INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

In collab with:

UNIVERSITAS STUDIORUM MEDIOLANENSIS

Technical
University of
Denmark

DTU

TOWARD A QUANTUM-ENHANCED HOLOMETER

Paolo Traina

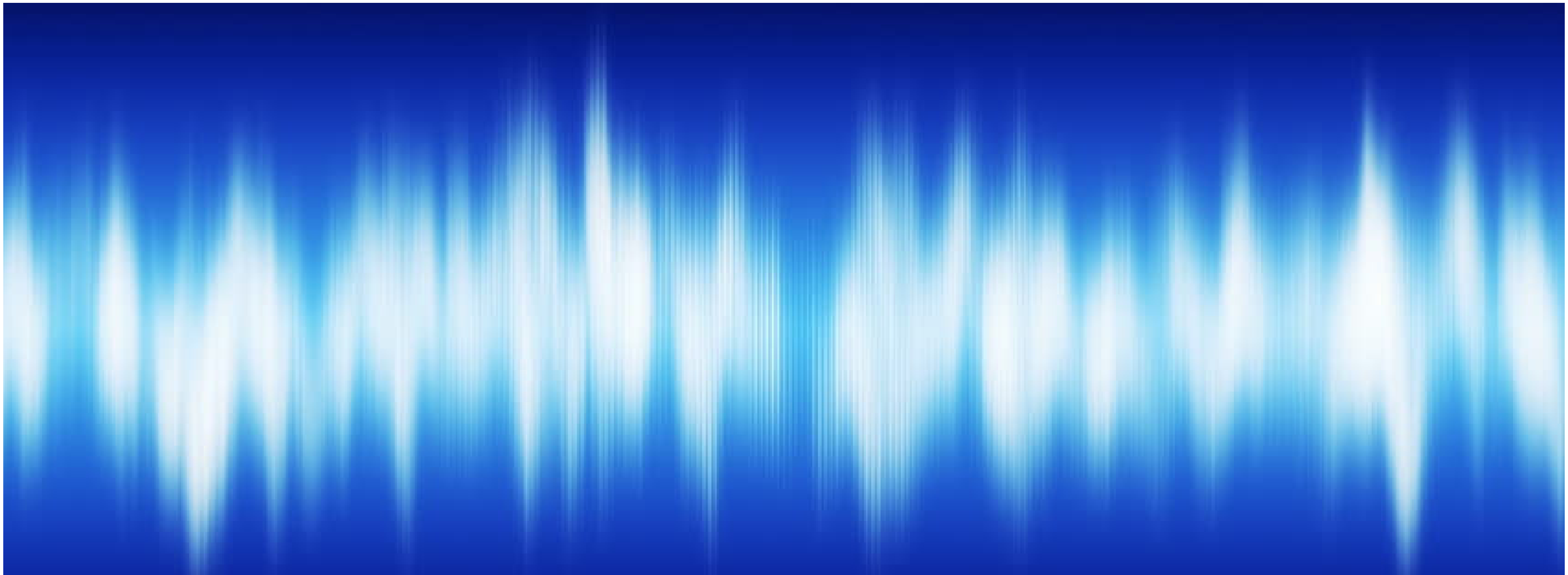
Workshop on Testing Fundamental Physics Principles

September 25 2017 - Corfù

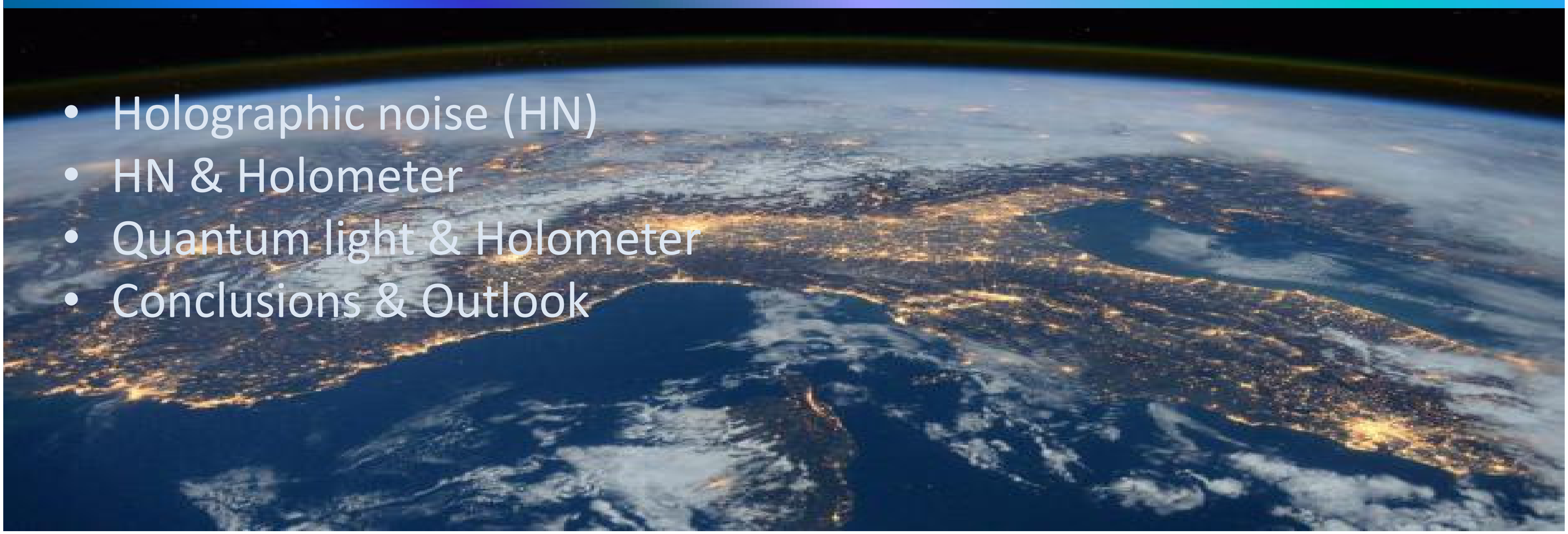
John
Templeton
Foundation

cost Action MP 1405
Quantum Structure of Spacetime

MIUR
MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

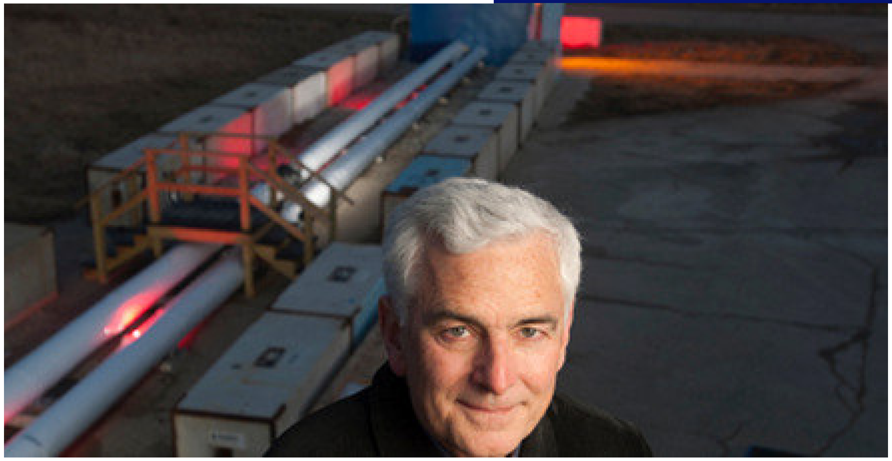


Outline



- Holographic noise (HN)
- HN & Holometer
- Quantum light & Holometer
- Conclusions & Outlook

