FROM TODAY INTO THE NEXT DECADE

FILLING THE GAP WITH 3RD GEN DETECTORS

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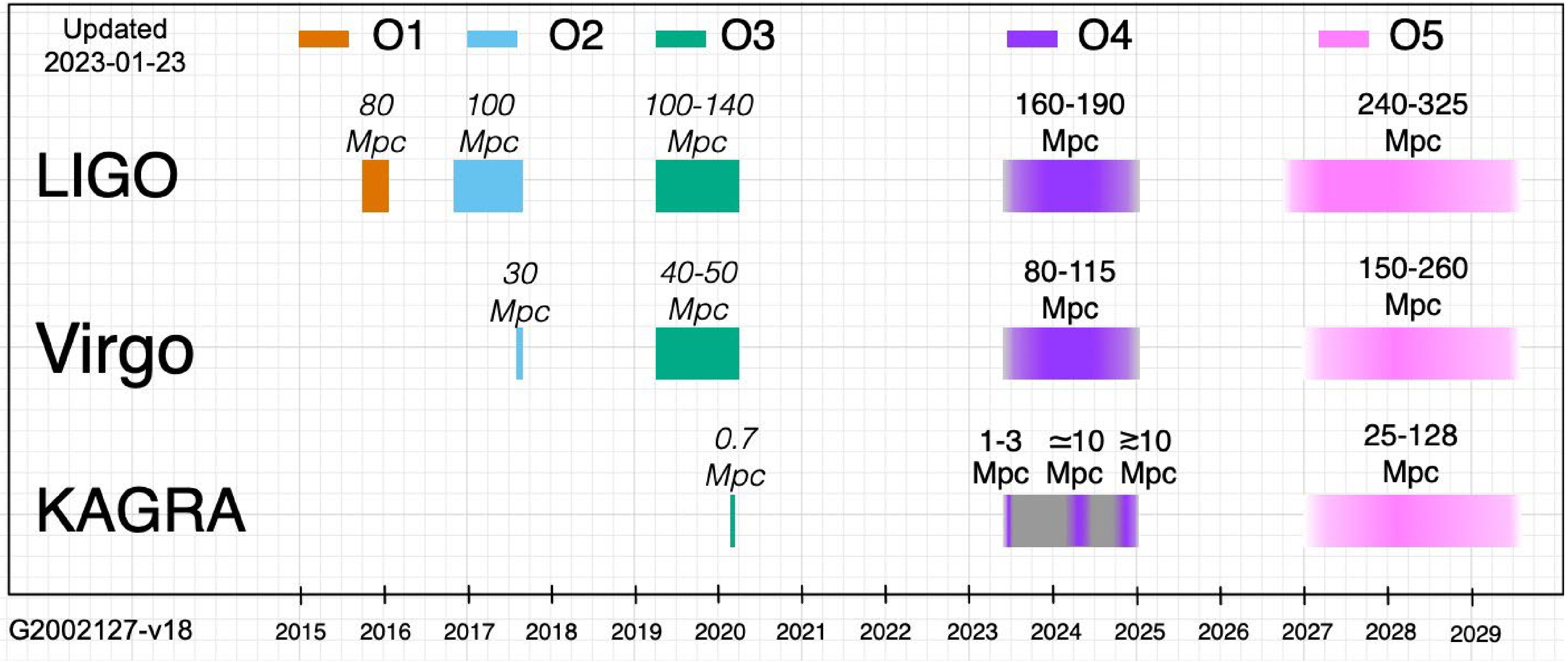
Virgo spokesperson

