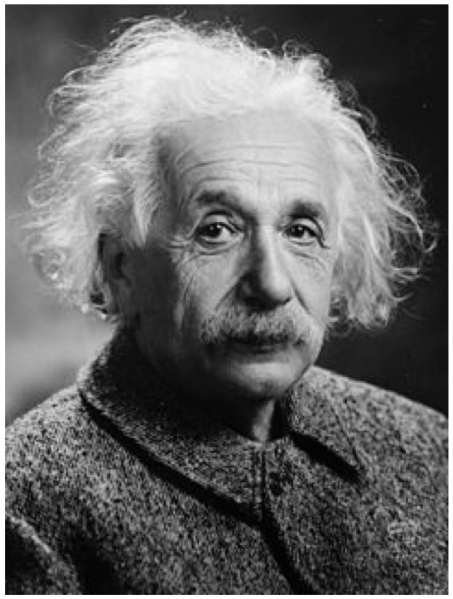
Electrons: waves, particles ... or jellies?

Sharif QI Group

6th August 2020

(Angelo Bassi – University of Trieste & INFN)

“The trouble with quantum mechanics”



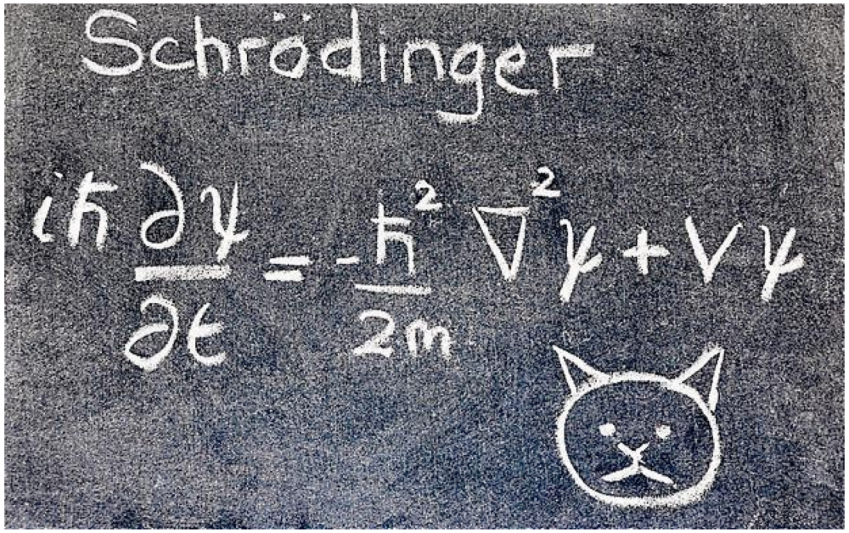
Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing.
Albert Einstein

I think I can safely say that no one understands quantum mechanics
Richard Feynman

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

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

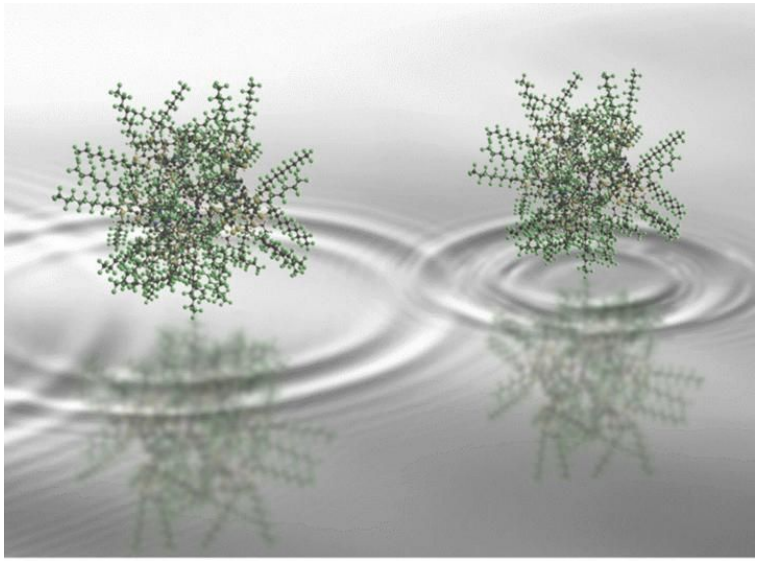


The Schrödinger equation is **linear**

Wave function: |here> + |there>

(to be normalized)

What does it mean?



Option A: particle

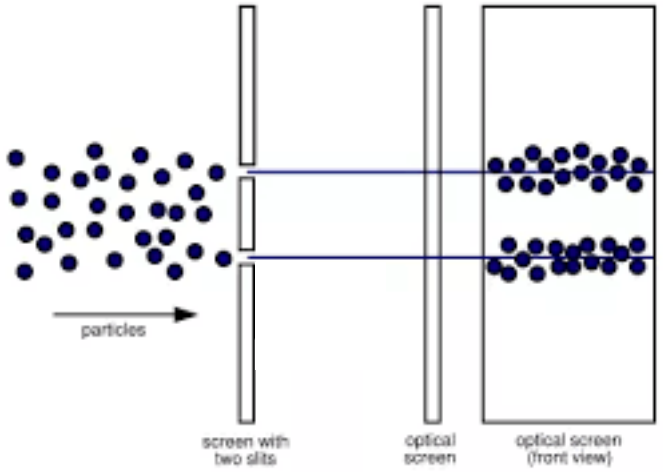
|here> + |there> means that a particle is **either here or there**; we are simply ignorant about its precise location. **The wave function is there to reflect our ignorance.**

This is the simplest explanation, which eventually leads to **Bohmian Mechanics.** But one has to accept two things:

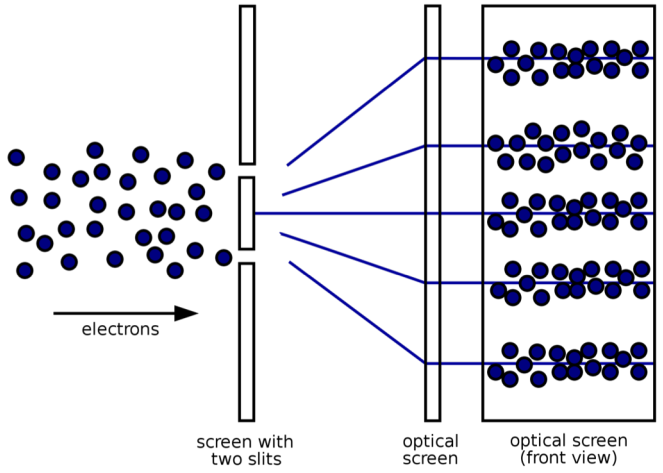
- Quantum Mechanics is **incomplete**, the wave function is not everything.
- The wave function **cannot simply reflect our ignorance**, otherwise one cannot explain the double slit experiment.

Double slit experiment

This is what classical particles do:



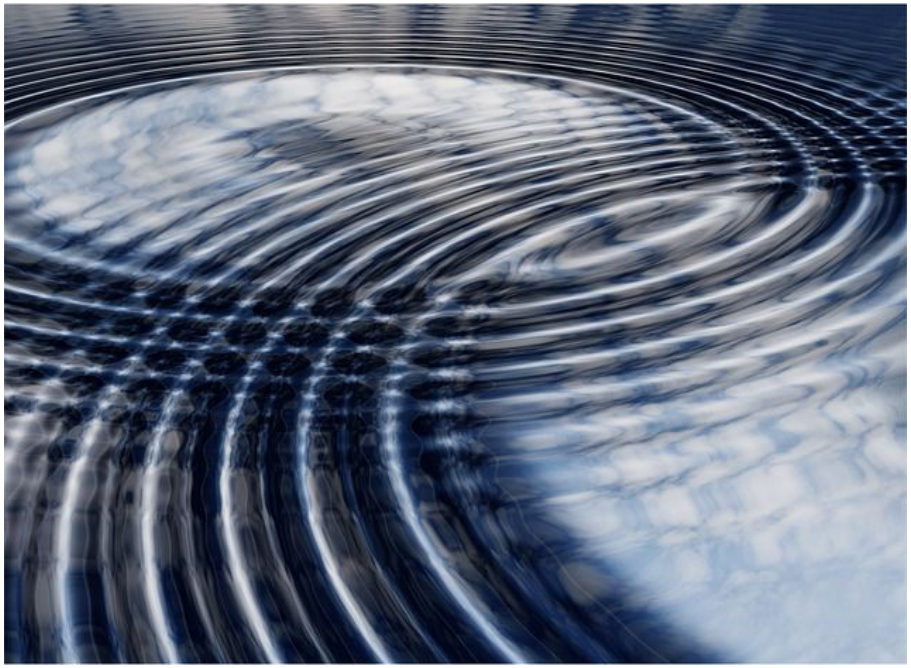
This is what quantum particles do: the wavefunction “guides” them



Bohmian Mechanics takes care of all these things.

Option B: wave

|here> + |there> means that the particle is **here and there**, like for any wave.



This is a more challenging explanation, which eventually leads to **collapse models** (I deliberately ignore Many Worlds). But one has to accept two things:

- Particles are not particles, they are not localized. They are waves.
- Upon measurements, particles are always well localized, never split in two (or more), like waves.

