



# **Experimental bounds on collapse models from gravitational wave detectors**

Workshop Quantum Foundations. The physics of “what happens” and the measurement problem

**Laboratori Nazionali di Frascati**

**24<sup>th</sup> - 26<sup>th</sup> May 2017**

Matteo Carlesso (University of Trieste & INFN)

# Exp. bounds on CM from GW detectors

- Continuous Spontaneous Localization (CSL) model
  - Opto-mechanical Systems
- Gravitational Wave Detectors
  - AURIGA
  - LIGO
  - LISA Pathfinder
- Experimental Bounds
  - CSL
  - Dissipative CSL

# Collapse models

Collapse models modify the Standard Quantum Mechanics to solve the Measurement problem

Adding stochastic and non-linear terms to Schrödinger eq.

Negligible microscopic action  
No effective collapse  
Quantum systems

Strong macroscopic action  
Rapid collapse  
Systems behave classically



# 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)

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

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

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

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

**Two parameters:**

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

$r_C$  = localization resolution

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

# 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)

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

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

It destroys superposition

Interferometric Experiments

- Matter-wave interferometry
- Entanglement with diamonds

It acts as a Brownian noise

Non-Interferometric Experiments

- Spontaneous X-ray emission
- Ultracold cantilever
- Gravitational wave detectors

