UNIVERSITY OF TRIESTE

DEPARTMENT OF PHYSICS

An introduction to spontaneous wave function collapse models and their experimental tests

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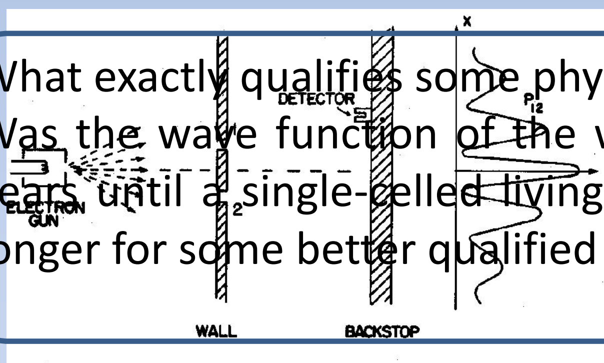
MALTA, 27/03/2017

THE MEASUREMENT PROBLEM

The Schrödinger equation:

- Linear
- Deterministic

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = H |\Psi(t)\rangle$$



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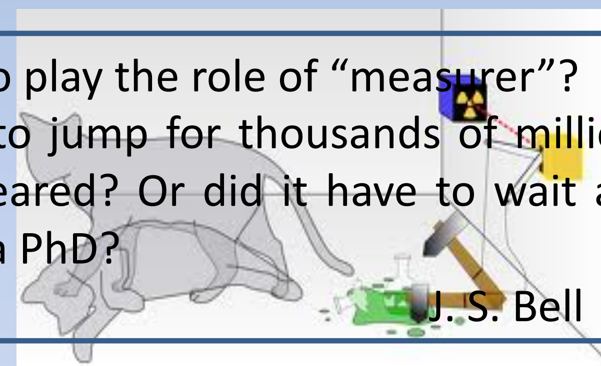


KO

What exactly qualifies some physical systems to play the role of "measurer"? Was the wave function 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?

J. S. Bell

The wave packet reduction postulate:

- Non Linear
- Stochastic

$$\frac{|a_1\rangle + |a_2\rangle}{\sqrt{2}} \xrightarrow{\text{measurement}} \begin{cases} \xrightarrow{\text{half of total cases}} |a_1\rangle \\ \xrightarrow[\text{half of total cases}]{} |a_2\rangle \end{cases}$$

There are two different laws for the evolution of the state vectors but it is not clear when to use which one.

THE GRW MODEL

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

1) Casual Localizations that follow a poissonian statistic with mean rate λ_i .

2) The localization around the point $\mathbf{a}$ is:

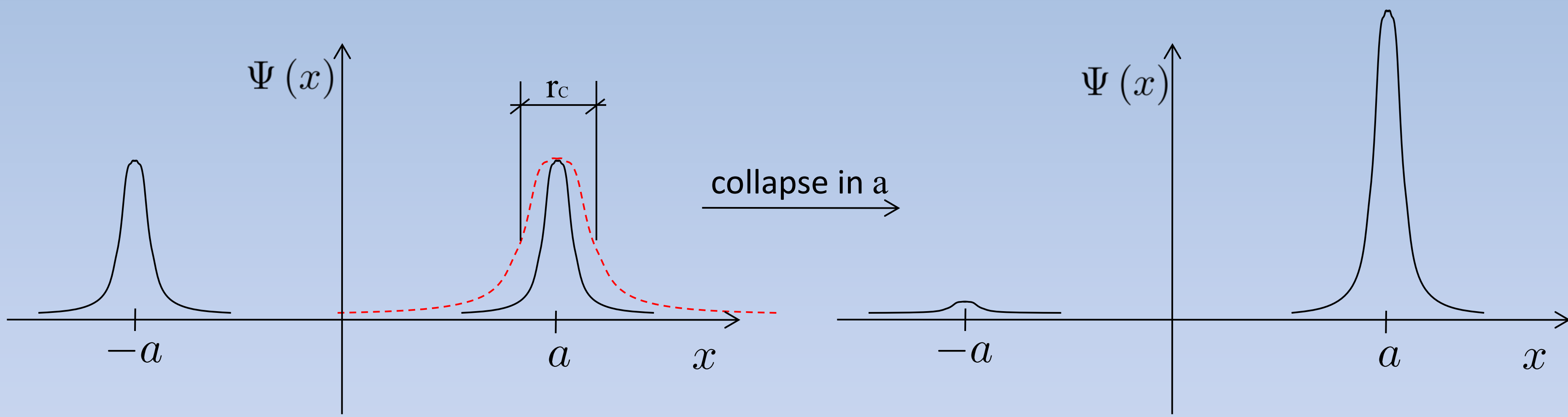
$$|\Psi\rangle \longrightarrow \frac{L^i_{\mathbf{a}}|\Psi\rangle}{\left\|L^i_{\mathbf{a}}|\Psi\rangle\right\|} \qquad \text{where} \qquad L^i_{\mathbf{a}} = \left(\pi r_c^2\right)^{-3/4} e^{-\frac{(\mathbf{q_i}-\mathbf{a})^2}{2r_c^2}}$$