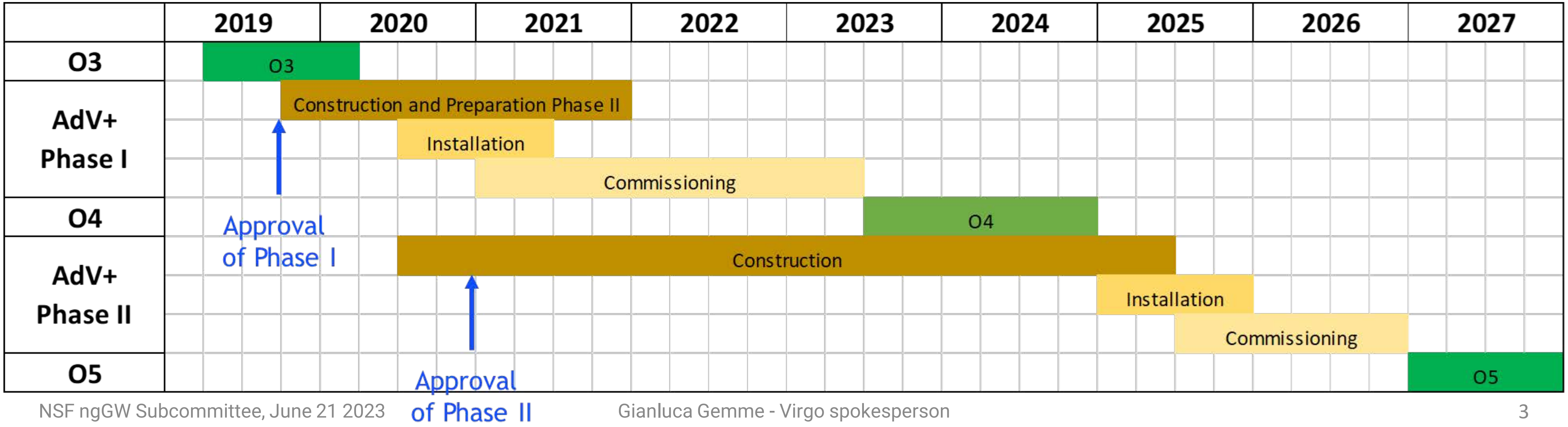
VIRGO UPGRADES AND OBSERVING RUNS

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



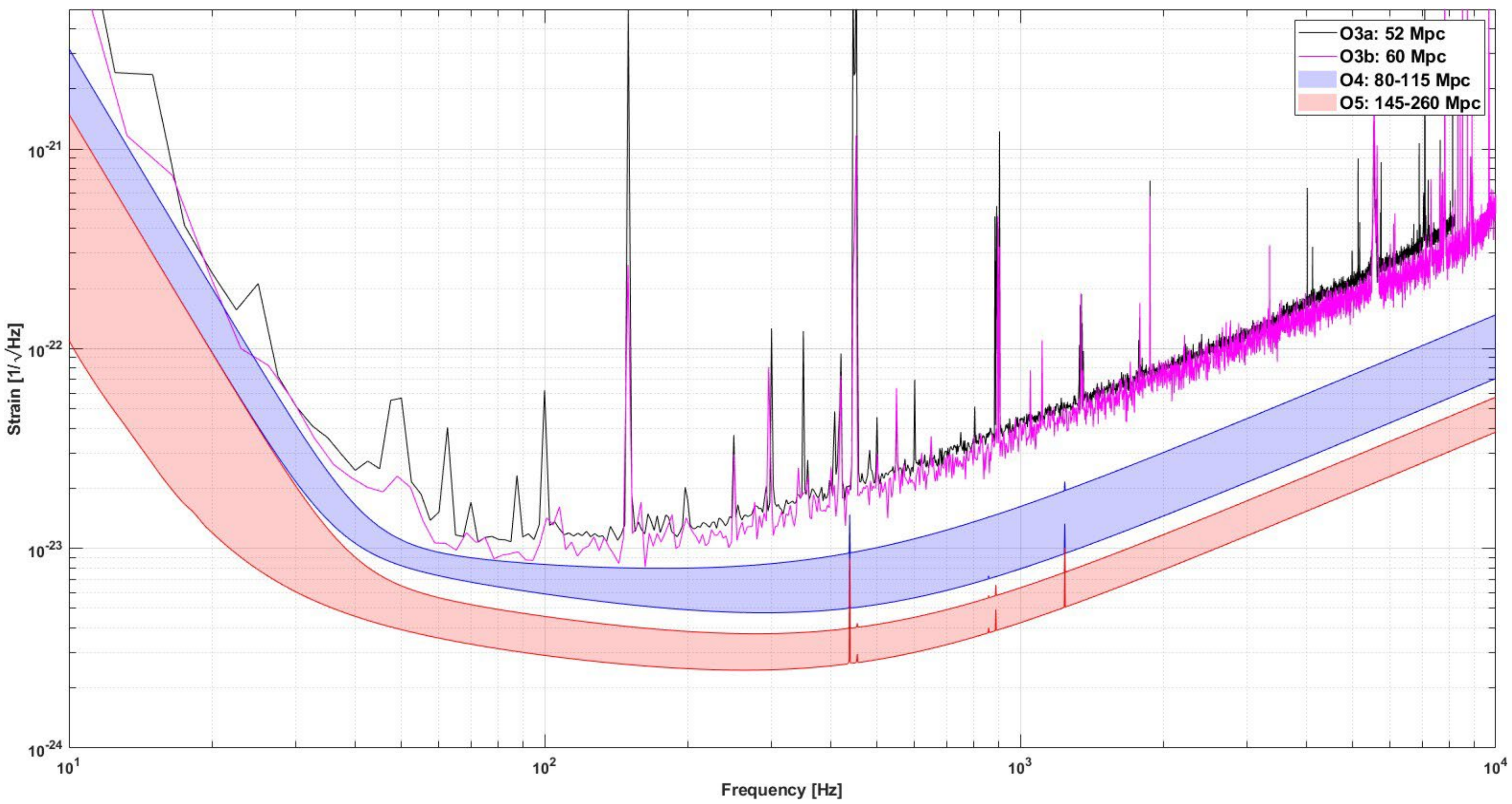
ADV+: A TWO-PHASE UPGRADE

- 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

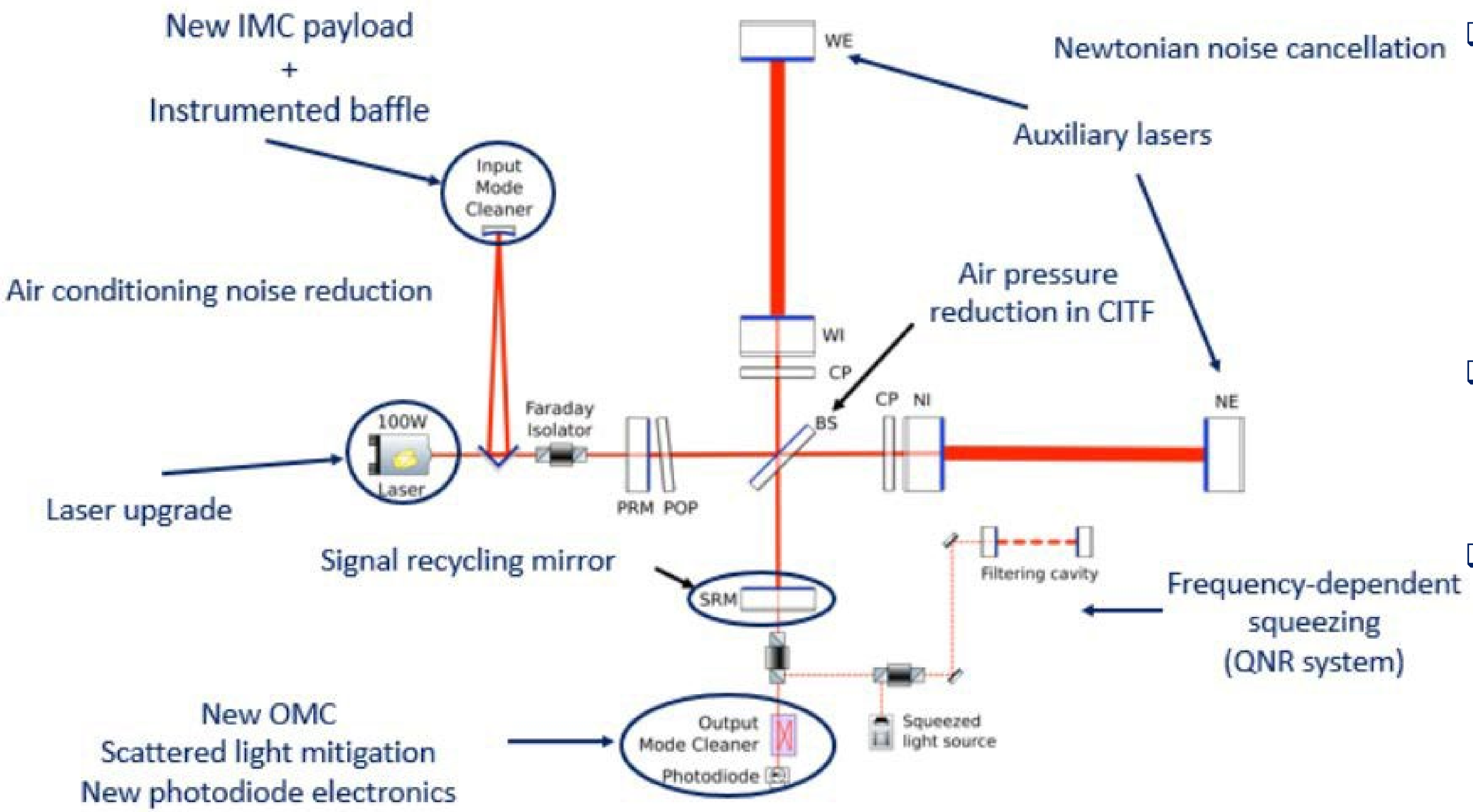
- Phase I: reduce quantum noise, hit against thermal noise
  - BNS range ~ 100 Mpc
- Phase II: lower thermal noise wall
  - BNS range ~ 200 Mpc



