Ground-based GW detectors in the next decade

Matteo Barsuglia (APC/CNRS)

With many inputs from LVK

MMAW, EGO, 10-12 September 2022

January 2022 meeting

- Roberto de Pietri: https://indico.in2p3.fr/event/25290/contributions/104281/attachments/68373/96104/LVK_O4alerts_MMA_Paris_Jan_2022.pdf
- Details of the alert implementation
- Numbers about rates and localizations

Outline

- O3 data taking – short summary
- Next decade: the roadmap
- A few words about the detectors
- LVK next O4 and O5 data takings
  - Detectors
  - Rates and localization capabilities
- Open data
- The post-O5 era (Virgo_nEXT and A#)
- ET vs Virgo

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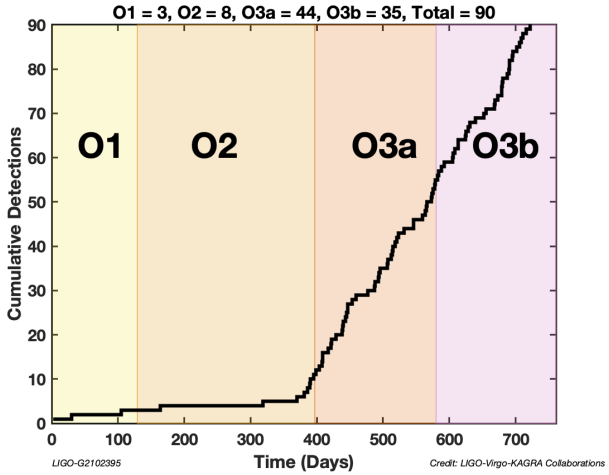
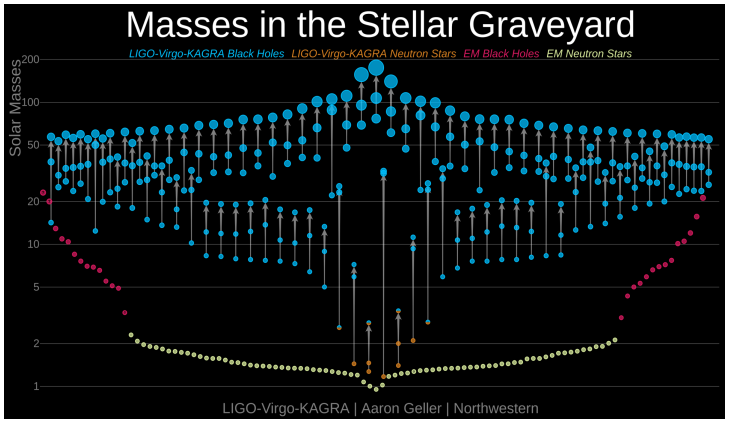
O3 (LVK) results – in short





- 6 new *exceptional* astrophysical systems published by LVK
- GWT3-catalog
- More distant sources wrt O3 (z ~ x 2)
- New tests of general relativity (i.e. harmonics of the GW signal)
- Population analysis (not only study of individual events)
- Upper limits on several sources and physical effects (i.e. GW background, lensing, specific dark matter candidates)

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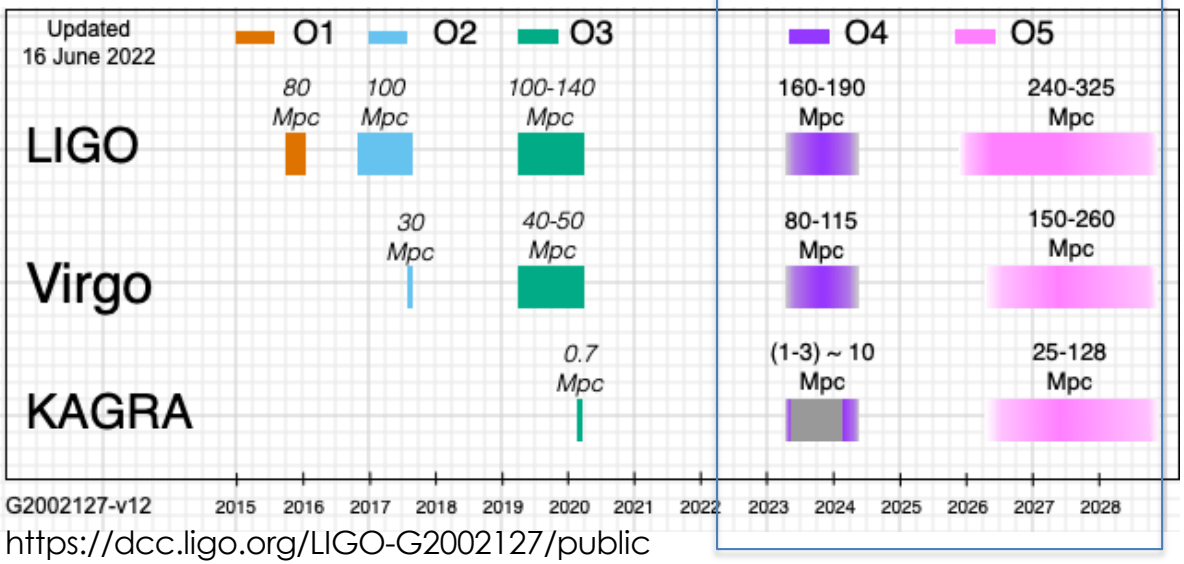
Ground based GW detectors
The (possible) roadmap

Current infrastructures

New infrastructures



https://dcc.ligo.org/LIGO-G2002127/public

Advanced Virgo+
Advanced LIGO+

- Virgo_nEXT
- A#

~ 2030-2035

- Einstein Telescope
- Cosmic Explorer

> 2036

TDR ready
Already funded

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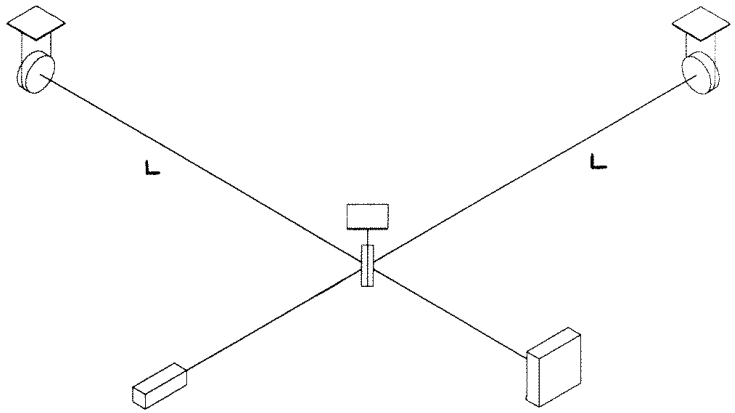
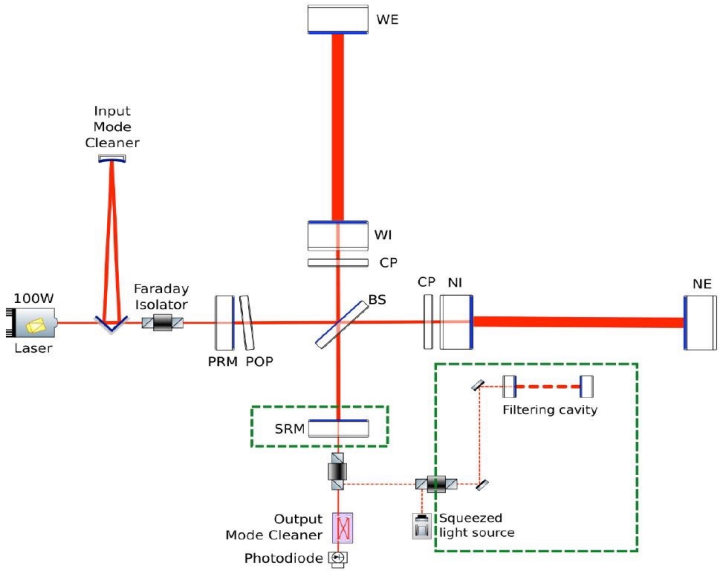
Ground based interferometric GW detectors

Modified Michelson interferometers (dual recycled fabry-Perot Michelson interferometers) with suspended test masses and use of frequency dependent quantum squeezing

- From ~ 1970' to 2015 → 10 orders of magnitude increase in sensitivity
- Suspended test masses / seismic isolation s
- Long arms, powerful lasers, suspended optical benches
- Recently: quantum « squeezing »

