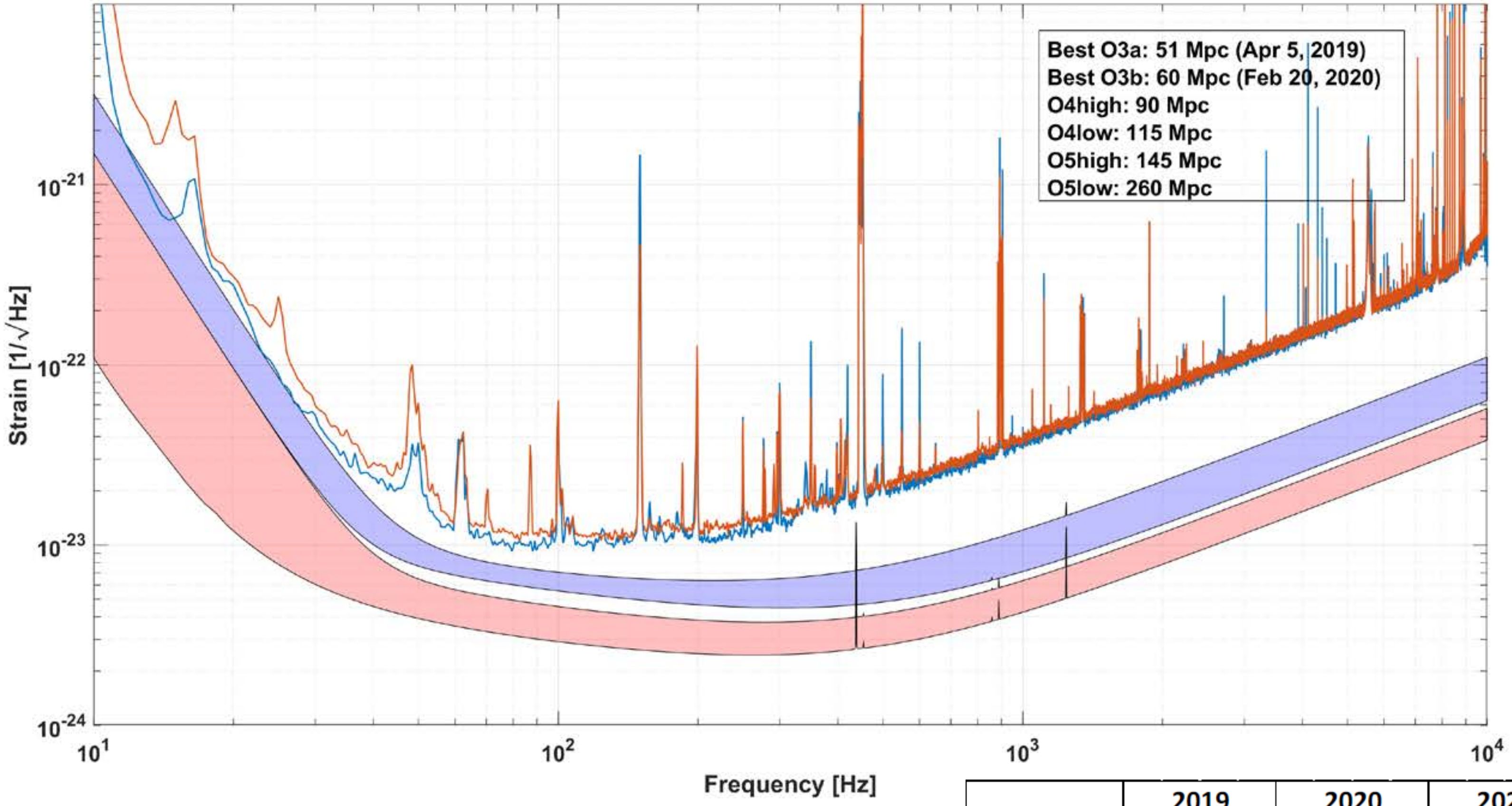
Status of Virgo commissioning: on the path towards the O4 run

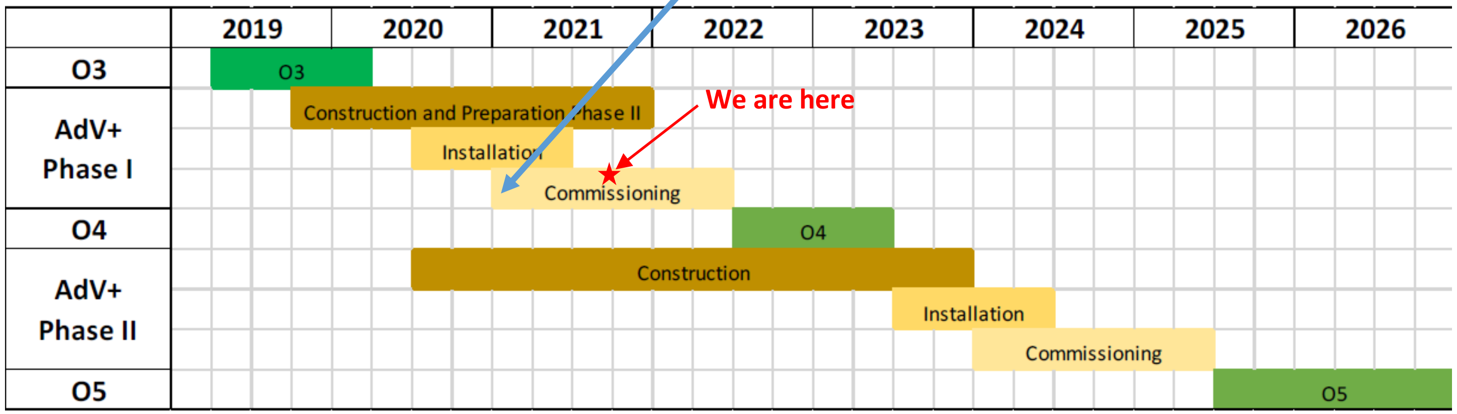
R. Gouaty, on behalf of the **Virgo Collaboration**

