# Dissipative and colored collapse models from the non-interferometric perspective

**Laboratori Nazionali** di **Frascati**

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# Outlook

- Continuous Spontaneous Localization (CSL) model
  - Connection between theory and non-interferometric experiments
- Colored CSL model
  - Intro
  - Theory and Experimental bounds
- Dissipative CSL model
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  - Theory and Experimental bounds

# Continuous Spontaneous Localization (CSL) model

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

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

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

Localization operator: in position

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

Noise : uncorrelated in space and time

Two parameters:

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

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

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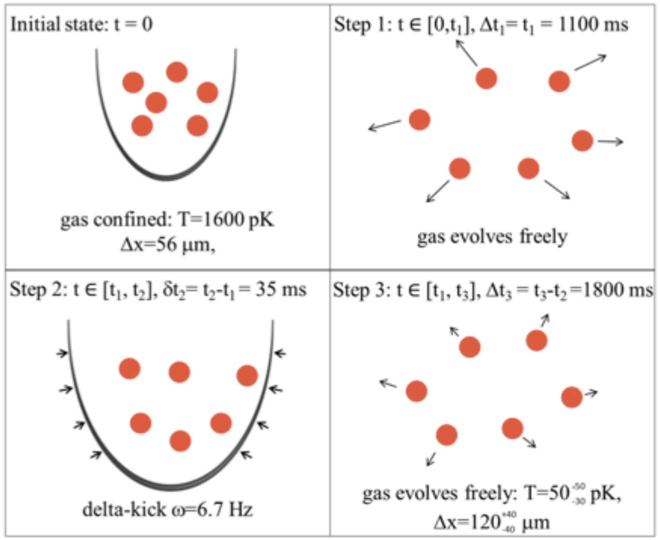
Cold Atoms

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



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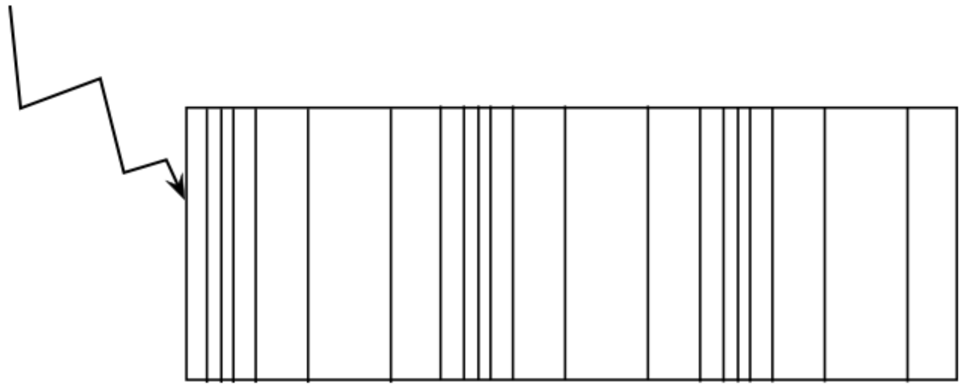
Phonon excitations

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



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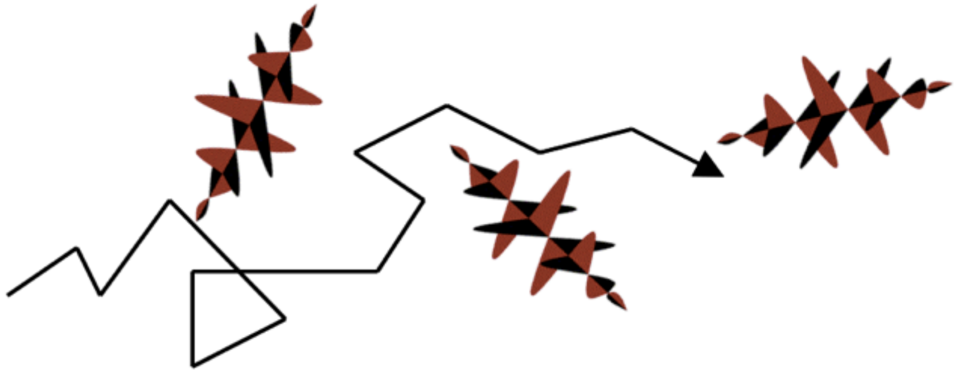
X-ray emission

Piscicchia *et al.*, Entropy **19** (2017).



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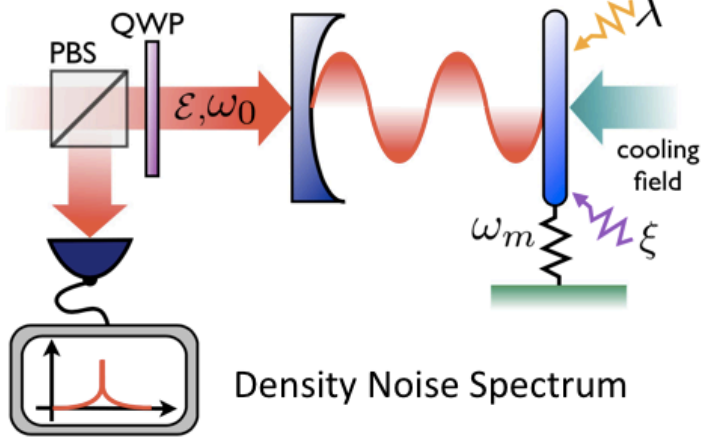
## Optomechanical systems

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).



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## Linear stochastic unravelling

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

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

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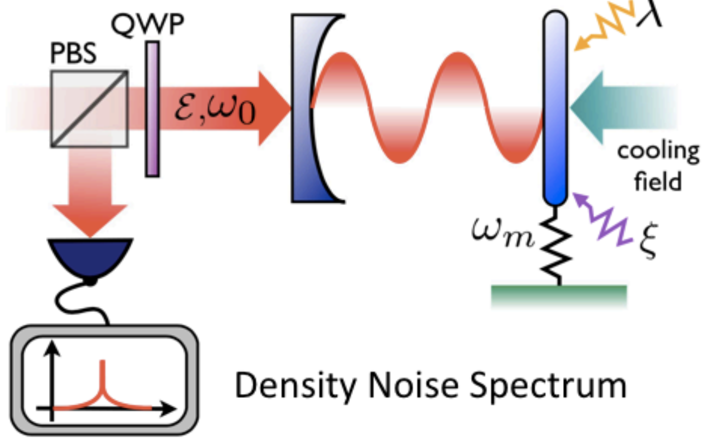
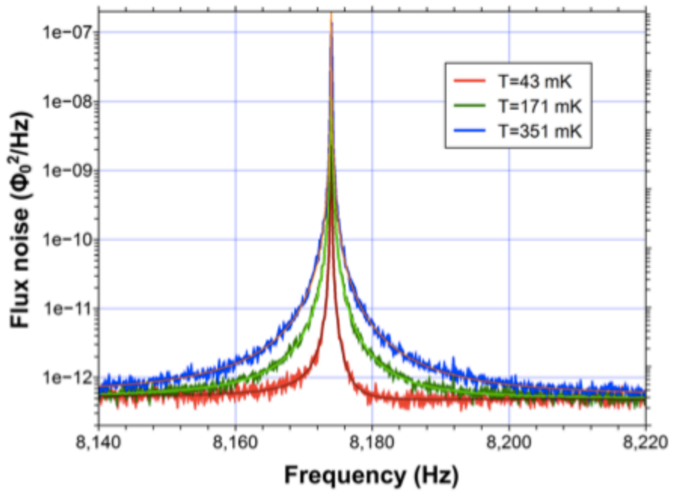


# Non-interferometric tests – theory

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




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

Density Noise Spectrum

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

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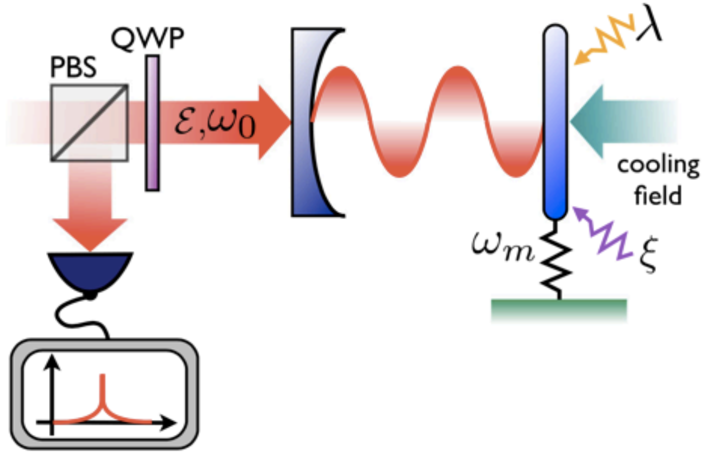

