Non-interferometric diagnostics of collapse models

Quantum Engineering of Levitated Systems
Benasque, 17th-21st September 2018

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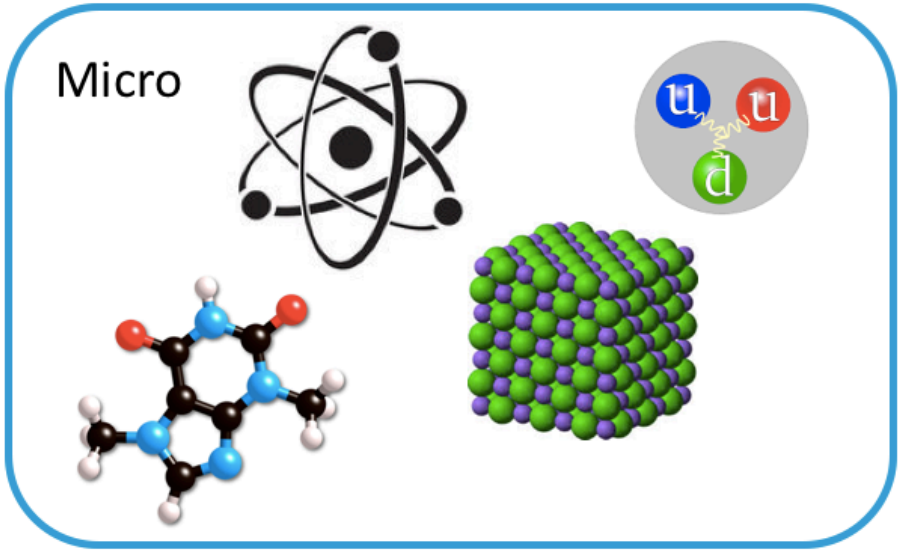
INFN Istituto Nazionale di Fisica Nucleare

Standard Quantum Mechanics

Quantum World



Classical World

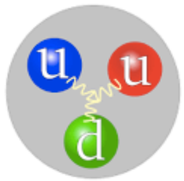
"The Copenhagen interpretation assumes a mysterious division between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics."

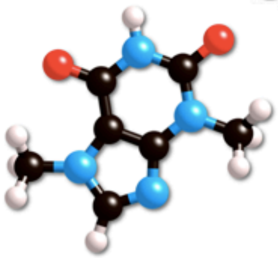
S. Weinberg, Phys. Rev. A 85, 062116 (2012)

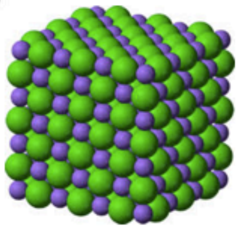
Standard Quantum Mechanics

Quantum World

Micro







Classical World

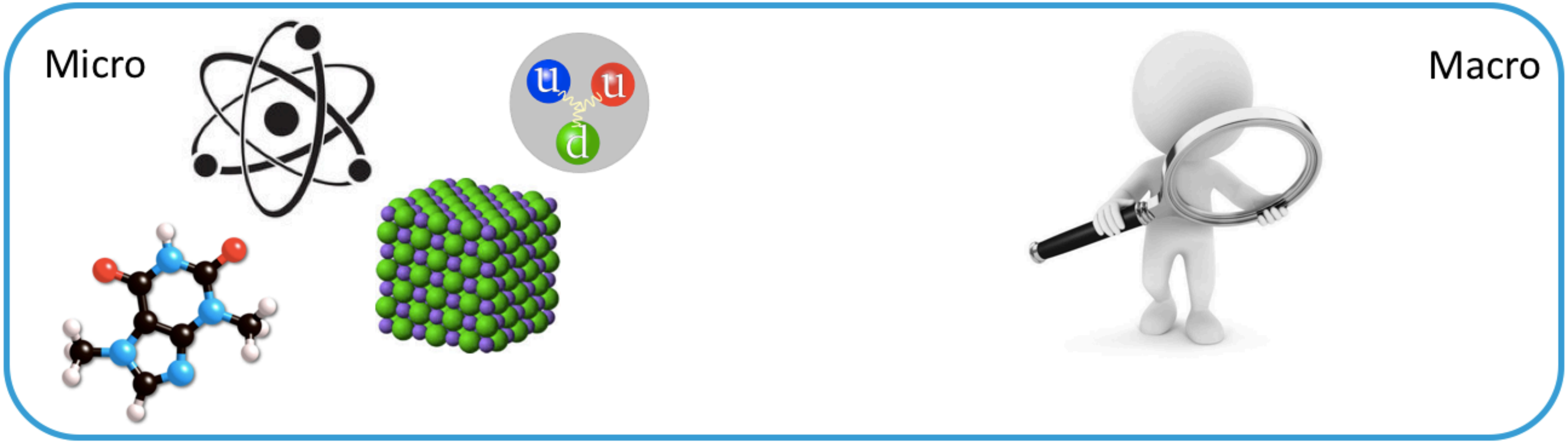
Macro

“What exactly qualifies some physical systems to play the role of 'measurer'?“

John Bell, Against ‘measurement’, Physics World, *Phys. World* **3** (8) 33 (1990)

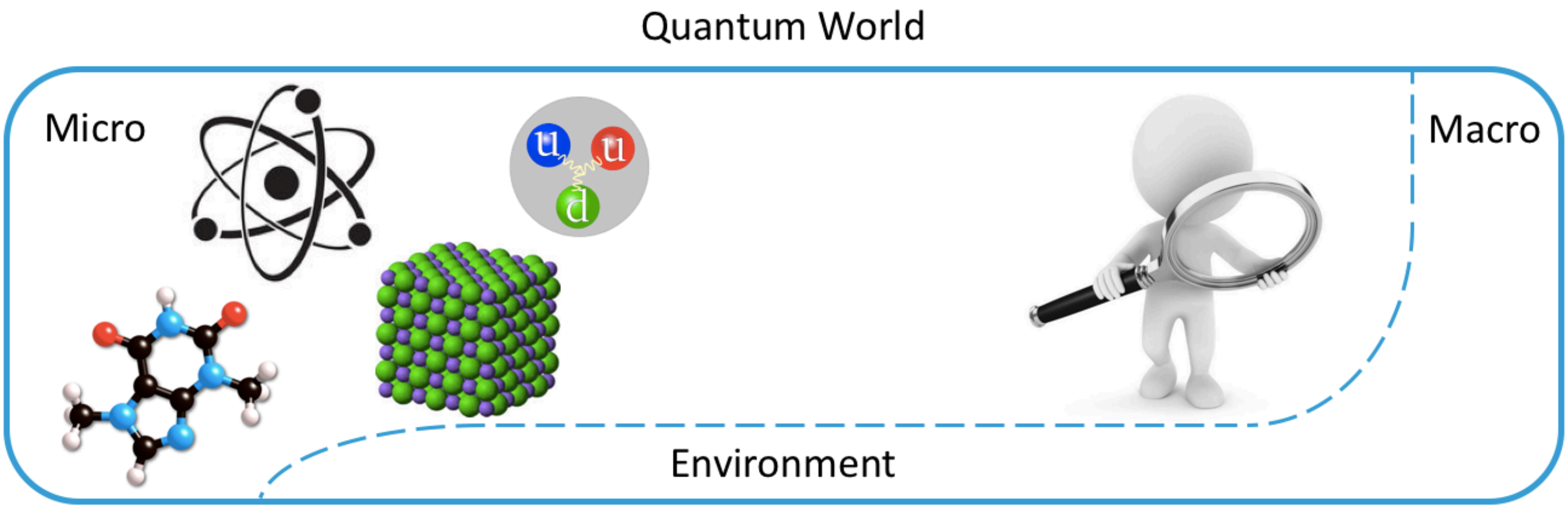
How we would like Quantum Mechanics to be

Quantum World



What is now the meaning of the wavefunction, now that there is no observer giving a probabilistic interpretation to it? Who measures and makes the wavefunction collapse? Why we do not observe superpositions of macroscopic systems?

Decoherence does not solve the problem

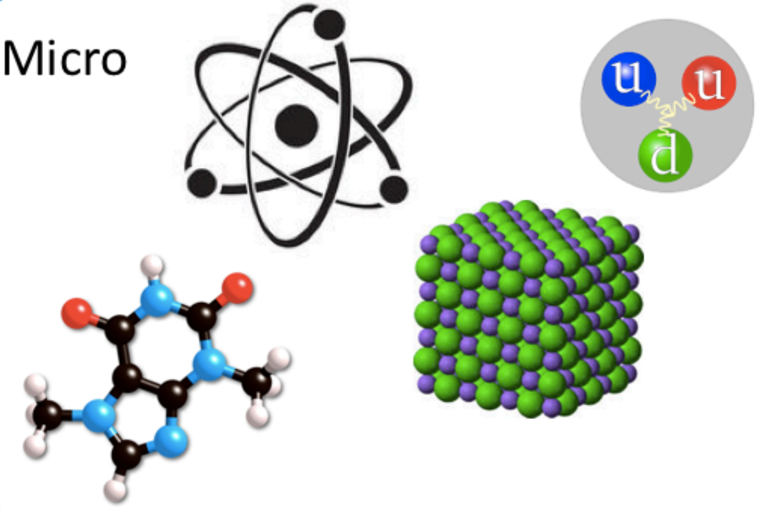


The division system-environment is arbitrary, and very much similar to the division quantum-classical in the Copenhagen interpretation.

Possible solutions

Quantum World

Micro



Macro

Bohmian Mechanics
Many Worlds
Collapse Models

Collapse models

Collapse models modify the Standard Quantum Mechanics to solve the measurement problem and the quantum-to-classical transition

Adding stochastic and non-linear terms to Schödinger eq.

Negligible microscopic action
No effective collapse
Quantum systems

Amplification mechanism

Strong macroscopic action
Rapid collapse
Systems behave classically

Continuous Spontaneous Localization model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}\hat{H}dt + \frac{\sqrt{\gamma}}{m_0}\int d\boldsymbol{y} \left(\hat{M}(\boldsymbol{y}) - \langle \hat{M}(\boldsymbol{y})\rangle\right) dW_t(\boldsymbol{y}) + \right.$$
$$\left. - \frac{\gamma}{2m_0^2}\int d\boldsymbol{y} \left(\hat{M}(\boldsymbol{y}) - \langle \hat{M}(\boldsymbol{y})\rangle\right)^2 dt \right] |\psi_t\rangle$$

Stochastic, Non-linear equation. Collapse occurs in **space**

$$\hat{M}(\boldsymbol{y}) = \frac{m}{(2\pi\hbar)^3}\sum_\alpha \int d\boldsymbol{Q}\, e^{\frac{i}{\hbar}\boldsymbol{Q}\cdot(\hat{\boldsymbol{x}}_\alpha - \boldsymbol{y})} e^{-\frac{r_C^2}{2\hbar^2}\boldsymbol{Q}^2}$$

Mass proportional
The **amplification mechanism**
is **automatically implemented**

$$\mathbb{E}[dW_t(\boldsymbol{x})dW_s(\boldsymbol{y})] = \delta(\boldsymbol{x} - \boldsymbol{y})dt$$

Two parameters:

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

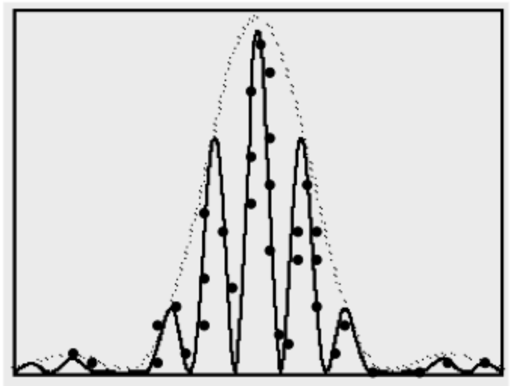
$$r_C = \text{localization resolution}$$

