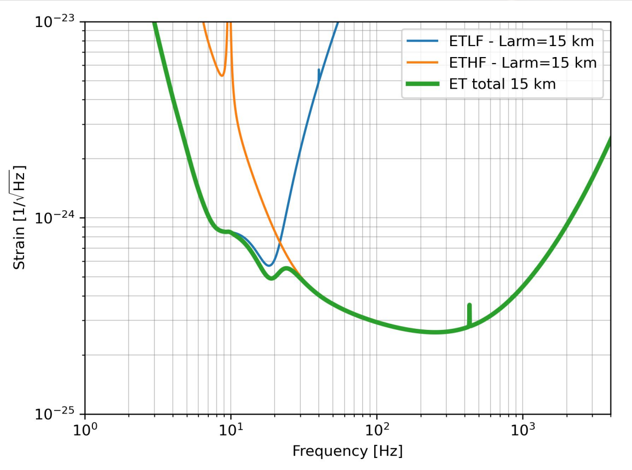
Einstein-Podolsky-Rosen quantum entanglement for future gravitational-wave detectors

Francesco De Marco on behalf of the EPR working group
Sapienza University of Rome and INFN Roma1

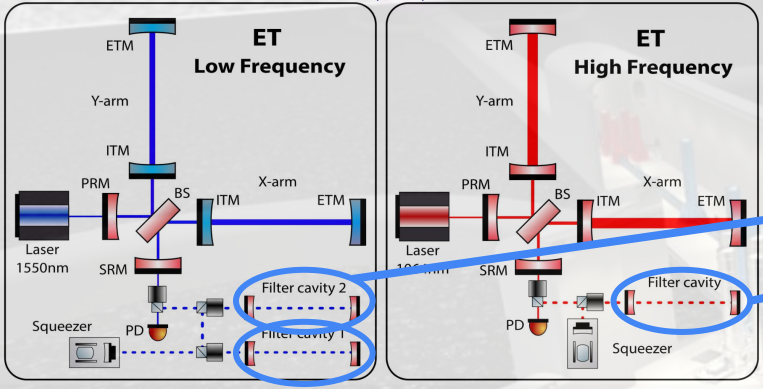
INFN Workshop on Future Detectors - Sestri Levante (GE), 17-19 March 2025

Quantum noise in ET EINSTEIN TELESCOPE

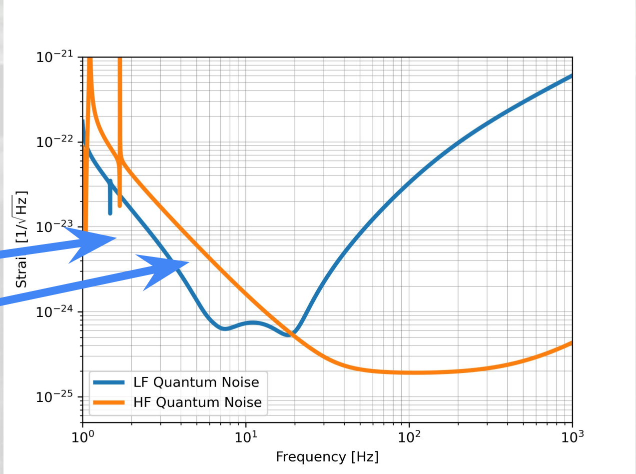


Credits: ET official document ET-0028A-20 (2020)

- The Einstein Telescope (ET) is the next-generation gravitational-wave observatory
- Underground and cryogenic
- 10 km Triangle vs 15 km 2L
- High R&D effort for cutting-edge technologies!



