EmQM15

Emergent Quantum Mechanics 2015

Vienna, 23-25 October 2015

Models of spontaneous wave function collapse: what they are, and how they can be tested.

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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

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

$\langle A\rangle_t = \langle\psi_t|A|\psi_t\rangle \longrightarrow$ nonlinear

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

This form is **fixed** by the requirement of **no-faster-than-light signaling** and **norm conservation** (Adler's book on Trace Dynamics).

Collapse due to Gravity?

Penrose, Diosi …

No one really knows.

But the gravitational coupling to matter is the right one for the collapse…

almost the right one

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

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

Higher order, **non-linear terms**

A different theory of gravity would be needed.

Side note on the Schrödinger-Newton equation: it is not a collapse equation in the sense of collapse models. But it does collapse the wave function, and it could serve to discriminate whether gravity is quantum or fundamentally classical

(A. Großardt *et al.*, ArXiv:1510.01696)

CSL model and its variations

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)

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

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

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

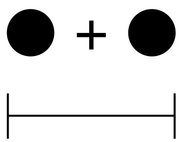
Two parameters

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

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

The collapse rate

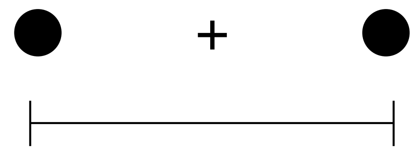
Small superpositions



$\ll r_C$

Collapse NOT effective

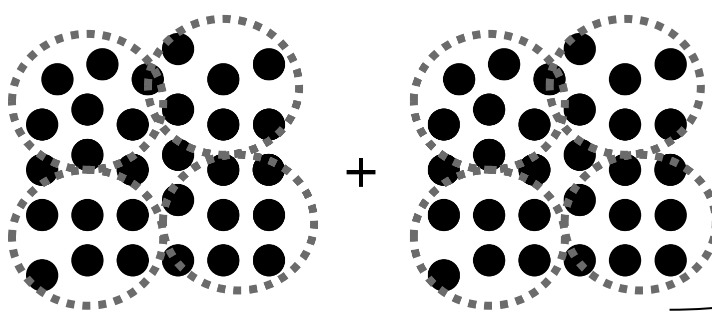
Large superpositions



$\geq r_C$

Collapse effective

$$\Gamma = \lambda n^2 N$$



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

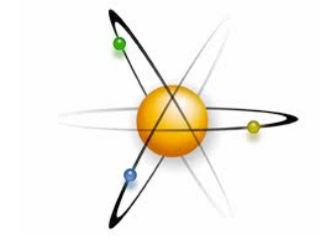
Many particles

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

Matter-wave interferometry world mass record: 10^4 amu (Vienna, 2013)

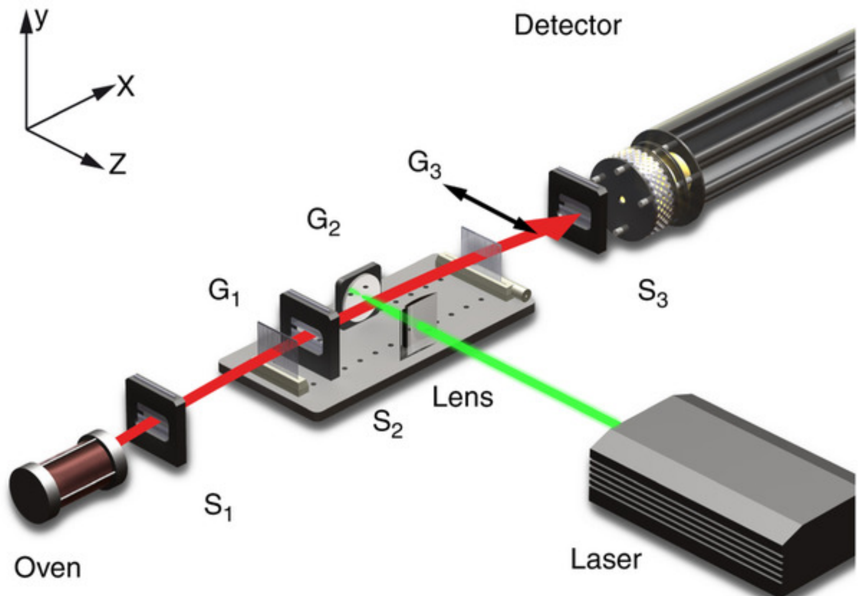
Brief history of matter-wave interferometry:

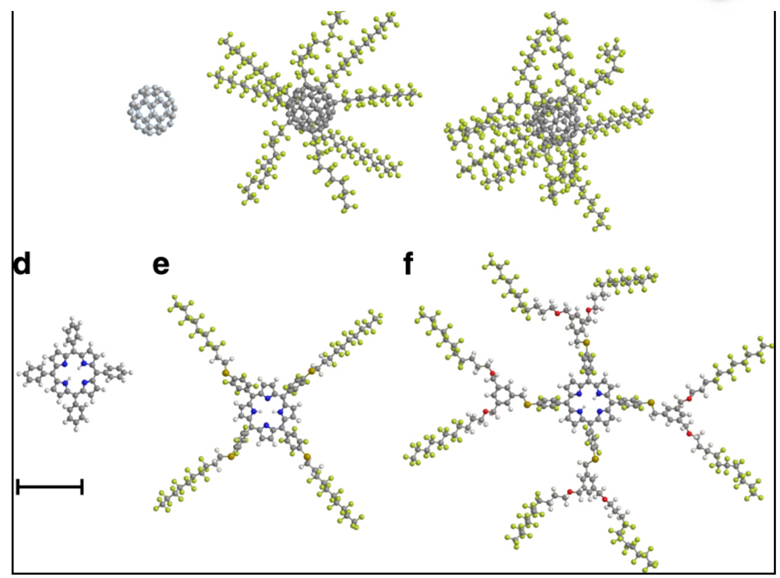
- **C_{60} (720 AMU)**
  M. Arndt et al, *Nature* 401, 680 (1999)
- **C_{70} (840 AMU)**
  L. Hackermüller et al, *Nature* 427, 711 (2004)
- **$C_{30}H_{12}F_{30}N_2O_4$ (1,030 AMU)**
  S. Gerlich et al, *Nature Physics* 3, 711 (2007)
- **Largest Molecule (10,000 AMU)**
  S. Eibenberger *et al.* PCCP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

