ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Quantum enhanced measurements

from ultra-high sensitivity in absorption measurements
to detection of quantum gravity effects

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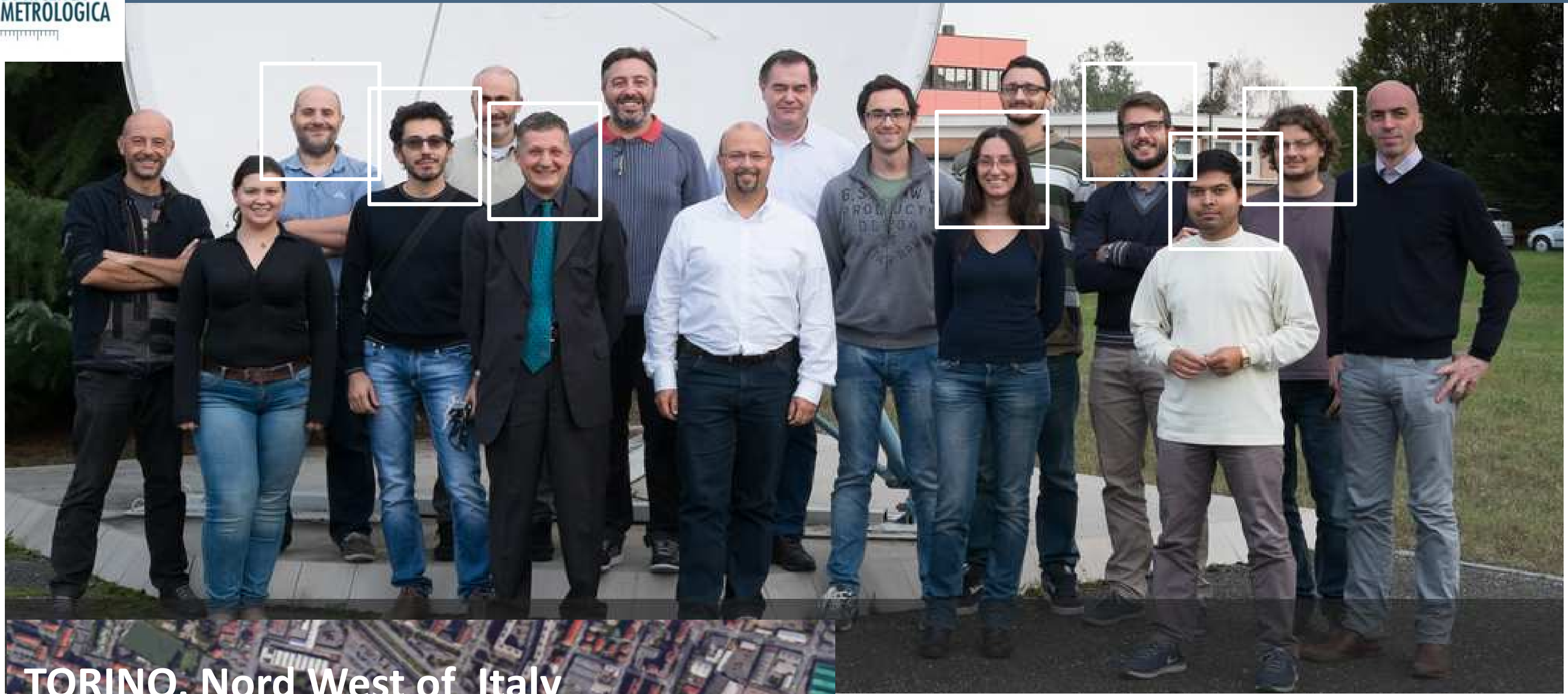
Our team: Quantum Optics Group at INRIM



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- **Alessio Avella**
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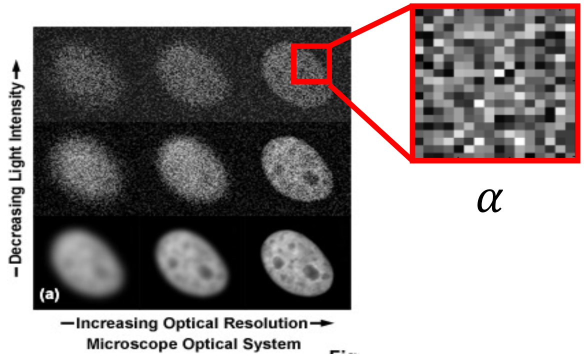
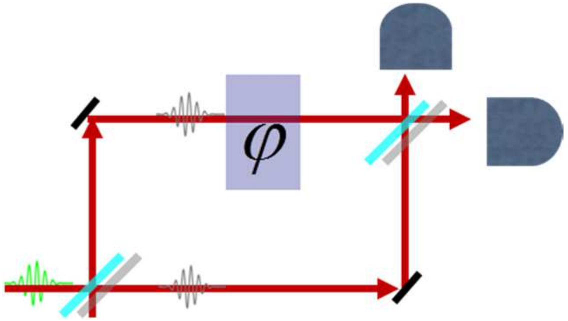
- **Siva Pradyumna (PhD)**
- **Nigam Samataray (Former PhD)**
- **Fabio Scafirimuto(Former M Th)**
- **Marco Genovese**

- Optical measurements are widespread in many branch of science.
- They are simple to be experimentally implemented and they can be used for a lot of different scopes, from development of new technologies to investigation of more fundamental questions.

Imaging and absorption measurements



Interferometry and phase measurements



Using classical light, said N the mean number of photons in the beam, it holds:

$$\Delta\alpha_{cl} \geq \frac{1}{\sqrt{N}}$$

Shot noise limit

$$\Delta\phi_{cl} \geq \frac{1}{\sqrt{N}}$$

N.B. Light power cannot be increased arbitrarily!

Motivation

If classical light is used, we are limited by the shot noise.

- It comes from the quantization of the field and is an unovoidable limit in sensitivity.
- It scales as $^1/_{\sqrt{N}}$ but often we cannot increase N arbitrarly.
- In high precision experiments it can be the principal source of uncertainty, in these cases going beyond the shot noise limit would be extremely important.