3) The probability of localization around $\mathbf{a}$ is given by: $P^i(\mathbf{a}) = \left\|L^i_{\mathbf{a}}|\Psi\rangle\right\|^2$

4) Between two localizations the system's state evolves following the Schrödinger equation:

$$i\hbar\frac{d}{dt}|\Psi(t)\rangle = H|\Psi(t)\rangle$$

LOCALIZATION MECHANISM

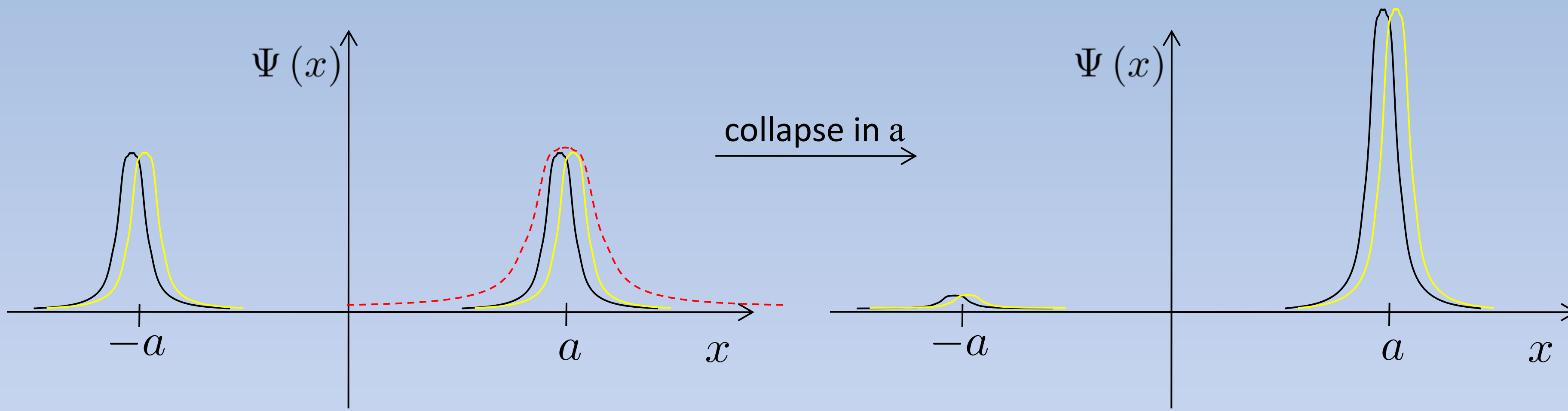


$$\Psi(x) = \frac{\psi_{-a}(x)+\psi_{a}(x)}{\sqrt{2}} \longrightarrow \Psi(x) = \psi_{a}(x)$$

$$P\left(\mathbf{a}\right) = \left\| L_{\mathbf{a}} \left|\Psi\right\rangle \right\|^{2} \simeq \frac{1}{2} = P\left(-\mathbf{a}\right) \qquad P\left(\mathbf{0}\right) \simeq 0$$

Localization/correlation length : $r_C = 10^{-7}\ \mathrm{m}$

AMPLIFICATION MECHANISM



$$\Psi(x;y) = \frac{\psi_{-a}(x)\phi_{-a}(y) + \psi_a(x)\phi_a(y)}{\sqrt{2}} \xrightarrow[\Lambda = \lambda_1 + \lambda_2]{} \psi_a(x)\phi_a(y)$$

For a system with N particles: $\Lambda = N\lambda$

$\lambda = 10^{-17}\ \mathrm{s}^{-1}$ ⟶ for few particles low probability of collapse