NANOQUESTFIT: 10^5 AMU
EU Project under FP7

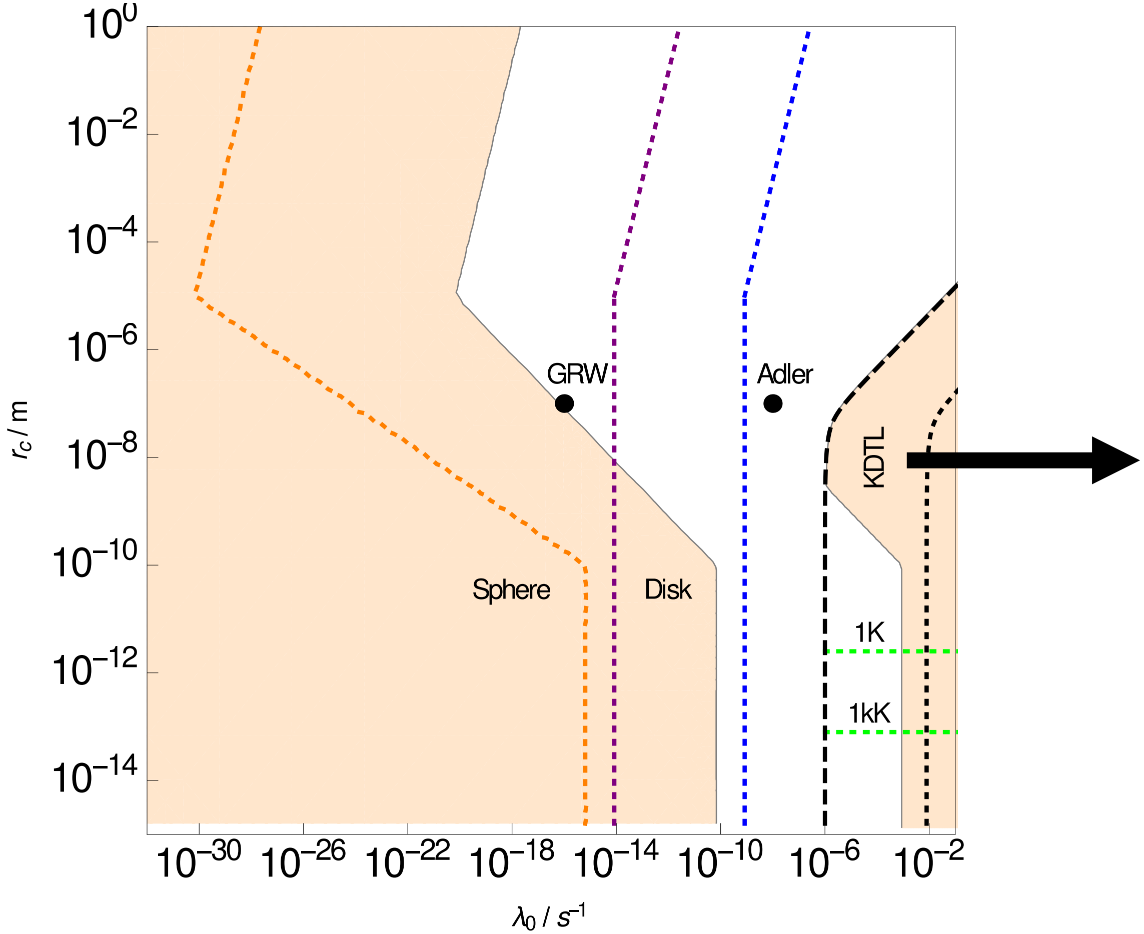
Future experiments: ~10^6 AMU
K. Hornberger *et al.*, Rev. Mod. Phys. 84, 157 (2012)
P. Haslinger *et al.*, Nature Phys. 9, 144 (2013)

MAQRO consortium for a space mission with ESA (micro-gravity)





Matter-wave interferometry
Upper bounds on the collapse parameters



The exclusion zone is pretty much insensitive to the type of collapse model: CSL, dissipative CSL, non-Markovian CSL.

Matter-wave interferometry provides a general test of collapse models

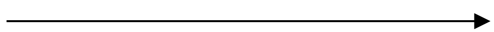
M. Toros and A. Bassi, work in progress

Spontaneous photon emission

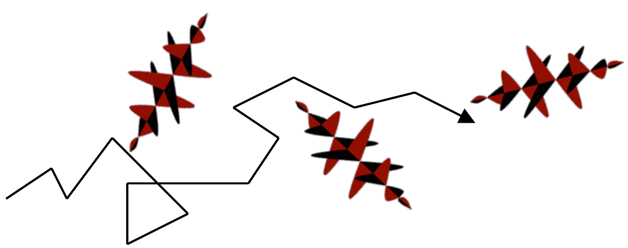
S. Donadi, D.-A. Deckert, A. Bassi, *Ann. Phys.* 340, 70 (2014) and references therein

