EPR experiment in Virgo

Einstein-Podolsky-Rosen experiment for quantum noise reduction in gravitational wave detectors

Valeria Sequino (INFN sez. Genova)

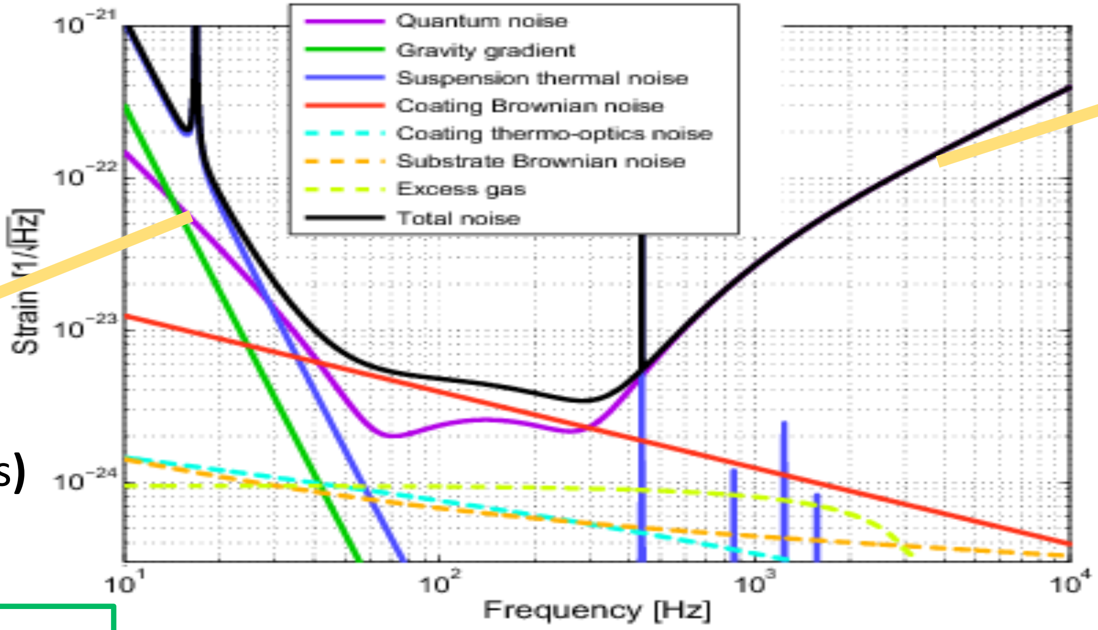
on behalf of the Virgo Collaboration

1st Vacuum Fluctuations at Nanoscale and Gravitation: theory and experiment
April 28th-May 3th, 2019 Orosei

Quantum noise in the current GW detectors

Interferometric GW detectors work in dark fringe condition: **vacuum fluctuations** entering the dark port of an interferometer is responsable for quantum noise.

Attended sensitivity curve



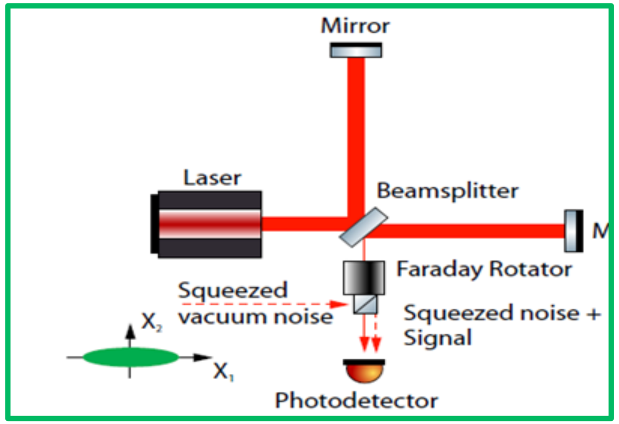
RADIATION PRESSURE NOISE (RPN)

(**amplitude** quadrature fluctuations)

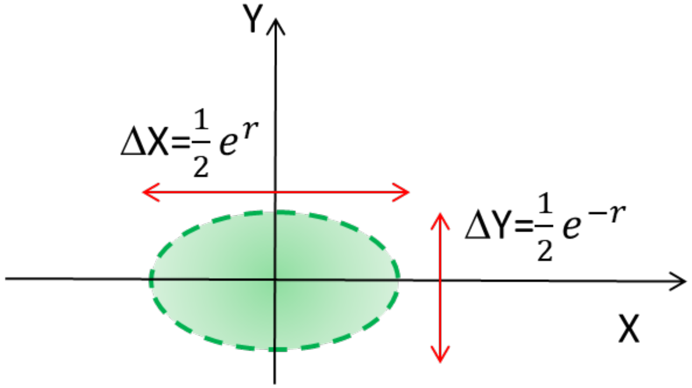
SHOT NOISE (SHN)

(**phase** quadrature fluctuations)

Current detectors are only limited by shot noise

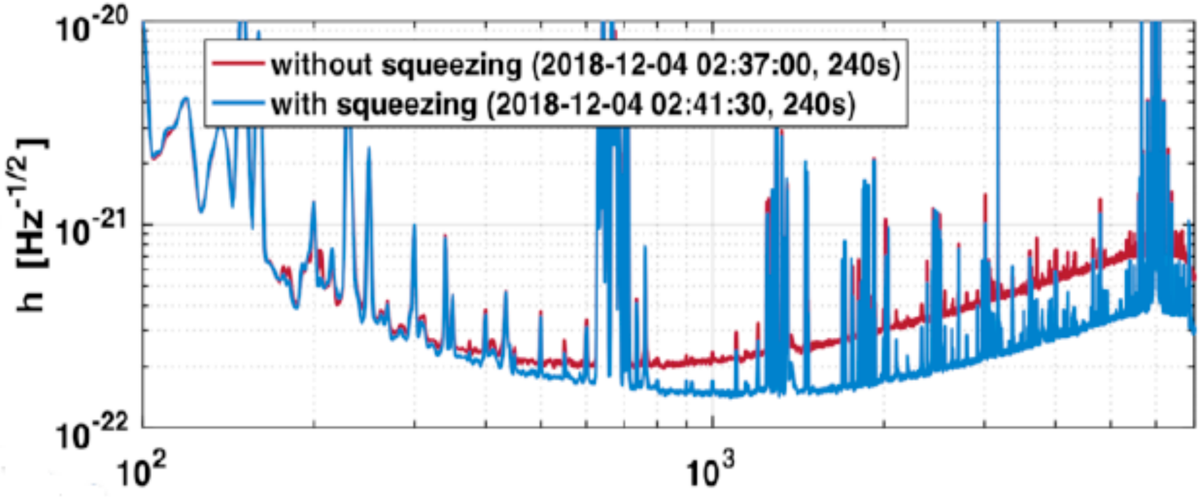


Injection of a reduced phase fluctuation (phase squeezed) vacuum field from the dark port

