

Gravity “theory overview”

Daniel Carney



Outline

GW detection basics

Classical signals

Quantum signals



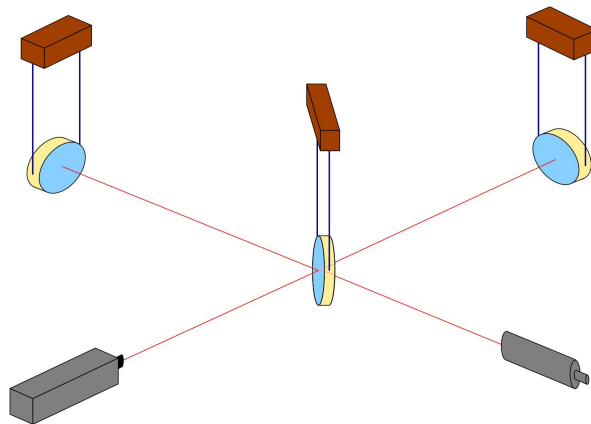
Holometer @ Fermilab, c. 2014

GW detection basics

What is a GW and how do you detect one?

Noise, sensitivity, strain PSDs, quantum limits

LIGO, axion cavity examples



<https://www.universetoday.com/articles/gravitational-wave-detectors-how-they-work>

GW detection basics

What is a gravitational wave?

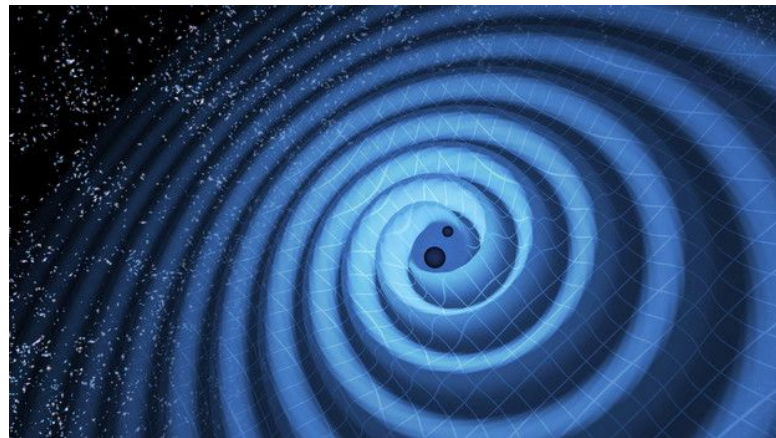
Small distortion (h) of spacetime metric (g):

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Units: $[h_{\mu\nu}] \sim \Delta x/L = \text{dimensionless ("strain")}, \ll 1$

How to detect it? Various equivalent views, e.g.:

1. Drives length variation
2. Drives anything with stress energy



LIGO @ Caltech

GW detection basics

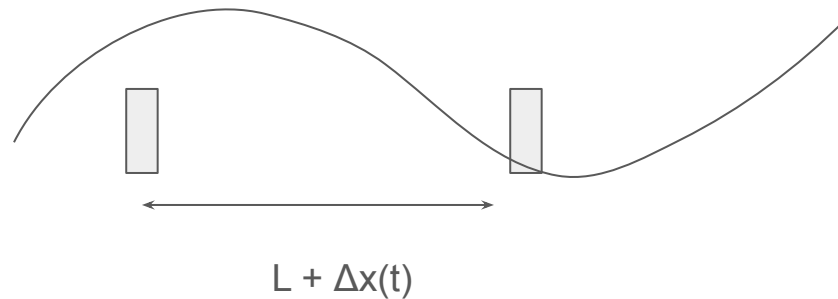
$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ How to detect $h_{\mu\nu}$? Various equivalent views, e.g.:

1. Drives length variation

$$L_{\text{proper}}(t) = \int_0^L \sqrt{g_{\mu\nu} dx^\mu dx^\nu} \approx L + \int_0^L h_{zz}(t) dz$$

Example: distance between two mirrors

$\Delta x(t)$



GW detection basics

$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ How to detect $h_{\mu\nu}$? Various equivalent views, e.g.:

2. Drives anything with stress energy

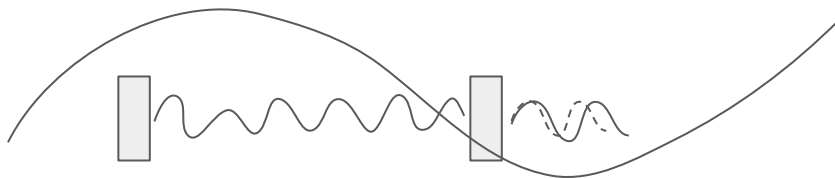
$$V_{\text{int}} = \int d^3\mathbf{x} h_{\mu\nu} T_{\text{detector}}^{\mu\nu}$$

Example: laser between mirrors



input frequency ω , output ω

$$T_{00} = \mathbf{E}^2 + \mathbf{B}^2$$



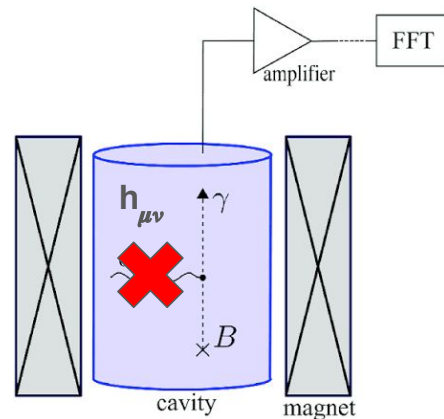
Input frequency ω , output ω plus small sideband component at $\omega + \omega_{\text{GW}}$

GW detection basics

Some paradigmatic examples: laser interferometers, axion haloscopes



$$L_{\text{proper}}(t) = \int_0^L \sqrt{g_{\mu\nu} dx^\mu dx^\nu} \approx L + \int_0^L h_{zz}(t) dz$$



$$V_{\text{int}} = \int d^3\mathbf{x} h_{\mu\nu} T_{\text{detector}}^{\mu\nu} \quad T_{00} = \mathbf{E}^2 + \mathbf{B}^2$$

GW detection basics

What sets the sensitivity of a GW detector? Generally characterized by noise power spectral density (PSD). This basically encodes Brownian-type noise. For example, mirror motion/position readout in interferometer has noise