ADV+ PHASE I

O4: May 2023 - Jan 2025

ADVANCED VIRGO+ PHASE I

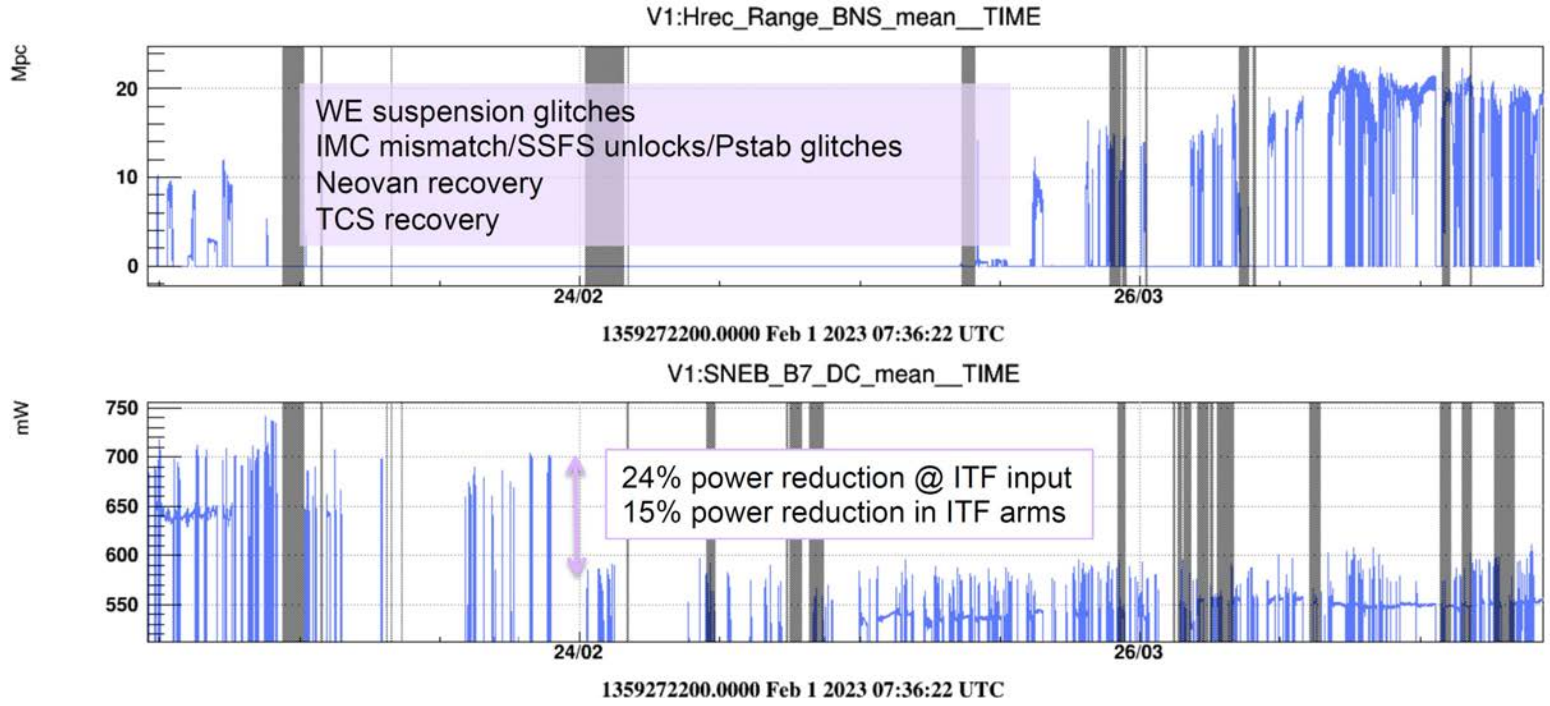


- Installation within a year despite pandemic
  - Main interferometer complete in December 2020
  - Quantum noise reduction system complete in April 2021
- Commissioning
  - Started in January/May 2021 for main ITF/QNR system
- Two aspects fundamentally new (in Virgo)
  - Signal recycling
  - Frequency-dependent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

O4 COMMISSIONING

- 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…
  - Mirror thermal noise higher than expected