But…

Quantum light can improve the information gained /photon !

Therefore, using opportune "quantum states of light" it is possible to go below the shot noise limit.

→ **Quantum enhanced measurements**

Quantum states for imaging applications

- Quantum states of light can offer important advantages in imaging protocols, in particular in presence of low illumination level.

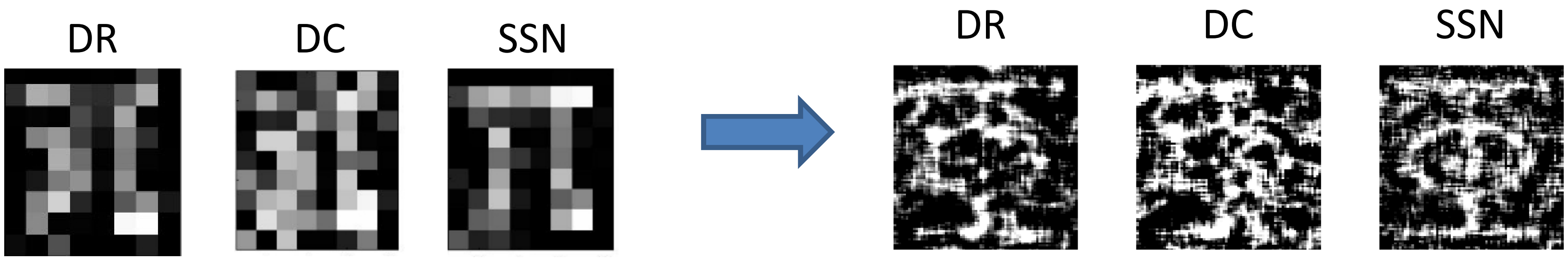
PHYSICAL REVIEW A **77**, 053807 (2008)

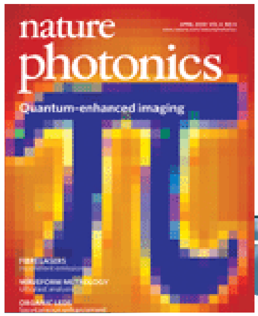
High-sensitivity imaging with multi-mode twin beams

E. Brambilla, L. Caspani, O. Jedrkiewicz, L. A. Lugiato, and A. Gatti
INFM-CNR-CNISM, Dipartimento di Scienze Fisiche e Matematiche, Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy
(Received 28 September 2007; revised manuscript received 20 December 2007; published 8 May 2008)

- Sub-shot noise imaging has been realized in our labs in 2010.

From a proof of principle experiment we've recently moved toward real applications implementing a sub shot-noise microsope.





72 pixels at full resolution
Resolution $L = 480\,\mu m$

[G. Brida *et al*, Nat. Phot. 4, 227 (2010)
PRA 83, 033811 (2011)]

8000 pixels at full resolution
Resolution $L = 5\mu m$

[Samantaray N, Ruo-Berchera I, Meda A, Genovese M,
Light: Science and Appl. 6, e17005(2017)]

Quantum states and interferometric schemes

- Advantages of quantum optical states in intereferometric schemes have been studied theoretically in the '80 by Caves.

PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)

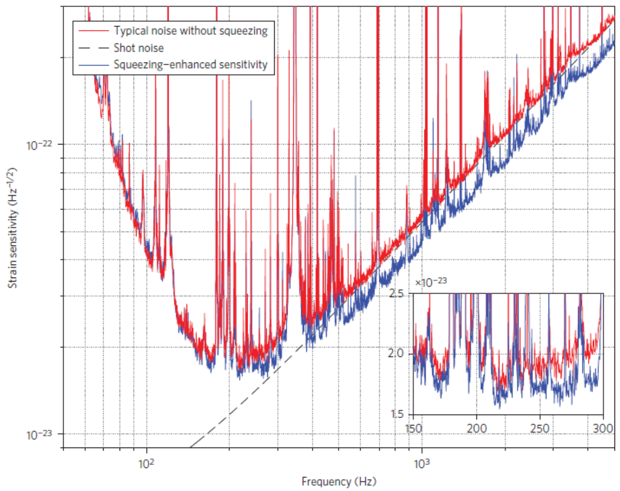
- Recently their use has been experimentally implemented in the field of gravitational wave detection, where high sensitivity is required.

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*

2.15 ± 0.05 dB improvement



Quantum states of light

They are optical states which cannot be described by the semi-classical theory of light.

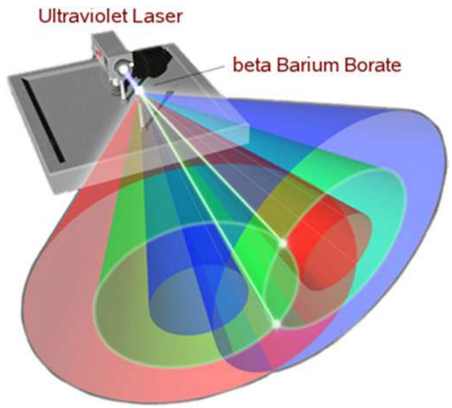
- They can have properties very far from the coherent states
- Not every quantum state is easly experimentally realizable!

For example, Fock states have fantastic potential properties but their realization for high *n* is extremely challenging.

We focus on two states, easily experimentally implementable with current technologies and used in our labs.

Squeezed vacuum
Twin-Beam state (TWB)

Experimentally these states are obtained by non linear optical wave mixing processes: pairs of photons are emitted into degenerate (single-mode squeezing, e.g. squeezed vacuum) or non degenerate (TWB) modes.