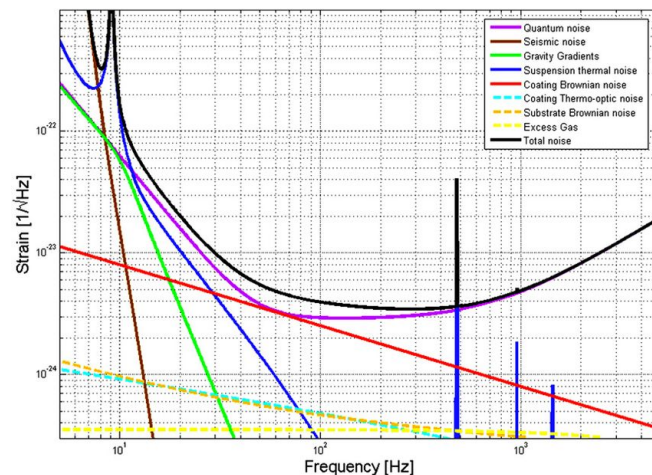
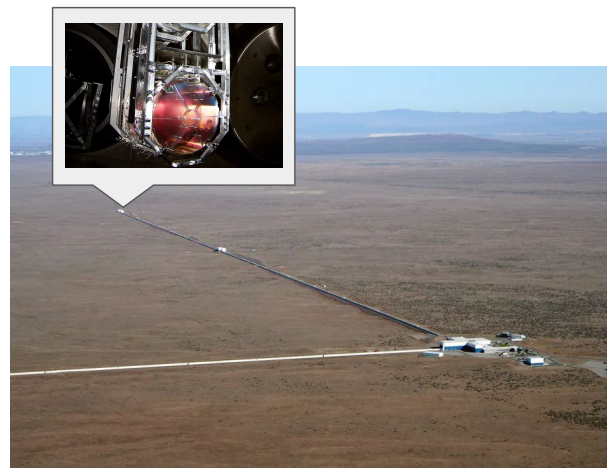
$$S_{xx}(\nu) = \int_{-\infty}^{\infty} dt \langle x(t)x(0) \rangle \quad S_{hh} = S_{xx}/L^2$$

$[S_{xx}] \sim \text{distance}^2/\text{freq} \rightarrow [S_{hh}] \sim \text{strain}^2/\text{freq}$.

Often quoted in square root [e.g., strain/sqrt(Hz), see right]

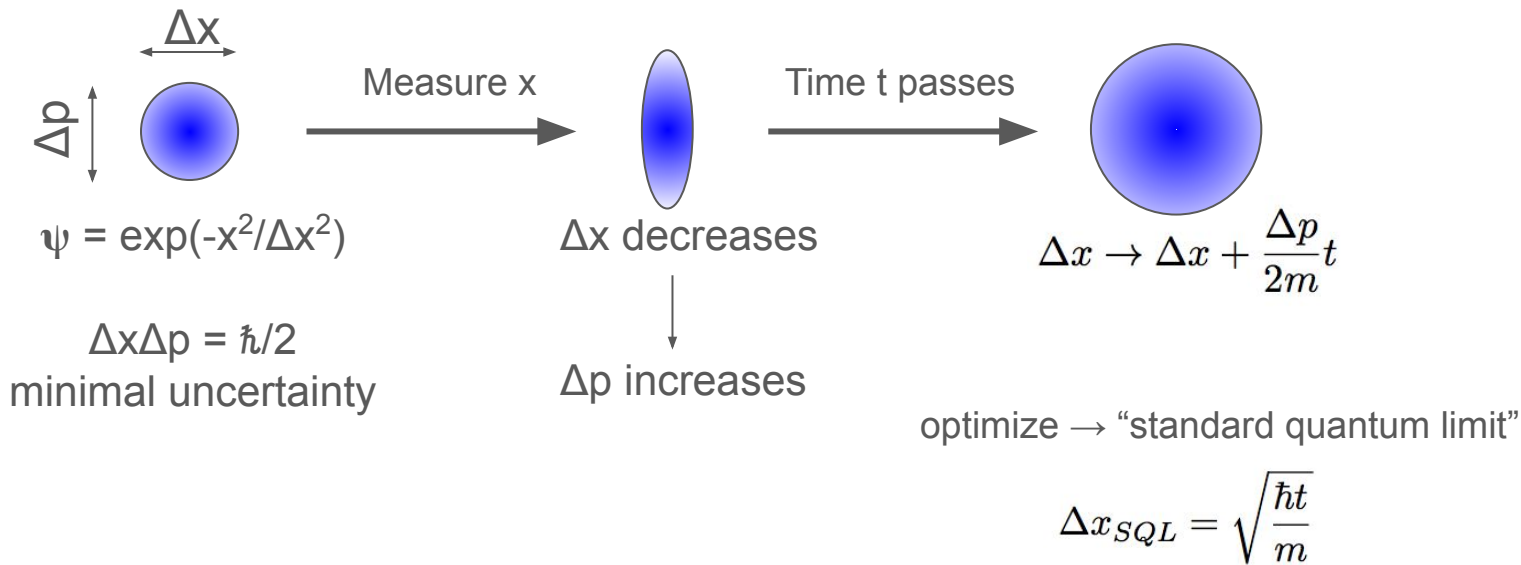
Interpretation: monochromatic signal, observed for time T

$$h_{\text{sig}} = h_0 \cos(\omega t) \implies \text{SNR} = \frac{h_0}{\sqrt{S_{hh}(\omega)/T}}$$



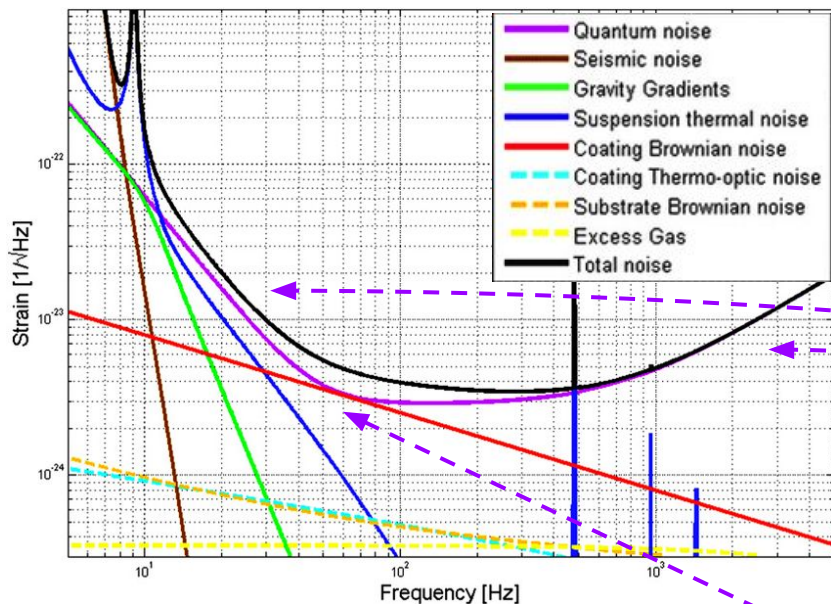
GW detection basics

Quantum noise in GW detectors is increasingly important. The physics of this noise is a bit dependent on the specific architecture, but generally comes from Heisenberg uncertainty:



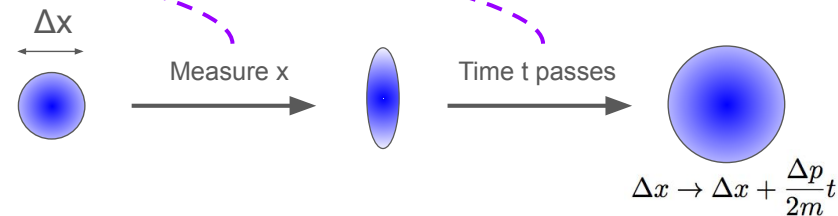
LIGO: $m \sim 40 \text{ kg}$, $t \sim (100 \text{ Hz})^{-1} \rightarrow \Delta x \sim 10^{-19} \text{ m} \rightarrow \Delta h \sim 10^{-22}$

GW detection basics



High frequency: first step hard (need more photons/unit time). “Shot noise”

Low frequency: second step is hard (waiting more time/measurement). “Backaction noise”



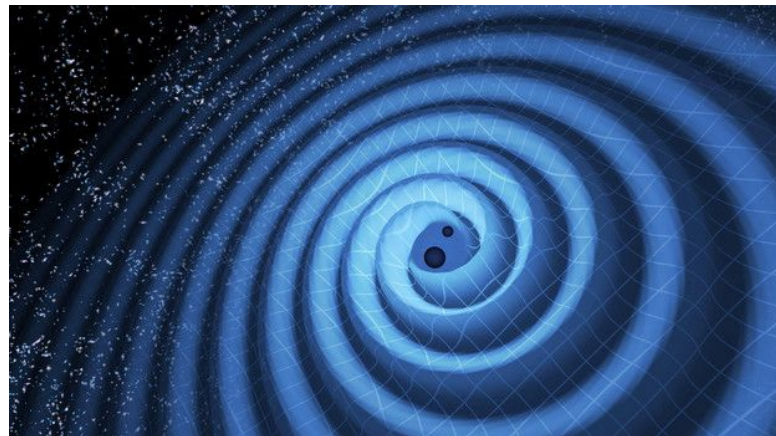
Minimum: “SQL” $\Delta x^2 = 1/m\omega$ = ground state variance of the mirror’s position

GW detection basics

Recap:

- A gravitational wave literally means a distortion of the spacetime metric
- Many equivalent ways to think about the observable effect; e.g. causes lengths to change, particles to move, EM fields to distort, ...
- Quantum limits to detection $\sim$ Heisenberg uncertainty of the detector itself. Can be evaded in many ways (see Vicky Xu, Konrad Lehnert lectures)

Reference for this stuff, esp. quantum issues:
Beckey, Morocco, Carney 2311.07270



Outline

GW detection basics

Classical signals

Quantum signals



Classical signals

Frequency band coverage in ~existing detectors

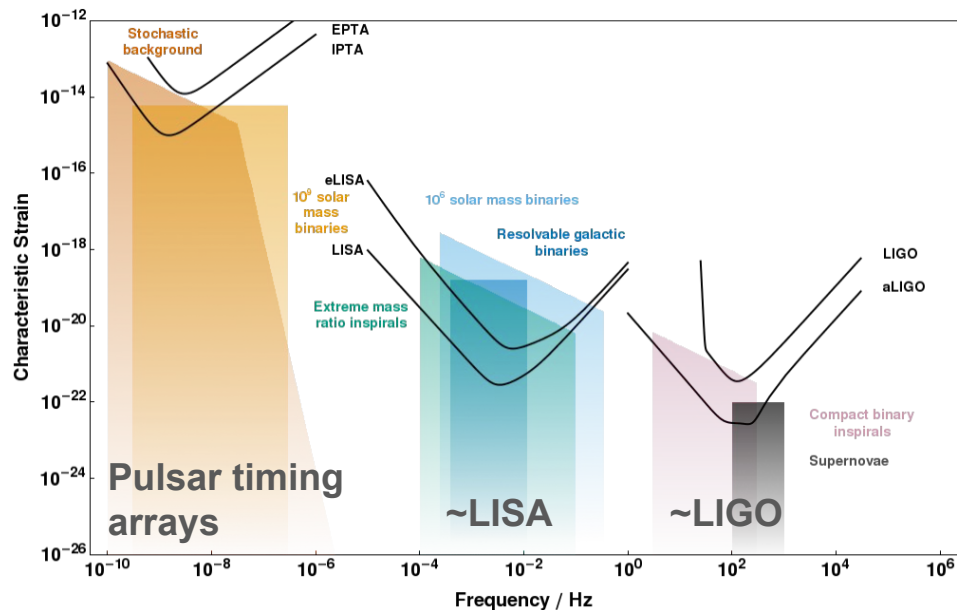
Some signals of interest

Elementary constraints on some of these

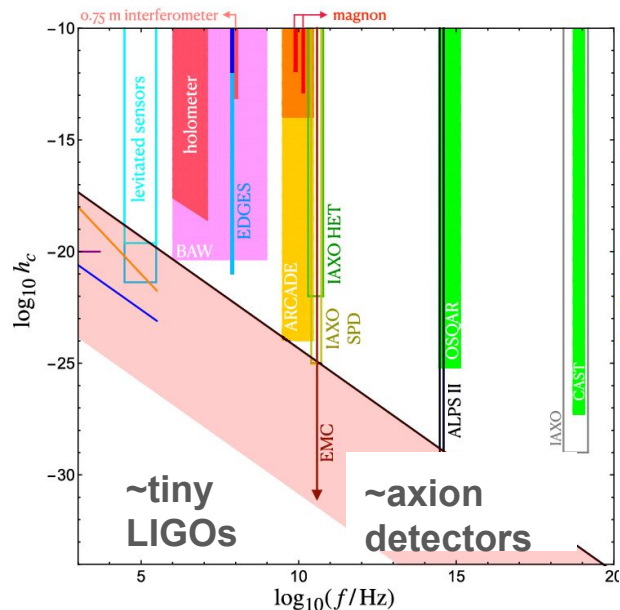


Classical signals

Frequency band coverage of existing and ~planned detectors:



Moore, Cole, Berry 1408.0740

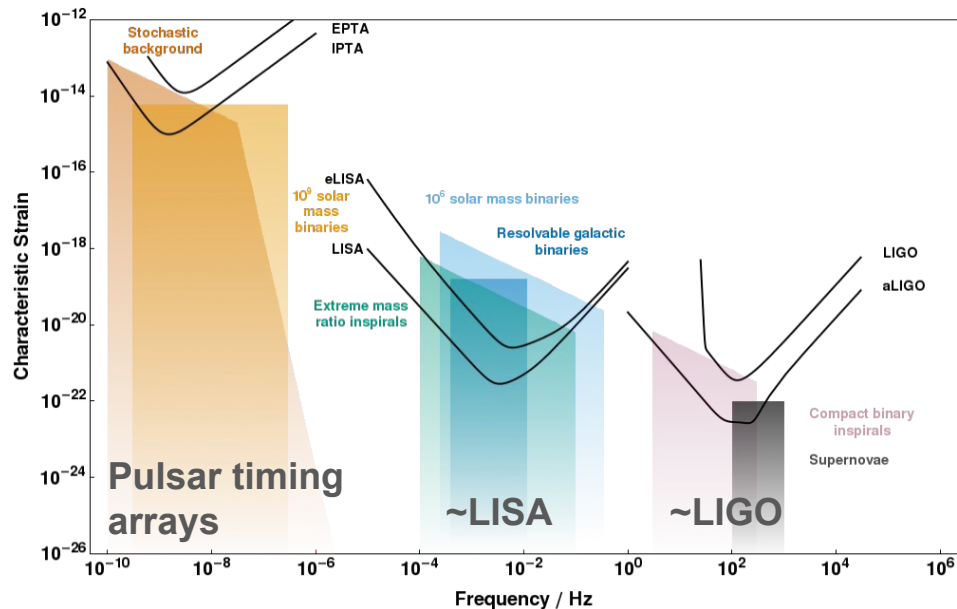


Aggarwal et al. 2011.12414

Classical signals

How about signals of interest? Low (< 1 kHz) frequency has many interesting targets:

- 1 Hz – 1 kHz: LIGO stuff (binary mergers with $M \sim 1\text{-}100 M_{\text{sun}}$)
- $10^{-3} - 1$ Hz: heavier binaries ($f \sim 1/M$)
- $< 10^{-3}$ Hz: stochastic backgrounds (e.g., from unresolvable binaries and possible primordial stuff)