Holographic Noise



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

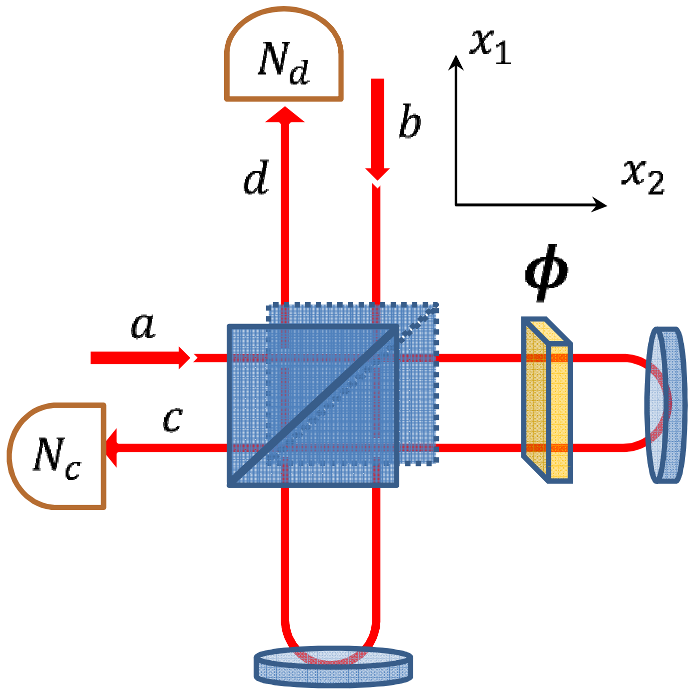
$$[\hat{x}_i, \hat{x}_j] = \hat{x}_k \epsilon_{ijk} i c t_P / \sqrt{4\pi}$$

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

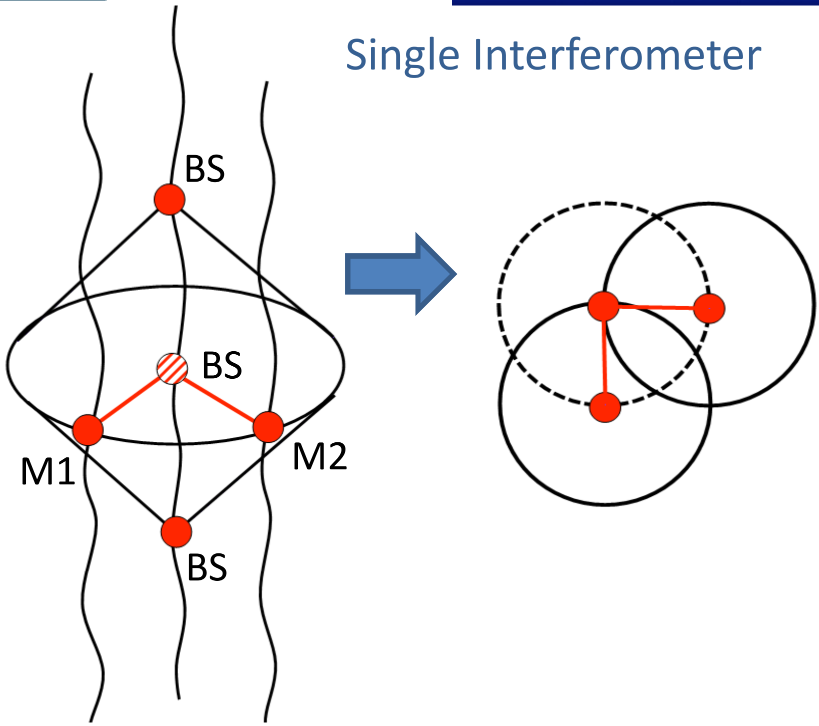
$$\langle [X(t) - X(t+\tau)]^2 \rangle = c^2 t_P \tau (2/\pi)$$
$$\tau << 2L/c$$

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)

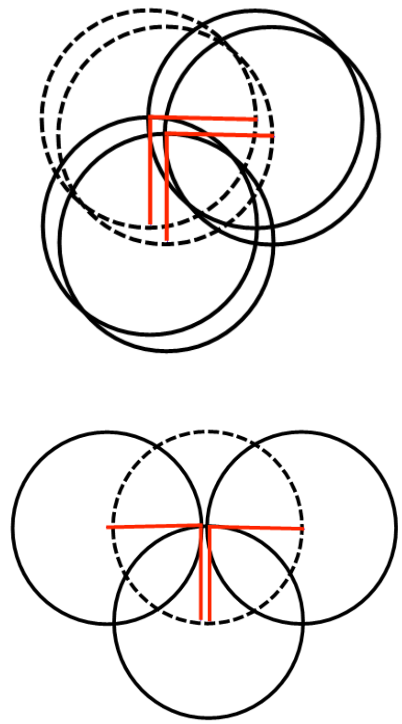
G. Hogan, Arxiv: 1204.5948
G. Hogan, Phys. Rev. D 85, 064007 (2012)

Holographic Noise and the Holometer

Single Interferometer



Holometer



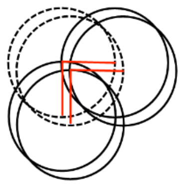
«Overlapping» space-time volume

«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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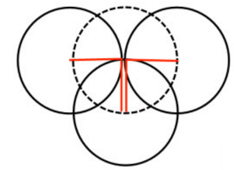

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AIM: HN detected by measuring the phase covariance $\mathcal{E}_{\|}\left[\delta\phi_1\delta\phi_2\right]$ between the two interferometers of the holometer

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

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

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

linearization

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

The uncertainty should be reduced as much as possible

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

PRL **110**, 213601 (2013)

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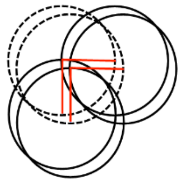
The model



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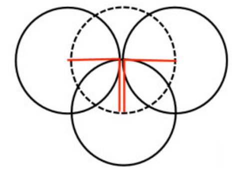

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Phases covariance uncertainty

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

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

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

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

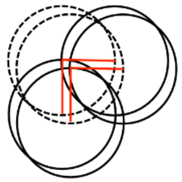
$f_x(\phi_1,\phi_2)$ pdf of phase fluctuations due to HN

$x = \parallel, \perp$

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

PRL **110**, 213601 (2013)

The model



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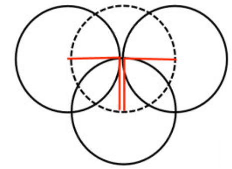

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Phases covariance uncertainty $\mathcal{U}(\delta\phi_1\delta\phi_2) \approx \sqrt{\dfrac{\mathrm{Var}_{\parallel}\left[\widehat{C}(\phi_1,\phi_2)\right] + \mathrm{Var}_{\perp}\left[\widehat{C}(\phi_1,\phi_2)\right]}{\left[\langle \partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right]^2}}$

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

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

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

0-th order contribution to PSs covariance unc.: $\mathcal{U}^{(0)} = \dfrac{\sqrt{2\,\mathrm{Var}\left[\widehat{C}(\phi_{1,0},\phi_{2,0})\right]}}{\left|\langle \partial^2_{\phi_1,\phi_2}\widehat{C}(\phi_{1,0},\phi_{2,0})\rangle\right|}$

