Spontaneous wave function collapse models: an introduction

Training school: Are spin-statistics connection and quantum theory exact? The endeavor for the theory beyond standard quantum mechanics

LNF-INFN Frascati, 19th – 21st December 2016

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Motivation

It would seem that the theory is exclusively concerned about 'results of measurement', and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of 'measurer'? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system . . . with a PhD? If the theory is to apply to anything but highly idealised laboratory operations**, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?**

The GRW model is based on the acceptance of the fact that the Schrodinger dynamics, governing the evolution of the wavefunction, has to be modified by the inclusion of stochastic and nonlinear effects.

Against ‘measurement’

JOHN BELL

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

The GRW model

Systems are described by the **wave function**, which evolves according to the following dynamics.

The wave function is subject to **random jumps**, independently for each “particle”:

$$\psi \longrightarrow \frac{\psi^i_{\mathbf{x}}}{\|\psi^i_{\mathbf{x}}\|}, \qquad \psi^i_{\mathbf{x}} = \hat{L}^i_{\mathbf{x}}\psi, \qquad \hat{L}^i_{\mathbf{x}} = \frac{1}{(\pi r_C)^{3/4}} \exp\left[-\frac{(\hat{\mathbf{q}}_i - \mathbf{x})^2}{2r_C^2}\right]$$

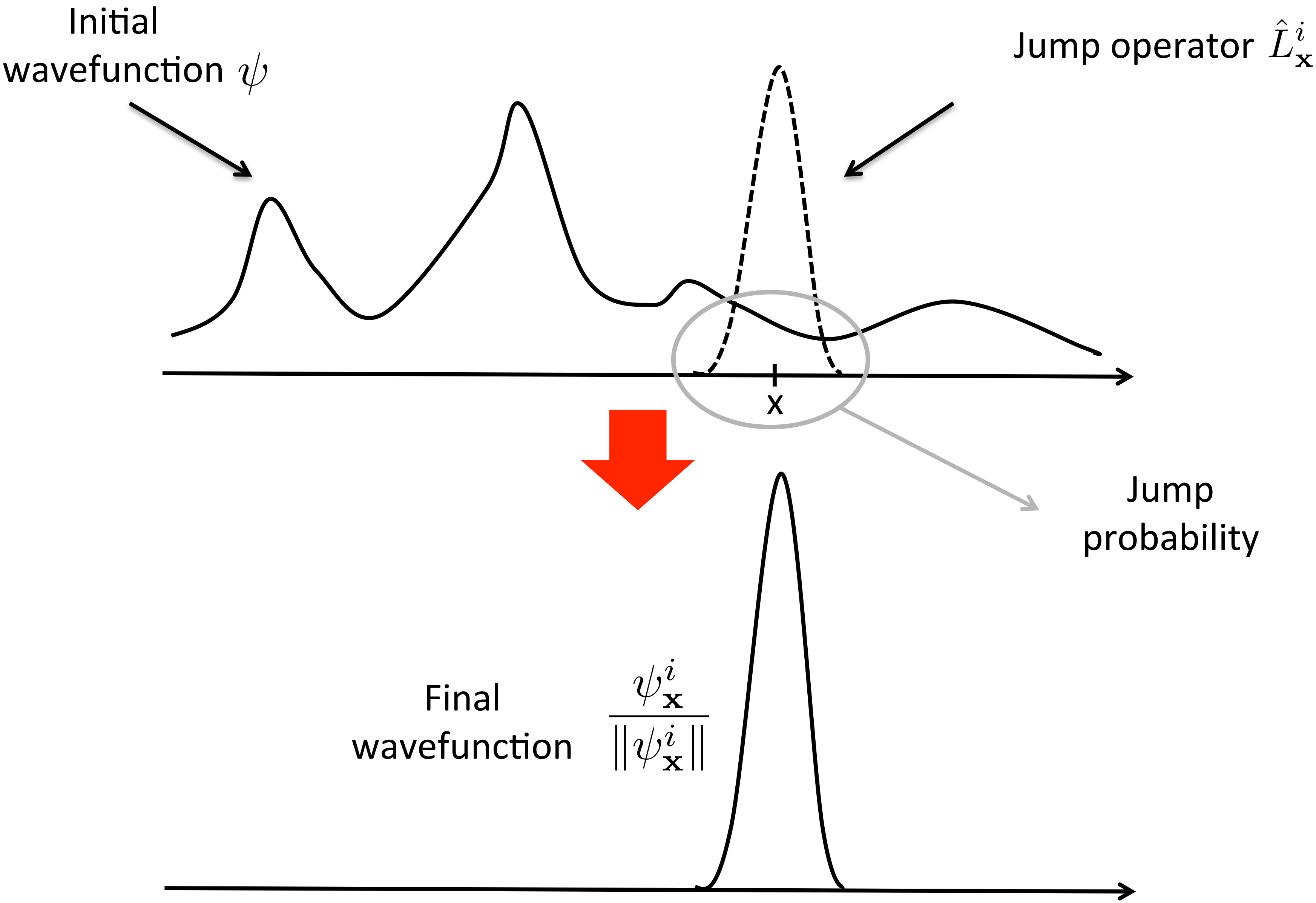
i = degree of freedom (“i’th particle” of a multi-particle system), **x** = point in space, q_i = position operator of the “i’th particle”.

