Post-O5 scenario for LVK collaborations

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On behalf of the post-O5 teams and of the LIGO/VIRGO/KAGRA collaboration

ET Symposium, June 2022, Budapest.

VIR-0605A-22

Post-O5 committees

Virgo

Instrument Science: M. Barsuglia, M. Carpinelli, O. Chaibi, V. Fafone (chair), G.Gemme, S. Hild, P. Puppo, E. Tournefier; Observational Science and Data Analysis: T. Dal Canton, E. Milotti, S. Nissanke (chair), C. Palomba, T. Regimbau

Ligo

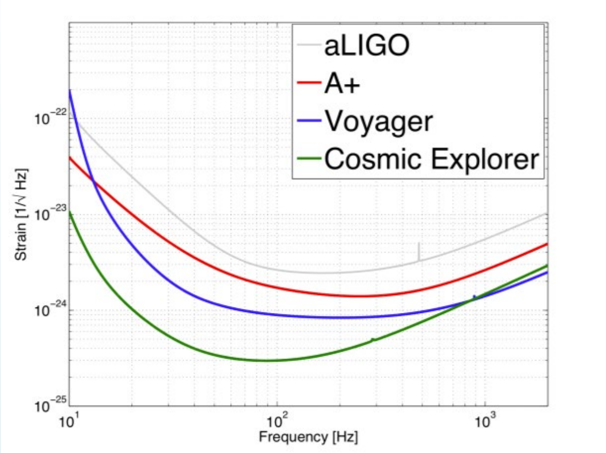
P. Fritschel (chair), B. Lantz, D. Ottaway, S.Ballmer, R. Adhikari, M. Evans, P. Schmidt, J. Driggers, A. Effler, K. Dooley, G. Gonzalez, S. B. Farr , K. Kuns, D. Reitze, A. Lazzarini, P. Brady

Focus on possible upgrades on existing ITFs for Virgo(_nExt) and Ligo (A#)

- Higher power: **1.5 MW** in the arms (doubling from A+)
    - Lasers, thermal compensation, parametric instability mitigation
- Higher levels of squeezing: **10 dB**
    - Reduced optical losses, improved mode-matching
- Larger Test Masses: **100 kg**
    - Beam sizes remain the same
- Test Mass Suspension Upgrades
- Coatings
- Seismic Isolation improvements

Voyager

- CONCEPT FOR A **NEW DETECTOR IN THE CURRENT FACILITIES**;
- DESIGNED TO MAXIMIZE THE OBSERVATIONAL REACH OF THE INFRASTRUCTURE AND **DEMONSTRATE THE KEY TECHNOLOGIES TO BE USED FOR 3G OBSERVATORIES** IN NEW INFRASTRUCTURES.
- USE **HEAVY (CA. 200 KG) CRYOGENIC MIRRORS** WITH **IMPROVED COATINGS** AND UPGRADED SUSPENSIONS MADE OF **ULTRA-PURE SILICON AT A TEMPERATURE OF 123 K**
- USE THE EXISTING VACUUM ENVELOPE
- A LASER WAVELENGTH OF VOYAGER ~ 1.5um – 2um



