Workshop on the development of innovative tools for new collaborations within gravitational wave detection experiments

JGW-G2214029

# KAGRA filter cavity project
# and
# frequency dependent squeezing experiment at TAMA

Y. Zhao on behalf of the KAGRA collaboration

2022.4.15

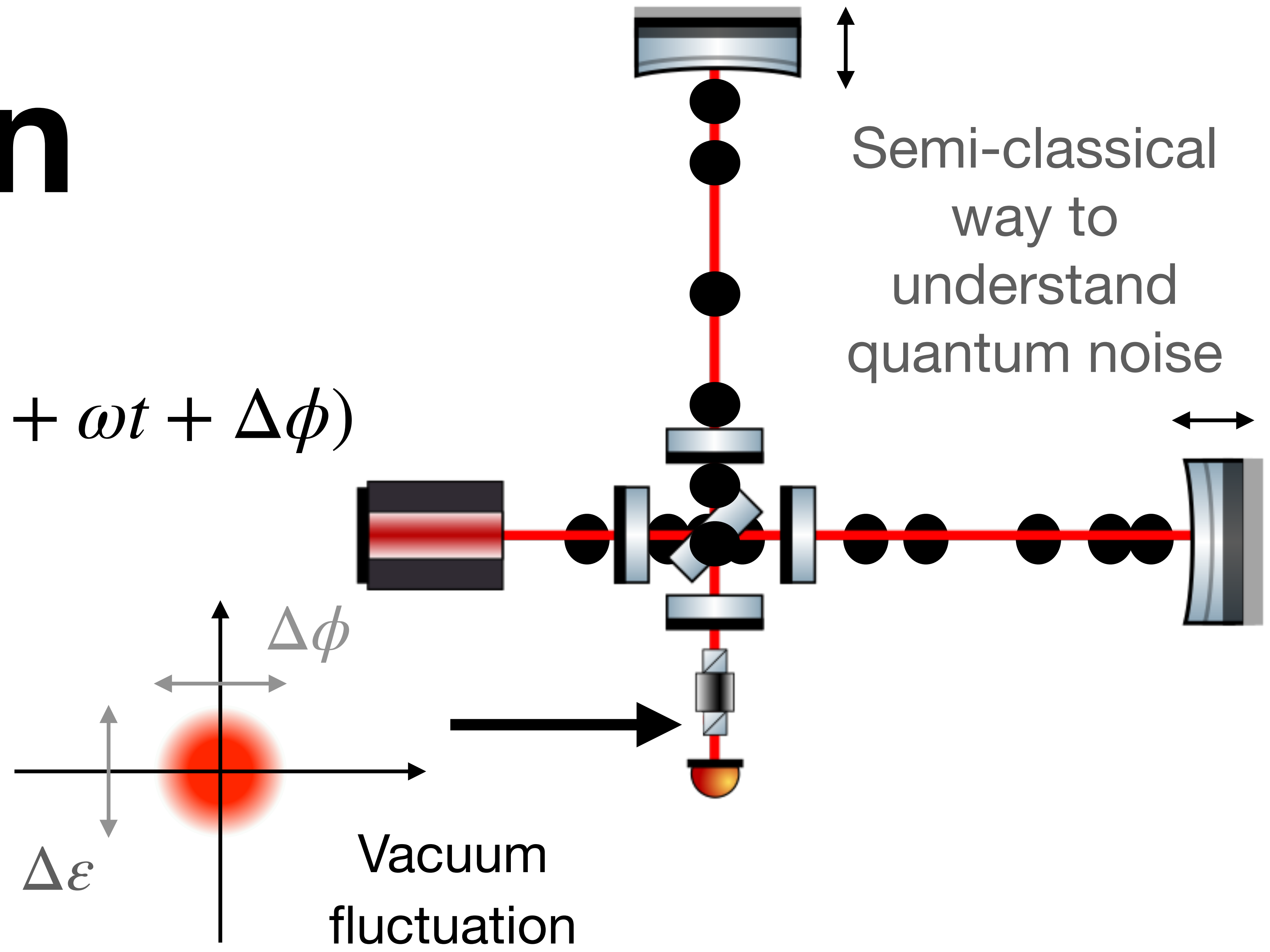
# Outline

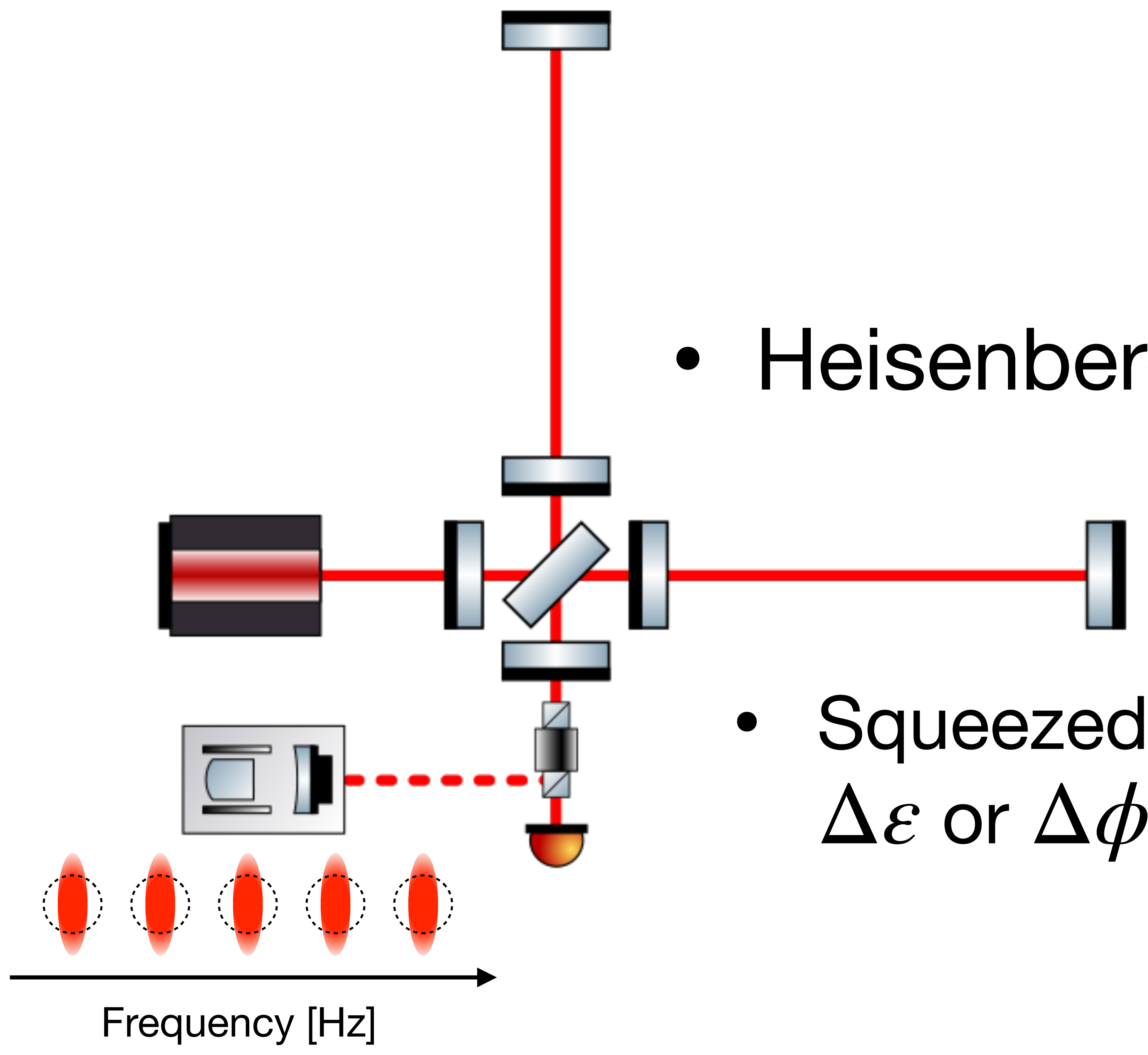
- Quantum noise of gravitational wave detectors and its reduction
- KAGRA filter cavity project
- Frequency dependent squeezing experiment at TAMA

# Quantum noise and its reduction

- Quantum nature of light:
  - Zero point energy
  - Heisenberg uncertainty principle

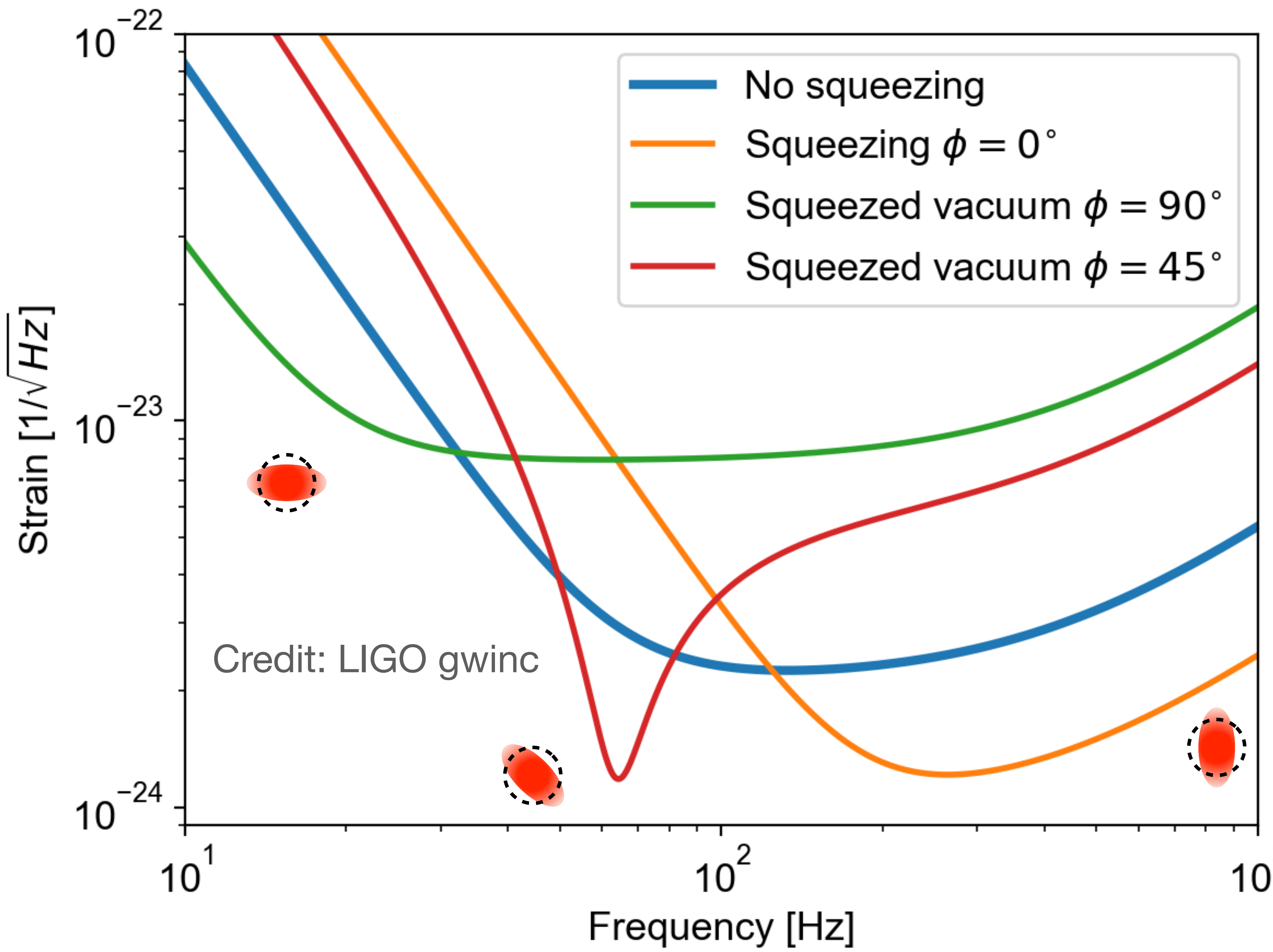
- Zero point energy gives quantum noise $\varepsilon(z,t) = \Delta\varepsilon \sin(kz + \omega t + \Delta\phi)$
  - Radiation pressure noise (from $\Delta\varepsilon$) causes mirror motion
  - Shot noise (from $\Delta\phi$) appears at the photo detection


Semi-classical way to understand quantum noise



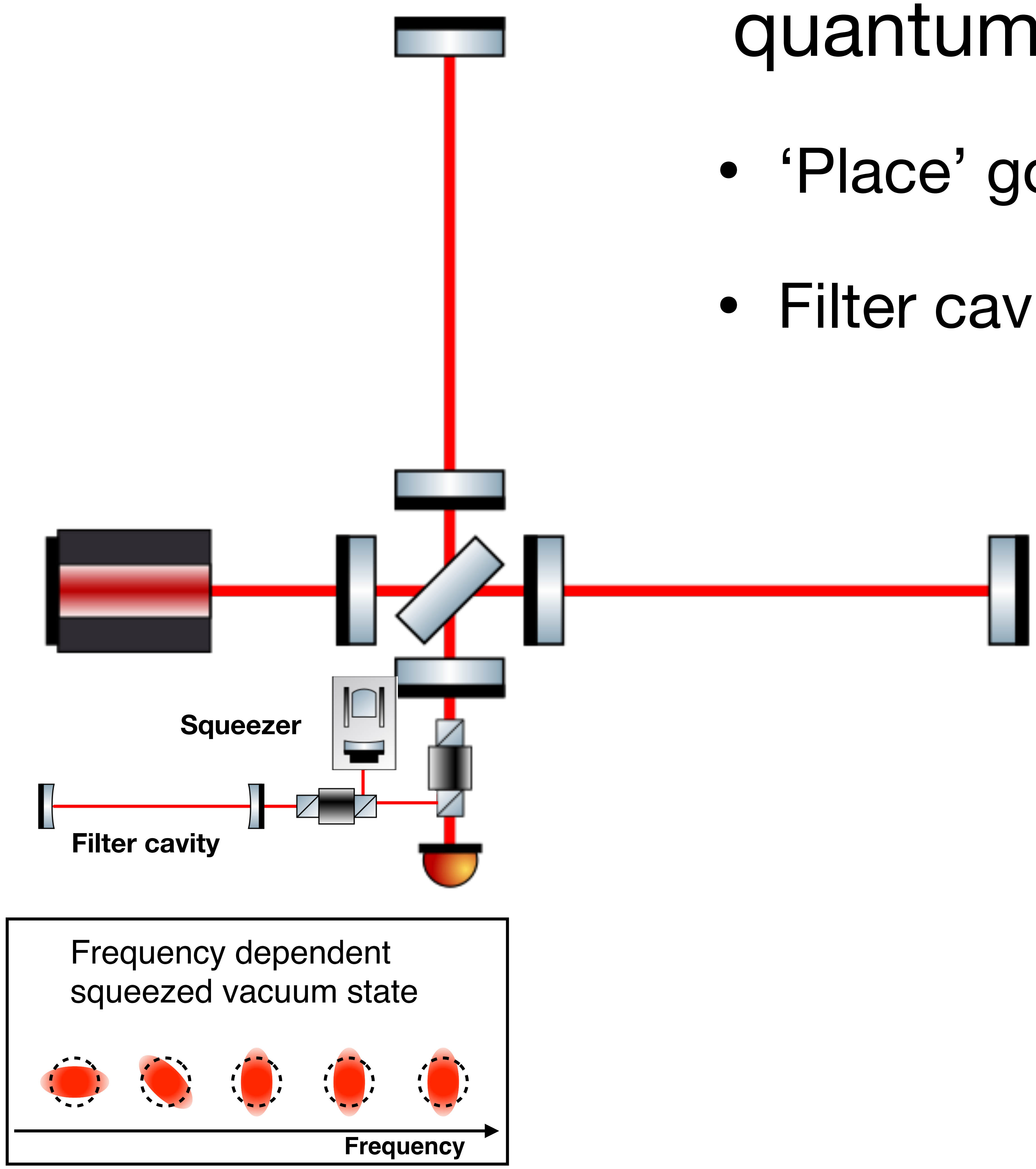
- Heisenberg uncertainty principle

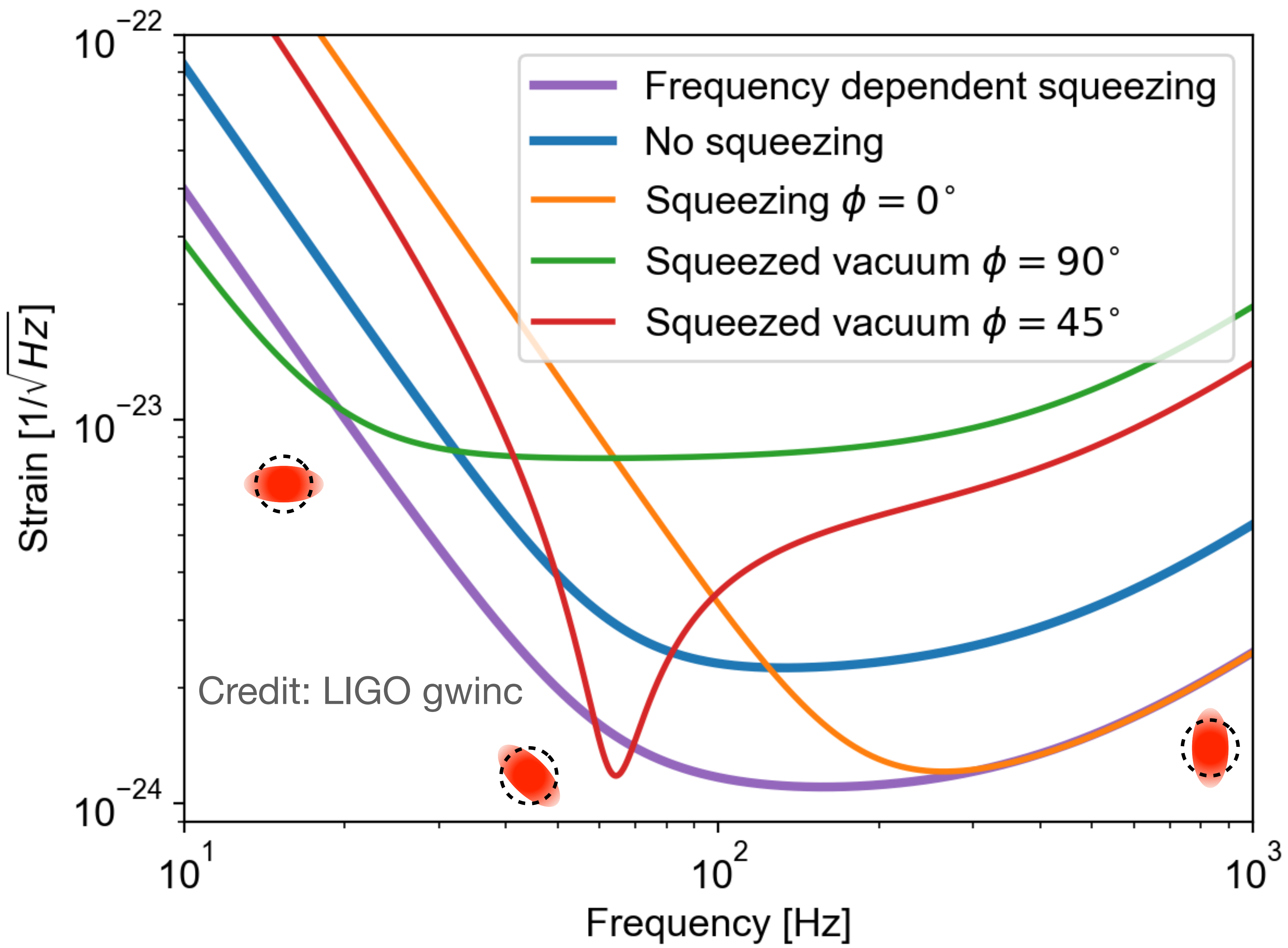
- Squeezed state can reduce either $\Delta\varepsilon$ or $\Delta\phi$, but not simultaneously


Credit: LIGO gwinc

# Broadband quantum noise reduction

- Frequency dependent squeezing can make broadband quantum noise reduction
  - ‘Place’ good squeezed angle at good frequency
  - Filter cavity can impose this frequency dependence





