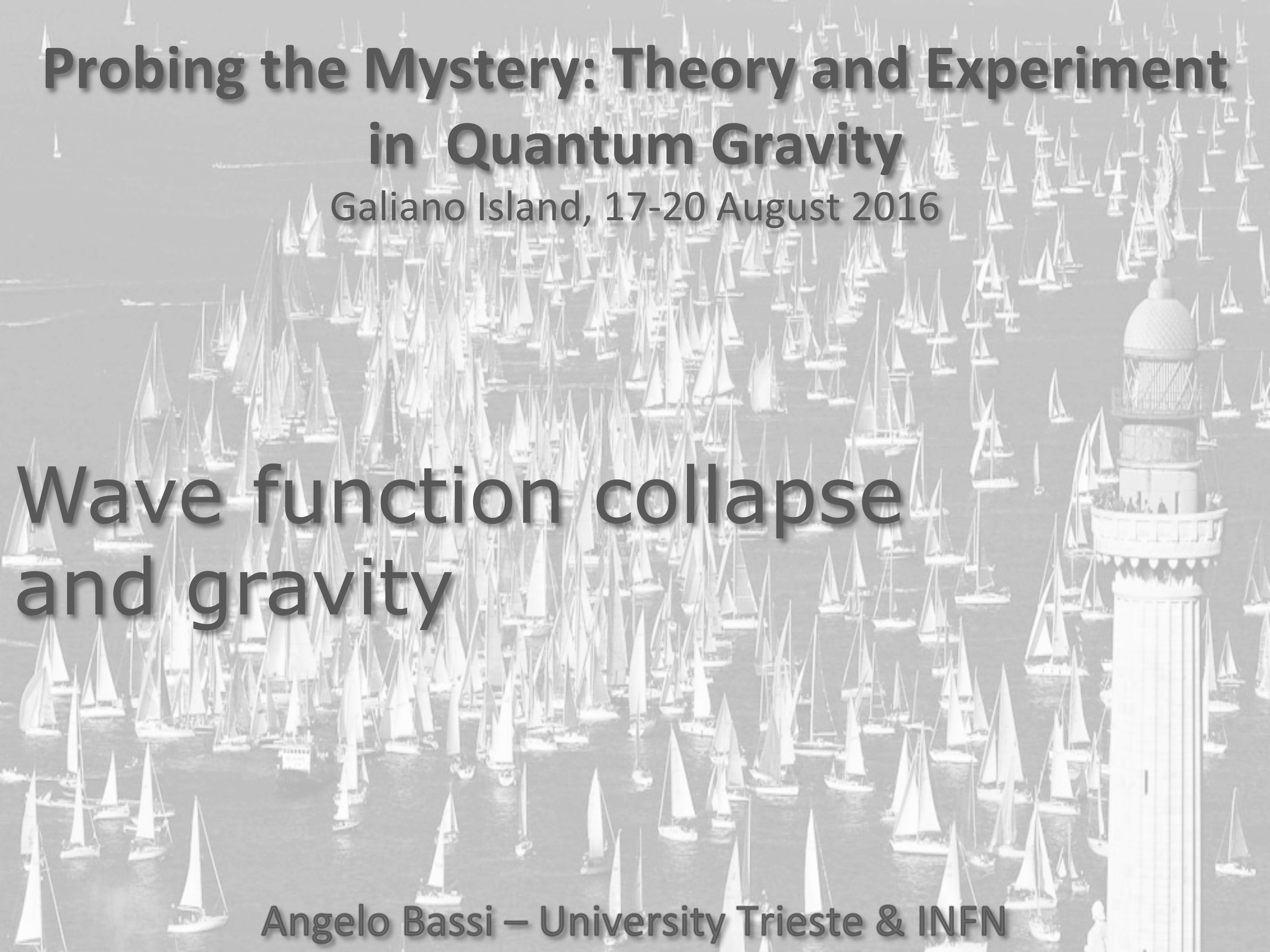


Probing the Mystery: Theory and Experiment in Quantum Gravity

Galiano Island, 17-20 August 2016

Wave function collapse and gravity

Angelo Bassi – University Trieste & INFN

Collapse models: What they are

G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986)