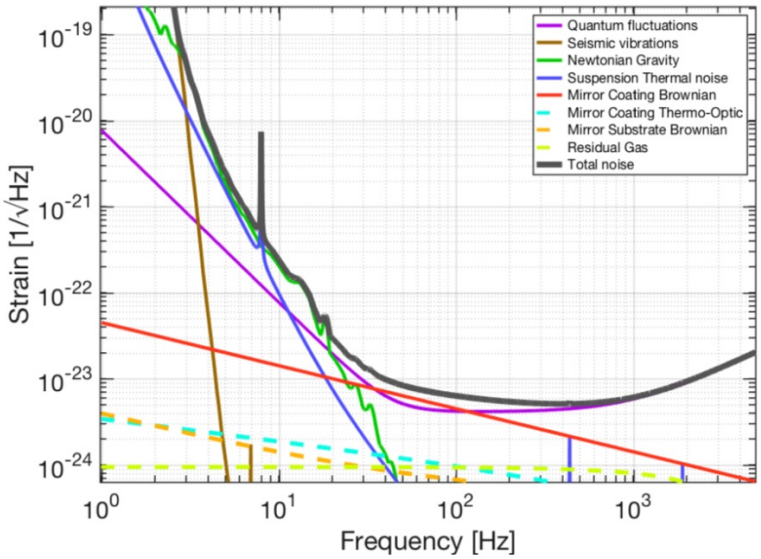




Noise sources

A possible classification:

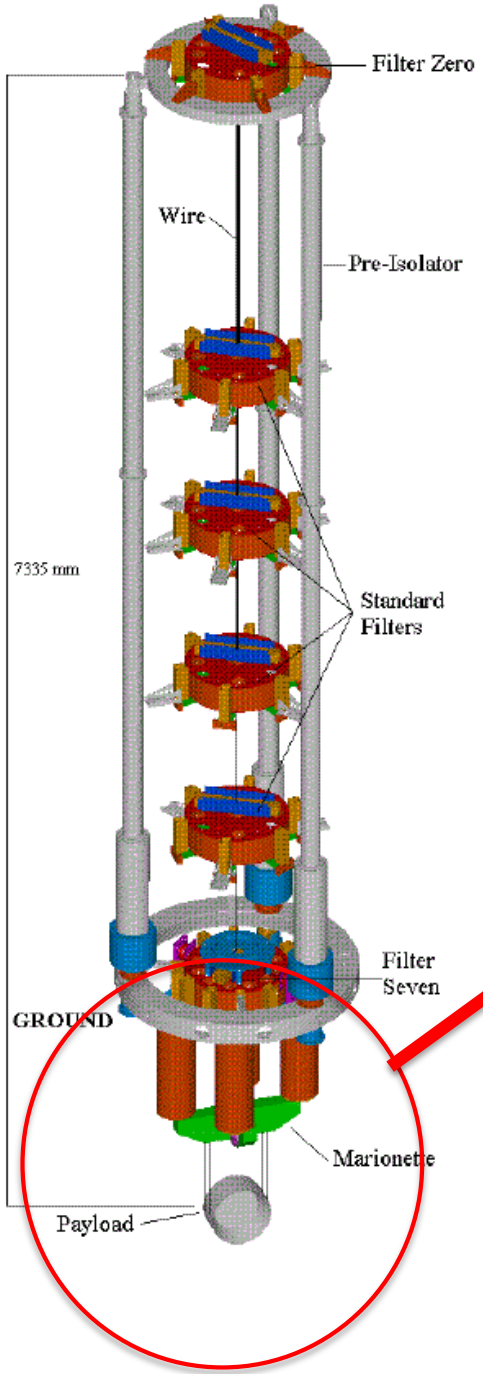
- Fundamental noises (from *first principles*)
  - Quantum, thermal
- Technical noises
  - Laser, electronics, vacuum pressure
- Enviromental noises (from the environment)
  - Seismic, acoustic, magnetic

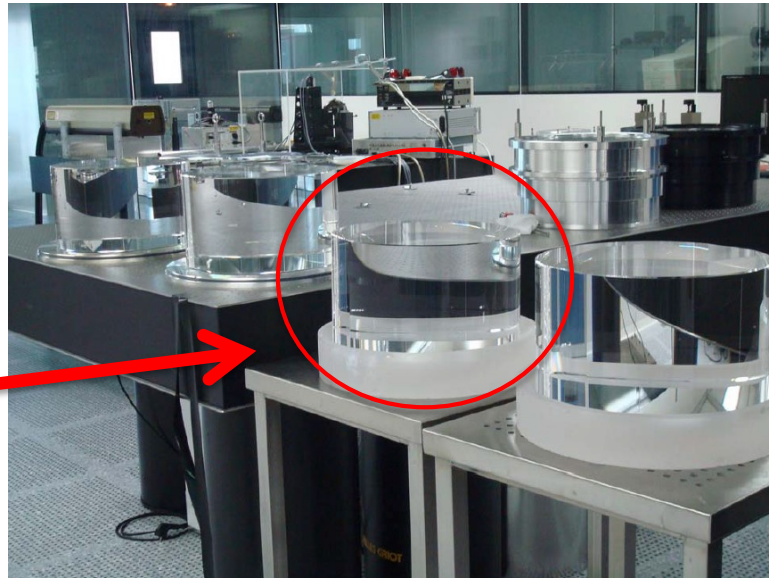


Another classification:

- Displacement noises (create a real displacement): seismic, thermal
- Read-out noises (ability of the instrument to sense test-mass mition) quantum, electronic noises of the readout

