

Il rumore quantistico nei rivelatori di Onde Gravitazionali e le tecniche per ridurlo

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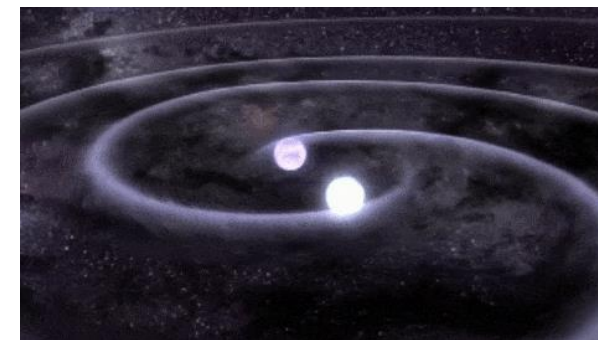


Istituto Nazionale
di Fisica Nucleare

WORKSHOP ET@TO, JUNE 16° 2022 - TORINO

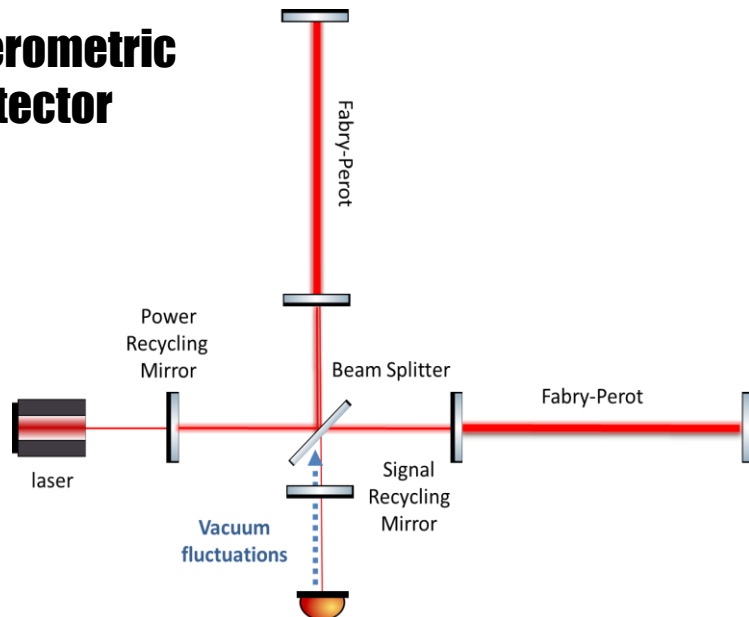
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Gravitational waves

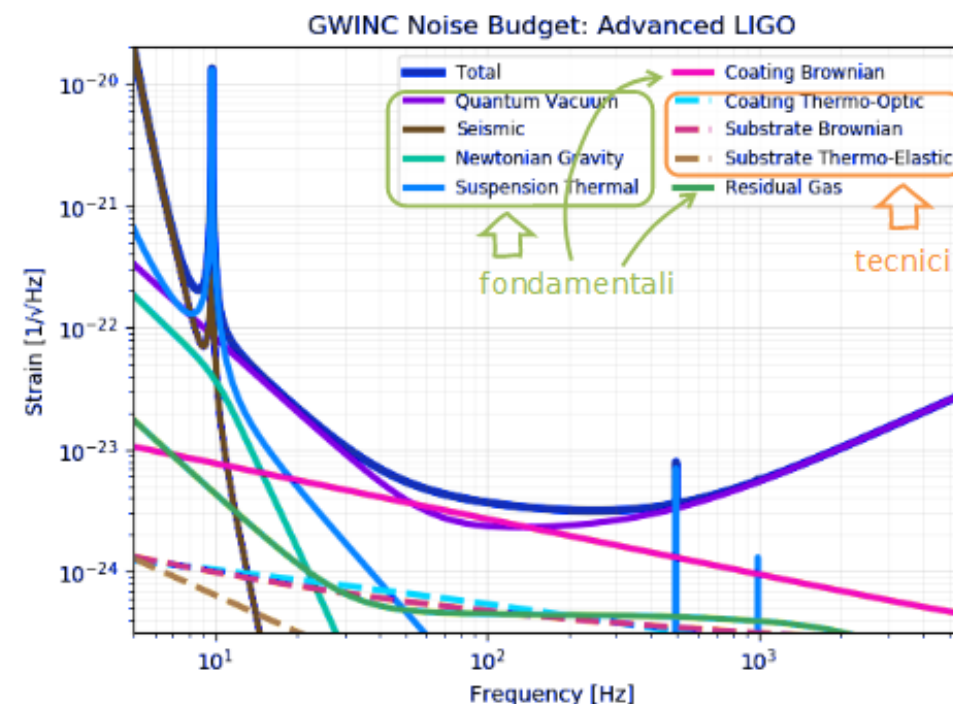


Gravitational waves (GWs) are **very small perturbations** of the space time, so small that their effect on the test masses of a GW interferometric detector can be even confused with the effect of **vacuum fluctuations**!

Interferometric GW detector

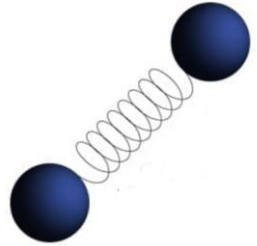


Main sources of noise



What are vacuum fluctuations?

Harmonic oscillator



Mechanical Harmonic Oscillator

$$\mathcal{H} = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 q^2$$

Quantum harmonic oscillator

$$\hat{\mathcal{H}} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2 \hat{q}^2$$

$$\hat{q} = \sqrt{\frac{\hbar}{2m\omega}}(\hat{a}^\dagger + \hat{a})$$

$$\hat{p} = i\sqrt{\frac{m\hbar\omega}{2}}(\hat{a}^\dagger - \hat{a})$$

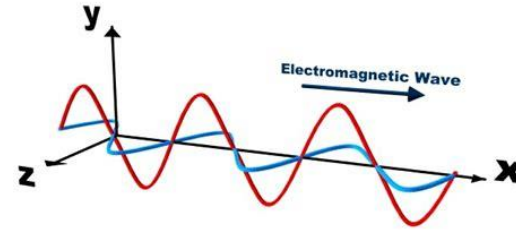
$$\mathcal{H} = \hbar\omega \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right)$$

$$E_n = \hbar\omega \left(n + \frac{1}{2} \right)$$

zero-point energy

$$E_0 = \frac{1}{2}\hbar\omega$$

Light wave



Electro-magnetic oscillator

$$\mathcal{H} = \frac{1}{2} \int \left(\epsilon_0 E^2 + \frac{B^2}{\mu_0} \right) dV$$

Quantized e.m field

$$\hat{\mathcal{H}}_R = \sum_k \sum_\lambda \hbar\omega_k \left(n_{k\lambda} + \frac{1}{2} \right) \quad E_n = \frac{1}{2} \sum_k \sum_\lambda \hbar\omega_k n_{k\lambda}$$

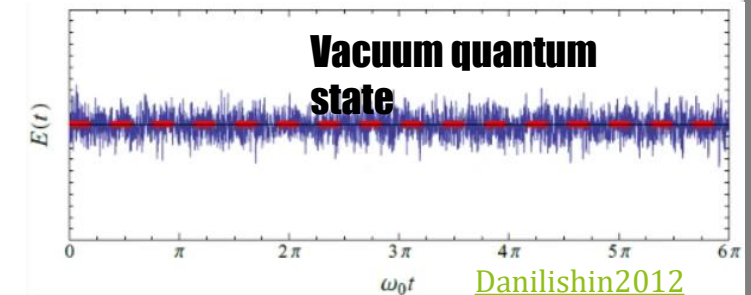
$$E_R = E_n + E_0$$

vacuum fluctuations

$$E_0 = \frac{1}{2} \sum_k \sum_\lambda \hbar\omega_k$$

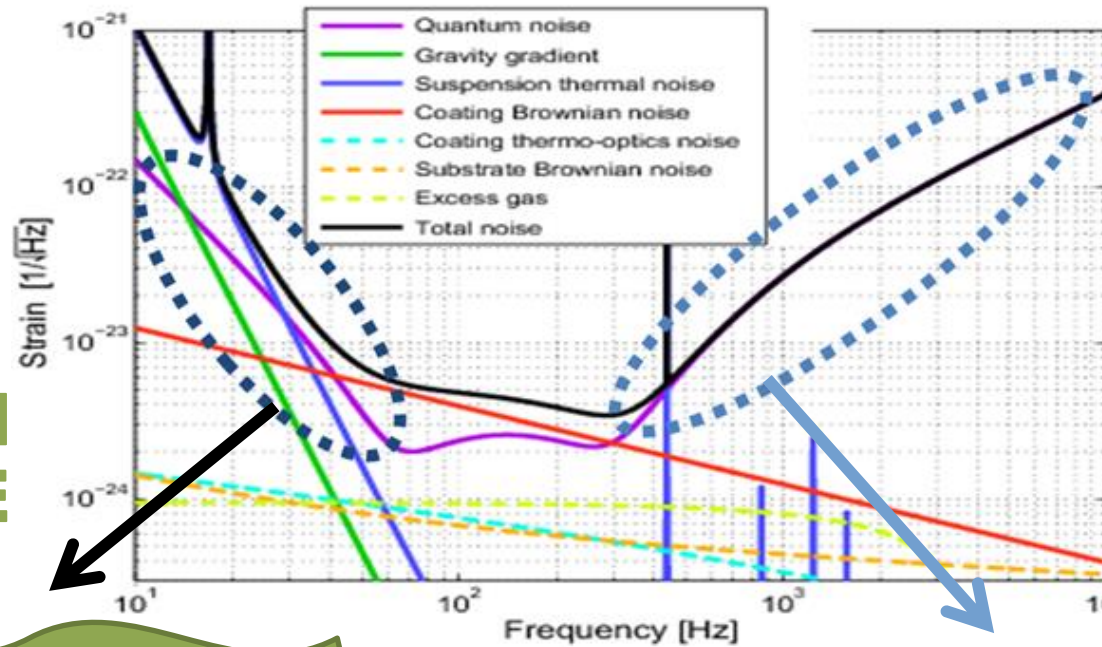
$\mathbf{k} \rightarrow$ mode

$\lambda \rightarrow$ polarization



Quantum noise in Advanced Virgo

Frequency-dependent response of the instrument

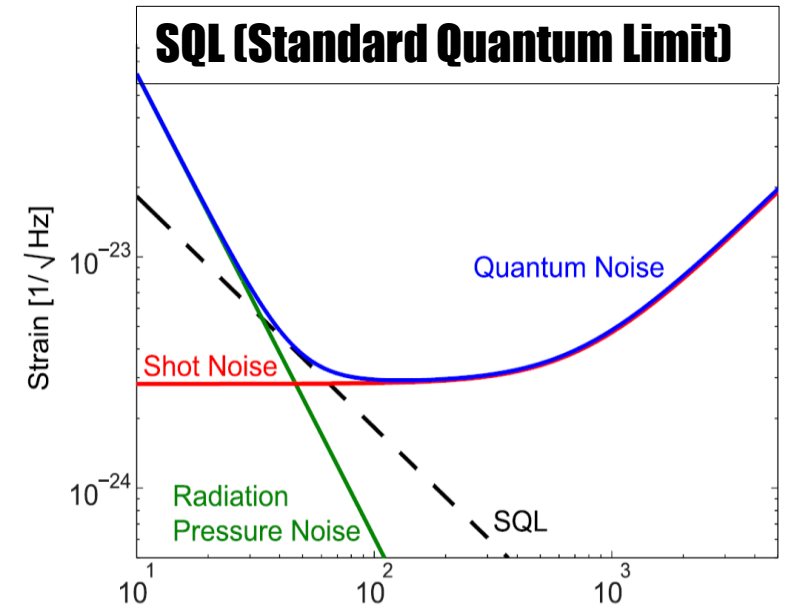


**RADIATION
PRESSURE
NOISE**

Vacuum amplitude-fluctuations, more evident at lower frequencies.

