Testing collapse models and gravity with levitated optomechanics

ECT* workshop
Quantum sensing and fundamental physics with levitated mechanical systems

Matteo Carlesso
(University of Trieste, INFN and Queen's University Belfast)

Outline

Collapse models

Gravity models

Motivation

Theory

Experiments

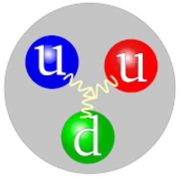
Collapse models

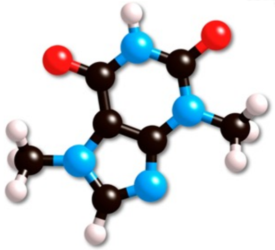
Limits of the Quantum Superposition Principle

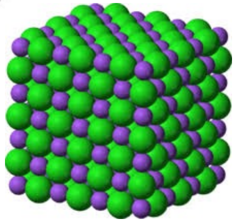
Quantum World

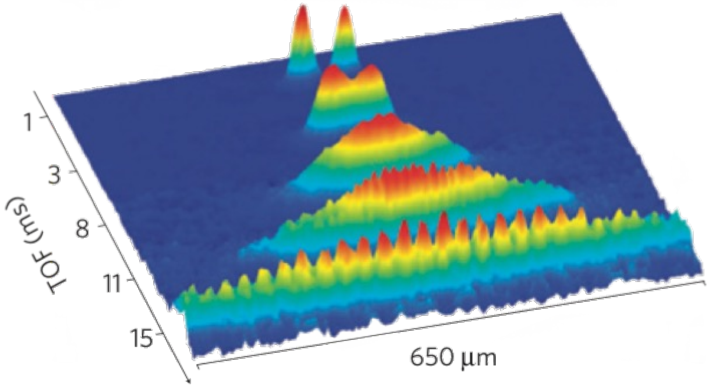
Classical World

Micro







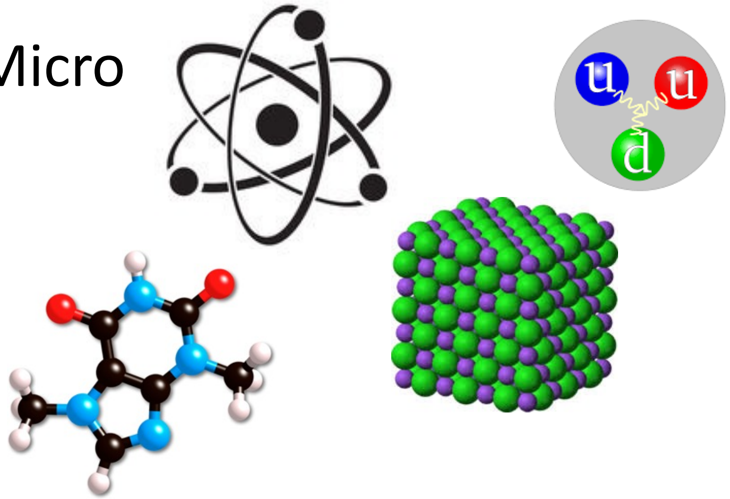


Macro

Standard Quantum Mechanics

Quantum World | **Classical World**

Micro



Macro

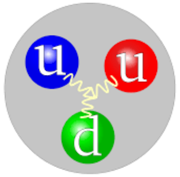
"The Copenhagen interpretation assumes a mysterious division between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics."

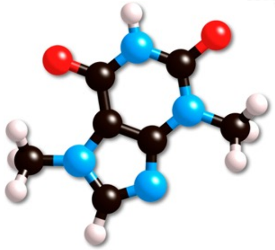
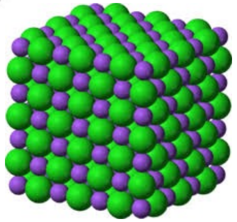
S. Weinberg, Phys. Rev. A 85, 062116 (2012)

Quantum Mechanics wonna be

Quantum World — Classical World

Micro

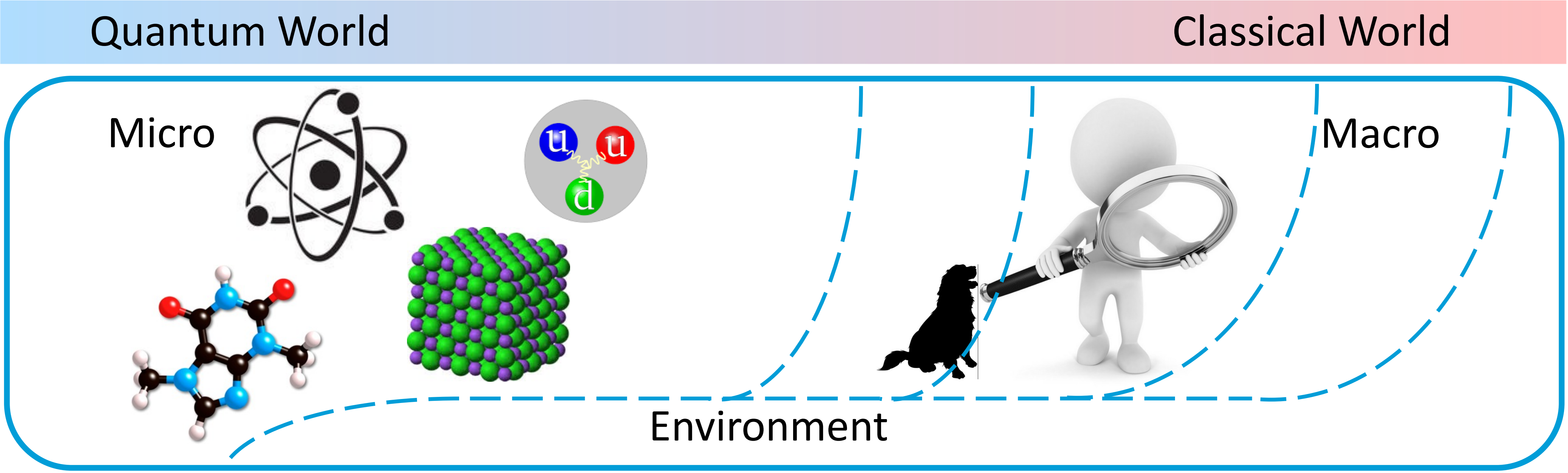




Macro

“What exactly qualifies some physical systems to play the role of 'measurer’?“

John Bell, Against ‘measurement’, Physics World, *Phys. World* **3** (8) 33 (1990)

Quantum Mechanics + Decoherence

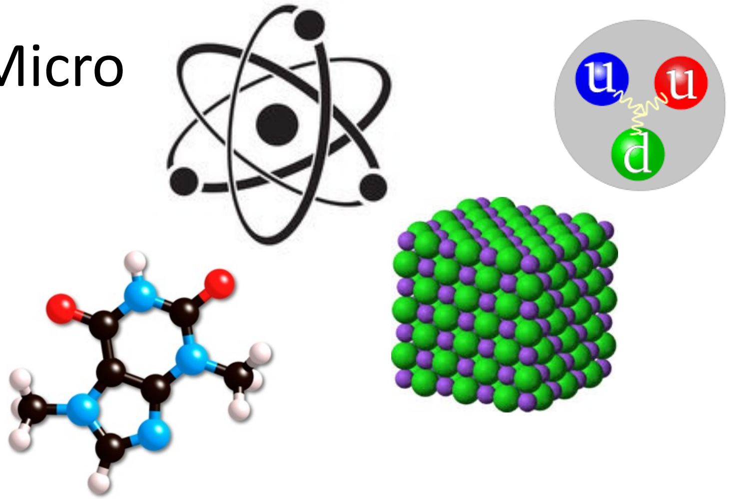


The division system-environment is arbitrary, and similarly to the division quantum-classical in the Copenhagen interpretation.

Possible solutions

Quantum World Classical World

Micro



Macro

Bohmian Mechanics
Many Worlds
Collapse Models

Collapse models – a modified quantum theory

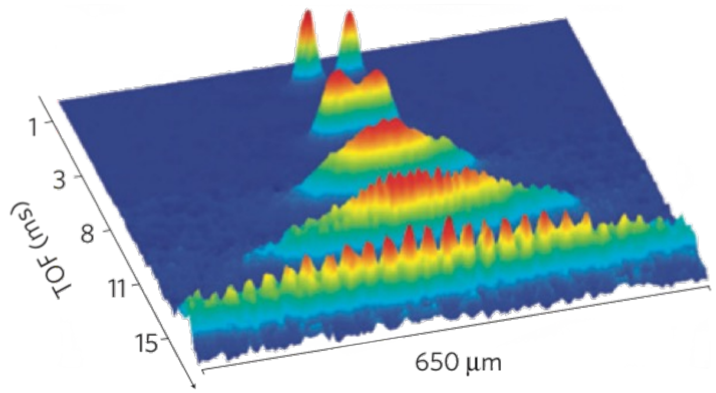
Stochastic noise

Non-linear wavefunction dynamics

Negligible microscopic action
No effective collapse
Quantum systems

Strong macroscopic action
Rapid collapse
Systems behave classically

Amplification mechanism



General structure of the dynamical equation

$$\mathrm{d}|\psi_t\rangle = \left[-\frac{i}{\hbar}\hat{H}\mathrm{d}t + \int \mathrm{d}^3\mathbf{x} \left(\hat{M}(\mathbf{x}) - \langle \hat{M}(\mathbf{x})\rangle_t\right) \mathrm{d}W_t(\mathbf{x}) - \frac{1}{2}\int \mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{y}\, \mathcal{D}(\mathbf{x}-\mathbf{y}) \prod_{\mathbf{q}=\mathbf{x},\mathbf{y}} \left(\hat{M}(\mathbf{q}) - \langle \hat{M}(\mathbf{q})\rangle_t\right) \mathrm{d}t \right] |\psi_t\rangle$$

Q. Hamiltonian

Measured operator (mass density, position, …)

Non-linear term

White noise

Noise's spatial correlation

Two main models

Continuous Spontaneous Localization (CSL) model

Fully phenomenological model

$$\mathcal{D}_{\mathrm{CSL}}(\mathbf{x}-\mathbf{y}) = \frac{\lambda}{m_0^2} \exp\left(-|\mathbf{x}-\mathbf{y}|^2/4r_C^2\right)$$

λ collapse rate

r_C correlation length

Diósi-Penrose model

Gravity-related model

$$\mathcal{D}_{\mathrm{DP}}(\mathbf{x}-\mathbf{y}) = \frac{G}{\hbar}\frac{1}{|\mathbf{x}-\mathbf{y}|}$$

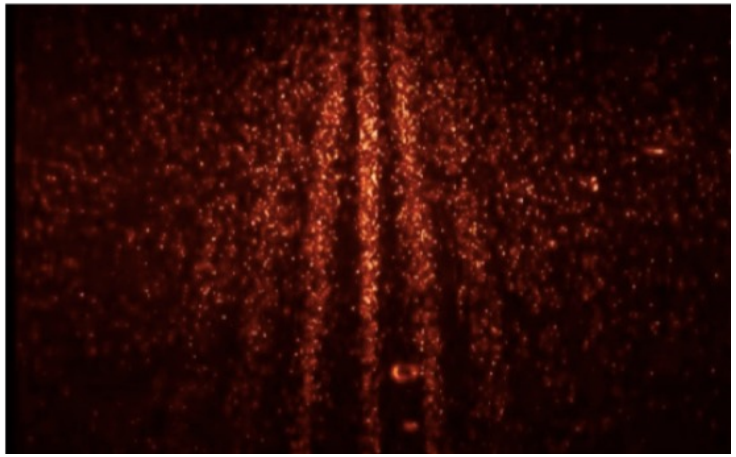
R_0 spatial cutoff
gravity regularization at small distances

Experiments

Destruction of quantum superposition

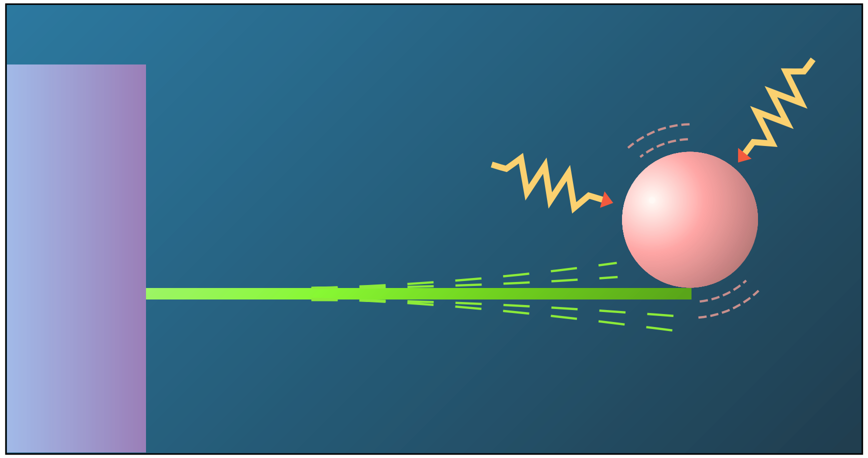
Interferometric Experiments

$$\Delta V = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$



Extra jiggling due to collapse noise

$$S_{xx}(\omega) = \frac{1}{4\pi} \int d\Omega \, \langle \{ \tilde{x}(\omega), \tilde{x}(\Omega) \} \rangle$$



