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

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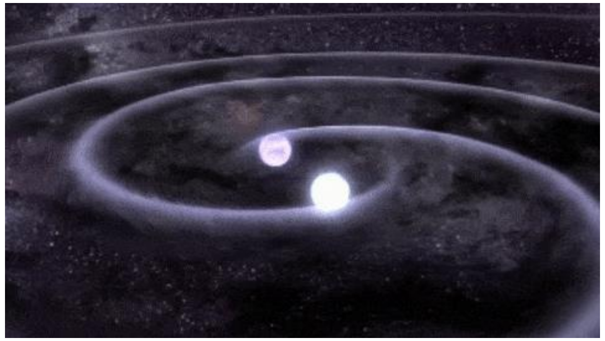
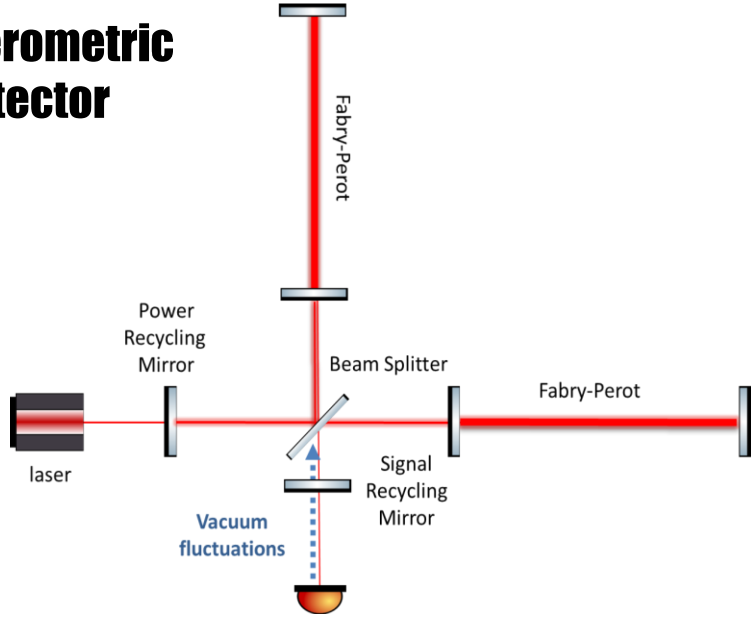
Gravitational waves

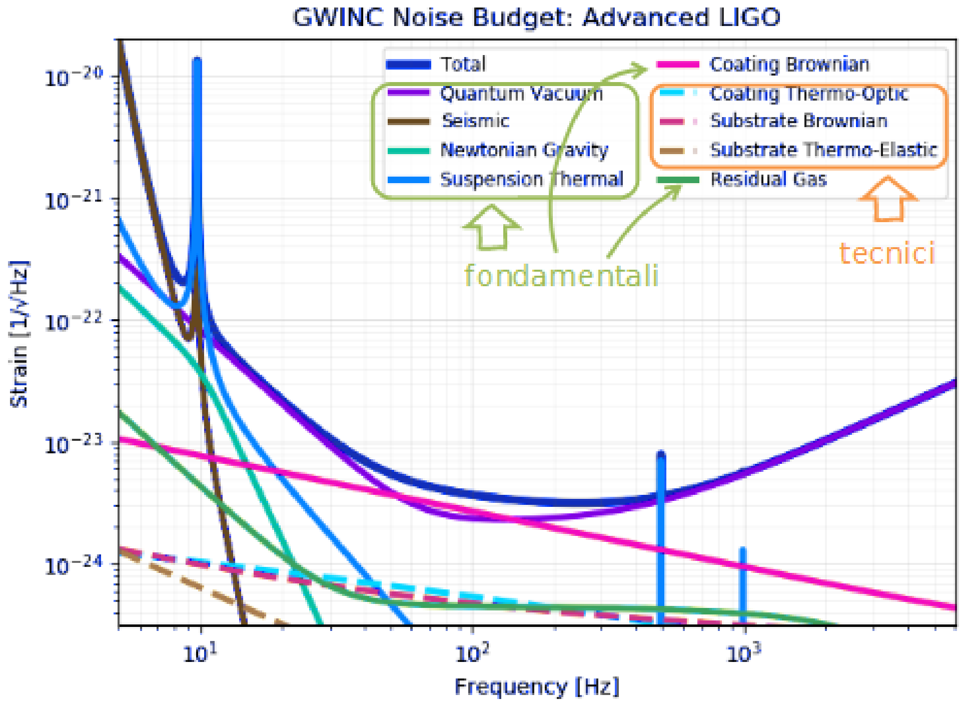


Gravitational waves (GWs) are **very small perturbations** of the space time, so small that their effect on the test masses of a GW interferometric detector can be even confused with the effect of **vacuum fluctuations**!

Interferometric GW detector

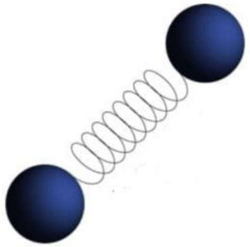


Main sources of noise



What are vacuum fluctuations?

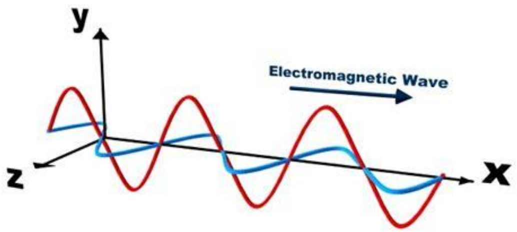
Harmonic oscillator



Mechanical Harmonic Oscillator

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

Light wave



Electro-magnetic oscillator

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

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

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

Quantized e.m field

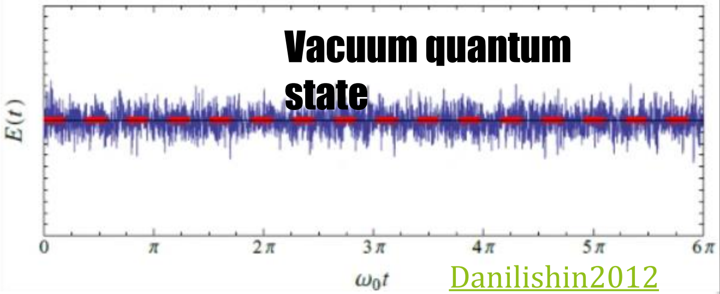
$$\hat{\mathcal{H}}_R = \sum_k \sum_\lambda \hbar\omega_k \left(n_{k\lambda} + \frac{1}{2}\right) \qquad E_n = \frac{1}{2}\sum_k\sum_\lambda \hbar\omega_k n_{k\lambda}$$

$$E_R = E_n + E_0$$

vacuum fluctuations

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

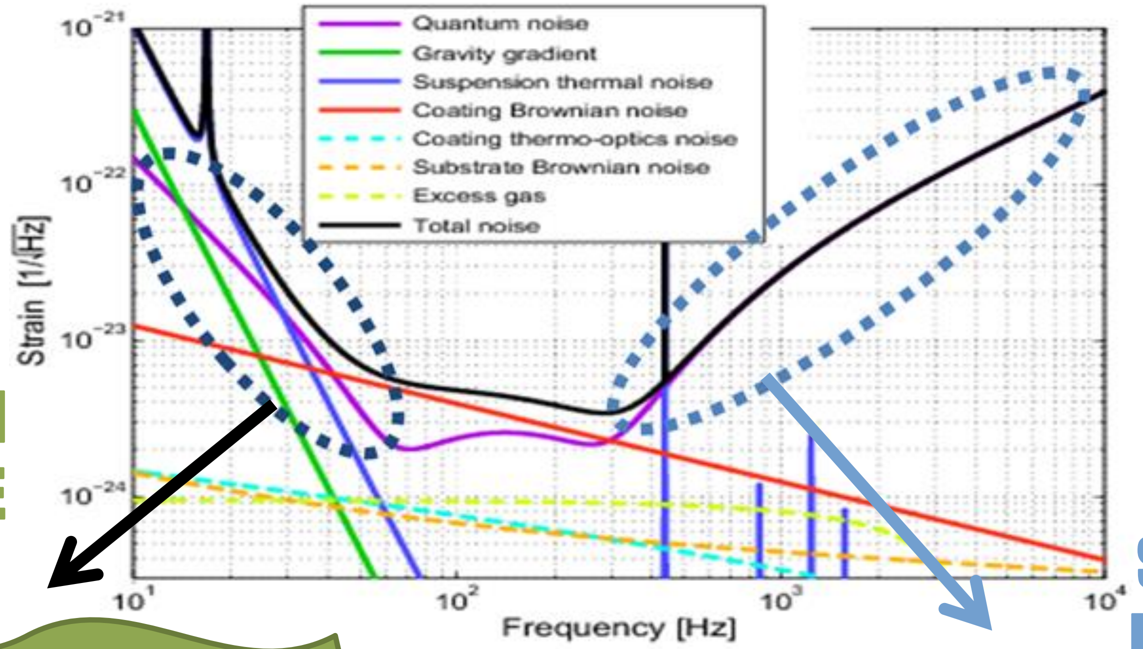
k→ mode
λ→polarization



Danilishin2012

Quantum noise in Advanced Virgo

Frequency-dependent response of the instrument

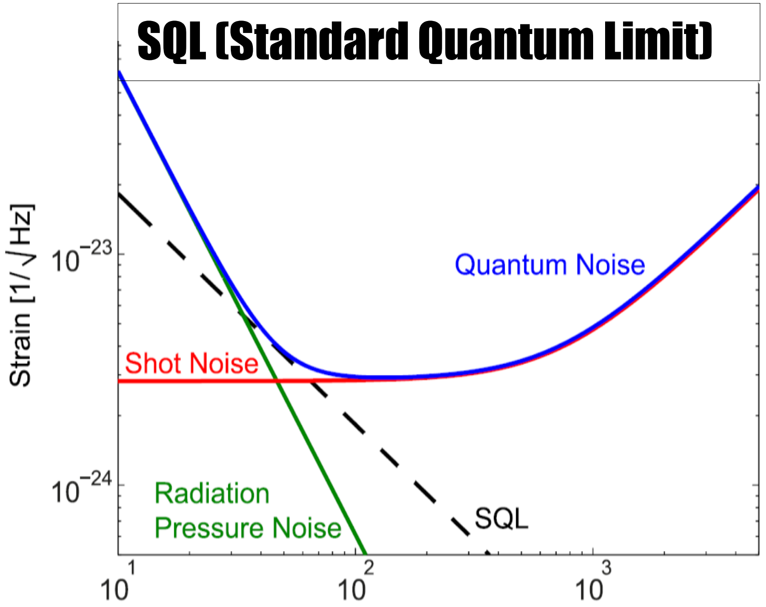


RADIATION PRESSURE NOISE

Vacuum amplitude-fluctuations, more evident at lower frequencies.

