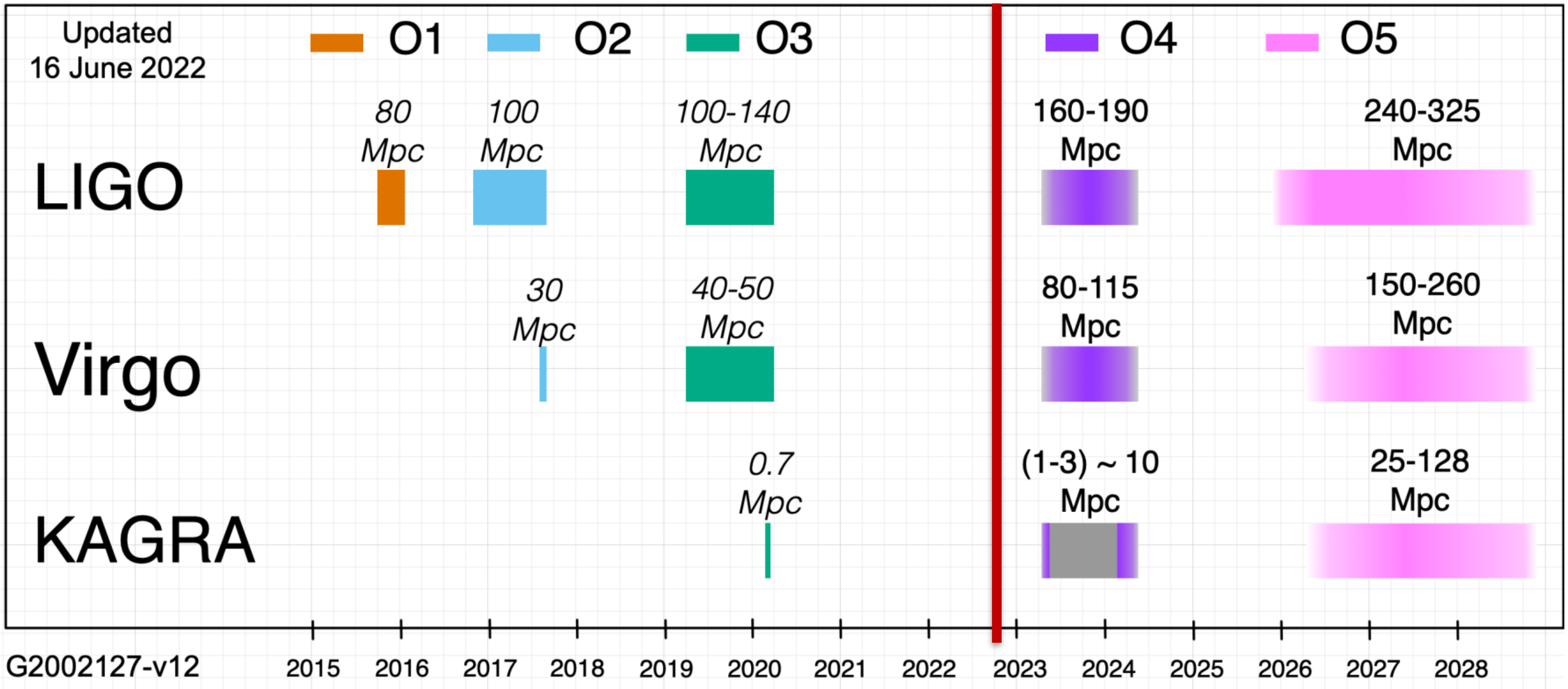
Virgo_nEXT
Pushing the Virgo infrastructure to its EXTremes

October 10th 2022

Edwige Tournefier (LAPP)

