Beyond Standard-Model physics with ion trap methods

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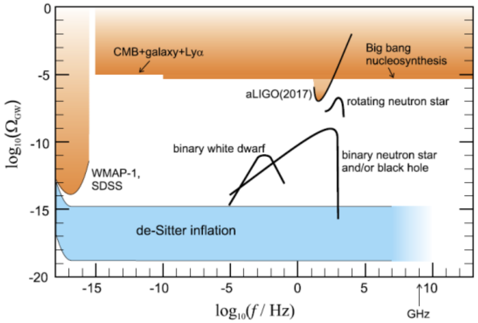
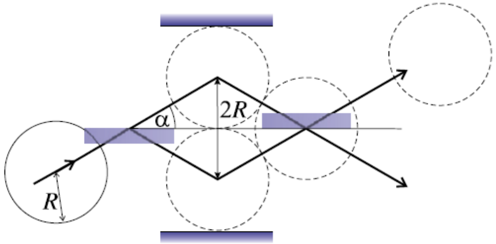
1. Physics Letters A 381 (2017) 3905–3908

Matter-wave coherence limit owing to cosmic gravitational wave background

Andrew M. Steane

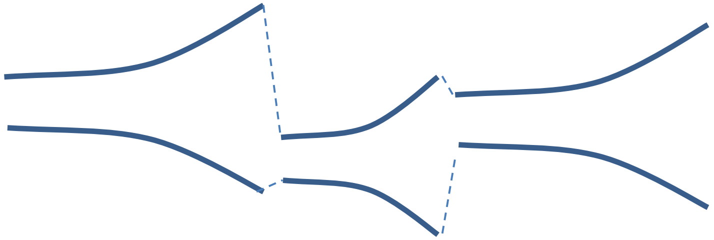


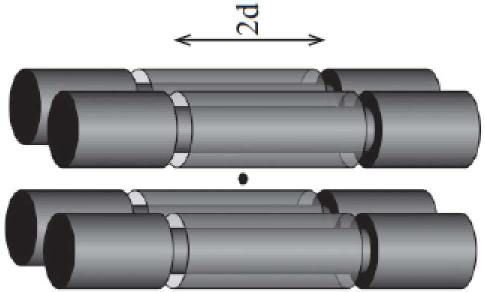


2. PHYSICAL REVIEW A **95**, 032112 (2017)

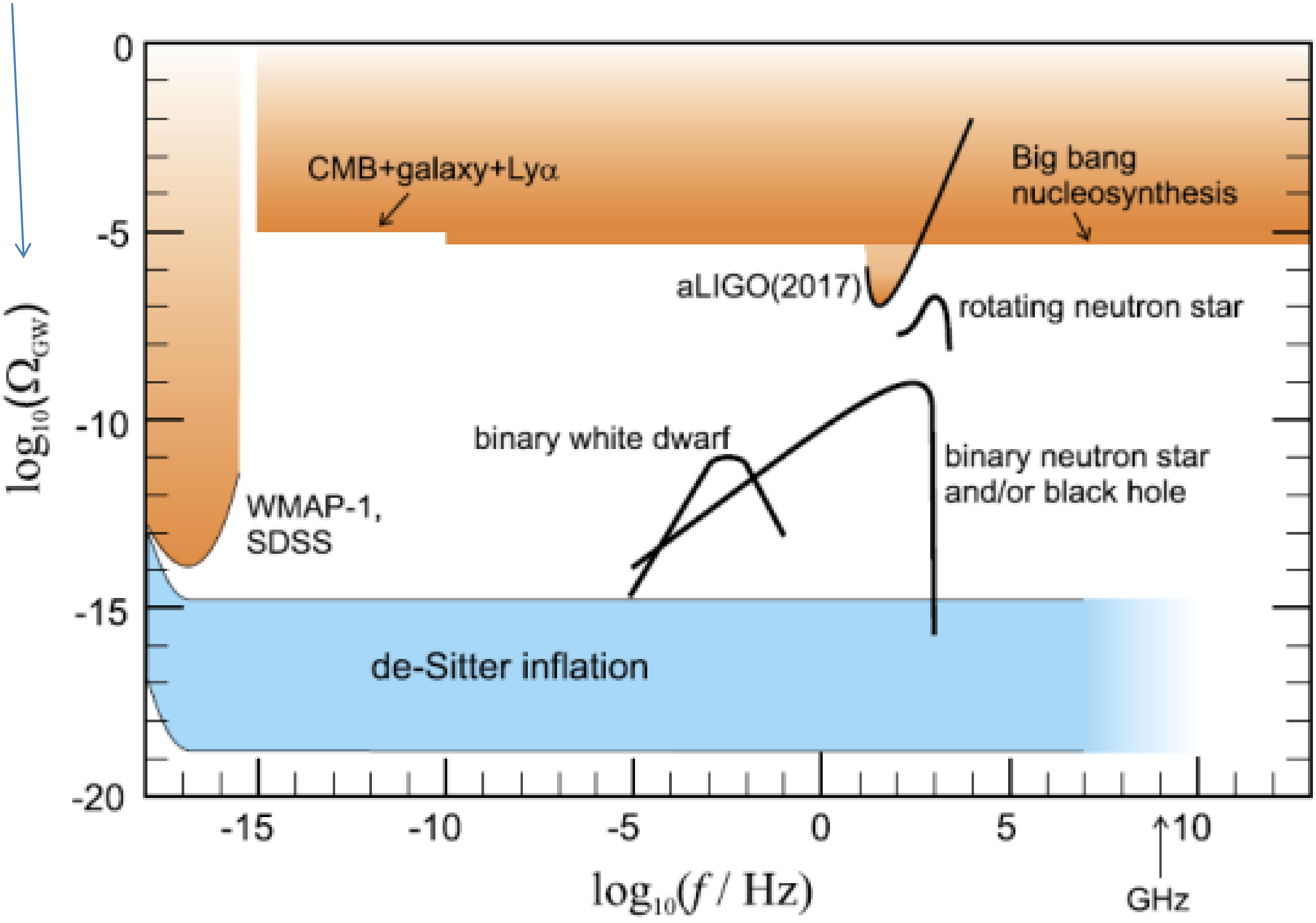
Detecting continuous spontaneous localization with charged bodies in a Paul trap

