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POLITECNICO DI TORINO

DTU Technical University of Denmark

Quantum enhanced correlated interferometry for Planck scale physics

Elena Losero

e.losero@inrim.it

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

BeCOMe

EMPIR-17FUN01 - BeCOMe

Light-matter interplay for optical metrology beyond the classical spatial resolution limits

SIQUST

EMPIR-17FUN06 - SIQUST

Single-photon sources as new quantum standards

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COST Action MP1405

NATO OTAN

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FQXi FOUNDATIONAL QUESTIONS INSTITUTE

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FET Open project - Pathos

The Time Machine Factory 2019 – Torino – September 22-25

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Our team


Siva Pradyumna


Elena Losero


Paolo Traina


Ivo P. Degiovanni


Marco Genovese


Christian S. Jacobsen


Tobias Gehring

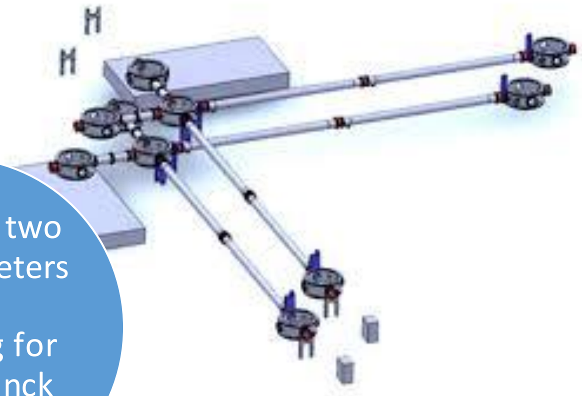

Ulrik L. Andersen


Ivano Ruo-Berchera


Massimo Zucco


Stefano Olivares (Univ. Milano)

Introduction



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

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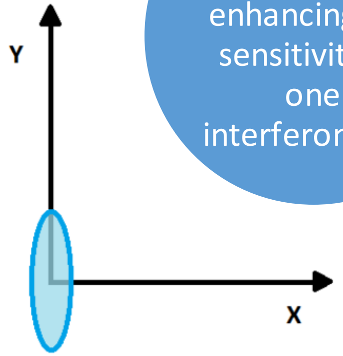
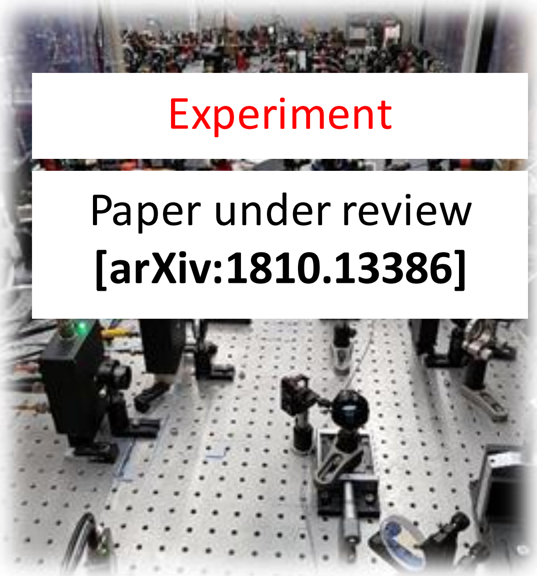


Quantum light can help in enhancing the sensitivity of one interferometer

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

Theory

[PRL **110**, 213601 (2013), PRA **92**, 053821 (2015)]



Experiment

Paper under review **[arXiv:1810.13386]**

New theories for Planck scale

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

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

$$[\hat{x}_i, \hat{x}_j] = \hat{x}_k \epsilon_{ijk} i c t_P / \sqrt{4\pi}$$

$$t_p = 5.40 \times 10^{-44}\ \mathrm{s}$$

Fundamental space-time uncertainty principle called "**holographic noise (HN)**"

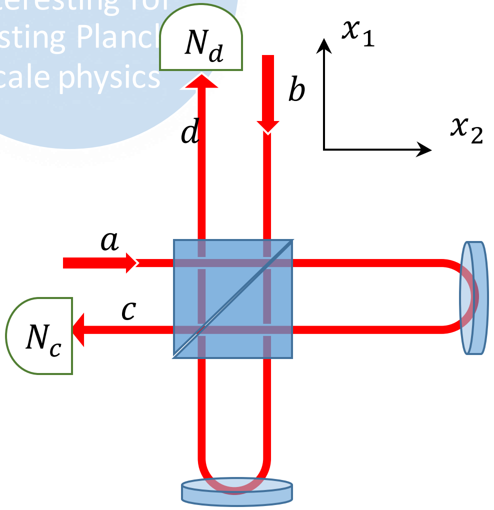
[C. Hogan, Arxiv: 1204.5948; C. Hogan, PRD 85, 064007 (2012)]:

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.

can be interesting for testing Planck scale physics



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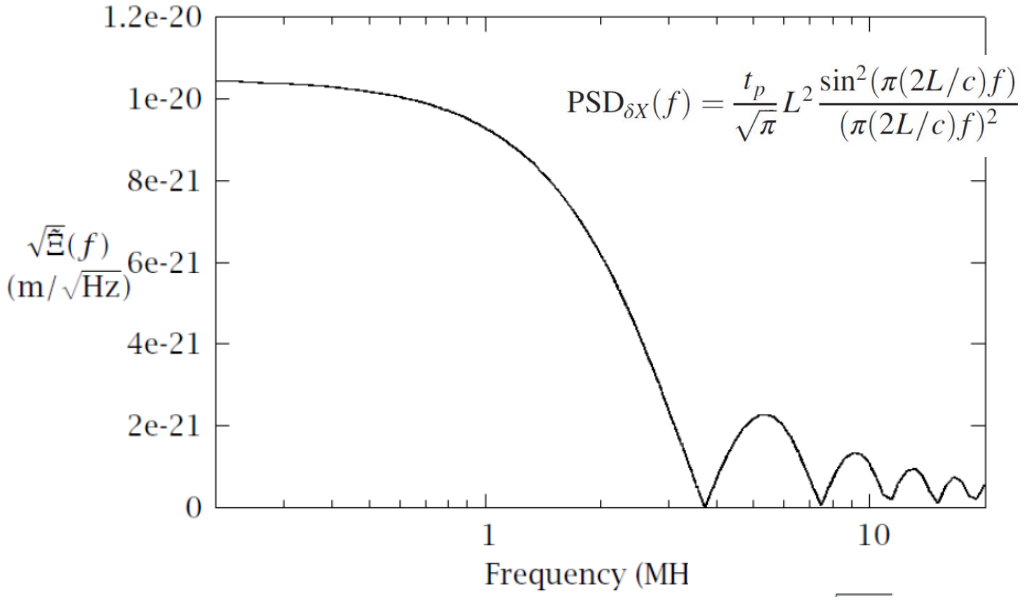


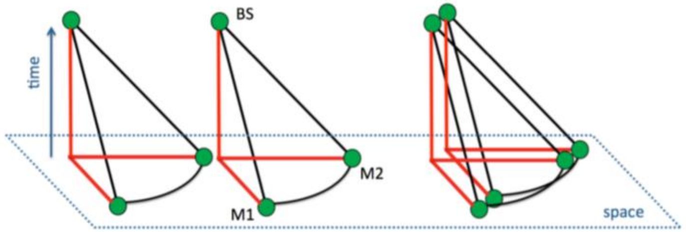
HN spectrum: for L ~ 40 m the maximum is in the MHz region

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

Correlated interferometers for HN

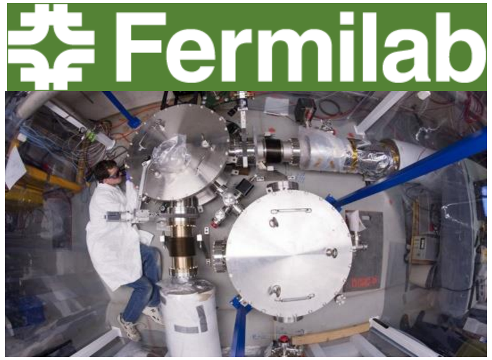
HN should be correlated in the two interferometers if they are in the same space time volume

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



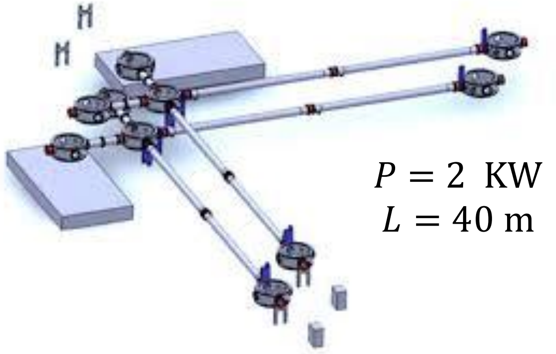
Even if the HN is hidden by the photon shot noise in one interferometer, it could emerge in the cross-correlation between two of them.
Shot noise is uncorrelated and therefore is statistically washed away.