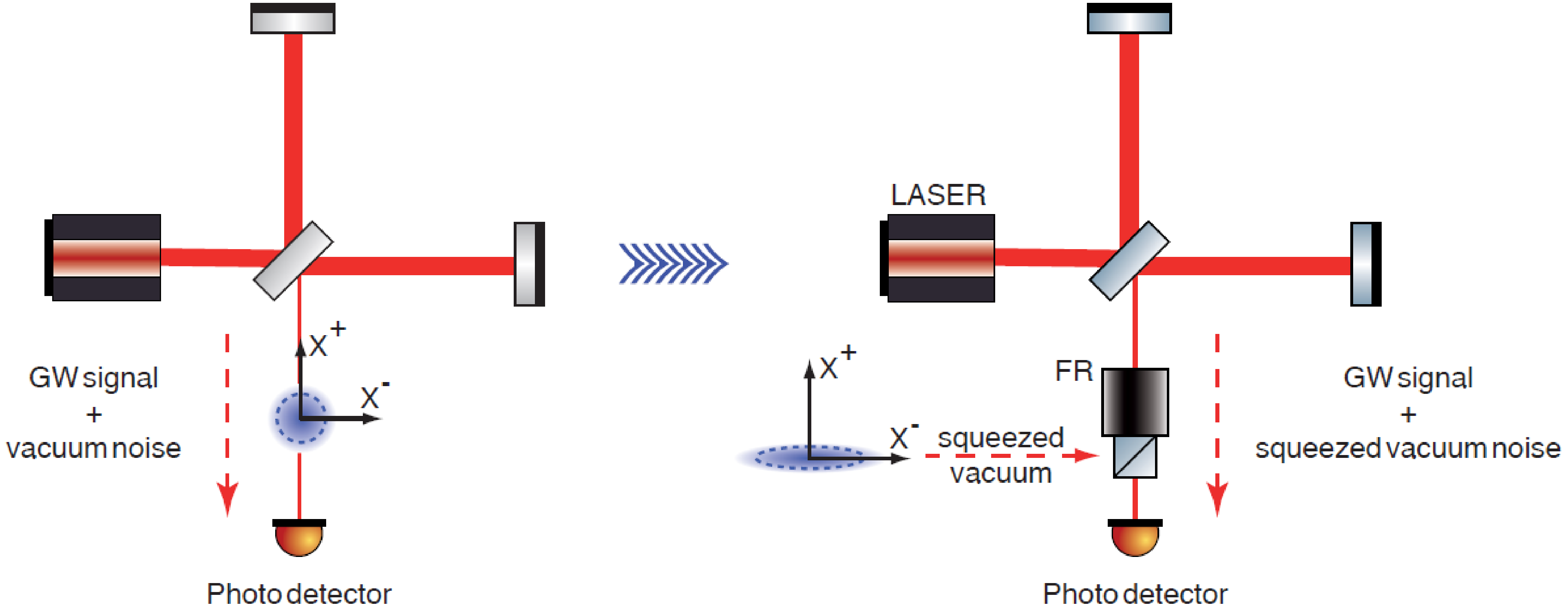
SHOT NOISE

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 Uncertanty Principle

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

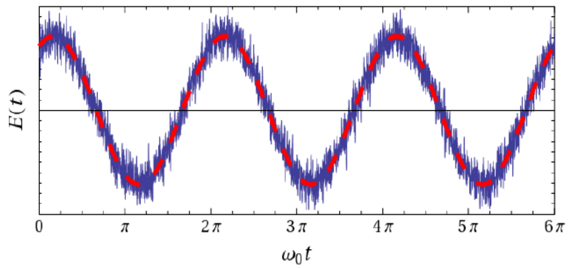
Minimumuncertainty states

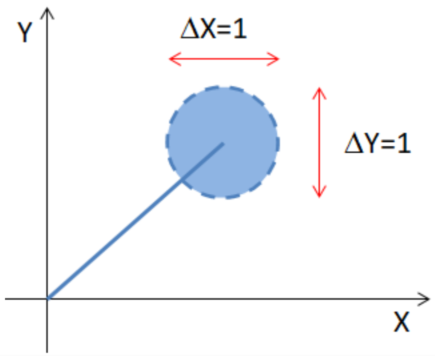
$$\left\langle \left(\Delta \hat{X}\right)^2 \right\rangle \left\langle \left(\Delta \hat{Y}\right)^2 \right\rangle = 1$$

Squeezed states of light

Coherent states

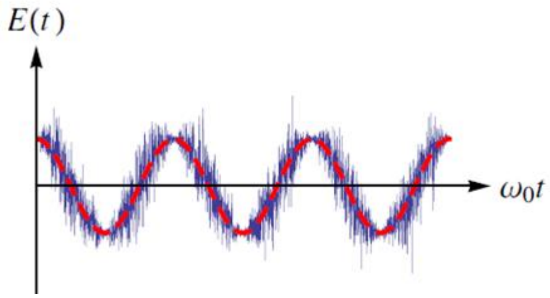
$$\left\langle \left(\Delta \hat{X}\right)^2 \right\rangle_c = \left\langle \left(\Delta \hat{Y}\right)^2 \right\rangle_c = 1$$

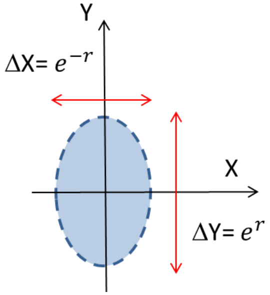




Amplitude-squeezed states

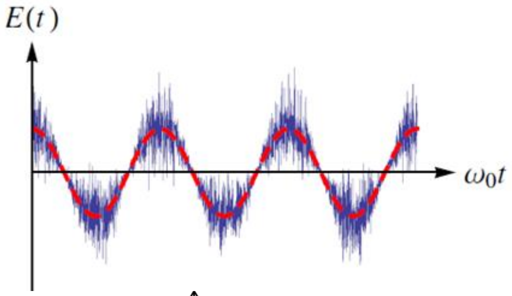
$$\left\langle \left(\Delta \hat{X}\right)^2 \right\rangle_s = e^{-r} \qquad \left\langle \left(\Delta \hat{Y}\right)^2 \right\rangle_s = e^{r}$$

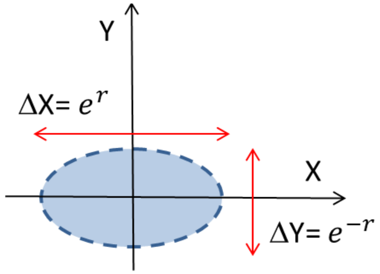




Phase-squeezed states

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





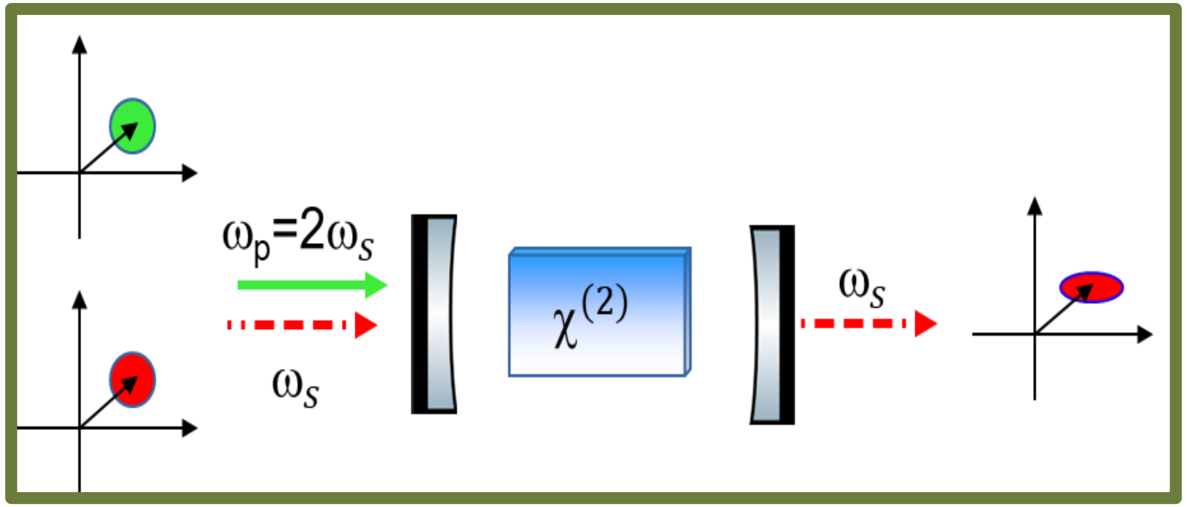
Squeezed vacuum generation via OPO

Nonlinear processes

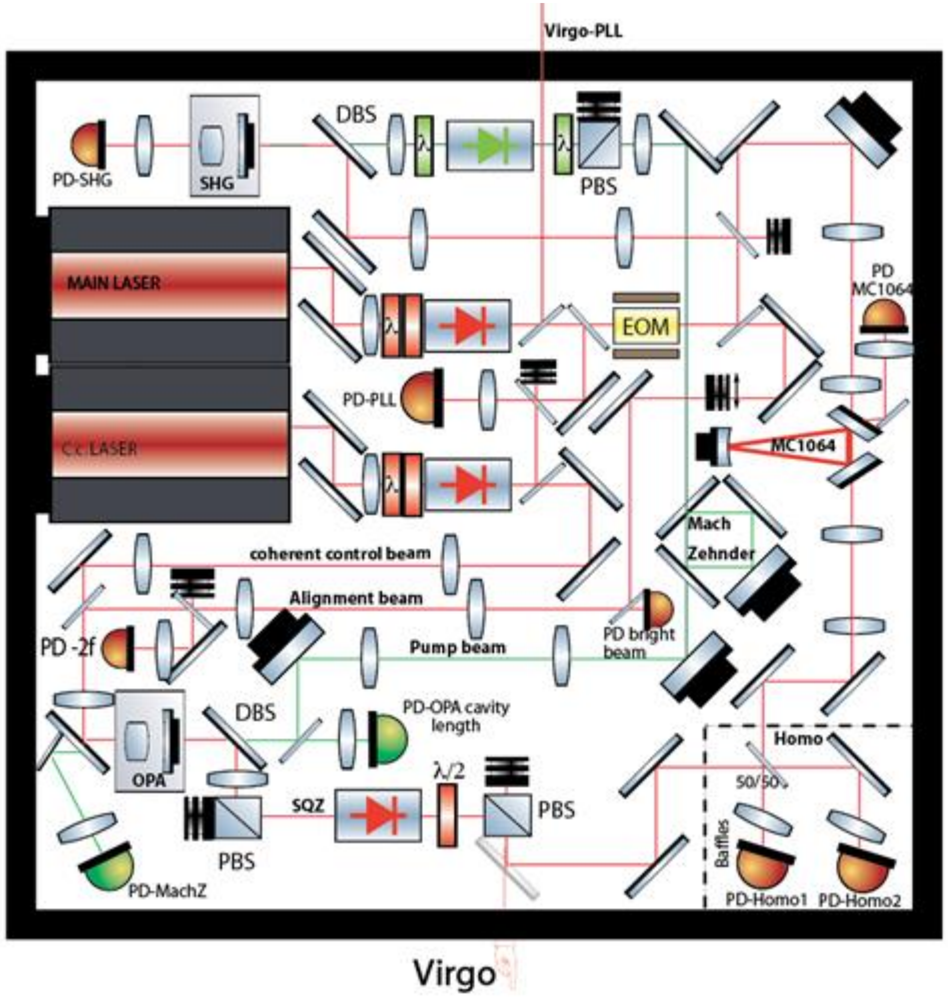
Higher order polarization effects in media