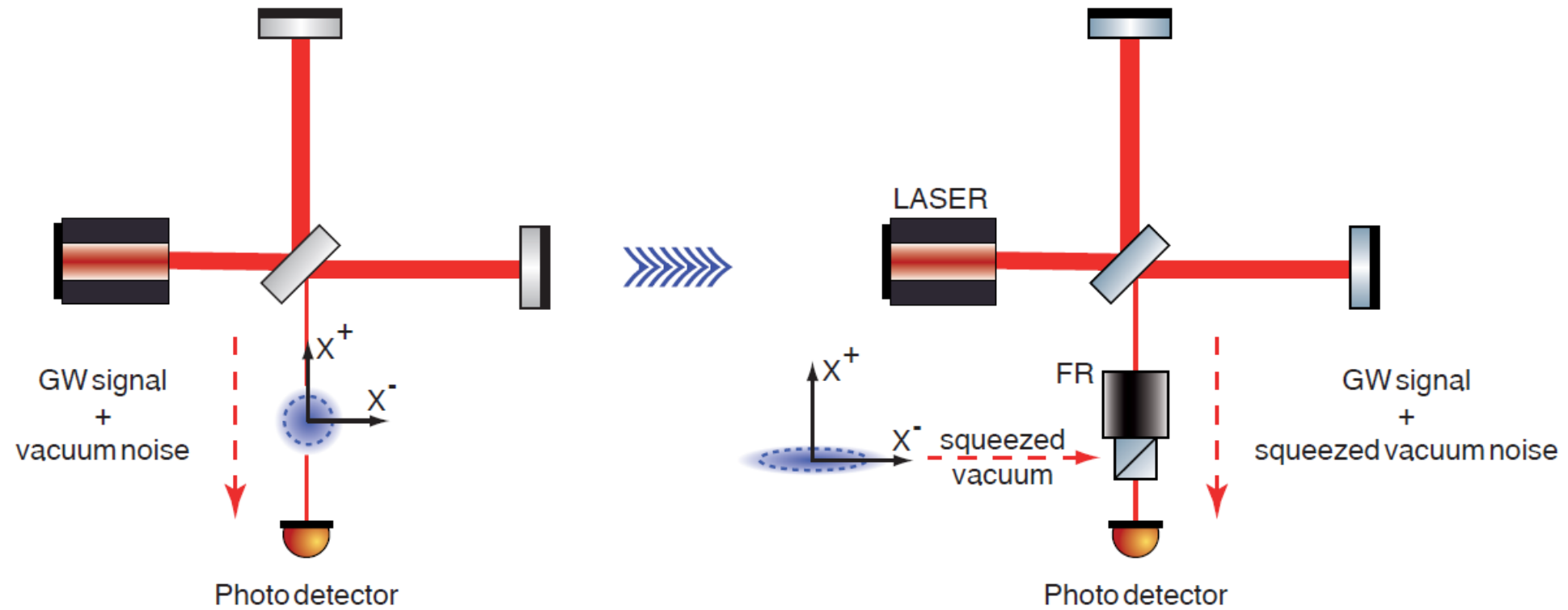
**SHOT
NOISE**

Vacuum phase-fluctuations more evident at higher frequencies



Proposed solution: squeezed vacuum state injection

C. M Caves. Physical Review D, 23(8):1693, 1981



Towards the definition of squeezed states of light

Electro-magnetic field in terms of quadrature operators

$$\hat{E}_x = E_0 \sin(kz) \left(\hat{X} \cos \omega t + \hat{Y} \sin \omega t \right)$$

Amplitude quadrature

Phase quadrature

$$\hat{X} = \sqrt{\frac{m\omega}{2\hbar}} \hat{q} = \frac{1}{2}(\hat{a}^\dagger + \hat{a})$$

$$\hat{Y} = \frac{1}{\sqrt{2m\hbar\omega}} \hat{p} = \frac{1}{2}i(\hat{a}^\dagger - \hat{a})$$

Heisenberg Uncertainty Principle

$$\langle (\Delta \hat{X})^2 \rangle \langle (\Delta \hat{Y})^2 \rangle \geq 1$$

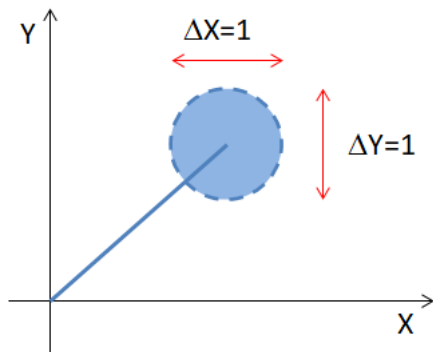
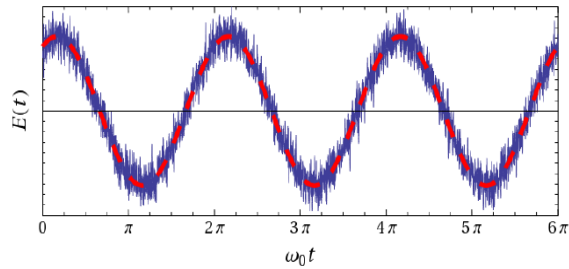
Minimum uncertainty states

$$\langle (\Delta \hat{X})^2 \rangle \langle (\Delta \hat{Y})^2 \rangle = 1$$

Squeezed states of light

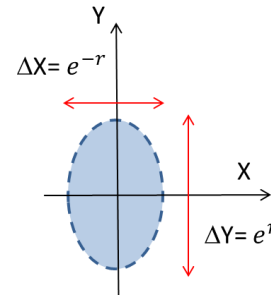
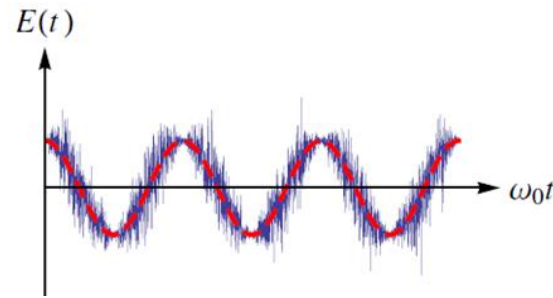
Coherent states

$$\langle (\Delta \hat{X})^2 \rangle_c = \langle (\Delta \hat{Y})^2 \rangle_c = 1$$



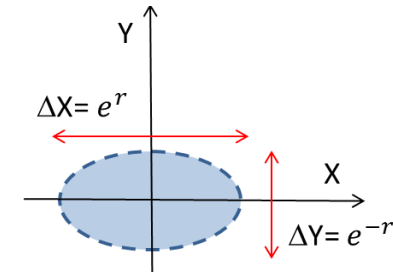
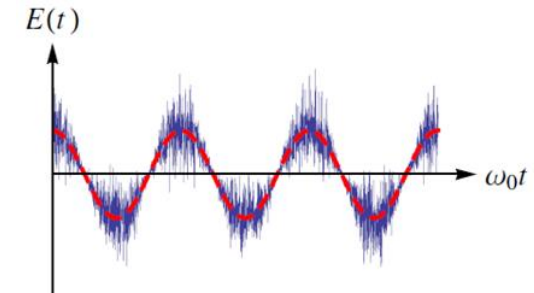
Amplitude-squeezed states

$$\langle (\Delta \hat{X})^2 \rangle_s = e^{-r} \quad \langle (\Delta \hat{Y})^2 \rangle_s = e^r$$



Phase-squeezed states

$$\langle (\Delta \hat{X})^2 \rangle_s = e^r \quad \langle (\Delta \hat{Y})^2 \rangle_s = e^{-r}$$



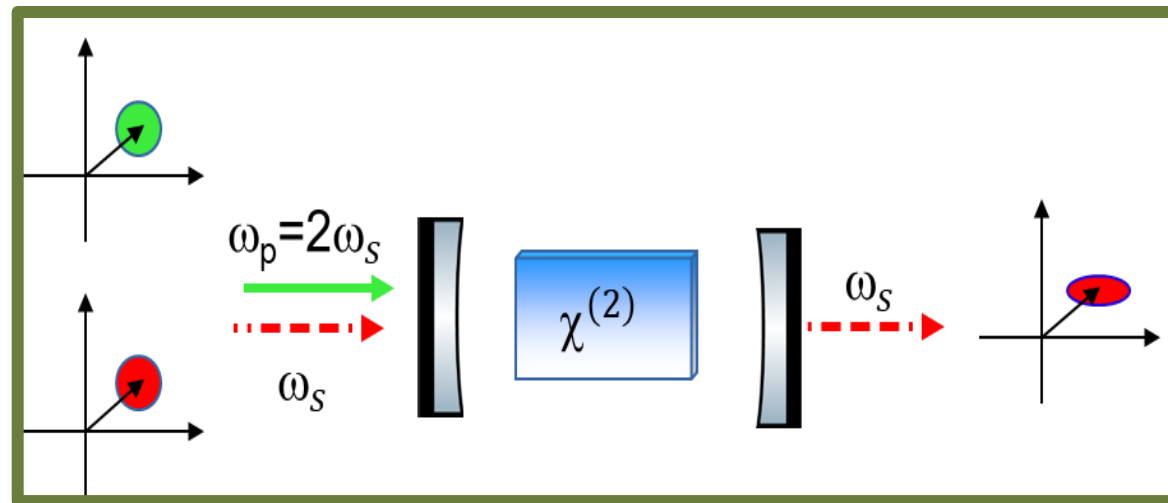
Squeezed vacuum generation via OPO

Nonlinear processes

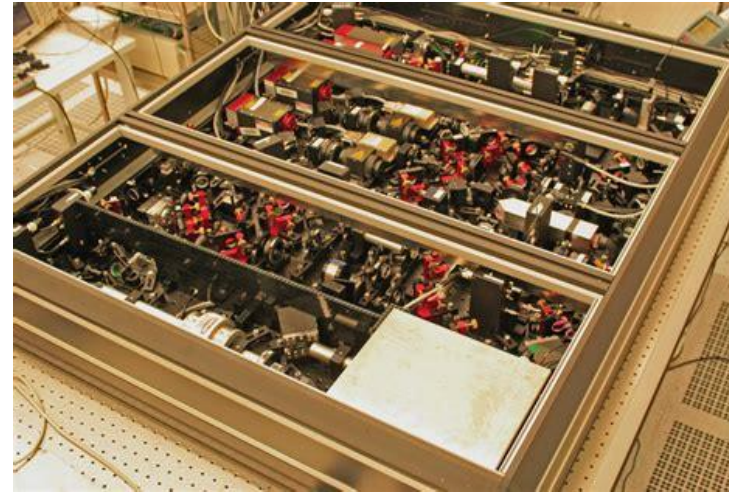
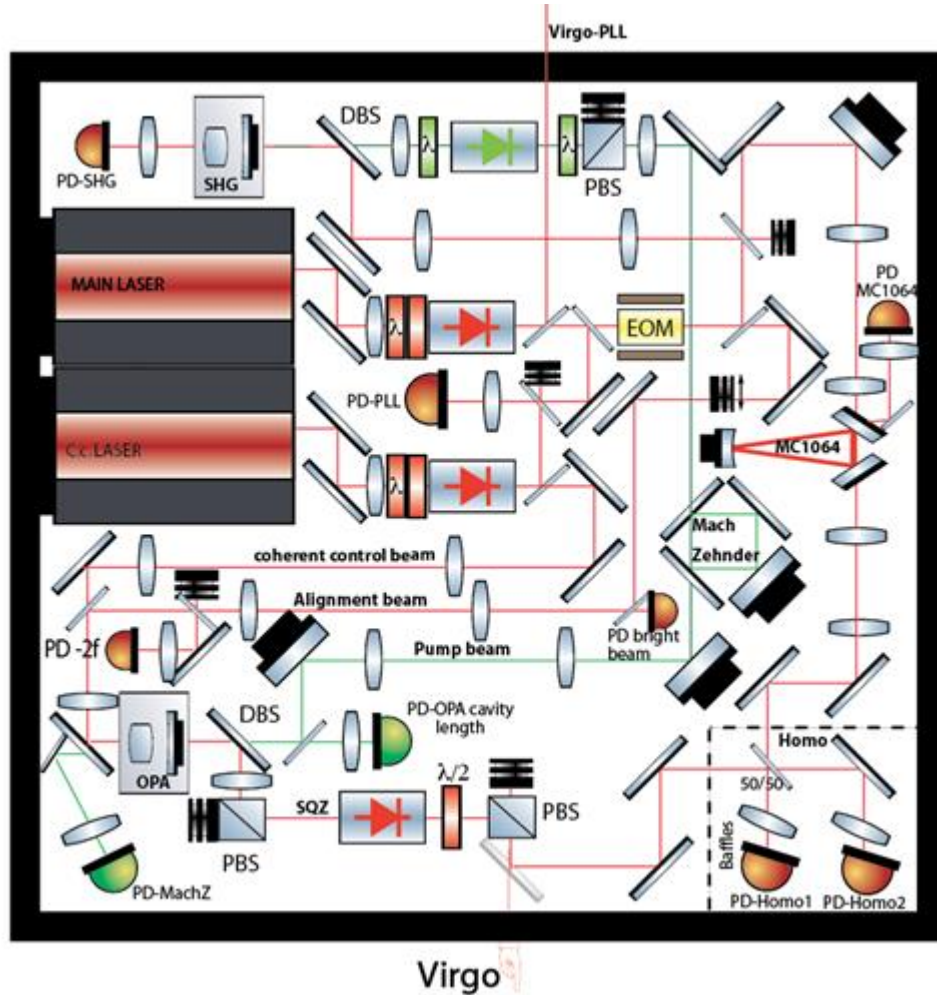
Higher order polarization effects in media

$$P(E(t)) = \epsilon_0(\chi^{(1)}E(t) + \chi^{(2)}E(t)^2 + \chi^{(3)}E(t)^3 + \dots)$$

