Gravitational-wave interferometric detectors and the Virgo experiment

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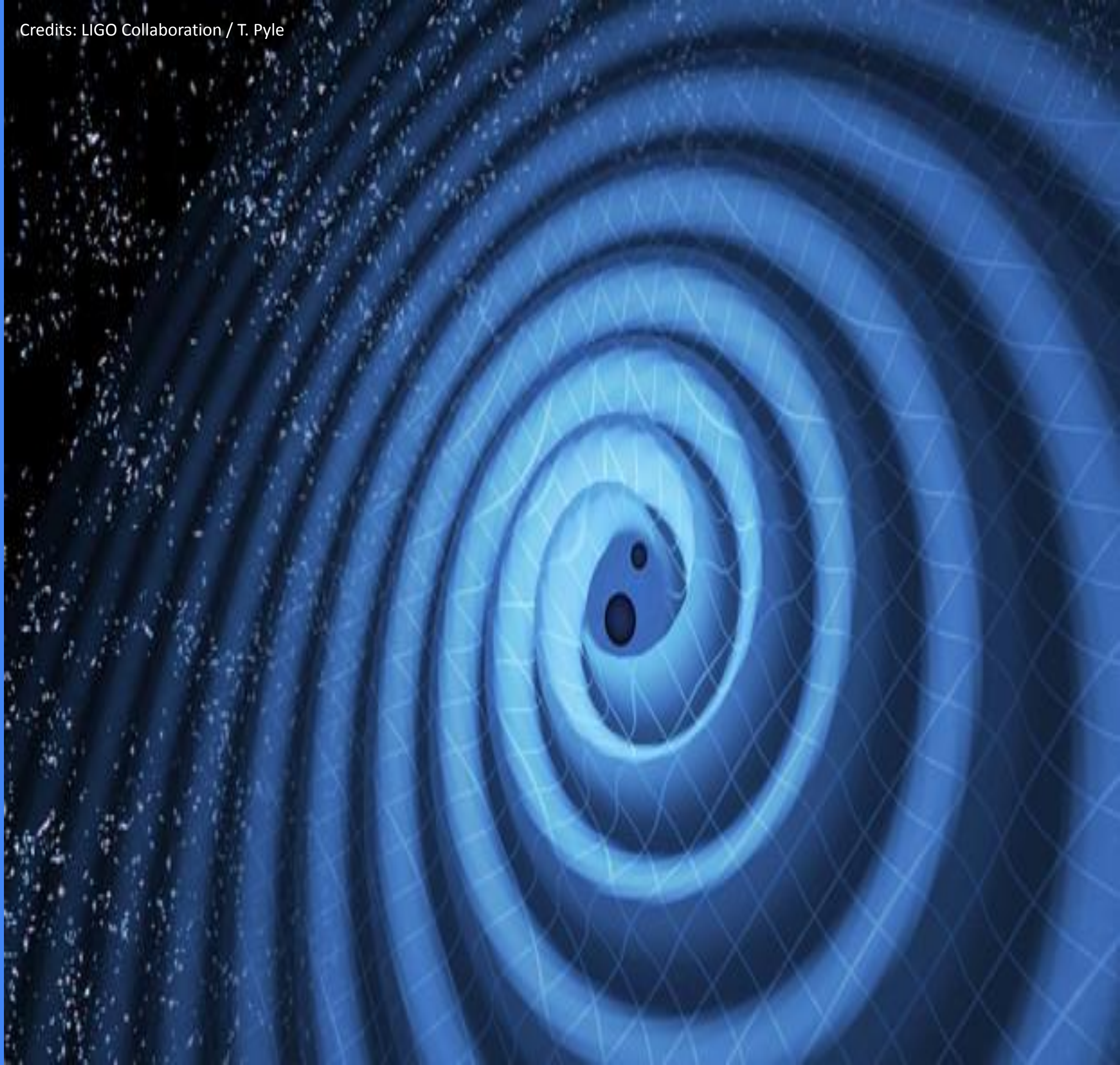
Young@INFN - Sapienza University, 11th April 2024

SAPIENZA UNIVERSITÀ DI ROMA

VIRGO

INFN Istituto Nazionale di Fisica Nucleare

1. Gravitational Waves



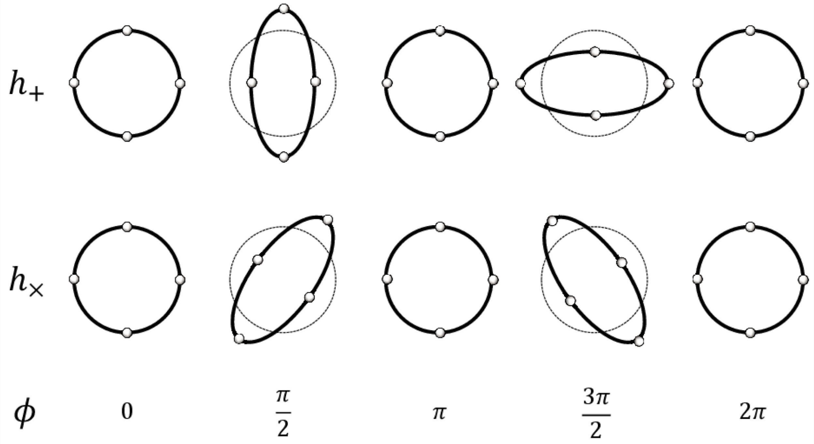
Gravitational-waves (GWs)

- Predicted by Einstein (1916): GR equations do have a wave solution!
- A GW can be seen as a *space-time strain* $h = \Delta L/L$
- In the Transverse-Traceless (TT) gauge:

$$h_{ij}^{TT}(t,\mathbf{x}) = \frac{4G}{c^4}\frac{1}{r}\int d^3\mathbf{x}'\, T_{ij}\left(t - \frac{r}{c} + \frac{\mathbf{x}'\cdot\hat{\mathbf{n}}}{c}, \mathbf{x}'\right)$$

- with no sources (masses):

$$h^{TT}(t,z) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos\left[\omega(t - z/c)\right]$$



Credits: Królak, Patil - Universe 2017, 3(3), 59

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HUGE suppression factor: $h \lesssim 10^{21}$ on Earth

amplitude ∝ r^{-1}

- with no sources (masses):

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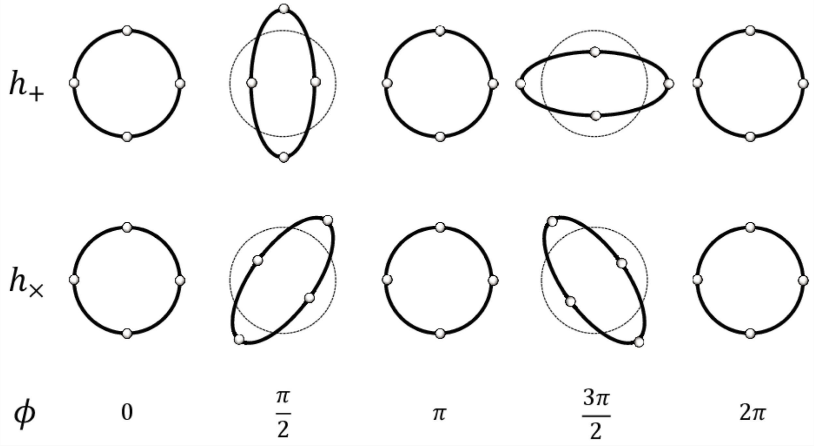
travels at *c*

2 transverse polarizations: h_+ and $h_\times$



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Gravity at its strongest regime

- GWs are (almost) not perturbed by matter
- Generated in very strong regime (remind the suppression factor!)

