



# LABORATORY TESTS ON DARK ENERGY



This Sloan Digital Sky Survey image shows an example of a galaxy cluster (bright spots). Dark energy may be pushing galaxies within each cluster away from one another.

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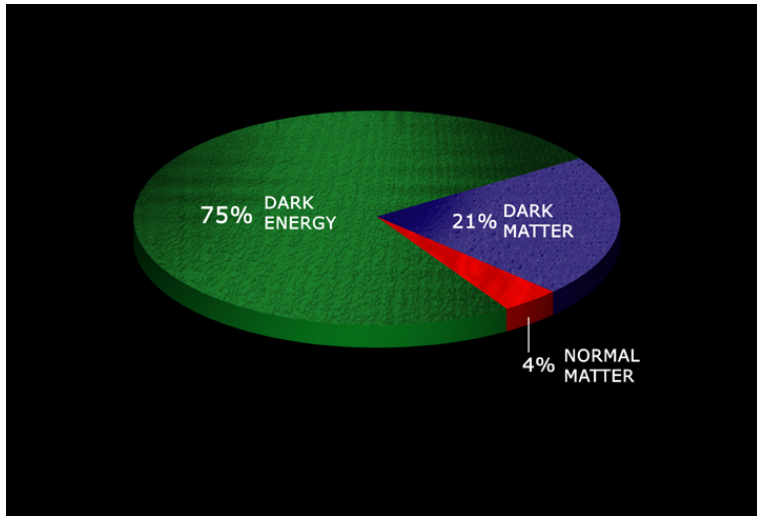
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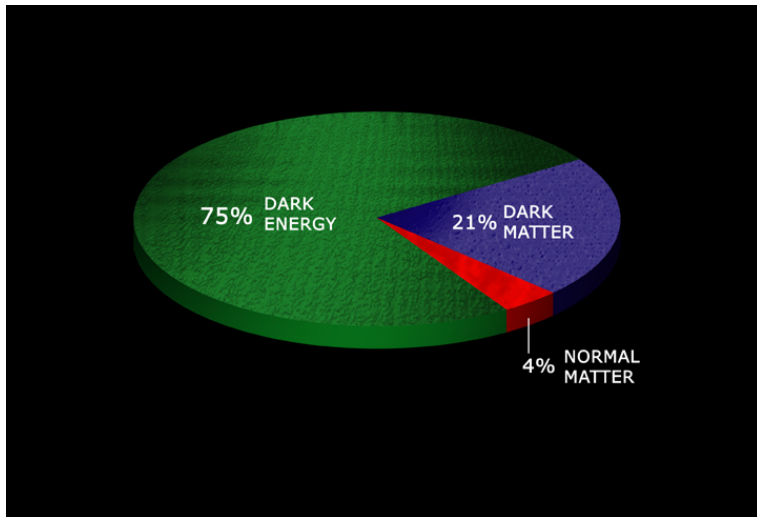


# 1 Introduction





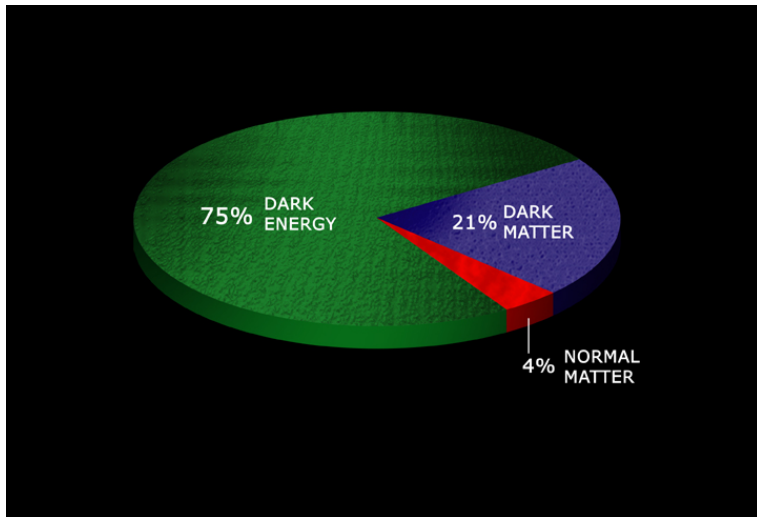
# 1 Introduction



Nobody really knows what dark energy is!