HOLOMETER

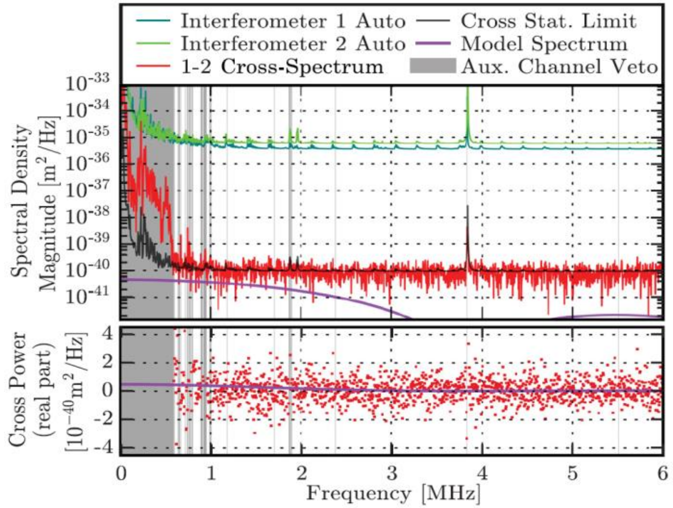


[PRL **117**, 111102 (2016)]

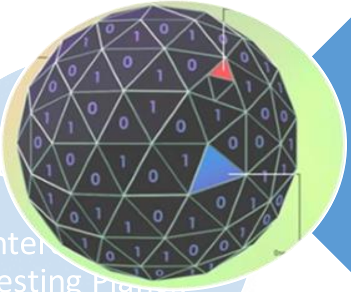
HN lower bounded to $10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ in the MHz region of the spectrum after 165 h of acquisition.



$P = 2\ \mathrm{KW}$
$L = 40\ \mathrm{m}$



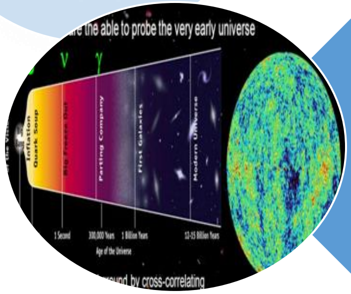
Other applications of correlated interferometry



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)]

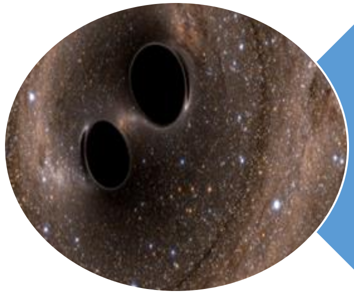


Stochastic Gravitational Wave Background

(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)]



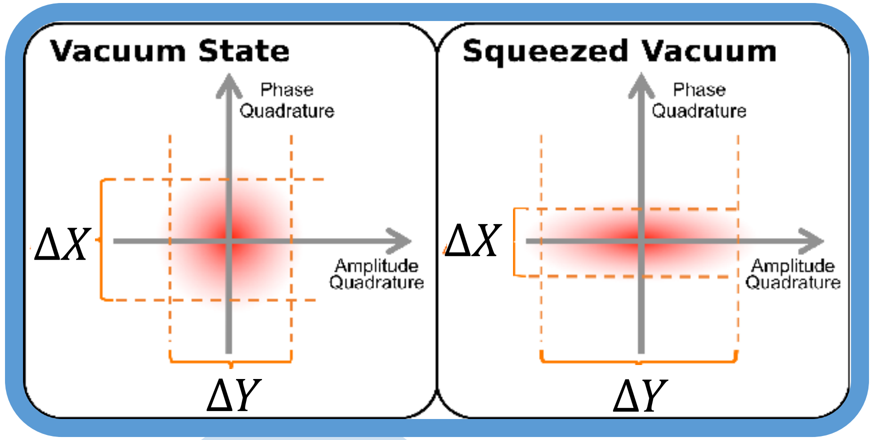
Traces of primordial blackholes

[MHz gravitational wave constraints with decameter Michelson interferometers, PRD 95, 063002 (2017)]

Quantum light in one interferometer (theory)

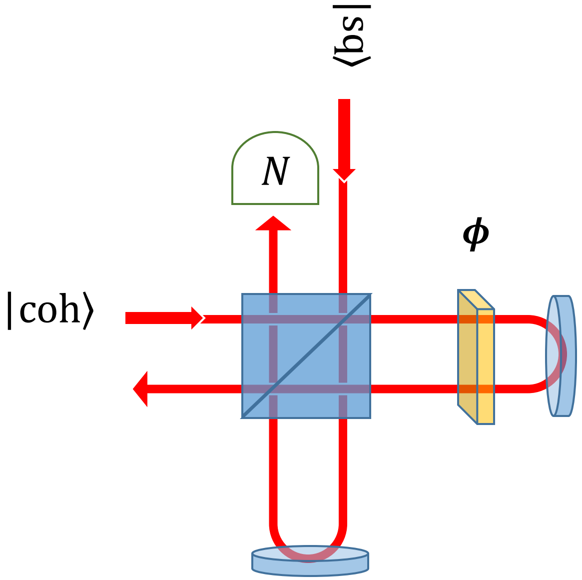
Vacuum Squeezed states of light are injected from the antisymmetric port.

$$|\Psi(\lambda)\rangle_a = S_a(\xi)|0\rangle_a \qquad S_a(\xi) = \exp\left(\frac{1}{2}(\xi^* a^2 - \xi a^{+2})\right) \qquad \xi = re^{i\theta}$$



$$X = \frac{a + a^+}{2}$$

$$Y = \frac{a - a^+}{2i}$$



Uncertainty on one of the quadrature is below the vacuum

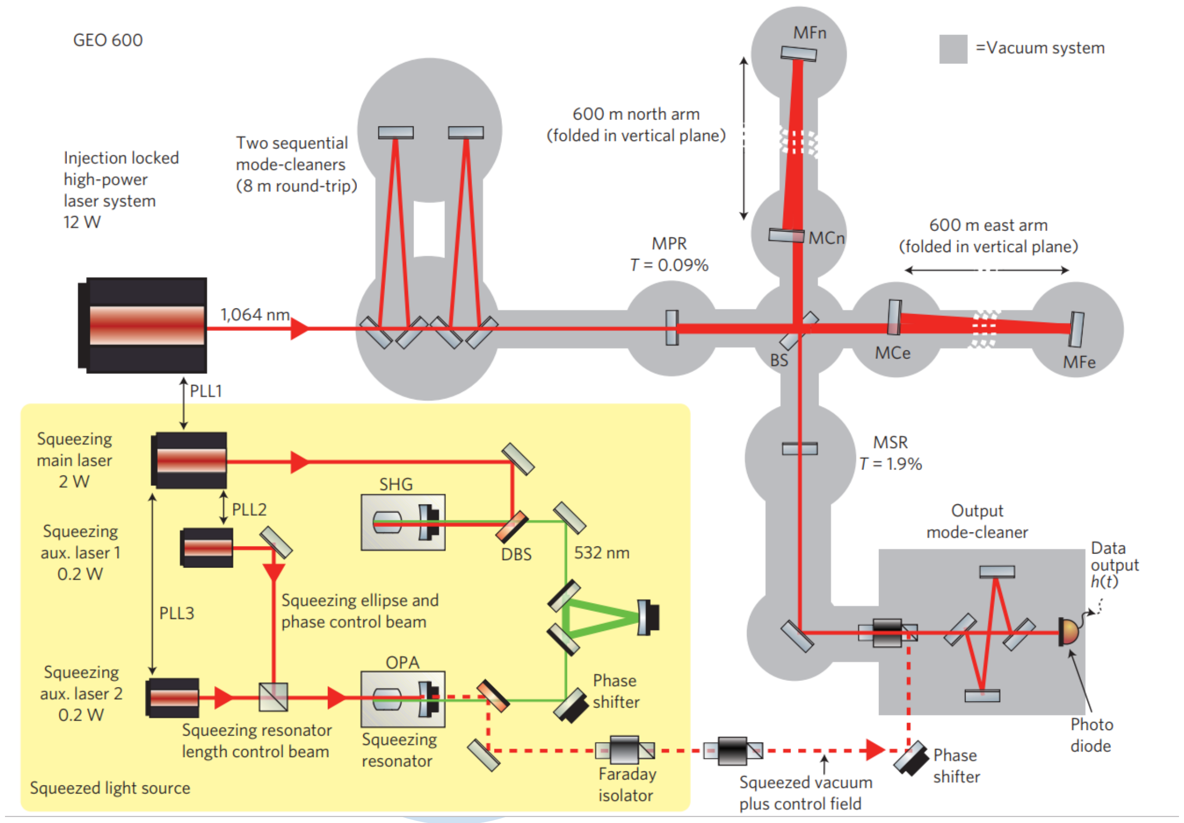
$$\Delta^2 X = \frac{e^{-2r}}{2} \;\Rightarrow\; \begin{array}{l} \mathrm{Var}(N)_{SQ} < \mathrm{Var}(N)_{SNL} \\ \mathrm{Var}(\phi)_{SQ} < \mathrm{Var}(\phi)_{SNL} \end{array}$$

