# Experimental bounds on collapse models from gravitational wave detectors

**QTSpace meets in Malta**

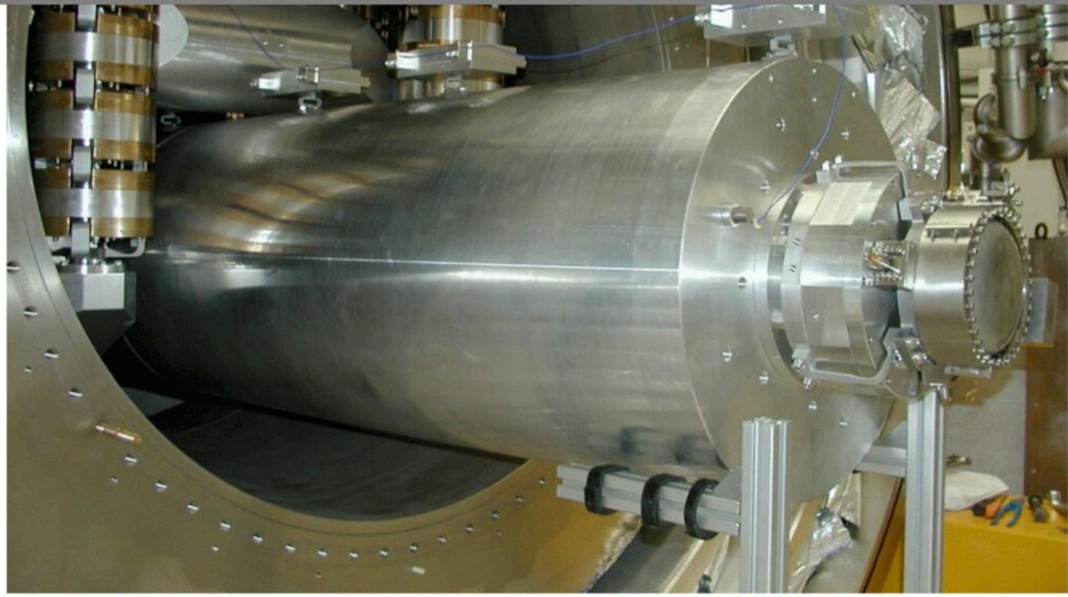
**Valletta, 27th - 30th March 2017**

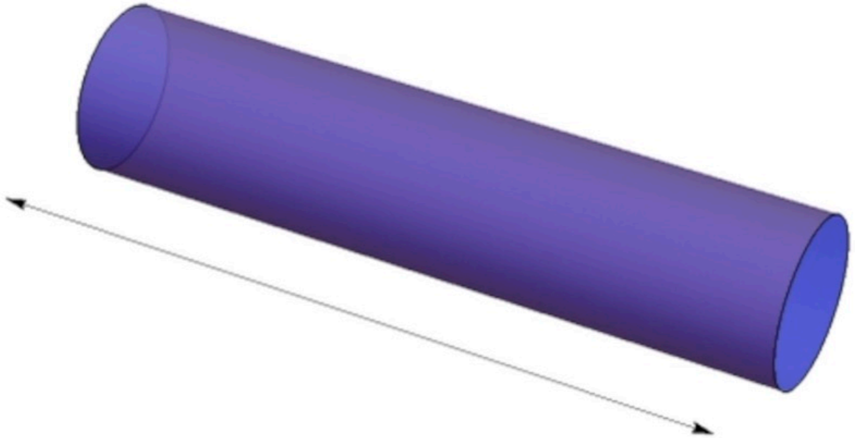
Matteo Carlesso (University of Trieste & INFN)