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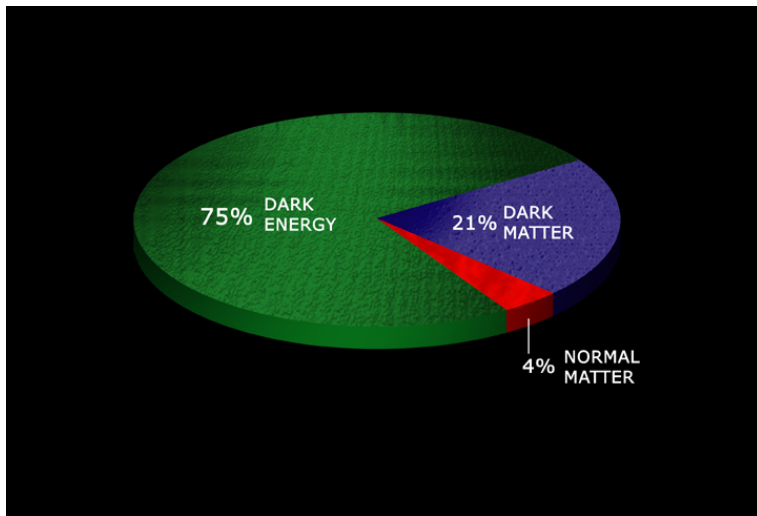


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Eq. of state  $w = p/\rho \approx -1$ .



## 1 Introduction



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Observational evidence for dark energy from

- supernovae (accelerated expansion of universe)
- cosmic microwave background fluctuations
- large-scale structure

Many different **theoretical models** for dark energy:

- just a cosmological constant
- vacuum energy of suitable scalar fields
- quintessence
- phantom fields
- Born-Infeld quantum condensates
- Chaplygin gas
- fields with nonstandard kinetic terms
- chaotic scalar fields
- modifications of gravity
- ...



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Most observations consistent with  $w = -1$  (constant dark energy).

In the following I describe a

[new model for constant dark energy in the universe](#)

(C.Beck and M.C. Mackey, astro-ph/0703364),

which has several advantages as compared to other dark energy models:

1. just based on virtual photons —no exotic scalar fields such as the quintessence field needed
2. dark energy identified as ordinary [electromagnetic vacuum energy](#)
3. generates a small cosmological constant for [natural](#) values of parameters (no fine-tuning)
4. is testable by [laboratory experiments](#) on the earth.



## 2 A new model: Electromagnetic dark energy

Quantum field theory formally predicts infinite vacuum energy density:

$$\rho_{vac} = \frac{1}{2}(-1)^{2j}(2j + 1) \int_{-\infty}^{+\infty} \frac{d^3k}{(2\pi)^3} \sqrt{\mathbf{k}^2 + m^2} \quad (1)$$

( $j$  spin,  $m$  mass). One such infinite contribution comes from electromagnetic vacuum fluctuations (virtual photons).

For photons ( $m = 0$ ) the above integral can be formally written as

$$\rho_{vac} = \frac{2}{c^3} \int_0^\infty \frac{1}{2} h\nu \cdot 4\pi\nu^2 d\nu = \infty \quad (2)$$

Relation between a given vacuum energy density  $\rho_{vac}$  and the cosmological constant  $\Lambda$ :

$$\Lambda = 8\pi G \rho_{vac} \quad (3)$$

To construct realistic model that generates a **small** amount of vacuum energy density  $\rho_{vac} = \rho_{dark}$ , assume that virtual photons (or any other bosons) can exist in **two different phases**:

- A **gravitationally active** phase where they contribute to the cosmological constant  $\Lambda$ , and a
- **gravitationally inactive** phase where they do not contribute to  $\Lambda$ .

