Status of the squeezing for Advanced Virgo and EPR project

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On behalf Virgo Collaboration

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Summary

- Squeezed states of light
- Generation of SL
- Squeezed light in IGWD

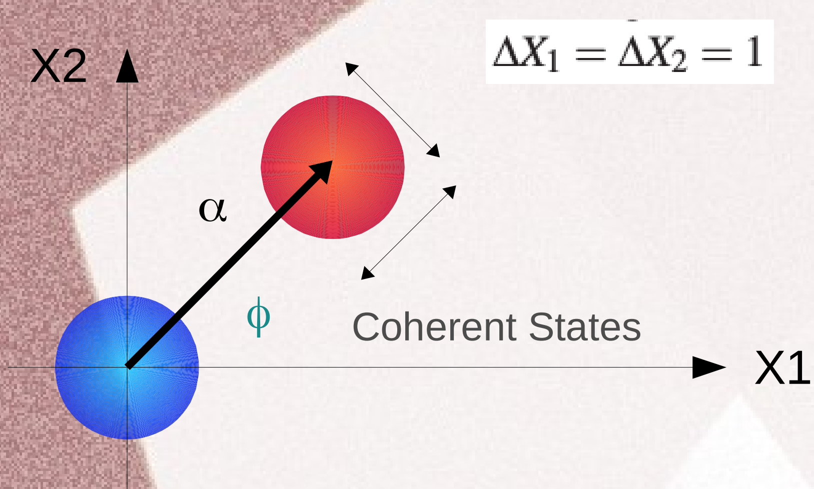
(Interferometric Gravitational Wave Detectors)

- Status of AdV squeezing
- EPR squeezing in IGWD

Squeezed State of Light

Squeezed State of Light

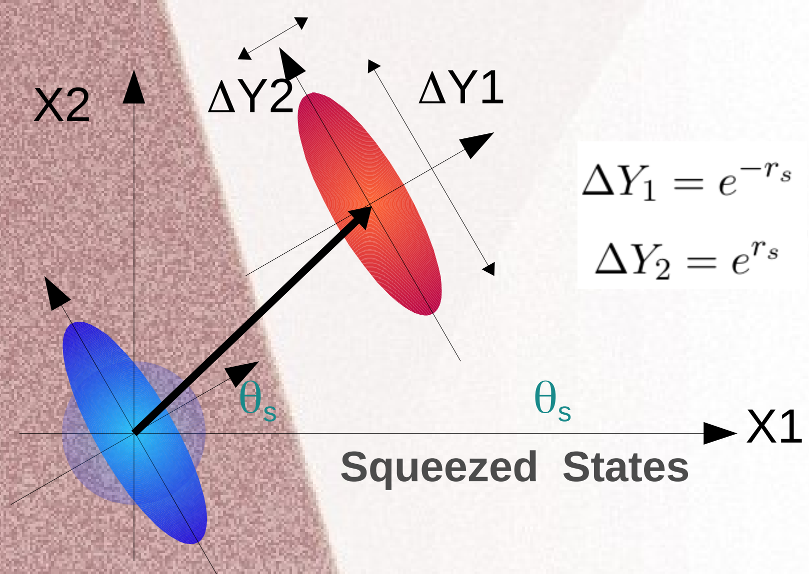
Minimum Uncertainty States $\Delta X_1 \Delta X_2 = 1$



A bright beam (α>0) has
the same fluctuation of the vacuum

Light as '*sensitive*' element

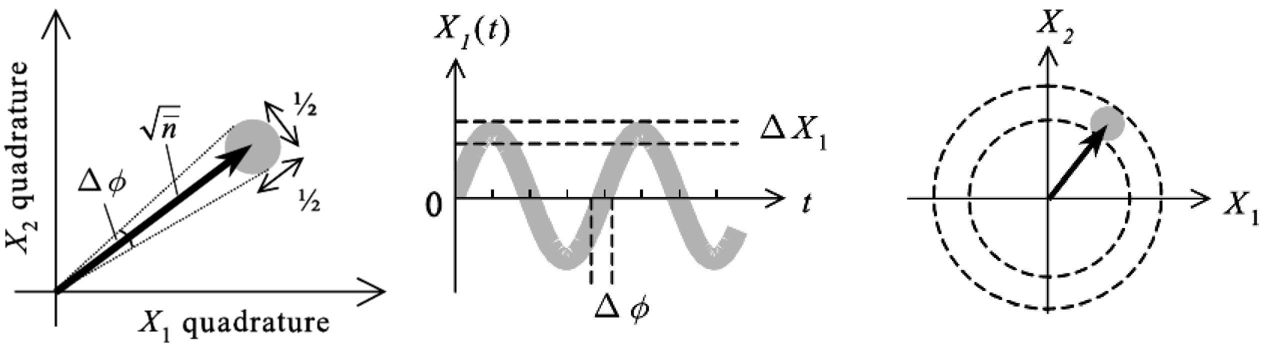
its intrinsic quantum fluctuations
Determines the final sensitivity



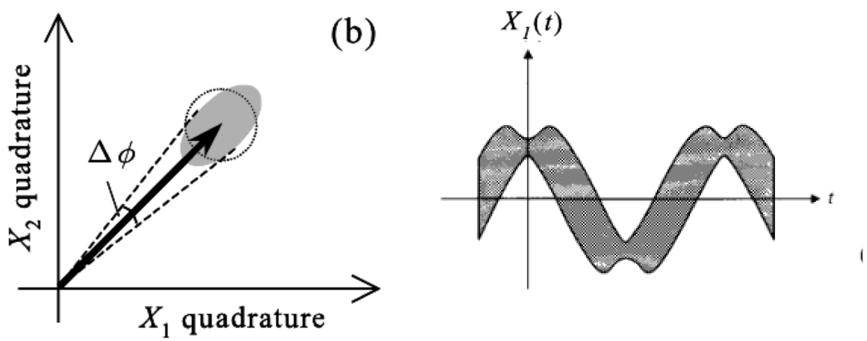
We cannot violate the uncertainty principle
but
we can squeeze the quantum fluctuations on
one quadrature and 'use' that quadrature
as sensitive element

Squeezed States

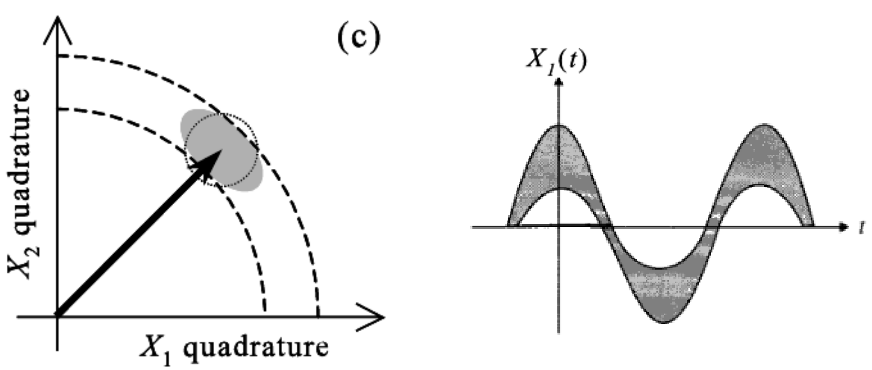
Squeezed State of Light



Coherent State



Phase Squeezed State



Amplitude Squeezed State

Generation of Squeezed Light

Generation of Squeezed Light

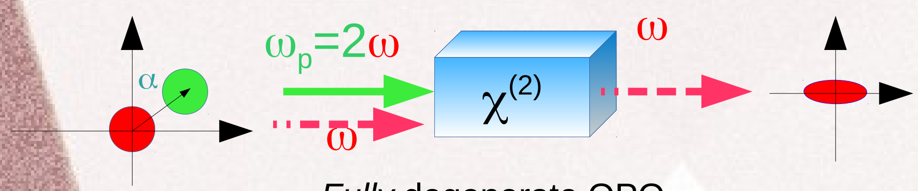
Squeezed states → ***quadrature fluctuations correlated***

- **Non linear process in dielectric medium:** →

  - *Kerr medium*

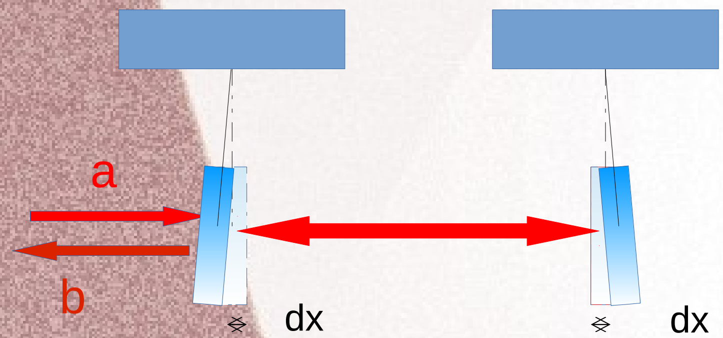
  - *Optical Parametric Oscillator (OPO) below threshold*

the 3th and
2th order nonlinear
susceptibilities
induces
the correlation between
the phase and amplitude
fluctuations



Fully degenerate OPO
(polarizations and frequencies degeneracy)

