Status of Advanced VIRGO+: Phase I and Phase II

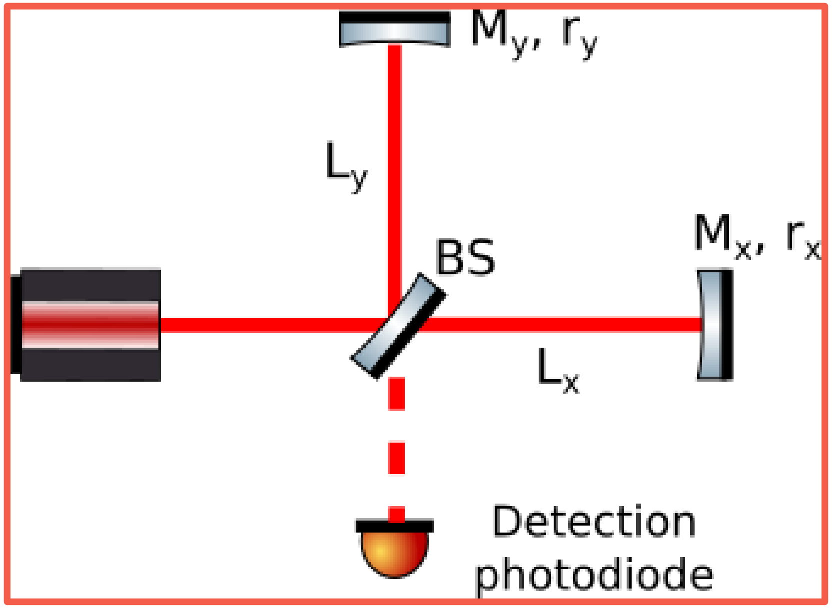
J. Casanueva for the Virgo Collaboration

1st generation of GW detectors: Virgo

- Gravitational wave detectors measure a differential effect on free falling masses
  - Michelson interferometer
  - Core optics suspended

Interference depends on the phase difference between the Michelson arms→ *sensitive to length difference*

Detect a change in the output power



Reach the **maximal sensitivity** → *maximize the SNR* at the detection photodiode

Figures of merit of the detector

- **Sensitivity**: minimum amplitude of a gravitational wave (h) that the detector is able to detect.
  - The target sensitivity of Virgo was of the order of 10^{-20} m.
- **BNS Range**: distance (in Mpc) at which a «typical» BNS (1.4 solar mass), averaged over all the possible orientations, would be detected by a single interferometer with a SNR of 8
  - This is used very often because it summarizes the detector performance in one single number

!

A simple Michelson doesn’t allow to reach such high sensitivities!

FABRY-PEROT CAVITIES

Optical resonator: allows light to circulate in a closed path

- **Resonance:** maximum power resonating inside the cavity

$$\Phi = 2 \cdot k \cdot L = N \cdot 2 \cdot \pi$$

$$E_{cav} = E_1 \cdot \frac{t_1}{1 - r_1 \cdot r_2 \cdot e^{2ikL}}$$

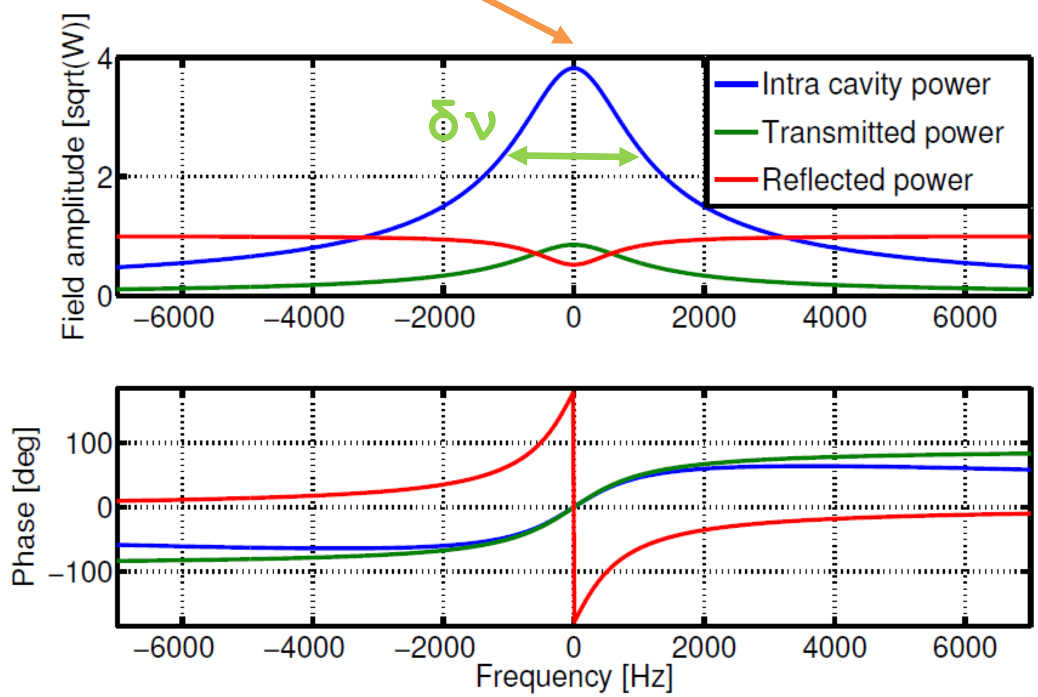
It depends on **k** and **L**!

- **Finesse:** quantifies the quality factor of the cavity

$$P_{cav} / P_{in} \approx 2 \cdot F / \pi = \text{Opt. Gain}$$

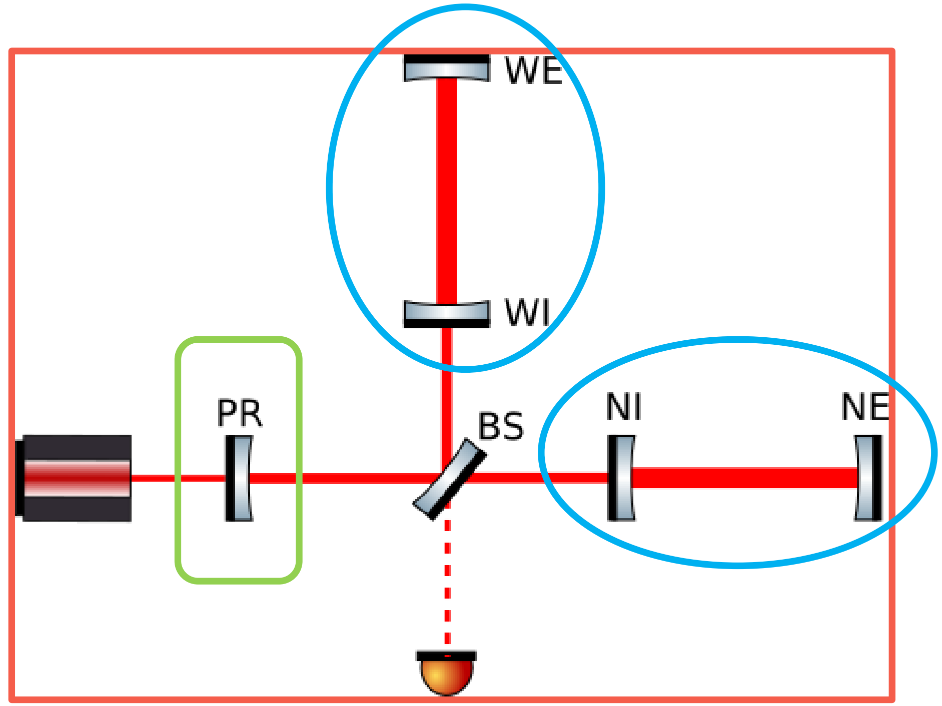
- **Linewidth:** FWHM of the resonance of the cavity

$$\delta\nu = c / (F \cdot 2 \cdot L) = FSR / F$$



VIRGO GRAVITATIONAL WAVE DETECTOR

- **Fabry-Perot cavities** in the arms -> increase the optical path
  - Optical resonators: the light is reflected back and forth
  - **Optical gain** of Virgo+ arm cavities ~100 → ~300 km!
- **Power Recycling Cavity** -> increase the circulating power
  - Recycles the light reflected back towards the laser
  - The sensitivity is improved by sqrt(OG_{PRC})

