TEQ Steering Committee Meeting

Delft – 9th November 2018

MINUTES

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

The members present at the Meeting are:

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

The chair presents the agenda, with added items with respect to what communicated prior to the meeting (see attachment). The agenda was adopted by the SC members.

2. Review of the first of month of activity

The Chair summarizes the main information of the TEQ project and lists the past TEQ SC meetings and TEQ official meetings.

- ✓ Kick off meeting: 2nd February 2018 (Trieste, IT)
- ✓ WG meeting: 28th March 2018 (London, UK)
- ✓ WG meeting: 22nd June 2018 (Southampton, UK)
- ✓ Workshop + SC meeting: 7th – 8th November 2018 (Delft, NL)

The next TEQ SC meetings will be on 25th February 2019 in Brussels, the Review Meeting will be in Brussels on 26th February 2019.

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

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

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

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

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

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

Local Committee: Angelo Bassi, Irene Spagnul

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

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

4. Publications – EU policy on open access

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

5. Discussion of the deliverables due by the end of the year

The Chair recaps deliverables that were already done and deposited to date. The partners discuss on the deliverables that are due by the end of December 2018 (month12).

TUD (D2): discussion on the main aspects of the Deliverable D2 among the partners on the basis of the draft developed by the corresponding WP lead beneficiary.

Presentation from UCL (P. Barker) on work done, followed by discussion.

INFN (D6): discussion on the main aspects of the Deliverable D6 among the partners on the basis of the draft developed by the corresponding WP lead beneficiary.

QUB (D14): discussion on the main aspects of the Deliverable D14 among the partners on the basis of the draft developed by the corresponding WP lead beneficiary.

UoS (D10): discussion on the main aspects of the Deliverable D10 among the partners on the basis of the draft developed by the corresponding WP lead beneficiary.

Presentations from UoS (H. Ulbricht and A. Vinante) on work done followed by discussion.

The Chair reminds the partners to use the Deliverable template available on the TEQ Website (Communication kit).

6. Financial report

The Chair presents a financial sheet with main budget lines for each partner and main expenditure per given period (month 1-10) for UniTS. The partners give feedback on their expenditure situation at the given moment. No critical issues are raised – expenditures are proceeding as planned.

7. Recruitment plan

The Chair presents the Recruitment plan and invites partners to give updates. Discussion of the situation on recruitment for each partner. No critical issues are raised.

Here below the situation by partner:

- ✓ UniTS: delay on recruitment of the administration officer (expected) + recruitment procedure of RTDA (senior researcher) ongoing.
- ✓ OEAW: gives the new recruitment plan for the project development.
- ✓ QUB: had to replace the PostDoc. New PostDoc will start on month 13.
- ✓ TUDelft: ok
- ✓ UCL: little delay on recruitment of technician.
- ✓ UoS: ok
- ✓ AU: ok
- ✓ INFN: recruitment of electrical engineer is delayed and temporarily replaced with researcher.

Partners are asked to update the document and send it back to the lead partner as soon the possible.

8. Preparation of the review meeting (26.02.2019)

The Chair presents the draft agenda and the partners discuss the content of the presentation to be done at the review meeting and the setup of the presentations.

9:00 – 9:15 R. Borissov (chair) Introduction, tour du table
9:15 – 9:45 Overview by the coordinator
9:45 – 10:30 WP 1
Coffee (10:30 to 11:00)
11:00 – 11:45 WP2
11:45 – 12:30 WP3
Lunch (12:30 to 13:30)
13:30 – 14:15 WP4
14:15 – 14:30 WP5 - Management
14:30 – 14:45 WP6 - Dissemination
14:45 – 15:15 Financial data
15:15 – 15:45 Innovation potential discussion
15:45 – 16:15 General discussion
16:15 – 16:45 Assessment preparation by monitors and PO
16:45 – 17:00 R. Borissov Closing

9. Continuous reporting

Irene Spagnul (UniTS) presents the Continuous reporting sections and contents on the EU Participant Portal. The reporting is ongoing and the partners are encouraged to feed the reporting with their data through the lead partner UniTS.

10. Milestones

The partners discuss the project milestones, in particular the first one (due at month 12): Preparation of NCs (WP1 – lead beneficiary AU).

11. Deliverables for 2019

The Chair gives an overview of the Deliverables due in 2019 (months 13-24).

12. Next SC Meeting

The Chair presents the next SC Meetings for 2019:

Where: Brussels

When: 25th February 2019 (day before the review meeting, also for the rehearsal)

Structure: full-day meeting, internal to the consortium.

The Following SC meeting will be in connection to the workshop September 2019 in Trieste.

13. AOB

14. Closing

Angelo Bassi, Chair, wraps up the discussion on management issues and thanks everyone for the hard work and the fruitful collaboration.

ANNEX: Presentation SC Meeting _ Angelo Bassi

Attachment I. Agenda

(added items underlined)

1. Welcome by the SC chair and adoption of agenda

2. Review of the first months of activity
   - Relevant dates
   - Past SC meetings & official meetings
   - Website and information therein
   - Communication and Dissemination activities

3. Mid-term workshop on "*Redefining the foundations of physics in the quantum technology era*"

4. Publications – EU policy on open access

5. Discussion of deliverables due by the end of the year

6. Financial report

7. Recruitment Plan – update

8. Preparation for the review meeting (26.02.2019)
   - Draft Agenda
   - Discussion on how to present in a coordinated way

9. <u>Continuous Reporting</u>

10. <u>Milestones</u>

11. <u>Deliverable (from year 2)</u>

12. <u>Next SC meeting</u>

13. AOB

14. Closing

Testing the large-scale limit of quantum mechanics

TEQ

European Commission

Steering Committee Meeting

Delft 9th November 2018

Angelo Bassi - Chair

1. Welcome and adoption of agenda

Angelo Bassi - UniTs & chair
Catalina Curceanu – INFN
Peter Barker – ULC
Mauro Paternostro – QUB
Michael Drewsen – AU
Liberato Manna & Arjan Houtepen – TUD & Local Host
Hendrik Ulbricht – UoS
Alessio Belenchia (replacing Caslav Brukner) – OEAW

A warm welcome to Irene Spagnul, TEQ's Administrative Officer

Agenda of SC Meeting

AGENDA

1. Welcome to the SC members and adoption of agenda
2. Review of the first months of activity
   - Relevant dates
   - Past SC meetings & official meetings
   - Website and information therein
   - Communication and Dissemination activities
3. Mid-term workshop on *"Redefining the foundations of physics in the quantum technology era"*
4. Publications – EU policy on open access
5. Discussion of deliverables due by the end of the year
6. Financial report
7. Recruitment Plan – update
8. Preparation for the review meeting (26.02.2019)
   - Draft Agenda
   - Discussion on how to present in a coordinated way
9. <u>Continuous reporting</u>
10. <u>Milestones</u>
11. <u>Deliverables (from year 2)</u>
12. <u>Next SC meeting</u>
13. AOB
14. Closing

2. Review of the first months of activity
relevant dates

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

Next SC meeting: 25th February in Brussels
Review meeting: 26th February in Brussels

2. Review of the first months of activity

past SC meetings & official meetings

Kick off meeting: 2nd February 2018 (Trieste, IT)

WG meeting: 28th March 2018 (London, UK)

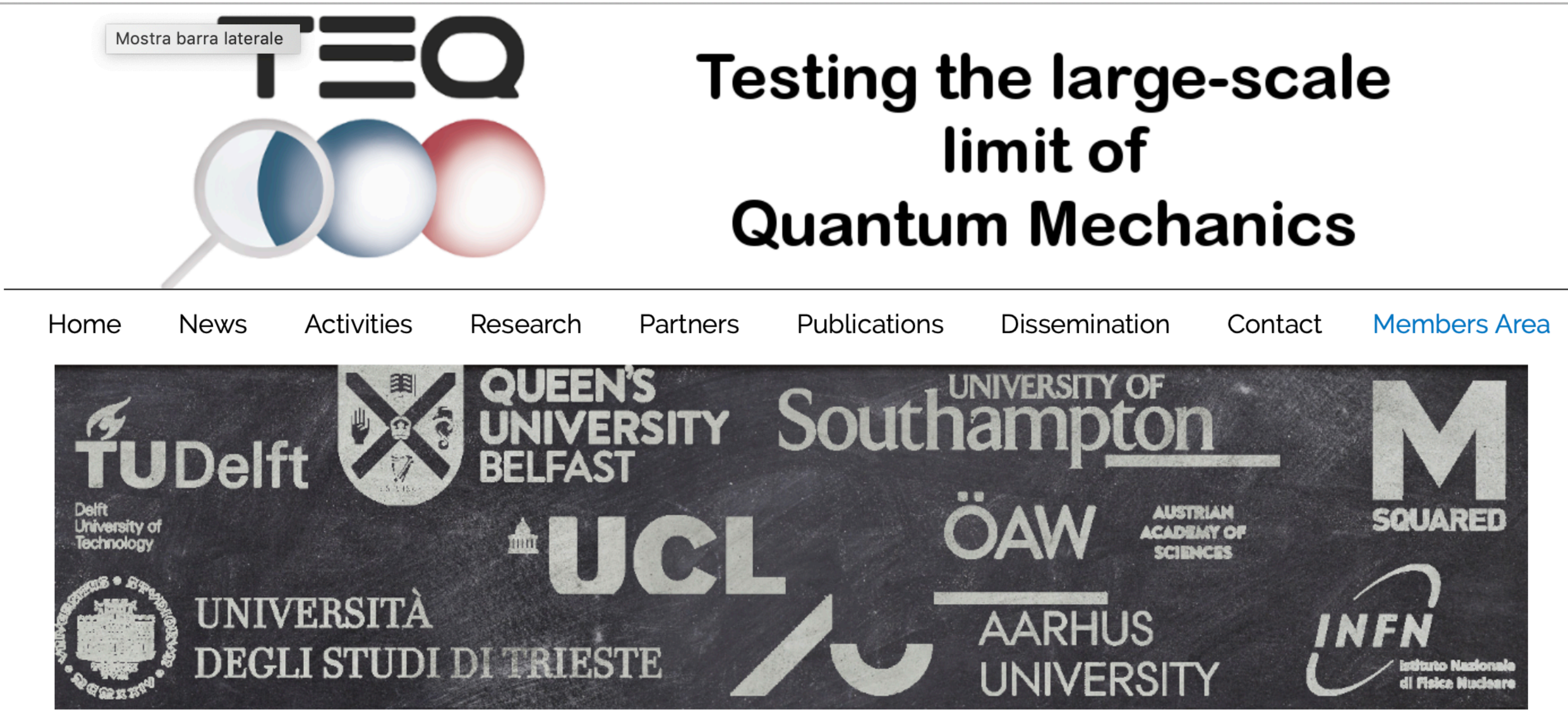
WG meeting: 22nd June 2018 (Southampton, UK)

Workshop + SC meeting: 7th – 8th November 2018 (Delft, NL)

2. Review of the first months of activity

website and information therein

www.tequantum.eu
www.facebook.com/TEQuantum
www.twitter.com/TEQuantum



2. Review of the first months of activity

communication and dissemination activities

	Website	**OpenAire**	EU Portal
Publications	13	11	Copied from OpenAire + manual
Preprints	27 (13+14)		
Talks	54		
Press Releases	3		
Newsletters	2		
Press Articles	18		
Multimedia	1		

Irene Spagnul (Administrative Officer - UniTs)

Catalina Curceanu (Press Officer - INFN)

3. Mid-term workshop

FROM THE GA: *…organization of a workshop on the topic of "Redefining the foundations of physics in the quantum technology era", which will be held in Trieste in the second year of TEQ's lifetime. We will invite 20 leading figures in the communities relevant to TEQ to contribute to a 4- day workshop open to participants outside the Consortium and will have two objectives: fostering new collaborations among the participants (mixing experimental and theoretical efforts), leading to new proposals for funding, increasing the visibility of the area at the core of TEQ, and identifying new directions and problems to tackle. Ideally, this will become the 1st of a series of workshops on the themes addressed by our Work Plan […]* The participation of about 100 attendees is estimated, including TEQ members, their students, and researchers external to TEQ

3. Mid-term workshop

Place: Trieste, IT

Dates (4 days): Week of September 16^{th} 2019

Local Committee: Angelo Bassi, Irene Spagnul

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

4. Publications
EU policy on open access

Irene Spagnul (Administrative Officer − UniTs)

5. Discussion of deliverables due by the end of the year

WP No	Del Rel.	Del No	Title	Lead Beneficiary	Nature	Dissemin	Est. Del. Date (	Receipt Date
WP5	D5.1	D19	Website	UNITS	Website	Public	28 Feb 2018	15 Mar 2018
WP6	D6.1	D24	Press releases	UNITS	Website	Public	31 Mar 2018	28 Mar 2018
WP5	D5.2	D20	Data Management Plan	UNITS	ORDP: (	Public	30 Jun 2018	28 Jun 2018
WP1	D1.2	D2	1-Colloidal NCs	TU Delft	Report	Public	31 Dec 2018	
WP2	D2.1	D6	Low noise electronics	INFN	Report	Public	31 Dec 2018	
WP3	D3.1	D10	Low noise environment	SOUTH...	Report	Public	31 Dec 2018	
WP4	D4.1	D14	Calibration of decoherence	QUB	Report	Public	31 Dec 2018	
WP6	D6.2	D25	Popular press articles	UNITS	Website	Public	31 Dec 2018	
WP6	D6.5	D28	Dissemination and Exploitat	UNITS	Report	Confide	31 Dec 2018	

6. Financial report

	Direct Personnel costs (as per MoU)	Direct Personnel costs (as of today)	Other Direct costs (as per MoU)	Other Direct costs (as of today)	Indirect costs	TOTAL
UniTs	417.008,00	60.785,46	80.000,00	2.513,34	124.252,00	*621.260,00*
INFN	200.000,00		107.500,00		76.875,00	*384.375,00*
UCL	222.703,00		192.494,00		103.799,25	*518.996,25*
QUB	309.259,00		44.500,00		88.439,75	*442.198,75*
AU	275.000,00		137.500,00		103.125,00	*515.625,00*
TUD	251.572,00		63.500,00		78.768,00	*393.840,00*
UoS	239.997,00		342.396,00		145.598,25	*727.991,25*
OEAW	265.000,00		32.900,00		74.475,00	*372.375,00*
M2	175.000,00		140.850,00		78.962,50	*394.812,50*
Total	*2.355.539,00*		*1.141.640,00*		*874.294,75*	*4.371.473,75*

7. Recruitment Plan
update

First update
at the kick off meeting
2nd February 2018

8. Preparation for the review meeting

draft agenda (Brussels, 26th February 2019)

9:00 – 9:15	R. Borissov (chair)	Introduction, tour du table
9:15 – 9:45		Overview by the coordinator
9:45 – 10:30		WP 1
Coffee (10:30 to 11:00)		
11:00 – 11:45		WP2
11:45 – 12:30		WP3
Lunch (12:30 to 13:30)		
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14:45 – 15:15		Financial data
15:15 – 15:45		Innovation potential discussion
15:45 – 16:15	General discussion	
16:15 – 16:45	Assessment preparation by monitors and PO	
16:45 – 17:00	R. Borissov	Closing

8. Preparation for the review meeting
discussion - how to present it in a coordinated way

Structure • Common ppt template • 30 minutes + 15 discussion? • For each WP: Overview (units & PM involved, objectives, tasks, deliver.)	**WP1 – Trapping (45')** Speaker: M. Drewsen	**WP2 – Cooling (45')** Speaker: P. Barker
Overview - coordinator (30') • Welcome • Scientific project • Impact • Consortium • Presentation of WPs • Milestones, deliverables…	**WP3 - Testing (45')** Speaker: H. Ulbricht	**WP4 – Enabling (45')** Speaker: M. Paternostro
Financial data (30') Speaker: I. Spagnul (?) • Overall budget • Budget of each unit – year 1	**WP5 – Management (15')** Speaker: A. Bassi • Meetings & activities • CA, DEP, DMP, RP … • Setup website	**WP6 – Dissemination (15')** Speaker: C. Curceanu • Overview - statistics • Talks & interviews • Newsletters • Press articles & releases • Quantum Cafè

9. Continuous Reporting

Irene Spagnul (Administrative Officer − UniTs)

10. 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

11. Deliverables (from year 2)

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

12. Next SC meeting

Where: Brussels
When: 25th February 2019 (day before the review meeting, also for the rehearsal)
Structure: Half-day meeting, internal to the consortium.

Following SC meeting – in connection to the workshop
September 2019

13. AOB

14. Closing

Many thanks for the collaboration

See you in Brussels!

Testing the large-scale limit of Quantum Mechanics

Opto-electric feedback cooling in a linear Paul trap

Thomas Penny

UCL Optomechanics

Contents

- Introduction
- The Experiment
- Mass Loss
- Parametric Feedback Cooling
- Conclusions

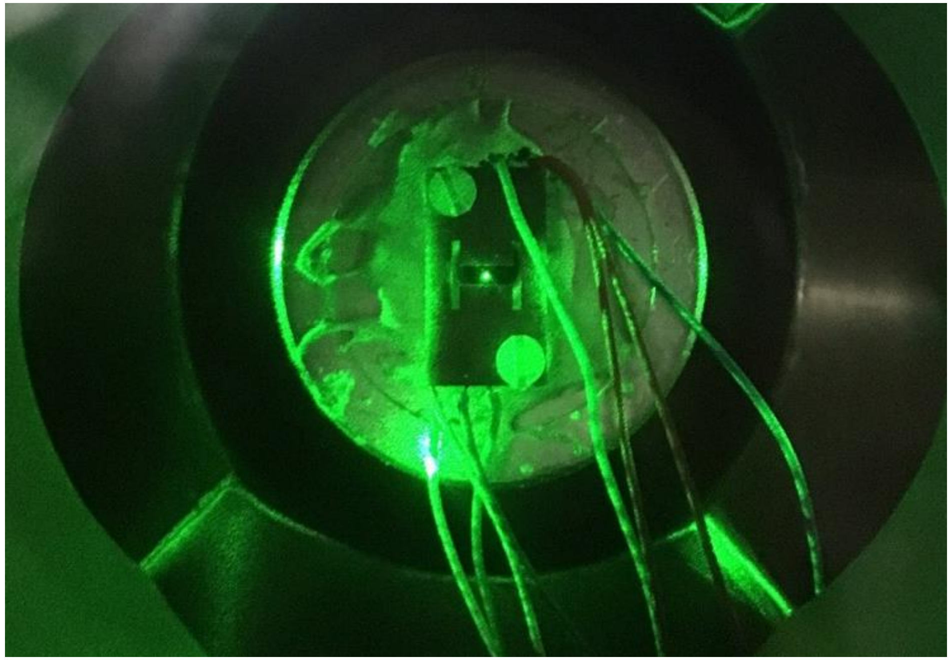
Introduction

Motivation

Measuring heating rates from collapse models

Particles levitated in Paul Trap are well isolated

Need to cool to make the heating rates more dominant

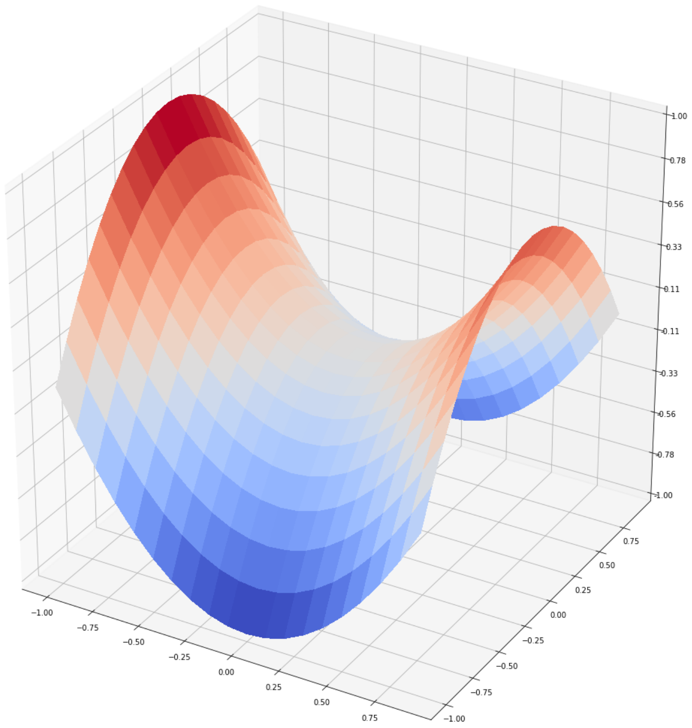


Dynamic Electric Field

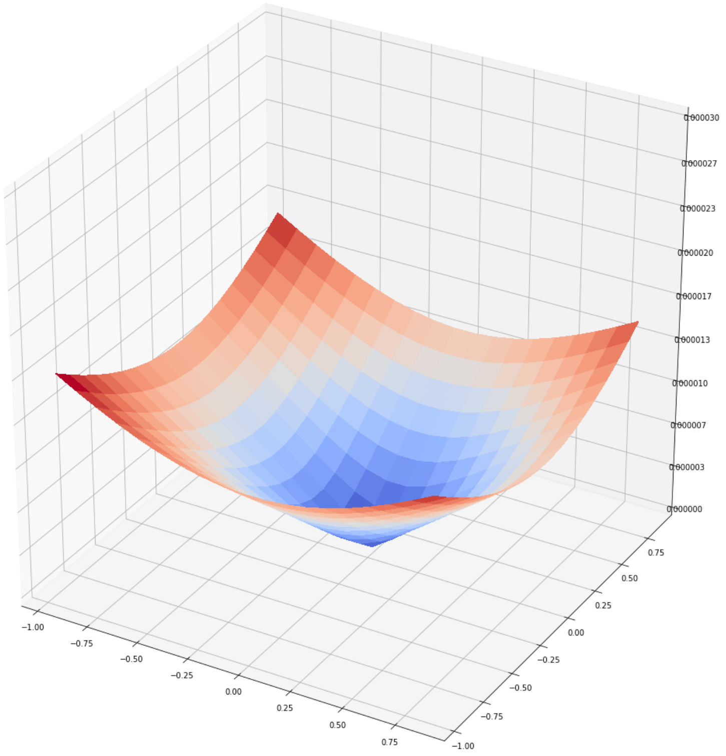
$$V(x, y, z) = V_0(\alpha' x^2 + \beta' y^2 + \gamma' z^2)$$

$$\alpha' + \beta' + \gamma' = 0$$

$$\frac{q}{4m{\omega_d}^2}|\nabla V(x, y, z)|^2$$



Anti-Trapping ⟶ Trapping



Motion in a Paul Trap

$$x(t) \approx 2AC_0\cos(\beta_x \frac{\omega_d t}{2})[1 - \frac{q_x}{2}\cos(\omega_d t)]$$

$$|a_x|, {q_x}^2 \ll 1$$

$$\beta_x \approx \sqrt{a_x + {q_x}^2/2}$$

$$a_x = \frac{4qU_0\alpha}{m\omega_d} \qquad q_x = \frac{2qV_0\alpha'}{m\omega_d}$$

Motion in a Paul Trap

$$x(t) \approx 2AC_0 \cos(\beta_x \frac{\omega_d t}{2})[1 - \frac{q_x}{2}\cos(\omega_d t)]$$

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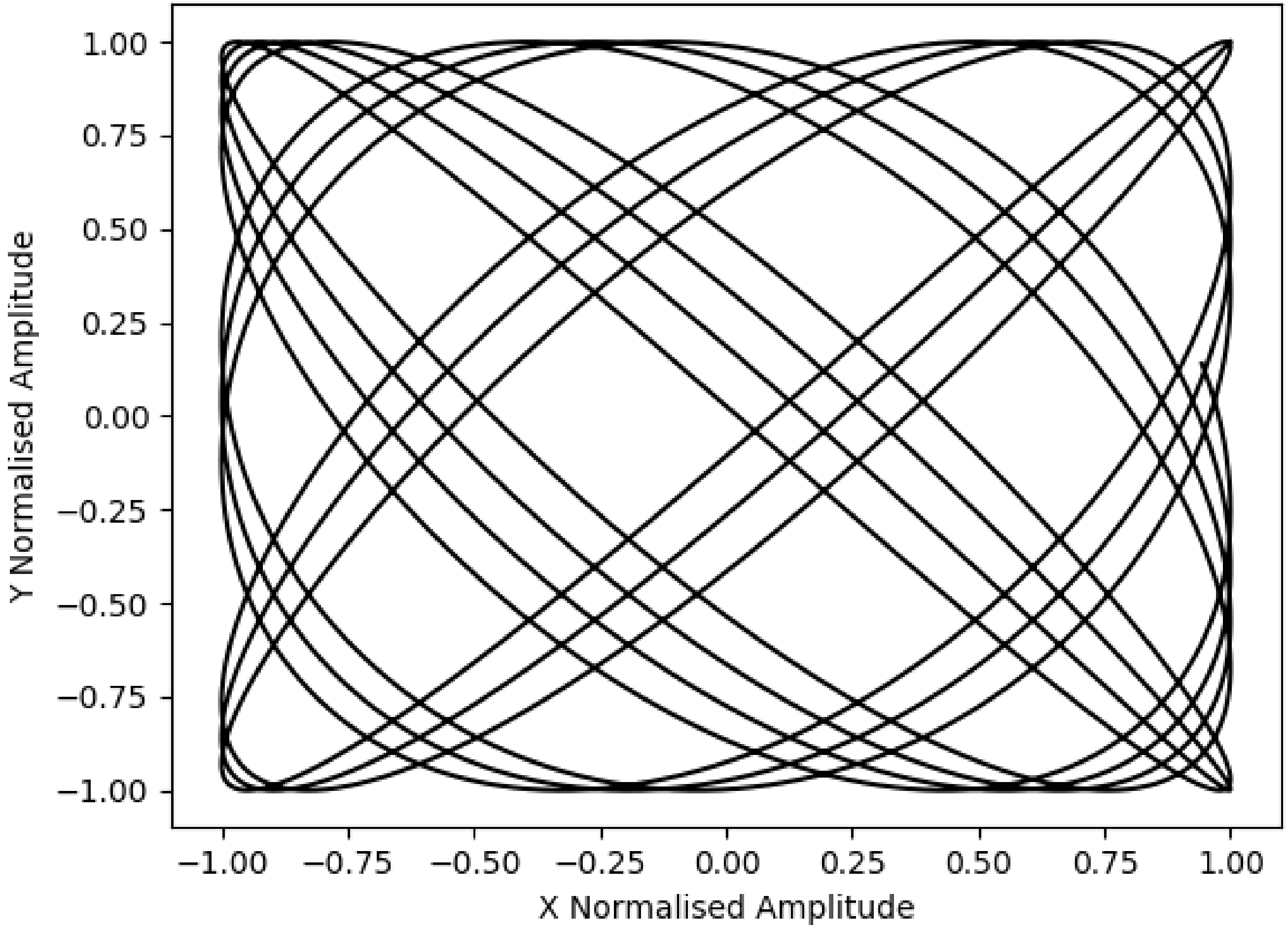


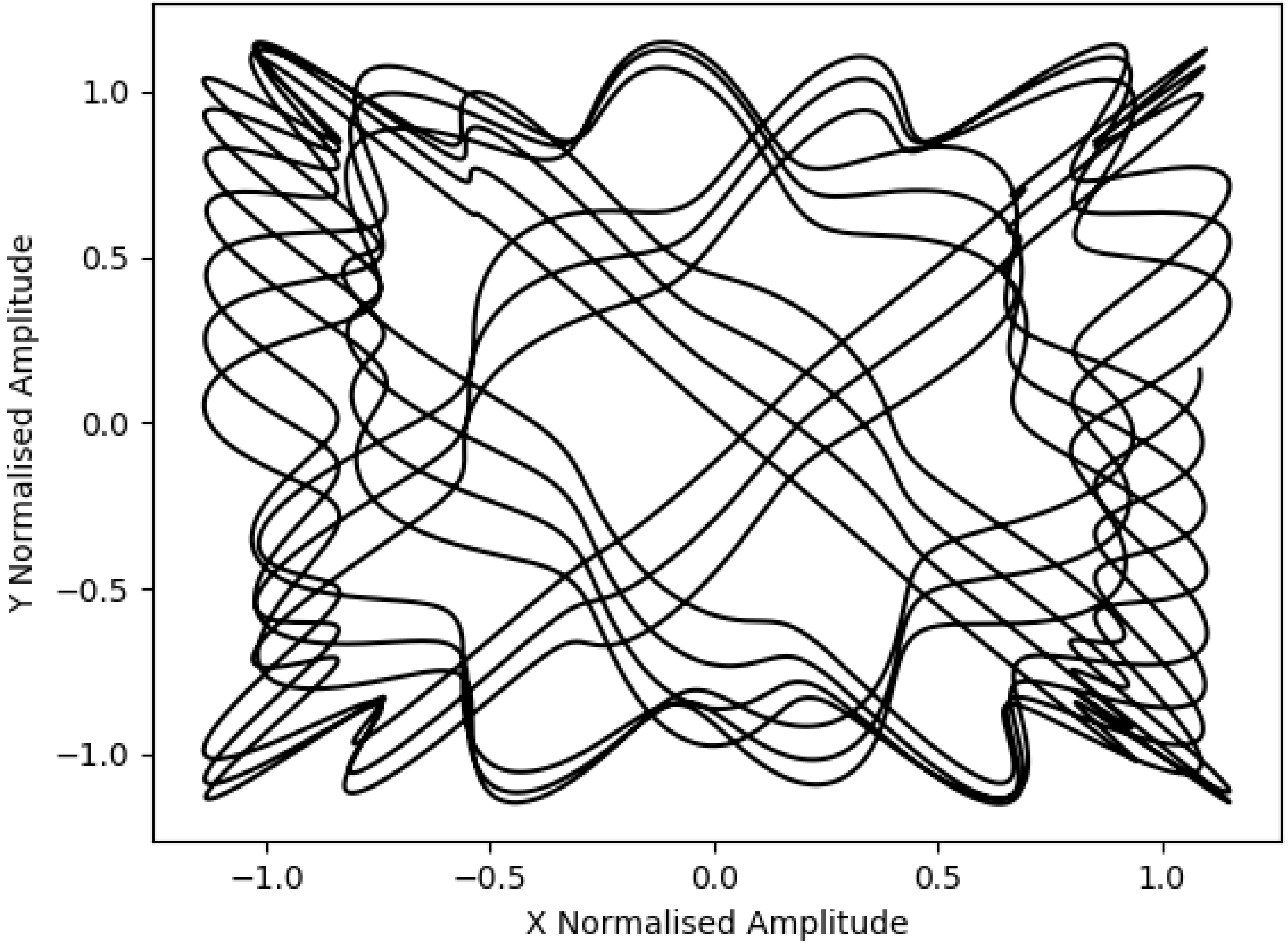
Motion in a Paul Trap

$$x(t) \approx 2AC_0\cos(\beta_x \frac{\omega_d t}{2})[1 - \frac{q_x}{2}\cos(\omega_d t)]$$

$$|a_x|, {q_x}^2 \ll 1$$

$$\beta_x \approx \sqrt{a_x + {q_x}^2/2}$$

$$a_x = \frac{4qU_0\alpha}{m\omega_d} \qquad q_x = \frac{2qV_0\alpha'}{m\omega_d}$$



Secular Frequency

$$\omega_x = \sqrt{\left(\frac{qV_0\alpha'}{m\omega_d}\right)^2 - \frac{qU_0\alpha}{m}}$$

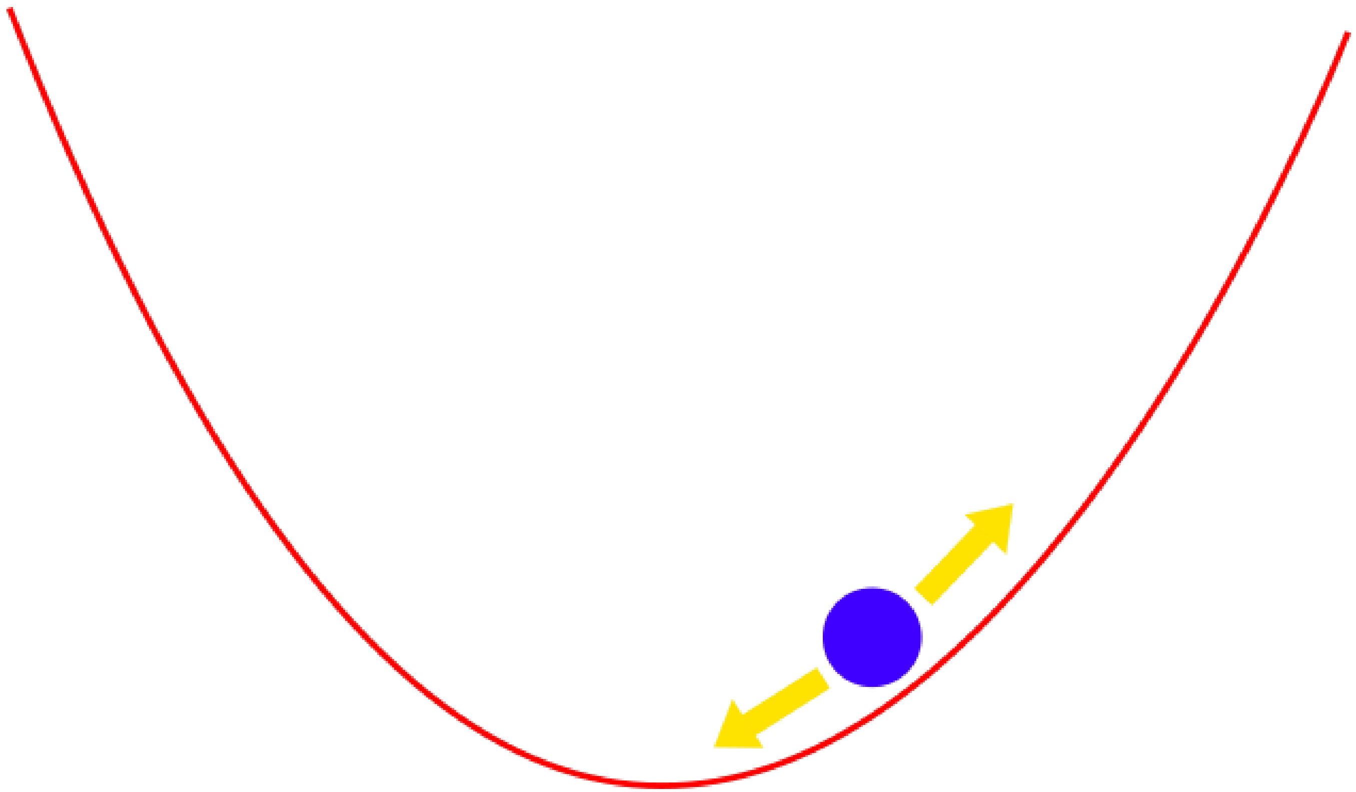
$$\omega_y = \sqrt{\left(\frac{qV_0\beta'}{m\omega_d}\right)^2 - \frac{qU_0\beta}{m}}$$

$$\omega_z = \sqrt{\left(\frac{qV_0\gamma'}{m\omega_d}\right)^2 + \frac{qU_0\gamma}{m}}$$

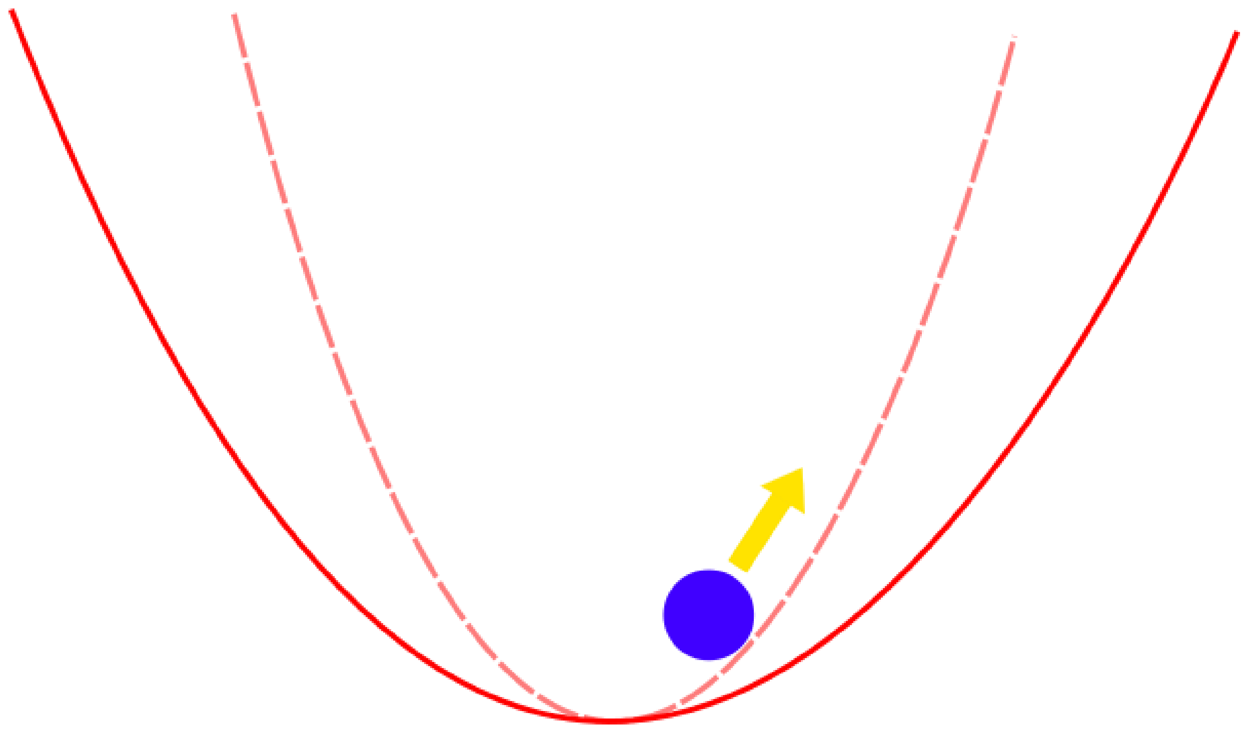
V_0	RF Voltage Amplitude
U_0	DC Voltage Amplitude
ω_d	Drive Frequency
$\frac{q}{m}$	Charge to mass ratio of trapped particle

$\alpha' = 2.7 \times 10^9$
$\beta' = \alpha'$
$\gamma' = 10^6$
$\alpha = 1.2 \times 10^6$
$\beta = -2.6 \times 10^5$
$\gamma = 8.5 \times 10^5$