Astrophysics

- source study
- multi-messenger observations

Cosmology

- BH population
- H_0 tension
- Primordial GW

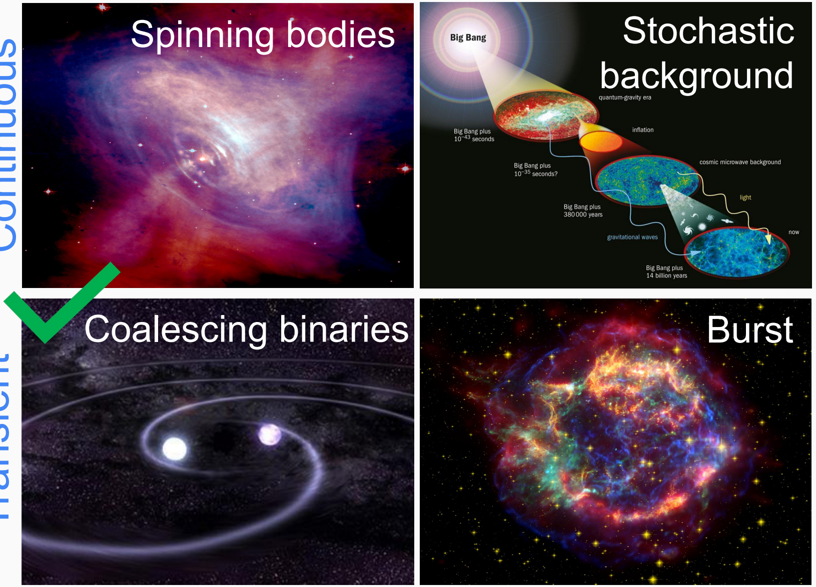
Fundamental physics

- Neutron Star EOS

GW sources

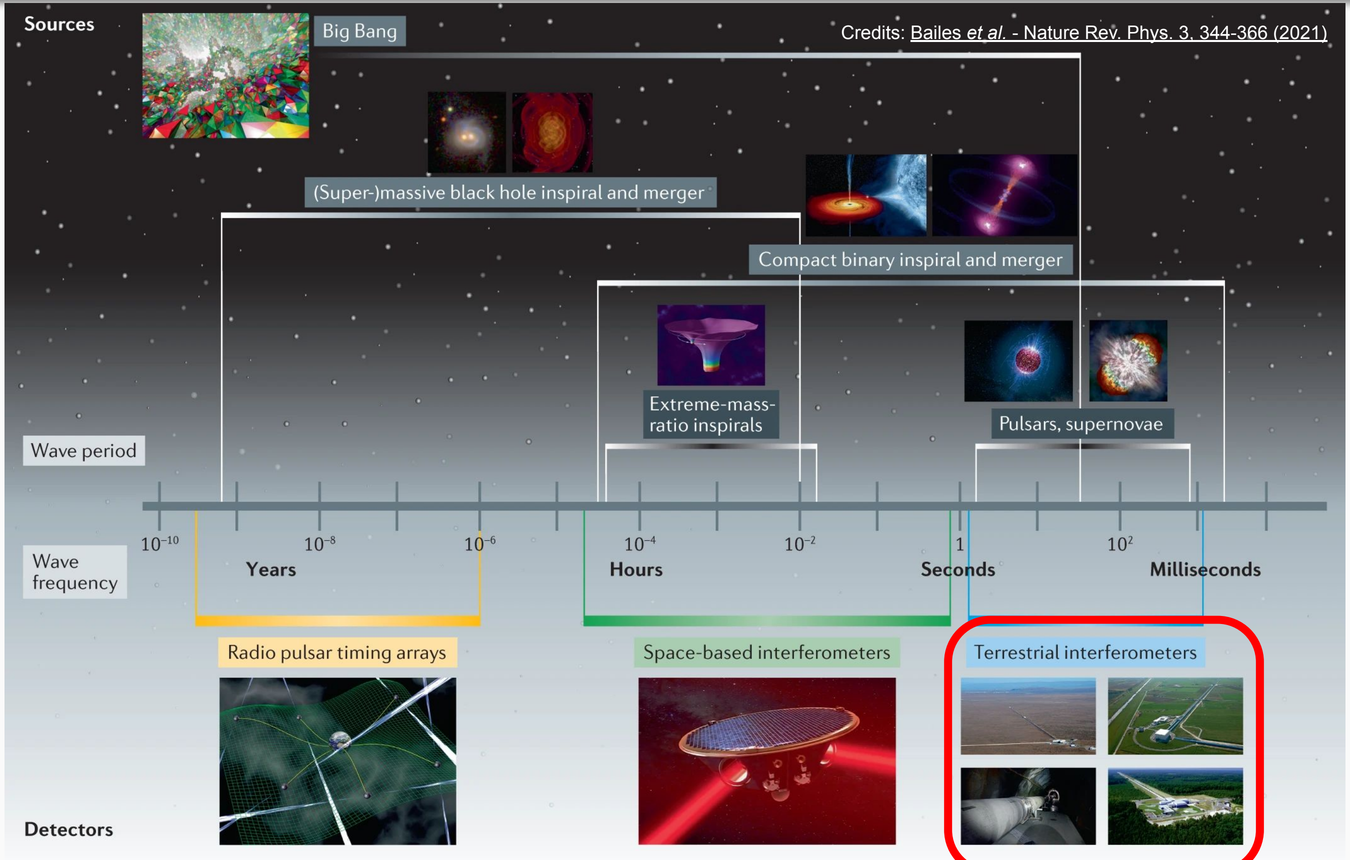
Modeled | Unmodeled

Continuous | Transient



See next talk by F. Attadio…

GW spectrum

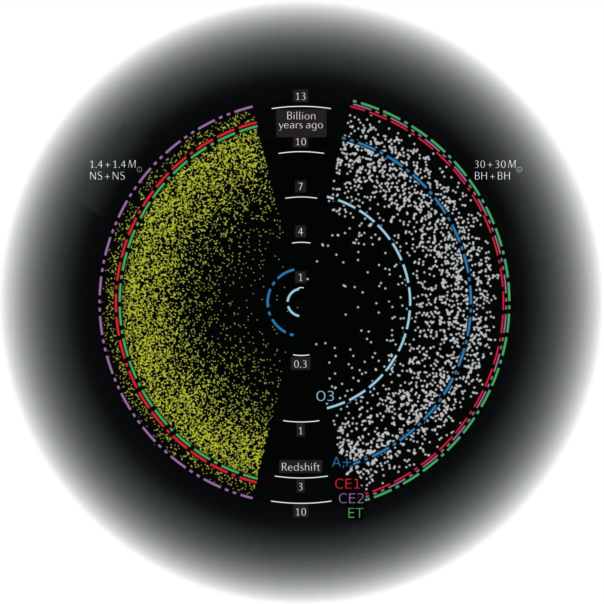


As with e.m. observations, different wavelength regimes require very different approaches!

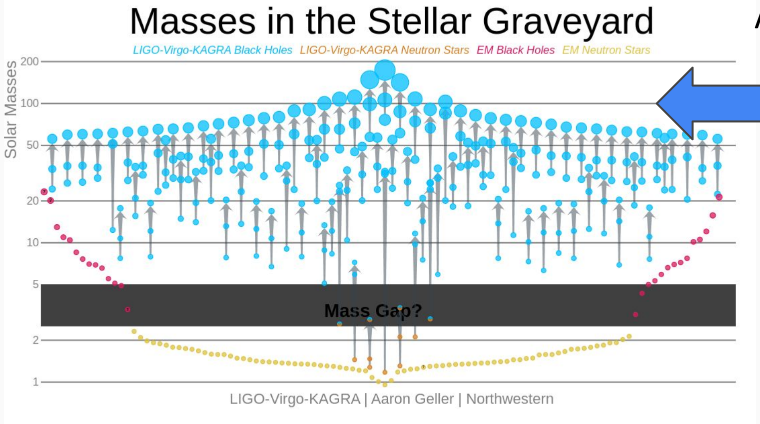
State-of-the-art of GW detections

- A better sensitivity improves our astrophysical reach
- Figure of merit: Binary Neutron Star Horizon (today **~55-60 Mpc for Virgo**)

Worldwide network of GW detectors



Credits: Bailes *et al.* - Nature Rev. Phys. 3, 344-366 (2021)



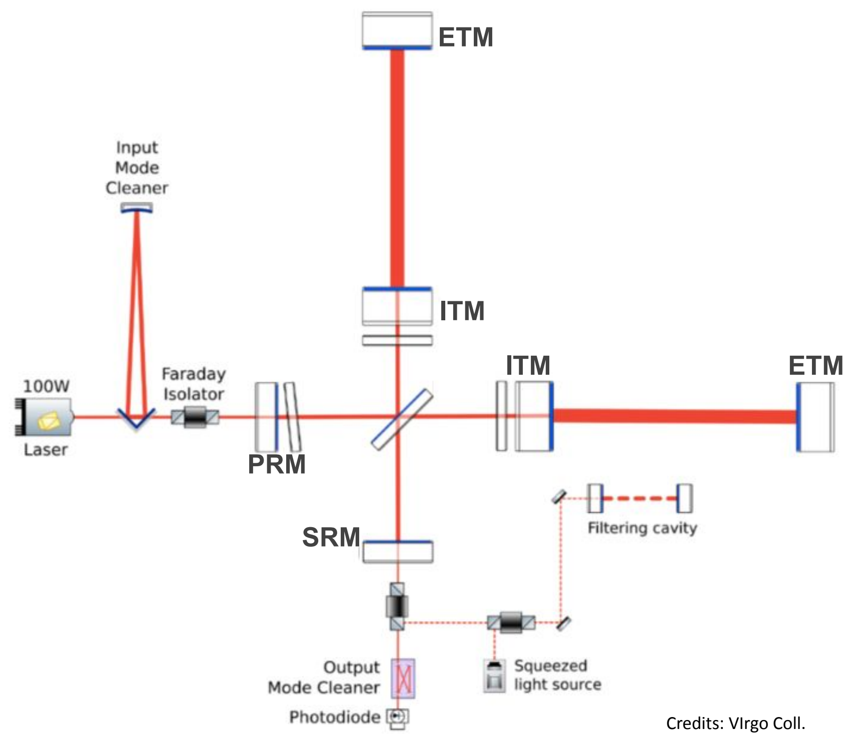
And the observations?

- 90 events in the past observing runs (O1, O2, O3)
- O4a started on **May 24th, 2023** with LIGO detectors
- O4b started **yesterday!**
- **82 event candidates** at April 11th, 2024

Check out the public alerts web page and keep counting!

2. Ground-based detectors

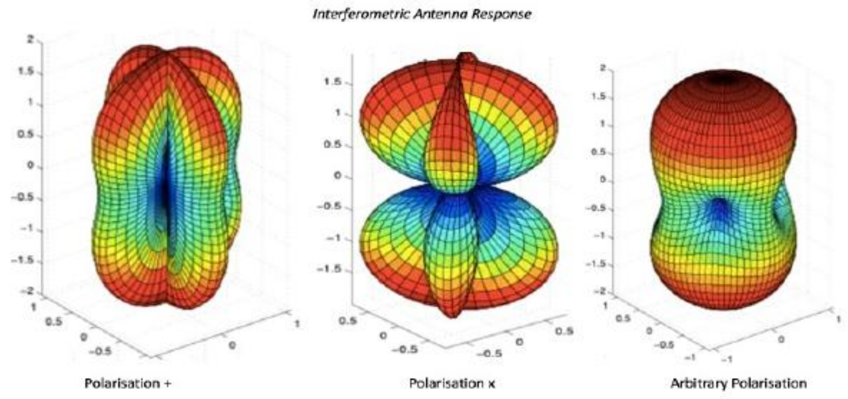
Earth-based interferometers



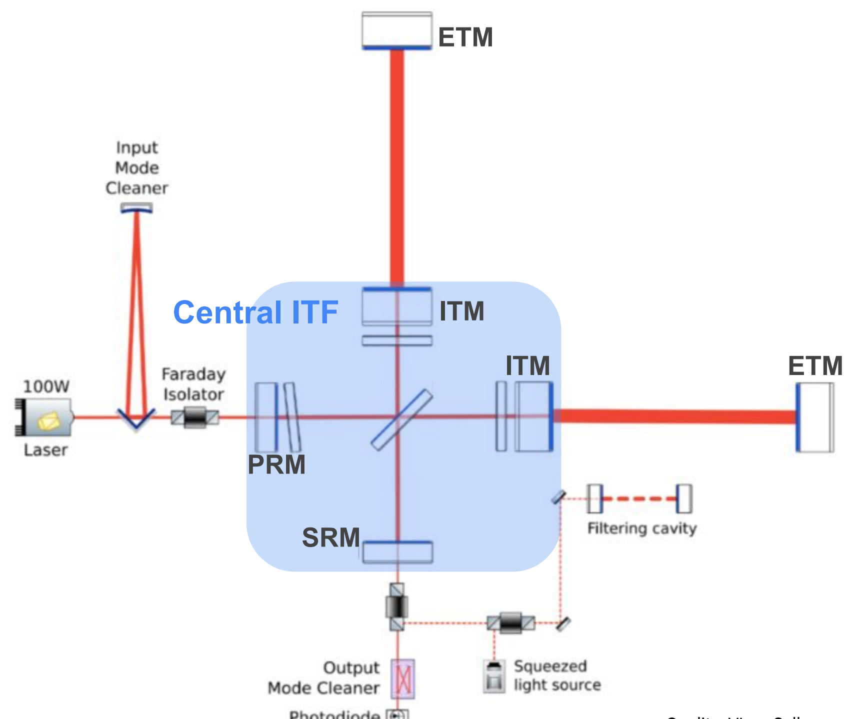
- Dual-recycled Michelson interferometer (ITF) with km-long Fabry-Perot (FP) arm cavities
- Test masses (mirrors) are displaced by the passage of a GW
- Differential measurement of **GW amplitude**

$$\Delta\phi = \omega_L \Delta t \simeq \frac{4\pi L}{\lambda_L} h_+$$

- Broad frequency and angular response, with some blind spots: antenna pattern



Earth-based interferometers



Credits: VIrgo Coll.

