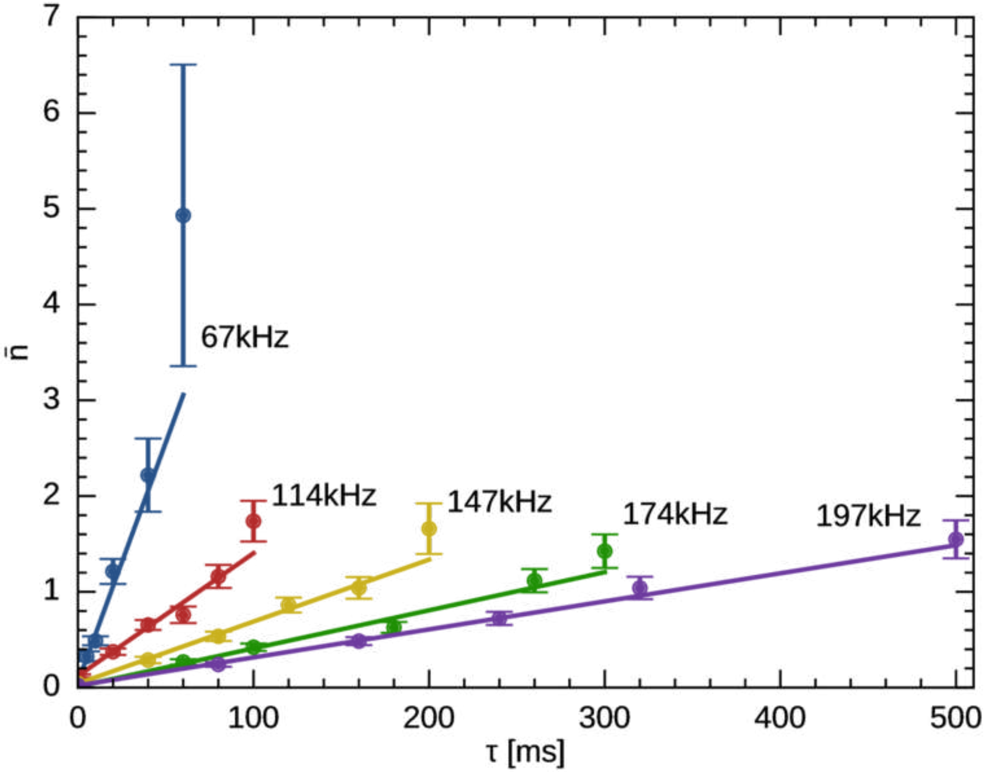
Heating rates



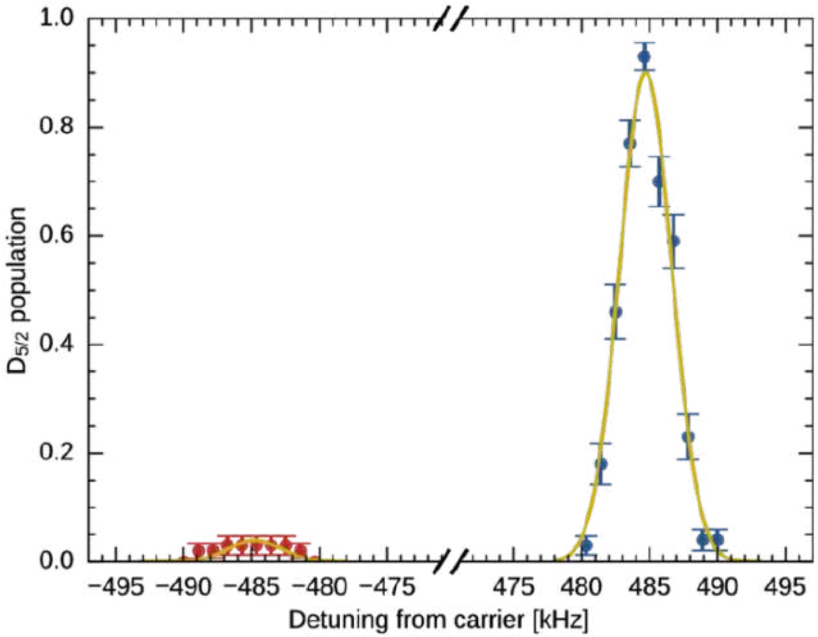
Cooling

Wait time τ

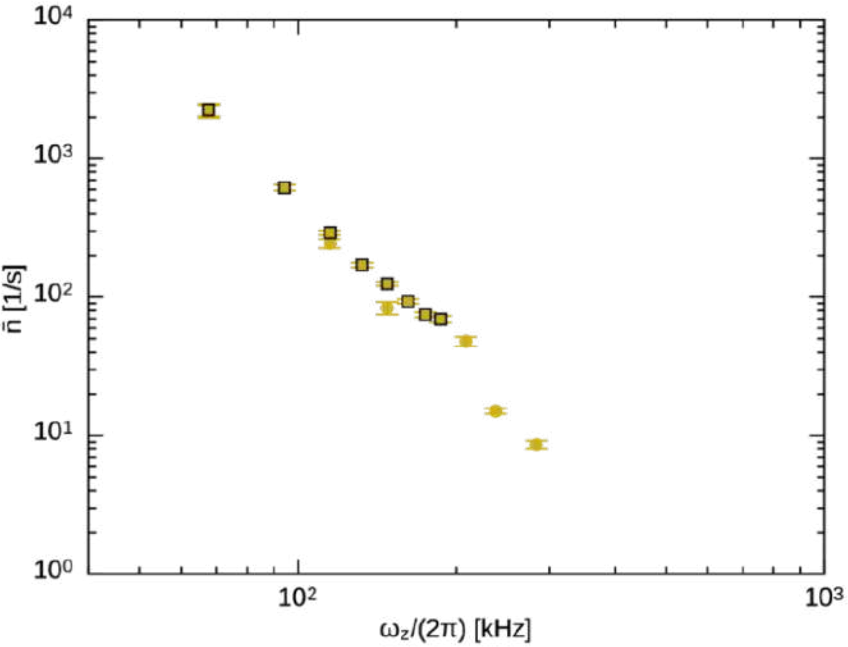
Sideband probe

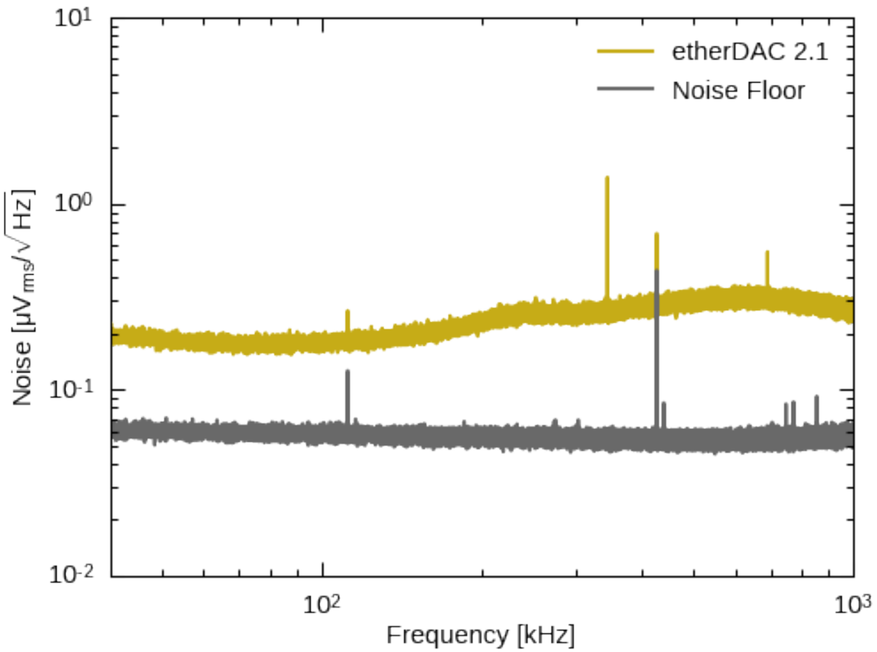


$$\bar{n} = \frac{h_{rsb}}{h_{bsb} - h_{rsb}}$$

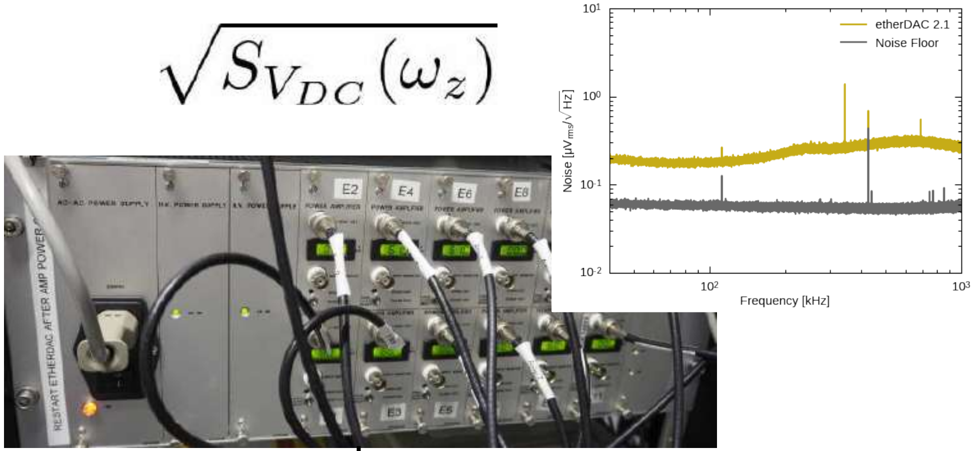


Heating rates of a single $^{40}Ca^+$

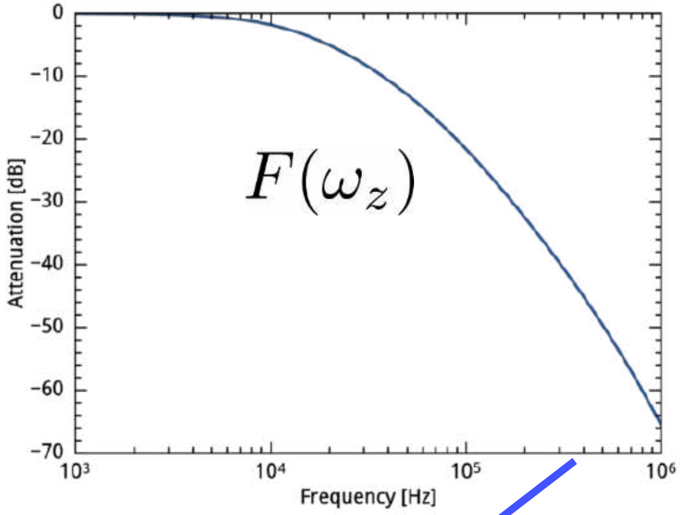




$$\sqrt{S_{V_{DC}}(\omega_z)}$$



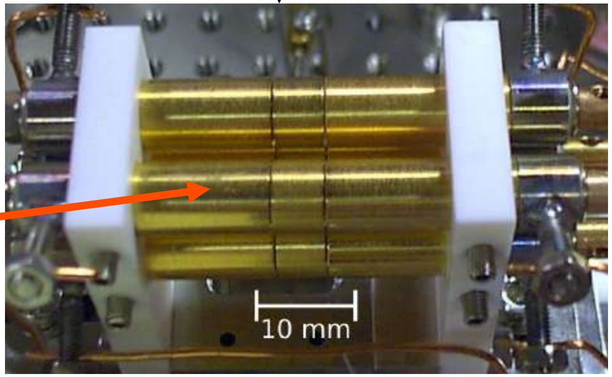
DC Supply



RF/DC Mixer

$$D = 56 \text{ mm}$$

$$S_V(\omega_z)$$

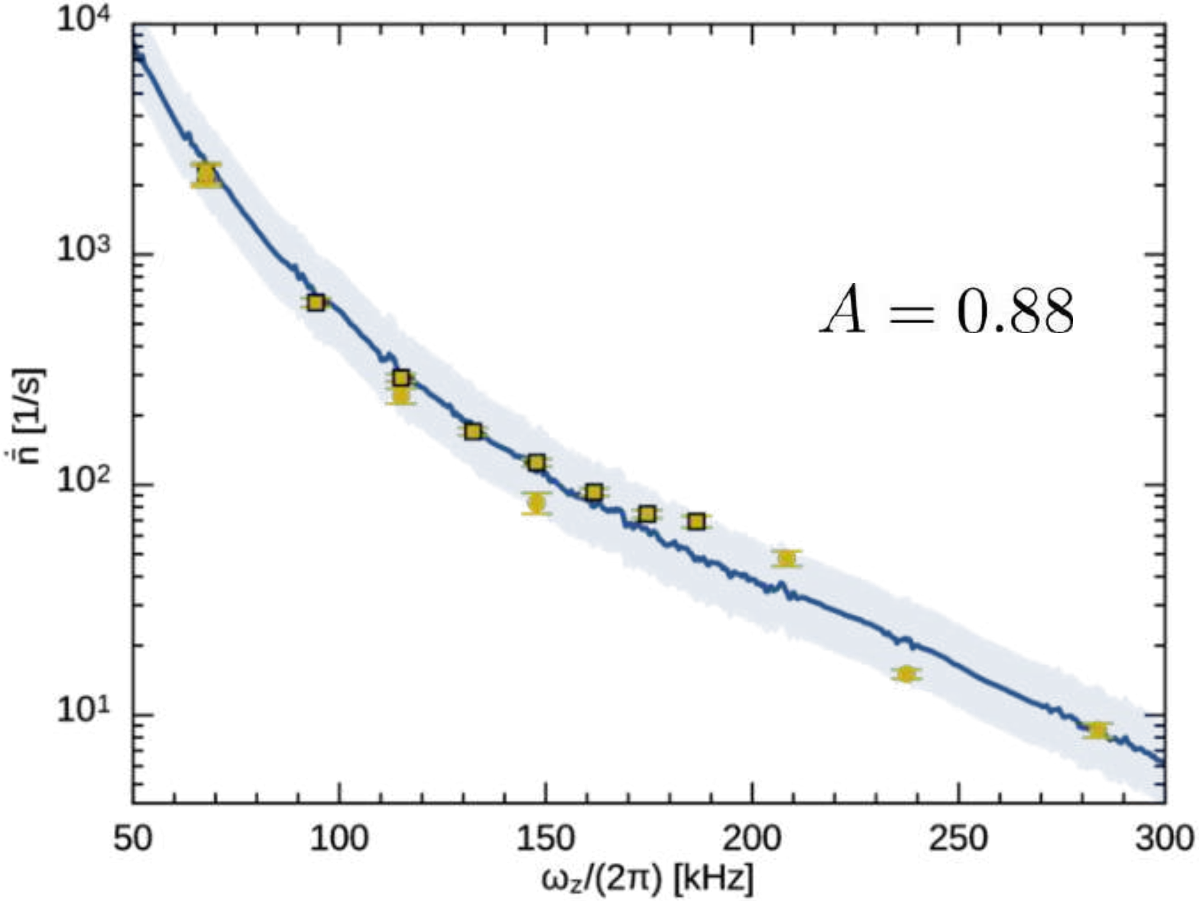


$$\dot{n} \simeq \frac{e^2}{4m\hbar\omega_z} S_E(\omega_z)$$

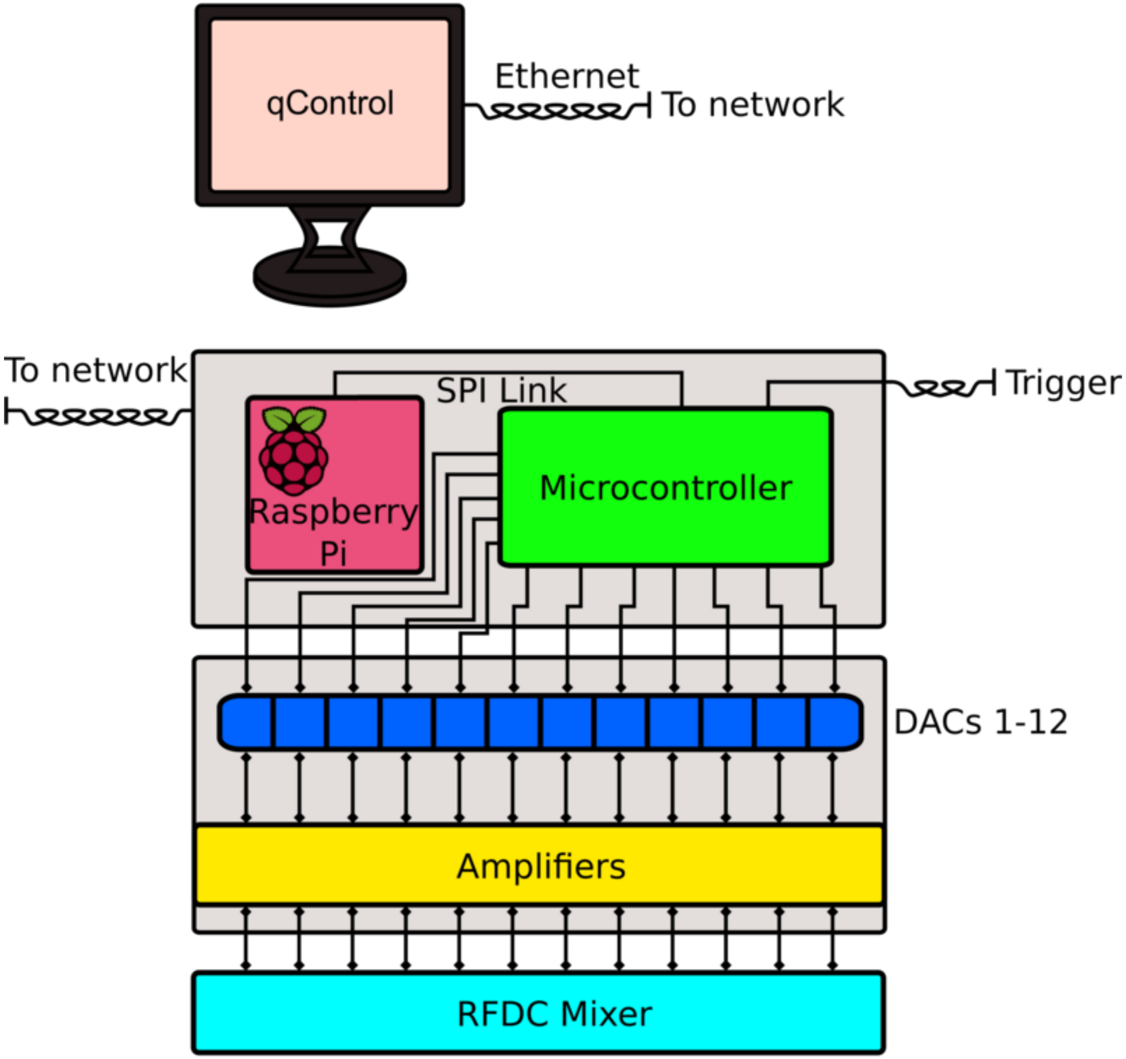
z

Heating rate model – single ion

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



