⟨Quantum|Gravity⟩Society

Comments on Graviton Detection

Daniel Carney

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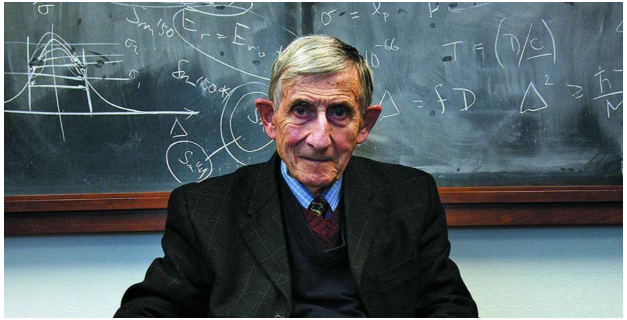
BERKELEY LAB



Is a Graviton Detectable?

Poincare Prize Lecture

International Congress of Mathematical Physics

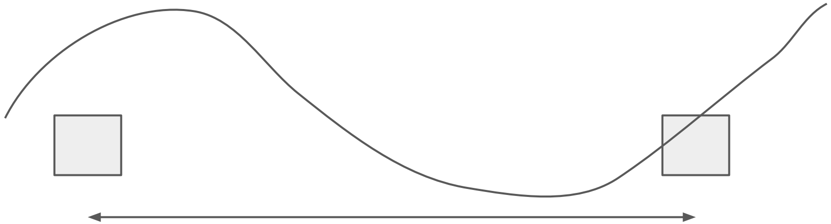
Aalborg, Denmark, August 6, 2012

Freeman Dyson, Institute for Advanced Study, Princeton, New Jersey

Can we build a GW detector so sensitive that it will click when it absorbs a single graviton?

Dyson: no.

Dyson's argument, part 1



Strain of a single graviton $h \sim L_{planck}\ \omega$

→ Displacement between mirrors you need to detect is $\Delta x \sim h\ D \sim L_{planck}$

But, Heisenberg uncertainty $\Delta x\ \Delta p \sim M\ \Delta x^2/\Delta t \geq \hbar$

→ $\mathbf{D \leq G_N\ M/c^2}$

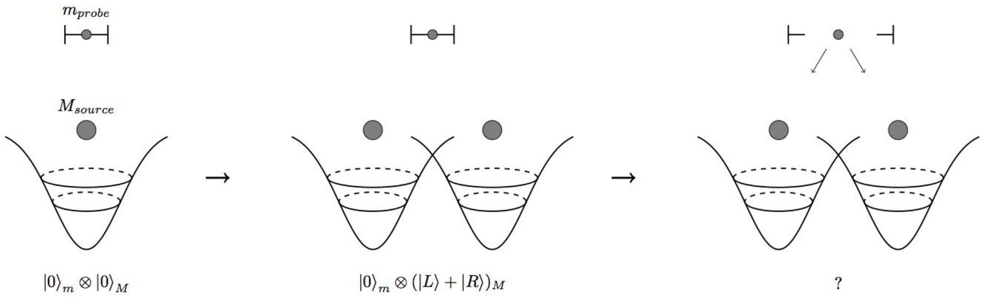
The detector has to be within its own Schwarschild radius. If you tried to build a LIGO than can detect single gravitons, it will collapse into a black hole!

Two alternative paths

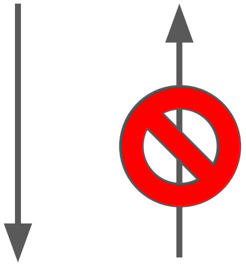
- Perform Bell-type gravitational entanglement measurements
[see also talks by Bob Wald, Markus Aspelmeyer]

- Figure out loophole or counter example to Dyson

Entanglement experiments and gravitons



$$\mathcal{L}_{\text{int}} = \frac{1}{m_{\text{pl}}} h^{\mu\nu} T_{\mu\nu}$$



$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$$

$$\hat{V} = \frac{G_N m_1 m_2}{|\hat{\mathbf{x}}_1 - \hat{\mathbf{x}}_2|}$$

Obvious: Graviton exists ⇒ will observe entanglement via Newton potential

(“Gravitons exist” = in the sense of effective field theory [see talk by John Donoghue]).

But converse: Observe entanglement via Newton ⇒ graviton exists

does not automatically follow! One can only draw this second conclusion under some assumptions, or with additional experiments.

