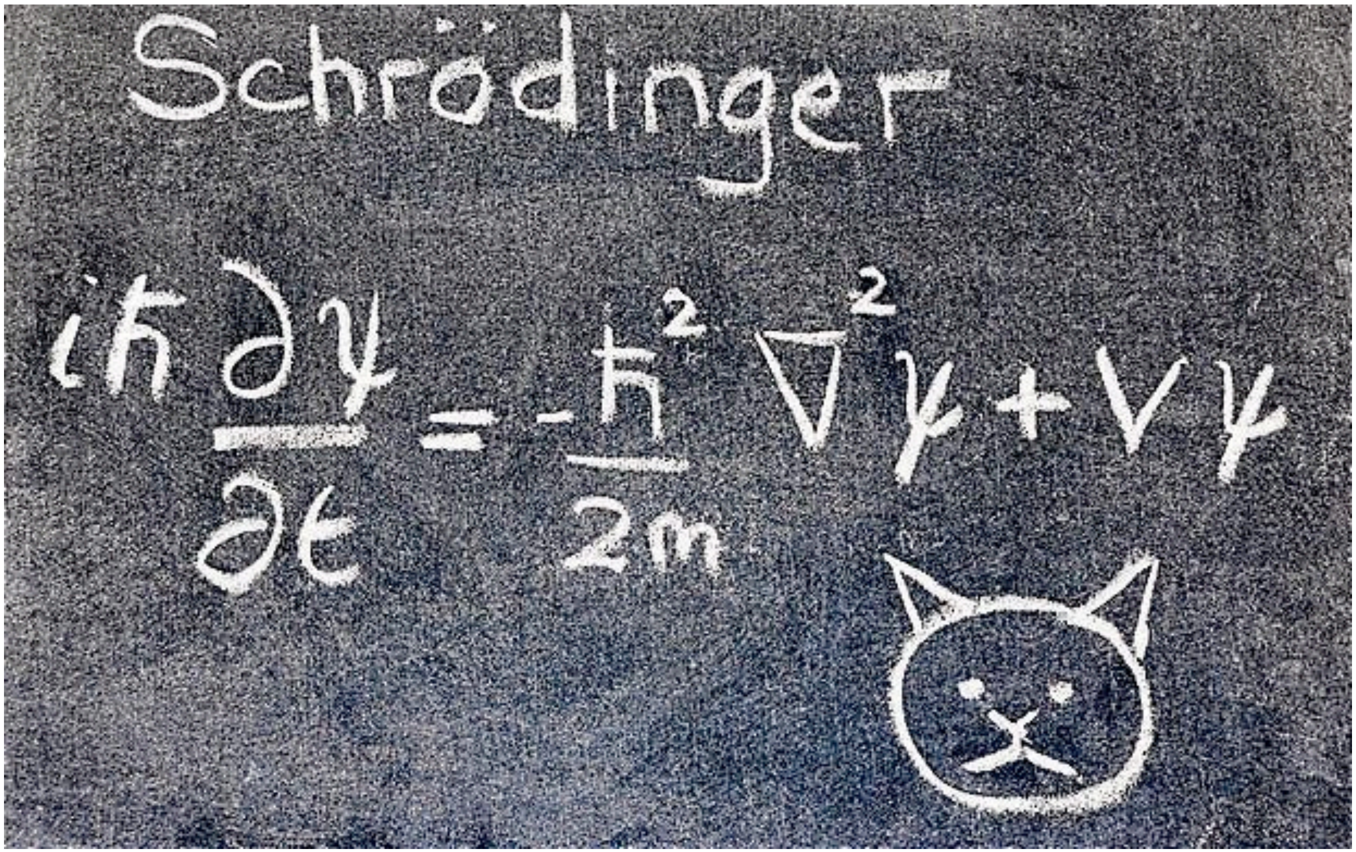
Models of spontaneous wave function collapse and optomechanics

Quantum Interfaces with Nano-opto-electro-mechanical devices: Applications and Fundamental Physics

Erice, 1st – 5th August 2016

(Angelo Bassi – University of Trieste & INFN)

Quantum Mechanics



Linearity ➔ Superposition Principle ➔ Schrödinger's cat ➔ Measurement Problem

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)

