# VIRGO: STATUS AND FUTURE PROSPECTS

THE VIRGO PATH TOWARDS O4, O5 AND THE POST-O5 ERA

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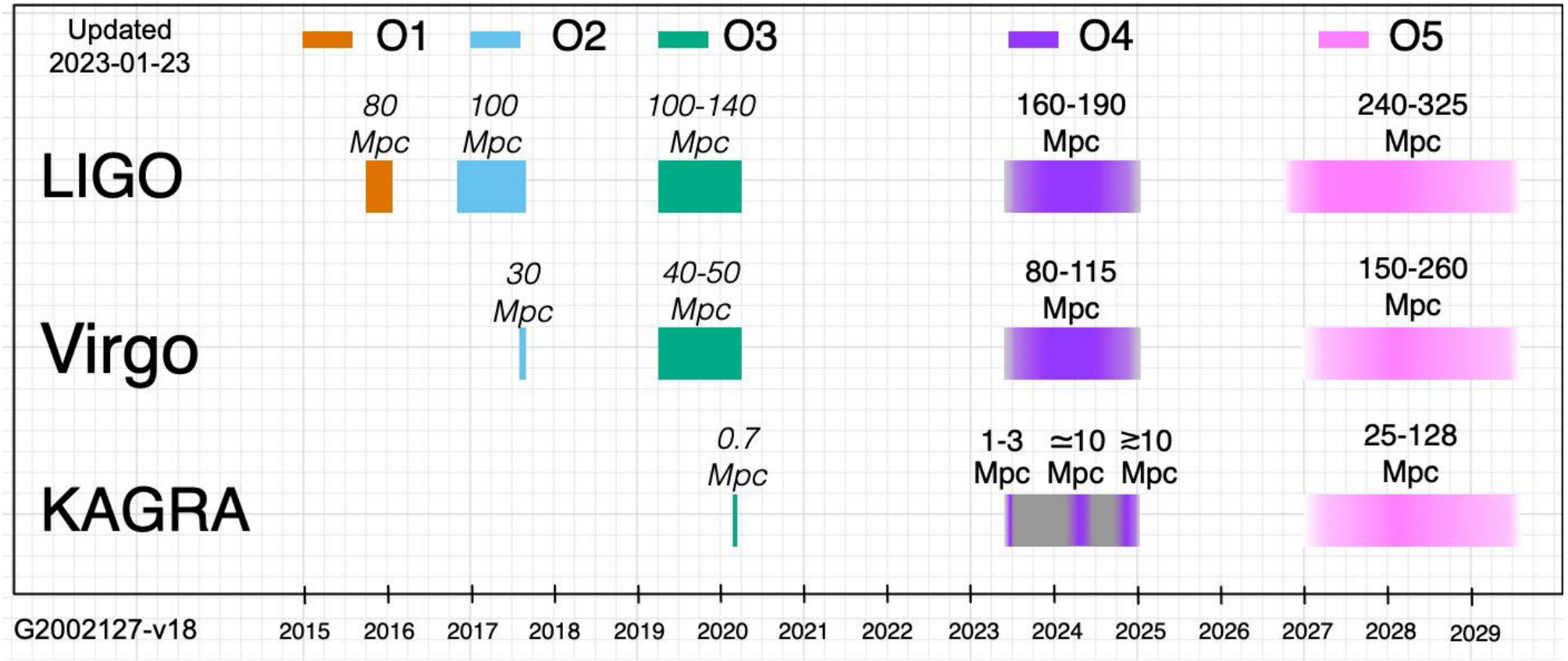
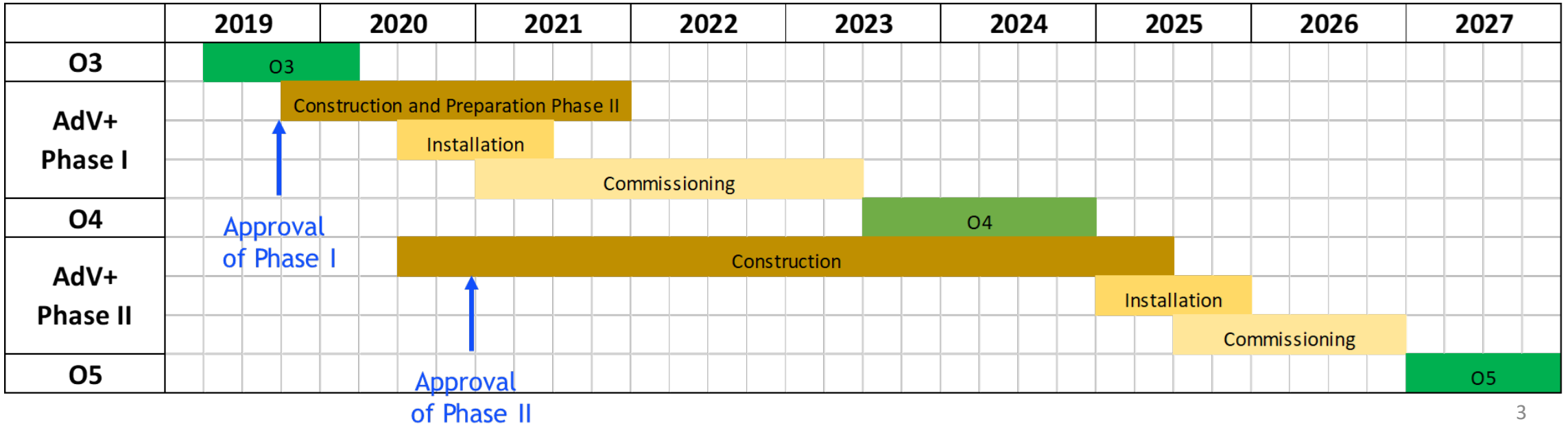
# VIRGO UPGRADES AND OBSERVING RUNS

Advanced Virgo configuration(s) → AdV+ Phase I → AdV+ Phase II → Virgo_nEXT concept