Cautionary tale: gravity in d=2+1

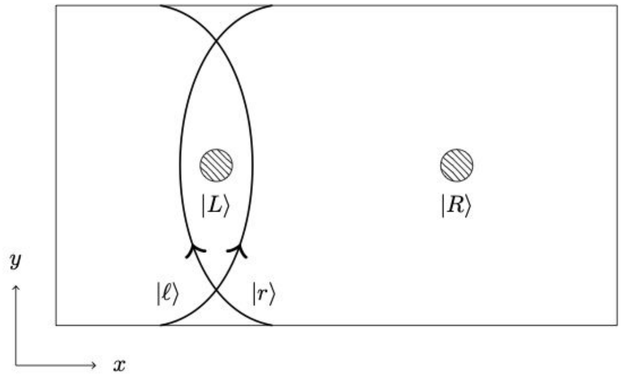
$$S = \int d^3x \sqrt{-g} \left[\frac{R}{16\pi G_N} + \mathcal{L}_{\text{matter}} \right]$$

In d=2+1, there are no propagating gravitational degrees of freedom, i.e., no gravitons.

But can entangle particles via “braiding”. Same physics as Aharonov-Bohm effect, topological quantum computer.

→ Lorentz-invariant field theory, which predicts gravitational entanglement, and has no gravitons.

Why would the conclusion be different in d=3+1?



Deser, Jackiw, ‘t Hooft 1984
Witten 1988, Carlip 1989

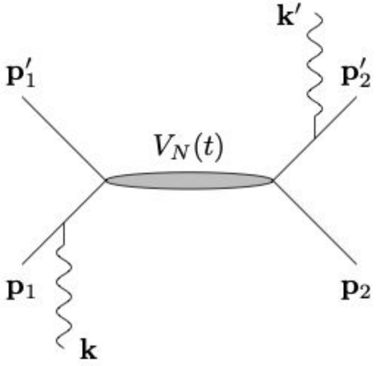
Scattering amplitude analysis

Let's analyse a prototypical gravitational entanglement experiment in the language of scattering amplitudes.
[see talks by Cliff Cheung, John Donoghue]

The experiments can be described by purely non-relativistic Newtonian 1/r interaction.

Theorem: any unitary, Lorentz invariant model which reproduces the 1/r scattering amplitude necessarily has quantized gravitational radiation in the asymptotic states.

"Alice measures her particle"

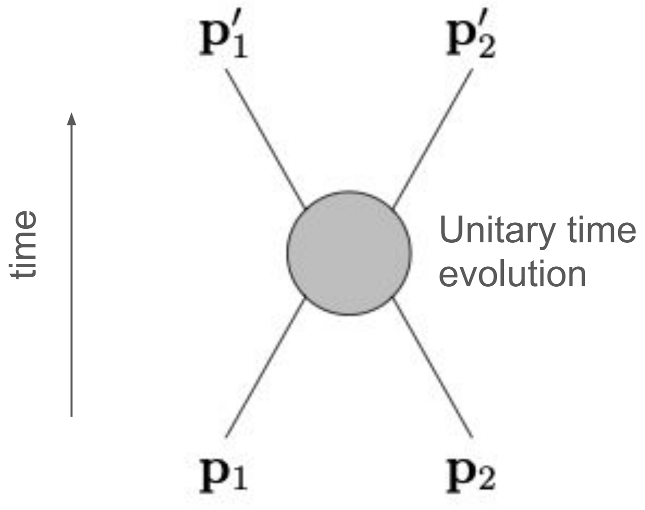


"Bob prepares his test particle"

Carney, "Newton, entanglement, and the graviton", 2108.06320

Unitarity + Lorentz invariance

Output = scattering wavepackets



Input = scattering wavepackets

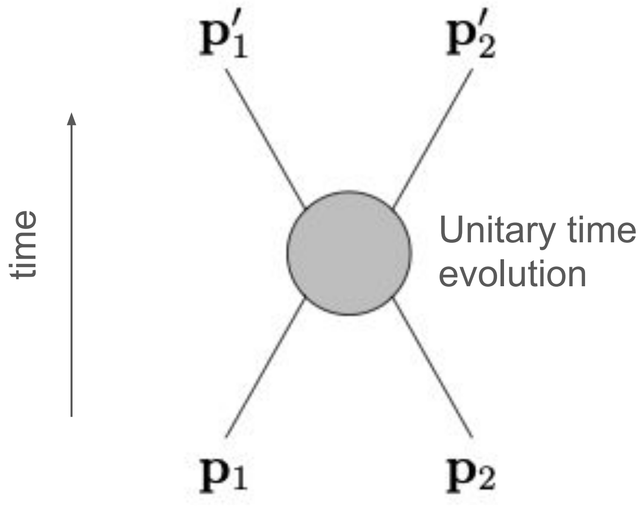
$$S = U(t = -\infty \to t = +\infty)$$

Rules:

1. Unitarity: $S^{\dagger}S = 1$.
2. Lorentz invariance: input/output transform as unitary representations U of Lorentz group, and $U^{\dagger}SU = S$.

