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Status of the frequency dependent squeezed vacuum source development at TAMA

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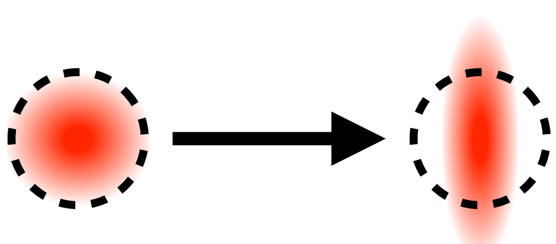

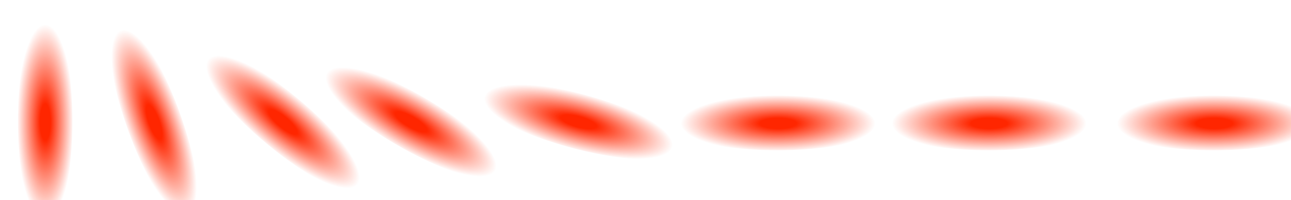

Content

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  - Quantum noise of aLIGO and advanced Virgo in O3
- Frequency dependent squeezed vacuum source at TAMA
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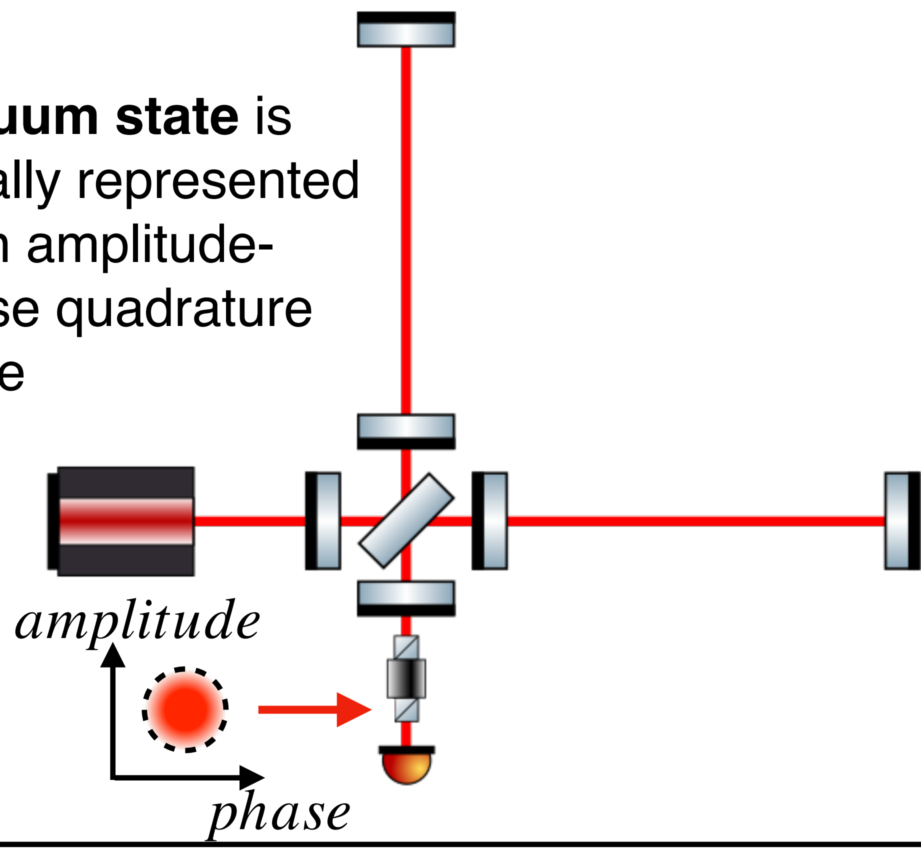
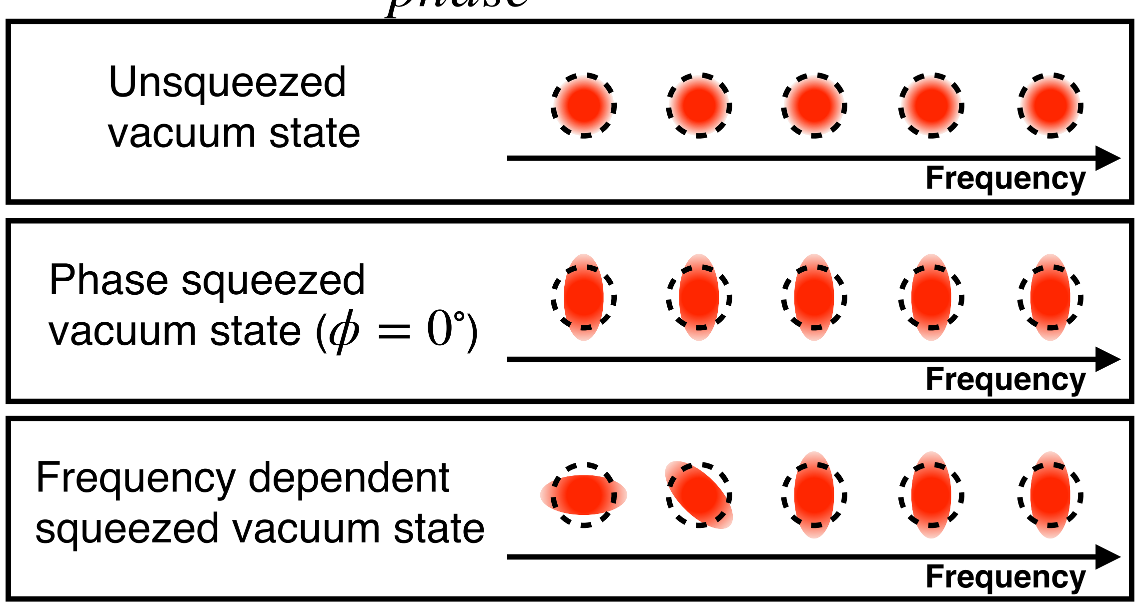
- Summary and Future plan

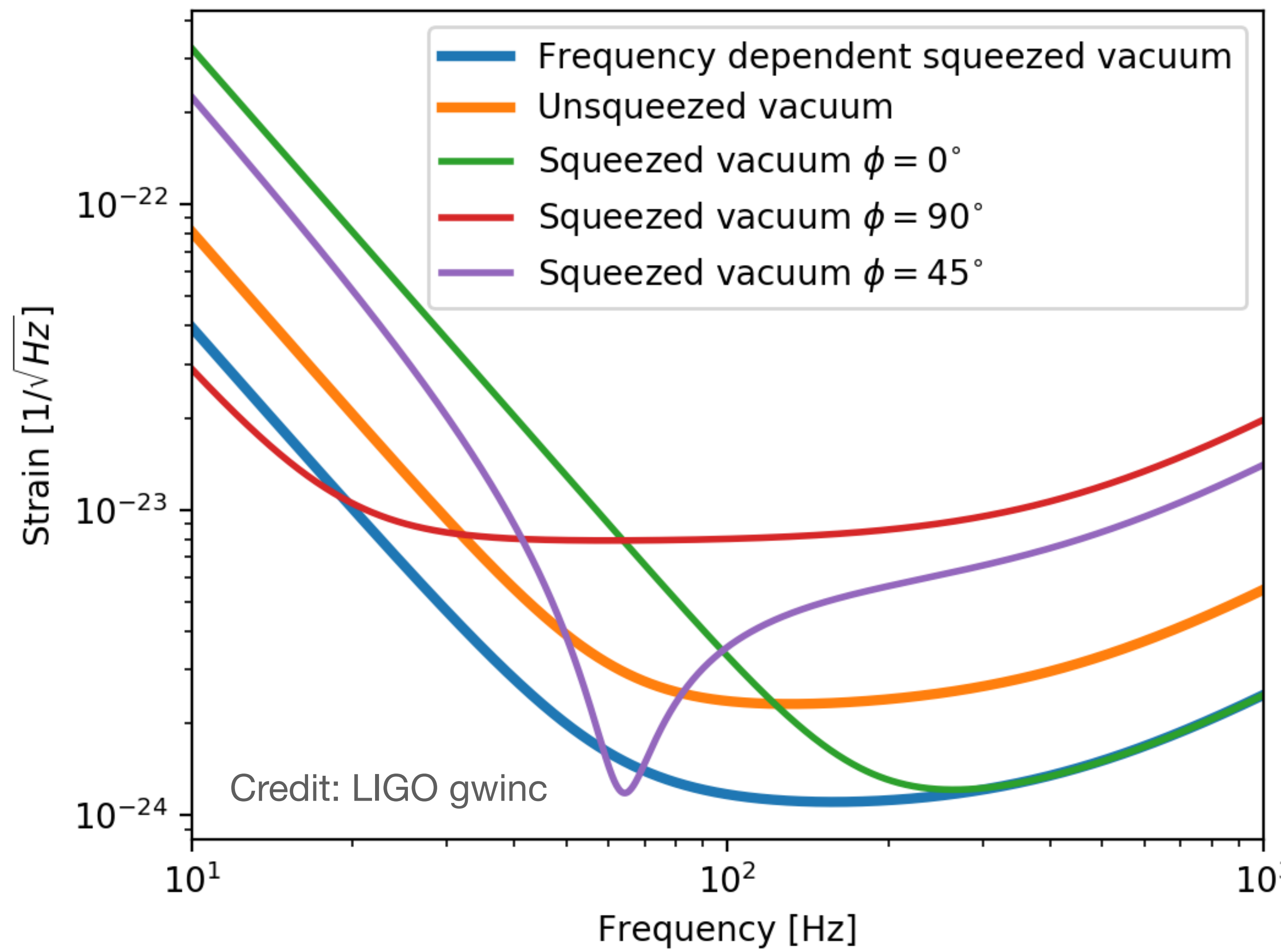
Quantum noise and vacuum state

- **Quantum Noise** of gravitational wave detectors comes from the vacuum state entering interferometer’s output port

Vacuum state is usually represented in an amplitude-phase quadrature plane



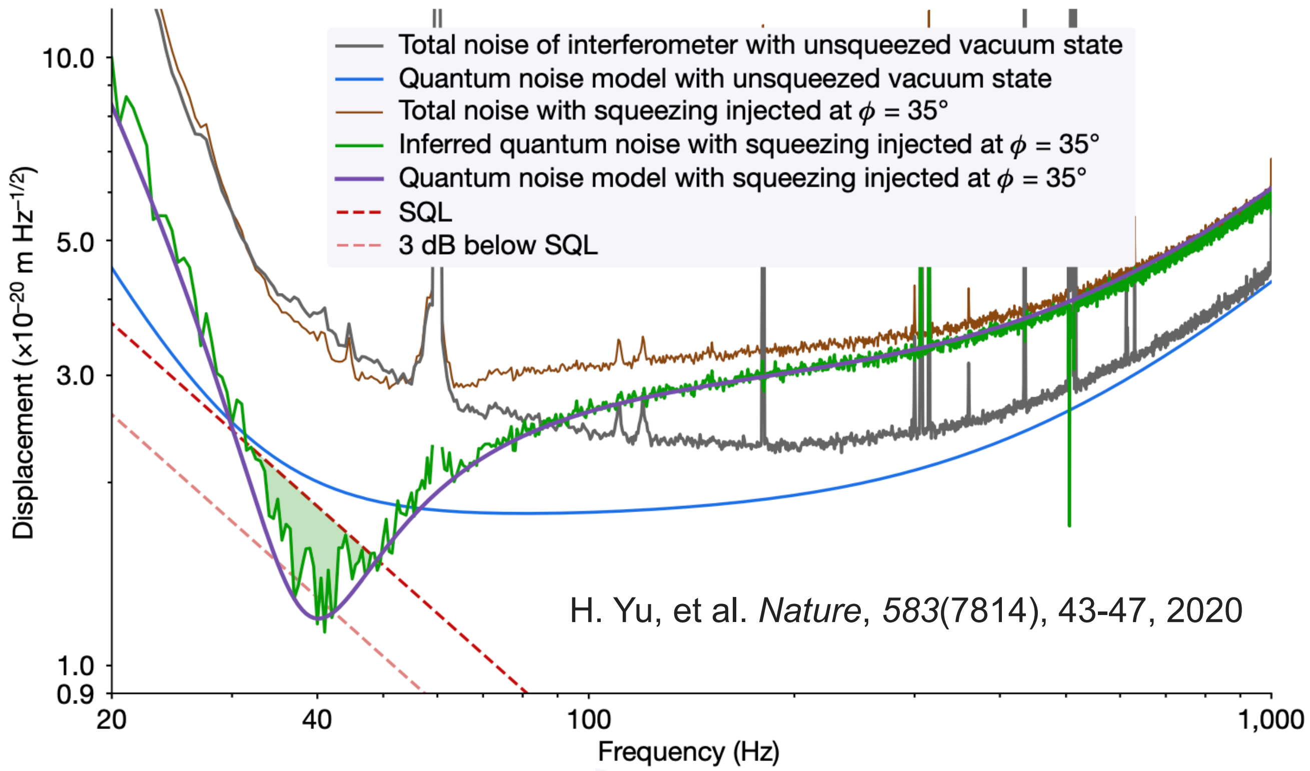




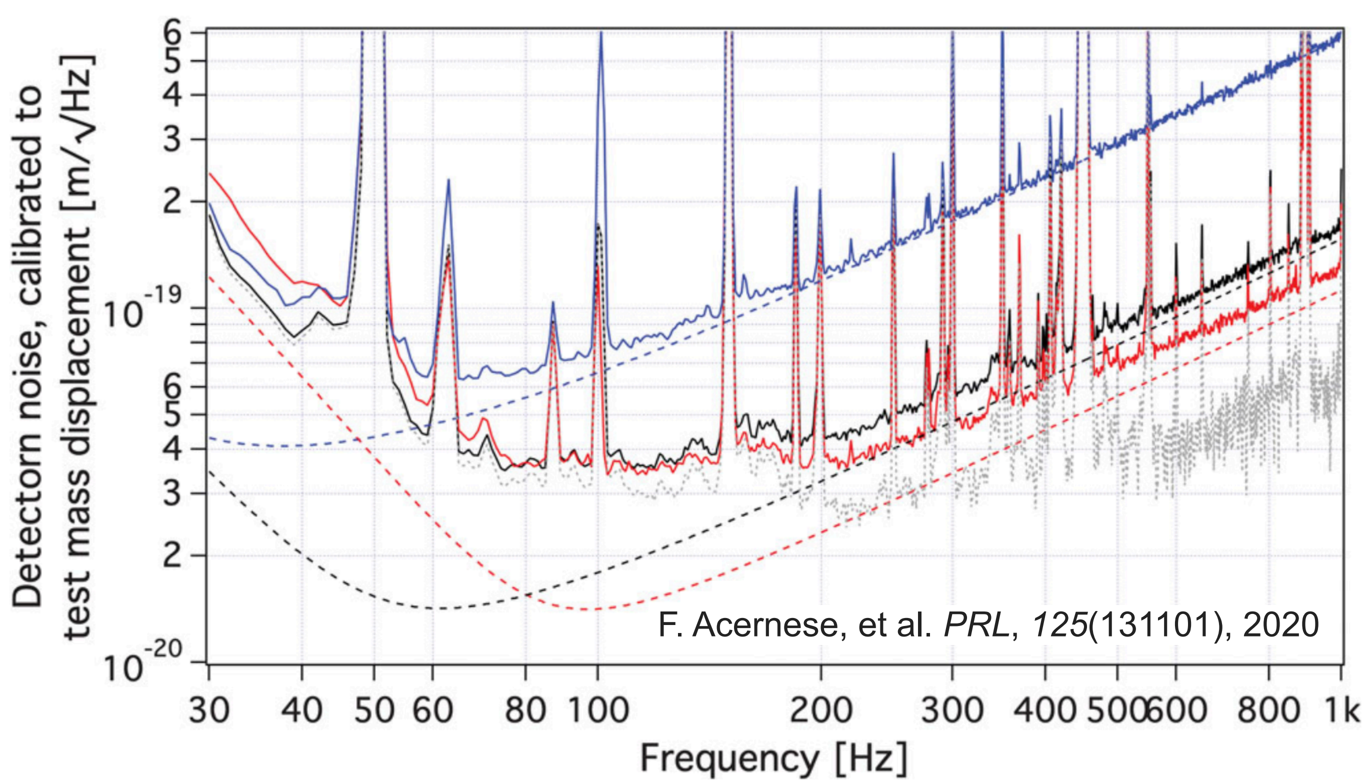
Frequency dependent squeezed vacuum needs good angle at specific frequency, which is realized by filter cavity in this plot

Quantum noise of aLIGO and advanced Virgo in O3

- Advanced gravitational wave detectors, such as aLIGO and advanced Virgo, are starting to see that quantum noise limits the entire detection bandwidth