Credit: LIGO gwinc

# Expected KAGRA quantum noise in O5

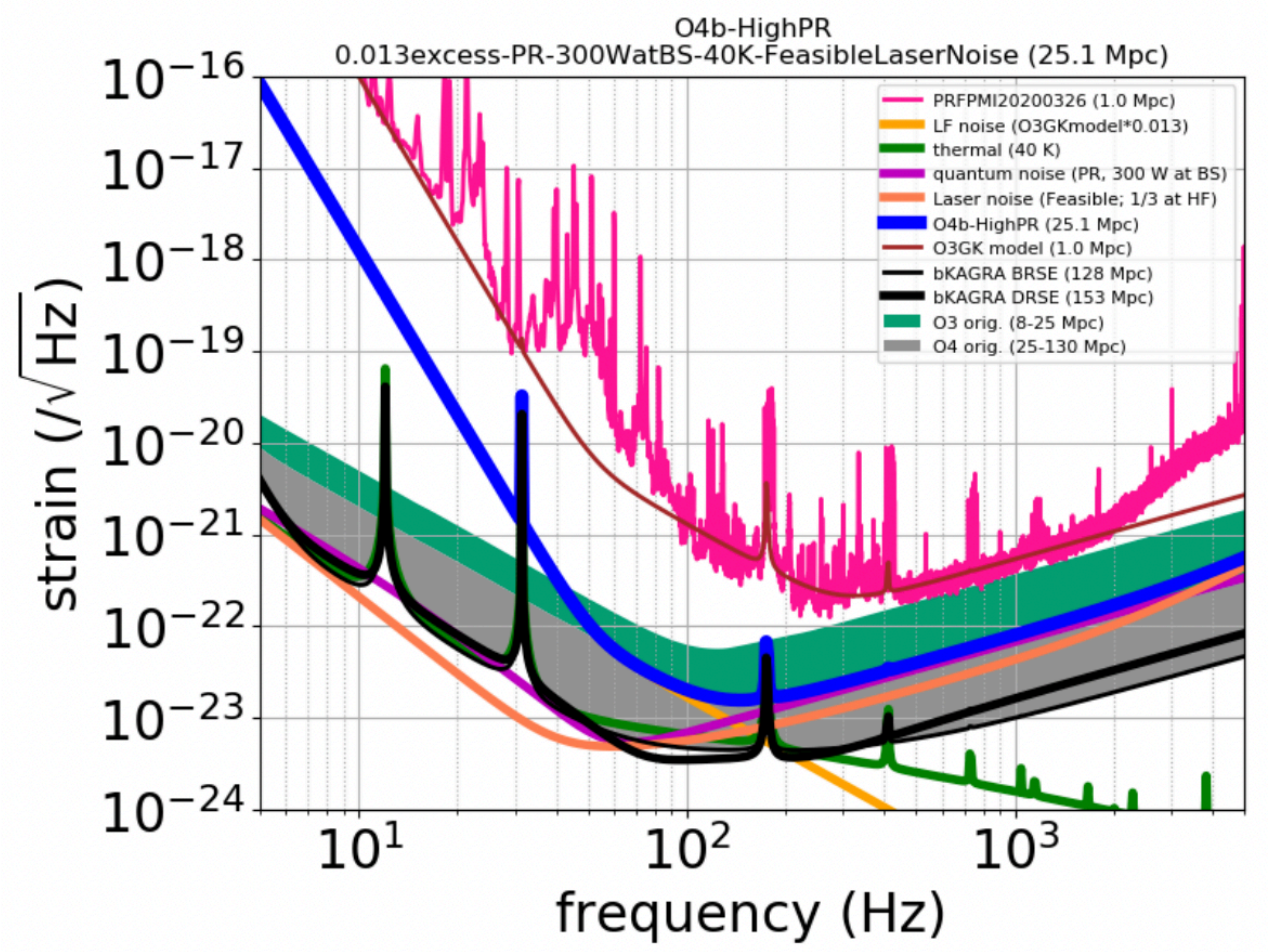


Figure is cited from Y. Michimura JGW-T1809078

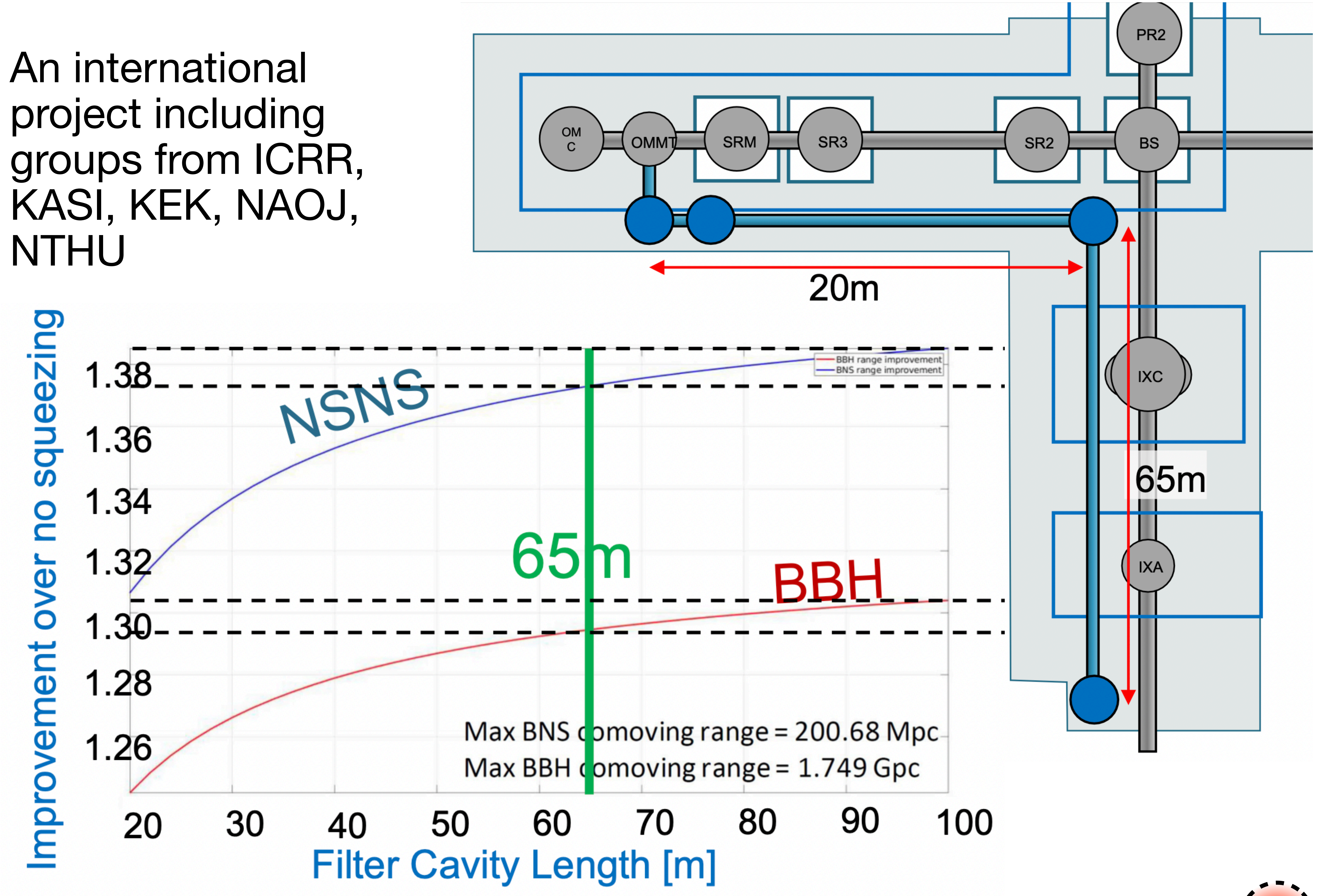
- The blue curve is expected to be highly possible to achieve
- In this case, the use of frequency independent squeezing could be very beneficial (assuming frequency noise can be further reduced)
- If 3dB squeezing can be achieved, it is equivalent to increase laser power by a factor of 2
- If design sensitivity can be achieved, the use of frequency dependent squeezing will be very beneficial

# KAGRA filter cavity (KFC) project

- 65m filter cavity
- Still in design phase
- Not yet funded

- An international project including groups from ICRR, KASI, KEK, NAOJ, NTHU

- Right side figure shows KAGRA sensitivity improvement as a function of filter cavity length
- Filter cavity round trip losses are fixed to be 25ppm

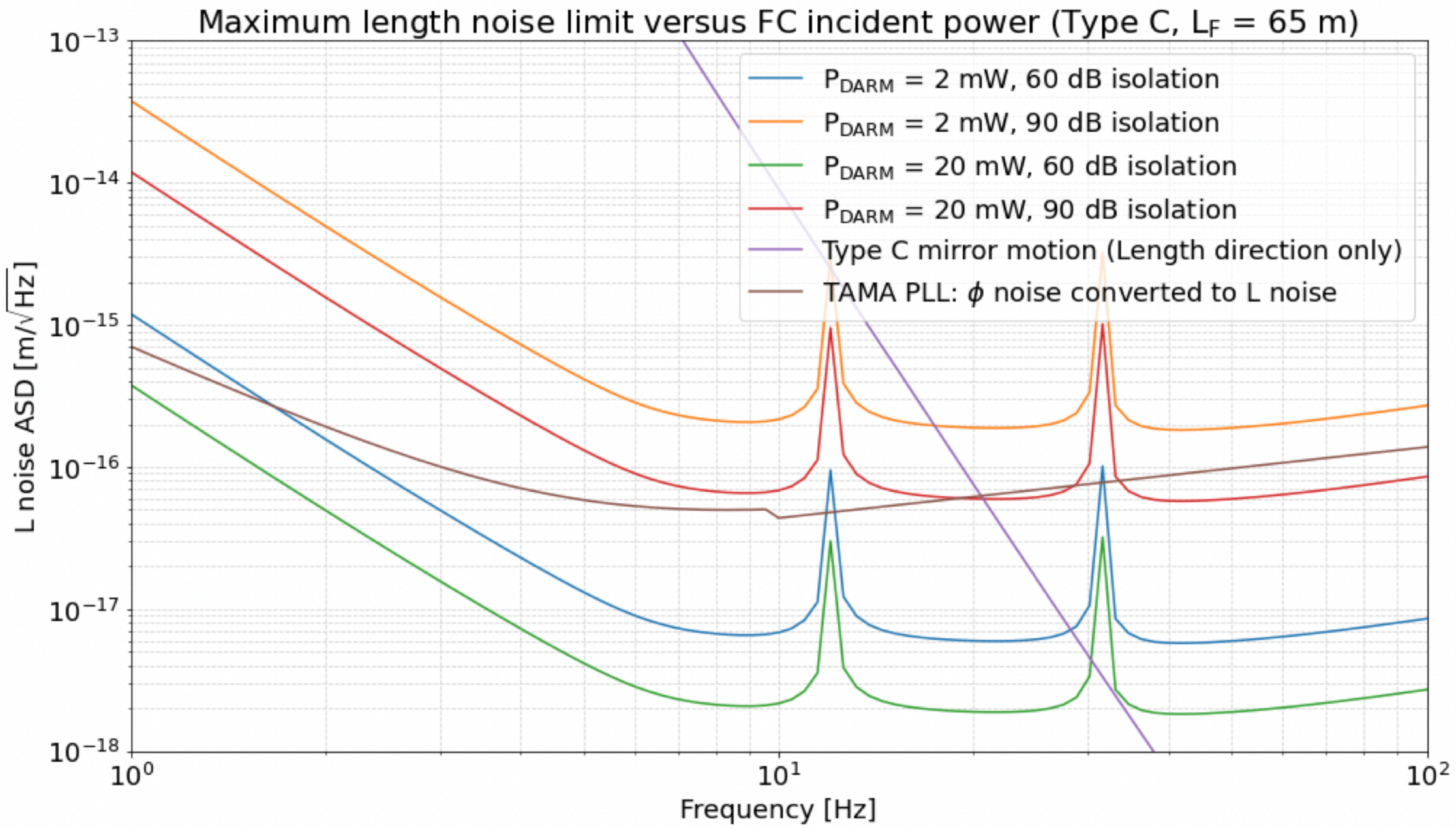


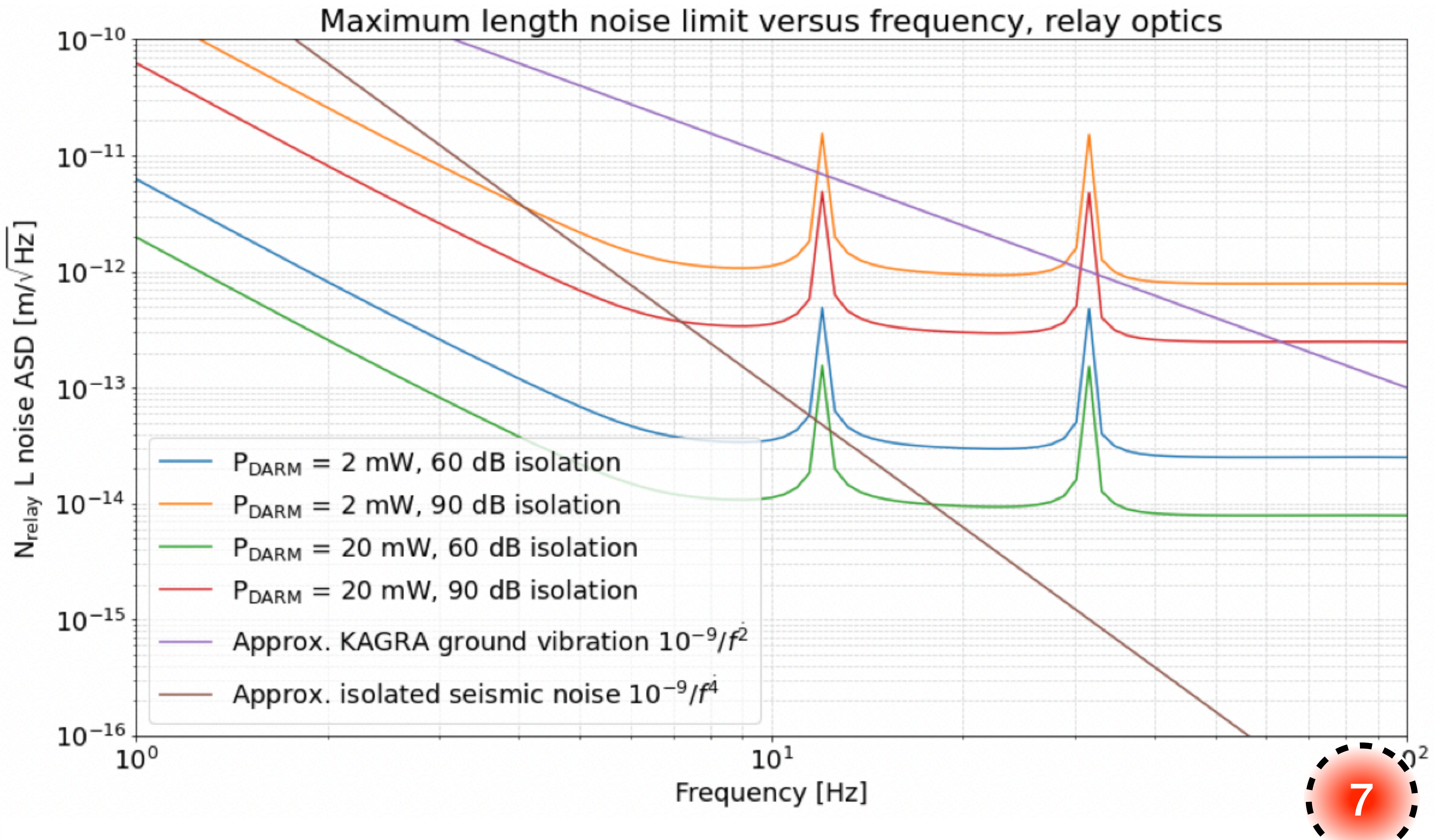
This page is from Y. Aso JGW-G2213986 and M. Eisenmann G2113322

# KFC scattered noise calculation

- To estimate which type of suspension for filter cavity mirrors and relay optics
- To evaluate how many Faraday isolators
- Get information about interferometer dark port power

This page is from M. Page JGW-2113443 and G2213980

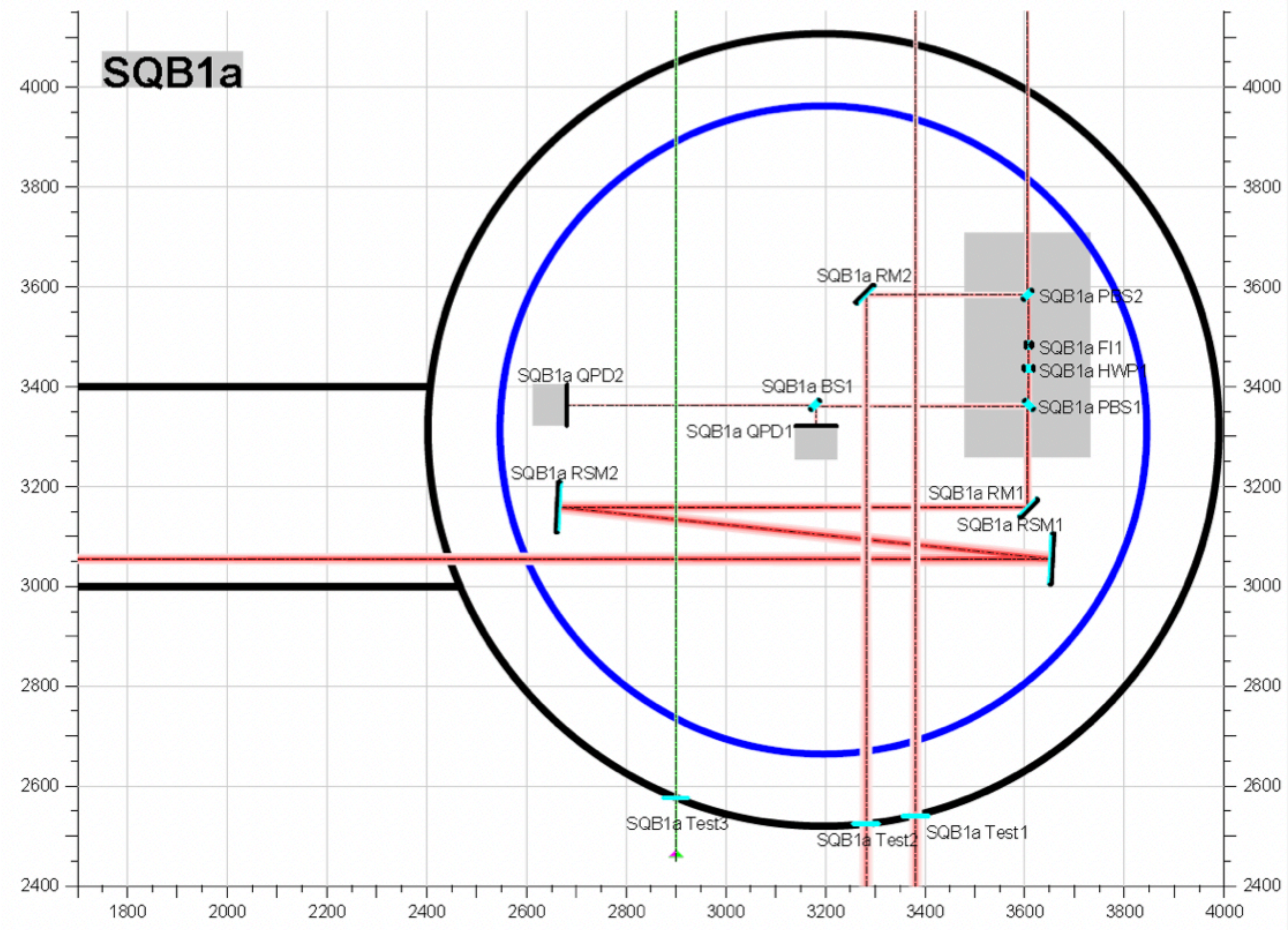

Maximum length noise limit versus FC incident power (Type C, $L_F$ = 65 m)

