Report on the quantum gravity workshop at Kyoto

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Contents

- **Overview of the workshop**
  基研研究会「巨視的量子現象と量子重力」
  YITP Workshop “Macroscopic Quantum Phenomena and Quantum Gravity”
- **Review of some papers from the workshop**
  A. Ito, J. Soda, EPJC 80, 545 (2020)
  S. Kanno, J. Soda, PRD 99, 084010 (2019)
  E. D. Herbschleb, H. Kato, T. Makino, S. Yamasaki & N. Mizuochi, Nature Communications 12, 306 (2021)
  S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein, A. Bassi, Nature Physics 17, 74 (2021)
  A. Datta, H. Miao, Quantum Science and Technology 6, 045014 (2021)
  D. Carney, H. Müller, J. M. Taylor, PRX Quantum 2, 030330 (2021)
  S. Kanno, J. Soda, J. Tokuda, PRD 104, 083516 (2021)
  Y. Kamiya, R. Cubitt, L. Porcar, O. Zimmer, G. N. Kim, S. Komamiya, AIP Conference Proceedings 2319, 040017 (2021)
- **Some other topics from the workshop**
  Weak gravity conjecture
  Emergent gravity (entropic gravity)
  Holographic principle
  Chameleon dark energy

- 17 pages in total

The Workshop

- 基研研究会「巨視的量子現象と量子重力」
  YITP Workshop “Macroscopic Quantum Phenomena and Quantum Gravity”
  http://www2.yukawa.kyoto-u.ac.jp/~qg21/
- 16 talks in 4 days (October 11-14, 2021)
- In-person only workshop limited to 50 people
- No banquet, only one coffee break a day
- My first in person workshop & visit to Kyoto since February 2020 (QFilter Workshop @ Kyoto)

The Program

１０月１１日（月）	１０月１２日（火）	１０月１３日（水）	１０月１４日（木）
	9:30 - 10:30 松本 伸之	9:30 - 10:30 松村 央	9:30 - 10:30 徳田 順生
休憩＆議論			
11:00 - 11:30 Opening	11:00 - 11:30 J.G. Santiago-Condori	11:00 - 11:30 三木 大輔	11:00 - 11:30 片山 春菜
11:30 - 12:30 早田 次郎	11:30 - 12:10 前田 新也 議論	11:30 - 12:00 杉山 祐紀 12:00-12:30 山本 一博	11:30 - 12:30 神谷 好郎
ランチ＆議論			12:30 - 13:00 Closing 議論
14:30 - 15:30 山本 慧	14:30 - 15:30 水落 憲和	14:30 - 15:30 堀田 昌寛	
休憩＆議論			
16:00 - 16:30 菅野 優美	16:00 - 16:30 吉野 裕高	16:00 - 16:30 古郡 秀雄	
議論			

Gravity induced entanglement

Decoherence from gravitons

Pendulum

State estimation

Magnon, axion, high frequency GWs

Optomechanics and entanglement

Quantum-circuit black hole lasers

Electromagnetically induced entanglement

Slow neutrons

Testing quantumness of gravity

Surface acoustic waves

Legget-Garg inequality

Quantum information

NV-center

Gravitational memory effect

Quantumness of primordial GWs

Schrodinger-Newton, Károlyházy, DP model

Some Papers

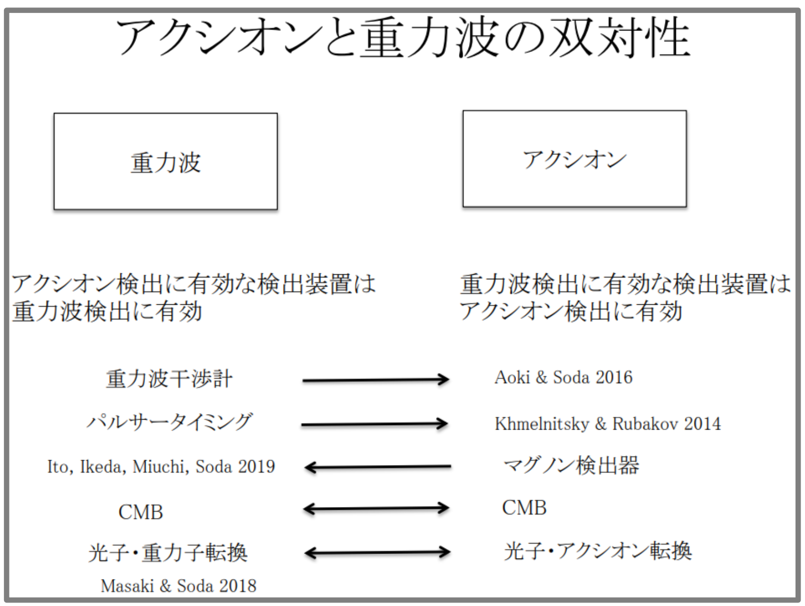
Disclaimer:
- One slide for one paper
- I did not read the whole story, and most of my understanding is from the workshop presentations and discussions

