EPR experiment for a broad-band quantum noise reduction in gravitational wave detectors

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on behalf of the EPR squeezing group

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GRASS Padova 2019

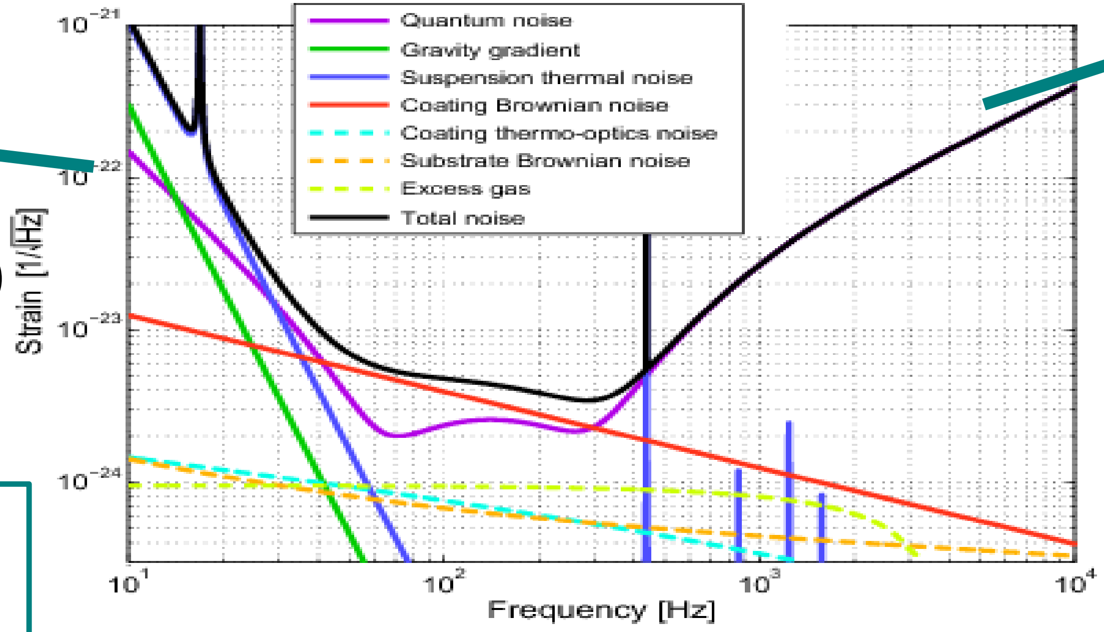
Quantum noise in the current GW detectors

vacuum fluctuations entering the dark port of an interferometer are responsable for quantum noise

RADIATION PRESSURE NOISE (RPN)

(**amplitude** quadrature fluctuations)

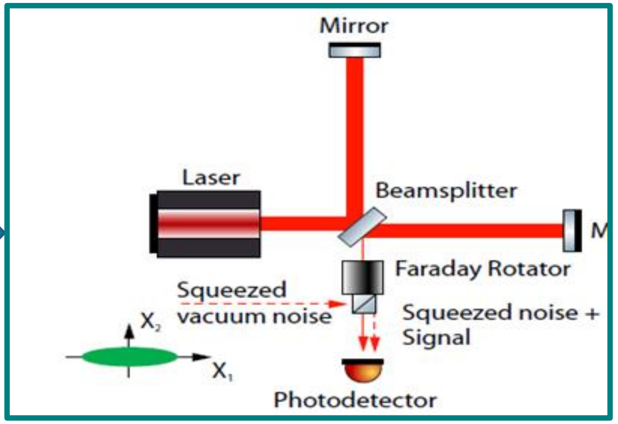
Attended sensitivity curve



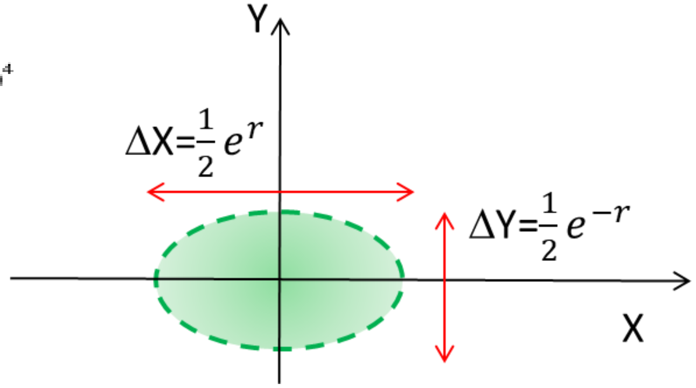
SHOT NOISE (SHN)

(**phase** quadrature fluctuations)

Current detectors are only limited by shot noise

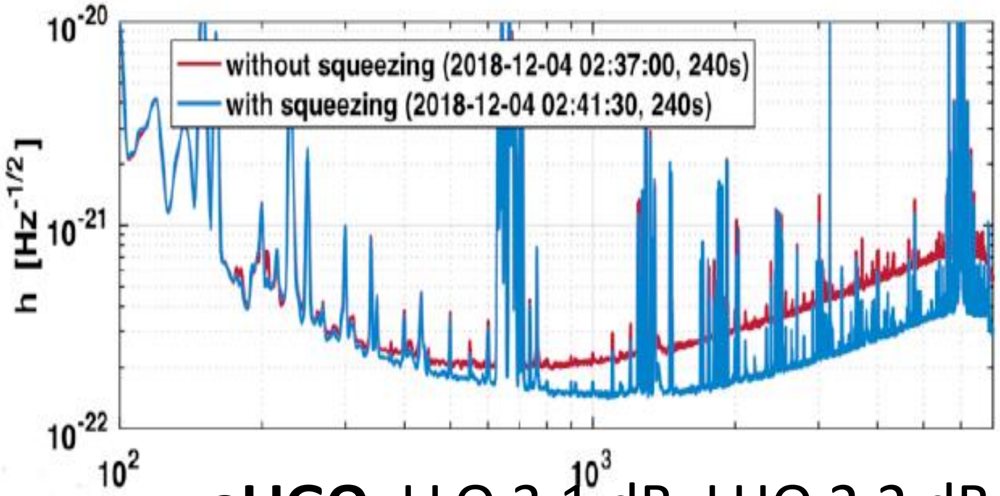


Injection of a reduced phase fluctuation (phase squeezed) vacuum field from the dark port

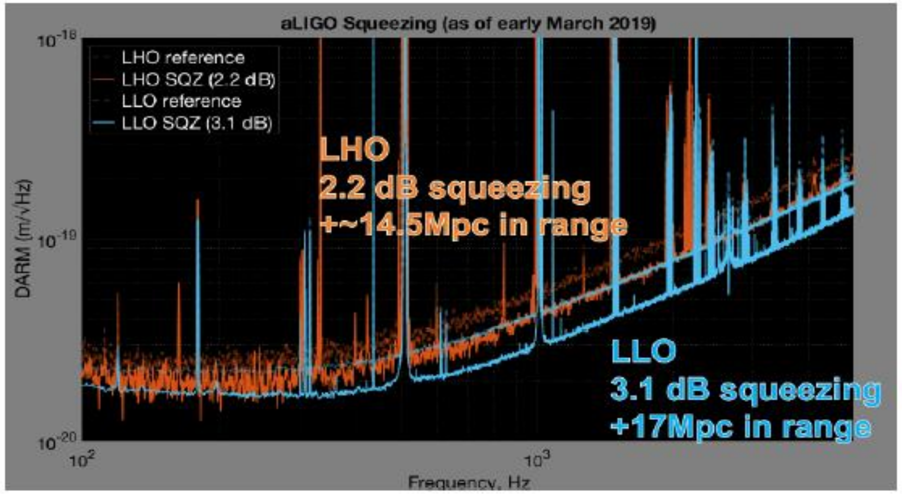


Sensitivity improvement using Frequency Independent Squeezing

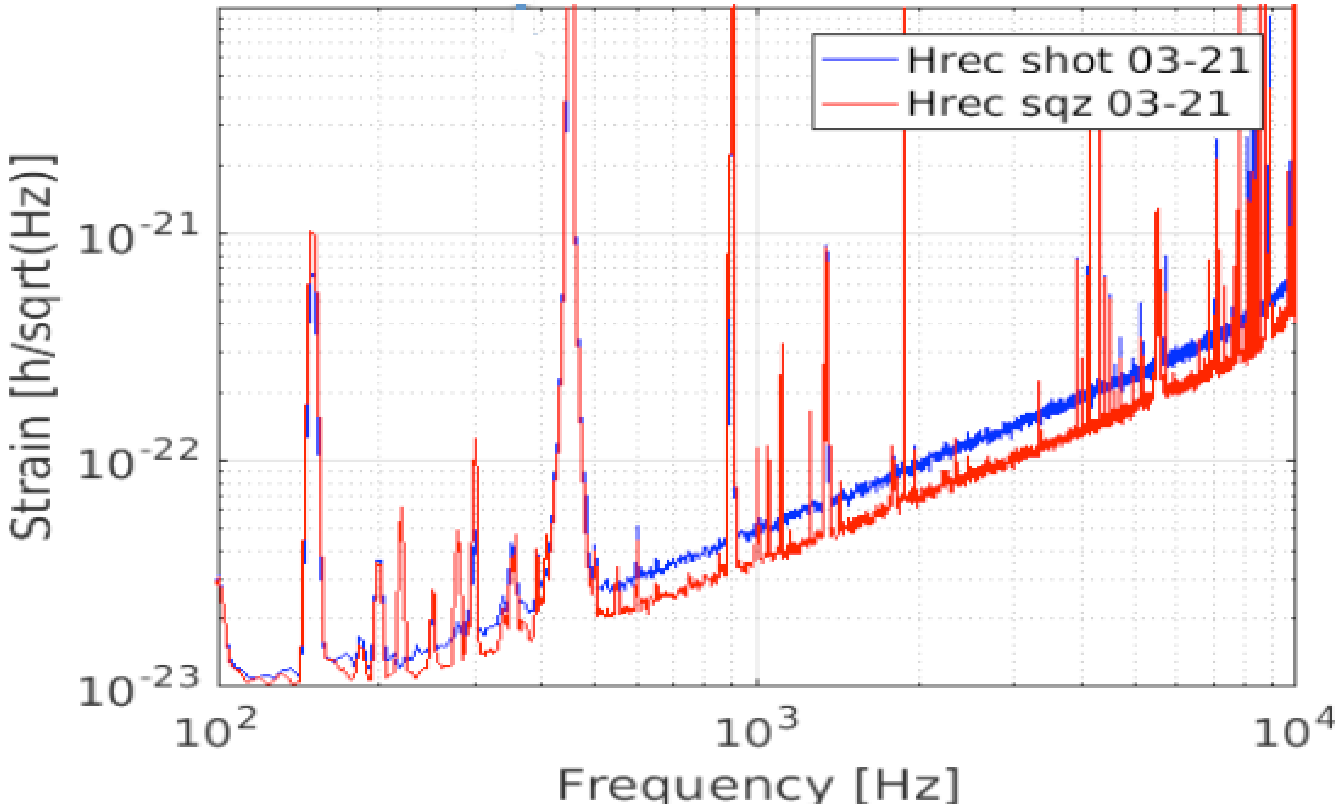
GEO600: 6 dB (see talk F.Bengamin's talk)



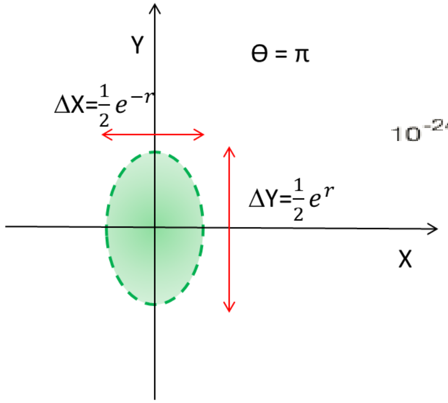
aLIGO: LLO 3.1 dB, LHO 2.2 dB

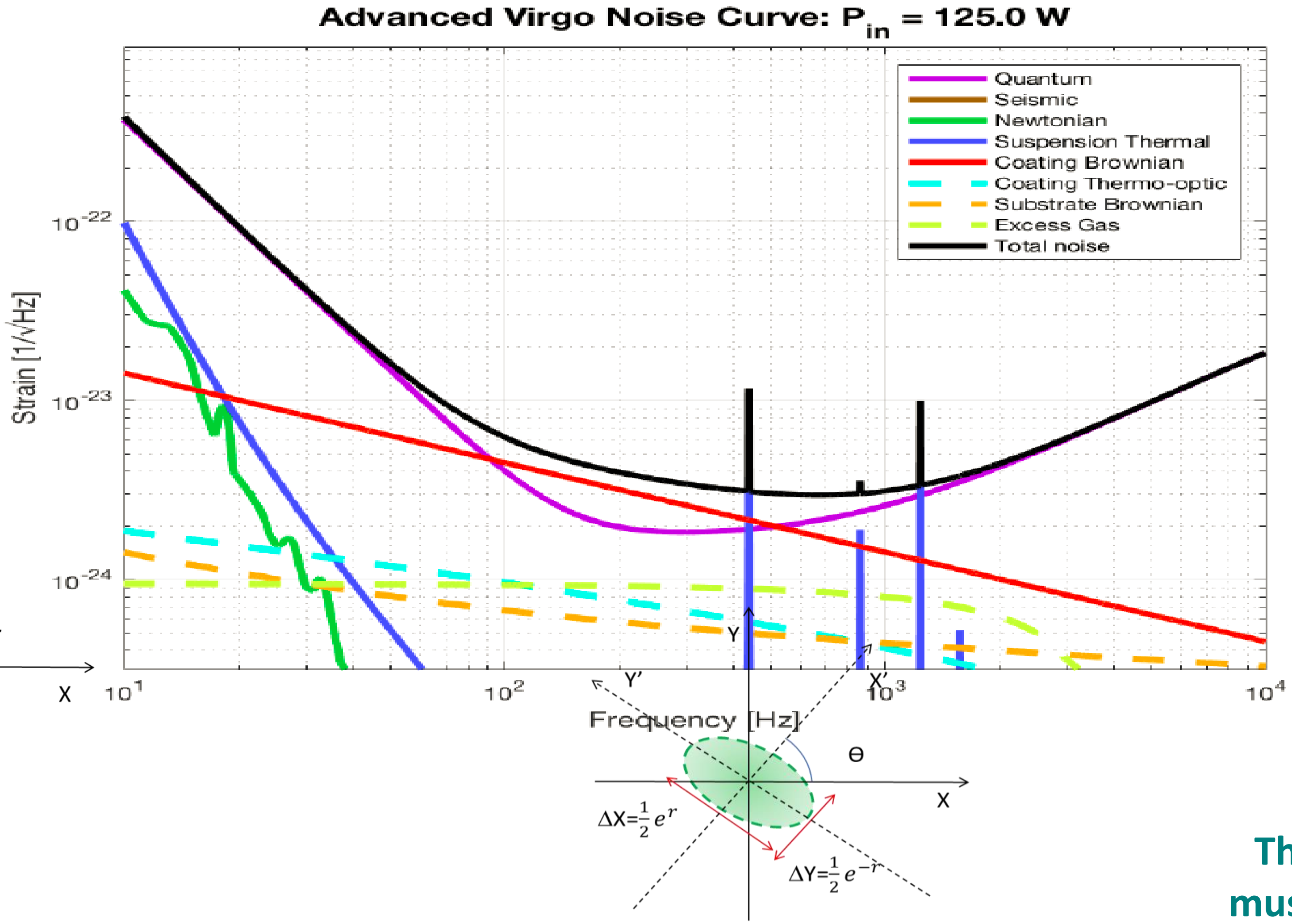


Advanced Virgo: 3.1 dB
(in collaboration with AEI)