The jumps are **random in time** (distributed according to a Poissonian distribution with mean frequency λ), **and in space** (with probability density $||\psi^i_{\mathbf{x}}||^2$)

In between jumps, the wave function evolves according to the **Schrödinger equation.**

Note. Two phenomenological parameters: λ and r_C.

The jump


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

Diffusion Process in Hilbert Space

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

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

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

nonlinearity

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

stochasticity

All of quantum (and classical) mechanics follows

(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)

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

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

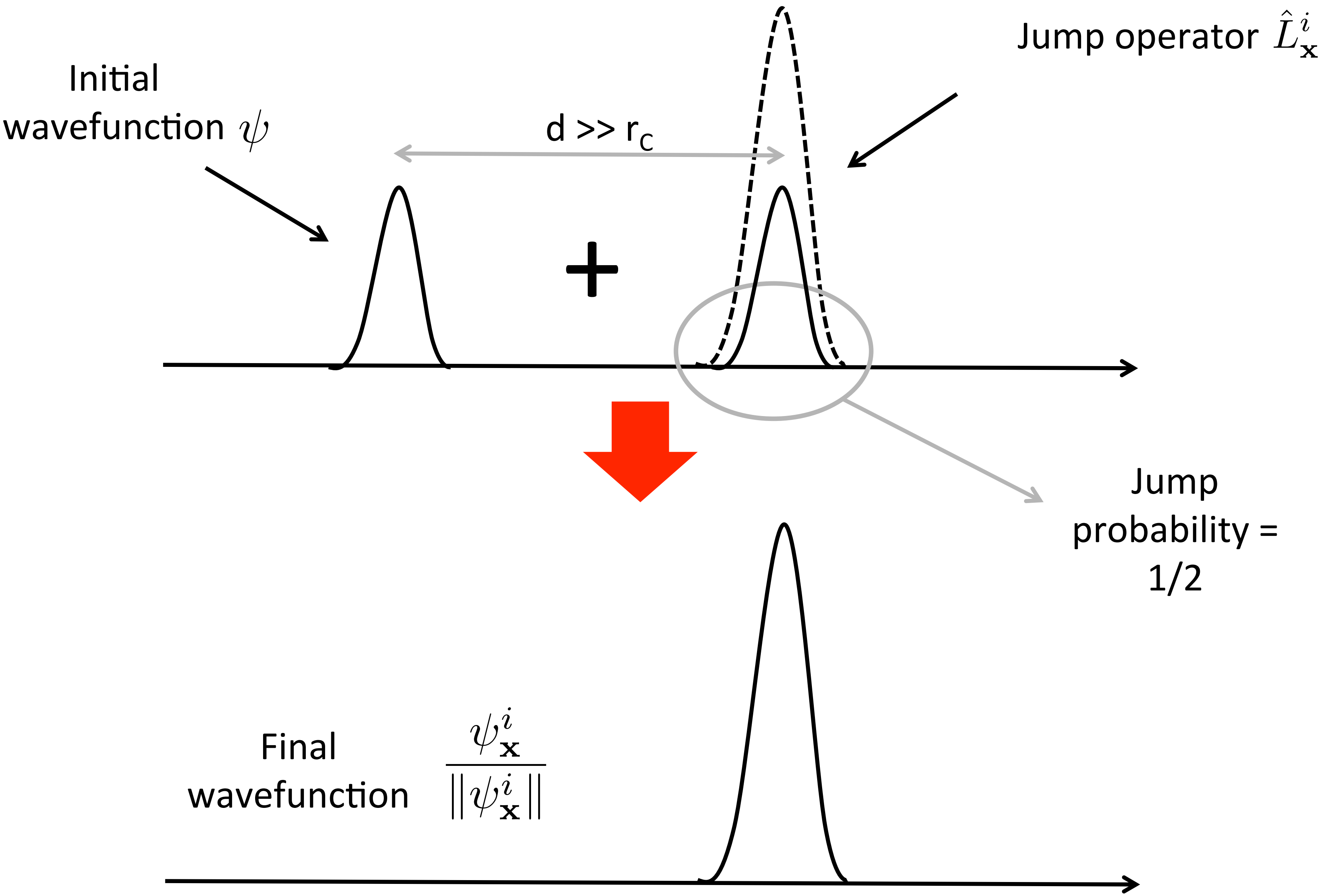
The operators are function of the space coordinate. **The collapse occurs in space.**