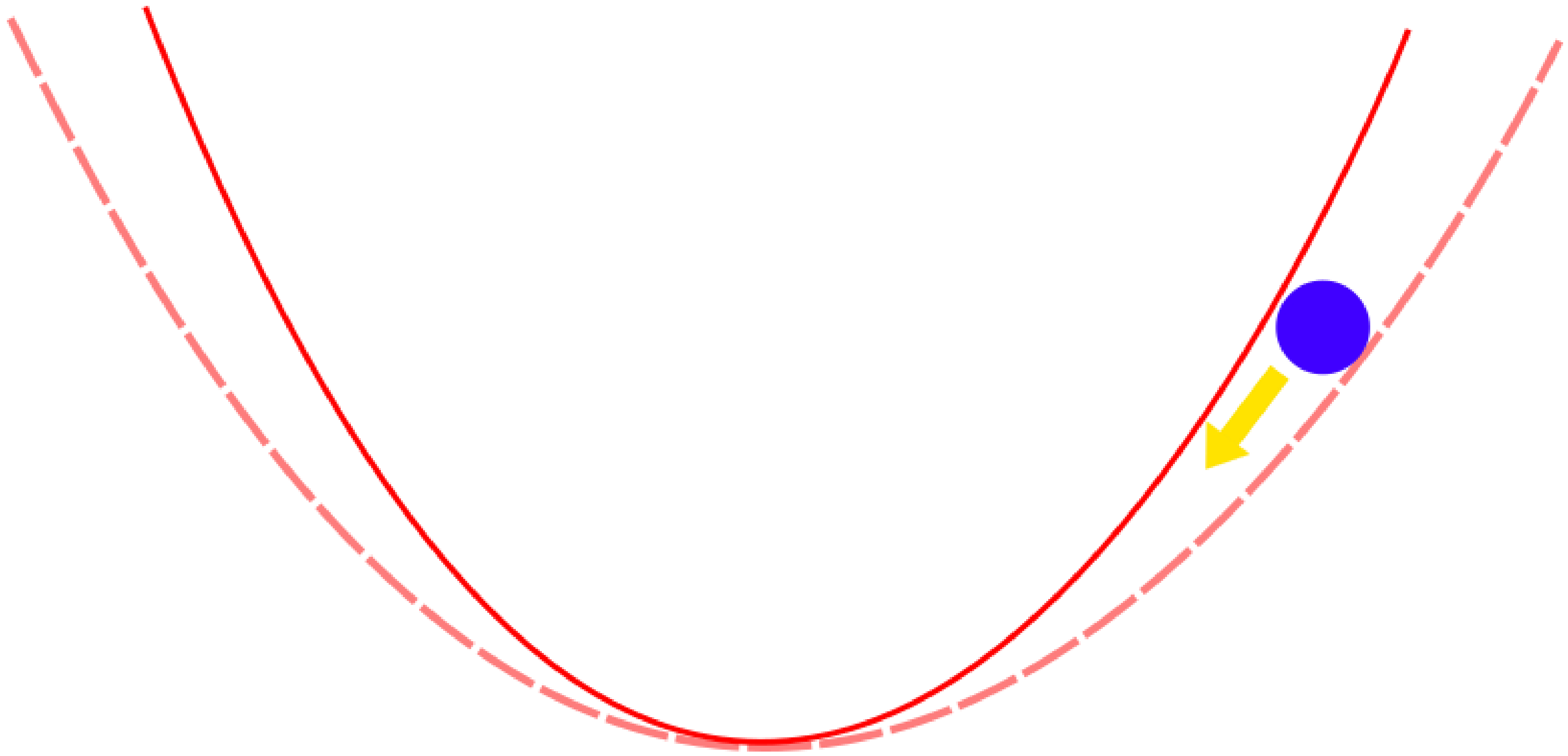
Parametric Feedback Cooling



Parametric Feedback Cooling

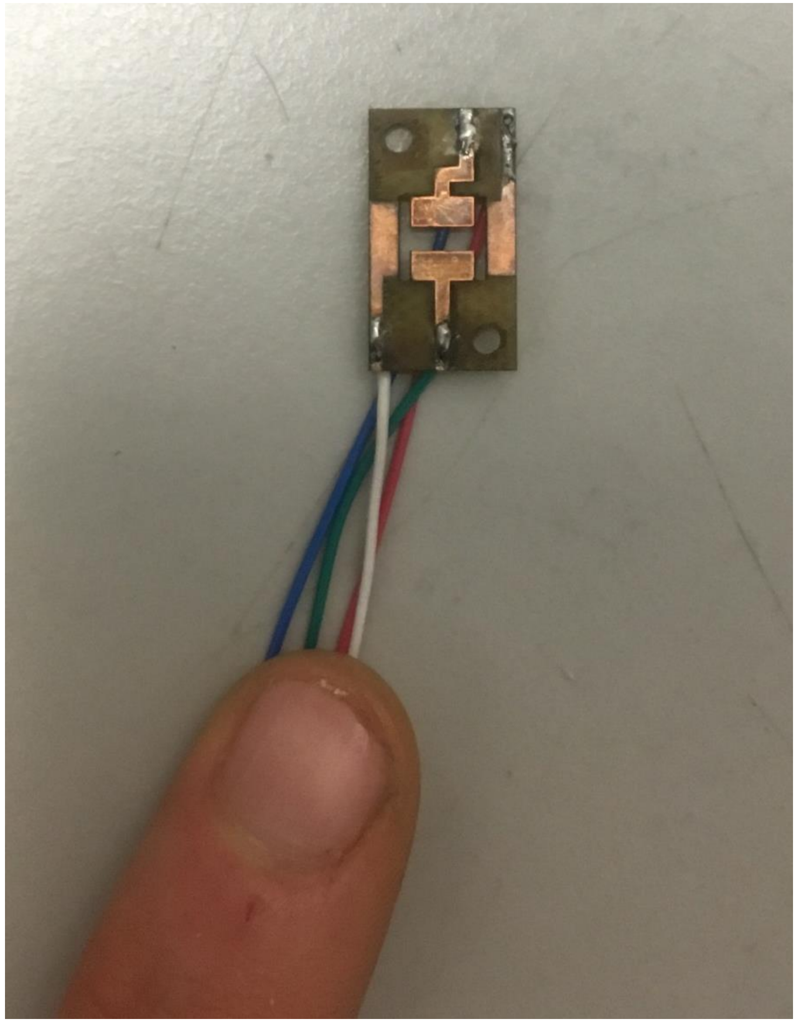


Parametric Feedback Cooling

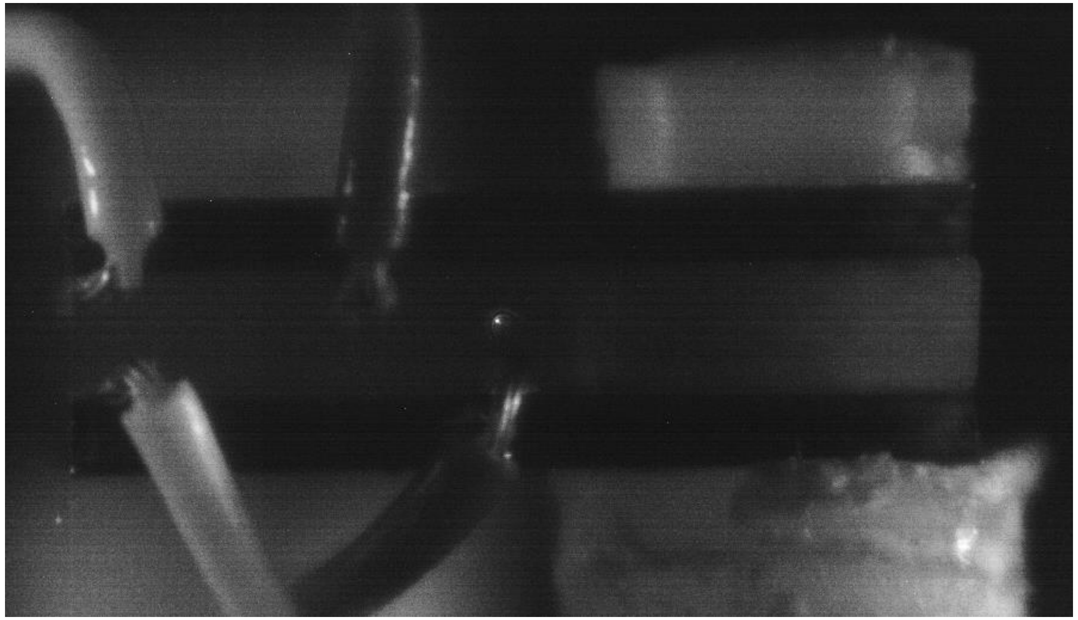


The Experiment

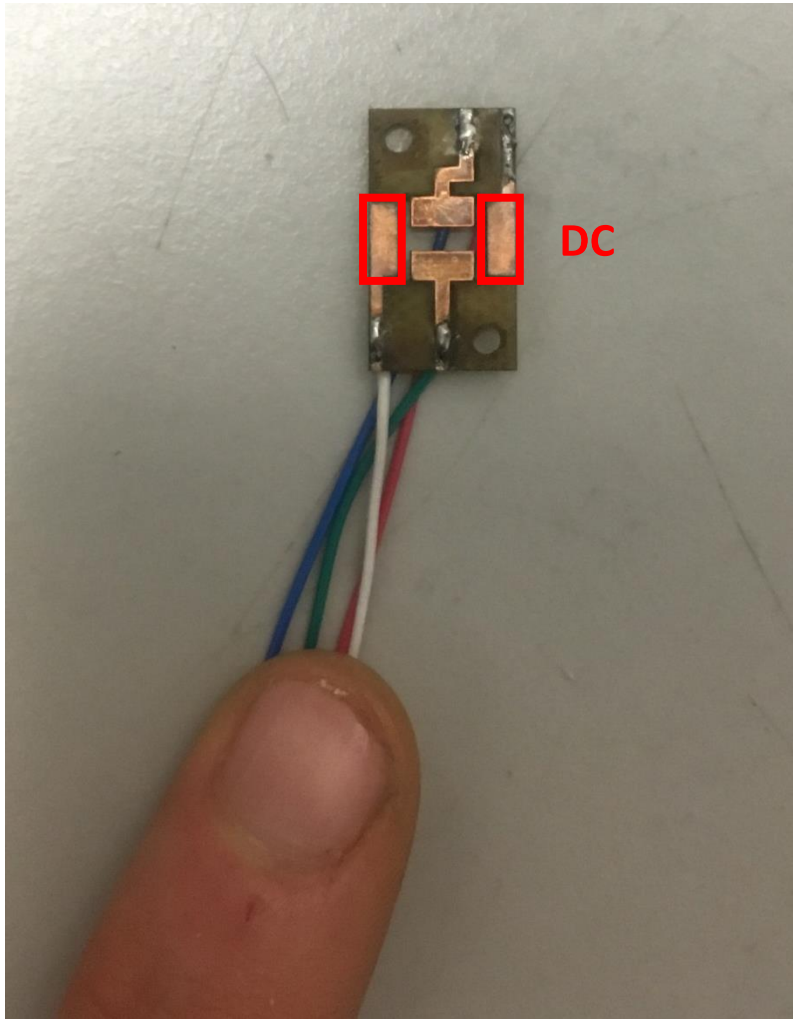
Paul Trap



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



Paul Trap



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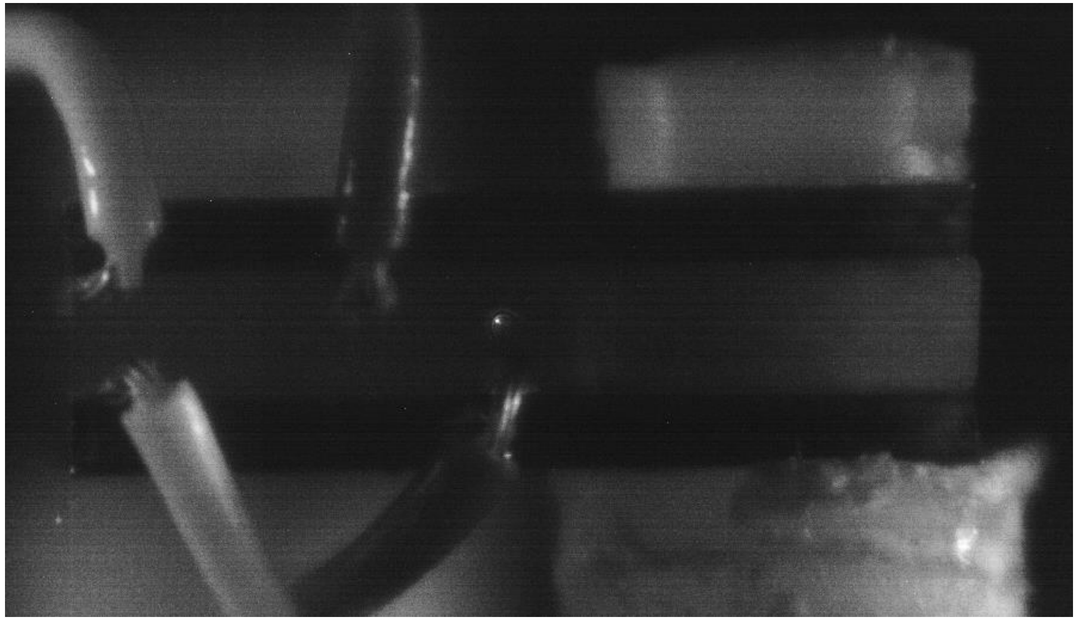
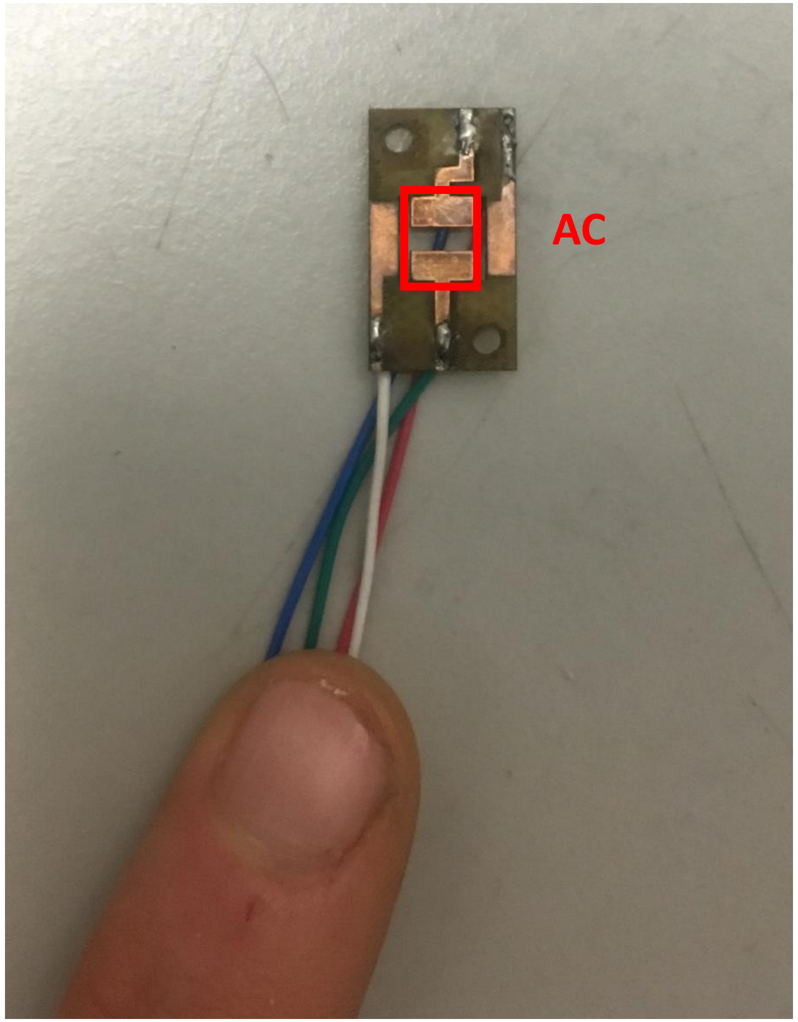
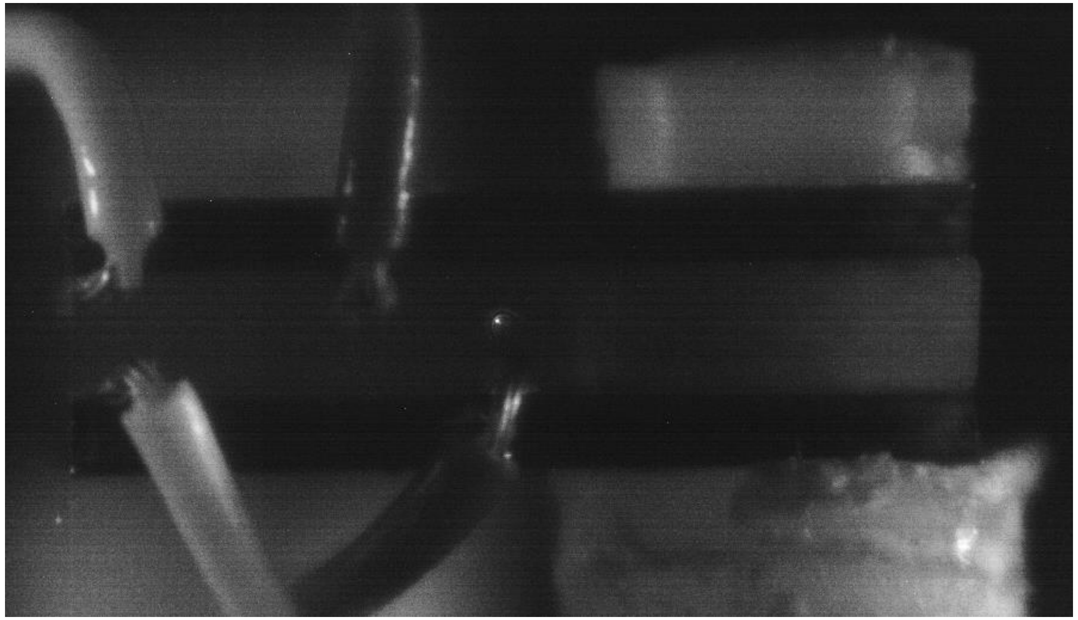
$$\omega_d = 2kHz - 8kHz$$



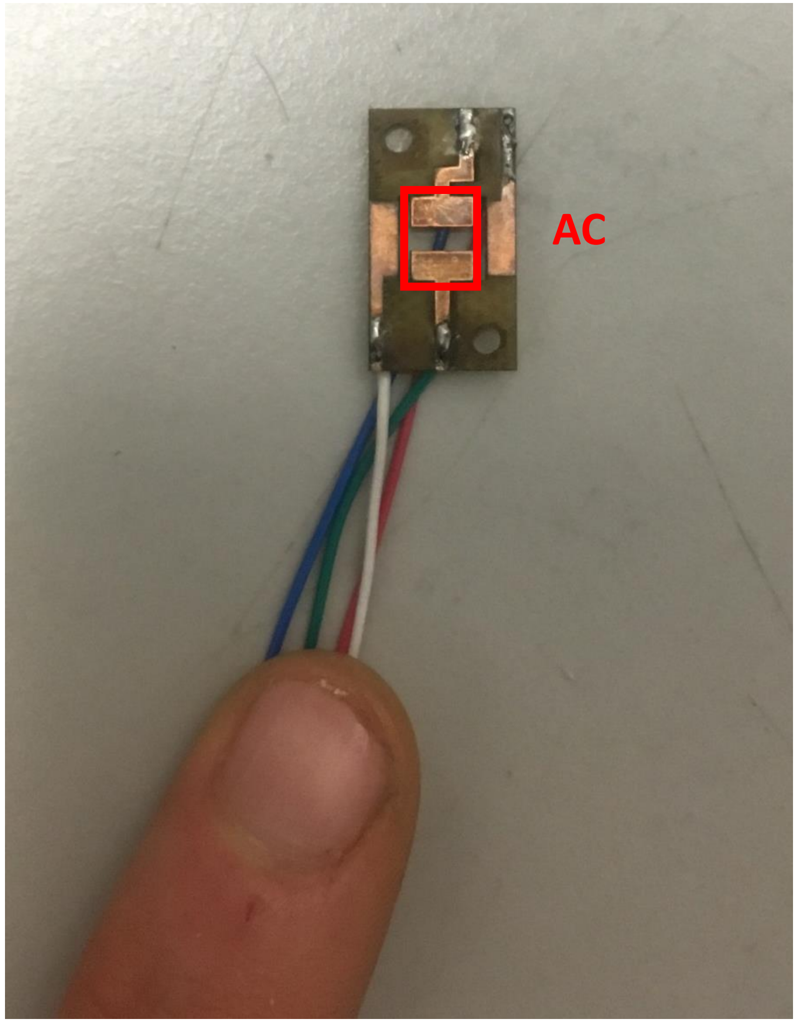
Paul Trap



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



Paul Trap



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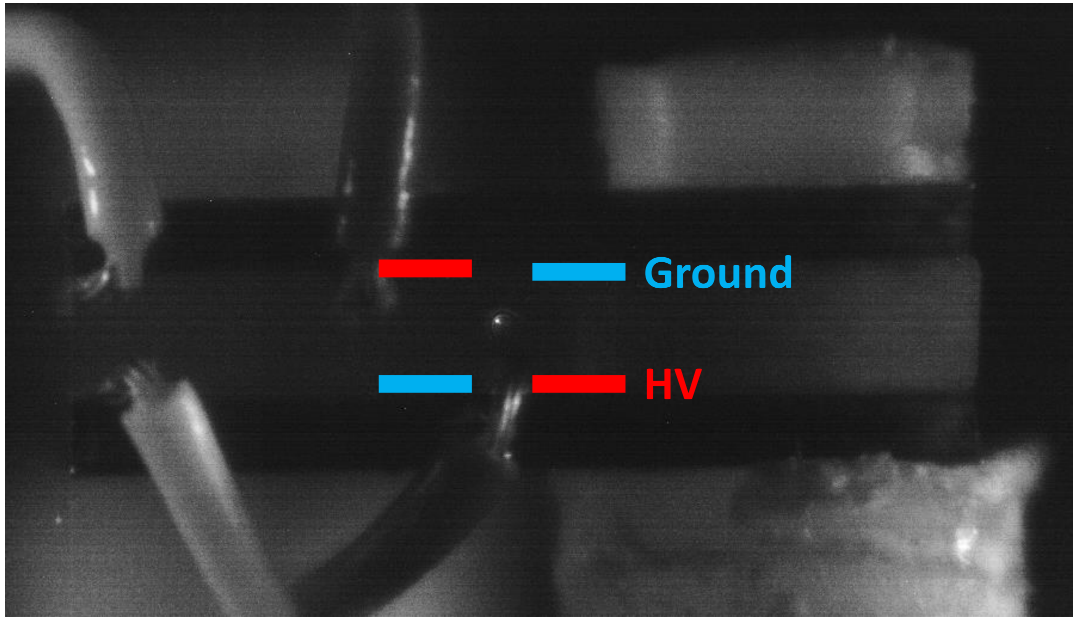
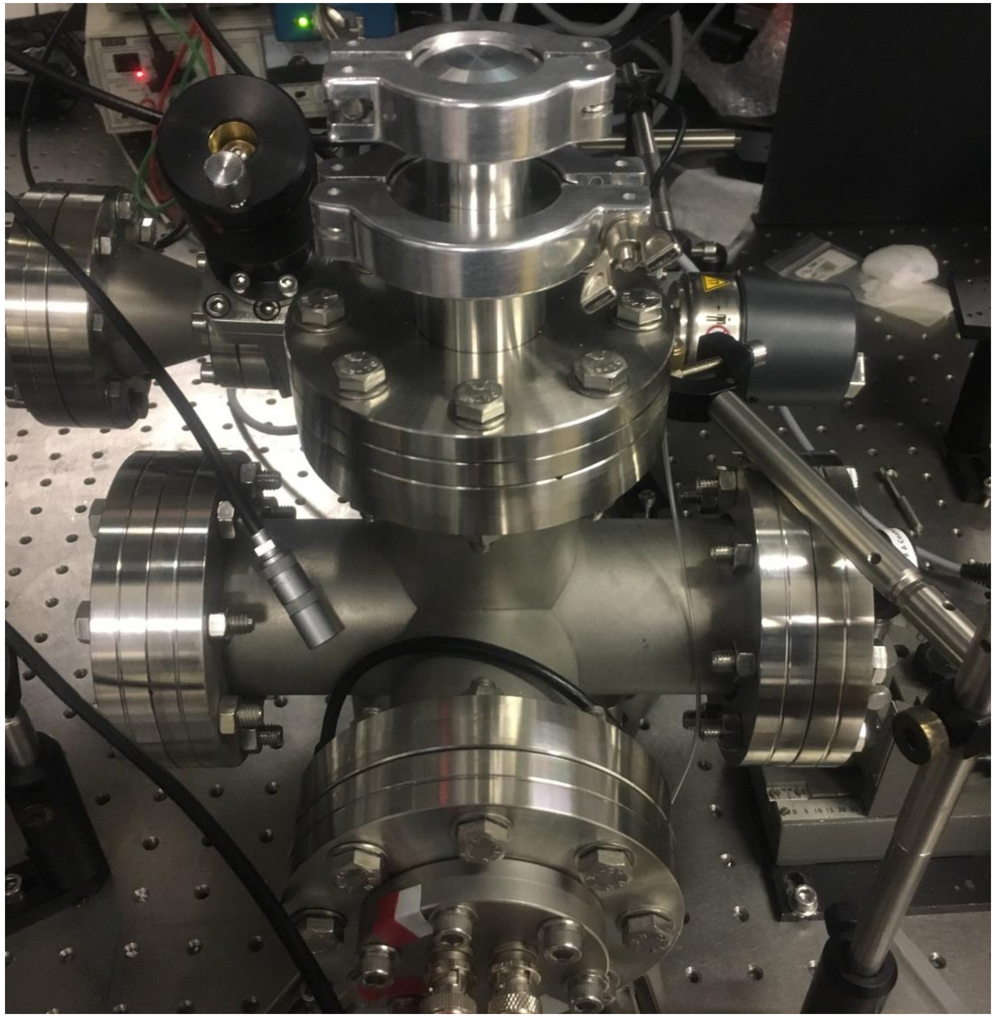
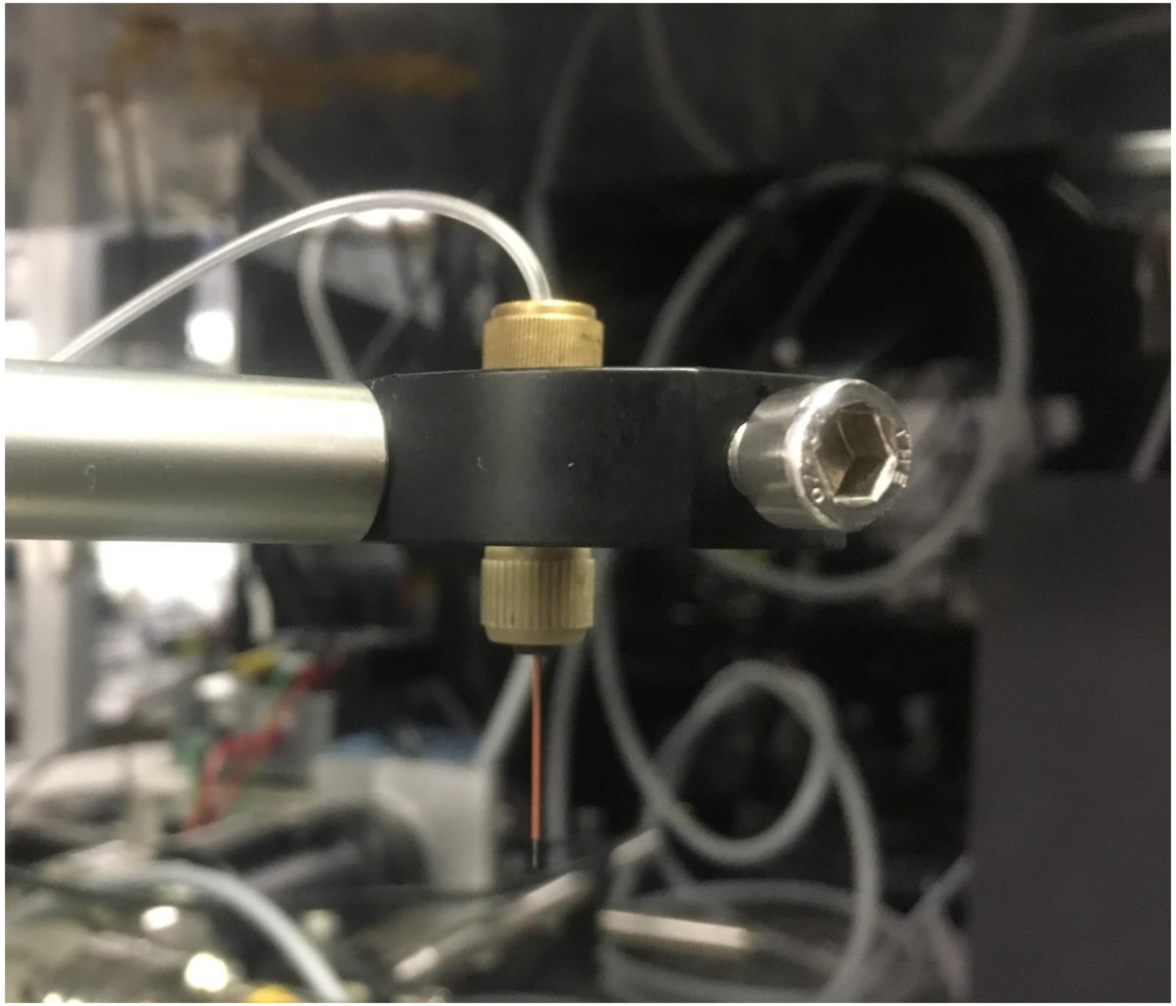