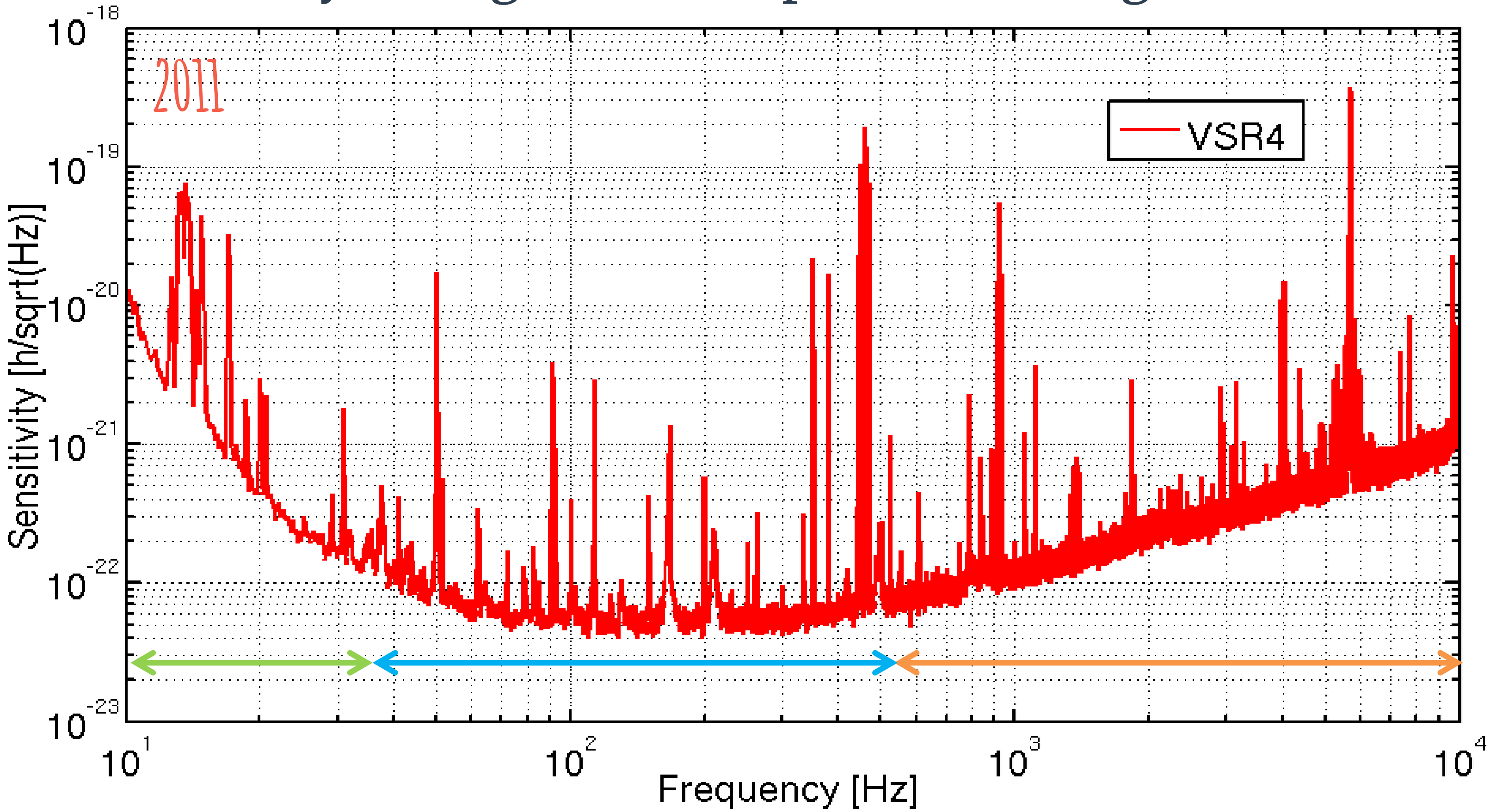


- Virgo project was approved in 1993
- Construction started in 1996
- Four Virgo observing runs, Last in 2011

VIRGO+ SENSITIVITY

1st generation of GW detectors didn't make any detection

- Best sensitivity of Virgo+ -> 12 Mpc of BNS Range



Thermal noise (suspensions)

Thermal noise (coating)

Quantum noise (shot noise)

2ND GENERATION: THE ADVANCED DETECTORS

THERMAL NOISE

- Monolithic suspensions
- Increase beam size @Cavity mirrors

Change of the geometry of the optical cavities -> **even more Marginally stable Recycling Cavities**

QUANTUM NOISE

- **Increase Optical Gain** of the arms (to 350) and the PRC (to 38)
- **Increase Input power ->** increase mirror mass
- **Frequency Independent Squeezing**

TECHNICAL NOISE

- DC Readout -> decrease readout noise
- Scattered light mitigation -> Suspended detection benches + vacuum

Marginally stable cavities

- An optical resonator is stable when it exists a Gaussian beam that can resonate inside it
- It depends on gemetrical considerations ONLY

$$g_1 = 1 - \frac{L}{R_1}$$
$$g_2 = 1 - \frac{L}{R_2}$$

$0 < g_1 g_2 < 1$

Recycling cavities are **marginally stable** ($1-g_1g_2 \sim 0.19e-5$)

What does it mean?

- HOMs (non-gaussian) resonate very close to the fundamental mode *-> almost degenerate cavity*
- Very sensitive to misalignments, mismatch and any optical aberrations
  - Optical losses, Offsets and Double-zero crossings in the error signals, variable optical configuration

(1) I. Nardecchia, Detcting gravitational waves with Advanced Virgo, Galaxies 2022

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WHAT CAN WE DO TO MITIGATE IT?

- Thermal Compensation System is critical to mitigate these effects
  - It *compensates for the optical aberrations* both cold (due to manufacturing defects) and hot (due to the increase of power)

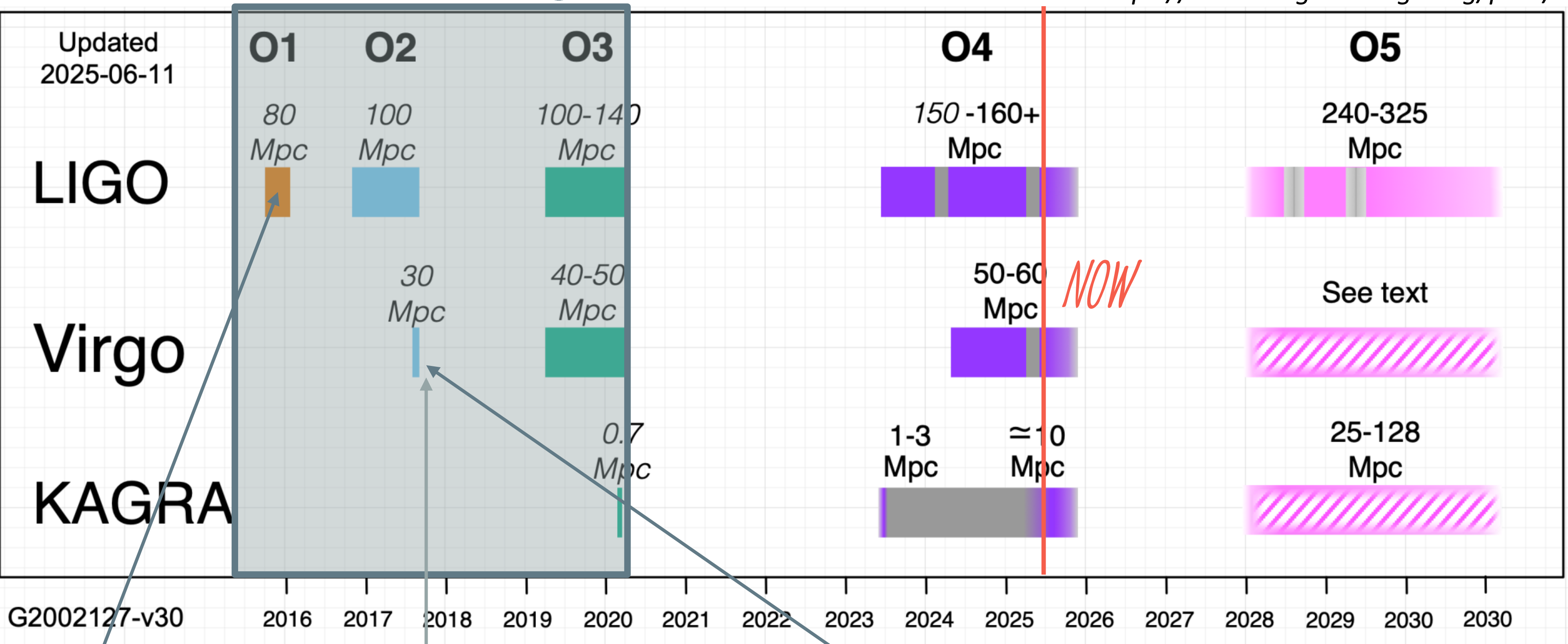
AdV TCS[1]