Ying Li, Andrew M. Steane, Daniel Bedingham, and G. Andrew D. Briggs

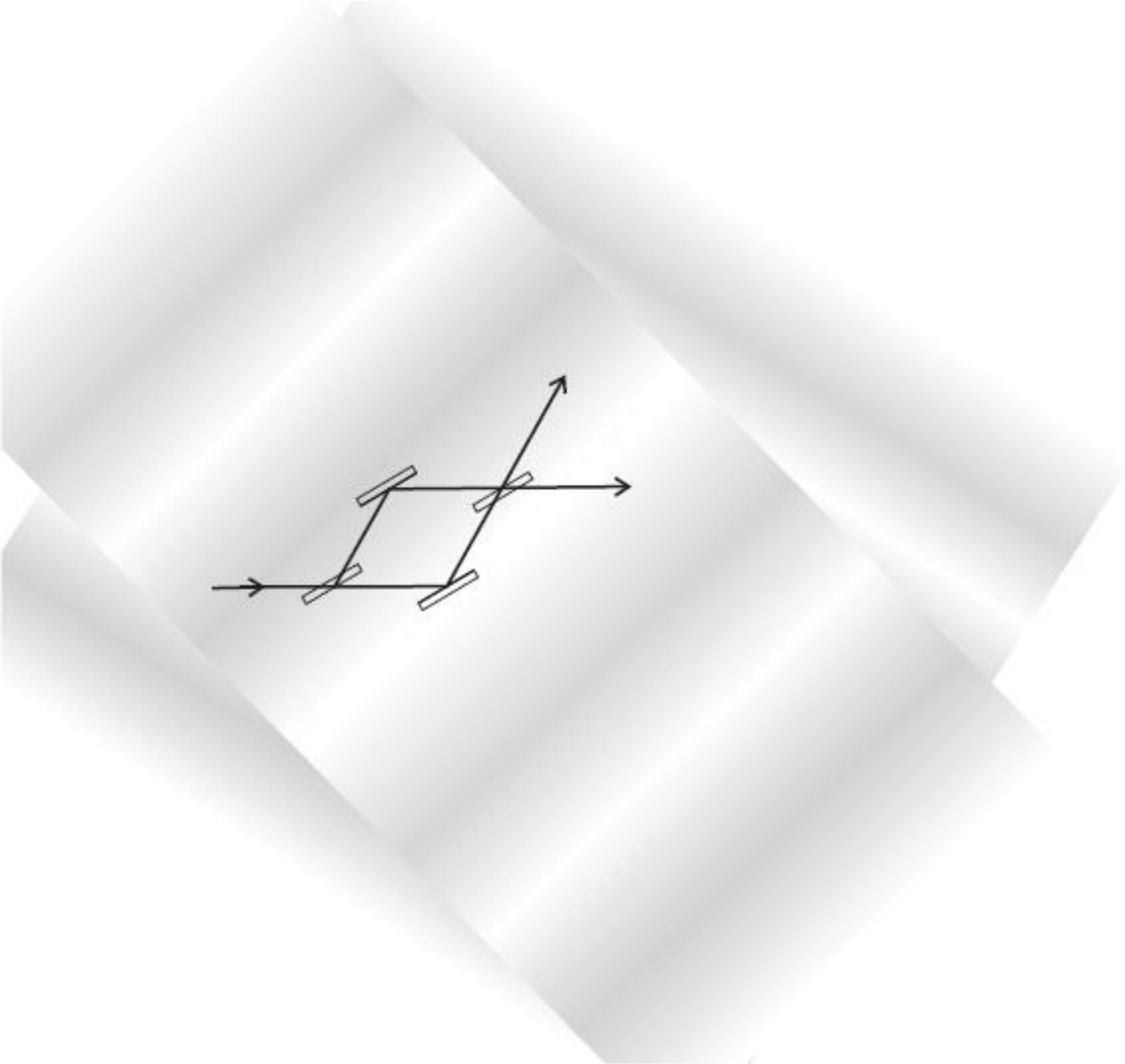


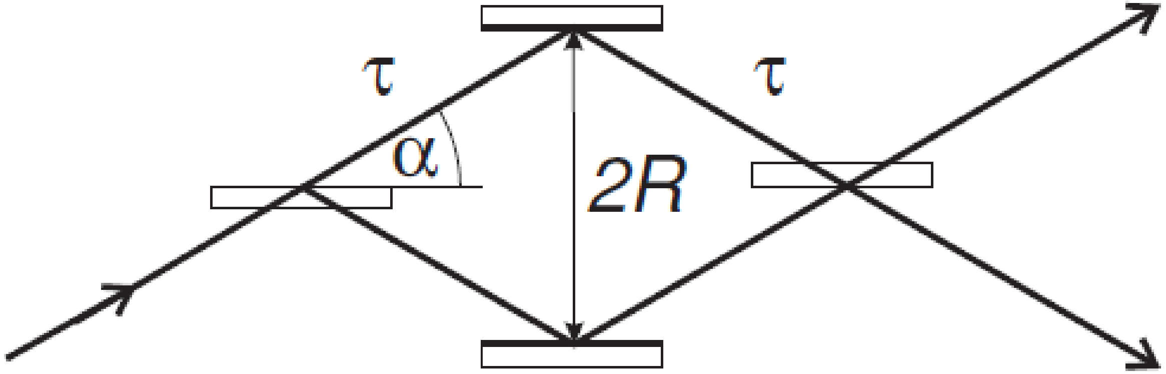


$\Omega_{\mathrm{GW}} \equiv \frac{1}{\rho_c c^2} f \frac{\mathrm{d}\rho(f)}{\mathrm{d}f}$ (Dimensionless measure of g-wave spectral energy density)



Gravitational wave background
→ wash out interference of matter waves





Following Lamine, Jaekel and Reynaud, Eur. Phys. J. D **20**, 165 (2002);
Lamine, Hervé, Lambrecht, Reynaud, PRL **96**, 050405 (2006)

Gravitational plane wave $h_{ij} e^{-ik_\mu x^\mu} = \frac{(\mathbf{e}_i \mathbf{e}_j)^*}{\sqrt{2}} h e^{-ik_\mu x^\mu}$.
Interferometer phase for particle of mass m, velocity $\mathbf{v} \ll c$:

$$\phi = \frac{E}{2\hbar} \int_{\tau_\mathrm{i}}^{\tau_\mathrm{f}} h_{ij} \mathbf{v}^i \mathbf{v}^j \mathrm{d}\tau = \frac{mc^2}{2\sqrt{2}\hbar} h \int_{\tau_\mathrm{i}}^{\tau_\mathrm{f}} (\mathbf{e} \cdot \mathbf{v})^2 e^{-ik_\mu x^\mu} \mathrm{d}\tau$$

⟶ variance when g-waves are randomly fluctuating:

$$\Delta\phi^2 = \int \frac{\mathrm{d}\omega}{2\pi} \quad \underset{\substack{\text{g-wave} \\ \text{noise} \\ \text{spectrum}}}{S_h[\omega]} \quad \underset{\substack{\text{interferometer} \\ \text{response}}}{A[\omega]} \quad \underset{\substack{\text{high-pass} \\ \text{filter}}}{\frac{\omega^2}{\omega^2+\Gamma^2}}$$

$$\Delta\phi^2 = \frac{24 H_0^2 \Omega_{\rm GW}}{\pi \hbar^2} m^2 (v\tau)^4 \int_0^\infty \frac{\sin^4(x/2)}{x^3(x^2+1/100)} {\rm d}x$$

$$\boxed{\simeq 290.6 \frac{H_0^2 \Omega_{\rm GW}}{\hbar^2} \rho^2 R^{10}}$$

e.g. $\Delta\phi^2 = \pi^2$, $\Omega_{\rm GW} = 10^{-14}$, $\rho = 2650$ kg/m^3 (silica)

$$\to R \simeq 2 \text{ mm.}$$

Conclusion:

You cannot observe interference of a 4 mm (0.2 gram) lump of ordinary matter, at path separation 4 mm, unless you somehow suppress or actively servo for the cosmological gravitational wave background (assuming there is one!)