Advanced Virgo+ project

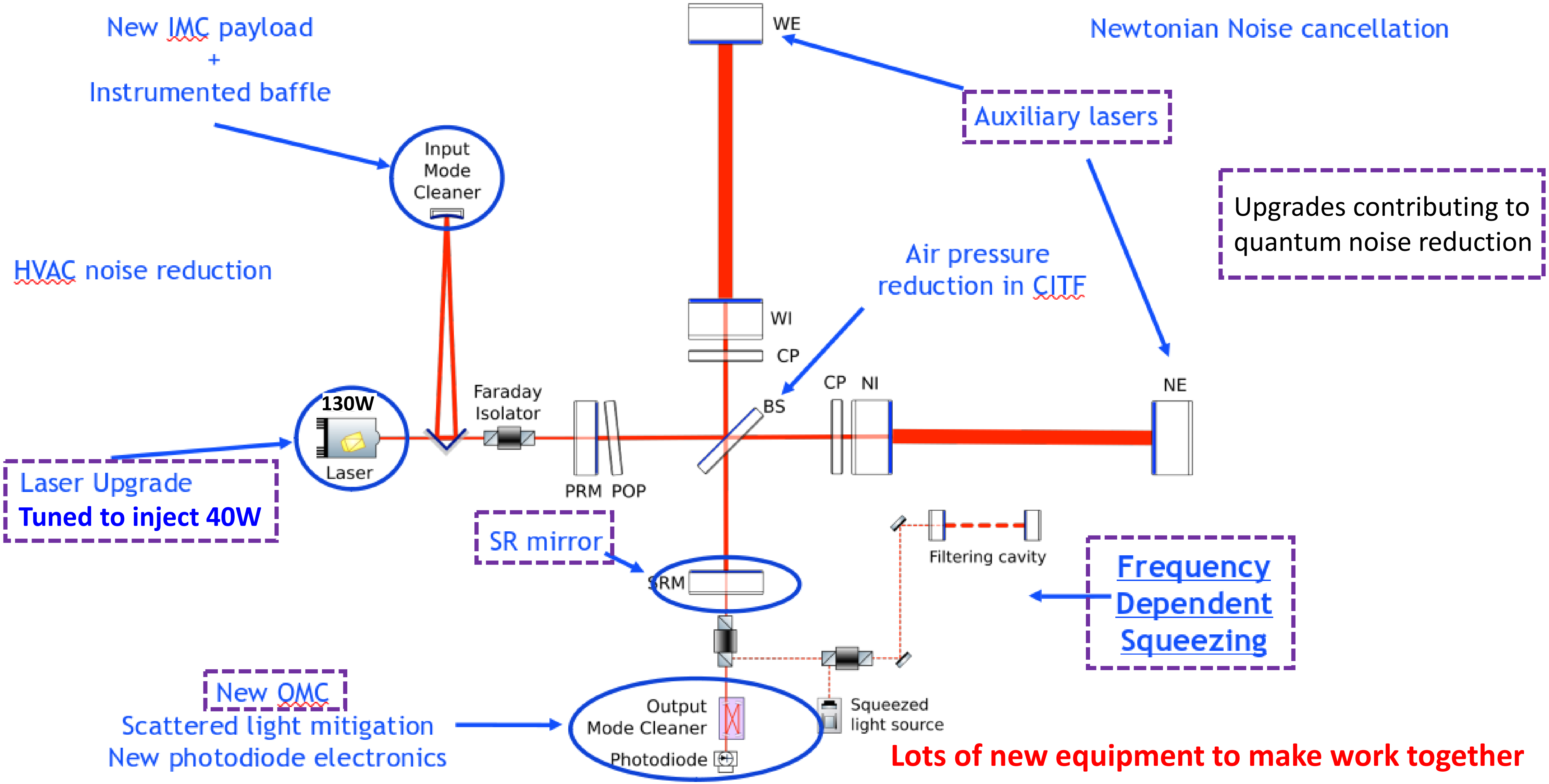


- **Phase I:** reduce quantum noise.
  → BNS range ~100 Mpc
- **Phase II:** lower the thermal noise wall
  → BNS range: 200 Mpc or more

Commissioning of phase I started in January 2021



Advanced Virgo+ upgrades



Commissioning: main goals

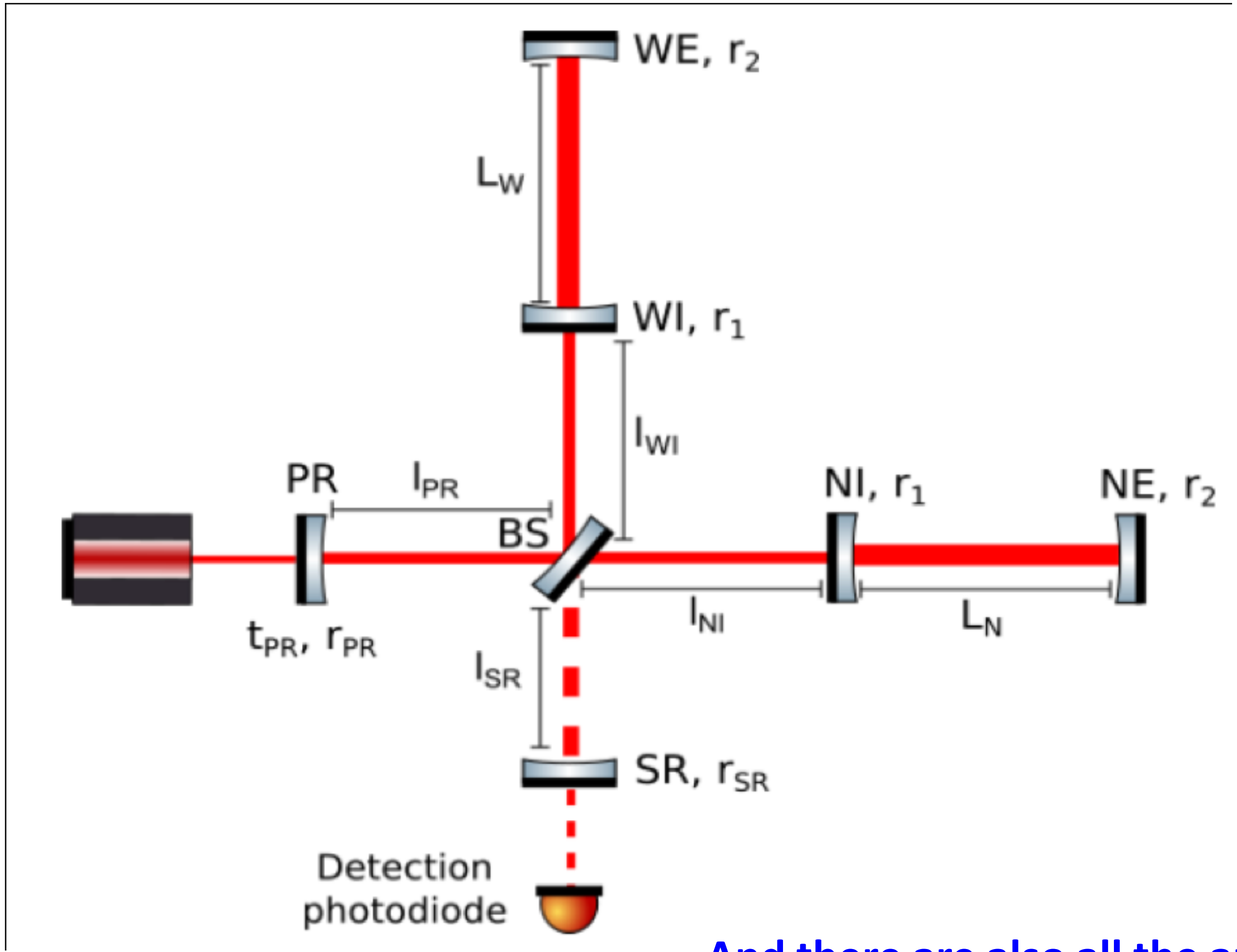
- **Control the dual recycled interferometer with 40W of input power**
  - Redesign of the lock acquisition to deal with the new optical configuration:
    - Involve an auxiliary green laser beam to control the Fabry-Perot cavities during the lock acquisition of the central interferometer with the signal recycling
  - Power injected in the interferometer gradually increased: 25W, **40W**
  - Correct thermal effects with thermal compensation system