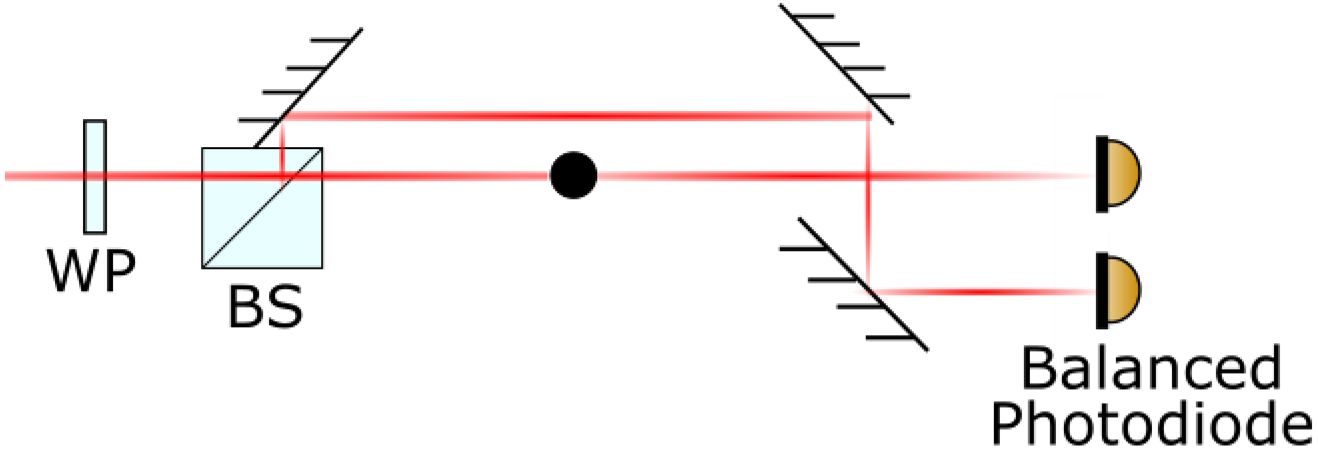
Loading

UCL



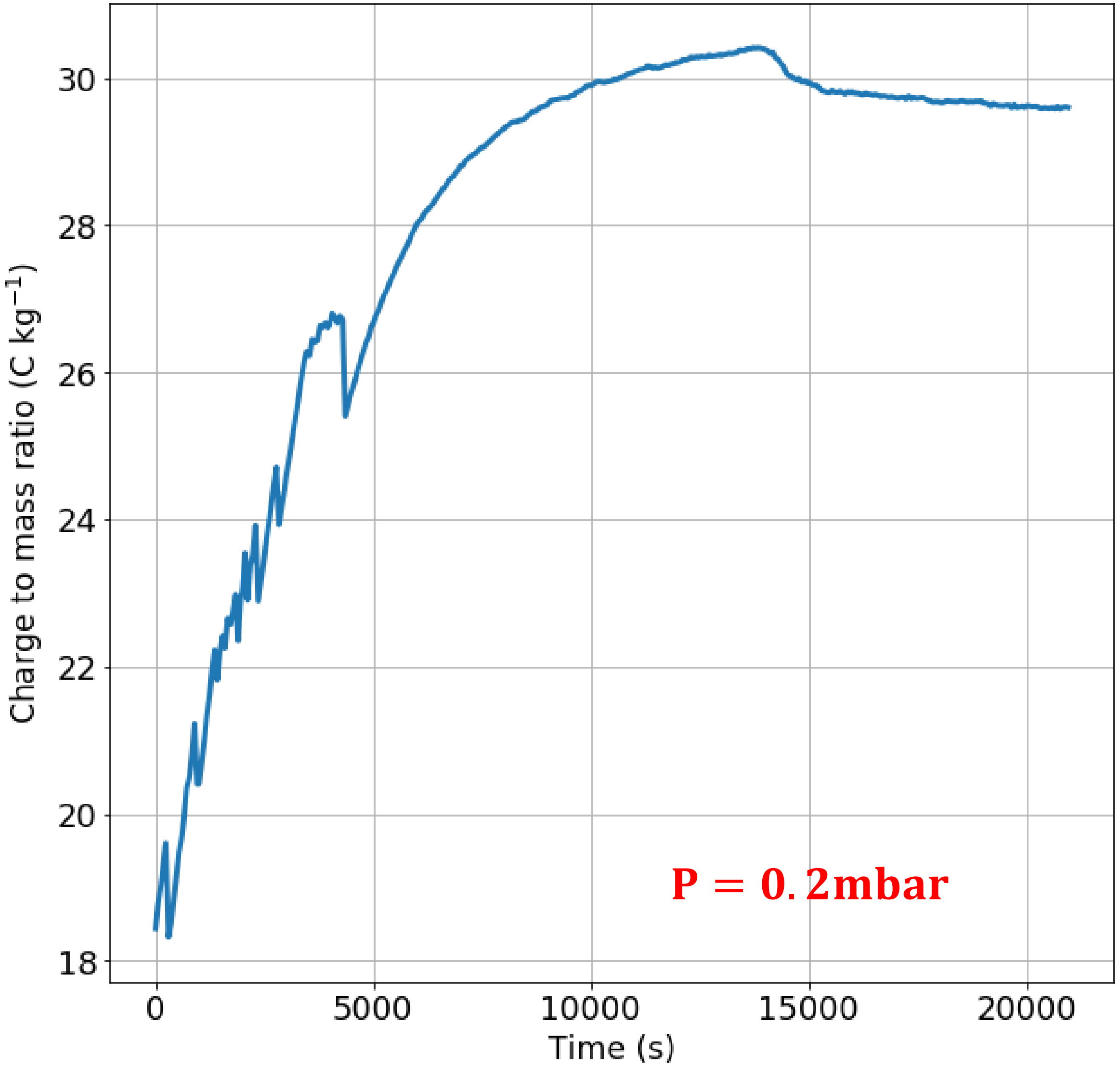


Detection

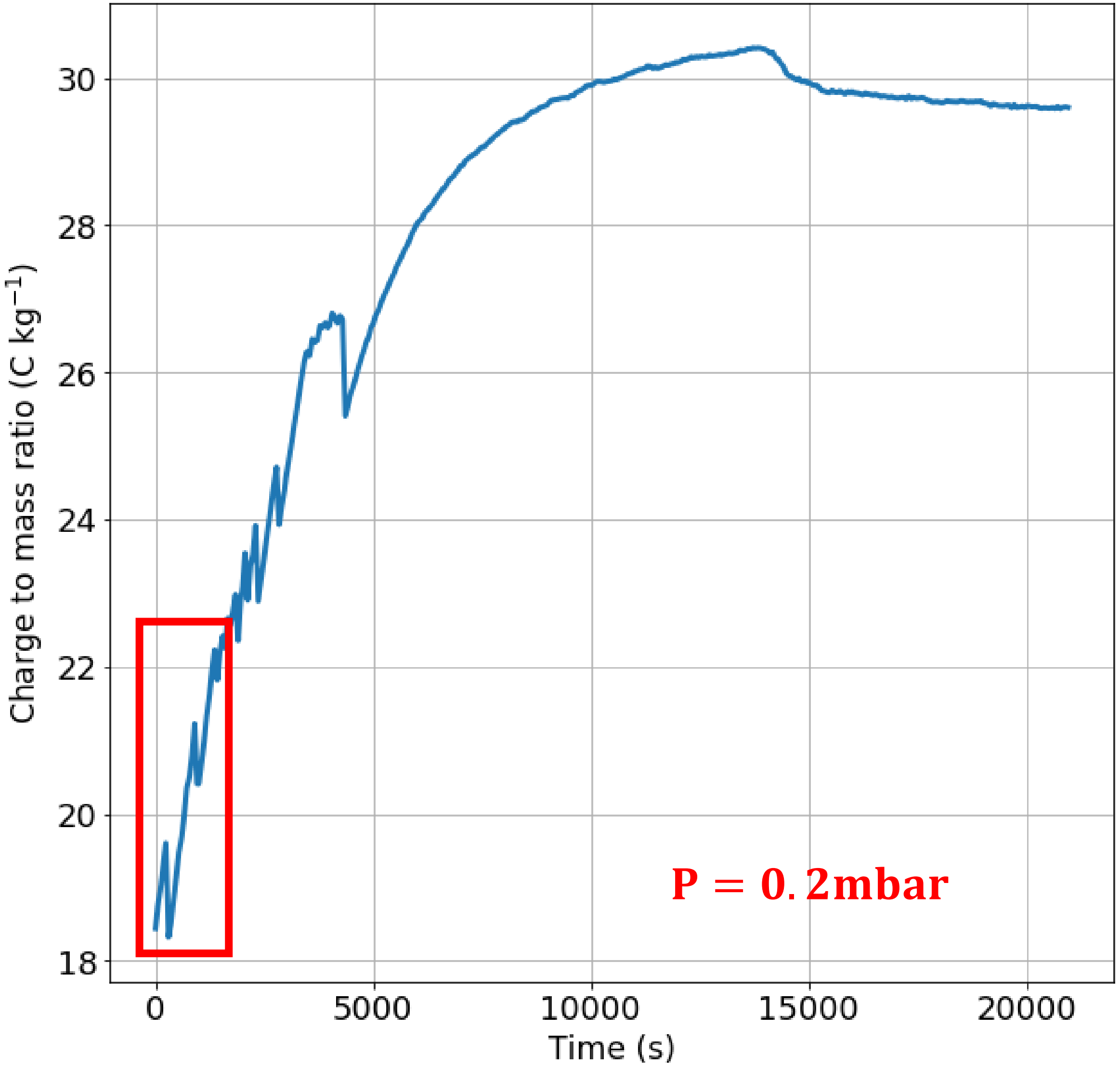


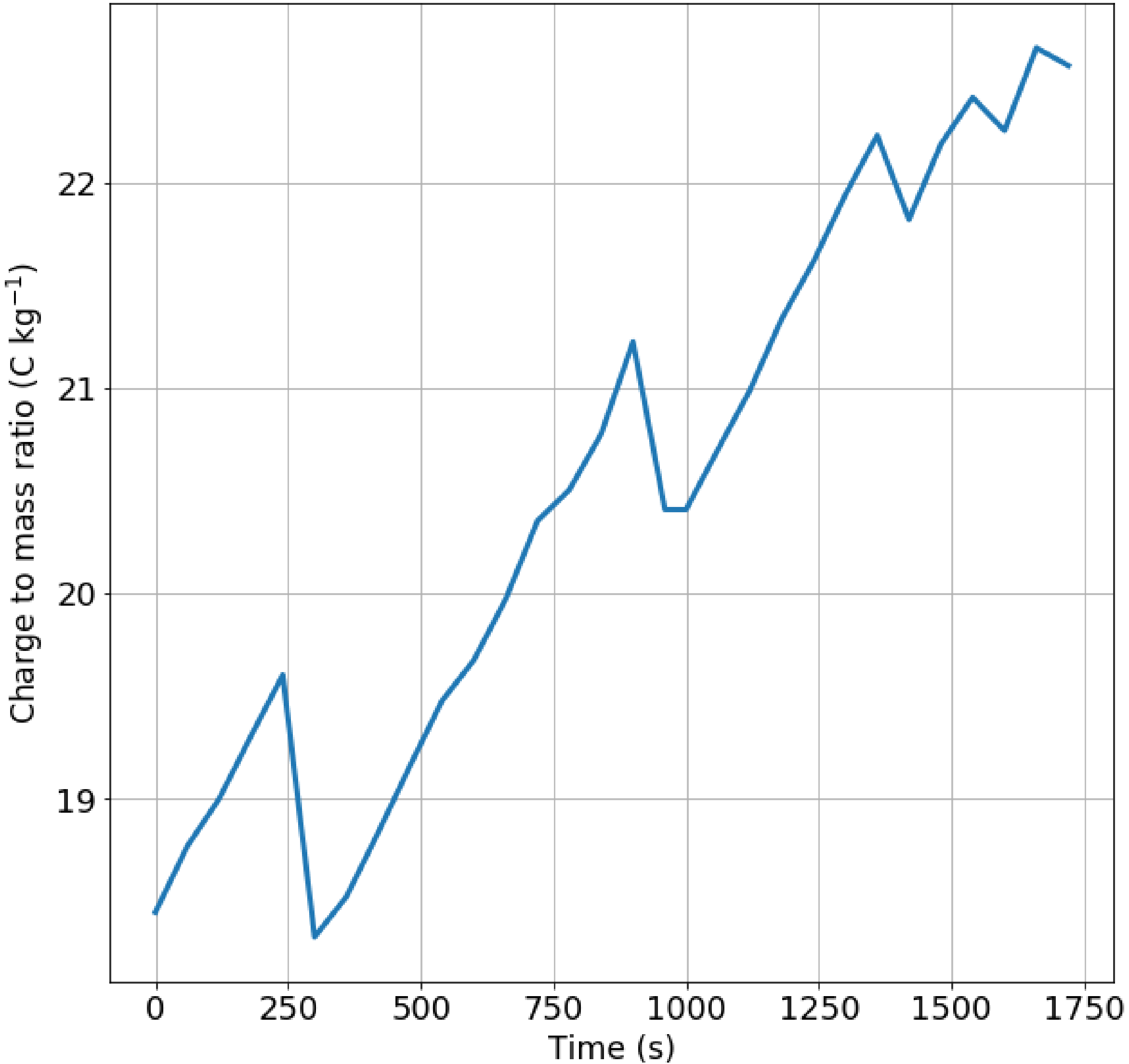
Mass Loss

Large Mass Change

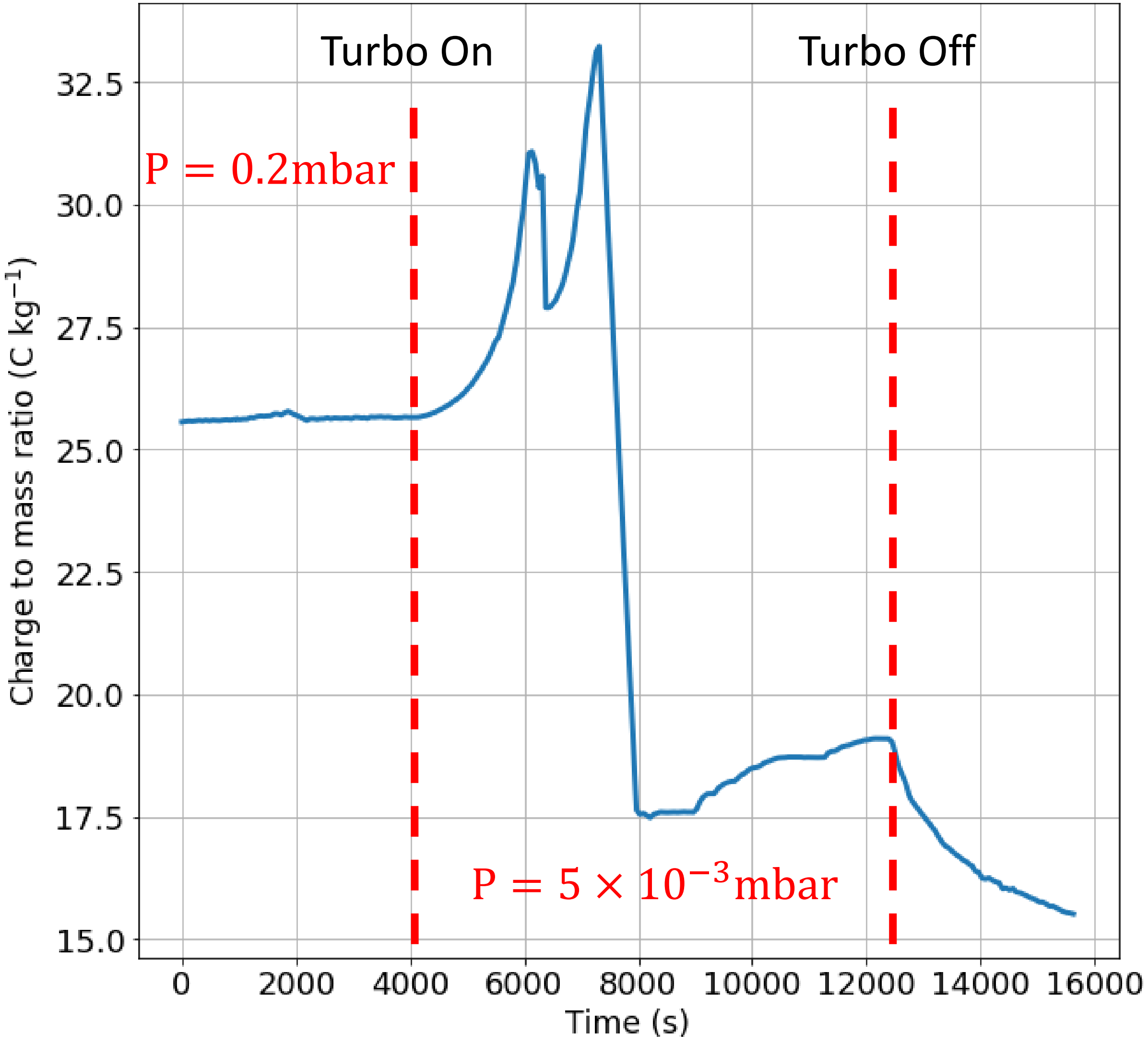


Large Mass Change

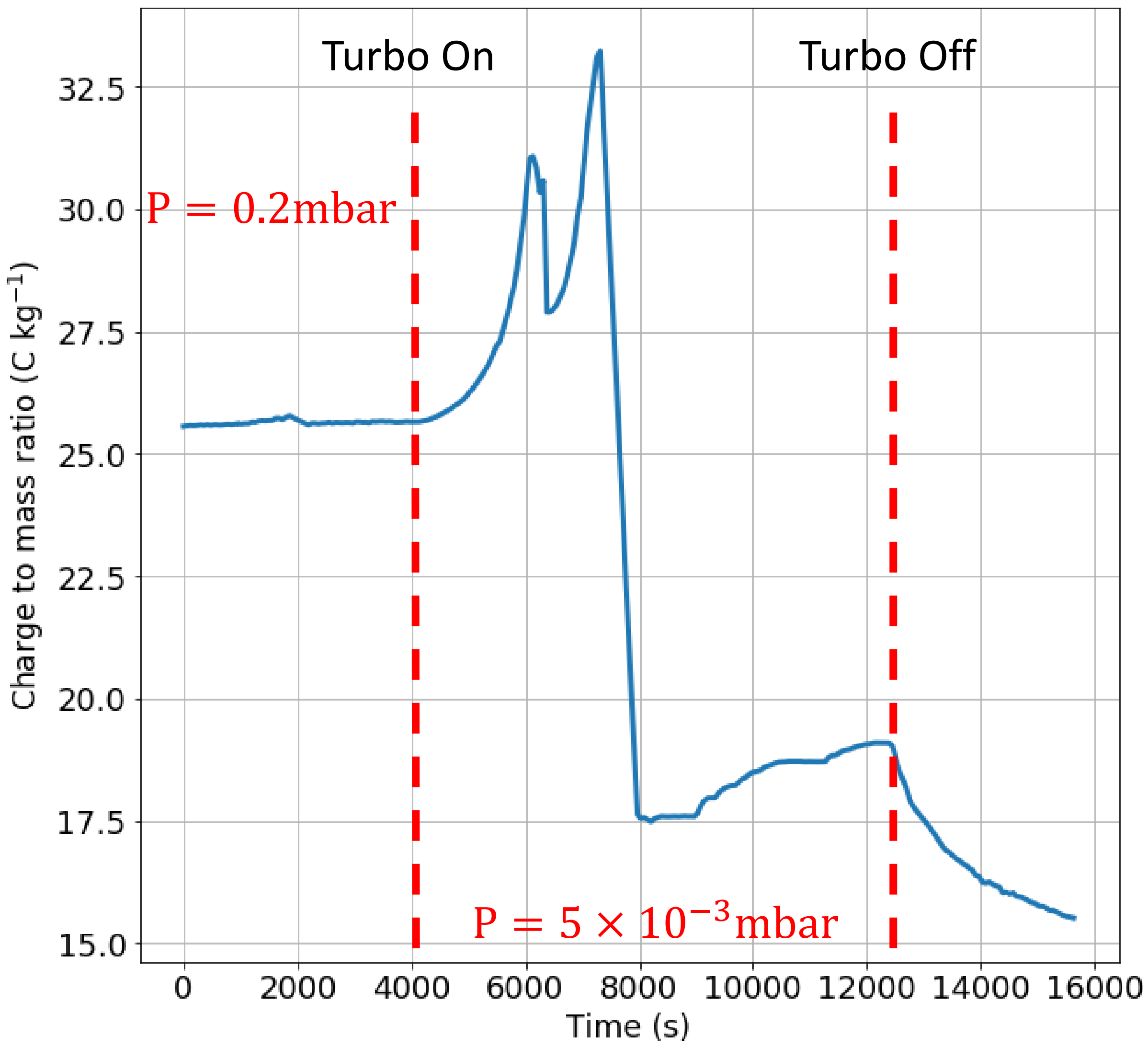


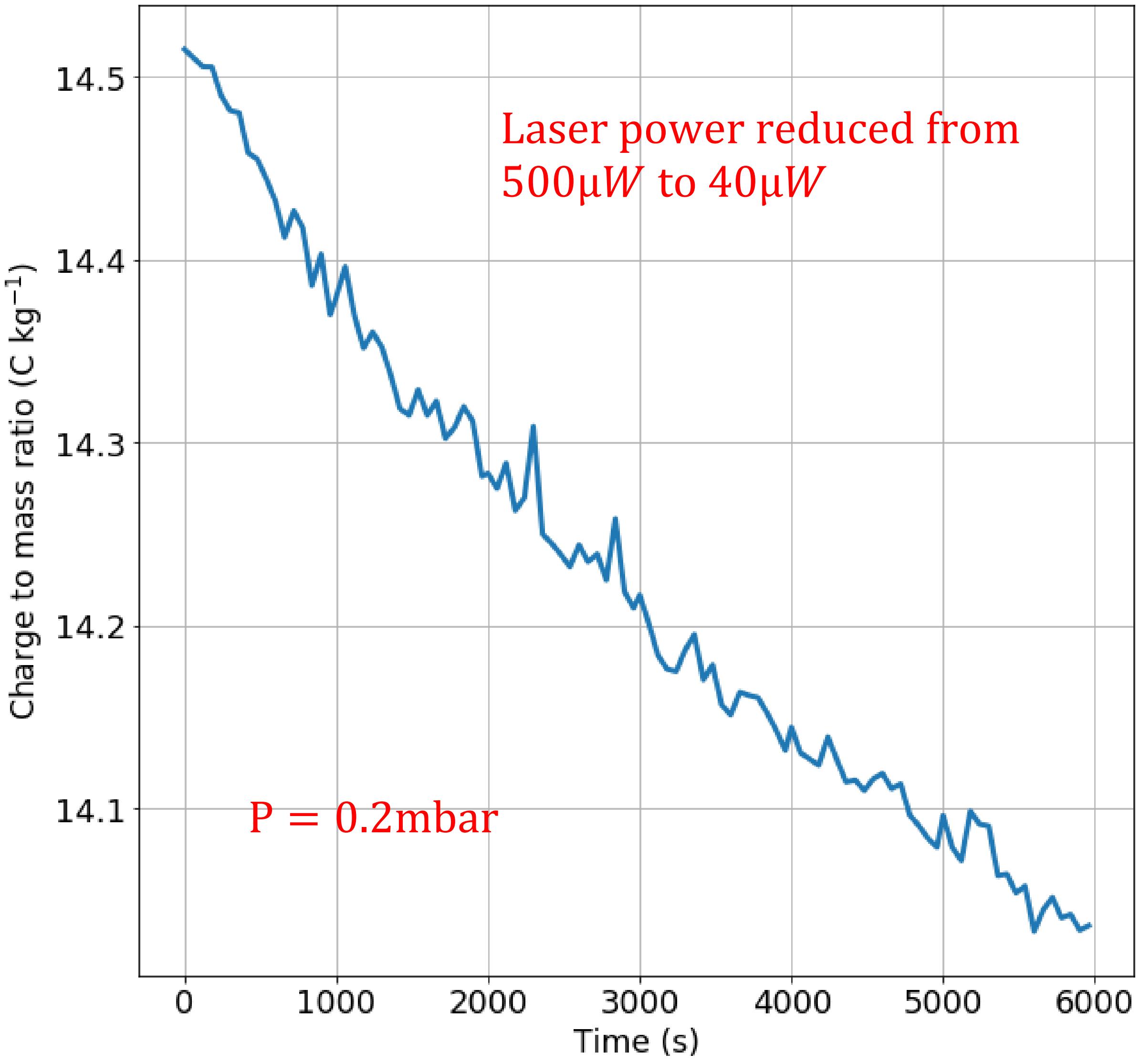


Pressure and Temperature Affects



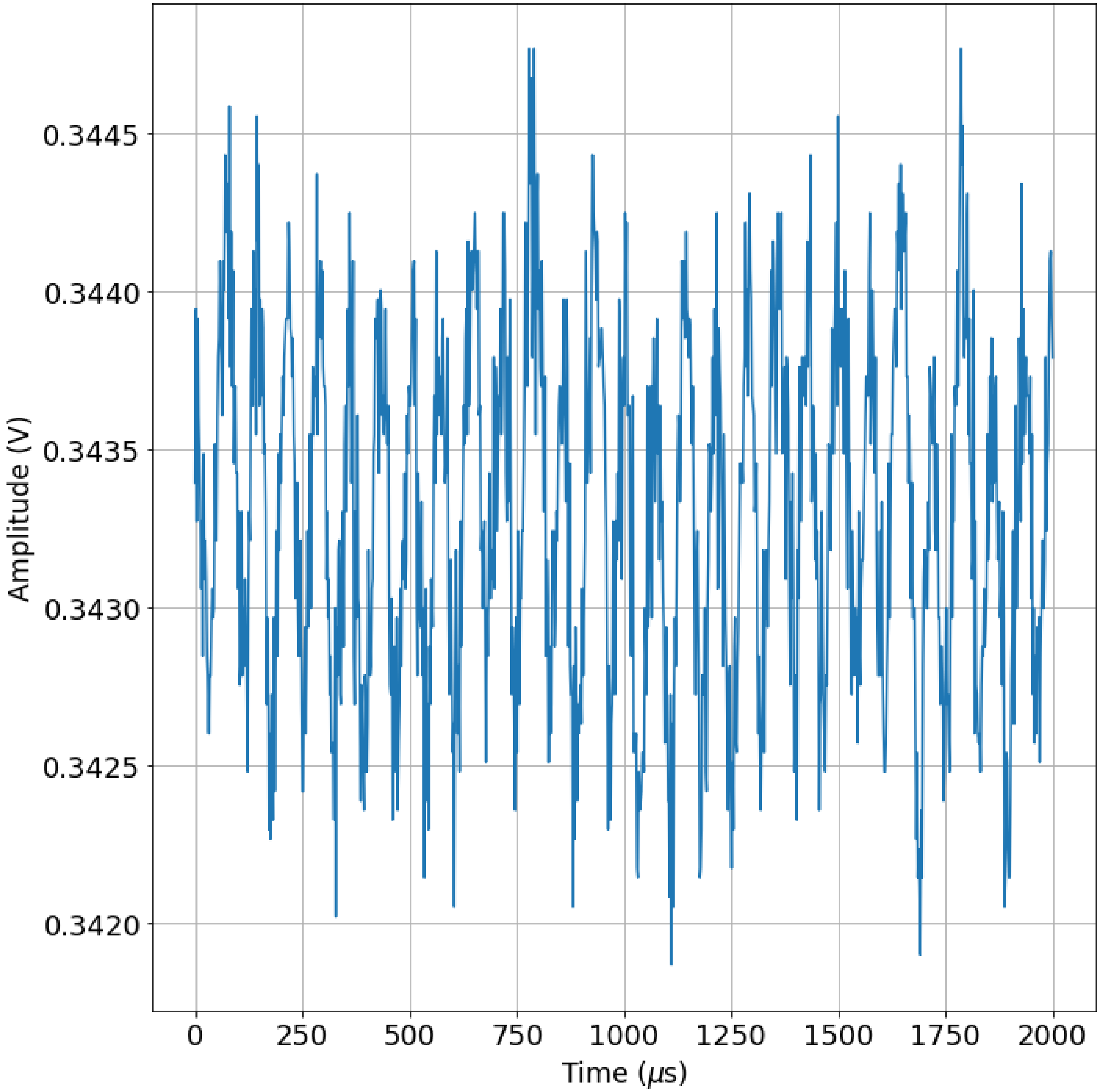
Pressure and Temperature Affects

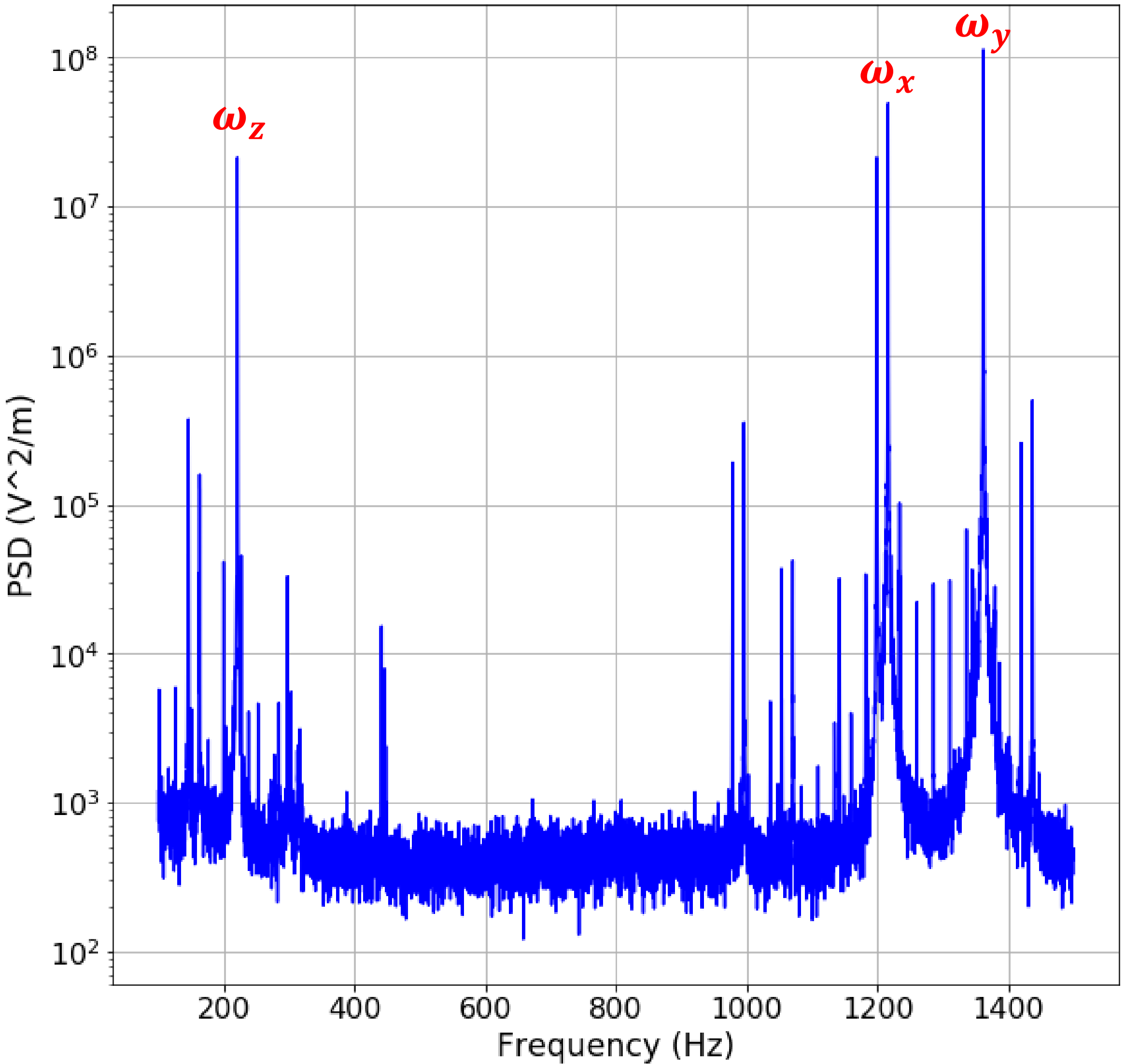




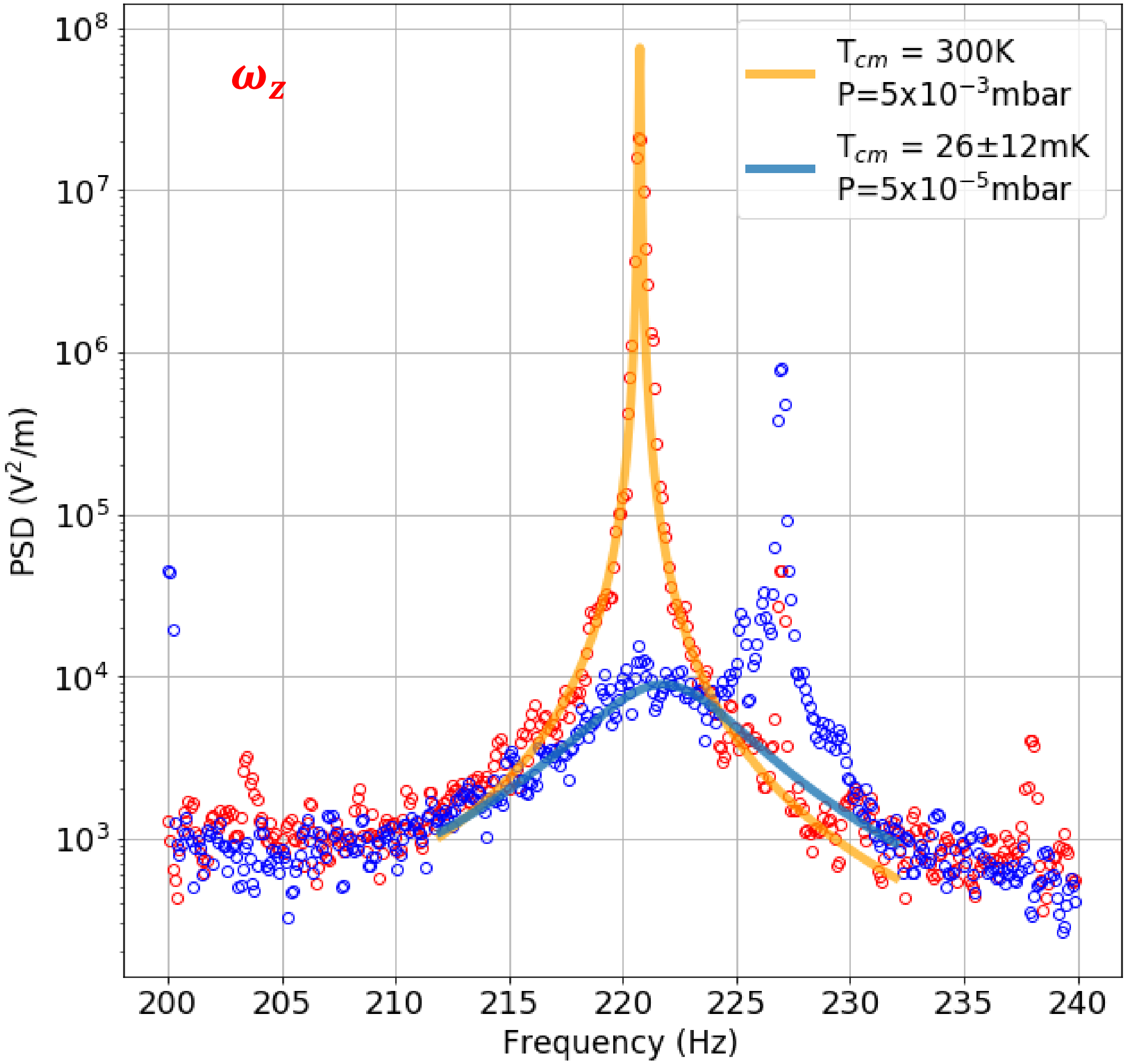
Parametric Feedback Cooling

Find the Secular Frequency





Cooling to 26mK



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

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

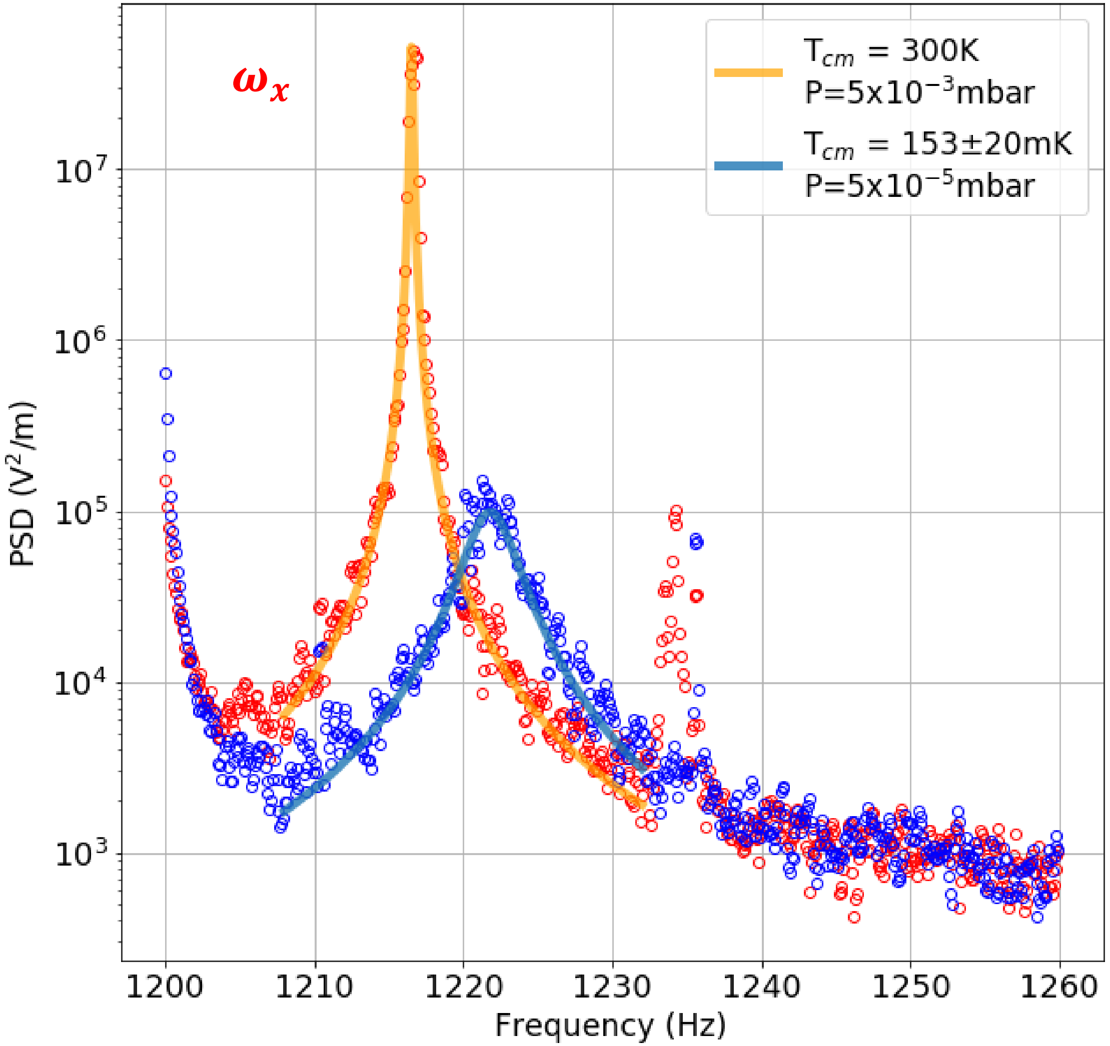
Γ_0 Environmental Damping

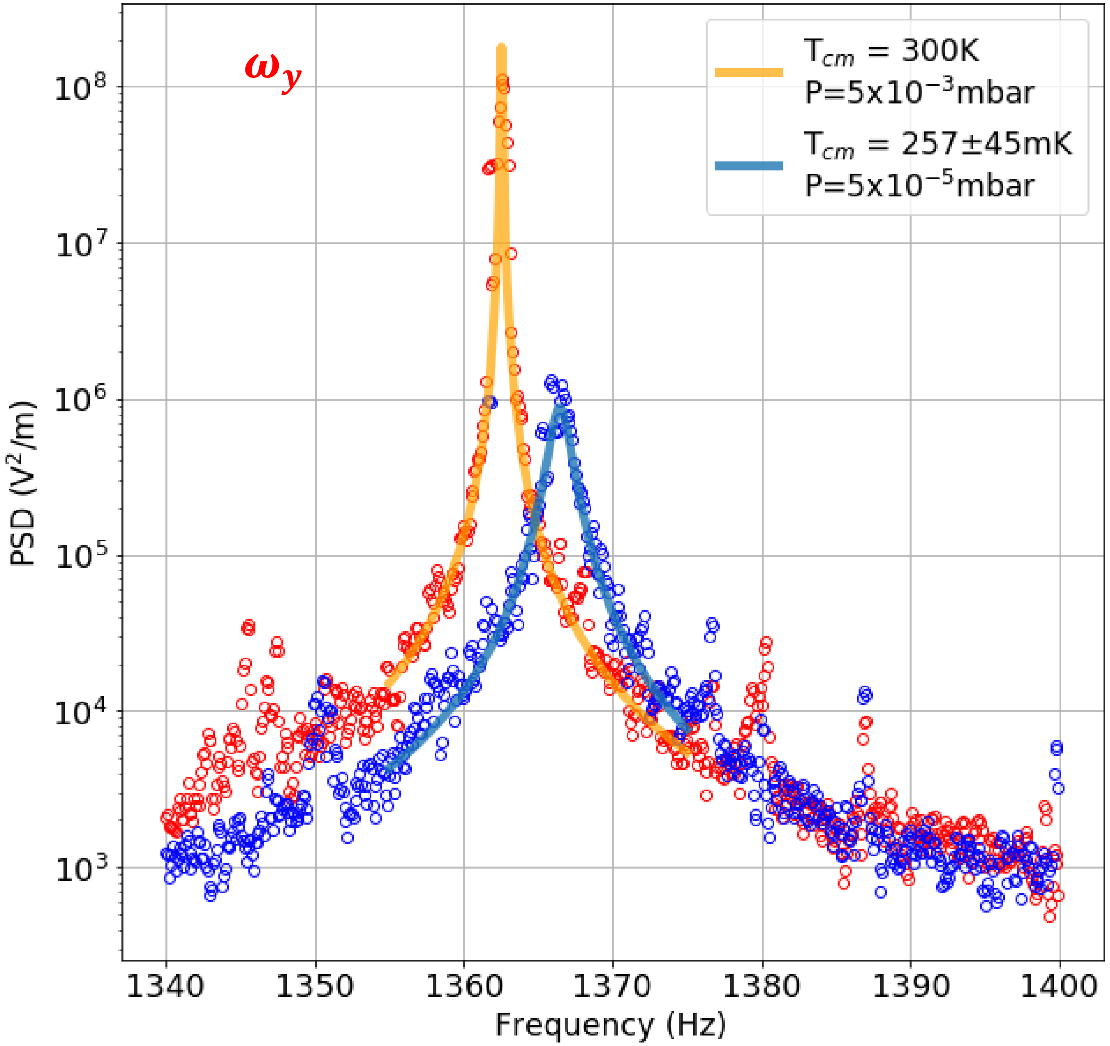
$\delta\Gamma$ Additional Feedback Damping

Ω_0 Natural Frequency

$\delta\Omega$ Frequency Shift from Feedback

Cooling to 26mK





Conclusions

- Mass change significant and detrimental to experiment
- Likely due to contaminants from loading

- Cooling two orders of magnitude lower than previously reported in Paul Trap
- Could be improved by lower pressure or better detection

Gerard P. Conangla, Andreas W. Schell, Raúl A. Rica, and Romain Quidant, *Nano Letters* **2018** *18* (6), 3956-3961
Pavel Nagornykh, Joyce E. Coppock, and B. E. Kane , *Appl. Phys. Lett.* **106**, 244102 (2015)

Status of the LNF activities on electronics

TEQ MEETING

DELFT, November 8 2018

Istituto Nazionale di Fisica Nucleare

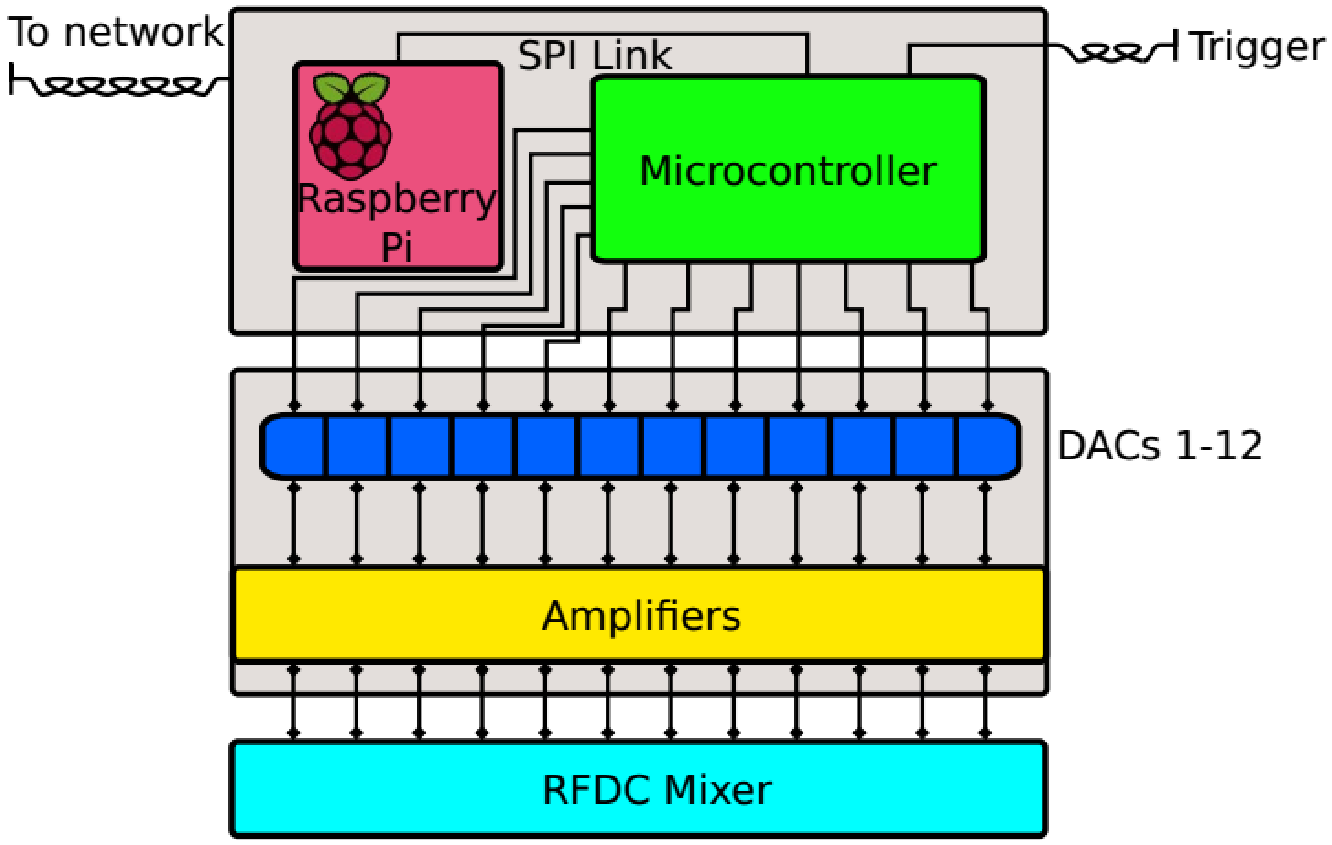
Power Supply Requirements

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

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

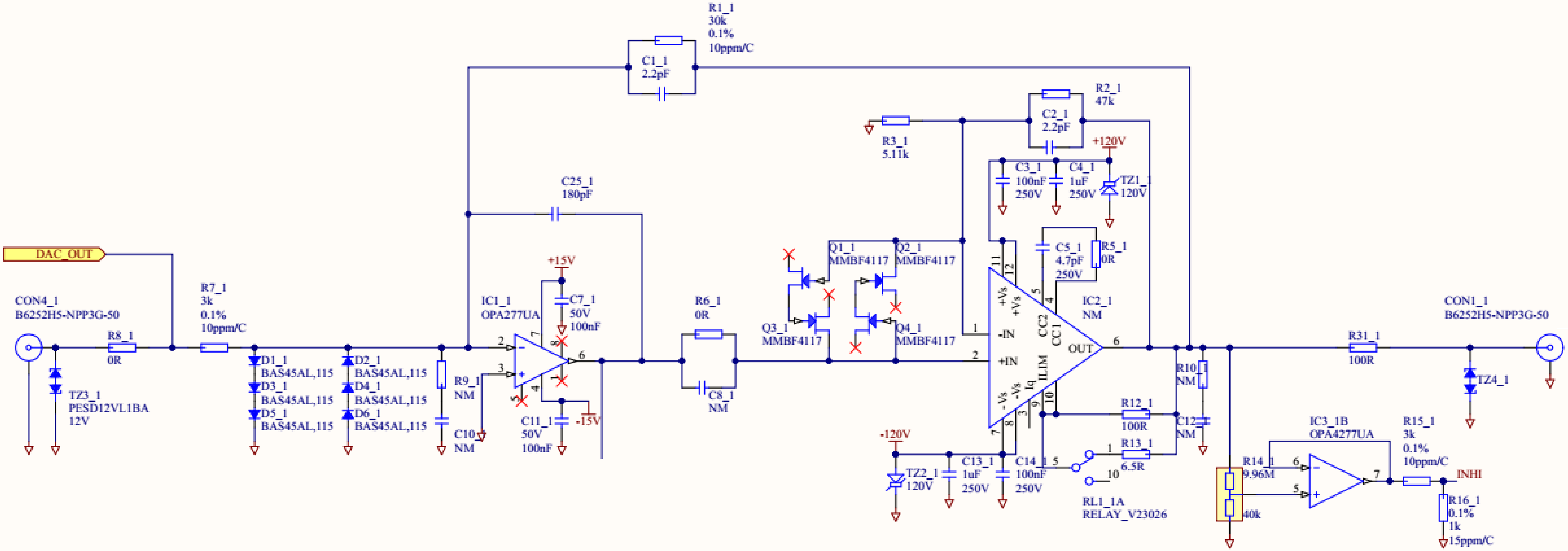
(V) $S_V^{DC}(\omega) \leq 5 \cdot 10^{-16} \; V^2/Hz$ @ $\omega = 100 - 1000\,Hz$ AND $V_{DC} = 50\,V$

Current Power Supply Apparatus



- Raspberry π *microcontroller*
- AD5791 DAC
- Custom HV amplifier
- RF DC Mixer

Amplifier Schematic



Power Supply Requirements

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

DC GAIN = 10 OK

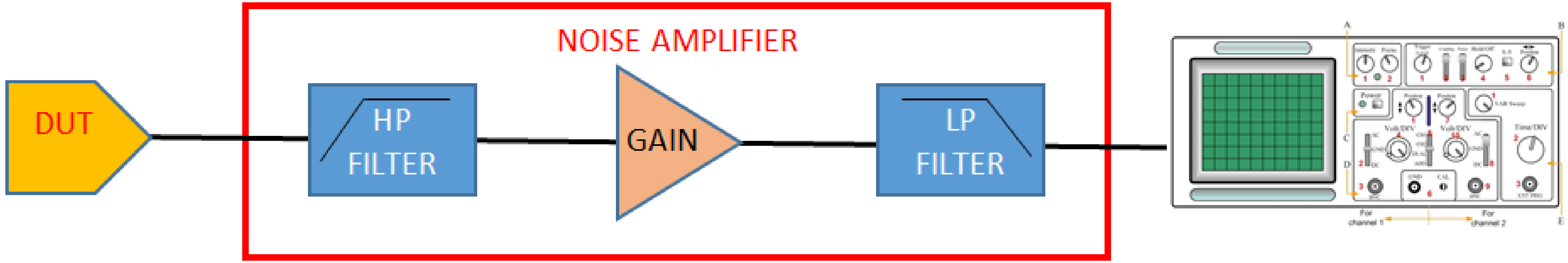
Bandwidth = 300kHz OK

NOISE…

Among all specifics, noise is indeed the most critical.