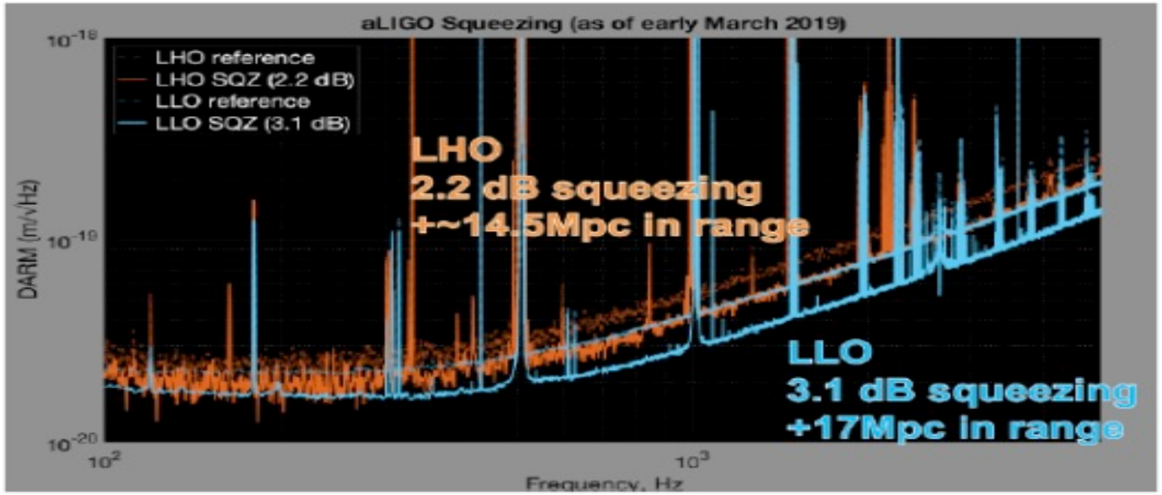


Sensitivity improvement using Frequency Independent Squeezing

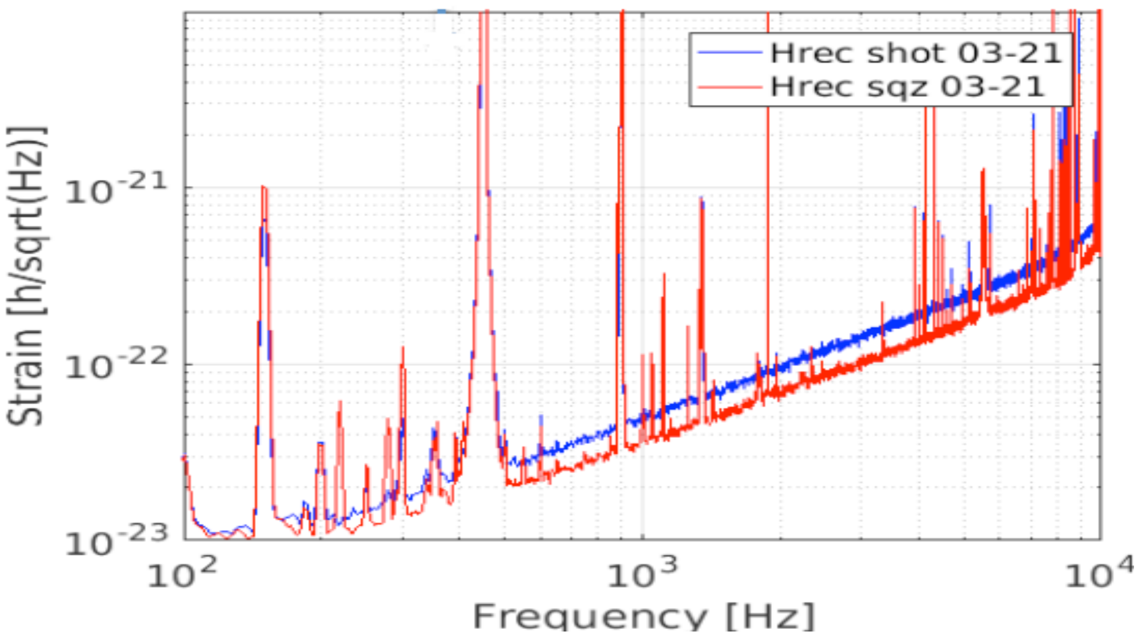
GEO600: 6 dB



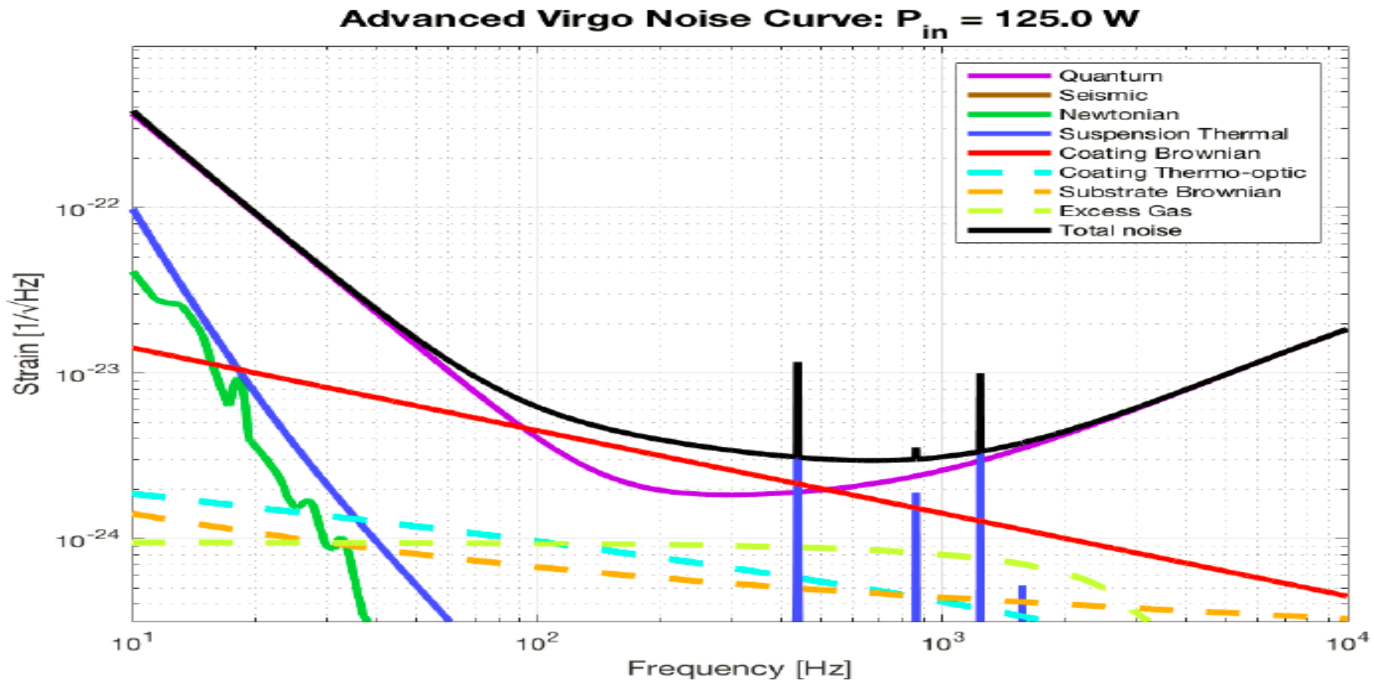
aLIGO: LLO 3.1 dB, LHO 2.2 dB



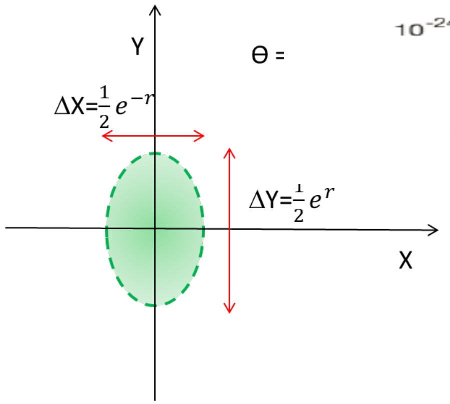
Advanced Virgo: 3.1 dB
(collaboration with AEI)

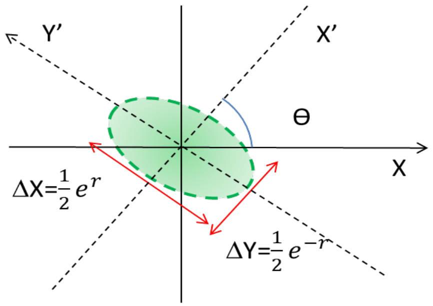


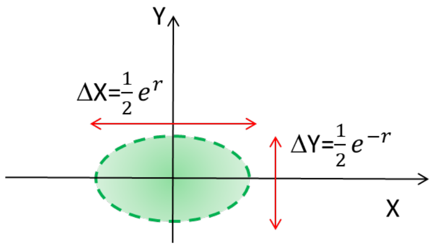
Need for a Frequency Dependent Squeezing (FDS) in the next generation detectors



J.P. Zendri
(VIR-0335A-19)



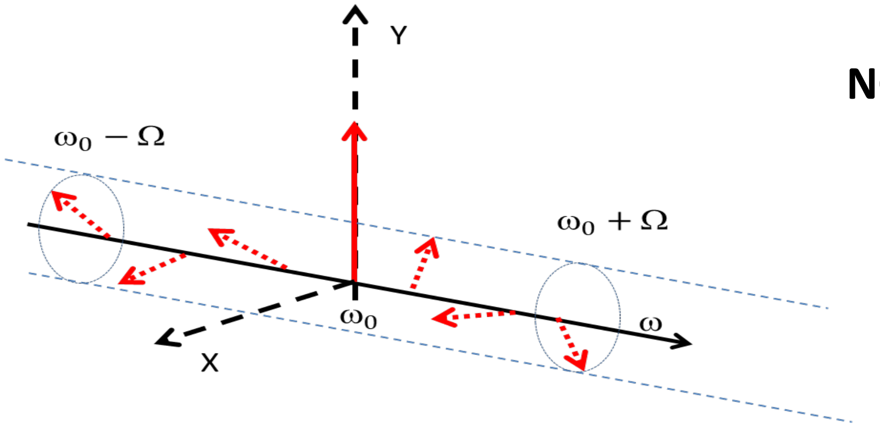




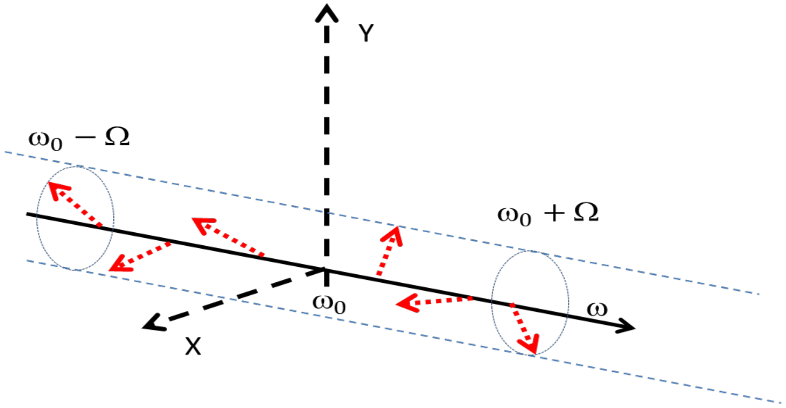
FREQUENCY DEPENDENT Squeezing angle rotation

