Rencontres des Jeunes Physicien·ne·s – Collège de France

Reducing quantum noise in gravitational-wave detectors

using squeezed states of light

November, 29th 2019

Catherine Nguyen

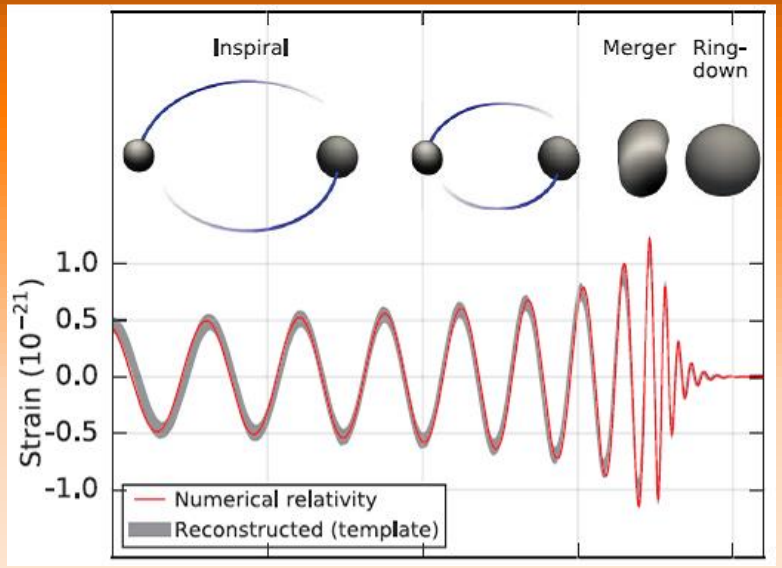
On behalf of Virgo Collaboration (EPR-squeezing collaboration)

(APC – INFN)

Outline

- **Introduction : gravitational-waves detection**
- **Sensitivity and quantum noise**
- **Squeezing techniques to reduce quantum noise**

First direct detections ever !



GWs are ripples in the fabric of spacetime induced by accelerating bodies.

- Strain : $h = \frac{\Delta L}{L}$

- **GW150914 - September, 14th 2015 : first detection ever!**

- First direct detection by LIGO network
- 100 years after Einstein's predictions

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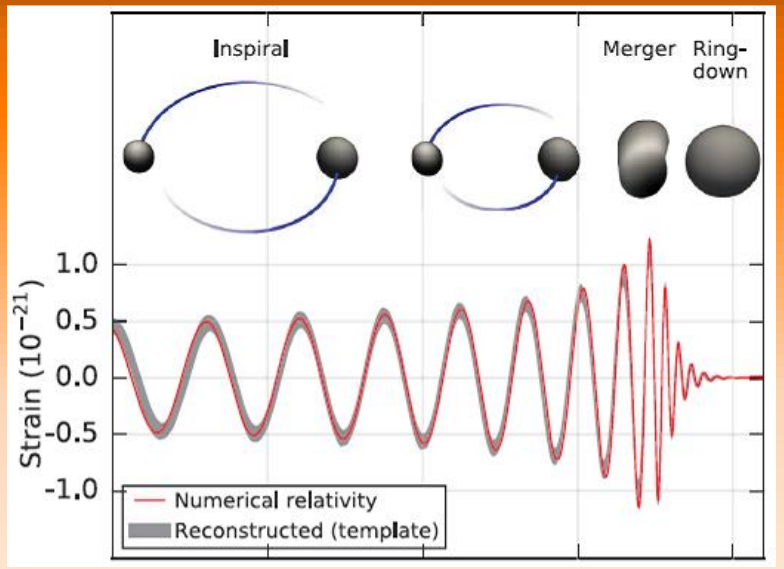

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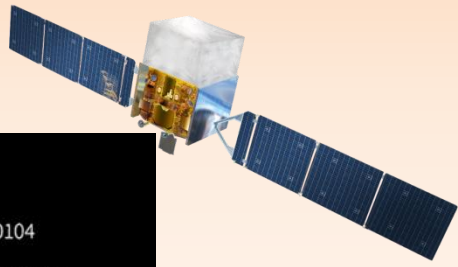
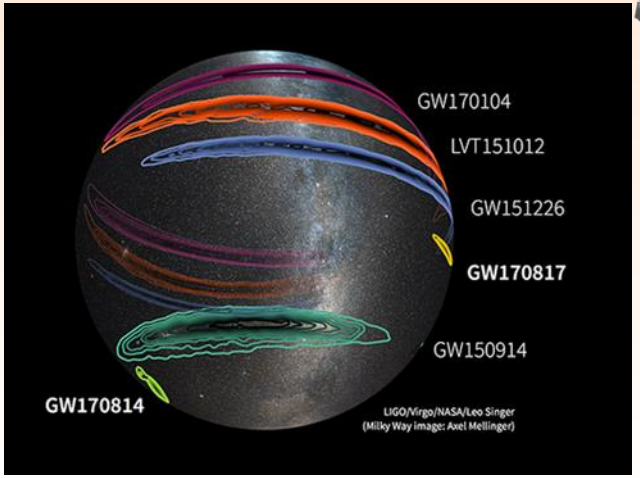


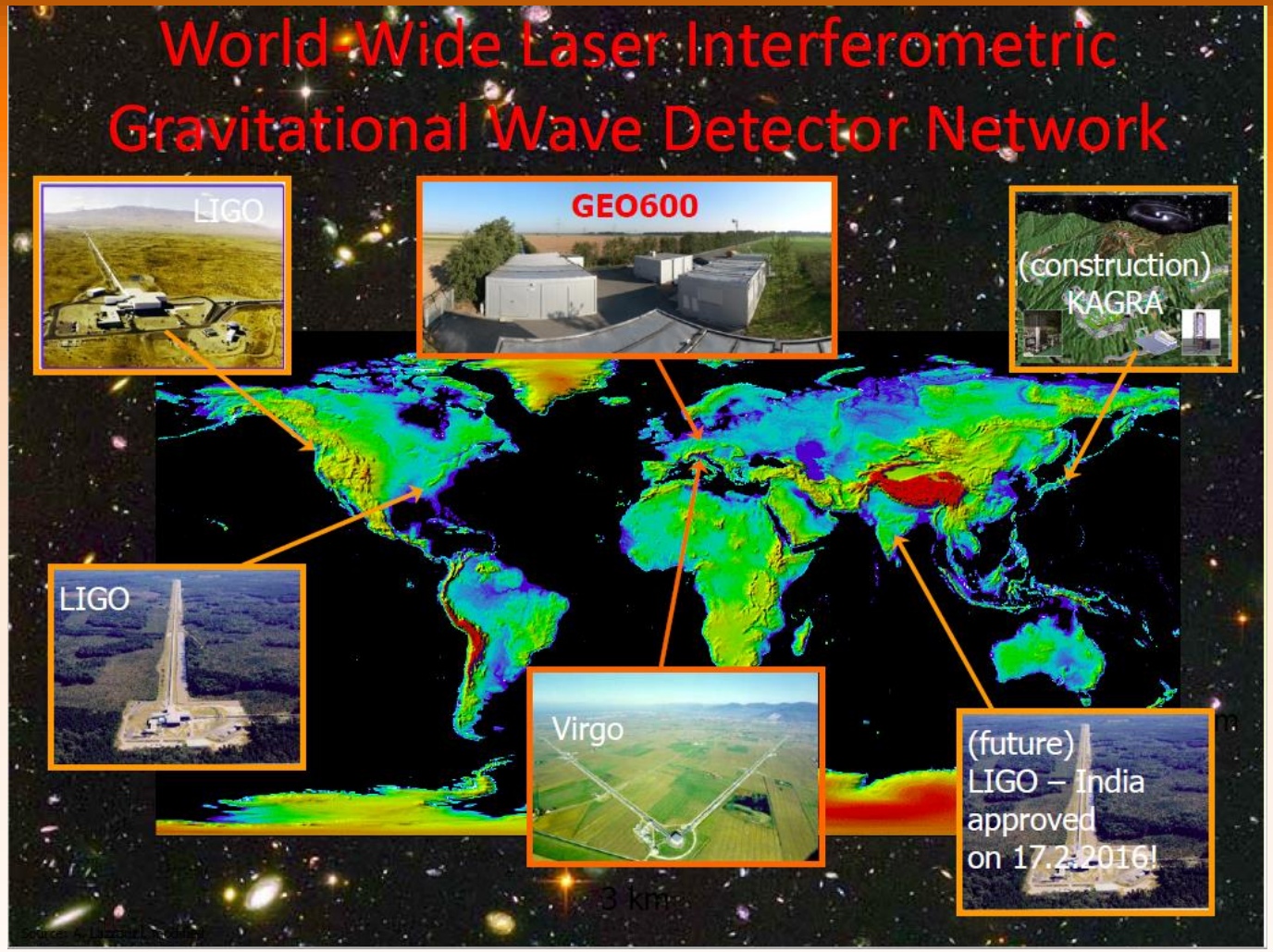
- **August, 17th 2017: historical event GW170817**