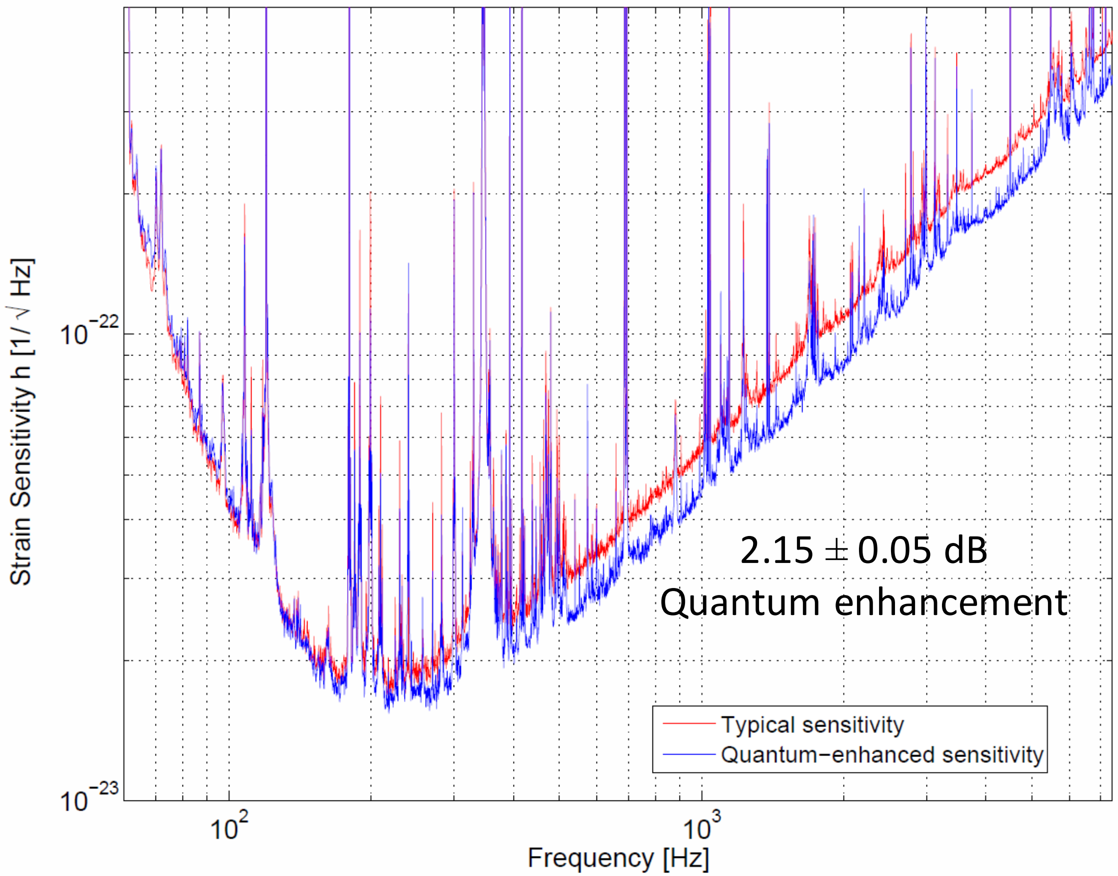
Vacuum squeezed states of light from can enhance the phase sensitivity of an interferometer

[Caves, PRD **23**, 1693 (1981)]

Squeezed light experimentally works!

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





[R. Schnabel et al., Nature Commun. **1**, 121 (2010), Ligo, Nature Phys. **7**, 962 (2011)]
And many others

Coming back to our question…

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

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Quantum light can help in enhancing the sensitivity of one interferometer

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

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Quantum light in two interferometers

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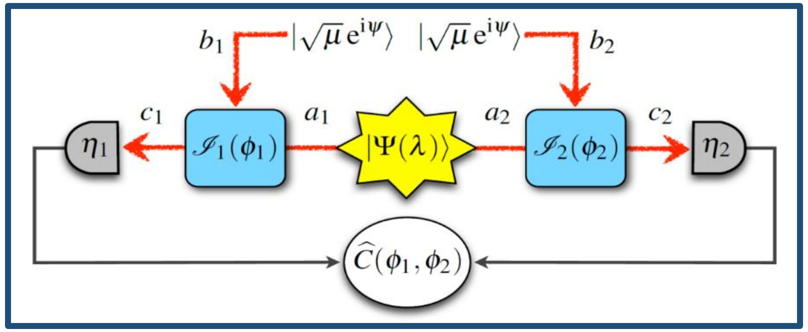

[PRL **110**, 213601 (2013), PRA **92**, 053821 (2015)]

SQ x SQ

Two independent squeezed states

$$|\Psi(\lambda)\rangle_{a_1 a_2} = S_{a_1}(\xi_1) S_{a_2}(\xi_2) |0\rangle_{a_1} \otimes |0\rangle_{a_2}$$

Quadrature squeezing

$$\Delta^2 X_1 = \frac{e^{-2r_1}}{2} \qquad \xi_1 = r_1 e^{i\theta_1}$$

$$\Delta^2 X_2 = \frac{e^{-2r_2}}{2} \qquad \xi_2 = r_2 e^{i\theta_2}$$

TWB

Two mode squeezing (Twin Beam)

$$|\Psi(\lambda)\rangle_{a_1 a_2} = S_2(\xi)|00\rangle_{a_1 a_2} = \exp(\,(\xi^* a_1 a_2 - \xi\, a_1^\dagger a_2^\dagger))|00\rangle$$

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

- 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:

$$\Delta^2 (X_1 - X_2) = \frac{e^{-2r}}{2} \qquad \xi = r e^{i\theta}$$

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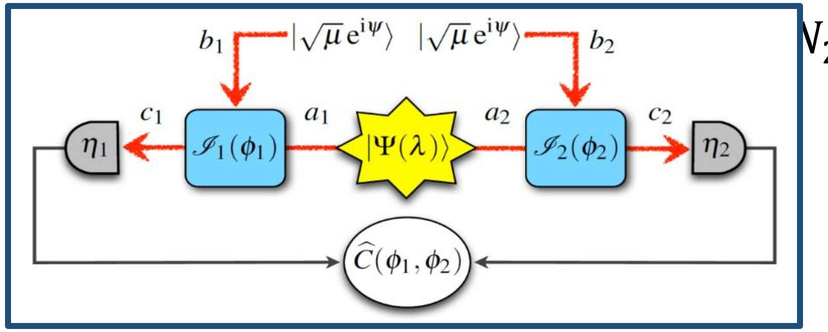
Quantum light in two interferometers



[PRL **110**, 213601 (2013), PRA **92**, 053821 (2015)]

SQ x SQ

Two independent squeezed states

$$\langle \Delta^2(\Delta N_1 \Delta N_2)\rangle_{SQ\times SQ} < \langle \Delta^2(\Delta N_1 \Delta N_2)\rangle_{SNL}$$

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

Correlated signal can emerge better from the noise.