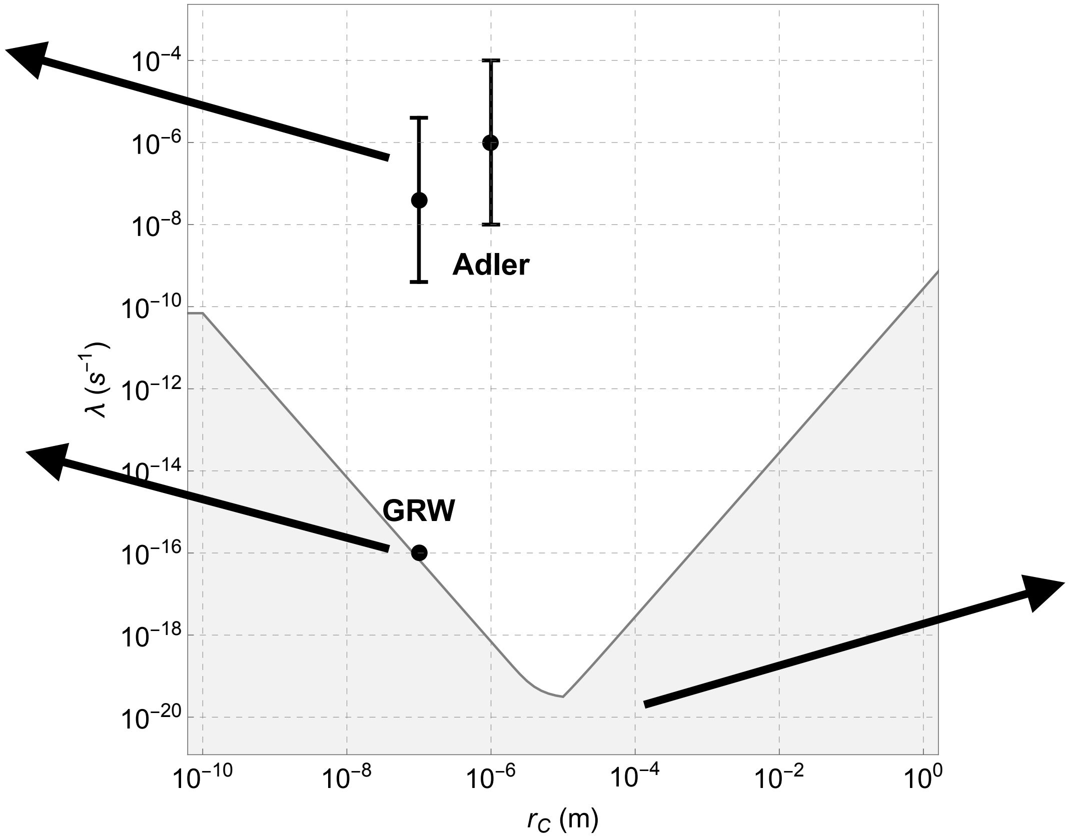
Parameters' space

Adler's proposed values

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

GRW's proposed values

Ghirardi *et al.,* Phys. Rev. D **34**, 470 (1986)

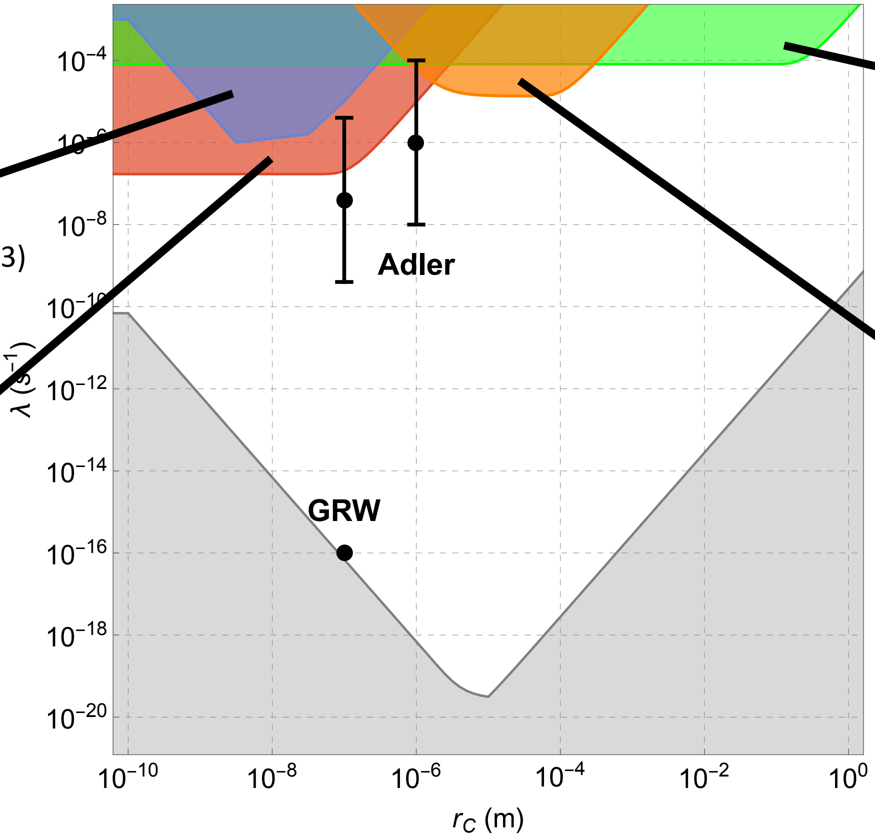


Theoretical lower bound

Toros *et al.,* Phys. Lett. A **381**, 3921 (2017)

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

Interferometric Tests



Kapitza Dirac Talbot Lau

Eibenberger *et al.,* Phys. Chem. Chem. Phys. 15, 14696 (2013)
Toros *et al.,* J. Phys. A **51**, 115302 (2018)

Macromolecules

Fein *et al.,* Nat. Phys **15**, 1242 (2019)

Atom fountain

Kovachy *et al.,* Nature **528**, 530 (2016)

Diamonds

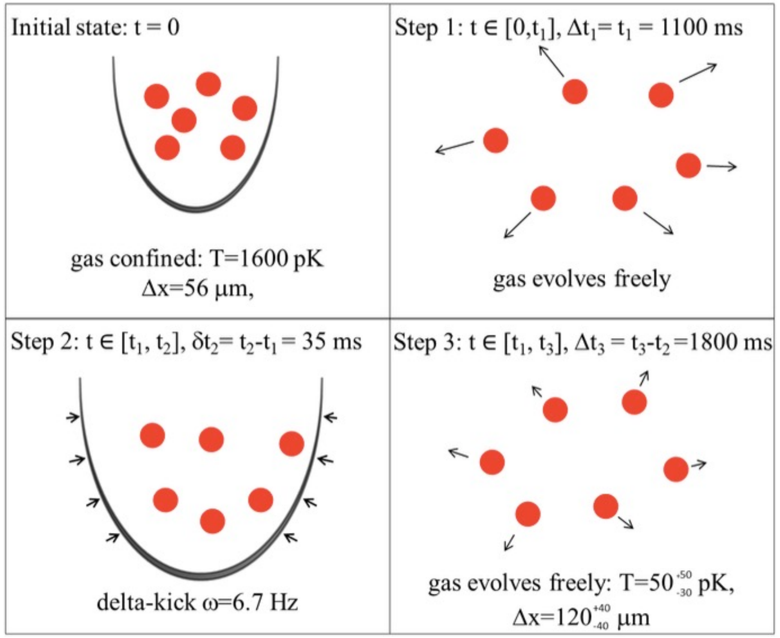
Lee *et al.,* Science **334**, 1253 (2011)
Belli *et al.,* Phys. Rev. A **94**, 012108 (2016)

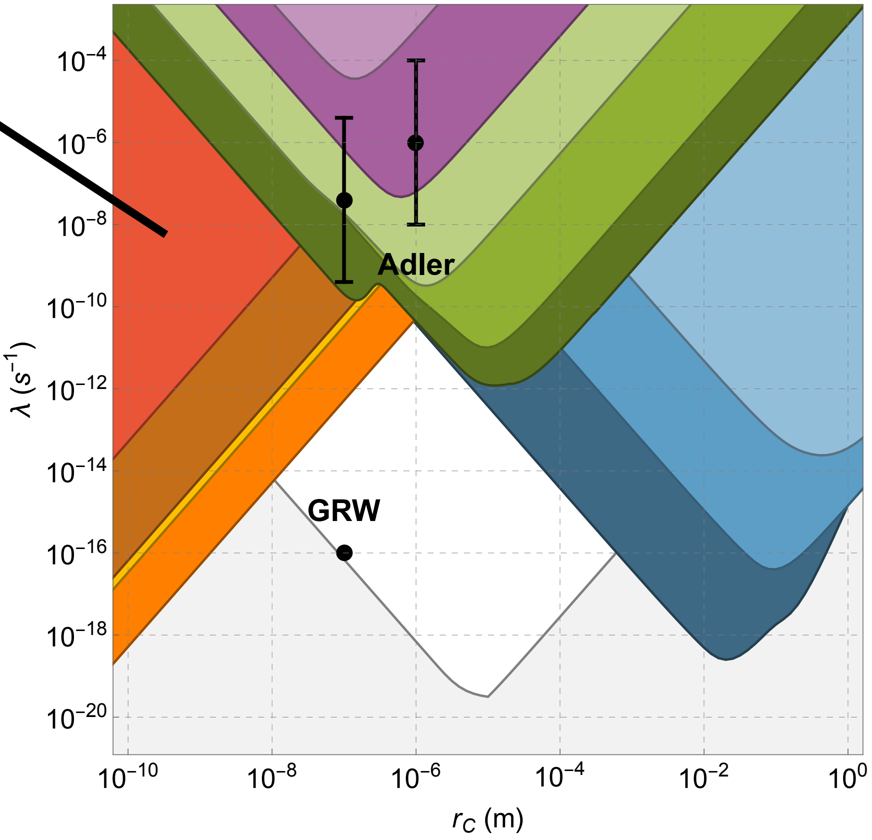
Review Paper: Arndt & Hornberger, Nature Physics **10**, 271-277 (2014)

Non-interferometric Tests

Cold Atoms

Kovachy *et al.*, Phys. Rev. Lett. **114**, 143004 (2015)
Bilardello *et al.*, Physica A, **462**:764-782 (2016)





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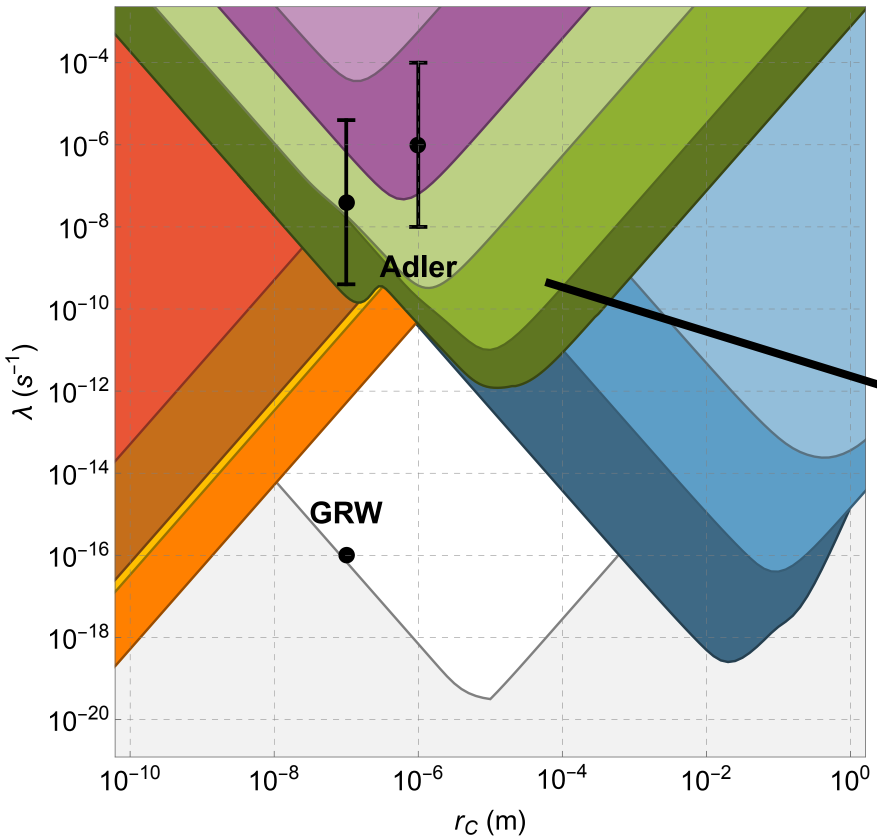
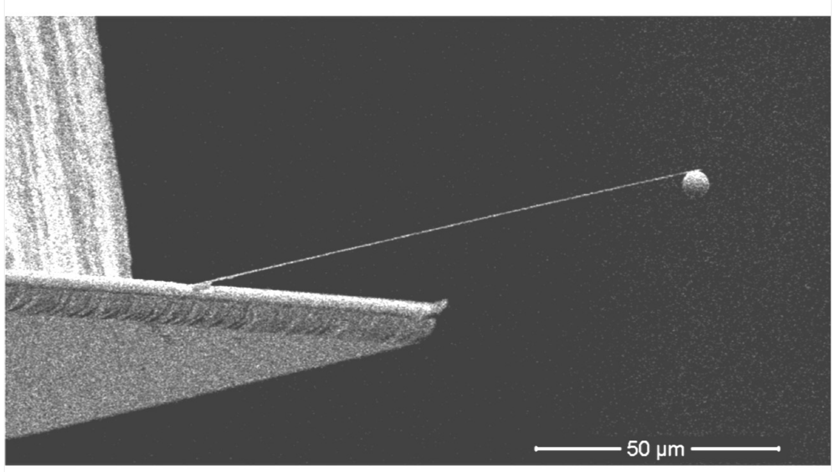
Non-interferometric Tests



Nanomechanical cantilevers

Vinante *et al.*, Phys. Rev. Lett. **116**, 090402 (2016)
Vinante *et al.*, Phys. Rev. Lett. **119**, 110401 (2017)



Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

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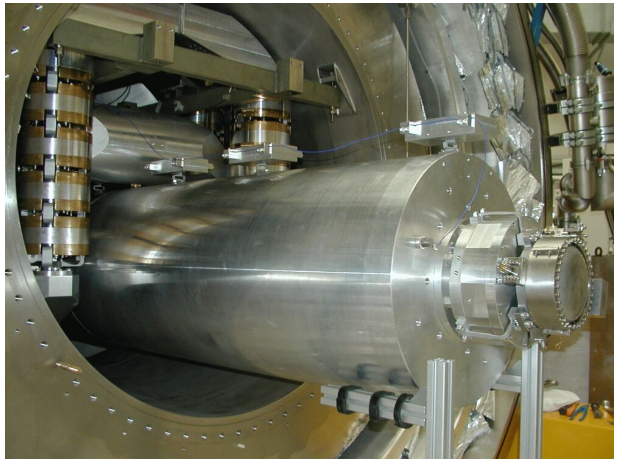

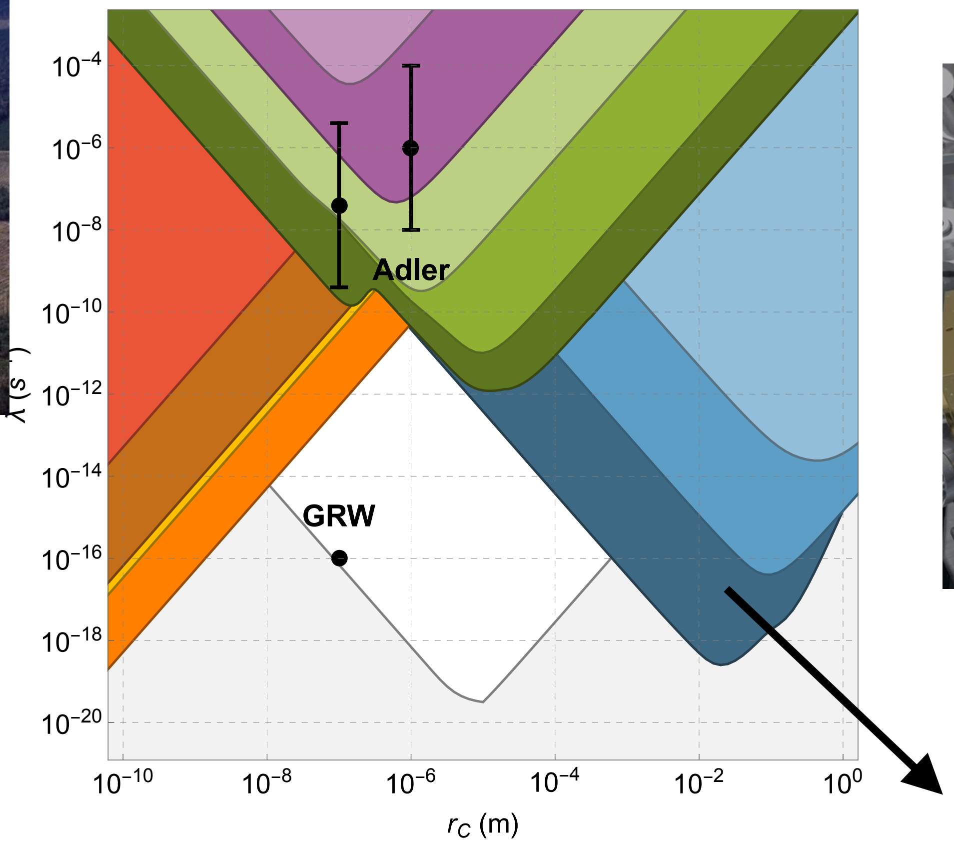

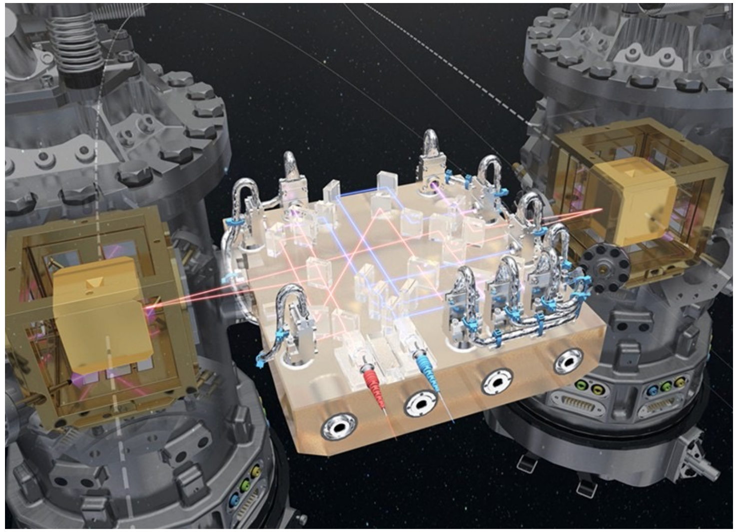

Gravitational wave detectors
Auriga, LIGO, LISA Pathfinder
Carlesso *et al,* Phys. Rev. D ***94***, 124036 (2016)

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

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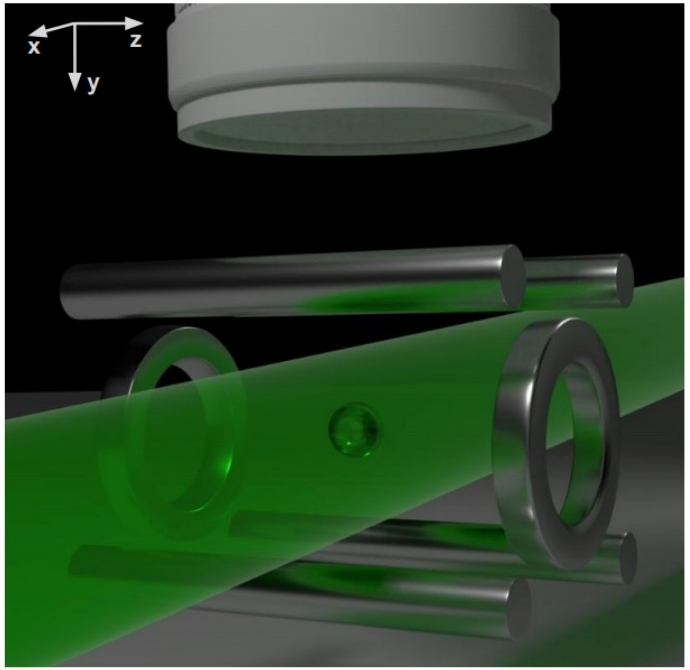
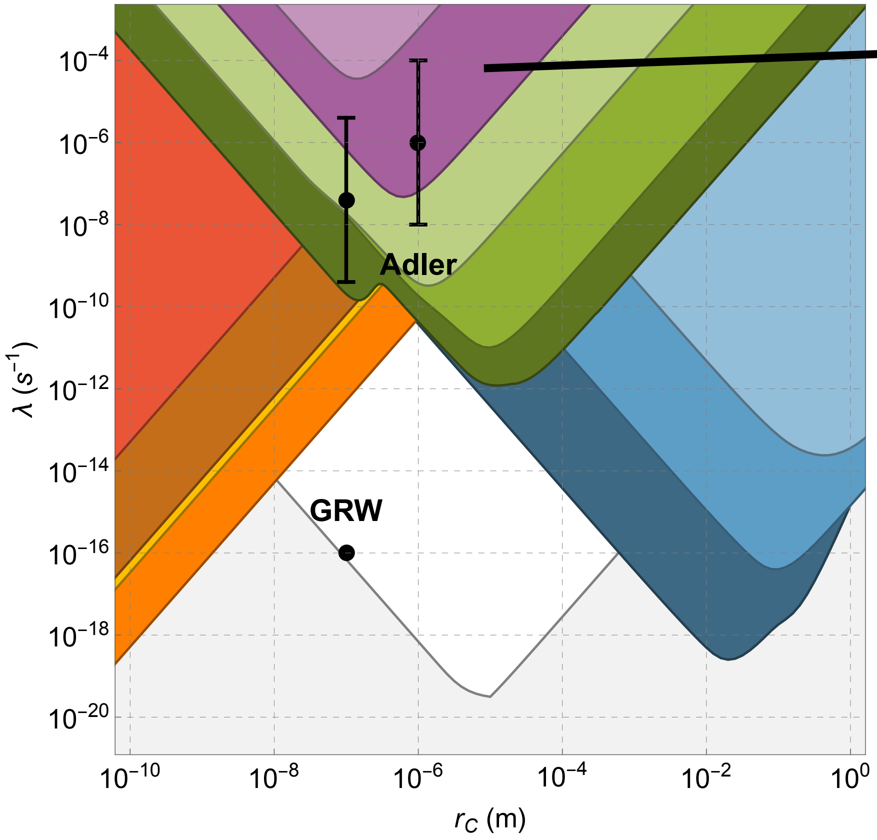
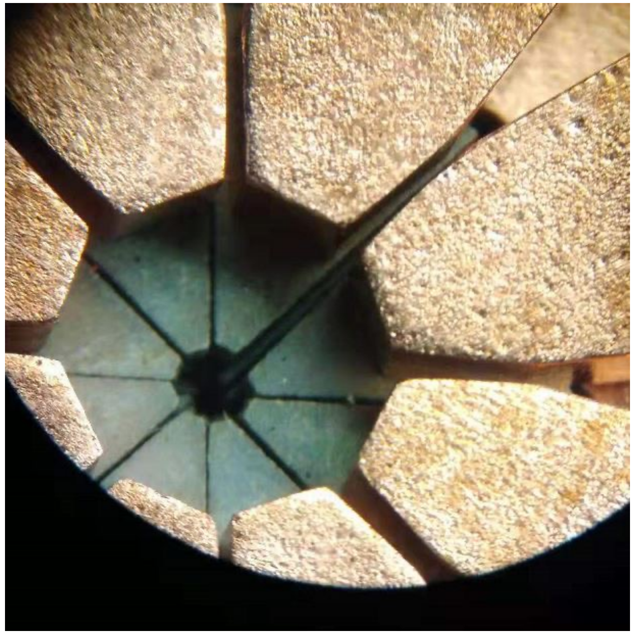




Levitated nano-oscillators

Pontin *et al.*, Phys. Rev. Res. **2**, 023349 (2020)
Zheng *et al.*, Phys. Rev. Res. **2**, 013057 (2020)



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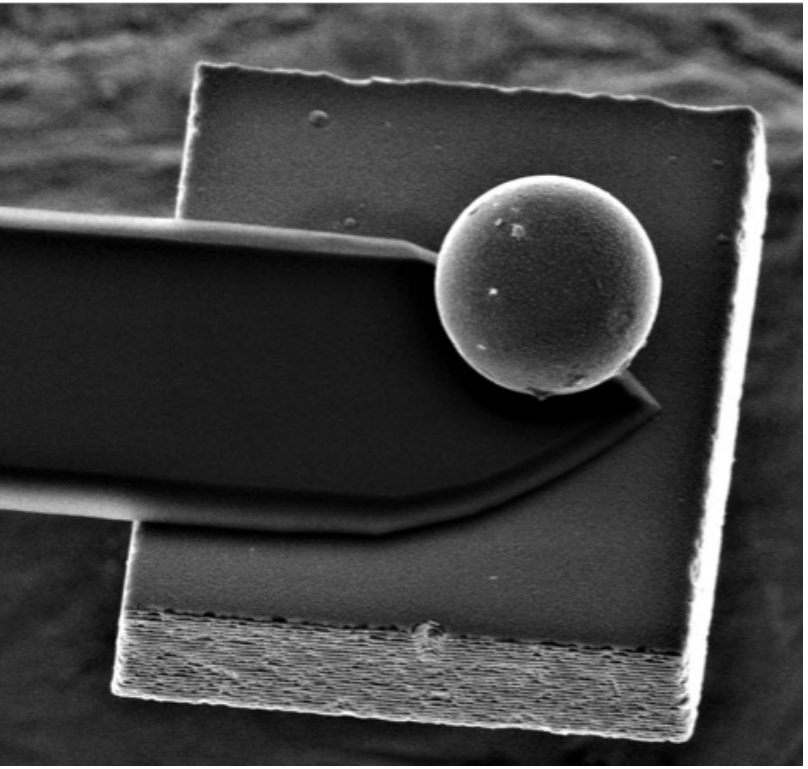

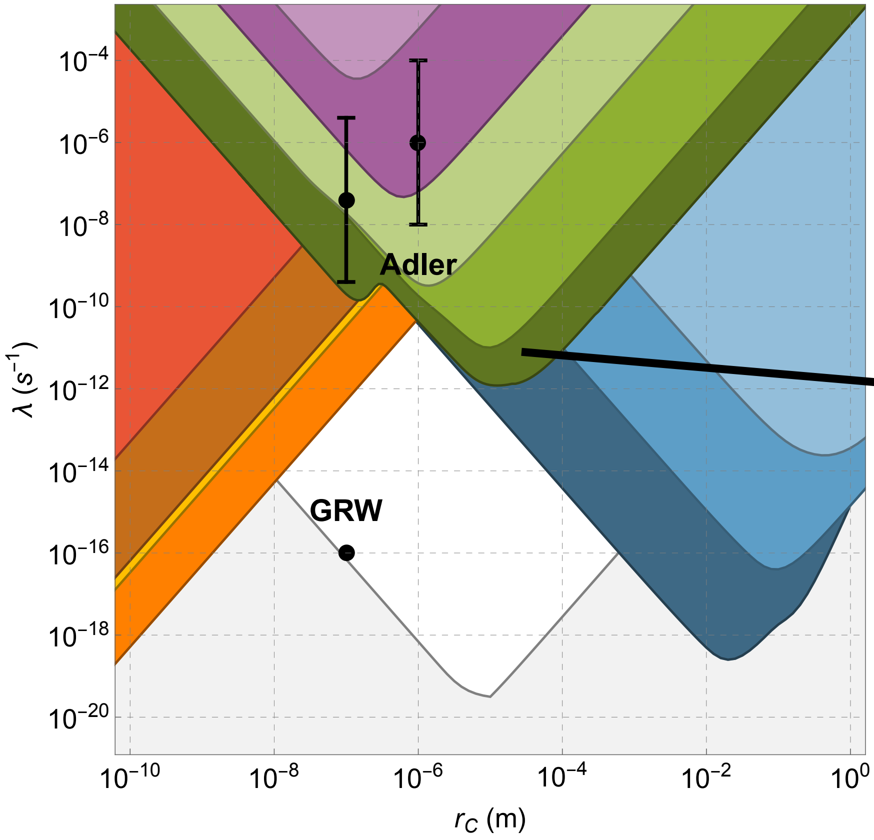

Nanomechanical cantilevers

Vinante *et al.*, Phys. Rev. Lett. **125**, 100404 (2020)

