Quantum noise reduction in Gravitational Wave Interferometers

Barbara Garaventa
on behalf of the QNR Virgo collaboration

PUMA22

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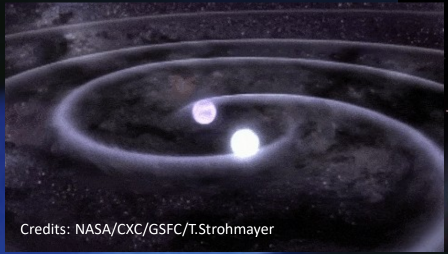
- **Introduction**
- How to detect Gravitational Waves
- Quantum Noise
- How to mitigate Quantum Noise
- Quantum Noise reduction in Advanced Virgo Plus
- EPR experiment: Genoa Laboratory contribution
- Conclusions

Introduction

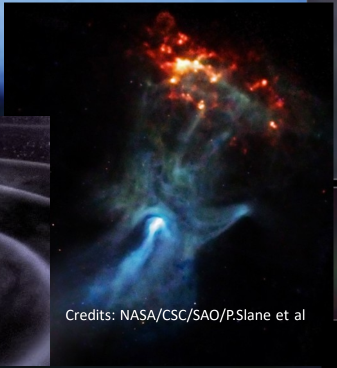
Gravitational Waves (GWs)

Ripples in spacetime
due to violent astrophysics events

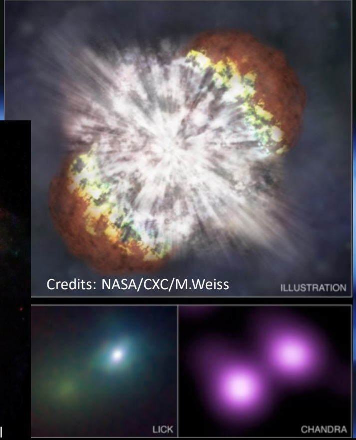
Predicted in 1916 by Albert Einstein with the theory of General Relativity



Credits: NASA/CXC/GSFC/T.Strohmayer



Credits: NASA/CSC/SAO/P.Slane et al

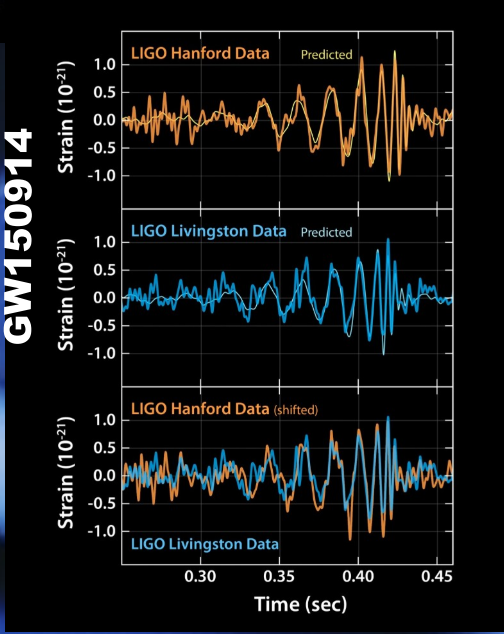


Credits: NASA/CXC/M.Weiss

Einstein's Equation

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{curvature of spacetime}} = (\underbrace{8\pi G}_{\text{constants}}) \underbrace{T_{\mu\nu}}_{\text{energy and momentum}}$$

First direct observation in 2015 by the LIGO and VIRGO collaborations (GW150914), using data from the two LIGO interferometers



