Collapse models make particles jiggle… and emit photons

The Hitchhiker's Advanced Guide to Quantum Collapse Models and their impact in science, philosophy, technology and biology

31st October – 4th November 2022

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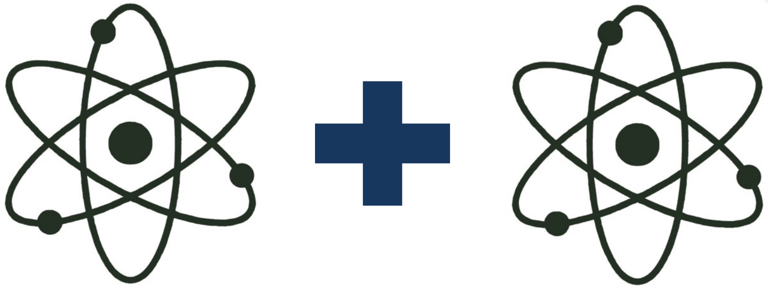
Quantum superpositions



Microscopic superpositions

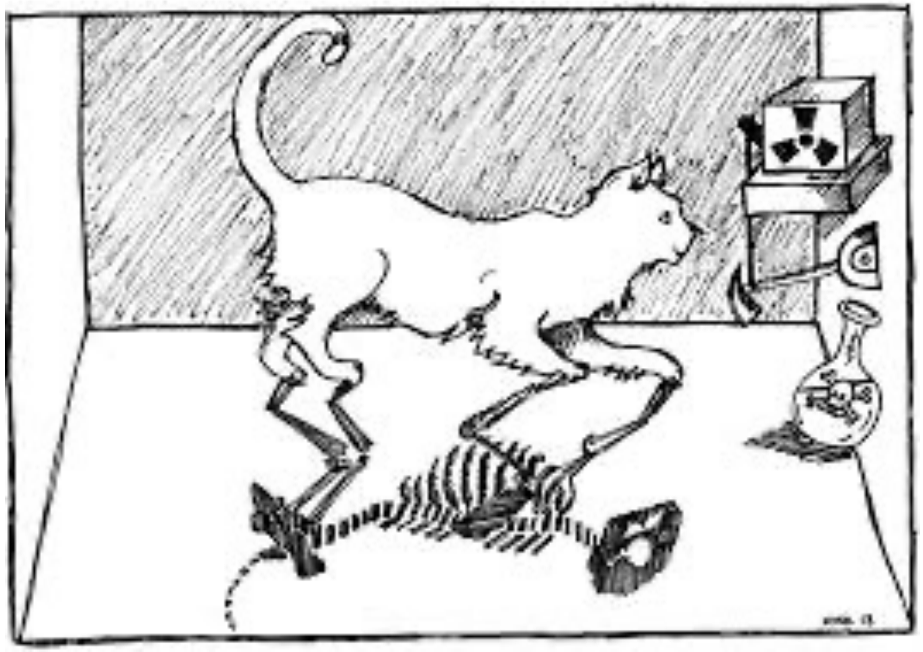
Experimentally verified

Cats are made of atoms + linearity of the theory

Macroscopic

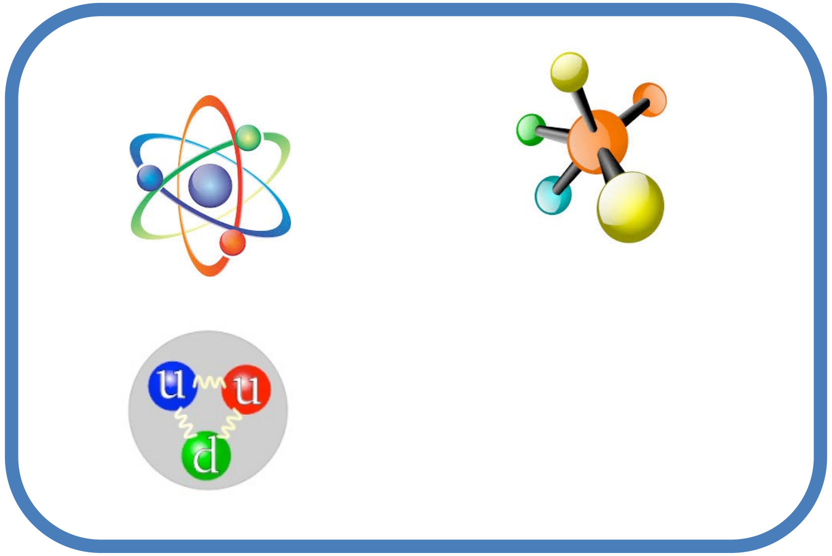
superpositions

Never seen



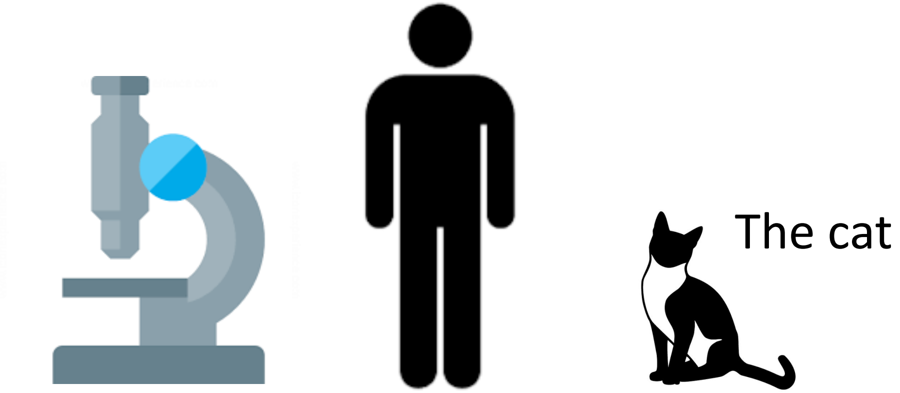
Standard Quantum Mechanics

Quantum world



Quantum - Classical divide

Classical world

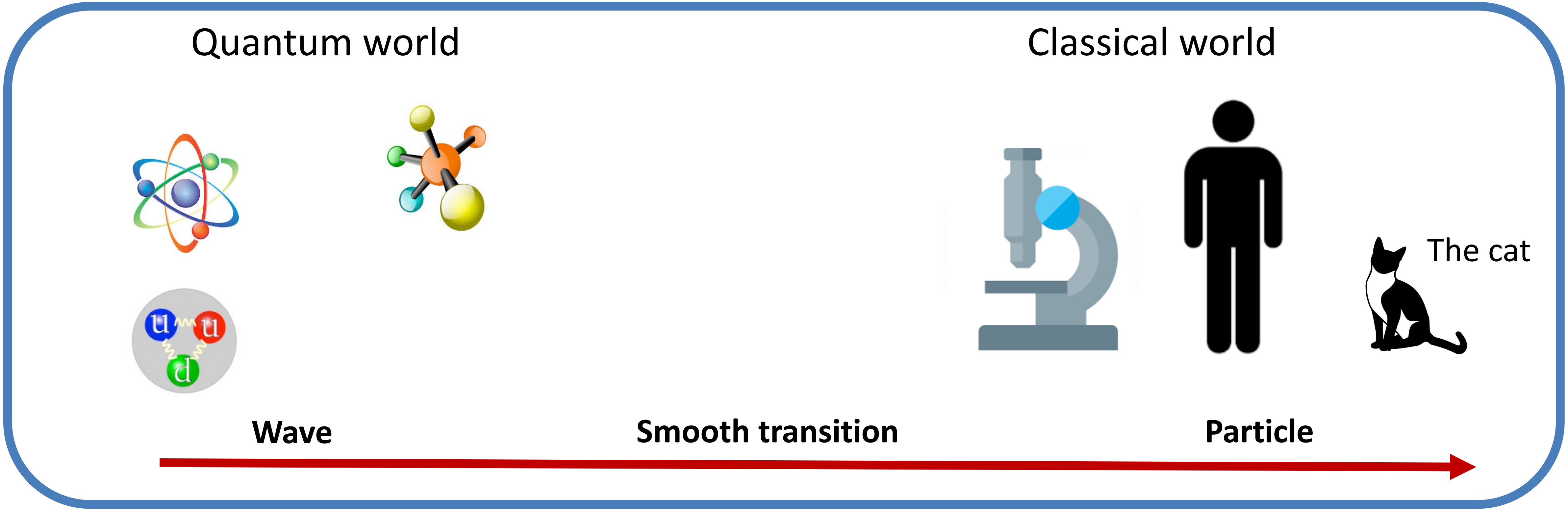


The wave function gives the probabilities of outcomes of measurements

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)

Spontaneous wave function collapse



The Schrödinger equation is **modified**. The new dynamics is **nonlinear** in such a way to describe the quantum micro-world, the classical macro-world, as well as the transition from one to the other.

G.C. Ghirardi et el., *Phys. Rev. D* 34, 470 (1986)

The dynamics of collapse models

A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003), A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht, *Rev. Mod. Phys.* 85, 471 (2013)

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

Nonlinear

Stochastic

Quantum mechanics + collapse in space