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

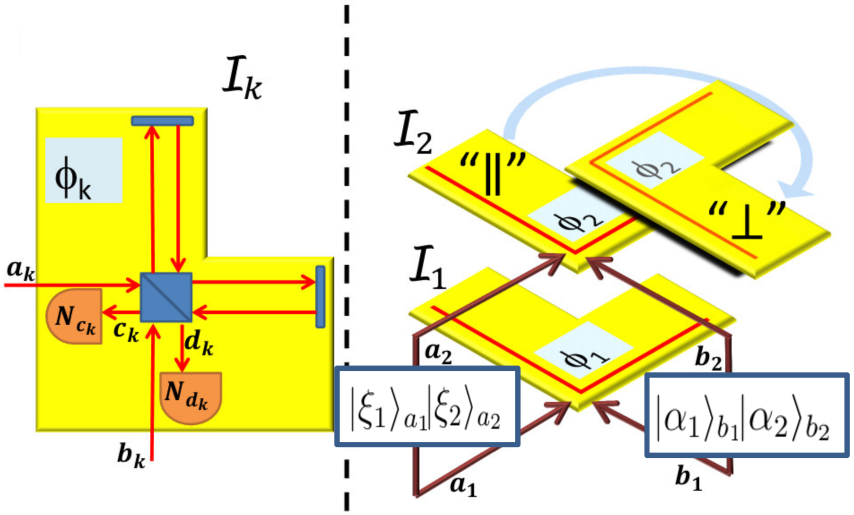
One- and two-mode squeezed light in correlated interferometry

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 product of the squeezed quadratures

$$\widehat{C}(\phi_1,\phi_2) = \{Y_1(\phi_1) - \mathscr{E}[Y_1]\}\{Y_2(\phi_2) - \mathscr{E}[Y_2]\}$$



0-th order contribution to PSs covariance unc.:

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

$\Phi_0 << 1$

In the presence of losses η:

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

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

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

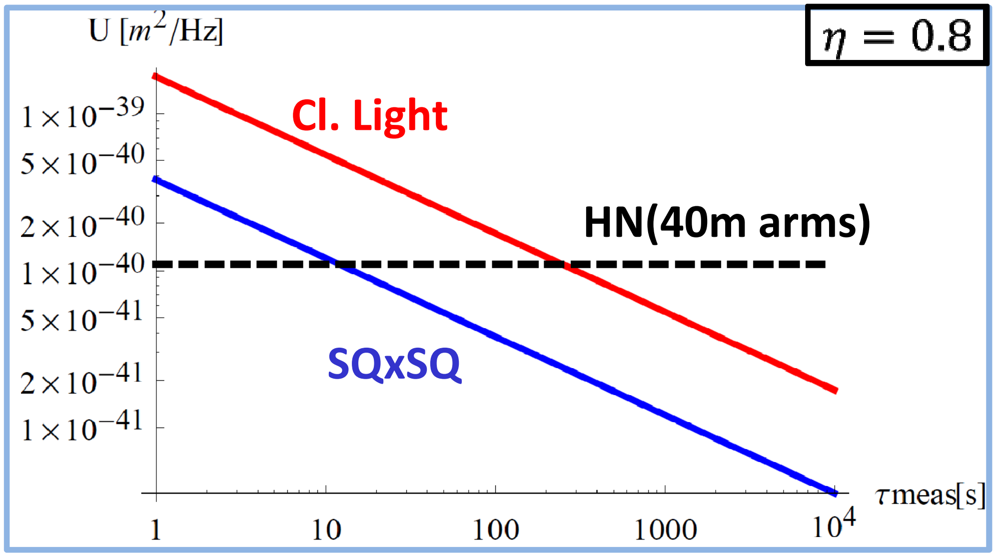
$$\lambda \ll 1 \text{ and } \mu \gg 1$$

μ: mean # photons coherent light

λ: mean # photons squeezed light

$$\mathscr{U}^{(0)}_{\rm cl} = \sqrt{2}/\eta\mu\cos^2(\phi_0/2)$$

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

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

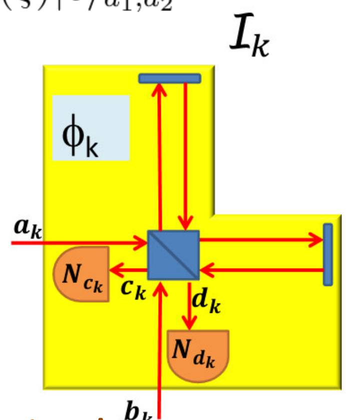
Does quantum correlated light help in coupled interferometers?

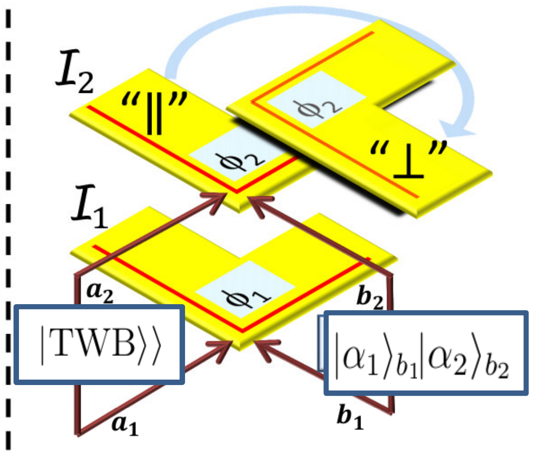
Twin-Beam light in the *a*'s ports: $|\mathrm{TWB}\rangle\rangle_{a_1,a_2} = S_{12}(\zeta)|0\rangle_{a_1,a_2}$

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

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 SQUARE of the photon # difference in *c*'s ports

$$\widehat{C}(\phi_1,\phi_2) = [N_1(\phi_1) - N_2(\phi_2)]^2$$

Does quantum correlated light help in coupled interferometers?

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

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

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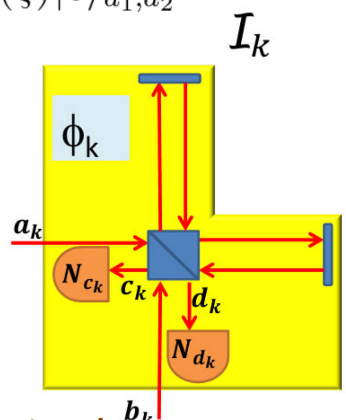

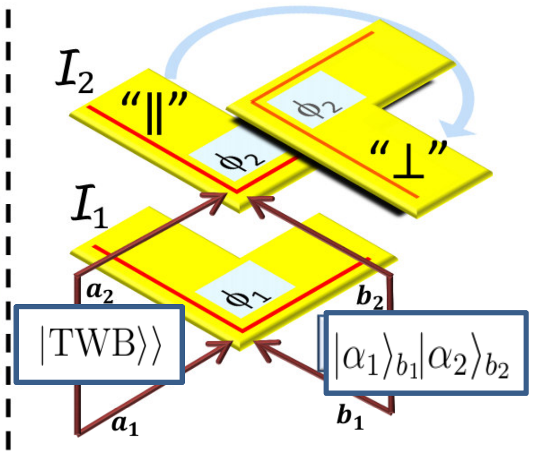

$\widehat{C}(\phi_1, \phi_2)$ is the SQUARE of the photon # difference in *c*'s ports

$$\widehat{C}(\phi_1,\phi_2) = [N_1(\phi_1) - N_2(\phi_2)]^2$$

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

Does quantum correlated light help in coupled interferometers?