Quantum noise is addressed with squeezed light + **filter cavities**

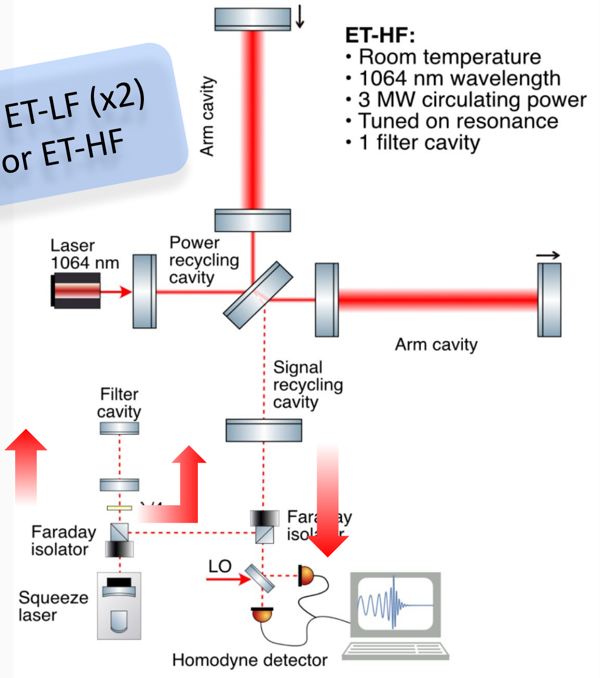


Quantum noise reduction via EPR entanglement

Today: squeezer + **detuned** filter cavity L=300 m

- long, high-finesse and suspended cavity
- works only for tuned interferometer

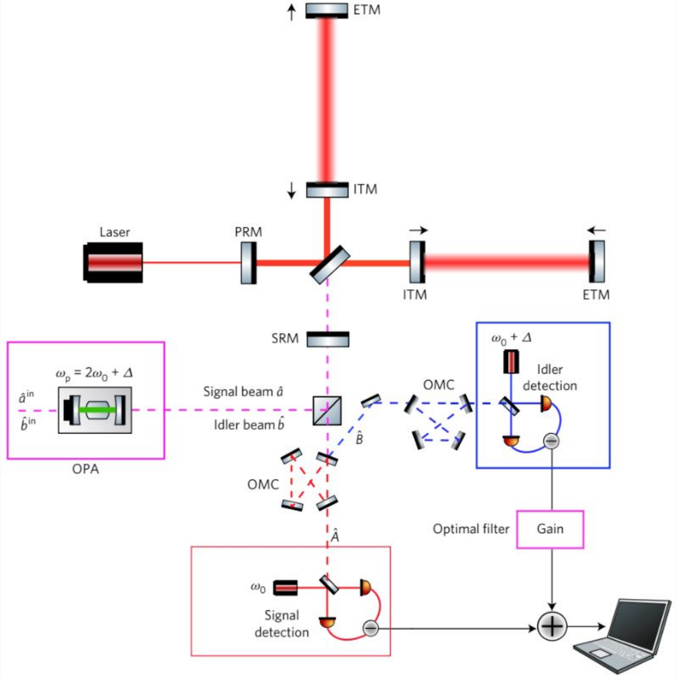
L=5 km for ET-LF (x2)
L=1 km for ET-HF



Credits: Korobko - Galaxies 13 (1), 11 (2025)

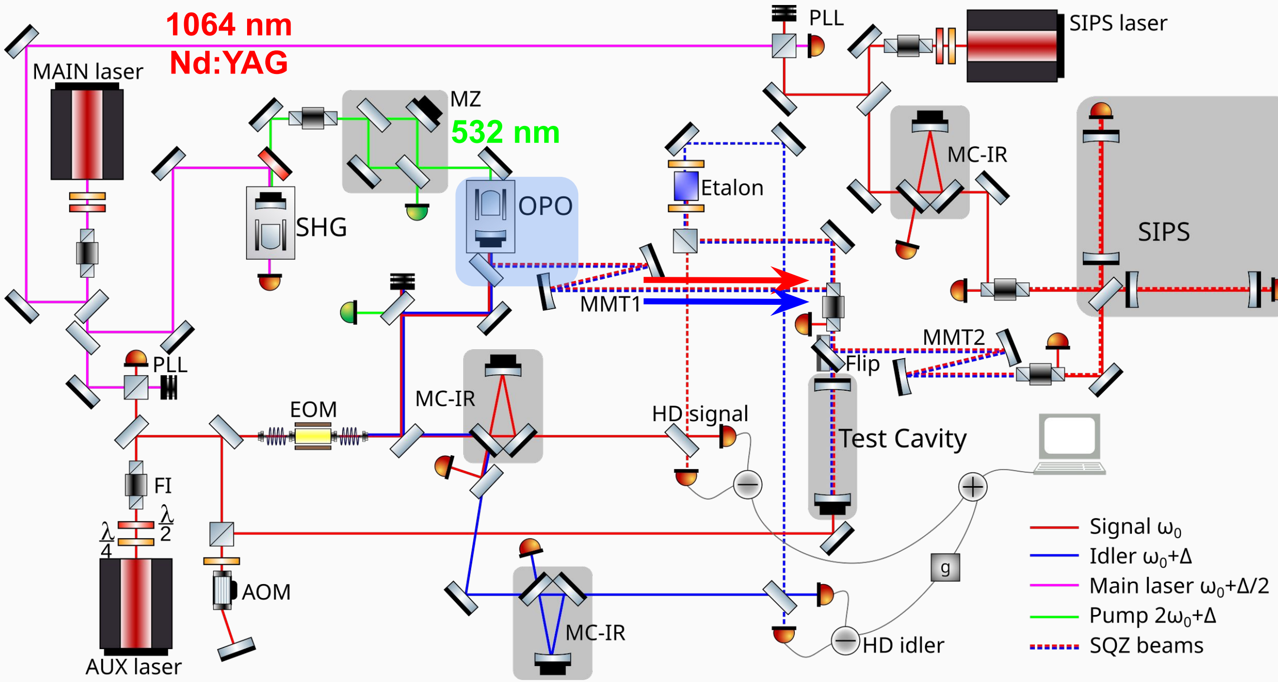
EPR conditional squeezing

- avoids filter cavity
- can work with detuned interferometer

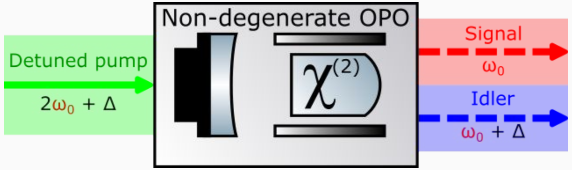


Credits: Ma *et al.* - Nature Phys 13, 776–780 (2017)