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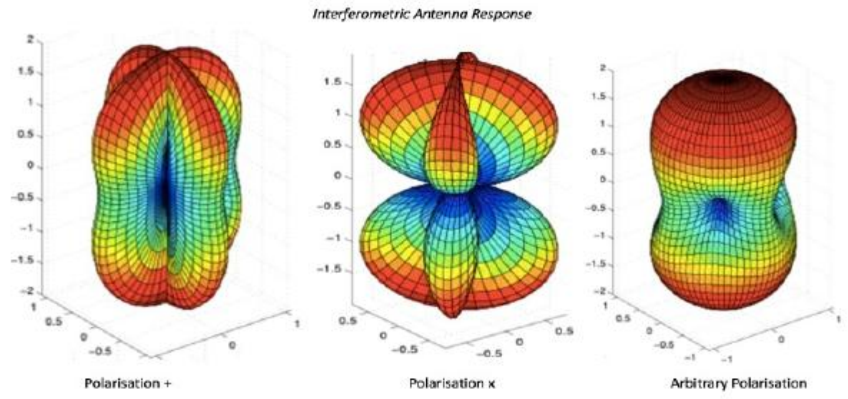

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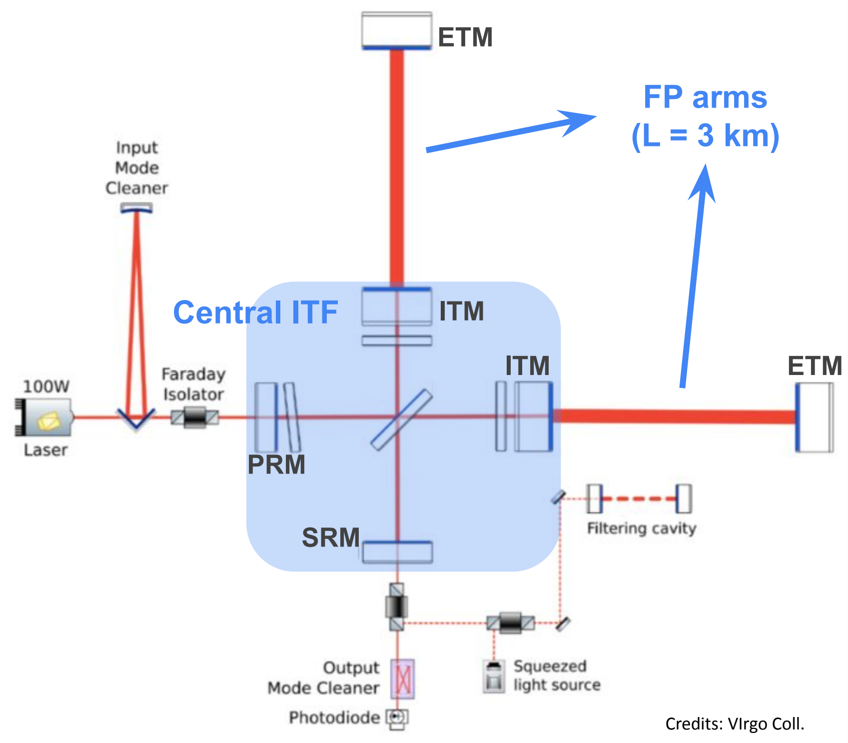

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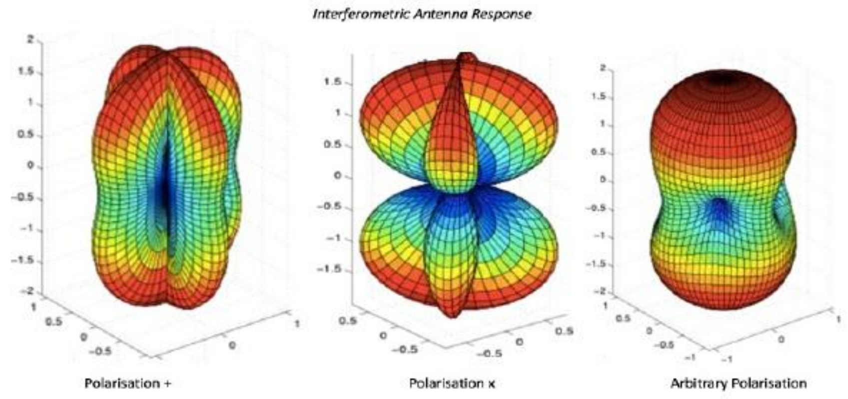
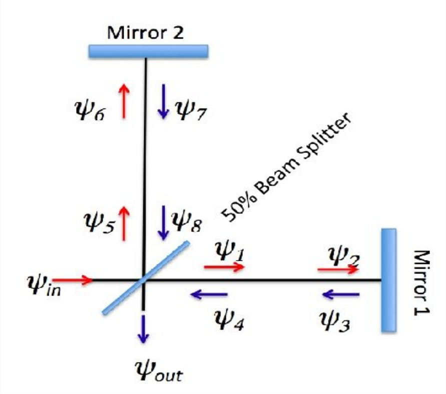


Why Fabry-Perot (FP) arms?



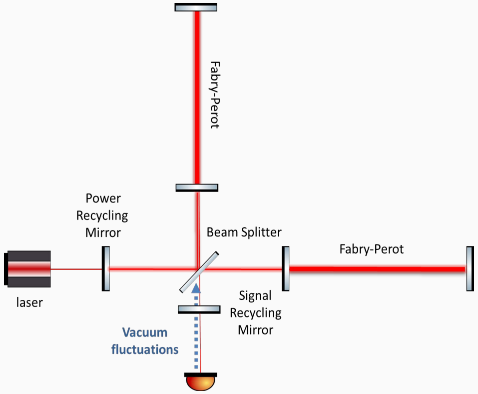
Michelson ITF

$$\Delta\phi \simeq \frac{2\pi}{\lambda_L}(L_x + L_y)h$$

Differential measurement

Approximations!

- GW much longer than ITF
- best directional sensitivity
- no modulation sidebands in the laser
- equal ITF arms length

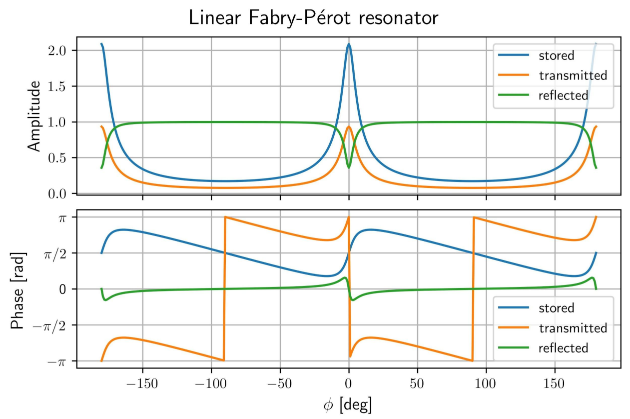


Michelson ITF with FP arms

FP gain FP cut-off

$$\Delta\phi(\omega) \simeq \frac{2\pi}{\lambda_L}(L_x + L_y)\frac{2\mathcal{F}}{\pi}\frac{1}{\sqrt{1+(\omega/\omega_p)^2}}h$$

$$\mathcal{F} = 460 \qquad \omega_p \approx 2\pi \cdot 50\mathrm{Hz}$$



Sensitivity curve

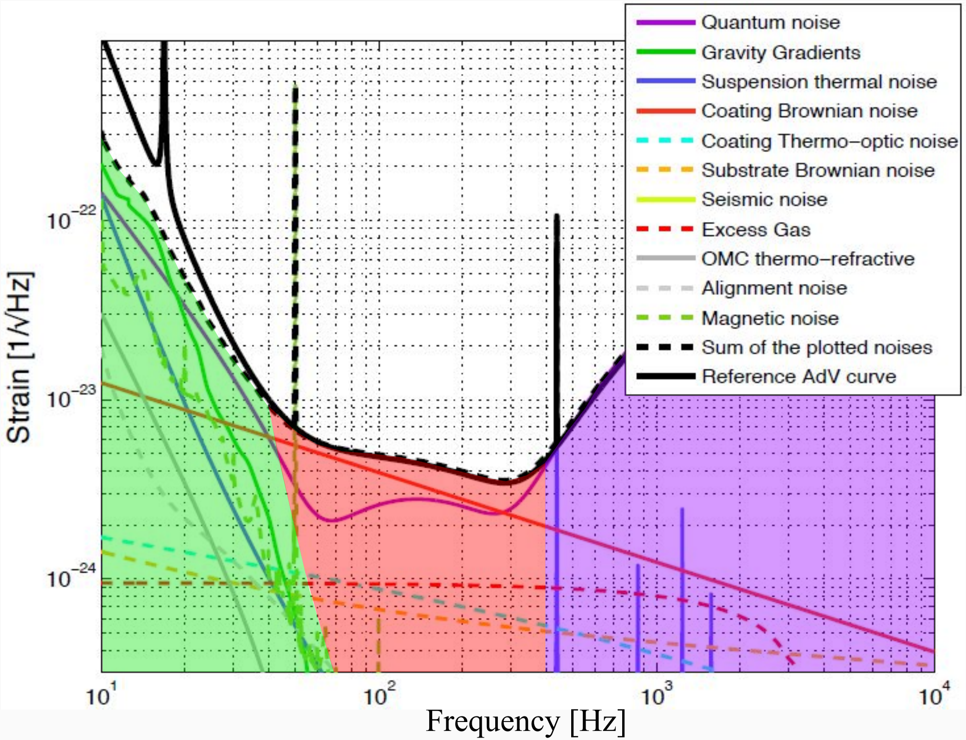
ASD of (independent and stationary!) noise sources:

$$\mathcal{N}(f) = \sqrt{2 \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} n(t) e^{-i2\pi f t}\, dt \right|^2}$$

“Fundamental” noise sources:

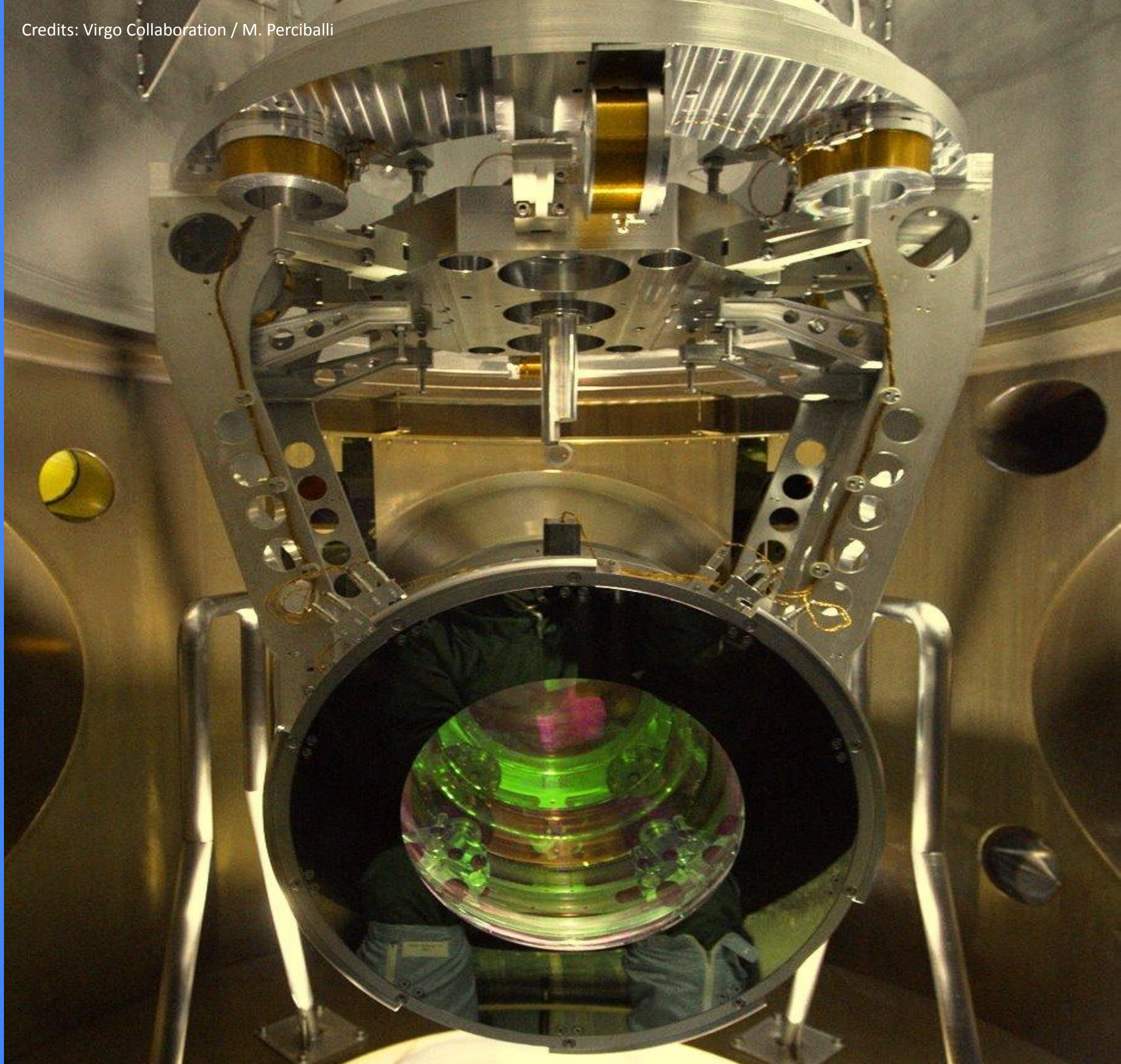
- Seismic noise
- Thermal noise
- Quantum noise

…but there are many other noises :(
Reducing their contribute is the main effort of experimental physicists in GW!