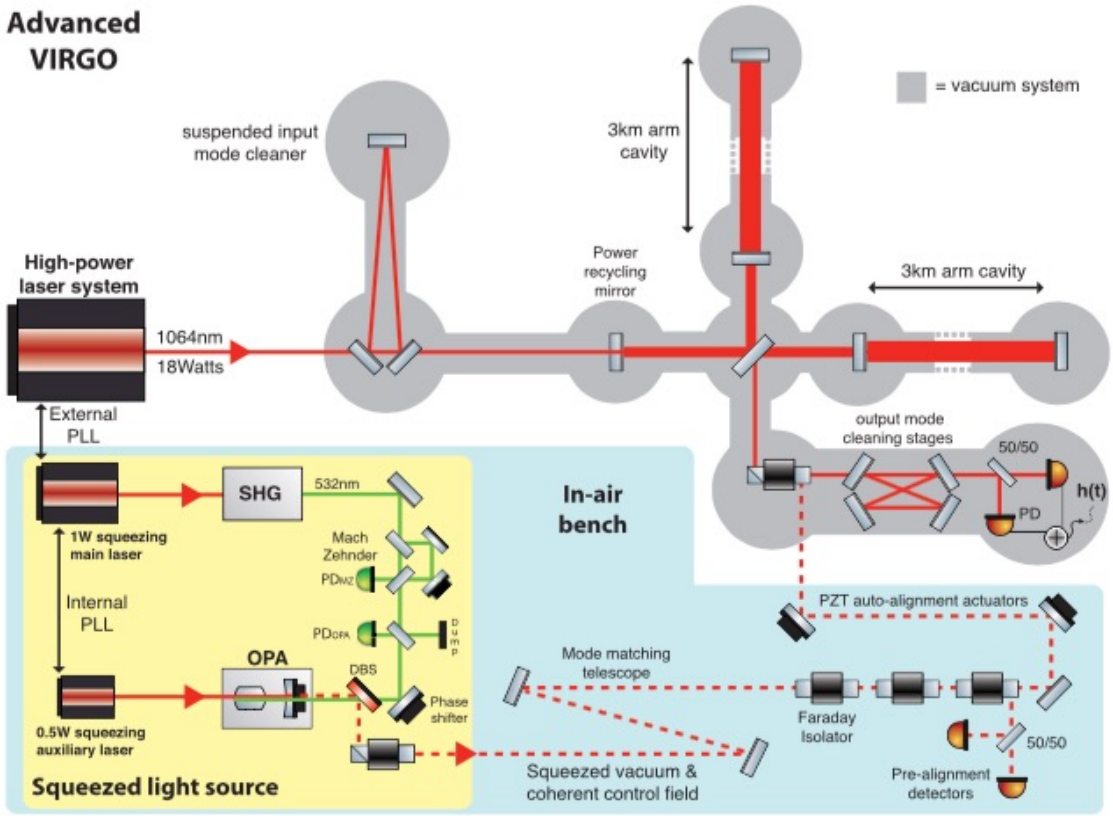
Suspensions and mirrors

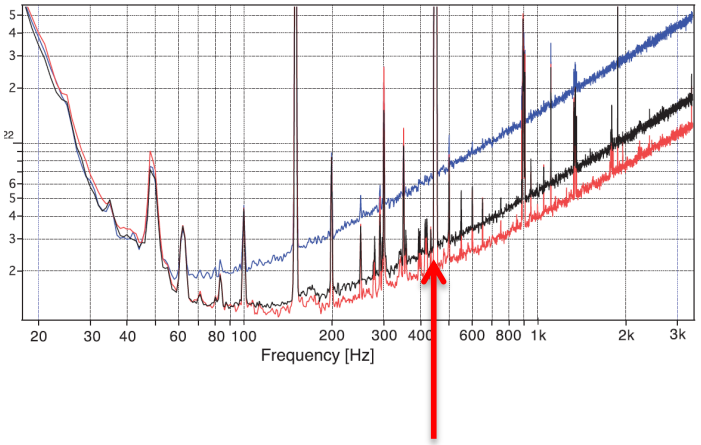




Fused silica 40 km blocks
Flatness < 1 nm RMS

Quantum squeezing





Squeezed vacuum injected

F. Arcenese, et al. (Virgo Collaboration), *Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light*, Phys. Rev. Lett. 123, 231108 (2019)

Technologies (and possible R&Ds)

- High-power and stabilized lasers
- Mirrors coatings, polishing, substrate, metrology
- Squeezing
- Scattering metrology, baffles
- Low noise electronics
- Adaptive optics : mode-matching, thermal compensation systems
- Low dissipation coatings (amoprhous and cristalline)
- Sensors (accelerometers, tiltmeter, infrasound microphones)
- Very sensitive calibration devices (optical, Newtonian)

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Connections with (non exhaustive):

Geophysics
Quantum physics
Laser and mirror technologies
Sensors
Machine learning

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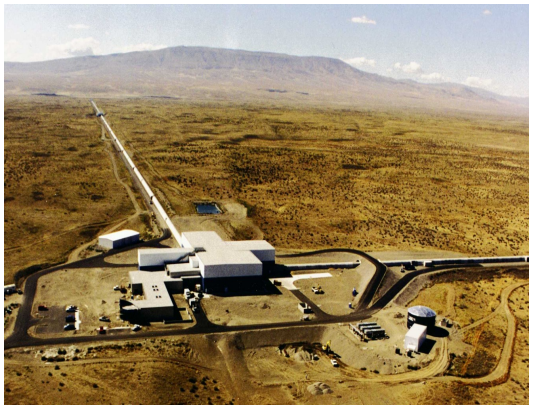
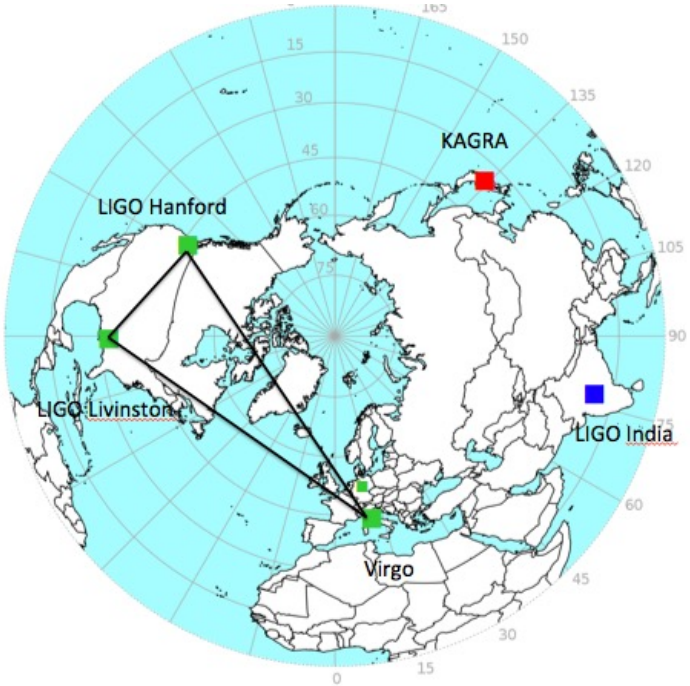
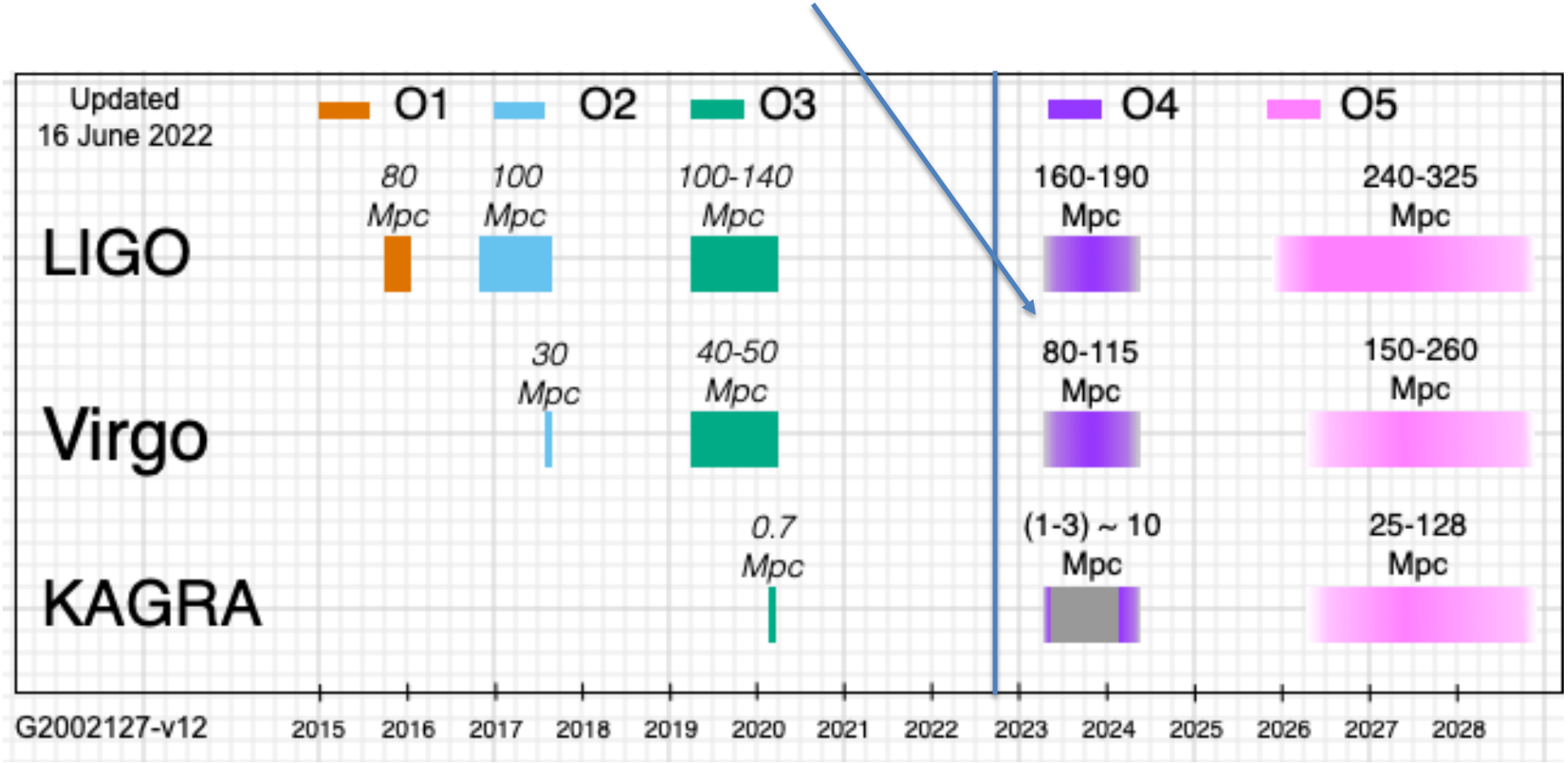
The second generation network



