FQT2015 – Is Quantum Theory Exact?

Wave function collapse and gravity

Angelo Bassi – University Trieste & INFN

Gravitational decoherence

Standard QM + (quantum/classical, weak-field limit) GR

$$i\hbar \frac{d}{dt} |\psi_t\rangle = [H + V_G] \, |\psi_t\rangle$$

coupling between the quantum system and metric perturbation $h_{\mu\nu}$

$$h_{\mu\nu}(\mathbf{x}, t) \longrightarrow \text{Earth's gravity}$$

- Neutron interferometry
  (R. Collela *et al., PRL* 34, 1472 - 1975)
- Pikovski et al. effect
  (I. Pikovski *et al*. *Nature Physics* - 2015)

$$h_{\mu\nu}(\mathbf{x}, t) \longrightarrow \text{gravitational waves}$$

- Decoherence in position
  (B. Lamine *et al., PRL* 96, 050405 - 2006)
- Decoherence in energy
  (M.P. Blencowe, *PRL* 111, 021302 - 2013)

Decoherence vs. Collapse

Decoherence ➔ standard QM ➔ linear dynamics ➔ no collapse

S.L. Adler, *Stud. Hist. Philos. Mod. Phys.* 34**,** 135 (2003).

And J. Bell, of course!

To have wave-function **collapse**, one needs a **nonlinear** dynamics

The only known example of such a dynamics is that **of collapse models**

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

Spatial correlation of the noise (white in time) — **Nonlinearity** — **Stochasticity**

Why collapse due to gravity?

No one really knows why.

Idea: GR, as we know it, it is an effective theory. The underlying theory is radically different.

Perhaps the effective coupling of QM with gravity is:

$$\frac{d}{dt}|\psi_t\rangle = \left[-\frac{i}{\hbar} H + \int d^3\mathbf{x}\, \hat{M}(\mathbf{x}) h(\mathbf{x}, t) + O(\hat{M}, h) \right] |\psi_t\rangle$$

Anti-Hermitian coupling between mass density and gravity ➔ no grav. waves (S.L. Adler, arXiv:1401.0353)

Higher order, **non-linear terms**

We end up with the equation of collapse models by asking for norm conservation and no-faster-than-light signalling

(S.L. Adler, book on "Trace Dynamics")

Diosi – Penrose model

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

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}H\,dt + \int d^3\mathbf{x}\,(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) \right.$$
$$\left. - \frac{1}{2}\int d^3\mathbf{x}d^3\mathbf{y}\,G(\mathbf{x}-\mathbf{y})(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t)(\hat{M}(\mathbf{y}) - \langle\hat{M}(\mathbf{y})\rangle_t)dt\right]|\psi_t\rangle$$

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

$$G(\mathbf{x}) = \frac{G}{\hbar}\frac{1}{|\mathbf{x}|} \longrightarrow$$ **Gravity.** And no other free parameter.

Criticism. 1. Model not derived from basic principles. 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)

Diosi – Penrose model

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: quantum superposition ➔ spacetime superposition ➔ energy uncertainty ➔ decay in time (R. Penrose, *Gen. Rel. Grav*. 28, 581 - 1996)

It **diverges** for point-like particles.

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

Diosi – Penrose model

Now the model depends on a parameter, the **cut-off R_0**.

Diosi's proposal: $R_0 = 10^{-15}$ m = Compton wavelength of a nucleon

This is justified by the requirement that the model is **non-relativistic**

However, because the noise shakes the particles, it **pumps energy** at a rate of 10^{-4} K/s for a nucleon, which is unacceptable.

Ghirardi, Grassi and Rimini proposed to set **$R_0 = 10^{-7}$ m,** leading to an energy increase of 10^{-28} K/s, which is fully acceptable

The price to pay is the introduction of a large cut off, which at present has **no justification.**

Dissipative DP model

M. Bahrami, A. Smirne and A. Bassi, *Phys. Rev.* A 90, 062105 (2014)

From the analogy with collisional decoherence, the reason for the overheating problem with the DP model is clear. **Dissipative effects have not been included.**

Inclusion of dissipative effects

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

$$\downarrow$$

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

Now the “environment” can “detect” the momentum of the particle and **thermalizes its motion to its own temperature.**

Dissipative DP model

Now we have two parameters: Temperature of the noise, and spatial cut-off

Choice

T = 1 K. Justified on cosmological considerations

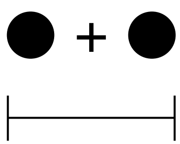
R_0 = 10^{-15} m. Non-relativistic limit

It does not work. To make a collisional analysis, it is as if the system is kicked by a "graviton" with mass = 10^{11} amu, which for microscopic and mesoscopic systems would amounts to drastic momentum changes.