PRL **110**, 213601 (2013)

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: $|\alpha_k\rangle_{b_k} = D_{b_k}(\alpha_k)|0\rangle_{b_k}$

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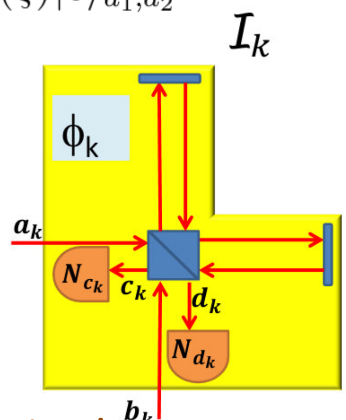
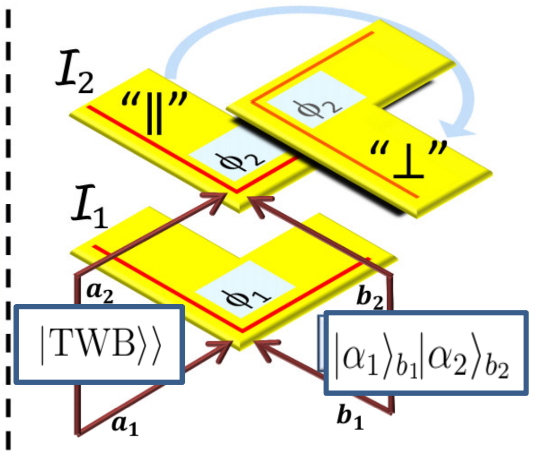




$\widehat{C}(\phi_1,\phi_2)$ is the SQUARE of the photon # difference in *c*'s ports

$$\widehat{C}(\phi_1,\phi_2) = [N_1(\phi_1) - N_2(\phi_2)]^2$$

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

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)

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

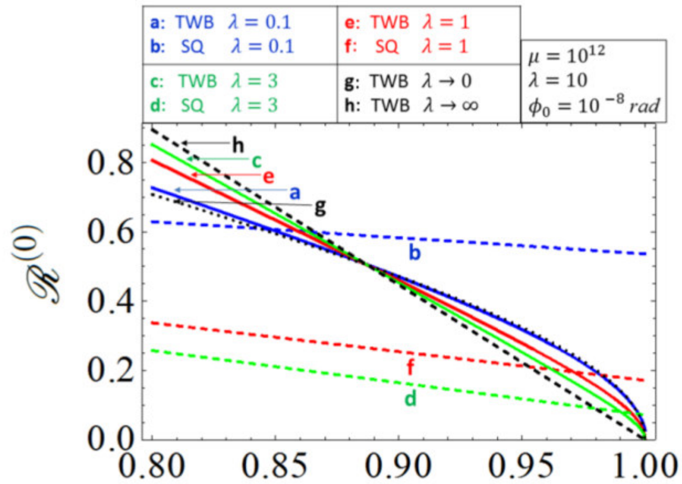
$\mu \gg \lambda \gg 1$

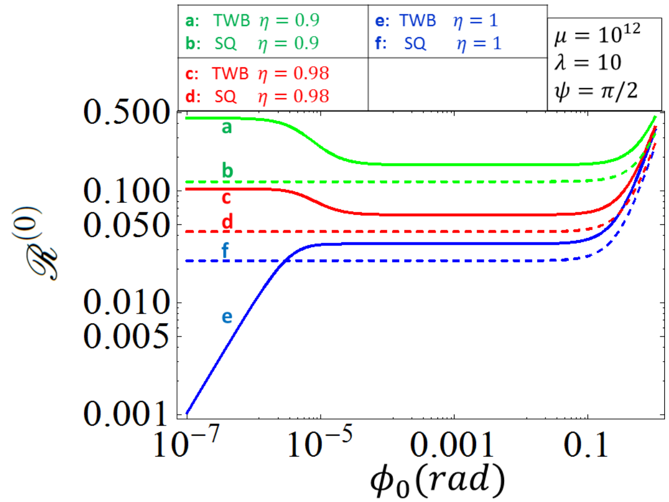
$$\mathcal{U}^{(0)}_{\mathrm{TWB}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx 2\sqrt{5}\,(1-\eta)$$

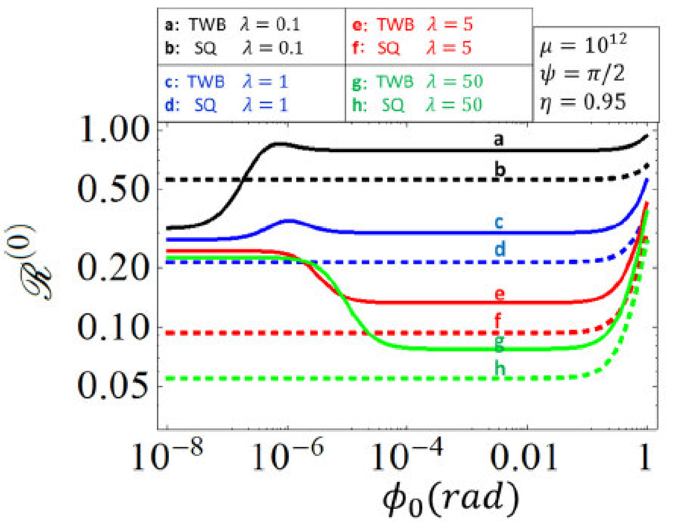
(Squeezed light)

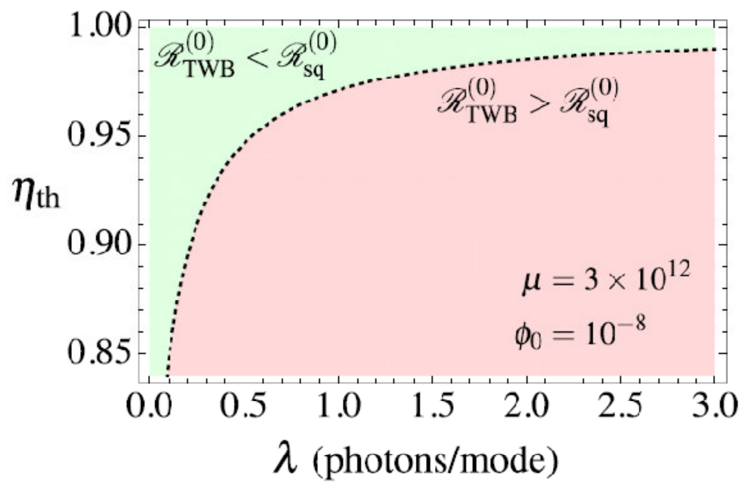
$$\mathcal{U}^{(0)}_{\mathrm{SQ}}/\mathcal{U}^{(0)}_{\mathrm{CL}} \approx (1-\eta)+\eta/(4\lambda)$$

Quantum light in Coupled Interferometers









PRA 92, 053821 (2015)

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The TAKE-AWAY

- HN is due to the "possible" Quantum Geometric structure of the Space-Time at the Planck-length scale
- HN may have "observable" effect at the macroscopic scale $\rightarrow$ Holometer (2 coupled interferometers)
- Quantum light enhance the sensitivity of the Holometer below the "Shot-Noise" limit
  - Squeezed light generally performs better than TWB ($\lambda >> 1$)
  - Twin-Beam provides in an ideal case a complete suppression of the shot-noise contribution (0!!!!)
  - Losses (effectively) affect this enhancement

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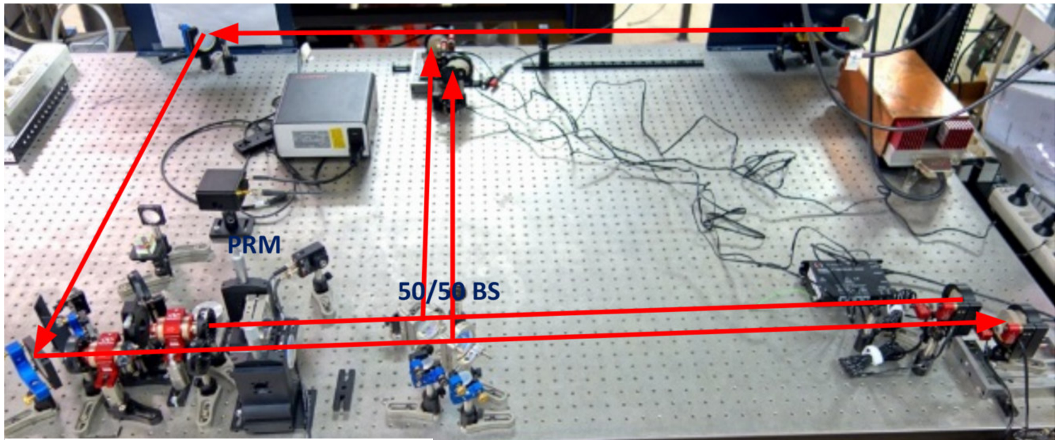
Experimental Setup