EPR working principle



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



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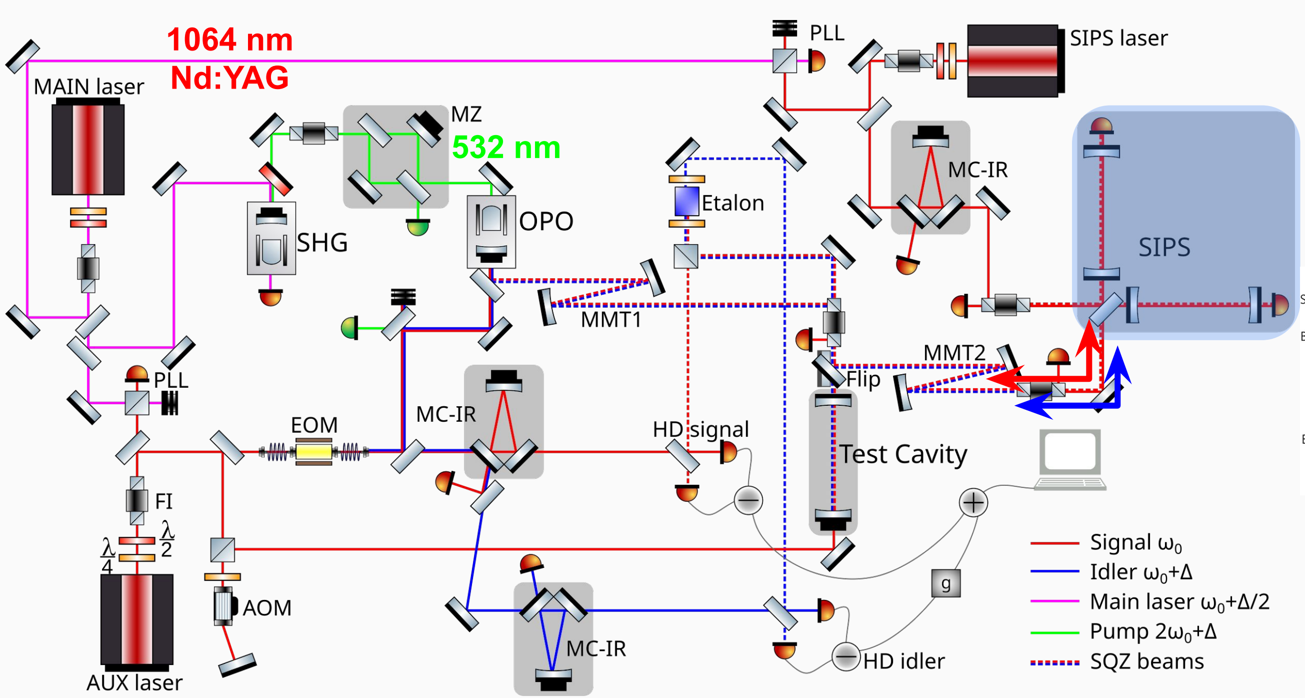
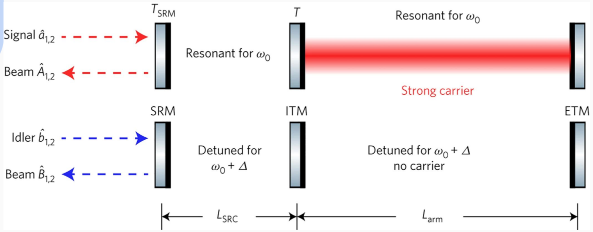


1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ
2. The **idler** sees the interferometer as a filter cavity and acquires frequency-dependence



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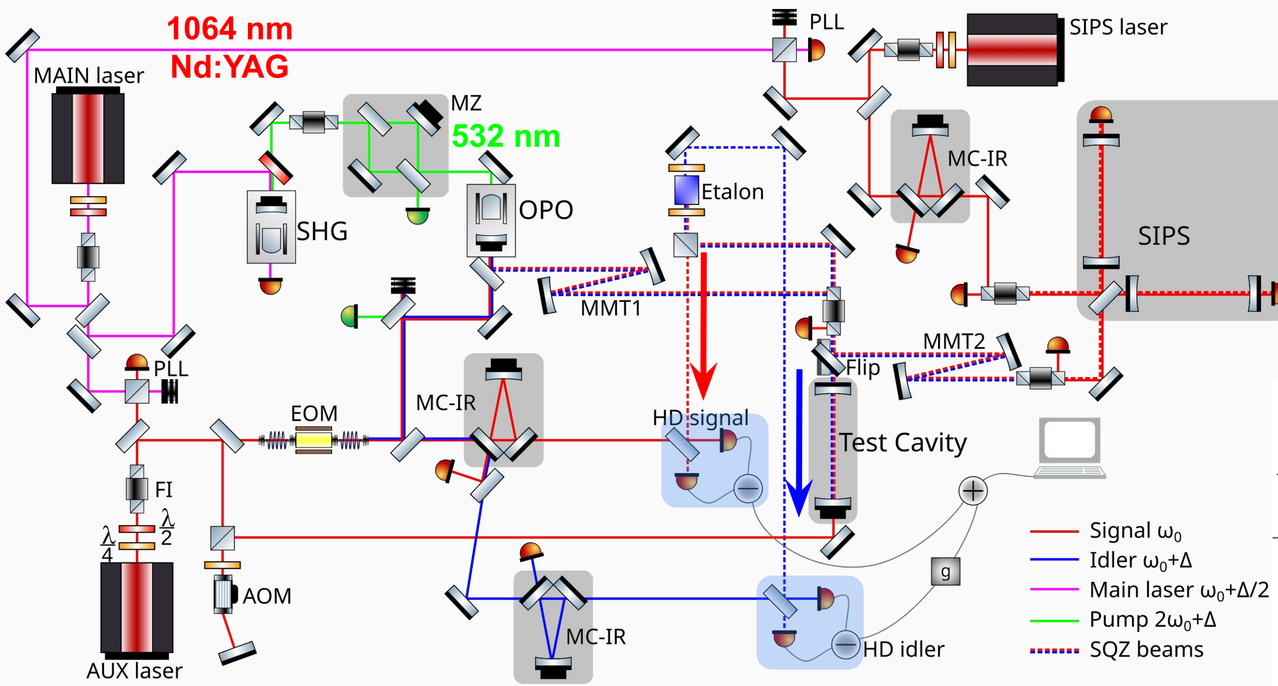
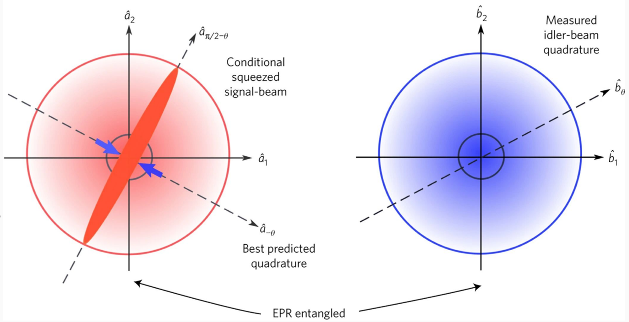