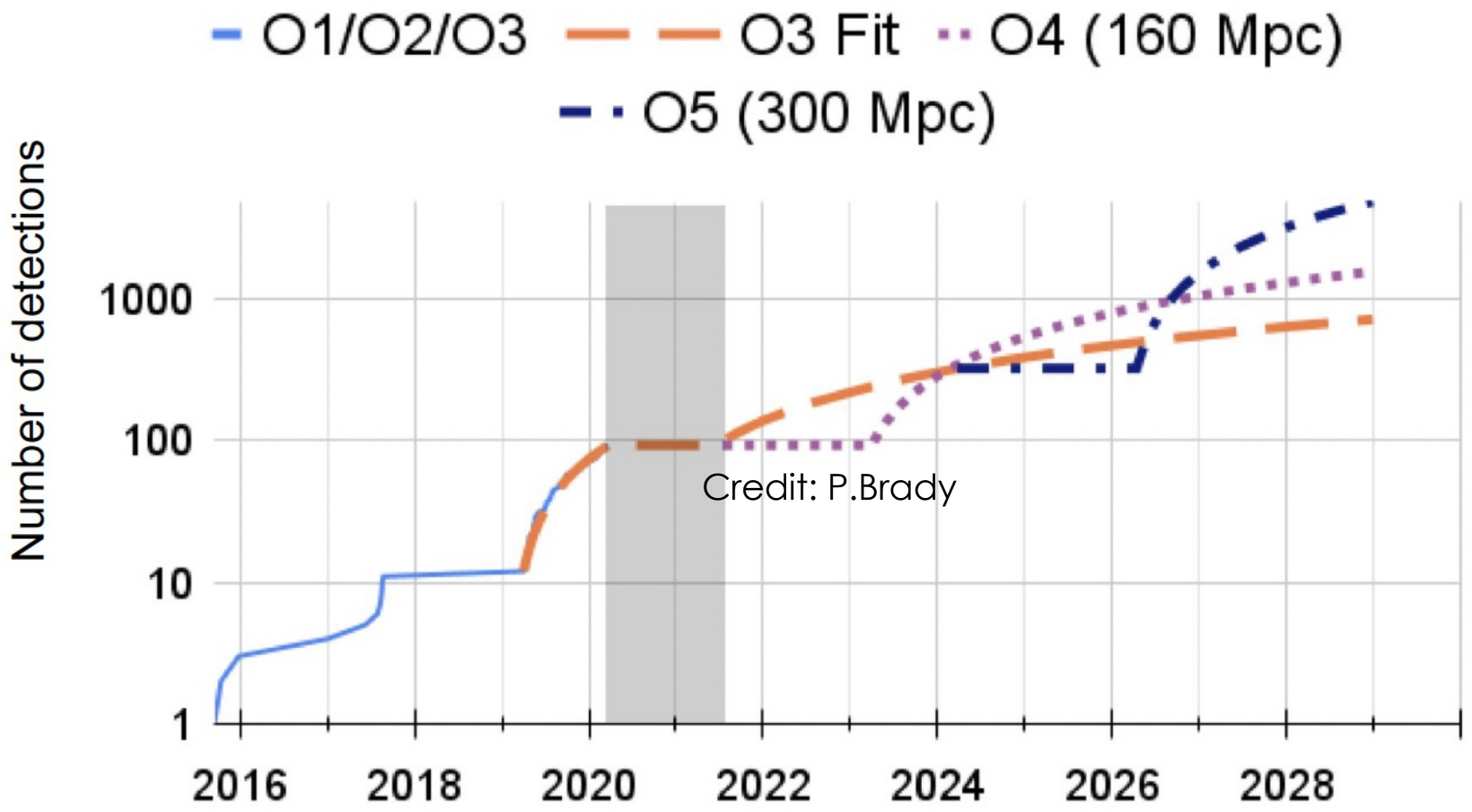


The next data takings

O4 March 2023



Alternate observing periods with upgrades

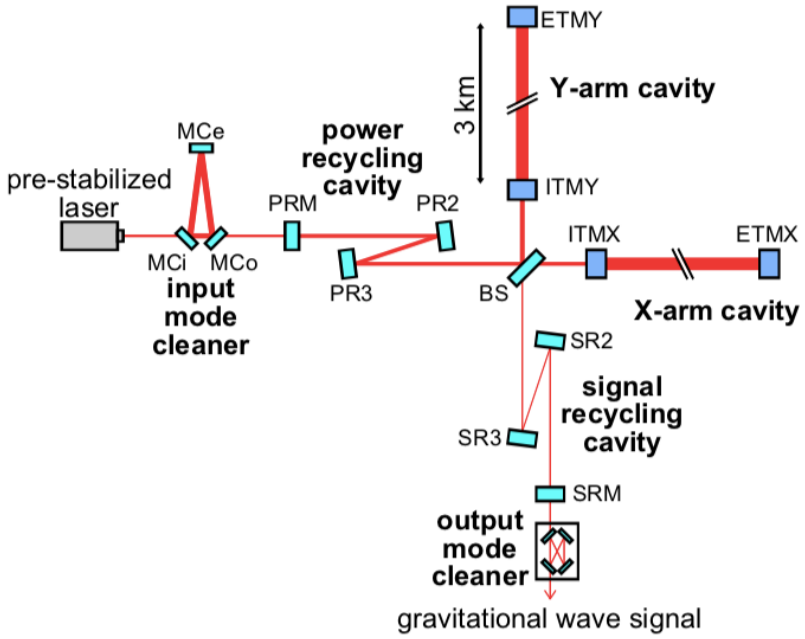


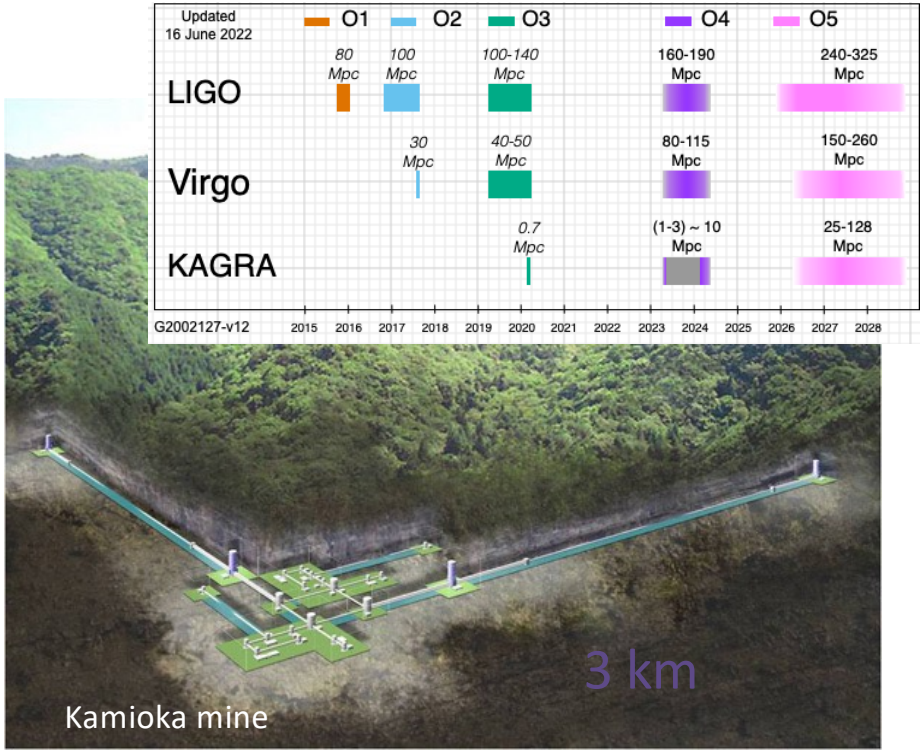
Credit:P.Brady

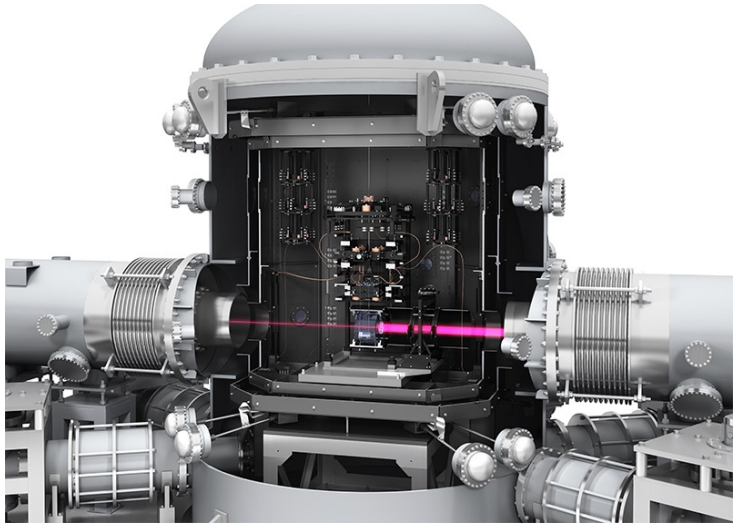
KAGRA

Japanese "2.5" Generation detector

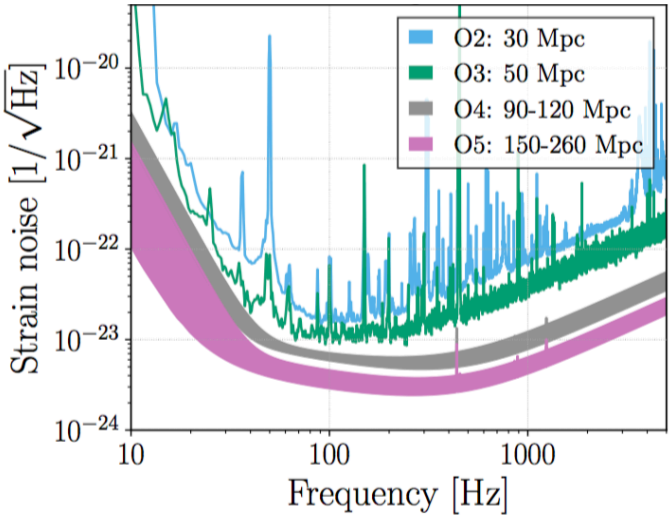
- Undeground
- Cryogenic

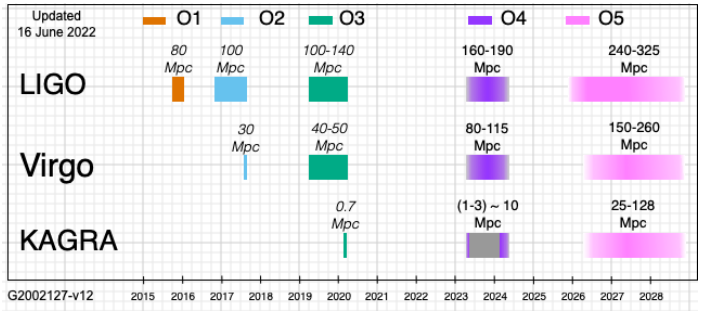




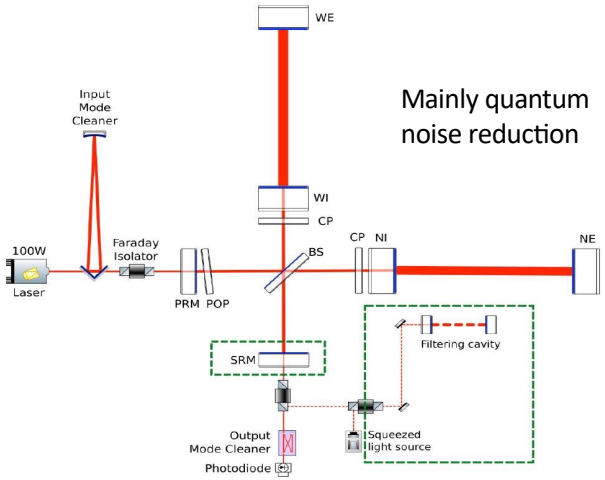


Advanced Virgo+