(new additional property of ordinary (virtual) photons)

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Let  $|\Psi|^2$  be the number density of gravitationally active photons in the frequency interval  $[\nu, \nu + d\nu]$ . Then

$$\rho_{dark} = \int_0^{\infty} \frac{1}{2} h\nu |\Psi|^2 d\nu \quad (4)$$

The standard choice  $|\Psi|^2 = \frac{2}{c^3} \cdot 4\pi\nu^2$  makes sense in the low-frequency region but leads to a divergent vacuum energy density for  $\nu \rightarrow \infty$ . Hence we conclude that  $|\Psi|^2$  must exhibit more complicated type of behavior in the high frequency region. In the following we construct a **Ginzburg-Landau type theory** for  $|\Psi|^2$ .

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Analogy:

- In superconductors:  $|\Psi|^2 =$  number density of **superconducting electrons**
- Here:  $|\Psi|^2 =$  number density of **gravitationally active photons** (in vacuum)

Ginzburg-Landau free energy density given by

$$F = a|\Psi|^2 + \frac{1}{2}b|\Psi|^4 \quad (5)$$

where  $a$  and  $b$  are temperature dependent coefficients.

Choose same temperature dependence as in Ginzburg-Landau theory of superconductivity.

After some calculations one obtains (details in C. Beck and M.C. Mackey, astro-ph/0703364):

$$|\Psi|^2(\nu) = \frac{8\pi}{c^3}\nu^2 \left(1 - \frac{\nu^4}{\nu_c^4}\right) \quad (6)$$

$$F(\nu) = \frac{1}{2}a_0\frac{8\pi}{c^3}\nu^2 \left(1 - \frac{\nu^2}{\nu_c^2}\right)^2, \quad (7)$$

valid for  $\nu < \nu_c$ . For  $\nu \geq \nu_c$  one has  $|\Psi|^2(\nu) = 0$  and  $F(\nu) = 0$ .

Model exhibits a **phase transition** at a **critical frequency**  $\nu_c$  where gravitational activity of photons ceases to exist.

Number density  $|\Psi|^2$  of gravitationally active photons in the interval  $[\nu, \nu + d\nu]$  is nonzero for  $\nu < \nu_c$  only. In this way we obtain a finite dark energy density when integrating over all frequencies:

$$\rho_{dark} = \int_0^{\infty} \frac{1}{2} h\nu |\Psi|^2 d\nu \quad (8)$$

$$= \frac{4\pi h}{c^3} \int_0^{\nu_c} \nu^3 \left(1 - \frac{\nu^4}{\nu_c^4}\right) d\nu = \frac{1}{2} \frac{\pi h}{c^3} \nu_c^4 \quad (9)$$

The astronomically observed dark energy density in the universe of about  $3.9 \text{ GeV}/m^3$  implies

$$\nu_c = 2.01 \text{ THz} \quad (10)$$



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Note that in our model virtual photons exist (in the usual quantum field theoretical sense) for both  $\nu < \nu_c$  and  $\nu \geq \nu_c$ , hence there is no change either to quantum electrodynamics (QED) nor to measurable QED effects such as the Casimir effect at high frequencies. The only thing that changes at  $\nu_c$  is the **gravitational** behavior of virtual photons. This is a new physics effect at the interface between gravity and electromagnetism, which solely describes the **gravitational** properties of virtual photons.

There are two free parameters in this dark energy model,  $a_0$  and  $h\nu_c$ . Remarkably, our model gives the correct amount of dark energy density in the universe if the **parameters have similar order of magnitude as in superconductors of solid state physics**.

What are typical parameter values in solid state physics? The Bardeen-Cooper-Schrieffer (BCS) theory yields the prediction [?]

$$a_0 = -\alpha kT_c, \quad (11)$$

where

$$\alpha := \frac{6\pi^2}{7\zeta(3)} \frac{kT_c}{\mu}. \quad (12)$$

Here  $\mu$  denotes the Fermi energy of the material under consideration. For example, in copper  $\mu = 7.0$  eV, and the critical temperature of a YBCO (Yttrium-Barium-Copper Oxid) high- $T_c$  **superconductor** is around 90 K. This yields typical values of  $kT_c \sim 9 \cdot 10^{-3}$  eV and  $\alpha \sim 8 \cdot 10^{-3}$ .