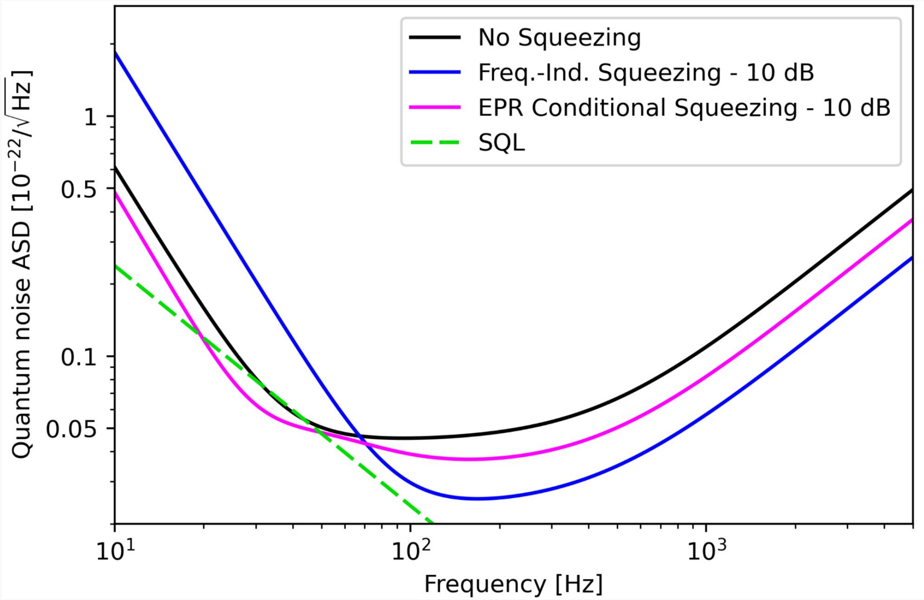
1. **Signal** and **idler** are vacuum squeezed beams, EPR-entangled and detuned by Δ
2. The **idler** sees the interferometer as a filter cavity and acquires frequency-dependence
3. Combined measurement transfers the frequency dependence to the **signal** via EPR entanglement



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

Simulation of EPR effect in GW detectors

- Fundamental to assess potential advantage w.r.t. filter cavity for ET and 3rd gen detectors
- Lack of a tool for EPR simulation available to the GW community
- We aim to provide EPR results in all the possible configuration with our `EPRsimulator`



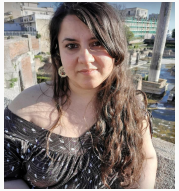
Preliminary result with realistic losses in Advanced Virgo+ (150 ppm arms, 300 ppm BS, 10% INJ and DET)

De Marco *et al.* - Nucl. Instr. and Meth. for Phys. A 1070, 170008 (2025)

Highlights and next steps

- It is crucial to enhance the astrophysical outreach of modern and future GW detectors to probe new models in astrophysics, cosmology and fundamental physics
- The EPR experiment will investigate an alternative technique to achieve freq.-dependent squeezing with less infrastructural effort
- An experimental demonstration in the 100 Hz - 10 kHz band would be fundamental in view of ET and next-gen detectors
- First squeezing data will be collected by the first half of 2025
- Expansion of the setup and development of controls for EPR testbed (see Wajid Ali's talk) to be completed by the end of 2025

Thank you for your attention!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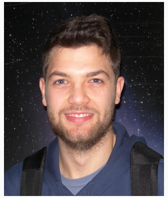

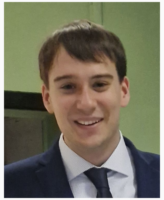
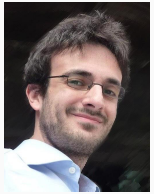

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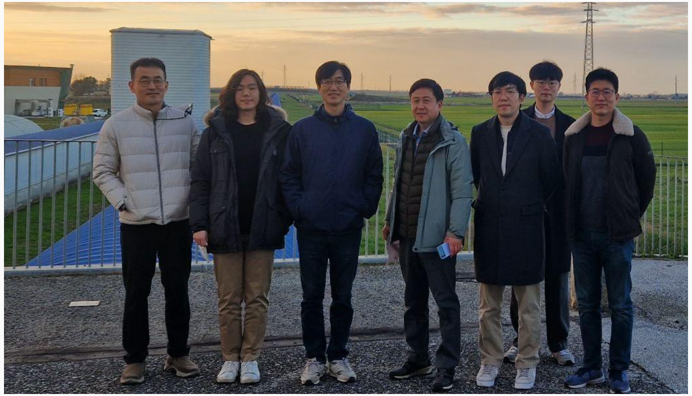
Soojong Pak (KHU)
June-Gyu Park (Yonsei University)
Sumin Lee (KHU)
Yunjong Kim (KASI)
Kyungmin Kim (KASI)



Byeong-Joon Park (KASI)