- **Inject Frequency Dependent Squeezing in the interferometer**
  - Started with the commissioning of the new FDS system (filter cavity of 300 m + new optical benches)

- **Noise hunting and noise mitigation to reach the targetted sensitivity**

Interferometer longitudinal degrees of freedom

Five longitudinal degrees of freedom to be controlled + laser frequency stabilization



$$DARM = \frac{L_N - L_W}{2}$$

$$CARM = \frac{L_N + L_W}{2}$$

$$MICH = l_{NI} - l_{WI}$$

$$PRCL = l_{PR} + \frac{l_{NI} + l_{WI}}{2}$$

$$SRLC = l_{SR} + \frac{l_{NI} + l_{WI}}{2}$$

And there are also all the angular degrees of freedom to be controlled !

Lock acquisition

- **Goal: Bring the interferometer to its final working point**
- Error signals extracted from photodiodes at different optical ports
  - interferometer reflection (B2)
  - power recycling pick-off (B4)
  - dark fringe beam (B1p)

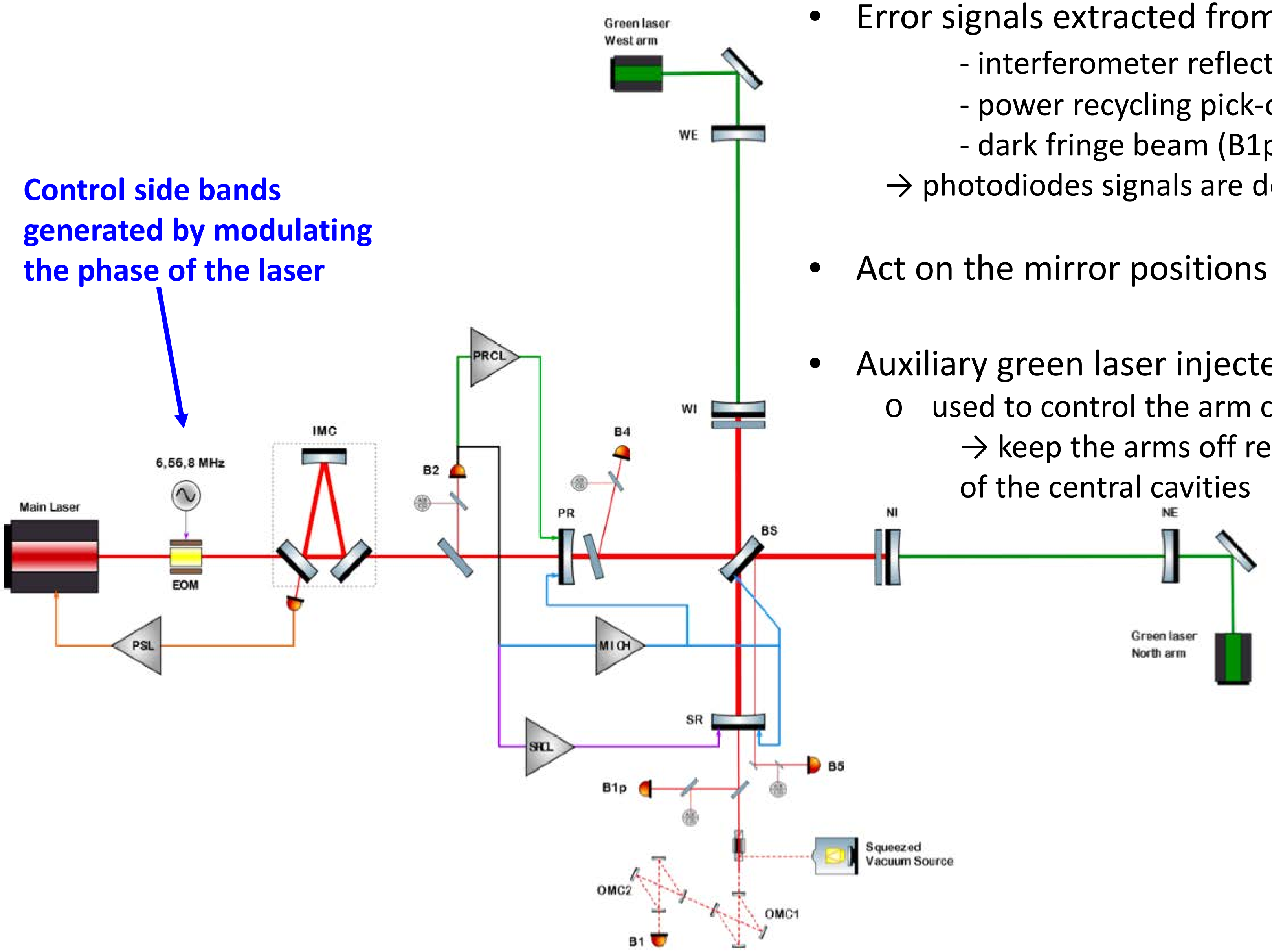
  → photodiodes signals are demodulated at the frequencies of the side bands