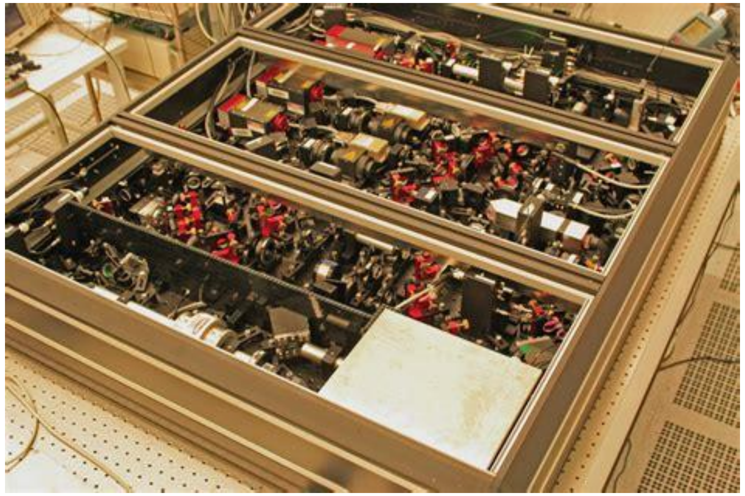
$$P(E(t)) = \epsilon_0(\chi^{(1)}E(t) + \chi^{(2)}E(t)^{(2)} + \chi^{(3)}E(t)^{(3)} + ..)$$

Optical Parametric Oscillator (OPO)

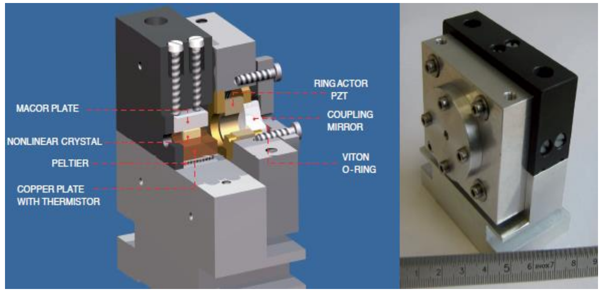


A squeezed light source is not just an OPO...

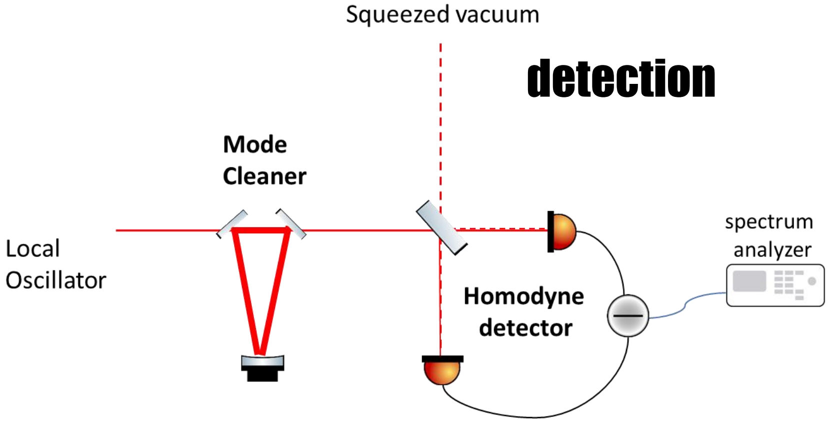




generation



Many of these components need to be controlled.



detection

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

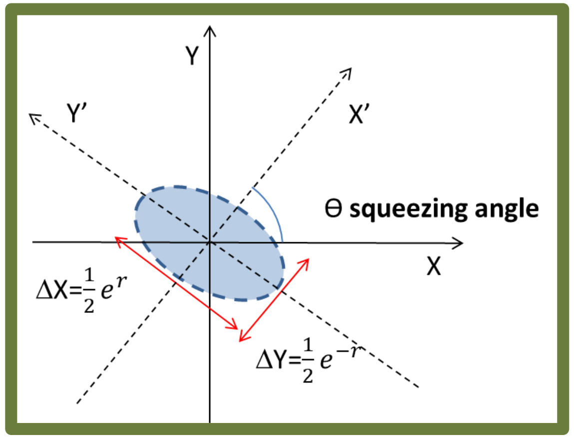
Quantum engineering of squeezed states for quantum communication and metrology

H Vahlbruch[1], S Chelkowski, K Danzmann and R Schabel
Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Callinstr 38 30167 Hannover, Germany
E-mail: henning.vahlbruch@aei.mpg.de

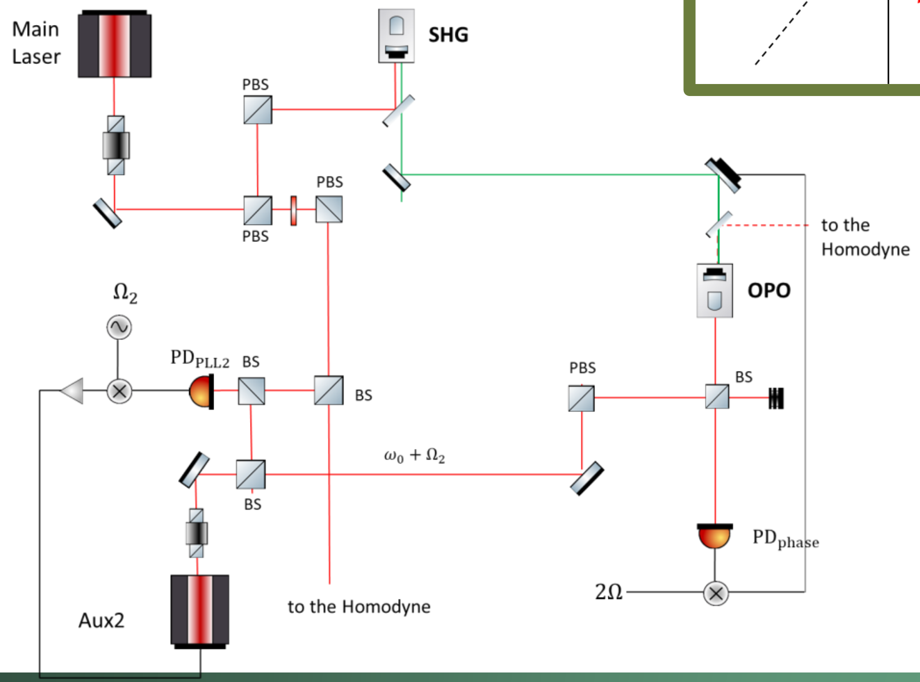
New Journal of Physics **9** (2007) 371
Received 29 August 2007

2007: Squeezing in AUDIO-FREQUENCY band

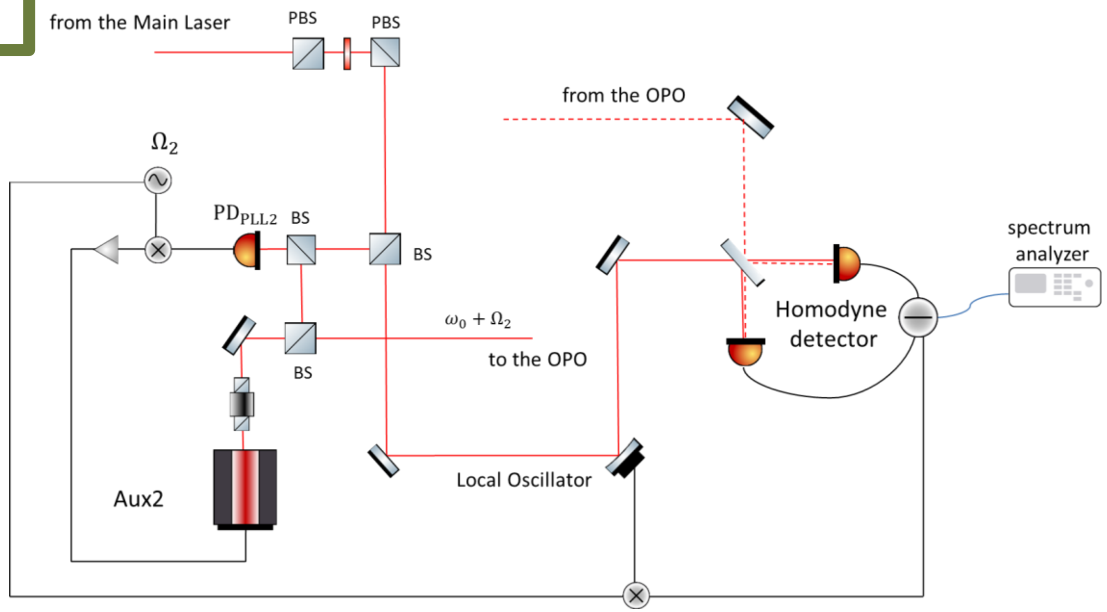
How does it mean squeezing in audio-frequency band?