Unitarity

Output = scattering wavepackets



Input = scattering wavepackets

$$S = U(t = -\infty \to t = +\infty)$$

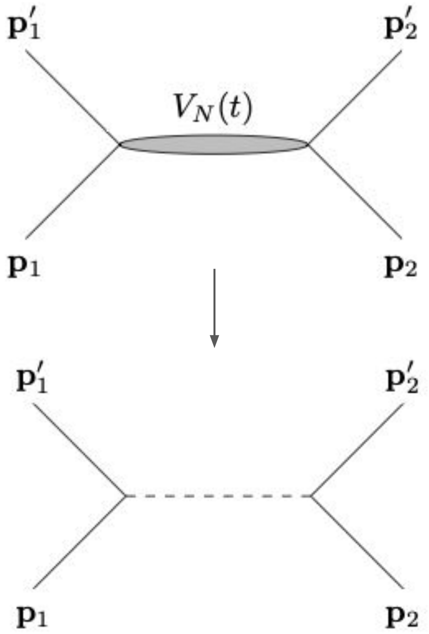
We will use unitarity in the form of the optical theorem: expand S matrix as

S = 1 + i M

Then unitarity $S^\dagger S = 1$ requires non-trivial interference relations between unscattered waves (1 term) and scattered waves (i M term):

$i (M - M^\dagger) = M^\dagger M$

Lorentz “bootstrap”



Central idea: demand that the non-relativistic scattering amplitudes that describe the experiment are the non-relativistic limit of a Lorentz-invariant amplitude.

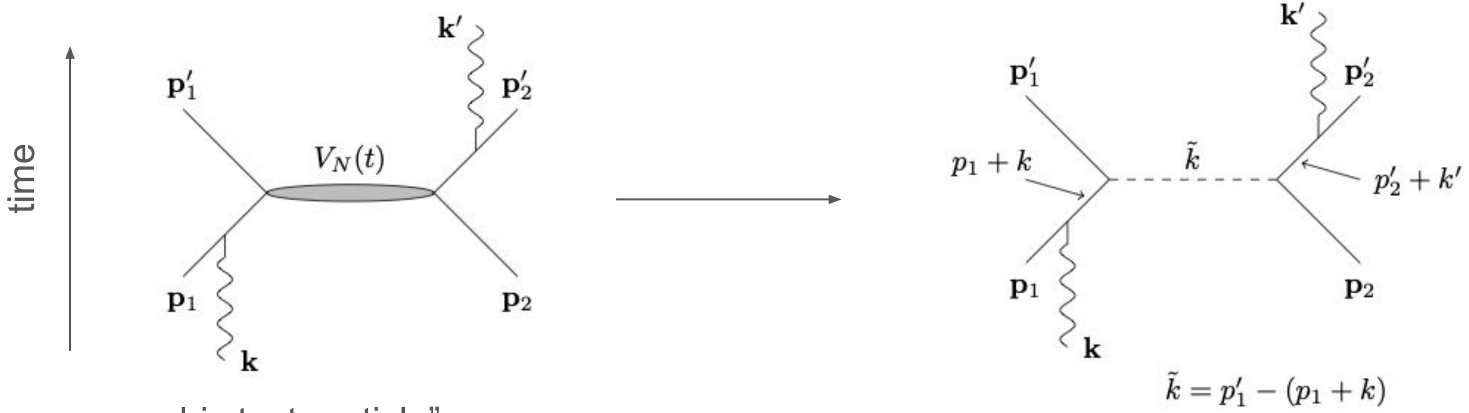
Example: consider 2 → 2 Newtonian scattering. To lowest order in the weak coupling (first Born approximation),

$$\mathcal{M}_{\mathbf{p}_1\mathbf{p}_2\to\mathbf{p}_1'\mathbf{p}_2'} = \langle \mathbf{p}_1'\mathbf{p}_2'|V|\mathbf{p}_1\mathbf{p}_2\rangle = \frac{G_N m^2}{(\mathbf{p}_1'-\mathbf{p}_1)^2+\mu^2} \longrightarrow \frac{G_N m^2}{(p_1'-p_1)^2+\mu^2}$$

Here μ is a regulator we’ll take to zero later. This is the ~unique Lorentz-invariant extension.