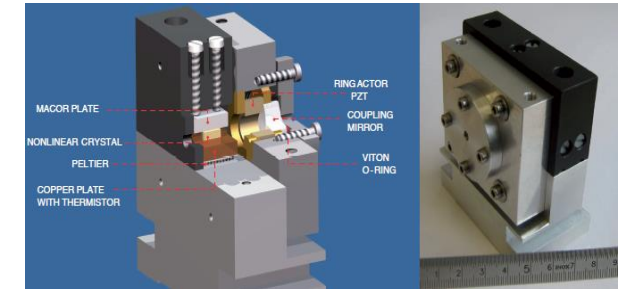
Optical Parametric Oscillator (OPO)



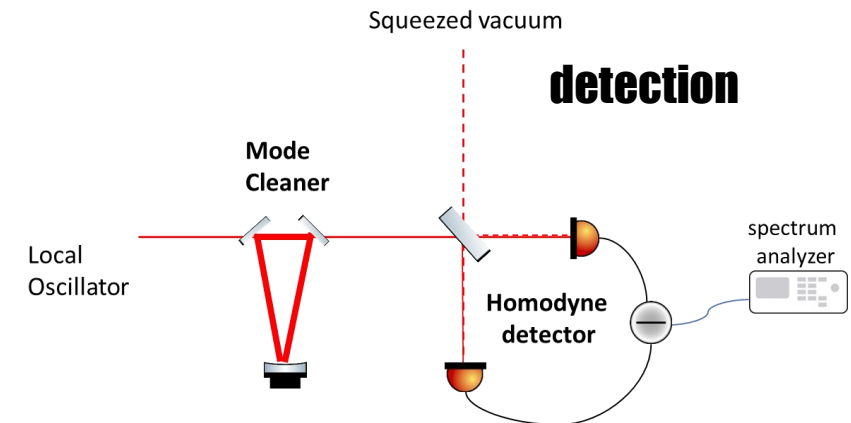
A squeezed light source is not just an OPO...



generation



Many of these components need to be controlled.



Squeezed states in audio-frequency band

VOLUME 55, NUMBER 22

PHYSICAL REVIEW LETTERS

25 NOVEMBER 1985

Observation of Squeezed States Generated by Four-Wave Mixing in an Optical Cavity

R. E. Slusher

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

L. W. Hollberg

AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

B. Yurke, J. C. Mertz, and J. F. Valley^(a)

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 27 August 1985)

1985: Squeezing in **RADIO-FREQUENCY** band

NOT ENOUGH FOR A GW DETECTOR...

New Journal of Physics

The open-access journal for physics

Quantum engineering of squeezed states for quantum communication and metrology

H Vahlbruch¹, S Chelkowski, K Danzmann and R Schnabel

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and
Leibniz Universität Hannover, Callinstr 38 30167 Hannover, Germany

E-mail: henning.vahlbruch@aei.mpg.de

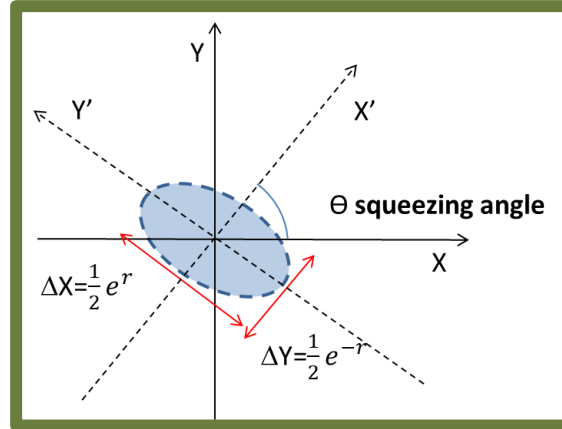
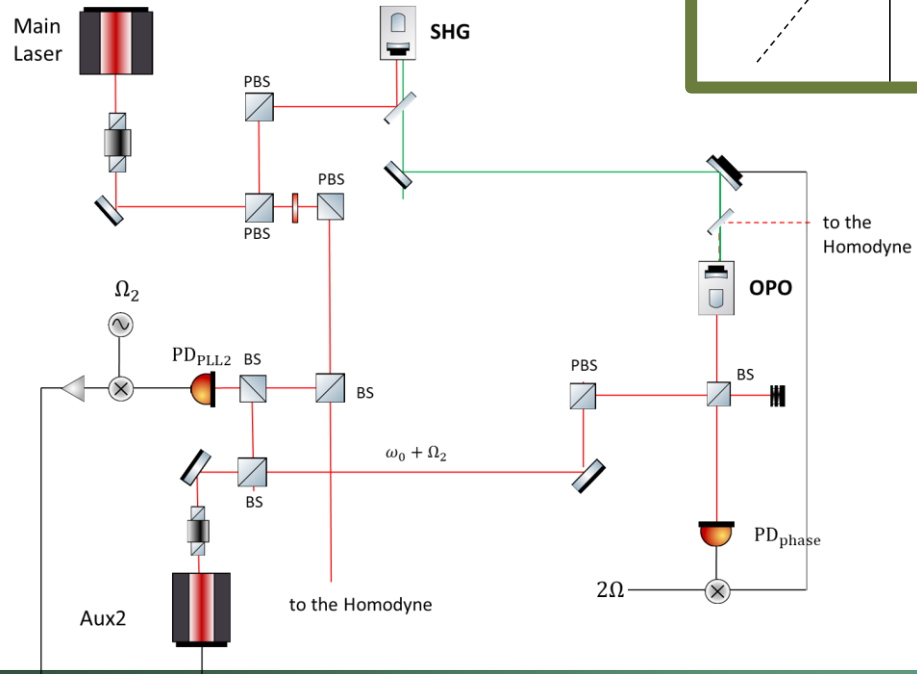
New Journal of Physics **9** (2007) 371

Received 29 August 2007

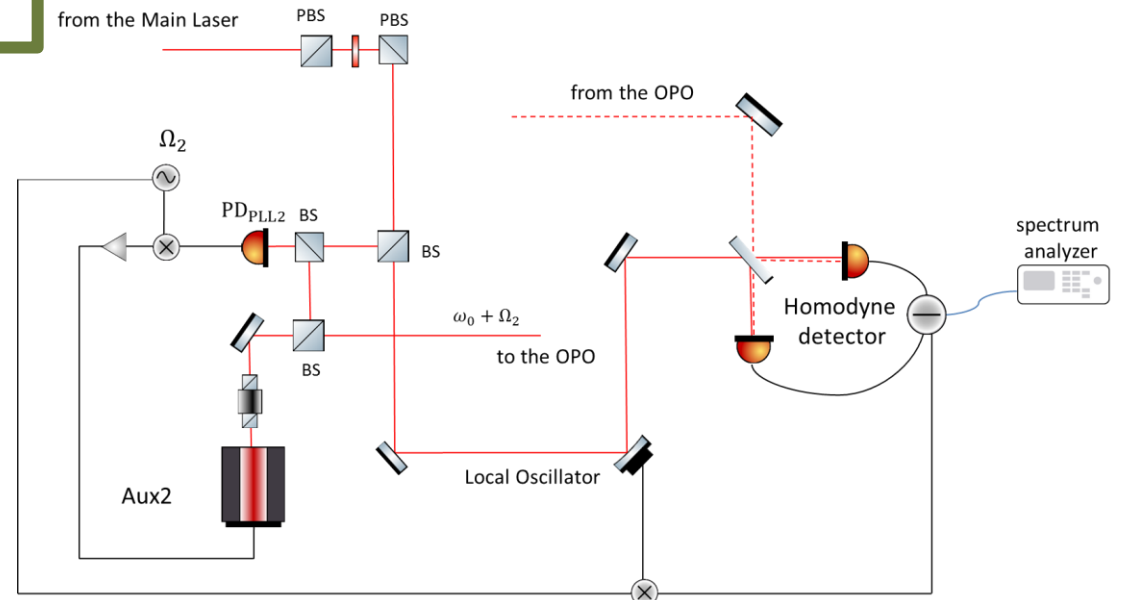
2007: Squeezing in **AUDIO-FREQUENCY** band

How does it mean squeezing in audio-frequency band?

Pump beam phase stabilization



Local Oscillator beam phase stabilization



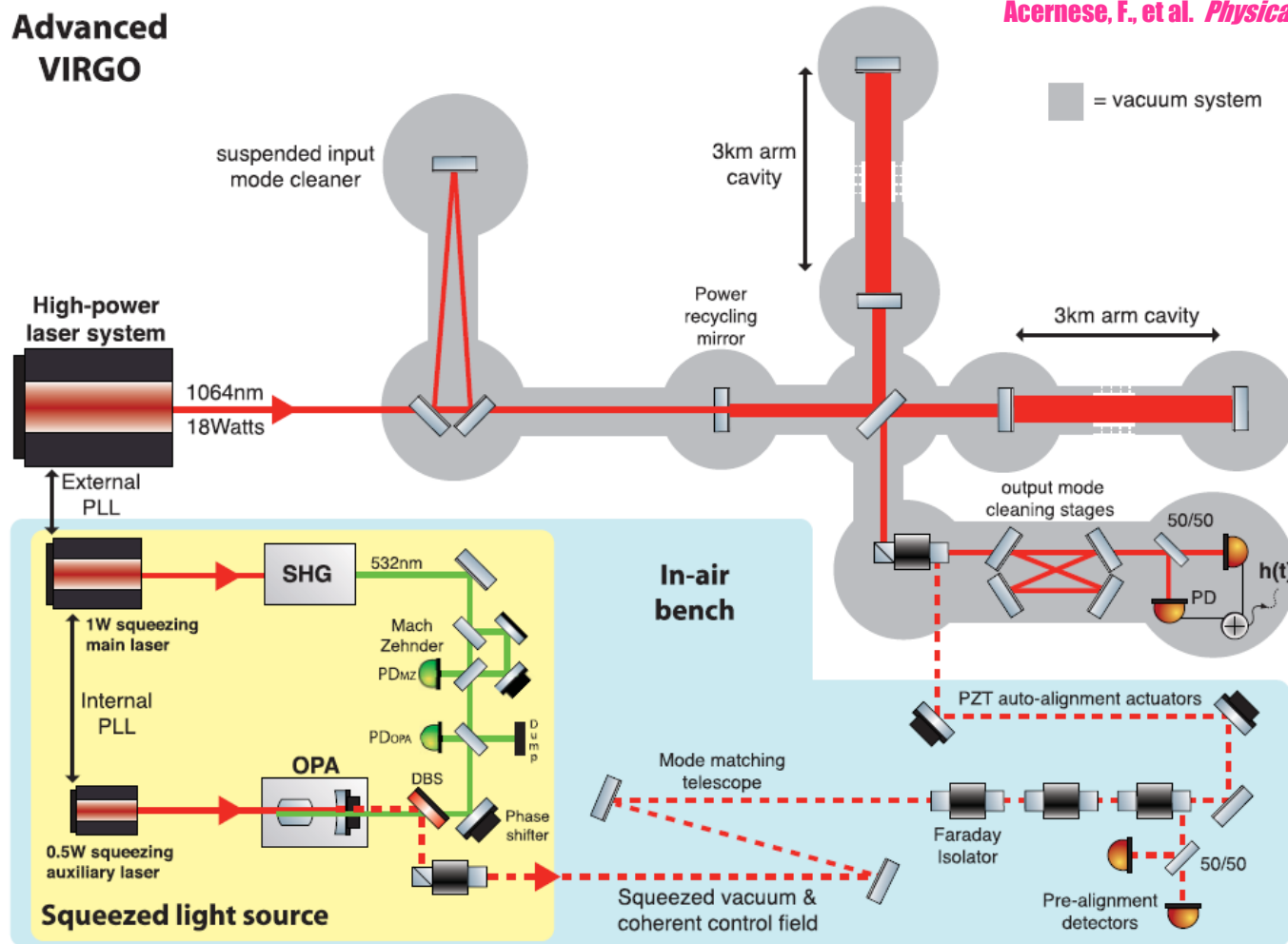
Quantum noise reduction techniques in GW interferometers