$\lambda_{macro} = N\lambda \simeq 10^{6}\ \mathrm{s}^{-1}$ ⟶ for macrosystems the collapse is instantaneous

THE CSL MODEL

(CONTINUOUS SPONTANEOUS LOCALIZATIONS MODEL)

G.C. Ghirardi, P. Pearle and A. Rimini, Phys. Rev. A **42**, 78 (1990).

$$d|\psi_t\rangle = \Big[-\frac{i}{\hbar}H\,dt + \frac{\sqrt{\gamma}}{m_0}\int d\mathbf{x}\,\Big(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_{\psi_t}\Big)\,dW_t(\mathbf{x})$$
$$-\frac{\gamma}{2m_0}\int d\mathbf{x}\,d\mathbf{y}\,g(\mathbf{x}-\mathbf{y})\Big(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_{\psi_t}\Big)\Big(N(\mathbf{y}) - \langle N(\mathbf{y})\rangle_{\psi_t}\Big)dt\Big]|\psi_t\rangle$$

Schrödinger

Stochasticity

Non linearity

$$\gamma = \lambda 8\pi^{3/2} r_C^3$$
$$N(\mathbf{x}) = m\psi^\dagger(\mathbf{x})\psi(\mathbf{x})$$

$$\mathbb{E}\left[dW_t(\mathbf{x})dW_t(\mathbf{y})\right] = g(\mathbf{x}-\mathbf{y})dt$$

$$g(\mathbf{x}-\mathbf{y}) = \frac{e^{-(\mathbf{x}-\mathbf{y})^2/4r_C^2}}{(4\pi r_C^2)^{3/2}}$$

- First model valid also for identical particles;
- Localization in space;
- Amplification mechanism.

ROBUST TO GENERALIZATIONS

- Dissipative effects
- Non-Markovian effects

DIOSI-PENROSE (DP) MODEL

L. Diósi, Phys. Rev. A **40**, 1165–1174 (1989)
R. Penrose, Gen. Relativ. Gravit. **28**, 581–599 (1996)

IDEA: Is wave function collapse induced by gravity?

Same structure of CSL model with:

$$\frac{\sqrt{\gamma}}{m_0} \longrightarrow \sqrt{\frac{G}{\hbar}} \qquad N(\mathbf{x}) \rightarrow f(\mathbf{x}) = \frac{M}{V}\theta\left(R - |\mathbf{q} - \mathbf{x}|\right)$$

$$dW_t(\mathbf{x}) \longrightarrow dW_t^{DP}(\mathbf{x}) \qquad \mathbb{E}\left[dW_t^{DP}(\mathbf{x})dW_t^{DP}(\mathbf{y})\right] = \frac{dt}{|\mathbf{x} - \mathbf{y}|}$$

- Introduction of finite volume for particles necessary to avoid divergences.

- For $R = 10^{-15}\ \mathrm{m}$ $\longrightarrow$ unacceptable heating: for a gas of proton $\Delta T = 10^{-4}\ \mathrm{K/s}$

- For $R = 10^{-7}\ \mathrm{m}$ $\longrightarrow$ $\Delta T = 10^{-28}\ \mathrm{K/s}$ ok but arbitrary value.

- With dissipation one can take $R = 10^{-15}\ \mathrm{m}$ but the model is valid only for systems with mass larger than $m = 10^{11}\ \mathrm{amu}$

SCHRÖDIGER-NEWTON (SN) MODEL

L. Diósi, Phys. Lett. A **105**, 199–202 (1984)

SEMI-CLASSICAL GRAVITY

IDEA:
- matter quantum
- metric classical

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} \langle \psi | \hat{T}_{\mu\nu} | \psi \rangle$$

Under the assumptions:

1) Weak gravitational field: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
2) Non-relativistic regime : $v \ll c$