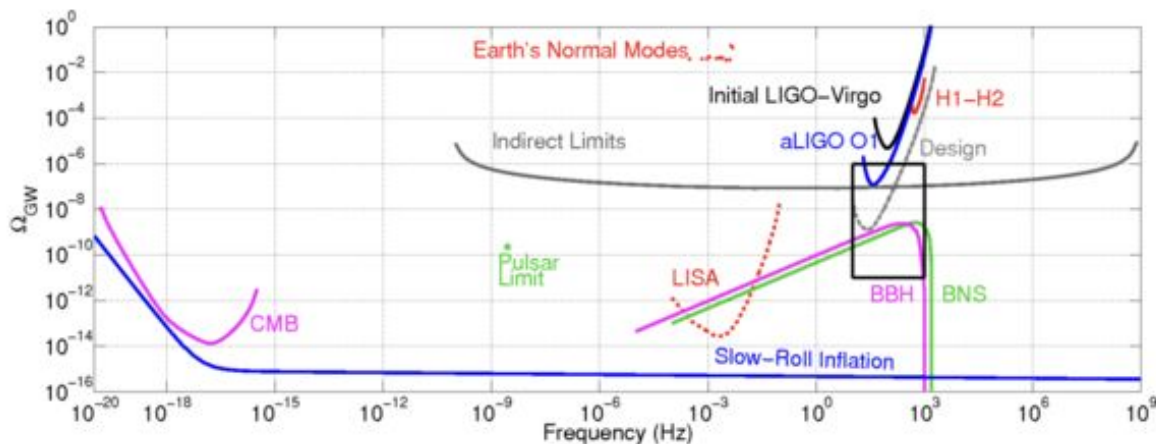


Moore, Cole, Berry 1408.0740

Classical signals

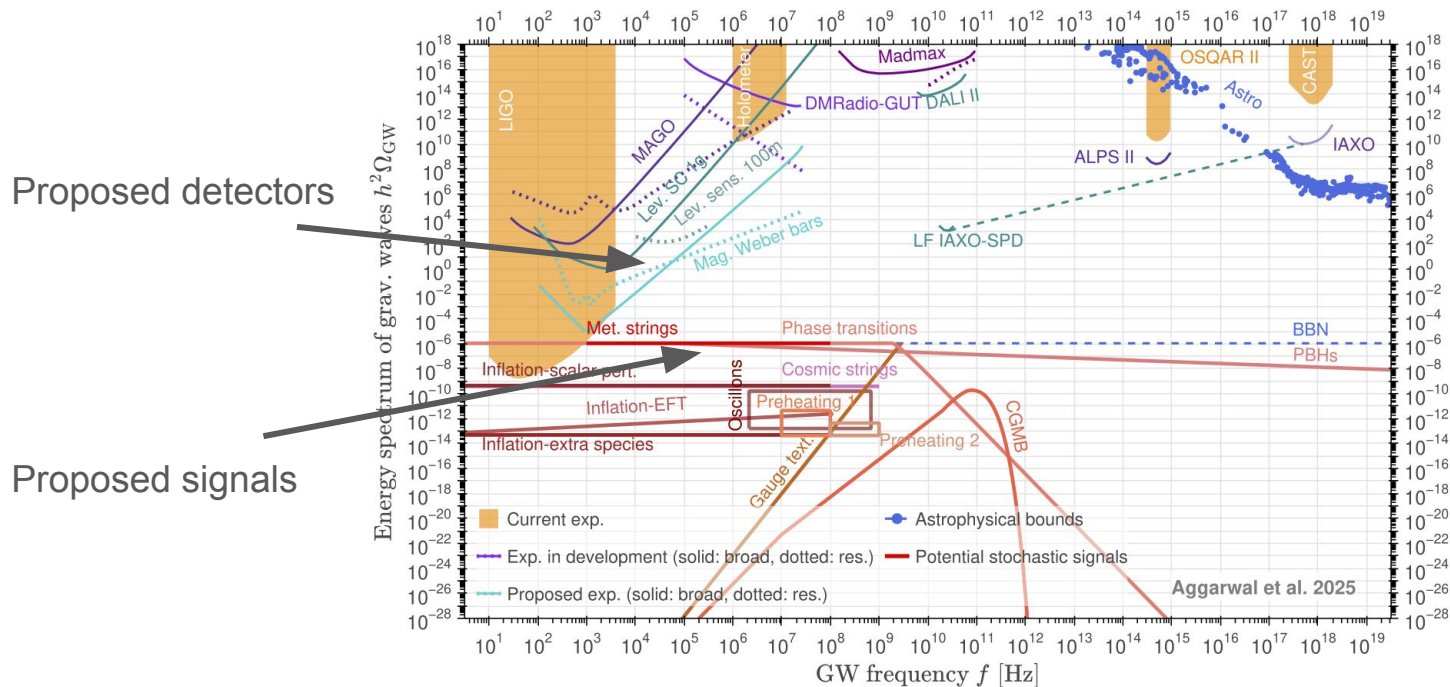
“ $< 10^{-3}$ Hz: stochastic backgrounds (e.g., from unresolvable binaries and possible primordial stuff)”

- Inflationary primordial background is true holy grail... but is it detectable at all? 🤔



Classical signals

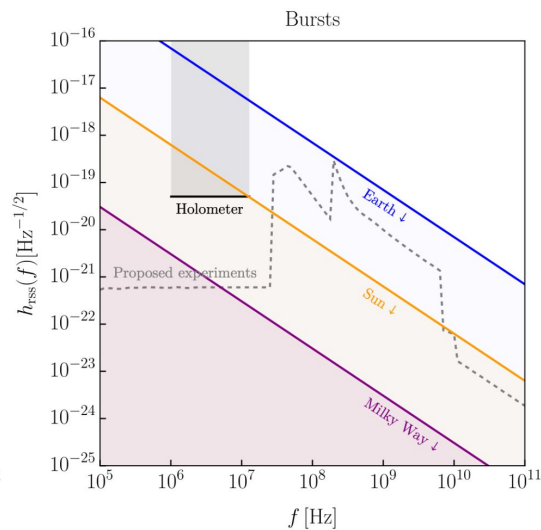
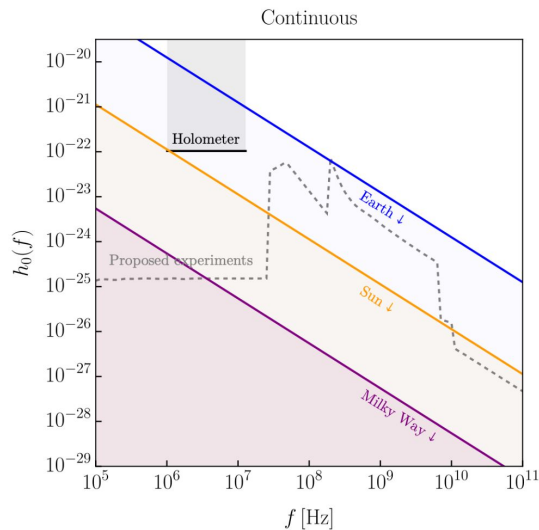
At higher frequency (> 1 kHz), many proposed detectors, but not many known signals that are both interesting and detectable...



Classical signals

At very high frequency (> 100 kHz),
~model-independent bounds from energetics:

- For GWs permeating everywhere (e.g., between galaxies), very strong bounds from universe not over-closing due to too much energy density, BBN, CMB, ...
- Could imagine local (e.g., in-galaxy) sources, but these are still constrained by bounds on total mass loss of binaries, Galaxy itself, ...



Classical signals

Recap:

- Well-motivated signals at < 1 kHz, reasonable detector coverage planned
- Landscape at > 1 kHz less well understood, pretty tightly constrained at theory level...



Outline

GW detection basics

Classical signals

Quantum signals

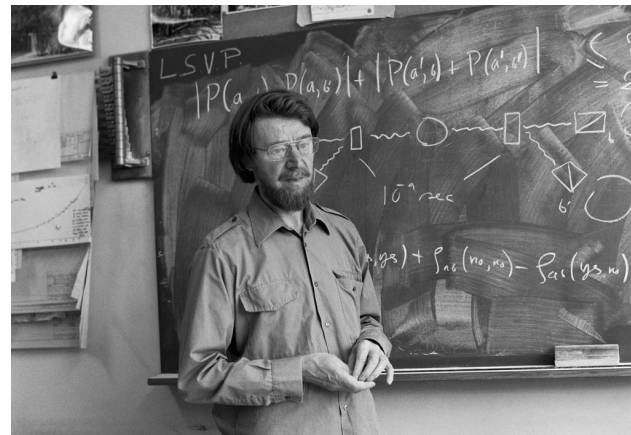


Quantum signals

What is the basic question?

Graviton detection

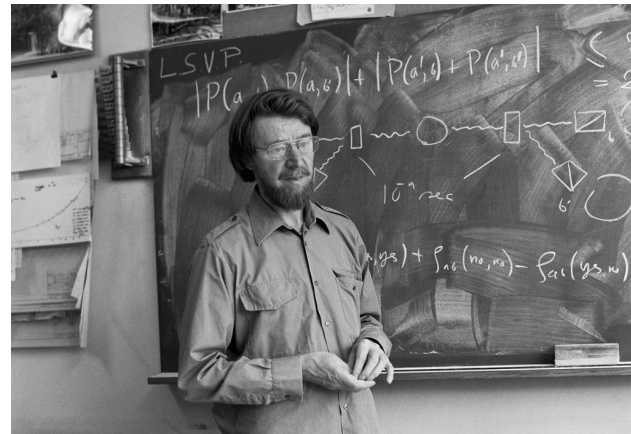
Tabletop experiments



Quantum signals

Key question:

What is a signal that requires a quantum description of the gravitational field?