- **Ring heaters** in the test masses and the PR mirror
- **CO2 lasers** acting at the Input test masses (centrally and with a Double Axicon System)

Phases of ADVANCED VIRGO project

Advanced Virgo

https://observing.docs.ligo.org/plan/



14^{th} Sep 15

First detection of a GW

14^{th} Aug 17

First **triple** detection of a GW

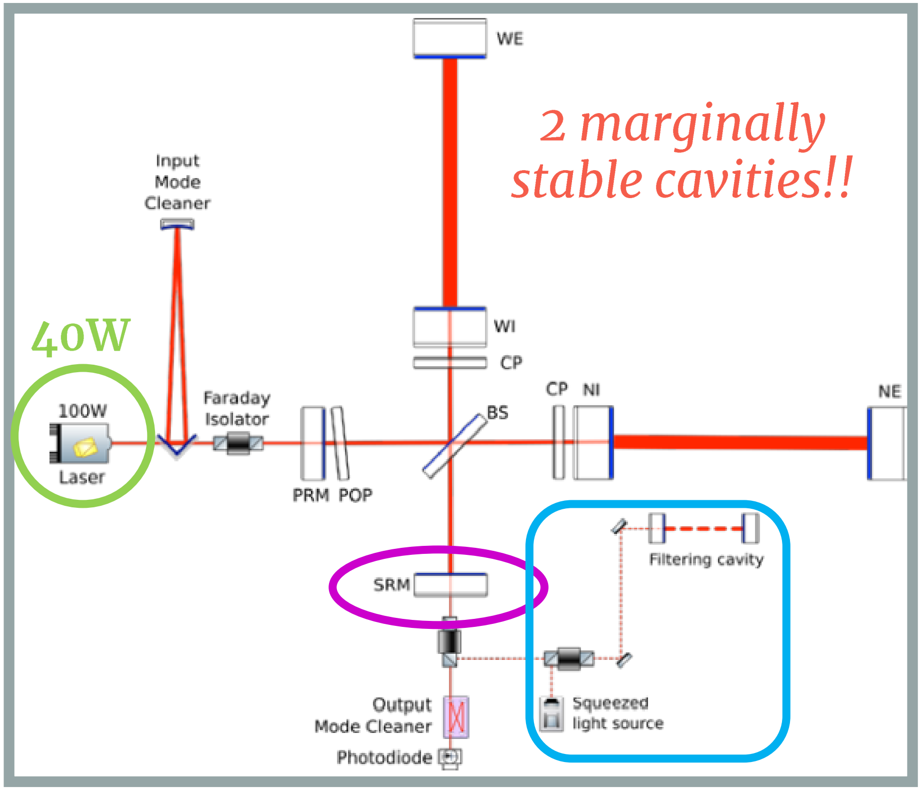
17^{th} Aug 17

First detection of a BNS with EM counterpart

Upgrades for AdV+ Phase I

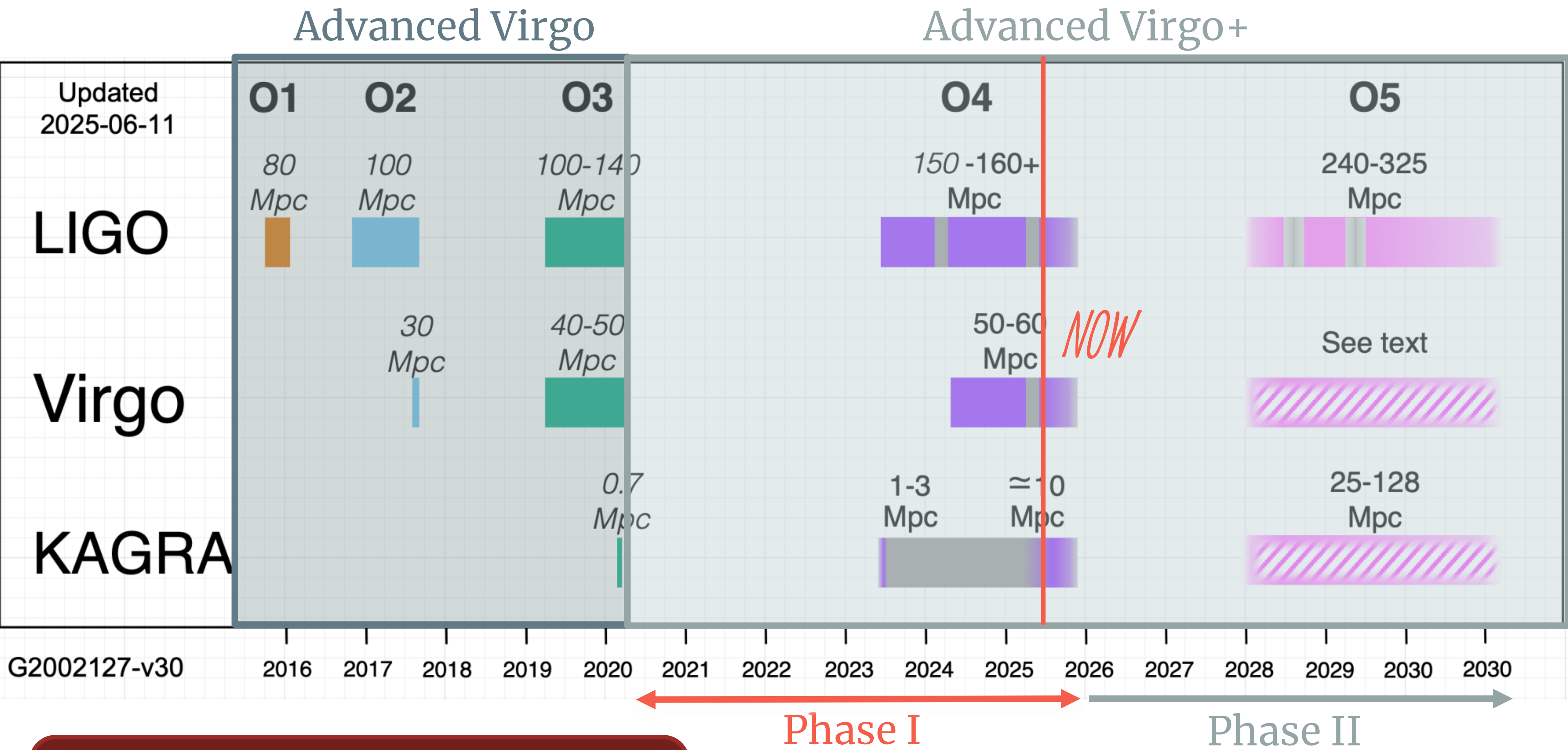
Advanced Virgo Plus Phase I – Design Report – Virgo Collaboration-VIR-0596A-19