❑ First detection of a neutron stars coalescence, by 3 detectors

❑ First event ever with electromagnetic counterpart and gamma rays bursts thanks to the localization precision



Ground-based Gravitational-wave detectors



Internal Final Presentation – ESA http://sci.esa.int/lisa/

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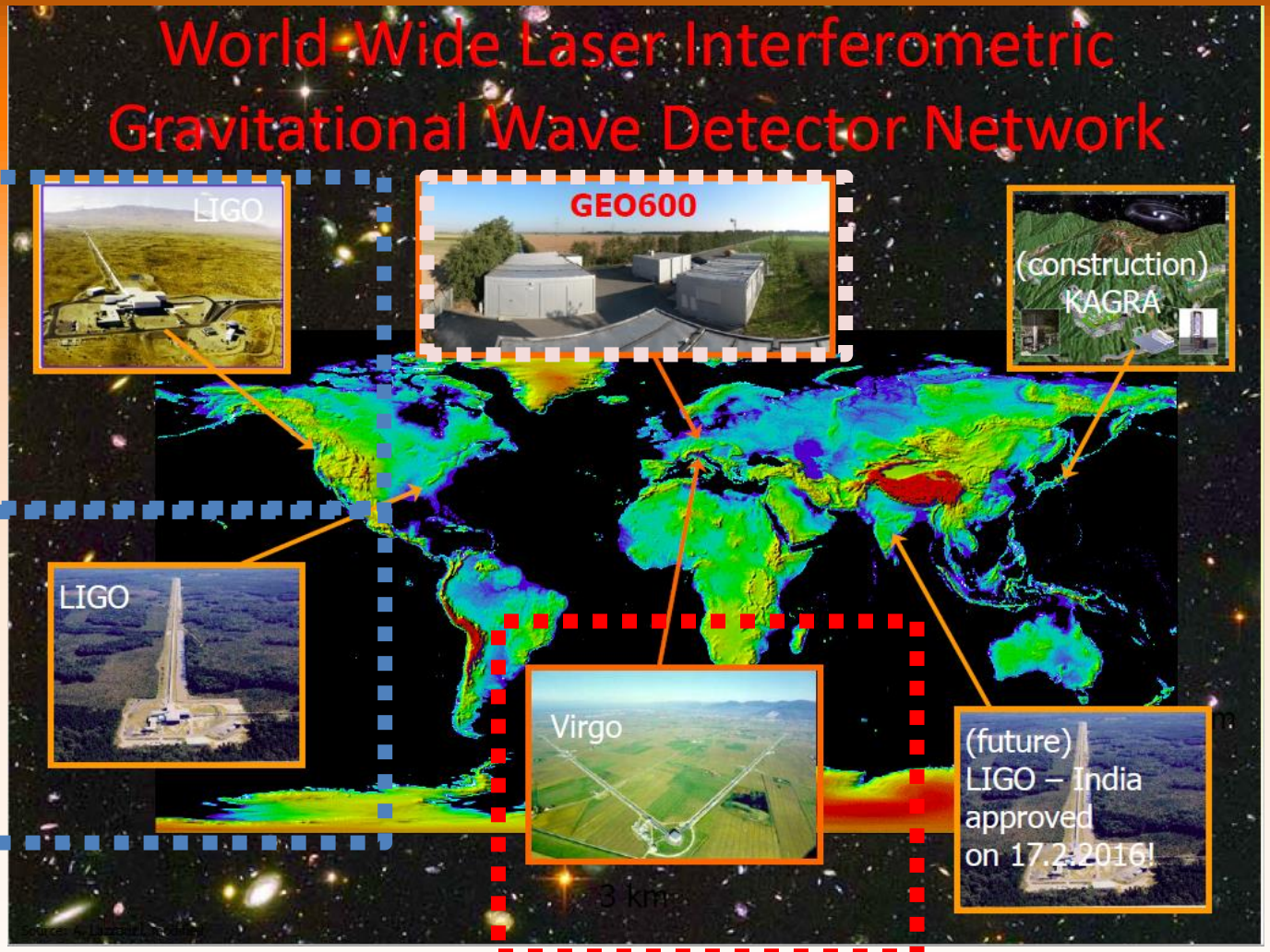

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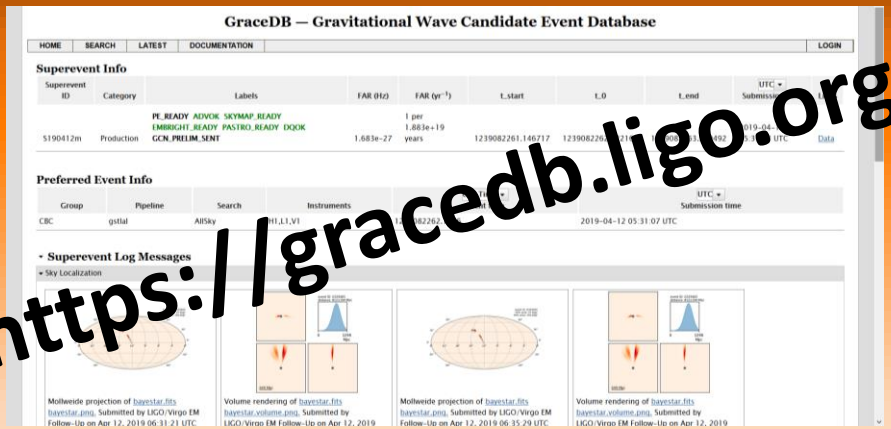
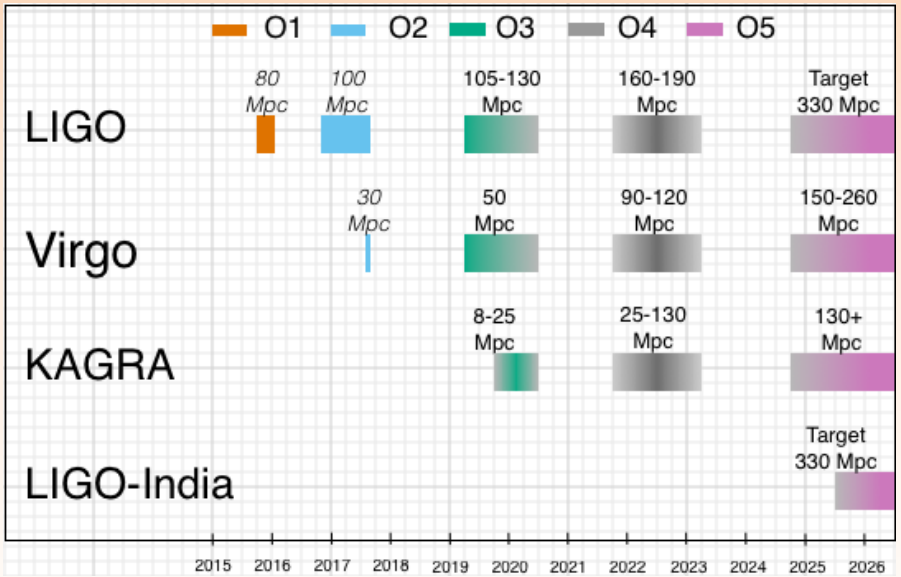
Observation Run O3 and future