Two parameters

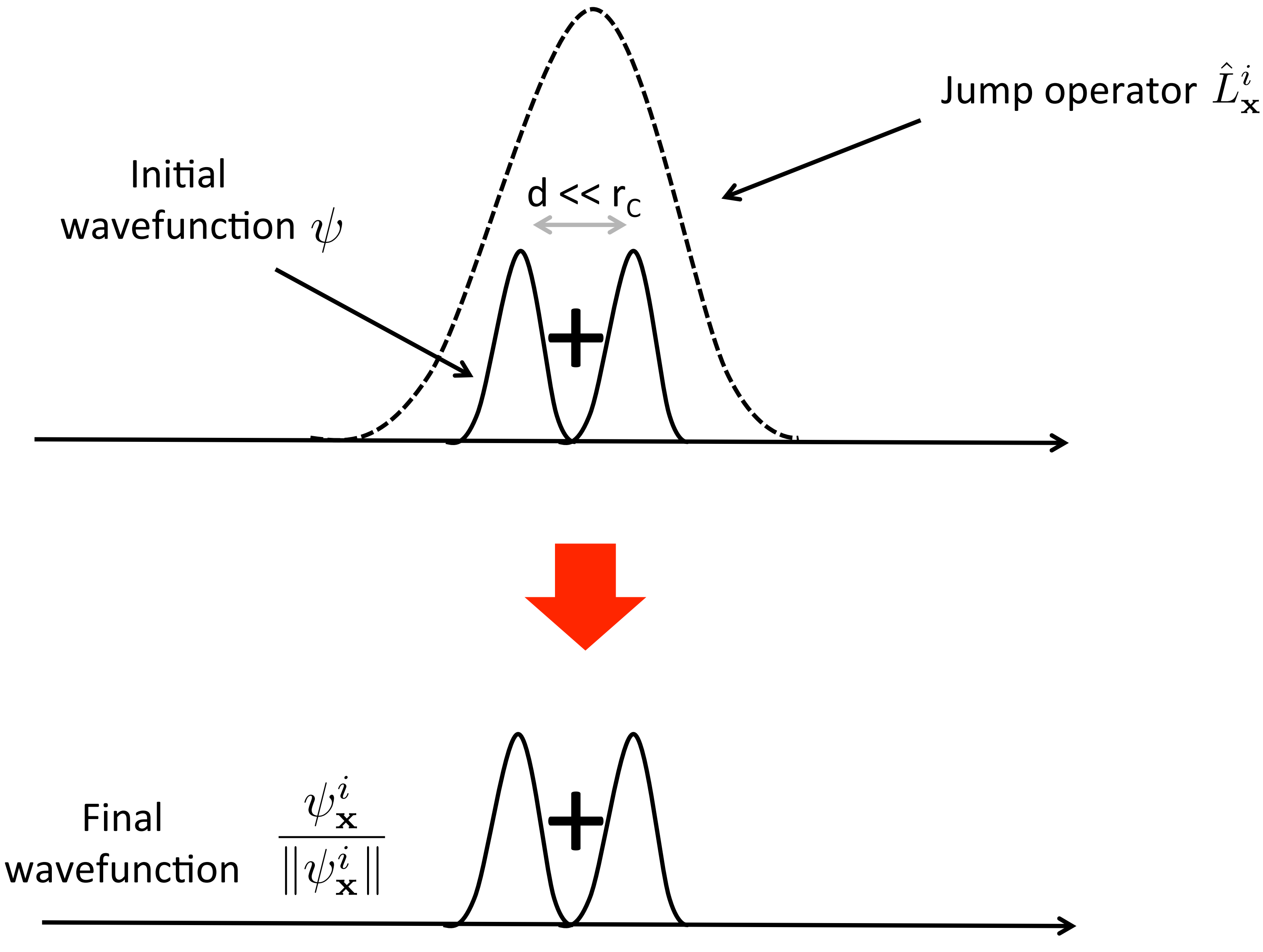
$$\gamma = \text{collapse strength} \qquad r_C = \text{localization resolution}$$

