INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Technical University of Denmark

QUANTUM-ENHANCED HOLOMETER REALIZATION

Paolo Traina

COST ACTION MP1405 – Quantum Structure of Spacetime

Bratislava, February 11 2019

John Templeton Foundation
cost Action MP 1405 Quantum Structure of Spacetime
MIUR

EMPIR EURAMET
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Outline

- INTRO: why correlating interferometers?
- EXPERIMENT
- RESULTS (I): independent squeezed states
- RESULTS (II): twin beam-like correlations
- Conclusions & Outline

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Why correlating interferometers?

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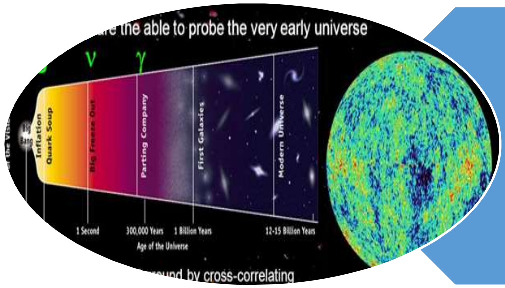
Research of stochastic signal by correlating interferometers



Stochastic Gravitational Wave Background

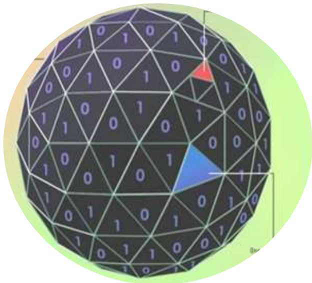
(10^{-36} to 10^{-32} seconds after the Big Bang, whereas the CMB was produced approximately 300,000 years later)

[Search for a Stochastic Background of 100-MHz Gravitational Waves with Laser Interferometers, PRL 101, 101101 (2008)]

[Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGOs First Observing Run. Phys. Rev. Lett., 118:121101, 2017]

Traces of primordial blackholes

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



Fundamental noise at the plank 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)]

[Models of exotic interferometer cross-correlations in emergent space-time. Class. and Quantum Grav., 35(20), 204001 (2018)]

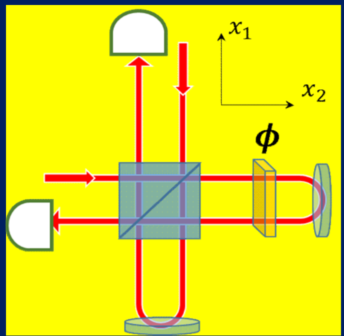
Research of stochastic signal by correlating interferometers

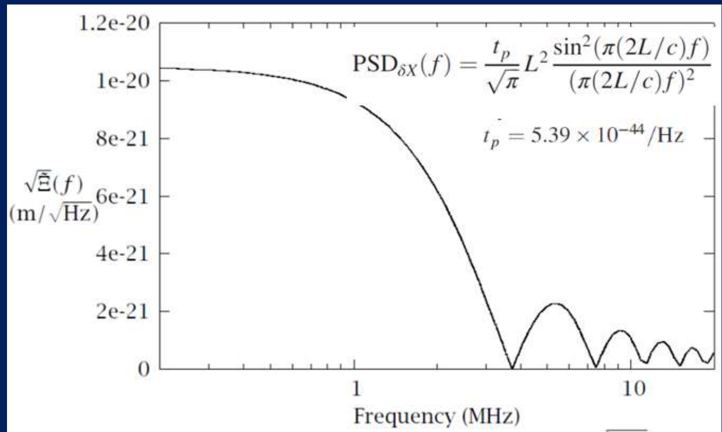
Heuristic QG theories predicts non-commutativity of position/rotational variables at Planck scale

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

Fundamental space-time uncertainty principle
(Holographic Noise)

Likely detectable in Michelson interferometer





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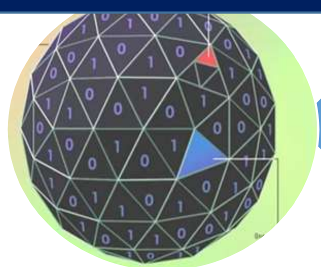
PRD 95, 063002 (2017)]



Fundam... scale in quantum gravity model

[First Measurements of Hig... s-Spectra from a Pair of Large Michelson Interferom... 17, 111102 (2016)]

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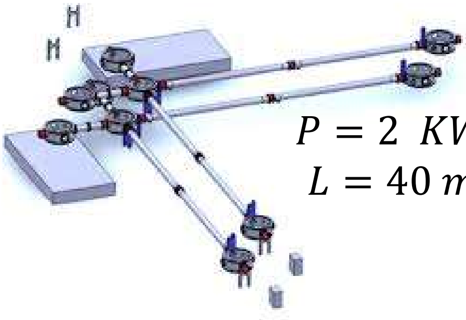
PRL 117, 111102 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

First Measurements of High Frequency Cross-Spectra from a Pair of Large Michelson Interferometers

HOLOMETER

Fermilab



$P = 2\ KW$

$L = 40\ m$

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, if they are in the same space time volume (waiting longer enough..)

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PRL 117, 111102 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

First Measurements of High Frequency Cross-Spectra from a Pair of Large Michelson Interferometers

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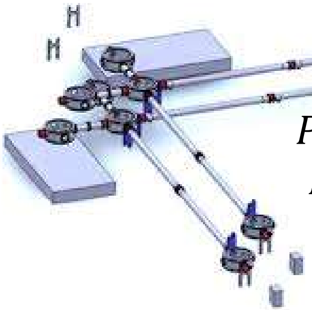

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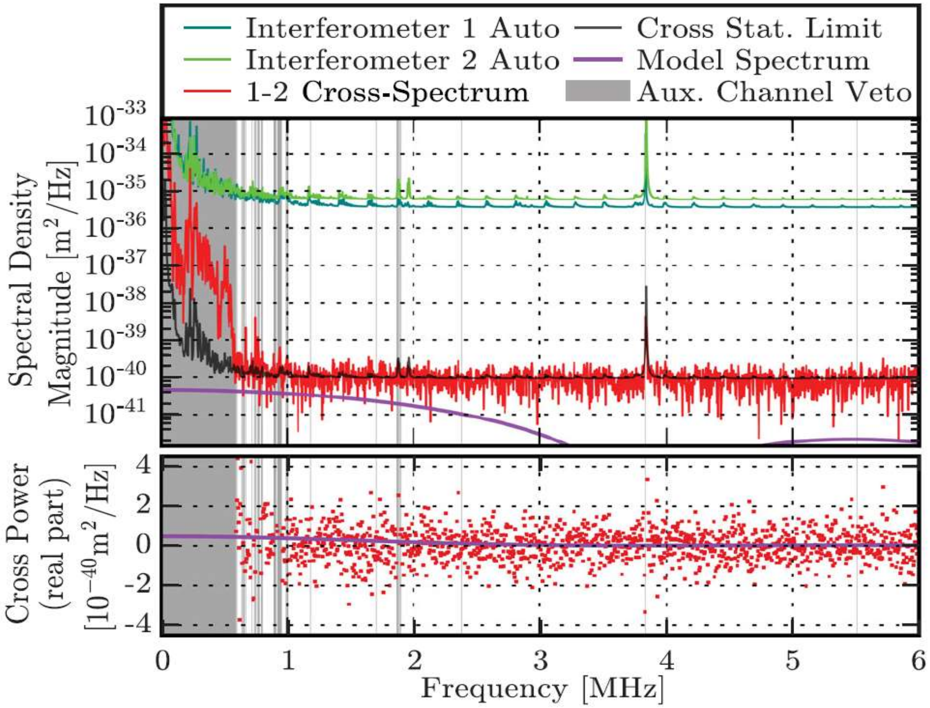
HN lower bounded to $10^{-21} m/\sqrt{Hz}$ in the MHz region of the spectrum after 165 h of acquisition.



PRL **117,** 111102 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

First Measurements of High Frequency Cross-Spectra from a Pair of Large Michelson Interferometers

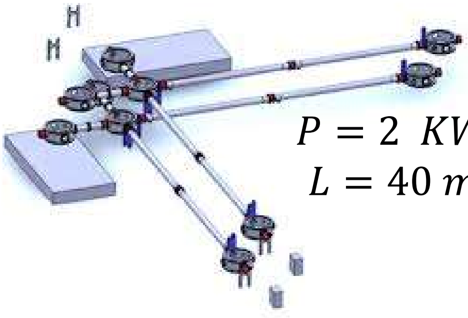
IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. **35** (2018) 204001 (35pp) https://doi.org/10.1088/1361-6382/aadea4

Models of exotic interferometer cross-correlations in emergent space-time

Craig Hogan[1,2] **and Ohkyung Kwon**[2,3,4]

HOLOMETER
Fermilab



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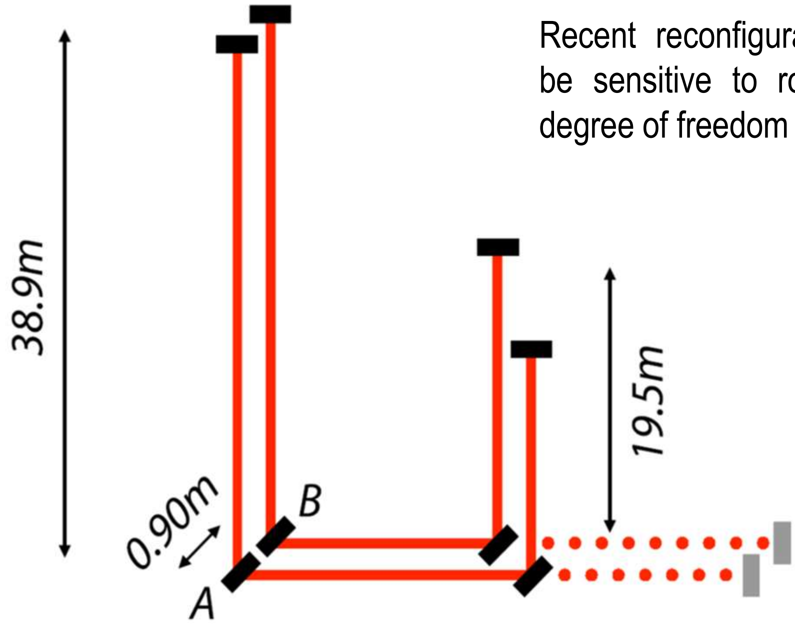


Recent reconfiguration to be sensitive to rotational degree of freedom

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, if they are in the same space time volume (waiting longer enough..)

Quantization of the Electromagnetic Field

Classical → ***Quantum***

Classical

$$\mathbf{E}(\mathbf{r},t) = \sum_{\mathbf{k}} \hat{\epsilon}_{\mathbf{k}} \mathscr{E}_{\mathbf{k}} \alpha_{\mathbf{k}} e^{-i\nu_k t + i\mathbf{k}\cdot\mathbf{r}} + \text{c.c.},$$

$$\mathbf{H}(\mathbf{r},t) = \frac{1}{\mu_0} \sum_{\mathbf{k}} \frac{\mathbf{k} \times \hat{\epsilon}_{\mathbf{k}}}{\nu_k} \mathscr{E}_{\mathbf{k}} \alpha_{\mathbf{k}} e^{-i\nu_k t + i\mathbf{k}\cdot\mathbf{r}} + \text{c.c.}$$

$$\alpha_{\mathbf{k}} \quad \alpha_{\mathbf{k}}^*$$

Unitless Coefficients

Quantum

$$\mathbf{E}(\mathbf{r},t) = \sum_{\mathbf{k}} \hat{\epsilon}_{\mathbf{k}} \mathscr{E}_{\mathbf{k}} a_{\mathbf{k}} e^{-i\nu_k t + i\mathbf{k}\cdot\mathbf{r}} + \text{H.c.},$$

$$\mathbf{H}(\mathbf{r},t) = \frac{1}{\mu_0} \sum_{\mathbf{k}} \frac{\mathbf{k} \times \hat{\epsilon}_{\mathbf{k}}}{\nu_k} \mathscr{E}_{\mathbf{k}} a_{\mathbf{k}} e^{-i\nu_k t + i\mathbf{k}\cdot\mathbf{r}} + \text{H.c.}$$

$$a_{\mathbf{k}} \quad a_{\mathbf{k}}^\dagger$$

Quantum Operators

$$[a_{\mathbf{k}}, a_{\mathbf{k}}^\dagger] = 1$$

Energy of a single mode quantum EM field

$$\mathscr{H}_{\mathbf{k}} = \hbar\nu_k \left(a_{\mathbf{k}}^\dagger a_{\mathbf{k}} + \frac{1}{2} \right)$$

$$\mathscr{H}_{\mathbf{k}} |n_{\mathbf{k}}\rangle = \hbar\nu_k \left(n_{\mathbf{k}} + \frac{1}{2} \right) |n_{\mathbf{k}}\rangle$$

$$|n\rangle = \frac{(a^\dagger)^n}{\sqrt{n!}} |0\rangle$$

Quadrature Operators

$$X_1 = \frac{1}{2}(a + a^\dagger)$$ **"Amplitude" or "Position"**

$$X_2 = \frac{1}{2i}(a - a^\dagger)$$ **"Phase" or "Momentum"**

$$[X_1, X_2] = \frac{i}{2} \quad \longrightarrow \quad \Delta X_1 \Delta X_2 \geq \frac{1}{4}$$

Heisenberg's Unc. Relation

Coherent States

Coherent State: eigenstate of the annihilation operator

$$a|\alpha\rangle = \alpha|\alpha\rangle$$

Displacement operator: $D(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$

$$|\alpha\rangle = D(\alpha)|0\rangle \qquad D^{-1}(\alpha) a D(\alpha) = a + \alpha$$

Mean photon number: $\langle\alpha|a^\dagger a|\alpha\rangle = |\alpha|^2$

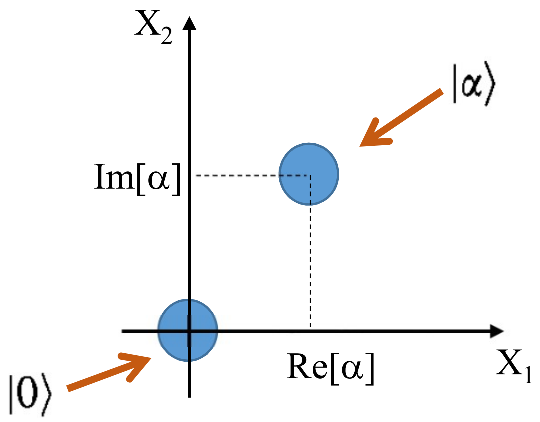
Photon number statistics: $p(n) = \langle n|\alpha\rangle\langle\alpha|n\rangle = \frac{\langle n\rangle^n e^{-\langle n\rangle}}{n!}$ $\qquad \langle n\rangle = |\alpha|^2$

Quadrature operators

$$(\Delta X_1)^2 = \langle\alpha|X_1^2|\alpha\rangle - (\langle\alpha|X_1|\alpha\rangle)^2 = \frac{1}{4}$$

$$(\Delta X_2)^2 = \frac{1}{4}$$

$$\Delta X_1 \Delta X_2 = \frac{1}{4}$$



$$X_1 = \frac{1}{2}(a + a^\dagger)$$

$$X_2 = \frac{1}{2i}(a - a^\dagger)$$

Squeezed States

Hamiltonian of a degenerate parametric process: $\mathcal{H} = i\hbar\left(g a^{\dagger 2} - g^* a^2\right)$

(Unitary) "Squeeze" Operator : $S(\xi) = \exp\left(\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}\right)$ $\quad \xi = r\exp(i\theta)$

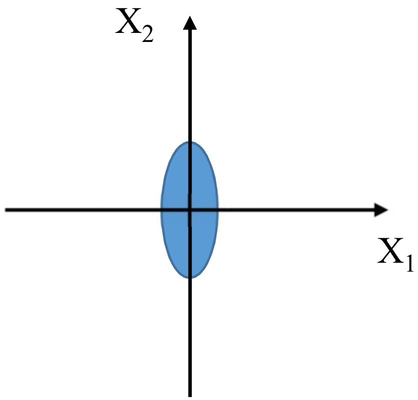
$$\begin{cases} S^\dagger(\xi) a S(\xi) = a\cosh r - a^\dagger e^{i\theta}\sinh r \\ S^\dagger(\xi) a^\dagger S(\xi) = a^\dagger \cosh r - a e^{-i\theta}\sinh r \end{cases}$$

Squeezed Vacuum: $|\xi\rangle = S(\xi)|0\rangle$

$$(\Delta X_1)^2 = \frac{1}{4}e^{-2r}$$

$$(\Delta X_2)^2 = \frac{1}{4}e^{2r}$$

$$\boxed{\Delta X_1 \Delta X_2 = \frac{1}{4}}$$



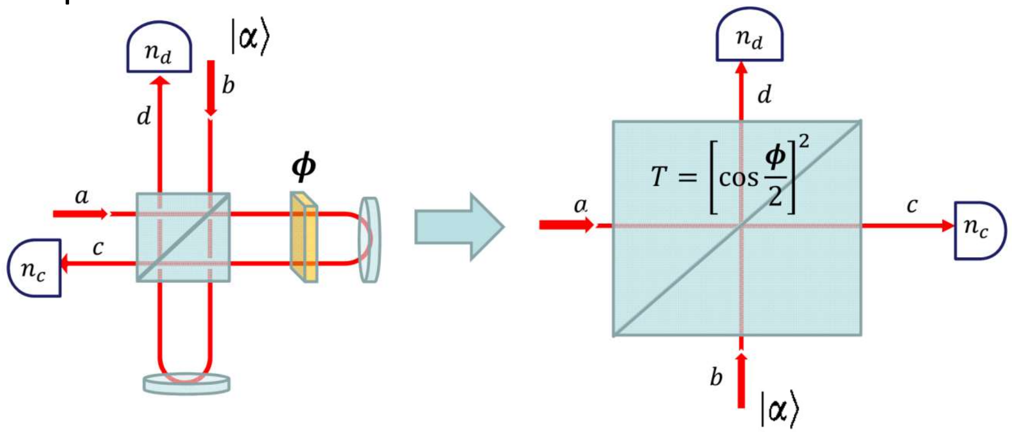
$X_1 = \frac{1}{2}(a + a^\dagger)$

$X_2 = \frac{1}{2i}(a - a^\dagger)$

Squeezed Vacuum can be obtained with an OPO operating under threshold

Phase measurement in an interferometer

The input-output relations of the mode operators of an interferometer are the same of a BS with T (given by the the phase $\boldsymbol{\phi_p}$)



- $|0\rangle$ **in** a**-port,** $|\alpha\rangle$ **in** b**-port**

$$\langle n_{cd}\rangle = |\alpha|^2 \cos\phi_p$$

$$(\Delta n_{cd})^2 = |\alpha|^2$$

$$\Delta\phi = \frac{\Delta n_{cd}}{|\partial\langle n_{cd}\rangle/\partial\phi_p|} = \frac{1}{\sqrt{\langle n\rangle}}$$

Shot-Noise Limit

$$\langle n\rangle = |\alpha|^2$$

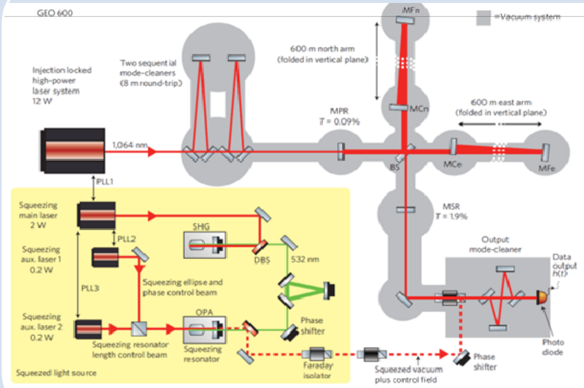
- $|\xi\rangle$ **in** a**-port,** $|\alpha\rangle$ **in** b**-port** ($\theta = 2\phi_l$)