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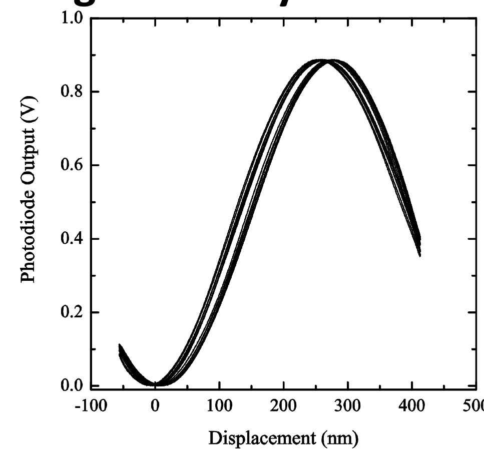
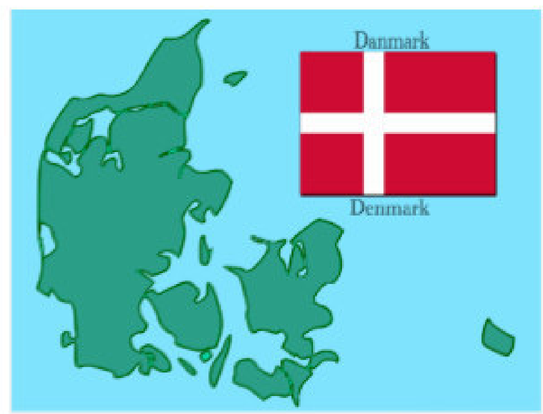
Fringe visibility: 99.8%

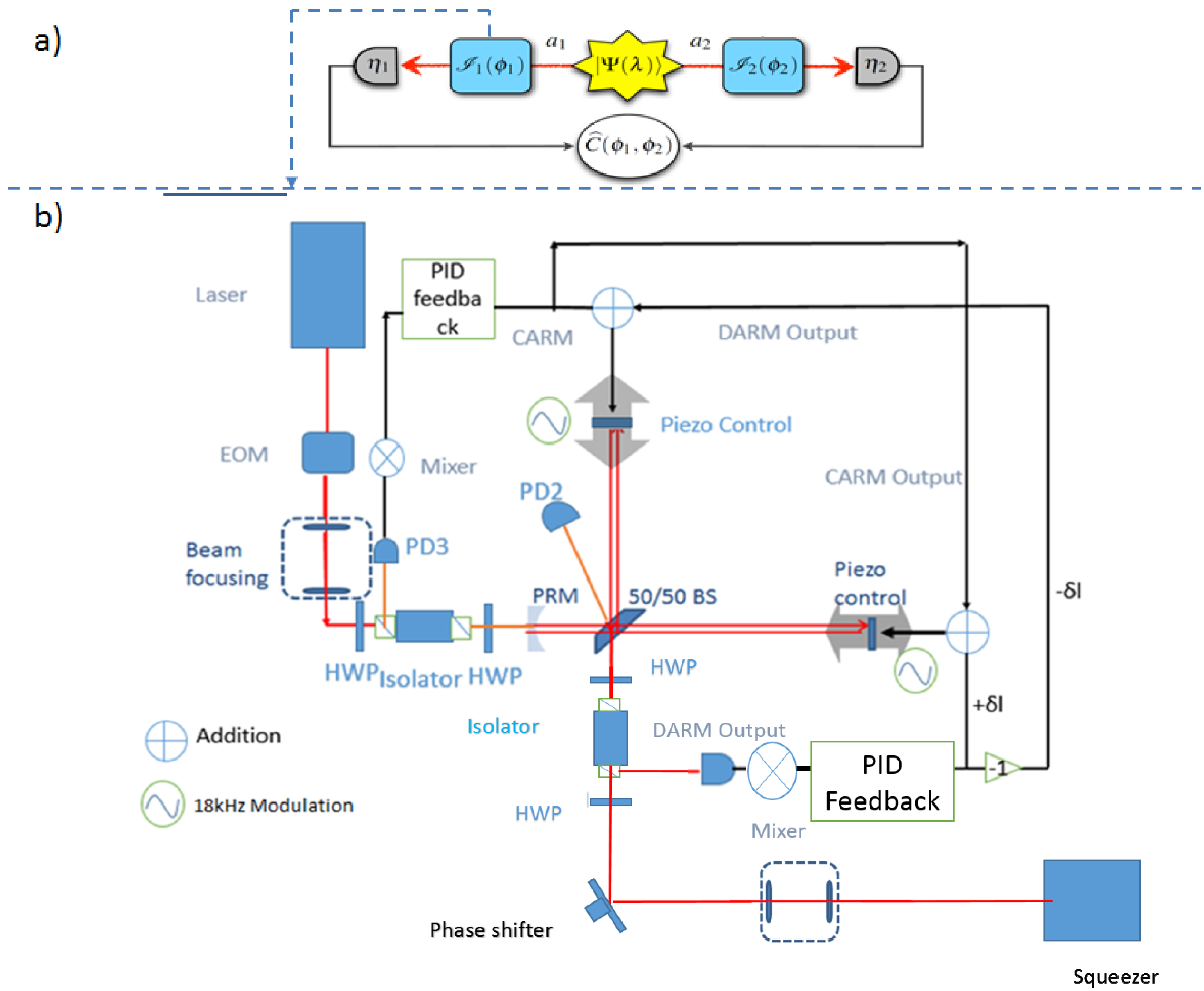




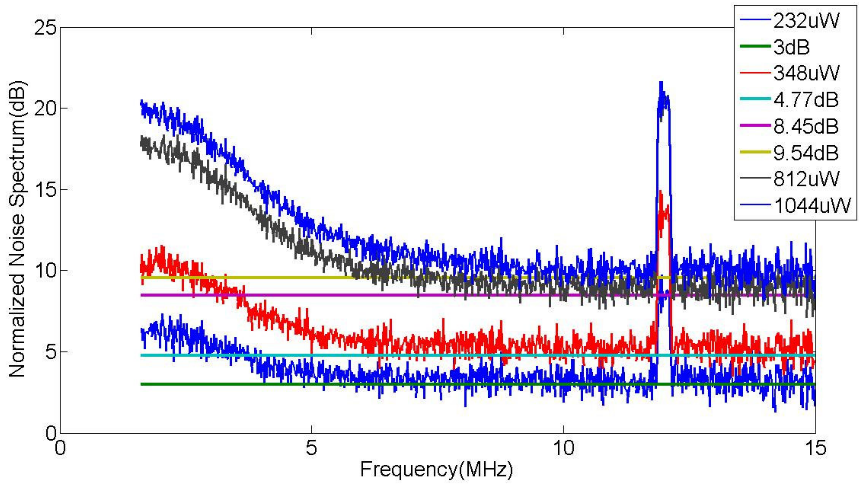
Technical University of Denmark

DTU

Experimental Setup



Preliminary results



- The main loss factors :modematching, quantum efficiency of the photodiode and the transmission of the faraday Isolator.
- We are currently improving on the modematching between the squeezed light and the interferometer field.
- the second interferometer is ready and measure the cross correlations between the outputs of the two interferometers is upcoming.

