# Fundamental Tests of Quantum Mechanics

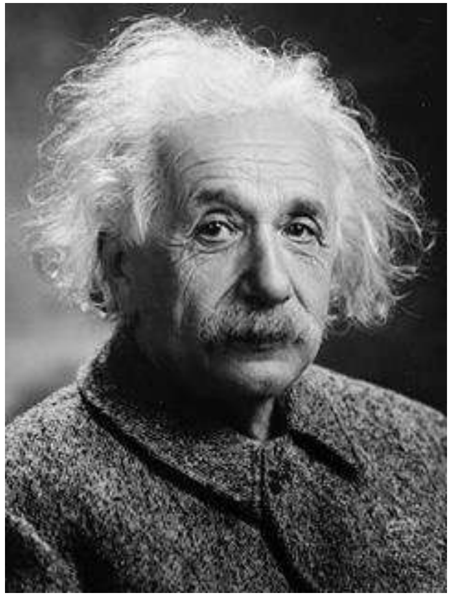
**Perspectives on Quantum Sensing and Computation for Particle Physics**

6 July 2021

Angelo Bassi

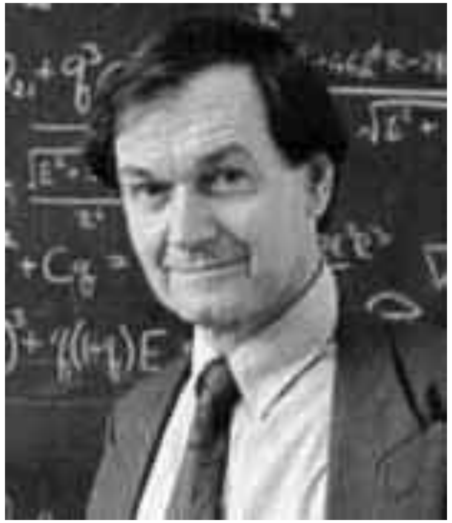
University of Trieste & INFN - Italy

# “The trouble with quantum mechanics”



*Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing.*
**Albert Einstein**

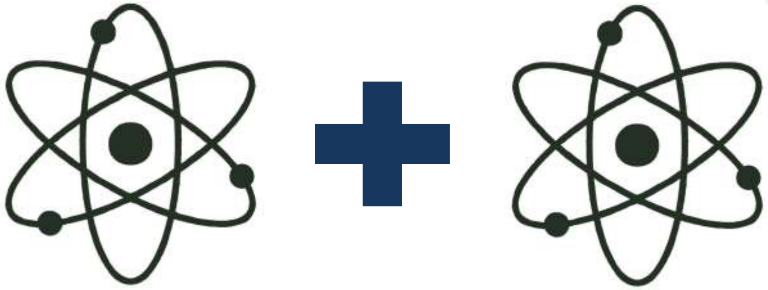
*I’m not as sure as I once was about the future of quantum mechanics.*
**Steven Weinberg**



I believe that one must strongly consider the possibility that quantum mechanics is simply wrong when applied to macroscopic bodies
**Roger Penrose**

*If you push quantum mechanics hard enough it will break down and something else will take over – something we can’t envisage at the moment.*
**Anthony J. Leggett**

# Quantum superpositions



Microscopic superpositions

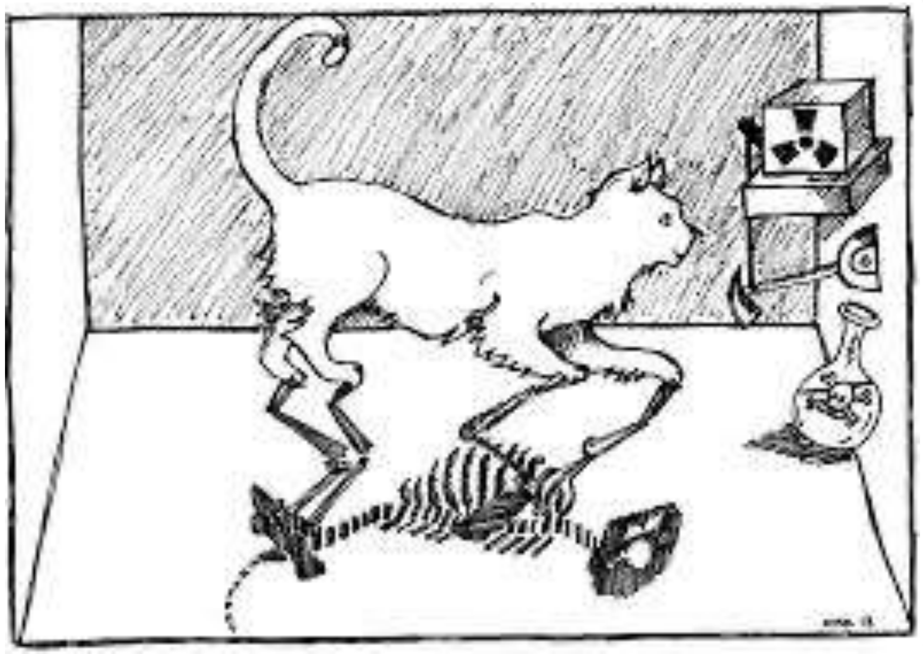
Experimentally verified

Cats are made of atoms + linearity of the theory

Macroscopic

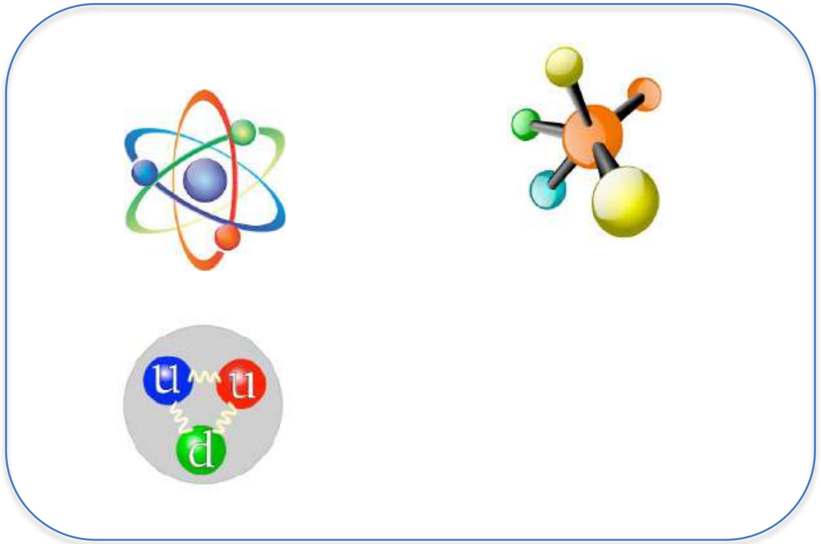
superpositions

Never seen



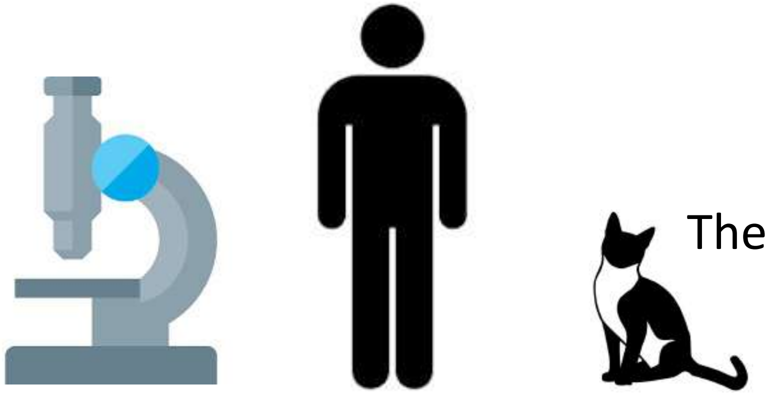
# Standard Quantum Mechanics

Quantum world



Quantum - Classical divide

Classical world




The wave function gives the probabilities of outcomes of measurements

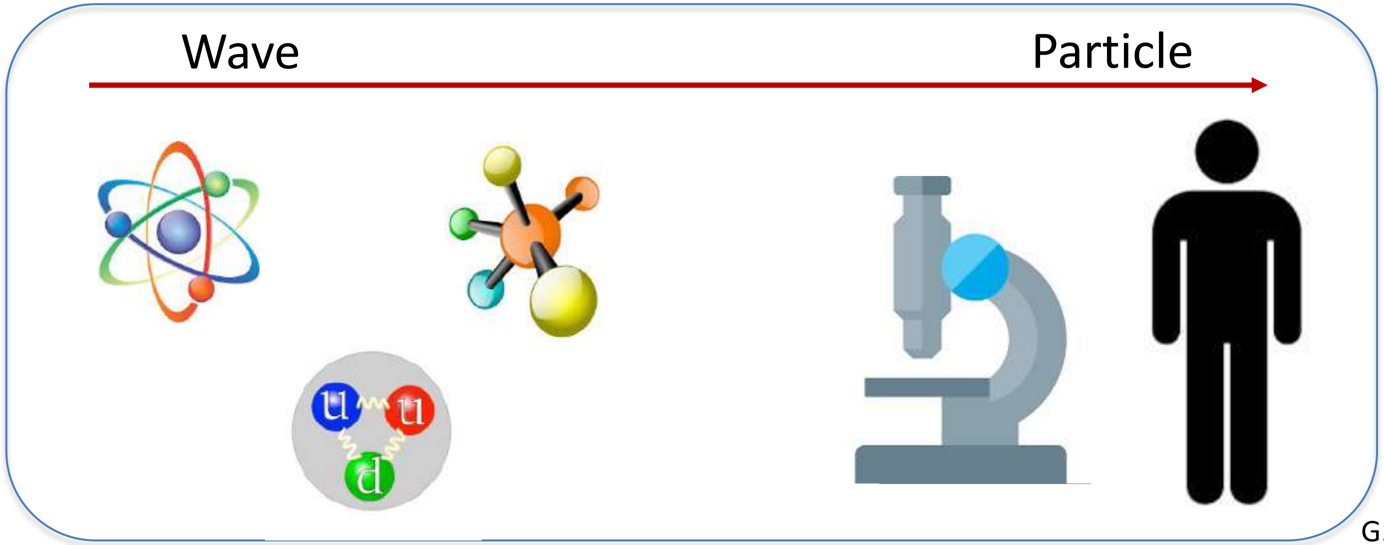
The Copenhagen interpretation assumes a **mysterious division** between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics […]

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

# A solution: Models of 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.

A unique, modified, quantum world




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).