- A. Ito, J. Soda, EPJC 80, 545 (2020)
  A formalism for magnon gravitational wave detectors
- S. Kanno, J. Soda, PRD 99, 084010 (2019)
  Detecting nonclassical primordial gravitational waves with Hanbury-Brown–Twiss interferometry
- E. D. Herbschleb, H. Kato, T. Makino, S. Yamasaki & N. Mizuochi, Nature Communications 12, 306 (2021)
  Ultra-high dynamic range quantum measurement retaining its sensitivity
- S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein, A. Bassi, Nature Physics 17, 74 (2021)
  Underground test of gravity-related wave function collapse
- A. Datta, H. Miao, Quantum Science and Technology 6, 045014 (2021)
  Signatures of the quantum nature of gravity in the differential motion of two masses
- D. Carney, H. Müller, J. M. Taylor, PRX Quantum 2, 030330 (2021)
  Using an Atom Interferometer to Infer Gravitational Entanglement Generation
- S. Kanno, J. Soda, J. Tokuda, PRD 104, 083516 (2021)
  Indirect detection of gravitons through quantum entanglement
- Y. Kamiya, R. Cubitt, L. Porcar, O. Zimmer, G. N. Kim, S. Komamiya, AIP Conference Proceedings 2319, 040017 (2021)
  Experimental search for Non-Newtonian forces in the nanometer scale with slow neutrons

A. Ito, J. Soda, [EPJC 80, 545 (2020)]

Magnon GW detector

- Axion detector can be used also for GW (and vise versa)
- They placed new constraints on 8.2 GHz and 14 GHz continuous GWs using existing data from magnon experiment



http://www.kylab.sci.waseda.ac.jp/darkon2019/

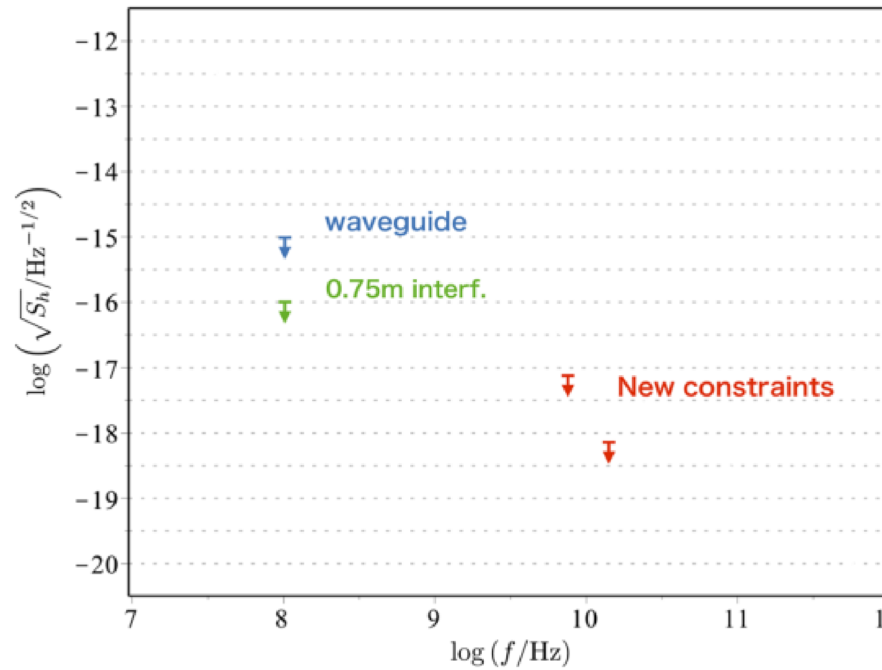


Fig. 1 Several experimental sensitivities and constraints on high frequency gravitational waves are depicted. The blue color represents an upper limit on stochastic gravitational waves by waveguide experiment using an interaction between electromagnetic fields and gravitational waves [20]. The green one is the upper limit on stochastic gravitational waves, obtained by the 0.75 m interferometer [19]. Our new constraints on continuous gravitational waves are plotted with a red color, which also represent the sensitivity of the magnon gravitational wave detector for stochastic gravitational waves

Since statistical properties of CW GWs and axions are different, I think this is more like a sensitivity rather than (strict) constraint.

S. Kanno, J. Soda, [PRD 99, 084010 (2019)]

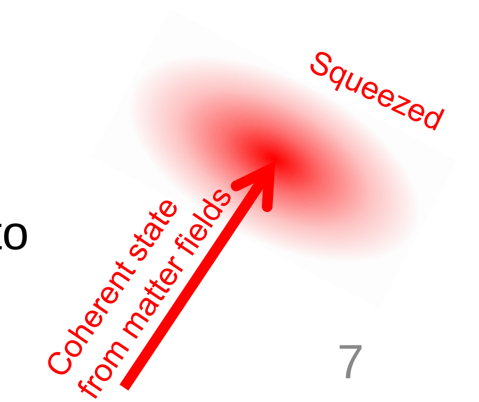
Nonclassical Primordial GWs

- Primordial GWs from inflation arise out of quantum fluctuations from space-time
- During inflation, this fluctuation is squeezed (phase quadrature is squeezed)
- If the number of gravitons detected follows sub-Poissonian statistics, we can prove the quantumness of primordial GWs
- This can be done using Hanbury-Brown–Twiss interferometer which measures intensity-intensity correlations

Quantum version of autocorrelation?