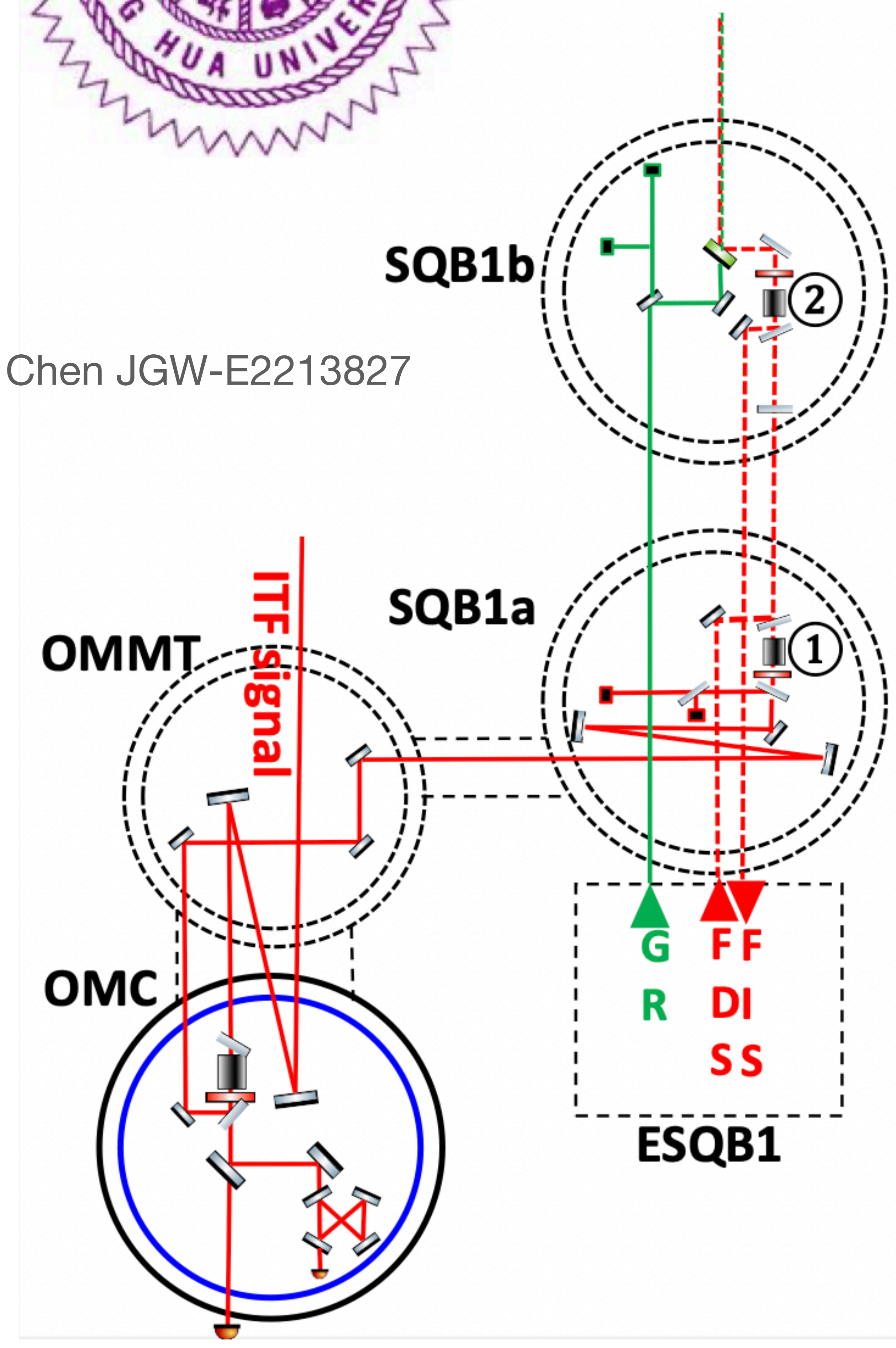

Maximum length noise limit versus frequency, relay optics

# KFC faraday isolator and interface optics

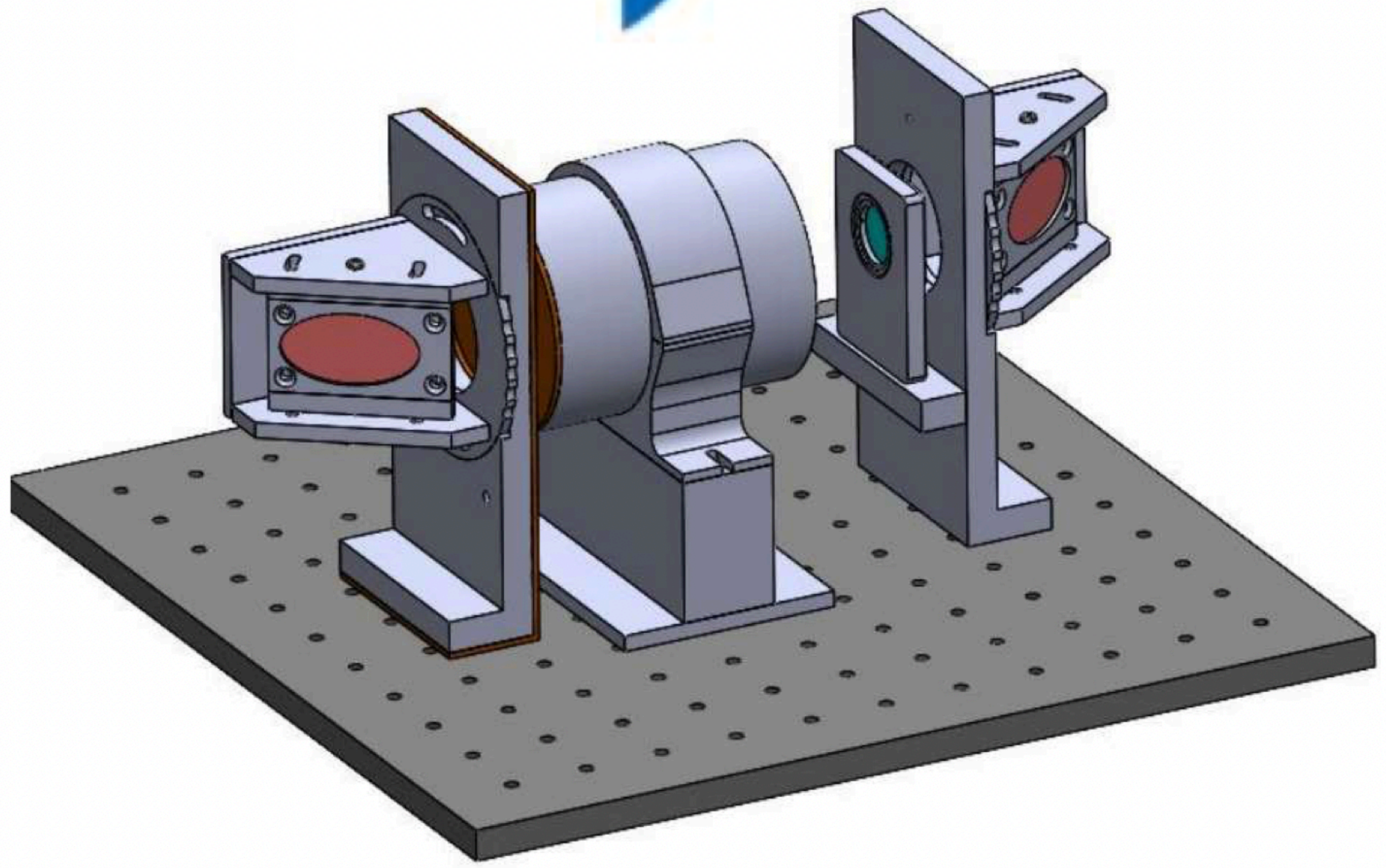
- Interface optics design
- Simulate beam size and path
- Design telescope
- Decide alignment control sensor position

From H. Chen JGW-E2213827





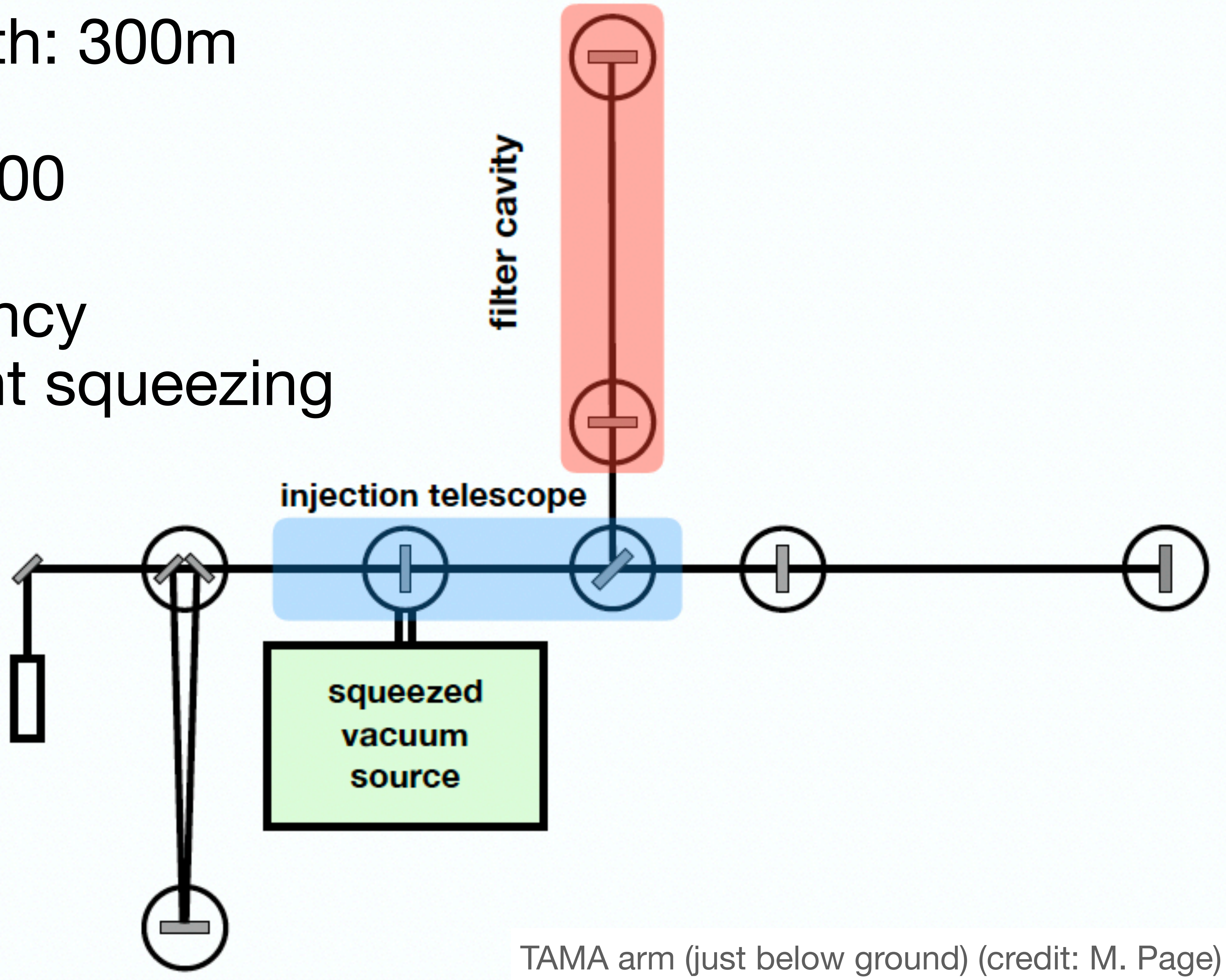
- Customized faraday isolator to achieve low optical losses and high isolation



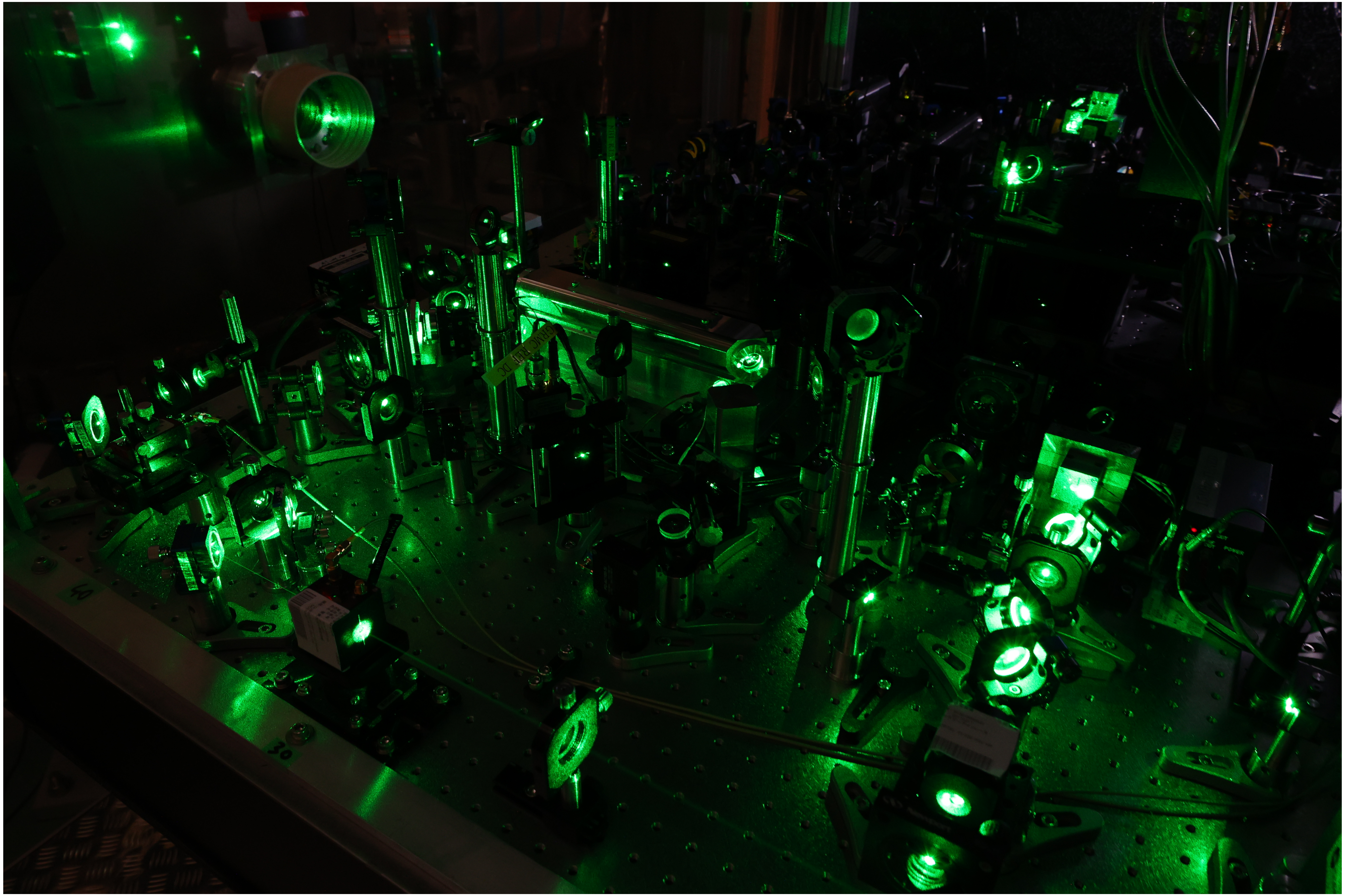
From J. G. Park JGW-G2213830

# Frequency dependent squeezing experiment at TAMA (overview)

- Our goal: full scale filter cavity prototype to demonstrate frequency dependent squeezing with rotation at 70Hz
  - Cavity length: 300m
  - Finesse: 4400
  - 9dB frequency independent squeezing

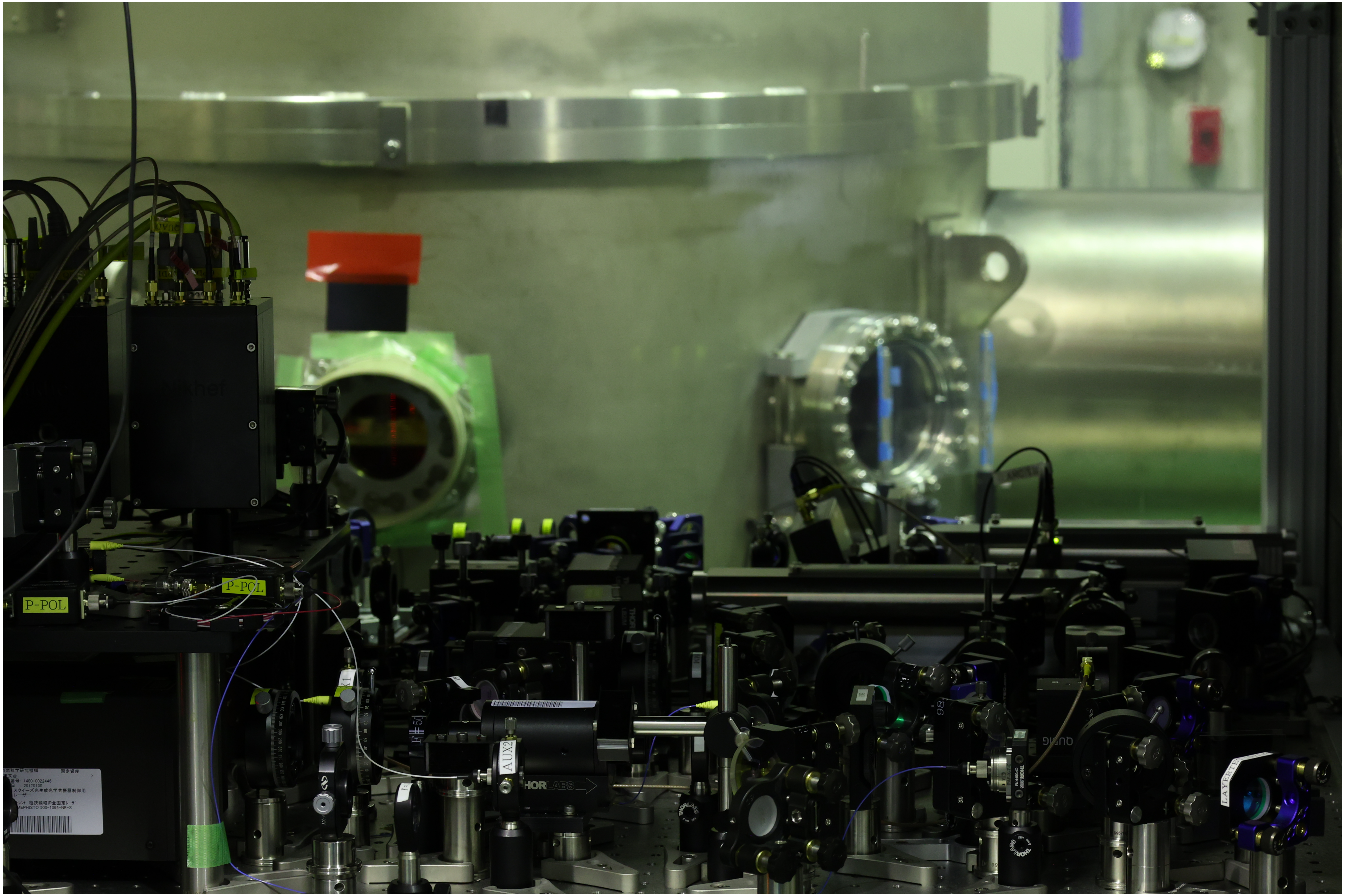


TAMA arm (just below ground) (credit: M. Page)



# Squeezed vacuum source left side

Credit:
Michael Page



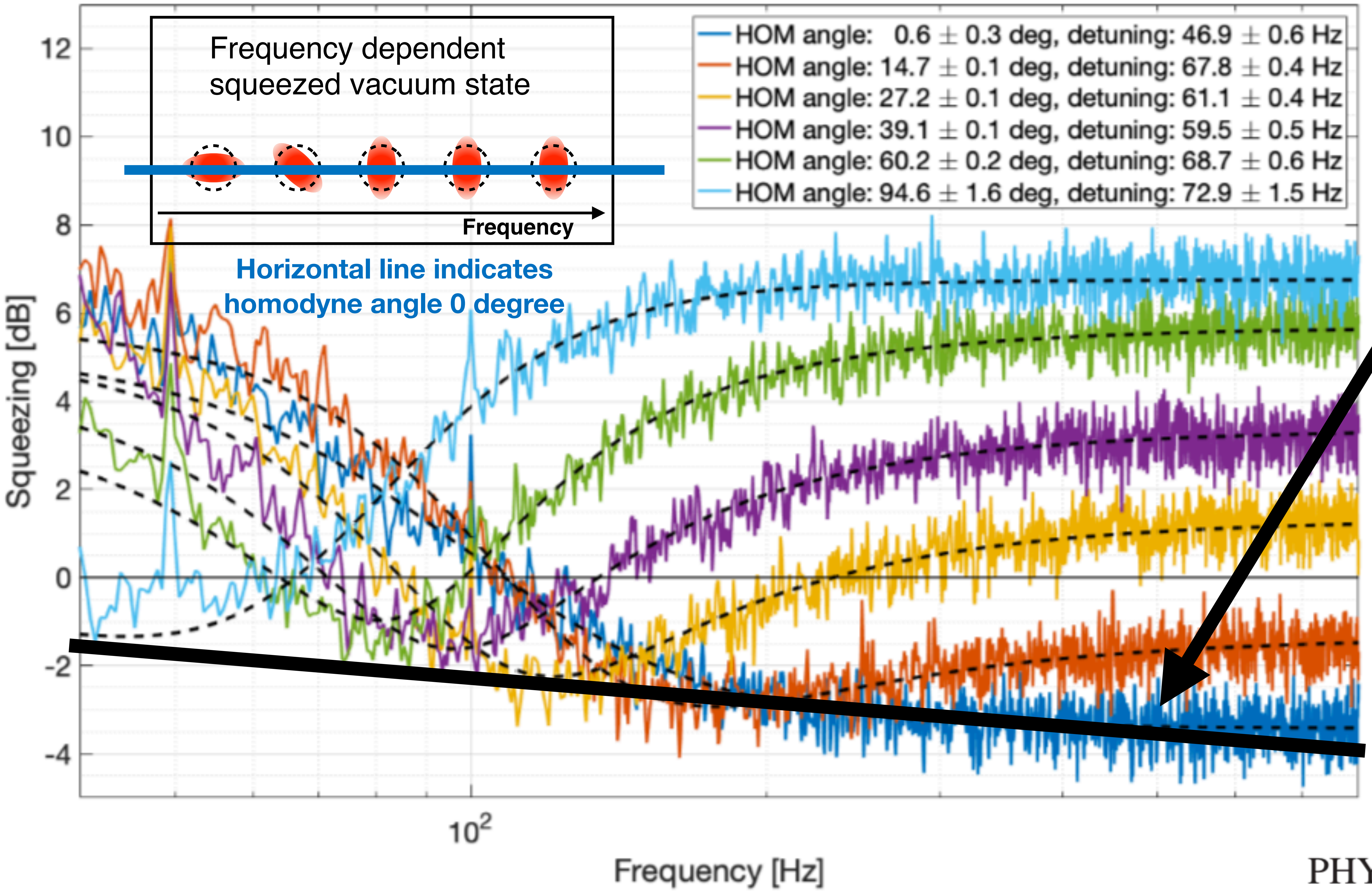
Squeezed vacuum source right side

and

The first entered vacuum chamber

Credit:
Michael Page

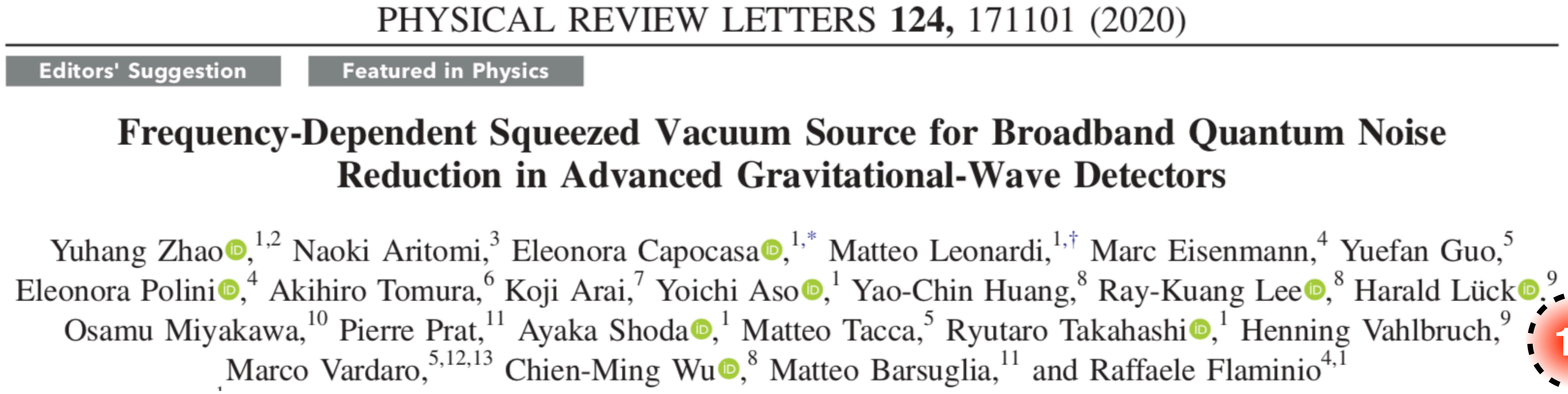
# Frequency dependent squeezing measurement



**Horizontal line indicates homodyne angle 0 degree**

- Assuming filter cavity parameters (300m, round trip losses smaller than around 100ppm, input mirror transmissivity 0.136%) and $\Omega_{SQL} \simeq 70\,\mathrm{Hz}$, and filter cavity has linewidth $\sim \Omega_{SQL}/\sqrt{2}$ and is detuned by linewidth, *gravitational wave detector senses only the squeezed quadrature*
- If we use our squeezer and filter cavity for KAGRA, we expect a quantum noise reduction at all frequencies (1dB at low frequency and 3.4dB at high frequency)
- We are one of the first teams achieved this result around the world, which is suitable for advanced gravitational wave detectors