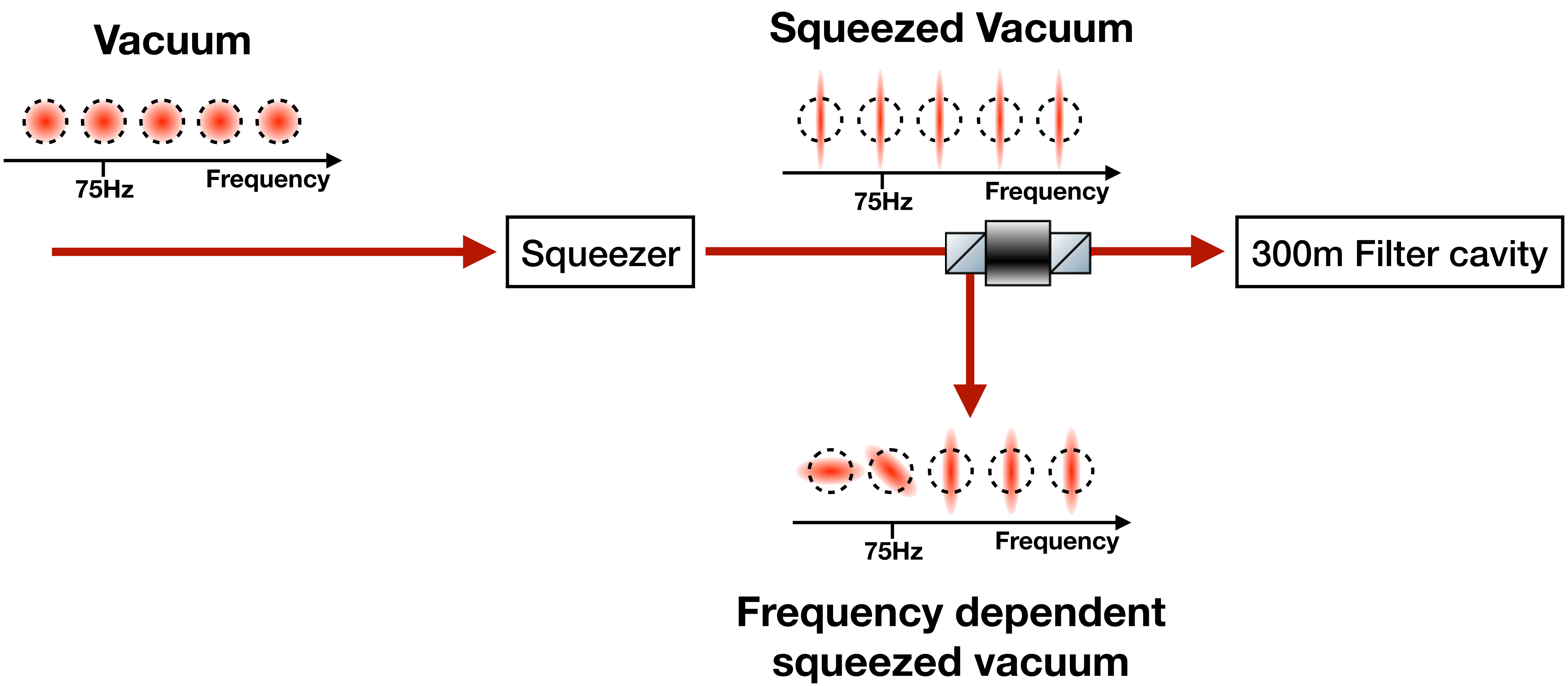
- LIGO has seen the light quantum effect interacting with heavy mirrors
- With a good squeezing phase, LIGO went beyond SQL



- Virgo has seen the light quantum effect interacting with heavy mirrors
- With squeezed vacuum injection, Virgo low frequency radiation pressure noise increased

Frequency dependent squeezed vacuum source at TAMA

- An audio-frequency squeezer and a full-scale filter cavity prototype have been constructed by using TAMA facilities



Frequency dependent squeezed vacuum source at TAMA

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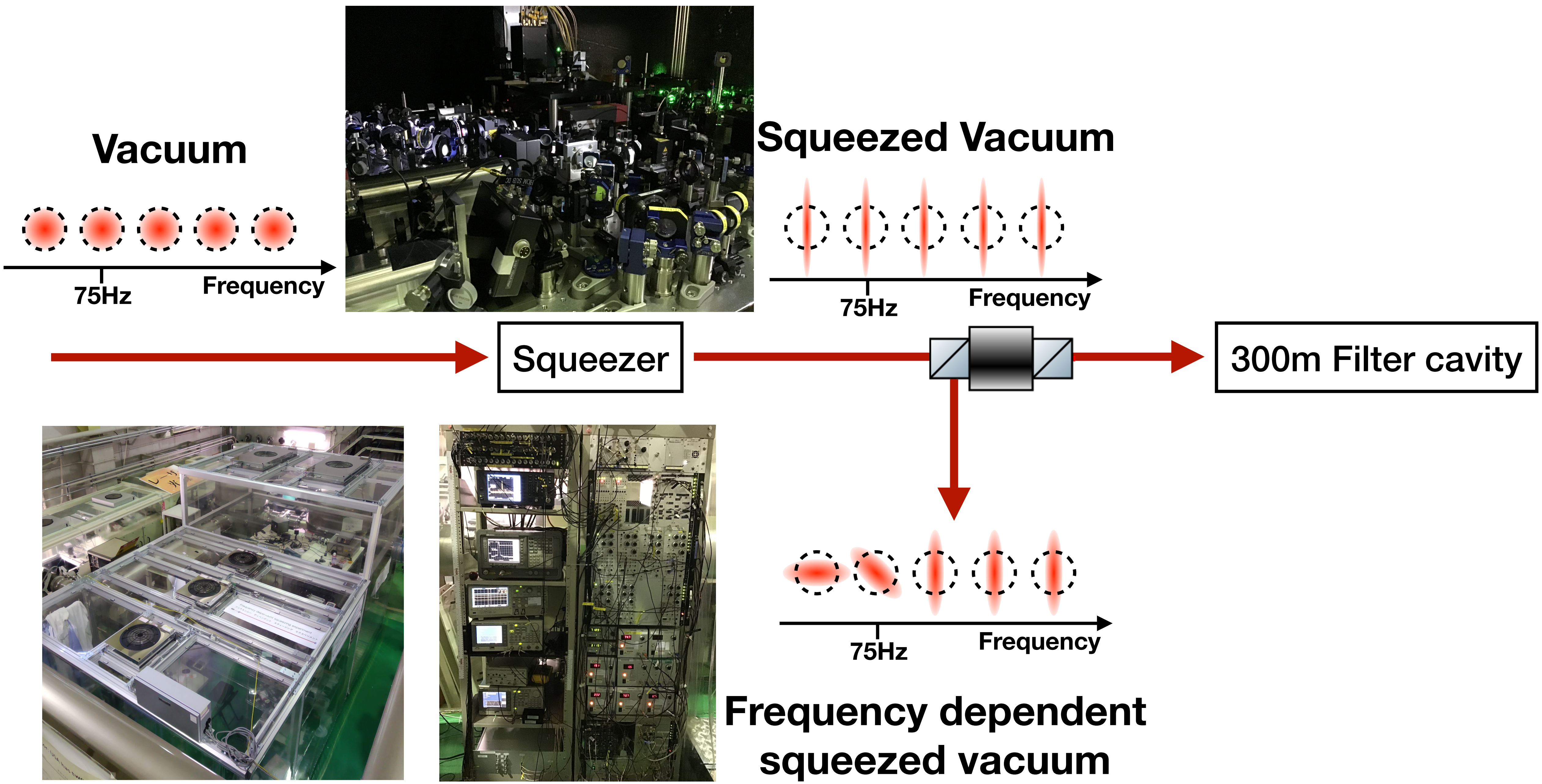
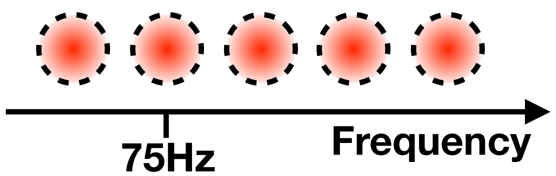
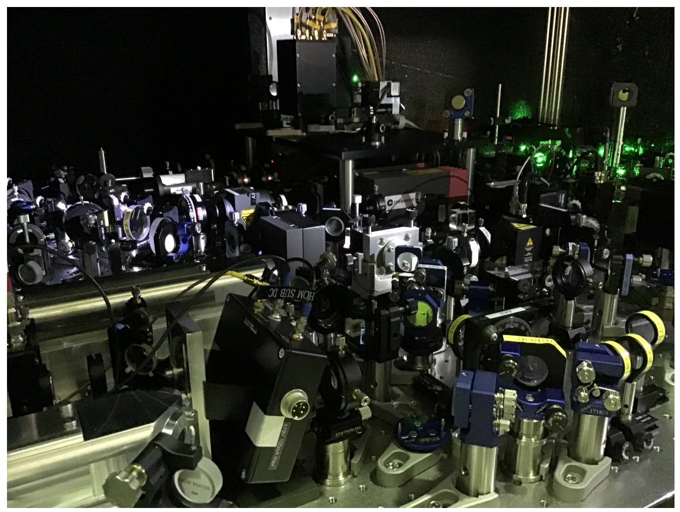


Frequency dependent squeezed vacuum source at TAMA

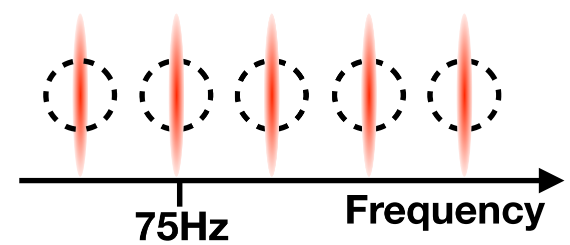
- An audio-frequency squeezer and a full-scale filter cavity prototype have been constructed by using TAMA facilities

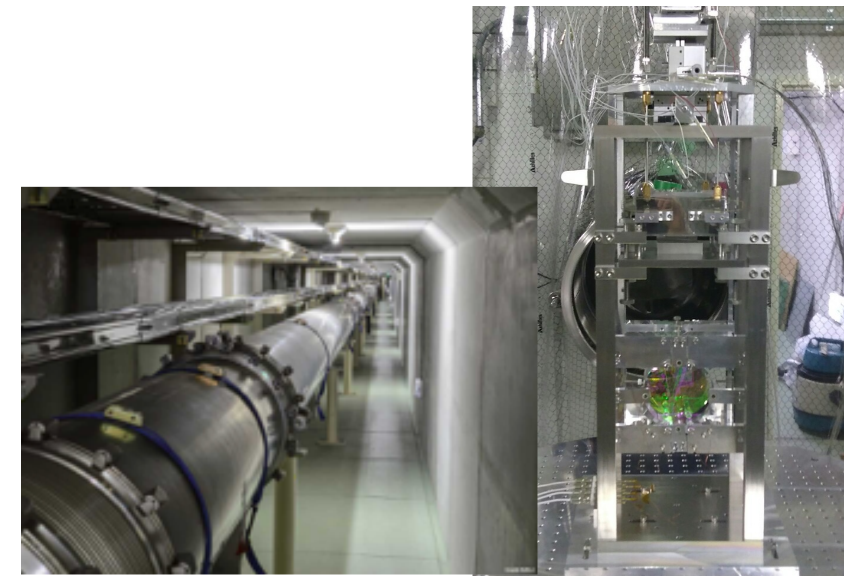
Vacuum



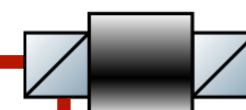


Squeezed Vacuum

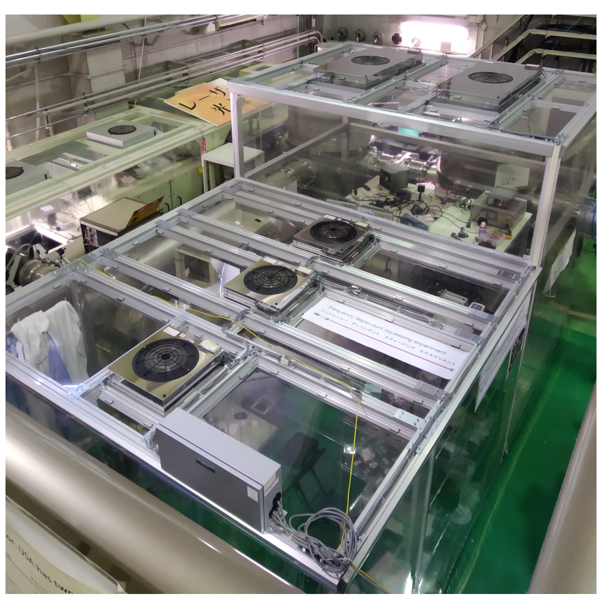


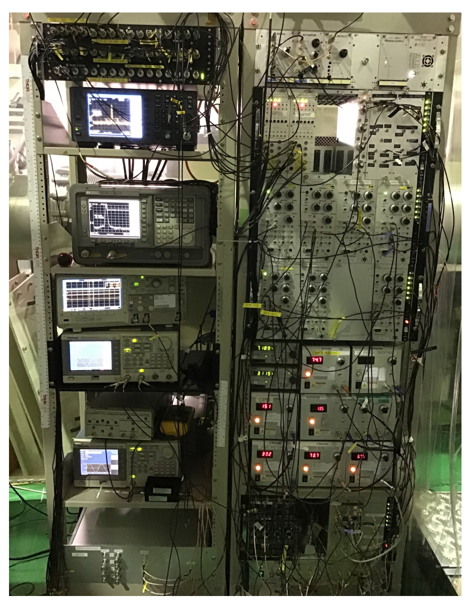


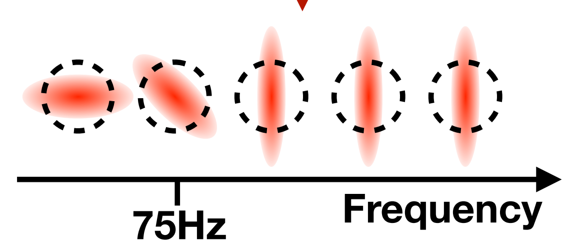
Squeezer



300m Filter cavity



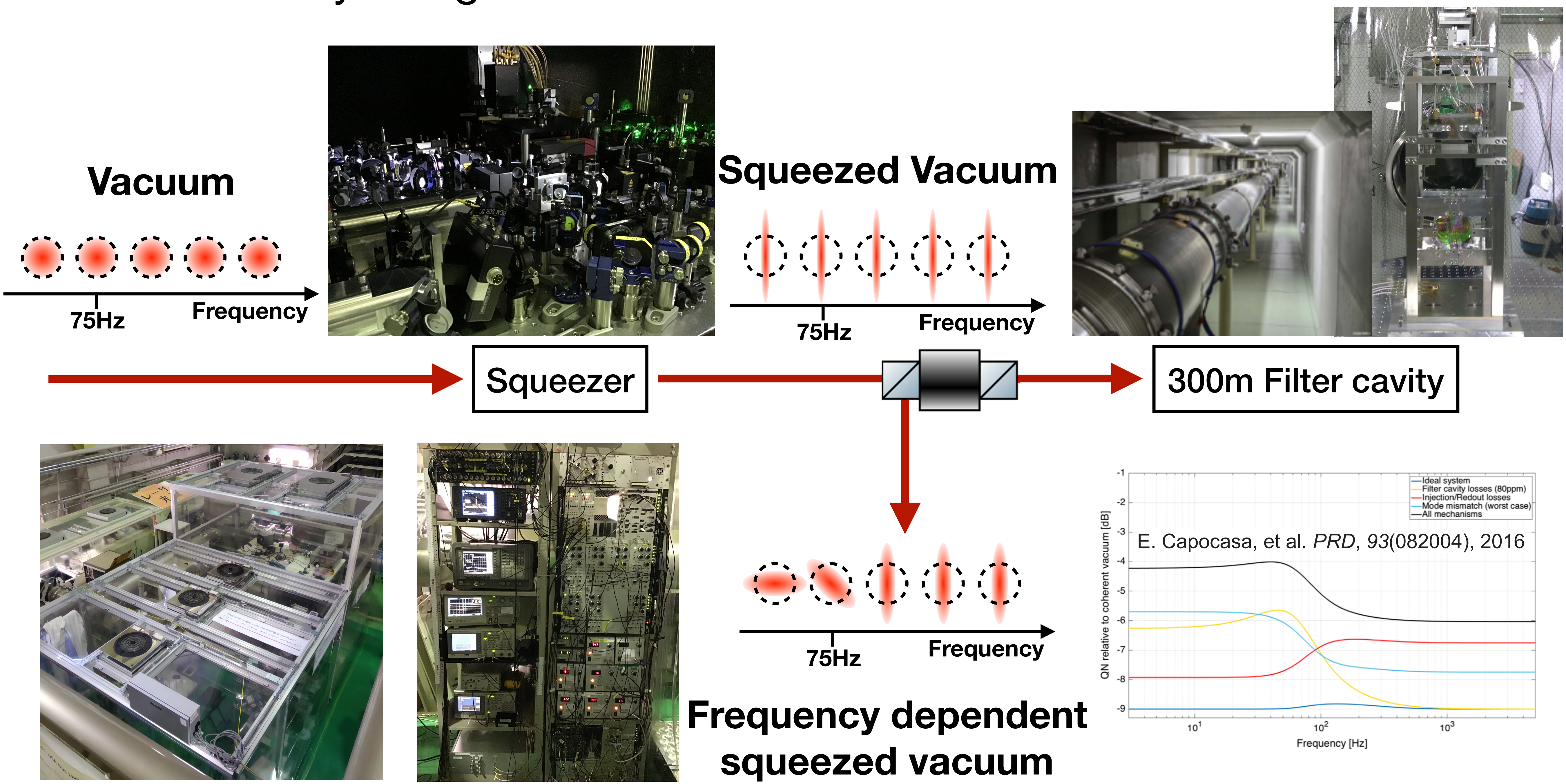




Frequency dependent squeezed vacuum

Frequency dependent squeezed vacuum source at TAMA

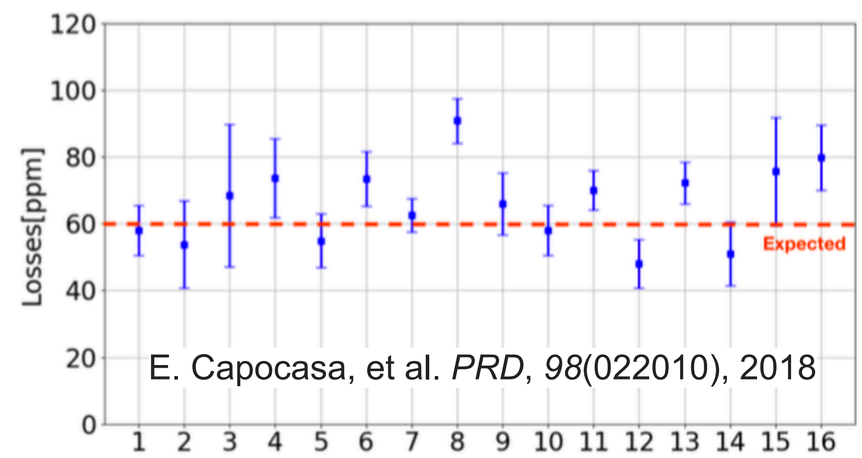
- An audio-frequency squeezer and a full-scale filter cavity prototype have been constructed by using TAMA facilities