Very small perturbations ($\Delta L \sim 10^{-18}$ m) → **Laser Interferometry**

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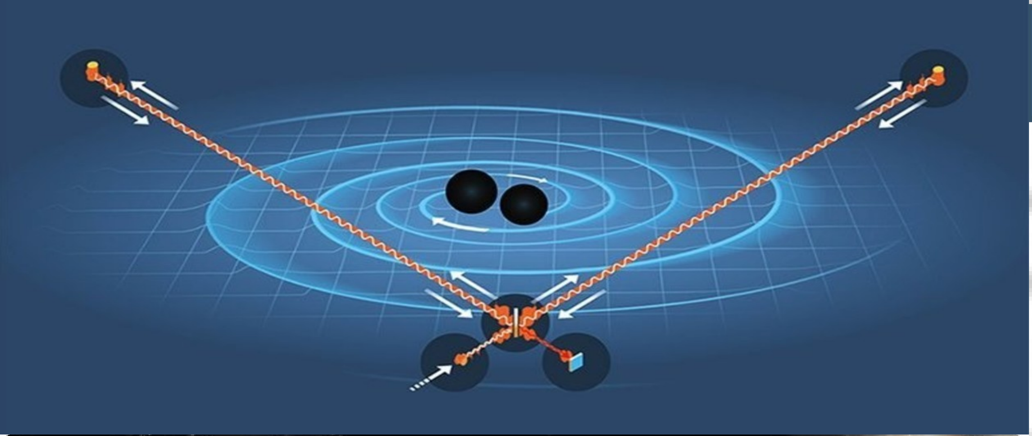
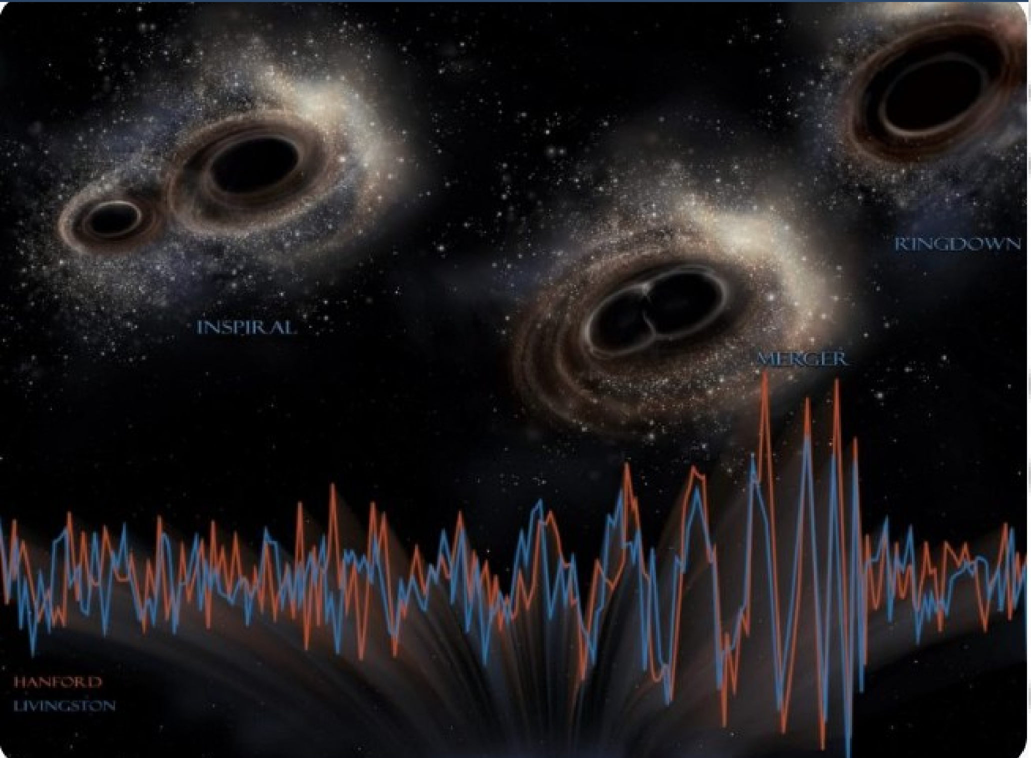
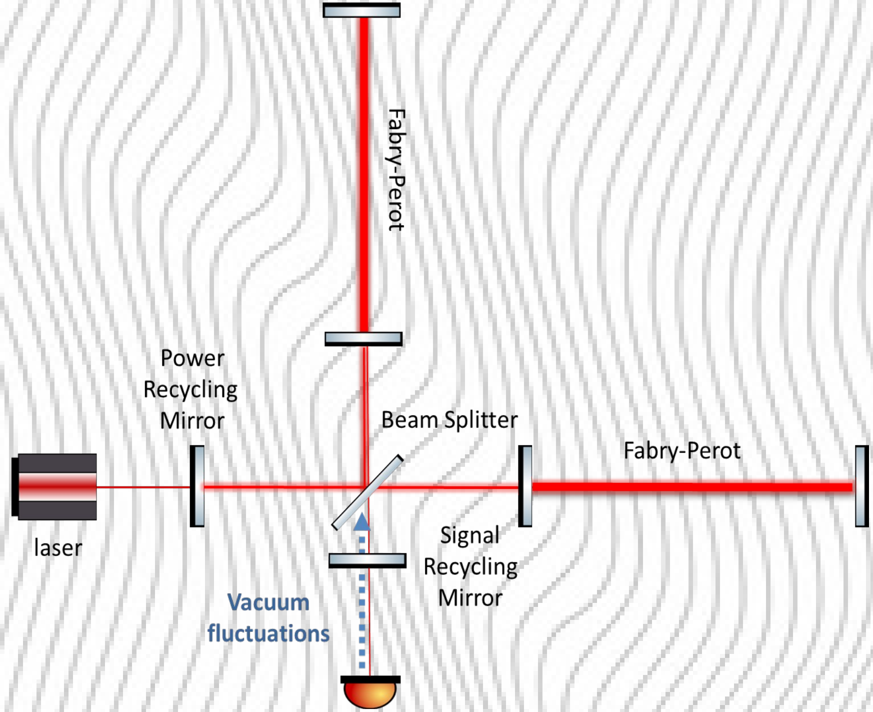
How to detect Gravitational Waves





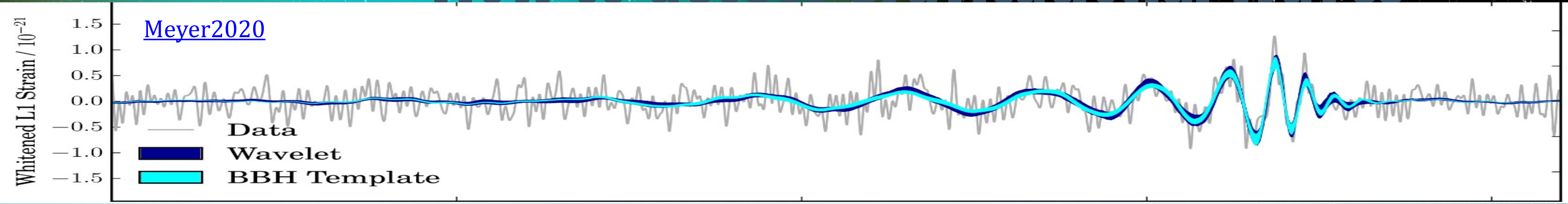
✔ Laser Interferometry



The arms are stretched and compressed in the opposite direction, oscillating at the frequency of the GW.

