Quantum Noise Reduction with Squeezing in Gravitational Wave Detectors, and upgraded technologies

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on behalf of the Virgo QNR working group

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Outline

- **Quantum Noise in Gravitational Wave (GW) detectors**
- **Quantum Noise Reduction (QNR) in GW detectors using squeezing**
- **Improved Astrophysical reach with squeezing in Virgo during O3**
- **Broadband QNR using Frequency Dependent Squeezing (FDS)**
- **QNR system in Virgo build for O4 and current status**
- **Squeezing for future ground-based detector: Einstein Telescope (ET)**
- **Alternative FDS technique based on Einstein Podolsky Rosen (EPR) quantum entangled squeezing**

Second generation ground-based GW interferometric detectors

Michelson interferometers with Fabry-Perot (FP) arm-cavities, and suspended Test Mass mirrors

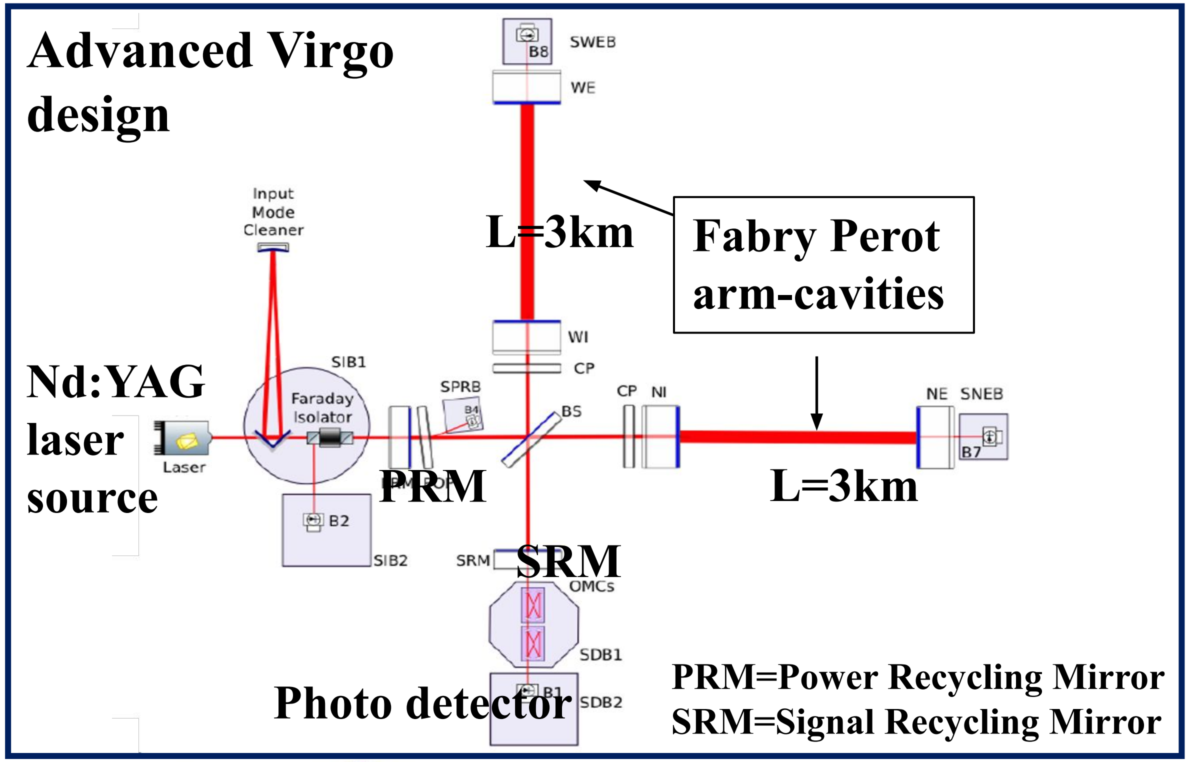
- **very sensitive detectors** ($\Delta L \sim 10^{-18}$m)
- **free-falling Test Masses**

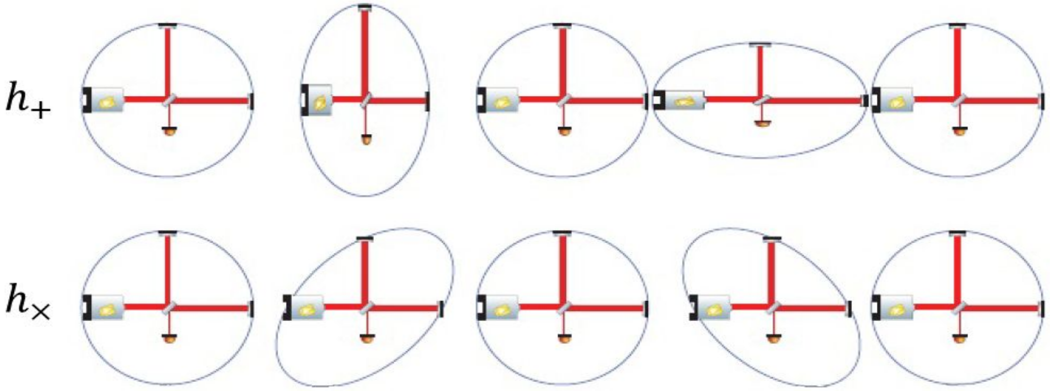
The passage of a GW squeezes or streches the optical path in the two arms, resulting as a **phase difference** $\boldsymbol{\Delta\phi}$ of the 2 laser beams recombining on the detector:

$$\Delta\phi = \frac{4\pi}{\lambda}\Delta L \approx \frac{4\pi}{\lambda}\boldsymbol{h_0} L \frac{2\mathcal{F}}{\pi}$$

$\boldsymbol{h_0}$ = GW signal $\quad G = 2\mathcal{F}/\pi$ = FP gain

L = arm-length $\quad \mathcal{F}$ = FP finesse



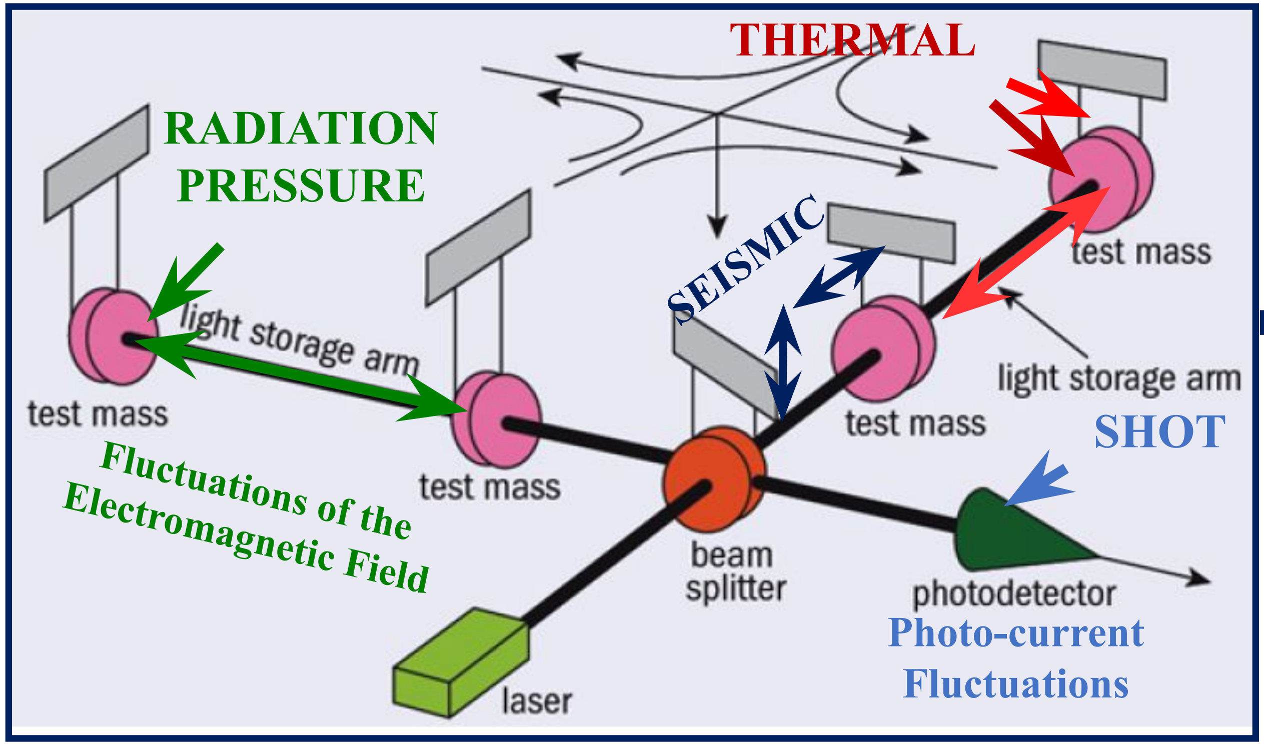


Status of Advanced Virgo and upgrades before next observing runs, *Physica Scripta, Vol. **96**, Issue 12 (2021)*

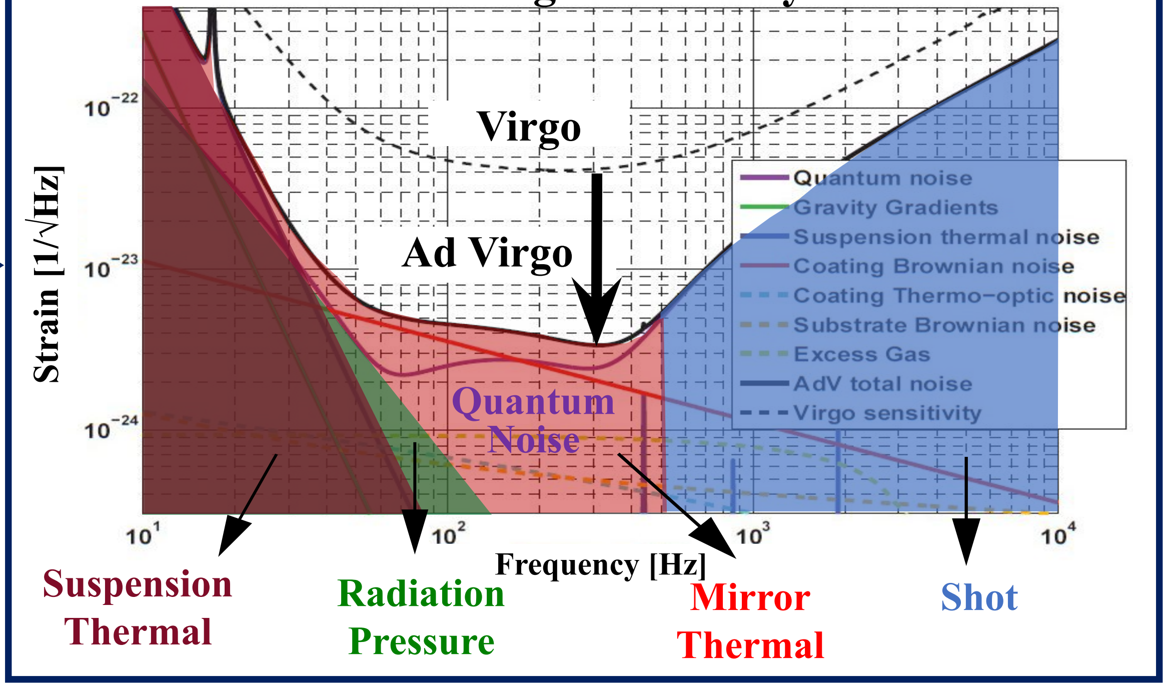
Noise sources in a GW interferometer (ITF)

External disturbances can hide GW signal ➡ must be reduced below the intrinsic noise

All these noises ➡ translate into the sensitivity curve of the GW detector



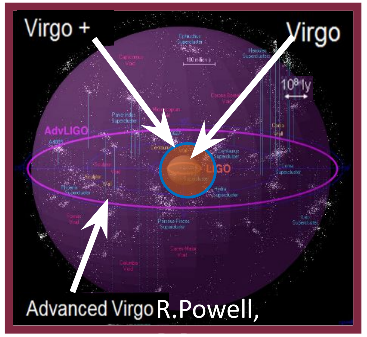
Advanced Virgo Sensitivity Curve



Main Upgrades of Advanced Virgo

Higher Laser input Power: 20W → 60W
Heavier mirror Test Masses: 20kg → 42kg
Thermal Compensation System (TCS)
Frequency Independent Squeezing (FIS)

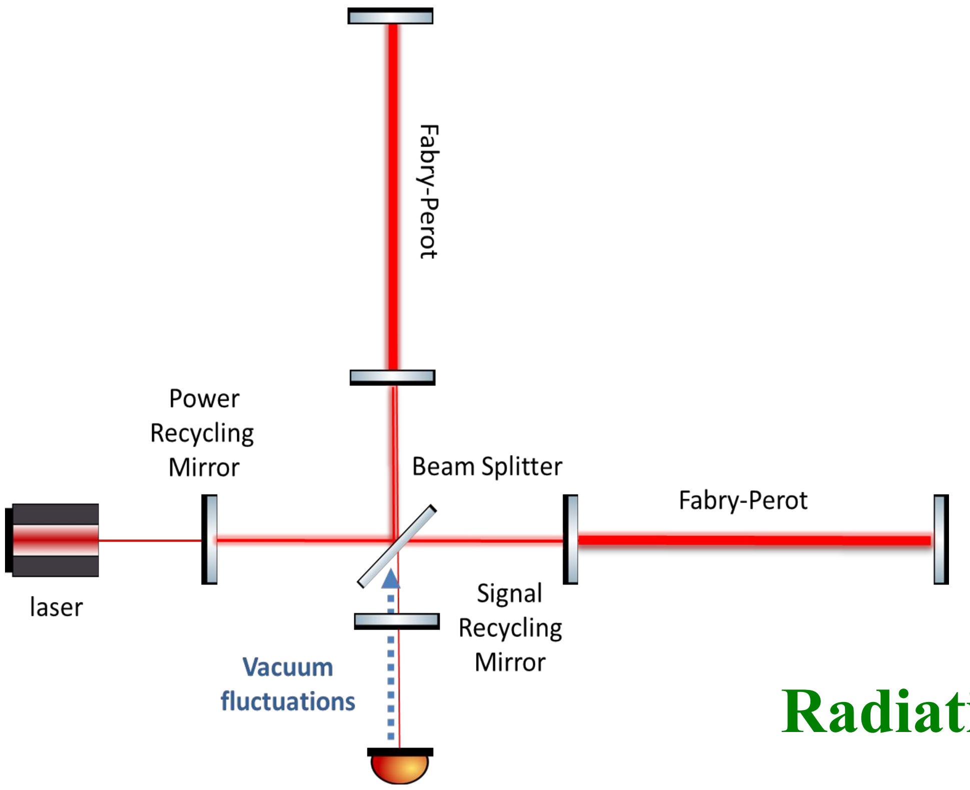
Compared to starting Virgo:
Sensitivity 10 times higher →
Detection Rate 1000 times higher
(volume of observable Universe
1 thousand times bigger!)