- Signal Recycling Mirror installation
  - New cavity to shape the sensitivity
- Increase Input power
  - Up to 40W
- Frequency Dependent SQZ
  - Decrease further the quantum noise (broadband)



- Injection of Auxiliary Lasers at the end mirrors– for Double Recycling Cavities control
- Installation of diaphragms and baffles – for scattered light mitigation

PHASES OF ADVANCED VIRGO PROJECT

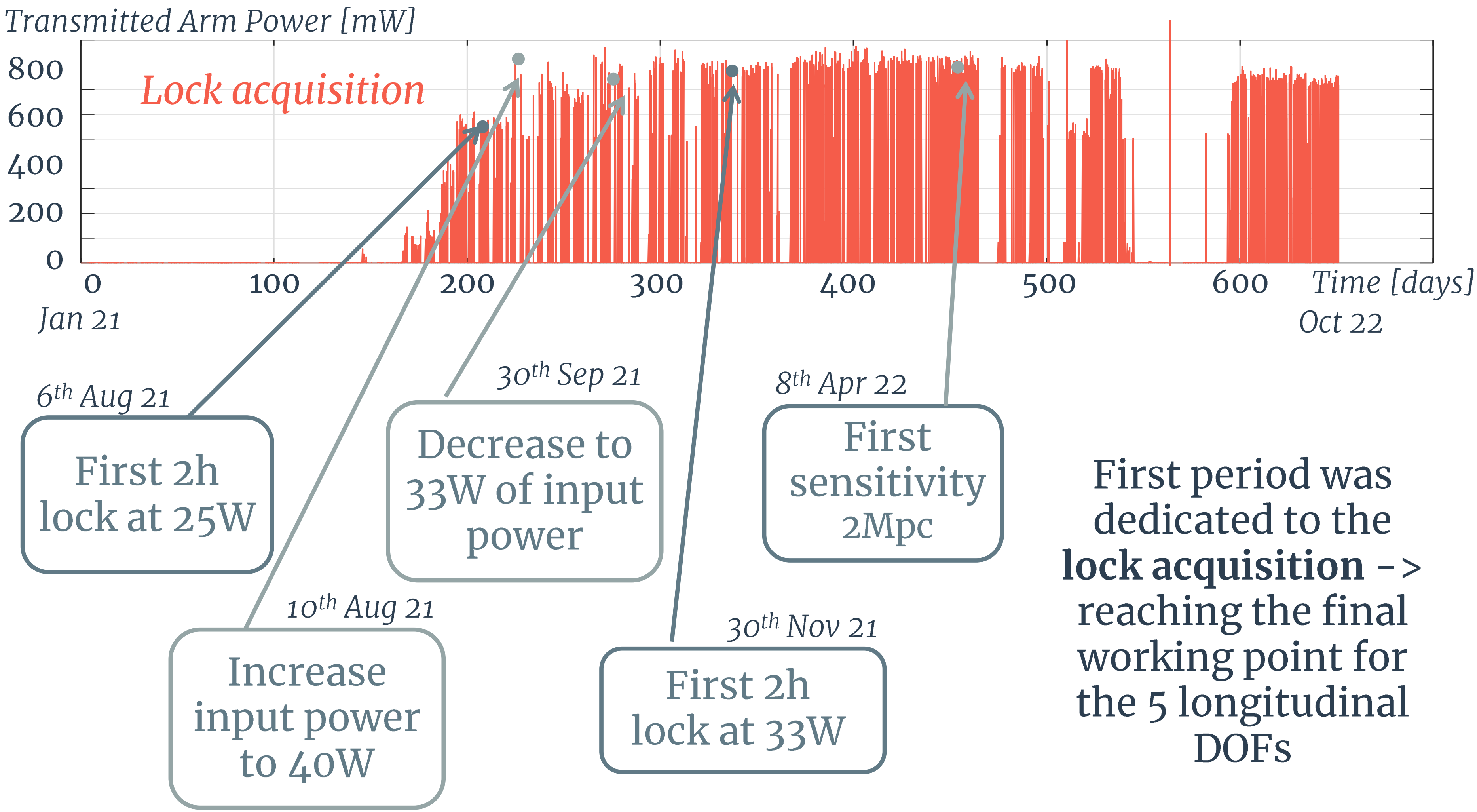


Installation + Commissioning lasted 4 years!

WHY?

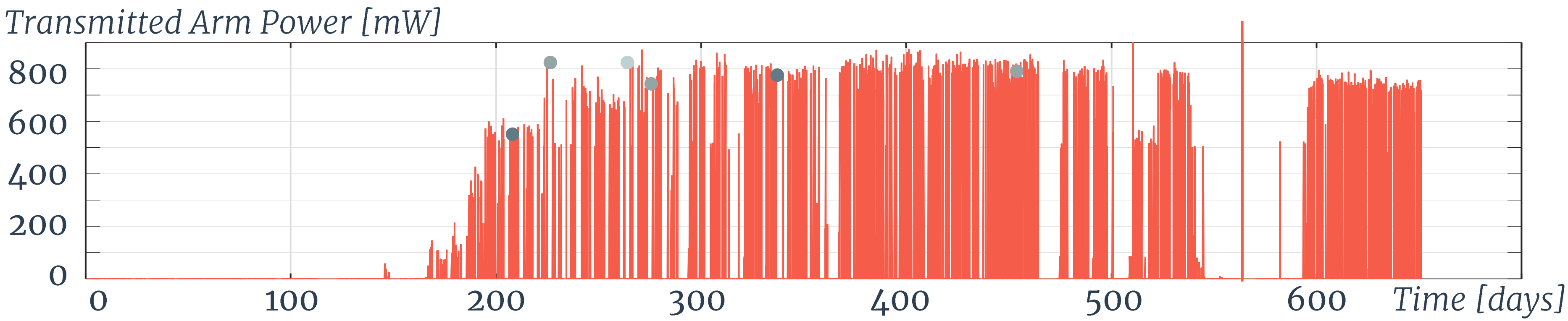
End of O4 run has been moved to the 16th of November 2025

Commissioning overview



First period was dedicated to the **lock acquisition** -> reaching the final working point for the 5 longitudinal DOFs

Commissioning overview



- Locks duration not consistent (few minutes to few hours) so it was difficult to perform proper characterization studies / measurements

1. We started to observe "jumps"

Bistabilities of the working point

2. Interferometer optical response was not as expected:

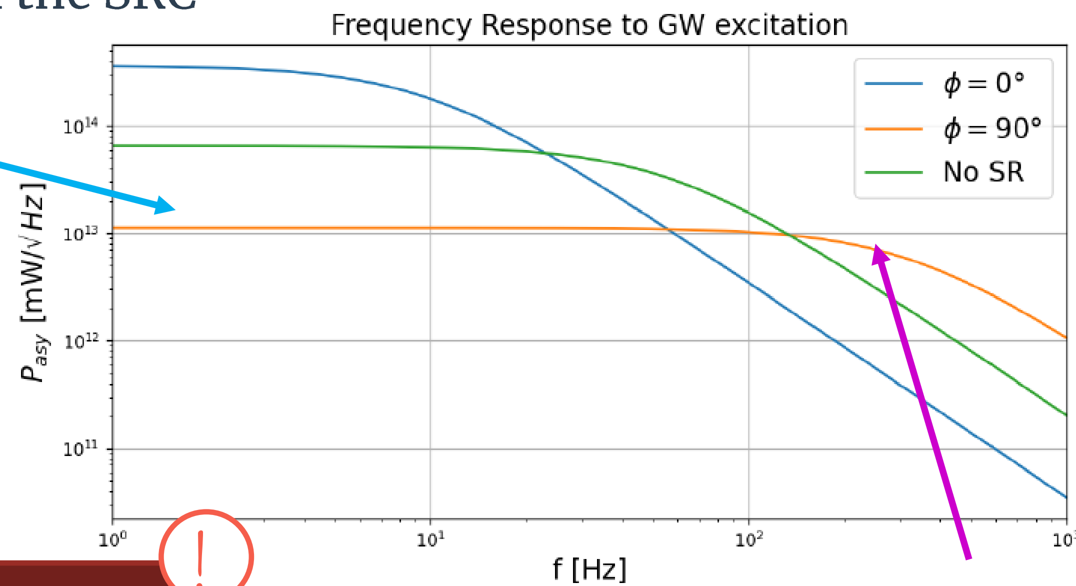
High Optical Spring (40Hz)
Low Double Cavity Pole (250Hz)

(1) M. Valentini,The longitudinal control for the Advanced Virgo+ gravitational wave detector, PhD, 2022

Interferometer optical response

- Interferometer optical response is differential -> depends on the Signal Recycling Cavity and the Differential length of the arms
    - **Broadband configuration**: Carrier beam resonant in the arms and anti-resonant in the SRC

Optical gain
-> as high as posible



!