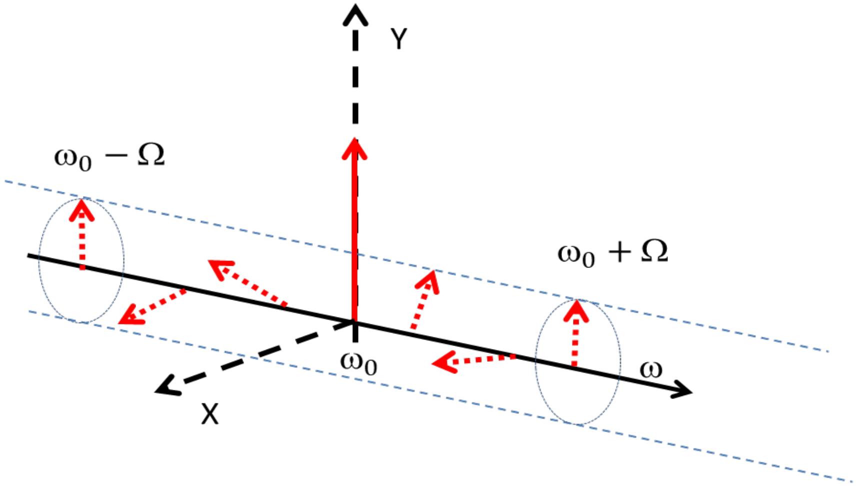
Sideband representation of quantum noise

coherent field | coherent vacuum field

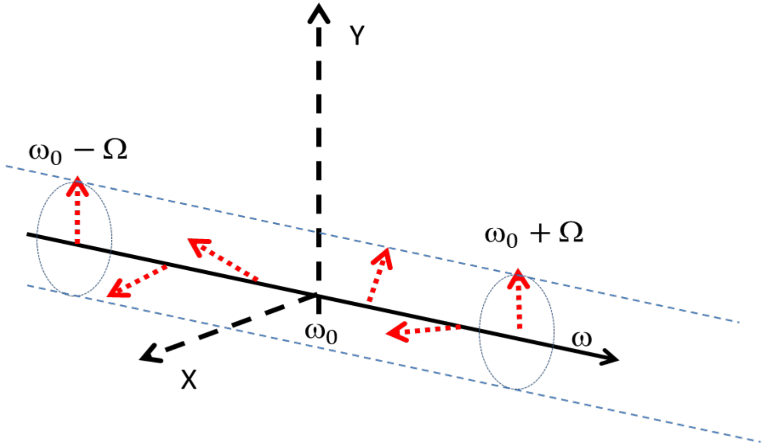


NO-SQUEEZING





SQUEEZING AT THE FREQUENCY Ω



Filter Cavity (FC) for a frequency dependent angle rotation

What does it happen if we inject a squeezed field in a cavity? A cavity has a frequency dependent response

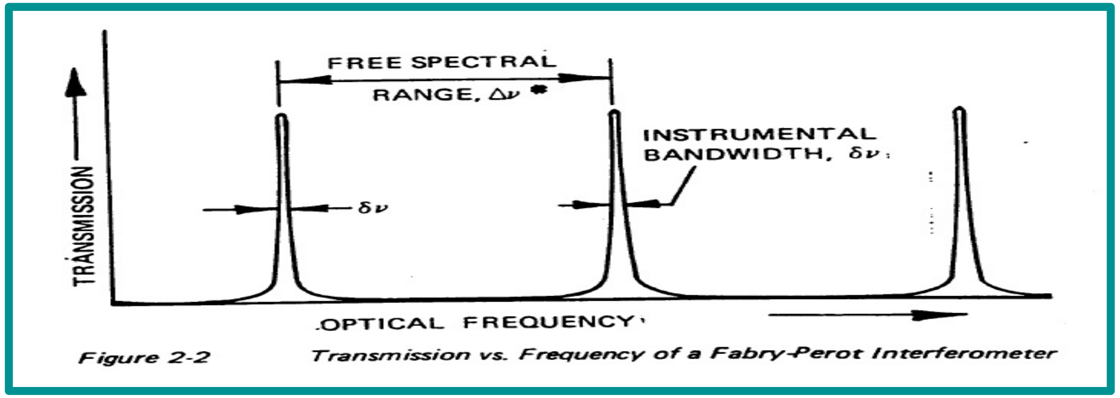


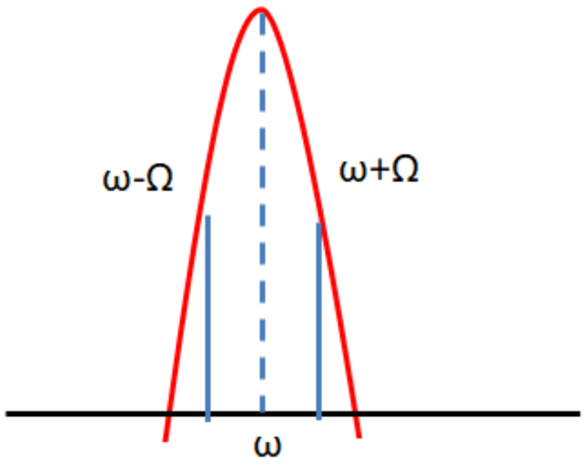
Figure 2-2 *Transmission vs. Frequency of a Fabry-Perot Interferometer*

Rotation induced by a Fabry-Perot cavity at a frequency Ω

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

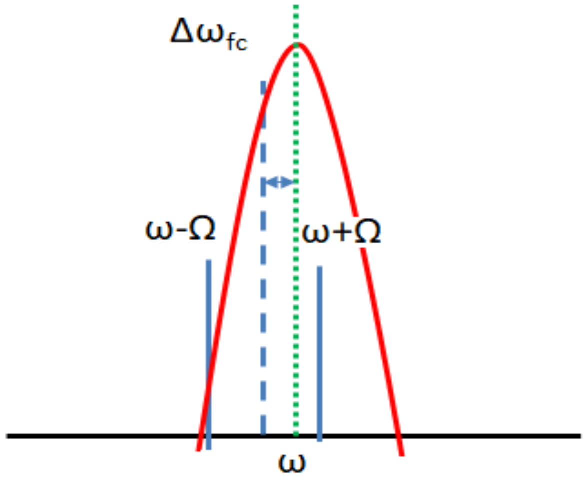
<

TUNED CONFIGURATION



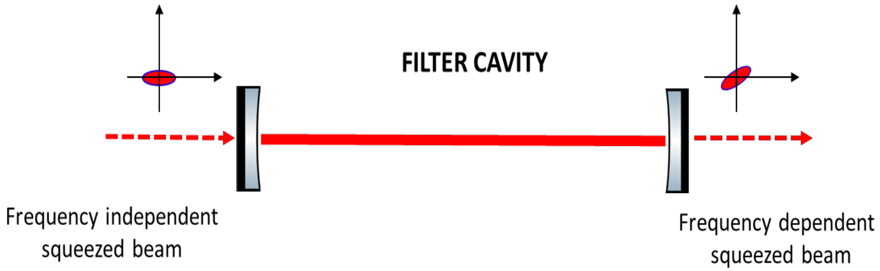
Quantum noise sidebands experience the same rotation

DE-TUNED CONFIGURATION



Quantum noise sidebands experience different rotations

Cavity parameters to take into account
- linewidth γ_{fc}
- detuning $\Delta\omega_{fc}$



A **detuned** Fabry-Perot cavity can rotate the squeezing angle in a frequency-dependent way

Filter Cavity state of the art 1

For a broadband QN reduction in GW detectors

case of a lossless cavity

$$\theta_{fc}(\Omega) = \arctan\left(\frac{\Omega_{SQL}}{\Omega}\right)^2$$

FREQUENCY DEPENDENT

The crossover frequency depends on ITF parameters

$$\Omega_{SQL} = \left(\frac{t_{sr}}{1+r_{sr}}\right)\frac{8}{c}\sqrt{\frac{P_{arm}\omega_0}{mT_{arm}}}$$

RPN→SHN

Filter Cavity parameters we need

$$\Delta w_{fc} = \gamma_{fc} = \frac{\Omega_{SQL}}{\sqrt{2}}$$

ALREADY DEMONSTRATED

- **2005:** first demonstration in MHz region.
  The cavity length was L=0.5 m (**Chelkowski et al. Phys. Rev. A 71 (Jan, 2005) 013806**)
- **2015:** first demonstration in kHz region.
  The cavity length was L=2 m (**Oelker et al. Phys. Rev. Lett. 116 (Jan, 2016) 041102**)

Filter Cavity state of the art 2

Need to have a long cavity:

- minimize the ratio between the round trip losses (RTL) and the cavity length

(**F. Ya. Khalili, Phys. Rev. D 81, 122002 (2010)**)