TWB

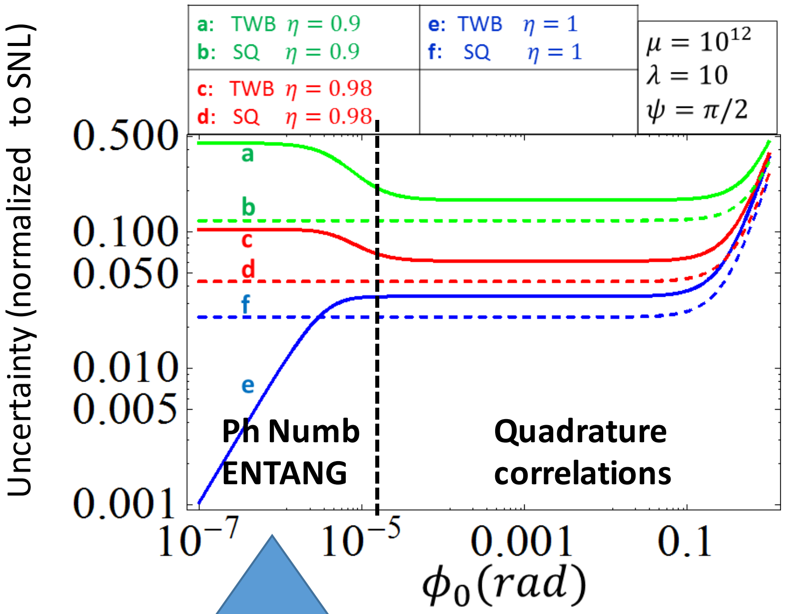
Two mode squeezing (Twin Beam)

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

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

Obs: the quantity *C* considered is different in the two cases

Theoretical results



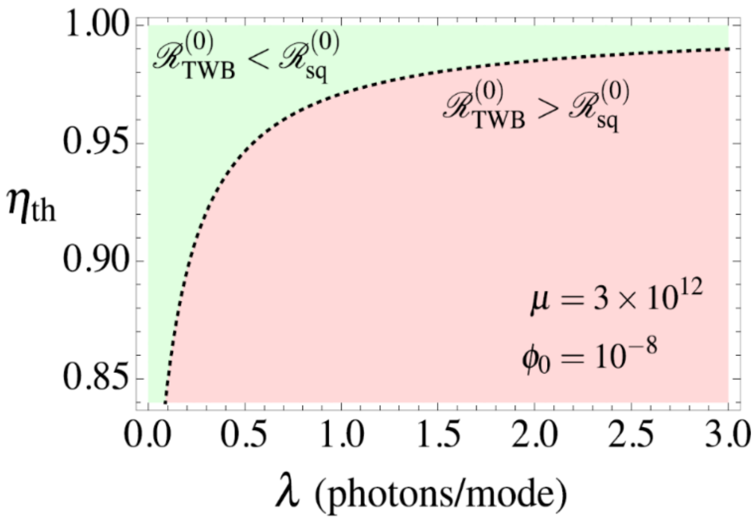
TWB leads to disruptive advantages!

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

...Unfortunately this regime is extremely challenging for real experiments

- ϕ_0 central working phase
- η detection efficiency
- λ number of photon of quantum light
- μ number of photon of coherent state

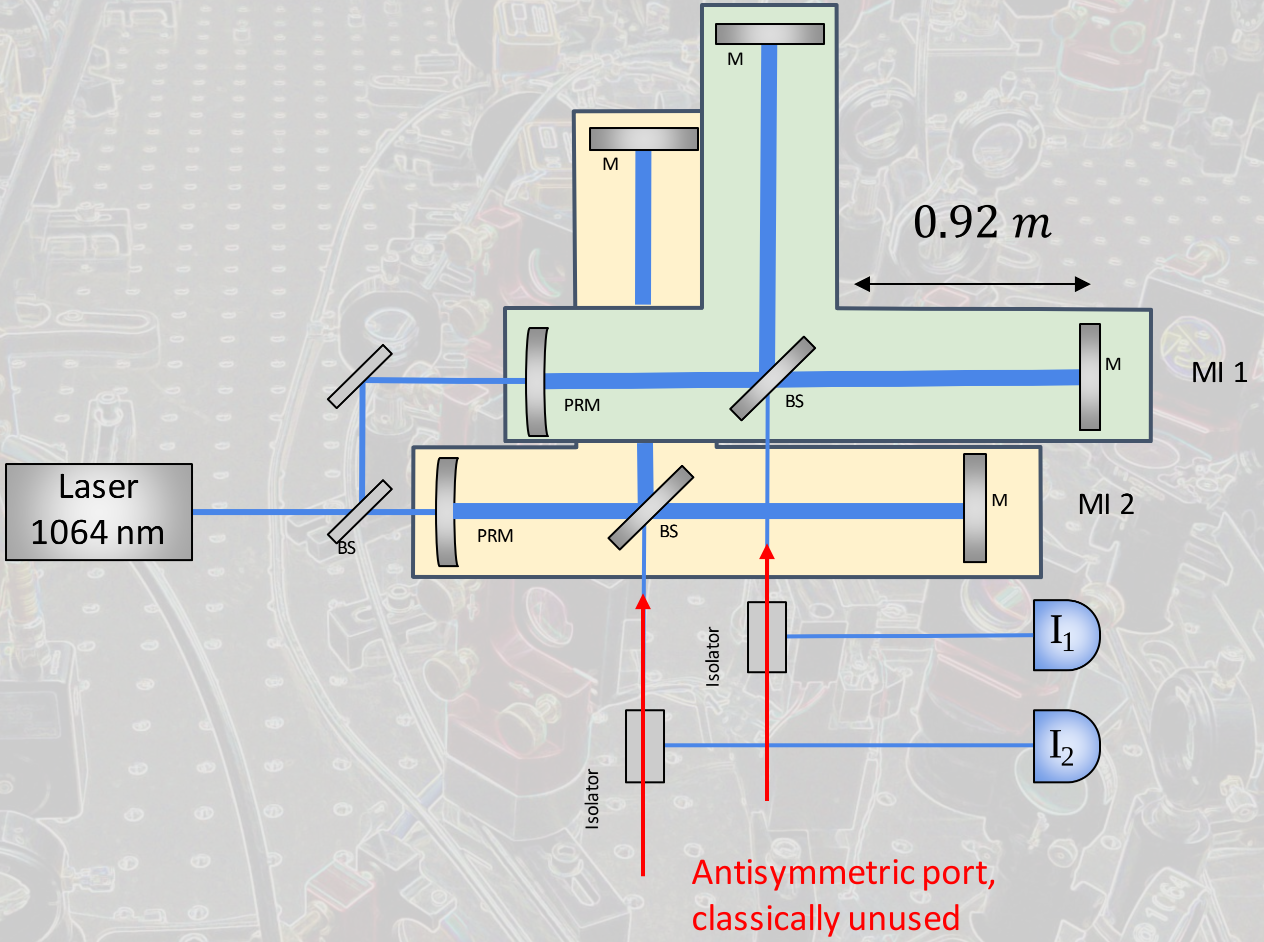
Green region is for TWB advantage with respect to double squeezing



[PRL **110**, 213601 (2013), PRA **92**, 053821 (2015)]