ANY defect impacts directly the interferometer performance.
Even worse with the SRC!

Double cavity pole
-> as high as possible

(1) M. Mantovani, et al., The Advanced Virgo+ status, Journal of Physics: Conference series, Vol. 2429

(2) J. Casanueva, Status of Advanced Virgo+, GWADW, Isola d'Elba, 2023

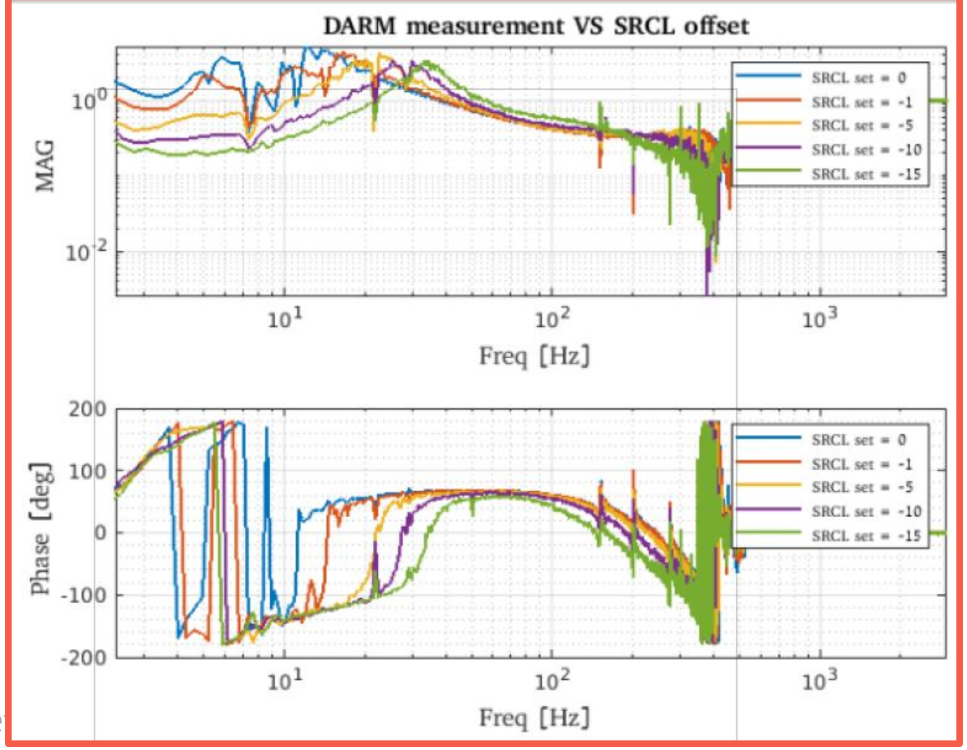
Recycling cavities mismatch

- **Optical Spring**: optomechanical effect that appears when cavity is off-resonance -> implies the existance of offsets in the error signals
- Low **Double Cavity Pole** implies high losses in the Signal Recycling Cavity
- **Bistable working point** implies a significant amount of HOMs

1. The PRM and SRM are mismatched by ~40m
2. The cold PRC is in the unstable region

Simulations of Interferometer response and LIGO's experience pointed towards **PRC and SRC mismatch** as the cause

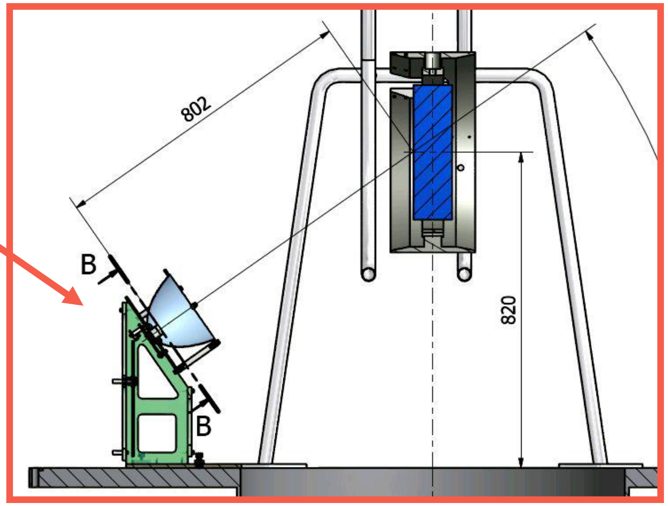
(1)

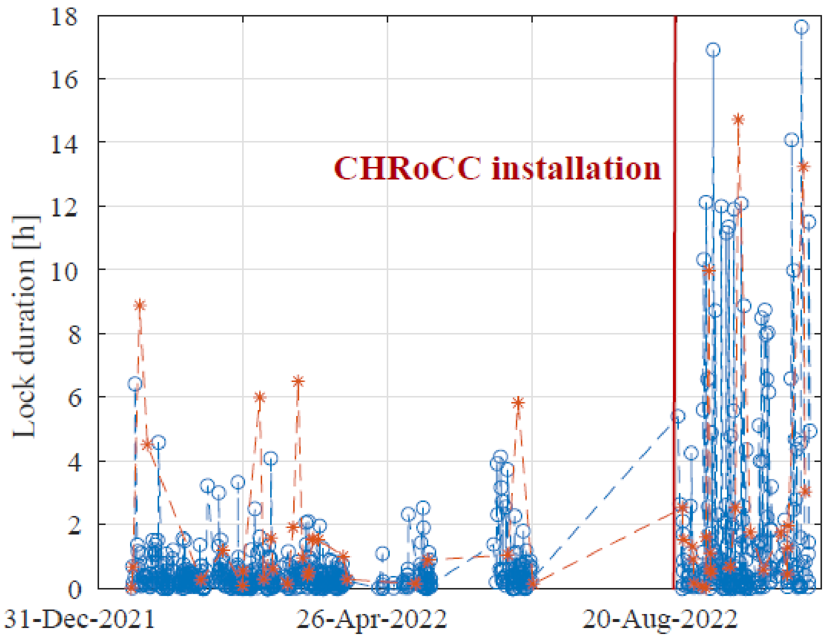


(1) M. Mantovani, et al., The Advanced Virgo+ status, Journal of Physics: Conference series, Vol. 2429

THERMAL TUNING

- Installed a heat source to shine in the PR mirror and modify its Radius of curvature to improve the matching and the stability