- longer is the cavity less is the losses influence (**VIR-0660A-18**) →lower finesse

IN PROGRESS

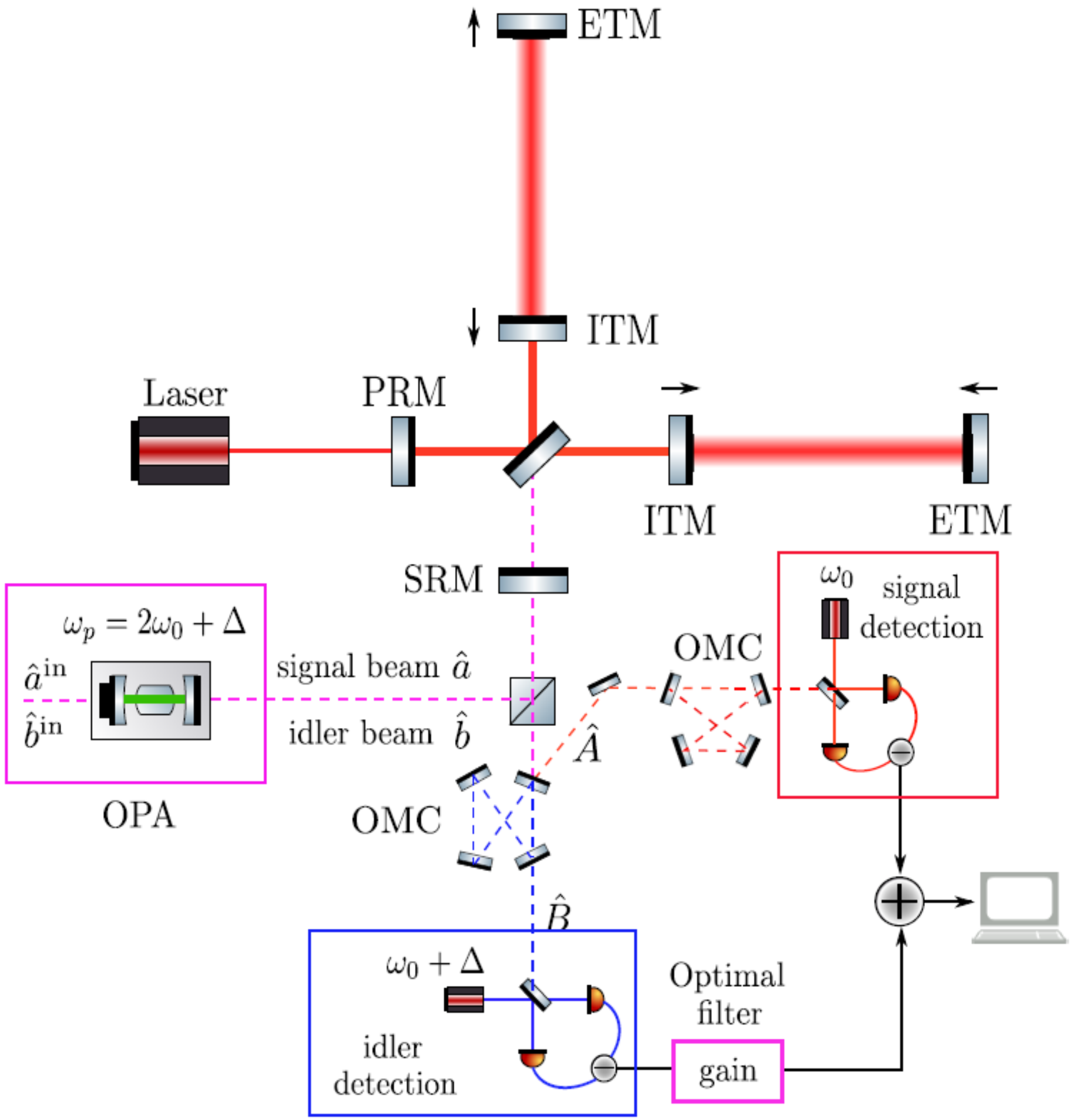
- **TAMA** National Astronomical Observatory of Japan (NAOJ): plan for a FC 300m long and a rotation frequency 70 Hz. Plan to have FDS in 2020 (**LIGO-G1900573**)

PLANNED

- **Advanced Virgo: design for a FC in progress, plan to use it in O4**
- **LIGO**Plan to develop in LIGO a FC for a rotation angle at about 50Hz

Proposed alternative to Filter Cavity: Frequency Dependent Squeezing via EPR entanglement

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



ITF de-tuned for the idler

ITF like a Filter Cavity for Idler

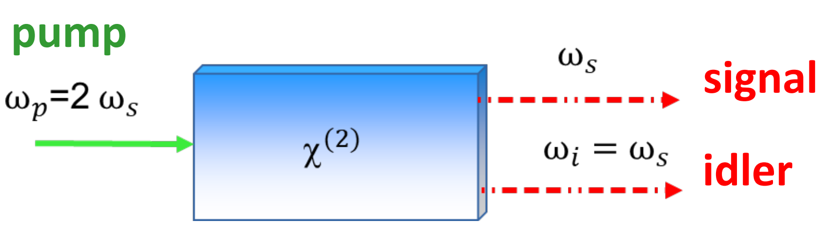
Idler frequency-dependent squeezed

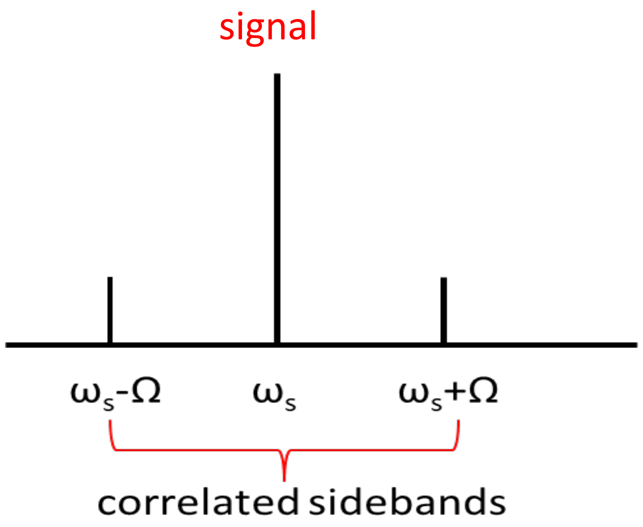
Measurement of an idler fixed quadrature

SIGNAL CONDITIONALLY SQUEEZED IN A FREQUENCY DEPENDENT WAY

Einstein-Podolsky-Rosen (EPR) entangled signal and idler beams

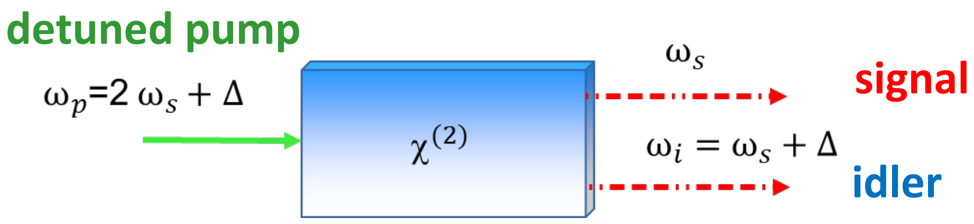
DEGENERATE OPO

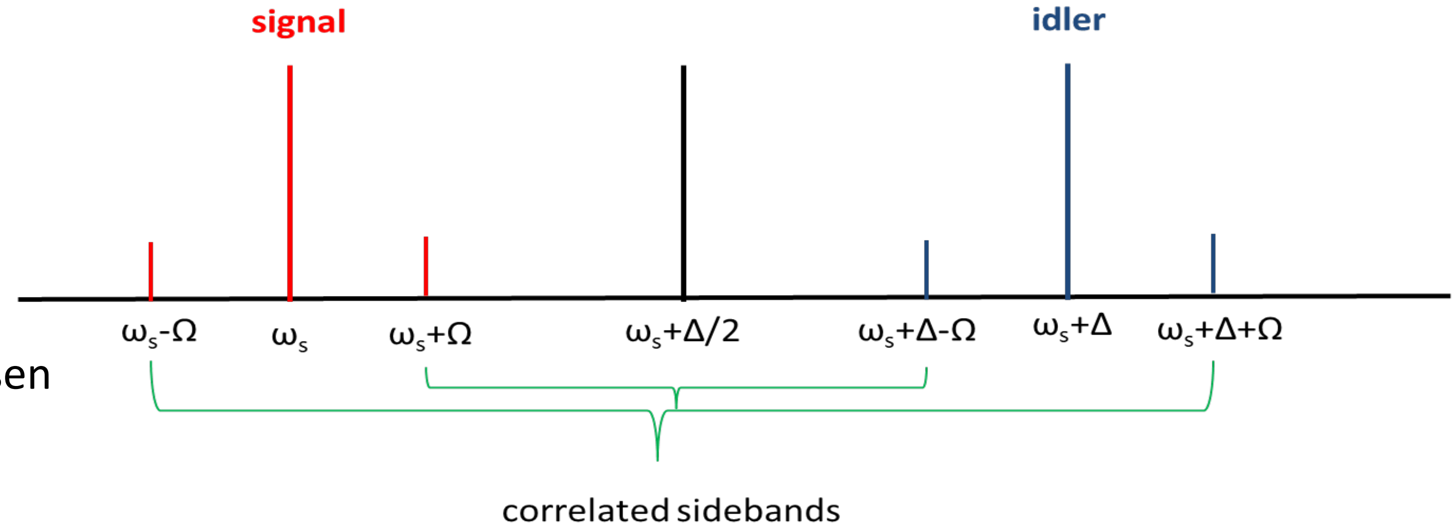




$\omega_S \rightarrow$ ***interferometer frequency***

NON-DEGENERATE OPO





The two produced beams are Einstein-Podolsky Rosen (EPR) entangled

Comparison with Filter Cavity

Loss sources

- Loss due to arm cavities (90 ppm per round trip, around~ 4%)
- Loss due to Signal Recycling Cavity (2000 ppm per RT)
- Input and Readout losses

