State of the art of squeezing application to GW detectors

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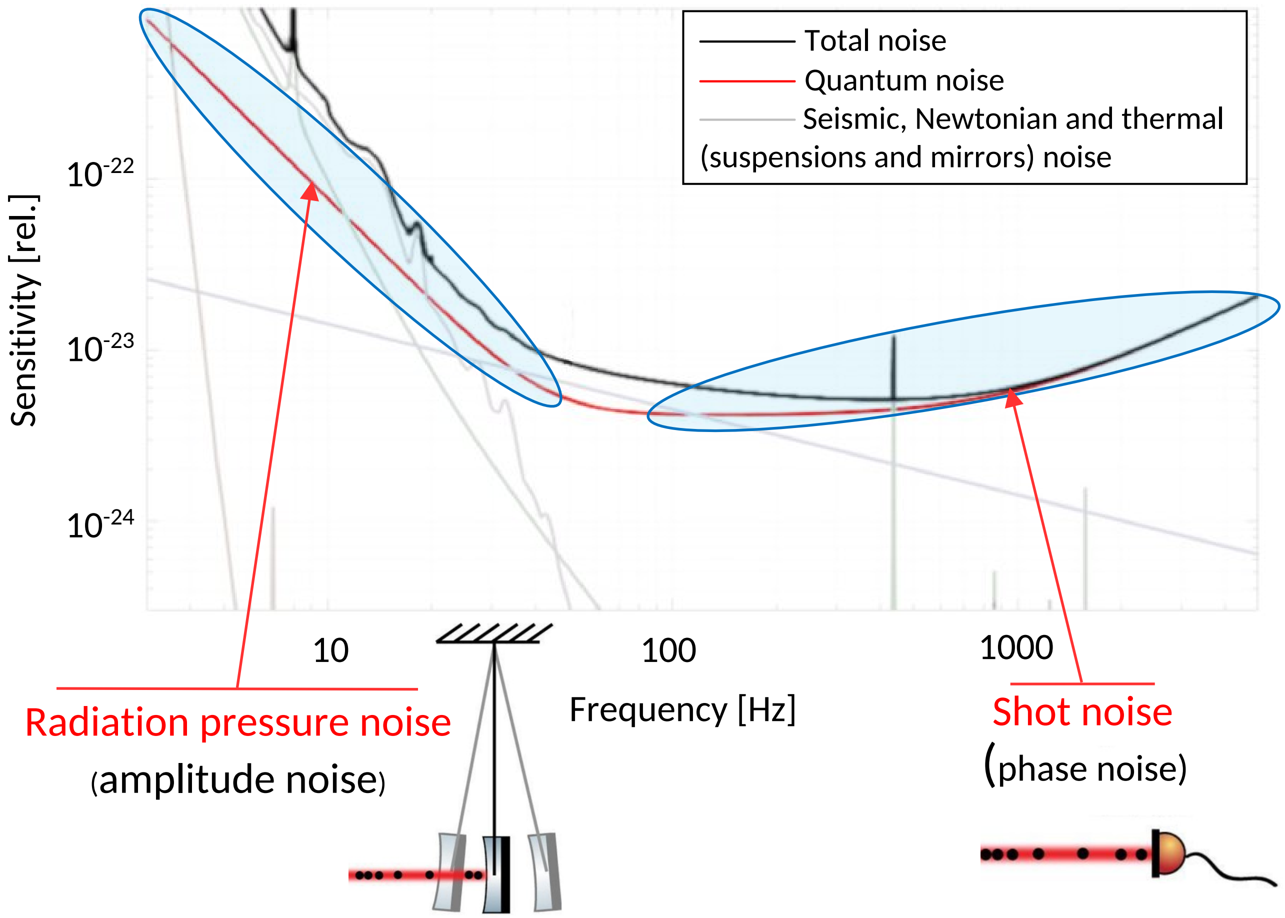
Sensitivity curve



- Quantum noise is limiting sensitivity at high frequencies
  - shot noise due to laser phase noise
- and close to limiting noises at low frequencies
  - radiation pressure noise due to laser amplitude noise