# CSL - Theoretical model

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

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

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

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

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

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

**Linear stochastic unravelling**

It gives the same **expectation values!**

# CSL - Theoretical model

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

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

**Langevin equations**

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

$$F_{\text{CSL}} = \frac{i}{\hbar}[\hat{V}_{\text{CSL}}, \hat{p}]$$

**Density Noise Spectrum**

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

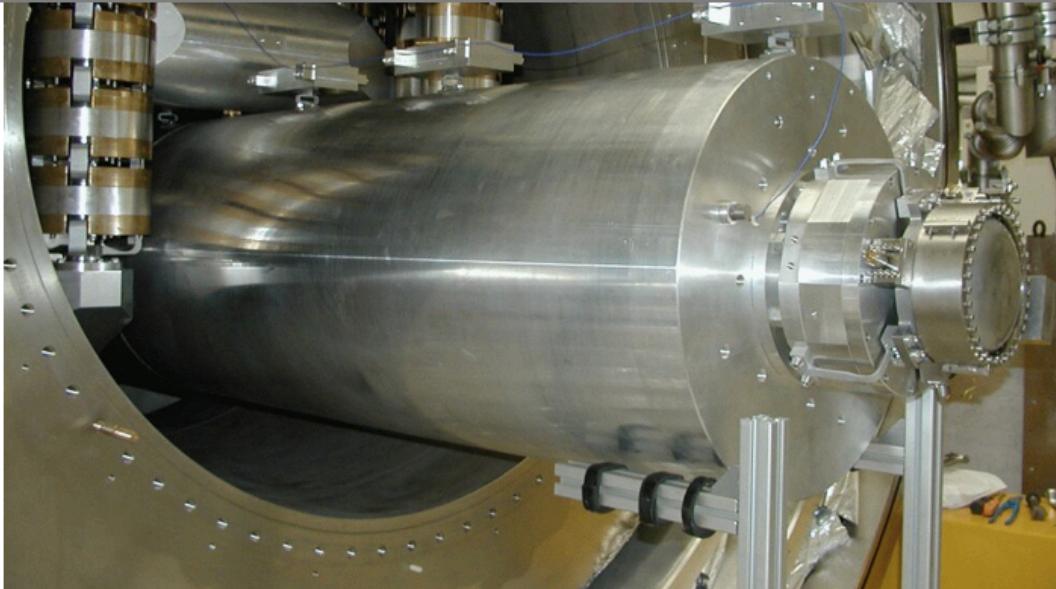
**Thermal contribution**

**CSL contribution**

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

# Gravitational Wave Detectors

AURIGA



# Gravitational Wave Detectors

LIGO

Hanford



Livingston



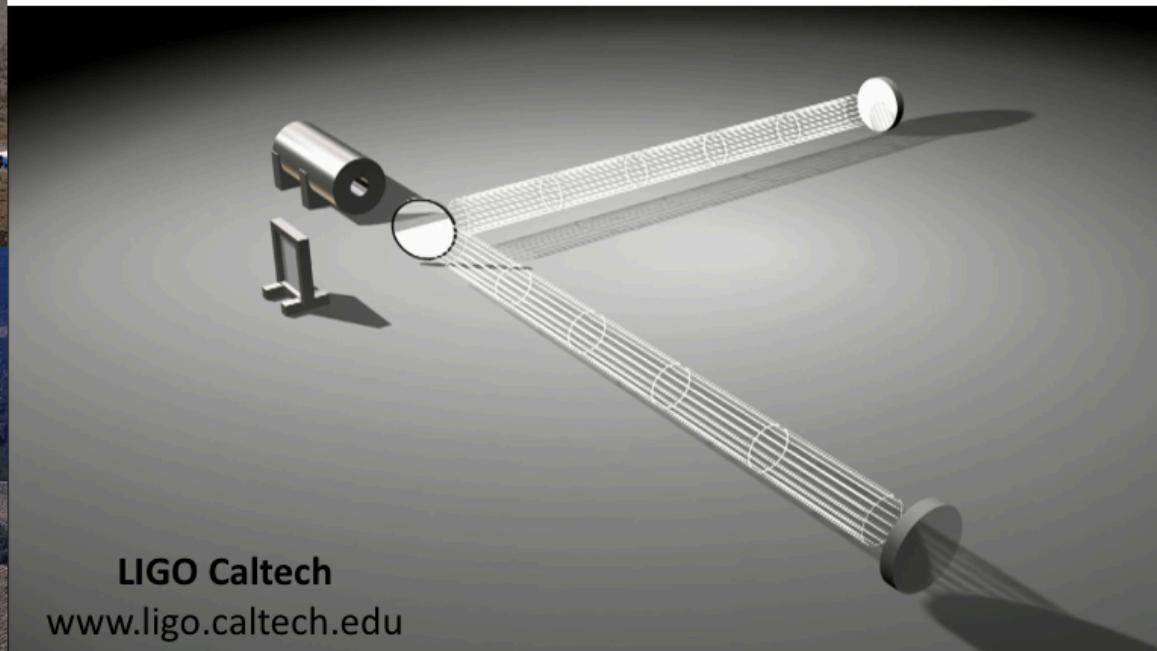
PRL 116, 061102 (2016)

