Wave function collapse, gravity and cosmology

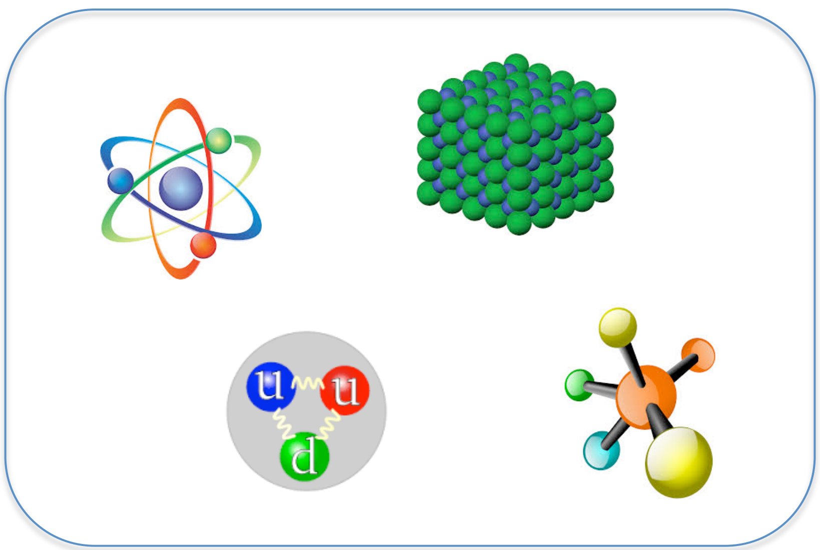
IAP – Paris

4th December 2017

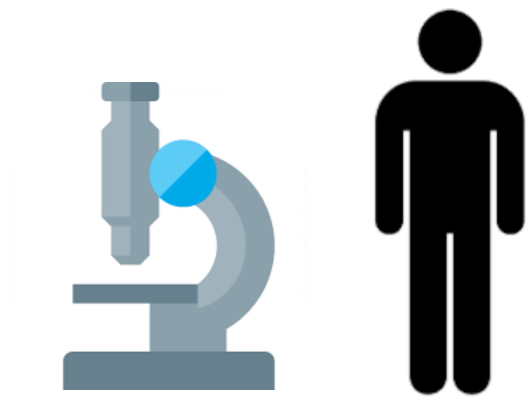
(Angelo Bassi – University of Trieste & INFN)

Standard Quantum Mechanics

Quantum world



Classical world



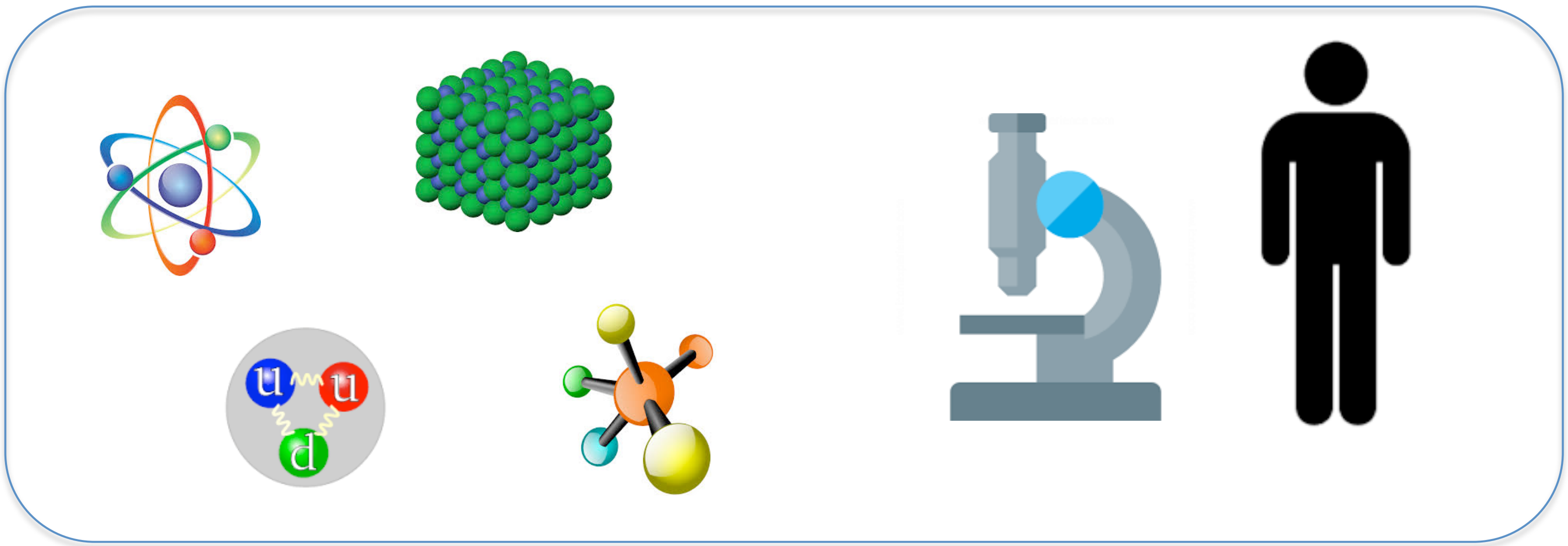
The wave function gives the probabilities of outcomes of measurements

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)

Modern (practical understanding of) Quantum Mechanics

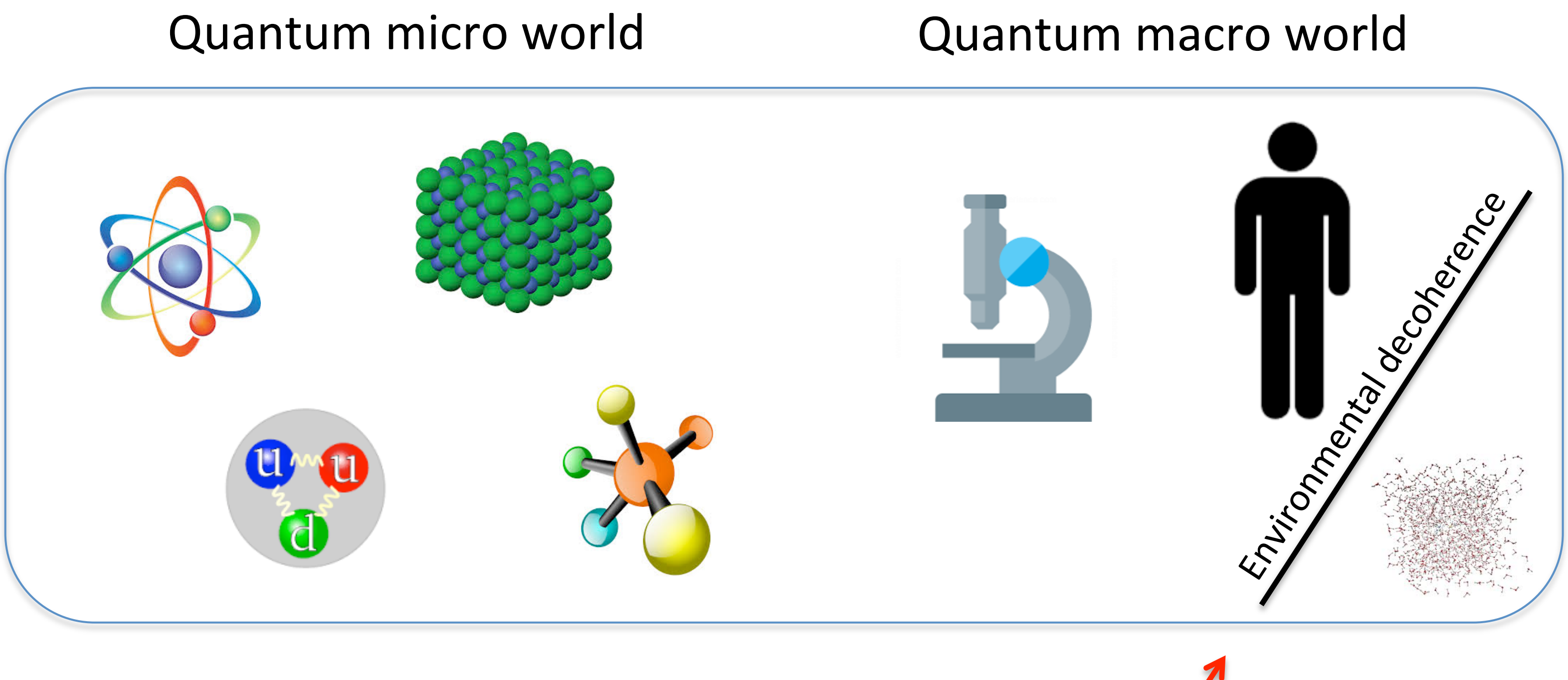
Quantum micro world

Quantum macro world



Problem: **What is the meaning of the wave function, now that there is no external observer? Who collapses the wave function?** ➔ Schrödinger's cat paradox

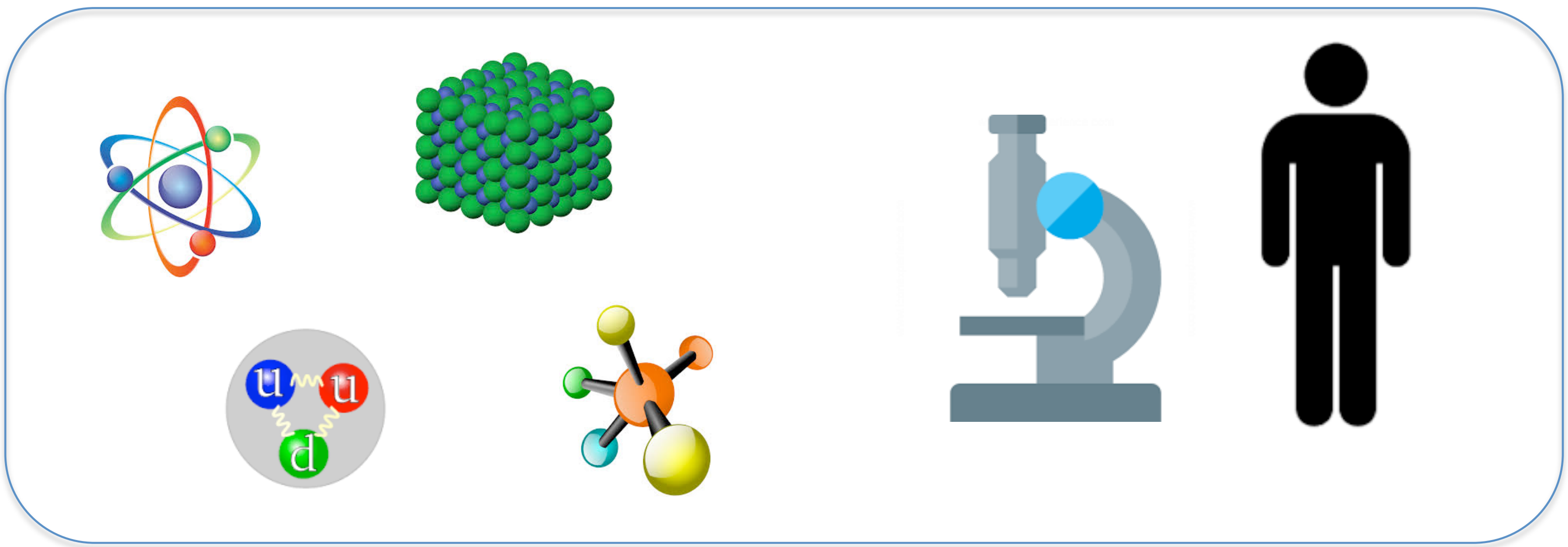
Modern (misunderstanding of) Quantum Mechanics



Problem: The division system-environment is **arbitrary,** and very much similar to the division quantum-classical in the Copenhagen interpretation.