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t) a^\dagger(t+\tau) a(t+\tau) a(t) \rangle}{\langle a^\dagger(t) a(t) \rangle \langle a^\dagger(t+\tau) a(t+\tau) \rangle}, \qquad (24)$$

- In the case of light (photons), this can be done by measuring the power with a photodiode
- In the case of GWs (gravitons), this can be done by measuring the GWs with a GW detector
- Direction of coherent state and the squeezed angle needs to be matched so that it is squeezed in amplitude



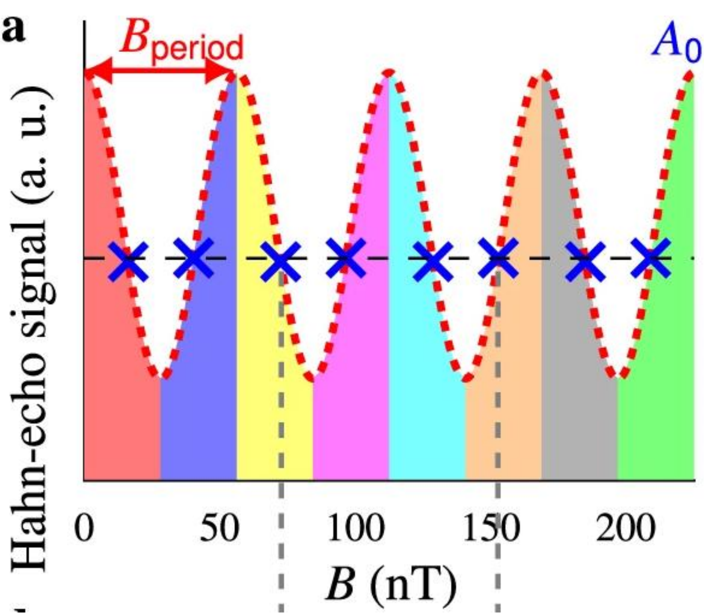
We can measure the phase of GWs but not for the light. Intensity of GWs?

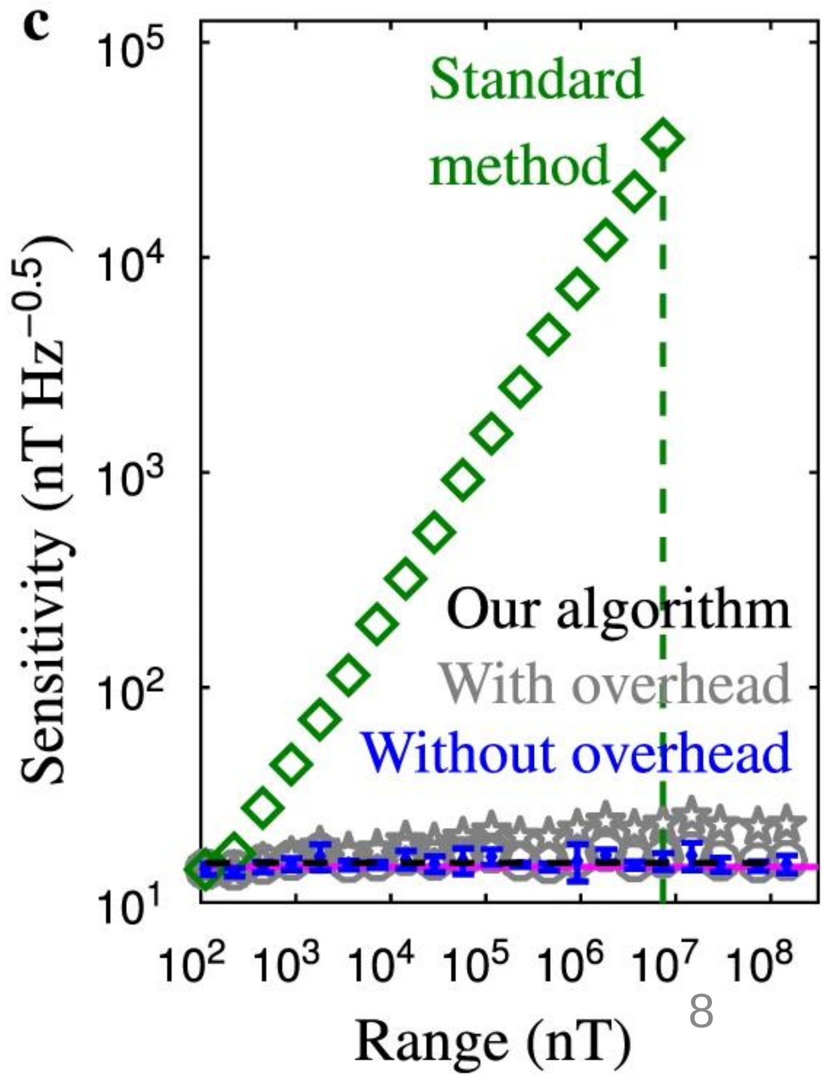
E. D. Herbschleb, H. Kato, T. Makino, S. Yamasaki & N. Mizuochi, [Nat. Commun. 12, 306 (2021)]