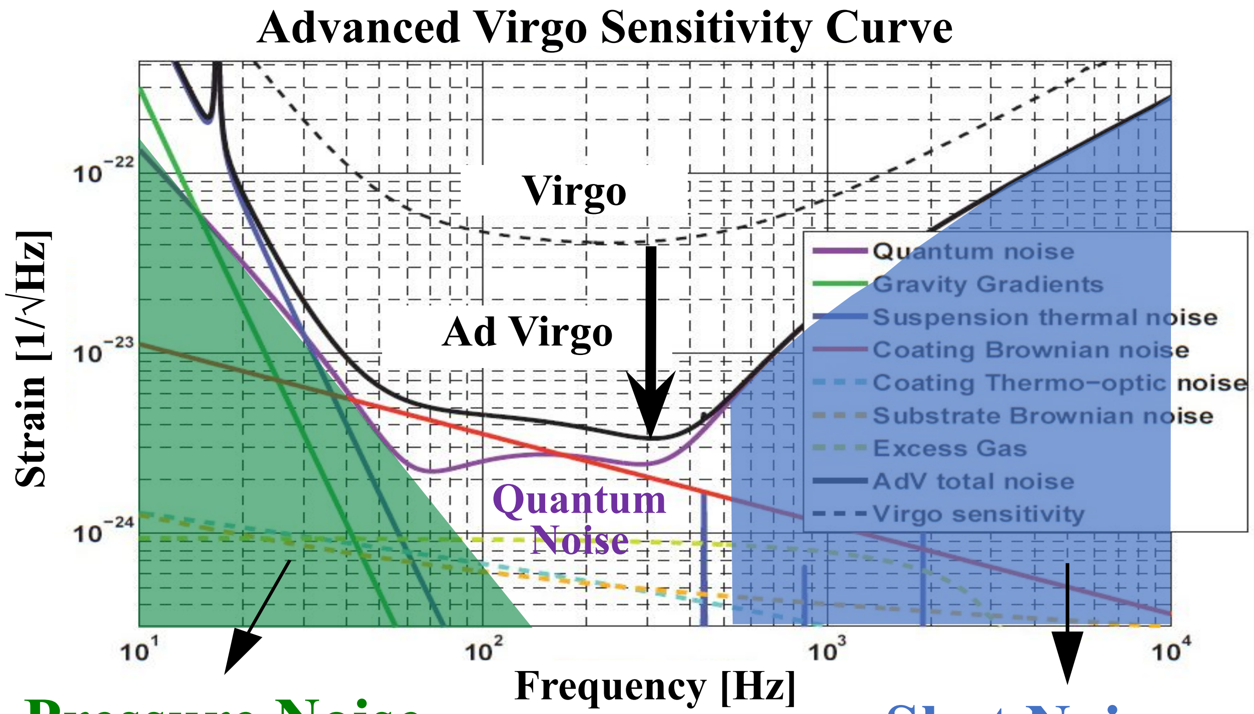


All these improvements allowed to achieve GW detections!

Quantum Noise in GW interferometers

Quantum Noise in a GW interferometer comes from the vacuum field fluctuations entering from the dark port of the interferometer





Radiation Pressure Noise

Shot Noise

Vacuum amplitude-fluctuations, more evident at lower frequencies

Vacuum phase-fluctuations, more evident at higher frequencies

Quantum Noise in GW interferometers

Shot Noise (SN)

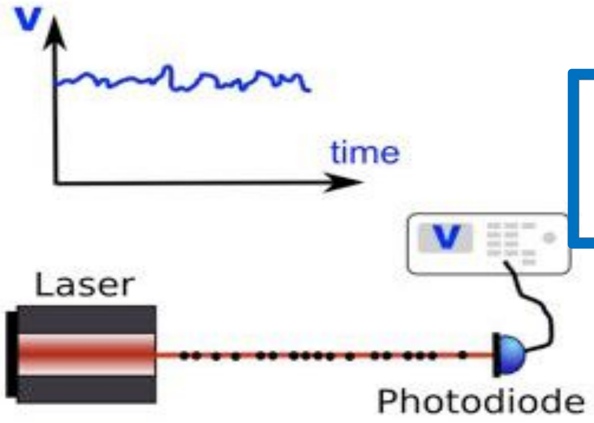
sensing noise

Photons arriving on the photo-detector (dark port) follow a Poisson distribution in time, determining an uncertainty on the number of photons arriving on the detector: **photo-current fluctuations**

Radiation Pressure Noise (RPN)

back-action noise

Photons impinging on the suspended mirror transfer their momentum (RP force) and due to EM field fluctuations inside the cavity they induce:
mirror position fluctuations



Phase Noise

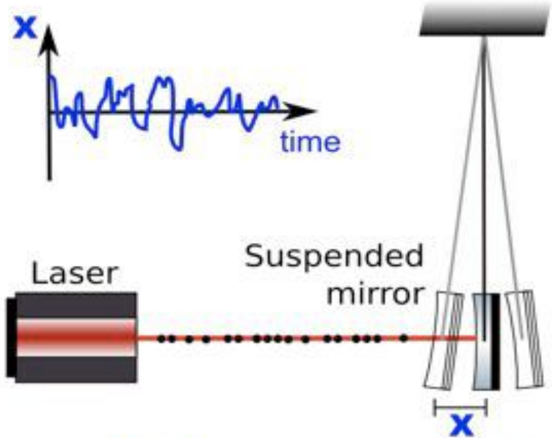
$$X_{shot}(\omega) = \frac{1}{8\,\mathcal{F}}\sqrt{\frac{2h\lambda c}{P_{las}}}$$

$\mathcal{F}$=finesse Fabry Perot arm-cavity
P_{las}=incident laser power

Amplitude Noise

$$X_{RP}(\omega) = \frac{2\mathcal{F}}{m\omega^2}\sqrt{\frac{8hP_{las}}{(2\pi)^2\lambda c}}$$

λ= laser wavelength
m= mirror mass



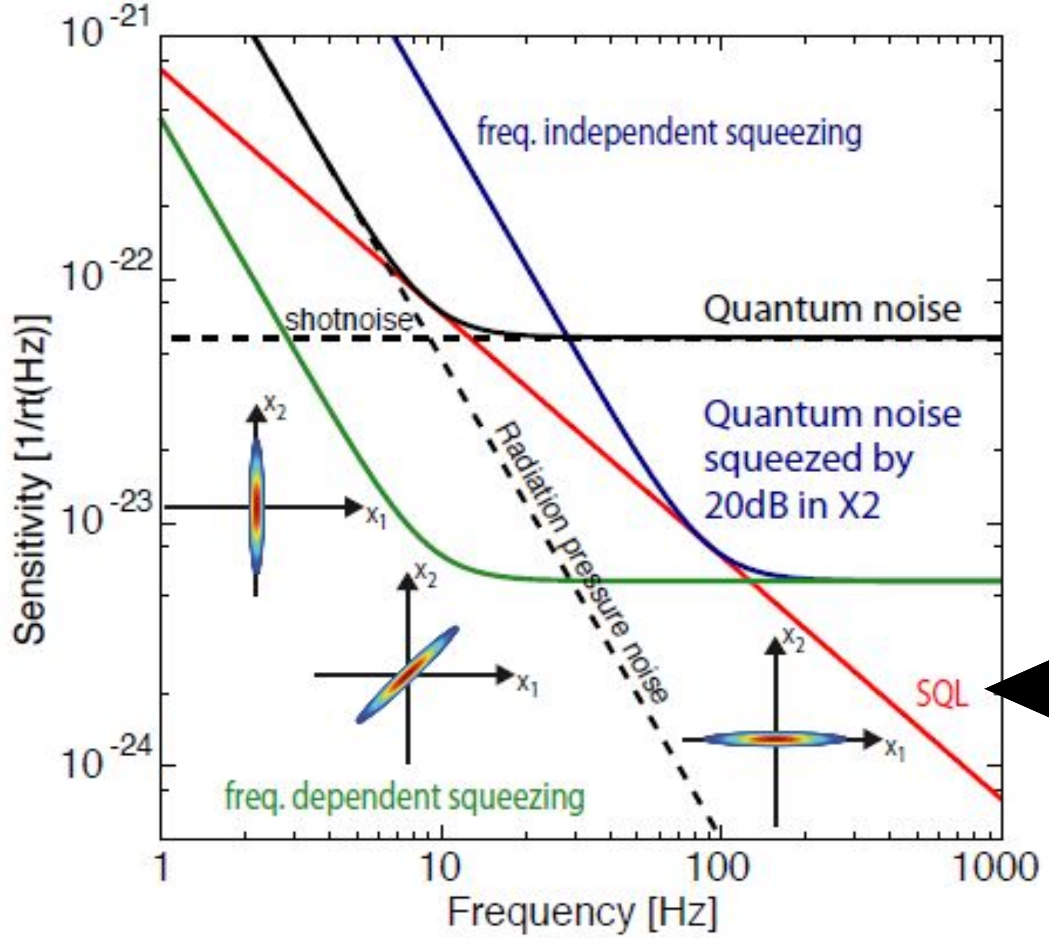
Quantum Noise (QN) is the **uncorrelated** sum of them:

$$h_{QN}(\omega) = \sqrt{{h_{shot}}^2(\omega) + {h_{RP}}^2(\omega)}$$

Standard Quantum Limit

Quantum Noise (QN) is the **uncorrelated** sum of:

$$h_{QN}(\omega) = \sqrt{h_{shot}{}^2(\omega) + h_{RP}{}^2(\omega)}$$



Credits H.Vahlbruch, (2008)

Shot Noise

$$X_{shot}(\omega) = \frac{1}{8\,\mathcal{F}}\sqrt{\frac{2h\lambda c}{P_{las}}}$$

Radiation Pressure Noise

$$X_{RP}(\omega) = \frac{2\mathcal{F}}{m\omega^2}\sqrt{\frac{8hP_{las}}{(2\pi)^2\lambda c}}$$

The minimum achievable **Quantum Noise**, at a given frequency, is obtained when P_{las} is such that both Shot Noise and Radiation Pressure Noise are equal:

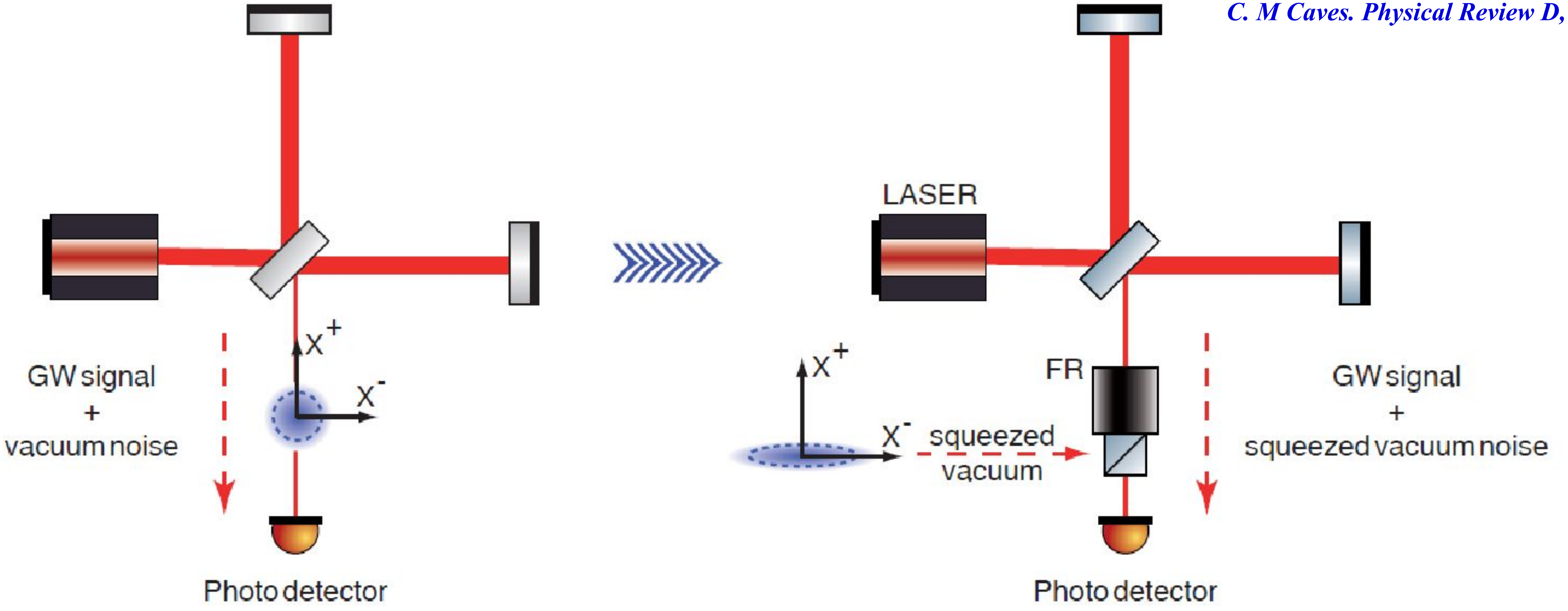
Standard Quantum Limit (SQL)

To improve GW detector's sensitivity we should implement a technique capable to overcome SQL in all its frequency band

Proposed solution: squeezed vacuum state injection

Quantum Noise in a GW interferometer comes from the vacuum field fluctuations entering from the dark port of the interferometer….

C. M Caves. Physical Review D, 23(8):1693, 1981



…but if we inject **squeezed vacuum field** we can reduce it!

Why?

Squeezed states of light

If we write the Electro-magnetic field in terms of quadrature operators:

$$\hat{E}_x = E_0 \sin(kz)\left(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t\right)$$

Amplitude quadrature uncertainty ➡ $\Delta\hat{X}_1$ **Radiation Pressure Noise**

Phase quadrature uncertainty ➡ $\Delta\hat{X}_2$ **Shot Noise**

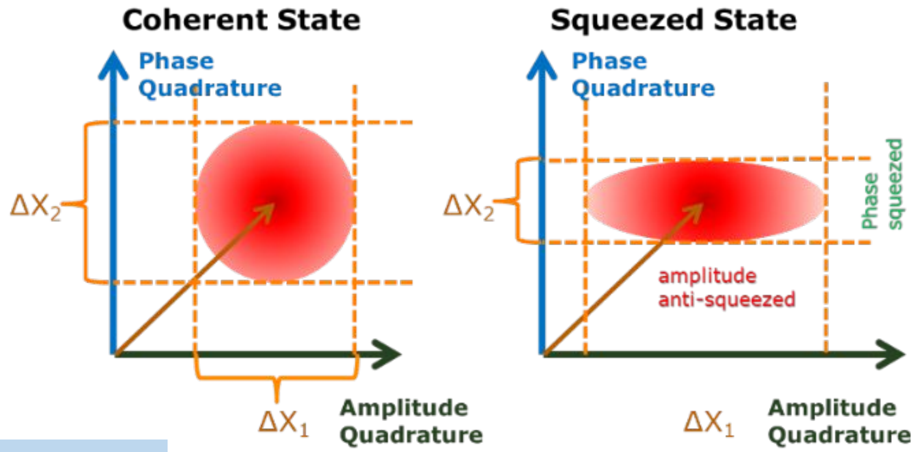
RPN and SN are related to the uncertainties of EM-field quadratures

It follows that SN and RPN are linked by the **Heisenberg Uncertainty Principle** $\left\langle(\Delta\hat{X}_1)^2\right\rangle\left\langle(\Delta\hat{X}_2)^2\right\rangle \geq \frac{1}{16}$

MINIMUM UNCERTAINTY STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle\left\langle(\Delta\hat{X}_2)^2\right\rangle = \frac{1}{16}$

COHERENT STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle = \left\langle(\Delta\hat{X}_2)^2\right\rangle$

SQUEEZED STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle < \left\langle(\Delta\hat{X}_2)^2\right\rangle$ $\left\langle(\Delta\hat{X}_1)^2\right\rangle > \left\langle(\Delta\hat{X}_2)^2\right\rangle$



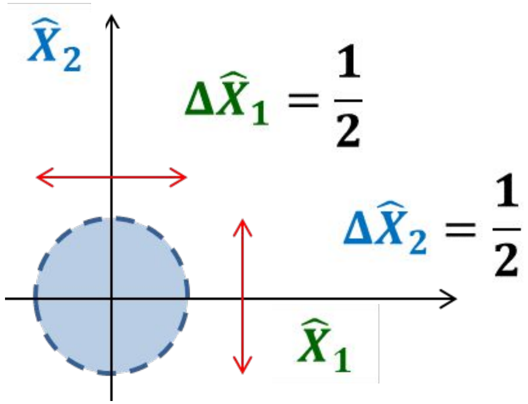
SQL can be seen as a manifestation of the Heisenberg Uncertainty Principle

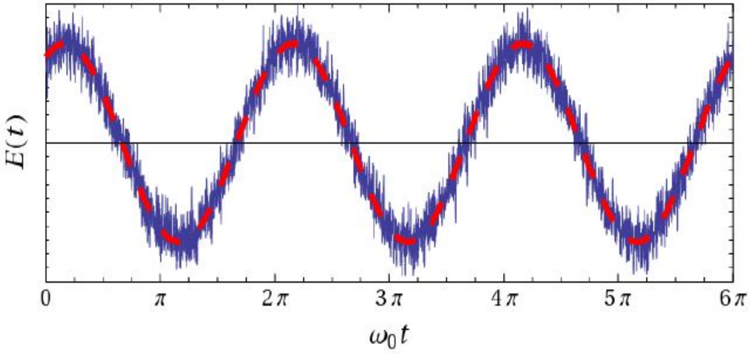
Squeezed states of light

MINIMUM UNCERTAINTY STATE $\left\langle (\Delta \hat{X}_1)^2 \right\rangle \left\langle (\Delta \hat{X}_2)^2 \right\rangle = \frac{1}{16}$

COHERENT STATE

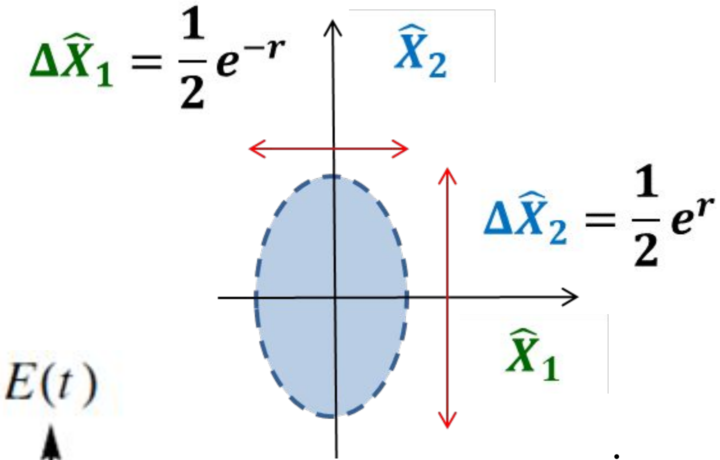
$$\left\langle (\Delta \hat{X}_1)^2 \right\rangle = \left\langle (\Delta \hat{X}_2)^2 \right\rangle$$



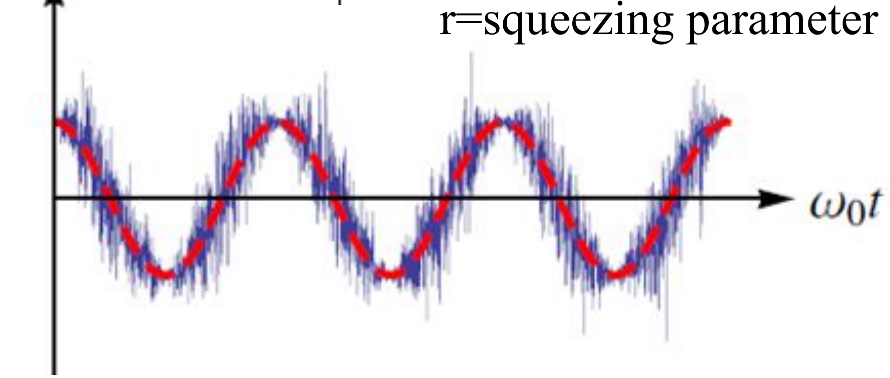


AMPLITUDE-SQUEEZED STATE

$$\left\langle (\Delta \hat{X}_1)^2 \right\rangle < \left\langle (\Delta \hat{X}_2)^2 \right\rangle$$

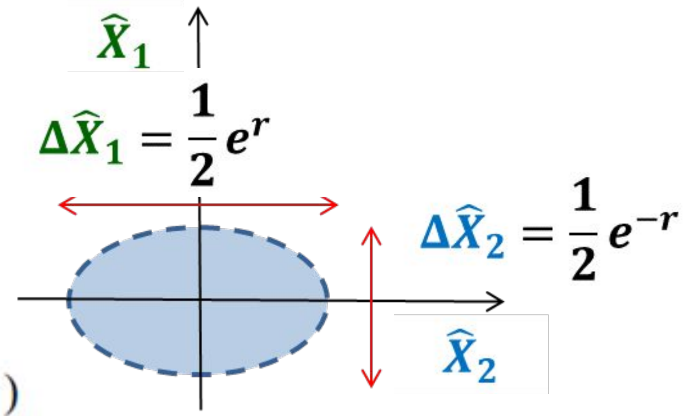


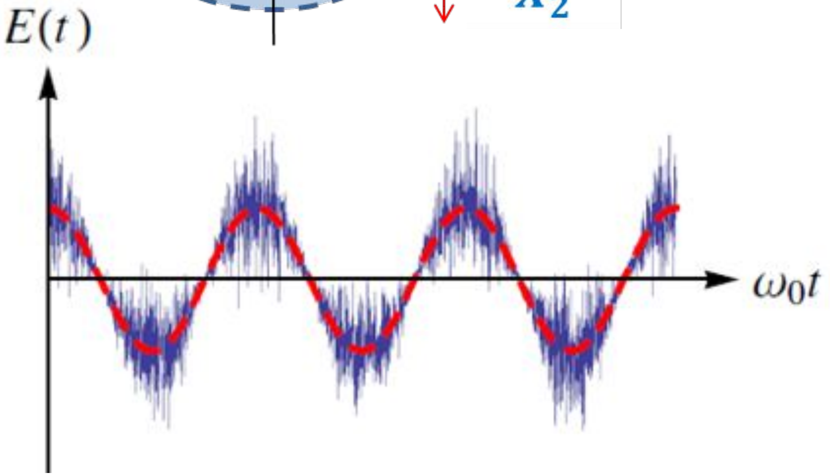
r=squeezing parameter



PHASE-SQUEEZED STATE

$$\left\langle (\Delta \hat{X}_1)^2 \right\rangle > \left\langle (\Delta \hat{X}_2)^2 \right\rangle$$

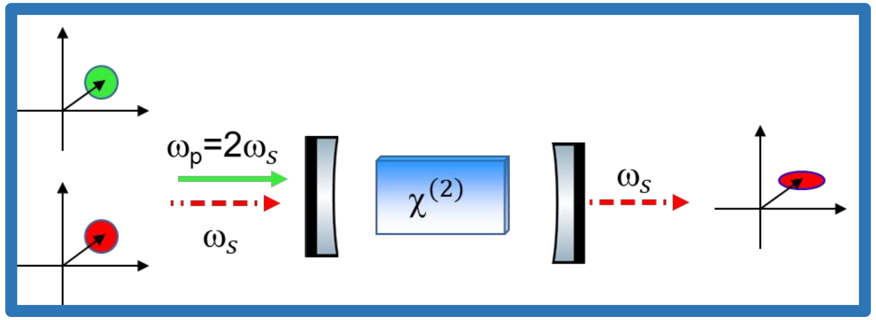




Squeezed vacuum generation

Squeezed-states of light can be produced via a **second order non-linear crystal** amplified in a non linear cavity called

Optical Parametric Oscillator (OPO)



