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Testing spontaneous collapse models with mechanical experiments

Andrea Vinante

Department of Physics and Astronomy, University of Southampton, SO17 1BJ, United Kingdom

E-mail: `A.Vinante@soton.ac.uk`

Abstract. Spontaneous collapse models (CM) have been proposed as a possible solution of the quantum measurement problem. In CM the unitary evolution of the wave function is modified by stochastic corrections which lead to a dynamical reduction at macroscopic level. Unlike interpretations of quantum mechanics, CM predict departures from standard theory that can be experimentally tested. Here, we focus on one of these predictions, a universal force noise acting on any mechanical system. In particular, we discuss recent bounds on collapse models set by ultracold cantilevers experiments and gravitational wave detectors. First notable results are a partial exclusion of the CSL parameters proposed by Adler and a full exclusion of an early model based on quantum gravity ideas.

1. Introduction

Spontaneous wave function collapse (or dynamical reduction) models (CM) [1, 2, 3, 4, 5] have been proposed to reconcile the linear and deterministic evolution of quantum mechanics with the nonlinearity and stochasticity of the measurement process. According to CM, random collapses in space (i.e. localizations) of the wave function of any system occur spontaneously, independently of measurement processes, leading to a progressive spatial localization. The collapse rate scales with the size of the system, in such a way as to produce rapid localization of any macroscopic system, while giving no measurable effect at the microscopic level, where standard quantum mechanics holds. Importantly, collapse models lead to a natural solution of the measurement problem, by predicting the emergence of well-defined outcomes in any measurement process in agreement with the Born rule, provided that the measurement system is macroscopic.

The standard collapse model described in literature is the Continuous Spontaneous Localization (CSL) [2, 3]. It can be regarded as a continuous version of the earliest collapse model introduced in 1986 by Ghirardi, Rimini and Weber (GRW) [1], and solves some technical issues of the latter. CSL is characterized by two phenomenological constants, a collapse rate λ and a characteristic length r_C, which characterize respectively the intensity and the spatial resolution of the spontaneous collapse process. λ and r_C are free parameters which should be derived, or bounded, by experiments. Other relevant collapse models are the Diosi-Penrose gravitational model [6, 7, 8, 9] and quantum gravity inspired models [10, 11].

The direct effect of collapse models such as CSL is to destroy quantum superpositions, resulting in a loss of coherence in interferometric matter-wave experiments [12, 13, 14]. In

addition, the noise field associated with the collapse leads, unavoidably, to the violation of the energy conservation. So called non-interferometric tests have been proposed to look for these effects. Such tests include spontaneous emission of x-rays [15, 16], force noise in mechanical systems [17, 18, 19, 20, 21, 22, 23, 24] and spontaneous heating of bulk matter [25] or ultracold atoms [26, 27].

In this paper, I will review recent experimental progress in testing collapse models by means of non-interferometric mechanical experiments and discuss possible future developments.

2. Models
2.1. The CSL model
The CSL master equation can be written as [4]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{\rho}(t) = -\frac{i}{\hbar}\left[\hat{H}, \hat{\rho}(t)\right] + \mathcal{L}_{\mathrm{CSL}}[\hat{\rho}(t)], \tag{1}$$

where $\hat{H}$ describes the free evolution of the system and $\mathcal{L}[\hat{\rho}(t)]$ is a Lindblad term. In the case of a rigid body undergoing small displacements in a given direction z, with the motion described in terms of the center of mass coordinate, the CSL term can be written as [21]:

$$\mathcal{L}_{\mathrm{CSL}}[\hat{\rho}_{\mathrm{CM}}(t)] = -\eta\,[\hat{q}, [\hat{q}, \hat{\rho}_{\mathrm{CM}}(t)]], \tag{2}$$