# Outline

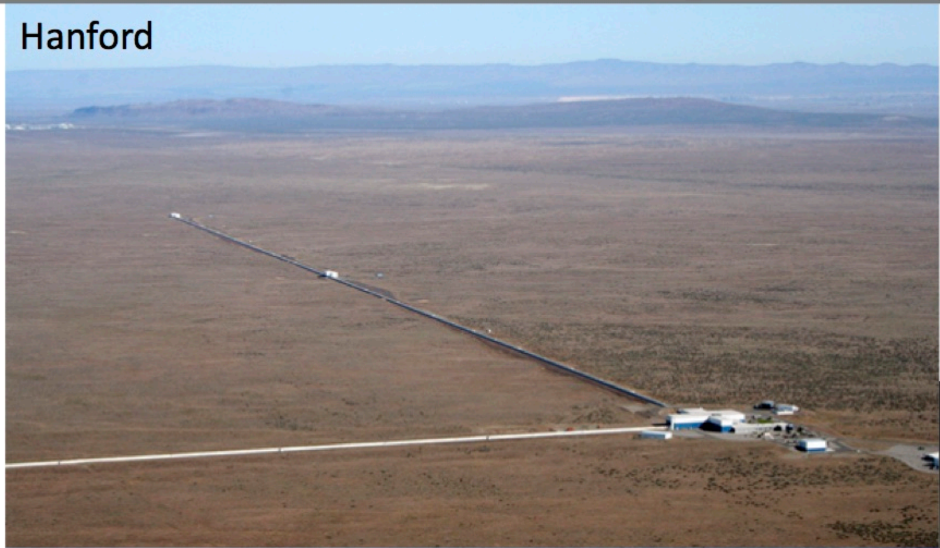
- Gravitational Wave Detectors
  - AURIGA
  - LIGO
  - LISA Pathfinder
- Continuous Spontaneous Localization (CSL) model
  - Opto-mechanical Systems
- Experimental Bounds