1985: Squeezing in RADIO-FREQUENCY band

VOLUME 55, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1985

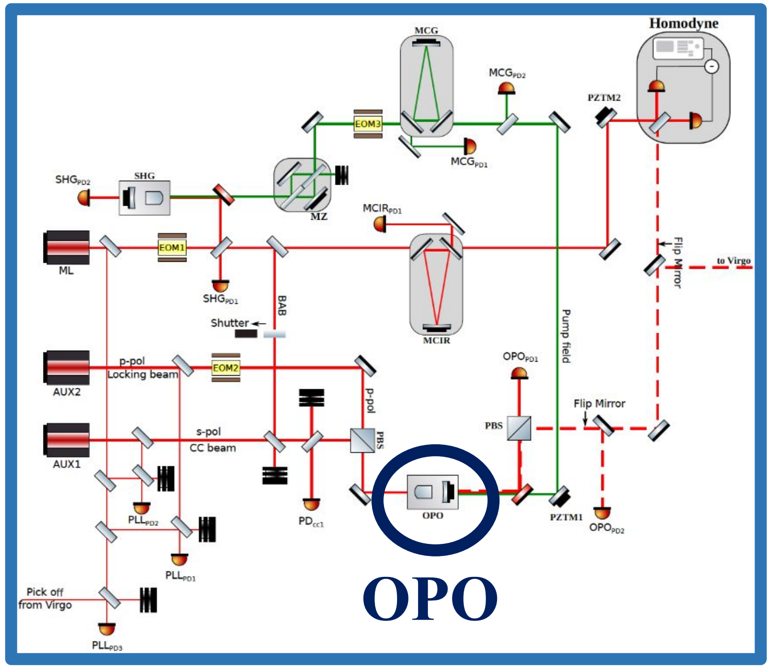
Observation of Squeezed States Generated by Four-Wave Mixing in an Optical Cavity

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)



2007: Squeezing in AUDIO-FREQUENCY band

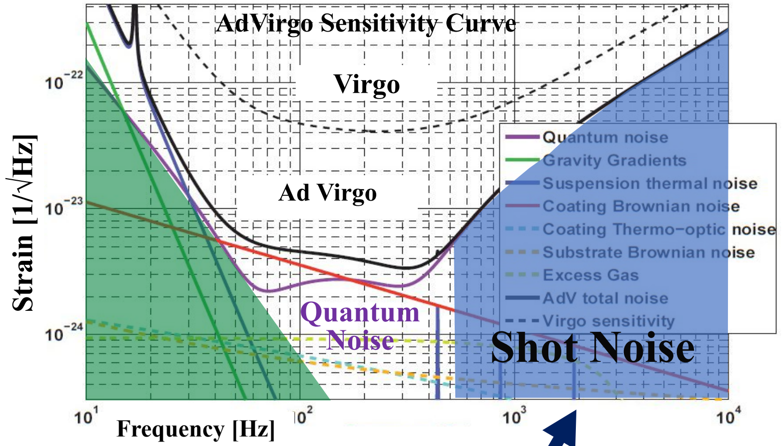
New Journal of Physics
The open-access journal for physics

Quantum engineering of squeezed states for quantum communication and metrology

H Vahlbruch[1], S Chelkowski, K Danzmann and R Schnabel
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

Squeezing in Advanced Virgo during O3

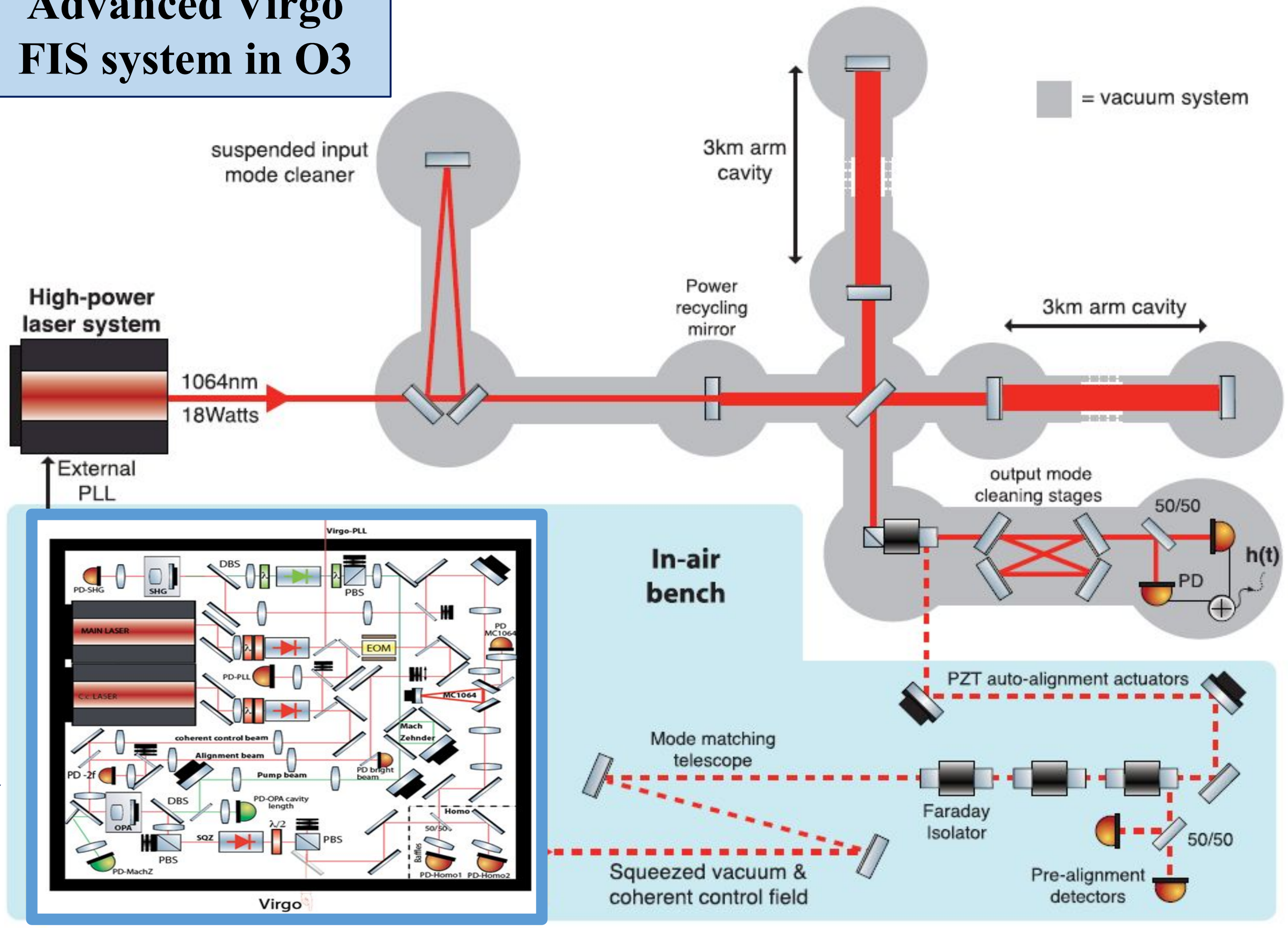


Only high frequency
QN reduction needed

Need for squeezed states with reduced noise in the phase quadrature

phase-squeezed Frequency Independent Squeezing (FIS)

Advanced Virgo FIS system in O3

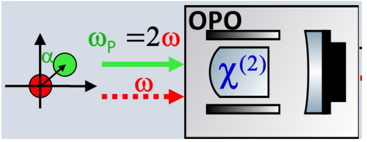


A complete squeezing source is much more complex than a simple OPO !

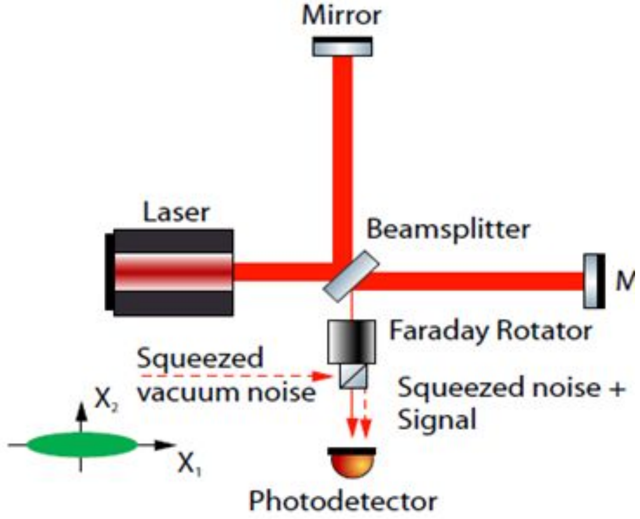
Phys. Rev. Lett. ***123***, 231108 (2019)

QN improvement in O3 with Frequency Independent Squeezing

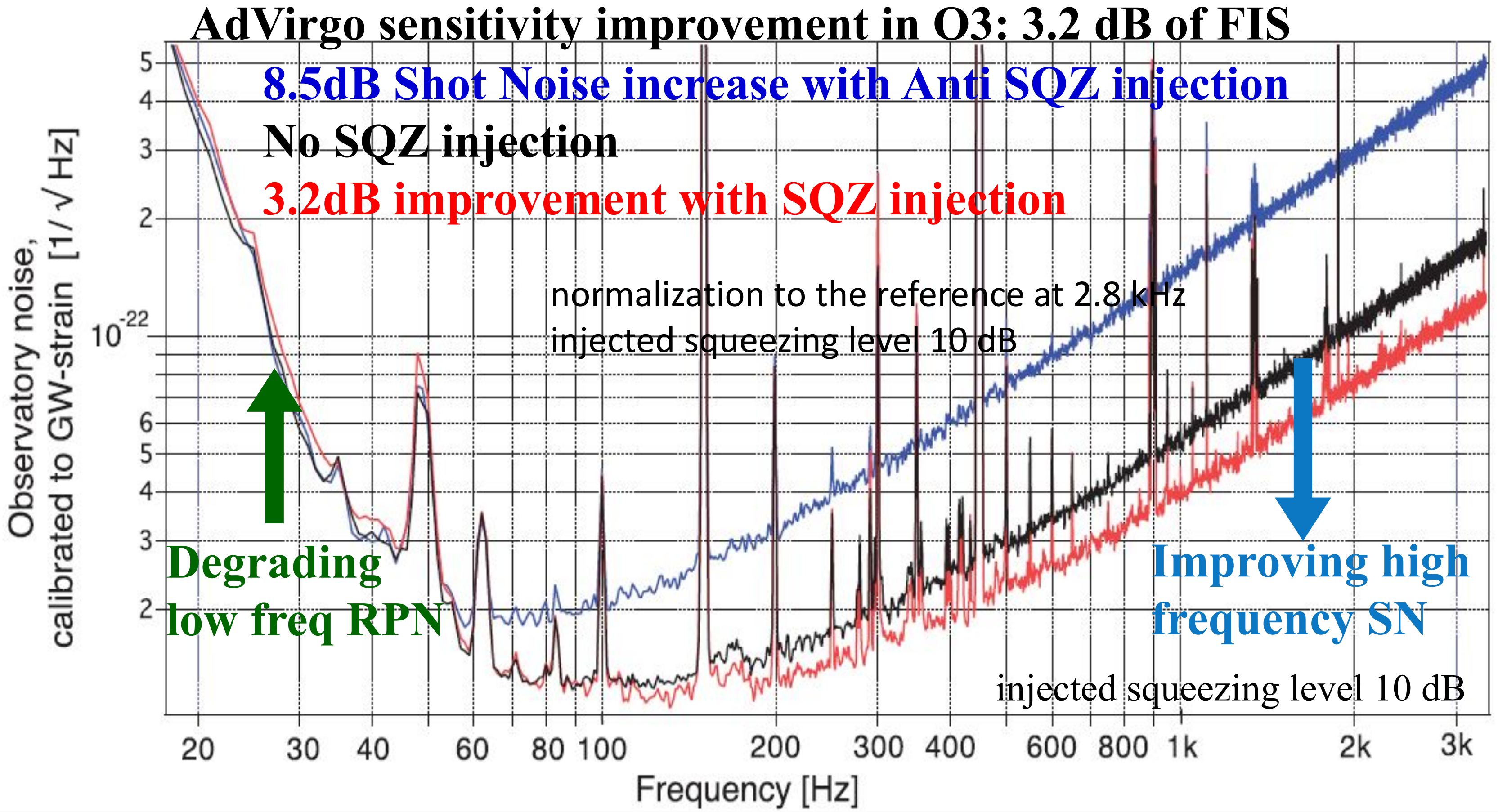
Phase squeezed vacuum field generated from an Optical Parametric Oscillator (OPO)



injected from the **dark port**
improved Shot Noise at high freq.
degraded Radiation Pressure Noise at low freq.



Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light, *Phys. Rev. Lett.* ***123***, *231108 (2019)* QRPN observed in AdV: *Phys. Rev. Lett* ***125***, *131101 (2020)*



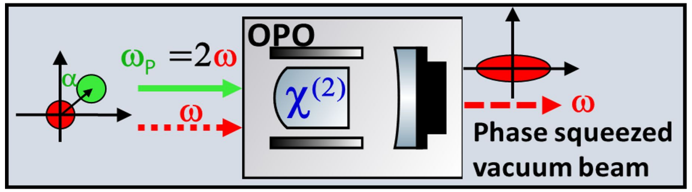
5% - 8% overall sensitivity improvement of the detector (BNS horizon)
16% - 26% BNS detection rate increase

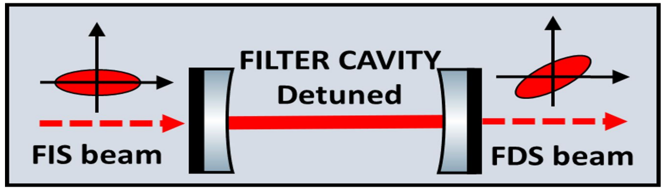
For broadband QN reduction → Frequency Dependent Squeezing (squeezing ellipse rotation)

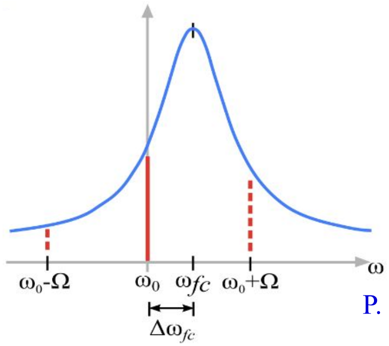
Frequency Dependent Squeezing: Filter Cavity (FC)

FIS squeezer with OPO

Filter Cavity







Detuning about half-bandwidth of arm cavity gives optimal compensation

P. Kwee, et al. *Phys. Rev. D*, 90, (2014)

Reflected FIS field acquires a freq. dependent phase shift

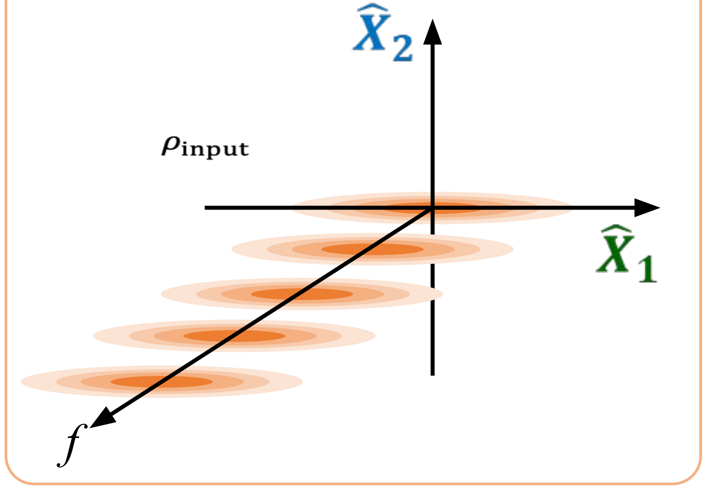
→ SQZ angle θ_{fc} rotation at freq Ω

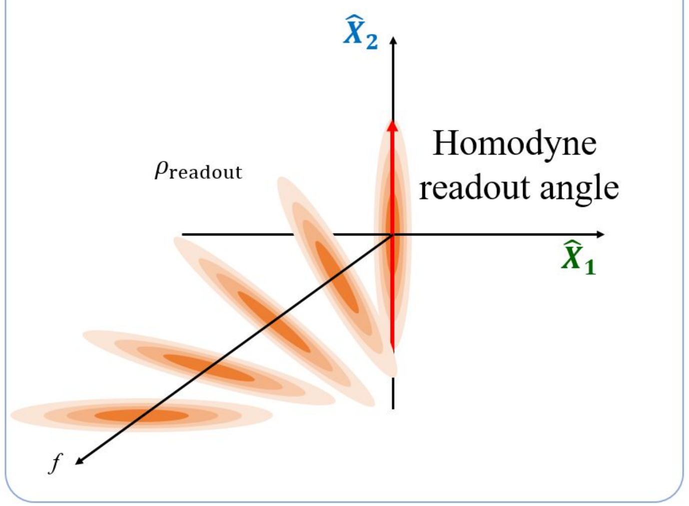
$$\theta_{fc}(\Omega) = arctg\left(\frac{2\,\gamma_{fc}\,\Delta\omega_{fc}}{\gamma_{fc}{}^2 - \Delta\omega_{fc}{}^2 - \Omega^2}\right)$$

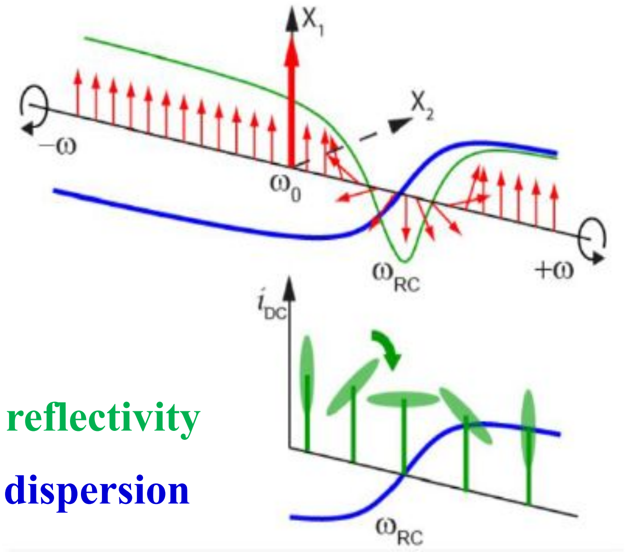
FC resonance $\omega_{fc} = \omega_0 + \Delta\omega_{fc}$

Linewidth γ_{fc} = FWHM/$\mathcal{F}$

Detuning $\Delta\omega_{fc}$







FP-cavity reflectivity

FP-cavity dispersion

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

- **2022-2023: Filter Cavity in in Advanced Virgo+ → cavity length L=285 m**

F. Acernese et al. (Virgo Collaboration) H. Vahlbruch, M. Mehmet, H. Luck and K. Danzmann, "Frequency-Dependent Squeezed Vacuum Source for Advanced Virgo Gravitational-Wave Detector" *Physical Review Letters* 131 (2023): 041403. *https://doi.org/10.1103/PhysRevLett.131.041403*

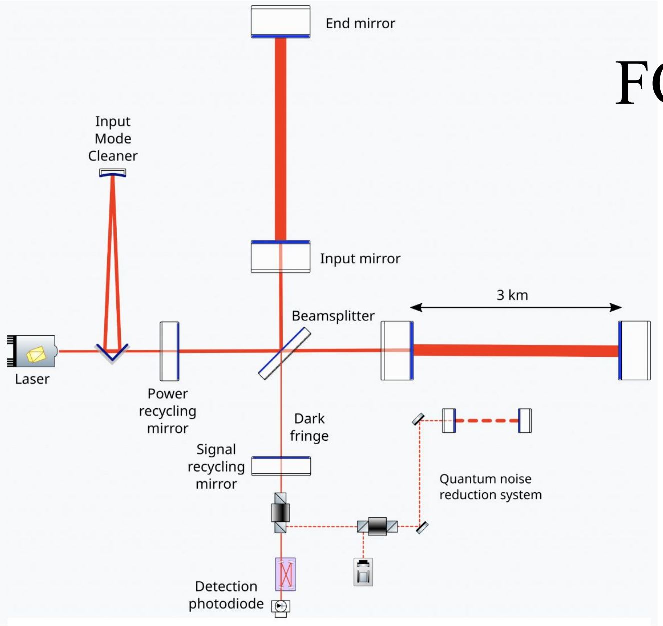
8.5 dB of generated squeezing up to 5.6 dB QN suppression measured at high freq., 2dB close to FC resonance frequency (due to intracavity losses).

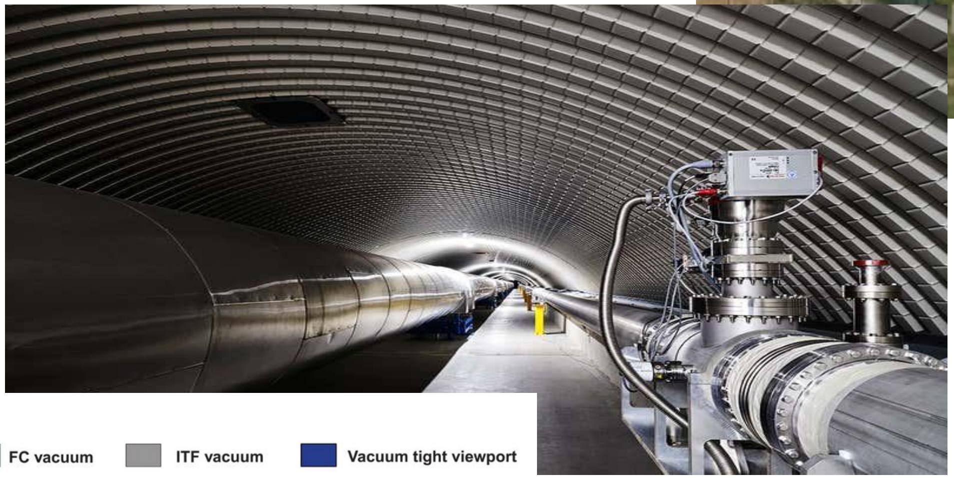
Frequency Dependent Squeezing in Advanced Virgo+: Filter Cavity

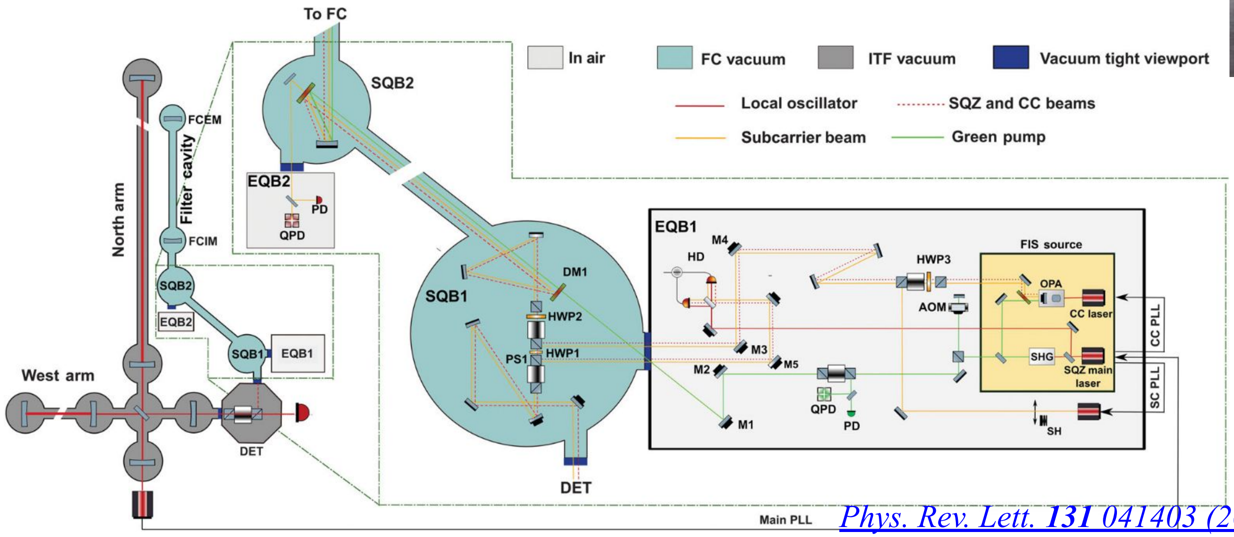
AdV+ required squeezing angle rotation: 20-30 Hz → Need for a cavity linewidth of the same order

Cavity Length L=285 m

FC parallel to the ITF North Arm







Phys. Rev. Lett. **131** 041403 (2023)

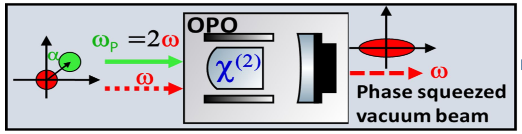
The cavity must be **detuned** with respect to the frequency of the squeezed beam:

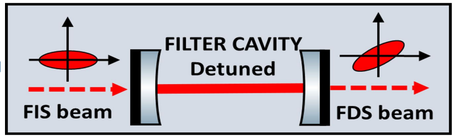
- Locking with an external IR laser (Sub Carrier)
- Locking with green (F=100 @ 532 nm)