Parametric Down Conversion (PDC)

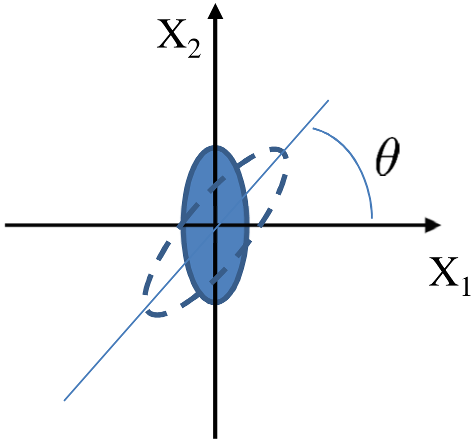
Squeezed vacuum states

$$|\zeta\rangle = S(\zeta)|0\rangle \quad \text{where} \quad S(\zeta) = \exp\left(\frac{1}{2}\zeta^* a^2 - \frac{1}{2}\zeta a^{+2}\right)$$ Squeezing Operator

$\zeta = r\,\exp(i\theta)$ r, squeezing parameter

- Photon number statistics:

$$\langle n\rangle = \sinh^2 r \qquad (\Delta n)^2 = 2\cosh^2 r\,\sinh^2 r$$



- Quadrature operators have uncertainty:

$$X_1 = \frac{1}{2}(a + a^+) \qquad X_2 = \frac{1}{2i}(a - a^+)$$

$$[X_1, X_2] = {}^{i}/_{2} \qquad \Delta X_1 \Delta X_2 \geq {}^{1}/_{4}$$

$$(\Delta X_1)^2_{sq} = {}^{1}/_{4}\, e^{-2r} \quad < (\Delta X_1)^2_{coh}$$
$$(\Delta X_2)^2_{sq} = {}^{1}/_{4}\, e^{2r} \quad > (\Delta X_1)^2_{coh}$$

saturates Unc. Relation

$$\Delta X_1 \Delta X_2 = {}^{1}/_{4}$$

Twin-beam state (TWB)

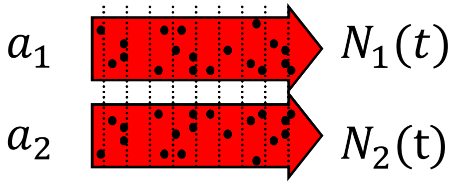
$$|\Psi^{TWB}\rangle_{12} = S_{12}(\zeta)|0\rangle_{a_1}|0\rangle_{a_2} \quad \text{where} \quad S_{12}(\zeta) = \exp(\zeta a_1^{+} a_2^{+} - \zeta^{*} a_1 a_2)$$

- Twin-beam in the Fock basis:

$$|\Psi^{TWB}\rangle_{12} = S_{12}(\zeta)|0\rangle_{a_1}|0\rangle_{a_2} = \sum_{m=0}^{\infty} c_m |m,m\rangle_{a_1 a_2}$$

- The two modes are maximally entangled in the photon number:

$$\langle\Psi^{TWB}\left|\left(m_{a_1} - m_{a_2}\right)^{M}\right|\Psi^{TWB}\rangle_{a_1 a_2} = 0$$



$$\sigma = \frac{Var(N_1 - N_2)}{\langle N_1 + N_2\rangle} = 1 - \eta < 1$$

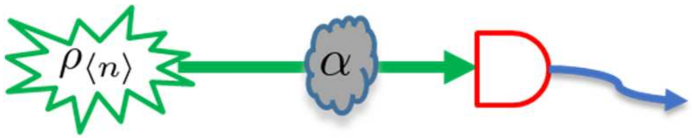
η: system losses

Ideal TWB $\sigma = 0$;
Coherent state $\sigma = 1$

- The two-modes are also correlated in quadratures :

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

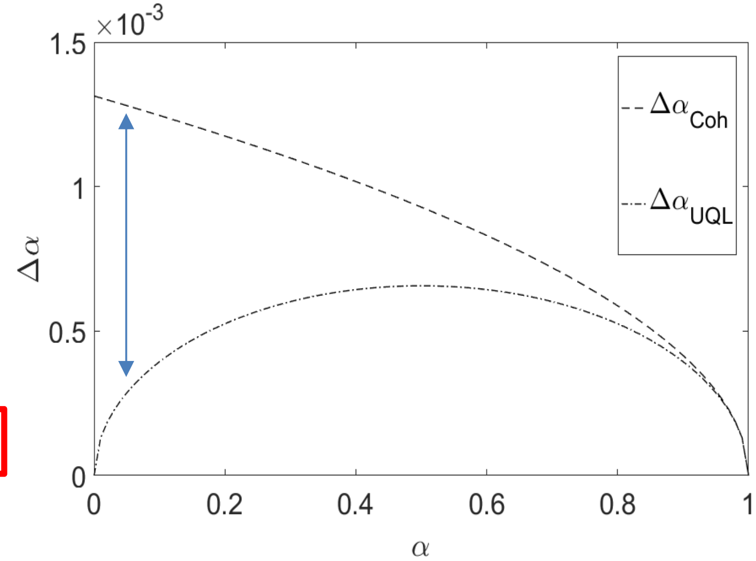
Absorption estimation: theoretical approach



α is the absorption of the sample

With which uncertainty can we estimate it?

- Ultimate quantum limit (UQL): $$\Delta\alpha_{UQL} = \sqrt{\frac{\alpha(1-\alpha)}{\langle n\rangle}}$$



Best quantum enhancement for small absorption

Which estimator can we use?

$$\alpha_{DR} = 1 - \frac{N_P}{\langle N_R\rangle}$$

Most intuitive estimator, single mode strategy

$\langle N_R\rangle$ is the average number of photons in absence of the sample

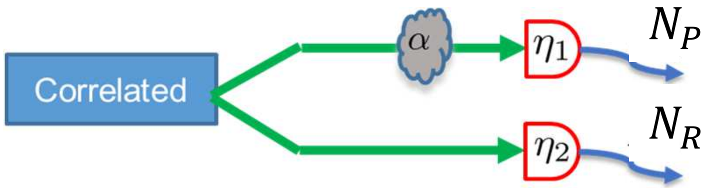
- For coherent state: $$\Delta\alpha_{Coh} = \sqrt{\frac{1-\alpha}{\langle n\rangle}}$$

- Fock states reaches UQL with limitations: $$\Delta\alpha_{UQL} = \Delta\alpha_{Fock} \qquad \langle n\rangle \geq 1$$

[Adesso G., *et al*, PRA, 79(4), 040305 (2009)]