Squeezed states of light

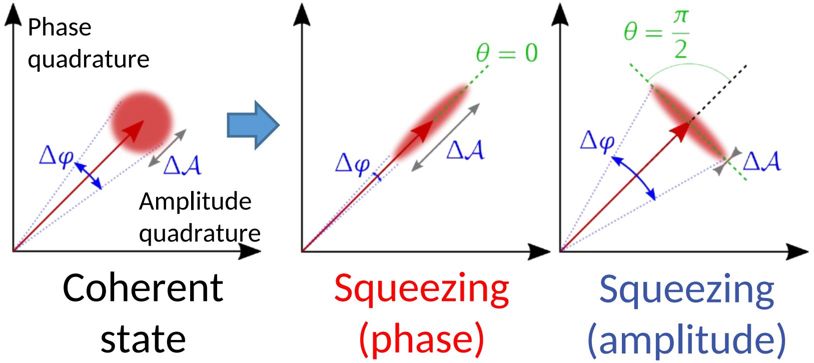
can be used to reduce quantum noise

Take advantage of quantum properties of light

- Heisenberg uncertainty relation:

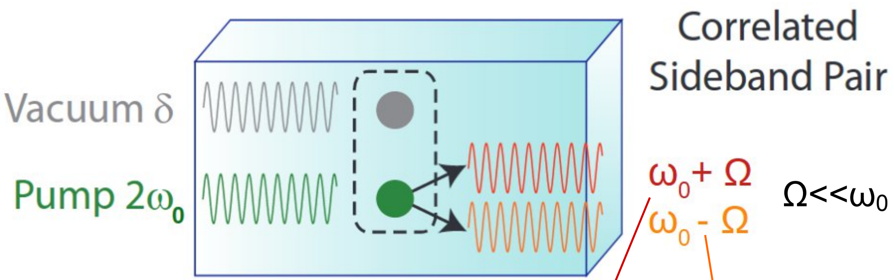
$$\Delta A \times \Delta\varphi \geq 1$$

- It is possible to reduce noise in one quadrature (phase or amplitude) at the cost of increasing noise in the other one



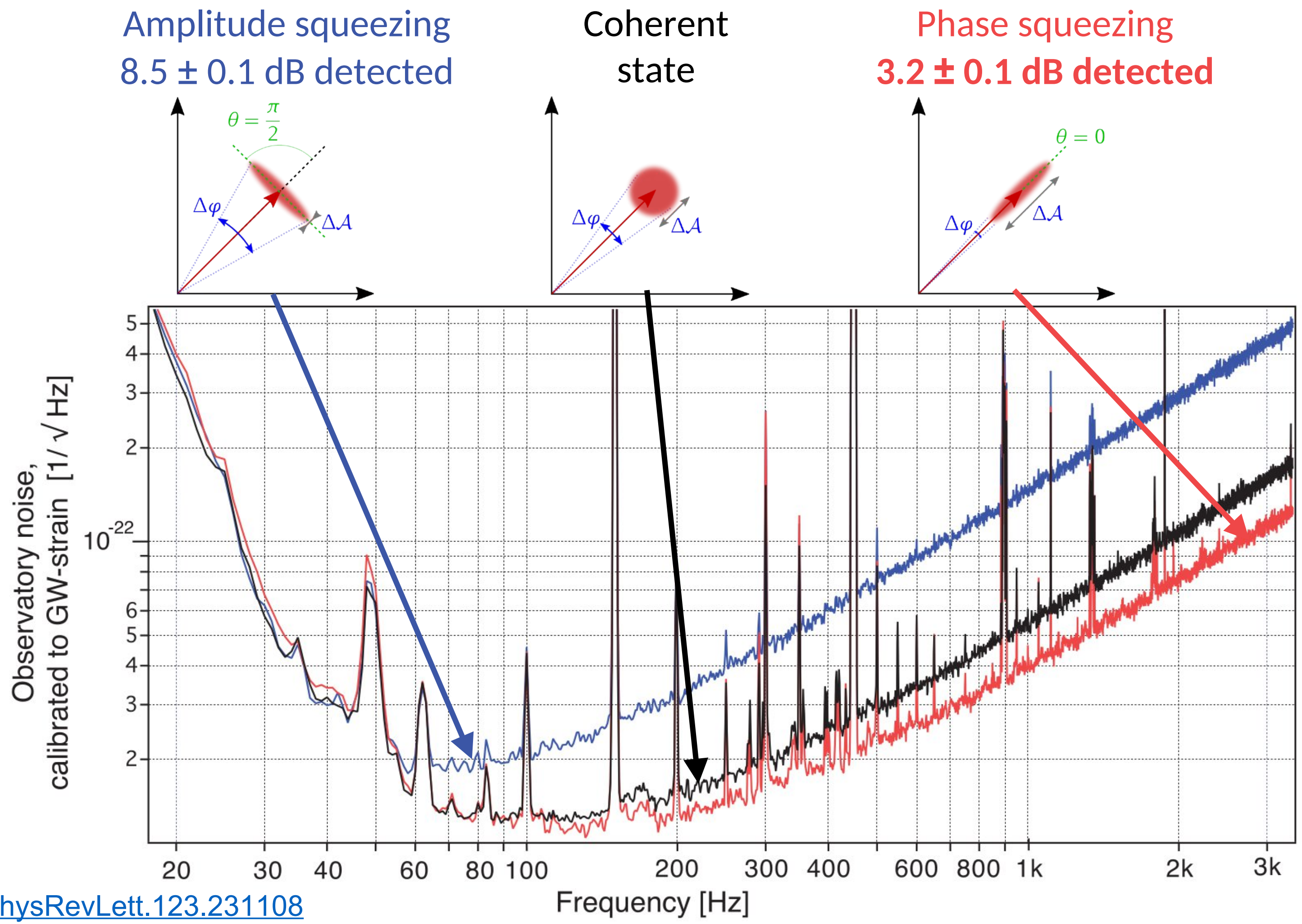
2-photon squeezing production via nonlinear interaction

