Detecting single gravitons with quantum sensing

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and Igor Pikovski

Arxiv:2308.15440 (2023)
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Stockholm University
General Sir John Monash Foundation

Overview

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4. Semi-classical VS Quantum

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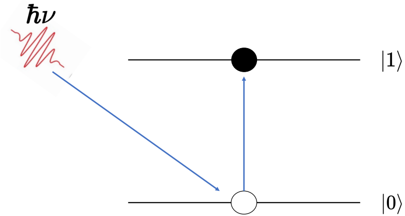

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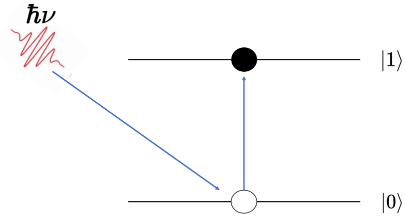

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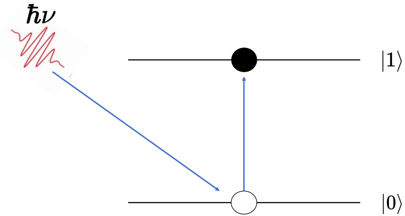

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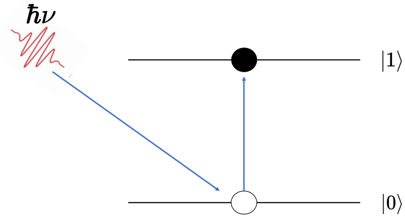

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2. The photo-electric effect works on exactly the same principle, but $|0\rangle \rightarrow |k\rangle$, where $|k\rangle$ is a state in the continuum of excited states.
3. Original studies of photon detections - stimulated processes (photo-electric effect). Modern view: 'detection' is only when there is a single-photon-input'.

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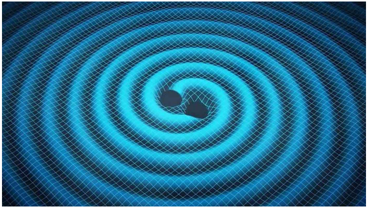

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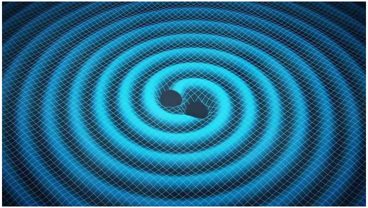

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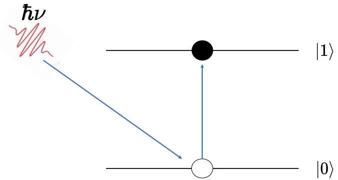

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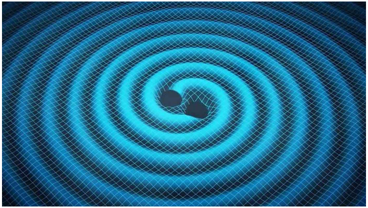

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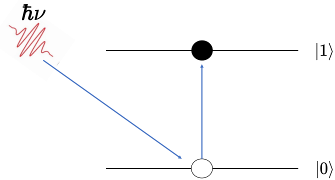

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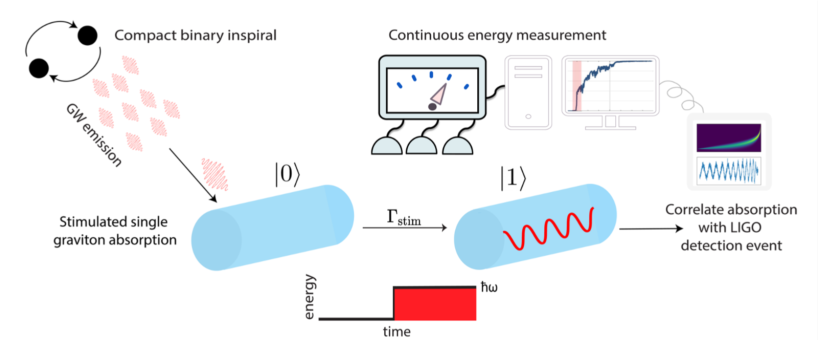
Our answer: Yes!
Tobar, Manikandan, Beitel, Pikovski Arxiv:2308.15440 (2023)
Quantum-jumps between energy levels of a massive quantum acoustic resonator, induced by a gravitational wave.

