LISA pathfinder appreciably constrains collapse models

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LISA Pathfinder's measurement of a relative acceleration noise between two free-falling test masses with a square root of the power spectral density of 5.2 ± 0.1 fm s$^{-2}/\sqrt{\text{Hz}}$ [1] appreciably constrains collapse models. In particular, we bound the localization rate parameter, λ_{CSL}, in the continuous spontaneous localization model (CSL) to be at most $(2.96 \pm 0.12) \times 10^{-8}$ s^{-1}. Moreover, we bound the regularization scale, σ_{DP}, used in the Diosi-Penrose (DP) model to be at least 40.1 ± 0.5 fm. These bounds significantly constrain the validity of these models. In particular: (i) a lower bound of $2.2 \times 10^{-8\pm 2}$s^{-1} for λ_{CSL} has been proposed in [2] (although a lower bound of about 10^{-17}s^{-1} is sometimes used), in order for the collapse noise to be substantial enough to explain the phenomenology of quantum measurement, and (ii) 40 fm is larger than the size of any nucleus, while the regularization scale has been proposed to be the size of the nucleus [3, 4].

Introduction.— Spontaneous collapse models are modifications of quantum mechanics which have been proposed to explain why macroscopic objects behave classically, and to solve the measurement problem. The most widely studied collapse models are the continuous spontaneous localization (CSL) and the Diosi-Penrose (DP) models.

The CSL model is parametrized by two scales: λ_{CSL}, which sets the strength of the collapse noise, and r_{CSL}, which sets the correlation length of the noise. For a nucleon in a spatial superposition of two locations separated by a distance much greater than r_{CSL}, λ_{CSL} is the average localization rate [2]. The quantity r_{CSL} has usually been phenomenologically taken to be 100 nm [5].

The DP model adds stochastic fluctuations to the gravitational field, and is mathematically equivalent to the gravitational field being continuously measured [5–7]. The latter statement leaves the DP model with no free parameters, but a regularization parameter, σ_{DP}, is usually introduced to prevent divergences for point masses.

Nimmrichter *et al.*, in [7], show that the effect of these collapse models on an optomechanical setup, where the center of mass position of a macroscopic object is probed, can be summarized by an additional white noise force, $F(t)$, acting on the system, and with a correlation function of

$$\langle F(t)\, F(z)\rangle = D_C \delta(t-z)\,. \tag{1}$$

For CSL, D_C is given by

$$D_{\text{CSL}} = \lambda_{\text{CSL}} \left(\frac{\hbar}{r_{\text{CSL}}}\right)^2 \alpha \tag{2}$$

with α a geometric factor [7]. For a cube with length $b \gg r_{\text{CSL}}$,

$$\alpha \approx \frac{8\pi\rho^2 r_{\text{CSL}}^4 b^2}{\text{amu}^2} \tag{3}$$

where ρ is the material density. For the DP model, D_C is given by

$$D_{\text{DP}} \approx \frac{G\hbar}{6\sqrt{\pi}} \left(\frac{a}{\sigma_{\text{DP}}}\right)^3 M\rho \tag{4}$$

with M the test mass' mass, and a the lattice constant of the material composing the test mass [7].

An optomechanics experiment would need to have very low force noise over some frequency range to significantly constrain collapse models. LISA pathfinder, a European Space Agency mission, measures the relative acceleration noise between two free-falling test masses at a record accuracy of $\sqrt{S_a} = 5.2 \pm 0.1$ fm s$^{-2}/\sqrt{\text{Hz}}$ for frequencies between 0.7 mHz and 20 mHz [1], and so is a promising platform to test collapse models. We will use S_a to provide an upper bound on λ_{CSL}, and a lower bound on σ_{DP}.

Constraining the collapse models.— We can bound the parameters of collapse models by measuring the force noise of a test mass in an experiment, and attributing unknown noise to the stochastic force $F(t)$.

In LISA pathfinder, the contribution of known stray forces, such as Brownian thermal noise, to S_a is not precisely known. As a result, we attribute all relative acceleration noise to the collapse models' stochastic forces:

$$S_a = 2S_F/M^2, \tag{5}$$

where M is the mass of the test mass, and $S_F = 2D_C$ is the single sided spectrum of the collapse force. The factor of 2 in Eq. (5) follows from the collapse noise on each test mass adding up, because the spontaneous collapse force acts independently on each of the two test masses, which are separated by about 38 cm, a distance much larger than r_{CSL} and σ_{DP}. Therefore, we can place an upper bound on D_C of:

$$D_C \le D_C^{\max} = M^2 S_a/4. \tag{6}$$

Using Eq. (2), we can then bound λ_{CSL} to

$$\lambda_{\mathrm{CSL}} \leq \lambda_{\mathrm{CSL}}^{\max}, \tag{7}$$

with

$$\begin{aligned}\lambda_{\mathrm{CSL}}^{\max} = 2.96 \times 10^{-8}\ \mathrm{s}^{-1} \times \frac{S_a}{2.7 \times 10^{-29}\ \mathrm{m}^2\mathrm{s}^4/\mathrm{Hz}} \\ \times \left(\frac{M}{1.928\ \mathrm{kg}}\right)^{4/3} \times \left(\frac{19881\ \mathrm{kg/m}^3}{\rho}\right)^{4/3} \\ \times \left(\frac{100\ \mathrm{nm}}{r_{\mathrm{CSL}}}\right)^2,\end{aligned} \tag{8}$$