→ Measurement of light interference to the detector

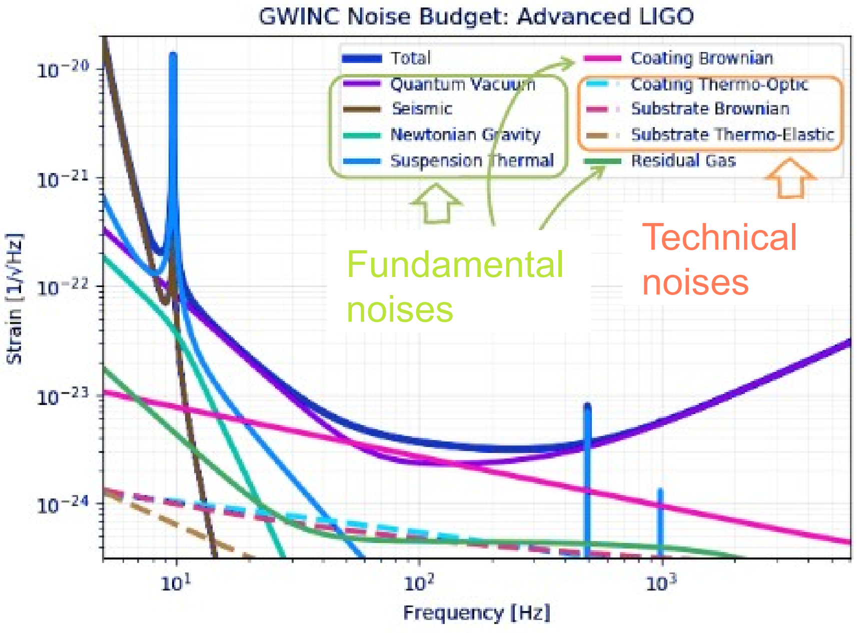
How to detect Gravitational Waves



Identify the waveform of a GW by comparing the signals arriving at the detector with those expected for a GW

Noises are phenomena that can simulate or hide GW signals

Main sources of noise



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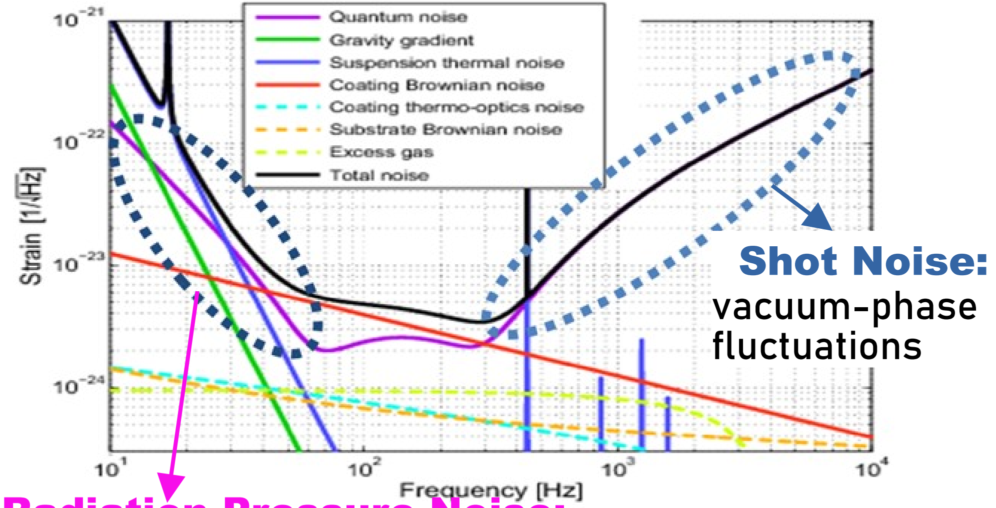
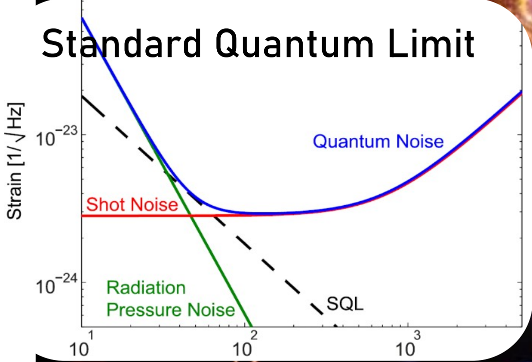
Quantum Noise

GW effects on the test masses of interferometer can be confused with the effect of vacuum fluctuations of the optical fields that entering from the dark port of the detector.

Quantum Noise limits the entire bandwidth





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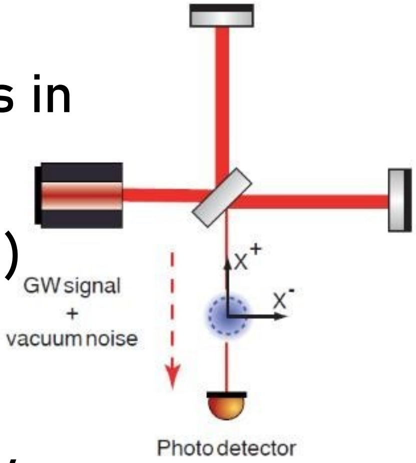
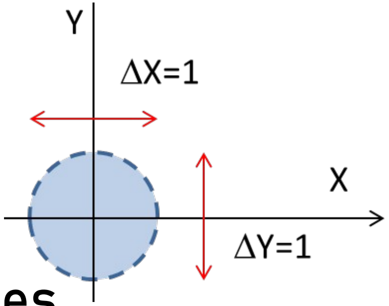
Quantum Noise

- Electro-magnetic fields in terms of quadrature operators (amplitude $\hat{X}$ and phase quadratures $\hat{Y}$)