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

The continuous dynamics (simplified)

$$d|\psi\rangle_t \;=\; \Bigg[\underbrace{-\frac{i}{\hbar}Hdt}_{\text{quantum}} \;+\; \underbrace{\sqrt{\lambda}(A - \langle A\rangle_t)dW_t - \frac{\lambda}{2}(A - \langle A\rangle_t)^2 dt}_{\text{collapse}}\Bigg]|\psi\rangle_t$$

$$\langle A\rangle_t \;=\; \langle\psi_t|A|\psi_t\rangle \;\longrightarrow\; \text{nonlinear}$$

The wave function is dynamically and stochastically driven by the noise W_t towards one of the eigenstates of the operator A

This equation describes microscopic physics, macroscopic physics, and what happens in quantum experiments (Born rule, collapse …)

(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)

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

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

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

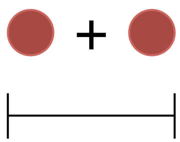
Two parameters

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

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

The collapse rate

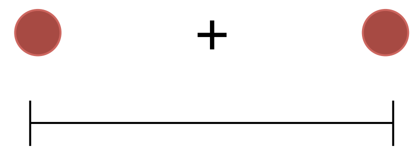
Small superpositions



$\ll r_C$

Collapse NOT effective

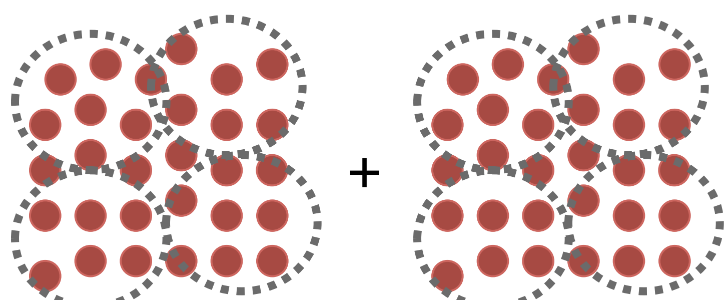
Large superpositions



$\geq r_C$

Collapse effective

$$\mathbf{\Gamma = \lambda n^2 N}$$



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

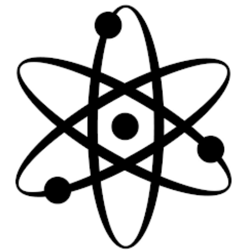
Many particles

Fast collapse

classical behavior

CSL Parameters

Microscopic world (few particles)



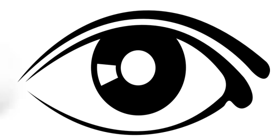
$$\lambda \sim 10^{-8\pm2}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)

Mesoscopic world: Latent image formation + perception in the eye (~ 10^4 - 10^5 particles)

S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)



$$\lambda \sim 10^{-17}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world (> 10^{13} particles)

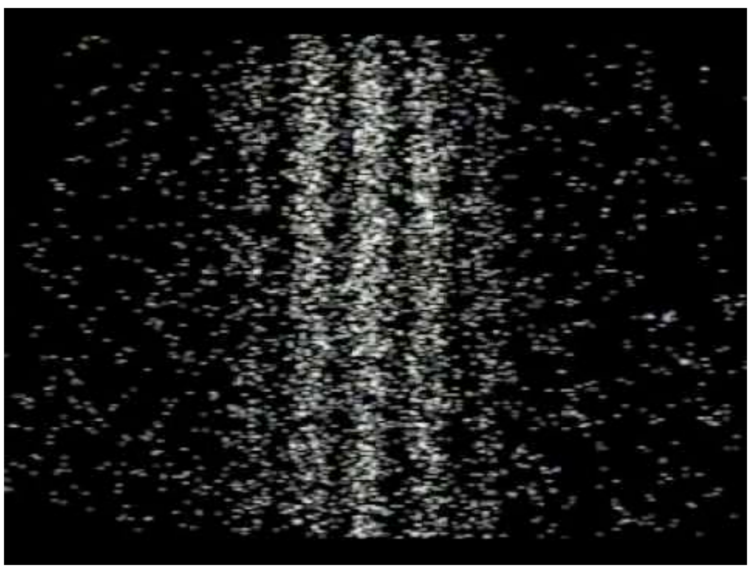
G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