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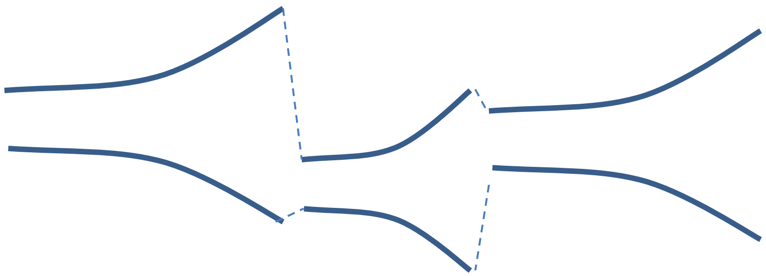

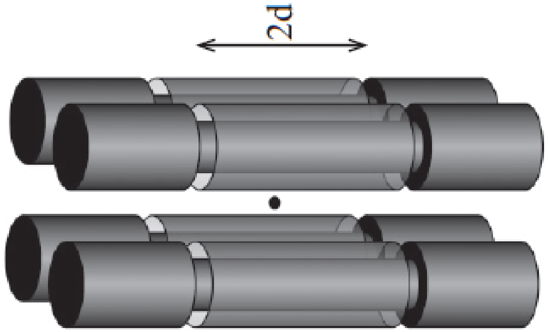

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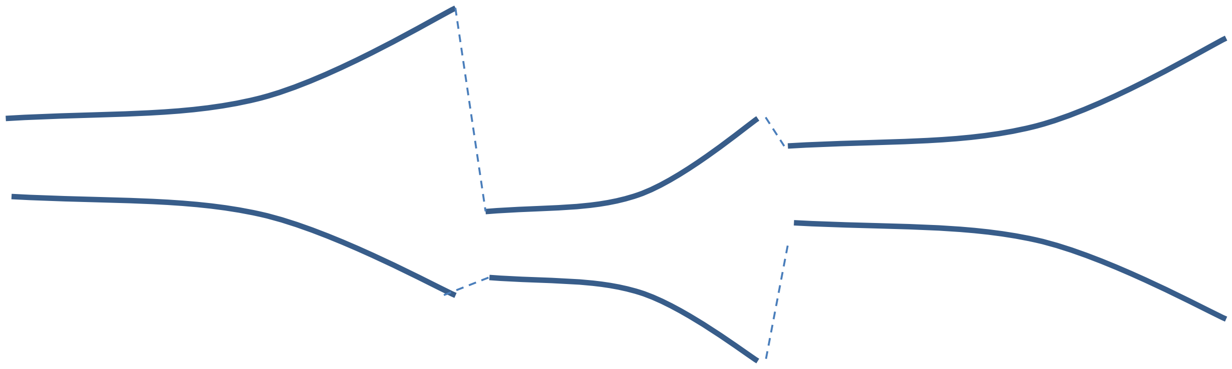
“CSL” (Continuous Spontaneous Localization)

- A generalization of the idea of Ghiradi, Rimini, Weber (1986), building on Pearle (1976).
- Stochastic nonlinearity in fundamental dynamics.
- Ad-hoc tinkering with Schrodinger’s equation ?

--- No.

- A way of capturing the phenomenological impact of various models of a more general fundamental theory (trace dynamics, gravity, …)

Diffractive spreading interrupted by spontaneous "collapse"



collapse rate per nucleon λ

critical length scale r_C

decay rate of off-diagonal element of $\rho(\mathbf{r}, \mathbf{r}')$ is

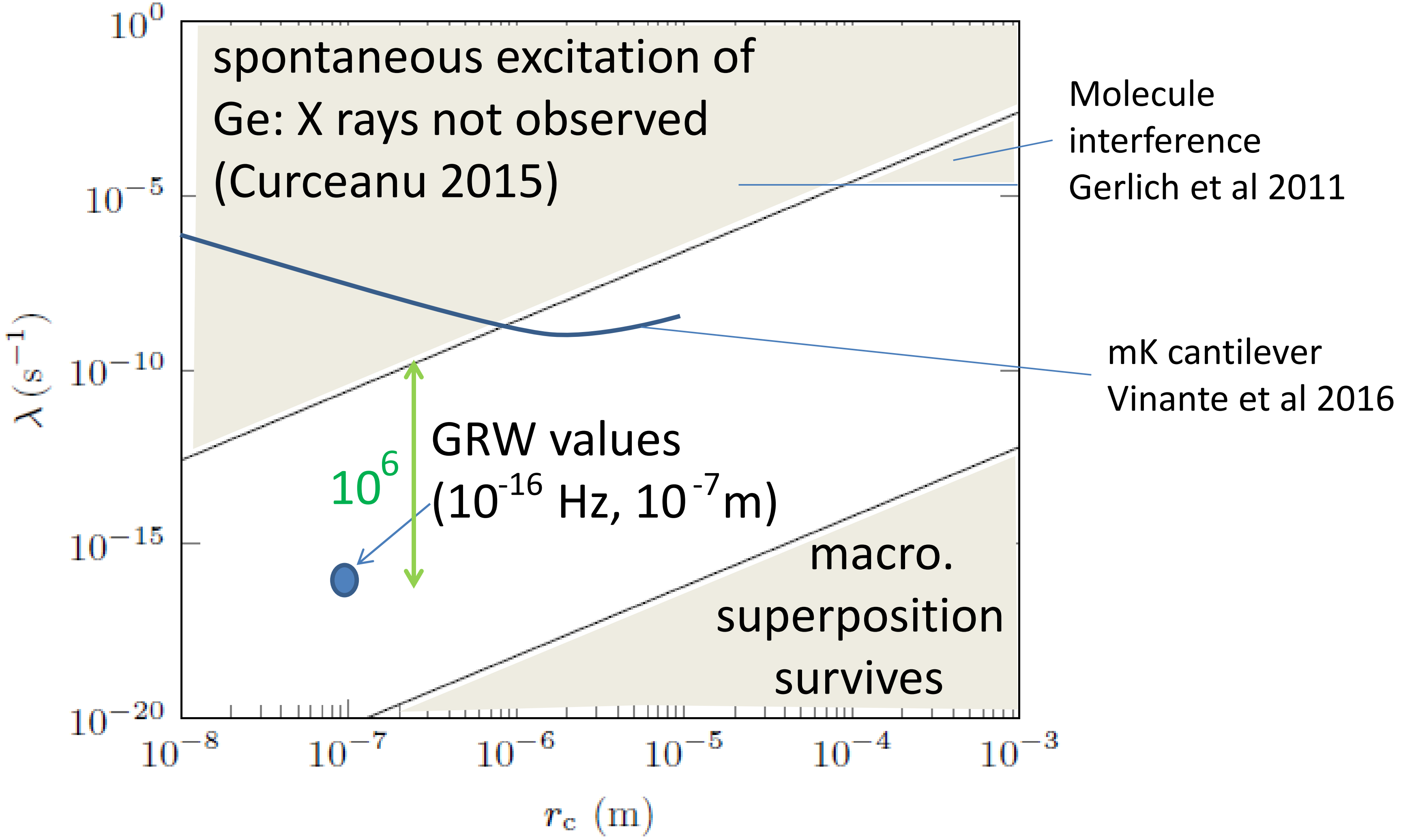
$$\lambda(1 - e^{-|\mathbf{r}-\mathbf{r}'|^2/4r_C^2})$$

Density matrix for a blob of matter, in position basis.