Pump beam phase stabilization



Local Oscillator beam phase stabilization

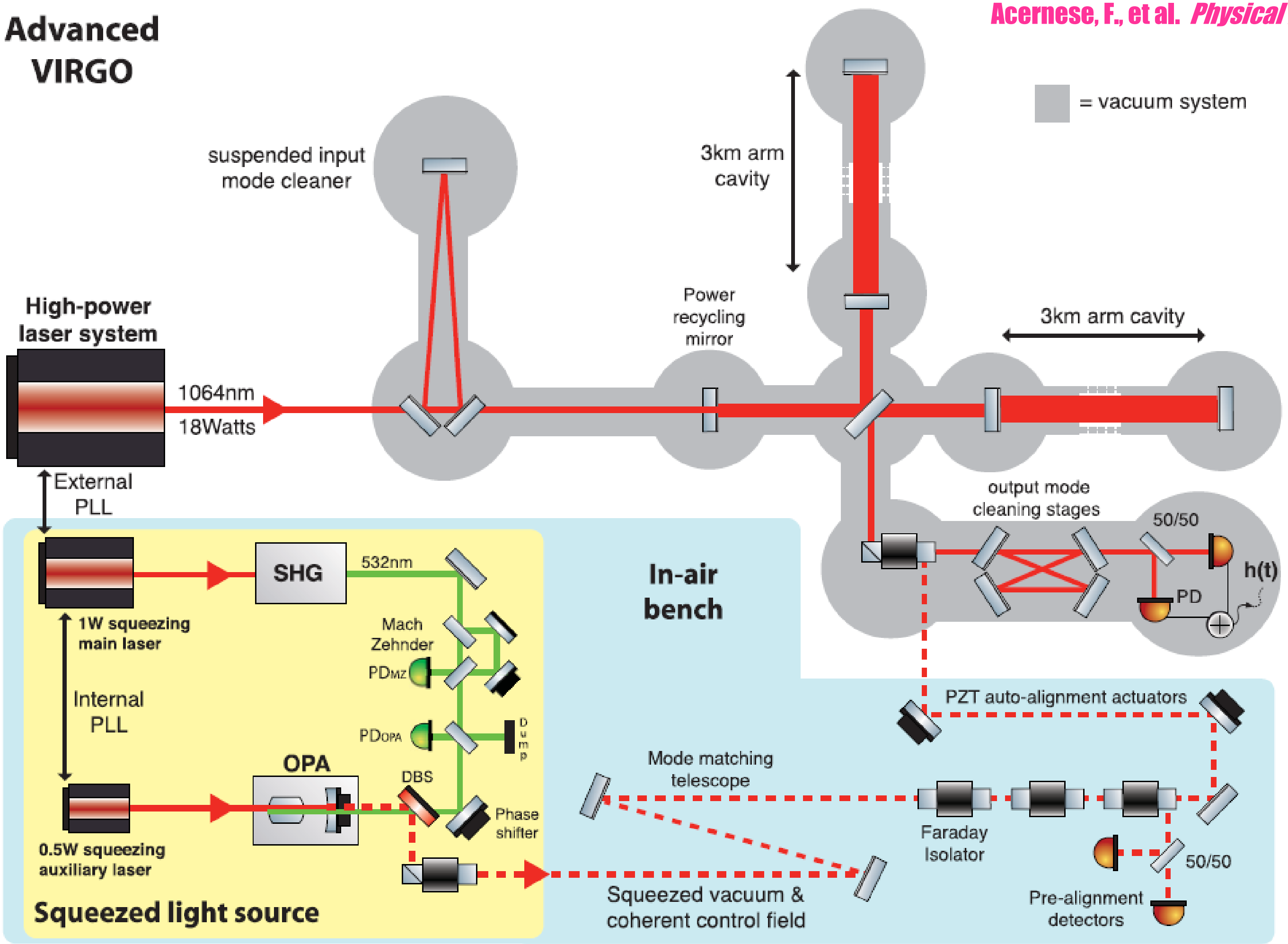


Quantum noise reduction techniques in GW interferometers

Part II

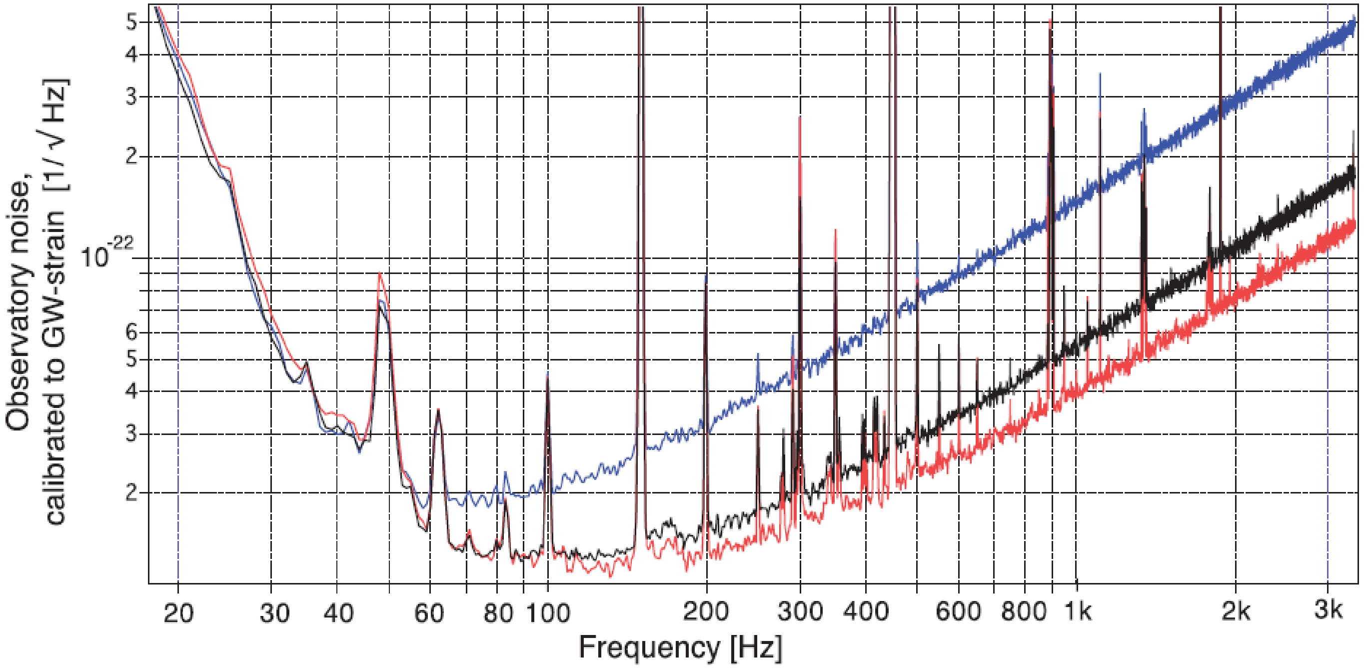
Squeezer – Interferometer Interface

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

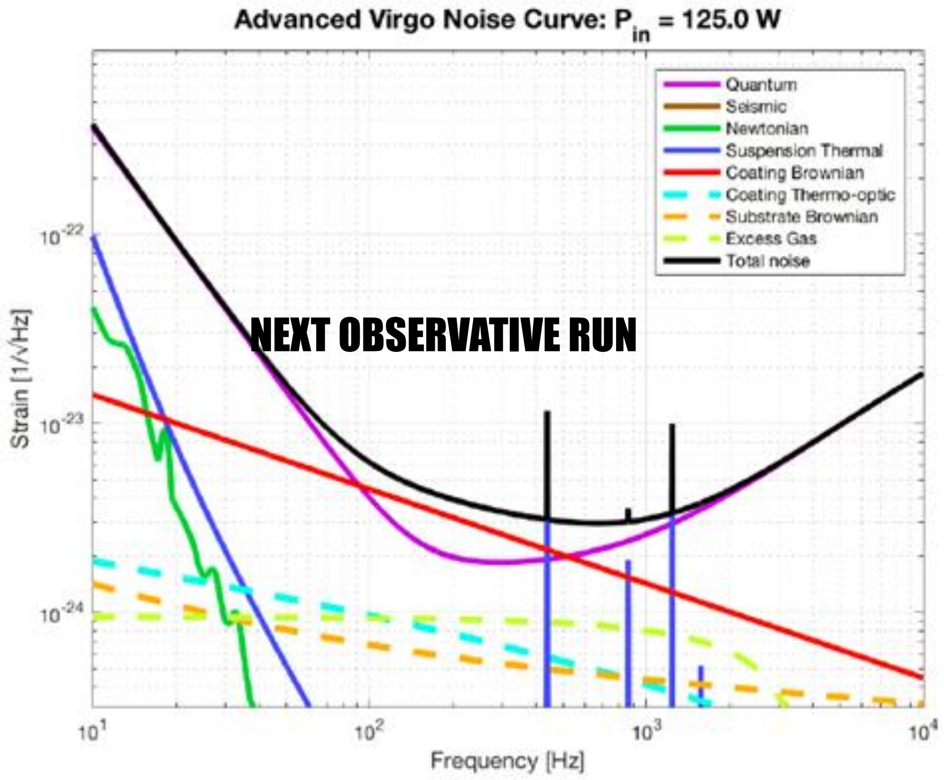
Measured squeezing level: 3.2 ± 0.1 dB

Measured anti-squeezing level: 8.5 ± 0.1 dB

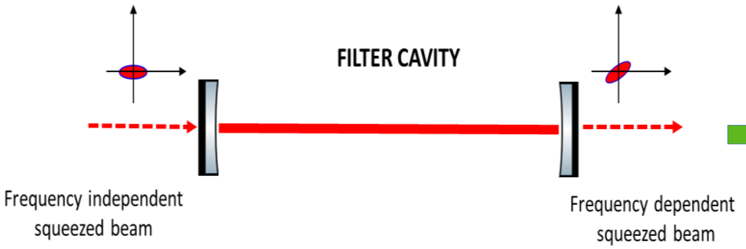
normalization to the reference at 2.8 kHz
injected squeezing level about 10 dB

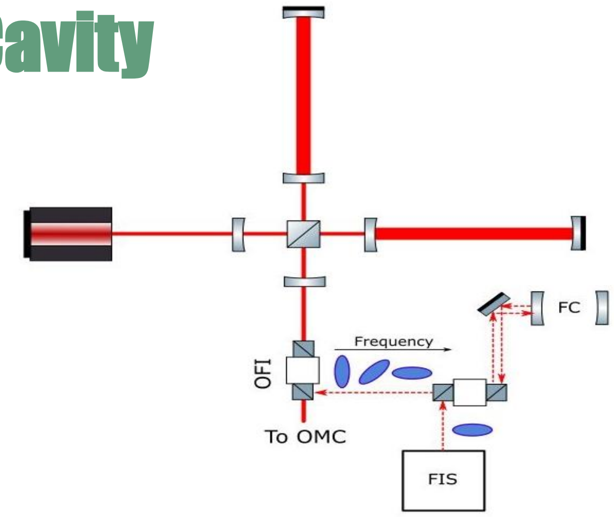
Acernese, F., et al. *Physical Review Letters* 123.23 (2019): 231108.

Need for a Frequency-Dependent Squeezing (FDS)



1. Filter Cavity



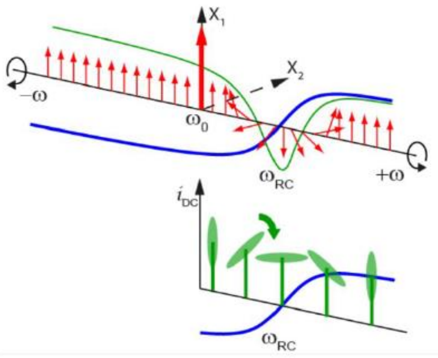


FDS angle rotation:

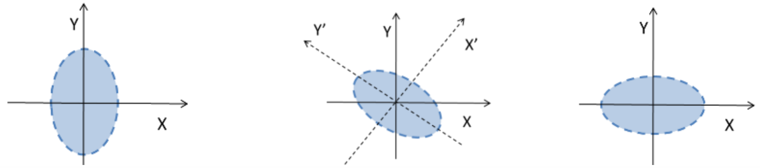
$$\theta_{fc}(\Omega) = \arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2}\right)$$

$\Delta\omega_{fc}$ Detuning

γ_{fc} Cavity linewidth



Broadband QN reduction



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 KAGRAgravitational-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