Mateusz Bawaj | Andrea Svizzeretto

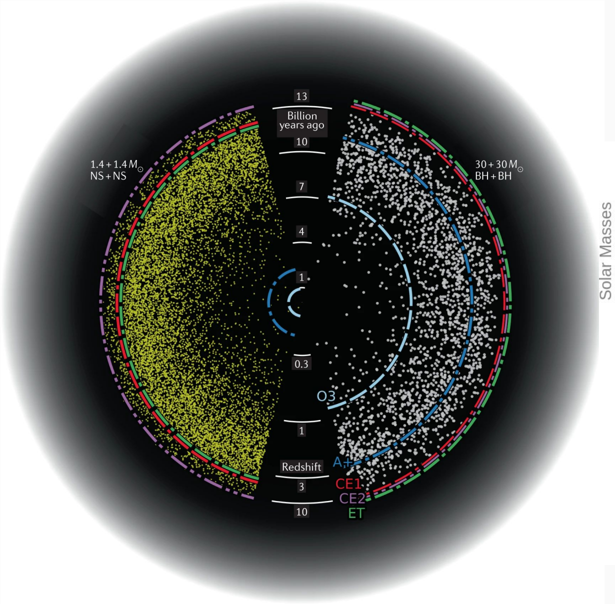
University of Perugia
INFN-Perugia

Backup slides

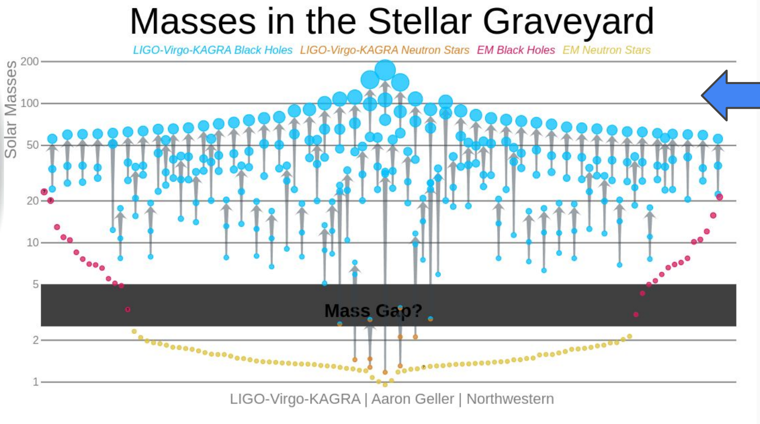
Gravitational-wave astronomy

- Detector figure of merit: Binary Neutron Star Horizon (today **~50-55 Mpc for Virgo, ~160 Mpc for LIGOs**)
- Multimessenger astronomy!

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)

- O4 run ongoing
- **195 detection candidates** at Feb 13th, 2025

Check out the [public alerts web page] and keep counting!

Gravity at its strongest regime

- GWs are (almost) not perturbed by matter
- Generated in very strong regime

Astrophysics

- source study
- multi-messenger observations

Cosmology

- BH population
- H_0 tension
- Primordial GW

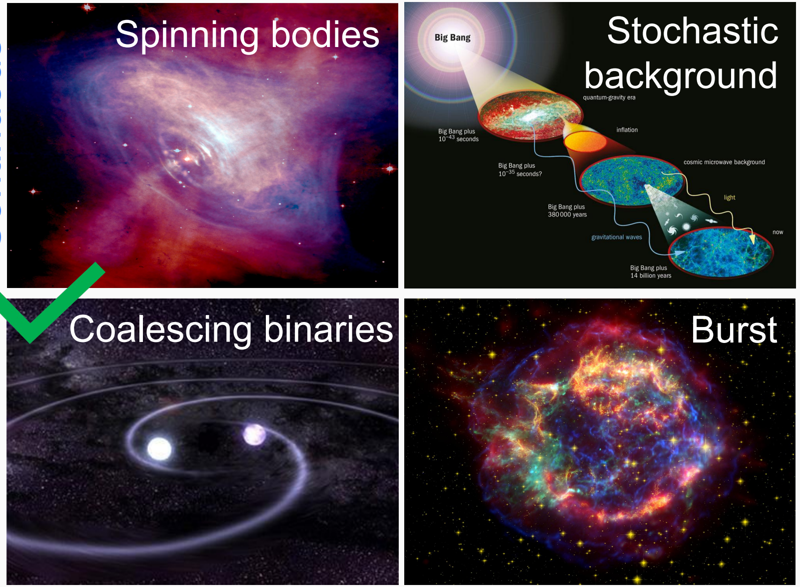
Fundamental physics

- Neutron Star EOS

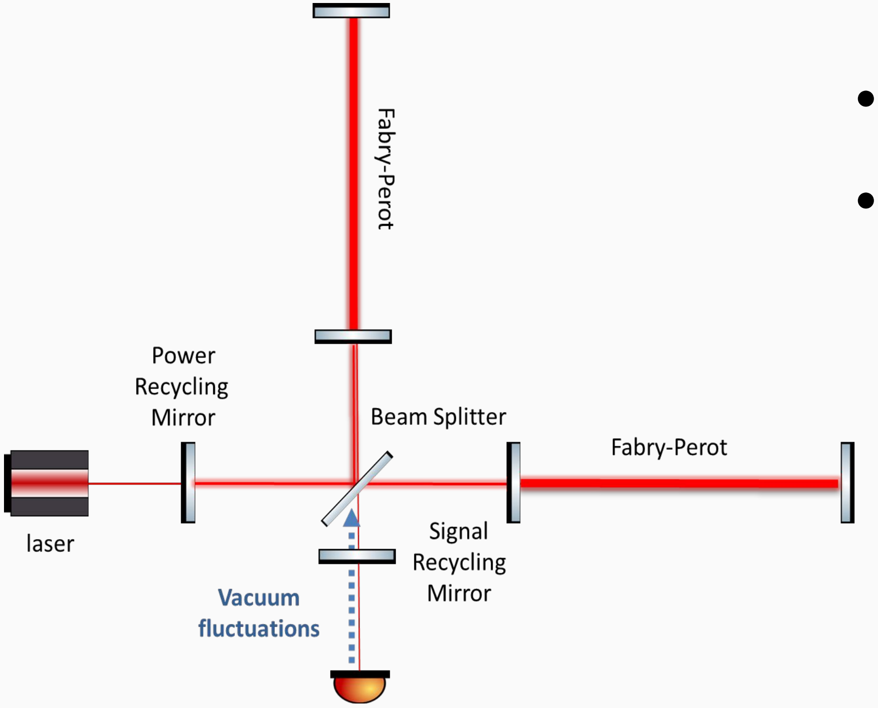
GW sources

Modeled | Unmodeled

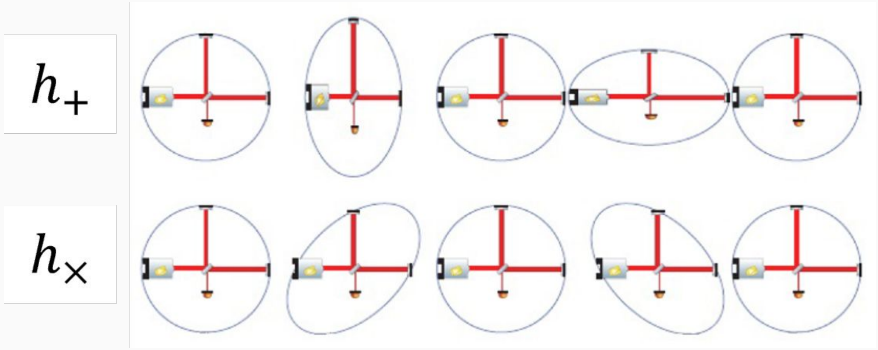
Continuous | Transient



Gravitational-wave (GW) interferometers



- GWs were predicted by Einstein (1916): “ripples” of space-time fabric
- Detected through dual-recycled Michelson interferometer (ITF) with km-long Fabry-Perot (FP) arm cavities
- Test masses (mirrors) are displaced by the passage of a GW