Absorption estimation: Two-Mode (TM) approach

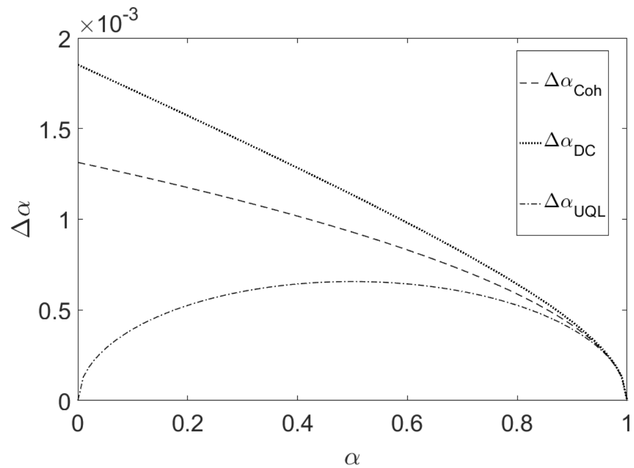
The experimental approach must take into account the importance of **unbiased strategy**, therefore a two-mode approach is the most appropriate.



Classical or quantum correlation

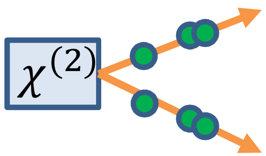
- **Proposed TM estimator:** $\alpha_{TM} = 1 - \frac{N_P}{N_R}$

$$\Delta\alpha_{TM} = \sqrt{\frac{(1-\alpha)[2\sigma(1-\alpha)+\alpha]}{\langle N_R \rangle}}$$



Classically at best $\sigma = 1$ ($\Delta\alpha_{DC}$)

Twin-beam, in the lossless detection case ($\sigma = 0$):



$$\Delta\alpha_{TM}^{(TWB)} = \sqrt{\frac{\alpha(1-\alpha)}{\langle N \rangle}} = \Delta\alpha_{UQL}$$

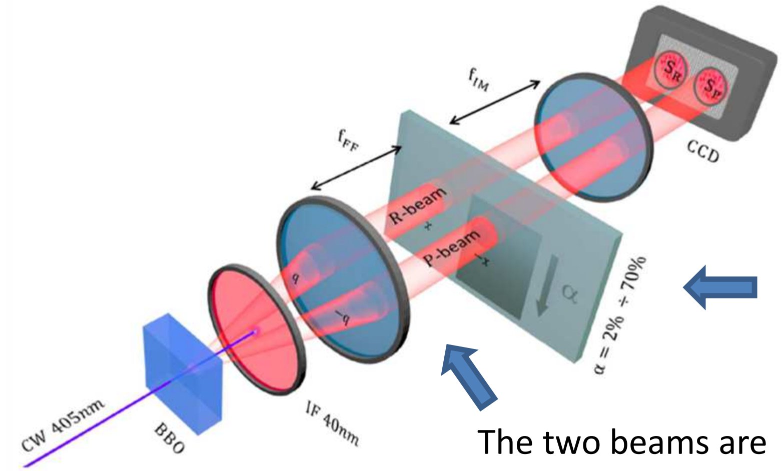
$\forall \langle N \rangle$!!

Twin beam reaches the UQL unconditionally for any N

Role of losses for different estimators is deeply discussed in [E. Losero et al. arXiv:1710.09307]

Experimental implementation at INRiM

The experimental set-up



From each image N_P and N_R are collected by a CCD and estimation of α is performed

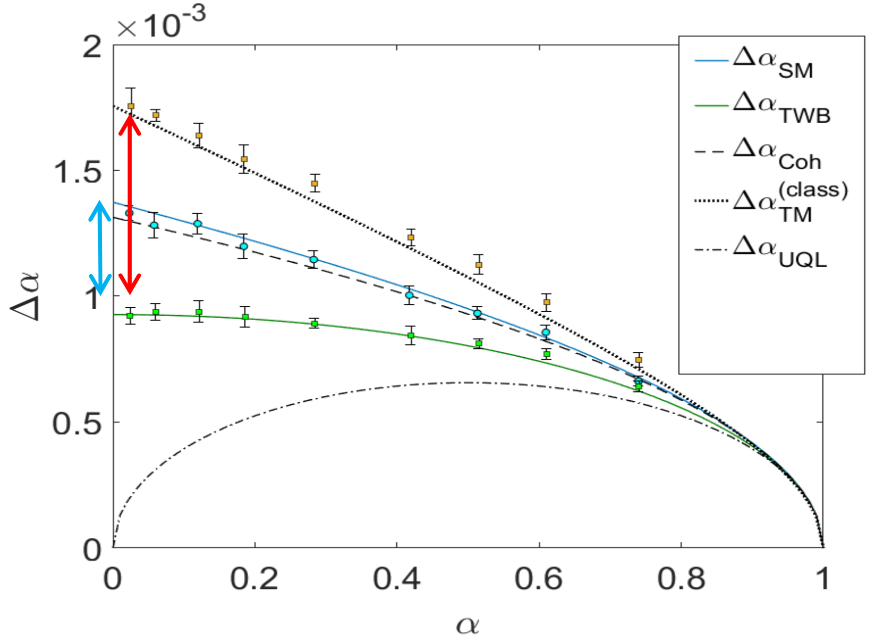
$$\alpha_{TM} = 1 - \frac{N_P}{N_R}$$

$$\alpha_{DR} = 1 - \frac{N_P}{\langle N_P^0 \rangle}$$

The probe beam *(P)* passes trought the sample, the reference *(R)* goes to the detector

The two beams are perfectly correlated in the photon number

TWB generation by PDC



TWB advantage over TM cl **>2**

TWB advantage over SM **>1.4**

Best quantum advantage reported in optical loss estimation

Toward an experimental quantum gravity

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

$$l_P = 1{,}6 \cdot 10^{-35}\, m$$
$$t_P = 5{,}4 \cdot 10^{-44} s$$
$$E_P = 1{,}2 \cdot 10^{19} GeV$$

In particular, according to C. Hogan, phenomenological theory:

C. Hogan

$$[x_i, x_j] = x_k \epsilon_{ijk} i c t_P / \sqrt{4\pi}$$

$$\Delta x_1 \Delta x_2 \geq l_P^2/2$$

holographic uncertainty principle

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

- Due to the presence of l_P this noise is negligible at normal scales, therefore an experimental confirmation of this model is extremely challenging.