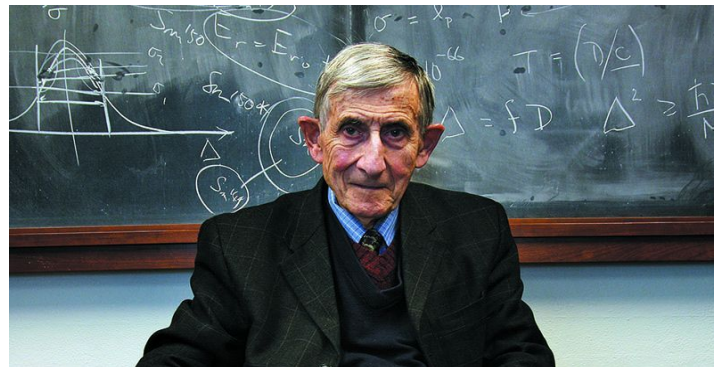


Quantum signals

Let's start with an old question due to Dyson:

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

Dyson's answer: no.



Is a Graviton Detectable?

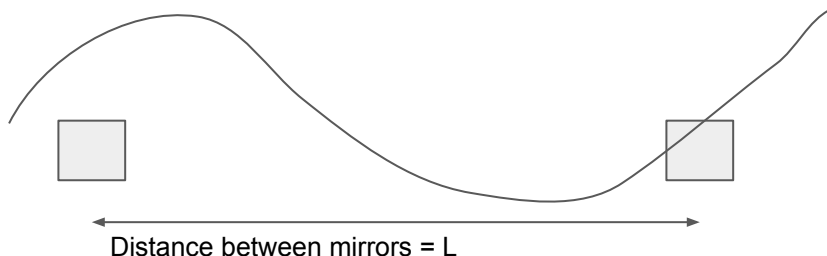
Poincare Prize Lecture

International Congress of Mathematical Physics

Aalborg, Denmark, August 6, 2012

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

Quantum signals



Model single graviton as strain field $h \sim L_{\text{pl}} \omega$

Optimum detection efficiency when $L \sim 1/\omega$

→ Displacement between mirrors you need to detect is $\Delta x \sim h L \sim L_{\text{pl}}$

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

→ **$L \leq G_N M / c^2$**

The detector has to be within its own Schwarzschild radius. If you tried to build a LIGO sensitive to a single graviton strain, it collapses into a black hole!

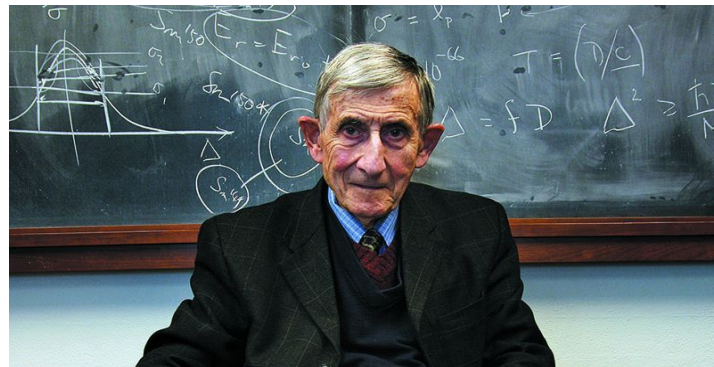
Quantum signals

Let's start with an old question due to Dyson:

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

Dyson's answer: no.

Recently, this conclusion has supposedly been challenged by some new ideas for “graviton detection”. But I want to throw some cold water on this.



Is a Graviton Detectable?

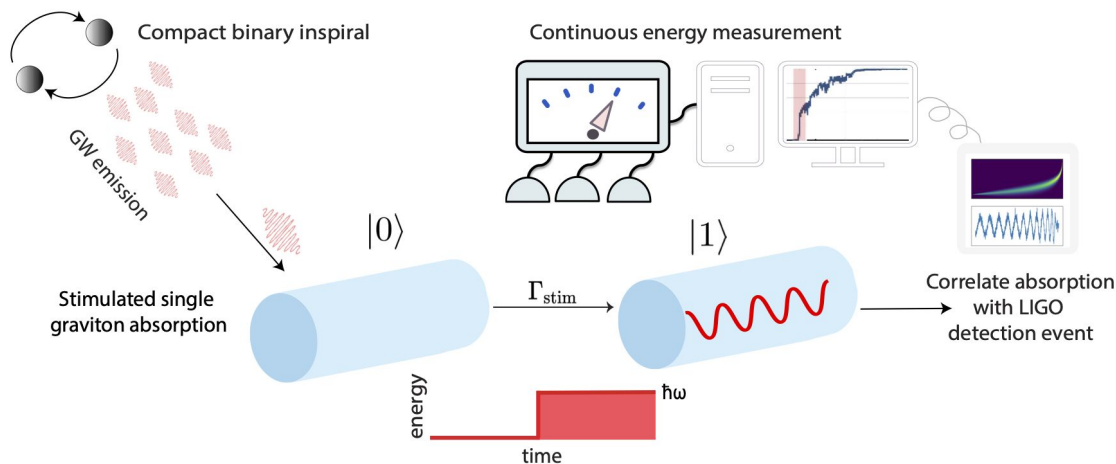
Poincare Prize Lecture

International Congress of Mathematical Physics

Aalborg, Denmark, August 6, 2012

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

Quantum signals



One such proposal, with much fanfare: Tobar, Manikandan, Beitel, Pikovski 2308.15440

Weber bar: gravitational wave $\rightarrow$ vibration $\rightarrow$ voltage

Fancy quantum Weber bar: gravitational wave (“graviton”) $\rightarrow$ phonon $\rightarrow$ voltage

This “detects gravitons”. It might even work, and it can operate in the LIGO band, so there are known signals. But the right question is: can it distinguish between classical GR and gravitons?

Quantum signals

“Can it distinguish between classical GR and gravitons?”

