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Testing spontaneous collapse models using mechanical systems

FBK-CNR & University of Trento

Corfu2017

The Quantum Measurement Problem

Two different dynamics in Standard Quantum Mechanics

1) Ordinary evolution: Linear and Deterministic

$$\psi = a\psi_1 + b\psi_2$$

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$

2) Measurement process: Nonlinear (Reduction postulate) & Stochastic (Born Rule)

$$\psi = a\psi_1 + \cancel{b\psi_2}$$

$$P(\psi_1) = |a|^2$$

Standard Quantum Mechanics works well with reduction postulate

BUT

What is precisely a measurement ? When does collapse happens?
Is the collapse something "fundamental"?
Quantum cosmology. Who measured the universe?
…

Possible answers

1) "*Shut-up and calculate*" (D. Mermin)

2) Decoherence = Entanglement system - environment
Explains quantum to classical transition, BUT

- No collapse (just more and more entanglement)
- Reduction postulate still needed to explain definite outcomes

3) Interpretations (Copenhagen, Many-Worlds , and a lot more …)
Not experimentally testable
Physics $\Rightarrow$ Metaphysics

4) Quantum mechanics is incomplete → Hidden variables (Böhmian)

5) Quantum mechanics is an approximated theory → Collapse models

Continuous Spontaneous Localization (CSL)

Schrödinger equation + Stochastic term (collapse field)

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}H\,dt + \sqrt{\lambda}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt\right]|\psi_t\rangle$$

Stochastic modification replace the collapse postulate of standard quantum mechanics!

- Collapse terms couple to the system mass
  1) negligible at microscale (atoms,molecules, …) $\Rightarrow$ quantum
  2) dominant beyond some mass scale $\Rightarrow$ classical
- Measurement-based "collapse" and Born rule follow from dynamics

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2 phenomenological constants (free parameters)

- Correlation Length r_C

  (N = number density of nucleons, "smeared" over r_C)

  conventional "literature value" $r_C = 10^{-7}$ m

- Collapse rate λ

  Lower bounds (to guarantee collapse at "macroscopic" or "mesoscopic" scale)

  $\lambda \sim 10^{-16}\ s^{-1}$ @ $r_C = 10^{-7}$ m following Ghirardi, Rimini, Weber (GRW)

  $\lambda \sim 10^{-8}\ s^{-1}$ @ $r_C = 10^{-7}$ m following Adler

Experimental test of collapse models

Collapse models CAN BE TESTED !
(unlike interpretations of quantum mechanics)

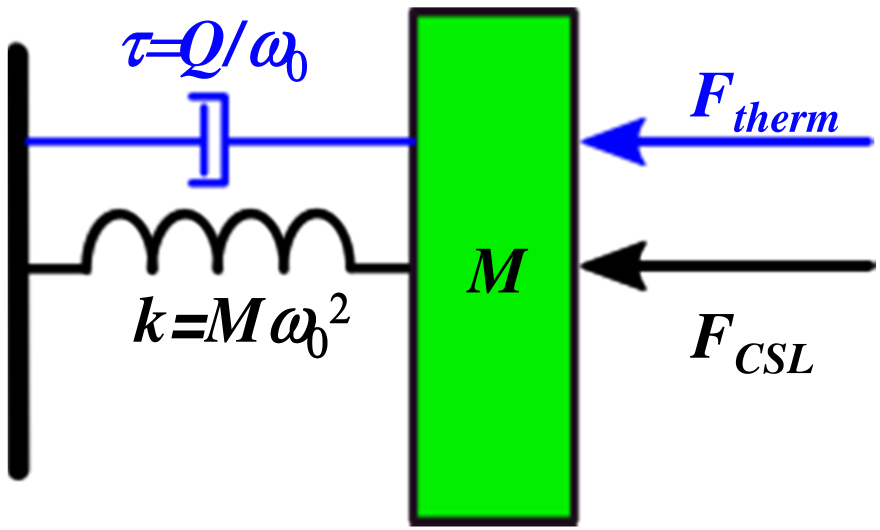
1) Direct (Interferometric): collapse of massive quantum superpositions

Experimentally very demanding !

2) Indirect (non-interferometric): violation of energy conservation

- X-ray spontaneous emission from free electrons
- Spontaneous diffusion / heating / force noise in mechanical resonators

Random Collapses → Momentum kicks → Stochastic driving force



$$\frac{d\langle E\rangle}{dt} = \frac{k_B \mathrm{T}}{\tau} - \frac{\langle E\rangle}{\tau}$$

$$\frac{d\langle E\rangle}{dt} \propto F_{CSL}$$

$$\langle E\rangle = k_B \mathrm{T} + \Delta E_{CSL} = k_B(T + \Delta T_{CSL})$$

S. Nimmrichter et al, PRL 113 020045 (2014)
L. Diosi, PRL 114, 050403 (2015)
A. Vinante et al, PRL 116, 090402 (2016)

$$k_B \Delta T_{CSL} = \frac{Q}{2m\omega_0} \cdot \hbar^2 \eta$$

Mechanical resonator response

Spectral density of CSL force noise S_{ff}

Diffusion / Force noise η depends on:

- CSL parameters λ, r_c
- Geometry
- Material

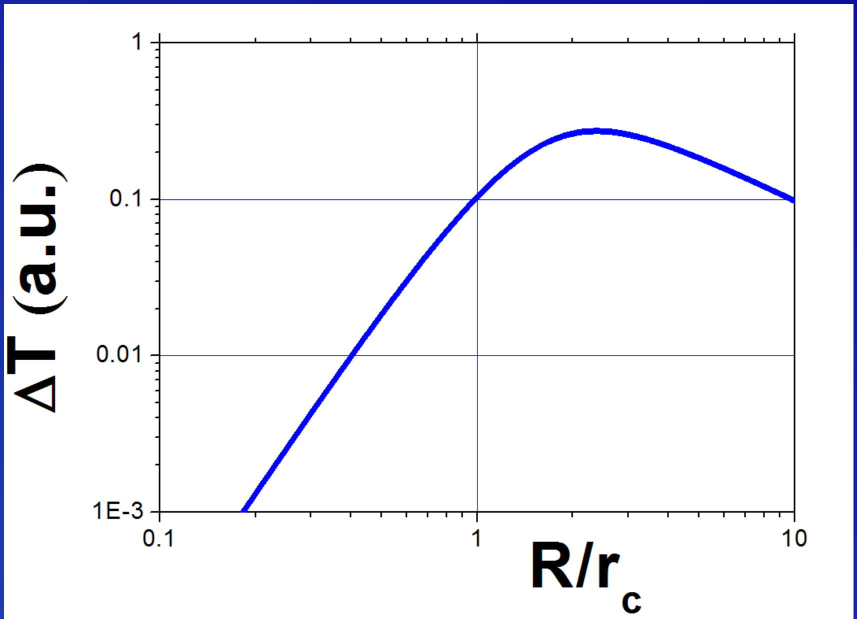
$$\eta_j = \frac{\gamma_{\mathrm{CSL}}}{m_0^2} \iint \frac{e^{-\frac{|\mathbf{r}-\mathbf{r}'|^2}{4r_C^2}}}{(2\sqrt{\pi}\, r_C)^3} \frac{\partial \varrho(\mathbf{r})}{\partial r_j} \frac{\partial \varrho(\mathbf{r}')}{\partial r'_j} \mathrm{d}^3\mathbf{r}\, \mathrm{d}^3\mathbf{r}'$$

$$= \frac{\gamma_{\mathrm{CSL}}}{m_0^2} \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3} \mathbf{k}_j^2\, e^{-\mathbf{k}^2 r_C^2} |\tilde{\varrho}(\mathbf{k})|^2$$

[$\gamma_{CSL} = (4\pi r_c^2)^{3/2} \lambda$]

Exact solution for a sphere

$$\eta_s = \frac{2\sqrt{\pi}\,\gamma_{\rm CSL}\,\varrho^2_{\rm sphere}\,R^2}{3m_0^2 r_C}\left(1-\frac{2r_C^2}{R^2}+e^{-\frac{R^2}{r_C^2}}\left(1+\frac{2r_C^2}{R^2}\right)\right)$$