High Dynamic Range NV-center

- NV-center based magnetic field measurements can have higher dynamic range than SQUID etc., since it works under high DC magnetic field
- Demonstrated a dynamic range of ~10^7 using a new algorithm
  by combining multiple pulse periods
  in an optimal way (as far as I understand)

We should be able to use this as a displacement sensor…





S. Donadi, K. Piscicchia, C. Curceanu, L. Diósi, M. Laubenstein, A. Bassi, Nat. Phys. 17, 74 (2021)

Natural DP model Ruled Out

- Diósi–Penrose model (gravity-related wave function collapse)
- If a charged particle accelerates and deaccelerates due to noise from DP, it will emit radiation and the radiation rate depends on the cut-off length R_0
- Dedicated experiment at Gran Sasso to measure the radiation emission rate of germanium crystal

Effect of electromagnetic force for this experiment, considering this uses charged particles?

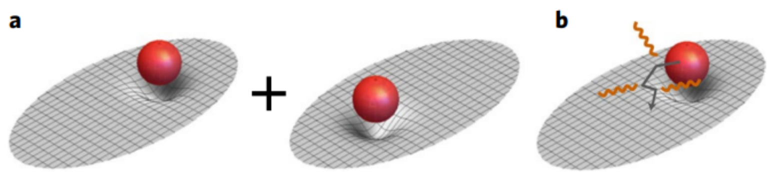


Fig. 1 | The Diósi-Penrose (DP) model of gravity-related wave function collapse. a, According to quantum gravity, a spatial quantum superposition of a system (red sphere) generates a superposition of different spacetime curvatures (grey sheets), corresponding to the possible different locations of the system. Penrose argues that a superposition of different spacetimes is unstable and decays in time, making the system's wave function also collapse. He provides an estimate for the time of collapse as given in equation (1), which is faster for a larger system, similar to that suggested earlier by Diósi. **b**, The master equation of the DP model (equation (3)) predicts not only the collapse of the wave function, but also an omnipresent Brownian-like diffusion (represented by the grey arrow) for each constituent of the system. When the constituents are charged (protons and electrons), the diffusion is accompanied by the emission of radiation (wavy orange lines), with a spectrum that depends on the configuration of the system. This is given by equation (4) in the range $\Delta E = (10\text{–}10^5)$ keV of photon energies. The predicted radiation emission is faint but potentially detectable by an experiment performed in a very low-noise environment. We performed such an experiment to rule out the original parameter-free version of the DP model.

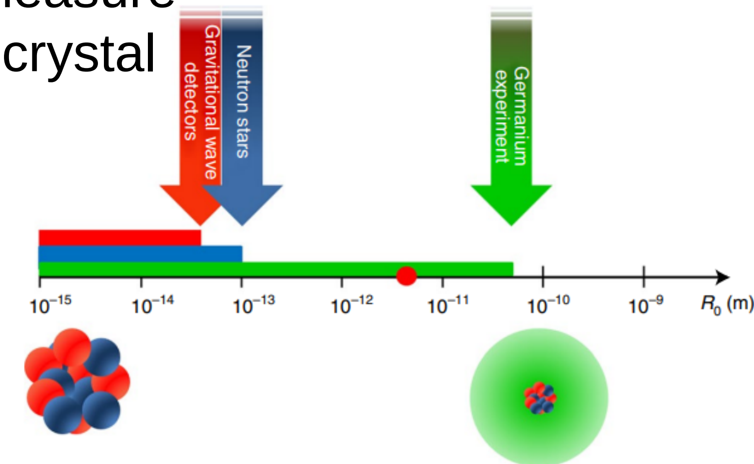


Fig. 5 | Lower bounds on the spatial cutoff R_0 of the DP model. According to Penrose, $R_0 = 0.05 \times 10^{-10}$ m for the germanium crystal used in the experiment (red circle on the horizontal scale). Our experiment sets a lower bound on R_0 at 0.54×10^{-10} m (green bar and arrow), which is one order of magnitude larger than predicted following Penrose's argument. Therefore, this parameter-free version of the DP model is excluded. The figure shows also previous lower bounds in the literature, similarly based on the monitoring of the Brownian-like diffusion predicted by the DP model. They refer to data analysis from gravitational wave detectors[36] ($R_0 \geq (40.1 \pm 0.5) \times 10^{-15}$ m, red bar and arrow) and neutron stars[42] ($R_0 \gtrsim 10^{-13}$ m, blue bar and arrow). The figure shows the range of hypothetical values of R_0, from the size of a nucleus (red-blue cluster) to beyond that of an atom (green halo surrounding the red-blue nucleus).