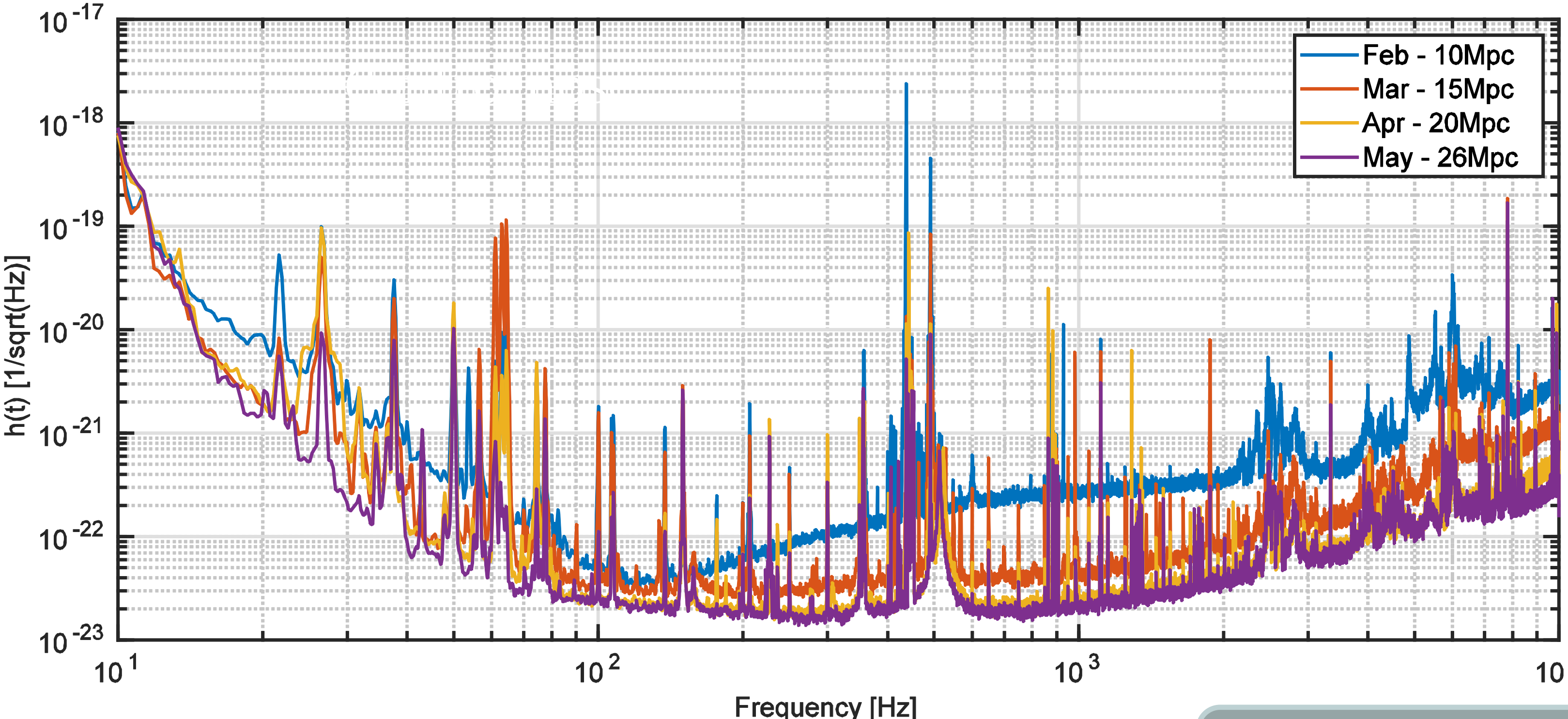




- The CHRoCC together with the other termal actuators allowed the first one-night long lock

How do we improve the sensitivity from 3Mpc?

Improving sensitivity



2023 Commissioning

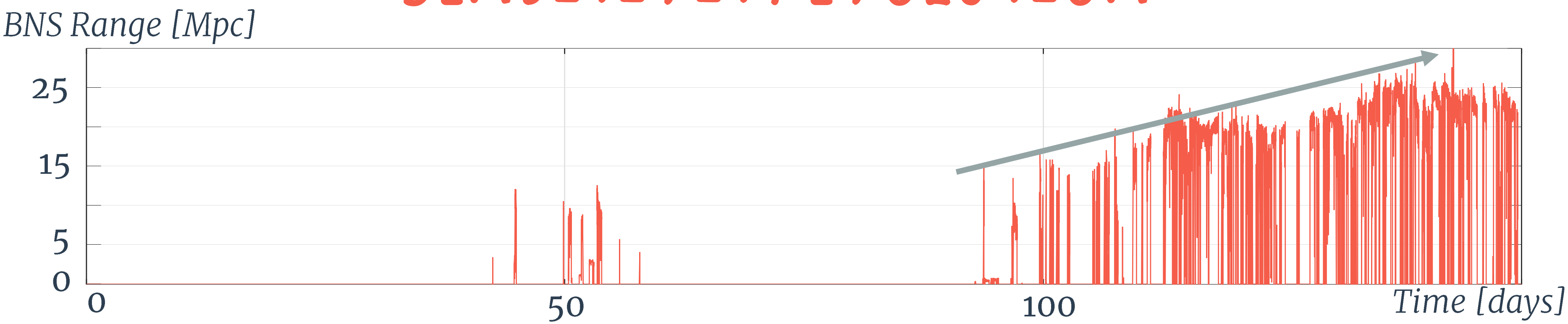
- The OMC had large optical losses -> Replace the OMC
- The fibered laser had high technical noise -> Put back the old laser
- RAMs subtraction, point absorber mitigation, new EOM...

WI fibers break

- Problem with a magnet!
- Power shortages

Sensitivity evolution

Only 26Mpc...