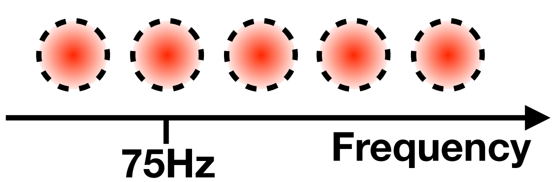
To achieve 6dB frequency dependent squeezing with rotation around 75Hz

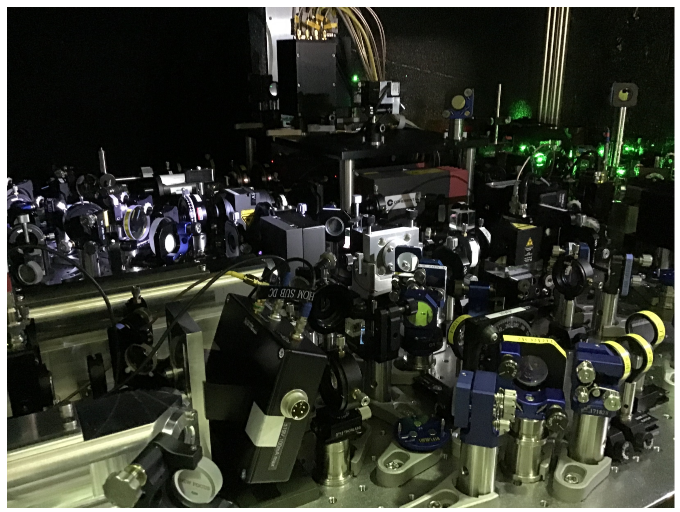
Frequency dependent squeezed vacuum source at TAMA

- An audio-frequency squeezer and a full-scale filter cavity prototype have been constructed by using TAMA facilities

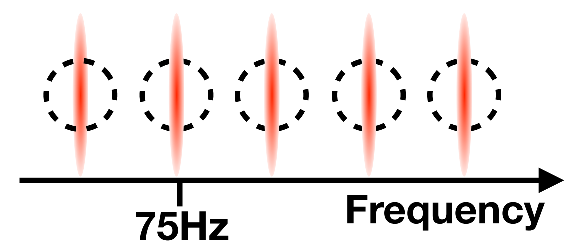


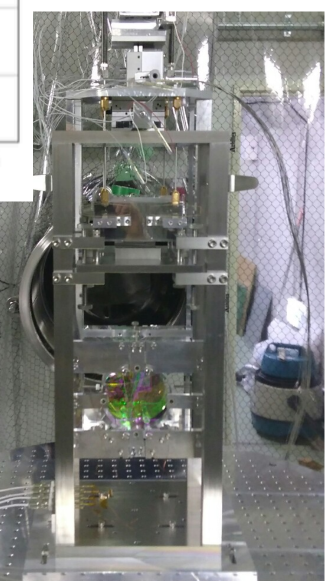
Vacuum

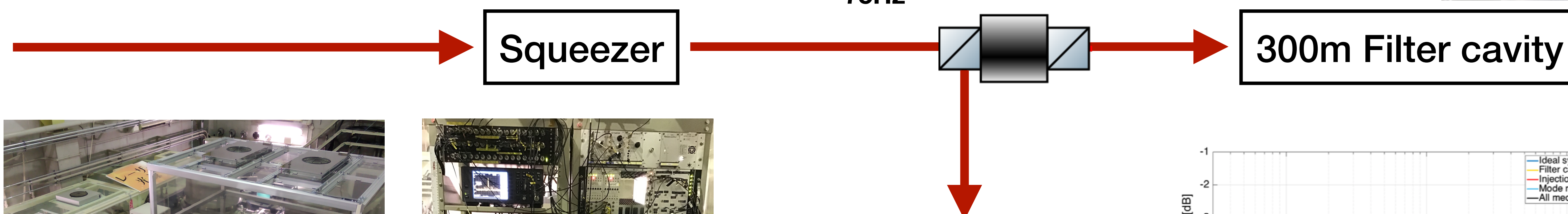


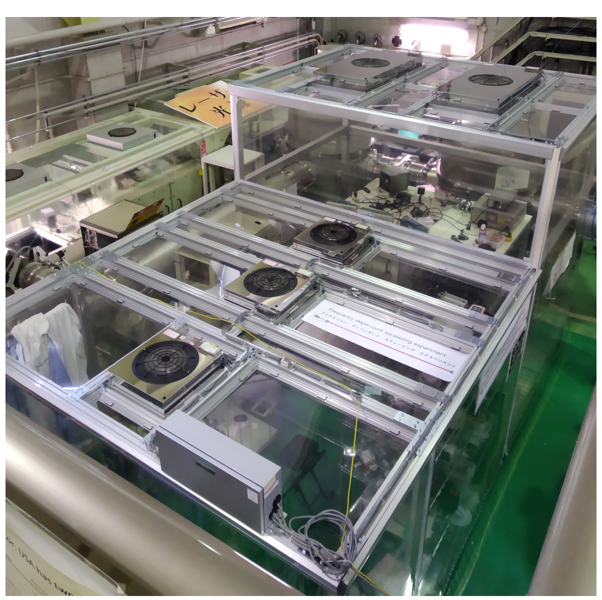


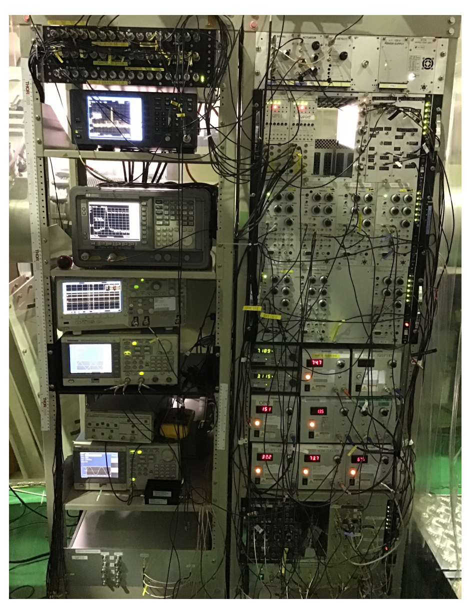
Squeezed Vacuum

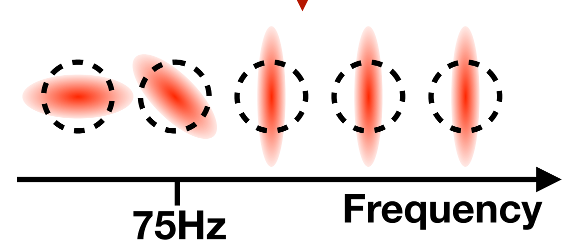




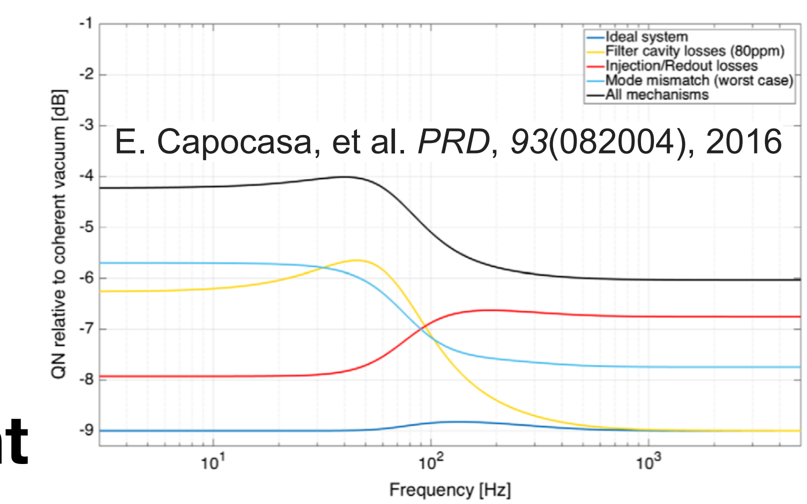






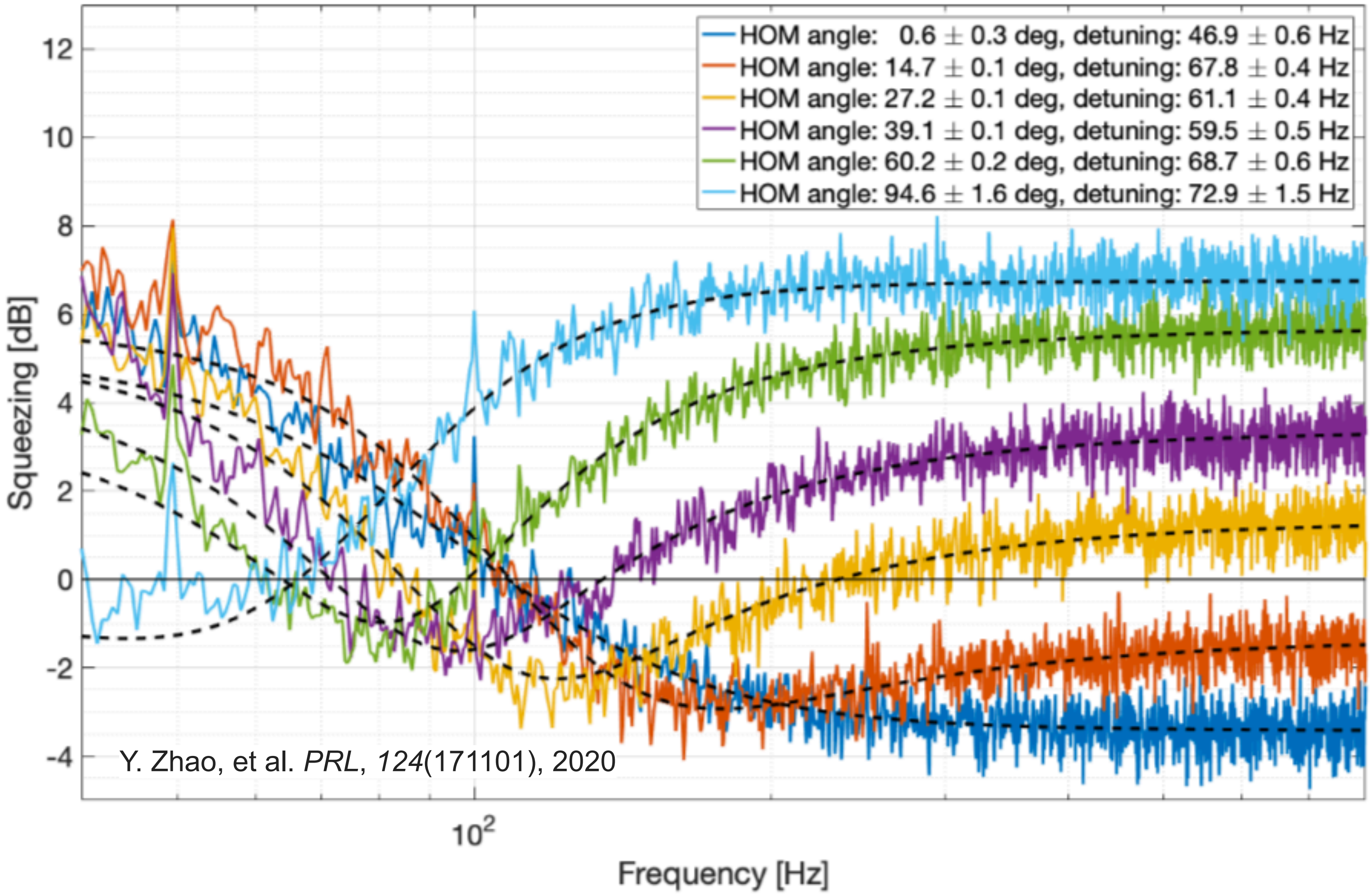


Frequency dependent squeezed vacuum



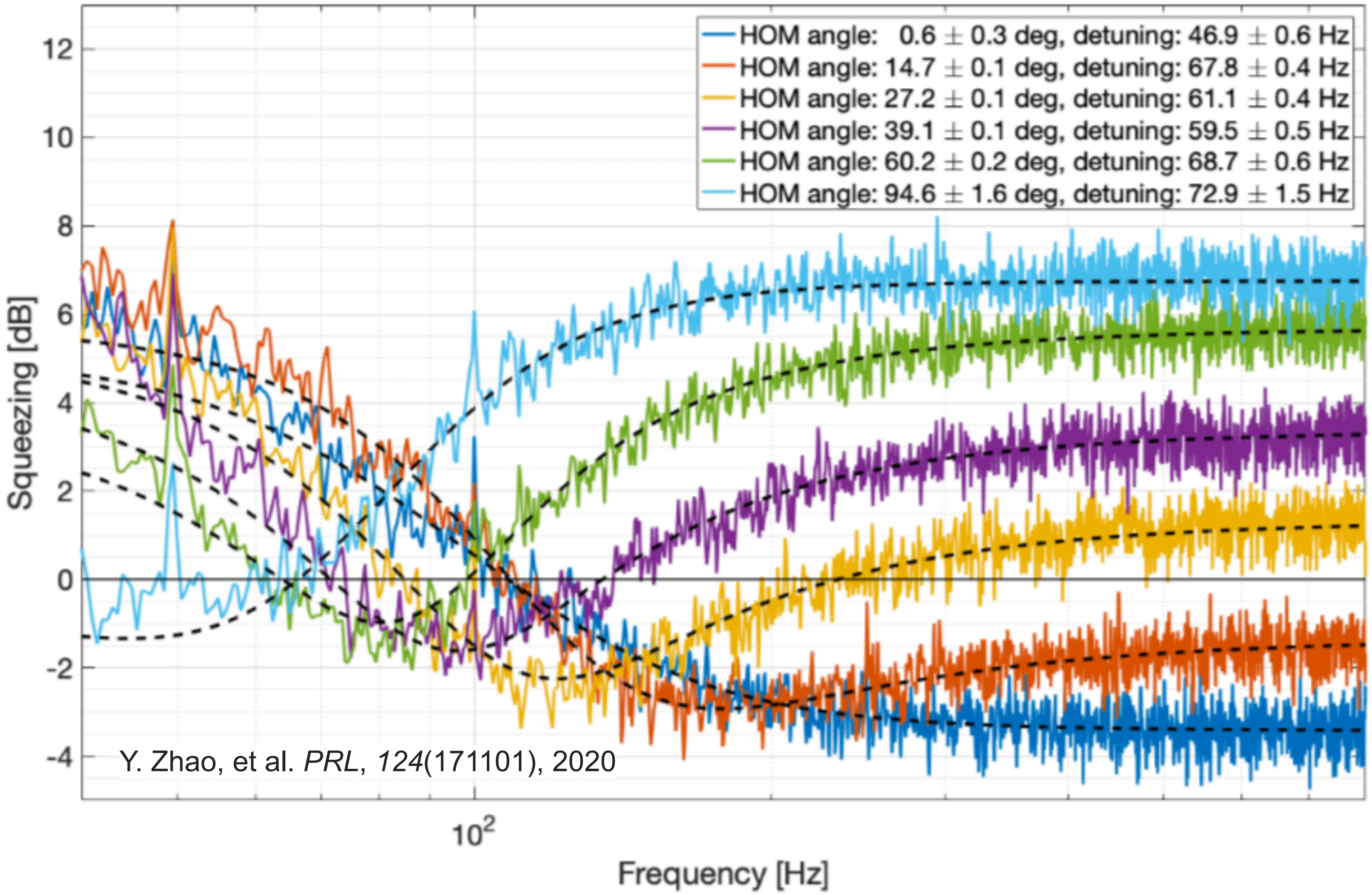
To achieve 6dB frequency dependent squeezing with rotation around 75Hz

Frequency dependent squeezed vacuum source at TAMA



- 3.4dB squeezing above rotation frequency
- 1dB squeezing below rotation frequency
- Rotation below 100Hz