- A pair of entangled infrared photons is created from a single green photon



Squeezing ellipse angle: $\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2} \ [\pi]$

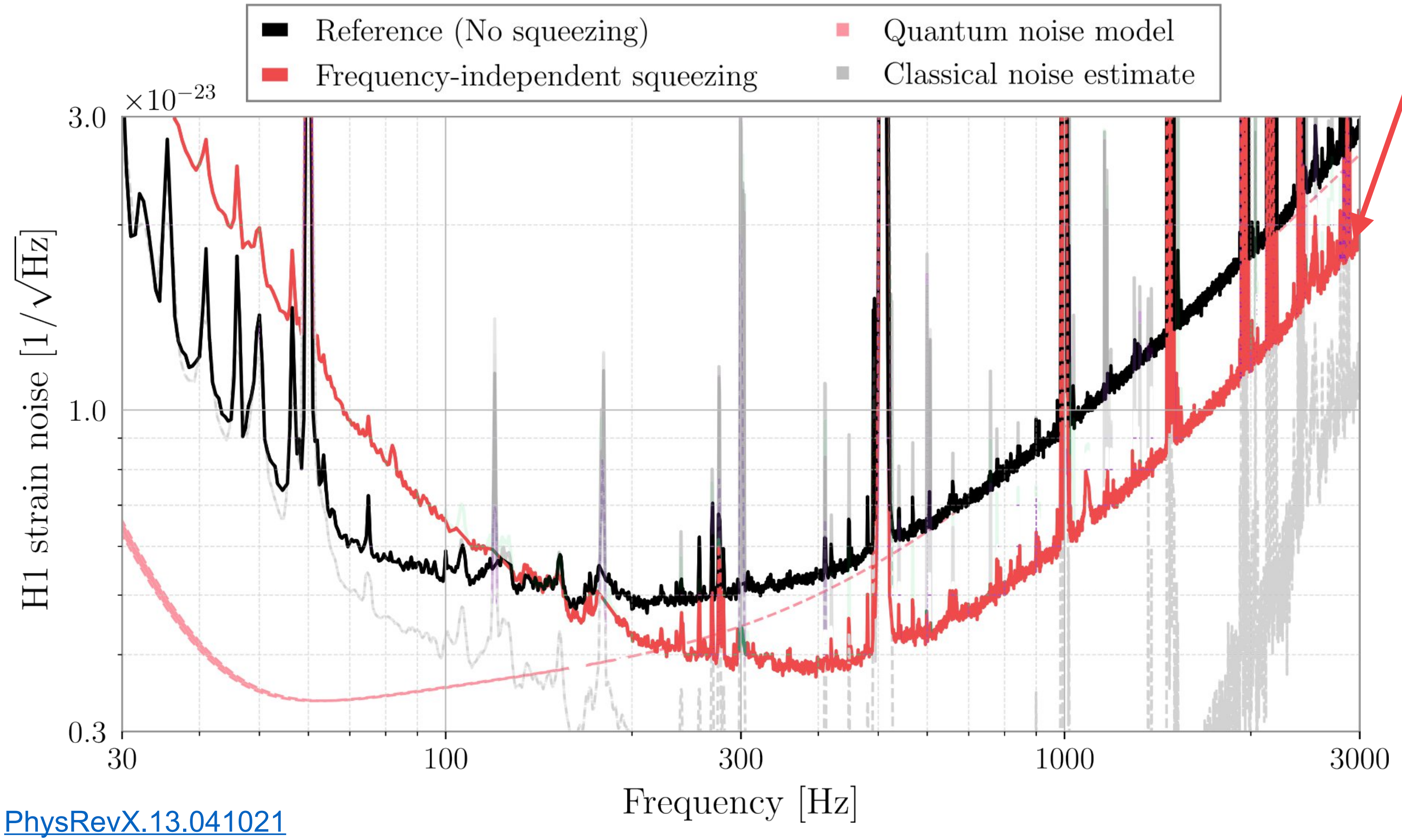
Virgo state of the art during O3



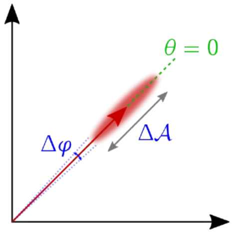
PhysRevLett.123.231108

- 10 dB of frequency **independent** squeezing (FIS) generated
  - 5%–8% increase of the binary neutron star horizon
  - Squeezing applied for more than 99% of the science time.
- No clear loss of sensitivity at low frequencies with phase squeezing due to other noises