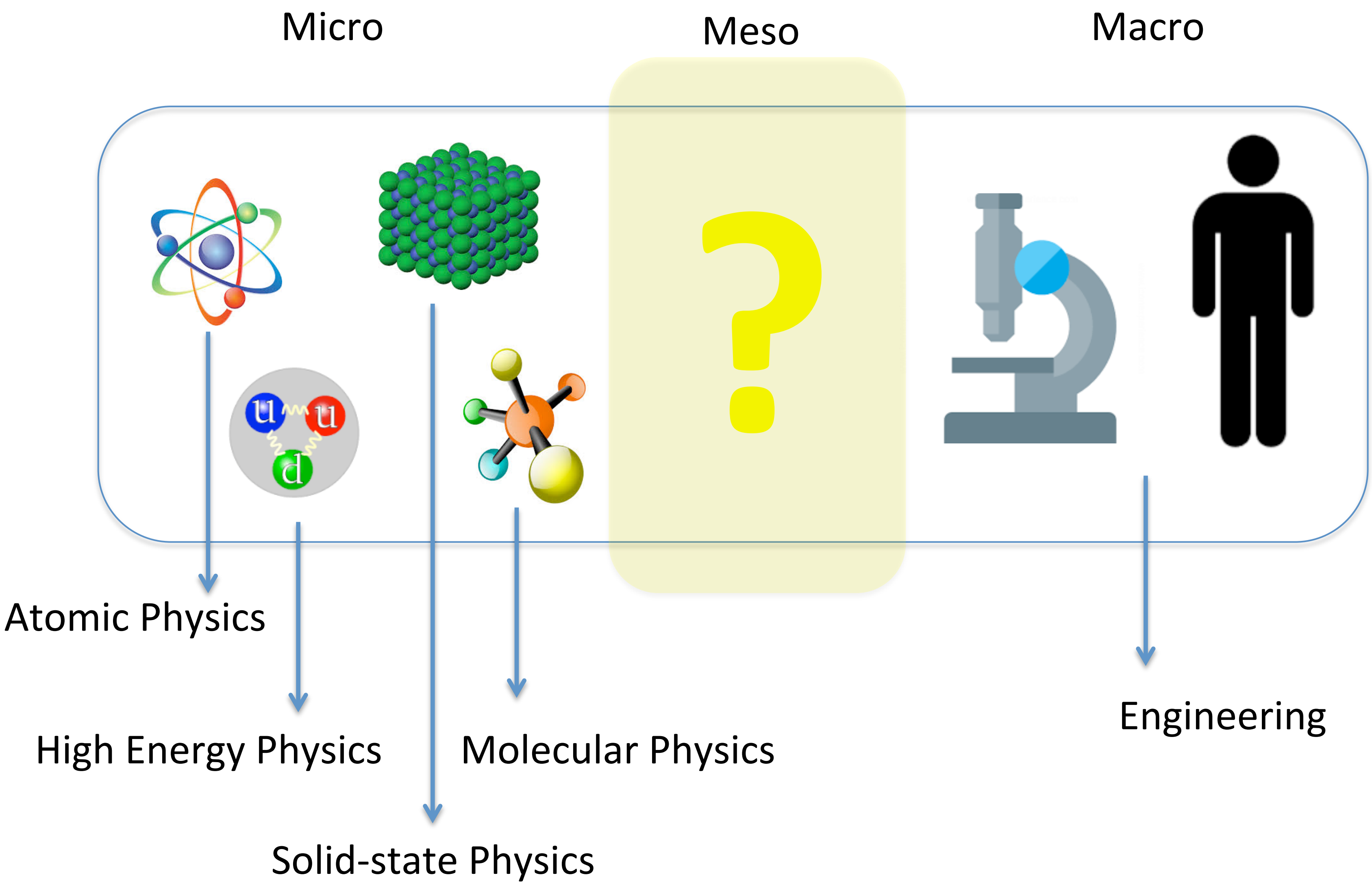
Ways to fix Quantum Mechanics

Quantum world



Bohmian Mechanics
Many Worlds
Information/Relational Interpretations
Collapse models

Experimentalist’s point of view



Collapse models: nonlinear & stochastic modifications of the Schrödinger equation

J.S.Bell
Speakable and Unspeakable in Quantum Mechanics

E.P. Wigner
in: Quantum Optics, Experimental gravity and Measurement theory, Plenum, NY (1983)

A.J. Leggett
Supplement Progr. Theor. Phys. 69, 80 (1980)

H.P. Stapp
In: Quantum Implications: Essay in Honor of David Bohm, Routledge & Kegan Paul, London (1987)

S. Weinberg
Phys. Rev. Lett. 62, 486 (1989).

R. Penrose
In: Quantum Concepts of Space and Time, Oxford U.P. (1985)

S.L. Adler
Quantum Theory as an emergent phenomenon, CUP (2009)

G.C. Ghirardi, A. Rimini, T. Weber
Phys. Rev. D 34, 470 (1986)

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

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

What then must be done about the shortcomings of quantum mechanics? One reasonable response is contained in the legendary advice to inquiring students: “Shut up and calculate!” There is no argument about how to use quantum mechanics, only how to describe what it means, so perhaps the problem is merely one of words. **On the other hand, the problems of understanding measurement in the present form of quantum mechanics may be warning us that the theory needs modifications** (Weinberg)

How to modify the Schrödinger equation?

The **no-faster-than-light condition** heavily constraints the possible ways to modify the Schrödinger equation.

In particular, it requires that **nonlinear terms** must always be accompanied by appropriate **stochastic terms.**

N. Gisin, *Hel. Phys. Acta* 62, 363 (1989). *Phys. Lett. A* 143, 1 (1990)

N. Gisin and M. Rigo, *Journ. Phys. A* 28, 7375 (1995)

J. Polcinski, *Phys. Rev. Lett*. 66, 397 (1991)

H.M. Wiseman and L. Diosi, *Chem. Phys.* 268, 91 (2001)

S.L. Adler, “Quantum Theory as an Emergent Phenomenon”, C.U.P. (2004)

A. Bassi, D. Dürr and G. Hinrichs, *Phys. Rev. Lett.* 111, 210401 (2013).

L. Diosi, *Phys. Rev. Lett.* 112, 108901 (2014)

M. Caiaffa, A. Smirne and A. Bassi, arXiv:1612.04546, Phys. Rev. A (2017, to appear)

Diffusion Process in Hilbert Space

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

$$d\psi_t \;=\; \left[-\frac{i}{\hbar}\hat{H}dt + \sqrt{\lambda}(\hat{q} - \langle\hat{q}\rangle_t)dW_t - \frac{\lambda}{2}(\hat{q} - \langle\hat{q}\rangle_t)^2 dt\right]\psi_t$$

$$\langle\hat{q}\rangle_t = \langle\psi_t|\hat{q}|\psi_t\rangle$$

nonlinearity

$$W_t \;=\; \text{standard Wiener process}$$

stochasticity

All of quantum (and classical) mechanics follows

A. Bassi, D.G.M. Salvetti, "The quantum theory of measurement within dynamical reduction models" J. Phys. A. 40, 9859 (2007)

(Mass-proportional) CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

$$\boxed{\begin{aligned}\frac{d}{dt}|\psi_t\rangle = \Bigg[&-\frac{i}{\hbar}H + \frac{\sqrt{\gamma}}{m_0}\int d^3x\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,dW_t(\mathbf{x}) \\ &-\frac{\gamma}{2m_0^2}\int\int d^3x d^3y\, G(\mathbf{x}-\mathbf{y})\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,(M(\mathbf{y}) - \langle M(\mathbf{y})\rangle_t)\Bigg]|\psi_t\rangle\end{aligned}}$$

$$M(\mathbf{x}) = m a^\dagger(\mathbf{x})a(\mathbf{x}) \qquad\qquad G(\mathbf{x}) = \frac{1}{(4\pi r_C)^{3/2}}\,\exp[-(\mathbf{x})^2/4r_C^2]$$

The operators are function of the space coordinate. **The collapse occurs in space.**

Two parameters $\gamma = \text{collapse strength} \qquad r_C = \text{localization resolution}$

$$\lambda = \gamma/(4\pi r_C^2)^{3/2} = \text{collapse rate}$$

REVIEW: A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003)

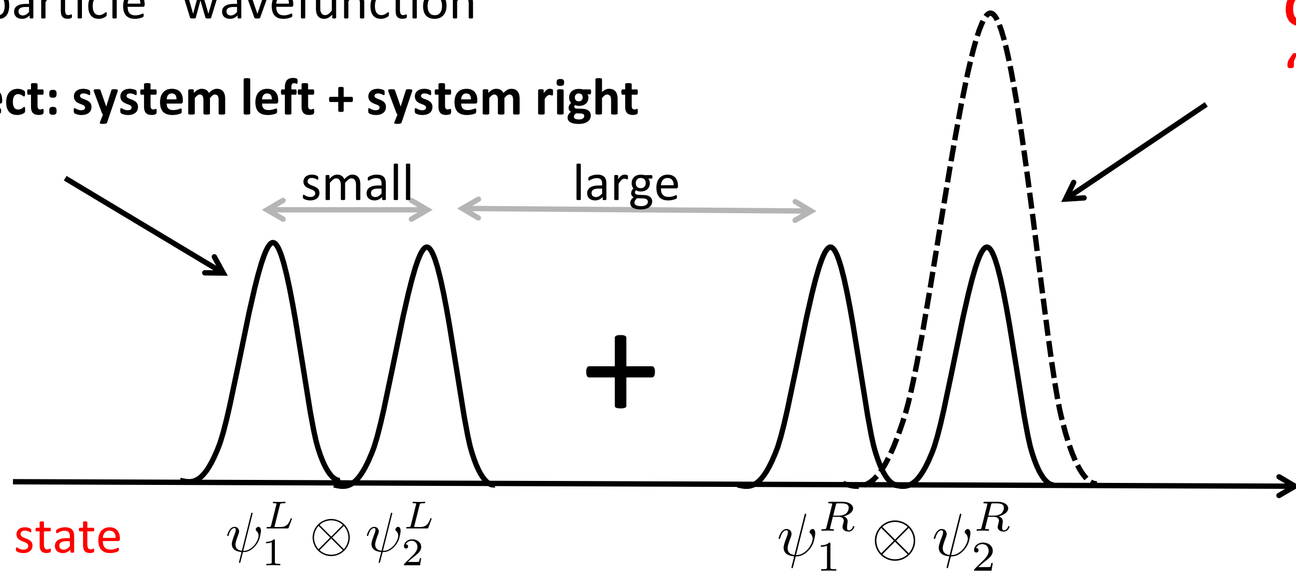
A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht, *Rev. Mod. Phys.* 85, 471 (2013)

Amplification mechanism

Initial “2-particle” wavefunction

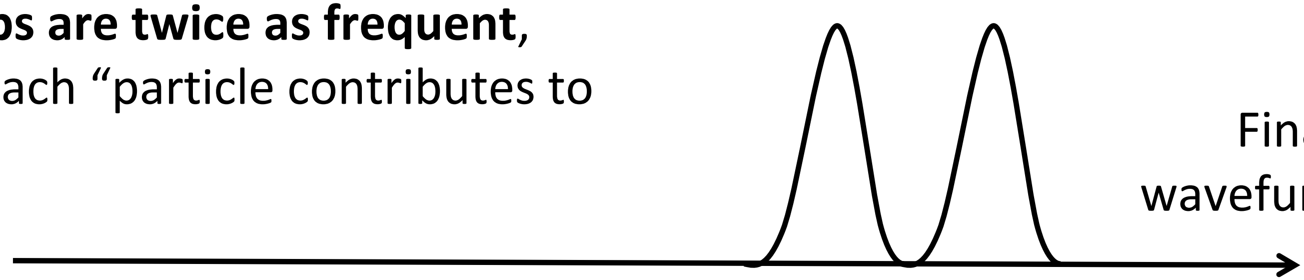
Rigid object: system left + system right