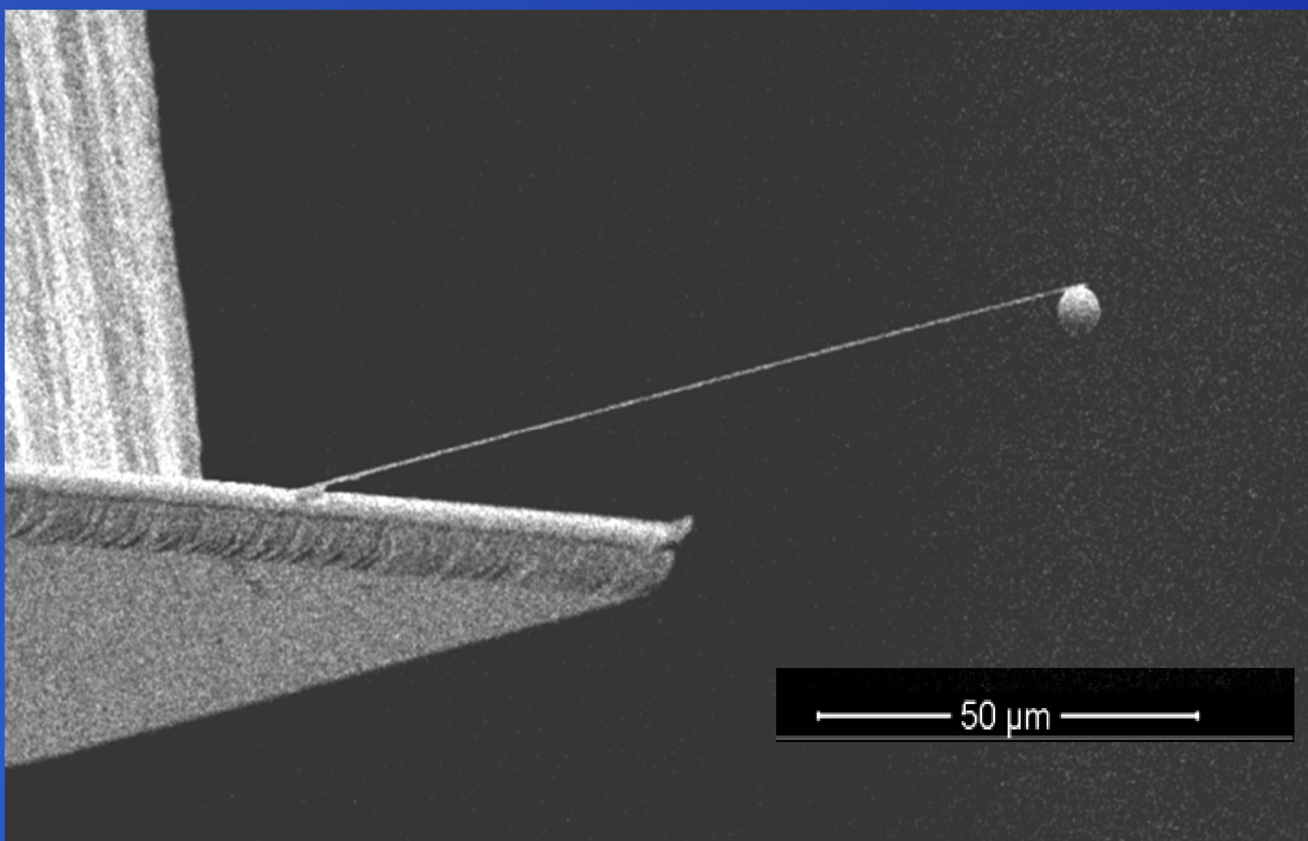
To maximize ratio ΔT/T=CSL noise/ thermal noise

- Low temperature T
- High $\tau = Q/\omega_0$ (low frequency, low loss)
- High ϱ
- $R \simeq r_C$

Experimental: Nanocantilevers

2011 @ (Kamerlingh Onnes Laboratory, Leiden University)

Silicon nanocantilever (IBM style, D. Rugar group)



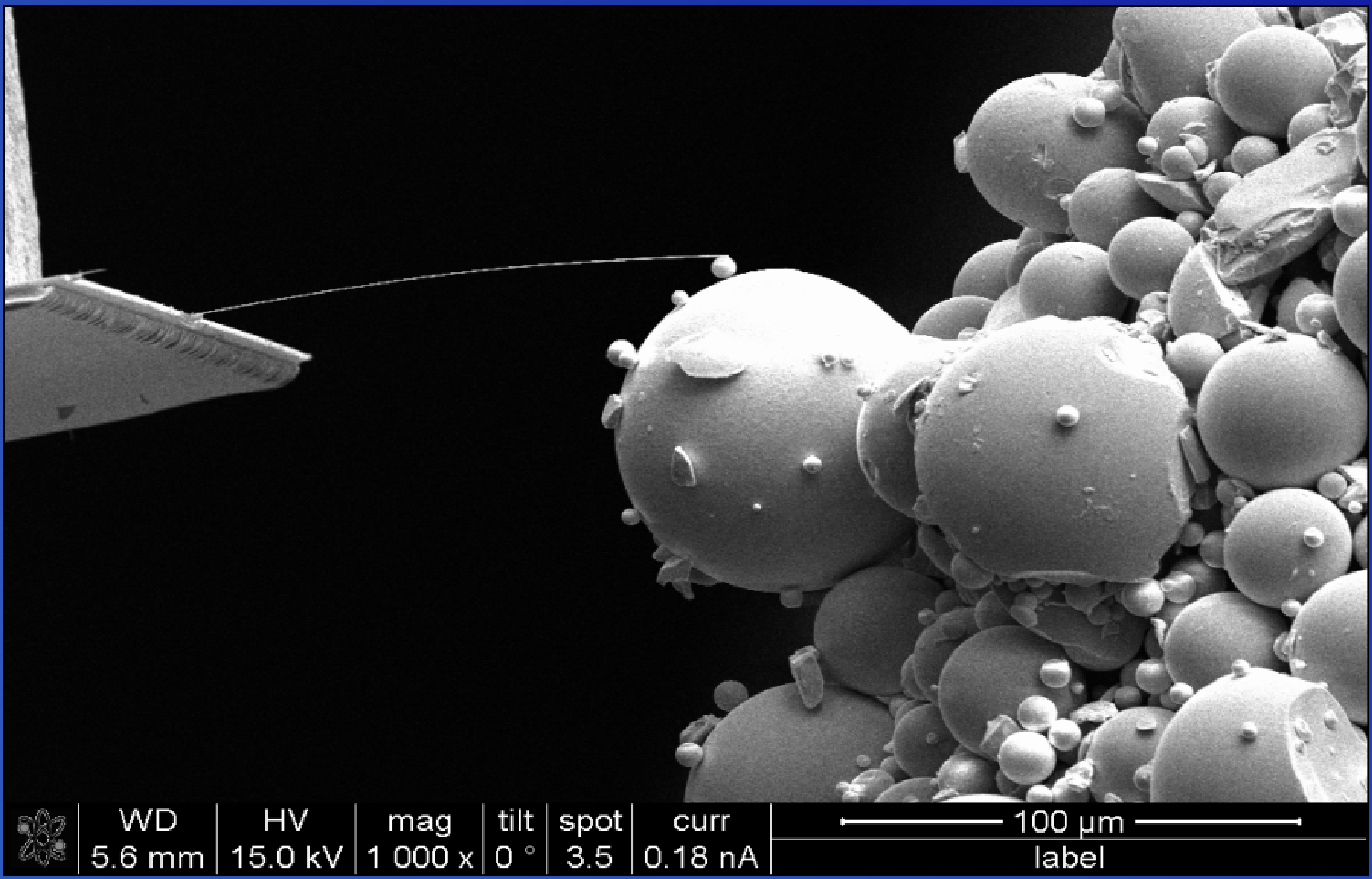
Very high aspect ratio

Thickness=100 nm
(close to standard rc)

Width=5 μm
Length=100 μm

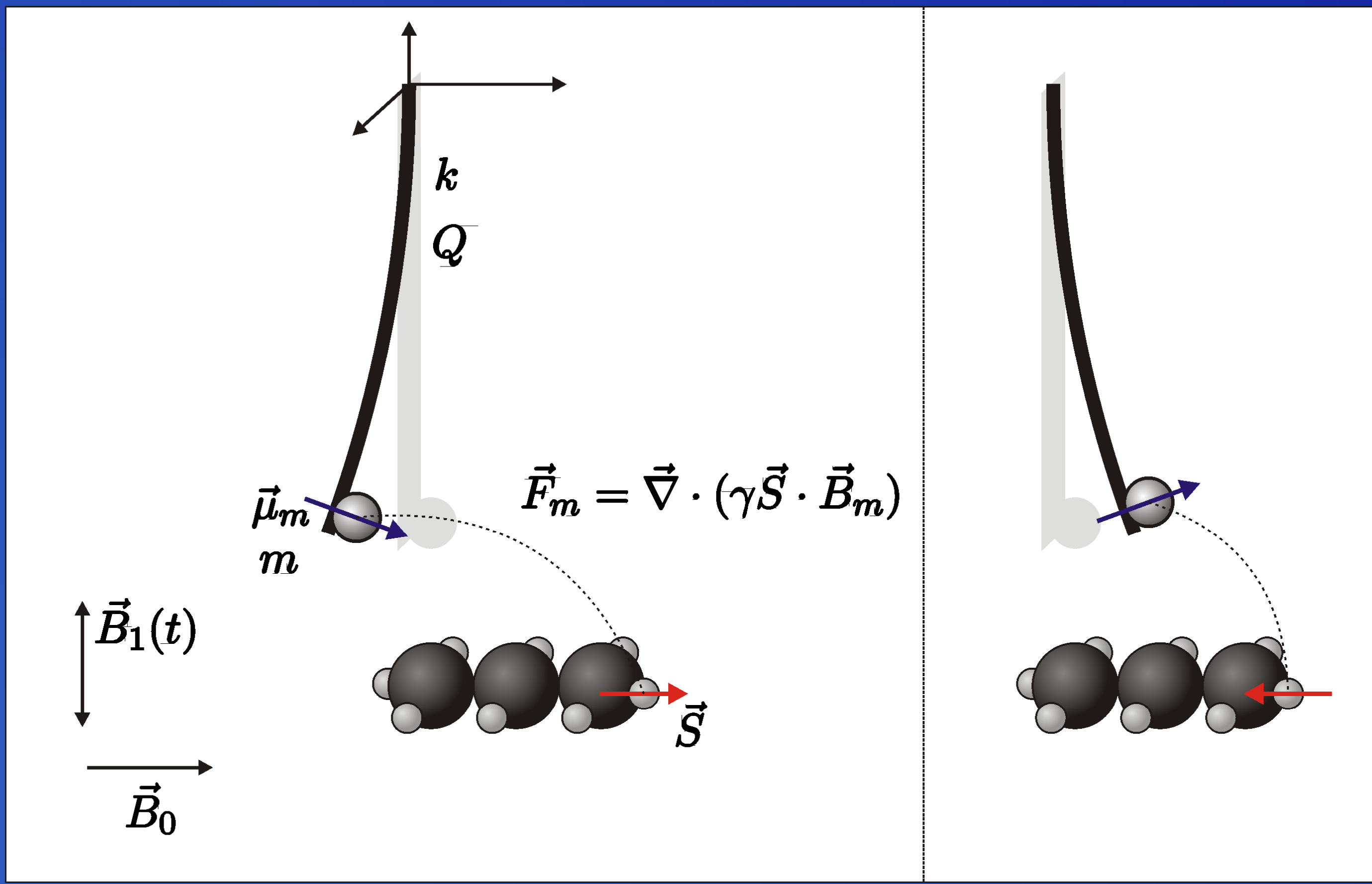
f_0=3084 Hz
Q=4×10^4

Attaching the Magnetic Particle



The context: Magnetic Resonance Force Microscopy

Couple mechanical motion to single (or a few) spins in a nearby sample



Spin inversions in the sample → Force on the cantilever

Experimental challenge very similar to that of collapse model tests

Very weak forces ($<10^{-18}$ N)