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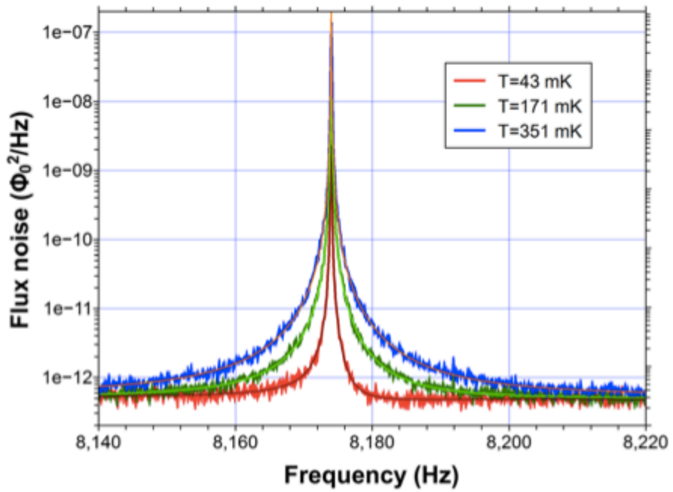


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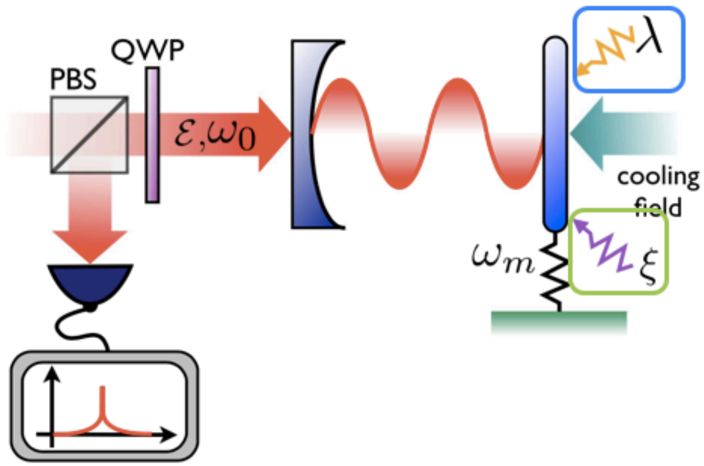

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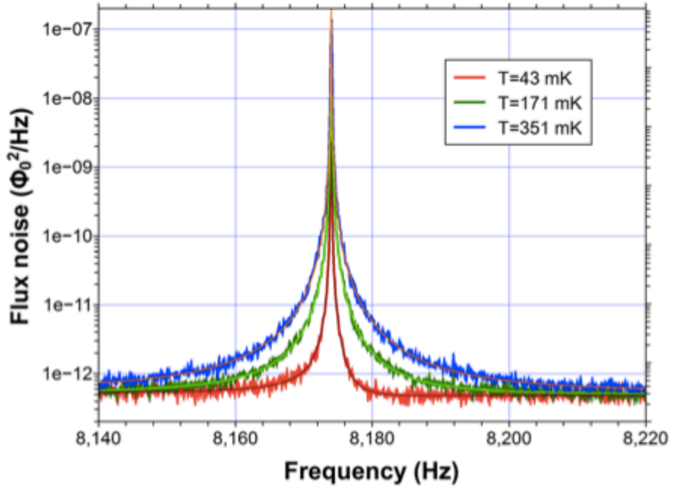


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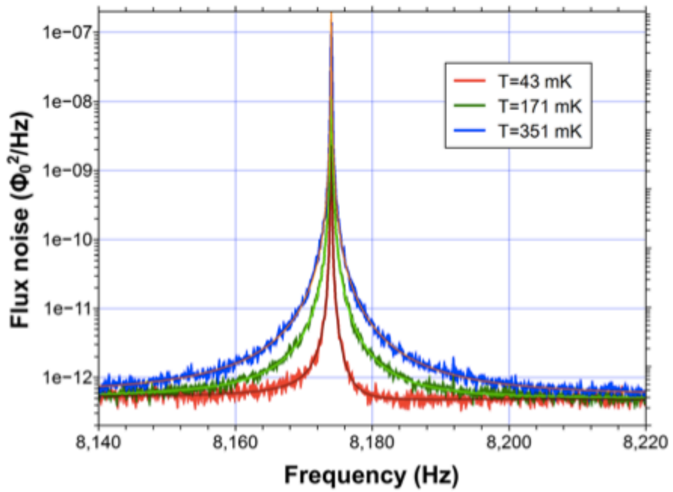
$$\frac{d}{dt}\hat{L}_x(t) = -I\omega_\phi^2\hat{\phi}(t) - \frac{D_\phi}{I}\hat{L}_x(t) + \hat{\xi}_{\mathrm{R}}(t) + \boxed{\tau^x_{\mathrm{CSL}}(t)}$$

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Carlesso *et al.*, ArXiv 1708.04812 (2017)

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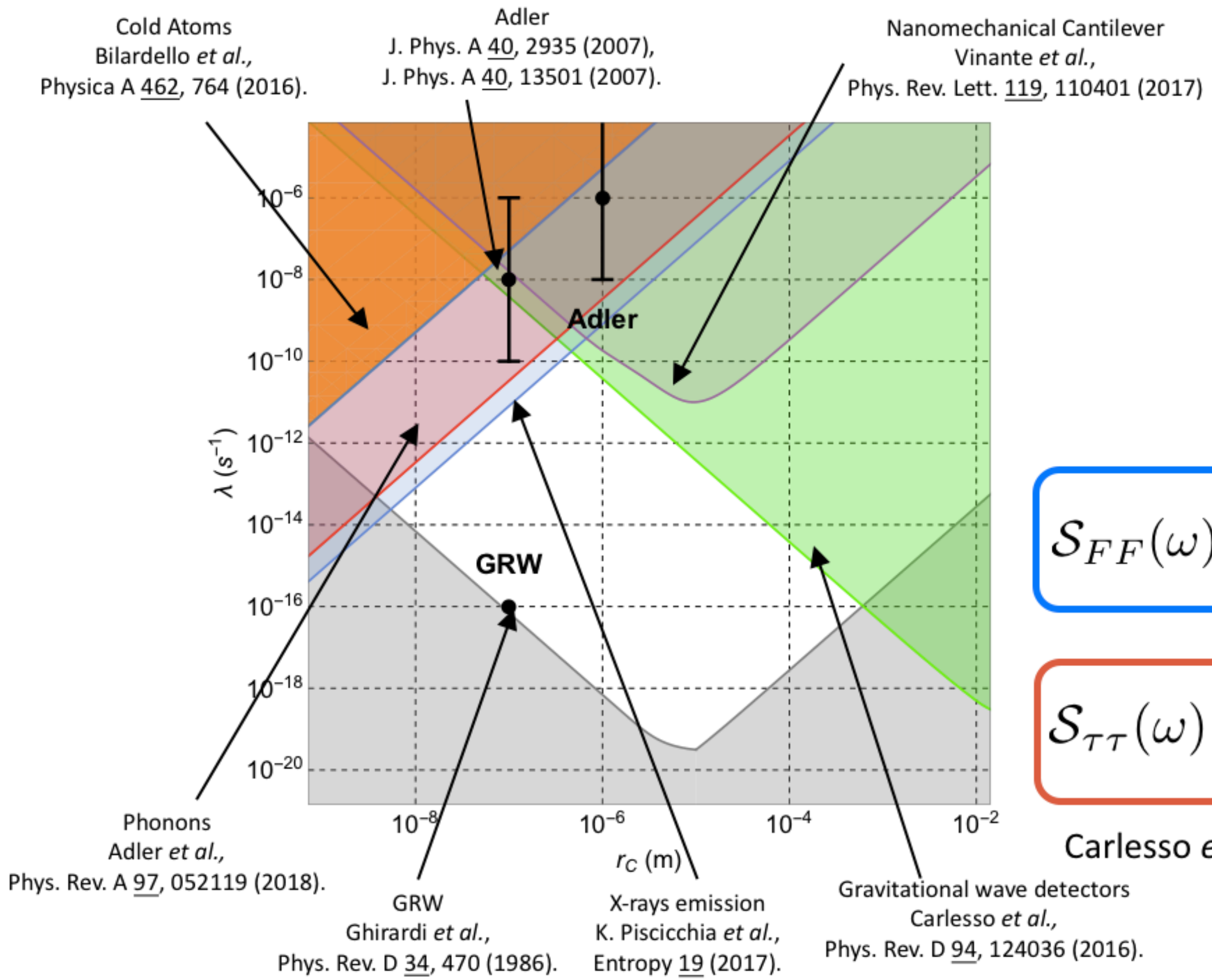


