Theorie, Univers et Gravitation
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Institut Henri Poincaré (IHP)

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Outline

Sensing Quantum Nature of Primordial Gravitational Waves using Quantized Electromagnetic Fields

1. Is gravity classical or quantum?
2. Gravitational Waves (GWs)
3. Primordial gravitational waves
4. Implication of squeezed PGWs on the quantum EM field

Further Studies?!

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Further Studies?!

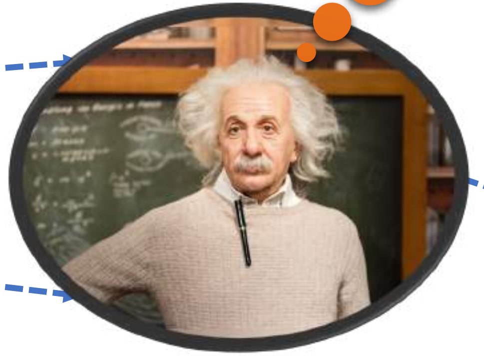
Is gravity classical or quantum?

The roadmap of physics

The laws of Nature must be invariant under coordinate transformations!

Classical mechanics → Quantum mechanics

Classical field theory → Quantum field theory



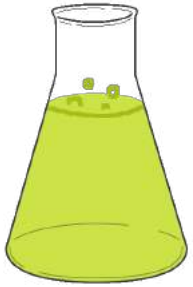
→ Quantum field theory in curved space-time → Is gravity classical or quantum?

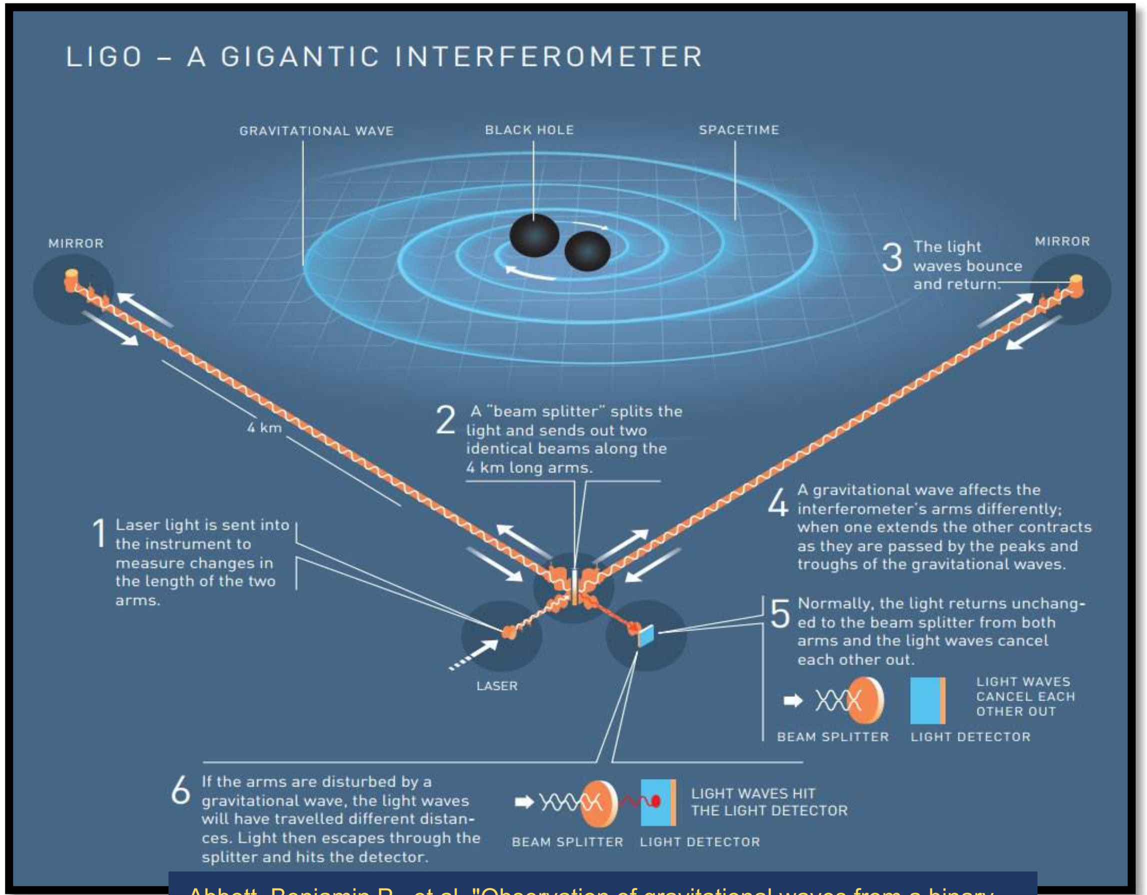
- GR breaks down when describing BH, the curvature diverges at the center of BH
- Quantum fluctuations play important role at distances smaller than the Planck length, or very high energy scales.
- Besides mathematical challenges of QG theory, we lake experimental data which could distinguish between the competing theories which have been proposed.