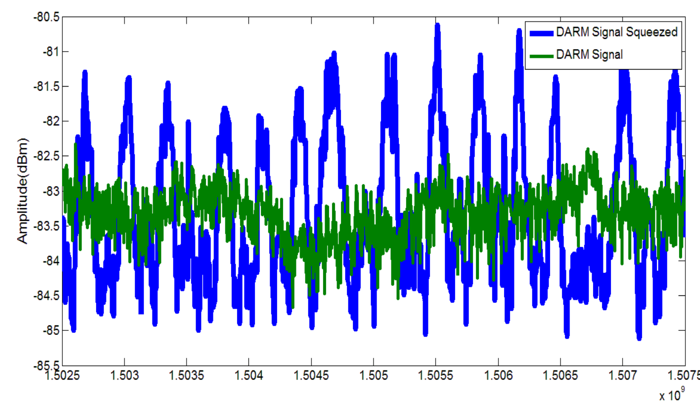


Figure: The blue curve represents the output of the DARM signal when the squeezed light was injected into the interferometer and the green one is the Shot Noise Limit of the DARM output. There is around 2dB of Squeezing at 5MHz.

THANK YOU!

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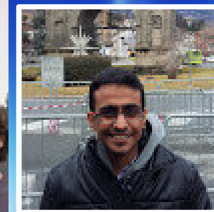
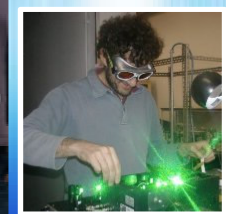
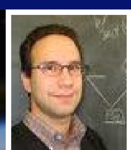




P. T., I. P. Degiovanni, I. Ruo Berchera, S. Pradyumna, N. Samataray, M. Zucco, M. Genovese

UNIVERSITAS STUDIORUM MEDIOLANENSIS



Stefano Olivares

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Ulrik Andersen

Tobias Gehring

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John Templeton Foundation

cost Action MP 1405 Quantum Structure of Spacetime

MIUR

Q-SecGroundSpace

Quantization of the Electromagnetic Field

Classical → *Quantum*

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

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

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

Unitless Coefficients

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

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

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

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"**

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

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

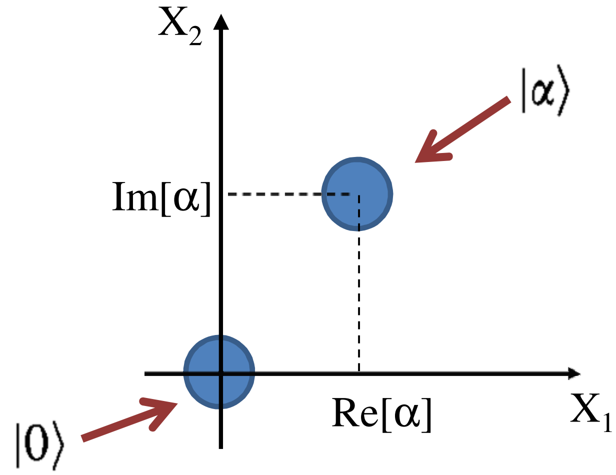
Photon number statistics: $p(n) = \langle n|\alpha\rangle\langle\alpha|n\rangle = \frac{\langle n\rangle^n e^{-\langle n\rangle}}{n!}$ $\quad \langle n\rangle = |\alpha|^2$

Quadrature operators

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

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

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



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

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

Squeezed States

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

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

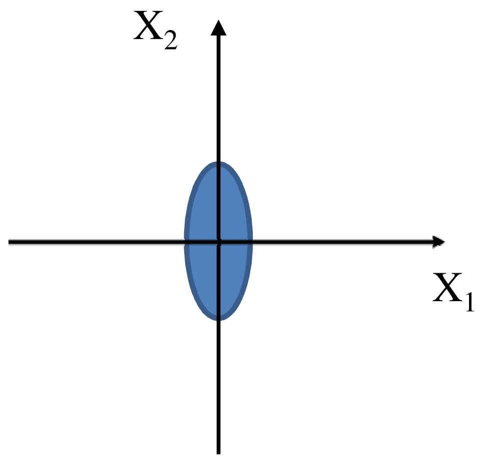
$$\begin{cases} S^\dagger(\xi) a S(\xi) = a\cosh r - a^\dagger e^{i\theta}\sinh r \\ S^\dagger(\xi) a^\dagger S(\xi) = a^\dagger \cosh r - a e^{-i\theta}\sinh r \end{cases}$$

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

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

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

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



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

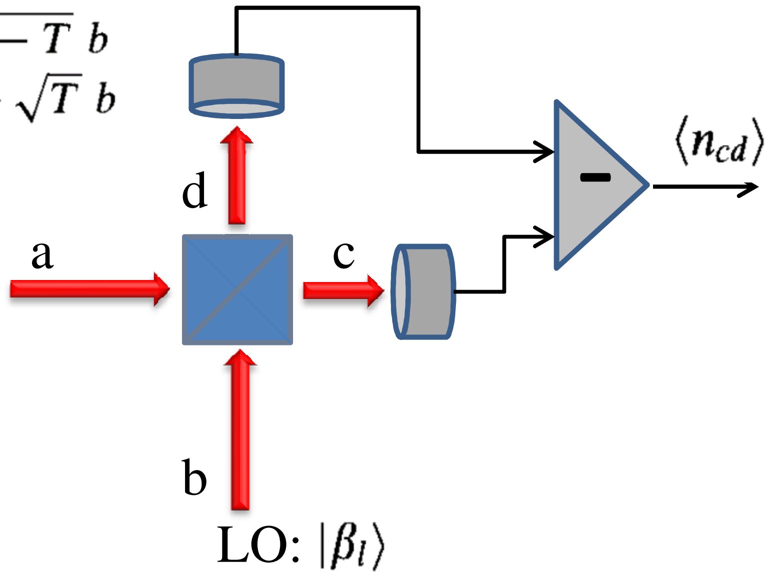
$$X_2 = \frac{1}{2i}(a - a^\dagger)$$

Squeezed Vacuum can be obtained with an OPO operating under threshold

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:

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

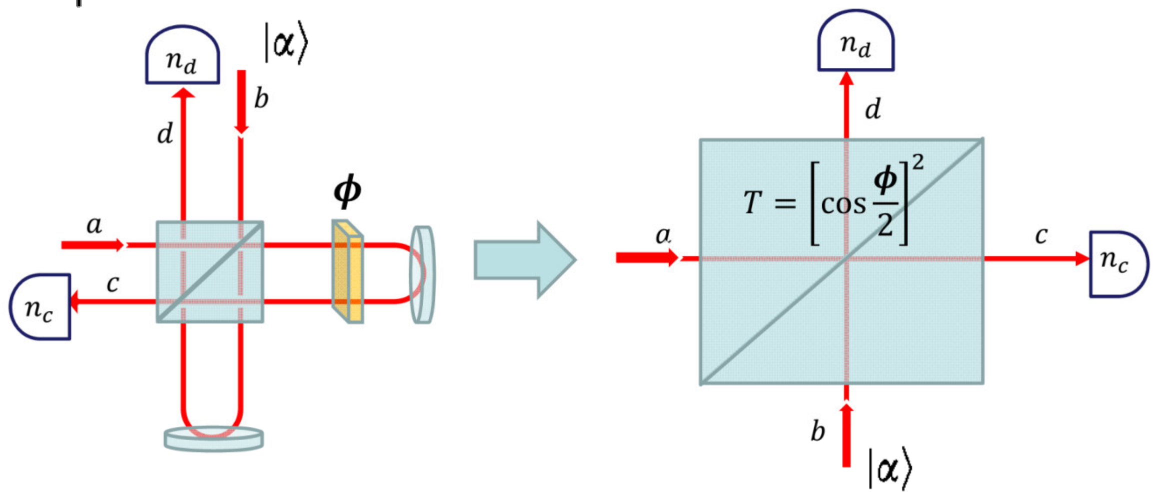
$$\langle n_{cd}\rangle = -2|\beta_l|\langle X(\phi_l + \pi/2)\rangle$$