LIGO-Virgo-KAGRA observing plan



Now

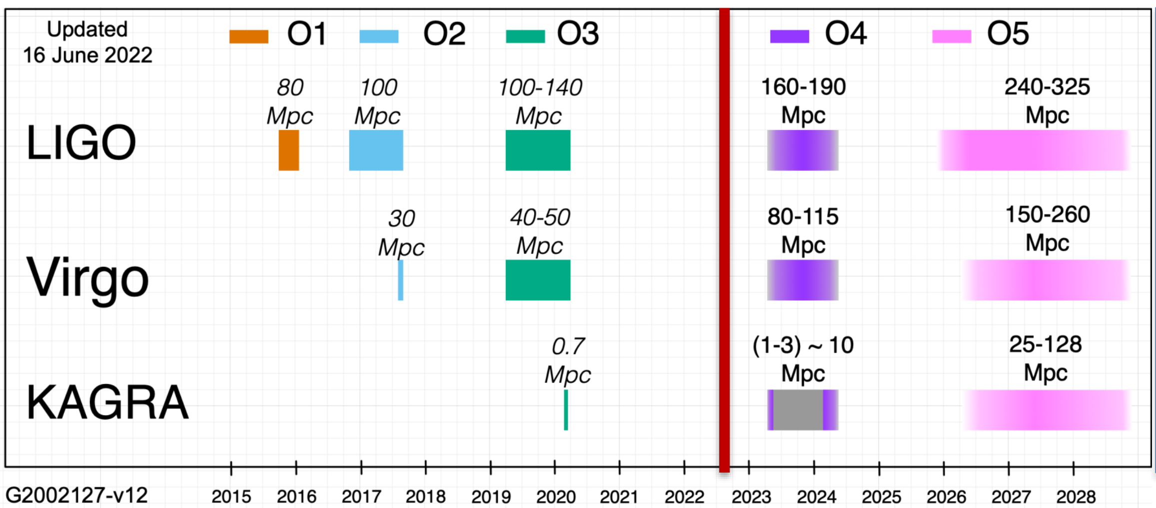
Advanced Virgo,
Advanced LIGO

Advanced Virgo+,
Advanced LIGO+

Upgrade of the current infrastructures

Current infrastructures

New infrastructures



Now

Advanced Virgo,
Advanced LIGO

Advanced Virgo+,
Advanced LIGO+

A#	Cosmic Explorer
Virgo_nEXT	Einstein Telescope
2030 - >2035	>2035

The concept study of Virgo_nEXT

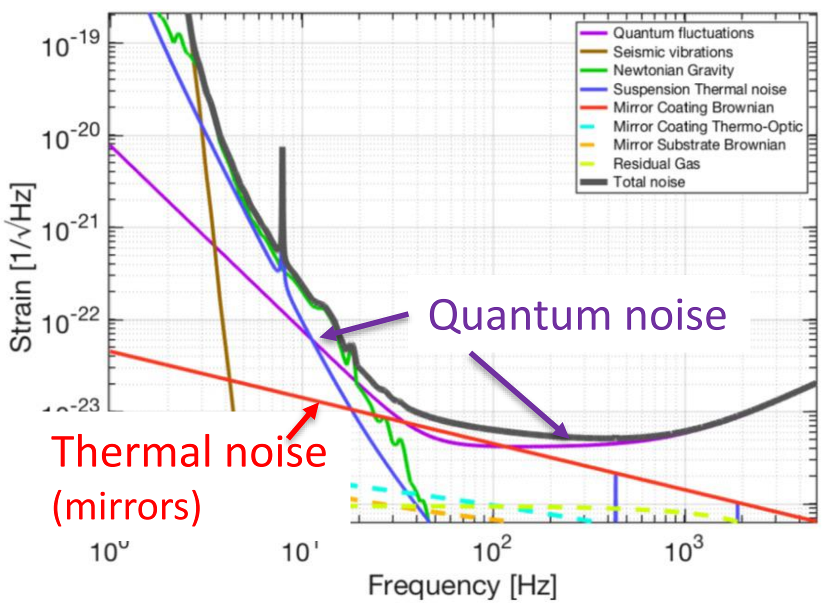
- A concept study for a new, substantial Virgo upgrade aiming to exploit the infrastructure to its limits
  - Show that there is the science case for a new, sustainable investment
  - Identify needed R&D lines and synergies with 3G

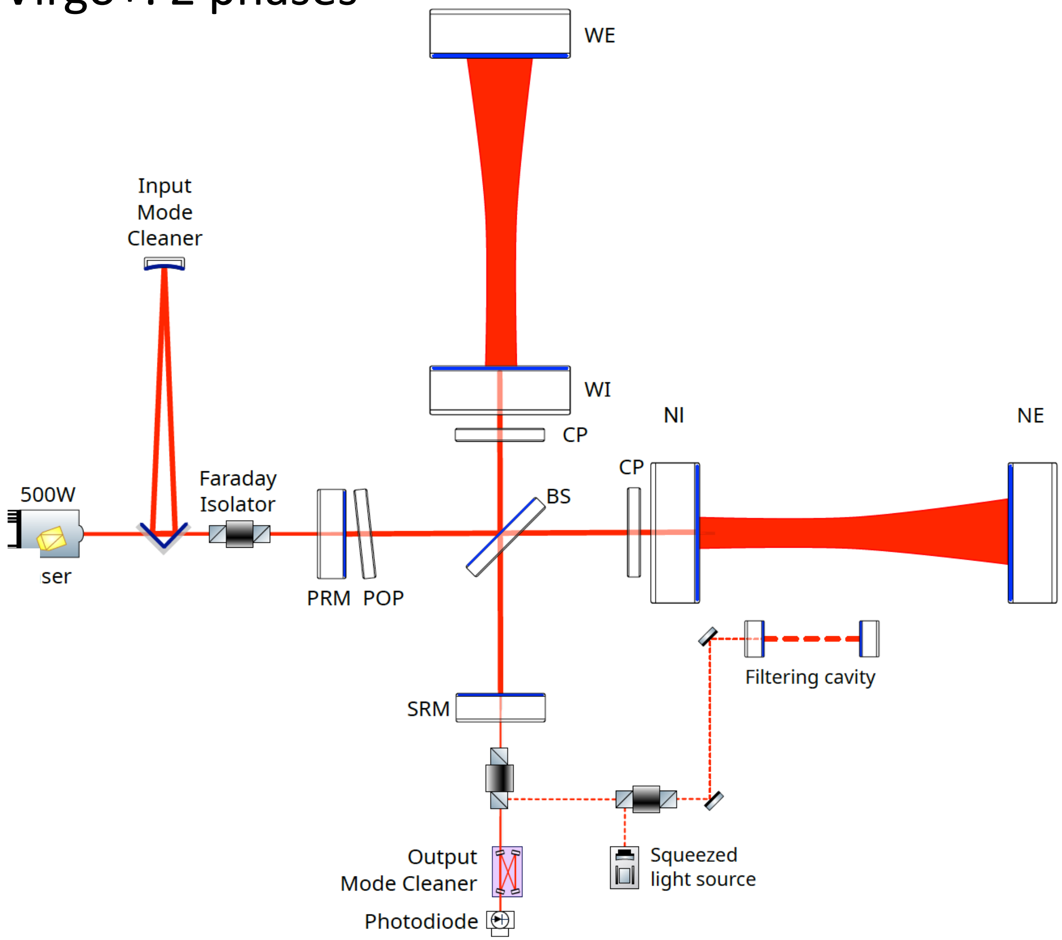
- Boundary conditions:
  - Budget: similar to AdV/AdV+
  - Timeline: compatible with the network plans
  - Technology which might be reasonably mature for an installation in ~ 2028

- Initial study document released but **not yet a baseline design**
  - Detailed plans on installation, commissioning, observing periods vs intermediate upgrades, is beyond the scope of this initial study