Is gravity classical or quantum?

- Many proposed thought experiments to search for quantum gravity, maybe feasible in future.

- Can gravitational wave detectors help us revealing *quantum nature* of gravity?





Abbott, Benjamin P., et al. "Observation of gravitational waves from a binary black hole merger." *Physical review letters* 116.6 (2016): 061102.

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Gravitational Waves(GWs)

- Accelerated charges emit EM radiation , Do accelerating masses emit Gravitational radiation?

  Yes! Einstein field equations in the weak (perturbation) limit, predict the existence of propagating waves with the speed of light, called "gravitational waves".

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

D'Alambert operator

source term

- From the field theoretical perspective, $h_{\mu\nu}(\mathbf{r}, t)$ is a rank-2 tensor field, living on the space-time manifold just like any other field.

Gravitational Waves(GWs)

- Treating the GWs field as a rank-2 classical field theory, one may **“Quantize”** this theory using the standard field theoretical tools.
  The excitation quanta of the corresponding quantum field are called “Gravitons”, analogue to the electromagnetic counterparts, “Photons”.

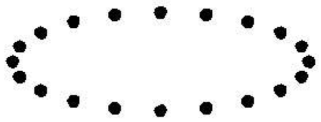
- In TT gauge, $h_{ij}(x)$ can be expanded in terms of the plane-wave solutions as

Starin field

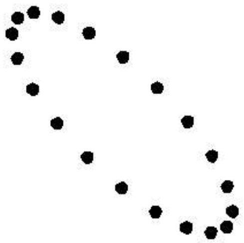
$$h_{ij}(\mathbf{r},t) = \sum_{\gamma=+,\times} \int \frac{d^3\mathbf{K}}{(2\pi)^{3/2}} \hat{e}^{\gamma}_{ij}[\hat{K}] \left(h_\gamma(\mathbf{K}) e^{-i(\Omega t - \mathbf{K}\cdot\mathbf{r})} + c.c. \right)$$

polarization tensors

$$\begin{cases} \hat{e}^{+}_{ij} = n_i n_j - m_i m_j \\ \hat{e}^{\times}_{ij} = n_i m_j + m_i n_j \end{cases}$$



+ polarization GW



× Polarization GW

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Primordial Gravitational Waves(GWs)

Does exist any gravitational source which produce non-classical GW radiation?