$\hat{q} = \hat{z}$ being the position operator of the center-of-mass, and:

$$\eta = \frac{2\lambda}{m_0^2}\iint \mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{r}'\,\exp\left(-\frac{|\mathbf{r}-\mathbf{r}'|^2}{4r_C^2}\right)\frac{\partial\varrho(\mathbf{r})}{\partial z}\frac{\partial\varrho(\mathbf{r}')}{\partial z'} \tag{3}$$

$$= \frac{(4\pi)^{\frac{3}{2}}\lambda\,r_C^3}{m_0^2}\int\frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\,k_z^2\,e^{-\mathbf{k}^2 r_C^2}\,|\tilde{\varrho}(\mathbf{k})|^2 \tag{4}$$

with $\mathbf{k} = (k_x, k_y, k_z)$, $\tilde{\varrho}(\mathbf{k}) = \int \mathrm{d}^3\mathbf{x}\,e^{i\mathbf{k}\cdot\mathbf{r}}\,\varrho(\mathbf{r})$ and $\varrho(\mathbf{r})$ the mass density distribution of the system. In the latter expressions m_0 is the nucleon mass, λ and r_C are free parameters. The CSL term causes a collapse of the wave function in the coordinate space, i.e. a localization of the center of mass, and therefore a loss of quantum coherence as an effect of the collapse process.

The CSL dynamics is characterized by two phenomenological parameters: the collapse rate λ, which represents the rate of localization of a single nucleon, and the characteristic length r_C, which is related to a smearing of the mass-density function. These are free parameters of the model which should be derived, or bounded, by experiments. The standard conservative values suggested by GRW are $\lambda \simeq 10^{-16}$ s^{-1} and $r_C = 10^{-7}$ m [1, 2] and are sufficient to guarantee almost instantaneous localization of macroscopic objects. A strongly enhanced value for the collapse rate has been suggested by Adler [28], motivated by the requirement of making the wave function collapse effective at the level of latent image formation in photographic process. The values suggested by Adler are $\sim 10^{9\pm2}$ times larger than standard values at $r_C = 10^{-7}$ m, and $\sim 10^{11\pm2}$ times larger at $r_C = 10^{-6}$ m.

Besides causing localization, the CSL term expressed by Eq. (2) describes a diffusion of the center of mass, and η can be interpreted as diffusion constant [17, 18]. In other words, the center of mass of a rigid body will undergo a brownian motion due to the action of the continuous collapse-localization process. This consideration is at heart of so called non-interferometric methods to look for CSL. More generally, the existence of a fundamental CSL collapse mechanism necessarily implies the appearance of a universal force noise, acting on any massive object, with (one-sided) power spectral density $S_{ff} = 2\hbar^2\eta$. A simple consequence is

that for a mechanical resonator in equilibrium with a thermal bath at temperature T, the mean energy is given by [21, 22]:

$$\langle E \rangle = k_B T + \frac{\hbar^2 \eta Q}{2m\omega_0}, \tag{5}$$

i.e. CSL predicts a net excess of energy with respect to the classical equipartition value.

Therefore, one can look for CSL effects by continuously monitoring a mechanical resonator and measuring its mean energy as a function of temperature. The equipartition term $k_B T$ can be characterized and subtracted, and the hypothetical CSL term can be estimated or bounded. A more general procedure, valid also for free masses, is to monitor the free dynamics of the system and infer the power spectral density of the force noise acting on it. This is given, in the thermal limit $k_B T \gg \hbar\omega$ and in absence of technical noise, by:

$$S_{ff} = \frac{4k_B T m\omega}{Q} + 2\hbar^2 \eta. \tag{6}$$

Accurate measurements as a function of the temperature T and the damping factor $\gamma = m\omega/Q$ allow to isolate the thermal term and to estimate or bound the collapse-noise term.

