Towards low-energy tests of quantum gravity

From quantum gravity phenomenology to graviton detection

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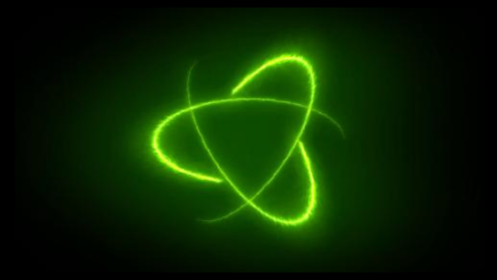
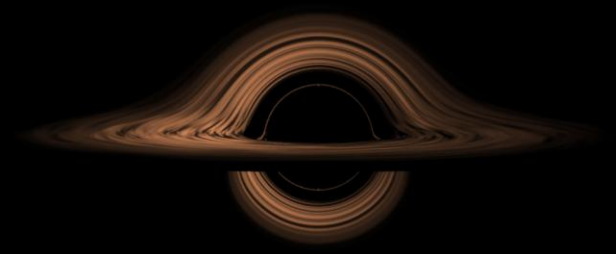
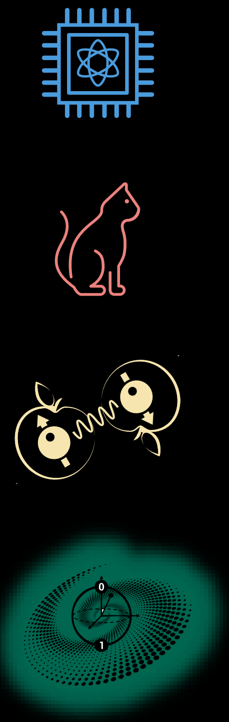
PIKOVSKI GROUP: INTERFACE OF QUANTUM & GRAVITY



Where do gravity & quantum meet?

Experiments?





Theory of:

- Quantum optics & information
- Quantum sensing
- Macroscopic quantum systems
- Gravity effects in QM
- Quantum signatures of gravity
- Foundations of QM and GR

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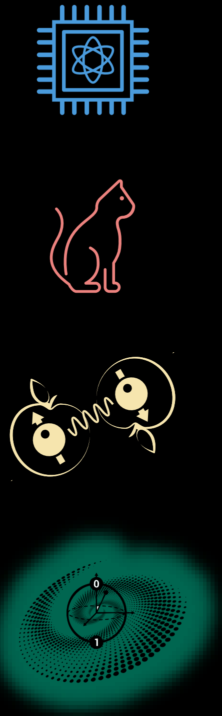
PIKOVSKI GROUP: INTERFACE OF QUANTUM & GRAVITY

Alex Johnson
Poster on:
"Quantum Sensing through Quantum Error Correction"

Thomas Beitel:
Poster on
"Graviton Detection and Its Quantum Aspects"



Theory of:

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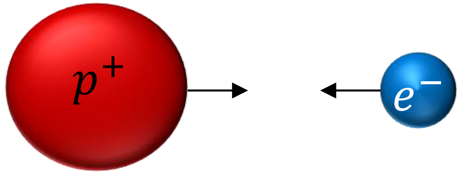
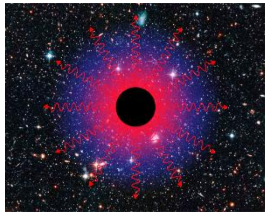
DEMOTIVATION: NO HOPE OF TESTING QUANTUM GRAVITY?

- Gravity is extremely weak. Compare F_E to F_G between e^- and p^+: $\frac{F_E}{F_G} = 10^{39}$



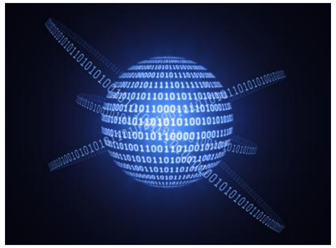
- Planck-scale on extreme scales:

  $10^{-35}m \sim 10^{44}Hz \sim 10^{19}GeV \sim 22\mu g$



- Hawking radiation: $T \sim 1\, nK\, [\frac{M}{60M_\odot}]^{-1}$
- Graviton cross-section: $\sigma \sim L_p^2 \cong 10^{-70}m^2$
- Detecting a single graviton with Ligo: $\frac{\Delta L}{L} \sim 10^{-40}$

- Maximum information: Bekenstein bound $I \sim 10^{43}[\frac{r}{1km}][\frac{M}{1kg}]$ bits



Until recently: common wisdom that no table-top experiment can test QGR

OVERVIEW: TOWARDS LOW-ENERGY TESTS OF QUANTUM GRAVITY

- First steps to testing quantum gravity: gravitational "decoherence"

  W. Marshall, C. Simon, R. Penrose, D. Bouwmeester. PRL 91, 130401 (2003);
  D. Kleckner, I. Pikovski* et al. NJP 10, 095020 (2008)*

- New domain: quantum gravity phenomenology in table-top experiments

  I. Pikovski, M. Vanner, M. Aspelmeyer, M. Kim, Č. Brukner. Nature Physics 8, 393-397 (2012)
  P.A. Bushev et al., PRD ,066020 (2019)

- Indirect test of expected quantum gravity: gravitational entanglement

  Bose et al. PRL 119, 240401 (2017), Marletto, Vedral. PRL 119, 240402 (2017)
  V. Fragkos, M. Kopp*, I. Pikovski. AVS Quantum Sci. 4, 045601(2022)*

- Direct probe of (linear) quantum gravity: Graviton detection

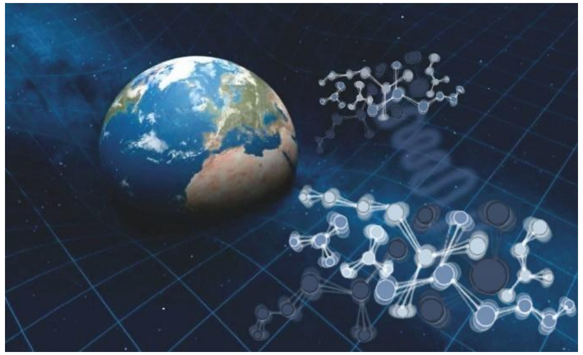
  S. Boughn, T. Rothman. Classical and quantum gravity, 23, 5839 (2006)
  G. Tobar, S. Manikandan*, T. Beitel, I. Pikovski. Nature Commun. 15, 7229 (2024)*

GRAVITATIONAL COLLAPSE OF THE WAVE FUNCTION

- Traditionally: search for a *quantum* theory of gravity

Canonical	Covariant	Path integral
$H\,\psi[g_{ij}] = 0$	$g_{\mu\nu} = \tilde{g}_{\mu\nu} + h_{\mu\nu}$	$\int \mathcal{D}[field\ histories]\, e^{\frac{i}{\hbar} Action}$
Hamiltonian quantization	Perturbative QFT on a background	Functional integral quantization
Wheeler-DeWitt	*Supergravity*	*Discrete quantum gravity*
Loop quantum gravity	*String theory*	*Spin foam*

- But could quantum mechanics be incorrect?
- Penrose: "Classicalize" quantum mechanics: postulated collapse of the superposition principle

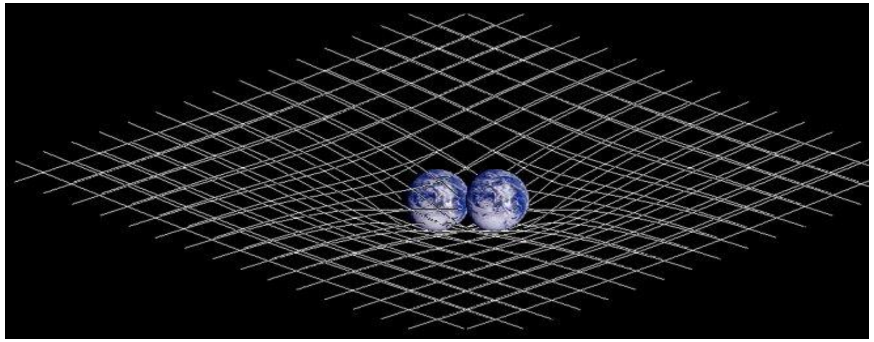


GRAVITATIONAL COLLAPSE OF THE WAVE FUNCTION ARGUMENT

Penrose‘s proposal: Gravity responsible for **breakown** of unitarity. His argument:

R. Penrose. General relativity and gravitation, 28, 581-600 (1996)

- A massive object in a superposition: Include its gravitational field.
- Two different space-times provide different time evolution “d/dt“ in evolution equation
- In GR one cannot compare two distinct space-time structures



- Cannot find *single* time evolution operator - unitary evolution of superposition will have intrinsic error.
- Try to quantify error in identification of the two spacetimes:

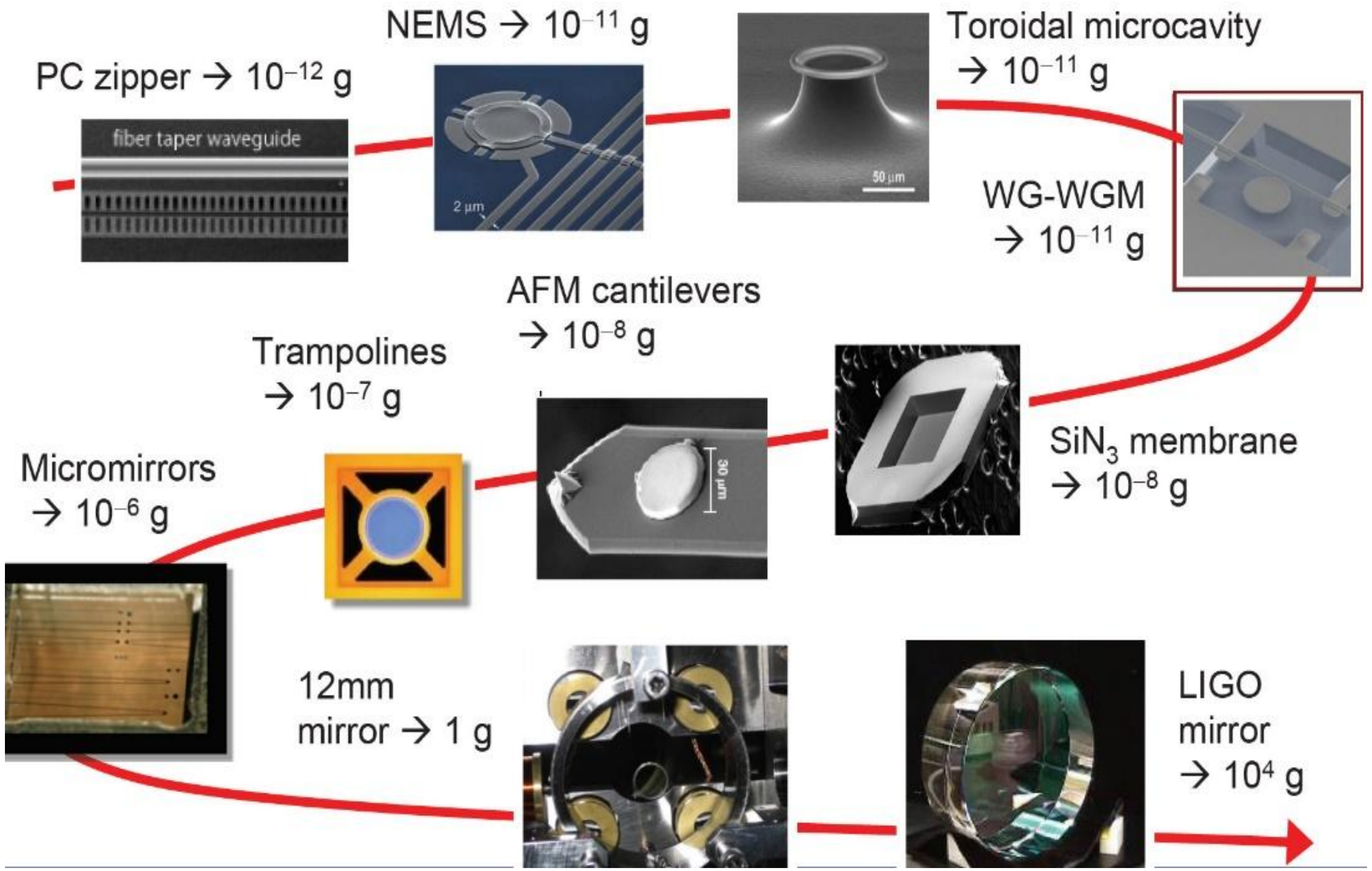
$$\Delta E = -G \int d^3x \int d^3y \, \frac{(\rho(x) - \rho'(x))(\rho(y) - \rho'(y))}{|x-y|} \qquad \tau_G \approx \hbar/\Delta E$$

Significant for masses $m \gtrsim 1ng$

- Hopeless to reach such massive superpositions?

BIRTH OF OPTOMECHANICS

Quantum optomechanics

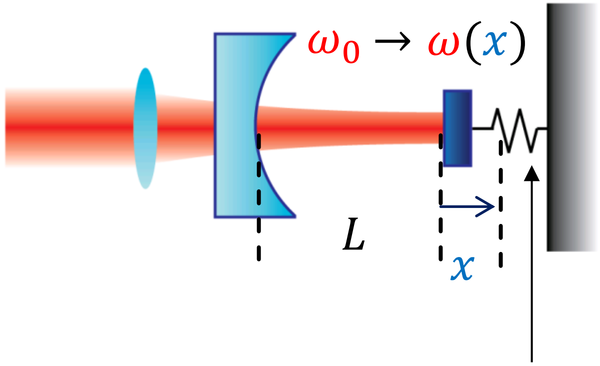


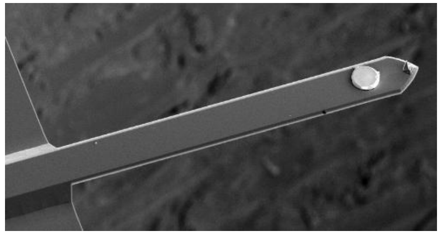
Taken from: N. Mavalvala, *Les Houches lecture* (2015)

- 1995-1999: optomechanics theory developed
- New physical regime of quantum mechanics
- Enables the study of macroscopic quantum systems

OPTO-MECHANICS

Light in a cavity displaces a small mirror by radiation pressure:
Massive mechanical oscillator interacts with light.





Opto-mechanical interaction:

i. Free cavity: $\hat{H} = \hbar\omega_0\hat{n}_L$, $\quad \omega_0 = \frac{4\pi c}{n\,L}$

ii. Radiation pressure changes $L \to L + x$: $\quad \omega_0 \to \omega_0\,(1 - \frac{x}{L})$

iii. Quantize $x \to \hat{x}_m$

$$\hat{H} = \hbar\omega_m\hat{n}_m + \hbar\omega_L\hat{n}_L - \hbar g_0\hat{n}_L\hat{X}_m, \qquad g_0 = \frac{\omega_L}{L}\sqrt{\frac{\hbar}{m\omega_m}}$$ coupling rate

- Quantum mechanics with macroscopic and massive objects. Mirrors can have mass of pg – kg
- Possibility to explore quantum physics on a novel scale.