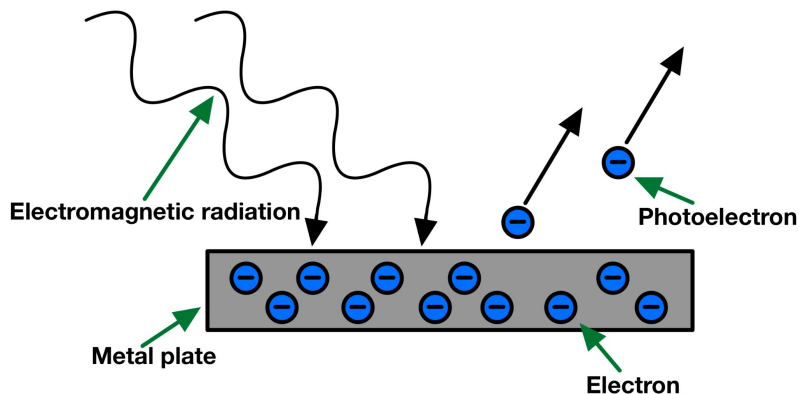
$$\hat{H}_Q = \hat{H}_{\text{det}} + \hat{H}_h + \int d^3\mathbf{x} \hat{h}_{\mu\nu} \hat{T}^{\mu\nu}$$

Quantized metric fluctuations $\rightarrow h = \text{operator}$

$$\hat{H}_{\text{SC}} = \hat{H}_{\text{det}} + H_h + \int d^3\mathbf{x} h_{\mu\nu} \hat{T}^{\mu\nu}$$

“Classical” gravity: $h = \text{classical random variable}$,
maybe drawn from probability distribution $P(h)$

Quantum signals

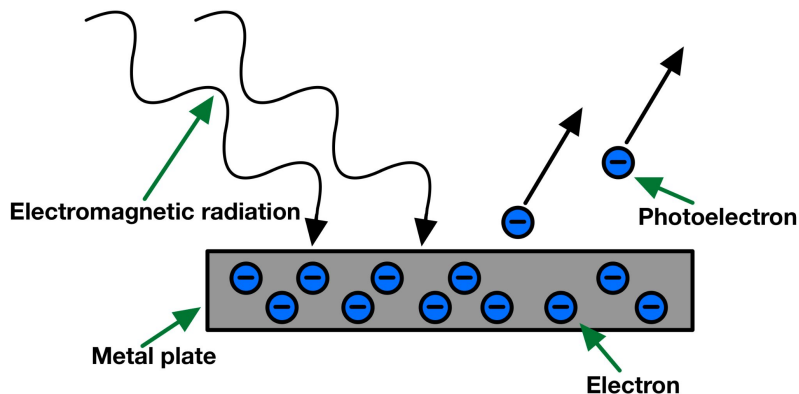


Easy to understand by appealing to EM case.
Consider either quantum or classical EM fields:

$$\hat{H}_Q = \hat{H}_{\text{det}} + \hat{H}_A + \frac{e}{m} \hat{\mathbf{p}} \cdot \hat{\mathbf{A}}$$
$$\hat{H}_{\text{SC}} = \hat{H}_{\text{det}} + H_A + \frac{e}{m} \hat{\mathbf{p}} \cdot \mathbf{A}$$

Classical,
random $P_{\text{cl}}(A)$

Quantum signals



Easy to understand by appealing to EM case.
Consider either quantum or classical EM fields:

$$\hat{H}_Q = \hat{H}_{\text{det}} + \hat{H}_A + \frac{e}{m} \hat{\mathbf{p}} \cdot \hat{\mathbf{A}}$$

$$\hat{H}_{\text{SC}} = \hat{H}_{\text{det}} + H_A + \frac{e}{m} \hat{\mathbf{p}} \cdot \mathbf{A}$$

Classical,
random $P_{\text{cl}}(\mathbf{A})$

Textbook perturbation theory leads to identical predictions for excited electron events:

$$\frac{dP(g \rightarrow c)}{dt} \approx \eta I(t) \Theta(\omega - \Delta)$$

→ “single photon/graviton detection” does not require a photon/graviton explanation!

Glauber 1963

Carney, Domcke, Rodd arXiv:2308.12988

Carney 2408.00094

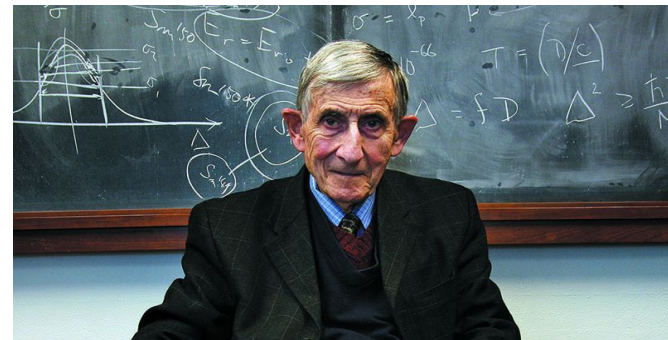
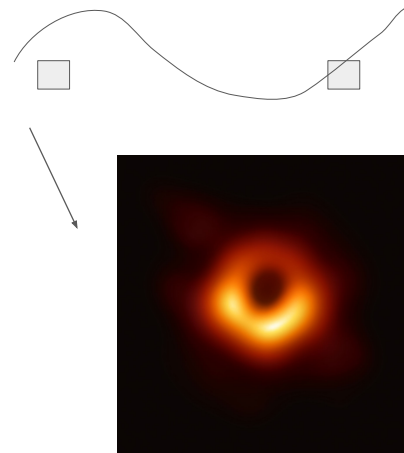
Quantum signals

Dyson: scaling LIGO to be sensitive to a strain of “single graviton” $h \sim L_{\text{pl}} \omega$ is fundamentally impossible. Why?
Quantum noise of detector itself.

Does the single “graviton $\rightarrow$ phonon” Weber bar detector idea contradict this? No: it assumes a massive number of incident gravitons, then detector absorbs $\sim$ few of these, which overcomes the low detector efficiency $\eta \sim 10^{-20}$

Dyson’s argument is about building something with efficiency $\eta \sim 1$! But that’s what is needed to see a signal that you can *only* explain with gravitons.