$$M(\mathbf{x}) = m a^\dagger(\mathbf{x}) a(\mathbf{x}) \qquad \langle M(\mathbf{x})\rangle_t = \langle \psi_t | M(\mathbf{x}) | \psi_t \rangle$$

Collapse operator ~ position

$$\mathbb{E}[dW_t(\mathbf{x})] = 0 \qquad \mathbb{E}[dW_t(\mathbf{x}) dW_t(\mathbf{y})] = \mathcal{G}(\mathbf{x}-\mathbf{y}) dt$$

Noise driving the collapse

$$\mathcal{G}(\mathbf{x}) = \frac{\lambda}{m_0^2}\, e^{-\mathbf{x}^2/4r_C^2}$$

CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989).

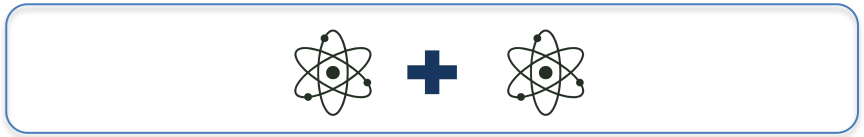
G.C. Ghirardi et al., *Phys. Rev. A* 42, 78 (1990)

$$\mathcal{G}(\mathbf{x}) = \frac{G}{\hbar}\frac{1}{|\mathbf{x}|}$$

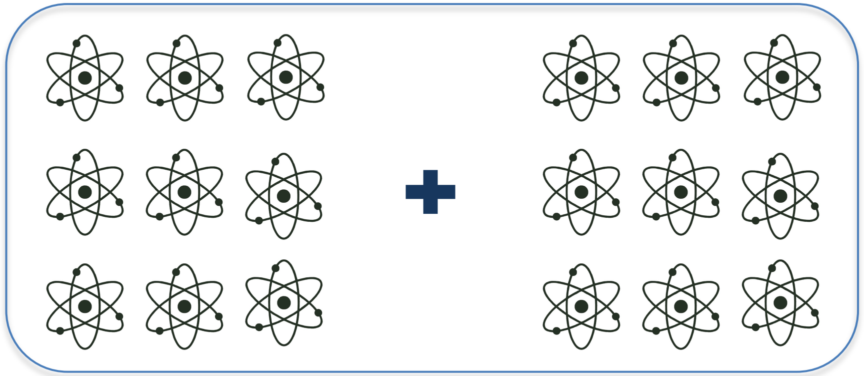
DP model

L. Diosi, Phys. Rev. A 40, 1165 (1989)

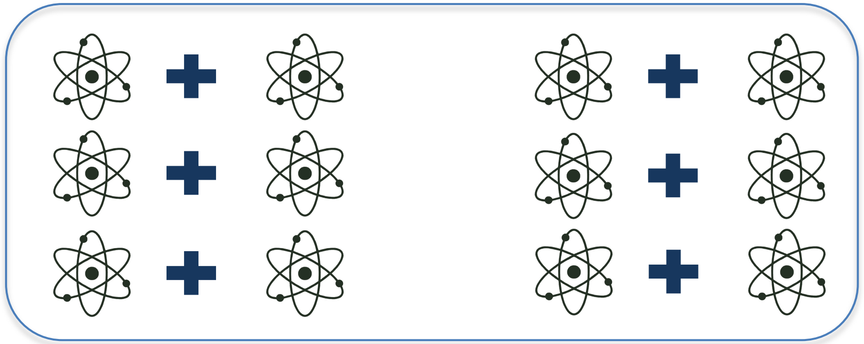
Collapse dynamics in a nutshell



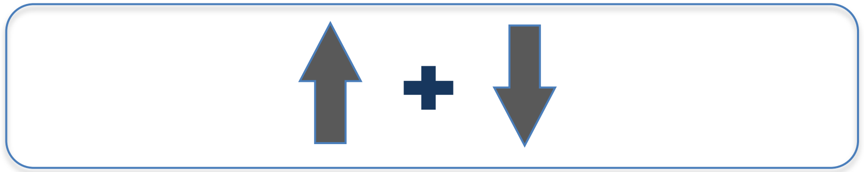
Microscopic superposition in space. Collapse very weak, modulo tiny deviations



Macroscopic superposition in space. Collapse very strong. The larger the delocalization in space and the number of particles, the faster the collapse



Many-body single-particle superpositions in space. Collapse very weak, modulo tiny deviations

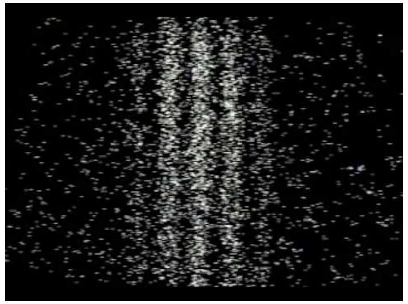


Superpositions in other d.o.f. very weak if they do not imply delocalization in space

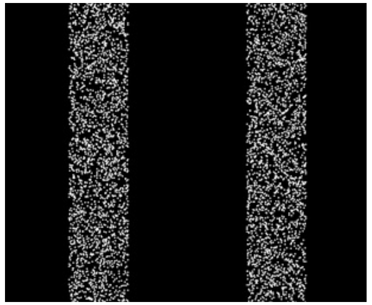
How to test collapse models

Interferometric experiments

Create a large superposition, in terms of mass, distance and duration, a perform a “double slit” experiment