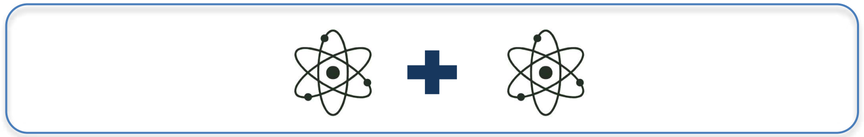
G.C. Ghirardi et al., *Phys. Rev. A* 42, 78 (1990)

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

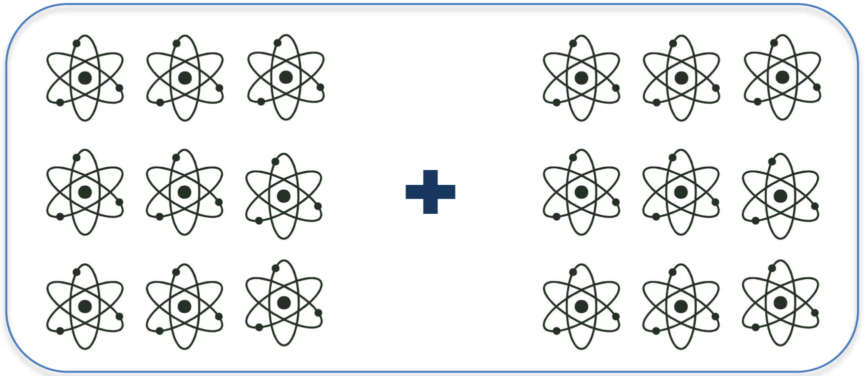
DP model

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

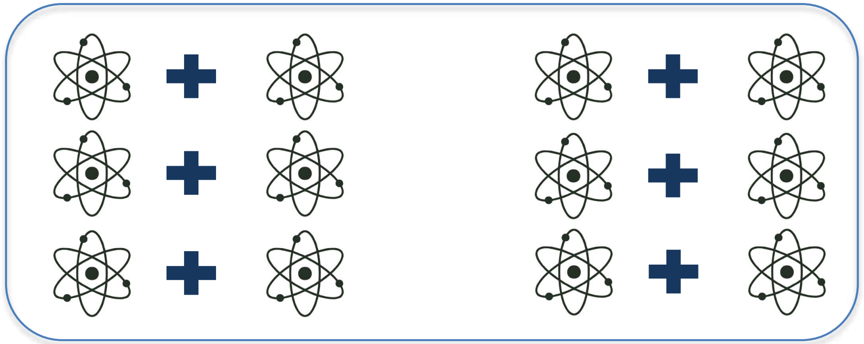
# Collapse dynamics in a nutshell



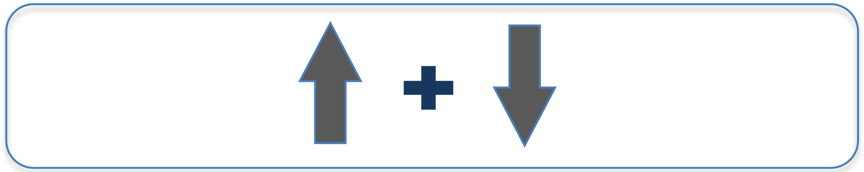
Microscopic superposition in space. Collapse very weak, modulo tiny deviations



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

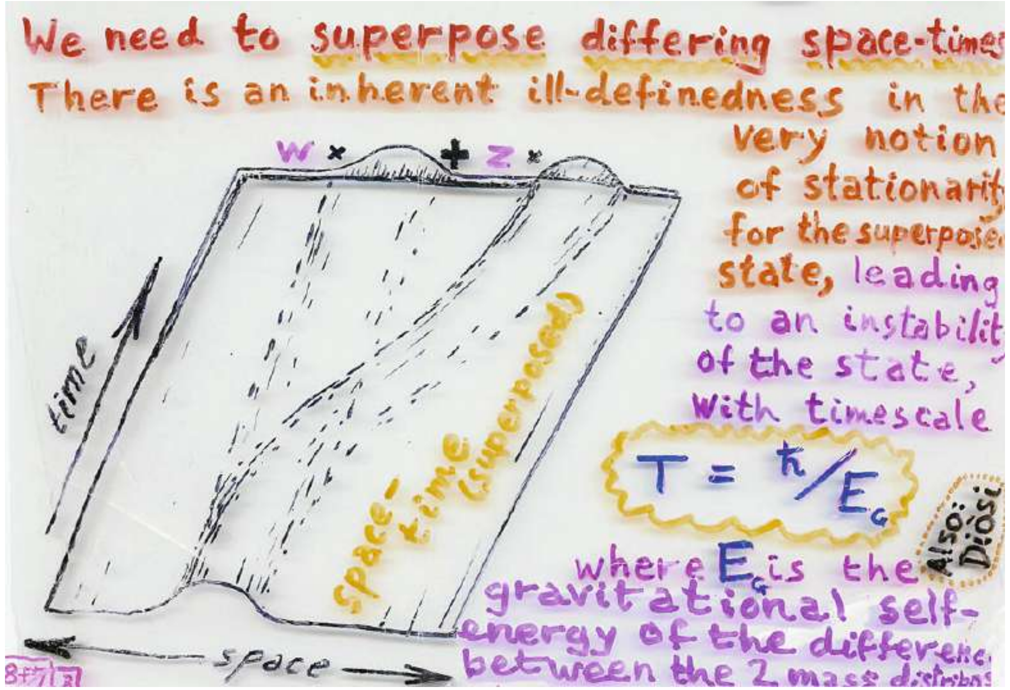


Superpositions in other d.o.f. very weak if they do not imply delocalization in space

# Penrose and collapse

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

… ***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'? … 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.*




Credits: R. Penrose

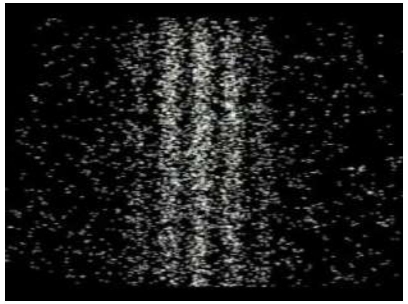
**Penrose's idea:** quantum superposition ➔ spacetime superposition ➔ energy uncertainty ➔ decay in time

The DP master equation, previously shown, is the simplest way to implement these ideas into a dynamical model.

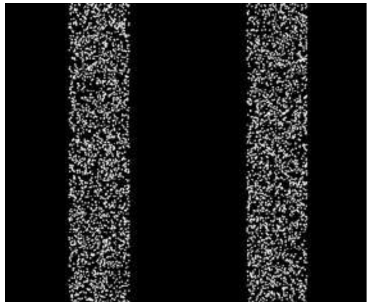
# How to test collapse models

## Interferometric experiments

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

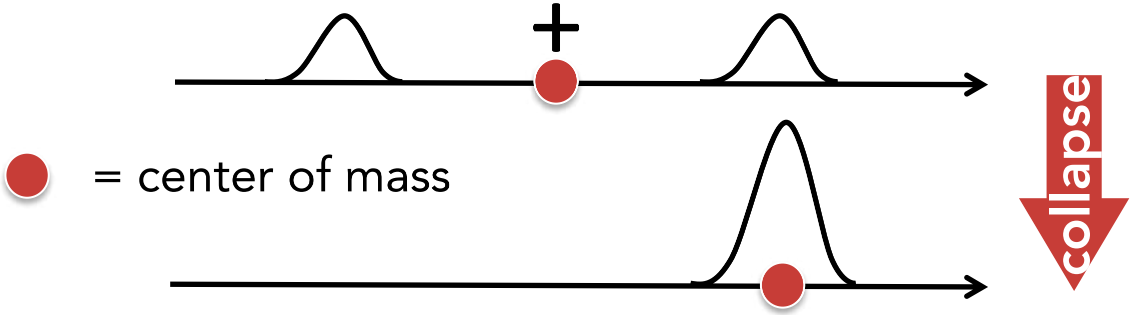


Prediction of
quantum mechanics
(no environmental noise)



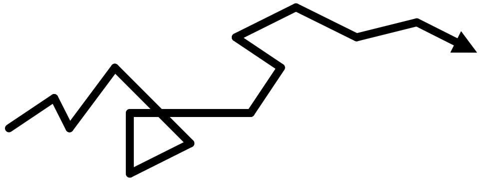
Prediction of
collapse models
(no environmental noise)

## Non interferometric experiments




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

Prediction of
quantum mechanics
(no environmental noise)



Prediction of
collapse models
(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

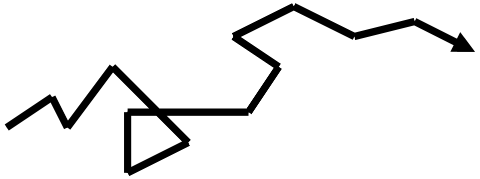
− They are a **direct test** of collapse models and an **indirect test** of the quantum superposition principle.

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

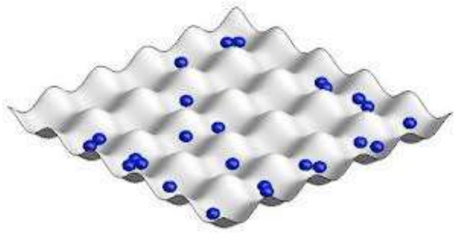
# How to test the collapse noise

**Quantum Mechanics**

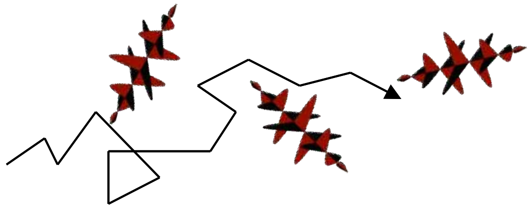
**Collapse models**



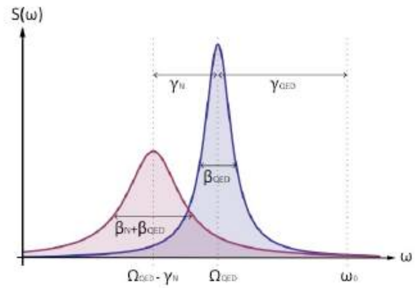
A **gas** will **expand** (heat up) faster than what predicted by QM



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



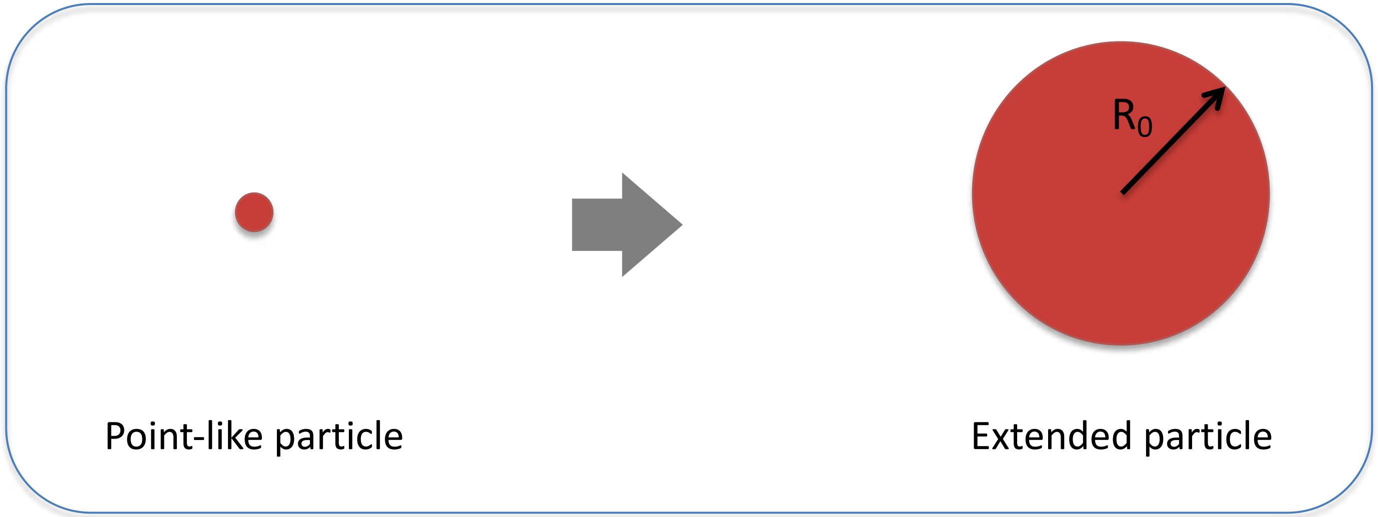
A **cantilever**'s motion cannot be **cooled down** below a given limit



# Test of the DP model

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

The model needs to be **regularized** (→ particles with finite size), otherwise integrals diverge




How do we choose the size?