Part II

Squeezer – Interferometer Interface

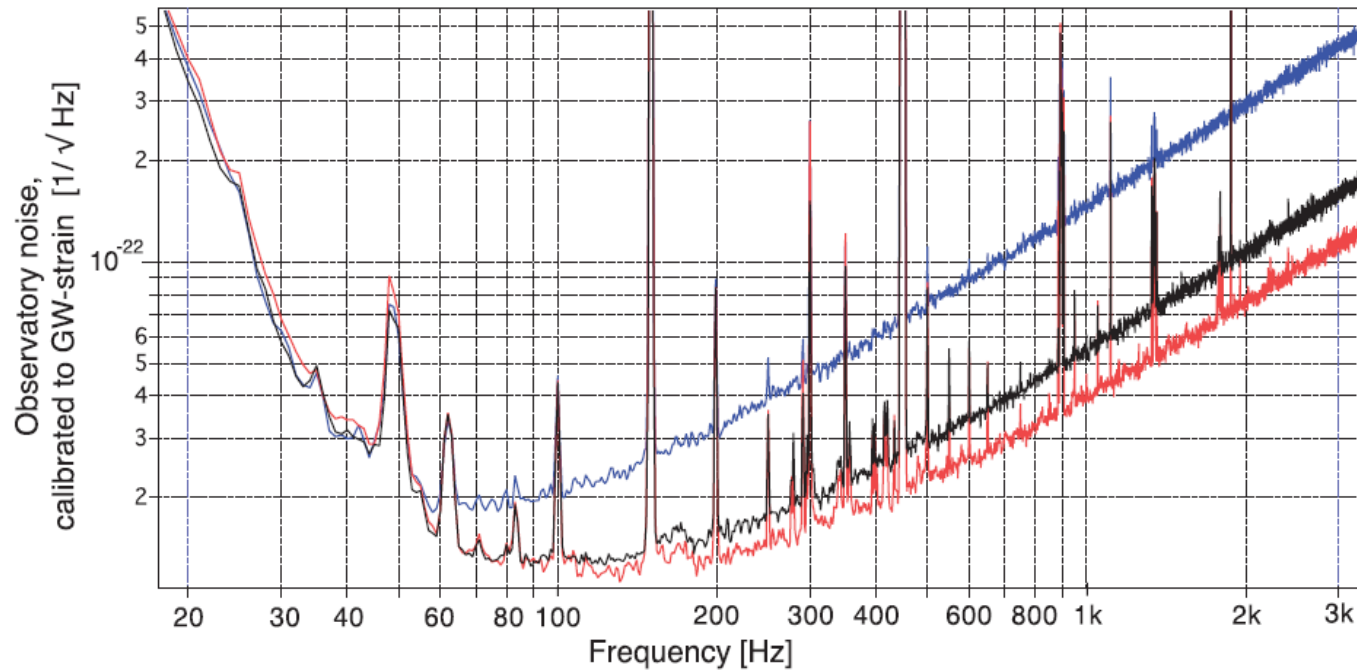
Advanced
VIRGO

Acernese, F., et al. *Physical Review Letters* 123.23 (2019): 231108.



Sensitivity improvement of a GW detector

Frequency-Independent Squeezing (FIS)



- absence of squeezed light
- **with squeezing**
- **with anti-squeezing**

Results

Measured squeezing level:

3.2 ± 0.1 dB

Measured anti-squeezing level:

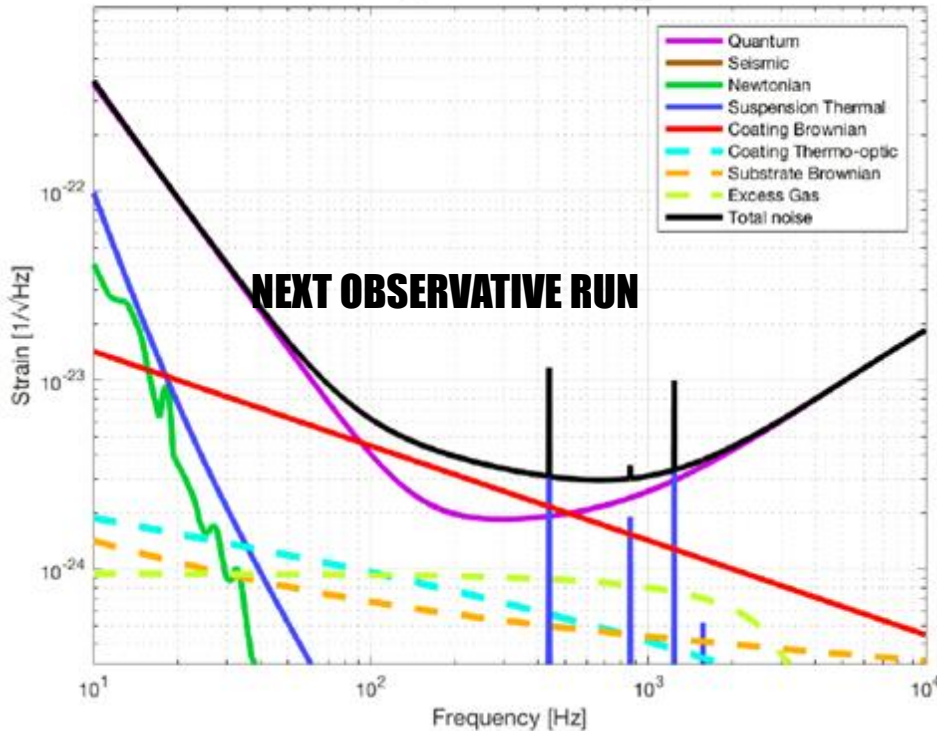
8.5 ± 0.1 dB

**normalization to the reference at 2.8 kHz
injected squeezing level about 10 dB**

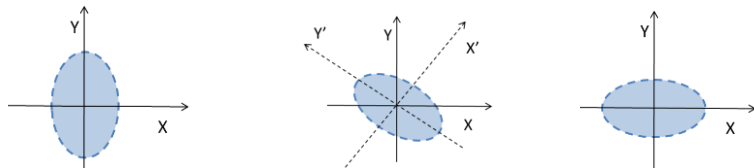
Acernese, F., et al. *Physical Review Letters* 123.23 (2019): 231108.

Need for a Frequency-Dependent Squeezing (FDS)

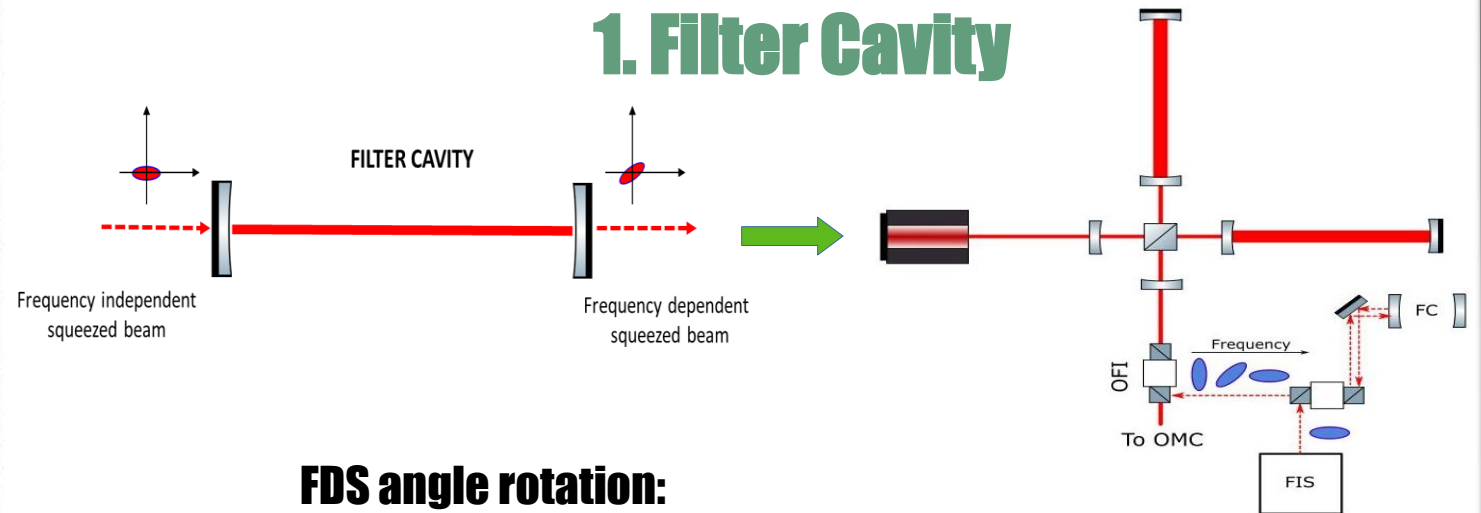
Advanced Virgo Noise Curve: $P_{in} = 125.0$ W



Broadband QN reduction



1. Filter Cavity

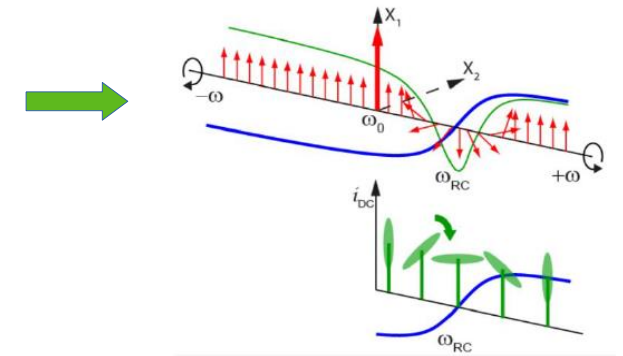


FDS angle rotation:

$$\theta_{fc}(\Omega) = \arctan \left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2} \right)$$

$\Delta\omega_{fc}$ Detuning

γ_{fc} Cavity linewidth



Filter cavity: state of the art

- **2005: first demonstration in MHz region → cavity length $L=0.5$ m**

Chelkowski et al. *Phys. Rev. A* 71 (Jan, 2005) 013806

- **2015: first demonstration in kHz region → cavity length $L=2$ m**

Oelker et al. *Phys. Rev. Lett.* 116 (Jan, 2016) 041102

- **2020: first demonstration below 100 Hz → cavity length $L=300$ m**

Zhao, Yuhang, et al. "Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors." *Physical Review Letters* 124.17 (2020): 171101.

Frequency of interest for Gravitational Wave detectors

Need for hundred meter long cavity → less squeezing degradation induced by cavity losses

T. Isogai, J. Miller, P. Kwee, L. Barsotti, and M. Evans, "Loss in long-storage-time optical cavities", *Opt. Express* 21 no. 24, (Dec, 2013) 30114{30125}

E. Capocasa et al. "Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector", *Phys. Rev. D* 93 (Apr, 2016) 082004.

**Preliminary measurements done also in Advanced Virgo Plus
(results not yet published)**

Filter cavity in Advanced Virgo Plus

Parallel to the ITF North Arm



CAVITY MIRRORS

- diameter $d=15$ cm;
- radius of curvature $RoC= 558$ m;
- round-trip losses $I < 40$ ppm