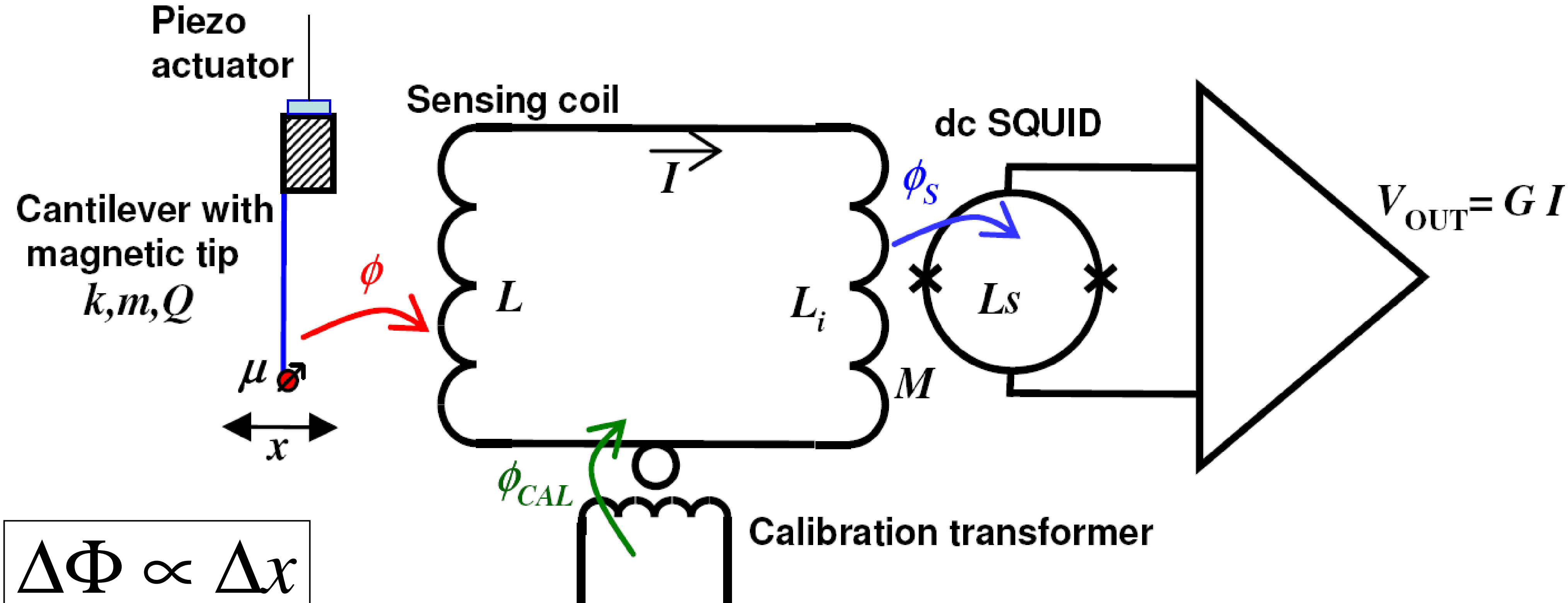
Need lowest possible force noise

⇩

Only fundamental limit: thermal noise: $S_{ff} = \frac{4k_B T m \omega_0}{Q}$

Try to cool to lowest possible temperature (~ 10 mK)

SQUID-based detection



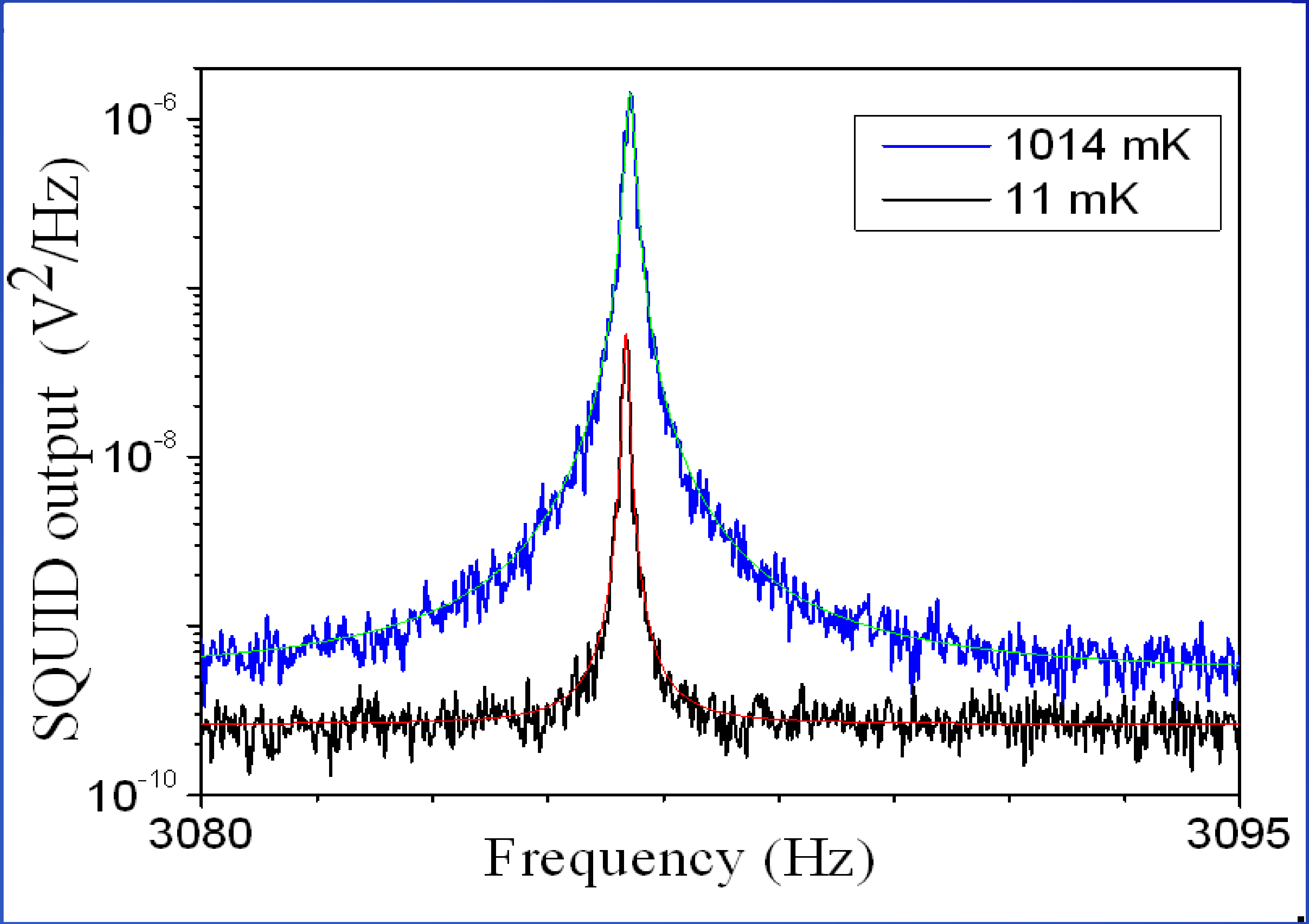
$$\Delta\Phi \propto \Delta x$$

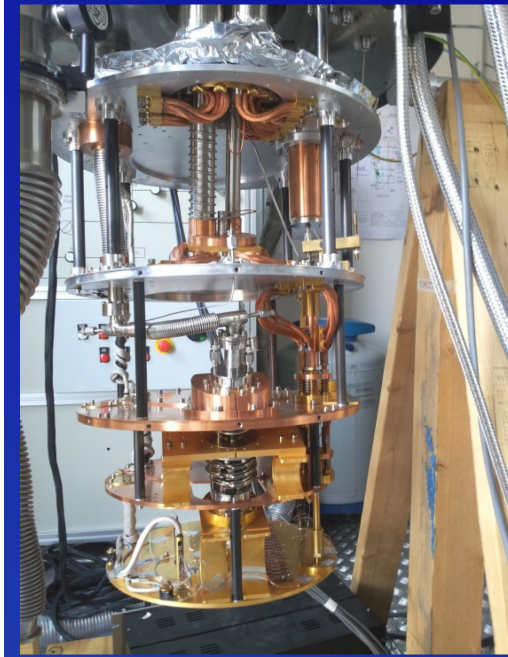
Magnetic detection

Heating effects due MUCH LOWER than in optical laser detection !