- **Empty cavity with suspended mirrors: Ponderomotive Squeezing**



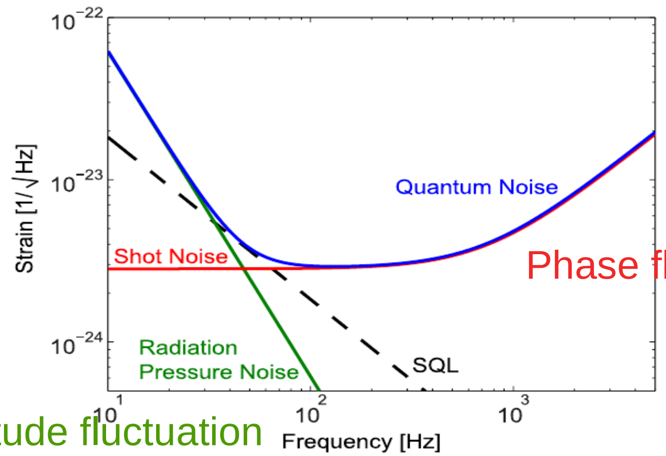
the **radiation pressure on the mirror** that is free to oscillate ***induces a coupling*** **between its position and the intensity of the light beam**

Correlation between
the **phase and amplitude quadrature** of the output state

Squeezing for GWD

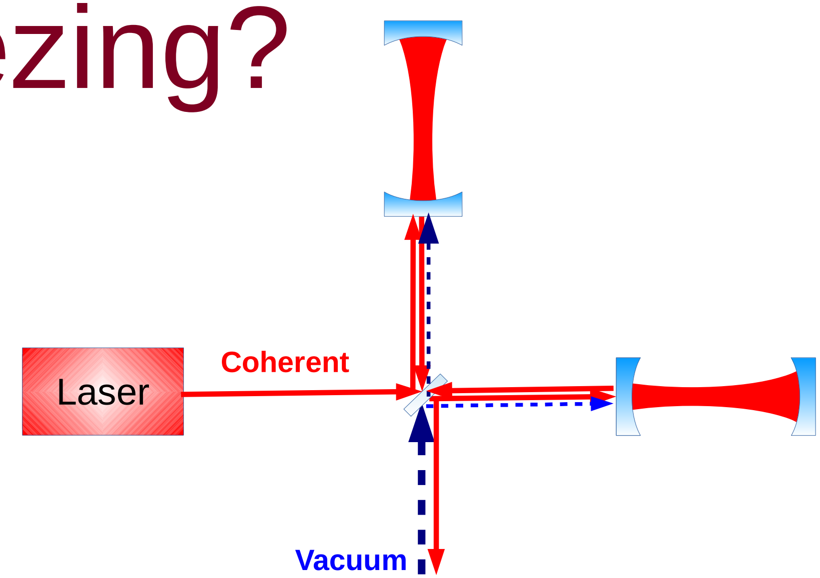
Why Squeezing?

C. M. Caves, '**Quantum noise in an interferometer**'
Phys. Rev. D 23 (1693–1708), 1981



Phase fluctuation

Amplitude fluctuation

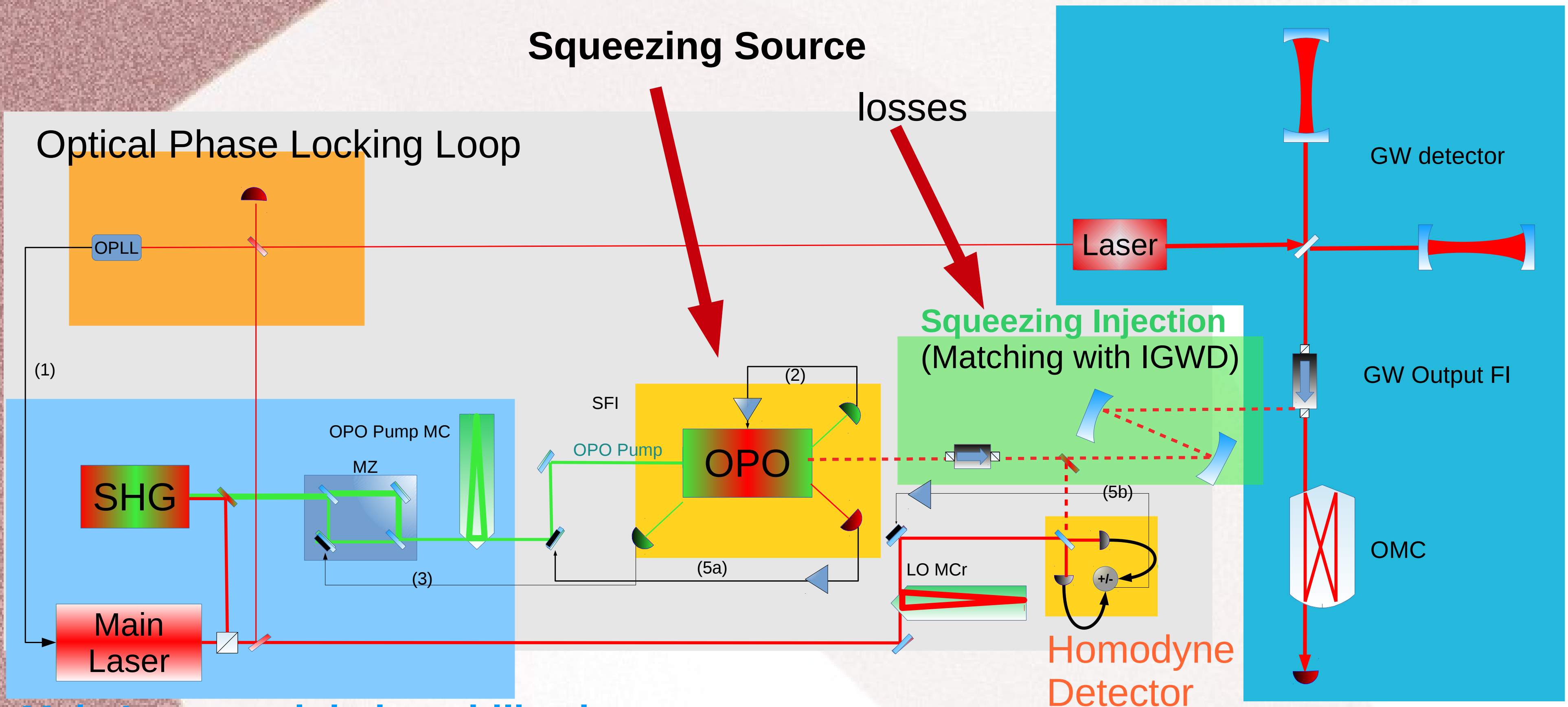


Noise in the output as beat between the coherent input beam and the vacuum that enters in the unused port of a beam splitter (dark port of interferometer)

Vacuum Squeezed in the unused port

Noise Reduction
(sensitivity improvement)

Typical Squeezer Set-Up for GW interferometer



Main Laser and their stabilization

And mode cleaner system:

Green OPO pump

Homodyne Local Oscillator

Alignment beam

Homodyne Detector

(detection of squeezing)

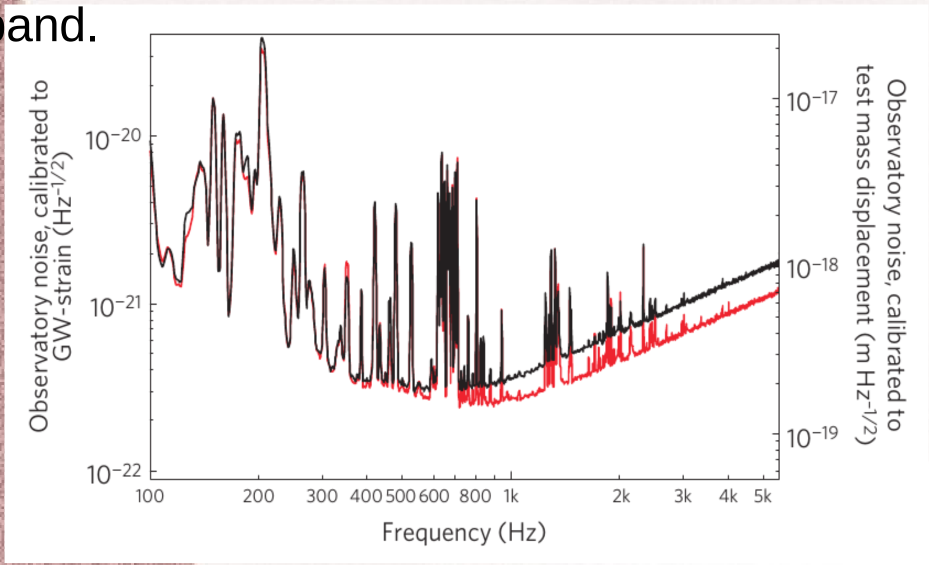
LEGENDA

LO: homodyne Local Oscillator
MC=Mode Cleaner cavity
SHG: Second Harmonic Generator
FI: Faraday Isolator
OMC:output Mode Cleaner cavity

First Experimental Sensitivity Enhancement

- GEO600

broadband noise reduction of up to 3.5 dB (red trace) in the shot-noise-limited frequency band.