→

- Two squeezed beams: double losses

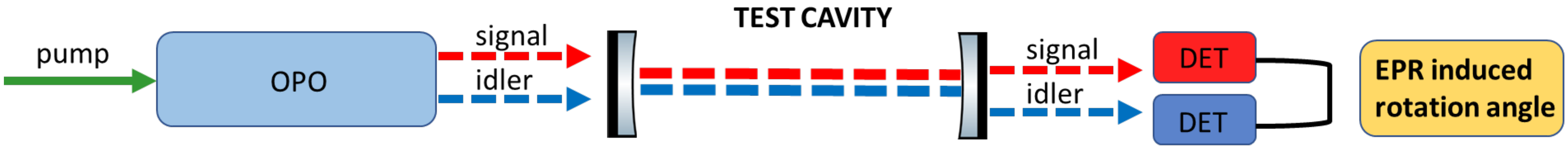
- Need for two Homodyne Detectors and extra OMC

BUT

- Less expensive
- Avoids the 1ppm/m round trip losses for the FC
- **Flexible vs Signal Recycling Cavity configuration**

Table-top demonstrator

Test of the EPR induced rotation angle by injecting the two entangled beams in a cavity instead of the interferometer



A recent demonstration was performed by the Quantum Optics group of Prof. Schnabel at Institute for Laser Physics and University of Hamburg, Germany, using a simplified setup.
(results shown at the LVC that took place in Geneve in March 2019. Talk: “Demonstration of Interferometer Enhancement through EPR Entanglement”. Speaker: Jan Gniesmer)

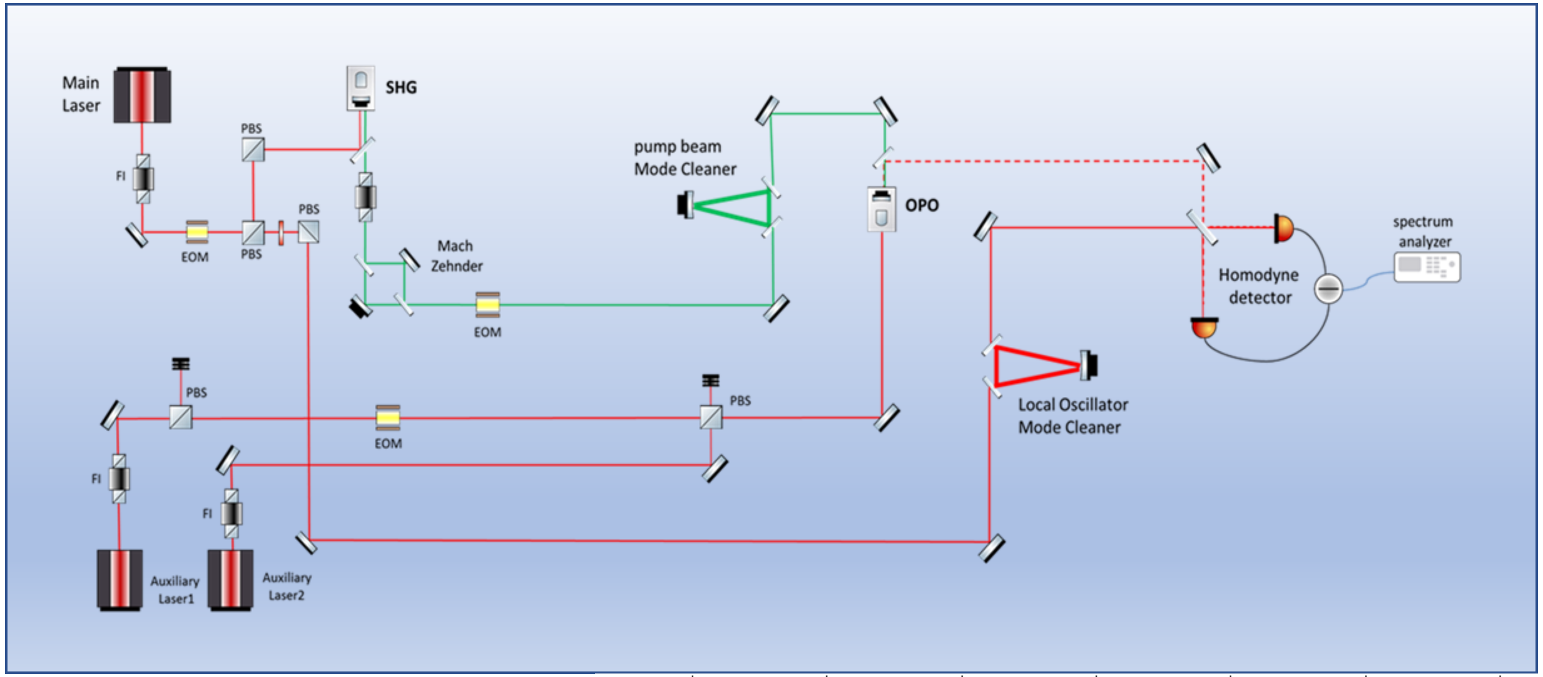
We also propose a table-top demonstrator starting from a test facility for FIS demonstration that we already develeped at the EGO site.

Our demonstrator will be tested on SIPS setup (INFN comm. 5 Roma1) that is a RPN sensitive system. We expect to see noise reduction below 2 kHz.

SIPS experiment (L.Naticchioni et al.)

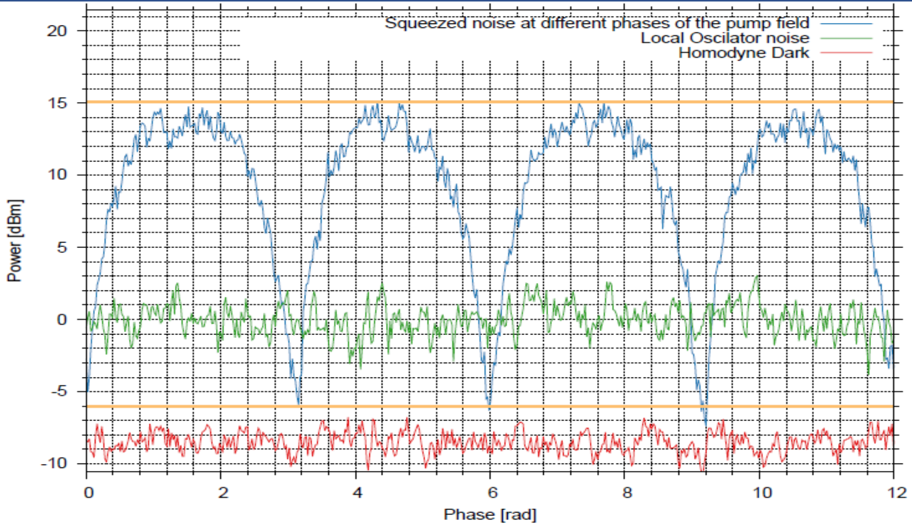
Starting point

Squeezing experiment already developed

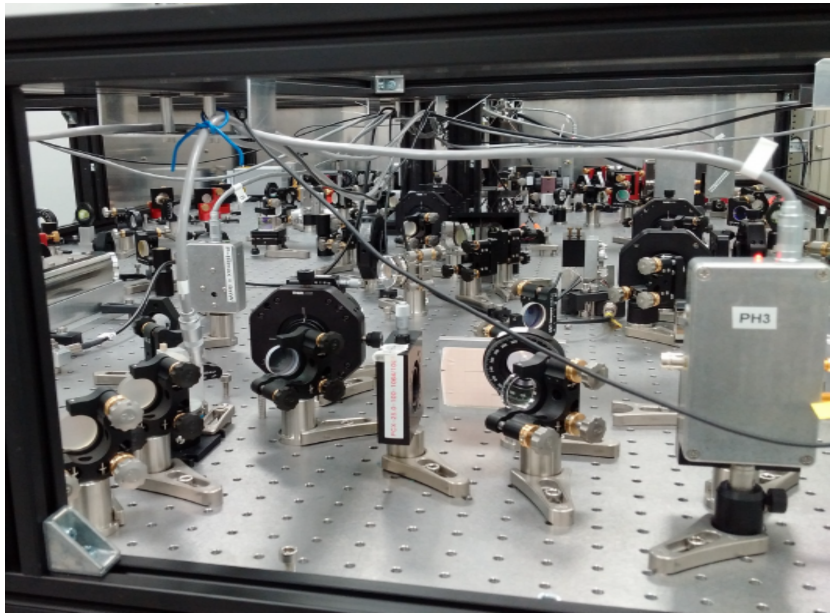


-6 dB of SQZ
15 dB of anti-SQZ
Central freq: 1 MHz

(M.Vardaro, PhD thesis)