OPTO-MECHANICS

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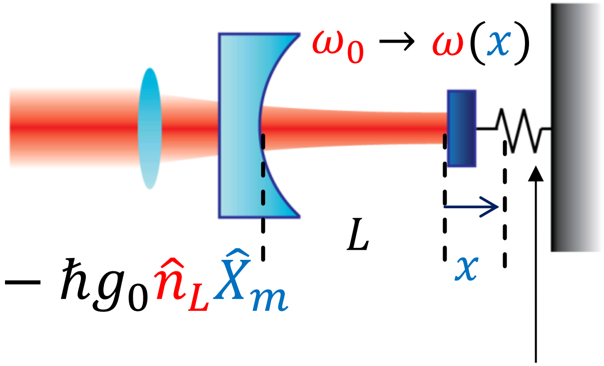
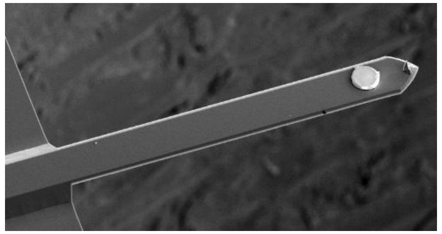




Opto-mechanical Unitary: $\hat{U} = e^{-i\hat{H}t/\hbar}$ $\quad$ $\hat{H} = \hbar\omega_m\hat{n}_m + \hbar\omega_L\hat{n}_L - \hbar g_0\hat{n}_L\hat{X}_m$

Transform using: $\hat{S} = e^{-i\kappa\,\hat{n}_L(\hat{b}-\hat{b}^\dagger)}$ $\quad$ $\kappa = \dfrac{g_0}{\omega_L}$

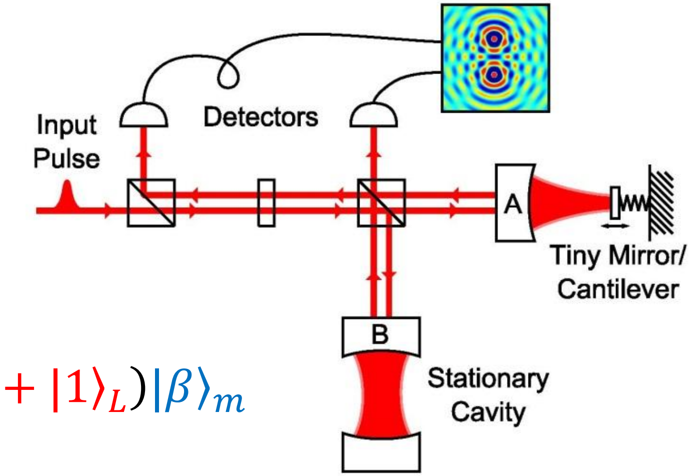
$$\hat{S}\hat{b}_m\hat{S}^\dagger = \hat{b}_m + \kappa\hat{n}_L$$

$$\hat{U} = \hat{S}^\dagger\hat{S}\hat{U}\hat{S}^\dagger\hat{S} = e^{-i\omega_L t\hat{n}_L} e^{-i\kappa^2\omega_L t\hat{n}_L^2}\hat{S}^\dagger e^{-i\omega_m t\hat{n}_m}\hat{S}$$

Use BCH to swap $\hat{S}^\dagger$and $e^{-i\omega_m t\hat{n}_m}$

$$= e^{-i\omega_L t\hat{n}_L} e^{-i\kappa^2\hat{n}_L^2(\omega_L t-\sin(\omega_L t))}\underbrace{e^{-i\kappa\hat{n}_L(\hat{b}^\dagger(1-e^{i\omega_m t})-\hat{b}(1-e^{-i\omega_m t}))}}_{\text{Photon-dependent displacement } \hat{D}(\kappa\hat{n}_L(1-e^{i\omega_m t}))} e^{-i\omega_m t\hat{n}_m}$$

PROPOSED EXPERIMENT TO TEST PENROSE COLLAPSE



Idea: Use single photon in superposition to create and read out quantum superposition of a much larger system.

W. Marshall, C. Simon, R. Penrose, D. Bouwmeester. PRL 91, 130401 (2003);
D. Kleckner, I. Pikovski et al. NJP 10, 095020 (2008)

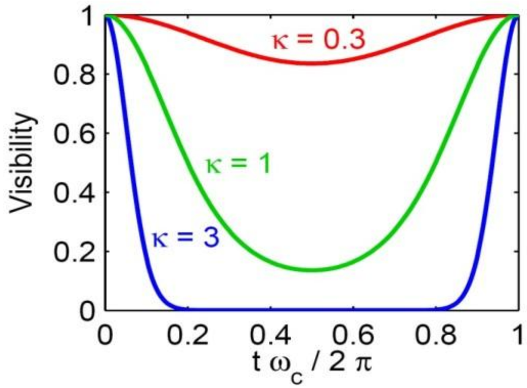
In one arm, a tiny mirror is displaced by the photon: $|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|0\rangle_L + |1\rangle_L)|\beta\rangle_m$

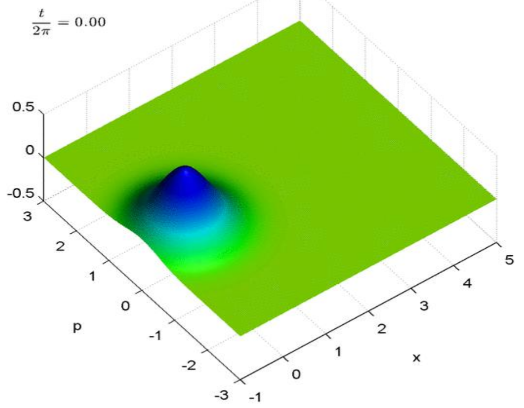
$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_L \left|\beta e^{-i\omega_m t}\right\rangle_m + e^{i\varphi}|1\rangle_L \left|\beta e^{-i\omega_m t} + \kappa\left(1 - e^{-i\omega_m t}\right)\right\rangle_m\right)$$

$\kappa = \frac{g_0}{\omega_L}$ single photon coupling rate

Mirror is probed by measuring quantum interference of the photon:

Interference periodically vanishes due to which-path-information: $V = e^{-\kappa^2(1-\cos(\omega_m t))}$

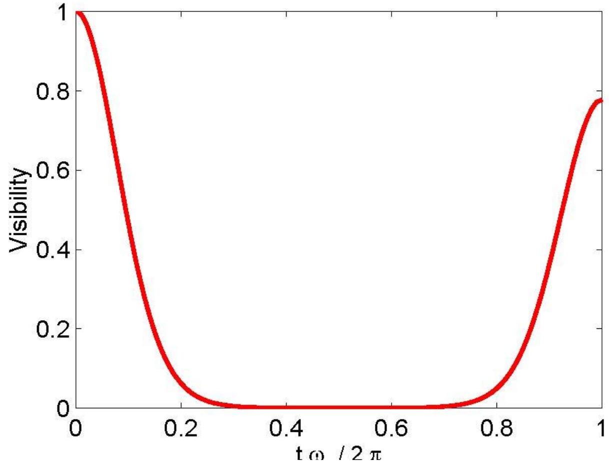




Macroscopic superposition if: $\boxed{\kappa \gtrsim 1/\sqrt{2}}$

(One photon displaces mirror strongly enough)

PROPOSED EXPERIMENT TO TEST PENROSE COLLAPSE

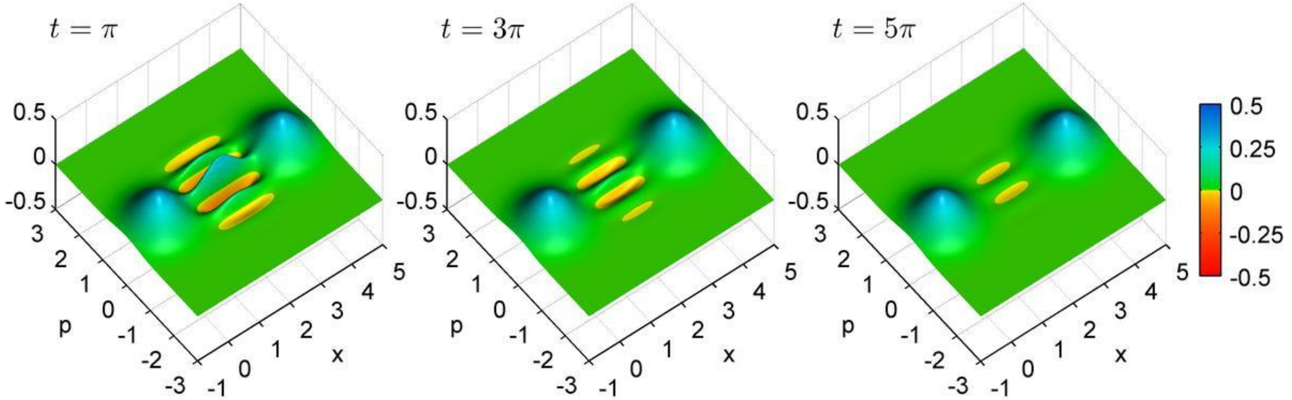


Signature of Penrose collapse: No full revival!

Effect: Reduction of visibility revival peaks. But so does decoherence:

- Phonon dissipation
- Thermal bath
- Scattering of surrounding particles
- Impurities in cantilever
- …

Penrose collapse estimate
(granular mass of size a) :



$$\Delta E = 2Gmm_1\left(\frac{6}{5a} - \frac{1}{\Delta x}\right) \quad (\text{given: } \Delta x \geq 2a$$

$$\tau_G \approx \begin{cases} 1ms & a = 10^{-15}m \\ 1s & a = \sqrt{\frac{\hbar}{m\omega_c}} \end{cases}$$

Hard to this day, but lots of experimental effort

D. Kleckner, I. Pikovski et al. New Journal of Physics 10, 095020 (2008)

FROM COLLAPSE TO QUANTUM GRAVITY PHENOMENOLOGY

- Much work has been done towards testing gravitational collapse
- From around ~2012: New ideas on testing *other* aspects of quantum gravity

Testing speculative models of quantum gravity

Marshall et al 2003
Pikovski et al 2012
Bekenstein 2012
Kafri et al 2014
Belenchia et al 2016
Oppenheim 2023
…

High-precision test of new physics beyond QM, GR.

Caveat:
Tests only *speculative* models.
Likely only null-measurements (?)

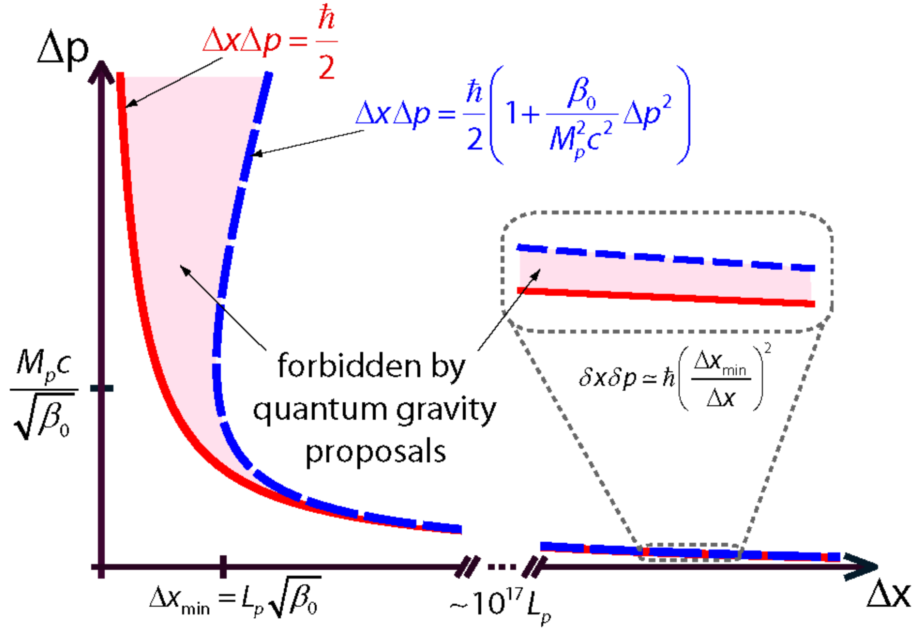
MODIFIED UNCERTAINTY RELATIONS

No complete theory of quantum gravity to date. Few known concrete predictions.

Modified uncertainty relations common to most approaches to quantum gravity:

$$\Delta x\, \Delta p \geq \frac{\hbar}{2}\left(1+\beta_0 \frac{\Delta p^2}{M_{Pl}^2 c^2}\right)$$

(L. Garay, Int. J. Mod. Phys. A10, 145 (1995)
E. Witten, Physics Today 49, 24 (1996))



Key features:

- Restricts allowed state-space
- Minimal physical length $\Delta x_{min} = L_{Pl}\sqrt{\beta_0}$
- Parametrized by free parameter β_0
- Planck-length effect for $\beta_0 \sim 1$

Phenomenologically: can be incorporated into quantum theory through modified algebra

MODIFIED UNCERTAINTY RELATIONS

Many suggested canonical commutator deformations, e.g.:

$$[\hat{X},\hat{P}]_\beta = i\left(1+\beta_0\frac{p_0^2\hat{P}^2}{M_{Pl}^2c^2}+\ldots\right)$$

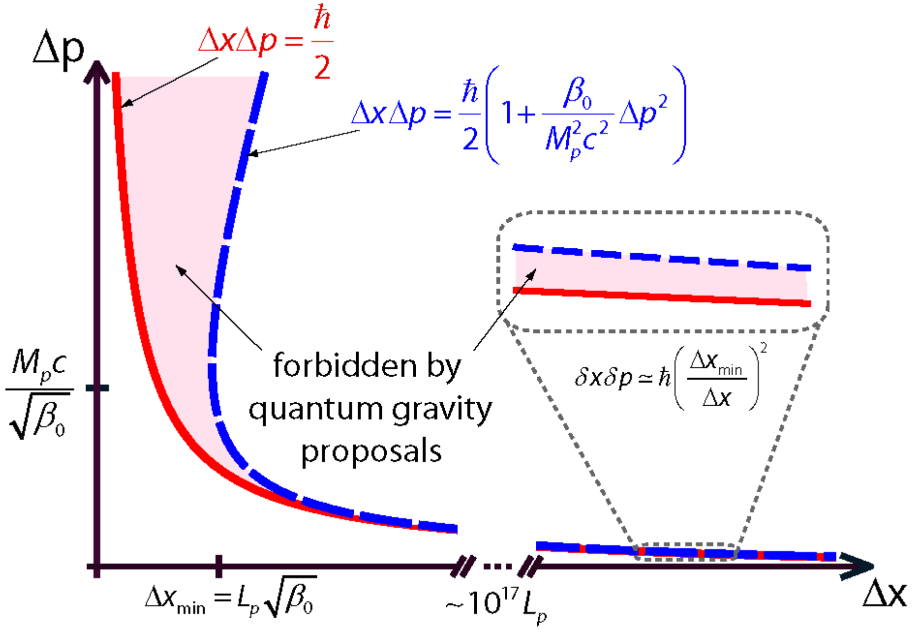
(A. Kempf, G. Mangano and R. Mann, PRD, 52, 2 (1995))

$$[\hat{X},\hat{P}]_\mu = i\sqrt{1+2\mu_0\frac{\left(p_0\hat{P}/c\right)^2+m^2}{M_{Pl}^2}+\cdots}$$

(M. Maggiore, Phys. Lett. B, 319 (1993))

$$[\hat{X},\hat{P}]_\gamma = i\left(1-\gamma_0\frac{p_0\hat{P}}{M_{Pl}c}+\gamma_0{}^2\frac{p_0^2\hat{P}^2}{M_{Pl}^2c^2}+\cdots\right)$$

(A. F. Ali, S. Das and E. C. Vagenas, Phys. Lett. B, 678 (2009))



Examples:

Ions in harmonic trap: $\frac{p_0^2}{M_{Pl}^2c^2}\sim10^{-60}$ Optomechanics: $\frac{p_0^2}{M_{Pl}^2c^2}\sim10^{-40}$

Experimental bound from quantum systems as of 2012: $\beta_0<10^{33}$

OPTOMECHANICAL SCHEME

Based on displacements in phase space:

$$\hat{D}(\alpha) = e^{\alpha\hat{a}^{+} - \alpha^{*}\hat{a}} = e^{i\sqrt{2}\mathrm{Re}[\alpha]\,\hat{X} - i\sqrt{2}\mathrm{Im}[\alpha]\,\hat{P}}$$

$$\hat{D}(\beta)\hat{D}(\alpha) = \hat{D}(\alpha+\beta)\, e^{i\,Im[\alpha^{*}\beta]}$$

$$\hat{D}(-\beta)\hat{D}(-\alpha)\hat{D}(\beta)\hat{D}(\alpha) = e^{2\,i\,Im[\alpha^{*}\beta]}$$

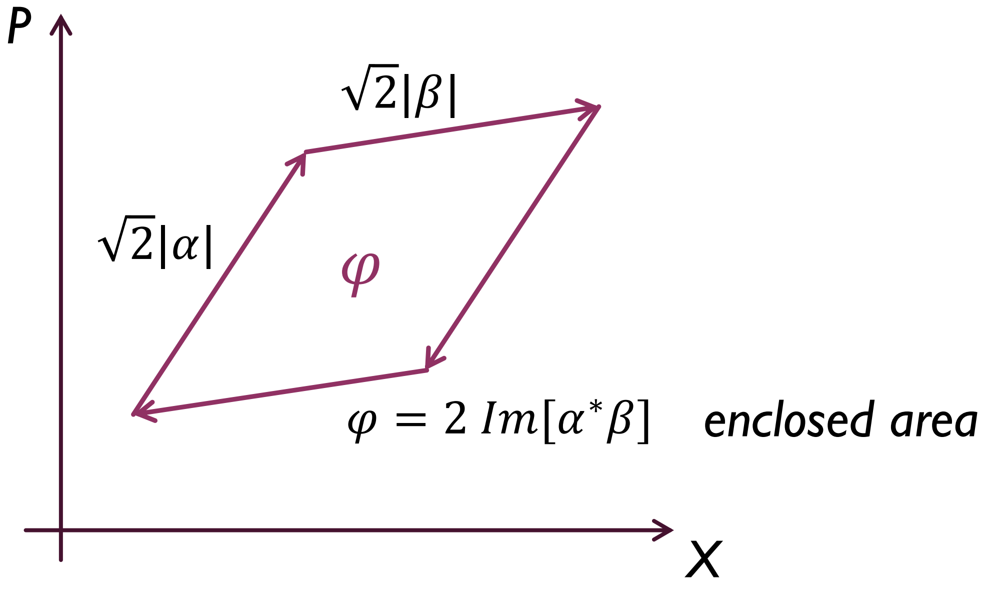
- Results in an overall phase
- State independent
- Arises due to $[\hat{X},\hat{P}] \neq 0$