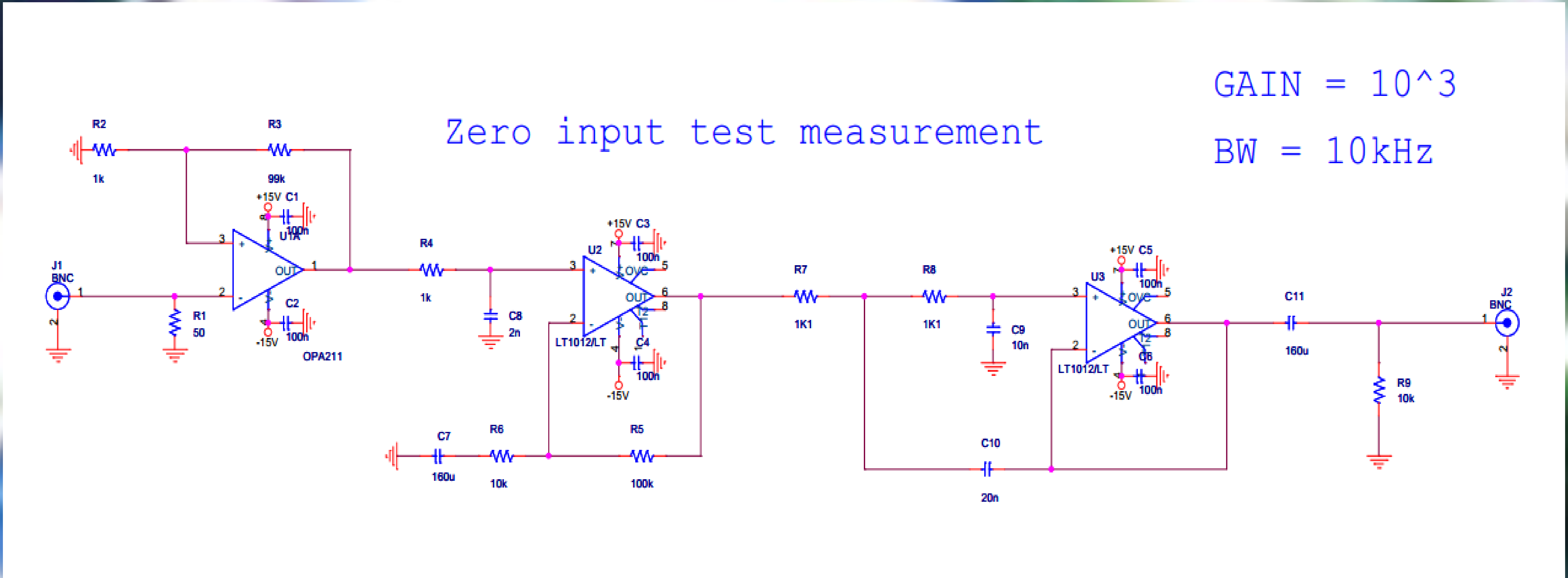
Amplifier NOISE measurement

Block diagram of a noise amplifier

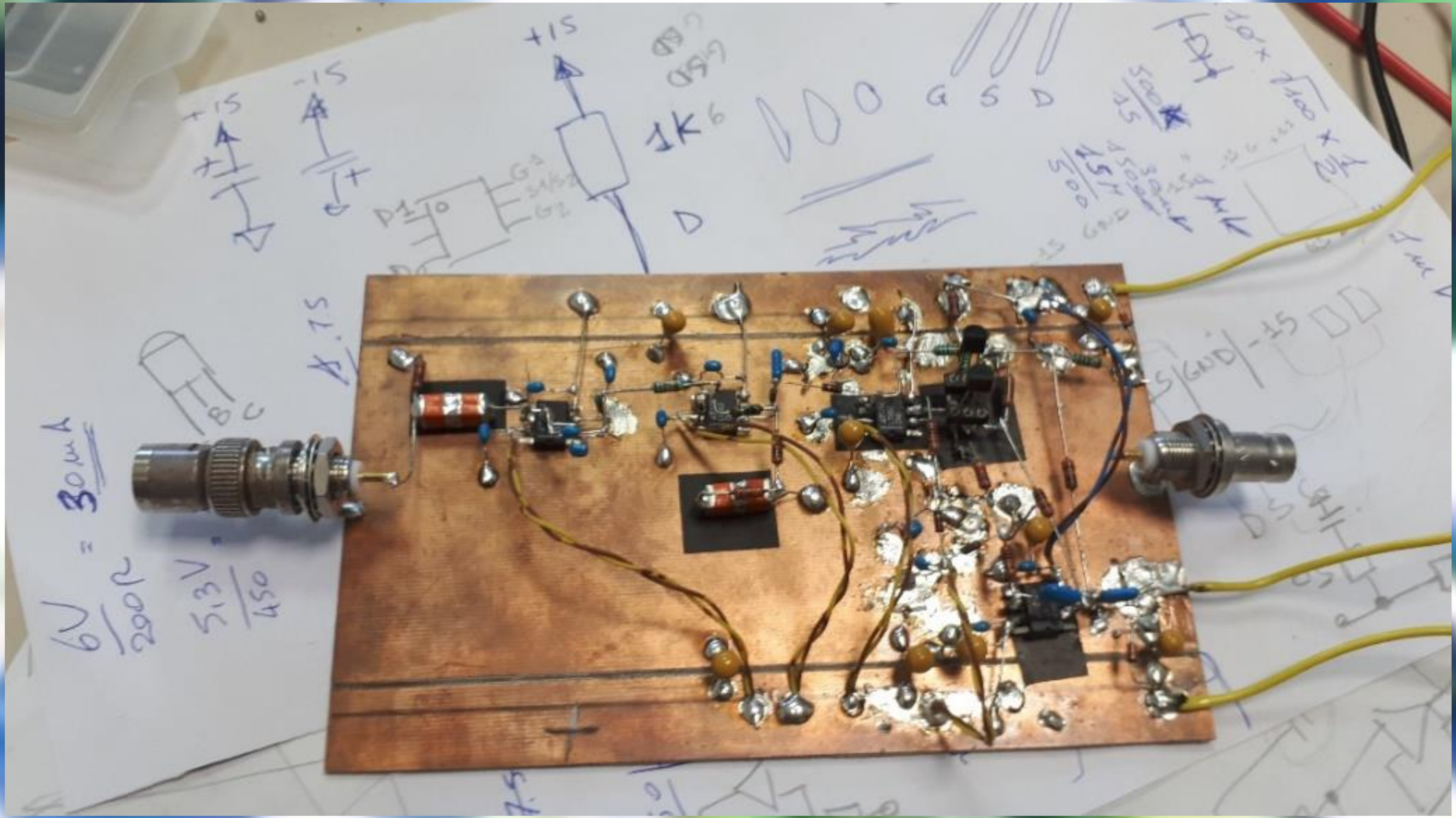


Gain x √BW must be in the order of $10^5 \div 10^6$

Amplifier NOISE measurement



Amplifier NOISE measurement

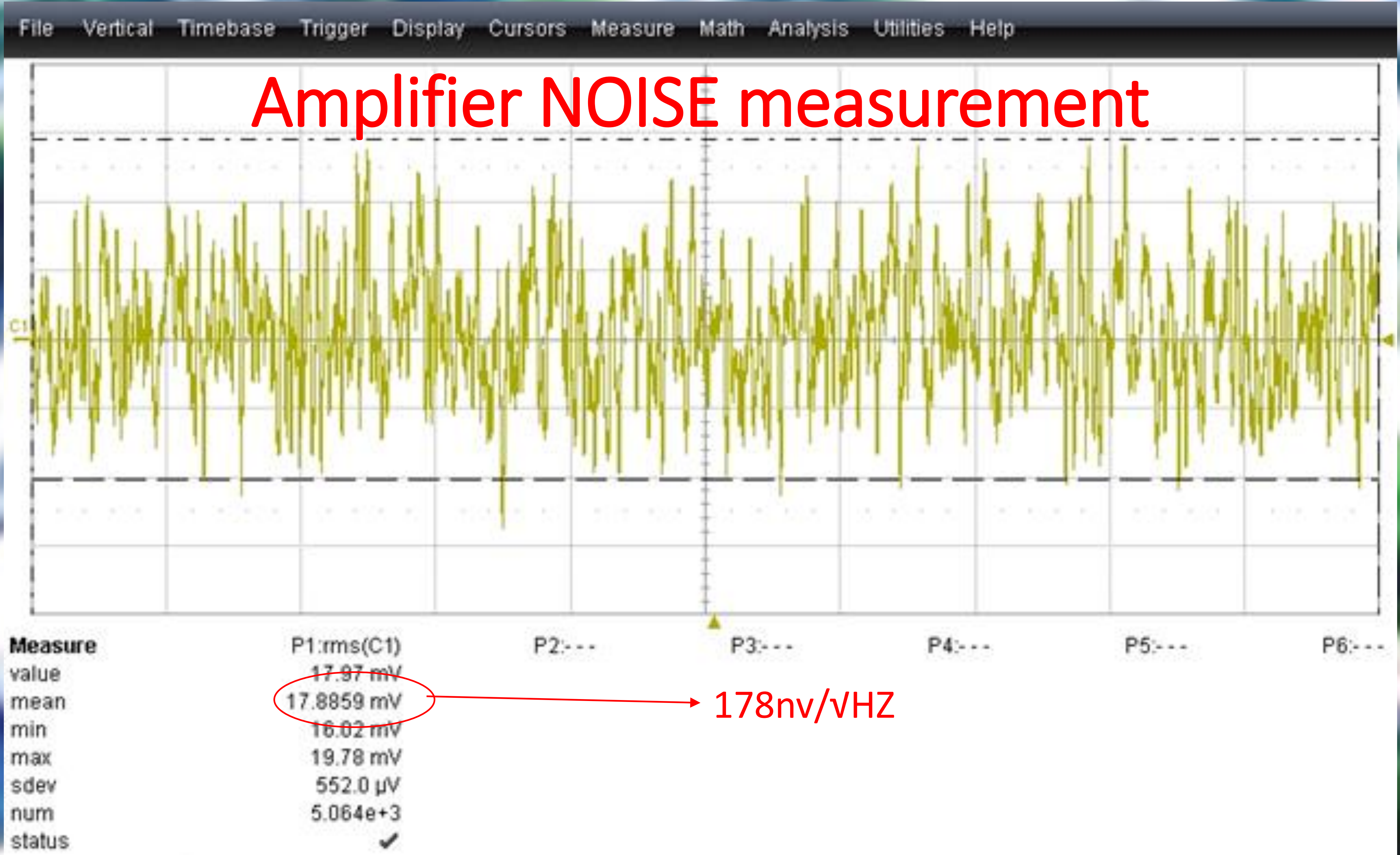


Gain 10^6

BW 10Hz

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

Amplifier NOISE measurement

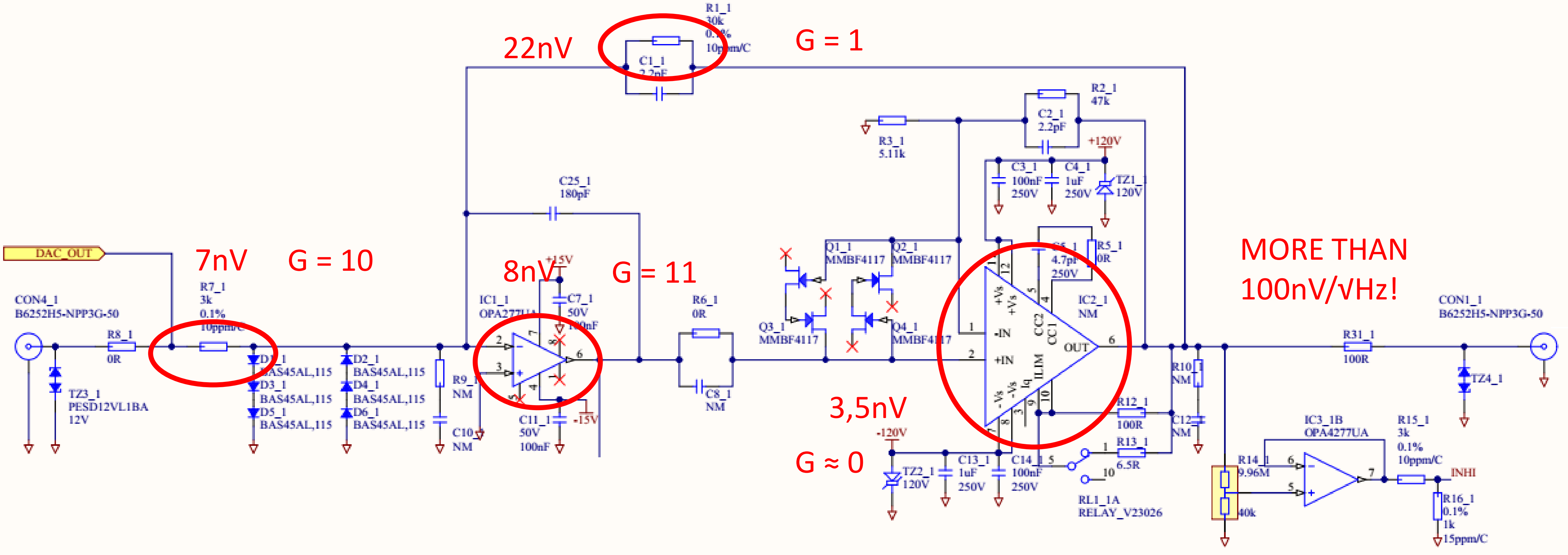


Amplifier NOISE analysis

NOISE analysis include:

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

Amplifier NOISE analysis

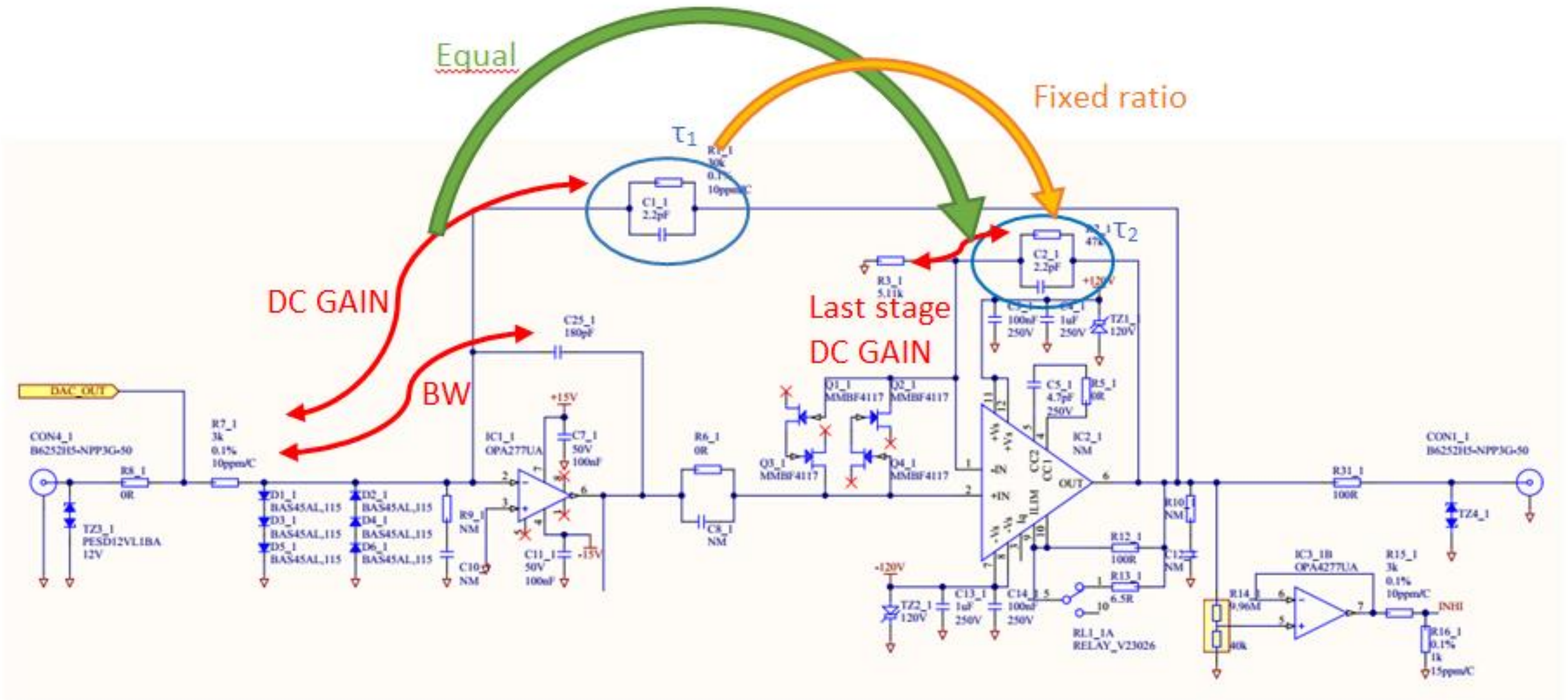


Power Supply Adjustements

Current design can be salvaged with a few expedients:

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

Power Supply Adjustements



Power Supply Adjustements

Possible solution is to replace:

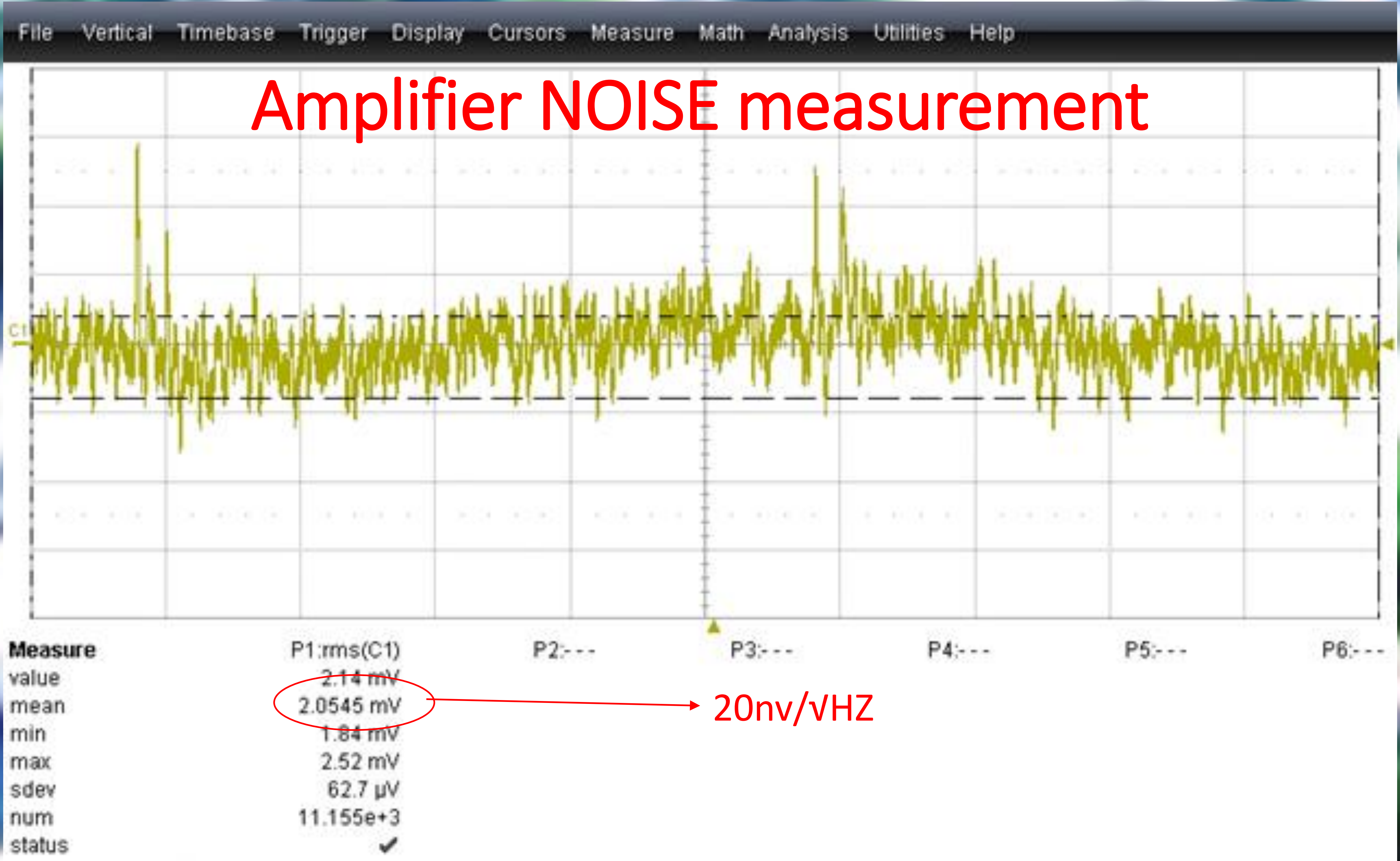
- R_1=2K5 R_7=250R C_1=27pF C_{25}=2,2nF
- OPA277 replaced with OPA211 (same package, 1nV of noise)

Result is…

20nV/√Hz of noise!

NOISE Measurement Ongoing!

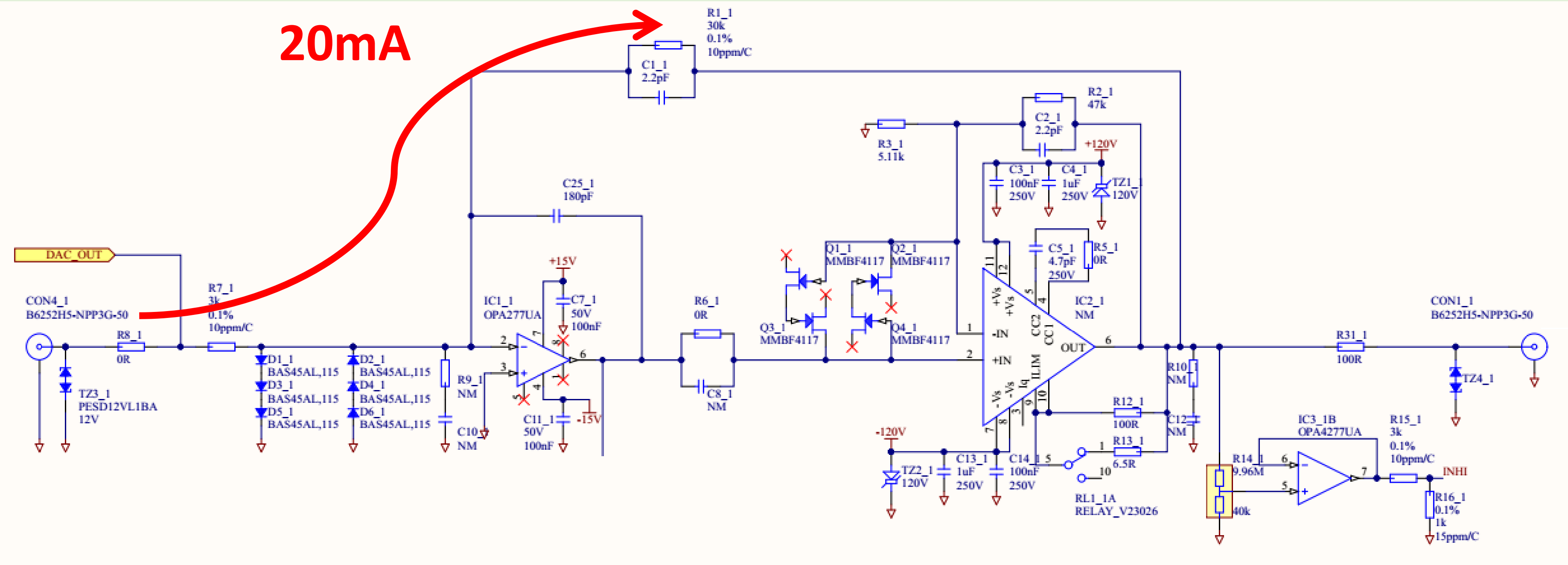
Amplifier NOISE measurement



Drawbacks

Advantages always comes with disadvantages:

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



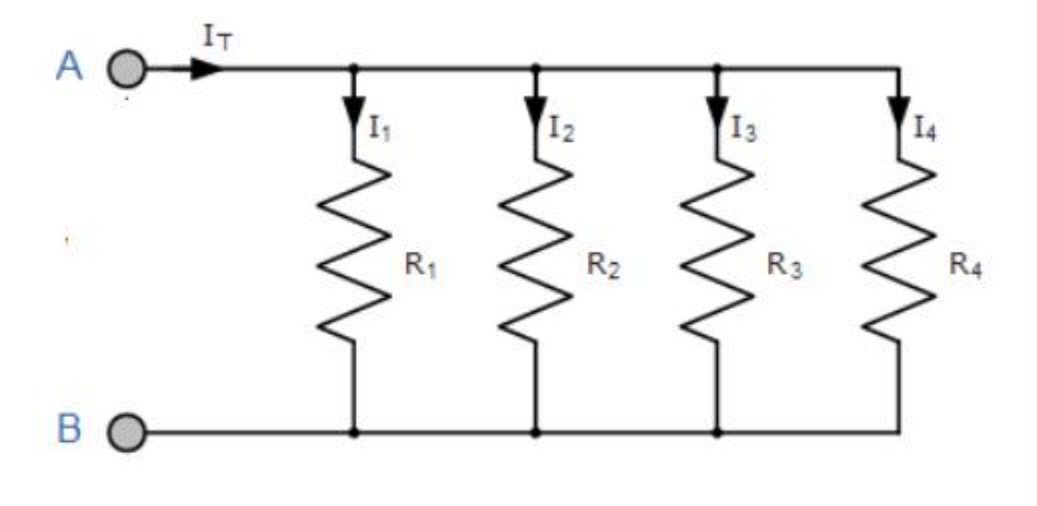
Drawbacks

Advantages always comes with disadvantages:

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

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

Solutions



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

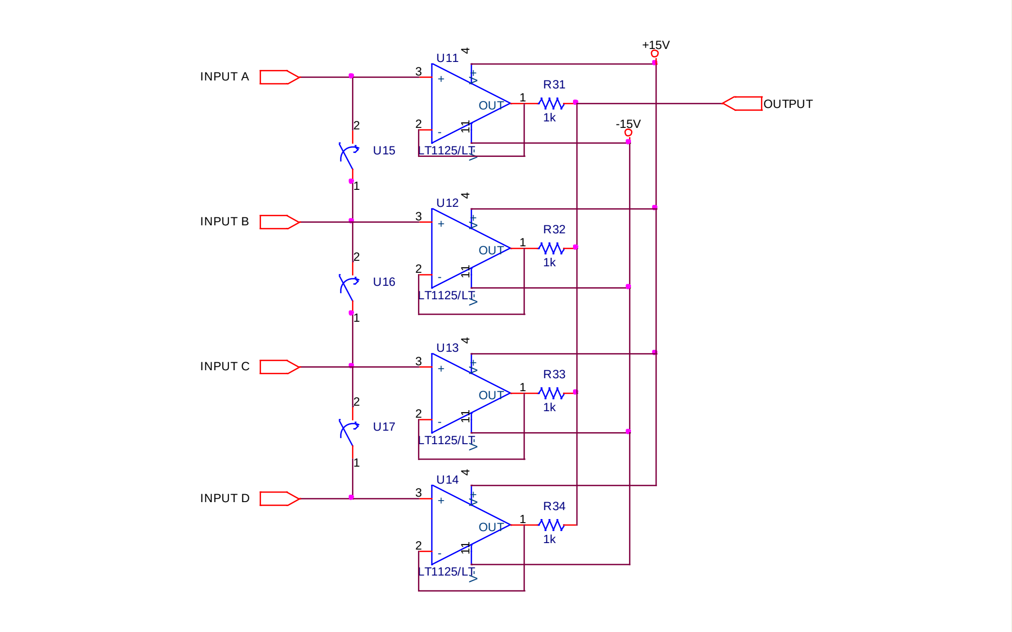
The heat generation is equally split.

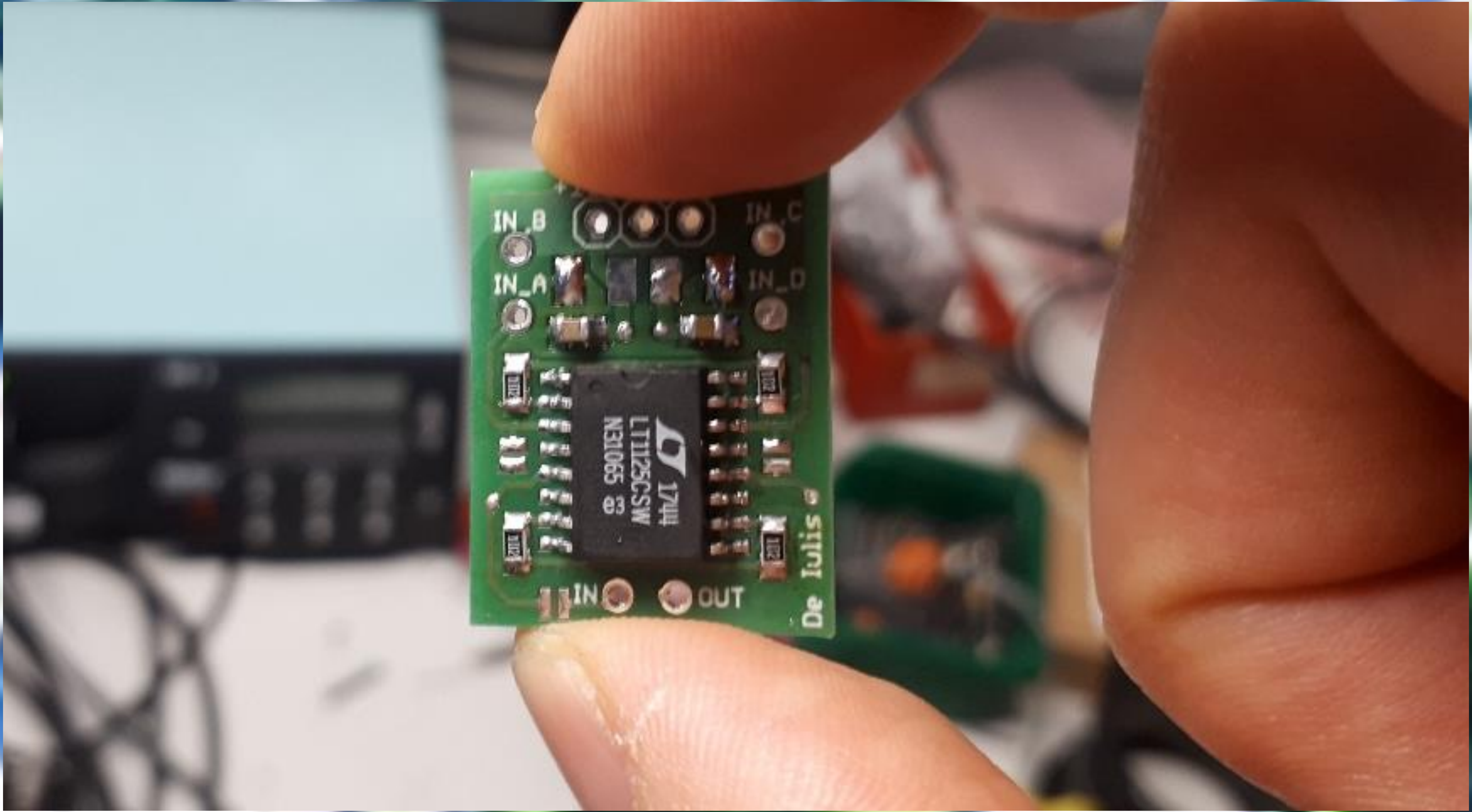
0.1% tolerance, 10ppm thermal drift, 250mW resistors can be easily found.

Axial resistor recommended

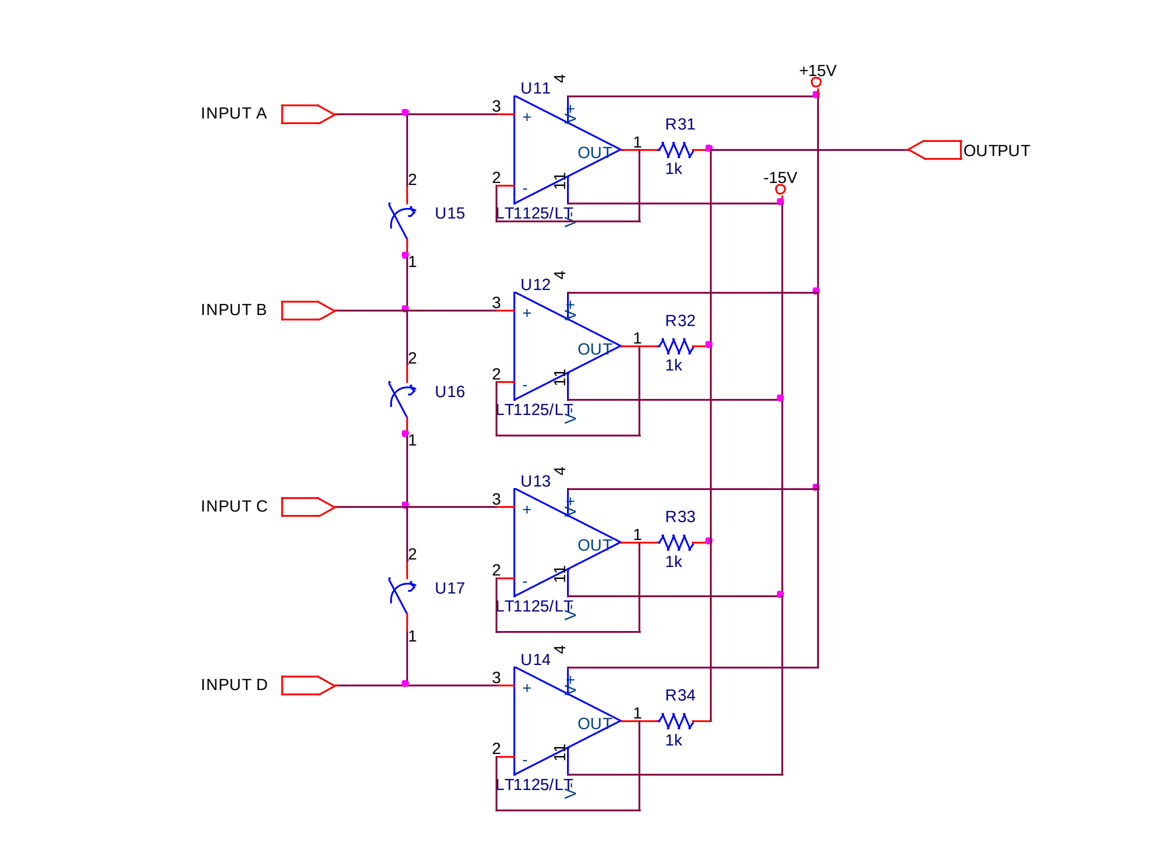
Solutions

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




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

Solutions



This block replaces R_7.