- Act on the mirror positions with electro-magnetic actuators

- Auxiliary green laser injected through the end mirrors:
  - used to control the arm cavity length independently from the main IR beam

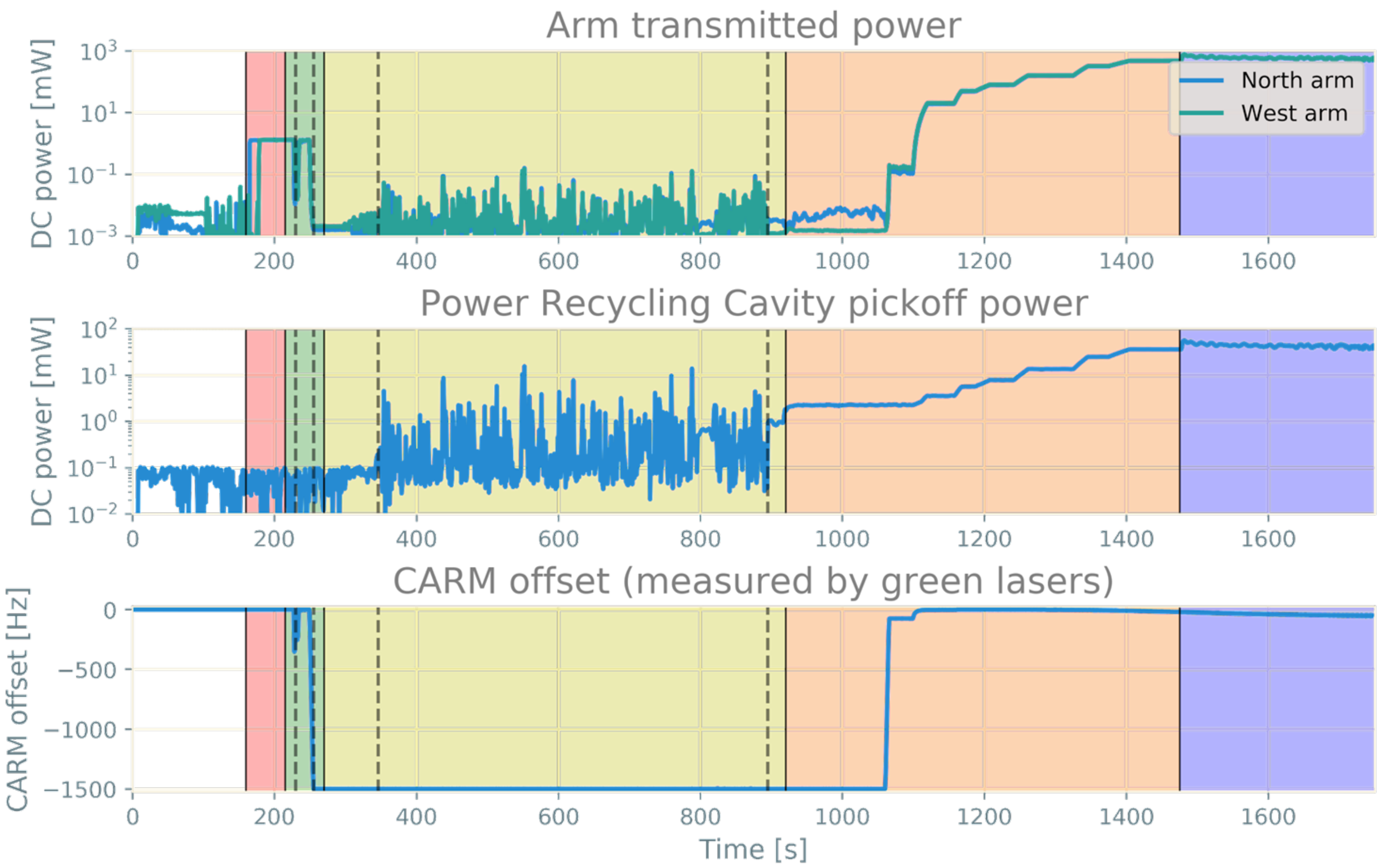
    → keep the arms off resonance for the IR beam during the lock acquisition of the central cavities

Control side bands generated by modulating the phase of the laser



Lock acquisition

Independent lock of arm cavities on the IR beam
Handoff of the arm lock to the auxiliary green lasers Addition of 1.5 kHz of common arm (CARM) offset
Lock of the DRMI (Dual Recycled Michelson) central interferometer
Progressive reduction of the CARM offset
“Jump” to 0 offset, engagement of the remaining loops, handoff to the final error signals.
TODO: DARM DC offset, Output Mode Cleaner lock, low noise controls, noise subtractions, squeezed light injection...



- Only first step in red is the same as during O3
- Rest completely changed because of signal recycling installation