DC supply


qControl

Ethernet

To network

To network

SPI Link

Trigger

Raspberry Pi

Microcontroller

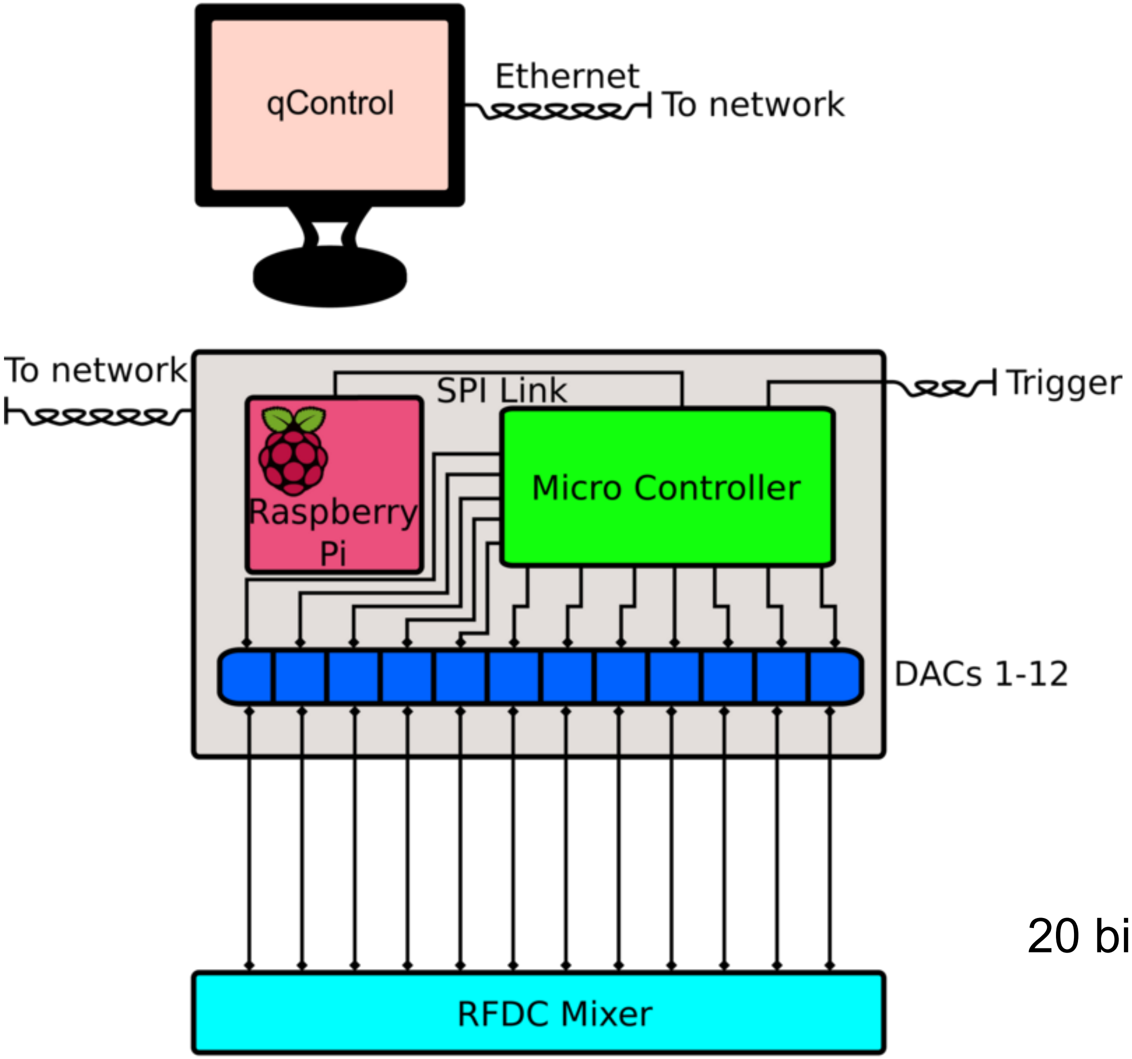
DACs 1-12

Amplifiers

RFDC Mixer

EtherDAC
2.1

DC supply

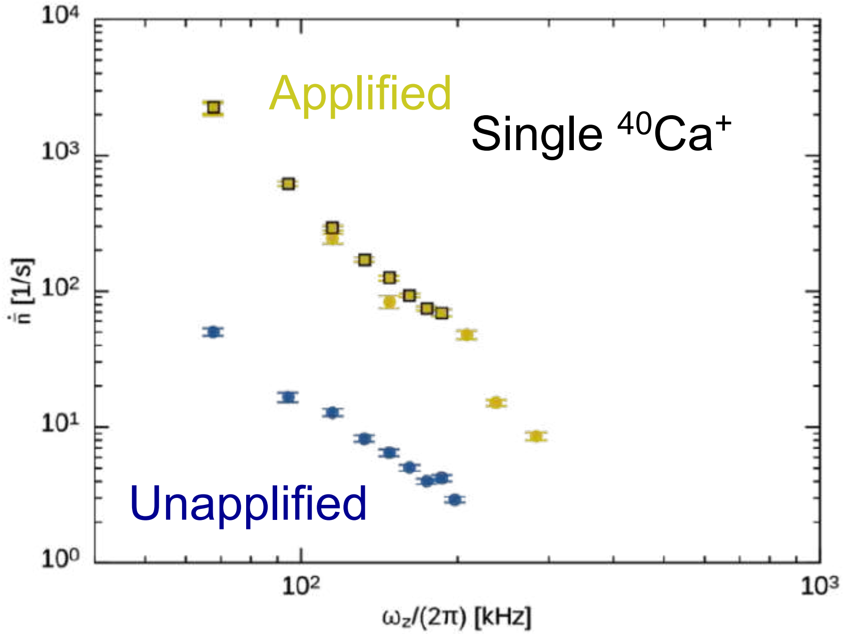


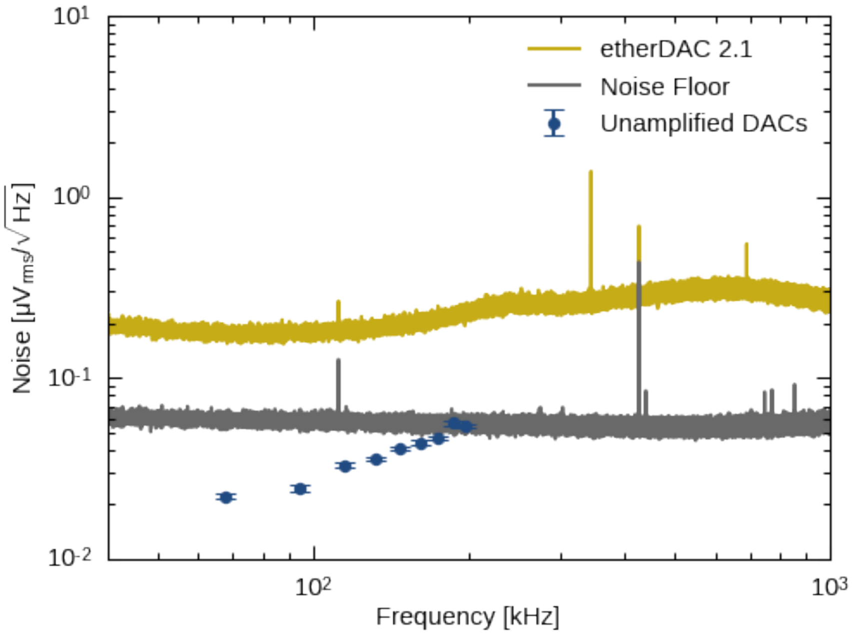
EtherDAC
1.0

20 bit DAC: These exp.: -1->10 V
Next step: -10 -> 10 V

Heating rates with unamplified (DAC) supply

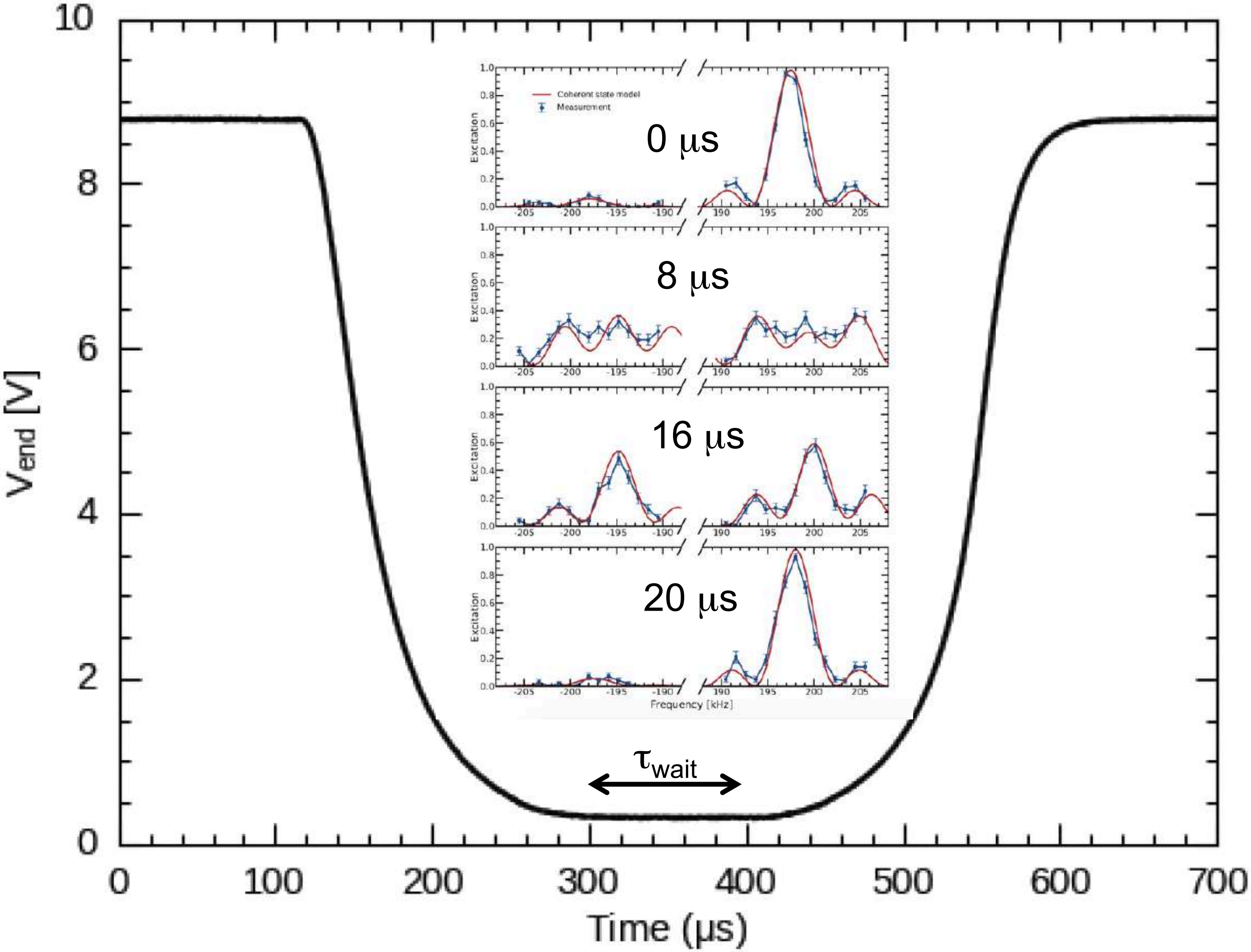
$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4m\hbar\omega_z} F(\omega_z)^2 \frac{S_{V_{DC}}(\omega_z)}{D^2}$$





~20 times lower heating!

Motional kicks due to ramping



IV) Unresolved issues

I) Integrating of optical elements (Imaging and cooling)

II) CNP loading

III) Resistive cooling (Circuitry at 4K or lower?)