Experimental set-up: The classical part

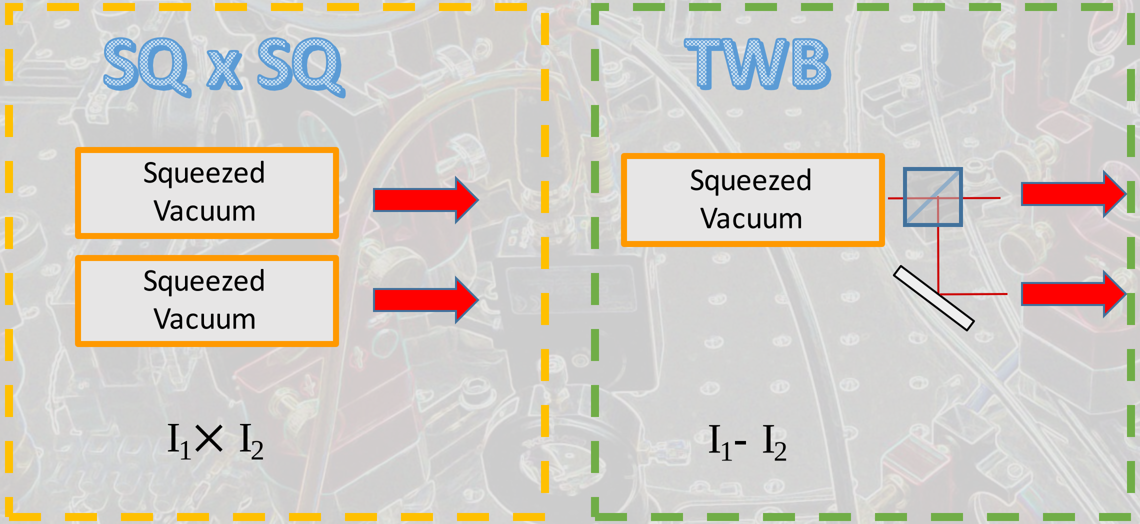
- Read-out AS port operated close to the dark fringe (LIGO, HOLOMETER)
- 2-D Power recycling cavity 90% reflectivity (gain =10)
- We focus around 13.5 MHz, being the system shot-noise limited at this frequency

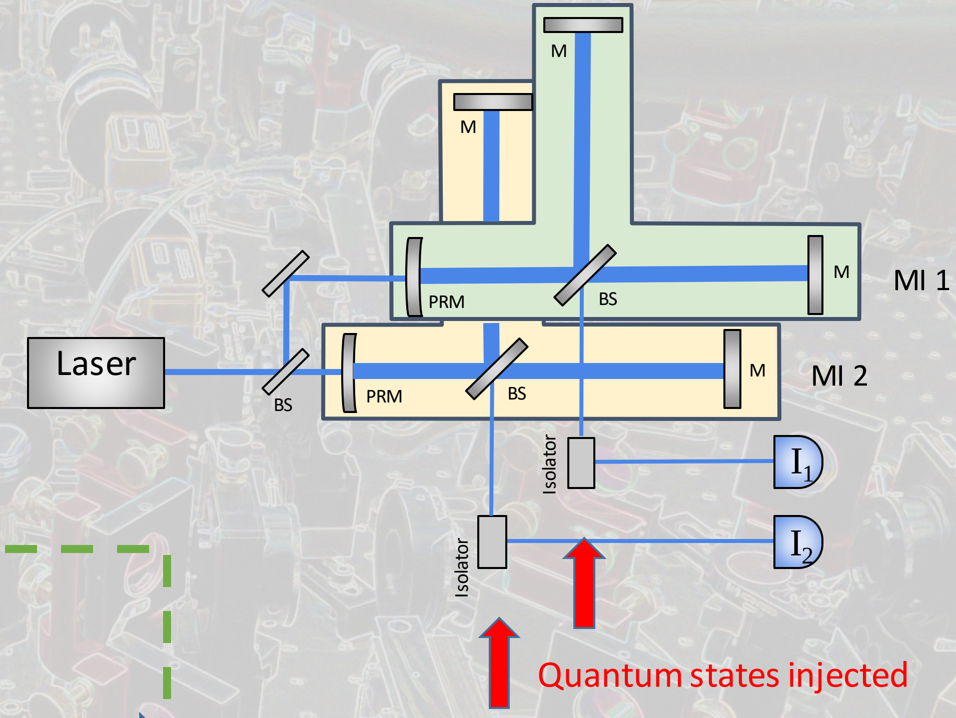


[arXiv:1810.13386]

Experimental set-up: Quantum states injected

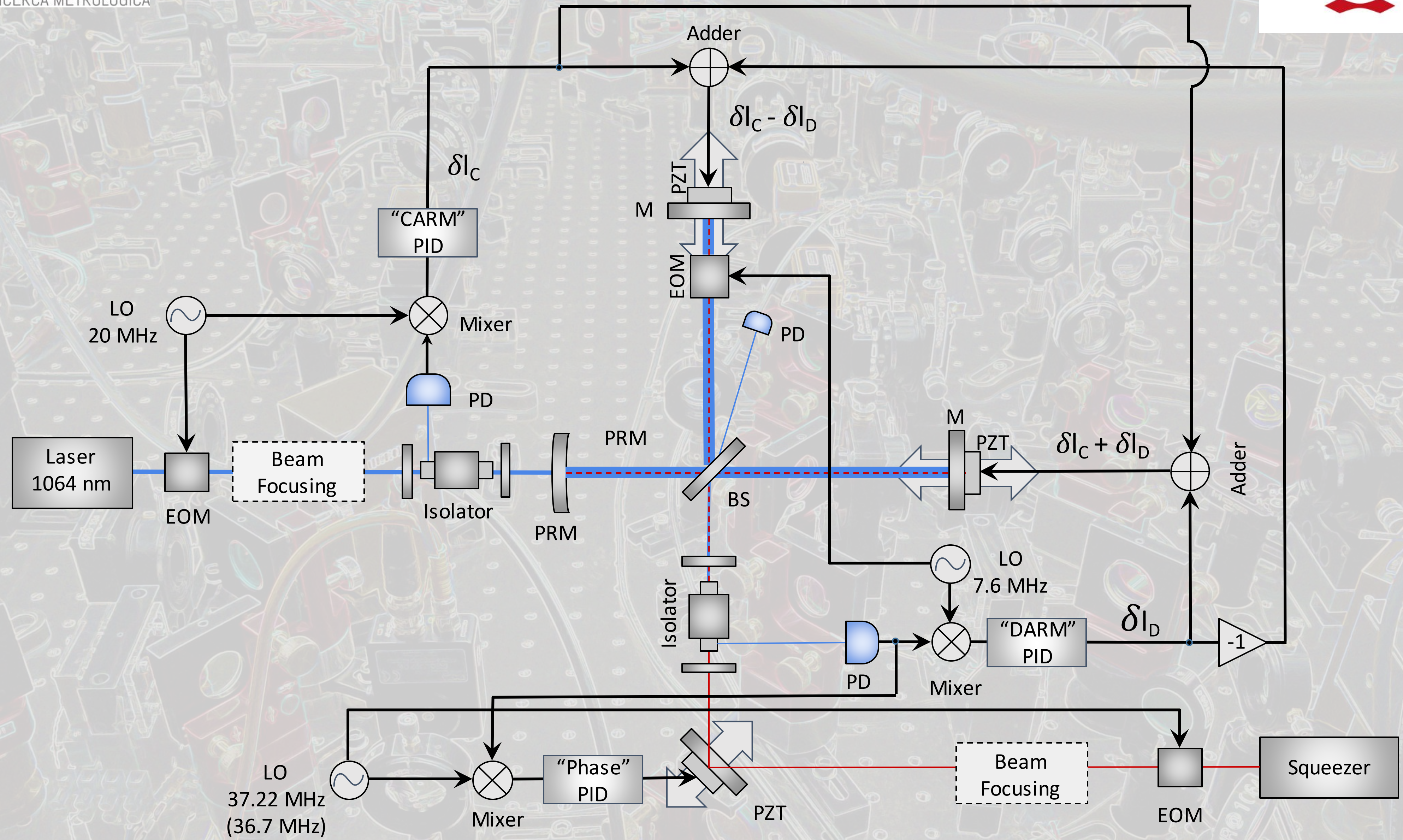
- Two possibility explored
- Data are differently analyzed in the two cases
- Instead of a real TWB we consider a single squeezed beam split by a BS: they present same correlation between quadrature