Advanced Virgo +

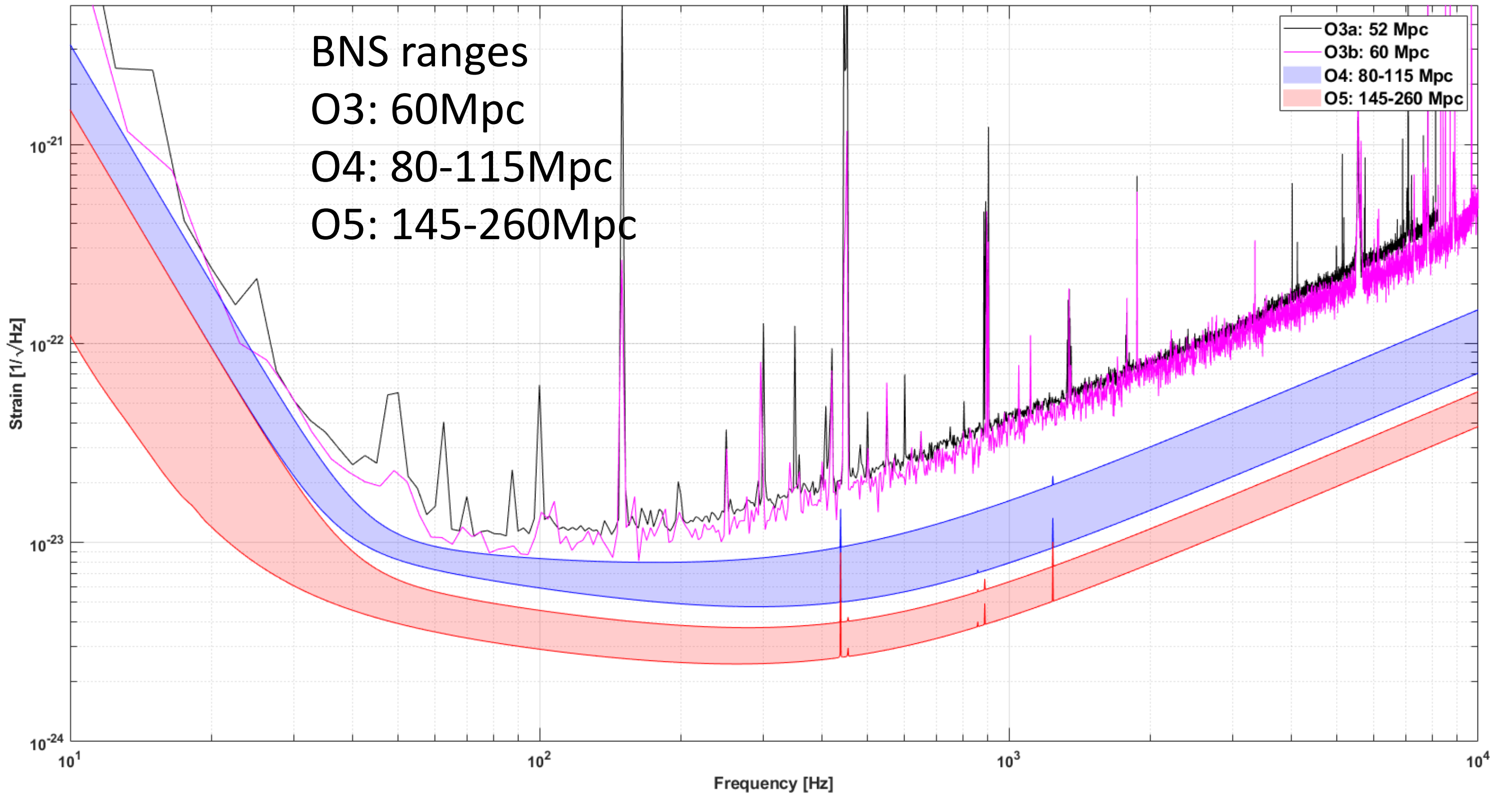
- From Advanced Virgo to Advanced Virgo+: 2 phases
  - Reduce quantum noise (O4 run)
    - Higher laser power
    - Squeezing technique
    - Signal recycling (RSE)
  - Lower thermal noise (O5 run)
    - Larger beams
    - New coatings





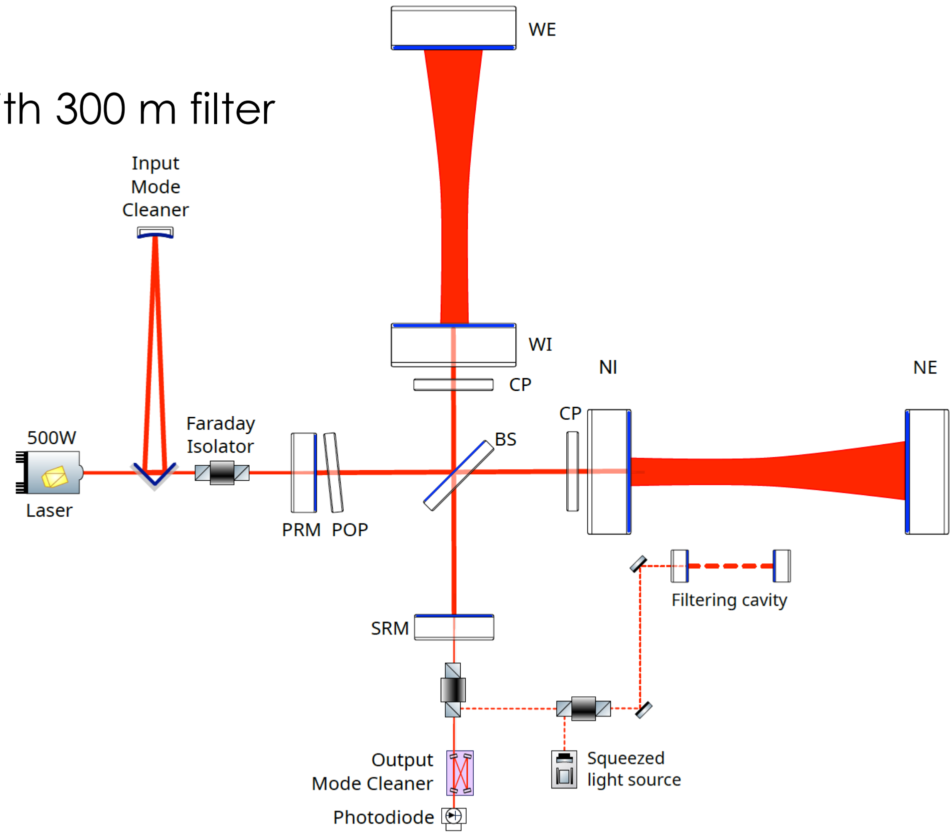
See Eleonora Capocasa's presentation

Advanced Virgo+ sensitivities



Virgo_nEXT detector configuration

- Same optical configuration as AdV+ O5
  - Dual recycled interferometer
  - Frequency dependent squeezing with 300 m filter cavity
- Further reduction of quantum noise and thermal noise
  - Higher laser power
  - Reduce thermal noise
  - Improve squeezing performances
  - Heavier mirrors



Virgo_nEXT parameters

Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
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
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
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 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

Quantum noise reduction

Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
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
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High power: stable cavities

- **High-power laser**
  - Present max power: 130 W for O4 and O5 with fiber amplifier
  - Same technology tested up to 350W
  - no fundamental limitations to reach 500 W