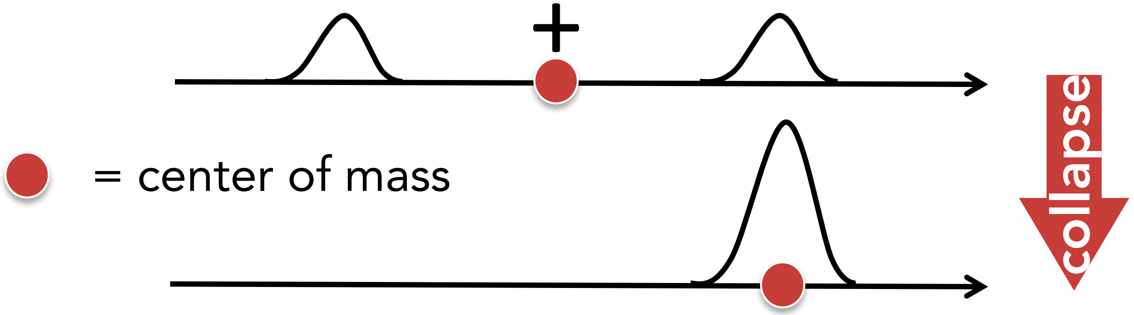
Prediction of
quantum mechanics
(no environmental noise)



Prediction of
collapse models
(no environmental noise)

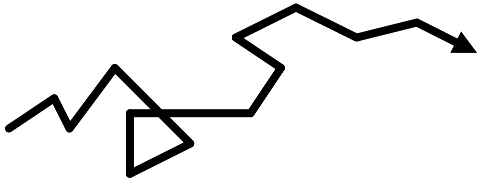
Non interferometric experiments

S. Donadi, L. Ferialdi & A. Bassi, “Collapse dynamics are diffusive”, arXiv:2209.09697



A collapse of the wave function changes the position of the center of mass ➔ **Collapse-induced Brownian motion**

Quantum prediction
(no environmental noise)



Collapse prediction
(no environmental noise)

Advantages and disadvantages

Interferometric experiments

+ These are a **direct test** of the quantum superposition principle and of collapse models.

− They are **difficult**. The whole field of quantum optomechanics boomed also with the aim of creating macroscopic quantum states.

Non interferometric experiments

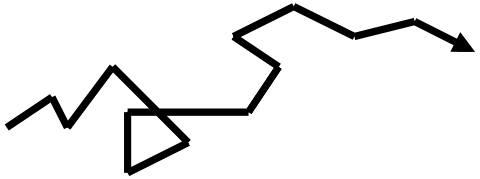
− They are a **direct test** of collapse models and an **indirect test** of the quantum superposition principle.

+ They are **easier** because **no quantum superposition** is needed to test the collapse-induced Brownian motion.

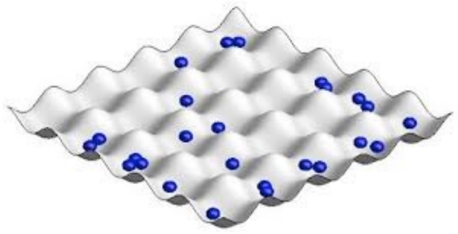
How to test the collapse noise

Quantum Mechanics

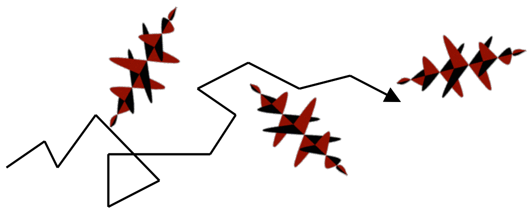
Collapse models



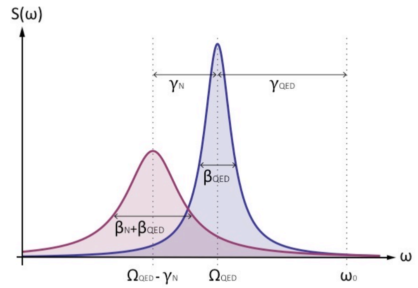
A **gas** will **expand** (heat up) faster than what predicted by QM



Charged particles will **emit** radiation, whereas QM predicts no emission



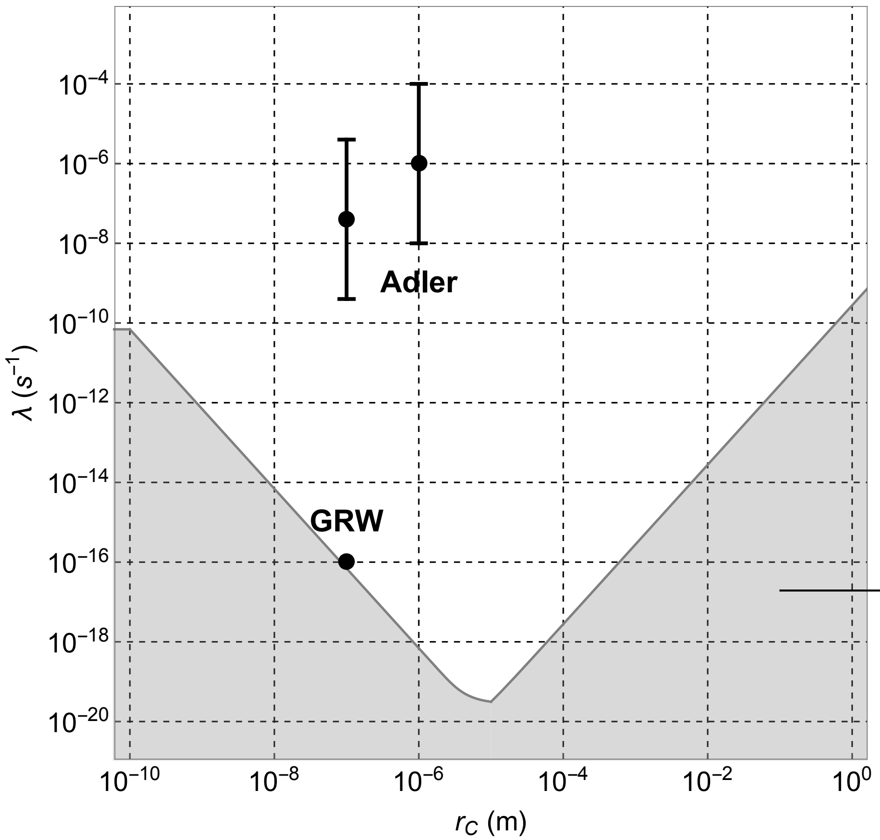
A **cantilever**'s motion cannot be **cooled down** below a given limit



Tests of the CSL model

$$\mathcal{G}(\mathbf{x}) = \frac{\lambda}{m_0^2}\, e^{-\mathbf{x}^2/4r_C^2}$$

Two phenomenological parameters. λ measures the strength of the collapse, r_C the space resolution of the collapse. m_0 is a reference mass, equal to that of a nucleon