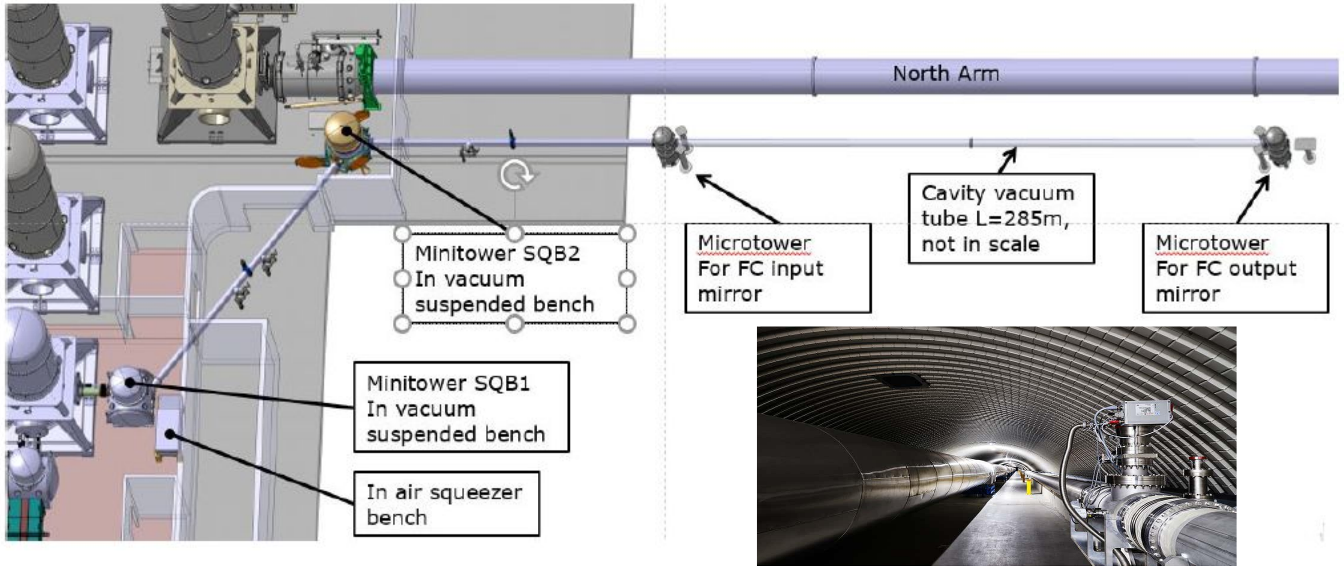
FDS in AdVirgo+ for O4: Filter Cavity

INFRASTRUCTURE for FC installed along North Arm

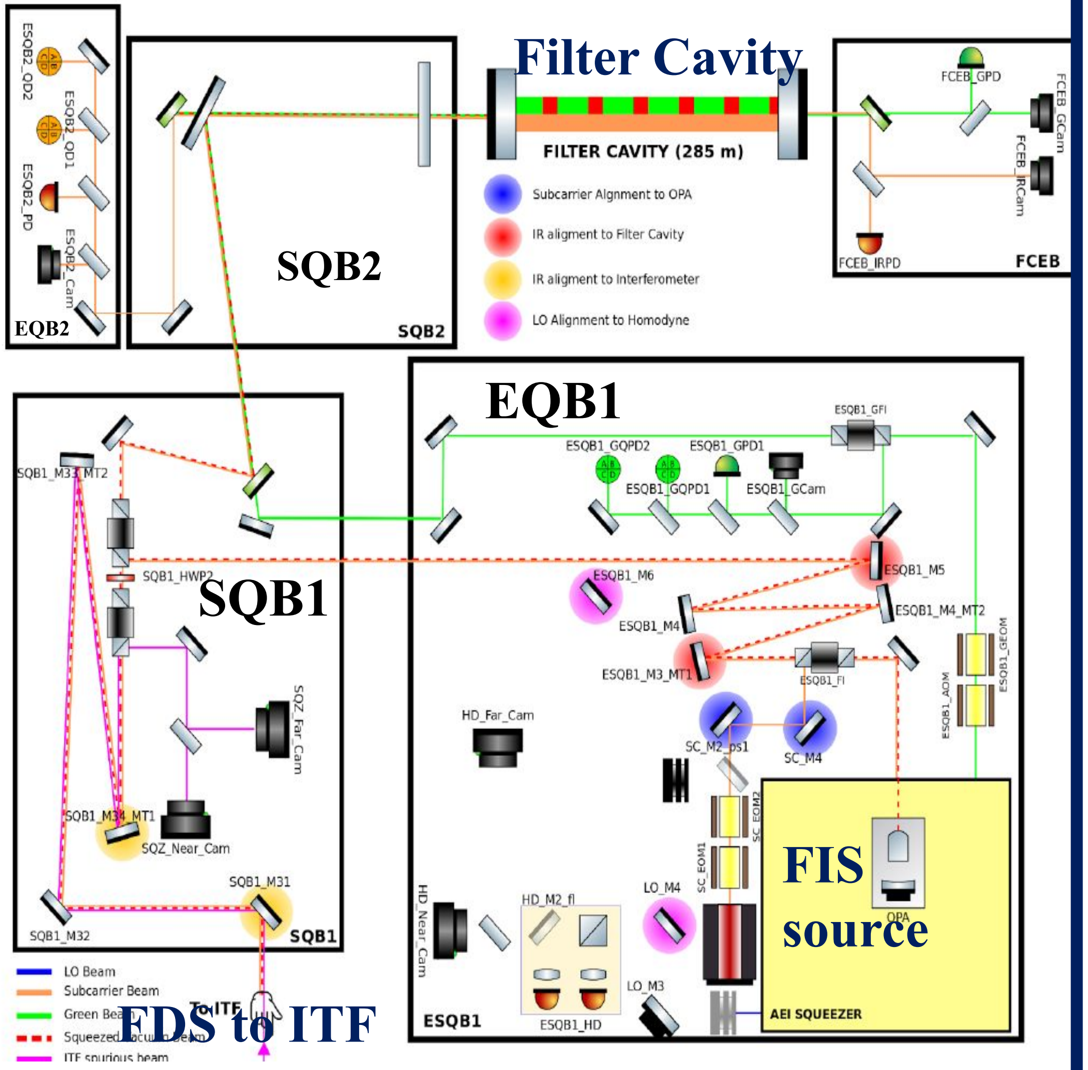
FIS squeezer with OPO + Filter Cavity







Optical in air and suspended in vacuum benches for connecting FC with ITF and FIS source



FC main features:

- Length 285 m
- mirrors diameter 150 mm
- RoC of mirrors 558 m
- finesse 11000 (1064 nm)
- finesse 100 (532 nm)
- SQZ angle rotation at 20-30Hz
- round-trip losses < 40 ppm

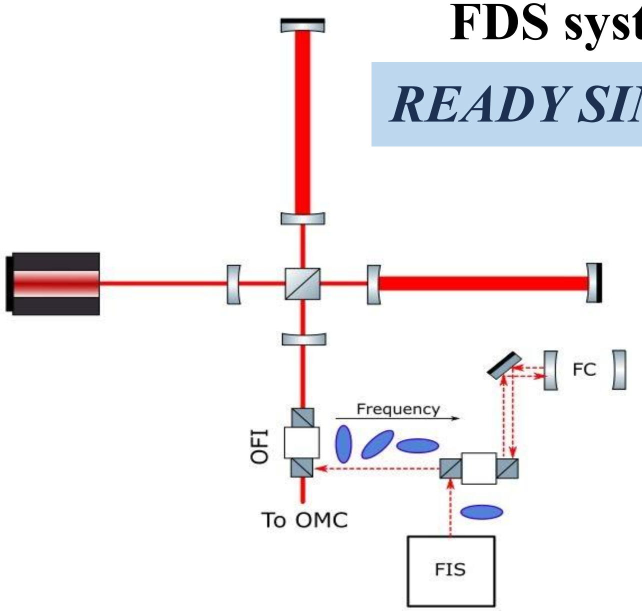
FDS in AdVirgo+ for O4: Filter Cavity

FDS system installed in 2020-21 during Covid-19 pandemic

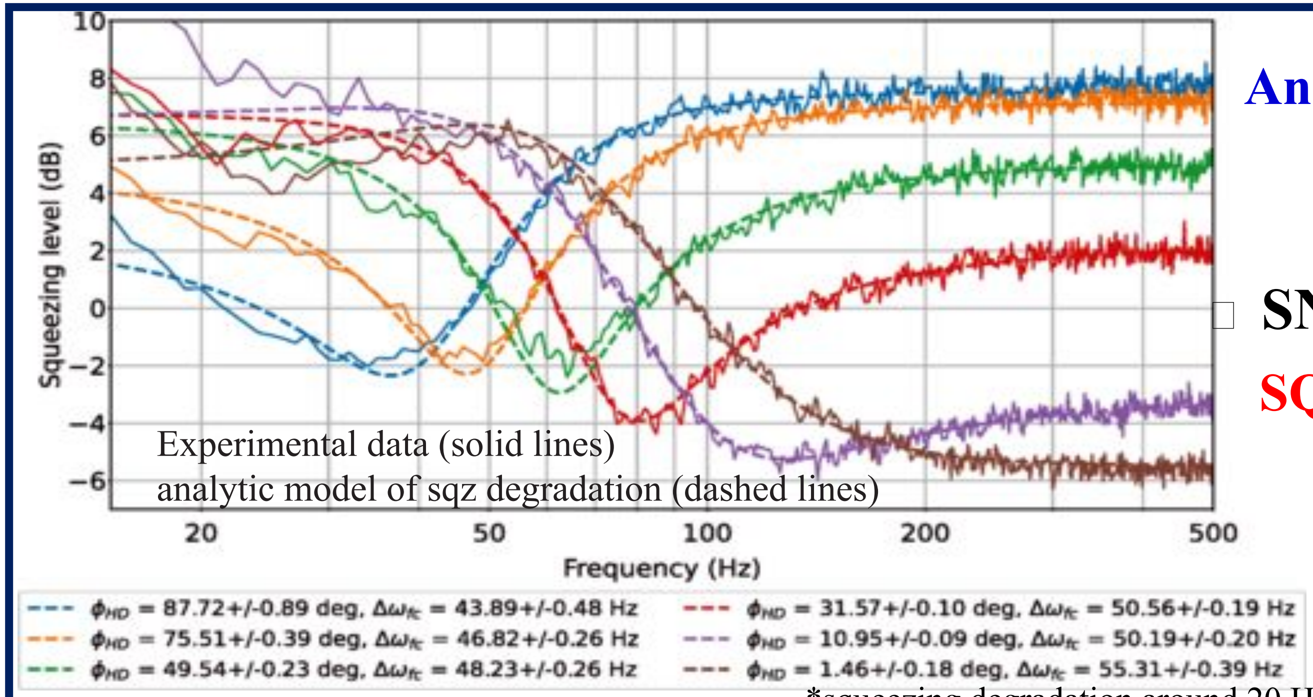
READY SINCE 2021

FDS successfully tested as a stand-alone system!

Paper published: FDS Vacuum Source for Advanced Virgo Gravitational-Wave Detector, *Phys. Rev. Lett.* ***131*** *041403 (2023)*



Degradation parameter	Measured value	O4 design
Injection losses (%)	10 ± 1	13
FC round-trip losses (ppm)	50–90	60
Mode mismatch SQZ-FC (%)	1.5 ± 1	2
Phase noise—rms (mrad)	30 ± 20	40
FC length fluctuation—rms (Hz)	~1	1



Anti-SQZ

SN level

SQZ

Measurements done by varying LO-SQZ beams phase difference, FC detuning (44-55) Hz

*squeezing degradation around 20 Hz due to stray light issues

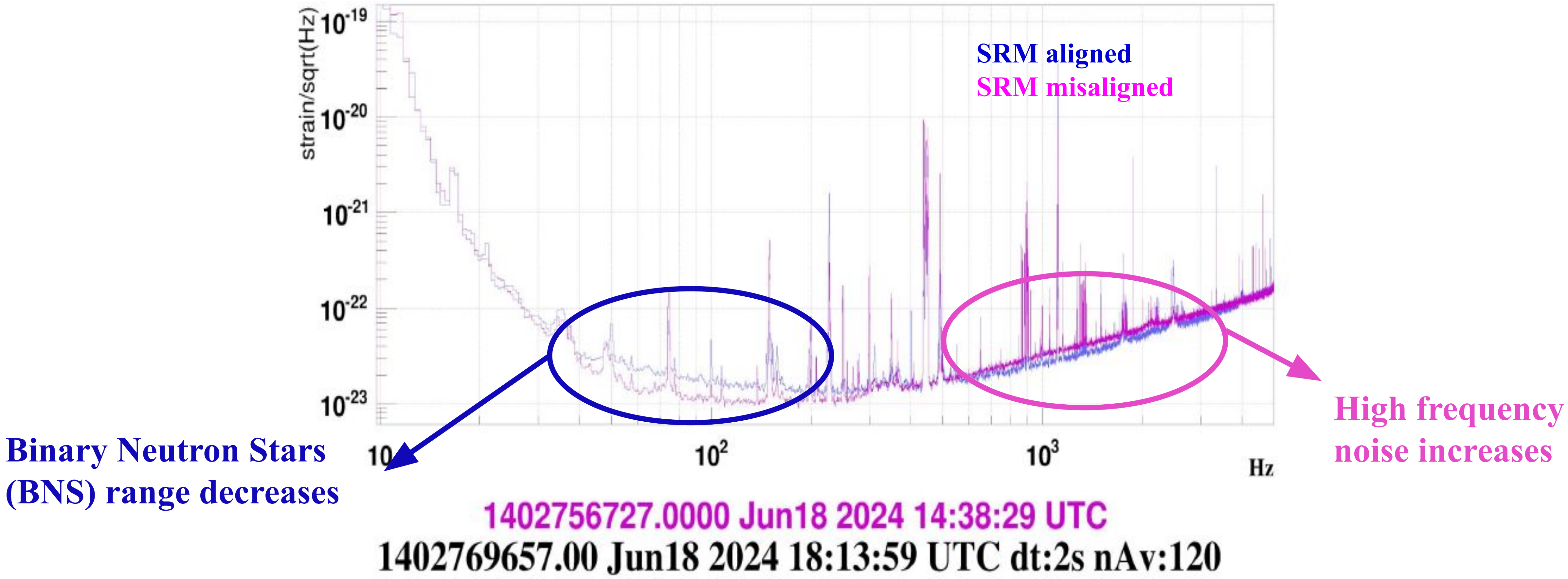
In AdV+ we expect a reduction of:
- up to 4.5 dB for the Shot Noise
- 2 dB for the Rad. Press. Noise

With 8.5 dB of SQZ generated, we measured:
up to 5.6 dB QNR at high freq. and 2dB QNR close to FC resonance

Up to 9% BNS and BBH detection range → 29% increase in volume of observable Universe

Squeezing in Virgo during O4

At present, AdVirgo+ sensitivity is affected by a mystery $1/f^{2/3}$ noise.
In order to reshape the sensitivity curve the signal recycling mirror (SRM) has been misaligned by 2 μrad.