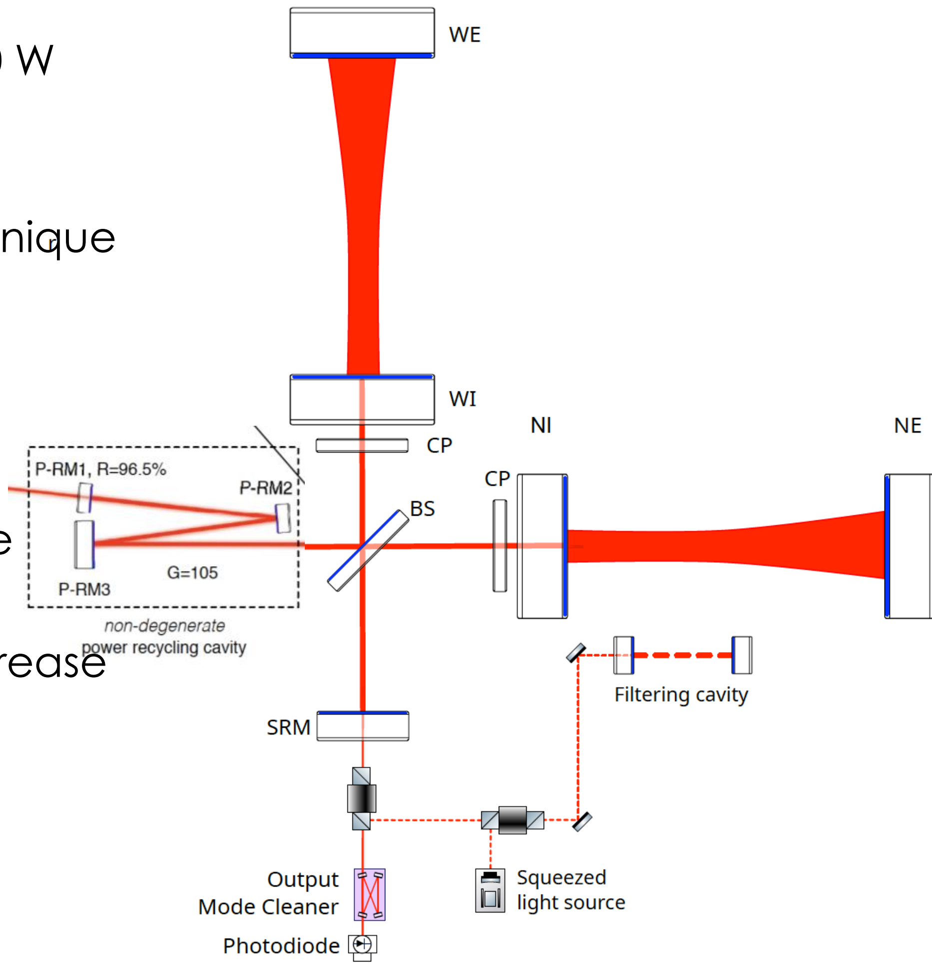
- **Aberration Control (mostly thermal effects):**
  - Sensors: R&D on wavefront sensing technique
  - Actuators: non spherical aberrations
    new technologies envisaged

- **Recycling cavities**
  - Recycling cavities are almost degenerate
  - Sensitivity to thermal effects is enhanced

  ⇒ Might reach a limit to the laser power increase

⇒ Use stable recycling cavities?
- large infrastructure work needed

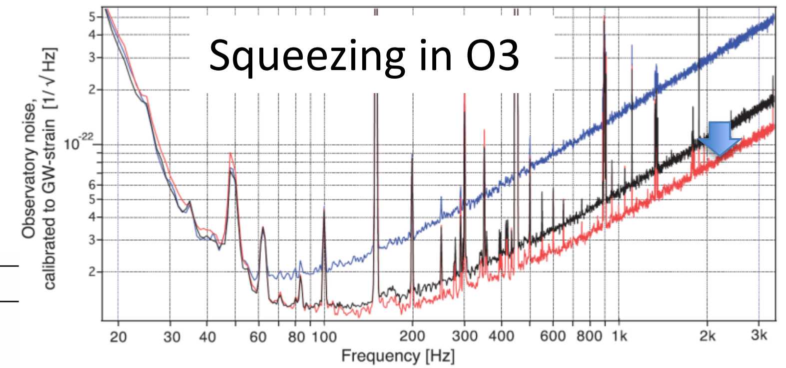
-> Under study



Squeezing: target 10 dB

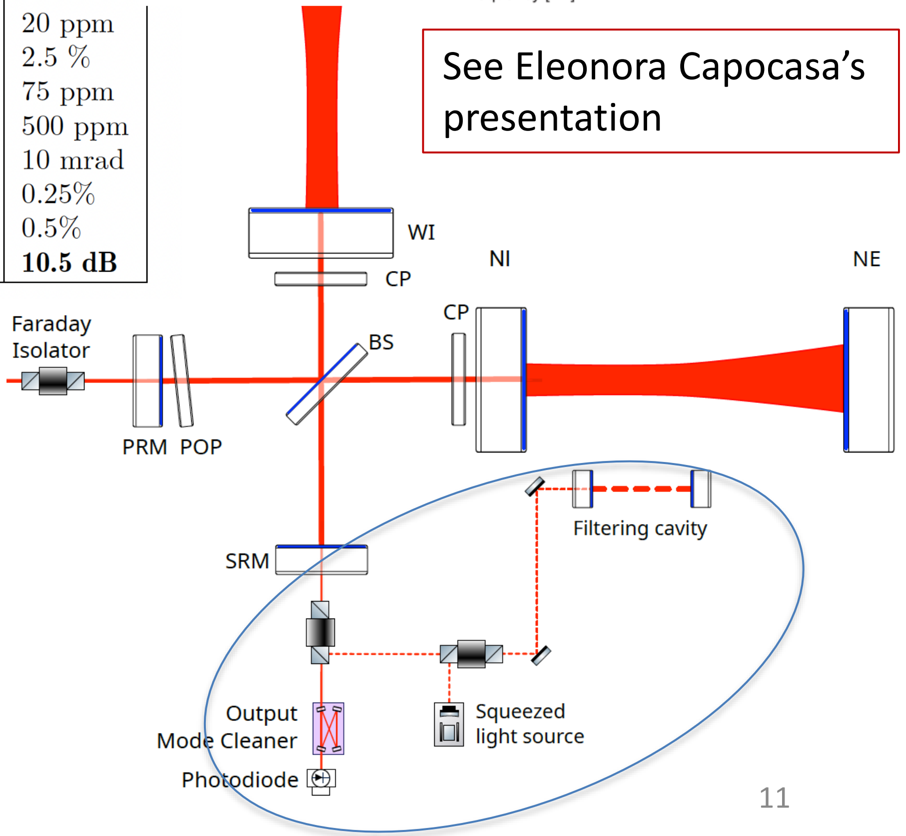
Squeezing is very sensitive to losses

- Reduce optical losses
- Reduce phase noise



Parameter	O5	Initial post-O5	VnEXT
Injected squeezing	12 dB	12 dB	15 dB
injection losses	6.5%	5.5%	1.8%
FC losses	30 ppm	30 ppm	20 ppm
Readout losses	6%	4.5%	2.5 %
Arm-cavity roundtrip losses	75 ppm	75 ppm	75 ppm
Signal extraction cavity (SEC) roundtrip losses	1000 ppm	1000 ppm	500 ppm
Phase noise	25 mrad	15 mrad	10 mrad
Mismatching squeezing - filter cavity	0.5%	0.5%	0.25%
Mismatching squeezing - interferometer	2%	1%	0.5%
Measured squeezing at high-frequency	**5.5 dB**	**7.5 dB**	**10.5 dB**

See Eleonora Capocasa's presentation



Mirrors and coatings

Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
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Mirrors and coatings