Collapse on “particle” 2



Entangled state

Such **jumps are twice as frequent**, because each “particle contributes to them



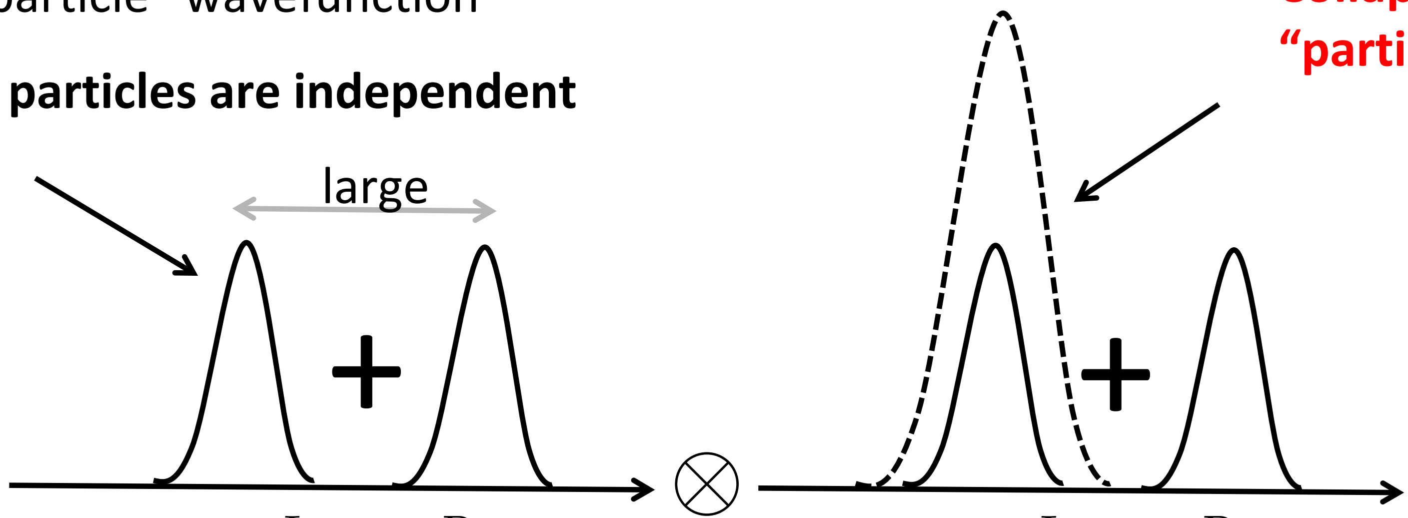
Final wavefunction

However

Initial “2-particle” wavefunction

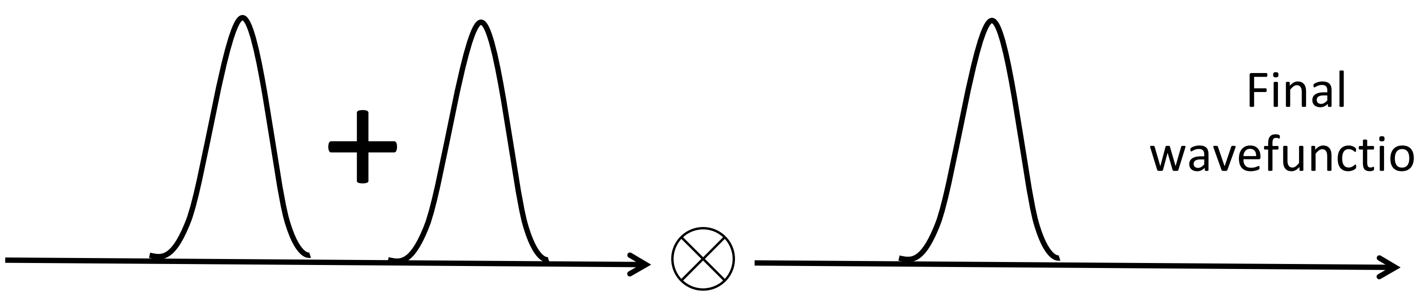
Ideal gas: particles are independent

Collapse on “particle” 2



Factorized state $\psi_1^L + \psi_1^R$ $\qquad \psi_2^L + \psi_2^R$

The jump on one particle did not affect the state of the other particle!



Final wavefunction

Choice of the parameters (GRW)

$$\boldsymbol{\lambda = 10^{-16}\ s^{-1}}$$

For single isolated particles jumps almost never occur. However, for macroscopic objects

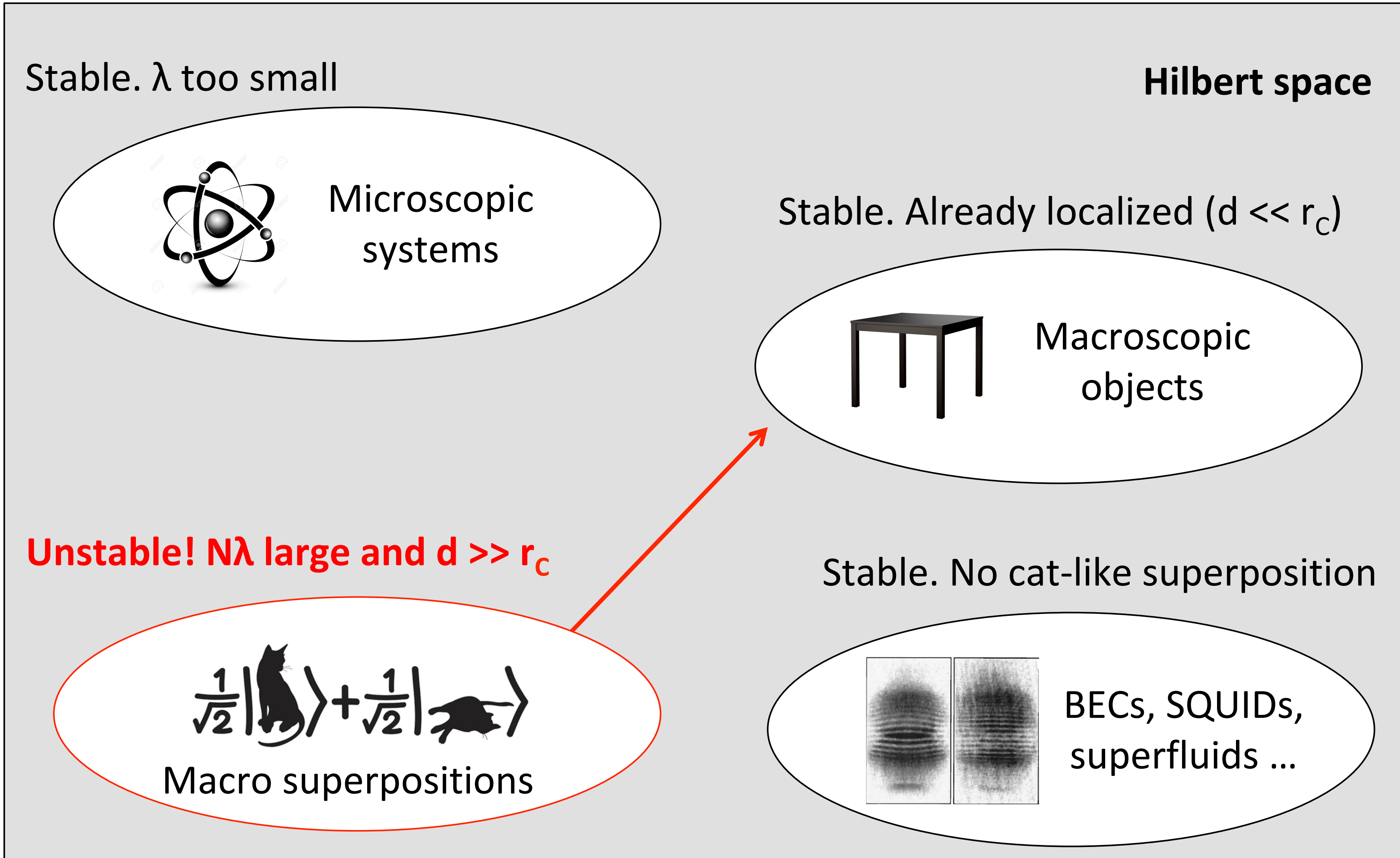
$N\ \lambda = 10^{24} \times 10^{-16}\ s^{-1} = 10^{8}\ s^{-1}$

Macro-objects are almost instantly localised

$$\boldsymbol{r_C = 10^{-7}\ m}$$

Mesoscopic distance. Microscopic superpositions are not affected. Macroscopic superpositions are.

The overall picture



Experiments

Interferometric Experiments

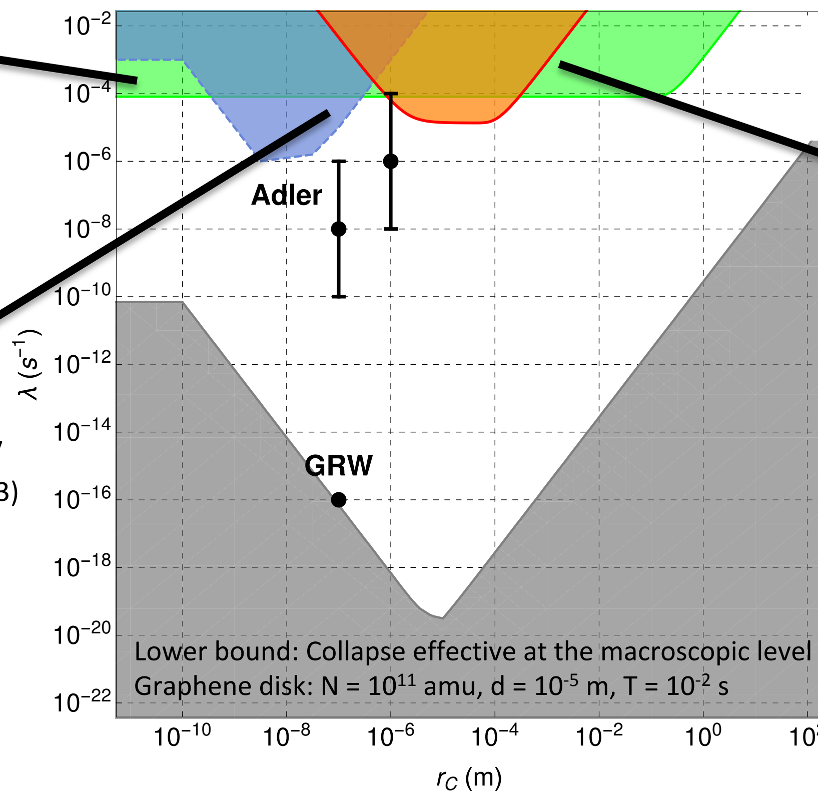
Atom Interferometry

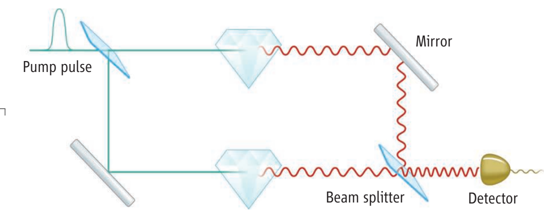
T. Kovachy *et al.*, Nature <u>528</u>, 530 (2015)

M = 87 amu

d = 0.54 m

T = 1 s





Entangling Diamonds

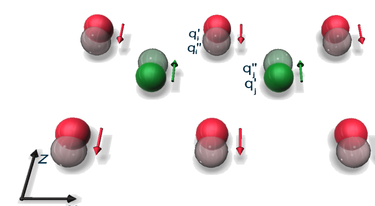
K. C. Lee *et al.*, Science. <u>334</u>, 1253 (2011).