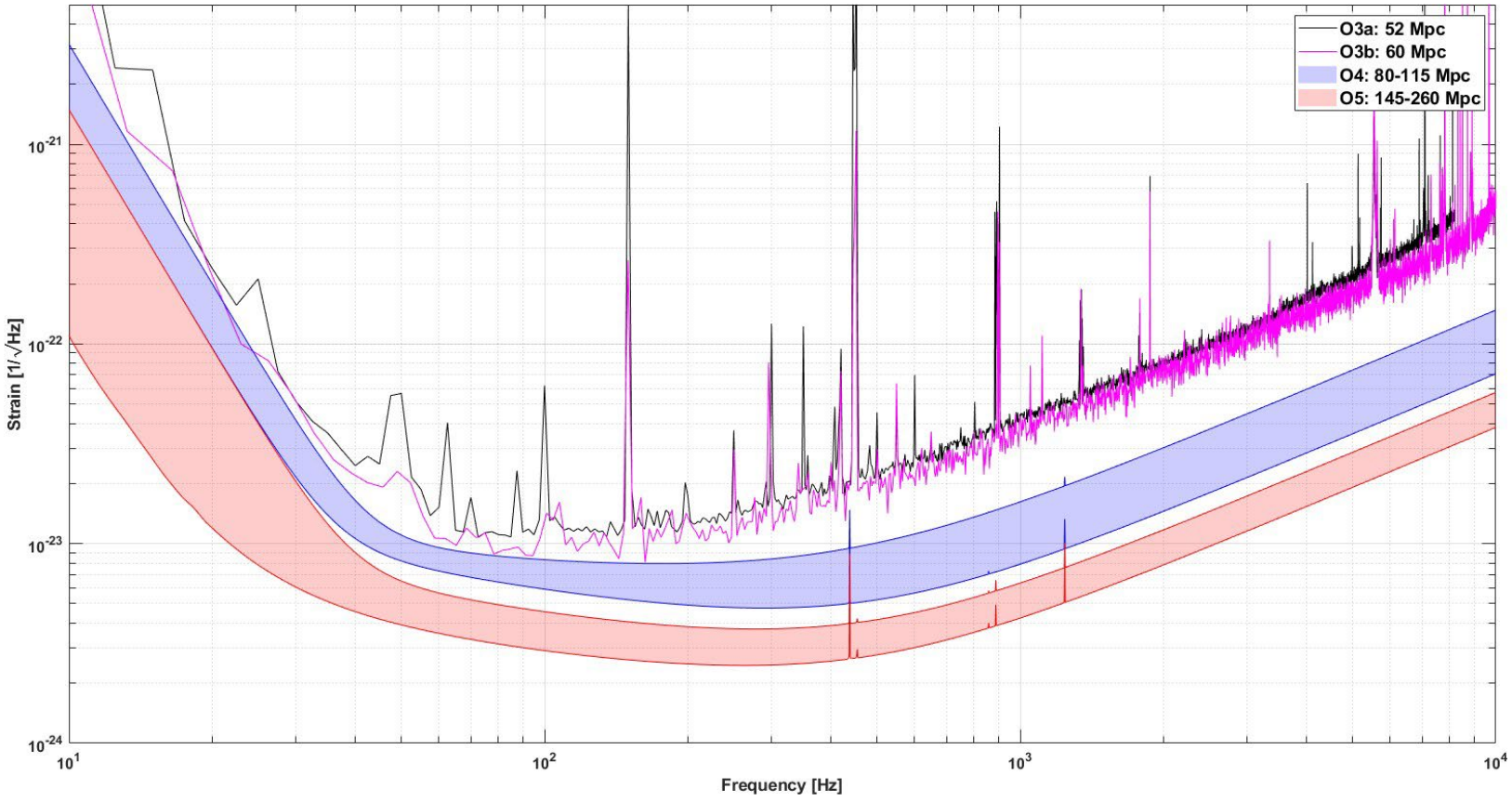
# ADV+: A TWO-PHASE UPGRADE

- Phase I (before O4 run/2023-24)
  - Mainly an upgrade to reduce quantum noise: no mirrors change
  - Reduction of technical noises
  - Preparation of Phase II
- Phase II (before O5 run/2027-28)
  - More invasive upgrade to reduce thermal noise: mirrors change