Can be used for quantum computing

Milburn, Schneider, James, Fortschr. Phys. 48, 801(2000),
Sørensen, Mølmer, Phys. Rev. A 62, 022311 (2000)

Phase space quadratures:

$$\hat{X} = \frac{1}{\sqrt{2}}(\hat{a} + \hat{a}^{+}), \qquad \hat{P} = \frac{1}{\sqrt{2}i}(\hat{a} - \hat{a}^{+})$$



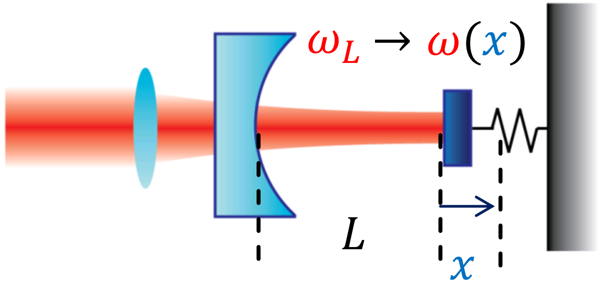
Implemented to create a phase gate for ions

Leibfried et al., Nature 422, 27 (2003)

OPTOMECHANICAL SCHEME

Light a in cavity displaces a small mirror by radiation pressure:

$$\hat{H} = \hbar\omega_m \hat{n}_m + \hbar\omega_L \hat{n}_L - \hbar g_0 \hat{n}_L \hat{X}_m$$



Pulsed opto-mechanical setting:

M. Vanner, I. Pikovski et al. PNAS 108, 16182 (2011)

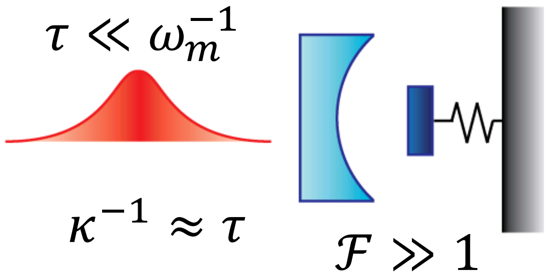
$$\hat{H} \approx \hbar\omega_L \hat{n}_L - \hbar g_0 \hat{n}_L \hat{X}_m$$

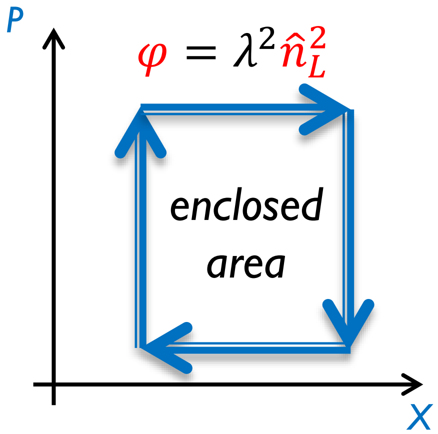
Single quadrature displacement

$$\hat{U}(\tau) \approx e^{i\lambda \hat{n}_L \hat{X}_m} \qquad \lambda = g_0 \tau \propto \mathcal{F}$$

Free evolution after interaction:

$$\hat{U}(t+\tau) = e^{i\lambda \hat{n}_L (\hat{X}_m \cos\omega_m t - \hat{P}_m \sin\omega_m t)}$$





4 iterations:

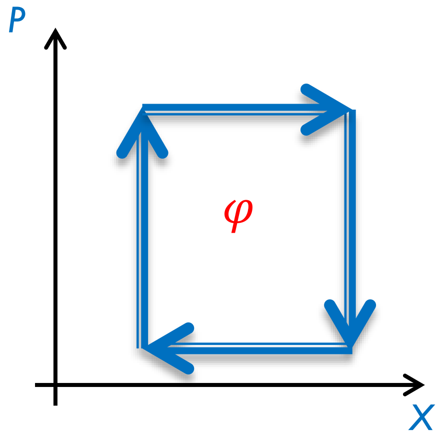
$$\hat{\xi} = e^{i\lambda \hat{n}_L \hat{P}}\, e^{-i\lambda \hat{n}_L \hat{X}}\, e^{-i\lambda \hat{n}_L \hat{P}}\, e^{i\lambda \hat{n}_L \hat{X}} = e^{-i\lambda^2 \hat{n}_L^2}$$

Self-Kerr non-linearity on the light, independent of the mechanics

I. Pikovski, M. Vanner, M. Aspelmeyer, M. S. Kim, Č. Brukner. *Nature Physics 8, 393-397 (2012)*

OPTOMECHANICAL SCHEME

$$\hat{\xi} = e^{i\lambda \hat{n}_L \hat{P}} e^{-i\lambda \hat{n}_L \hat{X}} e^{-i\lambda \hat{n}_L \hat{P}} e^{i\lambda \hat{n}_L \hat{X}} = e^{-\sum_{k=1}^{\infty} \frac{(\lambda \hat{n}_L)^{k+1}}{k!} [\hat{X},\hat{P}]_k}$$



- In quantum mechanics: $[\hat{X},\hat{P}] = i$ $\quad \hat{\xi}_{QM} = e^{-\, i\lambda^2 \hat{n}_L^2}$
- Alternative theories: $[\hat{X},\hat{P}] = i\mathrm{F}(\hat{X},\hat{P})$ $\quad \hat{\xi} = e^{-\, i\lambda^2 \hat{n}_L^2 + \epsilon(\hat{n}_L^k)}$

Any arbitrary deformed algebra will show in $\hat{\xi}$

$$\beta = \beta_0 \frac{\hbar \omega_m m}{(M_{Pl} c)^2} \ll 1$$

- $[\hat{X},\hat{P}]_1 = i(1+\beta \hat{P}^2)$
- $[\hat{X},\hat{P}]_2 = i^2 2\beta \hat{P} + O(\beta^2)$
- $[\hat{X},\hat{P}]_3 = i^3 2\beta + O(\beta^2)$
- $[\hat{X},\hat{P}]_4 = O(\beta^2)$

Example: β-modification

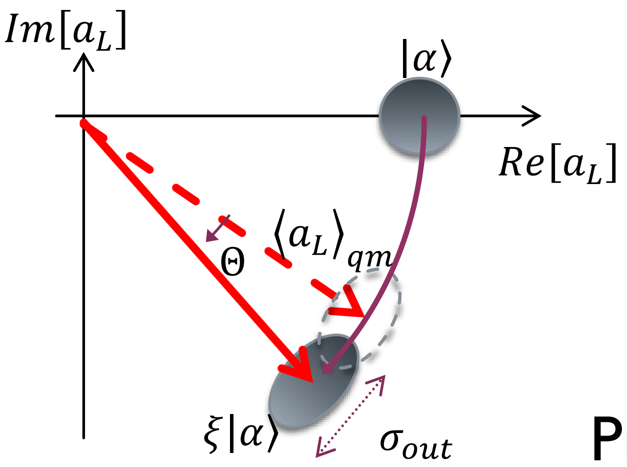
$$[\hat{X},\hat{P}] = \mathrm{i}(1+\beta_0 \frac{p_0^2 \hat{P}^2}{M_{Pl}^2 c^2}),$$

Hence: $$\hat{\xi}_\beta = e^{-i\, \lambda^2 \hat{n}_L^2}\, e^{-i\beta(\lambda^2 \hat{n}_L^2 \hat{P}^2 + \lambda^3 \hat{n}_L^3 \hat{P} + \frac{1}{3}\lambda^4 \hat{n}_L^4)}$$

OPTOMECHANICAL SCHEME

Measurement on the light: detect the mean phase change

$$\langle \hat{a}_L \rangle = \langle \alpha | \hat{\xi}^{+} \hat{a}_L \hat{\xi} | \alpha \rangle \cong \langle \hat{a}_L \rangle_{QM} \, e^{-i\,\Theta([\hat{X},\hat{P}]_{mod})}$$

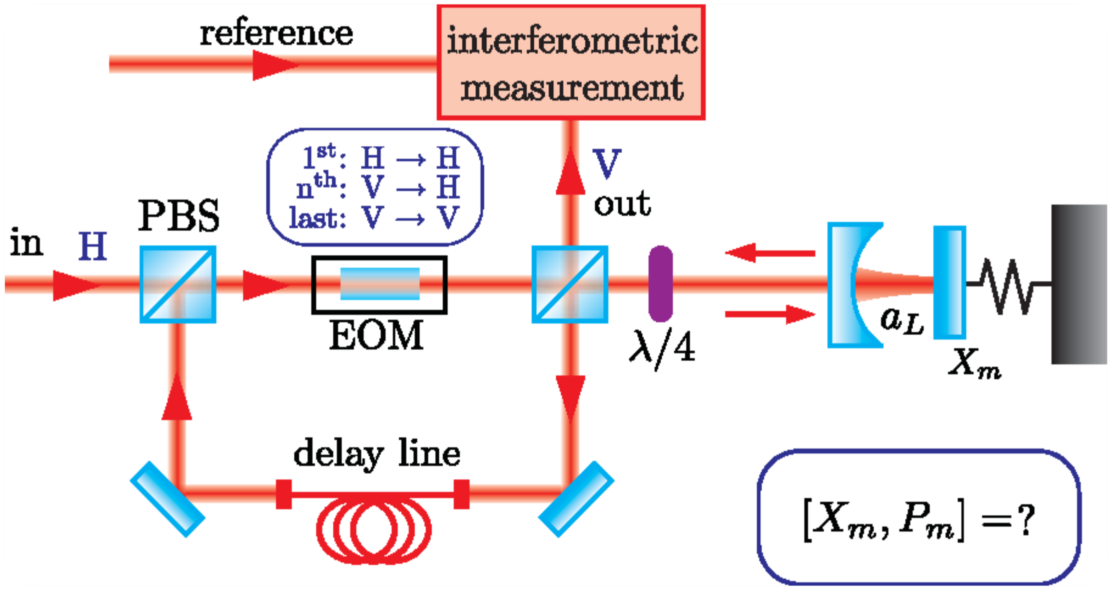


Θ for various models:

$$\mu_0 \frac{32\hbar\mathcal{F}^2 m N_p}{M_P^2 \lambda_L^2 \omega_m} \qquad \gamma_0 \frac{96\hbar^2\mathcal{F}^3 N_p^2}{M_P c \lambda_L^3 m \omega_m} \qquad \beta_0 \frac{1024\hbar^3\mathcal{F}^4 N_p^3}{3M_P^2 c^2 \lambda_L^4 m \omega_m}$$

Proposed experimental setup:

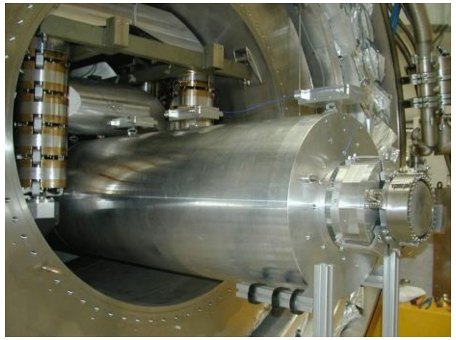
- Single optical pulse
- Short opto-mechanical interaction
- Pulse storage for ¼ mechanical period
- 4 iterations
- Homodyne readout



Deformations of center-of-mass observable even for $\beta_0, \mu_0, \gamma_0 \lesssim 1$

I. Pikovski et al. *Nature Physics 8, 393-397 (2012)*

NEW EXPERIMENTAL BOUNDS WITH HIGH-Q RESONATORS

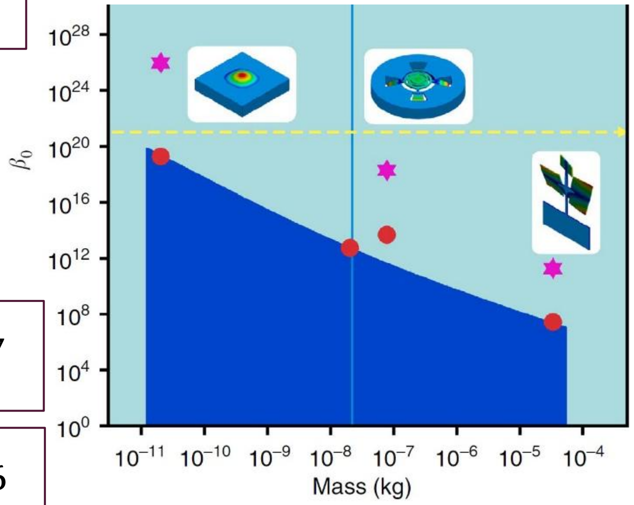


Tests of commutator deformations by F. Marin et al (AURIGA collaboration):

- Change in normal modes: anomalous ground state energy $E = \frac{\beta}{2}\hbar\omega$
- Experiment: compare to measured modal temperature in AURIGA

F. Marin et al., Nature Physics 9, 71–73 (2013)

Measured: $\beta_0 < 10^{33}$

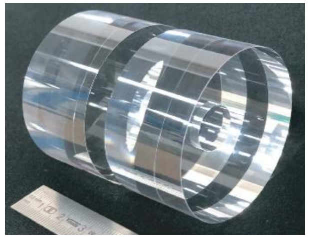


- Change in harmonic motion: Modified amplitude and frequency of motion $A(t) = A_0\left(\sin\omega t + \frac{\beta}{8}A_0\cos 3\,\omega t\right)$ $\omega = \left(1 + \frac{\beta}{2}A_0\right)\omega_0$

M. Bawaj et al, Nature Comm. 6, 7503 (2015)

Measured: $\beta_0 < 3 \times 10^7$

Using Sapphire bar in Bushev & Tobar groups:



P.A. Bushev et al., PRD ,066020 (2019)

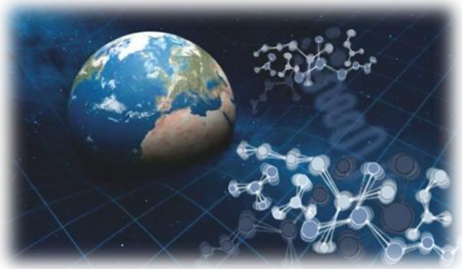
Measured: $\beta_0 < 5 \times 10^6$

So far only classical systems! Also stringent bounds from classical dynamics

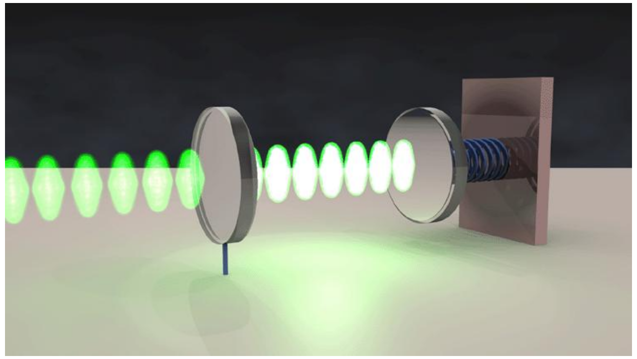
C. Quesne, V. Tkachuk. PRA 81, 012106 (2010); S. Kumar, M. Plenio. Nat. commun. 11, 1-8 (2020)

SUMMARY: QUANTUM GRAVITY PHENOMENOLOGY

Table-top tests of quantum gravity start to become possible

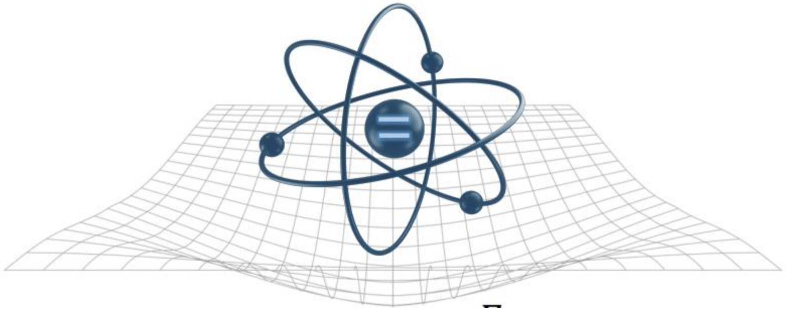


Relies on novel technology and creativity



Could we also observe “conservative ”quantum gravity as expected?