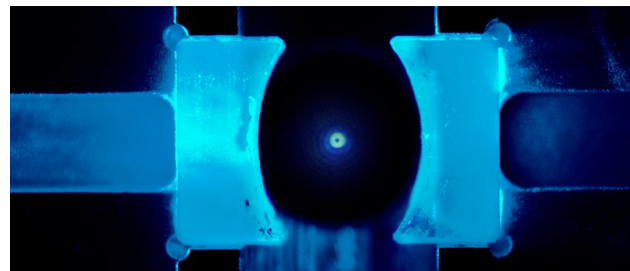
General conclusion: intrinsic quantum noise of any constructible detector $\gg$ quantum noise of GW signal



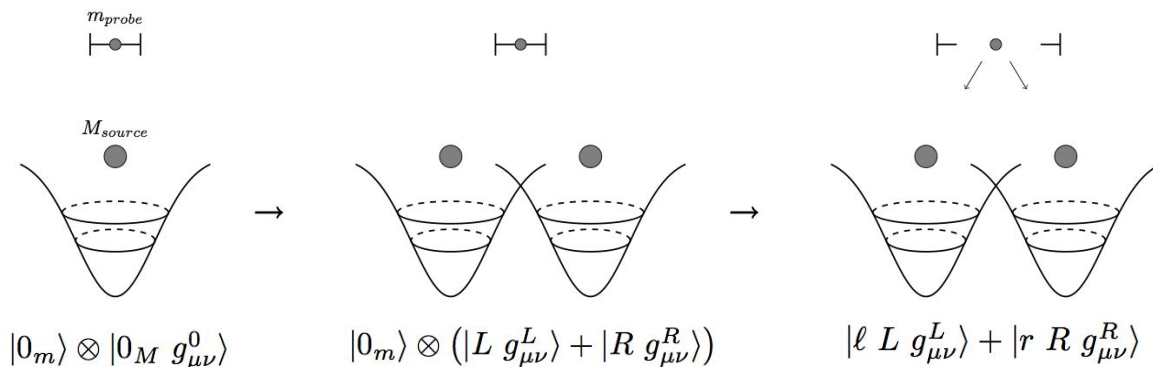
Quantum signals

I want to end on a more positive. Note. I think that there actually is a ~practical path to answering the question: “Is gravity quantum?”

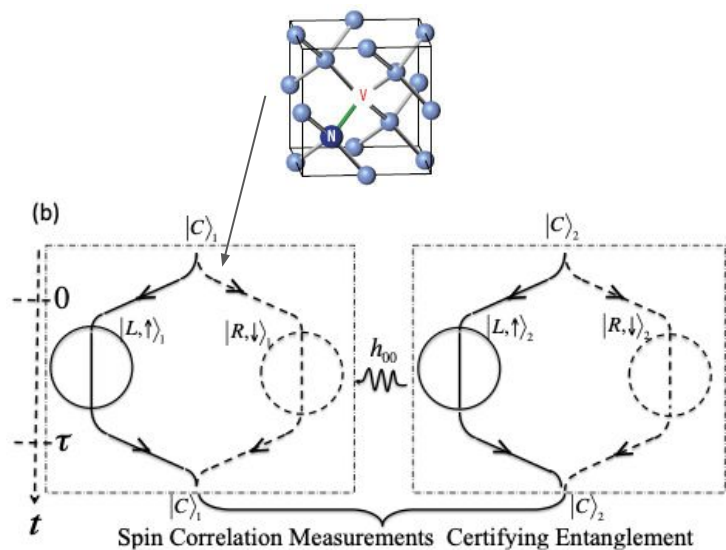
- Can the gravitational field be put into quantum superposition?
- Can we measure this directly?



From Markus Aspelmeyer



Quantum signals

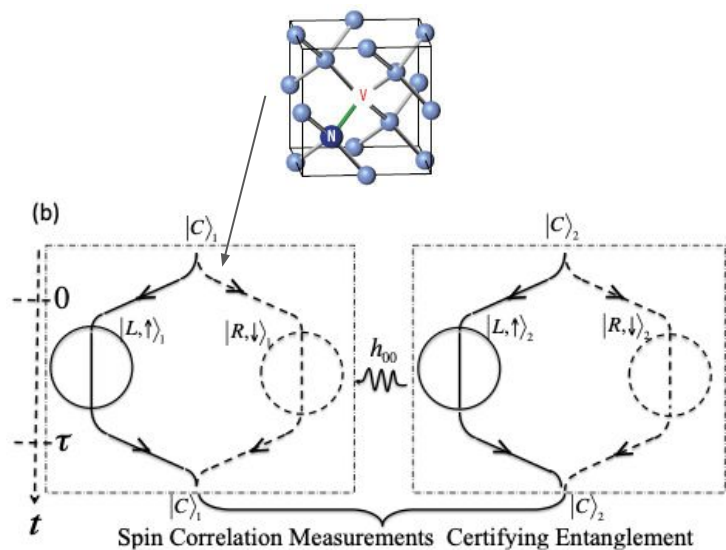


One concrete experimental proposal:

$$|LL\rangle \rightarrow |LL\rangle + |LR\rangle + e^{i\Delta\phi}|RL\rangle + |RR\rangle$$

$$\Delta\phi = \frac{G_N m^2 \Delta x \Delta t}{\hbar d^2} \approx 60 \times \left(\frac{m}{1 \text{ ng}} \right)^2 \left(\frac{\Delta x}{1 \text{ } \mu\text{m}} \right) \left(\frac{\Delta t}{1 \text{ s}} \right) \left(\frac{1 \text{ mm}}{d} \right)^2$$

Quantum signals



$$\Delta\phi = \frac{G_N m^2 \Delta x \Delta t}{\hbar d^2} \approx 60 \times \left(\frac{m}{1 \text{ ng}} \right)^2 \left(\frac{\Delta x}{1 \text{ } \mu\text{m}} \right) \left(\frac{\Delta t}{1 \text{ s}} \right) \left(\frac{1 \text{ mm}}{d} \right)^2$$

All of these parameters are extremely challenging to achieve, especially B field gradient, coherence time.

Example: gas collisions cause $\Gamma_{\text{deco}} \sim nAv \sim 10^8 \text{ Hz}$ for $P \sim 10^{-14} \text{ torr}$, $T \sim 4 \text{ K}$ He gas

Difficult, but I think some version of this is going to get done in my lifetime

There are other experimental setups I think are more promising, but nobody really knows until one works...

Recap and outlook

- Gravitational waves = distortion of spacetime metric
- Detecting this is hard and often requires quantum sensing, i.e., sensors whose quantum mechanical uncertainties dominate the noise budget
- Lots of good classical signals at < 1 kHz, landscape > 1 kHz needs to be better understood
- In terms of quantum signals, “detecting gravitons” is either impossible or pointless, depending on your semantic preferences
- Detecting gravitational entanglement is definitely interesting, *maybe* possible...