$$r_C = 1/\sqrt{\alpha} \sim 10^{-5}\mathrm{cm}$$

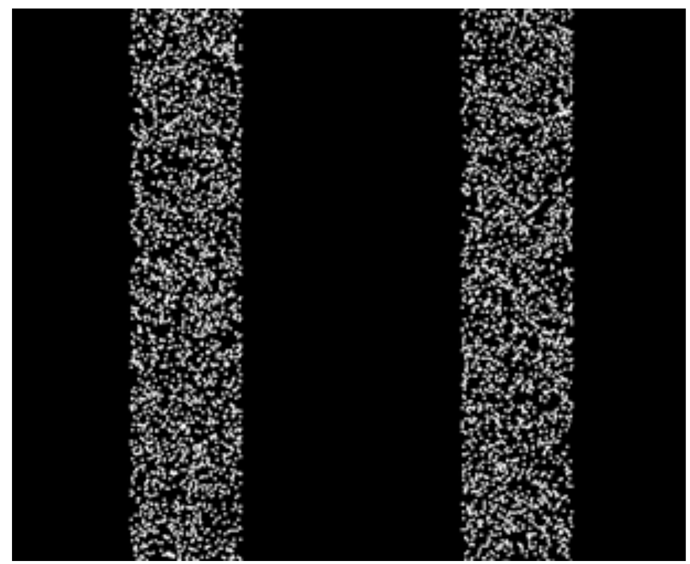
Increasing size of the system

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

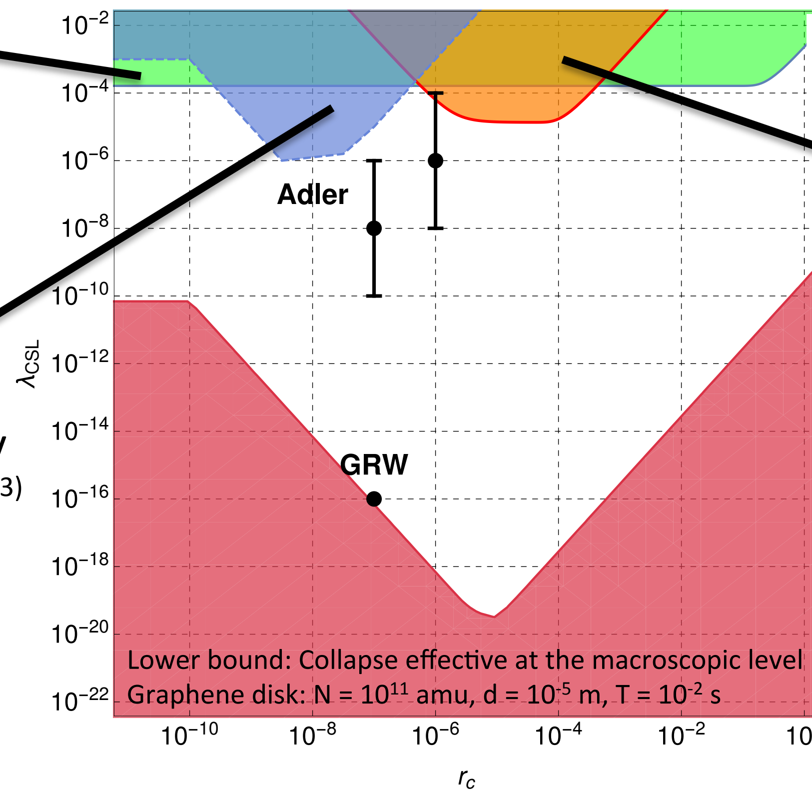
Atom Interferometry

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

M = 87 amu

d = 0.54 m

T = 1 s



Molecular Interferometry

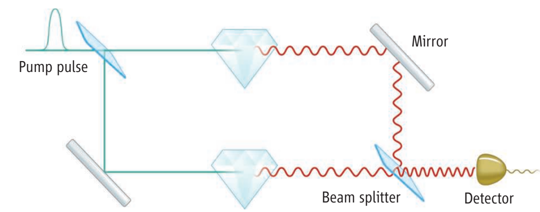
S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M. Toros *et al.*, ArXiv 1601.03672

M = 10^4 amu

d = 10^{-7} m

T = 10^{-3} s



Entangling Diamonds

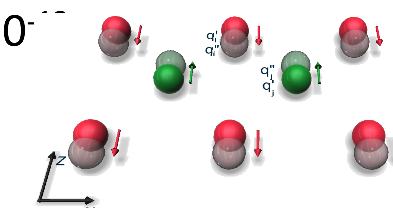
K. C. Lee *et al.*, Science. 334, 1253 (2011).