Option C: none

|here> + |there> means that the particle is **neither here or there…**

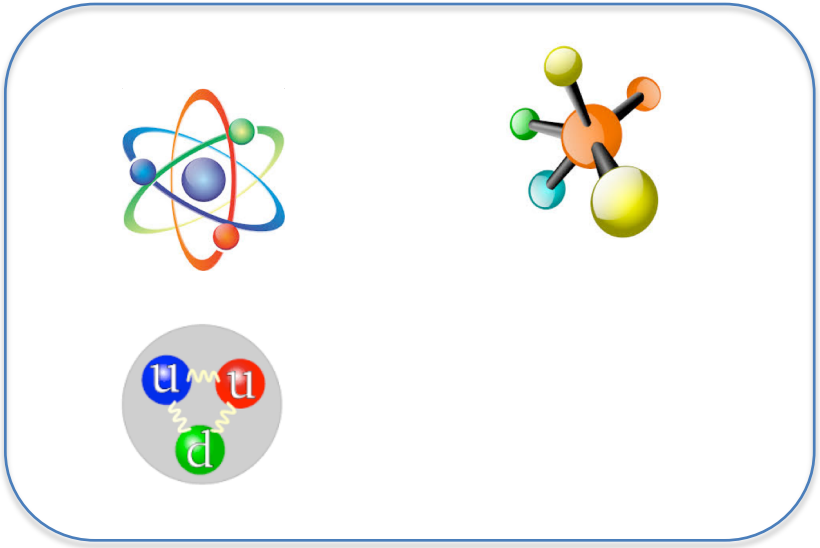
In a sense, this is the official solution. Only in a sense...

The official position is **the wave function is not about the state of the particle, but about the outcomes of measurements:**

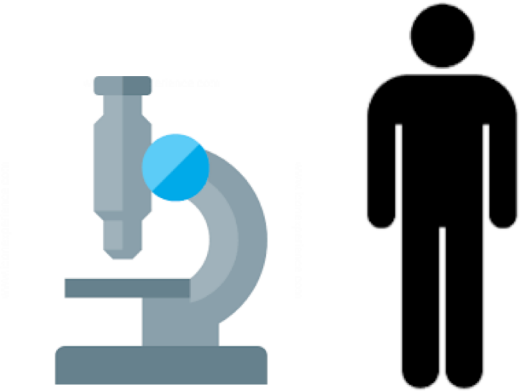
The square modulus of the wave function gives the probability that, in a position measurement, the particle is found to be here or there

Standard Quantum Mechanics

Quantum world



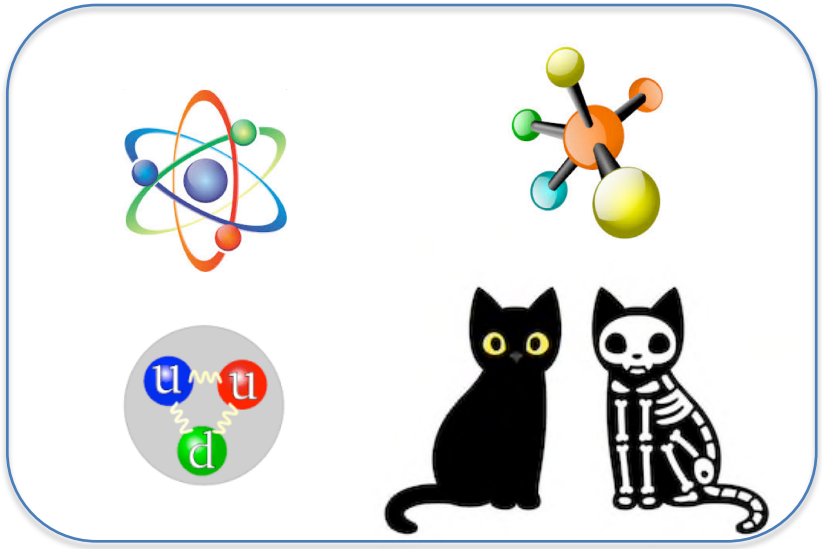
Classical world



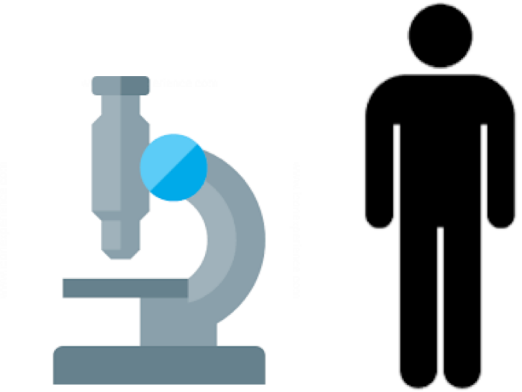
The wave function gives the probabilities of outcomes of measurements

The cat…

Quantum world



Classical world

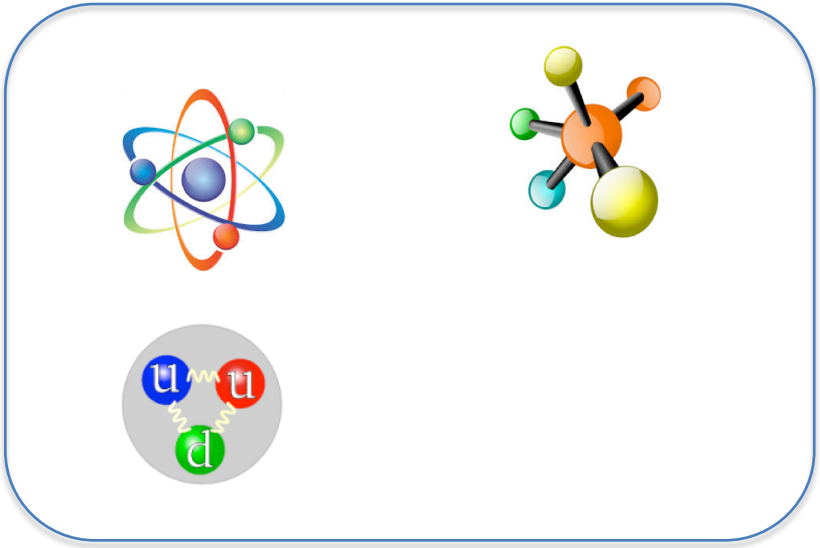


The wave function gives the probabilities of outcomes of measurements

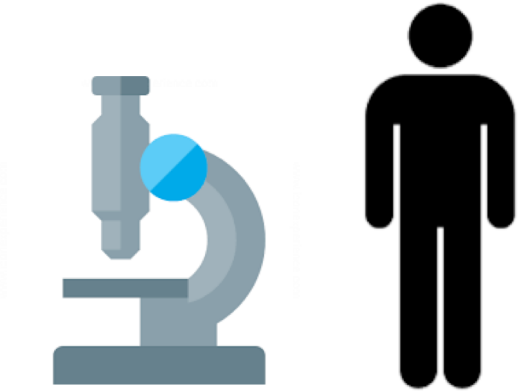
???

The Problem with 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)

Solutions

Bohmian Mechanics

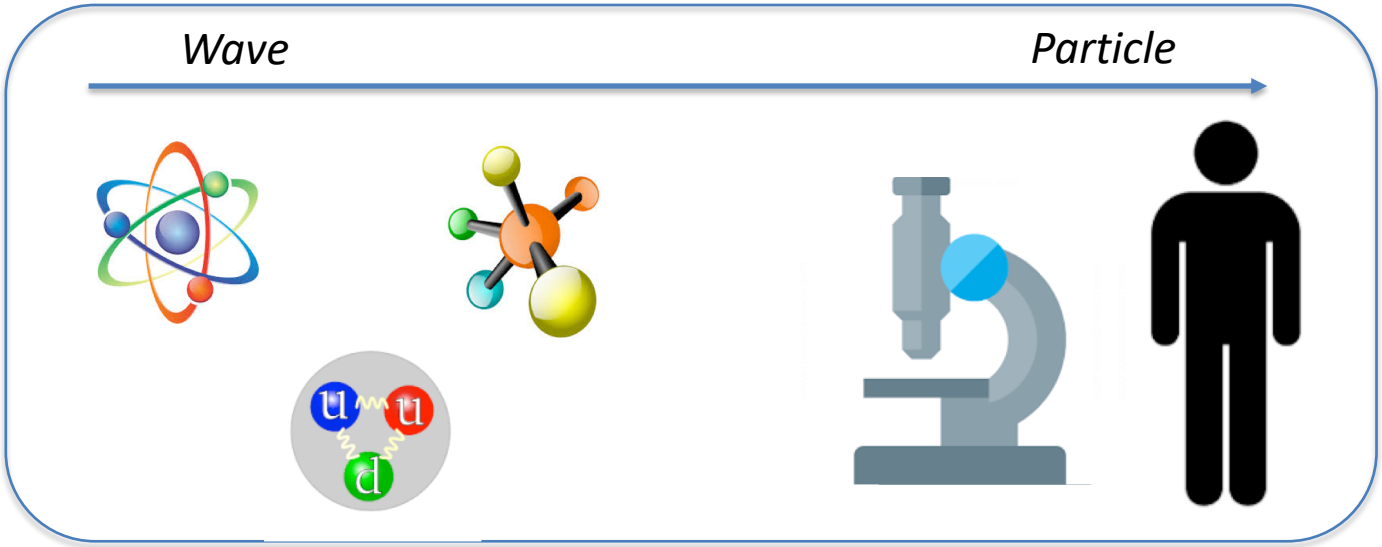
The cat is always **either here or there.**

The wave function is there to guide the cat.

Collapse models

The wave function does describe the state of the system*. Microscopic systems are quantum (linearity), macroscopic systems are not (breakdown of linearity).

This is implemented by modifying the Schrödinger equation. The new dynamics is **nonlinear** and describes the quantum micro-world, the classical macro-world, as well as the transition from one to the other.