**Penrose**: Solution of the Schrödinger-Newton equation

**Diòsi**: Compton wavelength (original idea, later abandoned)

# The theory

S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, *Nature Physics* **17**, 74 (2021)

The photon emission rate - number of emitted photons per unit time and unit frequency $\omega_k$ - to first perturbative order is:

$$\frac{d\Gamma_t}{d\omega_k} = \frac{2}{3}\frac{Ge^2N^2N_a}{\pi^{3/2}\varepsilon_0 c^3 R_0^3 \omega_k}$$

valid for $\lambda \in (10^{-5}–10^{-1})$ nm, i.e. energies $E \in (10–10^5)$ keV.

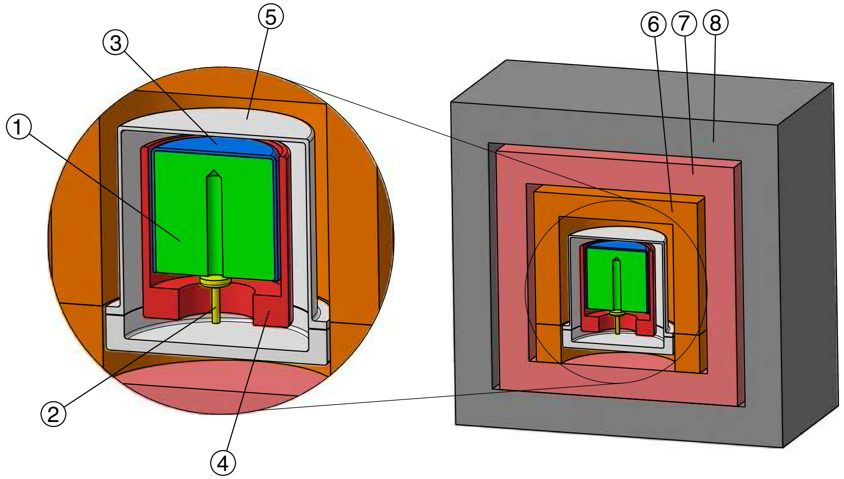
where a sum over all polarizations and direction of propagation of the the emitted photons is taken.

G = gravitation's constant, e = electric constant, $\varepsilon_0$ = dielectric constant, c = speed of light

N = atomic number, $N_a$ = total number of atoms, $R_0$ = DP's free parameter, $\omega_k$ = photon's frequency

# The experiment

S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, *Nature Physics* **17**, 74 (2021)



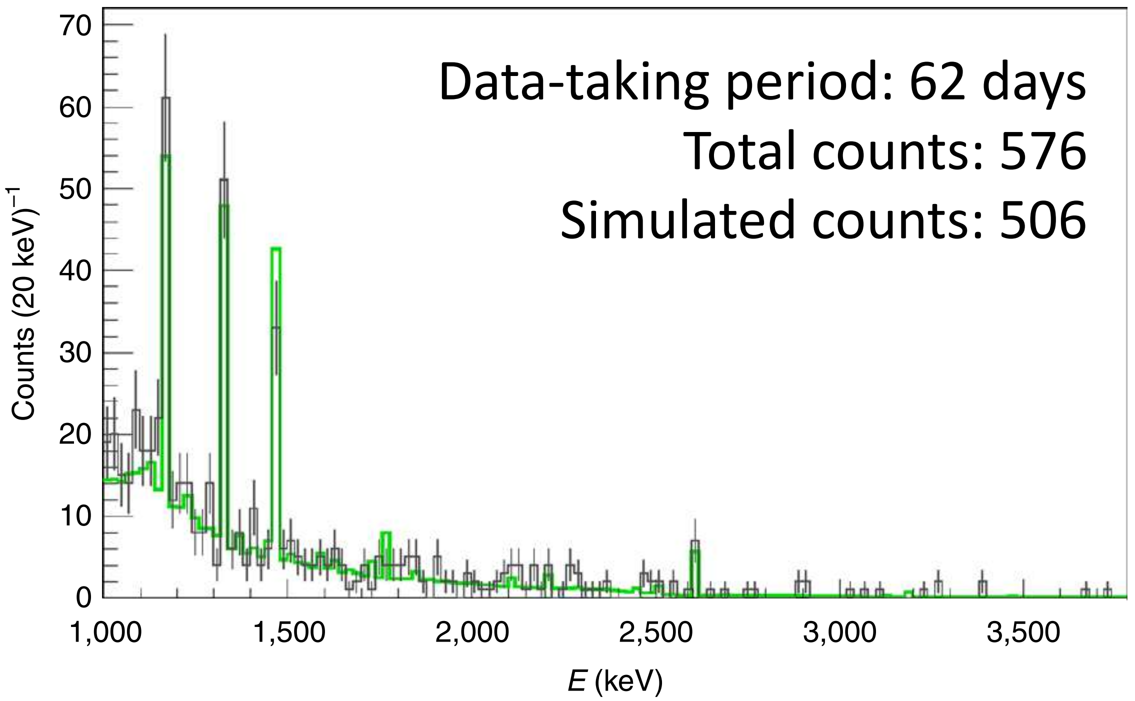

The experiment. Credits: Massimiliano De Deo, LNGS

The laboratories. Credits: LNGS-INFN

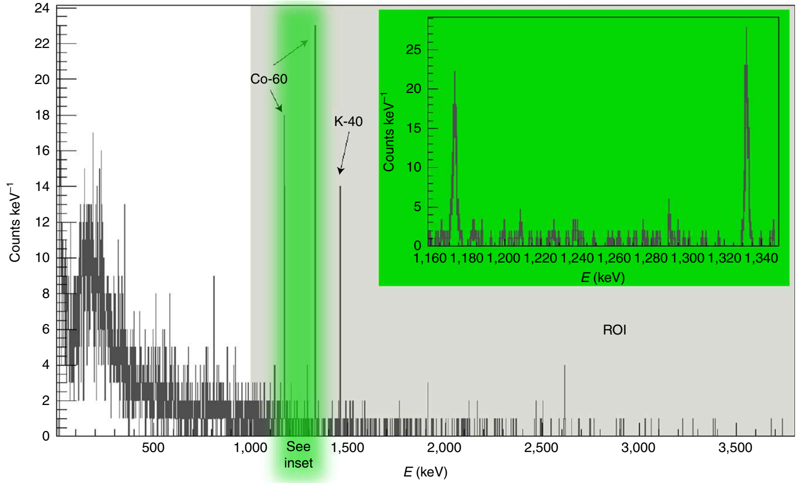
**Schematic representation of the experimental set-up.** The experimental apparatus is based on a coaxial p-type high-purity germanium detector, with the dimensions of 8.0 cm diameter and 8.0 cm length; the active volume is 375 cm³. The detector is shielded by layers of electrolytic copper and pure lead. The inner part of the apparatus consists of the following main elements: 1, germanium crystal; 2, electric contact; 3, plastic insulator; 4, copper cup; 5, copper end-cup; 6, copper block and plate; 7, inner copper shield; 8, lead shield. In order to minimize the radon contamination an air-tight steel casing (not shown) encloses the shield and is continuously flushed with boil-off nitrogen from a liquid nitrogen storage tank.

# The analysis

S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, *Nature Physics* **17**, 74 (2021)



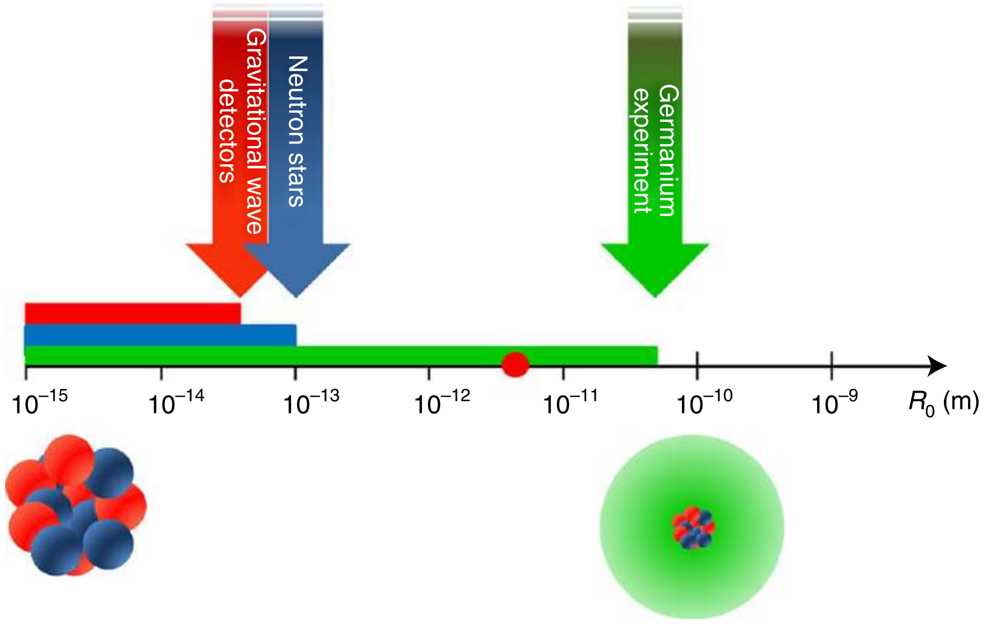

**Comparison between the measured and the simulated background spectra.** The measured emission spectrum is shown in the ROI as a dark-grey histogram. The simulated background distribution is shown in green for comparison. The simulation is based on a Geant4 validated MC characterization of the whole detector. The MC has as input the measured activities of the residual radionuclides for each material present in the experimental set-up.




The simulation accounts for the emission probabilities and the decay schemes, the photon propagation and interactions in the materials of the apparatus and the detection efficiencies.

# The results

S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, *Nature Physics* **17**, 74 (2021)




**Lower bounds on the spatial cutoff $R_0$ of the DP model.**
According to Penrose, $R_0 = 0.05 \times 10^{-10}$ m for the germanium crystal used in the experiment (red circle on the horizontal scale).

Our experiment sets a lower bound on $R_0$ at $0.54 \times 10^{-10}$ m (green bar and arrow).

The figure shows also previous lower bounds in the literature:

- data analysis from gravitational wave detectors*, $R_0 \geq (40.1 \pm 0.5) \times 10^{-15}$ m, red bar and arrow
- Data from neutron stars**, $R_0 \gtrsim 10^{-13}$ m, blue bar and arrow.

* B. Helou, B. Slagmolen, D. E. McClelland and Y. Chen, *Phys. Rev. D* **95**, 084054 (2017).
** A. Tilloy and T. M. Stace, *Phys. Rev. Lett.* **123**, 080402 (2019).

# The conclusion

S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein and A. Bassi, *Nature Physics* **17**, 74 (2021)

**The DP model**, which is the simplest way to model dynamically Penrose's idea of gravity-induced wave function collapse, where the free parameter $R_0$ is chosen according to Penrose's prescription, **is excluded**.