LIGO state of the art squeezing starting O4 – part 1



Phase squeezing
4.0 dB detected



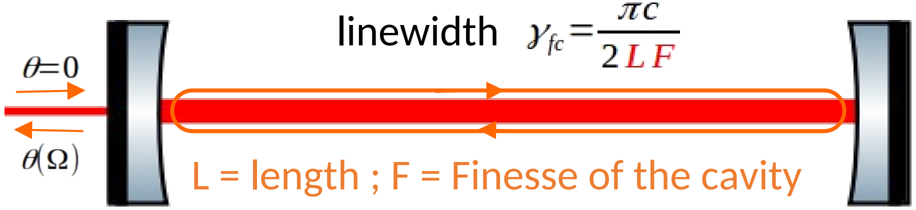
PhysRevX.13.041021

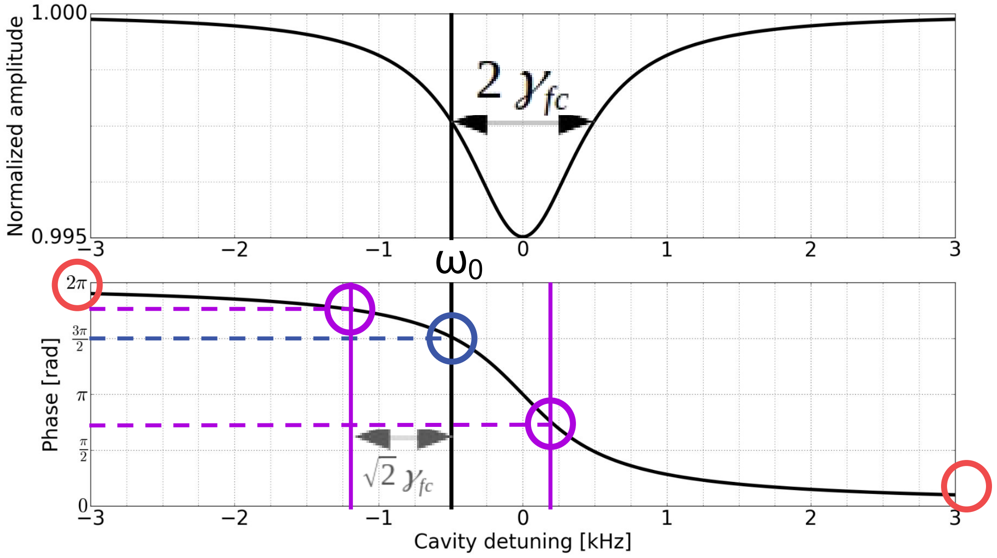
- ~17 dB of frequency independent squeezing (FIS) generated
  - 4.0 dB detected in Hanford
  - 5.8 dB detected in Livingston
- Clear loss of sensitivity at low frequencies with phase squeezing
  - Other noise sources have been reduced