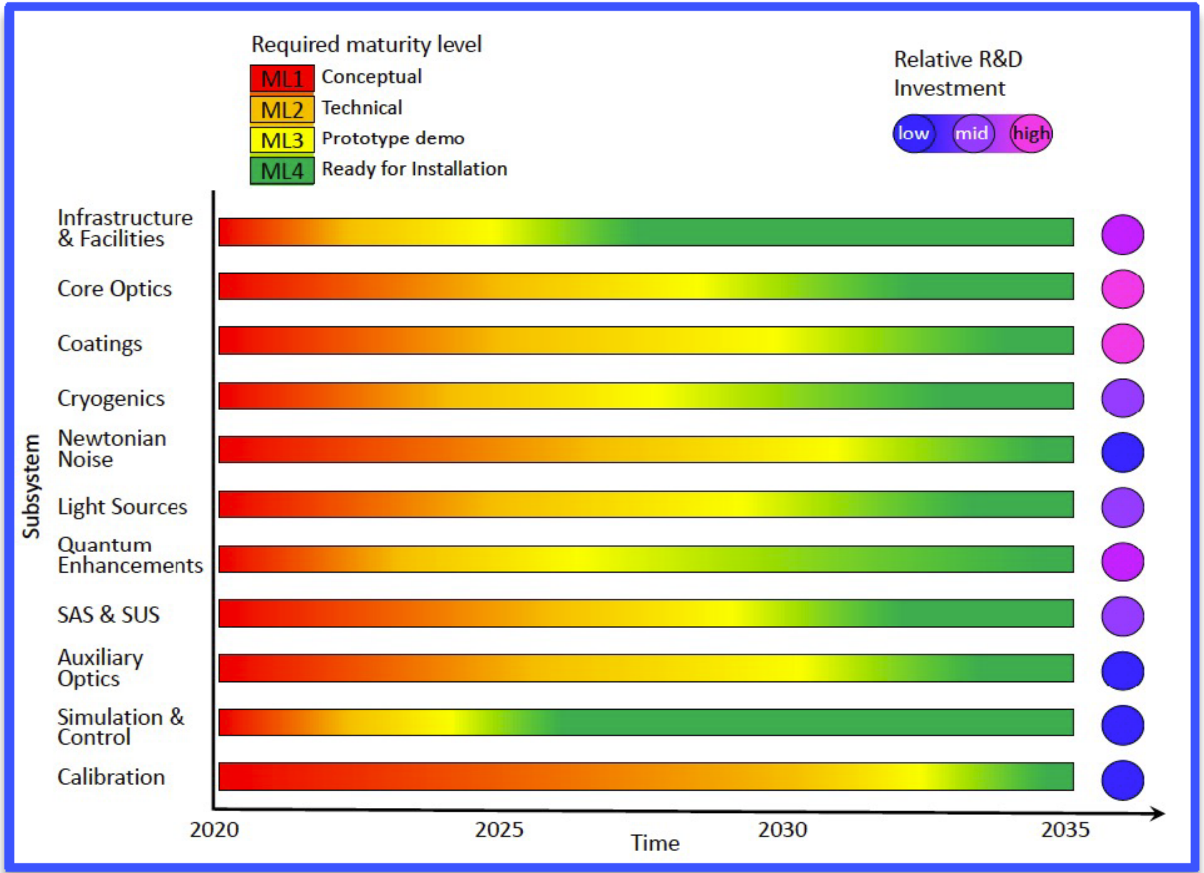
LIGO-T1400316–v4

A Cryogenic Silicon Interferometer for Gravitational-wave Detection, R.Adhikari et al., arXiv:2001.11173

Voyager

- Voyager team is in the process of assessing the Voyager technologies using the Technology Readiness Level (TRL) approach used in NASA, DoD, etc.
  - TRLs measure the maturity of a technology on a scale of 1 to 9 (9 most mature)
  - A TRL of 6 or above is generally seen as the requirement for proceeding with a project
  - One definition of TRL 6: *System/subsystem model or prototype demonstration in a relevant environment.*
- We'll be looking to apply the TRL assessment to the other (existing interferometer) upgrades as well as appropriate

Technology Readiness Roadmap

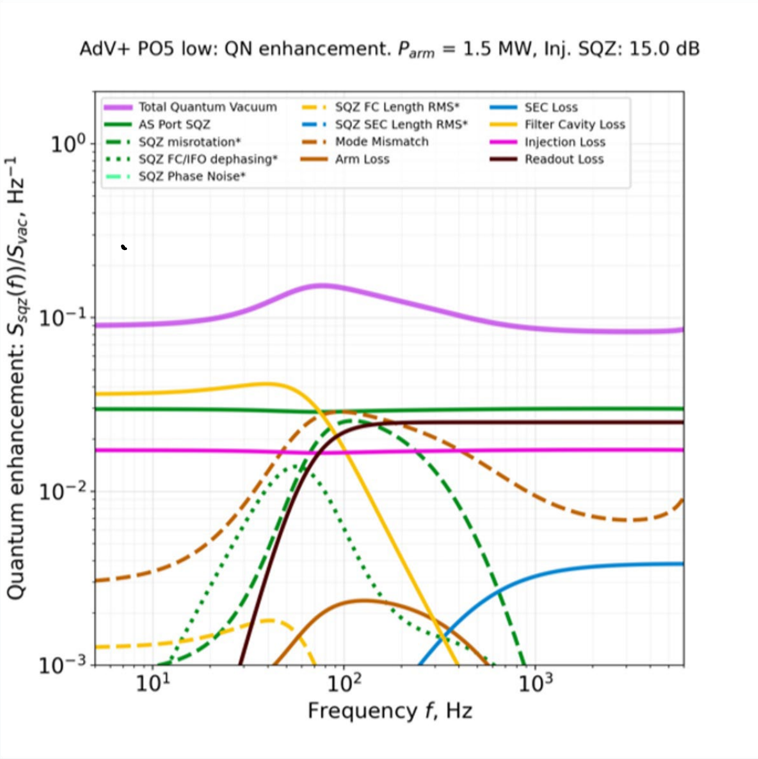


From D. Reize, talk on GWIC at 2nd EPS Meeting on Gravitation

Quantum Noise: FD Squeezing

Goal: 10 dB frequency-dependent squeezing observed

	O5	post O5
Injected SQZ	12 dB	15 dB
OPO losses	1%	1%
Injection losses	6.5%	1.8%
FC losses	30 ppm	20 ppm
Readout losses	6%	2.5%
Arm losses	75 ppm	75 ppm
SEC losses	1000 ppm	500 ppm
Phase noise	25 mrad	10 mrad
MM SQZ->FC	0.5%	0.25%
MM SQZ->ITF	2%	0.5%
Measured SQZ	**5.5 dB**	**~10.5 dB**