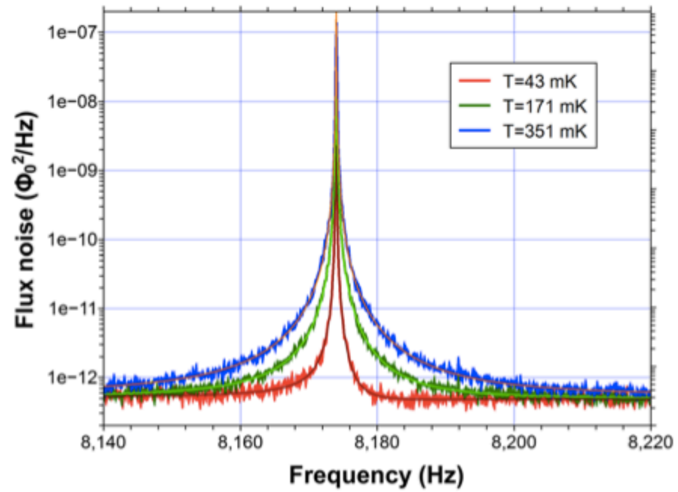


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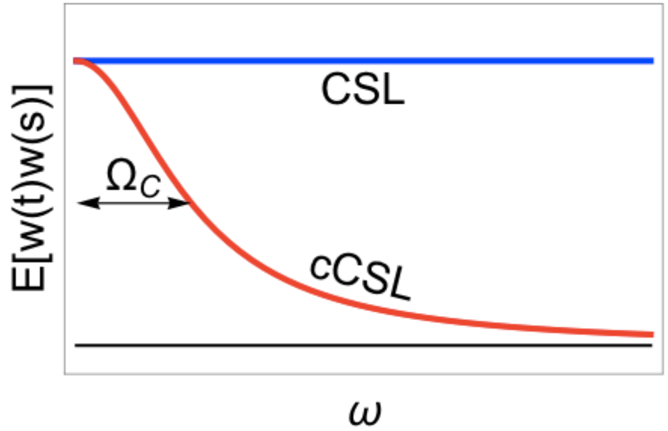
- The noise spectrum is flat (white noise)
  - Approximation of a realistic noise, which is instead characterized by a frequency cutoff
  - ➢ Colored extension of the model



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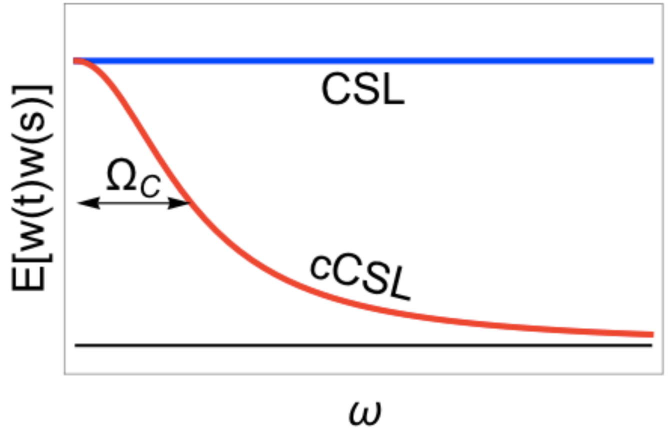
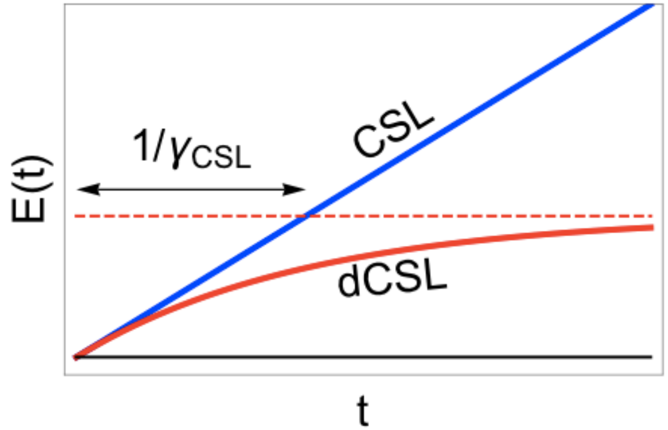



- The noise leads to infinite energy for the system
  - Approximation of a finite temperature noise
  - ➢ Dissipative extension of the model



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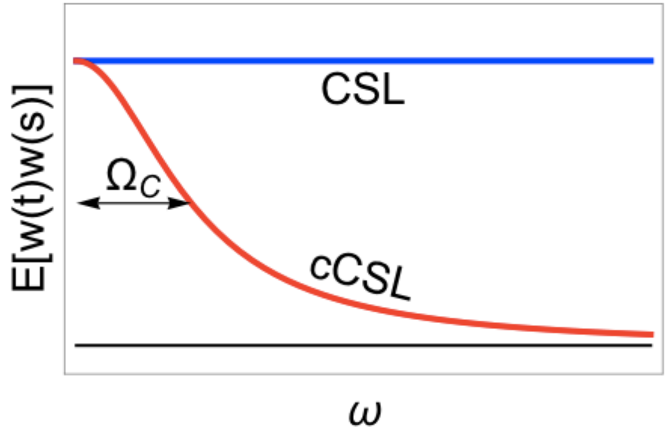

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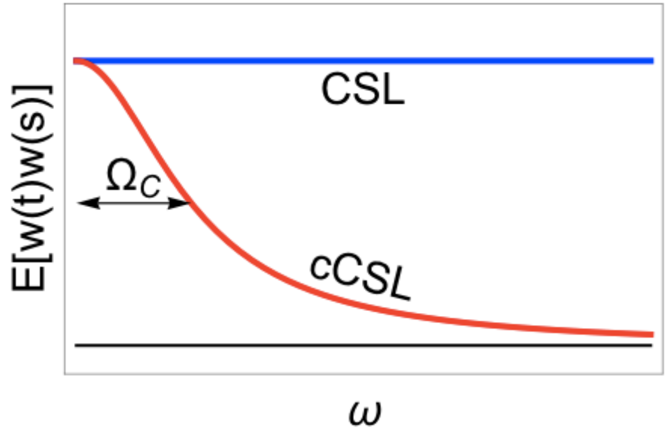


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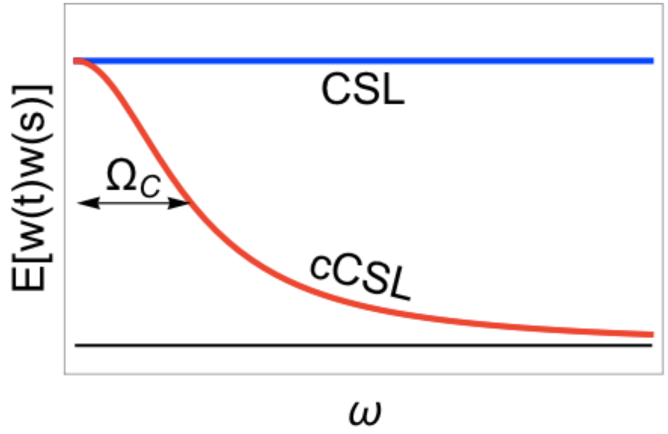


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Langevin equations

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White noise case

$$\mathbb{E}\left[F_{\text{CSL}}(t)F_{\text{CSL}}(s)\right] = \hbar^2\eta\delta(t-s)$$

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

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

White noise case

$$\mathbb{E}\left[F_{\mathrm{CSL}}(t)F_{\mathrm{CSL}}(s)\right] = \hbar^2\eta\delta(t-s)$$

↓

Colored noise case

$$\mathbb{E}\left[F_{\mathrm{CSL}}(t)F_{\mathrm{CSL}}(s)\right] = \hbar^2\eta f(t-s)$$

# Colored CSL model

Langevin equations

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

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

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Frequency dependent
CSL contribution