Theory of frequency dependent squeezing

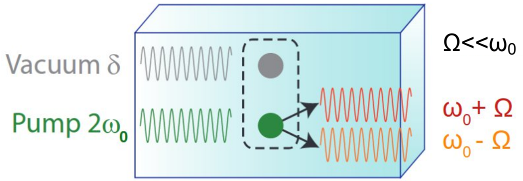
Filter cavity

- FIS in phase enter the cavity => θ = 0





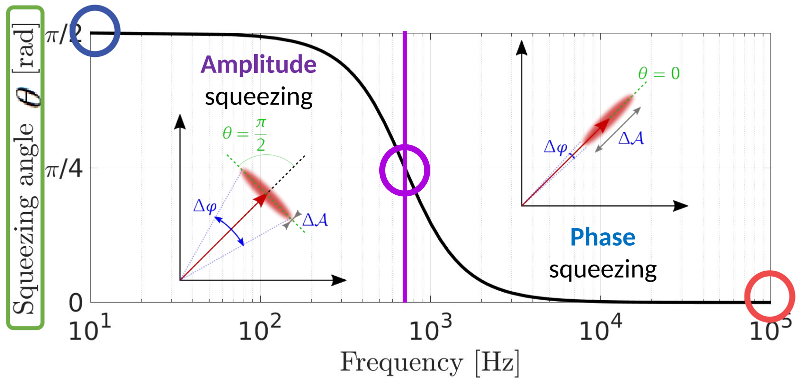
Squeezing angle



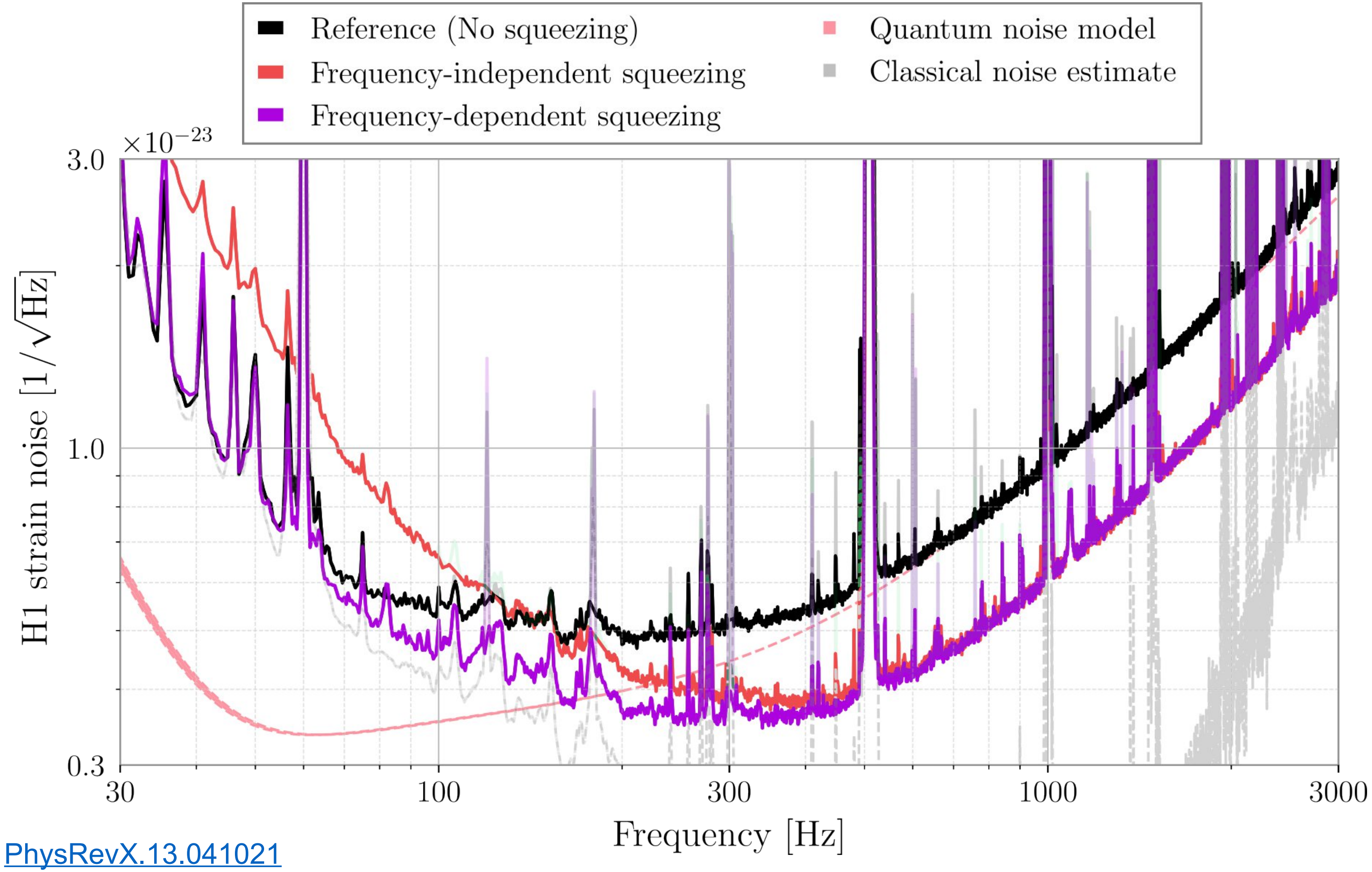
$$\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2} \; [\pi]$$

- After reflection on the filter cavity :
  - If $\Omega >> \sqrt{2}\gamma_{fc} \Rightarrow 2\theta = 0 + 2\pi \Rightarrow \theta = \pi = 0\ [\pi]$
  - If $\Omega = \sqrt{2}\gamma_{fc} \Rightarrow 2\theta = 3\pi/4 + 7\pi/4 \Rightarrow \theta = 5\pi/4 = \pi/4\ [\pi]$