[C. Hogan, Arxiv: 1204.5948; C. Hogan, Phys. Rev. D 85, 064007 (2012)]

Holographic noise in one interferometer

The presence of holographic noise in one interferometers manifests as a noise which affects the position of the beam-splitter.
Its order of magnitude can be estimated as:

$$\Delta X \sim \sqrt{L\, l_P}$$

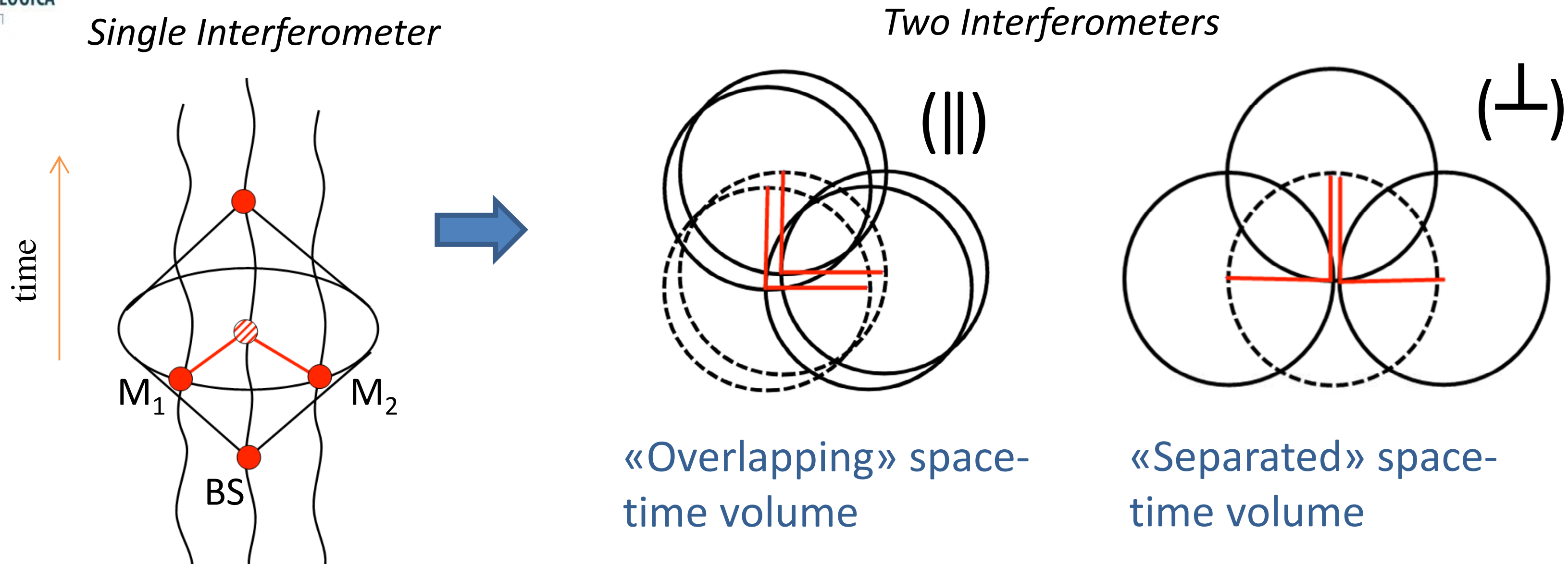
- an interferometer is able to «accumulate» the hologrphic noise, $\Delta X \propto \sqrt{L}$
- Due to l_P the holographic noise is covered by other noises!

To overpass this problem Hogan proposed the so called «**holomete**r»

The holometer is a system of two Michelson interferometers placed close to each other, whose arms can be placed in two different configurations.

Experimentally realized at Fermilab, $L \sim 40m$

Holographic noise in the holometer



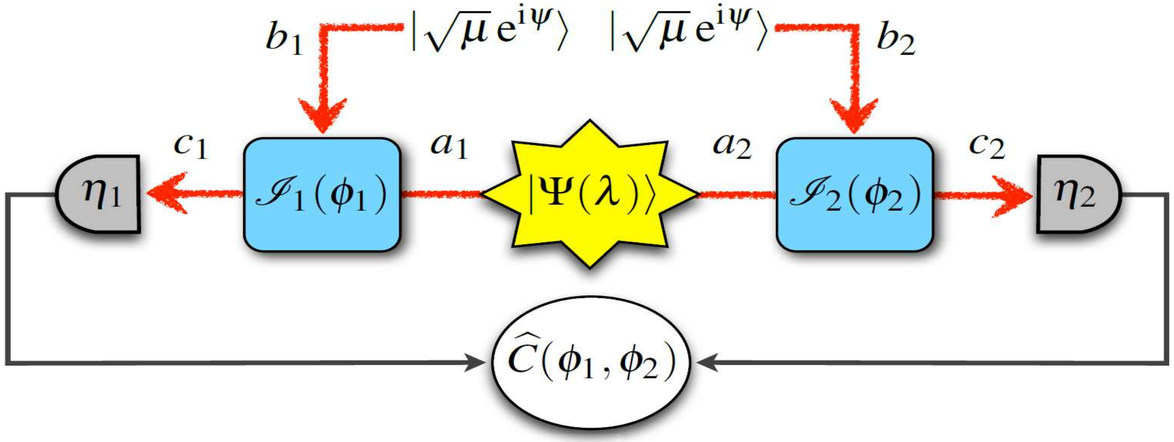
@**Fermilab** HOLOMETER : *principle of operation*