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

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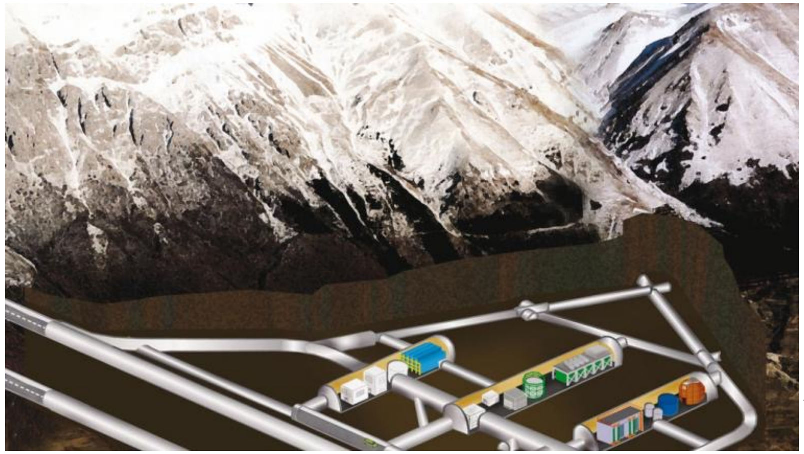

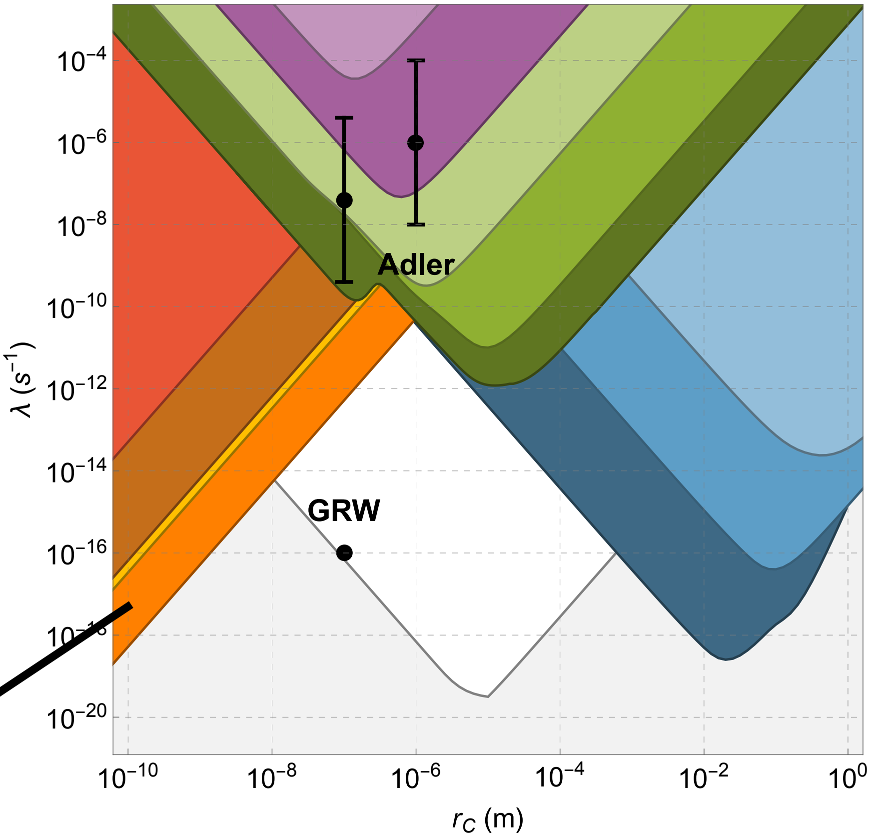

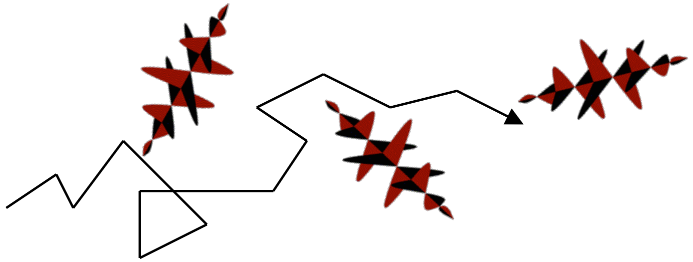

X-rays emission

Donadi *et al,* Eur. Phys. J. C ***81***, 1 (2021)

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

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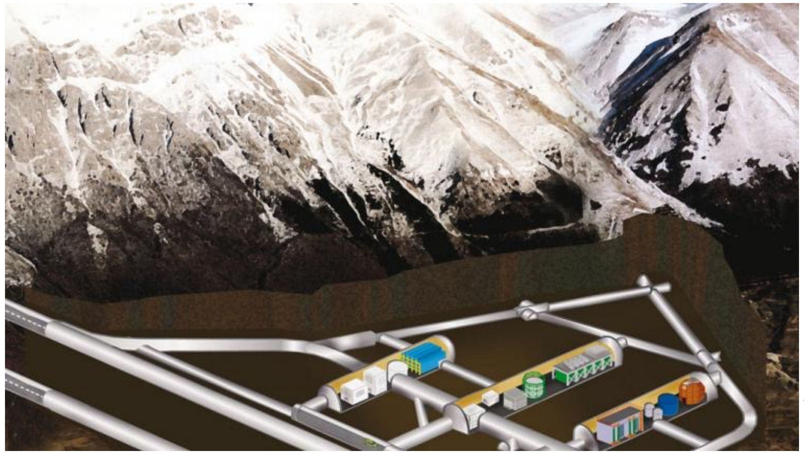
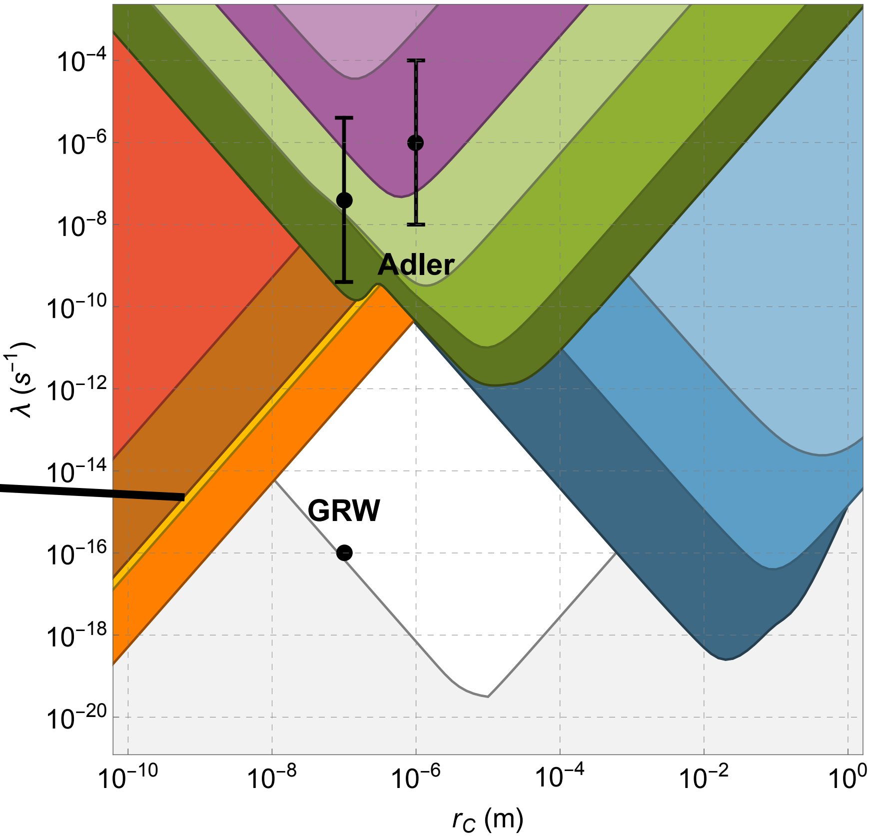
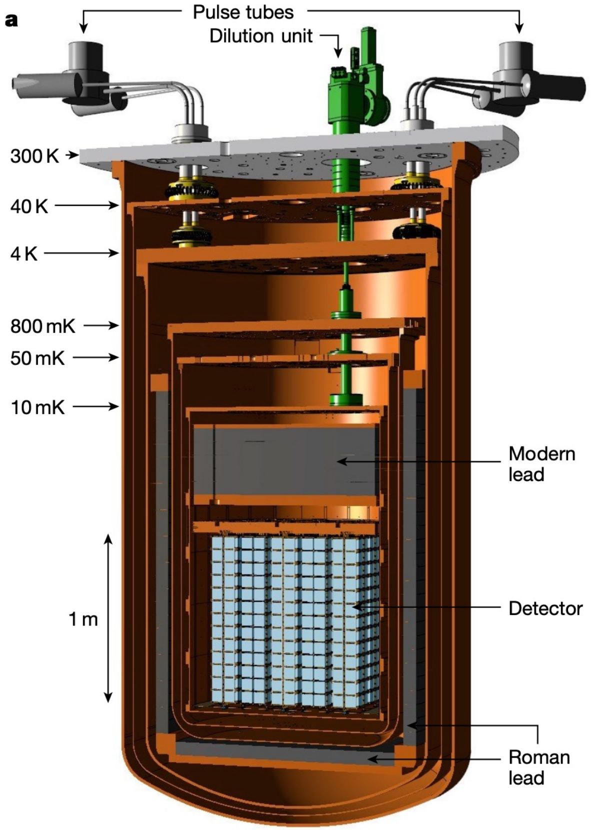






Phonon Spectrum

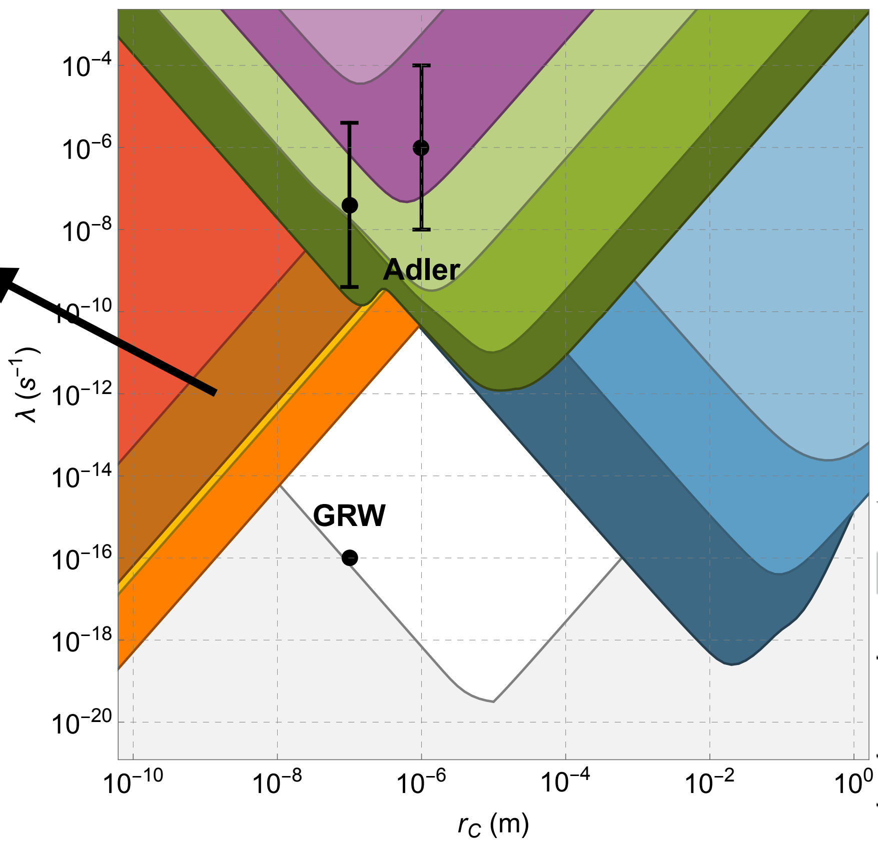
Adler *et al.,* Phys. Rev. A **97**, 052119 (2018).
Bahrami, Phys. Rev. A **97**, 052118 (2018).