- However
- Working point is drifting
- Backscattering below 30-50Hz


PHYSICAL REVIEW LETTERS **124,** 171101 (2020)

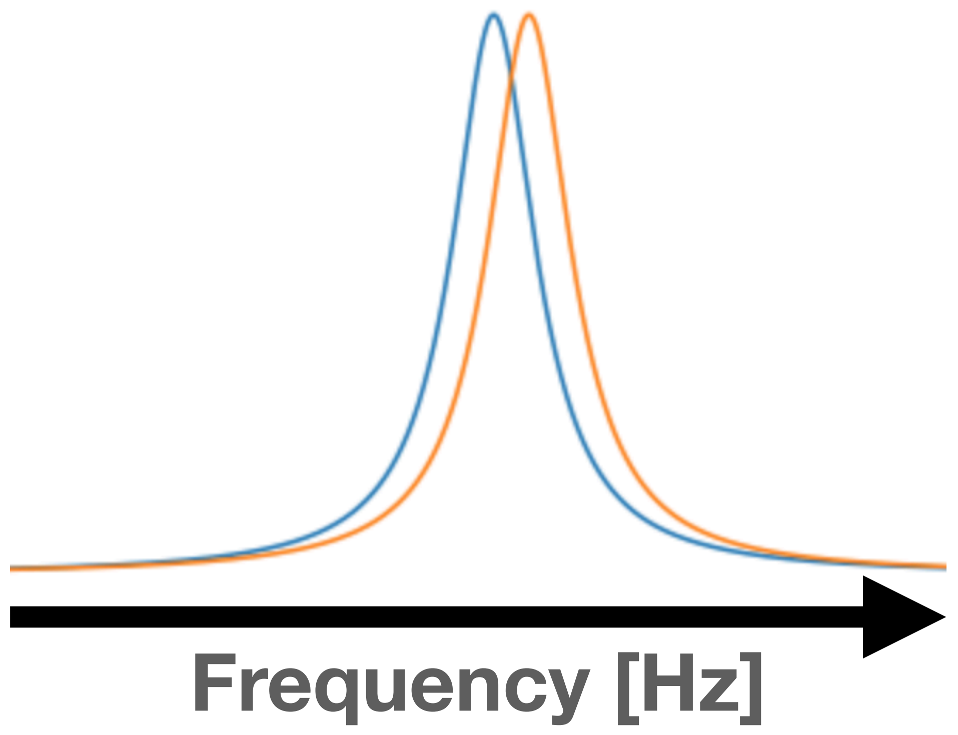
Editors' Suggestion Featured in Physics

**Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors**

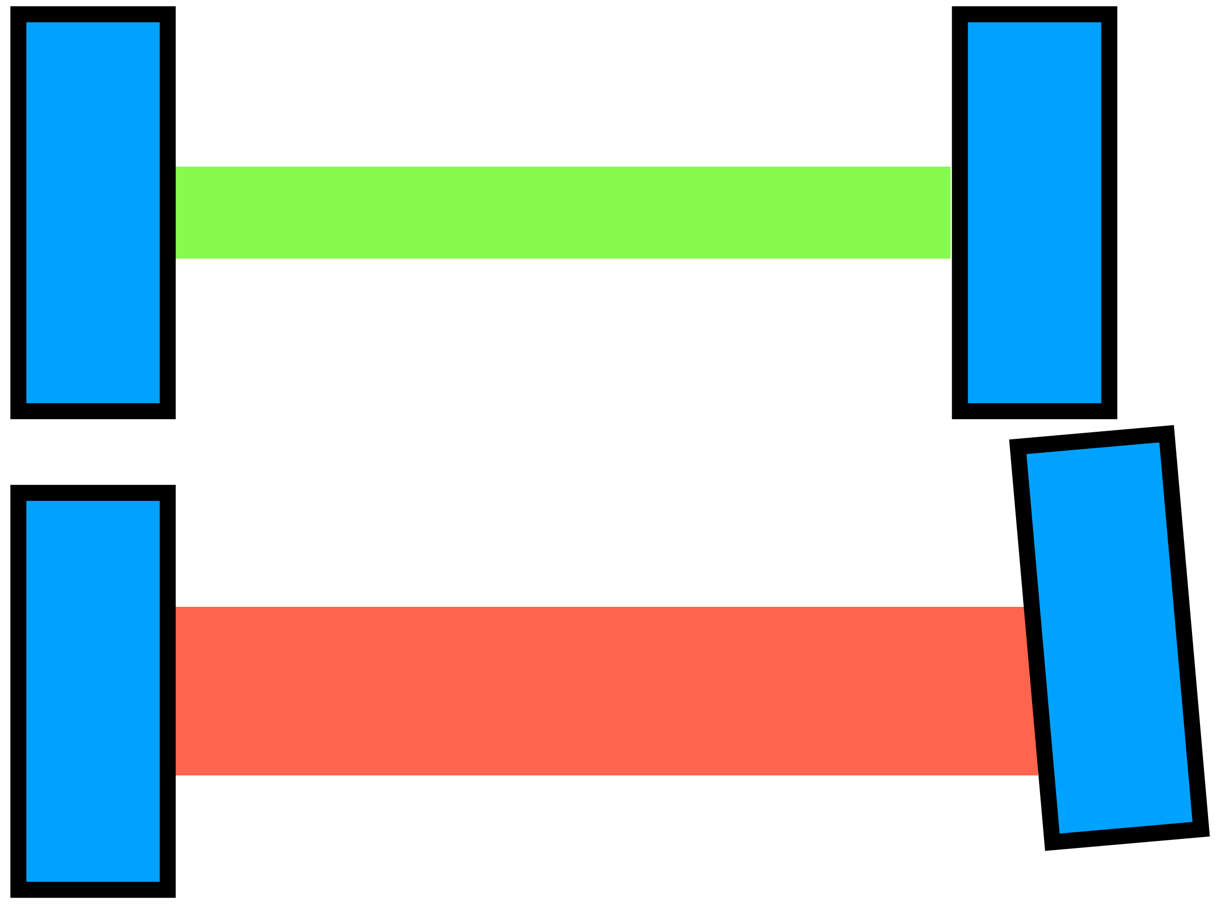
Yuhang Zhao,[1,2] Naoki Aritomi,[3] Eleonora Capocasa,[1,*] Matteo Leonardi,[1,†] Marc Eisenmann,[4] Yuefan Guo,[5] Eleonora Polini,[4] Akihiro Tomura,[6] Koji Arai,[7] Yoichi Aso,[1] Yao-Chin Huang,[8] Ray-Kuang Lee,[8] Harald Lück,[9] Osamu Miyakawa,[10] Pierre Prat,[11] Ayaka Shoda,[1] Matteo Tacca,[5] Ryutaro Takahashi,[1] Henning Vahlbruch,[9] Marco Vardaro,[5,12,13] Chien-Ming Wu,[8] Matteo Barsuglia,[11] and Raffaele Flaminio[4,1]

# Control filter cavity with green beam

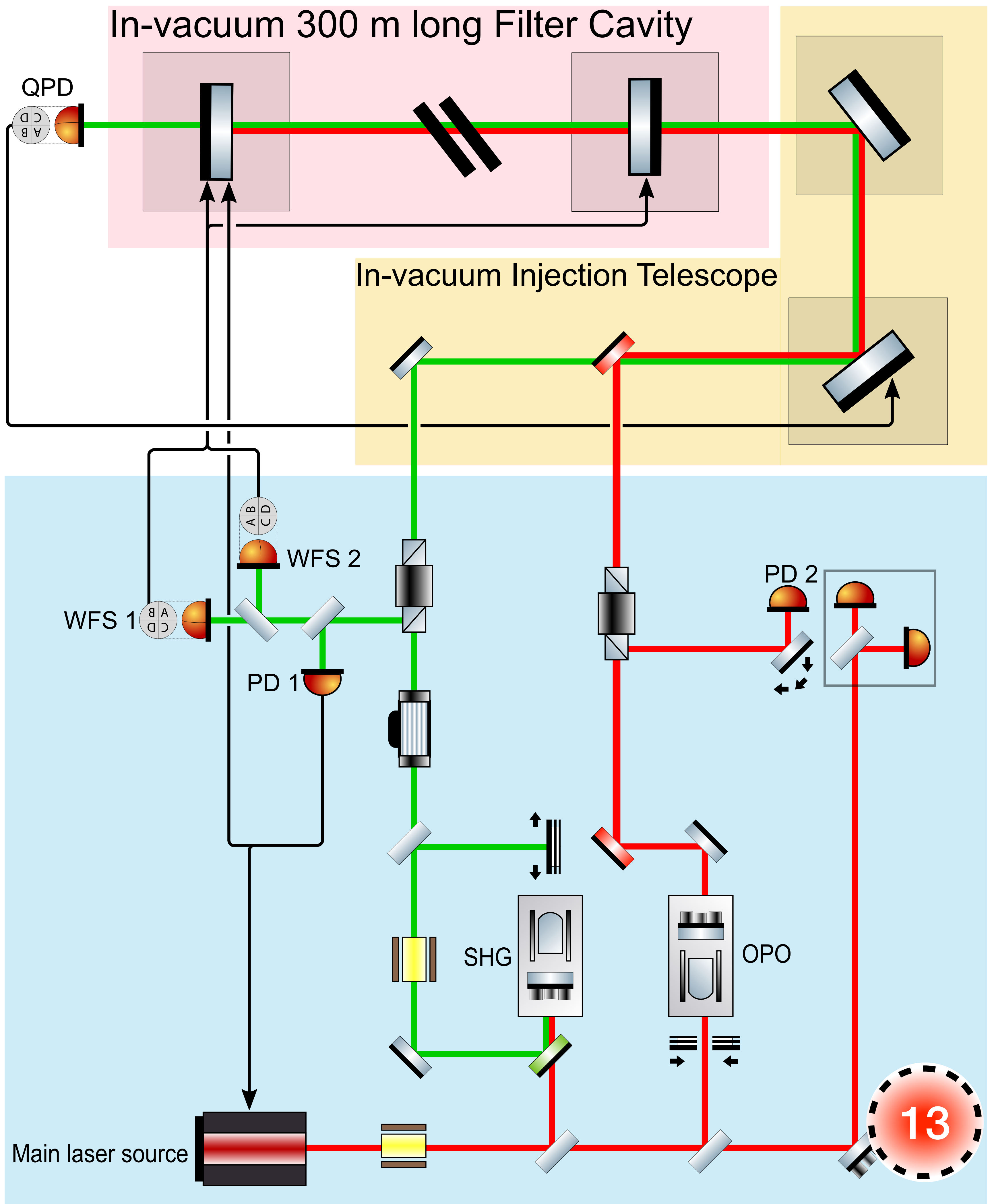
- Since squeezed vacuum contains only negligible power, auxiliary control fields are needed