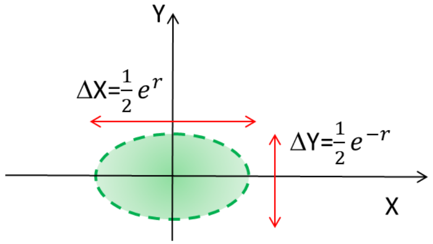


Need for a Frequency Dependent Squeezing (FDS) in the next generation detectors





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



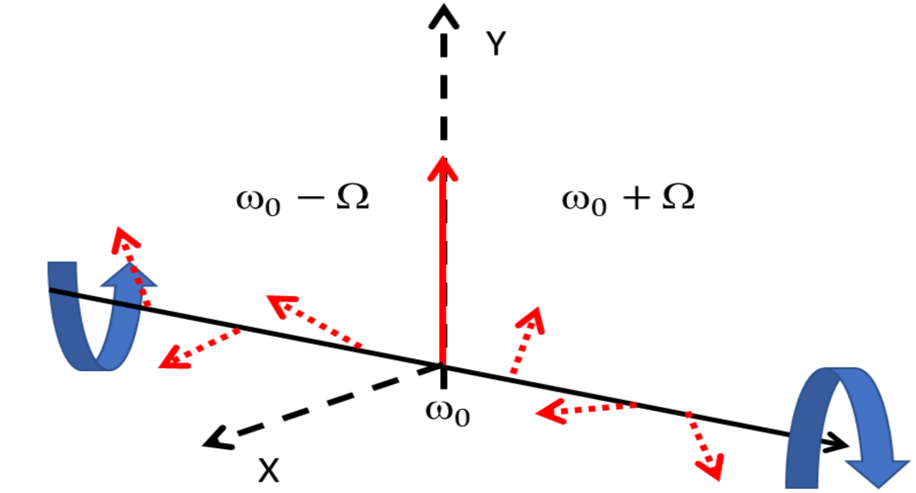
The squeezed quadrature must be always aligned with the gravitational signal

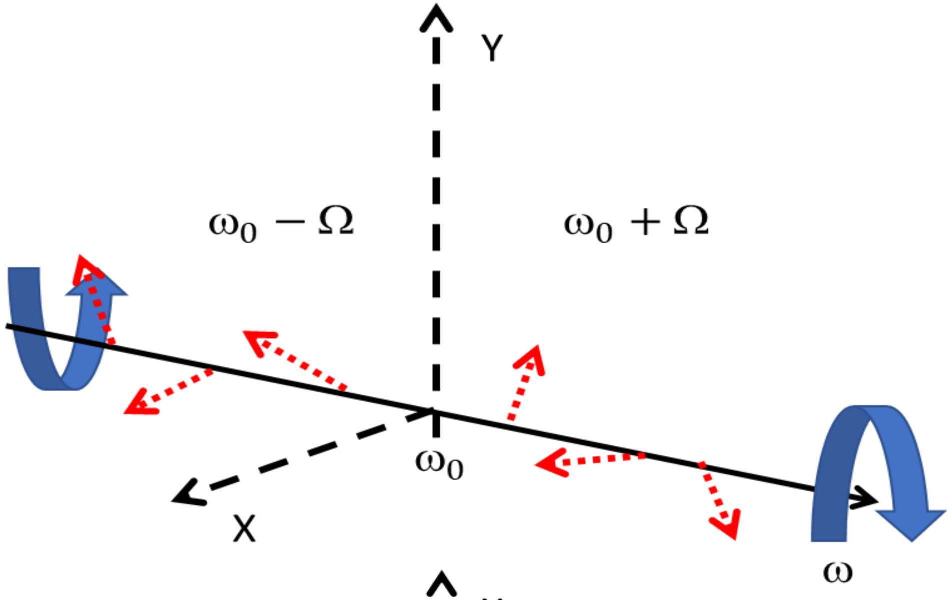
FREQUENCY DEPENDENT Squeezing angle rotation

Sideband representation of quantum noise

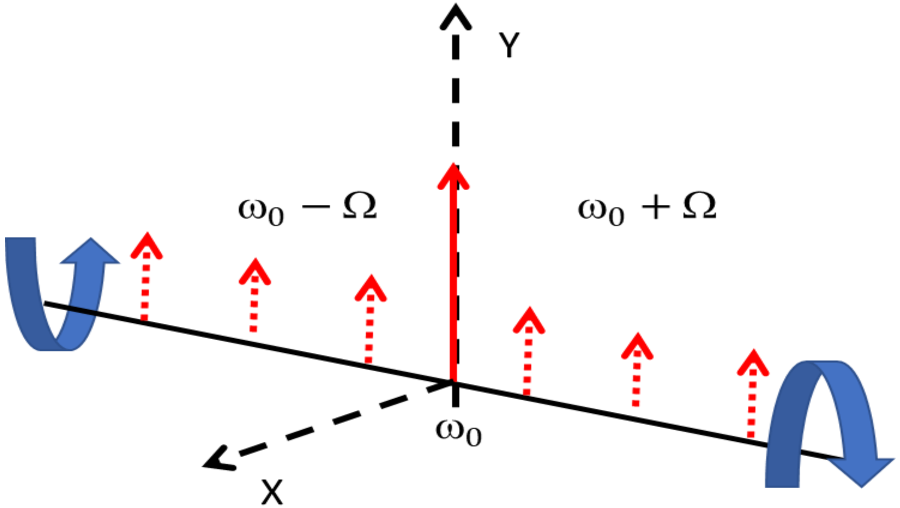
coherent field | **coherent VACUUM field**

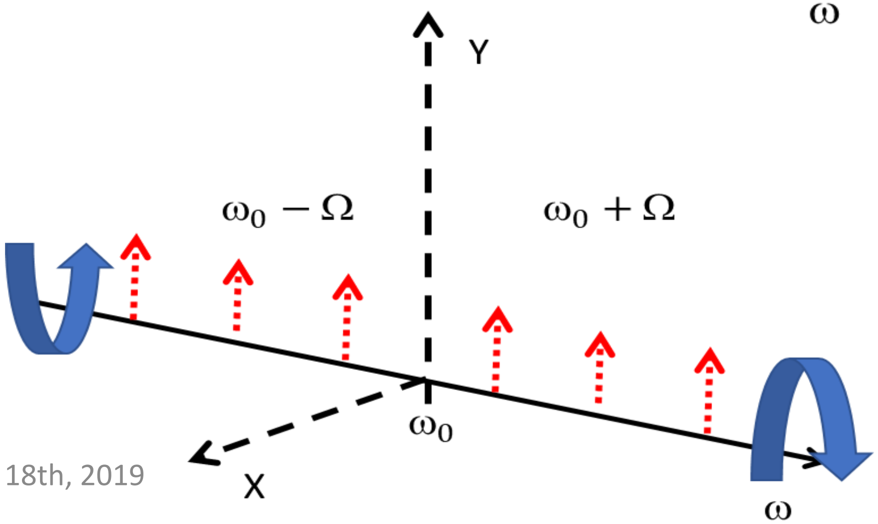
NO-SQUEEZING





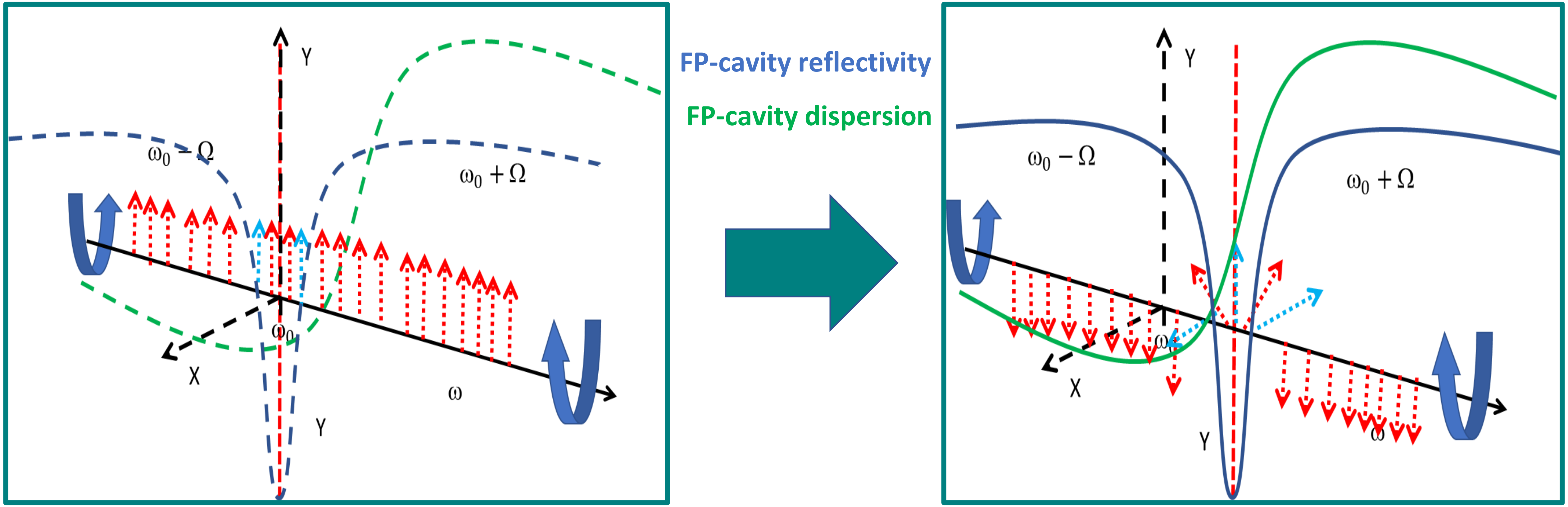
SQUEEZING





Fabry-Perot cavity frequency dependent response

What does it happen if we inject a squeezed field in a cavity?



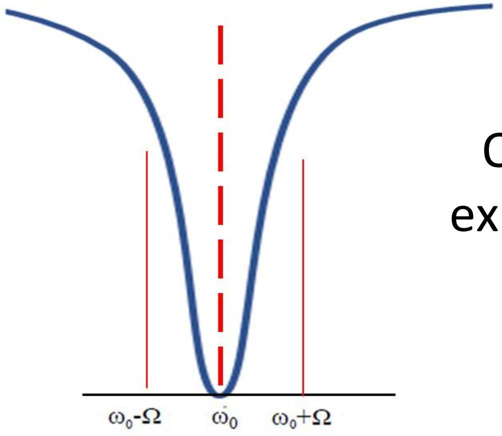
Why a detuned Filter Cavity ?