R&D on squeezing needed: source, losses, noise

Quantum Noise: High Power

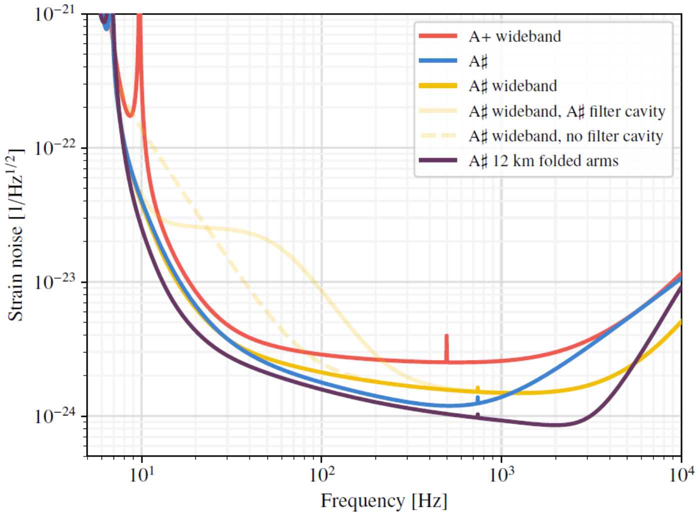
- **Aim for about 280 W input, yielding 1.5MW in the arms**
- **High power laser sources have been successfully demonstrated**
  - 398W by coherent combining @AEI
  - Up to 350W with phosphosilicate fiber @ Bordeaux
- **Parametric Instability**
  - 105kg ITMs as well as ETMs
  - Passive dampers
  - Active damping to be explored using auxiliary lasers
- **Aberration Control (TCS) - high-level tasks**
  - Lensless RH: tune RoC, keeping lens in the substrate constant
  - Correction of residual non-spherical aberration
  - Wavefront sensing technique upgrade
  - Thermal-defocus free wavefront sensing technique
  - Other R&Ds (diffractive optic elements, alternative wavelength)

LIGO

High frequency upgrades

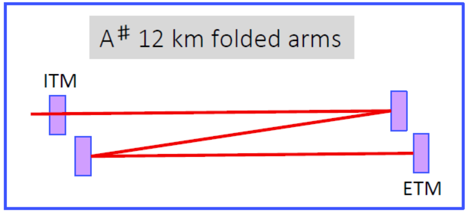
LSC

D Ganapathy et al, PRD 103 022002 (2021)



$A^{\#}$ & ~~A+~~ wideband:

- More signal recycling to further widen the arm cavities
- Filter cavity re-optimization
- At the expense of sensitivity at mid-frequencies, by ~1.5x



*D Martynov et al., PRD **99** 102004 (2019)*

From Peter Fritschel LVK meeting, March 2022 LIGO-G2200545-v1

Coating Thermal Noise

- **Amorphous coating→ improvement of a 3-4 factor on loss angle**
  - Materials and deposition procedures
- **Crystalline oxides coatings → a factor of 13 reduction on loss angle**
  - Materials development and deposition technique (only 300 mm area so far)
  - coating transfer and bonding

Technological problems to be solved :

- **Origin of Absorption (point absorbers)**
  - development of a model for absorption in amorphous coatings
  - investigation on correlations between absorption and contaminants
- **Metrology**
  - Loss angle measurement at low temperatures
  - Crystalline materials characterization
  - Spectroscopic investigations