Conclusion: the DP model seems to work only for mesoscopic and macroscopic systems. The threshold has no relation to gravity, the Plank mass (m_P = 10^{19} amu) or the nonrelativistic limit.

The collapse rate

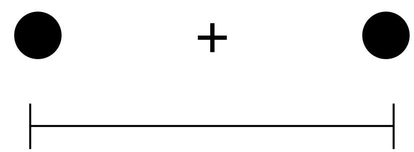
Small superpositions



$\ll r_C$

Collapse NOT effective

Large superpositions

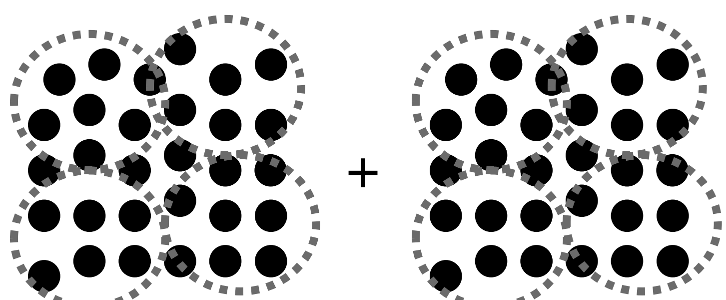


$\geq r_C$

Collapse effective

↓

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



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

Collapse rate in the DP model

For a composite system, the center-of-mass wave function satisfies a single-particle equation, with

$$\Gamma_{DP}^{M}(\mathbf{Q}) = \Gamma_{DP}(\mathbf{Q})\big|_{\text{unit mass}} \left|\rho(\mathbf{Q})\right|^2$$

with $\rho(\mathbf{Q})$ the Fourier transform of the mass distribution of the system.

The collapse rate is about 10^{-15} s^{-1} for a typical nano-sphere with mass M = 10^9 amu and radius R = 50 nm.

(S. Nimmrichter *et al. Phys. Rev. Lett.* 113, 020405 - 2014)

The Schrödinger-Newton equation

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

quantum spread — gravitational collapse

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)

- SN equation derives from classical gravity + quantum matter (described by ψ)
- It is not a collapse equation. No right collapse. No Born rule
- It does faster-than-light signalling
- Turning it into a collapse equation implies radical changes