Selected for a **Viewpoint** in *Physics*  
PHYSICAL REVIEW LETTERS

week ending  
12 FEBRUARY 2016

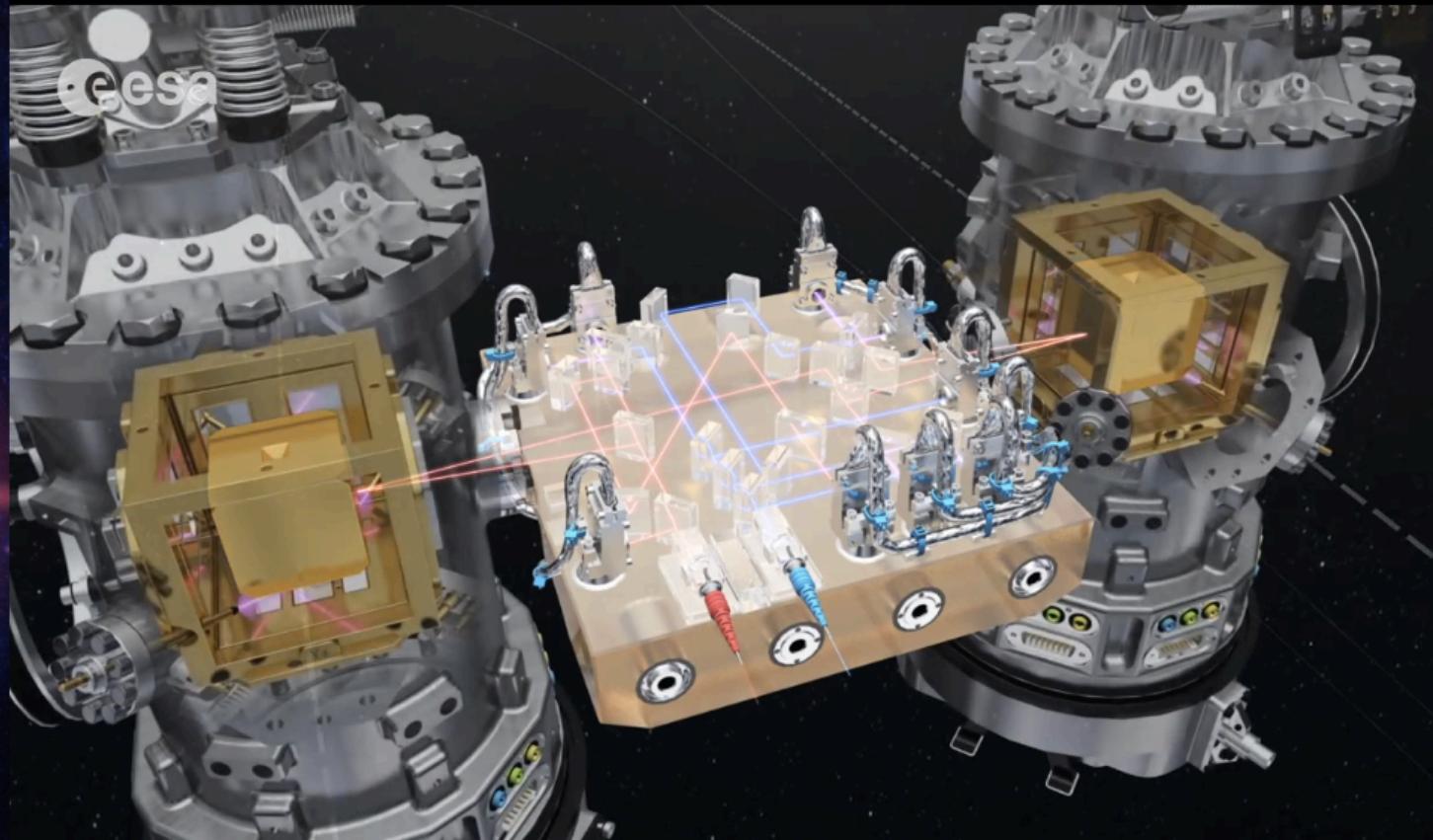
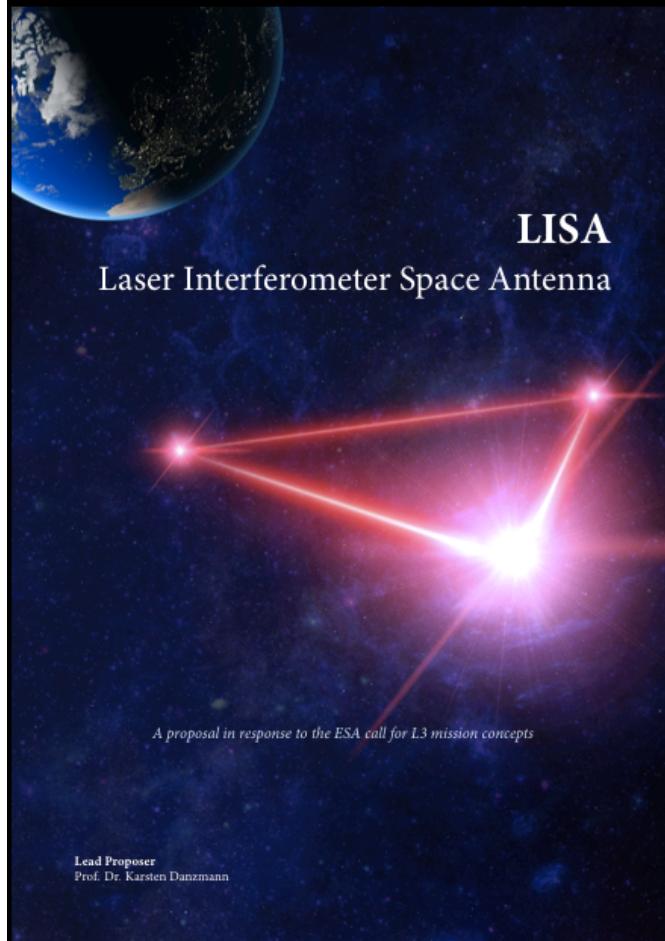
B. P. Abbott *et al.*<sup>\*</sup>  
(LIGO Scientific Collaboration and Virgo Collaboration)  
(Received 21 January 2016; published 11 February 2016)