In both situations, in order to increase the sensitivity to CSL noise, one has to maximize the ratio between the CSL-induced noise and the thermal noise. In practice this means lowest possible temperature T, highest possible time constant $\tau = Q/\omega$, and highest possible η/m ratio. While the first two conditions merely express the requirement of lowest possible rate of energy exchange with the thermal bath, the third condition leads to consequences which are peculiar to the model details. For CSL we can distinguish two relevant limits. When the characteristic size L of the system is small, $L \ll r_C$, then $\eta \propto m^2$ and thus $\eta/m \propto m$. When the characteristic length of the system (along the direction of motion) L is large, $L \gg r_C$, then $\eta \propto \rho^2 A$ and thus $\eta/m \propto \rho/L$, where ρ is the mass density and A is the area transverse to the motion [21, 22]. The expressions in the two limits imply that, for a well defined characteristic length r_C, the optimal system is a plate or disk with thickness $L \sim r_C$ and the largest possible density ρ.

2.2. The Diosi-Penrose model
Besides CSL, other models have been proposed, attempting to provide a connection of the wave function collapse to specific mechanisms, in particular to gravity. On the one hand, gravity is the only known force that we have not been able to merge with quantum theory, despite enormous theoretical efforts. Indeed, there is no compelling evidence that gravity must be quantized. On the other hand, collapse models suggest that any breakdown of the quantum superposition principle has to be related to a mass-proportional localizing mechanism, pointing to gravity as a natural candidate.

Among the supporters of this point of view, Penrose argues that the quantum superposition principle is in fundamental contradiction with the general covariance principle of general relativity [6, 7]. Therefore, he suggests that superpositions of a massive object in different spatial positions can survive only for a finite time $\tau \sim \hbar/\Delta E$ where ΔE is a properly defined difference between the self-gravitational energies associated to the two states. In other words, the quantum superposition principle must be broken at fundamental level by gravity.

Another attempt in his direction was done by Diosi [8]. His model is similar to CSL, with a different kernel for the the localization integral. The intensity of the collapse rate would be determined by gravity, while a phenomenological length scale r_{DP}, analogous to r_C, is necessary to avoid exceedingly large violations of energy conservation [9]. Experimentally, values of r_{DP} as low as the nuclear size 10^{-15} m are allowed, although values $r_{DP} \sim r_C = 10^{-7}$ m have been suggested as more reasonable [9]. Notably, the collapse time scale predicted by Diosi coincides with the one heuristically suggested by Penrose [6, 7]. This is the reason motivating the denomination of Diosi-Penrose (DP) model in literature.

The DP model leads to localization and diffusion similar to CSL. The diffusion constant η_{DP} is given by [22]:

$$\eta_{DP} = \frac{G\rho m}{6\sqrt{\pi}\hbar} \left(\frac{a}{r_{DP}}\right)^3,\tag{7}$$

where a is the lattice constant and G is the gravitational constant.

Experimentally, Eqs. (5) and (6) hold exactly in the DP model as in CSL, by replacing η with η_{DP}. The requirements of lowest possible T and longest possible time constant $\tau = Q/\omega$ remain unchanged. A notable difference from CSL is that the diffusion constant η_{DP} does not show any shape dependence. In particular, for the relevant case of large size $L \gg r_{DP}$, the ratio η_{DP}/m, which determines the experimental sensitivity, depends only on the density. In other words there is no optimal size or shape.

Another peculiarity of the DP model is that it is characterized by a single free parameter. While a null result experiment will exclude a given region of the CSL two-parameter space $\lambda - r_C$, in the DP case it will set a lower bound on the r_{DP} parameter.

2.3. The Ellis model

Another model was proposed by Ellis and coworkers [10, 11], based on quantum gravity considerations. The wave function of a massive object would be effectively localized by the interaction with a bath of quantum wormholes which characterize the spacetime structure at the Planck length scale. As such, the Ellis model is not strictly speaking a collapse model, rather it is a decoherence model, where decoherence is induced by practically unaccessible degrees of freedom.

As long as the wavelength of wormholes is much longer than the characteristic magnitude of the motion of the system, decoherence can be effectively described by Eq. (2), with diffusion constant [29]:

$$\eta_E = \frac{(m_0 c)^4 m^2}{(\hbar m_{Pl})^3},\tag{8}$$

where m_{Pl} is the Planck mass and c is the speed of light. Compared to CSL and DP models, the Ellis model is parameter-free, which allows for unambiguous experimental falsifiability.