Suspension Thermal Noise

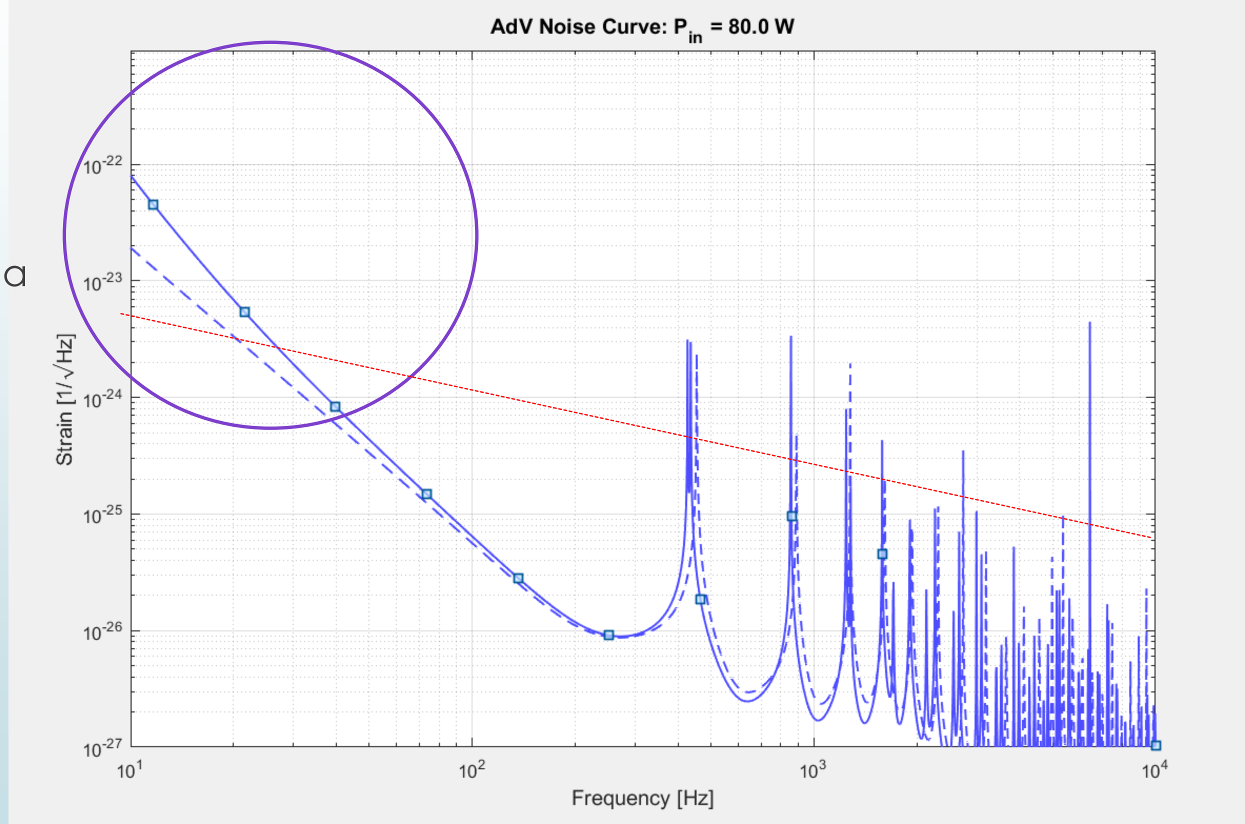
All large test masses with a monolithic intermediate mass

→ **triple pendulum** The use of a penultimate mass allows the losses coming from the marionette to be filtered.

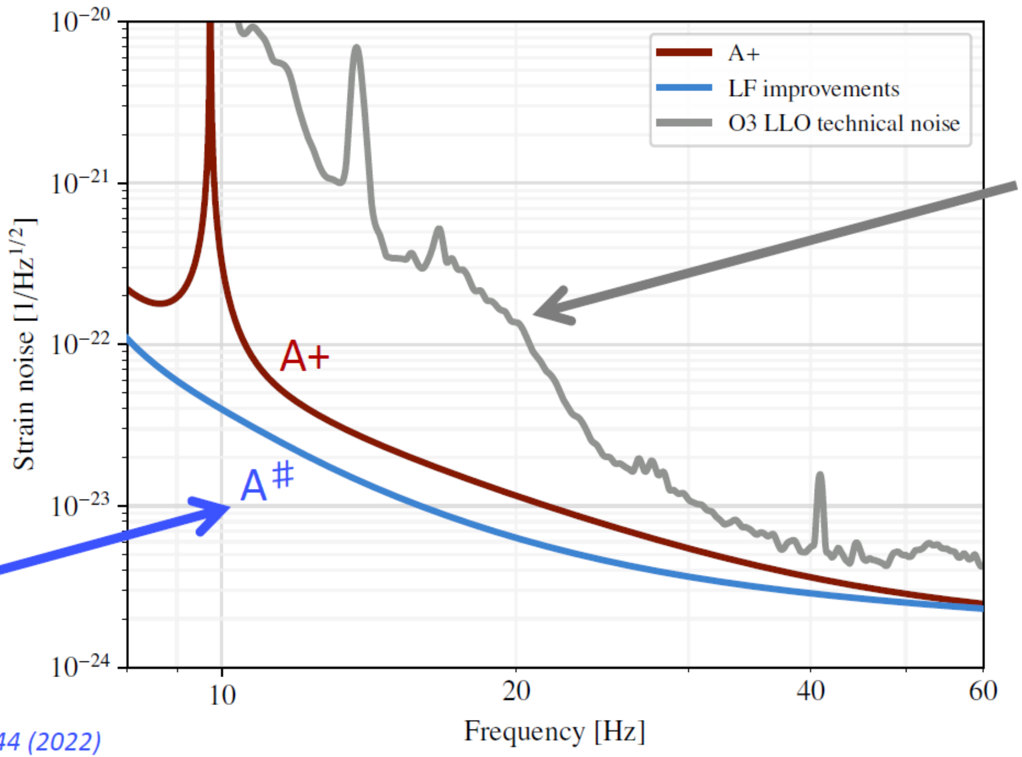
→**Relevant gain in the low frequency range**