Possible experimental tests

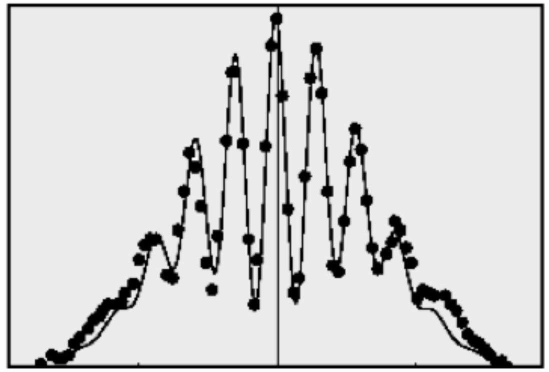
It destroys superposition

Interferometric Experiments

$$\Delta V = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$



Quantum Mechanics



QM + Collapse-like effects

Interferometric CSL tests

Atom Interferometry

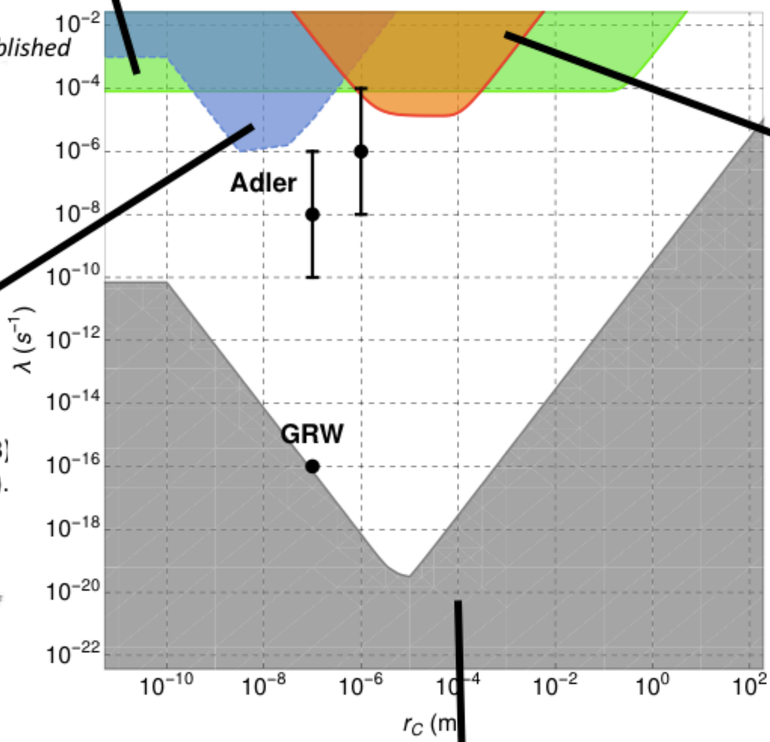
T. Kovachy *et al.*, Nature 528, 530 (2015)

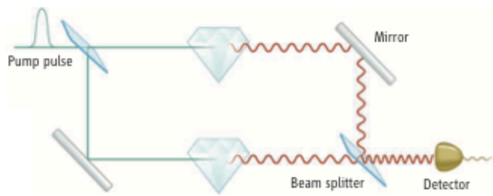
M. Carlesso *et al.*, *to be published*

M = 87 amu

d = 0.54 m

T = 1 s





Entangling Diamonds

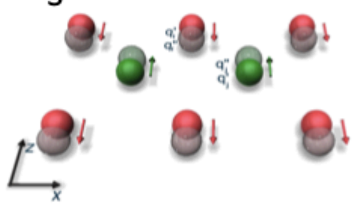
K. C. Lee *et al.*, Science. 334, 1253 (2011).

S. Belli *et al*, Phys. Rev. A 94, 012108 (2016).

M = 10^{16} amu

d = 10^{-11} m

T = 10^{-12} s



Molecular Interferometry

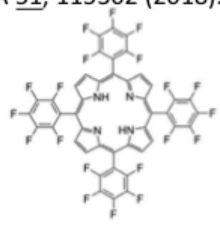
S. Eibenberger *et al.* PCCP 15, 14696 (2013)

M. Toros *et al.*, J. Phys. A 51, 115302 (2018).

M = 10^{4} amu

d = 10^{-7} m

T = 10^{-3} s



TPPF20

M. Toros *et al.*, Phys. Lett. A 381, 3921 (2017).

Lower bound: Collapse effective at the macroscopic level

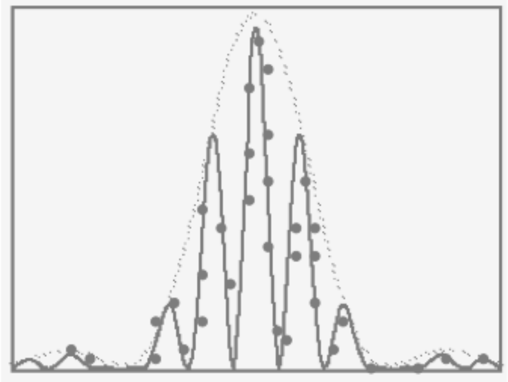
Graphene disk: N = 10^{11} amu, d = 10^{-5} m, T = 10^{-2} s

Possible experimental tests

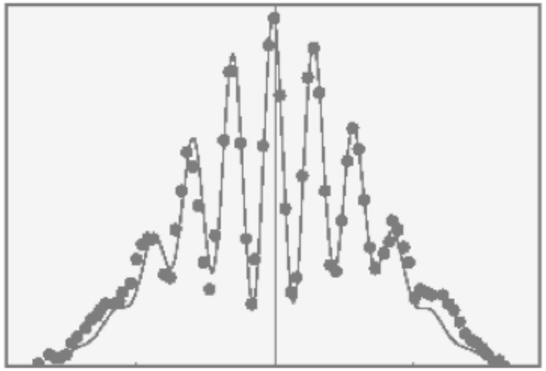
It destroys superposition

Interferometric Experiments

$$\Delta V = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$



Quantum Mechanics

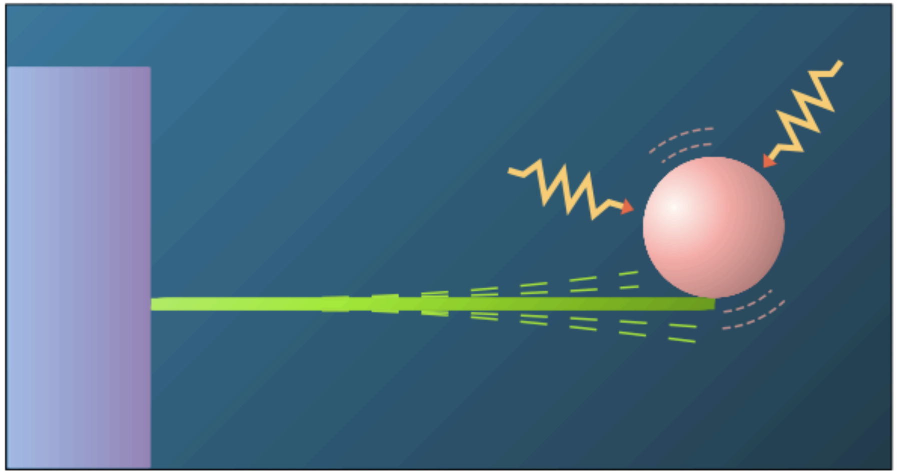


QM + Collapse-like effects

It acts as a Brownian noise

Non-Interferometric Experiments

$$S_{xx}(\omega) = \frac{1}{4\pi}\int d\Omega \, \langle\{\tilde{x}(\omega), \tilde{x}(\Omega)\}\rangle$$



Non-Interferometric CSL tests

It can be mimicked by adding a **stochastic potential**

$$d\,|\psi_t\rangle = -\frac{i}{\hbar}\left(\hat{H} + \hat{V}_{\mathrm{CSL}}\right) dt\,|\psi_t\rangle$$

$$\hat{V}_{\mathrm{CSL}} = -\frac{\hbar\sqrt{\lambda}}{\pi^{3/4} r_C^{3/2} m_0} \int d\boldsymbol{y}\, \hat{M}(\boldsymbol{y}) w(\boldsymbol{y}, t)$$

$$\frac{d}{dt}\hat{x}(t) = \frac{\hat{p}(t)}{M}$$

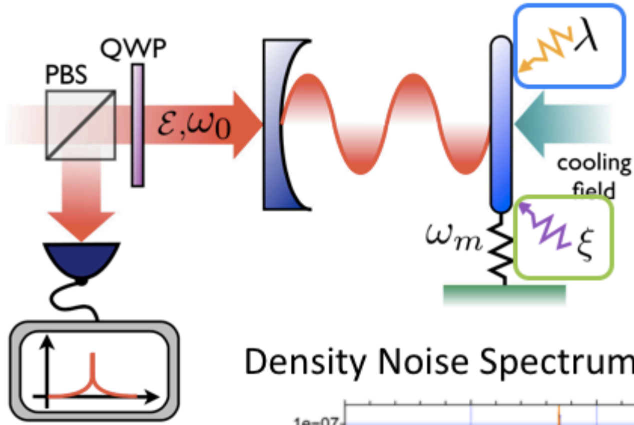
$$\frac{d}{dt}\hat{p}(t) = -M\omega_0^2\hat{x}(t) - \gamma\hat{p}(t) + \boxed{\xi(t)} + \boxed{F_{\mathrm{CSL}}(t)}$$

Density Noise Spectrum

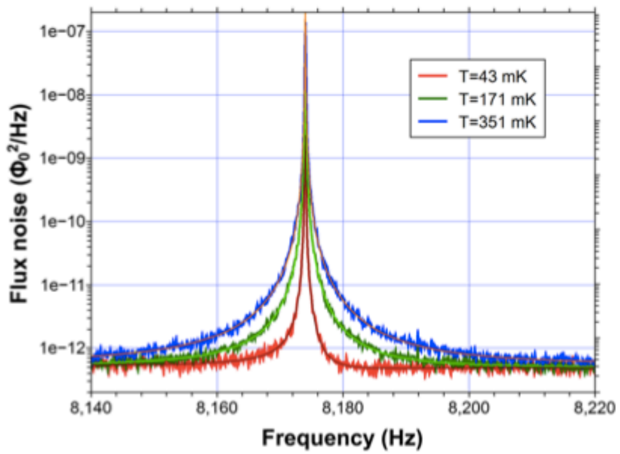
$$S_{xx}(\omega) = \frac{1}{4\pi}\int d\Omega\, \langle\{\tilde{x}(\omega), \tilde{x}(\Omega)\}\rangle$$
$$= \frac{1}{m^2}\frac{\boxed{2m\gamma k_B T} + \boxed{S_{FF}(\omega)}}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}$$

Optomechanical systems

Bahrami *et al.*, Phys. Rev. Lett. **112**, 210404 (2014),
Nimmrichter *et al.*, Phys. Rev. Lett. **113**, 020405 (2014),
Diòsi, Phys. Rev. Lett. **114**, 050403 (2015).



Density Noise Spectrum

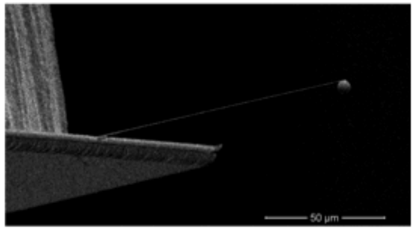


Vinante *et al.*,
Phys. Rev. Lett. **119**, 110401 (2017).