• = Theoretical guesses

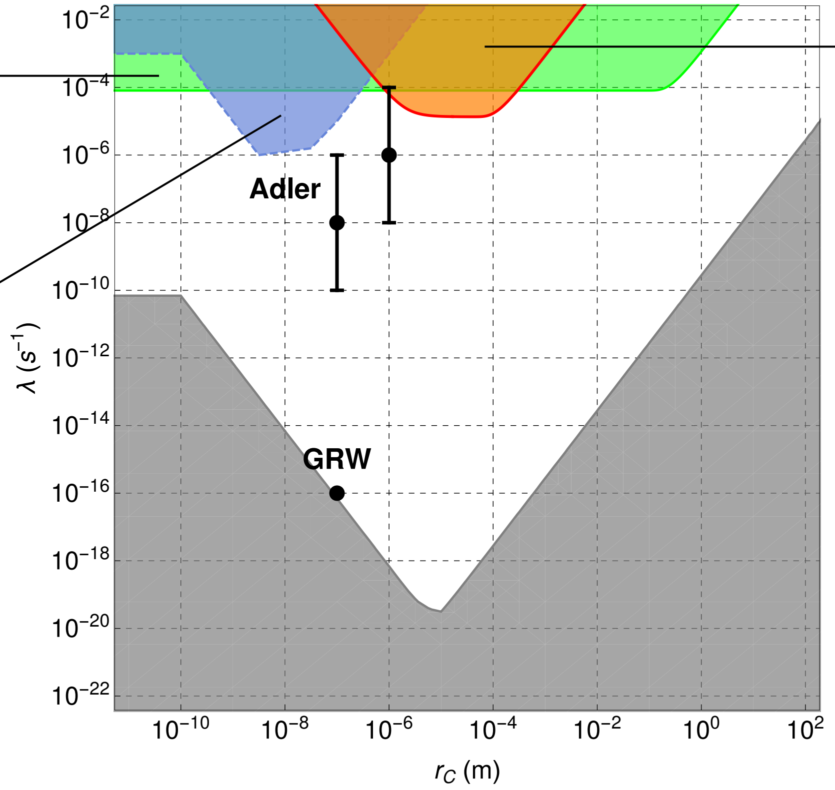
Lower bound: for such values of the parameters, the collapse is too weak and ineffective at the "macroscopic" level. Working assumption: a graphene disk with N = 10^{11} amu, delocalized over d = 10^{-5} m, should collapse in T = 10^{-2} s

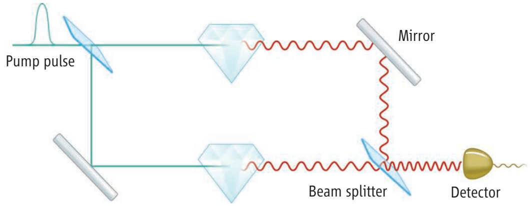
Interferometric Experiments

Atom Interferometry

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

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

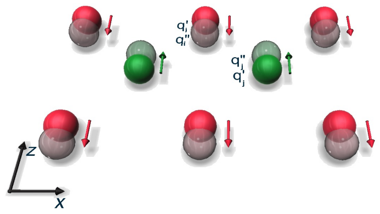




Entangling Diamonds

K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al.*, PRA 94, 012108 (2016).
B. Schrinski *et al.*, ArXiv:2209.06635.

M = 10^{16} amu
d = 10^{-11} m → in reality much smaller
T = 10^{-12} s



Molecular Interferometry

Y.Y Fein *et al.,* Nature Physics 15, 1242 (2019)
M. Toros *et al.,* PLA 381, 3921 (2017)

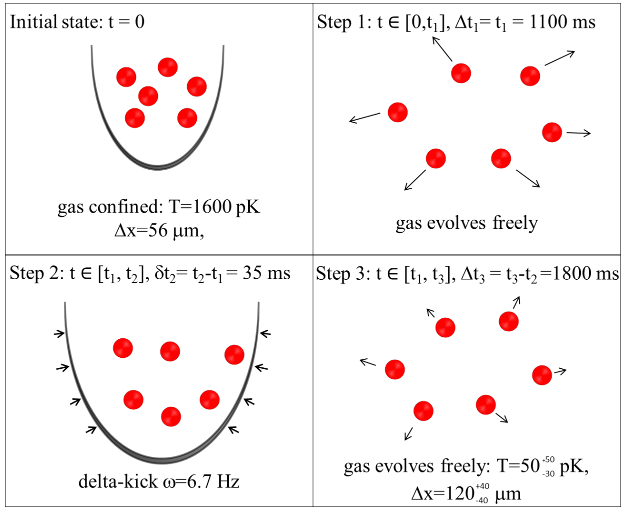
M = 10^5 amu
d = 10^{-7} m
T = 10^{-3} s

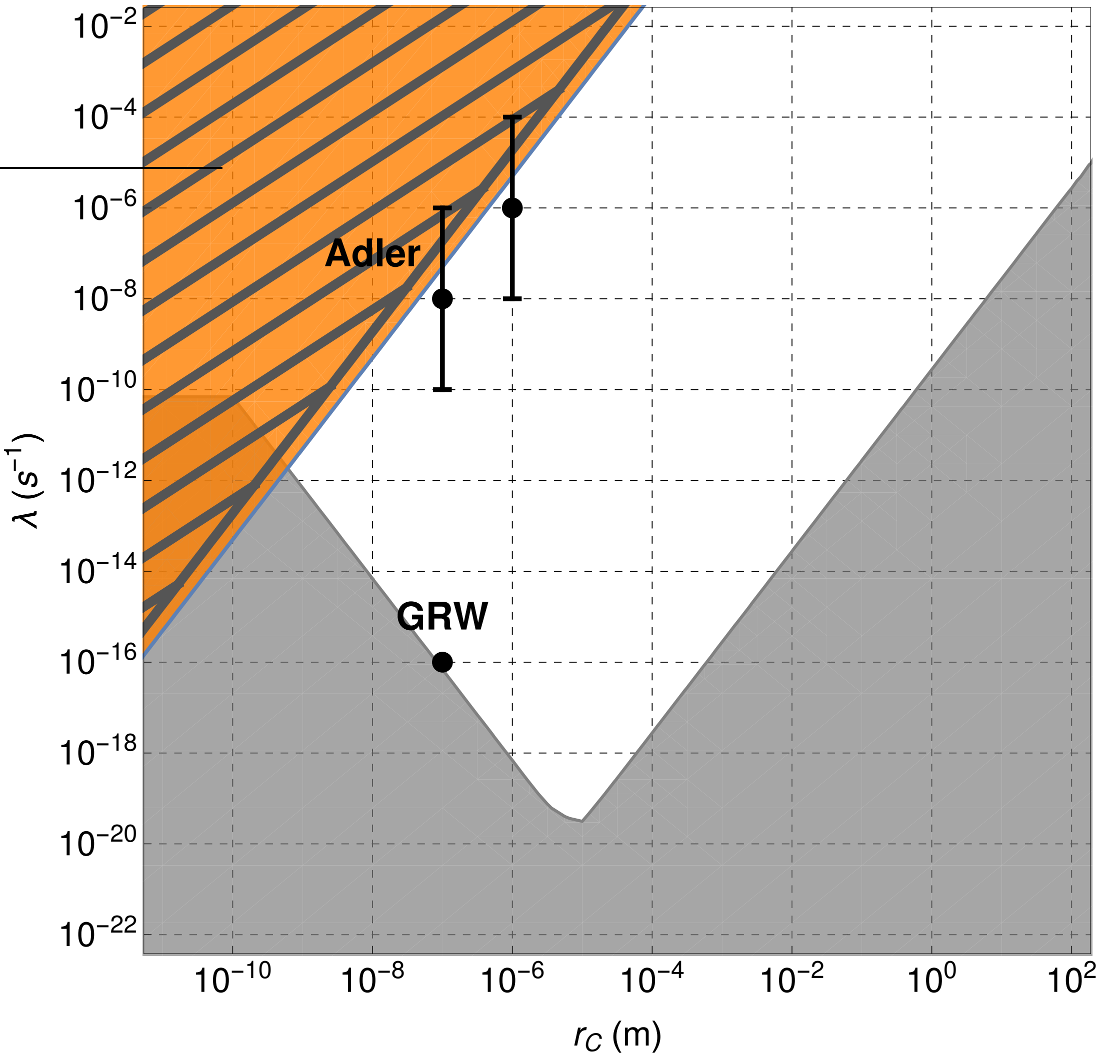
To improve interferometric tests, it will likely be necessary to go to micro-gravity environment in outer space → MAQRO