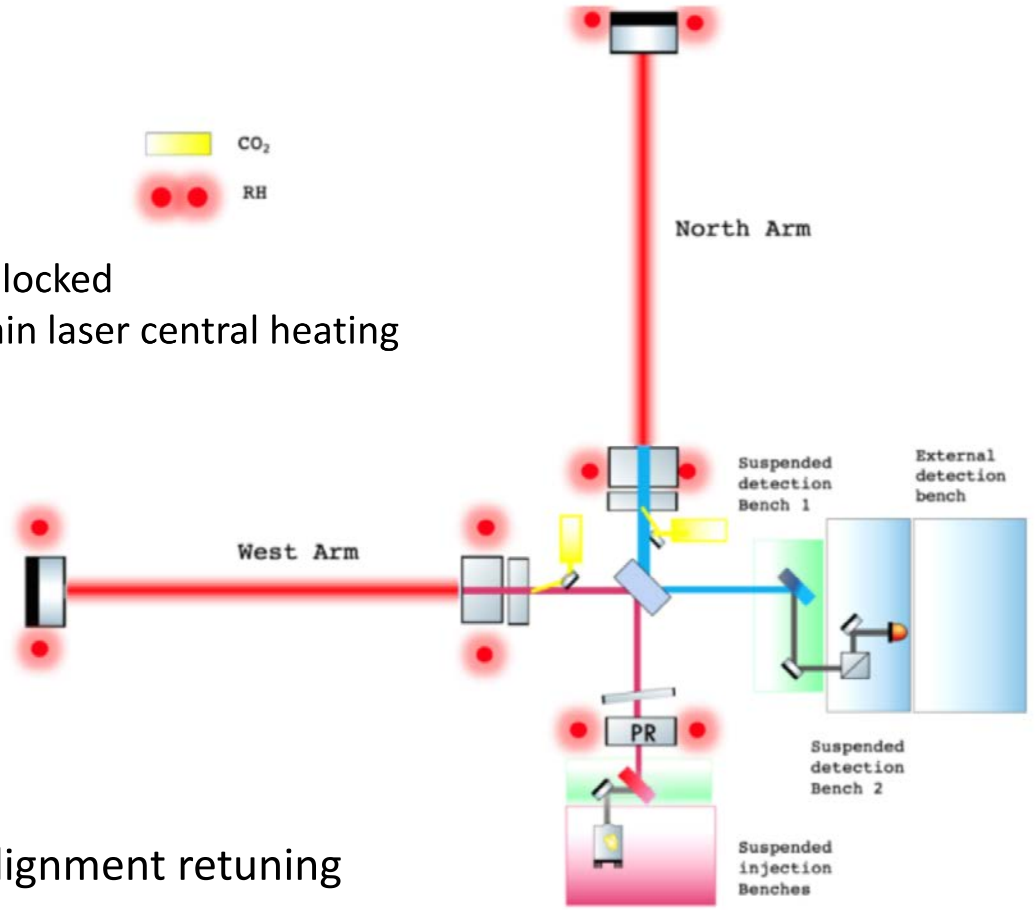
Interferometer thermal tuning

- When interferometer is locked at dark fringe with null CARM offset
  - Large power stored in the arm cavities (goal is to have ~200kW)
  - Interferometer becomes « hot » → thermal aberrations → degradation of control signals → working point no longer reliable
  - **Thermal aberrations need to be compensated**

- Interferometer cold defects also need to be corrected

- **Several actuators**
  - Ring Heater - change curvature of mirrors
  - Central heating - CO2 laser keeping mirrors hot when intereferometer unlocked
  - Double Axicon - CO2 laser with doughnut shaped beam correcting for main laser central heating
  - Beam spot on mirrors to mitigate the effect of point absorbers
  - Input mirror temperature to change their reflectivity (Etalon)

- **Several observables**
  - Carrier and side-band power at different port of interferometer
  - Beam shape from cameras, sideband shape from phase-camera
  - *Mode decomposition with output mode cleaner*
  - *Noises coupling (laser frequency noise, scattered light, …)*

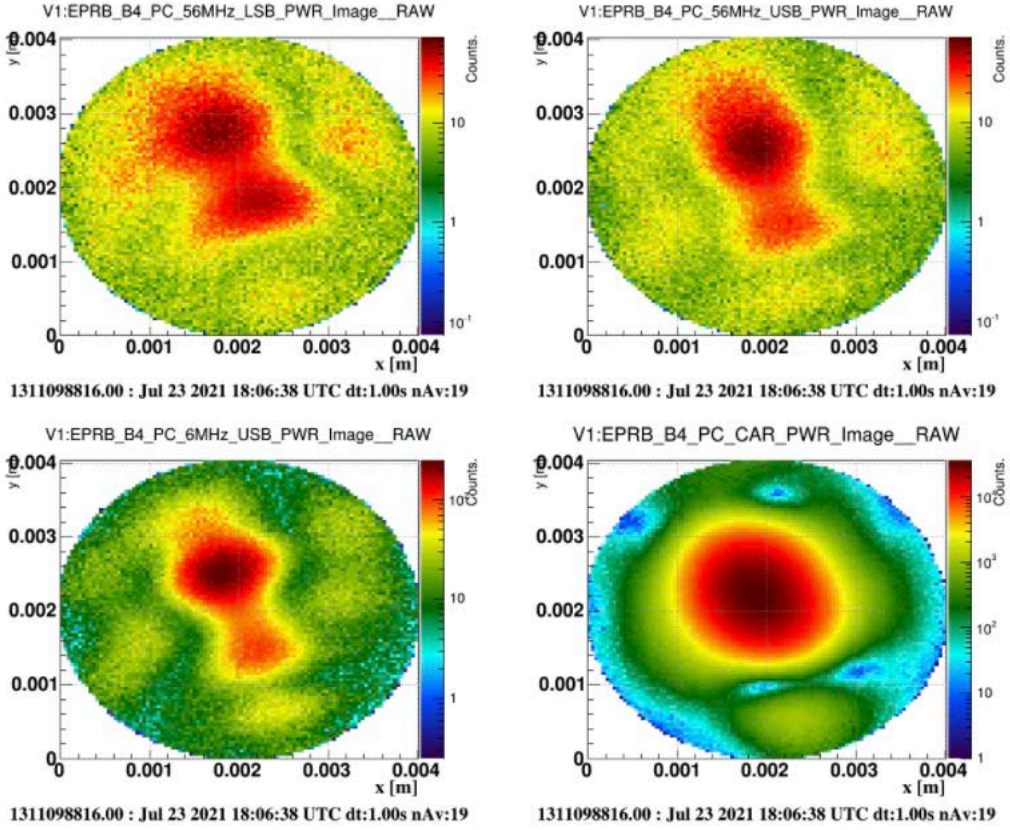


- Each action is slow: several hours thermal response, interferometer alignment retuning