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

M = 10^{16} amu

d = 10^{-11} m

T = 10^{-}



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

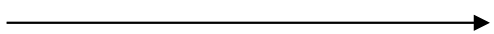
Non interferometric tests

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)

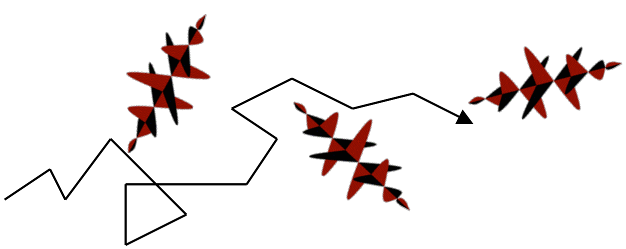
The collapse induces a **Brownian motion** on the system

Charged free particle

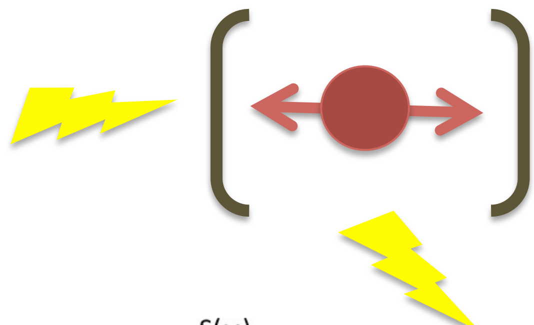
1. Quantum mechanics



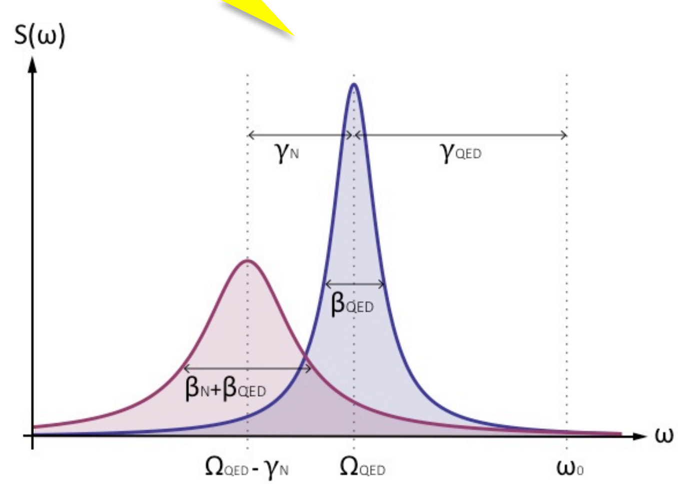
2. Collapse models



Spontaneous photon emission

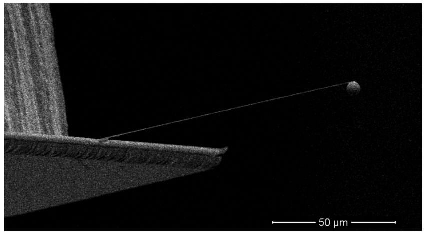


Nano-particle in a optical cavity



Extra shift and broadening

Non-Interferometric Experiments

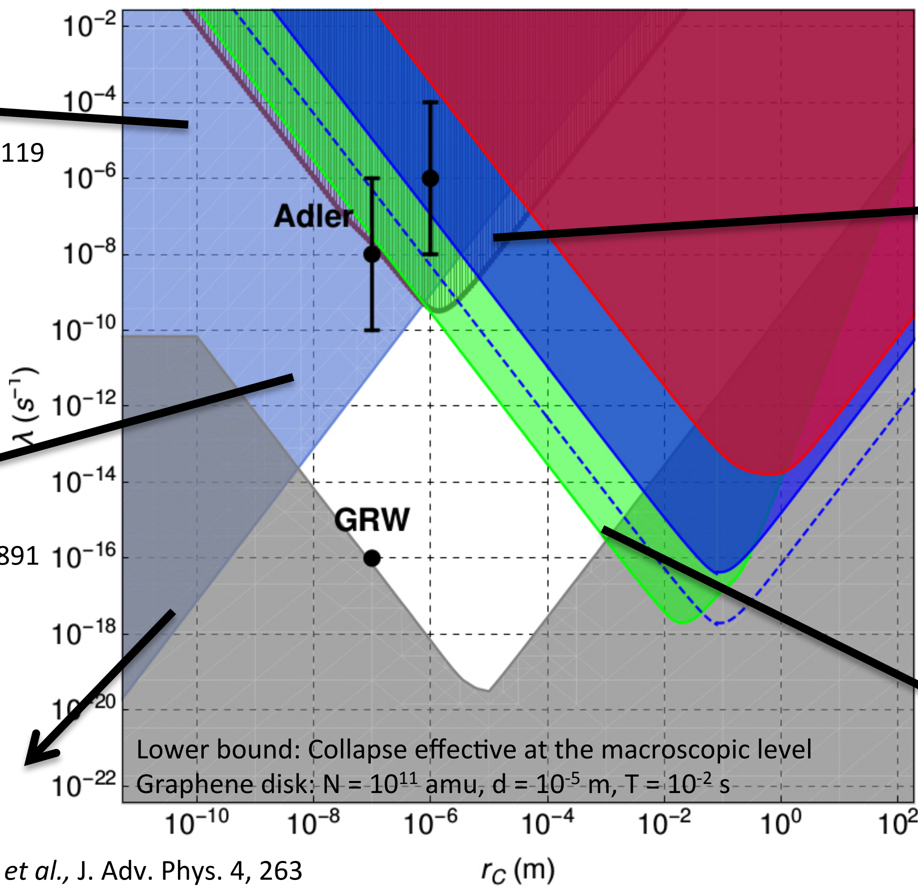


Cold Atom Gas
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)

M = 87 amu
T = 30 s

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

M = 87 amu
T = 1 s



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

$M = 10^{14}$ amu
$T = \infty$

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

M = 1 Kg
T = days / months

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

$M = 10^{30}$ amu
$T = \infty$

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

Beyond CSL

The collapse is driven by a random noise. In the CSL model, the noise is white and no dissipative effects are included.

This makes the model relatively easy to work with, but not physically realistic.

Progress has been made in generalizing CSL, both with a colored spectrum, as well as with dissipation.

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)