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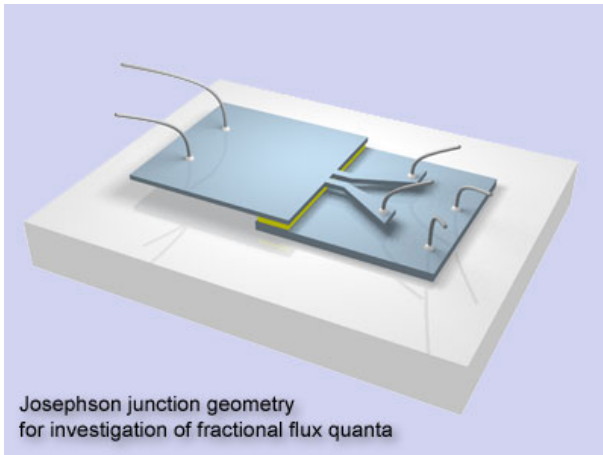
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Our **electromagnetic dark energy model** works well if we choose the **universal** parameters describing the vacuum as  $a_0 = -\alpha_{el} h\nu_c$ , where  $h\nu_c \sim m_\nu c^2 \sim 8 \cdot 10^{-3}$  eV (typical neutrino mass scale) and  $\alpha = \alpha_{el} \approx 1/137 \approx 7.3 \cdot 10^{-3}$ .



### 3 Josephson junctions as detectors for zeropoint fluctuations



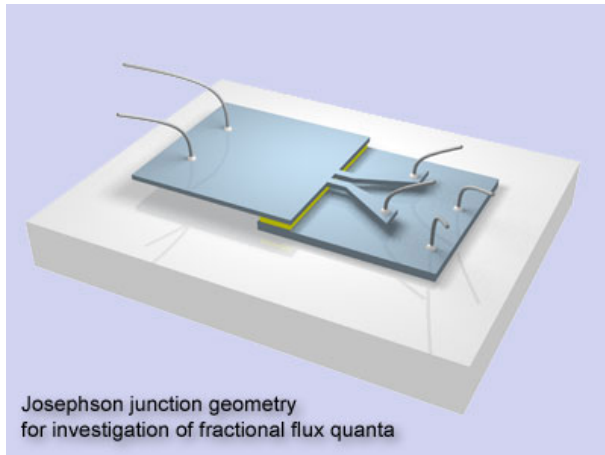
A Josephson junction consists of two superconductors with an insulator sandwiched in-between.

These device can be used to [measure high-frequency stochastic currents](#) induced by [zeropoint fluctuations](#).

Reason why this works: Fluctuation Dissipation Theorem and ac Josephson effect  
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(has nothing to do with Casimir effect or van der Waals forces!)

Experimentally confirmed: Measured noise currents through Josephson junctions have a power spectrum given by

$$S(\nu) = \frac{2h\nu}{R} \coth\left(\frac{h\nu}{kT}\right) = \frac{4}{R} \left( \frac{1}{2}h\nu + \frac{h\nu}{\exp(h\nu/kT) - 1} \right).$$

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First term due to zeropoint fluctuations, second one due to ordinary Bose-Einstein statistics. [Experimental verification](#) (Koch et al 1982) up to frequencies of 0.5 THz

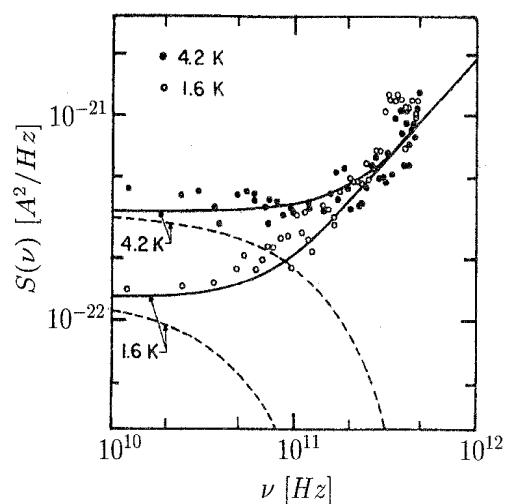


Fig.1: Spectral density of current noise as measured in Koch et al.'s 1982 experiment. Solid line: prediction including zeropoint fluctuations. Dashed line: without zeropoint term.