→**Gain in LF control noise**

→**SA chain reviewed to improve seismic noise filtering and sensors**



Low frequency improvements



Fibers stressed to 1.6 Gpa
Roll mode at 9.6 Hz

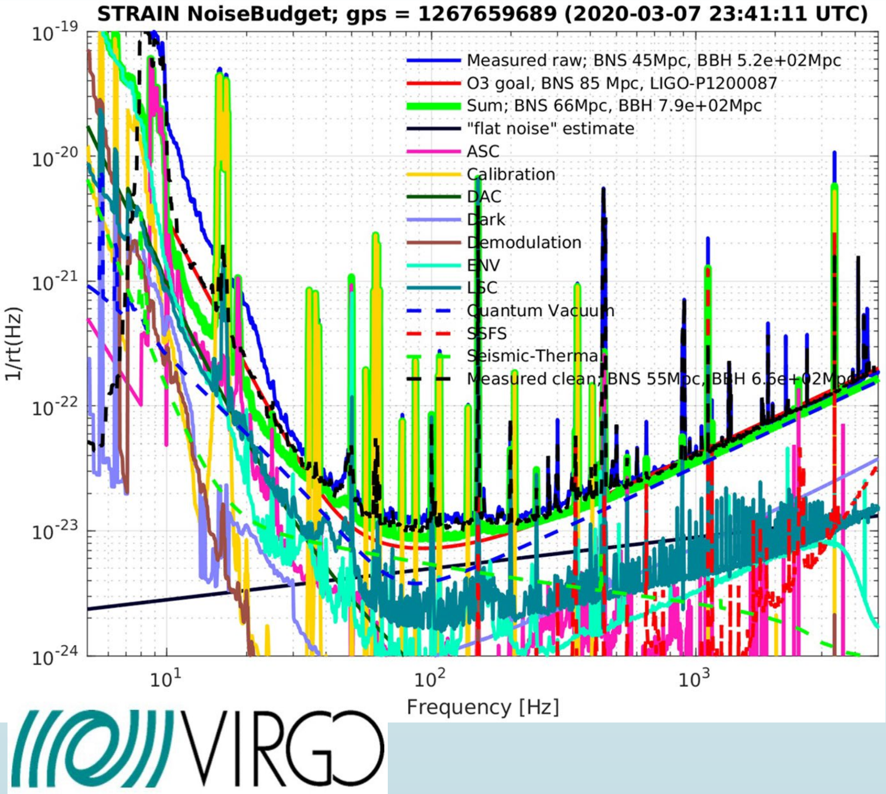
*A Cumming et al., PRA **17** 024044 (2022)*

Low frequency excess due to controls noise is addressed through:

- Better seismic isolation
- Better suspensions: less cross-coupling to angles
- Larger test masses

From Peter Fritschel LVK meeting, March 2022 LIGO-G2200545-v1

Further actions



- **Newtonian noise:** upgrades with different types of sensors and/or deployments outside the buildings;
- **Residual gas noise:** the noise level due to residual gas a factor of 2 better than in O5 (factor > 4 in terms of pressure):
  - improved pumping of towers.
  - bake-out of the 3km UHV pipes. The goal residual pressure in the arms is 1E-9 mbar (H_2 dominant)
- **Other technical noises** improvements (R&Ds)