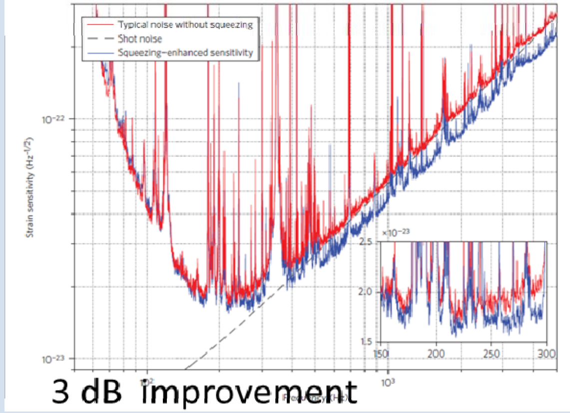
$$\langle n_{cd}\rangle = (\langle n\rangle + \sinh^2 r)\cos\phi_p \cong \langle n\rangle\cos\phi_p$$

$$(\Delta n_{cd})^2 = \langle n\rangle e^{-2r} + \sinh^2 r$$

Below the Shot-Noise Limit

$$\Delta\phi = \frac{\Delta n_{cd}}{|\partial\langle n_{cd}\rangle/\partial\phi_p|} = \frac{e^{-r}}{\sqrt{\langle n\rangle}}$$





Squeezed light in gravitational wave detectors

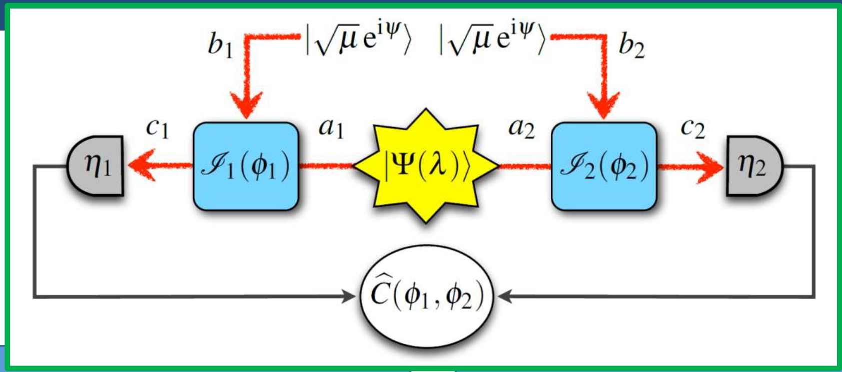
A sub-shot noise PS measurement in a **single** interferometer (e.g. gravitational wave detector) was suggested exploiting squeezed light

[Caves, PRD **23**, 1693 (1981), Kimble et al., PRD **65**, 022002 (2001)]

...

and recently realized at Geo 600 and LIGO

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



Two independent squeezed states

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

Quadrature squeezing

$$\Delta^2 X = \frac{e^{-2}}{2} \rightarrow \langle \Delta^2 \phi \rangle_{SQ} = \langle \Delta^2 \phi \rangle_{SNL} \left(e^{-2r} + \frac{1-\eta}{\eta} \right)$$

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

Photon noise reduction in each interferometer helps in the detection of correlated signals

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

Two mode squeezing (Twin Beam)

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

- **Quadrature correlations:**

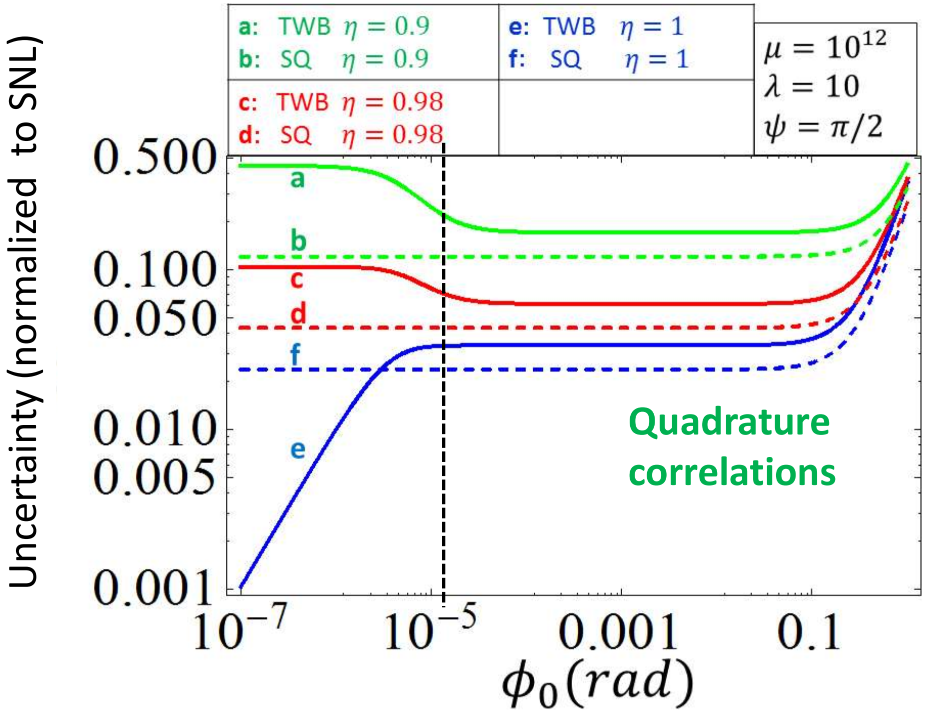
$$\Delta^2(X_1 - X_2) = \frac{e^{-2r}}{2} \qquad \Delta^2(Y_1 + Y_2) = \frac{e^{-2r}}{2}$$

- **Photon number ENTANGLEMENT**

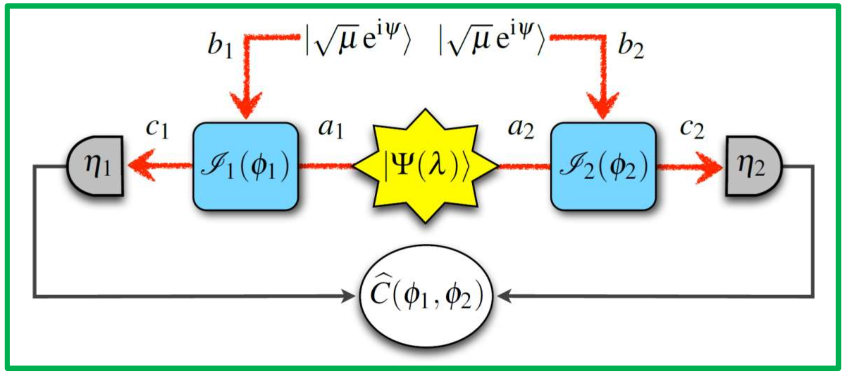
$${}_{a_1,a_2}\langle \Psi(\lambda)|(m_1 - m_2)^M|\Psi(\lambda)\rangle_{a_1,a_2} = 0$$

$$\Delta^2(N_1 - N_2) = 0$$

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



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



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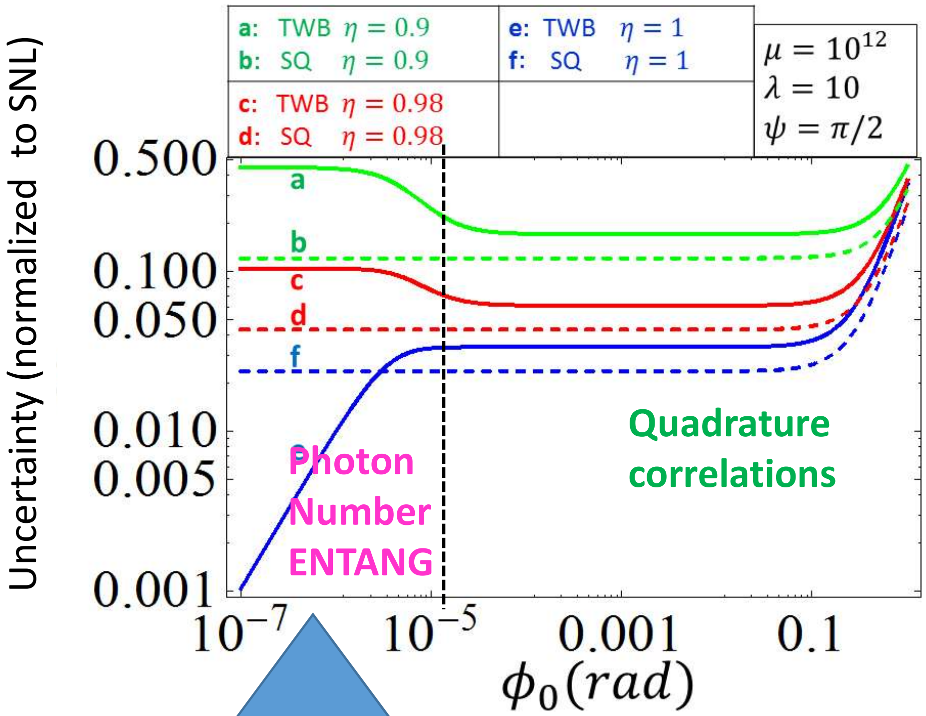

TWB is transmitted at the read-out ports while coherent is completely reflected

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

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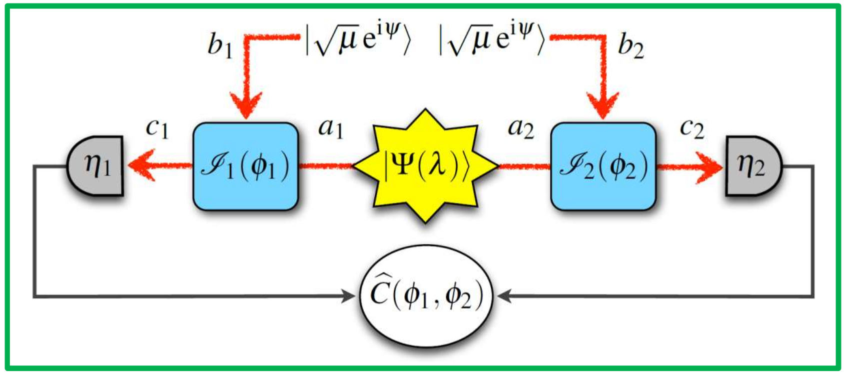

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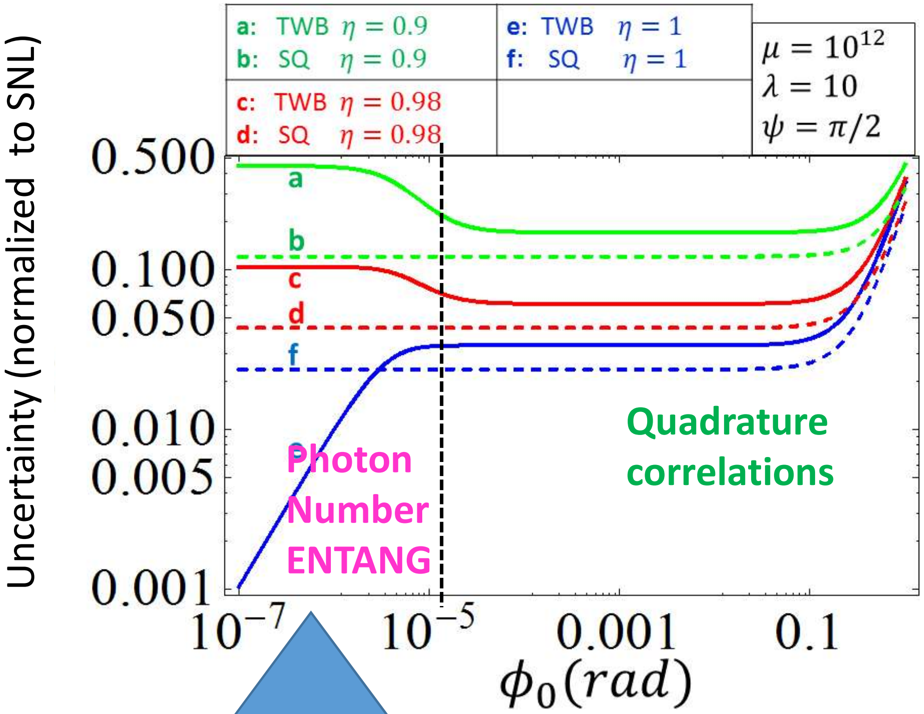

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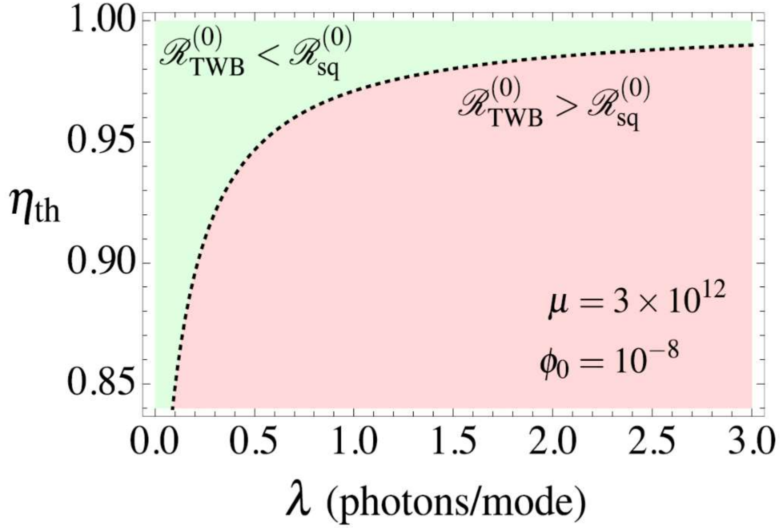
Green region is for TWB advantage with respect to double squeezing

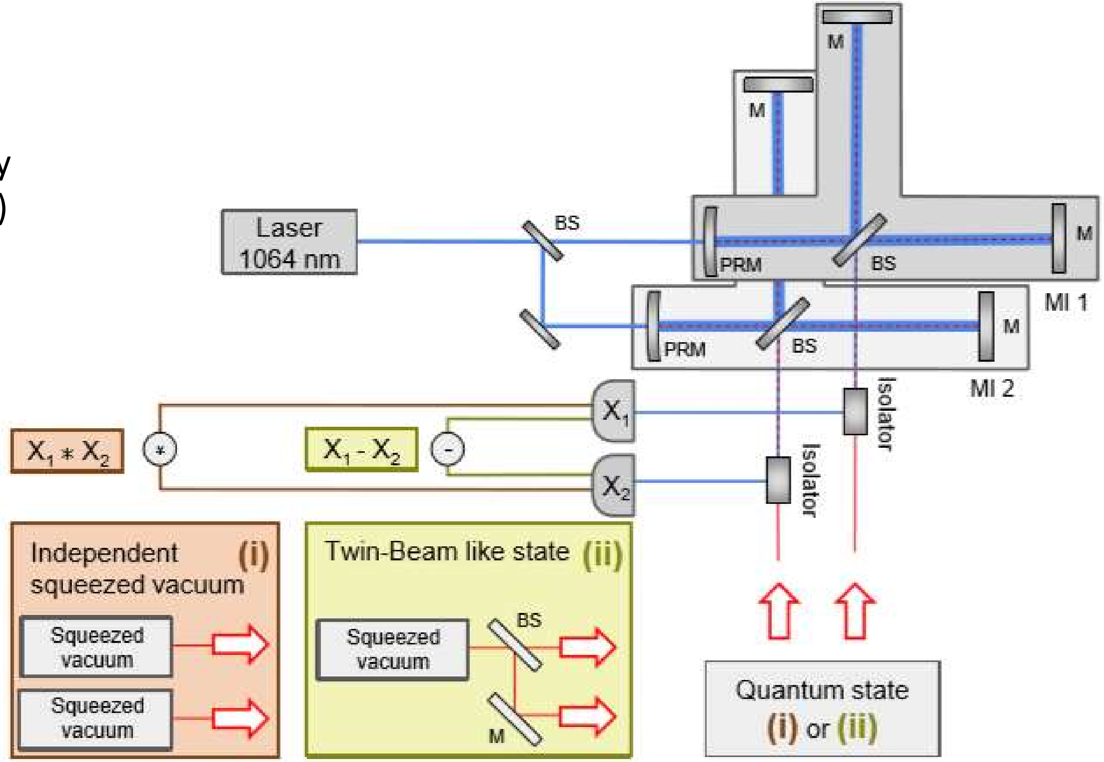


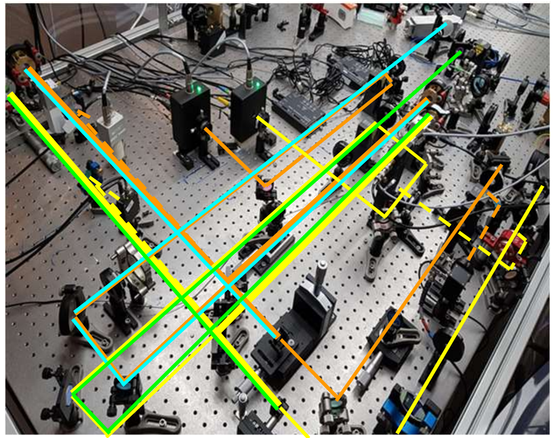
PRL **110**, 213601 (2013), PRA **92**, 053821 (2015)

EXPERIMENT

Quantum Holometer setup (simplified scheme)

- Read-out AS port operated close to the dark fringe (LIGO, HOLOMETER)
- 2-D Power recycling cavity 90% reflectivity (gain =10)





Quantum Holometer setup (simplified scheme)

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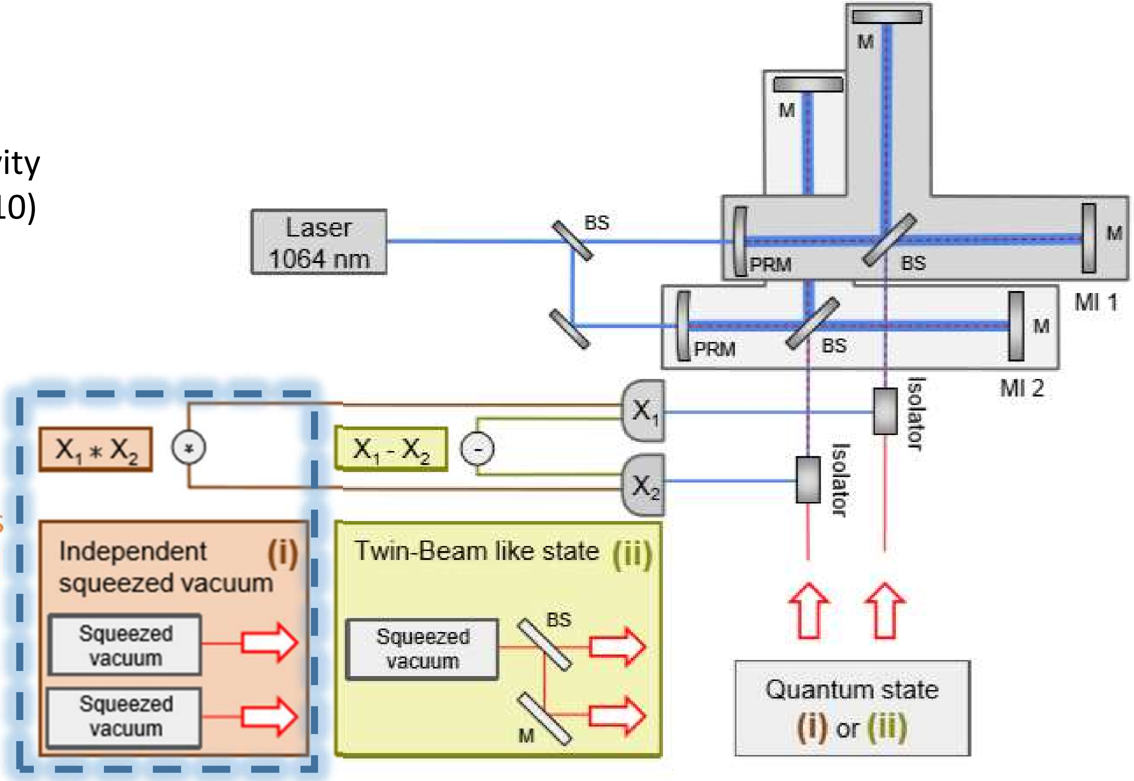
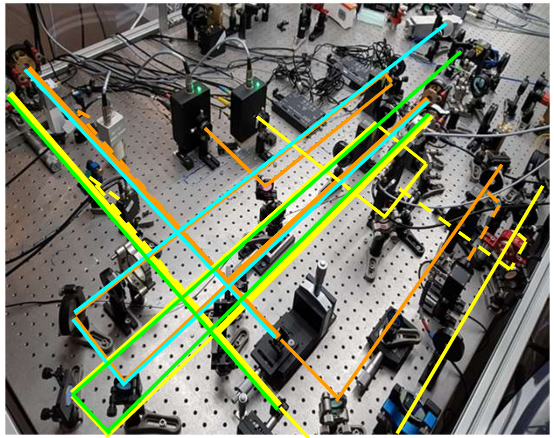
Alternatively:

- Two independent squeezing are injected
- Cross spectrum or cross correlation is measured





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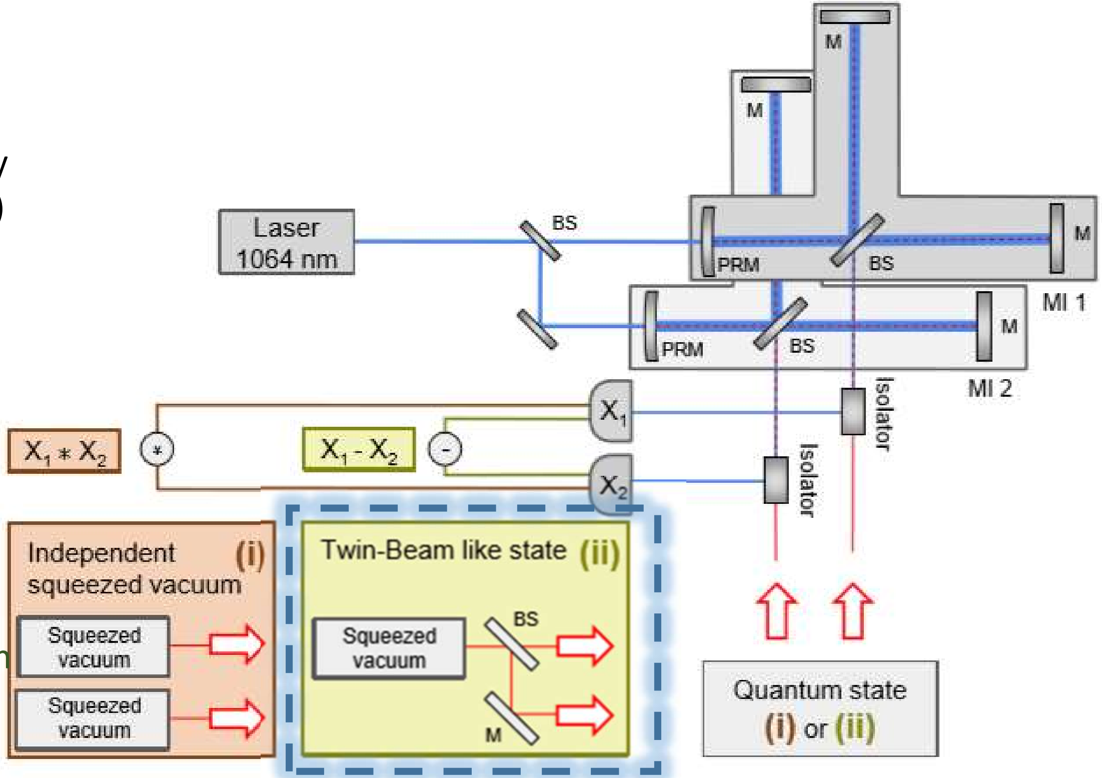
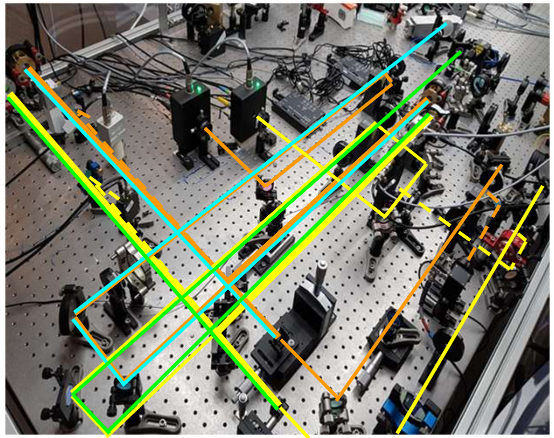
- 2-D Power recycling cavity 90% reflectivity (gain =10)

Alternatively:

- Two independent squeezing are injected
- Cross spectrum or cross correlation is measured
- Twin beam like correlation are injected
- The output difference is measured

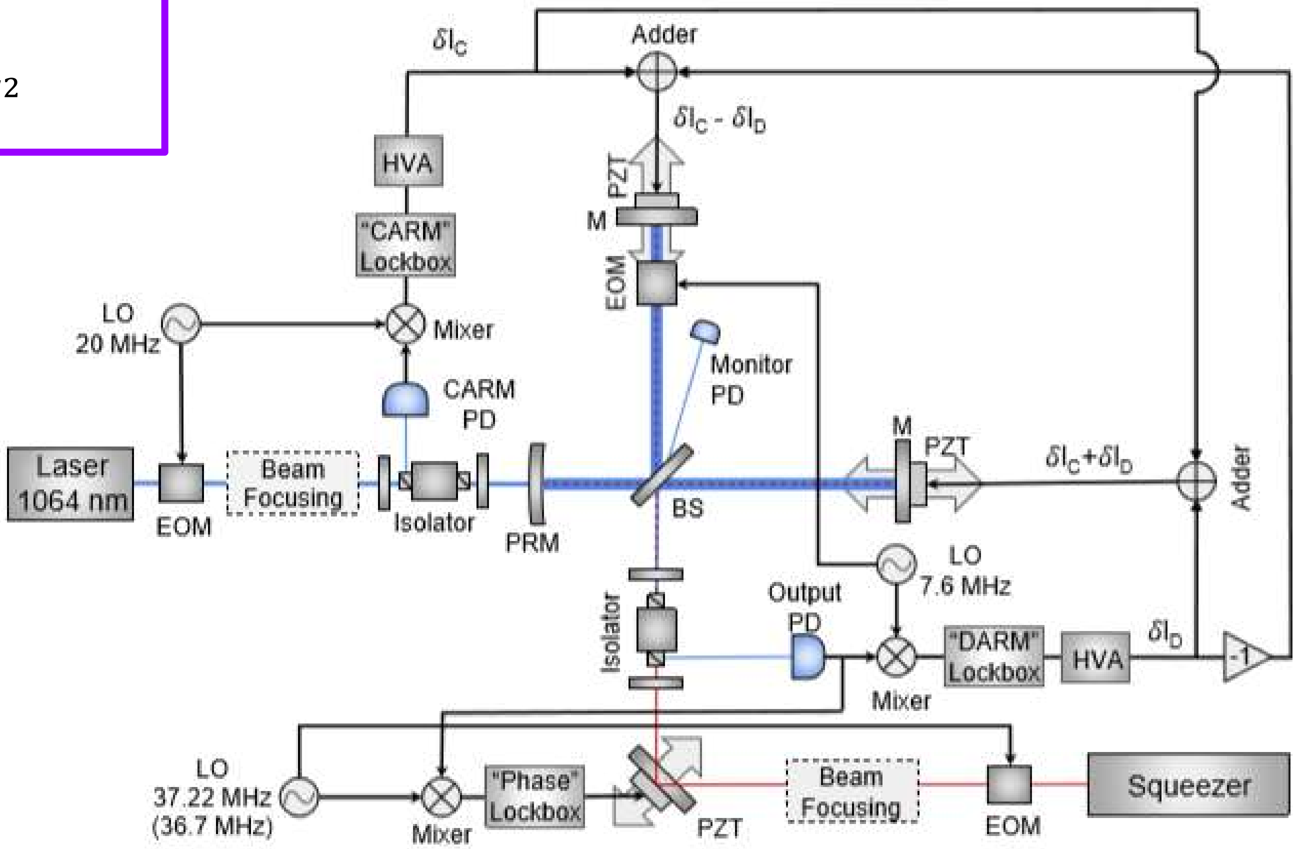




Quantum Holometer setup (Single interferometer)

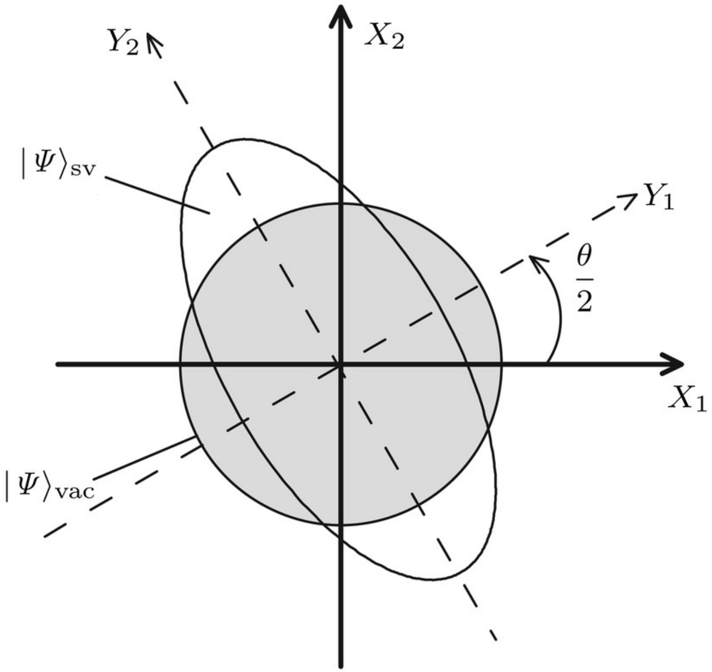
CARM ⇨ $\frac{L_1 + L_2}{2}$

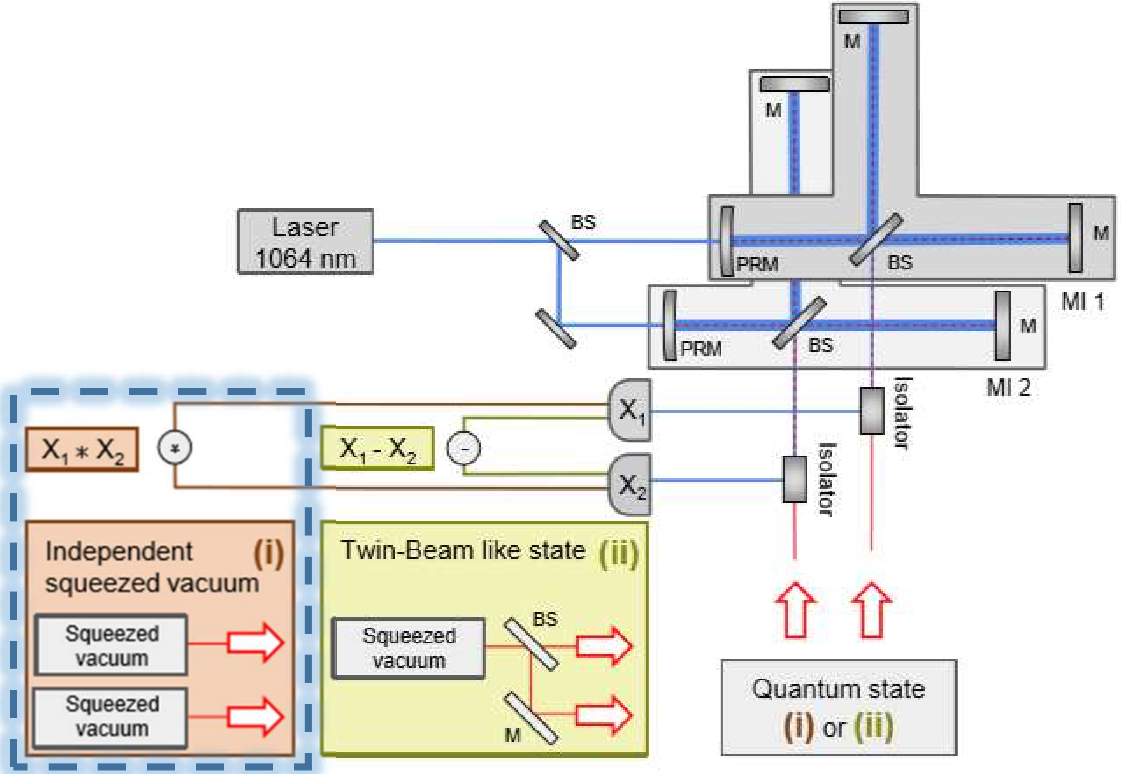
DARM ⇨ $L_1 - L_2$



RESULTS (I):
Independent squeezed states

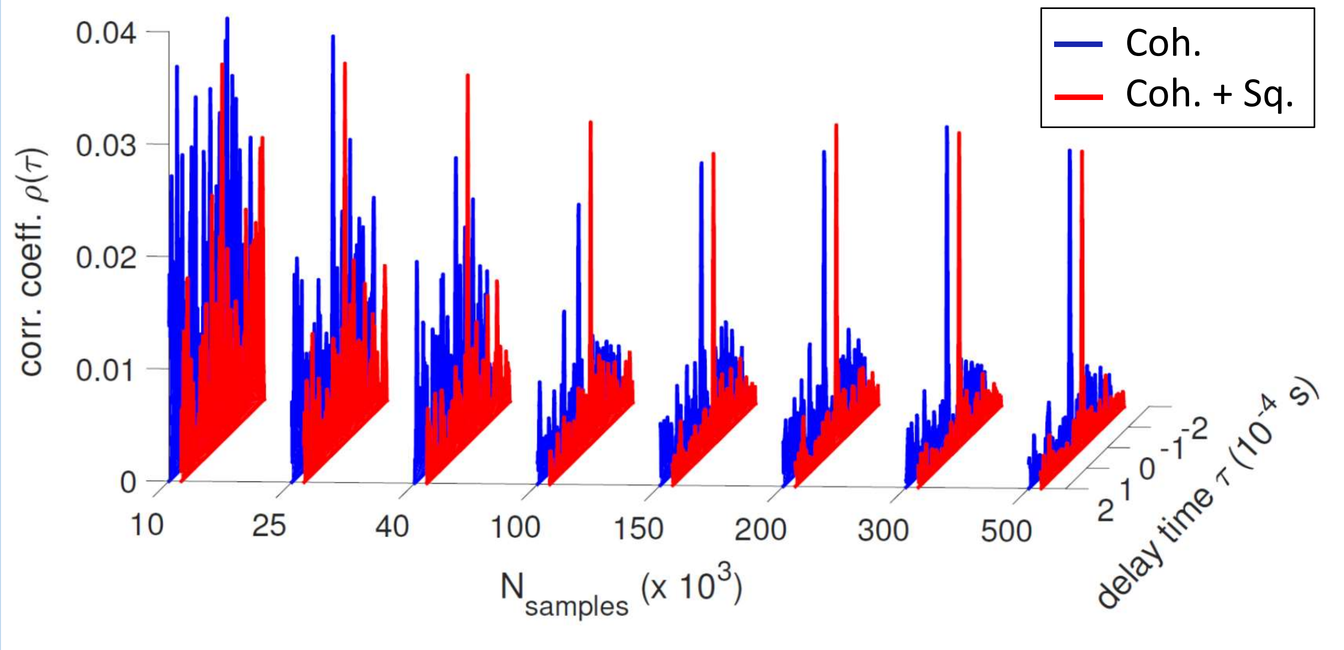
INDEPENDENT SQUEEZED STATES





Temporal Cross-correlation of the interferometers (SQxSQ)

$$\rho(\tau) = \frac{|\mathrm{Cov}(I_1(t) I_2(t+\tau))|}{\sqrt{\mathrm{Var}(I_1(t))\mathrm{Var}(I_2(t))}}$$



- 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 (number of samples)
- Noise floor halved by SQ injection

arXiv:1810.13386v2 [quant-ph]

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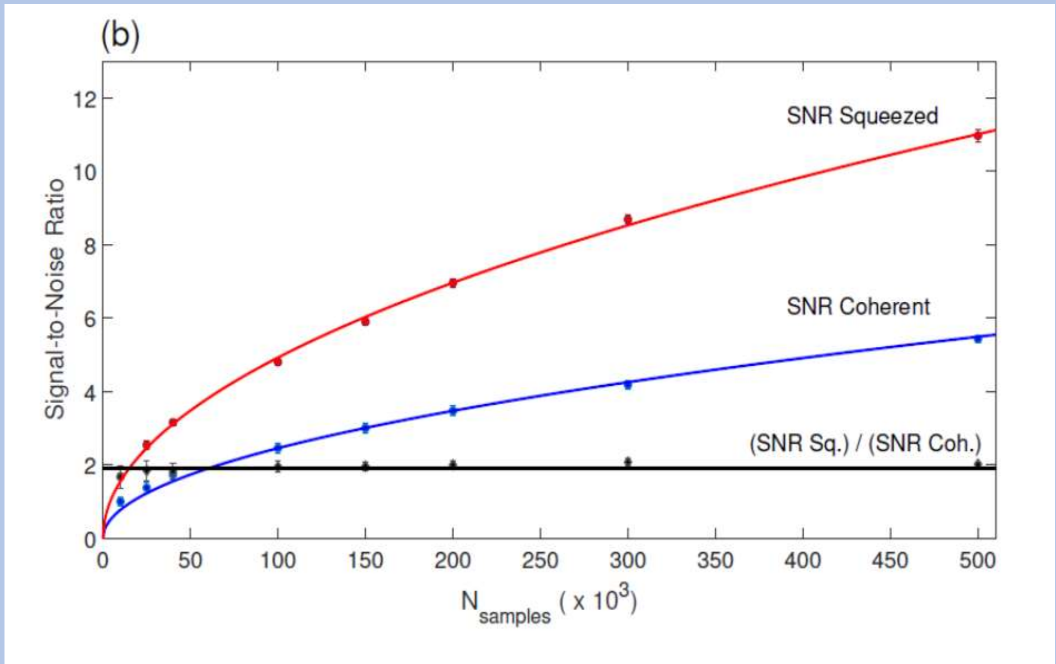
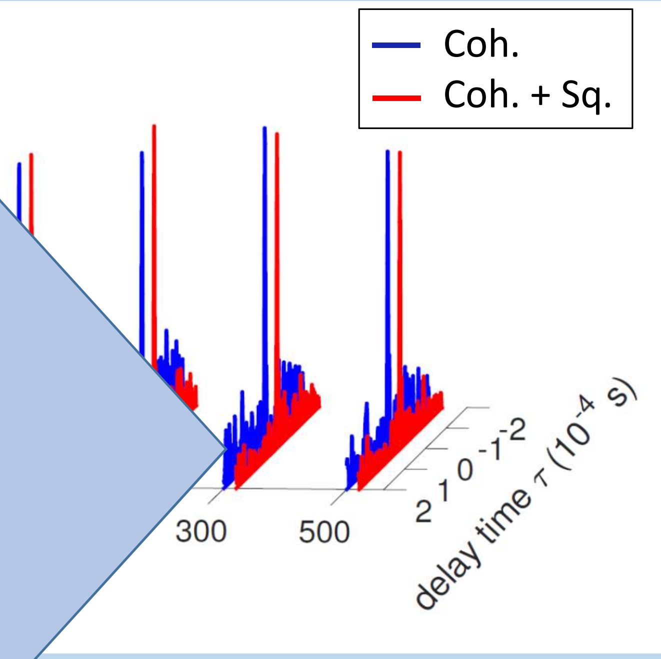
Temporal Cross-correlation of the interferometers (SQxSQ)



- SNR improves with the usual statistical scaling $\sqrt{N_{sample}}$
- SNR is twice when squeezing is injected



…ed (about 1/5 of the shot noise level)