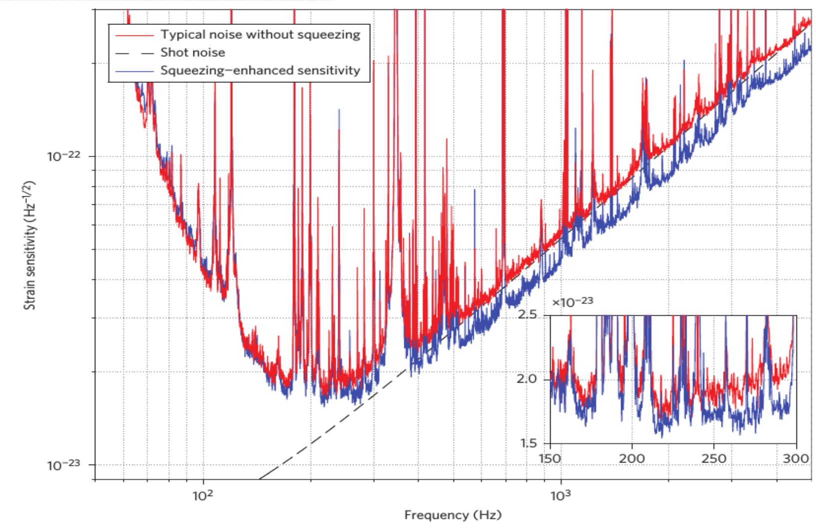


Losses 10 dB produced, 3.5 dB injected

LIGO Scientific Collaboration et al.
“A gravitational wave observatory operating beyond the quantum shot-noise limit”.
In: Nature Physics 7.12 (2011), pp. 962–965.

- LIGO H1 detector

up to 2.15 dB in the shot-noise-limited frequency band

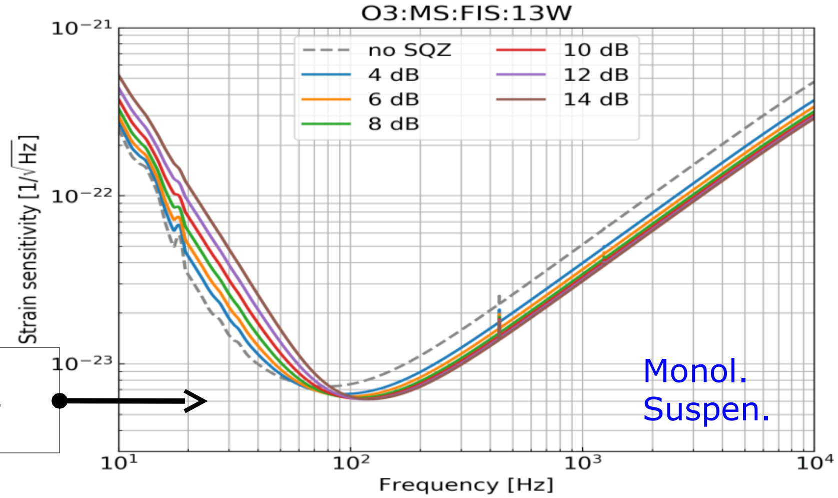


Losses 10.3 dB produced, 2.15 dB injected

J Aasi et al.
“Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light”.
In: Nature Photonics 7.8 (2013), pp. 613–619.