Non-Interferometric CSL tests

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

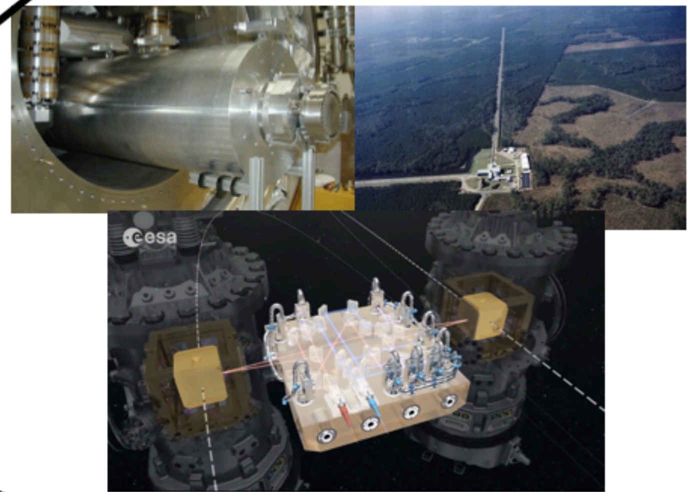
M = 10^{14} amu
T = ∞

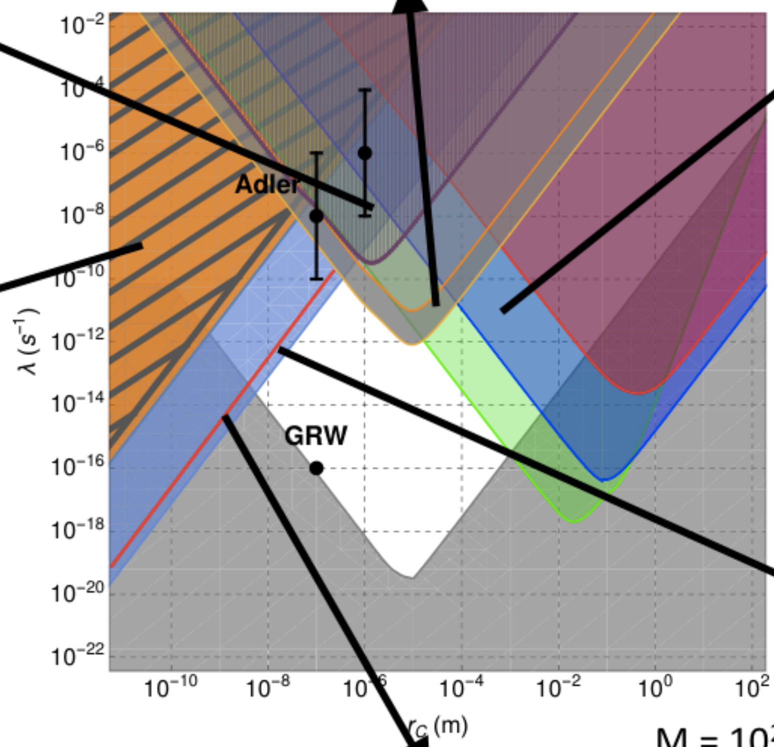


Improved Nanomechanical Cantilever
Vinante *et al.*, Phys. Rev. Lett. 119, 110401 (2017).

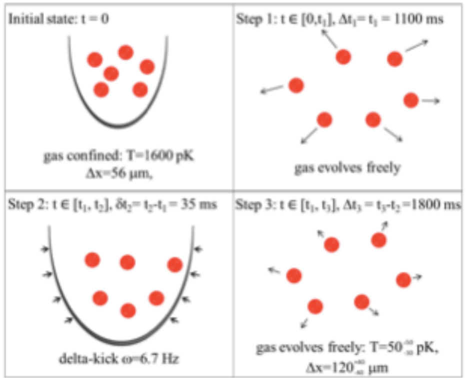
Gravitational wave detectors
Carlesso *et al.*, Phys. Rev. D 94, 124036 (2016).

M = $10^{26\text{-}30}$ amu
T = ∞





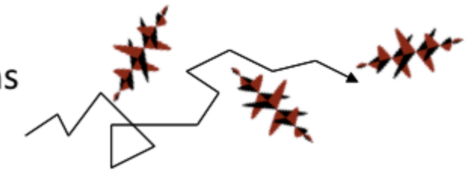
Cold Atoms
Bilardello *et al.*, Physica A, 462:764-782 (2016).



M = 87 amu
T = 1 s

X-rays emission
Piscicchia *et al*, Entropy *19*(7), 319 (2017)

M = 10^{26} amu
T = days / months

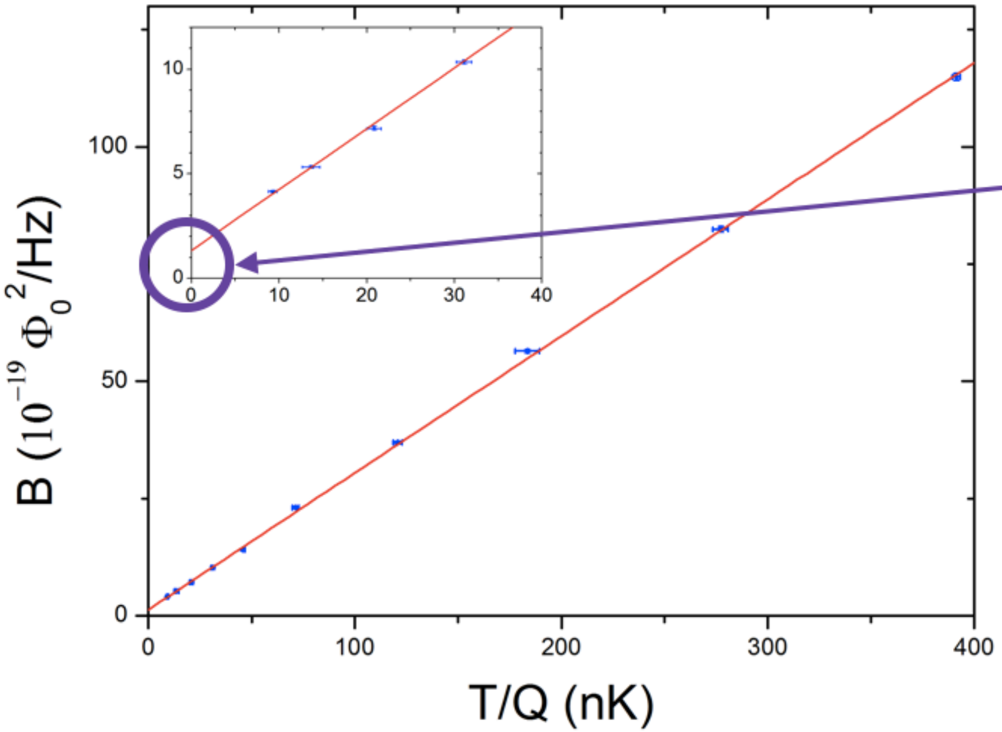


Phonon Spectrum
Adler *et al.*, Phys. Rev. A 97, 052119 (2018).
Bahrami, Phys. Rev. A 97, 052118 (2018).

Nanomechanical Cantilever

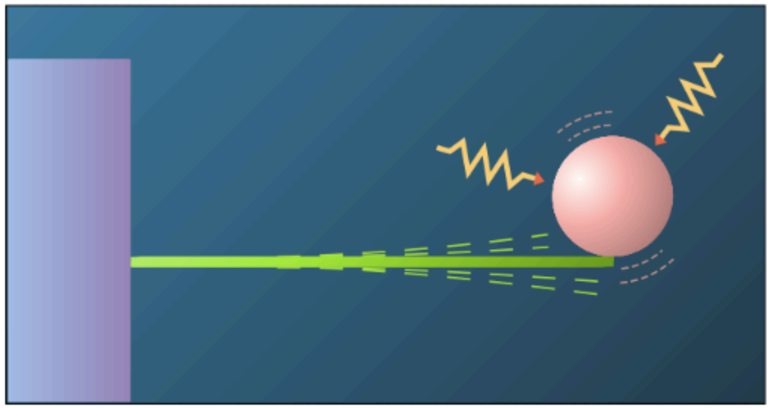
$$S_{xx}(\omega) = \frac{1}{4\pi}\int d\Omega\ \langle\{\tilde{x}(\omega), \tilde{x}(\Omega)\}\rangle = \frac{1}{m^2}\frac{2m\gamma k_{\mathrm{B}}T + S_{FF}(\omega)}{(\omega_0^2-\omega^2)^2+\gamma^2\omega^2}$$

$$\Delta T^{\mathrm{V}}_{\mathrm{CSL}} = \frac{S_{FF}(\omega)}{2k_B m\gamma_m}$$

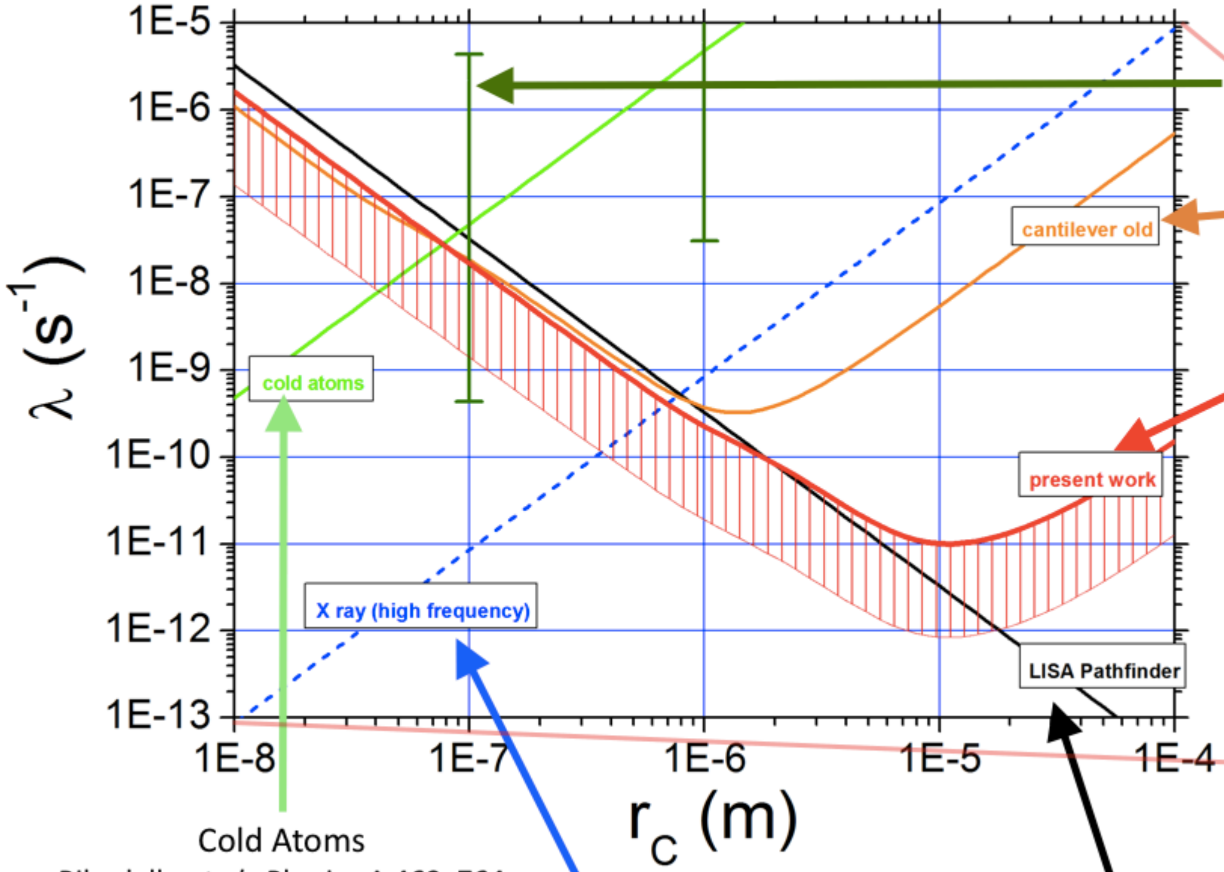


Improved Nanomechanical Cantilever

Vinante *et al.*, Phys. Rev. Lett. 119, 110401 (2017)



Nanomechanical Cantilever



Adler
J. Phys. A 40, 2935 (2007),
J. Phys. A 40, 13501 (2007).

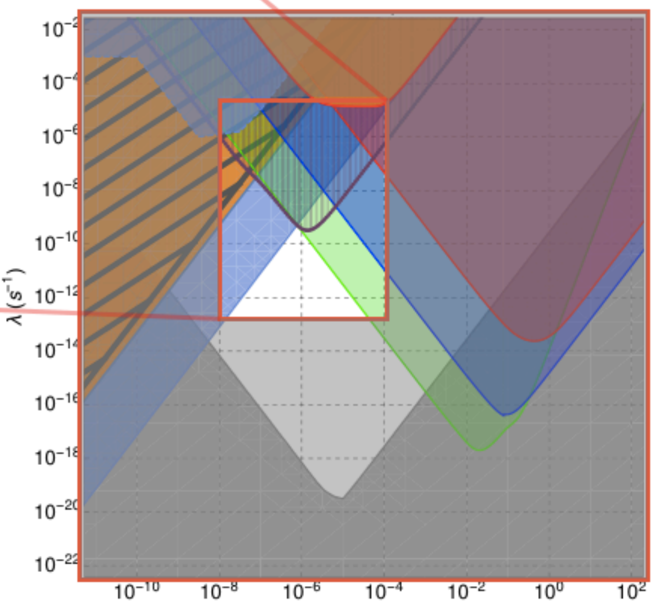
Nanomechanical Cantilever
Vinante *et al.*,
Phys. Rev. Lett. 116, 090402 (2016).