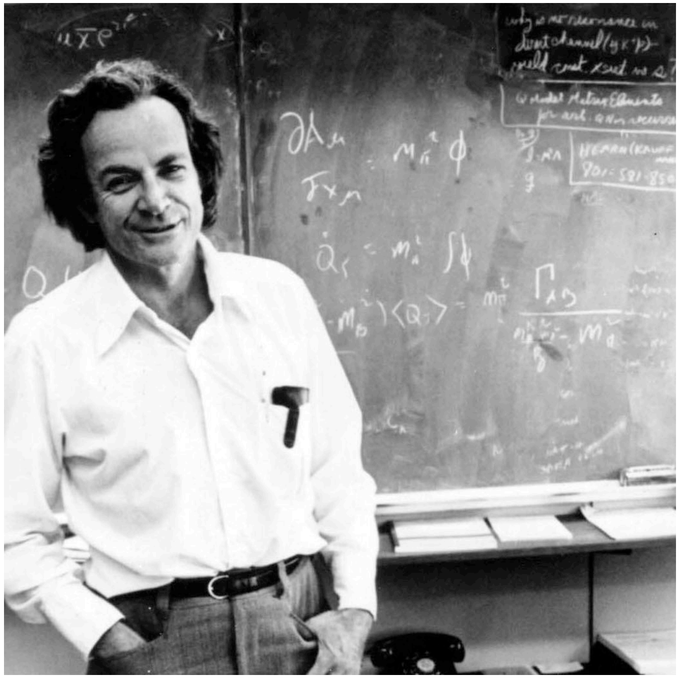
They are nonlinear and stochastic (phenomenological) modifications of the Schrödinger equation, which include the collapse of the wave function

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

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

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

About the measurement problem



“Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 10^9 B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance. By what philosophy will the universe without man be understood?”

[Lecture Notes on Gravitation]

Side note: Linear theories are often approximations of nonlinear ones. There is no surprise if the same will turn out to be true for Quantum Theory

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, *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)

(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)

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

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

$$w_t(\mathbf{x}) \equiv \frac{d}{dt}W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[w_t(\mathbf{x})] = 0 \quad \mathbb{E}[w_t(\mathbf{x})w_s(\mathbf{y})] = \delta(t-s)G(\mathbf{x}-\mathbf{y})$$

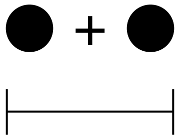
Two parameters

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

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

The collapse rate

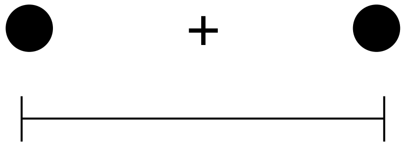
Small superpositions



$\ll r_C$

Collapse NOT effective

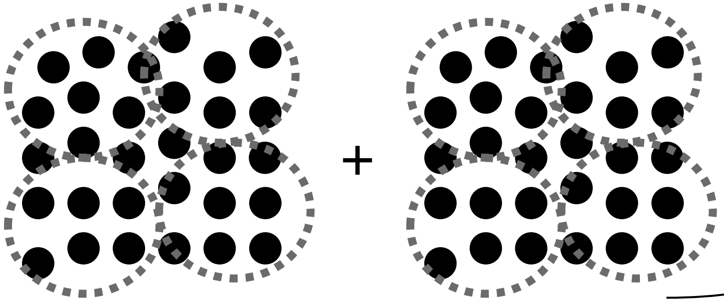
Large superpositions



$\geq r_C$

Collapse effective

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



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

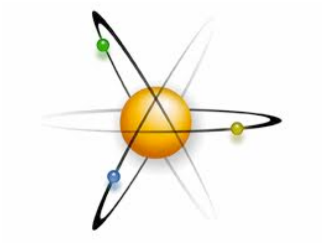
Many particles

Fast collapse

classical behavior

The collapse rate of the CSL model

Microscopic world
(few particles)