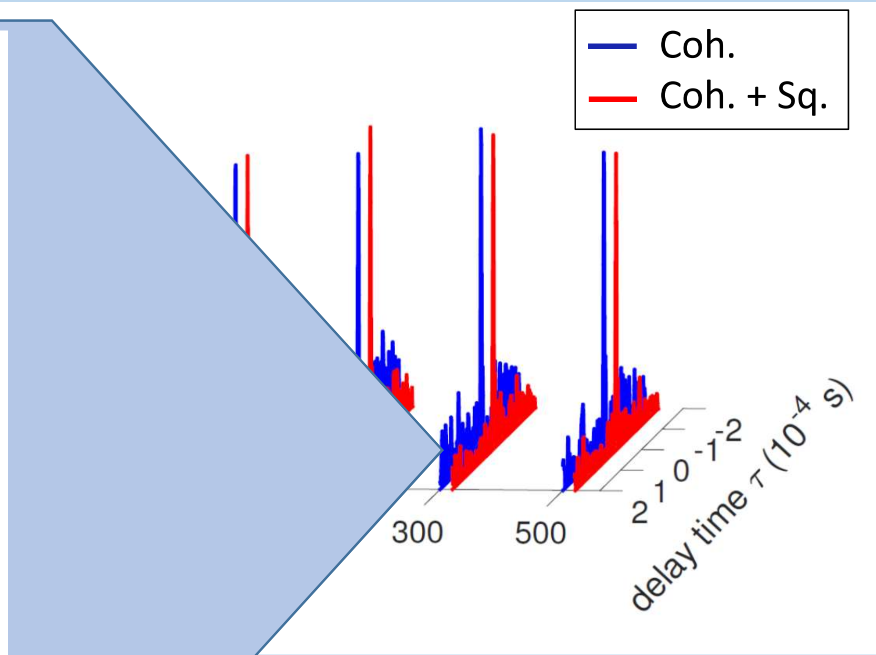
…queezing in each interferometer

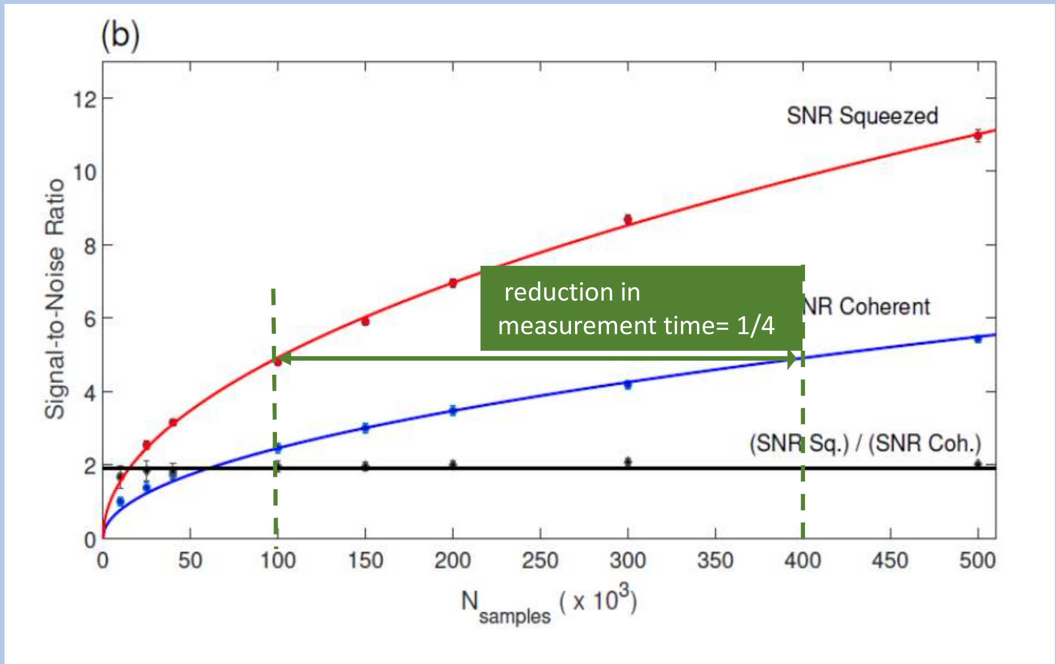
…merges at the increasing of the measurement time (number of samples)

- Noise floor halved by SQ injection

arXiv:1810.13386v2 [quant-ph]

Temporal Cross-correlation of the interferometers (SQxSQ)





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

- ...ed (about 1/5 of the shot noise level)
- ...queezing in each interferometer
- ...merges at the increasing of the measurement time (number of samples)
- Noise floor halved by SQ injection

arXiv:1810.13386v2 [quant-ph]

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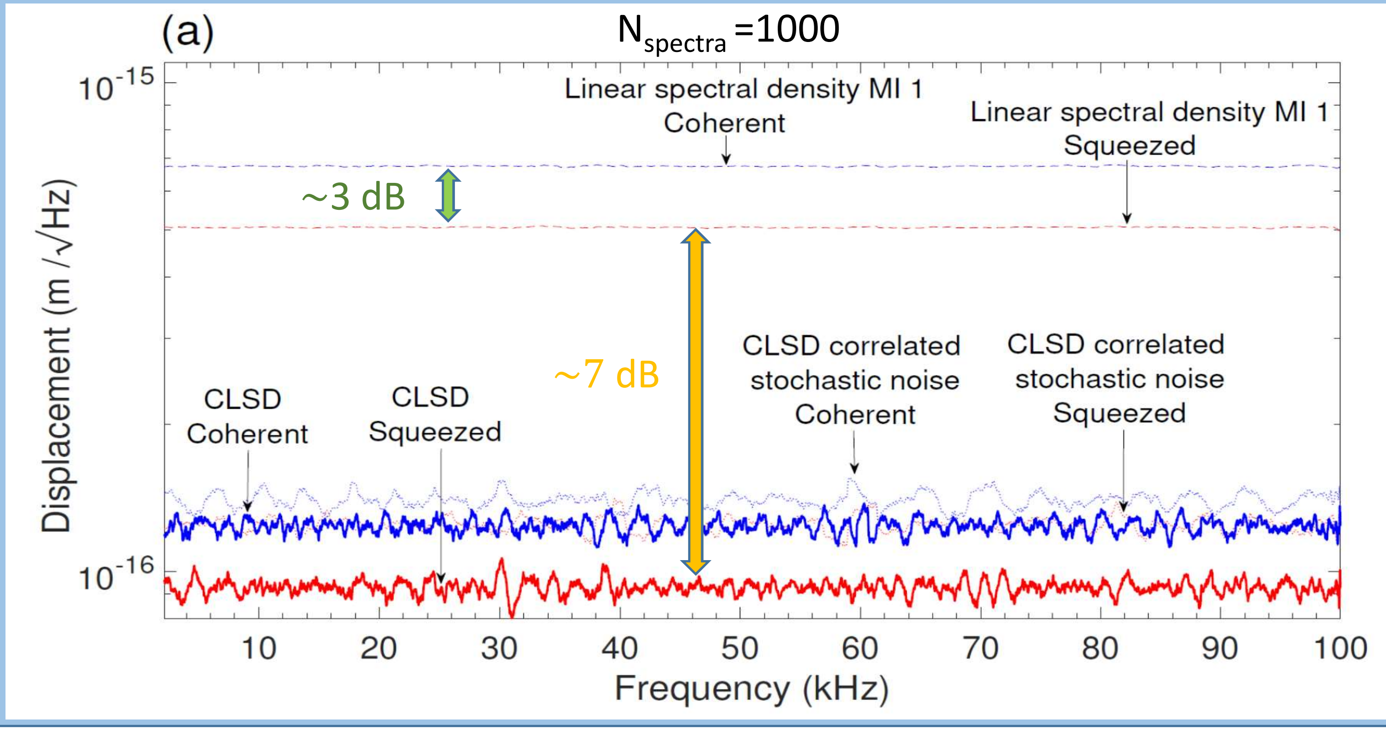
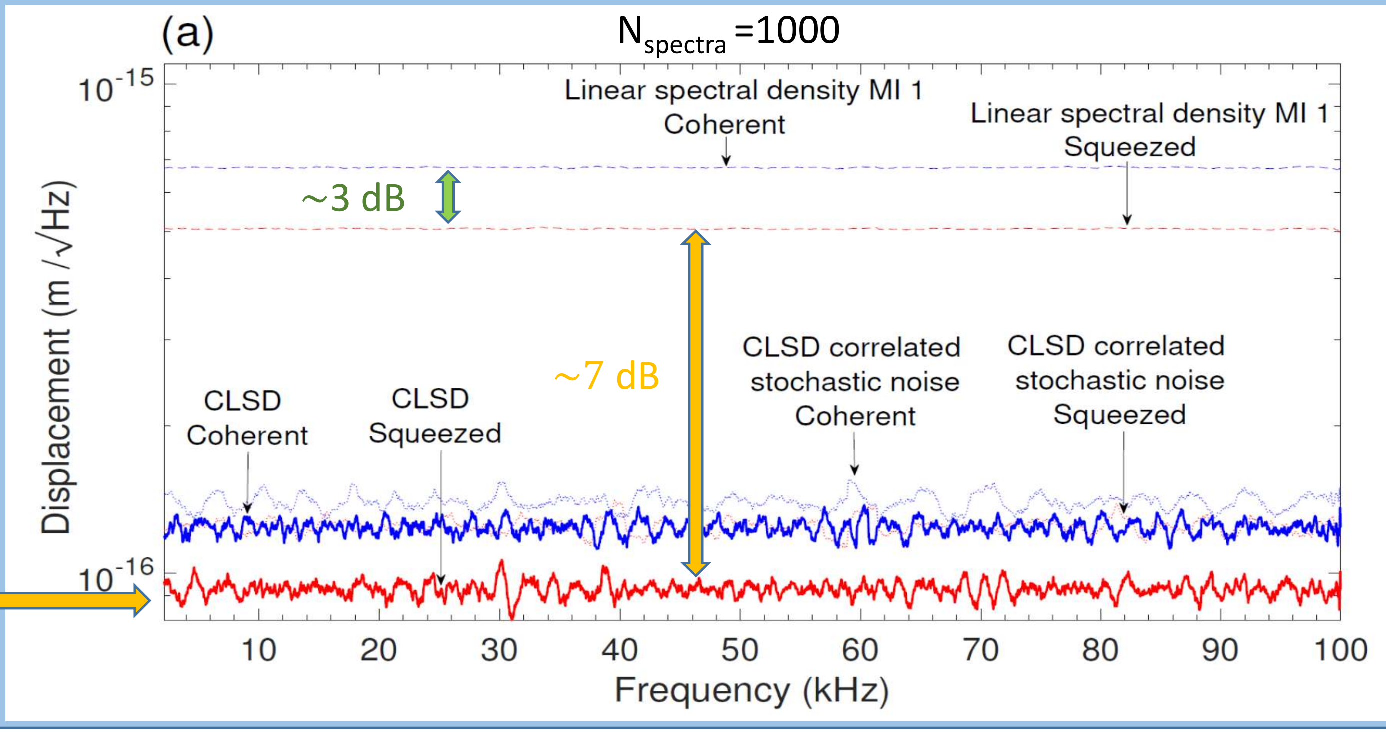
Cross- Linear Spectral Density (SQxSQ)



- The C-LSDs are evaluated in a BW=100KHz down-mixed at 13.5 MHz

arXiv:1810.13386v2 [quant-ph]

Cross- Linear Spectral Density (SQxSQ)

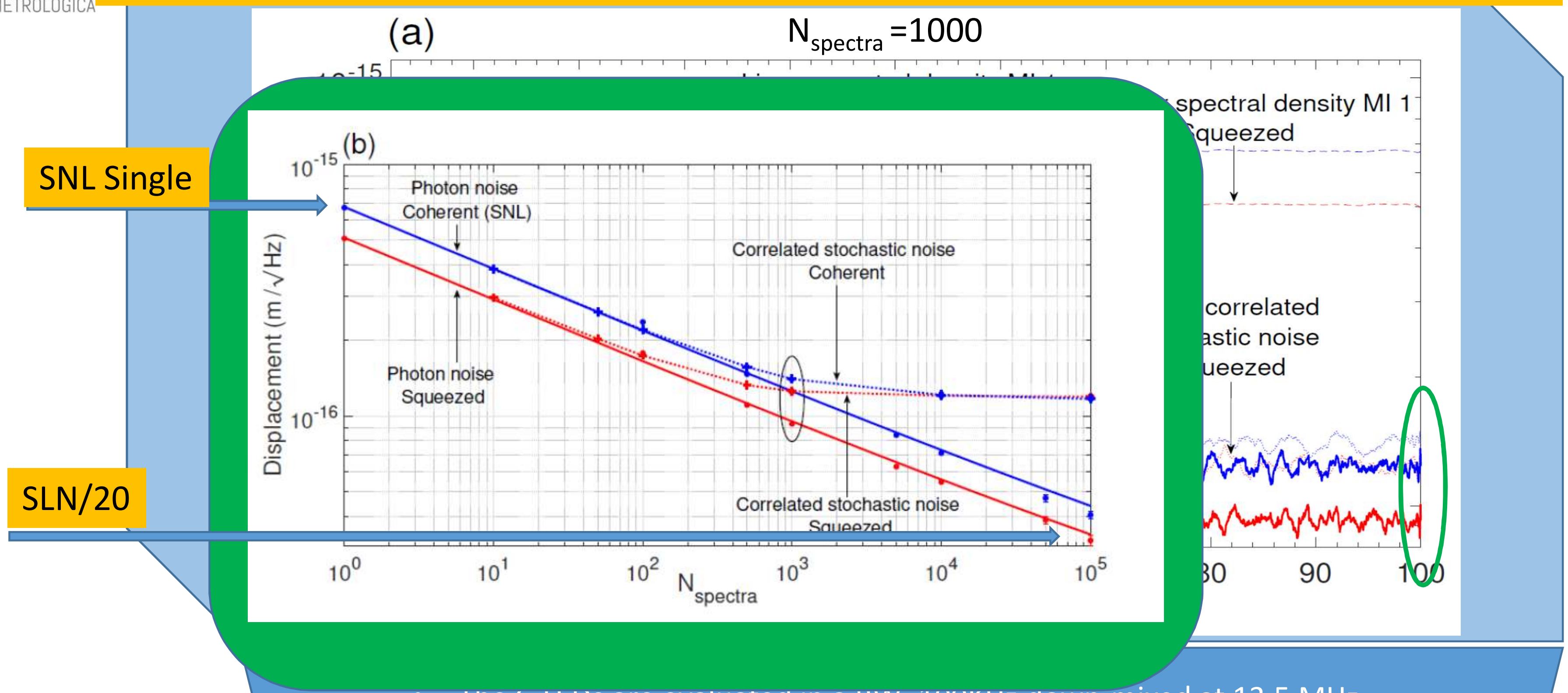


Sensitivity to correlated signals

- The C-LSDs are evaluated in a BW=100KHz down-mixed at 13.5 MHz
- A correlated noise is injected (amplitude around 1/5 of the photon shot noise of each interf.)

arXiv:1810.13386v2 [quant-ph]

Cross- Linear Spectral Density (SQxSQ)



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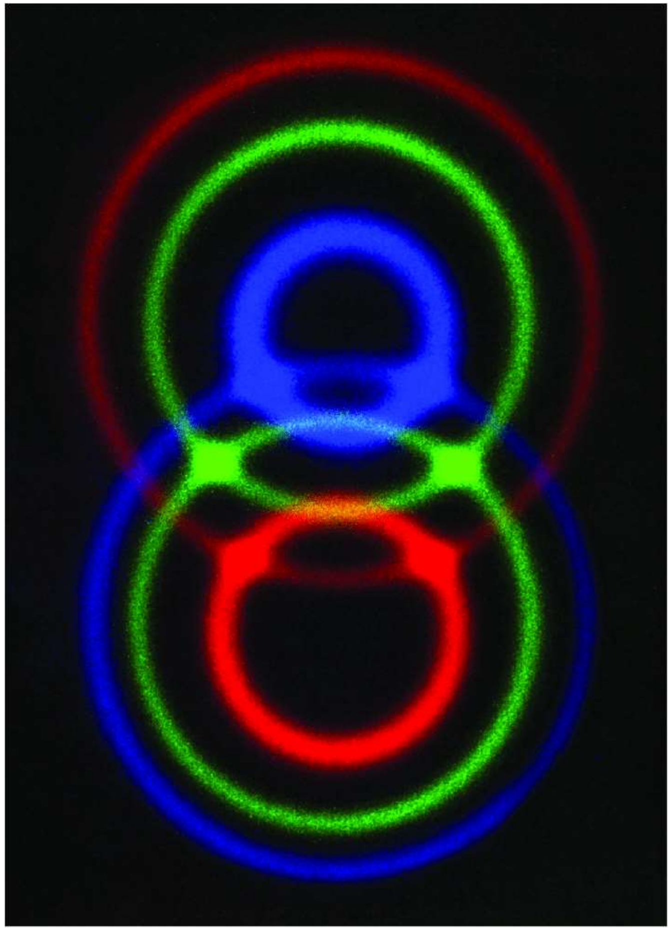
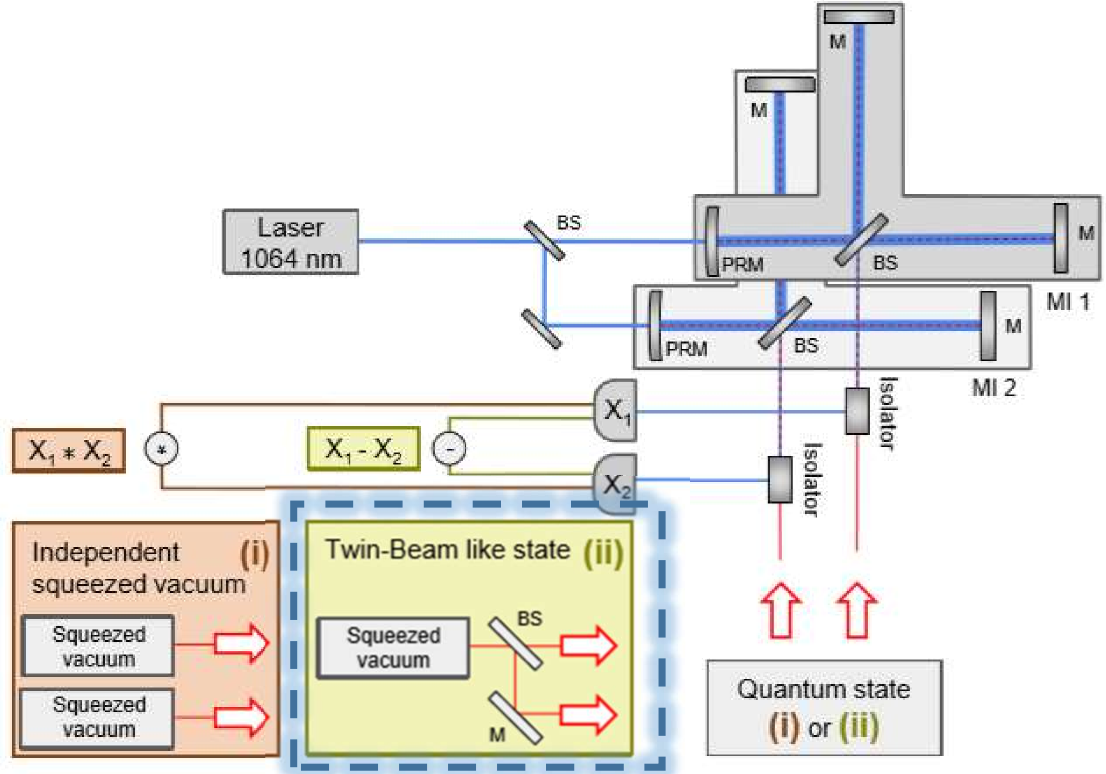
arXiv:1810.13386v2 [quant-ph]