where we have used the fact that the LISA pathfinder test masses are cubes with a mass of 1.928 kg [1], and a density ρ that is the weighted average of the alloy (73% Au and 27% Pt) of which they are made out of [8]. S_a is presented without an explicit dependence on frequency, because the collapse force noise is frequency-independent, and so S_a at any frequency provides a bound on λ_{CSL}. The best bound comes from the frequency at which S_a is at a minimum. For LISA pathfinder, S_a is at a minimum of 2.7×10^{-29} $\mathrm{m}^2\mathrm{s}^4/\mathrm{Hz}$ in the frequency range 0.7 mHz and 20 mHz [1].

In addition, using Eq. (4), we can bound σ_{DP} to

$$\sigma_{\mathrm{DP}} \geq \sigma_{\mathrm{DP}}^{\min}, \tag{9}$$

with

$$\begin{aligned}\sigma_{\mathrm{DP}}^{\min} = 40.1\ \mathrm{fm} \times \frac{a}{4\ \text{Å}} \times \left(\frac{2.7 \times 10^{-29}\ \mathrm{m}^2\mathrm{s}^4/\mathrm{Hz}}{S_a}\right)^{1/3} \\ \times \left(\frac{1.928\ \mathrm{kg}}{M}\right)^{1/3} \times \left(\frac{\rho}{19881\ \mathrm{kg/m}^3}\right)^{1/3}.\end{aligned} \tag{10}$$

Discussion.— LISA pathfinder places strong constraints on the CSL and DP collapse models. The upper bound on λ_{CSL} presented in this article is three orders of magnitude lower than the bound 10^{-5} s^{-1}, which Feldmann and Tumulka [9] calculated from Gerlich *et al.*'s matter wave inteferometry experiment of organic compounds up to 430 atoms large [10]. Another matter wave interferometry experiment from the same group [11] places a bound of 5×10^{-6} s^{-1}, as calculated in [12].

Our calculated rate of 2.96×10^{-8} s^{-1} is comparable to bounds on λ_{CSL} obtained from measuring spontaneous heating from the collapse noise. In [13], an upper bound of about 2×10^{-8} s^{-1} is obtained by analyzing the excess heating of a nanocantilever's fundamental mode. The same experiment also places a lower bound on σ_{DP} of about 1.5 fm, which is much lower than the bound obtained in this article. Furthermore, Bilardello *et al.* place a bound of 5×10^{-8} s^{-1} [14], by analyzing the heating rate of a cloud of Rb atoms cooled down to picokelvins [15]. Note that Bilardello *et al.*'s bound depends on the temperature of the CSL noise field, and on the reference frame with respect to which the CSL noise field is at rest with [14]. The standard formulation of CSL has the collapse noise field at a temperature of infinity, but the theory could be modified to incorporate different temperatures. The incorporation of dissipation within CSL is based on the dissipative CSL (dCSL) theory proposed by Smirne and Bassi [16].

A record upper bound of 10^{-11} s^{-1} is placed in [17] by examining the spontaneous x-ray emission rate from Ge. This bound could be greatly reduced if the collapse noise is non-white at the very high frequency of 10^{18} s^{-1} [5]. In addition, we note that other bounds have been obtained from cosmological data, the lowest of which, 10^{-9} s^{-1}, is from the heating of the intergalactic medium [2]. However, this bound is also sensitive to the temperature of the collapse noise field [16]. Moreover, our interest in this article is for controlled experiments.

The calculated value for the upper bound $\lambda_{\mathrm{CSL}}^{\max}$ from the LISA pathfinder data of $(2.96 \pm 0.12) \times 10^{-8}$ s^{-1} significantly constrains the CSL model because it overlaps with some of the lower bounds on λ_{CSL} proposed in the literature. Indeed, Adler investigates the measurement process of latent image formation in photography and places a lower bound of $\lambda_{\mathrm{CSL}} \simeq 2.2 \times 10^{-8\pm2}$ s^{-1} [2]. Moreover, Bassi *et al.* place a lower bound of $\lambda_{\mathrm{CSL}} \simeq 10^{-10\pm2}$ s^{-1} by investigating the measurement-like process of human vision of six photons in a superposition state [18]. Note that a lower bound of about 10^{-17} s^{-1}, proposed by Ghirardi, Pearle and Rimini [19], is also sometimes considered. Its justification comes from the requirement that an apparatus composed of about 10^{15} nucleons settle to a definite outcome in about 10^{-7} s or less [20].

Finally, the calculated value for $\sigma_{\mathrm{DP}}^{\min}$ of 40.1 ± 0.5 fm is larger than the size of any nucleus. This makes a good case for ruling out the DP model if σ_{DP} is to be chosen as the size of a nucleus.

Note.— M. Carlesso *et al.* in [21] have also calculated upper bounds to CSL which agrees with our calculation. They indicate that preliminary results were presented at 115th Statistical Mechanics Conference, Rutgers University 8-10 May 2016, and at the Quantum Control of Levitated Optomechanics Conference, Pontremoli, 18-20 May 2016. We were not aware of these presentations.

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