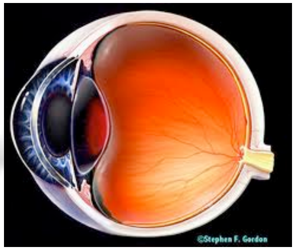
$$\lambda \sim 10^{-8\pm2}\mathrm{s}^{-1}$$

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)

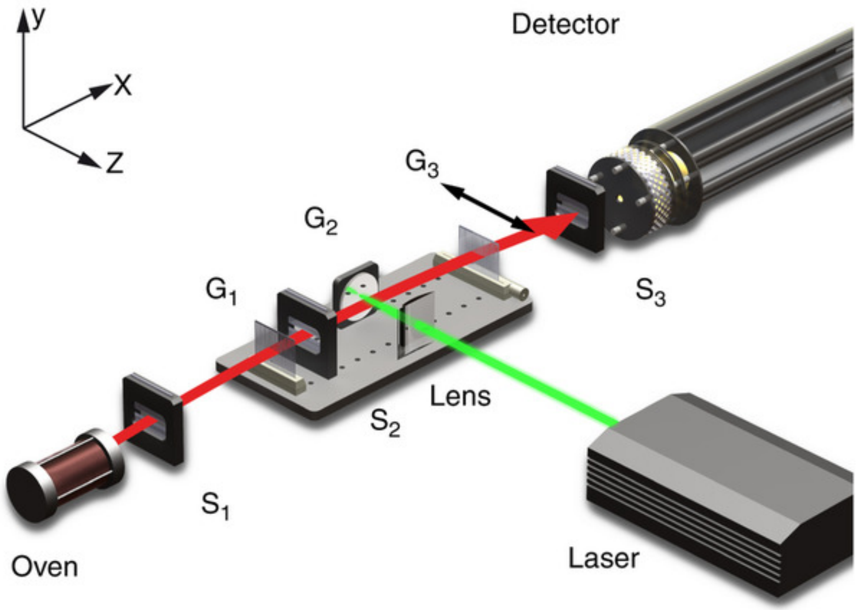
Macroscopic world
(> 10^{13} particles)

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

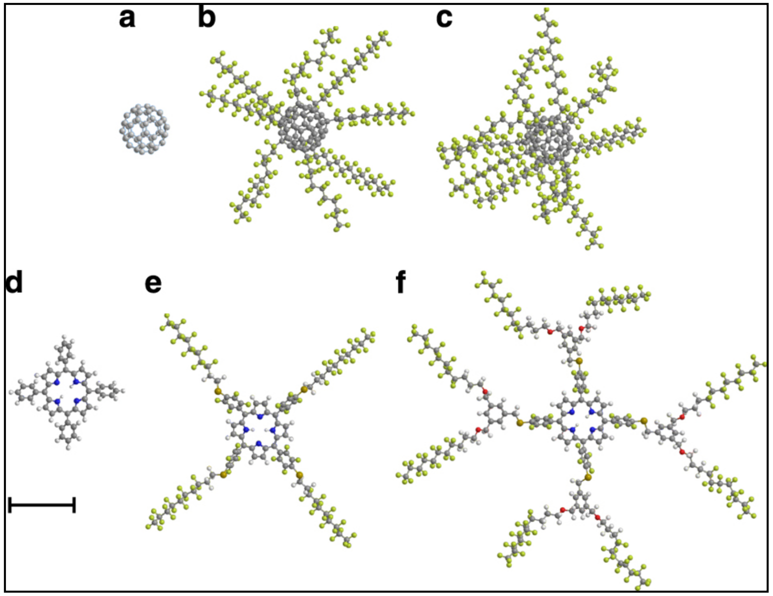
$$r_C = 1/\sqrt{\alpha} \;\sim\; 10^{-5}\mathrm{cm}$$

