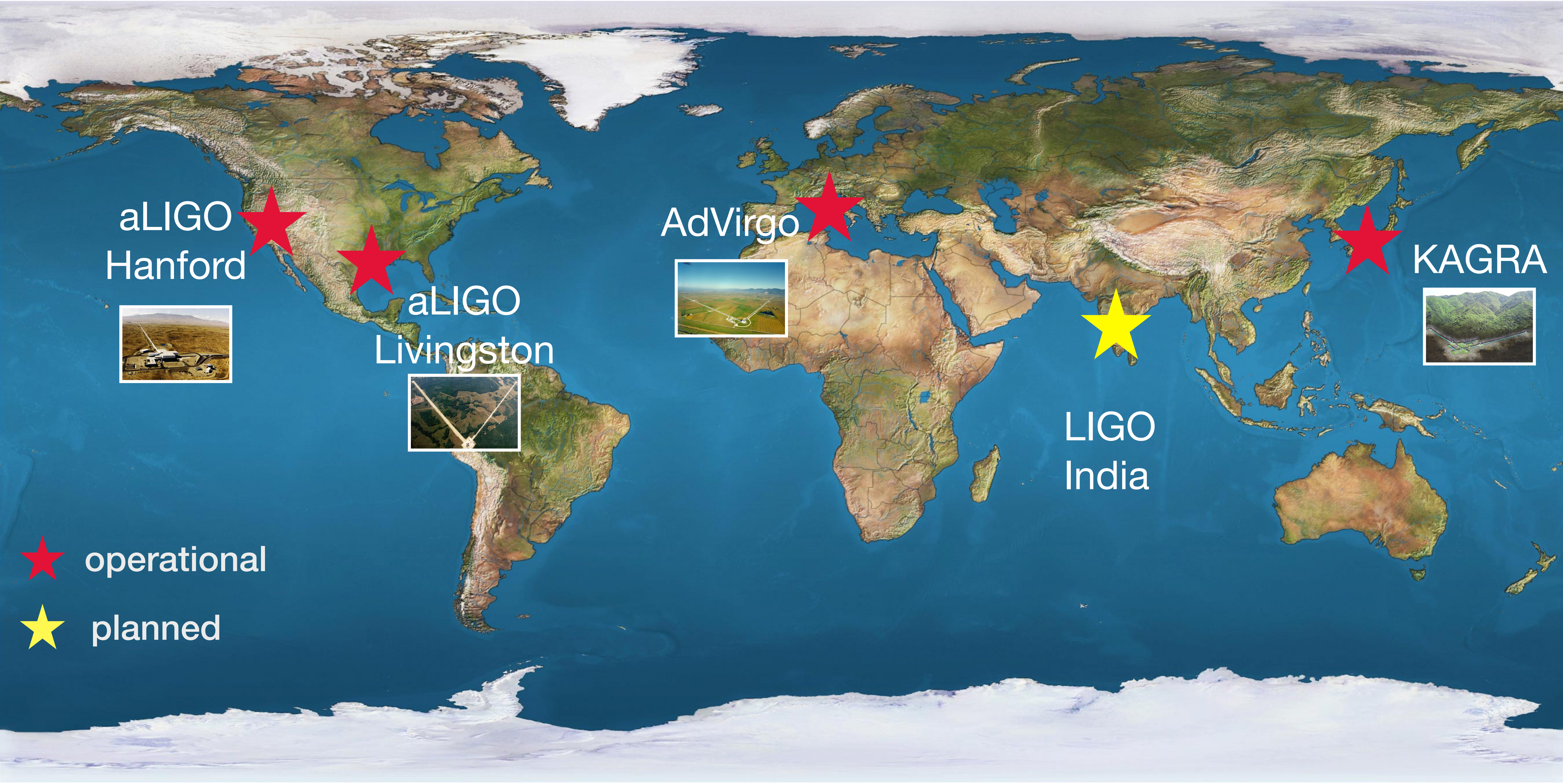
Sixième Assemblée Générale du GdR Ondes Gravitationnelles