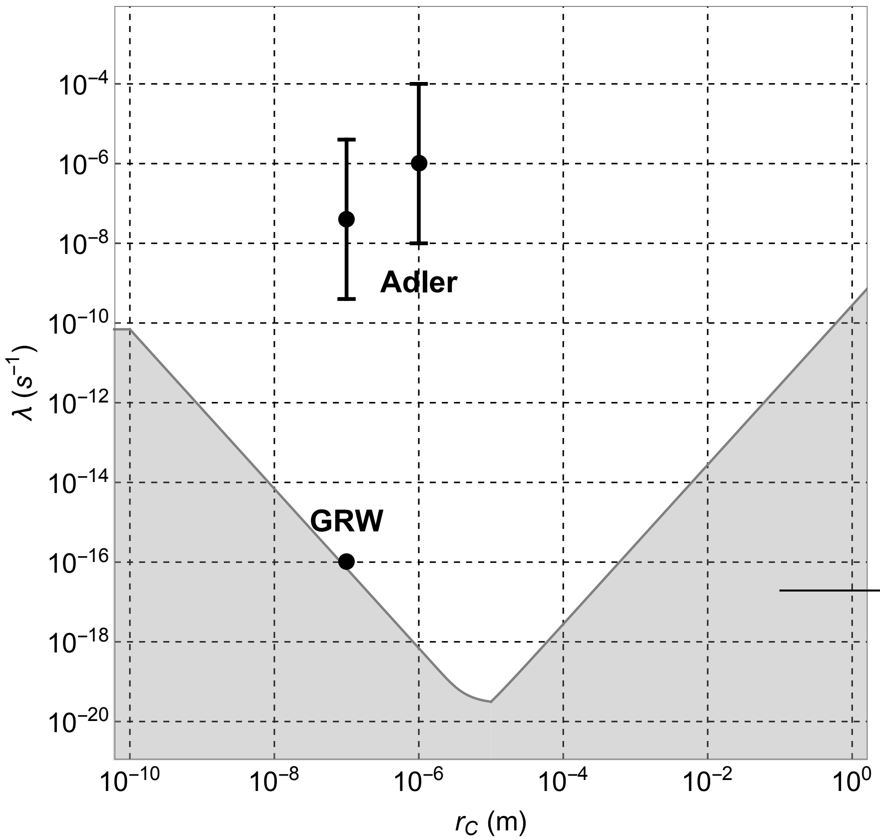
Possible **ways out**:

- Let the parameter $R_0$ completely free. The price to pay is that it is not clear how to give a meaning to it
- Enrich the dynamics = add new parameters. This is possible, as done for other collapse models
- Devise a new theory, which goes beyond quantum theory - the solution invoked by Penrose. This is ambitious work in progress
- Others …

# Tests of the CSL model

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

Two phenomenological parameters. $\lambda$ 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

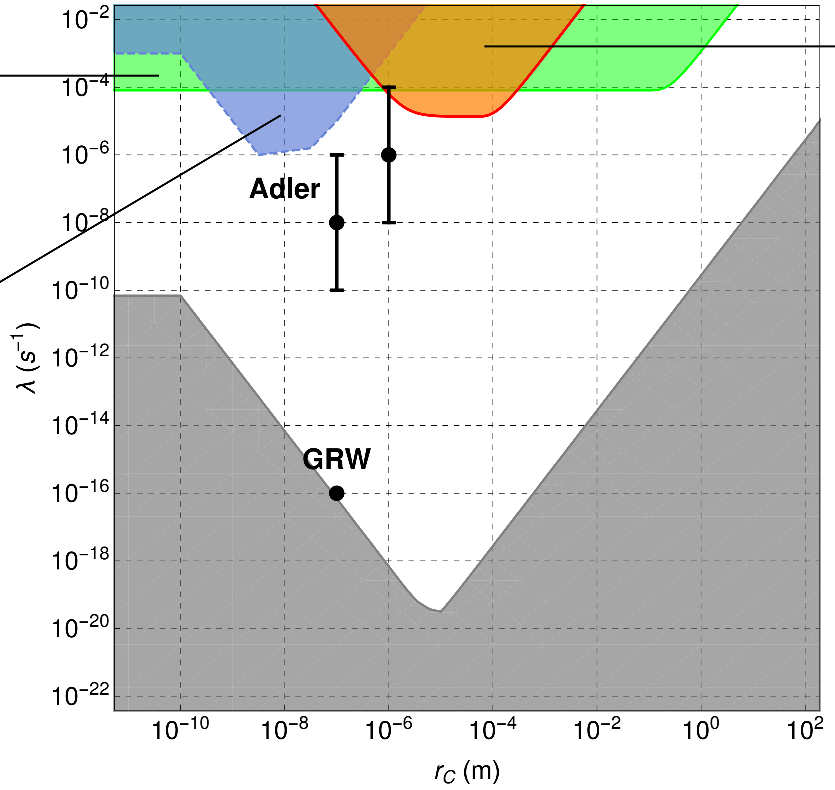

Atom Interferometry

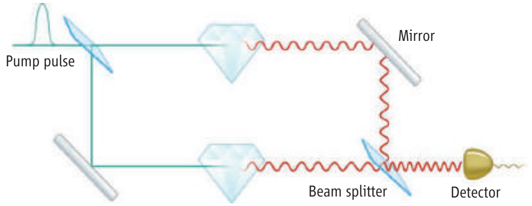
T. Kovachy *et al.*, Nature 528, 530 (2015)

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)

Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M. Toros *et al.,* ArXiv 1601.03672

M = $10^4$ amu

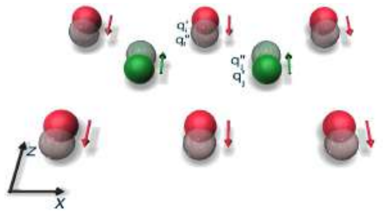
d = $10^{-7}$ m

T = $10^{-3}$ s

M = $10^{16}$ amu

d = $10^{-11}$ m → in reality much smaller

T = $10^{-12}$ s

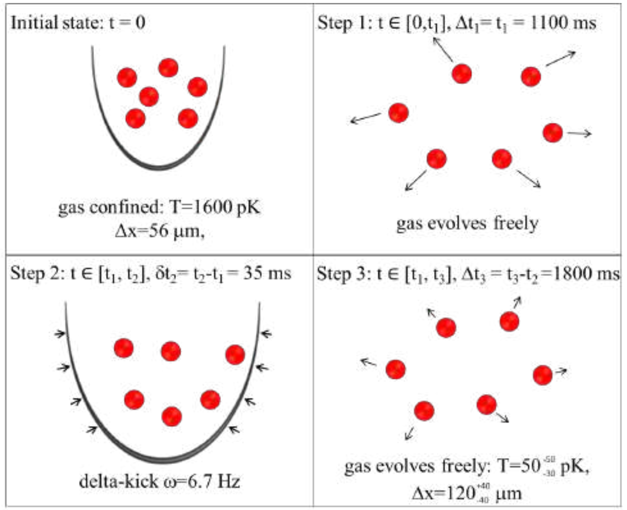


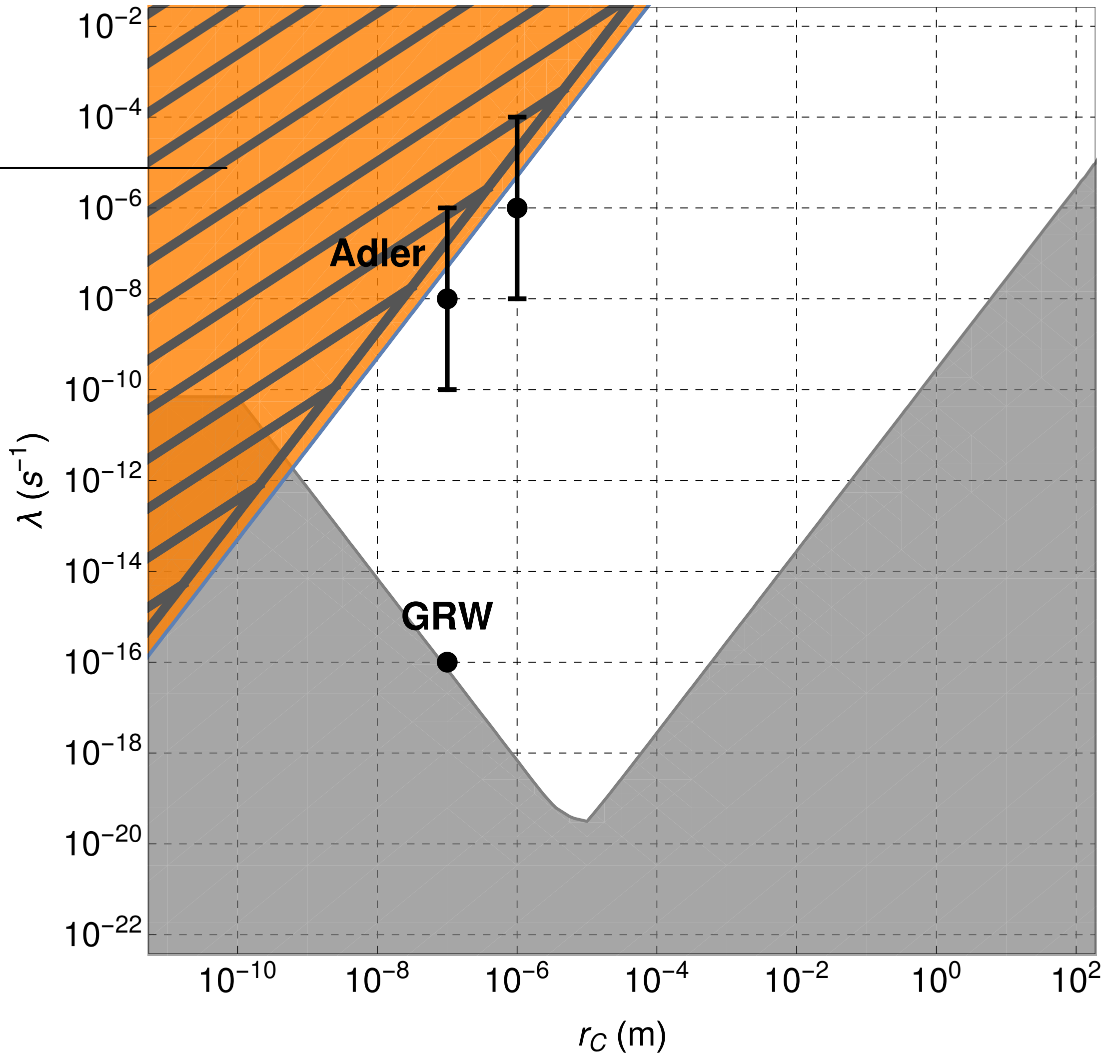

To improve interferometric tests, it will likely be necessary to go to micro-gravity environment in outer space → MAQRO

# Non - Interferometric Experiments

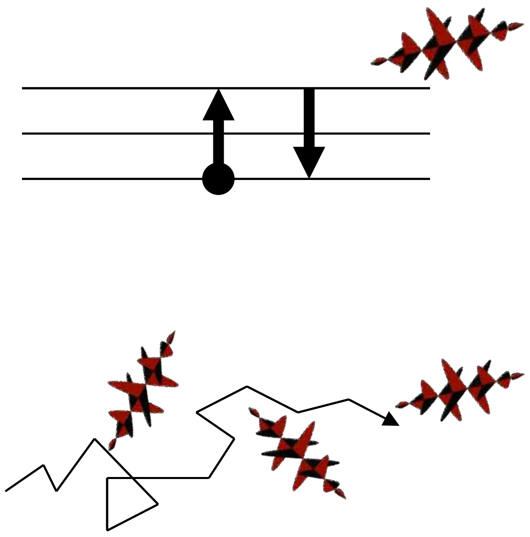
**Cold atom gas**

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)

