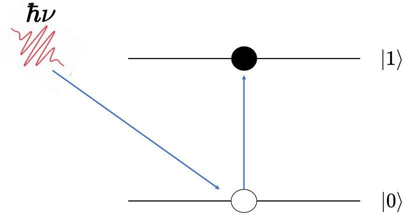
Detecting single gravitons with quantum sensing

Germain Tobar*, *Sreenath K Manikandan**, *Thomas Beitel*, and Igor Pikovski

Arxiv:2308.15440 (August, 2023)
Ultra-High-Frequency Gravitational Waves: Where to Next?
CERN 4-8 December 2023

Particle detection for gravitational waves



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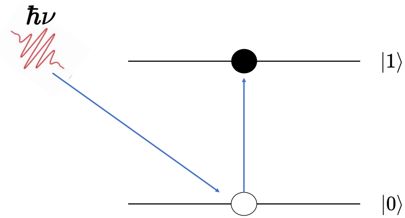

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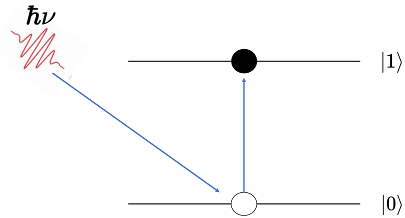

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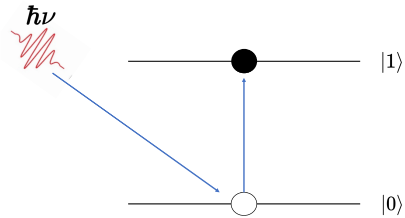

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2. The photo-electric effect works on exactly the same principle, but $|0\rangle \to |k\rangle$, where $|k\rangle$ is a state in the continuum of excited states.
3. Original studies of photon detections - stimulated processes (photo-electric effect).

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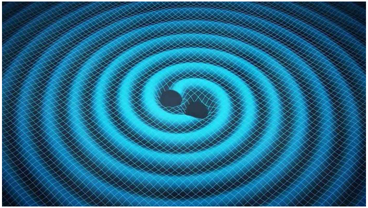

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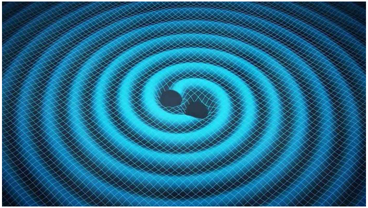
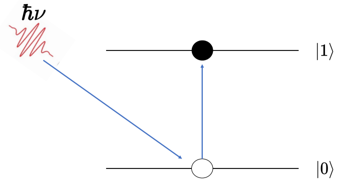


Particle-detection processes



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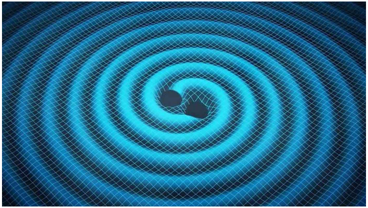

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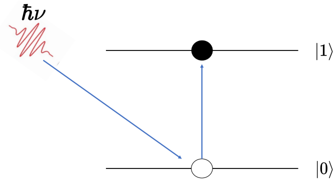

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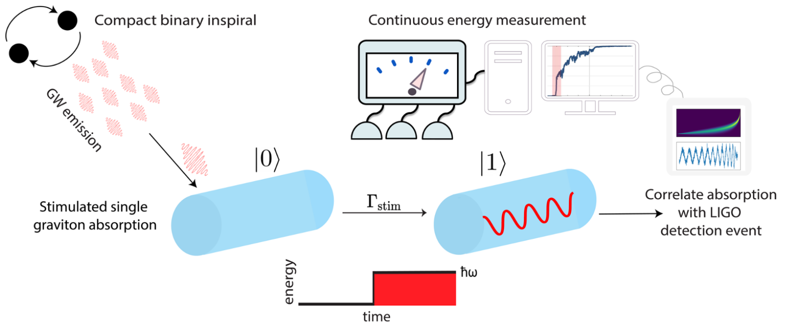
Our answer: Yes!
Tobar, Manikandan, Beitel, Pikovski Arxiv:2308.15440 (2023)
Quantum-jumps between energy levels of a massive quantum acoustic resonator, induced by a gravitational wave.

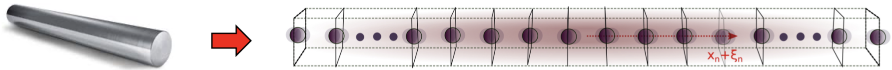
Particle detection for gravitational waves

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)



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:



Now, take the example of a Niobium-cylinder:

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

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

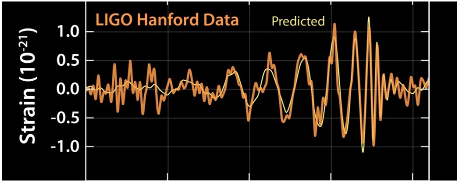
Orders of magnitude larger than the atom, but still vanishingly small!

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

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

Chirping Gravitational Waves

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



Expected signal

For the response of the BAR to a Primordial BH-BH merger of chirp mass $5 \times 10^{-4} M_{\odot}$, and a rare event with $h_0 = 10^{-16}$, the required BAR detector parameters are

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$$\begin{aligned} \text{BAR detector resonance frequency}: \ f &= 5.5 \ \text{MHz} \\ \text{Required enivironmental temperature}: 0.6 \ \text{mK} \\ \text{Required Q} - \text{ factor}: 10^{10} \\ \text{Optimal detector mass}: 10 \ \text{g} \end{aligned} \tag{2}$$

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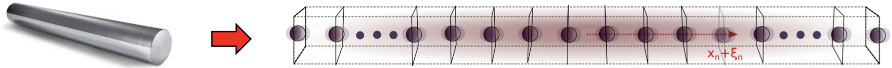

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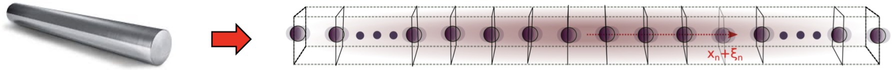

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Chirping gravitational waves

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What parameters have been achieved?