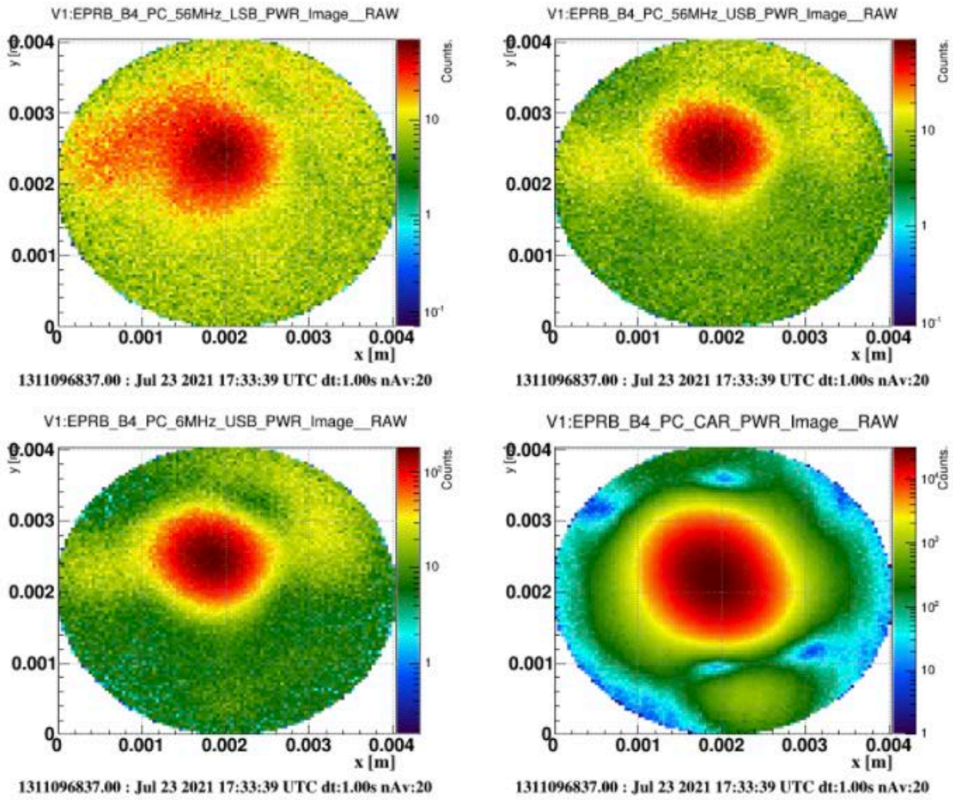
Interferometer thermal tuning

Example of thermal tuning, with interferometer locked at dark fringe, 25W of input power

Double Axicon System turned off



Double Axicon System turned on



Improving the wavefront profile of the beam circulating inside the recycling cavity

Interferometer control: main achievements

- First lock (few min duration) of the full interferometer in dark fringe achieved on July 14th, with 25W

- Stability improved with thermal compensation and interferometer alignment → **achieved two hours of stable lock on Aug 6th, with 25W**

- Tuning of interferometer with input power increased at 40 W (goal for O4 run):

  - **Lock at 40W of more than one hour achieved on Sep 9th**, with limited power in the arm:
    - locking with 160kW in the FP cavities (goal is 200kW) and quickly decaying to 120kW

  - End mirror ring heaters switched on in order to correct the radius of curvature of the end mirrors
    - **Allowed to lock with 190 kW in the FP cavities, decaying to 170 kW**
    - Lock became unstable due to larger thermal effects

  - Today's situation: Input power temporary reduced to 33W:
    - Ease the recovery of a good working point (with ring heaters on) with lower thermal effects
    - Input power should be restored to 40W within a few weeks.

  - The short term priority is to finalize the tuning of the interferometer working point in order to reach a stable lock at 40W, with low losses in the arms and an optimized contrast defect.

Frequency Dependent Squeezing commissioning

- **Goal of FDS**: reduce shot noise at high frequency **and** radiation pressure noise at low frequency

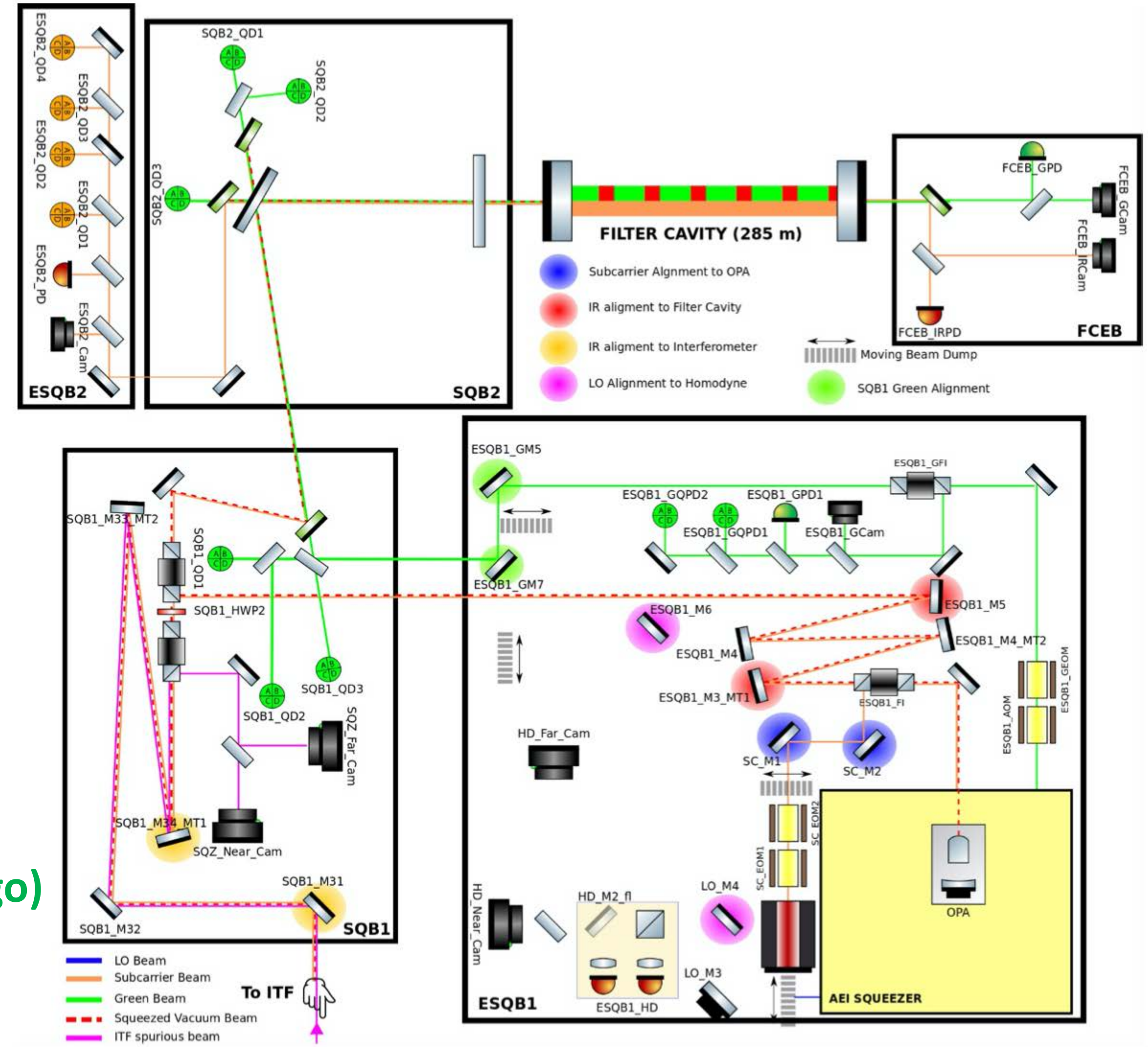
→ Need to rotate the squeezing angle as a function of frequency