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

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

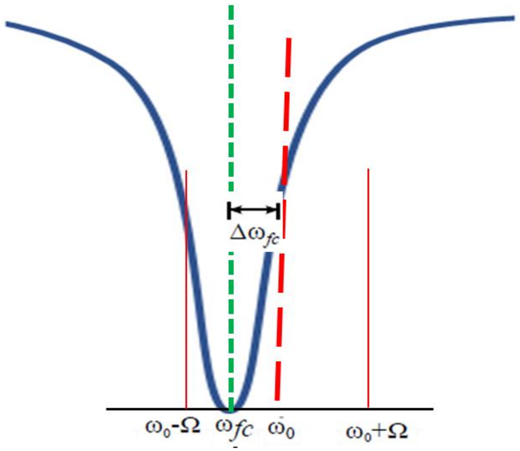
Cavity parameters to take into account

- linewidth γ_{fc}
- detuning $\Delta\omega_{fc}$



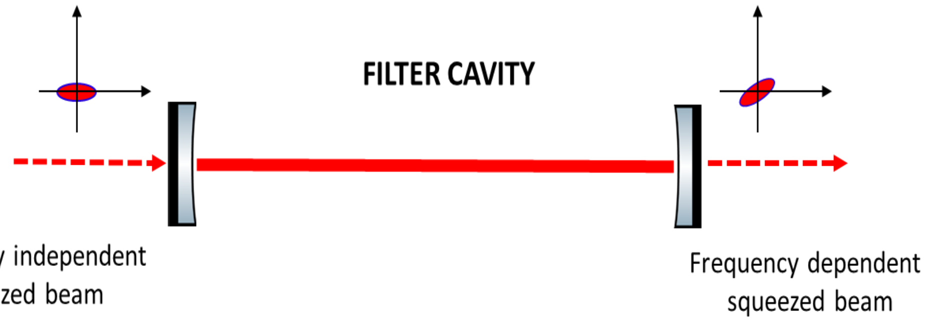
Quantum noise sidebands experience the same rotation

TUNED CONFIGURATION



Quantum noise sidebands experience different rotations

DE-TUNED CONFIGURATION



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

The crossover frequency depends on ITF parameters

Filter Cavity parameters we need

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

FREQUENCY DEPENDENT ROTATION
case of a lossless cavity

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

RPN→SHN

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

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)

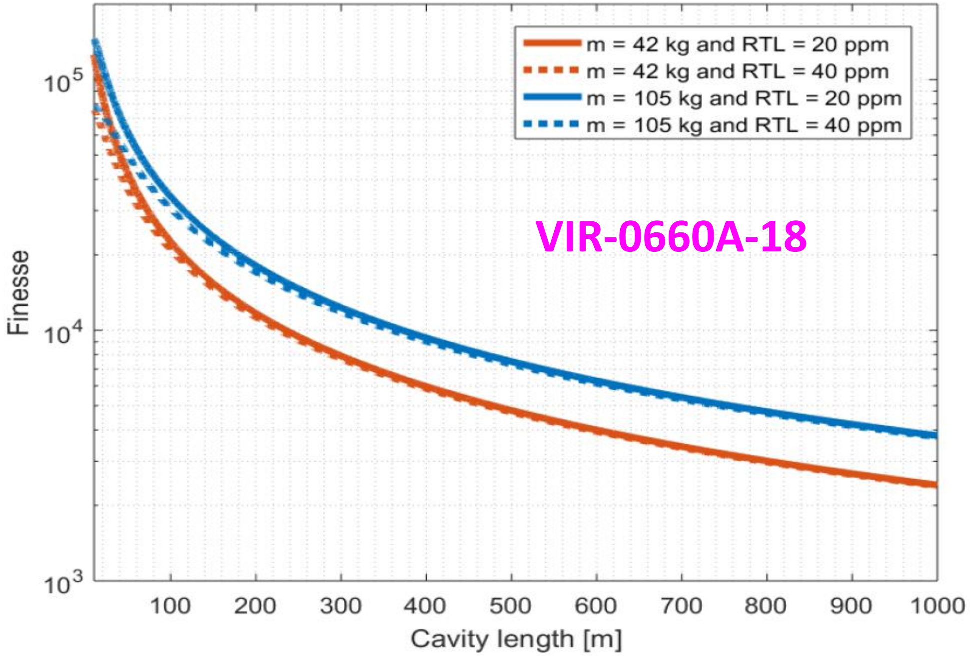
Filter Cavity state of the art 2

Need to have a long cavity:

$$\gamma_{fc} = \frac{\pi c}{2L_{fc}F_{fc}} = \sqrt{\frac{2}{(2-\epsilon)\sqrt{1-\epsilon}}}\frac{\Omega_{SQL}}{\sqrt{2}}$$

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

longer is the cavity less is the losses influence
→lower finesse



IN PROGRESS

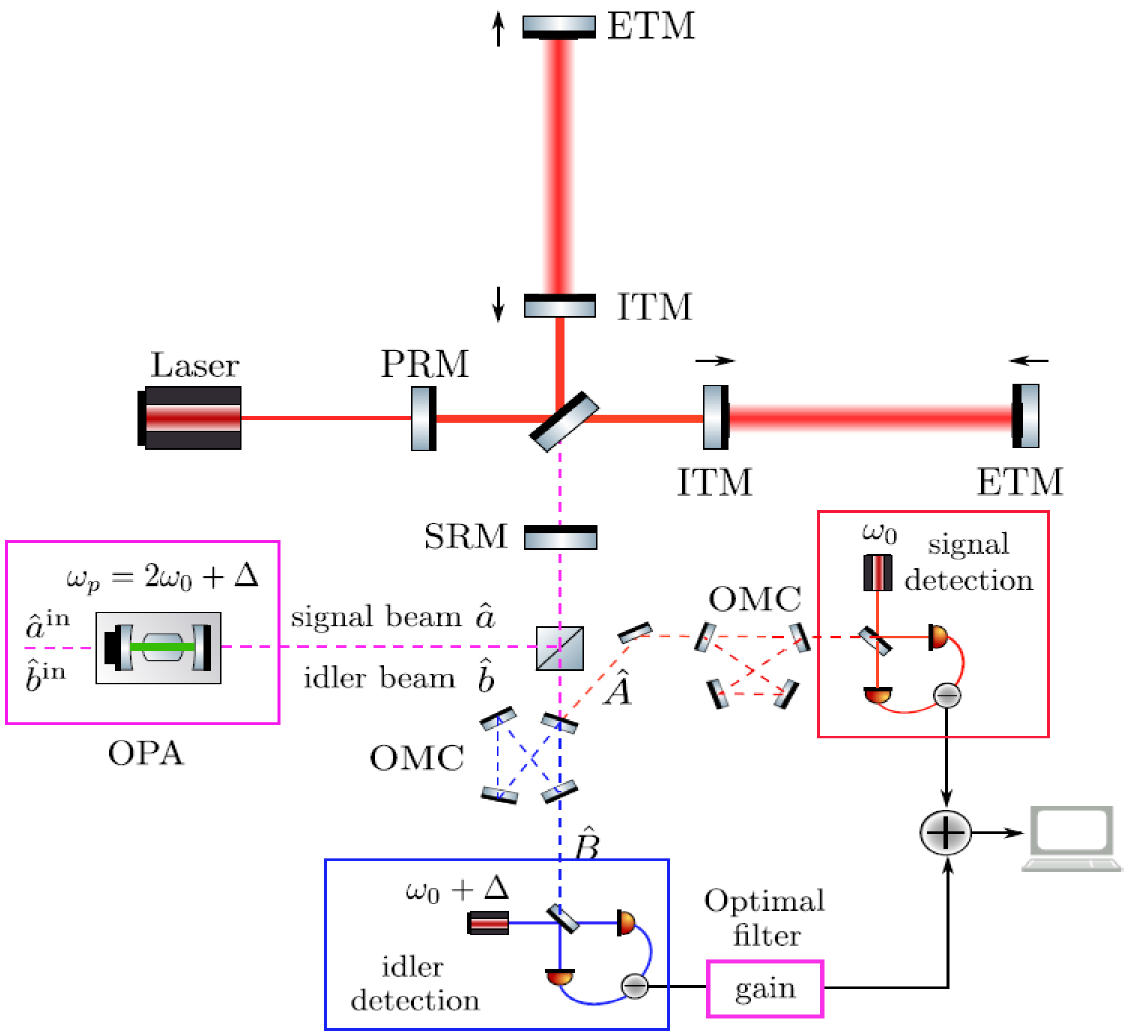
- **TAMA** National Astronomical Observatory of Japan (NAOJ): plan for a FC 300m long and a rotation frequency 70 Hz. Plan to have FDS in 2020 (**see M.Leonardi's talk**)

PLANNED

- **Advanced Virgo: design for FC implementation 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

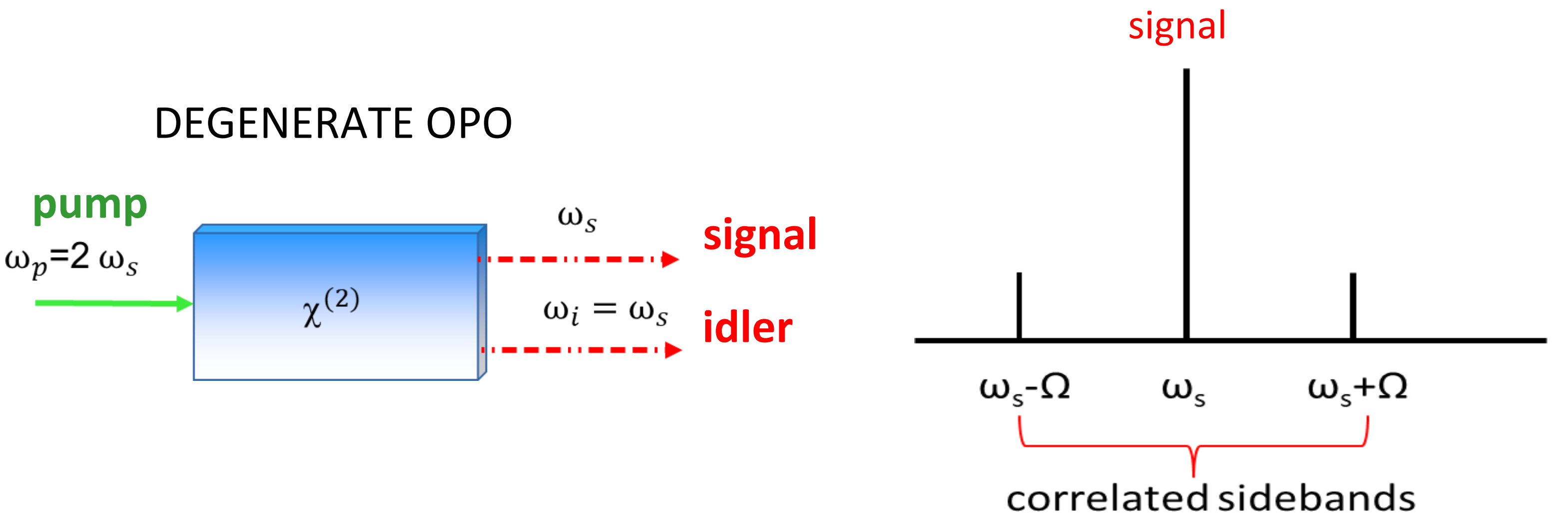
Idler frequency-dependent squeezed

Measurement of an idler fixed quadrature

SIGNAL CONDITIONALLY SQUEEZED IN A FREQUENCY DEPENDENT WAY

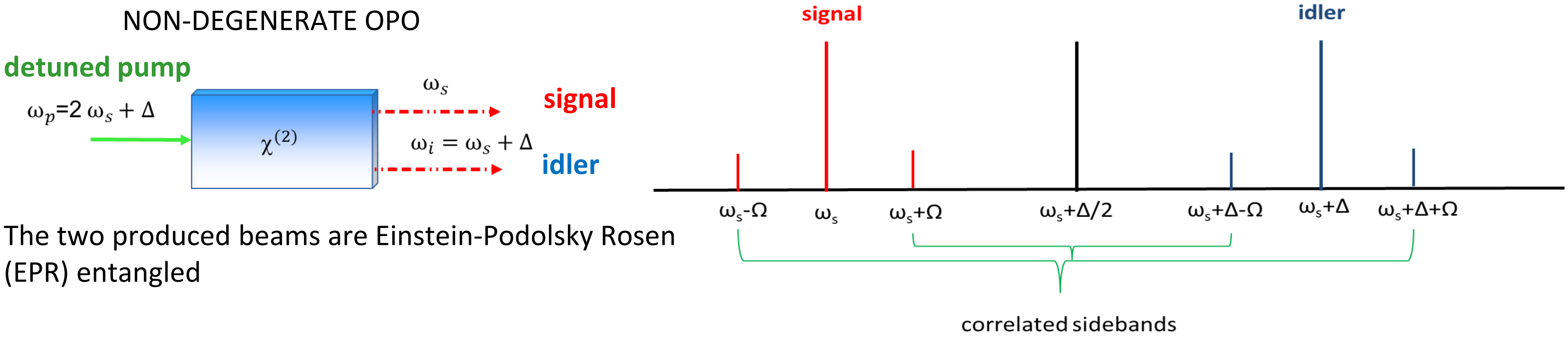
Einstein-Podolsky-Rosen (EPR) entangled signal and idler beams