Comparison of Parameters

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

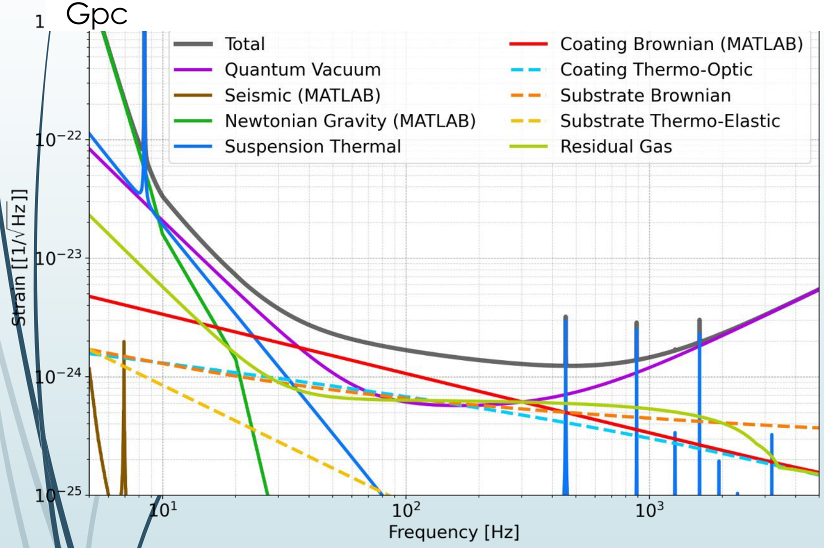
VIRGO

LIGO

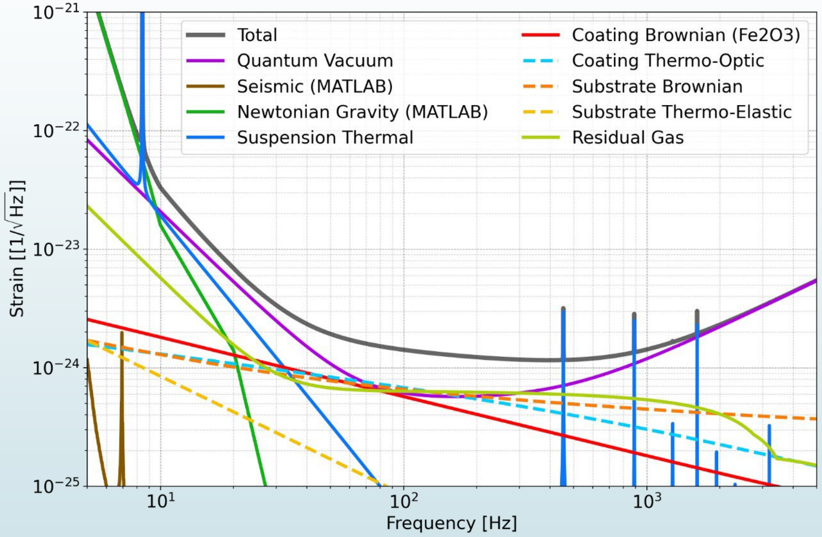
Parameter	Units	A+	A$^\sharp$	STO	Voyager
Arm power	kW	750	1500	1500	3000
Laser wavelength	µm	1	1	1	2
Test mass material		Silica	Silica	Silica	Silicon
Temperature	K	295	295	295	123
Mass	kg	40	100	200	200
Observed squeezing	dB	7	10	10	7
Rayleigh wave suppression	dB	0	6	20	20
Horiz. susp. pt. at 1 Hz	pm/$\sqrt{\text{Hz}}$	10	10	0.1	0.1
Final susp. stage blade		No	No	Yes	Yes
Filter cavity length	m	300	300	4000	300

Noise Budget

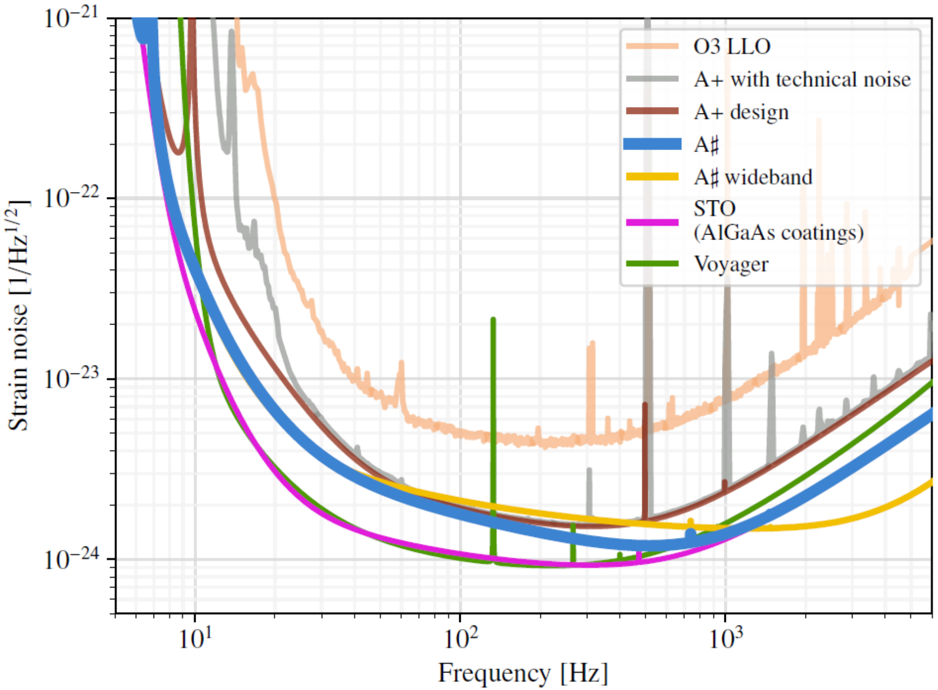
VnEXT (amorphous coating) BNS =440 Mpc, BBH = 3.0 Gpc



VnEXT (crystalline coating) BNS =500 Mpc, BBH = 3.3 Gpc



- Jupyter notebook and data of sensitivity curves available on TDS: VIR-0138D-22. https://tds.virgo-gw.eu/ql/?c=17784
- Sensitivity code available at: https://gitlab.et-gw.eu/et/isb/interferometer/adv_noisebudget