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

Example: “large” superposition



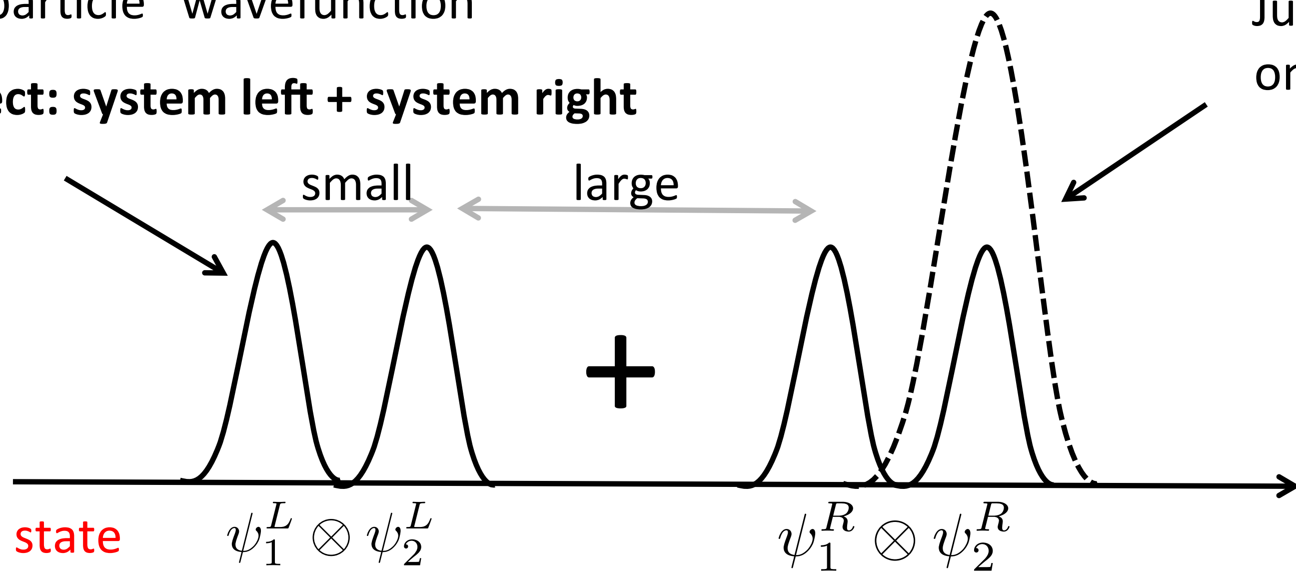
Example: "small" superposition



Amplification mechanism

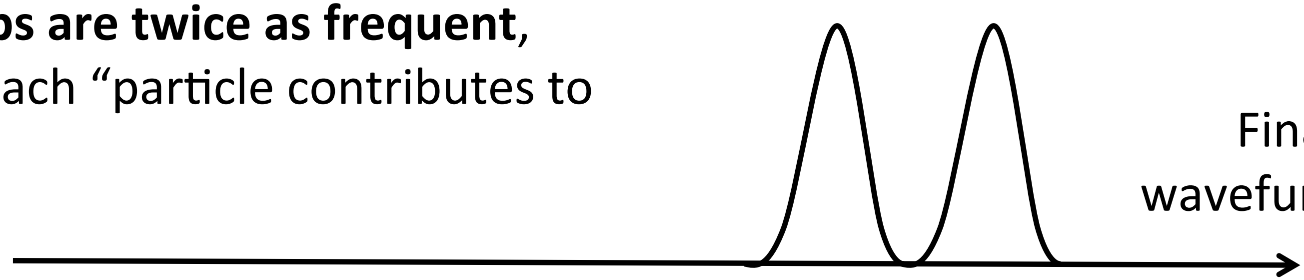
Initial “2-particle” wavefunction

Rigid object: system left + system right



Entangled state

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



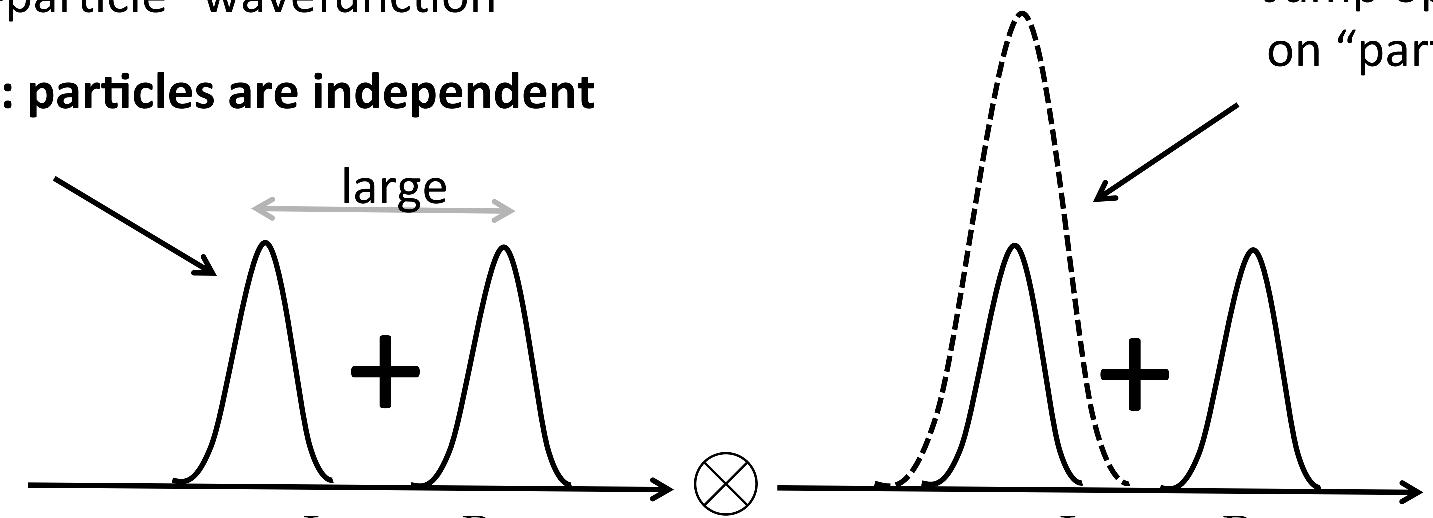
Final wavefunction

However

Initial “2-particle” wavefunction

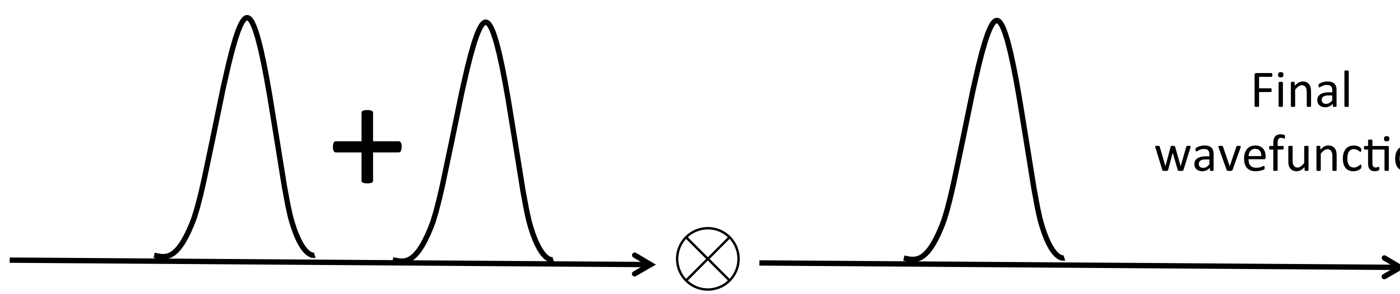
Ideal gas: particles are independent