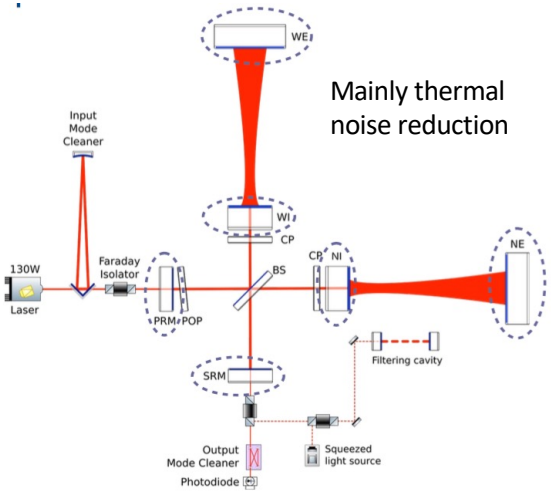


Phase 1

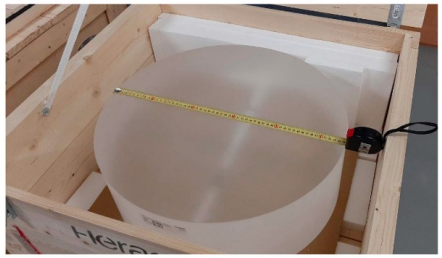


Mainly quantum noise reduction

Phase 2



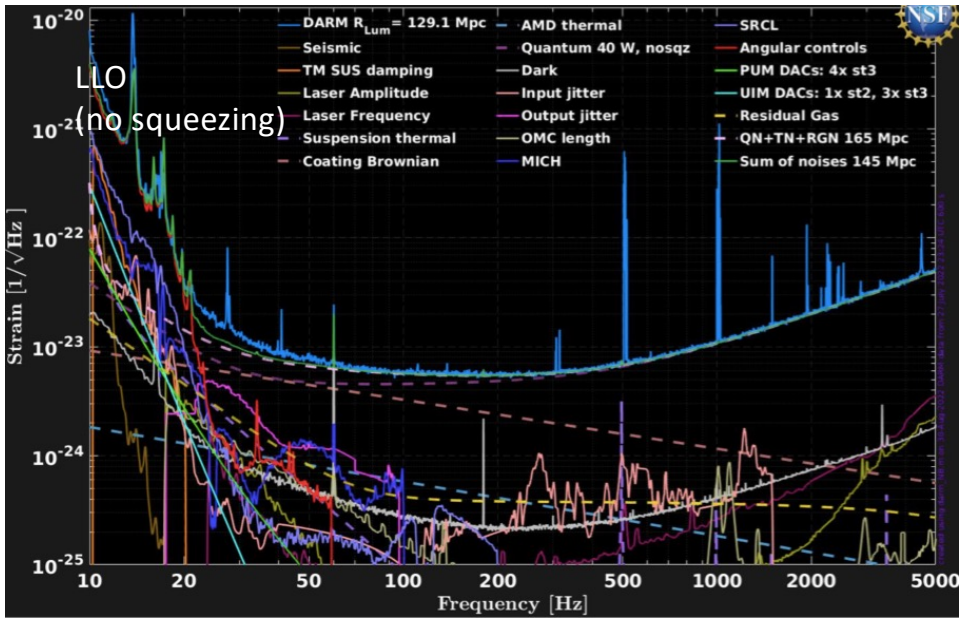
Mainly thermal noise reduction



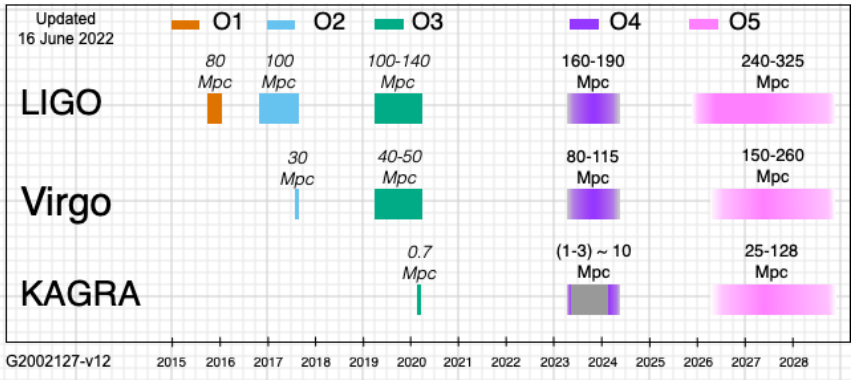
Advanced LIGO+ status

Main actions toward O4

- Test mass replacement to remove point absorbers
- Frequency dependent squeezing (filter cavity to be commissioned)
- Power increase (400 kW in the arms)
- Techical noise reduction