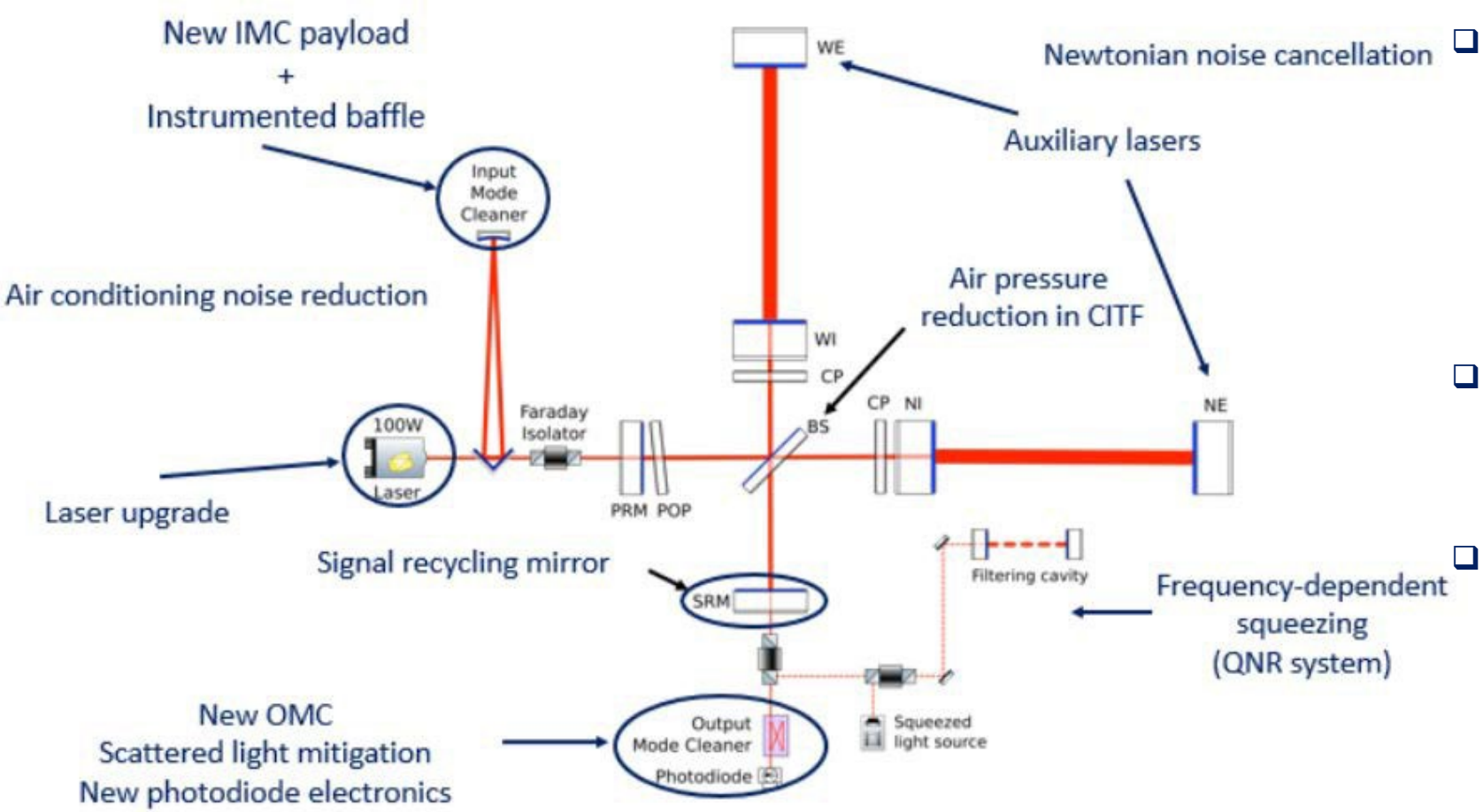


# ADV+ DESIGN SENSITIVITY

- Phase I: reduce quantum noise, hit against thermal noise
  - BNS range ~ 100 Mpc
- Phase II: lower thermal noise wall
  - BNS range ~ 200 Mpc



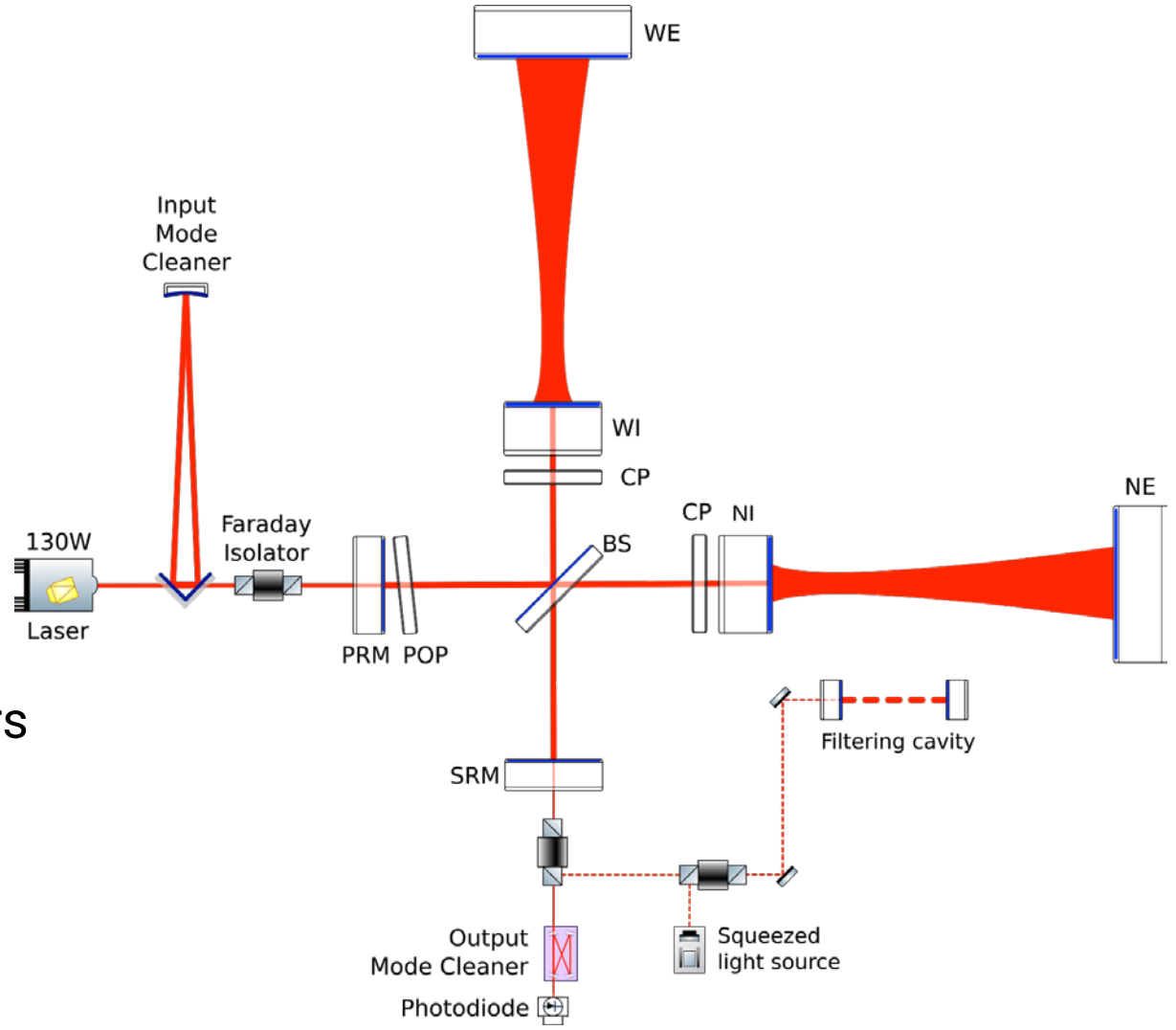
# ADVANCED VIRGO+ PHASE I




- Installation within a year despite pandemic
  - Main interferometer complete in December 2020
  - Quantum noise reduction system complete in April 2021
- Commissioning
  - Started in January/May 2021 for main ITF/QNR system
- Two aspects fundamentally new (in Virgo)
  - Signal recycling
  - Frequency-dependent squeezing