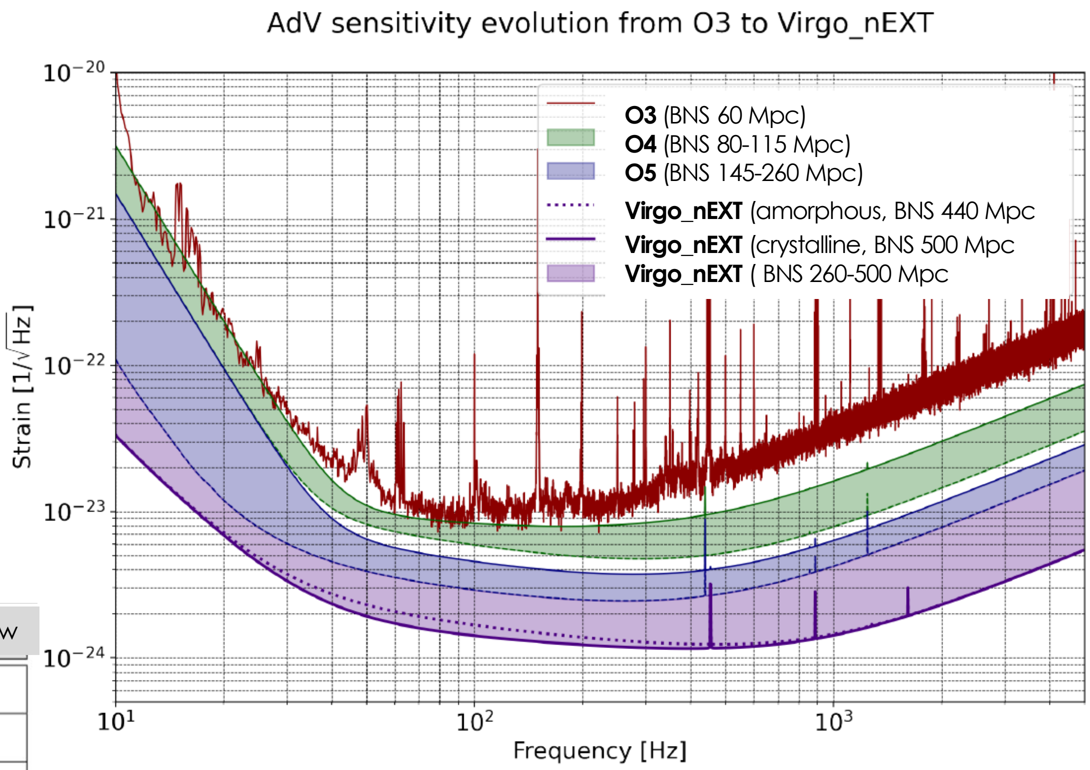
A$^{\#}$ versus A+:

- *Low frequencies*: close to a factor of 2 reduction
- *High frequencies*: factor of 2 reduction
- *Mid frequencies*: minimal reduction, limited by coating thermal noise