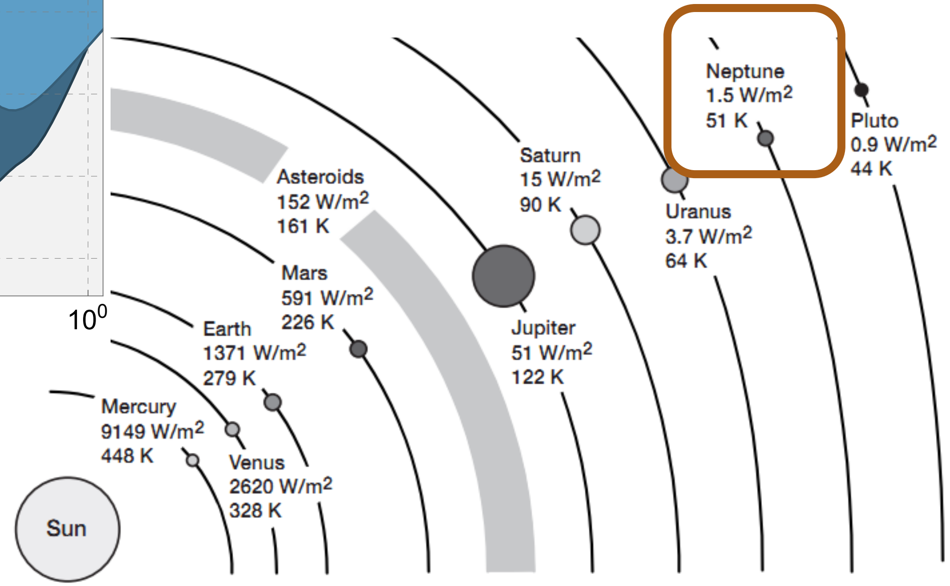
Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

Non-interferometric Tests

Neptune

S.L. Adler *et al.*, *Phys. Rev. D* **99**, 103001 (2019)





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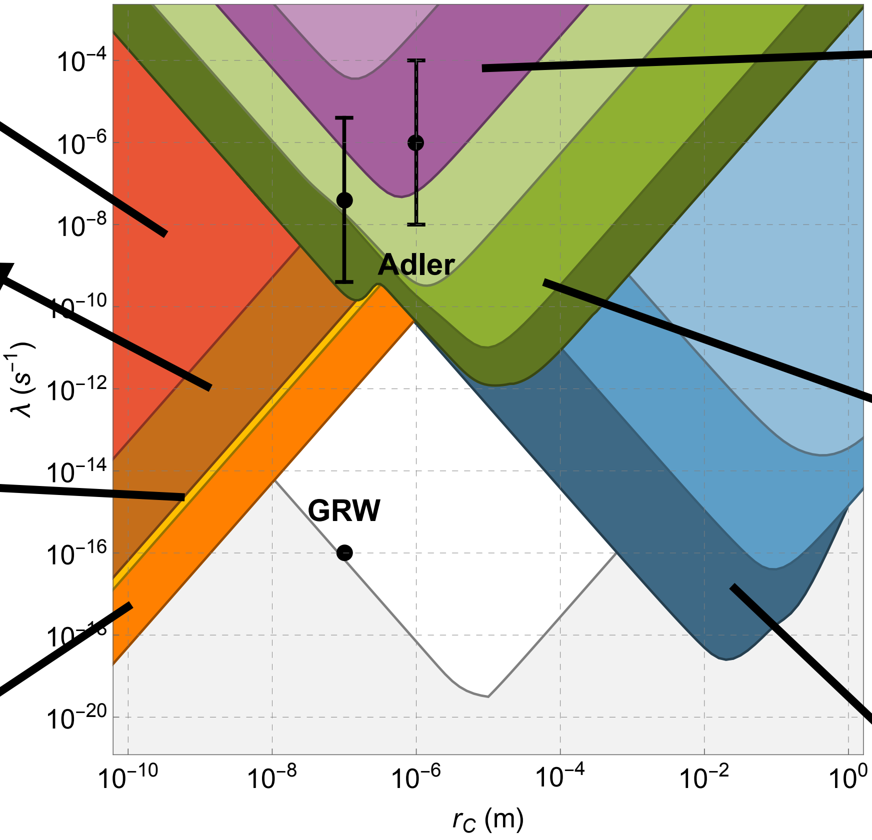

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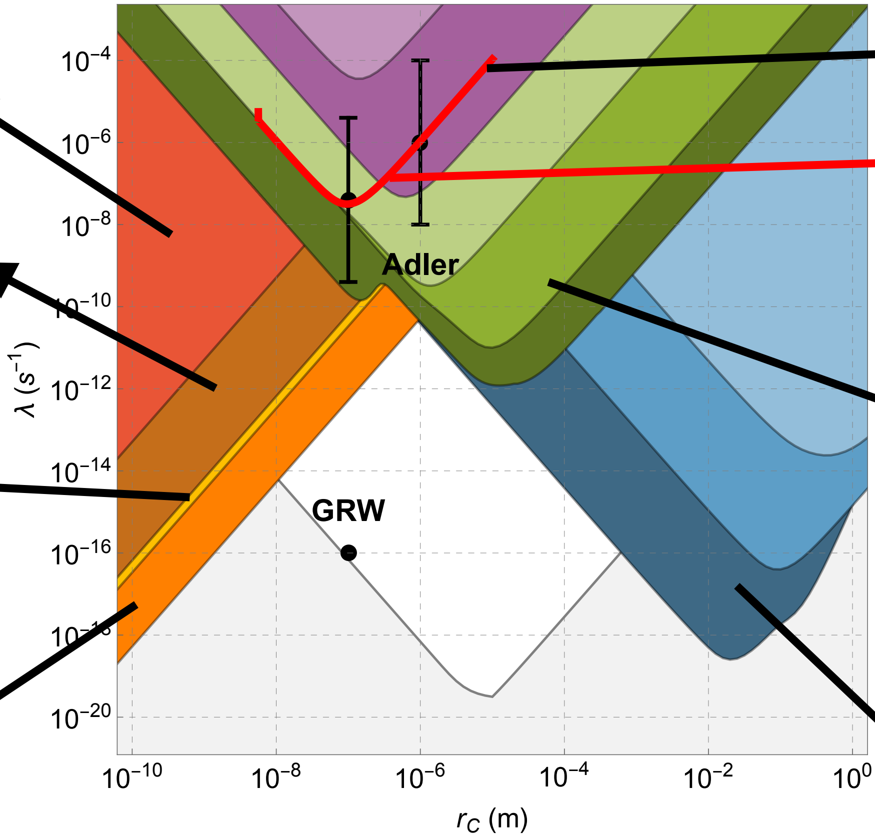

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Zheng *et al.*, Phys. Rev. Res. **2**, 013057 (2020)
Dania et al, ArXiv 2304.02408

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Gravitational wave detectors Auriga, LIGO, LISA Pathfinder

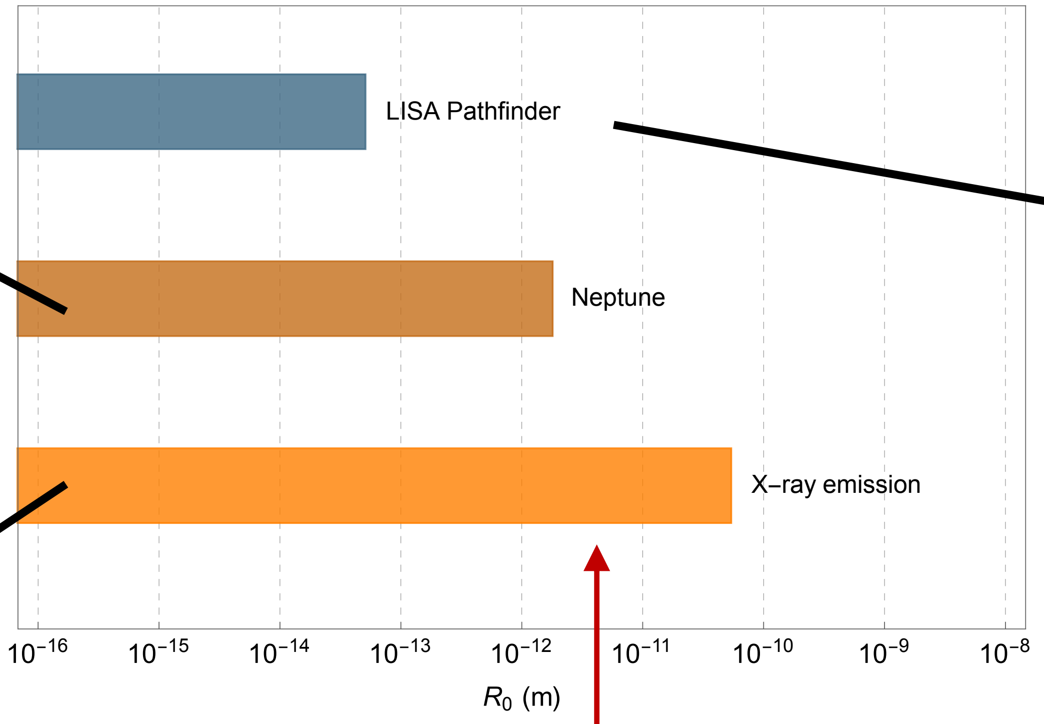
Carlesso *et al*, Phys. Rev. D ***94***, 124036 (2016)

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

Non-interferometric Tests - DP

Neptune

MC *et al.* Nature Phys. **18**, 243-250 (2022)



Gravitational wave detector LISA Pathfinder

Helou et al. Phys. Rev. D **95**, 084054 (2017)

X-rays emission

Donadi *et al, Nature Phys.* ***17****, 74-78 (2021)*

Penrose's argument is excluded: DP is effectively ruled out

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

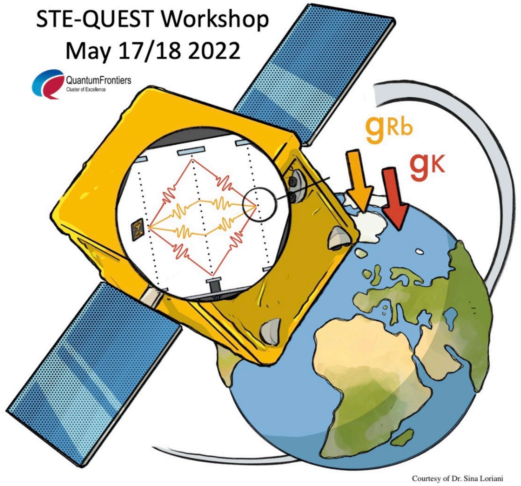
Future? Space experiments!

Option on ground: drop towers

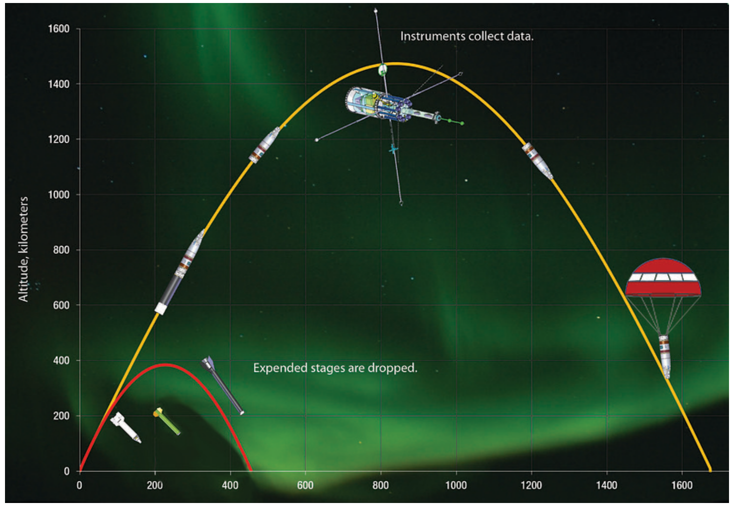
Bremen drop tower:
Up to 4.6s of free-fall time, 9.2s with the catapult
3 runs/day

Einstein elevator:
Around 4s of free-fall time with the catapult
300 runs/day

Belenchia *et al.*, *Phys. Rep.* **951**, 1 (2022)

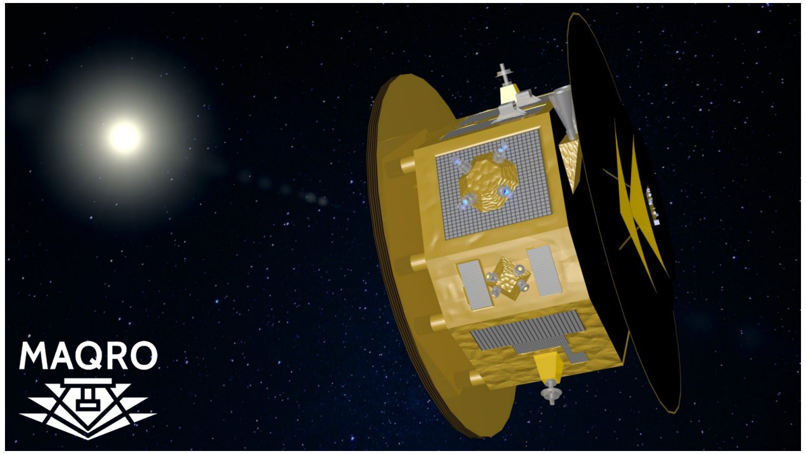


Options in space

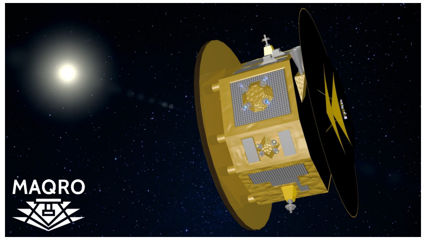


Sounding rockets:
Around 5-10 minutes of free-fall time

International Space Station (ISS)