Non - Interferometric Experiments

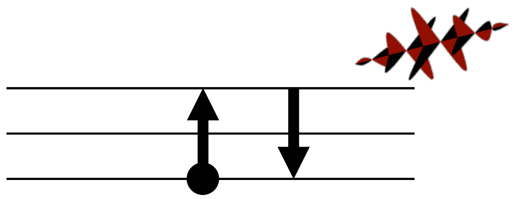
Cold atom gas

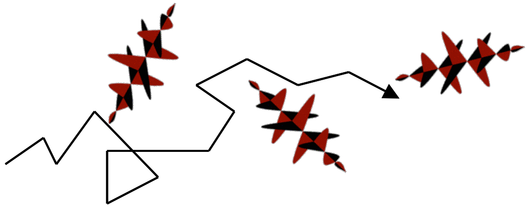
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.*, Physica A 462, 764 (2016)



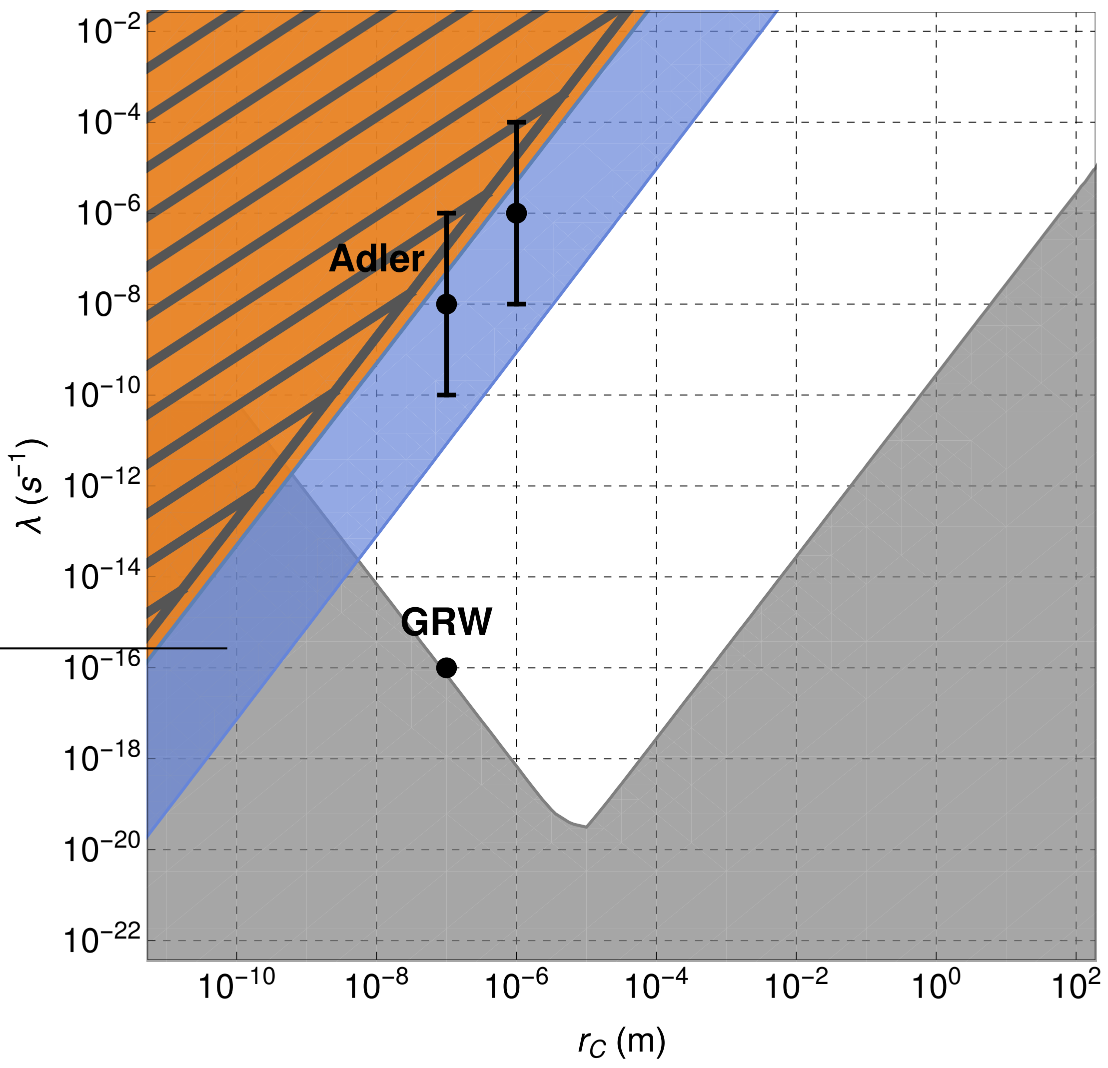


Non - Interferometric Experiments



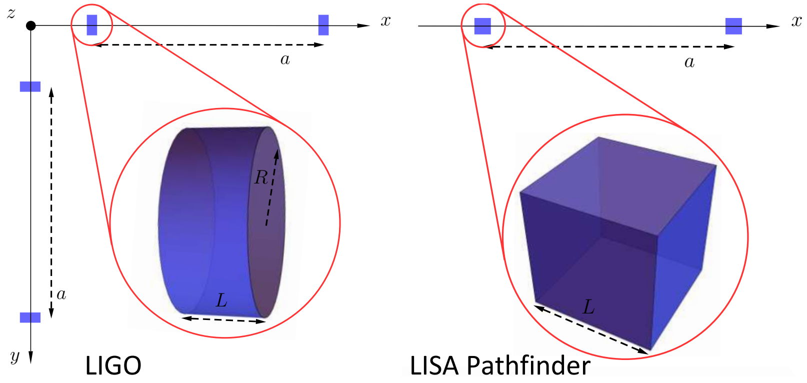