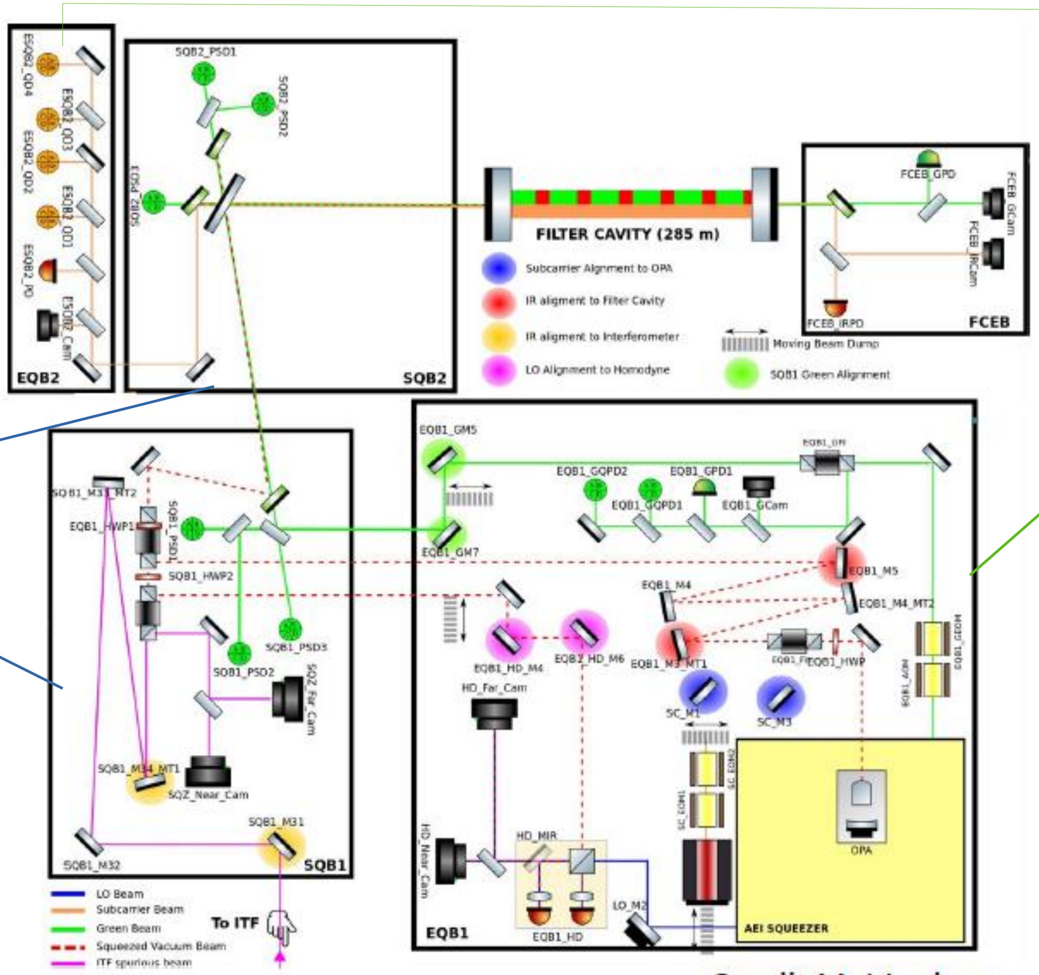
CAVITY MIRRORS

- **diameter d=15 cm;**
- **radius of curvature RoC= 558 m;**
- **round-trip losses l< 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