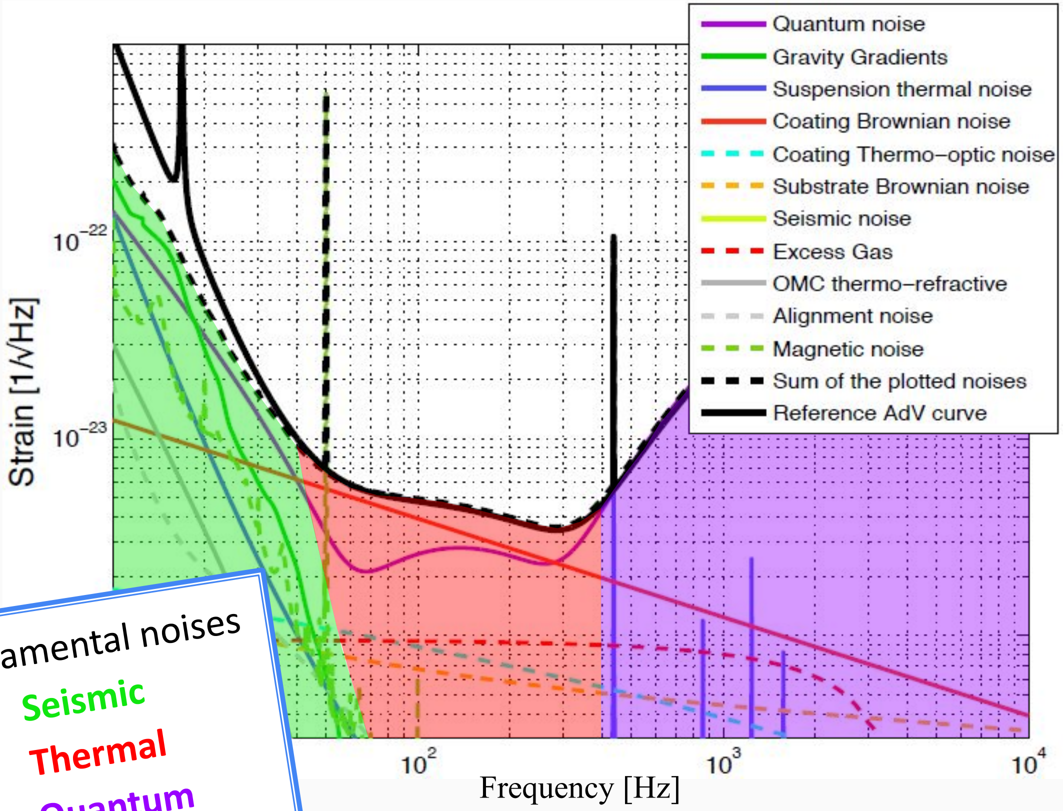


- Differential measurement of **GW strain**

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

Sensitivity curve

- Amplitude Spectral Density of (independent and stationary!) noise sources
- Expressed in terms of equivalent strain amplitude
- Bandwidth: 10 - 1000 Hz
  - ✓ Compact Binary Coalescence
  - ○ Burst
  - ○ Continuous Waves
  - ○ Astrophysical background



Fundamental noises
- Seismic
- Thermal
- Quantum

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

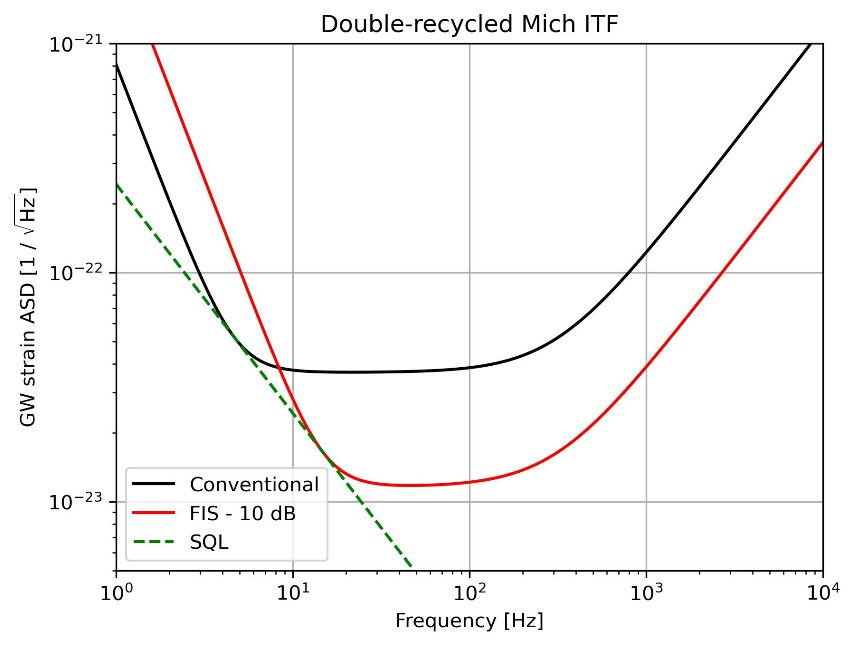
Quantum noise in GW detectors

- Originated by vacuum field entering the output port of the interferometer
- 2 contributions
  - back-action: Radiation-Pressure Noise
  - detection: Shot Noise
- They meet at the **Standard Quantum Limit**

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

Standard Quantum Limit (SQL)