Unified dynamics for microscopic and macroscopic systems
(title of the original GRW paper)

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:

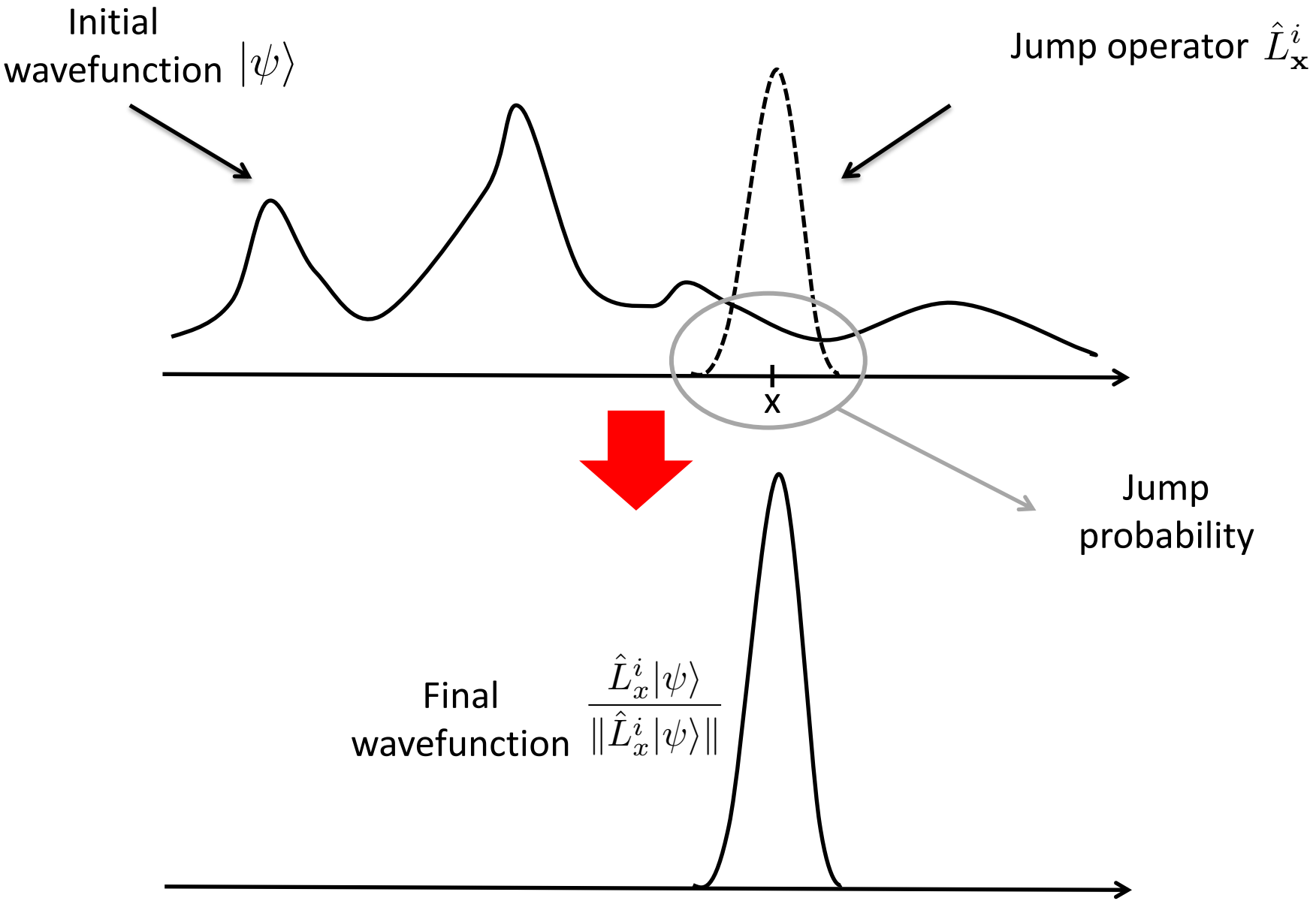
$$|\psi\rangle \rightarrow \frac{\hat{L}_x^i|\psi\rangle}{\|\hat{L}_x^i|\psi\rangle\|} \qquad \hat{L}_x^i = \left(\frac{1}{\pi r_C^2}\right)^{\frac{3}{4}} e^{-\frac{(\hat{q}_i - x)^2}{2r_C^2}}$$

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

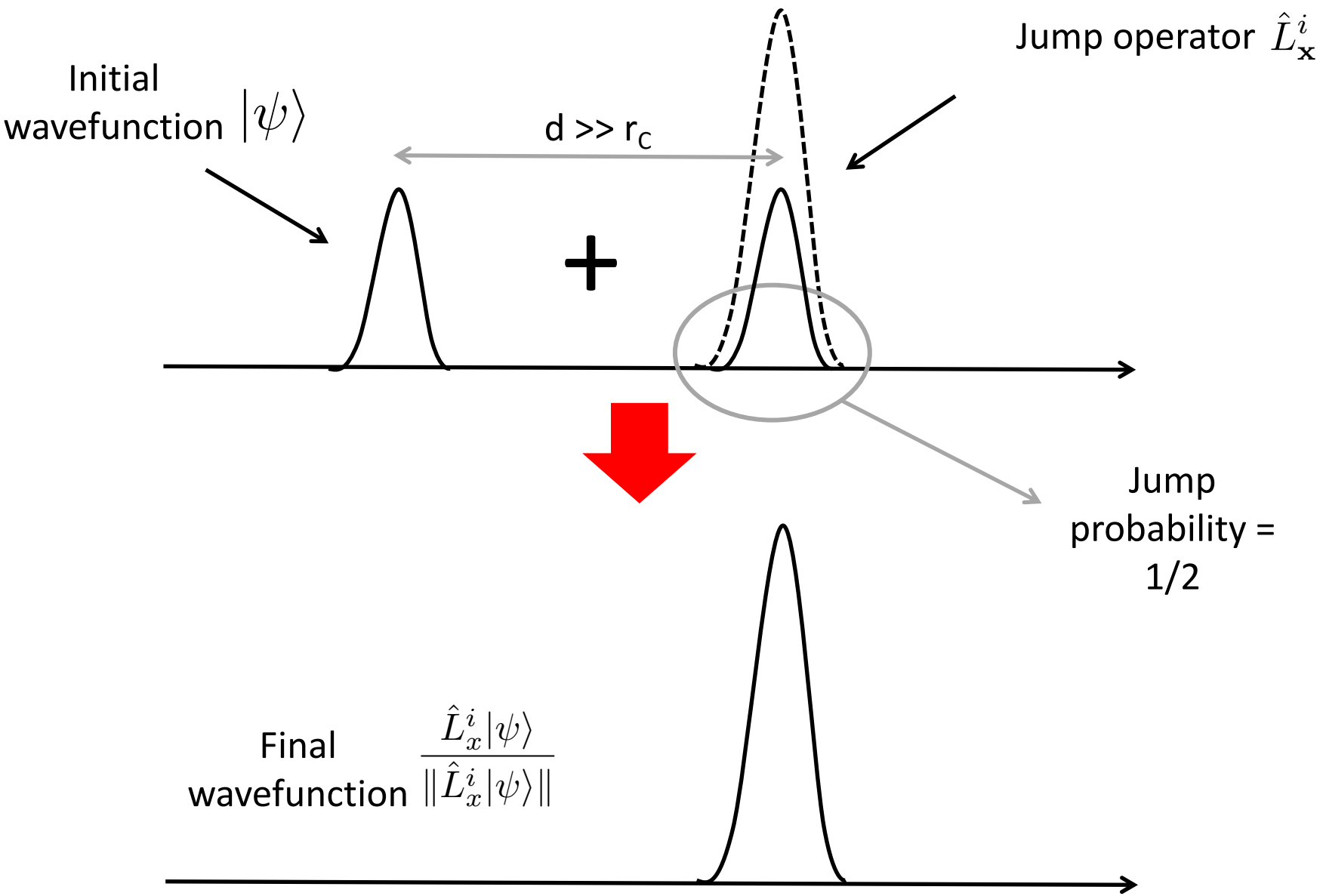
➔ Collapses are random in space and time