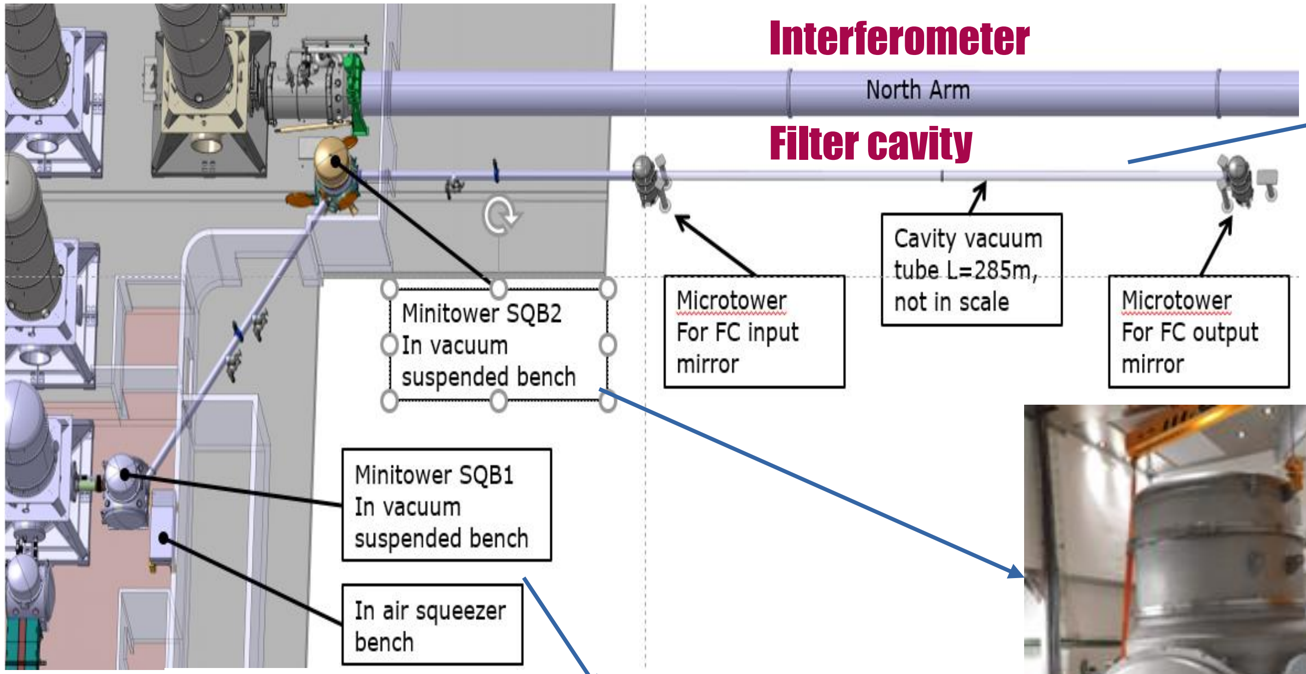
Credit M. Vardaro

Not suspended benches

Suspended benches

AdV+ FDS vacuum system

Detection

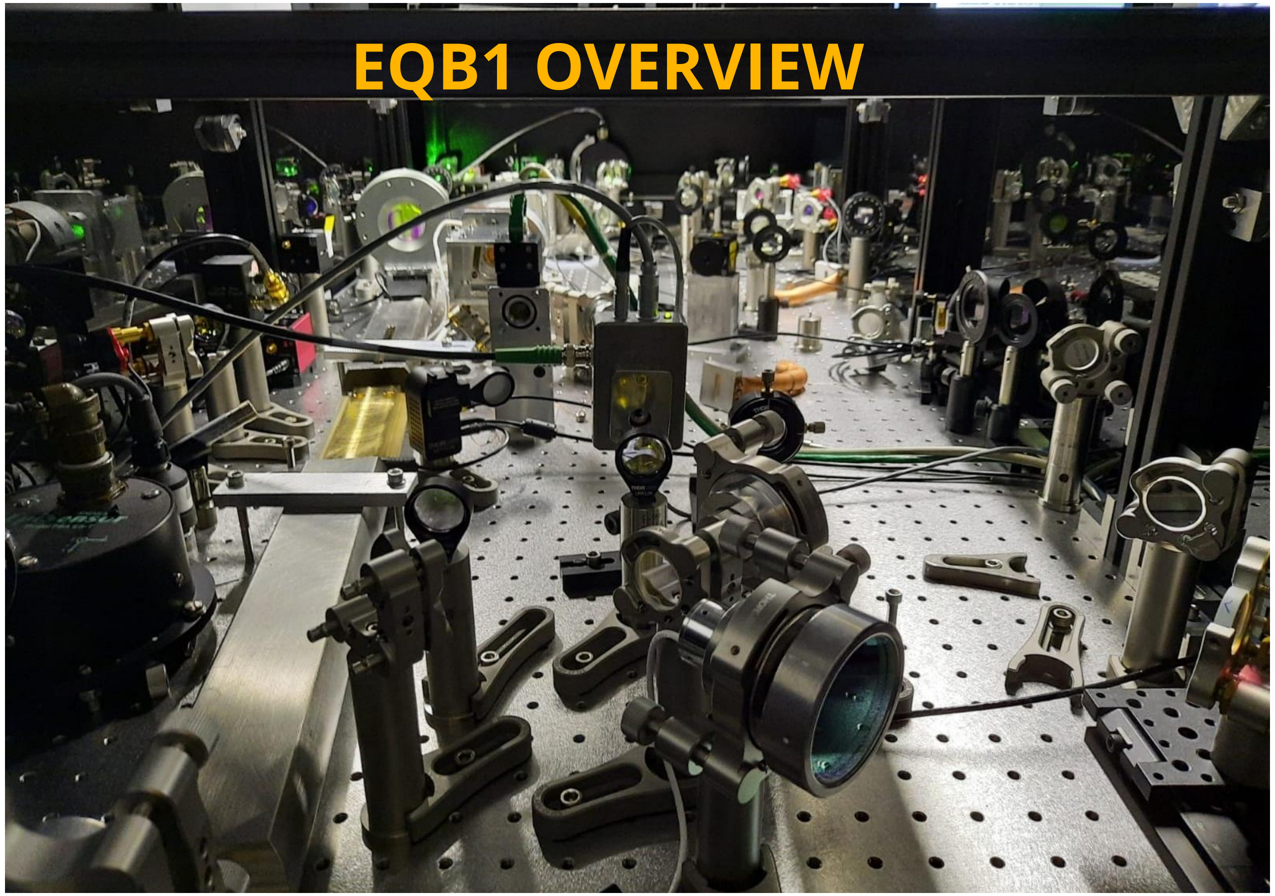


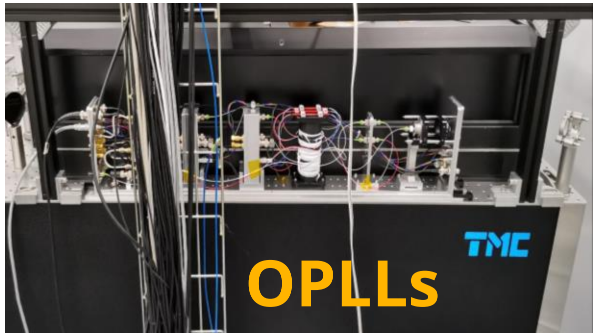
Filter cavity

SQB1 tank

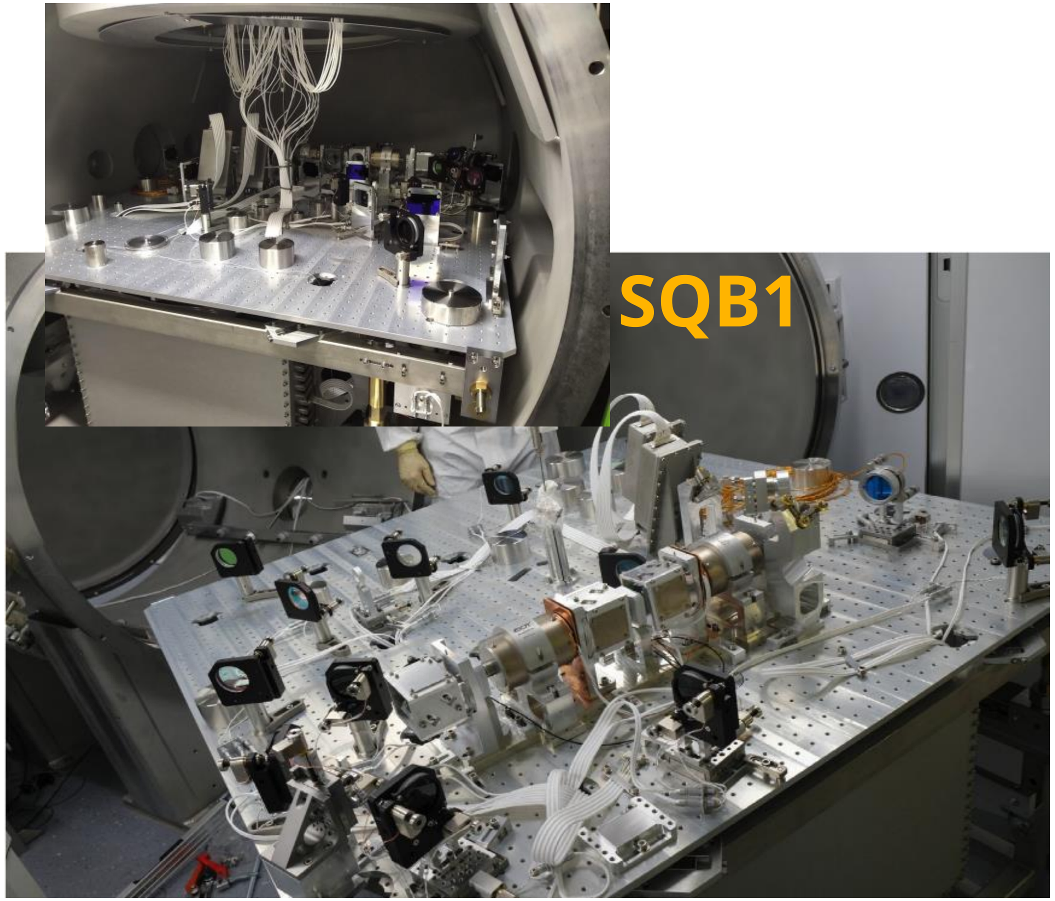
SQB2 tank

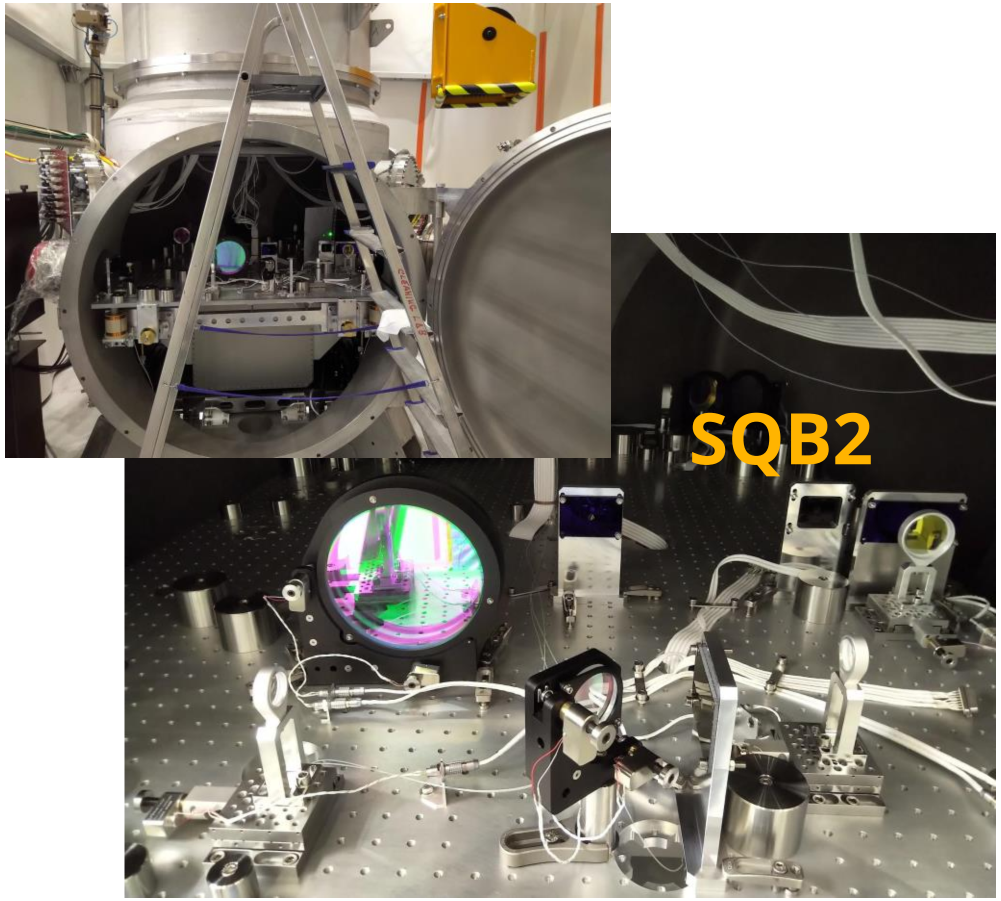
AdV+: in-air external squeezing bench (EQB1)



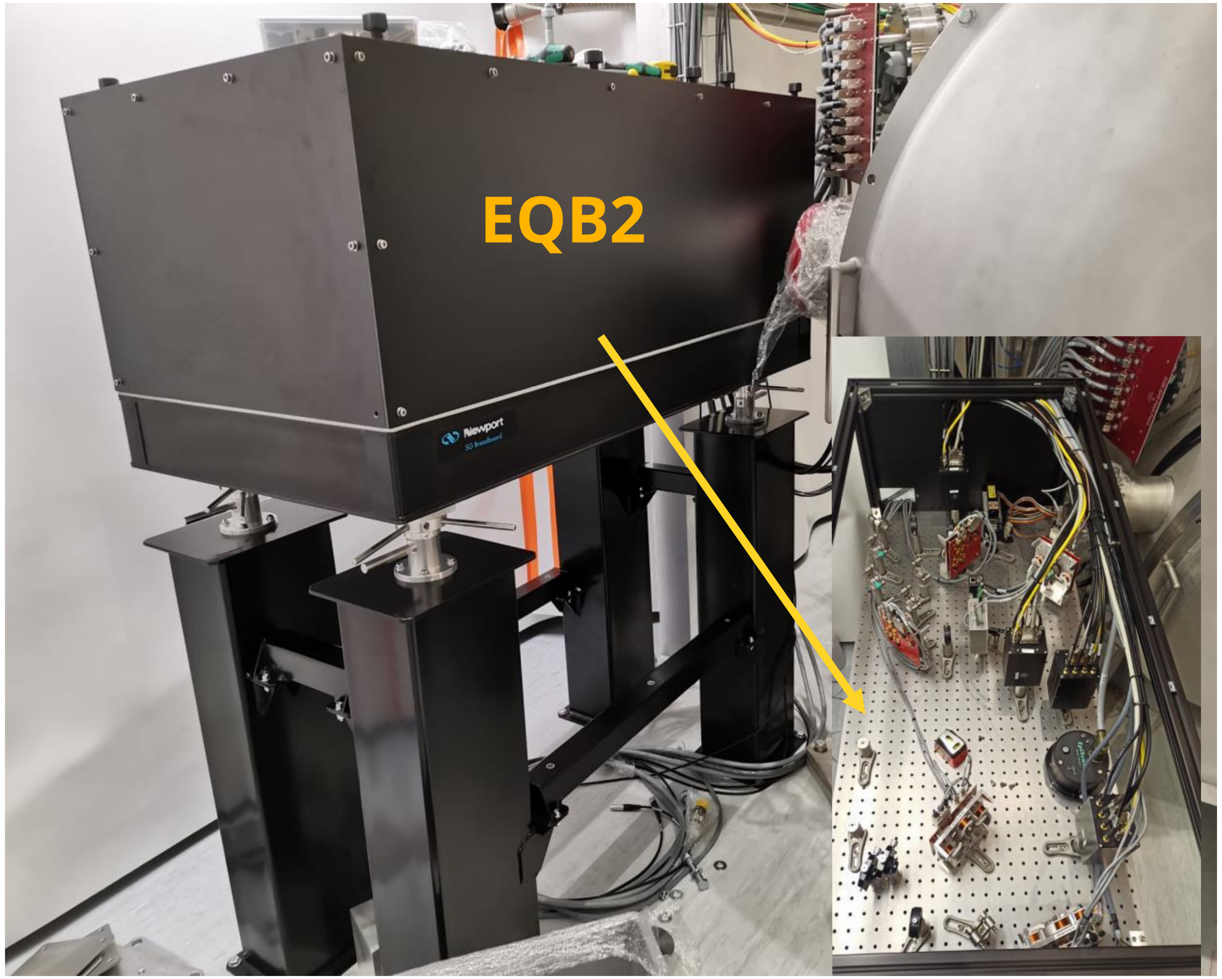


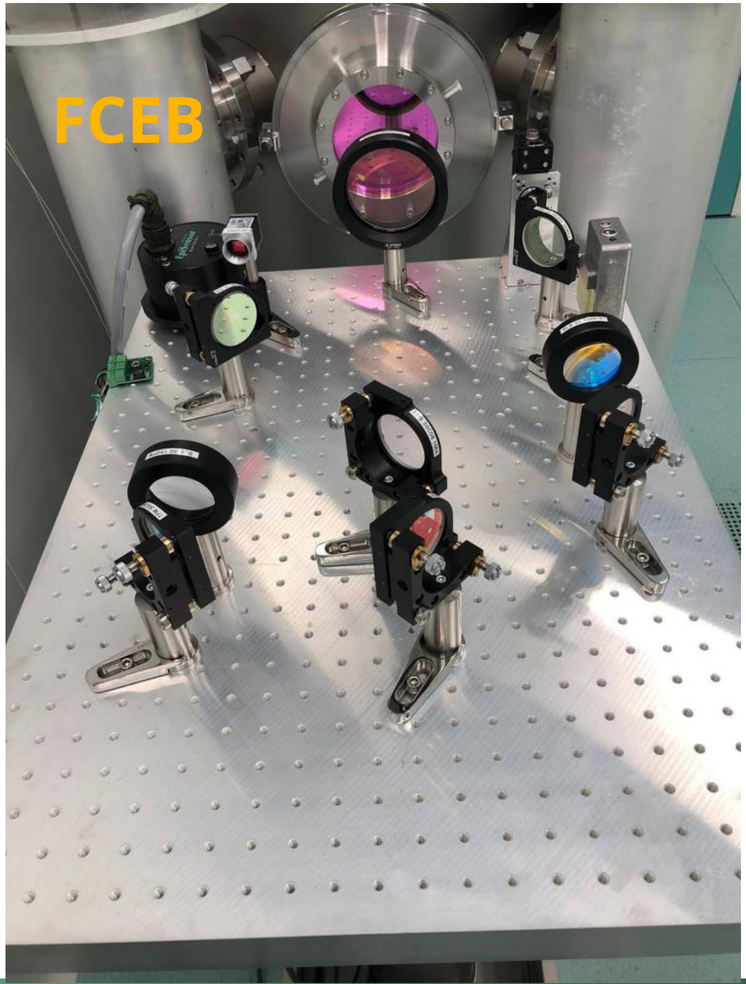
AdV+: in-vacuum suspended squeezing benches