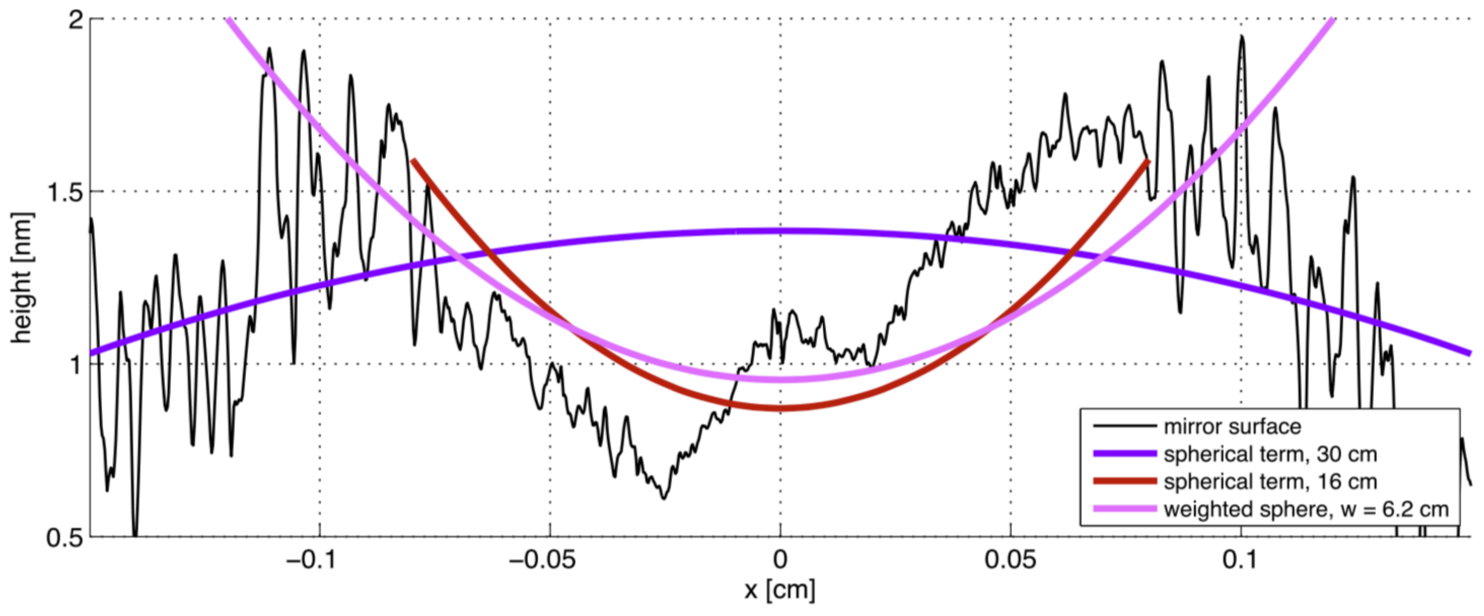


- Same cavity
- Green/Infrared overlapping

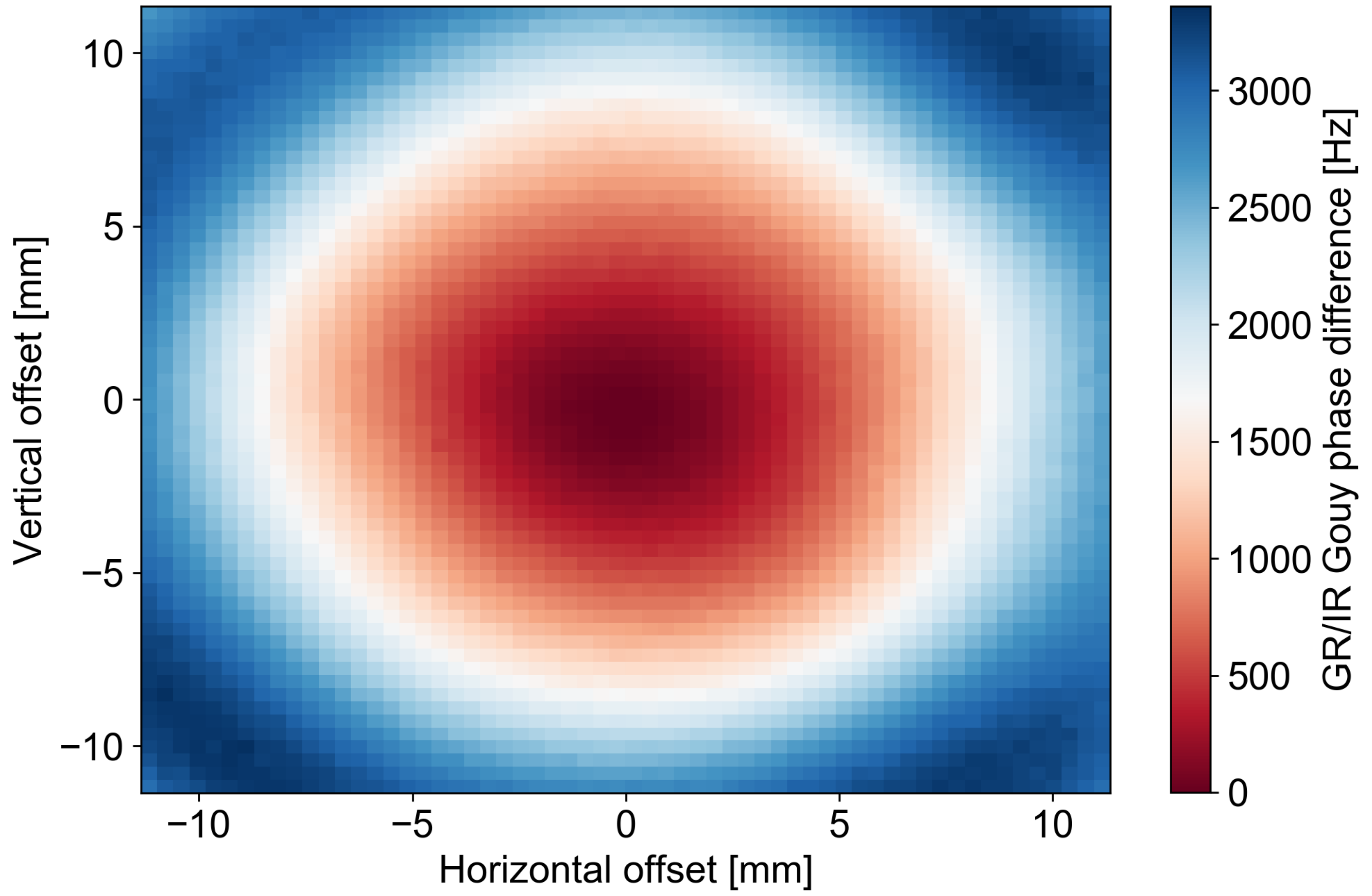


- Different mirror wavefront error
- Results in different optical axis

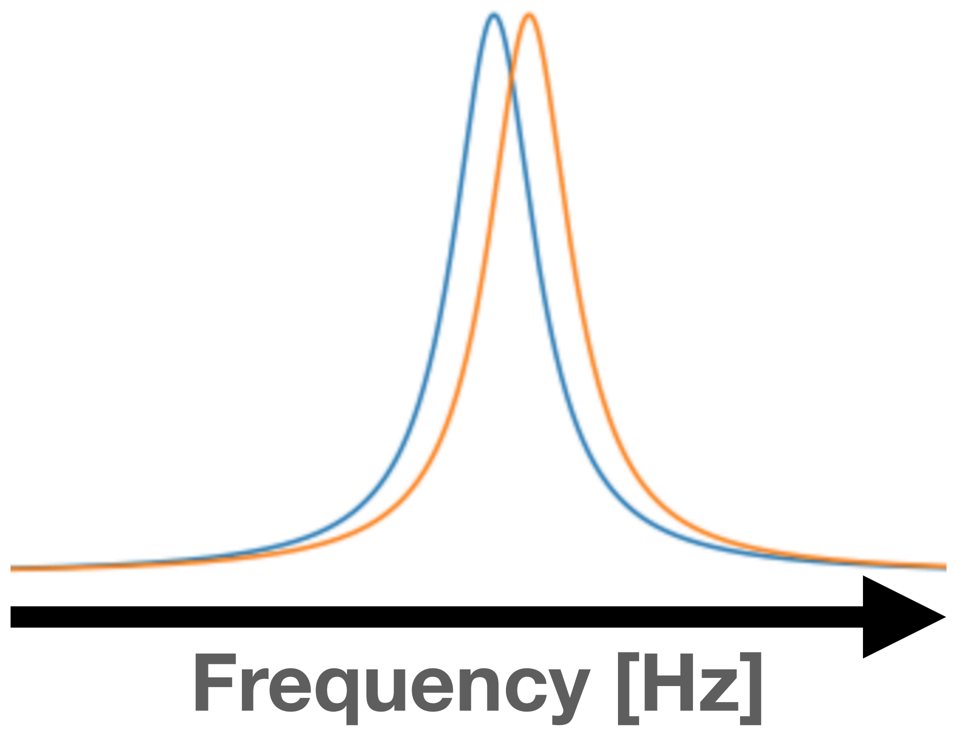




Living Review of Relativity, C. Bond et al, 19, 2016



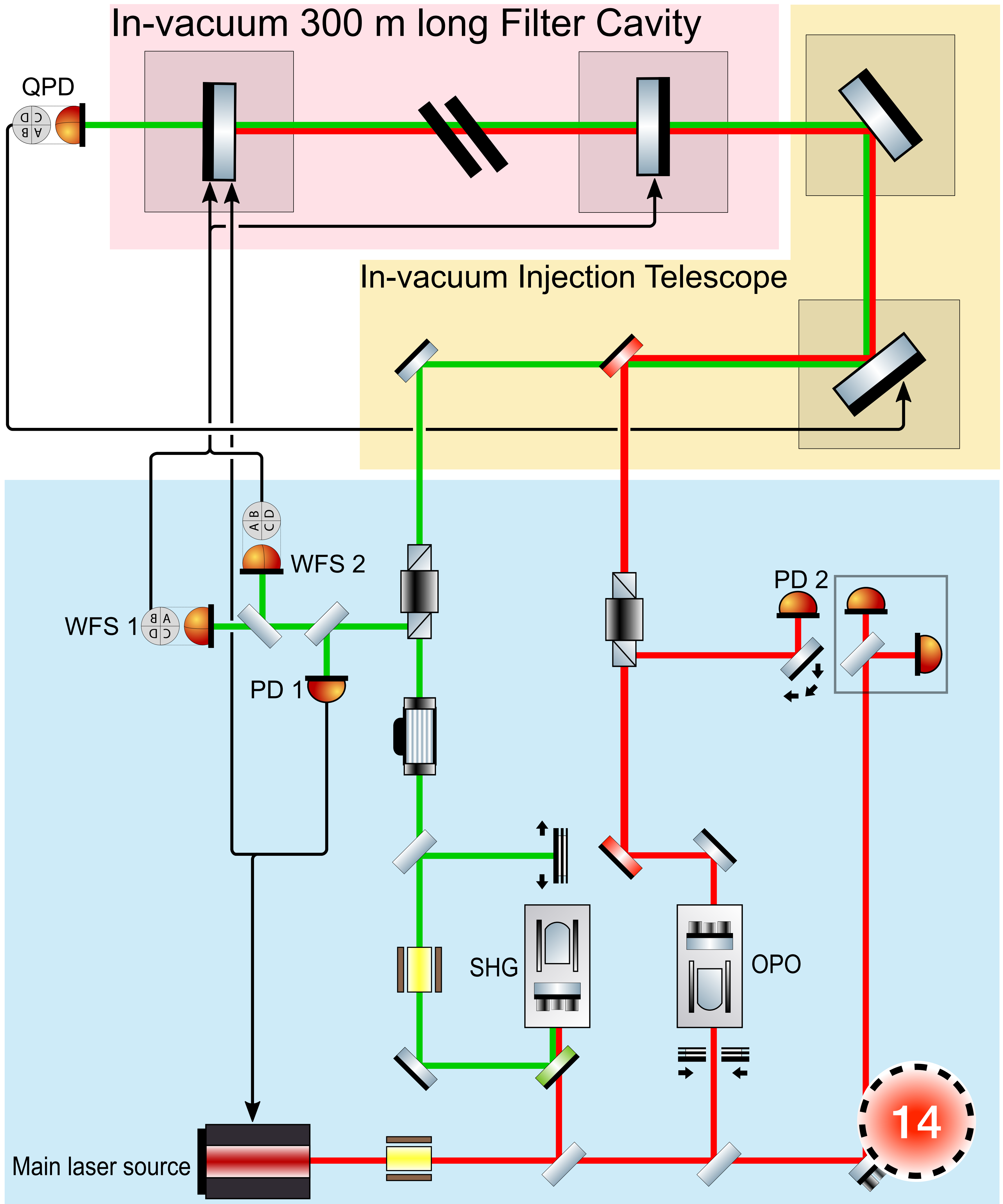
# Control filter cavity with green beam



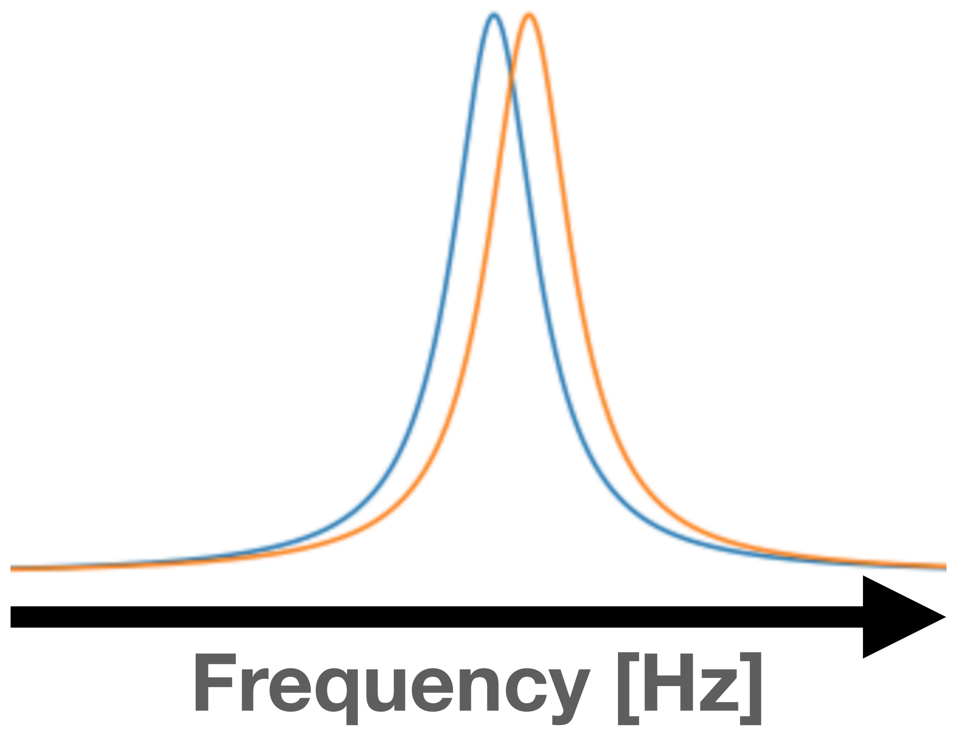
- Due to an AOM on green beam, a initial detuning condition for green and infrared beams cannot be held (infrared detuning will be induced)

$$\Delta_{\mathrm{d}}\ (\mathrm{Hz}) = (\mathrm{f}_{\mathrm{AOM}} \bmod \mathrm{FSR}') \times \mathrm{FSR}'/2$$

- This infrared detuning shows up when
  - Cavity length change
  - Green control beam frequency change
  - Cavity unlock and lock reacquired
- Virgo filter cavity sub-carrier control scheme should have the same issue, but I heard a novel mitigation method will be employed



# Control filter cavity with green beam



- A Pound-Drever-Hall control method utilize phase modulation $m_p$ to extract signal, but there will be unavoidable amplitude modulation $m_a$ to add noise

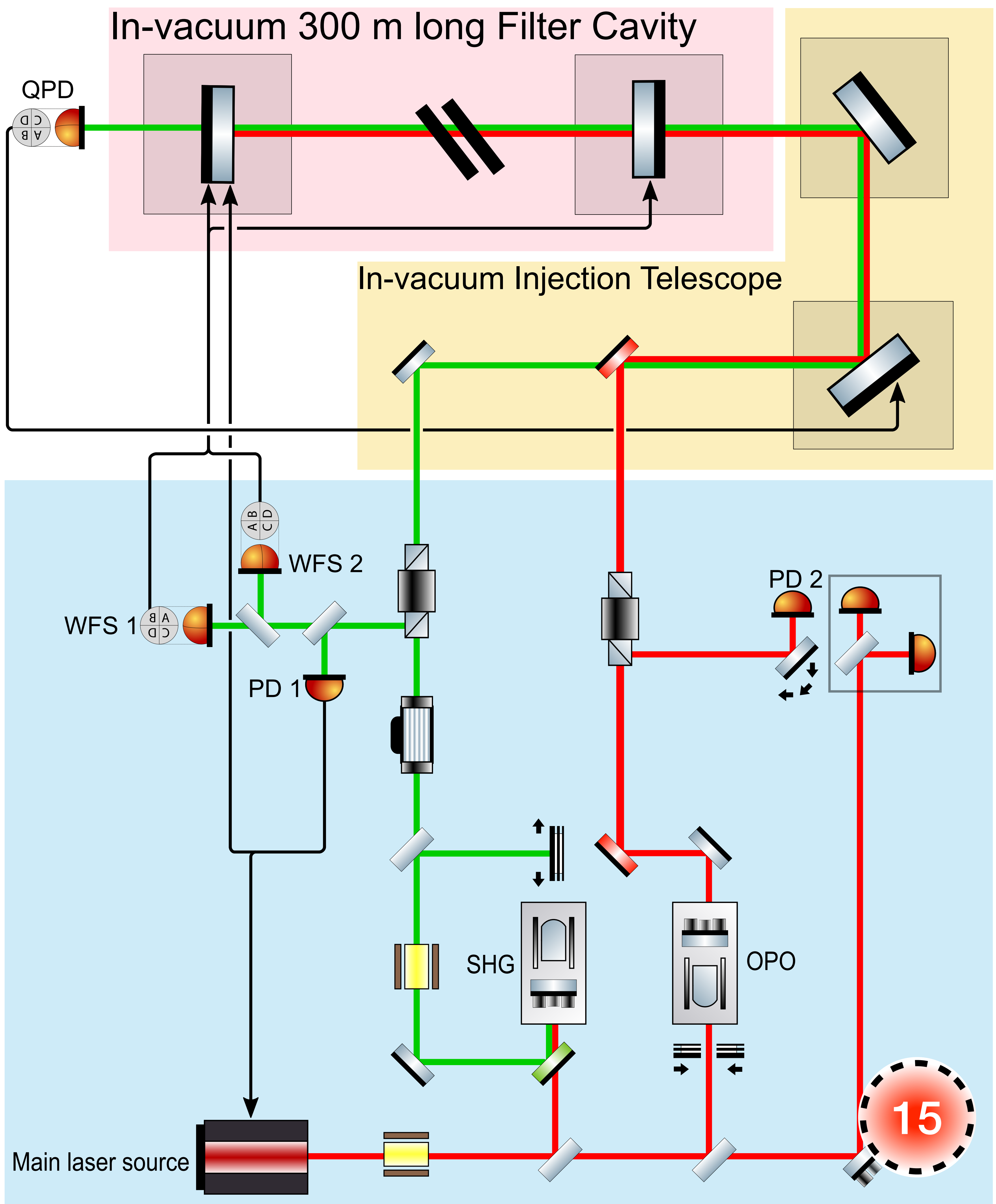
$$E = E_0 e^{i(\omega_0 t + m_p \cos(\omega_m t))}\underline{(1 + m_a \cos(\omega_m t + \phi))}$$

We get a DC power with magnitude $m_a E_0^2$ after demodulation at $\omega_m$

- According to our measurement of 4Hz detuning drift caused by residual amplitude modulation, we have

$$\frac{m_a}{m_p} \simeq 0.01$$

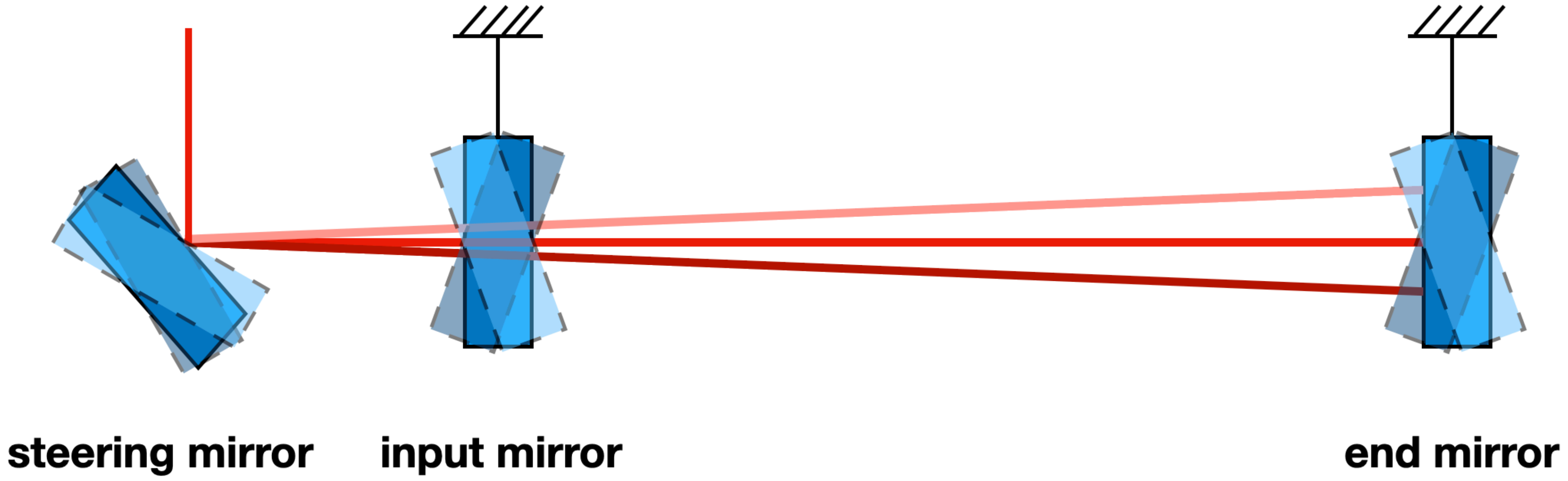
- An EOM with crystal wedged by 4 degree should make the above ratio reduced by a factor of 100