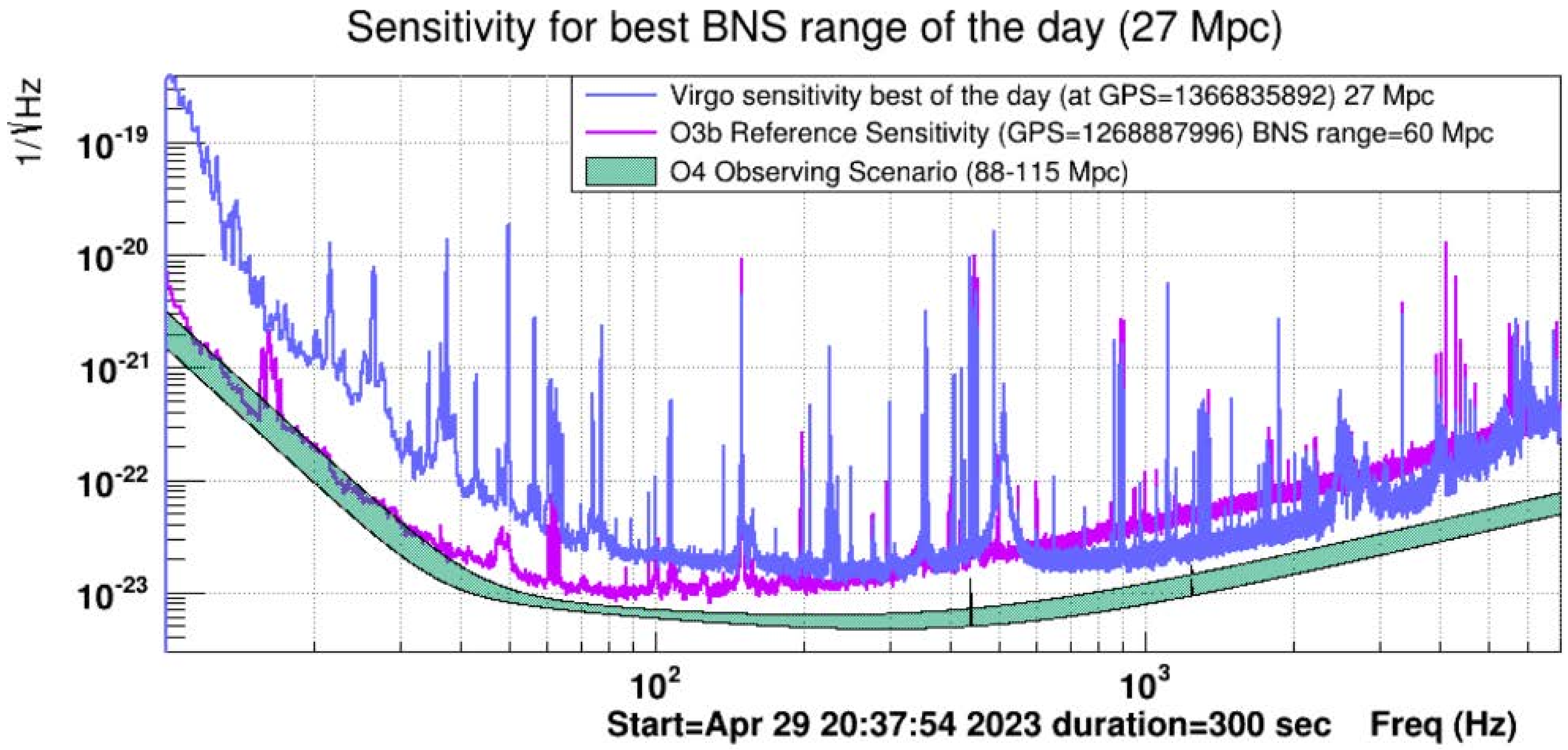
RECYCLING CAVITIES DEGENERACY

- ❑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

- ❑Unable (so far) to solve the above issues by tuning the thermal actuators
  - →further lowered the power to 23 W (Feb 2023)


THE NORTH COAST

VIRGO BEST SENSITIVITY (APRIL 2023)



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
  - Limited impact of Virgo on network science reach
- On May 3, the Virgo Steering Committee decided that the Virgo detector would 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

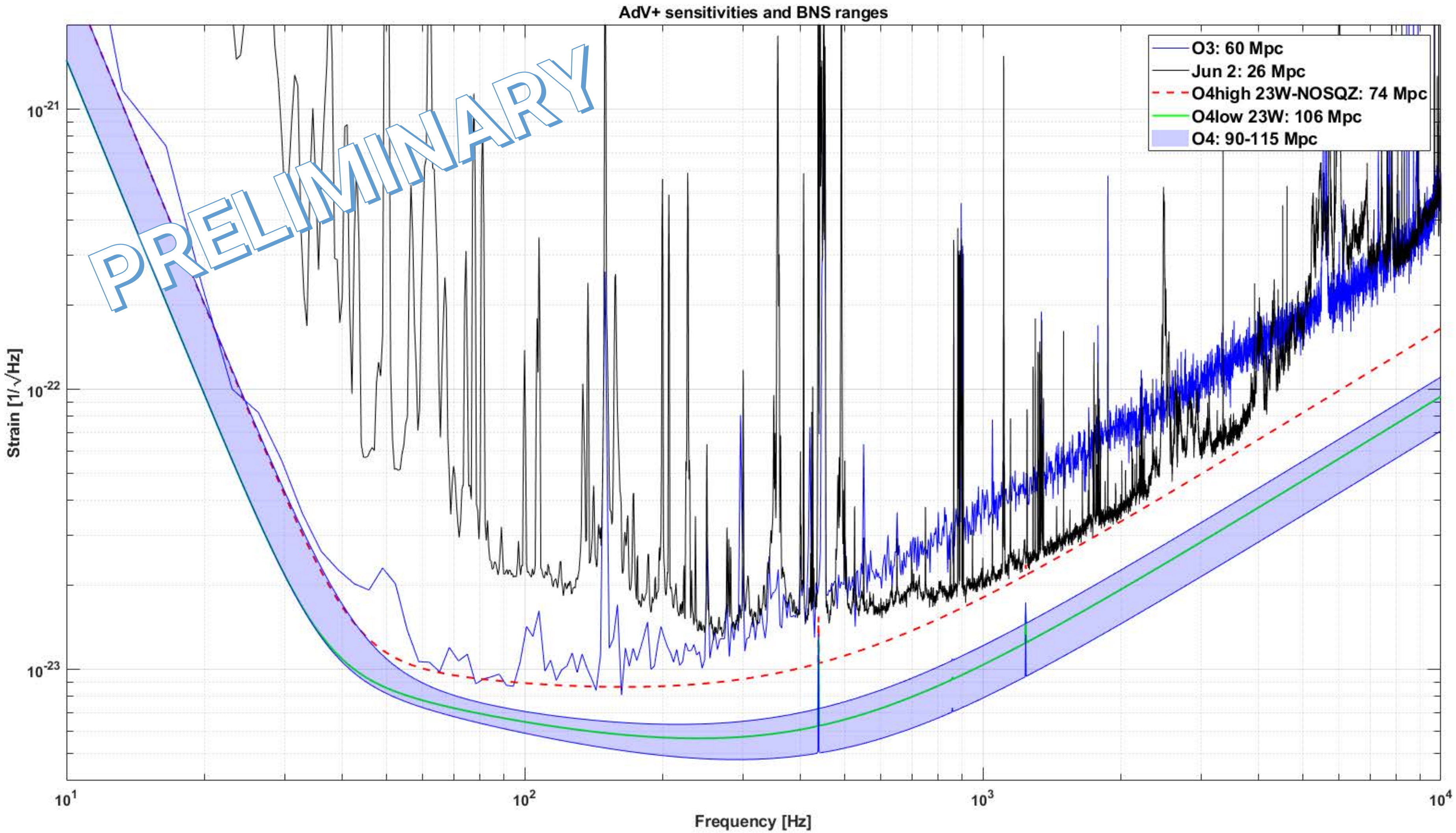
TAKEAWAYS

- Commissioning is taking much longer than expected (mostly) due to structural problem: marginally stable recycling cavities in Virgo optical layout →
  - We are late
  - We have to run at low power → lower sensitivity