## Observation of Gravitational Waves from a Binary Black Hole Merger



LIGO Caltech  
[www.ligo.caltech.edu](http://www.ligo.caltech.edu)

# Gravitational Wave Detectors LISA Pathfinder



# CSL experimental bounds

Nanomechanical Cantilever  
 Vinante, Bahrami, Bassi, Usenko,  
 Wijts and Oosterkamp  
*Phys. Rev. Lett.* **116**, 090402 (2016).

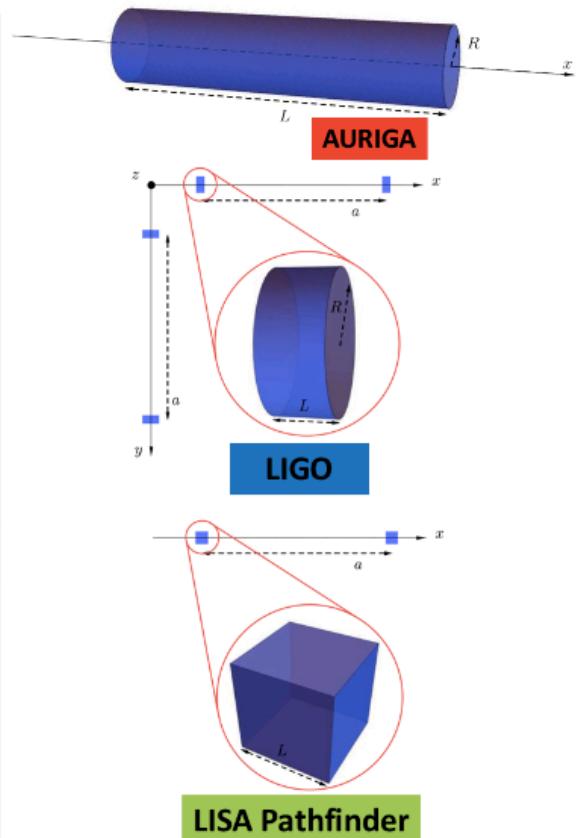
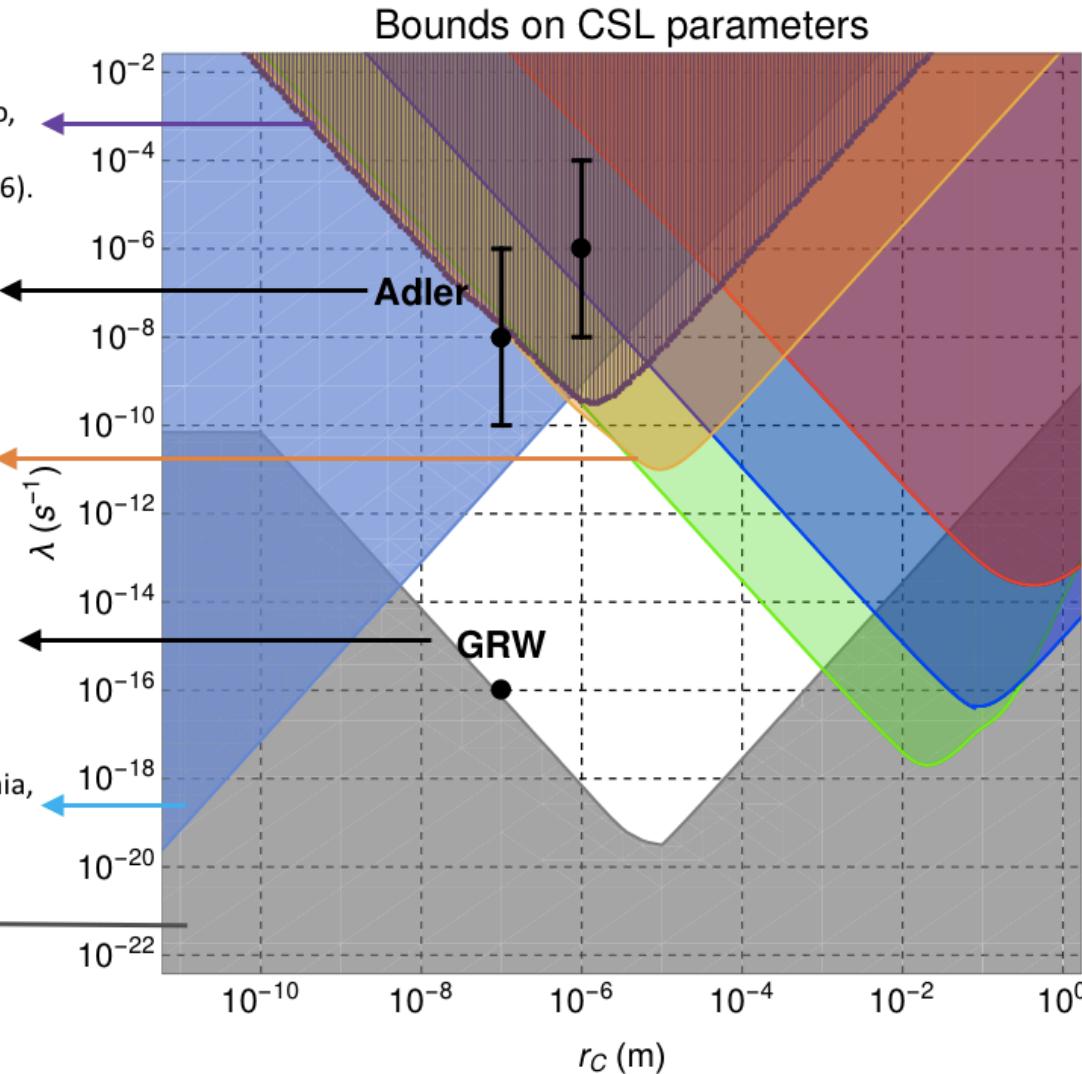
Adler  
*J. Phys. A* **40**, 2935 (2007),  
*J. Phys. A* **40**, 13501 (2007).

Nanomechanical Cantilever  
 Vinante, Mezzena, Falferi,  
 M.C. and Bassi  
*ArXiv*, 1611.09776.

GRW  
 Ghirardi, Rimini, Weber,  
*Phys. Rev. D* **34**, 470 (1986).

X-rays emission  
 Curceanu, Hiesmayr, and Piscicchia,  
*J. Adv. Phys.* **4**, 263 (2015).

Theoretical bound  
 Toroš and Bassi,  
*ArXiv*, 1601.03672.



M.C., Bassi, Falferi and Vinante,  
*Phys. Rev. D* **94**, 124036 (2016).

## Dissipative extension of CSL model

Although CSL model consistently solve the Measurement problem, it has some undesired features. The most important is the energy increment.