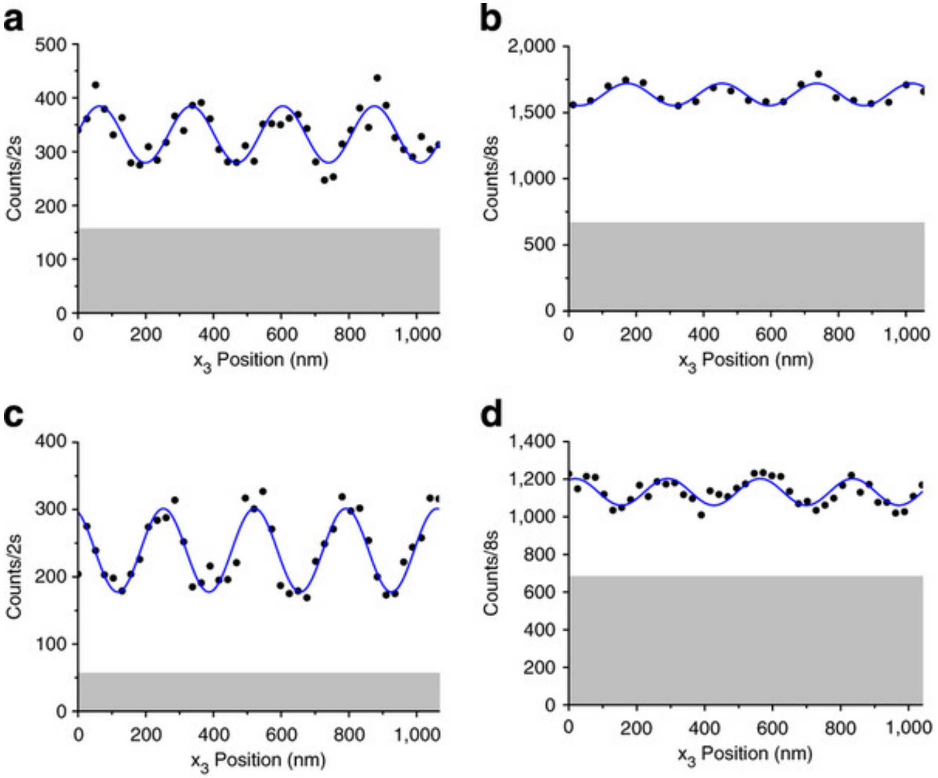
Increasing size of the system

World mass record in matter-wave interferometry 2013 - Vienna: 10,000 amu



Kapitza-Dirac Talbot-Lau Interferometer

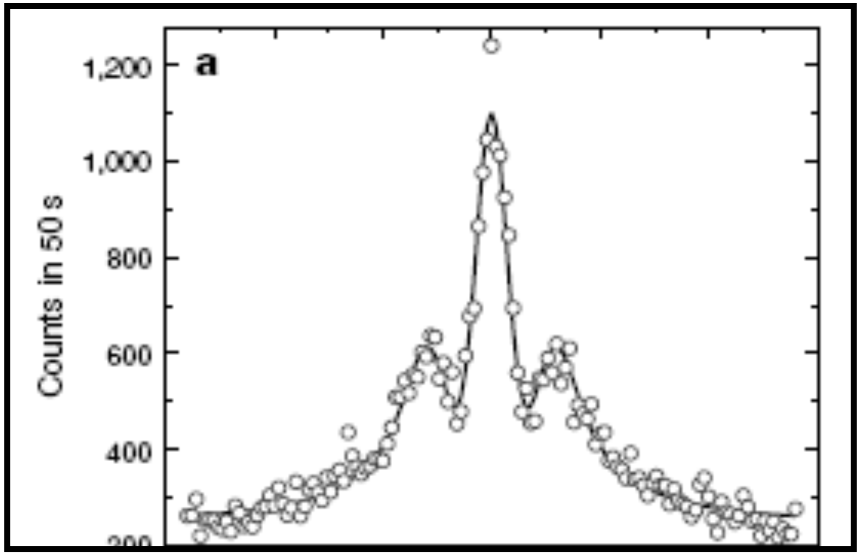




Matter-wave interferometry

Diffraction of macro-molecules:

- **C_{60} (720 AMU)**
  M. Arndt et al, *Nature* 401, 680 (1999)
- **C_{70} (840 AMU)**
  L. Hackermüller et al, *Nature* 427, 711 (2004)
- **$C_{30}H_{12}F_{30}N_2O_4$ (1,030 AMU)**
  S. Gerlich et al, *Nature Physics* 3, 711 (2007)
- **Larger Molecules (10,000 AMU)**
  S. Eibenberger *et al.* PCCP 15, 14696 (2013)



C_{60} diffraction experiment

The experimental bounds are some 2 orders of magnitude higher than Adler's proposed value (therefore some 10 orders of magnitude away from GRW's proposed value)

Future experiments: ~10^6 AMU
K. Hornberger *et al.*, Rev. Mod. Phys. 84, 157 (2012)
P. Haslinger *et al.*, Nature Phys. 9, 144 (2013)

→

NANOQUESTFIT: 10^5 AMU
EU Project under FP7

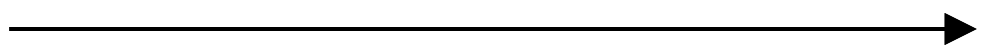
Outer space for higher masses? MAQRO consortium for space mission with ESA

Spontaneous photon emission

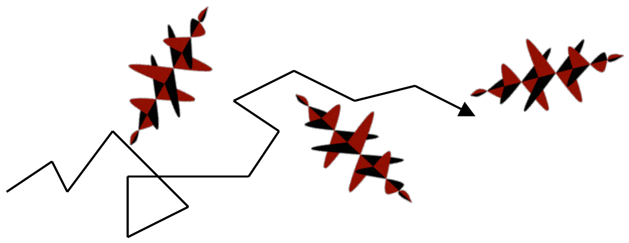
S. Donadi, D.-A. Deckert, A. Bassi, *Ann. Phys.* 340, 70 (2014) and references therein

FREE PARTICLE

1. Quantum mechanics

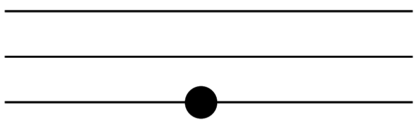


2. Collapse models

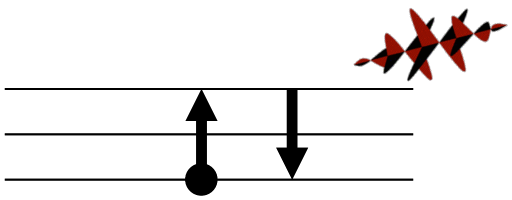


BOUND STATE

1. Quantum mechanics



2. Collapse models



1. One needs to introduce mass proportionality in the model
2. Adler's value for λ is ruled out by 3 orders of magnitude, unless the noise spectrum has a cut off below 10^{18} Hz. (ArXiv 1501.04462)

Strongest upper bound on the collapse parameter λ

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	**-3**	**Heating of protons in the universe**	**4**
Proton decay	**10**	**Heating of Interstellar dust grains**	**7**