AdV+: in-air auxiliary benches





What we want to do in ET

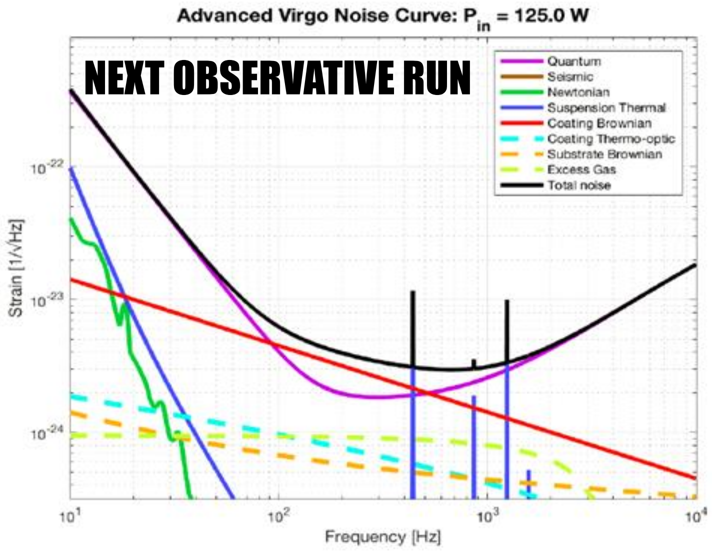
Part III

Other squeezing activities in ET

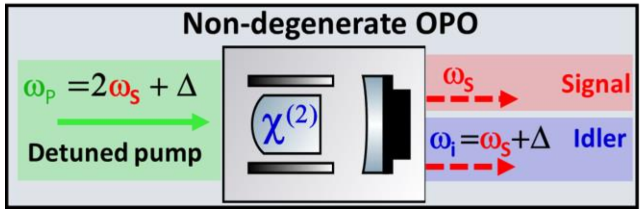
Subgroups

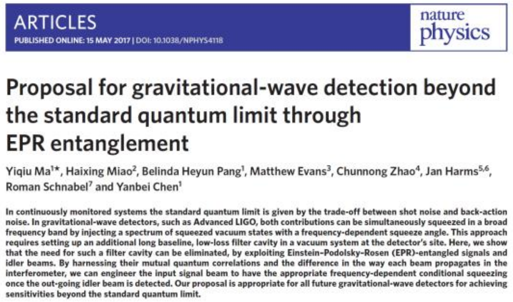
- **Phase noise** (Valeria Sequino: valeria.sequino@na.infn.it)
- **pyGWINC**
- **EPR squeezing** (Mateusz Bawaj: mateusz.bawaj@unipg.it)
- **SQZ source 1550 nm**
- **SQZ source 1064 nm**
- **Global design**
- **Filter Cavity 1064 nm**
- **Filter Cavity 1550 nm**
- **2um R&D**

Need for a Frequency-Dependent Squeezing (FDS)



2. EPR entangled beams





ARTICLES

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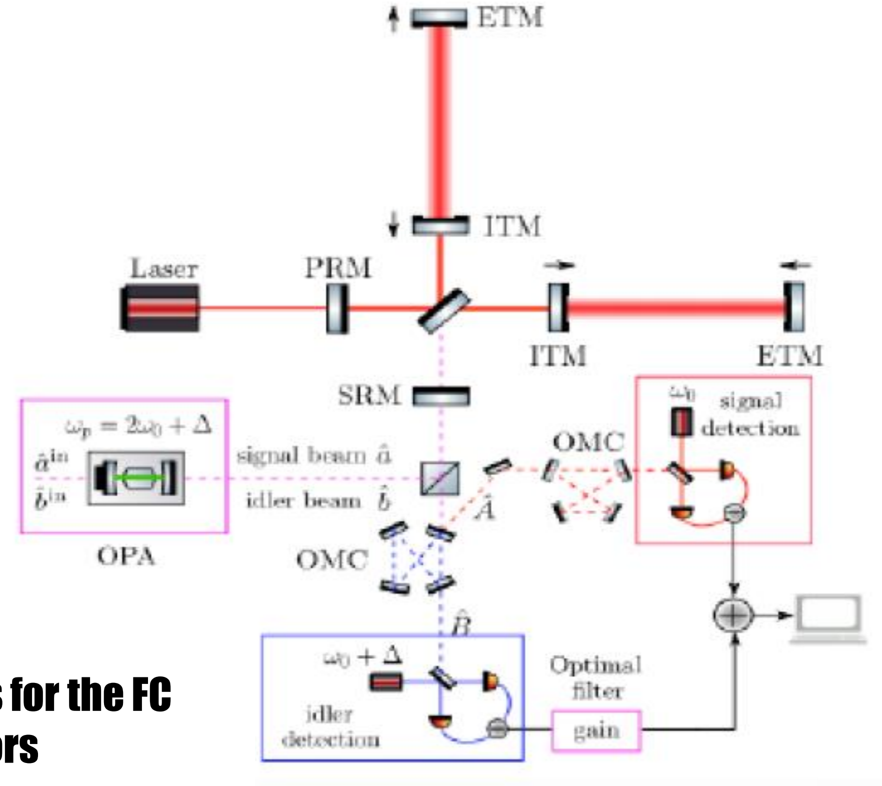
nature physics

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

Yiqiu Ma[1*], Haixing Miao[2], Belinda Heyun Pang[1], Matthew Evans[3], Chunnong Zhao[4], Jan Harms[5,6], Roman Schnabel[7] and Yanbei Chen[1]

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 in a vacuum system 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.

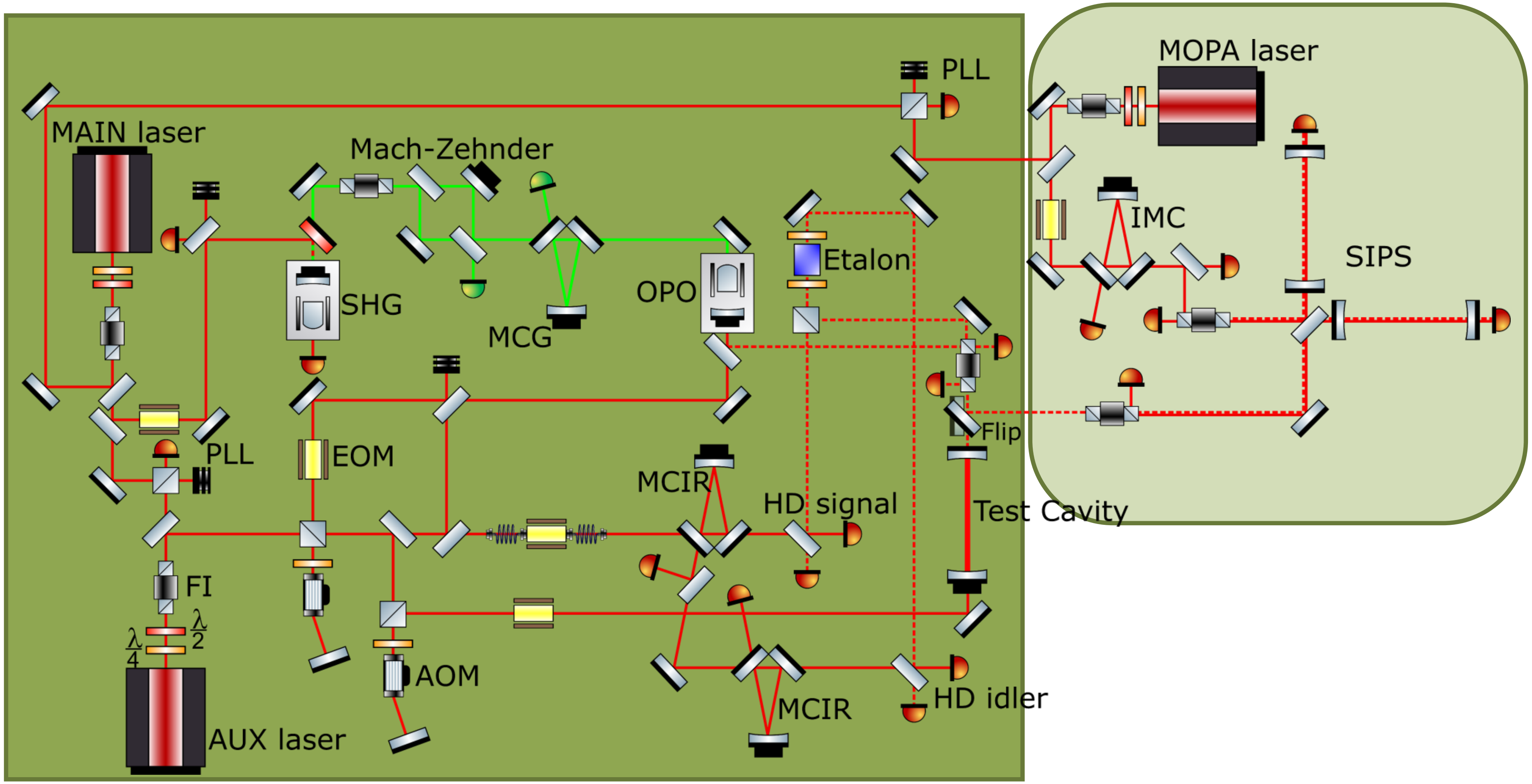


ITF both GW detector and the filter cavity (FC)

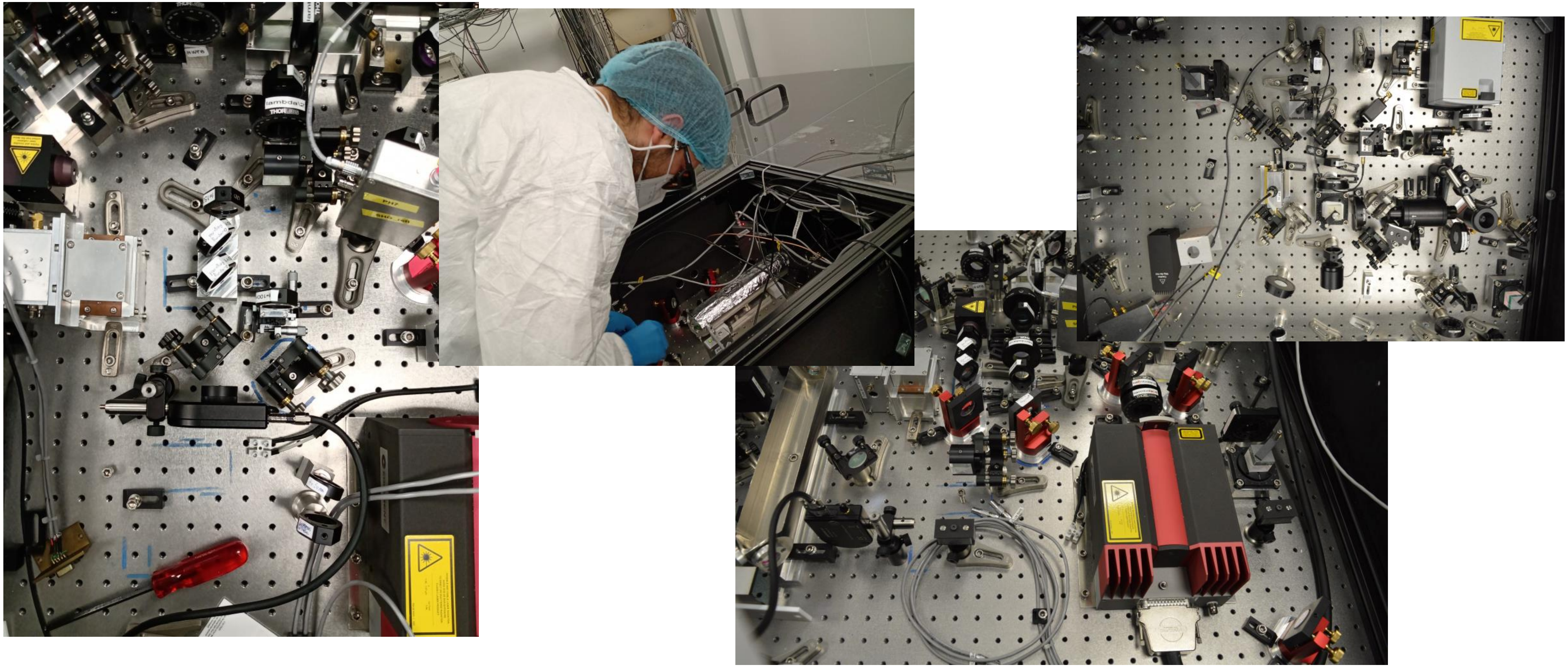
Advantages: less expensive, more compact setup, avoids the 1ppm/m round trip losses for the FC