3. Experiments

3.1. Overview

We consider here two classes of experiments which have been shown to be suitable in testing collapse models: (a) micro- and nano-mechanical systems developed in the context of force microscopy technologies and (b) macroscopic experiments to detect weak forces, such as gravitational wave detectors.

Force microscopy technologies are nowadays a standard tool in applied physics and surface science. The invention of atomic force microscopy (AFM) [30] has been awarded by the Nobel Prize. AFM is based on very sensitive cantilevers, featuring atomically sharp tip, which can be used to map the surface of a sample with atomic resolution by detecting the tip-surface force. One of the most extreme versions of force microscopy is the so called magnetic resonance force microscopy (MRFM), which combines magnetic resonance imaging with ultrasensitive microcantilevers to yield three-dimensional maps of a sample with nanometer resolution. This technique is very demanding, and has led to the development of very sensitive nanocantilevers with relatively low frequency in the kHz range, high quality factor, and to their operation at very low temperature down to the millikelvin regime [31]. According to Eqs. (5) and (6) these systems are natural candidates to detect collapse-induced noise. Furthemore, their size compares favourably with the theoretically suggested CSL length scale [2, 28].

Macroscopic experiments such as torsion pendulums and gravitational wave detectors [32, 33] are by design force sensors with exquisitely low force noise. These experiments consist of macroscopic mechanical systems with high quality factor and typically very low frequency, in the Hz or sub-Hz range. According to Eqs. (5) and (6) they are obvious candidates to detect or bound collapse-induced force noise. The main strong feature with respect to other systems is the operation at low frequency, which requires extreme care in mechanical isolation from environmental noise. The only limitations come from being macroscopic and thus far from the theoretically suggested CSL length scale [2, 28], and from the fact that these experiments are normally operated at room temperature. However, resonant bar gravitational wave detectors [33] and prototype of future interferometric detectors have been operated at cryogenic temperature as well.

3.2. Ultracold cantilevers

The first serious attempt to exploit mechanical resonators to bound the parameters of collapse models, in particular the CSL model, was done by Vinante et al. in 2016 [34]. The system described in the latter work is a MRFM nanocantilever cooled to temperatures down to 10 mK. A magnetic microsphere was attached to the cantilever free end to allow low noise magnetic detection using a SQUID. The original motivation of this solution was to provide a way to operate a MRFM nanocantilever at millikelvin temperature avoiding the overheating typical of laser-based detection. This goal was successfully achieved, as the cantilever thermal noise was found in good agreement with the equipartition theorem down to 25 mK [31]. From this observation an upper bound on any non-thermal contribution, including hypothetical CSL noise, was estimated. An exclusion curve on the CSL parameter space was then derived (Fig. 1, orange line) [34].

The main notable result was the first partial exclusion of the CSL parameters suggested by Adler, in particular the full exclusion of the parameters suggested at $r_C = 10^{-6}$. However the experiment was far from being optimized. The spherical geometry is not the one that maximizes the effect of CSL-induced noise, and the density of the material is three times lower than the densest known materials, such as osmium or iridium. Moreover, the quality factor in this experiment, $Q \sim 10^5$ was not really high.

A second similar experiment was reported later [35] with cantilever and magnetic sphere roughly 10 times larger than the previous one. The cantilever was a standard AFM cantilever, featuring a very large quality factor, up to 10^7 at 20 mK. Very accurate measurements of the force noise were performed and, according to Eq. (6), the thermal contribution was characterized and subtracted. In contrast with the first experiment, a residual force noise was revealed. The ultimate origin of this noise is still unexplained. Further measurements have shown that it is not related to back-action from the SQUID and likely not due to vibrational noise.

For the purpose of testing CSL, the experiment is still able to enlarge the exclusion region. The exclusion line is shown in red in Fig. 1. If the source of excess noise were explained, the bound would be improved by one order of magnitude (dashed red line in Fig. 1). Of course, the excess noise could be in principle explained as CSL noise as well, and it would be compatible with the CSL effect predicted by Adler. However, given the latest data from LISA Pathfinder (see next section), this explanation seems unlikely.