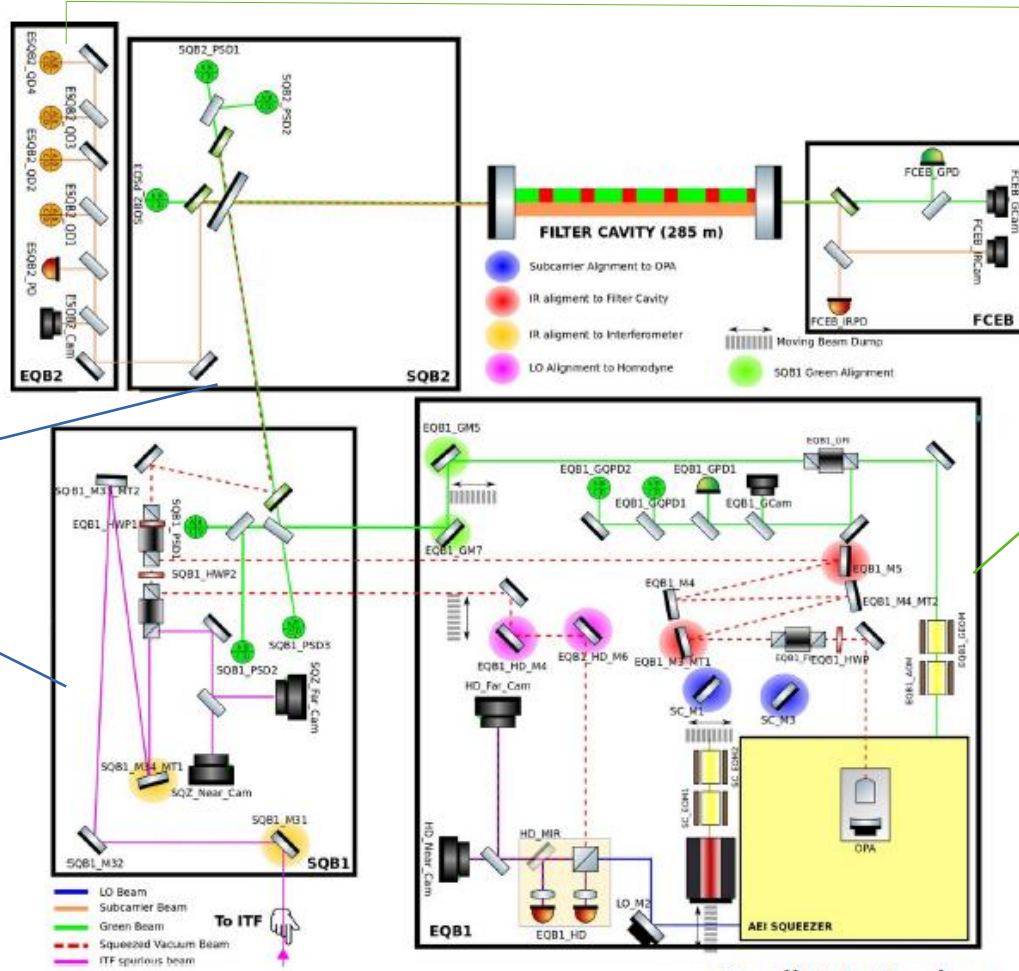


AdV+ required squeezing angle rotation: 20-30 Hz



- length $L=285$ m;
- finesse $F=11000$ (@1064 nm)

Advanced Virgo Plus (AdV+): FDS overall conceptual design



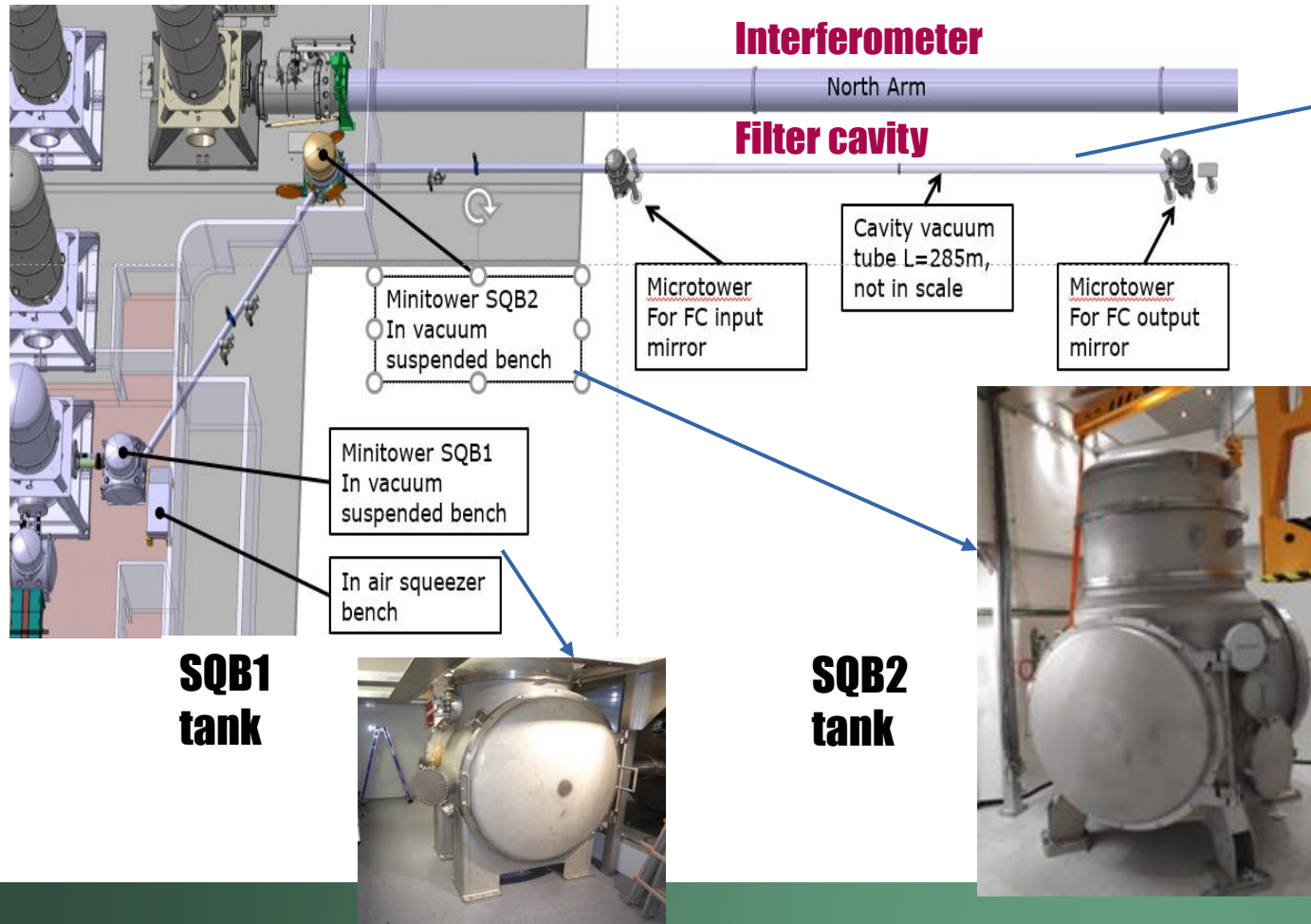
Not suspended benches

Suspended benches

Credit M. Vardaro

AdV+ FDS vacuum system

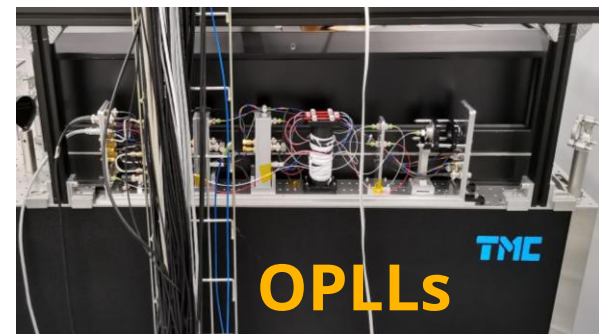
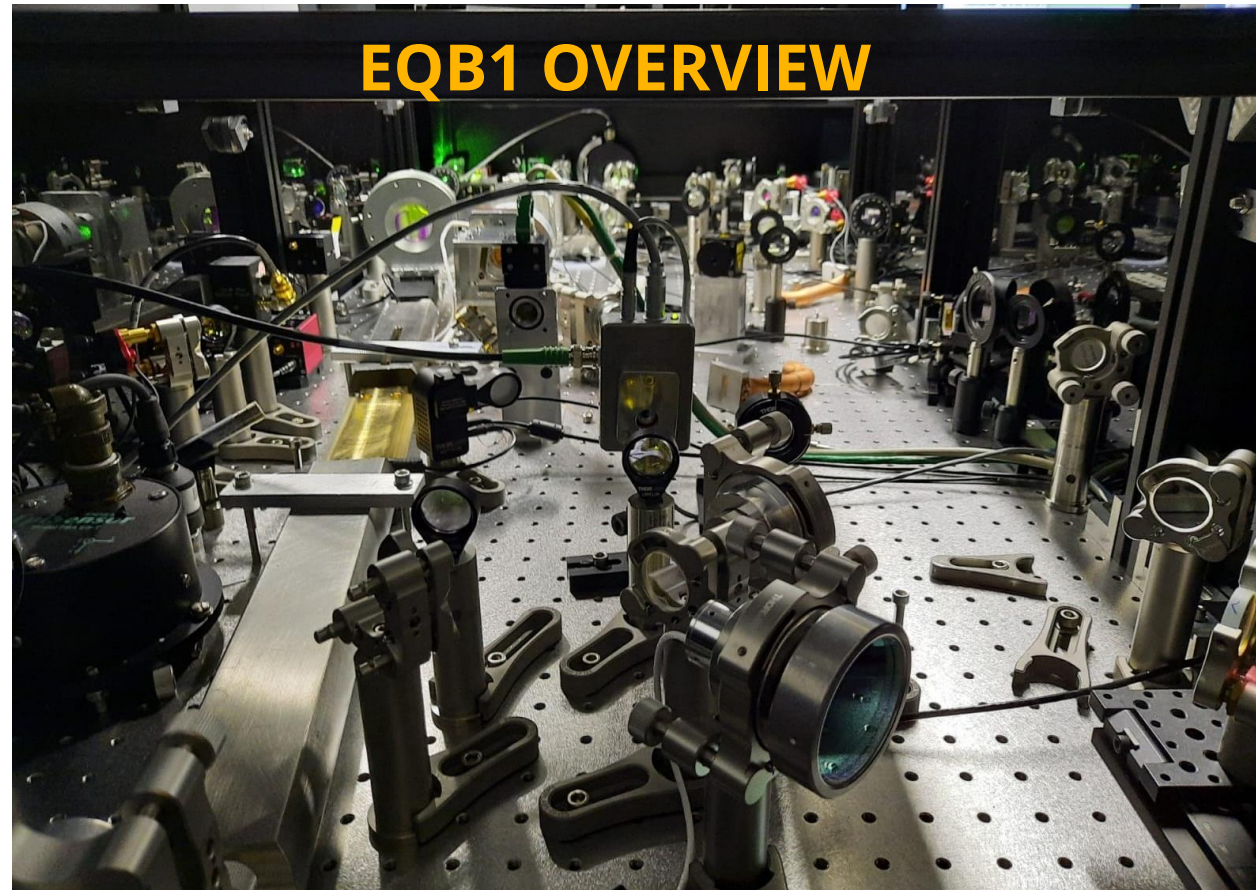
Detection