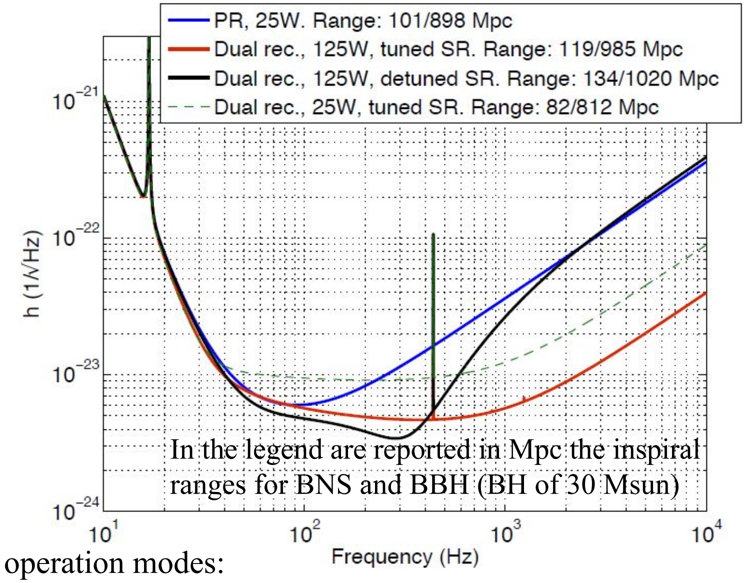


losses originated from SRC degeneracy affect the squeezing performances

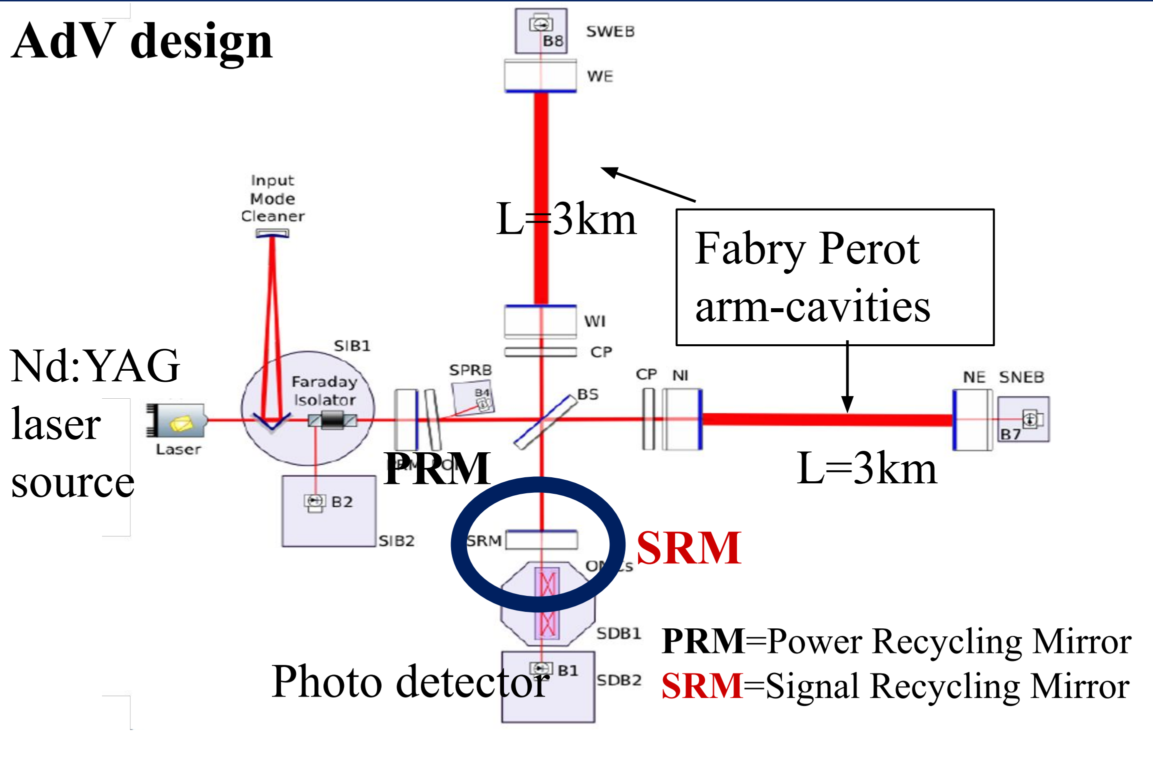
Signal Recycling Mirror (SRM) installed for O4

Tuning SRM parameter changes the sensitivity curve shape, optimizing it for different astrophysical sources

- changing SRM transmissivity → influences ITF **bandwidth**
- tuning SRM position → changes the **freq. of max. sensitivity**



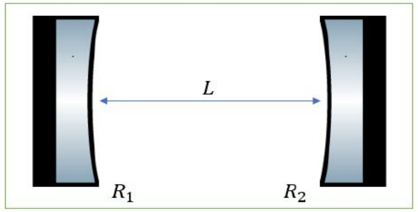
In the plot 4 different operation modes:
- **power recycled, 25 W** no SR
- **dual recycled, 125 W**, wideband SR tuning
- **dual recycled, 125 W,** detuned SR optimized for BNS inspiral range
- **dual recycled, 25 W,** tuned SR



…but recycling cavities are «marginally stable»

Stability condition

$$0 < \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) < 1$$



An optical cavity is **marginally stable** when this product is near to one of the limits of this interval.

Squeezing in Virgo during O4

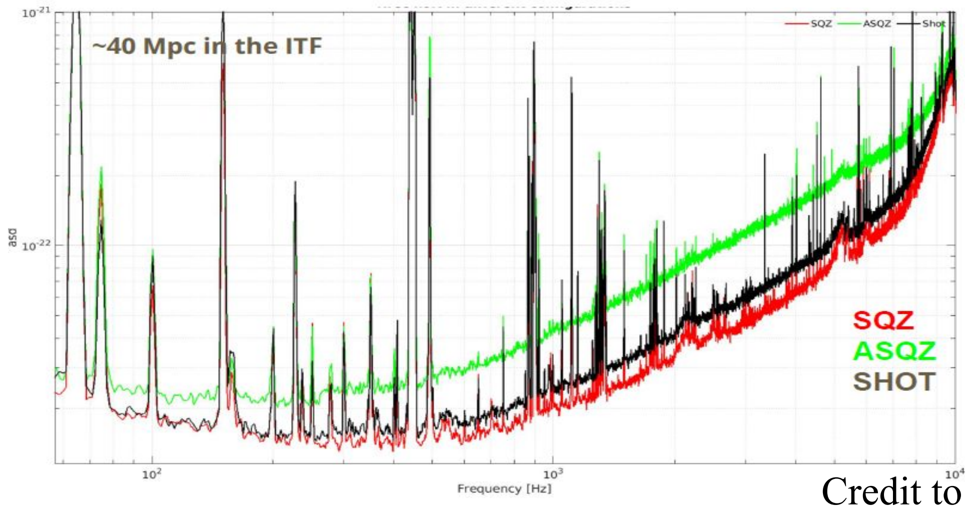
AdVirgo+ commissioning in O4 difficult due to marginally stable recycling cavities (PR+SR):

- **HOMs** (high order modes) resonating and amplified in PR and SR cavities
- **Input beam noises transmission**
- **ITF contrast degradation**
- **FDS squeezing not exploited:** losses originating from the SRC degeneracy also affect the squeezing performances due to the beam shape mismatch between the SQZ beam injected from the dark port and the ITF output beam. We measured losses: (2.40 ± 0.01) %. This problem was not found during O3 when SRM was not present.

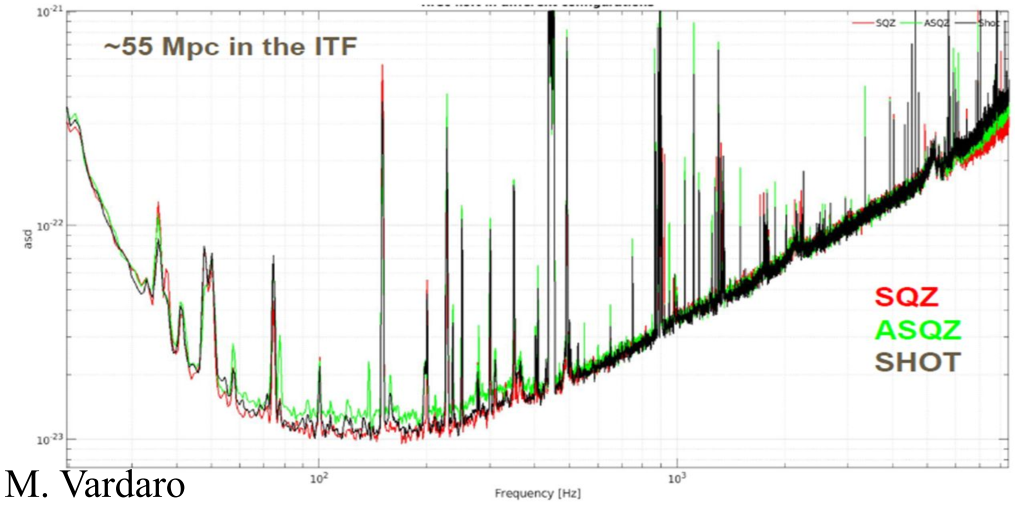
These issues worsen as the power is increased → reaching design value of AdVirgo input power (125W) impossible

The squeezing efficiency improves with SRM aligned, decreases with SRM misaligned

Signal Recycling Mirror aligned



Signal Recycling Mirror mis-aligned



Credit to M. Vardaro

On April 10th 2024 AdVirgo+ joined O4b run with SRM misaligned to increase BNS range

Not possible to use FDS, but Frequency Independent Squeezing (FIS) injected

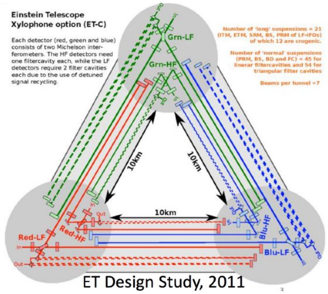
Sensitivity increased by 2-3 Mpc (5% overall sensitivity improvement in BNS horizon) with FIS injected

Third generation of GW detectors: Einstein Telescope (ET)

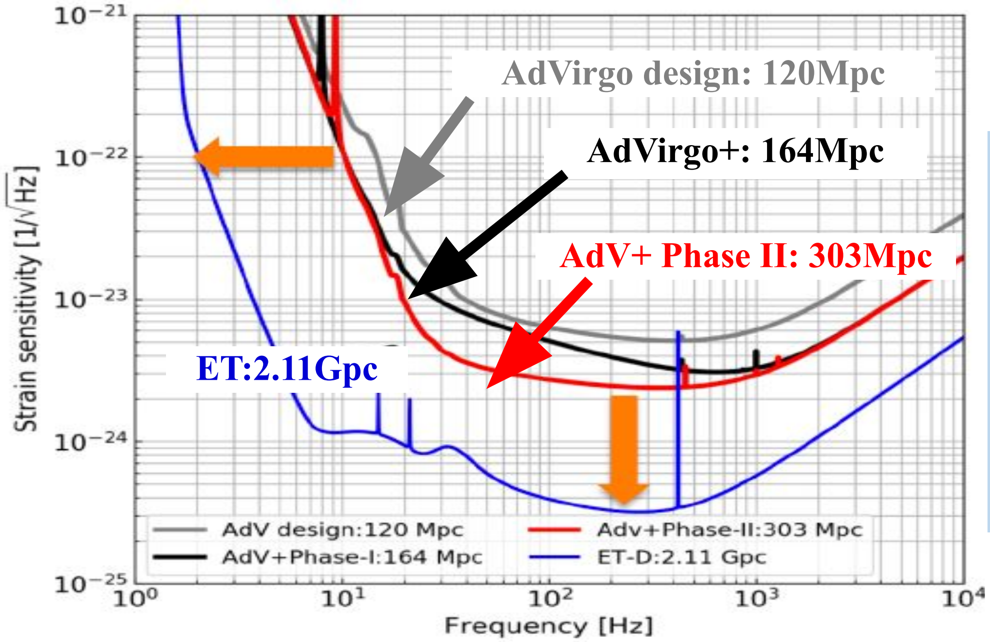
Target: 10^5 to 10^6 events/year

Expected detectable sources:
Merging BH throughout the whole universe and reconstruct BH demography
Investigate primeval universe and connections with particle physics