Frequency dependent squeezed vacuum source at TAMA



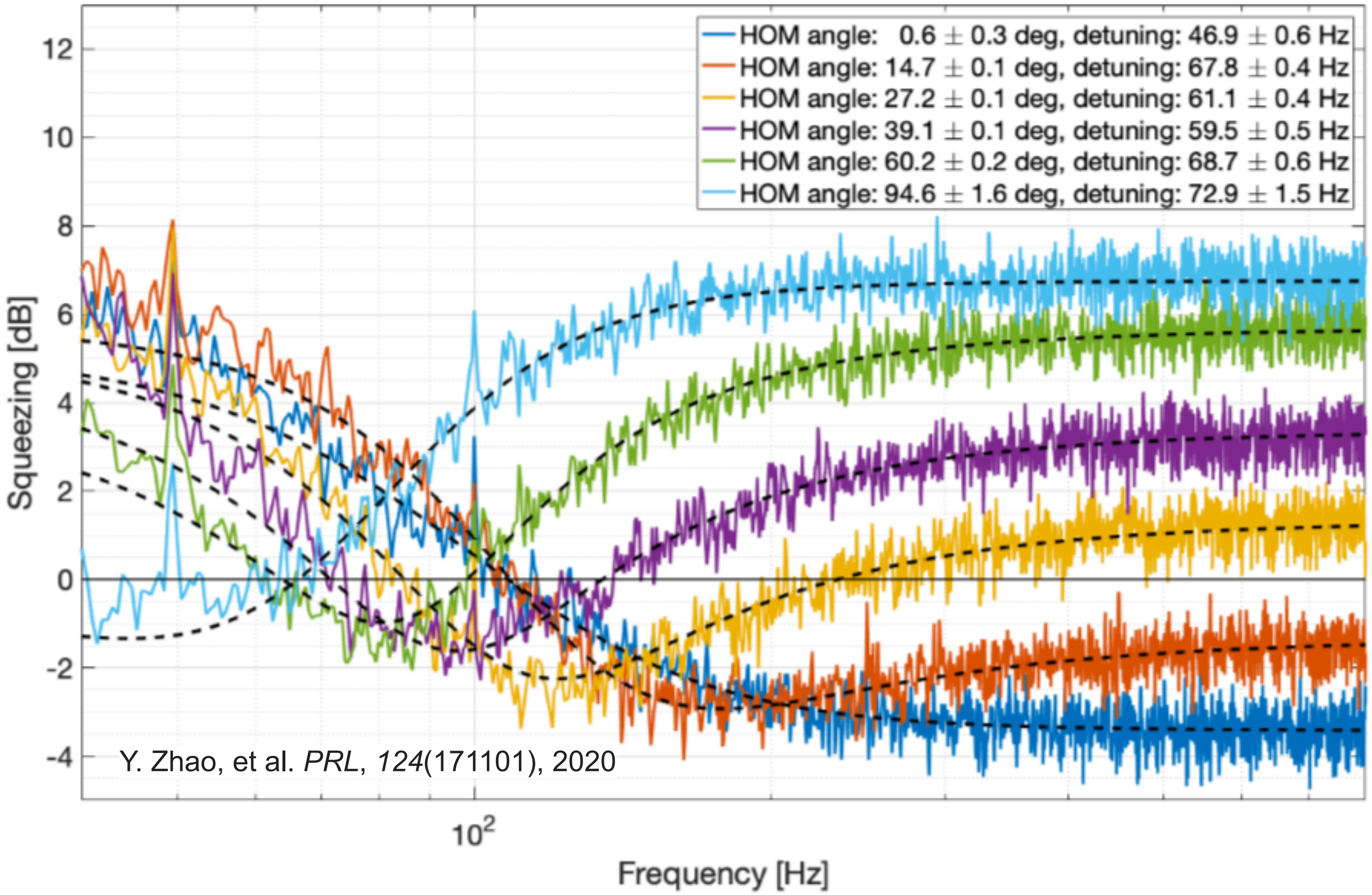
- 3.4dB squeezing above rotation frequency

- 1dB squeezing below rotation frequency

Squeezing at all frequencies

- Rotation below 100Hz

Frequency dependent squeezed vacuum source at TAMA



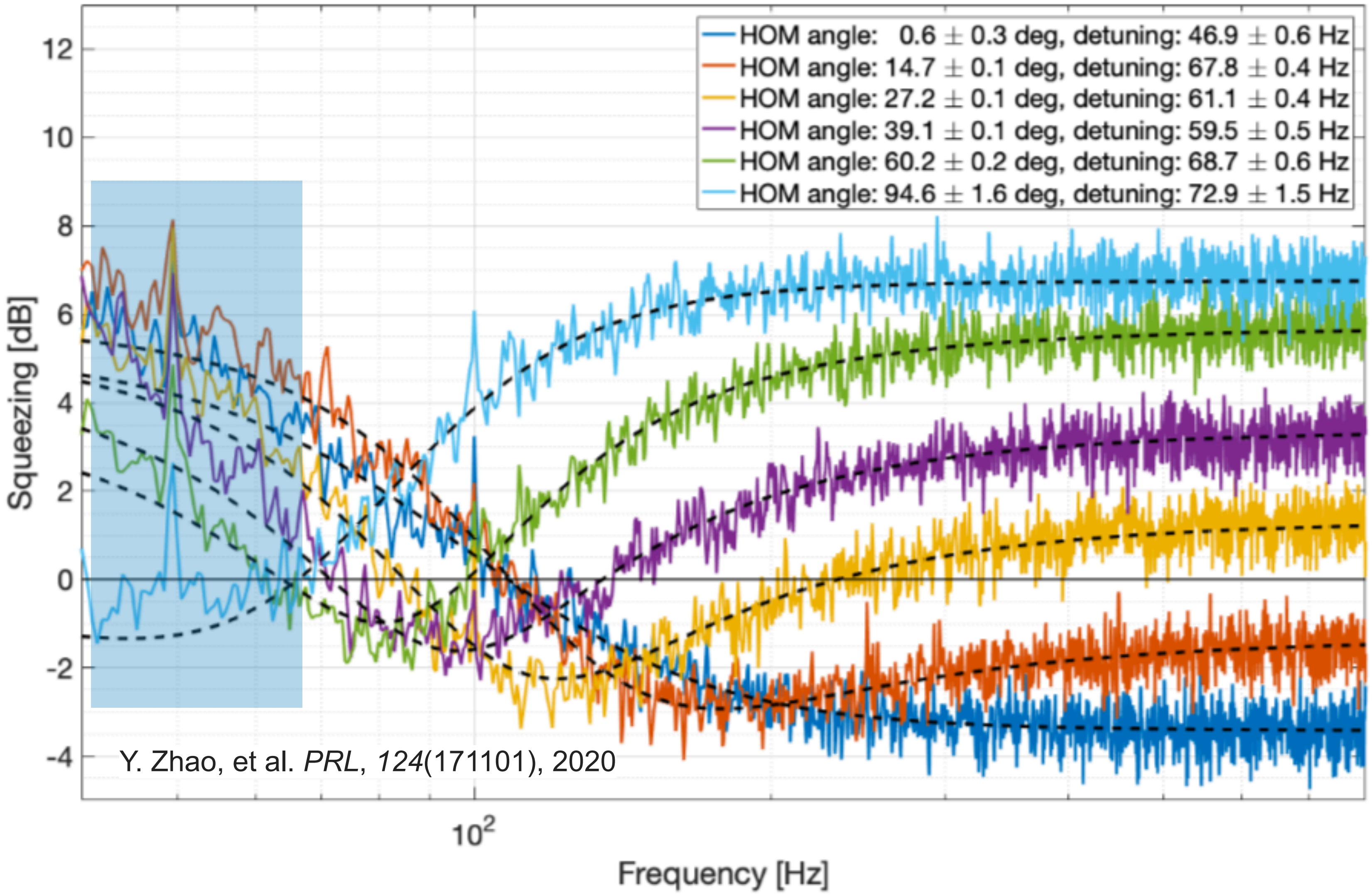
- 3.4dB squeezing above rotation frequency
- 1dB squeezing below rotation frequency

Squeezing at all frequencies

- Rotation below 100Hz

Appropriate rotation frequency

Frequency dependent squeezed vacuum source at TAMA



- 3.4dB squeezing above rotation frequency
- 1dB squeezing below rotation frequency

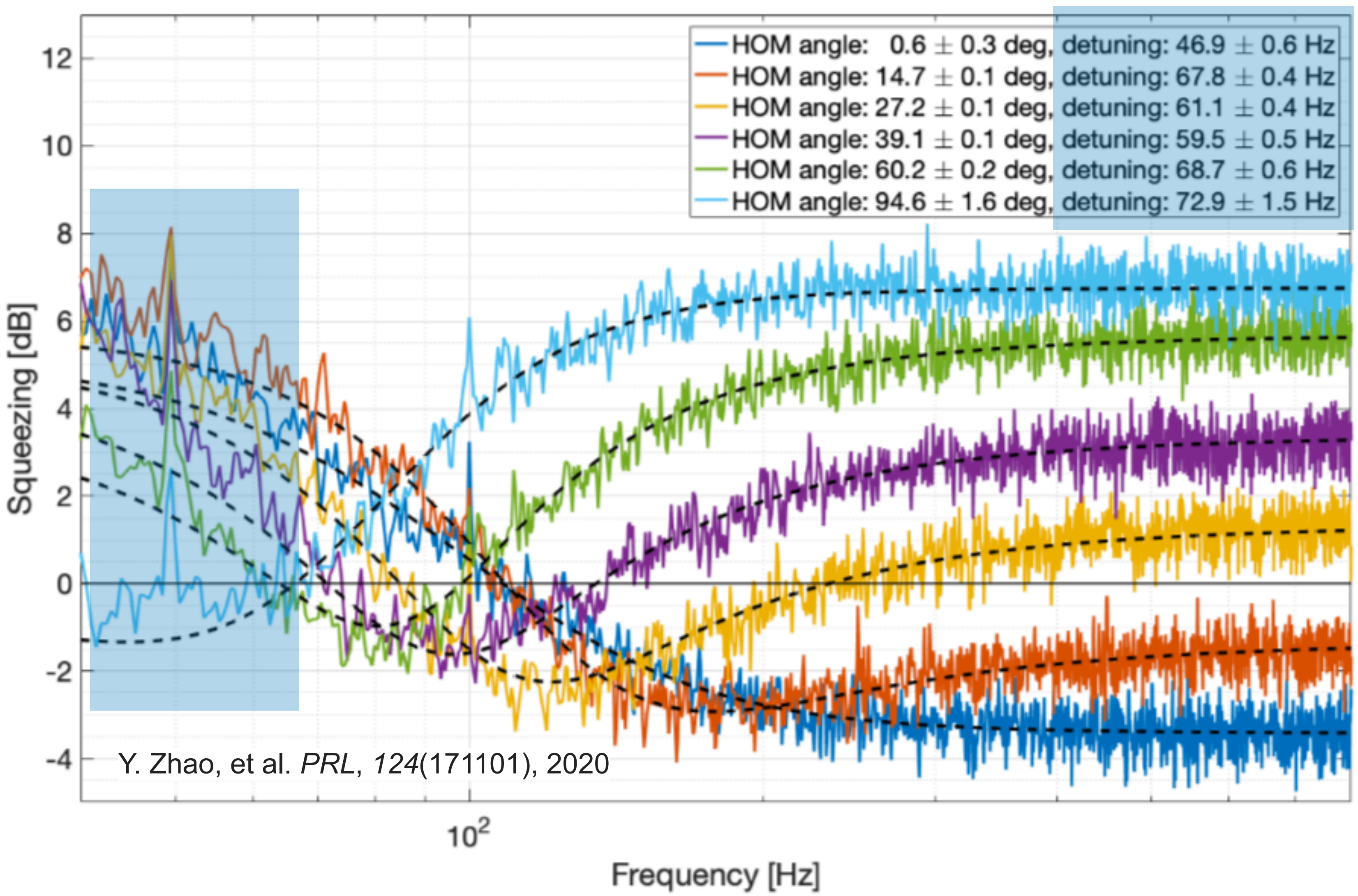
Squeezing at all frequencies

- Rotation below 100Hz

Appropriate rotation frequency

- Low frequency unstable classical noise

Frequency dependent squeezed vacuum source at TAMA



- 3.4dB squeezing above rotation frequency
- 1dB squeezing below rotation frequency

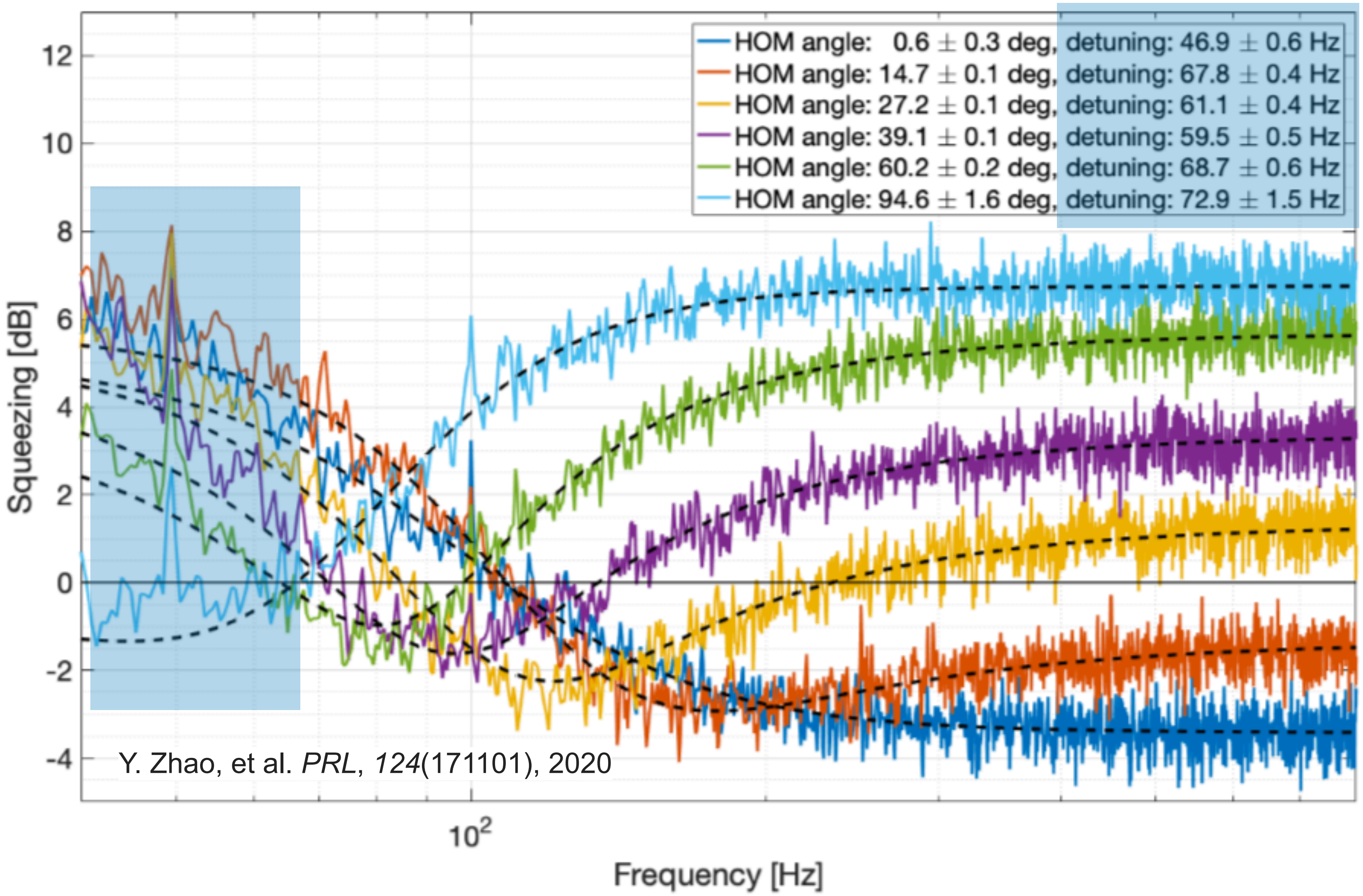
Squeezing at all frequencies

- Rotation below 100Hz

Appropriate rotation frequency

- Low frequency unstable classical noise
- Filter cavity unstable detuning

Frequency dependent squeezed vacuum source at TAMA



- 3.4dB squeezing above rotation frequency
- 1dB squeezing below rotation frequency

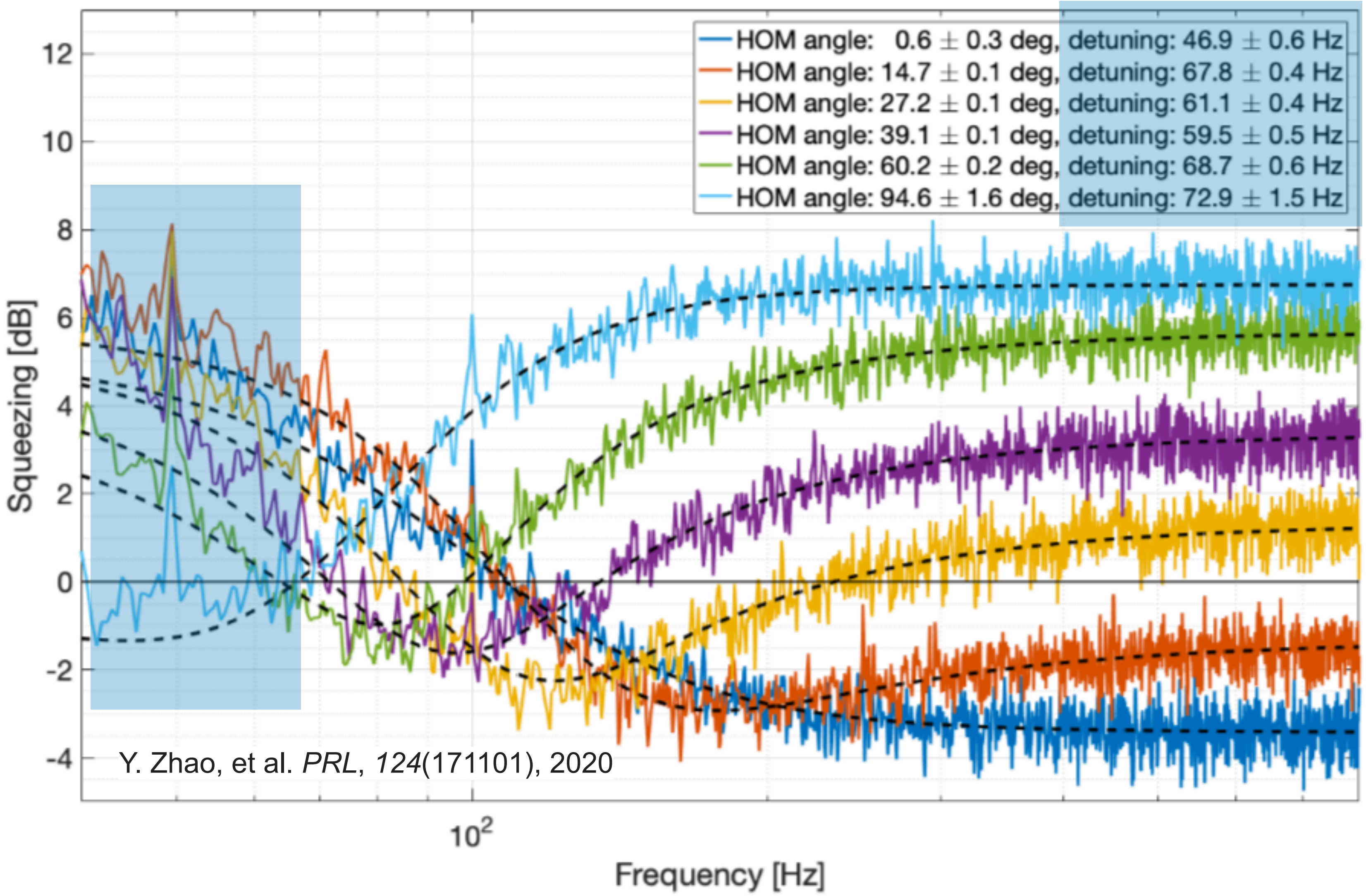
Squeezing at all frequencies

- Rotation below 100Hz

Appropriate rotation frequency

- Low frequency unstable classical noise
- Filter cavity unstable detuning
- Squeezing degradation mechanisms were understood and need to be treated