RESULTS (II):
Twin beam – like correlations

TWIN-BEAM-LIKE STATE



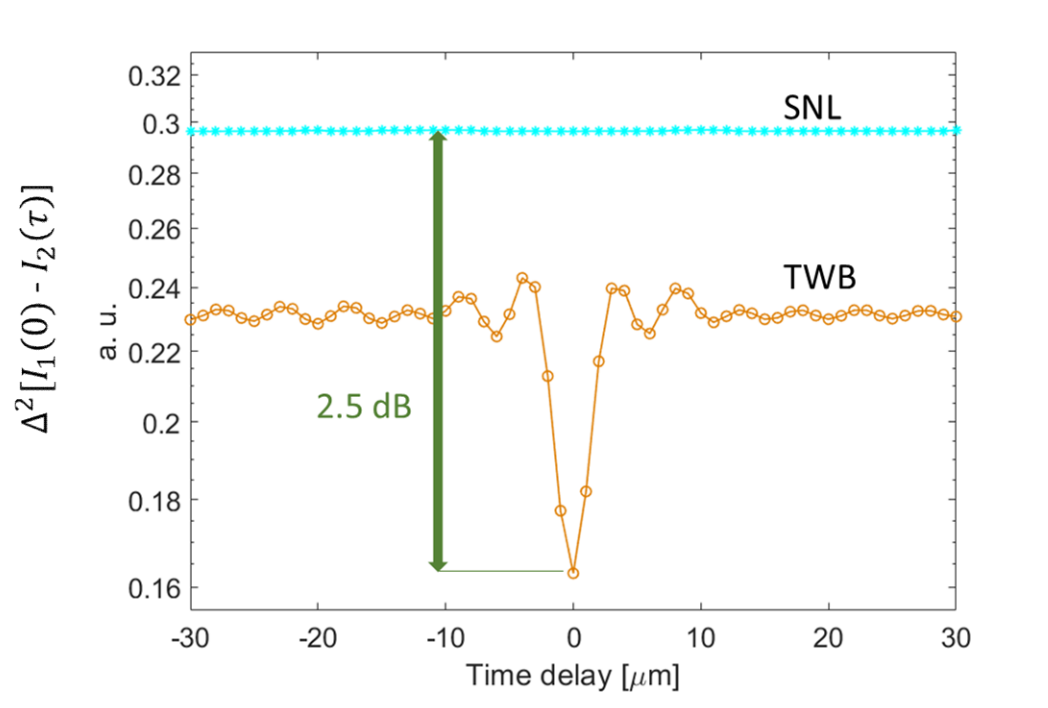


Variance of the photocurrent difference in function of the delay time (τ) (TWB)

- Quadrature correlation leads to noise reduction in the difference of the photon currents (NRF<1)

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

- 2.5 dB of squeezing measured
- Correlated noise is cancelled
- Uncorrelated noise is detectable below the SNL



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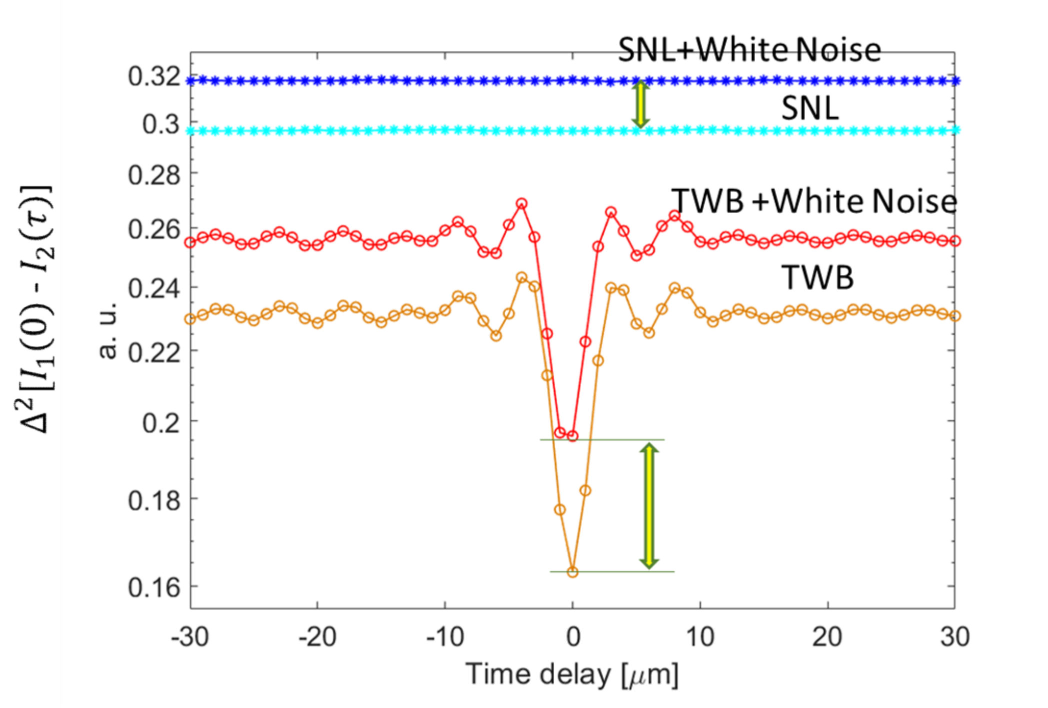
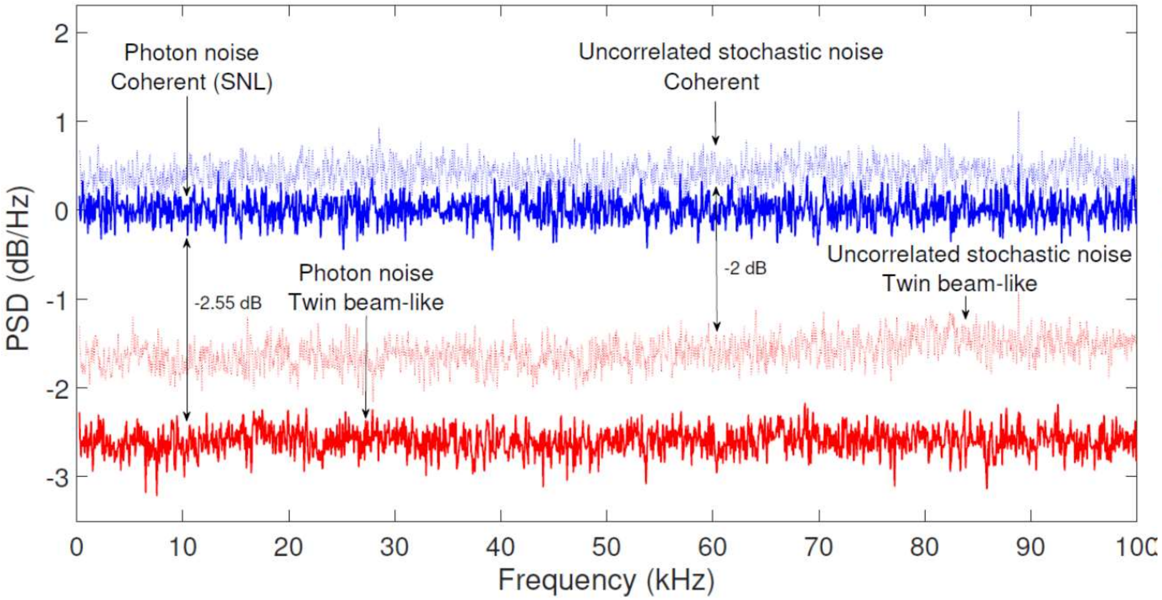


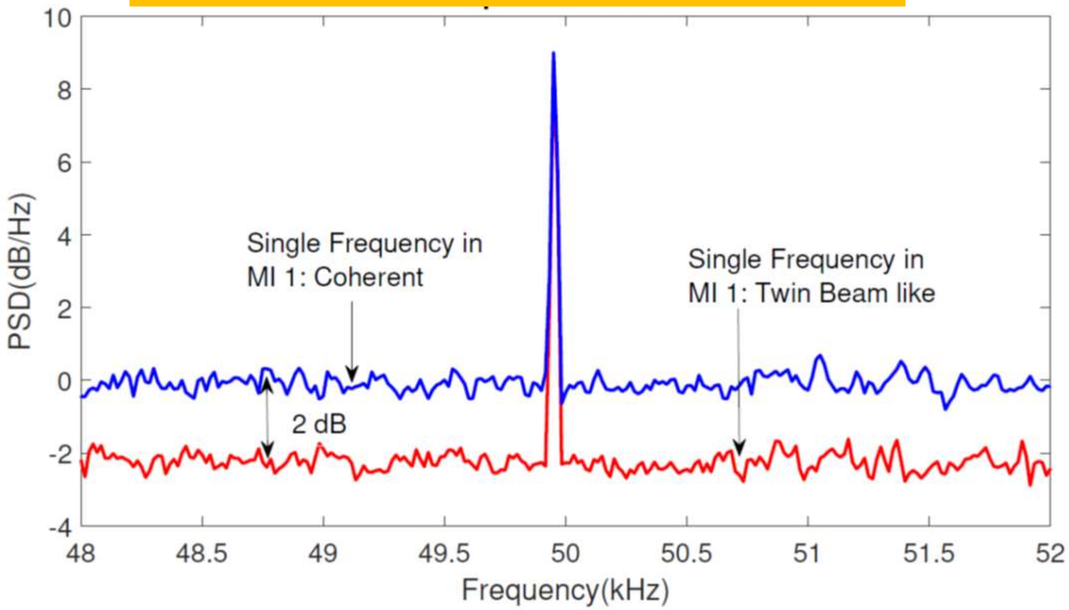
arXiv:1810.13386v2 [quant-ph]

…same information in the spectral domain

Uncorrelated White noise injected in both interf.s



Single frequency noise injected in a one interf.



arXiv:1810.13386v2 [quant-ph]

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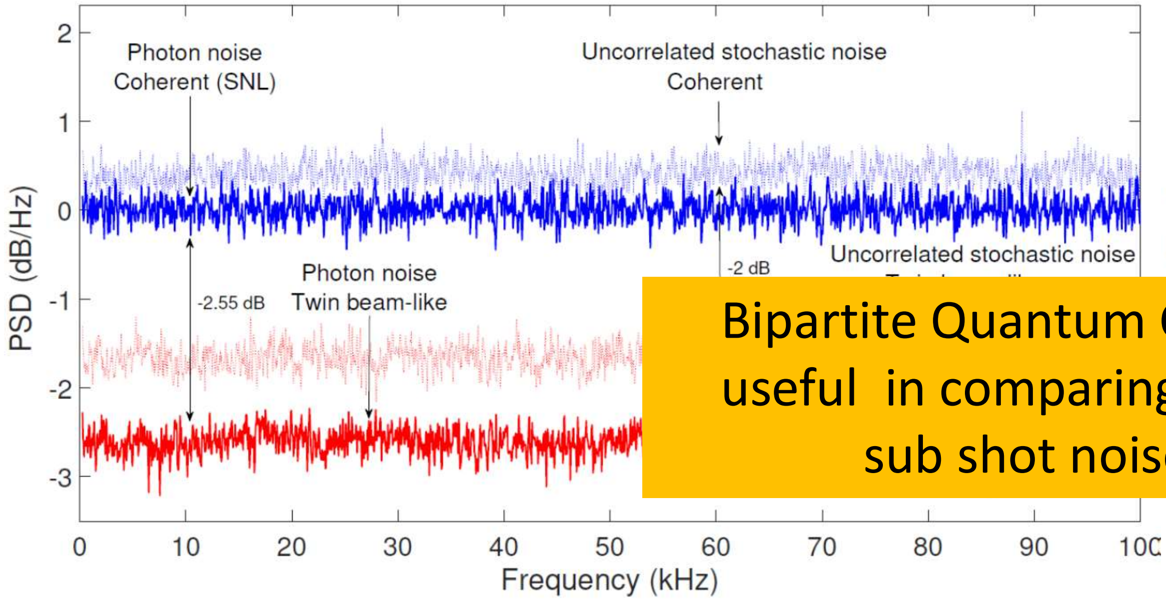

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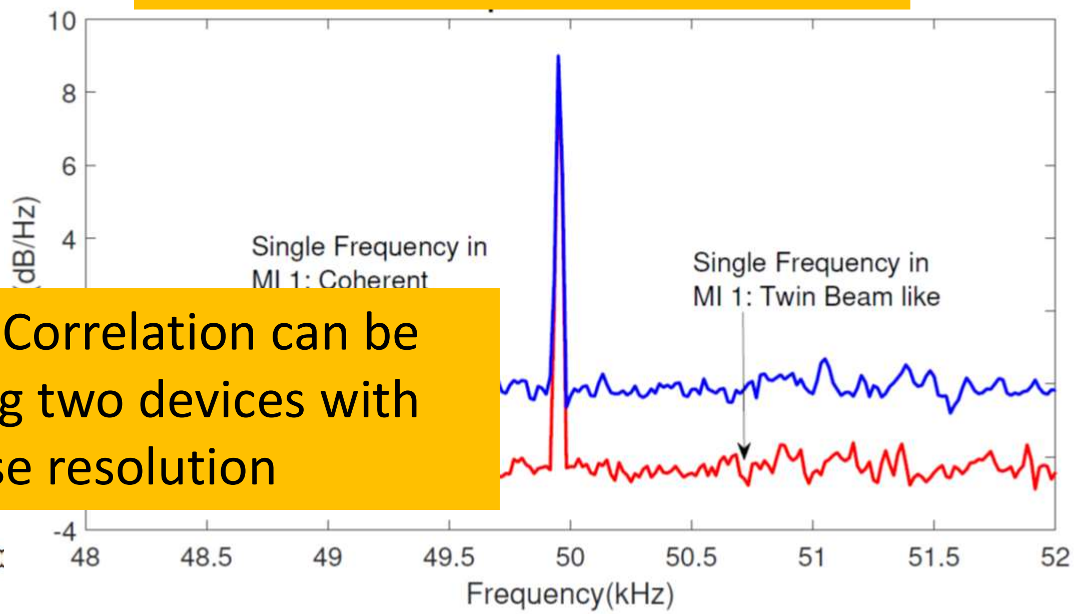
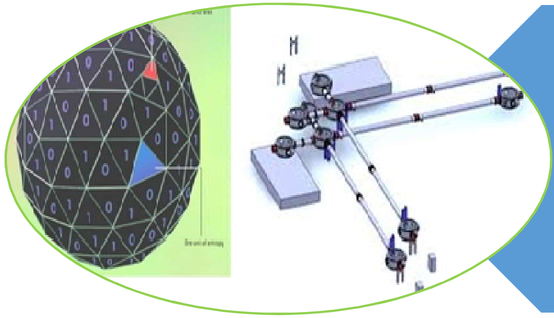


Bipartite Quantum Correlation can be useful in comparing two devices with sub shot noise resolution

arXiv:1810.13386v2 [quant-ph]

Conclusions
&
Outlook

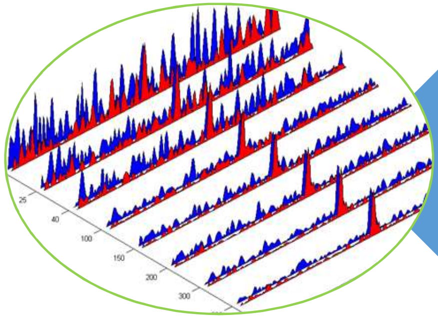
Conclusion



Detecting faint stochastic noises is important in fundamental physics quests

(gravitational wave background, Planck scale effects..)

Correlation techniques boost the sensitivity of the single device of orders of magnitude

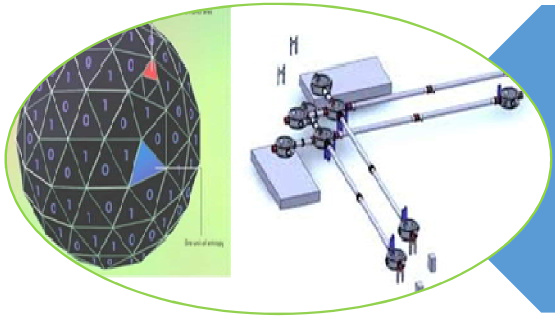


Squeezed light and TWB provide enhancement in comparing signals in two interferometers (TWB could reach in principle disruptive advantage, but challenging in practice)

We have reported a table top experiment mimicking the design of large scale devices demonstrating significant quantum advantage

S. T. Pradyumna et al,
Quantum enhanced correlated interferometry for fundamental physics tests
arXiv:1810.13386v2 **[quant-ph]** (2018)

Conclusion



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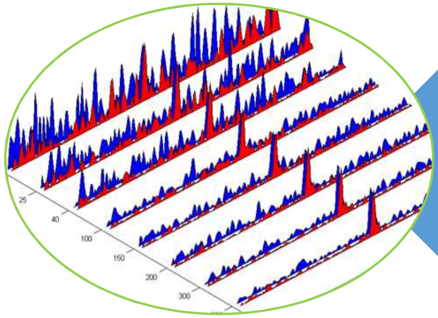

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Thanks for your attention!

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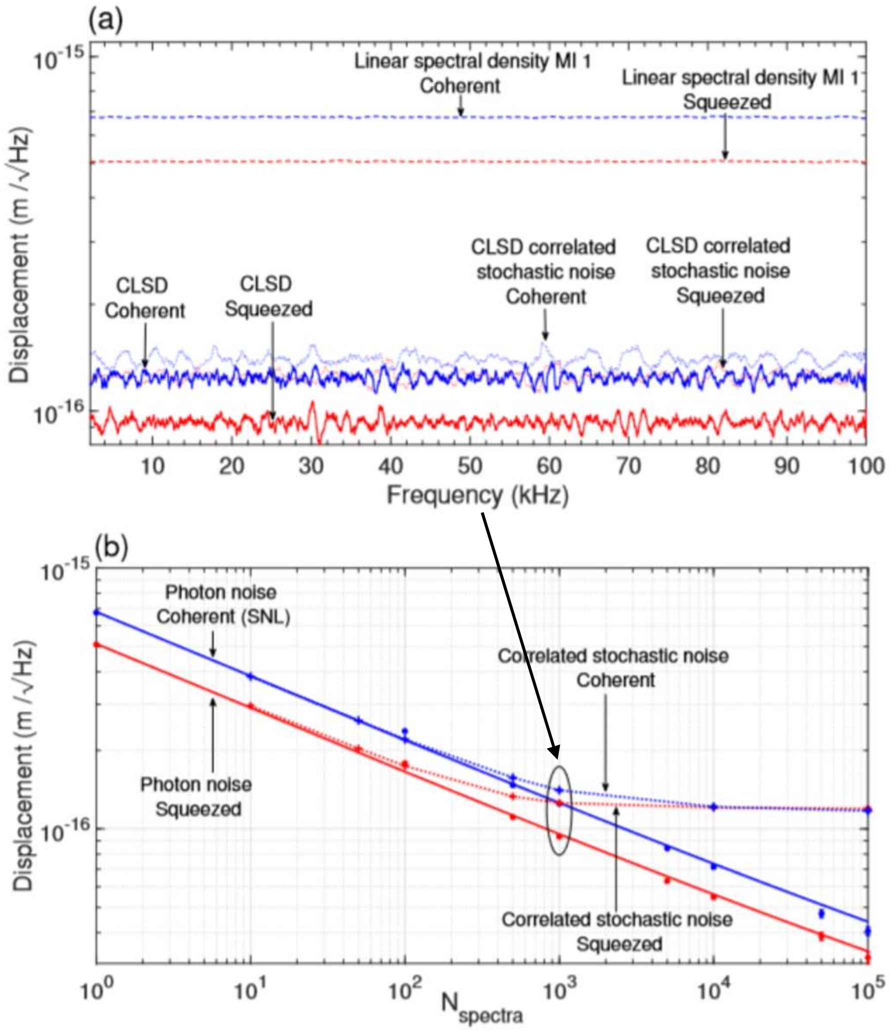
BACK-UP SLIDES

INDEPENDENT SQUEEZED STATES (Spectral domain)



Cross Linear Spectral Density

The same stochastic signal was injected in both interferometers, with an amplitude well below the sensitivity of the single MI (approximately 1/5 of the SNL)

Sampling rate: 500 ksample/s
Acquisition time 20 s

While almost a factor of 5.6 of improvement in sensitivity is gained by the cross-spectra statistical averaging, an additional factor of 1.35 is obtained from the injection of squeezed states.