Improved Nanomechanical Cantilever
Vinante *et al.*, Phys. Rev. Lett. 119, 110401 (2017)

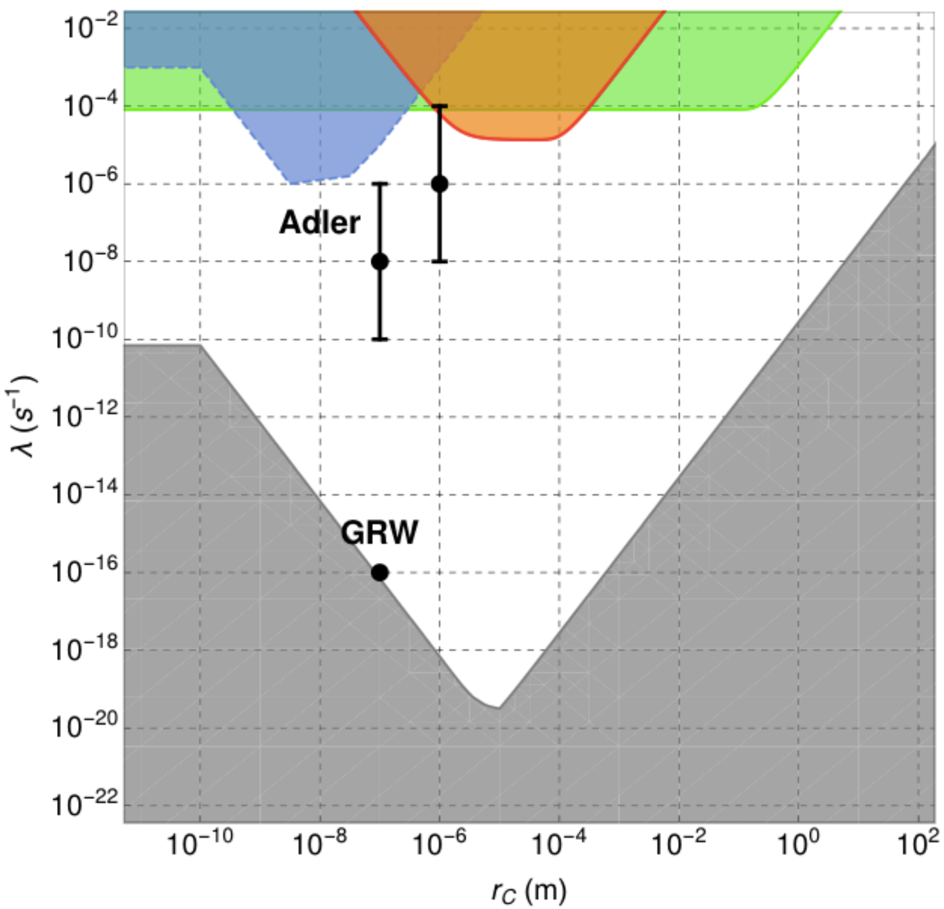
Cold Atoms
Bilardello *et al.*, Physica A 462, 764 (2016).

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

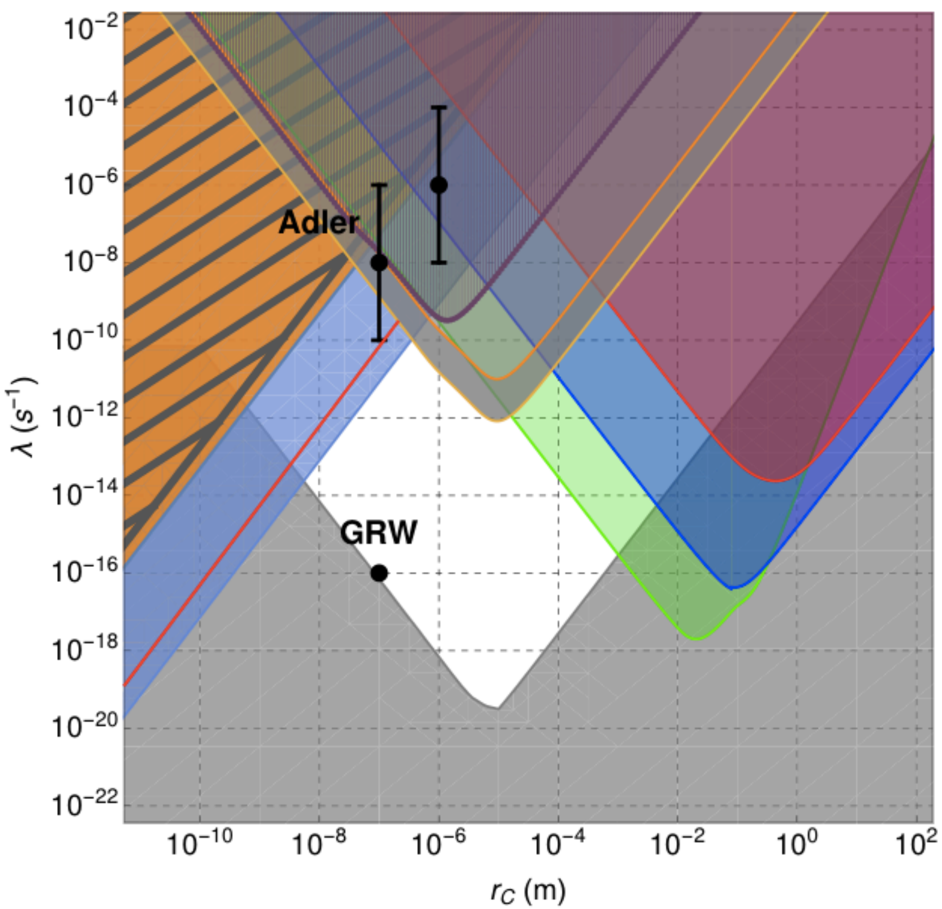
Gravitational wave detectors
Carlesso *et al.*, Phys. Rev. D 94, 124036 (2016).



Experimental bounds



Interferometric Experiments

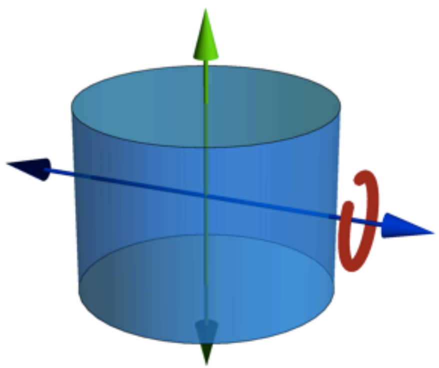


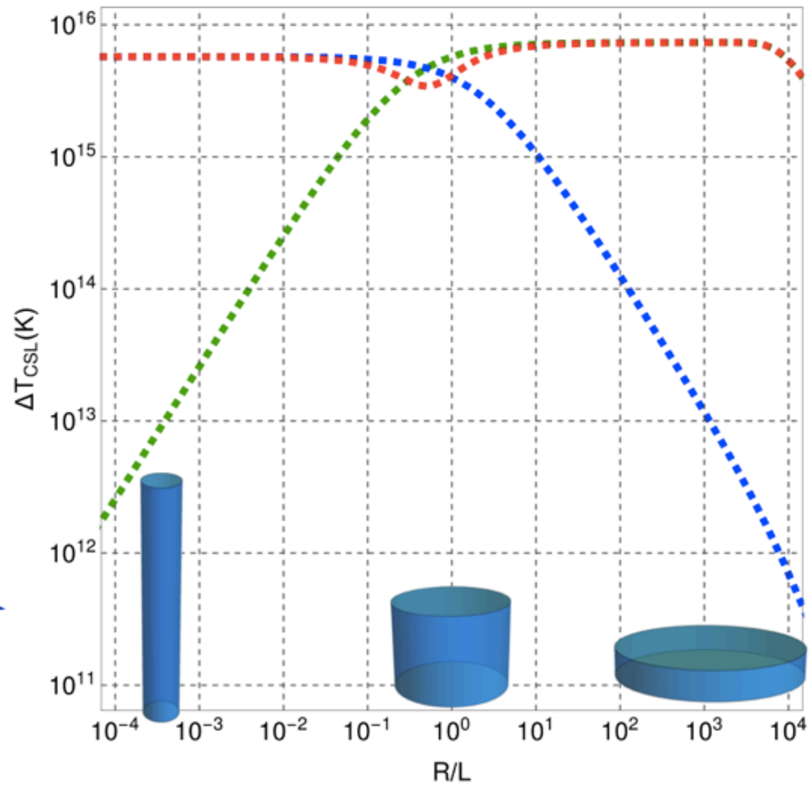
Non-Interferometric Experiments

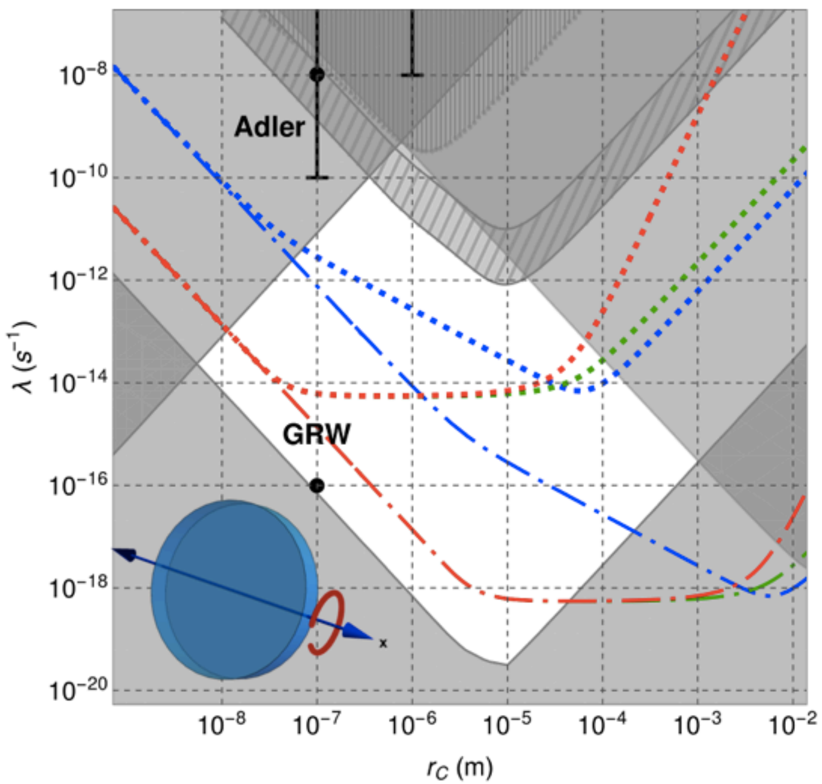
Rotational degrees of freedom

$$\mathcal{S}_{FF}(\omega) = \frac{1}{4\pi}\int d\Omega \, \langle\{\tilde{F}(\omega), \tilde{F}(\Omega)\}\rangle$$

$$\mathcal{S}_{\tau\tau}(\omega) = \frac{1}{4\pi}\int d\Omega \, \langle\{\tilde{\boldsymbol{\tau}}(\omega), \tilde{\boldsymbol{\tau}}(\Omega)\}\rangle$$



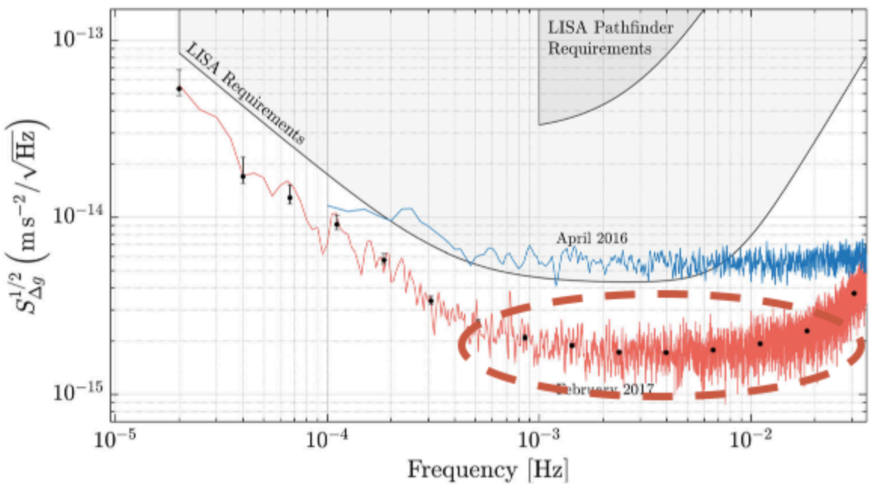




Schrinski *et al.,* J. Opt. Soc. Am. B **34** C1 (2017); Carlesso *et al.*, New J. Phys. **20** 083022 (2018).