O. Usenko et al., Appl. Phys. Lett. 98, 133105 (2011)

Noise spectrum at SQUID output (~ 10 minutes averaging)

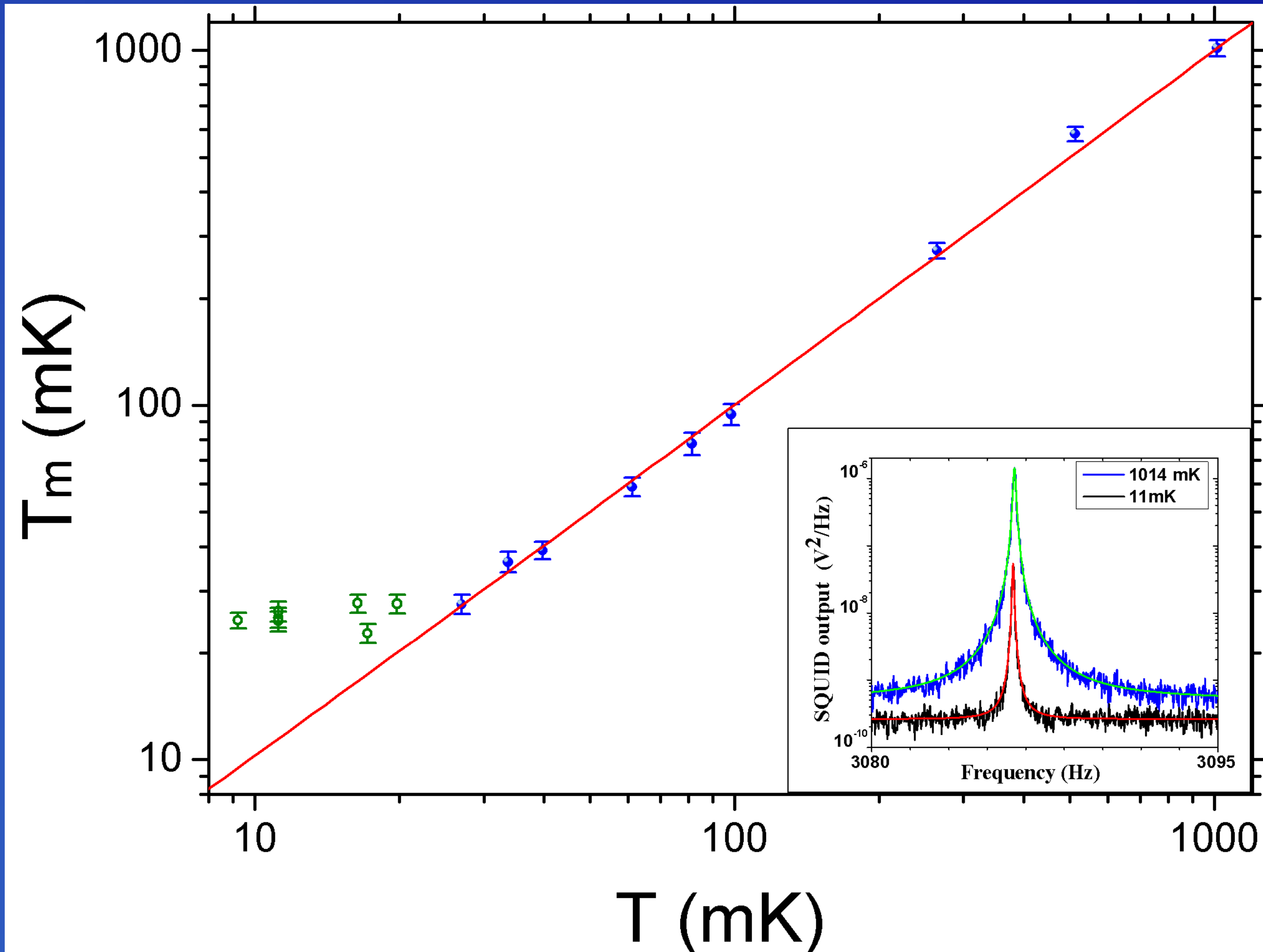




PULSE-TUBE DILUTION REFRIGERATOR

Area under peak $\propto$ Mean Resonator Energy

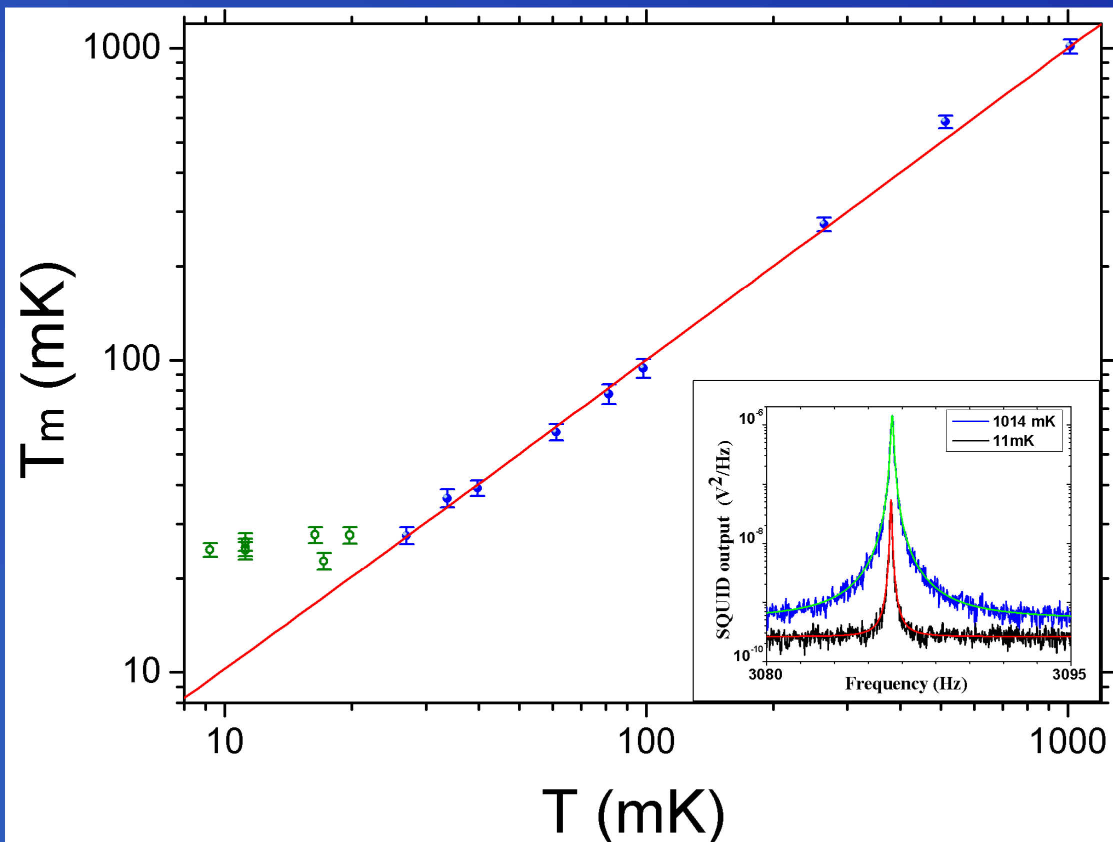
Mean Energy $\frac{\langle E \rangle}{k_B}$ vs Temperature



Force noise $S_{ff}=5\times10^{-19}$ N/√Hz @ T_m~25 mK

Can we do a test of collapse models? Non-thermal energy: how much?

CSL (as other effects...) would cause a finite positive intercept



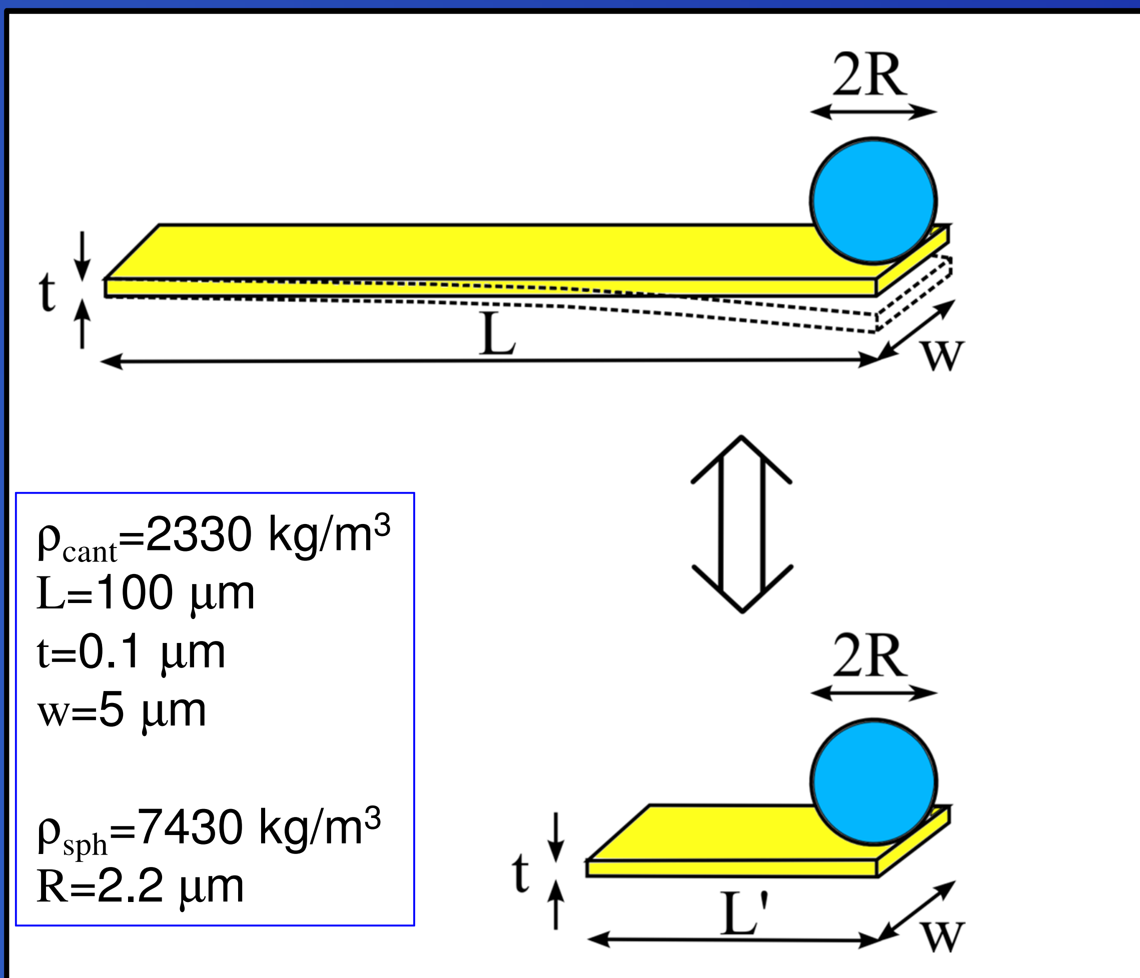
$T_m = T + \Delta T_{CSL}$

$\Delta T_{CSL} < 2.5$ mK
(95% C.L.)