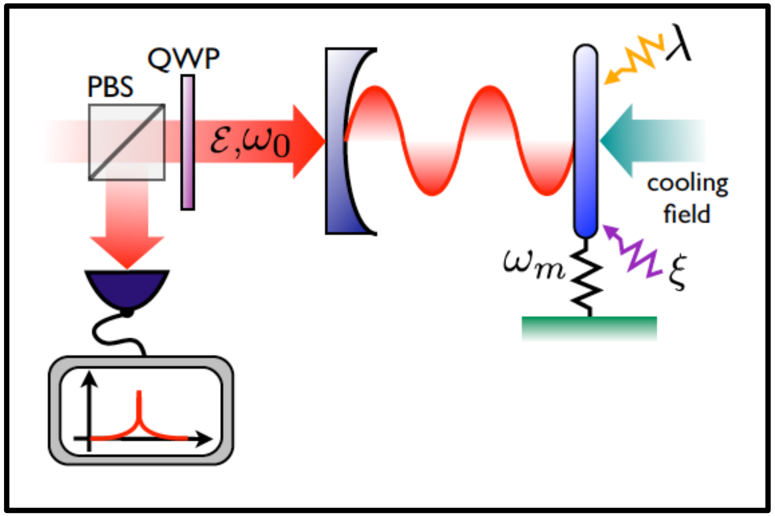
S.L. Adler and A. Bassi, *Science* 325, 275 (2009) - Updated

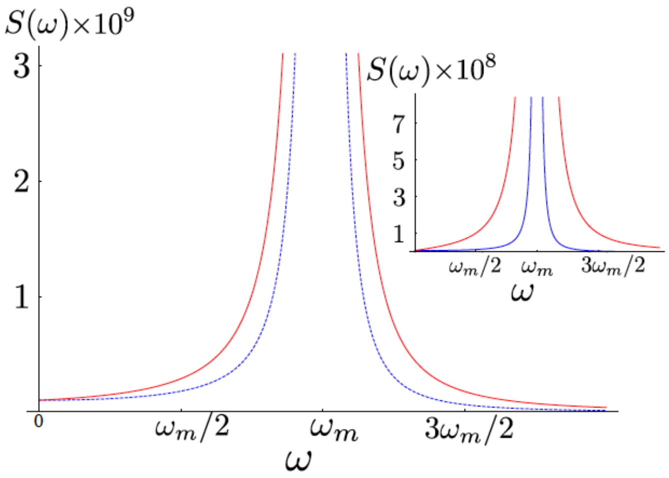
Collaboration with C. Curceanu

Collaboration with M. Arndt

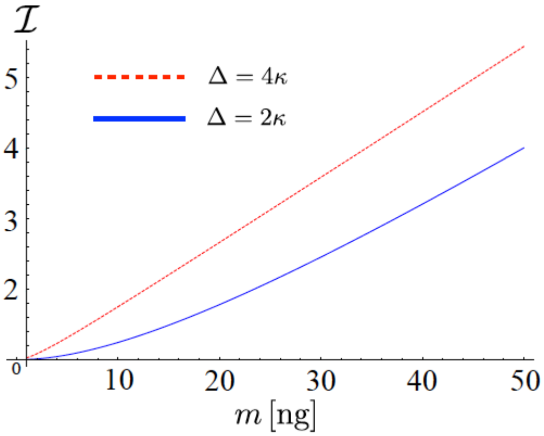
Non interferometric tests with opto-mechanical systems

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





- Collapse noise affects mechanical motion of opto-mechanical systems, read out by optics
- Broadening effect modeled by input/output theory of opto-mechanics.
- Factor of 5 effect for cooled mechanics predicted for realistic experimental conditions to test Adler CSL.
- Can also be applied to levitated opto-mechanics



Diosi – Penrose model

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

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

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

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

⟶ **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 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