ITF optomechanical coupling



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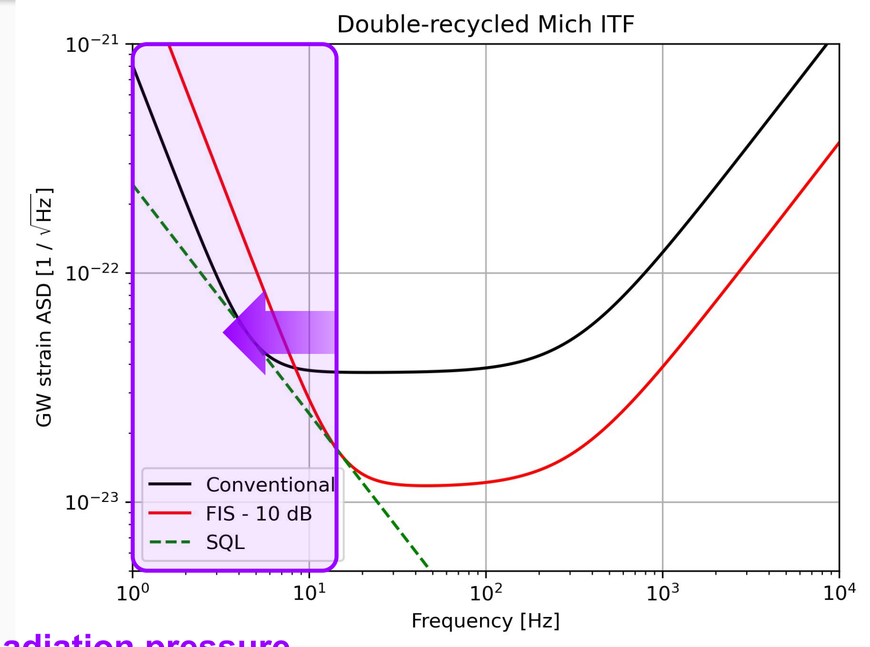
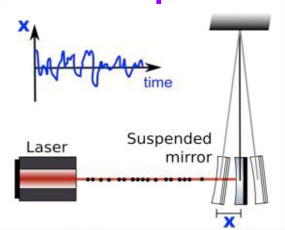


Radiation pressure



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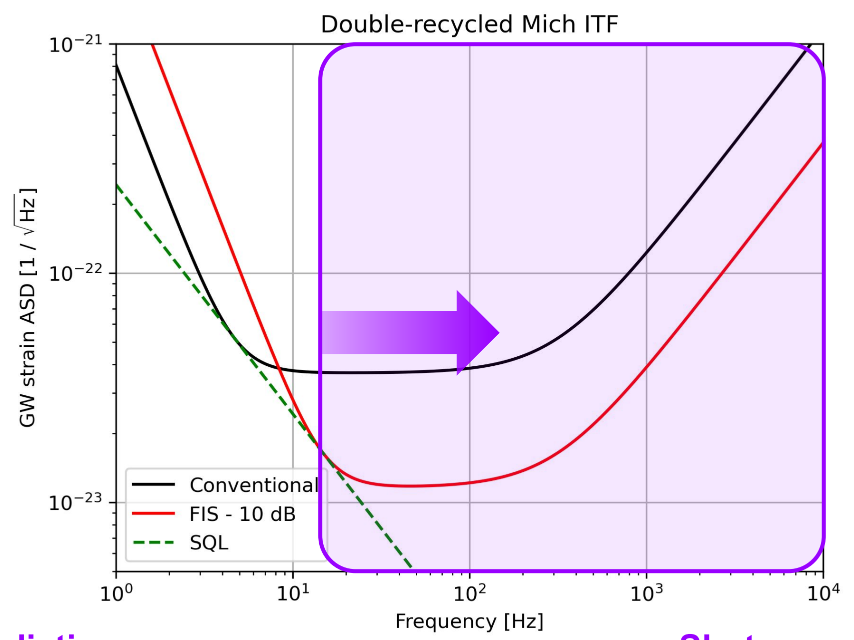

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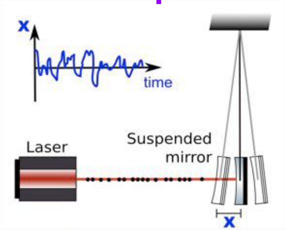
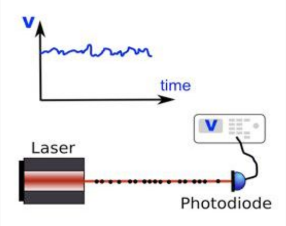


Shot



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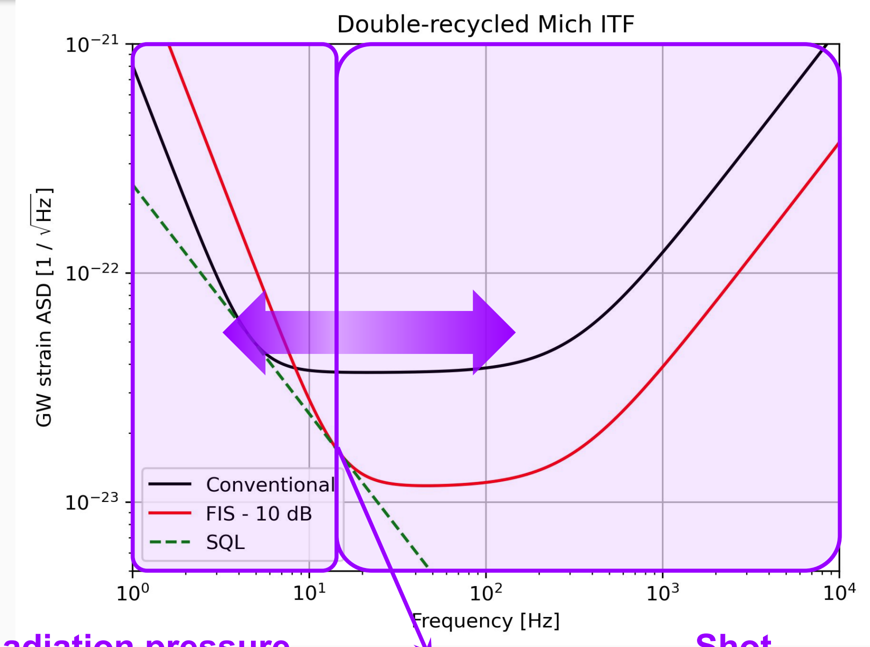