Connect to CSL parameters

Technical issues:

- Composite object : CSL force noise acts sphere + cantilever (correlations)
- Bending mode (flexural). Standard CSL formulas hold for rigid motion



Solution:

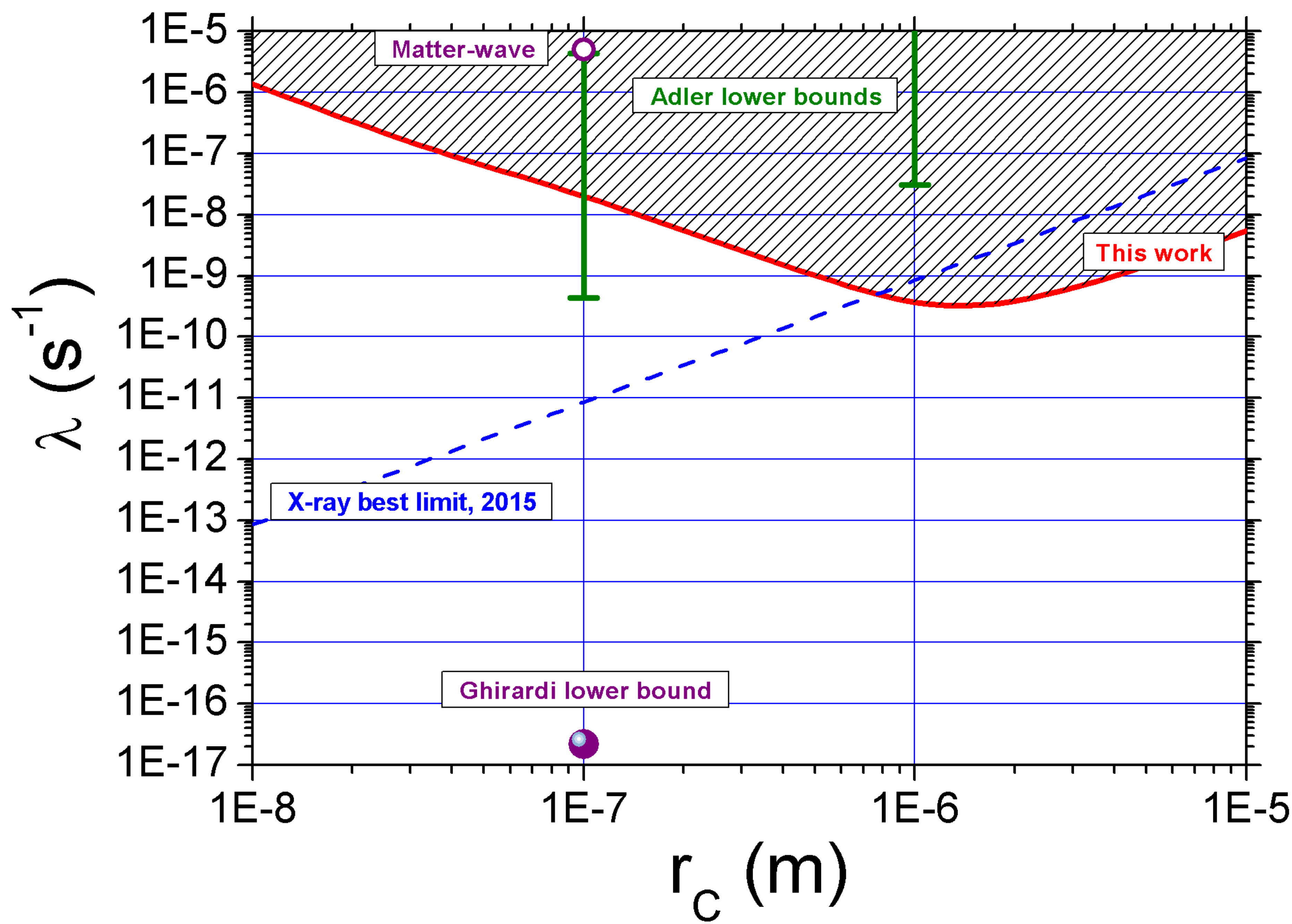
- Approximate cantilever bending motion with a rigid translation of a slab with effective mass/length:

$$L' \approx 0.236\, L$$

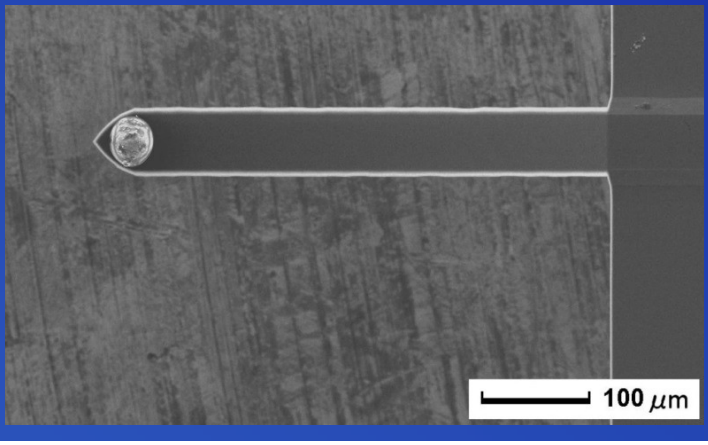
Collaboration with Trieste group
(M.Bahrami , A. Bassi)

Upper Limit

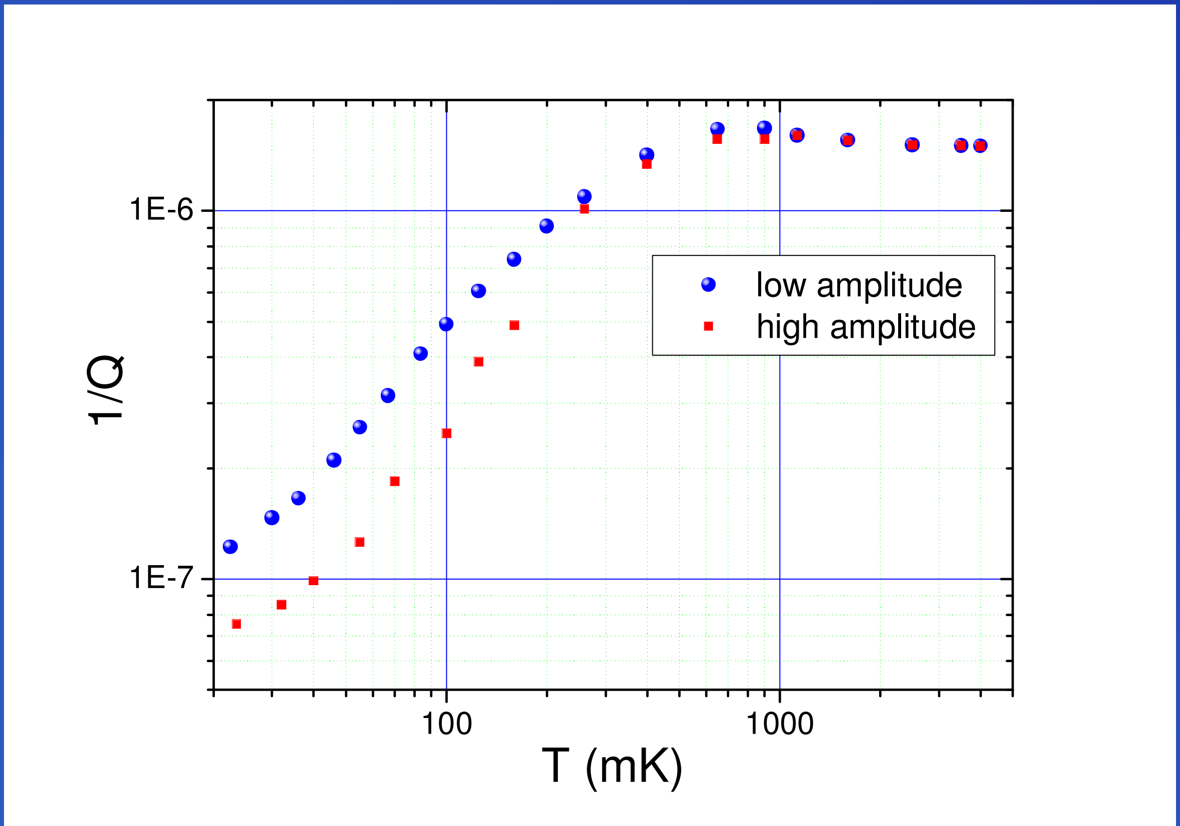
[A. Vinante et al, Phys. Rev. Lett. 116, 090402 (2016)]



New improved experiment in Trento (2016)



- Same idea, but thicker cantilever with higher Q
- AFM Silicon cantilever with bigger magnet (450x50x2 μm). Much stiffer (k=0.4 N/m)
- SQUID readout