S. Belli *et al.*, PRA 94, 012108 (2016)

M = 10^{16} amu

d = 10^{-11} m

T = 10^{-12} s



Molecular Interferometry

S. Eibenberger *et al.* PCCP <u>15</u>, 14696 (2013)

M. Toros *et al.*, ArXiv 1601.03672

M = 10^4 amu

d = 10^{-7} m

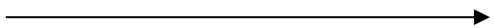
T = 10^{-3} s

To improve interferometric tests, it will likely be necessary to go to micro-gravity environment in outer space. COST Action QTSpace (www.qtspace.eu)

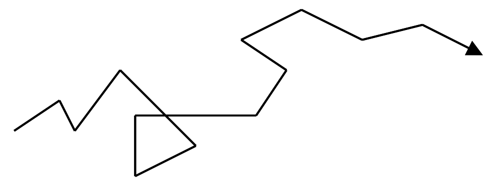
Non-interferometric tests

Center of mass motion of a quantum system (either simple or complex)

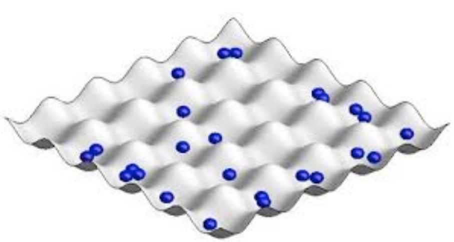
Quantum Mechanics



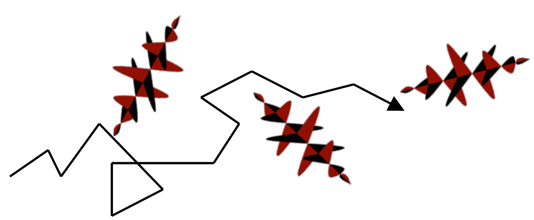
Collapse models



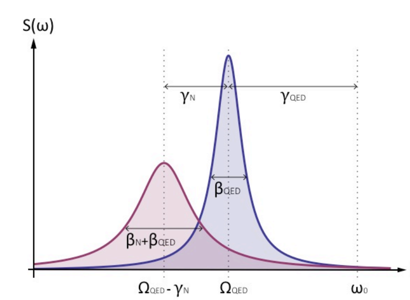
A **gas** will **expand** (heat up) faster than what predicted by QM



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



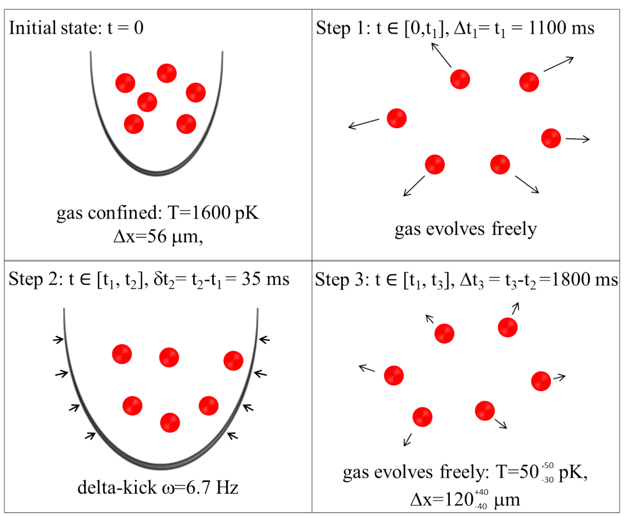
A **cantilever**'s motion cannot be **cooled down** below a given limit

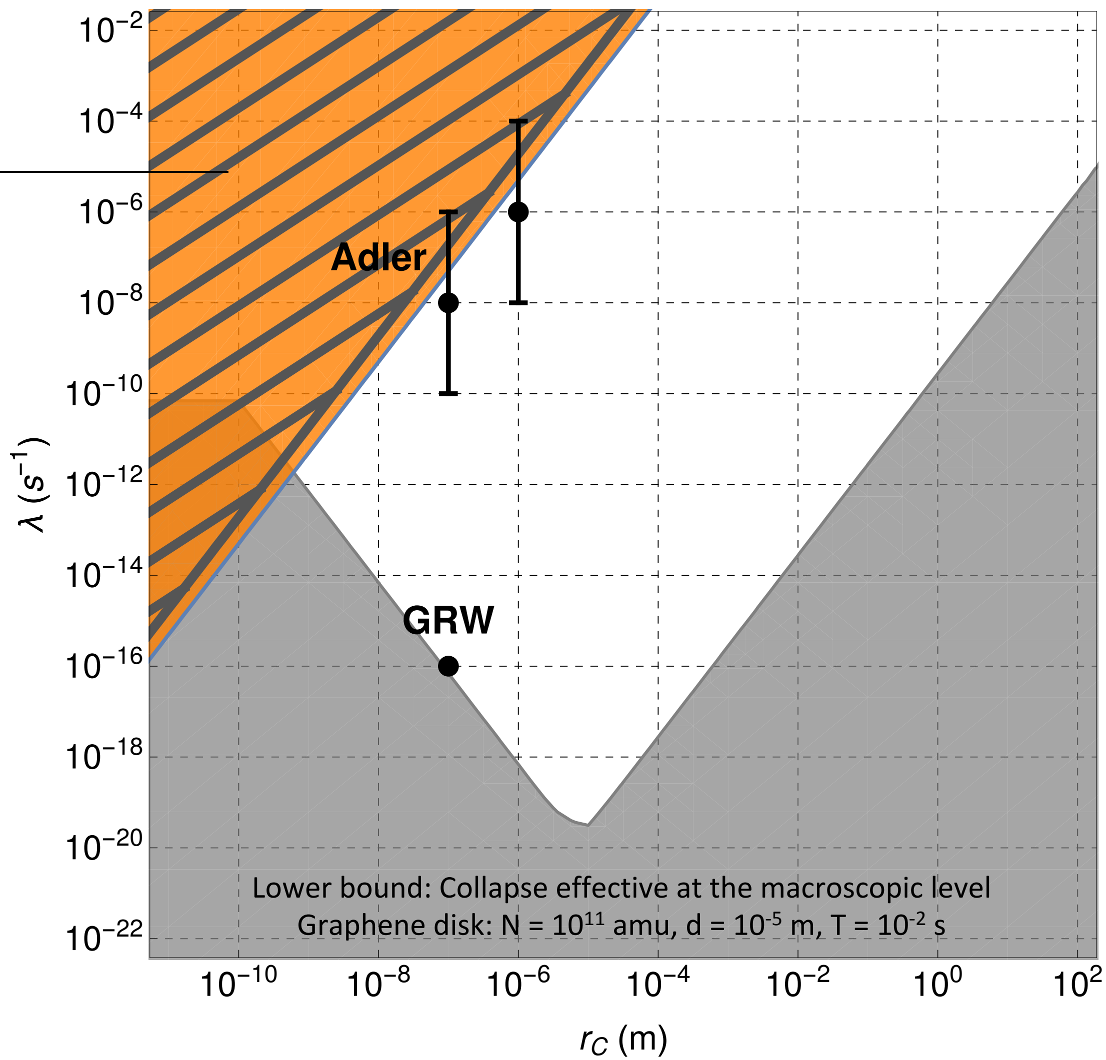


Non - Interferometric Experiments

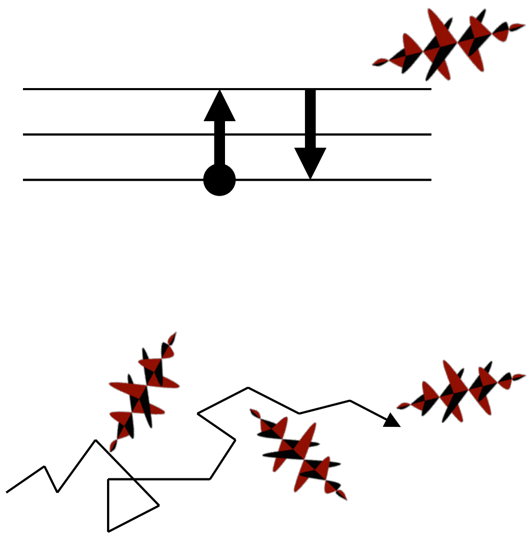
Cold atom gas

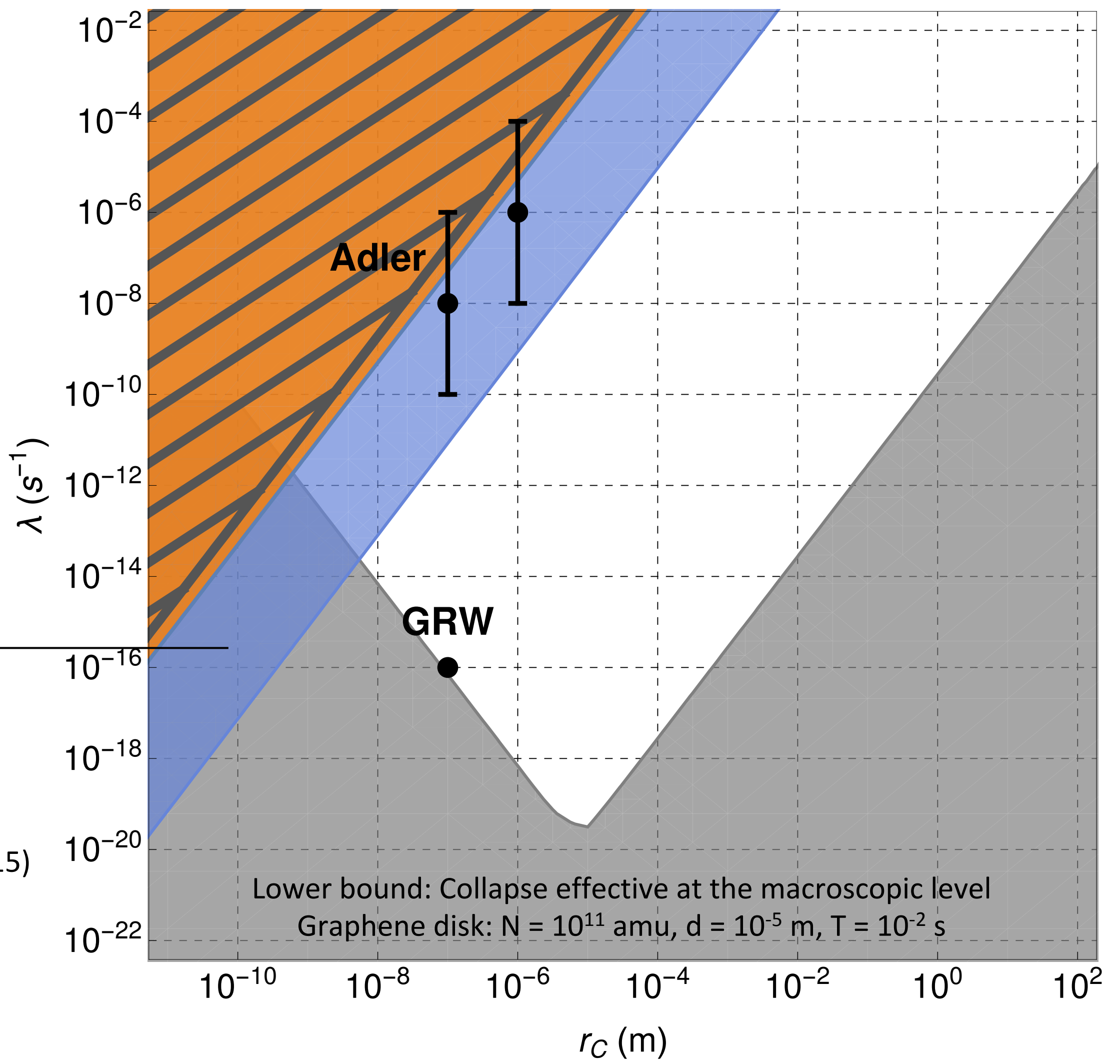
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.*, Physica A 462, 764 (2016)