# ADVANCED VIRGO+ PHASE II

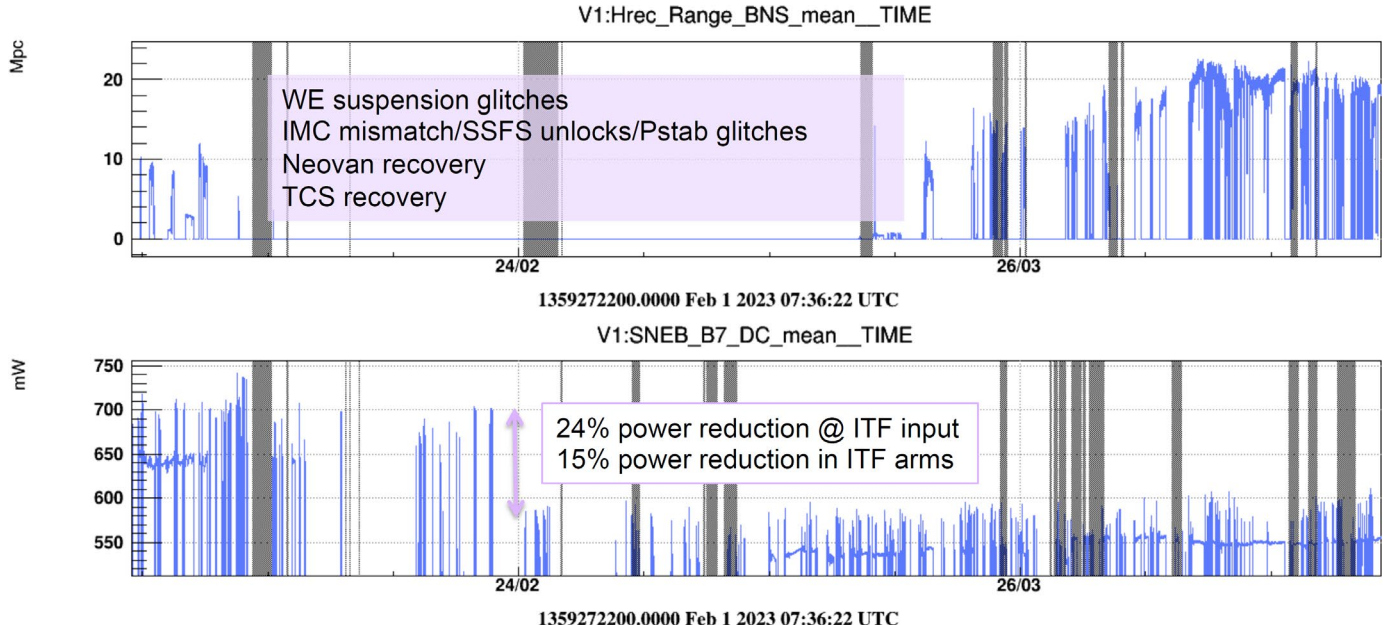
- Larger beams on end test masses
  - 6 cm radius ⇒ 10 cm radius
- Larger end mirrors
  - 35 cm diameter ⇒ 55 cm diameter
  - 40 kg ⇒ 100 kg
- Better mirror coatings
  - Lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of laser power
  - 40 W ⇒ 60 W ⇒ 80 W



# THE (VERY STEEP) PATH TOWARDS O4

# STATUS

- Stable and reproducible control of interferometer mostly achieved in fall 2022, after
  - Lowering input power from nominal 40 W to 33 W (further reduced to 23 W in Feb 2023)
  - Installing new thermal actuator to correct power-recycling mirror curvature
  - Learning to deal with signal-recycling cavity with resonating higher-order modes
    - Due to Virgo specific optical configuration: marginally-stable PR and SR cavities
- Many issues since then…



# MAIN ISSUES IN PAST MONTHS

- Failure of one test-mass payload

- Laser amplifier excess noise spoiling high-frequency sensitivity
  ➔ O3 laser amplifier restored

- Complexity from degeneracy of recycling cavities (see VIR-0047A-23)
  - Optical offsets in interferometer control signals
  - Excess of power on dark fringe before output mode-cleaner (contrast defect ~$10^{-3}$)
  - Usual figures-of-merit (e.g., sidebands recycling gain) not fully reliable
  - Issues in interferometer alignment reproducibility
  - Difficult fine-tuning of thermal-compensation system

  ➔ Input power further lowered to 23 W (Feb 2023)