Mirrors: no point defects , low scattering

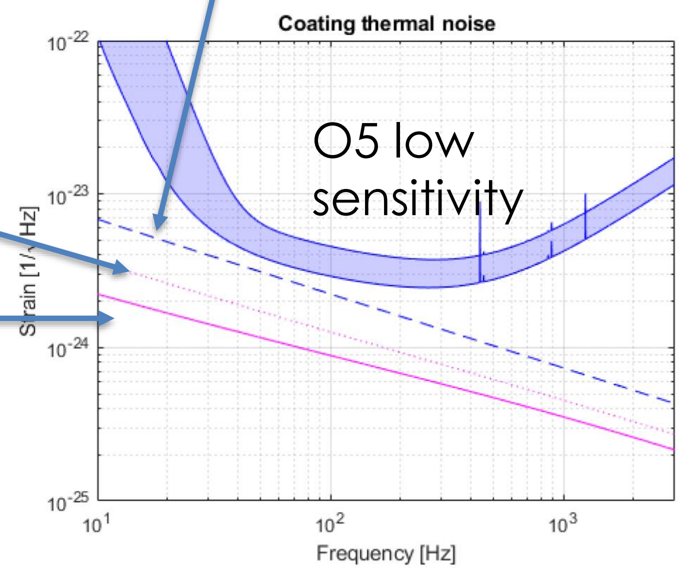
- developments ongoing at LMA for O5

Coatings: low thermal noise and low obsorption

Important R&Ds to be pursued:

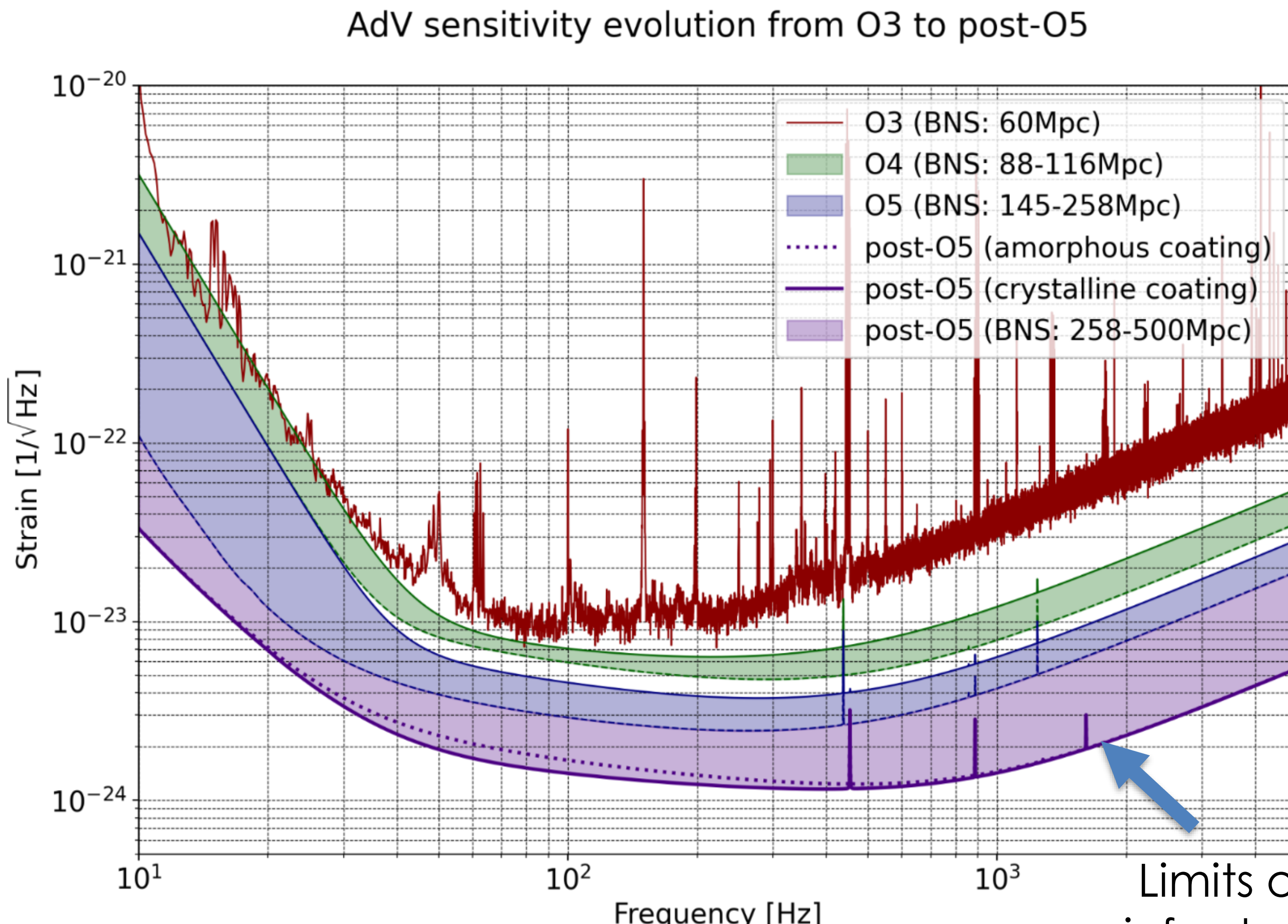
- **Amorphous coating**
  Additionnal improvements wrt O5?

- **Crystalline AlGaAs/GaAs coatings**
  - Promising but small surfaces
- **Crystalline oxides coatings**
  - Less mature but promising for large surfaces