Non - Interferometric Experiments

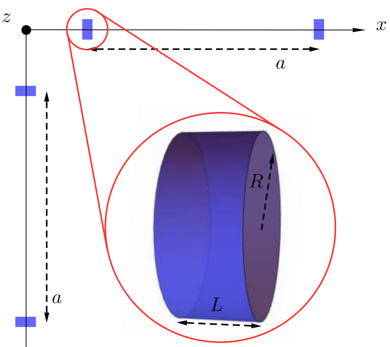




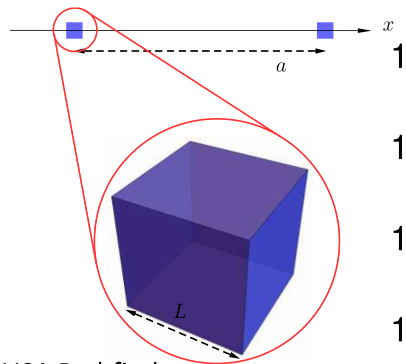
X rays

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

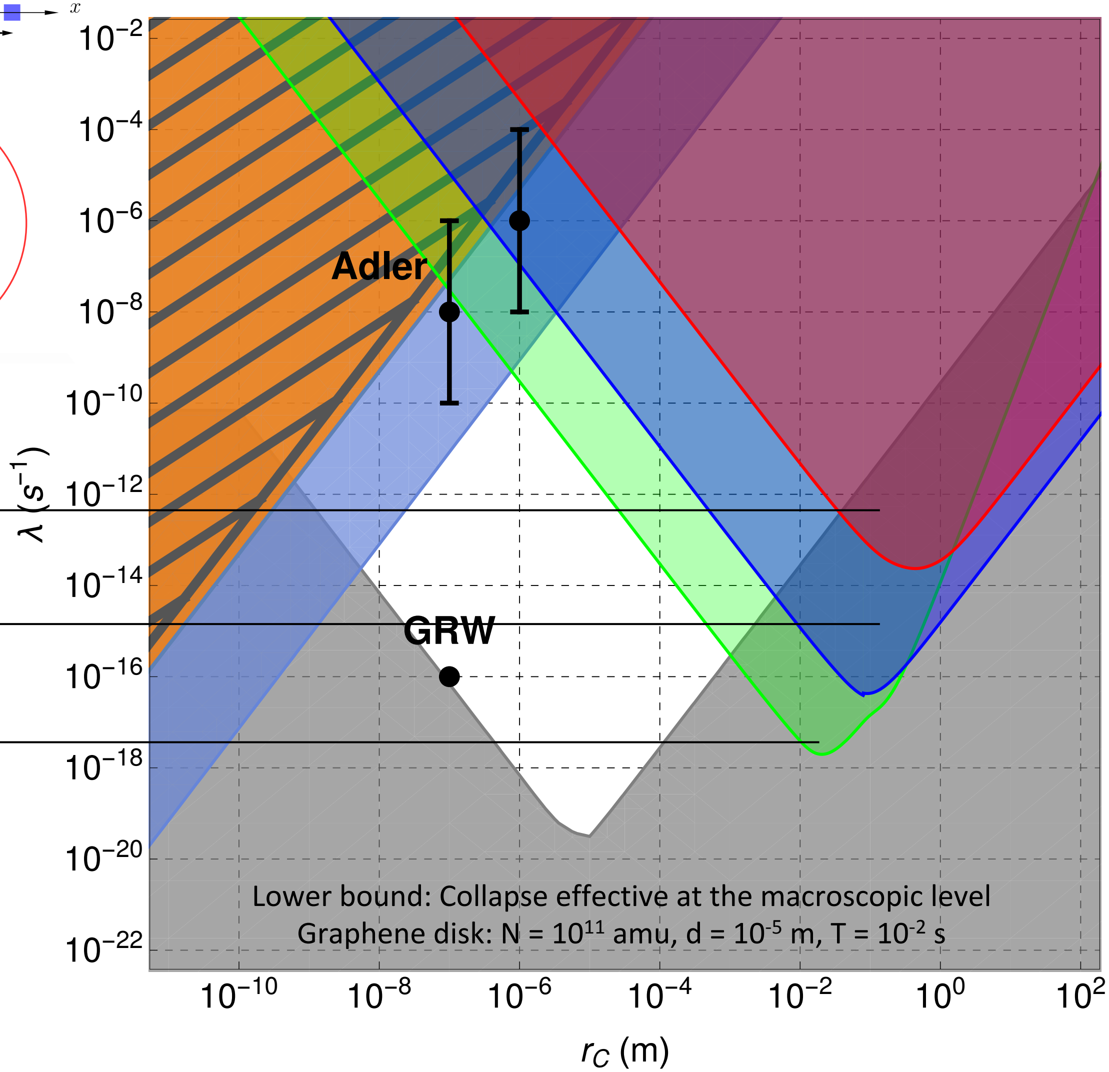
Non - Interferometric Experiments



LIGO



LISA Pathfinder

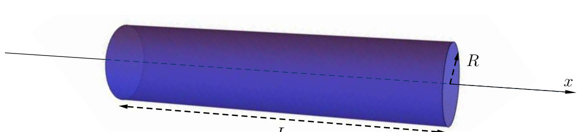


Auriga

Ligo

Lisa Pathfinder

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

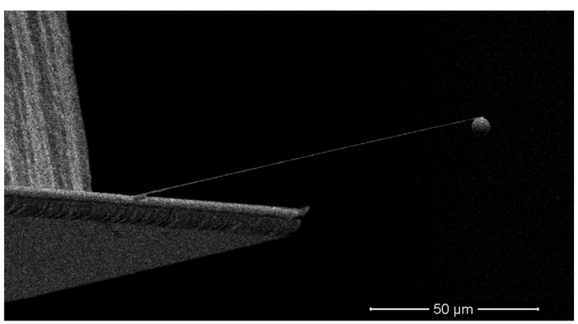


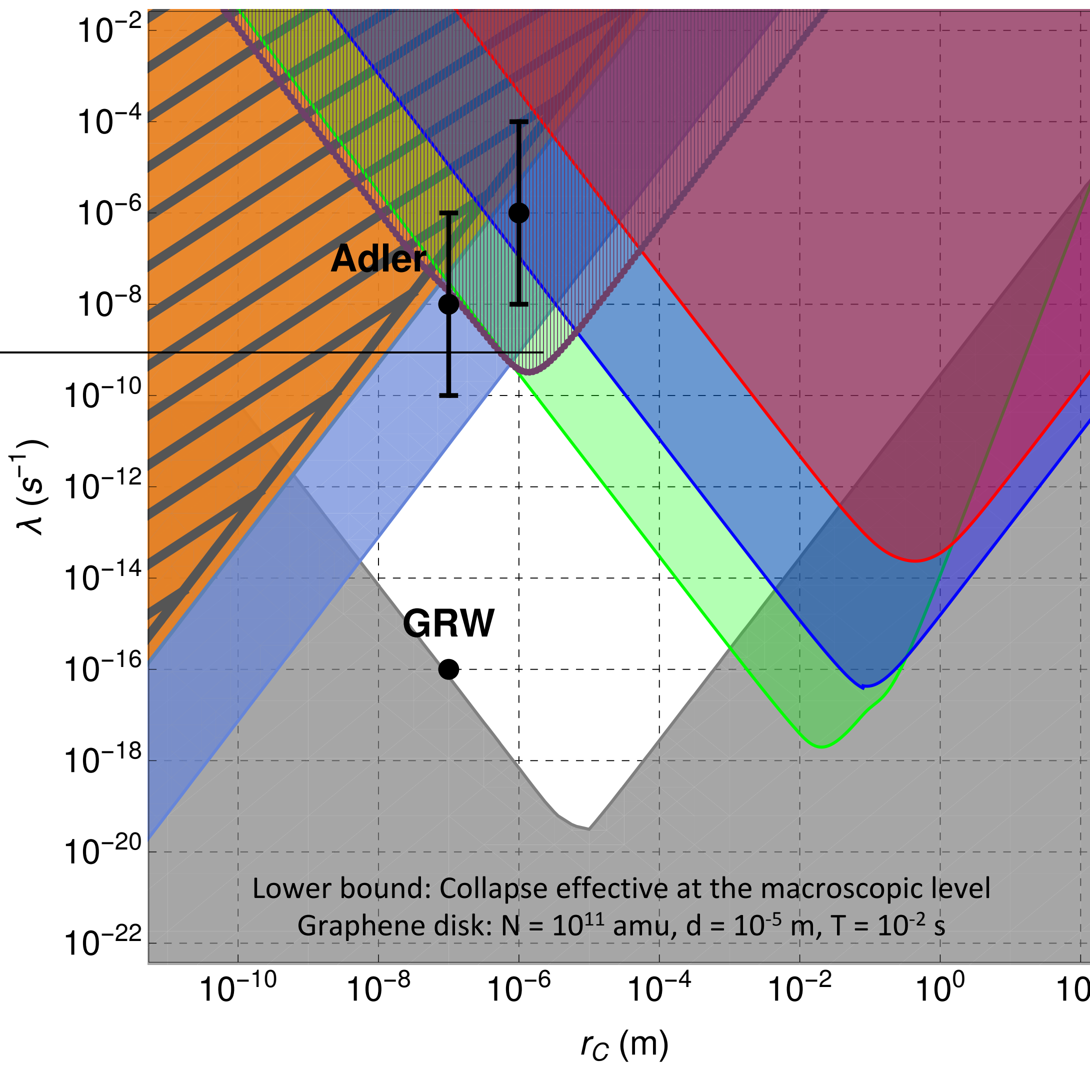
Auriga

Non - Interferometric Experiments

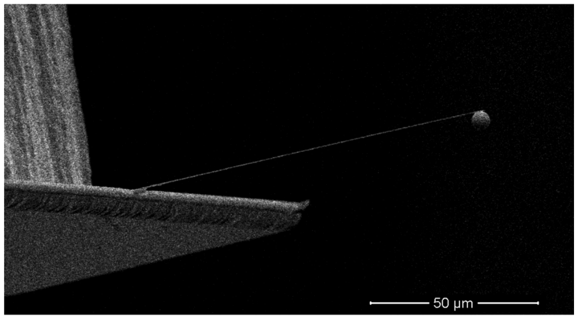
Cantilever

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





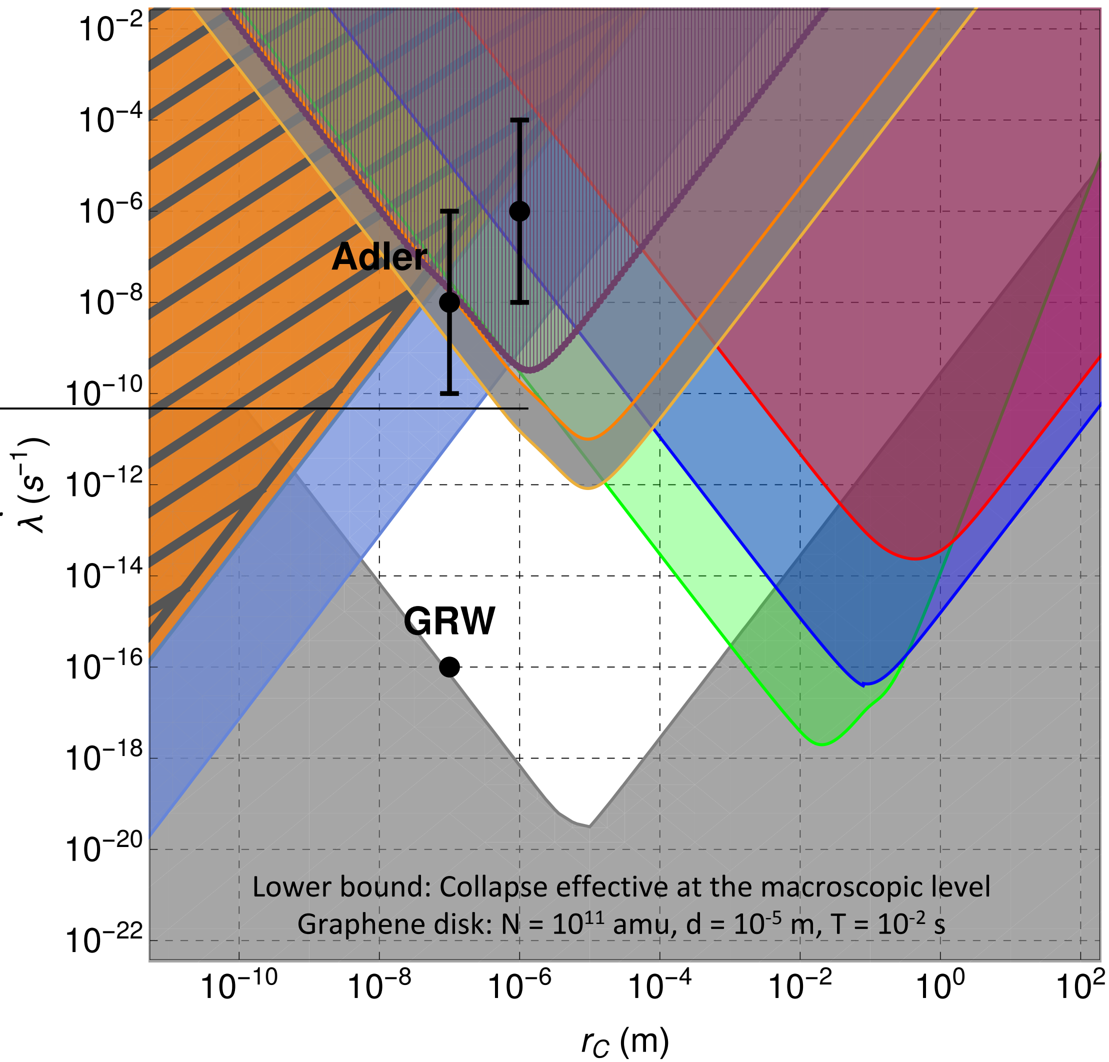
Non - Interferometric Experiments



Cantilever - update

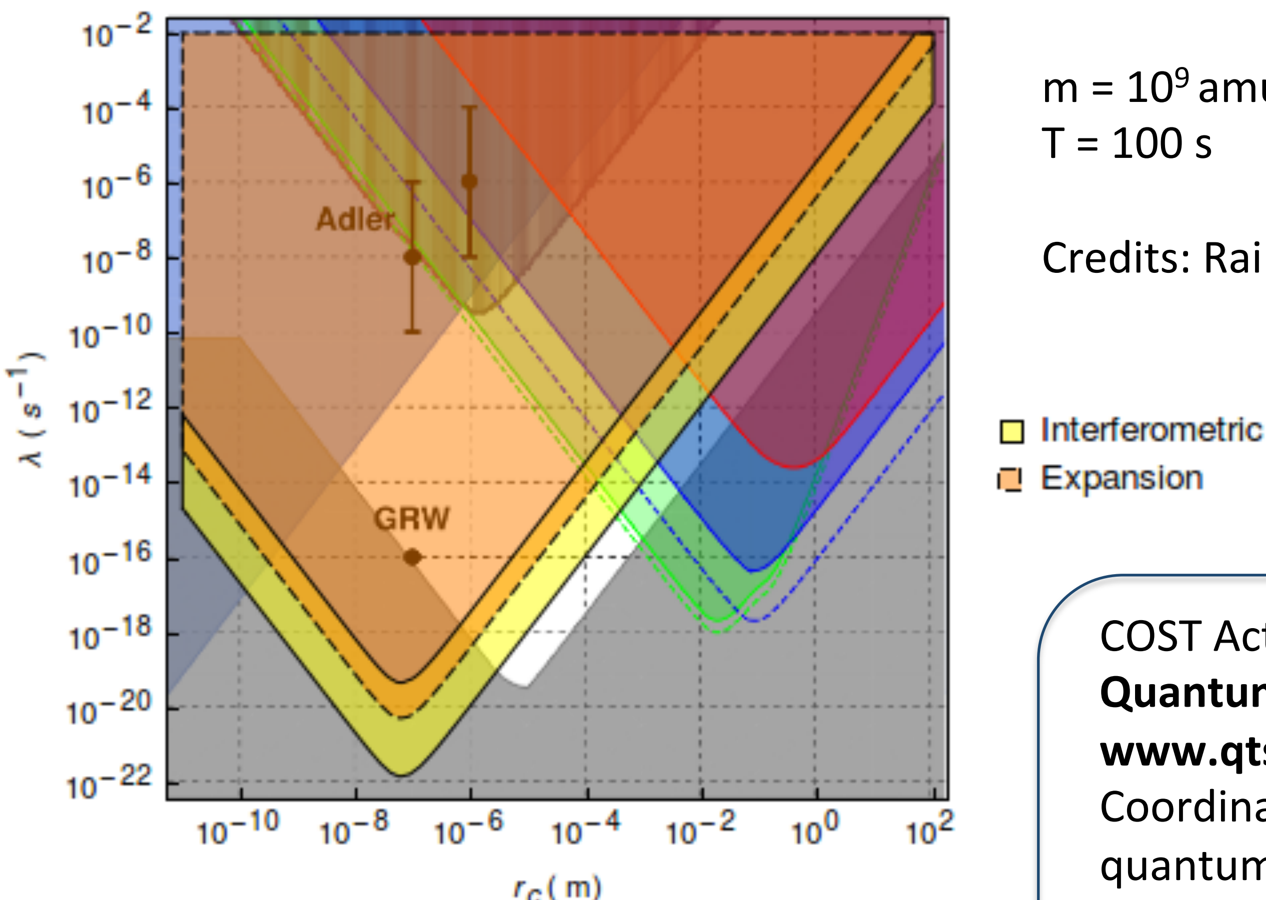
A. Vinante *et al., Phys. Rev. Lett. 119, 110401 (2017).*

"Here we report on a improved version of the cantilever experiment […] Unlike the previous cantilever experiment, we find evidence of a nonthermal excess noise of unknown origin. If interpreted as CSL-induced noise, this would be compatible with previous experimental bounds and in agreement with the collapse rate predicted by Adler"



New EU H2020
FET project "TEQ"

MAQRO
Macroscopic Quantum Resonator



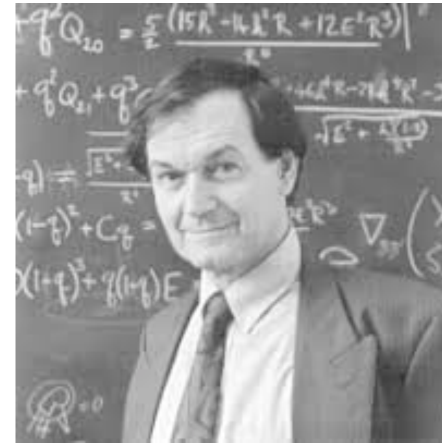
$m = 10^9$ amu
$T = 100$ s

Credits: Rainer Kaltenbaek (Uni. Vienna)

COST Action
Quantum Technologies in Space
www.qtspace.eu
Coordinate research activity for
quantum experiments in space

Collapse and gravity

It is an attempt to answer the question: why should the wave function collapse?



Fundamental properties of the collapse & the possible role of gravity

- It occurs in space
- It scales with the mass/size of the system

The obvious way to describe it mathematically, is to couple the noise field to the **mass density** (the stress-energy tensor, in a relativistic framework).

Gravity naturally provides such a coupling.

Moreover

The possibility is open for **gravity not to be quantum**, thus possibly providing the nonstandard (anti-hermitian, nonlinear) coupling necessary for the collapse.

REVIEW ARTICLE: A. Bassi, A. Grossardt and H. Ulbricht, "Gravitational Decoherence", Class. Quantum Grav. 34, 193002 (2017). ArXiv1706.05677

The Diosi – Penrose model

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

$$
\begin{aligned}
d|\psi_t\rangle \quad = \quad & \Big[-\frac{i}{\hbar}H dt + \int d^3\mathbf{x}\,(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t) dW_t(\mathbf{x}) \\
& - \frac{1}{2}\int d^3\mathbf{x} d^3\mathbf{y}\, G(\mathbf{x}-\mathbf{y})(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t)(\hat{M}(\mathbf{y}) - \langle\hat{M}(\mathbf{y})\rangle_t) dt\Big]\,|\psi_t\rangle
\end{aligned}