Ghiradi, Rimini, Weber suggested

$$\lambda \sim 10^{-16}\ \mathrm{s}^{-1}$$

$$r_c \sim 10^{-7}\ \mathrm{m}$$



Collett and Pearle, Found. Phys 33 (2003);
Bassi, Rev. Mod. Phys (2013);
Bera *et al*, Scientific reports (2015)

Various experimental approaches

Resonance of a (MEMS) cantilever

Spheres levitated by optical or magnetic forces

Sphere in a Paul trap (this work)

Just hang a sphere by a thread??

… space-based experiment …

Large Quantum Superpositions and Interference of Massive Nanometer-Sized Objects

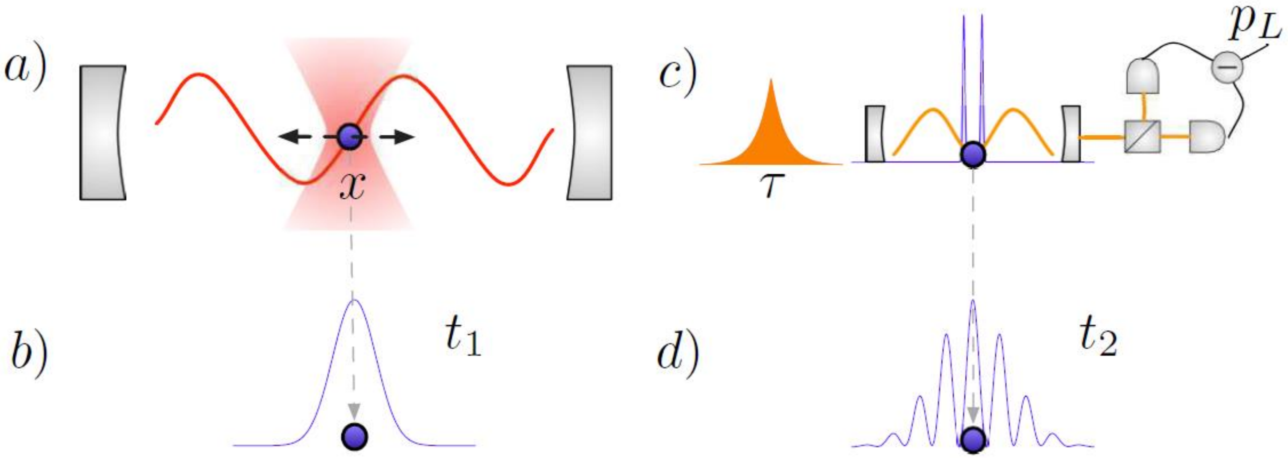
O. Romero-Isart,[1] A. C. Pflanzer,[1] F. Blaser,[2] R. Kaltenbaek,[2] N. Kiesel,[2] M. Aspelmeyer,[2] and J. I. Cirac[1]

(PRL 2011)

Proposal is “two-slit” interference of 40 nm dielectric sphere;