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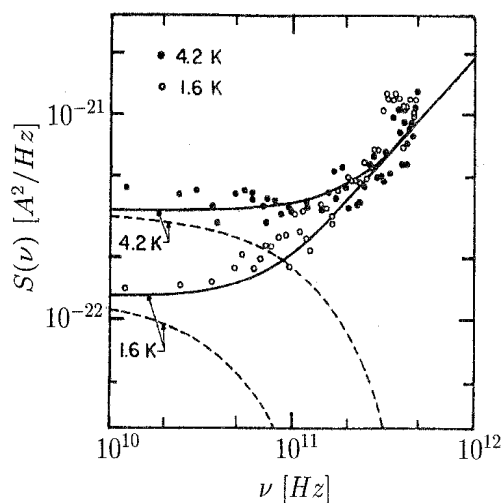


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Could there be some interesting behaviour near  $\nu_c \sim 2$  THz? C.B. and M.C. Mackey, Phys. Lett. B 605, 295 (2005)





#### 4 Possible measurable effects of dark energy in superconductors

We now describe how our gravitationally active photons could influence superconducting electrons in superconductors.

Denote the macroscopic wave function of gravitationally active photons by  $\Psi_G$  (previously this was denoted as  $\Psi$ ), and that of superconducting electrons (Cooper pairs) in a superconductor by  $\Psi_s$ . So far we only dealt with absolute values of these wave functions, but we now introduce phases  $\Phi_G$  and  $\Phi_s$  by writing

$$\Psi_s = |\Psi_s| e^{i\Phi_s} \quad (13)$$

$$\Psi_G = |\Psi_G| e^{i\Phi_G}. \quad (14)$$

In superconductors one has  $|\Psi_s|^2 = \frac{1}{2}n_s$ , where  $n_s$  denotes the number density of superconducting electrons. Similarly, in our model  $|\Psi_G|^2$  is proportional to the number density of gravitationally active photons.

Spatial gradients in the phase  $\Phi_s$  give rise to electric currents

$$\vec{j}_s = \frac{e\hbar}{m} |\Psi_s|^2 \nabla \Phi_s = -\frac{ie\hbar}{2m} (\Psi_s^* \nabla \Psi_s - \Psi_s \nabla \Psi_s^*), \quad (15)$$

Similarly, spatial gradients in the phase  $\Phi_G$  of gravitationally active photons generate a current given by

$$\vec{j}_G = \frac{\tilde{e}\hbar}{\tilde{m}} |\Psi_G|^2 \nabla \Phi_G = -\frac{i\tilde{e}\hbar}{2\tilde{m}} (\Psi_G^* \nabla \Psi_G - \Psi_G \nabla \Psi_G^*). \quad (16)$$

Whereas the strength of the electromagnetic current is proportional to the Bohr magneton  $\mu_B = \frac{e\hbar}{2m}$ , the strength of the current given by eq. (16) is proportional to a kind of 'gravitational magneton'  $\mu_G := \frac{\tilde{e}\hbar}{2\tilde{m}}$  whose strength is a priori unknown. Presumably,  $\mu_G$  is very small so that this current is normally unobservable in the vacuum.

In superconducting devices, however, the situation may be very different. Here both the phases  $\Phi_s$  and  $\Phi_G$  exist and the corresponding wave functions might interact. The strength of this interaction is a priori unknown since  $\Psi_G$  represents new physics. If the interaction strength is sufficiently strong then in equilibrium the phases may synchronize:

$$\Phi_s = \Phi_G. \quad (17)$$

If phase synchronization sets in, then fluctuations in  $\Phi_G$  would produce measurable stochastic electric currents of superconducting electrons given by

$$\vec{j}_s = \frac{e\hbar}{m} |\Psi_s|^2 \nabla \Phi_G. \quad (18)$$

These currents could only exist up to the critical frequency  $\nu_c$ . For  $\nu > \nu_c$  one has  $\Psi_G = 0$  and hence  $\nabla \Phi_G = 0$ . Noise currents that are produced by gravitationally active photons would thus cease to exist at a critical frequency  $\nu_c$  given by about 2 THz.