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

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

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 ϕ_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

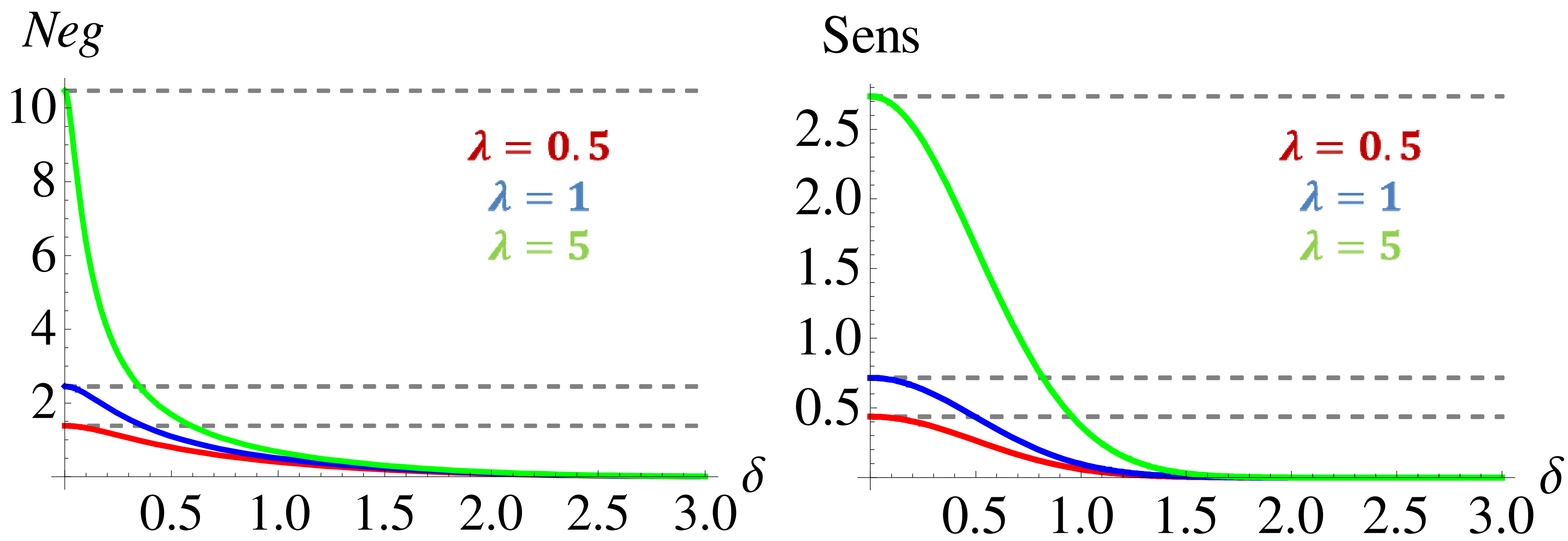
$$\Delta\phi = \frac{\Delta n_{cd}}{|\partial\langle n_{cd}\rangle/\partial\phi_p|} = \frac{e^{-r}}{\sqrt{\langle n\rangle}}$$

- 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

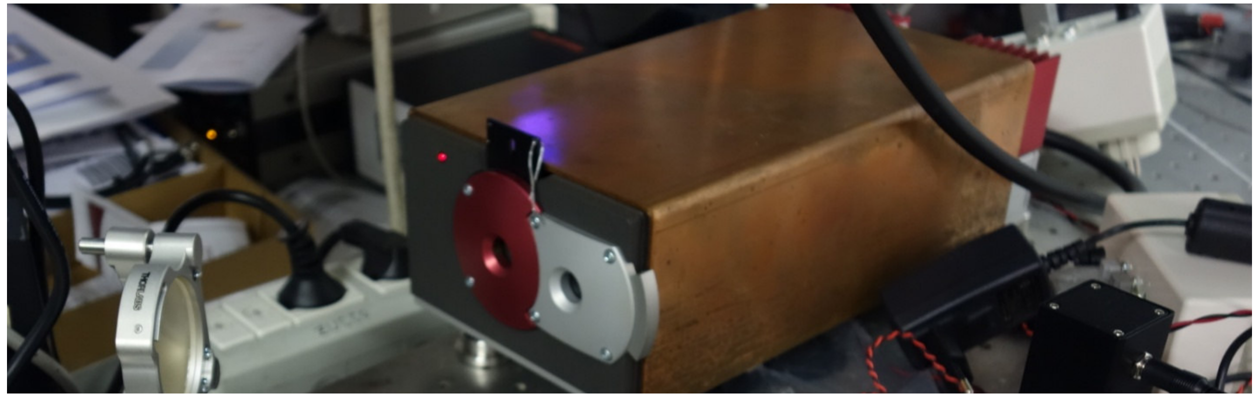
Is Entanglement related to the TWB quantum enhanchement?



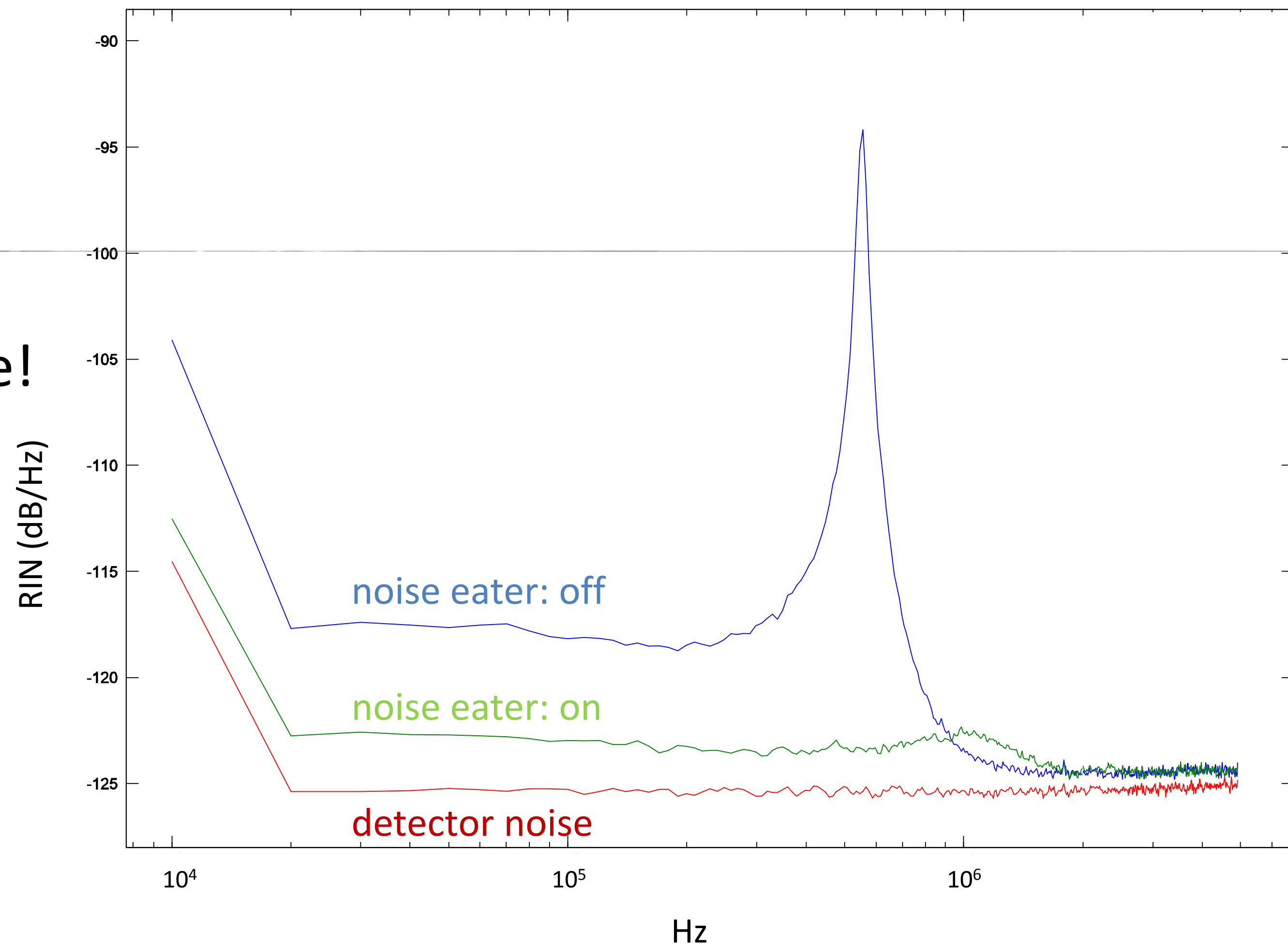
Indeed a clear role of entanglement, measured by negativity [see M.Roncaglia,A.Montorsi, M.G. Phys. Rev A 90, 062303 (2014)]**, is demonstrated.** This is due to the fact that the scheme requires not only perfect photon number correlation, but also a defined phase of the TWB for a coherent interference 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 : $S_2(\xi) = \exp\left\{\xi a^\dagger b^\dagger - \xi^* ab\right\}$ $\qquad \xi = re^{i\psi}$