LIGO-Virgo-KAGRA network: state of the art and future plans

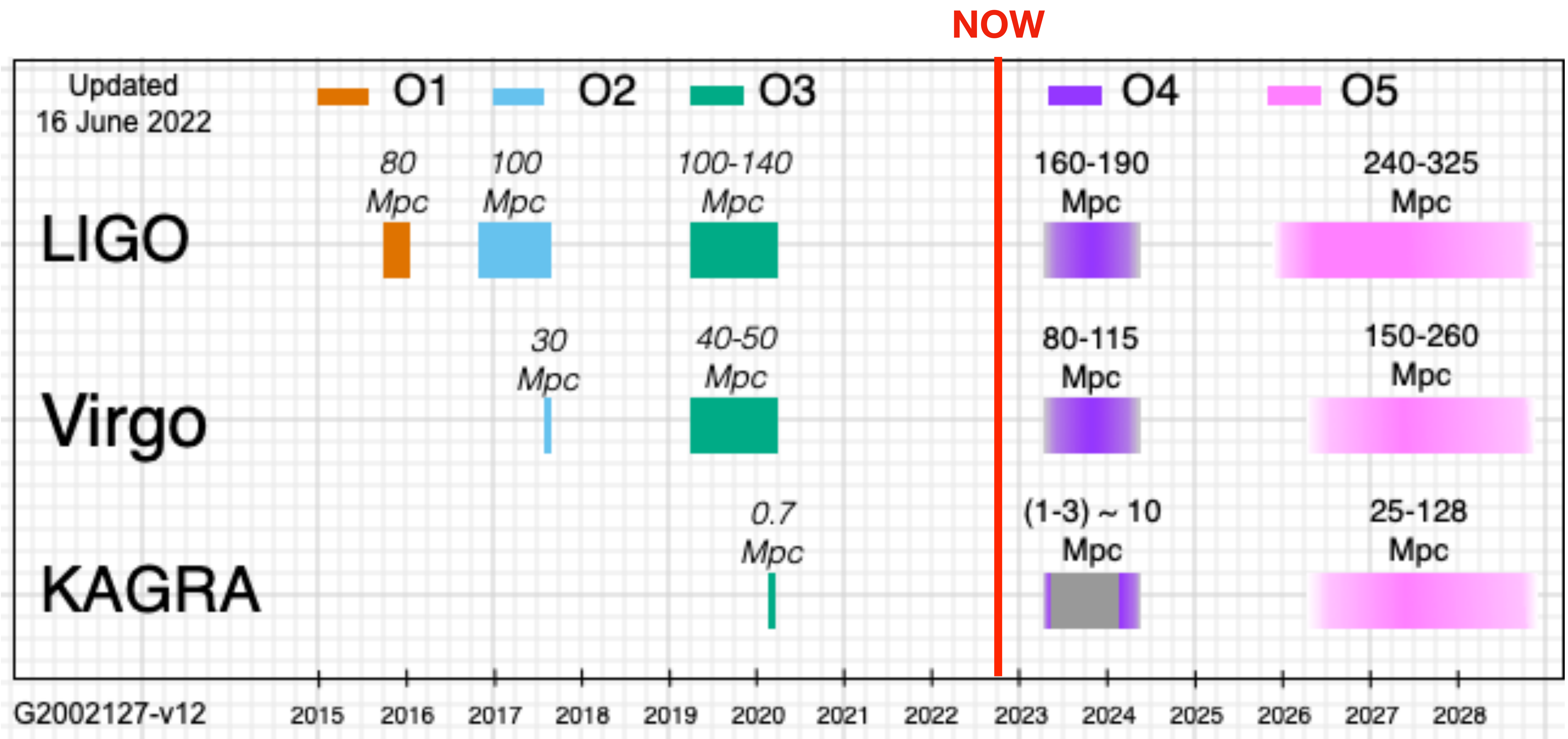
Eleonora Capocasa

Toulouse -11 Nov 2022

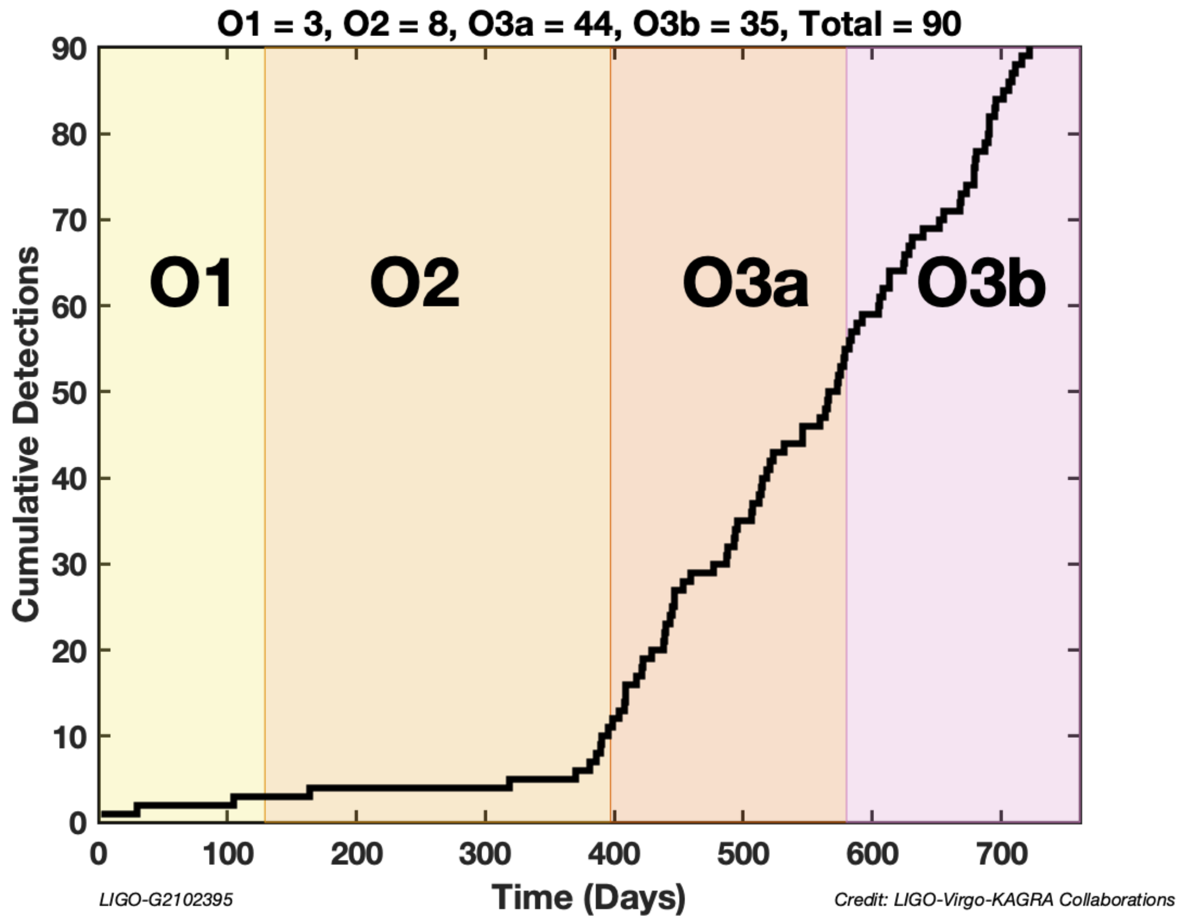