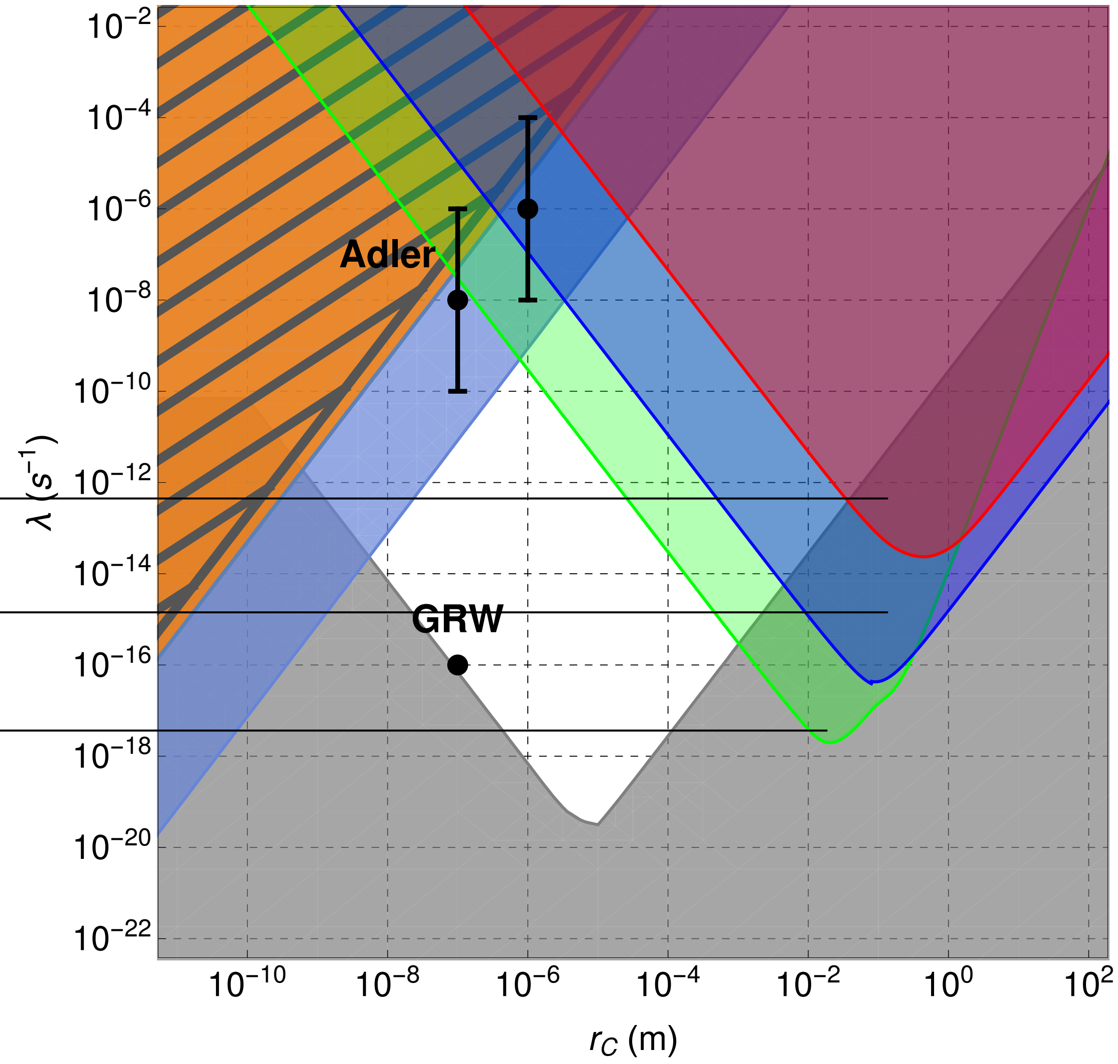
X rays



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

Non - Interferometric Experiments



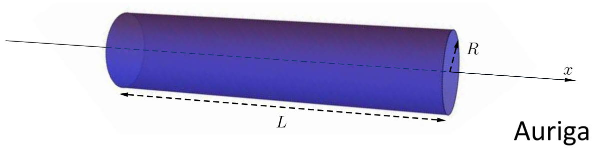


Auriga

Ligo

Lisa Pathfinder

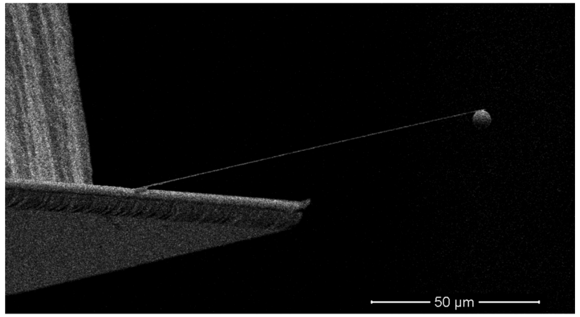
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