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

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

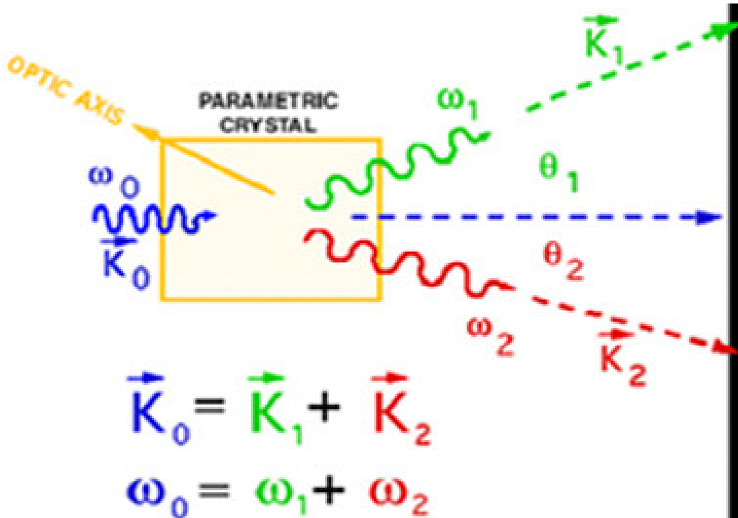
$$\mu = \cosh r$$

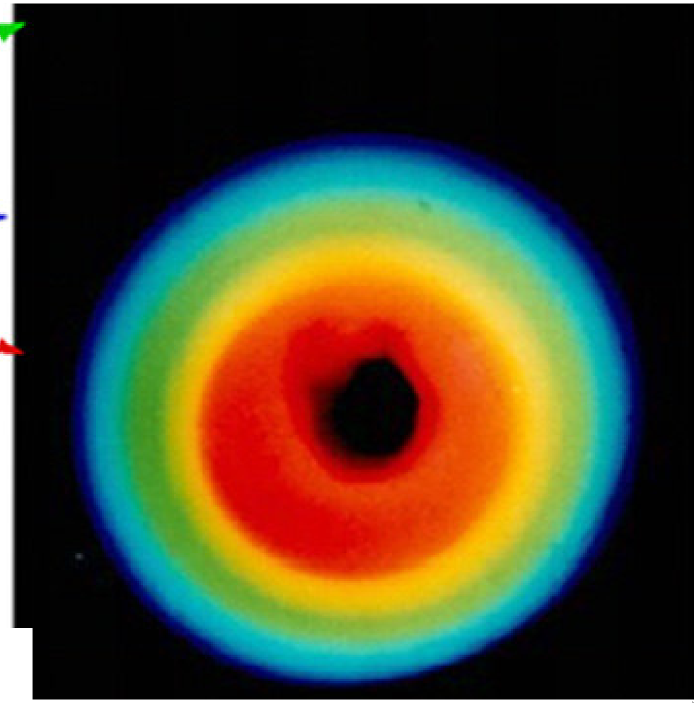
$$\nu = e^{i\psi} \sinh r$$

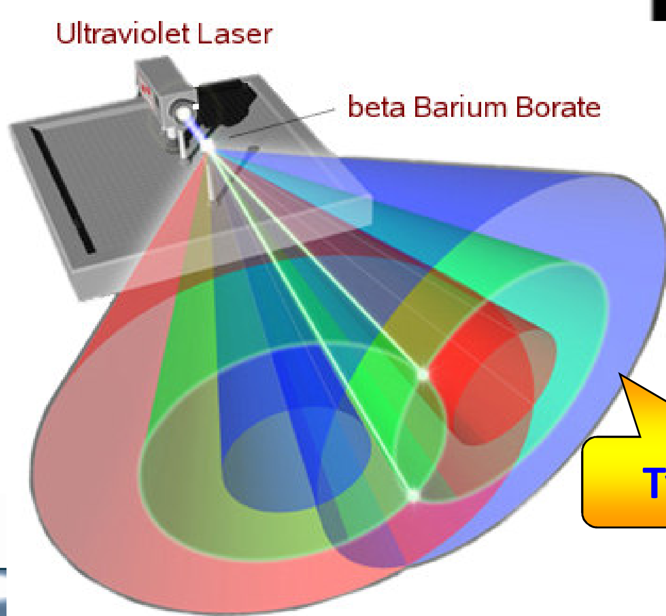
Twin Beam state: $|\mathrm{TWB}\rangle\rangle = S_2(\xi)|\mathbf{0}\rangle = \frac{1}{\sqrt{\mu}} \sum_{k=0}^{\infty} \left(\frac{\nu}{\mu}\right)^k |k\rangle \otimes |k\rangle$

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

PDC: a brief summary







Type-II PDC

Type-I PDC

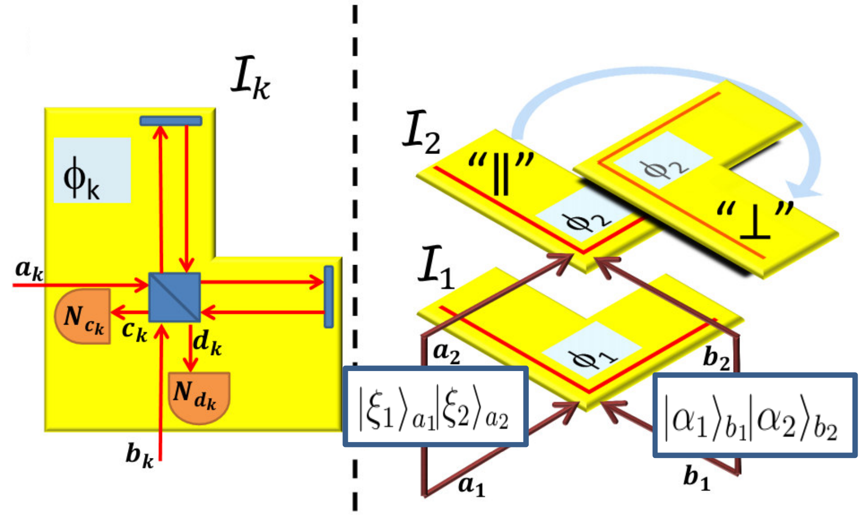
Does squeezed light help also in the case of the Holometer?

$\widehat{C}(\phi_1, \phi_2)$ 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.:

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

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

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

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