➔ Two parameters defining the model: λ and r_C

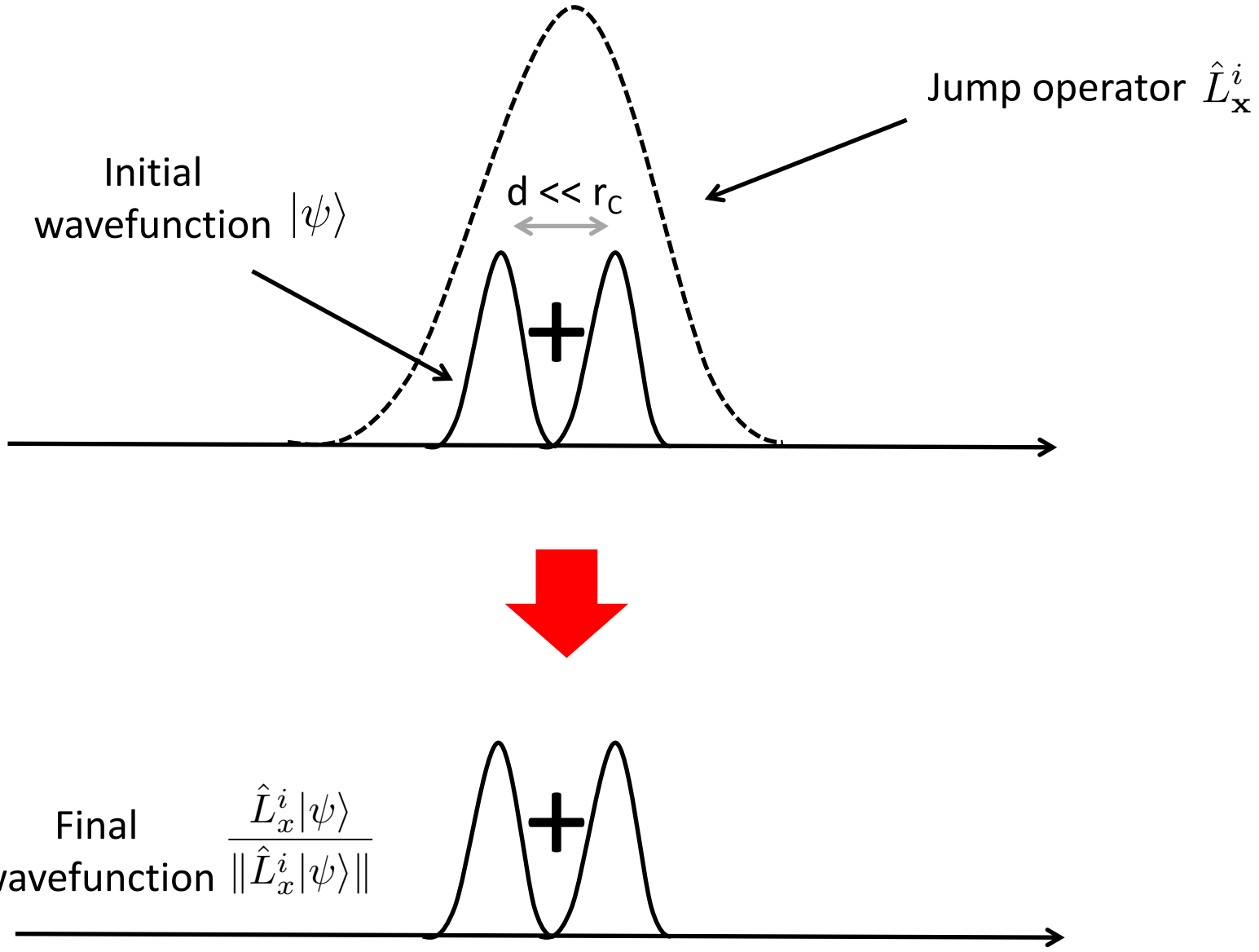
The jump


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

Example: “large” superposition



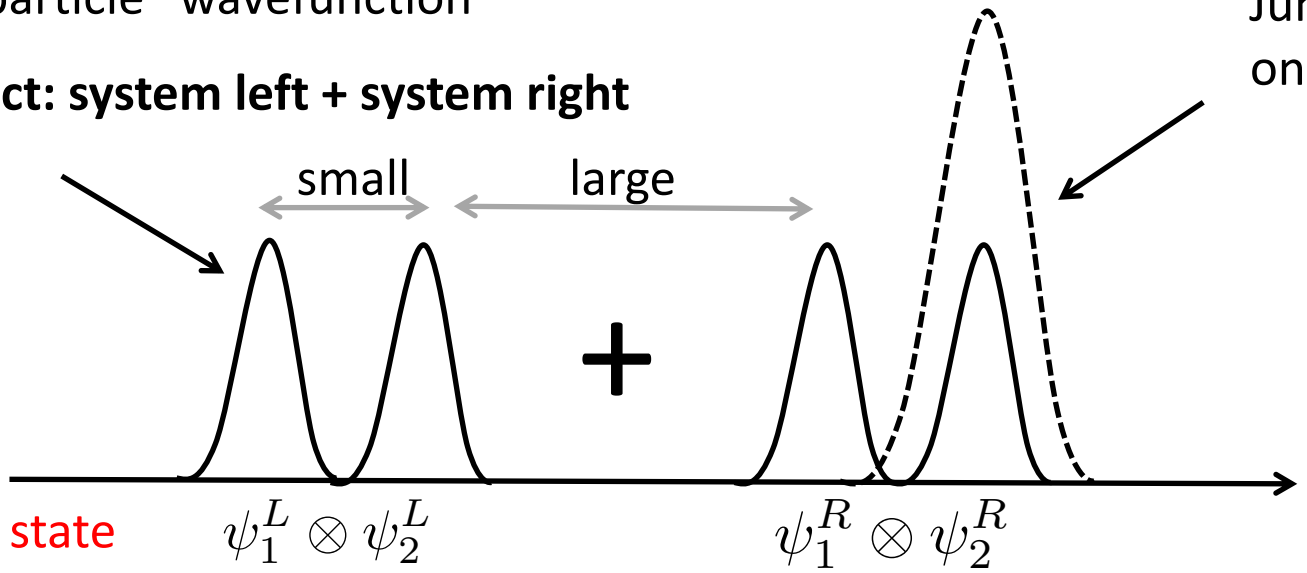
Example: “small” superposition



Amplification mechanism

Initial “2-particle” wavefunction

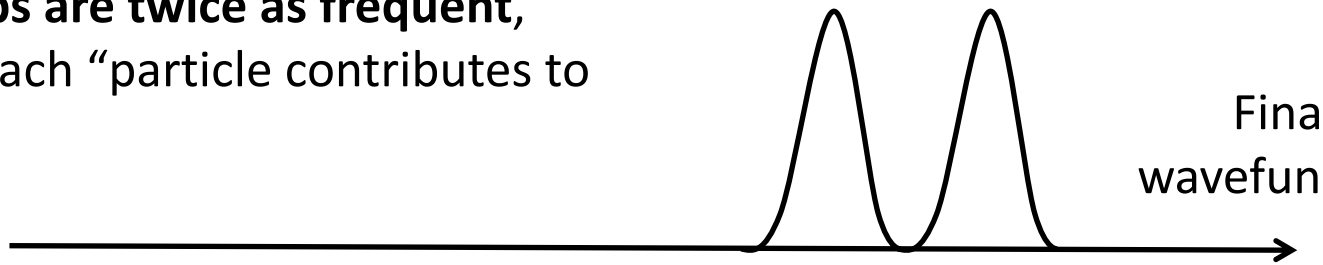
Rigid object: system left + system right