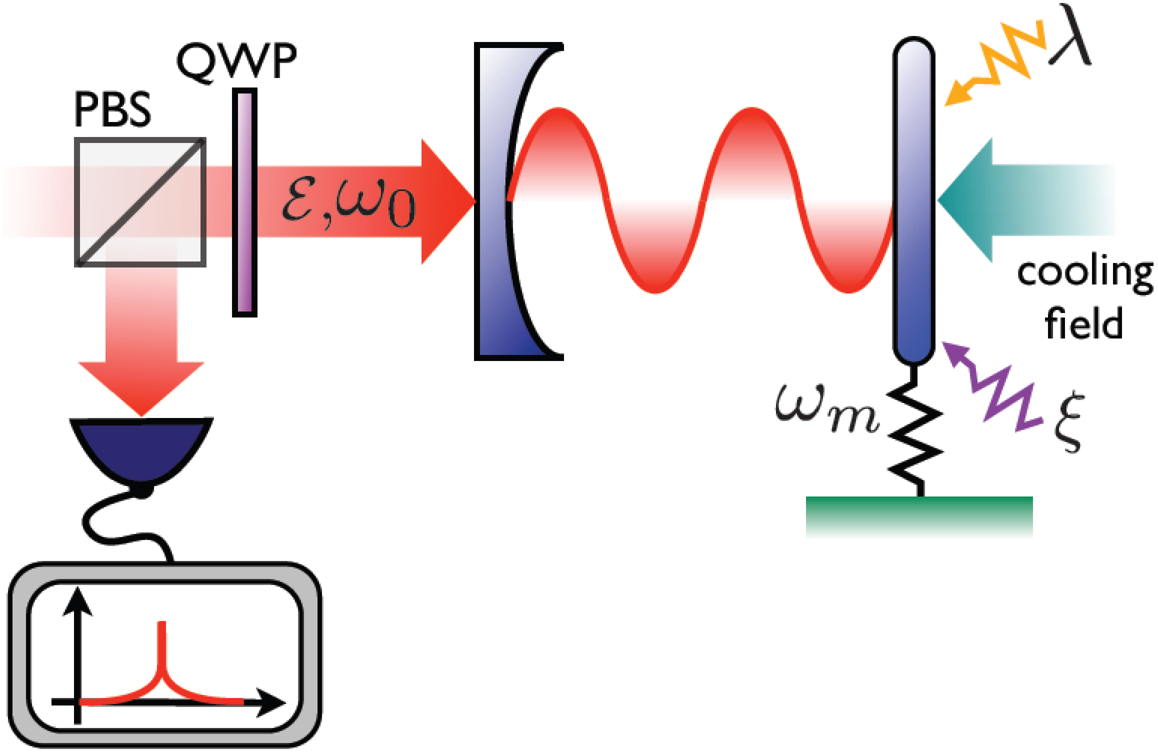
Preparation and detection aided by

cavity quantum optomechanics

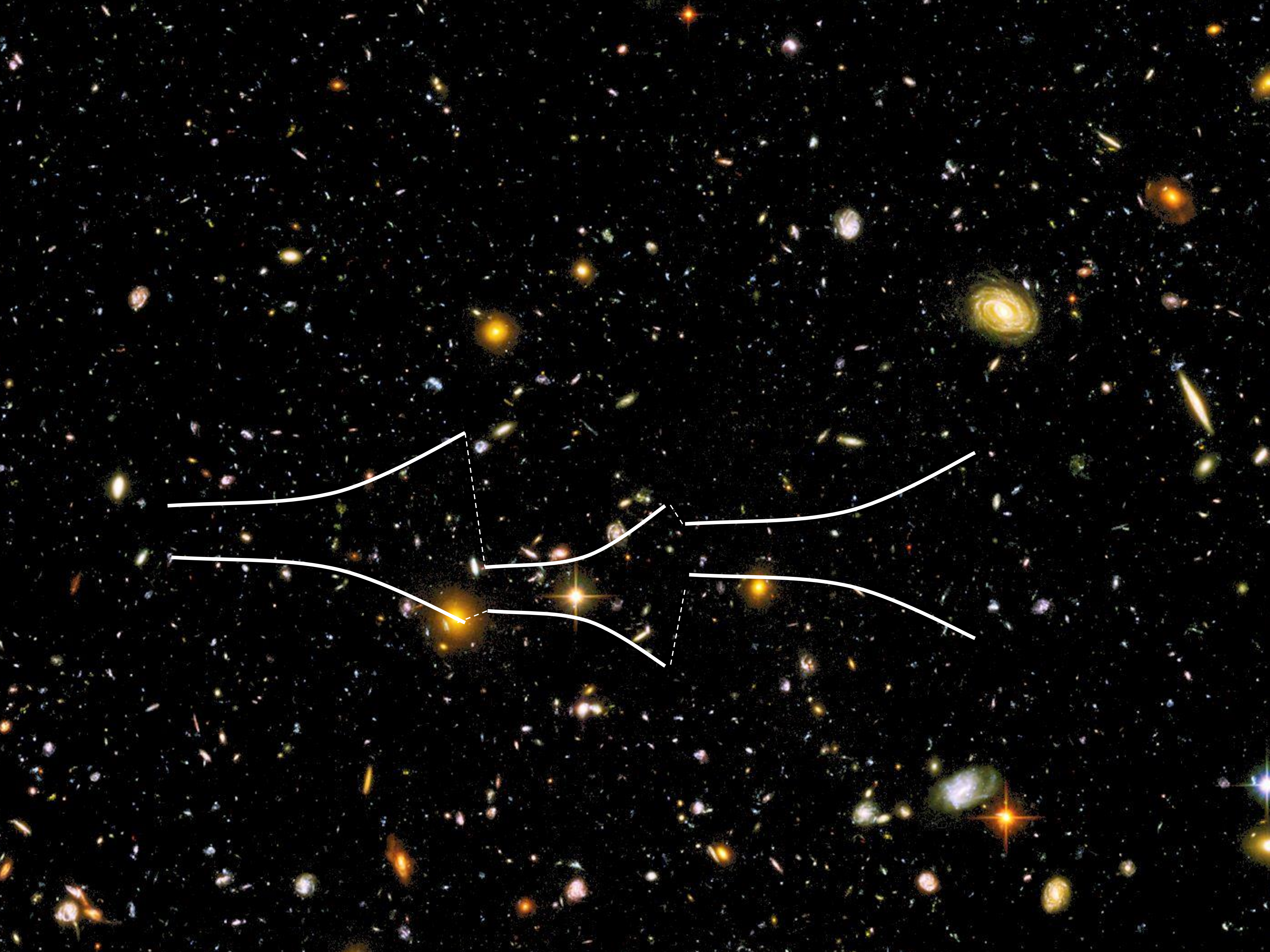


Bahrami, Paternostro, Bassi, Ulbricht (arXiv 2014)

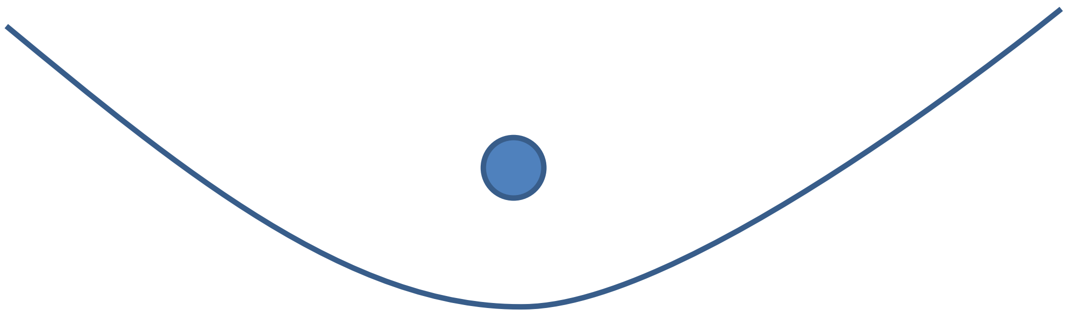
CSL modifies the spectrum of light interacting with radiation-pressure-driven mechanical oscillator.



underlying physics of the method to be presented …



Our method (following suggestion of Pearle)



- Cold ~1 micron sphere in a weak trap
- Watch it heat up
- Requires v. low noise and v. high vacuum

Heating effect of CSL (in some models)

Density = 22587 kg/m^2
(osmium)

$$\Upsilon = \chi \frac{\hbar^2 \lambda r_c \rho}{u^2}$$

Mass of 1 nucleon

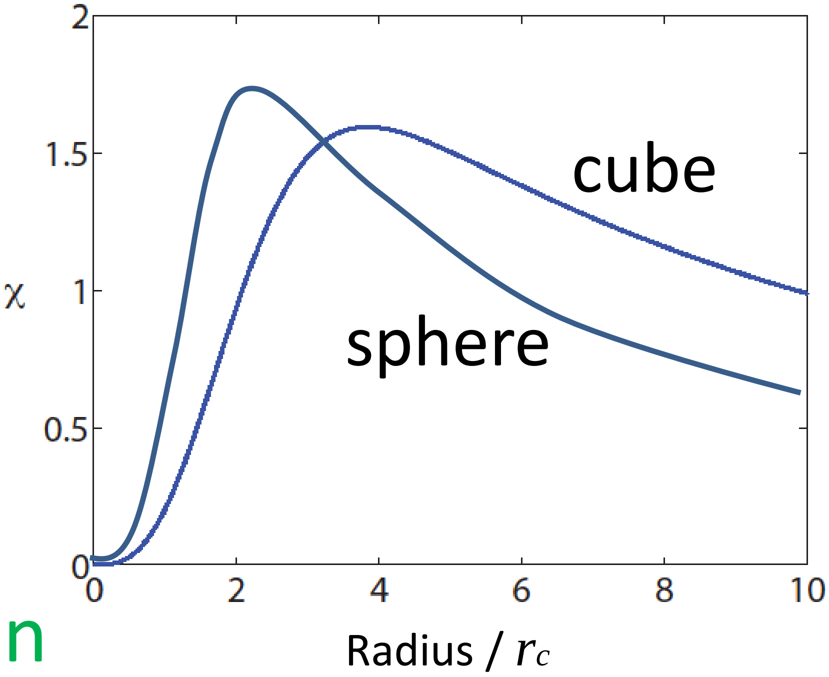
Dimensionless factor

At GRW parameters:

$$\Upsilon \simeq 1.57 \times 10^{-33}\,\mathrm{J/s}$$

$=$ 7 nK per minute

Existing bound ≈ 7mK per min



(At GRW parameters, sphere radius 0.24 micron, 8x10^{11} nucleons)

How to detect 10 nK?