- Squeezing source is basically the same as during O3 (yellow box) (but some parts replaced due to aging)
- Two new suspended benches
- A suspended 300m optical cavity
- Several new auxiliary beams, using both infrared and green light

→ a complex new system to make work

  - Longitudinal and angular control loops
  - Hunting for any sources of losses: scattered light, mode mismatch, polarization, …

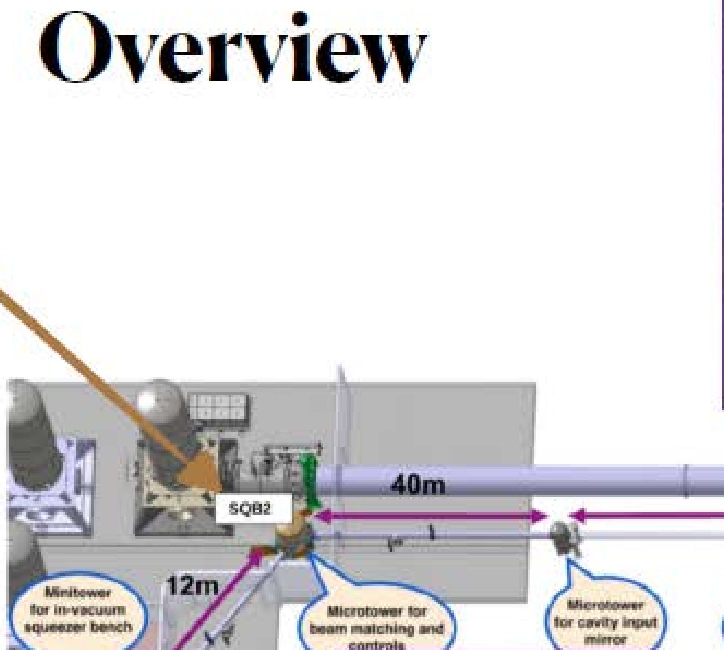
- **Filter cavity aligned and locked with green beam (June)**
- **Filter cavity aligned and locked with infrared beam (few days ago)**

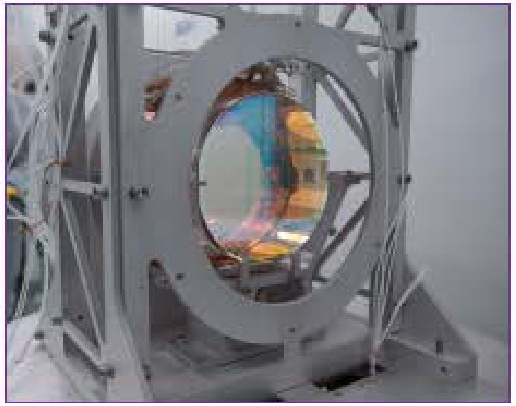


Next steps:

- Improve the control accuracy and noise hunting
- Aim to inject frequency dependent squeezing into interferometer by the end of 2021

Frequency Dependent Squeezing commissioning





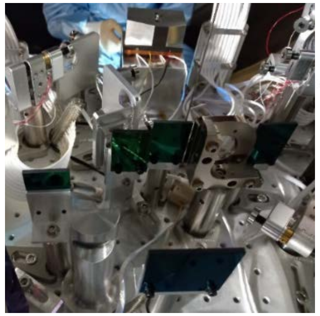
Other commissioning achievements (non-exhaustive list)

- **Improvement of the robustness of the Laser and injection system**
  - Problem of frequent fast unlocks solved after adding a second EOM as actuator

- **Scattered light noise mitigation**

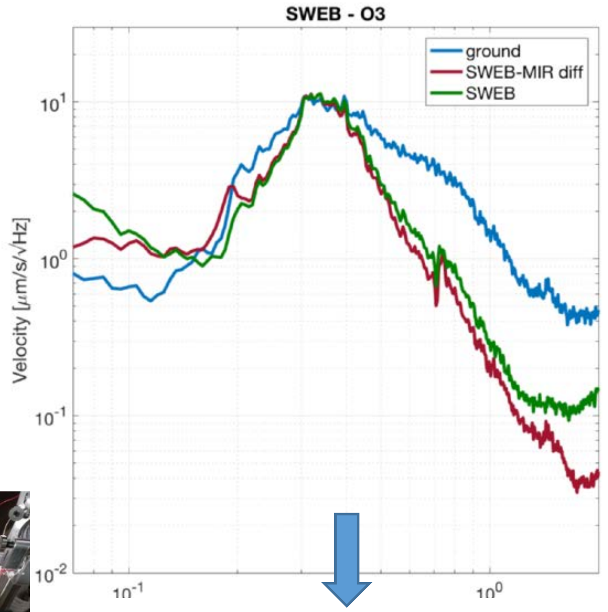
  - **Reduction of the residual motion between the suspended benches and the end mirrors**
    - Better sensors installed on the suspensions last year
    - Improvement of the control loops