Jump operator on “particle” 2



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

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

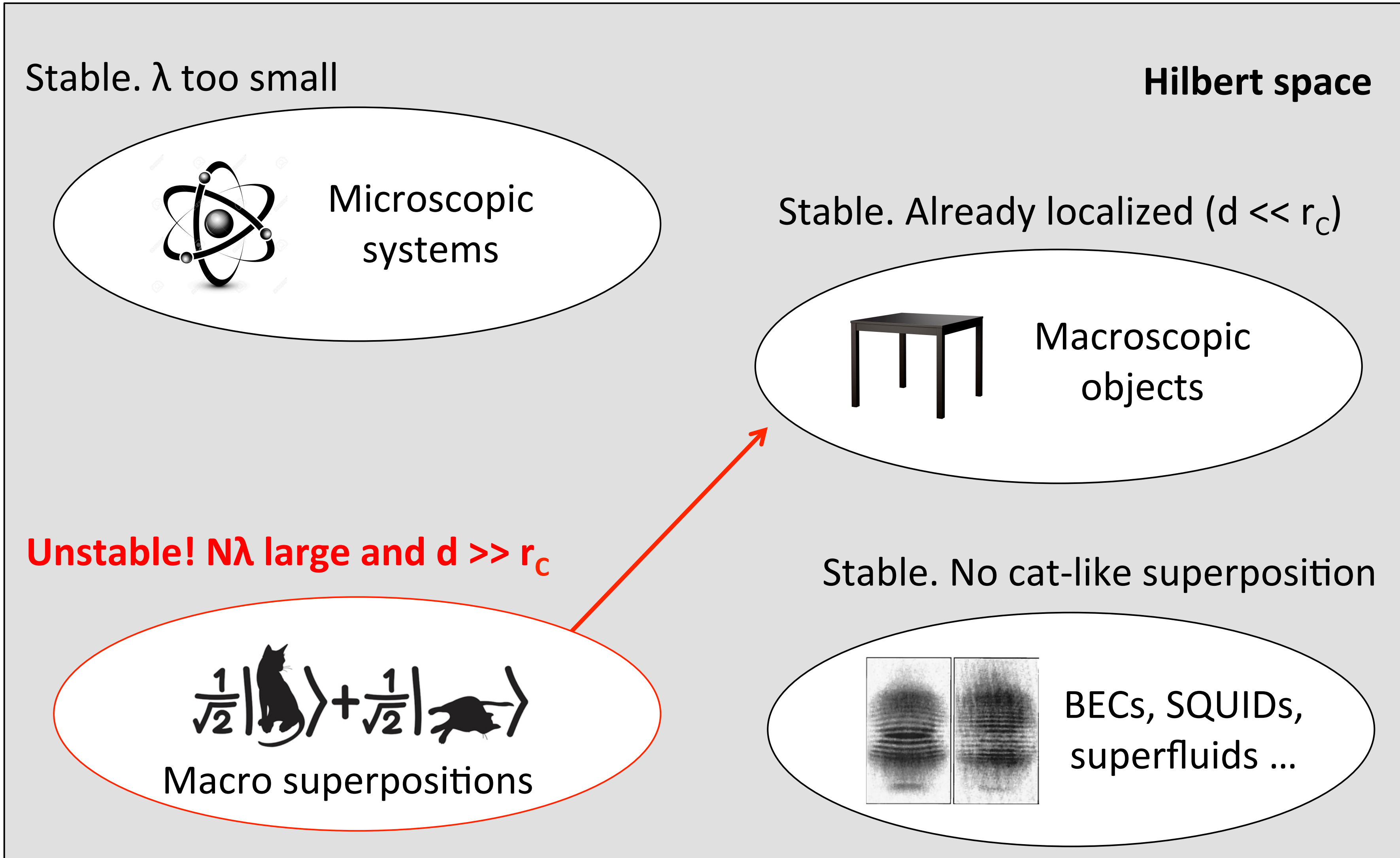
$N\,\lambda = 10^{24} \times 10^{-16}\ s^{-1} = 10^{8}\ s^{-1}$

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



Ontology

Collapse models

They are phenomenological models

The wave function is not fundamental in any way

Still looking for the underlying theory

No idea what the appropriate ontology is

GRW theory

Are they consistent theories of nature?