At 10 nK,

$k_B T \simeq 200\hbar\omega$ and $\Delta x \Delta p \simeq 200\hbar$

at $\omega = 2\pi \times (1\mathrm{Hz})$

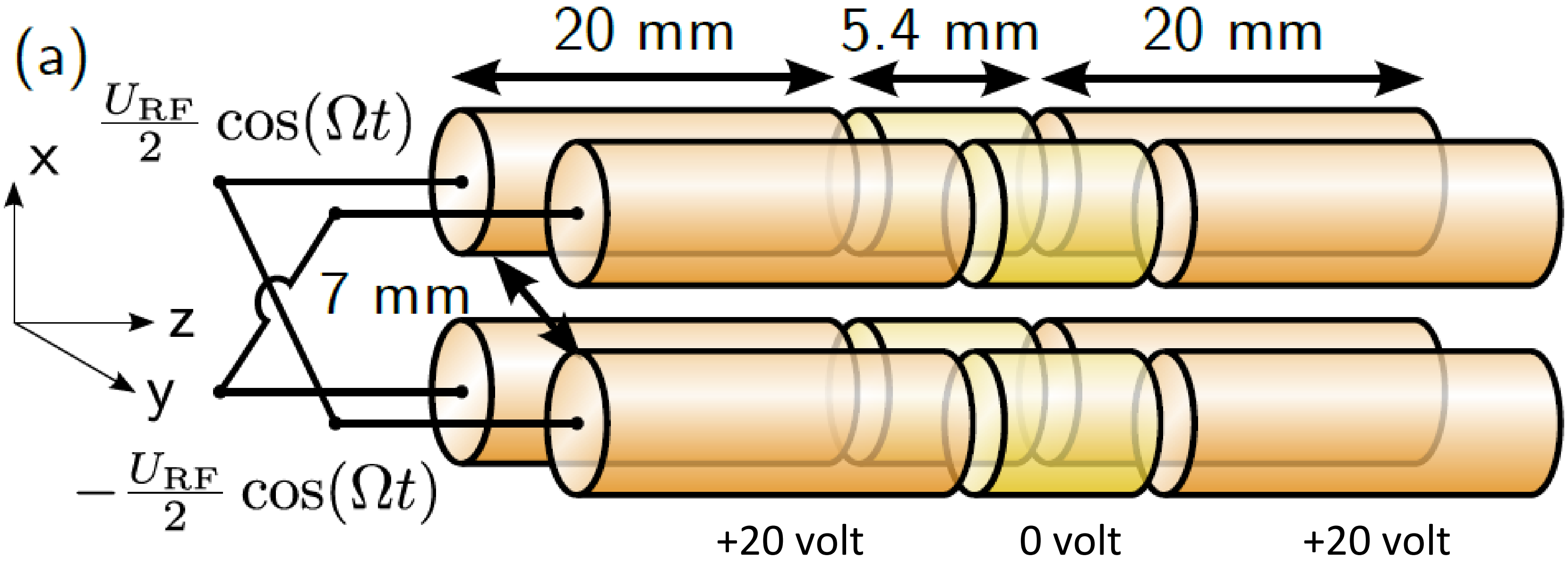
→ We require state preparation and detection at this level.

It is comfortably above standard quantum limit

→ achievable by laser interferometric position measurements

(sphere diameter ~ 0.5 micron)

Poulsen, Miroshnychenko and Drewsen (arXiv 2012)
Sub-Hz heating rate at room temperature



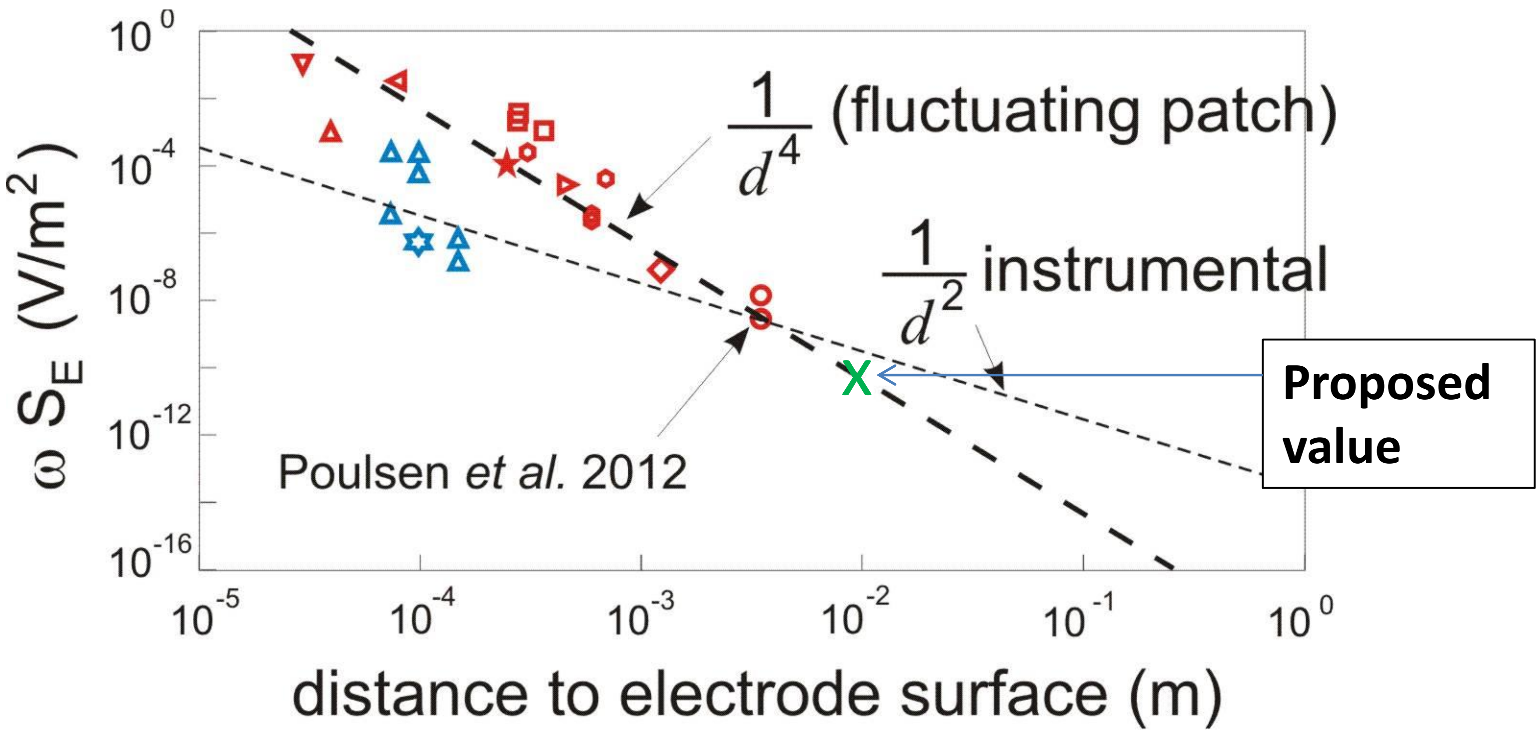
We require consider traps similar to this.
c.f. Millen *et al.*, PRL 114, 123602 (2015) (Barker, UCL)

electric field noise S_{E} (unit V/m per Hz)

Voltage fluctuations $$\langle V^2 \rangle = d^2 \int_0^\infty S_{\mathrm{E}}(\omega) f(\omega) \mathrm{d}\omega$$

COM heating rate in the trap $$\Gamma_{\mathrm{E}} = \frac{e^2}{4m} S_{\mathrm{E}}(\omega)$$