Maximum achieved sensitivity: **3×10^{-17} m/√Hz** (1/20 of SNL)

- Coherent case
- Squeezing injection

$$\delta x(\mathrm{m}/\sqrt{\mathrm{Hz}}) = \frac{\lambda}{2}\frac{V_{\mathrm{rms}}}{V_{\pi}}\frac{1}{\sqrt{BW}}$$

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Holographic Noise

Several QG theories (string theories, holographic theory, heuristic arguments from black holes,…) predict non- commutativity of position variables at Planck scale

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

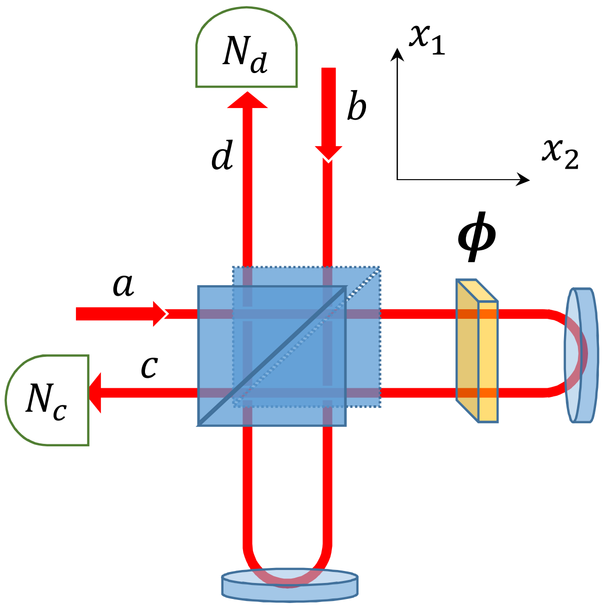
G. Hogan, Arxiv: 1204.5948
G. Hogan, Phys. Rev. D 85, 064007 (2012)

Sort of space-time uncertainty principle (*L*= radial separation)

$$\langle \hat{x}_\perp^2 \rangle = L c t_P / \sqrt{4\pi} = (2.135 \times 10^{-18}\mathrm{m})^2 (L/1\mathrm{m})$$

This new quantum uncertainty of space-time induces a slight random wandering of transverse position (called “holographic noise”)

Holometer (**Holo**graphic Interfero**meter**) @**Fermilab:** two coupled ultra-sensitive Michelson interferometers (40 m arms)



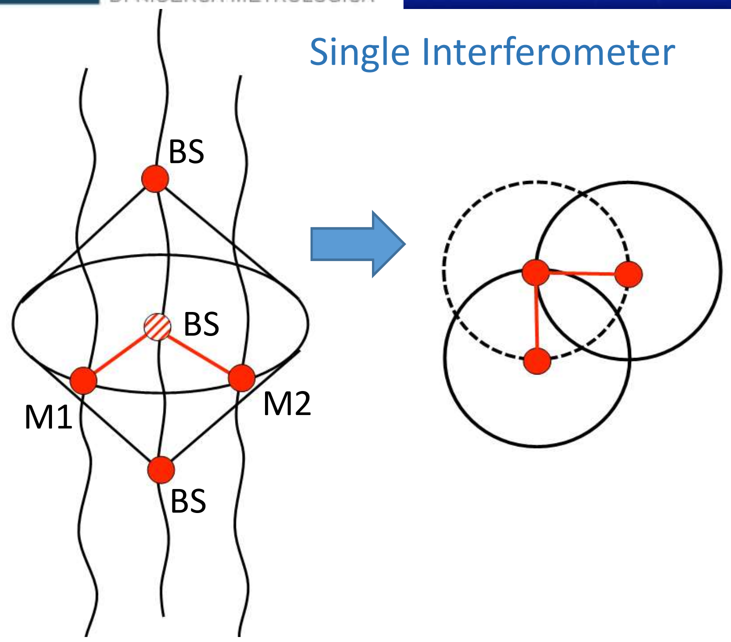
In Michelson interferometer the *phase shift (ϕ)* can be seen as a simultaneous measurement of the position of the beam splitter ($x_1 - x_2$).

Holographic noise accumulates as a *random walk* becoming detectable

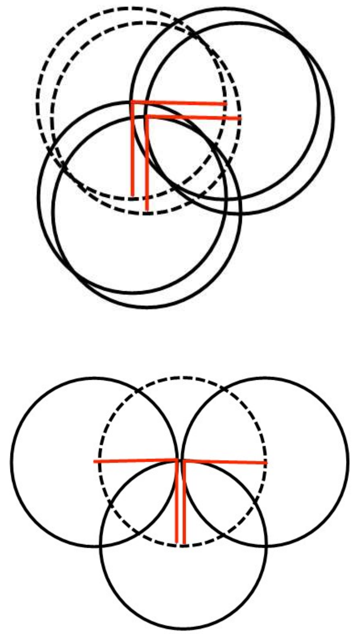
$$\langle [X(t) - X(t+\tau)]^2 \rangle = c^2 t_P \tau (2/\pi)$$
$$\tau << 2L/c$$

The random walk is bounded (an interferometer measures HN within the causal boundaries defined by a single light round trip)
($\tau = 2L/c$ the longest time over which differential random walk affects the measured phase)

G. Hogan, Arxiv: 1204.5948
G. Hogan, Phys. Rev. D 85, 064007 (2012)



Holometer



«Overlapping» space-time volume

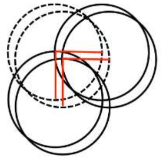
«Separated» space-time volume

HOLOMETER: *principles of operation*

• Evaluation of the cross-correlation between two equal Michelson interferometers occupying the same space-time volume

• Reference measurement: HN correlation «turned off» by separating the space-time volumes of the two interferometers

The model



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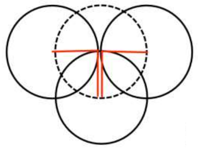

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AIM: HN detected by measuring the phase covariance $\mathcal{E}_{\parallel}\left[\delta\phi_1\delta\phi_2\right]$ between the two interferometers of the holometer

$$\delta\phi_k = \phi_k - \phi_{k,0}$$

$\widehat{C}(\phi_1,\phi_2)$: quantum observable measured at the output of the holometer

$$\mathcal{E}_{\parallel}\left[\delta\phi_1\delta\phi_2\right] \approx \frac{\mathcal{E}_{\parallel}\left[\widehat{C}(\phi_1,\phi_2)\right] - \mathcal{E}_{\perp}\left[\widehat{C}(\phi_1,\phi_2)\right]}{\langle\partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle}$$

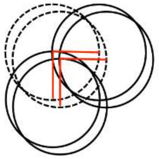
linearization $(\delta\phi_1,\delta\phi_2 \ll 1)$

The uncertainty should be reduced as much as possible

$$\mathcal{U}(\delta\phi_1\delta\phi_2) \approx \sqrt{\frac{\mathrm{Var}_{\parallel}\left[\widehat{C}(\phi_1,\phi_2)\right] + \mathrm{Var}_{\perp}\left[\widehat{C}(\phi_1,\phi_2)\right]}{\left[\langle\partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right]^2}}$$

PRL **110**, 213601 (2013)

The model



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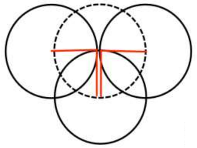

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Phases covariance uncertainty $\mathcal{U}(\delta\phi_1\delta\phi_2) \approx \sqrt{\dfrac{\mathrm{Var}_{\|}\left[\widehat{C}(\phi_1,\phi_2)\right] + \mathrm{Var}_{\perp}\left[\widehat{C}(\phi_1,\phi_2)\right]}{\left[\langle \partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right]^2}}$

$$\mathrm{Var}_x\left[\widehat{C}(\phi_1,\phi_2)\right] \equiv \mathcal{E}_x\left[\widehat{C}^2(\phi_1,\phi_2)\right] - \mathcal{E}_x\left[\widehat{C}(\phi_1,\phi_2)\right]^2$$

$$\mathcal{E}_x\left[\widehat{O}(\phi_1,\phi_2)\right] \equiv \int \langle \widehat{O}(\phi_1,\phi_2)\rangle\, f_x(\phi_1,\phi_2)\, \mathrm{d}\phi_1\ \mathrm{d}\phi_2$$

Quantum EV
$\mathrm{Tr}[\rho_{12}\widehat{C}(\phi_1,\phi_2)]$

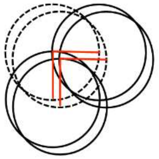
$f_x(\phi_1,\phi_2)$ pdf of phase fluctuations due to HN

$x = \|, \perp$

- $f_\perp(\phi_1,\phi_2) = \mathcal{F}^{(1)}_\perp(\phi_1)\mathcal{F}^{(2)}_\perp(\phi_2)$
- $\mathcal{F}^{(k)}_{\|}(\phi_k) = \mathcal{F}^{(k)}_\perp(\phi_k)$

PRL **110**, 213601 (2013)

The model



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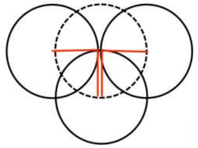

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Phases covariance uncertainty

$$\mathcal{U}(\delta\phi_1\delta\phi_2) \approx \sqrt{\frac{\mathrm{Var}_{\|}\left[\widehat{C}(\phi_1,\phi_2)\right] + \mathrm{Var}_{\perp}\left[\widehat{C}(\phi_1,\phi_2)\right]}{\left[\langle \partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right]^2}}$$

linearization $(\delta\phi_1, \delta\phi_2 \ll 1)$

Var_x

$$\mathrm{Var}_x\left[\widehat{C}(\phi_1,\phi_2)\right] = \mathrm{Var}\left[\widehat{C}(\phi_{1,0},\phi_{2,0})\right] + \Sigma_k\, A_{kk}\, \mathcal{E}_x\left[\delta\phi_k^2\right] + A_{12}\, \mathcal{E}_x\left[\delta\phi_1\delta\phi_2\right] + \mathcal{O}(\delta\phi^3)$$

0-th order

$$\mathcal{E}_x\left[\widehat{O}(\phi_1,\phi_2)\right] \equiv \int \langle\widehat{O}(\phi_1,\phi_2)\rangle\, f_x(\phi_1,\phi_2)\, d\phi_1\, d\phi_2$$

- *0-th order* independent from PSs fluctuations (i.e. HN)
- *0-th order* quantum light noise (shot-noise in the actual Holometer)

$f_x(\phi_1,\phi_2)$ pdf of phase fluctuations due to HN

$x = \|, \perp$

0-th order contribution to PSs covariance unc.:

$$\mathcal{U}^{(0)} = \frac{\sqrt{2\,\mathrm{Var}\left[\widehat{C}(\phi_{1,0},\phi_{2,0})\right]}}{\left|\langle \partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right|}$$

- $f_{\|}(\phi_1,\phi_2) = \mathcal{F}^{(1)}(\phi_1)\,\mathcal{F}^{(2)}(\phi_2)$

$$\mathrm{Var}\left[\widehat{C}(\phi_{1,0},\phi_{2,0})\right] = \langle\widehat{C}(\phi_{1,0},\phi_{2,0})^2\rangle - \langle\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle^2$$

- $f_{\|}(\phi_k) = f_{\perp}(\phi_k)$

Exploiting quantum light to beat the "shot-noise" level!

PRL **110**, 213601 (2013)

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Phys. Rev. Lett. 117, 111102 (2016)

Search for Space-Time Correlations from the Planck Scale with the Fermilab Holometer

Aaron S. Chou,[a] Richard Gustafson [b], Craig Hogan[a,c] Brittany Kamai[c,g], Ohkyung Kwon[c,e], Robert Lanza[c,d], Lee McCuller[c,d], Stephan S. Meyer[c], Jonathan Richardson[c], Chris Stoughton[a], Raymond Tomlin[a], Samuel Waldman[f], Rainer Weiss[d]

[a] *Fermi National Accelerator Laboratory;*
[b] *University of Michigan;*
[c] *University of Chicago;*
[d] *Massachusetts Institute of Technology;*
[e] *Korea Advanced Institute of Science and Technology (KAIST);*
[f] *SpaceX;*
[g] *Vanderbilt University*

Measurements are reported of high frequency cross-spectra of signals from the Fermilab Holometer, a pair of co-located 39 m, high power Michelson interferometers. The instrument obtains differential position sensitivity to cross-correlated signals far exceeding any previous measurement in a broad frequency band extending to the 3.8 MHz inverse light crossing time of the apparatus. A model of universal exotic spatial shear correlations that matches the Planck scale holographic information bound of space-time position states is excluded to 4.6σ significance.

Squeezed light in gravitational wave detectors!!

A sub-shot-noise PS measurement in a **single** interferometer (e.g. gravitational wave detector) was suggested exploiting squeezed light

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

*Kimble et al., PRD **65**, 022002 (2001)*

nature photonics LETTERS
PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.177

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

The LIGO Scientific Collaboration*

PRL **110,** 213601 (2013) PHYSICAL REVIEW LETTERS week ending 24 MAY 2013

Quantum Light in Coupled Interferometers for Quantum Gravity Tests

I. Ruo Berchera,[1] I. P. Degiovanni,[1] S. Olivares,[2] and M. Genovese[1]

[1] *INRIM, Strada delle Cacce 91, I-10135 Torino, Italy*
[2] *Dipartimento di Fisica, Università degli Studi di Milano, and CNISM UdR Milano Statale, Via Celoria 16, I-20133 Milano, Italy*
(Received 22 January 2013; published 21 May 2013)

PHYSICAL REVIEW A **92**, 053821 (2015)

One- and two-mode squeezed light in correlated interferometry

I. Ruo-Berchera,[1] I. P. Degiovanni,[1] S. Olivares,[2,3] N. Samantaray,[1,4] P. Traina,[1] and M. Genovese[1,5]

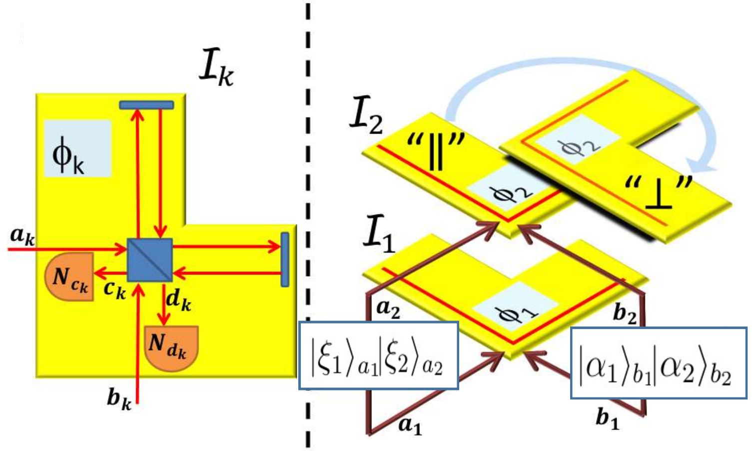
Does squeezed light help also in the case of the Holometer?

$\widehat{C}(\phi_1, \phi_2)$ is the covariance of photon # differences

$$\widehat{C}(\phi_1, \phi_2) = \Delta\hat{N}_{1-}(\phi_k)\ \Delta\hat{N}_{2-}(\phi_k)$$

$$\Delta\hat{N}_{k-}(\phi_k) = \hat{N}_{k-}(\phi_k) - \mathcal{E}\left[\hat{N}_{k-}(\phi_k)\right]$$

$$\hat{N}_{-}(\phi) = \hat{N}_c(\phi) - \hat{N}_d(\phi)$$



0-th order contribution to PSs covariance unc.:

$$\mathcal{U}^{(0)} = \frac{\sqrt{2\,\mathrm{Var}\left[\widehat{C}(\phi_{1,0}, \phi_{2,0})\right]}}{\left|\langle \partial^2_{\phi_1,\phi_2} \widehat{C}(\phi_{1,0}, \phi_{2,0})\rangle\right|} = \sqrt{2}\ \frac{\lambda + \mu\left(1 + 2\lambda - 2\sqrt{\lambda + \lambda^2}\right)}{(\lambda - \mu)^2} \qquad (\phi_0 = \frac{\pi}{2})$$

$$\mathcal{U}^{(0)}_{\mathrm{SQ}} \underset{\mu \gg \lambda \gg 1}{\approx} (2\sqrt{2}\lambda\mu)^{-1}$$

μ : mean # photons coherent light
λ : mean # photons squeezed light

i.e. $(4\lambda)^{-1}$ better than the CL case $\mathcal{U}^{(0)}_{\mathrm{CL}} \approx \sqrt{2}/\mu$

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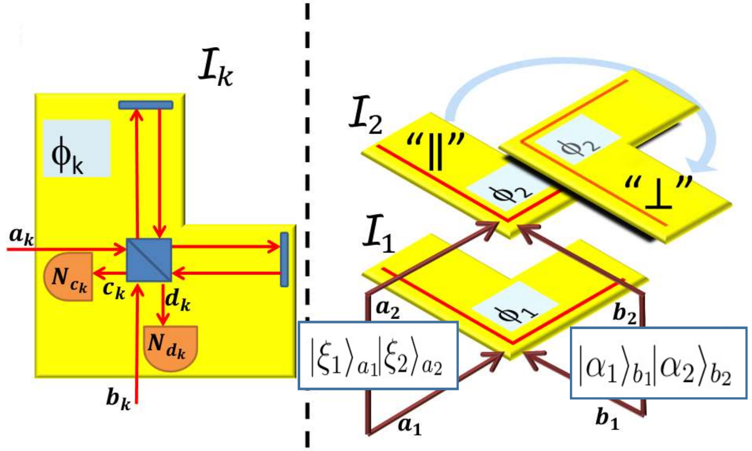

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In the presence of losses η :

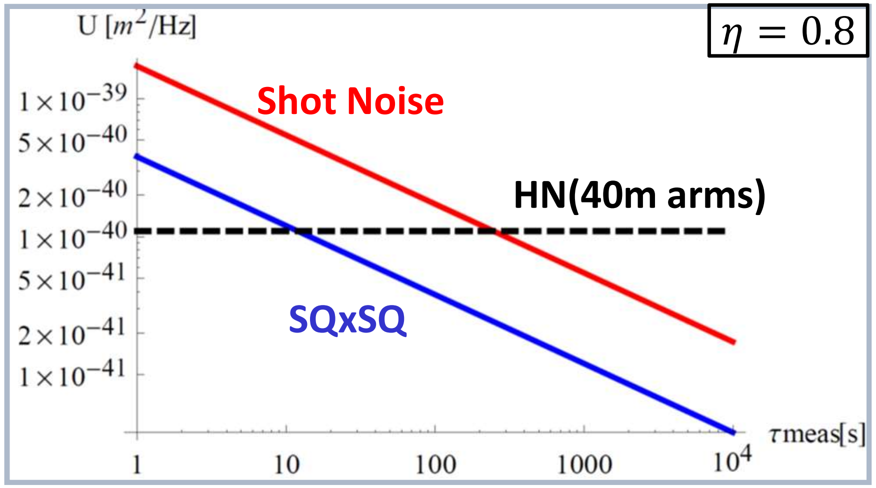
$$\mathcal{U}^{(0)}_{\mathrm{SQ}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx (1-\eta)+\eta/(4\lambda)^1$$

$$\mu \gg \lambda \gg 1$$

$$\mathcal{U}^{(0)}_{\mathrm{SQ}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx 1 - 2\eta\sqrt{\lambda}$$

$$\lambda \ll 1 \text{ and } \mu \gg 1$$

Regimes of interest for a real experiment



For SQXSQ, we expect a reduction of the measurement time of more than one order of magnitude

- $\lambda_{opt} = 1064$ nm.
- $\mu = 10, \eta = 0.8.$
- $P_{opt} = 2000$ W

$\tau_{sample} = 2L/c,$

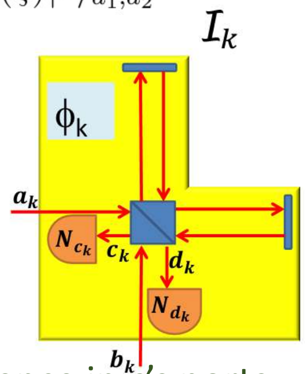
Does quantum correlated light help in coupled interferometers?