- Excess thermal noise from two mirrors (different origin) prevents further progress in sensitivity → to solve the problem a complex and long operation was needed → further delay

- We will join O4 later and with a worse sensitivity than expected

UPDATED SENSITIVITY



PLAN TO JOIN O4

- We have a clear plan for joining O4 between late summer and fall

- Target sensitivity for joining O4 around 70 Mpc not irrealistic (but need to be confirmed after full recovery). Could be further improved during the run

- To be done:
  - Reduce control noises at low frequency
  - Confirm possibility to reduce the transmission of laser noises through the degenerate signal recycling cavity
  - Verify the squeezing losses in the signal recycling cavity

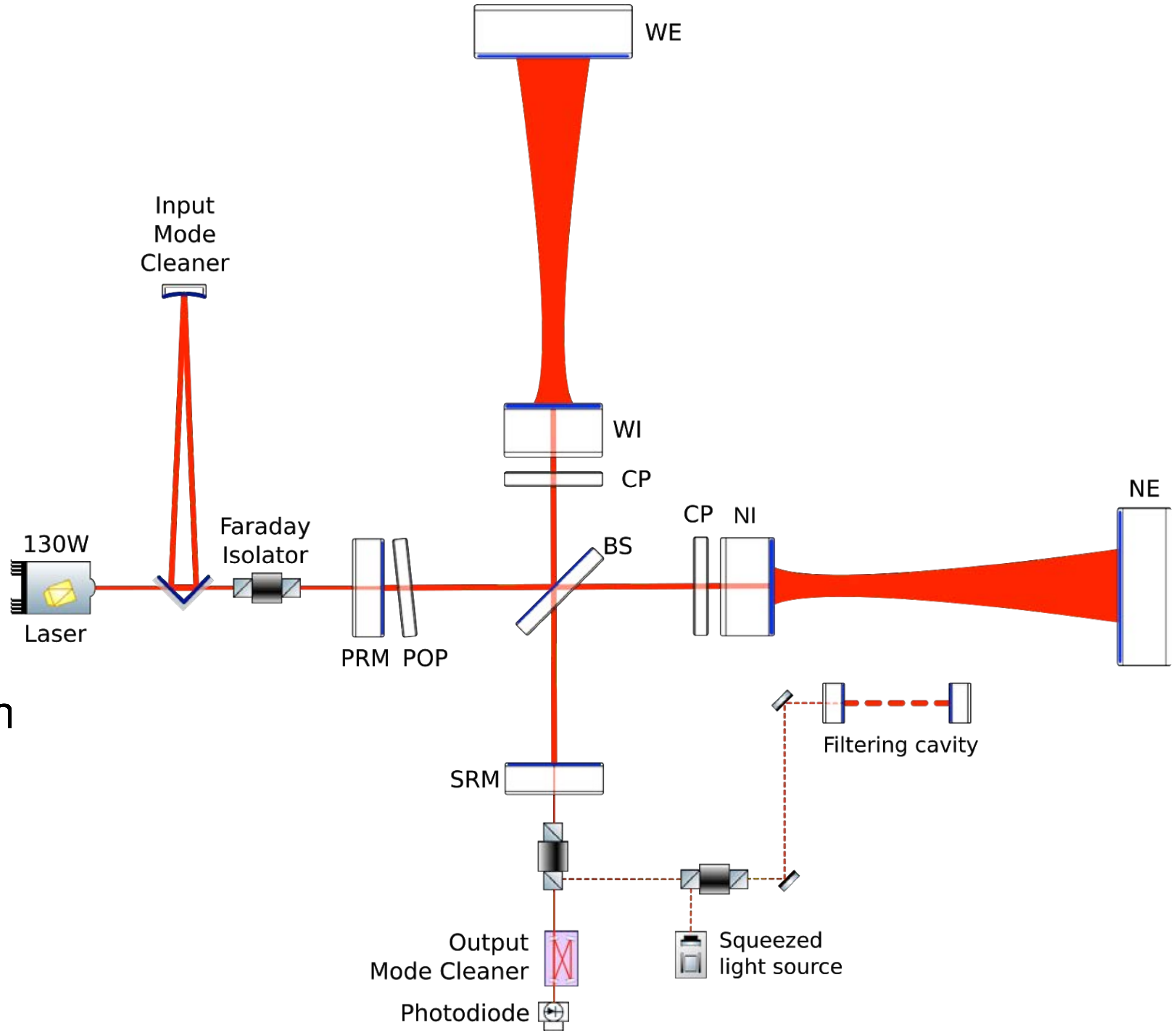
ADV+ PHASE II

O5: 2027 - 2029

ADVANCED VIRGO+ PHASE II

❑Main changes

- 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 m
- Further increase of laser power
  - 40W ⇒ 60W ⇒ 80 W
  - Original AdV design was 125 W



POST-O4 CONSEQUENCES

- 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

POSSIBLE WAYS OUT

- ❑ Continue to work at low power
  - ➢ How high in power can we go?
  - ➢ Simulations needed
- ❑ Remove the SR mirror and increase the power
  - ➢ How higher in power can we go?
  - ➢ Simulations needed
- ❑ Operate with detuned signal recycling cavity
  - ➢ Power on dark fringe will be decreased
  - ➢ Offset on locking signals to be managed
  - ➢ Simulations needed
- ❑ In all the three cases above, the effect on the squeezing is to be evaluated