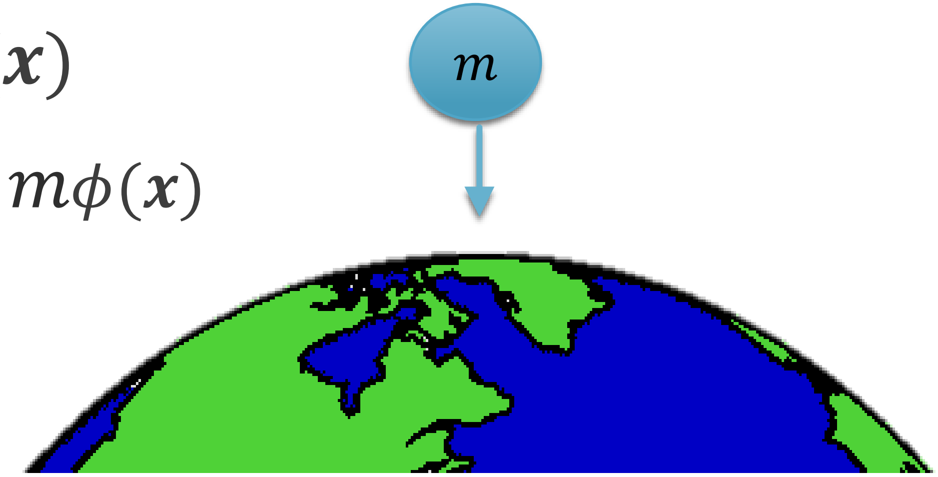
Surprisingly, yes!



COUPLING OF MATTER TO GRAVITY

Newtonian gravity: mass couples to potential $\phi(\boldsymbol{x})$

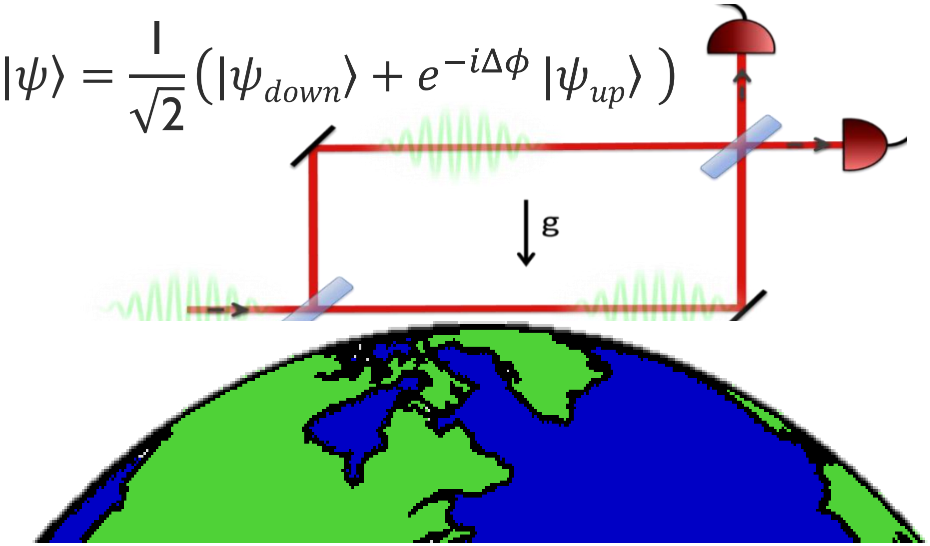
- Simple coupling captured by Hamiltonian $H = m\phi(\boldsymbol{x})$



Well tested also for quantum systems:

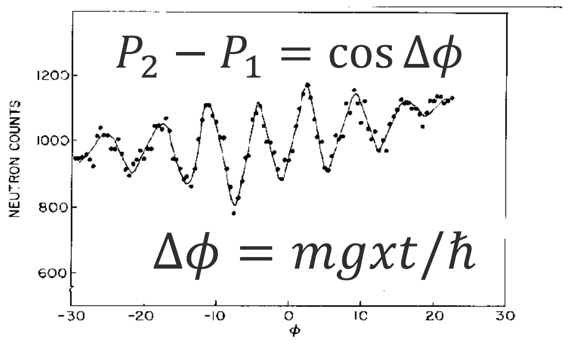
- Matter-wave superpositions acquire a phase

$$\Delta\varphi = m\Delta\phi\, t/\hbar$$



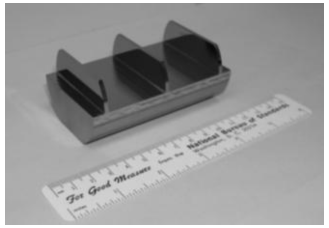
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\psi_{down}\rangle + e^{-i\Delta\phi}\,|\psi_{up}\rangle\right)$$

Observed in COW (neutrons) & atomic fountains

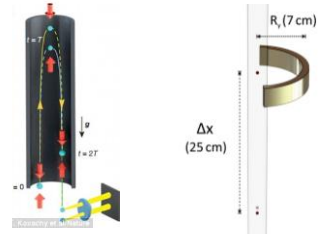


$$P_2 - P_1 = \cos\Delta\phi$$

$$\Delta\phi = mgxt/\hbar$$



Colella, Overhauser, Werner, PRL 34, 1472-1474 (1975)



Overstreet, Asenbaum, Curti, Kim, Kasevich. Science 375, 226-229 (2022)

HAMILTONIAN FOR INTERACTION WITH GRAVITY

Coupling between matter and linear general relativity:

$$\boxed{H_{int} = -\int d^3x \frac{1}{2} T_{\mu\nu} h^{\mu\nu}}$$

Why?

Einstein's equations: $R_{\mu\upsilon} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$

Equivalent action: $S = S_{EH} + S_M = \frac{c^4}{16\pi G} \int d^4x \sqrt{-g}\, R + S_M$

Variation in general: $\delta S(a, b, \ldots) \equiv \int d^4x \frac{\delta S}{\delta a} \delta a + \int d^4x \frac{\delta S}{\delta b} \delta b + \cdots$

Only gravity: $\frac{\delta S_{EH}}{\delta g^{\mu\nu}} = \frac{c^4}{16\pi G} \int d^4x \sqrt{-g} (R_{\mu\upsilon} - \frac{1}{2} R g_{\mu\nu}) \equiv 0$ Euler-Lagrange

With matter: $\delta S \equiv \int d^4x \frac{\delta S_{EH}}{\delta g^{\mu\nu}} \delta g^{\mu\nu} + \int d^4x \frac{\delta S_M}{\delta g^{\mu\nu}} \delta g^{\mu\nu} \equiv 0$ → $T_{\mu\nu} \equiv \frac{-2}{\sqrt{-g}} \frac{\delta S_M}{\delta g^{\mu\nu}}$

HAMILTONIAN FOR INTERACTION WITH GRAVITY

Coupling between matter and linear general relativity:

$$\boxed{H_{int} = -\int d^3x \frac{1}{2} T_{\mu\nu} h^{\mu\nu}}$$

Why?

$$T_{\mu\nu} \equiv \frac{-2}{\sqrt{-g}} \frac{\delta S_M}{\delta g^{\mu\nu}}$$

Linearize gravity: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\quad |h_{\mu\nu}| \ll |\eta_{\mu\nu}|$

flat Minkowski *Perturbation: "gravity"*

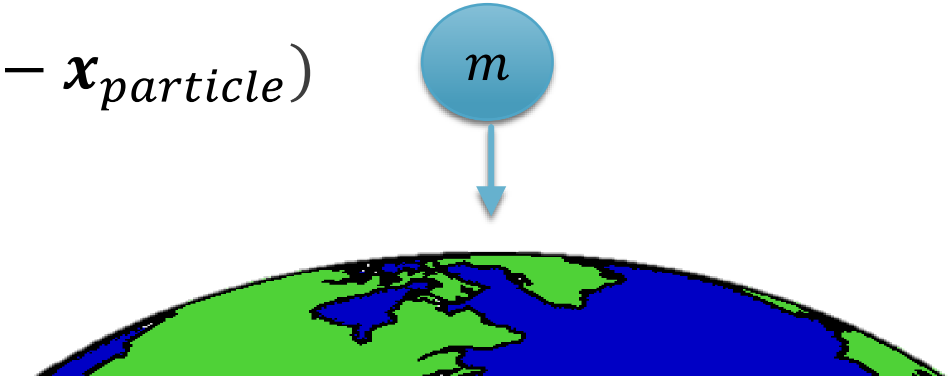
Keep only linear terms in $h_{\mu\nu}$

Linearized GR equations look a lot like Maxwell's E&M! Here: only coupling to matter

S_M now linear in $h^{\mu\nu}$ $(g^{\mu\nu} = \eta^{\mu\nu} - h^{\mu\nu})$: $\quad T_{\mu\nu} \equiv 2\frac{\delta S_M}{\delta h^{\mu\nu}} \quad \Leftrightarrow \quad S_M \equiv \frac{1}{2}\int d^4x\, T_{\mu\nu} h^{\mu\nu}$

Lagrange density $\mathcal{L} = \frac{1}{2} T_{\mu\nu} h^{\mu\nu}$ $\quad \Leftrightarrow \quad$ Hamiltonian $H = -\int d^3x\, \mathcal{L}$
(small velocities)

COUPLING OF MATTER TO GRAVITY



E.g.: Newtonian $h_{00} = -2\frac{\phi(\boldsymbol{x})}{c^2}$ $T_{00} = mc^2\delta(\boldsymbol{x} - \boldsymbol{x}_{particle})$

$$H_{int} = m\phi(\boldsymbol{x}_{particle})$$

E.g.: Gravitational wave in local frame

$T_{00} = mc^2\delta(\boldsymbol{x} - \boldsymbol{x}_{cm})$ $h_{00} = -R_{0i0j}x^i x^j$

$$h_{ij} = \mathcal{E}_{ij}h_0 e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

GW polarization *Plane wave, amplitude h_0*

Fermi normal coordinates → tidal force $R_{0i0j} = -\frac{1}{2c^2}\partial_0\partial_0 h_{ij}$

$$H_{int} = \frac{h_0}{4}m\omega^2\mathcal{E}_{ij}x^i x^j e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

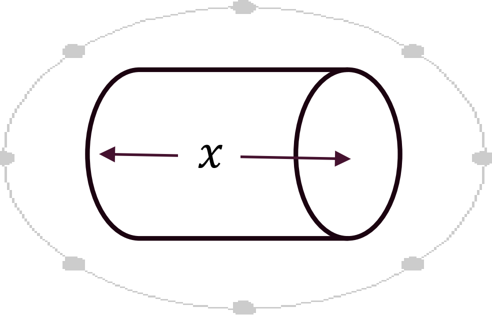
$\vec{k}\cdot\vec{x} \ll 1$

Long wavelength

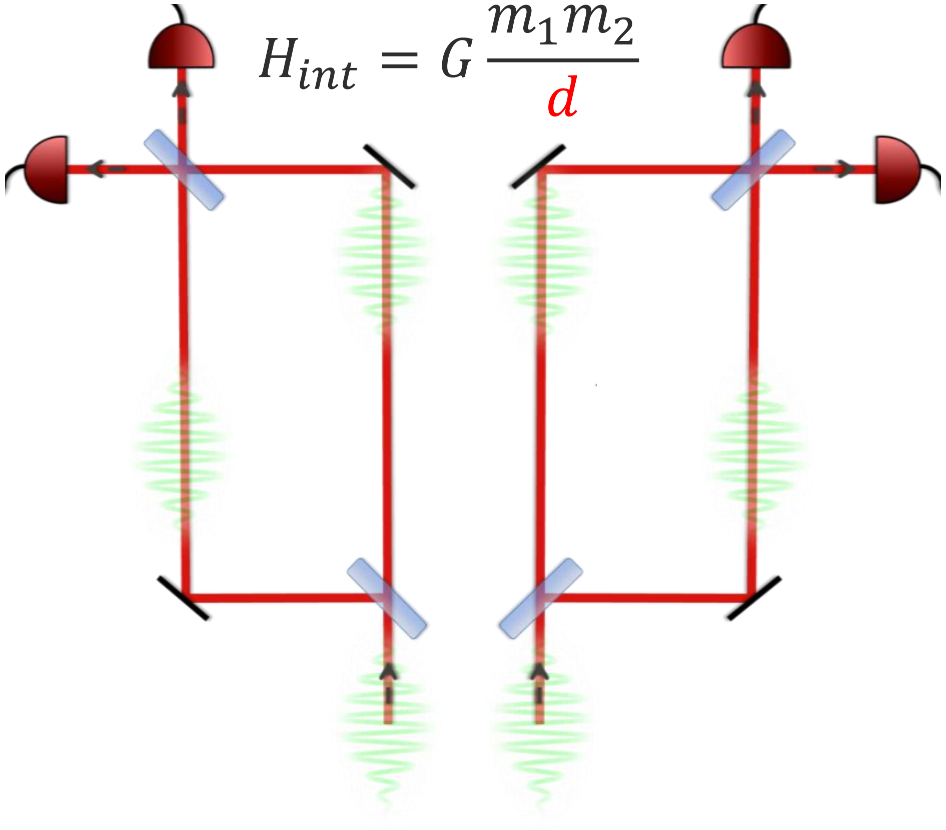
$\mathcal{E}_{ij} = \delta_{ix}\delta_{jx}$

Perpendicularly polarized

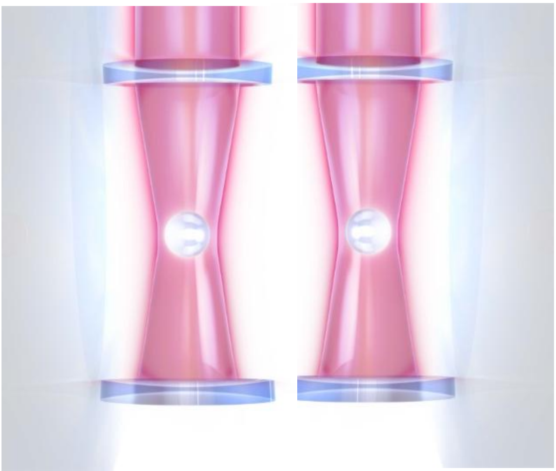
$$\boxed{H_{int} \approx \frac{h_0}{4}m\omega^2 x^2}$$



EXPERIMENTAL PROPOSAL: INDIRECT SIGNATURE OF GRAVITONS?



$$H_{int} = G\frac{m_1 m_2}{d}$$



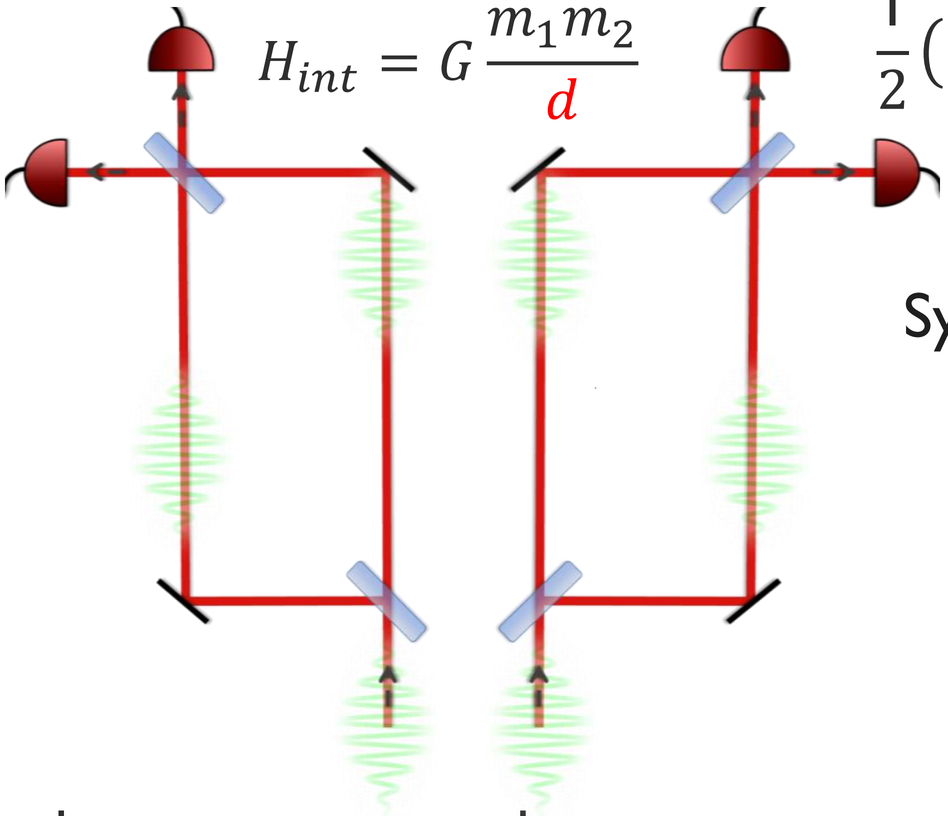
Basic idea:

- Probe if gravity can *generate* entanglement
- Sources of gravity are themselves in superposition
- Entanglement is between the masses, not entanglement of gravity

Bose et al. "Spin entanglement witness for quantum gravity." PRL 119, 240401 (2017)

Marletto, Vedral. "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity." PRL 119, 240402 (2017)

EXPERIMENTAL PROPOSAL: INDIRECT SIGNATURE OF GRAVITONS?