(Can multiply and add functions which are trivial near the pole $\Delta p^2 = -\mu^2$)

"Alice measures her particle"



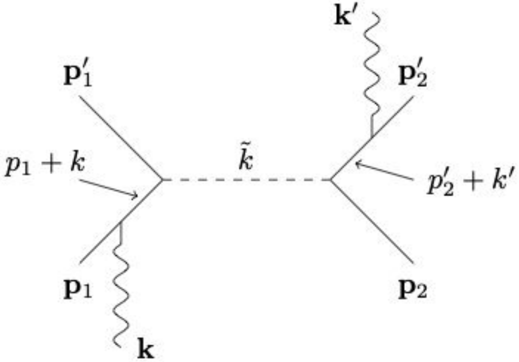
"Bob prepares his test particle"

Photon interaction strength

$$\mathcal{M}(\mathbf{k}\mathbf{p}_1\mathbf{p}_2 \to \mathbf{k}'\mathbf{p}_1'\mathbf{p}_2') \longrightarrow \left(\frac{\lambda}{(p_1+k)^2 + m^2 - i\epsilon}\right)\left(\frac{G_N m^2}{\tilde{k}^2 + \mu^2 - i\epsilon}\right)\left(\frac{\lambda}{(p_2'+k')^2 + m^2 - i\epsilon}\right)$$

Tree-level unitarity

$$\mathcal{M}(\mathbf{k}\mathbf{p}_1\mathbf{p}_2 \to \mathbf{k}'\mathbf{p}_1'\mathbf{p}_2') \longrightarrow \left(\frac{\lambda}{(p_1+k)^2+m^2-i\epsilon}\right)\left(\frac{G_N m^2}{\tilde{k}^2+\mu^2-i\epsilon}\right)\left(\frac{\lambda}{(p_2'+k')^2+m^2-i\epsilon}\right)$$



$\tilde{k} = p_1' - (p_1 + k)$

$$\text{Im}\,\mathcal{M} \sim G_N \lambda^2 = \frac{\lambda^2}{m_{\text{Pl}}^2}, \quad \text{at pole } \tilde{k}^2 = -\mu^2$$

What about unitarity?

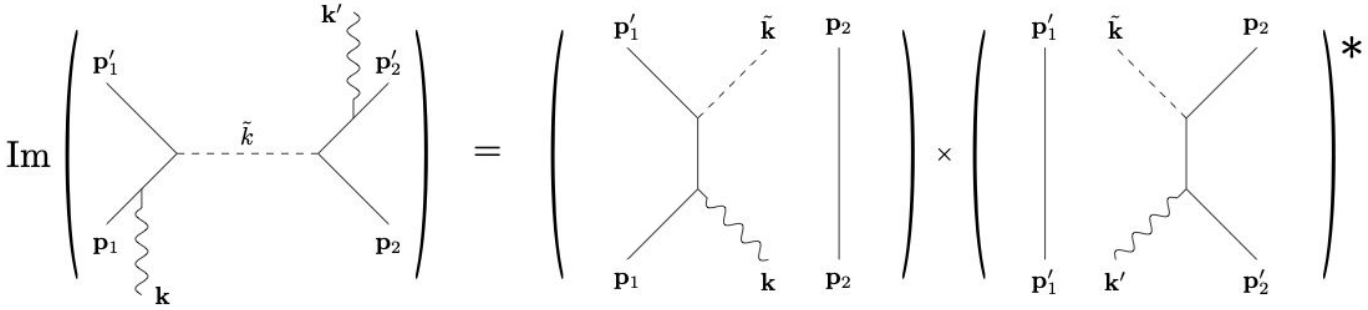
$$1 = S^\dagger S \iff \text{Im}\,\mathcal{M}_{\alpha\to\beta} = \sum_X \mathcal{M}(\alpha \to X)\mathcal{M}^*(\beta \to X)$$

With only X = massive particles + photons as scattering states, there is no amplitude $M \sim G_N^{1/2} \lambda$ ⇒ can't satisfy optical theorem ⇒ **unitarity is violated (probability is not conserved)**