# Colored CSL model – Case study

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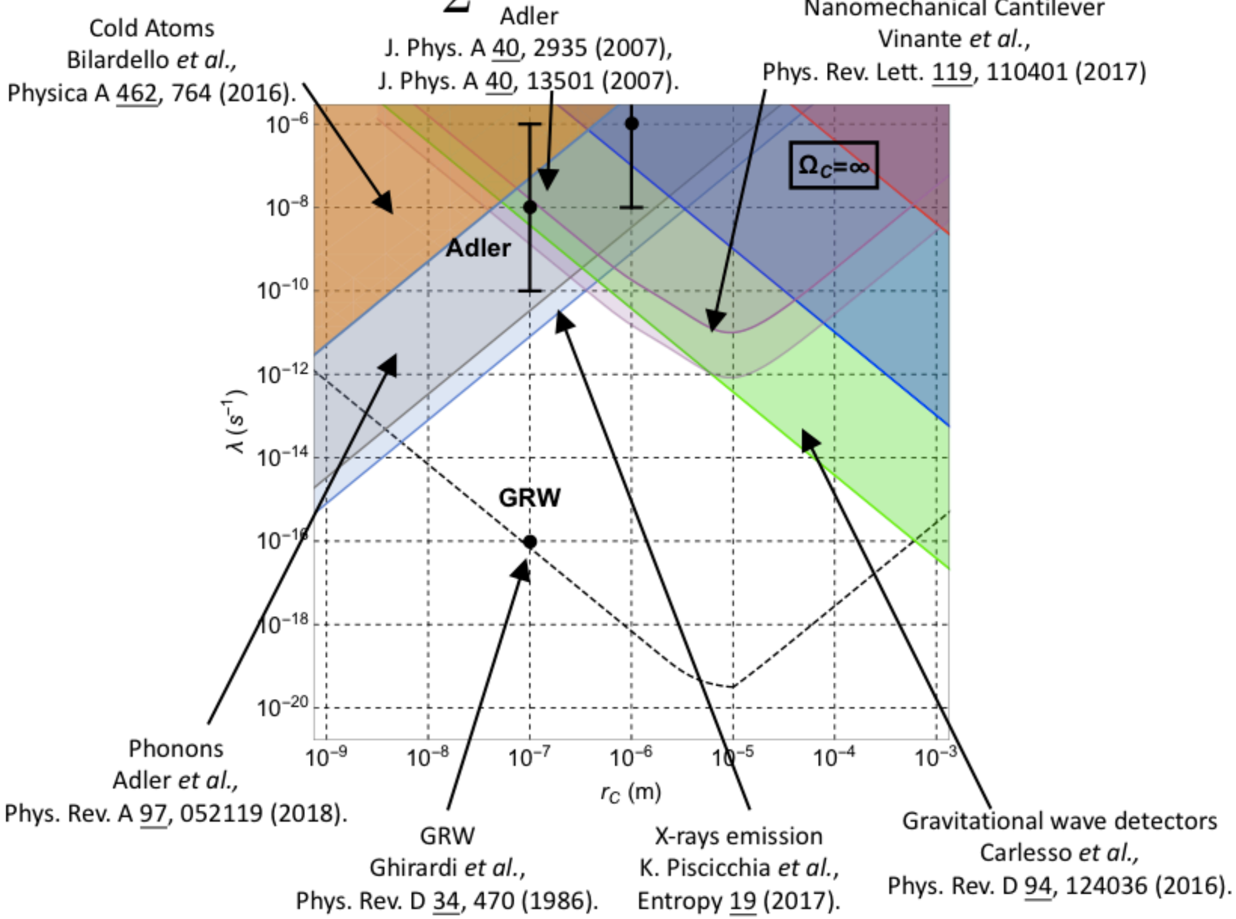

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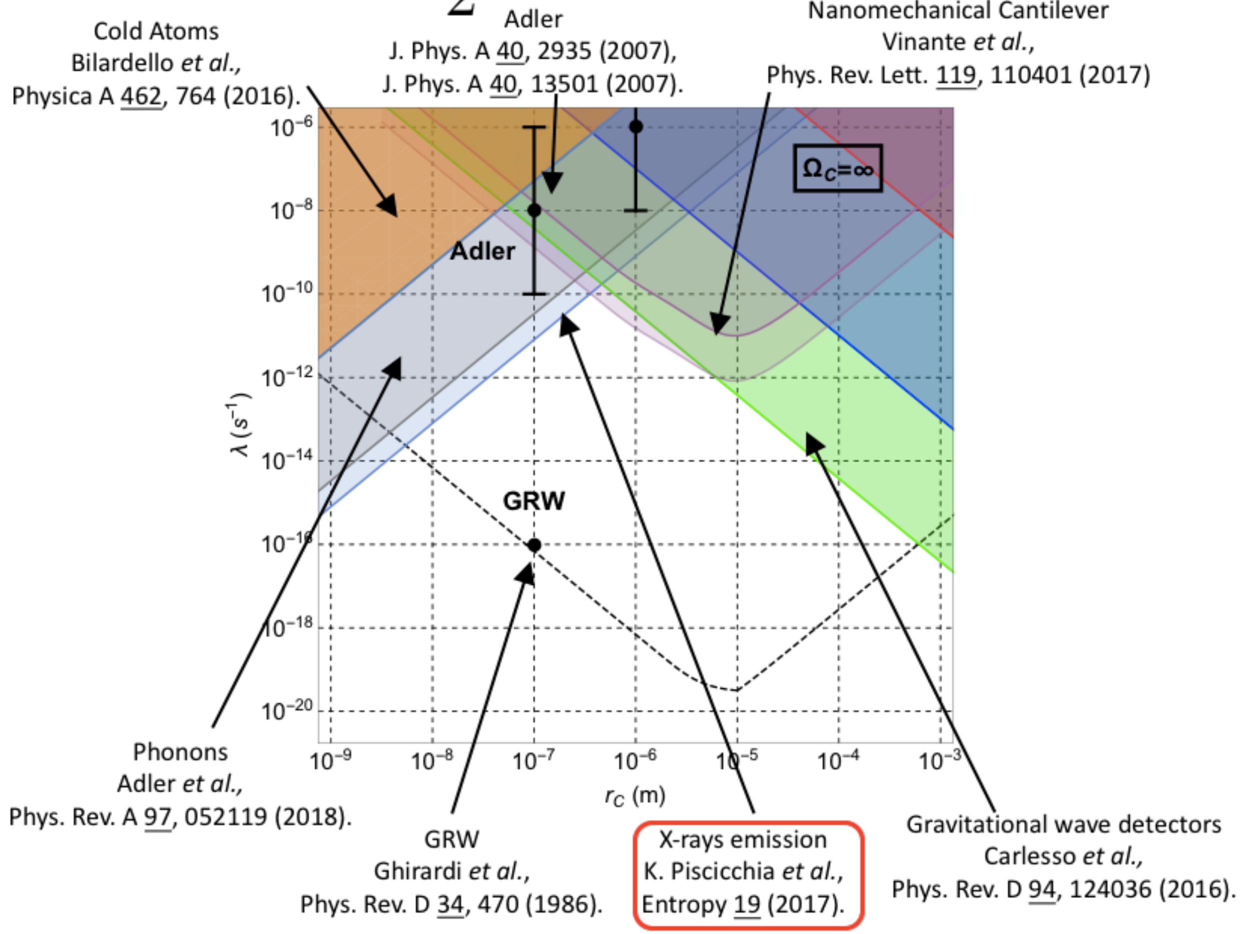


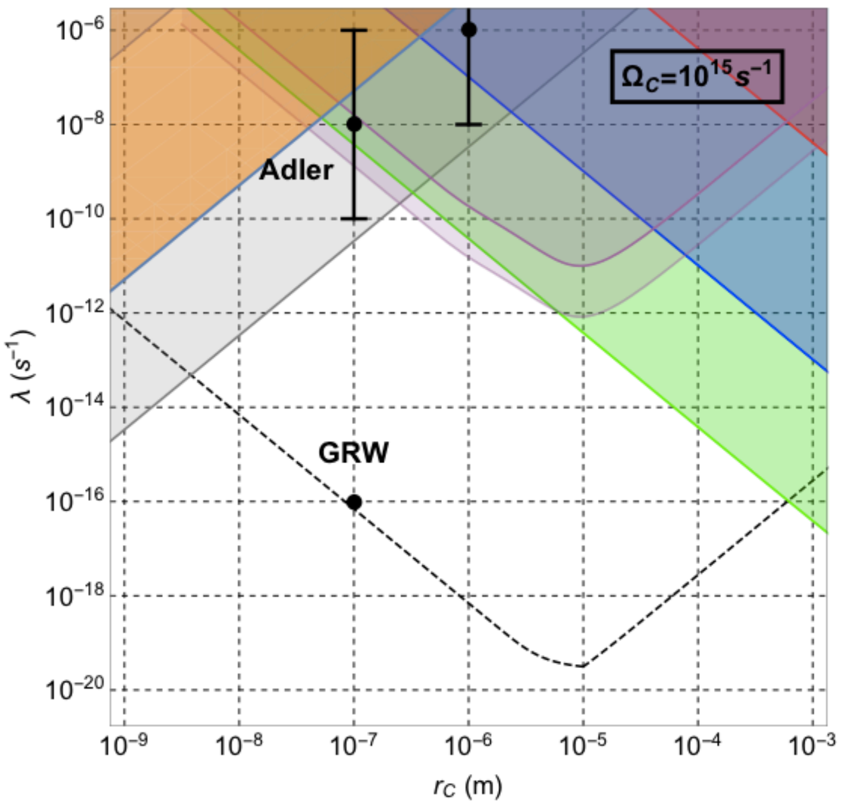


Carlesso, Ferialdi, Bassi, *ArXiv* 1805.10100 (2018)