$$H_{int} = G\frac{m_1 m_2}{d}$$

$$\frac{1}{\sqrt{2}}(|\psi_L\rangle + |\psi_R\rangle\ ) \otimes \frac{1}{\sqrt{2}}(|\chi_L\rangle + |\chi_R\rangle\ )$$

$$\frac{1}{2}\left(e^{i\varphi_{LL}}|\psi_L\rangle|\chi_L\rangle + e^{i\varphi_{LR}}|\psi_L\rangle|\chi_R\rangle + e^{i\varphi_{RL}}|\psi_R\rangle|\chi_L\rangle + e^{i\varphi_{RR}}|\psi_R\rangle|\chi_R\rangle\right)$$

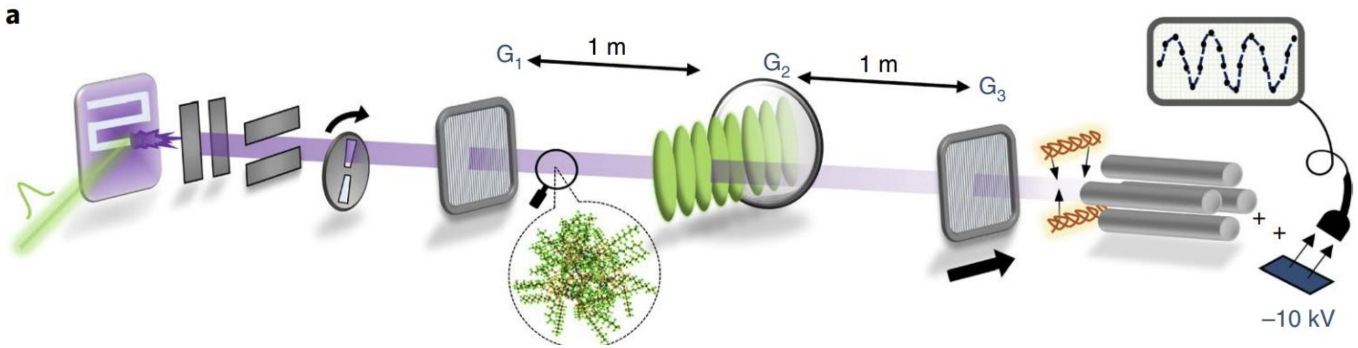
$\varphi_{ii} = G\frac{m_1 m_2 t}{d_{ii}\hbar}$ Entangled state, maximal: $t = \frac{\pi d_{LR}\hbar}{G m_1 m_2}$

System parameters: $d_{LR} = 0.25mm$ $m = 10^{-14}kg$ $t = 10s$

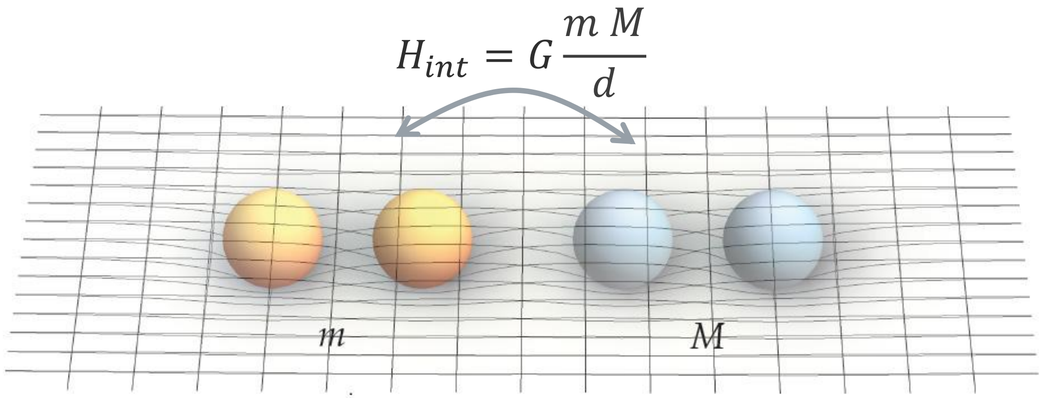
Extremely challenging

World-record today (Arndt group): 2,000 atoms

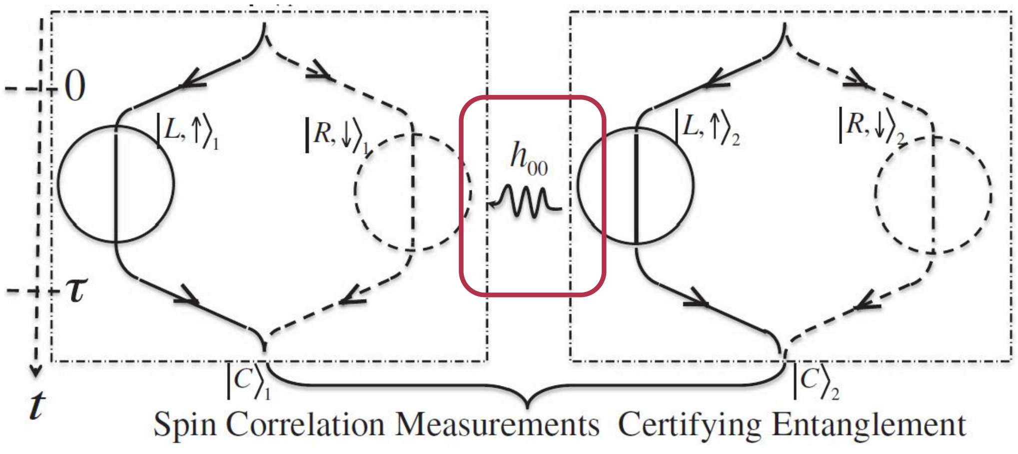
Y.Y. Fein et al.. *Nature Physics 15, 1242–1245* (2019)



EXPERIMENTAL PROPOSAL: INDIRECT SIGNATURE OF GRAVITONS?



Source of gravity is in superposition, creates superposed potential / space-time



Argument of authors:

Bose et al. PRL 119, 240401 (2017)
Marletto, Vedral. PRL 119, 240402 (2017)

If entanglement is mediated *locally*, then the mediator must be quantized

LOCC: Local operations and classical communication cannot increase entanglement

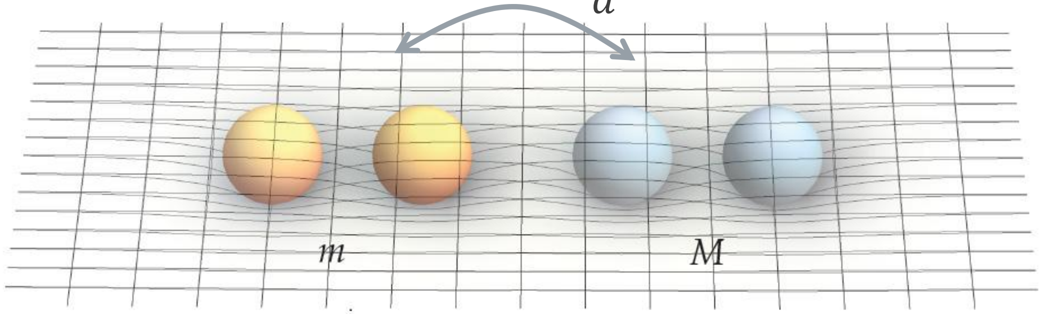
Why local operation? Exchange of a mediating particle → graviton

But this depends on additional *assumptions*

V. Fragkos*, M. Kopp*, I. Pikovski. "On inference of quantization from gravitationally induced entanglement" *AVS Quantum Sci. 4, 045601(2022)*

NEWTONIAN VIEW: ACTION AT A DISTANCE

$$H_{int} = G\frac{m\,M}{d}$$



From Newtonian perspective:

Entanglement generated via instantaneous interaction

$$\hat{H} = \sum_{i=1}^{N}\left(\frac{\hat{\vec{p}}_i^{\,2}}{2m} - \frac{m^2 G}{2}\sum_{j=1, j\neq i}^{N}\frac{1}{|\hat{\vec{x}}_i - \hat{\vec{x}}_j|}\right)$$

In what sense is gravity *in superposition*?

Use 2nd quantized language in this non-relativistic case:

Non-relativistic quantum field operator: $\hat{\psi}^\dagger(\vec{x}_1)|0\rangle = |\vec{x}_1\rangle$

$$\hat{H} = \int d^3x\left(\frac{\hbar^2}{2m}\nabla\hat{\psi}^\dagger(\vec{x})\nabla\hat{\psi}(\vec{x}) + m\hat{\Phi}(\vec{x})\hat{\psi}^\dagger(\vec{x})\hat{\psi}(\vec{x})\right)$$

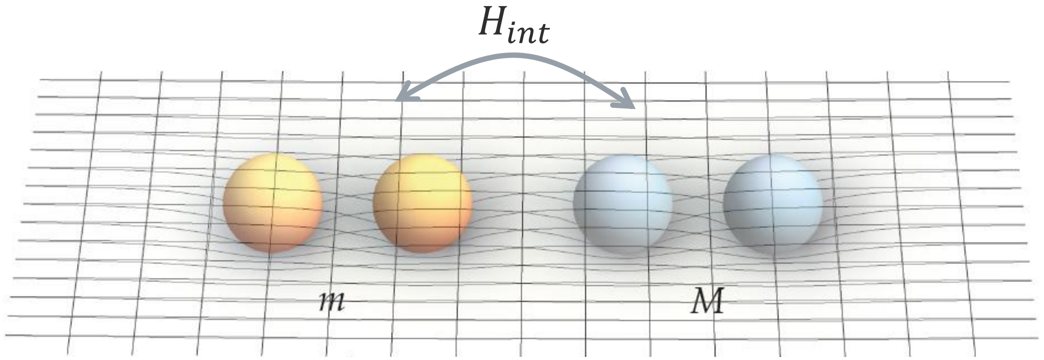
$$\nabla^2\hat{\Phi}(\vec{x}) = 4\pi G m\hat{\psi}^\dagger(\vec{x})\hat{\psi}(\vec{x})$$

Gravitational potential requires quantization:

$$\hat{\Phi}(\vec{x}, t) = -\,mG\int d^3x'\frac{\hat{\psi}^\dagger(\vec{x}\,')\hat{\psi}(\vec{x}\,')}{|\vec{x} - \vec{x}\,'|}$$

Shows: Insufficient to use mean field

RELATIVISTIC VIEW: FORMULATION #1



Relativistic perspective: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$H_{int} = -\frac{1}{2}\int d^3 r h_{\mu\nu}(\vec{r}) T^{\mu\nu}(\vec{r})$$

How is entanglement generated? Quantize?

Gupta, Proc. Phys. Soc. A 65, 161 (1952)

$$\hat{h}_{\mu\nu}(\vec{r}) = \int d^3k \sqrt{\frac{\hbar G}{c^2\pi^2\omega_k}}\left[\hat{a}_{\mu\nu}(\vec{k}) e^{i\vec{k}\cdot\vec{r}} + \hat{a}^{\dagger}_{\mu\nu}(\vec{k}) e^{-i\vec{k}\cdot\vec{r}}\right]$$

In Lorentz / de Donder gauge:

Has 10 quantized degrees of freedom $\hat{a}_{\mu\nu}$, not 2!

$$\partial^{\mu}\bar{h}_{\mu\nu} = 0 \text{ with } \bar{h}_{\mu\nu} \equiv h_{\mu\nu} - 1/2\, h^{\mu}_{\mu}$$

The 8 fictious d.o.f are removed by imposing $\left[\hat{a}_{3\nu}(\vec{k}) - \hat{a}_{0\nu}(\vec{k}) + \kappa \int_{t=t'} d^3x' D^{(+)}(\vec{x}-\vec{x}')\hat{T}_{0\nu}(\vec{x}')\right]|\chi\rangle = 0$

But: these `ghosts‘ contribute in virtual processes & entanglement

Simple toy model for entanglement: $|\Psi_0\rangle \equiv |0\rangle_A \otimes |0\rangle_B \otimes |\vec{0}\rangle_\gamma$

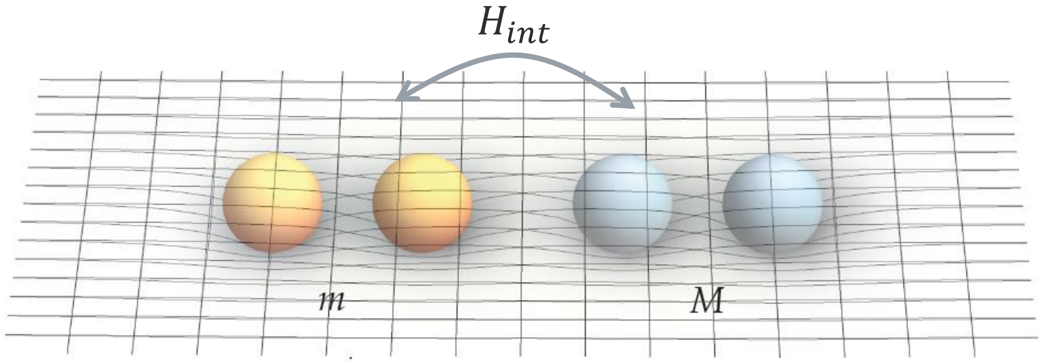
Franson, Phys. Rev. A 84, 033809 (2011)

$$|\Psi\rangle \simeq |\Psi_0\rangle + \varepsilon_L |\Psi_2\rangle \qquad |\Psi_2\rangle = |1\rangle_A \otimes |1\rangle_B \otimes |\vec{0}\rangle_\gamma \qquad \varepsilon_L = \sum_l \frac{\langle\Psi_2|\hat{H}_I \boxed{|l\rangle\langle l|} \hat{H}_I|\Psi_0\rangle}{(E_0 - E_1)(E_0 - E_l)}$$

These fictious mediators generate entanglement (not `normal‘ gravitons)

Also in Bose et al. PRD 105, 106028 (2022)

RELATIVISTIC VIEW: FORMULATION #2



Relativistic perspective: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$H_{int} = -\frac{1}{2}\int d^3 r h_{\mu\nu}(\vec{r}) T^{\mu\nu}(\vec{r})$$

How is entanglement generated? Quantize?

In Poisson gauge:

$$h_{00} = -2\phi$$
$$h_{0i} = w_i$$
$$h_{ij} = -2\psi\delta_{ij} + 2s_{ij}$$

s_{ij} : real GWs!

$\partial_j s_i^j = 0$ **and** $\partial_i w^i = 0$ *Bertschinger, MIT lecture notes (1999)*

Quantization of only 2 physical d.o.f. : $s_{ij}^{TT} \rightarrow \hat{s}_{ij}^{TT}$

After some algebra (*Bertschinger, MIT lecture notes*)

$$\hat{H}_{int} = -\int d^3 r\left(\hat{s}_{ij}^{TT}\hat{T}^{ij}\right) - \frac{G}{2}\int \frac{d^3 r d^3 r'}{|\vec{r}-\vec{r}'|}\left[-4\hat{f}_{\perp,i}(\vec{r}')\hat{T}^{0i}(\vec{r}) + \hat{T}_{00}(\vec{r}')\left(\hat{T}^{00}(\vec{r}) + \hat{T}_k^k(\vec{r}) - 2\hat{\Pi}^{||}(\vec{r})\right)\right]$$

subdominant in GIE

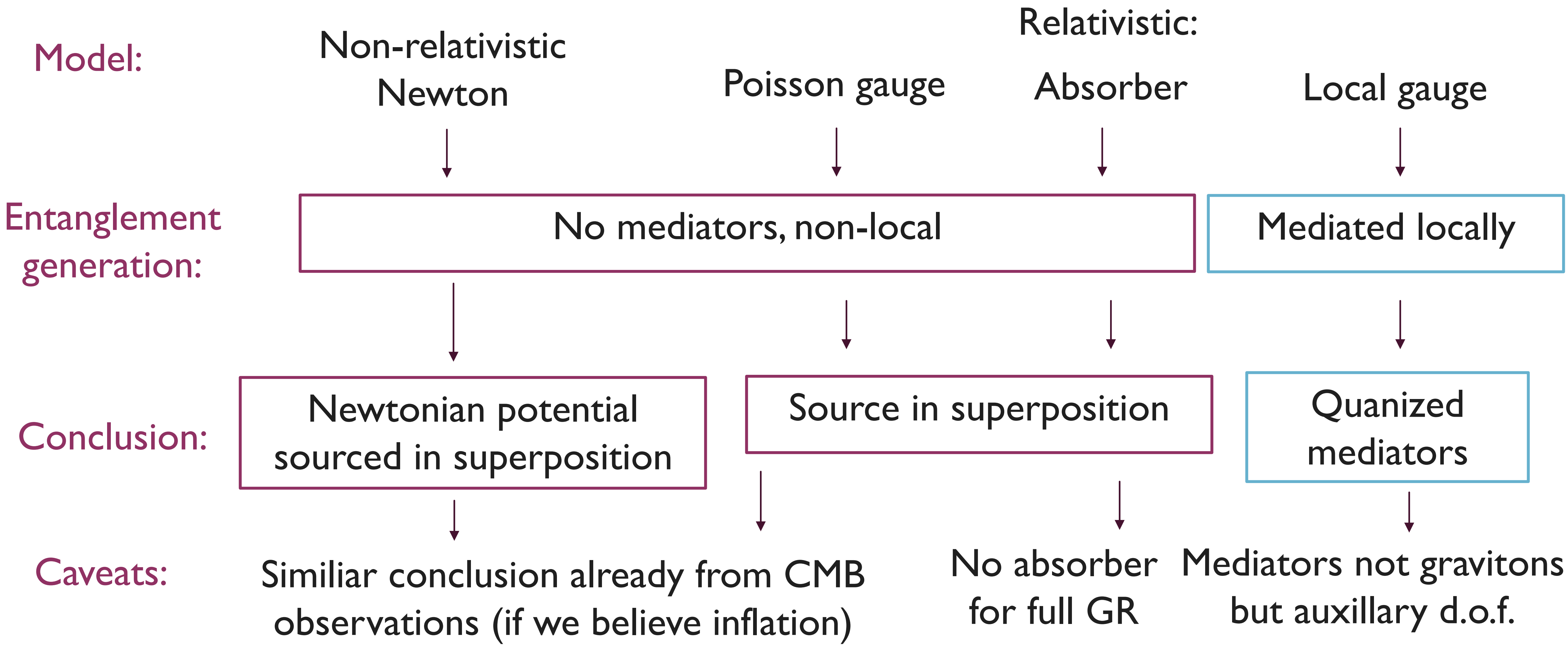
$\propto \hat{T}_{\perp}^{0i}$

Dominant entangling term

$\propto$ *Traceless stress-energy tensor*

Entanglement generated nonlocally without gravitational d.o.f., as in Newtonian case