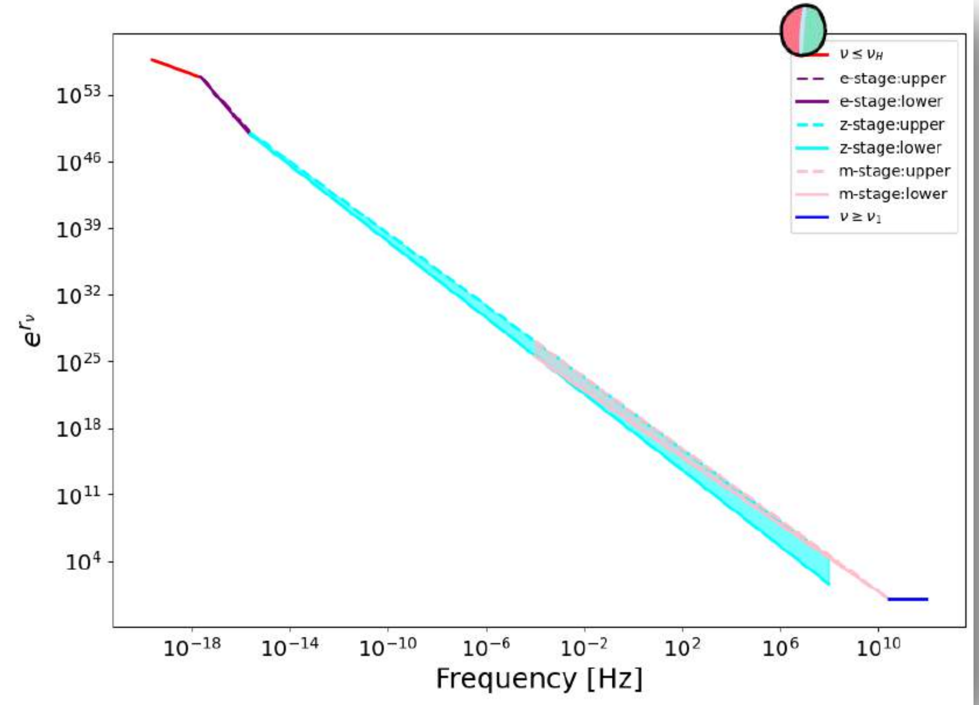
Unlike the EM field, unfortunately gravitational phenomena can not be handled or engineered easily.

But fortunately, Nature has done it in another place and time; in the inflationary epoch.

The primordial quantum fluctuations in the gravitational field at the very early Universe had evolved into the so-called "squeezed states", during the parametric amplification process powered by the pumping engine of the inflation.

$$e^{r_\nu(\eta)} = \frac{a(\eta)}{a(\eta_i)}$$

The beginning time of one expansion stage



The squeezed factor versus the frequency.

Zhang, Hongguang, Xilong Fan, and Yihui Lai. "Gravitons probing from stochastic gravitational waves background." *arXiv preprint arXiv:2105.05083* (2021).

Primordial Gravitational Waves (PGWs)

Reminder from QM:

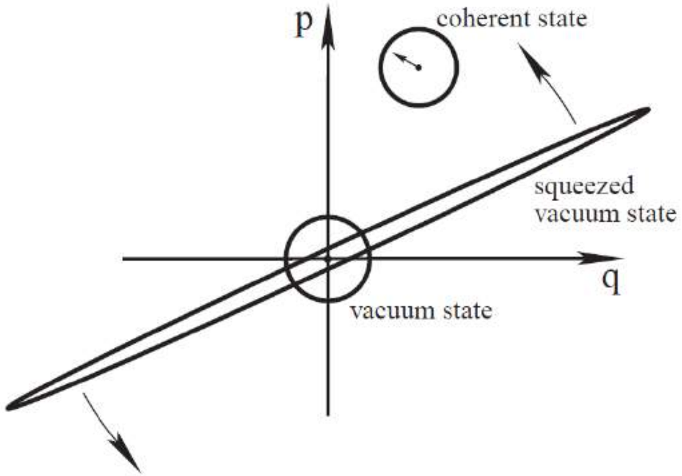
For any two non-commutative observables, the *Heisenberg uncertainty principle* states that:

$$\Delta\hat{A}\Delta\hat{B} \geq \frac{1}{2}\langle[\hat{A},\hat{B}]\rangle$$

Fluctuations in a squeezed state are bellower than that of the coherent state, while still minimizing the uncertainty principle.