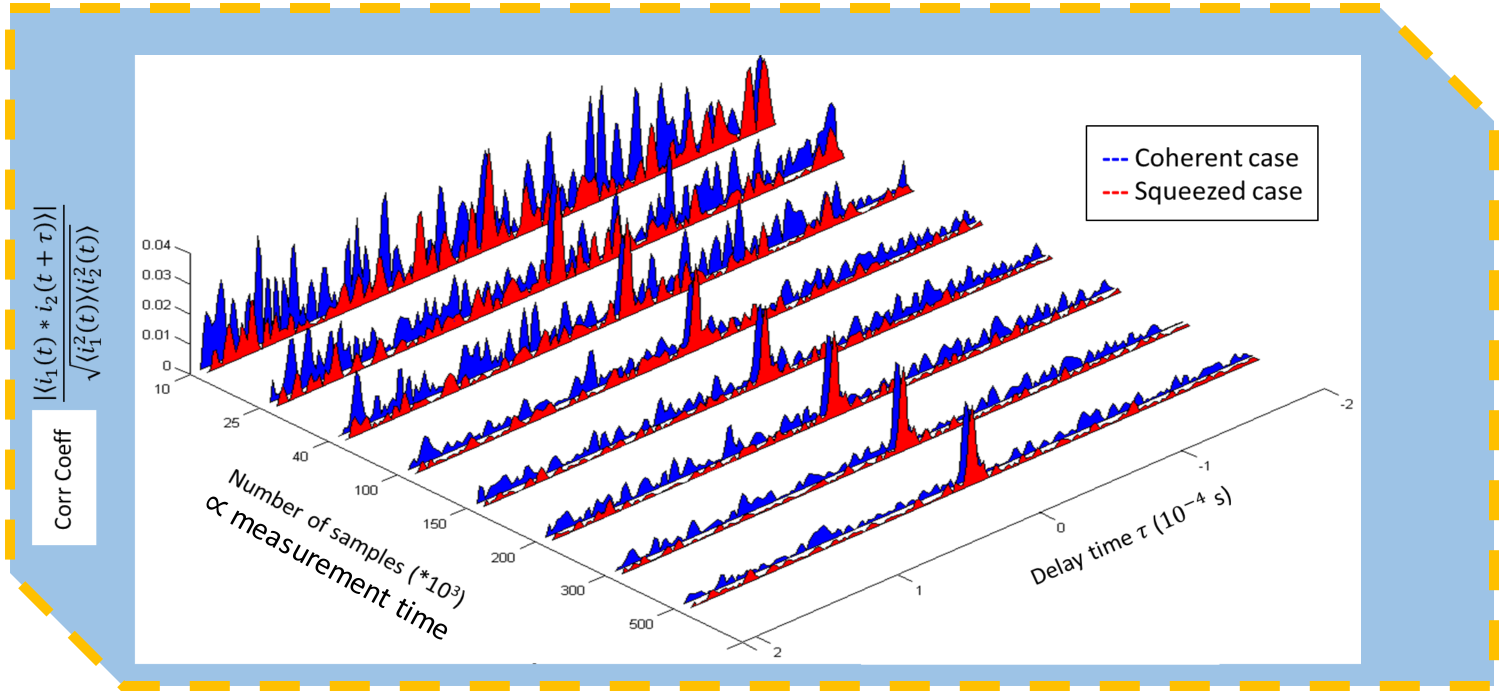
[arXiv:1810.13386]

Set-up details



Experimental results (time domain)

SQ x SQ



- 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

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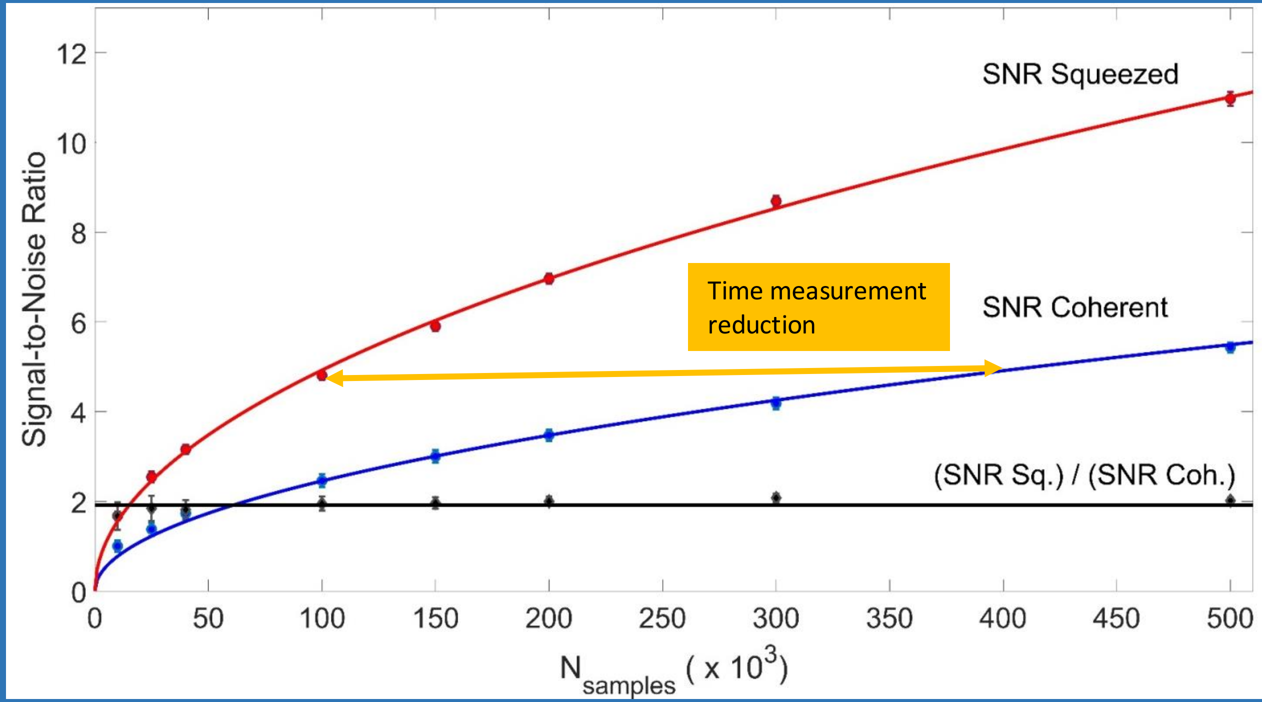
Experimental results (time domain)

SQ x SQ

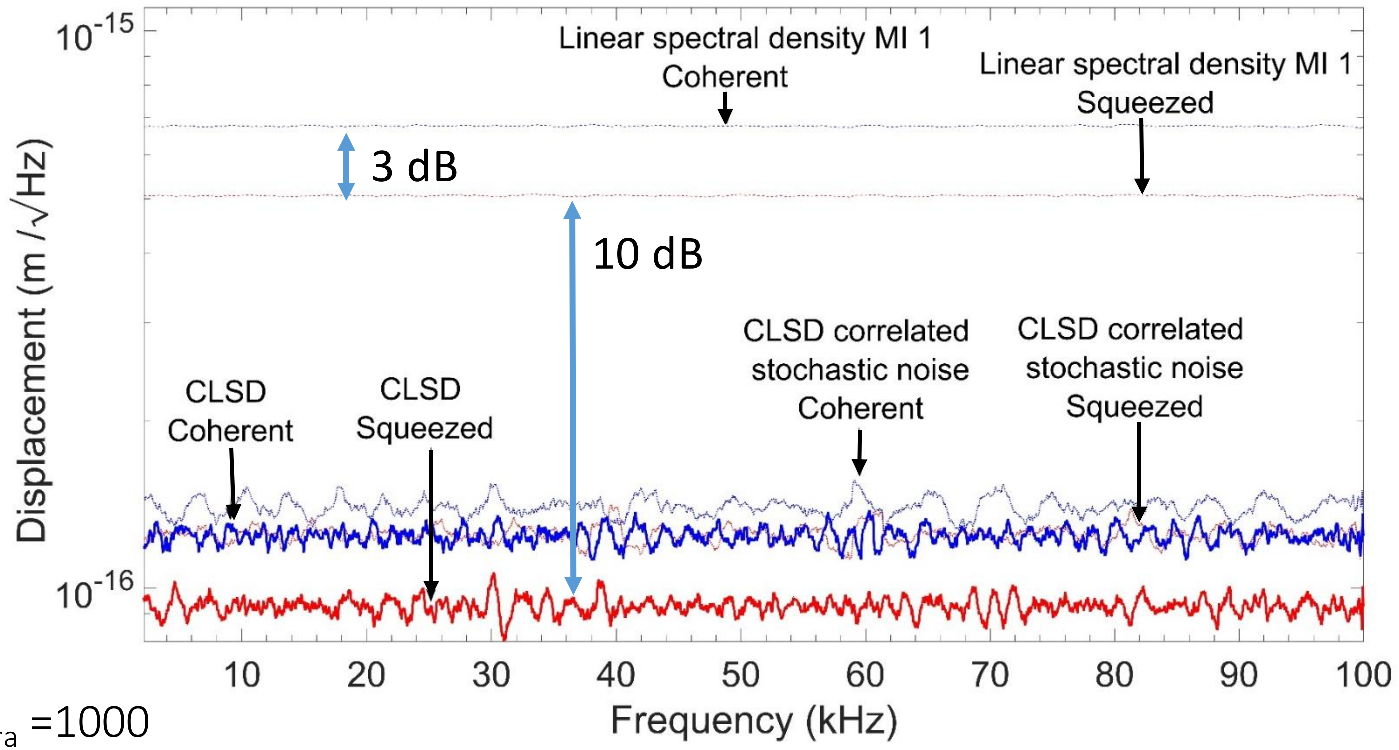


- SNR improves with the usual statistical scaling $\sqrt{N_{\text{samples}}}$
- SNR is twice when squeezing is injected
- 4 times reduction in the measurement time demonstrated