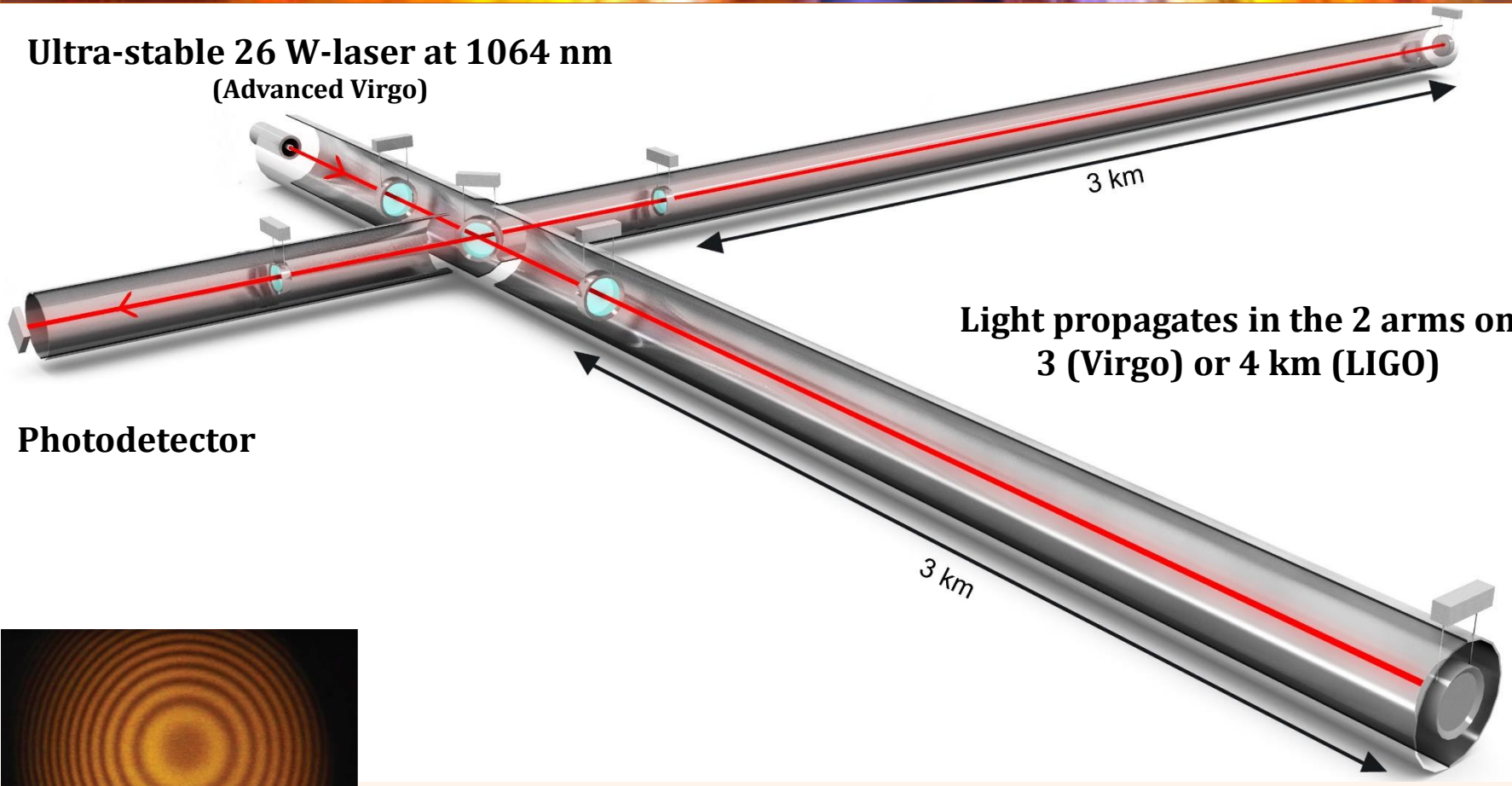


- O3 starts on April, 1st
- Public alert
- Roughly 1 alert/week



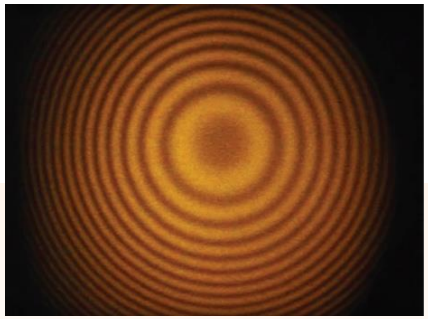
Laser interferometry : LIGO and Virgo detectors

Ultra-stable 26 W-laser at 1064 nm
(Advanced Virgo)



Light propagates in the 2 arms on 3 (Virgo) or 4 km (LIGO)

Photodetector



Interference figure

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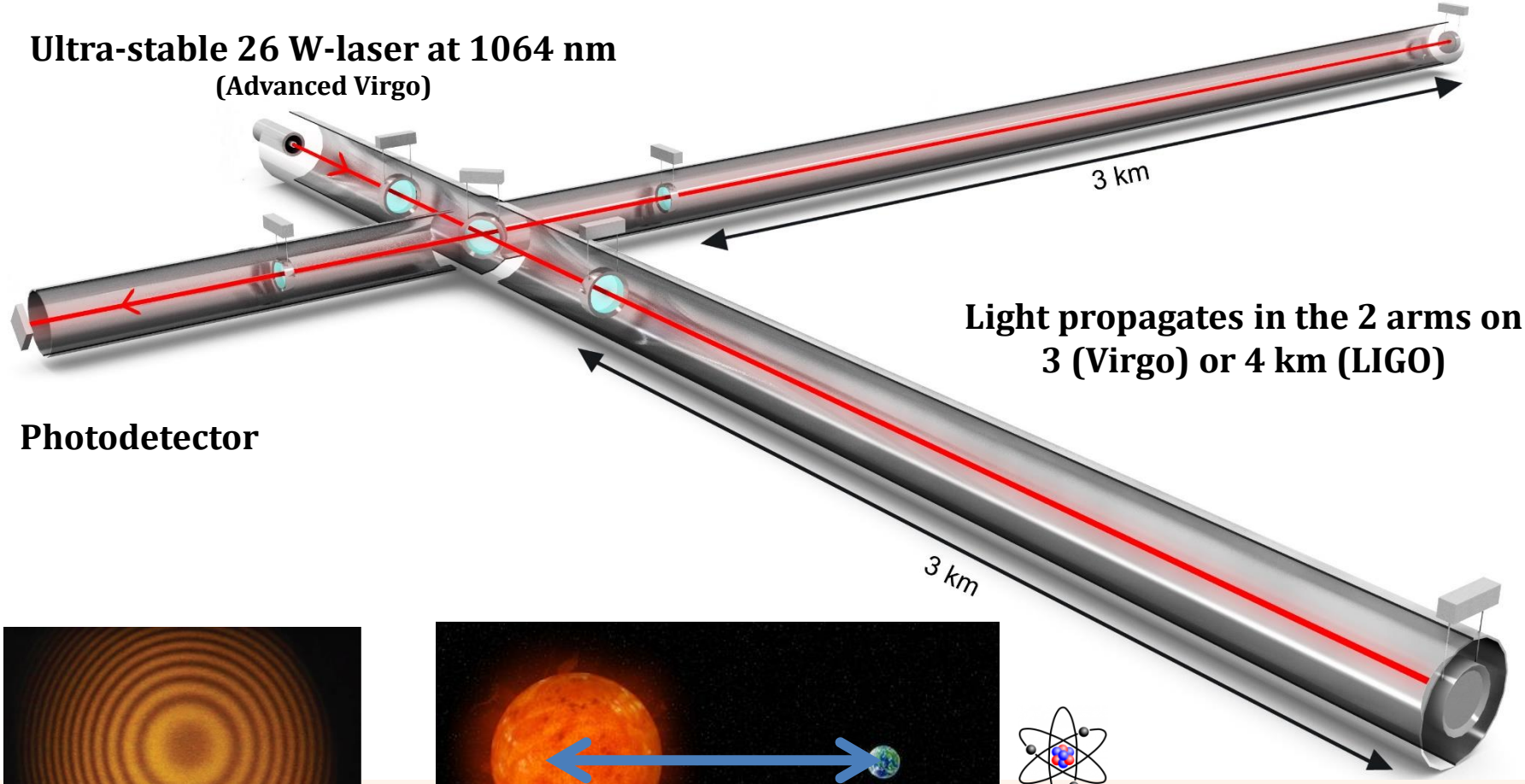