LISA Pathfinder – rotational d.o.f.

Armano *et al.*, Phys. Rev. Lett. ***120***, 061101 (2018).



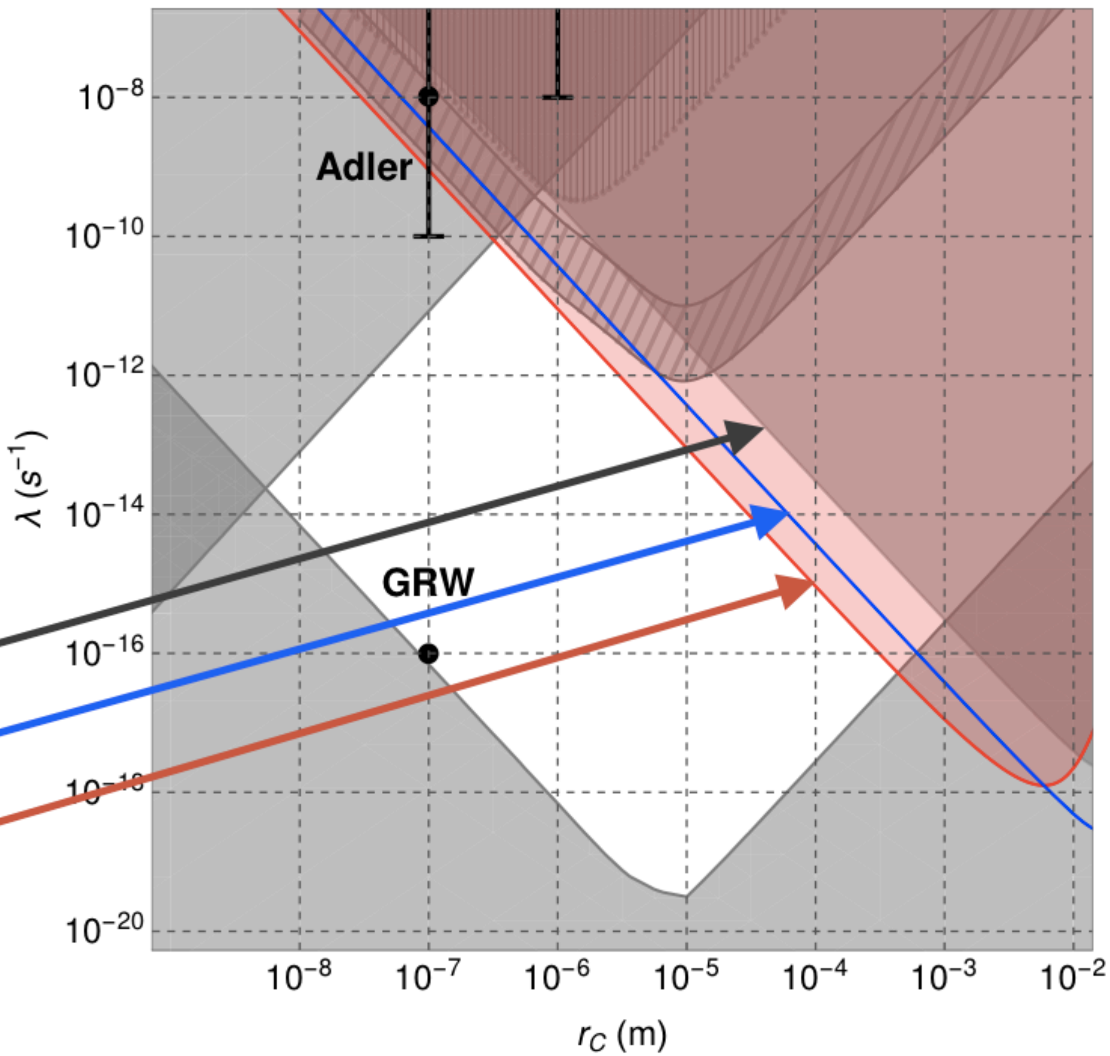
Armano *et al.*, Phys. Rev. Lett. ***116***, 231101 (2016).
Carlesso *et al.,* Phys. Rev. D **94**, 124036 (2016).

Armano *et al.*, Phys. Rev. Lett. ***120***, 061101 (2018).

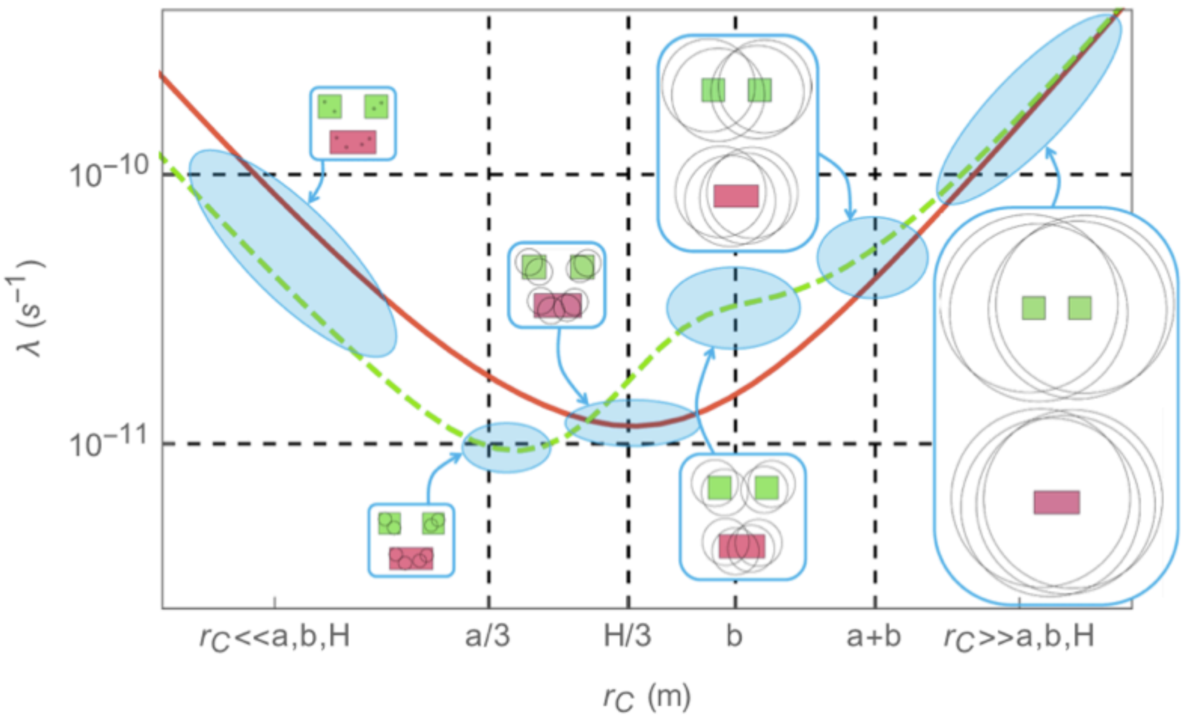
Carlesso *et al.*, *New J. Phys.* **20** 083022 (2018).

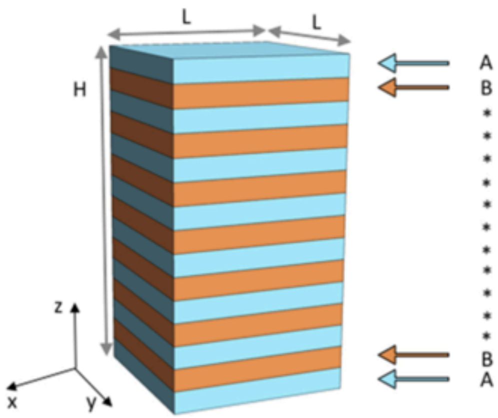
$$\mathcal{S}_{\mathcal{T}} = \mathcal{C} \times \mathcal{S}_F$$

(hypothetical bound)



Multilayer Cantilever



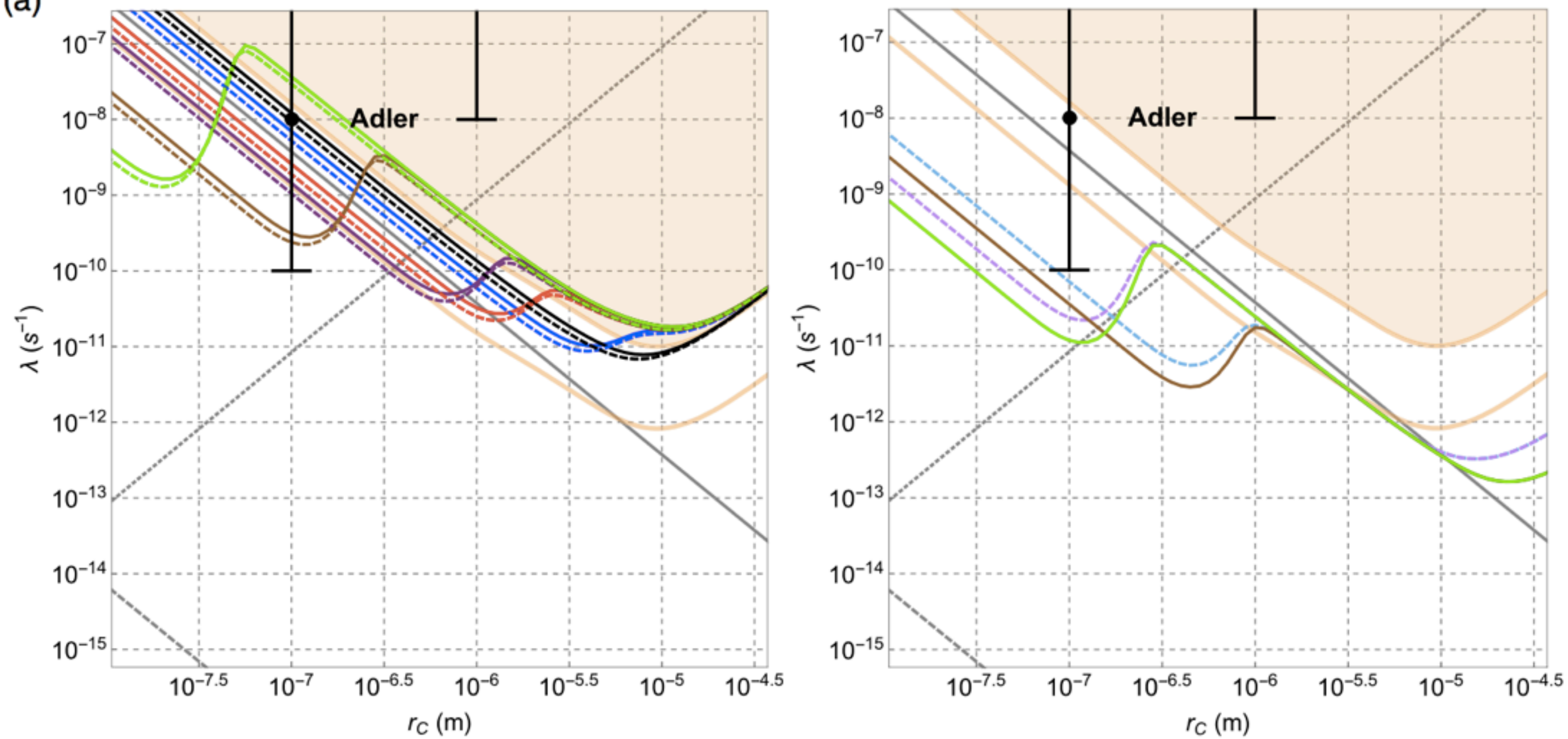


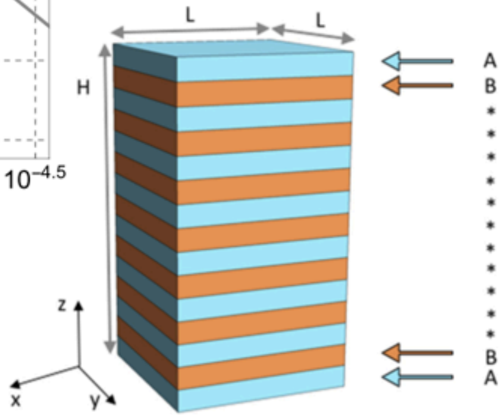
$$S_{xx}(\omega) = \frac{1}{m^2}\frac{2m\gamma k_{\mathrm{B}}T + S_{FF}(\omega)}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}$$