SUMMARY OF CONCLUSIONS FROM ENTANGLEMENT



Model:
Non-relativistic Newton
Poisson gauge
Relativistic:
Absorber
Local gauge

Entanglement generation:
No mediators, non-local
Mediated locally

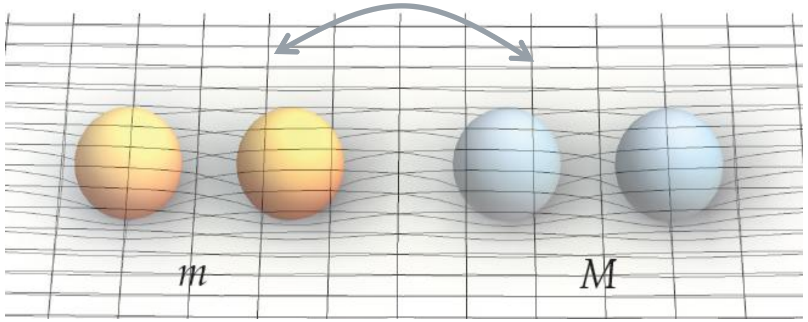
Conclusion:
Newtonian potential sourced in superposition
Source in superposition
Quanized mediators

Caveats:
Similiar conclusion already from CMB observations (if we believe inflation)
No absorber for full GR
Mediators not gravitons but auxillary d.o.f.

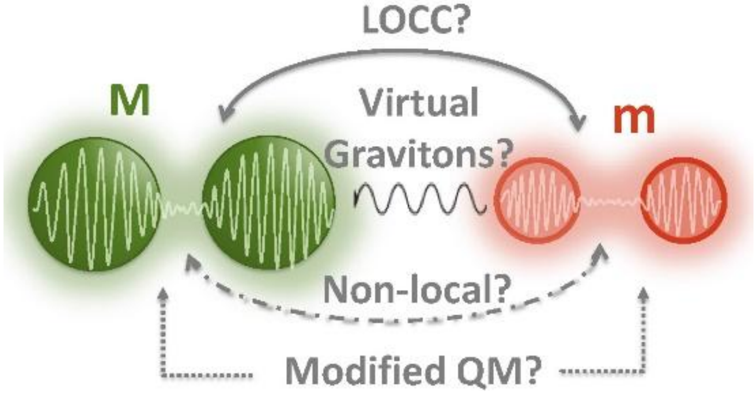
V. Fragkos*, M. Kopp*, I. Pikovski. "On inference of quantization from gravitationally induced entanglement" *AVS Quantum Sci. 4, 045601 (2022)*

SUMMARY: GRAVITATIONALLY INDUCED ENTANGLEMENT (GIE)

GIE will show quantum sources of gravity



Only test of a virtual "graviton" if we describe in one specific gauge



Could we also observe a real graviton directly?

Surprisingly, yes!

G. Tobar*, S. Manikandan*, T. Beitel, I. Pikovski. Nature Communications 15, 7229 (2024)

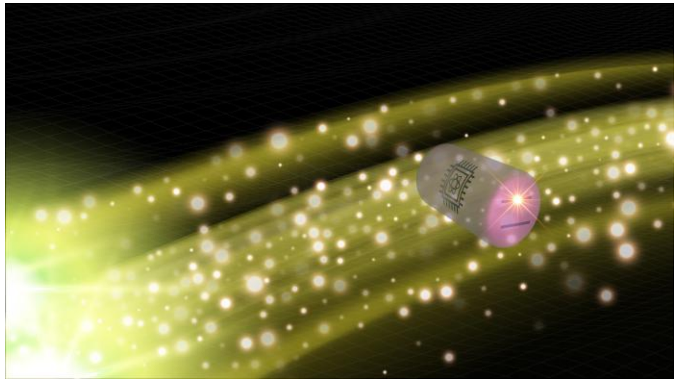


TABLE-TOP ROUTES TO QUANTUM GRAVITY

Testing speculative models

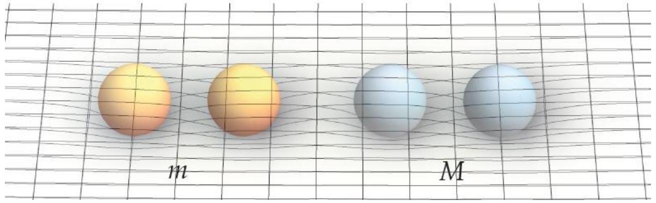
High-precision test of new physics beyond QM, GR.

Marshall et al 2003
Pikovski et al 2012
Bekenstein 2012
Kafri et al 2014
Belenchia et al 2016
Oppenheim 2023
…

Caveats:

Tests only *speculative* models.

Detecting entanglement mediated by gravity



Indirect test of QGR, assuming local mediator of entanglement

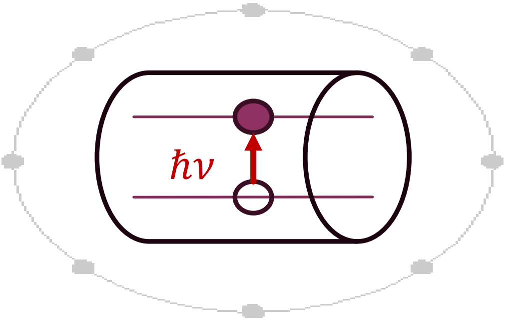
Bose et al 2017
Marletto Vedral 2017
Lami et al 2024
…

Caveats:

Interpretation ambiguous: no input on mediator quantization

Fragkos, Kopp, Pikovski. PRD 2022
Anastopoulos, Hu. C&QG, 2020

Detecting gravitons



Here: Observation of quantized energy exchange

G. Tobar*, S. Manikandan*, T. Beitel, I. Pikovski.
Nature Communications 15, 7229 (2024)

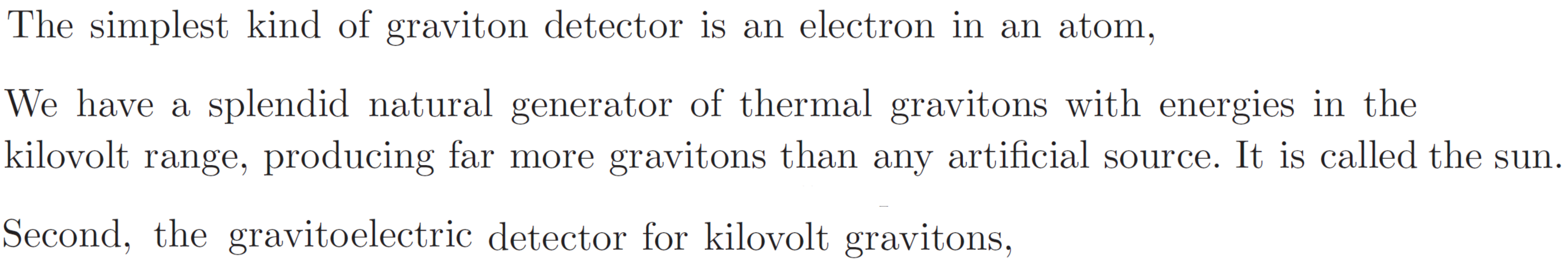
Probing expected single-graviton physics as predicted in linearized QGR

Caveats:

Cannot rule out some semi-classical models

DETECTING GRAVITONS: PHOTOELECTRIC ANALOGY

Dyson 2013, Journal of Modern Physics A 28, 1330041 (2013):

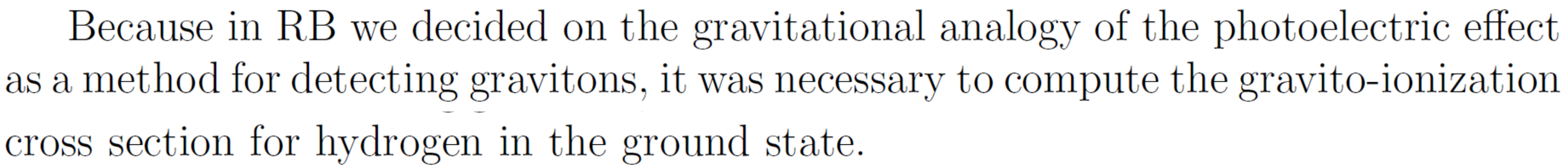


The simplest kind of graviton detector is an electron in an atom,

We have a splendid natural generator of thermal gravitons with energies in the kilovolt range, producing far more gravitons than any artificial source. It is called the sun.

Second, the gravitoelectric detector for kilovolt gravitons,

Rothman Boughn 2006, Classical and quantum gravity 23, 5839. (2006):



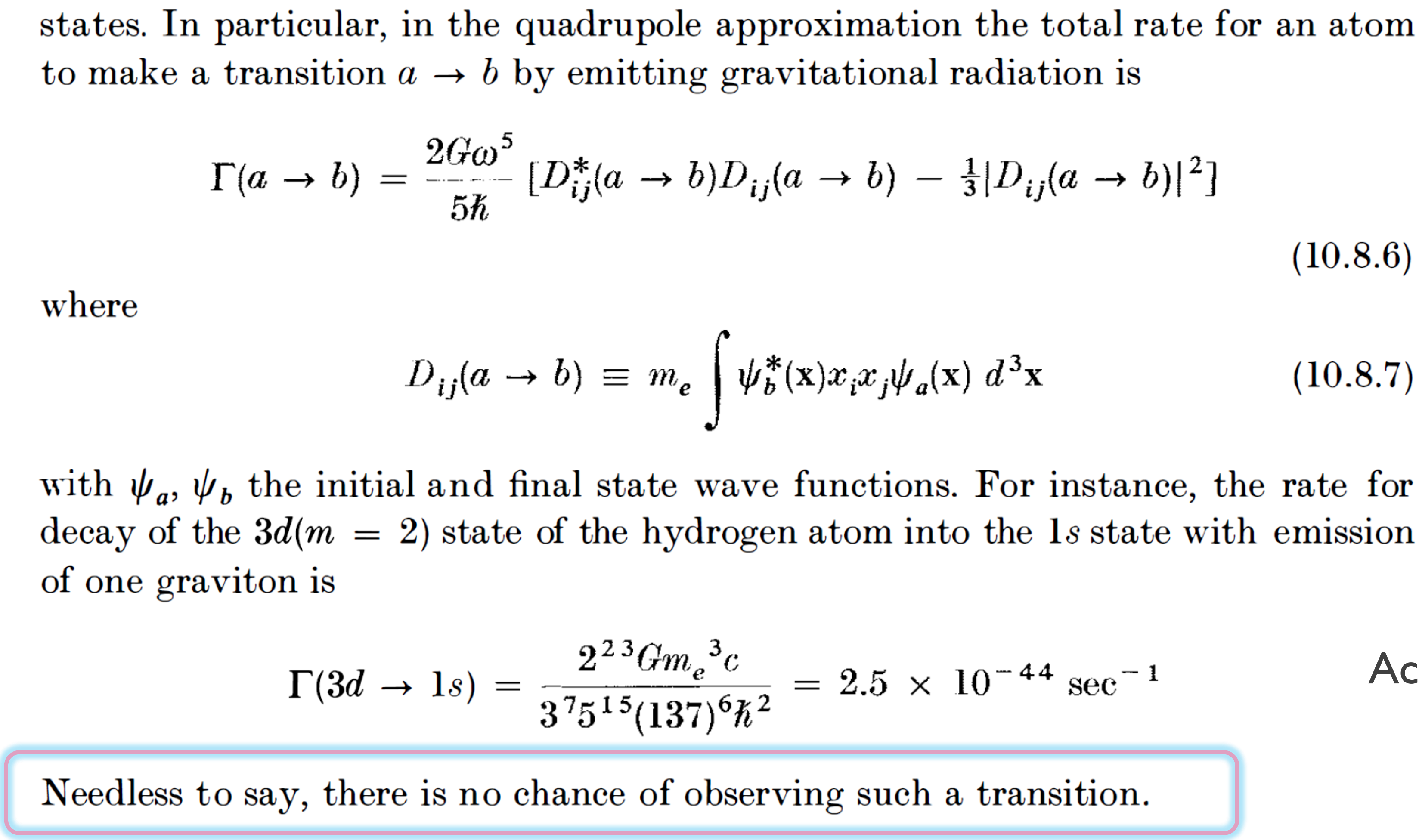
Because in RB we decided on the gravitational analogy of the photoelectric effect as a method for detecting gravitons, it was necessary to compute the gravito-ionization cross section for hydrogen in the ground state.

☑ Discrete energy E=hf

☑ Extracted from background

SINGLE GRAVITON PROCESSES IN QM

Weinberg, "Gravitation and Cosmology" 1972:



states. In particular, in the quadrupole approximation the total rate for an atom to make a transition $a \to b$ by emitting gravitational radiation is

$$\Gamma(a \to b) = \frac{2G\omega^5}{5\hbar}\left[D_{ij}^*(a \to b)D_{ij}(a \to b) - \tfrac{1}{3}|D_{ij}(a \to b)|^2\right] \tag{10.8.6}$$

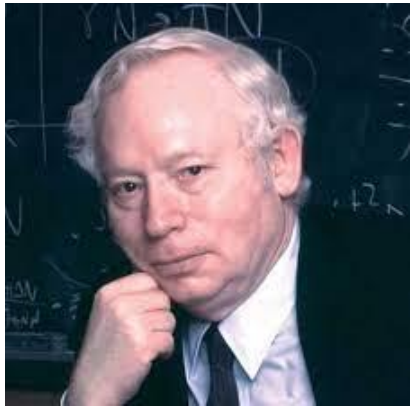
where

$$D_{ij}(a \to b) \equiv m_e \int \psi_b^*(\mathbf{x})x_i x_j \psi_a(\mathbf{x})\, d^3\mathbf{x} \tag{10.8.7}$$

with ψ_a, ψ_b the initial and final state wave functions. For instance, the rate for decay of the $3d(m = 2)$ state of the hydrogen atom into the $1s$ state with emission of one graviton is

$$\Gamma(3d \to 1s) = \frac{2^{23}Gm_e{}^3c}{3^7 5^{15}(137)^6\hbar^2} = 2.5 \times 10^{-44}\ \mathrm{sec}^{-1}$$

Needless to say, there is no chance of observing such a transition.