https://dcc.ligo.org/LIGO-G2201504



Main numbers for O4 and O5

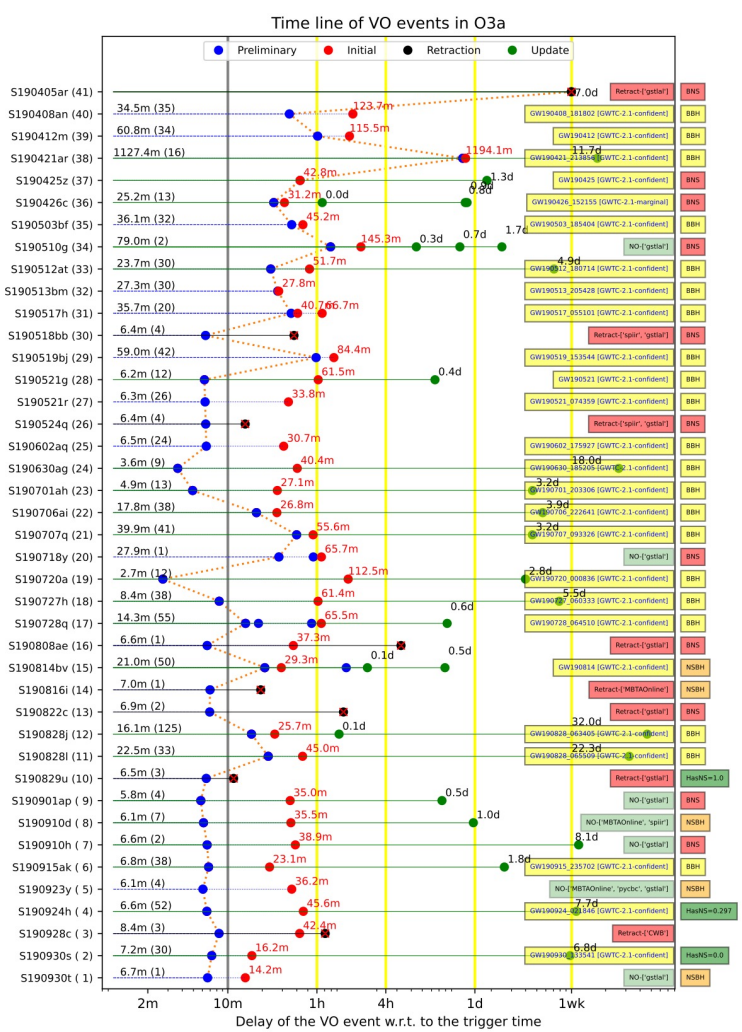
O3→ O4
~ x3 BBH (almost ~1 per day, total ~250/year)
O3→ O5
~x10 BBH (a few per day, total ~1000/year)

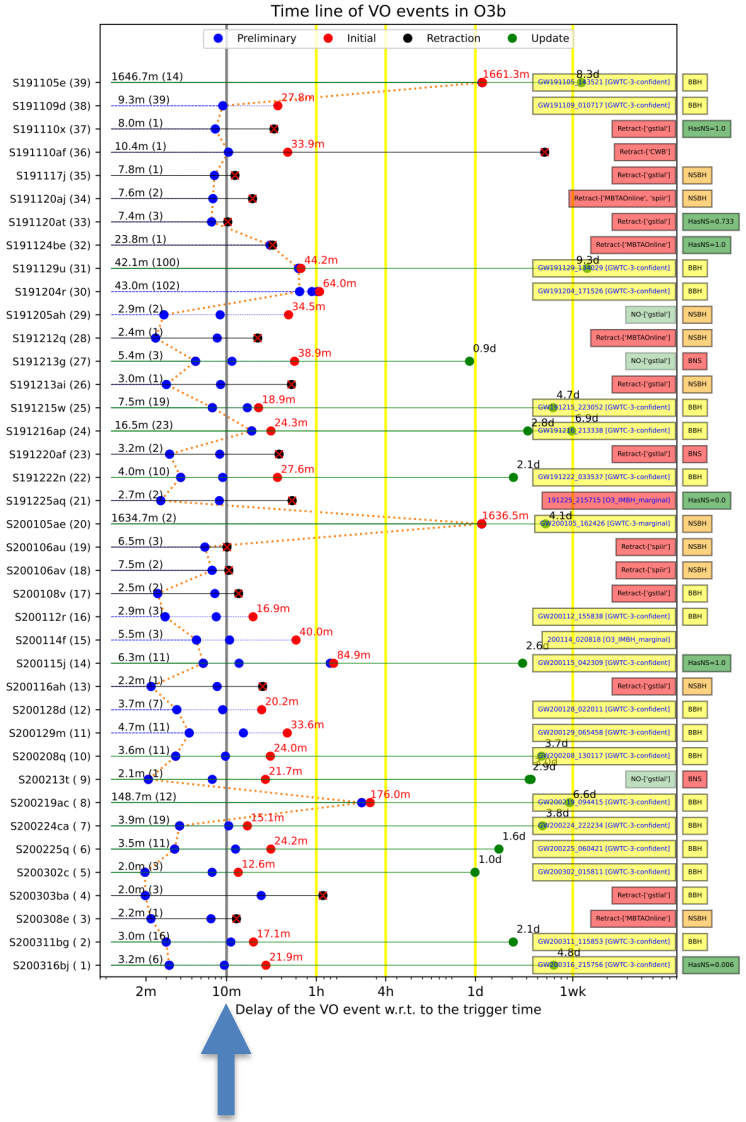
~ 5-10 BNS during O4

O4 ~ In average same online localization as O3 (KAGRA starts with 1 Mpc): a few hundreds sq deg for BNS

Alert time O4 goal ~ 1 min
(O3 preliminary ~10 min)

Alerts during O3





10 minutes

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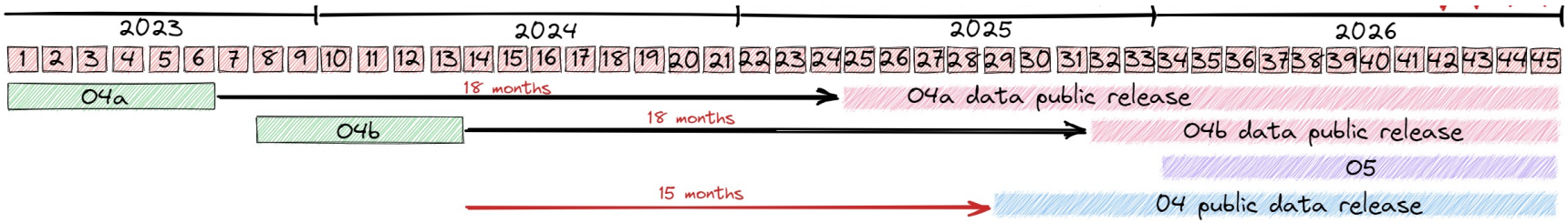
LVK open science center – GWOSC

- **GW Open Science Center – GWOSC**
  - Started in 2011 by Caltech under NSF impulse
- Release policy – Cadence & proprietary period
  - Releases will occur every 6 months, in blocks of 6 months of data, after **18 months** from the end of acquisition of each observing block
- So far data from LVK and GEO according to this schedule
  - O1: 2018 - O2: Feb 2019 - O3: Apr & Oct 2021 O3GK: Mar 2022
- Typical traffic: 100-200 users/day
- Scientists (in and outside LVK)
  - **Searches**: "bulk" data, DQ, calib systematics
  - **Astro population**: event catalog with param estimates
  - **Test of GR, waveform**: GW event with data snippet around the event
- University and high-school students
  - **Hands-on**: data analysis software and tutos