- Mirror thermal noise higher than expected

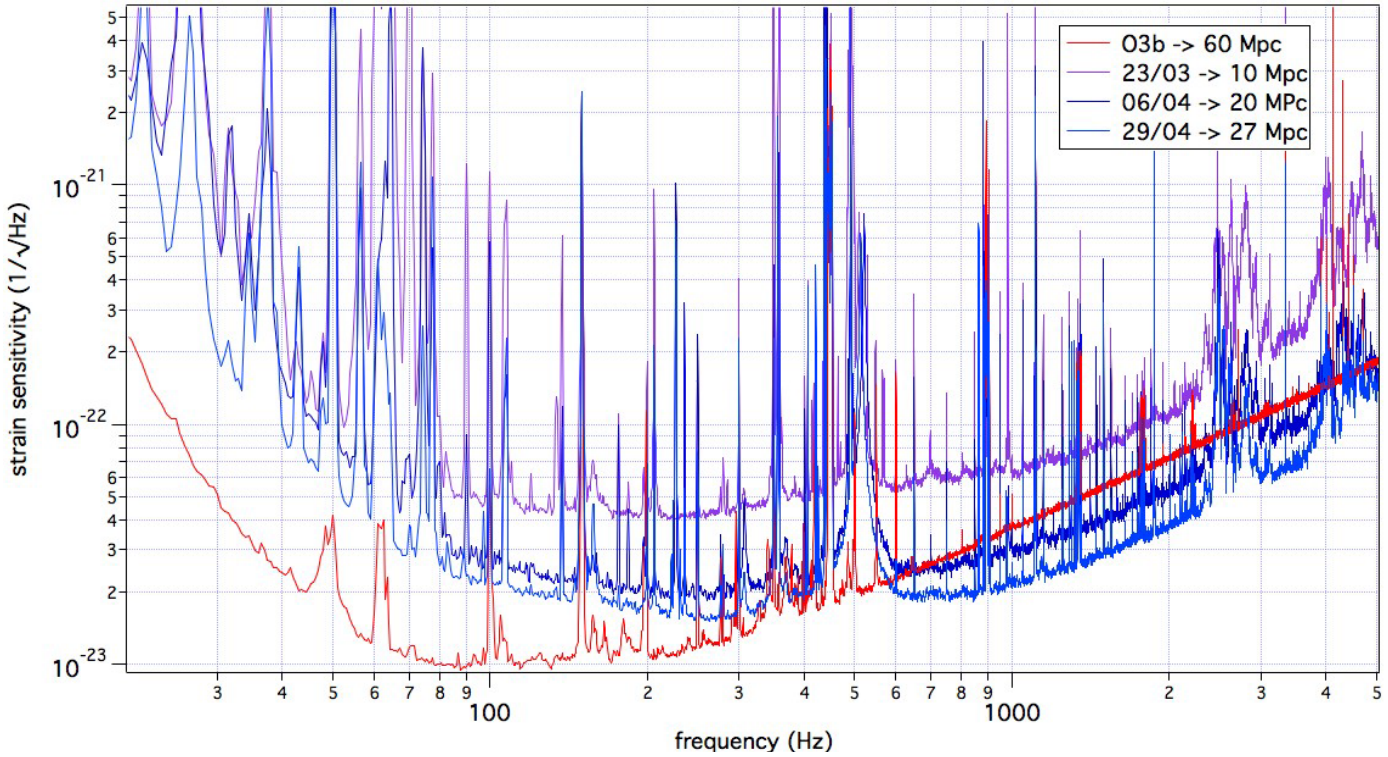
- …

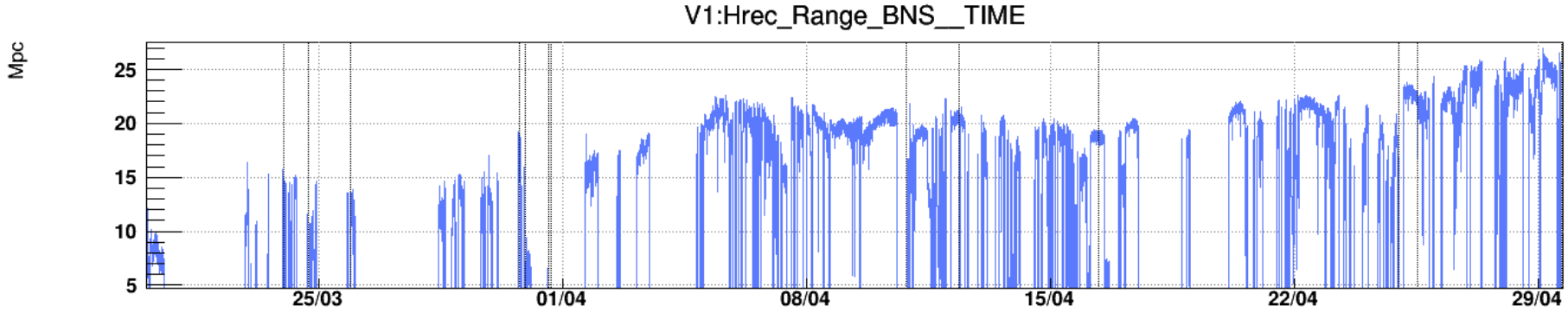
# WEST-INPUT PAYLOAD INCIDENT

- Vacuum chambers of four cavity mirrors vented in Nov 2022
  - To prepare point-absorbers mitigation-system installation
- Fused-silica fibers of West-input mirror broke during venting
- Problem already experienced 6 times in 2015-2016 (+ 2 during tests)
  - Understood to be due to small particles hitting fibers during venting/pumping
  - Solved by installing protections around fibers and changing pumping/venting layout
    - No failures since monolithic-suspensions re-installation in 2018
    - 2 full ventings and 4 low-pressure ventings done since then
- Payload dismounted, repaired and reinstalled in less than 2 weeks
- Additional protection prepared and installed before payload reinstallation

# GOOD PROGRESS NEVERTHELESS

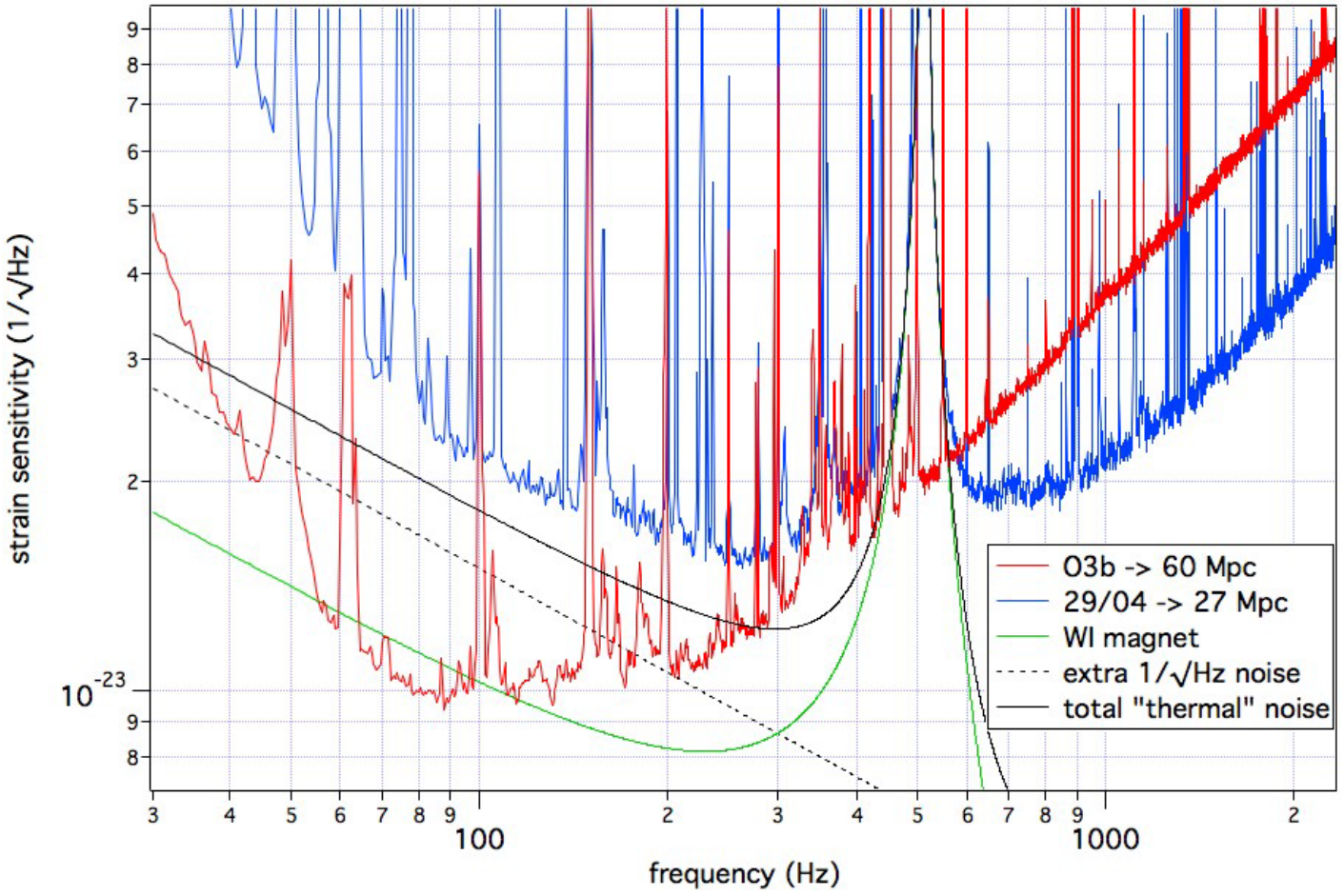
- Stable, automated lock in low-noise 2
- Progress on sensitivity
  - Several technical noises reduced
  - Better than O3 at high frequencies
    - O3 sensitivity crossed @ 350 Hz
    - Shot noise reached above 600 Hz
    - 1 dB of squeezing above 600 Hz
- But best BNS range ~27 Mpc



