Quantum enhanced correlated interferometry for Planck scale physics

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Introduction

Systems of two interferometers can be interesting for testing Planck scale physics.

Quantum light can help in enhancing the sensitivity of one interferometer.

Can quantum light enhance the sensitivity of a system of two interferometers?

Theory


Paper under review [arXiv:1810.13386]

Experiment
Several heuristic QG theories predicts non-commutativity of position variables at Planck scale:

\[
[x_i, x_j] = \hat{x}_k \epsilon_{ijk} i c t_P / \sqrt{4\pi}
\]

\[t_P = 5.40 \times 10^{-44} \text{s}\]

Fundamental space-time uncertainty principle called “**holo**graphic noise (HN)”

[C. Hogan, Arxiv: 1204.5948; C. Hogan, PRD 85, 064007 (2012)];

How can we have experimental access to this noise?
Looking for “macroscopic” effects

In a Michelson interferometer holographic noise accumulates as a random walk (bounded by a single light round trip, $\tau = 2L/c$) becoming detectable for $L$ sufficiently high.

- High sensitivity is required.
- How it can be distinguished by other noise sources?

[C. Hogan, Arxiv: 1204.5948; C. Hogan, PRD 85, 064007 (2012)]

HN spectrum: for $L \sim 40$ m the maximum is in the MHz region
Correlated interferometers for HN

HN should be correlated in the two interferometers if they are in the same space-time volume

\[ P = 2 \text{ KW} \]
\[ L = 40 \text{ m} \]

Even if the HN is hidden by the photon shot noise in one interferometer, it could emerge in the cross-correlation between two of them. Shot noise is uncorrelated and therefore is statistically washed away.

[HOLOMETER Fermilab]

HN lower bounded to \(10^{-20} \text{ m/}\sqrt{\text{Hz}}\) in the MHz region of the spectrum after 165 h of acquisition.

[C. Hogan, Arxiv: 1204.5948; C. Hogan, PRD 85, 064007 (2012)]

[PRL 117, 111102 (2016)]
Other applications of correlated interferometry

**Fundamental noise at the Planck scale in quantum gravity model**

- [First Measurements of High Frequency Cross-Spectra from a Pair of Large Michelson Interferometers, PRL 117, 111102 (2016)]
- [PRD 85, 064007 (2012)]

**Stochastic Gravitational Wave Background**

(10\(^{-36}\) to 10\(^{-32}\) seconds after the Big Bang, whereas the Cosmic Micro-wave Background was produced 300,000 years later)

- [Search for a Stochastic Background of 100-MHz GW with Laser Interferometers, PRL 101, 101101 (2008)]
- [Upper limits on a stochastic GW background using LIGO and Virgo interferometers, PRD 85, 122001 (2012)]

**Traces of primordial blackholes**

- [MHz gravitational wave constraints with decameter Michelson interferometers, PRD 95, 063002 (2017)]
Quantum light in one interferometer (theory)

Vacuum Squeezed states of light are injected from the antisymmetric port.

\[ |\Psi(\lambda)\rangle_a = S_a(\xi)|0\rangle_a \]

\[ S_a(\xi) = \exp \left( \frac{1}{2} (\xi^* a^2 - \xi a'^2) \right) \]

\[ \xi = re^{i\theta} \]

\[ X = \frac{a + a'^*}{2} \]

\[ Y = \frac{a - a'^*}{2i} \]

Uncertainty on one of the quadrature is below the vacuum

\[ \Delta^2 X = \frac{e^{-2r}}{2} \]

\[ \text{Var}(N)_{SQ} < \text{Var}(N)_{SNL} \]

\[ \text{Var}(\phi)_{SQ} < \text{Var}(\phi)_{SNL} \]

Vacuum squeezed states of light from can enhance the phase sensitivity of an interferometer

[Caves, PRD 23, 1693 (1981)]
Squeezed light experimentally works!

The use of vacuum squeezed states is now exploited in several gravitational wave detectors

2.15 ± 0.05 dB
Quantum enhancement

And many others
Coming back to our question...

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Quantum light in two interferometers

Two independent squeezed states

\[ |\Psi(\lambda)\rangle_{a_1 a_2} = S_1(\xi_1) S_2(\xi_2) |0\rangle_{a_1} \otimes |0\rangle_{a_2} \]

Quadrature squeezing

\[ \Delta^2 X_1 = \frac{e^{-2r_1}}{2} \quad \xi_1 = r_1 e^{i\theta_1} \]

\[ \Delta^2 X_2 = \frac{e^{-2r_2}}{2} \quad \xi_2 = r_2 e^{i\theta_2} \]

Two mode squeezing (Twin Beam)

\[ |\Psi(\lambda)\rangle_{a_1 a_2} = S_2(\xi)|00\rangle_{a_1 a_2} = \exp( (\xi^* a_1 a_2 - \xi a_1^+ a_2^+))|00\rangle \]

\[ \frac{1}{\sqrt{1 + \lambda}} \sum_{m=0}^{\infty} \left( e^{i\theta} \sqrt{\frac{\lambda}{1 + \lambda}} \right) |m, m\rangle_{a_1 a_2} \]