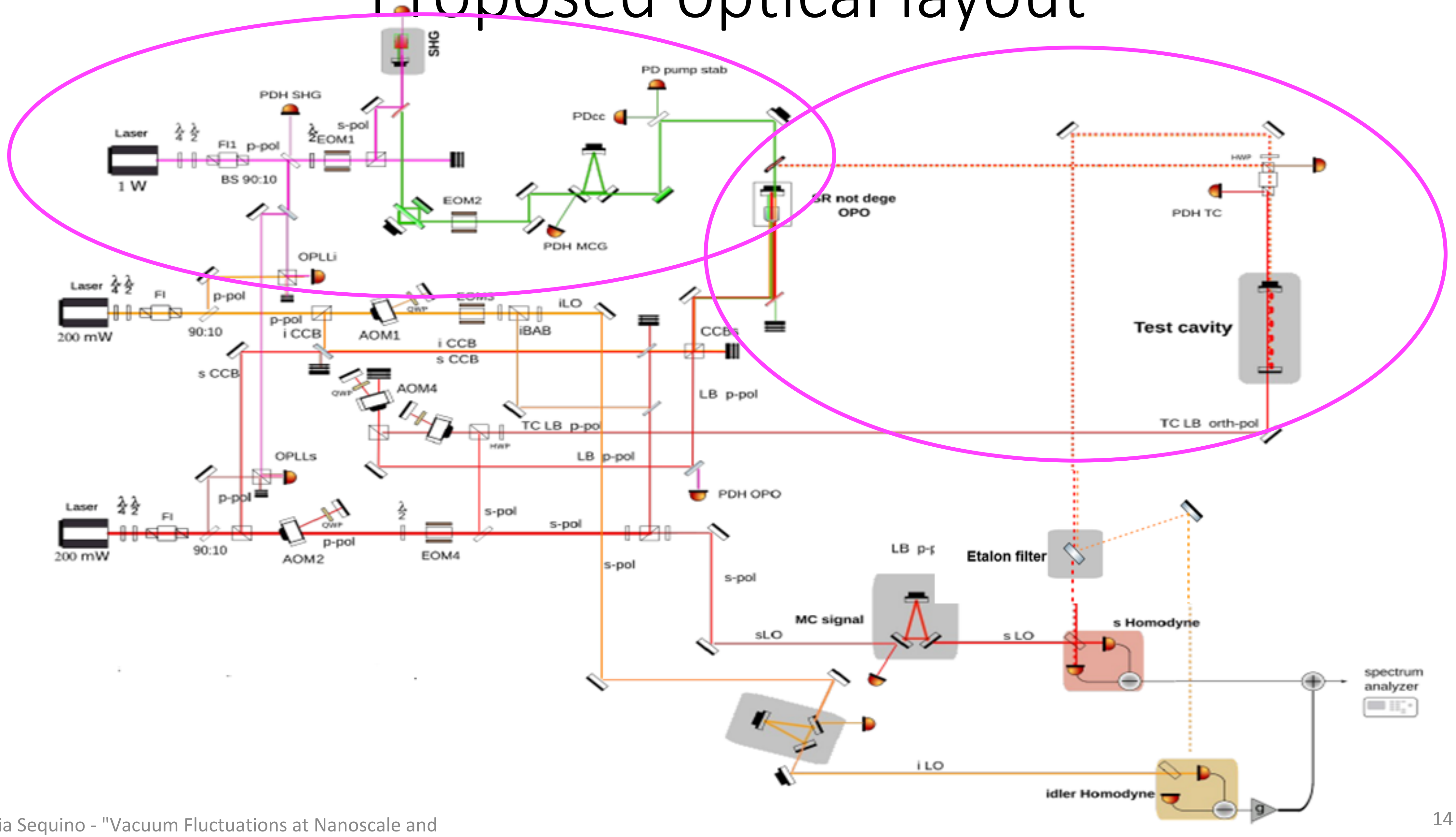


Located at the EGO site, at half of the west arm (1500 W)