FREE PARTICLE

1. Quantum mechanics

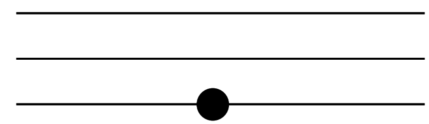


2. Collapse models

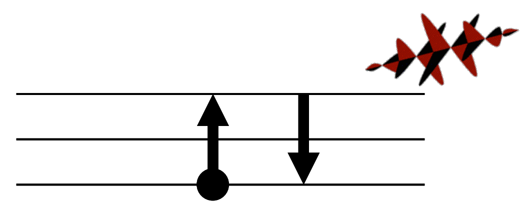


BOUND STATE

1. Quantum mechanics



2. Collapse models

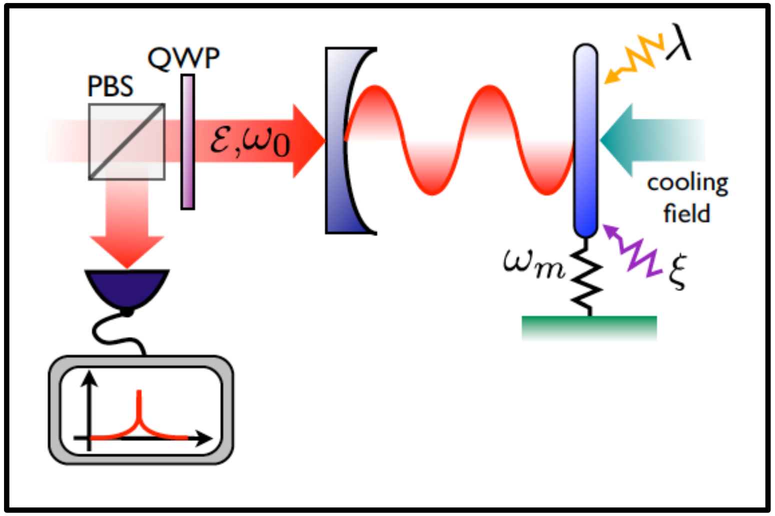


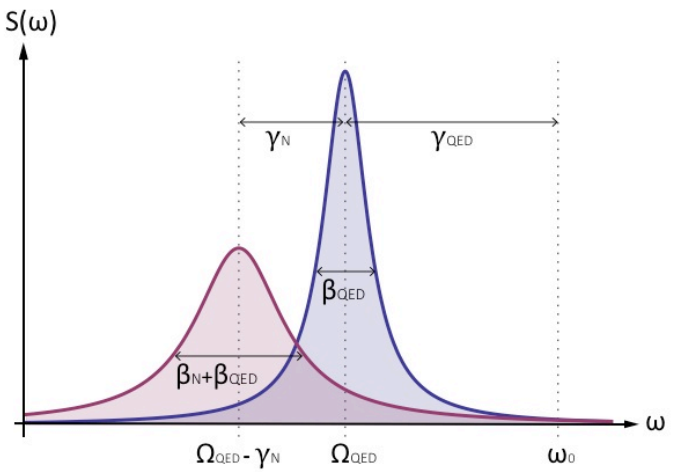
1. One needs to introduce mass proportionality in the model
2. Adler's value for λ is ruled out by 3 orders of magnitude, unless the noise spectrum has a cut off below 10^{18} Hz. (ArXiv 1501.04462)

Strongest upper bound on the collapse parameter λ

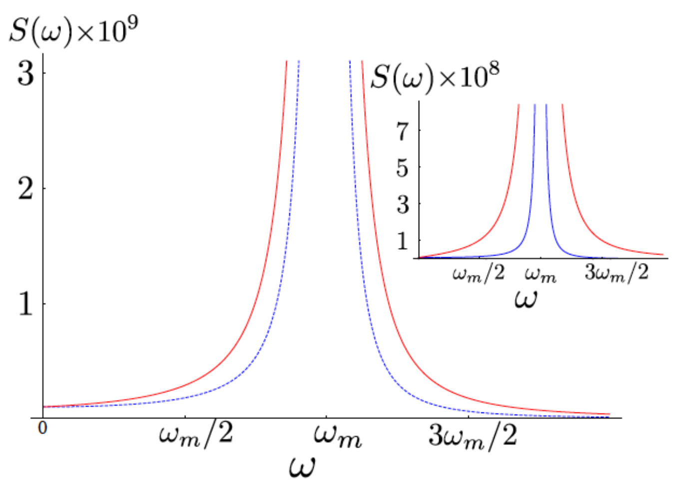
Non interferometric tests with opto-mechanical systems