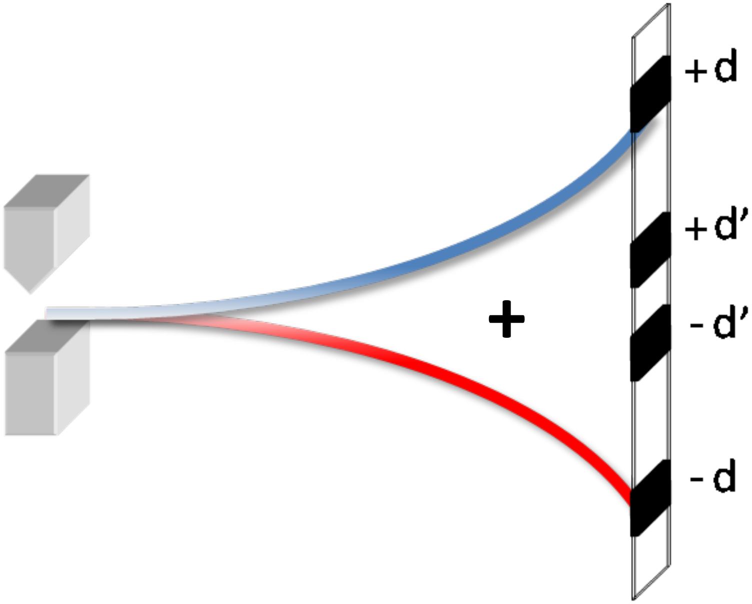
gravitational collapse

- It 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 in it

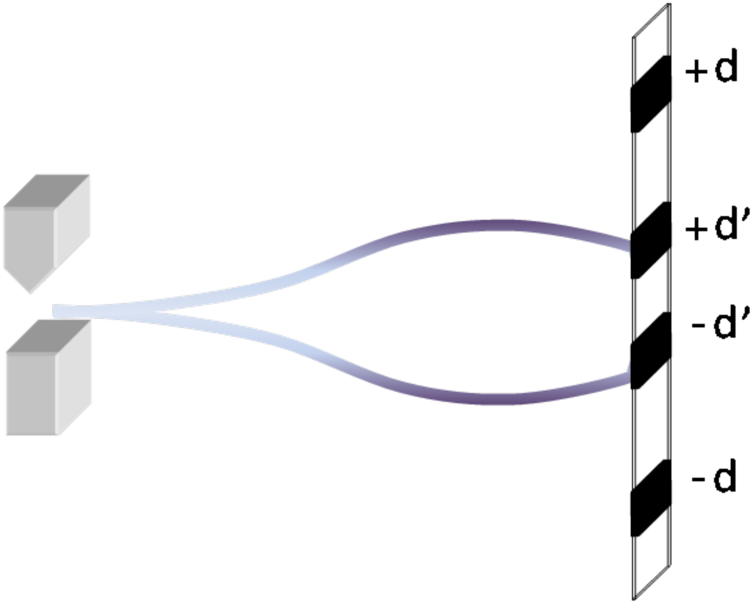
M. Bahrami, A. Grossardt, S. Donadi and A. Bassi, *New J. Phys.* 16, 115007 (2014)