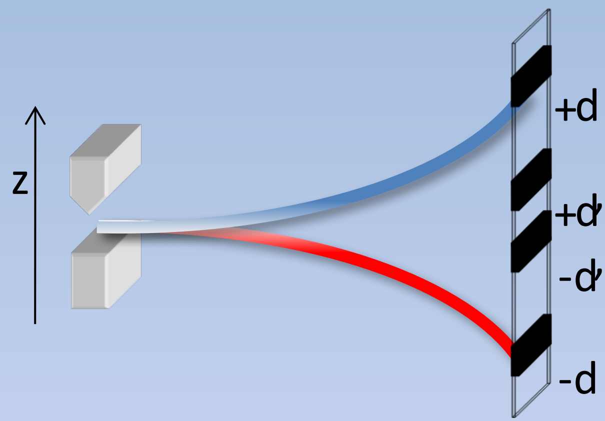
SCHROEDIGER-NEWTON EQUATION

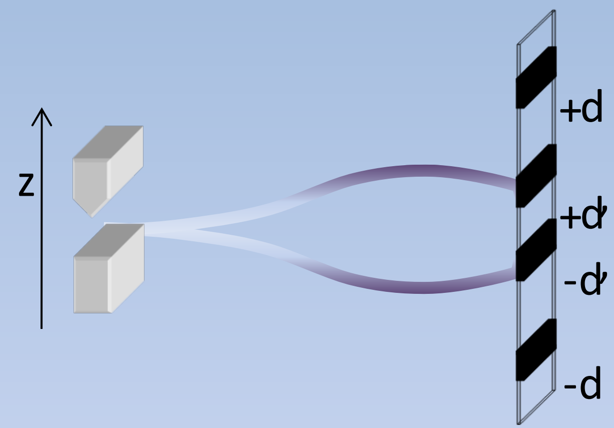
$$i\hbar \frac{d\psi(\mathbf{x},t)}{dt} = \left(-\frac{\hbar^2}{2m}\nabla^2 - Gm^2 \int d\mathbf{y} \, \frac{|\psi(\mathbf{y},t)|^2}{|\mathbf{x}-\mathbf{y}|} \right) \psi(\mathbf{x},t)$$

Standard evolution

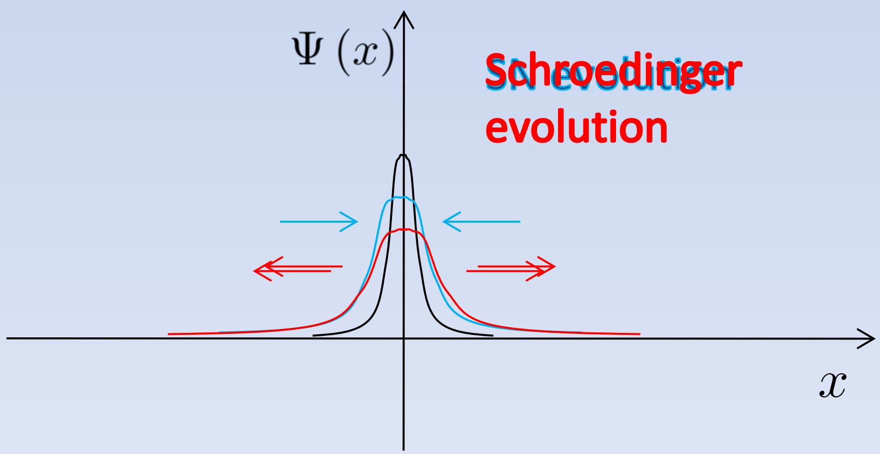
Non-linear self attraction between the different parts of the wave function