- Heisenberg Uncertainty Principle

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



- Laser light can be described by coherent states

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

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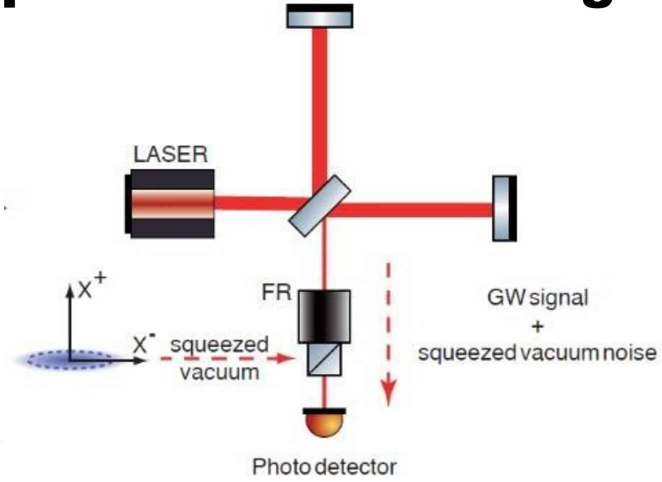
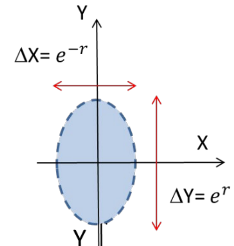
How to mitigate Quantum Noise

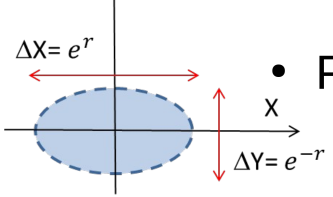
- **Squeezed States of Light:**





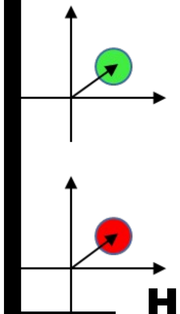
- Amplitude-Squeezed States

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

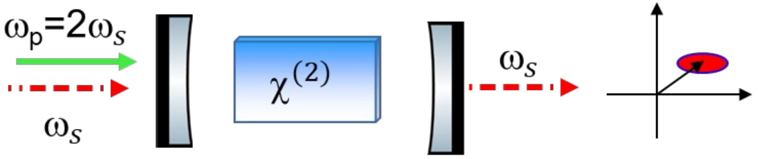


- Phase-Squeezed States

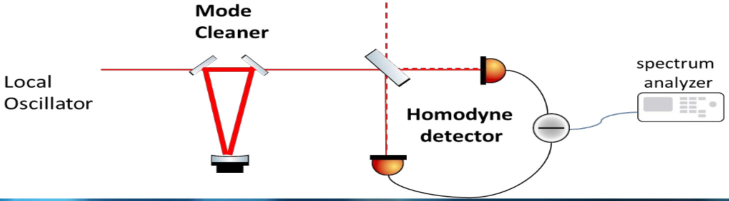
$$\left\langle \left(\Delta\hat{X}\right)^2\right\rangle_s = e^{r} \quad \left\langle \left(\Delta\hat{Y}\right)^2\right\rangle_s = e^{-r}$$



Non-linear optics (OPO) to generate squeezed vacuum



Homodyne Technique



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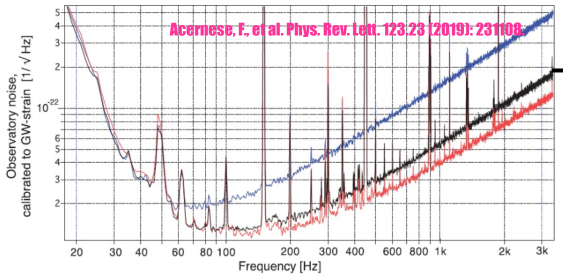
Quantum Noise reduction in Advanced Virgo Plus (AdV+)

Advanced Virgo (2019-2020):

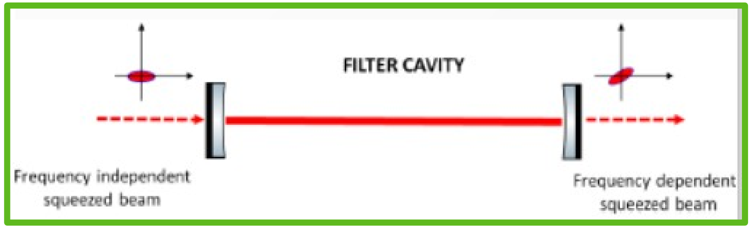
Frequency-independent squeezing **(FIS)** injection up to 3.2 dB (red curve)



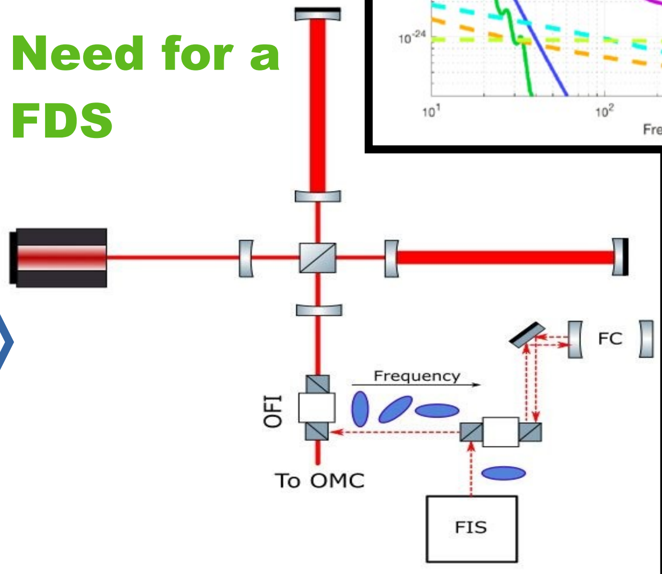
Absence of squeezed light

Advanced Virgo Plus (from 2023):