Carlesso *et al.*, *Phys. Rev. A* **98** 022122 (2018)

Multilayer Cantilever

(a)





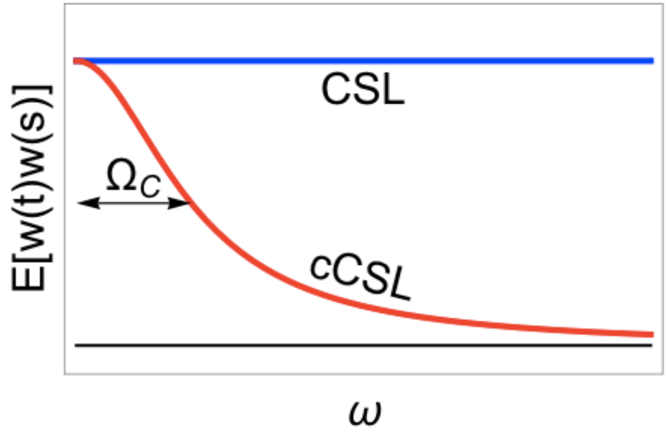
$$S_{xx}(\omega) = \frac{1}{m^2}\frac{2m\gamma k_{\mathrm{B}}T + S_{FF}(\omega)}{(\omega_0^2-\omega^2)^2+\gamma^2\omega^2}$$

Carlesso *et al.*, *Phys. Rev. A* **98** 022122 (2018)

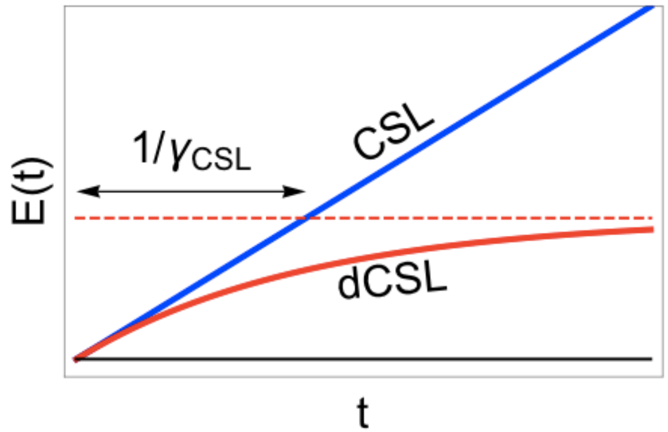
Extensions to the CSL model

Two weak points:

- The noise spectrum is flat (white noise)
  - Approximation of a realistic noise, which is instead characterized by a frequency cutoff
  - ➢ Colored extension of the model ~ 10^{12} Hz



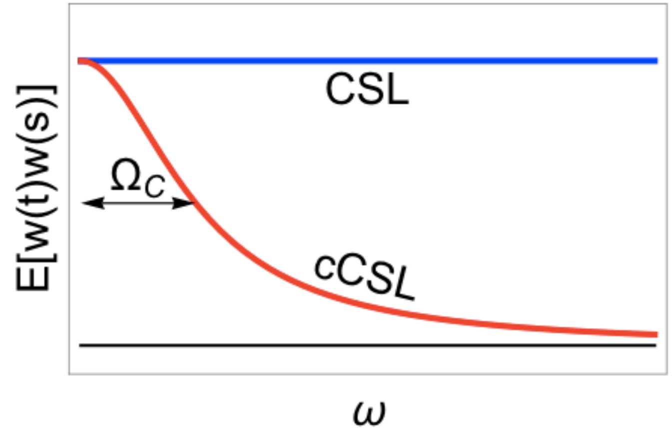
- The noise leads to infinite energy for the system
  - Approximation of a finite temperature noise
  - ➢ Dissipative extension of the model ~ 1 K



Extensions to the CSL model

Two weak points:

- The noise spectrum is flat (white noise)
  - Approximation of a realistic noise, which is instead characterized by a frequency cutoff
  - ➢ <u>Colored extension of the model ~ 10^{12} Hz</u>



$$\frac{\mathrm{d}|\psi_t\rangle}{\mathrm{d}t} = \left[-\frac{i}{\hbar}\hat{H} + \frac{\sqrt{\lambda}}{m_0}\int \mathrm{d}\mathbf{x}\hat{M}(\mathbf{x})w(\mathbf{x},t) - \frac{2\lambda}{m_0^2}\int \mathrm{d}\mathbf{x}\,\hat{M}(\mathbf{x})\int \mathrm{d}s f(t-s)\frac{\delta}{\delta w(\mathbf{x},s)}\right]|\psi_t\rangle$$

$$\mathbb{E}[w(\mathbf{x},t)w(\mathbf{y},s)] = \delta(\mathbf{x}-\mathbf{y})f(t-s)$$

$$d\,|\psi_t\rangle = -\frac{i}{\hbar}\left(\hat{H} + \hat{V}_{\mathrm{CSL}}\right)dt\,|\psi_t\rangle \qquad \hat{V}_{\mathrm{CSL}} = -\frac{\hbar\sqrt{\lambda}}{\pi^{3/4}r_C^{3/2}m_0}\int d\boldsymbol{y}\,\hat{M}(\boldsymbol{y})w(\boldsymbol{y},t)$$

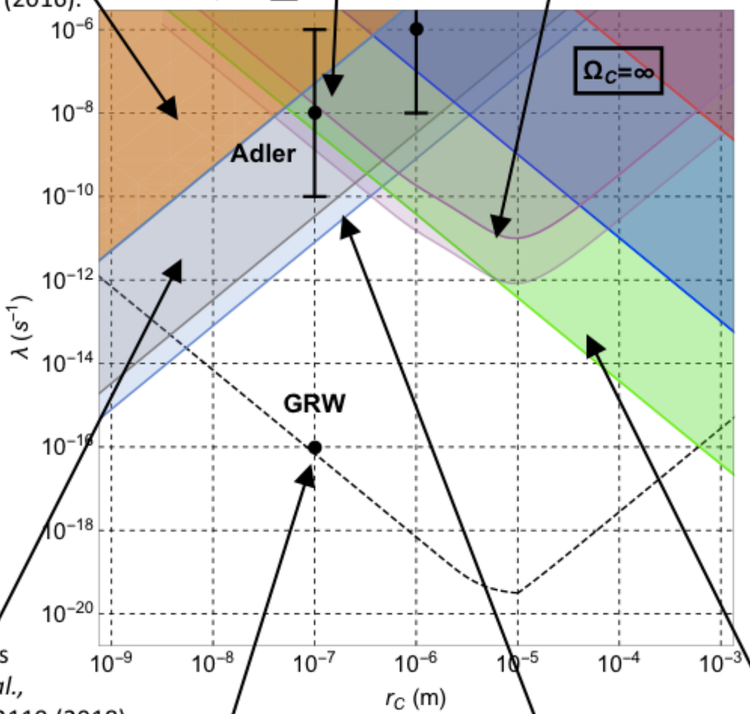
Colored CSL model

$$f(t-s) = \frac{\Omega_{\mathrm{C}}}{2} e^{-\Omega_{\mathrm{C}}|t-s|} \longrightarrow S_{FF}(\omega) = S_{FF}^{\mathrm{CSL}} \times \frac{\Omega_{\mathrm{C}}^2}{\Omega_{\mathrm{C}}^2 + \omega^2}$$

Cold Atoms
Bilardello *et al.*,
Physica A 462, 764 (2016).

Adler
J. Phys. A 40, 2935 (2007),
J. Phys. A 40, 13501 (2007).

Nanomechanical Cantilever
Vinante *et al.*,
Phys. Rev. Lett. 119, 110401 (2017)

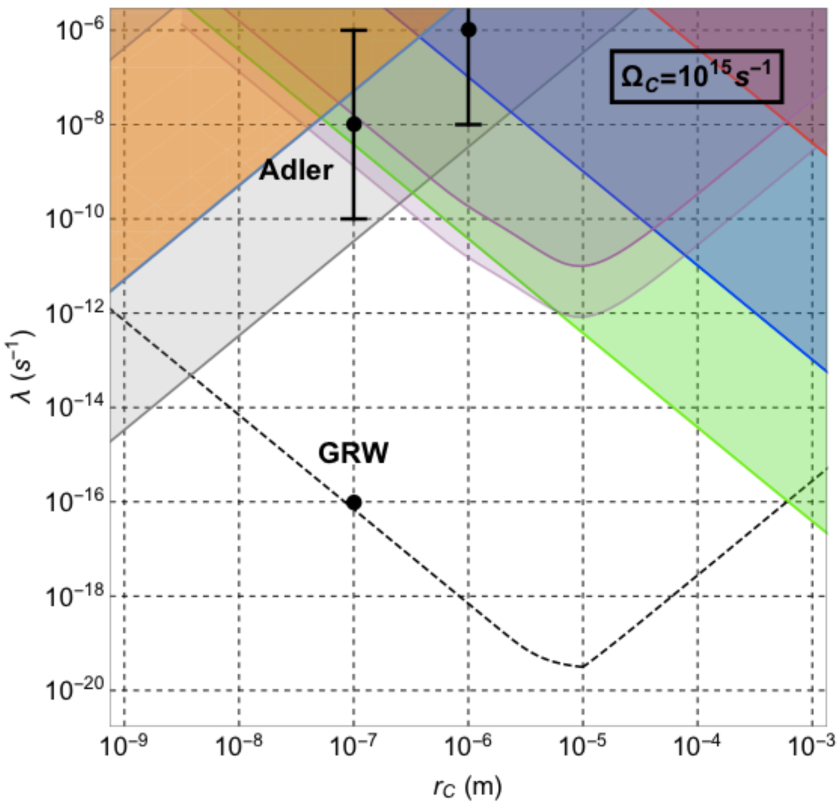


Phonons
Adler *et al.*,
Phys. Rev. A 97, 052119 (2018).

GRW
Ghirardi *et al.*,
Phys. Rev. D 34, 470 (1986).

X-rays emission
K. Piscicchia *et al.*,
Entropy 19 (2017).