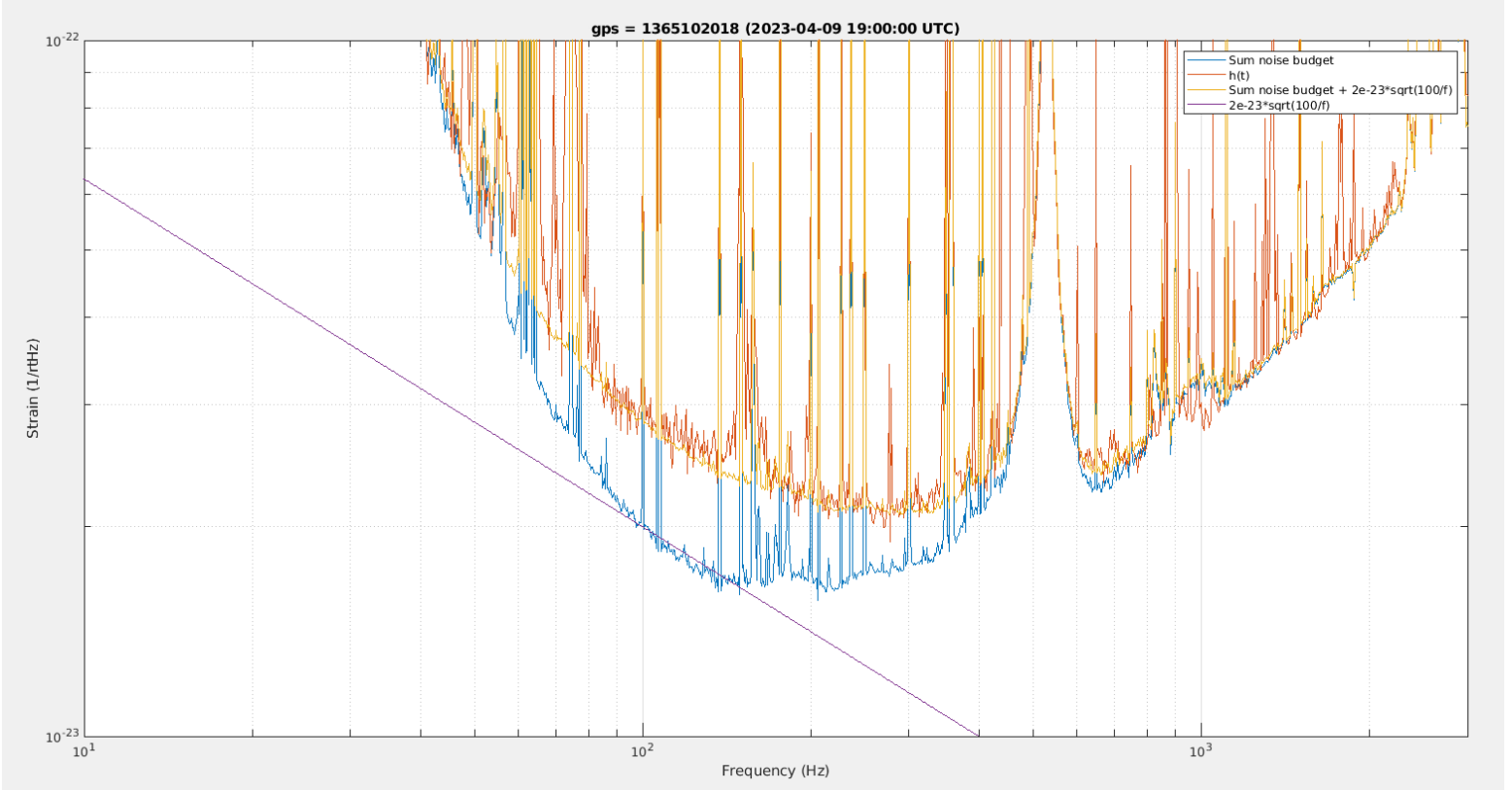
# EXCESS THERMAL NOISE: DAMAGED WI MIRROR MAGNET

- Loose magnet on WI mirror
  - A consequence of WI payload failure in November
- Broad ~500 Hz resonance can be fit with thermal noise model
- Can explain part of the measured noise but not all
- Simple model and FEM agree



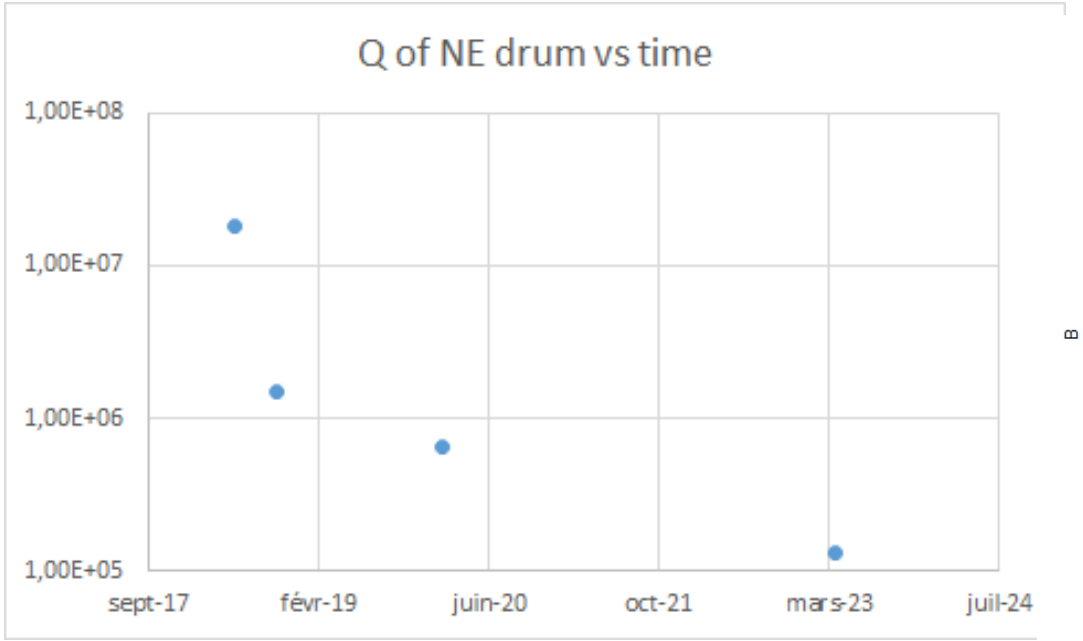
# EXCESS THERMAL NOISE: NORTH END MIRROR