IV) Probably more …

Department of Physics and Astronomy

UCL

Towards a controlled and reliable source of highly charged nanoparticles

A. Pontin

QUCLN

TEQ kick off meeting, Trieste, 2nd Feb. 2018

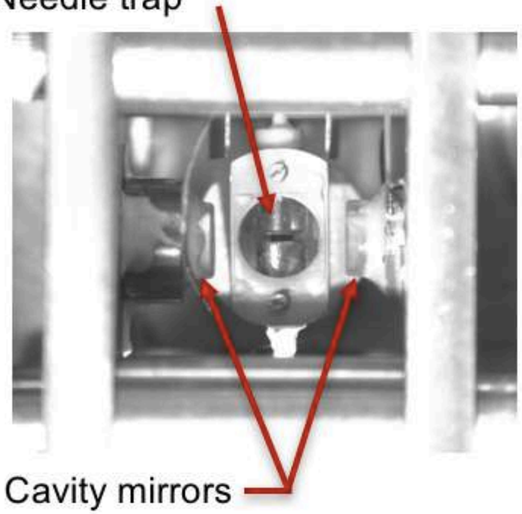
EPSRC
Engineering and Physical Sciences Research Council

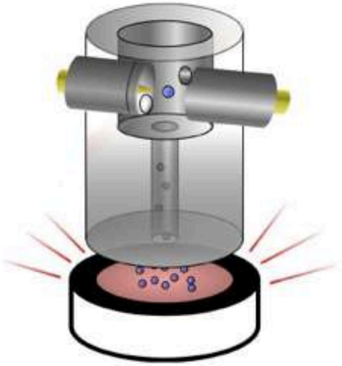
PCB linear Paul trap

Needle trap

- Reliable
- Compact
- Vacuum loading ~1mbar

- No control on charges
- Low frequency secular motion (few 100 Hz)
- Secular motion increases cavity dynamic complexity

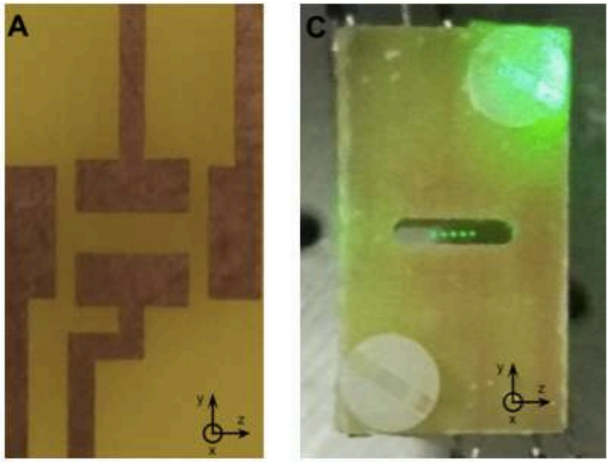




Piezo speaker (1.5kHz)

Linear trap

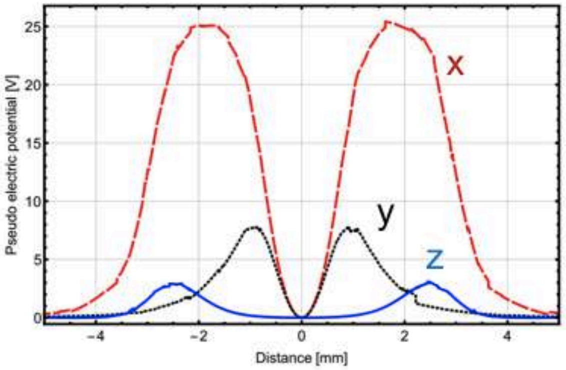
- Deeper trapping potential
- Ideally no micromotion along endcaps/cavity axis
- Easy to increase complexity

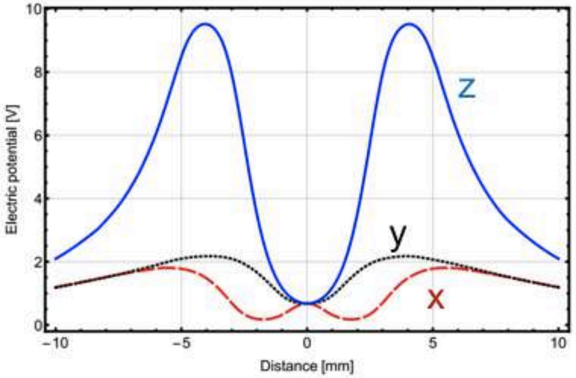


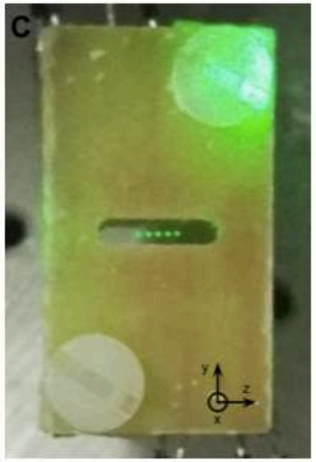
PCB trap characterization

FEM simulations to evaluate geometrical efficiencies

- η difference from ideal AC quadrupole field
- κ compares End caps to hyperbolic geometry
- ϵ identifies anti-trapped axes by End caps potential







$$\omega_x = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2}{2l^4\Omega^2} - \epsilon\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

$$\omega_y = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2}{2l^4\Omega^2} - (1-\epsilon)\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

$$\omega_z = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2\sigma^2}{2l^4\Omega^2} + 2\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

PCB trap characterization

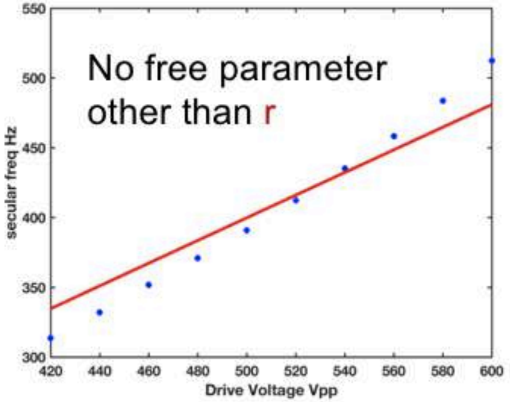
Secular frequencies measurement to estimate charge to mass ratio r=Q/m

- 1.02 μm silica spheres suspended in methanol
- Initially trapped at atmospheric pressure
- Injection with nebulizer

$$\omega_x = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2}{2l^4\Omega^2} - \epsilon\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

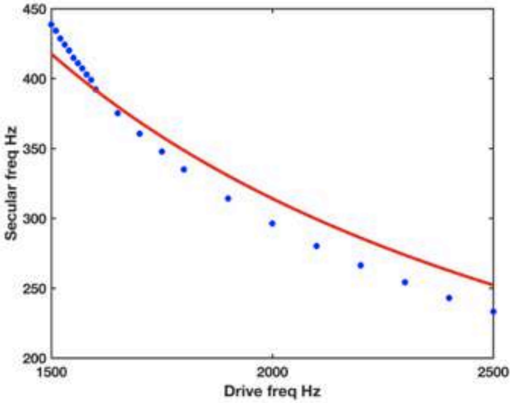
$$\omega_y = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2}{2l^4\Omega^2} - (1-\epsilon)\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

$$\omega_z = \sqrt{\frac{Q^2}{m^2}\frac{V^2\eta^2\sigma^2}{2l^4\Omega^2} + 2\frac{Q}{m}\frac{2U\kappa}{d^2}}$$

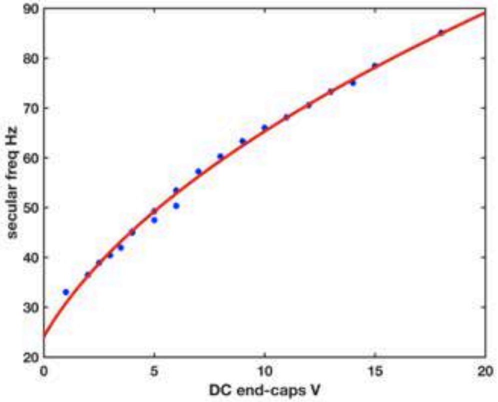


No free parameter other than r

$\omega_x = f(V_{AC}) \rightarrow$ q/m=0.23



$\omega_y = f(freq) \rightarrow$ q/m=0.47



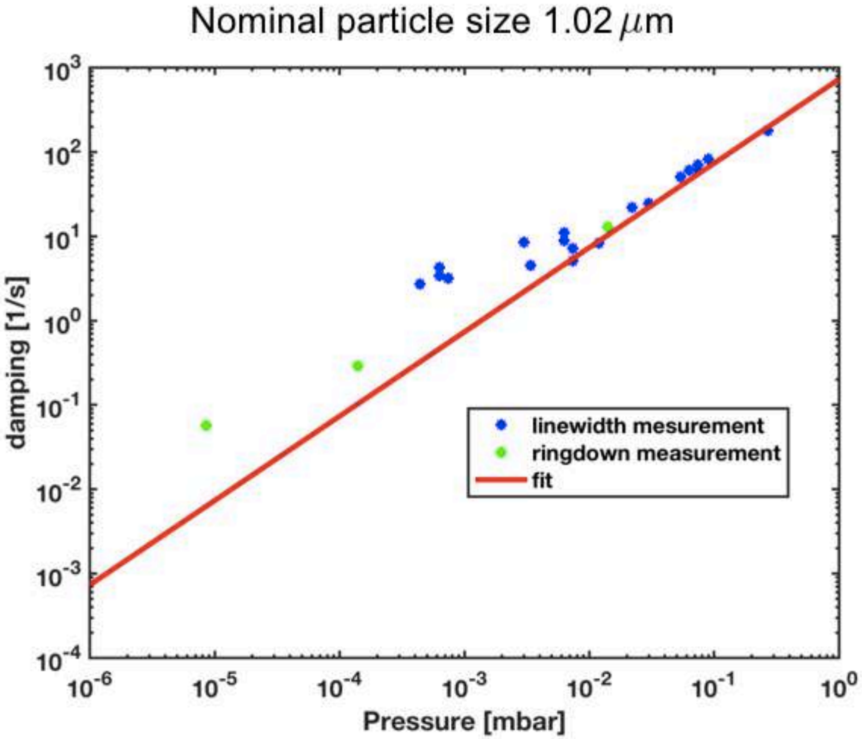
$\omega_z = f(U_{DC}) \rightarrow$ q/m=0.17

Model and trap assembly need refinement

Particle mass estimation

Estimation of the particle mass by measuring linewidth due to gas damping

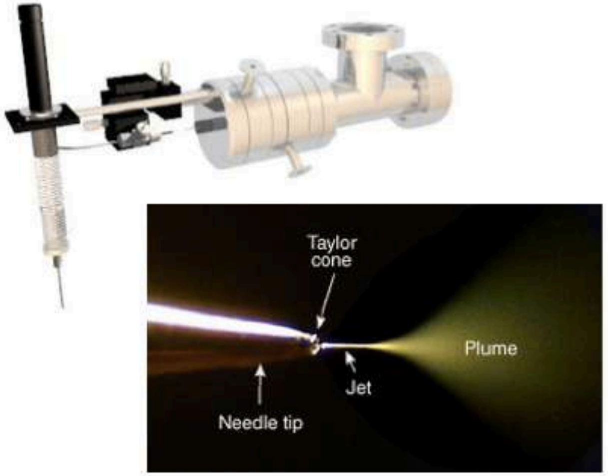
- Spectral linewidth measurement (blue dots) limited by
    - AC drive stability
    - Pressure gauge reliability
- Ringdown measurements (green dots) limited by
    - Excitation effectiveness (linewidth of 1mHz @10^{-5} mbar)
    - High order terms in the potential at high oscillation amplitudes



The two measurements, Q/m and linewidth, allow to estimate

Number of charges
~ 1 – 2 10^{3}

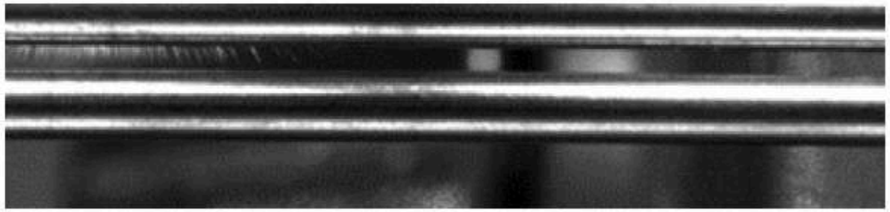
Electrospray injection



- 2 kV DC voltage on needle tip
- Single stage – one skimmer to operate at ~ 0.1 – 1 mbar
- 20 cm long quadrupole guide to preselect particles

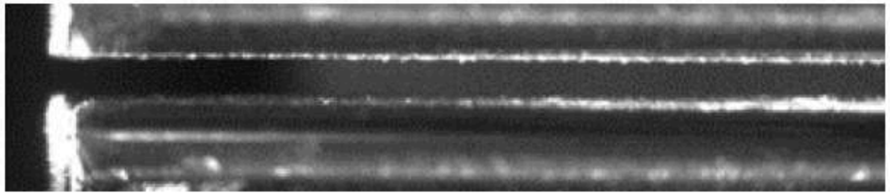
- Demonstrated trapping in the guide
- Developing transfer of a single particle to PCB trap

Atmospheric



600 nm particles

Vacuum
10^{-1} mbar



A low noise environment for quantum measurement:

Optical levitation, feedback cooling & laser refrigeration

A. T. M. Anishur Rahman & Peter F. Barker
Department of Physics & Astronomy
University College London
London, UK

Feburay 02, 2018

Outline

- Macroscopic quantum mechanics
- Sources of decoherence in quantum experiments
- Optical levitation in vacuum
- Parametric feedback cooling
- Laser refrigeration
- Future experiment

Macroscopic quantum mechanics

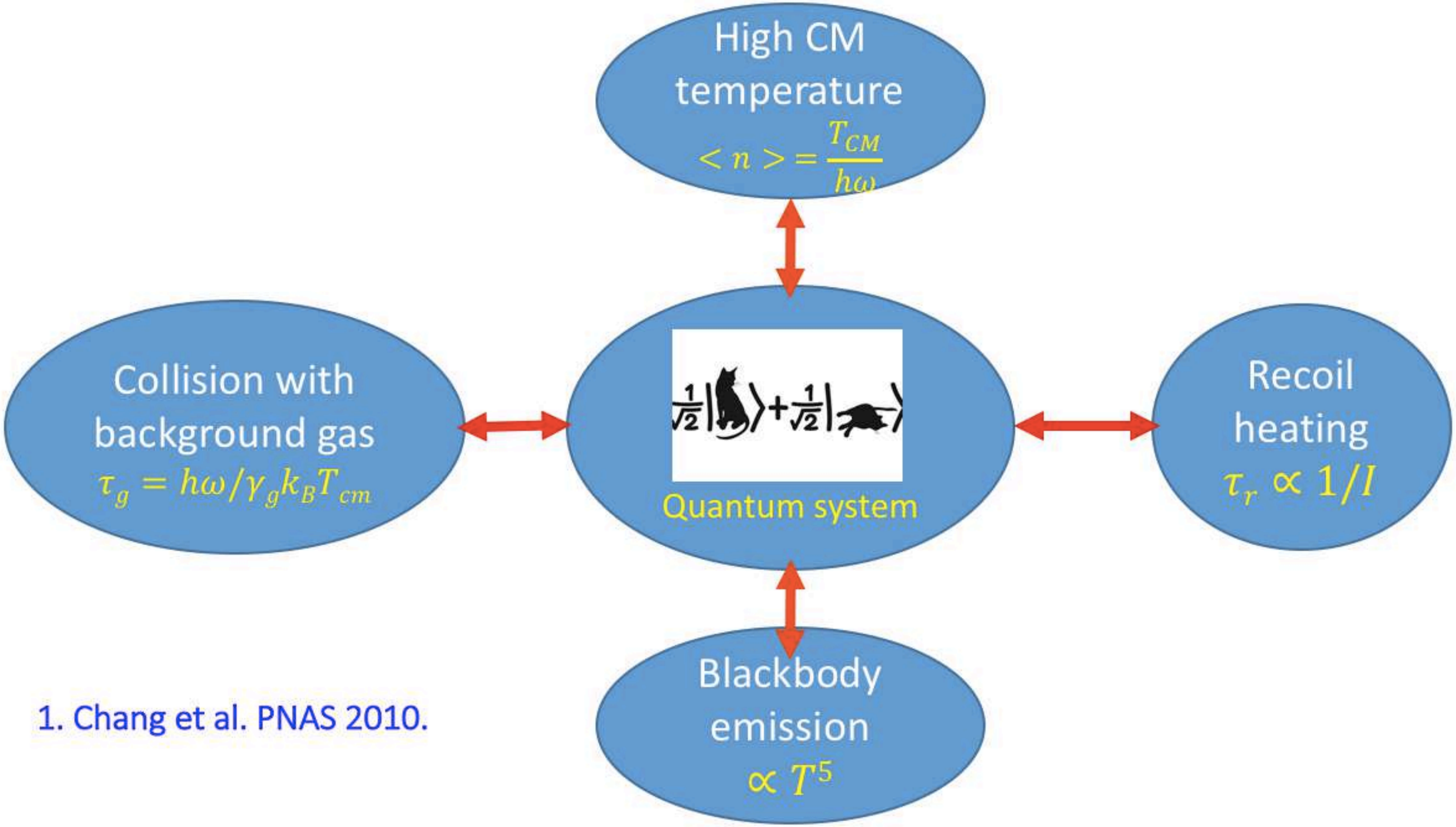
Interferometric schemes

- Matter-wave interferometry using BEC – Kovachy et al. Nat. 2015
- Levitated nanodiamond containing a NV centre – Wan et al. PRL, 2016 & Yin et al. PRA, 2013.
- Interferometry using cavity-optomechanics – Romaro-Isart et al. PRL, 2011.
- Others