A. Datta, H. Miao, Quantum Science and Technology 6, 045014 (2021)

Quantum Entanglement by Gravity

- No gravity
  - No frequency shifts, no squeezing
- With gravity
  - squeezing when differential mode measured at ω_+
  - no squeezing for common mode

Differential mode frequency

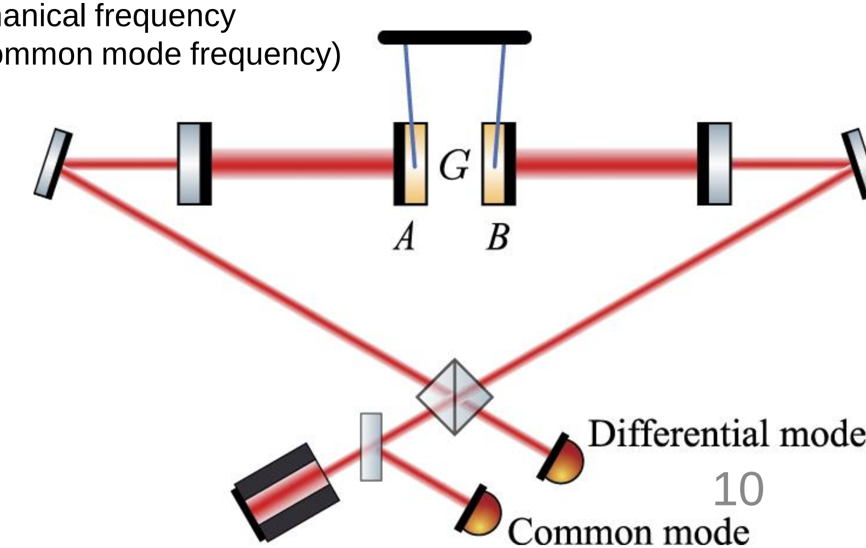
$$\omega_- = \omega_m\sqrt{1-\delta^2}, \quad \delta = \frac{2\omega_G}{\omega_m}, \quad \omega_G = \sqrt{\frac{Gm}{d^3}}.$$

Mechanical frequency
(= Common mode frequency)

- Semiclassical gravity (Schrodinger-Newton)
  - ω_+ and ω_- shift to ω_{SN}

$$\omega_{\rm SN} = \omega_m\sqrt{1-\frac{2C_2}{m\omega_m^2}}.$$

  - no squeezing at ω_{SN} but squeezing at ω_m
  - no entanglement



Quantum Entanglement

- Quantum entanglement cannot be generated with Local Operations and Classical Communication (LOCC)

R. Horodecki+, Rev. Mod. Phys. 81 865 (2009)

- If quantum entanglement mediated by gravity can be generated, we can prove that gravitational interaction is a quantum process (assuming causality)

D. Carney, H. Müller, J. M. Taylor, PRX Quantum 2, 030330 (2021)

Atom ITF & Mechanical Oscillator

- Thermal noise of mechanical oscillator does not matter (!?)

If gravitational perturbations are quantized into gravitons in analogy with the electromagnetic field and photons, the resulting graviton interactions should lead to an entangling interaction between massive objects. We suggest a test of this prediction. To do this, we introduce the concept of interactive quantum information sensing. This novel sensing protocol is tailored to provable verification of weak dynamical entanglement generation between a pair of systems. We show that this protocol is highly robust to typical thermal noise sources. Moreover, the sensitivity can be increased both using an initial thermal state and/or an initial phase of entangling via a nongravitational interaction. We outline a concrete implementation testing the ability of the gravitational field to generate entanglement between an atomic interferometer and a mechanical oscillator. Preliminary numerical estimates suggest that near-term devices could feasibly be used to perform the experiment.