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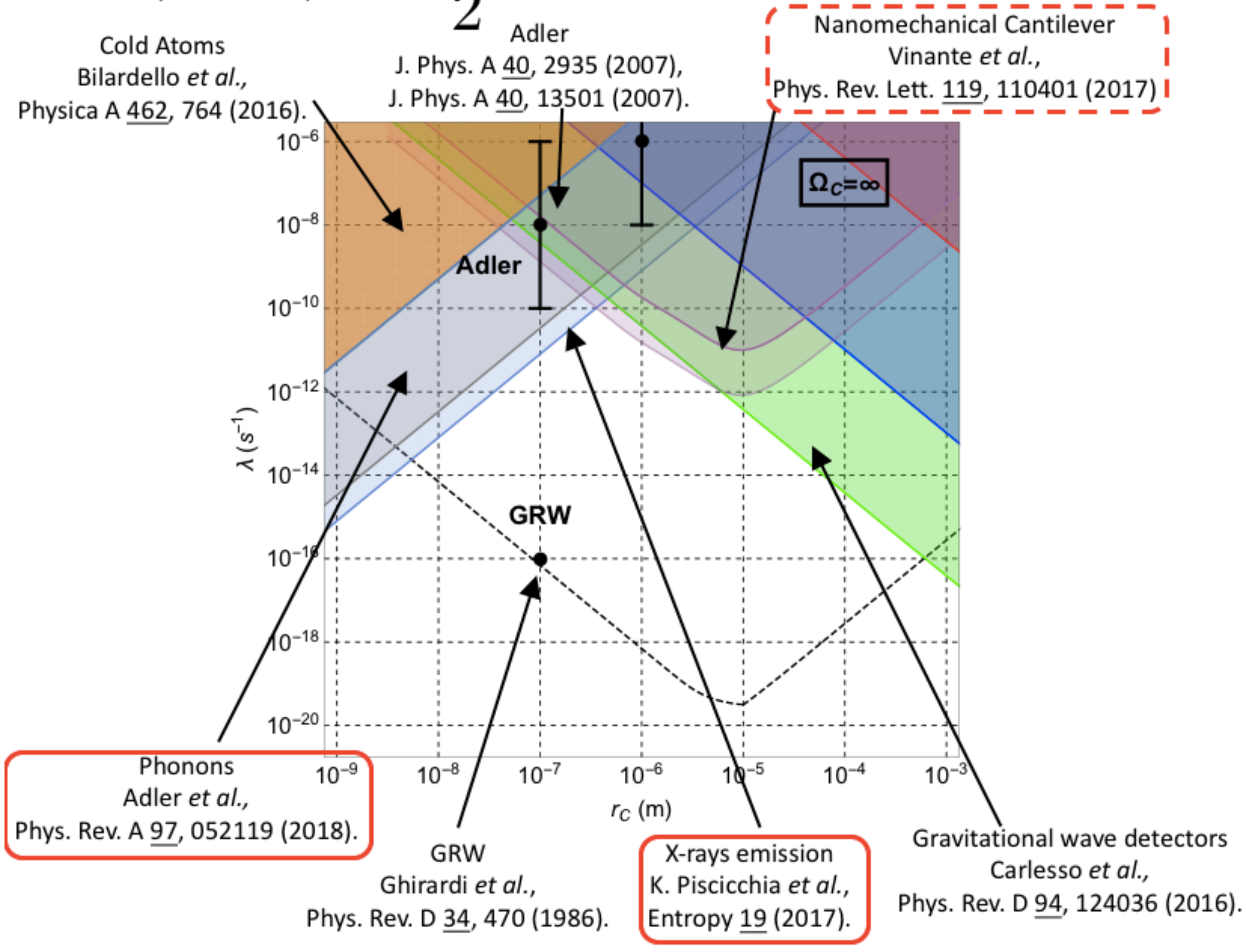


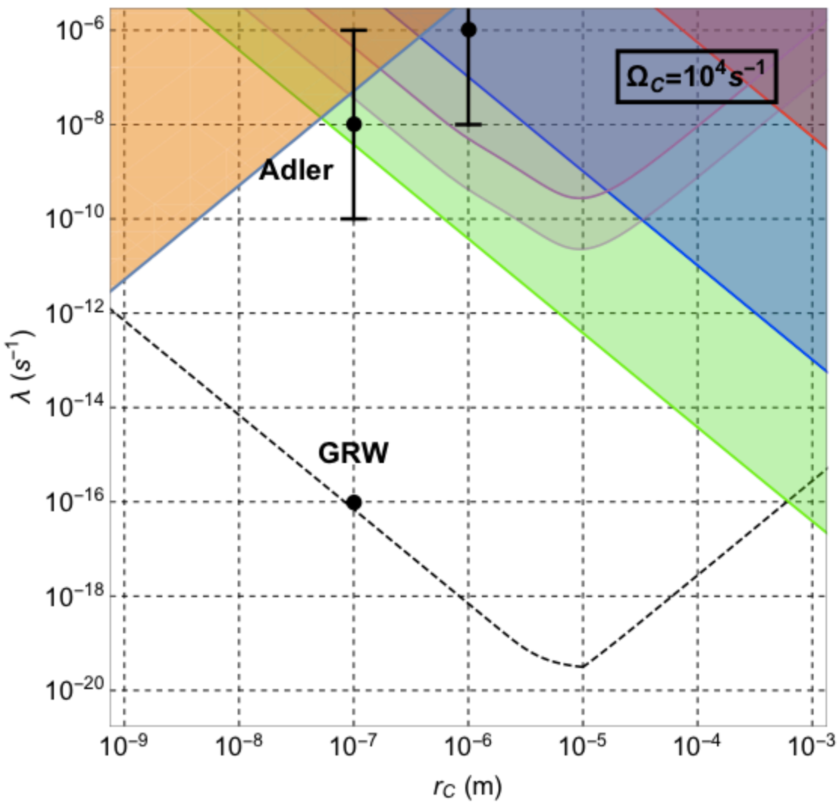


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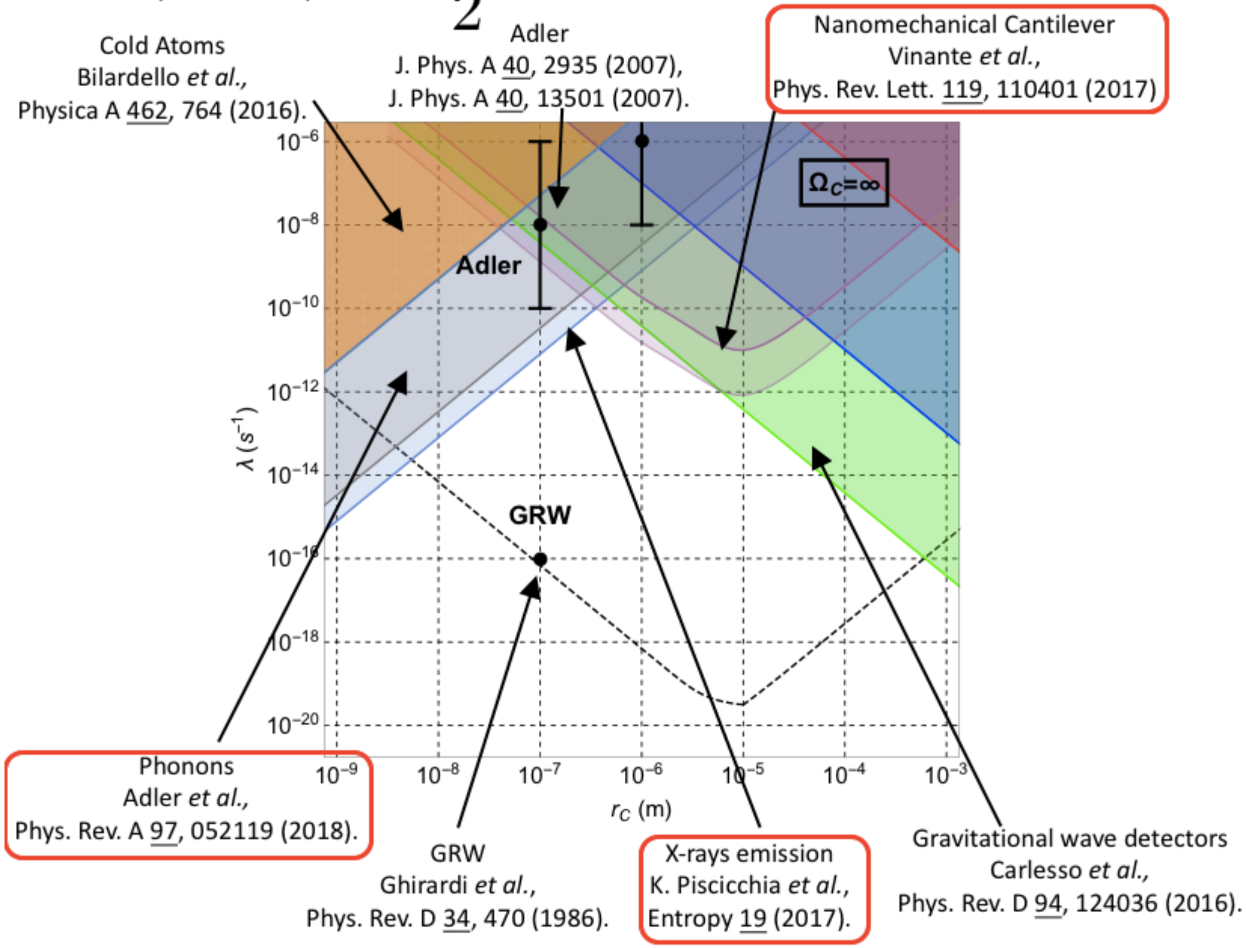