Interferometric experiments and the new models

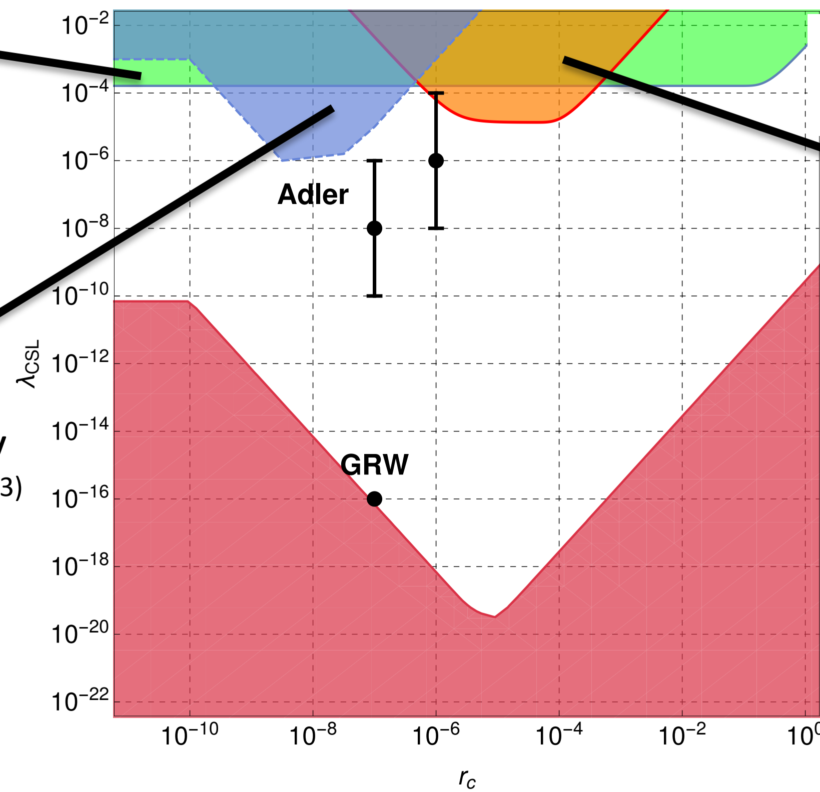
Atom Interferometry

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

M = 87 amu

d = 0.54 m

T = 1 s



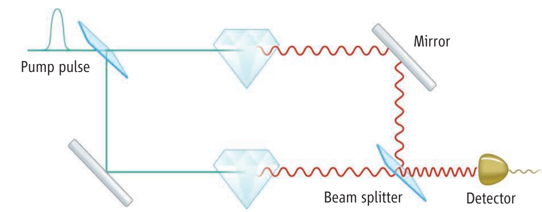
Molecular Interferometry

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

M = 10^4 amu

d = 10^{-7} m

T = 10^{-3} s



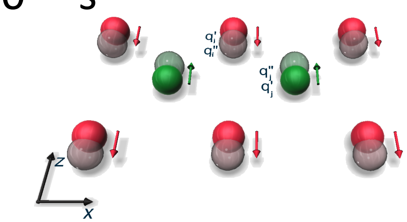
Entangling Diamonds

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

M = 10^{16} amu

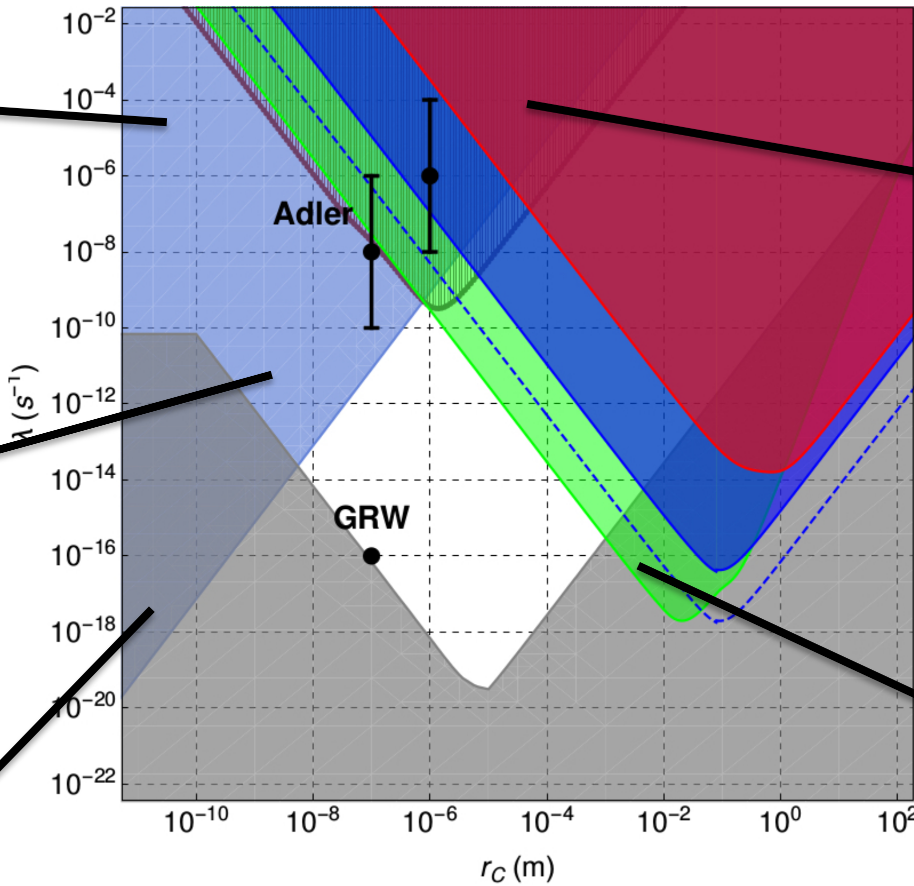
d = 10^{-11} m

T = 10^{-12} s



The new experimental bounds are robust against changes in the noise. It comes not as a surprise, as these are direct tests of the superposition principle

Non-Interferometric Experiments and the new models



Cold Atom Gas

Cantilever
Perhaps weakened if dissipation is taken into account

Cold Atom Gas
Weakened only for strong dissipation

X-Ray
Disappears for any reasonable cutoff in the spectrum

Gravitational wave detectors
Perhaps weakened if dissipation is taken into account

Collapse and gravity

Fundamental properties of the collapse

It occurs in space.

It scales with the mass of the system.

The possible role of gravity

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

Gravity provides such a coupling.

Problem

The coupling is not the standard one prescribed by quantum theory (which would be linear). No one knows why gravity should couple as prescribed by collapse models

Diosi – Penrose model

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

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

Same equation as that of the CSL model. The only difference is in the noise:

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

Gravity. And no other free parameter.

The localization time is:

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

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

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

Criticisms

1. The model is not derived following some guideline. It does not explain why gravity enters the game (expect for G).

2. G and 1/r do not appear in the coupling between matter and gravity, but in the correlation function of the noise. There is no reason for that to be the case. (Gravity induced vs. gravity related collapse model.)

3. The model diverges for point-like particles. One needs to introduce a cut off. Then the model depends on a parameter, the **cut-off R_0**.