- Probe is atom interferometer

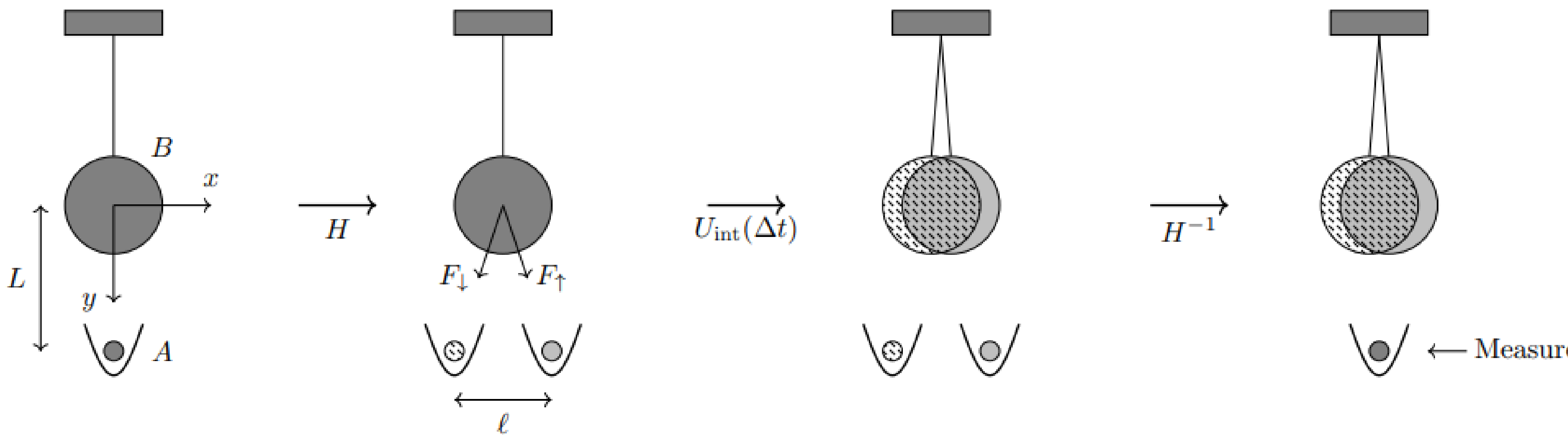


FIG. 1. Implementation of the basic protocol using an atom interferometer and a suspended pendulum (see Sec. VI). A trapped atom (labeled A) is prepared some distance L away from a mechanical resonator (B, here pictured as a pendulum). The atom is then put into a superposition of two different locations separated by ℓ, effecting a Hadamard gate H. This generates a state-dependent force between the atoms and resonator, leading to motion in opposite directions for some time Δt. Finally, the atom state is recombined using the inverse Hadamard gate and measured to check for decoherence caused by the atom-mechanical interaction. When the resonator undergoes a complete period of motion, its state no longer depends upon the atoms and coherence is recovered for the interferometer.

S. Kanno, J. Soda, J. Tokuda, [PRD 104, 083516 (2021)]

Decoherence from Gravitons

- There's noise from gravitons for gravitational wave detectors

M. Parikh, F. Wilczek, G. Zahariade, [IJMPD 29, 2042001 (2020)]

- Similarly, there's also a decoherence from gravitons through bremsstrahlung
- Decoherence time is ~20 sec for 40 kg, 40 km interferometer with a pendulum frequency of 1 kHz
- Not sure why this depends on the arm length

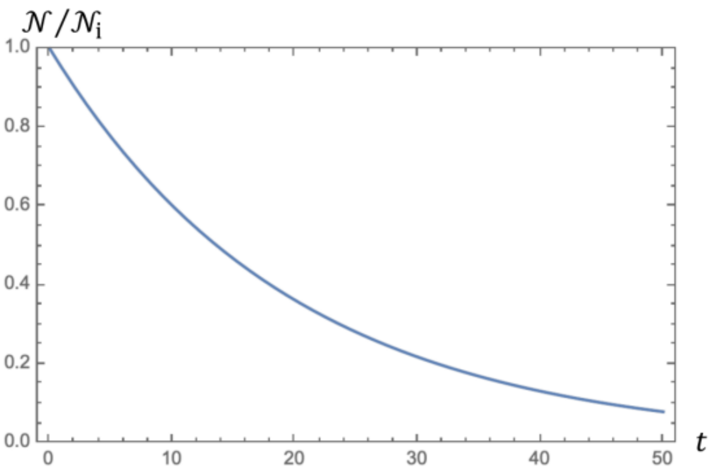
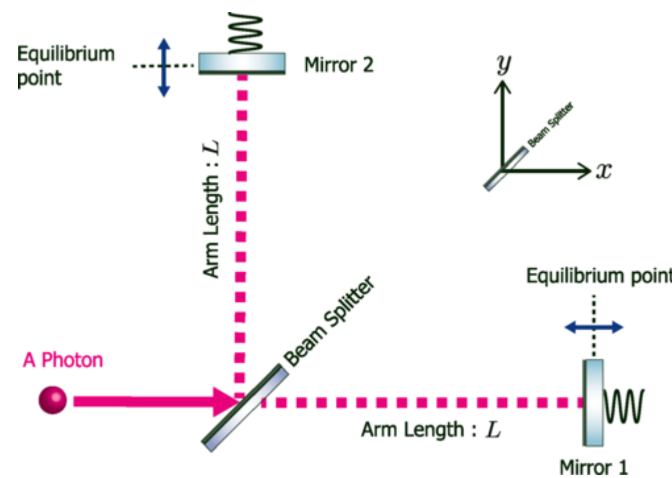


FIG. 2. Time evolution of negativity normalized by the initial value $\mathcal{N}_i$ for $\omega = 1$ kHz, $L = 40$ km, $m = 40$ kg, and $f_c = 10^9$ Hz. The negativity decays with the decoherence time 20 s.