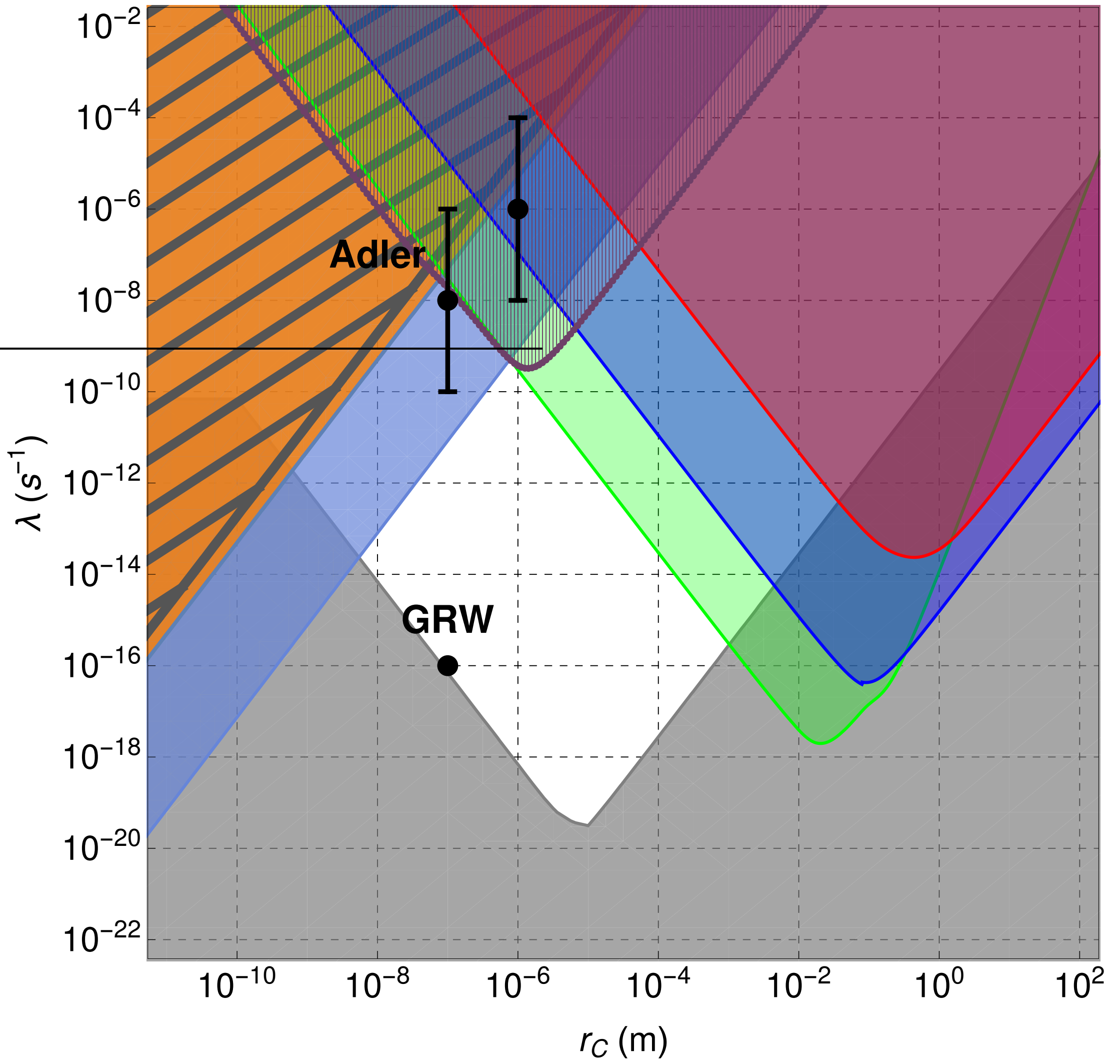


Non - Interferometric Experiments

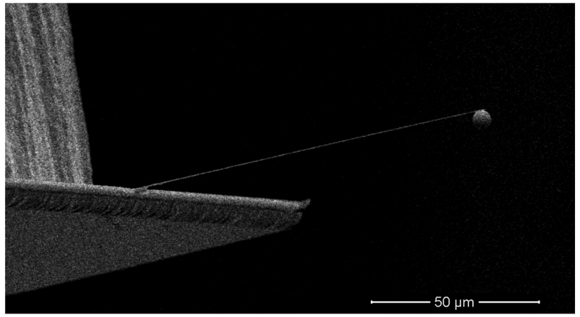
Cantilever

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



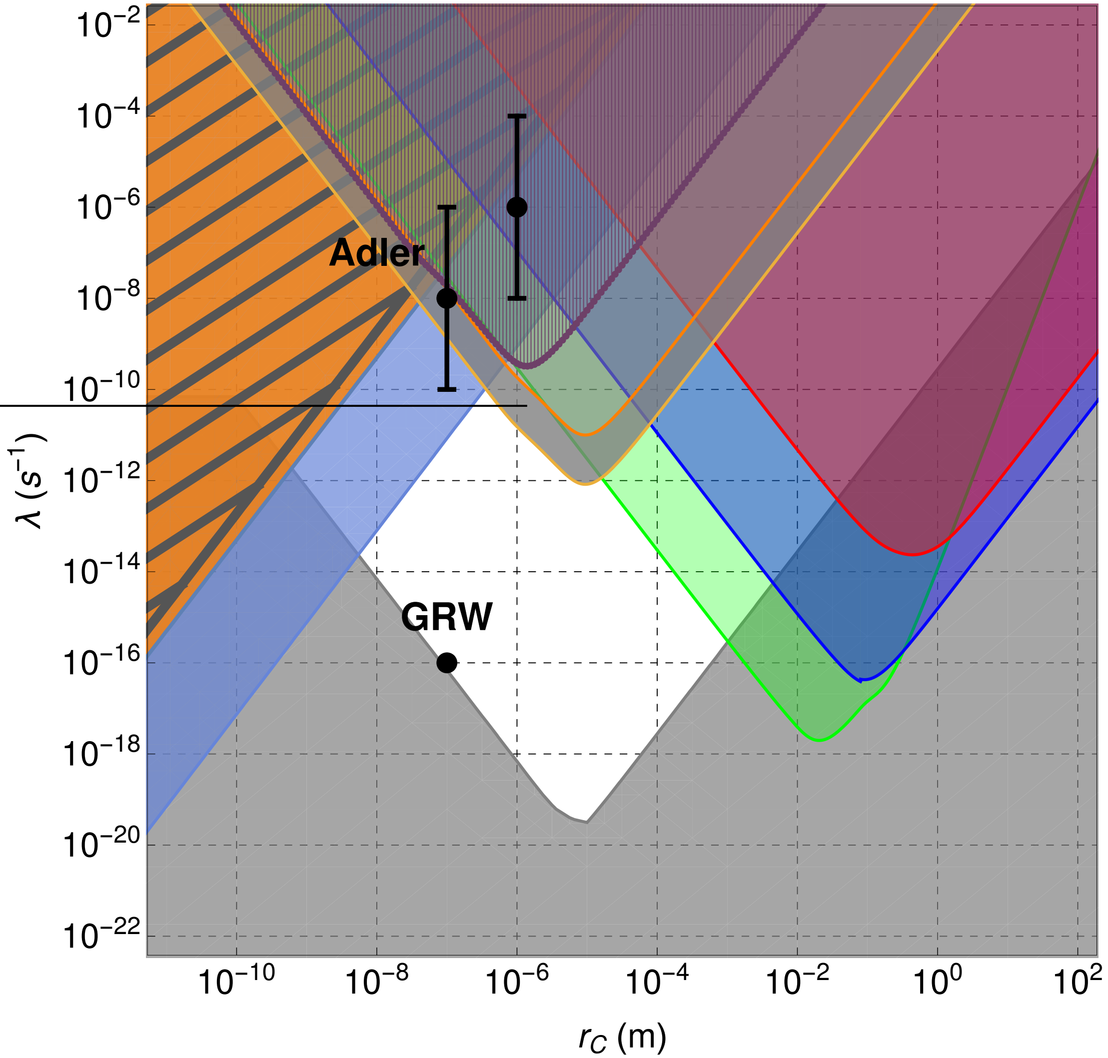


Non - Interferometric Experiments



Cantilever – update 1

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



Non - Interferometric Experiments

Radiation – Update 3

I. Kim, *ArXiv:2209.15082*

Cantilever - Update 2

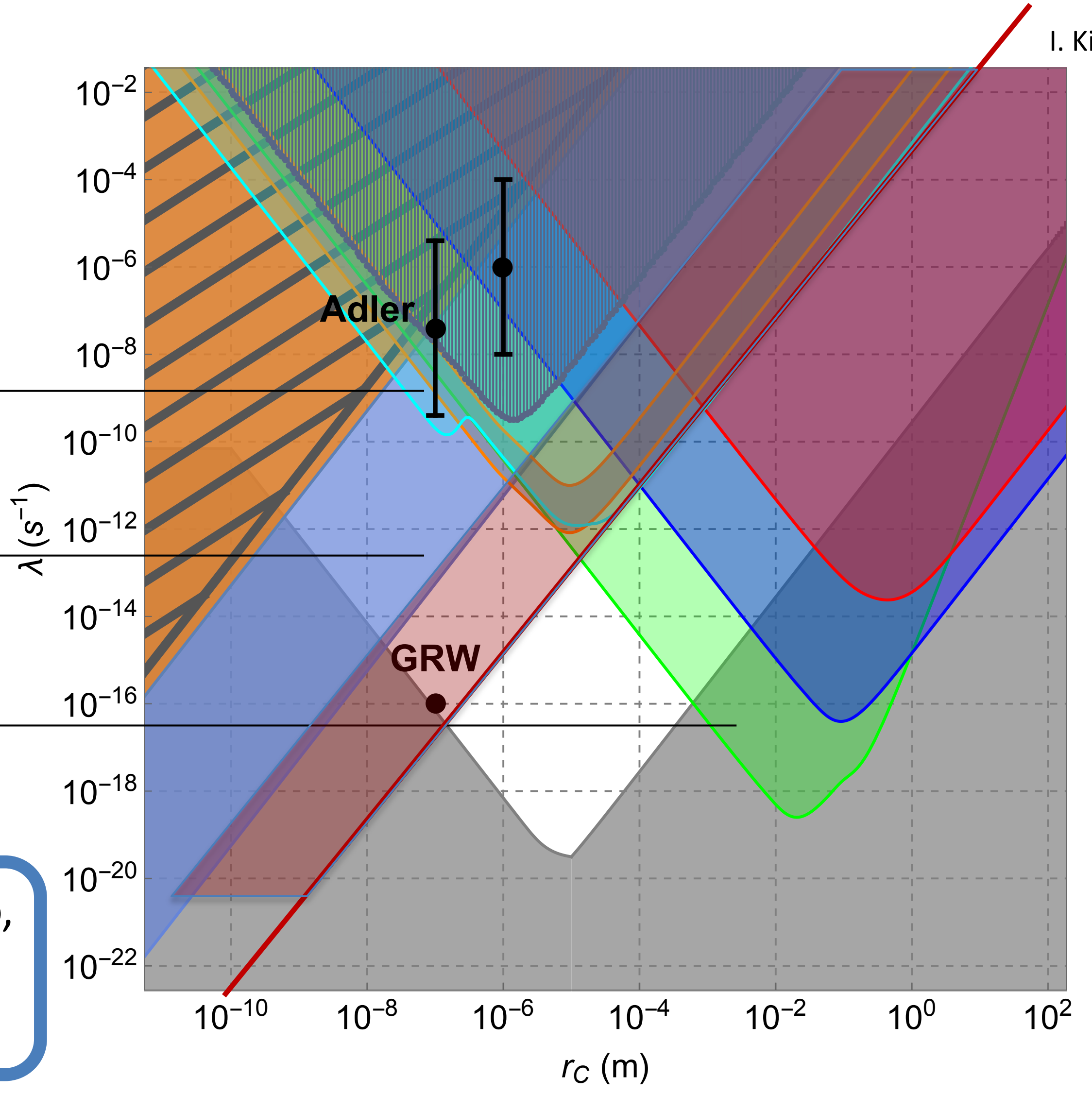
A. Vinante *et al., Phys. Rev. Lett. 125, 100404 (2020)*

Radiation – Update 1

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

Gravitational Wave detectors – Update 1

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