Yes (or perhaps) with an appropriate ontology

- Wave function ontology
- Mass density ontology
- Flash ontology
- Particle ontology

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, in preparation

Collapse models in space

REVIEW: A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003) **REVIEW**: A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht*, Rev. Mod. Phys.* 85, 471 (2013)	**White noise models** All frequencies appear with the same weight	**Colored noise models** The noise can have an arbitrary spectrum
Infinite temperature models No dissipative effects	**GRW / CSL** G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986) G.C. Ghirardi, P. Pearle, A. Rimini, *Phis. Rev. A* 42, 78 (1990) **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989) **DP** L. Diosi, *Phys. Rev. A* 40, 1165 (1989)	**Non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler & A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **Non-Markovian QMUPL** A. Bassi & L. Ferialdi, *Phys. Rev. Lett.* 103, 050403 (2009)
Finite temperature models Dissipation and thermalization	**Dissipative QMUPL** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). **Dissipative GRW & CSL** A. Smirne, B. Vacchini & A. Bassi *Phys. Rev. A* 90, 062135 (2014) A. Smirne & A. Bassi *Nat. Sci. Rept.* 5, 12518 (2015)	**Non-Markovian & dissipative QMUPL** L. Ferialdi, A. Bassi *Phys. Rev. Lett.* 108, 170404 (2012)

Three ontologies for GRW

Wave function ontology: there is only psi. End of the story. Because macro-superpositions never occur, this is consistent with our physical worldview.

Plus: Very economical

Minus: One has to accept that the 3D world of particles we have experience of, is an “illusion”. Problem with tails.

Mass density ontology: “project” the wave function to 3D space, and cerate a mass density distribution:

$$m(\mathbf{x},t) = \sum_{i=1}^{N} m_i \int d^{3N}q\, \delta^{(3)}(\mathbf{x}-\mathbf{q}_i)|\psi(q)|^2, \qquad q = (\mathbf{q}_1, ...\mathbf{q}_N)$$

Flash ontology: we are made of flashes, the points around which jumps occur.

Plus: These ontologies makes direct reference to the world as we perceive it.

Minus: One still needs the wave function. A nomological entity?

Relativistic Collapse models

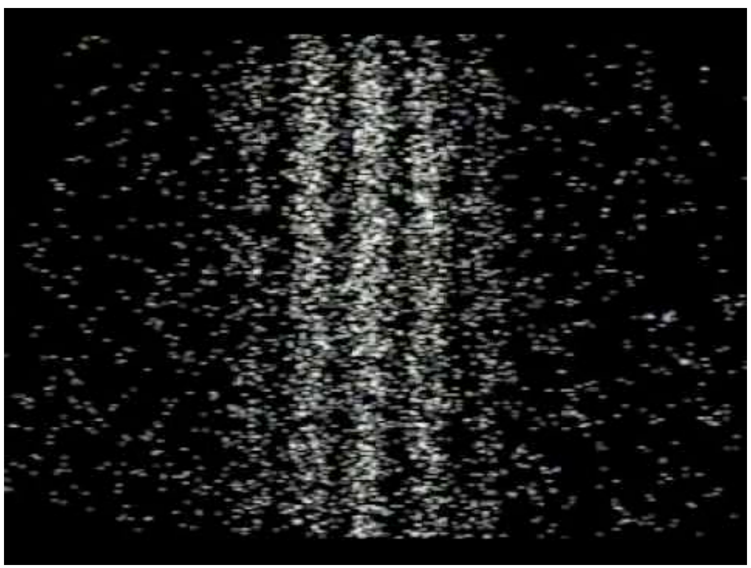
Several relativistic collapse models proposed. No one fully satisfactory so far.

Problem: they must be nonlocal, and that goes directly against relativity.

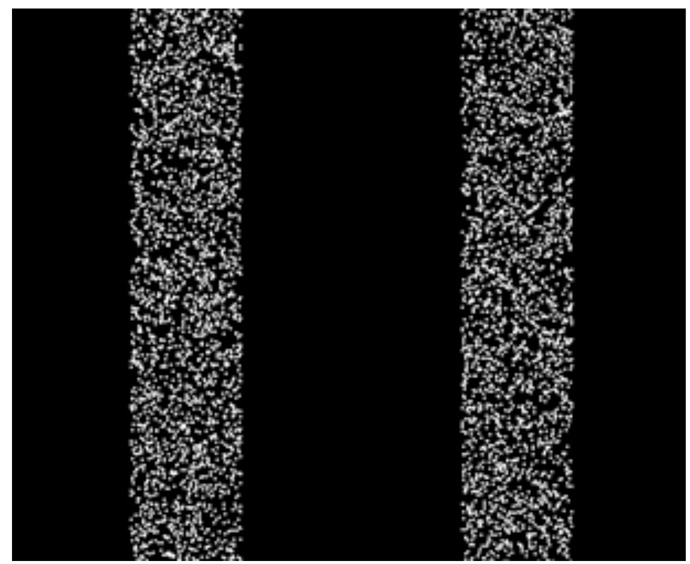
A proposal. Relativity is wrong. It is an approximation. There is a privileged reference frame (the cosmic one). That matches with the idea that the collapse is driven by a cosmological random field.