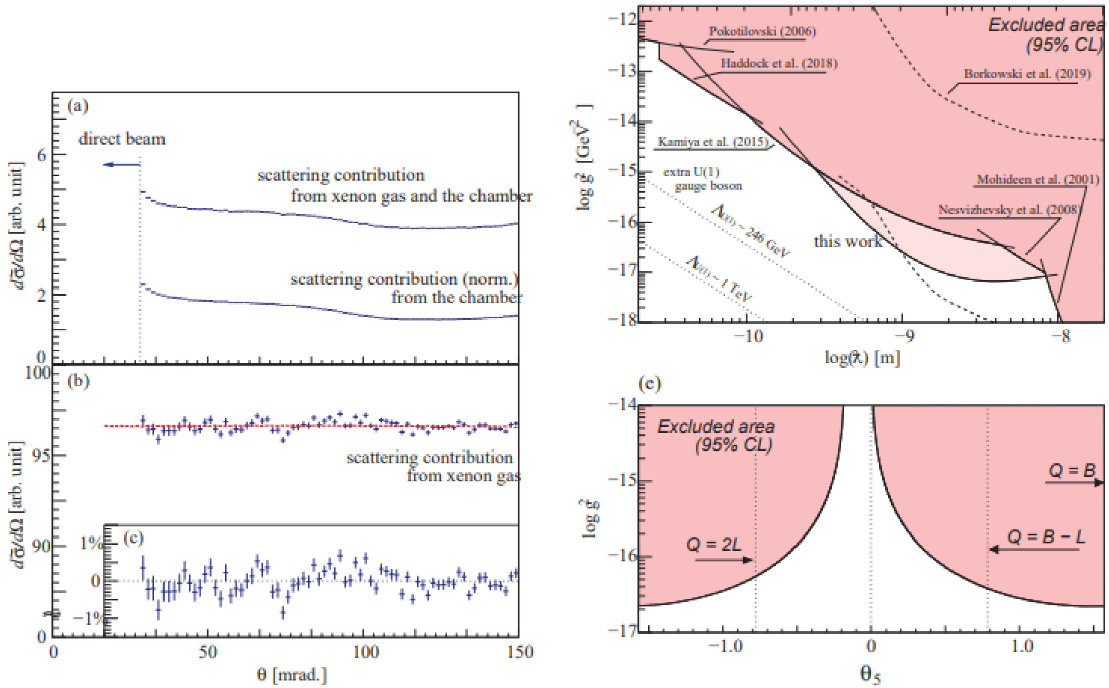


Cut-off frequency of primordial gravitational waves

Y. Kamiya+, AIP Conf. Proceedings 2319, 040017 (2021)

New Limit on Non-Newtonian Force

- Also new interpretation considering a charge of new interaction $Q = B\sin\theta_5 + (B-2L)\cos\theta_5$



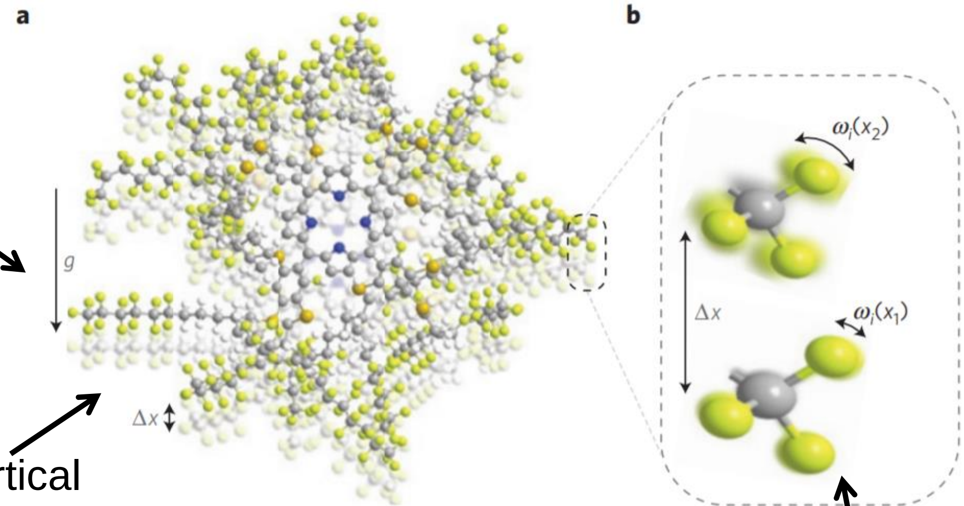
I'm interested to see this result converted into B-L coupling constant

FIGURE 2. (a) Measured angular distributions for the cat.4 data (above) and for the cat.2 data (below). The cat.2 distribution is normalized using the transmission of xenon gas. The contribution from beam background of the cat.0 data, not shown in the figure, is a flat distribution and smaller than the scattering data by three orders of magnitude. (b) Extracted angular distribution due to the scattering off the xenon gas. The red dashed line shows a best fit (see text). (c) Residuals from the best fit function. (d) Obtained 95% CL limits in the Yukawa-type g^2 - $\lambdabar$ parameter space ($\lambdabar \equiv 1/\mu$). The upper dashed line represents a result using spectroscopy of weakly bound Yb_2 molecule [15]. The lower dashed line shows the prospective precision of this new method. Theoretical predictions due to extra U(1) gauge bosons are shown as dashed lines for symmetry braking scales of $\Lambda_{U(1)} \sim 246$ GeV and ~ 1 TeV [5]. (e) Re-interpretation of our new limits for $\lambdabar = 1$ nm (as an example) to the model in which a coupling charge Q is expressed as a linear combination of the baryon and the lepton number, B and L, as a function of the mixing angle θ_5.