Particle detection for gravitational waves

You do not need a single graviton input, to infer the exchange of single energy quanta between matter and gravitational waves (as occurs in the photo-electric effect)



Single graviton processes

- Linearized quantum gravity, low energy regime: Bronstein 1935, Feynman 1963, Dyson 1969, Weinberg 1972, Lightman 1973, Boughn and Rothman 2006.

First quantize:

$$\hat{h}^{ij} = \sum_{\boldsymbol{k},\lambda} e^{ij}_{\boldsymbol{k},\lambda} h_{q\boldsymbol{k},\lambda} \hat{a} e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)} + cc \tag{1}$$

$$h_{qk,\lambda} = \sqrt{\frac{16\pi G\hbar}{c^2 v_k V}} \tag{2}$$

Then compute the graviton transition rate:

$$\Gamma_{\text{atom}}(3d2 \to 1s) = \frac{2\pi}{\hbar} \left| \left\langle 1s \left| \left\langle 1 \left| \widehat{H}_{\text{int}} \right| 0 \right\rangle \right| 3d2 \right\rangle \right|^2 \rho \approx 10^{-40} s^{-1}. \tag{3}$$

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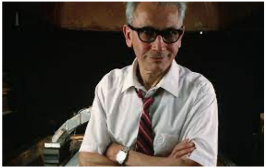
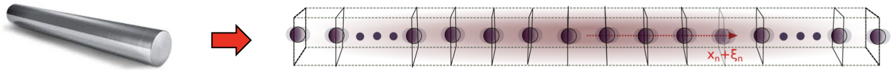
Massive acoustic resonators (Weber Bars)



Cho Adrian. 'Remembering Joseph Weber, the controversial pioneer of gravitational waves'. Science 12 (2016).

An enhancement to the graviton-matter interaction

Weber-BARs provide a macroscopic enhancement for the graviton-matter interaction as compared to the case where the matter is an atom:



$$H_{\text{int}} \approx -m \sum_n \frac{1}{4} \ddot{h}_{xx}(t)\,(x_n+\xi_n)^2 \approx -\frac{ML\ddot{h}_{xx}(t)}{\pi^2} \sum_{l=1,3,5..} \frac{(-1)^{\frac{l-1}{2}}}{l^2} \chi_l. \quad (4)$$

Now, take the example of a Niobium-cylinder:

$$\rho_m = 8570\frac{kg}{m^3} \qquad v_s = 5\frac{km}{s} \qquad 2R = L = 1m$$

$$\Gamma_{spon} = 10^{-33} s^{-1}$$

Orders of magnitude larger than the atom, but still vanishingly small!

We now consider stimulated emission and absorption

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

with the number of gravitons in the gravitational wave as:

$$|\alpha|^2 \approx N = \frac{h_0^2 c^5}{32\pi G\hbar\omega_l^2} \tag{6}$$

, the stimulated emission rate is

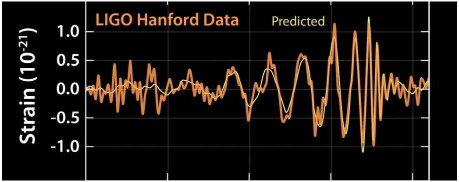
$$\Gamma_{\rm stim} = \frac{ML^2\omega_l^2}{4l^4\pi^5\hbar}h_0^2 = \frac{Mv_s^2}{4l^4\pi^3\hbar}h_0^2. \tag{7}$$

For an Aluminum BAR of Mass 1800 kg, and strain amplitude $h_0 = 5 \times 10^{-22}$ (GW150914), we obtain:

$$\Gamma_{\rm stim} \approx 1 \text{ Hz}. \tag{8}$$

Chirping Gravitational Waves

However, detected gravitational waves chirp, in which case need to solve by accounting for the time-dependent interaction:
$\widehat{H} = \hbar\omega \hat{b}^\dagger \hat{b} + \frac{L}{\pi^2}\sqrt{\frac{M\hbar}{\omega}}\ddot{h}(t)\left(\hat{b} + \hat{b}^\dagger\right).$