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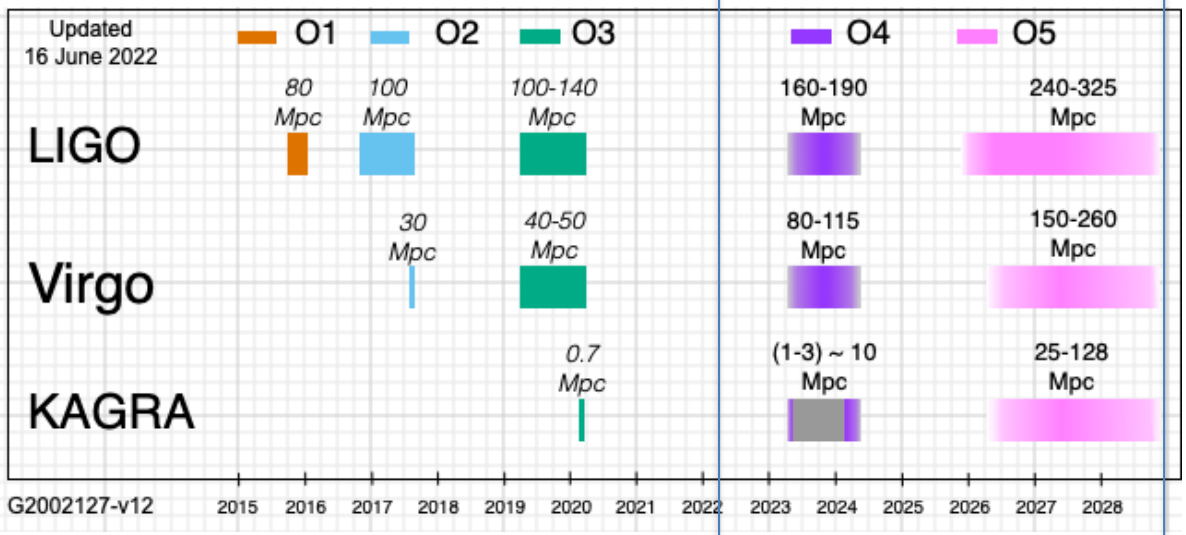
New infrastructures



https://dcc.ligo.org/LIGO-G2002127/public

Advanced Virgo+
Advanced LIGO+

- Virgo_nEXT
- A#

~ 2030-2035

- Einstein Telescope
- Cosmic Explorer

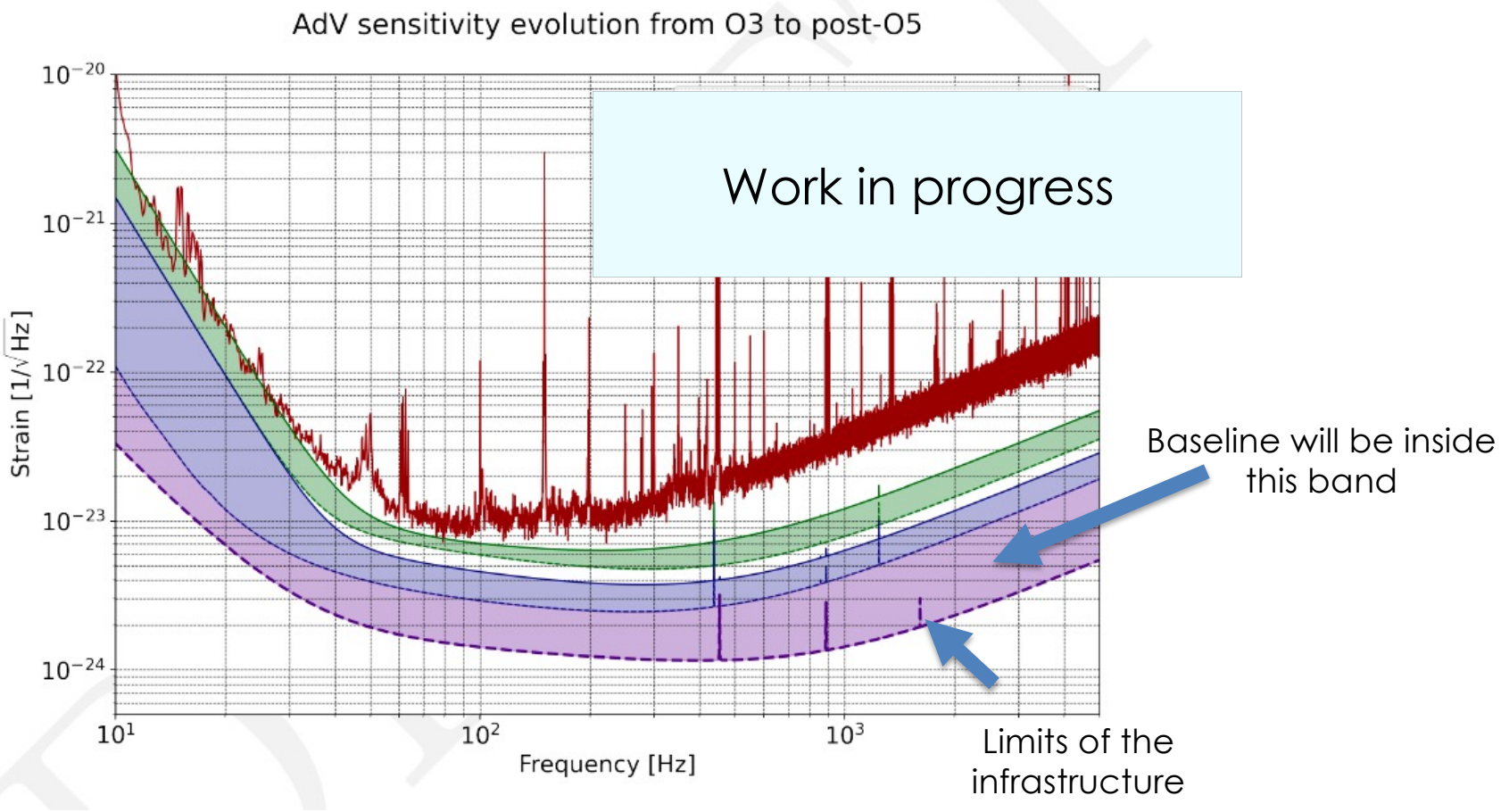
> 2036

TDR ready
Already funded

Virgo_nEXT concept study

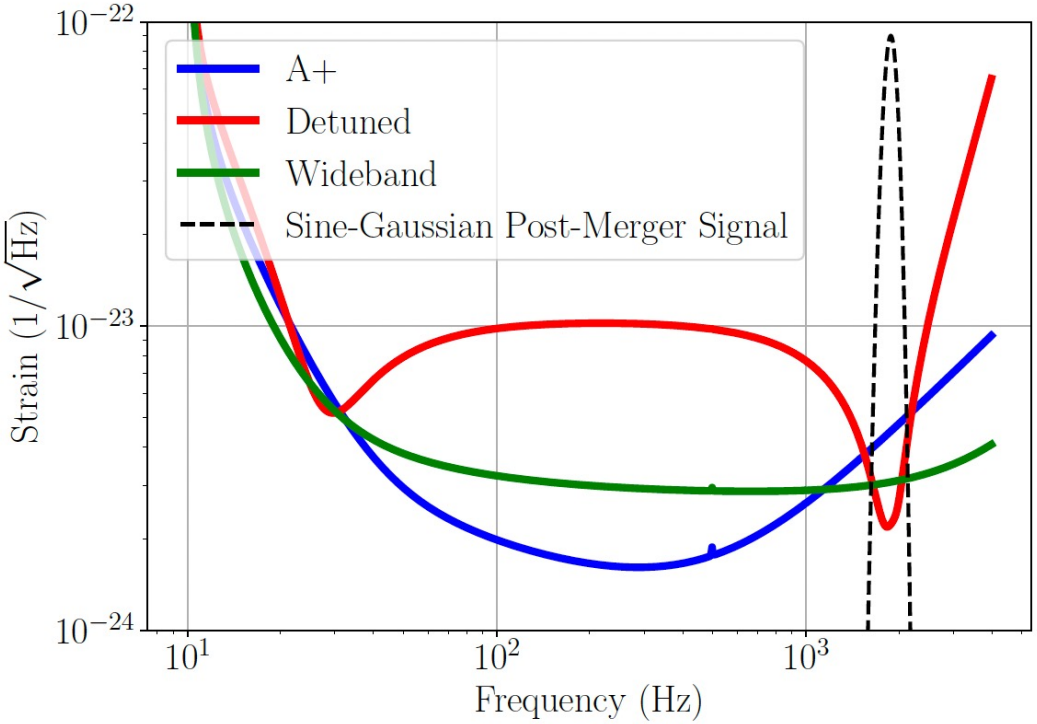
- The Virgo Collaboration produced a concept study for a new, substantial Virgo upgrade **aiming to exploit the infrastructure to its limits**
  - Show that there is the science case for a new, sustainable investment
  - Identify needed R&D lines and synergies with 3G
- Document (140 pages) – now Virgo only
- Submitted to the funding agencies
- **Not yet a baseline design**
  - Detailed plans on installation, commissioning, observing periods vs intermediate upgrades, is beyond the scope of this initial study
  - Plans to have a baseline in 2023

Virgo_nEXT sensitivity



- Similar effort in LIGO
- A#
- Official sensitivities and baseline under discussions

Possible shaping of the sensitivity



Tuning Advanced LIGO to kilohertz signals from neutron-star collisions, D.Ganapathy et al. https://arxiv.org/abs/2010.15735

Virgo_nEXT – A# within the global roadmap

- Reduce at the "dark ages" between Virgo and ET
- Pave the way to the 3rd generation (test technologies and risk reduction)
- Maintain community of high-level experimentalists for 3rd generation. Train a new generation of experts, those who will run ET
- Continue the Virgo (and LVK) scientific program of Virgo in the existing infrastructures.