I. Pikovski, M. Zych, F. Costa Č. Brukner, [Nature Physics 11, 668 (2015)]

Decoherence From Time Dilation

- Time dilation from Earth's gravitational field is responsible for decoherence, and this is universal



TPPF20 in a vertical superposition

Clock run slower

Universal decoherence due to gravitational time dilation

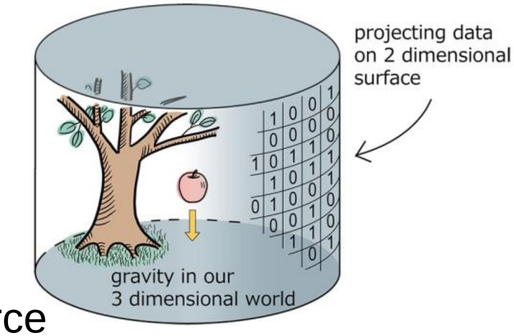
Igor Pikovski[1,2,3,4★], Magdalena Zych[1,2,5], Fabio Costa[1,2,5] and Časlav Brukner[1,2]

The physics of low-energy quantum systems is usually studied without explicit consideration of the background spacetime. Phenomena inherent to quantum theory in curved spacetime, such as Hawking radiation, are typically assumed to be relevant only for extreme physical conditions: at high energies and in strong gravitational fields. Here we consider low-energy quantum mechanics in the presence of gravitational time dilation and show that the latter leads to the decoherence of quantum superpositions. Time dilation induces a universal coupling between the internal degrees of freedom and the centre of mass of a composite particle. The resulting correlations lead to decoherence in the particle position, even without any external environment. We also show that the weak time dilation on Earth is already sufficient to affect micrometre-scale objects. Gravity can therefore account for the emergence of classicality and this effect could in principle be tested in future matter-wave experiments.

Some Open Questions

- Need for gravity experiments that can differentiate uniform acceleration and gravity?
- What is special about gravity which is different from electromagnetic force?
  - Equivalence principle
  - Cannot be shielded
- Quantum entanglement via gravity do not mean we have to quantize gravity; we can only kill Schrodinger-Newton. What are the further things we can do?
- Leggett-Garg inequality can be used?

Some Other Topics



https://www.ipmu.jp/en/node/2174

- Weak gravity conjecture

  There is at least one particle on which gravity is the weakest force

  ε_B-L > 1e-29 for neutrino (assuming lightest neutrino mass is 0.01 eV)

- Emergent gravity (entropic gravity)

  Gravity is not a fundamental interaction. Will it break the quantum coherence?

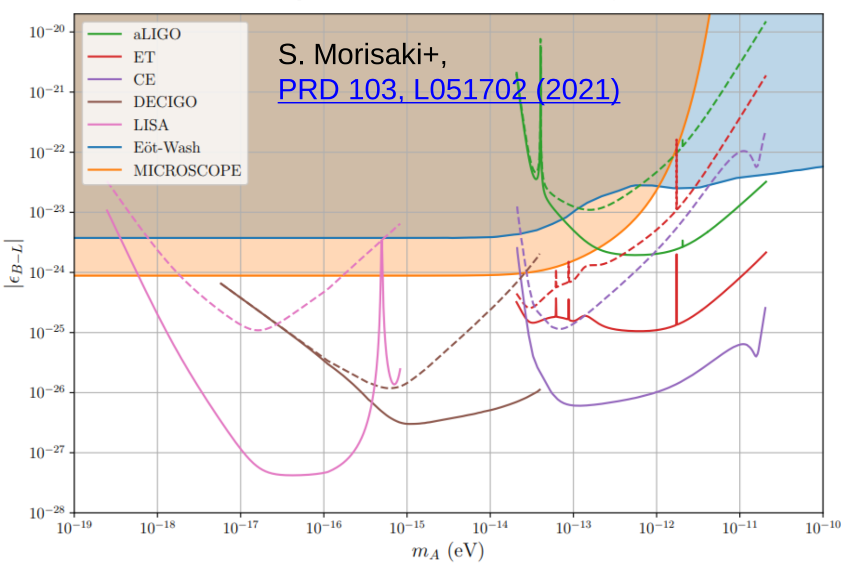
- Holographic principle

  Gravity doesn't have to be quantized? New ideas for Holometer?

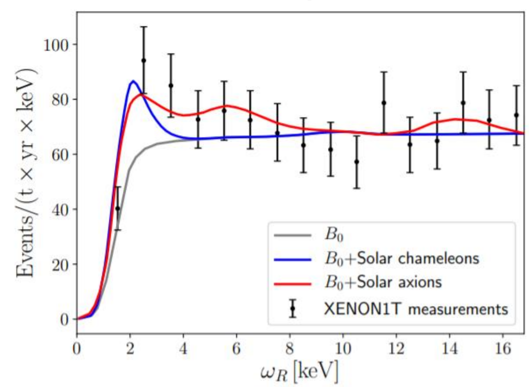
- Chameleon dark energy

  Various mass depending on ambient energy density

  Can explain accelerating universe, but evade fifth-force experiments



S. Morisaki+,
PRD 103, L051702 (2021)



S. Vagnozzi+,
PRD 104, 063023 (2021)

FIG. 1. Benchmark example of a solar chameleon fit to the XENON1T signal (event rate in units of ton^{-1} yr^{-1} keV^{-1} versus recoil energy in units of keV), representative of the best achievable fit within this scenario. The chameleon parameters are fixed to $\beta_e = 10^2$, $M_e = 10^{3.6}$ keV, $\beta_\gamma = 10^{10}$, $M_\gamma = 1000$ TeV, $\Lambda = 1\,\mu$eV, and $n = 1$. The black