- The **amplification** mechanism occurs for fluctuations of GWs in the inflationary era, resulting in a background of *highly-squeezed GWs* named as Primordial Gravitational Waves (PGWs).

- Detecting PGWs not only give us information about the mechanism generating them, but also affirm quantum nature of gravity.



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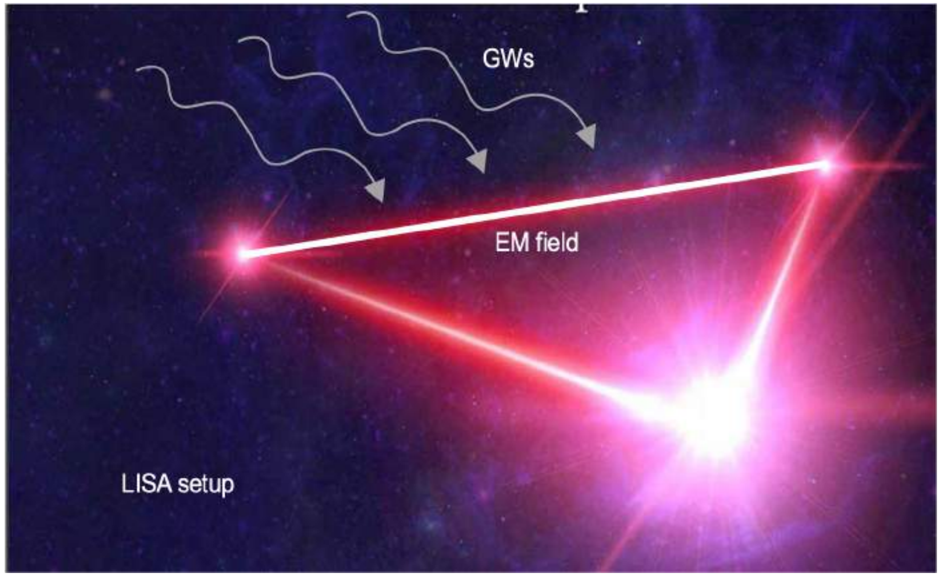
Implication of PGWs in the quantum EM field

Objective	How can we evidence quantumness of PGWs using GW detectors such as LISA or PTA?

- We have developed a formalism to describe the quantum interaction between EM field and GWs, within the Optical Medium Analogy (OMA).

Geometry (Gravity): $g_{\mu\nu}$ ⇒ Magneto-dielectric media: $\varepsilon_{ij} = \mu_{ij} = \delta_{ij} - h_{ij}(\mathbf{r}, t)$



- The ***Lagrangian*** of the coupled system determines the dynamics of the system; At the classical level, the Maxwell's equations are derived, and at the quantum level, the interaction Hamiltonian comes out.

$$L(t) = \frac{1}{2}\int d^3r\,\left(\varepsilon_{ij}(\mathbf{r},t)E^iE^j - \mu_{ij}^{-1}(\mathbf{r},t)B^iB^j\right)$$

Implication of PGWs in the quantum EM field

Objective: How can we evidence quantumness of PGWs using GW detectors such as LISA or PTA?

Results

- At the *classical* level, the well-know formula for the phase-shift of light in the time-delayed-interferometry setups, is recovered based on defining the "refractive index" of the medium.
- At the *quantum* level, the interaction Hamiltonian describing the coupling between EM field and GWs is derived, based on which the dynamics of the EM field observables is determined.
- Especially, the quadrature component of the EM field is of interest.

$$\hat{\chi}(t) = \hat{a} + \hat{a}^\dagger \quad \Rightarrow \quad \Delta\hat{\chi}(t) = \langle \hat{\chi}^2 \rangle - \langle \hat{\chi} \rangle^2$$

- The highly squeezed PGWs leaves a non-trivial behaviour on the variance of quadrature component, after a given "characteristic time scale".