   Diosi's original proposal: $R_0 = 10^{-15}$ m = Compton wavelength of a nucleon. This is justified by the requirement that the model is **non-relativistic.**

   However, this model **pumps energy** at a very high rate, contradicting experimental data. To avoid this, one has to introduce a large cut off, which at present has **no justification.**

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

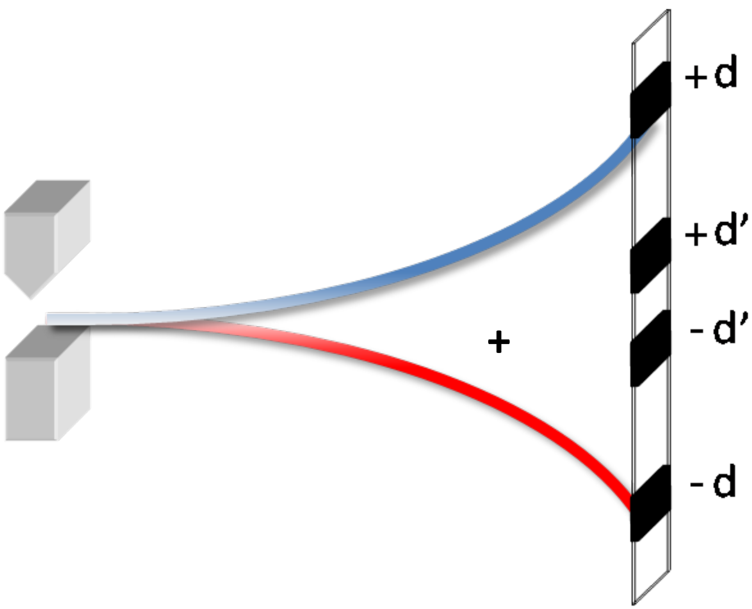
It comes from semi-classical gravity if taken **as a fundamental theory** = matter is fundamentally quantum and gravity is fundamentally classical, and they couple as follows

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

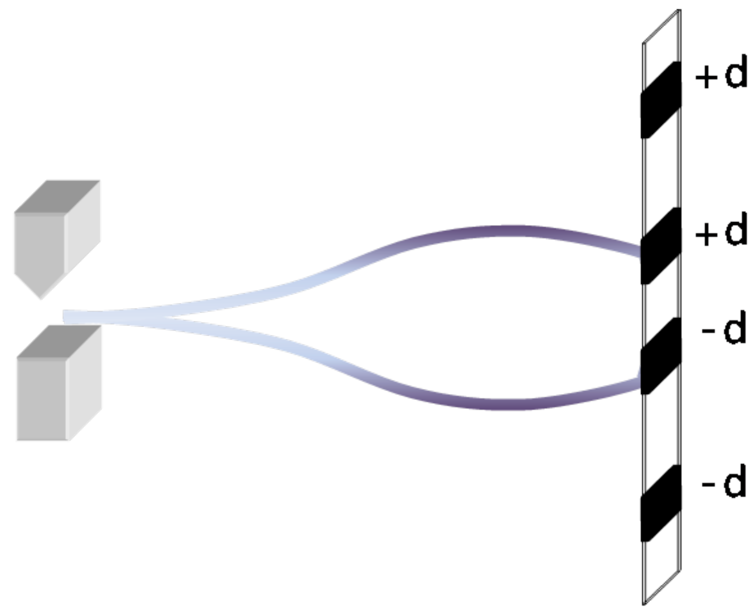
The term on the right is nonlinear in the wave function