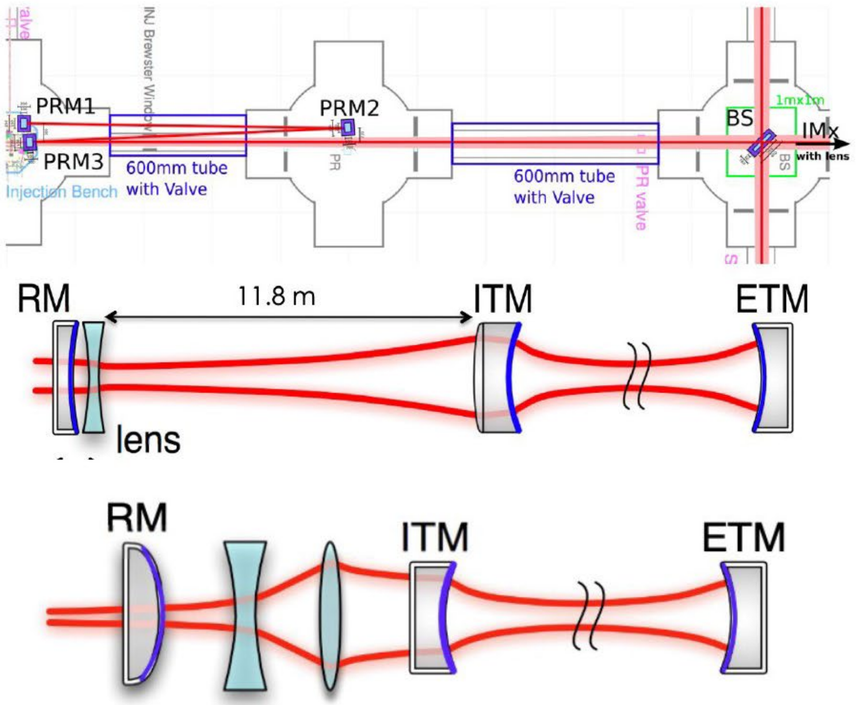
IMPLEMENT STABLE RECYCLING CAVITIES IN O5?

- Two families of solutions
  - Within the present infrastructure (“in”)
  - With addition infrastructure i.e. out of present infrastructure (“out”)
- Typical “in” solution has relevant development time and small construction time after O4
- Typical “out” solution has no development time but relevant construction time after O4
- Both approaches needs several new large optics for the recycling cavities
  - 3 years is a minimum to have new large optics
  - Some of this time can be bought if O4 is longer

NDRC "IN" SOLUTIONS ON THE TABLE

- Multipayloads
- Design using lenses

These solutions do not require new infrastructures, but need development



VIR-0025A-09

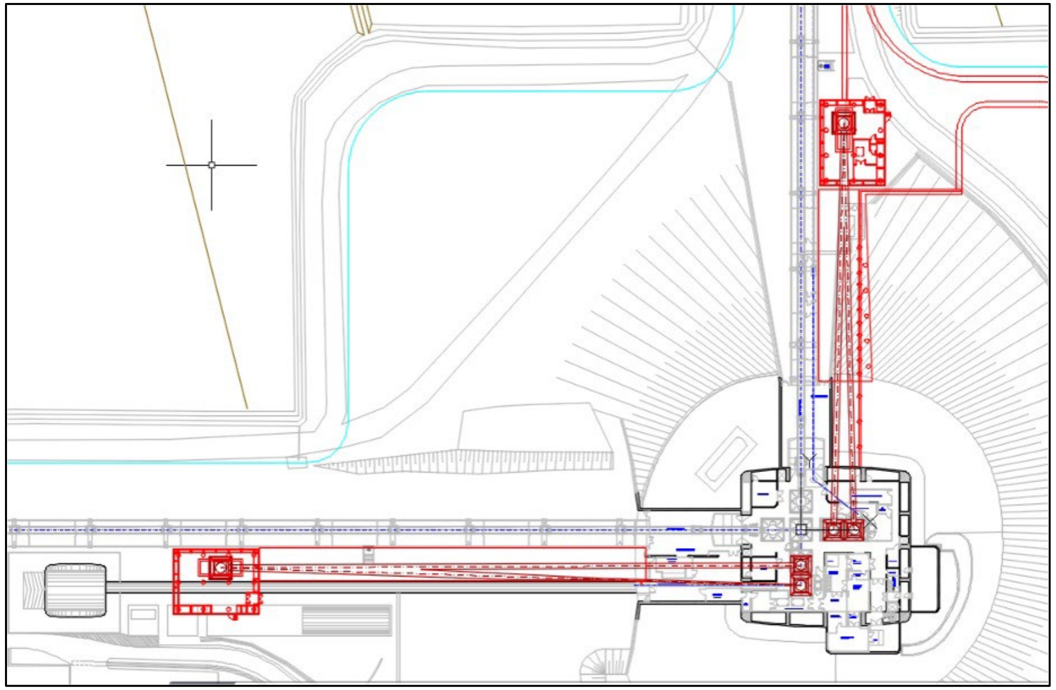
VIR-0350A-11

M Granata's thesis

G. Losurdo, VIR-0374A-23

NDRC “OUT” 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



VIR-1060A-22

- ❑ On the other hand this solution required add new buildings, new vacuum, new suspensions … O(~10M€) in 2011 + time
(~2.5 years for infrastructure works + integration and commissioning)

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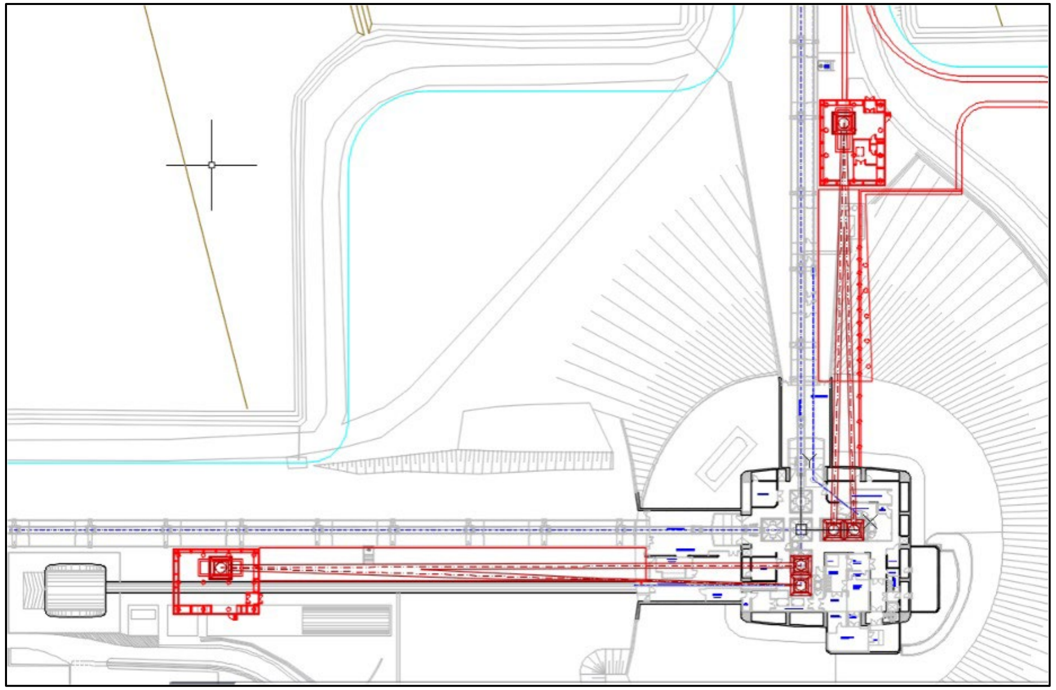