Tree-level unitarity

What happened? The “unitarity violation” is of a very precise form:

$$\underbrace{\mathrm{Im}\,\mathcal{M}(\mathbf{k}\mathbf{p}_1\mathbf{p}_2 \to \mathbf{k}'\mathbf{p}_1'\mathbf{p}_2')}_{G_N\lambda^2} = \underbrace{\mathcal{M}(\mathbf{k}\mathbf{p}_1\mathbf{p}_2 \to \tilde{k}\mathbf{p}_1'\mathbf{p}_2)}_{\sqrt{G_N}\lambda}\,\underbrace{\mathcal{M}^*(\mathbf{k}'\mathbf{p}_1'\mathbf{p}_2' \to \tilde{k}\mathbf{p}_1'\mathbf{p}_2)}_{\sqrt{G_N}\lambda}$$



⇒ to save unitarity, need to include these outgoing states of “radiation” in the sum over X

These are basically like graviton: must have mass $\mu \to 0$, and couple with strength $G_N^{1/2}$ m.

Interpretation

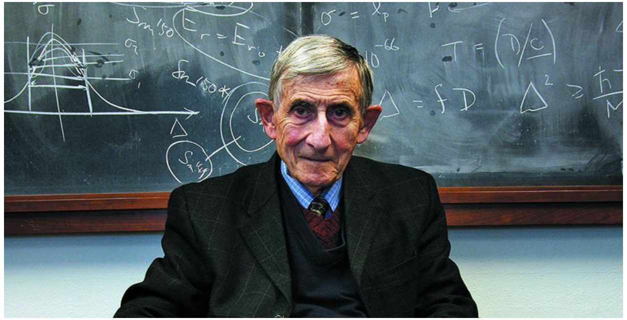
Newtonian entanglement + Lorentz invariance + unitarity
⇒ ∃ massless (or very light) boson which couples to mass ("graviton").

Basically, if you don't include the gravitational radiation, then the wavefunction after scattering will have the norm < 1, because we didn't include all the necessary basis states.

- Argument is insensitive to mediator spin–can be any integer. To detect spin-2 specifically, need a more refined experiment
- Unclear what happens if we drop unitarity or Lorentz invariance

Carney, "Newton, entanglement, and the graviton", 2108.06320

Revisiting Dyson’s arguments



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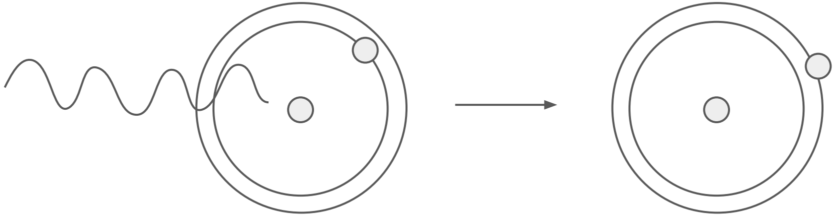
Freeman Dyson, Institute for Advanced Study, Princeton, New Jersey

Finally, I want to briefly revisit Dyson’s paper. Instead of a linear detector like LIGO, he also considered an absorptive detector:

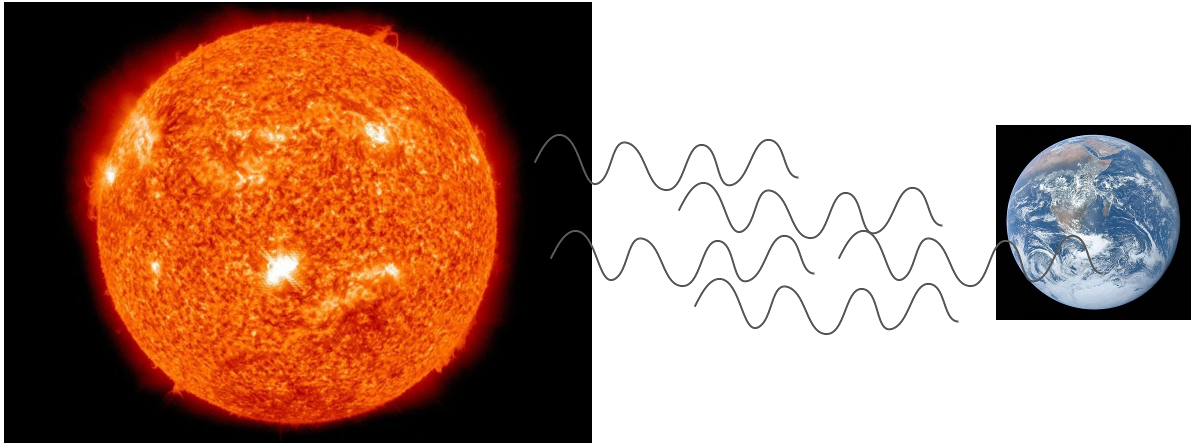


Rough estimate is that the absorption cross section

$\sigma \sim 4 \pi L_{pl}^2 \sim 10^{-65}$ cm^2

~40 orders smaller than p-p scattering
~25 orders smaller than typical dark matter searches