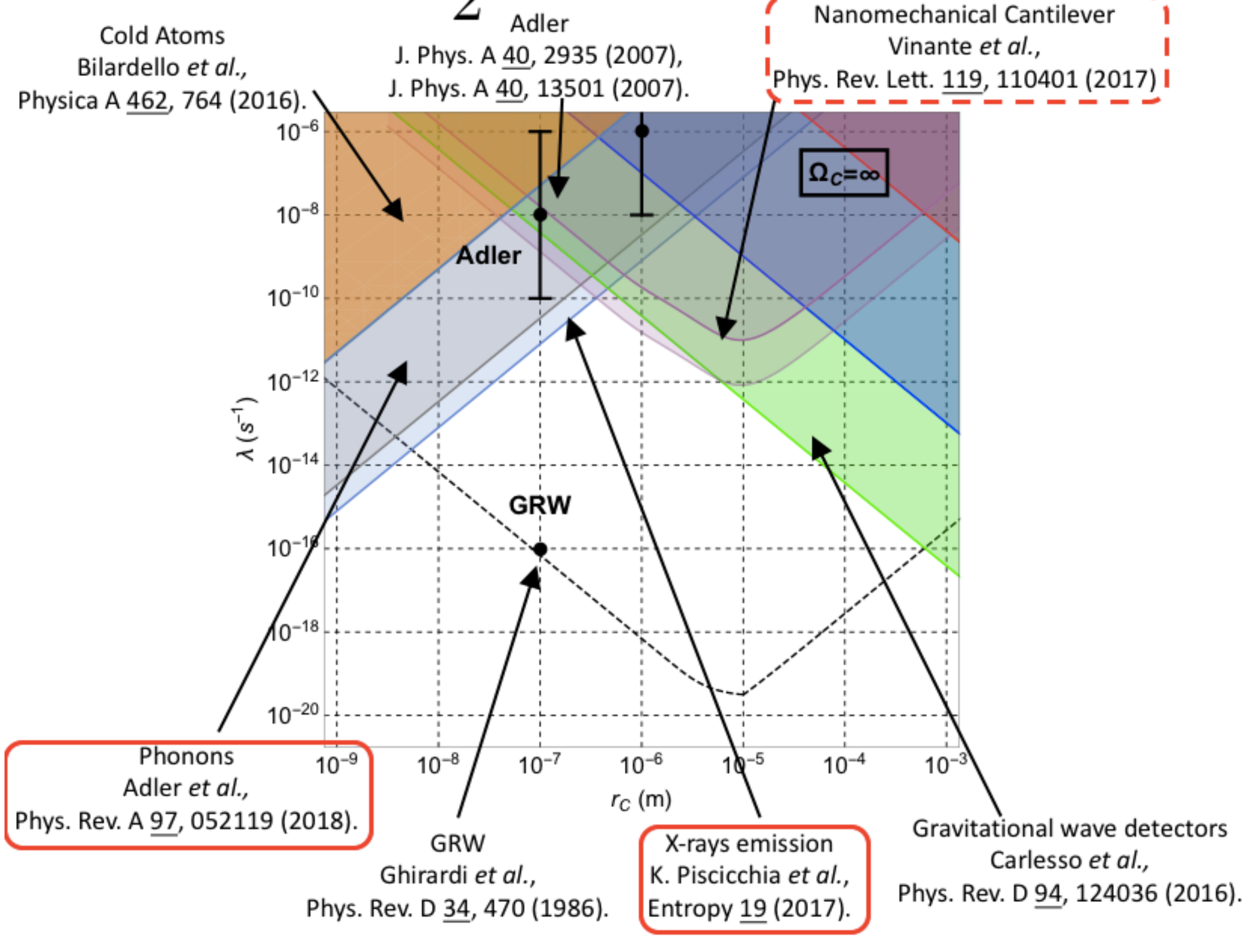
Gravitational wave detectors
Carlesso *et al.*,
Phys. Rev. D 94, 124036 (2016).

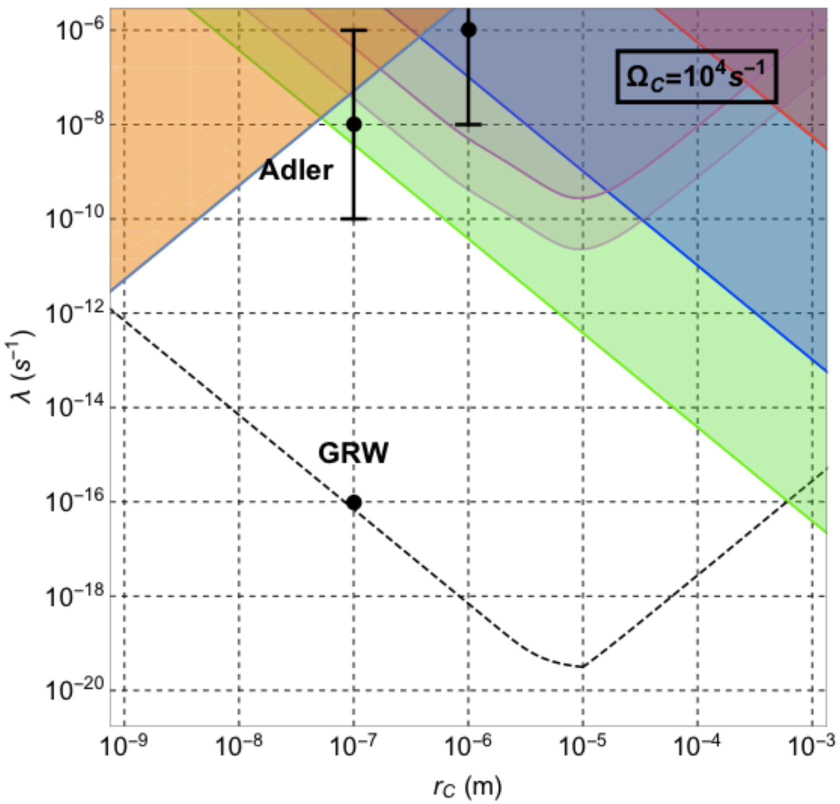


Carlesso, *et al.*, Eur. Phys. J. D 72, 159 (2018)

Colored CSL model

$$f(t-s)=\frac{\Omega_C}{2}e^{-\Omega_C|t-s|} \longrightarrow S_{FF}(\omega)=S_{FF}^{CSL}\times\frac{\Omega_C^2}{\Omega_C^2+\omega^2}$$

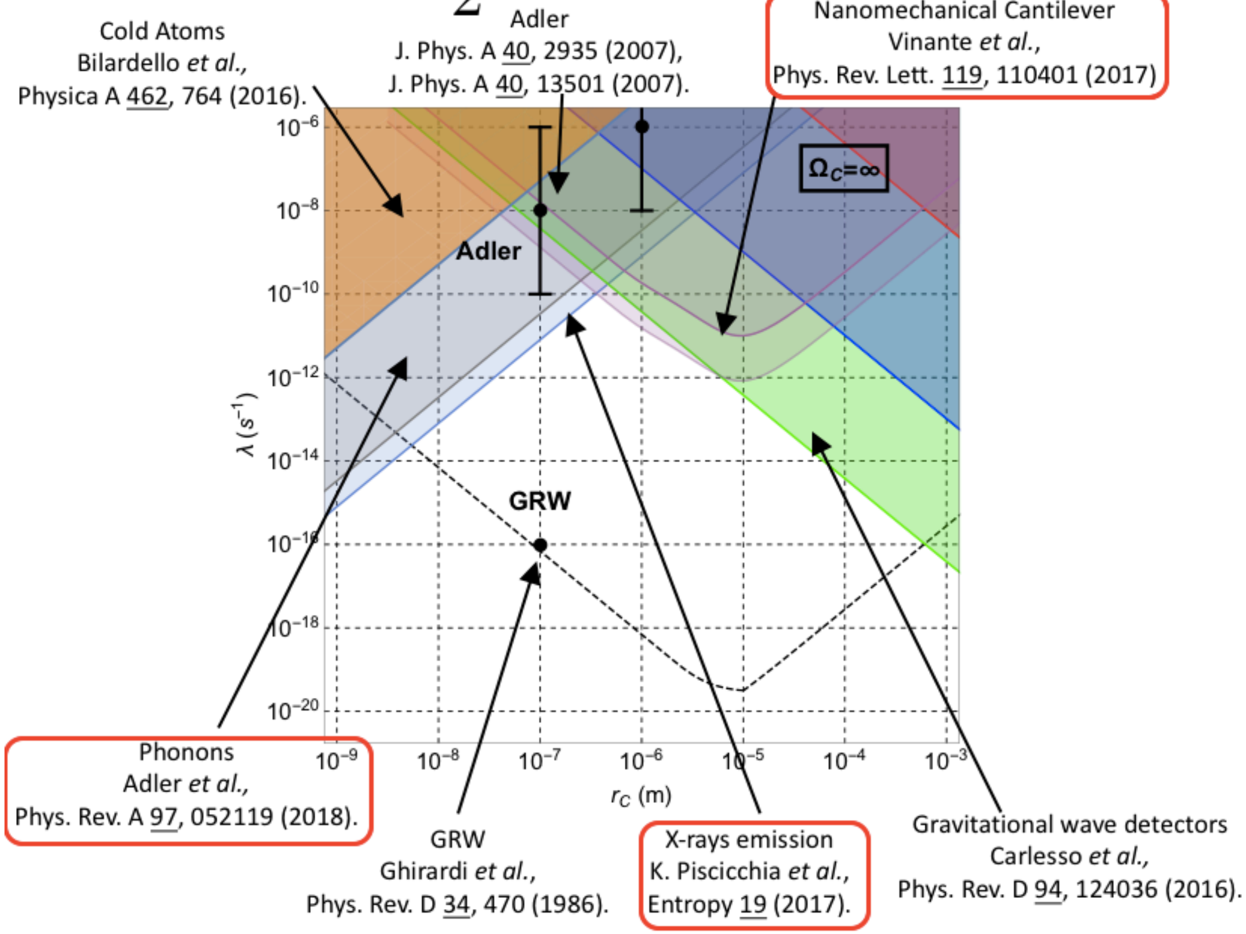


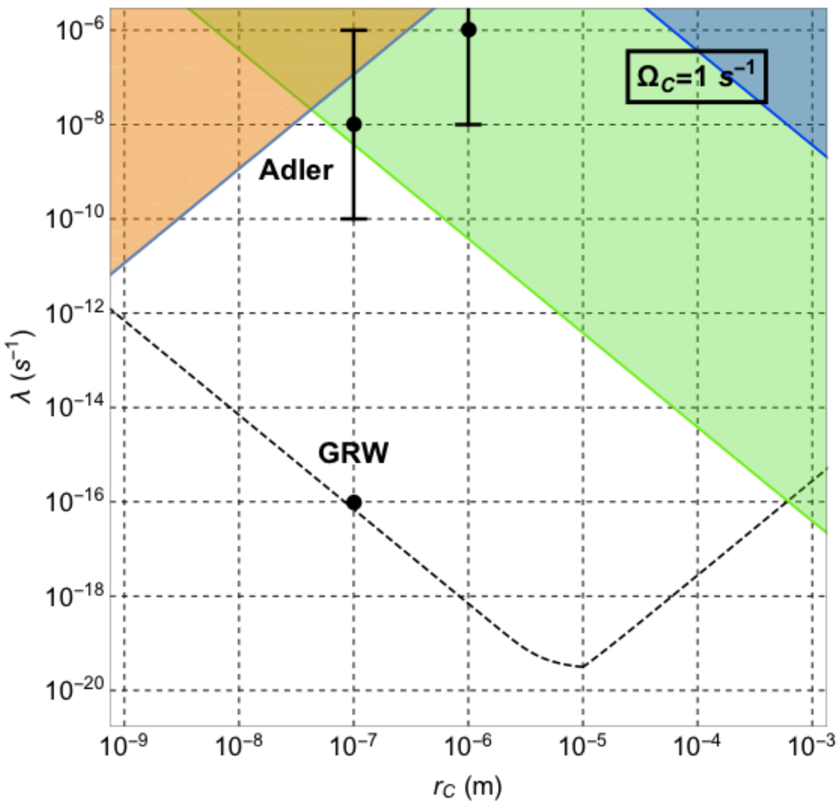


Carlesso, *et al.*, Eur. Phys. J. D 72, 159 (2018)

Colored CSL model

$$f(t-s) = \frac{\Omega_\mathrm{C}}{2} e^{-\Omega_\mathrm{C}|t-s|} \longrightarrow S_{FF}(\omega) = S_{FF}^{\mathrm{CSL}} \times \frac{\Omega_\mathrm{C}^2}{\Omega_\mathrm{C}^2 + \omega^2}$$





Carlesso, *et al.*, Eur. Phys. J. D 72, 159 (2018)

Dissipative CSL model

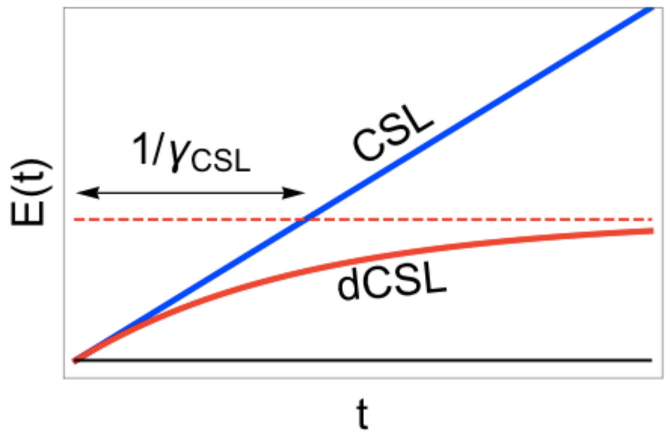
CSL model predicts an infinite energy increment!