  - If $\Omega = 0 \Rightarrow 2\theta = 3\pi/2 + 3\pi/2 \Rightarrow \theta = 3\pi/2 = \pi/2\ [\pi]$

Frequency Dependent Squeezing (FDS) is reflected



LIGO state of the art squeezing starting O4 – part 2

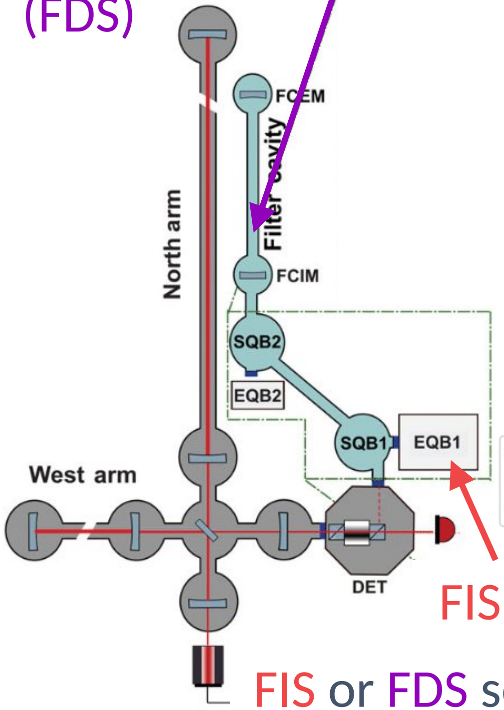


PhysRevX.13.041021

- 300-m filter cavity
- Frequency dependent rotation of the squeezing ellipse at ~30 Hz
  - No degradation of sensitivity below 60 Hz
  - Improvement wrt FIS in the 60 - 600 Hz range
- Increase in the astrophysical detection rate of up to 65%