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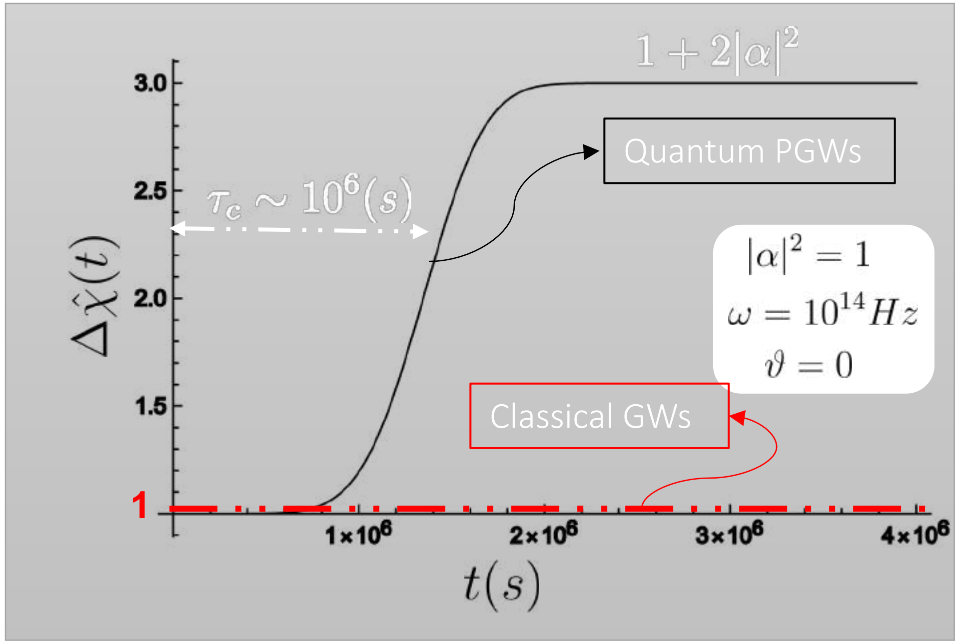
- Observing this behaviour not only verifies quantumness of gravity, but also gives information about the relic background of GWs.



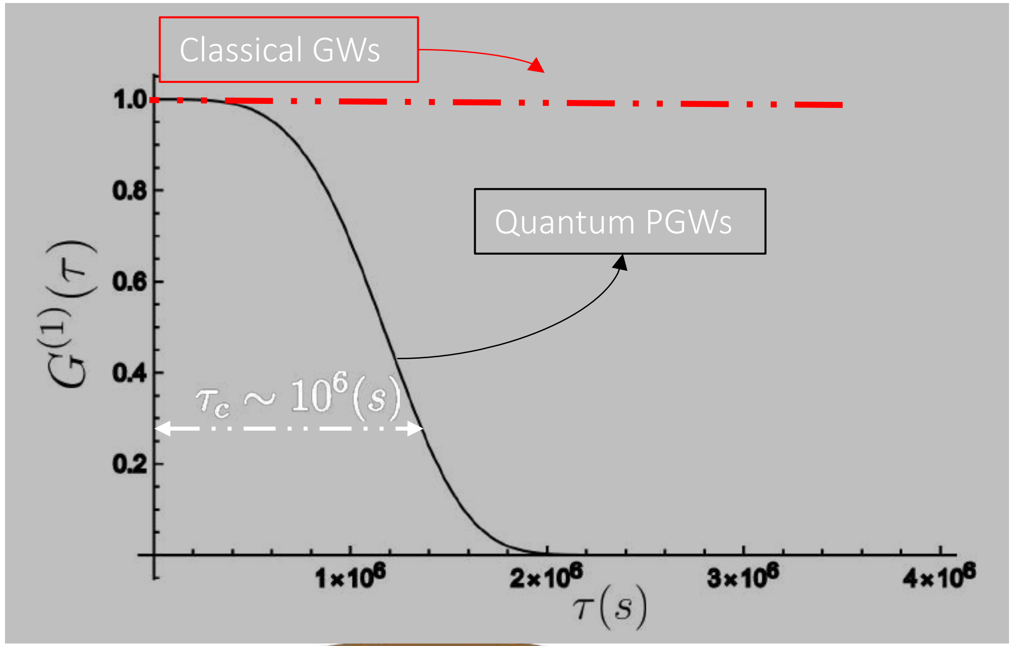
Implication of PGWs in the quantum EM field