AdV Expected sensitivity with Vacuum Phase Squeezed Injection

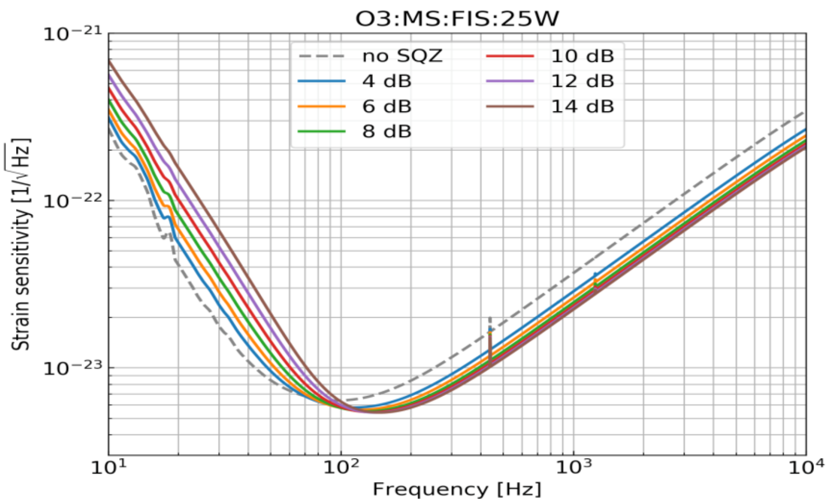
- Low Power: 13 watt

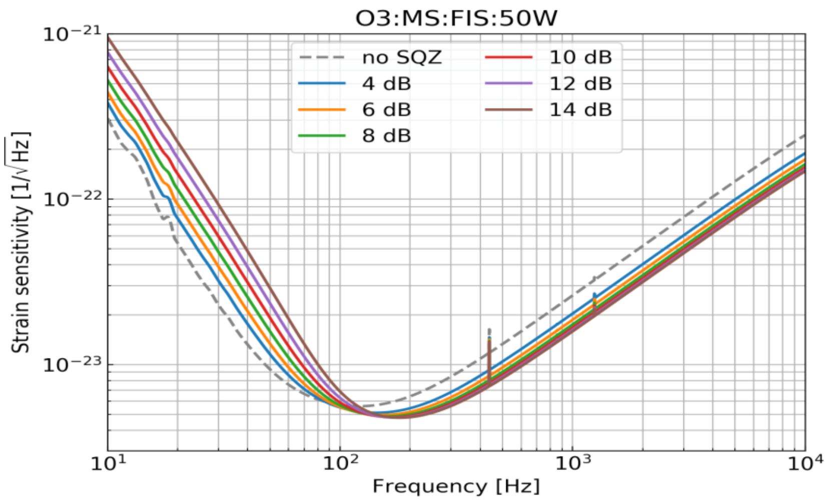


Same Horiz.
+ 4 dB at HF

Vacuum Phase Squeezed injection

- High Power

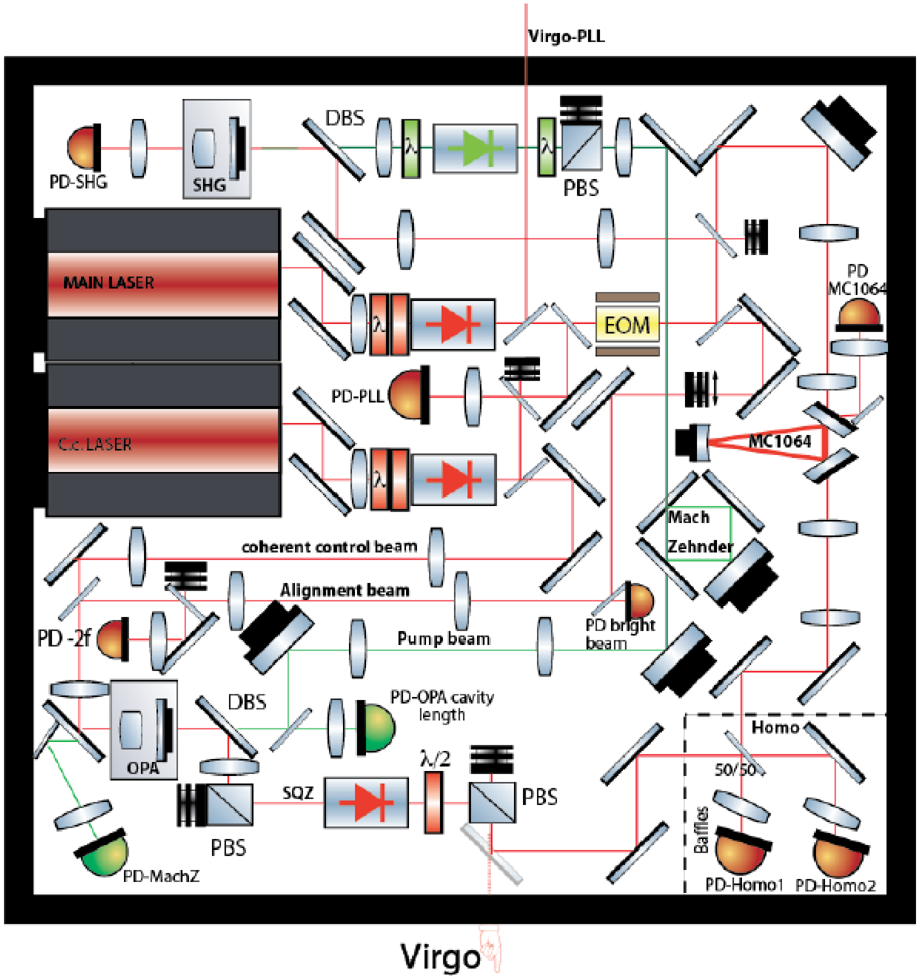




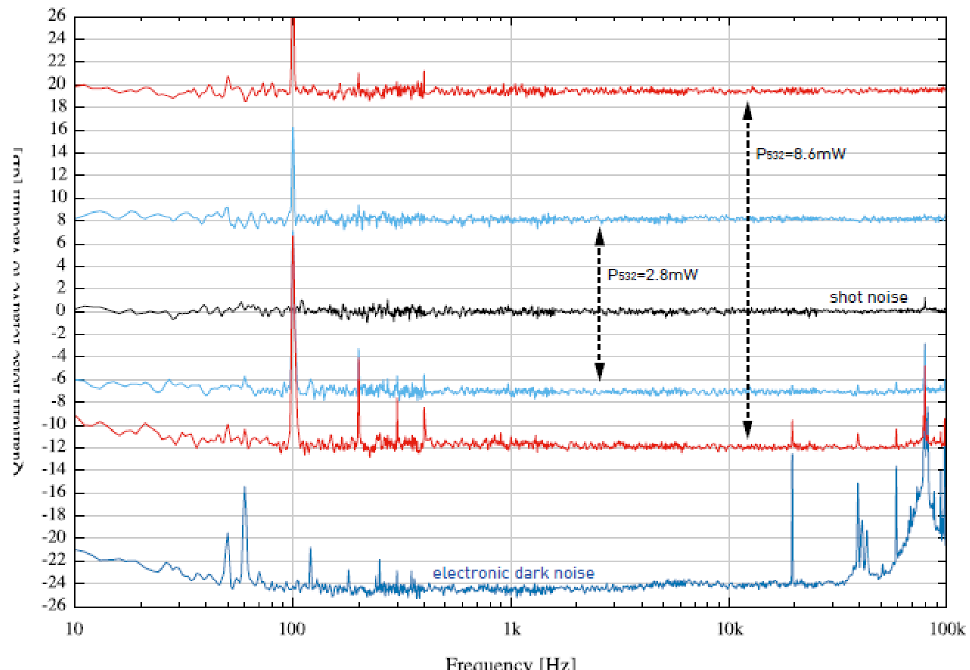
In general expected +(5÷10)% on NS-NS Horizon + 3 dB at HF.

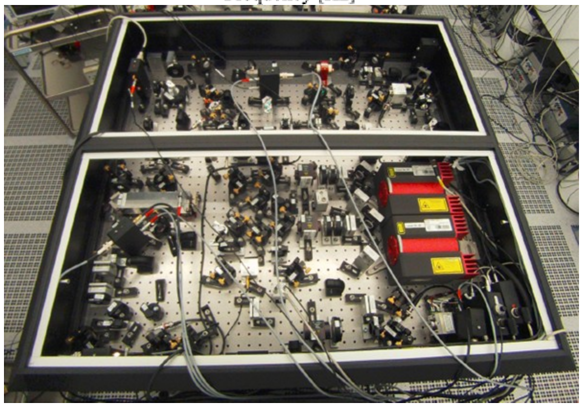
The AEI squeezer for AdVirgo

Resp: Hanning Vahlbruch (AEI)



Up to 12 dB of squeezing degree demonstrated in the audio band





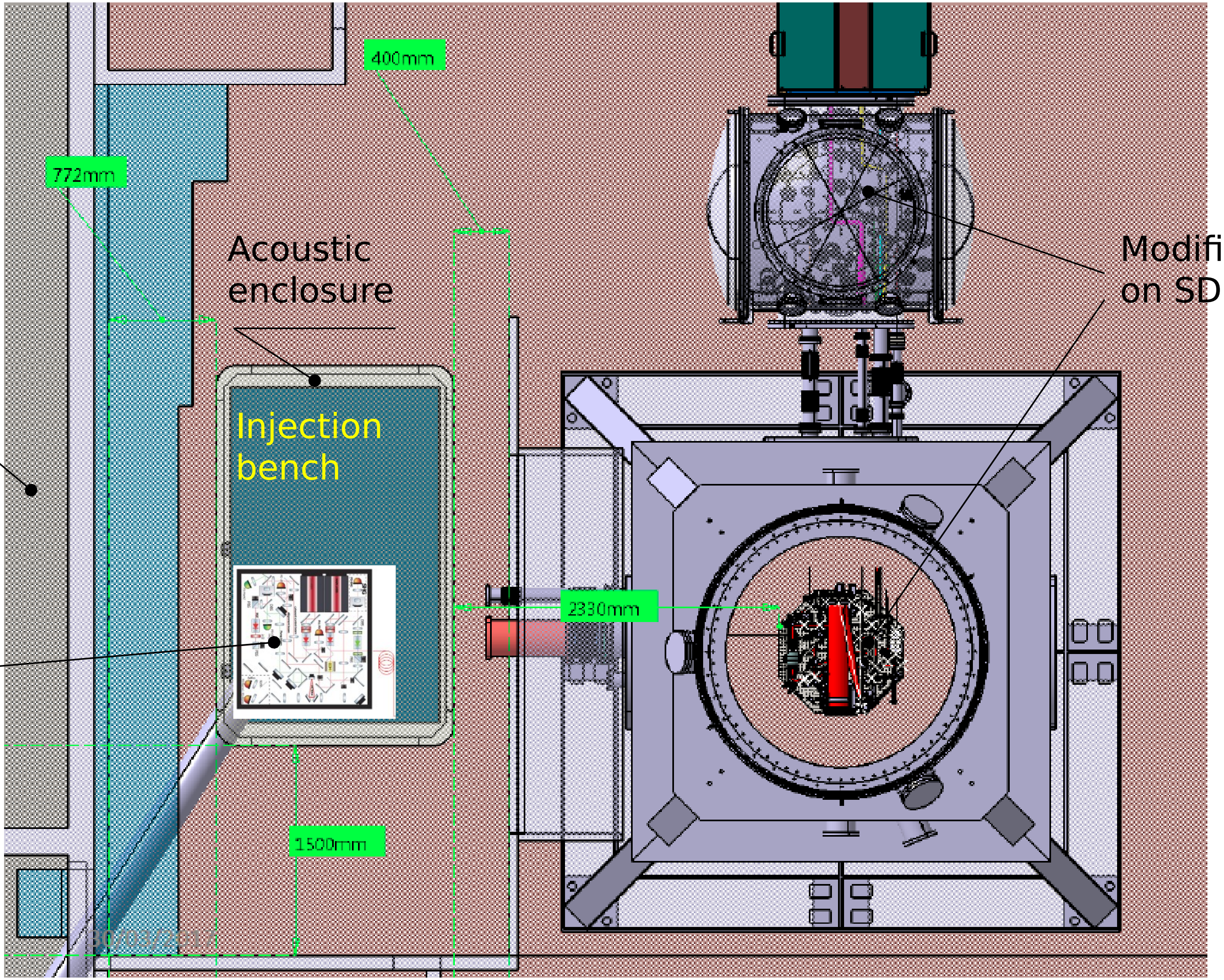
The AEI squeezer for AdVirgo

Resp: Hanning Vahlbruch (AEI)

Status

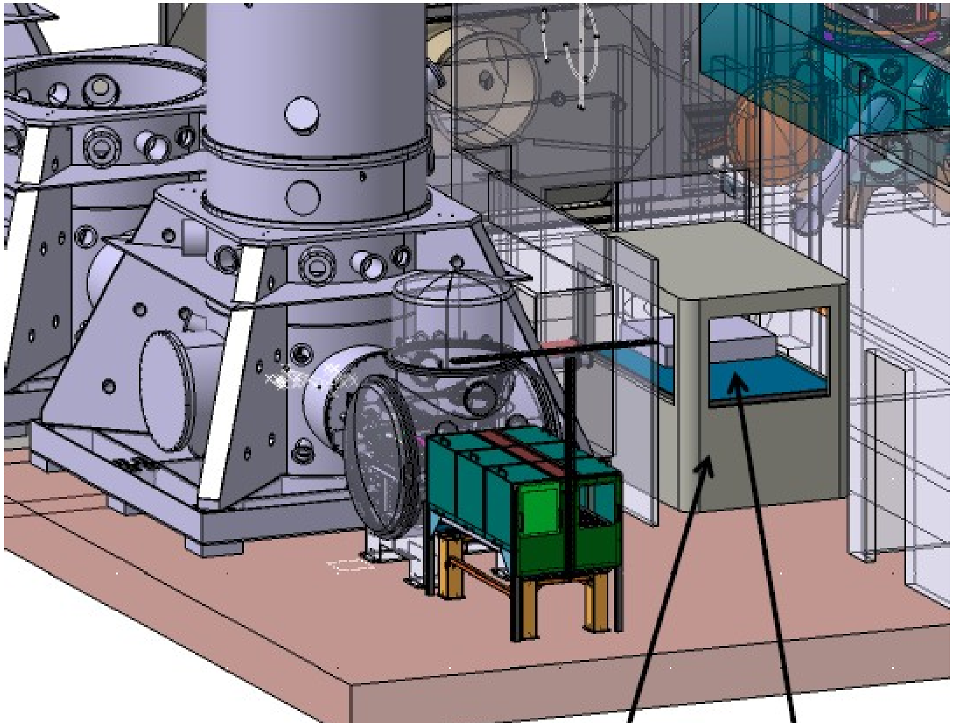
- The squeezer completed and operating in Hannover
- Jannuary 2018: delivered and installed in Cascina
- Febrary 2018: AdV PLL installed, Matching telescope installed