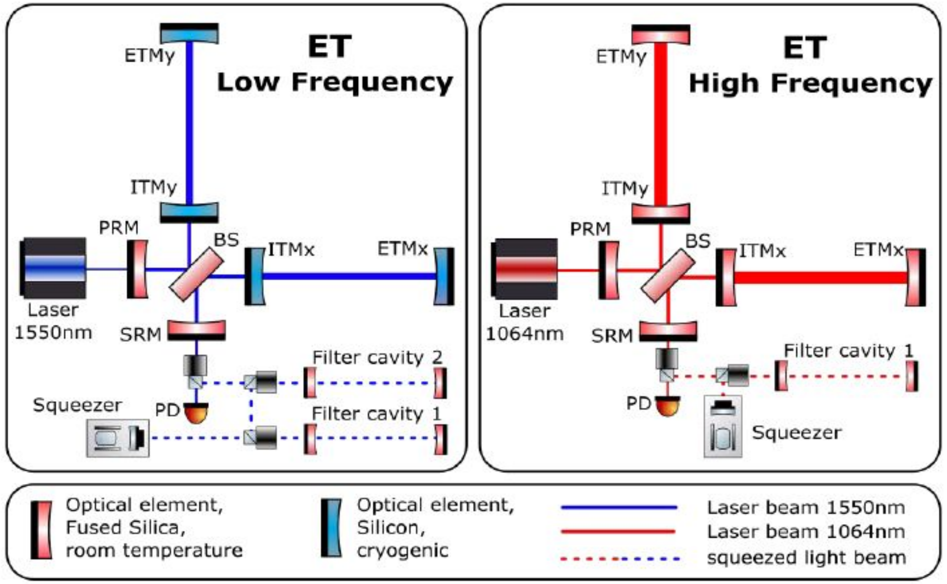
- **Equilateral triangle configuration= 3 detectors**
- **Arm cavities 10km long**
- **Underground (300m)**
- **Cooled mirrors (10K)**



Quantum Noise limited in all freq band



With FC technology
ET LF: 2 FCs
ET HF: 1 FC
Tot 9 FCs
each few km-long and underground!

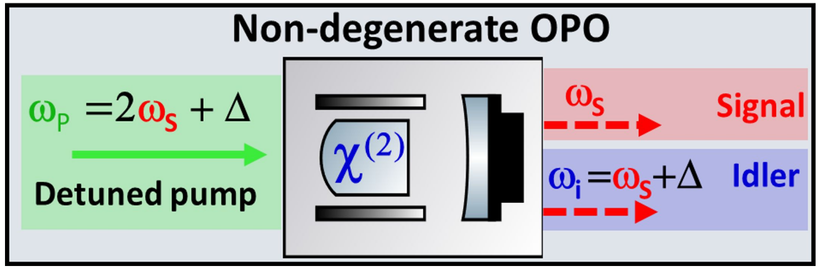


Important to develop more compact Quantum Noise Reduction Techniques

ET design report update 2020 ("long ESFRI document"), ET-0007A-20
Science Case for the Einstein Telescope, arXiv:1912.02622

FDS via Einstein Podolsky Rosen (EPR) quantum entanglement

De-tuned pump into non degenerate OPO produces
***Signal* and *idler* squeezed beams: EPR entangled**



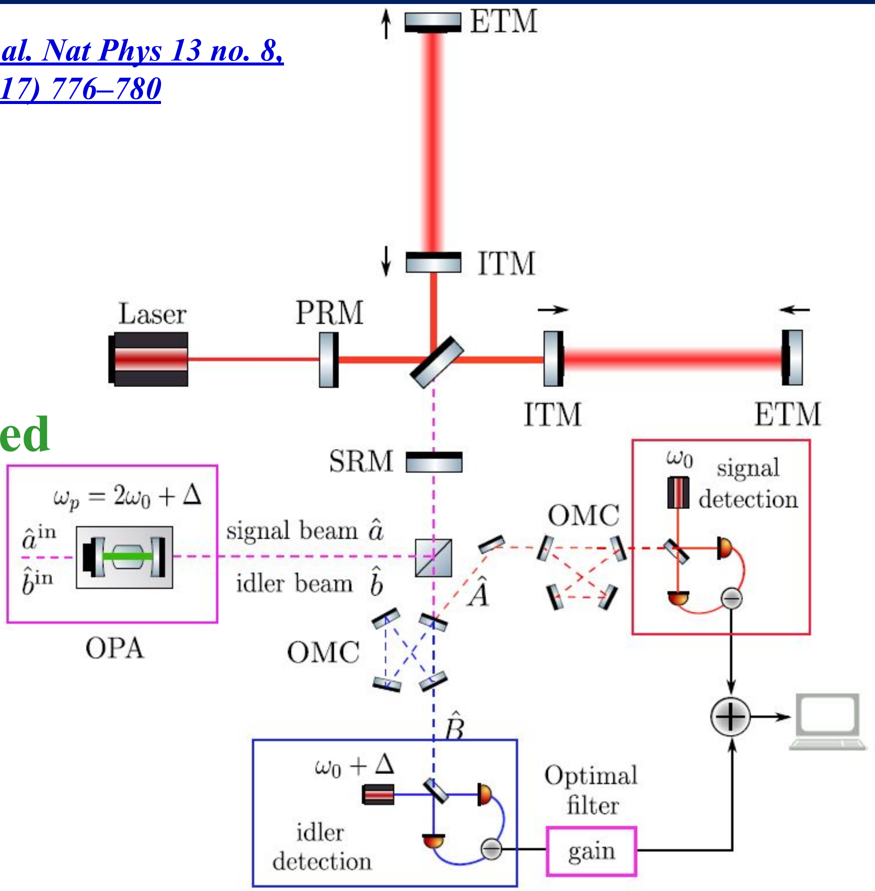
Signal and ***idler***
both injected into
ITF dark port

ITF acts like a Filter Cavity for idler: ITF de-tuned for the ***idler*** ($\omega_0 + \Delta$), so ***idler*** experiences ***FDS***

Combined measurement via twin HDs transfers the freq.-dependance of ***idler*** to the ***signal*** via EPR entanglement

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

De-tuned pump



Advantages wrt Filter Cavity

Less expensive, more compact setup*

Avoids the 1ppm/m round trip losses for the FC

More flexible vs Signal Recycling Cavity ITF configuration

*FC not required: EPR **is cheaper and more compact setup for QNR in GW detectors**! These benefits are even larger for the future generation GW detectors such as the Einstein Telescope.

Disadvantages wrt Filter Cavity

Two squeezed beams: double losses

2 Homodyne Detectors, Extra OMC

3dB intrinsic losses

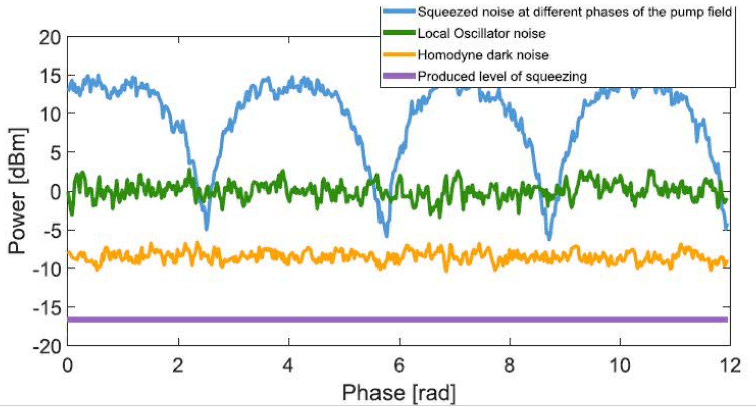
See F. De Marco's poster

EPR experiment: R&D for Virgo and ET

Our **FIS** (OPO-based) setup at Virgo R&D SQZ lab:
Automated source of squeezed vacuum states driven by finite state machine based software, *Rev. Sc. Instr. 92054504 (2021)*

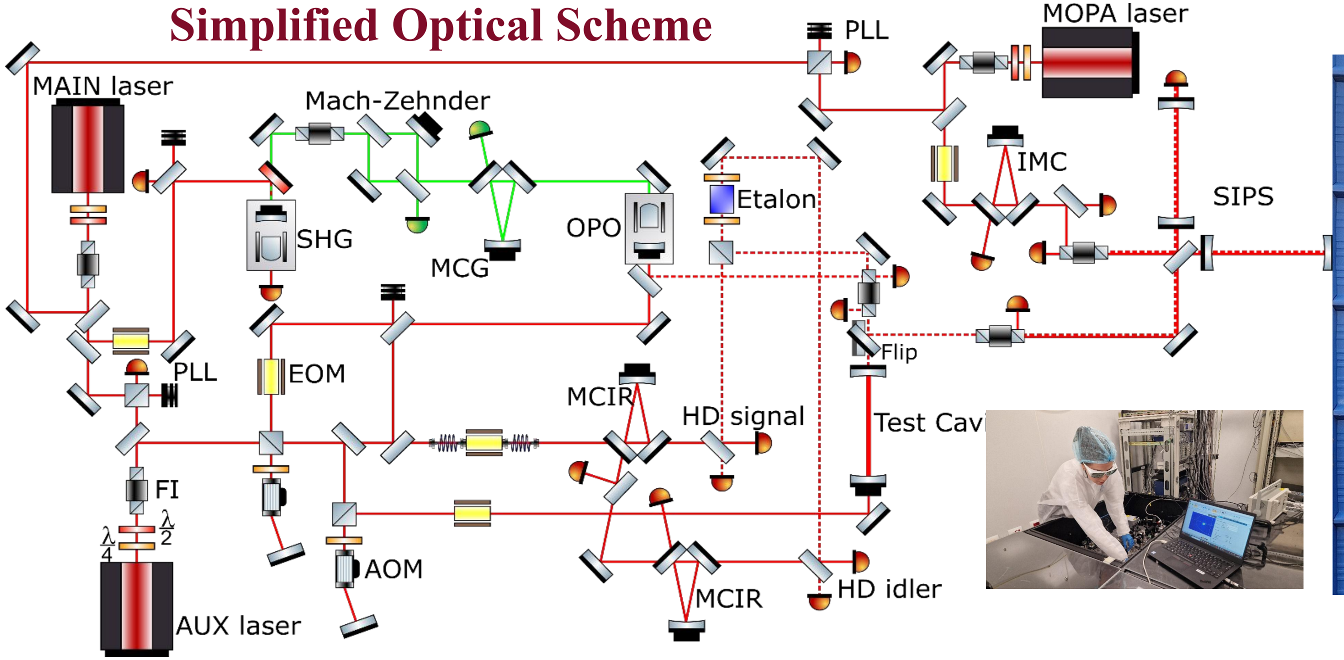
- Measured 6 dB of SQZ, 15 dB of anti-SQZ @ 1 MHz
- New control techniques with finite state machines

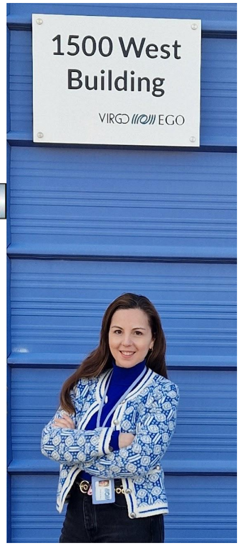
Since end 2022 under upgrade into an **EPR setup**



- **Novelty: inject EPR SQZ into SIPS** small-scale suspended ITF RPN-limited in the same freq. band of Virgo
- **SIPS suitable demonstrator of EPR principle before possible integration in large scale GW detectors**
- Expected QN reduction < 2 kHz

Simplified Optical Scheme





International collaboration (20 people):

- INFN branches/Univ.: RM1, NA, GE, PG
- South Korean Institutions: KASI, KHU, Yonsei Univ., KAIST (since 2019)

S. Di Pace et al. presented @ GRASS2019, IASS2022, ICNFP2022, GWADW2023
published @ https://doi.org/10.5281/zenodo.3569196

Conclusions and perspectives

- **FIS in O3 improved the astrophysical reach: 5-8% in BNS horizon 16- 26% BNS detection rate** *Phys. Rev. Lett.* ***123***, *231108 (2019)*
- **For broadband GW detectors sensitivity improvement Frequency Dependent Squeezing (FDS) required**
- **Filter Cavity (FC) is the technology now adopted in Virgo and LIGO**
- **FDS in Virgo is ready since 2021 and successfully tested as stand-alone system** *Phys. Rev. Lett.* ***131*** *041403 (2023)*
- **FDS squeezing not exploited in O4:** losses originating from the SRC degeneracy affect squeezing performances (beam shape mismatch between the SQZ beam injected from the dark port and the ITF output beam)
- **SRM "mis-aligned" to improve BNS range, FDS could not be exploited, but with FIS injected 2-3 Mpc improvement (about 5% in BNS horizon)**
- **New more efficient and compact FDS setups must be developed and tested for future generation detectors such as Einstein Telescope**
- **Einstein Podolsky Rosen (EPR) quantum entanglement squeezing is the most promising alternative to Filter Cavity**

Thanks For Your Attention

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