- Noise floor reduced by SQ injection

Experimental results (frequency domain)

SQ x SQ

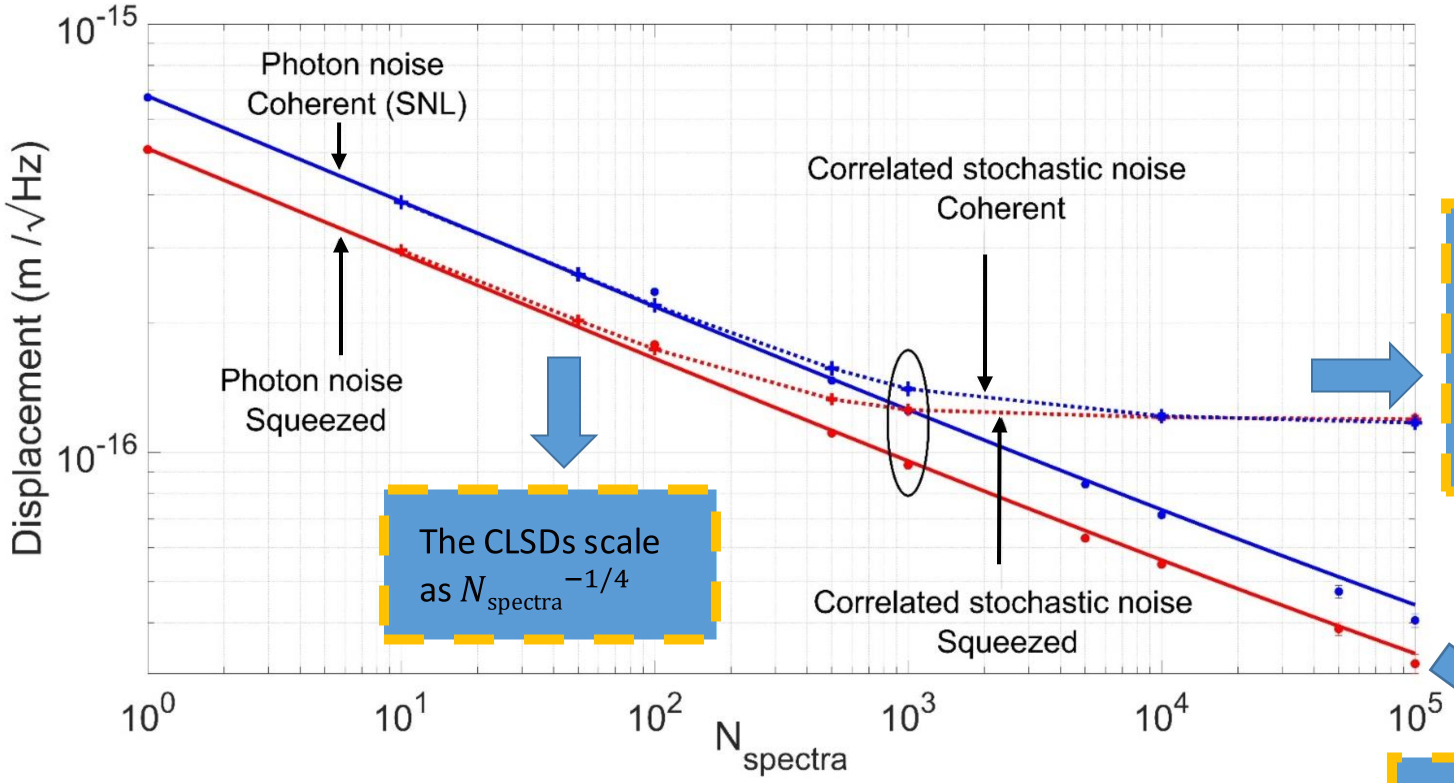


$N_{spectra} = 1000$

- 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

Experimental results (frequency domain)

SQ x SQ



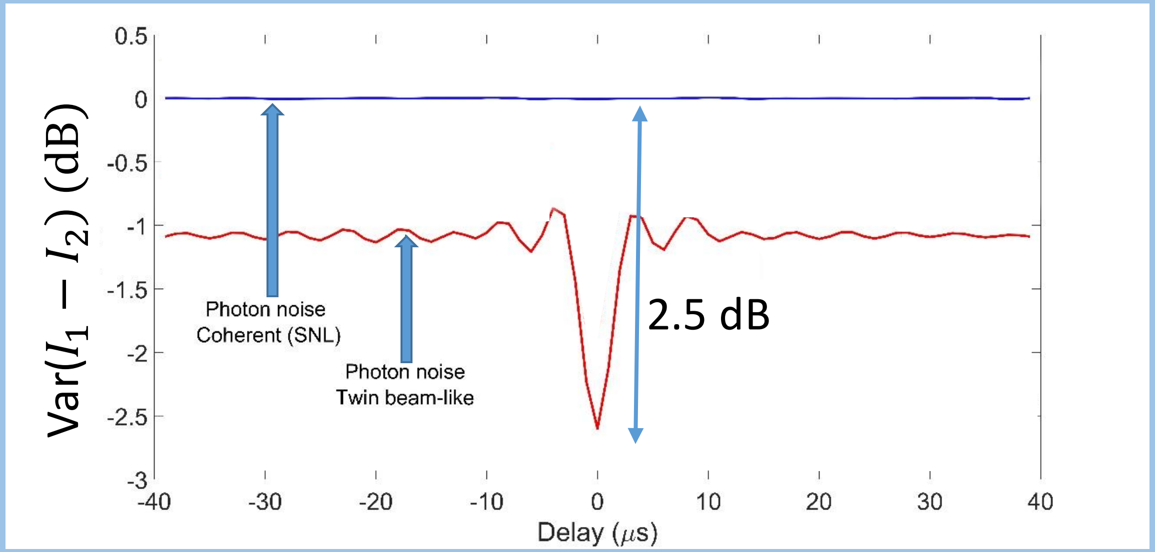
The CLSDs scale as $N_{\text{spectra}}^{-1/4}$

Plateau corresponding to the amplitude of the signal

The maximum sensitivity measured is $3 \cdot 10^{-17}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

Experimental results (time domain)