# Gravitational Wave Detectors **AURIGA**





# Gravitational Wave Detectors **LIGO**

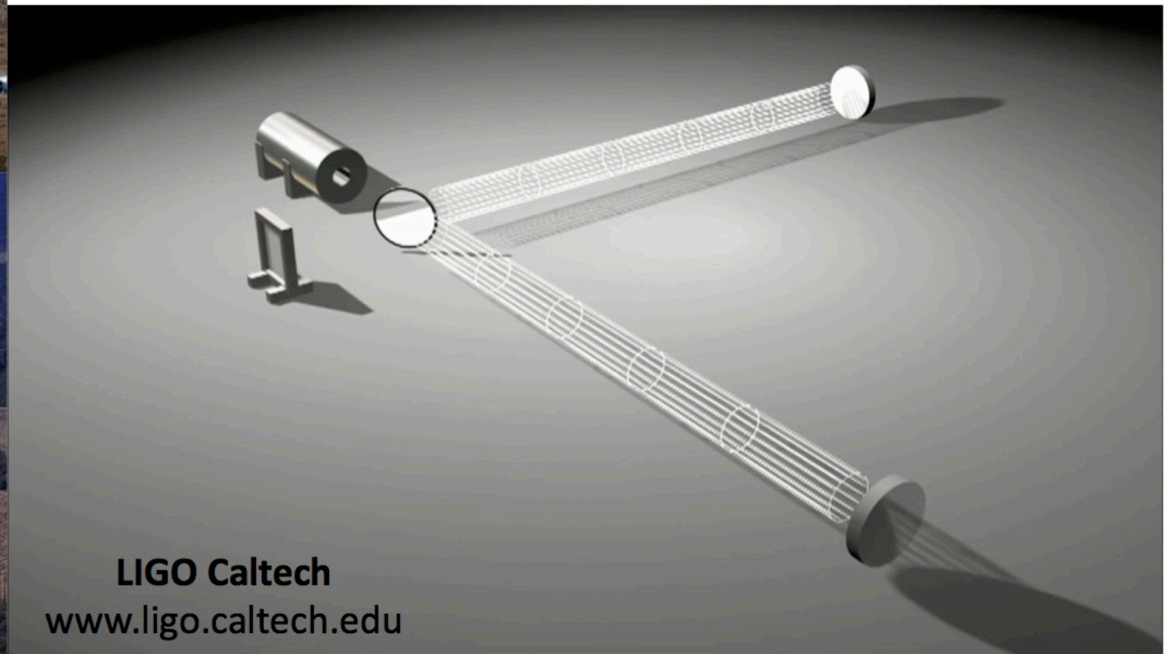




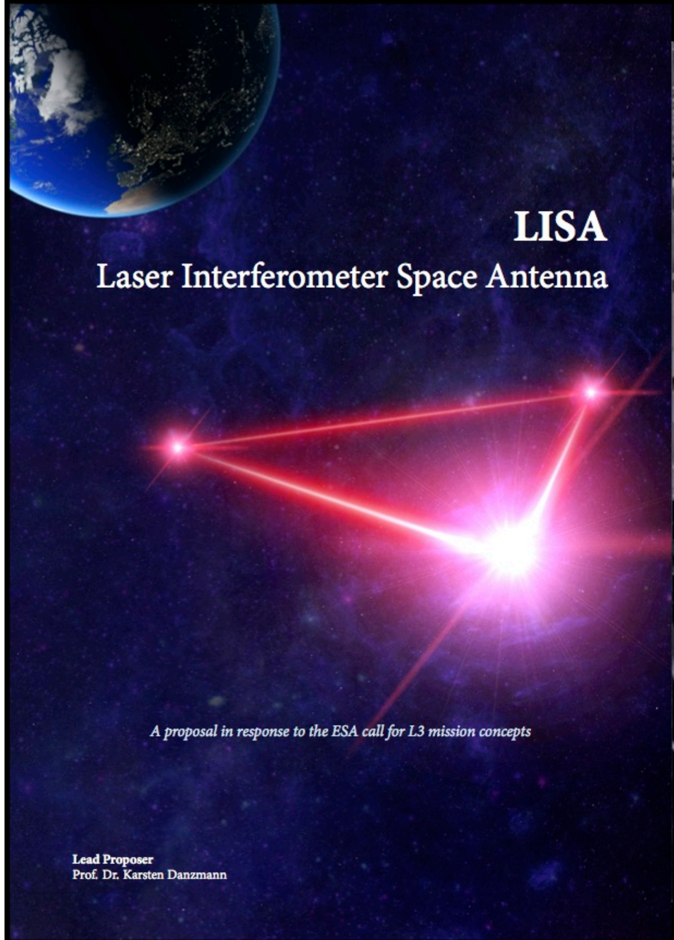
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

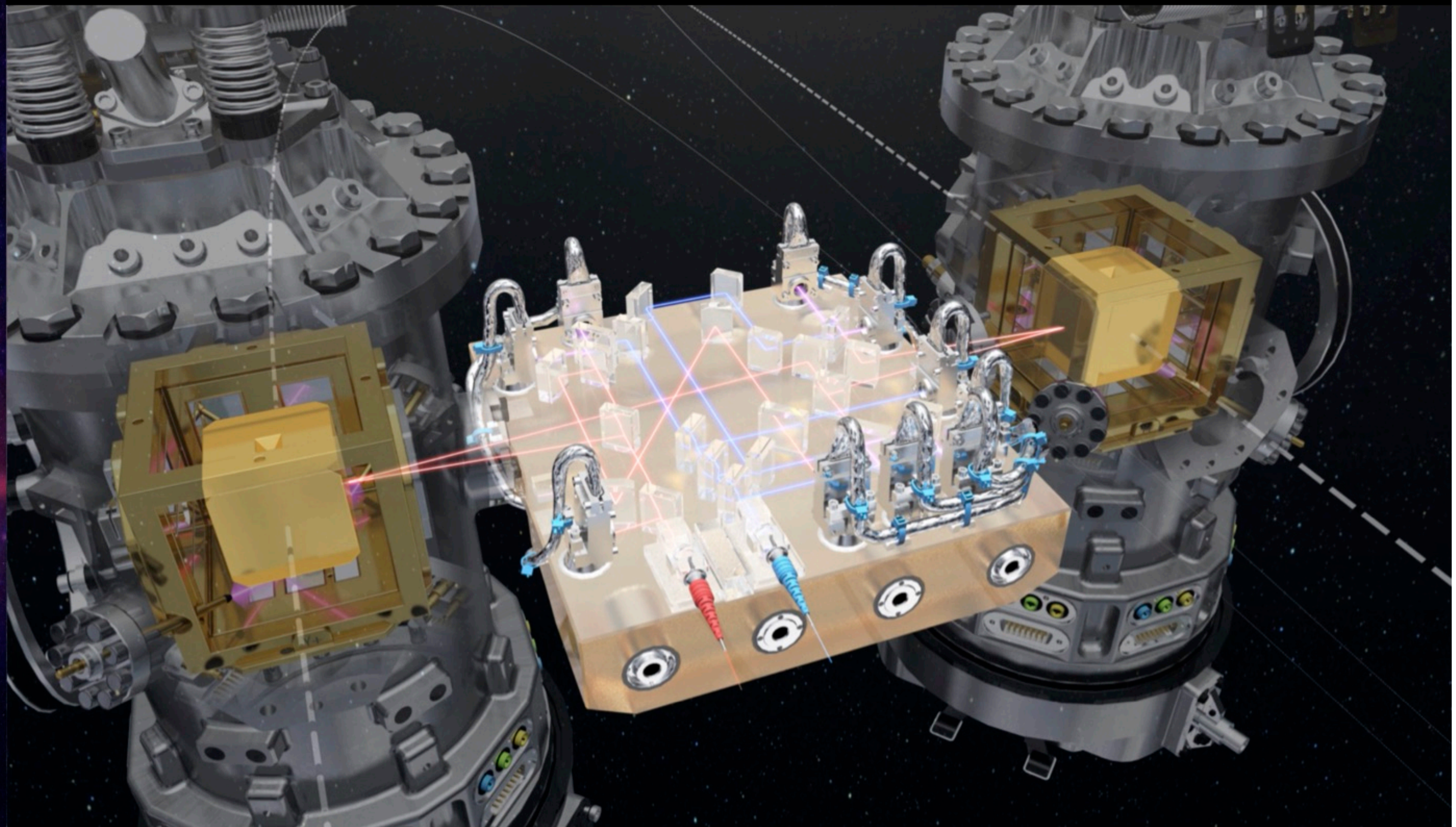
**Observation of Gravitational Waves from a Binary Black Hole Merger**