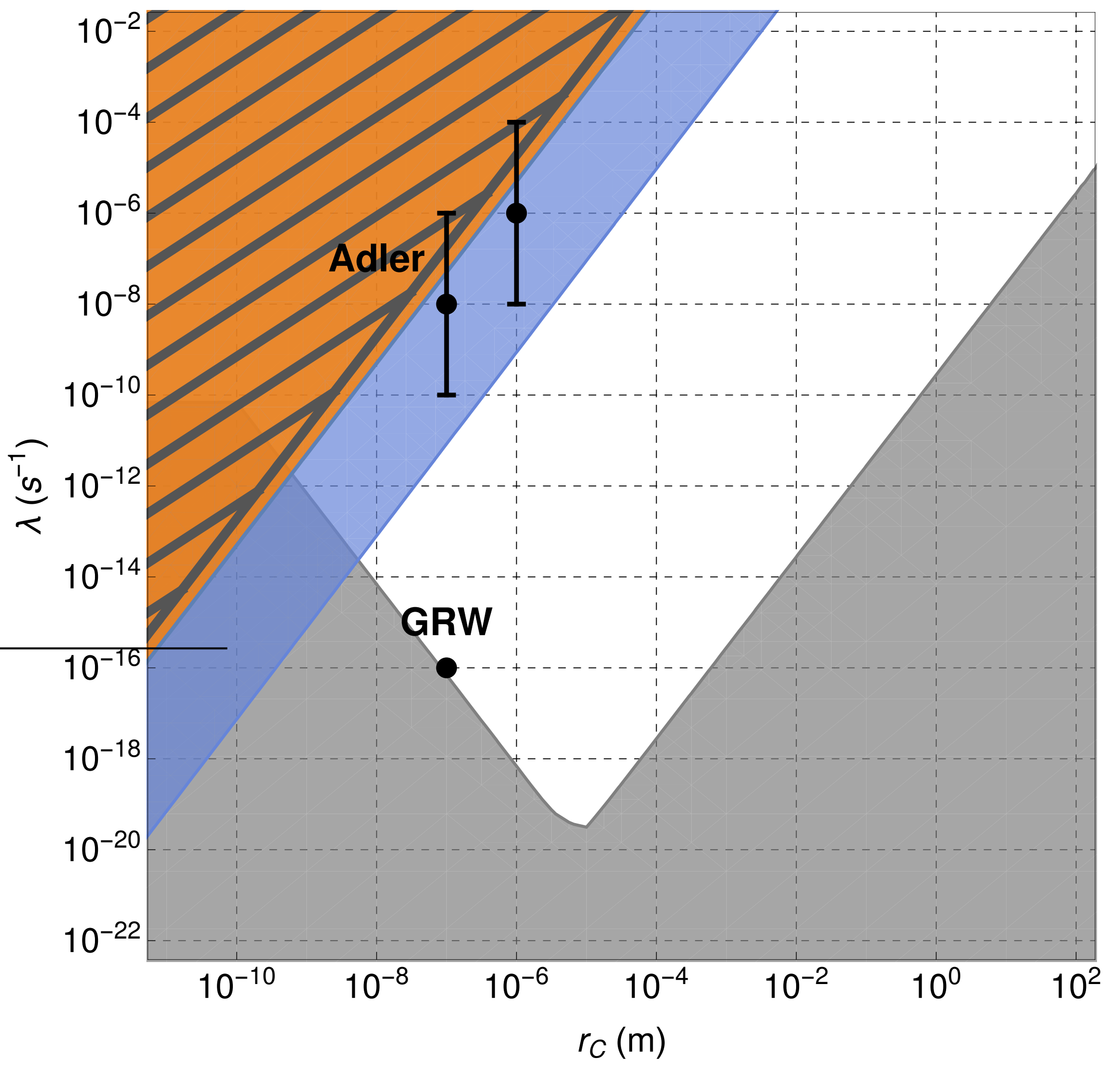


# Non - Interferometric Experiments

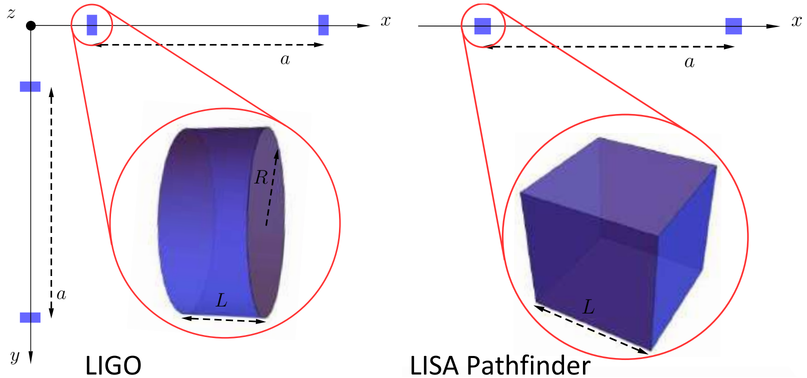


**X rays**

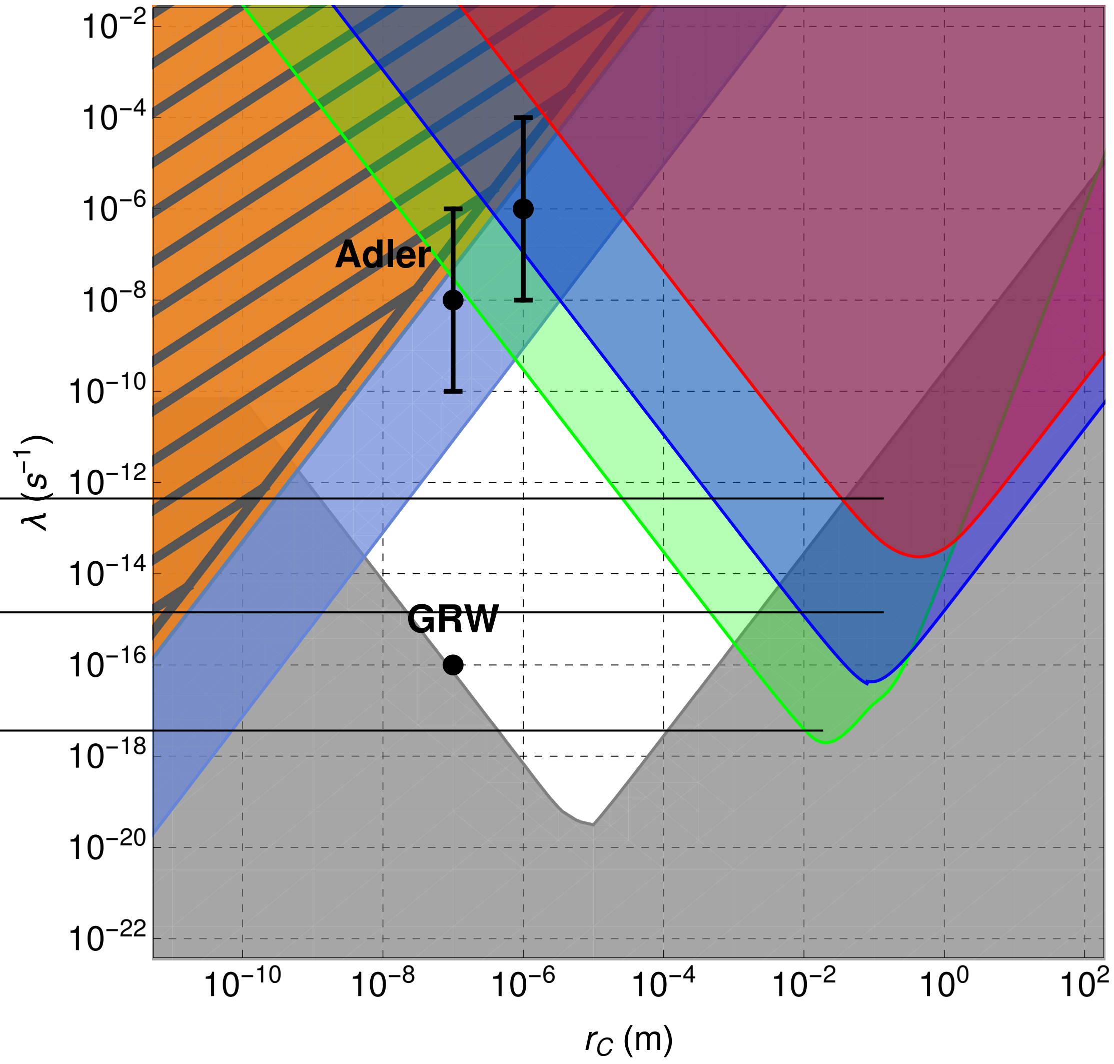



S.L. Adler *et al.*, Jour. Phys. A <u>40</u>, 13395 (2009)
S.L. Adler *et al.*, Journ. Phys. A <u>46</u>, 245304 (2013)
A. Bassi & S. Donadi, Annals of Phys. <u>340</u>, 70 (2014)
S. Donadi & A. Bassi, Jounr. Phys. A <u>48</u>, 035305 (2015)
C. Curceanu *et al.*, J. Adv. Phys. <u>4</u>, 263 (2015)
+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