Synergies with A# and 3G projects

Sensitivity

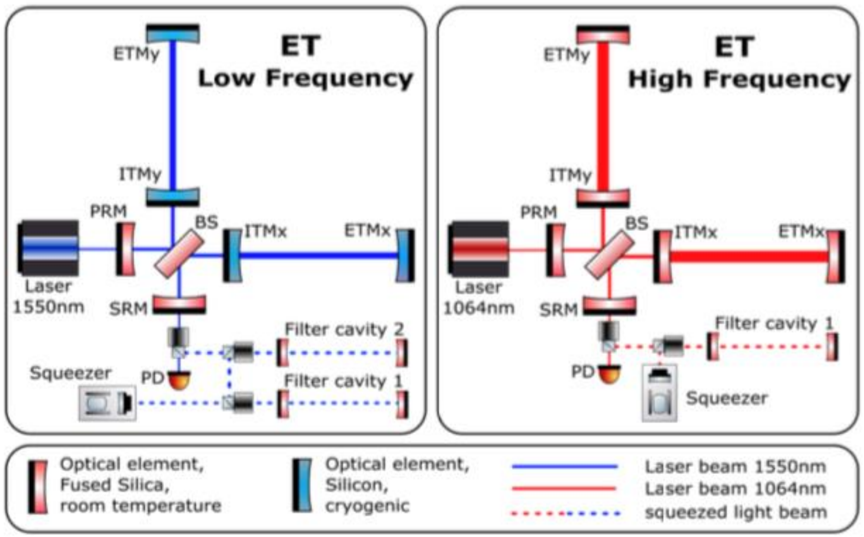


Limits of the infrastructure

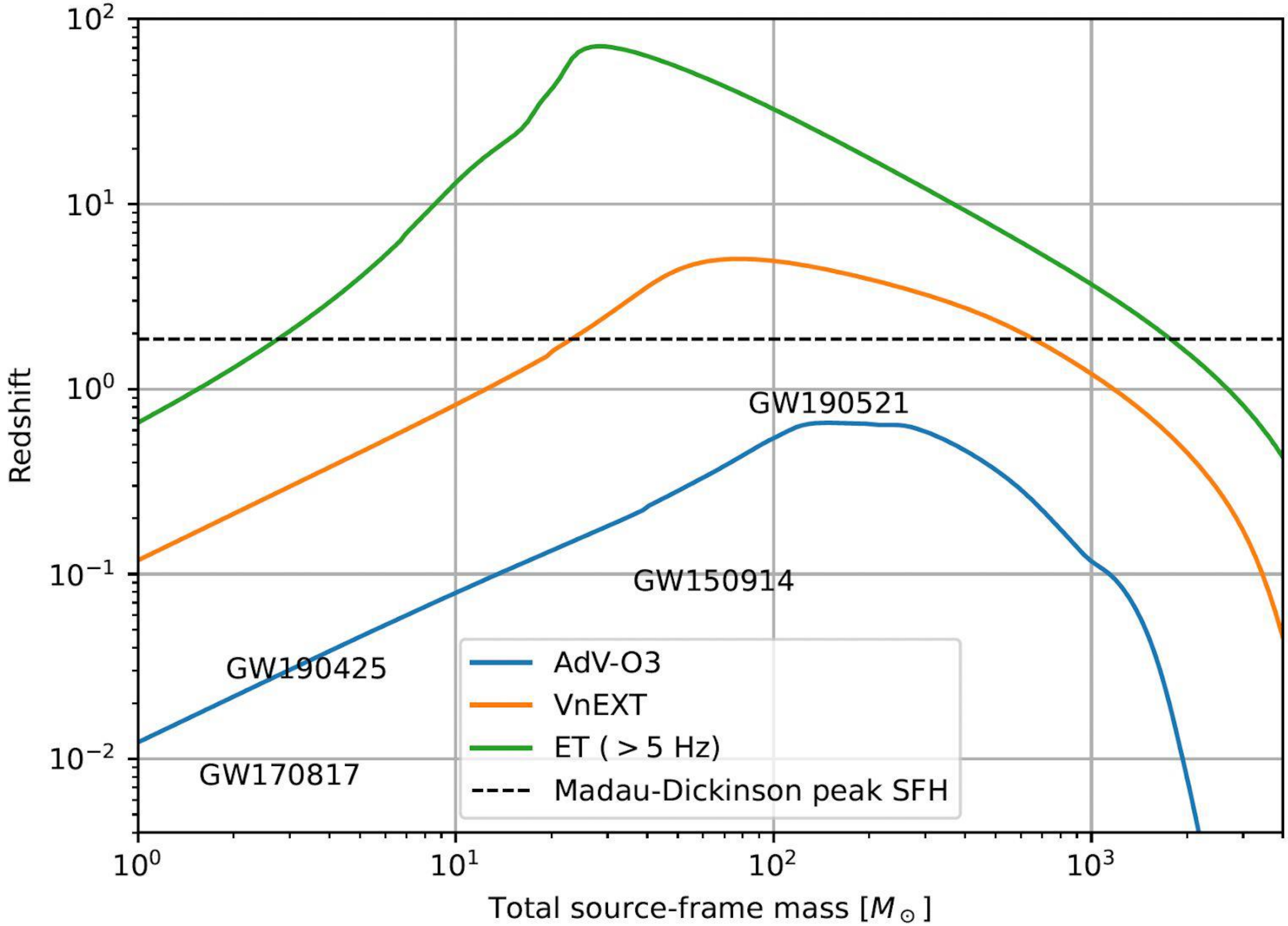
Synergies with ET

- Virgo_nEXT will develop many technologies relevant ET high frequency
  - Similar circulating power and test mass weight:
    - 1.5 MW and 105 kg (V_nEXT) vs 3 MW and 200 kg (ET)
  - Similar squeezing target (10 dB)
  - Low loss coatings

- Virgo_nEXT will contribute to the de-risking of ET by studying many technical noise sources on the **low-frequency region** (relevant for ET-LF and ET-HF)



Cosmological range of Virgo_nEXT for binaries

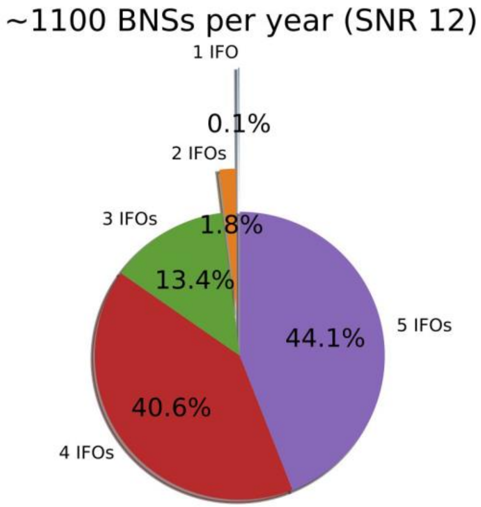


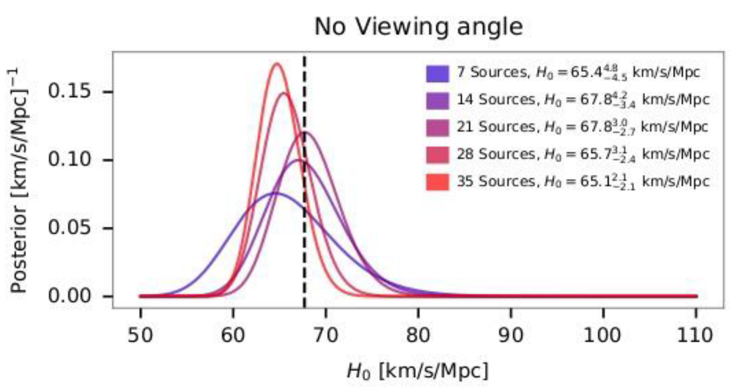
Science with Virgo_nEXT

- Binary black holes:
  - 14000 per year with SNR>8
  - Tests of GR
  - Primordial BBH