Actually $\Gamma = 5.7 \times 10^{-40}\, s^{-1}$

Boughn & Rothman 2006

SINGLE GRAVITON PROCESSES IN QM

Bronstein 1935, Feynman 1963, Dyson 1969, Weinberg 1972, Lightman 1973, Boughn & Rothman 2006

Interaction in linearized gravity: $$H_{int} = -\frac{1}{2} T_{\mu\nu} h^{\mu\nu}$$

Electron: $$T_{\mu\nu} = m_e u_\mu u_\nu = \frac{1}{m_e} p_\mu p_\nu$$

GWs in TT-gauge: $$h^{0\mu} = 0 \qquad h^{ij} = \frac{1}{\sqrt{V}} \sum_{\boldsymbol{k},\lambda} \varepsilon^{ij}_{\boldsymbol{k},\lambda}\, h_{\boldsymbol{k},\lambda}\, e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)} + cc$$

Normalization

Polarization

Polarization tensor

Fourier amplitudes

SINGLE GRAVITON PROCESSES IN QM

Quantize:

$$\hat{h}^{ij} = \sum_{\boldsymbol{k},\lambda} e^{ij}_{\boldsymbol{k},\lambda}\, h_{q\boldsymbol{k},\lambda} \hat{a}\, e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)} + cc$$

$$h_{q\boldsymbol{k},\lambda} = \sqrt{\frac{16\pi G\hbar}{c^2 \nu_{\boldsymbol{k}} V}}$$

Graviton transition rate:

$$\Gamma_{atom}\,(i \rightarrow f) = \frac{2\pi}{\hbar} \left| \langle i|\, \langle 0|\hat{H}_{int}|1\rangle\, |f\rangle \right|^2 \rho$$

$$\rho = \frac{V\nu^2}{2\pi^2 \hbar c^3}$$

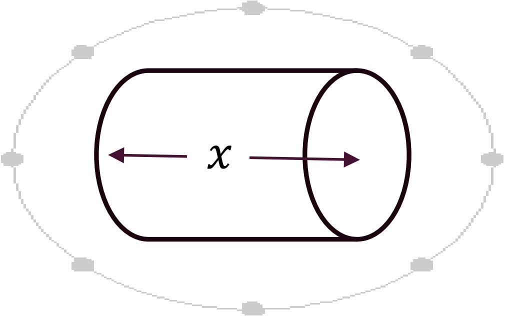
Density of graviton states

$$\Gamma_{atom}\,(3d \rightarrow 1s) = \frac{2\pi}{\hbar} \frac{m_e^2 \nu^4}{16 c^2} \frac{8\pi G\hbar}{\nu V} \frac{V\nu^2}{2\pi^2 \hbar c^3} \int d^3r\, \psi_{3d} r^2 \psi_{1s} \;\; \approx 10^{-40} s^{-1}$$

RECALL: COUPLING OF MATTER TO GRAVITY

We found before: Hamiltonian for interaction with GW

$$H_{int} = \frac{h_0}{4} m\omega^2 \varepsilon_{ij} x^i x^j e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$



$\vec{k}\cdot\vec{x} \ll 1$

Long wavelength

$\varepsilon_{ij} = \delta_{ix}\delta_{jx}$

Perpendicularly polarized

$$\boxed{H_{int} \approx \frac{h_0}{4} m\omega^2 x^2}$$

- Coupling of GW to matter
- $h_0$very, very small! $h_0 \lesssim 5 \times 10^{-22}$ (GW150914)
- $mx^2 = Q$: detector mass quadrupole moment

Joe Weber

Use big detector!

ACHIEVING OBSERVABLE GRAVITON PROCESSES

Three modifications make gravitons observable

G. Tobar*, S. Manikandan*, T. Beitel, I. Pikovski. Nature Communications 15, 7229 (2024)

A. Focus on acoustic modes in macroscopic quantum systems: $\sigma \gg L_p^2$

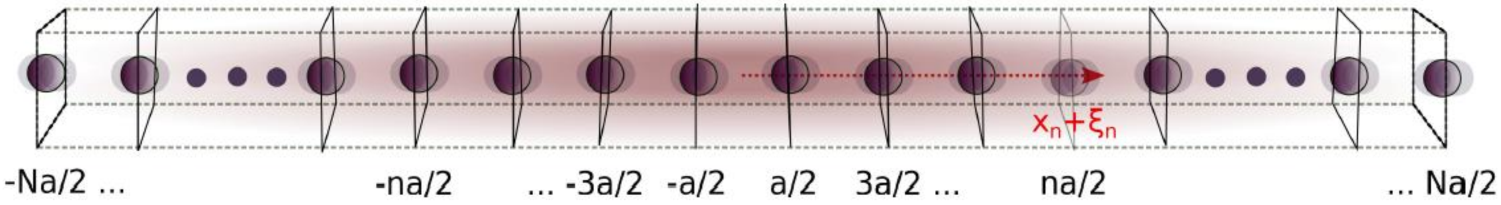
B. Focus on stimulated single graviton exchange during GW passage: $F \sim \frac{10^{28}}{m^2 s^1}$

C. Focus on quantum sensing of single discrete energy transitions: $\Delta E = hf$

When all three are met, one can achieve single graviton detection

A. MACROSCOPIC QUANTUM INTERACTION

$$H_{int} = -\frac{1}{2}h_{\mu\nu}T^{\mu\nu}$$



- $N+1$ atoms with mass m, distance a apart, $M = m(N+1)$
- Local inertial frame: $H_{int} = -\frac{1}{2}h_{00}T^{00}$. Tidal: $h_{00} = -R_{0a0b}x^a x^b = \frac{\ddot{h}_{xx}(t)}{2}(x_j+\xi_j)^2$
- $H_{int} = -\frac{m}{4}\ddot{h}_{xx}\sum_{j=-N}^{N}\left(2x_j\xi_j+\xi_j^2\right) = -\frac{ML\ddot{h}_{xx}}{\pi^2}\sum_{l=1,3,\ldots}^{N}\left((-1)^{\frac{l-1}{2}}\frac{1}{l^2}\chi_l\right) - \frac{M\,\ddot{h}_{xx}}{8}\sum_{l=0}^{N}\chi_l^2$
- N individual atom quadrupoles, but collective modes χ_l scaled up with M and L
- Quantized dominant interaction: $\hat{H}_{int} = \sqrt{M}L\ddot{\hat{h}}_{xx}\frac{\sqrt{\hbar}}{\sqrt{\omega_l}\,\pi^2}\sum_{l=1,3,\ldots}^{N}\frac{(-1)^{\frac{l-1}{2}}}{l^2}\left(\hat{b}_l+\hat{b}_l^\dagger\right)$

B. STIMULATED EMISSION & ABSORPTION

$$\Gamma_{stim}\,(1 \rightarrow 0) = \frac{2\pi}{\hbar}\left|\langle 1|\,\langle \alpha|\widehat{H}_{int}|\alpha\rangle\,|0\rangle\right|^2 \rho = \frac{|\alpha|^2 8GML^2\omega_l^4}{l^4\pi^4c^5}$$

$$|\alpha|^2 \approx N = \frac{h_0^2c^5}{32\pi G\hbar\omega_l^2}$$

$$\boxed{\Gamma_{stim} = \frac{ML^2\omega_l^2}{4l^4\pi^5\hbar}h_0^2 = \frac{Mv_s^2}{4l^4\pi^3\hbar}h_0^2}$$

ρ_m: mass density

$v_s = \frac{L\omega_l}{l\pi}$: sound speed

Joe Weber

Example: Aluminum bar $M = 1800\,kg$ $v_s = 5.4\frac{km}{s}$

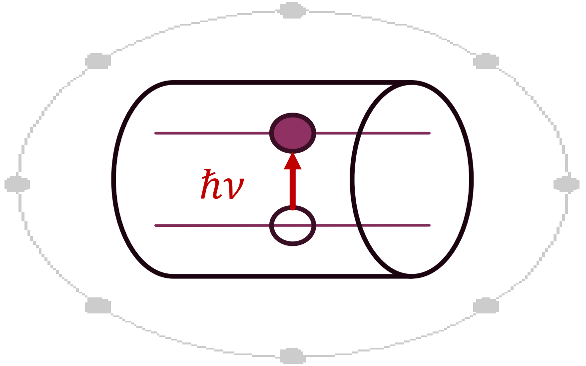
$h_0 = 5 \times 10^{-22}$ (GW150914)

$$\boxed{\Gamma_{stim} = 1\,Hz}$$

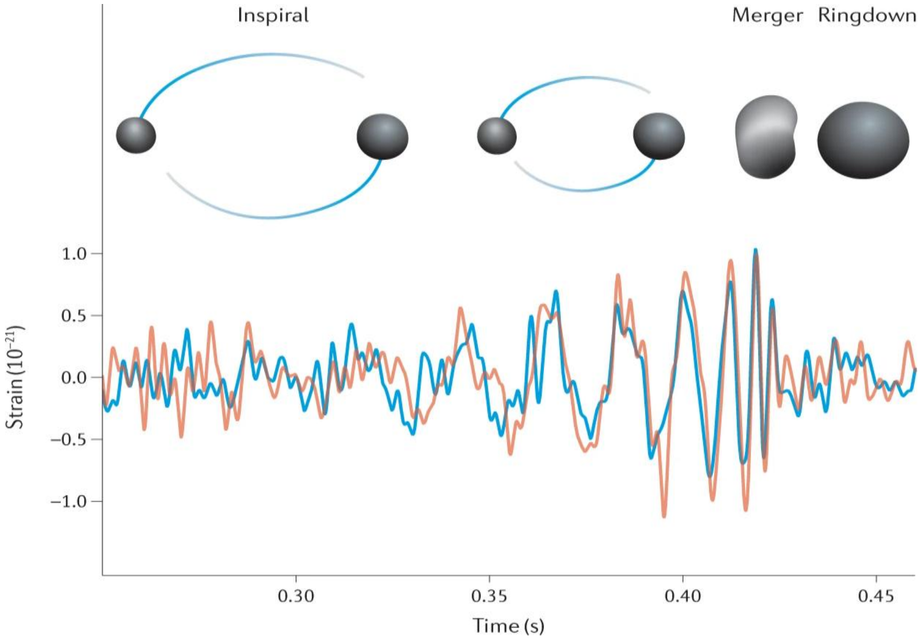
One graviton emitted/absorbed per second

QUANTUM HINTS FROM STIMULATED PROCESSES

- Can we see signatures of discrete exchange of energy between matter and gravity?
- Individual events indicate exchange of a single quantum of energy
- Resolve a single quantum jump by discrete energy due to absorption of single graviton
- Stimulated process, and discreteness: analogy to historic photoelectric effect



C. QUANTUM SENSING OF ENERGY



Bailes et al., Nat Rev Phys 3, 344–366 (2021)

Dynamics of quantum matter under GW:

$$\hat{H} = \hbar\omega\hat{b}^\dagger\hat{b} + \frac{L}{\pi^2}\sqrt{\frac{M\hbar}{\omega}}\ddot{h}(t)\left(\hat{b} + \hat{b}^\dagger\right)$$

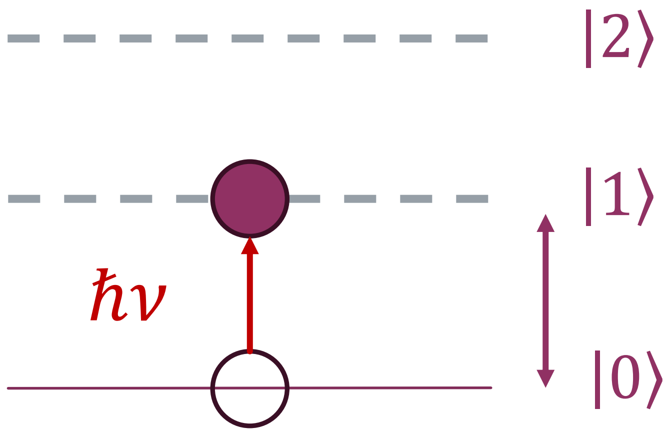
Results in the exact dynamics, found for example by Magnus expansion:

$$\boxed{\hat{U} = e^{-i\varphi}e^{-\omega t\hat{b}^\dagger\hat{b}}\hat{D}(\beta)}$$

$$\beta = -i\frac{L}{\pi^2}\sqrt{\frac{M\hbar}{\omega}}\int_0^t ds\,\ddot{h}(s)e^{i\omega s}$$

(analogous to quantum optics case: Glauber 1965)

C. QUANTUM SENSING OF ENERGY



Single energy transition probability: $P = |\langle 1|\widehat{U}|0\rangle|^2$

Maximized: $P_{max} = 0.37$, for $|\beta|_{max} = 1$

$$|\beta| = \frac{L}{\pi^2}\sqrt{\frac{M}{\omega\hbar}}\chi(h,\omega,t) \qquad \chi(h,\omega,t) = \left|\int_0^t ds\, \ddot{h}(s)e^{i\omega s}\right|$$

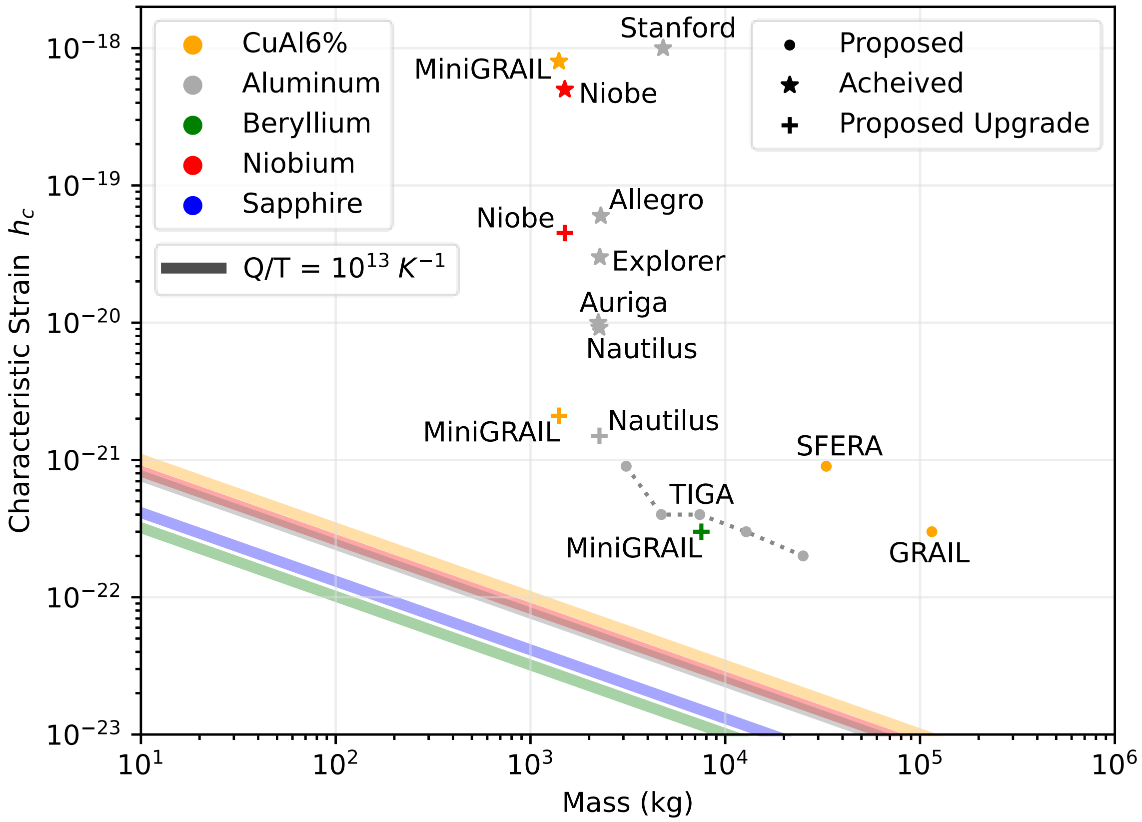
Ideal detector mass for single graviton detection:

$$\boxed{M = \frac{\pi^2\hbar\omega^3}{v_s^2\chi(h,\omega,t)}}$$

ESTIMATED PARAMETERS FROM GW SOURCES

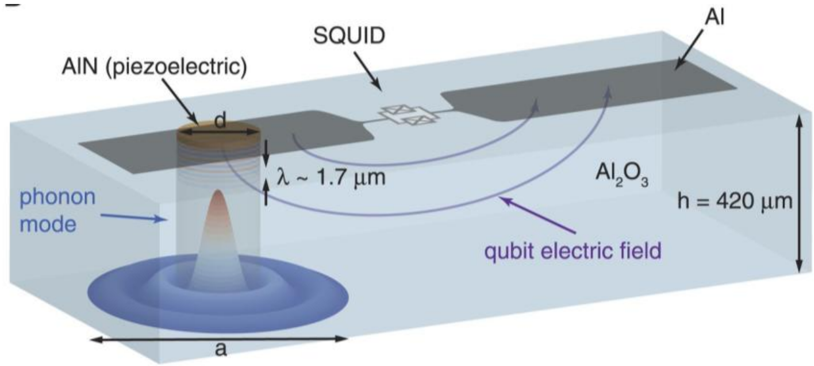
GW Source	**GW170817 (NS-NS merger)**	**GW170817 (NS-NS merger)**	**GW170608 (BH-BH merger)**	**GW150914 (BH-BH merger)**	**J1301+0833 (black-widow pulsar)**	**J1748−2446ad (fast-spinning pulsar)**	**A0620-00 (BH Super-radiance)**	**Primordial (rare BH-BH merger)**
$f = \frac{\omega}{2\pi}$	100 Hz	150 Hz	175 Hz	200 Hz	1085 Hz	1433 Hz	33 kHz	5.5 MHz
$h_0(f)$	2×10^{-22}	2×10^{-22}	2×10^{-22}	10^{-21}	$< 10^{-25}$	$< 10^{-25}$	3×10^{-21}	10^{-16}
M_c	1.19 $M_\odot$	1.19 $M_\odot$	7.9 $M_\odot$	28.6 $M_\odot$	Continuous	Continuous	Continuous	5×10^{-4} $M_\odot$
Material	Beryllium	Aluminum	Niobium	CuAl6%	Niobium	Superfluid He-4	Sapphire	Quartz
v_0	13 km/s	5.4 km/s	5 km/s	4.1 km/s	5 km/s	238 m/s	10 km/s	6.3 km/s
T	1 mK	1 mK	1 mK	1 mK	0.1 μK	0.1 μK	0.6 K	0.6 mK
Q-factor	10^{10}	10^{10}	10^{10}	10^{10}	10^{10}	10^{13}	10^{10}	10^{10}
M	~ 15 kg	~ 250 kg	~ 9 t	~ 6 t	> 52 t	> 20 t	~ 100 kg	~ 10 g