DEGENERATE OPO



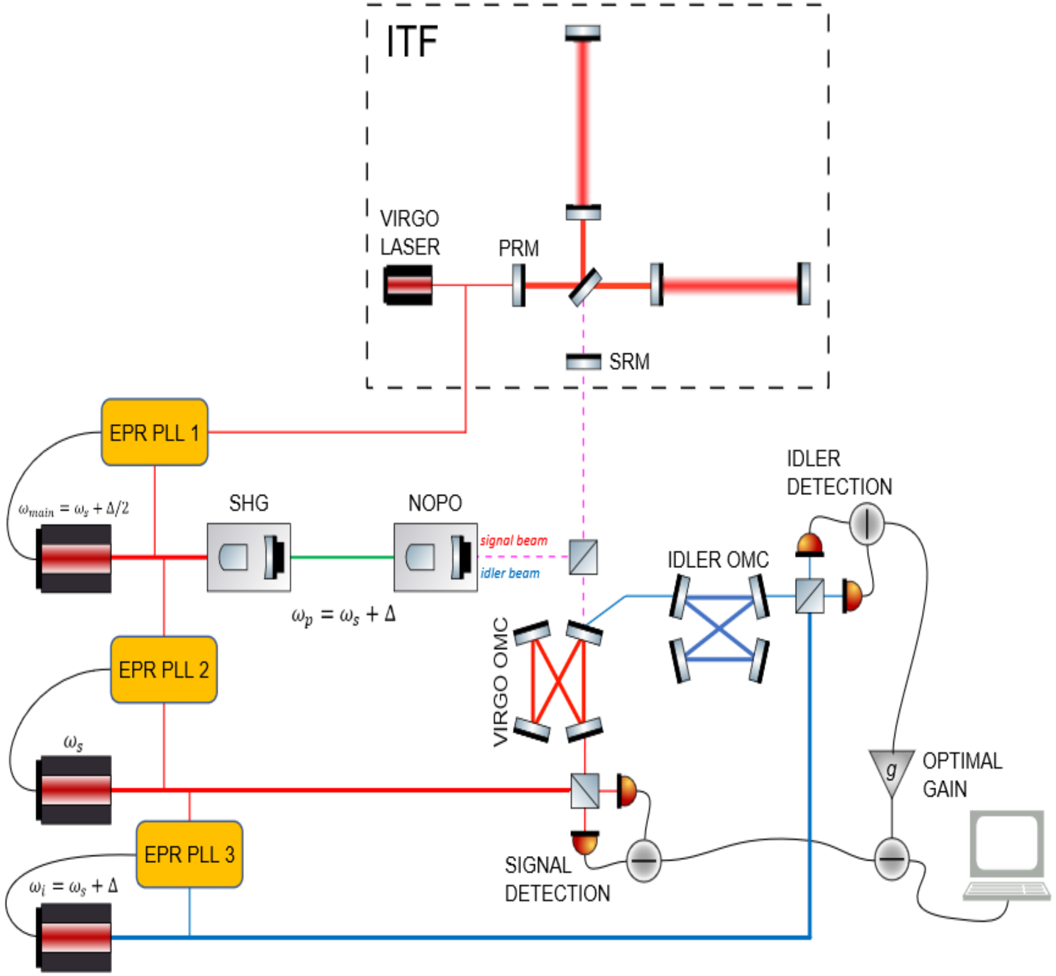
$\omega_s \rightarrow interferometer\ frequency$

NON-DEGENERATE OPO



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

Implementation of EPR in Advanced Virgo



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

Disadvantages wrt Filter Cavity

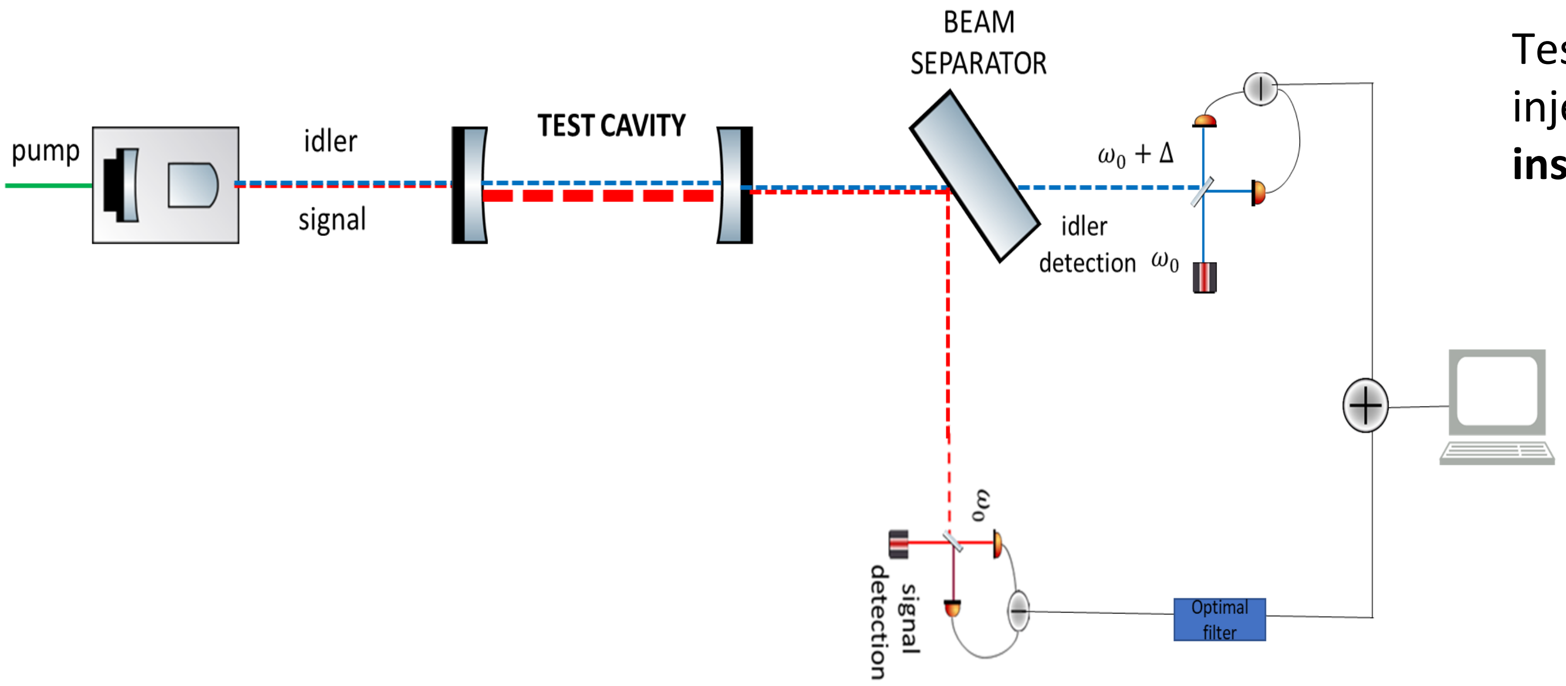
- ➢ two squeezed beams: double losses
- ➢ need for two Homodyne Detectors
- ➢ extra OMC

Advantages wrt Filter Cavity

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

Table-top demonstrator

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



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

A recent demonstration has been performed by the Quantum Optics group of Prof. Schnabel at Institute for Laser Physics and University of Hamburg, Germany, using a simplified setup. (Jan Gniesmer PhD Thesis)

Table-top demonstrator

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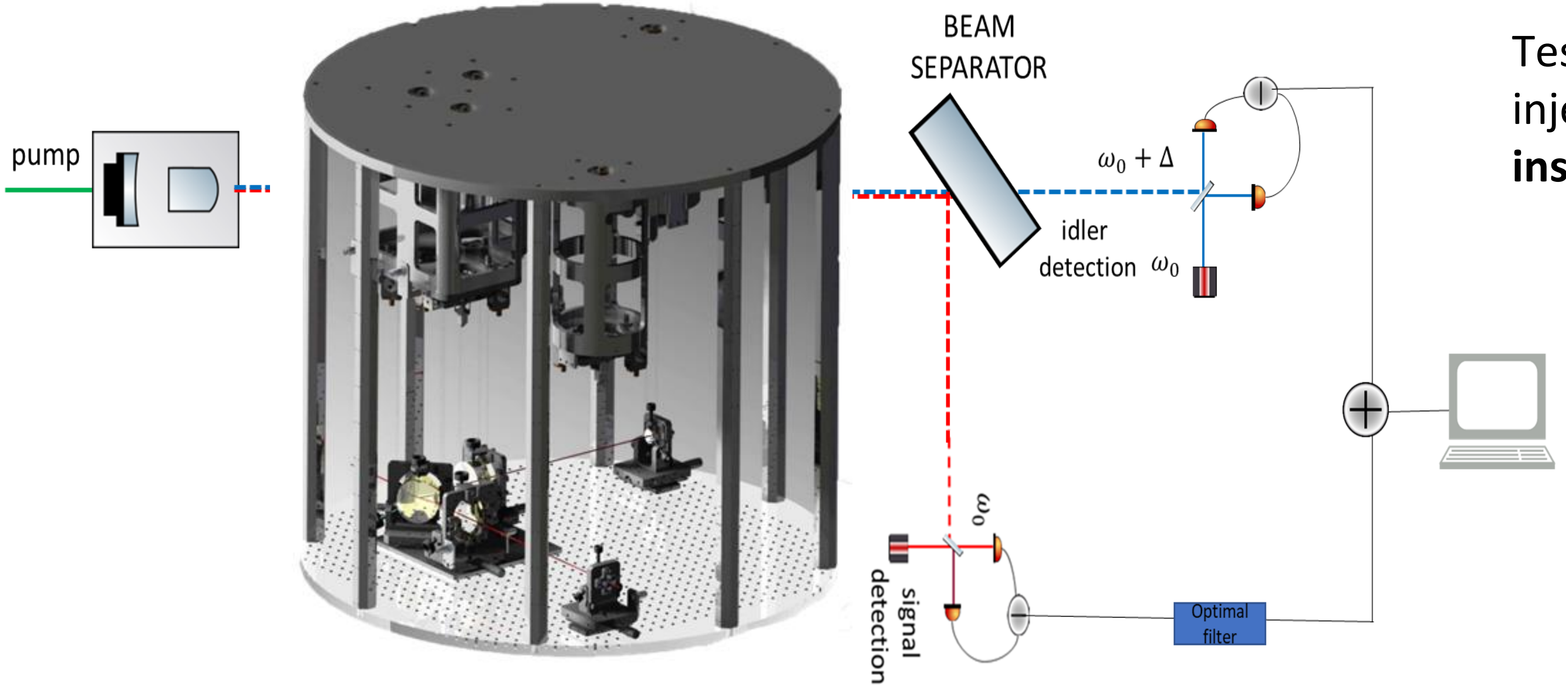

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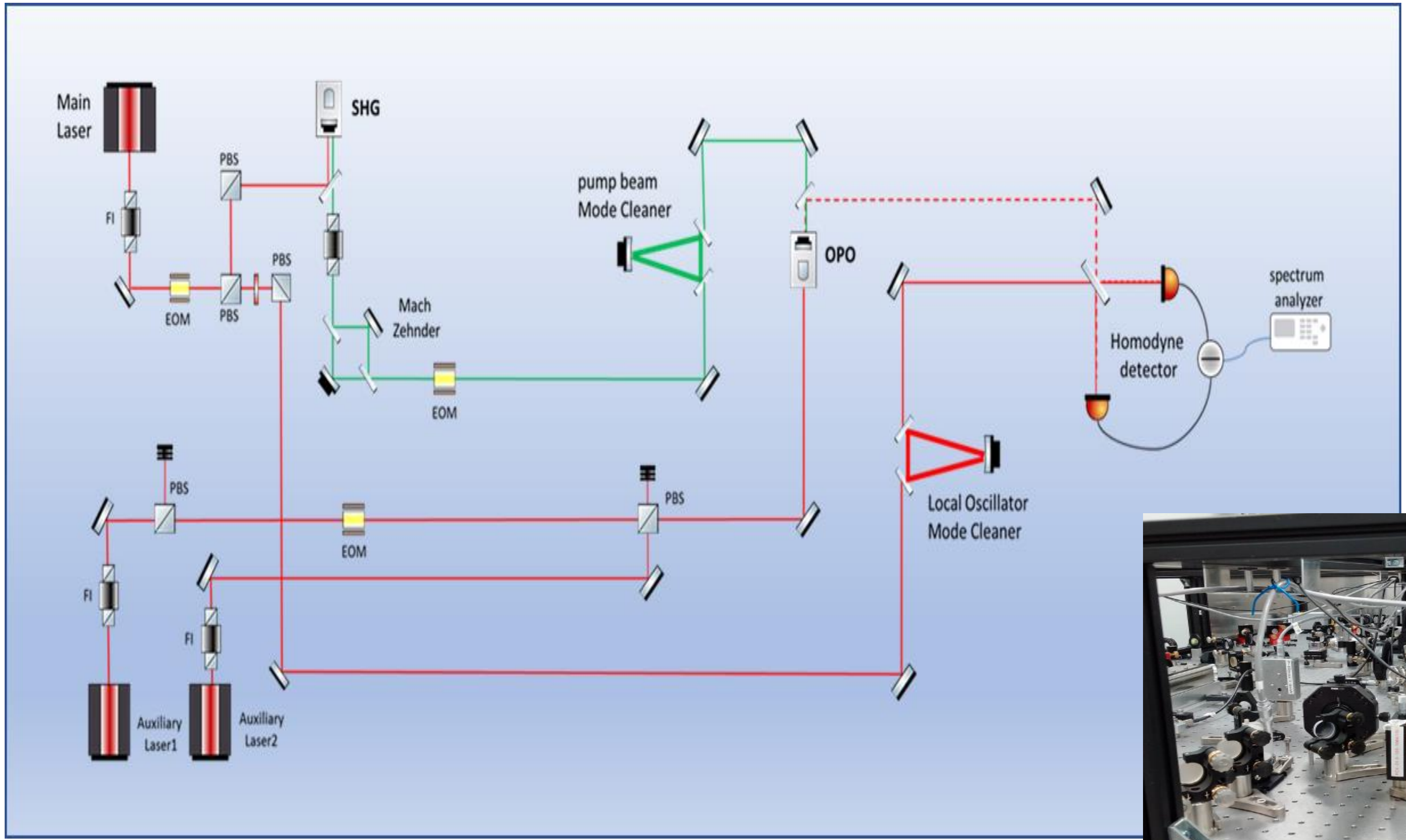
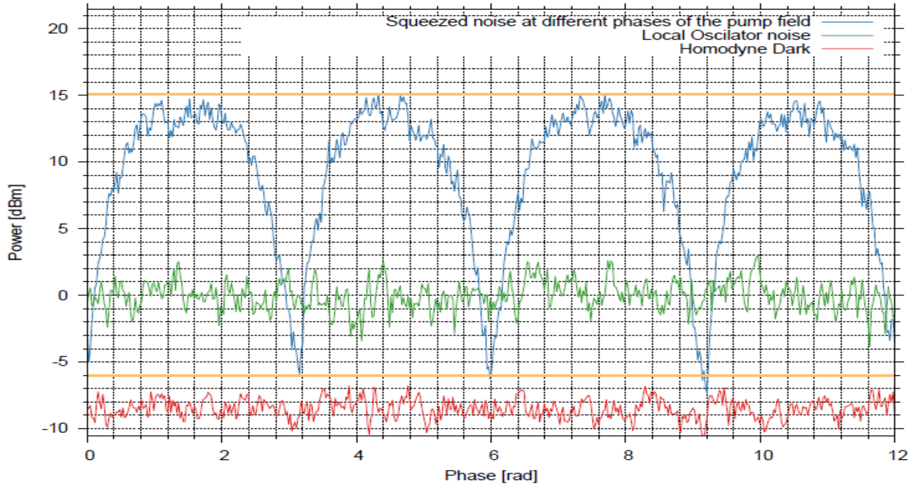
Our demonstrator will be tested on SIPS experiment that is a RPN sensitive system. We expect to see noise reduction below 2 kHz. **(see next talk by S.Di Pace's)**