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



# Gravitational Wave Detectors **LISA Pathfinder**



# Collapse models

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

- Adding stochastic and non-linear terms to Schödinger eq.

- Negligible microscopic action
  Systems still behave quantum-mechanically

- Strong macroscopic action
  Rapid collapse and systems behave classically

**Amplification mechanism**

# 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)

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

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

$$\hat{M}(\boldsymbol{x}) = m\hat{a}^\dagger(\boldsymbol{x})\hat{a}(\boldsymbol{x})$$

$$G(\boldsymbol{x}-\boldsymbol{y}) = \frac{1}{(4\pi r_C)^{3/2}}\, e^{-\frac{(\boldsymbol{x}-\boldsymbol{y})^2}{4r_C^2}}$$

**Two parameters:**

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

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

# Continuous Spontaneous Localization (CSL) model

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$$d\,|\psi_t\rangle = \left[-\frac{i}{\hbar}\hat{H}\,dt + \frac{\sqrt{\gamma}}{m_0}\int d\boldsymbol{x}\left(\hat{M}(\boldsymbol{x}) - \langle\hat{M}(\boldsymbol{x})\rangle_t\right)dW_t(\boldsymbol{x}) + \right.$$
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**Stochastic**, **Non-linear** equation. Collapse occurs in **space**

Does not only destroy superpositions in space!