# Non - Interferometric Experiments




LIGO LISA Pathfinder

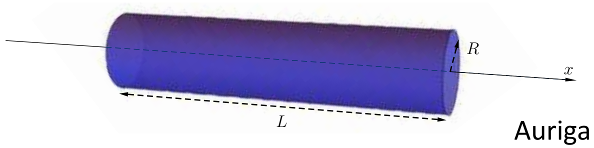



**Auriga**

**Ligo**

**Lisa Pathfinder**

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

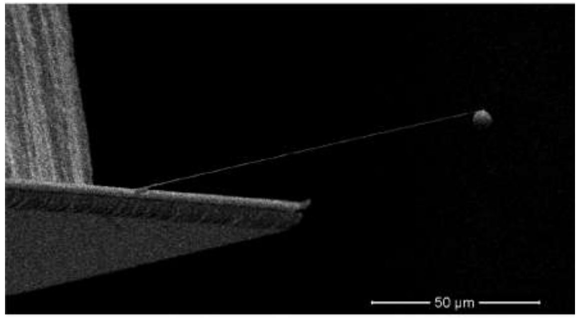


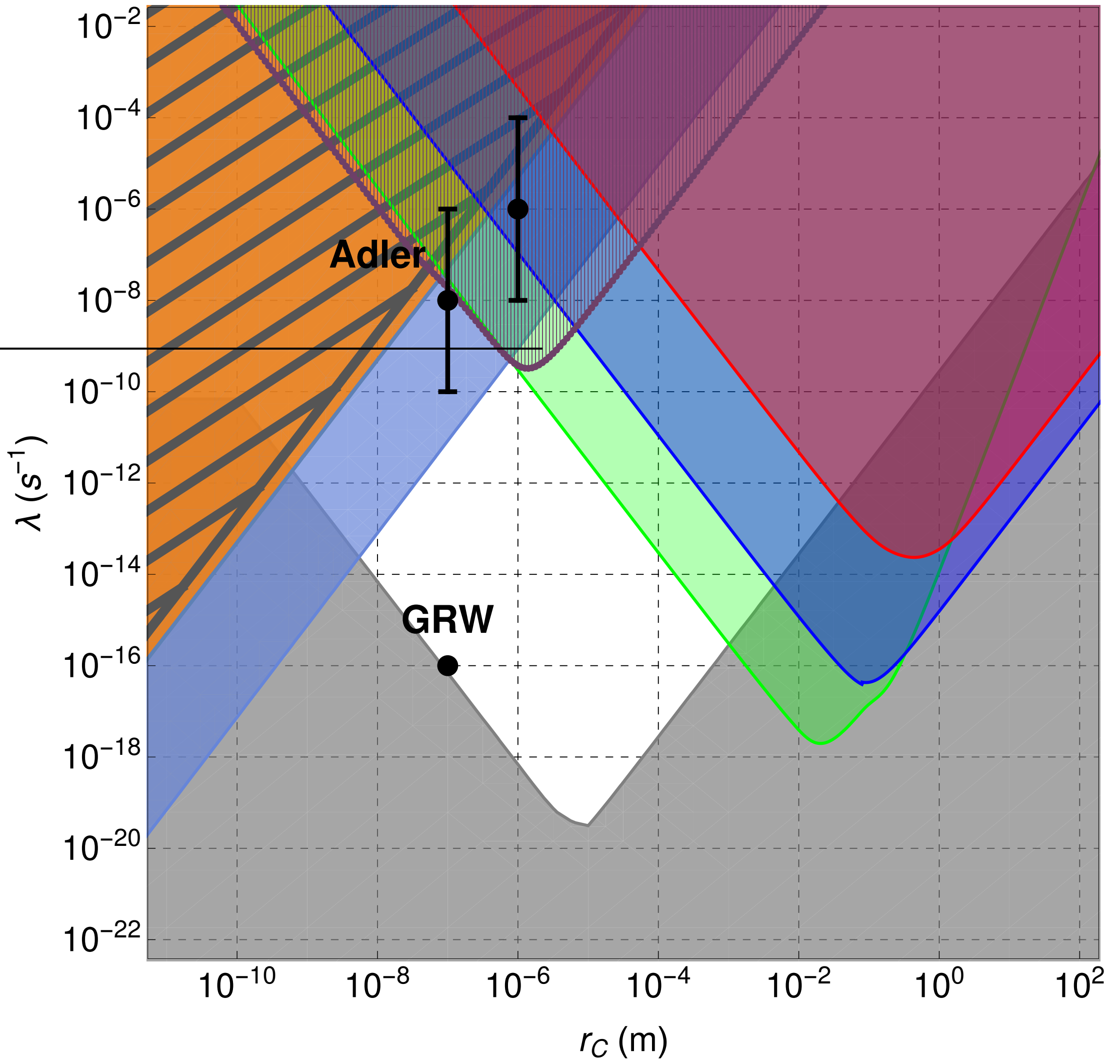

Auriga

# Non - Interferometric Experiments

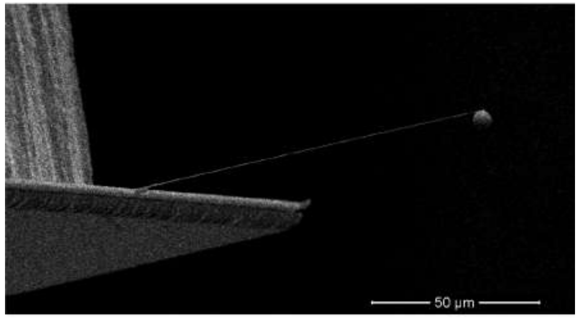
**Cantilever**

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



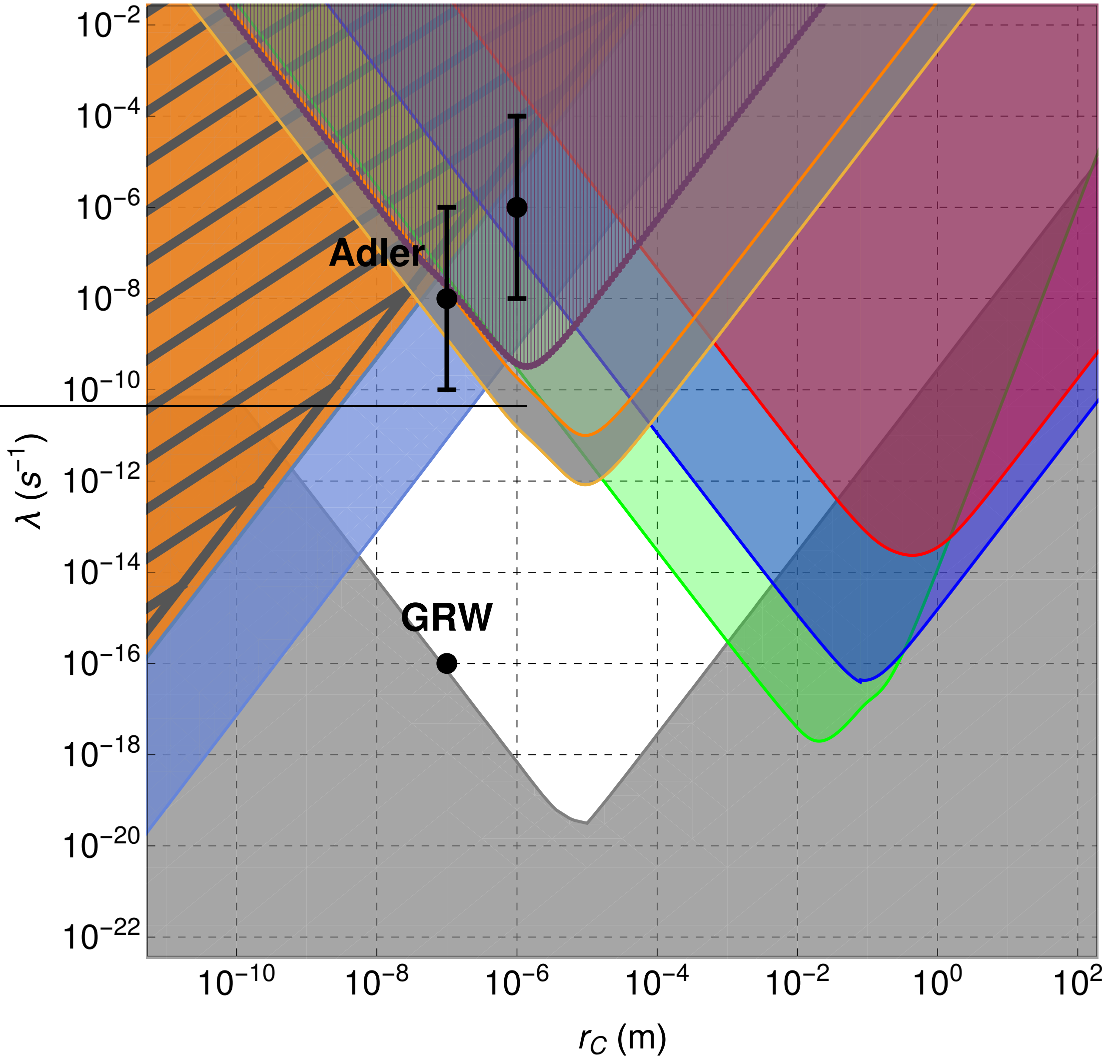



# Non - Interferometric Experiments




**Cantilever – update 1**

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



# Non - Interferometric Experiments

**Cantilever - Update 2**

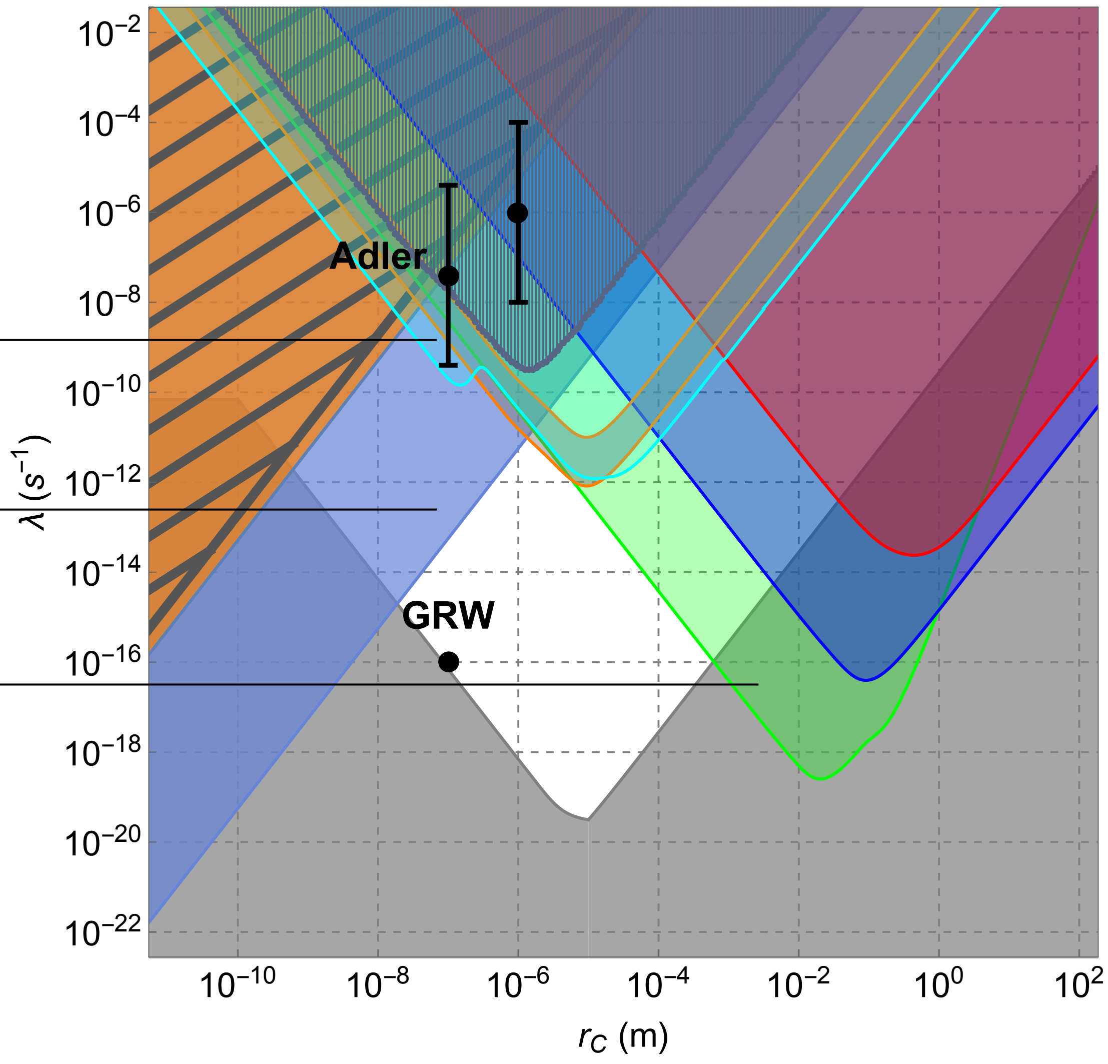
A. Vinante *et al., Phys. Rev. Lett. 125, 100404 (2020)*