Post-O5 strategy: a few strategic questions

- Fraction of commissioning/observing time in the post-O5 era ?
- Which would be the fundamental scientific questions after O5, in the decade « 2030 » (before the arrival of Einstein Telescope and Cosmic Explorer)?
- Which is the best strategy of data taking for the 4 (or 5) detectors (LIGO H, LIGO L, Virgo, KAGRA, LIGO India) ?

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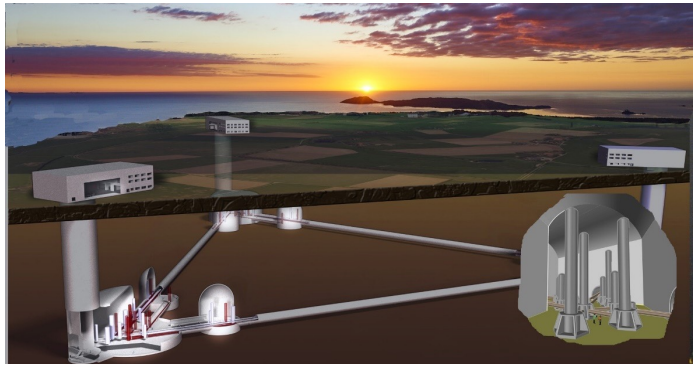
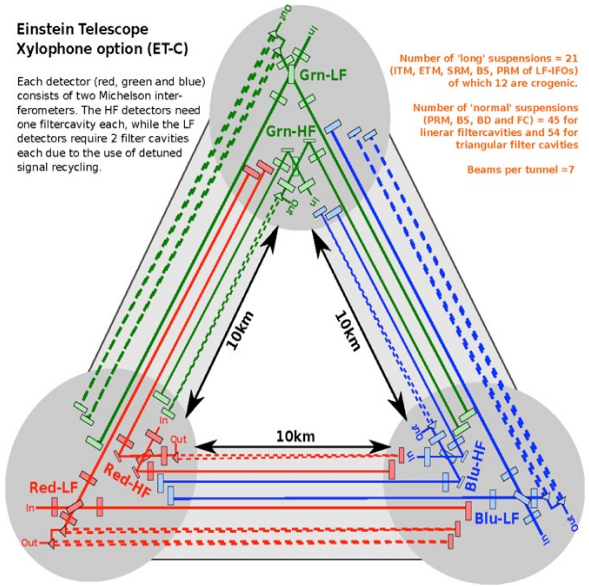
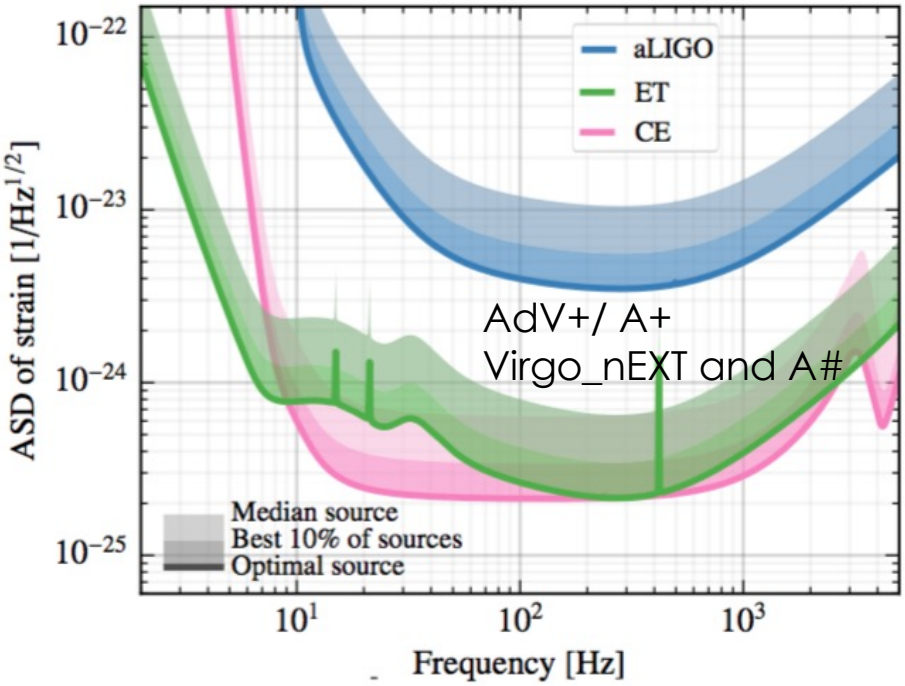
Einstein Telescope

- Underground
- 10- km long arms
- Triangle configuration → polarisation
- « Xylophone » (two combined detectors)
- Cryogenics (20 K) (thermal noise reduction)







Possible synergies R&D

Virgo-LIGO-KAGRA vs ET-CE

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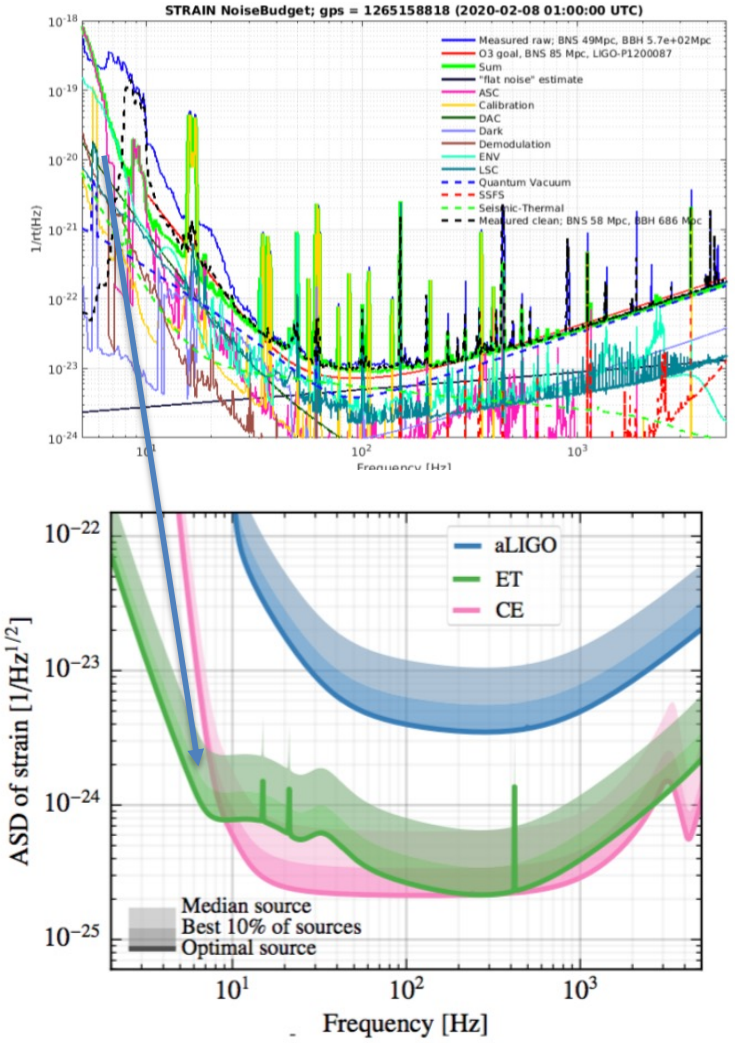

Summary

- O4: detectors under commissioning
- O5: detectors under construction
- O4 in march 2023, O5 in 2026
  - ~ 1 BBH per day in O4, ~ a few BBH during O5
  - ~ 5-10 BNS during O4
- Open data : O4 release strategy similar to O3
- Plans for Virgo_nEXT and A# (~ 2030)
  - Science
  - Synergies R&D Virgo/LIGO/KAGRA vs ET/CE