**<u>It acts as a Brownian noise.</u>**

Interferometric Experiments

- Matter-wave interferometry
- Entanglement with diamonds

Non-Interferometric Experiments

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

# Continuous Spontaneous Localization (CSL) model

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

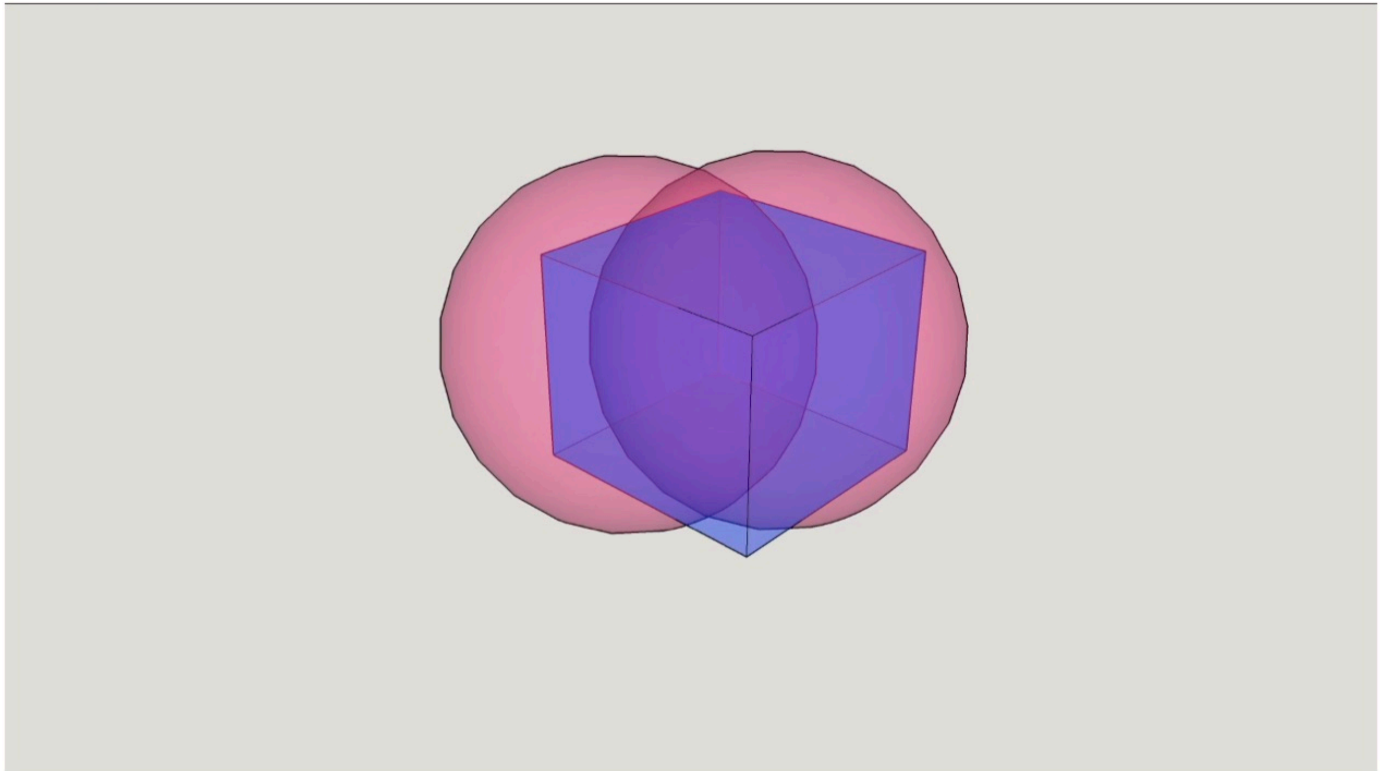
It can be mimicked by adding a **stochastic potential**

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

$$\hat{V}_{\mathrm{CSL}}(t) = -\frac{\hbar\sqrt{\lambda}}{\pi^{3/4}r_C^{3/2}m_0}\int d\boldsymbol{z}\,\hat{N}(\boldsymbol{z})w(\boldsymbol{z},t) \qquad \hat{N}(\boldsymbol{z}) = \sum_n m_n e^{\frac{(\boldsymbol{z}-\hat{\boldsymbol{q}}_n)^2}{2r_C^2}}$$