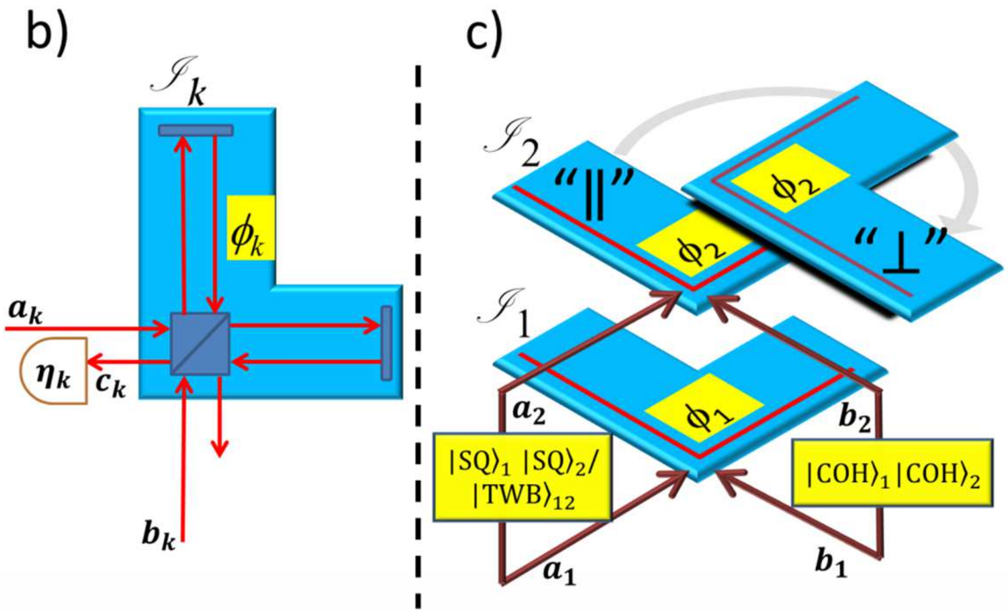
- holographic noise → correlated (in ‖ configuration)
- other sources of noise → uncorrelated (in ⊥ and ‖ both configuration); their contribution vanish over a sufficiently long integration time.

➡ Performing a measurement of cross correlation between the two interferometers output we can detect, with current technology, the holographic noise! ($L \sim 40\ m$)

- Control measurement can be performed «turned off» HN correlation just by separating the space-time volumes (⊥ conf.)

Can holometer performances improve using quantum light?



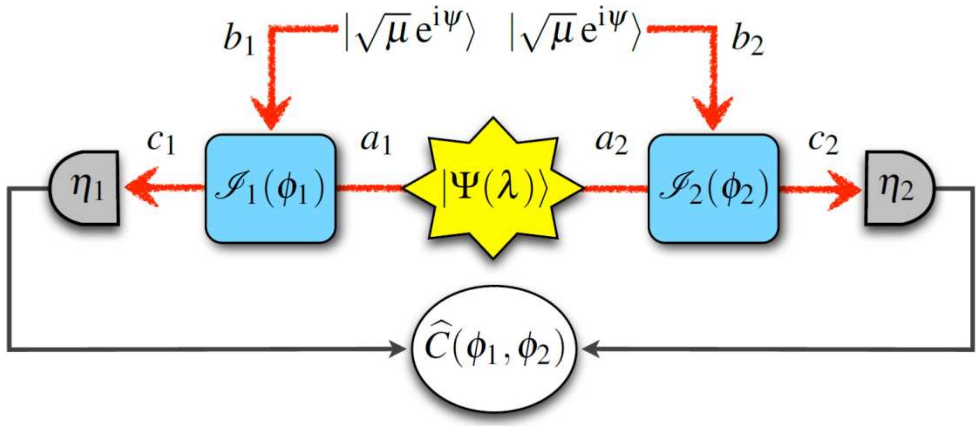


two different input states in the classically unused doors are considered:

- Squeezed vacuum state
- TWB

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

Squeezed vacuum states in input



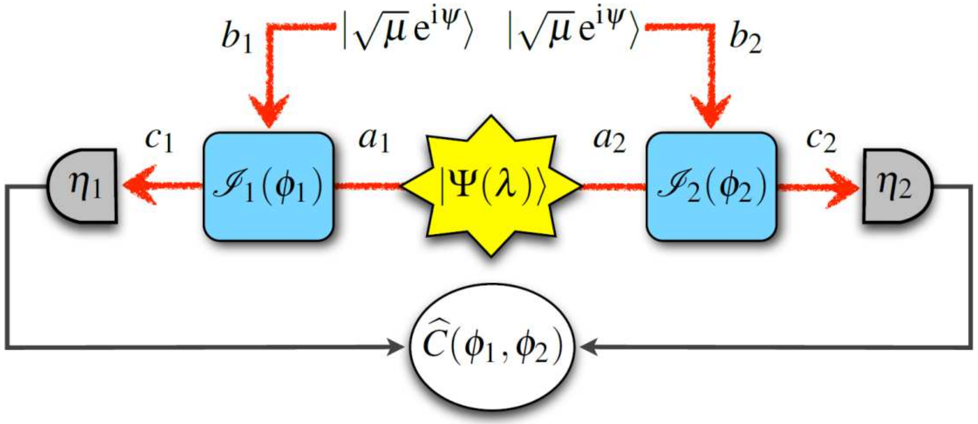
- **Quantum state:** $$|\xi\rangle_{a_1} \otimes |\xi\rangle_{a_2} = S_{a_1}(\xi)S_{a_2}(\xi)|0\rangle_{a_1} \otimes |0\rangle_{a_2}$$

- **Measured observable:** $$\widehat{C} = \{Y_1(\phi_1) - \mathscr{E}[Y_1]\}\{Y_2(\phi_2) - \mathscr{E}[Y_2]\}$$

- **Phase covariance est.:** $$\mathscr{E}_{\parallel}[\delta\phi_1\delta\phi_2] \approx \frac{\mathscr{E}_{\parallel}[Y_1Y_2] - \mathscr{E}_{\perp}[Y_1Y_2]}{\left\langle \partial^2_{\phi_1,\phi_2} Y_1(\phi_0)Y_2(\phi_0)\right\rangle}$$

- **Principle:** each squeezed state reduces the photon noise in each interferometer (still uncorrelated!), then the covariance performs statistical cancellation (like the Fermilab Holometer)