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

The Schrödinger-Newton equation

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

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

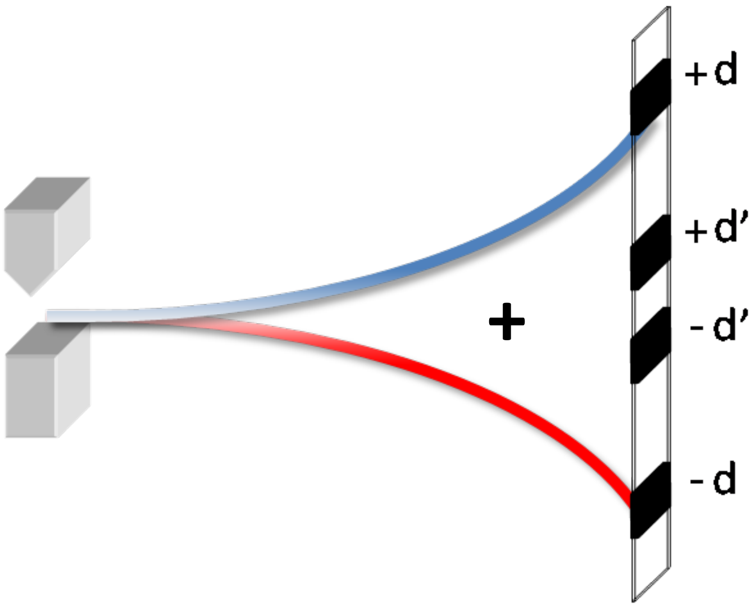
↓

This term is nonlinear in the wave function

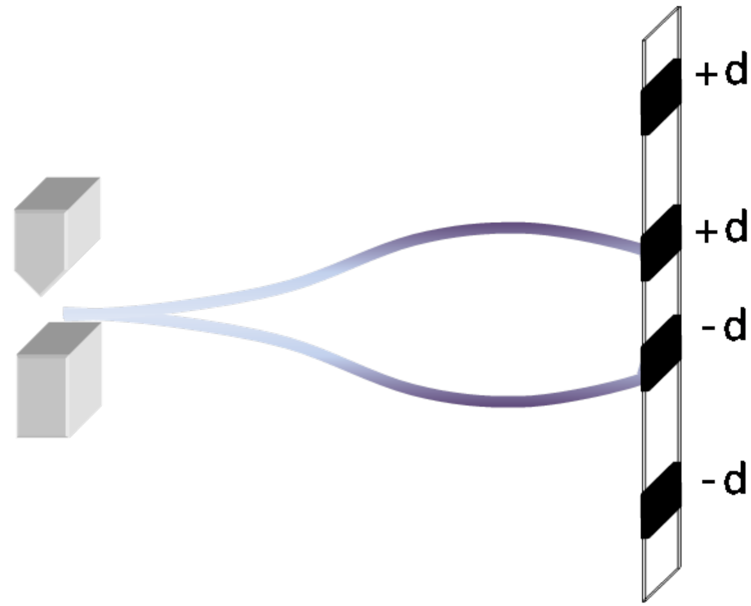
Note. This is not the usual understanding of semi-classical gravity.

The Schrödinger-Newton equation

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



Double slit experiment according to standard QM



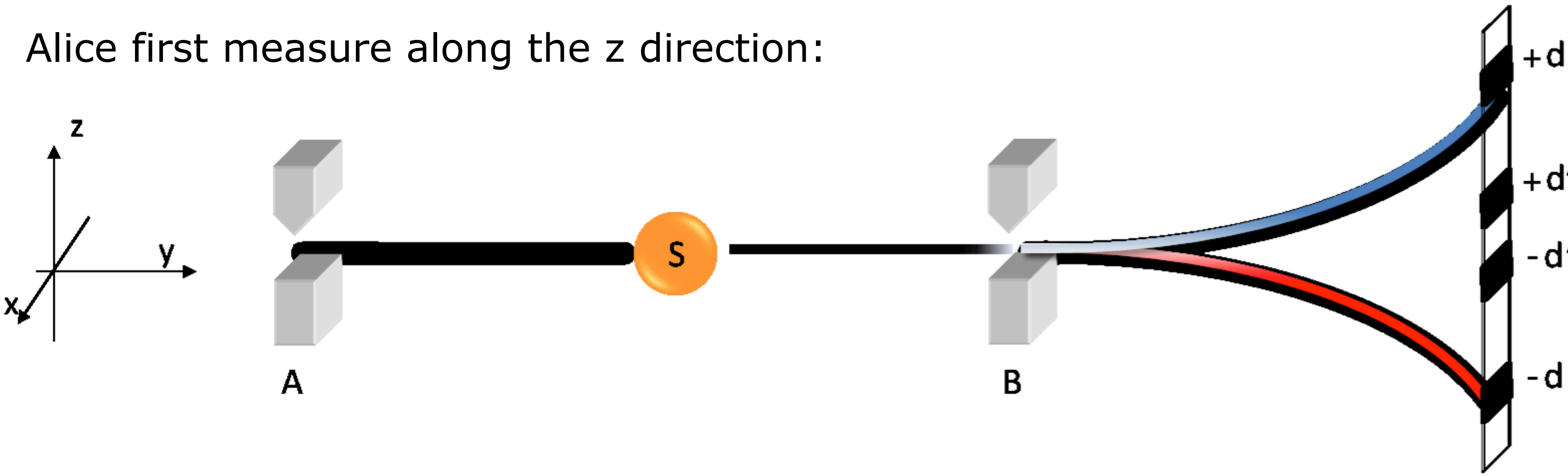
Double slit experiment according to the Schrödinger-Newton equation

But there are smarter ways of testing the equation (H. Yang *et al.*, *PRL* 110, 170401 - 2013)