**Radiation – Update 1**

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

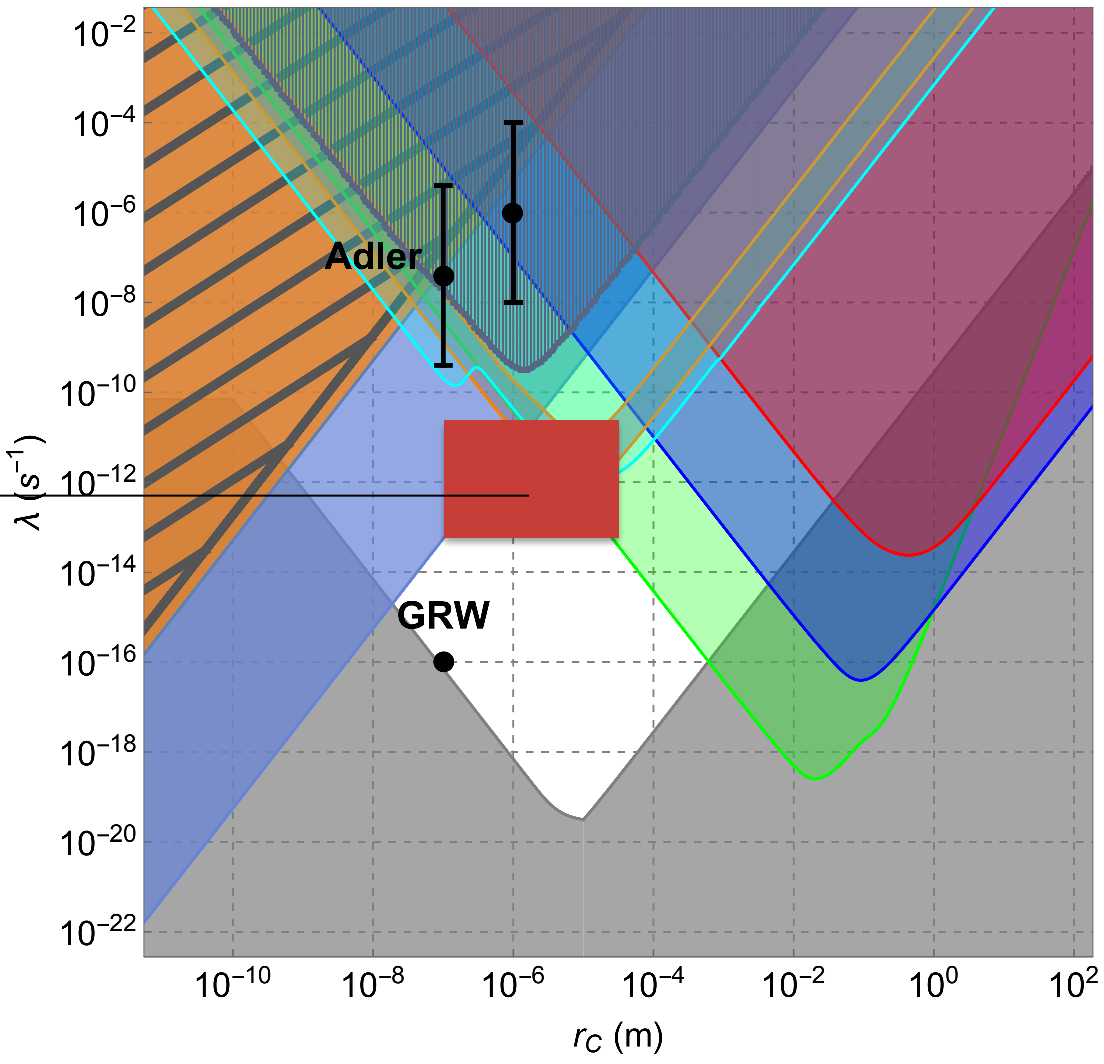
**Gravitational Wave detectors – Update 1**

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



# Non - Interferometric Experiments

**H2020 FET project**
**www.tequantum.eu**



# Acknowledgments

**The Group (www.qmts.it)**

- Postdocs: M. Carlesso, L. Ferialdi, S. Donadi
- Ph.D. students: A. Ghundi, M. Vischi

**Collaborations with:** S.L. Adler, M. Paternostro, H. Ulbricht, A. Vinante, C. Curceanu.

# The GRW model

Systems are described by the wave function. This evolves according to the Schrödinger equation, except that at random times (with frequency λ) they undergo spontaneous collapses:

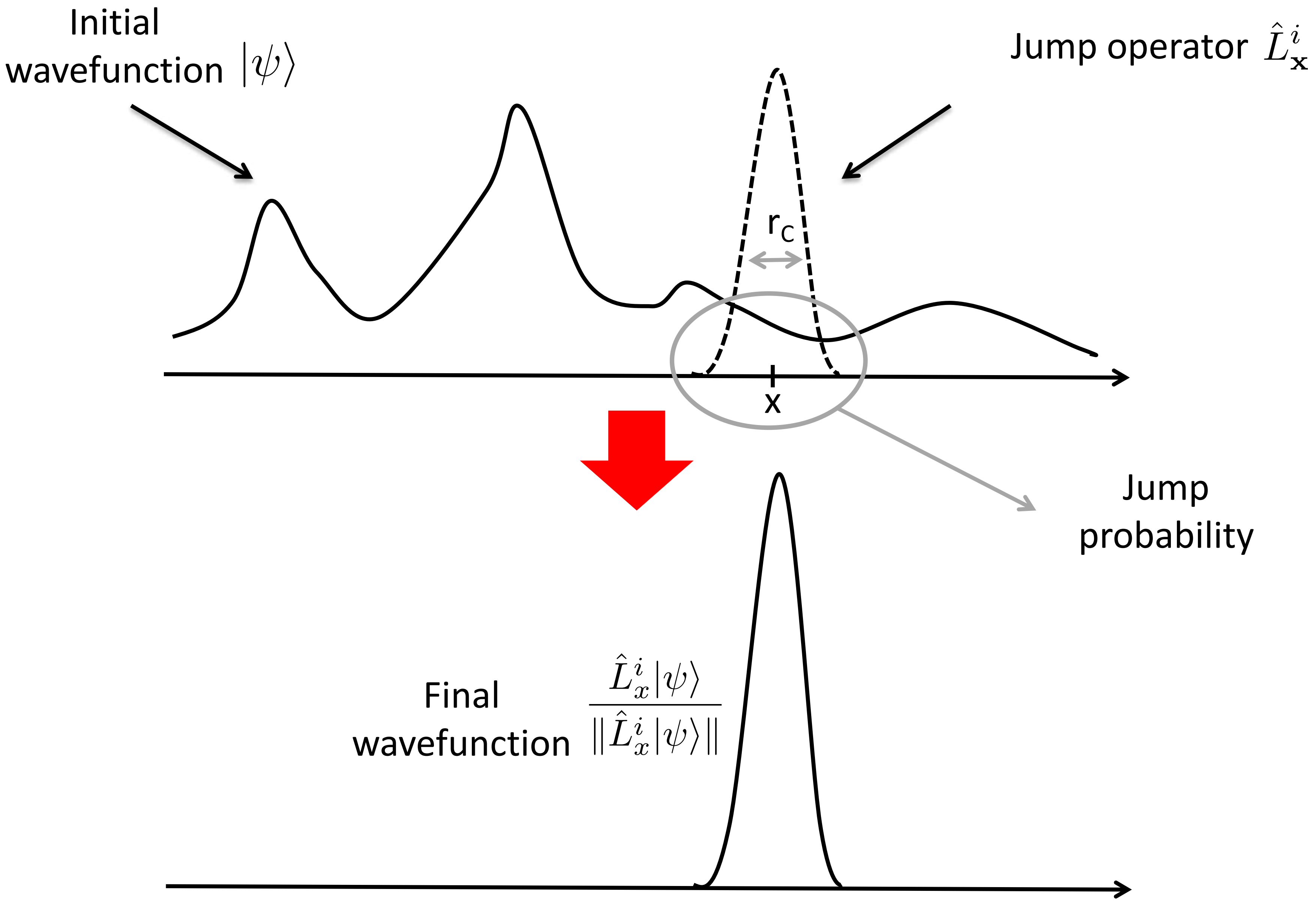
$$|\psi\rangle \to \frac{\hat{L}_x^i|\psi\rangle}{\|\hat{L}_x^i|\psi\rangle\|} \qquad \hat{L}_x^i = \left(\frac{1}{\pi r_C^2}\right)^{\frac{3}{4}} e^{-\frac{(\hat{q}_i - x)^2}{2r_C^2}}$$

The probability (density) for a collapse to occur around x is given by $\|\hat{L}_x^i|\psi\rangle\|^2$

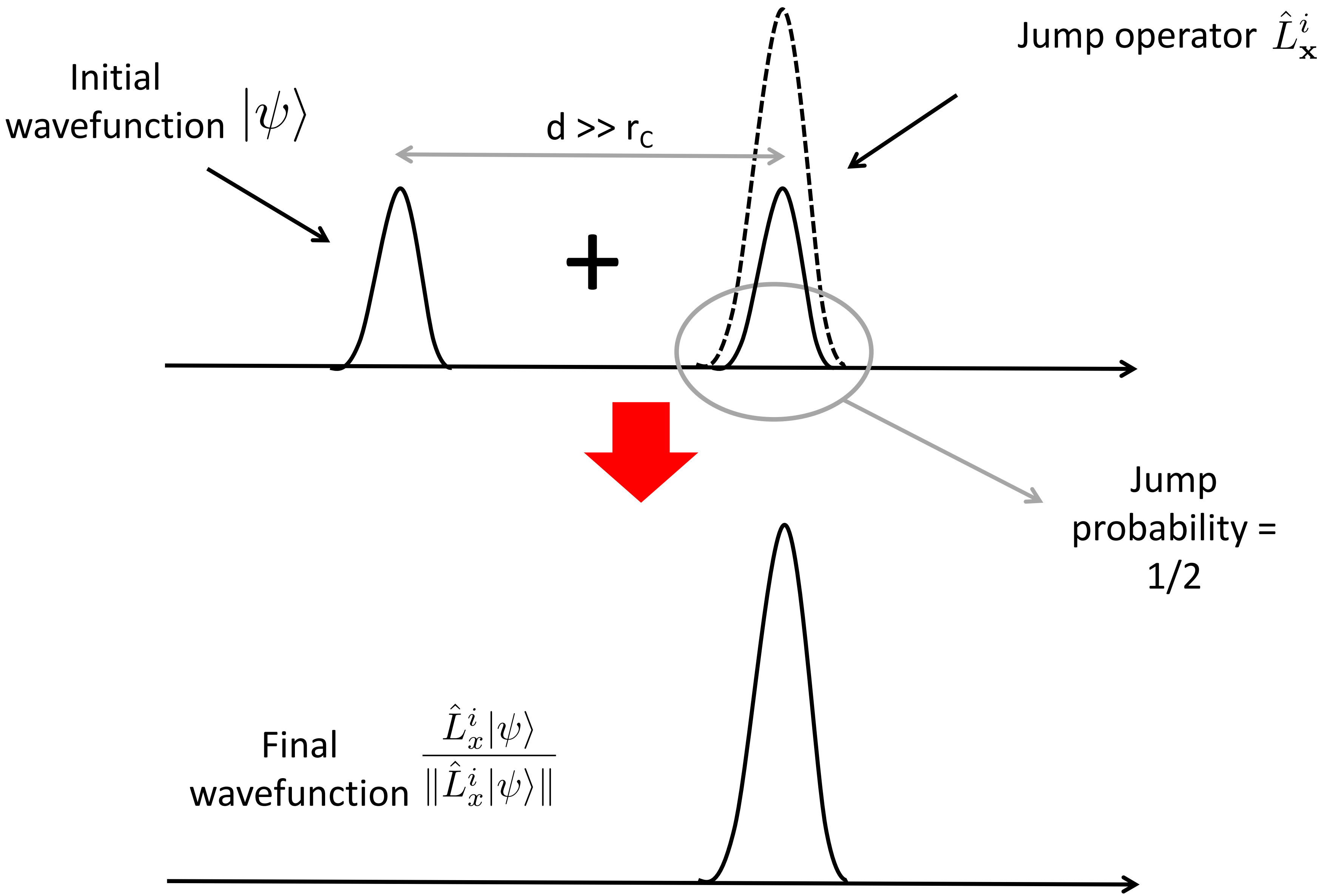
➔ Collapses are random in space and time