Second generation GW detector network

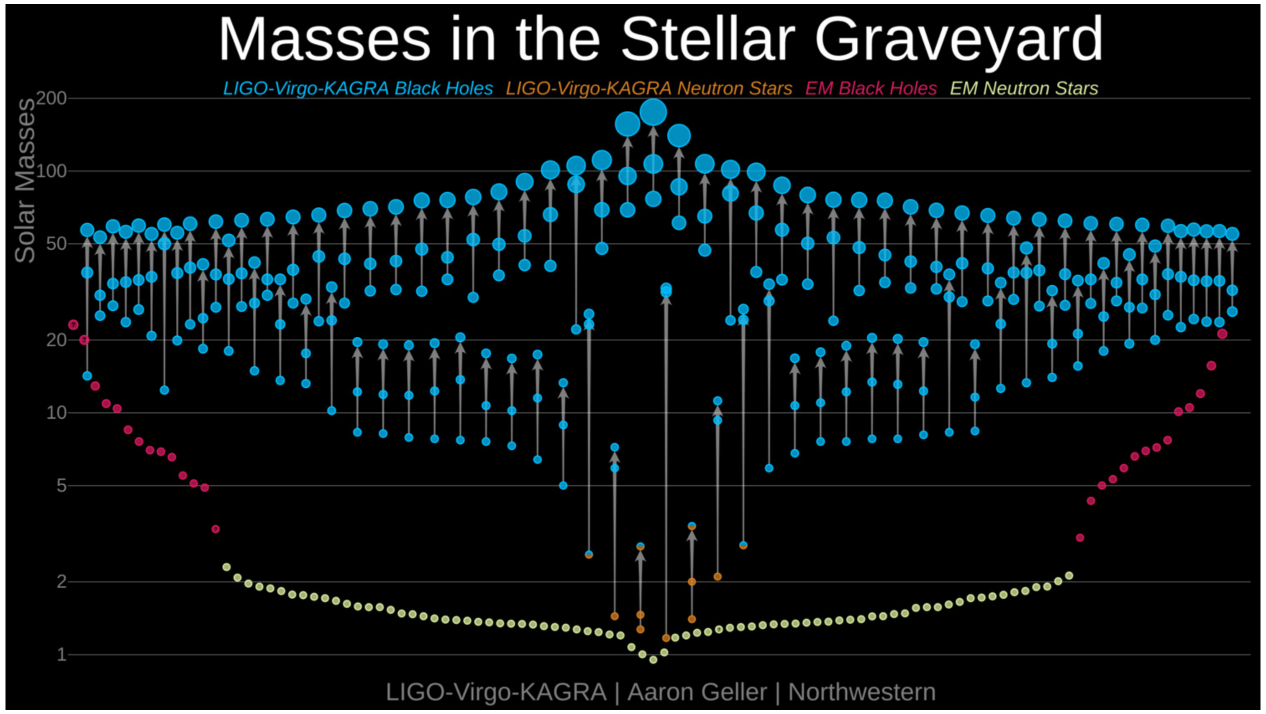


2G GW detector network observation plan



Observation summary

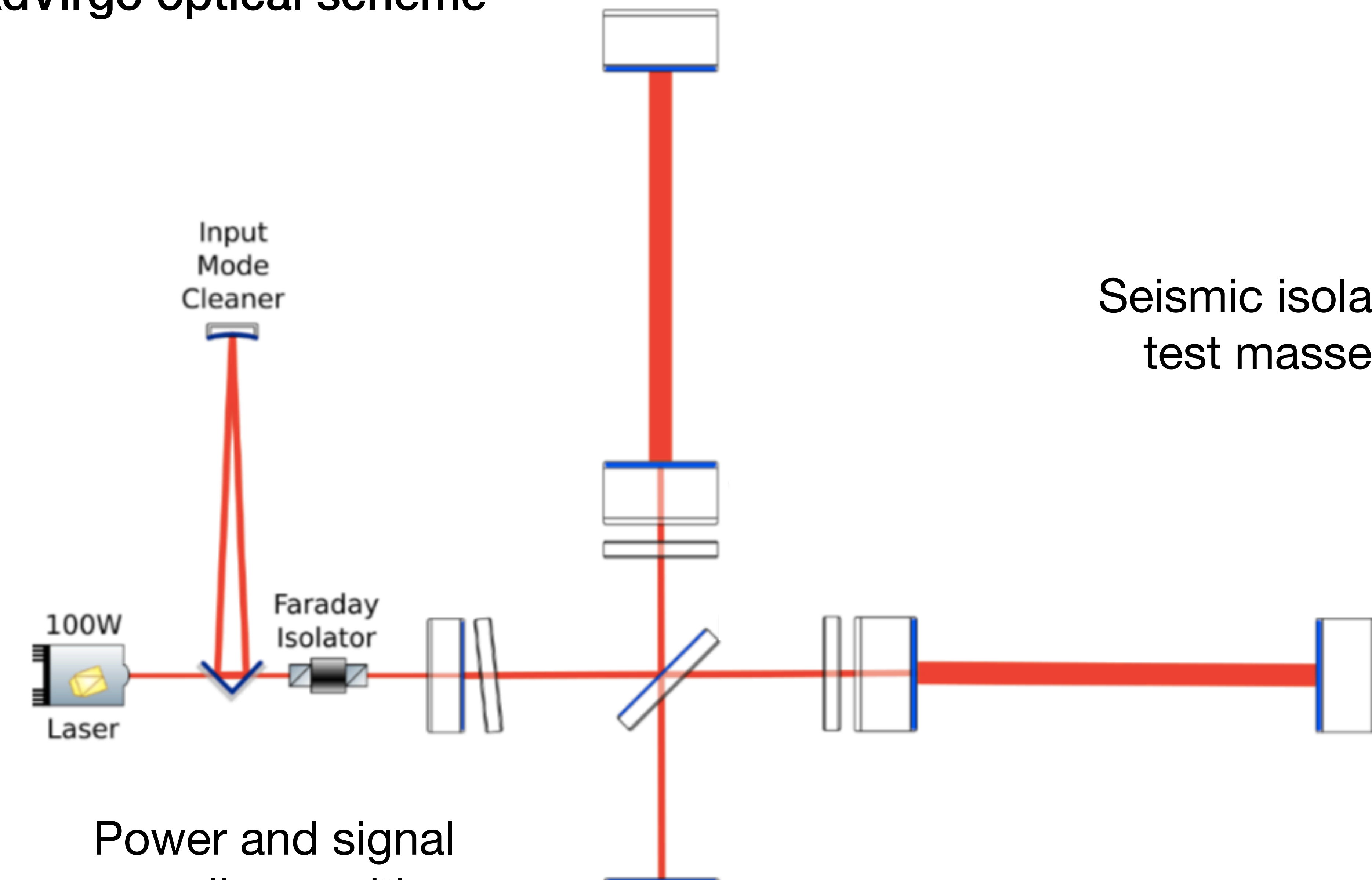


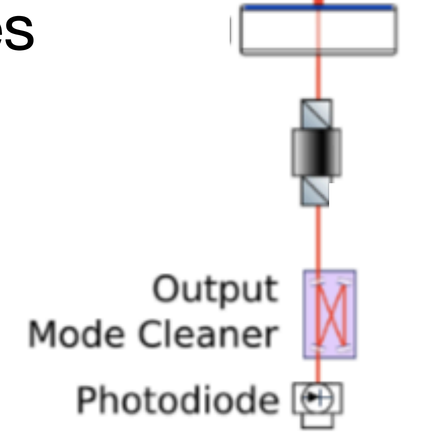


- 90 events detected so far
- Remarkable detection rate increase in O3
- Several "exceptional" events published
- Population analysis (not only study of individual events)
- Upper limits on several sources and physical effects (i.e. GW background, lensing, specific dark matter candidates)