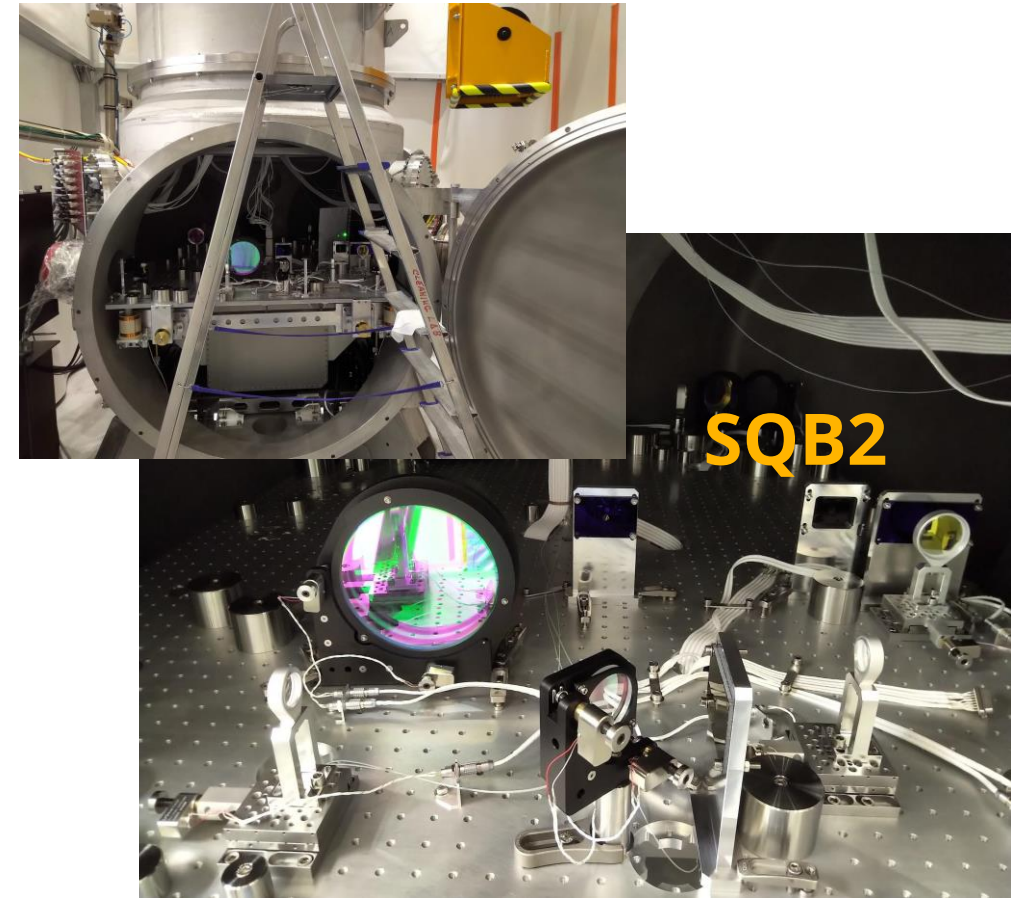
Filter cavity



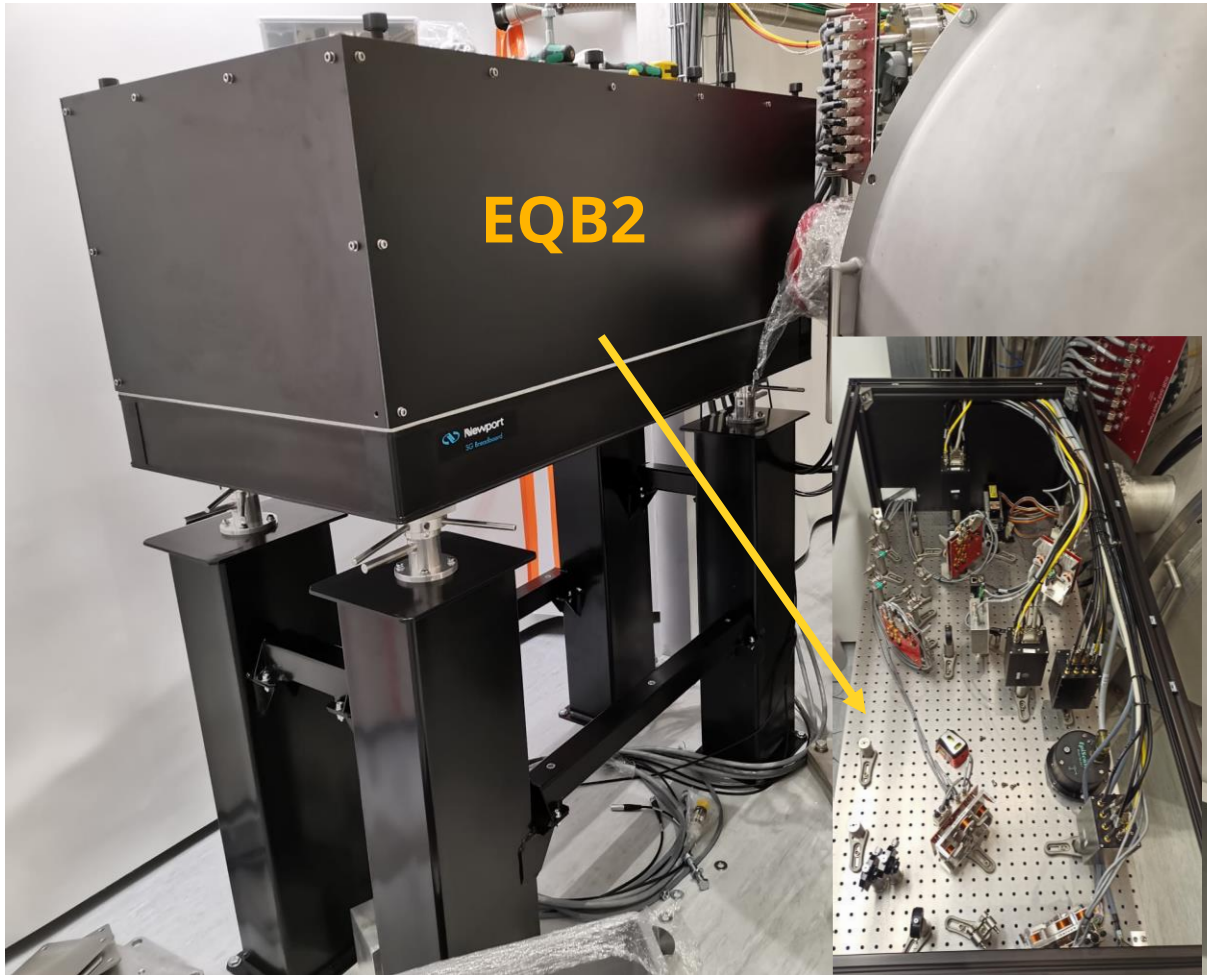
AdV+: in-air external squeezing bench (EQB1)



AdV+: in-vacuum suspended squeezing benches



AdV+: in-air auxiliary benches



What we want to do in ET

Part III

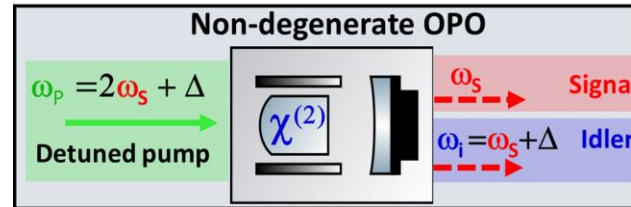
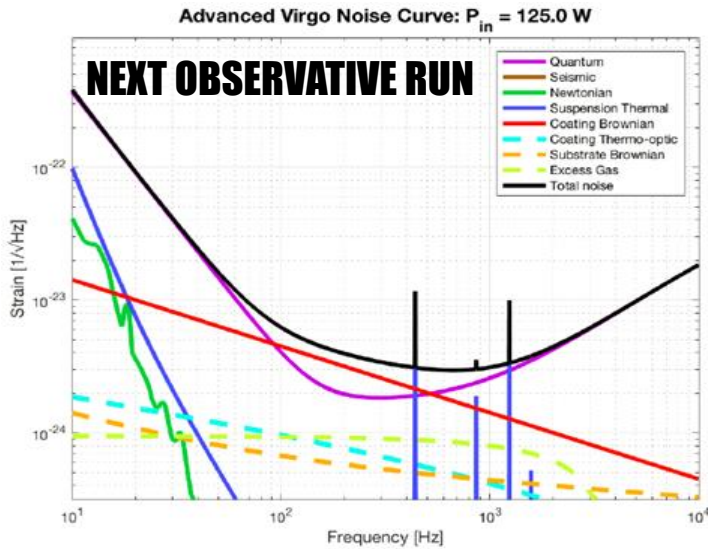
Other squeezing activities in ET

Subgroups

- Phase noise (Valeria Sequino: valeria.sequino@na.infn.it)
- pyGWINC
- EPR squeezing (Mateusz Bawaj: mateusz.bawaj@unipg.it)
- SQZ source 1550 nm
- SQZ source 1064 nm
- Global design
- Filter Cavity 1064 nm
- Filter Cavity 1550 nm
- 2um R&D

Need for a Frequency-Dependent Squeezing (FDS)

2. EPR entangled beams



ARTICLES

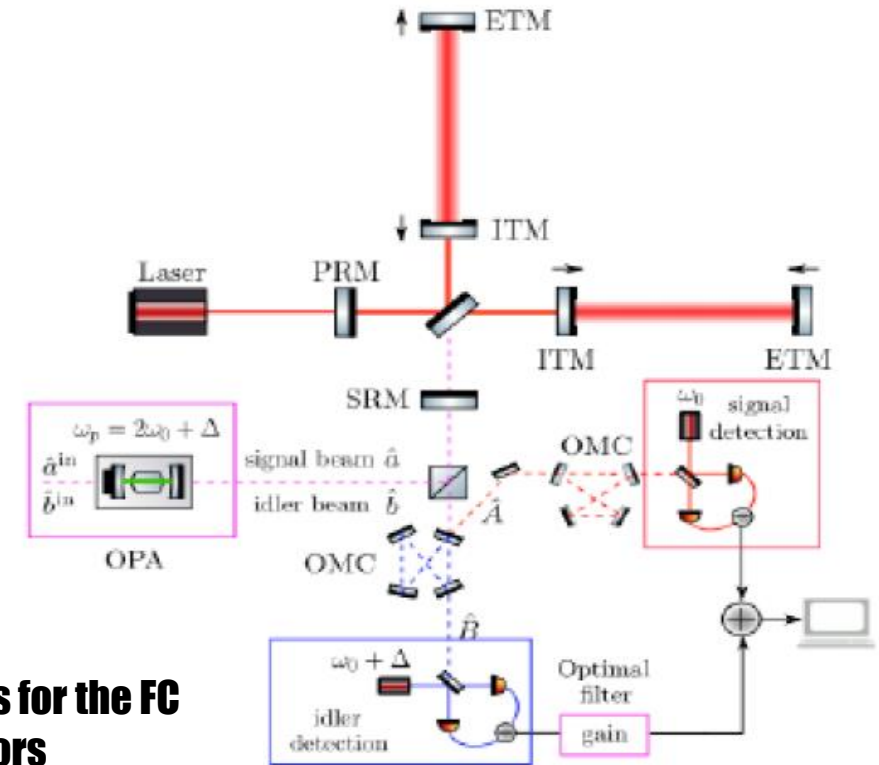
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4118

nature
physics

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

Yiqiu Ma^{1*}, Haixing Miao², Belinda Heyun Pang¹, Matthew Evans³, Chunrong Zhao⁴, Jan Harms^{5,6}, Roman Schnabel⁷ and Yanbei Chen¹

In continuously monitored systems the standard quantum limit is given by the trade-off between shot noise and back-action noise. In gravitational-wave detectors, such as Advanced LIGO, both contributions can be simultaneously squeezed in a broad frequency band by injecting a spectrum of squeezed vacuum states with a frequency-dependent squeeze angle. This approach requires setting up an additional long baseline, low-loss filter cavity at the detector's site. Here, we show that the need for such a filter cavity can be eliminated, by exploiting Einstein-Podolsky-Rosen (EPR)-entangled signals and idler beams. By harnessing their mutual quantum correlations and the difference in the way each beam propagates in the interferometer, we can engineer the input signal beam to have the appropriate frequency-dependent conditional squeezing once the out-going idler beam is detected. Our proposal is appropriate for all future gravitational-wave detectors for achieving sensitivities beyond the standard quantum limit.

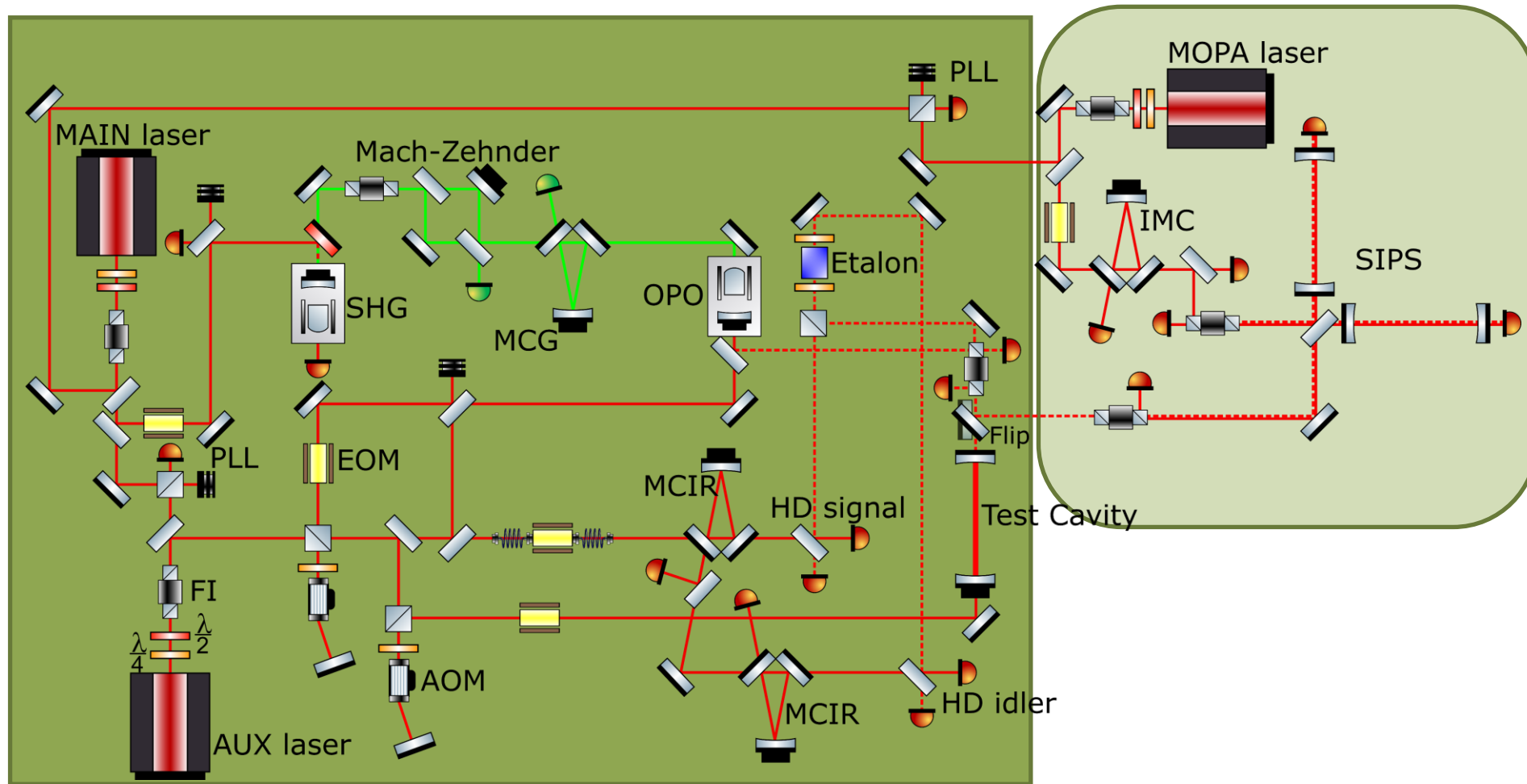


ITF both GW detector and the filter cavity (FC)