Non-interferometric schemes

- Search for the evidence of various wave function collapse mechanisms such CSL using levitated nanoparticle - Bahrami et al. PRL, 2014 & Goldwater et al. PRA, 2016.
- Others

Main sources of decoherence[1]



High CM temperature

$<n> = \frac{T_{CM}}{h\omega}$

Collision with background gas

$\tau_g = h\omega/\gamma_g k_B T_{cm}$

Quantum system

Recoil heating

$\tau_r \propto 1/I$

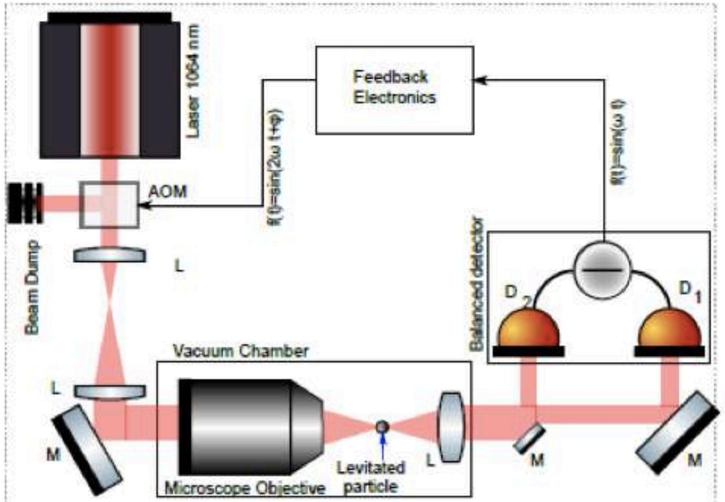
Blackbody emission

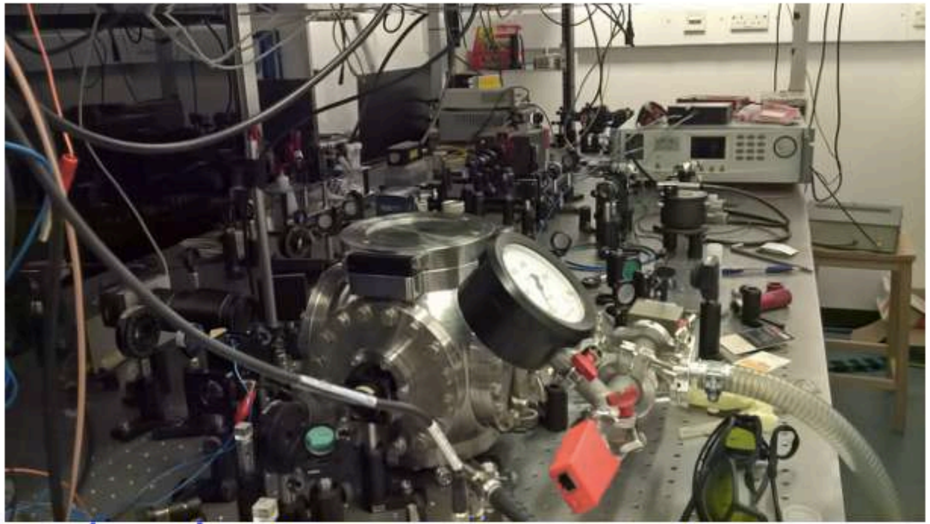
$\propto T^5$

1. Chang et al. PNAS 2010.

Controlling CM motion

Optical levitation in vacuum

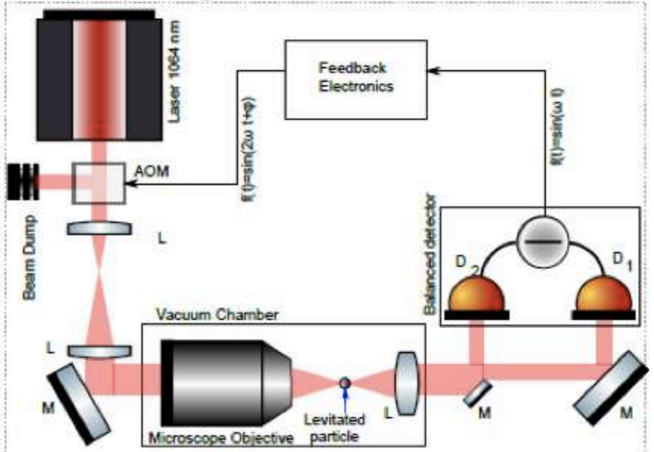


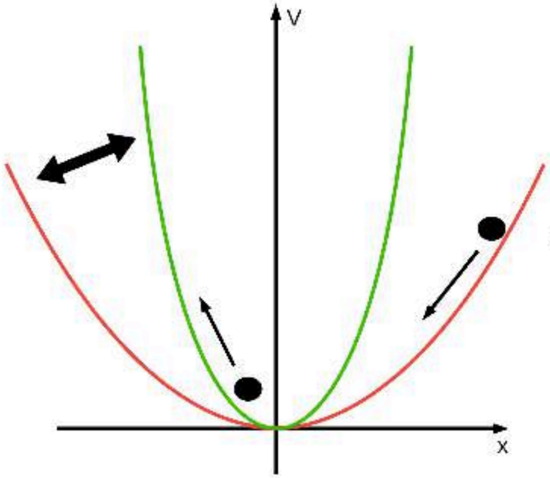


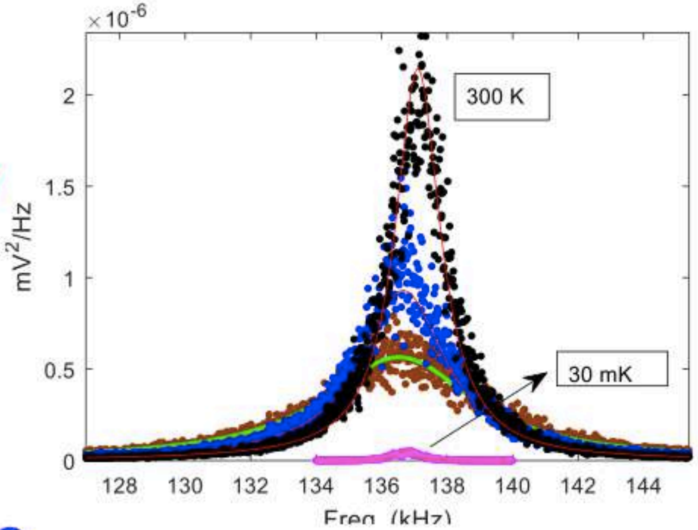
- Eliminates physical contact from the decohering environment
- High vacuum in combination with optical levitation removes decoherence due to gas molecules
- Absorption of light by levitated particles can be detrimental and can be a big source of decoherence

Parametric feedback cooling

- It controls the CM motion of a levitated nanoparticle
- Has been successfully used to reach sub-millikelvin CM temperature[2]







- Ground state how far or is it needed???

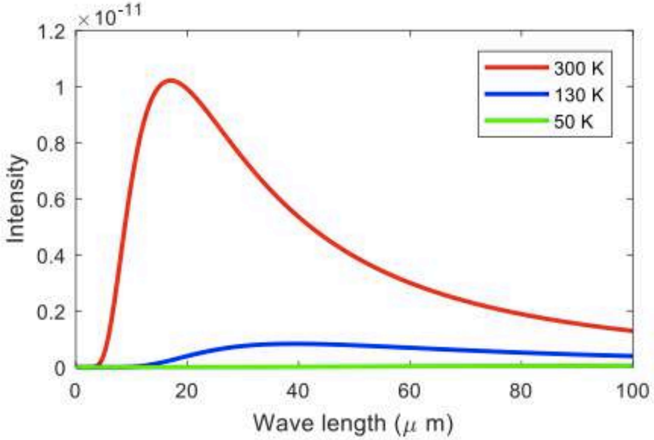
2. Jain et al. PRL 2016.

Controlling blackbody emission

Blackbody emission and it’s consequence

Plank’s law of blackbody emission

$$I(\omega) = \frac{h\omega^3}{\pi^2 c^2 (e^{\frac{h\omega}{k_B T}} - 1)}$$



- Damping rate due to blackbody emission -

$$\gamma_{BB} \propto (R_{\mathrm{BB}}/\omega_m)$$

where $R_{BB} = \int I(\omega) d\omega$.

- Number of oscillations before the oscillator excites by one quanta –

$$1/\gamma_{BB} \propto (\omega_m/R_{\mathrm{BB}})$$

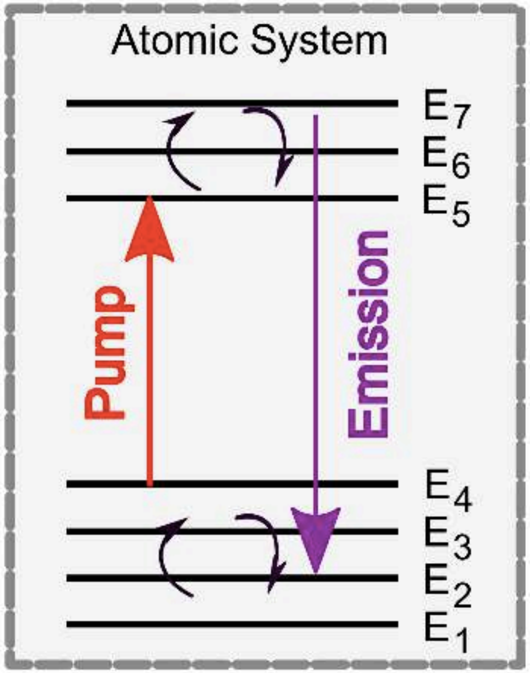
Laser refrigeration

- Controlling the internal temperature of a material using laser only
- Similar to laser cooling of atoms

  but it uses anti-Stokes fluorescence

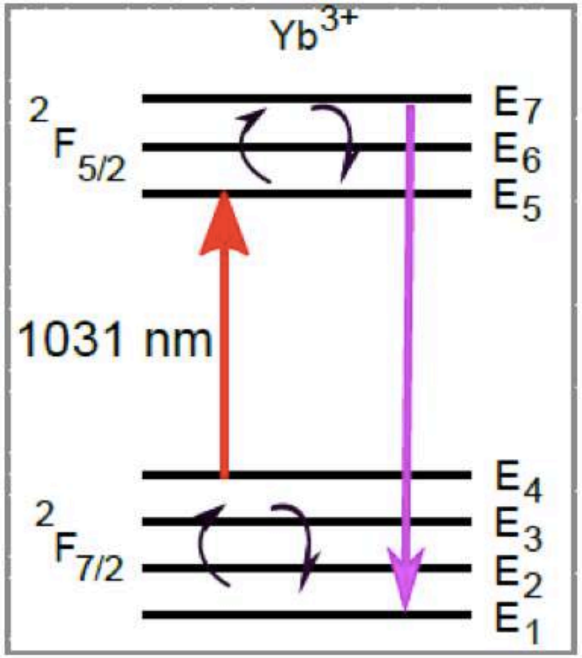
  for controlling the internal temp.
- Example of anti-Stoke fluorescence