Modified Michelson interferometers

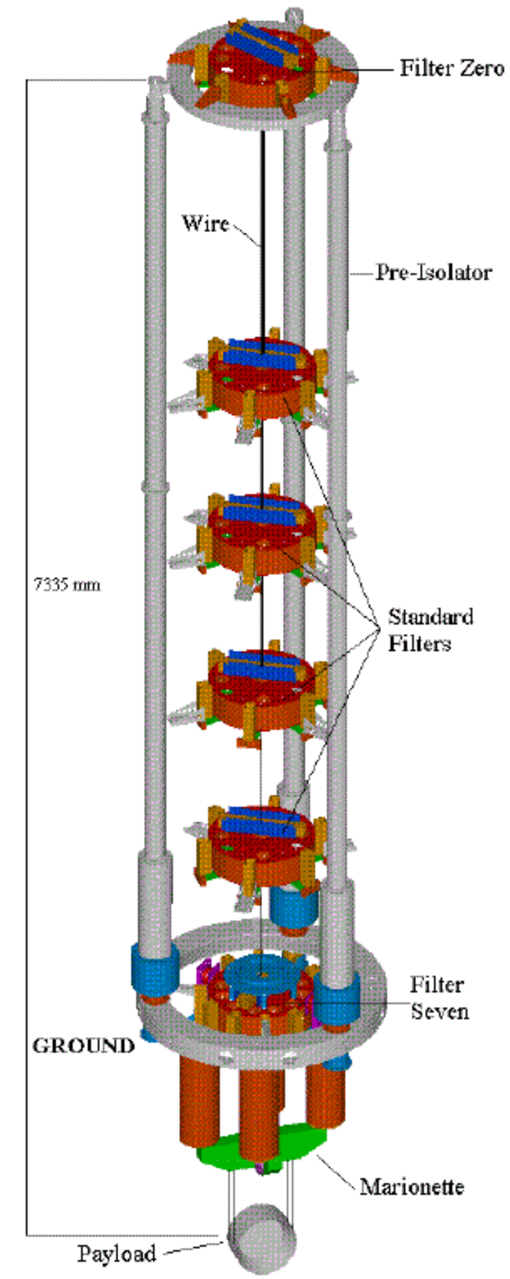
AdVirgo optical scheme

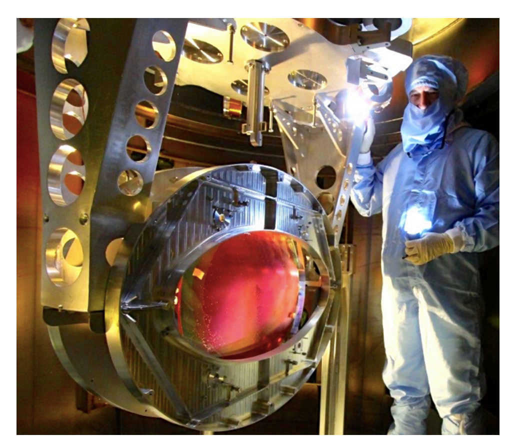




Power and signal recycling cavities