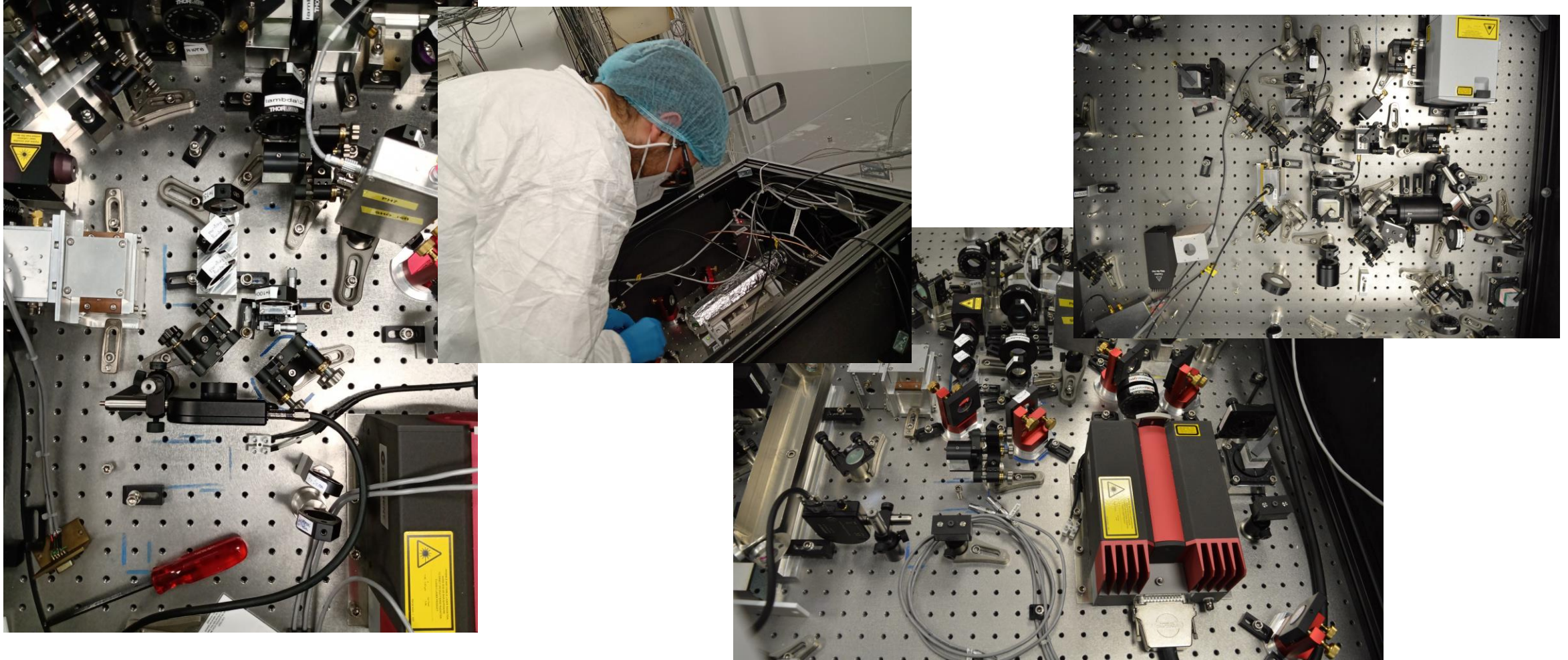
Advantages: less expensive, more compact setup, avoids the 1ppm/m round trip losses for the FC

Disadvantages: two squeezed beams so double losses, need for two Homodyne Detectors

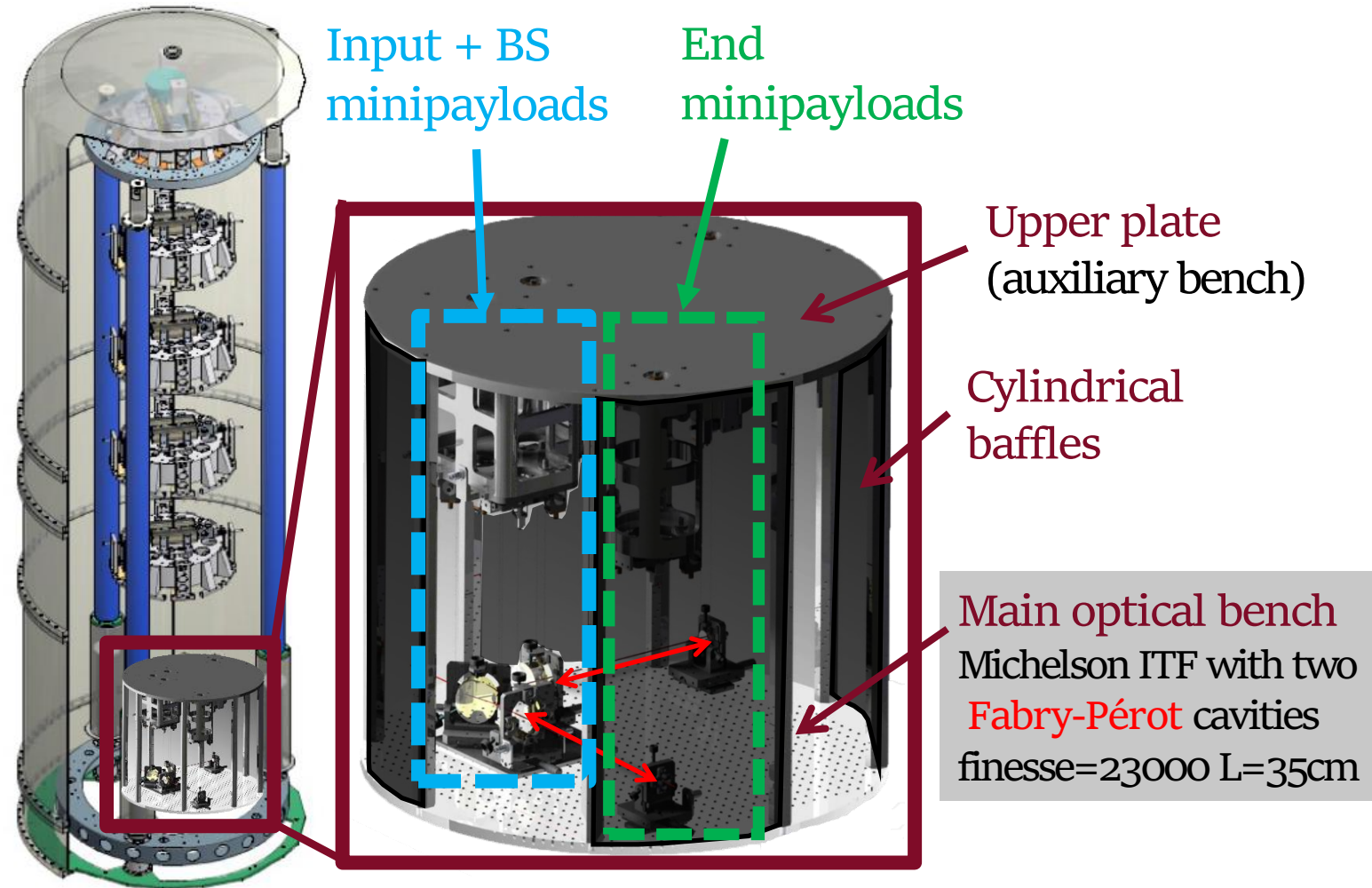
Our EPR experiment at the EGO site



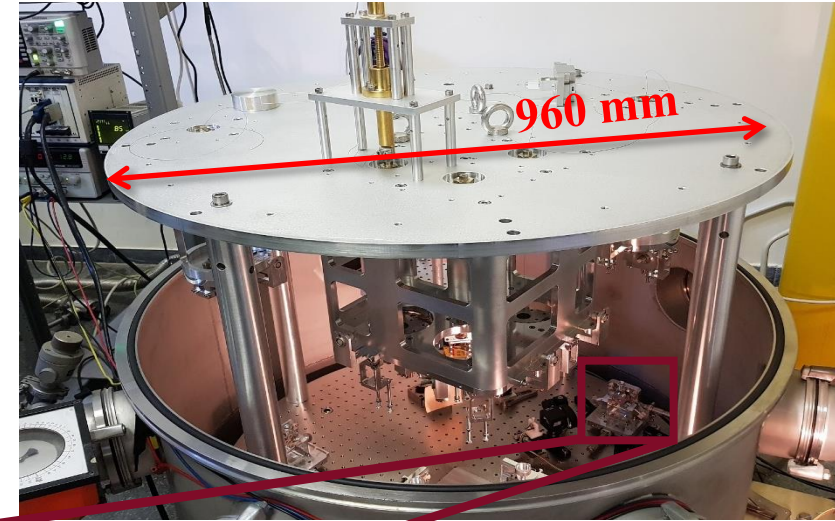
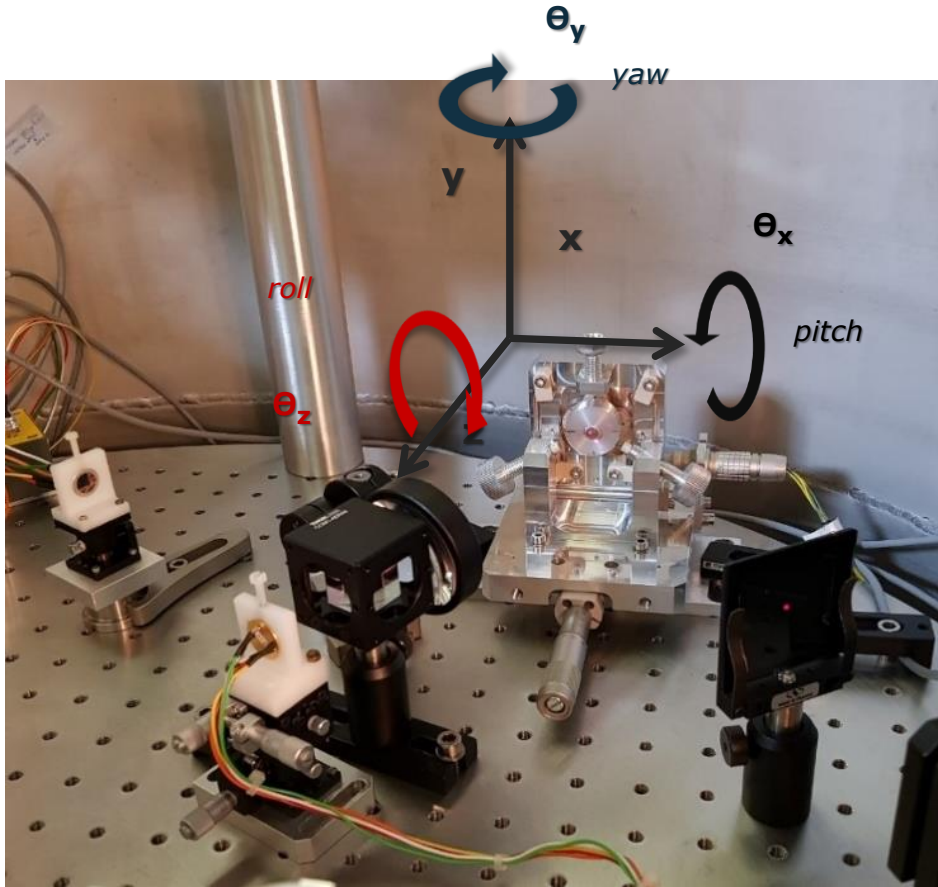
Some pictures of our EPR experiment



The small suspended interferometer



Some pictures small suspended interferometer



SAPIENZA
UNIVERSITÀ DI ROMA

Prototype Dummy
end
mirror

Test of local control of
suspended elements:
Coils behind mirror and
magnets glued on the
mirror
Coils-magnets also on the
marionette

Many calculations and simulations to do...

nature
physics

SUPPLEMENTARY INFORMATION
DOI: 10.1038/NPHYS5478

In the format provided by the authors and unedited.