VIR-1060A-22

In the end:

- limited financial resources
- the urge to be contribute early to the advanced detector network
- positive simulation results
- advanced TCS system

resulted in a decision to build Advanced Virgo with marginally stable recycling cavities

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 in FP cavities to a later phase?

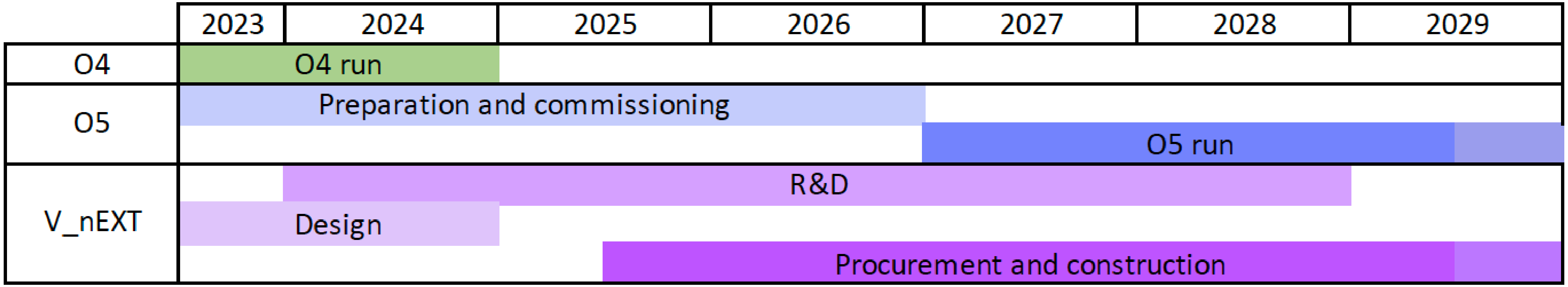
- ❑ Started a collaboration-wide discussion to study the possibility of installing stable cavities before O5: technical, financial, timing and risk assesement aspects
  - ➢ Goal is to prepare a plan to be presented at the EGO Council by the end of the year

VIRGO_nEXT

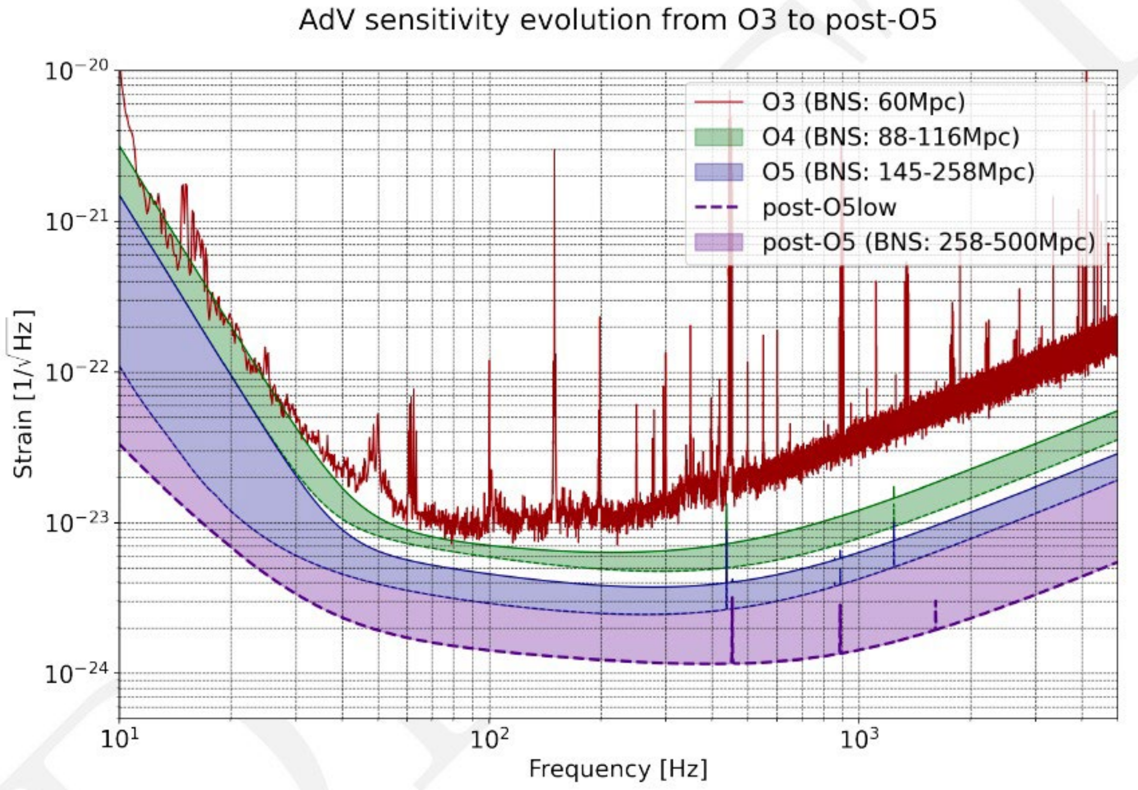
Post-O5: >2030

THE CONCEPT STUDY

- A concept study for a new, substantial Virgo upgrade to fill the decadal gap between the end of O5 and the beginning of 3G operation, aiming to exploit the infrastructure to its limits
  - Show that there is the science case for a new, sustainable investment
  - Identify needed R&D topics (and synergies with 3G)
  - Focus on possible upgrades keeping 1064 nm and room temperature
- Submitted to the funding agencies (EGO Council)
- Not yet a baseline design, to be delivered end of 2024