Credits: Virgo Coll. - Class. Quant. Grav. 32 024001 (2015)

3.
Noise sources

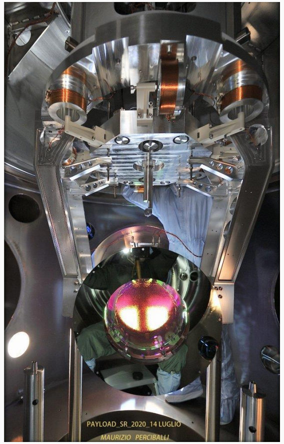


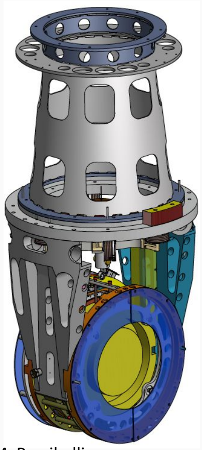
Credits: Virgo Collaboration / M. Perciballi

Seismic and environmental noise (<10 Hz)

- Relevant at low frequencies (micro-earthquakes, wind, sea activity…)
- Inverted pendulum + chain of pendulums with low proper frequency (0.6 Hz) to make a "cascade filter": **Superattenuator**
- Heavier end test masses

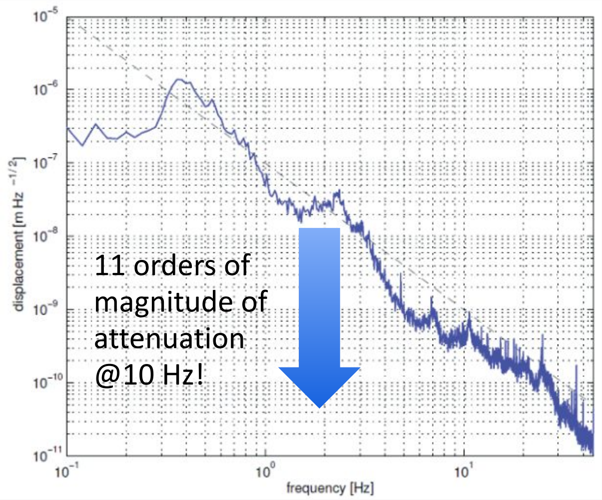
42 kg now → 105 kg O5



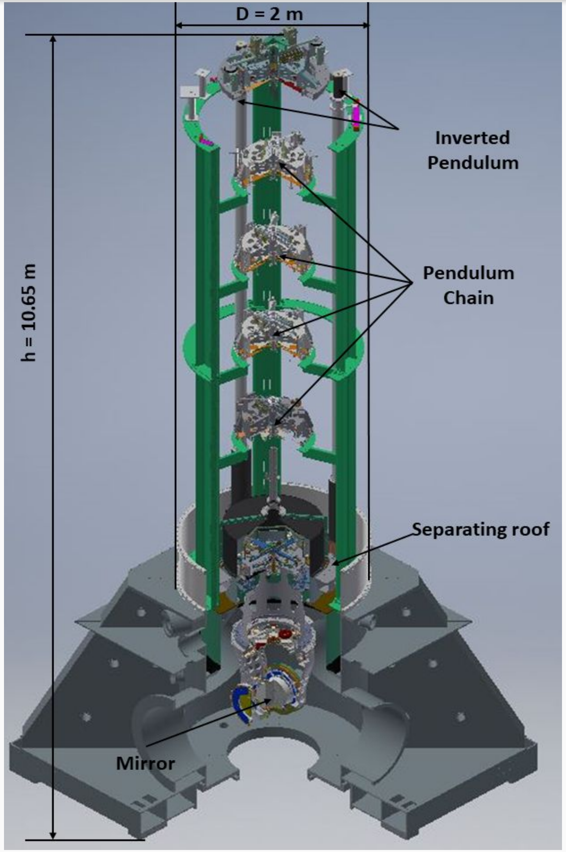


Credits: M. Perciballi

Seismic noise @Virgo site



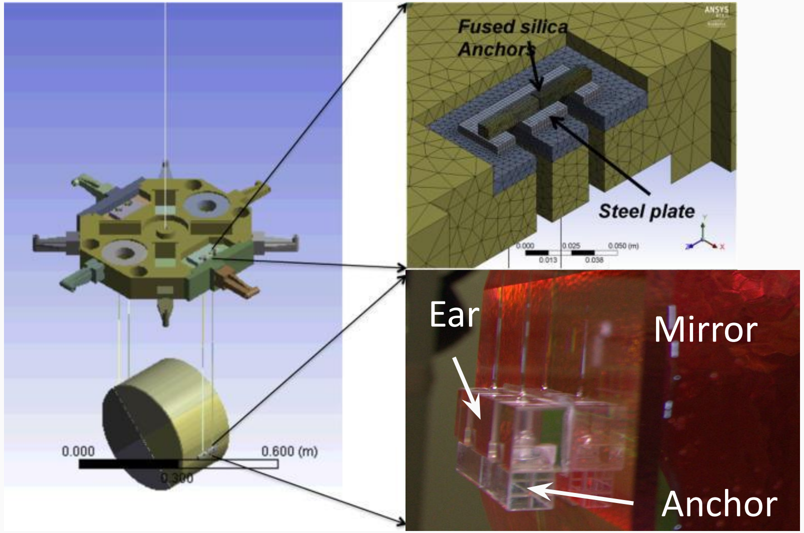
Credits: Virgo Coll. - Jour. of Low Frequency Noise, Vibration and Active Control 30(1):63-79 (2011)



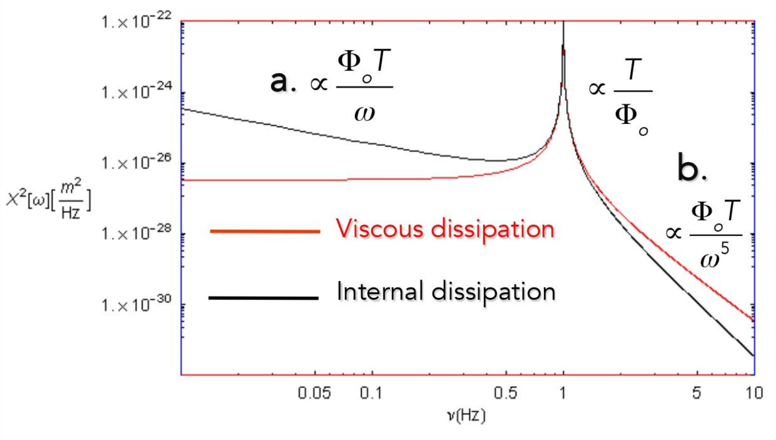
Thermal noise (<300 Hz)

- Any dissipation at non-zero temperature brings vibrational noise (Fluctuation-Dissipation Theorem)
- Relevant to ALL precision measurements!

$$S_x(\omega) \sim \begin{cases} \omega^{-1} & \text{if } \omega \ll \omega_0 \\ \omega^{-5} & \text{if } \omega \gg \omega_0 \end{cases}$$



Thermal noise of mirrors' pendulum motion



Many sources…

- Suspensions
- Bulk of the mirrors
- **Coatings**: very good from optical point of view, not from thermal one (active field of R&D)

…and solutions!

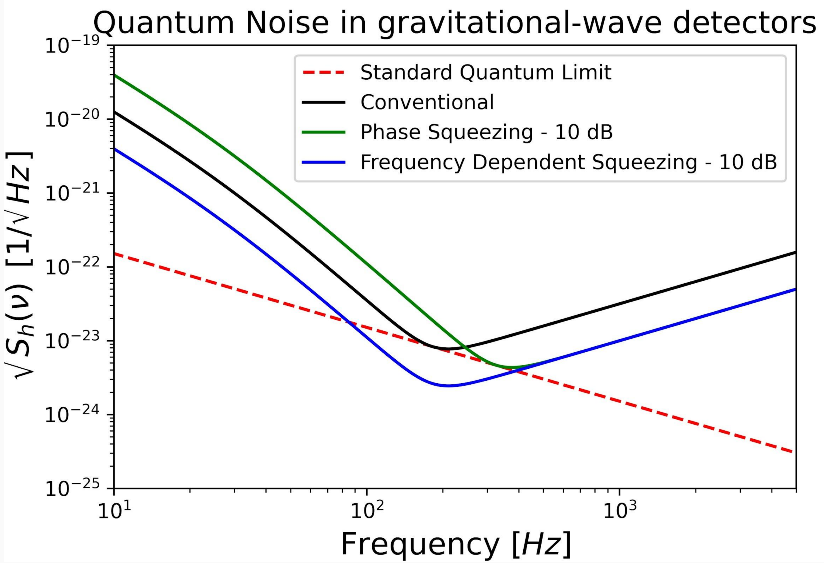
- monolithic suspensions
- better quality of materials
- lower optical power density (larger beams)
- cryogenics!! (KAGRA, ET…)

Quantum noise (>300 Hz)

- Macroscopic manifestation of the discreteness of laser light
- Originated by vacuum field entering the dark port of the ITF
- 2 contributions
  - back-action: Radiation-Pressure Noise (RPN)
  - detection: Shot Noise (SN)
- They meet at the **Standard Quantum Limit** (SQL), lowest frequency of quantum noise

$$S_h(\omega) = \frac{h^2_{SQL}}{2}\left(\frac{1}{\mathcal{K}(\omega)} + \mathcal{K}(\omega)\right)$$

Standard Quantum Limit (SQL) — ITF optomechanical coupling



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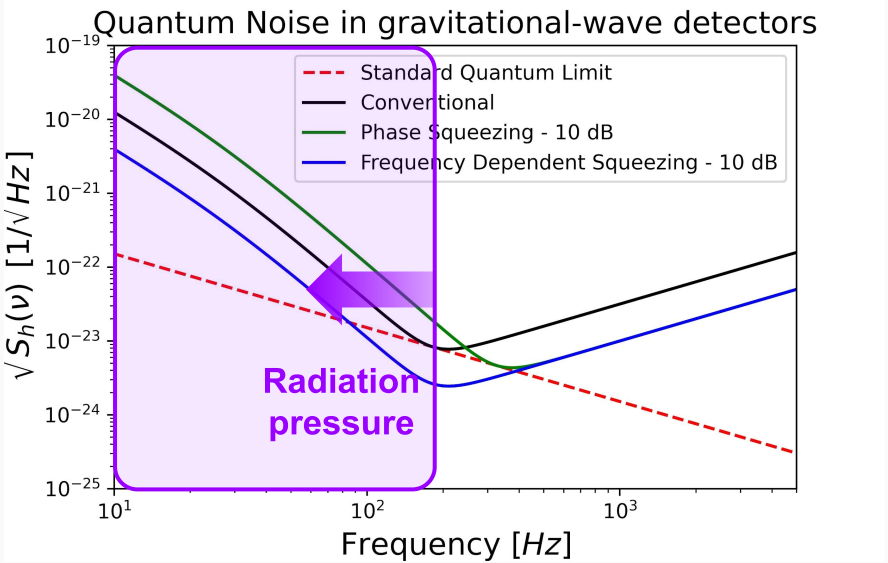