- Binary neutron stars:
  - ~3500 (1100) per year with SNR>8 (12)
    - 300 per year with $10 deg^2$
  - Several SGRBs-GW events per year

- Hubble constant measurement within ~5%





Summary

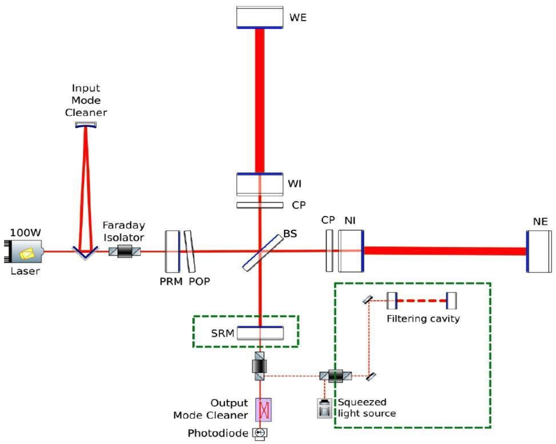
- We have a concept study for a new upgrade: Virgo_nEXT
- Same detector configuration as O5, with the open point of the stable recycling cavities
- Will move towards the baseline design.
- Ongoing discussions with LIGO post-O5 for synergies

Virgo_nEXT will

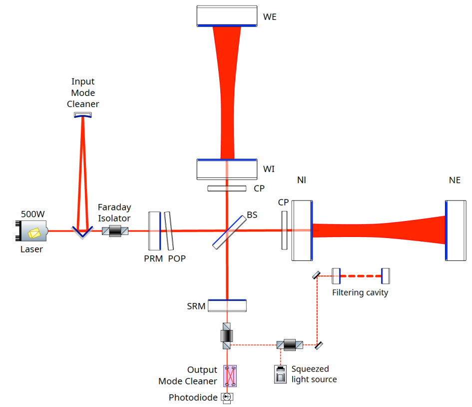
- Pave the way to the 3rd generation (test technologies, risk reduction)
- Maintain community of high-level experimentalists.
- Enhance the Virgo scientific reach with an existing infrastructure.

Extra slides

Mirrors



O4 → O5



- Fundamental experience with large test masses for Advanced Virgo+ phase 2
  - Same substrates for O5 and Virgo_nEXT
  - R&D at LMA on reduction of point defects and large angle scattering

High power: stable cavities

Long stable recycling cavities?

- Space problems in the central building

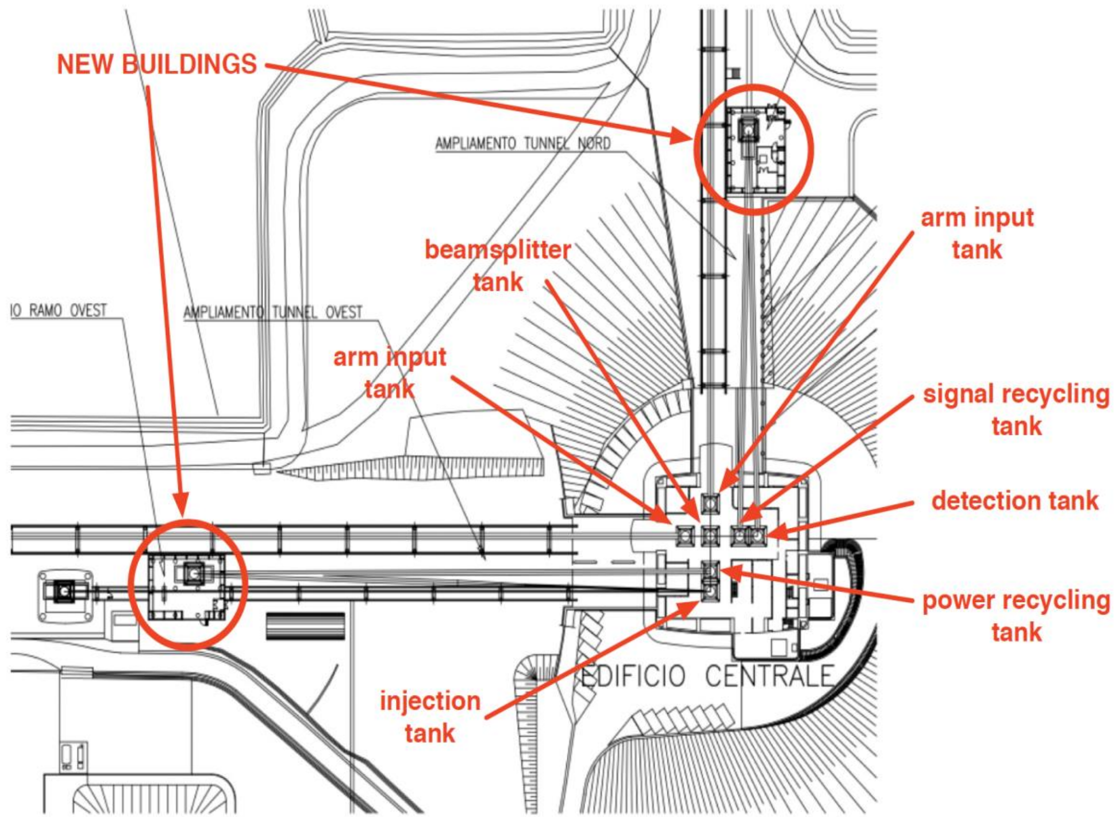
- Technical problems related to a multi-payload superattenuator

=> 180 m long cavities solution selected during Advanced Virgo design phase

- Discarded for Advanced Virgo for budget reasons

- Under study for V_nEXT

=> Technical study + cost estimate



Payloads

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Detailes synergies Virgo_nEXT vs ET