Twin-Beam state in input



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

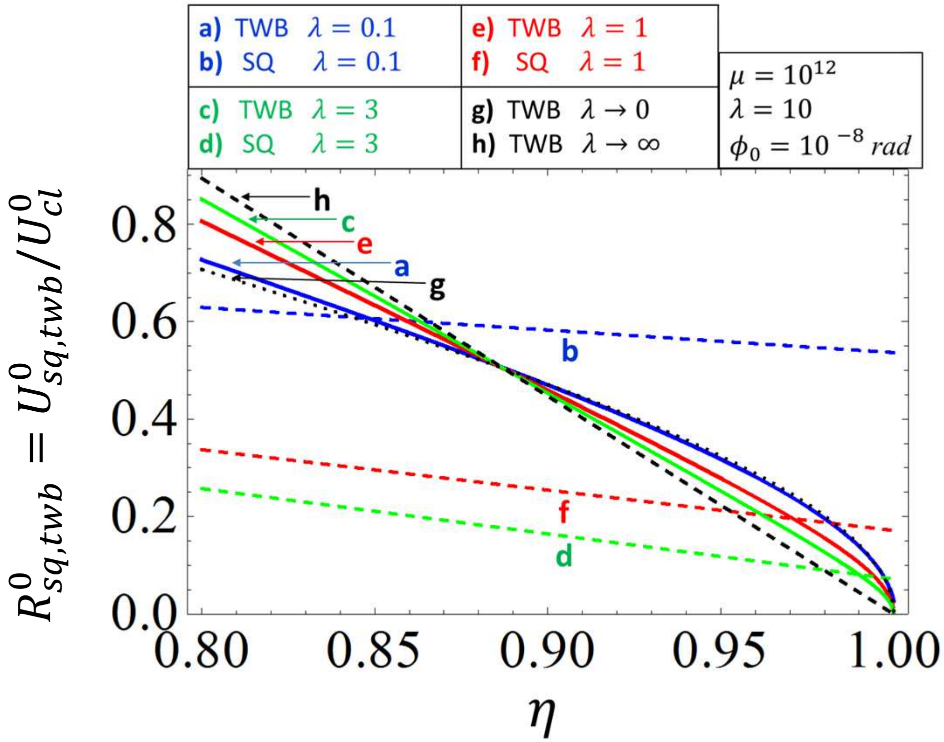
- **Measured observable:** $$\widehat{C}(\phi_1,\phi_2) = [N_1(\phi_1) - N_2(\phi_2)]^2 = N_1^2 + N_2^2 - 2N_1N_2$$

- **Phase covariance est.:** $$\mathscr{E}_{\parallel}[\delta\phi_1\delta\phi_2] \approx \frac{\mathscr{E}_{\parallel}[N_1N_2] - \mathscr{E}_{\perp}[N_1N_2]}{\langle \partial^2_{\phi_1,\phi_2} N_1(\phi_0)N_2(\phi_0)\rangle}$$

- **Principle:** noise in each interferometer is higher than shot-noise but they are perfectly correlated an can be subtracted (different from a statistical cancellation)

Theoretical expectation of the quantum enhancement

The performance of quantum light in the experimental situation striclty depends on the losses



$R^0 < 1$

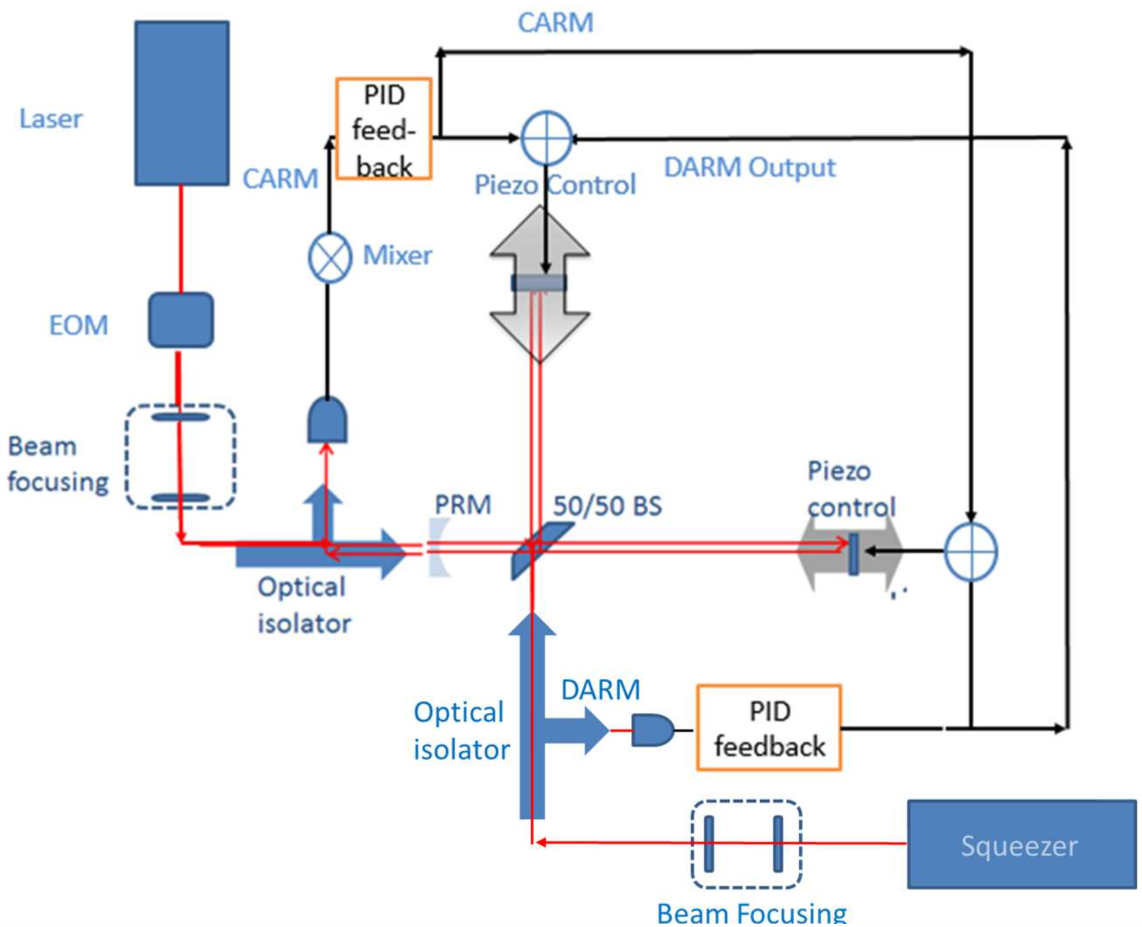
quantum enhancement!