$$

with (first-quantization formalism, N-particle system)

$$\hat{M}(\mathbf{x}) = \sum_{j=1}^{N} m_j \delta^{(3)}(\mathbf{x} - \hat{\mathbf{r}}_j) \qquad \hat{\mathbf{r}}_j = \text{position operator of particle } j$$

The noise is Gaussian, with average = 0, and correlation function

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

Gravity. And no other free parameter.

Limitation: Model not derived from basic principles, but assumed phenomenologically.

There is no justification as to why gravity should be responsible for the collapse.

If there is truth in the model, then quantum gravity as we know it is wrong.

Diosi – Penrose model

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

Single-particle master equation (Lindblad type, for collisional decoherence)

$$\frac{d}{dt}\rho_t = -\frac{i}{\hbar}[H,\rho_t] + \mathcal{L}[\rho_t]$$

$$\mathcal{L}[\rho_t] = \int d^3\mathbf{Q}\,\Gamma_{DP}(\mathbf{Q})\left(e^{i\mathbf{Q}\cdot\hat{\mathbf{r}}/\hbar}\rho_t e^{-i\mathbf{Q}\cdot\hat{\mathbf{r}}/\hbar} - \rho_t\right) \qquad \Gamma_{DP}(\mathbf{Q}) = \frac{Gm^2}{2\pi^2\hbar^2}\frac{1}{Q}$$

Then

$$\rho(\mathbf{x},\mathbf{x}',t) = e^{-t/\tau(\mathbf{x},\mathbf{x}')}\rho(\mathbf{x},\mathbf{x}',0)$$

$$\tau(\mathbf{x},\mathbf{x}') = \frac{\hbar}{U(\mathbf{x}-\mathbf{x}') - U(0)} \qquad U(\mathbf{x}) = -G\int d^3\mathbf{r}d^3\mathbf{r}'\,\frac{M(\mathbf{r})M(\mathbf{r}')}{|\mathbf{x}+\mathbf{r}-\mathbf{r}'|}$$

Penrose's idea

It **diverges** for point-like particles

Diosi – Penrose model

R. Penrose, *Gen. Rel. Grav*. 28, 581 - 1996

We have to consider carefully what a 'stationary state' means in a context such as this. In a stationary spacetime, we have a well-defined concept of 'stationary' for a quantum state in that background, because there is a Killing vector T in the spacetime that generates the time-translations. Regarding T as a differential operator (the '∂/∂t' for the spacetime), we simply ask for the quantum states that are eigenstates of T, and these will be the stationary states, i.e. states with well-defined energy values. [...] **However, for the superposed state we are considering here we have a serious problem.** For we do not now have a specific spacetime, but a superposition of two slightly differing spacetimes. How are we to regard such a 'superposition of spacetimes'? Is there an operator that we can use to describe 'time-translation' in such a superposed spacetime? Such an operator would be needed so that we can identify the 'stationary states' as its eigenvectors, these being the states with definite energy. It will be shown that there is a fundamental difficulty with these concepts, and that the notion of time-translation operator is essentially ill defined [...]