  from an atomic system

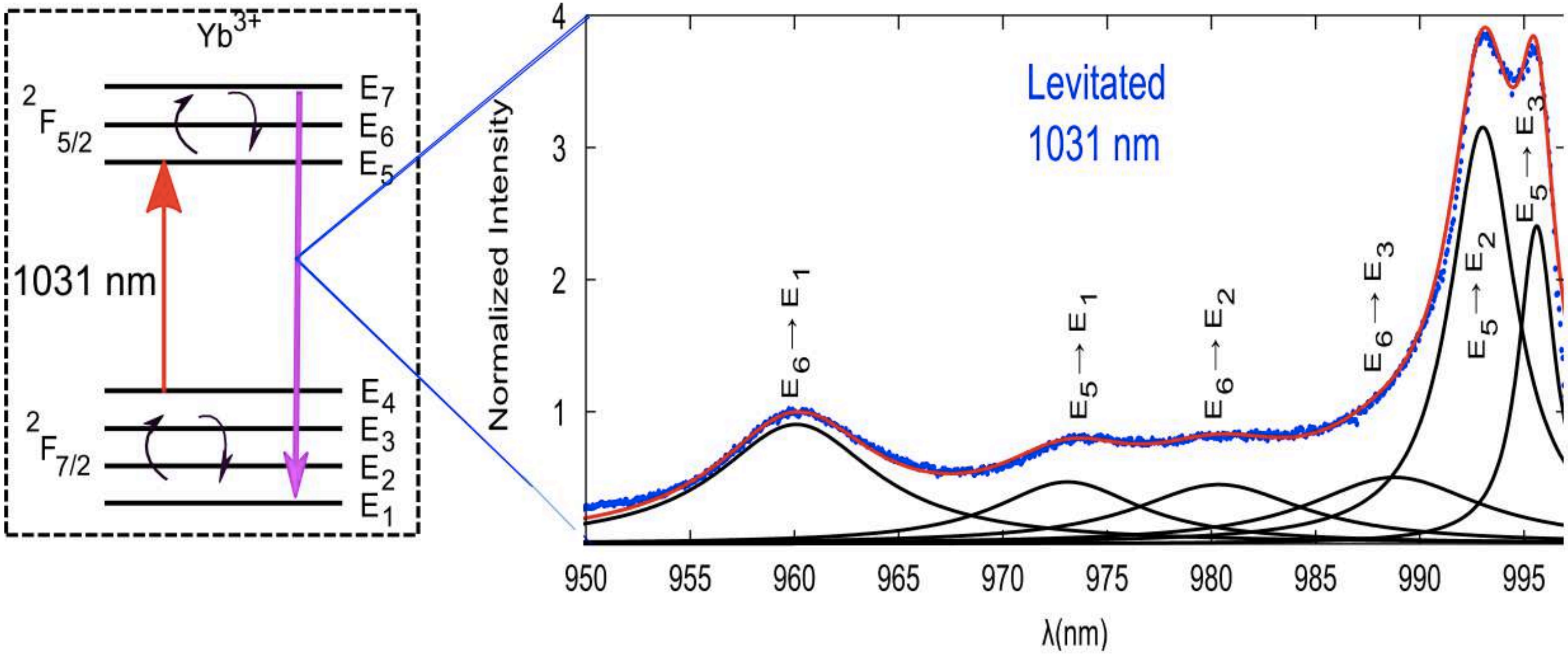


Conditions for optical refrigeration

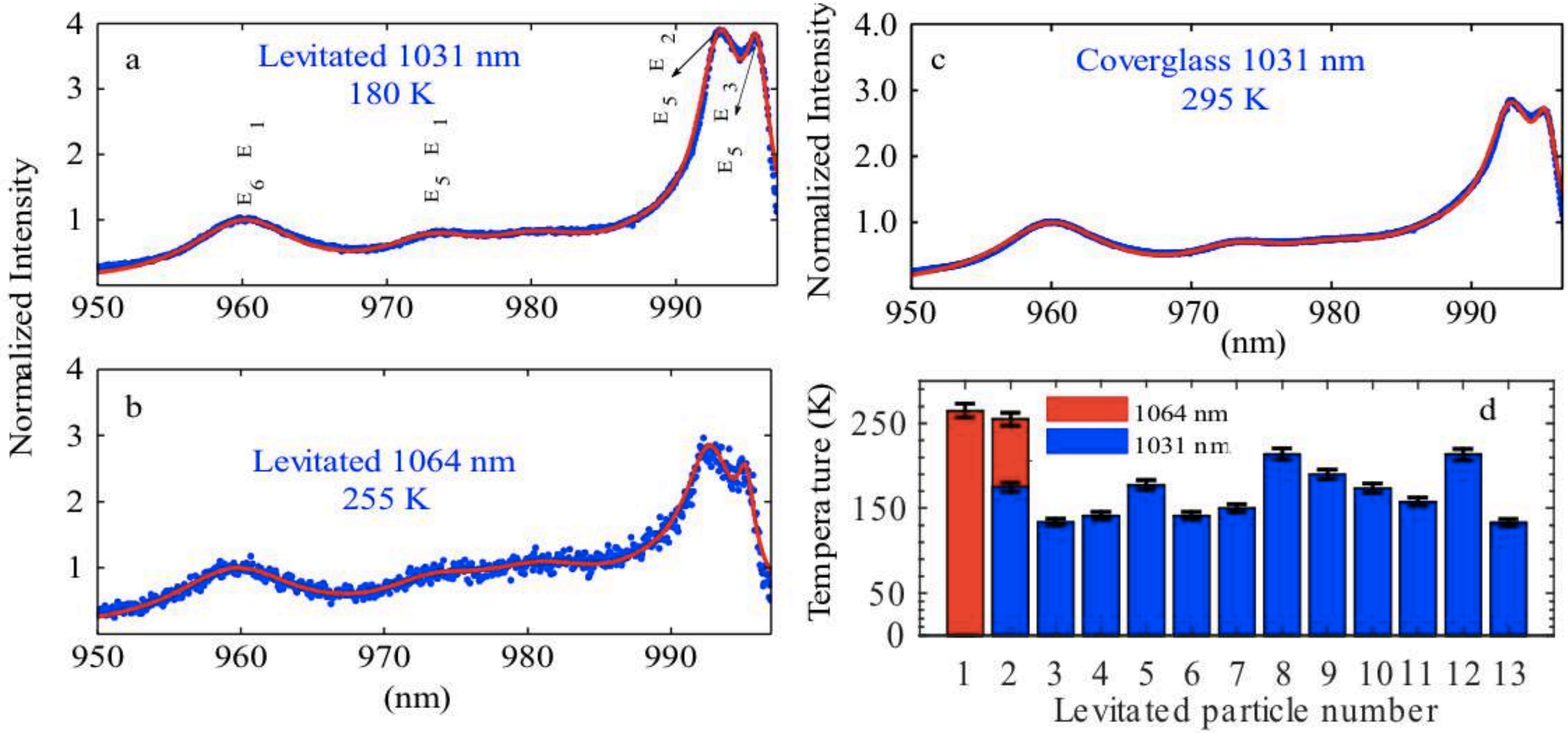
- Anti-Stokes fluorescence ($\lambda_f < \lambda$)
- Phonon energy of host materials must be low $< k_B T$
- Rapid thermalization of population in excited state
- Excited state lifetime should be longer than thermalization time



Anti-Stokes fluorescence from levitated Yb^{3+}: YLF nanocrystals



Controlling the internal temp. of levitated Yb^{3+}:YLF naonocrystals[3]



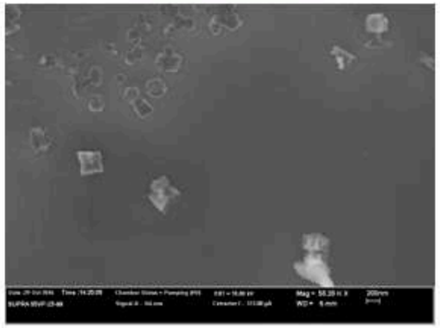
Temp. from Boltzmann distr. - $\frac{1}{T} = \frac{1}{T_0} + \frac{k_B}{\Delta E_{65}} \ln \frac{R}{R_0}$, where $R = \frac{I(E_6 \to E_1)}{I(E_5 \to E_2)}$ at T and $R_0 = \frac{I(E_6 \to E_1)}{I(E_5 \to E_2)}$ at T_0

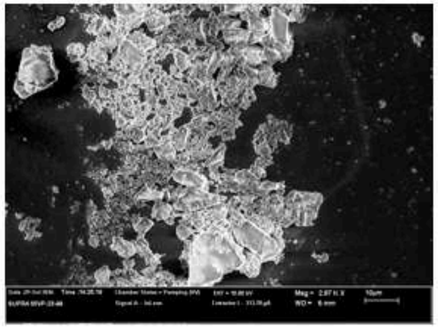
3. A. T. M. A. Rahman and P. F. Barker Nat. Photon. (2017).

Yb^{3+}:YLF nanoparticles

What we use now

Yb^{3+}:YLF + Mortar & Pestle

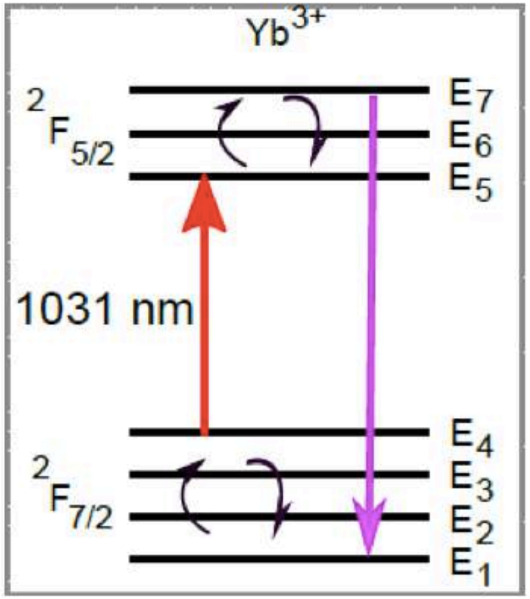




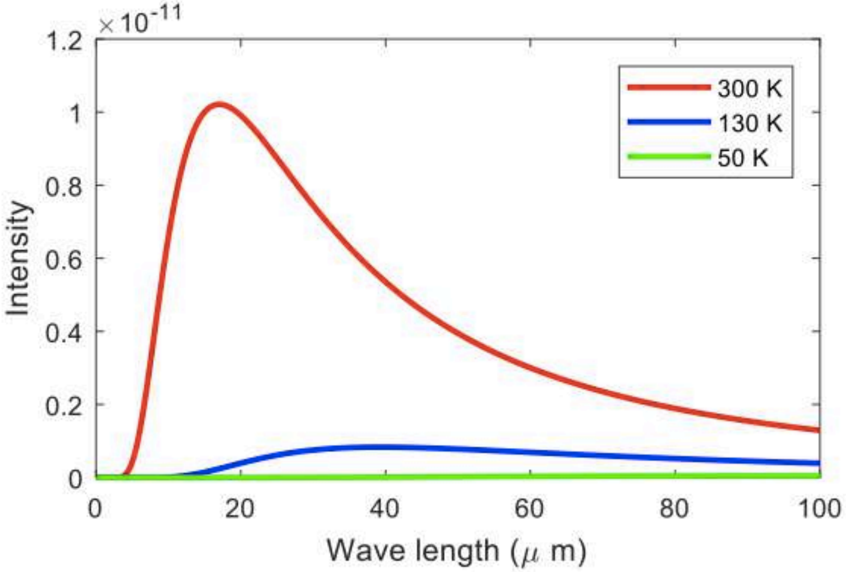
What will be good for us

- Yb^{3+}:YLF nanoparticles of regular & symmetric shapes
- Contamination free
- Variable percentage of Yb^{3+} doping
- With good quality crystal temp. close to 50 K is possible
- This will reduce blackbody emission by about four orders of magnitude

Given right laser and proper nanoparticles



We can reach 50 K



which is about 4 orders magnitude blackbody suppression

Temperature from PSD[3]

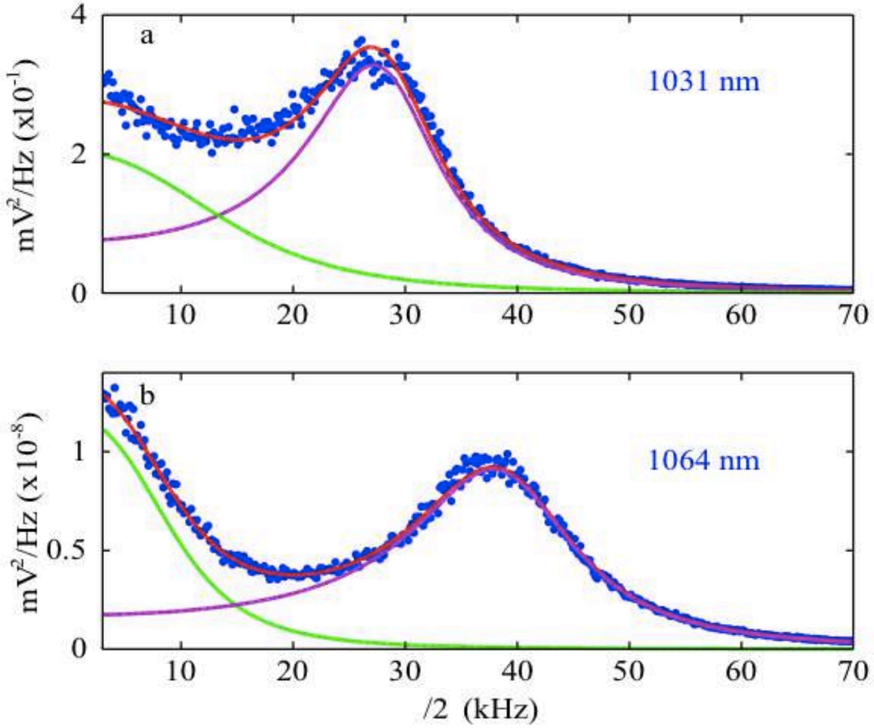
- Power spectral density – $S_x(\omega) = \frac{2k_B T}{M} \frac{\gamma}{(\omega^2 - \omega_0^2)^2 + \gamma^2 \omega^2}$

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

- Finally assuming $T_{1064\ \mathrm{nm}}$= 255 K,

$$T_{1031\ nm} = T_{1064\ nm} \frac{\gamma^2_{1031\ nm}}{\gamma^2_{1064\ nm}}$$

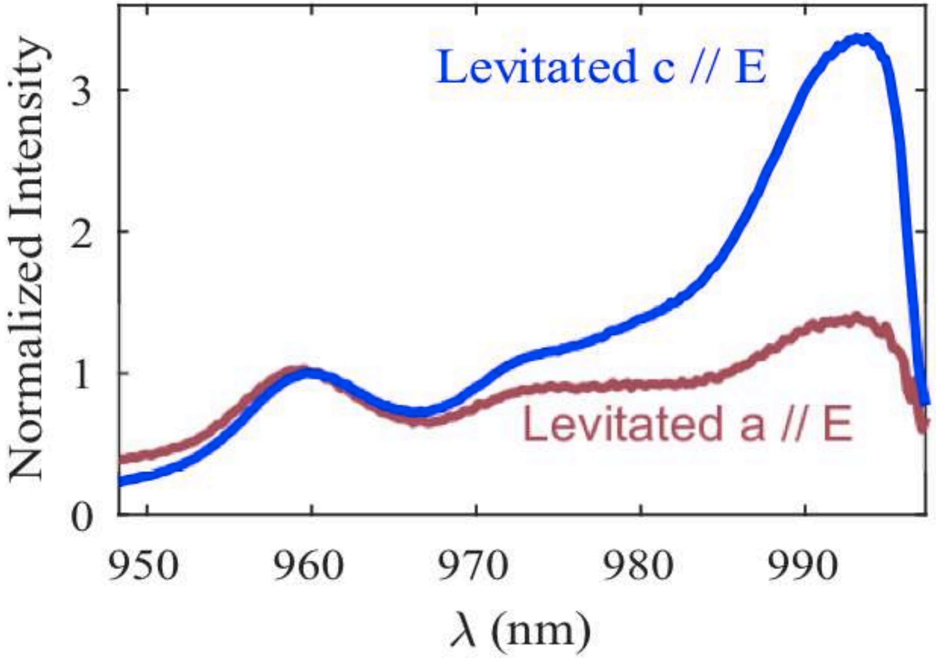
$$= 171 \pm 21\ \mathrm{K}$$



3. A. T. M. A. Rahman and P. F. Barker, Nat. Photon. (2017).

Birefringence of Yb^{3+}:YLF : self orientation[3]

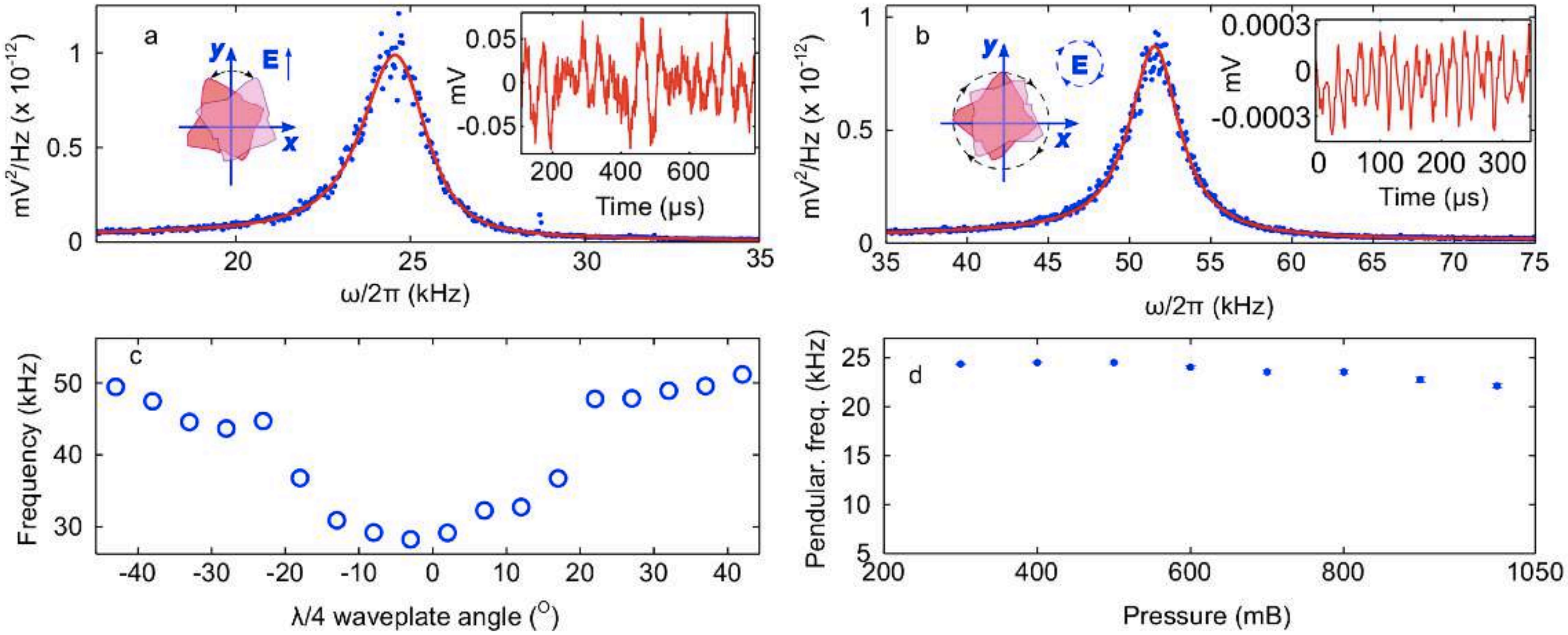
- Two orientations a // E & c // E
- Fluorescence and temp. depends on crystal orientation
- Trapping power > 50 mW : c // E
- Trapping power < 50 mW : a // E



3. A. T. M. A. Rahman and P. F. Barker, Nat. Photon. (2017).

Birefringence of Yb^{3+}:YLF -rotation & pendular motion[3]

- Pendular motion in linearly polarized light (Fig. a & d)



- Rotation in circularly polarized light (Fig. b & c)

3. ATM A. Rahman and P. F. Barker, Nat. Photon. (2017).

Tasks ahead

- Controlling CM and internal temperature together
- Yb^{3+}: YLF nanoparticles
- Needs a tuneable laser for a lower internal temperature
- Needs additional feedback electronics