Low noise stage (≈2nV).

Can give up to 80mA of current.

This buffer can also accept four independent inputs.

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

Grazie per l'attenzione!

TEQ MEETING

DELFT, November 8 2018

QUEEN'S UNIVERSITY BELFAST

Macrorealism in optomechanical systems

Marta Maria Marchese

TEQ Junior Workshop - TUD (Delft)

November 8th, 2018

Centre for Theoretical Atomic, Molecular and Optical Physics
CTAMOP
Queen's University Belfast

TEQ Testing the large-scale limit of quantum mechanics

Outline

- Formulation of Leggett-Garg inequalities (LGI) to test macroscopic coherence
- Protocol to create totally non-classical states in an optomechanical cavity
- Leggett-Garg Test on a hybrid optomechanical system

Leggett - Garg postulates[1]

(A1) Macroscopic realism per se:

a macroscopic system with two or more macroscopically distinct states available to it will at all times be in one or other of these states.

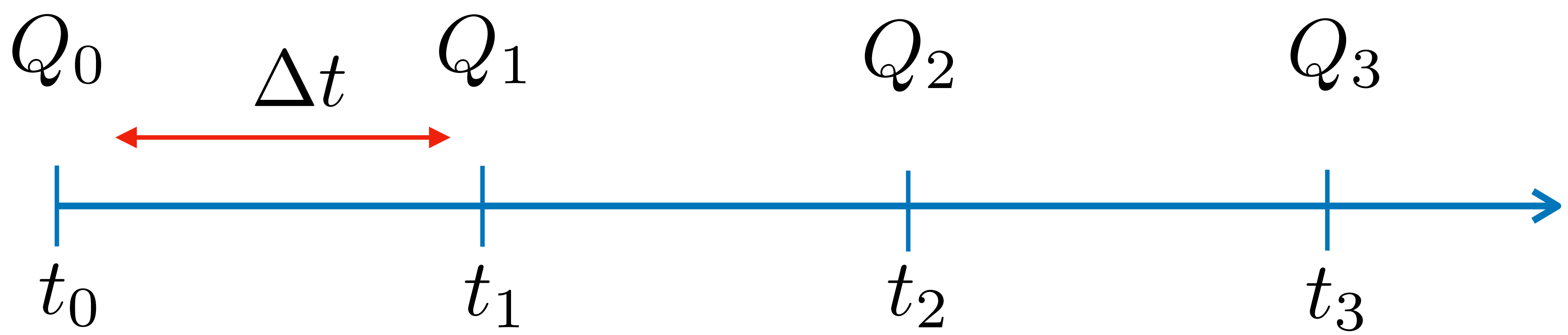
(A2) Non-invasive measurability at macroscopic level:

it is possible, in principle, to determine the states of the system with arbitrarily small perturbation on its subsequent dynamics.

[1]*A. J. Leggett, Anupam Garg, Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?, Phys. Rev. Lett. 54, (1985).*

Leggett - Garg function

Dichotomic observable $$Q(t_i) = Q_i = \pm 1$$

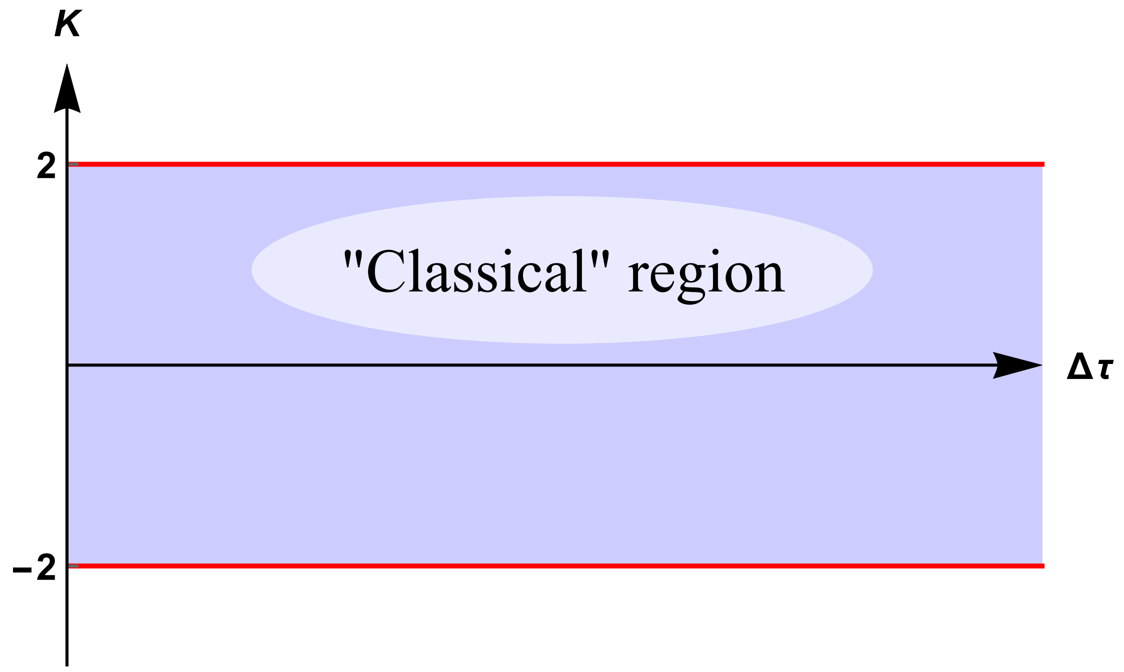


Temporal correlation function $$C_{i,j} \equiv \langle Q_i , Q_j \rangle = \sum_{Q_i , Q_j} Q_i Q_j P_{i,j}(Q_i , Q_j)$$

$$K \equiv C_{10} + C_{21} + C_{32} - C_{30}$$

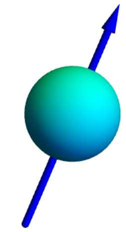
Leggett - Garg inequality

$$K \equiv |C_{10} + C_{21} + C_{32} - C_{30}| \leq 2$$



- Quantitative way to discern between Quantum and Classical dynamics
- All macrorealist theories fulfil the inequality
- **Violation:** at least one of the two assumptions fails

Single $\frac{1}{2}$ spin



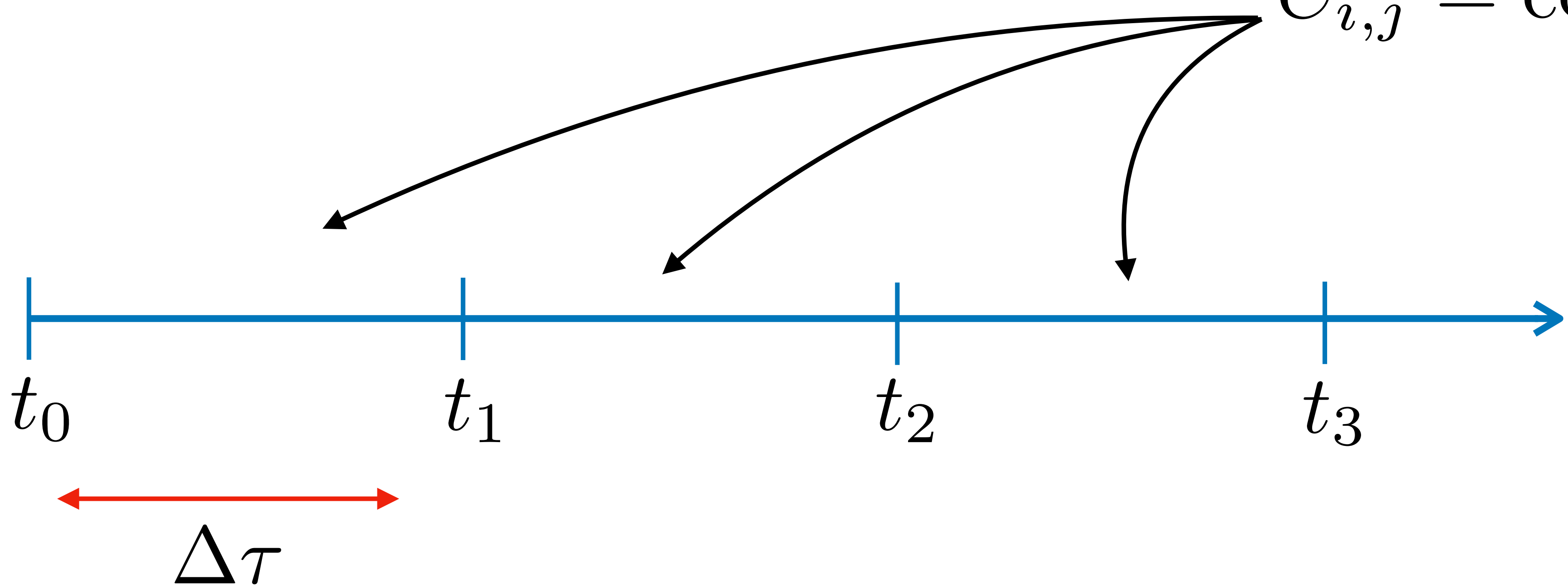
$$\hat{H} = \omega\hat{\sigma}_x$$

Dichotomic observable: $\hat{Q} = \hat{\sigma}_z$

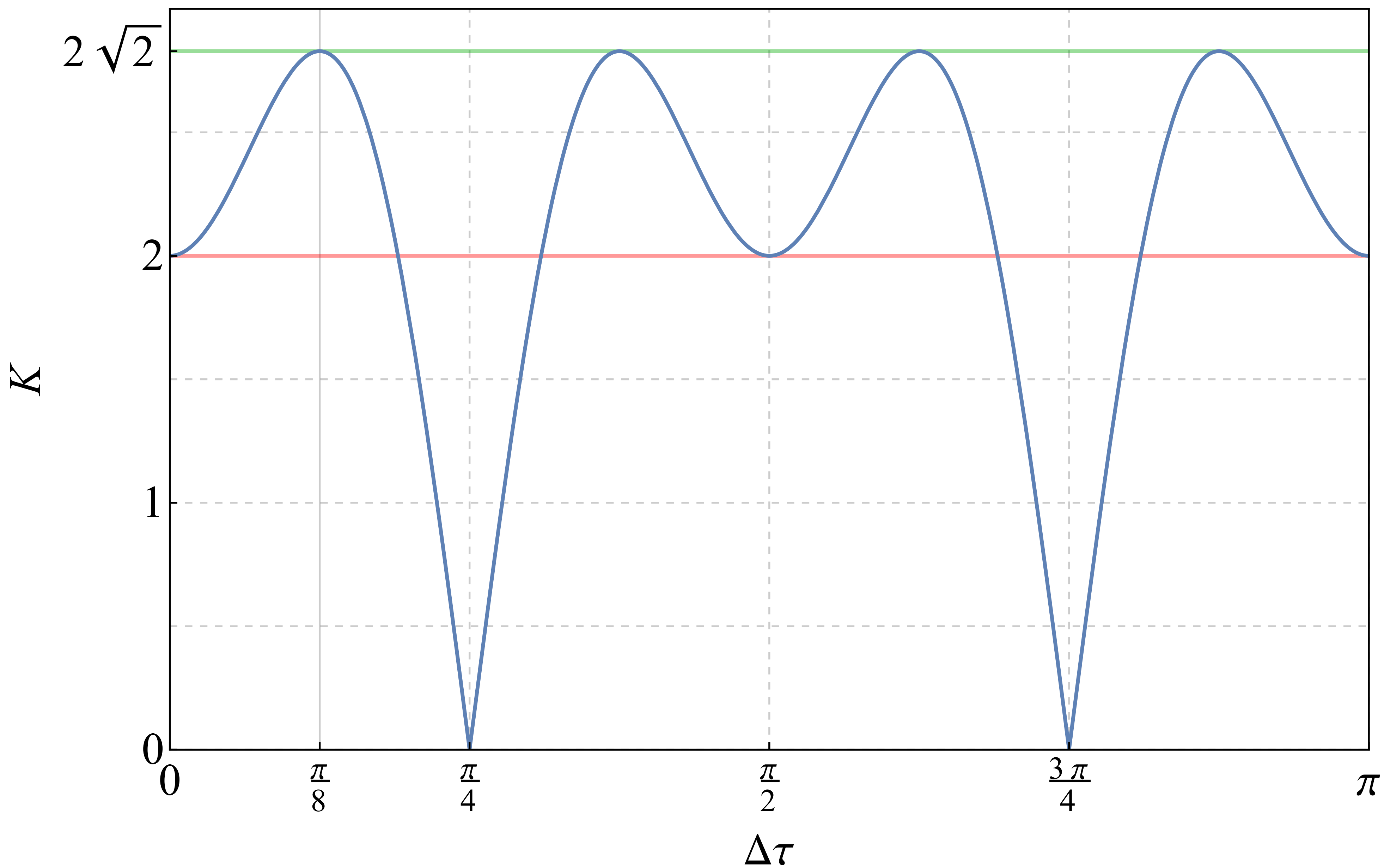
$|\uparrow\rangle$ $\quad Q =$ +1

$|\downarrow\rangle$ $\quad Q =$ -1

$$C_{i,j} = \cos(2\Delta\tau)$$

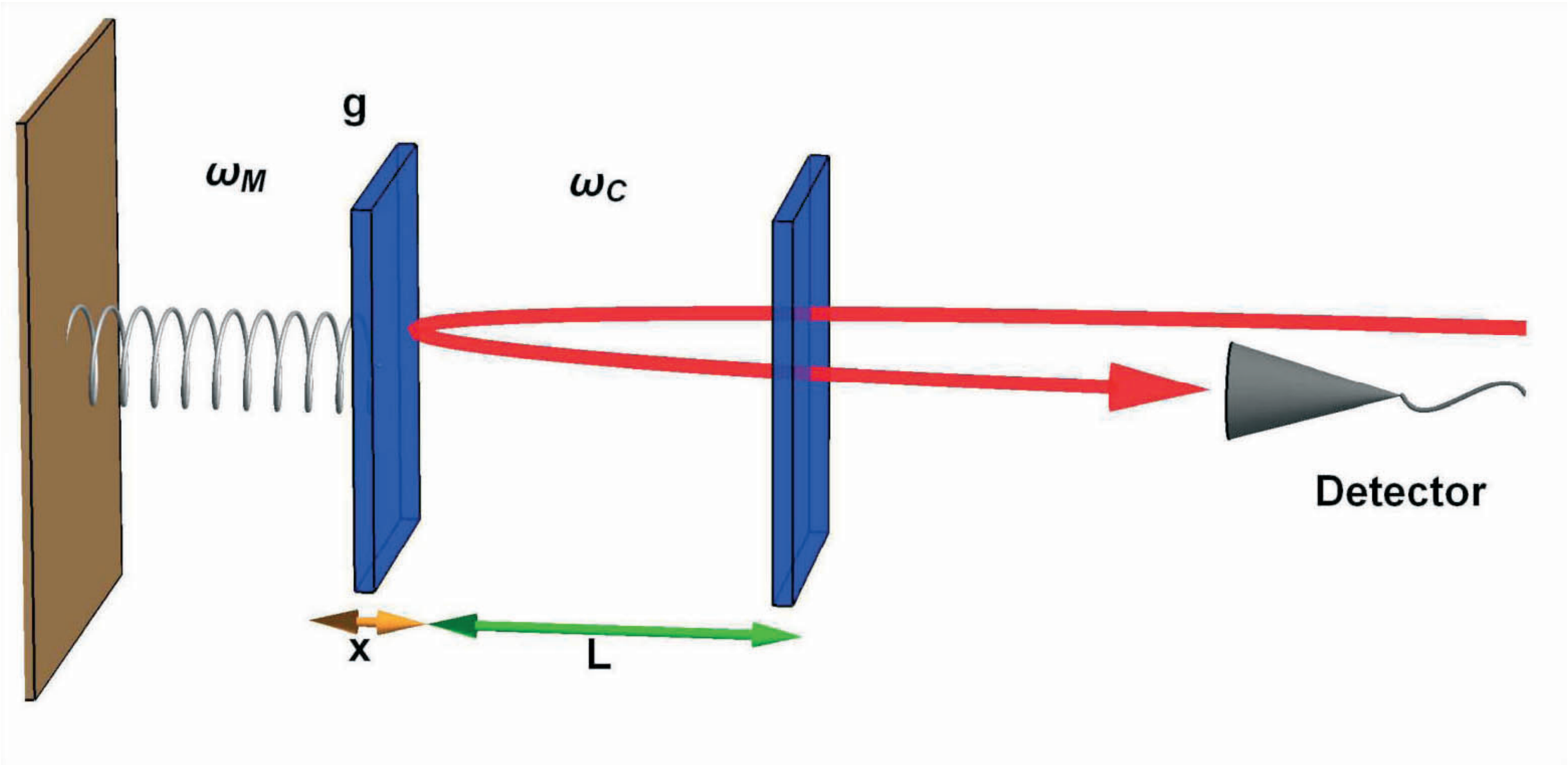


$$K = |3\cos(2\Delta\tau) - \cos(6\Delta\tau)| < 2$$



Optomechanical cavity

$$\hat{H} = \hbar\omega_C \hat{a}^\dagger \hat{a} + \hbar\omega_M \hat{b}^\dagger \hat{b} - \hbar g \hat{a}^\dagger \hat{a}(\hat{b}^\dagger + \hat{b})$$



Protocol to originate totally non-classical states of the mirror[2]

[2] *S. Bose, K. Jacobs, P. L. Knight, Preparation of Nonclassical States in Cavities with a Moving Mirror, Phys.Rev. A 56, 4175-4186, (1997)*

Unitary free evolution

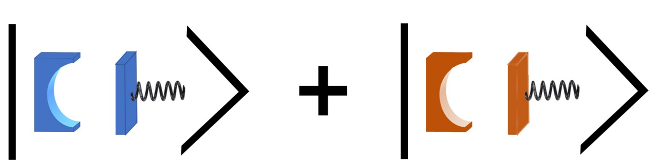
Initial state: $$|\psi(0)\rangle_{CM} = |\alpha\rangle_C \otimes |0\rangle_M$$

Evolved state: $$|\psi(t)\rangle_{CM} = \hat{U}(t)|\psi(0)\rangle_{CM}$$

Statistical mixture of the mirror states

$$\hat{\rho}_M = e^{-|\alpha|^2} \sum_n^\infty \frac{\alpha^{2n}}{n!} |\phi_n(t)\rangle\langle\phi_n(t)|$$

How can we create totally non-classical states for the mirror?



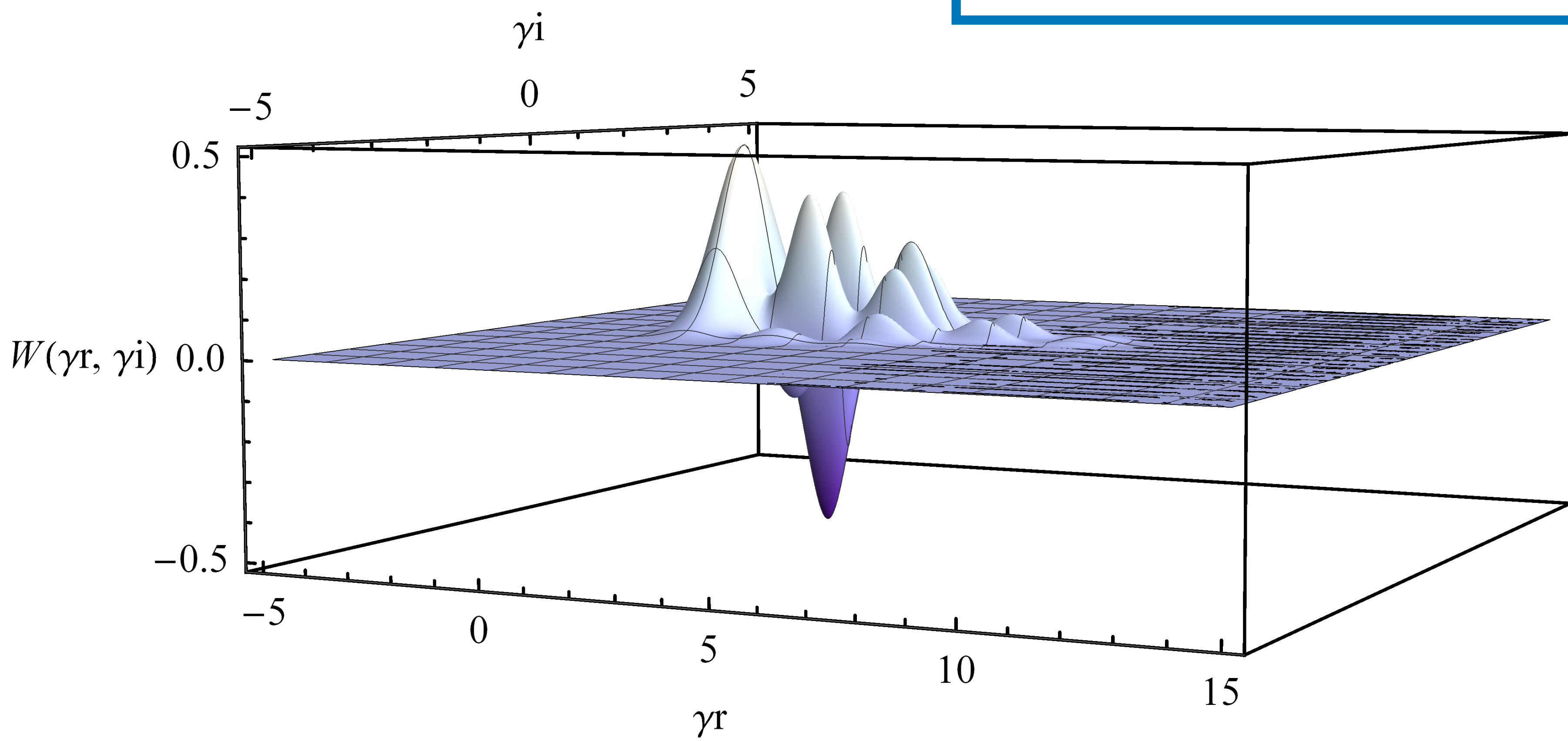
Projective measurement on the cavity field

$$\hat{\Pi}_C \equiv |x\rangle\langle x|$$

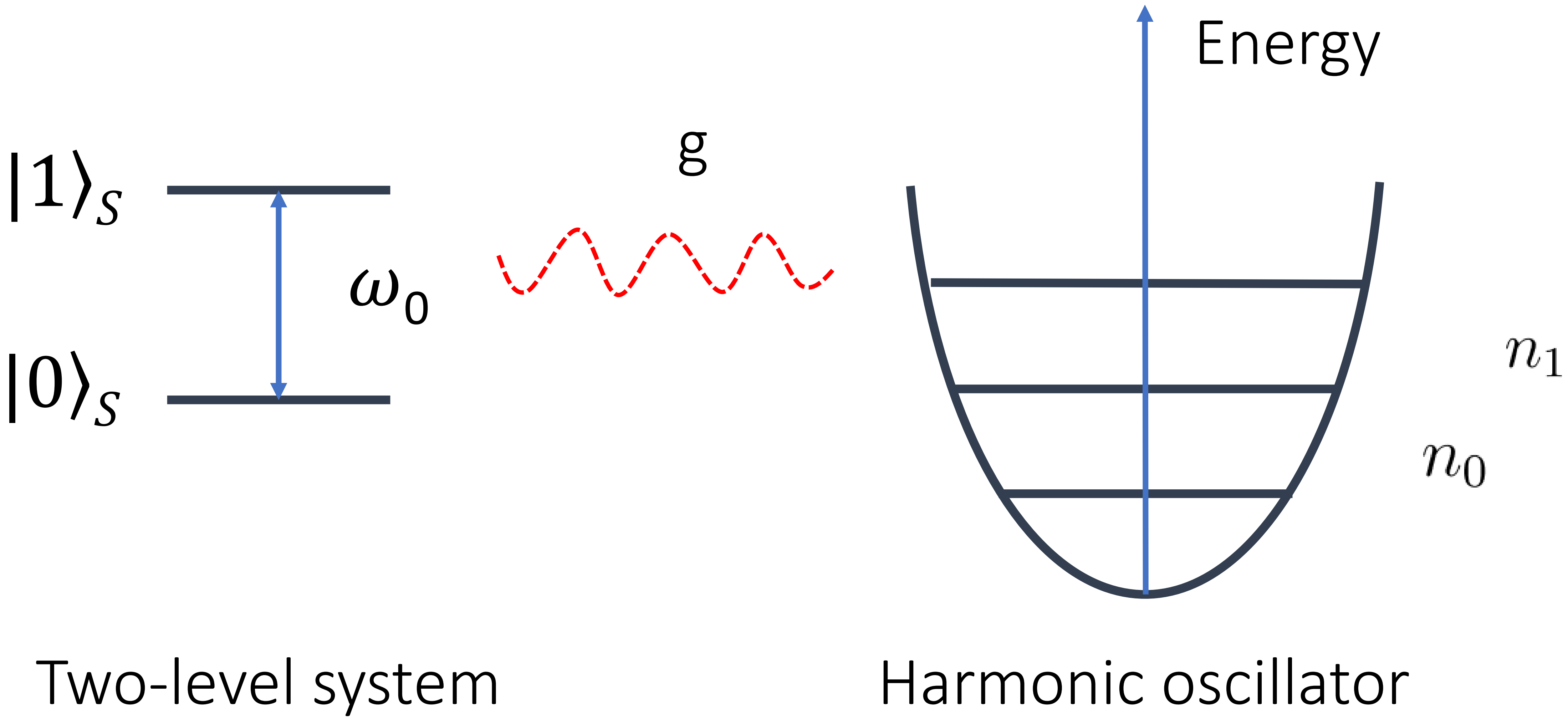
$$|\psi'(t)\rangle_{CM} = \hat{\Pi}_C |\psi(t)\rangle_{CM}$$

Superposition of coherent states

$$|\psi'(t)\rangle_M = \sum_{n=0}^{\infty} \beta_n(t) |\phi_n(t)\rangle$$



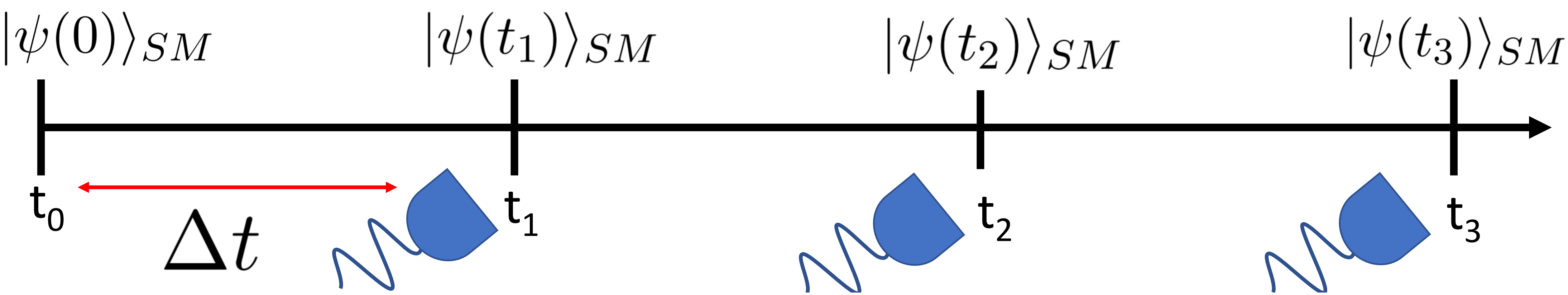
Test of LGI with hybrid optomechanical system



$$\hat{H} = \hbar\omega_0\hat{\sigma}_z + \hbar\omega_M\hat{b}^\dagger\hat{b} + \hbar g\hat{\sigma}_z(\hat{b}^\dagger + \hat{b})$$

We want to reproduce with the mirror the dynamic of the spin

Two-level system as ancilla



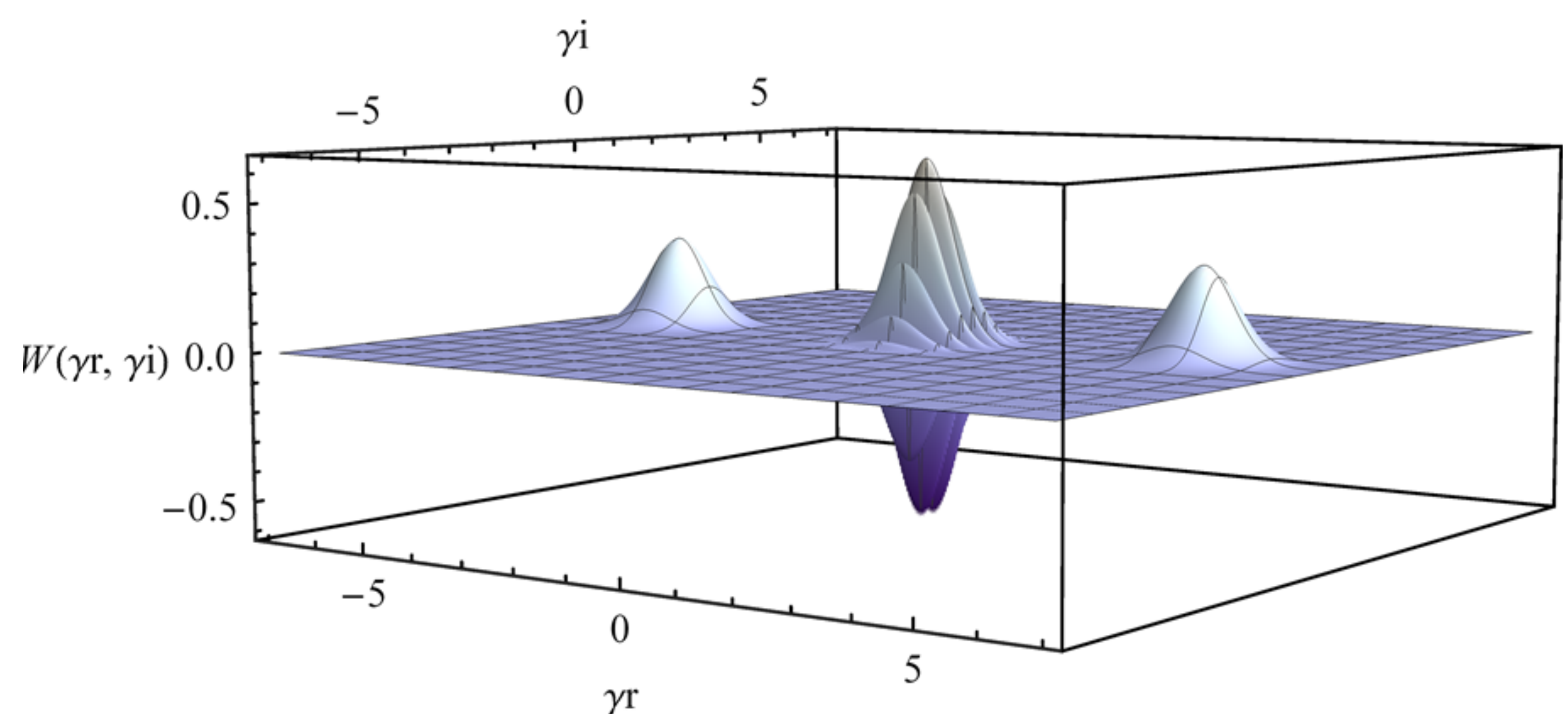
Test of the LGI for the mirror

Measurements of the coherent states of the mechanical oscillator

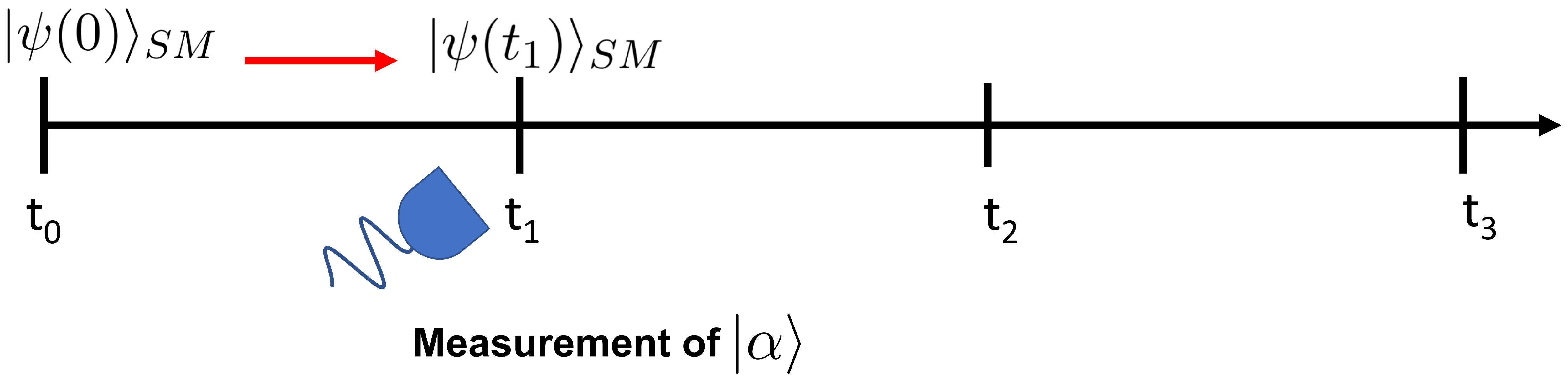
$$|\psi(0)\rangle_{SM} = \frac{(|1\rangle_S + |0\rangle_S)}{\sqrt{2}} \otimes |0\rangle_M$$

Time evolution map $\hat{\epsilon}(t) = \hat{\Pi}_+ \hat{U}(t)$

$$|\varphi(t)\rangle_M = \sqrt{\frac{1}{2(1+e^{-2|G|^2})}}\Big(|iG\rangle + |-iG\rangle\Big)$$



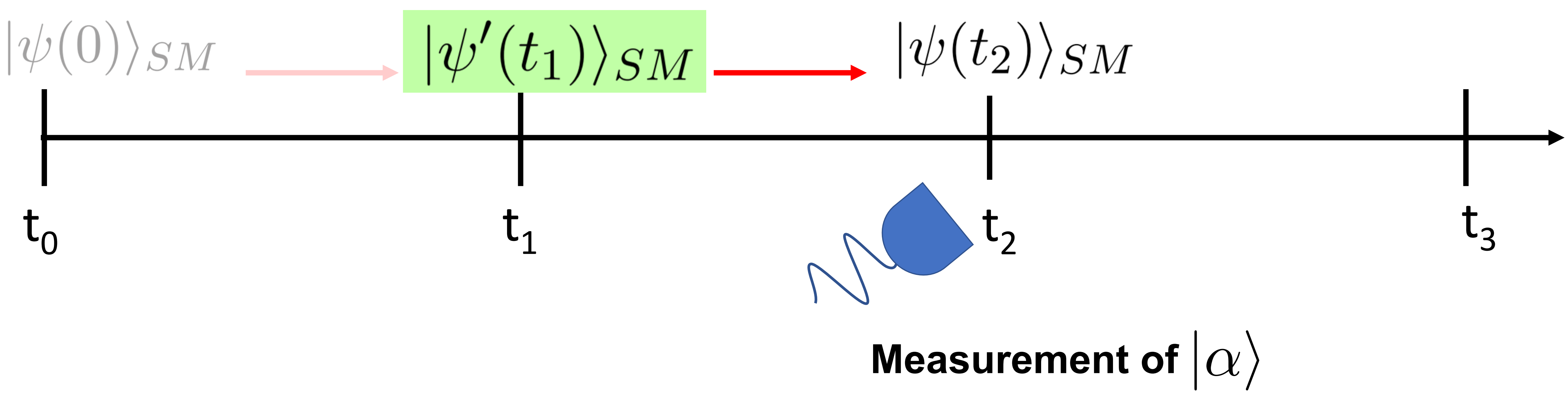
$$|\psi(0)\rangle_{SM} = |\alpha\rangle_M \otimes (\sin\tau|1\rangle_S + \cos\tau|0\rangle_S)$$



$$|\psi(t_1)\rangle_{SM} = \frac{(\sin\tau e^{-iG\alpha}|\alpha - iG\rangle_M + \cos\tau|\alpha\rangle_M)}{\sqrt{2}} \otimes |+\rangle_S$$

Reset the state of the ancilla

$$|\psi'(t_1)\rangle_{SM} = \frac{N_1}{\sqrt{2}}\big(\sin\tau e^{-iG\alpha}|\alpha - iG\rangle_M + \cos\tau|\alpha\rangle_M\big)$$
$$\otimes\big(A_\tau|1\rangle_S + B_\tau|0\rangle_S\big)$$



Dichotomization of the observable

In the limit $G \rightarrow \infty$:

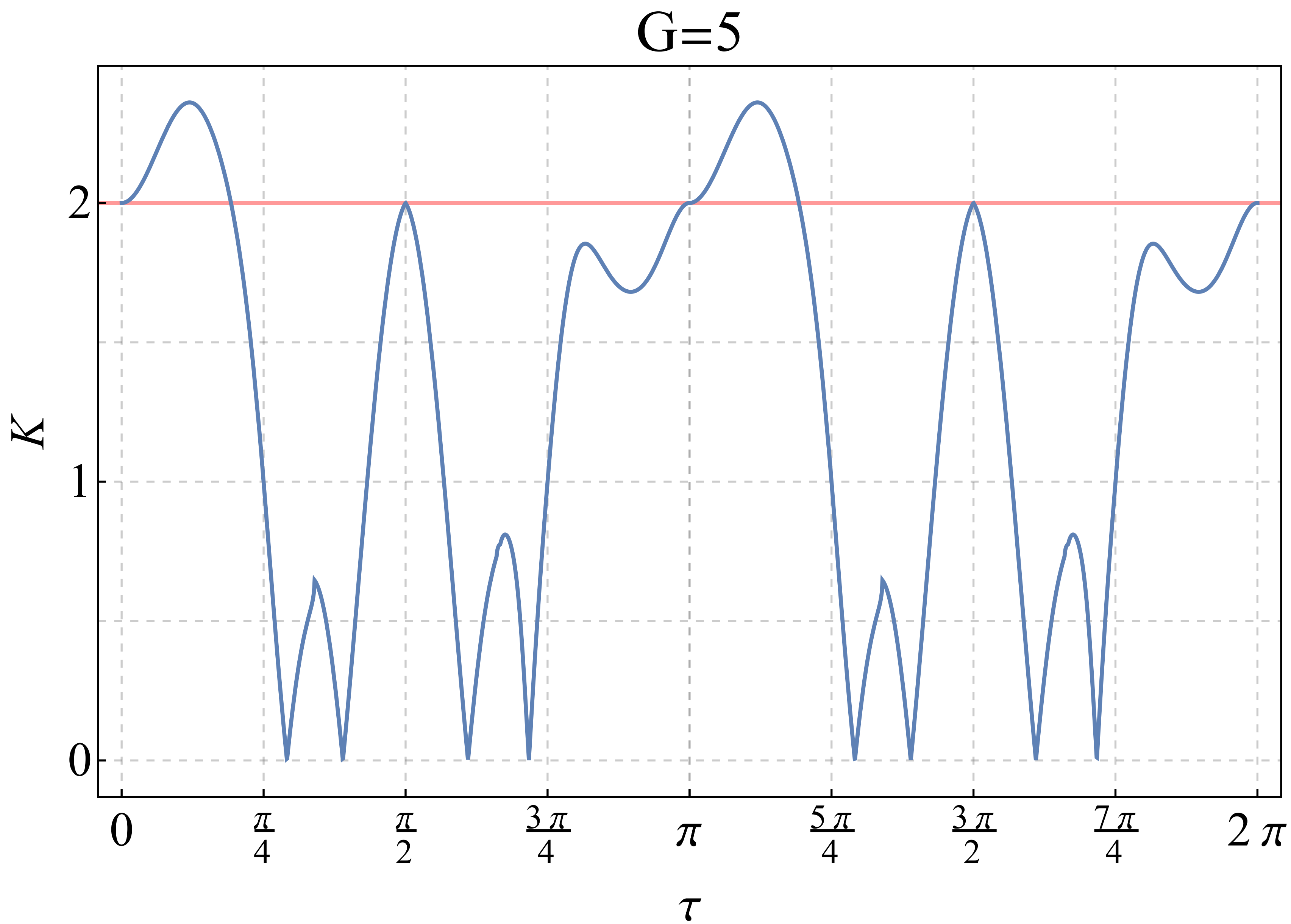
t_1 $\quad |\alpha\rangle \longrightarrow |0\rangle_L \qquad |\alpha - iG\rangle \longrightarrow |1\rangle_L$

t_2 $\quad |\alpha\rangle \longrightarrow |0\rangle_L \qquad \left\{ |\alpha - iG\rangle, |\alpha - 2iG\rangle \right\} \longrightarrow |1\rangle_L$