Jump operator on “particle” 2

Entangled state

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

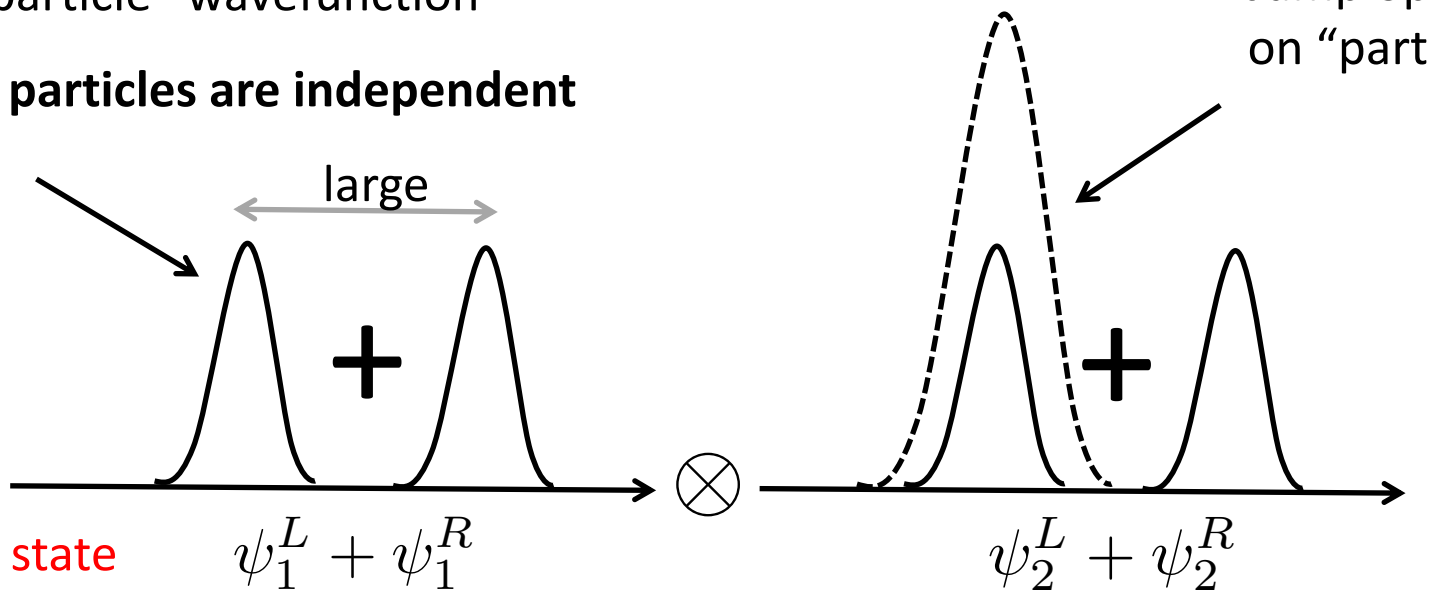


Final wavefunction

However

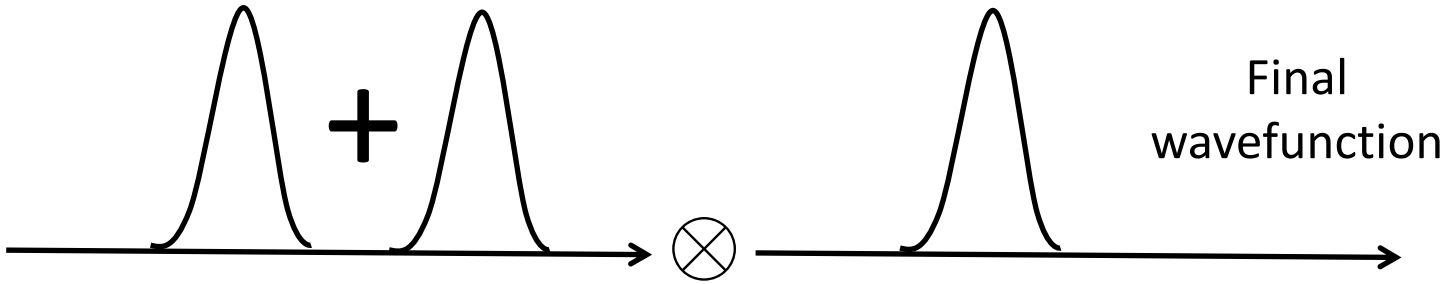
Initial “2-particle” wavefunction

Ideal gas: particles are independent



Factorized state

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



The overall picture

Hilbert space

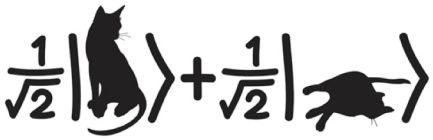
Stable. λ too small

Microscopic systems

Stable. Already localized ($d << r_C$)

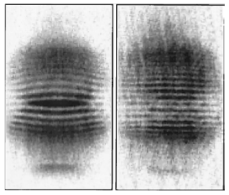
Macroscopic objects

Unstable! Nλ large and $d >> r_C$



Macro superpositions

Stable. No cat-like superposition



BECs, SQUIDs, superfluids …

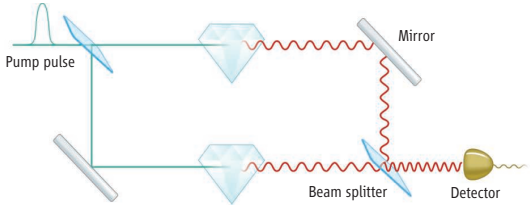
Experiments

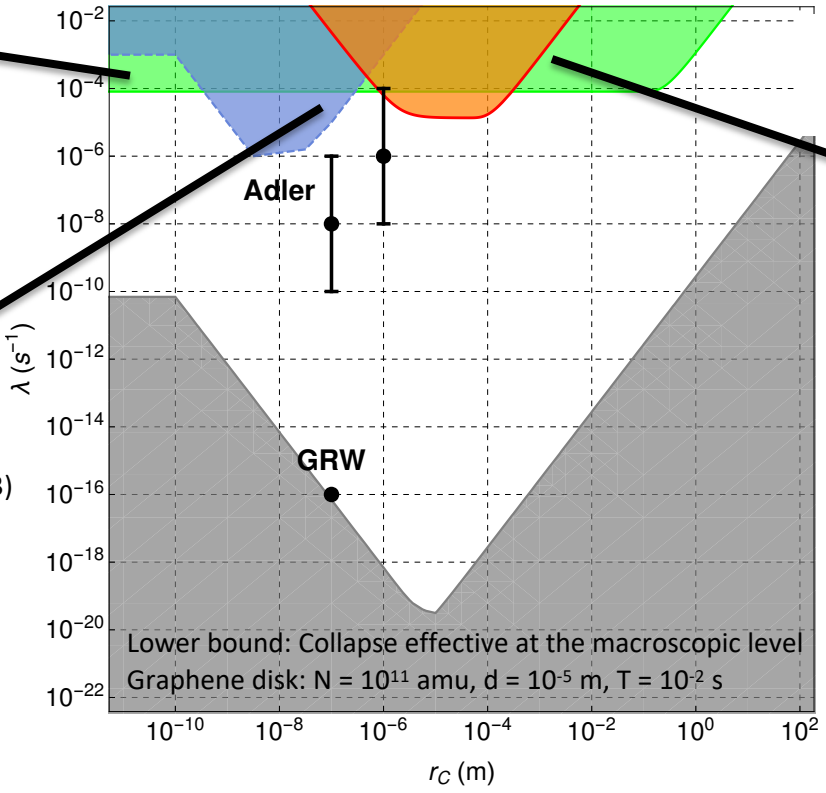
Interferometric Experiments

Atom Interferometry

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

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





Molecular Interferometry

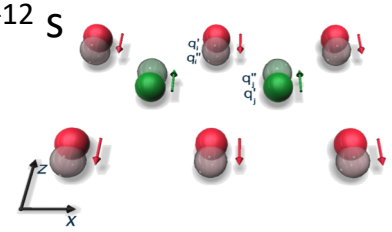
S. Eibenberger *et al.* PCCP 15, 14696 (2013)
M. Toros *et al.,* ArXiv 1601.03672

M = 10^4 amu
d = 10^{-7} m
T = 10^{-3} s

Entangling Diamonds

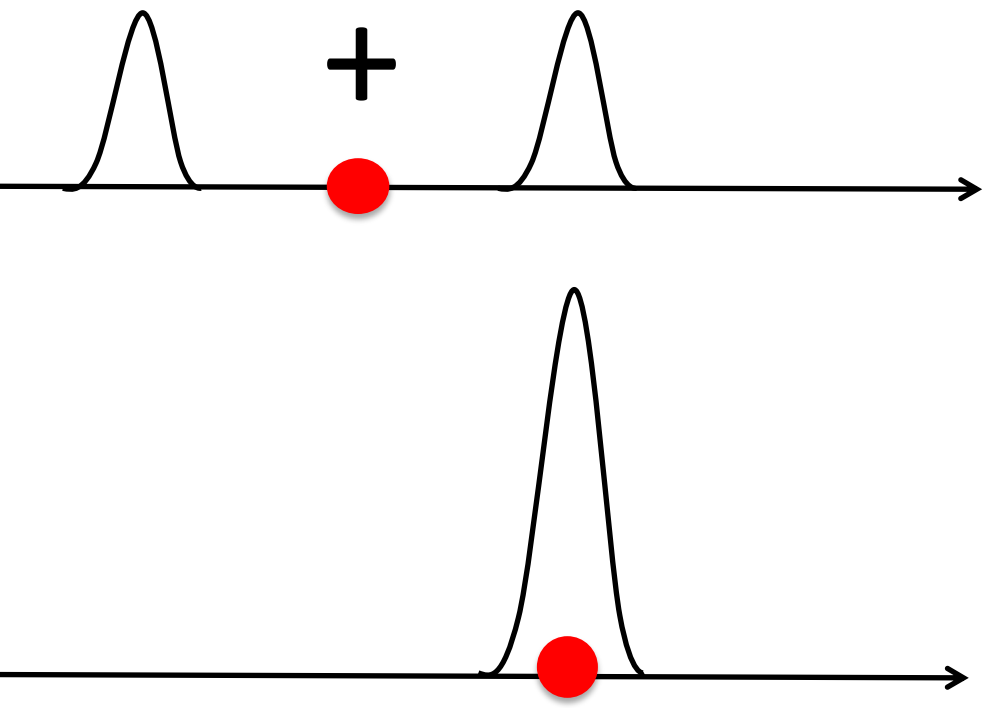
K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al.,* PRA 94, 012108 (2016)

M = 10^{16} amu
d = 10^{-11} m
T = 10^{-12} 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

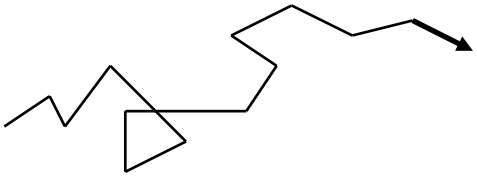


collapse

= center of mass

A localization of the wave function changes the position of the center of mass

Collapse-induced Brownian motion



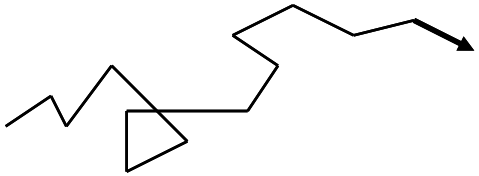
Also theoretical reasons for that

Non-interferometric tests

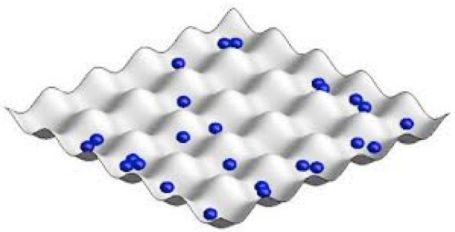
Center of mass motion of a quantum system (either simple or complex)

Quantum Mechanics

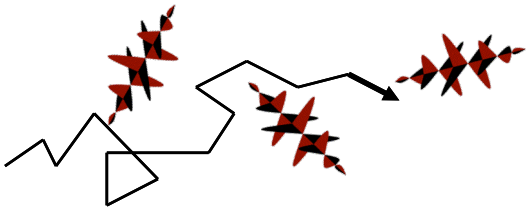
Collapse models



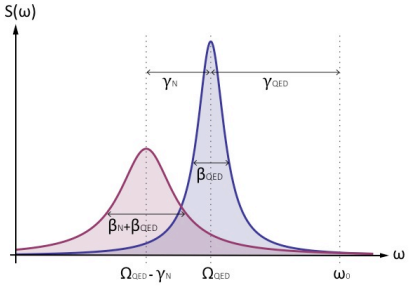
A **gas** will **expand** (heat up) faster than what predicted by QM