# Theoretical model

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



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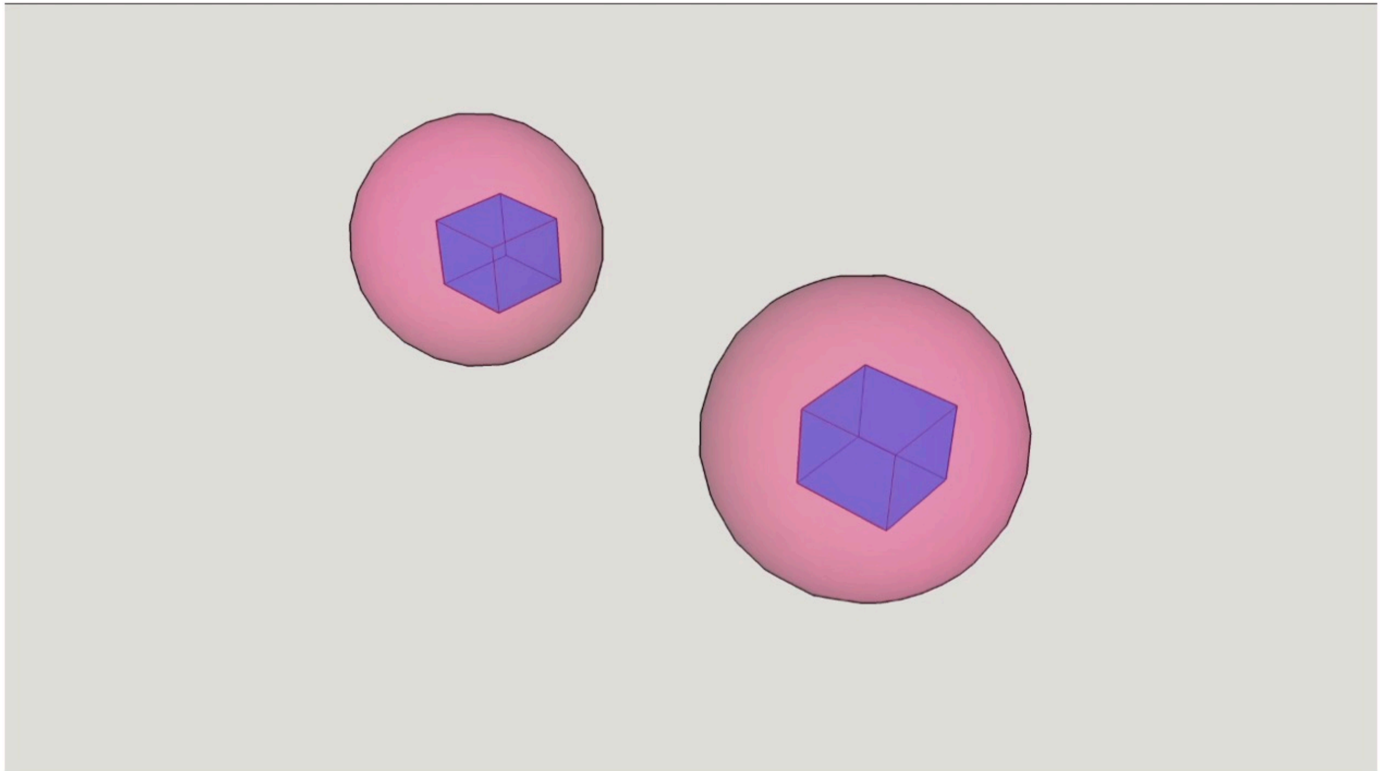


# Theoretical model

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

**Langevin equations**

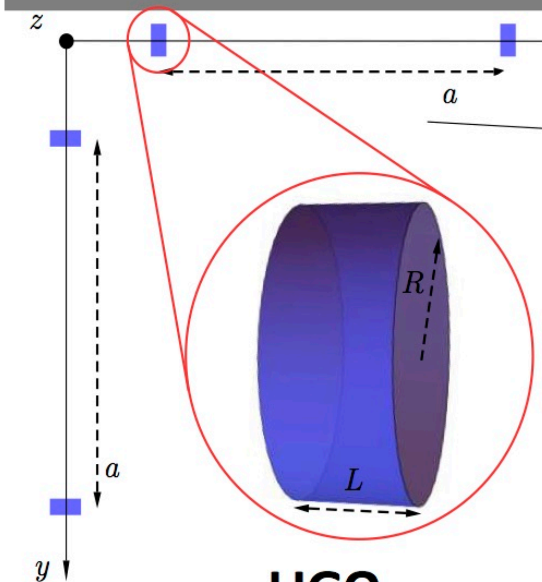
$$\frac{d}{dt}\hat{x}(t) = \frac{\hat{p}(t)}{M}$$

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

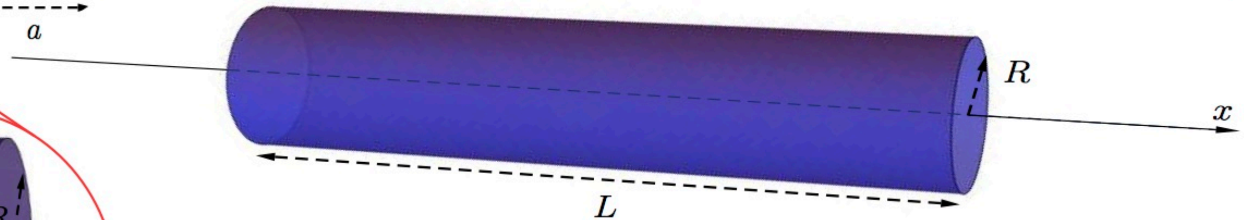
$$\mathcal{S}_{FF}(\omega) = \frac{1}{4\pi} \int d\Omega \, \langle \{ \tilde{F}(\omega), \tilde{F}(\Omega) \} \rangle$$