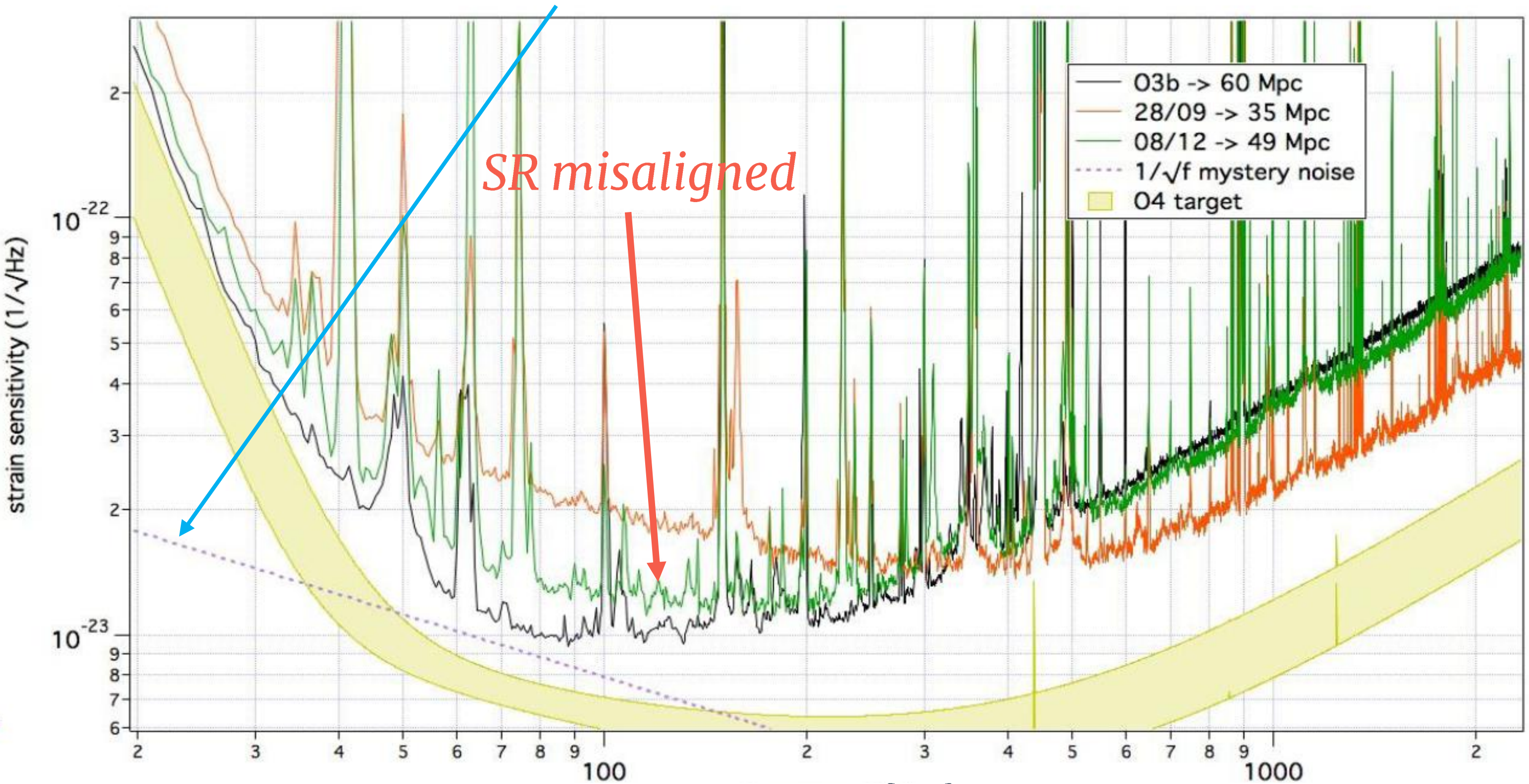
Tuning the working point

1. Reduce *coupling of the laser noise* -> by tuning the differential WP
2. Reduce and stabilize the *"symmetry" of the interferometer* (a.k.a. Common Mode Rejection Factor) -> by tuning the angular working point
3. Maximize the *Double Cavity Pole* -> by aligning the Signal Recycling Mirror
4. Minimize the *Optical Spring* -> by tuning the Signal Recycling Length

(1) F. Sorrentino, Report on the commissioning of the detector for the Virgo Council, VIR-1151A-23

NOISE HUNTING

- We focused on the noise hunting for the next months and we identified an *unknown source of limiting noise*



50 Mpc by the end of 2023!

We could maximize the BNS range by lowering the Double Cavity Pole in purpose -> SR misaligned

(1) E. Tapia, Mystery noise investigation update, VIR-0956A-24

LIMITING NOISE

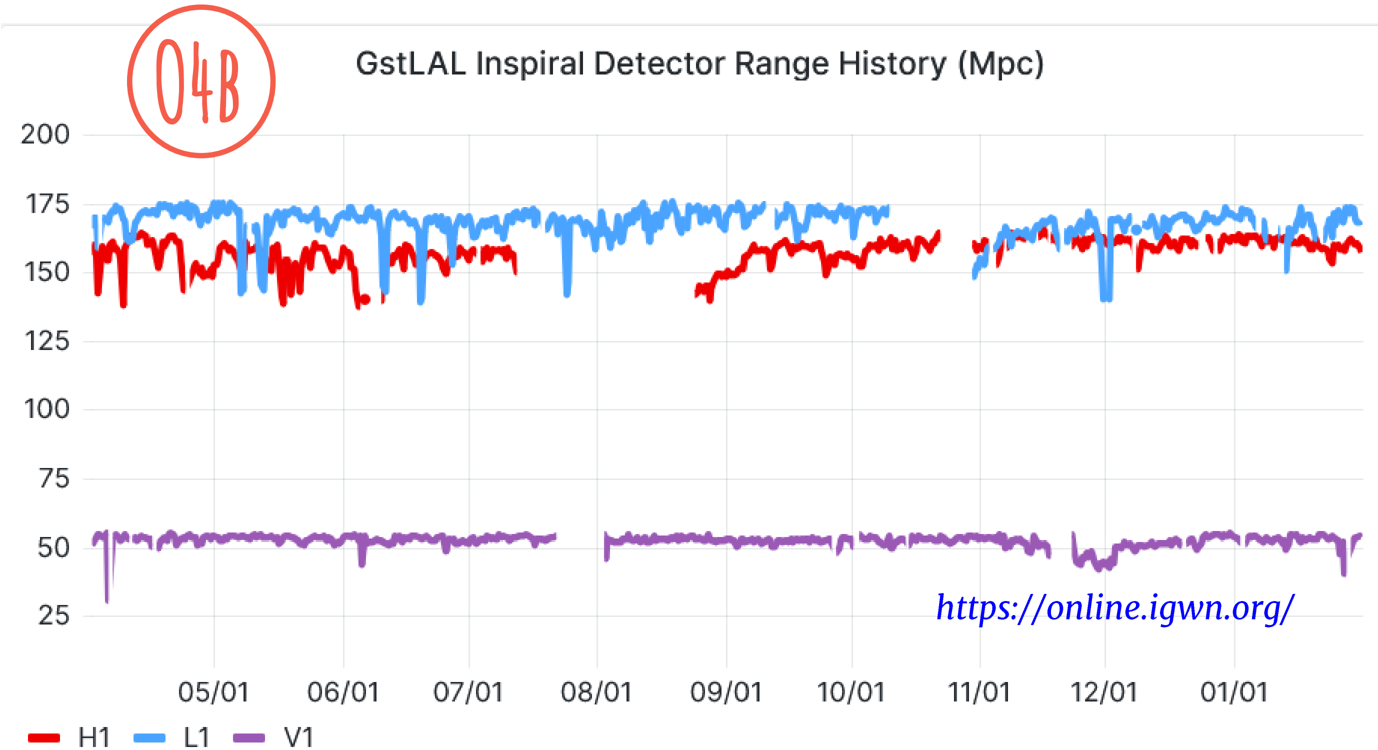
- As of today we haven't understood its origin, but we have spent a lot of time and effort in characterize it as much as posible[1]
  - It is the dominant contribution in the *20-100Hz region*
  - It has been measured as $1/f^{2/3}$ (precisely 0.66)
  - We managed to exclude few options: OMC noise, termal noise from test masses, displacement noise, polarization fluctuations on the interferometer or the detection Faraday isolator, sidebands amplitude noise, quantum noise, electronics noise of different kinds.

This implied months of tests and changes in the input power (including the correpsonding termal tuning)

Even during the Observing run we continue doing tests trying to understand its origin -> dedicated research group

O4 RUN

- Divided in 3 periods:
  - *O4a: May 2023- Jan 2024 (LIGO only, 53% joint obs. 2/2 detectors)*
  - ***O4b: April 2024 – Jan 2025** (LIGO and Virgo, 34% joint obs. 3/3 detcetors)*
  - *O4c: Jan 2025 – Present (LIGO, Virgo and KAGRA)*



https://online.igwn.org/

O4 is planned to last until 18 November of 2025

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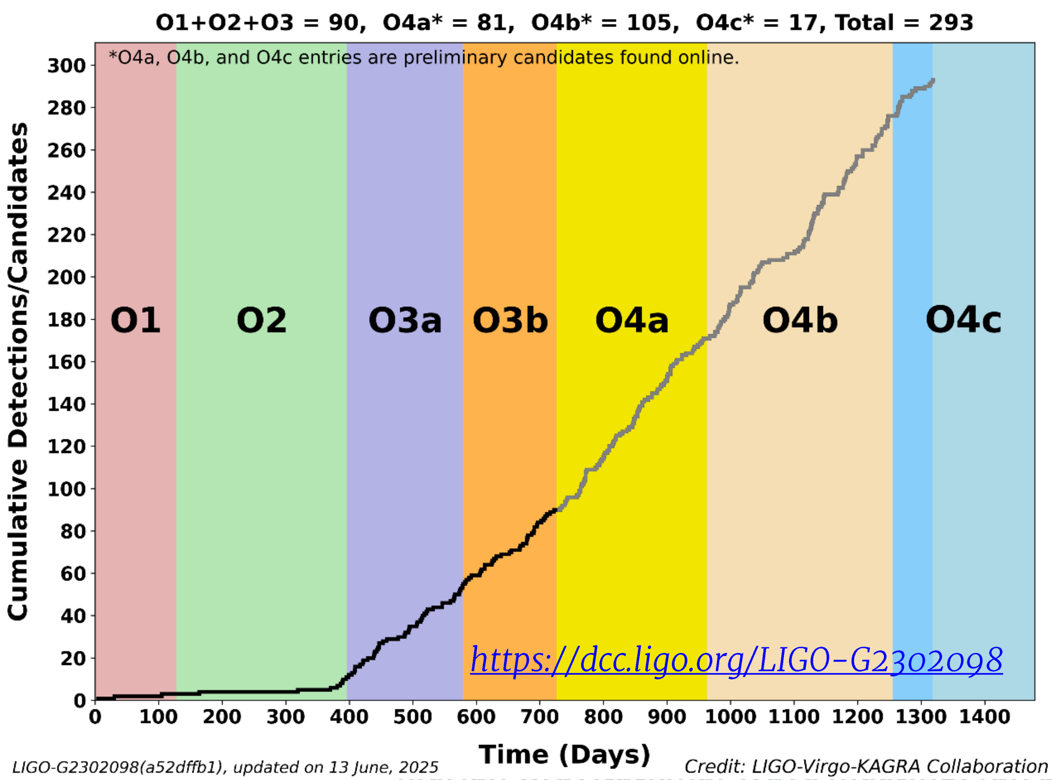