- Photon number entanglement:
  \[ \langle \Psi(\lambda) | (m_1 - m_2)^M |\Psi(\lambda)\rangle_{a_1 a_2} = 0 \]
  \[ \Delta^2 (N_1 - N_2) = 0 \]
- Quadrature correlations:

\[ \Delta^2 (X_1 - X_2) = \frac{e^{-2r}}{2} \quad \xi = r e^{i\theta} \]

[PLR 110, 213601 (2013), PRA 92, 053821 (2015)]
Quantum light in two interferometers

Two independent squeezed states

\[ \langle \Delta^2(N_1N_2) \rangle_{SQ\times SQ} < \langle \Delta^2(N_1N_2) \rangle_{SNL} \]

\[ \langle \Delta^2(\Delta\phi_1\Delta\phi_2) \rangle_{SQ\times SQ} < \langle \Delta^2(\Delta\phi_1\Delta\phi_2) \rangle_{SNL} \]

Correlated signal can emerge better from the noise.

Two mode squeezing (Twin Beam)

\[ \langle \Delta^2(N_1 - N_2) \rangle_{TWB} < \langle \Delta^2(N_1 - N_2) \rangle_{SNL} \]

Correlated signals are deleted in the subtraction, uncorrelated signals can emerge.

Obs: the quantity \( C \) considered is different in the two cases.
Theoretical results

- $\phi_0$ central working phase
- $\eta$ detection efficiency
- $\lambda$ number of photon of quantum light
- $\mu$ number of photon of coherent state

Green region is for TWB advantage with respect to double squeezing

$$\tau = (\cos \frac{\phi}{2})^2 \approx 1$$
$$\mu(1 - \tau)/\tau \lambda \ll 1$$

Unfortunately this regime is extremely challenging for real experiments

[PRL 110, 213601 (2013), PRA92, 053821 (2015)]
Experimental set-up:
The classical part

- Read-out AS port operated close to the dark fringe (LIGO, HOLOMETER)
- 2-D Power recycling cavity 90% reflectivity (gain =10)
- We focus around 13.5 MHz, being the system shot-noise limited at this frequency

[arXiv:1810.13386]
Experimental set-up:
Quantum states injected

- Two possibility explored
- Data are differently analyzed in the two cases
- Instead of a real TWB we consider a single squeezed beam split by a BS: they present same correlation between quadrature

[SQ x SQ]

[Squeezed Vacuum] [Squeezed Vacuum] [I₁ x I₂]

[TWB]

[Squeezed Vacuum] [Squeezed Vacuum] [I₁ - I₂]

[arXiv:1810.13386]
Experimental results (time domain)

- Correlated white noise injected (about 1/5 of the shot noise level)
- About 3dB of squeezing in each interferometer
- The cross correlation peak emerges at the increasing of the measurement time
- Noise floor reduced by SQ injection
Experimental results (time domain)

- SNR improves with the usual statistical scaling $\sqrt{N_{\text{samples}}}$
- SNR is twice when squeezing is injected
- 4 times reduction in the measurement time demonstrated
- Noise floor reduced by SQ injection
Experimental results
(frequency domain)

- A correlated white noise is injected (amplitude around 1/5 of the photon shot noise of each MI), its detection is easier when squeezing is injected
  - CLSD reduces the shot-noise contribution

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Experimental results (frequency domain)

The maximum sensitivity measured is $3 \cdot 10^{-17} \text{ m/√Hz}$.

The CLSDs scale as $N_{\text{spectra}}^{-1/4}$.

Plateau corresponding to the amplitude of the signal.

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Experimental results (time domain)

- Quadrature correlation leads to noise reduction in the difference of the photon currents

$$\Delta^2 [I_1 - I_2] < \text{SNL} = \langle I_1 + I_2 \rangle$$

- 2.5 dB of squeezing measured in the output subtraction
Experimental results
(time domain)

- Uncorrelated white noise injected
- The noise emerge better when TWB is used
- This enhancement might be applied to identify uncorrelated noise sources, such as scattering or unwanted resonances

\[ \text{Var}(I_1 - I_2) \text{ (dB)} \]

\[ 0.3 \text{ dB} \]

\[ 1 \text{ dB} \]
Experimental results (frequency domain)

Single MIs

Output subtraction

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Conclusions

Detecting faint stochastic noises is important in fundamental physics quests, to experimentally test Planck scale effects (gravitational wave background, quantum gravity fluctuations...)

Correlation techniques are used to boost the sensitivity of the single device of orders of magnitude. At the moment with only classical light.

Quantum light is currently used in single interferometers to boost their sensitivity below the SNL

Single mode Squeezed light and TWB provide an enhancement in the sensitivity of coupled interferometers

We have realized a table top experiment mimicking the design of large scale devices demonstrating quantum advantage, in two possible configurations

Combining cross-correlation techniques and quantum enhancement we have demonstrated 1-2 order of magnitude sensitivity improvement with respect to the single interferometer

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**Thanks for your attention!**

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