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



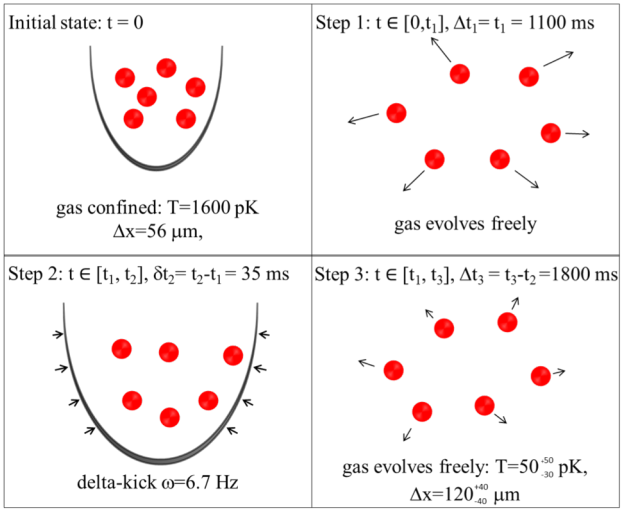
A **cantilever**'s motion cannot be **cooled down** below a given limit

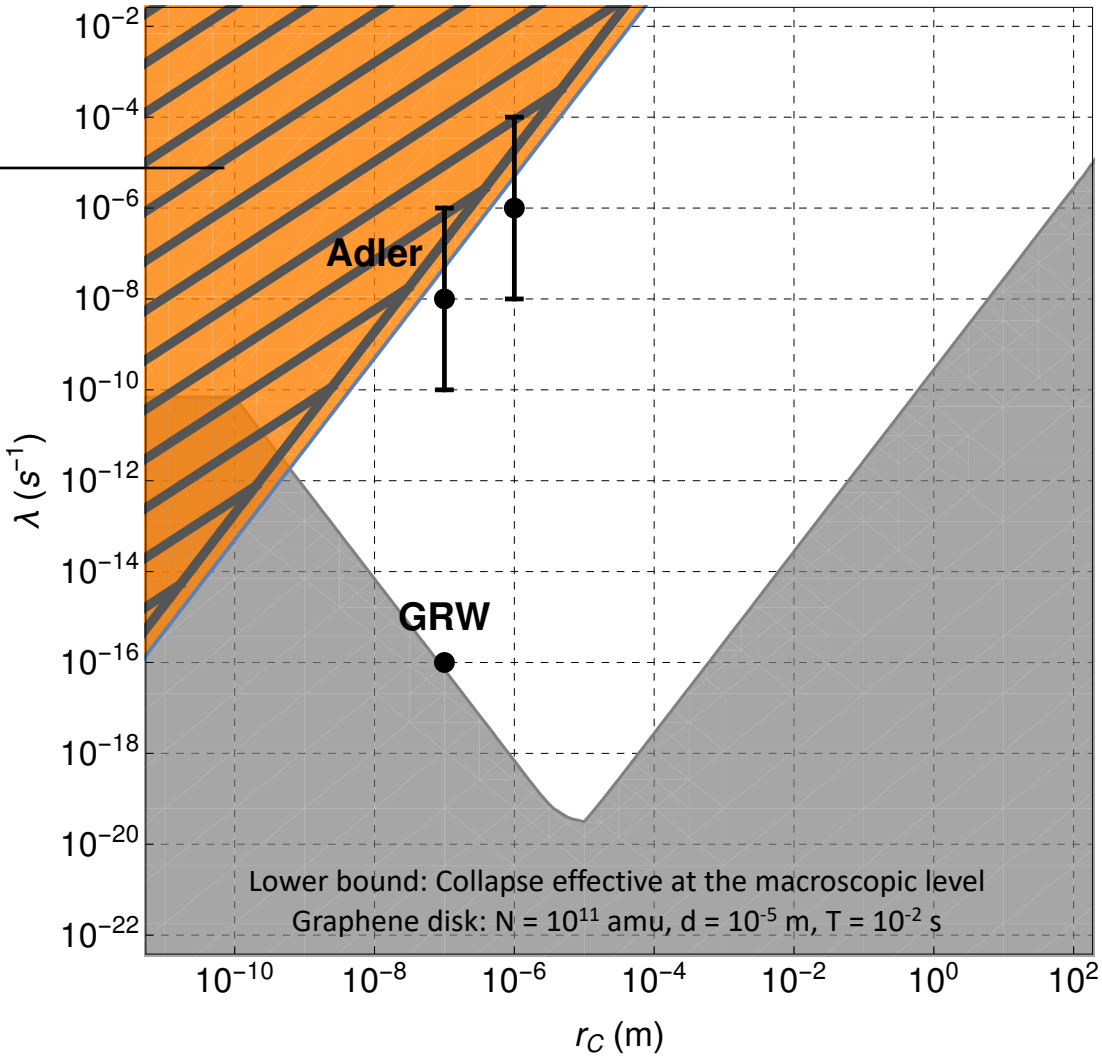


Non - Interferometric Experiments

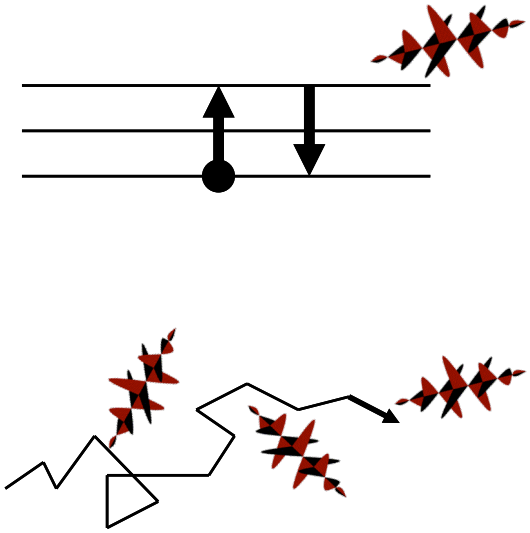
Cold atom gas

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)