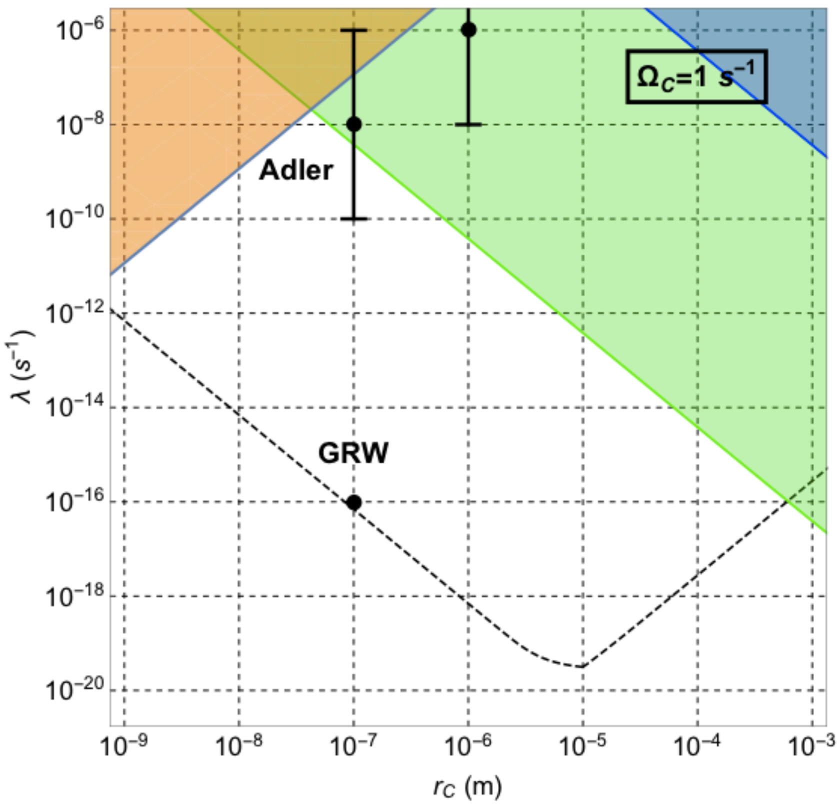


Carlesso, Ferialdi, Bassi, *ArXiv* 1805.10100 (2018)

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CSL model predicts an infinite energy increment!

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

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

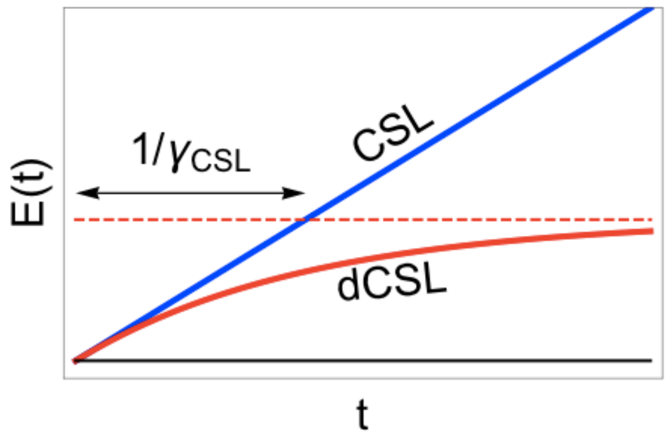
A new parameter is introduced to solve the problem: the CSL temperature $T_{\mathrm{CSL}}$

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

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

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

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



# Dissipative CSL model

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

$$d\,|\psi_t\rangle = \Big[-\frac{i}{\hbar}\hat{H}dt + \frac{\sqrt{\gamma}}{m_0}\int d\boldsymbol{y}\,\Big(\hat{L}(\boldsymbol{y}) - r_t(\boldsymbol{y})\Big)dW_t(\boldsymbol{y}) +$$

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CSL Temperature dependence

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

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

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$$d\hat{C} = \frac{\sqrt{\lambda r_C^3(4\pi)^{3/2}}}{m_0}\int d\boldsymbol{y}\,\left(\hat{L}(\boldsymbol{y})\,d\hat{B}^\dagger(\boldsymbol{y}) - \hat{L}^\dagger(\boldsymbol{y})\,d\hat{B}(\boldsymbol{y})\right),$$

Linear stochastic unravelling with a quantum noise

$$\mathbb{E}[d\hat{B}_t(\boldsymbol{x})] = \mathbb{E}[d\hat{B}_t^\dagger(\boldsymbol{x})] = \mathbb{E}[d\hat{B}_t^\dagger(\boldsymbol{y})d\hat{B}_t(\boldsymbol{x})] = 0$$
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$$d\hat{O}(t) = d\hat{\mathcal{U}}_t^\dagger\,\hat{O}\,\hat{\mathcal{U}}_t + \hat{\mathcal{U}}_t^\dagger\,\hat{O}\,d\hat{\mathcal{U}}_t + \mathbb{E}[d\hat{\mathcal{U}}_t^\dagger\,\hat{O}\,d\hat{\mathcal{U}}_t],$$

$$\frac{d}{dt}\hat{x}(t) = \frac{\hat{p}(t)}{M} + \frac{\Delta\hat{p}_{\mathrm{CSL}}(t)}{M}$$

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

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Nobakht, M.C., Donadi, Paternostro and Bassi, *To appear.*

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$$\gamma = \gamma_{\text{m}} + \gamma_{\text{CSL}}(\lambda, r_{\text{C}}, T_{\text{CSL}})$$

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# Dissipative CSL model

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

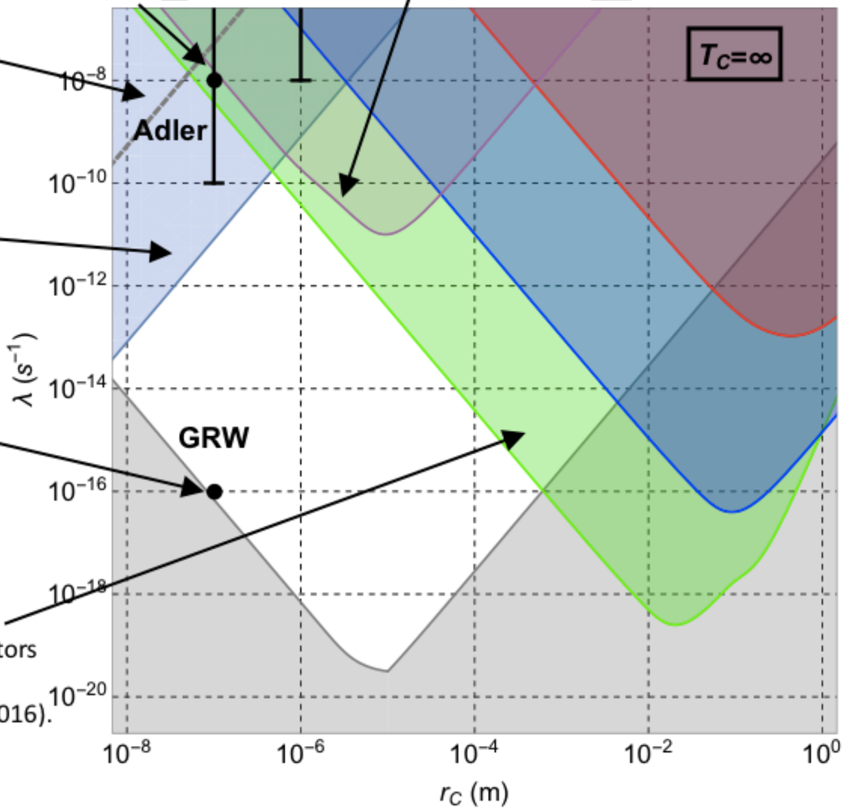
Adler
J. Phys. A 40, 2935 (2007),
J. Phys. A 40, 13501 (2007).