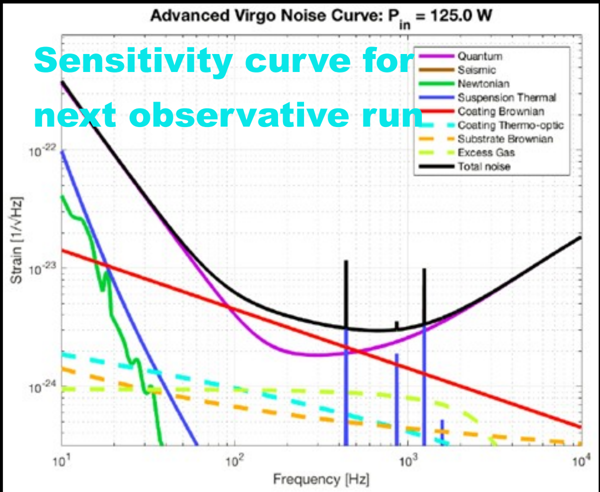
Frequency-dependent squeezing **(FDS)** achieved by a 300m long detuned cavty



Need for a FDS



Sensitivity curve for next observative run



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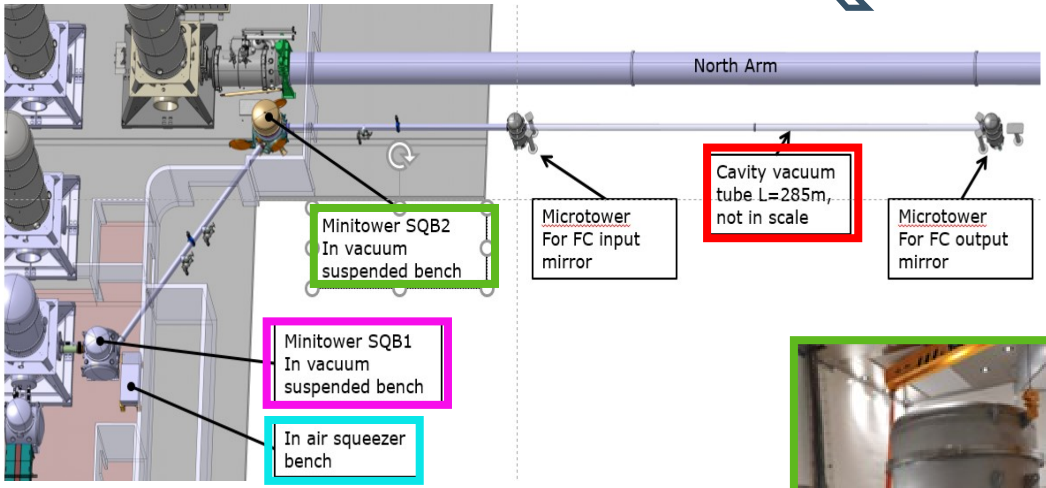
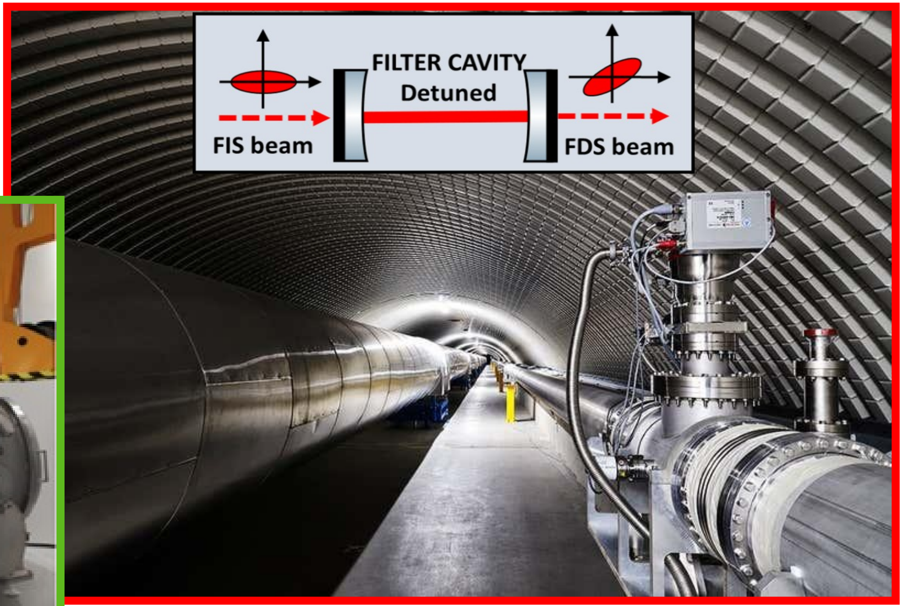
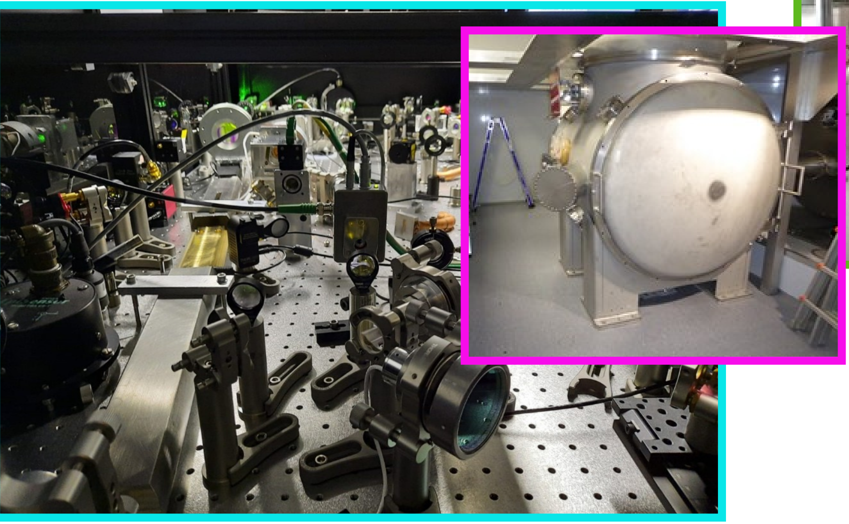
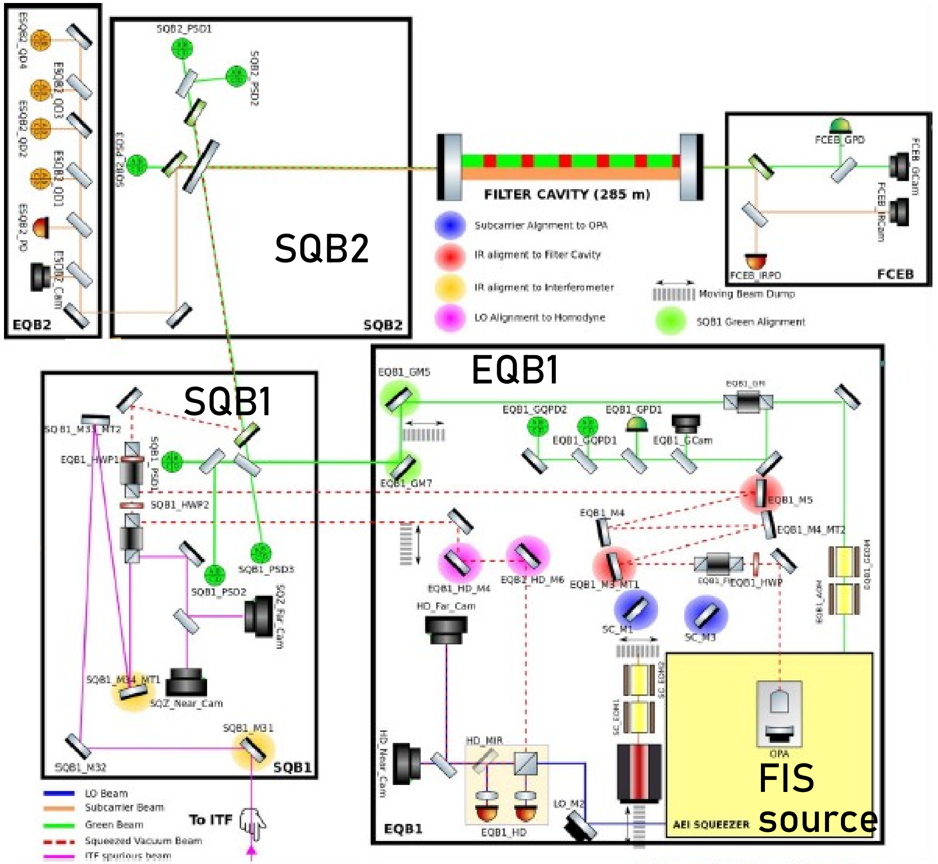
Quantum Noise reduction in AdV+