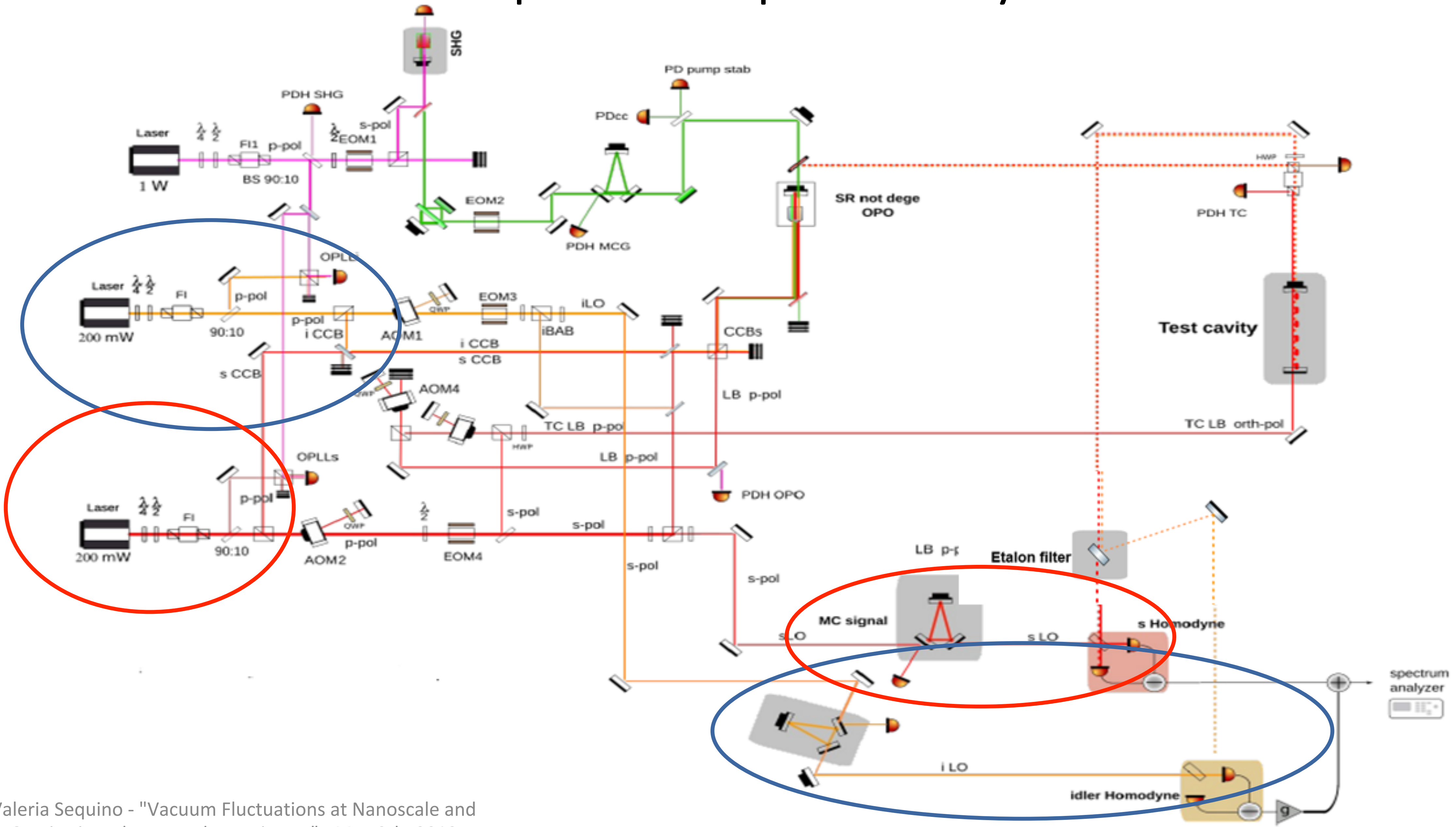


Our optical bench in 1500W

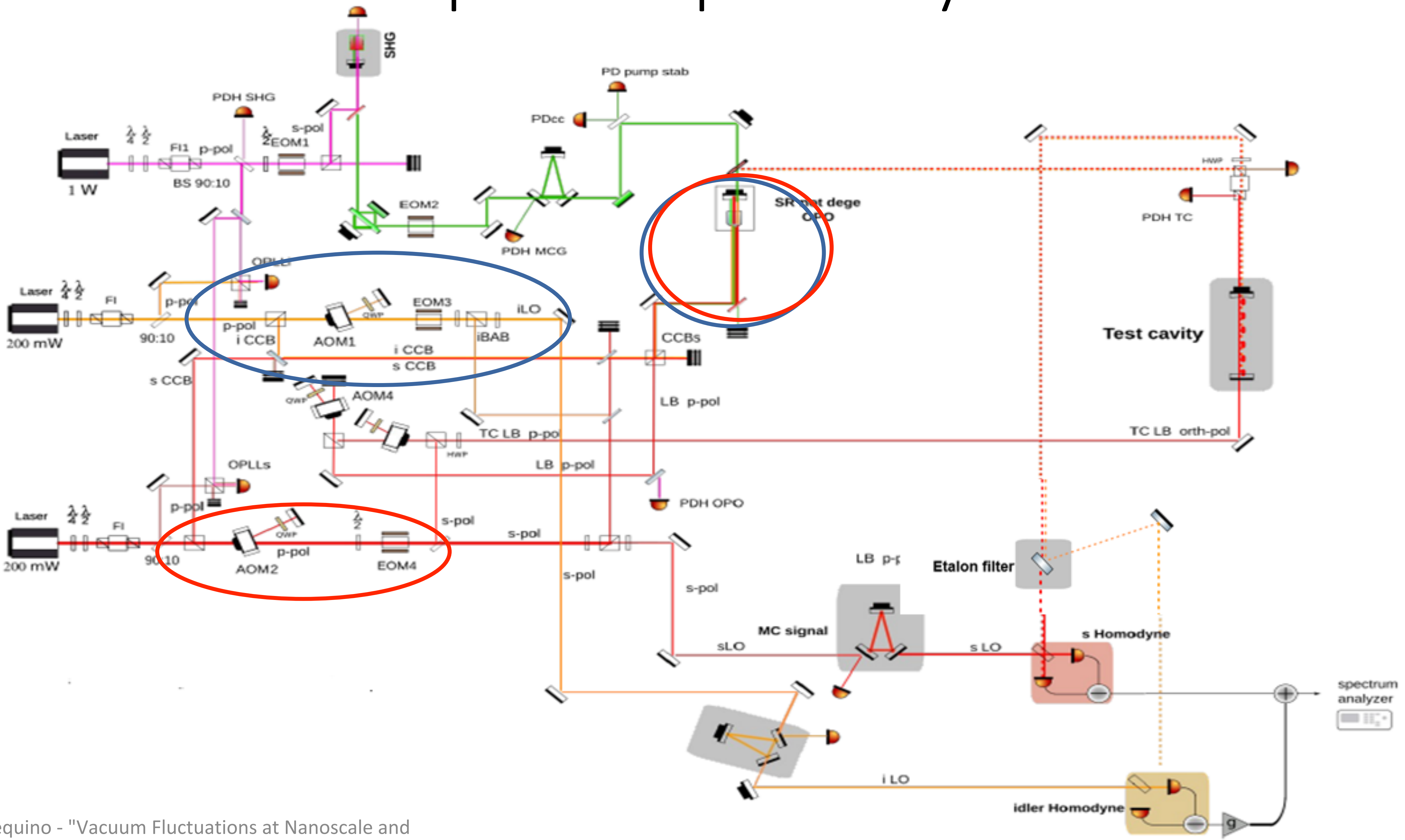
Proposed optical layout



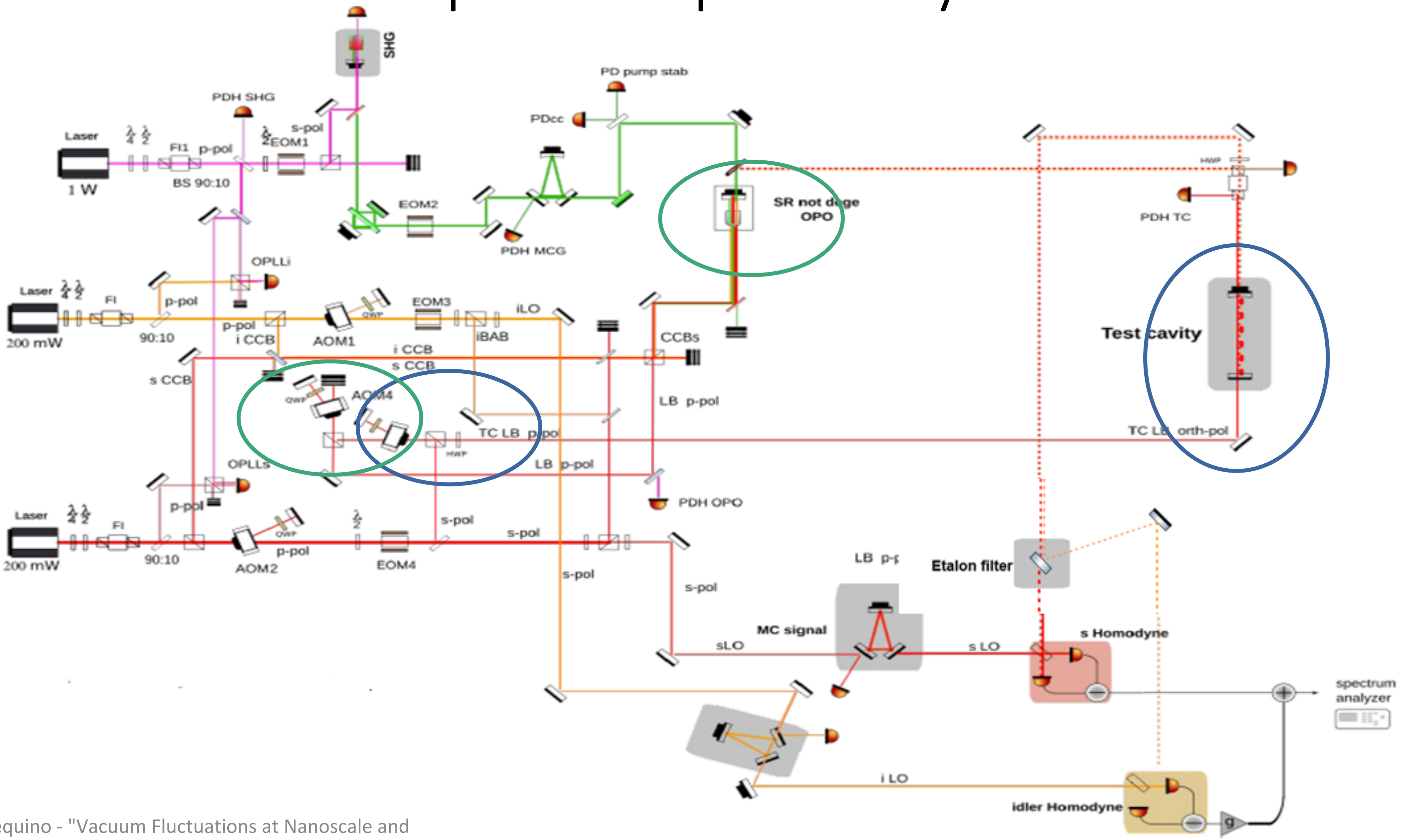
Proposed optical layout



Proposed optical layout

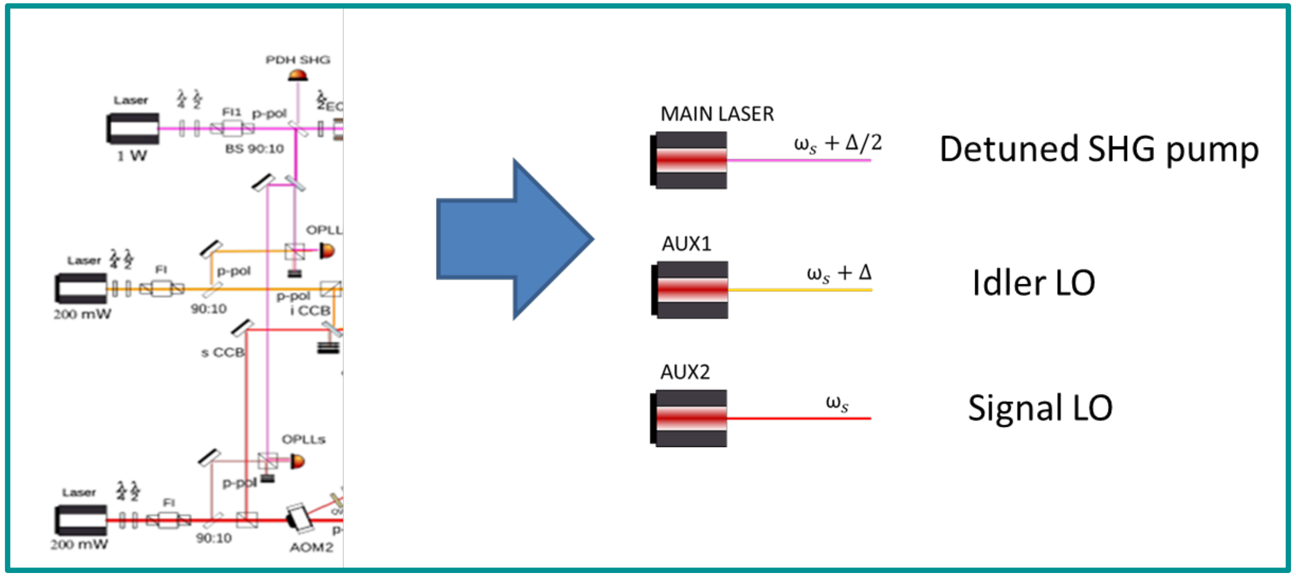


Proposed optical layout

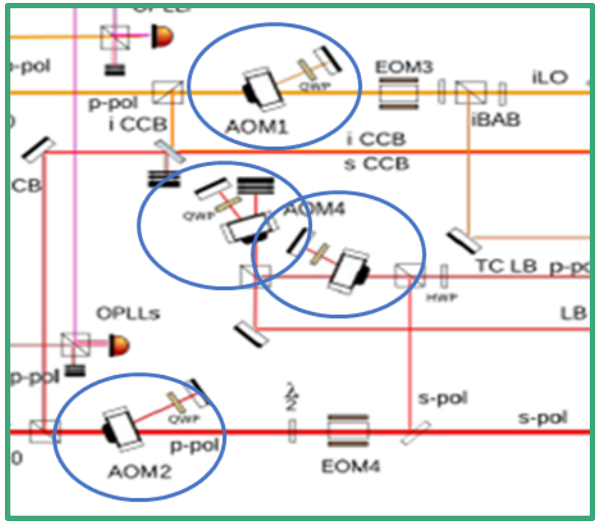


Changes w.r.t. to the present setup

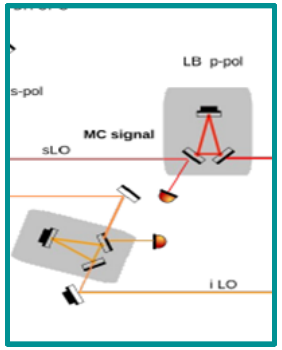
TWO FAST OPPLs (Δ~ 2GHz)



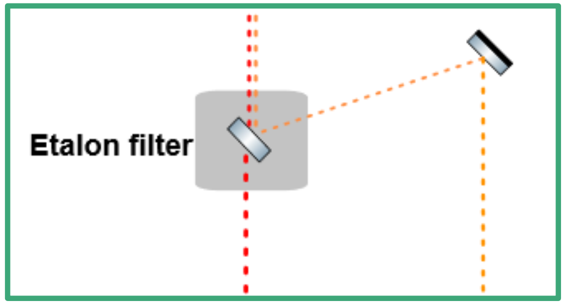
FOUR AOMs



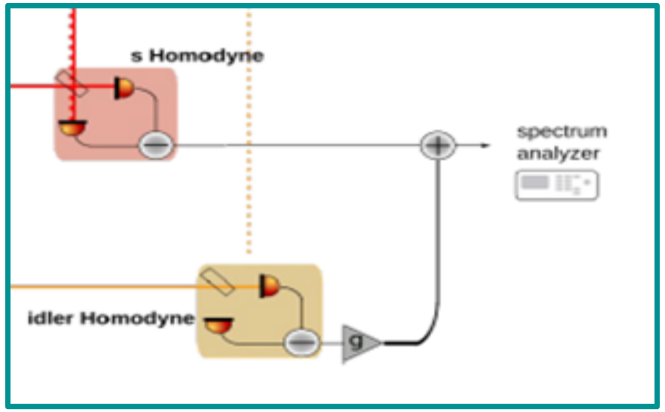
Extra MC



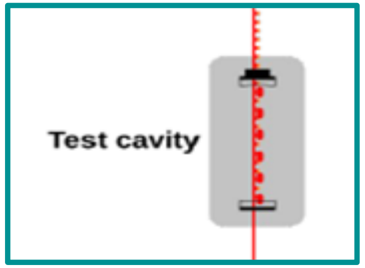
ETALON TO SEPARATE THE TWO BEAMS



TWO HDs



TEST CAVITY



Conclusions

- Present GW detectors: Frequency Independent Squeezing (FIS) already implemented

High frequency sensitivity improvement achieved for the present observative run (O3)

- Future detectors: Frequency Dependent Squeezing in order to achieve broadband quantum noise reduction. Two solutions presented:

    ❖ Filter cavity: planned for the next observative run (O4)

    ❖ EPR: experiment under construction (post O4, future detectors)

Thank you!!

Signal and Idler quadrature are EPR entangled

$$\hat{a}_1(\Omega) = \frac{\hat{a}(\omega_0+\Omega)+\hat{a}^\dagger(\omega_0-\Omega)}{\sqrt{2}}$$
$$\hat{a}_2(\Omega) = \frac{\hat{a}(\omega_0+\Omega)-\hat{a}^\dagger(\omega_0-\Omega)}{\sqrt{2}i}$$

$$\hat{b}_1(\Omega) = \frac{\hat{b}(\omega_0+\Delta+\Omega)+\hat{b}^\dagger(\omega_0+\Delta-\Omega)}{\sqrt{2}}$$
$$\hat{b}_2(\Omega) = \frac{\hat{b}(\omega_0+\Delta+\Omega)-\hat{b}^\dagger(\omega_0+\Delta-\Omega)}{\sqrt{2}i}$$

Amplitude and phase quadrature for signal and idler