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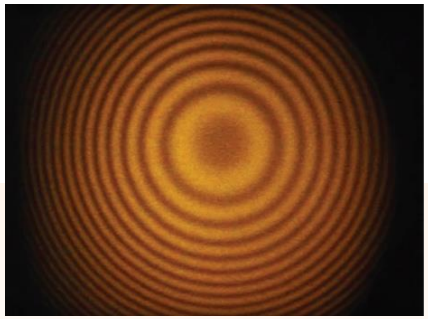

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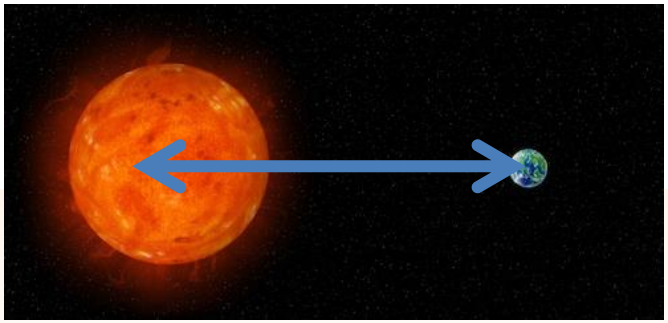
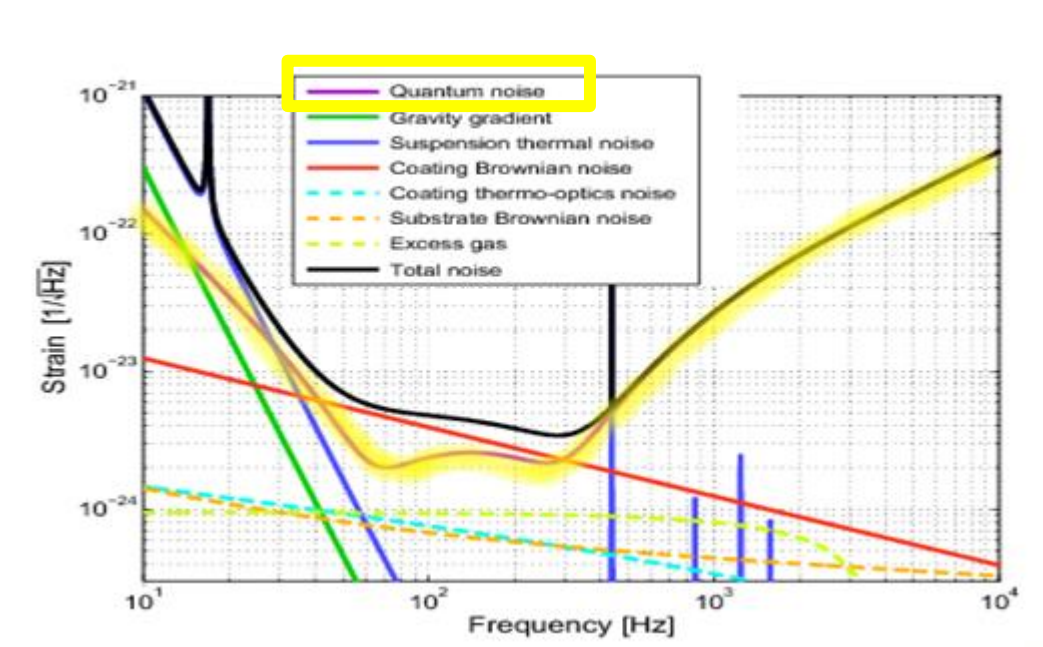


$h \sim 10^{-21}$!

Noise budget and quantum noise



Advanced Virgo sensitivity curve.

- **Quantum noise (QN) is one of the major sources of noise.**

Heisenberg uncertainty principle

At low frequency

Radiation pressure noise

does not limit the current Advanced Virgo sensitivity

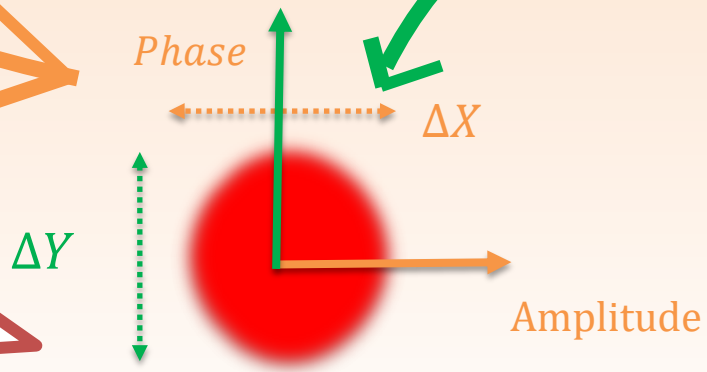
At high frequency

Shot noise

Limits the sensitivity at f > 400 Hz

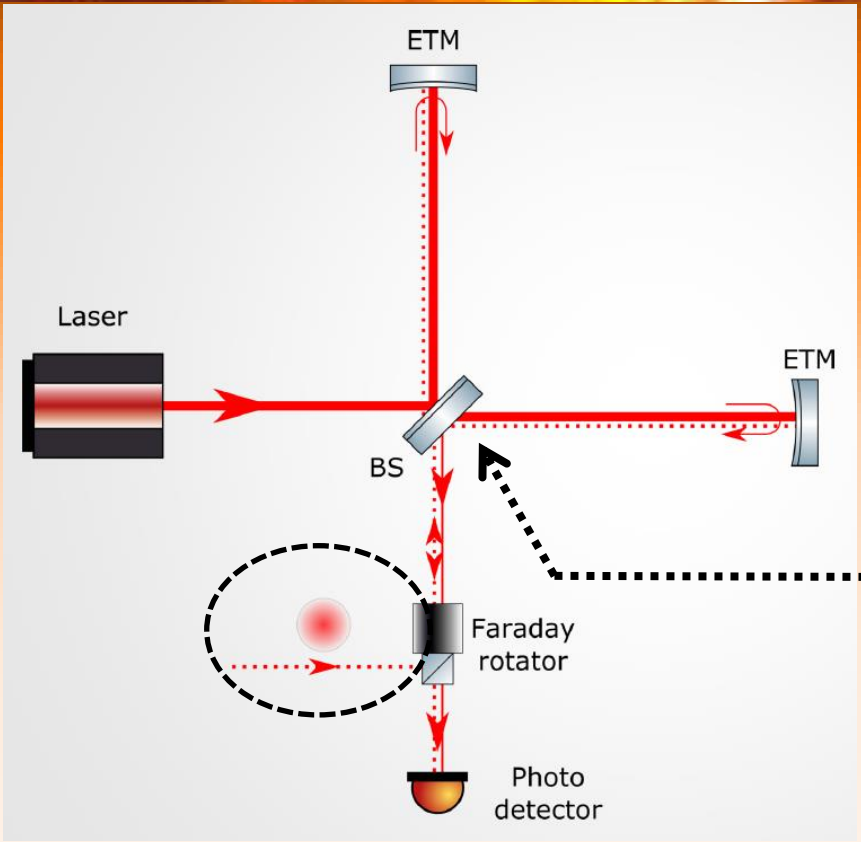
$$(\Delta X)^2(\Delta Y)^2 \geq \frac{1}{16}$$