- O4 significant detection candidates: **203** (228 Total - 25 retracted)
- 04 Low significance detection candidates: 3845 (Total)

Advanced Virgo+: Phase II

- We are currently finalizing the review of the technical studies on the possible upgrades for Phase II
  - The main target is to enhance the **sensitivity up to 100Mpc** while operating the detector in a reliable way
  - This is only possible with stable cavities
- The decision of the final set of upgrades that will be implemented is still under discussion -> more information on July

Main upgrade due to its complexity and impact on the detector optical configuration -> **Stable Recycling Cavities**

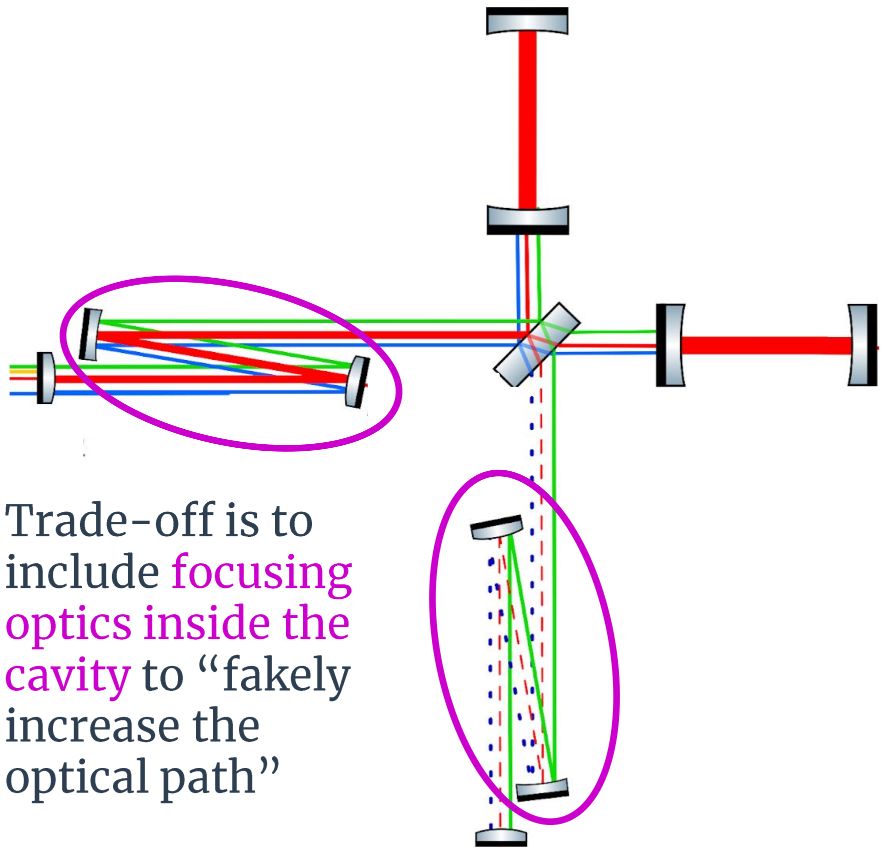
Stable cavities

$$g_1 = 1 - \frac{L}{R_1}$$
$$g_2 = 1 - \frac{L}{R_2}$$

- In order to increase the stability of the recycling cavities it is necessary to increase the length (R_2 is fixed!)
  - Not enough space for making it linear!

Infrastructure and Hardware

- Replace the vacuum tubes and towers to contain the new optics (different sizes!)
- Re-shuffle the detection benches
- New design for the suspended optics
- New mirrors



Trade-off is to include focusing optics inside the cavity to "fakely increase the optical path"

New optical configuration

- PRC and SRC are 35 and 38 m
- Same optical gains
- Gouy phase around 19 degrees

16m more!

Less than 1deg now!

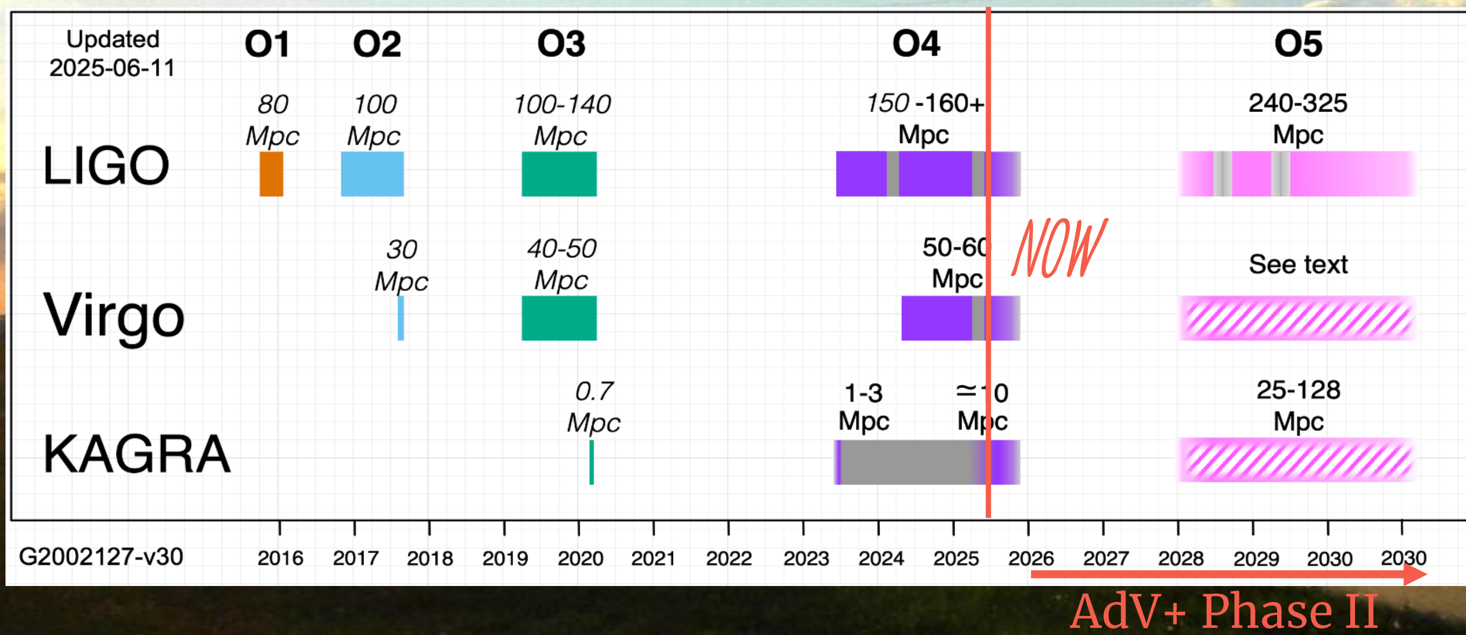
LIGO and KAGRA have similar designs

Advantages

- HOMs will be much more filtered -> less losses, smaller offsets in error signals and no bistabilities
- Less sensitivity to optical aberrations -> easier to increse the input power
- Better alignment error signal for the SR mirror

Major improvement in robustness which directly translates into easier commisisoning!

Next Steps: Phase II



- Works for the upgrades will start at the beginning of 2026
- The target sensitivity for O5 will depend on the set of upgrades installed