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

Yiqin Ma,¹ Haizong Mao,² Belinda Heyun Peng,³ Matthew Evans,³
Chunrong Zhao,⁴ Jan Hama,^{5,6} Roman Schnabel,⁷ and Yanbei Chen¹

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³Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

⁴School of Physics, University of Western Australia, Western Australia 6009, Australia

⁵University degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy

⁶INFN, Sezione di Firenze, Firenze 50019, Italy

⁷Institut für Laserphysik und Laseranwendung für Optische Quantentechnologien,
Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

(Dated: March 15, 2017)

This is a supplementary material for the paper: "Proposal for Gravitational-Wave Detection Beyond the Standard Quantum Limit using EPR Entanglement". The purpose of this material is to present the details about (1) the derivation of the sensitivity formula; (2) the choice of system parameters; (3) the effect of loss.

I. DERIVATION OF THE SENSITIVITY FORMULA

First, for each audio-sideband frequency Ω , the field input-output relations of the (pumped) OPA can be written as:

$$\begin{aligned} \hat{a}(\omega + \Omega) &= \mu \hat{a}_0(\omega + \Omega) + \nu \hat{b}_0(\omega + \Delta + \Omega), & \hat{b}(\omega + \Delta + \Omega) &= \mu \hat{b}_0(\omega + \Delta + \Omega) + \nu \hat{a}_0(\omega + \Omega); \\ \hat{a}^{\dagger}(\omega - \Omega) &= \mu^* \hat{a}_0^{\dagger}(\omega - \Omega) + \nu^* \hat{b}_0^{\dagger}(\omega + \Delta + \Omega), & \hat{b}^{\dagger}(\omega + \Delta - \Omega) &= \mu^* \hat{b}_0^{\dagger}(\omega + \Delta - \Omega) + \nu^* \hat{a}_0^{\dagger}(\omega + \Omega), \end{aligned} \quad (1)$$

where \hat{a} and \hat{b} describe the generated signal and idler fields near ω_0 and $\omega_0 \pm \Delta$, respectively. The fields \hat{a}_0 , \hat{b}_0 represent the vacuum fields entering into the squarer. The phenomenological coefficient μ and ν are determined by the $\chi^{(2)}$ -nonlinearity coefficient of the crystal and the pumping field strength [1]. Field commutation relation requires them to satisfy the relation $|\mu|^2 - |\nu|^2 = 1$. Since the phase of μ and ν can be absorbed into the definition of creation and annihilation operators, we can parametrize them as $\mu = \cosh r$ and $\nu = \sinh r$, where r is usually denoted to be the squeezing degree of the OPA. In the so-called two-photon formalism where we define:

$$\begin{aligned} \hat{a}_1(\Omega) &= \frac{\hat{a}(\omega + \Omega) + \hat{a}^{\dagger}(\omega - \Omega)}{\sqrt{2}}, & \hat{b}_1(\Omega) &= \frac{\hat{b}(\omega + \Delta + \Omega) + \hat{b}^{\dagger}(\omega + \Delta - \Omega)}{\sqrt{2}}, \\ \hat{a}_2(\Omega) &= \frac{\hat{a}(\omega + \Omega) - \hat{a}^{\dagger}(\omega - \Omega)}{\sqrt{2}}, & \hat{b}_2(\Omega) &= \frac{\hat{b}(\omega + \Delta + \Omega) - \hat{b}^{\dagger}(\omega + \Delta - \Omega)}{\sqrt{2}}, \end{aligned} \quad (2)$$

the relations in Eq. (1) then can be represented in another form (in the following, $\hat{a}_{1,2}(\Omega)$ and $\hat{b}_{1,2}(\Omega)$ will be simply written as $\hat{a}_{1,2}$ and $\hat{b}_{1,2}$):

$$\hat{a}_1 + \hat{b}_1 = e^r (\hat{a}_{01} + \hat{b}_{01}), \quad \hat{a}_1 - \hat{b}_1 = e^{-r} (\hat{a}_{01} - \hat{b}_{01}); \quad (3)$$

$$\hat{a}_2 + \hat{b}_2 = e^{-r} (\hat{a}_{02} + \hat{b}_{02}), \quad \hat{a}_2 - \hat{b}_2 = e^r (\hat{a}_{02} - \hat{b}_{02}). \quad (4)$$

(the $\hat{a}_{01,2}$, $\hat{b}_{01,2}$ are defined in the same way as Eq. (2)). EPR-type commutation relation $[\hat{a}_1 - \hat{b}_1, \hat{a}_2 + \hat{b}_2] = 0$ allows the existence of the state in which the fluctuations of quadrature combinations $(\hat{a}_1 - \hat{b}_1)/\sqrt{2}$ and $(\hat{a}_2 + \hat{b}_2)/\sqrt{2}$ are much below the vacuum level. Therefore \hat{b}_1 is correlated with \hat{a}_1 while \hat{b}_2 is correlated with $-\hat{a}_2$, and further more $\hat{a}_{-g} = \hat{a}_1 \cos \theta - \hat{a}_2 \sin \theta$ correlates with $\hat{b}_g = \hat{b}_1 \cos \theta + \hat{b}_2 \sin \theta$. Using homodyne detection scheme, \hat{a}_{-g} and \hat{b}_g can be measured. When we do conditioning by processing these measurement results, we assume the measurement result of the idler field quadrature \hat{b}_g is filtered with a filtering gain factor g and then combined with the signal field quadrature \hat{a}_{-g} , leads to:

$$\hat{a}_{-g}^{\text{out}} = \hat{a}_{-g} - g \hat{b}_g = (\hat{a}_1 - g \hat{b}_1) \cos \theta - (\hat{a}_2 + g \hat{b}_2) \sin \theta. \quad (5)$$

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for our proposed scheme.

In our design, the signal field sees an interferometer working in the resonant sideband extraction mode while the idler field sees the interferometer as a filter cavity. This filter cavity should rotate the idler field in its phase space by an angle $\Phi_{\text{rot}} = \arctan K$. Generally, for realizing such a rotation angle, two filter cavities are required [2] (for a

PPLEMENTARY INFORMATION

$$1 + (\nu - g\mu)^2. \quad (6)$$

or filtering" so that $S_{\text{rot},\text{rot}}$ takes its minimum value, r gain factor g_{opt} and conditional squeezing spectrum:

$$\frac{g}{\Delta\omega} = \frac{1}{\mu^2 + \nu^2} = \frac{1}{\cosh 2r}. \quad (7)$$

re the input-output relation for quantum noise field in

$$\frac{1}{\sqrt{1 + K^2}} (\hat{a}_1 \cos \xi - \hat{a}_2 \sin \xi), \quad (8)$$

out of the interferometer and $\xi = -\arctan 1/K$. If we monitor \hat{b}_g to maximally correlate with \hat{a}_1 in Eq. (8), accumulated by sidebands of the idler field during its is of the idler field Φ_{rot} by the interferometer defined in

$$+ \hat{b}_2 \cos \Phi_{\text{rot}}, \quad (9)$$

id and idler channel, we have:

$$|\mu|^2 S_{\hat{b}_1 \hat{b}_1} = g^2 S_{\hat{a}_1 \hat{a}_1} - g^2 S_{\hat{a}_1 \hat{a}_2}. \quad (10)$$

ter filter and a minimum variance given as:

$$\sqrt{1 + K^2} \tanh 2r, \quad (11)$$

$$\frac{S_{\hat{a}_1 \hat{a}_1}}{S_{\hat{b}_1 \hat{b}_1}} = \frac{1 + K^2}{\cosh 2r}. \quad (12)$$

can recover the Eq. (7) of the main text:

$$\left(K + \frac{1}{K} \right). \quad (13)$$

1 SETTING

ments

ion of the results from signal beam detection and idler parameter error will have a significant effect on the final r rotation angle to the sensitivity is roughly given by:

$$\frac{(\sinh 2r)^2}{\cosh 2r} \left(K + \frac{1}{K} \right) \delta \Phi^2. \quad (14)$$

even the correction term and the exact value is roughly be spectrum requires the error of the rotation angle to is of great importance to search the suitable parameters

($r, \Phi \in \mathbb{R}$).

while not on δL_{SRC} . Since $L_{\text{SRC}}^{\text{rot}}$ is typically of is effect on the value of required γ and δr , cing Δ and L_{SRC} in Eq. (18) to satisfy:

$$-(1 + R_{\text{SRC}}) + n\pi, \quad (22)$$

EMENTARY INFORMATION

is in the resonant sideband extraction mode, the accumulated around the transition frequency achieve the required rotation of the idler field, and fixed bandwidth γ and detuning δr of the signal \hat{a}_1 .

$$\gamma r. \quad (15)$$

additions

eter parameters can be seen in the interferometer

$$\frac{1}{\sqrt{1 + K^2}} \frac{dL_{\text{SRC}}}{d\omega} \frac{d\omega}{d\omega}. \quad (16)$$

er signal recycling cavity. They are given by [8]:

$$\frac{S_{\text{SRC}}}{S_{\text{SRC}}} = \frac{\sqrt{1 + K^2} \exp(2i\theta_{\text{SRC}})}{\sqrt{1 + K^2} \exp(2i\theta_{\text{SRC}})}. \quad (17)$$

main mirrors and the signal recycling mirror,

er signal recycling cavity given as:

$$. \quad (18)$$

$$\arg[\beta] = 0. \quad (19)$$

$$\frac{1}{\sqrt{1 + K^2}} \frac{dL_{\text{SRC}}}{d\omega} \frac{d\omega}{d\omega}. \quad (20)$$

g mirror and the input test mass mirror is given,

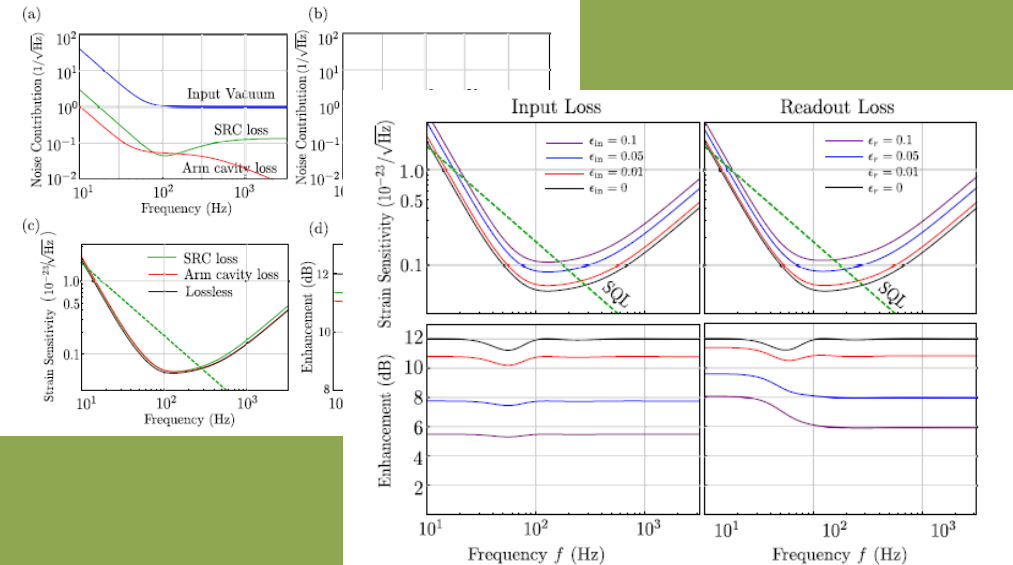
mean with respect to the signal beam Δ . [2] arms used in such a way so that arm cavity and signal recycling cavity for keeping the signal channel unaffected, the arm cavity (denoted by L_{ARM} and L_{SRC} , and $L_{\text{SRC}}^{\text{rot}}$, respectively) should be integer numbers

$$(r, \Phi \in \mathbb{R}). \quad (21)$$

while not on δL_{SRC} . Since $L_{\text{SRC}}^{\text{rot}}$ is typically of is effect on the value of required γ and δr , cing Δ and L_{SRC} in Eq. (18) to satisfy:

$$-(1 + R_{\text{SRC}}) + n\pi, \quad (22)$$

We need to deeply understand how EPR works in a GW interferometer and, in particular, in ET.



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30

WORKSHOP ET@TO, JUNE 16° 2022 - TORINO

If you are interested in contributing...

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