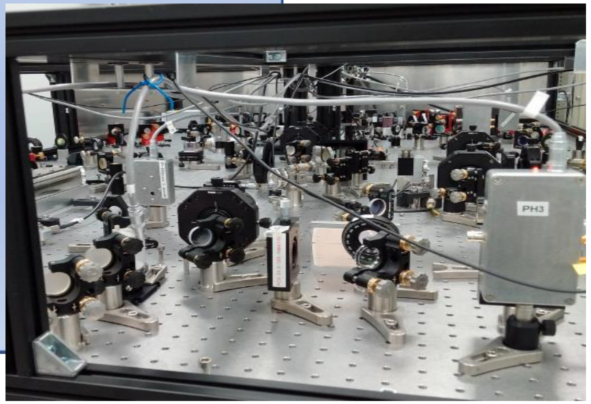
Starting point

- The **optical design** has been completed
- We will start from a frequency independent squeezing experiment that we realized in the past years and that now we are using to test new control techniques (**see M.Bawaj talk**)



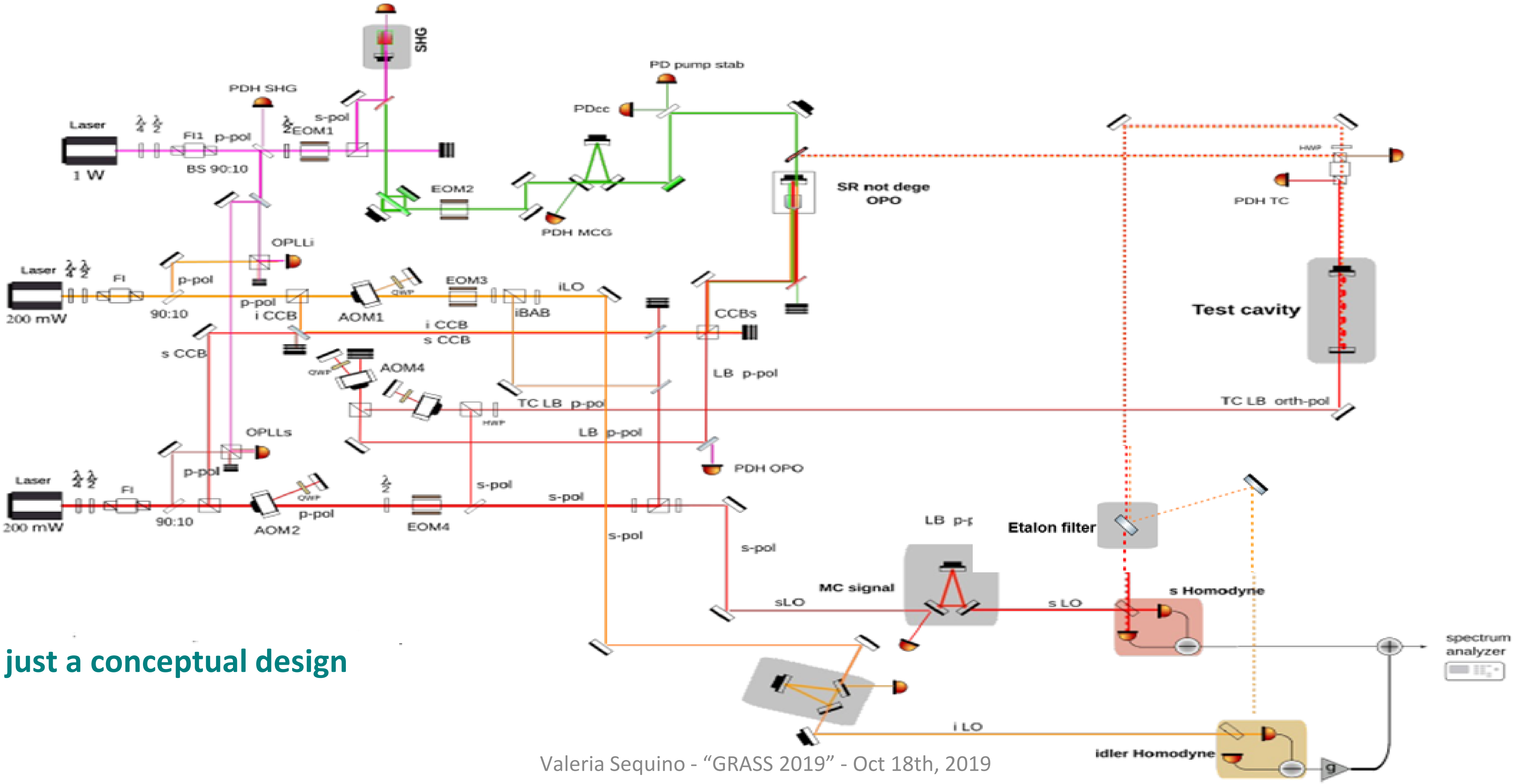


(M.Vardaro, PhD thesis)



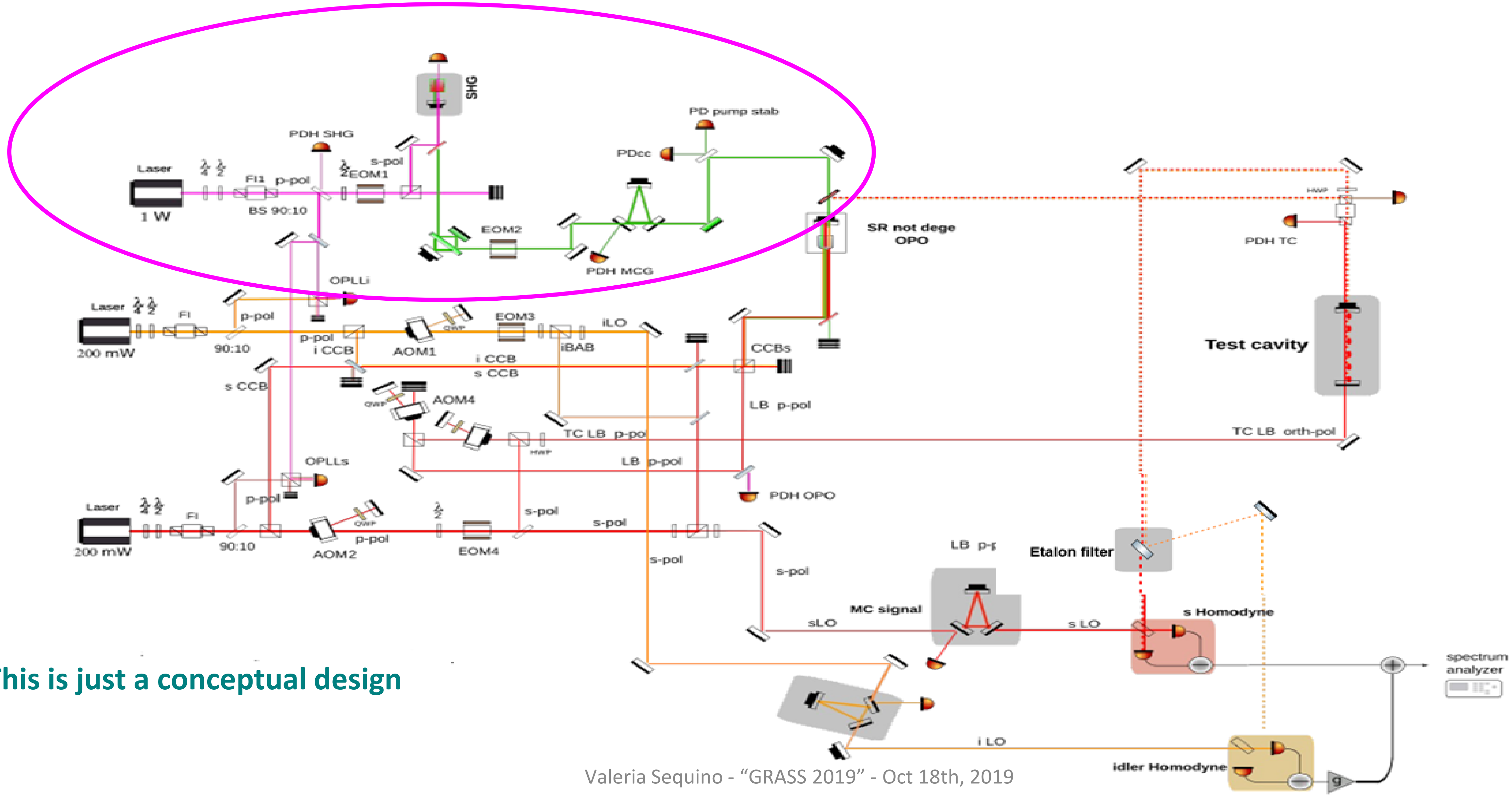
-6 dB of SQZ
15 dB of anti-SQZ
Central freq: 1 MHz

Conceptual design



This is just a conceptual design

Conceptual design



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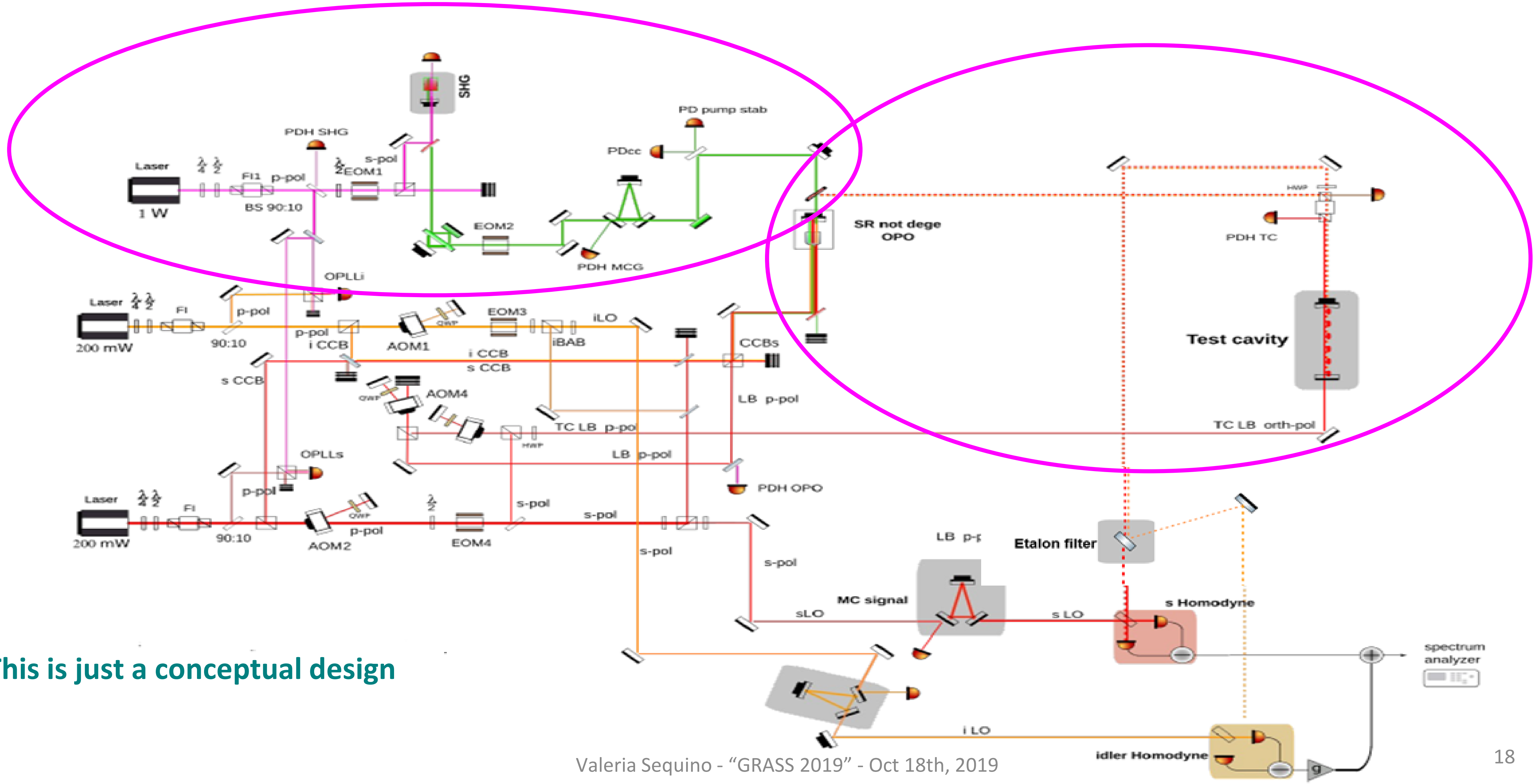