➢ **A multiplicative limit !**



Quantum fluctuations in quadrature space

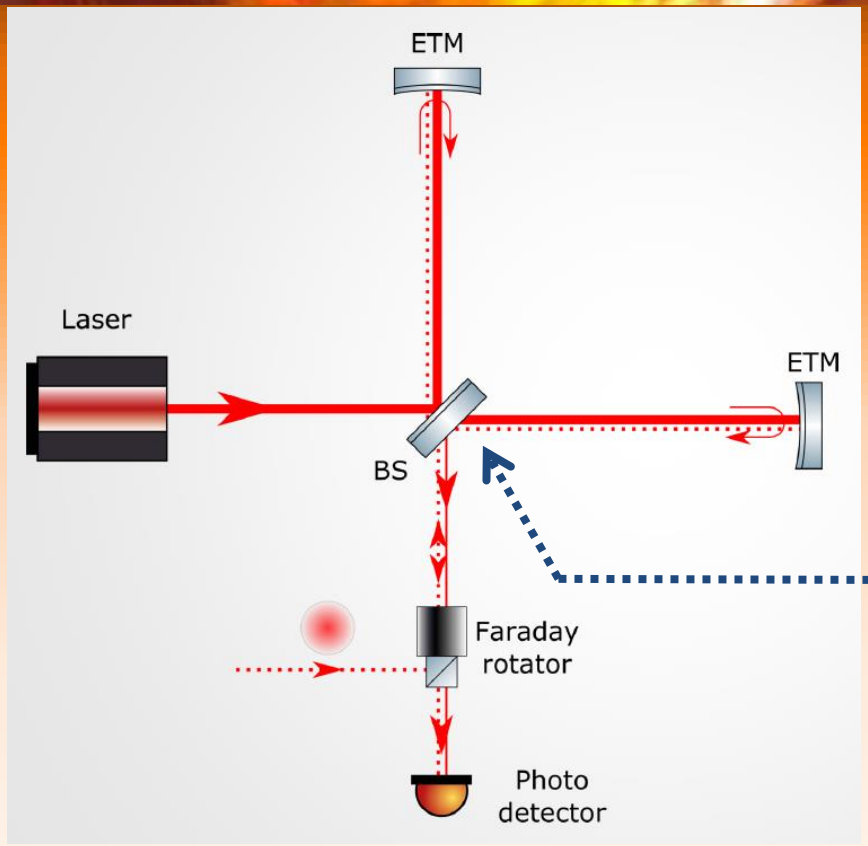
Origin of quantum noise

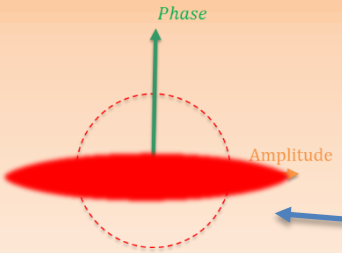


Quantum noise is due to *vacuum fluctuations* entering the *dark port* of the interferometer

Credit : Jan Gniesmer & Min Jet Yap

Solution : squeezing !

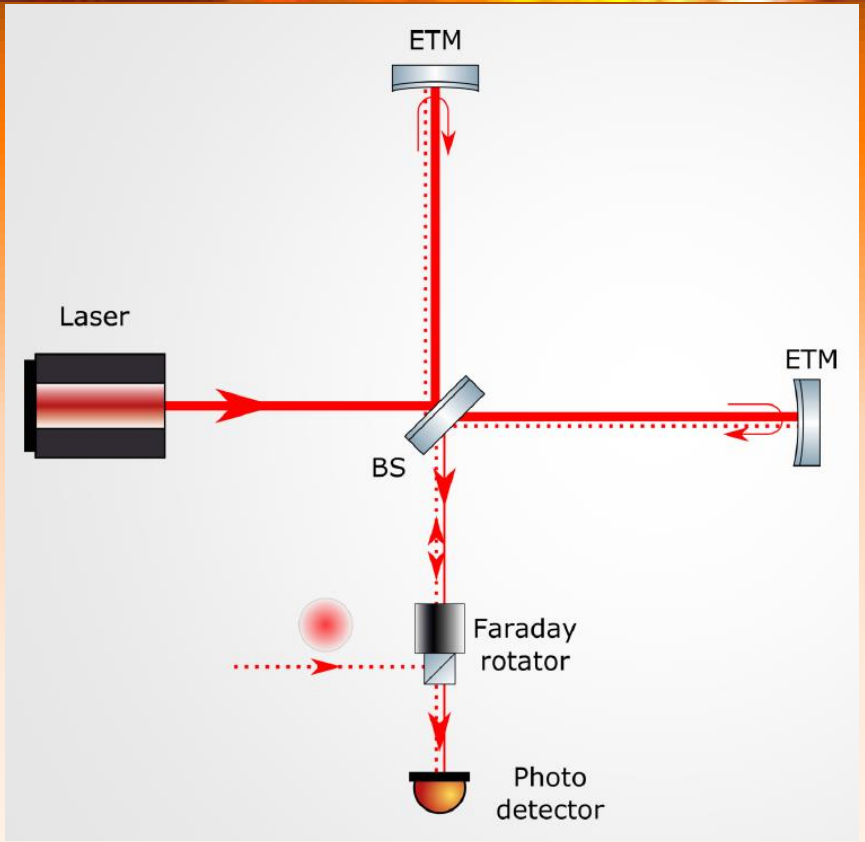


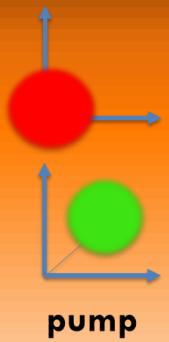


squeezing ellipse

Credit : Jan Gniesmer & Min Jet Yap

Frequency-independent squeezing (FIS)