Quantum Noise reduction in AdV+



FDS to ITF

Credit M. Vardaro

FDS OVERALL CONCEPTUAL DESIGN

2 SUSPENDED BENCHES (SQB1, SQB2)

3 NOT SUSPENDED BENCHES (EQB1 for the squeezing source, EQB2 and FCEB for control loops)

FILTER CAVITY:
parallel to the ITF North Arm;
length L=285 m;
finesse F=11000 (@1064 nm)

Coloured mirrors are motorized for the automatic alignment loops

AdV+ required squeezing angle rotation: 20-30 Hz

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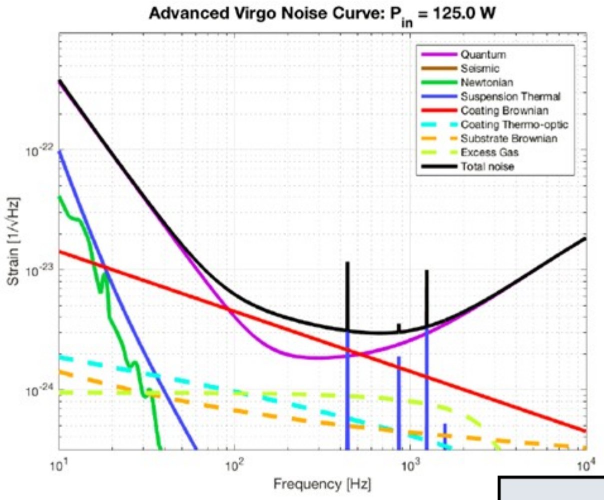
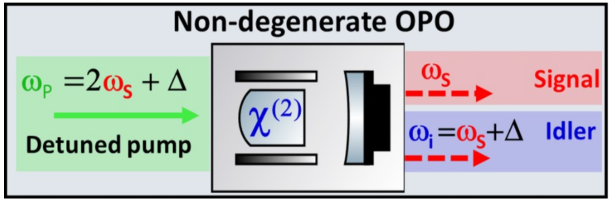
FDS: Einstein-Podolsky-Rosen experiment