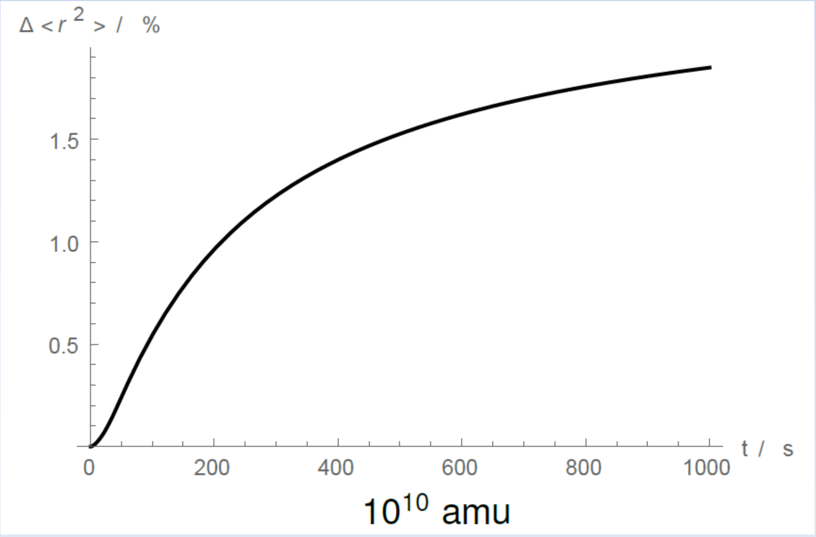
SUPERPOSITION EVOLUTION





SPREADING OF A WAVE-PACKET



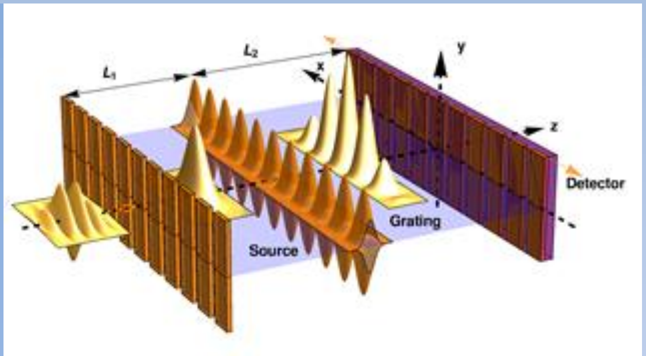


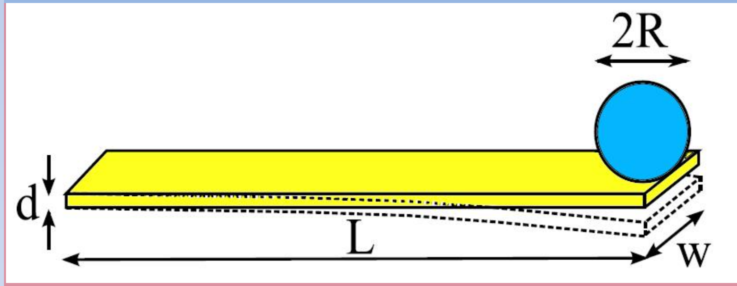
RELEVANT EXPERIMENTS

Matter-wave interferometry

S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor, and J. Tuxen. Phys. Chem. **15,** 14696 (2013).

M. Toros and A. Bassi. Link to Arxiv: http://arxiv.org/abs/1601.03672, http://arxiv.org/abs/1601.02931.

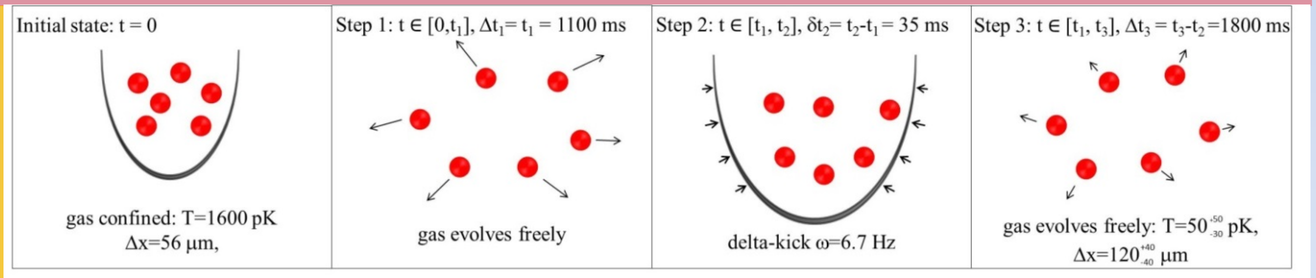




Cantilever

A. Vinante, M. Bahrami, A. Bassi, O. Usenko, G. Wijts, T.H. Oosterkamp, Phys. Rev. Lett. **116**, 090402 (2016).

Cold atoms



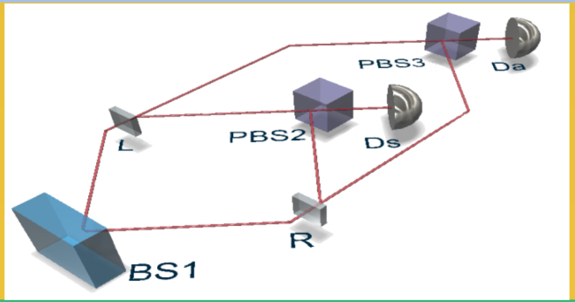
T. Kovachy, et al., Phys. Rev. Lett. **114**, 143004 (2015)
M. Bilardello, S. Donadi, A. Vinante and A. Bassi, Physica A **462**, 764-782 (2016).
F. Laloe, Franck, W. J. Mullin and P. Pearle, Phys. Rev. A **90** (5), 052119 (2014).