Rest of talk: work in progress with Nick Rodd and Valerie Domcke (CERN)



Consider using sun as the source. Bremsstrahlung gravitons created by interior collisions (Weinberg 1965)

Dyson estimates that if we could use every atom on earth as a detector, ~ 4 graviton detections per 5 billion years.

Can we get around this argument? Need a better source, as well as a detector that you can actually use.

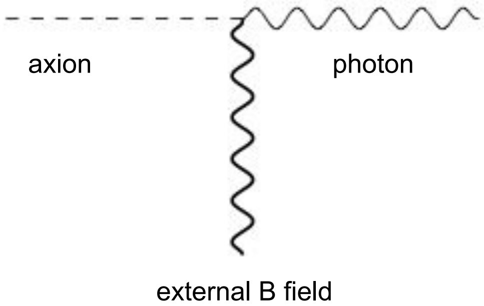
GW detection via photon detection

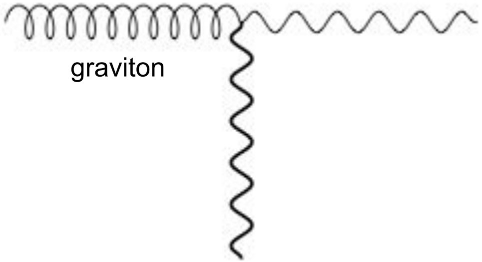
Need something that detects single graviton absorption events (i.e. can't use LIGO). Possibly can re-design the readout for this purpose.

However, there's a different and beautiful mechanism to do this, and lots of devices already exist. They are called axion haloscopes.

$$\mathcal{L} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\mathcal{L} = \frac{1}{m_{\rm pl}} h_{\mu\nu} T^{\mu\nu}_{\rm EM} \sim \frac{1}{m_{\rm pl}} h F^2$$





Raffelt, Stodolsky 1988

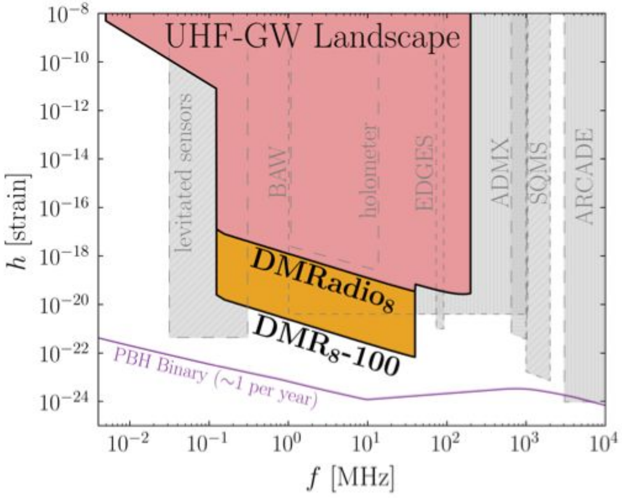
Picture: CAST experiment at CERN.

~10 Tesla LHC magnet strapped to an x-ray photodetector. Nominal strain sensitivity ~10^{-24}

In GW at that high frequency and strain, there are an enormous number of gravitons (thus you can beat the tiny cross section). However, the number density $n << 1/\lambda^3$. So any detection would be a “single graviton absorption event” in some sense.

However:

- Sources for x-ray frequency GW are exotic (~atom scale primordial BH mergers), although not ruled out
- Seeing single clicks is consistent with a classical wave and highly inefficient detector… (see Glauber 1963 or Loudon’s textbook for the argument in quantum optics)



Domcke, Garcia-Cely, Rodd 2202.00695

Outlook

- Experiments at some point will test if non-relativistic, Newtonian gravitational interaction is an entangling operator.

- If this is verified, gives evidence for graviton. But not a definitive proof w/o further assumptions (Lorentz invariance, unitarity/causality [see Bob Wald's talk]). To what extent can we relax or test those assumptions?

- Meanwhile, pursuing direct graviton detection may not be completely hopeless…!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