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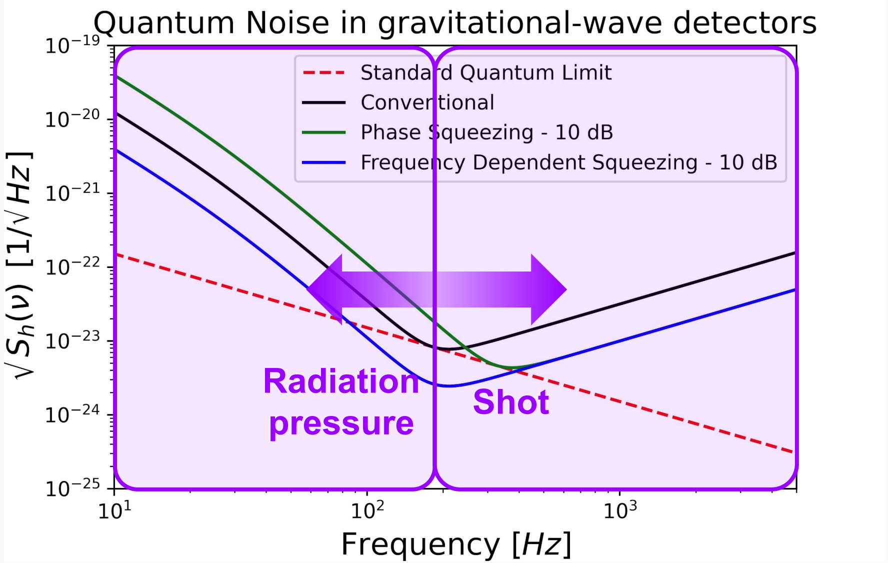

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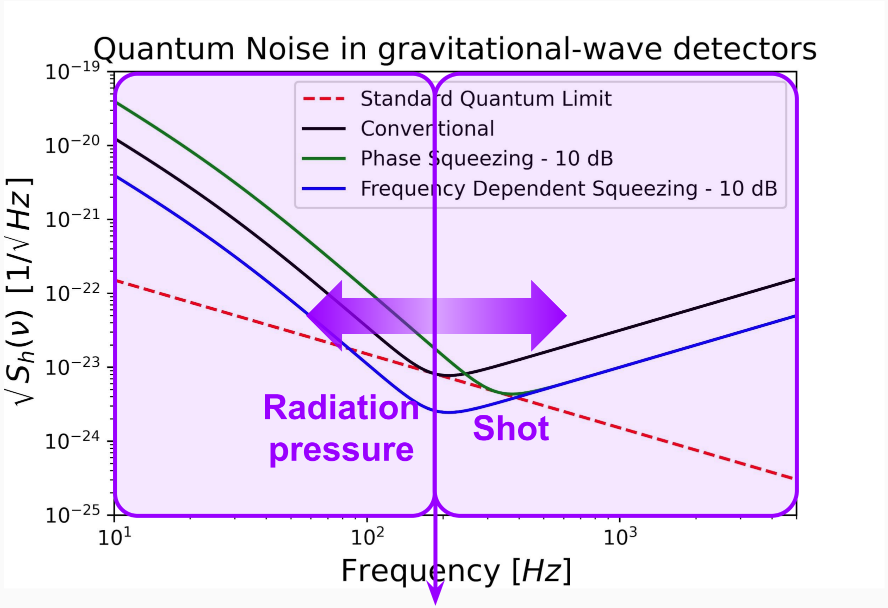

Standard Quantum Limit (SQL)

Quantum noise reduction with squeezing

Power spectrum of Quantum Noise:

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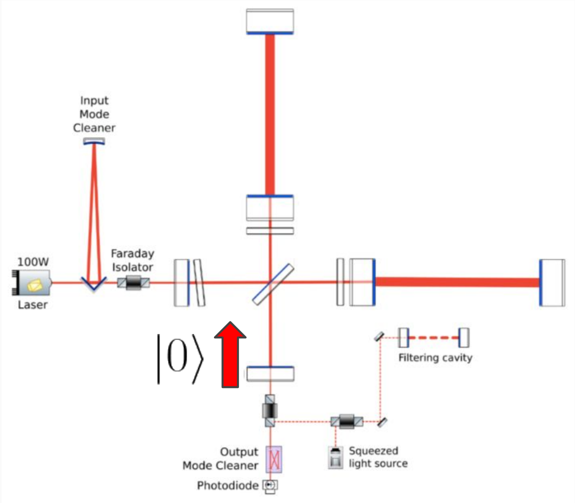
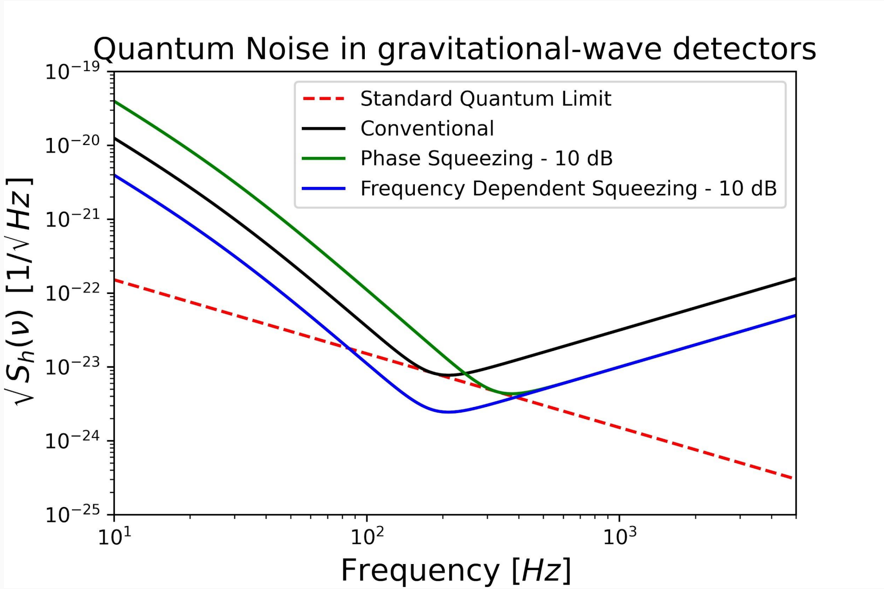
Standard Quantum Limit (SQL)

ITF optomechanical coupling



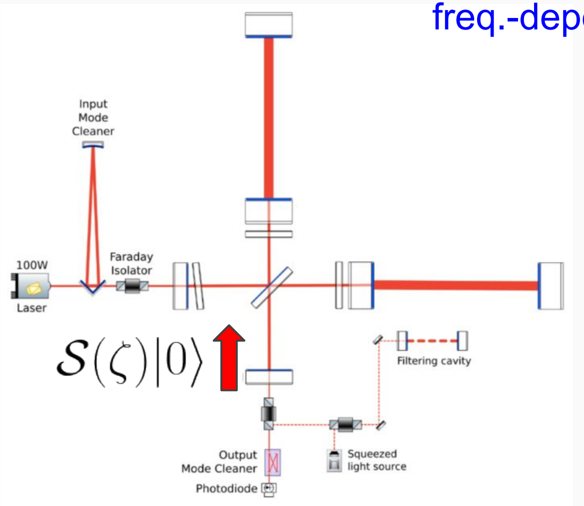


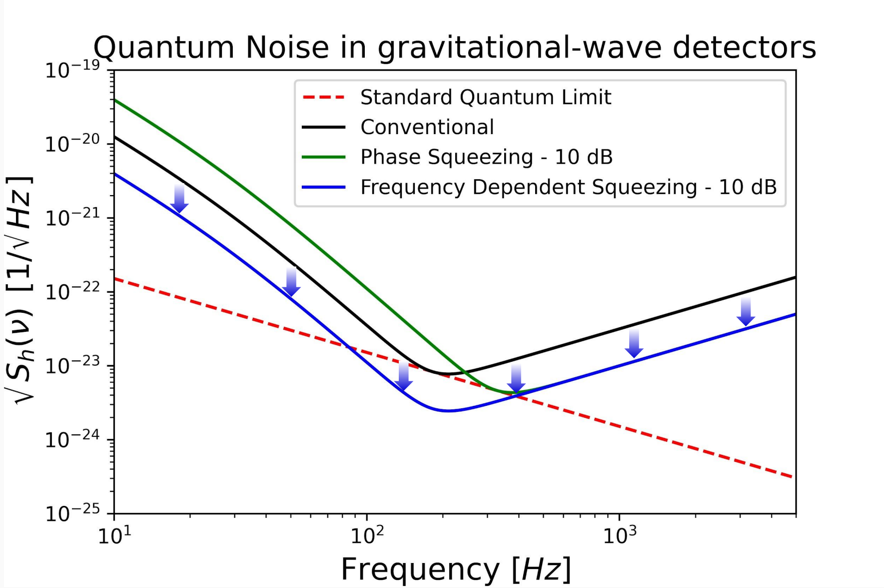
Quantum noise reduction with squeezing

Power spectrum of Quantum Noise:

$$S_h(\omega) = \frac{h^2_{SQL}}{2}\left(\frac{1}{\mathcal{K}(\omega)} + \mathcal{K}(\omega)\right) e^{-2r}$$

Suppression with
freq.-dependent squeezing



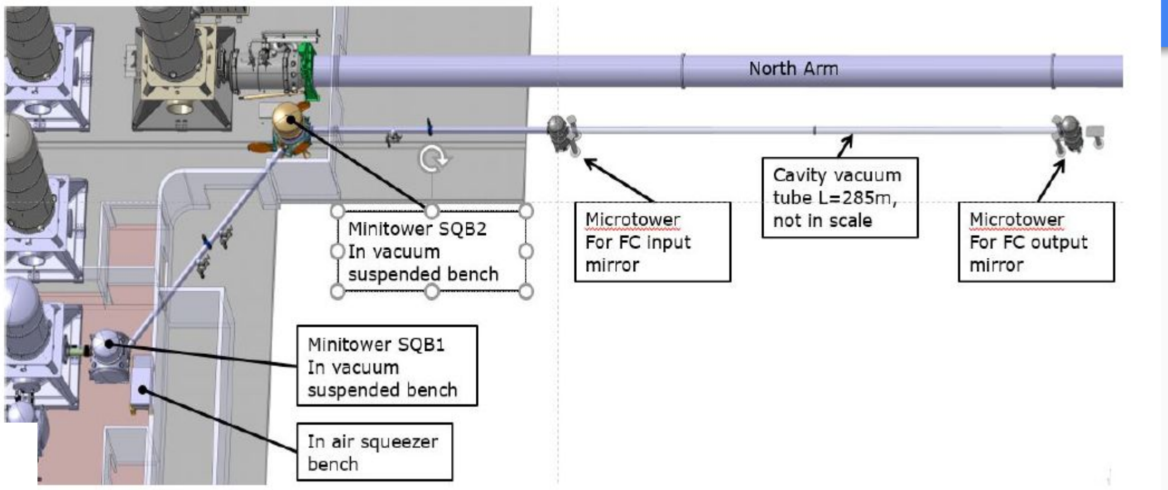


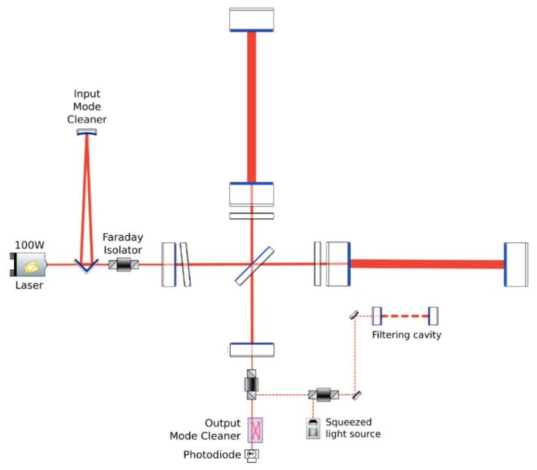
Provided a **specific tuning of the squeezing angle**, *Frequency-Dependent Squeezed* light reduces QN along the whole detection band!