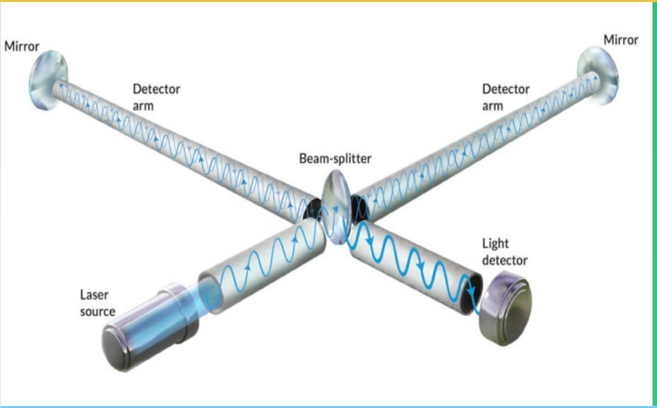
RELEVANT EXPERIMENTS

Entangling macroscopic diamonds

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

S. Belli, et al., Phys. Rev. A **94.1**, 012108 (2016).





Gravitational waves detection

B. P. Abbott, et al., Phys. Rev. Lett. **116.6**, 061102 (2016).

B. Helou, B. Slagmolen, D. E. McClelland, and Y. Chen, arXiv 1606.03637(2016).

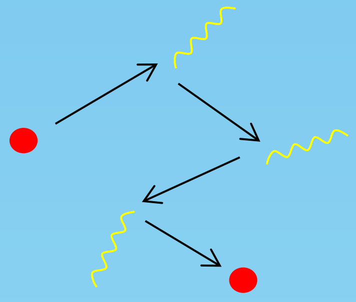
M. Carlesso, A. Bassi, P. Falferi, A.Vinante, Phys. Rev. D **94.12**, 124036 (2016).

Radiation emission

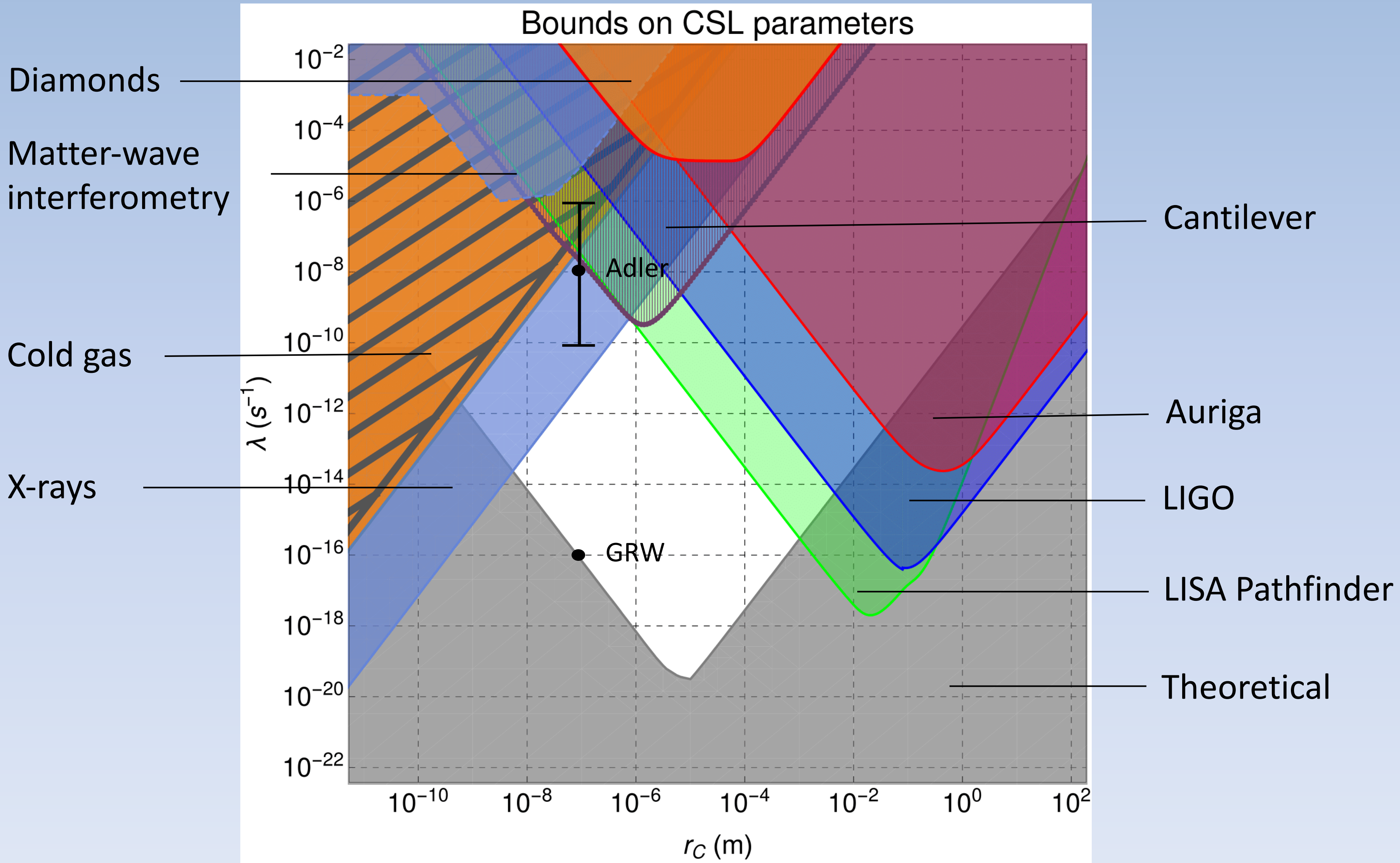
Q. Fu, Phys. Rev. A **56**, 1806 (1997).