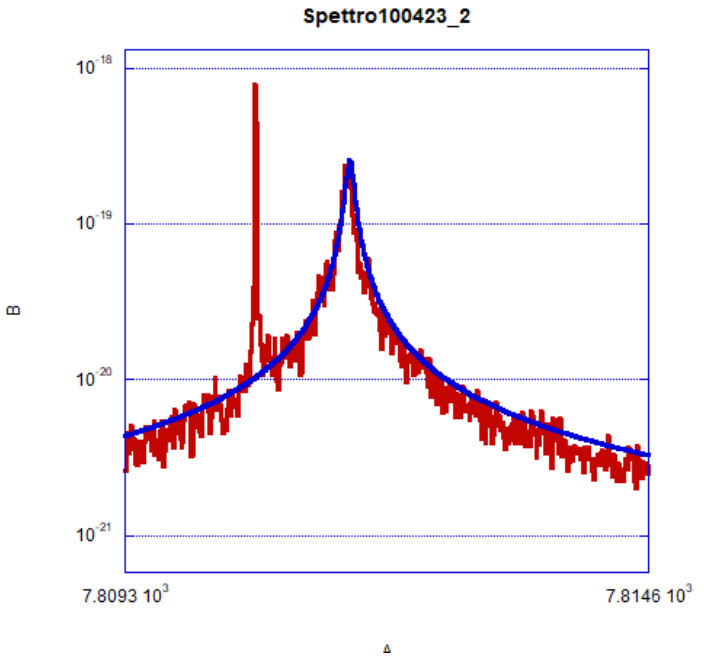
- Evidence of a (stable) 1/√f noise
- Bulk and violin modes of 4 test masses measured
- Hints that one mirror is producing excess thermal noise
  - Currently suspecting increased dissipation on NE bulk modes
- Significant limit to reach O4 target sensitivity

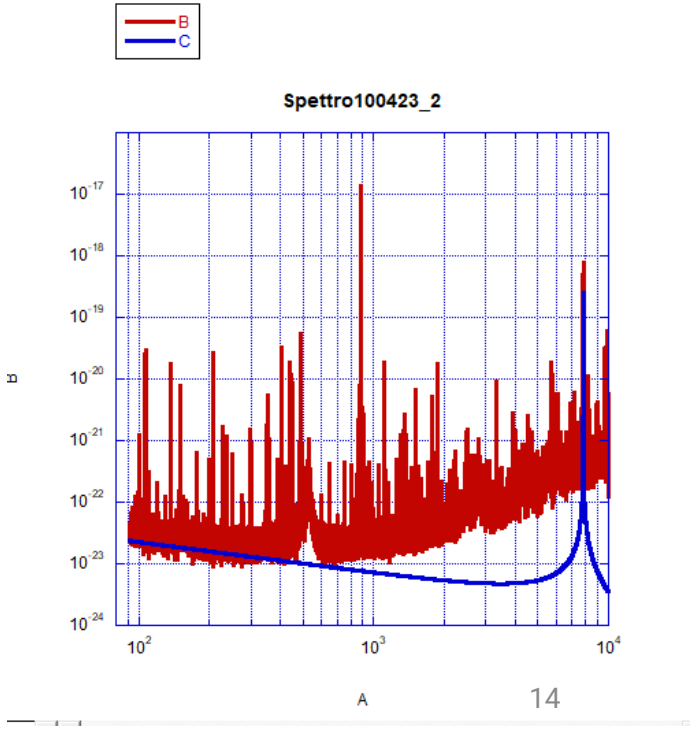


# EXCESS THERMAL NOISE: NORTH END MIRROR

- Since the NE mirror has been installed in 2017, its quality factor has decreased
  - Highest Q of the first few drum modes is about 2.5E5
  - The Q of the first drum mode is 1.3E5
    - To be compared to 2E6 for WI and more than 1E7 for NI and WE
  - Upper limit of NE mirror thermal noise cannot exclude observed noise
    - However this is an upper limit



# CONSEQUENCES FOR O4

- Marginally-stable recycling cavities are a structural weakness
  - But configuration might (hopefully) be manageable for O4
    - After much (on-going) effort
    - With low input power
- Yet current detector will not allow to start O4 on nominal start date with nominal sensitivity
  - Strong suspicion of excess thermal noise, would limit achievable sensitivity to ~30 Mpc
- On May 3, the Virgo Steering Committee decided that Virgo will not join O4 on May 24
  - Intervention on WI mirror to remove the damaged magnet
  - Intervention in NE tower to replace NE mirror
  - Few more months of commissioning to improve sensitivity

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# POST-O4 CONSEQUENCES

- Virgo_nEXT will need stable recycling cavities
  - Need for stable recycling cavities to achieve Virgo_nEXT target sensitivity reassessed in dedicated document meant to complement 2022 concept study
  - (coating thermal noise section also updated with dedicated study)