Penrose's idea: quantum superposition ➔ spacetime superposition ➔ energy uncertainty ➔ decay in time

Putting his reasoning into equations, Penrose come out with basically the same equations as Diosi's

Diosi – Penrose model

The model needs to be regularized (particles with finite size)

Diosi's proposal (*PRA* 40, 1165 - 1989)

$$\hat{M}(\mathbf{x}) = m\delta^{(3)}(\mathbf{x} - \hat{\mathbf{r}}) \quad \longrightarrow \quad \hat{M}(\mathbf{x})' = \frac{3}{4\pi R_0^3} \int d^3\mathbf{y}\,\theta(R_0 - |\mathbf{x} - \mathbf{y}|)\hat{M}(\mathbf{y})$$

Ghirardi, Grassi & Rimini's proposal (*PRA* 42, 1057 - 1990)

$$\hat{M}(\mathbf{x}) = m\delta^{(3)}(\mathbf{x} - \hat{\mathbf{r}}) \quad \longrightarrow \quad \hat{M}(\mathbf{x})' = \frac{1}{\sqrt{(2\pi R_0^3)^3}} \int d^3\mathbf{y}\, e^{-|\mathbf{x}-\mathbf{y}|^2/2R_0^2}\hat{M}(\mathbf{y})$$

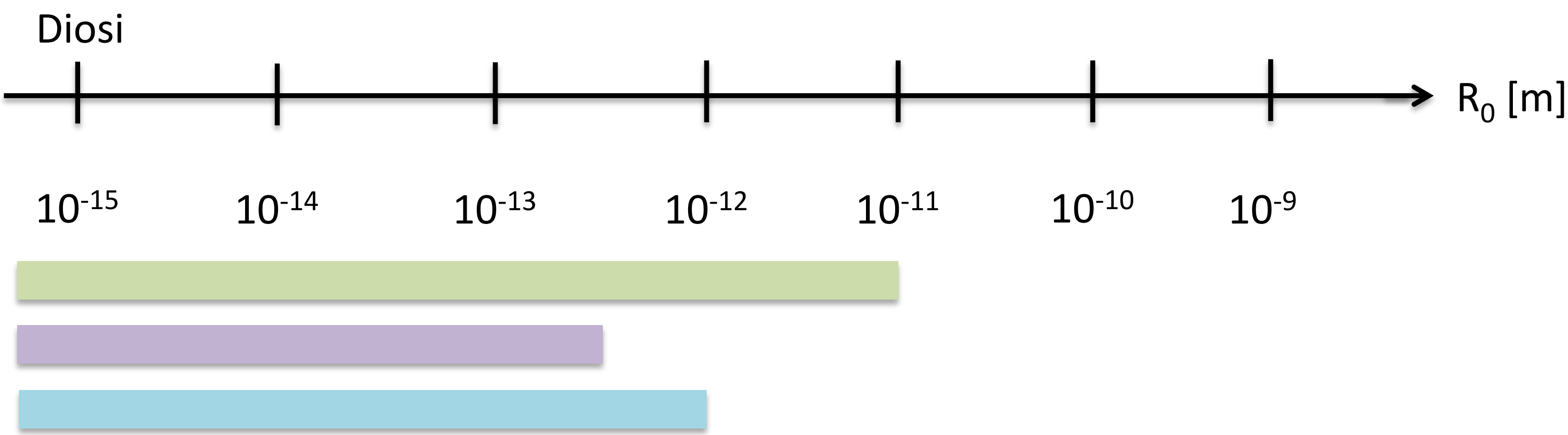
They are practically the same. We continue with the second one. In momentum space, it implies:

$$\Gamma_{DP}(\mathbf{Q}) = \frac{Gm^2}{2\pi^2\hbar^2}\frac{1}{Q} \quad \longrightarrow \quad \Gamma'_{DP}(\mathbf{Q}) = \Gamma_{DP}(\mathbf{Q})e^{-Q^2R_0^2/\hbar^2}$$

which amounts to a cut off on high momenta

Constraints on the cutoff

S. Donadi and A. Bassi, in preparation (2017)



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

Cold atoms [T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)]

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

Adler's idea

S. Adler, in Quantum Nonlocality and Reality: 50 Years of Bell's Theorem. Cambridge University Press (2016)

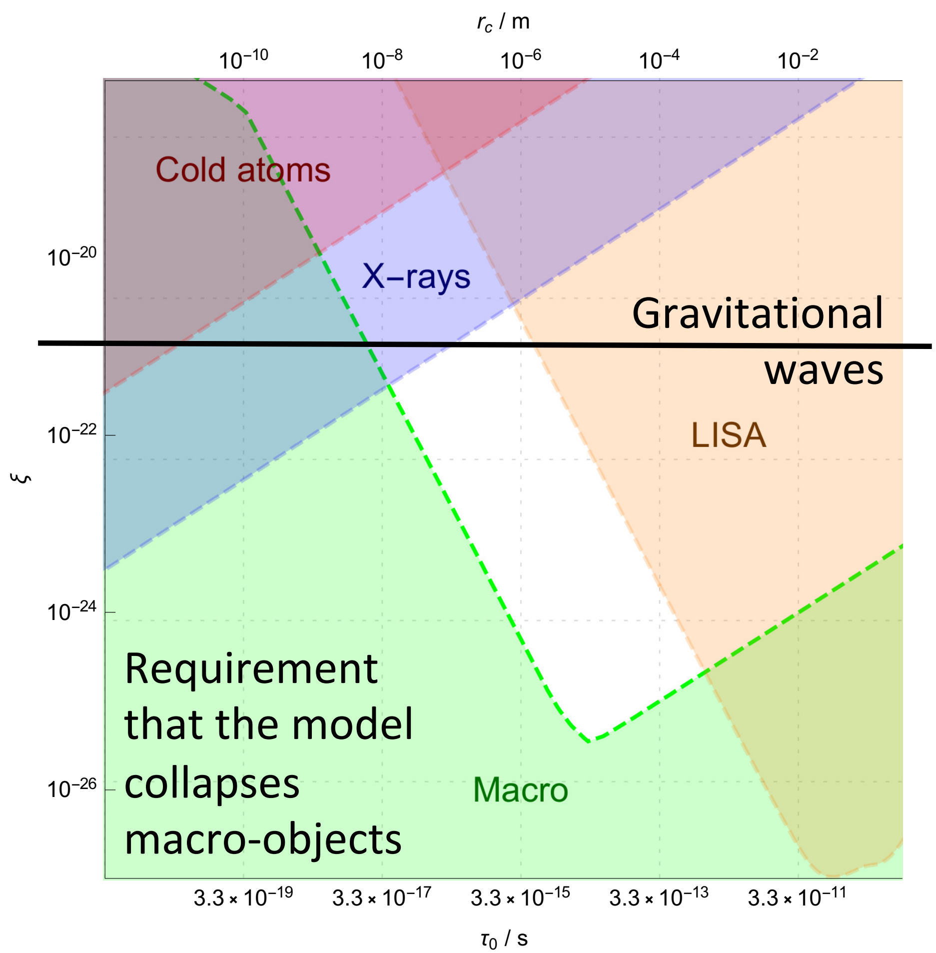
G. Gasbarri, M. Toros, S. Donadi & A. Bassi, Phys. Rev. D 96, 104013 (2017)

Motivation: the metric has **an irreducibly complex, rapidly fluctuating, component**, besides the usual real one. This component is responsible for the collapse. The correlation function of the noise is left unknown. This means that gravity is not quantum − Adler provides motivations for that.

The models has been **developed** (formal equation − rather messy − amplification mechanism, collapse properties) by Gasbarri et al. Everything works well.

Picture: bounds on the magnitude ξ of the complex fluctuations.

it is interesting to see that **weak complex fluctuations** − weaker than real waves recently measured by LIGO (10^{-21}) - are sufficient for an efficient collapse



The Schrödinger-Newton equation

$$i\hbar\frac{d}{dt}\psi(\mathbf{x},t)=\left(-\frac{\hbar^2}{2m}\nabla^2-Gm^2\int d^3y\frac{|\psi(\mathbf{y},t)|^2}{|\mathbf{x}-\mathbf{y}|}\right)\psi(\mathbf{x},t)$$

L. Diósi. Phys. Lett. A 105, 199 (1984).
R. Penrose, Gen. Relat. Gravit. 28, 581 (1996).
D. Giulini and A. Grossardt, *Class. Quantum Grav.* 29, 215010 (2012)

quantum spread

gravitational collapse

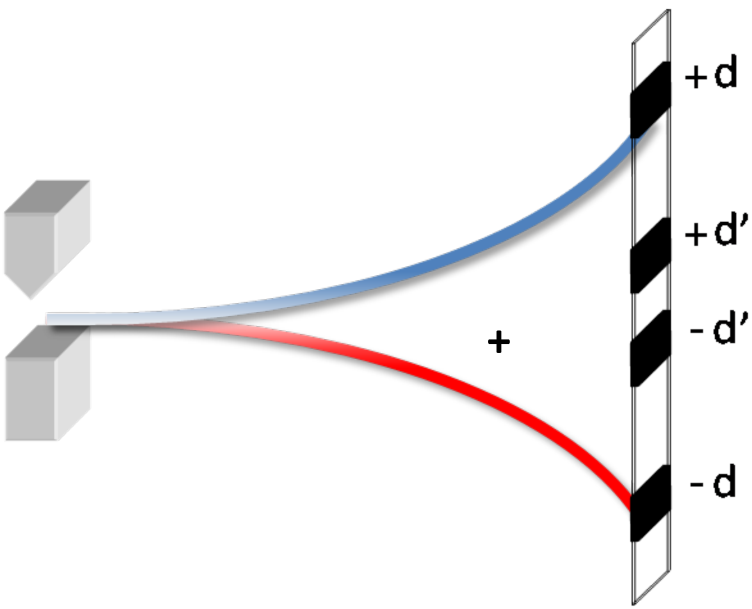
It comes from semi-classical gravity if taken **as a fundamental theory** = matter is fundamentally quantum and gravity is fundamentally classical, and they couple as follows

$$G_{\mu\nu}=\frac{8\pi G}{c^4}\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle$$

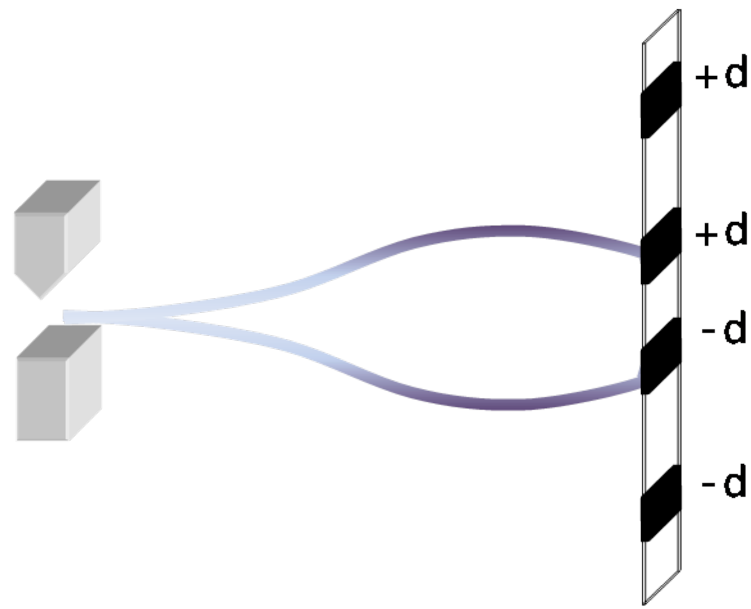
The term on the right is nonlinear in the wave function