A# noise spectrum and others

From Peter Fritschel LVK meeting, March 2022 LIGO-G2200545-v1

Sensitivity forecast for Virgo nEXT

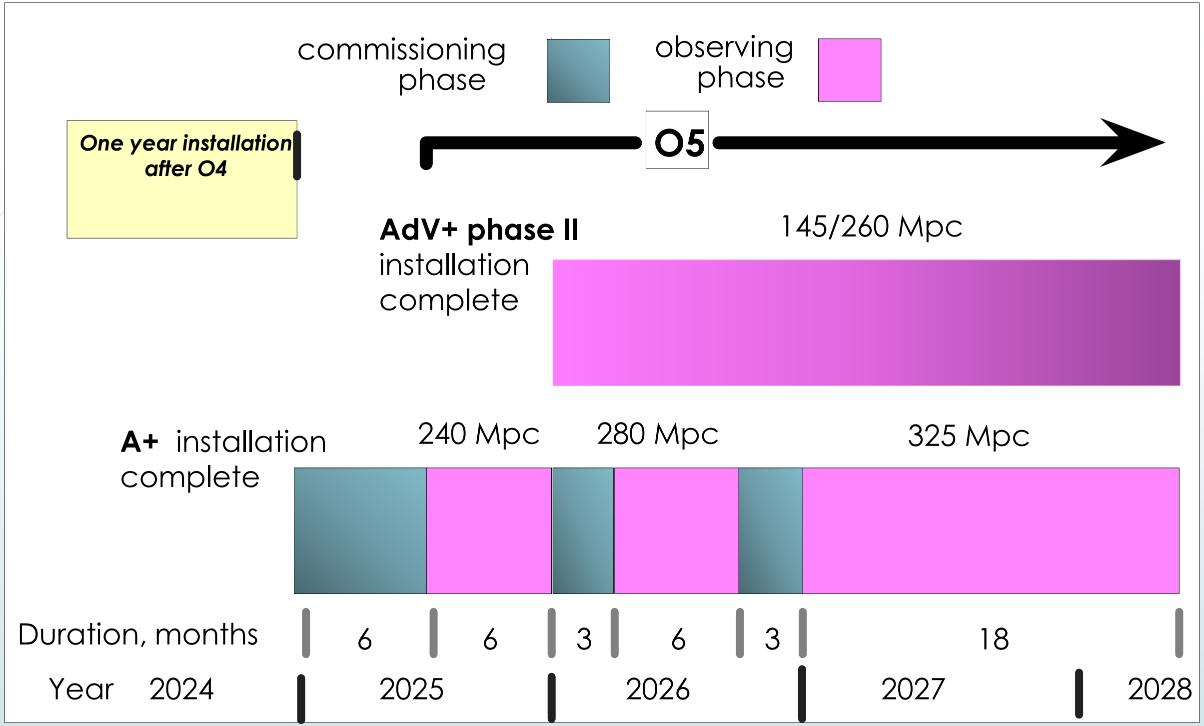


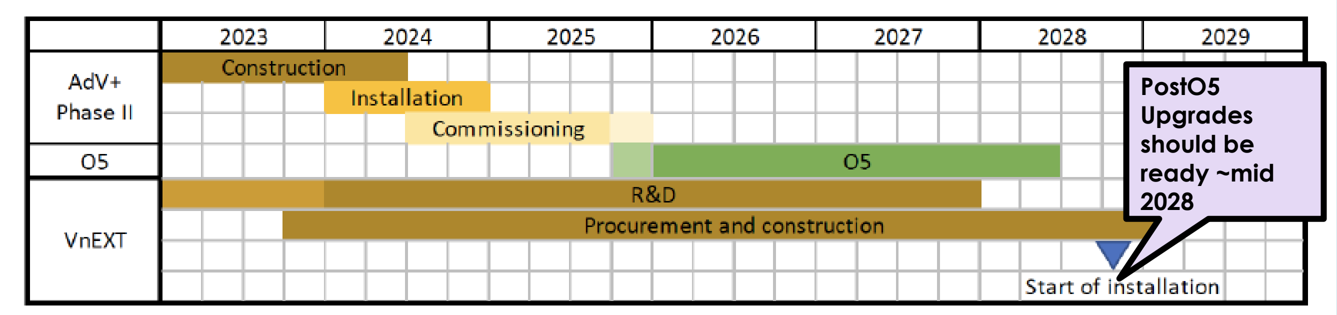
Source	O5 low	Virgo_nEXTlow
BNS range (Mpc)	258	500
BBH range ($30 + 30\,M_\odot$) (Mpc)	590	3320
Stochastic Omega	7.5e-10	2.3e-10
Supernova (kpc) [217]	18.3	51.0

Foreseen Timelines

KAGRA is also foreseen to joing O5 with an horizon spanning from 25 up to 120Mpc

But still **no postO5** plans are announced



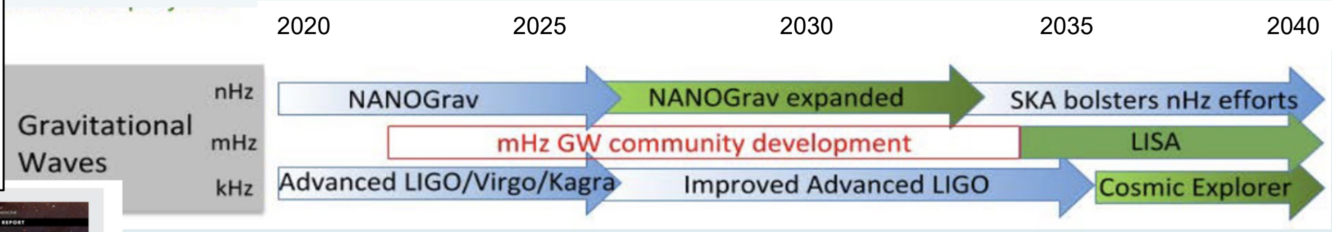


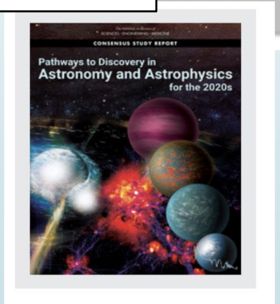
International scenario

Work is underway within LSC to scope detector upgrade options for post-O5

Pathways to Discovery in Astronomy and Astrophysics in the 2020s

Committee for a Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)





- KAGRA has not yet announced their plans for the post-O5 era.

Summary

- Work is ongoing to investigate the possibility of a further upgrade of Virgo/LIGO
- There is room for significant sensitivity improvement within the present infrastructures;
- Initial considerations on timeline worked out in order to start installation after O5 and leave rooms for years of post-O5 observation time
- Discussion on detailed plans for installation, commissioning, observing periods vs intermediate upgrades area being addressed in agreement with LIGO, and KAGRA at a later stage.
- Synergy with 3G detectors: the benefits of Virgo_nEXT (and A#) for 3rd generation in terms of development of technologies and risk reduction (e.g. technical noises at low frequency) are significant.
- Report from the post-O5 team released to the Virgo collaboration for feedback.