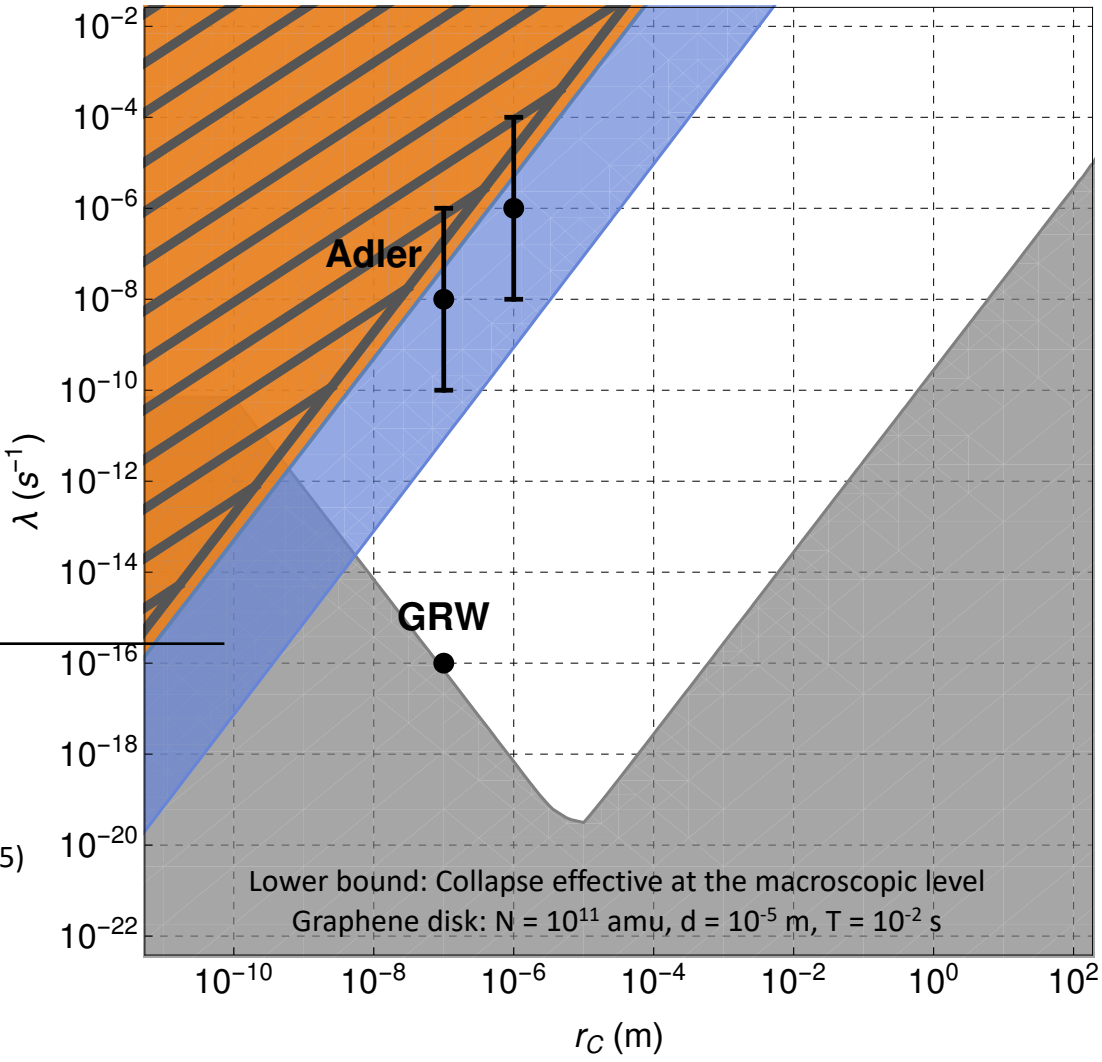


Non - Interferometric Experiments

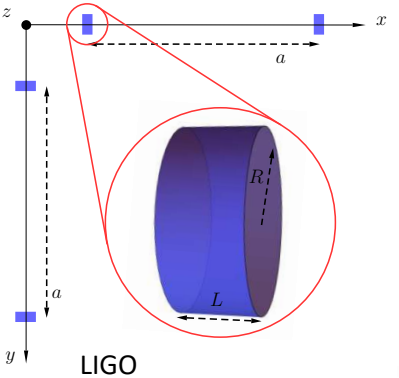


X rays

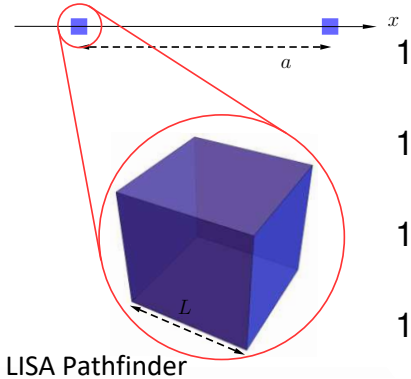
S.L. Adler *et al.,* Jour. Phys. A 40, 13395 (2009)
S.L. Adler *et al.*, Journ. Phys. A 46, 245304 (2013)
A. Bassi & S. Donadi, Annals of Phys. 340, 70 (2014)
S. Donadi & A. Bassi, Jounr. Phys. A 48, 035305 (2015)
C. Curceanu *et al.,* J. Adv. Phys. 4, 263 (2015)
+ several more