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

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

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

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

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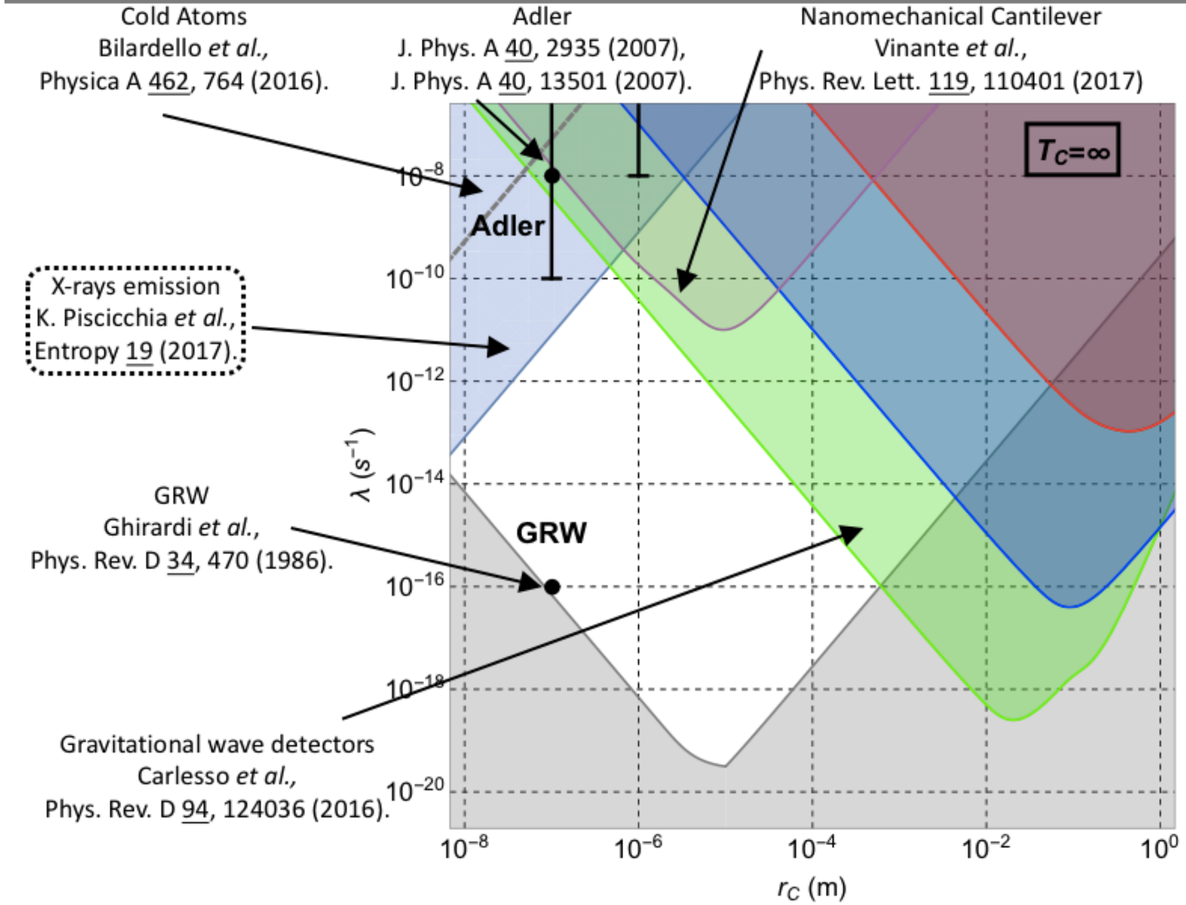


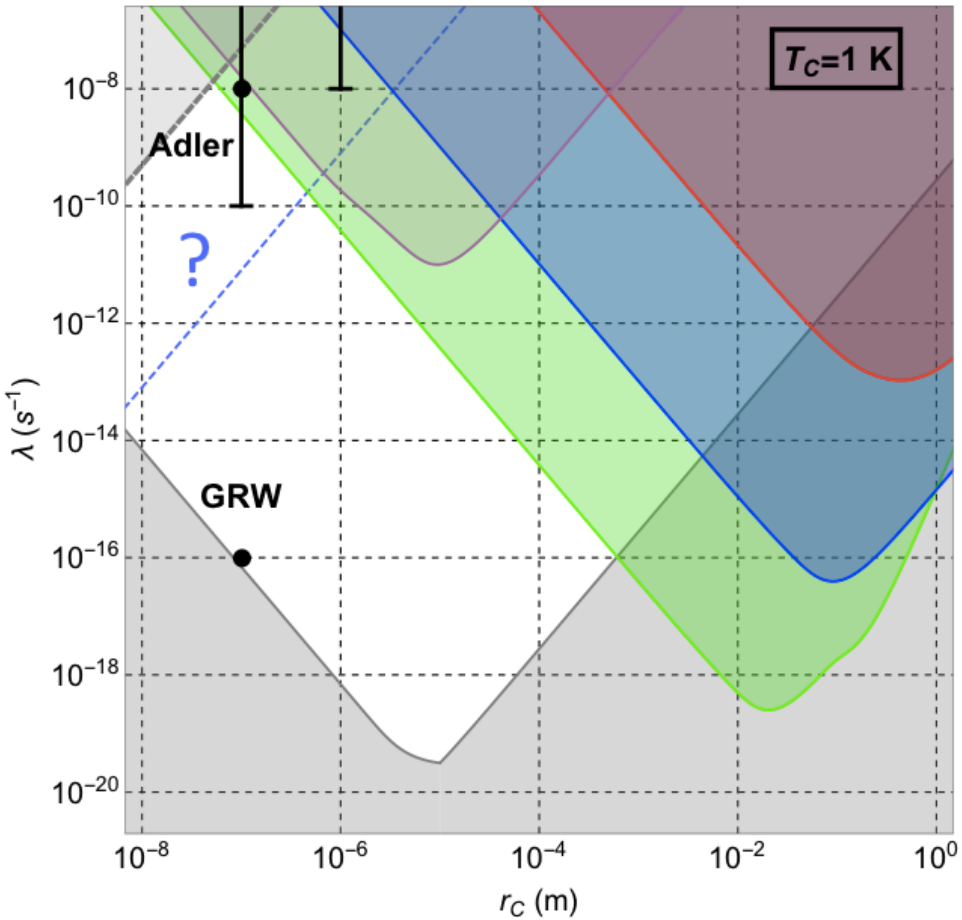


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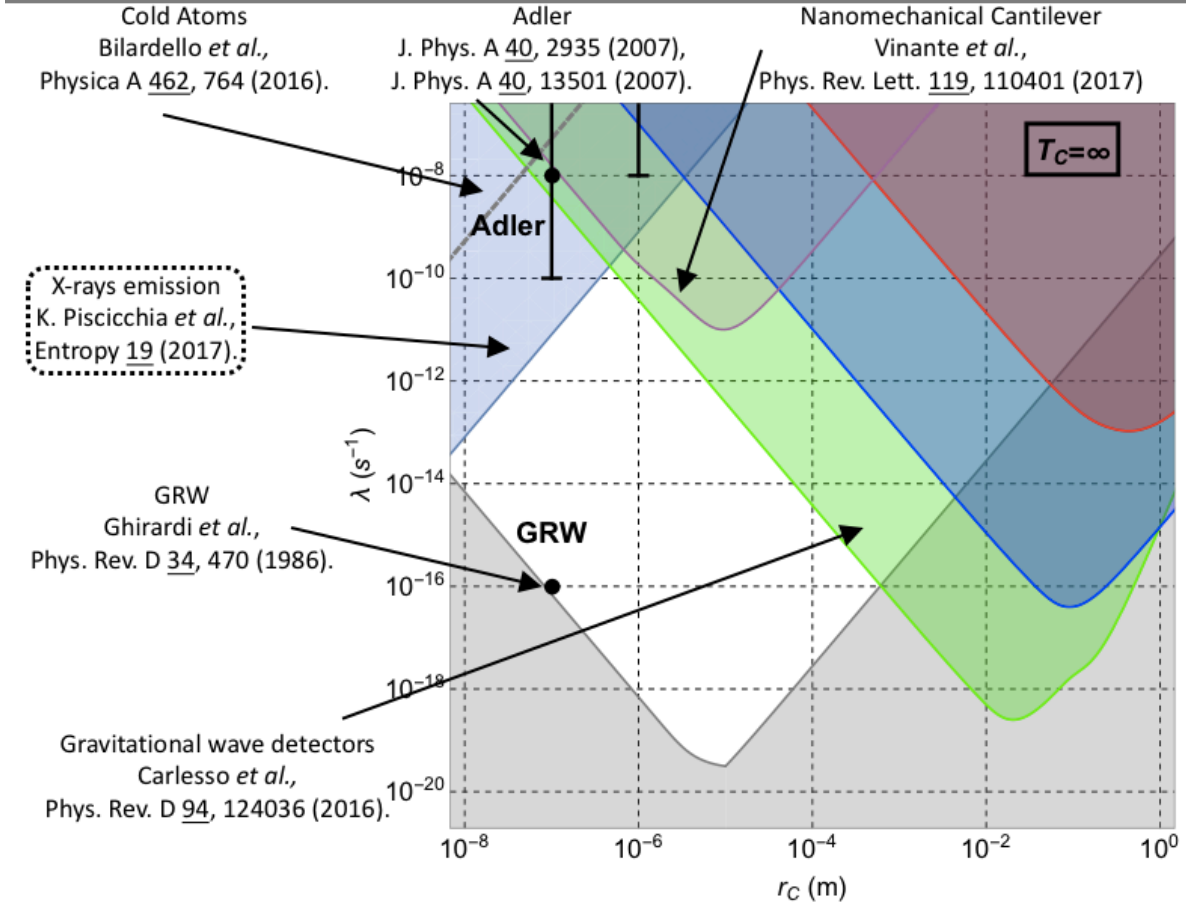