VIRGO_nEXT



Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low	ET_HF
Power injected	25 W	40 W	60 W	80 W	277 W	
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW	3 MW
PR gain	34	34	35	35	39	
Finesse	446	446	446	446	446	
Signal recycling	Yes	Yes	Yes	Yes	Yes	
Squeezing type	FIS	FDS	FDS	FDS	FDS	
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5	10 dB
Payload type	AdV	AdV	AdV	AdV	Triple pendulum	
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg	200 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg	
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm	
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm	
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6	
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6	
Newtonian noise reduction	None	1/3	1/3	1/5	1/5	
Technical noise	"Late high"	"Late low"	"Late low"	None	None	
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc	

VIRGO_nEXT

- ❑High power operation
  - ➢ Quality of the optics (point defects, optical absorptions)
  - ➢ Parametric instabilities
  - ➢ Compensation of thermal effects
  - ➢ ITF controllability
  - ➢ Achievable squeezing, losses
- ❑Coating thermal noise
- ❑Low frequency operation

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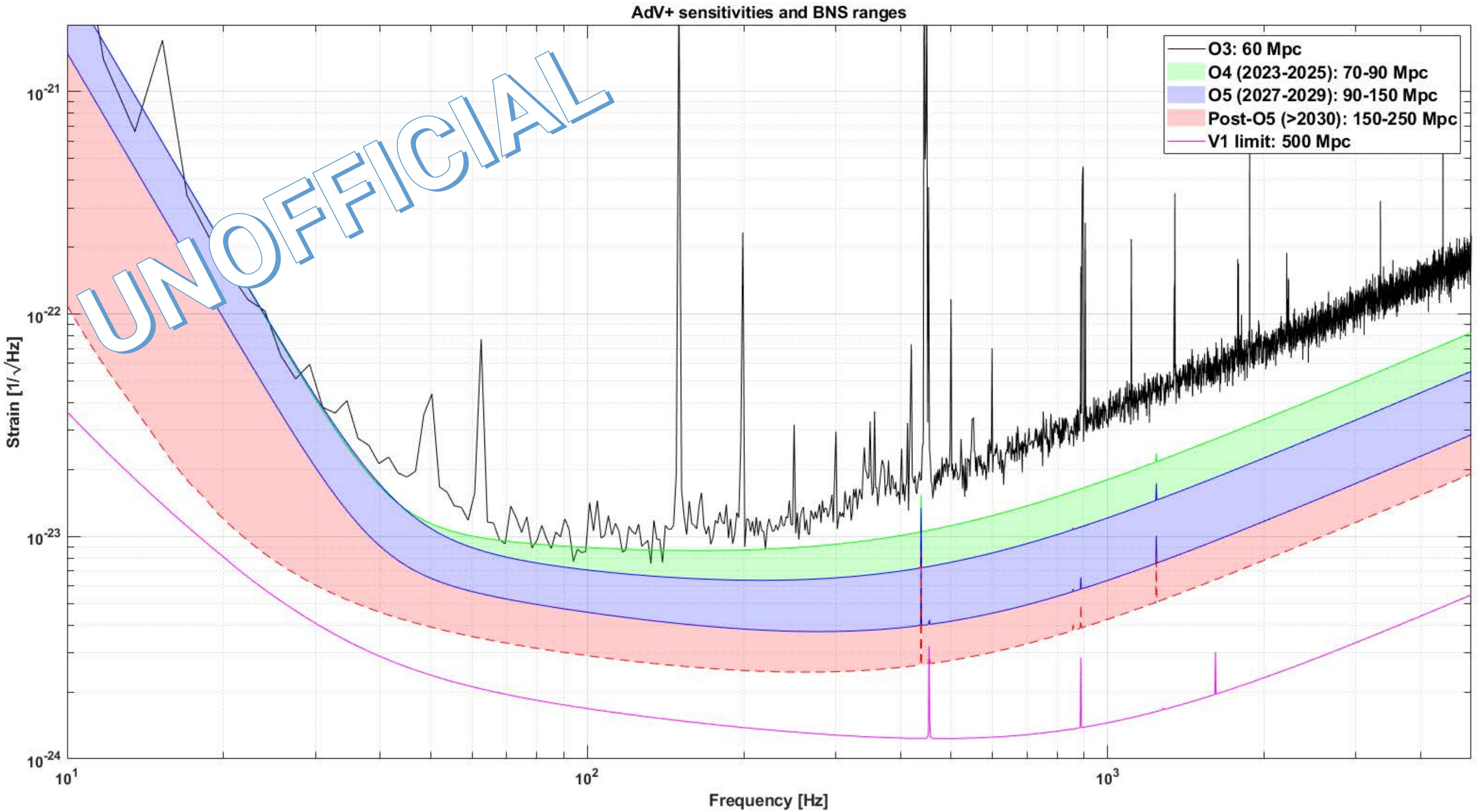
SYNERGIES WITH ET (INSTRUMENT SCIENCE)

- ❑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)



AdV+ sensitivities and BNS ranges
UNOFFICIAL
O3: 60 Mpc
O4 (2023-2025): 70-90 Mpc
O5 (2027-2029): 90-150 Mpc
Post-O5 (>2030): 150-250 Mpc
V1 limit: 500 Mpc
Strain [1/√Hz]
Frequency [Hz]

CONCLUSIONS

- ❑Experience with O4 commissioning strongly indicates that the possibility of installing stable recycling cavities before O5 must be seriously considered
  - ➢ Realistic options, timing, cost, impact on ongoing activities, impact on observing timeline
  - ➢ Today the only option that works «out of the box» is the «external» option: long recycling cavities, new buidings, new vacuum, new mirrors…but long time for implementation and high cost
  - ➢ Goal: present a mature proposal at the December Council meeting

- ❑The possibility of postponing the installation of large end masses should also be considered
  - ➢ Larger mirrors not useful until we will be limited by coating thermal noise
  - ➢ Today we don't have better coatings

- ❑The impact of Virgo on GW science (including the preparation for ET) depends critically on the choices we will make in the next few months