M. Carlesso, S. Donadi, L. Ferialdi, M. Paternostro, H. Ulbricht, A. Bassi,
Nature Physics 18, 243-250 (2022)

Non - Interferometric Experiments

Cantilever - Update 2

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

Radiation – Update 1

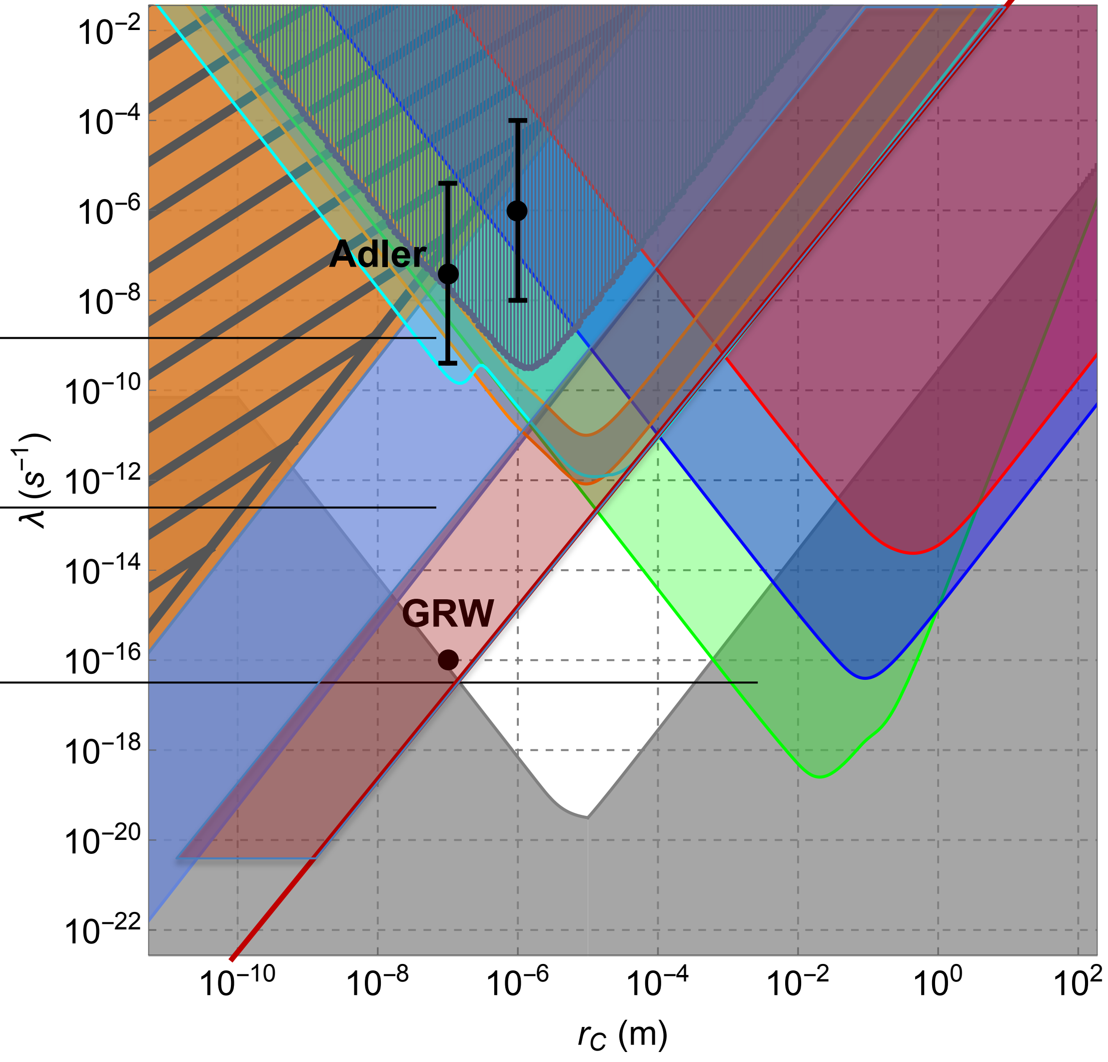
K. Pisicchia *et al., Entropy 19, 319 (2017)*

Gravitational Wave detectors – Update 1

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

Radiation – Update 3

I. Kim, *ArXiv:2209.15082*



Non-white noises will change the picture significantly

Acknowledgments

The Group (www.qmts.it)

- Postdocs: S. Donadi, J.L. Gaona Reyes
- Ph.D. students: F. Cesa, L. Figurato, A. Ghundi, M. Vischi, G. Di Bartolomeo

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