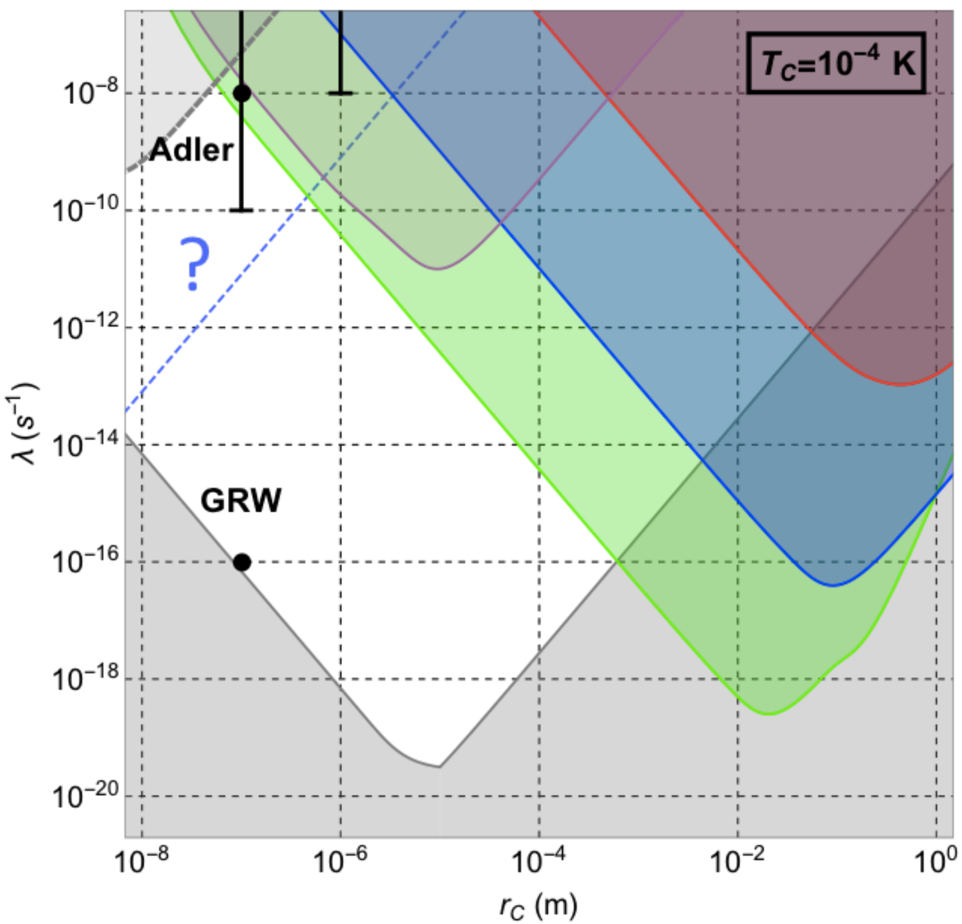


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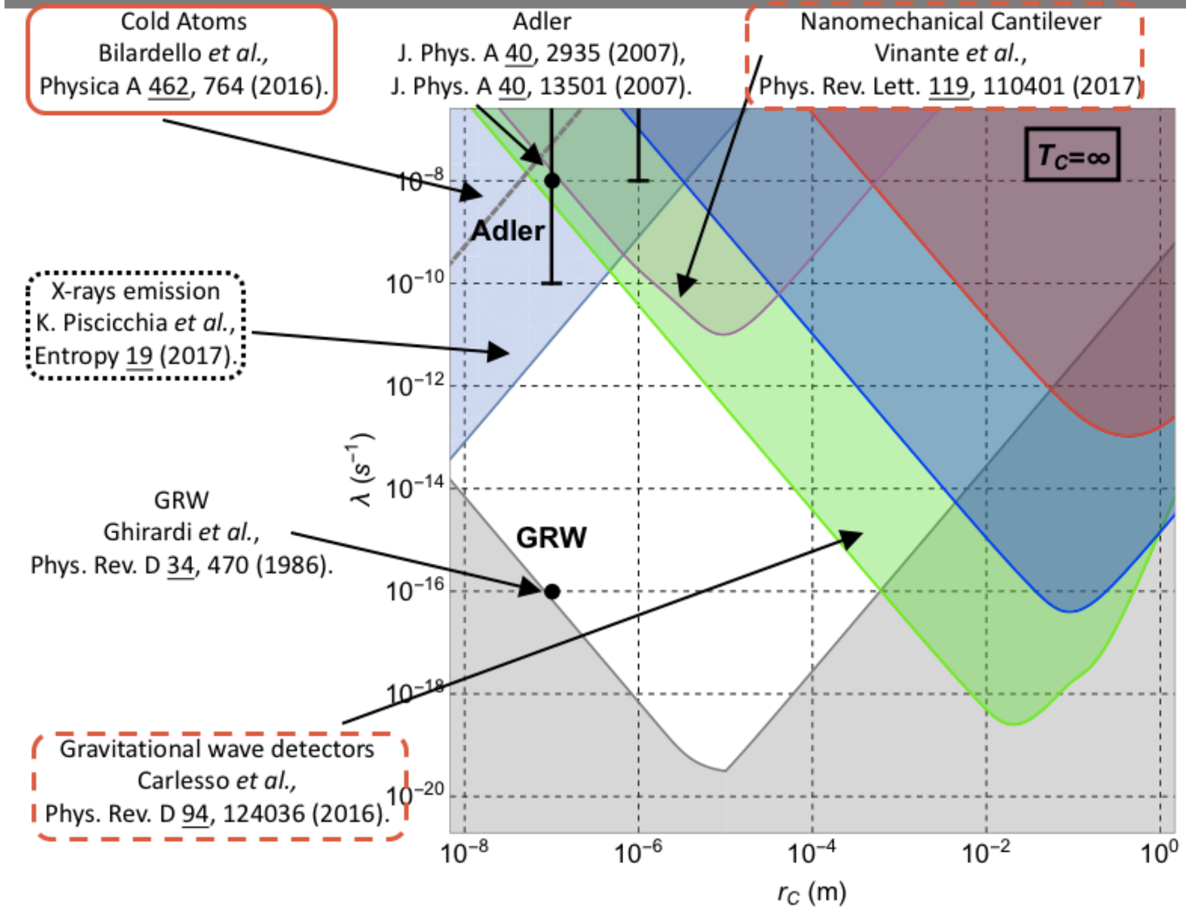


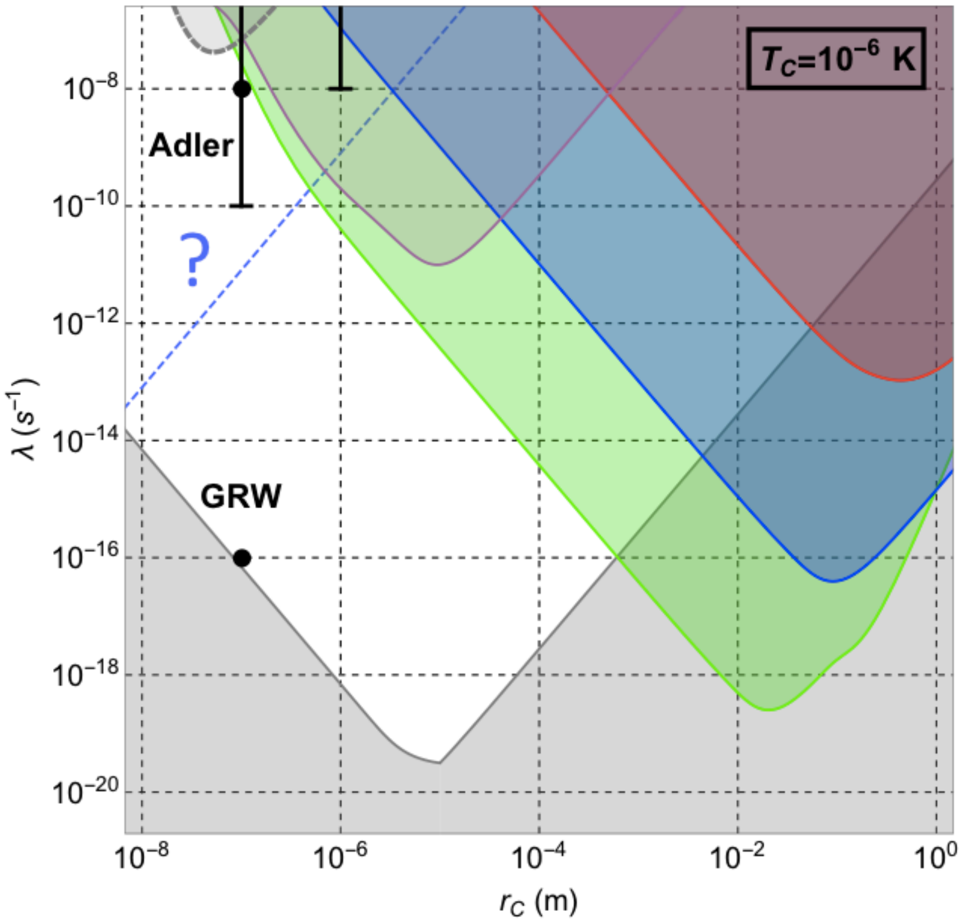


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