High Sensitivity Gravitational Wave Antenna with Parametric Transducer Readout

D. G. Blair, E. N. Ivanov, M. E. Tobar, P. J. Turner, F. van Kann, and I. S. Heng
Physics Department, University of Western Australia, Nedlands, Western Australia, 6009
(Received 4 April 1994; revised manuscript received 27 September 1994)

The ultracryogenic gravitational-wave detector AURIGA

M Cerdonio[1], M Bonaldi[2], D Carlesso[1], E Cavallini[3], S Caruso[1], A Colombo[1], P Falferi[2], G Fontana[4], P L Fortini[3], R Mezzena[4] + Show full author list
Published under licence by IOP Publishing Ltd
Classical and Quantum Gravity, Volume 14, Number 6
Citation M Cerdonio *et al* 1997 *Class. Quantum Grav.* **14** 1491
DOI 10.1088/0264-9381/14/6/016

Progress towards ground state cooling of a 1.5 tonne Niobium BAR, with $Q \sim 10^8$ and $f = 700$ Hz

More recently, near ground state cooling for lower masses (gram scale) and higher frequencies (MHz), with $Q \sim 10^{10}$.

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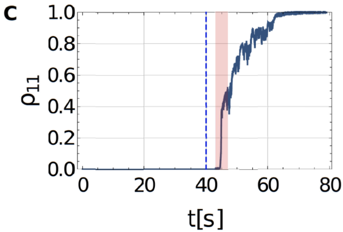

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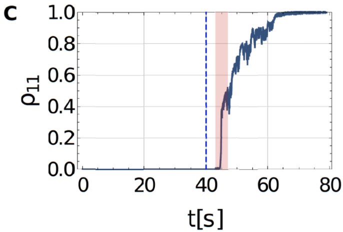
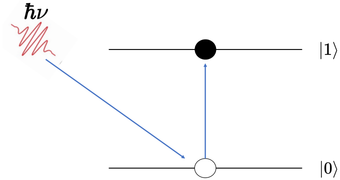


Gives a direct gravito-phononic analogue of the photo-electric case:



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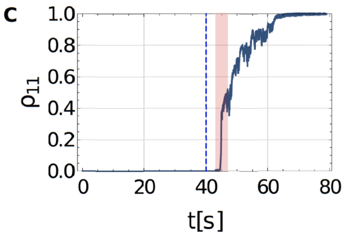

What has been achieved?

Parity measurement in the strong dispersive regime of circuit quantum acoustodynamics

Uwe von Lüpke, Yu Yang, Marius Bild, Laurent Michaud, Matteo Fadel & Yiwen Chu

Nature Physics **18**, 794–799 (2022) | Cite this article

Direct measurement of individual energy levels of microgram mass acoustic resonators

Photo-electric analogue

What has been achieved? Continuous measurement of massive mechanical resonators

Observing and Verifying the Quantum Trajectory of a Mechanical Resonator

Massimiliano Rossi, David Mason, Junxin Chen, and Albert Schliesser
Phys. Rev. Lett. **123**, 163601 – Published 14 October 2019

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- Threshold frequency: $P_{0\to 1} \approx \frac{h_0^2 \omega^3 M L^2}{\hbar \pi^4 (v-\omega)^2} \sin^2 \frac{(v-\omega)t}{2}$.
- Independence of ejected gravito-phonon energy ($\hbar\omega$) from the GW amplitude h.
- Time-scale for gravito-phonon production is the measurement strength.

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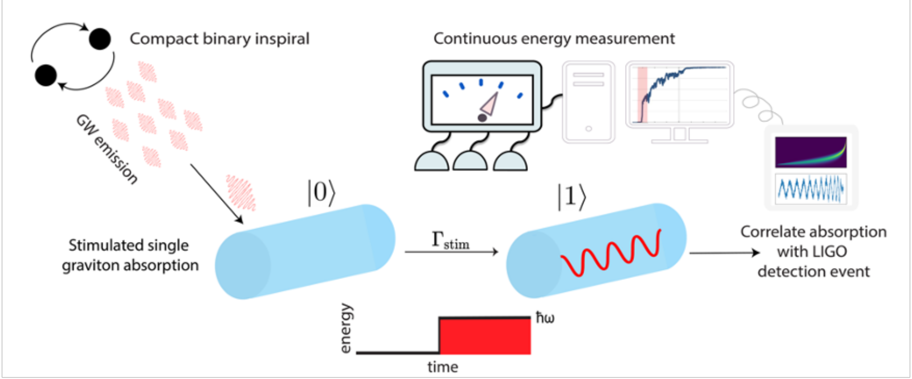
However, such semi-classical models must violate energy conservation for single discrete transitions in energy.
If energy is conserved, the experiment is inconsistent with the gravitational field treated as a classical-continuous wave that solves the linearised Einstein equations.

Protocol Summary



Conclusion

Tobar*, G., Manikandan*, S. K., Beitel, T., & Pikovski, I. Detecting single gravitons with quantum sensing (2023). arXiv:2308.15440.

Chirping gravitational waves

Optimise the mass for a single graviton exchange:

$$P_{\text{max}} = 0.36 \quad M = \frac{\pi^2 \hbar \omega^3}{v_0^2 \chi(h, \omega, t)}$$

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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

Gravitational photoelectric relation