Experimental tests

The obvious way to test collapse models is with matter-wave interferometry



Prediction of quantum mechanics
(no environmental noise)



Prediction of collapse models
(no environmental noise)

Interferometric Experiments

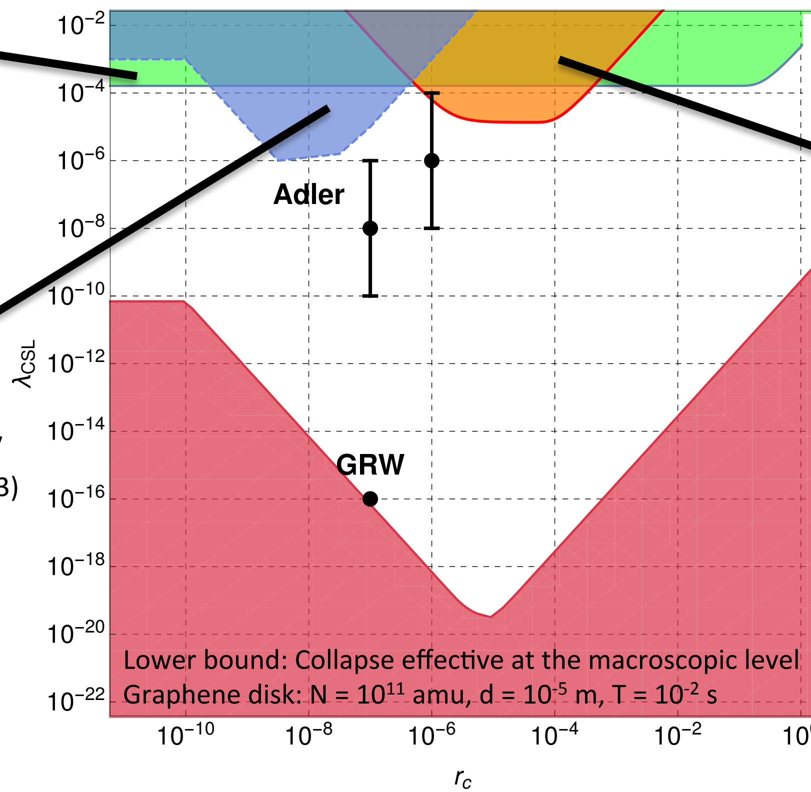
Atom Interferometry

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

M = 87 amu

d = 0.54 m

T = 1 s



Molecular Interferometry

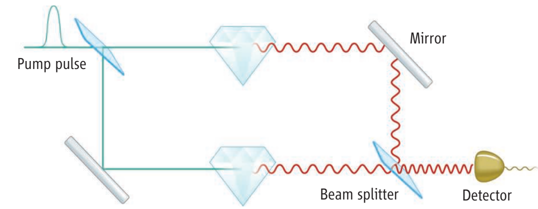
S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M. Toros *et al.*, ArXiv 1601.03672

M = 10^4 amu

d = 10^{-7} m

T = 10^{-3} s



Entangling Diamonds

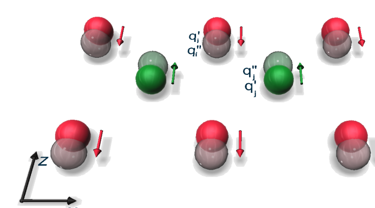
K. C. Lee *et al.*, Science. 334, 1253 (2011).

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 be necessary to go to micro-gravity environment in outer space. COST Action QTSpace. http://www.cost.eu/COST_Actions/ca/CA15220

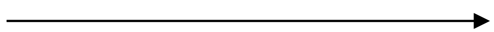
Non interferometric tests

M. Bahrami, M. Paternostro, A. Bassi, H. Ulbricht, *Phys. Rev. Lett.* 112, 210404 (2014). S. Nimmrichter, K. Hornberger, K. Hammerer, *Phys. Rev. Lett.* 113, 020405 (2014). L. Diósi, *Phys. Rev. Lett.* 114, 050403 (2015)

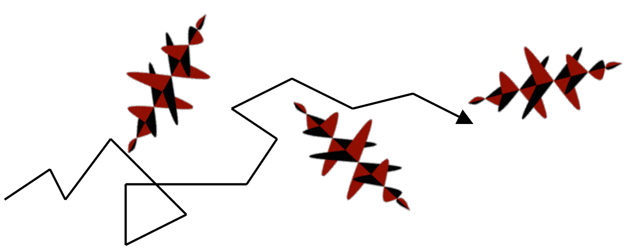
The collapse induces a **Brownian motion** on the system