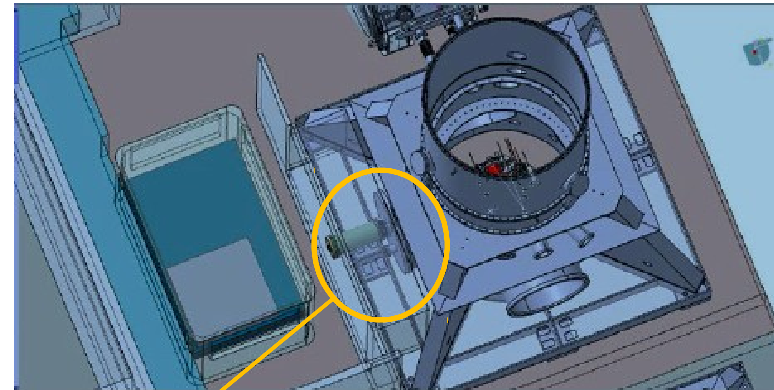
Installation layout



Infrastructures status

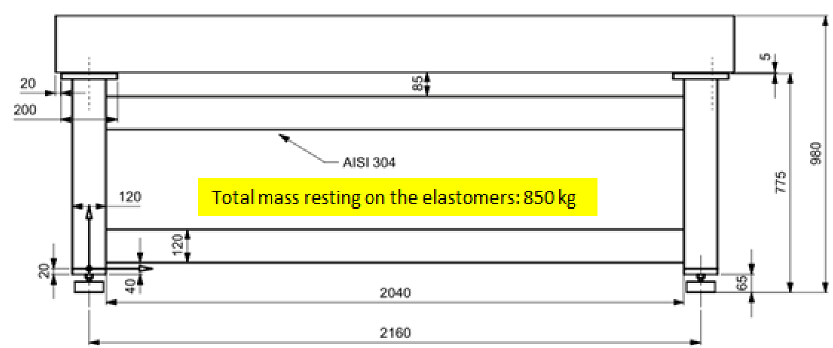
Virgo Detection Lab





New vacuum flanges
Resp: R.Gouaty (LAPP)

Steel rigid frame on simple elastomer pads. Resp: A. Bertolini (Nikhef)



Acoustic enclosure
Resp: F.Carbohnani (EGO)

Injection and matching telescope

Resp: Martina De Laurentis (INFN)

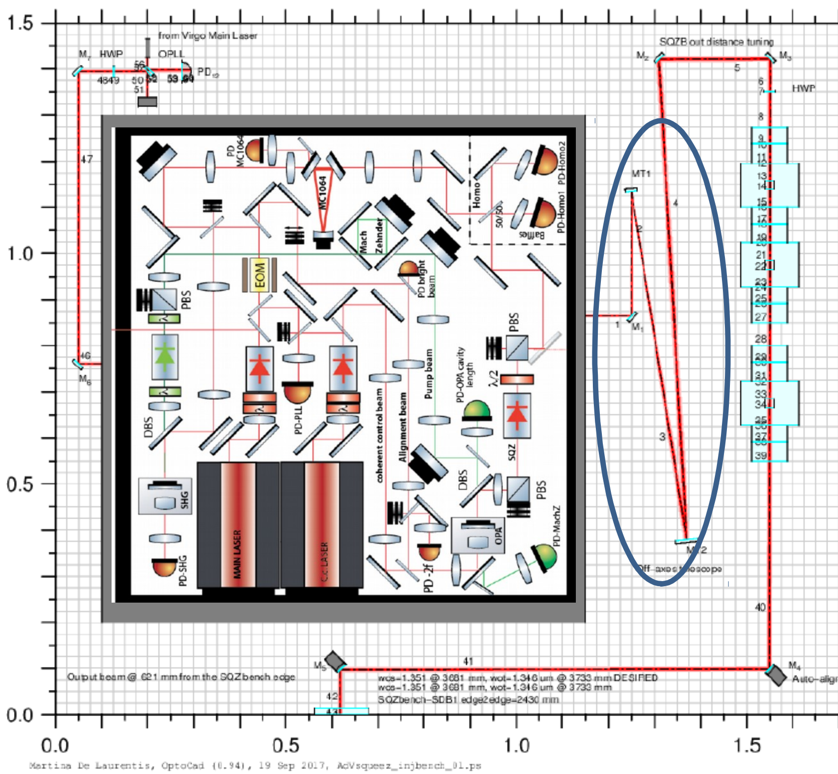
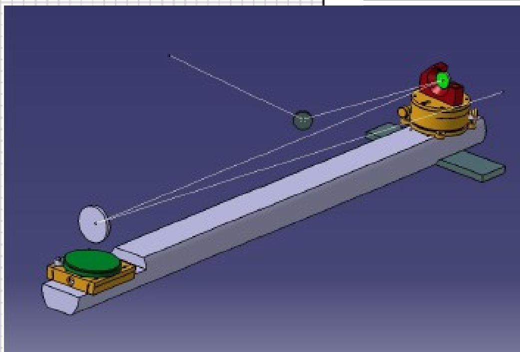
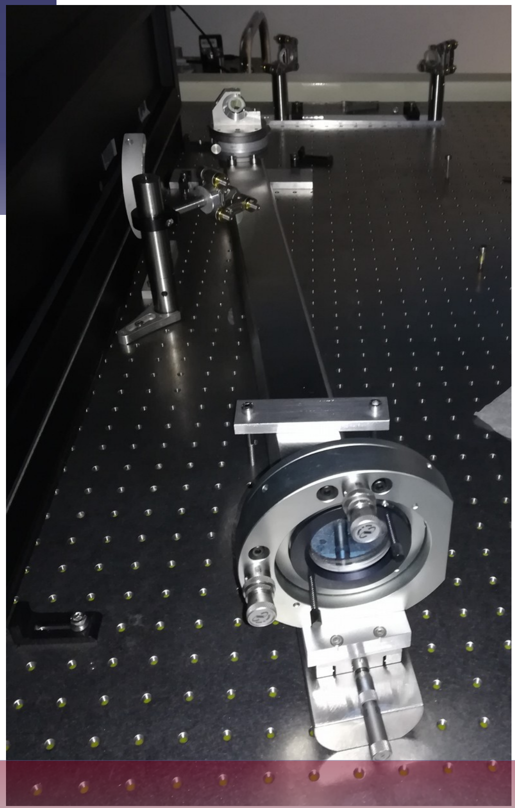


Table 14: **Telescope Parameters.**

$RoC1$	$250\ mm \pm 1\%$
$RoC2$	$-2000\ mm \pm 1\%$
d_1	$-650.0 \pm 2.5\ mm$
$dlenses$	$765.44 \pm 0.10\ mm$
θ_1	$4.50 \pm 0.1°$
θ_2	$2.84 \pm 0.05°$





Status
- Installed on the Squeezing bench

Planning
Apr 2018: commissioning

AdV squeezer

Planning June-July 2018: commissioning

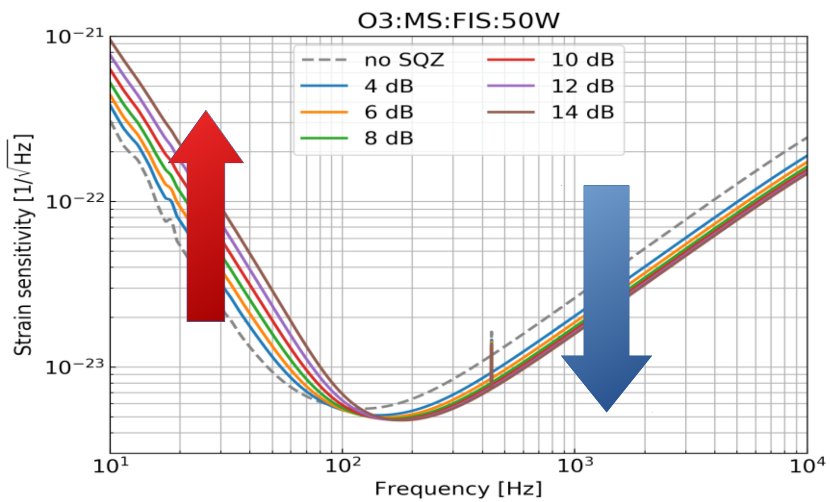
Vacuum Squeezed Injection in AdV for O3

Optimize the squeezing

Frequency Independent Squeezing

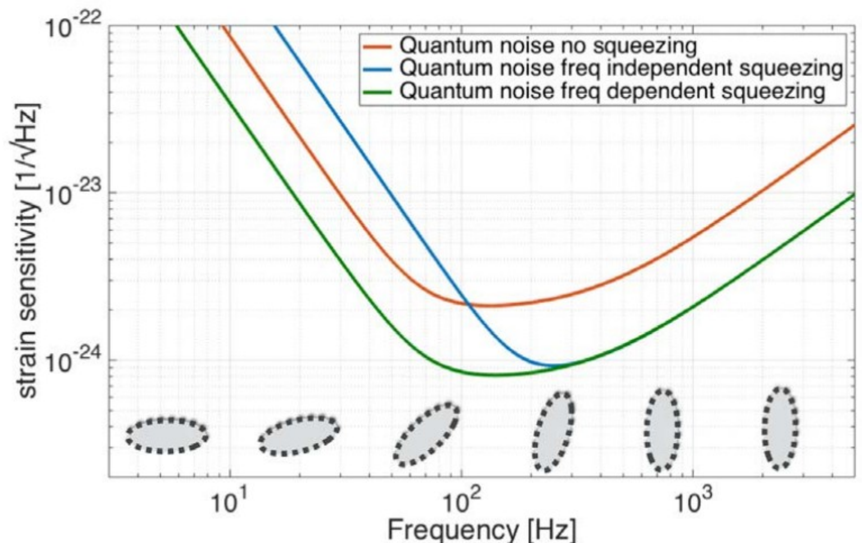
Squeezing the phase noise
Enlarges the amplitude noise