Using TWB R^0 drops to 0!

Uncertainty of phase correlation for TWB can be arbitrarily small (not depends on the intensity) thanks to entanglement! But it is very sensitive to losses.

The experimental set-up

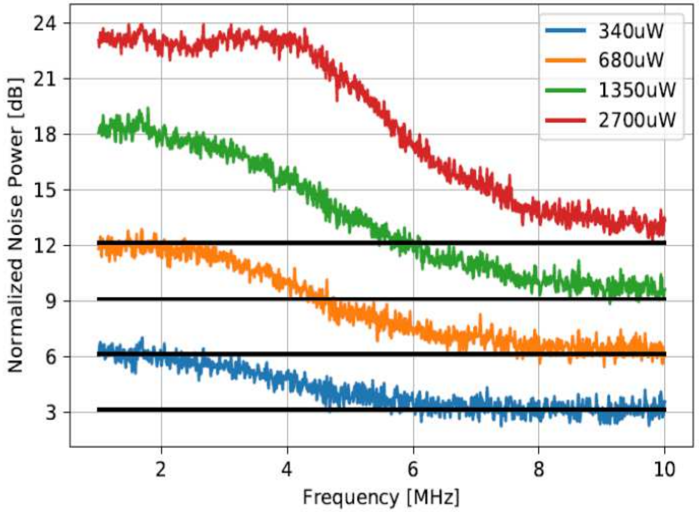
Scheme of one of the two Michelson interferometers, developed in strict collaboration with the Technical University of Denmark (DTU)



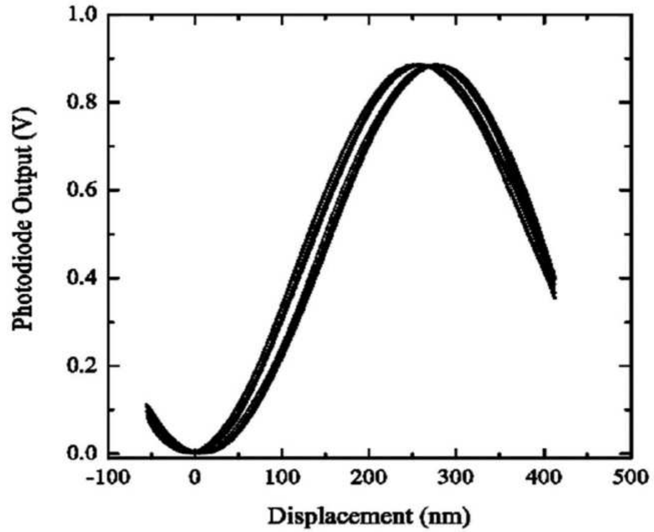
λ=1064nm
Δv=1kHz
r>99,8%
QE = 0,99
L = 0,8m
d=8cm

Preliminary measurements

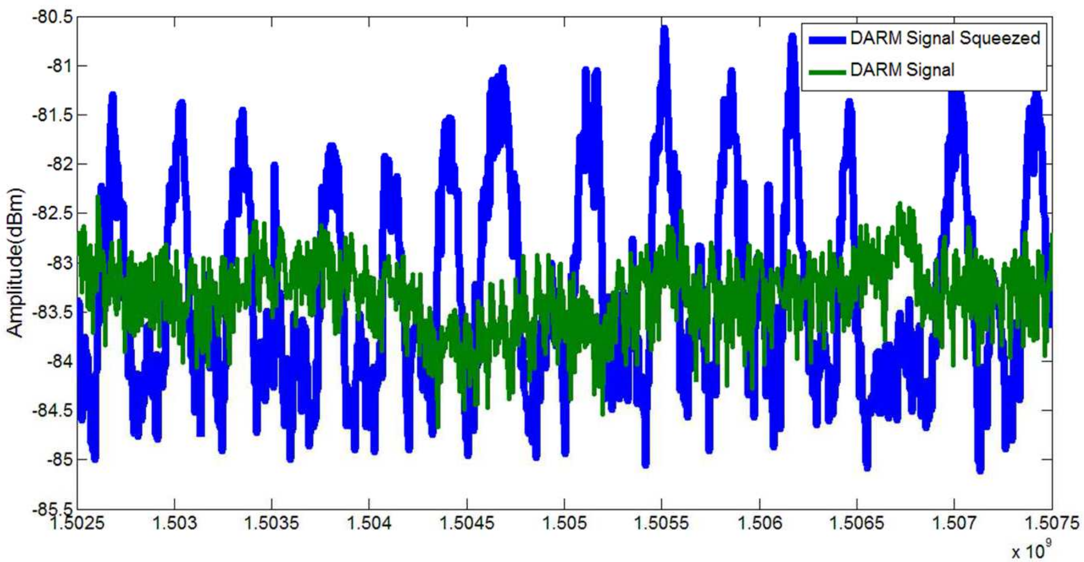
SHOT NOISE MEASUREMENTS ON LASER



VISIBILITY



SQUEEZING ESTIMATION (at the moment 1dB)



Next steps:

- Improvement of the squeezing
- Injection of TWB state
- Measurements on the coupled system

Final Remarks

- When using classical light the shot-noise limits the sensitivity of the measurement.
- Quantum light, in particular TWB and squeezed vacuum, permits to overcome this limit.
- In absorption measurement we demonstrate how TWB can lead in the ideal case to the UQL. Moreover the best sensitivity per photon never achieved has been experimentally demonstrated.
- In the holometer the use of quantum light can increase the sensitivity. This could offer the possibility of experimentally testing phenomenological models of quantum gravity.

THANK YOU!