**Density Noise Spectrum**

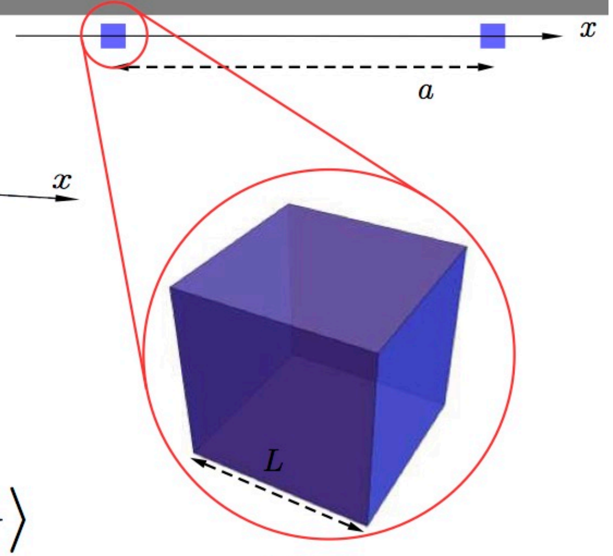
# Experimental model




LIGO




AURIGA




LISA Pathfinder

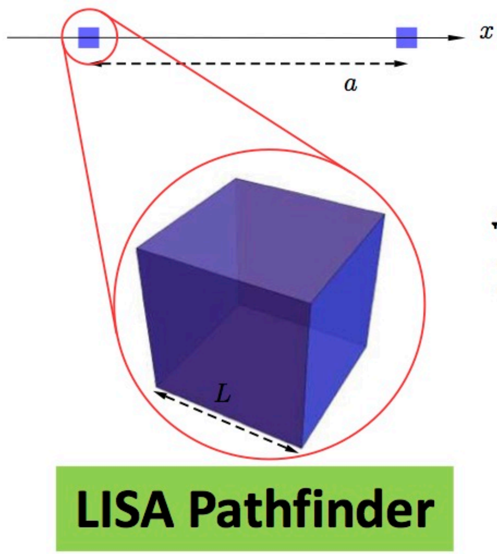
$$\mathcal{S}_{FF}(\omega) = \frac{1}{4\pi}\int d\Omega\, \langle\{\tilde{F}(\omega), \tilde{F}(\Omega)\}\rangle$$