- Increased optical power; resulting in similar radiation pressure dynamics as in ET-HF because in VnEXT the ratio of optical power to testmass weight (1.5 MW to 105 kg) will be roughly identical to ET-HF (3 MW and 200 kg).
- High power lasers systems delivering several 100W at a wavelength of 1064 nm and in a HG_{00} mode.
- Optical components (e.g. electro-optic modulators, Faraday isolators etc), in particular in the injection and input optics path, that can withstand the increased laser power.
- Development of mitigation strategies for parametric instabilities (PI), including passive dampers as well as active damping using spatially modulated auxiliary lasers.
- Improved thermal compensation systems (TCS). This includes e.g. higher power ringheaters, higher order mode actuators and improved wavefront sensing techniques.
- Improved coatings with a reduced point defect and point absorber density. Improved metrology for detection of point absorbers.
- Squeezed light sources with increased squeezing level (in air and in vacuum, TBD) based on reduced OPO losses.
- Optical components with reduced optical loss, in particular improved low-loss Faraday Isolators, low-loss free-space output modecleaners, etc.
- Development of improved mode matching sensors and actuators, both to reduce the losses inside the main interferometer, but also in the squeezed light injection path.
- Reduced phase noise on the squeezing ellipse via improved control strategies for the length and alignment sensing of the filter cavity.
- New coatings with lower mechanical loss and lower absorption. Amorphous coatings with new or optimized materials, deposition and heat treatment. Crystalline coatings of sufficient size and optical quality, plus relevant transfer and bonding technologies.
- Payloads with reduced suspension thermal noise based on triple stage payload with a fully monolith final stage consisting of the penulitimate mass and the test mass.
- Enhanced seismic isolation techniques: Compact, passive seismic isolation chains; Test of inertial platform in a real operation environment.
- Seismic Newtonian noise subtraction techniques based seismometer arrays and noise subtraction via e.g. Wiener filters.
- Scattered light mitigation, including scattered light tracing and detection methods, scattered light simulation tools, improved baffle materials etc.
- Improved sensors and control techniques for interferometric sensing and control, i.e. relevant alignment and longitudinal degrees of freedom.
- Digital-to-analog (DAC) converters with improved range.
- Improved environmental noise monitoring, i.e. for infrasound.
- Increased laser stabilization, i.e. reduced relative intensity noise (RIN) and jitter noise of the main laser and the input optics, as well as laser used for the photon calibrators (Pcal).
- Many technical noises need to be reduced, some 2 orders of magnitude with respect to O3, in order to reach the best possible VnEXT sensitivity. In order to achieve this goal significant R&D will have to be performed and one can anticipate also that new strategies and noise decoupling techniques will have to be developed for the controls. All these developments will pave the way for ET which is aiming at an even better sensitivity and pushing the low frequency wall towards lower frequencies.

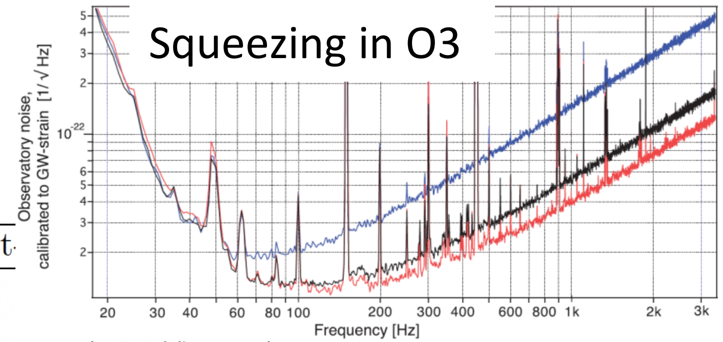
The main steps of the process

- Post-O5 Committee (2 sub-committees: science and detector) appointed on **February 2021**
- Decision to focus on upgrades keeping **1064 nm** and **room temperature.**
- Started discussions with LIGO
- First draft of the document in **spring 2022** - PO5 review committee appointed , open discussion in April at the Virgo Collaboration meeting
- Document presented to the EGO/Virgo **STAC in May 2022** and to the funding agencies - **EGO Council - in June 2022**
- Comments from the council:
  - *Investigate "reduced budget scenarios" (35M€ -> 25M€)*
  - *Investigate the feasibility of stable recycling cavities*
  - *Intensify the discussion with ET for joint developments*

- In **December 2022** next iteration with EGO Council
  - Expect feedback on final budget, define the technical design timeline, define decision points on various technical options

Squeezing: target 10 dB

Squeezing is very sensitive to losses
- Reduce optical losses
- Reduce phase noise

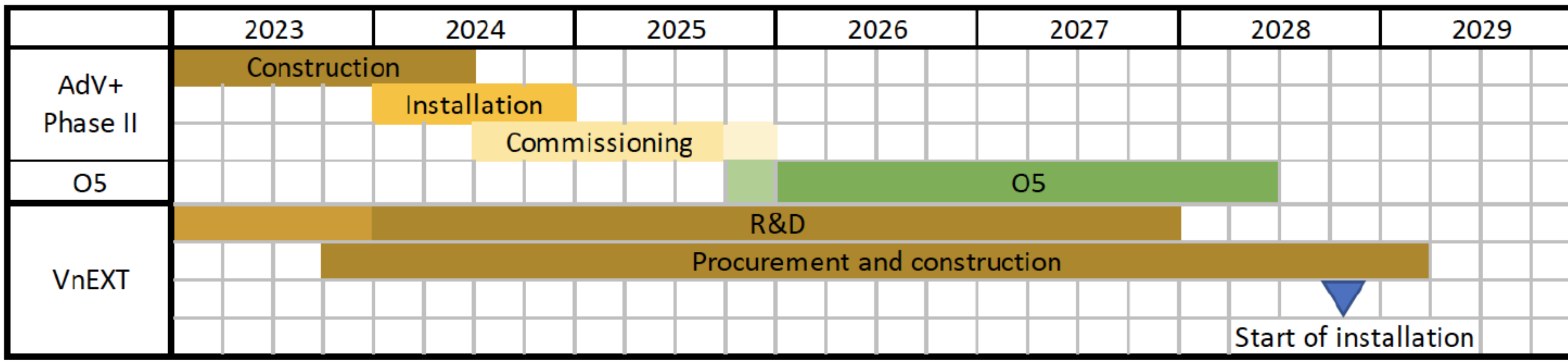


Parameter	O5	Initial post-	[illegible]
Injected squeezing	12 dB	12 dB	[illegible]
injection losses	6.5%	5.5%	[illegible]
FC losses	30 ppm	30 ppm	20 ppm
Readout losses	6%	4.5%	2.5 %
Arm-cavity roundtrip losses	75 ppm	75 ppm	75 ppm
Signal extraction cavity (SEC) roundtrip losses	1000 ppm	1000 ppm	500 ppm
Phase noise	25 mrad	15 mrad	10 mrad
Mismatching squeezing - filter cavity	0.5%	0.5%	0.25%
Mismatching squeezing - interferometer	2%	1%	0.5%
Measured squeezing at high-frequency	**5.5 dB**	**7.5 dB**	**10.5 dB**

- Squeezed light source: improve in-air OPO? Or OPO in vacuum?
- Injection losses: Improve Faraday isolators
- FC losses: better mirrors
- Readout losses: new OMC
- Phase noise: improve electronics/controls
- ITF losses: reduce reflection/scattering losses in central interferometer
- Mismatch: more sophisticated Mode-matching sensors and actuators

Incremental approach is possible

Preliminary planning



- Need discussions in the LVK on detailed plans after O5
  - fraction of observation time vs upgrade?
  - R&D investments ? Common projects?

- Mirrors represent 30% of the budget – and need ~ 3 years to be ready. When to start the production? When to change them ?