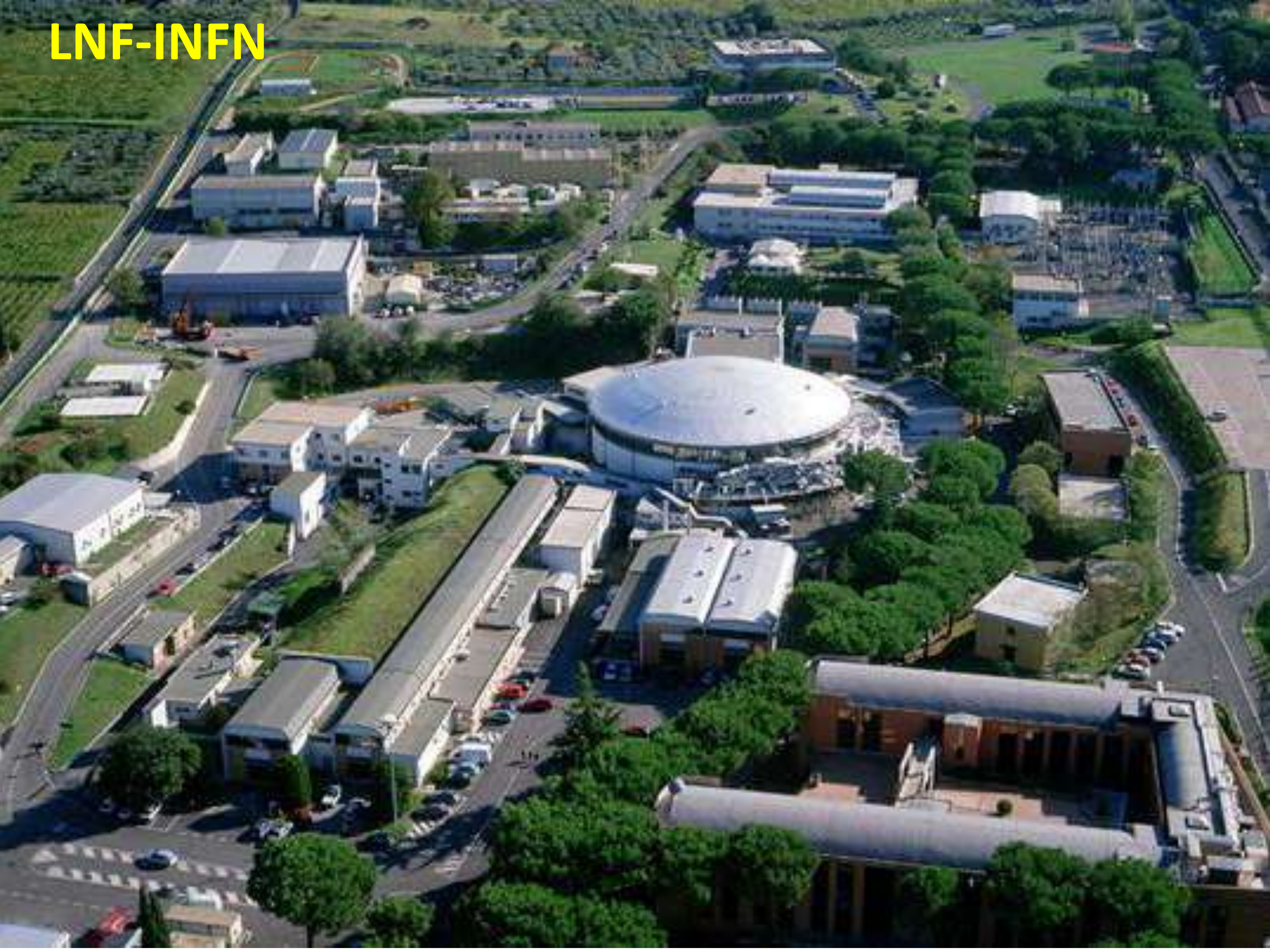
TEQ

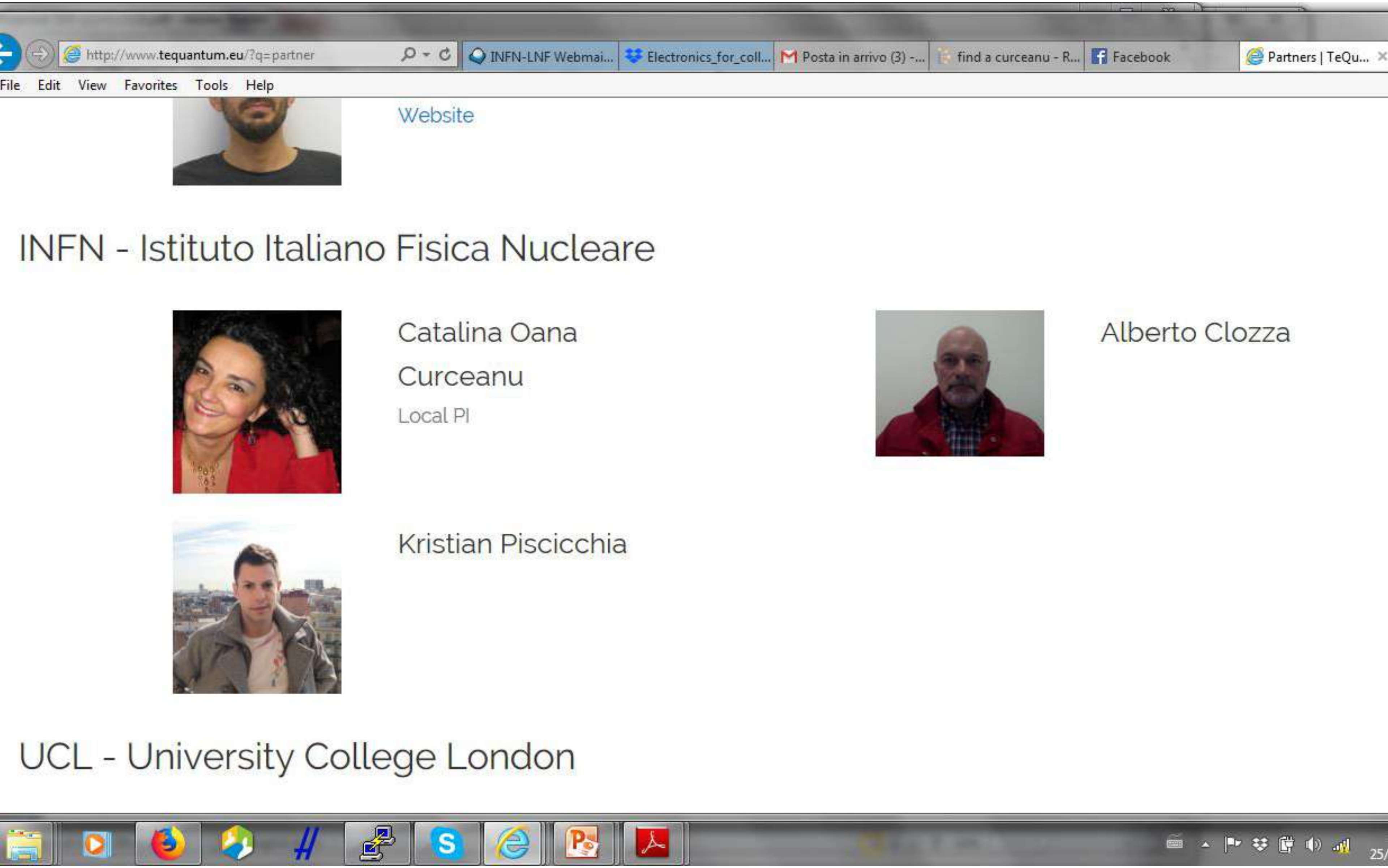
Testing the large-scale
limit of
quantum mechanics

TEQ kick off meeting
Trieste, 2nd February 2018
UniTs – Via Filzi 14

Catalina Curceanu
LNF-INFN

LNF-INFN





Website

INFN - Istituto Italiano Fisica Nucleare

Catalina Oana Curceanu

Local PI

Alberto Clozza

Kristian Piscicchia

UCL - University College London

LNF team

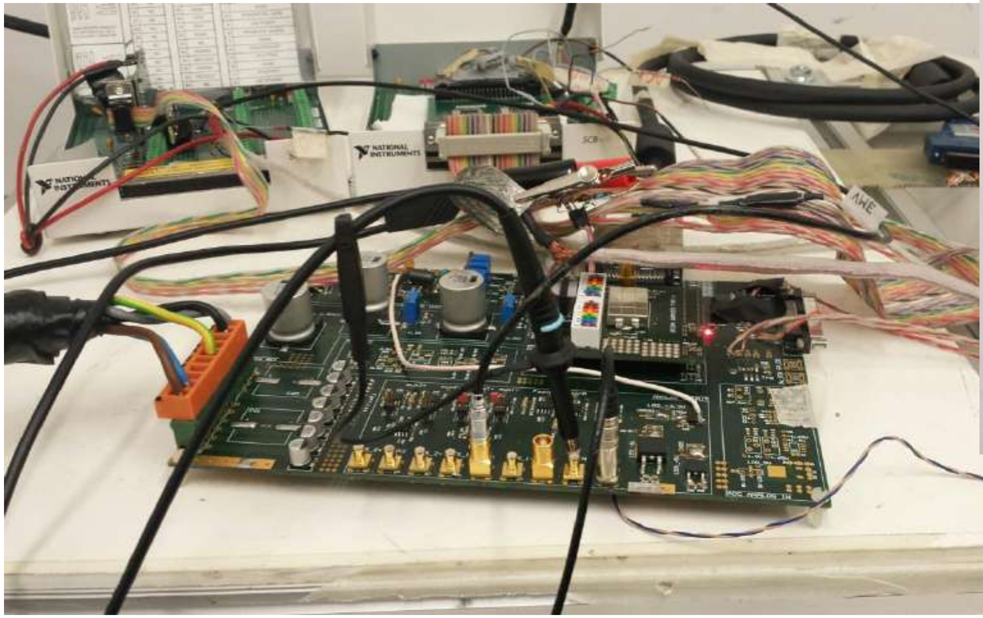
Core tasks attributed to INFN:

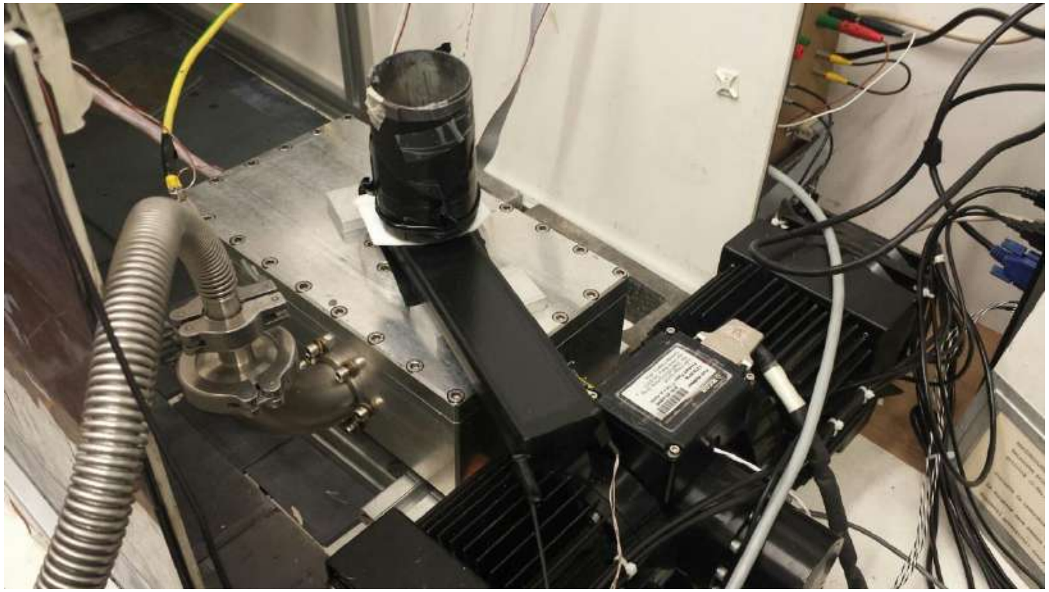
- Co-Leadership of WP2, WP5 and WP6.
- To develop extremely low-noise rf (10-100 kHz) and dc supplies to reduce particle heating.
- To develop and realize low-noise electronics necessary to process the information on the position change of the particle in all three spatial directions.
- To set up a vacuum chamber with closed-cycle cryostat to host the ultimate experiment.
- To participate to the assembly and tests of the setup and to final measurements.
- Co-leader for the management of the Consortium activities and the dissemination of the results associated with TEQ as per the terms of the Consortium Agreement.

Expertize:

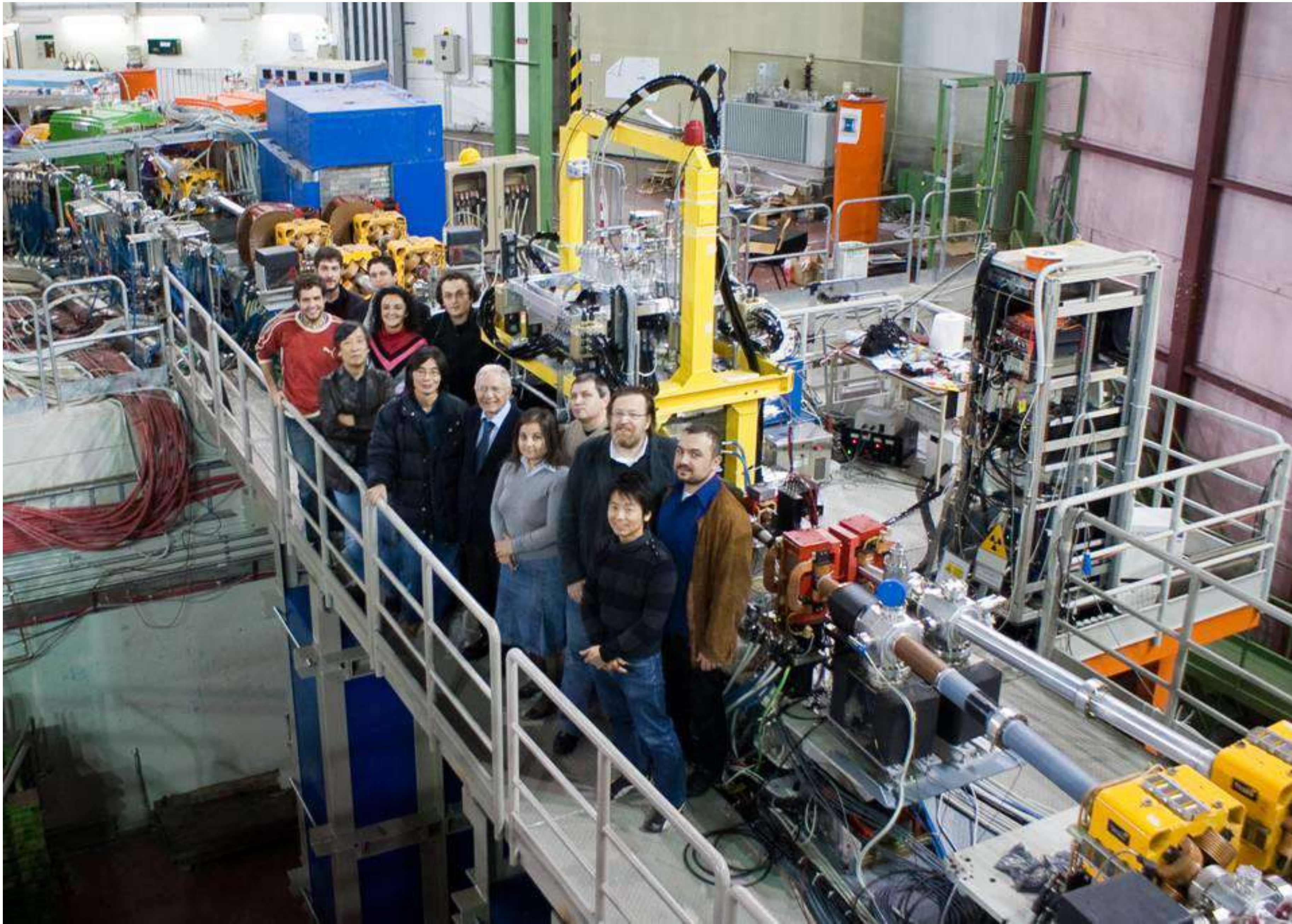
- Silicon Detectors: readout and DAQ, including vacuum and cryogenic systems
- Design and realization of low-noise and high-precision electronics
- Progettazione elettronica di precisione e basso rumore
- Design and realization of Power supply e signal processing
- PCB
- Software, slow control... (labview)
- Lab instrumetation use (NIM, VME) for high precision experiments