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

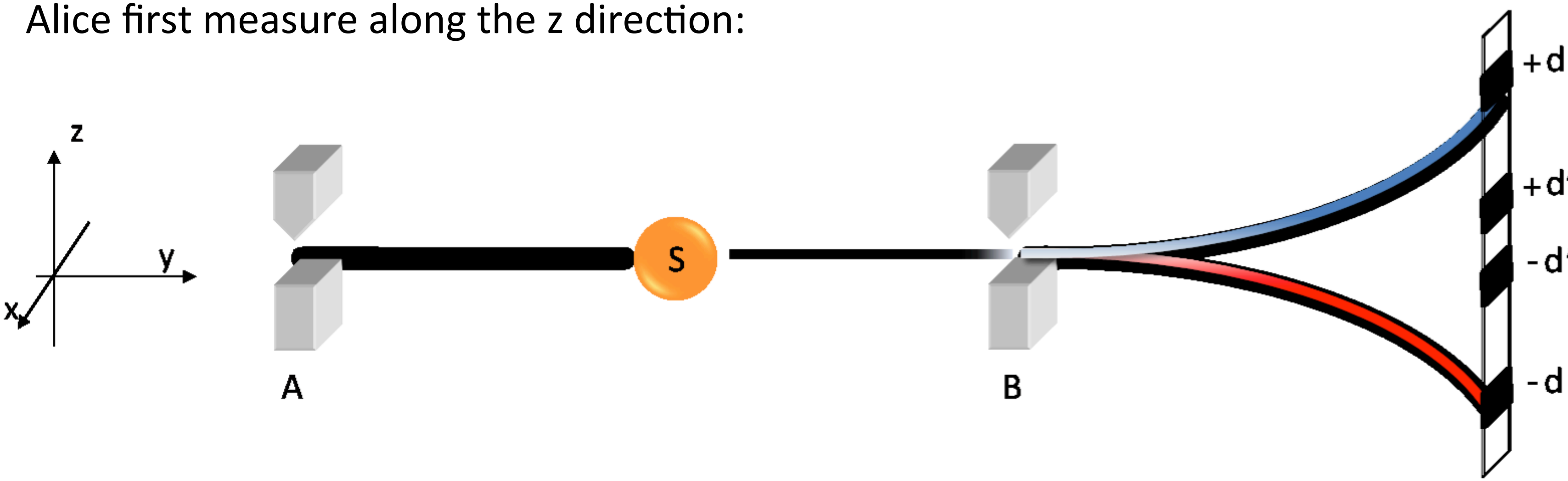
But there are smarter ways of testing the equation

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)

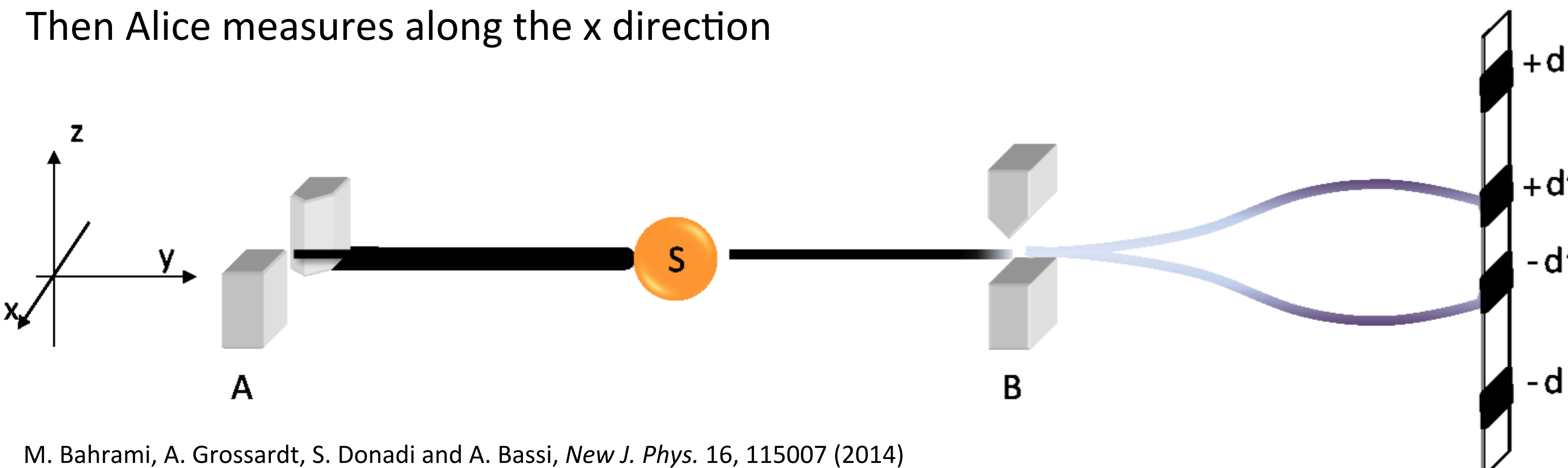
It does faster-than-light

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)

Acknowledgments

The Group (www.qmts.it)

- Postdocs: S. Donadi, F. Fassioli, A. Grossardt
- Ph.D. students: G. Gasbarri, M. Toros, M. Bilardello, M. Carlesso, S. Bacchi, L. Curcuraci
- Graduate students: A. Rampichini

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

UNIVERSITÀ DEGLI STUDI DI TRIESTE

www.units.it

INFN Istituto Nazionale di Fisica Nucleare

www.infn.it

cost

www.cost.eu