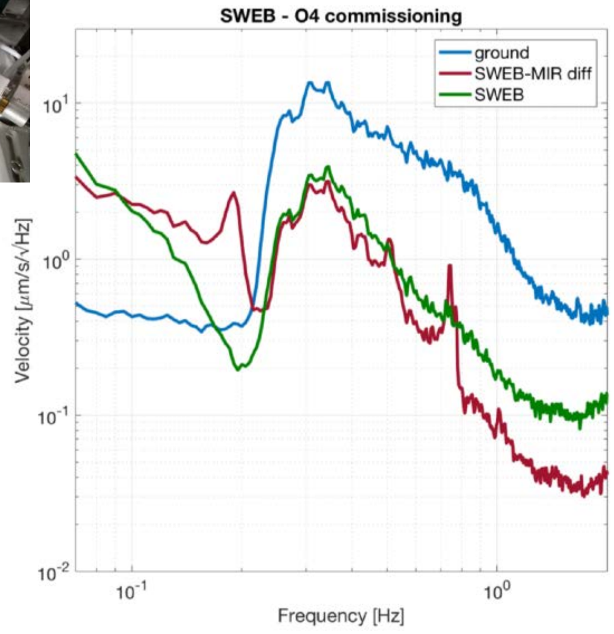
  - **Installation of absorbing glass beam dumps on the suspended benches**



- **Infrastructure noise hunting and mitigation**
  - Improvements and tests on the AHU air ducts in the terminal building
  - Slow down and optimization of the speed of AHUs fan and water pumps
  - Improved the seismic isolation and seismic decoupling of several HVAC system devices

- **Optical characterization of the interferometer**





Summary and next steps

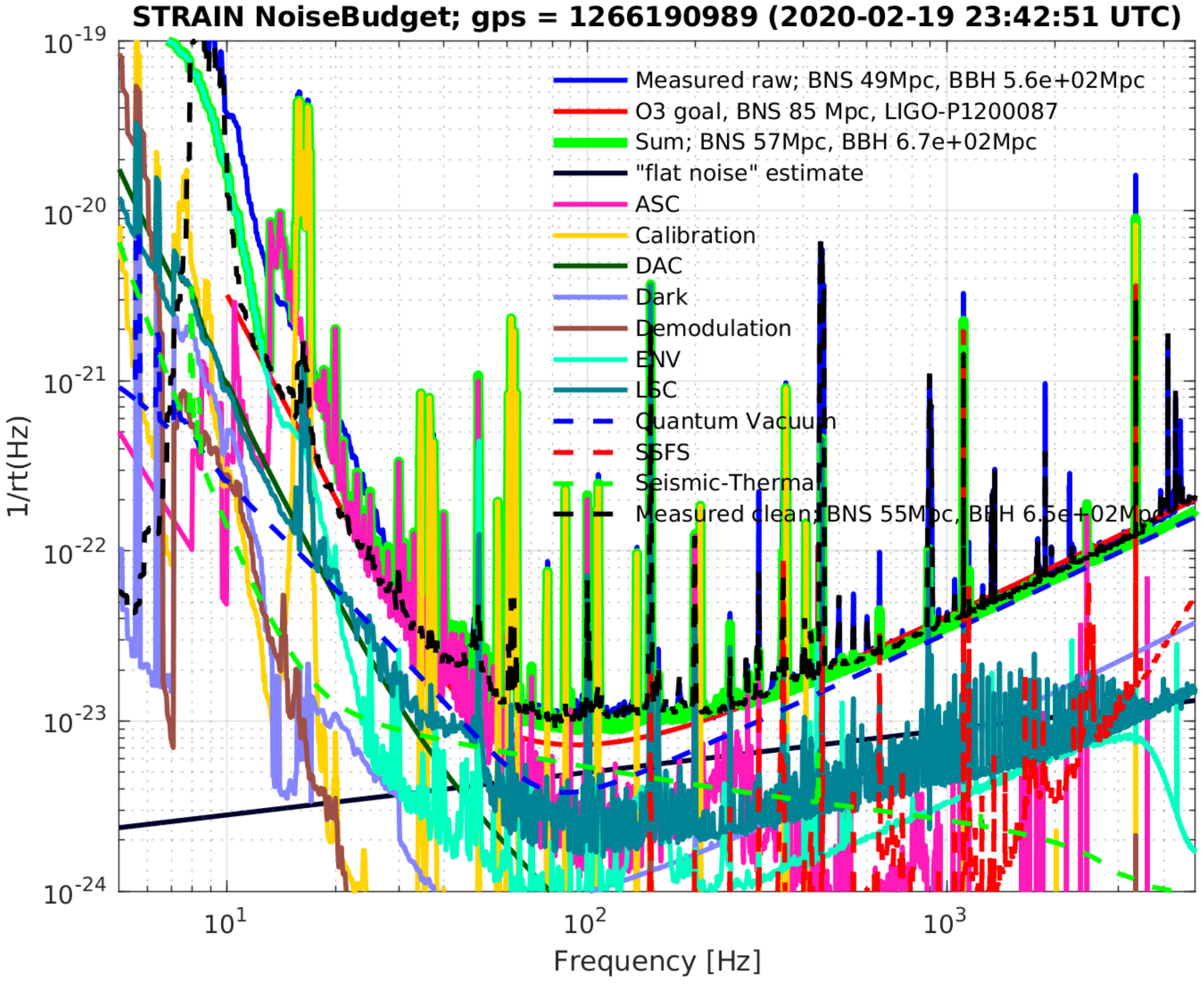
- **Lock of the full interferometer with 40W at dark fringe has been achieved** (but not yet the final working point)
- **Commissioning of the new Quantum Noise Reduction system in progress: filter cavity locked with green and infrared beams**

What's next:

- Finalize the tuning of the interferometer working point at 40W
- Bring the interferometer in low noise operation (DC readout for DARM control, low noise actuation, …)
- Produce the first sensitivity curve
- Intensify the noise hunting activities
- Inject frequency dependent squeezing into the interferometer

About noise hunting

Example of O3 noise budget



- Need to identify and solve dominating technical noises
- Starting with expected issues based on O3 experience:
  - control noises
  - electronic noises
  - scattered light noise

- Noise hunting will soon become the leading activity of the commissioning towards O4