vacuum

ω_0

$\omega_p = 2\omega_0$

pump

Non-linear optics

Credit : Jan Gniesmer & Min Jet Yap

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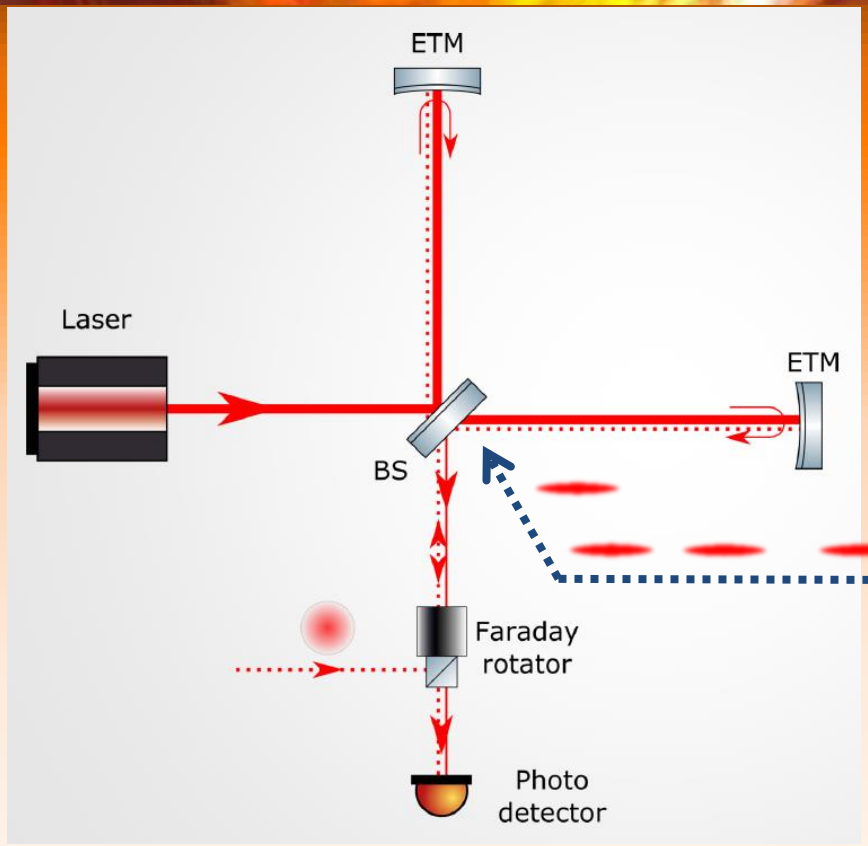
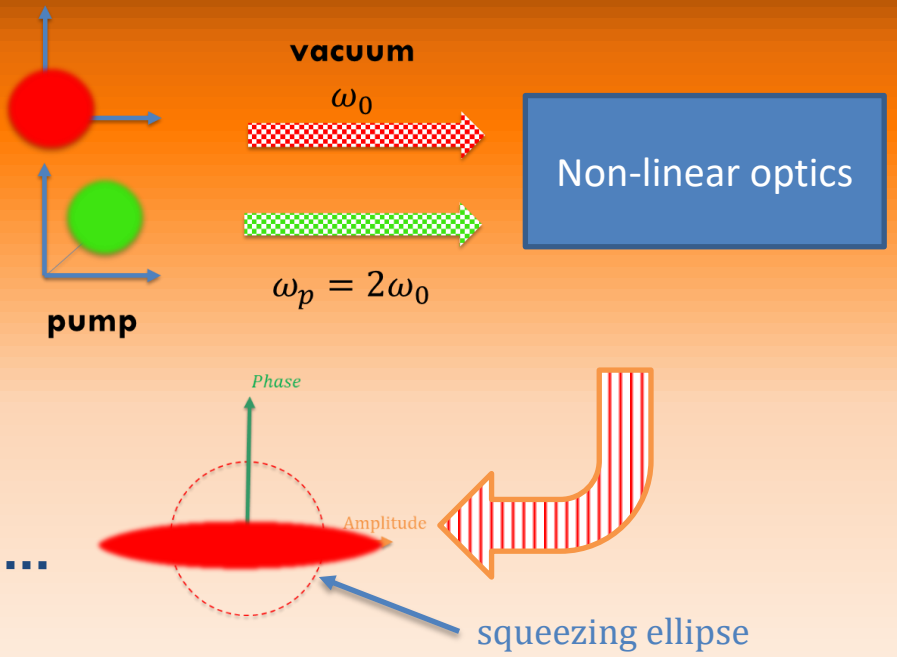
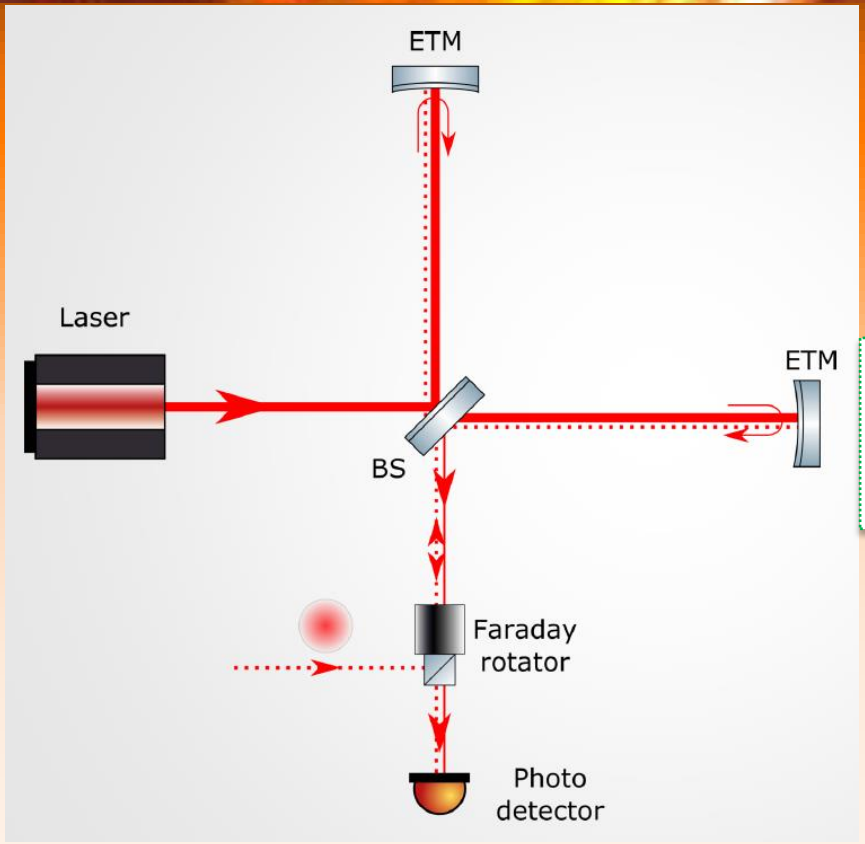




Jan Gniesmer & Min Jet Yap, GWADW 2019

PHASE-SQUEEZED VACUUM

Frequency-independent squeezing (FIS)



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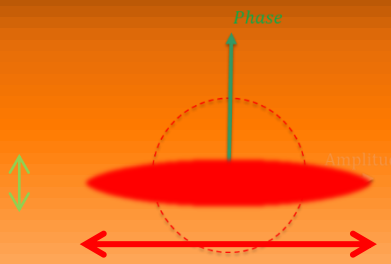


Shot noise

RPN

= Anti-squeezing

Sensitivity improvement

- **Advanced Virgo : 3.1 dB**
- **Advanced LIGO : L 3.1 dB, H 2.2 dB**
- **GEO 600: 6 dB**

Radiation pressure noise will limit...

- **Radiation pressure noise** will limit the future upgrade of Advanced Virgo.

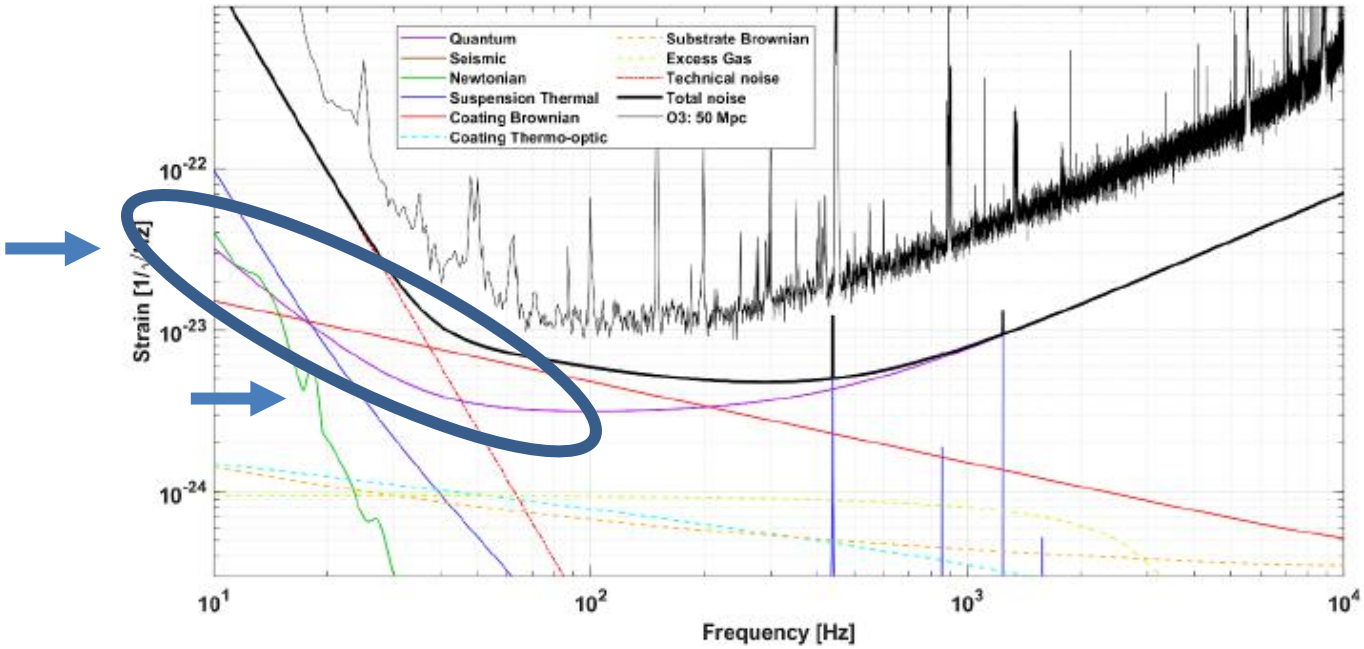
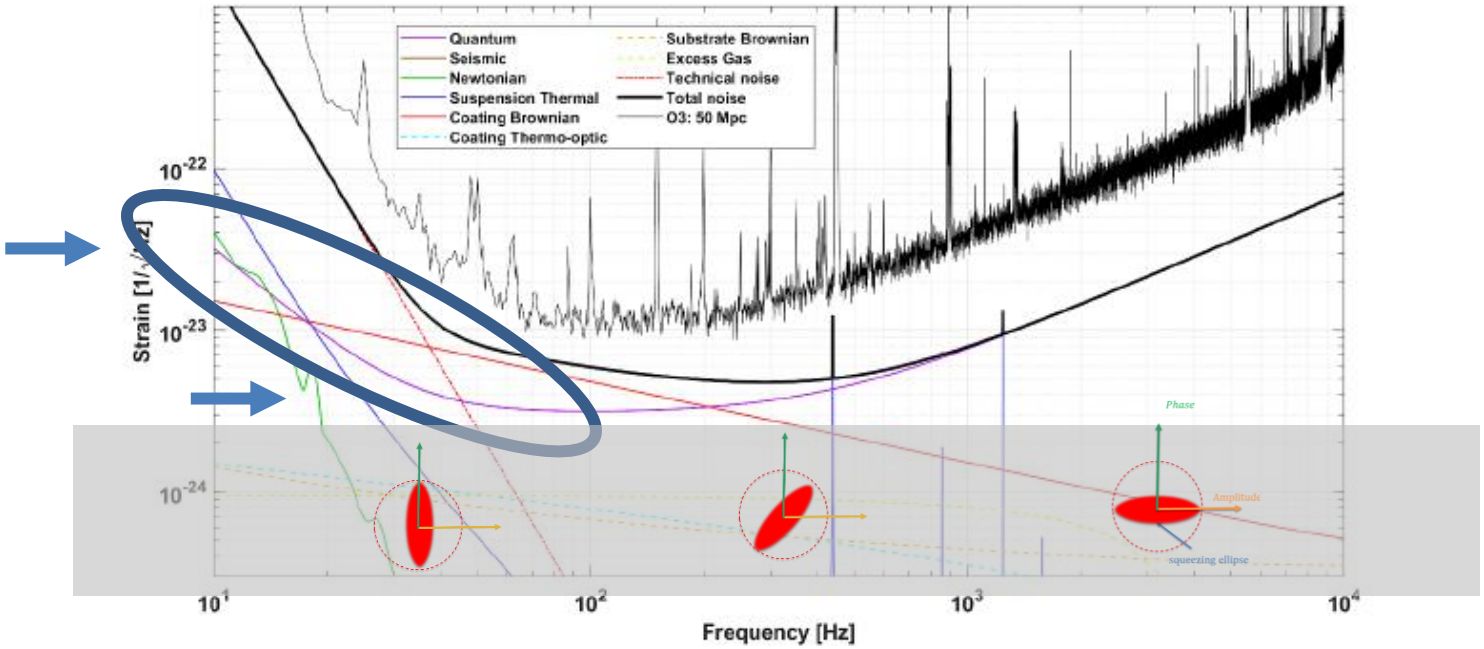