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

A new parameter is introduced to solve the problem: the CSL temperature  $T_{\text{CSL}} \simeq 1$  K

$$E(t) = e^{-\beta t} (E_0 - E_{\text{as}}) + E_{\text{as}}, \quad \beta = 4\chi \frac{\lambda}{(1 + \chi)^5}$$
$$E_{\text{as}} = \frac{3}{2} k_{\text{B}} T_{\text{CSL}} \quad \chi = \frac{\hbar^2}{8m_0 k_{\text{B}} T_{\text{CSL}} r_C^2}$$

# Dissipative extension of CSL model

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

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

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

$$\hat{L}(\mathbf{y}) = \frac{m}{(2\pi\hbar)^3} \sum_{\alpha} \int d\mathbf{Q} e^{\frac{i}{\hbar} \mathbf{Q} \cdot (\hat{\mathbf{x}}_{\alpha} - \mathbf{y})} \exp \left( -\frac{r_C^2}{2\hbar^2} |(1 + \chi) \mathbf{Q} + 2\chi \hat{\mathbf{p}}_{\alpha}|^2 \right)$$

$$r_t(\mathbf{y}) = \langle \psi_t | \hat{L}(\mathbf{y}) + \hat{L}^\dagger(\mathbf{y}) | \psi_t \rangle / 2$$

Noise temperature dependence

Momentum dependence

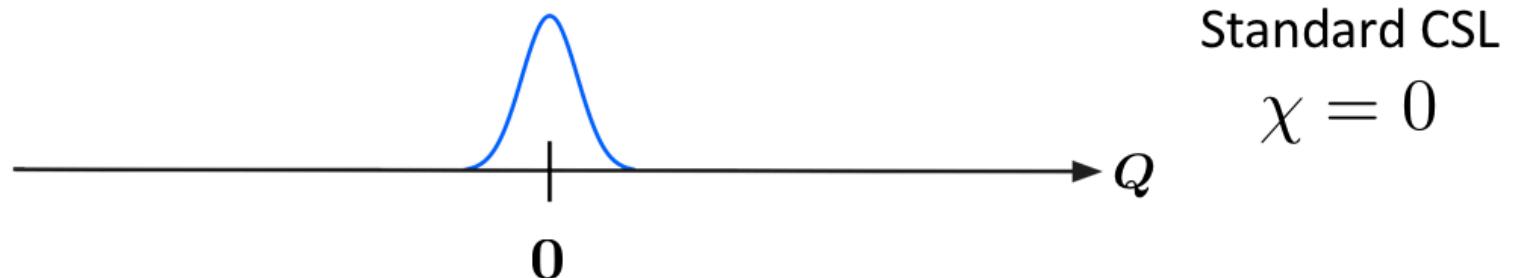
# Dissipative extension of CSL model

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

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

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

$$\hat{L}(\mathbf{y}) = \frac{m}{(2\pi\hbar)^3} \sum_{\alpha} \int d\mathbf{Q} e^{\frac{i}{\hbar} \mathbf{Q} \cdot (\hat{\mathbf{x}}_{\alpha} - \mathbf{y})} \exp \left( -\frac{r_C^2}{2\hbar^2} |(1 + \chi) \mathbf{Q} + 2\chi \hat{\mathbf{p}}_{\alpha}|^2 \right)$$