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

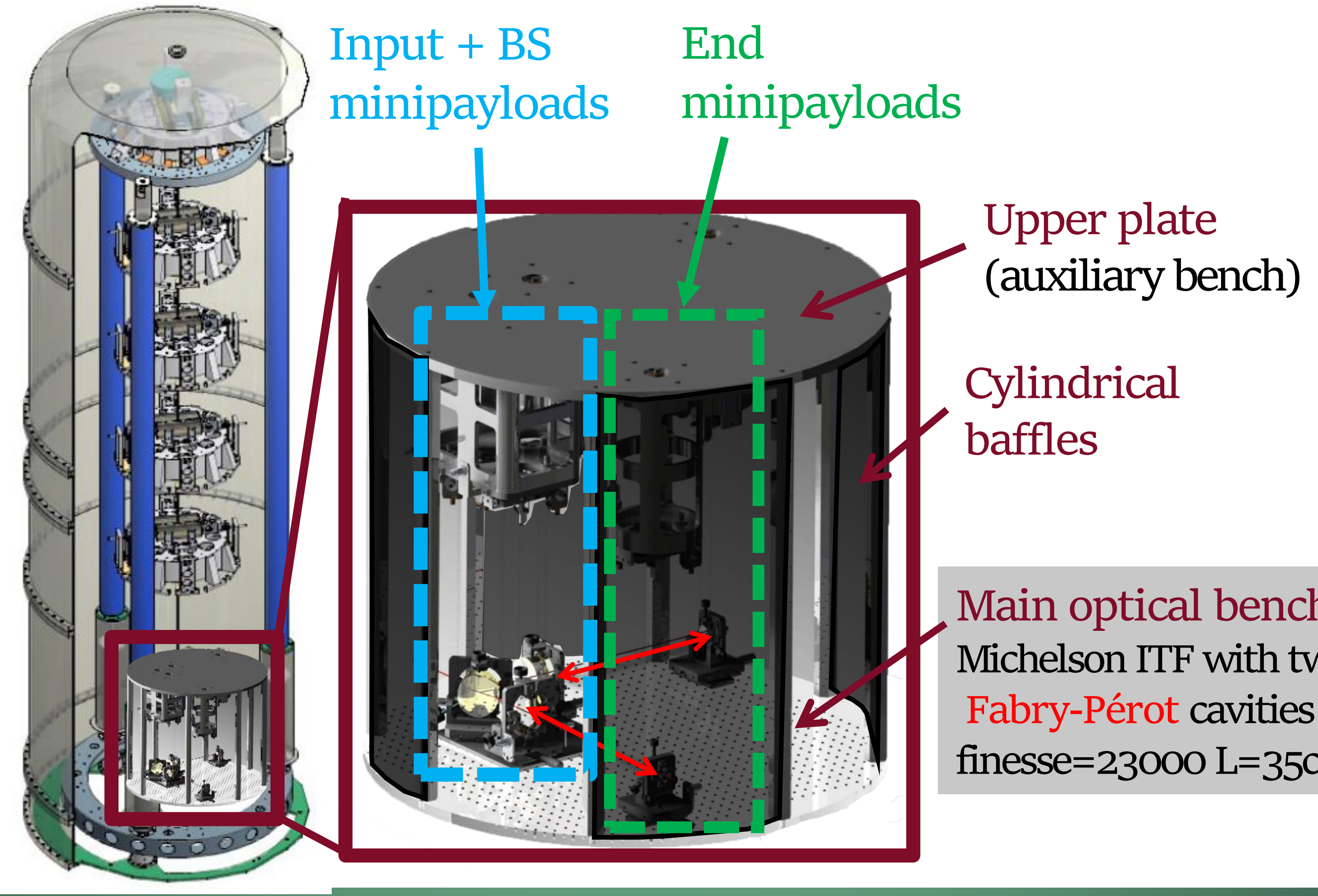
Our EPR experiment at the EGO site



Some pictures of our EPR experiment

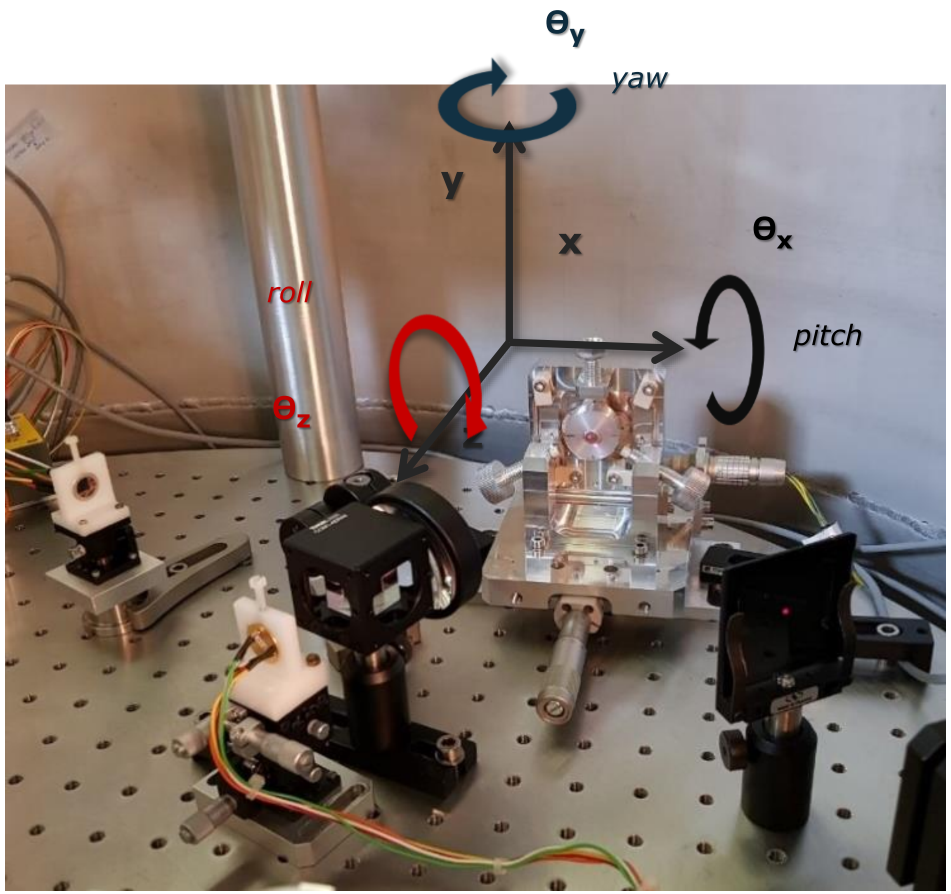


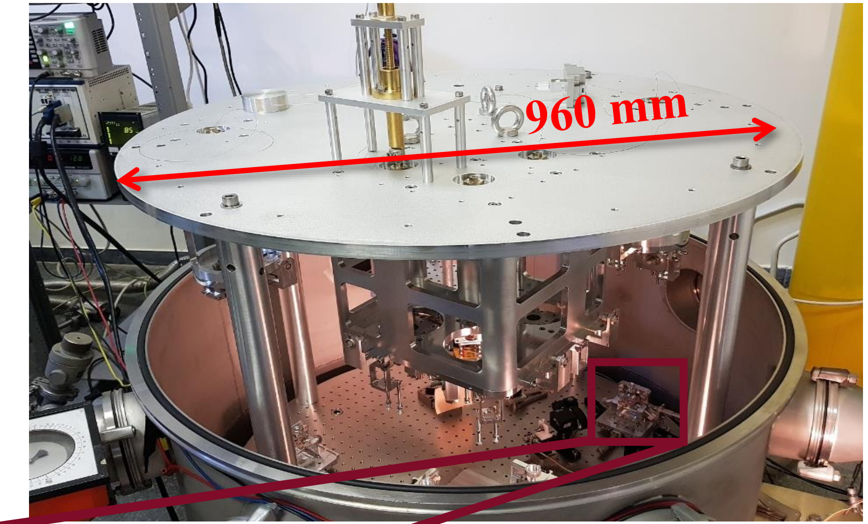
The small suspended interferometer

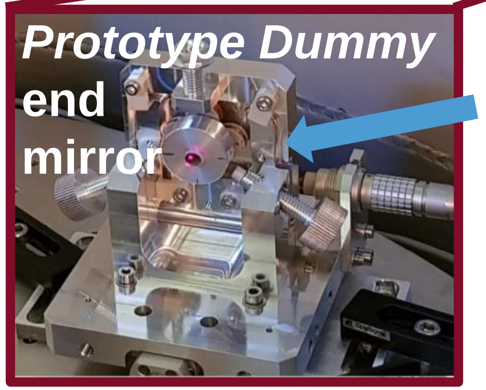


Main optical bench
Michelson ITF with two Fabry-Pérot cavities
finesse=23000 L=35cm

Some pictures small suspended interferometer



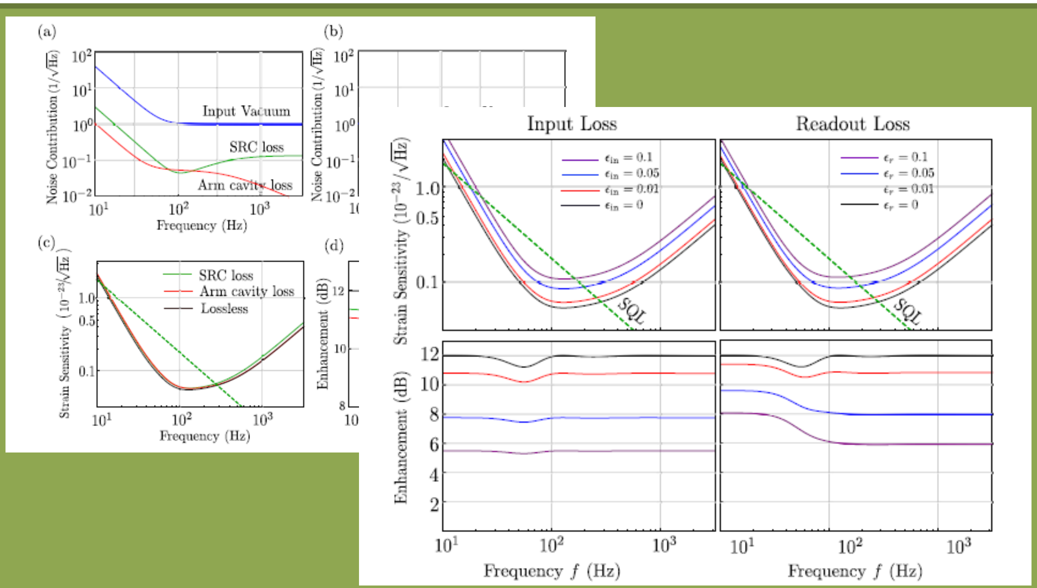




Test of local control of suspended elements:
Coils behind mirror and magnets glued on the mirror
Coils-magnets also on the marionette

Many calculations and simulations to do…

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



If you are interested in contributing…

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