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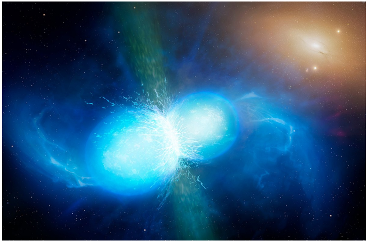

The dynamics can be solved analytically

$$|0\rangle \to \left|\beta(t)e^{-i\omega t}\right\rangle \quad |\beta| = \frac{L}{\pi^2}\sqrt{\frac{M}{\omega\hbar}}\chi(h,\omega,t) \quad \chi(h,\omega,t) = \left|\int_0^t ds\ddot{h}(s)e^{i\omega s}\right| \tag{9}$$

$$P_{0\to 1} = \left|\left\langle 1 \mid \beta e^{-i\omega t}\right\rangle\right|^2 = e^{-|\beta|^2}|\beta|^2$$
$$P_{\max} = \frac{1}{e} \to \sim 36\% \quad |\beta|_{\max} = 1 \tag{10}$$

Chirping gravitational waves

Optimise the mass for a single graviton exchange:

$$|\beta|_{\mathrm{max}} = 1 \quad M = \frac{\pi^2 \hbar \omega^3}{v_s^2 \chi(h, \omega, t)}$$

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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
$h_0(f)$	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	Sapphire	Aluminum	Niobium	CuAl6%	Niobium	Superfluid He-4	Sapphire	Quartz
v_0	10 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	~ 100 kg	~ 250 kg	~ 9 t	~ 6 t	> 52 t	> 20 t	~ 100 kg	~ 10 g

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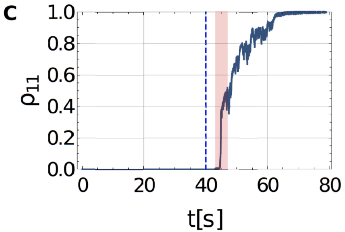

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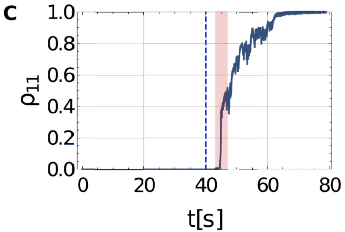
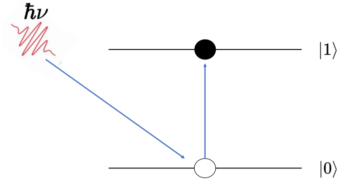


Gives a direct gravito-phononic analogue of the photo-electric case:



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In our gravito-phononic set-up, we have:

- Threshold frequency: $P_{0\to 1} \approx \frac{h_0^2\omega^3 ML^2}{\hbar\pi^4(\nu-\omega)^2}\sin^2\frac{(\nu-\omega)t}{2}$.
- Independence of ejected gravito-phonon energy ($\hbar\omega$) from the GW amplitude h.
- Non-zero gravito-phonon ejection probability at arbitrarily small times (follows from $P_{0\to 1}$ above).

Semi-classical vs Quantum

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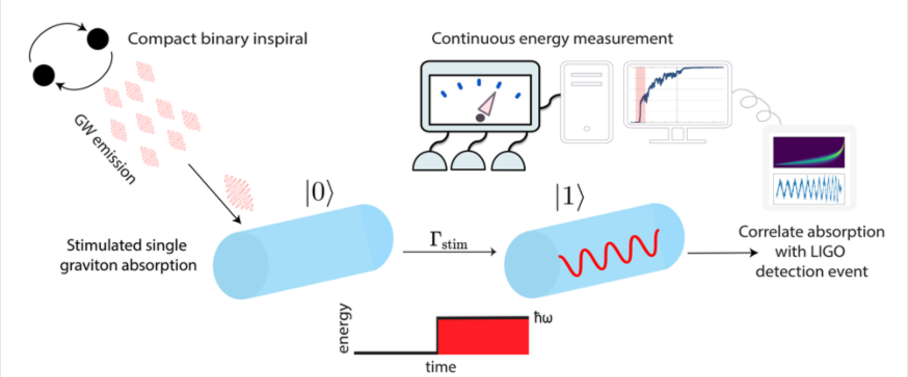
However, such semi-classical models must violate energy conservation for single discrete transitions in energy.
So our proposed *gravito-phononic effect* can function as an indirect test of the quantum nature of the gravitational field.

Protocol Summary



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