Figure 2. Anticipated best sensitivity of AdV+ during Phase I. For comparison the sensitivity at the beginning of O3 is shown.

Credit: Advanced Virgo PlusDesign Report (VIR-0596A-19)

Frequency-dependent squeezing (FDS)

We need **Frequency-dependent squeezing** to induce squeezed light ellipse rotation = broadband reduction of quantum noise



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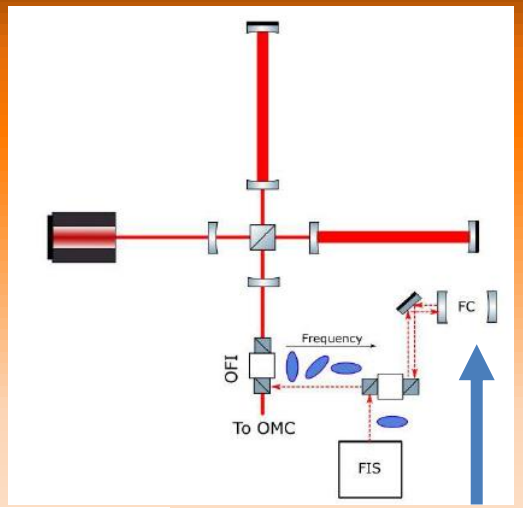
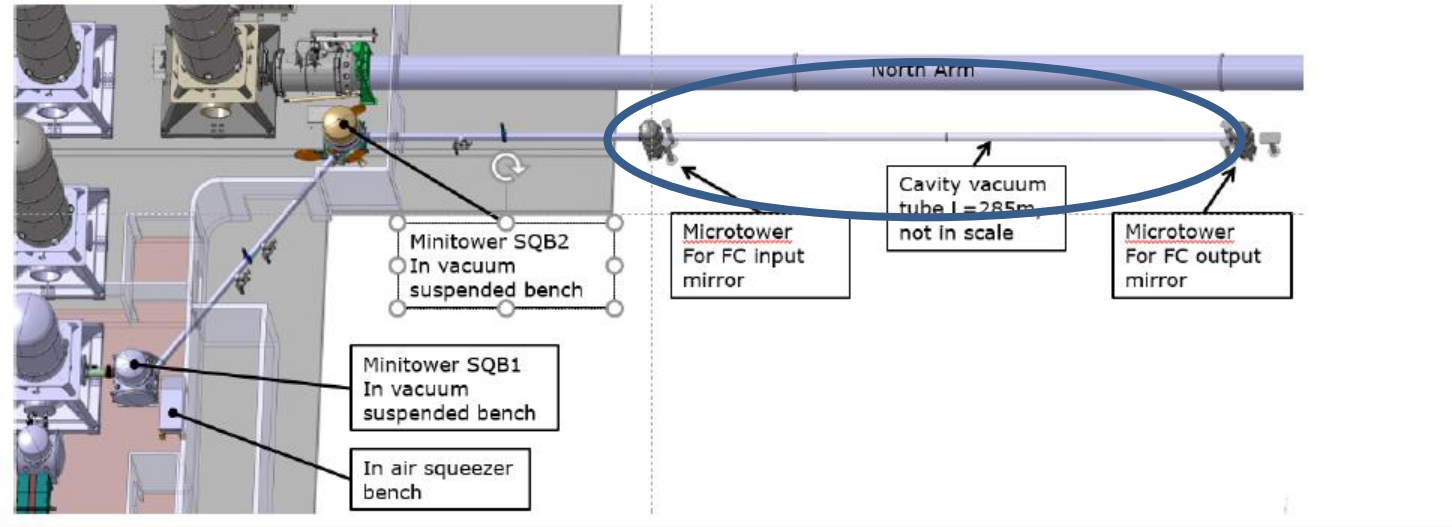
Solution for AdV+: Filter cavity (FC)

- Frequency-independent squeezing injected into a filter cavity (Fabry-Perot cavity)
- planned for O4 for AdV+ and aLIGO





Advanced Virgo Plus Design Report (VIR-0596A-19)

A new technique…with no filter cavity

nature physics

Article | Published: 15 May 2017

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

Yiqiu Ma ✉, Haixing Miao, Belinda Heyun Pang, Matthew Evans, Chunnong Zhao, Jan Harms, Roman Schnabel & Yanbei Chen

Nature Physics **13**, 776–780 (2017) | Download Citation ⬇

EPR entanglement technique : principles

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

1 **Detune pumping frequency** (of Δ)