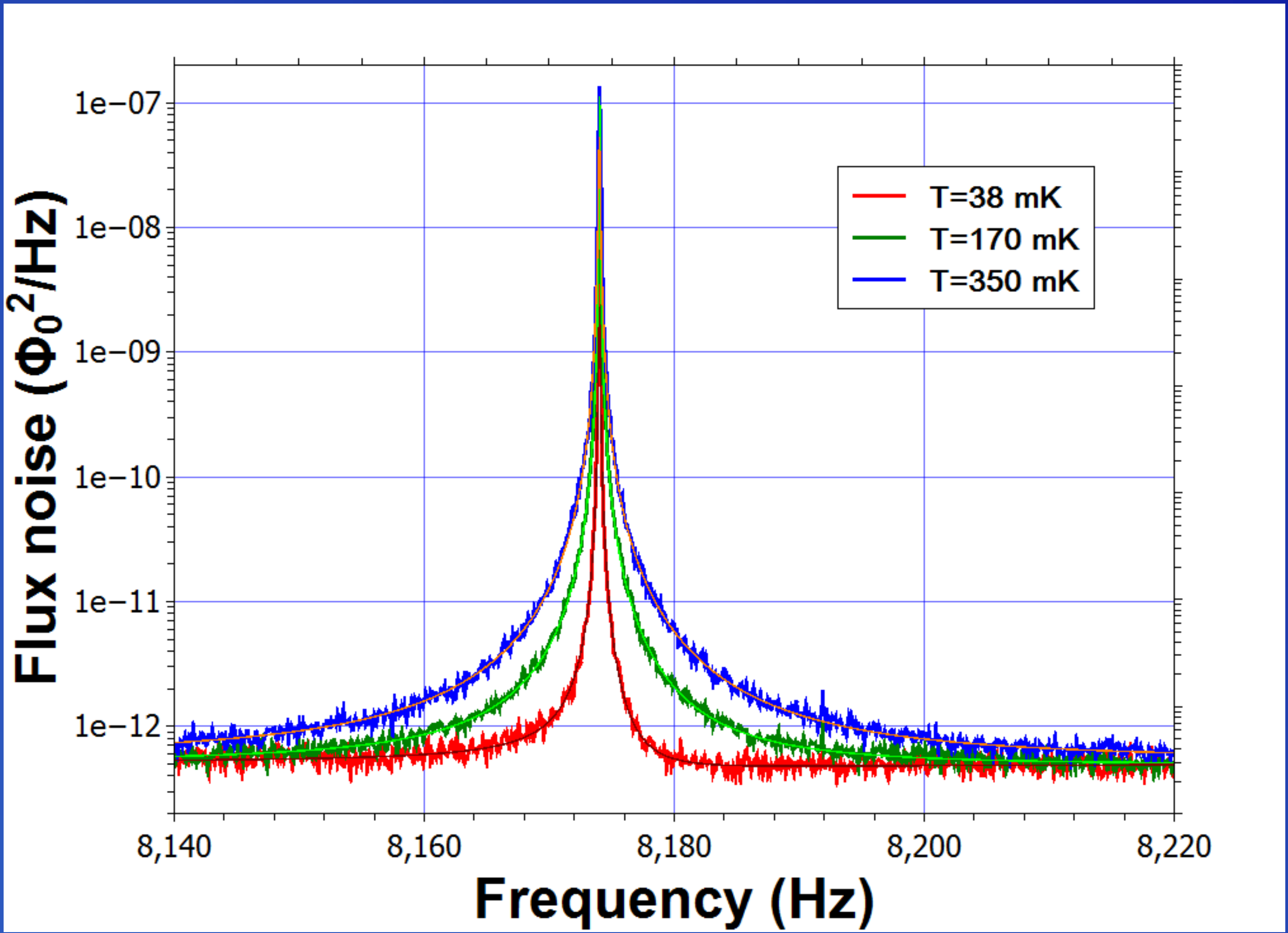
$f_0 \sim$ 8 kHz

Very high $Q \sim 10^7$ @ $T \ll$ 1K

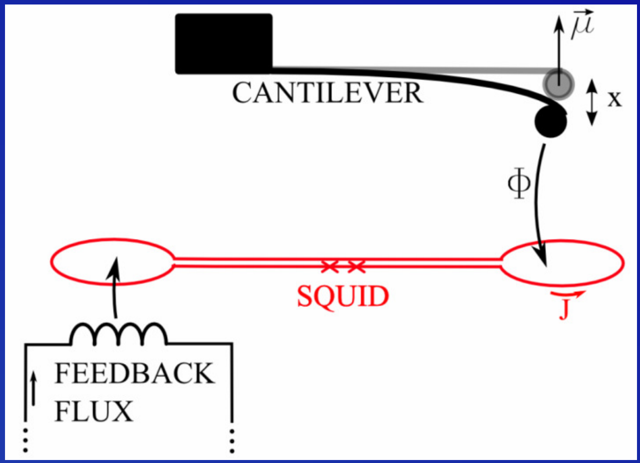
($\sim 10^5$ with submicron devices)

Low T, Low f_0, High Q !

Force noise at millikelvin temperature (Pulse-Tube Dilution)



Measurement scheme



Mechanical suspension

Attenuation > 80 dB
@ 8kHz

$$Fit = A + \frac{B(T,Q)\cdot f_0^{\,4} + C\cdot\left(f^2 - f_1^{\,2}\right)^2}{\left(f^2 - f_0^{\,2}\right)^2 + \left(ff_0/Q_a\right)^2}$$

$$B \propto S_{ff}$$

Cantilever thermal noise

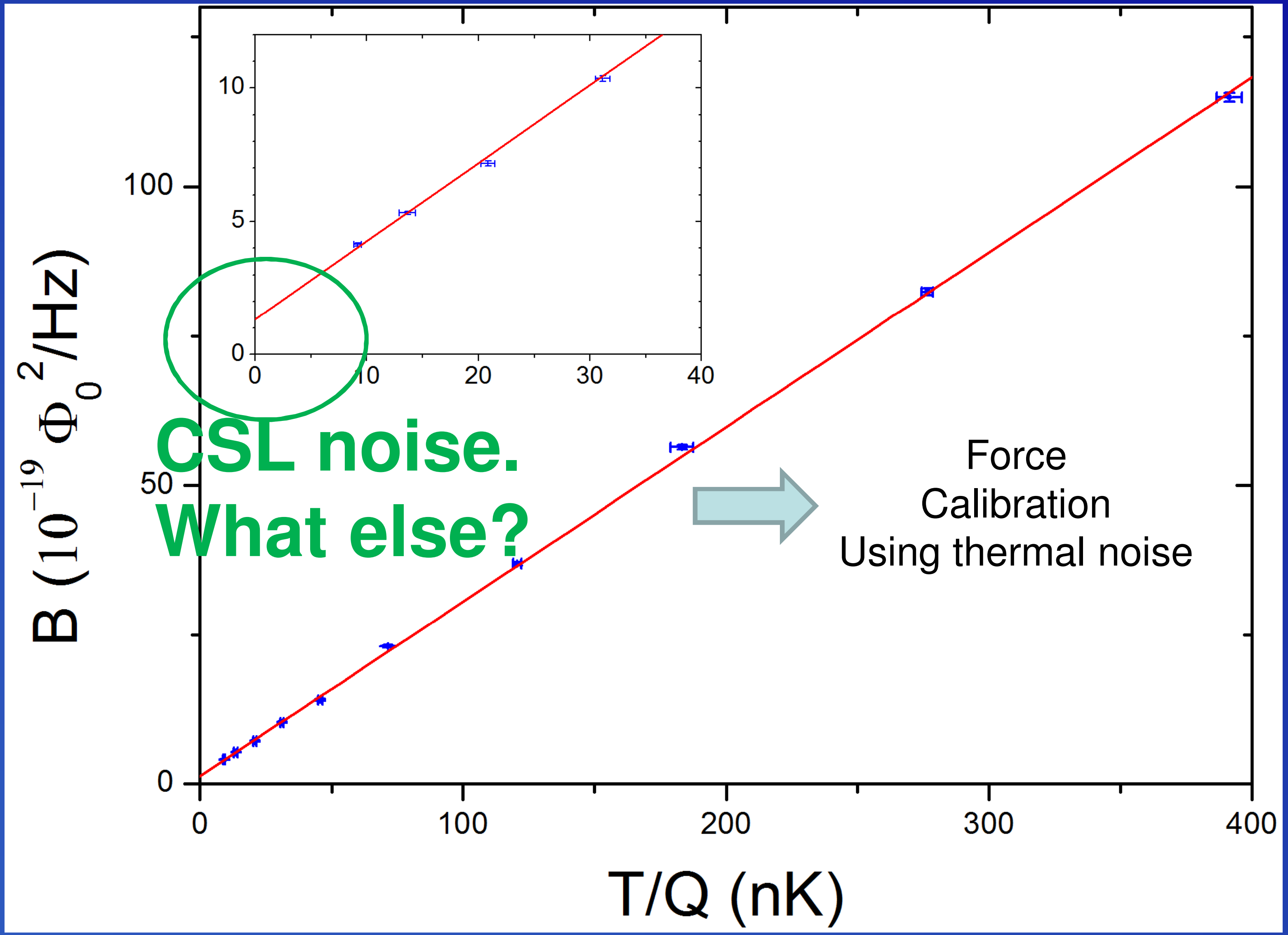
$$B \propto S_{ff} \propto \frac{T}{Q}$$

Nonzero Intercept !