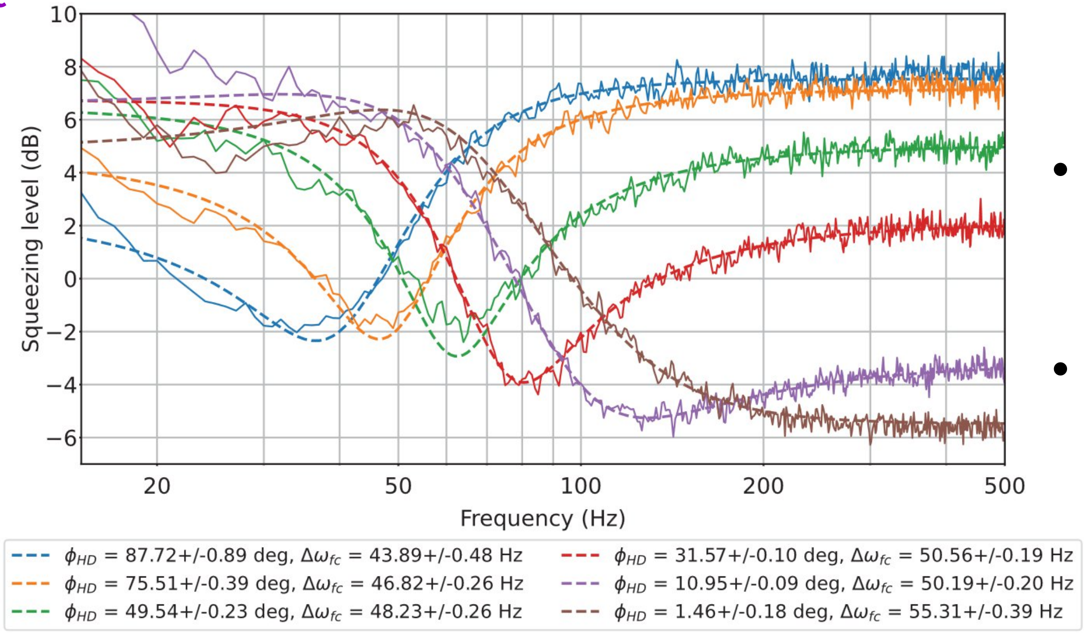
Virgo status starting O4b

Frequency Dependent rotation of Squeezing (FDS)



FIS generation

FIS or FDS sent to the ITF



- 285-m filter cavity installed and commissioned for FDS
- Frequency dependent rotation of the squeezing ellipse at ~45 Hz
- With 8.5 dB squeezing source, expect a reduction up to:
  - 4.5 dB of shot noise
  - 2 dB of radiation pressure noise

However, as other noise sources are still limiting at low frequencies, only frequency independent squeezing will be used on Virgo during O4

PhysRevLett.131.041403

Summary

- Squeezing during observing runs
  - Frequency independent squeezing used during O3 in both LIGO and Virgo detectors
  - Frequency dependent squeezing in O4 at LIGO
  - Virgo will use frequency independent squeezing for O4 (due to other noise sources still dominant at low frequencies)
- Level of squeezing reached
  - Up to ~6 dB quantum noise reduction at high frequencies in LIGO Livingston (like GEO)
  - 3-4 dB quantum noise reduction at high frequencies in Virgo/LIGO Hanford
- Losses are the sinews of war
  - Optical losses: LIGO at 25 % and Virgo at 32-41%
  - Squeezing phase noise: LIGO > 20mrad and Virgo at 40 mrad