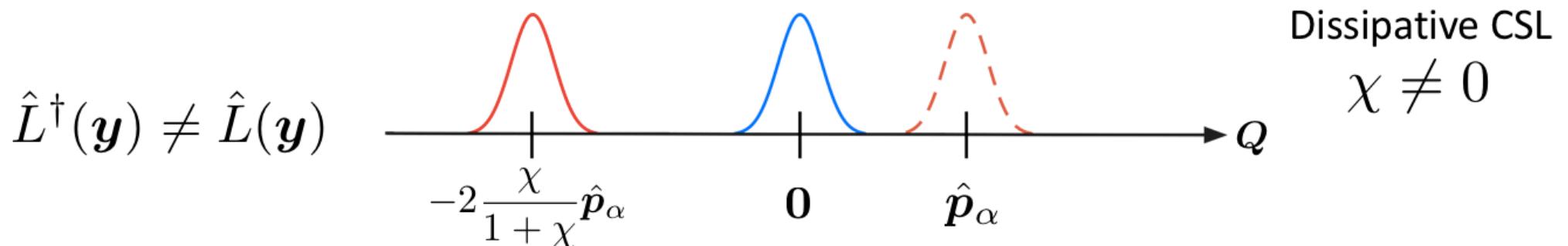
# Dissipative extension of CSL model

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

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

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

$$\hat{L}(\mathbf{y}) = \frac{m}{(2\pi\hbar)^3} \sum_{\alpha} \int d\mathbf{Q} e^{\frac{i}{\hbar} \mathbf{Q} \cdot (\hat{\mathbf{x}}_{\alpha} - \mathbf{y})} \exp \left( -\frac{r_C^2}{2\hbar^2} |(1 + \chi) \mathbf{Q} + 2\chi \hat{\mathbf{p}}_{\alpha}|^2 \right)$$



# Dissipative extension of CSL model

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

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

CSL model:

$$d|\psi_t\rangle = -\frac{i}{\hbar} (\hat{H} + \hat{V}_{\text{CSI}}) dt |\psi_t\rangle$$

Something similar?  
It does not give the  
same expectation values!

$$\hat{V}_{\text{CSL}} = -\frac{\hbar\sqrt{\lambda}}{\pi^{3/4} r_0^{3/2} m_0} \int d\mathbf{y} \hat{M}(\mathbf{y}) w(\mathbf{y}, t)$$

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

HOW?

# Dissipative extension of CSL model

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

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

CSL model:

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

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

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

$$d|\psi_t\rangle = \left\{ -\frac{i}{\hbar} \hat{H} dt + d\hat{C} - \frac{1}{2} \mathbb{E} \left[ d\hat{C}^\dagger d\hat{C} \right] \right\} |\psi_t\rangle$$

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

**Linear stochastic unravelling  
with a quantum noise**

$$\mathbb{E}[dB_t(\mathbf{x})] = \mathbb{E}[dB_t^\dagger(\mathbf{x})] = \mathbb{E}[dB_t^\dagger(\mathbf{y}) dB_t(\mathbf{x})] = 0$$

$$\mathbb{E}[dB_t(\mathbf{y}) dB_t^\dagger(\mathbf{x})] = \delta(\mathbf{y} - \mathbf{x}) dt$$

# Dissipative extension of CSL model

$$d|\psi_t\rangle = \left\{ -\frac{i}{\hbar} \hat{H} dt + d\hat{C} - \frac{1}{2} \mathbb{E} [d\hat{C}^\dagger d\hat{C}] \right\} |\psi_t\rangle = d\hat{\mathcal{U}}_t |\psi\rangle$$