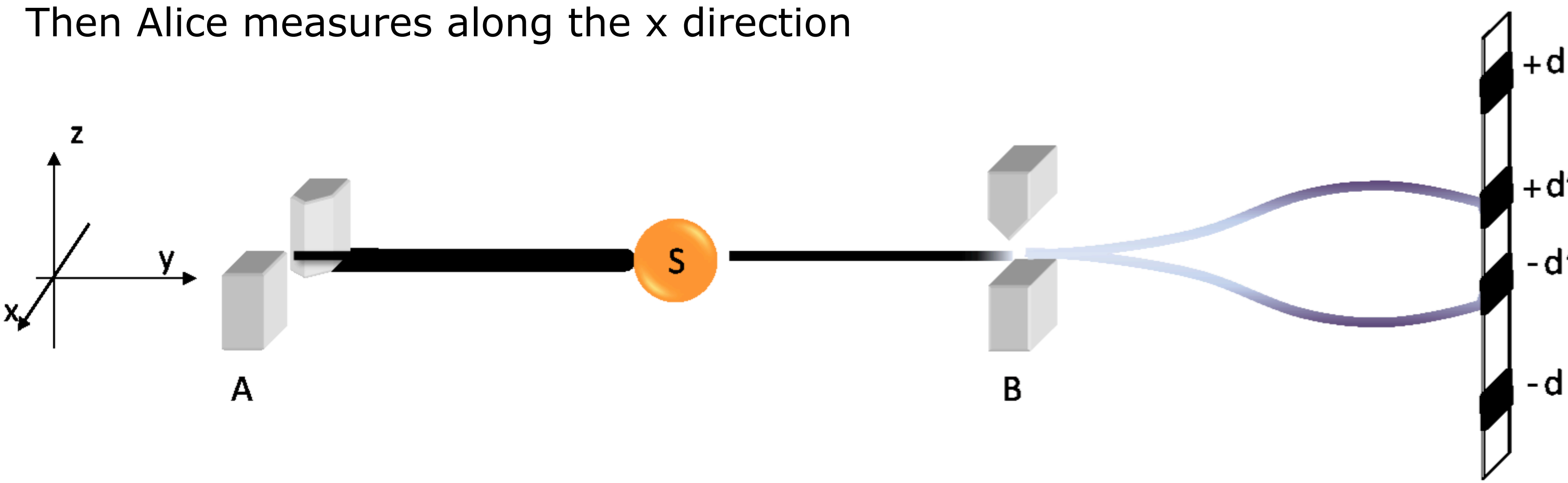
The Schrödinger-Newton equation

It **does faster-than-light signalling**. 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

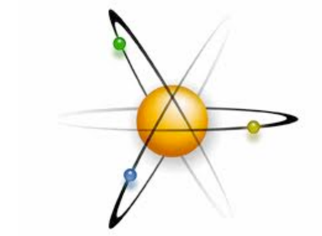


CSL model and variations on the theme

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, *PRL* 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 (ArXiv 1408:6446, to appear in Sci. Rept.)	**Non-Markovian & dissipative QMUPL** L. Ferialdi, A. Bassi PRL 108, 170404 (2012)

The collapse rate of the CSL model

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 bounds on the collapse rate

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
Matter-wave interference experiments	2	Dissociation of cosmic hydrogen	9
Decay of supercurrents (SQUIDs)	6	Heating of Intergalactic medium (IGM)	0
Spontaneous X-ray emission from Ge	-2	Heating of protons in the universe	4
Proton decay	10	Heating of Interstellar dust grains	7

S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

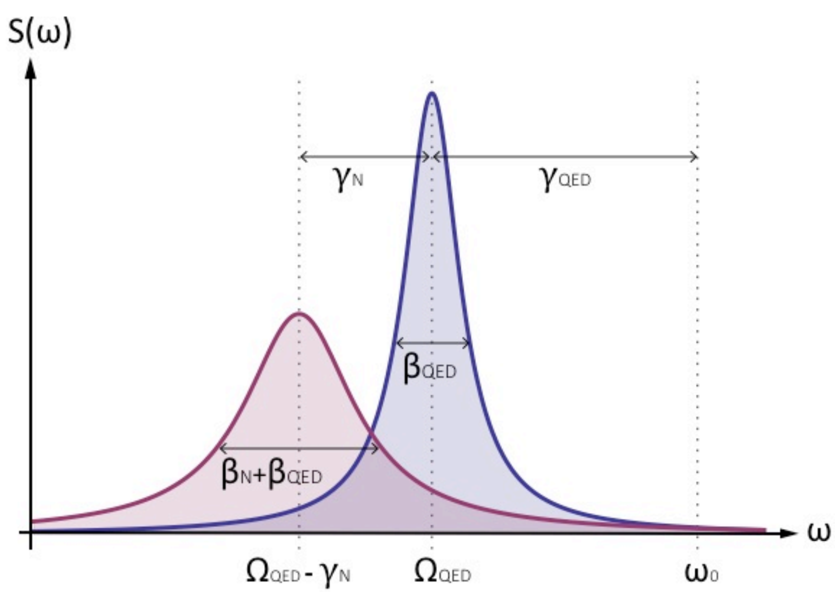
Collaboration with C. Curceanu

Collaboration with M. Arndt & H. Ulbricht

The future of the CSL model

1. The original CSL model will soon be ruled out by experimental data. The **dissipative** and **non-Markovian** models will survive.

2. Likely, these models will be tested in optomechanical systems, via the so-called "**non-interferometric tests**": analysis of the spectral properties of the motion of the nano-particle in the optomechanical cavity.



→ Extra shift and broadening due to the collapse noise

M. Bahrami, M. Paternostro, A. Bassi, H. Ulbricht, Phys. Rev. Lett. 112, 210404 (2014)

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- Graduate students: M. Caiaffa

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