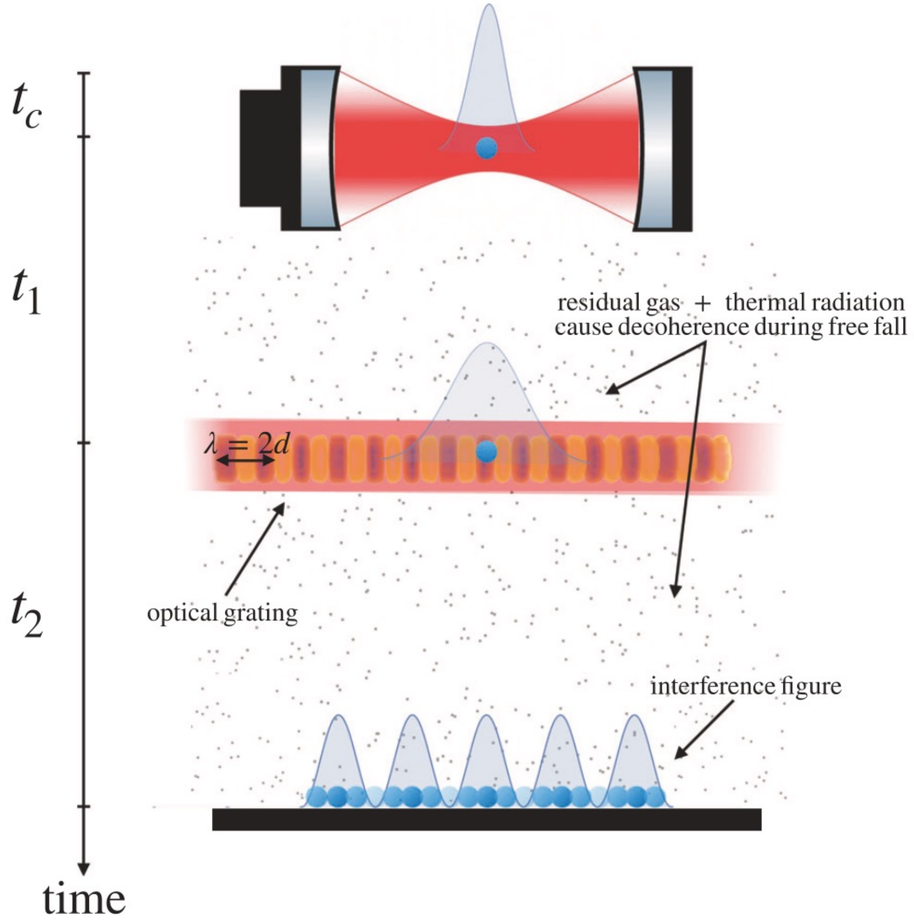


Dedicated experiments: STE-QUEST;
MAQRO & QFFP



Interferometric experiments in space with nanoparticles

MAQRO and QPPF investigate the possibility of performing near-field interferometric scheme with “large” particles on dedicated scientific space missions



(a) Nanoparticle is trapped and cooled in an optical cavity

(b) It is released and let evolve freely for a time t_1. Its coherent length needs to cover 2 adjacent “slits” of the optical grating

(c) A retro-reflected laser provides a pure-phase grating

(d) Free evolution of time t_2 needed to form the interference pattern

(e) Measurement of the particle via optical detection

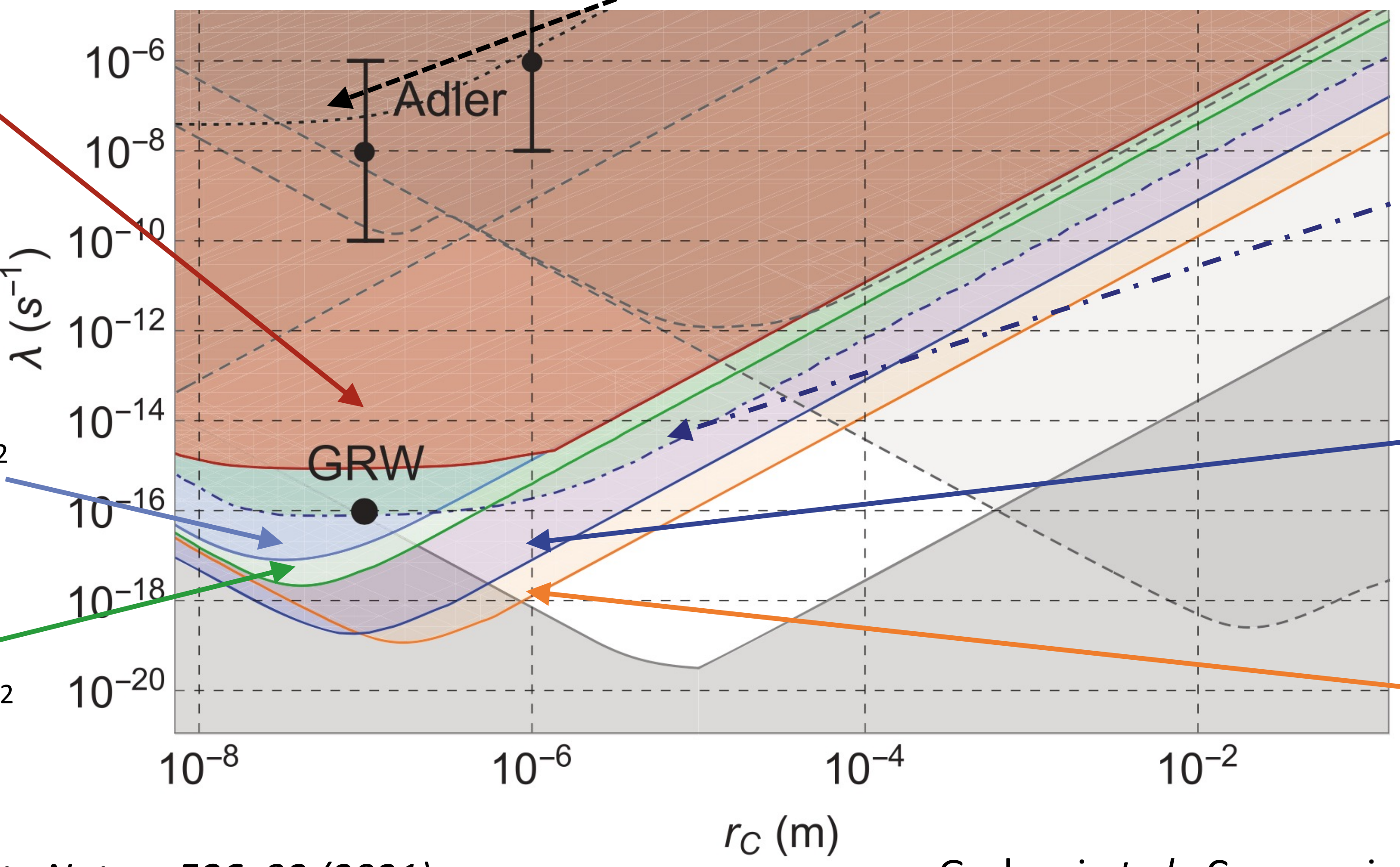
Kaltenbaek *et al.,*
EPJ Q. Tech. **3**, 5 (2016);
Gasbarri *et al.,*
Comm. Phys. **4**, 155 (2021);
Belenchia *et al.,*
Phys. Rev. A **100**, 033813 (2019)

Current state-of-the-art ground based exp. Fein *et al.* Nat. Phys. **15**, 1242 (2019)

$m=10^7$ amu
$t_1=t_2=12$ s
$E_L/a_L=1.1\times10^{-2}$ J/m^2

$m=10^8$ amu
$t_1=t_2=10$ s
$E_L/a_L=3.5\times10^{-4}$ J/m^2

$m=10^9$ amu
$t_1=t_2=10$ s
$E_L/a_L=8.7\times10^{-6}$ J/m^2



Hypothetical ground exp.
$M=10^7$amu
$t_1=t_2=9.95$s
[beyond what possible;
PRA **103**, 022214 (2021)]

$m=10^{10}$ amu
$t_1=t_2=50$s
$E_L/a_L=8.7\times10^{-6}$ J/m^2

$m=10^{11}$ amu
$t_1=t_2=50$ s
$E_L/a_L=2.2\times10^{-5}$ J/m^2

Belenchia *et at., Nature* ***596****, 32 (2021)*

Gasbarri *et al.*, Communications Physics **4**, 155 (2021)

Gravity models

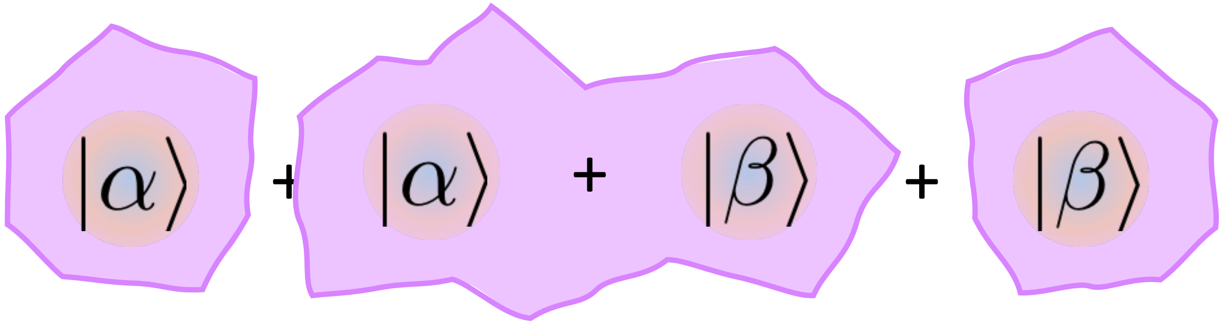
Problems at hand: how does the gravitational field of a superposition look like?

how two quantum system interact gravitationally?

Quantum scenario	Semi-classical scenario	Something else?

Prepare a “massive superposition”

$$|\alpha\rangle + |\beta\rangle$$



Gravity models

Problems at hand: how does the gravitational field of a superposition look like?

how two quantum system interact gravitationally?

Quantum scenario	Semi-classical scenario	Something else?

How to discriminate these two alternatives with low-energy experiments?

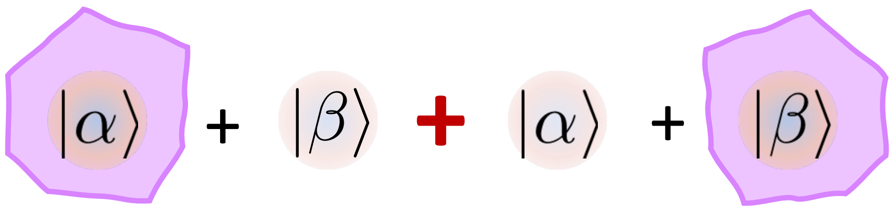
Different approaches based on the question we pose

- Entanglement generation (quantum scenario)
- Superposition of the gravitational field (quantum and classical scenario)
- Presence of extra noises (classical scenario)

How does the gravitational field of a superposition looks like?

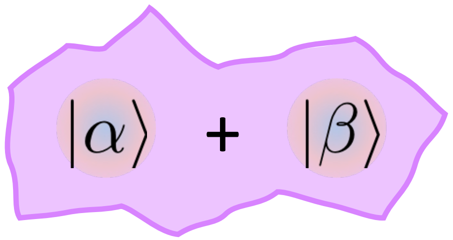
$$\psi(\mathbf{r}_1) = \frac{1}{\sqrt{2}}(\alpha(\mathbf{r}_1) + \beta(\mathbf{r}_1))$$

Quantum scenario



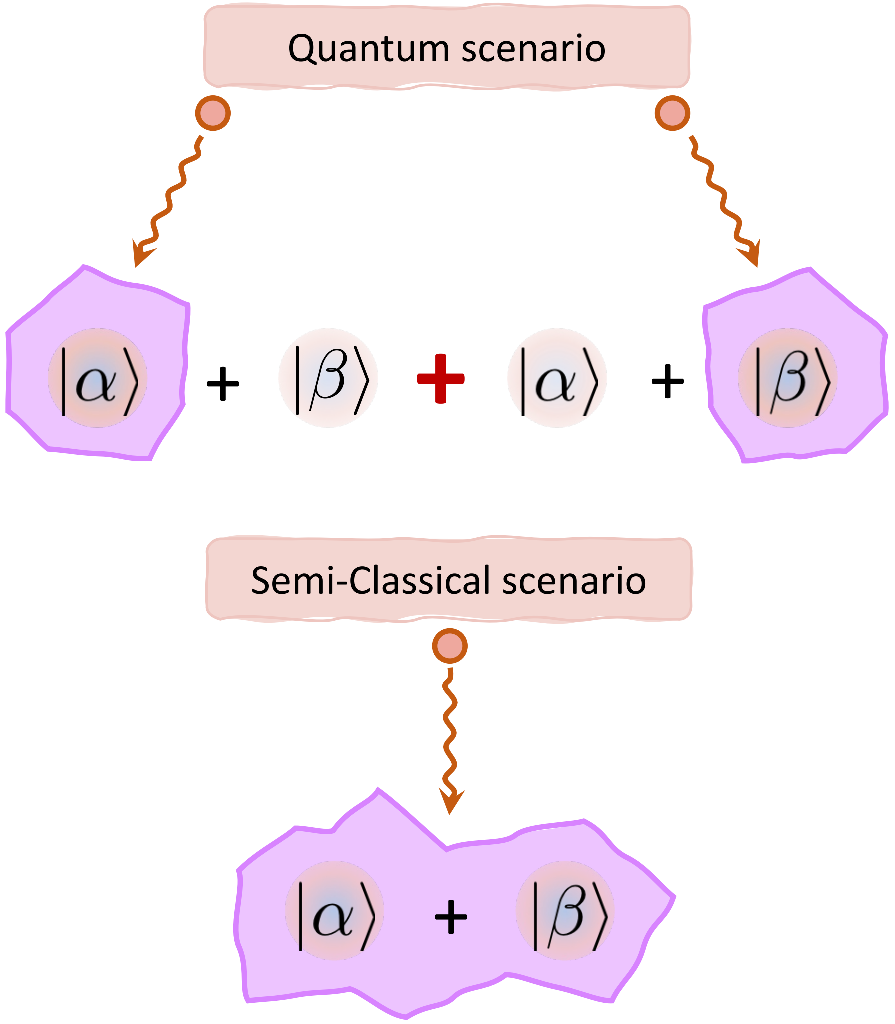
$$V_\gamma = -Gm_1m_2 \int \mathrm{d}^3\mathbf{r}_1 \frac{|\gamma(\mathbf{r}_1, t)|^2}{|\mathbf{r}_1 - \mathbf{r}_2|}$$

Semi-Classical scenario



$$V_{\mathrm{cl}} = -Gm_1\,m_2 \int \mathrm{d}^3\mathbf{r}_1 \frac{|\psi(\mathbf{r}_1, t)|^2}{|\mathbf{r}_1 - \mathbf{r}_2|}$$

How to test the two hypothesis?