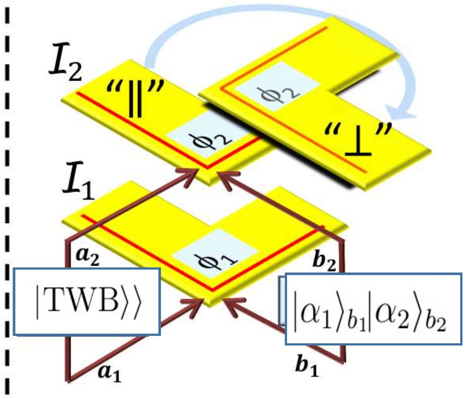
Twin-Beam light in the *a*'s ports: $|\mathrm{TWB}\rangle\rangle_{a_1,a_2} = S_{12}(\zeta)|0\rangle_{a_1,a_2}$

$$S_{12}(\zeta) = \exp(\zeta\ a_1^\dagger a_2^\dagger - \zeta^*\ a_1 a_2)$$

Coherent light in the *b*'s ports: $|\alpha_k\rangle_{b_k} = D_{b_k}(\alpha_k)|0\rangle_{b_k}$

$$D_{b_k}(\alpha_k) = \exp(\alpha_k\ b_k^\dagger - \alpha_k^*\ b_k)$$





$\widehat{C}(\phi_1,\phi_2)$ is the fluctuations of the photon # difference in *c*'s ports

$$\widehat{C}(\phi_1,\phi_2) = \Delta^2\left[\hat{N}_{c_1} - \hat{N}_{c_2}\right]$$

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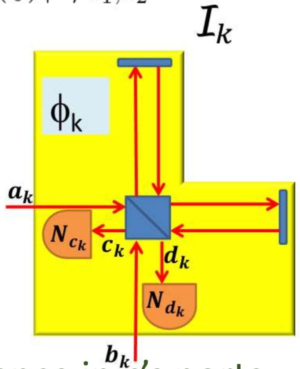

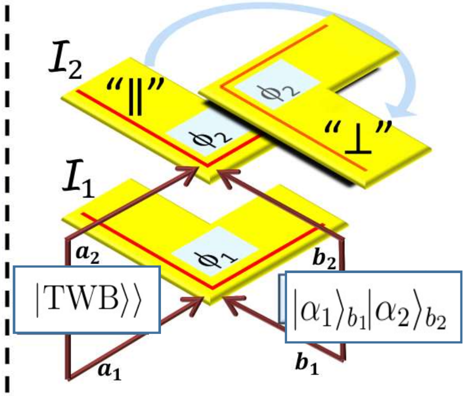

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$\phi_{k,0} = 0$ → $\mathcal{U}^{(0)}_{\mathrm{TWB}} = 0$

$$\langle\langle \mathrm{TWB}|(\hat{N}_{a_1} - \hat{N}_{a_2})^M|\mathrm{TWB}\rangle\rangle = 0,\ \forall M > 0$$

→ $\mathrm{Var}\left\{\Delta^2\left[\hat{N}_{c_1}(0) - \hat{N}_{c_2}(0)\right]\right\} = 0$

$$\left|\langle\partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right| = -\frac{1}{2}\sqrt{\lambda(1+\lambda)}\mu\cos[2(\theta_\zeta - \theta_\alpha)]$$

Does quantum correlated light help in coupled interferometers?

PRL **110**, 213601 (2013)

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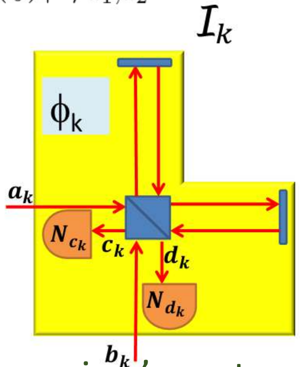

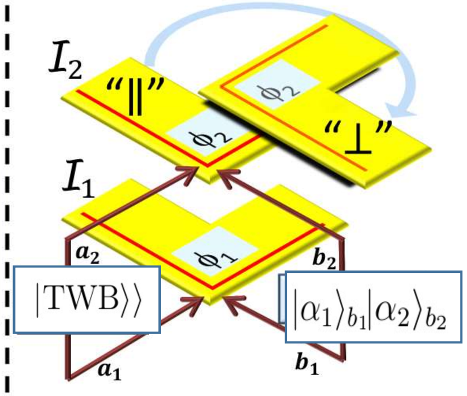

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In the presence of losses η:

$\lambda \ll 1$ and $\mu \gg 1$

$$\mathcal{U}^{(0)}_{\mathrm{TWB}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx \sqrt{2(1-\eta)/\eta}$$

(Squeezed light)

$$\mathcal{U}^{(0)}_{\mathrm{SQ}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx 1 - 2\eta\sqrt{\lambda}$$

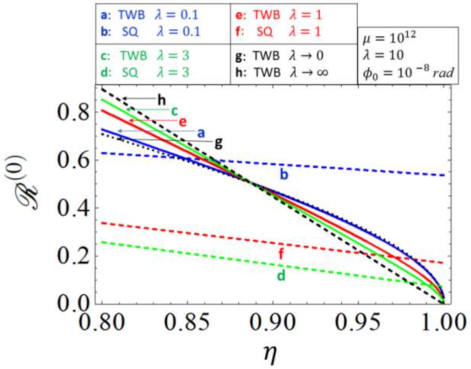
$\mu \gg \lambda \gg 1$

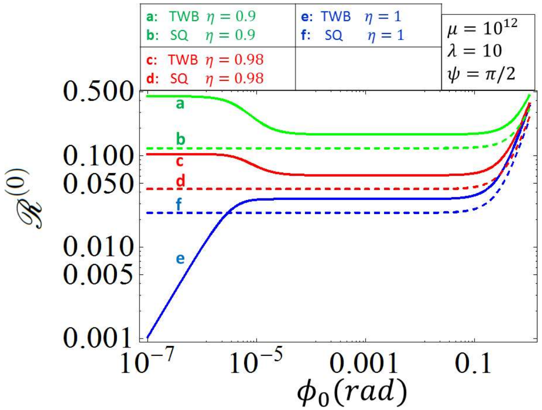
$$\mathcal{U}^{(0)}_{\mathrm{TWB}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx 2\sqrt{5}\,(1-\eta)$$

(Squeezed light)

$$\mathcal{U}^{(0)}_{\mathrm{SQ}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx (1-\eta) + \eta/(4\lambda)$$

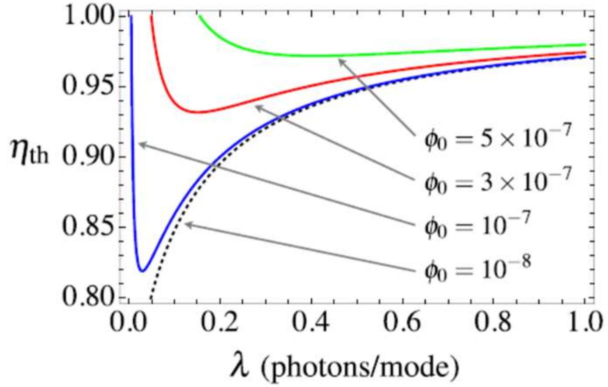
Quantum light in Coupled Interferometers





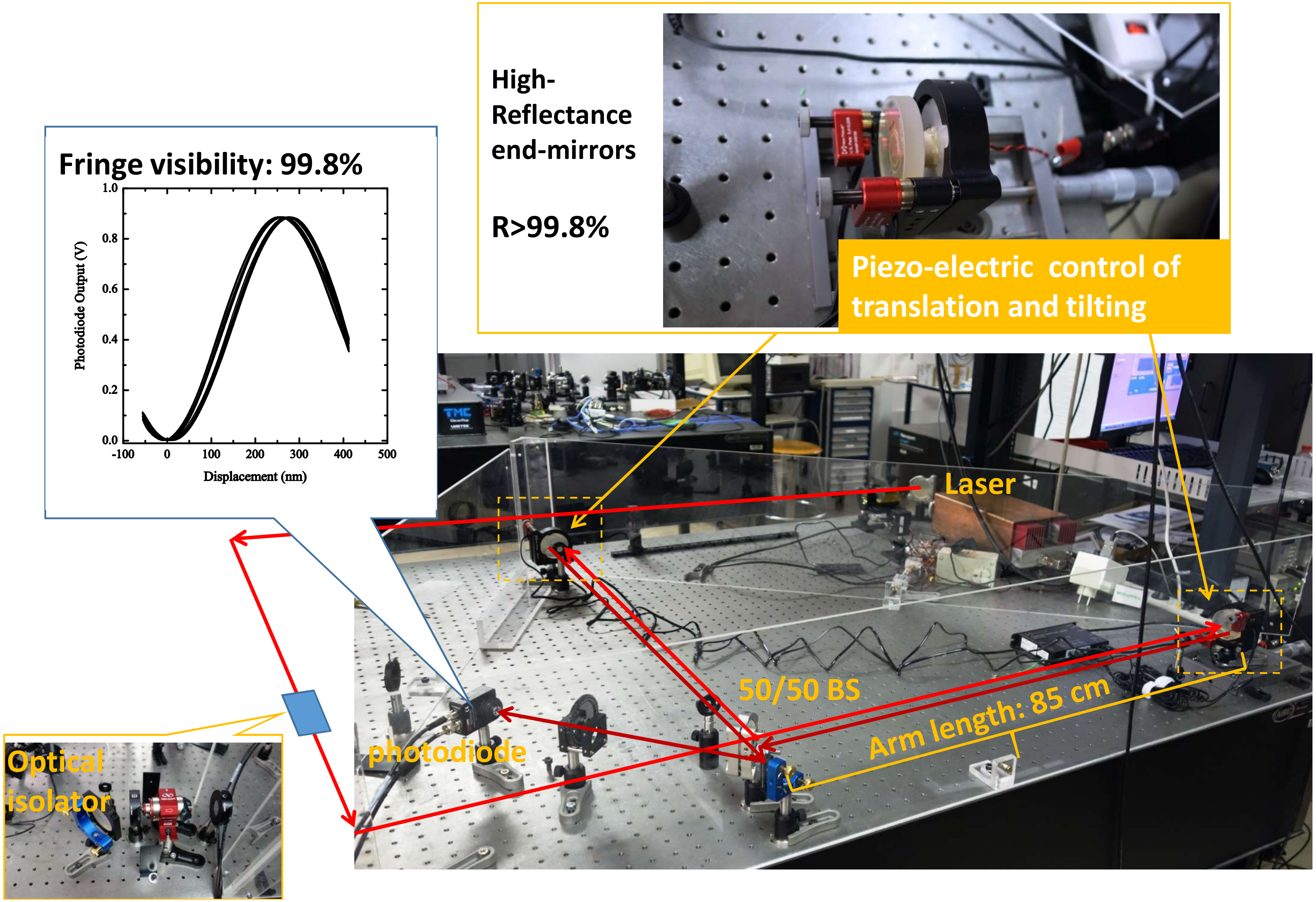
Quantum Enhancement Uncertainty $\approx \sqrt{2(1-\eta)/\eta}$

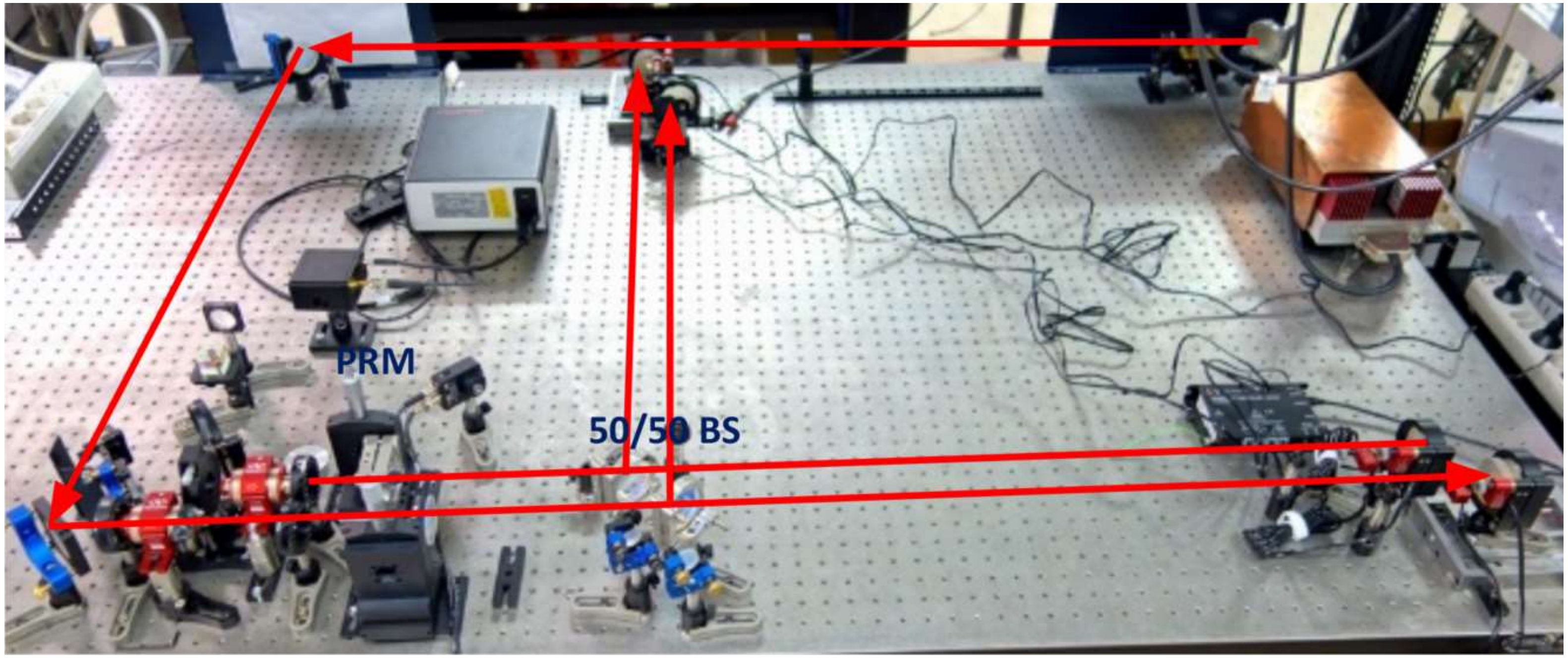
$\approx 0 \; (\eta \approx 1)$



PRA 92, 053821 (2015)

Michelson Interferometer : Preliminary Results

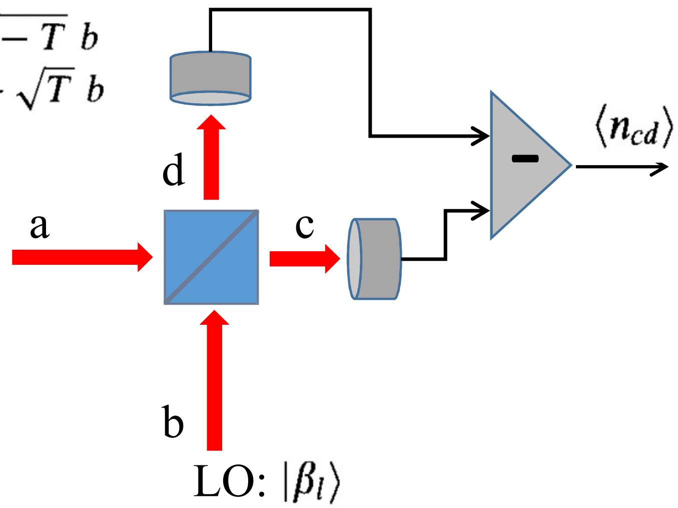



PRM
50/50 BS

How to measure Quadratures

BS transformation:

$$c = \sqrt{T}\, a + i\sqrt{1-T}\, b$$
$$d = i\sqrt{1-T}\, a + \sqrt{T}\, b$$



50:50 BS:

$$n_{cd} = c^\dagger c - d^\dagger d = -i(a^\dagger b - b^\dagger a)$$

$$\langle n_{cd}\rangle = -2|\beta_l|\langle X(\phi_l + \pi/2)\rangle$$
$$(\Delta n_{cd})^2 = 4|\beta_l|^2[\Delta X(\phi_l + \pi/2)]^2$$

$$X(\phi) \equiv X_\phi = \frac{1}{2}(ae^{-i\phi} + a^\dagger e^{i\phi})$$

nature photonics

LETTERS

PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.177

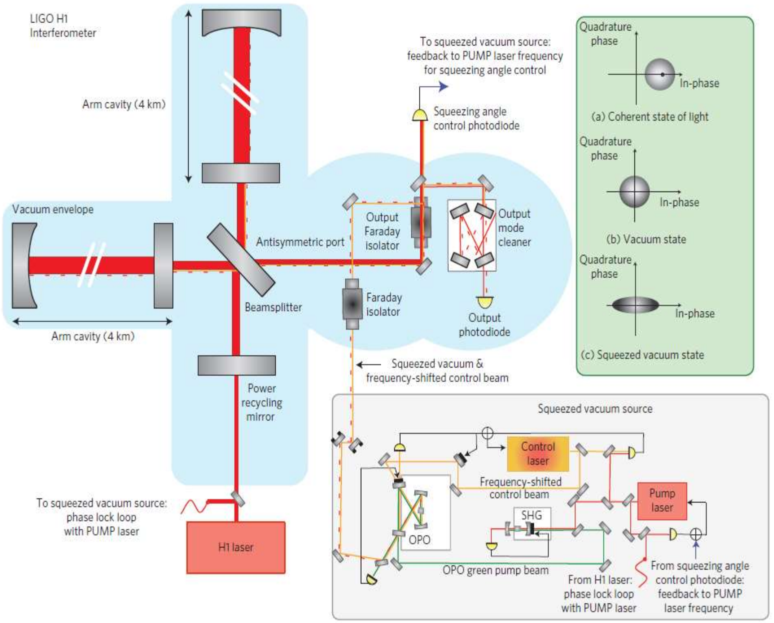
Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

The LIGO Scientific Collaboration*

$$S_{12}(\zeta)|0\rangle$$

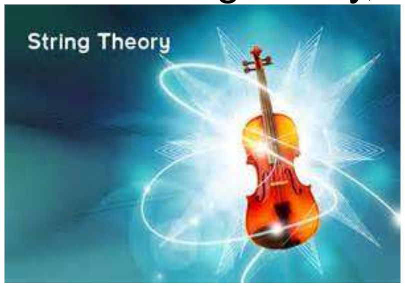
$$S_{12}(\zeta) = \exp(\zeta \; a_1^\dagger a_2^\dagger - \zeta^* \; a_1 a_2)$$

2.15 ± 0.05 dB improvement



An experimental quantum gravity?

- The dream of building a theory unifying general relativity and quantum mechanics, the so called quantum gravity has been a key element in theoretical physics research for the last 60 years.
- A HUGE theoretical work: string theory, loop gravity, ….



- However, for many years no testable prediction emerged from these studies. In the last few years this common wisdom was challenged: a first series of testable proposals concerned photons propagating on cosmological distances [AmelinoCamelia et al.], with the problem of extracting QG effects from a limited (uncontrollable) observational sample affected by various propagation effects.