COMPARISON TO PREVIOUS BAR DETECTORS

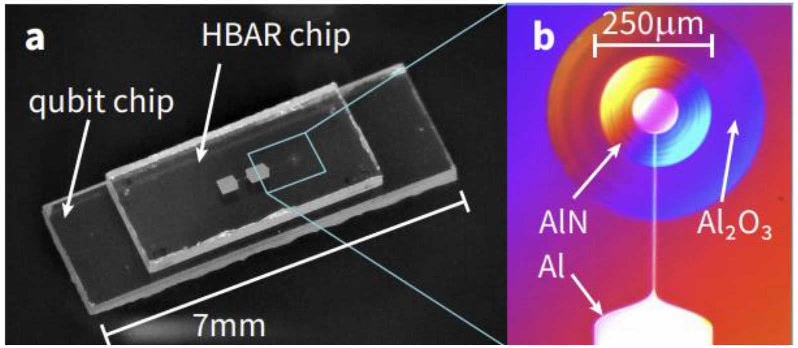


- If using the detector to simply detect gravitational waves: comparison to old and proposed bar detectors
- Lines show our envisioned strain sensitivity
- Need additional quantum sensing capability of energy levels

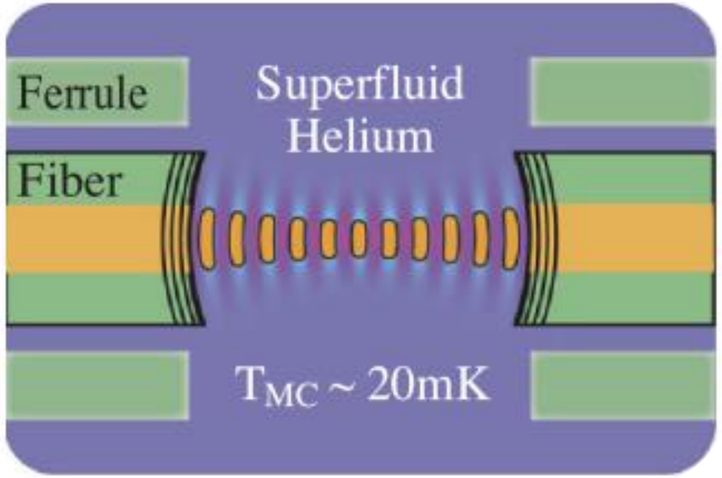
MEASURING INDIVIDUAL ACOUSTIC PHONONS



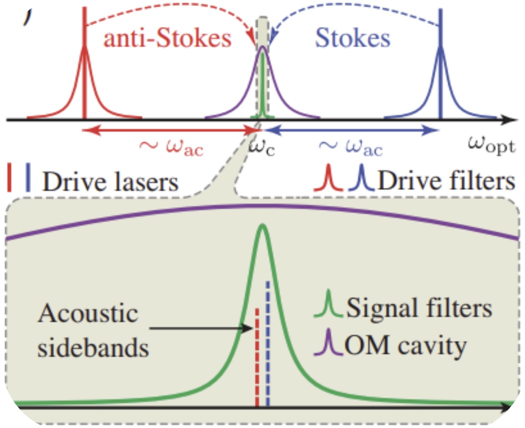
Chu, … Schoelkopf. *Science 358, 199-202 (2017)*

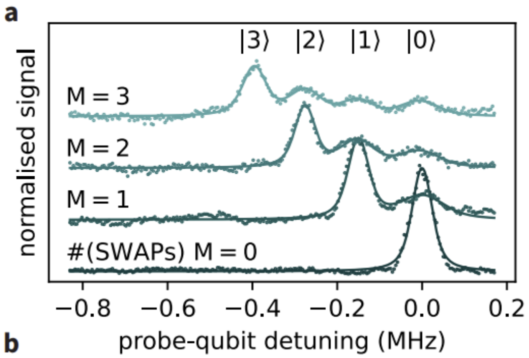


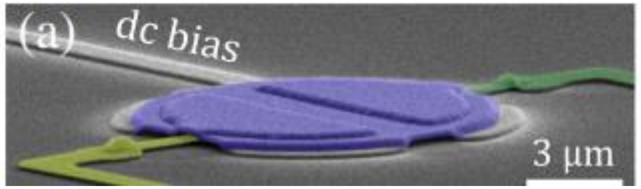
von Lüpke, … Chu. *Nature Physics 18, 794–799 (2022)*

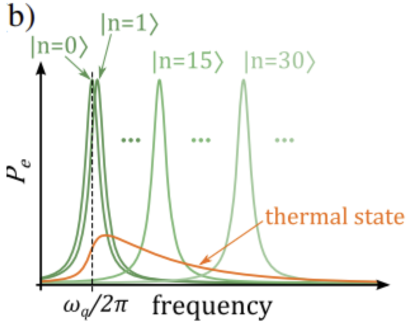


Patil, … Harris. *PRL 128, 183601 (2022)*









Viennot, Ma, Lehnert. *PRL 121, 183601 (2018)*

DETECTING SINGLE GRAVITONS WITH QUANTUM SENSING

Single graviton detection is possible

A. Focus on macroscopic quantum systems

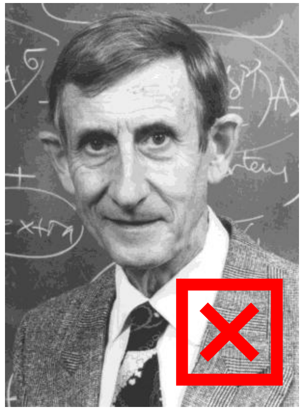
B. Focus on stimulated emission/absorption of single gravitons

C. Focus on quantum sensing of quantum jumps

D. Correlate to classical detections of gravitational waves

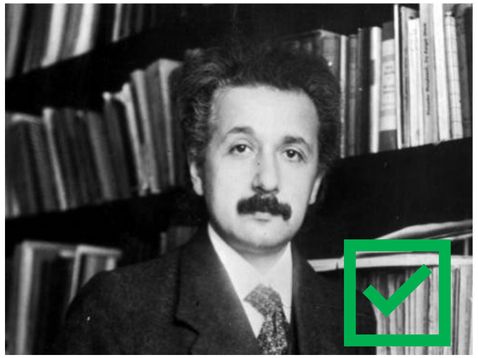
Tobar*, Manikandan*, Beitel, Pikovski.
Nature Communications 15, 7229 (2024)

Single gravitons can be detected in realistic experiments!



Dyson. "Is a graviton detectable?" *(2013)*

Weber. "Detection and Generation of Gravitational Waves" *(1960)*



Einstein. "Über einem die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" *(1905)*

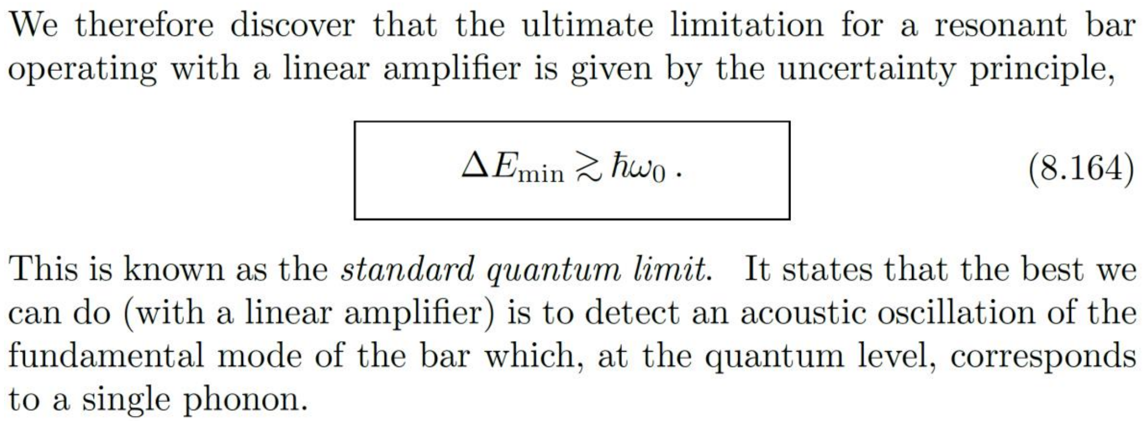
Gravito-phononic analogue of photoelectric effect, with quantum accoustic resonators

COMPARISON TO PREVIOUS RESULTS

Well-known in other community: resonant GW detection

$$\sigma \sim L_p^2 \frac{v_s M L}{\hbar} = \frac{G M L^2 \omega}{c^3}$$

Maggiore, "Gravitational Waves" 2008

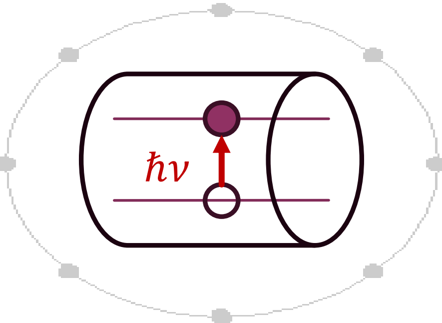


We therefore discover that the ultimate limitation for a resonant bar operating with a linear amplifier is given by the uncertainty principle,

$$\boxed{\Delta E_{\min} \gtrsim \hbar\omega_0 \,.} \qquad (8.164)$$

This is known as the *standard quantum limit*. It states that the best we can do (with a linear amplifier) is to detect an acoustic oscillation of the fundamental mode of the bar which, at the quantum level, corresponds to a single phonon.

Bars aimed to operate "at quantum limit", but only on average with position measurements



In our work: Use macro-system coupling, but still resolve *single* quantum jumps as in atoms

GRAVITONS VS PROOF OF QUANTIZATION

Would the experiment prove quantization of gravity?

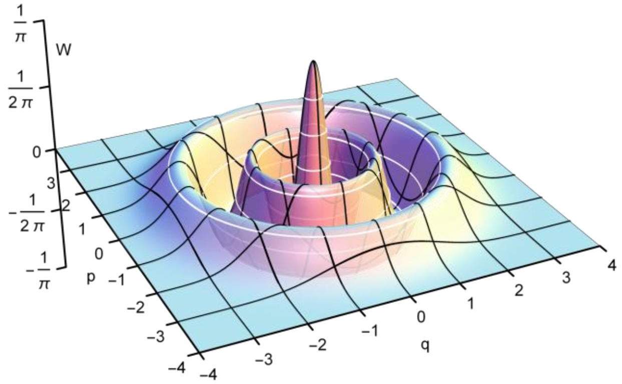
No!

A *semiclassical* description is possible, just like for the photoelectric effect

$$\hat{H}_{QGR} = g\,\ddot{\hat{h}}(t)\hat{x} \qquad \text{vs} \qquad H_{SC} = g\,\ddot{h}(t)\hat{x}$$

To rule out *this* semiclassical model, need more:

- Particle anti-bunching
- Sub-Poisson statistics
- HoM effect



GRAVITONS VS PROOF OF QUANTIZATION

We can’t distinguish this semi-classical model, but that’s not the goal

$$\hat{H}_{QGR} = g\,\ddot{\hat{h}}(t)\hat{x} \qquad \text{vs} \qquad H_{SC} = g\,\ddot{h}(t)\hat{x}$$

- A very specific model, violates energy conservation
- Artificial “test model”, not normal classical GR
- Many other models with “hybrid classical-quantum coupling”
- Even ruling out this model does not prove quantization
- Not a relevant benchmark

HISTORIC PERSPECTIVE: INSPIRATION FROM EARLY QM

What can we learn about quantization of gravity?

Mark Suppiah, Victoria Shenderov, Isabella Marotta (high school interns)

“Stimulated absorption of single gravitons: First light on quantum gravity”

arXiv:2407.11929

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The trustees are pleased to announce the Awards for Essays for 2024.

Selected for Honorable Mention this year were (listed in alphabetical order): Francesco Alessio and Michele Arzano; Spyros Basilakos, Dimitri V. Nanopoulos, Theodoros Papanikolaou, Emmanuel N. Saridakis and Charalampos Tzerefos; Elmo Benedetto, Christian Corda and Ignazio Licata; Nigel T. Bishop, Vishnu Kakkat, Amos S. Kubeka, Monos Naidoo and Petrus J. van der Walt; Philippe Brax and Pierre Vanhove; Molly Burkmar and Marco Bruni; Juan A. Cañas, A. Martin-Ruiz and J. Bernal; Raúl Carballo-Rubio and Astrid Eichhorn; Juanca Carrasco-Martinez; Man Ho Chan; S. Mahesh Chandran and S. Shankaranarayanan; Hong Zhe Chen; RY Chiao, NA Inan, DA Singleton, ME Tobar; Sayantan Choudhury; A. A. Coley; Bruno Arderucio Costa; Jesse Daas, Cristobal Laporte, Frank Saueressig and Tim van Dijk; John Bruce Davies; Arthur E. Fischer; T. R. Govindarajan; Eduardo Guendelman; Yuan K. Ha; Shahar Hod; Viqar Husain, Irfan Javed, Sanjeev Seahra and Nomann X; Lawrence M. Krauss, Francesco Marino, Samuel L. Braunstein, Mir Faizal and Naveed A. Shah; Philip D. Mannheim; Alexander I. Nesterov; Fabrizio Pinto; Tom Rudelius; Jorge G. Russo; Victoria Shenderov, Mark Suppiah, Thomas Beitel, Sreenath K.Manikandan and Igor Pikovski; Tejinder P. Singh; Slava G.Turyshev; C.S.Unnikrishnan; Jenny Wagner

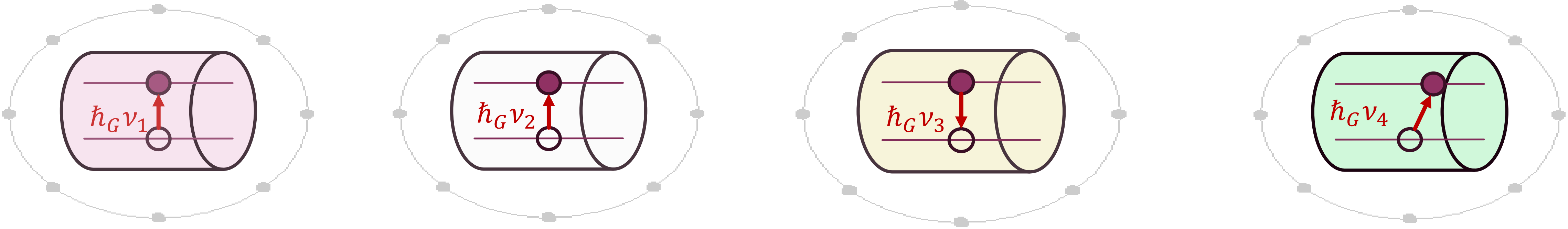
This announcement and abstracts of award-winning and honorable mention essays are posted on our web site, http://www.gravityresearchfoundation.org. The five award-winning essays are also posted on our website and will be published in the October 2024 SPECIAL ISSUE of the International Journal of Modern Physics D (IJMPD).

TESTING INTERACTION ON QUANTUM LEVEL

We propose several simple tests of linearized quantum gravity

$$H_{int} = -\frac{1}{2}\hat{T}_{\mu\nu}\hat{h}^{\mu\nu}$$

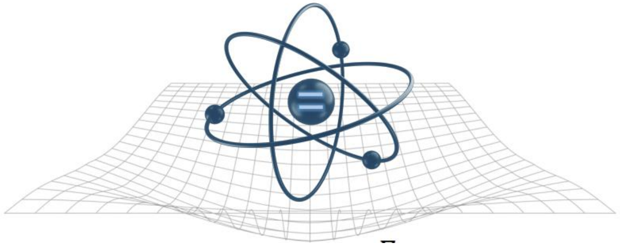
- Is energy content in graviton as expected? $\hbar_G = \hbar$?
- Is $\hbar_G$ universal for all matter?
- Same stimulated emission and absorption rates?
- Is it a spin-2 transition?
- Combine with other experimental input?



SUMMARY

- New quantum technologies open possibility of QGR experiments
- Push towards tests of gravitationally induced collapse of the wavefunction

- Other QGR models also testable in table-top setups: empirical input (and exclusion plots) for QGR



- Indirect test can provide hints of QGR, use quantum information concepts to show nonclassicality
- Direct detection of single gravitons is possible: macroscopic quantum resonators + sensing