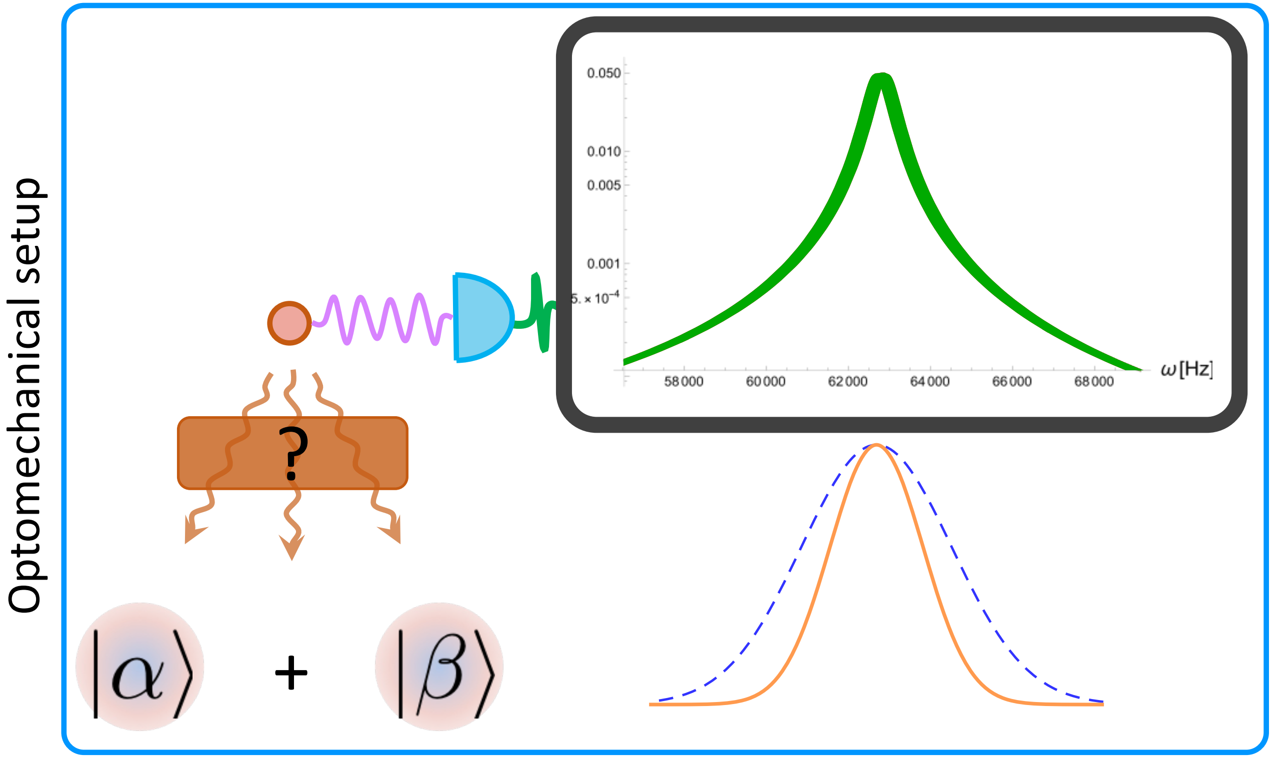


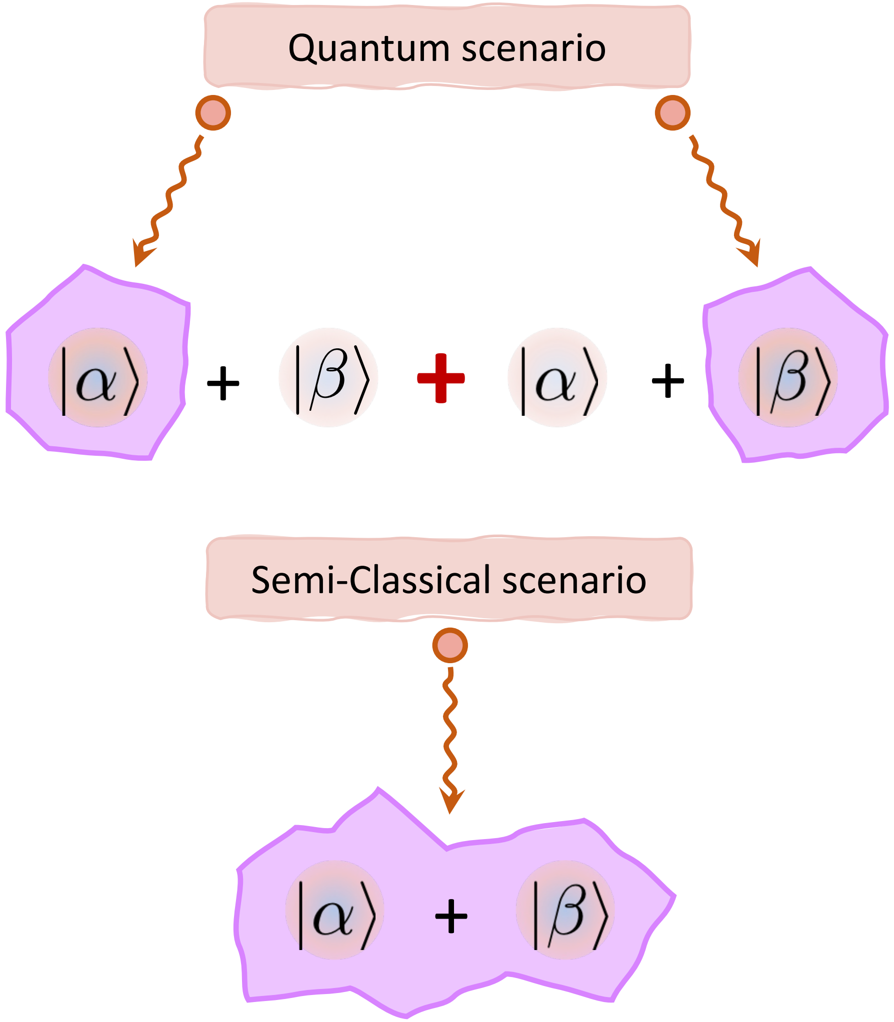
Is Gravity Quantum?

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

ArXiv 1507.05733 (2015)

$|\alpha\rangle + |\beta\rangle$ and add a quantum probe:





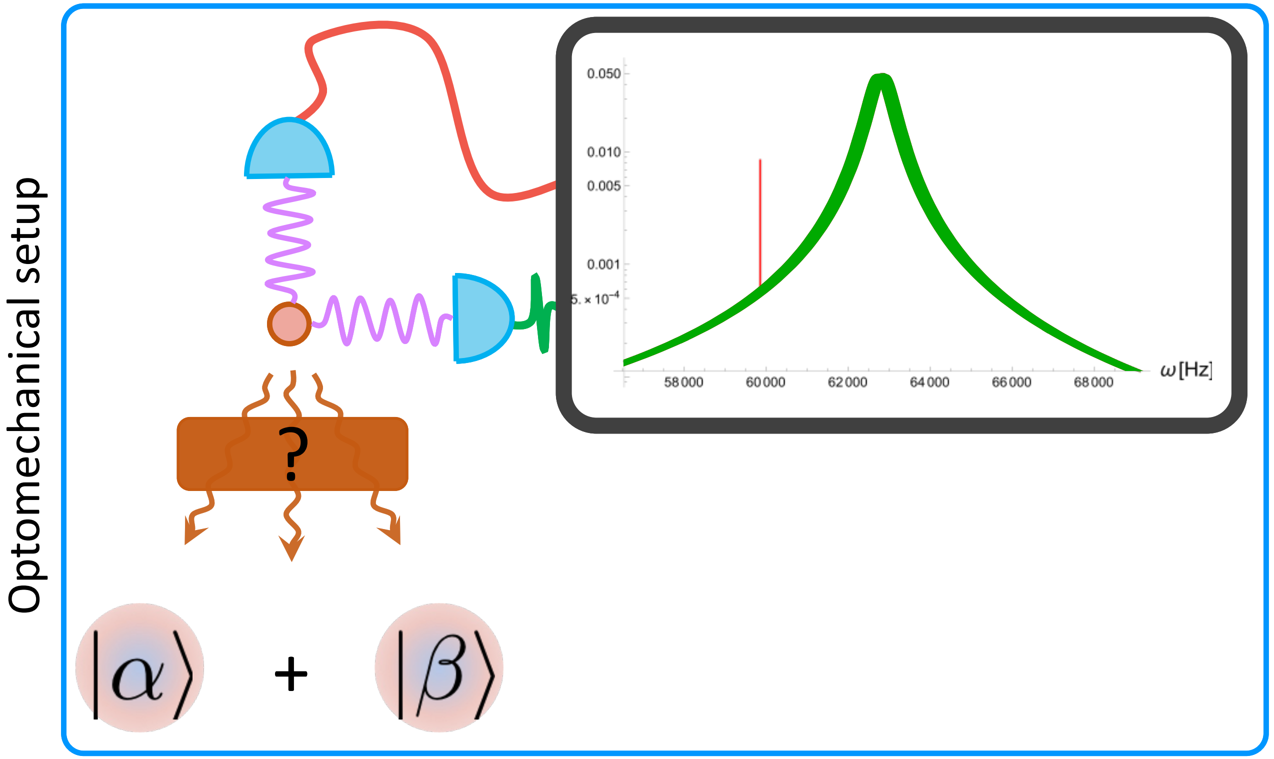
New Journal of Physics
The open access journal at the forefront of physics

Testing the gravitational field generated by a quantum superposition

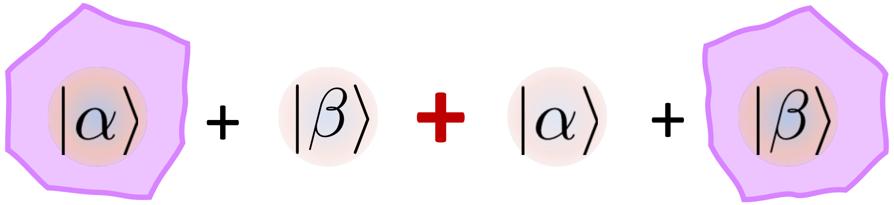
New Journal of Physics **21**, 093052 (2019)

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

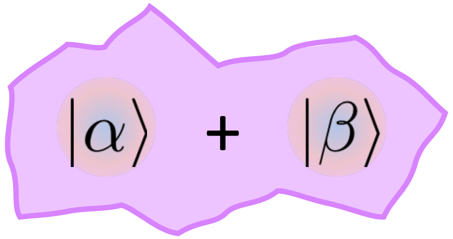
Test the motion along two directions



Quantum scenario



Semi-Classical scenario

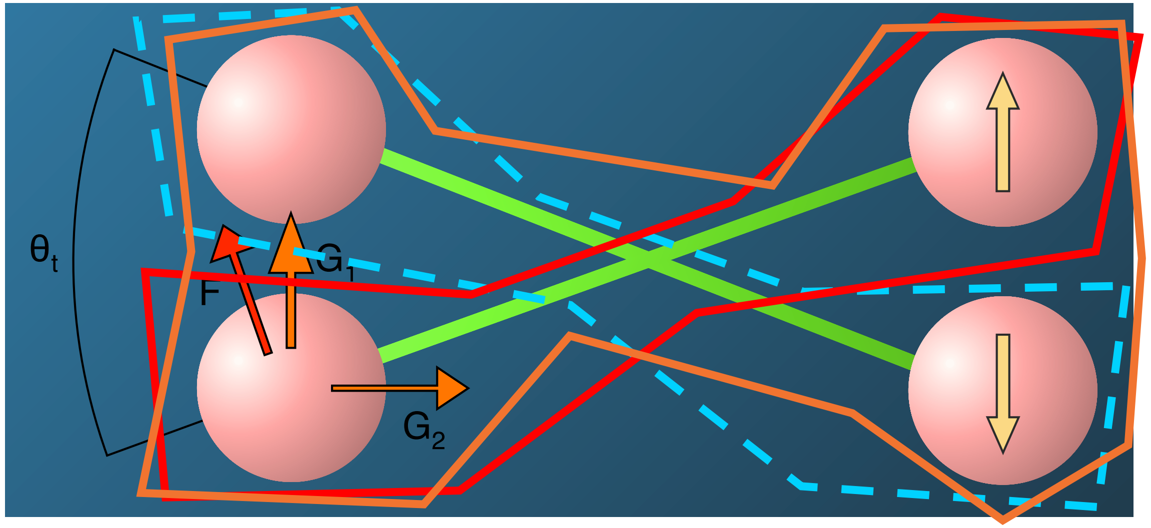


When Cavendish meets Feynman: A quantum torsion balance for testing the quantumness of gravity

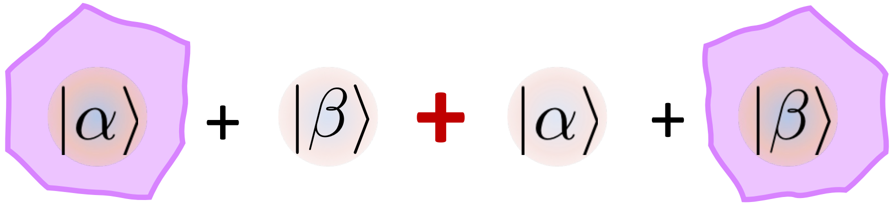
Matteo Carlesso,[1,2,*] Mauro Paternostro,[3,4] Hendrik Ulbricht,[5] and Angelo Bassi[1,2]

ArXiv 1710.08695 (2017)

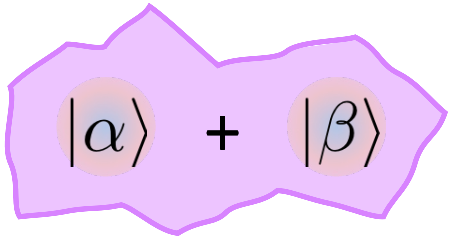
Using a single self-testing quantum system