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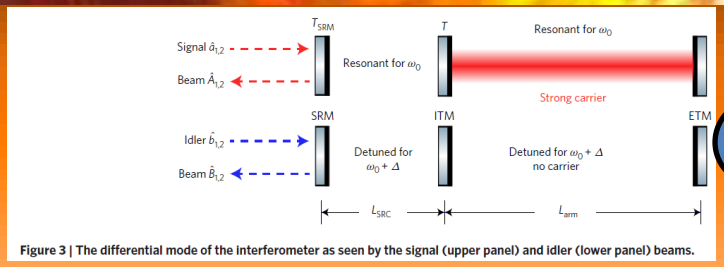
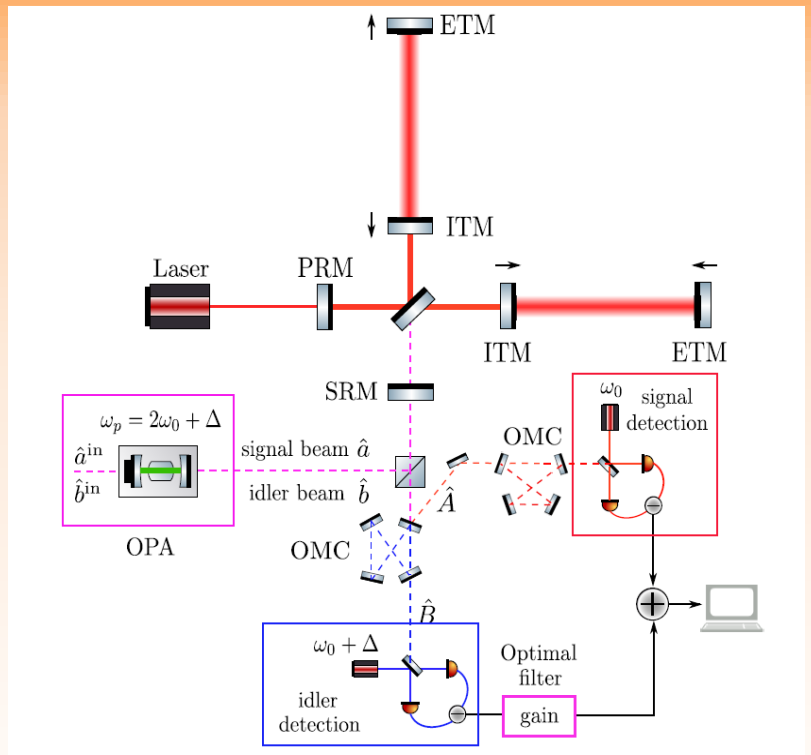


Figure 3 | The differential mode of the interferometer as seen by the signal (upper panel) and idler (lower panel) beams.

Credit: Y. Ma et al.

1 **Detune pumping frequency** (of Δ)

2 **Auto-filtering** of the signal and idler beams with the interferometer arm



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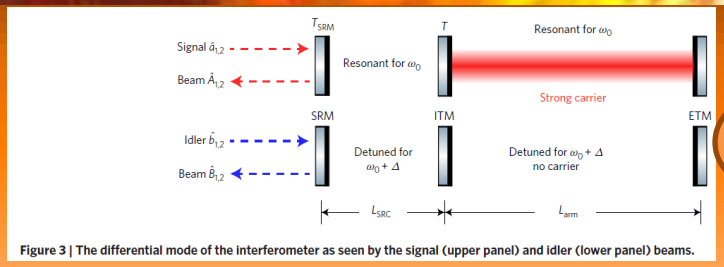

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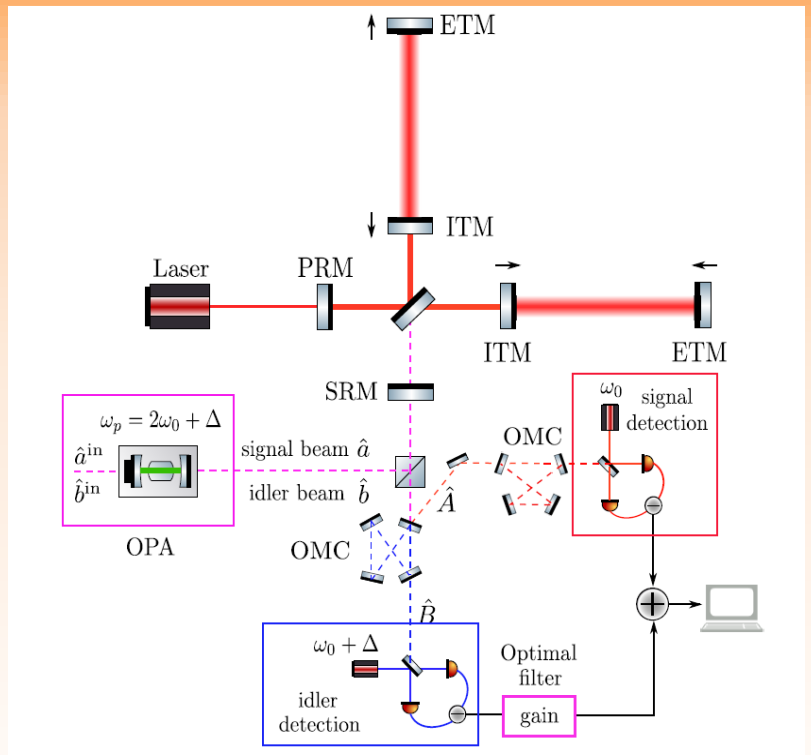

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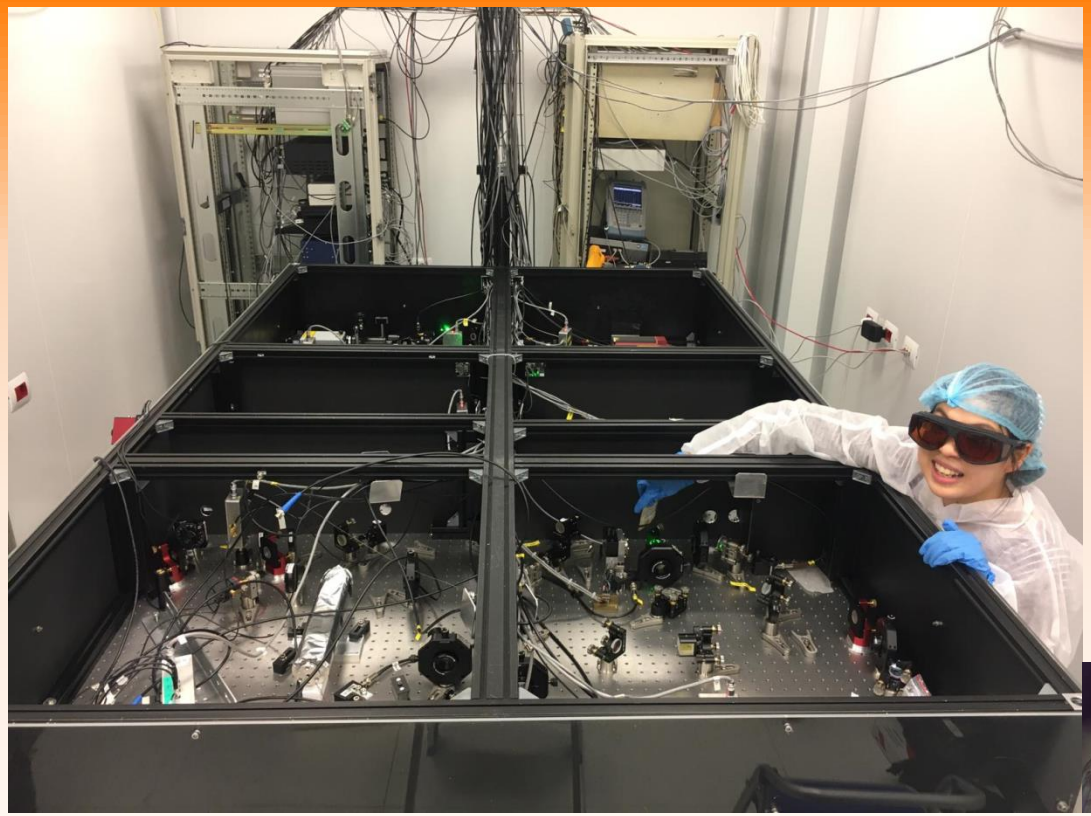
1. **Detune pumping frequency** (of Δ)
2. **Auto-filtering** of the signal and idler beams with the interferometer arm
3. **Detection**

CONDITIONNAL SQUEEZING WITH SQUEEZED SIGNAL IN A FREQUENCY-DEPENDENT WAY

Einstein-Podolsky-Rosen entanglement

On-going work on EPR experiment

- **EPR table-top experiment(Virgo collaboration – INFN/APC)**



Frequency-independent squeezing bench at Virgo site to be transformed in an EPR bench

Take-away messages

- **Frequency-dependent squeezing technique is needed for a broadband reduction of quantum noise.**
- **For future Observation Run, FDS technique using a filter cavity is planned for AdV+ and aLIGO.**
- **Squeezing using EPR entanglement is a technique to avoid using a filter cavity and an experiment will be built to test its application to Advanced Virgo.**
- **EPR squeezing is a promising technique for future detectors as Einstein Telescope.**


THANK YOU FOR YOUR ATTENTION !
ANY QUESTIONS ?