Wrong collapse

It **collapses** the wave function, but **not** as prescribed by the Born rule



Double slit experiment according to standard QM



Double slit experiment according to the Schrödinger-Newton equation

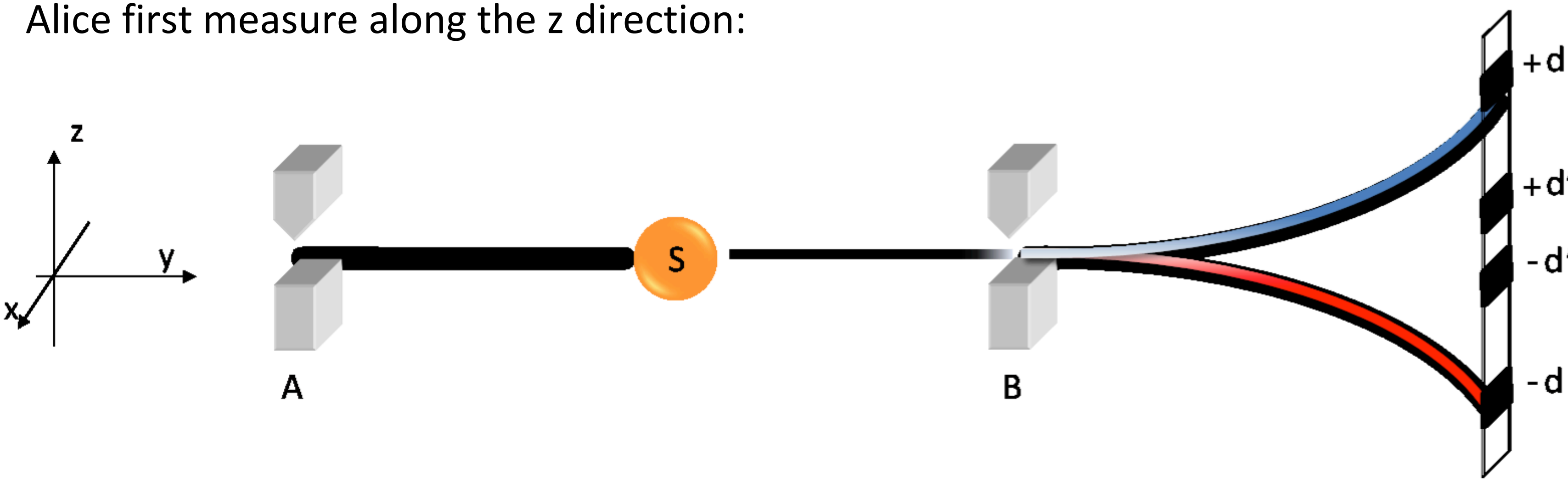
But there are smarter ways of testing the equation

H. Yang, H. Miao, D.-S. Lee, B. Helou, Y. Chen*, Phis. Rev. Lett.* 110, 170401 (2013)
A. Großardt, J. Bateman, H. Ulbricht, A. Bassi, *Phys. Rev. D* 93, 096003 (2016)

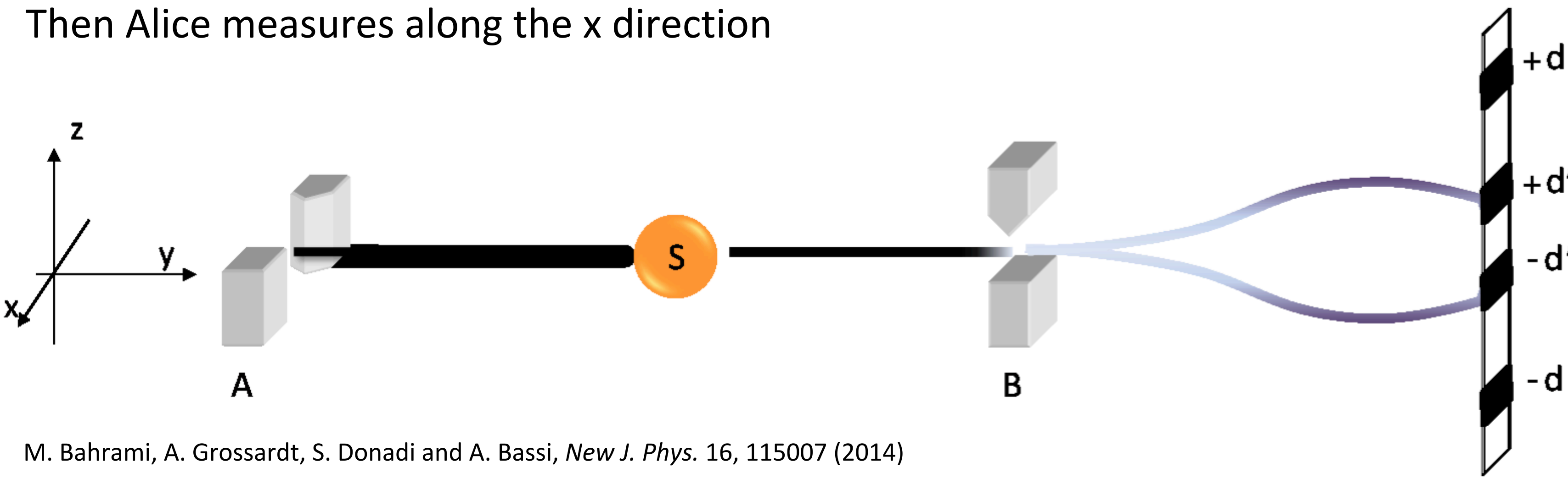
It does faster-than-light

Consider the usual “Alice & Bob sharing an entangled spin state” scenario.

Alice first measure along the z direction:



Then Alice measures along the x direction



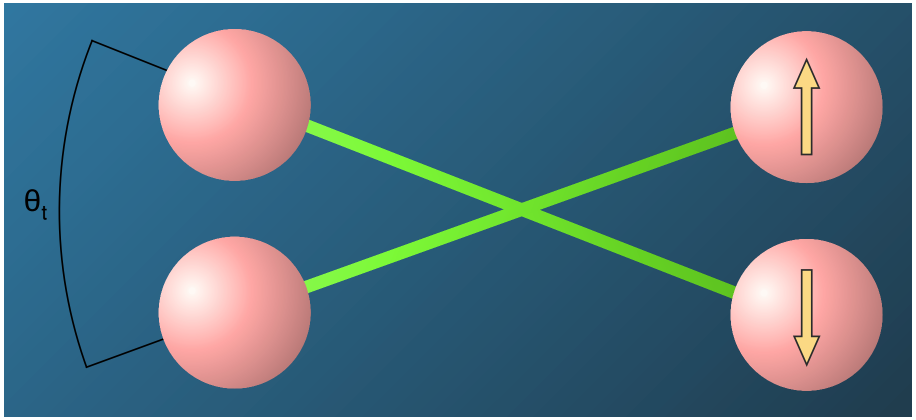
M. Bahrami, A. Grossardt, S. Donadi and A. Bassi, *New J. Phys.* 16, 115007 (2014)

Is gravity quantum?

M. Carlesso, M. Paternostro, H. Ulbricht and A. Bassi, “When Cavendish meets Feynman: A quantum torsion balance for testing the quantumness of gravity” ArXiv:1710.08695 (2017)

BACKGROUND: Are quantum gravity effects testable in the lab?

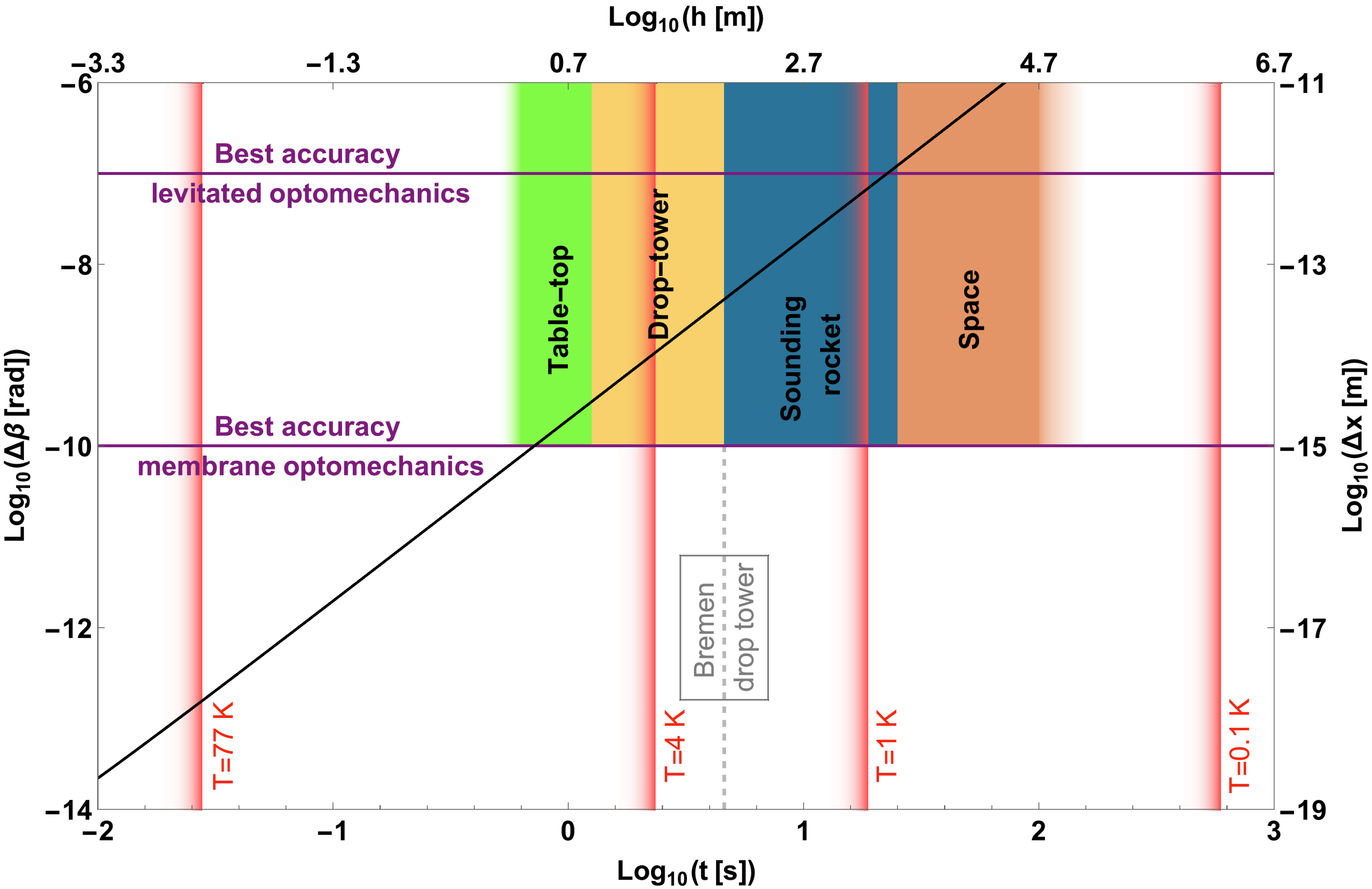
IDEA: Create a macroscopic (angular) superposition. If gravity is **quantum**, the superposition will persist. If gravity is **classical**, likely it will be reduced



Protocol

1. Take a nano-rod − with an angular degree of freedom − in lab vacuum
2. Cool its rotational motion close to the ground sate (few phonons)
3. Generate a spin superposition (via microwave π/2-pulse)
4. Transfer the spin superposition to a rotational superposition (via magnetic field)
5. Decouple the spin-angular superposition (spin measurement)
6. Allow for enough free evolution − long enough time (drop tower?)
7. Detect the angular state of the nano-rod

Is gravity quantum?



Feasible with current technology

Collapse and Cosmology

Some open problems in quantum gravity and cosmology

- Black hole information paradox
- Dark energy
- Emergence of classicality during the evolution of the universe

Collapse models offer a possible solution, thanks to the “extended” dynamics

- Black hole information paradox ➔ Non unitarity

  D. Bedingham, S.K. Modak, D. Sudarsky, Phys. Rev. D 94, 045009 (2016)

- Dark energy ➔ Energy non-conservation

  T. Josset, A. Perez, D. Sudarsky Phys. Rev. Lett. 118, 021102 (2017)

- Emergence of classicality during the evolution of the universe ➔ Collapse effect

  J. Martin, V. Vennin, P. Peter, Phys. Rev. D 86, 103524 (2012)

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