$$S_{(\hat{a}_1\pm\hat{b}_1)/\sqrt{2}} = e^{\pm 2r}$$
$$S_{(\hat{a}_2\pm\hat{b}_2)/\sqrt{2}} = e^{\mp 2r}$$

We will have squeezing-antisqueezing for **combination of signal and idler** quadratures

$$\hat{b}_1 - \hat{a}_1$$
$$\hat{b}_2 + \hat{a}_2$$

These quadrature combinations will be both squeezed

Measuring the idler quadrature

$$\hat{b}_\theta = \hat{b}_1\cos\theta + \hat{b}_2\sin\theta$$

we can **squeeze** the signal with a squeezing angle θ

$$\hat{a}_{-\theta} = \hat{a}_1\cos\theta - \hat{a}_2\sin\theta$$

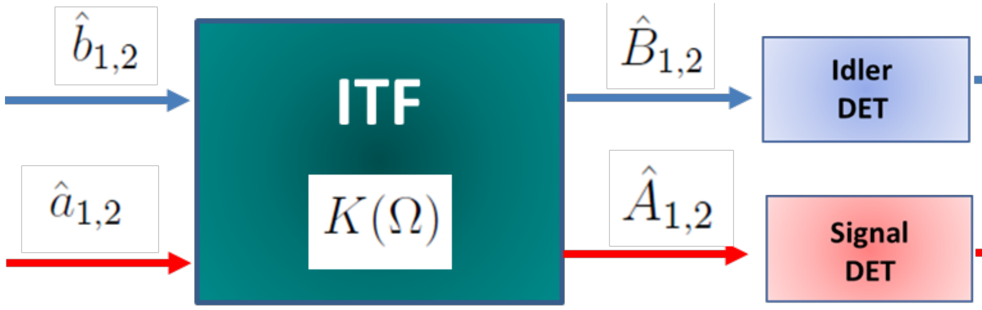
$$\hat{b}_{\theta_{itf}} = \hat{b}_1\cos\theta_{itf} + \hat{b}_2\sin\theta_{itf}$$

$$\hat{a}_{-\theta_{itf}} = \hat{a}_1\cos\theta_{itf} - \hat{a}_2\sin\theta_{itf}$$

Sensitivity detector improvement

$$K(\Omega) \equiv \arctan\left[\left(\frac{\Omega_{SQL}}{\Omega}\right)^2 \frac{\gamma_{itf}^2}{\Omega^2+\gamma_{itf}^2}\right]$$

Optomechanical coupling between vacuum fluctuations and test masses



$$\hat{B}_2 = e^{i\alpha}(-\hat{b}_1 \sin\Phi_{\text{rot}} + \hat{b}_2 \cos\Phi_{\text{rot}})$$

$$\Phi_{rot} = \arctan(K(\Omega))$$

$$\hat{A}_2 = e^{2i\beta}(\hat{a}_2 - K(\Omega)\hat{a}_1)$$
$$= e^{2i\beta}(\sqrt{1+K^2(\Omega)})(\hat{a}_1\cos\xi - \hat{a}_2\sin\xi)$$

$$\xi = -\arctan\left(\frac{1}{K(\Omega)}\right)$$

Contains SHN, RPN and output signal

To achieve the best sensitivity

$$\left(\hat{A}_2\right)_{opt} = \hat{A}_2 - g_{opt}\hat{B}_2$$

Wiener filter gain

$$g_{opt} = e^{i(2\beta-\alpha)}\sqrt{1+K^2(\Omega)}\tanh(2r)$$

FREQUENCY DEPENDENT SQUEEZED VARIANCE

$$S^{cond}_{\hat{A}_2\hat{A}_2} = \frac{1+K^2(\Omega)}{\cosh(2r)}$$