Frequency dependent squeezed vacuum source at TAMA



- 3.4dB squeezing above rotation frequency
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Squeezing at all frequencies

- Rotation below 100Hz

Appropriate rotation frequency

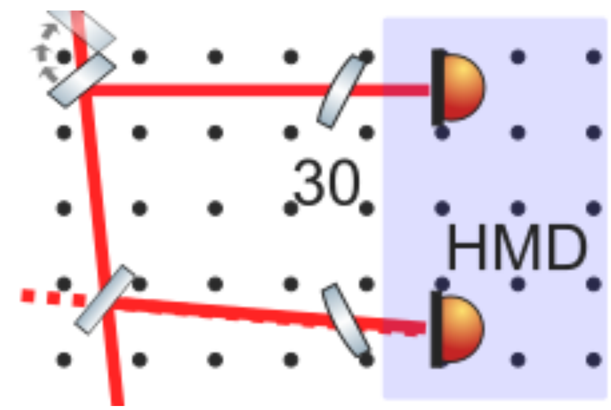
- Low frequency unstable classical noise
- Filter cavity unstable detuning
- Squeezing degradation mechanisms were understood and need to be treated

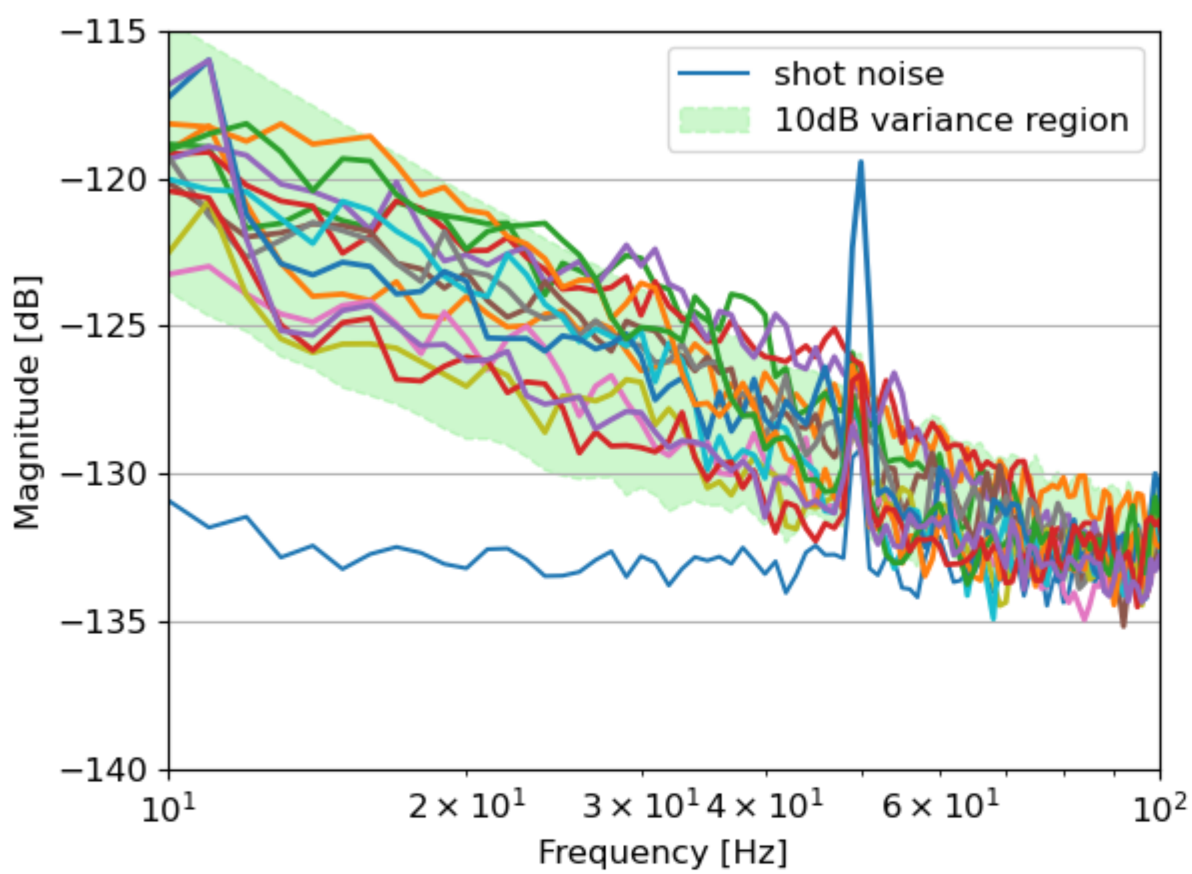
This talk updates the activities after this measurement

Low frequency noise investigation

- When characterizing frequency dependent squeezing, we have seen low frequency noise which is caused by **back scattered noise**

  - **To reduce back scattered noise:**
    - Tilt homodyne lens
      - ~20 deg was tilted while introducing 0.1% losses and astigmatism
    - Add Faraday isolator
      - 3% optical losses

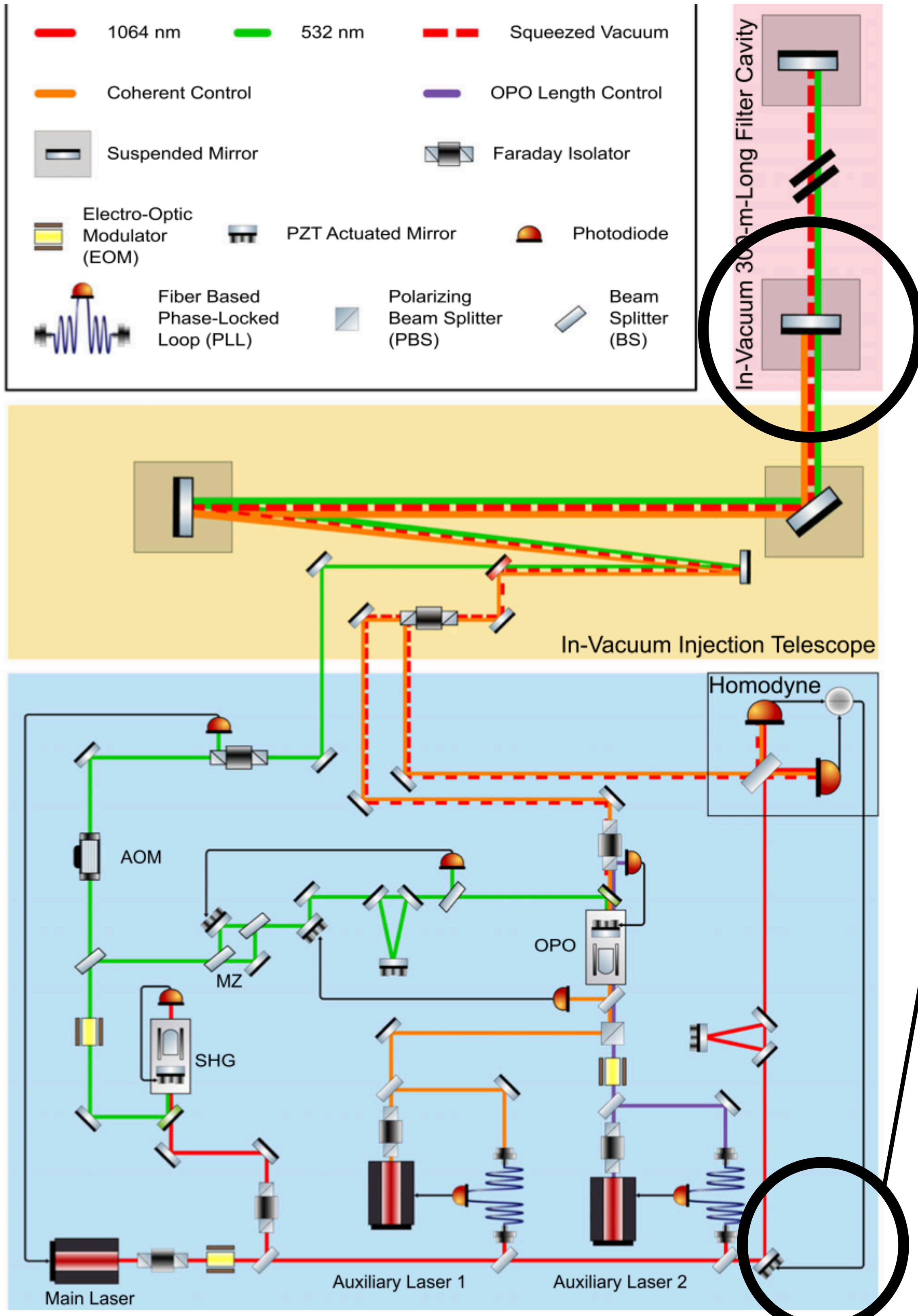




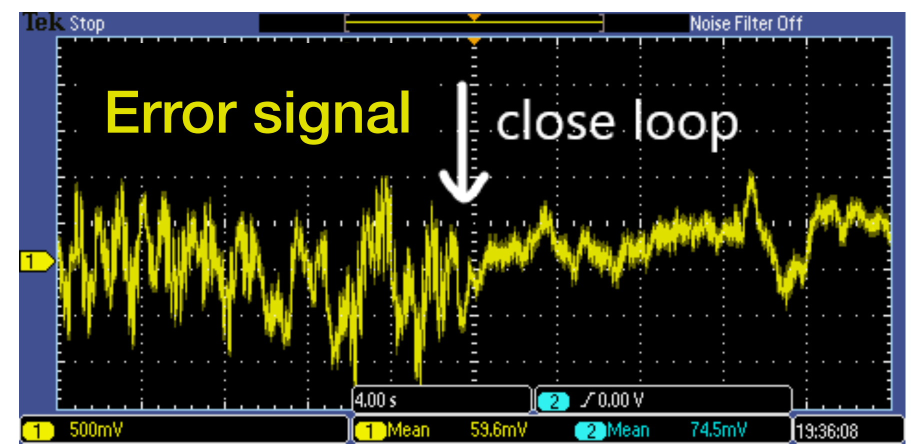
Difficult to check the back scattered noise reduction level due to the back scattered noise variance

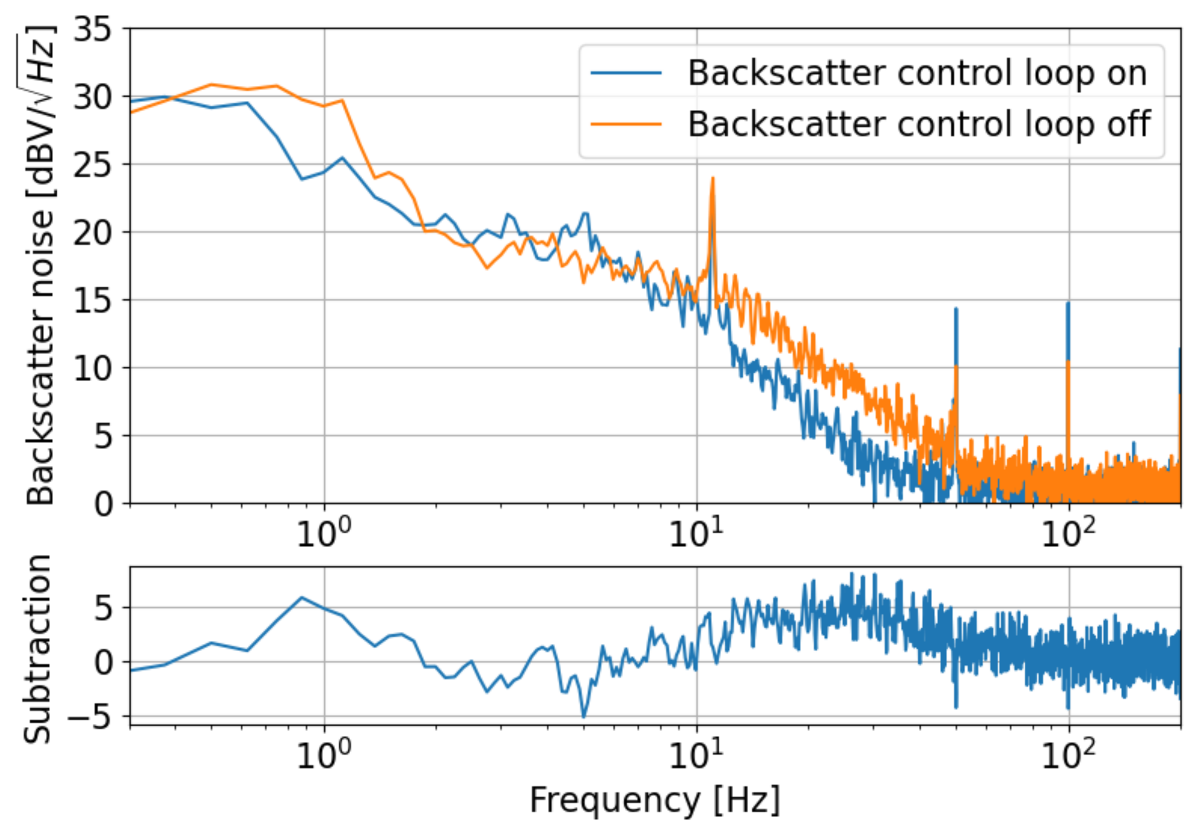
Low frequency noise investigation

- A loop was designed and demonstrated to be able to reduce back scattered noise



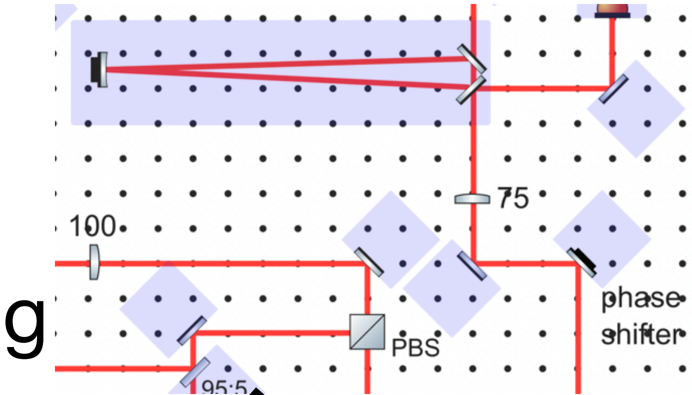
- **To control squeezing phase:**
  - Drive filter cavity input mirror
  - Drive phase shifter