Filter Cavity

- Squeezing ellipse can be rotated in a frequency-dependent manner with a detuned linear cavity (**Filter Cavity**)
- Central rotation angle @ ~50 Hz implies
  - Long cavity L=285 m
  - High finesse F=10000
- Round-trip losses in AdV+ FC: **50-90 ppm**

  Virgo Coll. - Phys. Rev. Lett. 131 041403 (2023)





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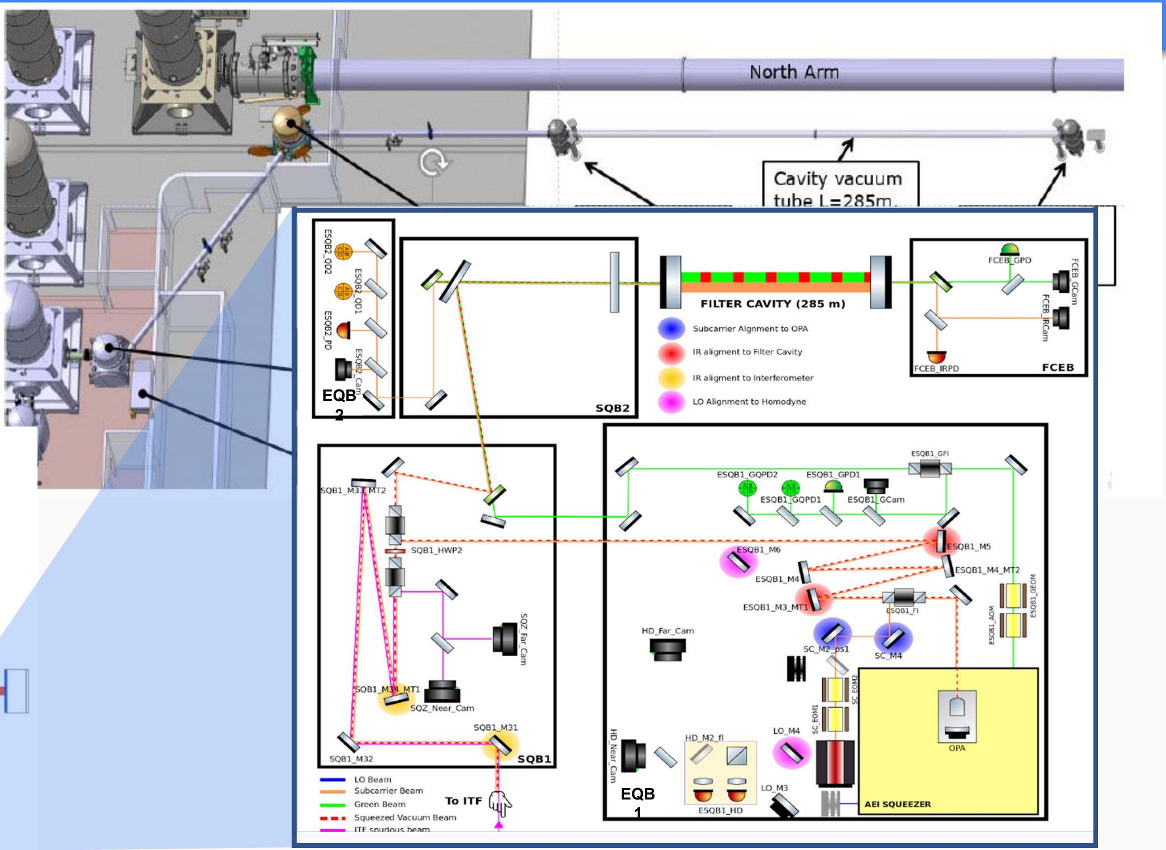
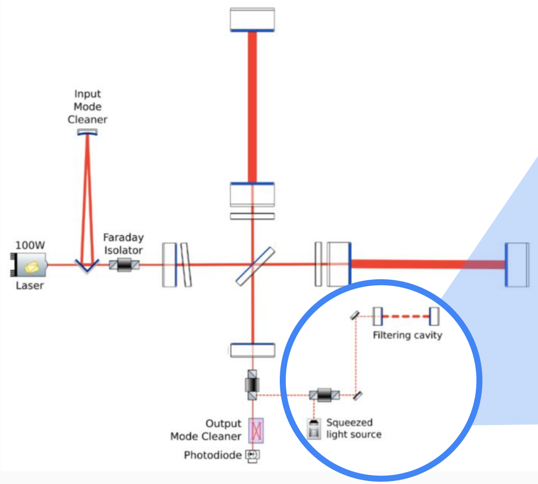




Credits: [Di Pace - Phys. Scr. 96 124054](#)

To wrap up…

1. GWs are “ripples of space-time” caused by strong acceleration of huge masses
2. They can be revealed on the Earth with long-baseline Michelson interferometers, such as LIGO, VIRGO and KAGRA
3. The most important noise sources are seismic, thermal and quantum noise. Higher laser power, heavier mirrors, low-dispersion materials and squeezing of light are the main measures to counter them
4. Frequency-dependent squeezing of light can be implemented through an external detuned cavity coupled to the main interferometer
5. Improving the sensitivity of GW detectors allow to build up a consistent catalog of observations and make new physics!

Thank you for your attention

Questions??

Email:
francesco.demarco@roma1.infn.it


Credits: Virgo Collaboration

Backup slides


Credits: Virgo Collaboration

GW interaction with the detector

- Michelson ITF only, and GW much longer than the ITF
- GW distorts space-time metric, affecting the propagation time in the arms

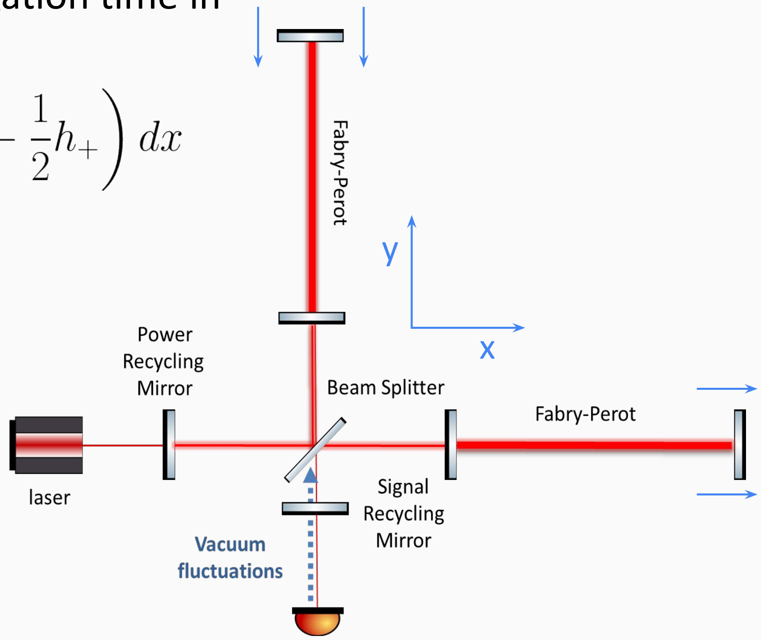
$$t_x \simeq \frac{2}{c}\int_0^L \left(1+\frac{1}{2}h_+\right) dx \qquad t_y \simeq \frac{2}{c}\int_0^L \left(1-\frac{1}{2}h_+\right) dx$$

- Phase shift at the output dark port

$$\Delta\phi = \omega_L \Delta t \simeq \frac{4\pi L}{\lambda_L} h_+$$

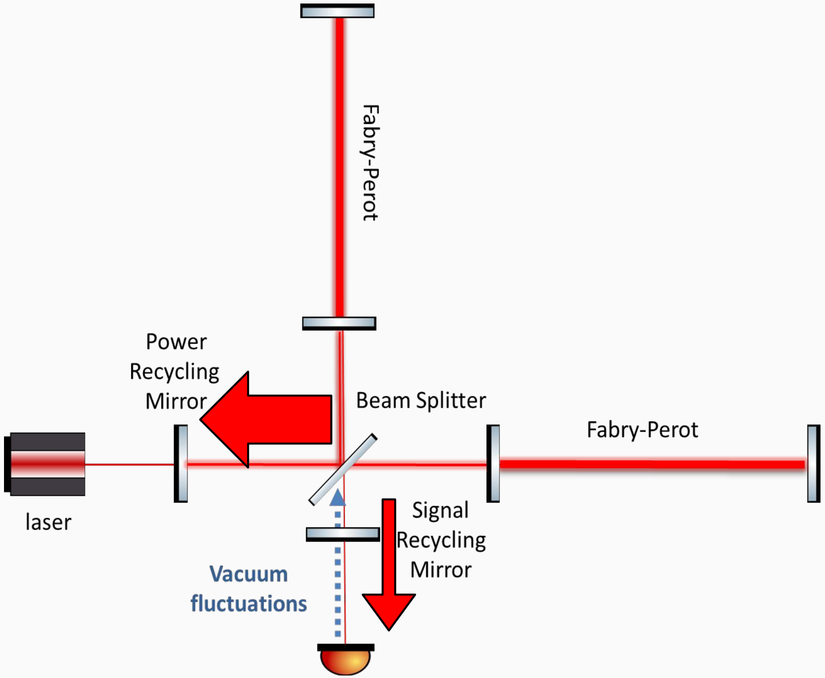
Typical values:

- FP arm length $L = 3\,\mathrm{km}$
  (4 km for LIGO, 3 km for KAGRA)
- GW strain $h \approx 10^{-21}$



Power Recycling

- The ITF is always kept close to *dark fringe condition*, i.e. destructive interference at the output (dark) port
- Power is almost entirely reflected back towards the laser source



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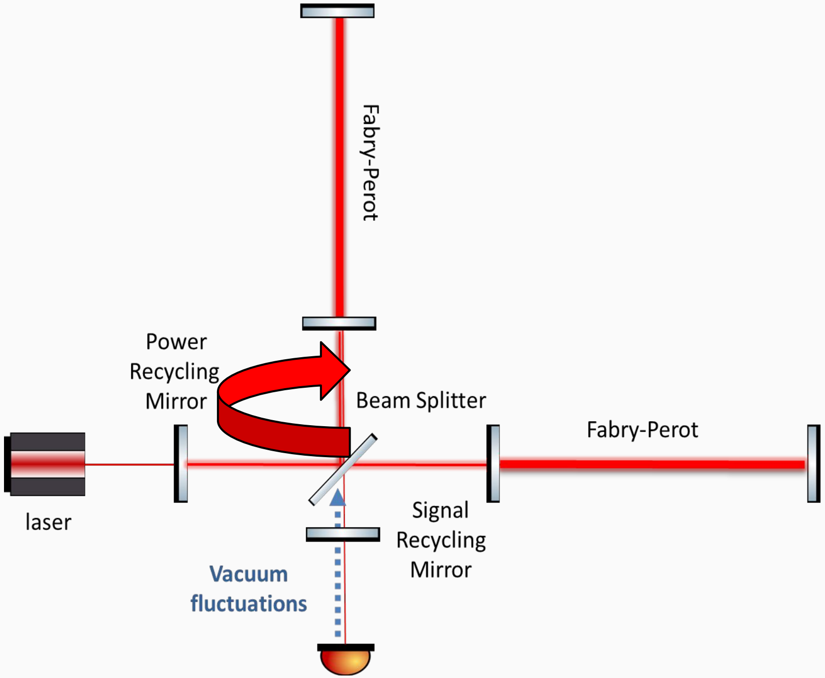