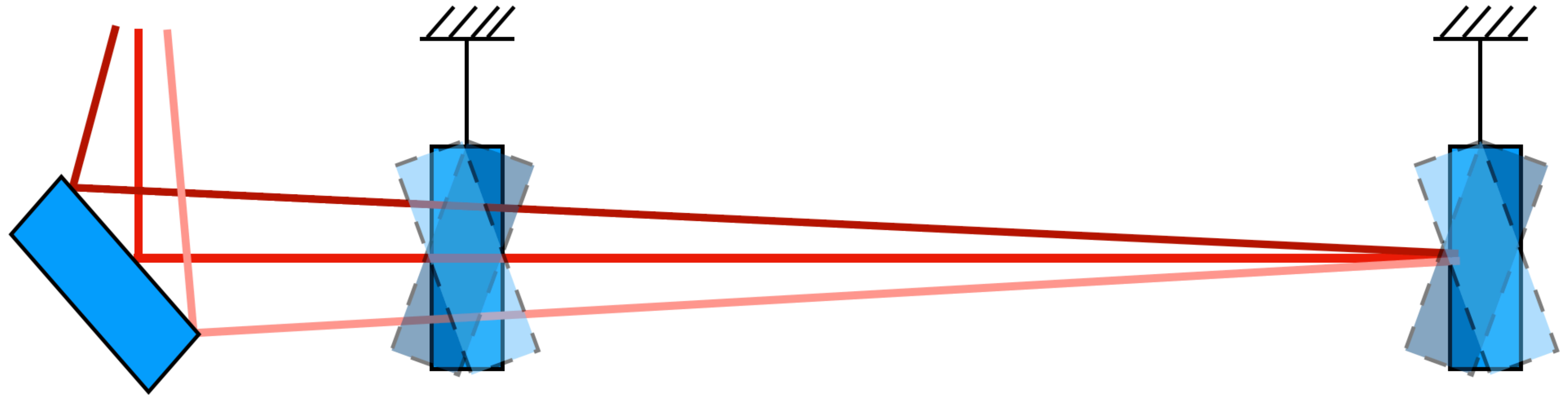


# Control filter cavity with green beam

- Check detuning change with filter cavity alignment change

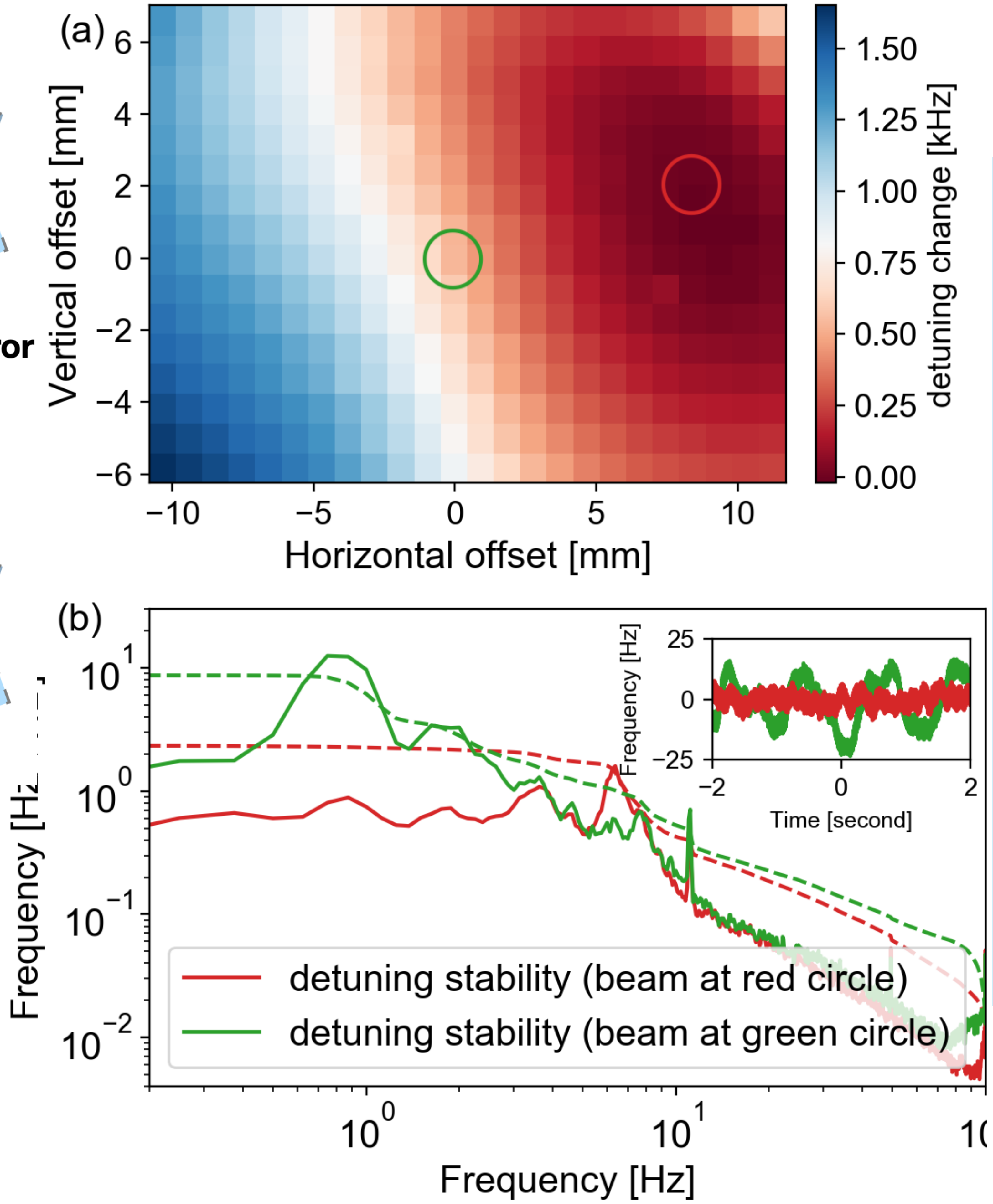
- Automatic alignment loop closed

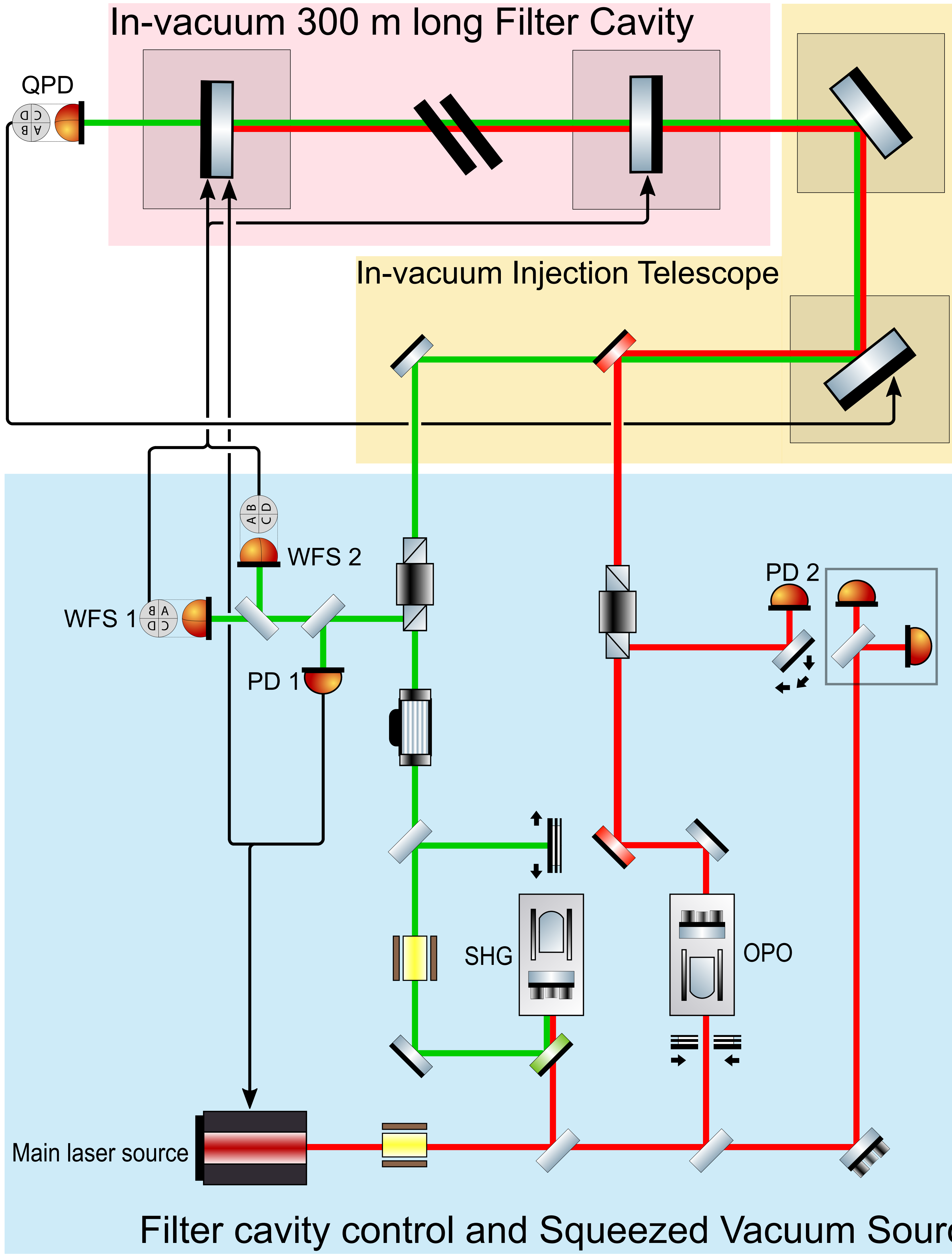




- Automatic alignment loop and pointing loop closed

- Detuning change when end mirror is scanned



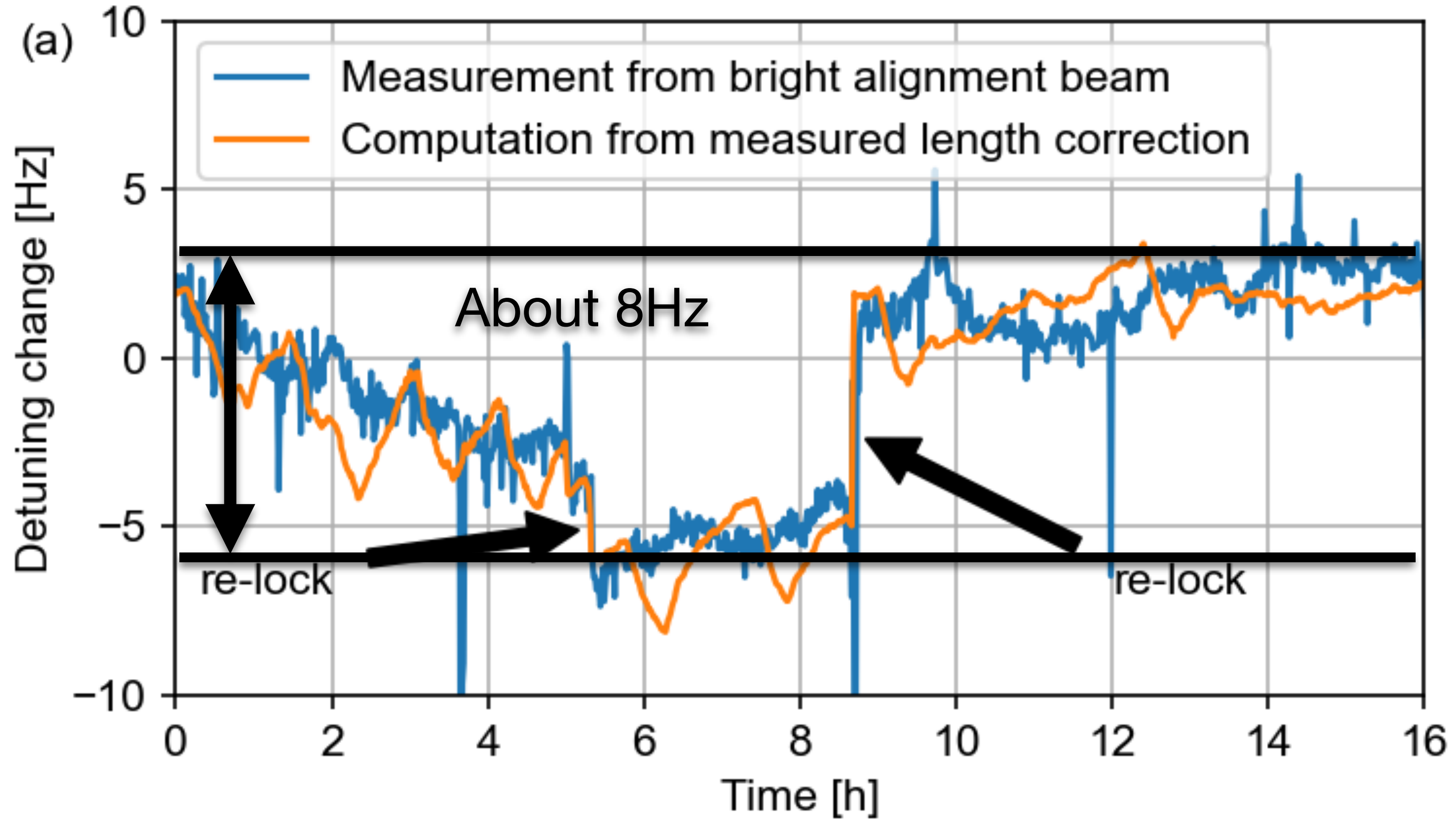


Filter cavity control and Squeezed Vacuum Sour

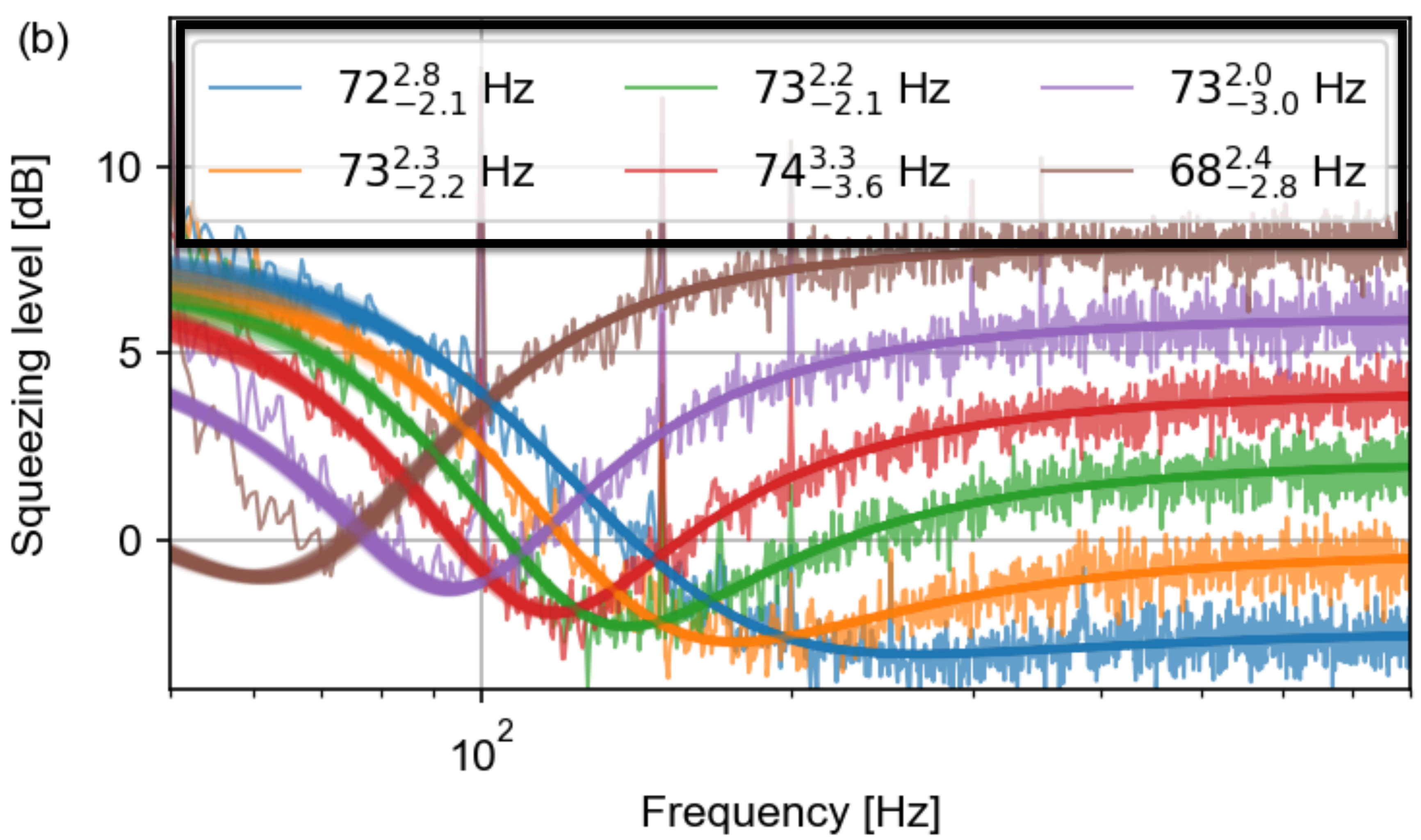
# Control filter cavity with green beam

- The filter cavity detuning is more sensitive to alignment change in this control scheme

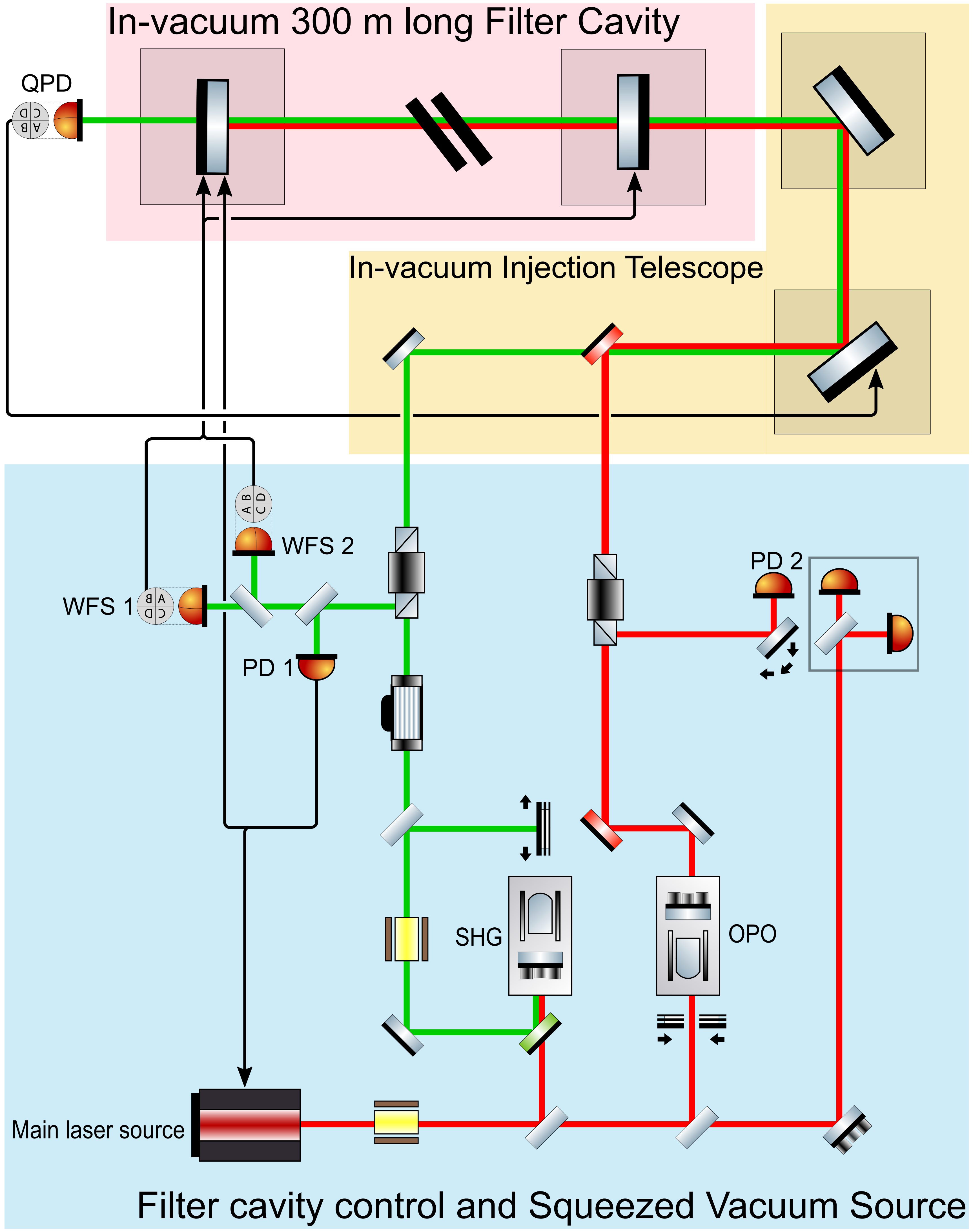
- After alignment is controlled with green, we see detuning fluctuation mainly from the AOM effect and residual amplitude modulation



About 6Hz



- A check from measuring frequency dependent squeezing proves the stability of detuning



Filter cavity control and Squeezed Vacuum Source

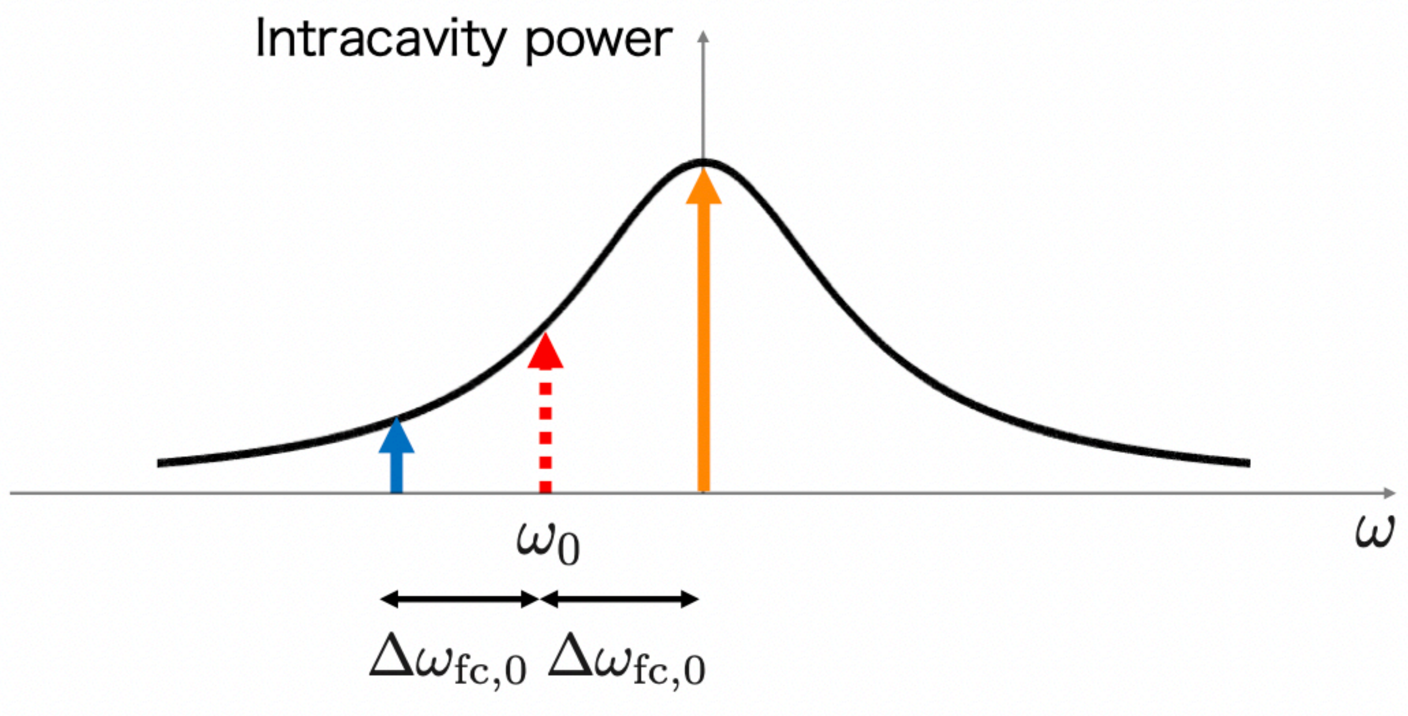
However, due to different optics used for green and infrared beams, this scheme cannot guarantee a proper detuning control after a few days

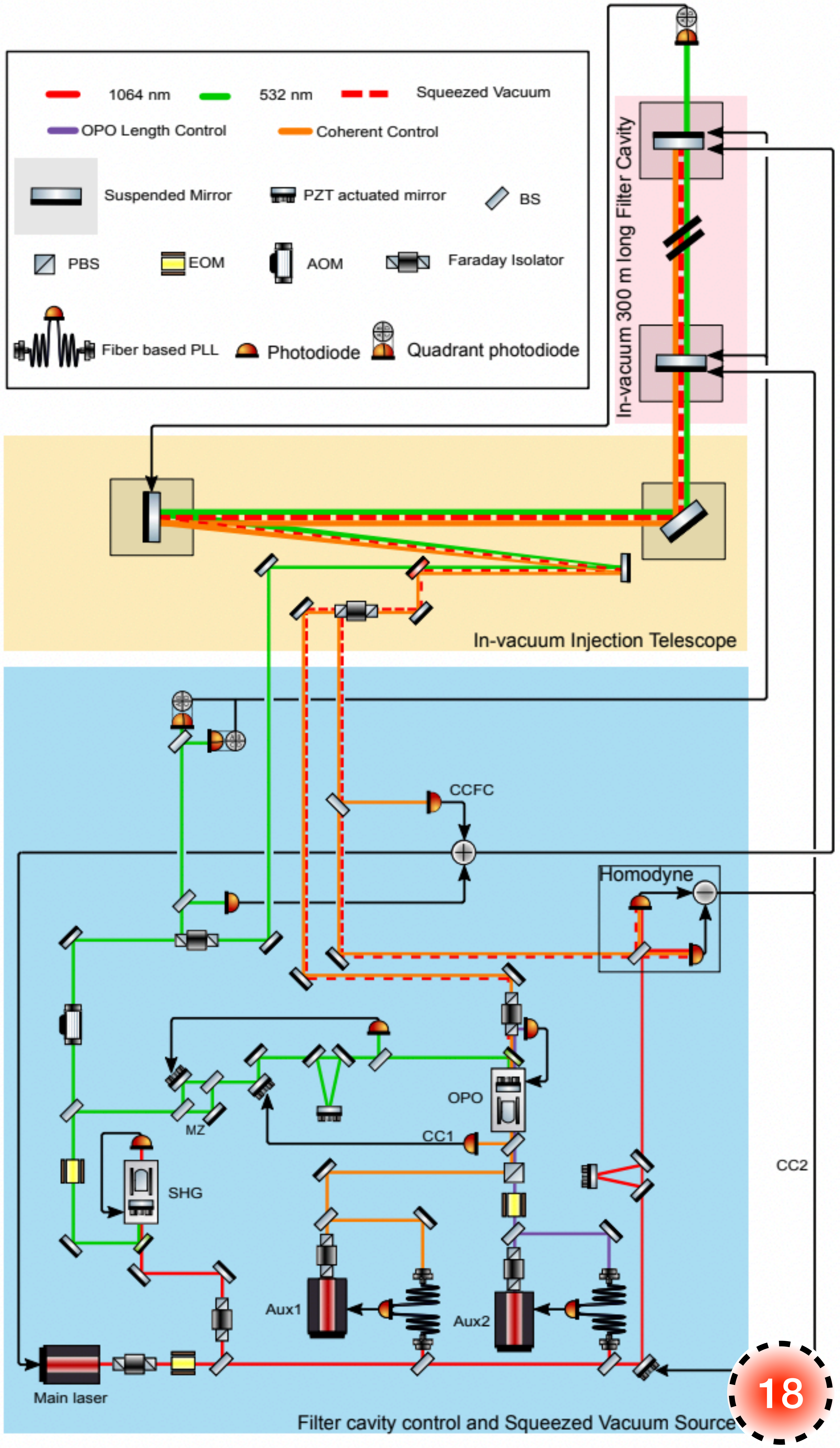
# Control filter cavity with Coherent control sidebands

- Coherent control fields are used for control squeezing phase relative to pump beam (to decide amplitude/phase squeezing) and local oscillator (to decide homodyne angle)

- However, when coherent control sidebands enter filter cavity, the relative phase between upper and lower sidebands gets modulated by filter cavity length noise. This modulation is utilized to lock filter cavity

- We demodulate the beat between upper and lower CC sidebands to get error signal. When a decent demodulation phase is chosen, we can lock one of the CC sideband on resonance