Quantum scenario



Semi-Classical scenario



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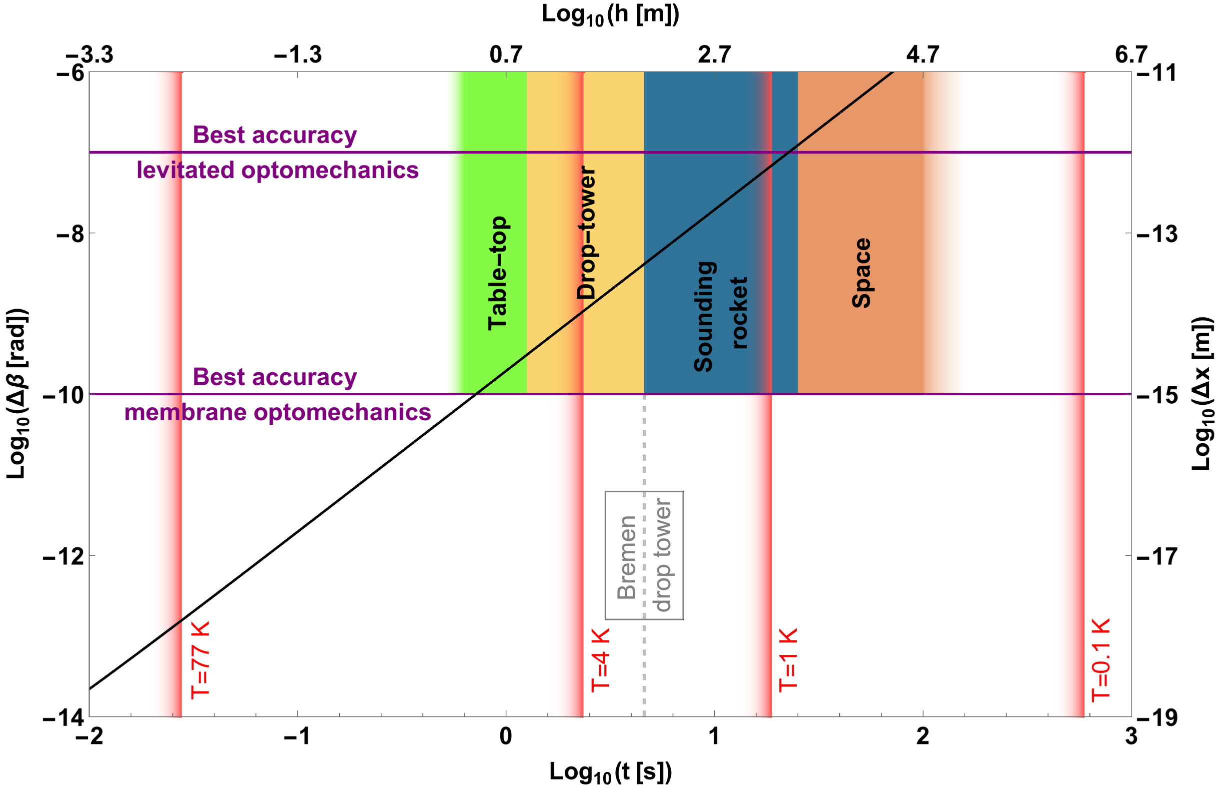
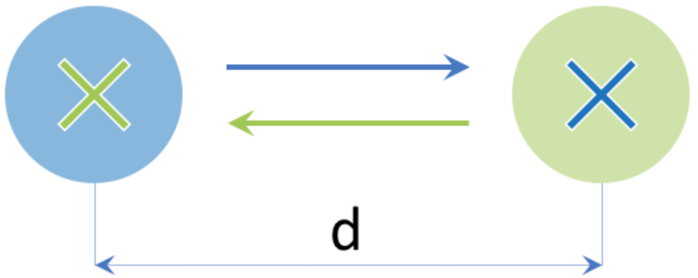


How two quantum system interact gravitationally?

I.e., How to reconcile the action of a classical mediator (gravity) with a quantum object?

Eventually, in quantum mechanics, one can do only two things:

- Apply a unitary evolution
- Measure the expectation values



A classical channel model for gravitational decoherence

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

New Journal of Physics **16**, 065020 (2014)

KTM model: Two harmonic oscillators, at distance *d*, which interact gravitationally

The “quantum” linearised interaction will be

$$\hat{H} = \hat{H}_0 + \hat{H}_{\mathrm{grav}} \qquad \hat{H}_0 = \sum_{\alpha=1}^{2} \frac{\hat{p}_\alpha^2}{2m_\alpha} + \tfrac{1}{2} m_\alpha \omega_\alpha^2 \hat{x}_\alpha^2 \qquad \hat{H}_{\mathrm{grav}} = K \hat{x}_1 \hat{x}_2 \qquad K = \frac{G m_1 m_2}{d^3}$$

How classical gravity acts:

1) Weak measurement of the position $\quad r_\alpha = \langle \hat{x}_\alpha \rangle + \frac{\hbar}{\sqrt{\gamma_\alpha}} \frac{\mathrm{d}W_{\alpha,t}}{\mathrm{d}t}$

2) Feedback dynamics $\quad \hat{H}_{\mathrm{grav}} \longrightarrow \hat{H}_{\mathrm{fb}} = \chi_{12} r_1 \hat{x}_2 + \chi_{21} r_2 \hat{x}_1$

KTM model: full dynamics 2 particles

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H}_0 + K\hat{x}_1\hat{x}_2, \hat{\rho}] - \sum_{\alpha=1}^{2}\left(\frac{\gamma_\alpha}{8\hbar^2} + \sum_{\substack{\beta=1 \\ \beta\neq\alpha}}^{2}\frac{K^2}{2\gamma_\beta}\right)[\hat{x}_\alpha, [\hat{x}_\alpha, \hat{\rho}]]$$

We mimicked the gravitational interaction!

An diffusive noise is the price to pay

Mimimising wrt $\gamma = \gamma_1 = \gamma_2$ one obtains $-\frac{K}{2\hbar}\sum_{\alpha=1}^{2}[\hat{x}_\alpha, [\hat{x}_\alpha, \hat{\rho}]]$ with $K = \frac{Gm_1m_2}{d^3}$

One can test the diffusion, and thus the model

Levitated optomechanics is a perfectly suitable platform for it

Principle of least decoherence for Newtonian semiclassical gravity

Antoine Tilloy and Lajos Diósi
Phys. Rev. D **96**, 104045 – Published 28 November 2017

Same idea as in the KTM model, but with continuous mass distributions

$$\hat{H}_{\text{grav}} = \frac{1}{2}\int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y}\mathcal{V}(\mathbf{x}-\mathbf{y})\hat{\mu}(\mathbf{x})\hat{\mu}(\mathbf{y})$$ with $$\mathcal{V}(\mathbf{x}-\mathbf{y}) = -\frac{G}{|\mathbf{x}-\mathbf{y}|}$$

is substituted to
1) measurement
2) feedback protocol

Full dynamics

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H}_0 + \hat{H}_{\text{grav}}, \hat{\rho}] - \int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y}D(\mathbf{x}-\mathbf{y})[\hat{\mu}(\mathbf{x}), [\hat{\mu}(\mathbf{y}), \hat{\rho}]]$$

$$D(\mathbf{x}-\mathbf{y}) = \left[\frac{\gamma}{8\hbar^2} + \frac{1}{2}(\mathcal{V}\circ\gamma^{-1}\circ\mathcal{V})\right](\mathbf{x}-\mathbf{y})$$

For $\gamma(\mathbf{x}-\mathbf{y}) = -2\hbar\mathcal{V}(\mathbf{x}-\mathbf{y})$ one gets the Diosi-Penrose model, which is the minimum decoherence model

Should all these models be disregarded?

The model describes an indefinite increase of energy due to gravity $\langle\hat{H}\rangle_t = \dfrac{\hbar G\sum_k m_k}{4\sqrt{\pi}R_0^3}t$.

Di Bartolomeo *et al.,* Phys. Rev. A **108**, 012202 (2023)

How one can implement dissipation

Case of the TD model with minimal decoherence, i.e. the Diosi-Penrose model

$$\hat{A}(\mathbf{x}) = \hat{\mu}(\mathbf{x}) + i\hat{\mu}_{\mathrm{I}}(\mathbf{x}) \quad \text{with} \quad \hat{\mu}_{\mathrm{I}}(\mathbf{x}) = -\frac{\hbar\beta}{4}\nabla_{\mathbf{x}}\hat{\boldsymbol{J}}(\mathbf{x})$$

mass density

current

$$\hat{A}(\mathbf{x}) = \sum_{k=1}^{N} \frac{m_k}{(2\pi\hbar)^3} \int d^3q\, e^{-\frac{i}{\hbar}\mathbf{q}\cdot(\mathbf{x}-\hat{\mathbf{x}}_k) - \frac{R_0^2}{2\hbar^2}[(1+\alpha_k)\mathbf{q}+2\alpha_k\hat{\mathbf{p}}_k]^2}$$

The model has a more fundamental flavour compared to standard dissipative version of DP

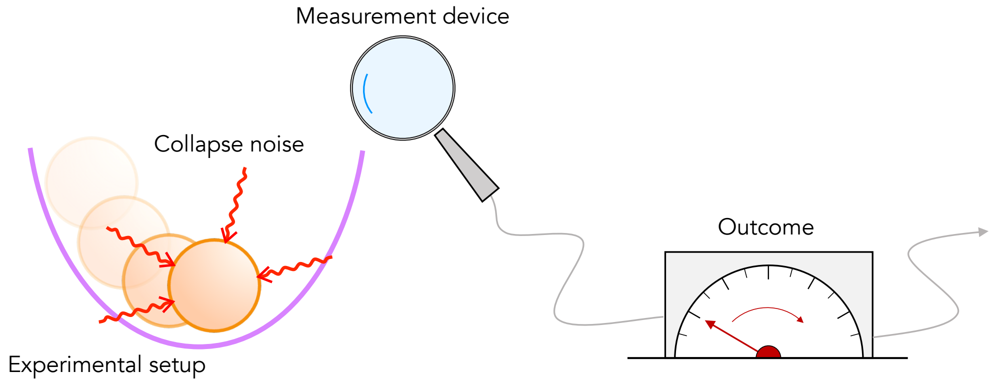
The same choice can be considered to construct the collapse operator in dissipative collapse models as the Continuous Spontaneous Localisation (CSL) model

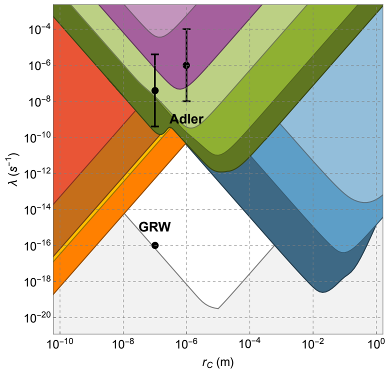
In both cases, one obtains an evolution for the energy reading

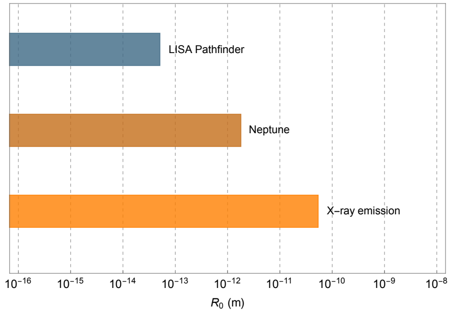
$$\frac{d}{dt}\langle\hat{H}\rangle_t = P - \Gamma\langle\hat{H}\rangle_t \quad \text{with} \quad P, \Gamma > 0$$ which gives a finite asymptotic energy

Summary

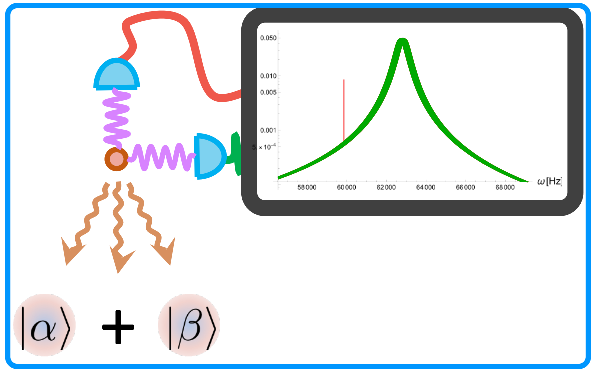
Collapse models

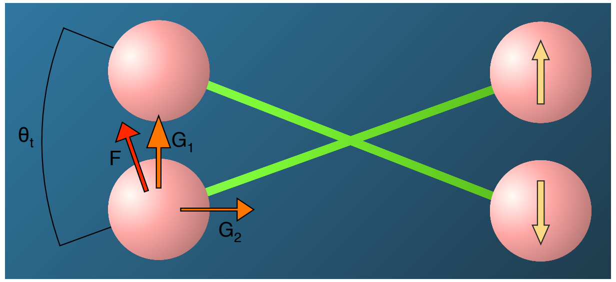






Gravity models





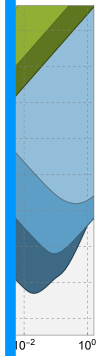
Summary

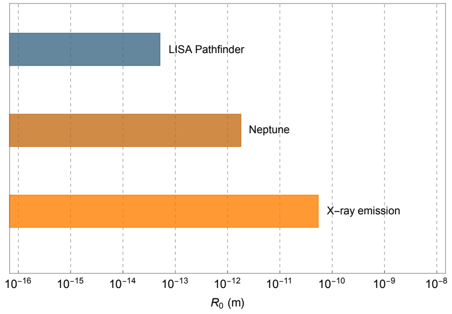
We are organising a School in Foundations

"Fundamental Problems in Quantum Physics 2023"

in Trieste, from 13 to 15 September 2023.

Info and registration at www.qmts.it/?q=fpqp2023





$|\alpha\rangle + |\beta\rangle$