3.3. Macroscopic experiments: LISA Pathfinder

The bounds on collapse models that can be inferred by macroscopic experiments have been recently discussed by Carlesso et al. [29]. Different experiments have been considered: cryogenic resonant bar detectors of gravitational waves, interferometric detectors of gravitational waves (LIGO), torsion pendulums. It was finally shown that the strongest bounds on collapse models
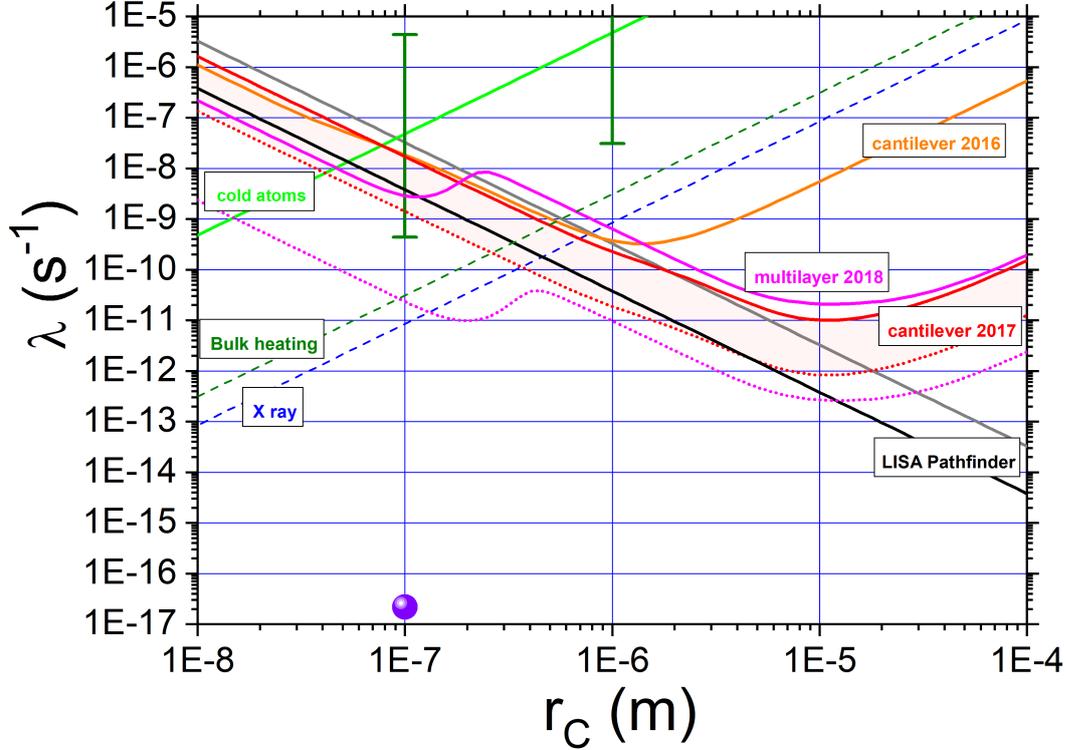
Figure 1. Upper limits on the CSL model collapse rate from different non-interferometric experiments. For each curve the region above the curve is excluded. Solid lines refer to actual experimental bounds, dashed lines to experimental bounds probing the CSL field at very high frequency, dotted lines to hypothetical bounds. Specifically, x-ray spontaneous emission (dashed blue) [16], bulk heating in solid matter (dashed dark green) [25], cold atoms (light green) [27], cantilever 2016 experiment (orange) [34], cantilever 2017 experiment (red) [35], LISA Pathfinder early data (gray) [29, 36] and final data (black) [37]. We also plot the potential improvement from the cantilever 2017 experiment if the excess noise were removed (dotted red line), and a very preliminary bound (magenta) and projected upper limit (magenta dotted) from ongoing cantilever experiments with optimized multilayer test mass. The theoretical parameters suggested by Adler [28] and GRW [1] are also shown.

are set by the recently launched space mission LISA Pathfinder (LPF) [36], the technological demonstrator of the space-born gravitational wave detector LISA.