For a nucleon we have $\Delta E = 10^{-15}\,\mathrm{K}$ in one year with $\begin{cases} \lambda = 10^{-17}\,\mathrm{s}^{-1} \\ r_C = 10^{-7}\,\mathrm{m} \end{cases}$

A new parameter is introduced to solve the problem: the CSL temperature T_{CSL}

$$E(t) = e^{-\beta t}\left(E_0 - E_{\mathrm{as}}\right) + E_{\mathrm{as}},$$

$$E_{\mathrm{as}} = \frac{3}{2} k_{\mathrm{B}} T_{\mathrm{CSL}}$$

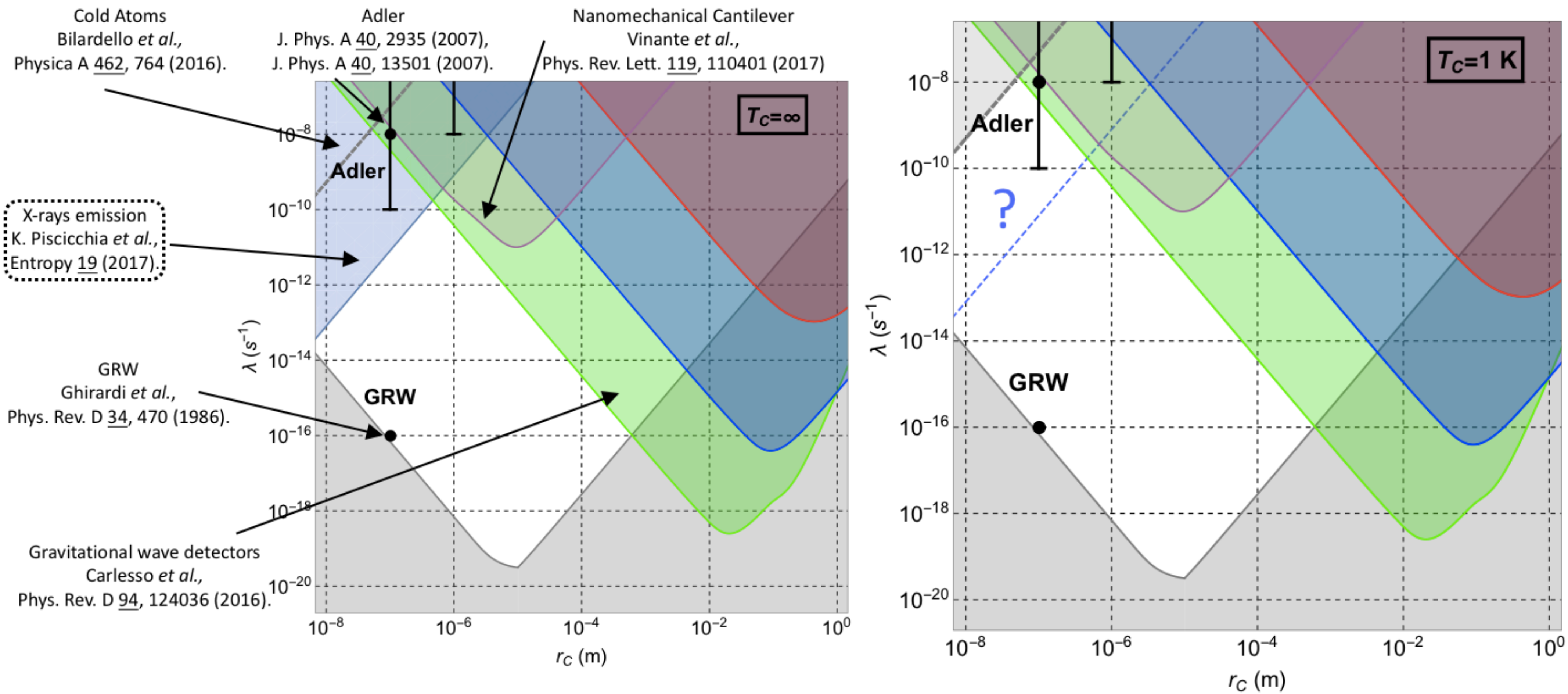


$$\beta = 4\chi \frac{\lambda}{(1+\chi)^5}$$

$$\chi = \frac{\hbar^2}{8 m_0 k_{\mathrm{B}} T_{\mathrm{CSL}} r_C^2}$$

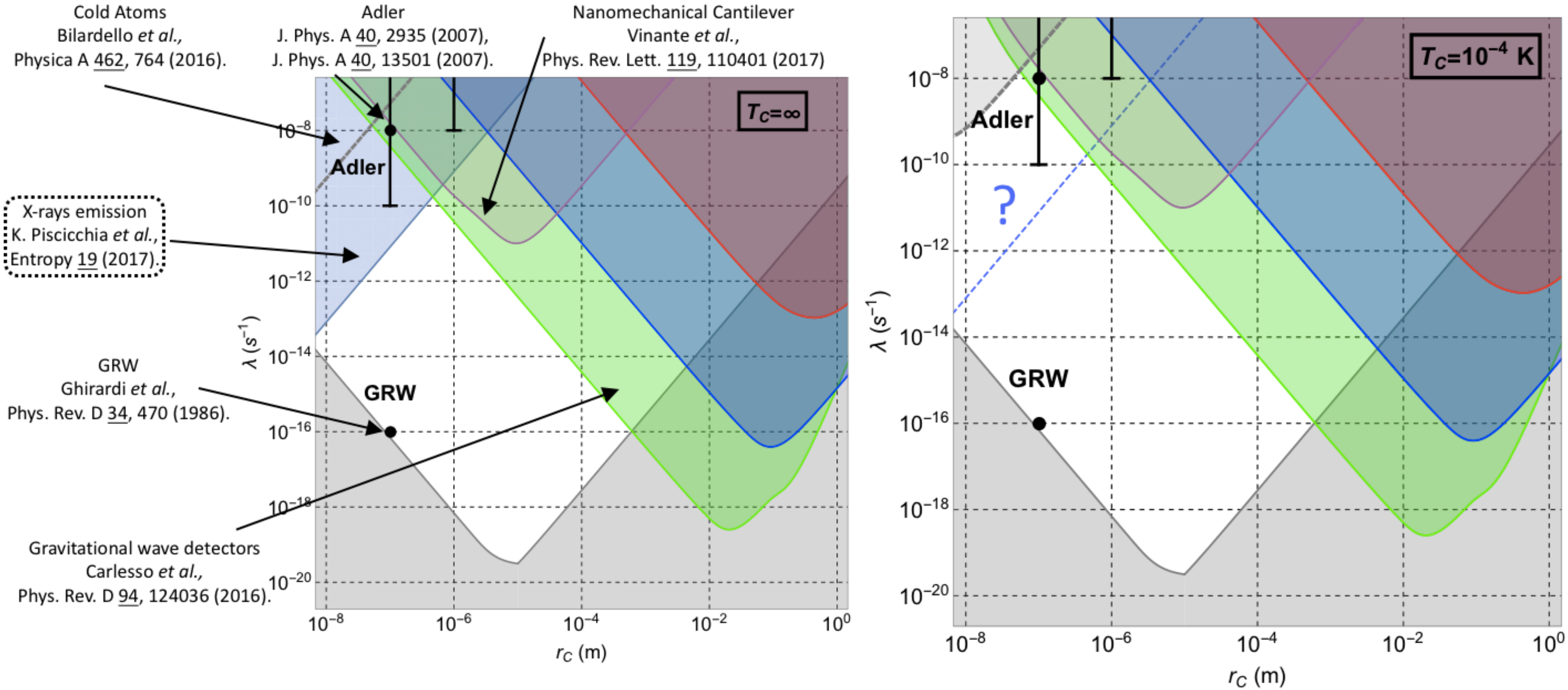
A. Smirne and A. Bassi, *Sci. Rep.* 5, 12518 (2015).

Dissipative CSL model



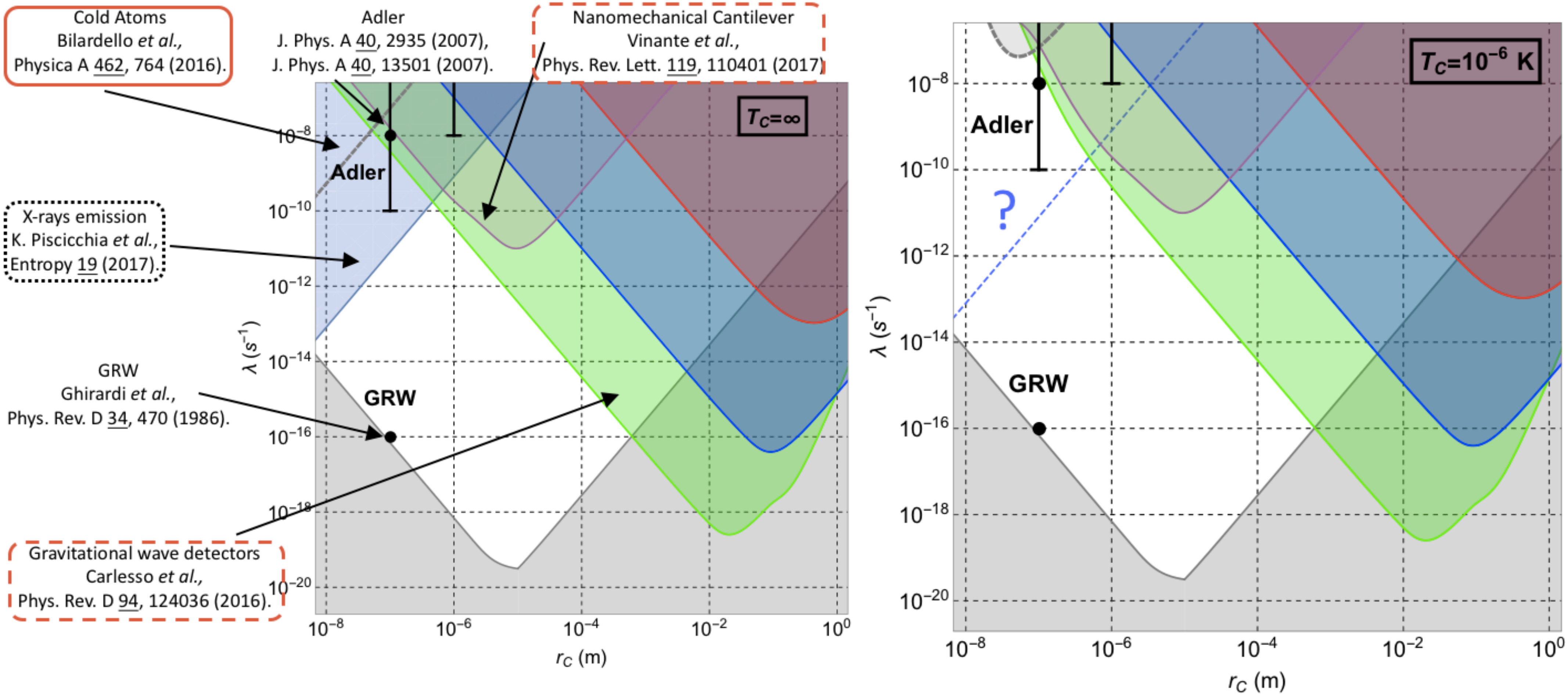
Nobakht, M.C., Donadi, Paternostro and Bassi, *ArXiv* 1808.01143 (2018)

Dissipative CSL model



Nobakht, M.C., Donadi, Paternostro and Bassi, *ArXiv* 1808.01143 (2018)

Dissipative CSL model



Nobakht, M.C., Donadi, Paternostro and Bassi, *ArXiv* 1808.01143 (2018)

Summary

- Non-interferometric tests impose strong bounds on collapse parameters
- A wide range of systems can be considered (size, form, materials, d.o.f, …)
- Several proposal can be implemented to push the bounds further
- Colored and dissipative extensions of CSL model: variations in the upper bounds