The Schrödinger-Newton equation

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



Double slit experiment according to standard QM



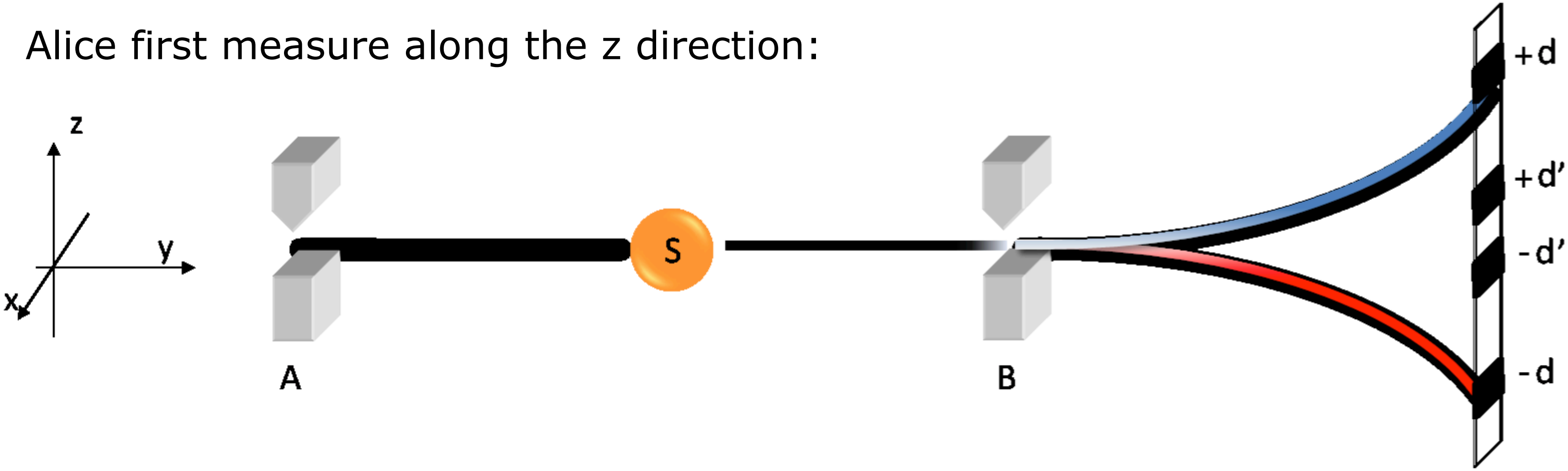
Double slit experiment according to the Schrödinger-Newton equation

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

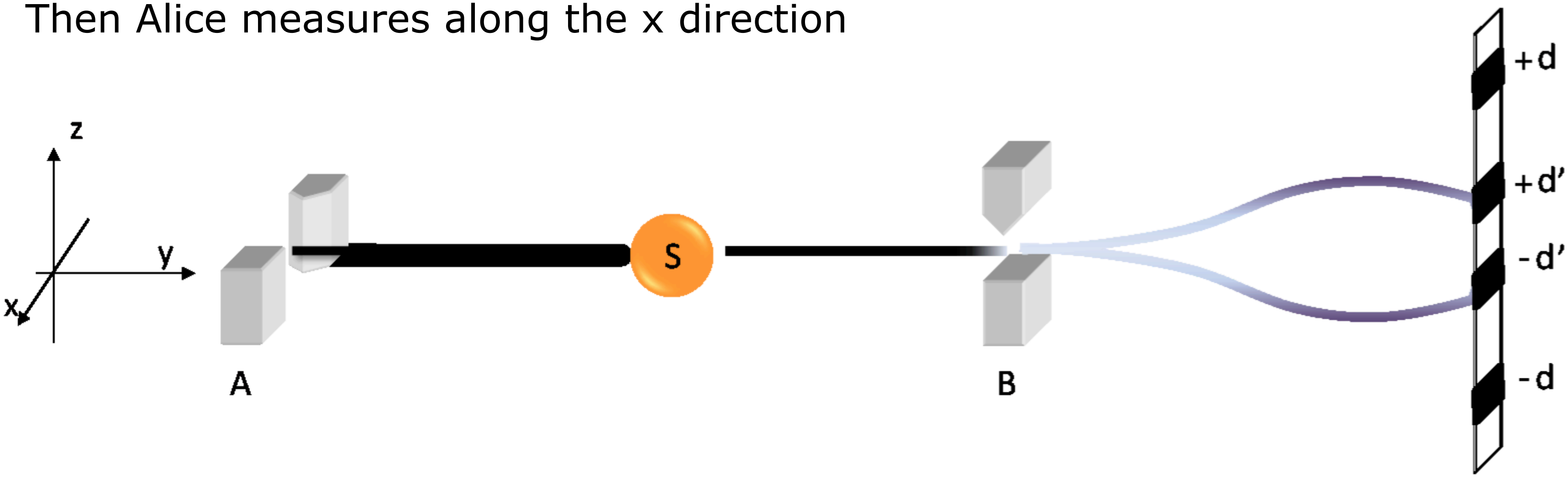
The Schrödinger-Newton equation

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



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- Graduate students: M. Caiaffa

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