Non - Interferometric Experiments



LIGO

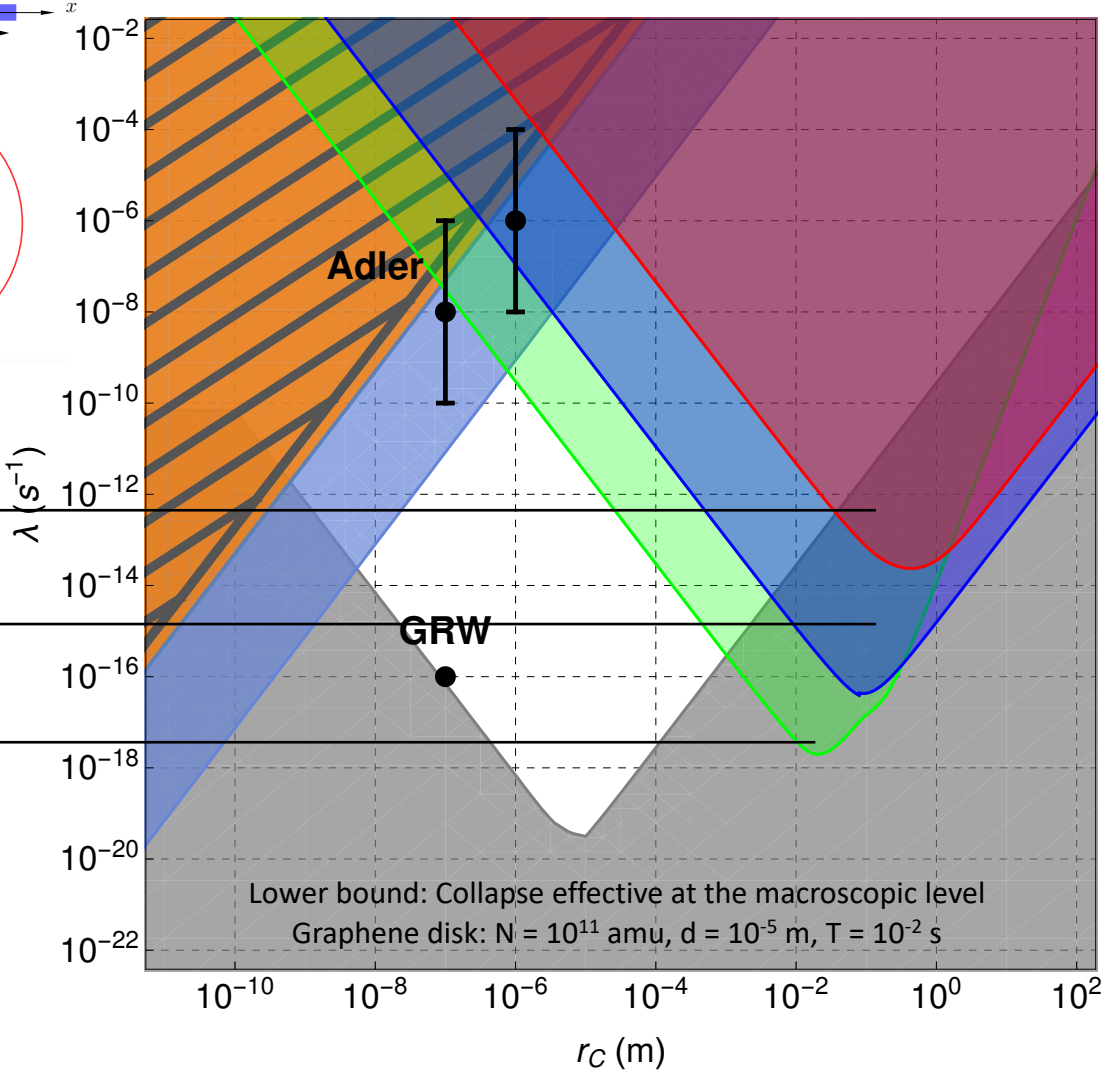


LISA Pathfinder

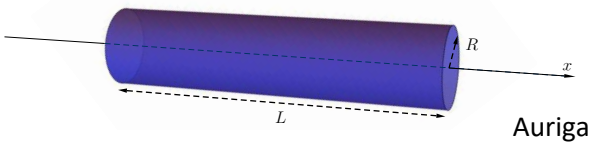
Auriga

Ligo

Lisa Pathfinder



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

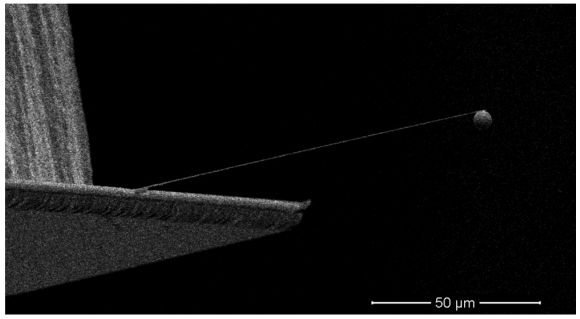


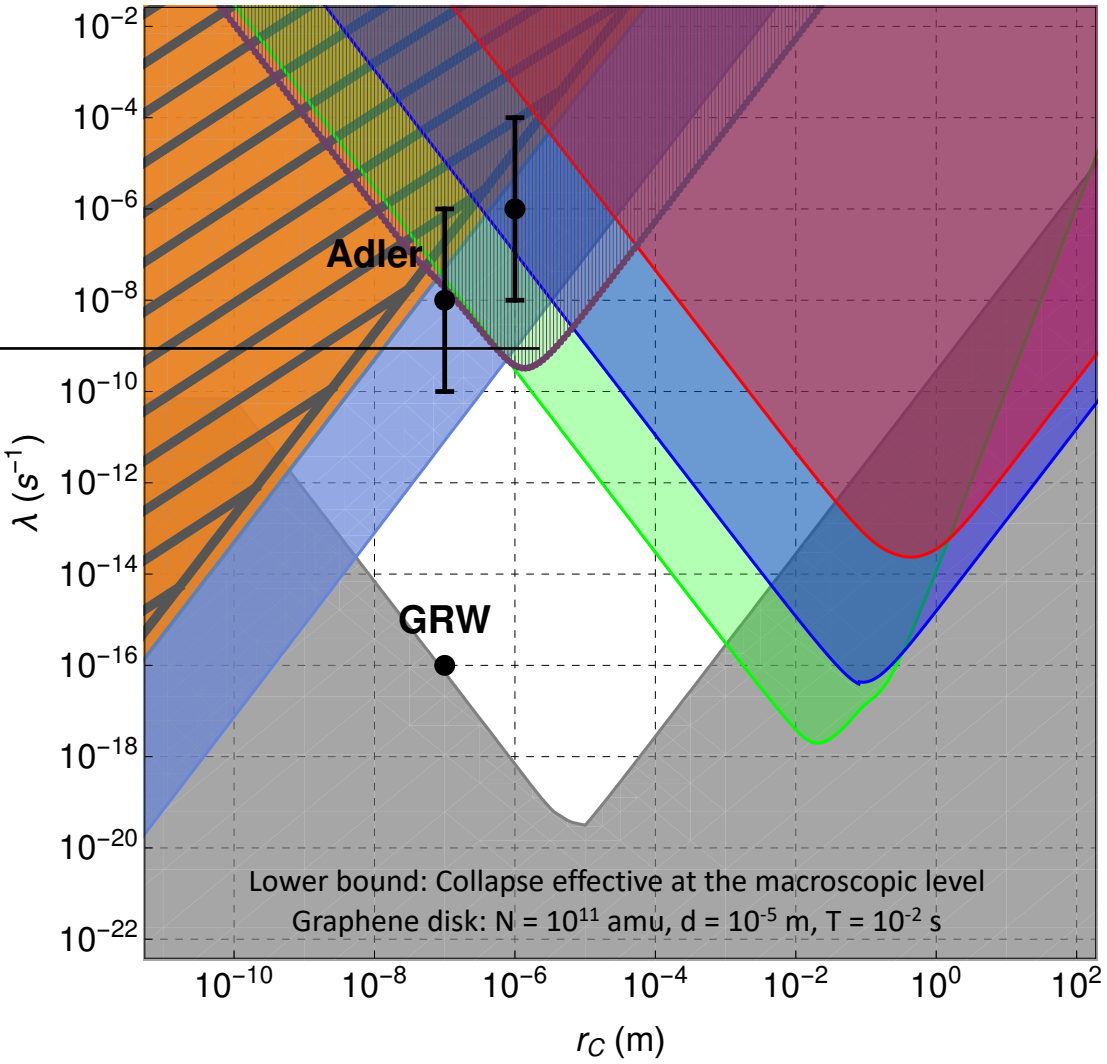
Auriga

Non - Interferometric Experiments

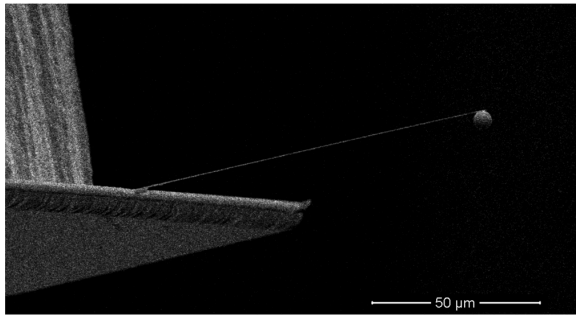
Cantilever

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



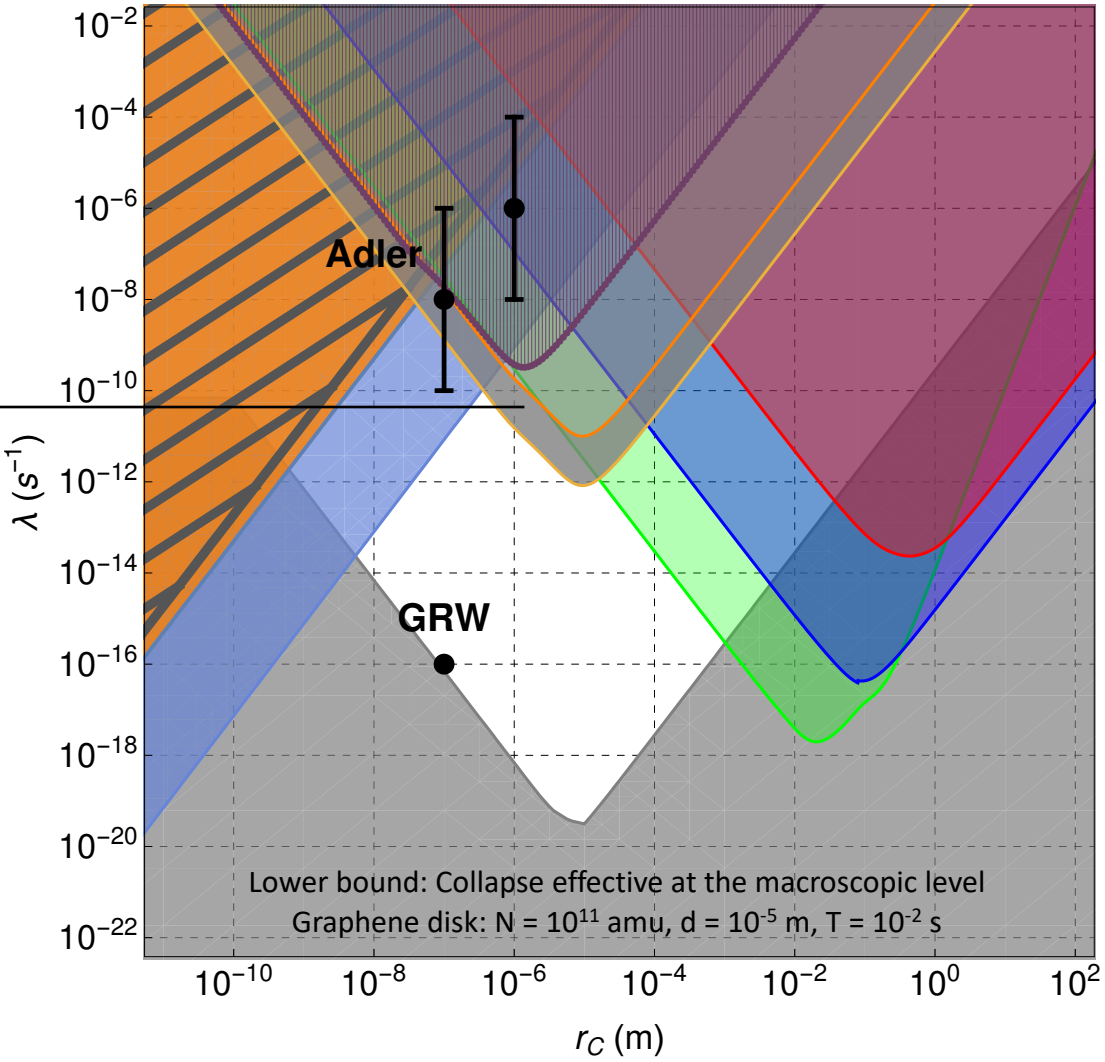


Non - Interferometric Experiments



Cantilever – update

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



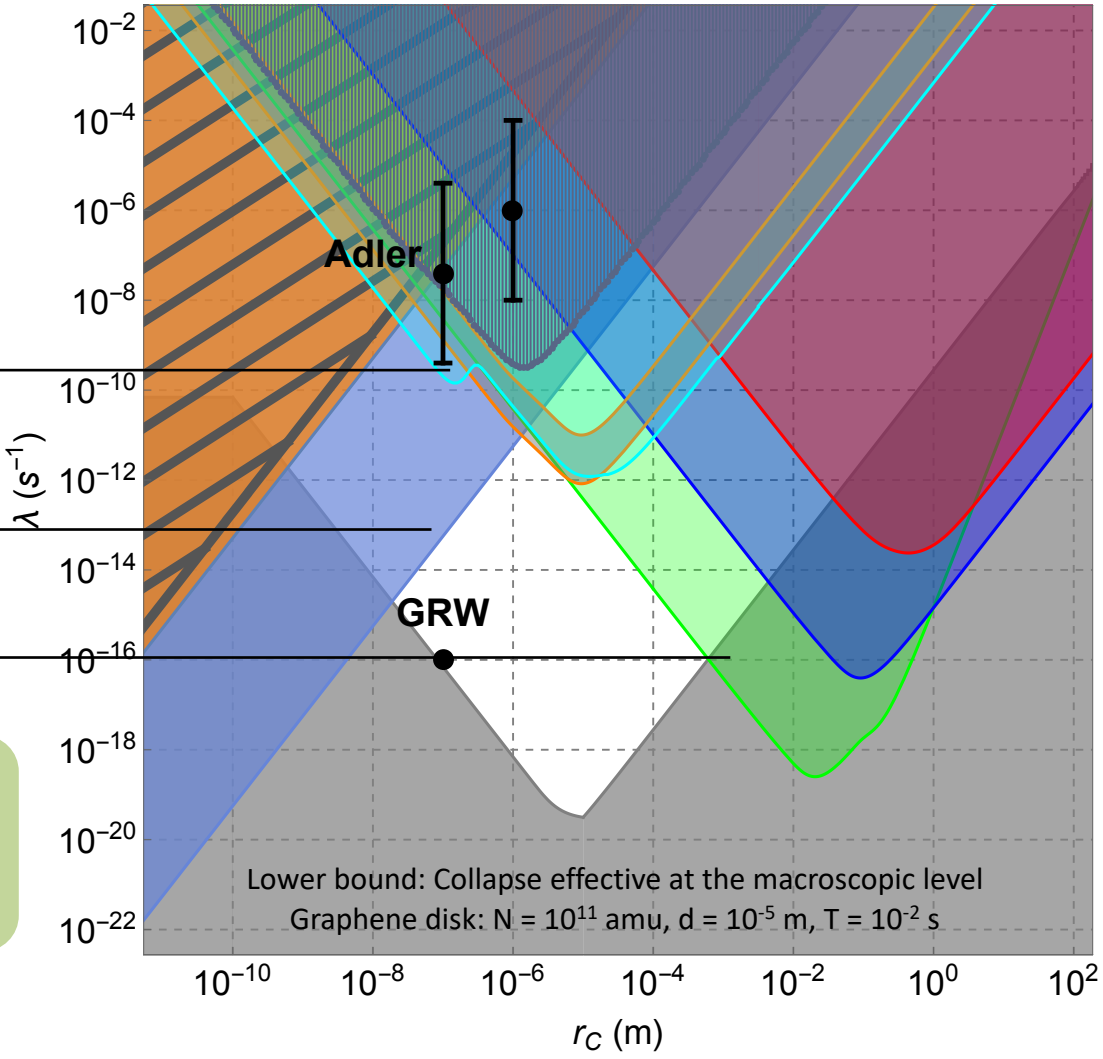
Non - Interferometric Experiments

Update 2

A. Vinante *et al., Phys. Rev. Lett. (2020), to appear.*

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

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



H2020 FET project
www.tequantum.eu

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The Group (www.qmts.it)

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

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