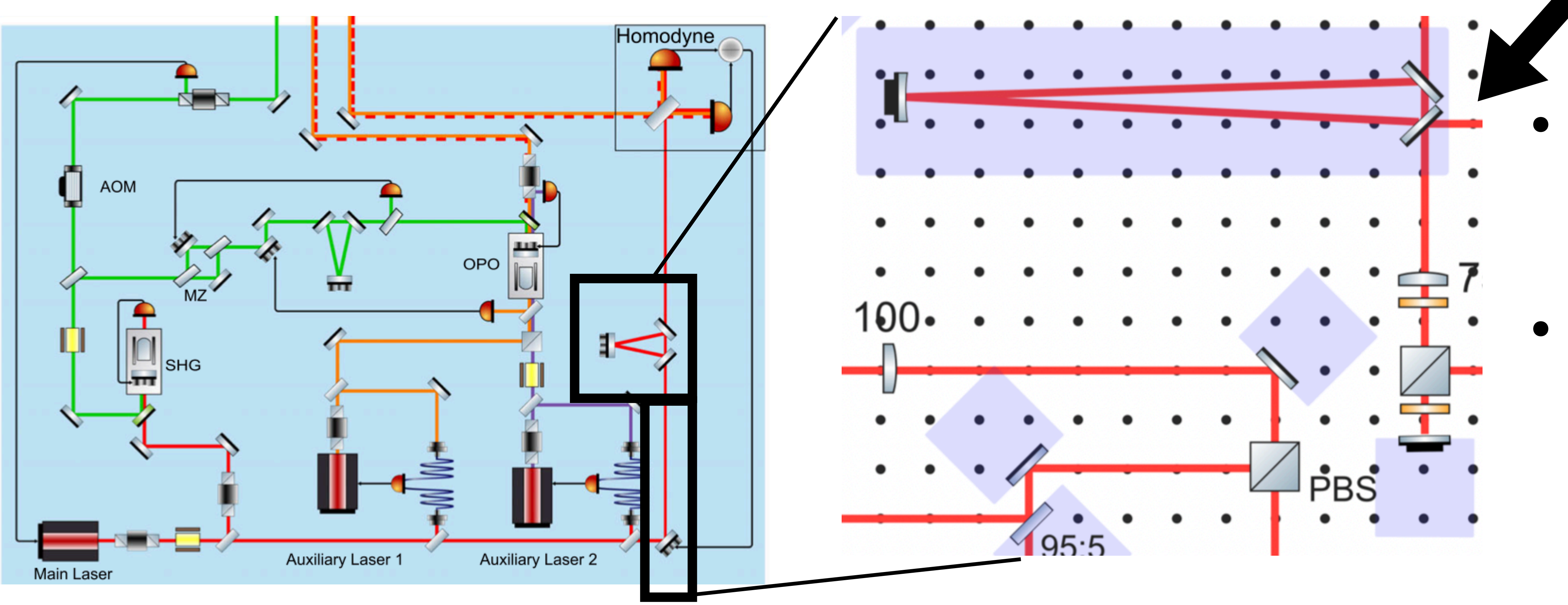




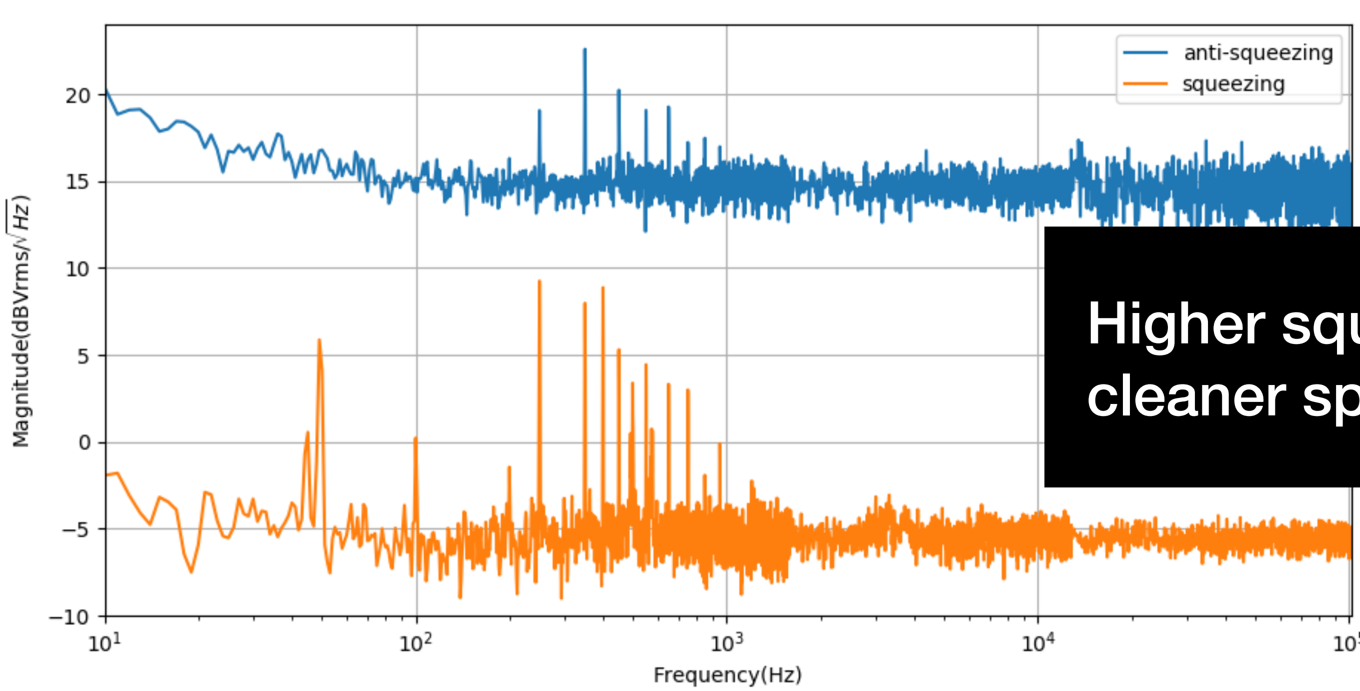
TAMA squeezer upgrade

- We upgraded the phase shifter to avoid noise coupling

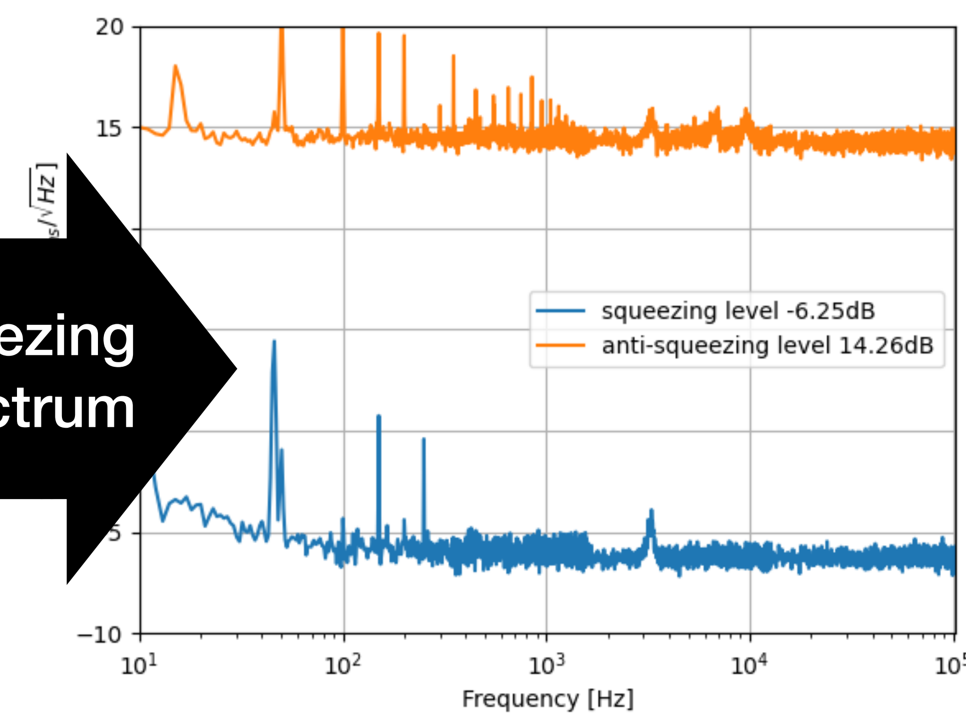




- Optical upgrade
- Mechanical upgrade

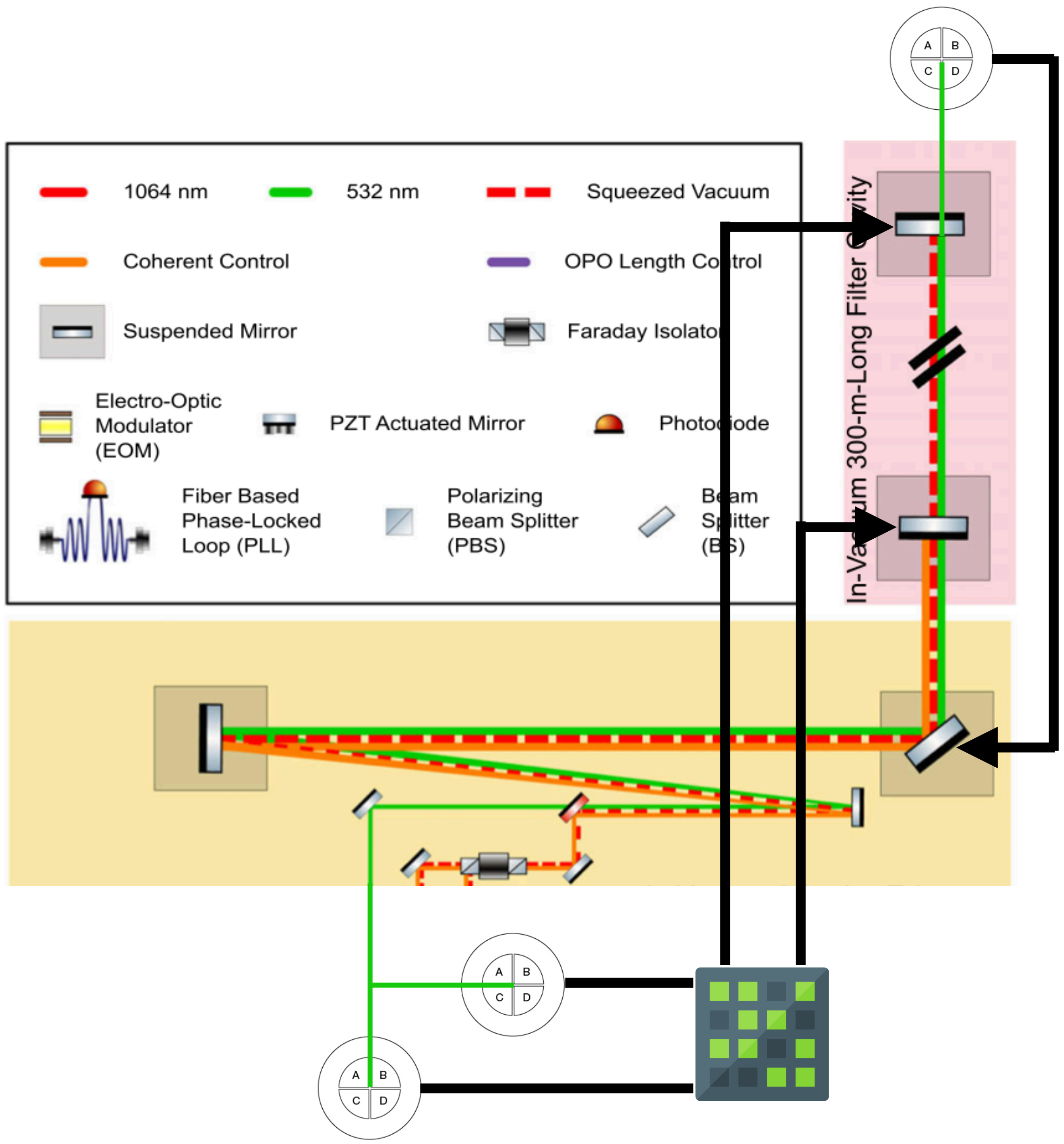


Higher squeezing cleaner spectrum

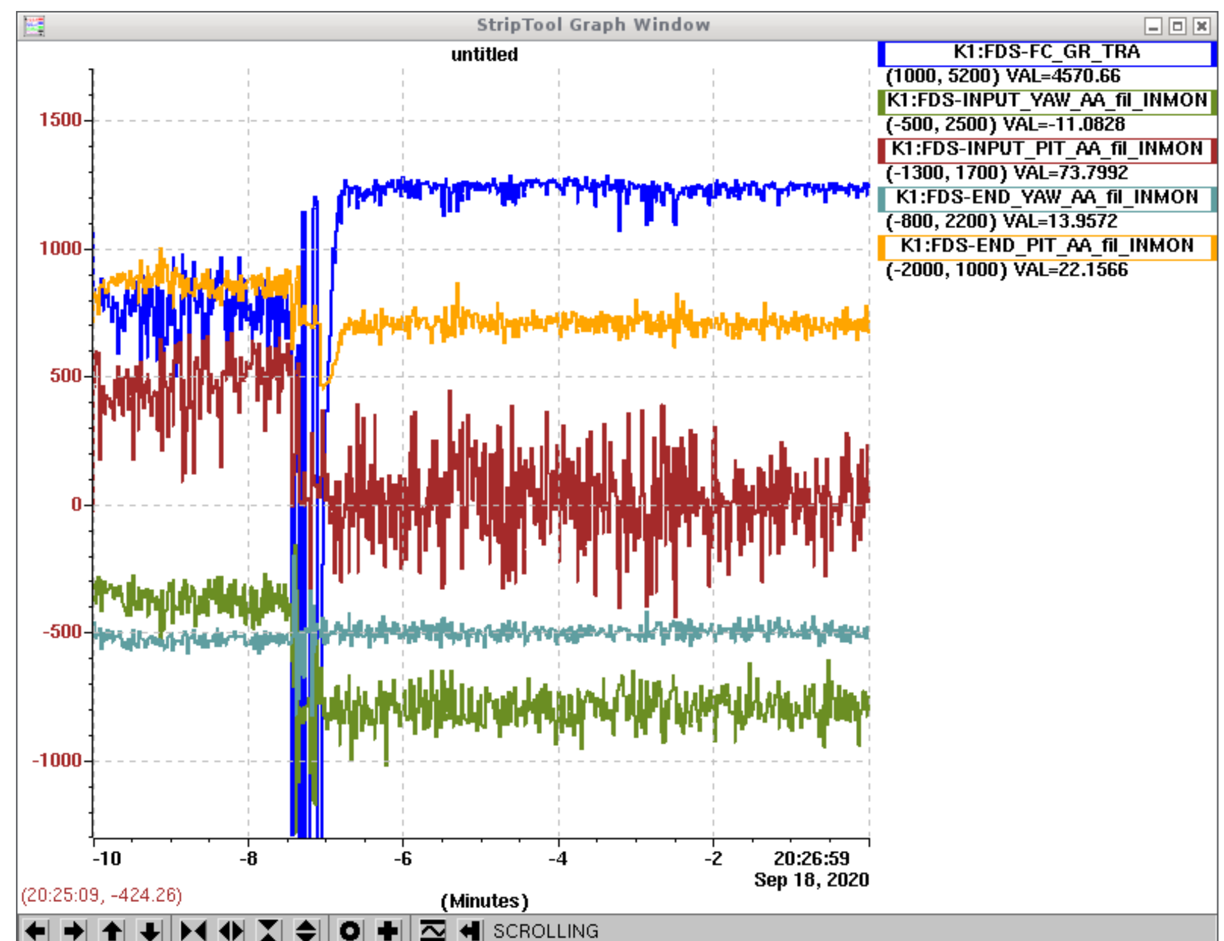


Filter cavity auto-alignment

- A green beam auto-alignment to filter cavity system was successfully implemented based on wavefront sensing

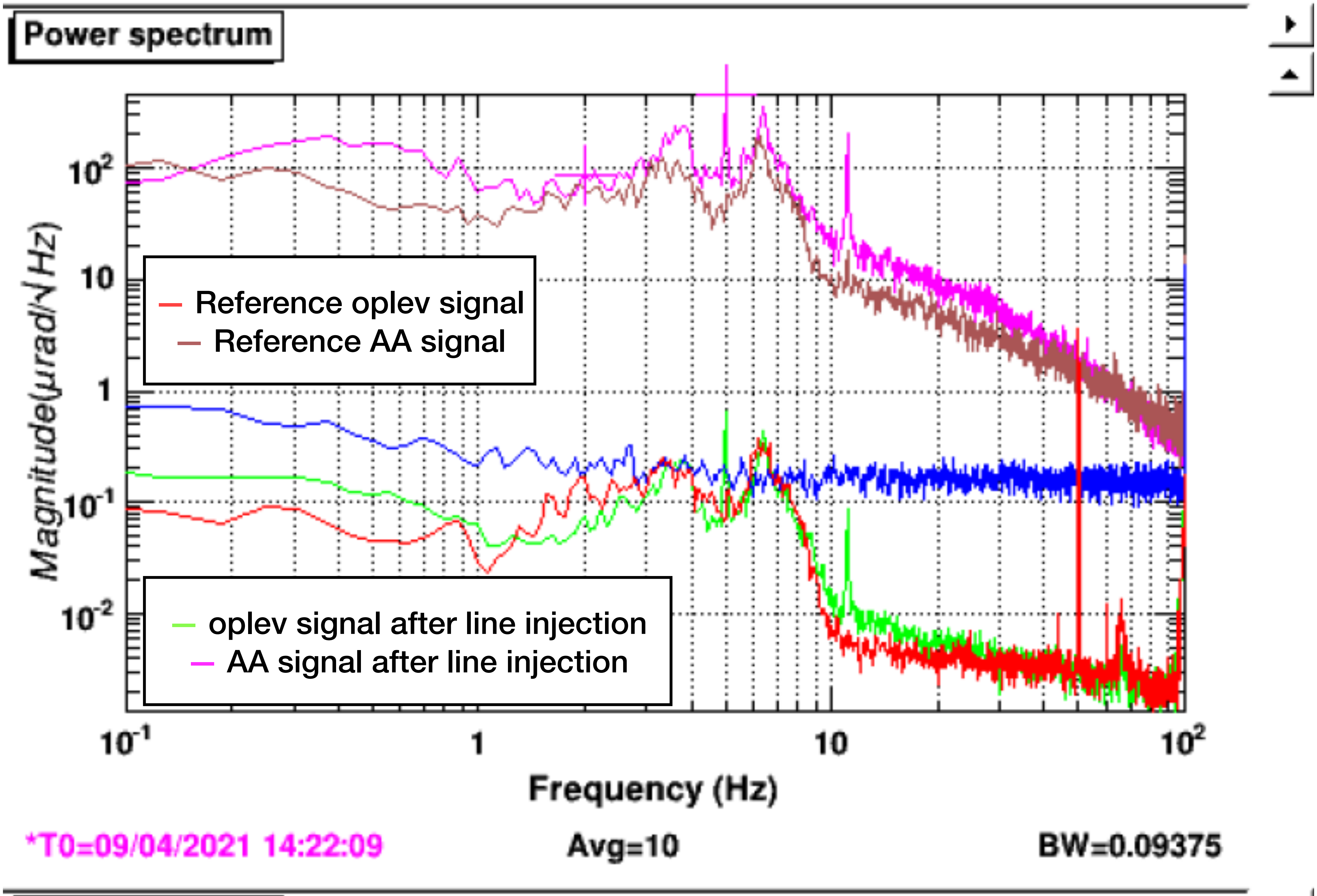


- The IR auto-alignment is achieved simultaneously with green because of their overlap