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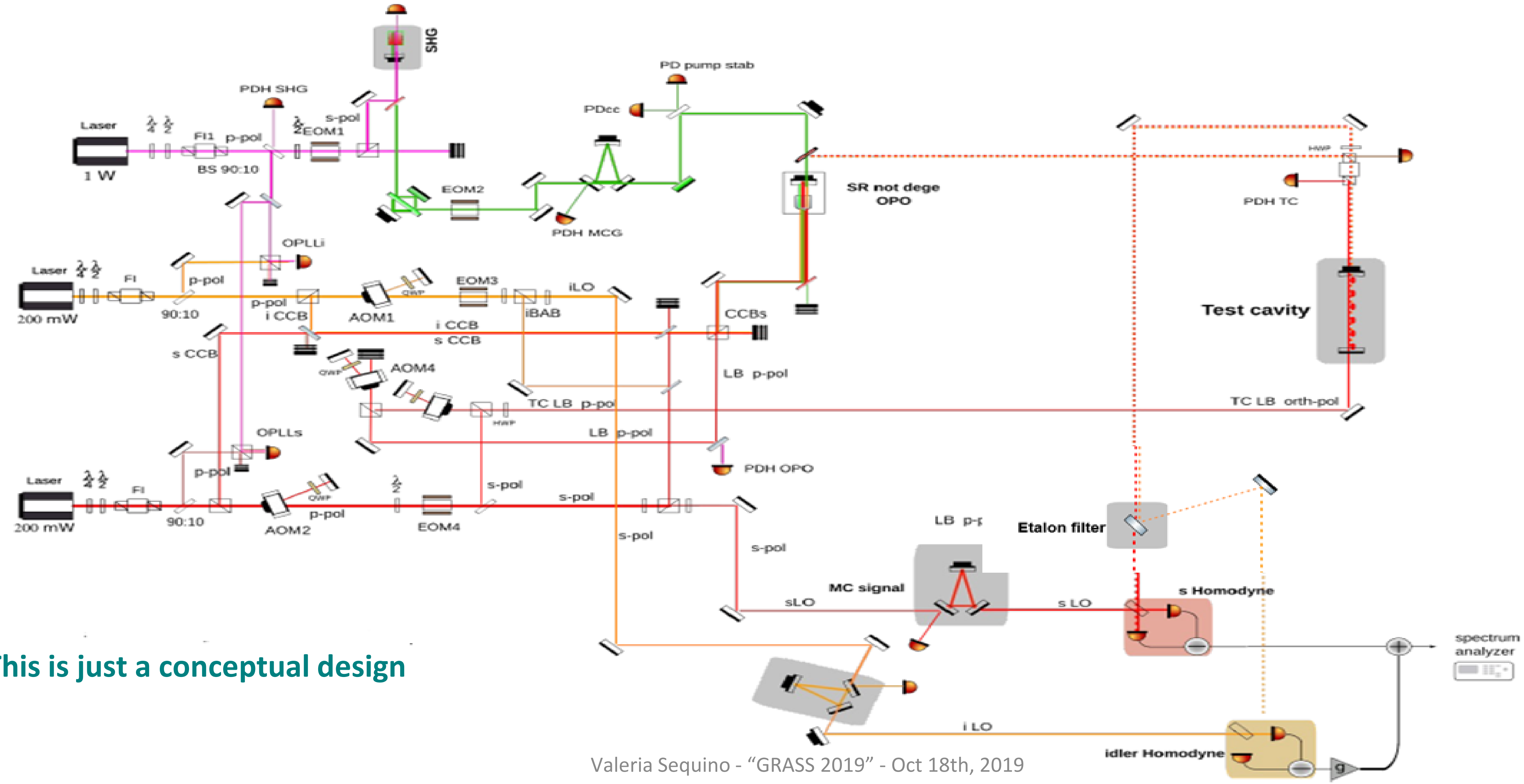

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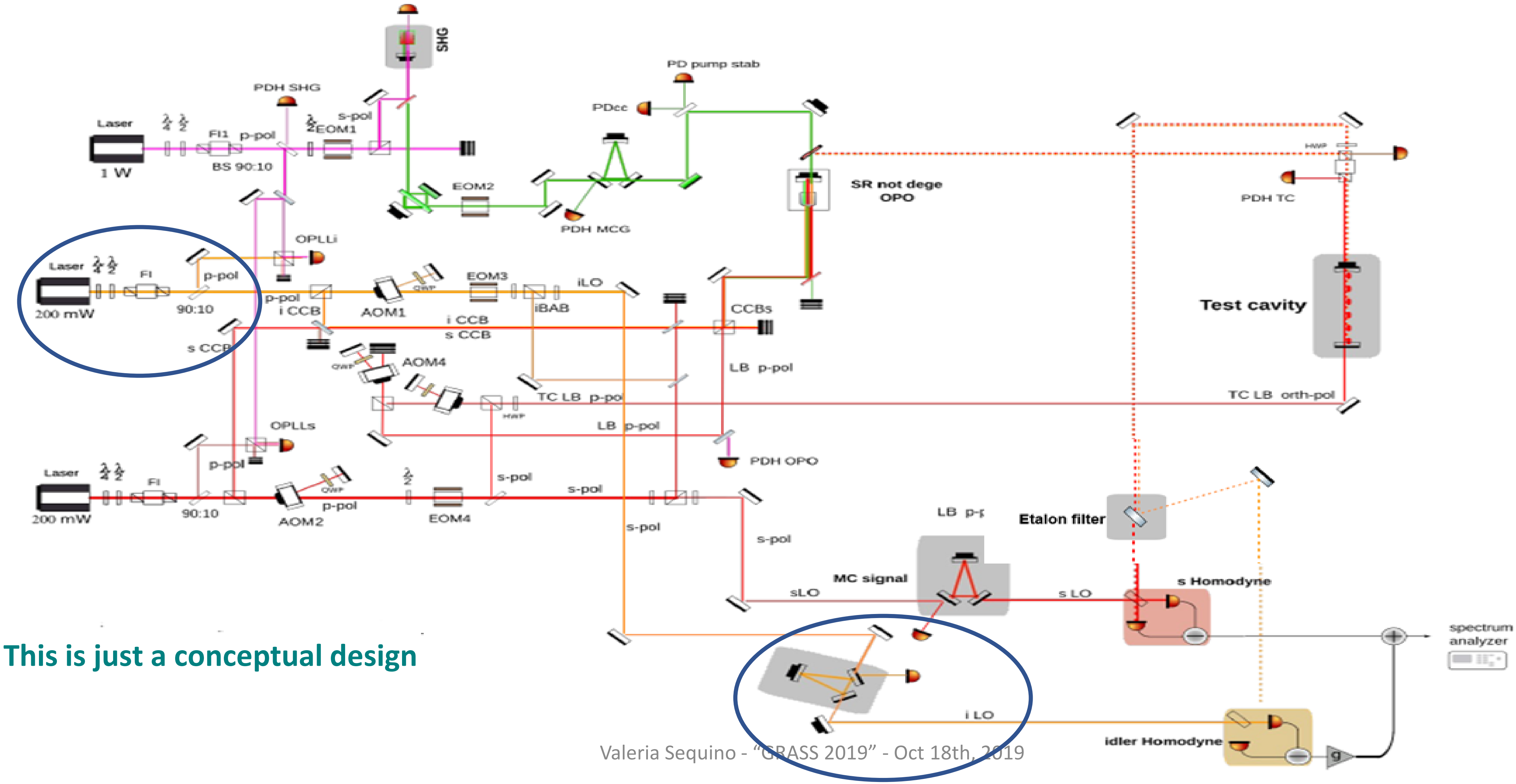

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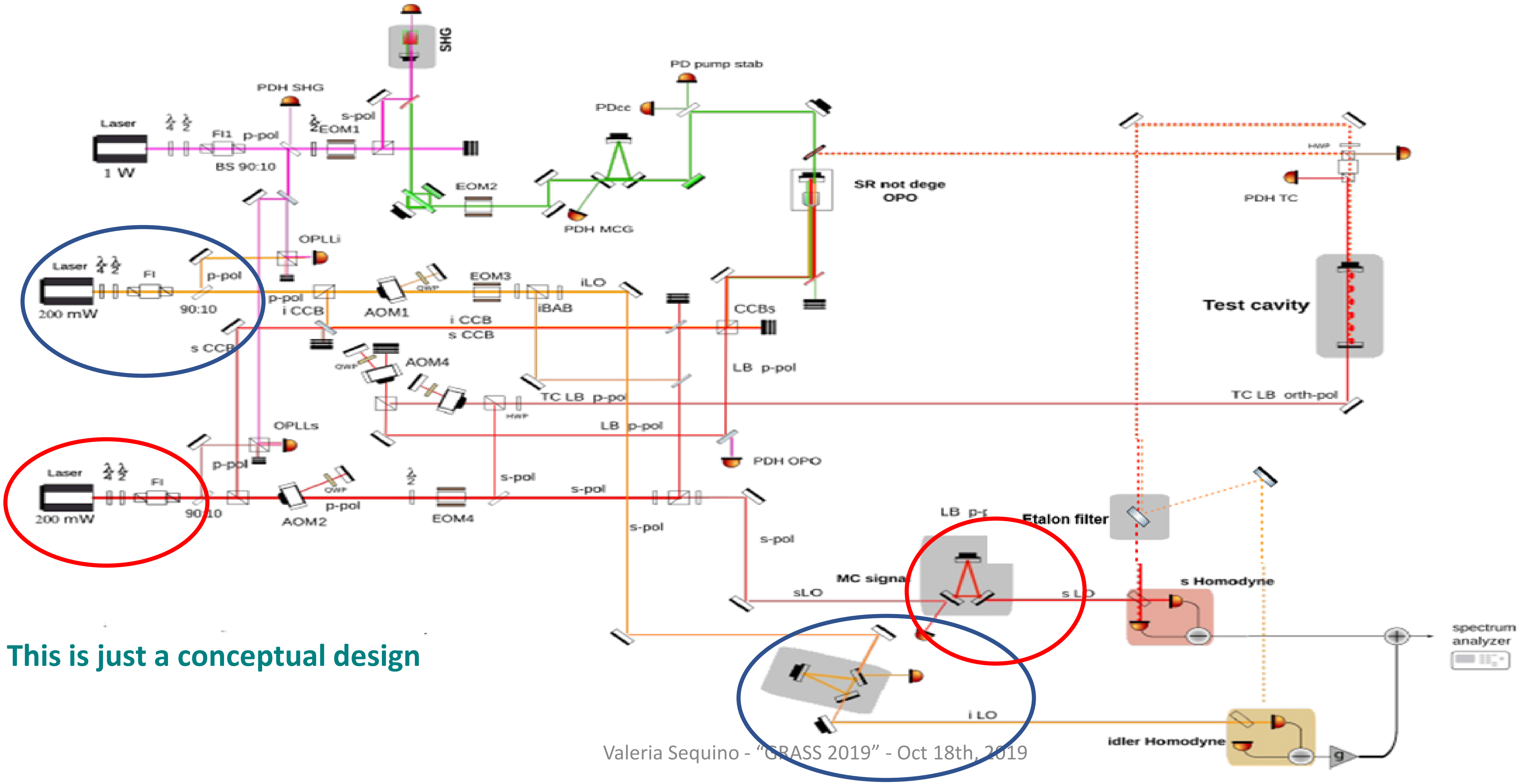

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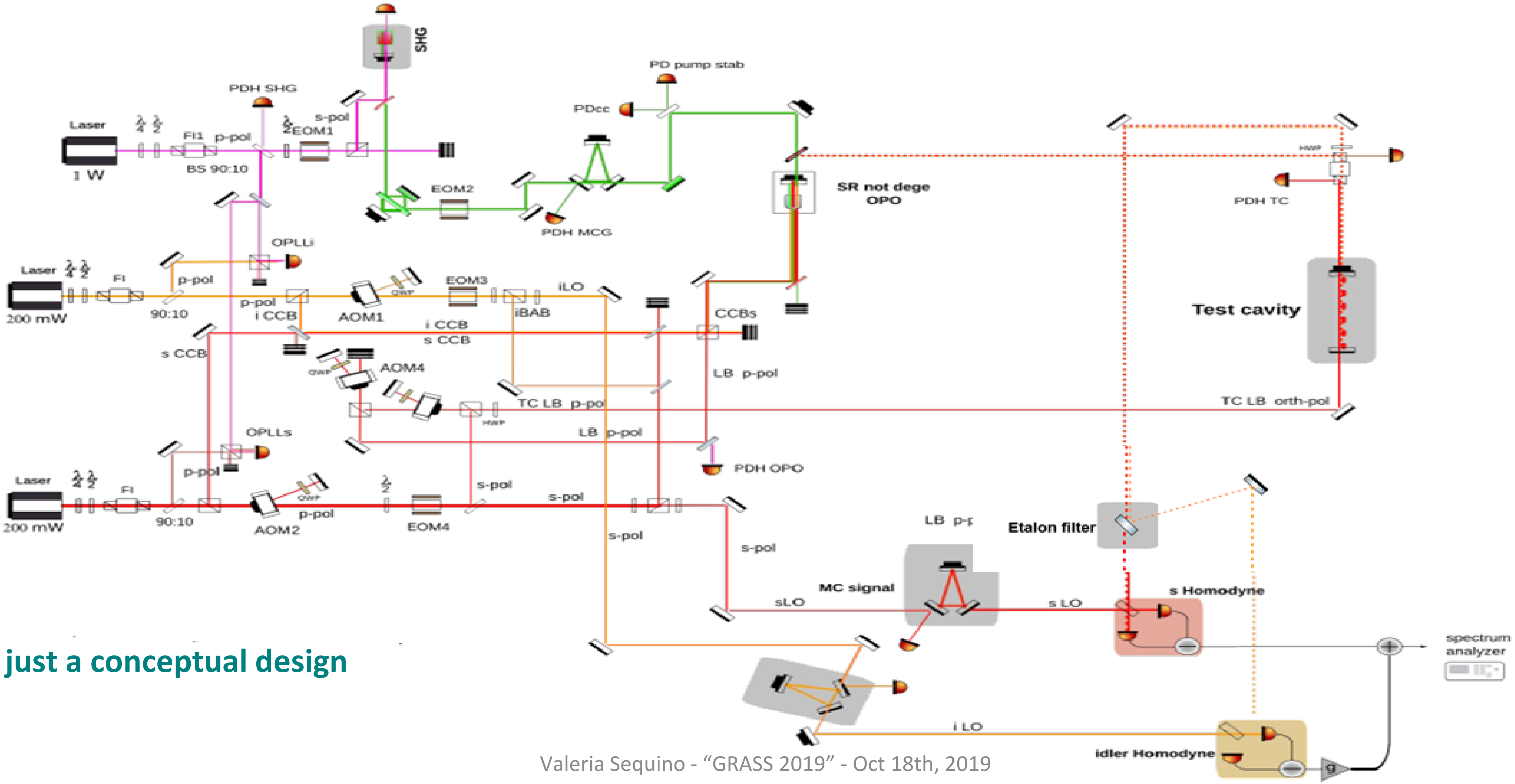