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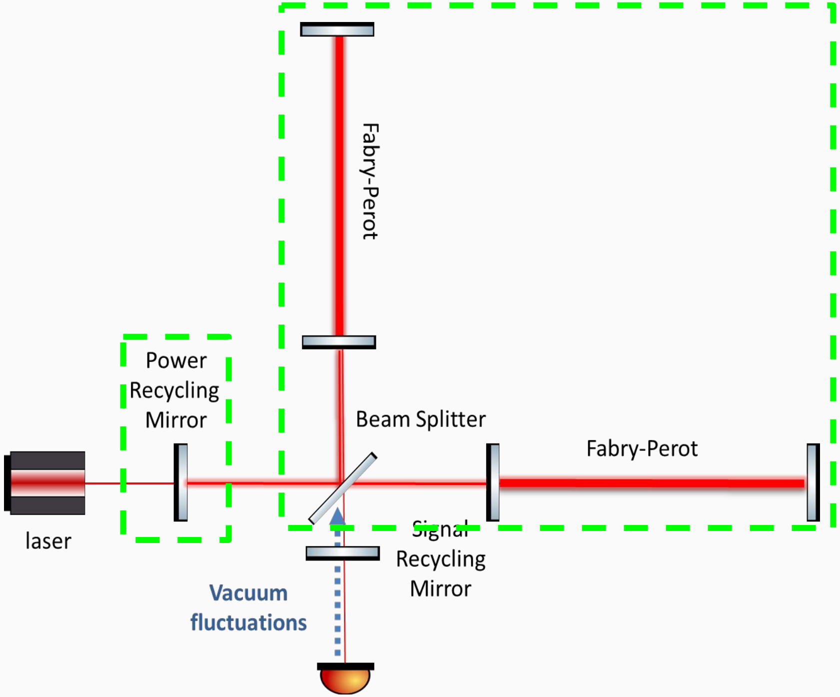
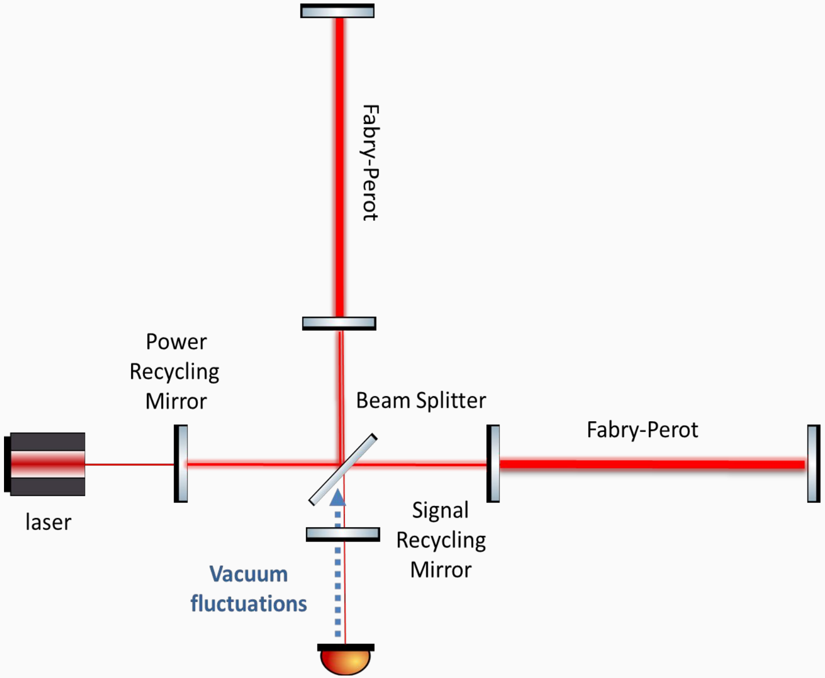
- It creates another cavity, with the ITF as equivalent end mirror



Signal Recycling

- Name is not so intuitive…
- FP cavities reduce the bandwidth

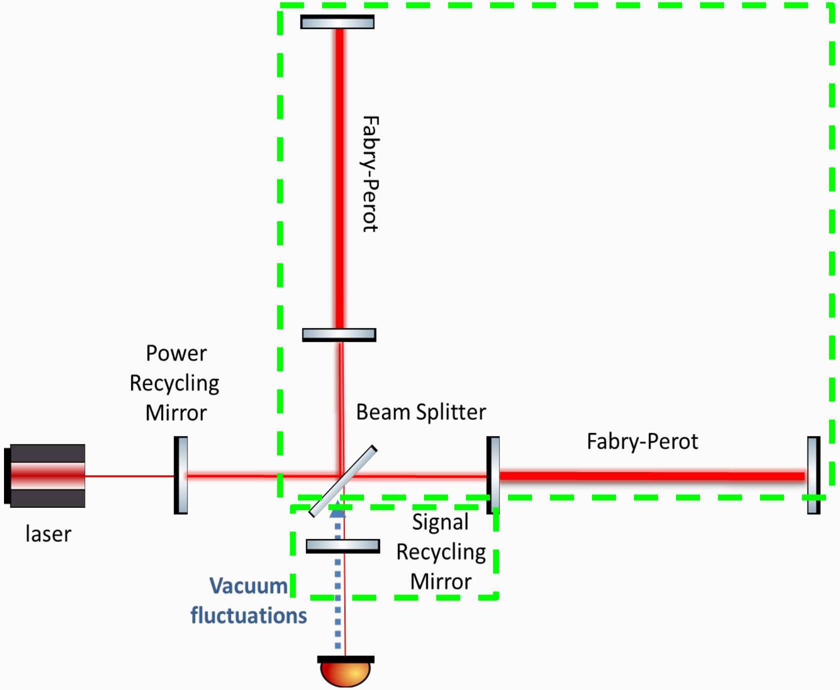


$$\gamma \simeq \frac{c\, t_{in}^2}{4\, L}$$

2π 50 Hz

Signal Recycling

- Name is not so intuitive…
- FP cavities reduce the bandwidth
- You want something to keep the optical power high, while recovering a better bandwidth: the Signal Recycling Mirror (SRM)!
- As the PRM, it adds an optical cavity which closes with the ITF itself



$$\gamma \simeq \frac{c\,t_{in}^2}{4\,L}$$

$$\gamma_{SR} \simeq \frac{c\,t_{in}^2}{4\,L}\,\frac{1 + r_{SR}}{1 - r_{SR}}$$

2π 50 Hz → **2π 430 Hz**

Squeezed states of light

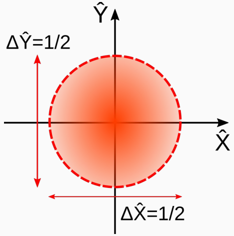
Quantized EM field: $\hat{E}(t) \propto \int_0^\infty d\omega \left(\hat{a}_\omega e^{-i\omega t} + \hat{a}^\dagger_\omega e^{+i\omega t}\right)$ → $\hat{E}(t) \propto \int_0^\infty d\omega \left(\hat{X}_\omega \cos(\omega t) + \hat{Y}_\omega \sin(\omega t)\right)$

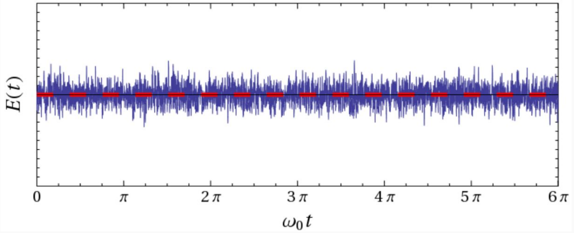
$\hat{X}_\omega$: Cosine (or amplitude) quadrature
Radiation Pressure Noise

$\hat{Y}_\omega$: Sine (or phase) quadrature
Shot Noise

Vacuum state:

$$|0\rangle$$





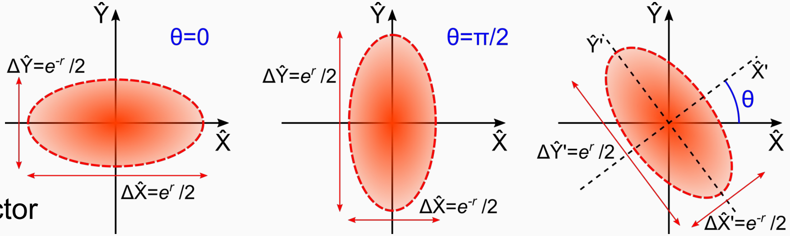
Credits: Danilishin, Khalili - arXiv:1203.1706 (2012)

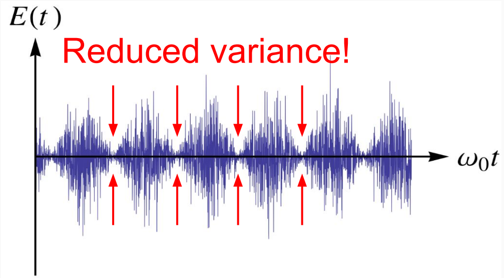
Squeezed vacuum state:

$$\mathcal{S}(\zeta)|0\rangle$$

$\zeta = re^{i\theta}$ Squeezing parameter

$r[\mathrm{dB}] = 20\log_{10}(e^r)$ Squeezing factor

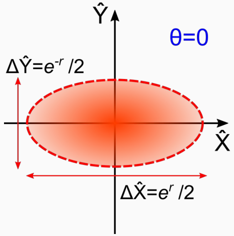


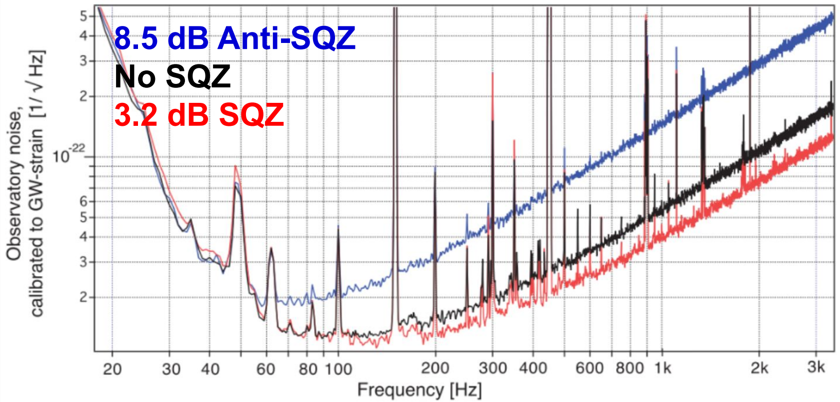


Squeezing in O3 and O4

O3: **Freq.-Independent Squeezing**

- Phase-squeezed light **3.2 dB**
- BNS range improved by 5 - 8 %
- Detection rate increased by 16 - 26 %

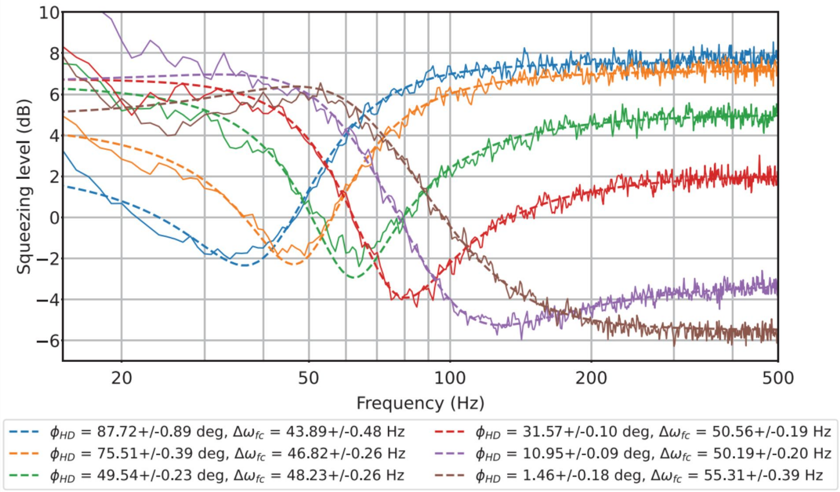




Credits: Virgo Coll. - Phys. Rev. Lett. 123 231108 (2019)