Orthogonality: $\langle\alpha|\alpha - iG\rangle = e^{-\frac{|G|^2}{2} - \frac{i}{2}(G\alpha^* + G^*\alpha)} \longrightarrow 0$

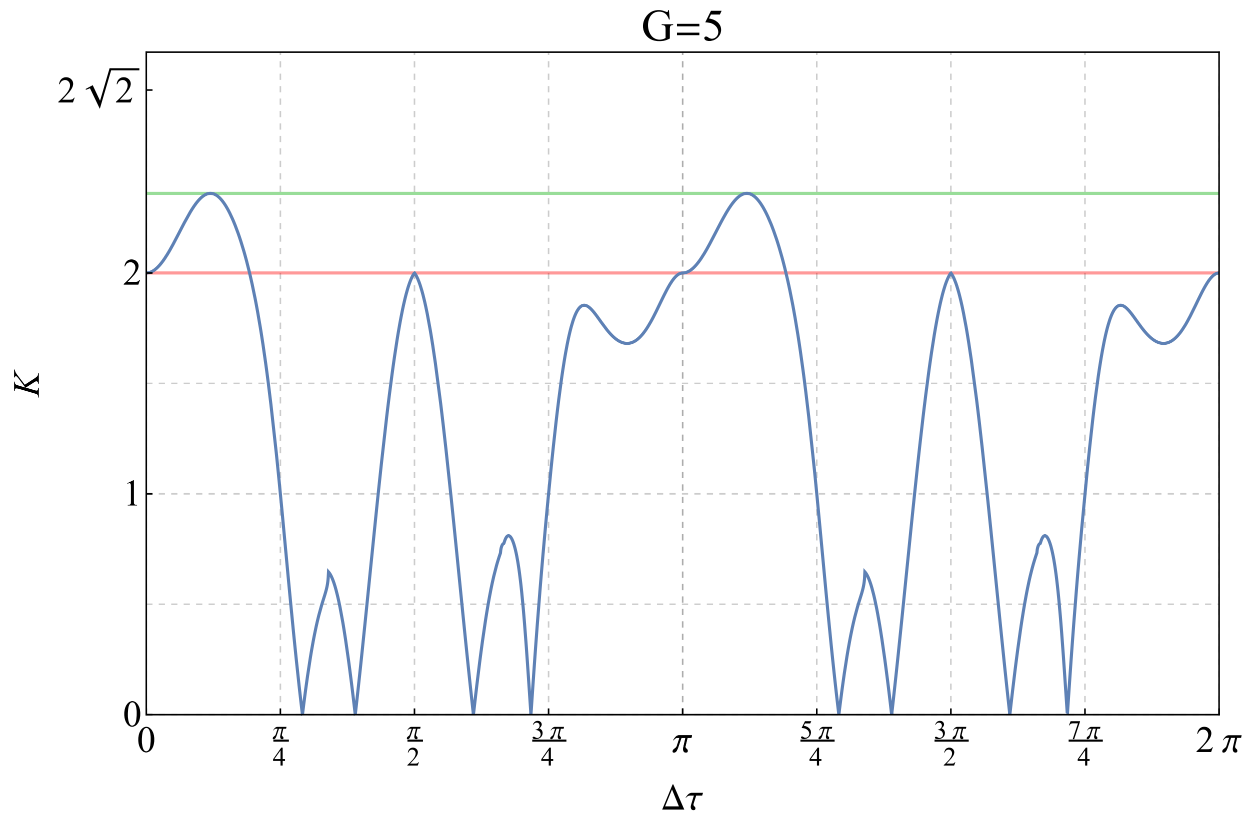
Completeness: $\hat{\Pi}_{0_L} = |\alpha\rangle\langle\alpha| \qquad \hat{\Pi}_{1_L} = \hat{1} - |\alpha\rangle\langle\alpha|$

Leggett-Garg Violation

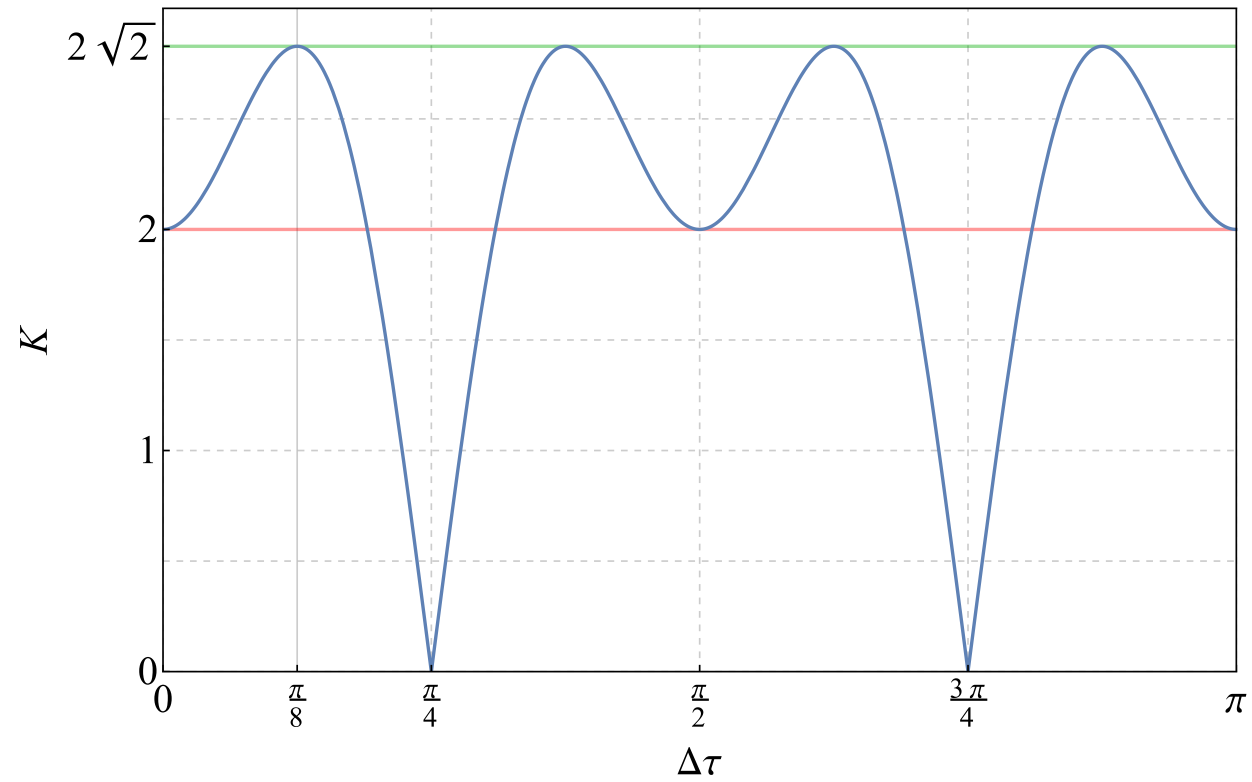


At least one of the two assumptions must fail

Oscillator



Spin



- Different periods due to small differences in correlation functions

- More similar to the spin case in the limit $G \to \infty$:

Conclusions

- Leggett-Garg inequalities enable us to infer a priori if a system can be treated classically or not

- Optomechanical cavities are particularly suitable to test these inequalities, because through the coupling with an ancillary system we are able to originate non-classical states of the mirror

- We studied an hybrid optomechanical system, in which a two-level system is coupled to an harmonic oscillator. We found a violation of the Leggett-Garg inequalities, meaning that a classical interpretation of the system has to be abandoned

Detection and control of optically levitated particles

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8/11/2018

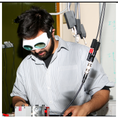
EPSRC Engineering and Physical Sciences Research Council
FQXi
JOHN TEMPLETON FOUNDATION
The Leverhulme Trust

Outline

- Southampton matter-wave group
- Levitated optomechanics
  - detection and control
  - ro-translational motion
- Testing a dynamical model
  - classical, quantum, CSL

Southampton matter-wave group

Professor Hendrik Ulbricht



Dr. Muddassar Rashid

Dr. Luca Ferialdi

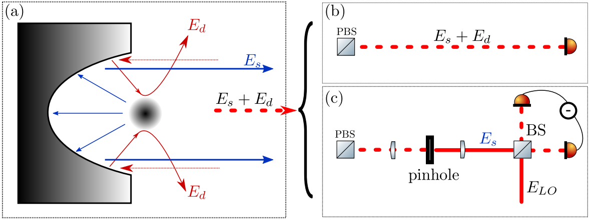
Dr. Andrea Vinante

Tiberius Georgescu

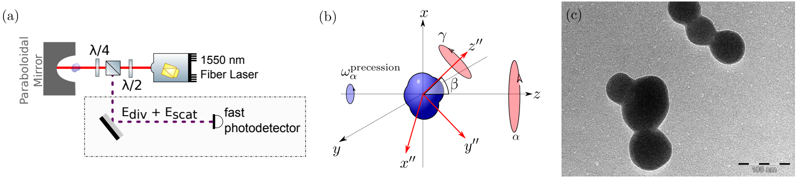
Ashley Setter

Chris Timberlake

Optically trapped particles and detection

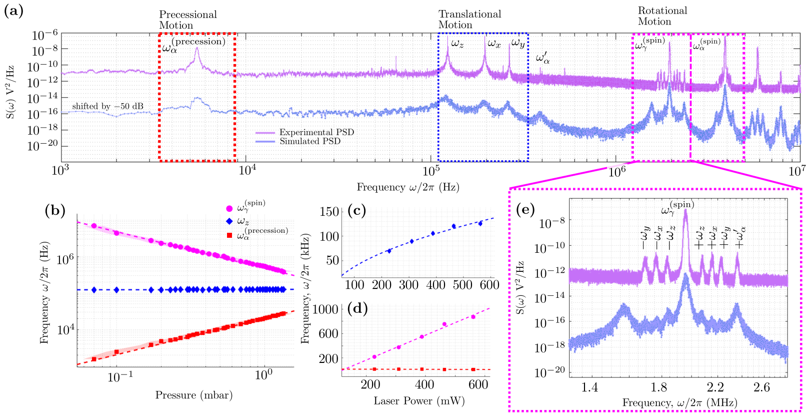


Ro-translational motion



Toroš, M., Rashid, M. and Ulbricht, H., 2018. *Detection of anisotropic particles in levitated optomechanics.* Physical Review A, 98, p.053803.

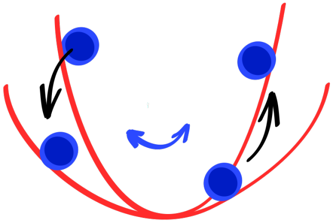
Ro-translational motion



Rashid, M., Toroš, M., Setter, A. and Ulbricht, H., 2018. *Precession Motion in Levitated Optomechanics*. arXiv preprint arXiv:1805.08042.

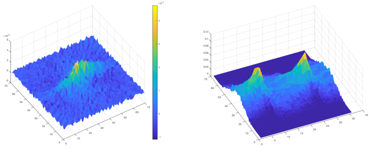
Estimation and control

- state estimation
  - ro-translational motion
- state control
  - cooling
  - driving
  - squeezing
  - displacement



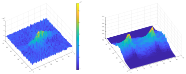
Setter, A., Toroš, M., Ralph, J.F. and Ulbricht, H., 2018. *Real-time Kalman filter: Cooling of an optically levitated nanoparticle.* Physical Review A, 97(3), p.033822.
Timberlake, C., Toroš, M., Hempston, D., Winstone, G., Rashid, M. and Ulbricht, H., 2018. *Experimental demonstration of Fano anti-resonance in levitated optomechanics.* arXiv preprint arXiv:1810.12680.

Testing a model - “inteferometry”

test type	“tomography based”
input	time-trace $I_{\text{exp}} \rightarrow$ reconstructed state $\hat{\rho}$
detection	dyne/protocol
visual aid	Wigner function 
generate non-classicality?	preparation protocol

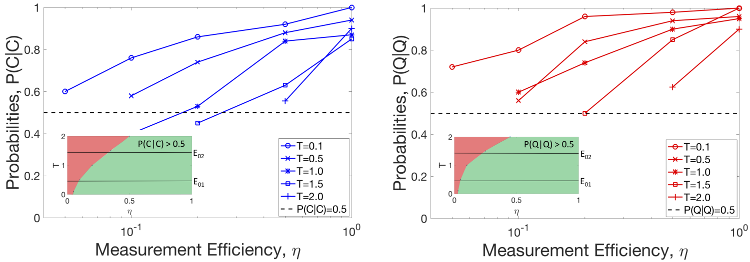
Rashid, M., Toroš, M. and Ulbricht, H., 2017. *Wigner function reconstruction in levitated optomechanics.* Quantum Measurements and Quantum Metrology, 4(1), pp.17-25.

Testing a model - "time-trace"

test type	**"tomography based"**	**"dynamical model selection"**
input	reconstructed state $\hat{\rho}$	time-trace I_{exp}
detection	protocol	dyne
visual aid	Wigner function 	/
generate non-classicality?	preparation protocol	nonlinearity

Ralph, J.F., Toroš, M., Maskell, S., Jacobs, K., Rashid, M., Setter, A.J. and Ulbricht, H., 2018. *Dynamical model selection near the quantum-classical boundary*. Physical Review A, 98(1), p.010102.

Optomechanical system with Duffing nonlinearity



Ralph, J.F., Toroš, M., Maskell, S., Jacobs, K., Rashid, M., Setter, A.J. and Ulbricht, H., 2018. *Dynamical model selection near the quantum-classical boundary*. Physical Review A, 98(1), p.010102.

Summary

- Levitated optomechanics and Southampton experiment
  - detection and control of ro-translational motion
  - dynamical model selection
- Applications
  - force and torque sensing
  - search for quantum features
  - beyond current theories

Contact

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FQXi
JOHN TEMPLETON FOUNDATION
The Leverhulme Trust

The synthesis and characterization of photon upconverting $Yb{:}YLiF_4$

Jence Mulder

Delft University of Technology

Department of Chemical Engineering

Opto-Electronic Materials Group

TU Delft

Role TU Delft in TEQ

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

- TU Delft & IIT


Prof. L. Manna - IIT


Dr. L. De Trizio - IIT


F. De Donato - IIT


Dr. A.J. Houtepen - TUD

TU Delft

Jence Mulder

- MSc Chemical Engineering – TU Delft
  - Master thesis @ OM group (Arjan Houtepen)
  - Internship @ IIT Genova (Liberato Manna and Luca de Trizio)
  - PhD @ OM group (Arjan Houtepen and Liberato Manna) for TEQ-project

TU Delft

Material requirements

The optimal NC:

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

TU Delft

Proposed materials

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

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Proposed materials

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

CdS, CdSe, CdTe, CdSe@CdS → Size difficulties

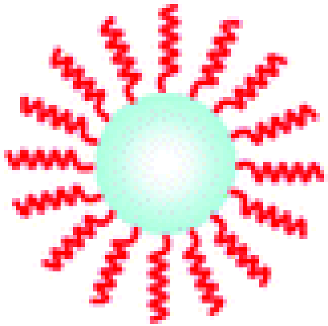
ZnSe, SiO_2 → Spherical

$Yb:YLiF_4$ → Size and shape fulfil requirements in theory

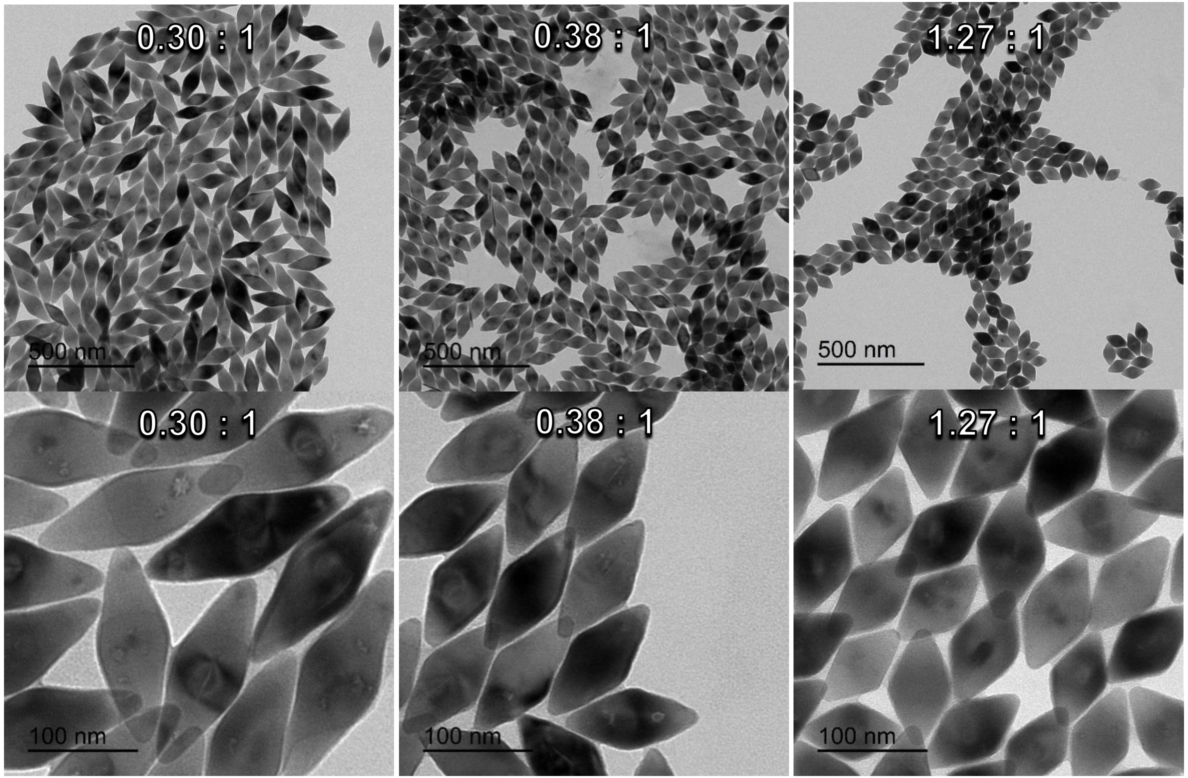
TU Delft

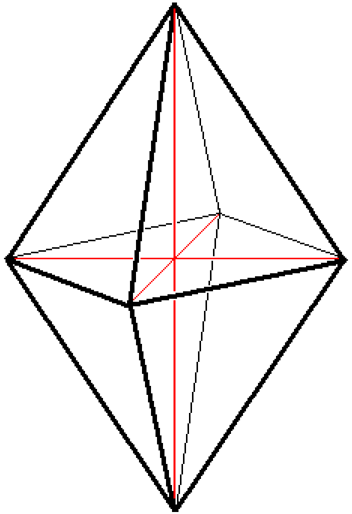
Synthesis

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



TEM Imaging samples (Yb : Y)





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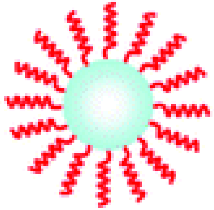
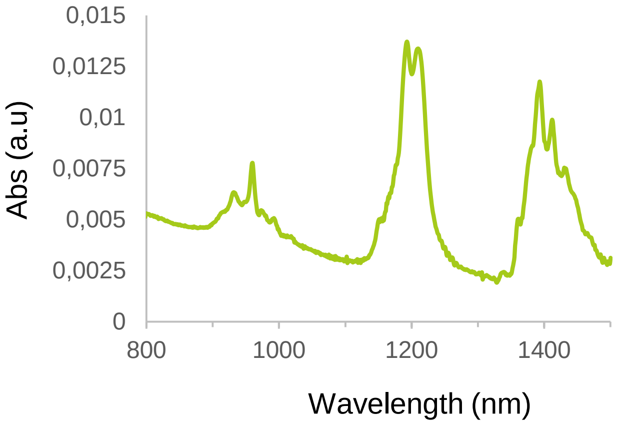
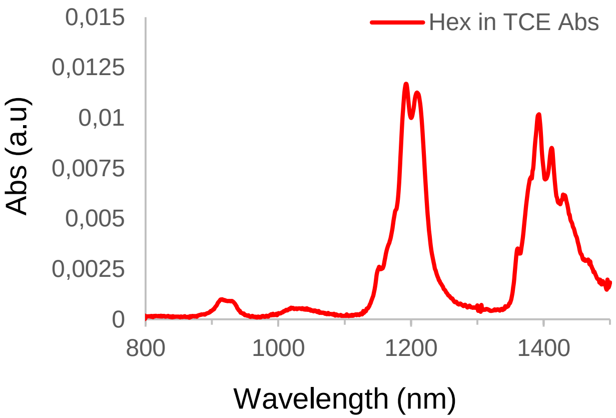
Absorption Spectroscopy



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





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

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

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Material requirements

The optimal NC:

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

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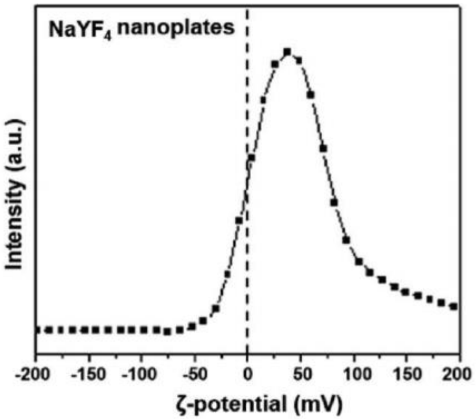
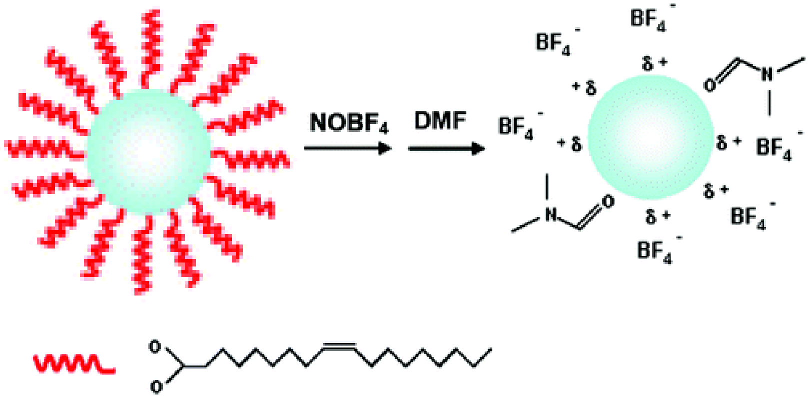
Ligand exchange

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

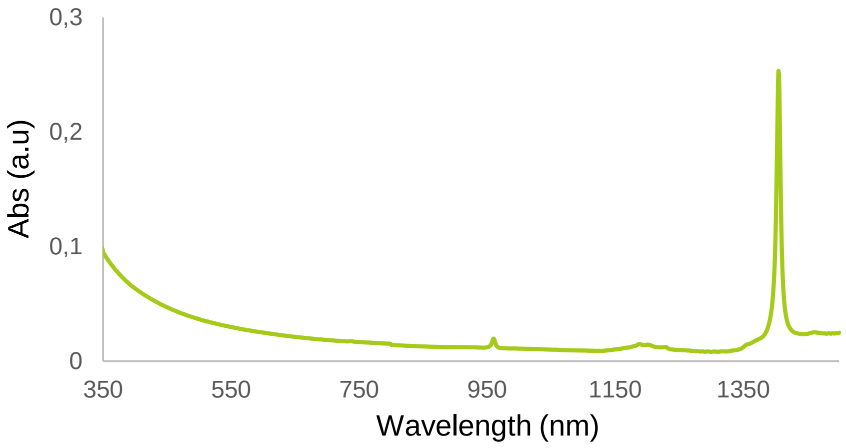


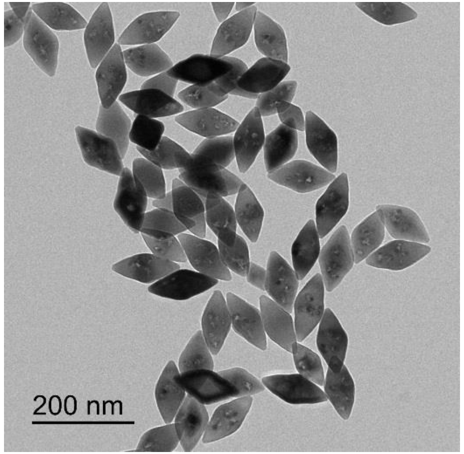


DOI: 10.1021/ja108948z

Absorbance change

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





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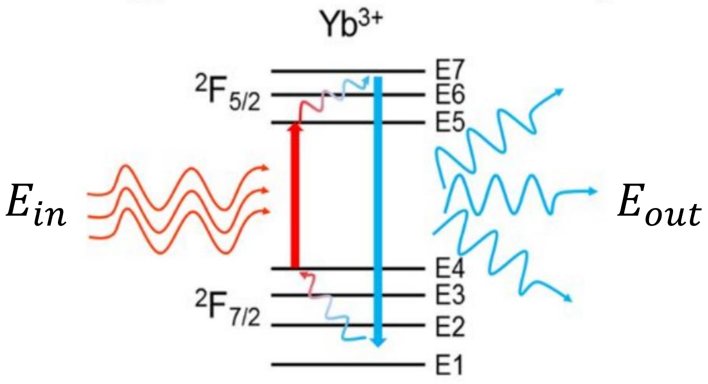
- Size ✓ 50 nm - 1µm, monodisperse
- Absorption ✓ very low at 1064 and 1550 nm
- Solvent ✓ polar, suitable for electrospray
- Charge ~ defined for surface
- Optical refrigeration → photon upconversion

Optical refrigeration principle

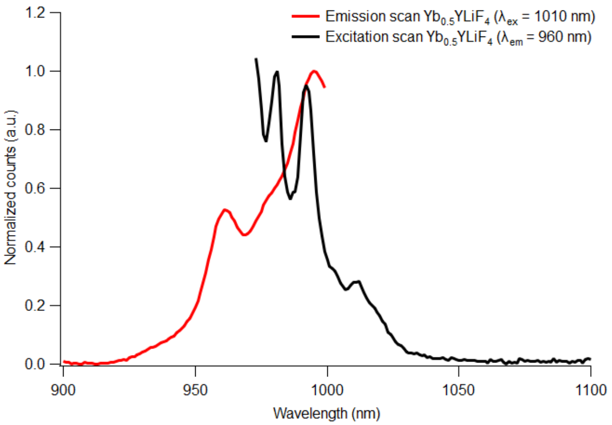
- Phonon-assisted anti-Stokes photoluminescence
- High quantum yield required for cooling

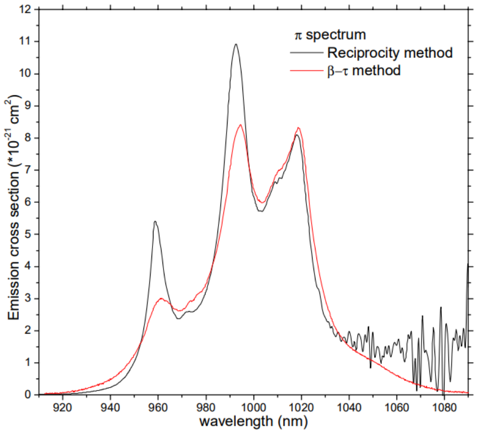


DOI: 10.1117/12.2080343

Emission and excitation spectroscopy

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





Material requirements

The optimal NC:

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

Outlook

- Size, shape, solvent and absorption parameters meet the requirements

- Charging surface is possible
- More analysis needed for defined charge

- Nanoparticles show upconversion
- Very high purity needed for required QY

TU Delft

Suggestions and feedback

- Please let me know if:
  - Parameters are indeed met
  - Parameters are missing
  - Particles can be measured to receive feedback

- Requests for samples
  - *J.T.Mulder@tudelft.nl*

TUDelft

Special Relativity and Spontaneous Collapse Outside the Light Cone

Caitlin Jones

November 7, 2018

Outline

1. Motivation and Background
2. Collapse and Relativity
3. Tumulka's Relativistic Collapse Model
4. Outlook

Background on Collapse Models and Special Relativity

- The original collapse models GRW and CSL are not relativistic
- Current experiments explore the low velocity regime
- There are some models proposed to be relativistic; Tulmulka's model [1], the one of Bedingham et al [2] and Tilloy's model [3],

Collapses in Different Frames

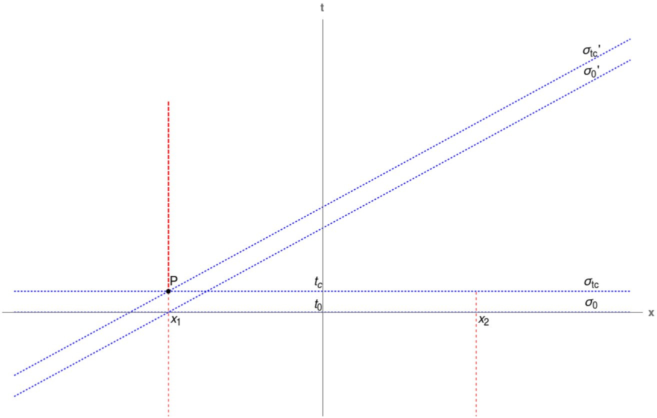


Figure: If a collapse occurs on σ_{t_c} then the state on σ_0' is not normalised.

Agreement with Special Relativity

Conditions for Consistency with Special Relativity

1. Observers in different inertial frames must be able to relate initial conditions.
2. The dynamics of the system must be Lorentz covariant.

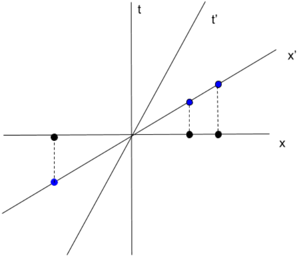
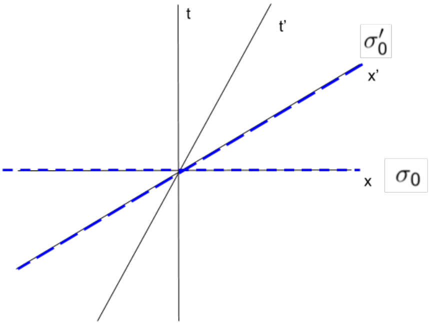


Figure: Initial conditions in two different inertial frames for classical particles in 1D.

Relativistic Quantum Mechanics without Collapses



$$U_{\sigma_0}^{\sigma_0'} = T\ \exp[-i\int_{\sigma_0}^{\sigma_0'} d^4x\mathcal{H}_I(x)]$$

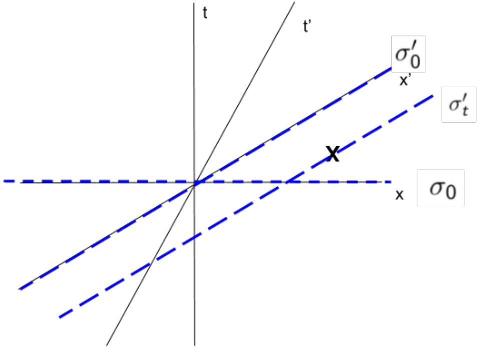
$$[\mathcal{H}_I(x), \mathcal{H}_I(y)] = 0$$

if x and y are spacelike

$$|\psi'_{\sigma_0'}(x')\rangle| = |\psi_{\sigma_0'}(x)\rangle$$

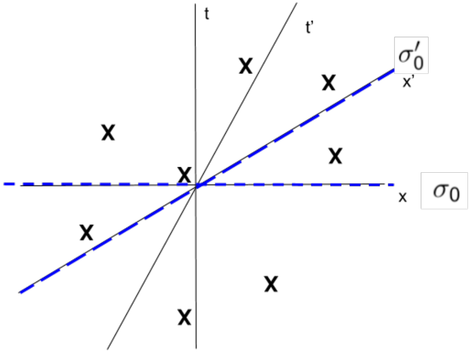
$$= U_{\sigma_0}^{\sigma_0'}|\psi_{\sigma_0}(x)\rangle$$

Quantum Mechanics with Collapses



$$|\psi_{\sigma'_0}(x)\rangle = \frac{U^{\sigma'_0}_{\sigma'_t}\hat{L}(X)U^{\sigma'_t}_{\sigma_0}|\psi_{\sigma_0}(x)\rangle}{|\hat{L}(X)U^{\sigma'_t}_{\sigma_0}|\psi_{\sigma_0}(x)\rangle|^2}$$

Quantum Mechanics with Spacelike Collapses



The position of all collapses between the two hypersurfaces must be known.

Relativity for Spontaneous Collapse Models

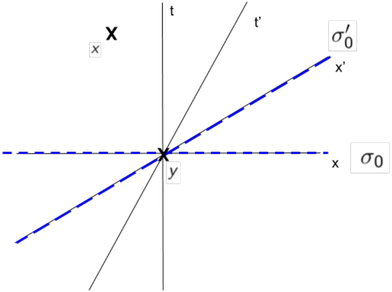


Figure: For Markovian collapse models the initial conditions are a point of collapse and state on the constant time hypersurface intersecting that point.

Then the dynamics must satisfy:

$$P(x|y, |\psi_{\sigma_0}\rangle) = P(x'|y', |\psi_{\sigma_0'}\rangle). \tag{3}$$

Tumulka's Relativistic Collapse Model

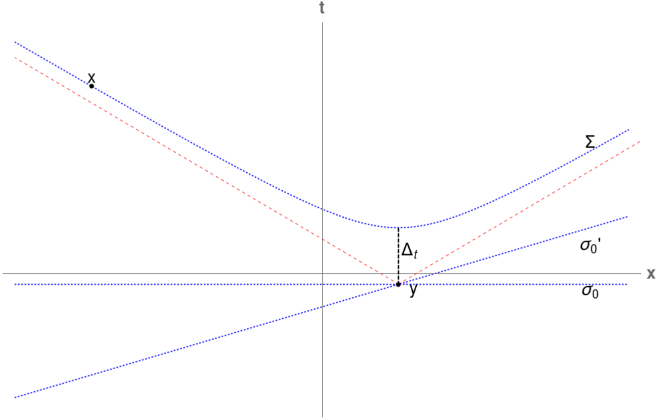


Figure: Here the dashed red line shows the future lightcone of y and the dotted blue lines show space-like hypersurfaces.

Tulmulka's model with interacting particles

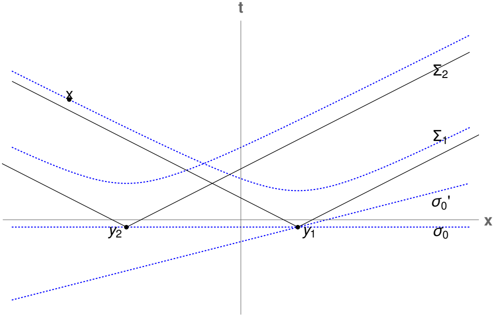


Figure: In a frame where the two initial points of collapse y_1 and y_2 are simultaneous then the state on Σ_1 or Σ_2 cannot be specified as:

$$[U_{\sigma_0}^{\Sigma_2}, \hat{L}(x)] \neq 0$$

Indistinguishable extension with time-like collapses

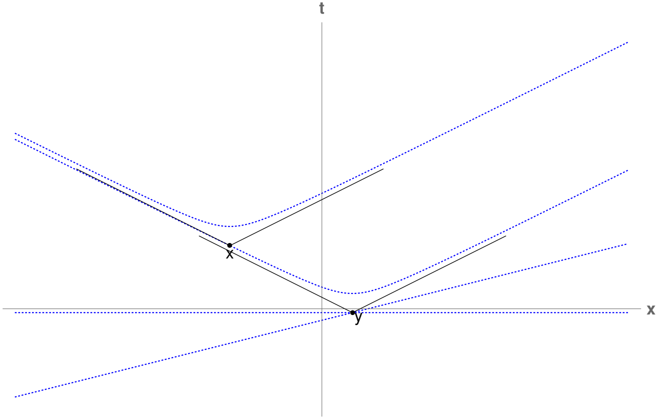


Figure: Subsequent collapses, here y then x, will be time-like to each other, so the indistinguishable extension is relativistic

Failure of indistinguishable extension

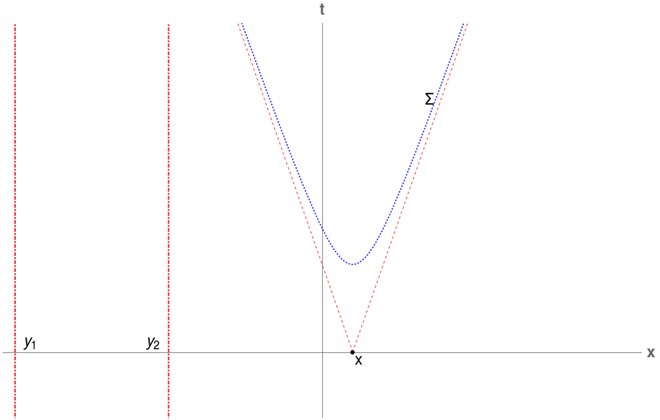


Figure: Two indistinguishable particles with one particle initially in a spatial superposition at $\underline{y}_1$ and $\underline{y}_2$.