Next Observative runs → Need for a **FDS**

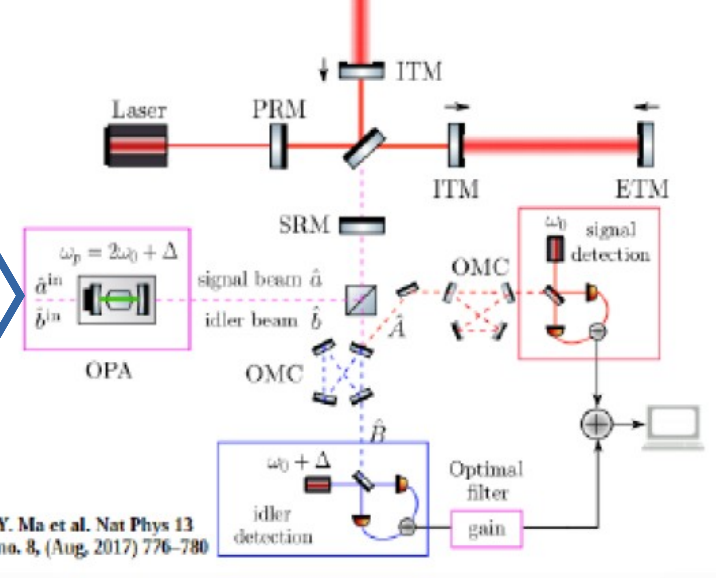


An alternative method to the filter cavity:

EPR ENTANGLED BEAMS



Signal and **idler** squeezed beams: EPR entangled

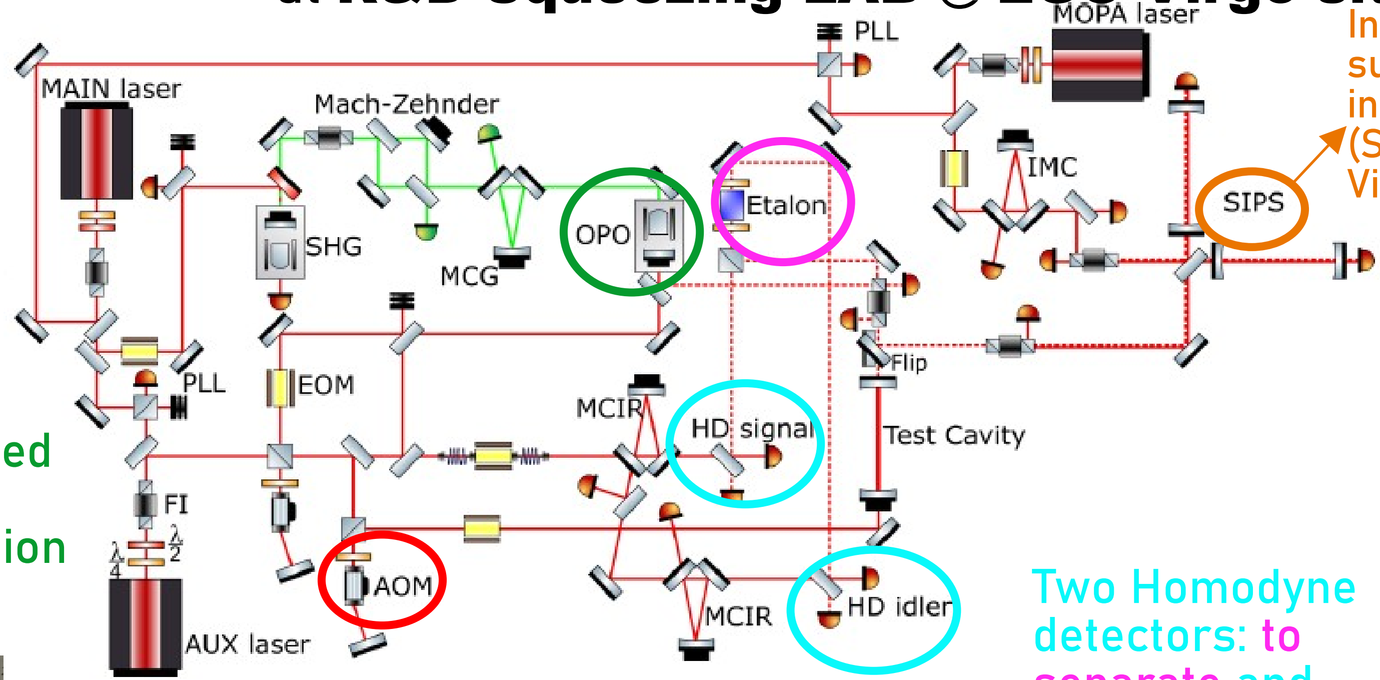


Y. Ma et al. Nat Phys 13 no. 8, (Aug. 2017) 776–780

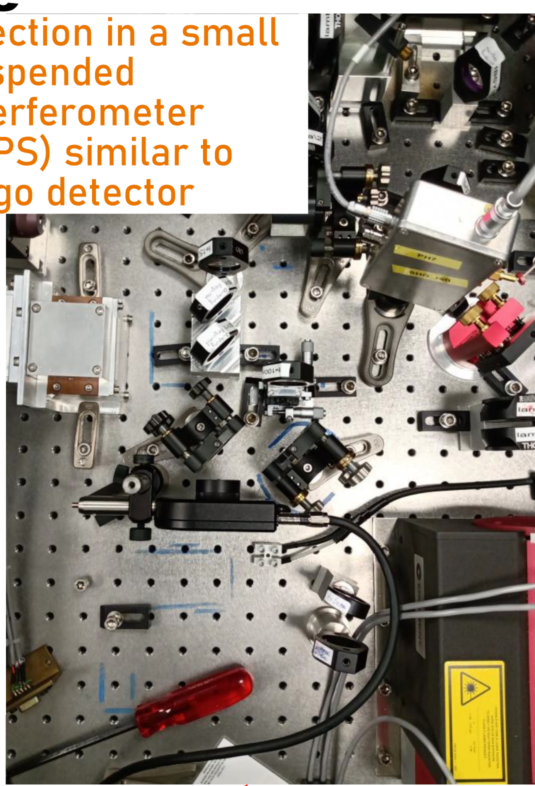
- Interferometer both GW detector and the filter cavity (FC)
- Advantages: less expensive, more compact setup; avoids the 1ppm/m round trip losses for the FC
- Disadvantages: two squeezed beams so double losses, need for two Homodyne Detectors