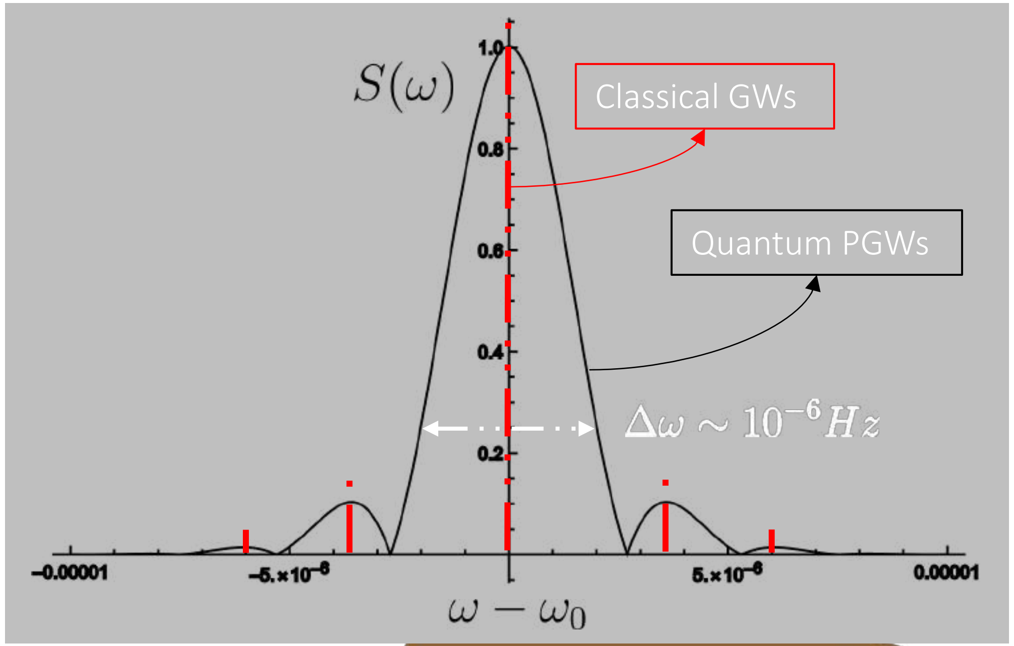
Objective How can we evidence quantumness of PGWs using GW detectors such as LISA or PTA?

Results

- The first order coherence function and the spectrum, show the line-width broadening of light, as a result of interaction with the highly squeezed PGWs.

$$G^{(1)}(\tau) = \langle \hat{a}^{\dagger}(0)\hat{a}(\tau)\rangle$$





General remarks

So far we considered those quantum observables of light which are based on photo-count experiment. However, what is practically measured in the real experiments such as LISA and PTA is the frequency shift of the EM signal, its auto-correlations or correlations between two or more signals. Therefore, one can in principle promote the classical descriptions, to see the effect of the quantized PGWs on the phase shift of light, or its correlations.

That the dynamical degrees of GWs also evolve in time as a consequence of interaction with EM field, is one of the main distinctions between quantum and classical descriptions. One can ask the question that what is the effect of EM field on the PGWs, and how much is it?

One interesting pure quantum phenomenon is entanglement generation between two subsystems under interaction by a "common" third subsystem. The question is, do the common GWs background cause entanglement generation between two initially separated light-signals or not? If yes, how much is the magnitude of the related entanglement measure? For the case of two typical pulsars, how does it depend on the orientation of the signals?

The other question is that does GWs induce "decoherency" in the laser light, and how much is it? Can one formulate the "non-unitary process" in the form of a Lindblad equation?