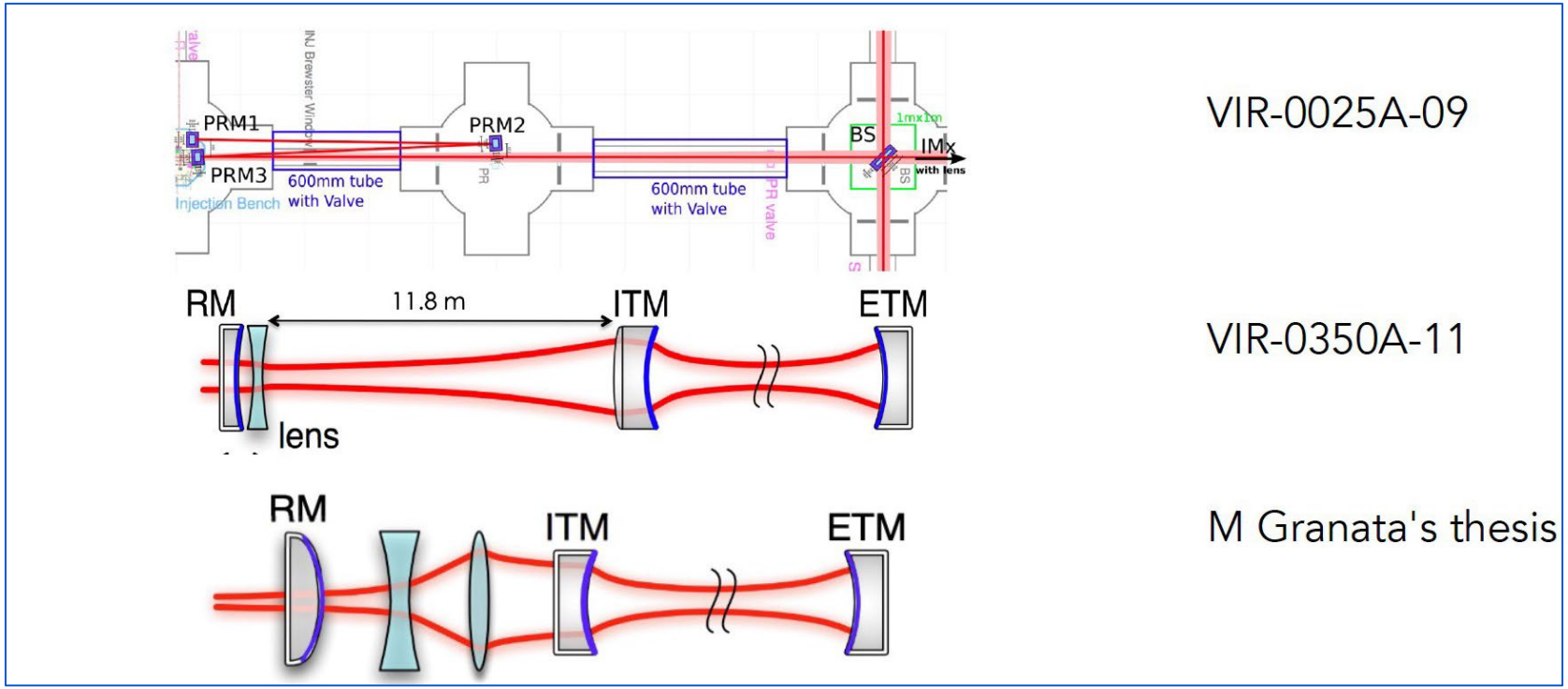
- What about O5? What does the O4 experience tell us ?
  - Will 18 months be enough for commissioning?
  - Is it realistic to increase the input power?
  - Is it viable to stick to marginally-stable recycling cavities?
  - Significant simulation effort required

- Identifying a technical solution to implement stable recycling cavities is a priority

# NDRC SOLUTIONS ON THE TABLE

- Multipayloads
- Design using lenses

These solutions do not require new infrastructures, but need development




VIR-0025A-09

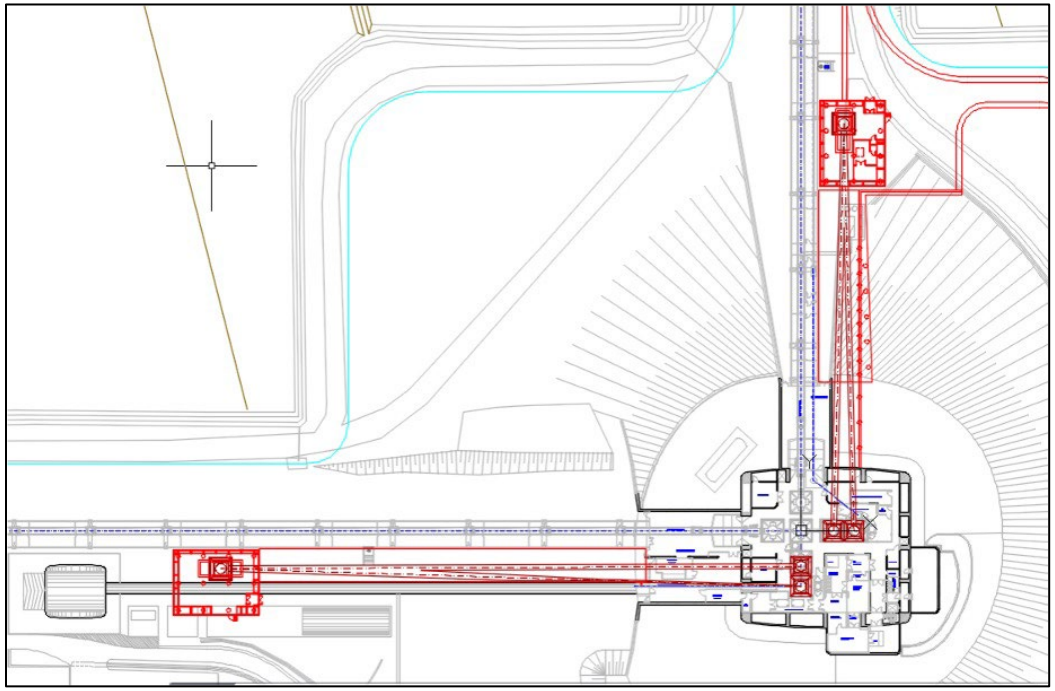
VIR-0350A-11

M Granata's thesis

G. Losurdo, VIR-0374A-23

# NDRC SOLUTIONS ON THE TABLE

- As alternative a design for an ‘external’ (outside the existing vacuum envelope) implementation was pushed forward (2010/2011)
- Pros:
  - did not require multiple payloads on a single superattenuator;
  - much longer cavities allowed for less strong RoC and hence resulted in much lower requirements of optics
- On the other hand this solution required add new buildings, new vacuum, new suspensions … O(~10M€) in 2011 + time



S.Hild et al, LVK, March 2023

# THE PATH FORWARD

- ❑ Options for anticipating the installation of stable cavities to before V_next must be assessed
- ❑ Extremely important is the **robustness and flexibility** of the possible solution identified

> From the STAC Report – Nov 2022: *It is important to try to retain some flexibility in the solution chosen – something which is too closely tailored to the present concept may cause trouble later on*

- ❑ A revision of the development program for phase 2 (and post-O5) is necessary and urgent
  - ➢ anticipation of the installation of stable cavities before O5?
  - ➢ postponement of the installation of heavy test masses to a later phase?

- ❑ The possibility of installing stable cavities before O5 needs to be studied in detail, from a technical, financial, timing and risk assesment perspectives

# SYNERGIES WITH ET (INSTRUMENT SCIENCE)

- ❑High power operation (laser, adaptive optics, parametric instabilities)
- ❑Frequency dependent squeezing
- ❑Large test masses (optics, suspensions)
- ❑New coatings
- ❑Low frequency operation (Virgo is a unique environment for these investigations and can contribute to the de-risking of ET by studying many technical noise sources and their interplay at the low-frequency end of the observation band)

- ❑Essential training of next generation of GW scientists (including the future leaders in the ET era)

# WRAP-UP

- ❑Virgo will not join O4 on May 24, but will join few months later
- ❑AdV+ phase 2 and V_nEXT concept must be revised
- ❑Synergies with ET on many crucial aspects
- ❑Virgo is working to improve its sensitivity and continue making important contributions to the field of gravitational wave astronomy