EPR (Einstein-Podolsky-Rosen) table-top experiment

at **R&D Squeezing LAB @ EGO-Virgo site**

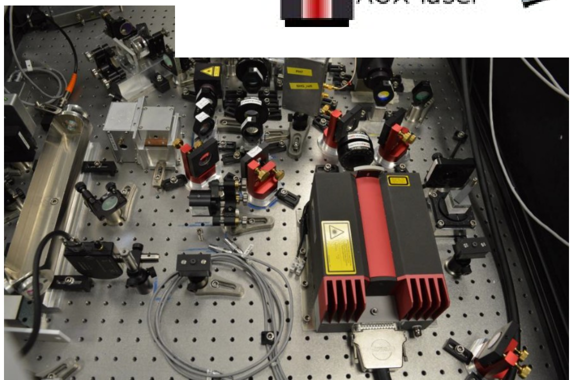


Injection in a small suspended interferometer (SIPS) similar to Virgo detector



Entangled beams production

Two Homodyne detectors: to separate and detect signal and idler beams

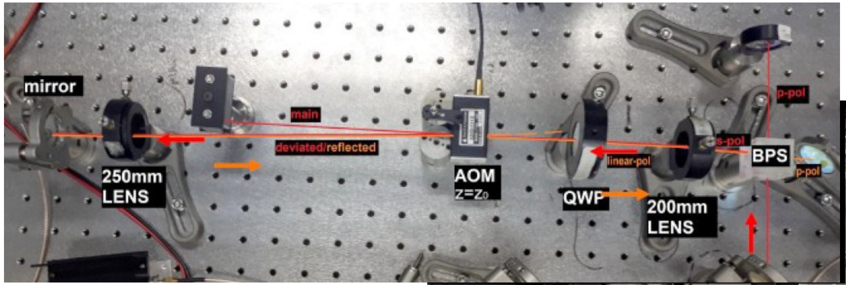


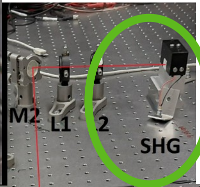
Some pictures of EPR optical bench already installed

Genoa Laboratory contribution on EPR experiment

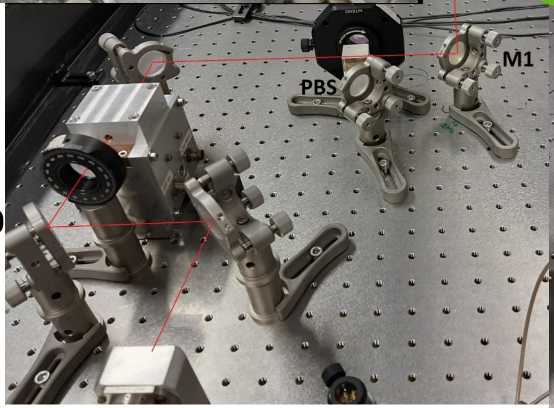
Some activities performed at Genoa laboratory for the EPR experiment:

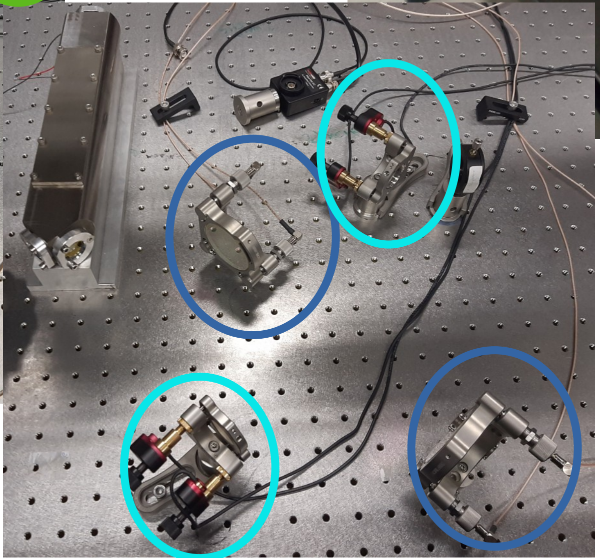
- Acousto-optic-modulator (AOM) tests





- **Optical cavities** test
- Development of the optical design
- **Actuators** test in order to develop automatic-alignment loops
- **Actuators** for remote alignment





Some pictures of Genoa laboratory

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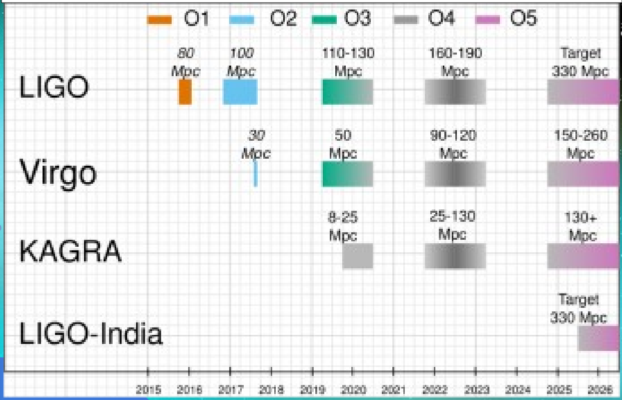
Conclusions

Evolution of the sensitivity of ground interferometers in the observation runs



For next observative run a **FDS is required** in order to mitigate Quantum noise in the entire bandwidth of the interferometer.

FDS injection allows **to explore a portion of the universe 10 times larger** than the last observation run.

The Genoa group collaborated directly in **AdV+** for the squeezing system, in **EPR experiment** and will collaborate also for the **Einstein Telescope**.

THANKS!

Any questions?

You can find me at:

barbara.garaventa@ge.infn.it