➔ Two parameters defining the model: λ and $r_C$

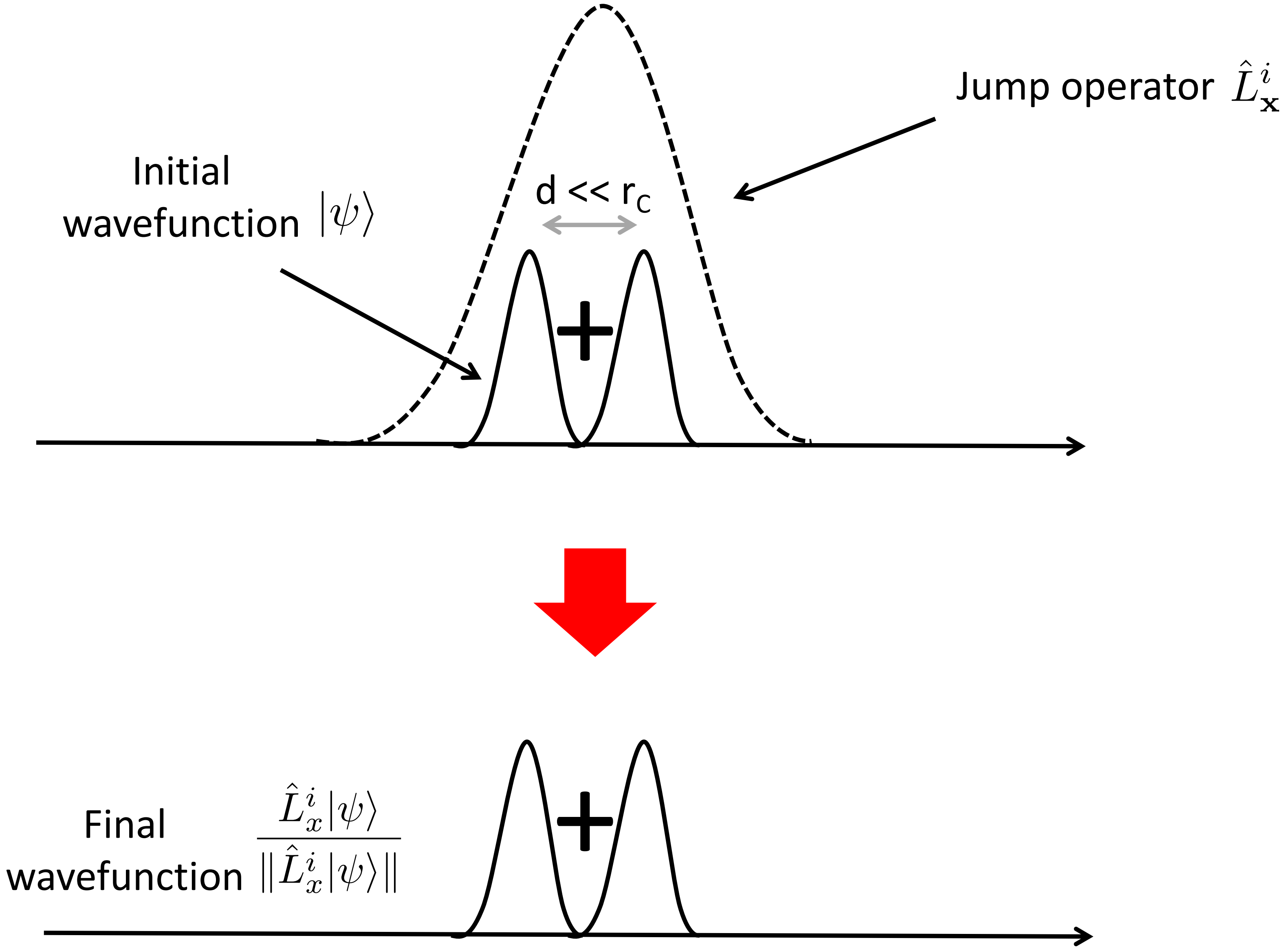
# The jump


Initial
wavefunction $|\psi\rangle$
Jump operator $\hat{L}^i_{\mathbf{x}}$
$r_C$
x
Jump
probability
Final
wavefunction $\frac{\hat{L}^i_x|\psi\rangle}{\|\hat{L}^i_x|\psi\rangle\|}$

# Example: “large” superposition



# Example: “small” superposition

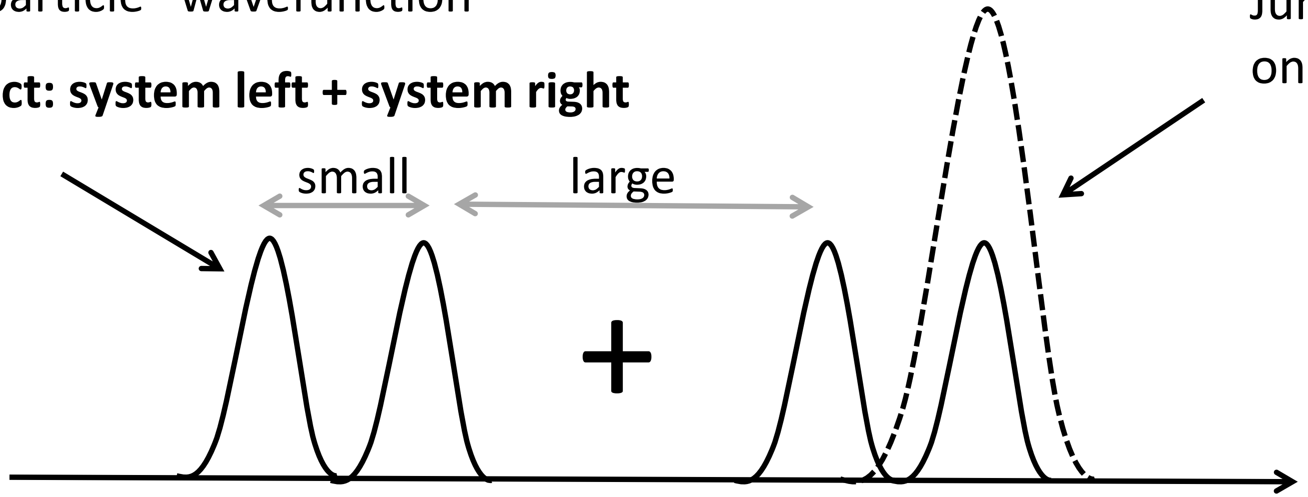


# Amplification mechanism

Initial “2-particle” wavefunction

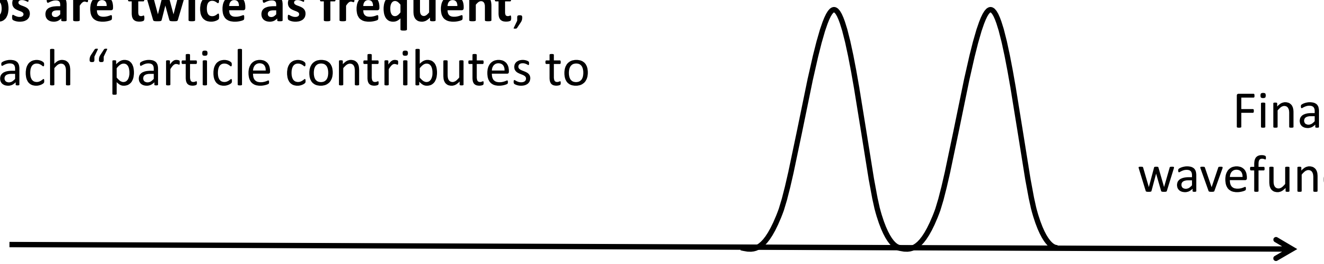
**Rigid object: system left + system right**

Jump operator on “particle” 2




Entangled state $\psi_1^L \otimes \psi_2^L$ $\psi_1^R \otimes \psi_2^R$

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



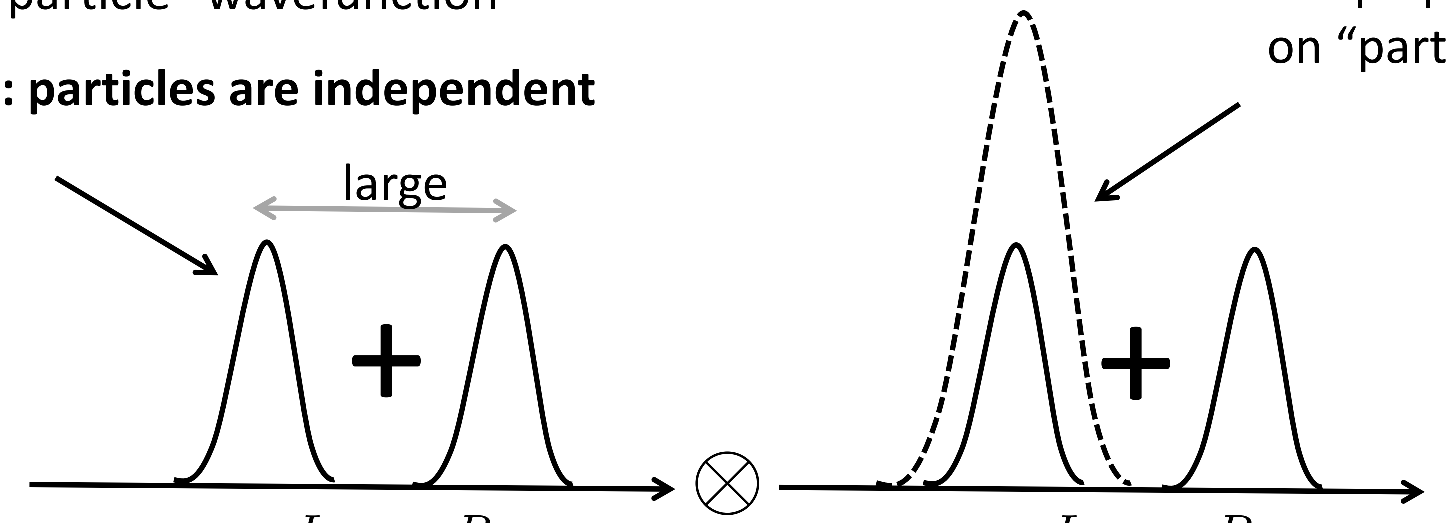
Final wavefunction

# However

Initial "2-particle" wavefunction

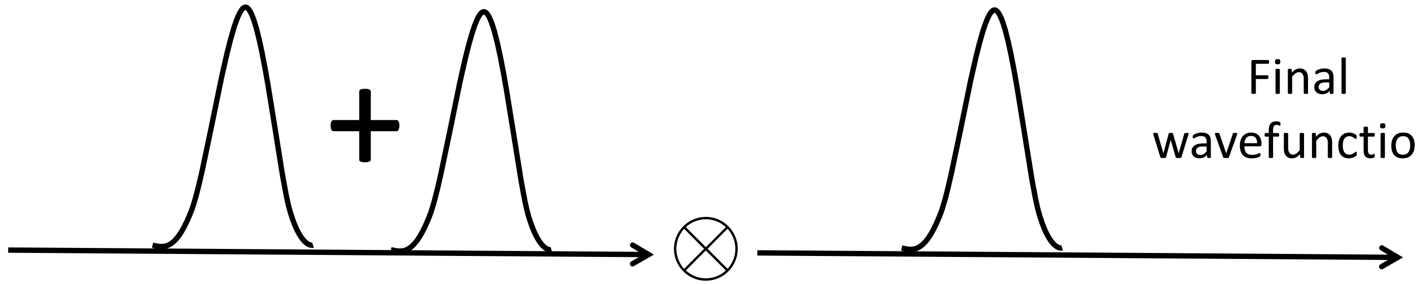
**Ideal gas: particles are independent**

Jump operator on "particle" 2




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

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



Final wavefunction