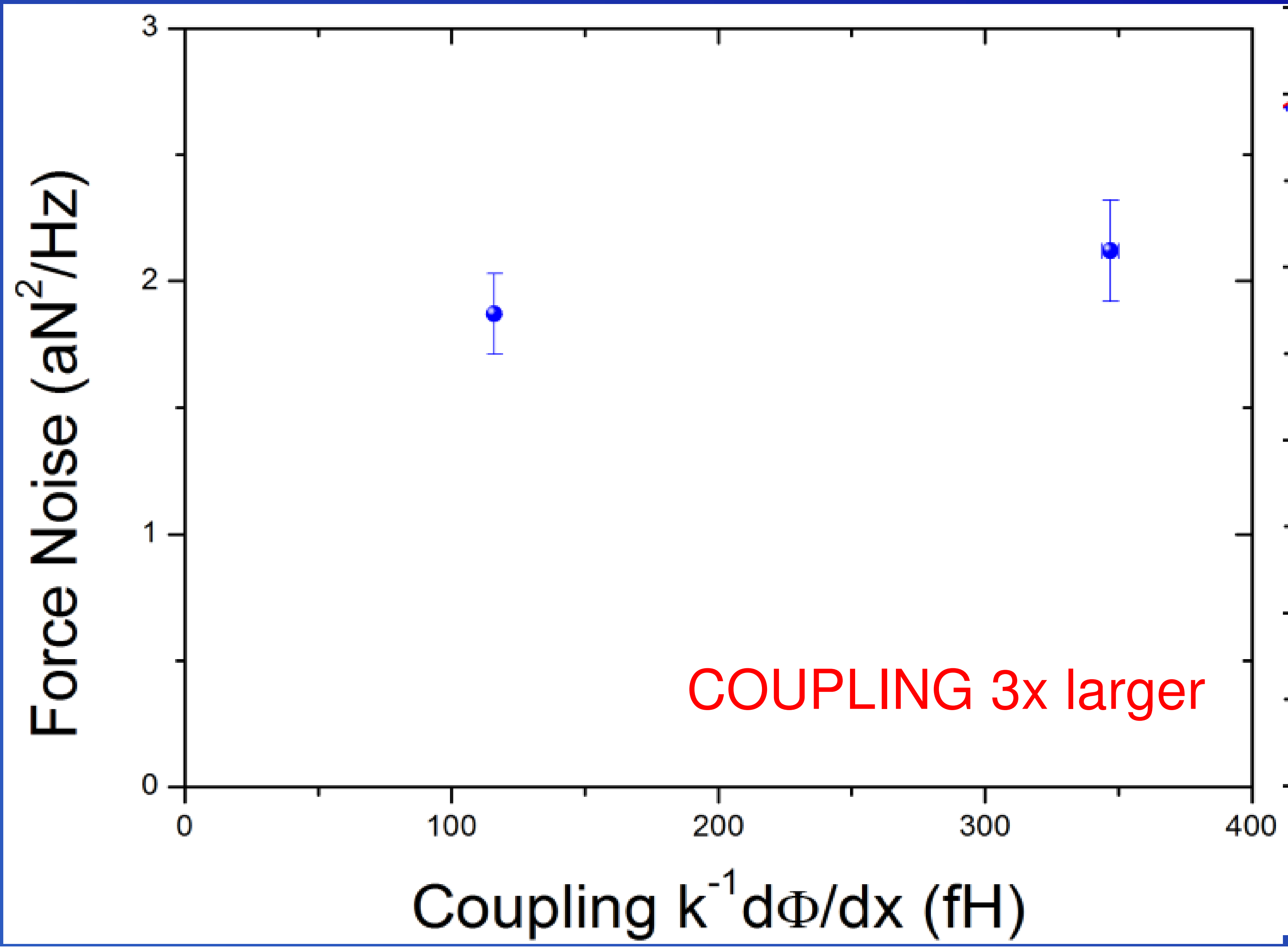
(1.27 ± 0.11)E-19 Φ_0^2/Hz

Residual Force Noise

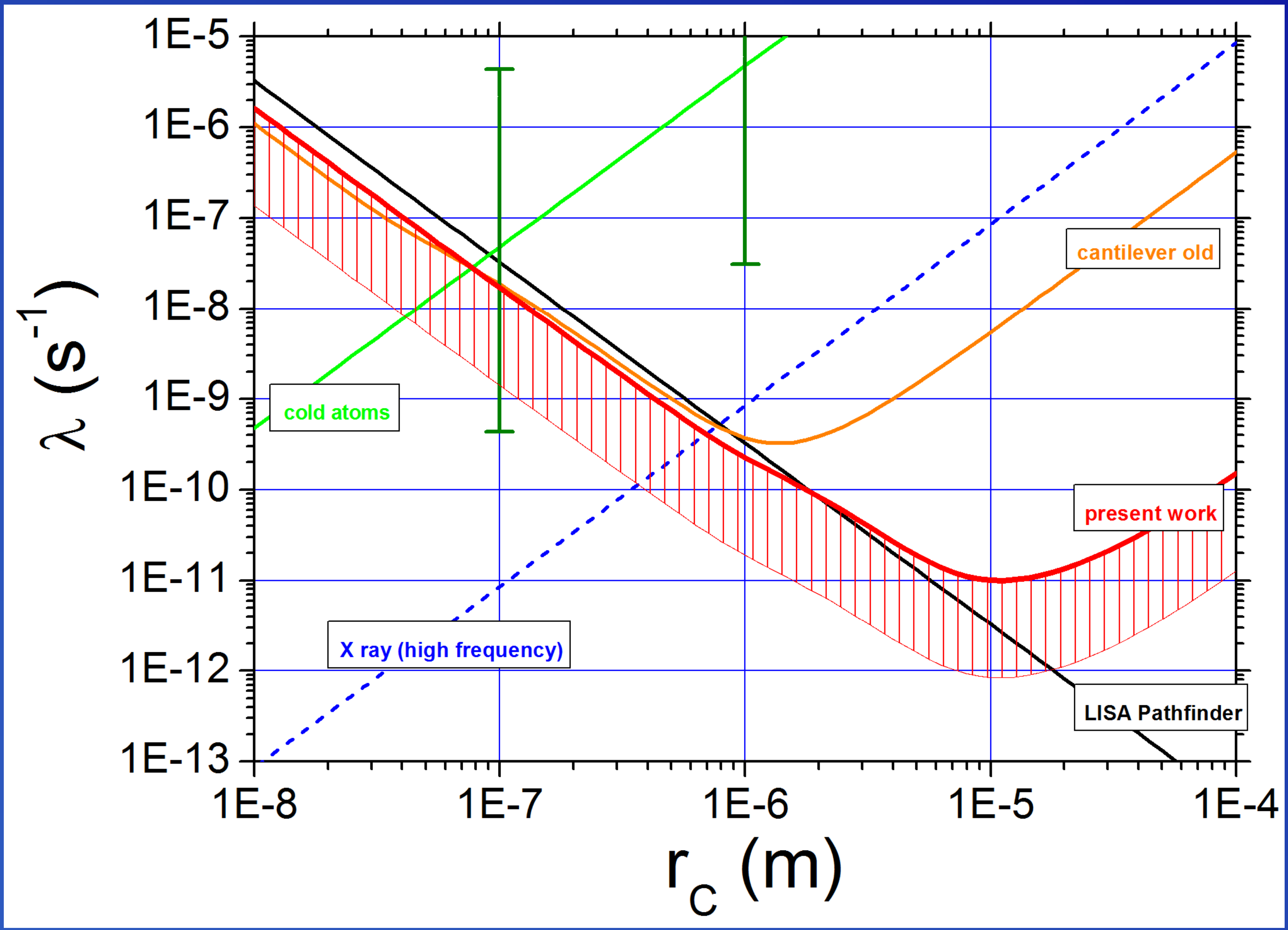
(1.87 ± 0.16) aN^2/Hz



Potential sources of nonthermal noise



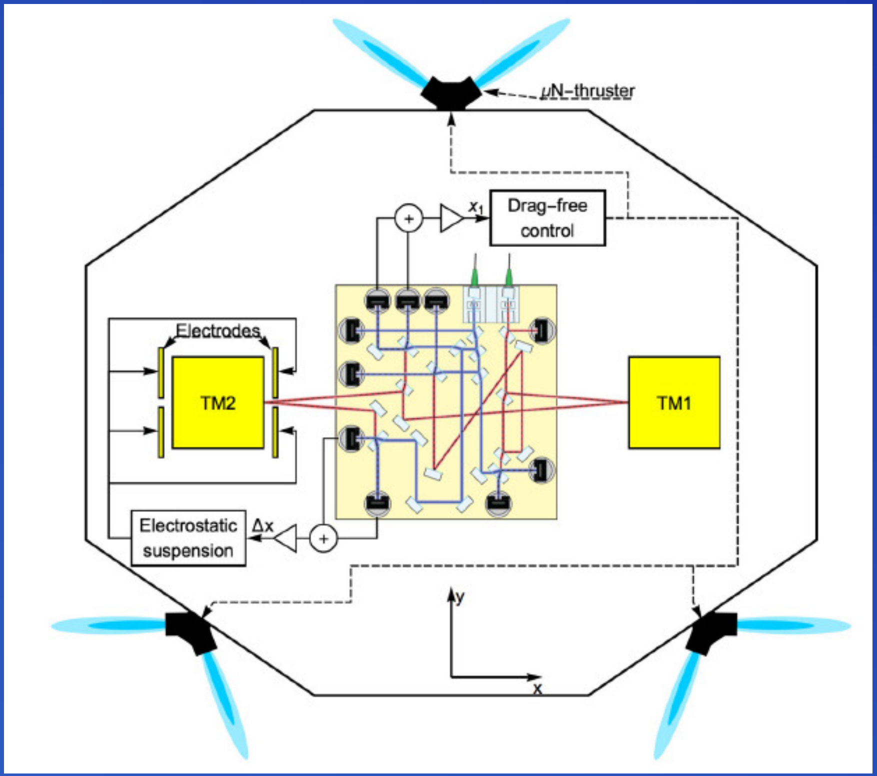
What can we say about CSL ?