We use them in experiments in nuclear and quantum physics

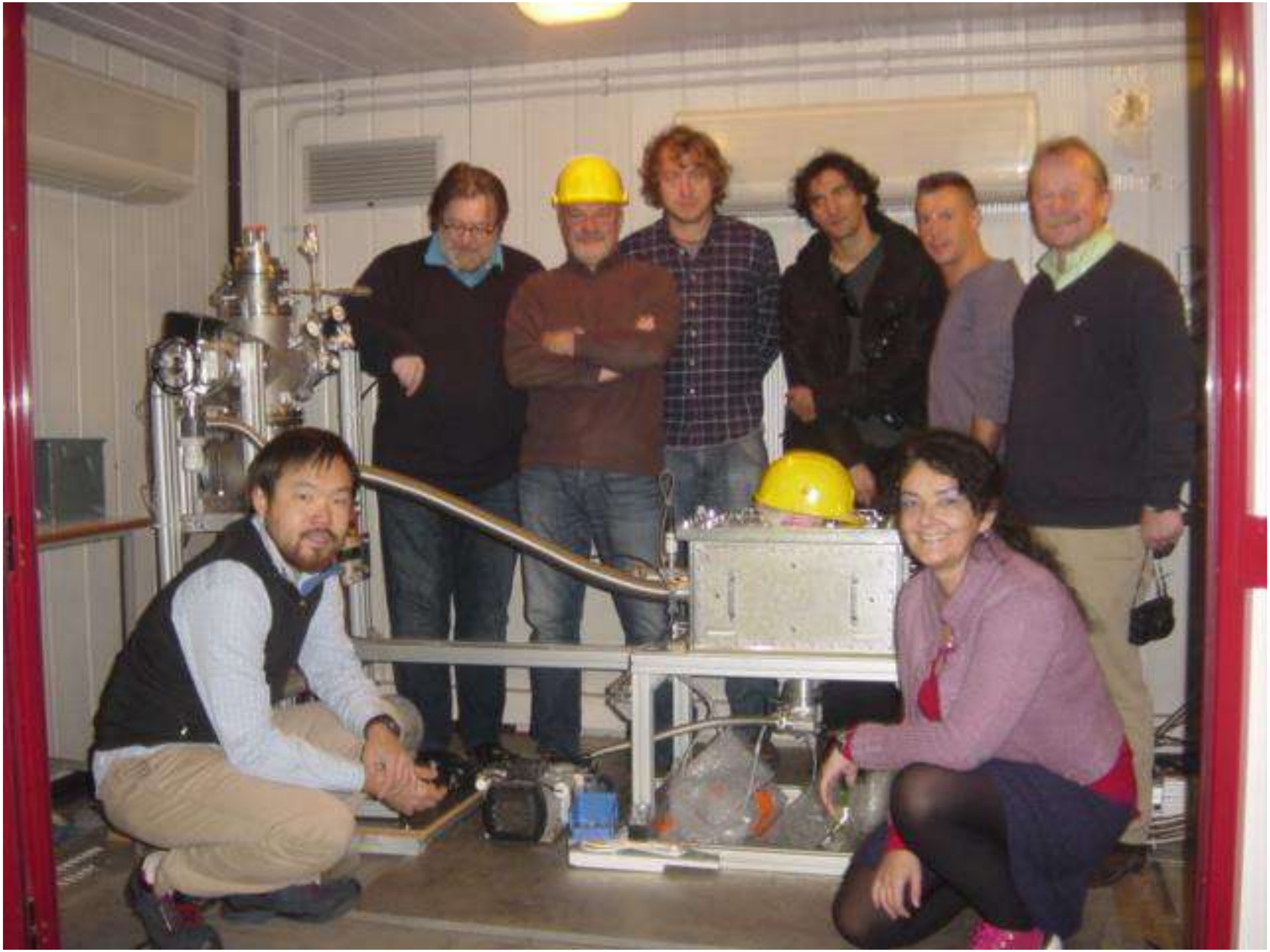

NATIONAL INSTRUMENTS
NATIONAL INSTRUMENTS
SCB
AHE



SIDDHARTA - LNF



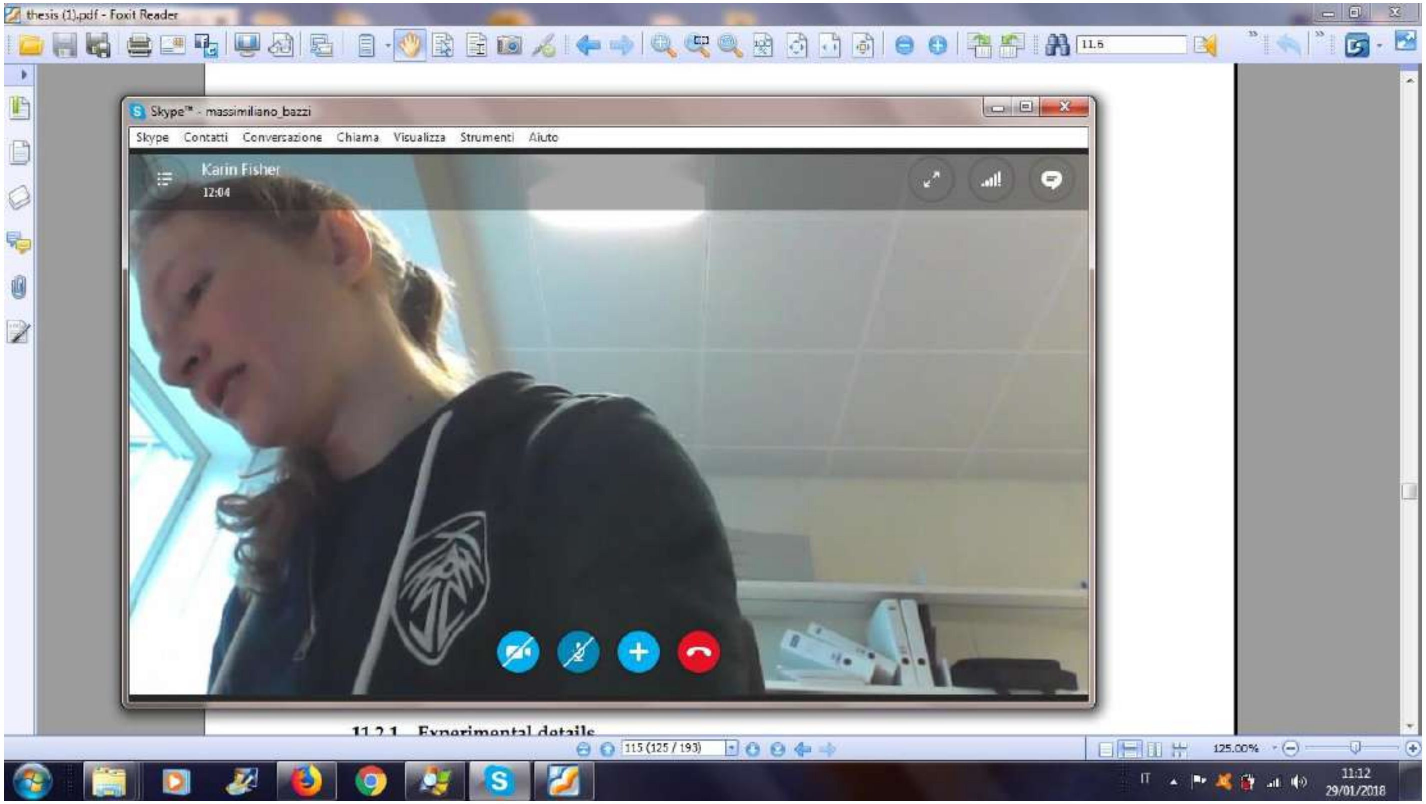
VIP2 at LNGS



We (Massimiliano Bazzi) are in contact with teams from:

AU - Aarhus University (Karin Fisher): modified version of our low-noise DAC-controlled DC supplies for our linear ion traps