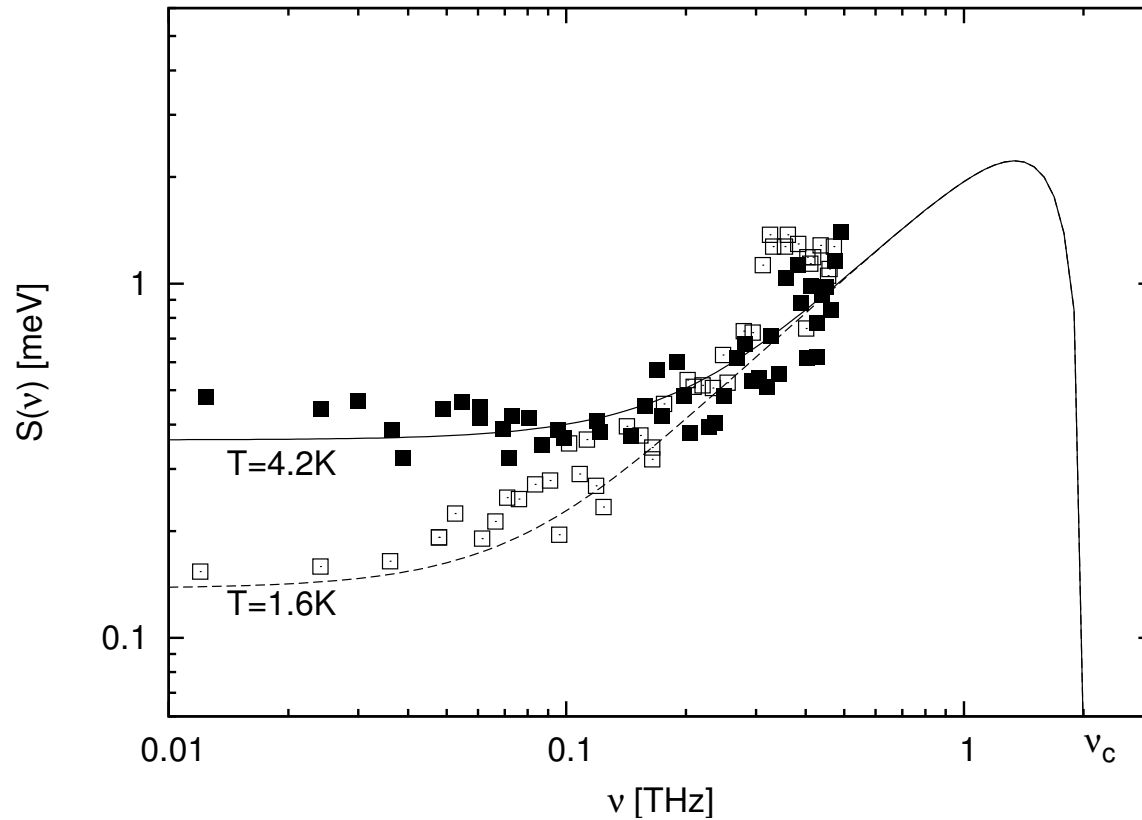


## 5 Theoretical predictions of quantum noise spectra and comparison with data

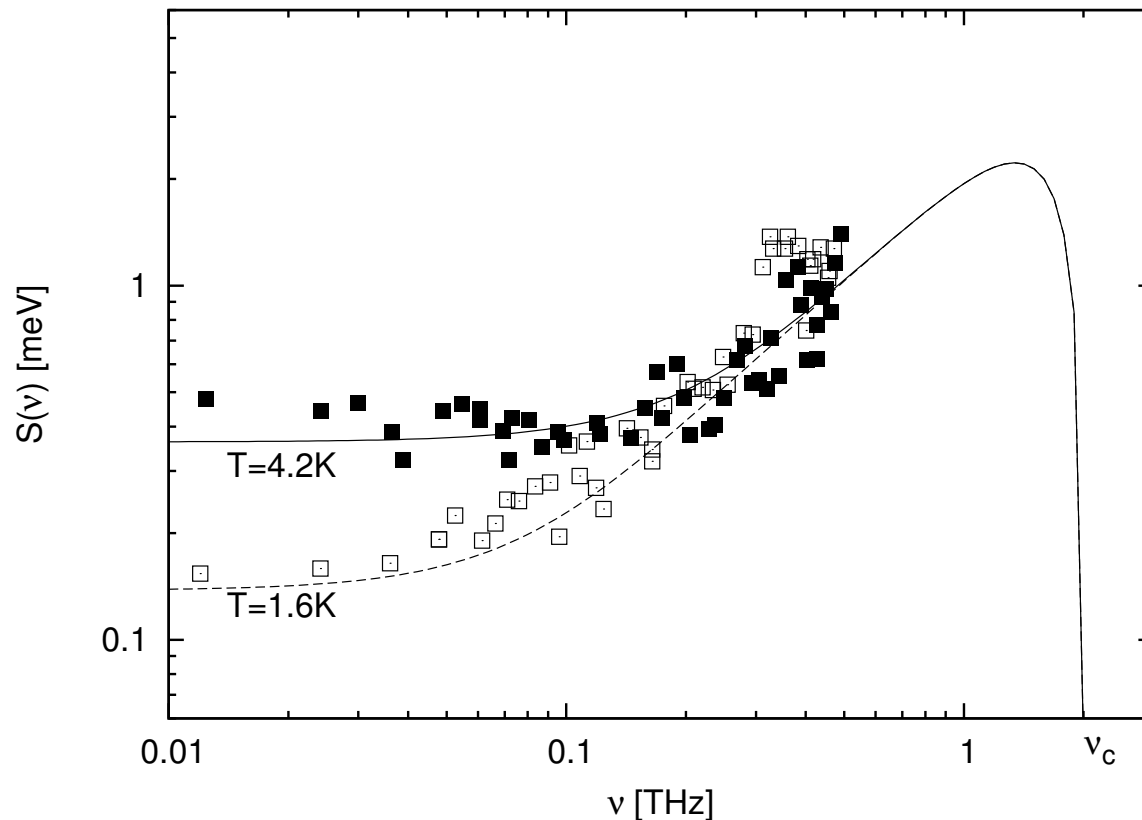
Our theory of electromagnetic dark energy allows for a coupling between the macroscopic wave functions  $\Psi_s$  describing superconducting electrons and the macroscopic wave function  $\Psi_G$  describing gravitationally active photons. Coupling strength a priori unknown, since this is new physics. For sufficiently strong coupling phase synchronization may set in, resulting in the following prediction for the quantum noise power spectrum in Josephson junctions:

$$\tilde{S}(\nu) = \frac{4}{R} \left[ \frac{1}{2} h\nu \left( 1 - \frac{\nu^4}{\nu_c^4} \right) + \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} \right]. \quad (19)$$

(C.B., M.C. Mackey, astro-ph/0703364)



Power spectrum  $S(\nu) := \frac{R}{4} \tilde{S}(\nu)$  as generated by gravitationally active photons at two different temperatures (solid and dashed lines) and comparison with the data of the experiment of Koch et al. Filled squares correspond to measurements at 4.2K, open squares to measurements at 1.6 K.



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New Josephson experiments are currently being built up at UCL (P. Warburton) and Cambridge (Z. Barber) which [will reach the THz region](#).



## 6 Summary

- We have introduced a new model for dark energy ('**electromagnetic dark energy**') where the gravitational behaviour of virtual photons is described by a Ginzburg-Landau-like theory.
- The model yields the correct amount of (constant) dark energy density in the universe for **natural** parameters.
- If phase synchronisation sets in, then these types of dark energy models lead to measurable effects in superconductors. Measured quantum noise spectrum in Josephson junctions should have a **cutoff** near **2.0 THz**.
- CMB spectrum is a property of **real** photons—our suggestion here is to do a kind of '**zeropoint fluctuation spectroscopy**' and look at power spectra generated by **virtual** photons as well.

All relevant references can be found in  
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