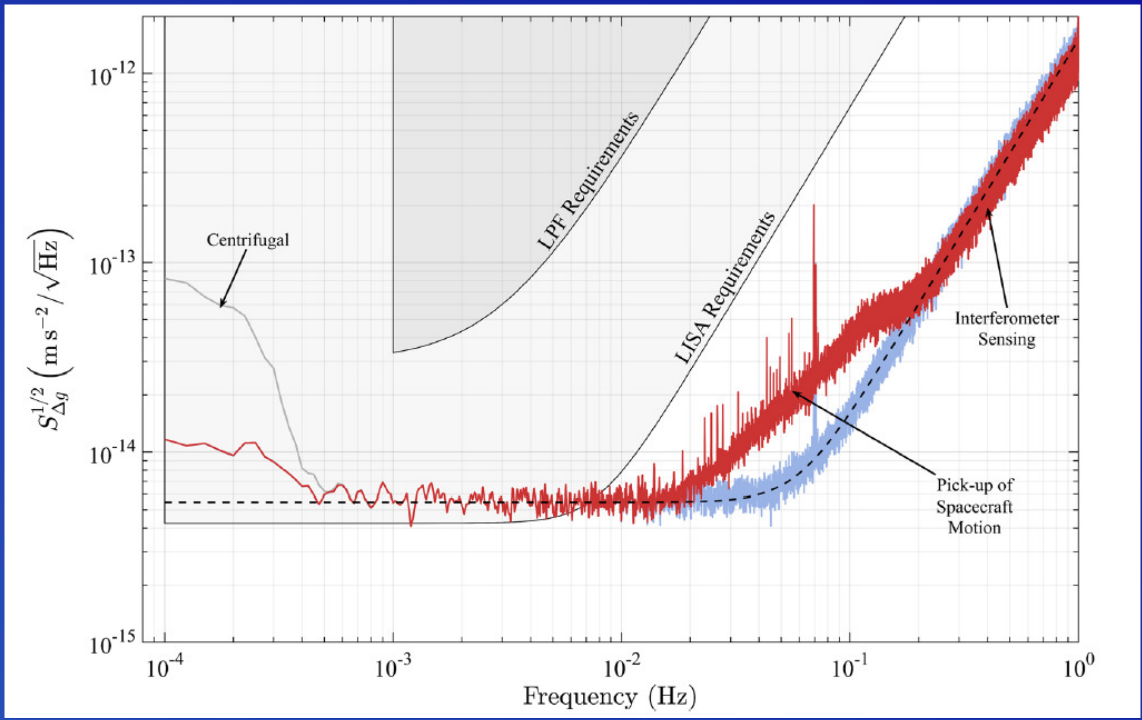


A.Vinante et al, Physical Review Letters, 119, 110401 (2017)

LISA Pathfinder

- 2 cubic test masses in near free-fall @ f>1 mHz   (AuPt, L=4.6 cm, M=2 kg)





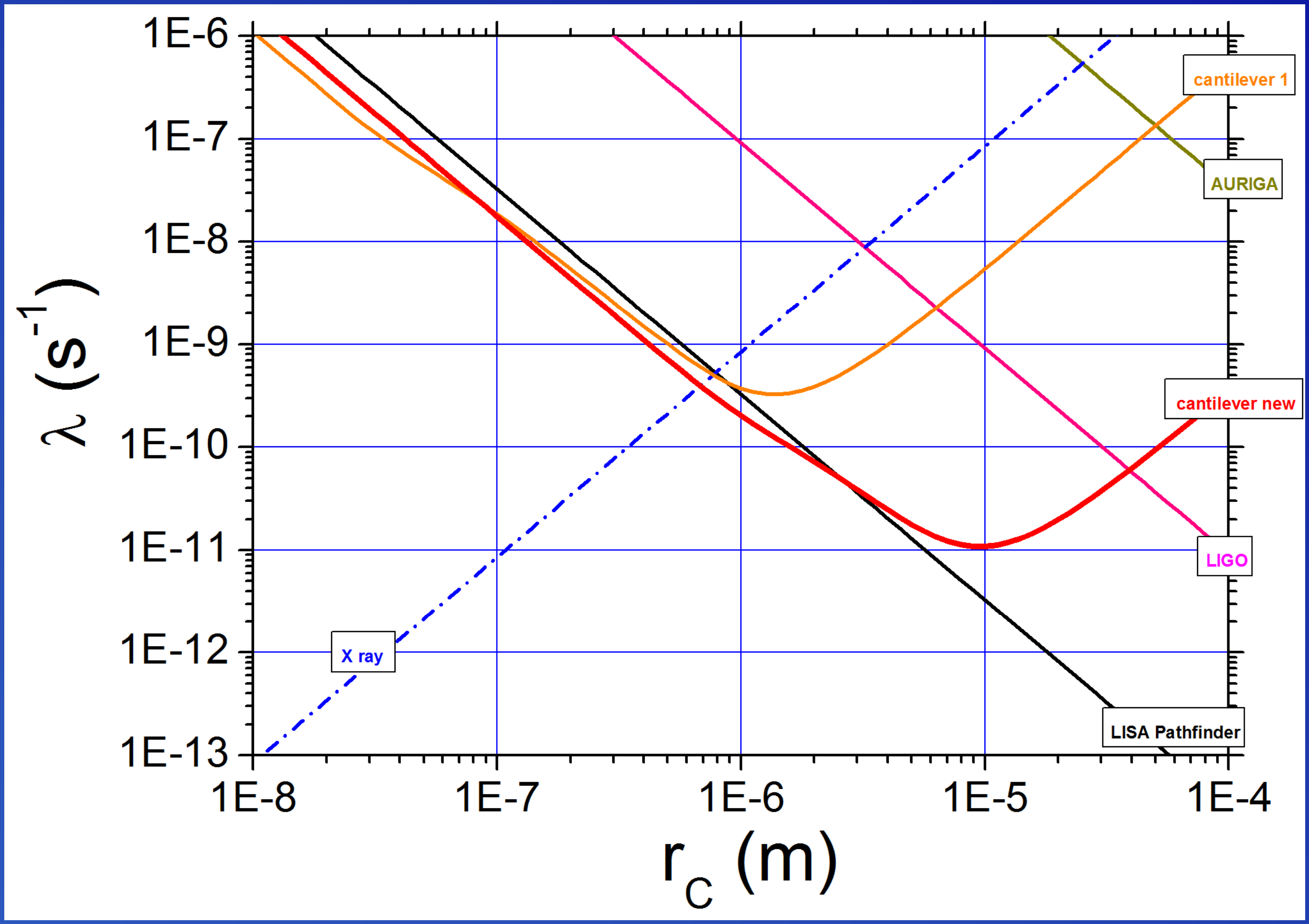
Lowest differential acceleration noise S_g=5.2 fm/s²/√Hz

force noise on single mass S_f=7.3 fN/√Hz

- Macroscopic masses
- Very low frequency !! (mHz)

M. Armano et al, Phys. Rev. Lett. 116, 231101 (2016)

Upper limits on CSL from LISA



M. Carlesso et al, Phys. Rev. D 94, 124036 (2016)

REMARKABLE: bound from LISA is comparable to nanomechanical systems at microscale!

Also Remarkable: Cantilever experiment cost ~ 10^4 €
LISA Pathfinder cost ~10^9 €

The Diosi-Penrose (DP) model

- According to Penrose, the superposition principle is incompatible with the covariance principle of General Relativity. Massive superposition collapse is determined by gravity.

- DP model tries to incorporate this idea, but is essentially similar to the CSL model. In contrast with the original Penrose proposal, there must be a free parameter (r_C as in CSL) to suppress "spontaneous heating" effects.

- Diffusion constant as in CSL (force noise):

$$\eta = \frac{Gm\rho}{6\pi^{1/2}\hbar}\left(\frac{a}{r_C}\right)^3$$

a: lattice constant

- LISA Pathfinder data provides a lower bound on r_c

$$r_c > 40 \text{ fm}$$

B. Helou et al, Phys. Rev. D 95 , 084054 (2017)

The Ellis model

- Proposed by people from high energy physics
  Inspired by ideas from Quantum Gravity
  Decoherence-like collapse of wavefunction would be caused by a bath of space-time wormholes at Planck length scale (spacetime "foam")
  J. Ellis, S. Mohanty and D.V. Nanopoulos, Phys. Lett. B 221, 113 (1989).

- Somehow resembles CSL, but no free parameters.
  Effective diffusion constant:

$$\eta_{\text{Ellis}} = \frac{(cm_0)^4 m^2}{(\hbar m_{\text{Pl}})^3}$$

- Present data from AURIGA-LIGO-LISA exclude Ellis model by many orders of magnitude !
  M. Carlesso et al, Phys. Rev. D 94, 124036 (2016)

- NOTE: Ellis model also recently excluded by matter-wave interferometry !
  J. Minar et al, Phys. Rev. A 94, 062111 (2016)

Outlook: how to further probe CSL parameter space ?

- Cantilevers can improve 2-3 orders of mag, but hard to do much better.
  Optimize geometry/material
  Lower frequency: factor 10-100. Hard (due to vibrations) but feasible !
  Cool to μK temperature? (seems crazy, but why not?)

- Optically/magnetically/electrically levitated micro/nanoparticles
  In principle ultrahigh Q achievable
  Very active research area.
  Needs technological development

- Levitated micro/nano particles in space
  Seems very promising, after LISA results
  Under consideration by ESA (MAQRO et al)

Conclusions

- Spontaneous wavefunction collapse models (CSL) are experimentally testable indeed!
- At present, best limits come from indirect "spontaneous heating" experiments: X-ray, ultracold cantilevers, LISA
- It is likely possible to improve of CSL cantilever experiments by at least 2 orders of magnitude.

Thanks to:

- Theory: A. Bassi group, Trieste. IT
- Cantilever Experiments: T. Oosterkamp group, Leiden, NL
- LISA: W. Weber, S. Vitale, Trento, IT

- CORFU2017 Organizers