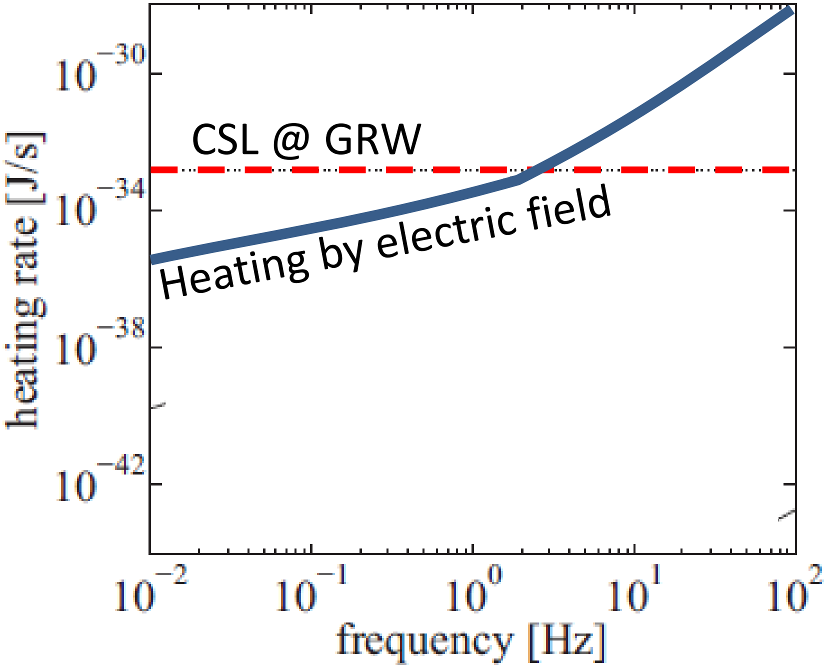
Model: $$S_E = [(b_1 + b_2 V_Q^2) d^{-2} + b_3 d^{-4}] \omega^{-1}$$



Proposed value

- Poulsen *et al.* achieved Vrms ≈ 200 --700 nV (1 electron at 3.5 mm gives 400 nV)
- we are assuming the SAME noise at the electrode surface
- and 1/f noise spectrum

→heating rate ~ 10 nK/min for trap vibrational frequency of a few Hz



Mechanical vibrations of the trap structure

Active stabilization of optical table by laser interferometry gives $10^{-10}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ between 10 mHz and 100 Hz

(state of art is about 10 times better)

Mechanical filters (i.e. spring / pendulum).

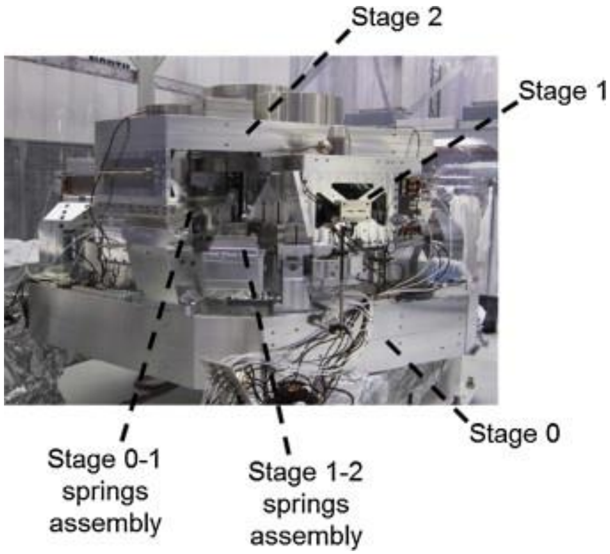
Use design study for Virgo experiment:

$$S_x = a_1^2 f^{-5} + a_2^2 (f_0^{20} + f^{20})^{-1} + a_3^2 f^{-1}$$

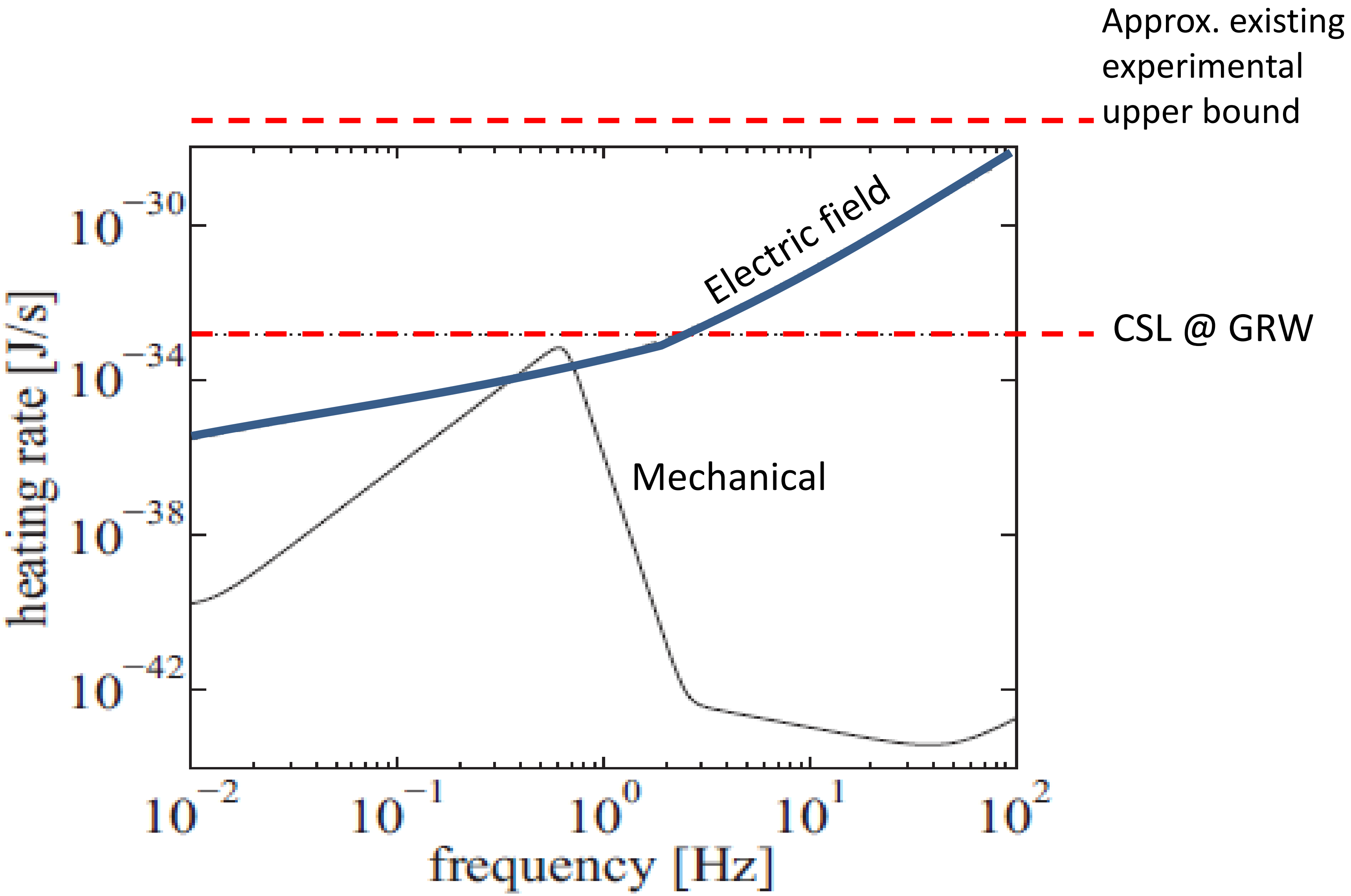
Thermal vibrations in pendulum suspensions;