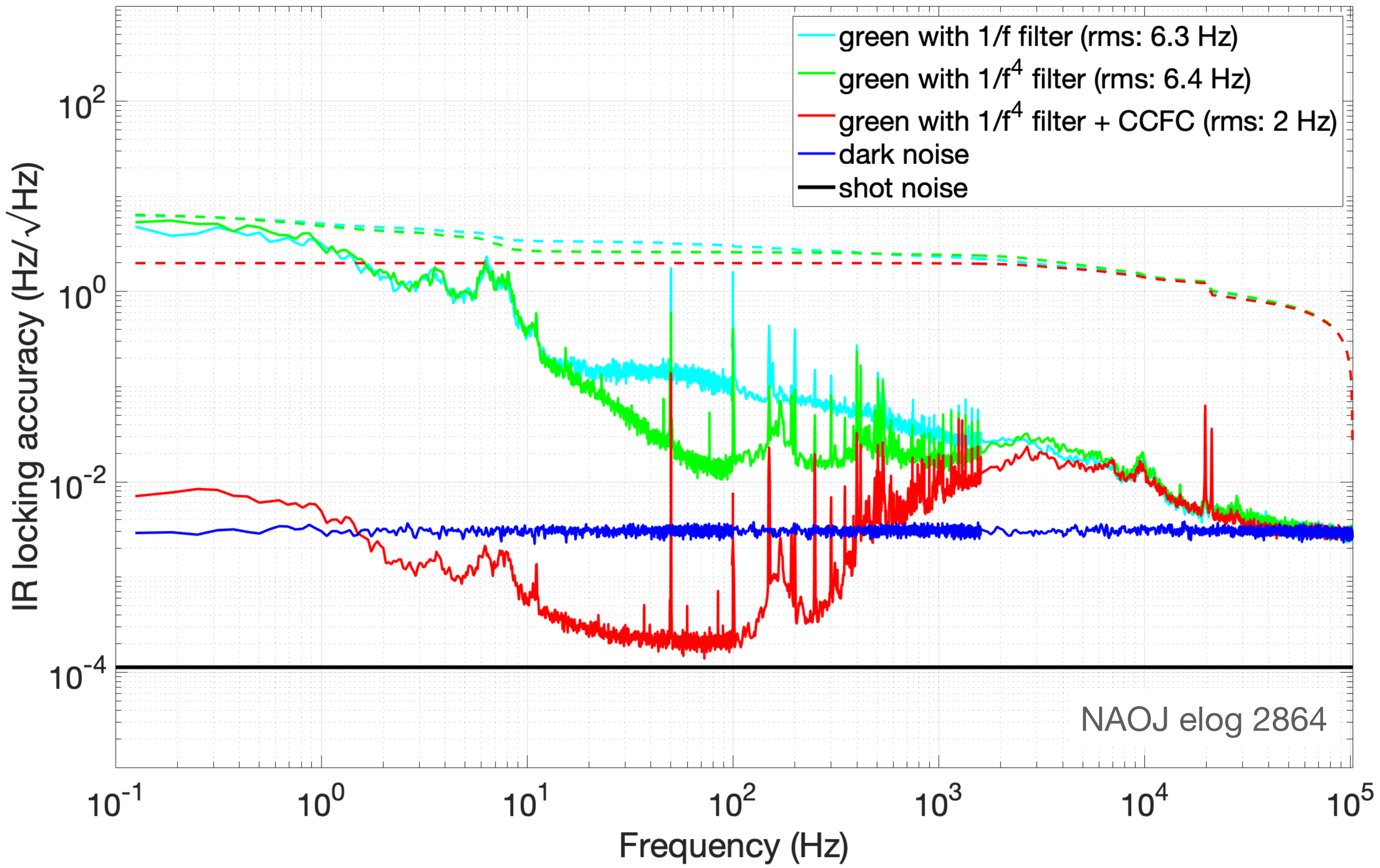




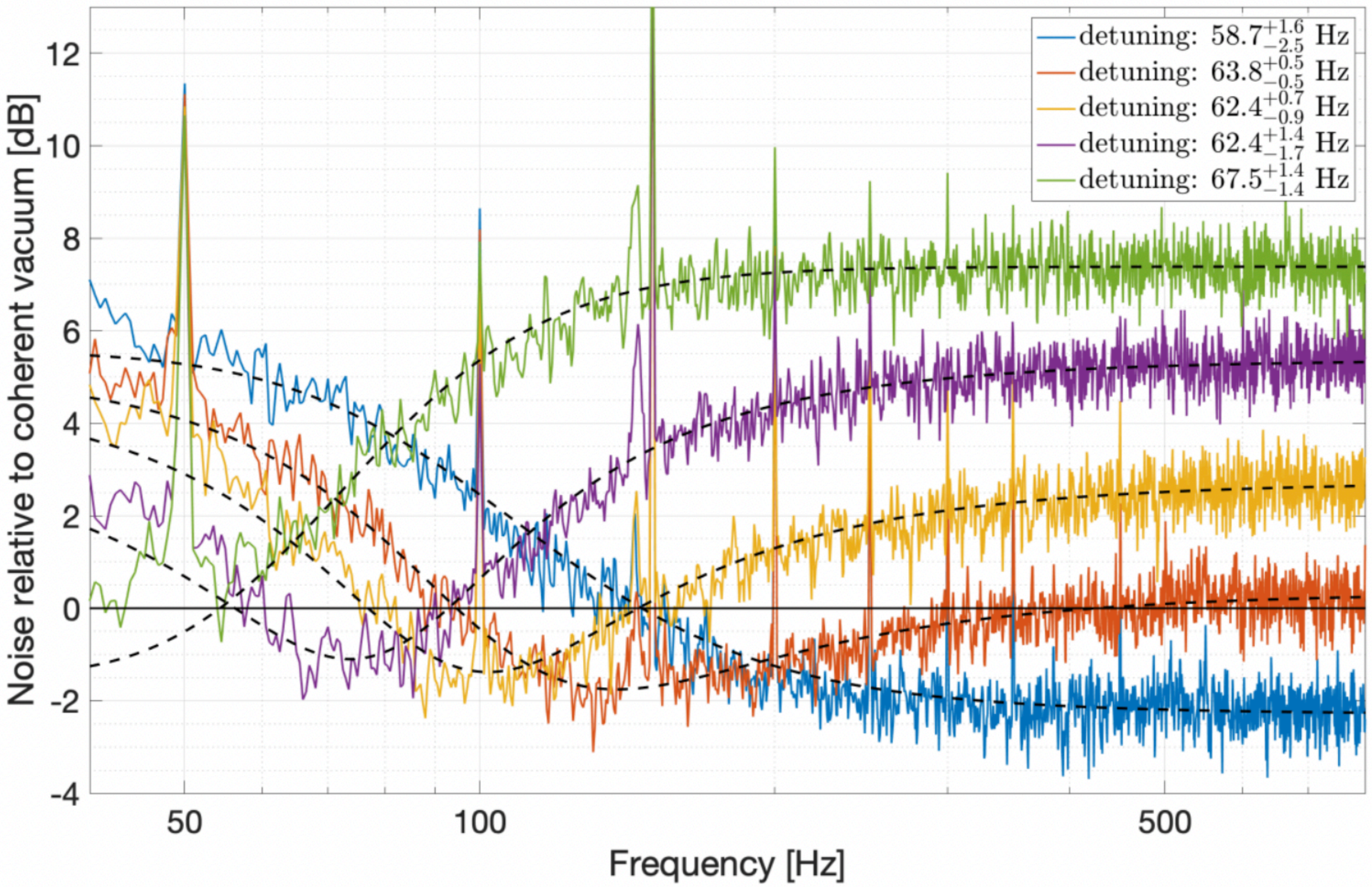
# Control filter cavity with Coherent control sidebands

- Coherent control sidebands locking can achieve locking accuracy much better than the green control method

- This is no relative misalignment between squeezing and coherent control sidebands



- However, the filter cavity alignment is not yet controlled by coherent control sidebands



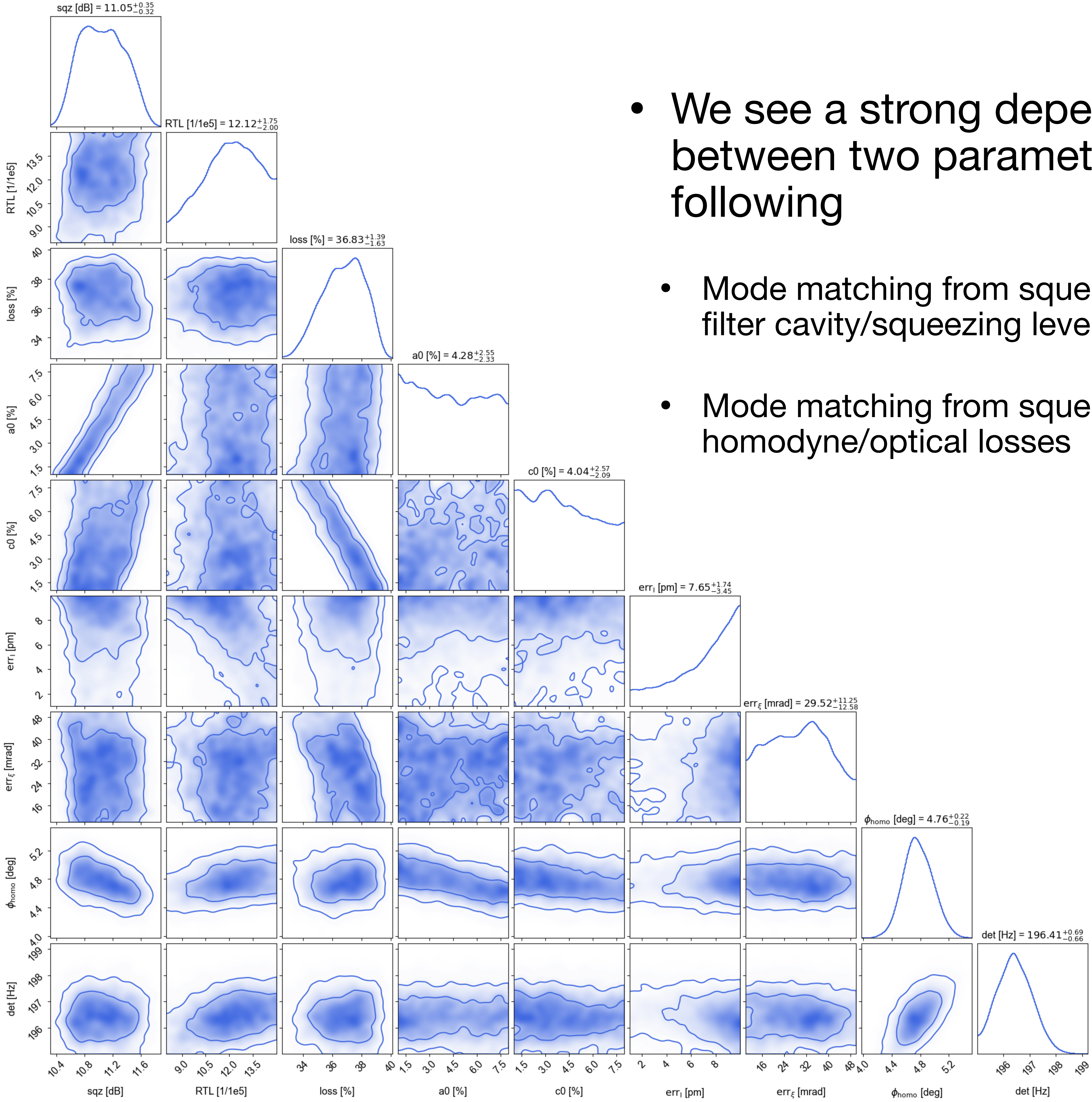
- A 9Hz detuning drift is observed in this scheme by checking frequency dependent squeezing

# About extracting filter cavity detuning information

- We use frequency dependent squeezing measurement to fit the detuning information

- In this fit, we usually let squeezing level, optical losses, homodyne angle and filter cavity detuning for free

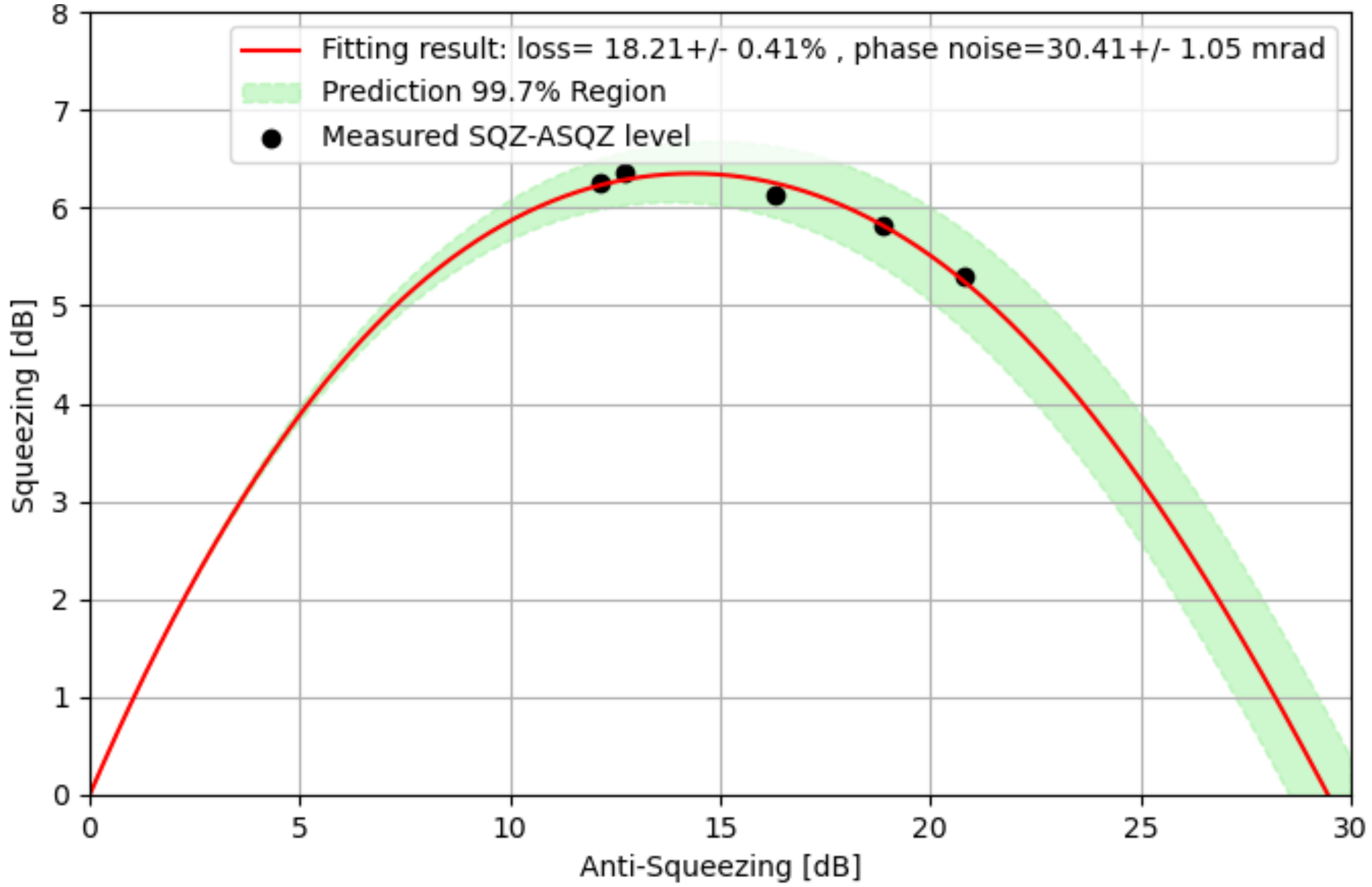
- However, other parameters could change or not well estimated. This will cause the estimation of detuning not accurate

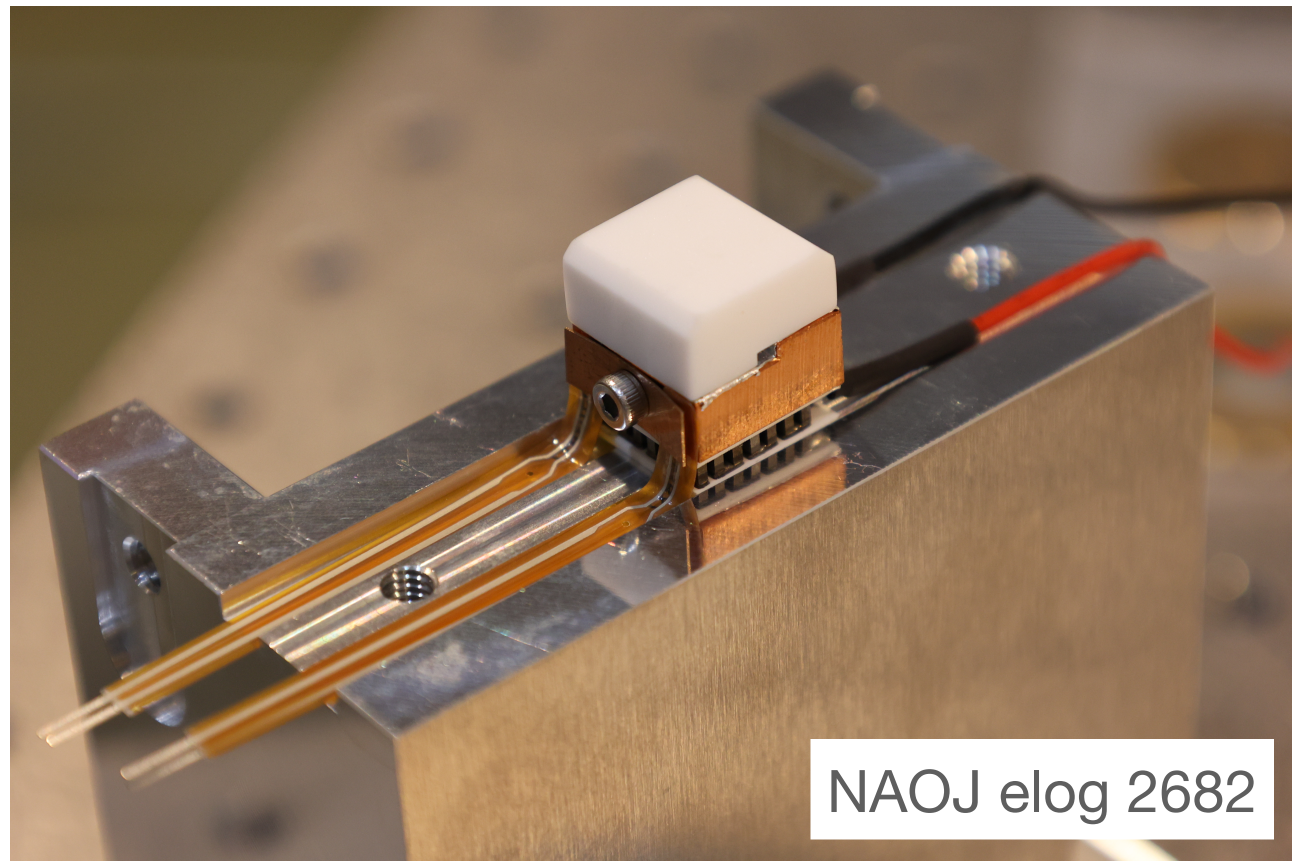


- We see a strong dependence between two parameters as following
  - Mode matching from squeezer to filter cavity/squeezing level
  - Mode matching from squeezer to homodyne/optical losses

# New OPO construction and characterization

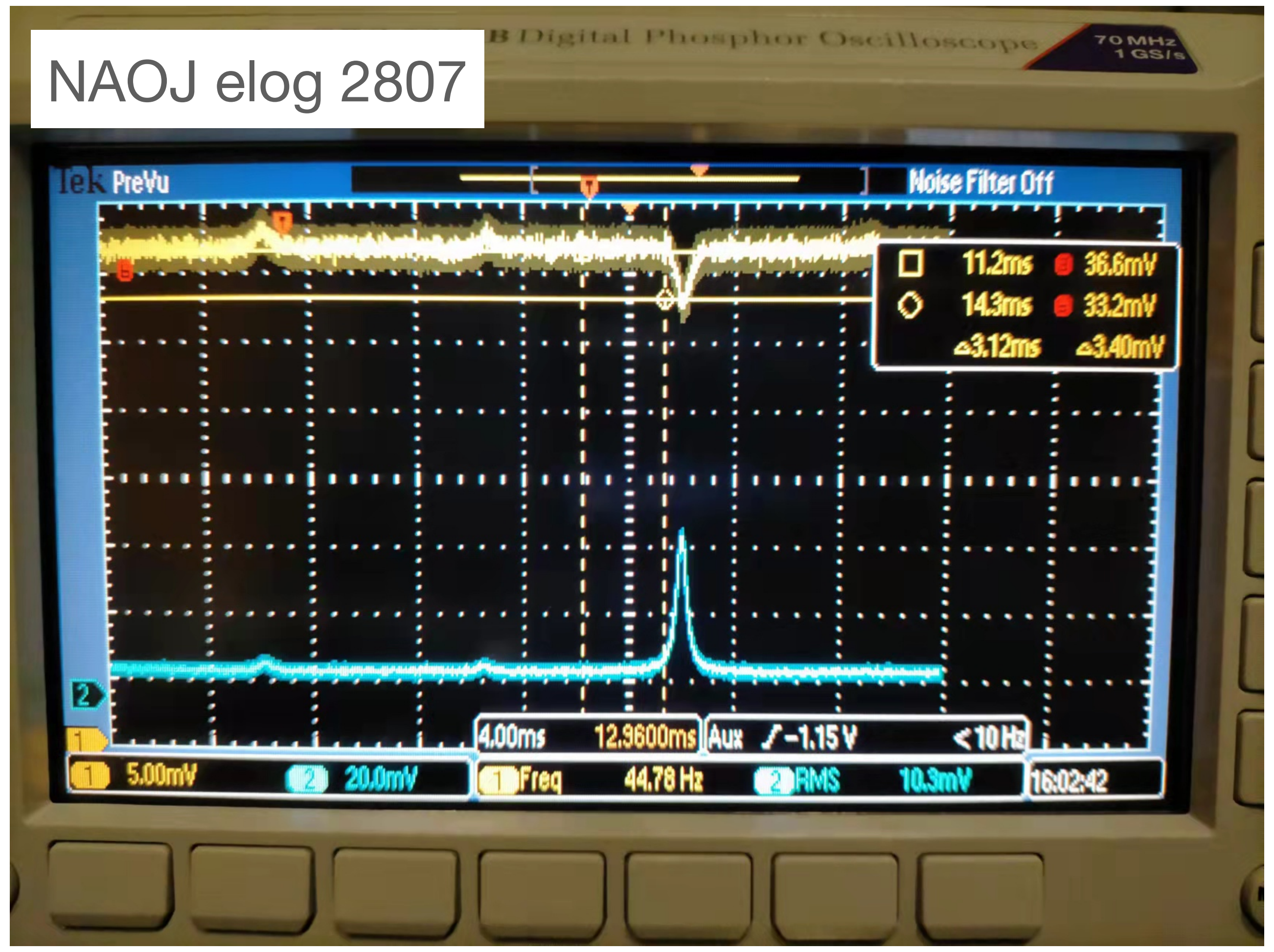
- Frequency independent characterization indicates a low OPO escape efficiency, thus a new OPO is constructed and going to be tested in terms of squeezing soon




NAOJ elog 2682


NAOJ elog 2781

- Losses in terms of
  - Dichroic mirror 1%
  - Faraday isolator 3%
  - Mirror losses/lenses losses 2%
  - Detection (in)efficiency 3%
  - Photodiode quantum (in)efficiency 0.5%
  - Photodiode AR coating 0.5%
  - Homodyne clearance (dark noise): 1%
  - OPO escape (in)efficiency 8.6%

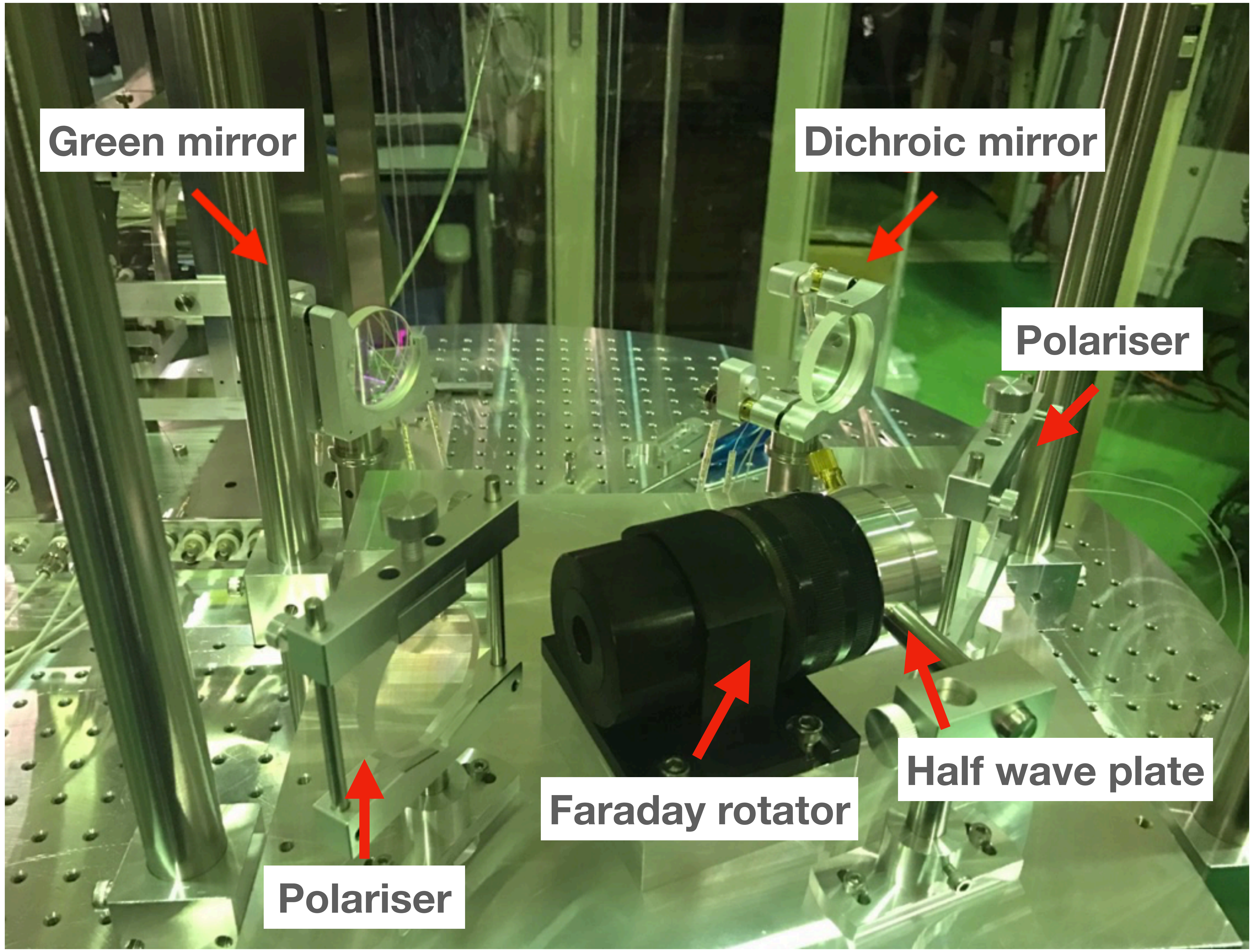

NAOJ elog 2807

From cavity scan, we extract OPO intra-cavity losses to be 0.2%.