S.L. Adler, A. Bassi and S. Donadi, J. Phys. A **46**, 245304 (2013).

C. Curceanu, B. C. Hiesmayr, K. Piscicchia. J. Adv. Phys. **4(3)**, 263–266 (2015).



EXCLUSION PLOT



WHY GOING TO SPACE?

Maqro2015

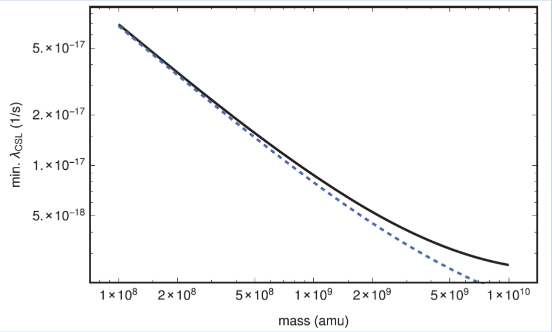
Interferometry: Masses in the range 10^8 - 10^{11} amu. Advantages:

1) More time for spreading: 10^2 s vs 10^{-3} s; ($\sigma_x(t) = f(t/m)$)

2) De Broglie wavelenght does not decrease too much; ($\lambda_{\text{db}} = h/mv$)

3) Masses increased by 4-7 orders of magnitude!

Wave function spread: Experiments are expected to test GRW values!
Relevant also for SN equation!



Cold atoms: - Time of experiment was only 2.8 sec because of gravity.
- Short time of experiment was limiting the cooling
- t=100s implies improving the bounds of 3 orders of magnitude.

$$\frac{\lambda}{r_C^2} \leq \frac{4\epsilon\sqrt{\langle \hat{\mathbf{v}}^2 \rangle_{t_0}} m_0^2}{\sqrt{N-1}\hbar^2 \underline{t^2}}$$

Rotation of a rod or a plane (?) : no friction and less decoherece effects

CONCLUSIONS

1) Collapse models: dynamical description of the wave function collapse.
   - modifications very little for microsystems;
   - but relevant for macrosystems.

2) Collapse models make different predictions compared to standard quantum theory.
   - many experiments set bounds on the parameters of the models;
   - still a large region of the exclusion plot is not excluded.

3) Micro gravity environment: essentialy the fact that systems can evolve freely for large times (order of 100 s) allows to improve current tests of several orders of magnitudes.

QUANTUM MECHANICS GROUP IN TRIESTE

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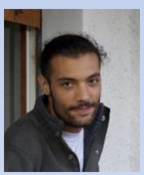
Stefano Bacchi (PhD)

Marco Bilardello (PhD)



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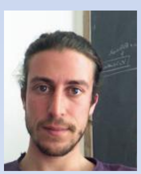

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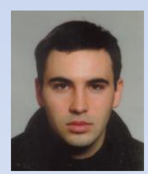

Marko Toros (PhD)

FINANCIAL SUPPORTS

INFN Istituto Nazionale di Fisica Nucleare

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THANKS