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

Langevin equations

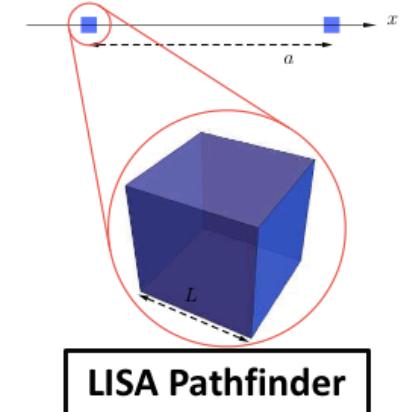
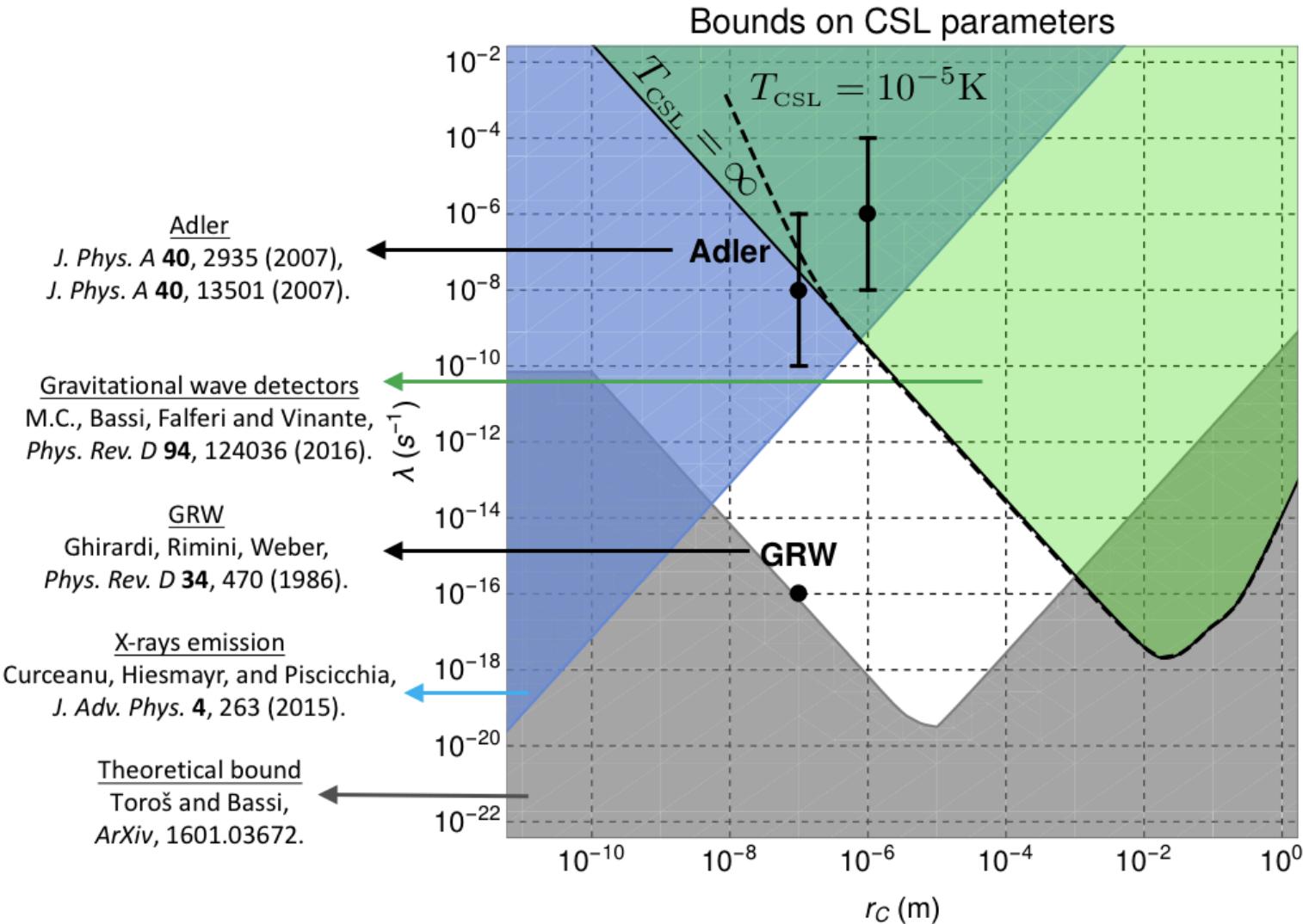
$$\frac{d}{dt}\hat{x}(t) = \frac{\hat{p}(t)}{M} + \frac{\Delta\hat{p}_{\text{CSL}}(t)}{M}$$

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

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

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

# CSL experimental bounds



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

$$r_C \rightarrow r_C + \left( \frac{\hbar^2}{8m_0 k_B T_{\text{CSL}}} \right) \frac{1}{r_C}$$

## Example

$$T_{\text{CSL}} = 1 \text{ K}$$

$$r_C \leq 2.5 \times 10^{-10} \text{ m}$$

# Conclusions

Gravitational Wave Detectors set important bounds on Collapse Models

LISA Pathfinder

CSL model

Dissipative CSL model

Bassi Group  
University of Trieste



UNIVERSITÀ  
DEGLI STUDI DI TRIESTE