In LPF, two identical AuPt cubic test masses are nominally in free-fall in space, protected by a spacecraft which follows the masses in such way to minimize the residual coupling. The goal of the mission was to assess the achievable accuracy of free-fall, by optically measuring the residual relative acceleration noise (or equivalently force noise) between the two test masses. Thanks to the very quiet space environment, it was possible to achieve an impressive low acceleration noise of 5.2 fm/(m/s^2)/$\sqrt{\text{Hz}}$ [36], eventually improved by a factor of three following a progressive reduction of residual gas pressure with time [37].

LPF and the future LISA mission are optimized for extremely low frequencies in the range from 10^{-4} Hz to 10^{-1} Hz. In this frequency range, LPF outperforms ground-based torsion pendulums by several orders of magnitude in force power spectral density. Ground

based gravitational wave detectors such as Advanced LIGO, despite the impressive mechanical attenuation, are outperformed too by LPF in terms of force noise, mainly because of the higher characteristic frequency. In fact the minimum of the force noise in LIGO is around 30 Hz [29].

The bounds on the CSL model that can be set using LPF data are easily calculated using Eq. (6). As in LPF there is no absolute calibration of the thermal noise, one assumes the worst case condition and attributes the all measured noise to CSL. The gray and black curves in Fig. 1 refer respectively to the first data released officially [36] and the final data [37].

3.4. Discussion
The bounds on CSL obtained from ultracold cantilevers and LPF are reported in Fig. 1, together with other relevant bounds from other experimental techniques, such as spontaneous emission of x-ray [16], spontaneous heating of bulk matter [25] and spontaneous heating of ultracold atoms [27]. In addition, the CSL parameters suggested by Adler (dark green bars) [28] and GRW (violet dot) [1] are shown.

We remark that the bound from x-ray relies on the strong assumption that the CSL noise field extends up to 10^{18} Hz. The bound may be easily evaded by a CSL noise field with a frequency cutoff. Similarly, bounds from bulk matter heating require noise extending up to 10^{11} Hz. In contrast the bounds from mechanical systems and cold atoms probe the CSL noise field at low frequencies, and are therefore considered more significant. On the other hand, bounds from matter-wave interferometry, which represent direct test of the quantum superposition principle, are so far are at the level of $\lambda \sim 10^{-6}$ s^{-1} [38], thus far weaker than those inferred from mechanical resonators.

As shown in Fig. 1, current mechanical bounds are seriously challenging the predictions of the collapse rate by Adler, based on the assumption that the wave function collapse is effective already at the mesoscopic scale [28]. In contrast, the more conservative prediction by GRW is still many orders of magnitude off, and its testing will require impressive improvements on the experimental side.

It is an interesting fact that, at the end of the day, experiments with so huge difference in the relevant parameters, such as ultracold cantilevers and LPF, provide a comparable bound on CSL. We can explain this remarkable coincidence with the help of Eqs. (6). As discussed in the theory section, in the relevant limit $L \gg r_C$, the CSL over thermal noise ratio scales as $\rho Q/(T\omega L)$. Referring to the cantilever experiment, the LPF experiment provides roughly a 10^1 times larger effective Q and 10^6 times lower ω, giving 7 orders of magnitude improvement. However, the temperature T and size L are respectively 10^4 and 10^3 times larger, resulting in a nearly exact compensation by 7 orders of magnitude. This gives also a clear indication of how the ultimate experiment to test CSL ought to be: very low frequency as in LPF, ultralow temperature and micrometer size as in the cantilever case. This calls for an experiment to be performed at ultralow temperature in a space environment.