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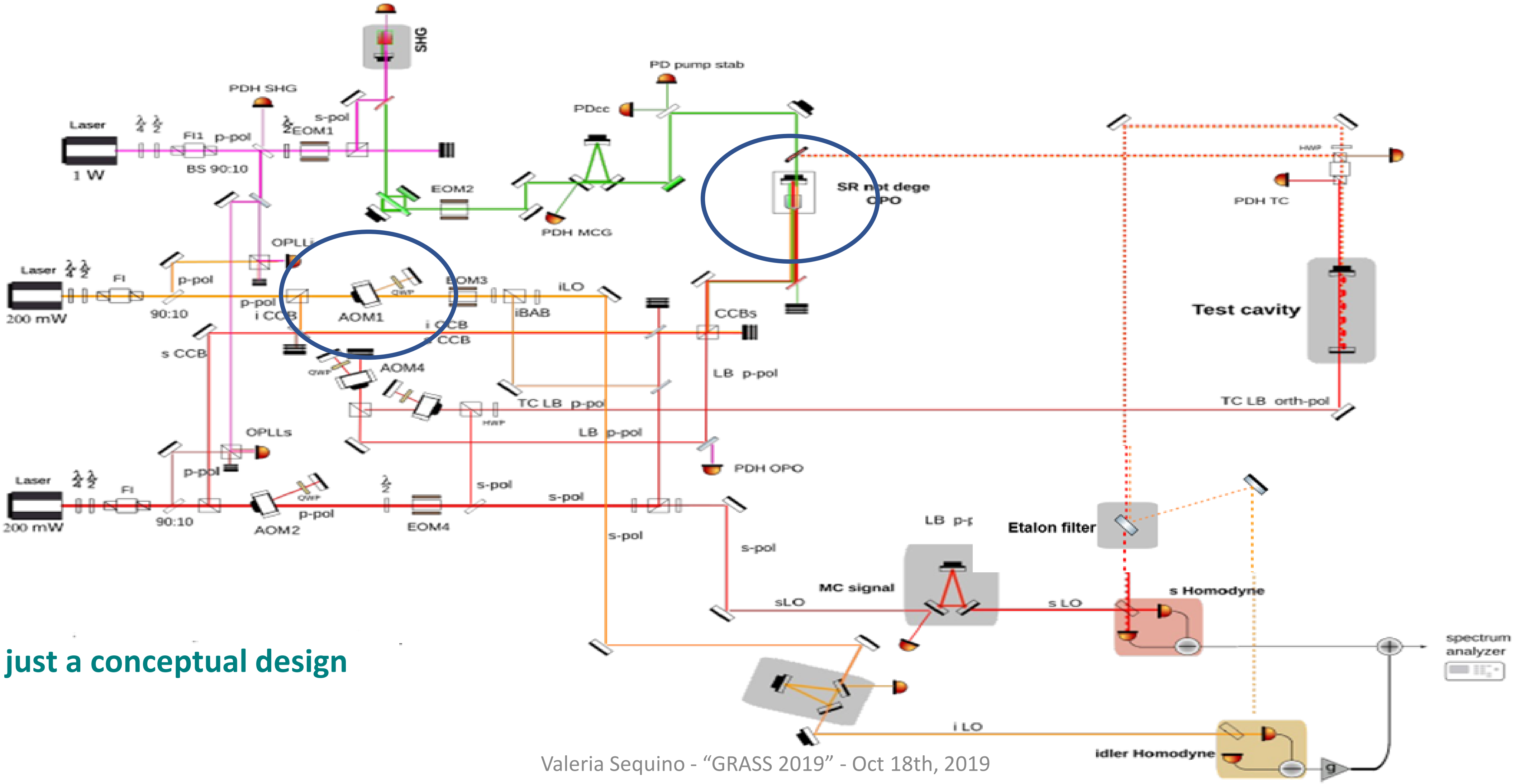

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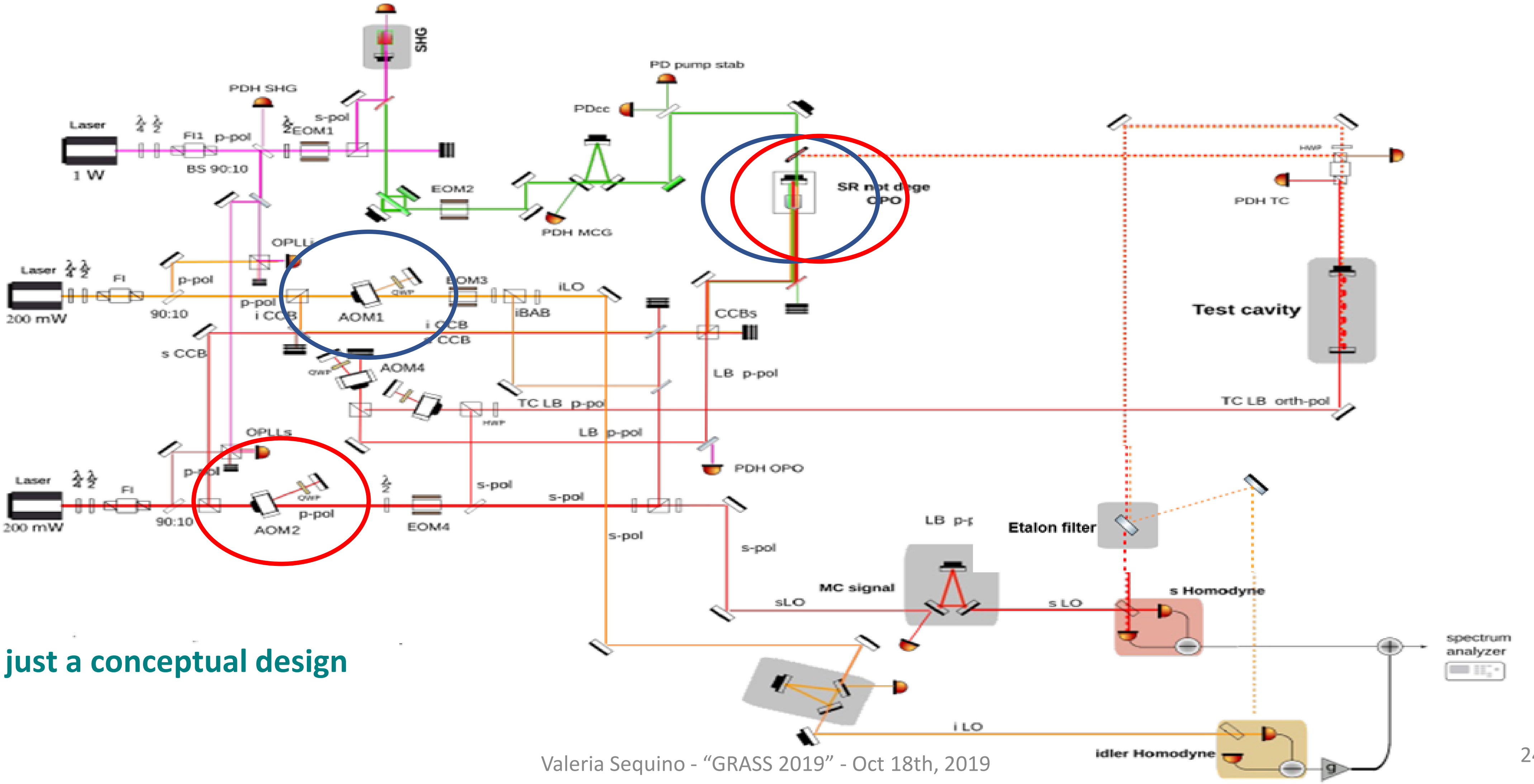

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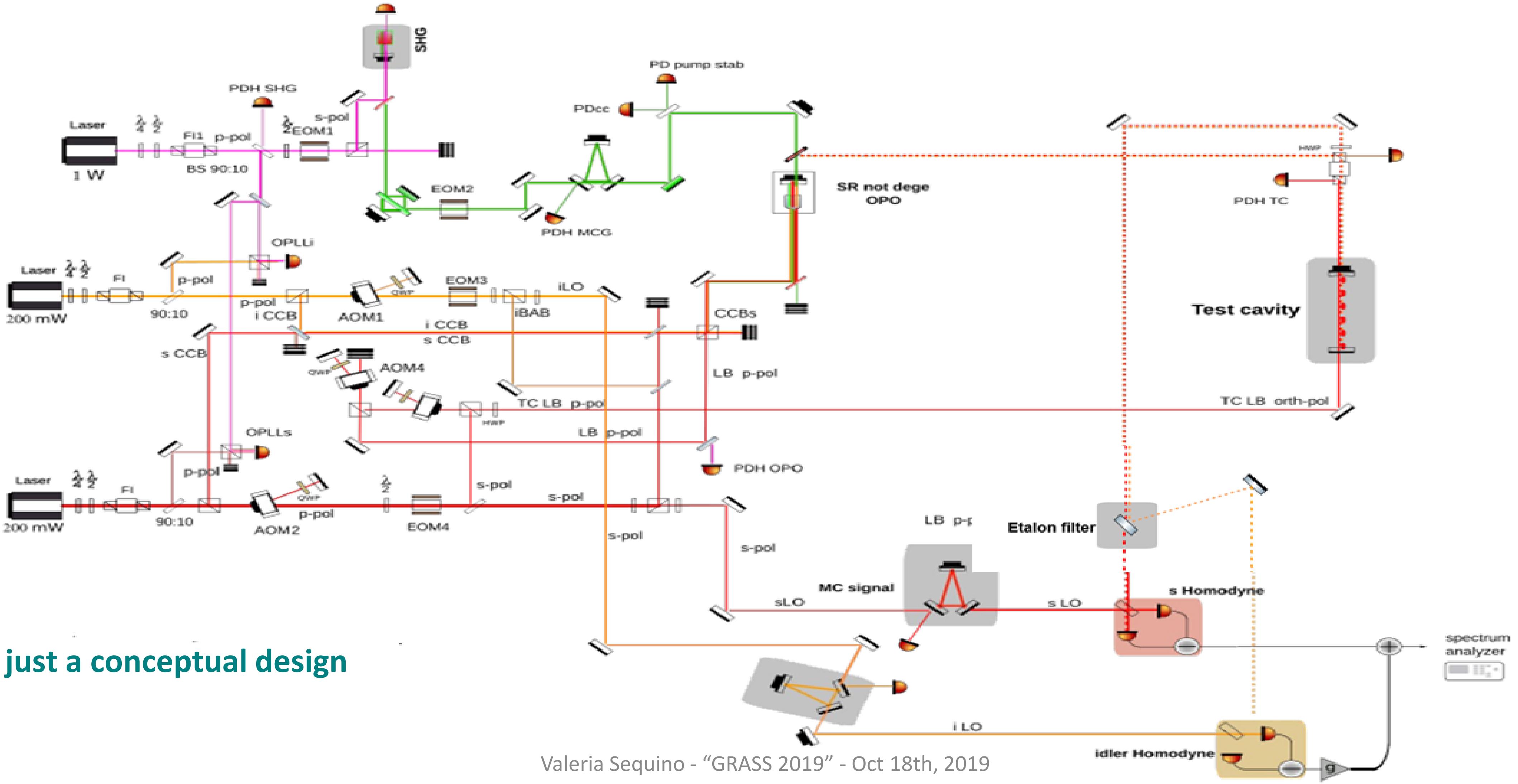