By increasing a lot the squeezing level injected, *the **sensitivity***
increases at high frequencies *but*
makes worsen at low frequencies

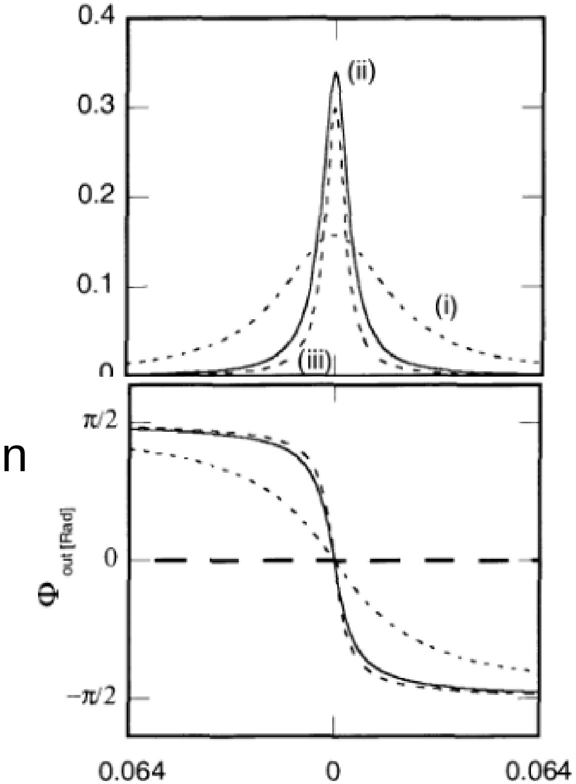


A **frequency dependent squeezing is needed:**
an optimized squeezing angle in each region of the detector band

Rotation of the squeezing ellipse dependent on the frequency



Optimize the squeezing



Frequency Dependent Squeezing

A **detuned cavity (Filter Cavity) acts as filter that in its band** (cavity linewidth)
rotates the field quadratures, thus the squeezing ellipse
According with the cavity detuning
(resonant frequency equal to the carrier of GW interferometer laser frequency)
the sidebans experience a different phase and quadratures rotation

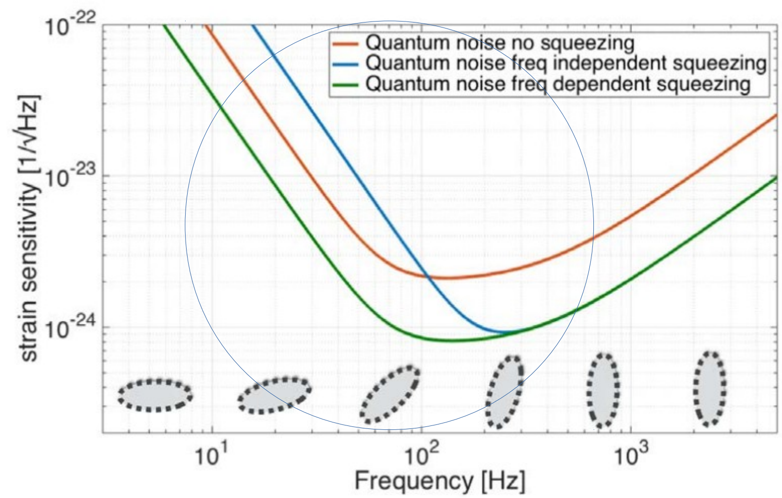
The squeezing angle can be suitable tuned in the detector band with a suitable choice of the cavity bandwidth and detuning

Narrow linewidth cavity are required (kHz)

For AdV Length~300 m and Finesse~500÷800

Cavity design very similar to the TAMA FC

SEE Matteo Barsuglai talk



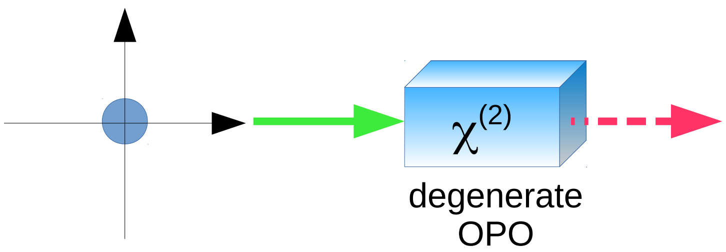
Frequency Dependent Squeezing

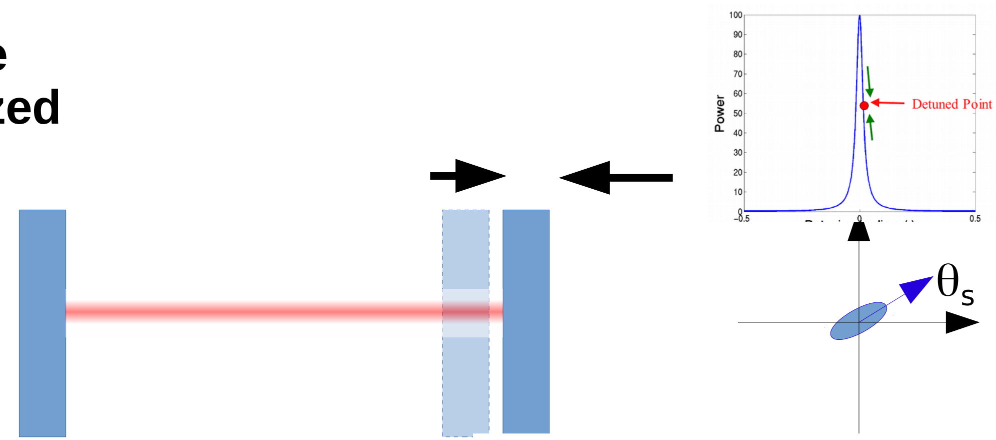
Detuned Fabry-Perot as optical filters →

frequency-independent squeezed quadrature

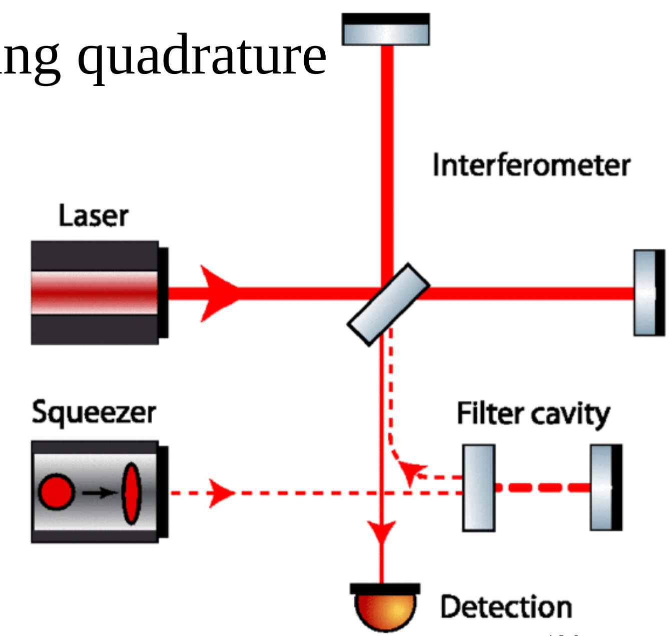
frequency-dependent squeezed quadrature

Can be **used with sources** that **generate *frequency-independent* Vacuum squeezed**





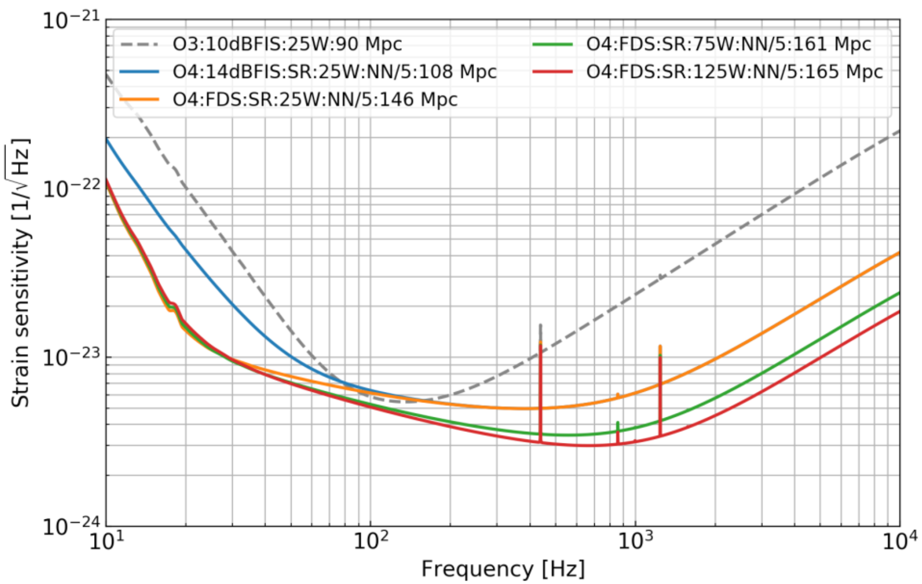
Degenerate OPO + detuned cavities to rotate the squeezing quadrature