Let us consider the DP model. In this case, there is no optimal length scale, and consistently it is found that the strongest bound on the characterstic length r_{DP} is set by LPF, roughly one order of magnitude better than cantilevers [39]. Specifically, using the final data of LPF [37], the lower bound $r_{DP} > 83$ fm is found, implying that r_{DP} must be larger than the size of any stable nuclei. This result does not appear so significant, for instance it is very far from the normalization length suggested by Ghirardi et al [9] of 10^{-7} m. However, it rules out some earlier speculation that the nuclear size could possibly set the DP model length scale [22].

Finally, let us consider the Ellis model. It is possible to show that current LPF data, but data from other macroscopic experiments as well, are inconsistent with the Ellis model, as they would have already been able to point out the associated noise expressed by Eq. (8) [29]. Remarkably, the same conclusion has been recently obtained by analyzing atom interferometry experiments [40]. This is perhaps the first example of a collapse model which is completely ruled

out by experiments.

4. Recent updates and outlook

We conclude with an update on ongoing measurements and an outlook of possible short and mid term progress.

Concerning macroscopic experiments, a significant improvement within the next 15 years seems unlikely. The LISA Pathfinder mission is over, and the LISA mission is scheduled to be launched in the early 2030s. Moreover, as the LPF mission has already achieved the free-fall requirement for LISA it is not clear if LISA will be able to improve over LPF force noise significantly. On the other hand, ground based experiment, such as advanced LIGO or similar detectors, are quite far from being significant with respect to bounding collapse models. Specifically, the upper limit on the CSL model is worse then the one from LPF by almost 4 orders of magnitude with the initial advanced LIGO data and 2 orders of magnitude with the final projected design sensitivity. However, the third generation of gravitational wave interferometers is expected to significantly improve the low frequency force noise, by means of cryogenic suspension and underground operation. This might perhaps allow to approach performance close to LPF.

In contrast, experiments with ultracold cantilevers or different micromechanical resonators have a better potential for improvement in the short-mid term, as they are far from being optimized. Improvements by 2-3 orders of magnitude appear possible in the near future by a combination of two main strategies. The first is moving to lower frequency, by means of softer resonators or larger mass. This will require a much better mechanical isolation, but entirely within reach. The second is an optimization of the test mass. In the first cantilever experiments the test mass was a magnetic sphere made of NdFeB. Far better results can be obtained by using disk geometries and high density materials such as Au or Pt as in LPF. Recent calculations show that the sensitivity to an hypothetical CSL noise field can be enhanced by using a multilayer test mass composed of alternate materials with high density contrast [41].

We have recently started a preliminary experiment with a multilayer test mass made of 47 layers of W and WO_3 of thickness 300 μm, attached on the same cantilever used in Ref. [35]. The first very preliminary measurements show a larger excess noise as in the simple cantilever experiment. Nevertheless, the bound on CSL at $r_C = 10^{-7}$ m, shown as magenta curve in Fig. 1, is already better than any other mechanical experiment, including LPF, although the improvement is marginal. An additional hypothetical curve is shown (magenta dotted curve) which assumes a further optimized multilayered mass with Au or W as heavy material and excess noise comparable with the one of Ref. [35]. This experiment would completely rule out the CSL collapse rate suggested by Adler, and would outperform LPF over the whole relevant range of r_C up to 10^{-5} m. In addition, it would be able to completely rule out the excess noise observed in [35] as a possible CSL effect. Needless to say, any further reduction of the force noise, for instance by removing the excess noise or reducing the effective T/Q factor, would further improve the bounds.

A more radical approach towards a huge improvement is to replace the cantilever with a optical, electrical or magnetic trap, i.e. by levitating a nano or micromechanical test mass. Operation under extreme vacuum and ultralow temperature conditions might in principle allow effective quality factors exceeding 10^{12}. However, we are far from a demonstration of this figure. Optomechanical levitation of nanoparticles is a hot topic of the latest years. For operation at very low temperature, electrical levitation by Paul traps or by magnetic levitation with superconductors appears more suitable. This approach is being explored by the TEQ Project, recently funded by EU. In order to exploit the extreme performance that may be achievable using levitated particles, space environment may be eventually necessary, as in the LPF case. An ambitious program in this direction is the proposed space mission MAQRO [42].

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