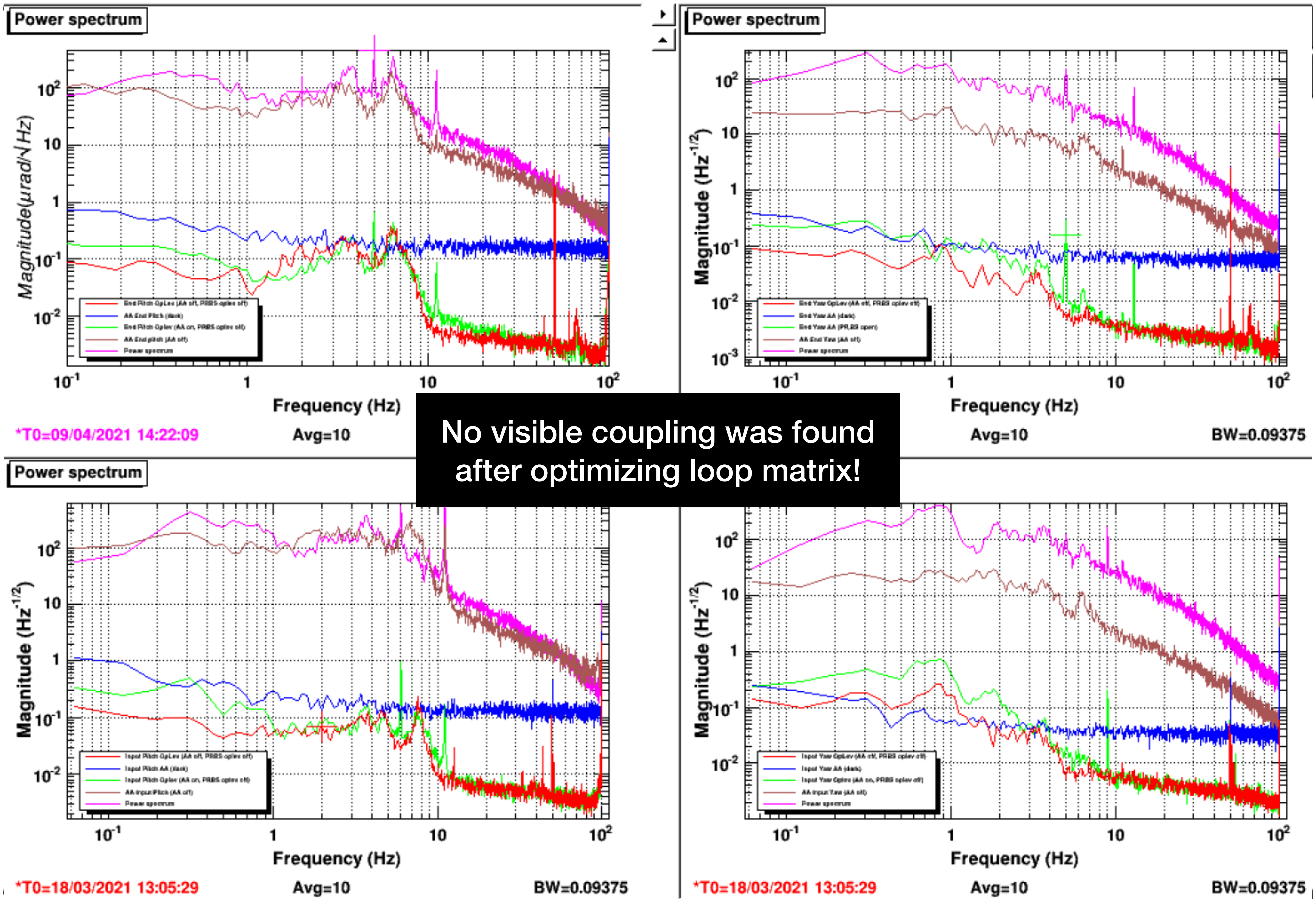


- The IR resonance can be kept decently after a green beam pointing loop implementation

Filter cavity auto-alignment



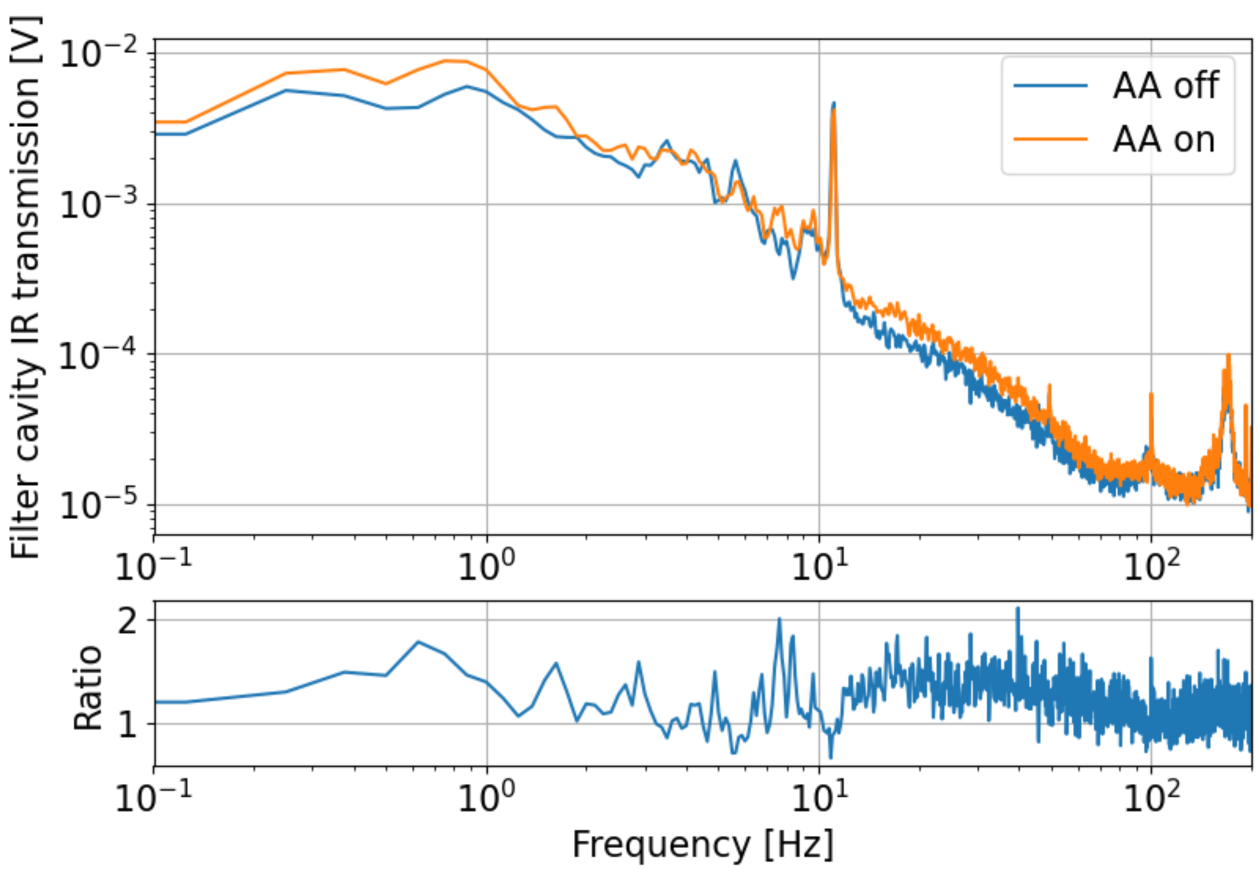
Filter cavity auto-alignment

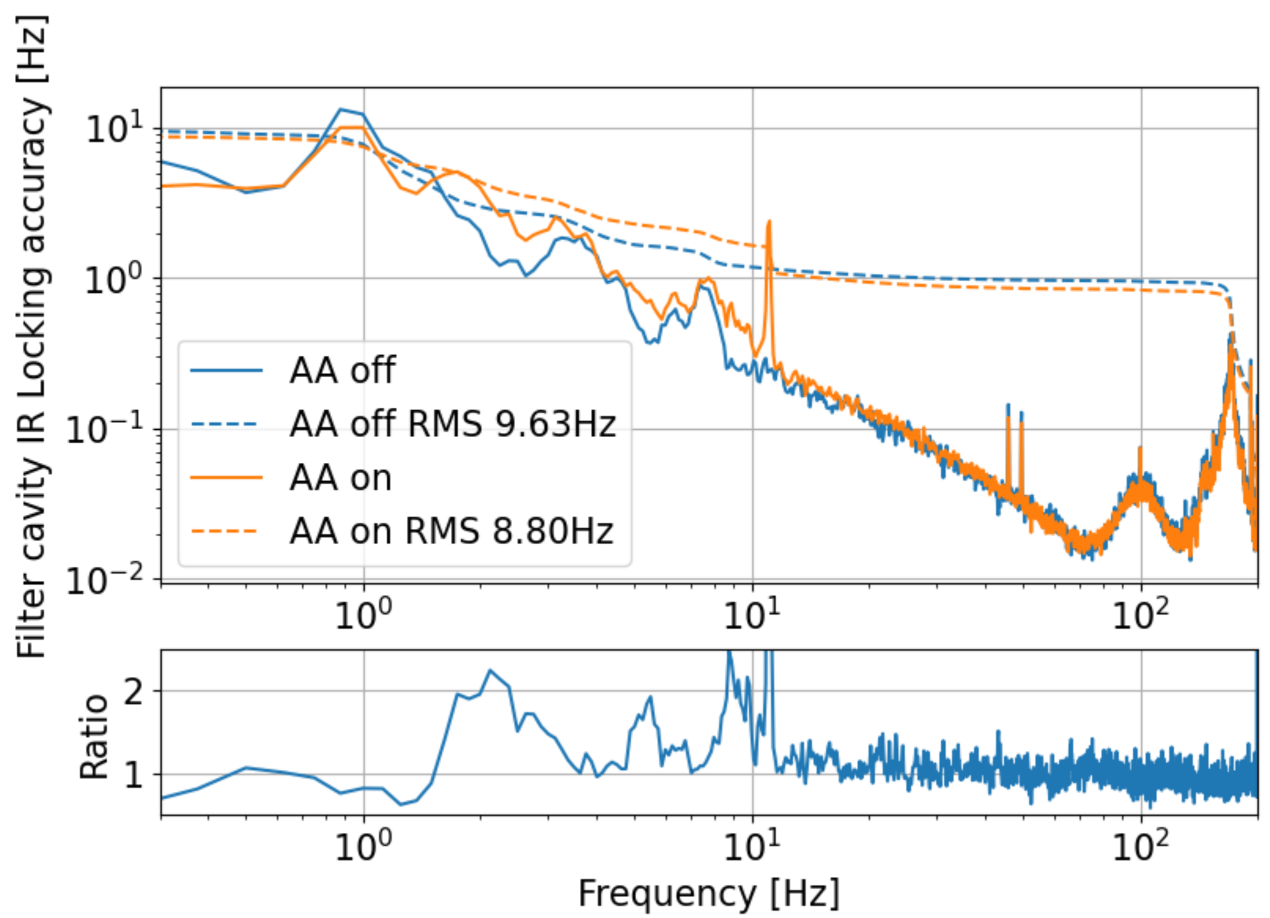


No visible coupling was found after optimizing loop matrix!

Filter cavity auto-alignment

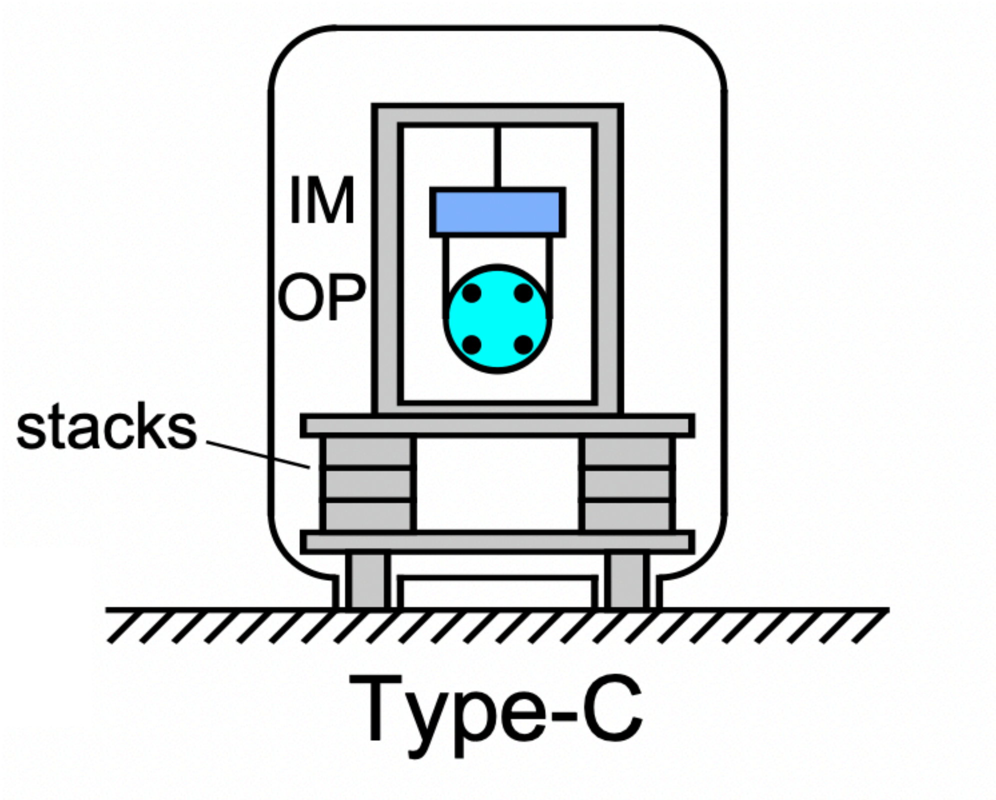
- The filter cavity auto-alignment is sensing and controlling the green beam, but also helps to stabilize IR beam
- We use a test IR beam to check the stability of filter cavity alignment and detuning

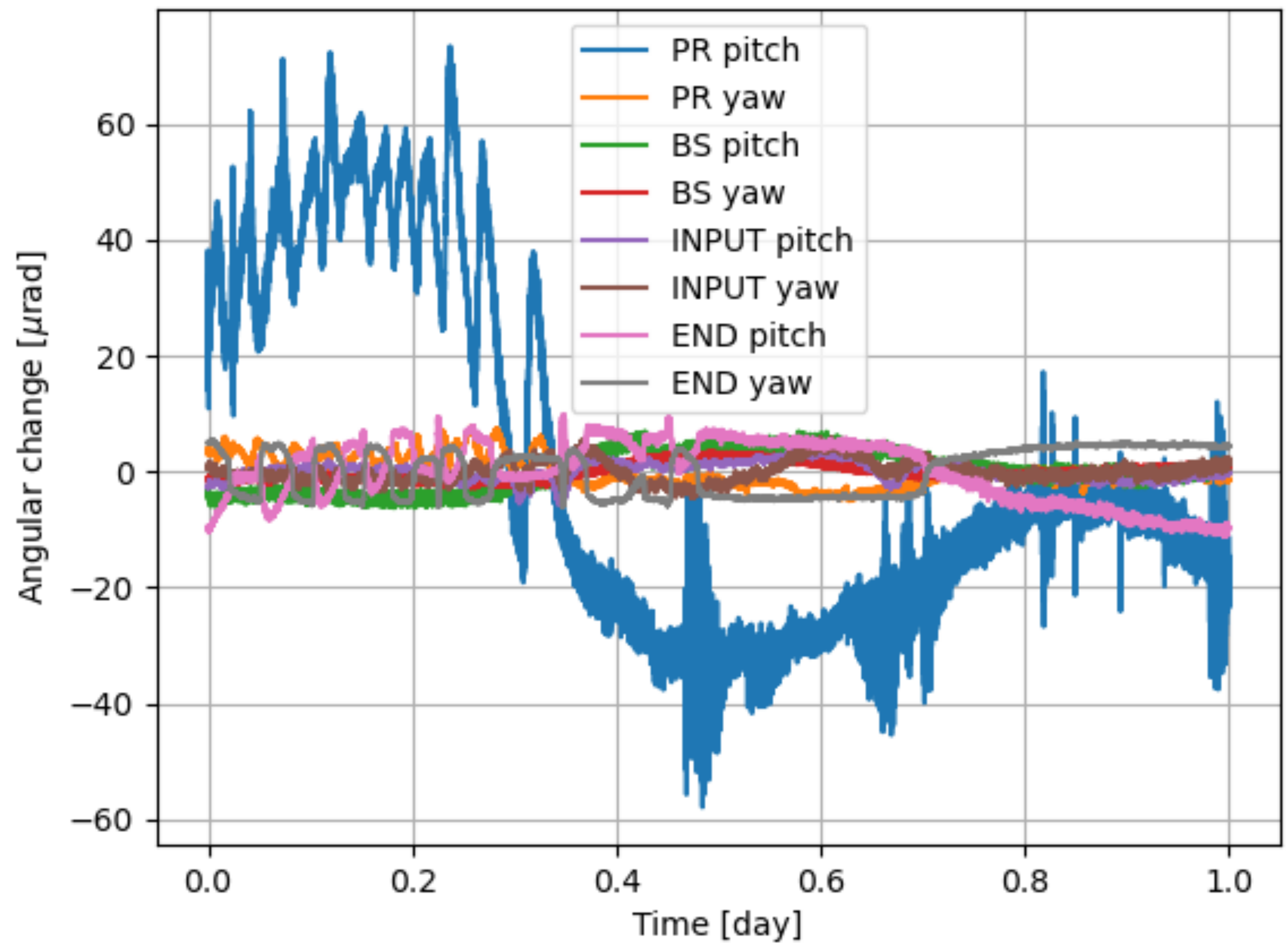




- IR beam intensity shows slight increase while AA loop on
- IR beam length noise is stabilized while AA loop on