O4: Commissioning of a **Freq.-Dependent Squeezing** apparatus with Filter Cavity

- 5.6 dB at high frequencies and 2 dB around FC resonance
- Performances in the ITF similar to O3 due to ITF configuration



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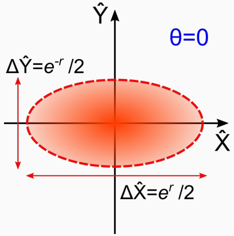

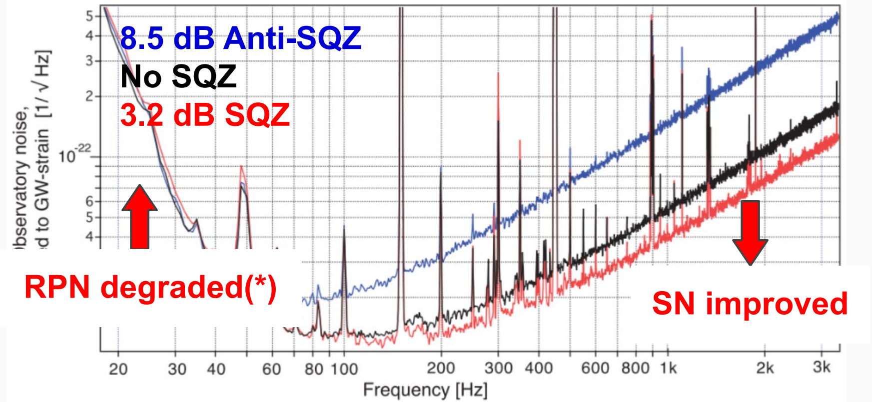

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(*) Covered by other low-freq. noise sources

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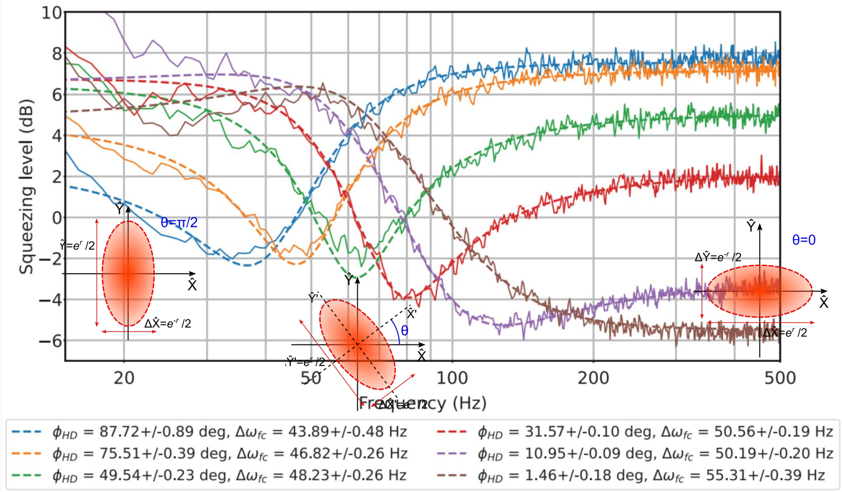

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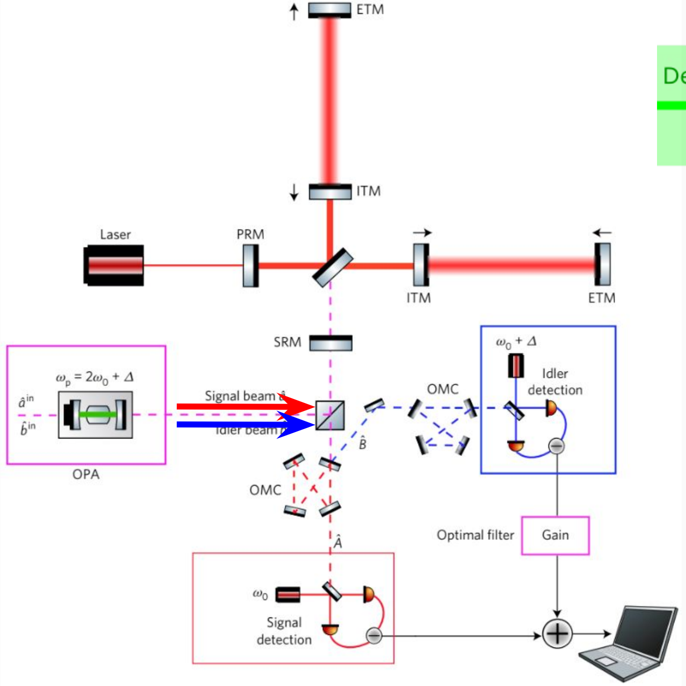
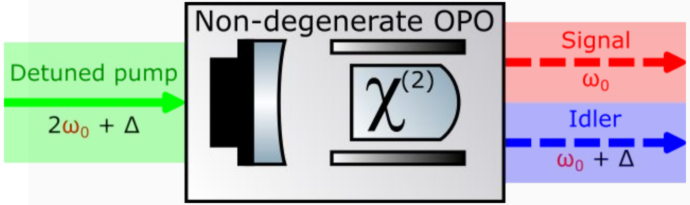
A novel approach: EPR squeezing





1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ

Pros:

- More compact and cheaper
- Avoids some optical losses

Cons:

- 2 squeezed beams to be handled

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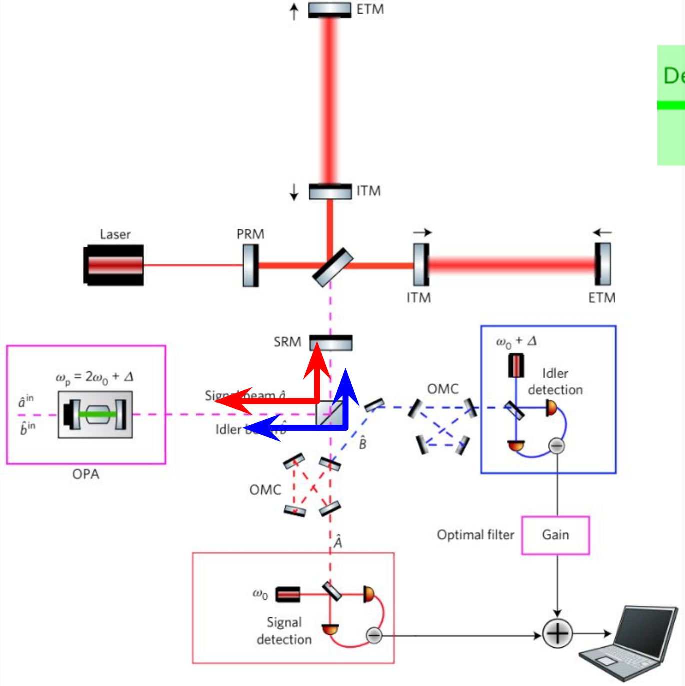

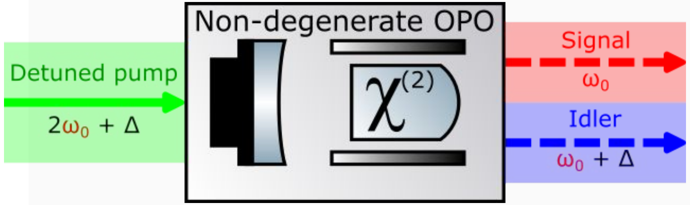

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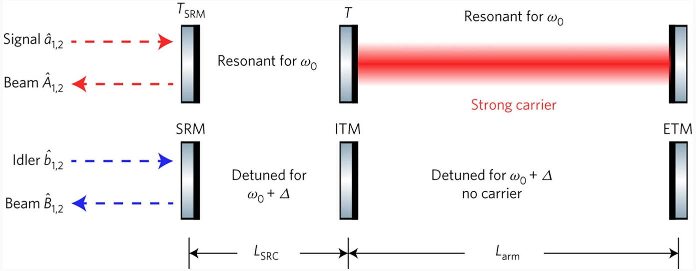

2. The **idler** acquires frequency-dependence in the ITF due to its detuning

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Credits: Ma *et al.* - Nature Phys 13, 776–780 (2017)

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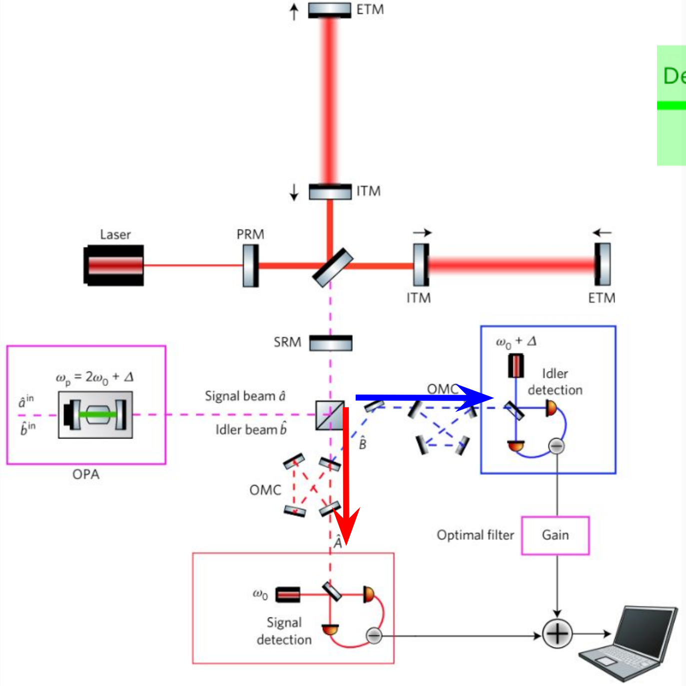

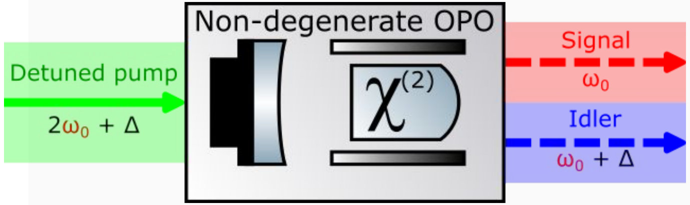

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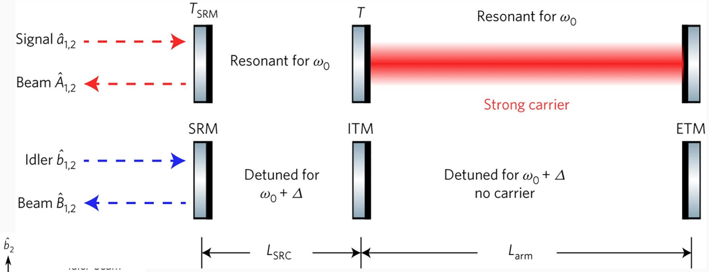

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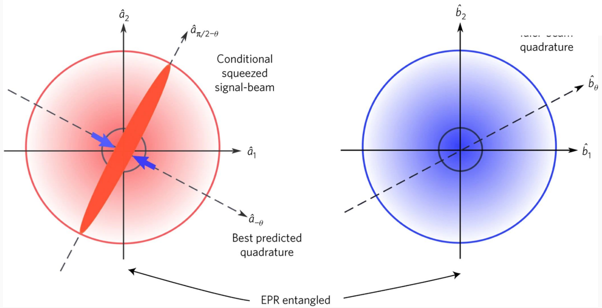

3. Combined measurement transfers the frequency dependence to the **signal** via **EPR entanglement**

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