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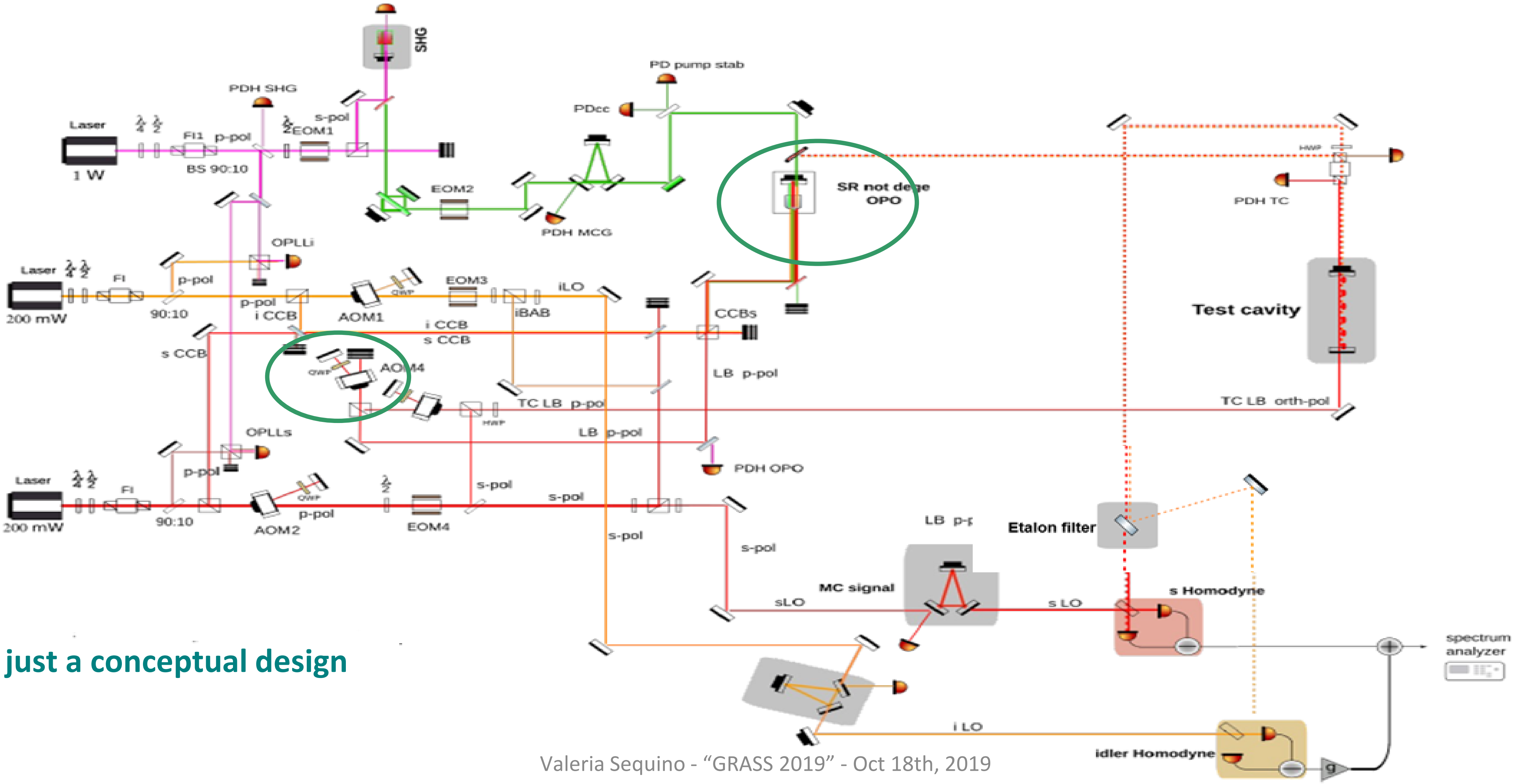

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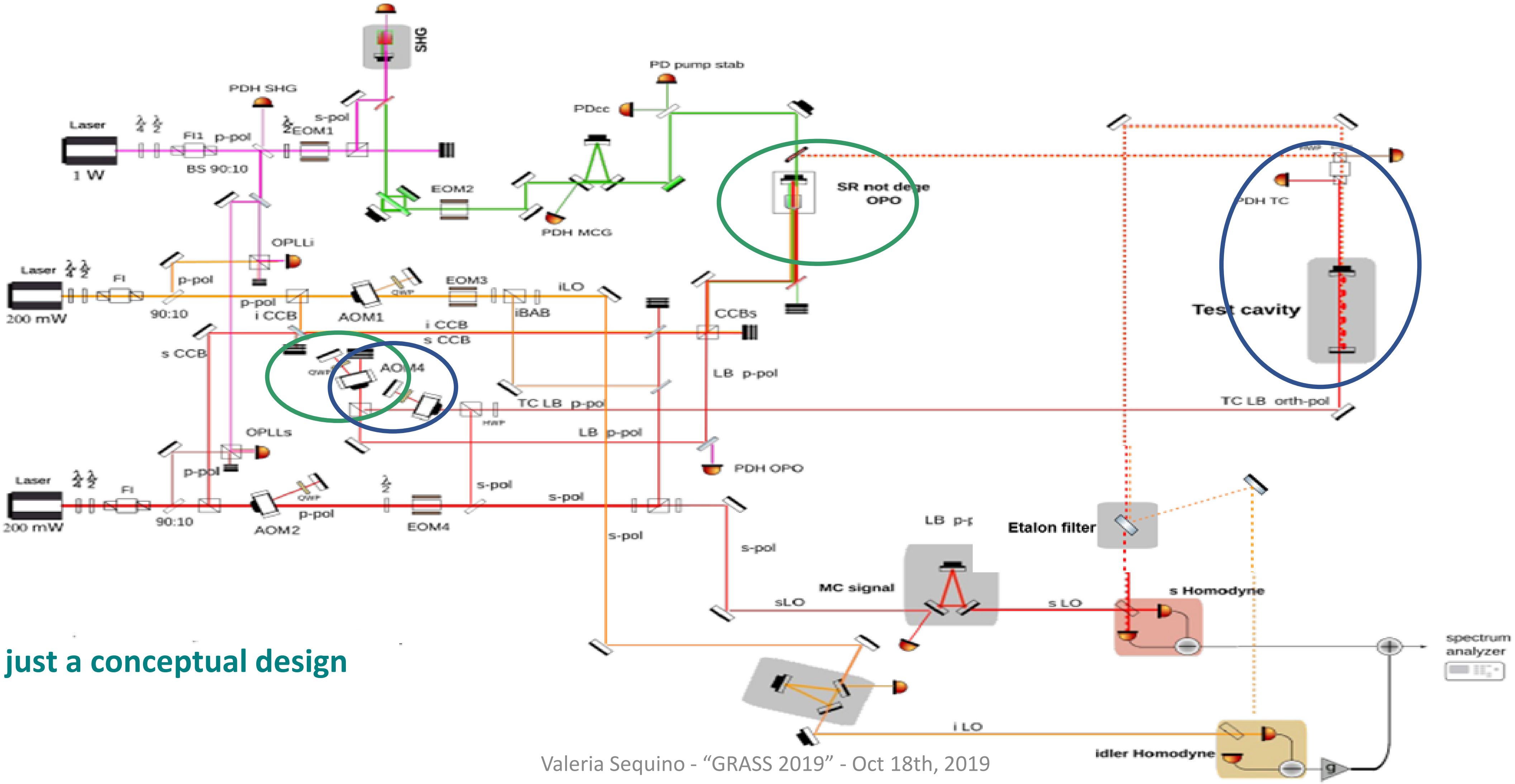
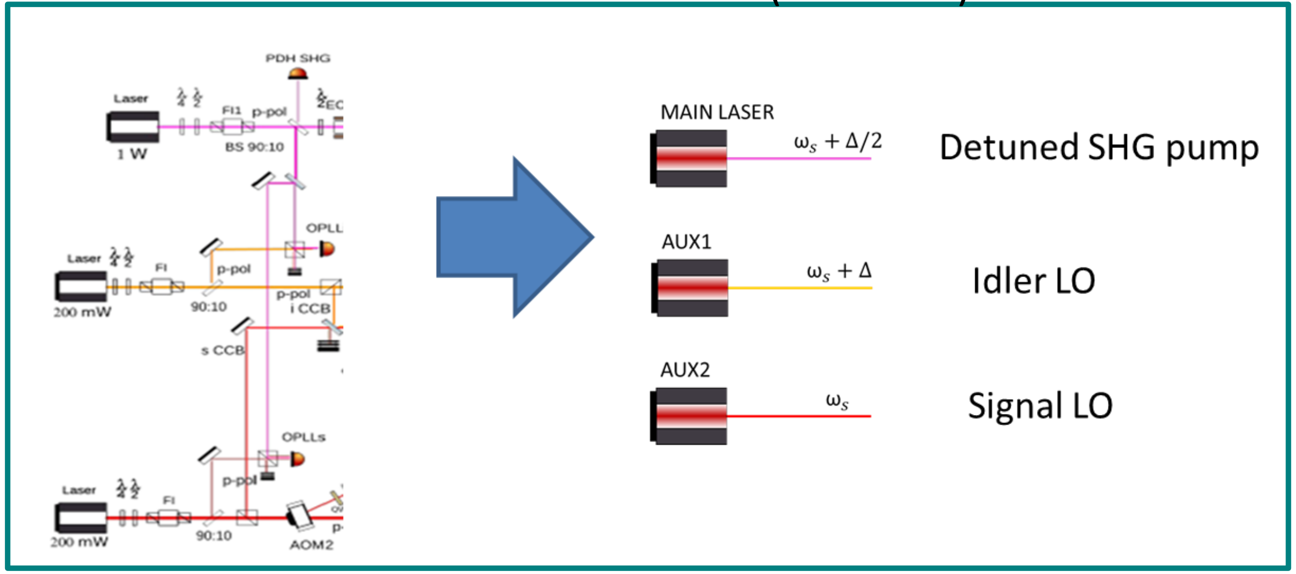


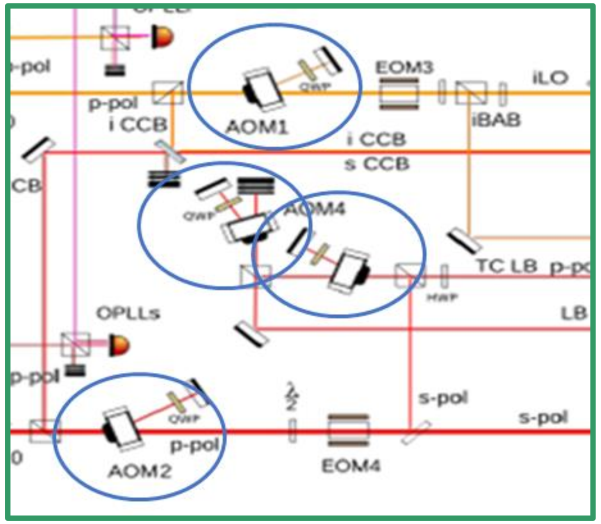
This is just a conceptual design

Changes w.r.t. to the present setup

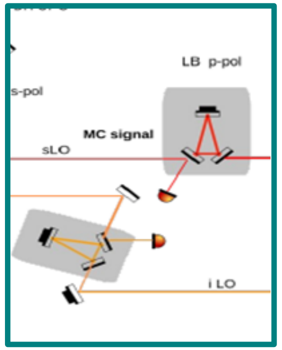
TWO FAST OPPLs (Δ~ 2GHz)



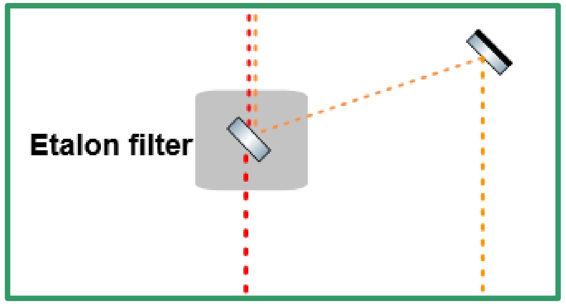
AOMs



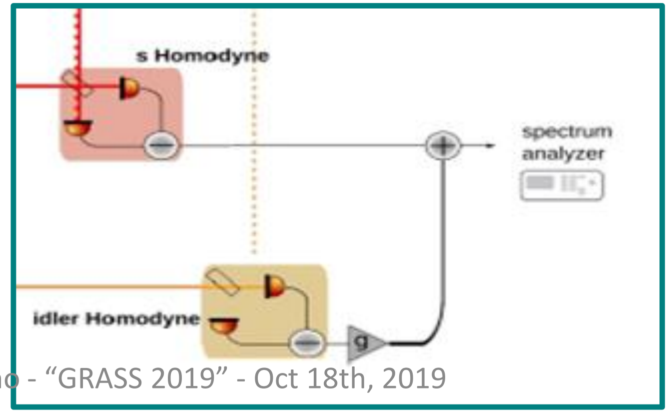
Extra MC



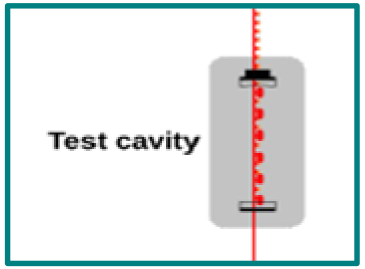
ETALON TO SEPARATE THE TWO BEAMS



TWO HDs



TEST CAVITY



Conclusions

- **Present GW detectors:** Frequency Independent Squeezing has been already implemented for high frequency sensitivity improvement achieved for the present observative run (O3)

- **Future detectors:** Frequency Dependent Squeezing is needed 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 for your attention

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

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

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

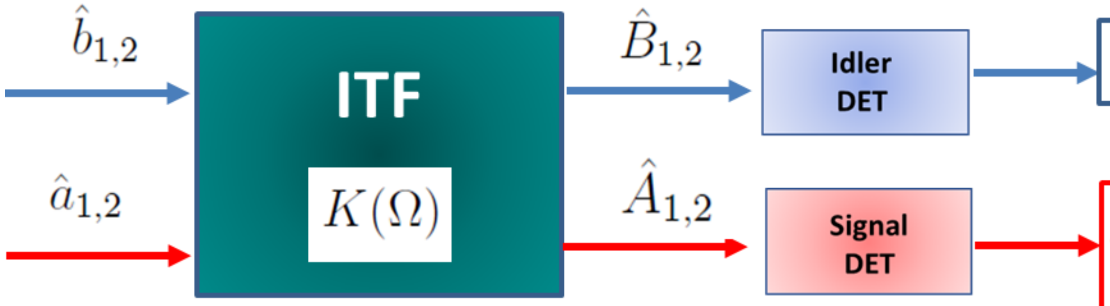
→

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

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



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

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

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

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

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

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