Filter cavity auto-alignment

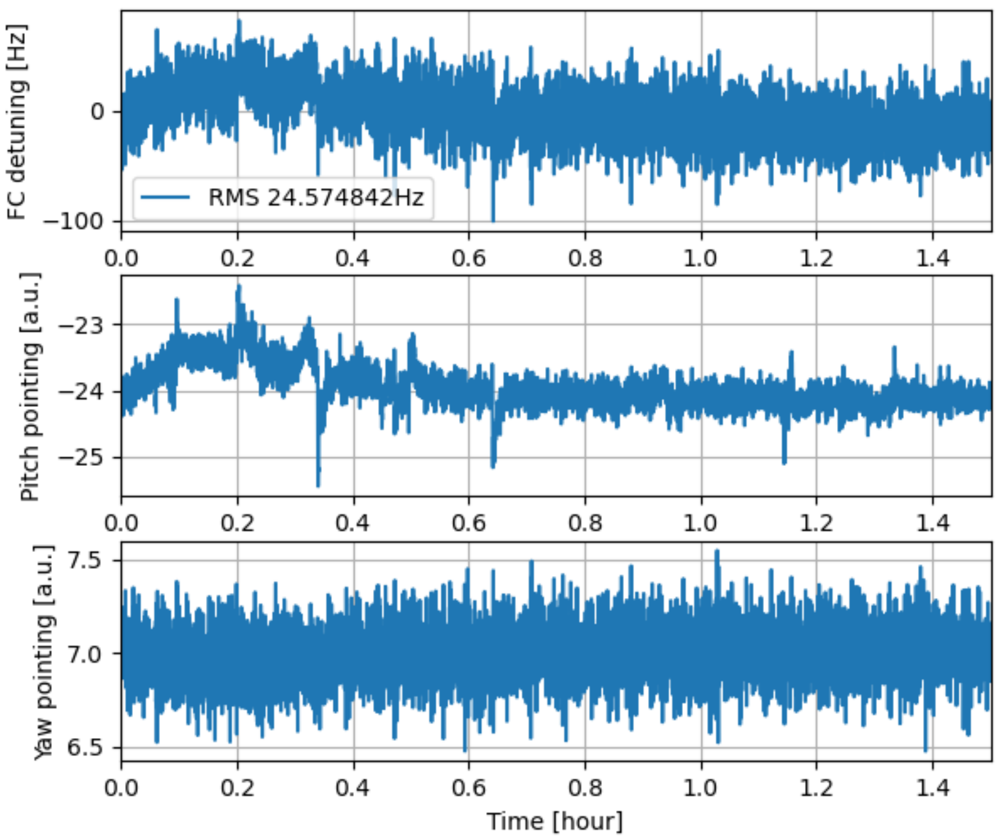


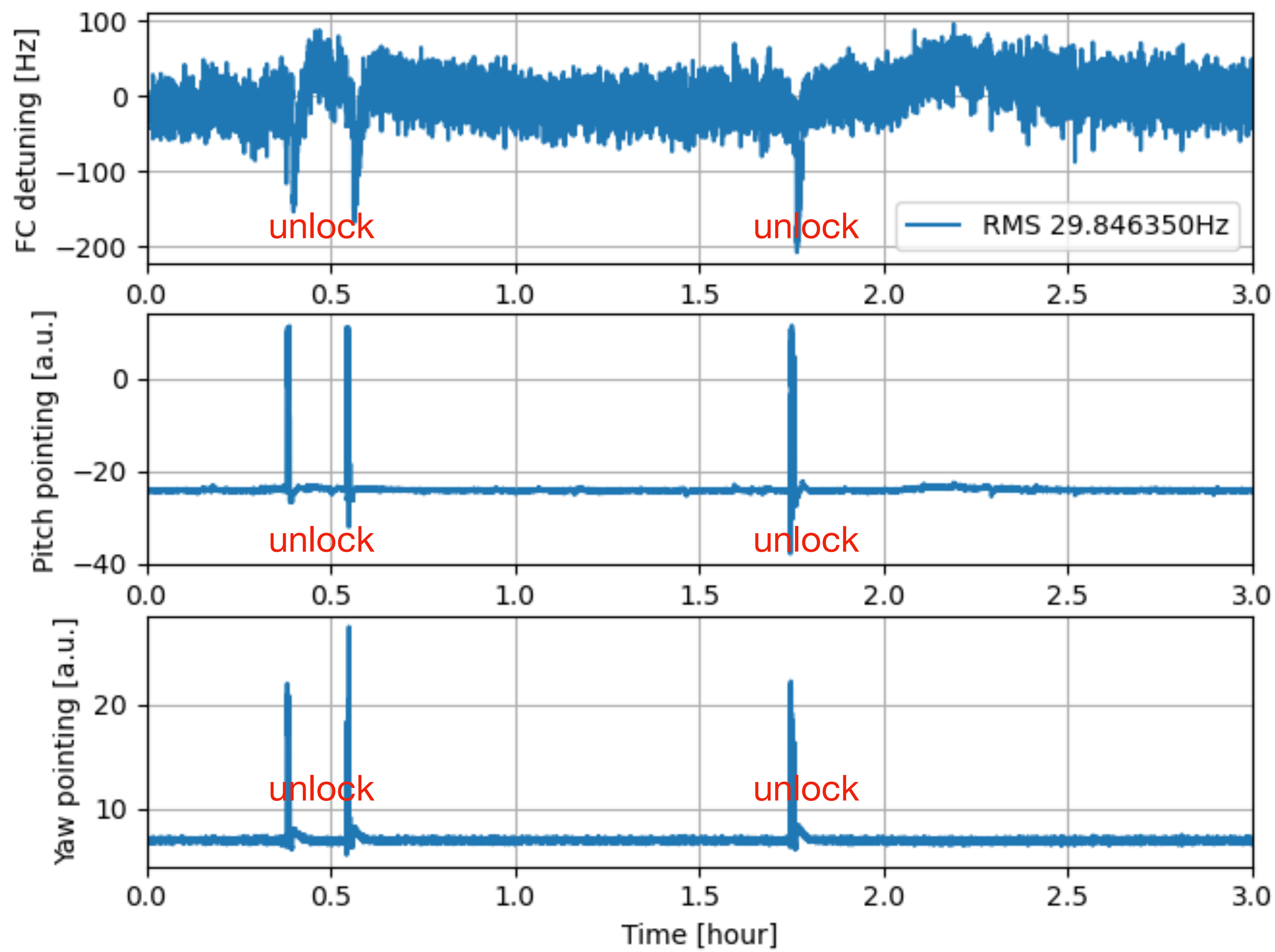


- TAMA suspended optics have relatively large temperature drift and high seismic noise (compared with LIGO/Virgo/KAGRA)
- The large mirror angular drift is currently compensated by a beam pointing loop

Filter cavity auto-alignment

- **Longterm stability**: filter cavity auto-alignment is important to stabilize the filter cavity alignment and detuning for squeezed vacuum



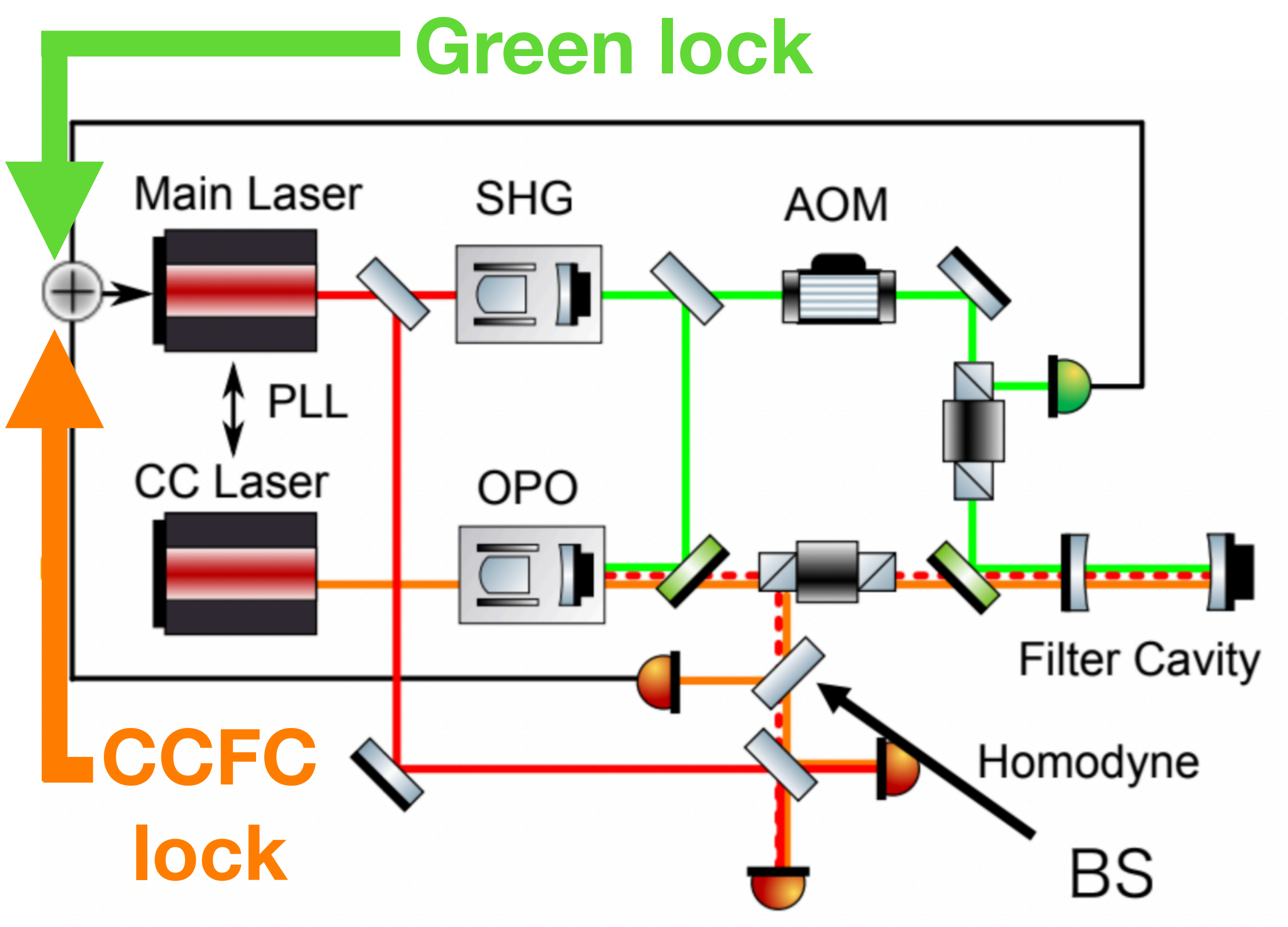


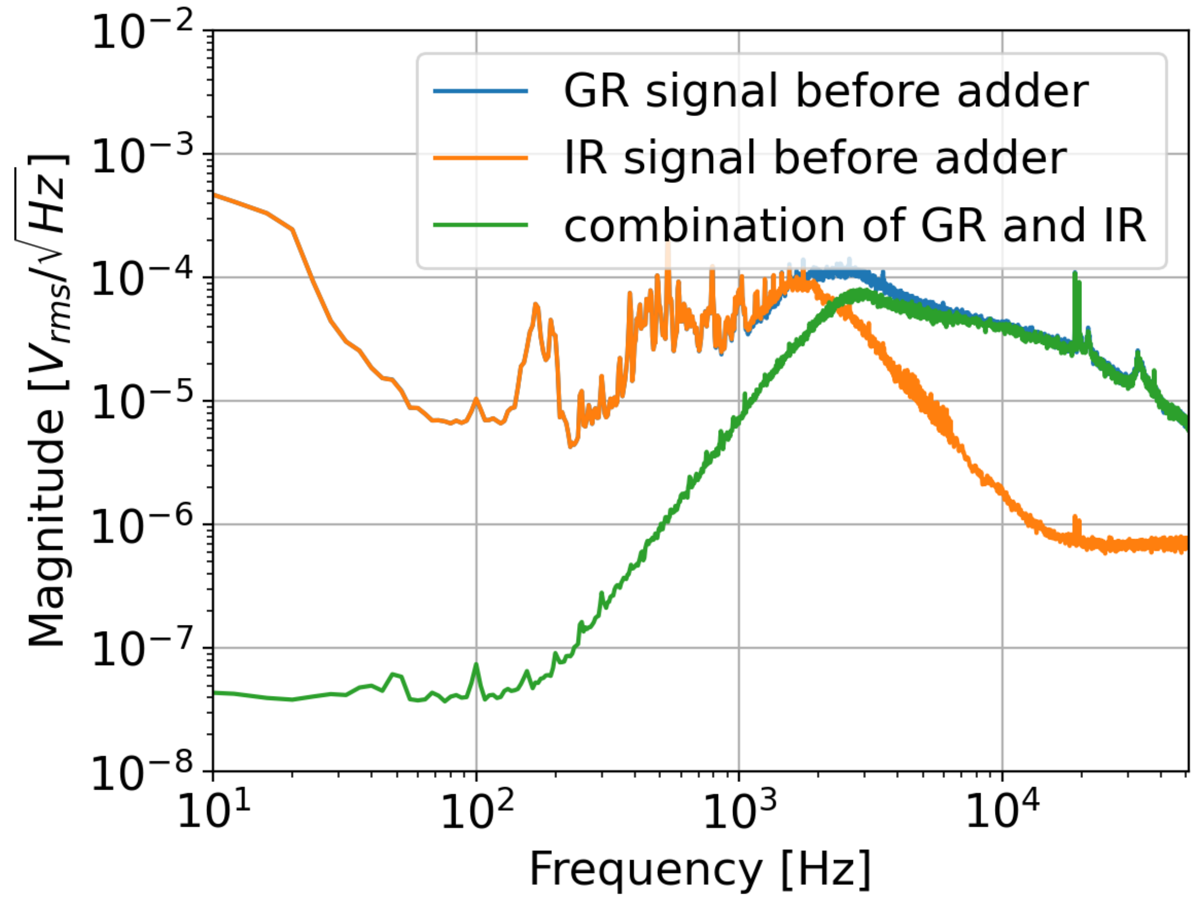
- The detuning change comes from the beam pointing change

- With auto-alignment, even after some unlock, the filter cavity goes back to almost exactly the same situation with before

Filter cavity new length control

- A pre-stabilized coherent control field reaching filter cavity with one sideband on-resonance and the other off-resonance, which tells us the filter cavity mirrors differential length information

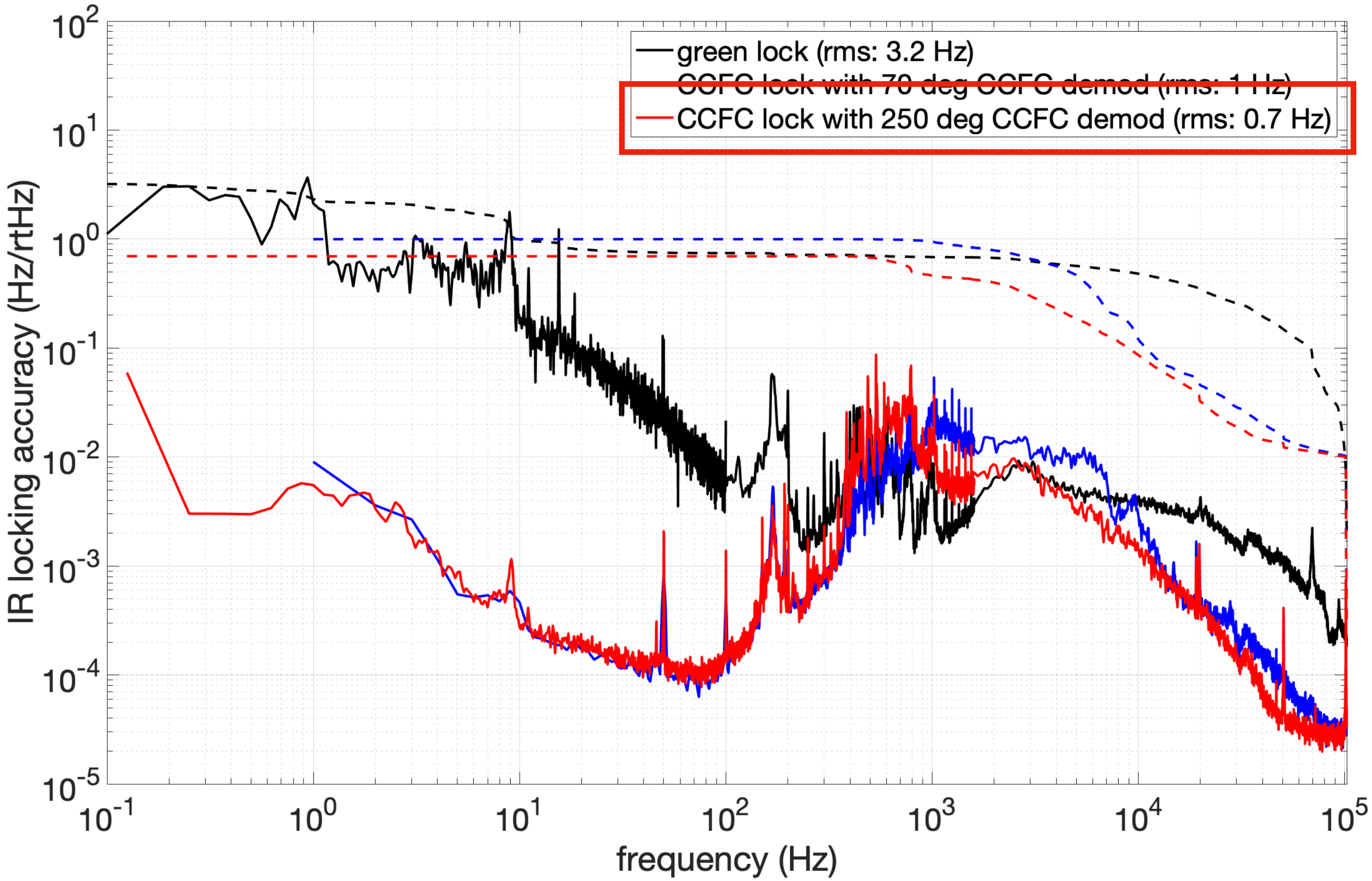




- This loop reduces IR length noise by introducing small length noise for GR

Filter cavity new length control

- A in-loop check of the IR length noise shows less than 1Hz noise is achieved



- Details in Naoki Aritomi's talk

Summary

- The frequency dependent squeezing low frequency noise was investigated. We designed a loop to reduce it by up to 5dB
- The frequency independent squeezing spectrum becomes cleaner and squeezing level is increased to 6.5dB
- A filter cavity auto alignment system was implemented, which pre-stabilizes filter cavity length noise to be less than 9Hz and guarantees a long term stability
- A new filter cavity IR beam length control scheme 'CCFC' was tested, which further reduced length noise to be less than 1Hz

Future plan

- We are installing a new OPO, purchasing a customized in-vacuum Faraday isolator, upgrading old TAMA oplev, filter cavity automation