Role of the entanglement

- The TWB state cis expressed as:

$$\rho TWB[\varphi] \ = \sum_{n,m}(1-t^2)t^{n+m}\mathrm{Exp}[i\varphi(n-m)]\,|n\rangle|n\rangle\langle m|\langle m| \qquad t = \tanh(\varsigma)$$

- We generate a mixed state ρmix that preserves the photon number correlation, simulating a Gaussian dephasing

$$\rho mix = \int d\varphi\, \rho TWB \frac{e^{-\frac{\varphi^2}{2\delta^2}}}{\sqrt{2\pi\delta^2}}$$

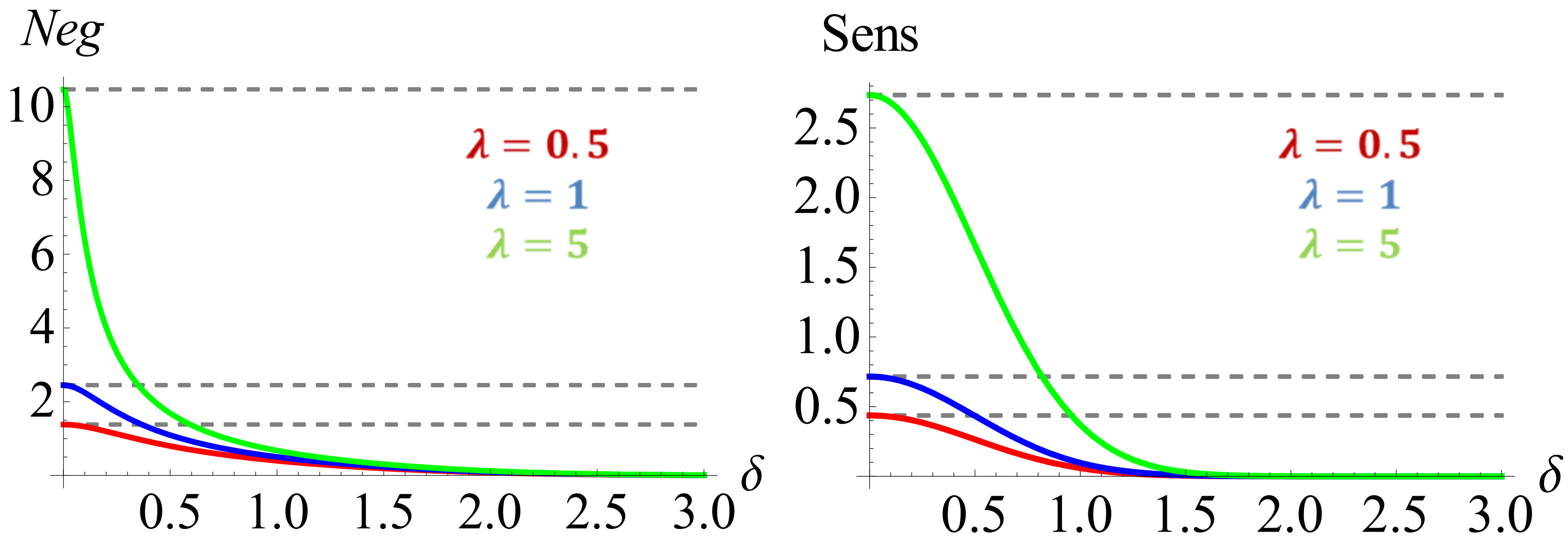
For δ=0 we have $\rho mix = \rho TWB,$

for δ=2π we have $\rho mix = \sum_n (1-t^2)t^{2n}\,|n\rangle|n\rangle\langle n|\langle n|$

- We studied the negativity and the sensitivity coefficient in function of the amplitude of the dephasing

Role of the entanglement

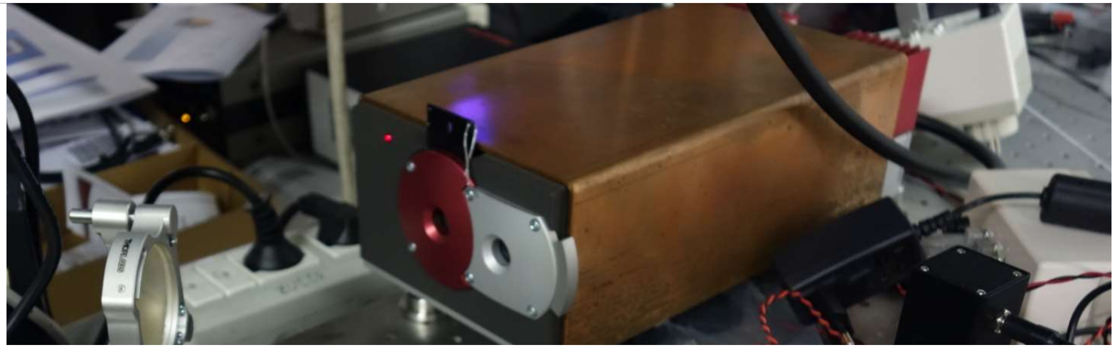
Is Entanglement related to the TWB quantum enhancement?



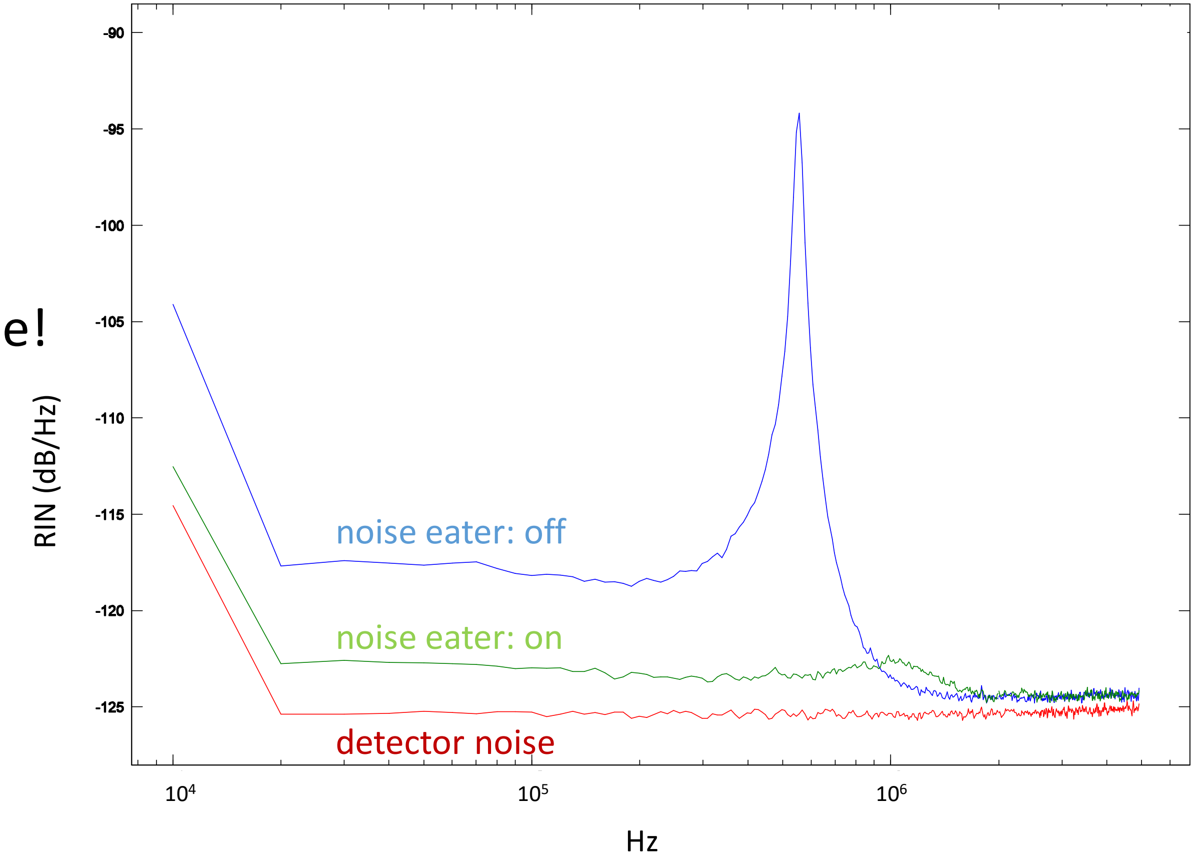
Indeed a clear role of entanglement, measured by negativity [see M.Roncaglia,A.Montorsi, M.G. Phys. Rev A 90, 062303 (2014)]**, is demonstrated.** This is due to the fact that the scheme requires not only perfect photon number correlation, but also a defined phase of the TWB for a coherent interference with the classical coherent field at the Beam Splitter.

The Laser

COHERENT MEPHISTO (cw)
Nd:YAG @ 1064 nm
Output power up to 2 W



Extremely low noise!



Does Q-correlated (Entangled) light help in coupled interferometers?

Twin-Beam state (or Two-mode squeezed vacuum)

Hamiltonian of a non-degenerate parametric process: $H \propto a^\dagger b^\dagger + h.c.$

(Unitary) Two-mode "Squeeze" Operator : $S_2(\xi) = \exp\left\{\xi a^\dagger b^\dagger - \xi^* ab\right\}$ $\qquad \xi = re^{i\psi}$

$$S_2^\dagger(\xi)\begin{pmatrix} a \\ b^\dagger \end{pmatrix} S_2(\xi) = \boldsymbol{S}_{2\xi}\begin{pmatrix} a \\ b^\dagger \end{pmatrix}$$

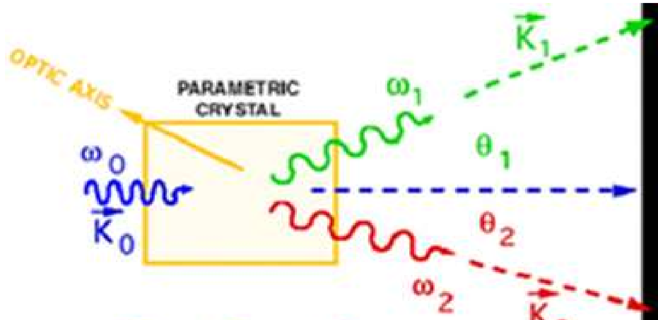
$$\boldsymbol{S}_{2\xi} = \begin{pmatrix} \mu & \nu \\ \nu^* & \mu \end{pmatrix}$$

$$\mu = \cosh r$$
$$\nu = e^{i\psi}\sinh r$$

Twin Beam state: $$|\mathrm{TWB}\rangle\rangle = S_2(\xi)|\mathbf{0}\rangle = \frac{1}{\sqrt{\mu}}\sum_{k=0}^{\infty}\left(\frac{\nu}{\mu}\right)^k |k\rangle \otimes |k\rangle$$

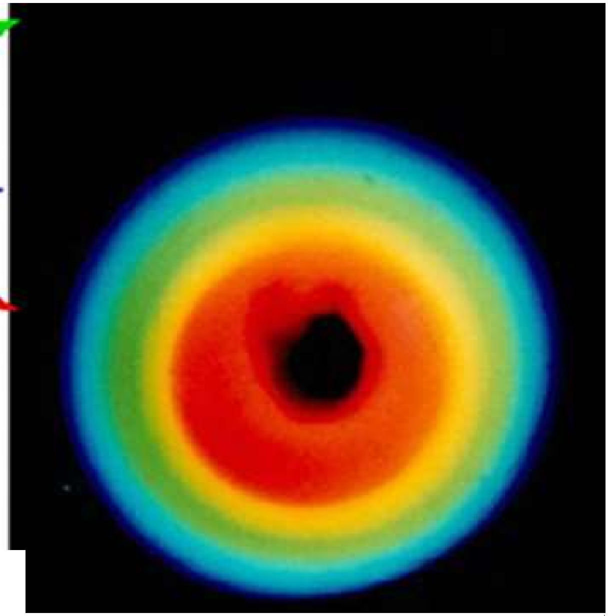
TWB shows **perfect correlation** in the **photon number**, i.e TWB is an eigenstate of the photon number difference

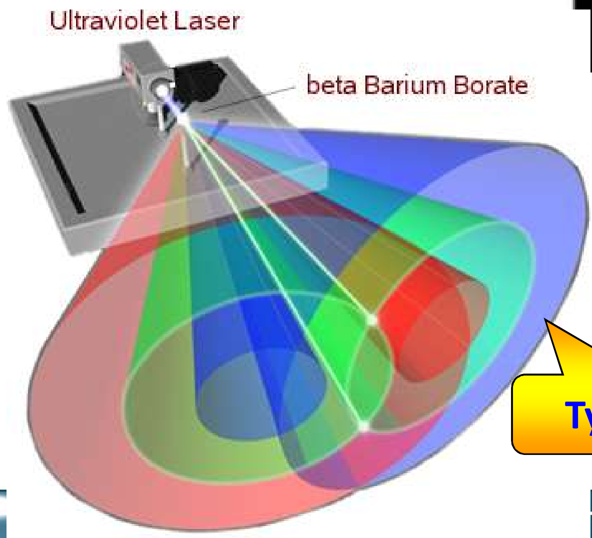
PDC: a brief summary



$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2$$

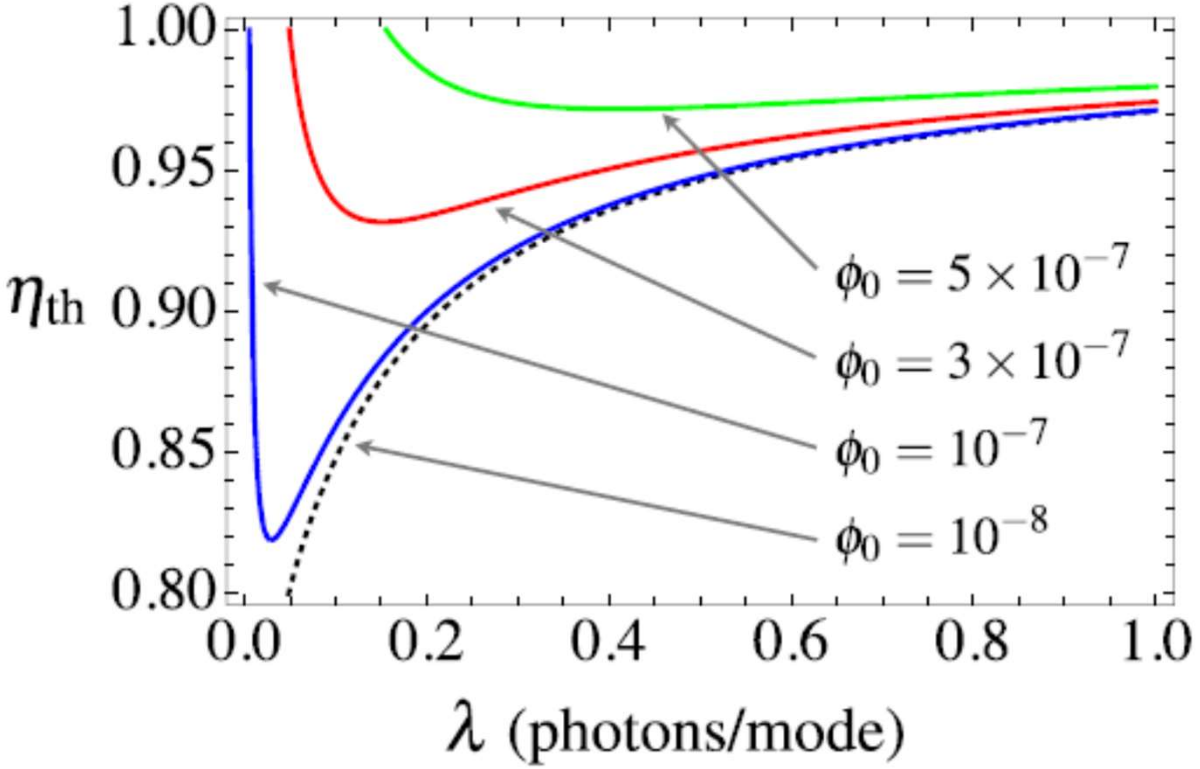
$$\omega_0 = \omega_1 + \omega_2$$





Type-II PDC

Type-I PDC



PRA 92, 053821 (2015)

Squeezed light in gravitational wave detectors!!

A sub-shot-noise PS measurement in a **single** interferometer (e.g. gravitational wave detector) was suggested exploiting squeezed light

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

*Kimble et al., PRD **65**, 022002 (2001)*

...

and recently realized at Ligo 600

*R. Schnabel et al., Nature Commun. **1**, 121 (2010)*

*Ligo, Nature Phys. **7**, 962 (2011)*

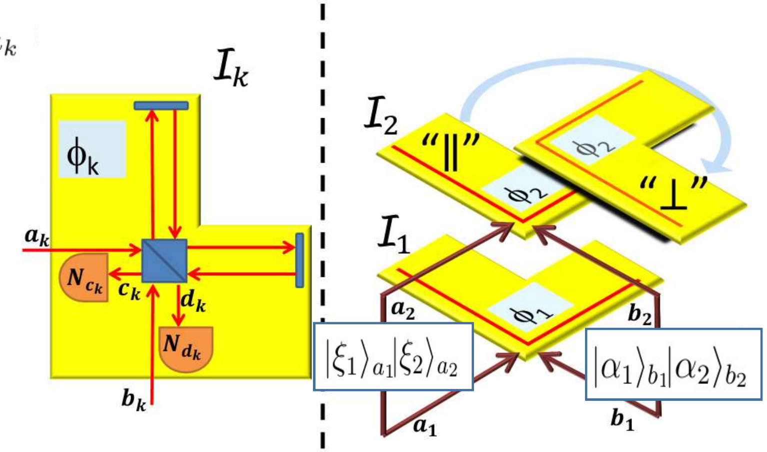
Does squeezed light help also in the case of the Holometer?

Squeezed light in the *a*'s ports: $|\xi_k\rangle_{a_k} = S_{a_k}(\xi_k)|0\rangle_{a_k}$

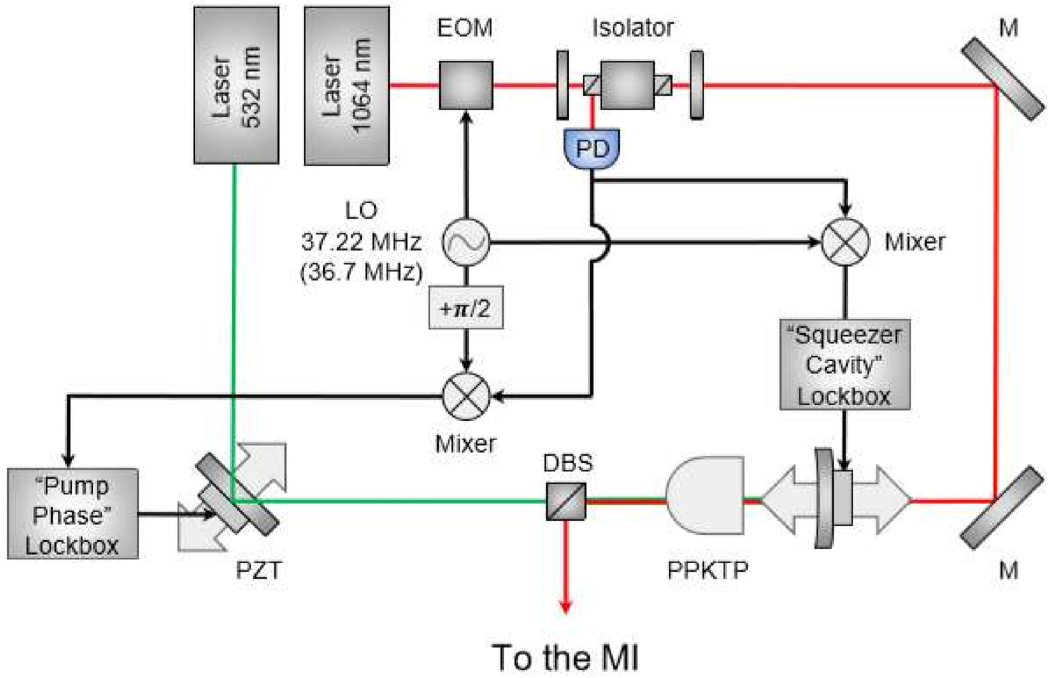
$$S_{a_k}(\xi_k) = \exp[\xi_k \, (a_k^\dagger)^2 - \xi_k^* \, (a_k)^2]$$

Coherent light in the *b*'s ports: $|\alpha_k\rangle_{b_k} = D_{b_k}(\alpha_k)|0\rangle_{b_k}$

$$D_{b_k}(\alpha_k) = \exp(\alpha_k \, b_k^\dagger - \alpha_k^* \, b_k)$$



Locking scheme



Schematic of the squeezed light source. PPKTP: potassium titanyl phosphate crystal. DBS: dichroic beam splitter. PZT: piezoelectric actuators. EOM: electro-optical modulator. LO: local oscillator. PD: photo-diode.