This should cause OPO escape efficiency of 97.5% (2.5% losses)

# In vacuum Faraday characterization and upgrade

- The in-vacuum Faraday isolator, used to extract frequency dependent squeezing from the filter cavity reflection, introduces optical losses of 11%



- The faraday rotator was found to be only able to rotate polarization by 47 degrees but not less
- We have bought a new Faraday rotator to replace it, but the delivery got delayed

# Summary

- Frequency dependent squeezing is a promising way to have broadband quantum noise reduction
- Several research groups are planning to realize frequency dependent squeezing for KAGRA
- TAMA, as a full-scale filter cavity prototype, is a test place for filter cavity length and alignment control methods

# Outlook

- Setting up optical levers for suspended mirrors, which could be used for mitigating back scatter noise
- Setting up new DGS system, which provides more data acquisition channels
- Investigating and reducing squeezing degradation sources, such as new OPO and Faraday isolator
- Considering to test the filter cavity alignment control with coherent control sidebands

# Thank you for your attention!

# Control filter cavity with green beam

- A Pound-Drever-Hall control method utilize phase modulation $m_p$ to extract signal, but there will be unavoidable amplitude modulation $m_a$ to add noise

$$E = E_0 e^{i(\omega_0 t + m_p \cos(\omega_m t))}(1 + m_a \cos(\omega_m t + \phi))$$

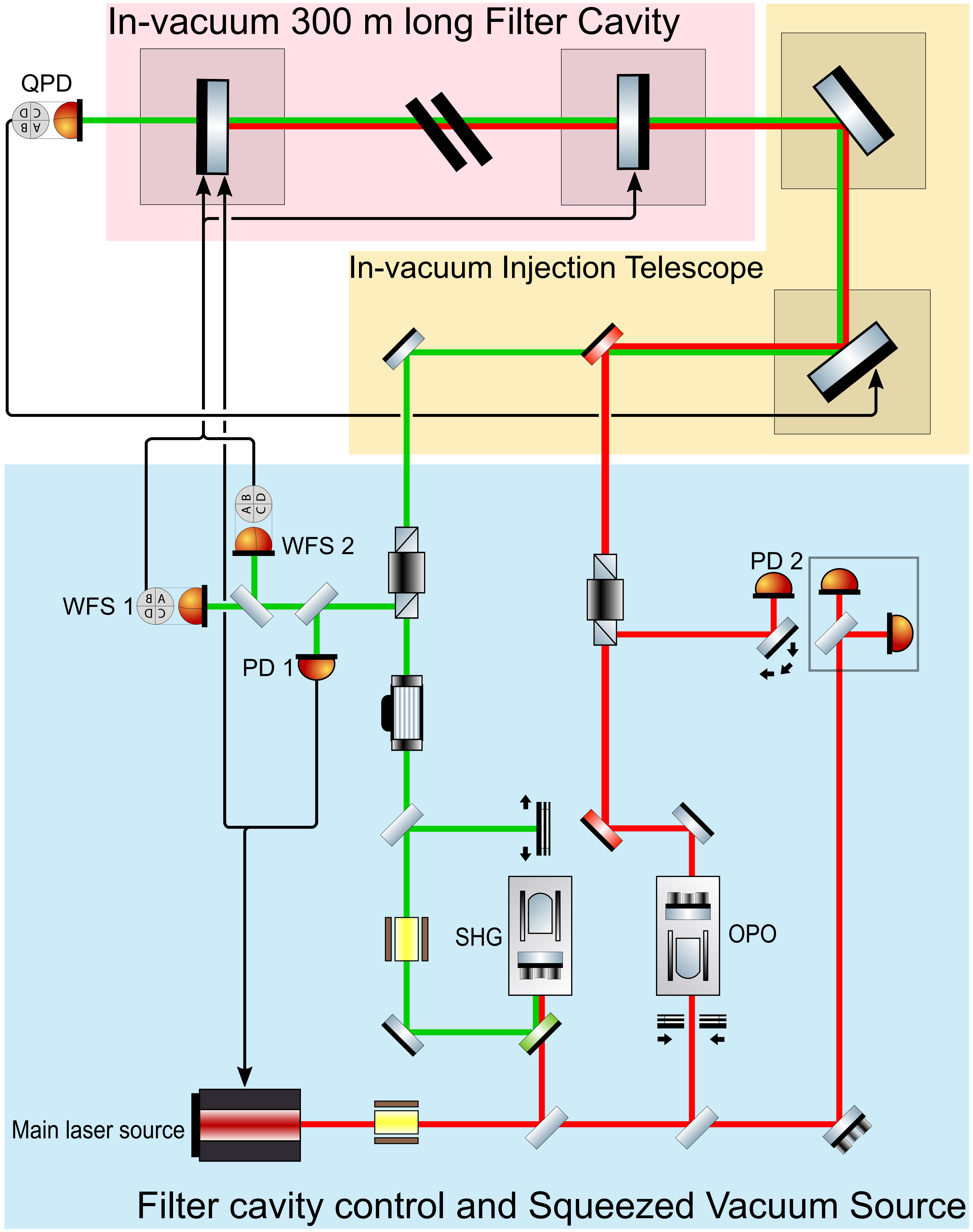
We get a DC power with magnitude $m_a E_0^2$ after demodulation at $\omega_m$

- We get influence of residual amplitude modulation as

$$G \times \eta \times m_a \times P \times \mathrm{TF}_{\mathrm{fc}}$$

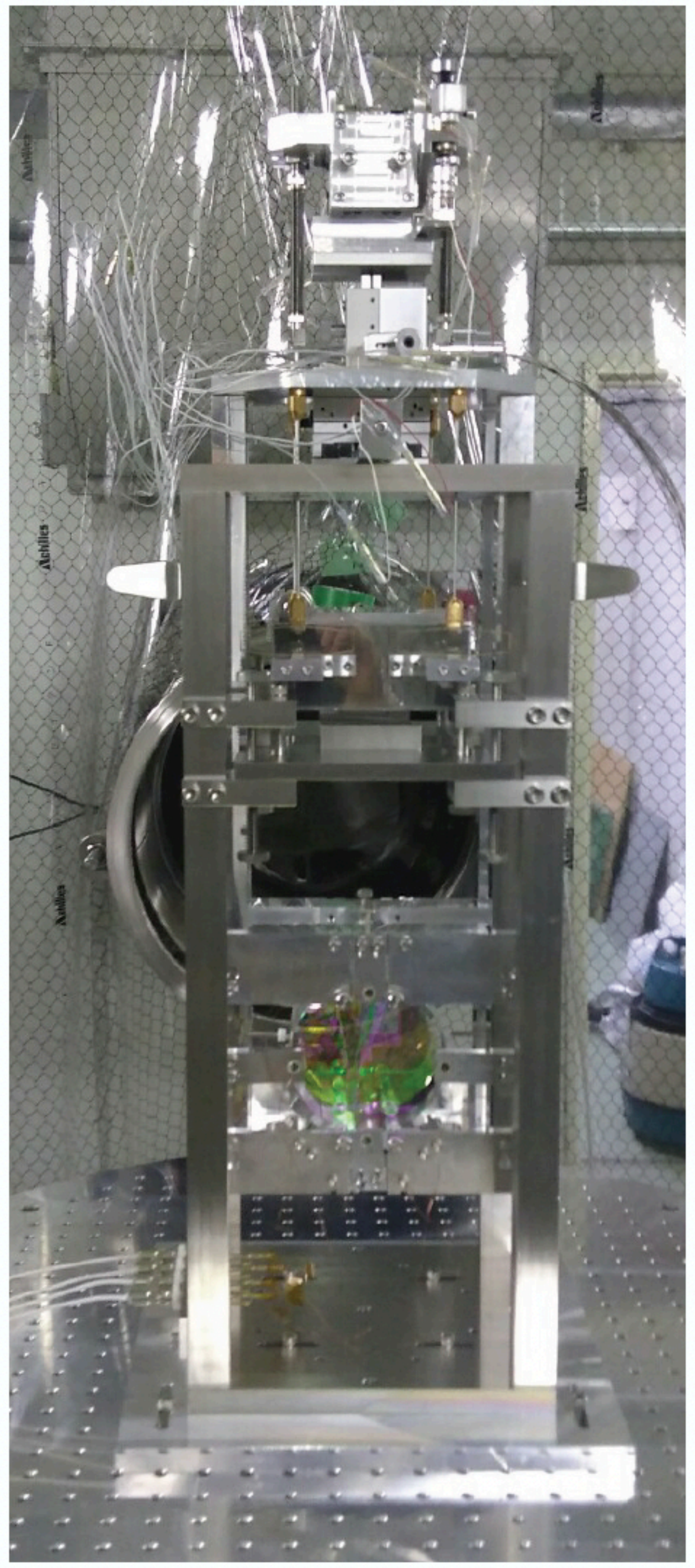
- G =16k is photo detector amplifier gain, $\eta$ = 0.65 is photo detector efficiency, $m_a$ = 0.3/100 is amplitude modulation depth, P = 1e-4 is the power reaching photo diode, $\mathrm{TF}_{\mathrm{fc}}$ = 670 is the transfer function between photo detector voltage output and detuning change

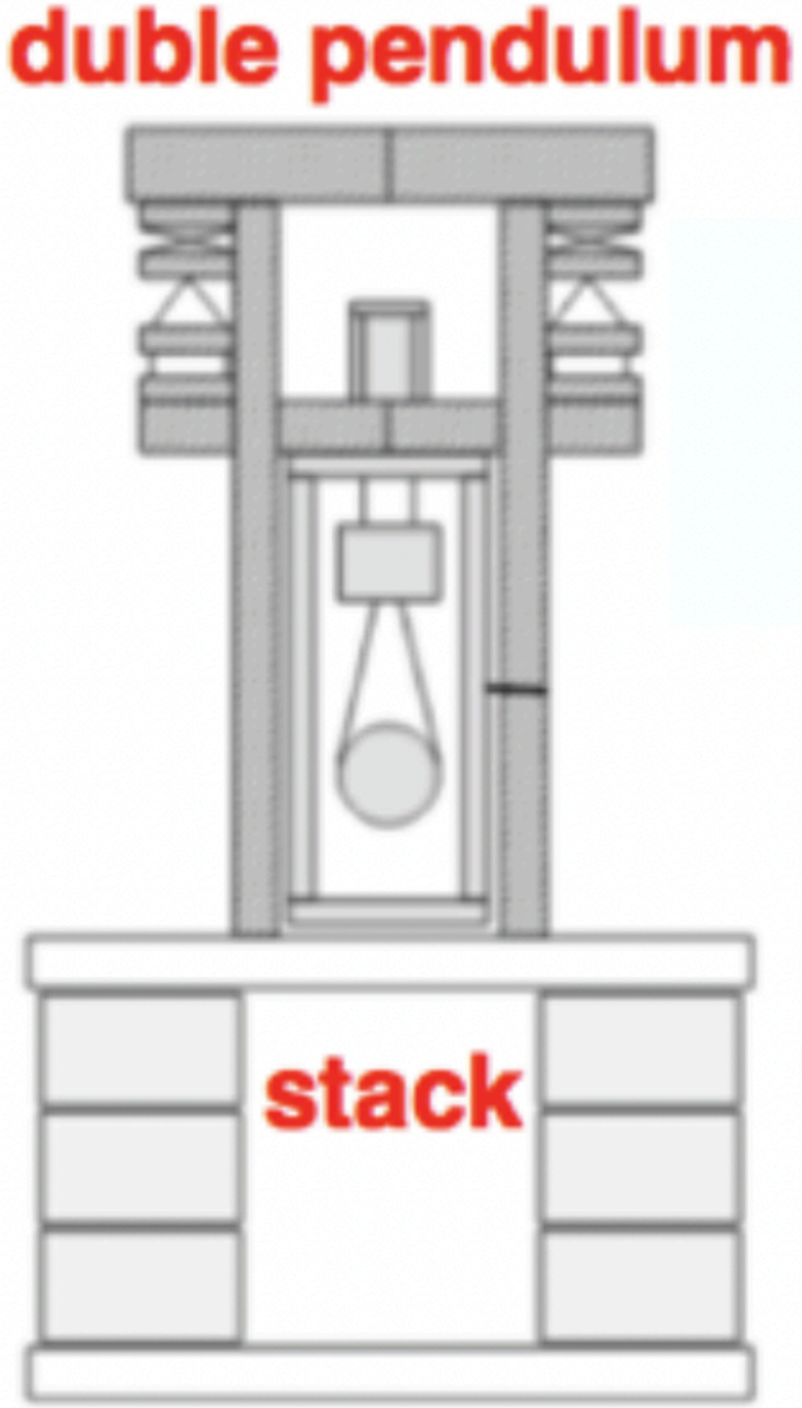
- We measured detuning fluctuation around 4Hz. Considering the above equation, the ratio between ma and mp is 0.02



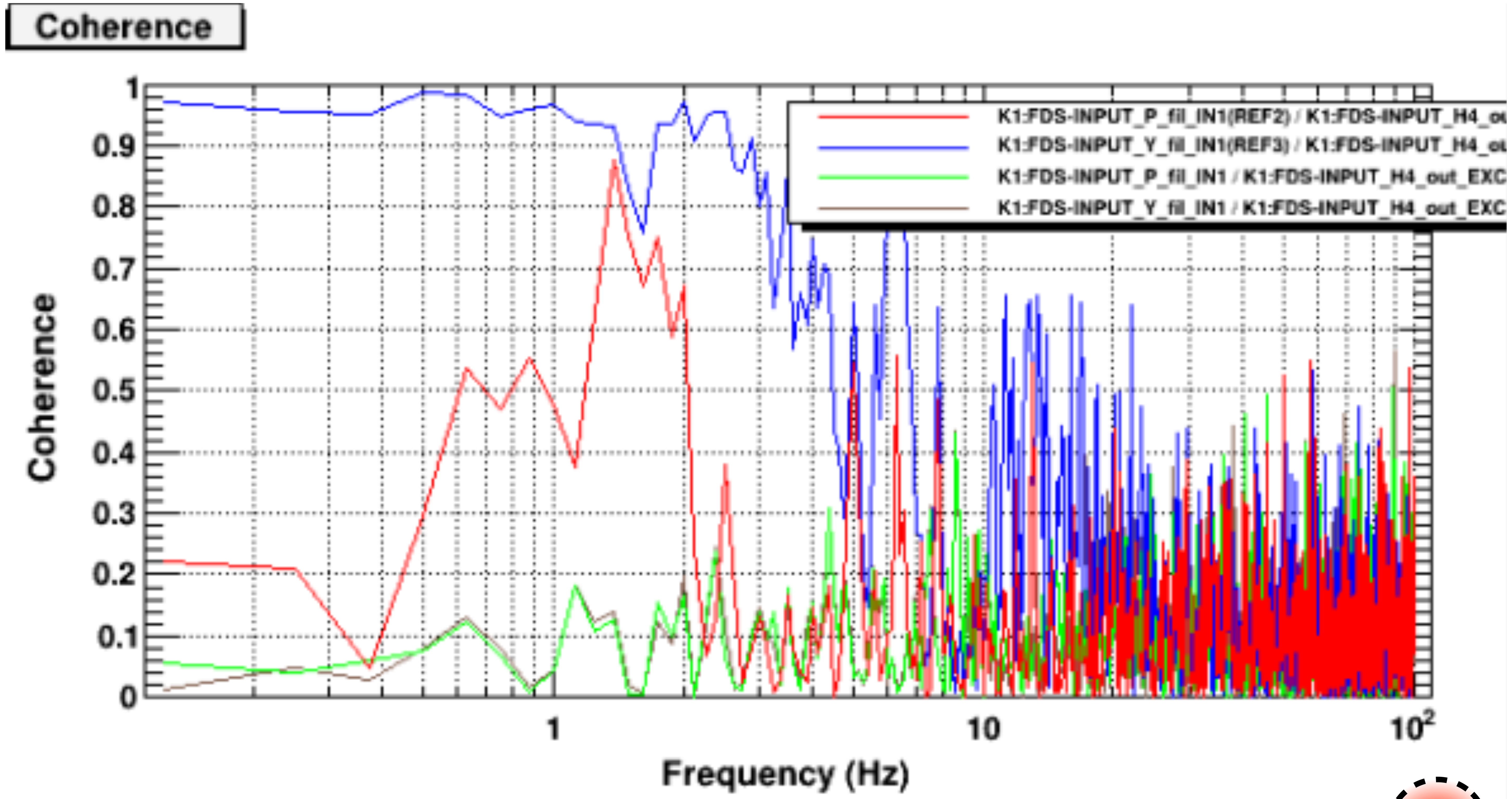
# Suspended mirrors magnet drop after earthquake

- Suspended mirrors position is controlled by coil-magnet, but earthquake causes magnet drop





- Automatic check of coil-magnet after earthquake
- Coherence of signal is a good indicator



# KAGRA quantum noise in O3GK

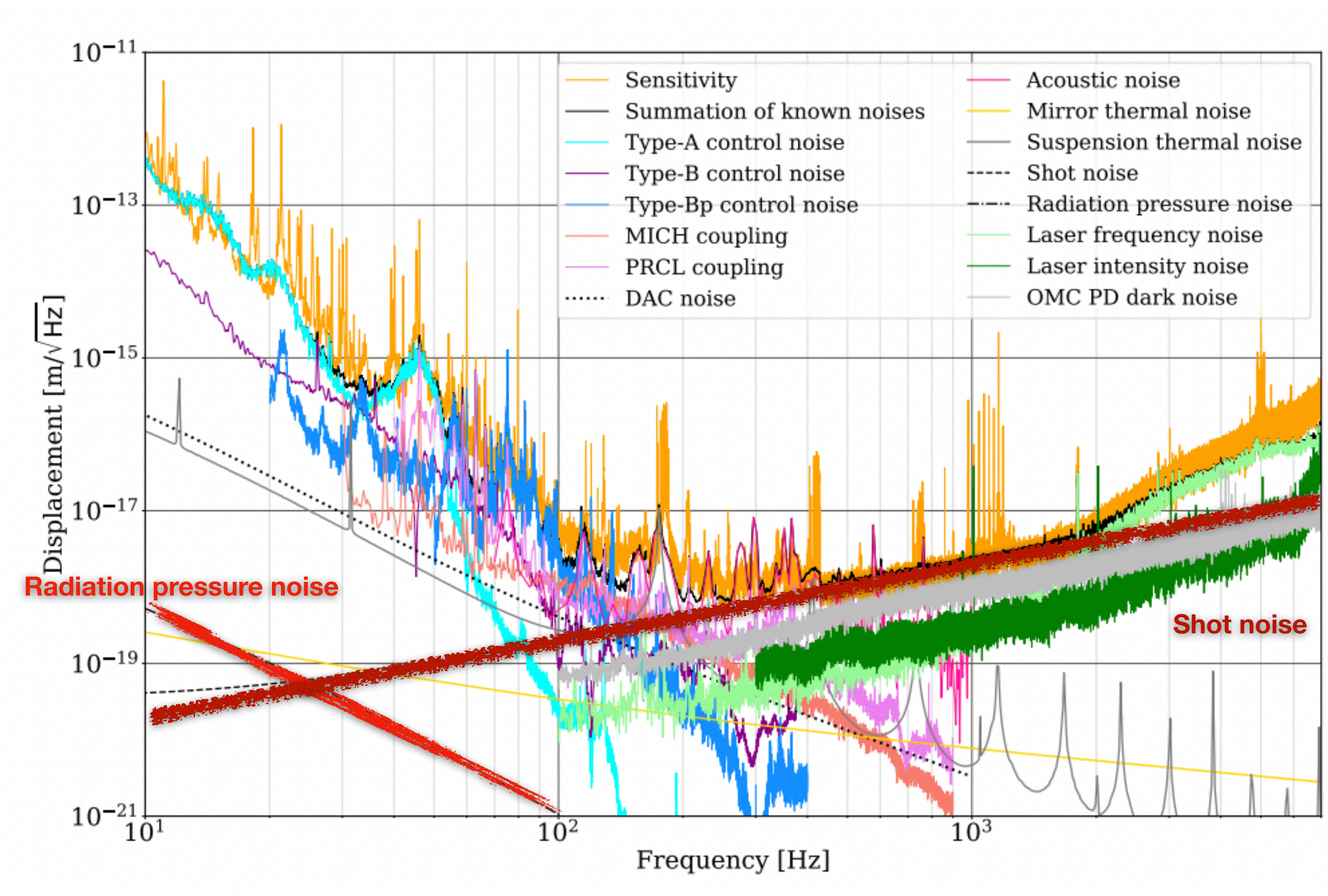


Figure is cited from KAGRA O3GK noise budget paper: arxiv 2203.07011

- Shot noise is limiting between 400Hz and 2kHz
- About 96% power is lost from interferometer output to detection PD
- 50W at BS