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



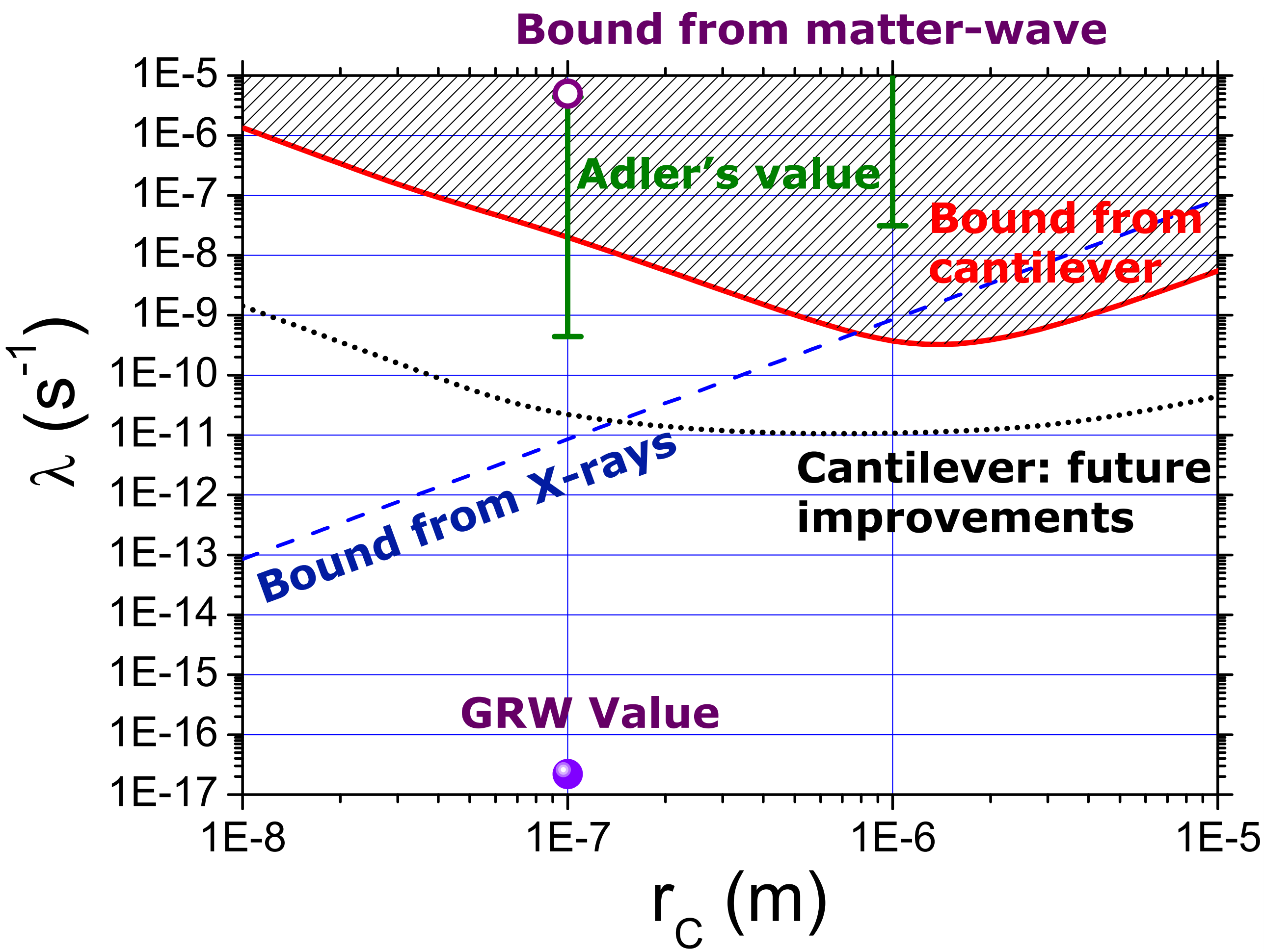


Qualitative behavior



Quantitative behavior

Experimental bounds from non-interferometric tests



Cantilever:
OK for CSL and non-Markovian CSL.
Probably not OK for dissipative CSL, with T = 1K.
ArXiv:1510.05791

X-ray:
OK for CSL and dissipative CSL.
Not OK for non-Markovian CSL, with cutoff below 10^{18} Hz
ArXiv:1501.04462

A. Vinante *et al.*, ArXiv 1510.05791

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- Graduate students: A. Rampichini

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