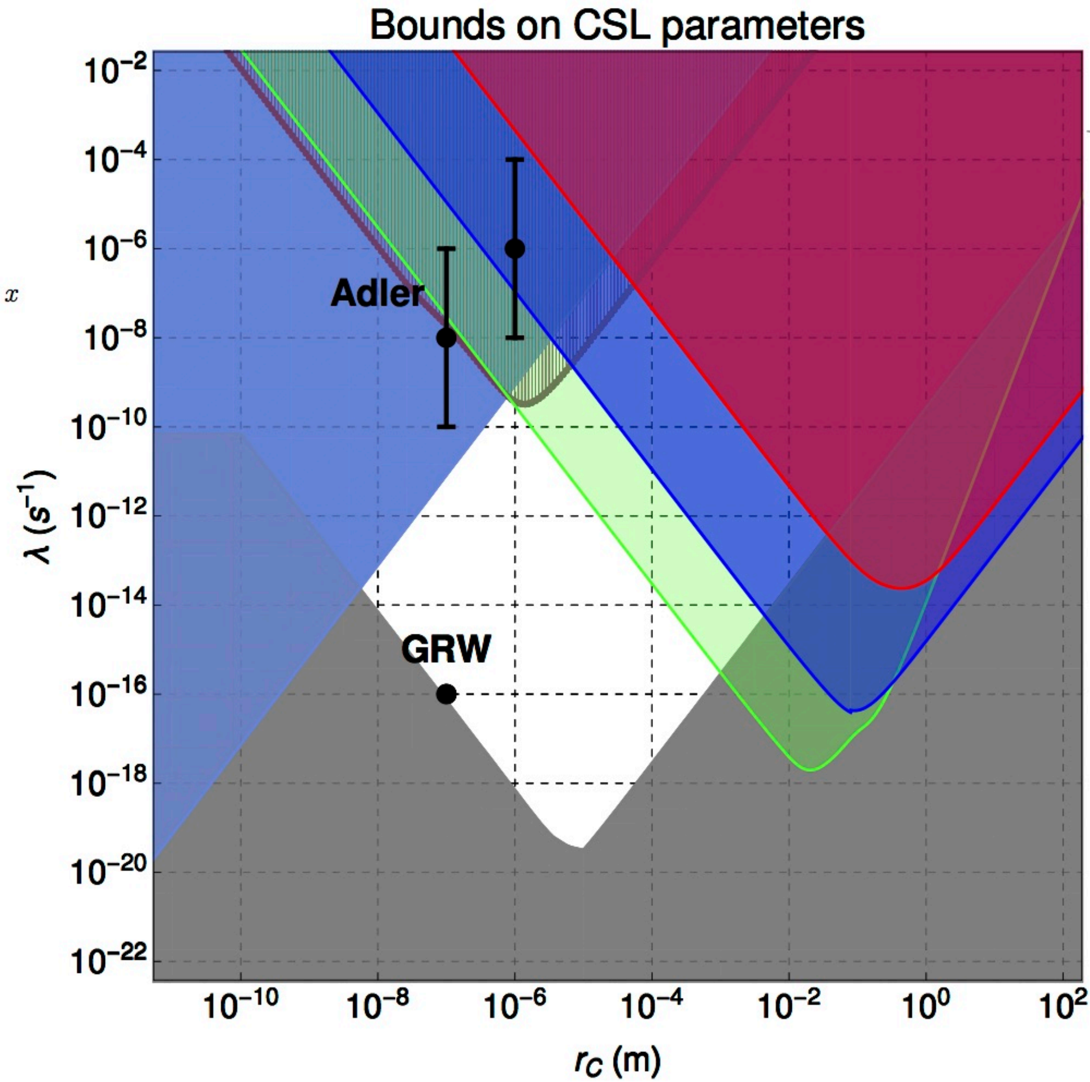
↓

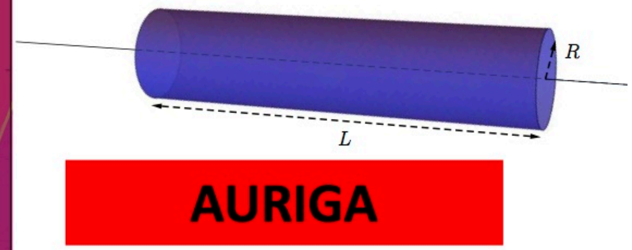
$$\mathcal{S}_{FF}(\omega) = \frac{\hbar^2 \lambda r_C^3}{2\pi^{3/2} m_0^2}\int d\boldsymbol{k} |\tilde{\mu}(\boldsymbol{k})|^2 (1 - e^{iak_x}) k_x^2 e^{-r_C^2 \boldsymbol{k}^2}$$

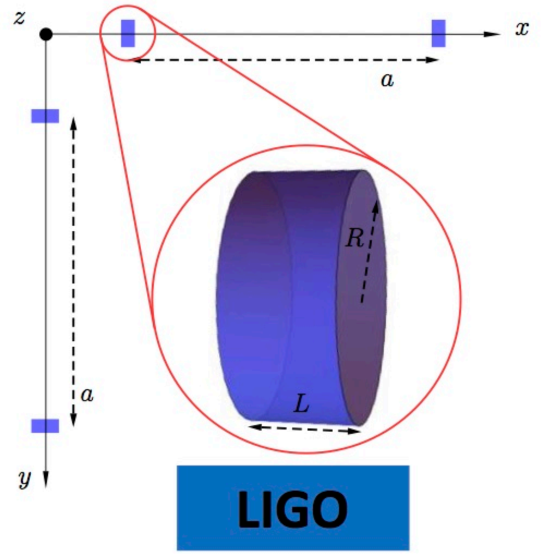
M.C., A. Bassi, P. Falferi and A. Vinante, *Phys. Rev. D* **94**, 124036 (2016).

# CSL experimental bounds



# Conclusions and Future Perspectives

Gravitational Wave Detectors set important bounds on Collapse Models

LISA Pathfinder

Can Space missions do more?

Relatively large systems
High precision
Small decoherence effects

# Acknowledgements

**The Group (www.qmts.it)**
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