Seismic vibrations after filtering;

Thermal vibrations of electrode surfaces

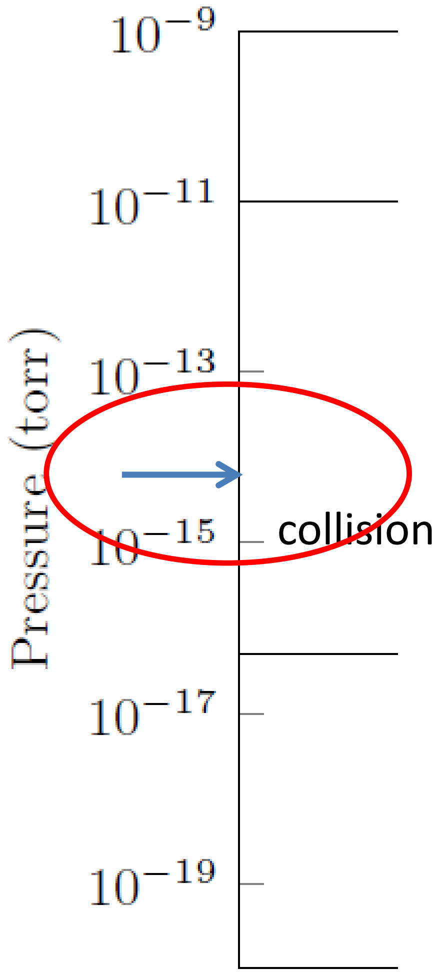


Stabilization unit in testing at LIGO Hanford


Approx. existing experimental upper bound
Electric field
CSL @ GRW
Mechanical
heating rate [J/s]
10^{-30}
10^{-34}
10^{-38}
10^{-42}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
frequency [Hz]

Collisions with background gas

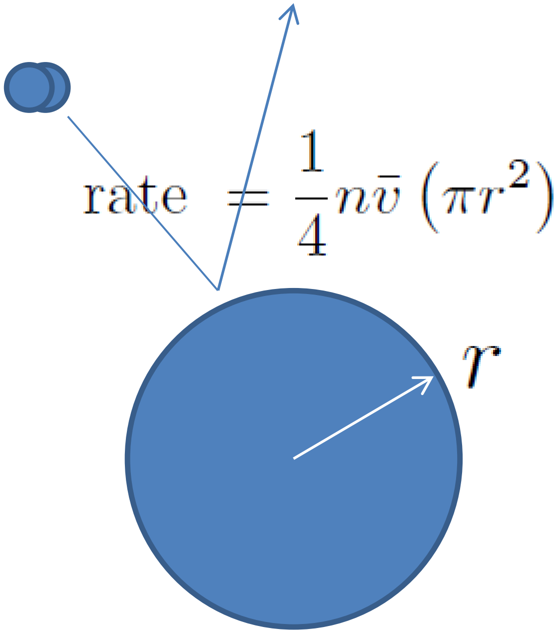
Diffusive heating rate $(m_{\mathrm{g}}/m)\,p\sigma\,\bar{v}$



Commonly observed pressure,
collision rate = 7 per second

collision rate = 3 per hour

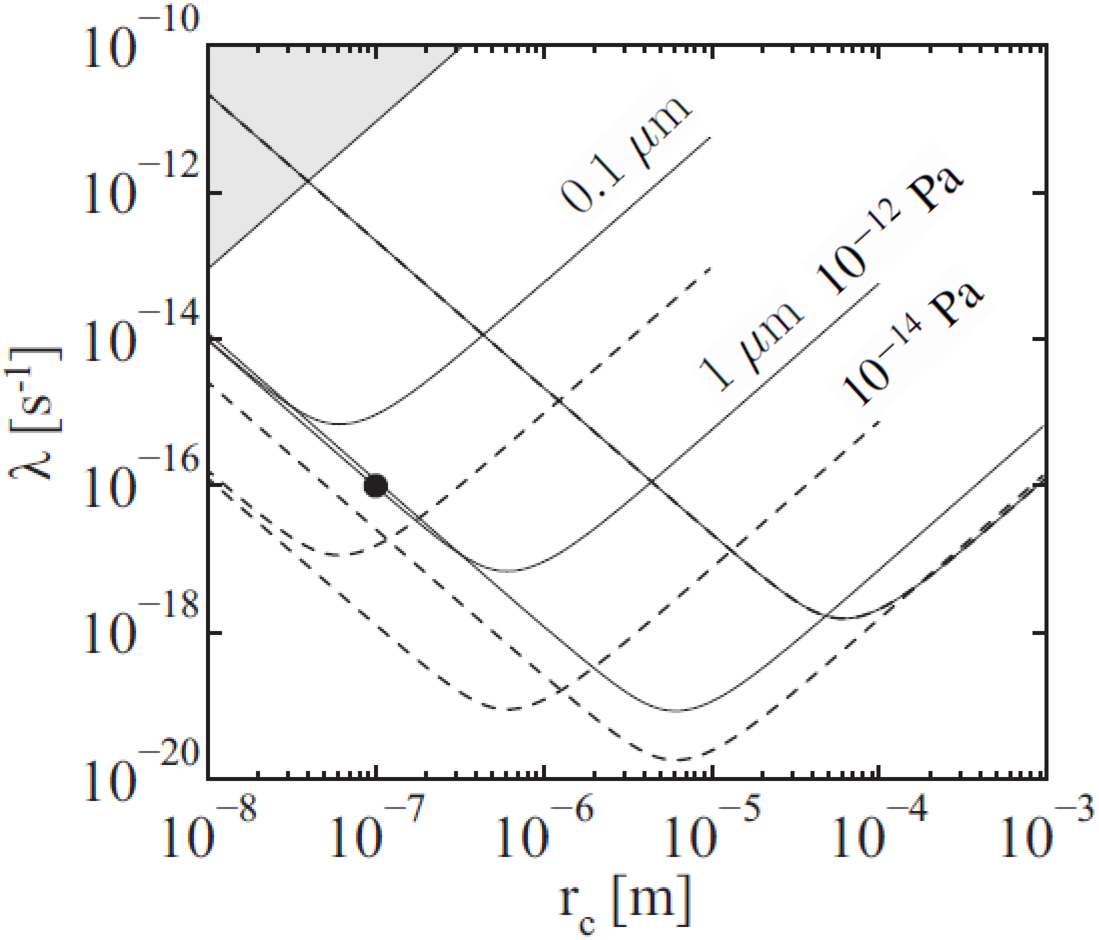
Lowest recorded pressure,
collision rate = 1 per 7 hours



$$\text{rate} = \frac{1}{4} n\bar{v}\left(\pi r^2\right)$$

$$\text{energy transfer} \simeq \frac{m_g}{m} k_{\mathrm{B}} T_g$$

$$\simeq \begin{cases} 120\,\text{nk at } T_g = 293\ \text{K} \\ 1.7\ \text{nk at } T_g = 4.2\ \text{K} \end{cases}$$



The central claim of this paper is that the Paul trap, operated in the parameter regime we have described and with optical detection, offers a sensitivity to heating from CSL that exceeds by many orders of magnitude that which has been predicted for existing proposals.