Outlook

- For models with point like collapses then in order to be Lorentz invariant then two initial observers must be able to relate their initial conditions
- Tulmulka's model cannot be extended to realistic particles
- I suspect that for a spontaneous collapse model to be consistent with special relativity the initial condition required must be a local.

[1] Roderich Tumulka.
A relativistic version of the Ghirardi–Rimini–Weber model.
Journal of Statistical Physics, 125(4):821–840, 2006.

[2] Daniel Bedingham, Detlef Dürr, GianCarlo Ghirardi, Sheldon Goldstein, Roderich Tumulka, and Nino Zanghì.
Matter density and relativistic models of wave function collapse.
Journal of Statistical Physics, 154(1-2):623–631, 2014.

[3] Antoine Tilloy.
Interacting quantum field theories as relativistic statistical field theories of local beables.
arXiv preprint arXiv:1702.06325, 2017.

Thank you for listening

Andrea Vinante

The TEQ detection "challenge"

University of Southampton, UK

How do you detect a nanoparticle in the Paul trap ?

Main Issue: internal heating due to light absorption

$\Rightarrow$ Light or not light?

Light:

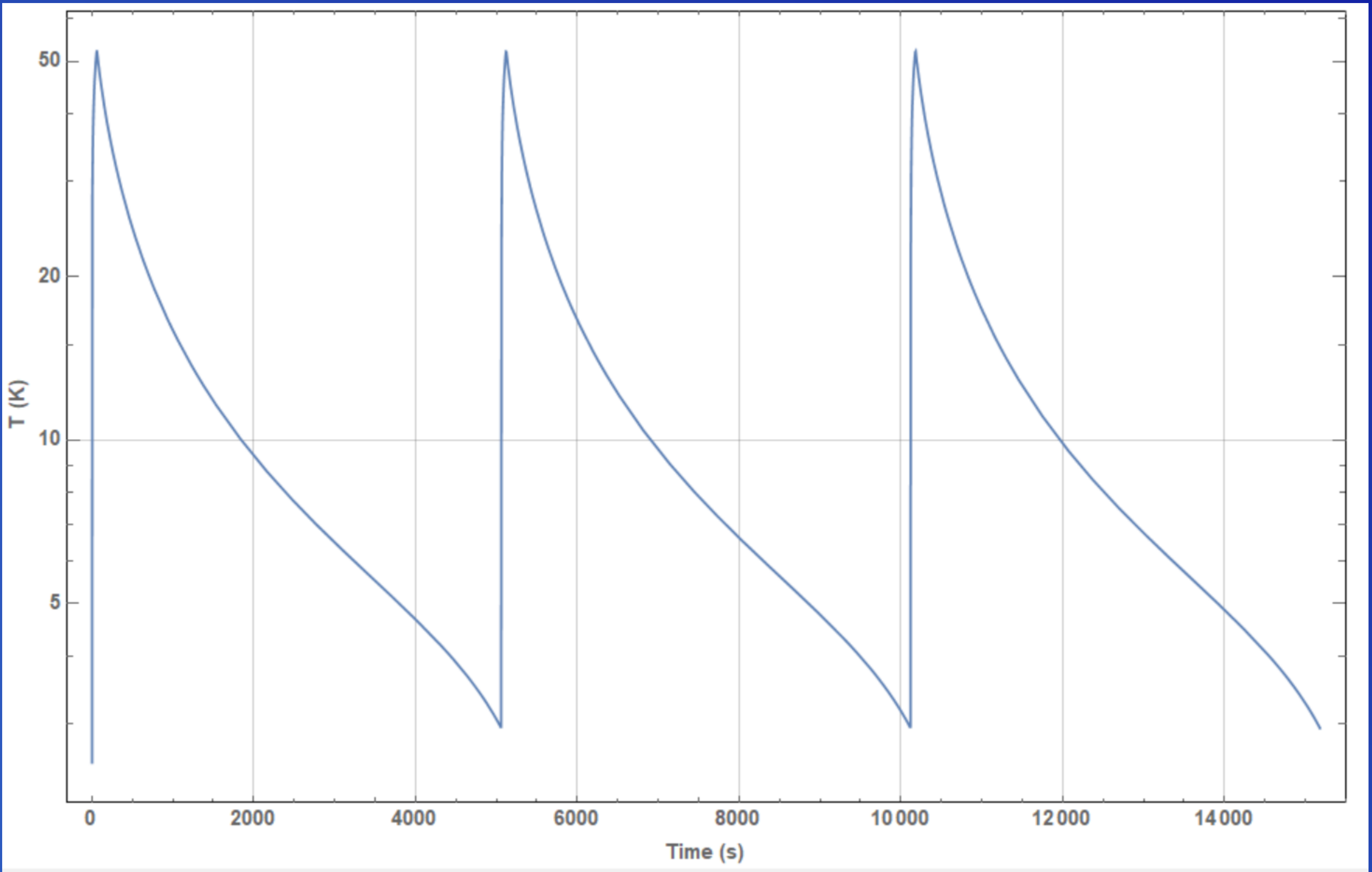
Optical cavity (UCL)

Optical “tweezer” = paraboloid mirror (UoS)

Not light ? Electrical Readout + SQUID (UoS)

Continuous vs stroboscopic

Internal heating @ “reasonable” optical power (~ fW absorption)



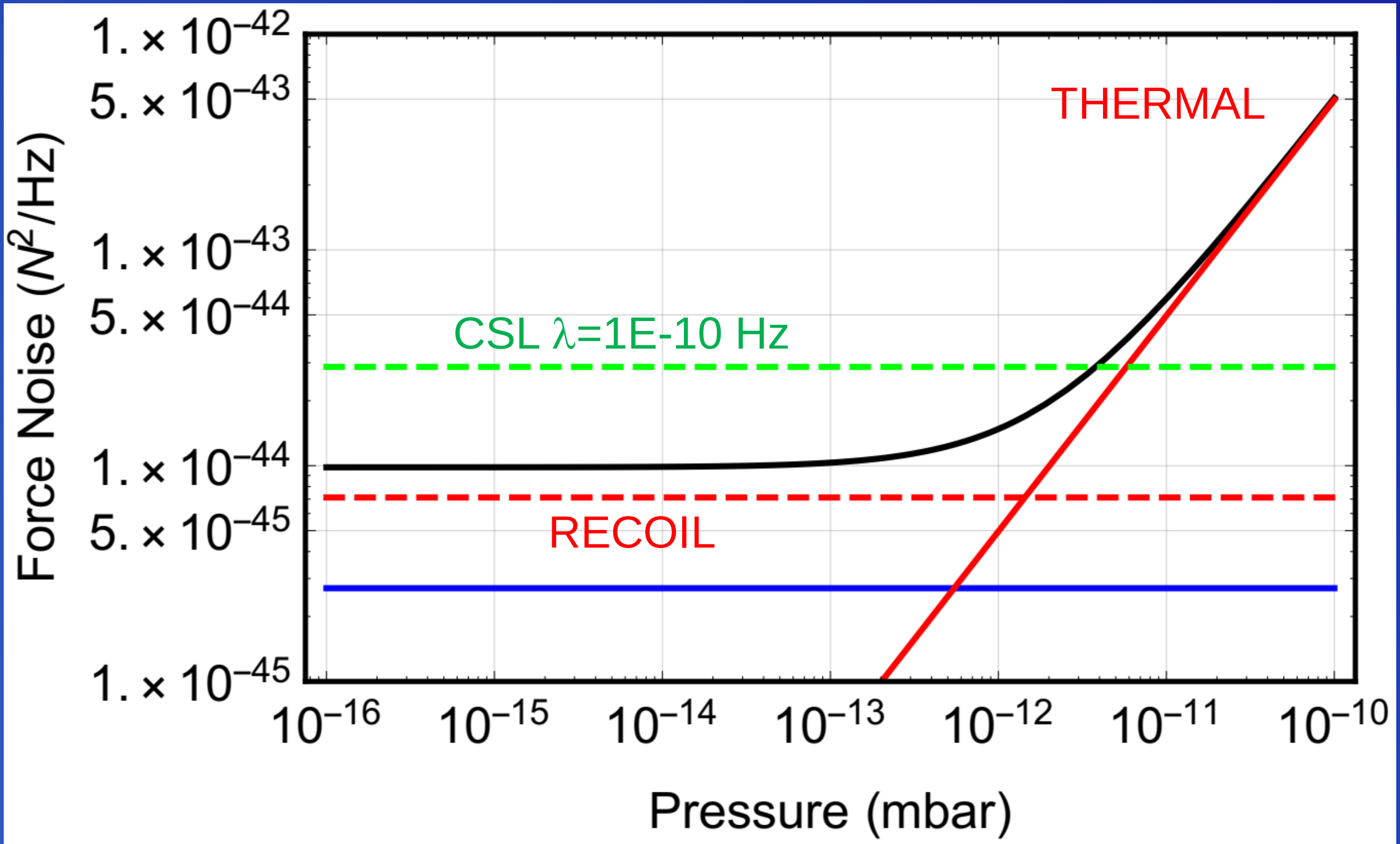
R=200 nm SiO2
Tgas=0.3 K
P=1E-12 mbar

Pabs=3E-15 W
t_on=1 minute
t_off=5000 seconds

Why do we care?

Thermal noise from gas collisions depends on internal temperature !

HEATING ISSUE
(optical cavity case)



For realistic fixed power !

R=200 nm SiO_2
T=0.3 K

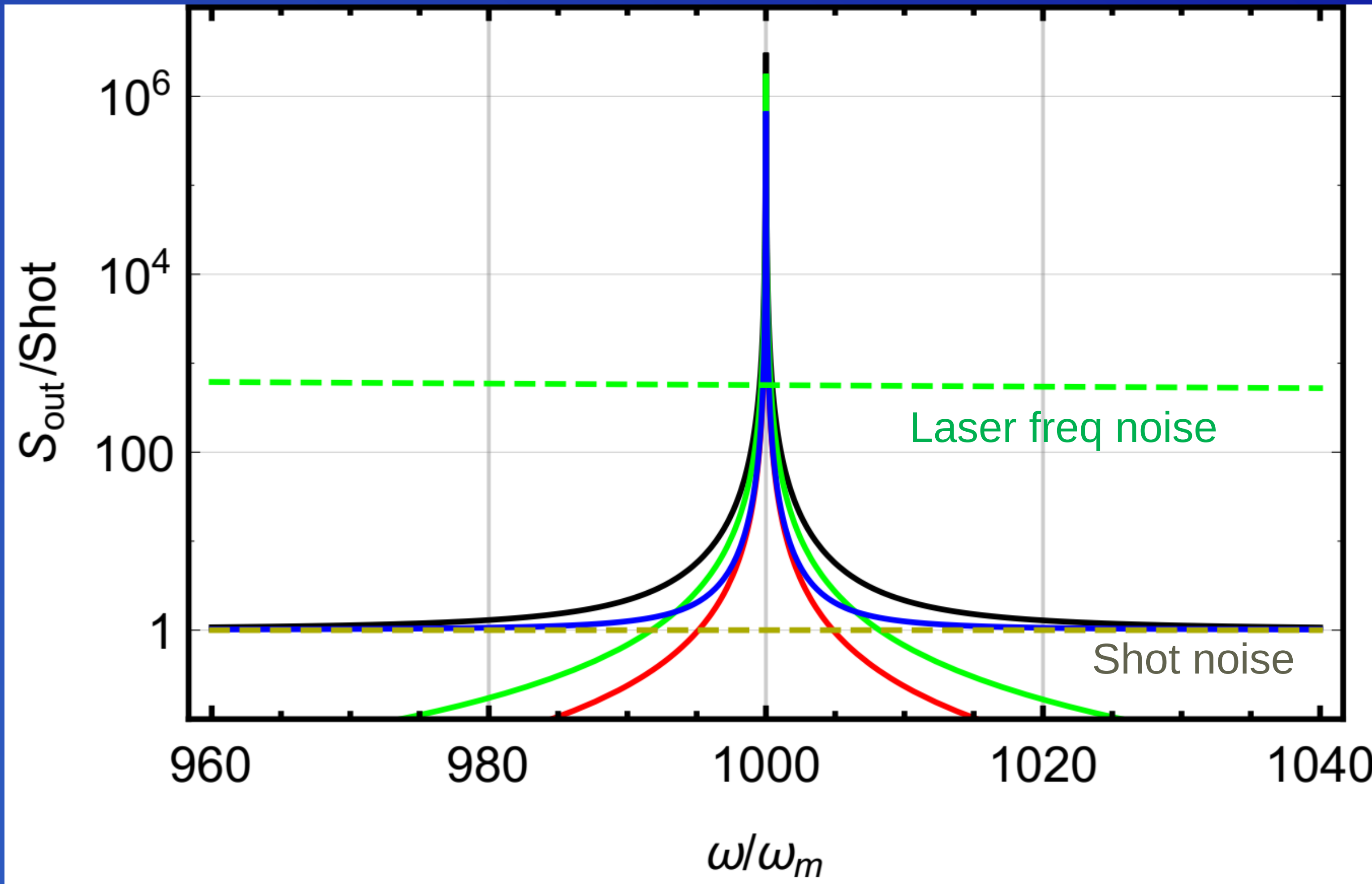
Pabs=3E-15 W
Teff=24 K

Alternative solutions

1) P<1E-12 mbar will be achieved ? ⇒ GET RID OF THERMAL NOISE (FROM GAS)

2) GET RID OF LIGHT

Spectrum (cavity)



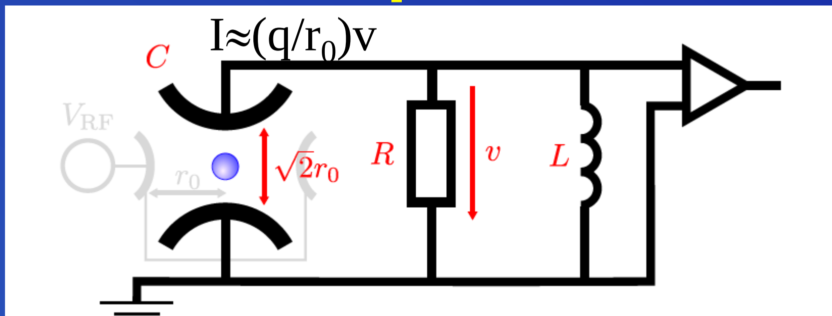
R=200 nm SiO2
T=0.3 K
P=5E-13 mbar

Pin=10 uW
Pabs=3E-15 W
Teff=24 K

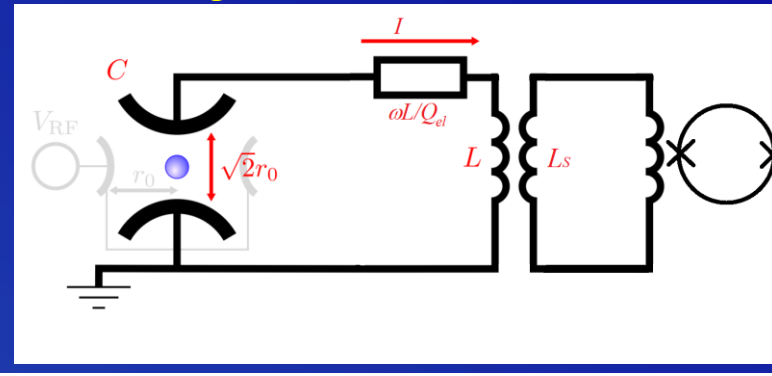
SIMILAR FIGURES FOR OPTICAL TWEEZER (PARABOLOID MIRROR):
WORK IN PROGRESS

Electrical readout (+ SQUID)

Paul trap + electrical + SQUID readout

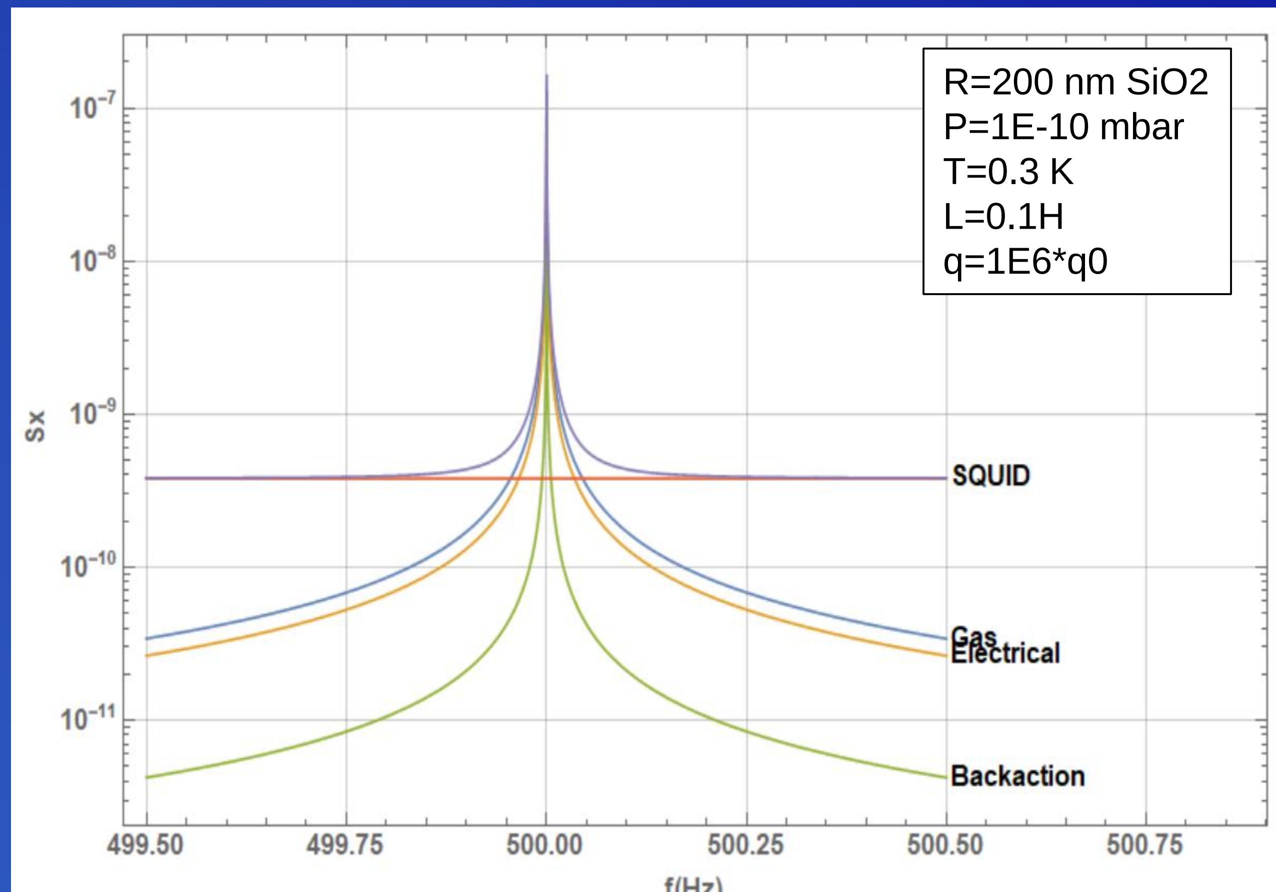


Goldwater and Millen, 2015

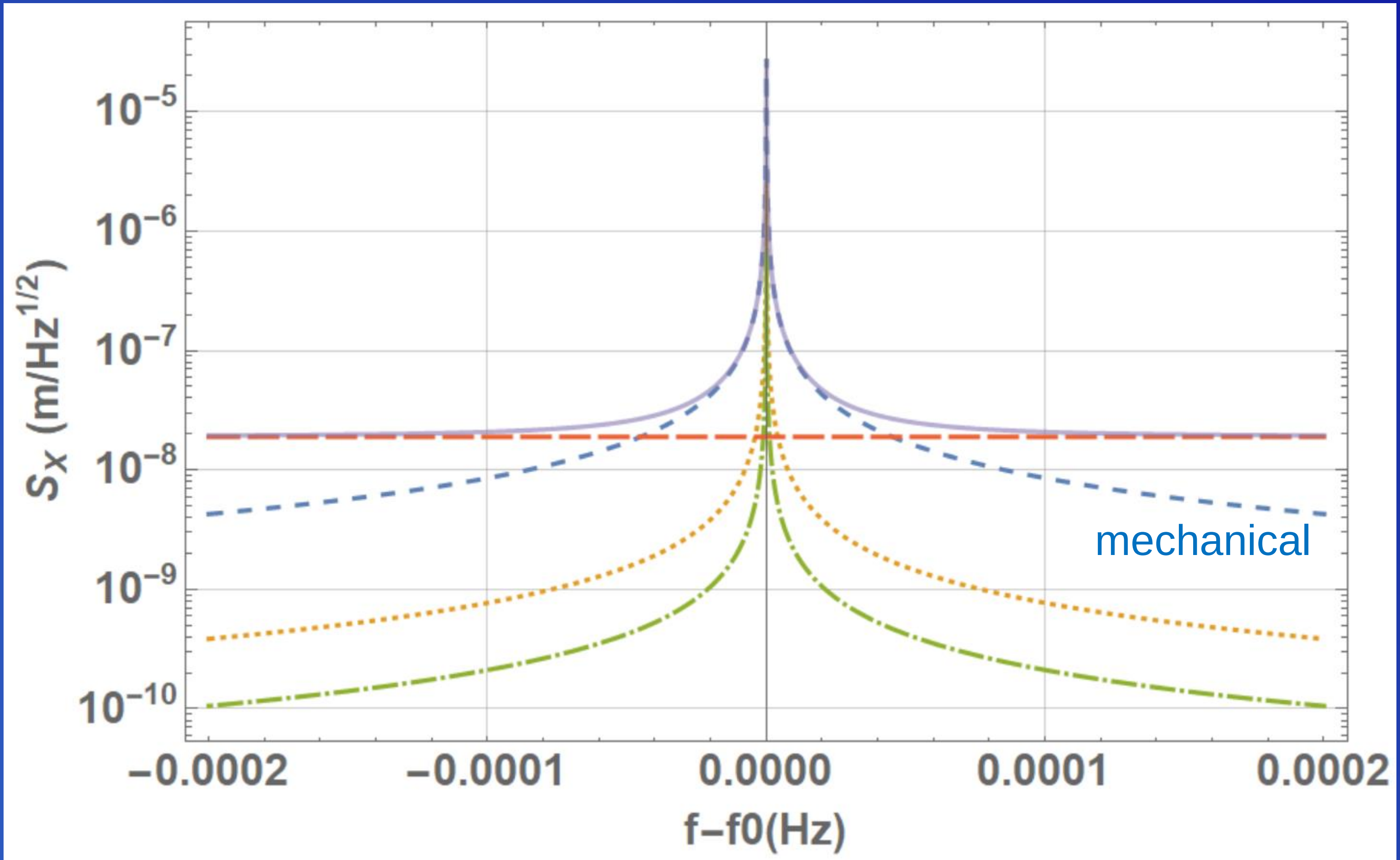


Advantages:
- no laser, no power dissipation
electrical circuit = cold environment
- Can use particle of any material

Issues:
- Handle big ac bias signal
- Low coupling, need large charge ($1E5$-$1E6$ q_0)
- Need big coil (L=0.1-1H)



More realistic charge (1000 e)

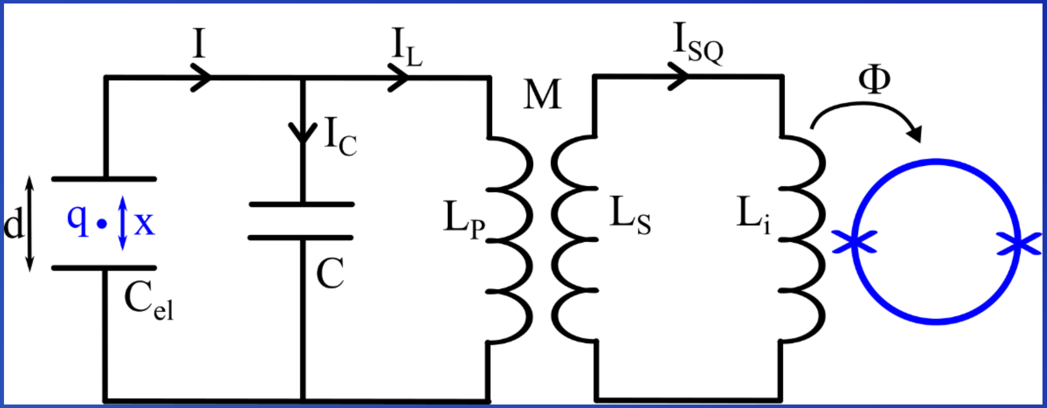


R=200 nm SiO2
P=1E-12 mbar
T=0.3 K
L=10 H
q=1E3*q0
f0=1 kHz

ULTRANARROW BANDWIDTH (= very long integration time, require high stability !!)

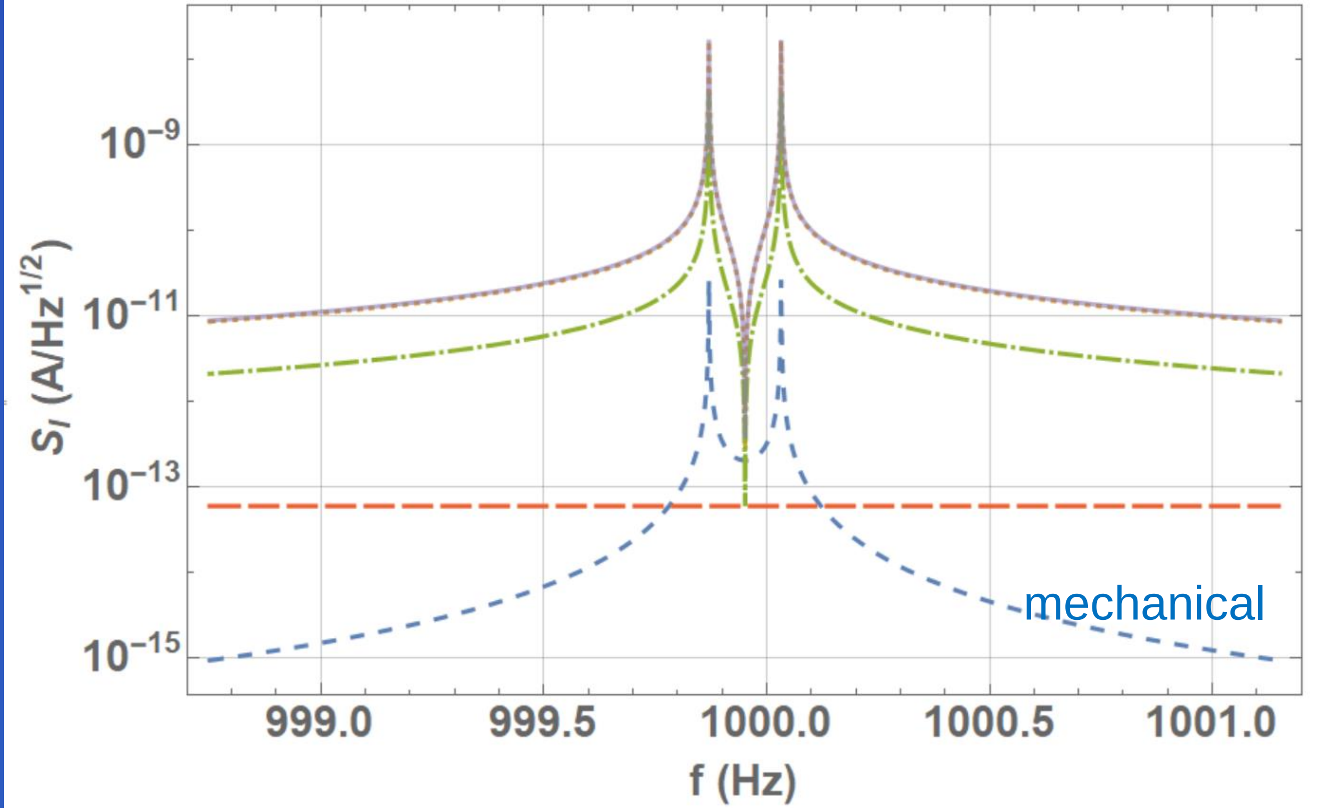
BUT ULTRALOW FORCE NOISE: λ<1E-13 Hz @ rc=1E-7 m !!!
λ<1E-15 Hz using an osmium particle …

Use a LC to increase coupling



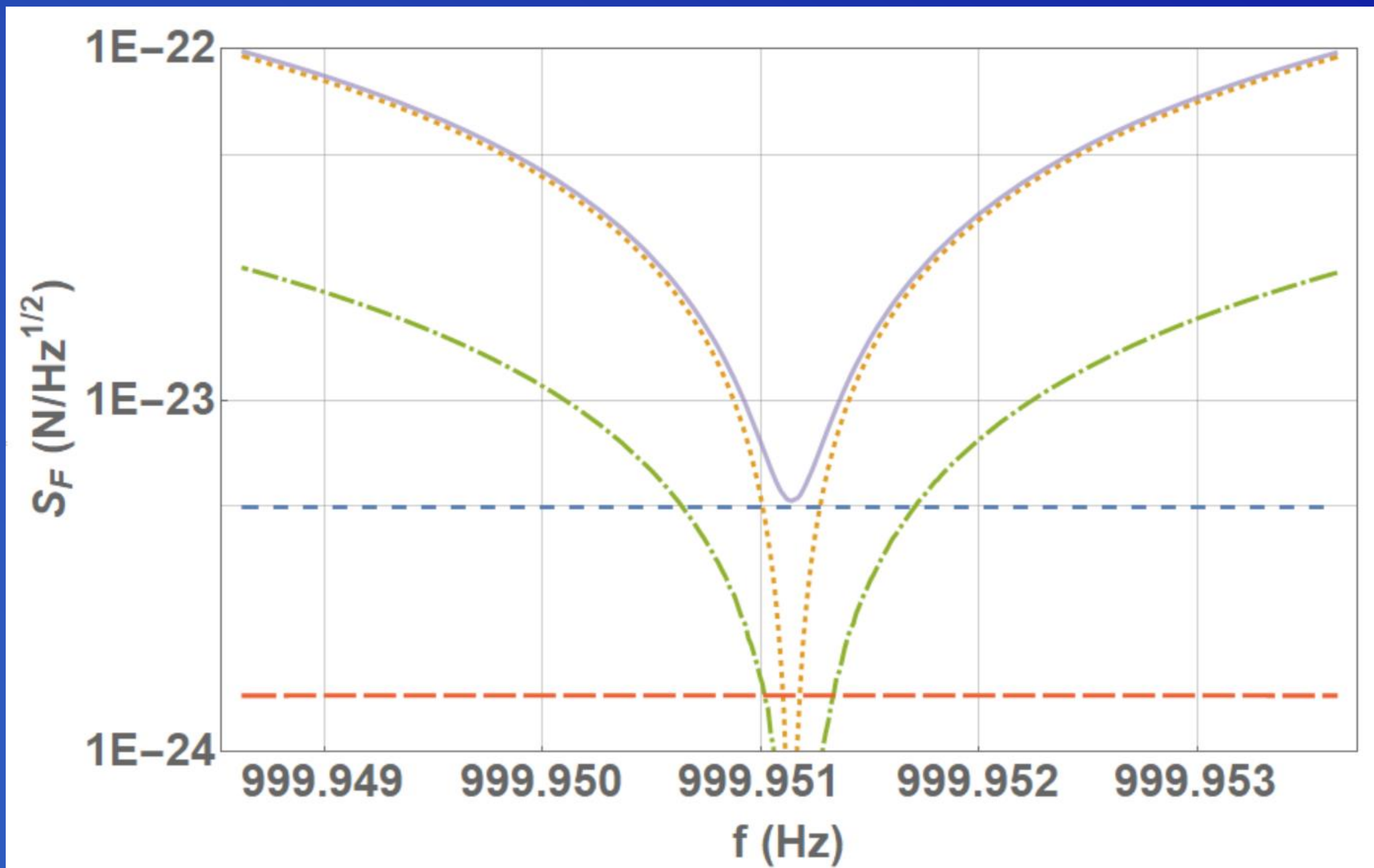
1) Mechanical and LC modes hybridize !
2) However: LC thermal noise (Q) is much worse than mechanical !

Good coupling:
(can see very well the particle)
BUT
Very bad force noise !



R=200 nm SiO2
P=1E-12 mbar
T=0.3 K
L=10 H
q=1E3*q0
f0=1 kHz

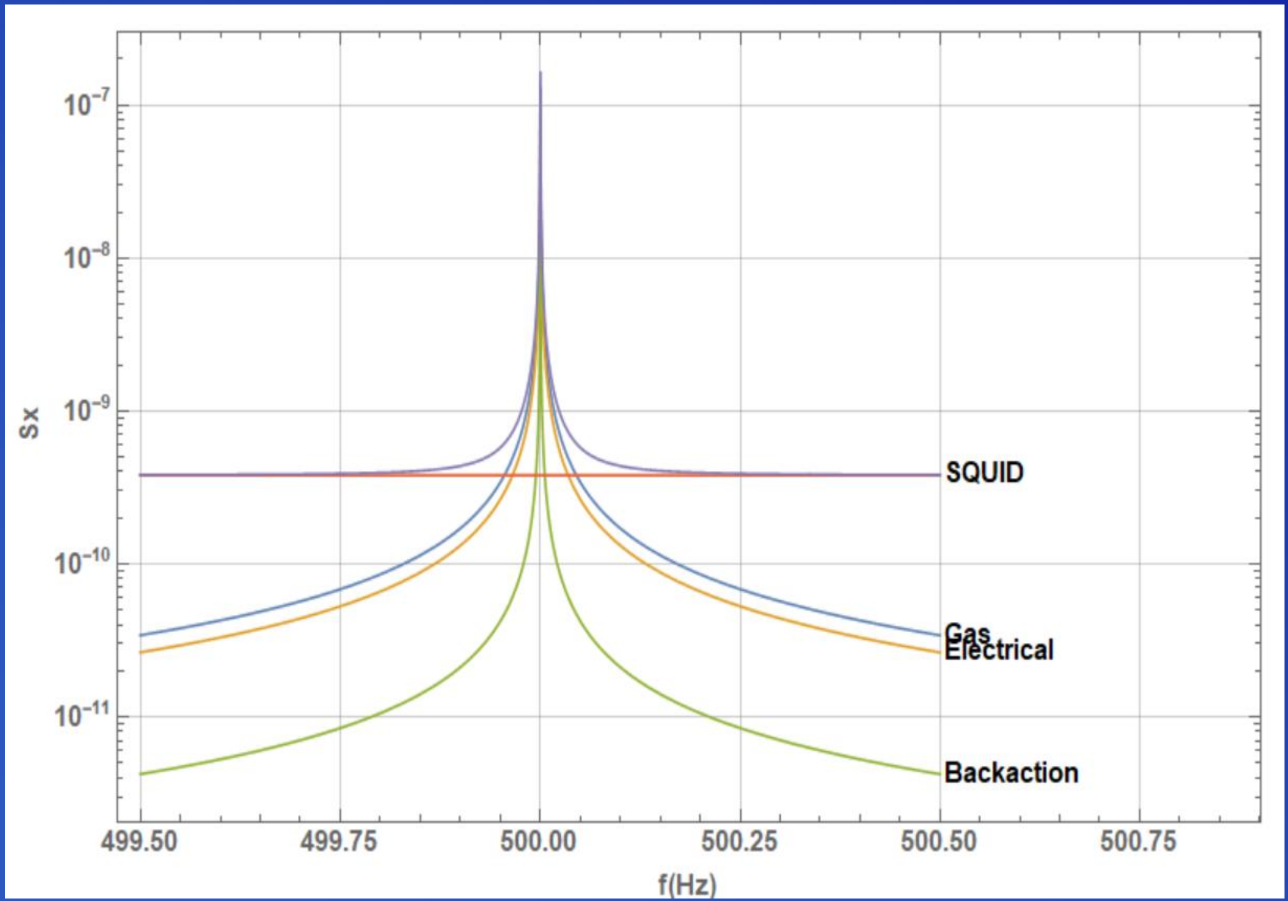
Mechanical noise is still dominant over a very narrow bandwidth!



	Optical	Electrical + SQUID
+	Very good position sensitivity (possibly close to SQL). Very flexible: can change parameters, coupling, alignment, play with other modes	No heating: potentially achieves a better force noise (lower T) Can work with any materials (osmium…) ⇒ x100 more sensitive to CSL
-	Internal heating ⇒ higher thermal noise (⇒need very low pressure <1E-13 mbar) Need very specific materials (silica= low ρ) Limit for CSL experiments May be hard to work at low frequency (cavity locking, frequency noise)	Coupling scales with charge. Needs at least 1E3 e ! Not very flexible (Cannot change coupling on-site) Needs a bulky superconducting coil (L~ 1 H) Likely very sensitive to crosstalk from bias ac lines

Continuous vs Stroboscopic

Continuous measurement (CM)

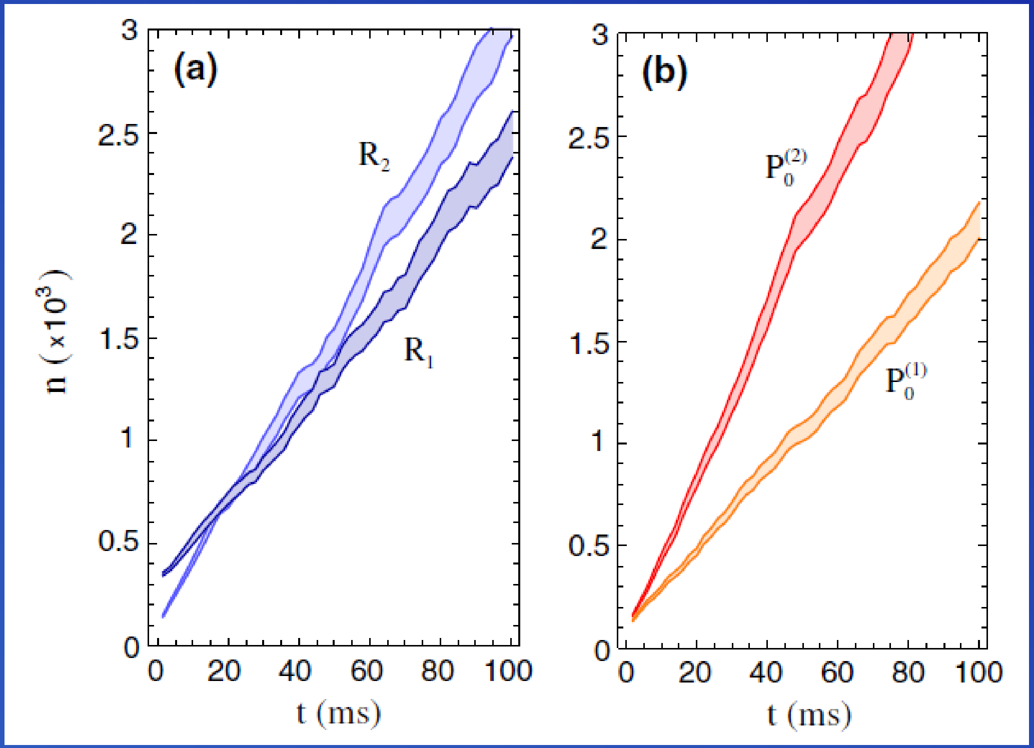


Relevant parameters:

1) Total force noise (Amplitude of lorentzian peak) $\Rightarrow$ Minimum detectable CSL force noise

2) Bandwidth over which mechanical noise overcomes detection noise $\Rightarrow$ Measurement time

Stroboscopic measurement (SM) (assume detection off during reheating)



Relevant parameters:

1) Reheating power rate $\Rightarrow$ Minimum detectable CSL force noise

2) Natural time constant $\Rightarrow$ Measurement time

Ideally:

SM has the advantage that you can turn off measurement during reheating (Evade BACK-ACTION & RECOIL)

But, in CM you can always (ideally) reduce at will the measurement back-action, at the expense of longer measurement time.