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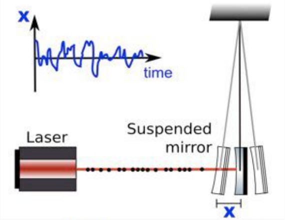

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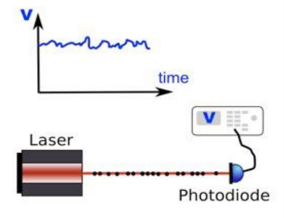
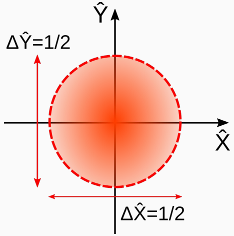
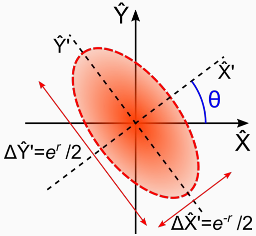


Quantum Noise reduction with squeezing

Vacuum states of light normally enter the interferometer from the output port





Squeezed states of light have reduced variance along one quadrature

r[dB] = 10 log$_{10}$(e^{2r})

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

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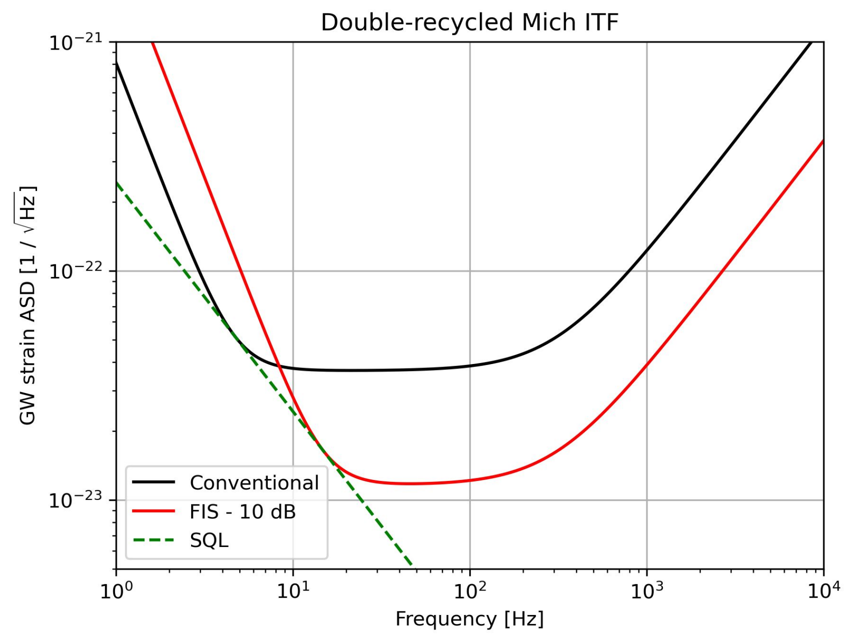

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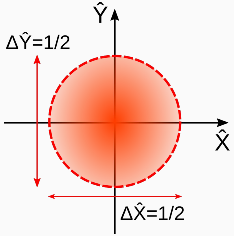

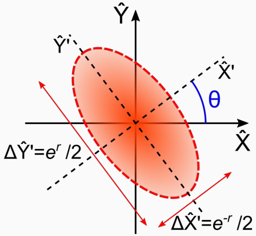

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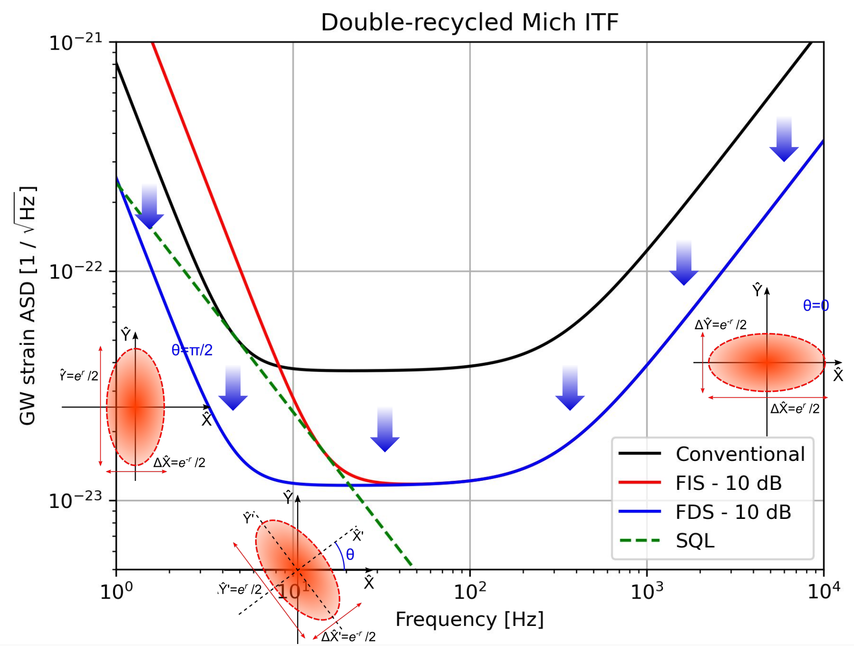
$$S_h(\omega) = \frac{h^2_{SQL}}{2}\left(\frac{1}{\mathcal{K}(\omega)} + \mathcal{K}(\omega)\right)\boxed{e^{-2r}}$$

Suppression with
freq.-dependent squeezing



Frequency-Dependent Squeezing (FDS) reduces quantum noise along the whole detection band!