For the GW detectors the FILTER CAVITY must have the full interferometer arms length or have a very very high mirrors reflectivity

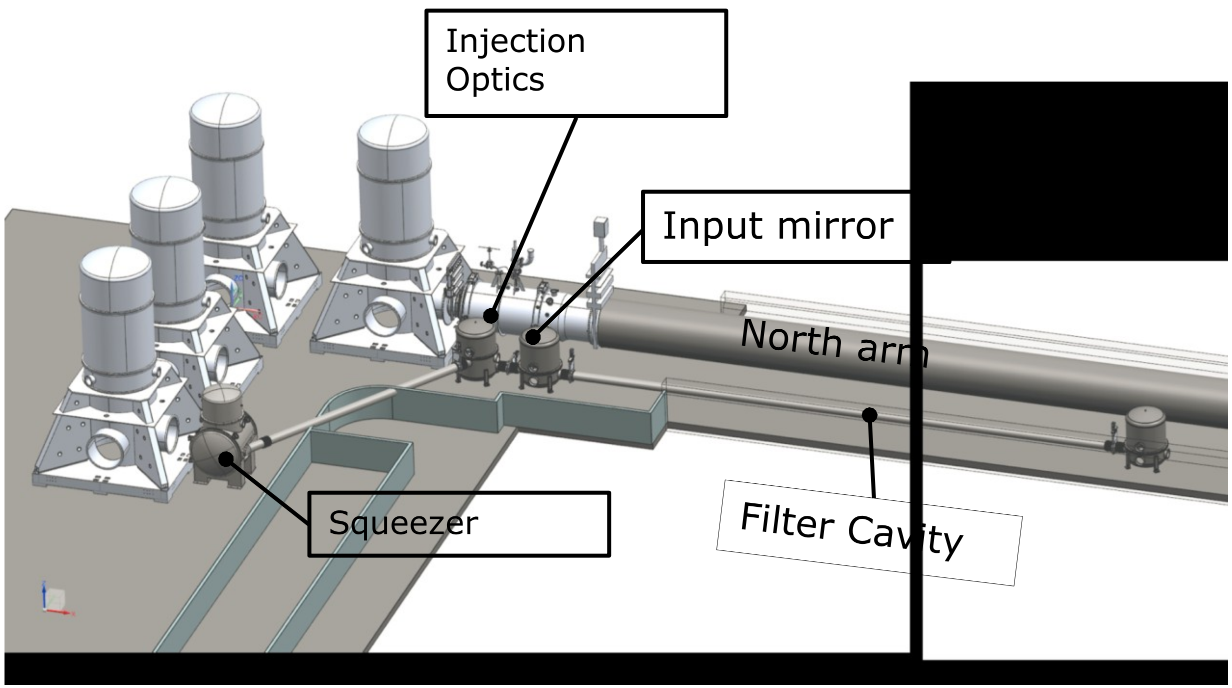
TRADE-OFF between them

FDS conceptual design (O4)



Target:
7-8 dB reduction of quantum noise at high frequency without degrading the low frequency sens.

The conceptual design including a preliminary costs list and a timeline should be ready by the end of the current Year



Alternative to the FD for FDS: use of EPR states

ARTICLES
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4118
nature physics

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

Yiqiu Ma[1*], Haixing Miao[2], Belinda Heyun Pang[1], Matthew Evans[3], Chunnong Zhao[4], Jan Harms[5,6], Roman Schnabel[7] and Yanbei Chen[1]

In this paper, they propose a novel strategy **to achieve broadband squeezing of the total quantum noise** via the preparation of EPR entanglement and the ***dual use of the interferometer as both the gravitational-wave detector and the filter,*** **eliminating the need for external filter cavities**

ADVANTAGES:
- no change in infrastructures
- suffers less from loss in the filter cavity compared to the design based on an auxiliary filter cavity (arm cavities have less loss)
DISADAVANTAGES:
- higher level of input and detection losses
(doubled, because signal and idler beams experience the same amount of loss during propagation)

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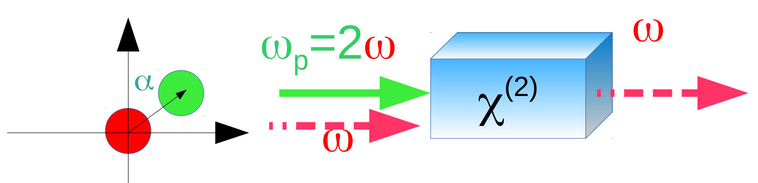
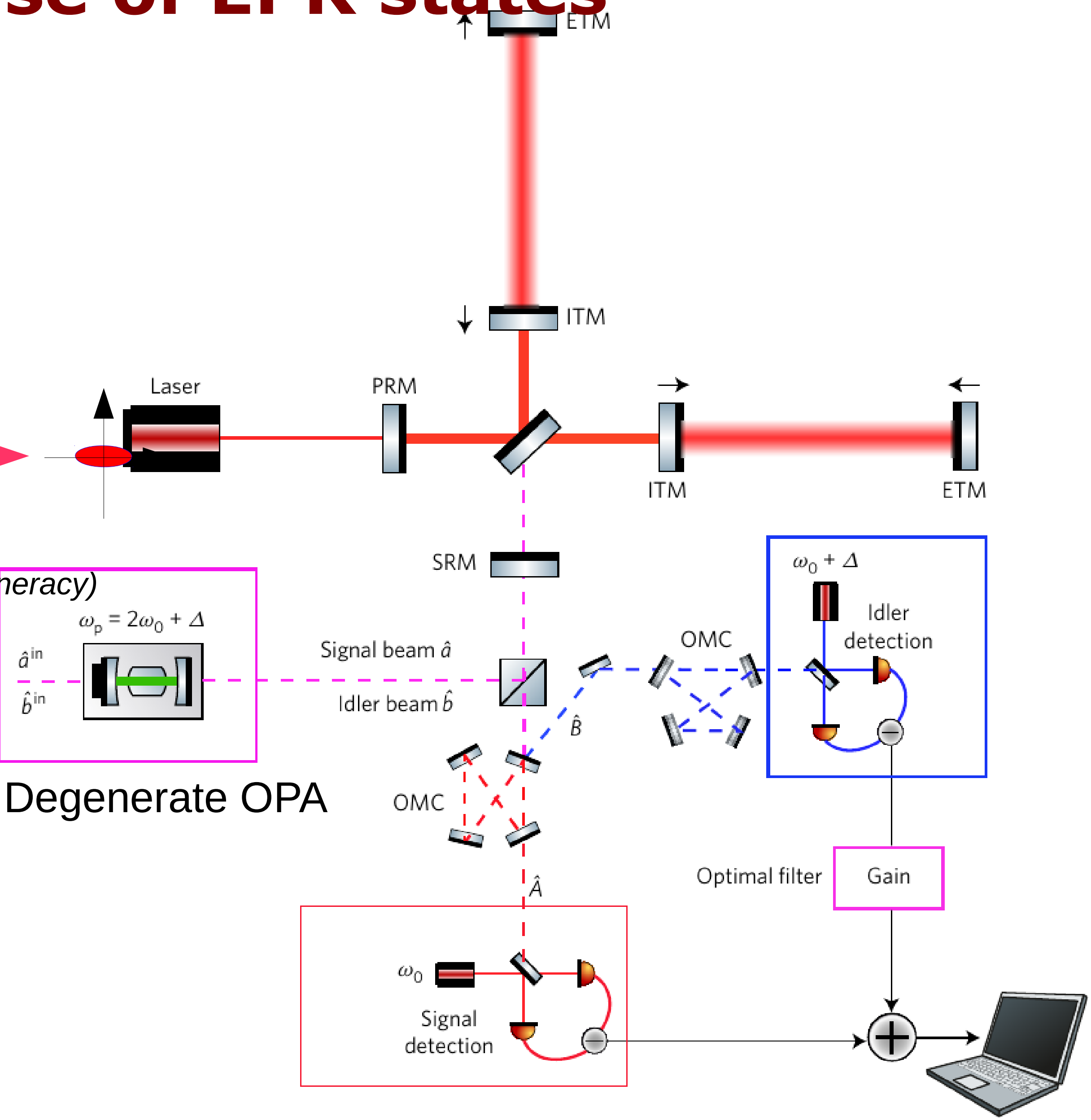
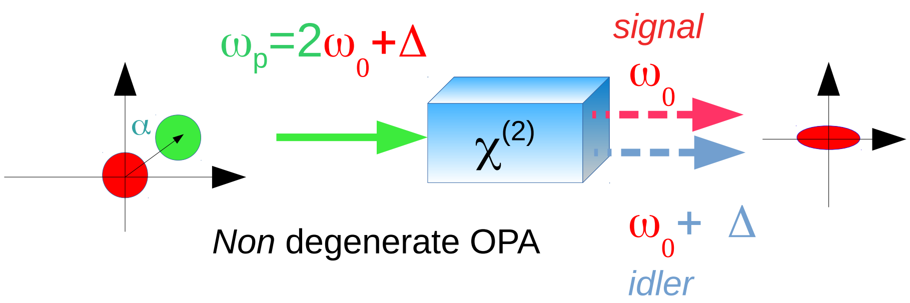