It turns out that the time required to resolve a given force noise is roughly the same !

In Real Life:

Many practical differences between the two implementations !
(CM requires long term stability, SM requires dealing with transients)

WHAT IS BETTER?

Open issues

1) Cryostat: what pressure P can we reach? (Crucial for optics)

2) Paul trap: how stable can the trap parameters be, upon micromotion compensation?
Very important for any continuous optical measurement (Hz bandwidth)
Crucial for a SQUID readout (<mHz bandwidth !!).

3) Optical case: are the general requirements worked out by Antonio realistic? (stability of the trap + vibrational noise + feedback cooling + compensation of scattering force).

4) SQUID option: is there a way to implement an electrical readout in the trap under design? Voltage cross-talk from the ac bias electrodes?
Maximum charge-on-particle we can realistically expect?
Other materials?

5) Do we really want to go for a stroboscopic scheme, or better leave this as a later option and consider initially only a continuous scheme (and thus optimize for it)?

Quantum Superposition of Massive Objects and the Quantization of Gravity

Alessio Belenchia

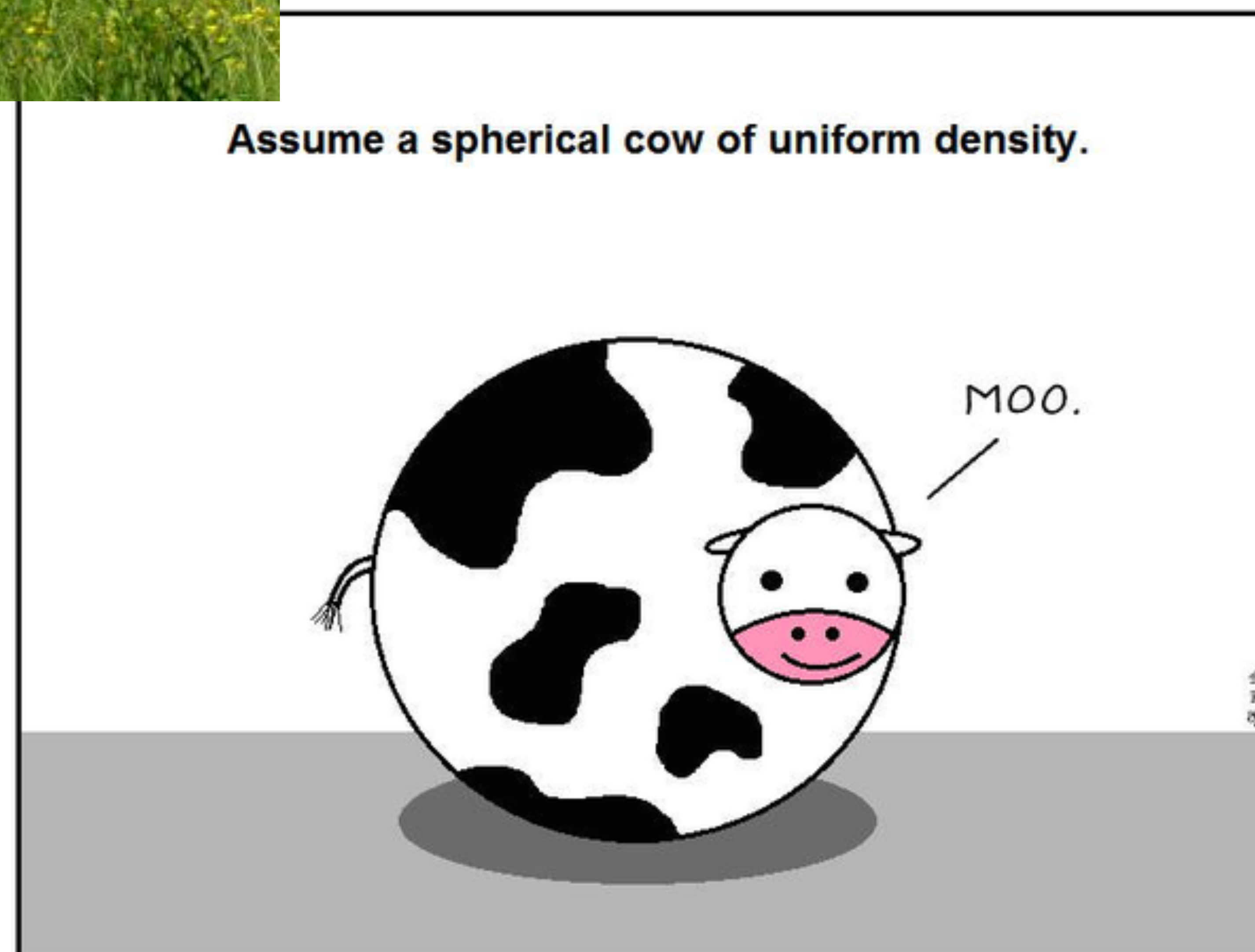
IQOQI-Vienna

TEQ meeting in Delft

TUDelft

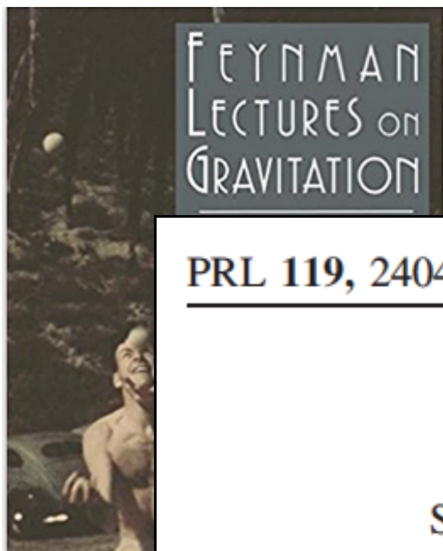
Delft, 8-9 November 2018

In collaboration with: R. M. Wald (Chicago), F. Giacomini, E. Castro, C. Brukner and M. Aspelmeyer (Vienna)


Assume a spherical cow of uniform density.
MOO.

A simple question*

Is gravity quantum as the other fundamental forces?



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 A...

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

Superposition of Massive Objects and Quantumness of Gravity

Q1: Can we argue that gravity ought to be quantum?

A1: Yes if we assume known physics to hold

Q2: How general is the argument?

A2: In order to avoid inconsistencies with known physics gravity must be quantum……however the last word is left to experiments

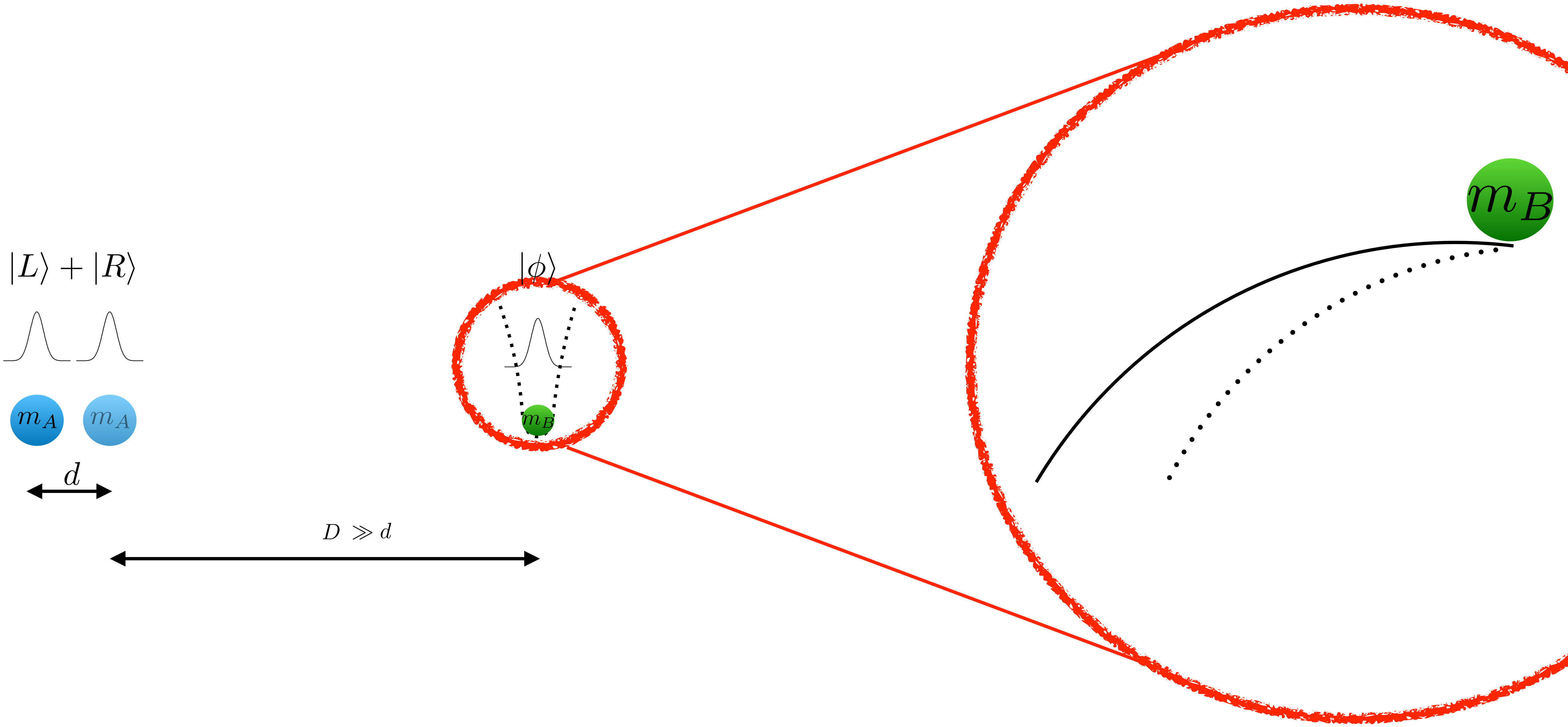
Take at home message:

A consistent picture for entanglement of massive objects through gravity necessarily requires (linearized) gravity to be quantum

Quantum superposition of Massive Objects and the Quantization of Gravity
AB, R. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner and M. Aspelmeyer
ArXiv: 1807.07015

1.A Gedankenexperiment

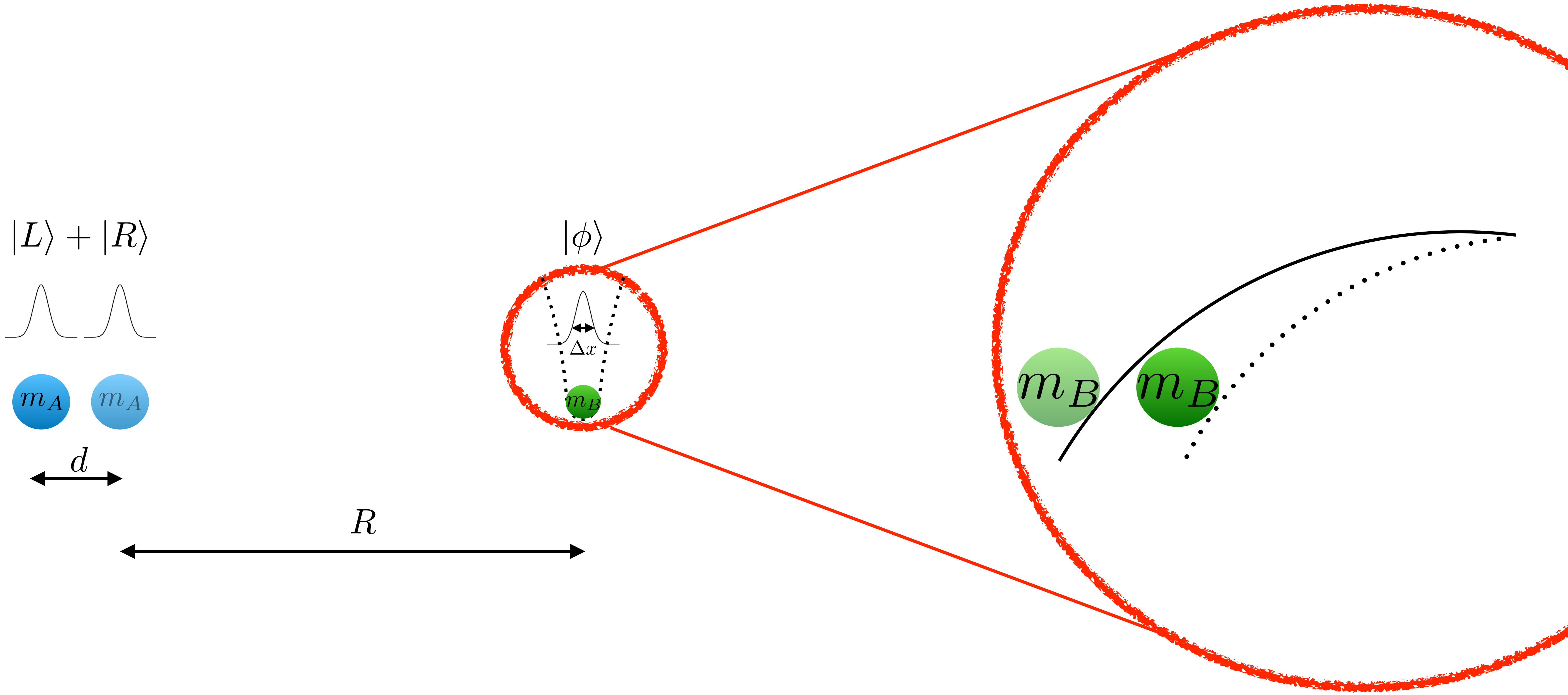
A gedankenexperiment:



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

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

A gedankenexperiment:

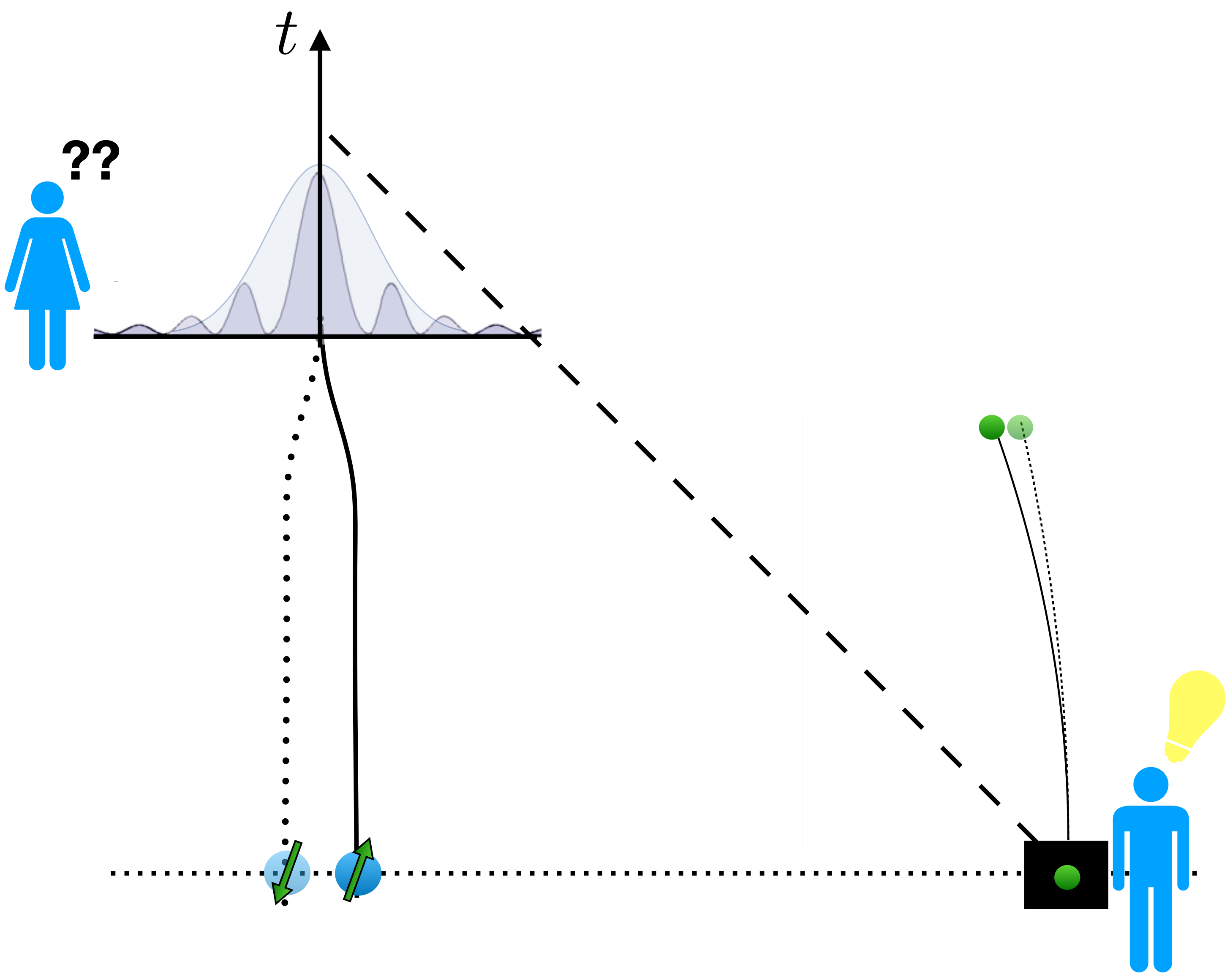


$$(|L\rangle|\uparrow\rangle + |R\rangle|\downarrow\rangle) \otimes |\phi_B\rangle \rightarrow |L\rangle|\uparrow\rangle|\phi_B^L\rangle + |R\rangle|\downarrow\rangle|\phi_B^R\rangle$$

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

- Up until now we have used Schrödinger eq. evolution with a Newton/Coulomb potential
- Implicit assumption: the gravitational/Coulomb potential can entangle the two particles
- “Weaker” assumption: Bob acquires “which-path” information on Alice

Guess What Game:



- Up until now we have used Schrödinger eq. evolution with a Newton/Coulomb potential
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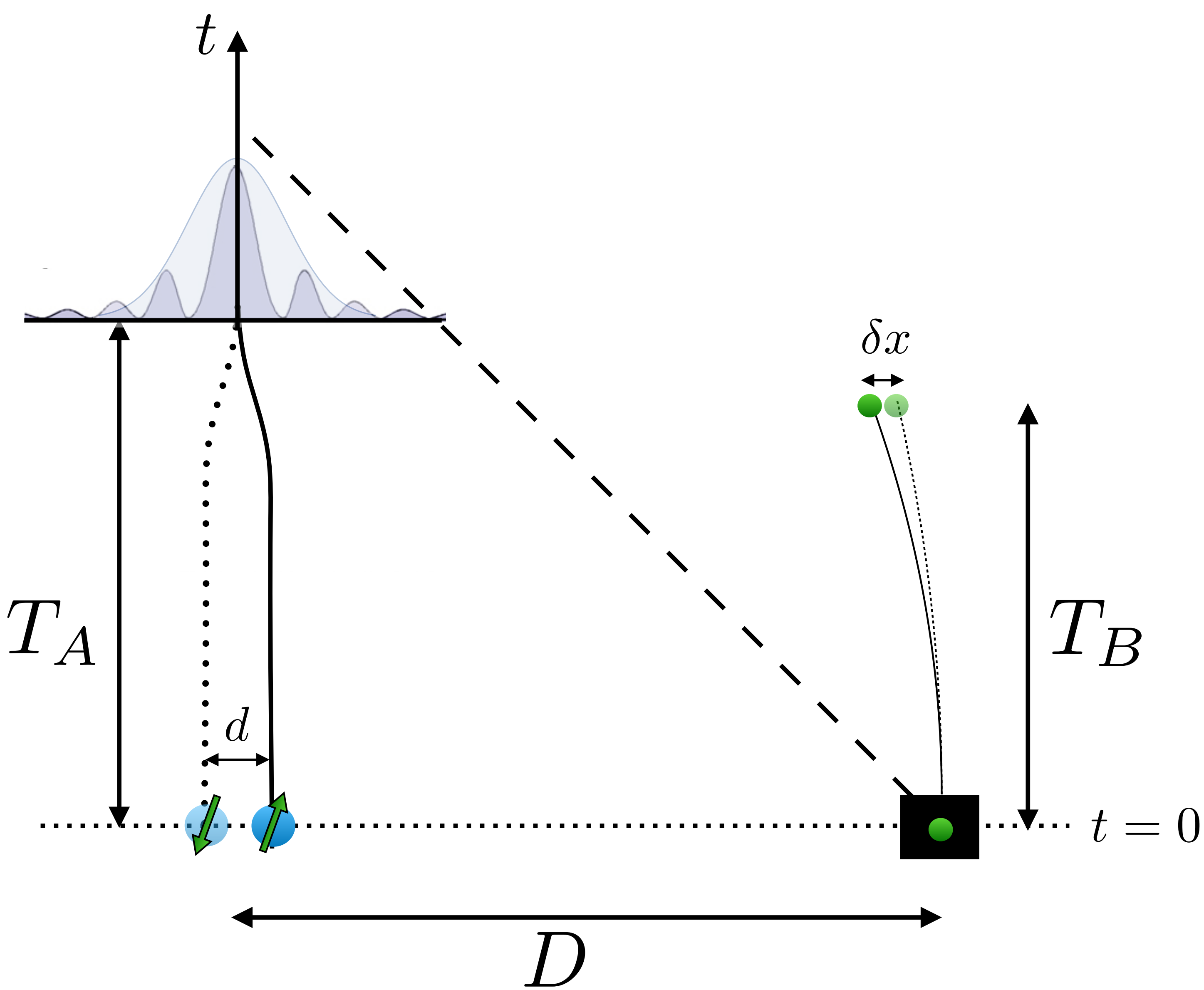
Guess What Game:

$$T_A, T_B < D$$



Causality:

If the two particles get entangled, Alice can discover what Bob did in a time less than the light-crossing time

Complementarity:

If we assume a priori that causality has to be respected , we find ourself in trouble with complementarity of quantum mechanics

2. EM case revisited

Quantum Vacuum Fluctuations

Limit* on charge localization due to fluctuations of the Electric field: $\Delta x \sim q/m$

In order to acquire significant which-path information

$$\boxed{\delta x_B > q_B/m_B}$$

*more stringent than Compton length localization only for q>1

Quantum Vacuum Fluctuations

Limit* on charge localization due to fluctuations of the Electric field: $\Delta x \sim q/m$

In order to acquire significant which-path information

$$\boxed{\delta x_B > q_B/m_B}$$

Quantized E.M. radiation

Effective (or fictitious) electric dipole moment of Alice superposition $\mathcal{D}_A = q_A d$

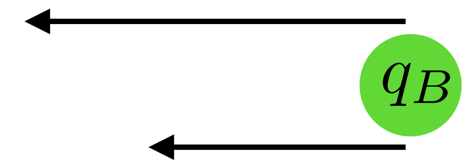
When Alice perform the interferometric experiment the dipole will reduced to zero in time T_A and radiation is emitted by the accelerated trajectory(ies)

*more stringent than Compton length localization only for q>1

Quantum Vacuum Fluctuations

$$\delta x_B > q_B / m_B$$

$$F_1 = q_B E_1 = k \frac{q_A q_B}{D^2}$$



$$F_2 = q_B E_2 = k \frac{q_A q_B}{(D+d)^2}$$

$$\delta x \sim \frac{q_B}{m_B} \frac{\mathcal{D}_A}{D^3} T_B^2$$

$$\frac{\mathcal{D}_A}{D^3} T_B^2 > 1 \; ^*$$

* reintroducing some constant we would have $\mathcal{D}_A T_B^2 / D^3 > 1/c^2$

Quantized E.M. radiation

(Estimate of the) energy radiated by Alice fictitious dipole

$$\mathcal{E} \sim \left(\frac{\mathcal{D}_A}{T_A^2}\right)^2 T_A$$

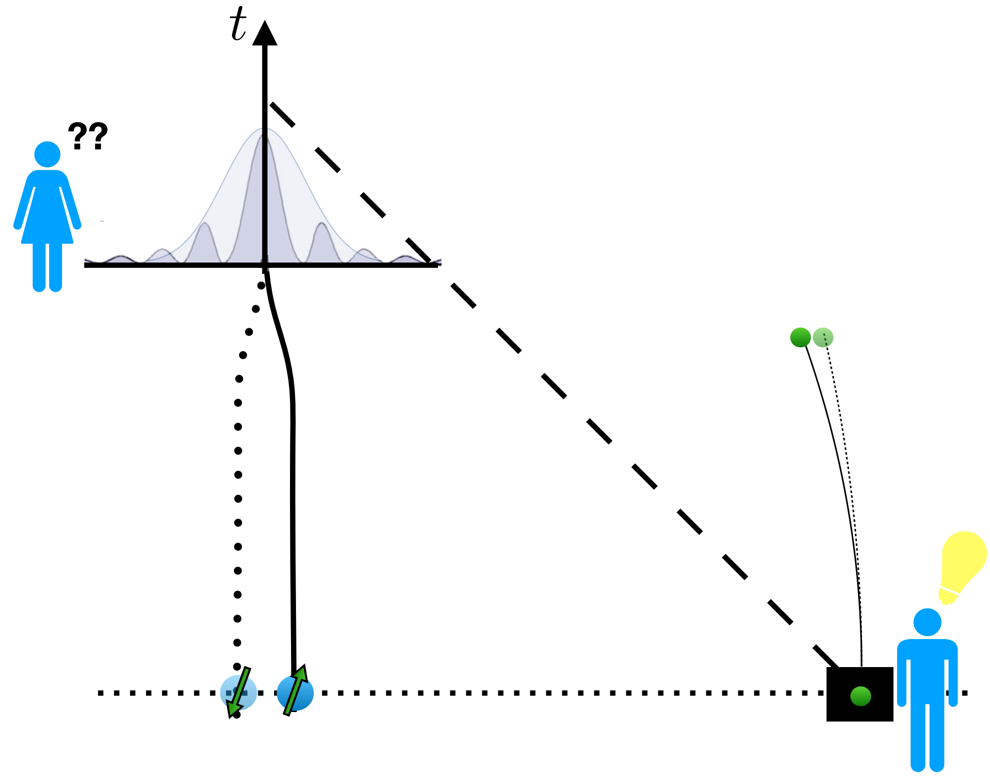
The degree of decoherence due to radiation can be estimated by requiring that no photon with characteristic frequency $1/T_A$ is emitted by the fictitious dipole*

$$\mathcal{D}_A < T_A$$

* A more detailed treatment can be obtained by looking at the overlap of the coherent states produced by the classical currents corresponding to the paths in the interferometer. This has been extensively studied and leads to the same result.

RESOLUTION OF THE "APPARENT" PARADOXES

$$T_A, T_B < D$$



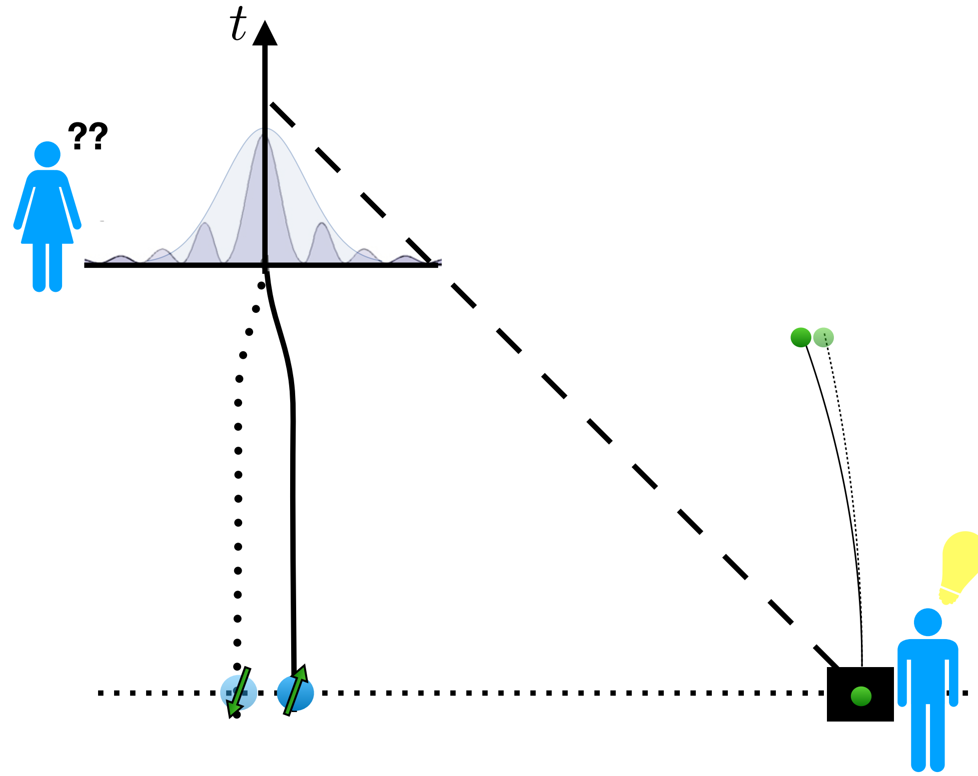
If $\mathcal{D}_A < T_A$ No entangling radiation from Alice

$$+$$

$$\frac{\mathcal{D}_A}{D^3} T_B^2 < 1$$ i.e. no which-path info for Bob

RESOLUTION OF THE "APPARENT" PARADOXES

$T_A, T_B < D$



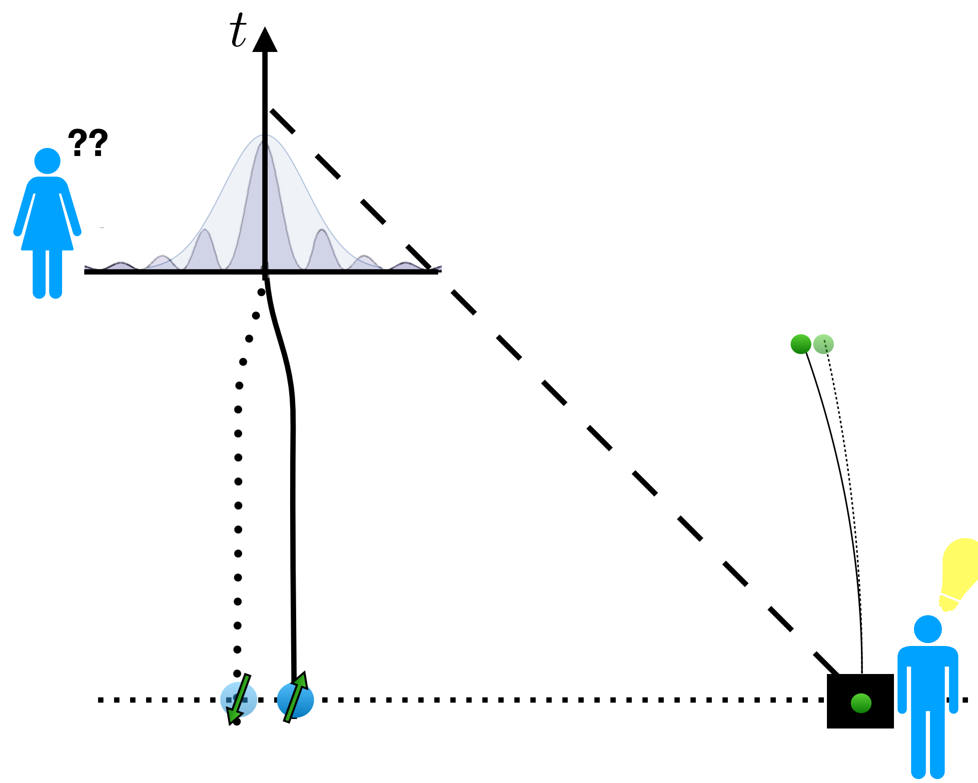
$\text{If } \mathcal{D}_A > T_A$

Alice gets decohered by radiation

Bob in this case can be able to acquire which-path information without any contradiction with complementarity

RESOLUTION OF THE "APPARENT" PARADOXES

$$T_A, T_B < D$$



3. Gravitational case

Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

*more stringent than Compton length localization only for m>1

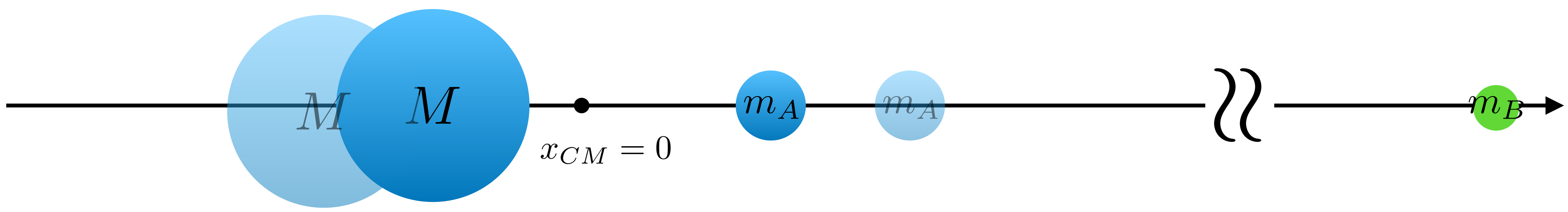
Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

Conservation of the center of mass:



$$\mathcal{D}_A^{\text{grav.}} = 0$$

*more stringent than Compton length localization only for q>1

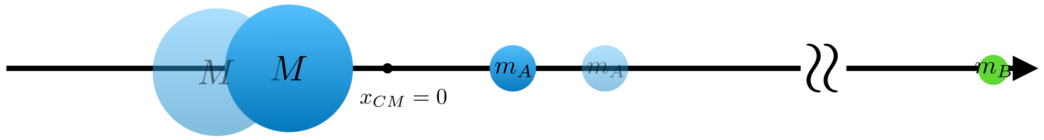
Quantum Vacuum Fluctuations

Limit* on mass localization due to fluctuations of the grav. field: $\Delta x \sim \ell_P$

In order to acquire significant which-path information

$$\boxed{\delta x_B > \ell_P}$$

$$\delta x_B \sim \frac{\mathcal{Q}_A^{(n)}}{D^{n+2}} T_B^2 > 1$$



*more stringent than Compton length localization only for q>1

Quantized gravitational radiation

(Estimate of the) energy radiated by Alice fictitious n-pole

$$\mathcal{E} \sim \left(\frac{\mathcal{Q}_A^{(n)}}{T_A^{n+1}} \right)^2 T_A$$

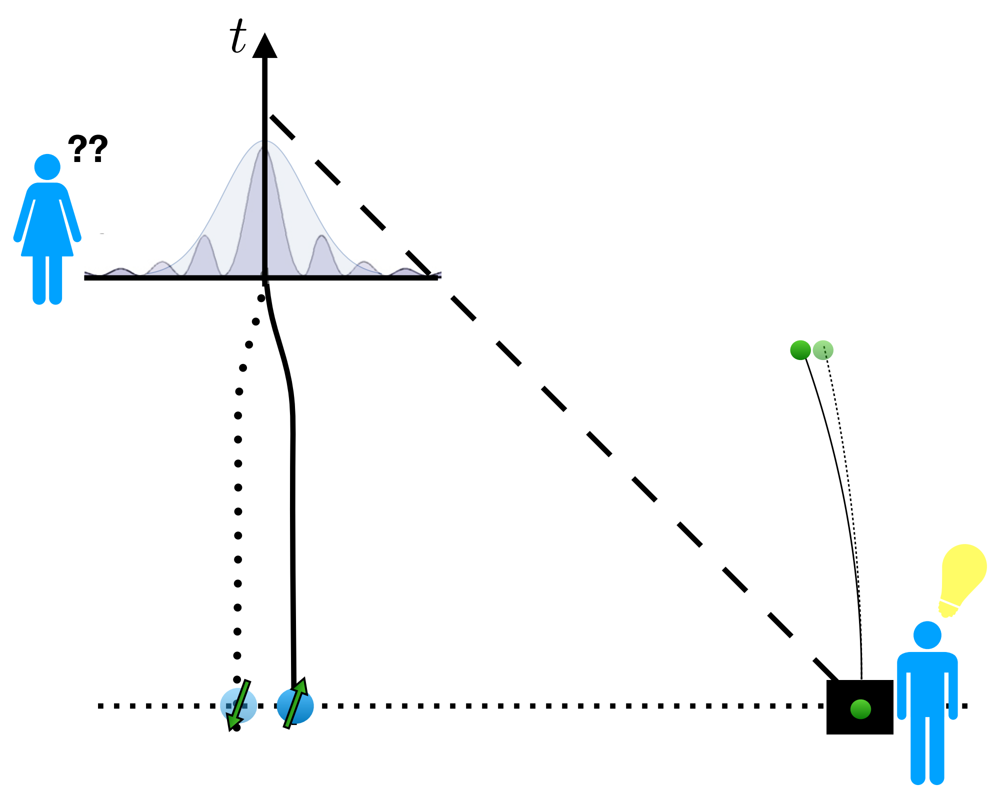
The degree of decoherence due to radiation can be estimated by requiring that no graviton with characteristic frequency $1/T_A$ is emitted by the fictitious n-pole *

$$\mathcal{Q}_A^{(n)} < T_A^n$$

* A more detailed treatment can be obtained by looking at the overlap of the coherent states produced by the classical currents corresponding to the paths in the interferometer. This leads to the same result.

RESOLUTION OF THE "APPARENT" PARADOXES

$$T_A, T_B < D$$



If $\mathcal{Q}_A^{(n)} < T_A^n$ No entangling radiation from Alice

$$+$$

$$\frac{\mathcal{Q}_A^{(n)}}{D^{n+2}} T_B^2 < 1$$ i.e. no which-path info for Bob

Conclusions

- **Gedankenexperiment shows inconsistencies if dynamical d.o.f.s are neglected**
- **Inconsistencies are resolved if: vacuum fluctuations + quantized radiation**

Limit Bob's ability to acquire which-path info

Decohere Alice superposition via entanglement with radiation

- **Gedankenexperiment shows inconsistencies if dynamical d.o.f.s are neglected**
- **Inconsistencies are resolved if: vacuum fluctuations + quantized radiation**

Limit Bob's ability to acquire which-path info

Decohere Alice superposition via entanglement with radiation

By treating the (linearized) gravitational field [or the e.m. field] as a quantum field a consistent analysis of the gedankenexperiment is obtained


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