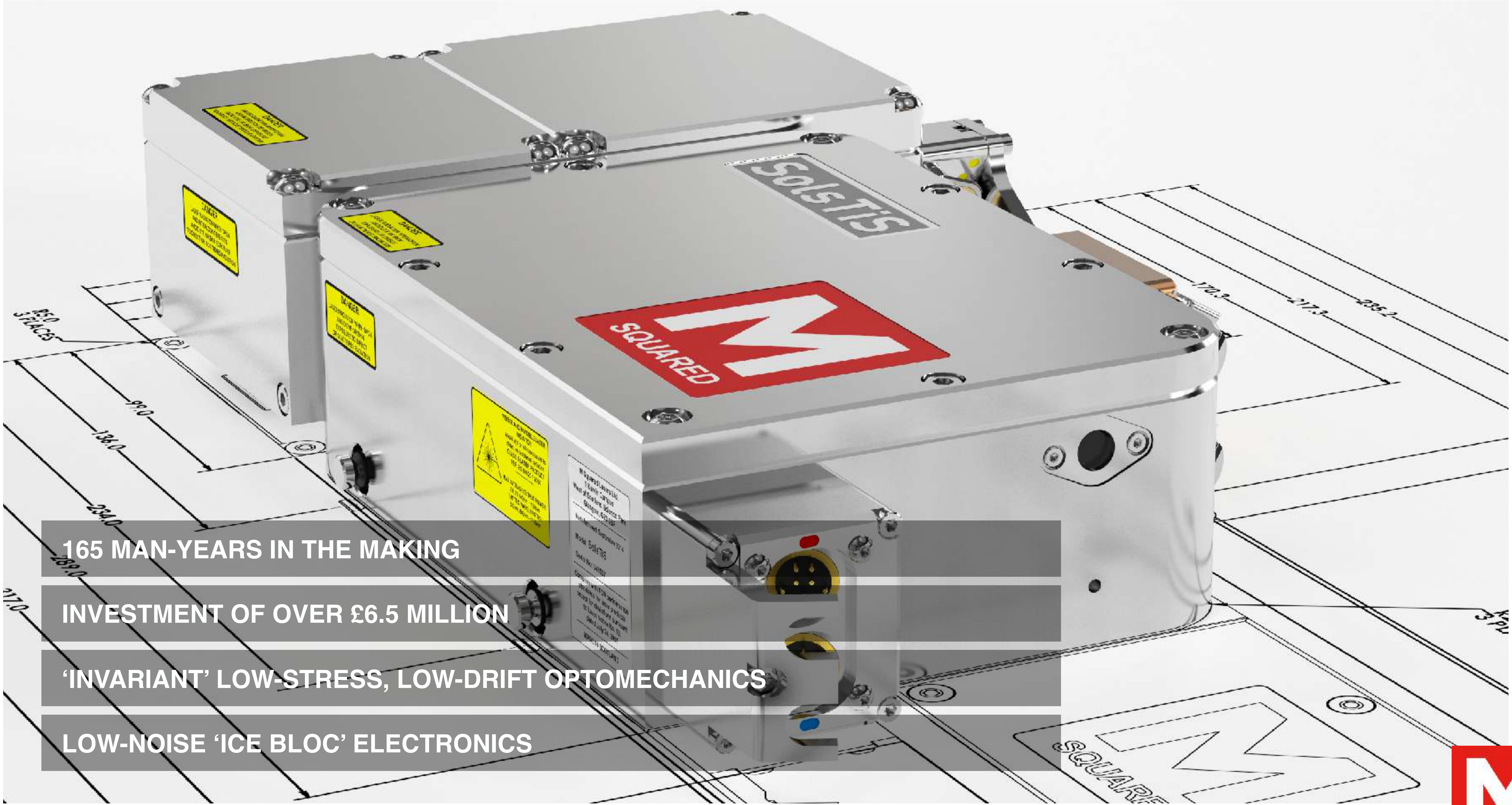
UoS - University of Southampton



M
SQUARED

TEQ KICK-OFF MEETING

2ND FEBRUARY 2018
JAMES R. P. BAIN, INNOVATION PROGRAMME MANAGER

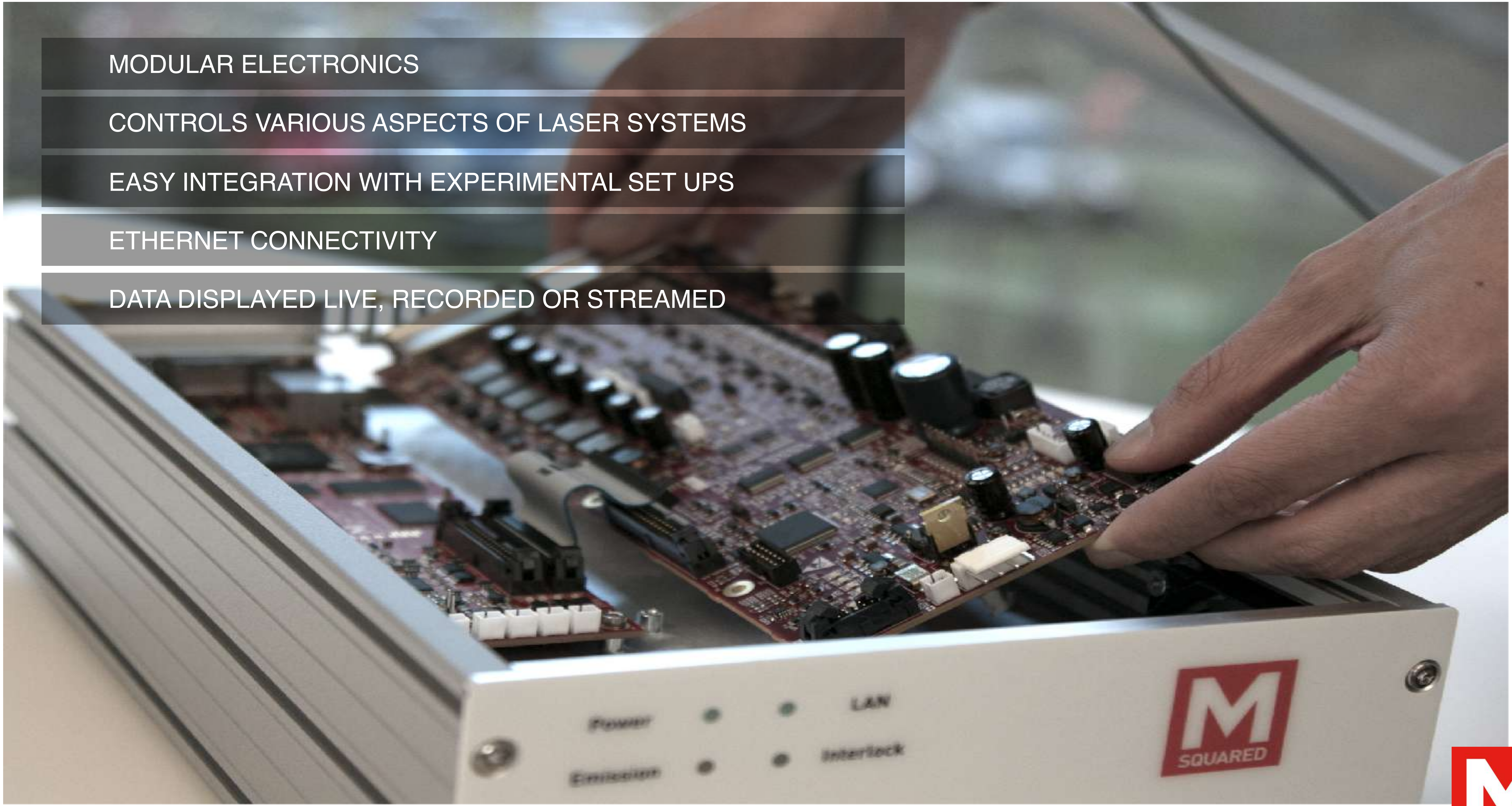


165 MAN-YEARS IN THE MAKING

INVESTMENT OF OVER £6.5 MILLION

‘INVARIANT’ LOW-STRESS, LOW-DRIFT OPTOMECHANICS

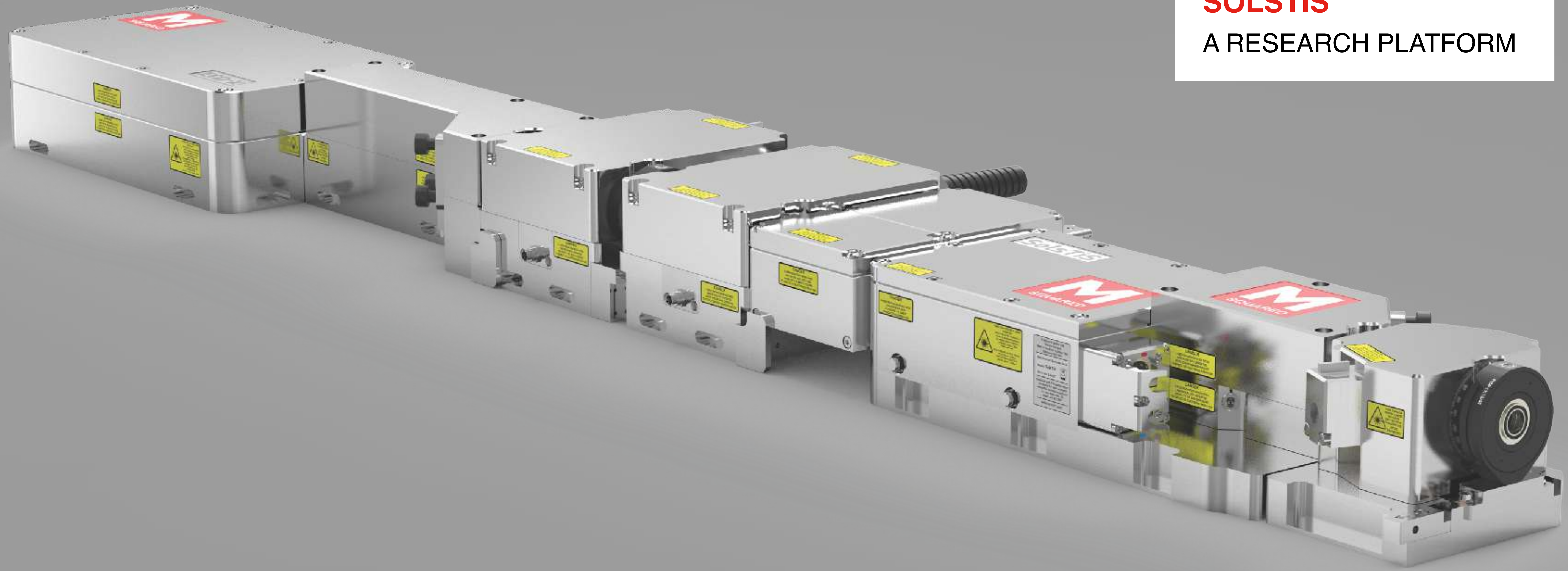
LOW-NOISE ‘ICE BLOC’ ELECTRONICS

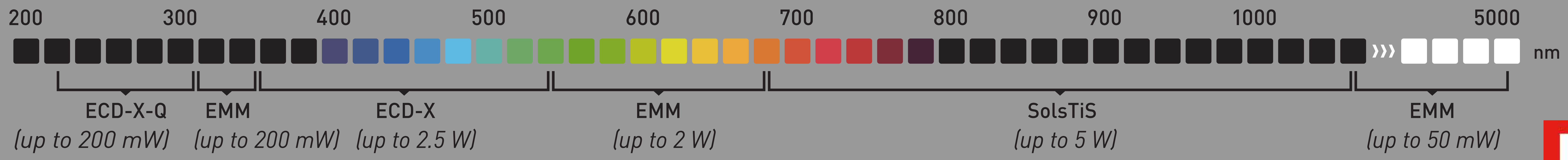


- MODULAR ELECTRONICS
- CONTROLS VARIOUS ASPECTS OF LASER SYSTEMS
- EASY INTEGRATION WITH EXPERIMENTAL SET UPS
- ETHERNET CONNECTIVITY
- DATA DISPLAYED LIVE, RECORDED OR STREAMED

SOLSTIS

A RESEARCH PLATFORM




200 300 400 500 600 700 800 900 1000 5000 nm

ECD-X-Q
(up to 200 mW)

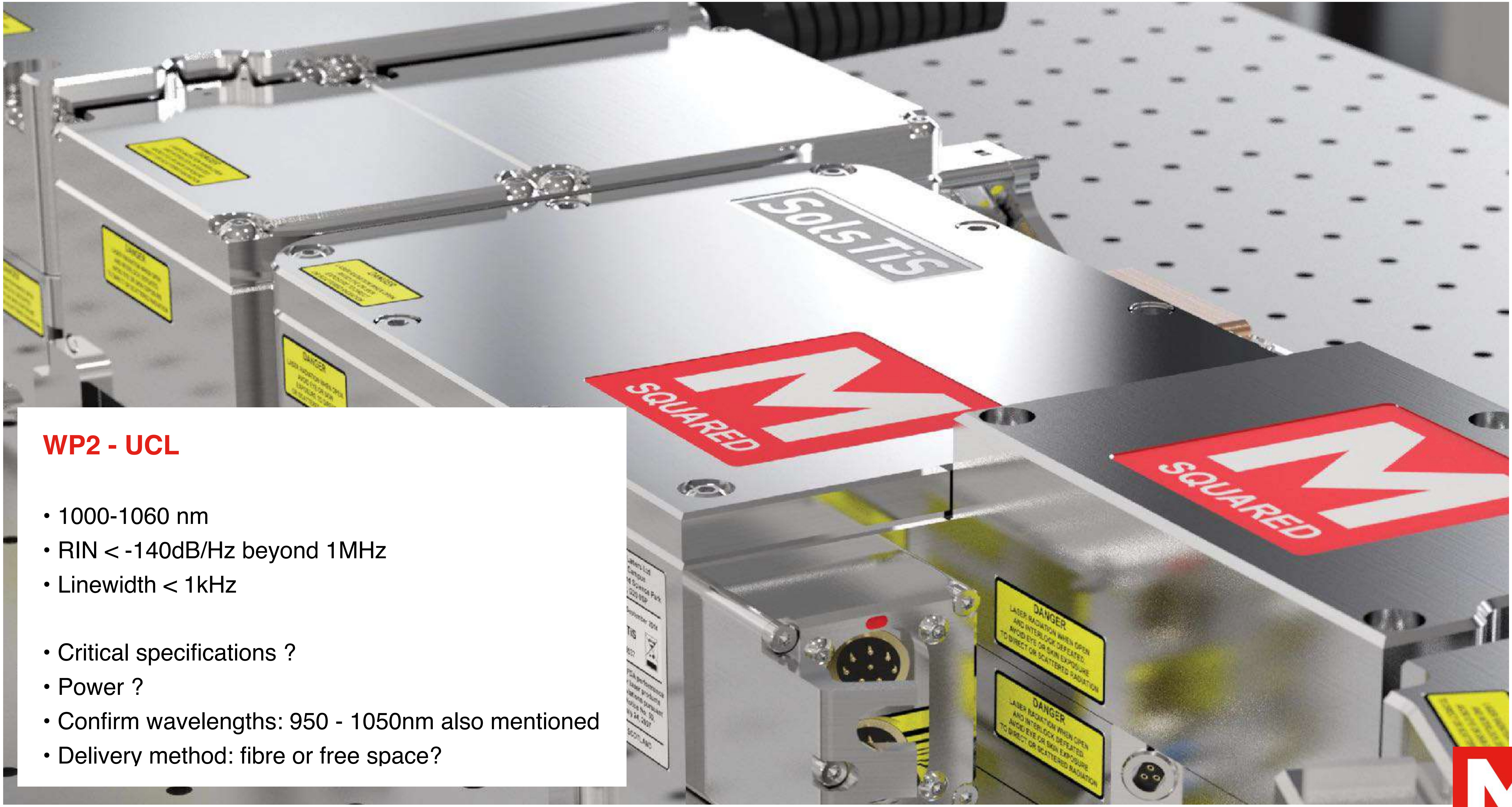
EMM
(up to 200 mW)

ECD-X
(up to 2.5 W)

EMM
(up to 2 W)

SolsTiS
(up to 5 W)

EMM
(up to 50 mW)



WP2 - UCL

- 1000-1060 nm
- RIN < -140dB/Hz beyond 1MHz
- Linewidth < 1kHz

- Critical specifications ?
- Power ?
- Confirm wavelengths: 950 - 1050nm also mentioned
- Delivery method: fibre or free space?

WP3 - UOS

- Short wavelength (doubled from TiS fundamental)
- RIN < -100dB/Hz

- Critical specifications ?
- Power ?
- Wavelengths 350-500 nm possible over 4 crystals
- Delivery method: fibre or free space?

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

THE LLOYDS BANK
NATIONAL
BUSINESS
AWARDS UK 2016
WINNER
2016

THE SUNDAY TIMES
SME EXPORT
TRACK
100
2017
LLOYDS BANK

THE QUEEN'S AWARDS
FOR ENTERPRISE:
INTERNATIONAL TRADE
2017

IOP INNOVATION
AWARDS
WINNER 2015
IOP Institute of Physics

THE QUEEN'S AWARDS
FOR ENTERPRISE:
INNOVATION
2016

THE SUNDAY TIMES
TECH
TRACK
100
2016
HISCOX

GROWING
BUSINESS
awards
amazon
WINNER 2016 INNOVATOR OF THE YEAR
M SQUARED

Minutes of the First Steering Committee Meeting

TEQ Kick-off Meeting

Trieste - 02 February 2018

1. Welcome to the Steering Committee (SC) Members

The SC is welcomed by Angelo Bassi, Chair. The SC members present at the Meeting are:

Angelo Bassi (UniTs),
Catalina Curceanu (INFN),
Anis Rahman, substituting Peter Barker (UCL)
Mauro Paternostro (QUB),
Michael Drewsen, substituting A. Dantan (AU)
Liberato Manna (TUD),
Hendrik Ulbricht (UoS),
Alessio Belenchia, substituting Caslav Brukner (OEAW),
James Bain, substituting Niels Hempler (M2).

The agenda of the meeting is approved.

2. Presentation of the management structure

A. Bassi recalls the structure of the SC and its functions and duties, as defined in the GA.

AU asks to replace A. Dantan with M. Drewsen as representative in the SC. The proposal is unanimously approved: M. Drewsen is from now member of the SC, representing AU.

A. Bassi proposes the following rules the e-voting (via email), which will be used each time a decision needs to be taken, which does not require a physical meeting:

- The Chair will send the SC a detailed description of the content and motivations of the e-vote.
- Five working days will be available for approval/rejection.
- The same voting rules apply as for physical meetings, as described in the GA.
- Tacit consensus will hold: None answer within five days implies an approval.

The proposal for e-voting is unanimously approved.

Minutes will be sent to the SC via email, and will be uploaded on the TEQ website (private area).

A. Bassi asks for the mandate to prepare a nomination of Press Officer and its duties, as well as other roles necessary for implementing TEQ, which will be submitted to the SC for e-vote. The request is unanimously approved.

3. Website

A. Bassi presents the TEQ website (www.tequantum.eu), which is ready and fully functioning, ahead of the scheduled deadline (month 2). It has been designed as declared in the GA. A. Bassi thanks M. Carlesso for the assistance in designing and developing the website.

4. Consortium Agreement (CA)

A. Bassi reports that the CA has been signed by all partners. A pdf copy of it, with all signatures in place, has been sent to partners on 30.01.2018. Hard copies of the CA are deposited at UniTs.

5. Budget

A. Bassi displays the Budget breakdown as per GA. The first instalment has been distributed to the partners on 29.01.2018 (orders sent to the bank), proportionally to the requested budget of each unit.

6. Milestones and Deliverables

Dr. Bassi displays the Milestones and the Deliverables of the Project. He highlights those related to the first year and those, which are been already achieved.

7. Dissemination & Exploitation Plan (DEP)

The DEP will be drafted by A. Bassi, based on what written in the GA, and will be sent to the SC for approval.

Regarding the newsletters, M. Paternostro proposes that they should contain

- Update of work done
- Changes in the composition of the consortium
- List of new publications
- List of talks, seminars, colloquia…
- Dissemination activities
- Any relevant information

L. Manna proposes that the Administrative Officer should take care of crafting and distributing the newsletters every three months, asking each partner for the material and required information.

A. Bassi opens the discussion about the workshop that is planned to take place in Trieste during year 2 of TEQ. He proposes September 2019 as an optimal date. The Steering Committee proposes as location the ICTP in Miramare. The proposal is unanimously approved. Availability at ICTP has to be checked.

8. Data Management Plan (DMP)

A. Bassi opens the discussion about the Data Management Plan. The points of the discussion are:

- The specific data to be saved,

- Where they should be saved,
- Whether the partner institutions have specific regulations about data management.

The DMP will be drafted by the Chair, based on what written in the GA, and will be sent to the SC for approval before month 6. Meanwhile, each partner checks with their administration on polices for data management.

9. Open Access

A. Bassi opens the discussion about Open Access. Different possibilities to implement it are discussed: In particular, it will be checked whether OpenAIRE applies for the H2020 projects and whether it can be used for TEQ.

Preprints will be posted on ArXiv and/or on the TEQ website. For paper accepted on Journals with a 6-month embargo policy, they will be uploaded on the ArXiv and/or on the TEQ website at the end of month 6.

10. Recruitment Plan

A. Bassi discusses the Recruitment Plan of each unit:

- UniTs: Delays with hiring of the Administrative Officer; in the meantime, administrative duties are shared between the PI and the Administration of UniTs. With respect to the original Proposal, also a PhD student has been hired within TEQ.
- AU: No change with respect to the GA.
- INFN: Change of the starting date of a PostDoc contract. Nothing critical.
- OEAW: A PhD student has been hired within TEQ.
- QUB: A PhD student is planned to be hired within TEQ.
- TUD: A suitable candidate has been identified for a PhD position, to be hired in the next future. A technician is planned to be hired for six mounts.
- UCL: Plan for a possible future position for a PhD student.
- UoS: No change with respect to the GA.
- M2: No change with respect to the GA.

Each partner will check whether a Declaration of Conformity is needed for the people who are hired.

11. Distribution of Tasks

A. Bassi proposes H. Ulbricht and M. Paternostro to be in charge of distributing tasks for the experimental and theory part, respectively. A. Bassi proposes a checkpoint of TEQ's activities, via Skype or via email, towards the end of June 2018. Both proposals are unanimously approved.

12. Plan for Review

A. Bassi opens the discussion on the Plan for Review, and the strategy to be adopted. The first Review Meeting is planned to take place in Brussels in February 2019. The SC agrees to ask for guidelines to the Project Office. The SC also agrees that:

- The PI of every unit should be present.
- The day before the meeting a "rehearsal" will take place.

13. Next physical Steering Committee Meeting

A. Bassi proposes November-December 2018 for the next physical meeting of the SC. The proposal is unanimously approved. A Doodle will be created to confirm the date of the meeting.

L. Manna proposes to host the meeting in Delft. The proposal is unanimously approved.

The SC agrees to extend the next SC Meeting to a two-day meeting for TEQ members, to present the research and results achieved, and discuss open problems.

14. AOB

None.

15. Closing

A. Bassi thanks the members of the SC for the meeting, and invites them to join for the dinner.

Trieste, 02 February 2018

ANNEXES

- Presentation by the TEQ Chair
- Recruitment Plan