Charged free particle

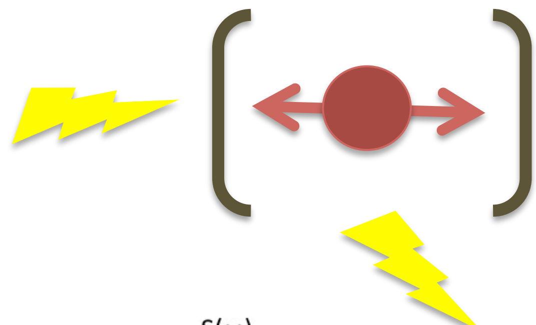
1. Quantum mechanics



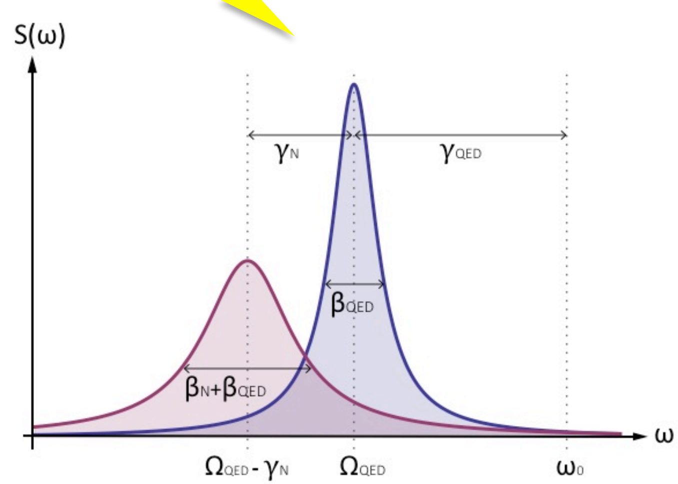
2. Collapse models



Spontaneous photon emission

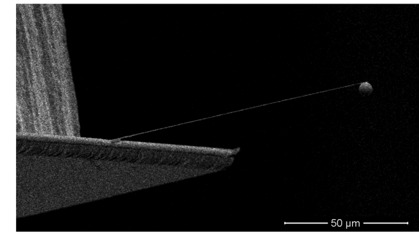


Nano-particle in a optical cavity



Extra shift and broadening

Non-Interferometric Experiments

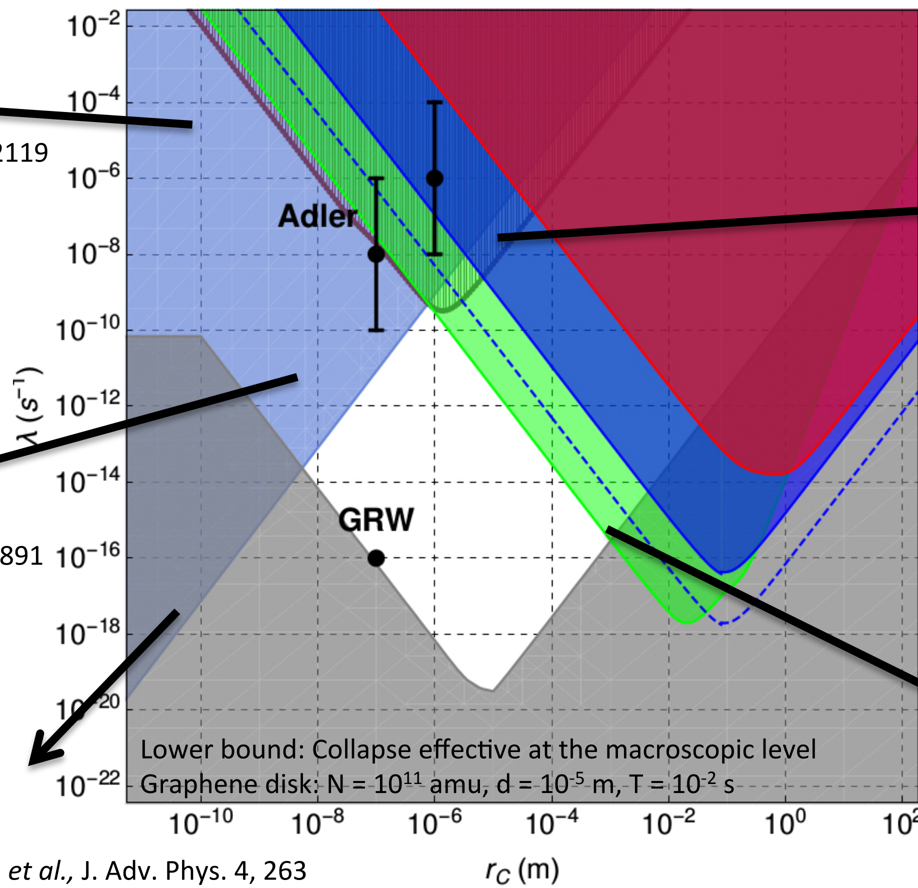


Cold Atom Gas
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)

M = 87 amu
T = 30 s

Cold Atom Gas
M. Bilardello *et al.*, ArXiv 1605.01891

M = 87 amu
T = 1 s



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

M = 1 Kg
T = days / months

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

M = 10^{14} amu
T = ∞

Gravitational wave detectors
M. Carlesso *et al.*, ArXiv 1606.04581

M = 10^{30} amu
T = ∞

Updated version of: S.L. Adler and A. Bassi:, *Science* *325,* 275 (2009)

Acknowledgments

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