TWB

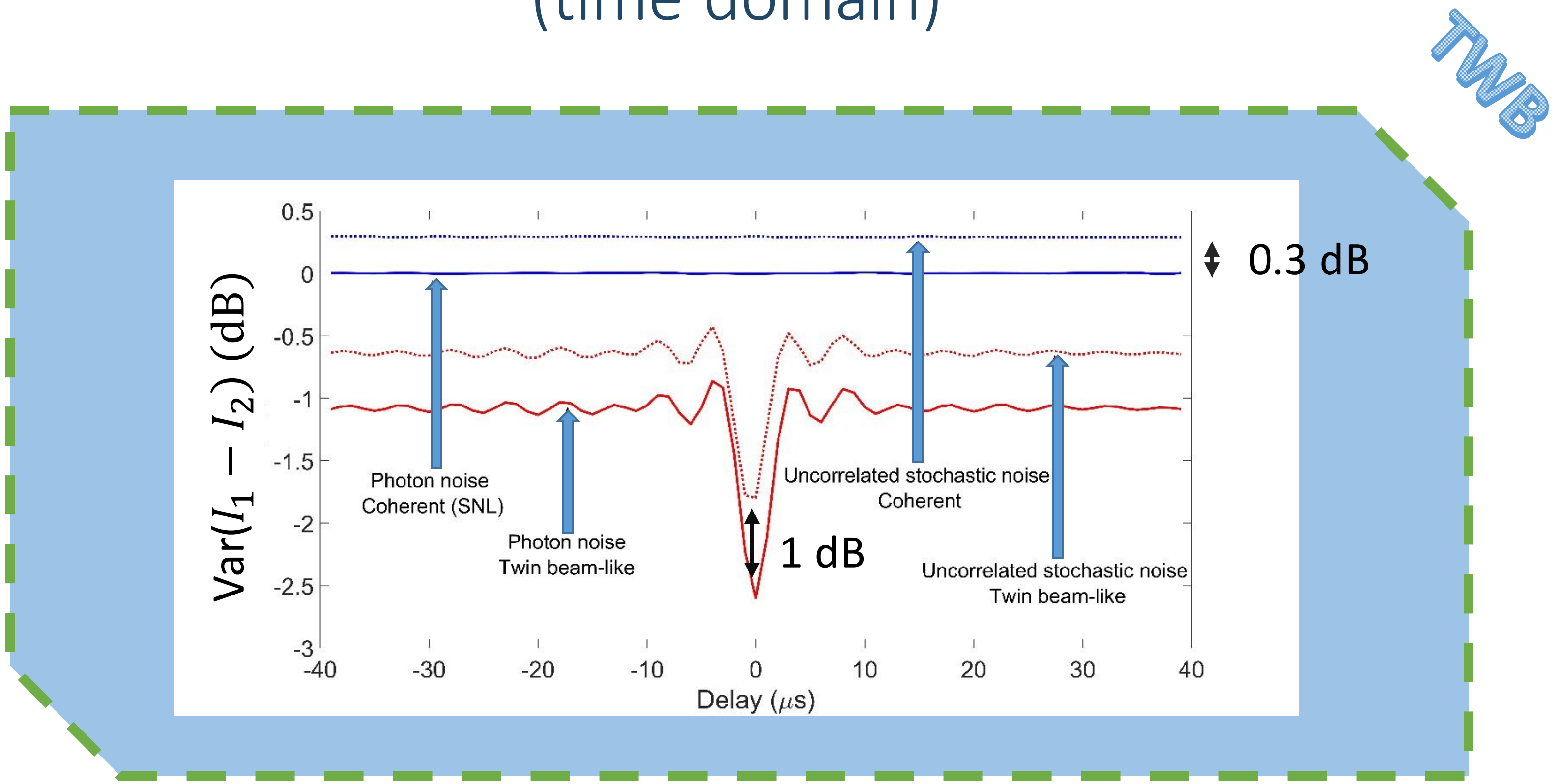


- Quadrature correlation leads to noise reduction in the difference of the photon currents

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

- 2.5 dB of squeezing measured in the output subtraction

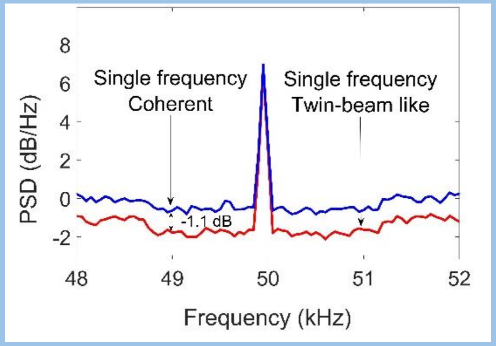
Experimental results (time domain)

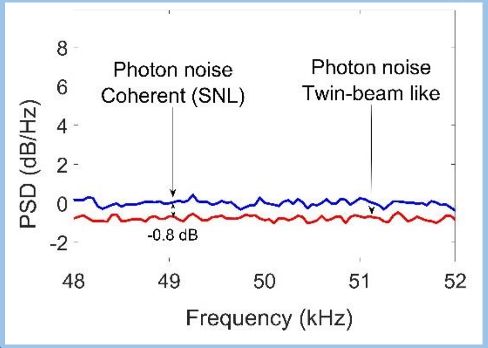


- Uncorrelated white noise injected
- The noise emerge better when TWB is used
- This enhancement might be applied to identify uncorrelated noise sources, such as scattering or unwanted resonances

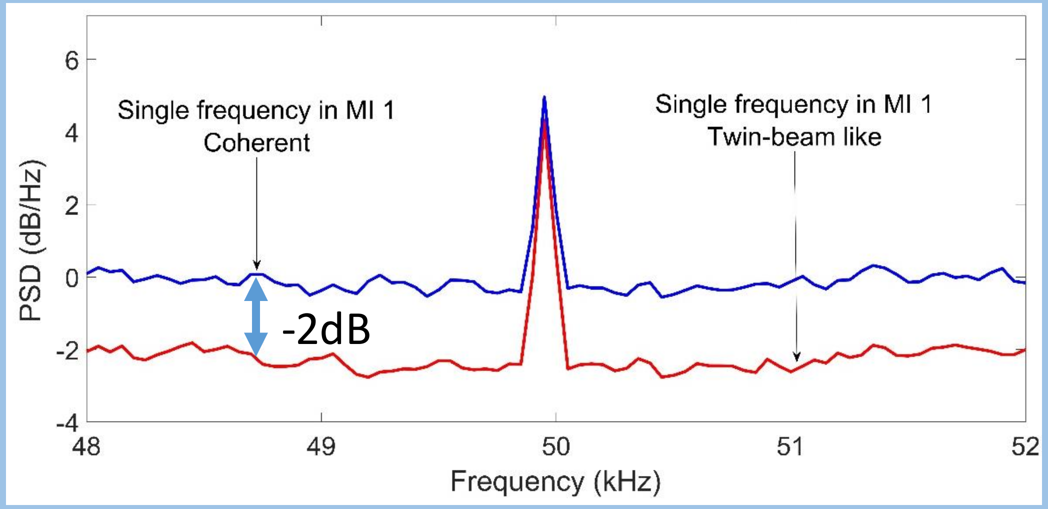
Experimental results (frequency domain)

Single MIs





Output subtraction



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Conclusions

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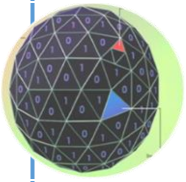
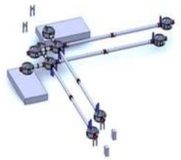


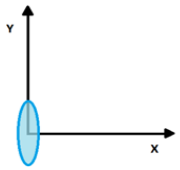
Detecting faint stochastic noises is important in fundamental physics quests, to experimentally test Planck scale effects

(gravitational wave background, quantum gravity fluctuations…)

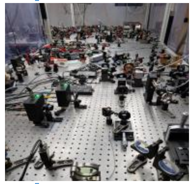


Correlation techniques are used to boost the sensitivity of the single device of orders of magnitude. At the moment with only classical light.

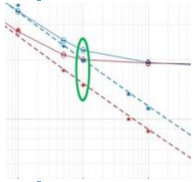
Quantum light is currently used in single interferometers to boost their sensitivity below the SNL



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

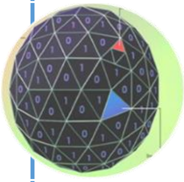


We have realized a table top experiment mimicking the design of large scale devices demonstrating quantum advantage, in two possible configurations



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

Conclusions



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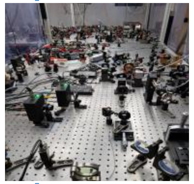

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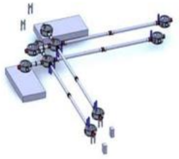

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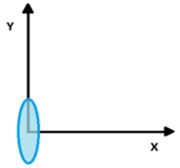

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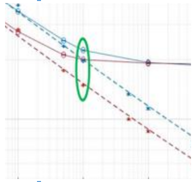

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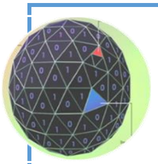

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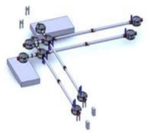
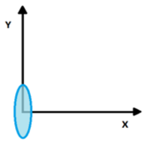
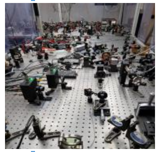


Correlation techniques are used to boost the sensitivity of the single device of orders of magnitude. At the moment with only classical light.

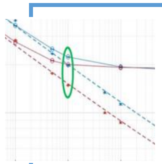
Quantum light is currently used in single interferometers to boost their sensitivity below the SNL



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

Thanks for your attention!