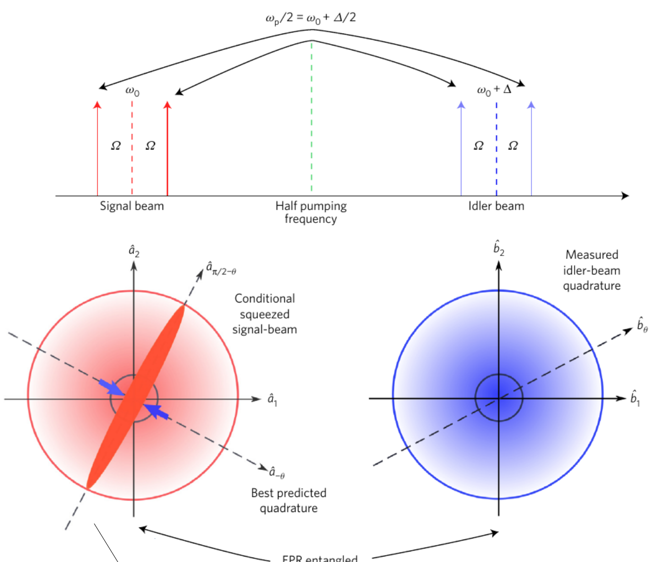
Fully degenerate OPO
(polarizations and frequencies degeneracy)

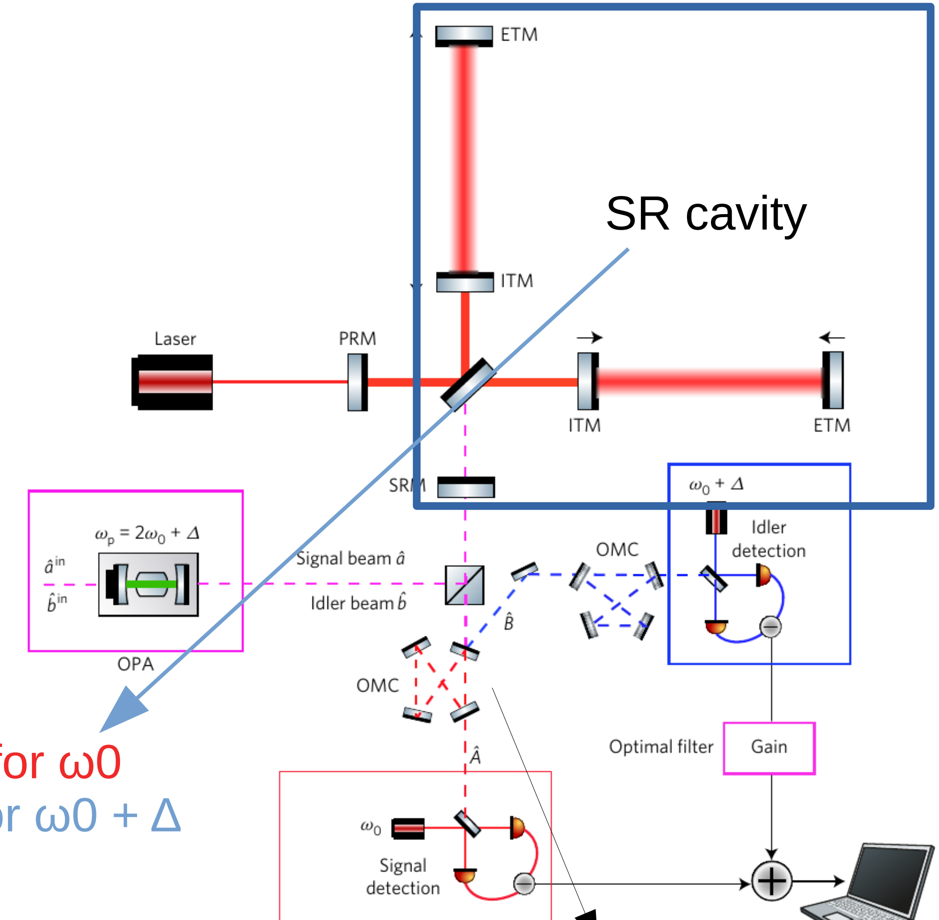


Non Degenerate OPA

Alternative to the FD for FDS: use of EPR states







Resonant for ω0
Detuned for ω0 + Δ
no carrier

Bandwith centered on ω0, < Δ => idler totally reflected

Rotation angle depending on Δ

Alternative to the FD for FDS: use of EPR states

ADVANTAGES:

- no change in infrastructures

- suffers less from loss in the filter cavity compared to the design based on an auxiliary filter cavity (arm cavities have less loss)

- it work with SR configuration

(in the case of FC two are needed)

DISADAVANTAGES:

- higher level of input and detection losses

(doubled, because signal and idler beams experience the same amount of loss during propagation)

Very low losses injection and detection systems

Squeezing in AdV Virgo

Actually Virgo has a group

supported by INFN

that is working on the development of the

EPR project

Alternative to the FD for FDS: use of EPR states

MANDATORY: reduce the **optical losses**

Very low losses injection and detection systems

Scatteering, absorption

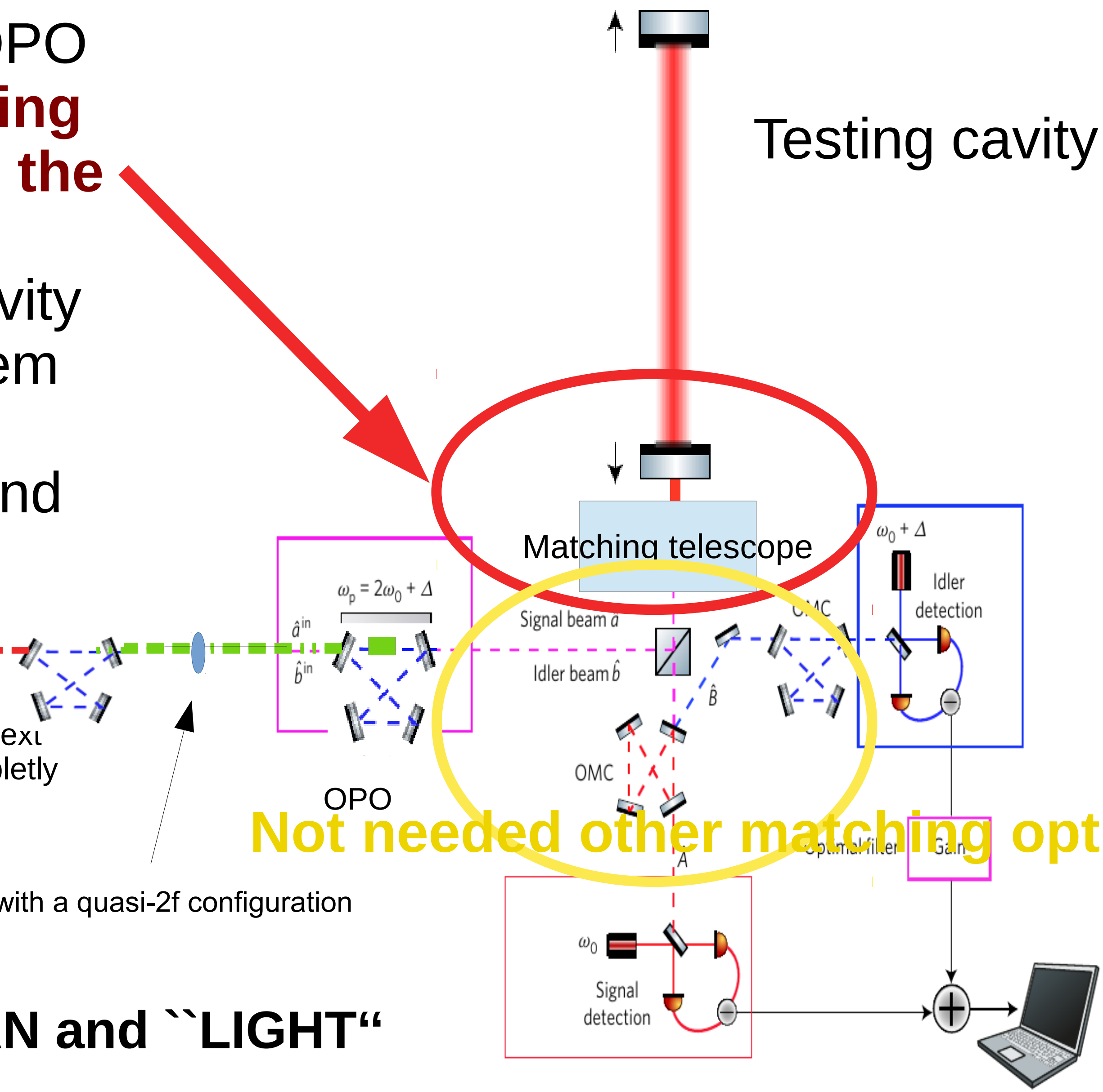
Matching losses

DESIGN VERY CLEAN and ``LIGHT"

BEFORE ALL: number of optics minimization

Twin cavities with collimated output

Having twin cavities (OPO and OMCs) the **matching optics are reduced to the matching telescope** between the testing cavity and the detection system (in the future, between the GW ITF and the DET system)



The aim of the next upgrade and for the next generation is to redesgn the DET to completly integrate the squeezer in the DETECTOR

Matching with a quasi-2f configuration

DESIGN VERY CLEAN and ``LIGHT“

Thank you!