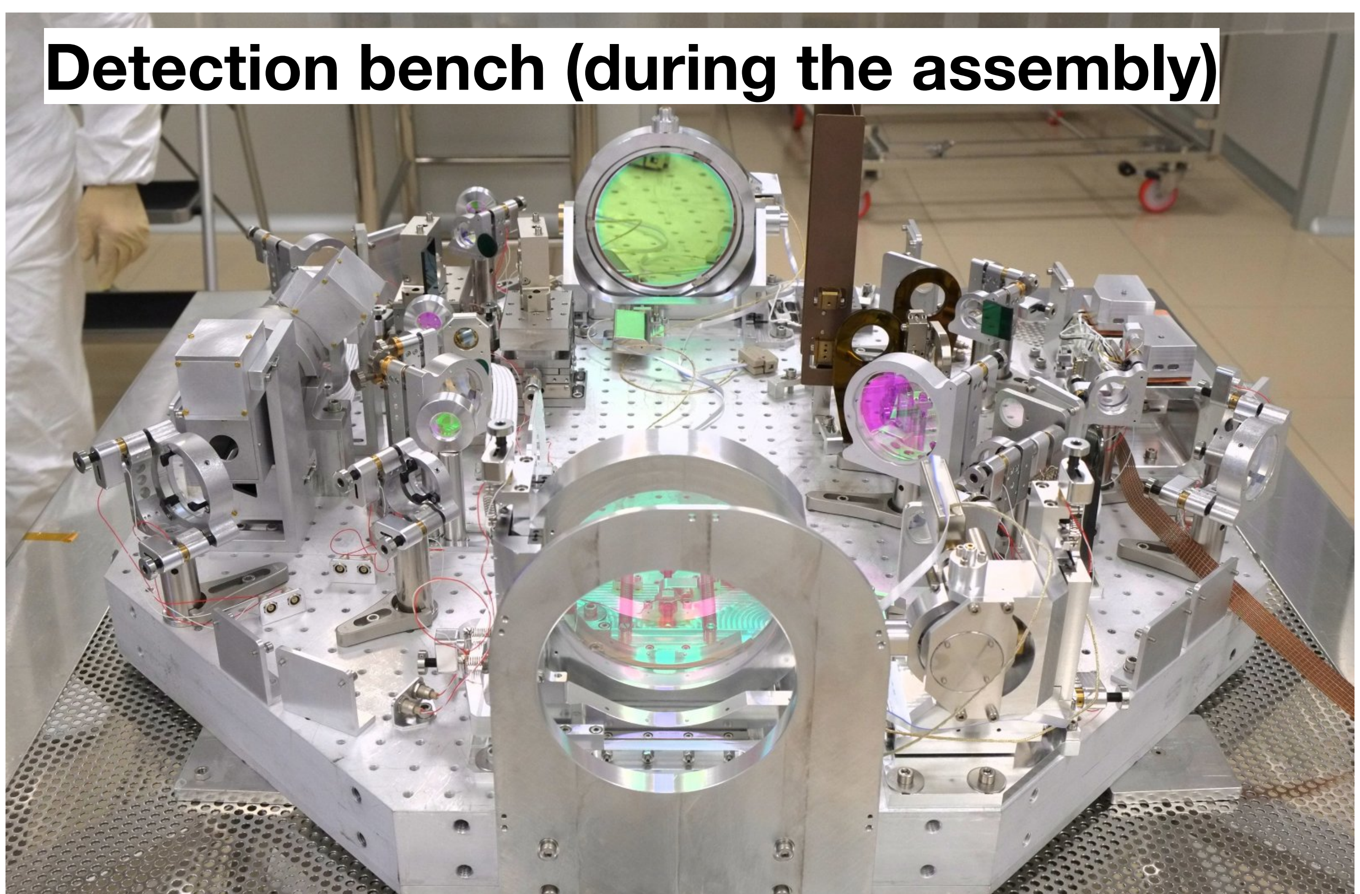
Seismic isolated test masses

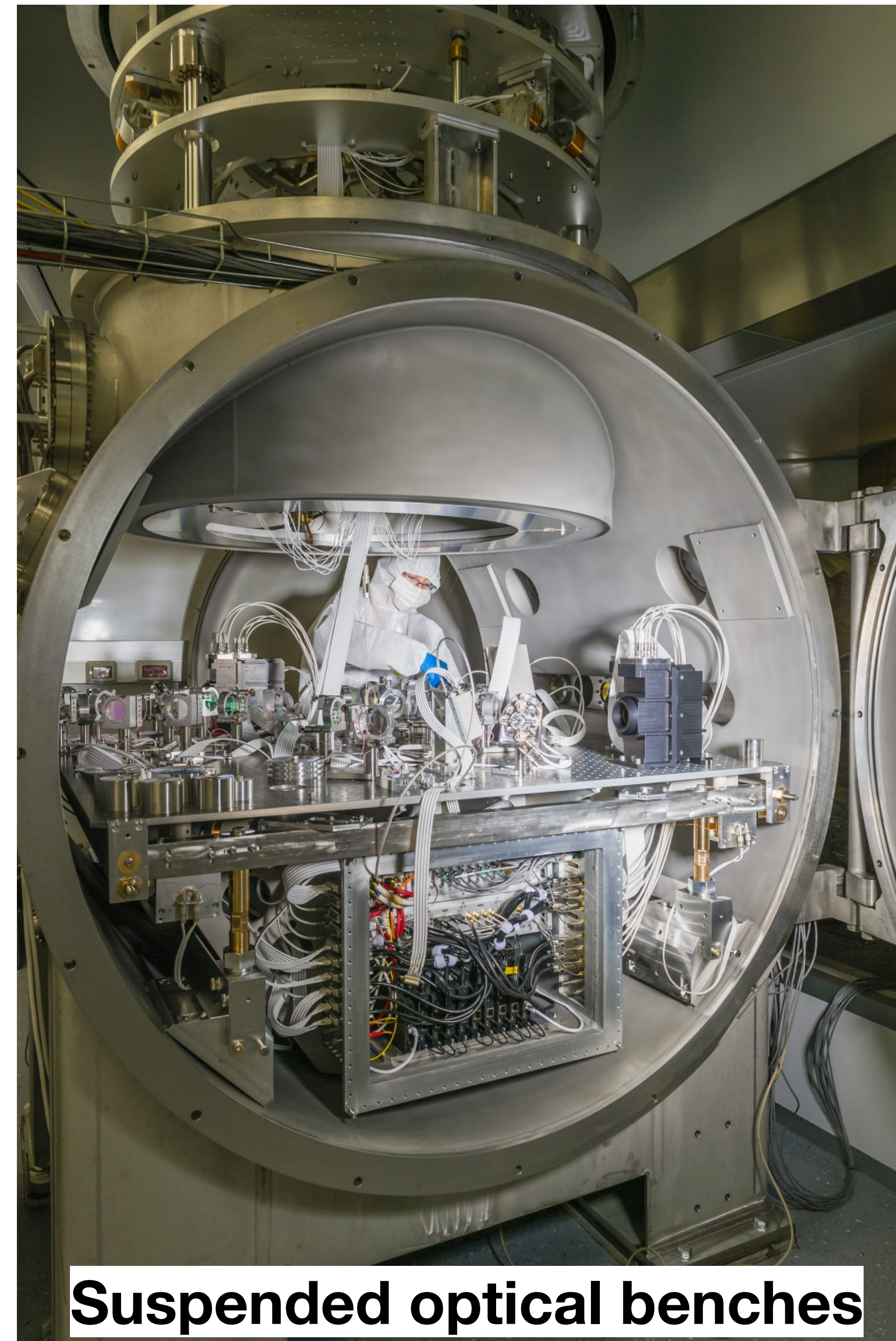




Fused silica mirrors
40 kg
Flatness < 1 nm RMS

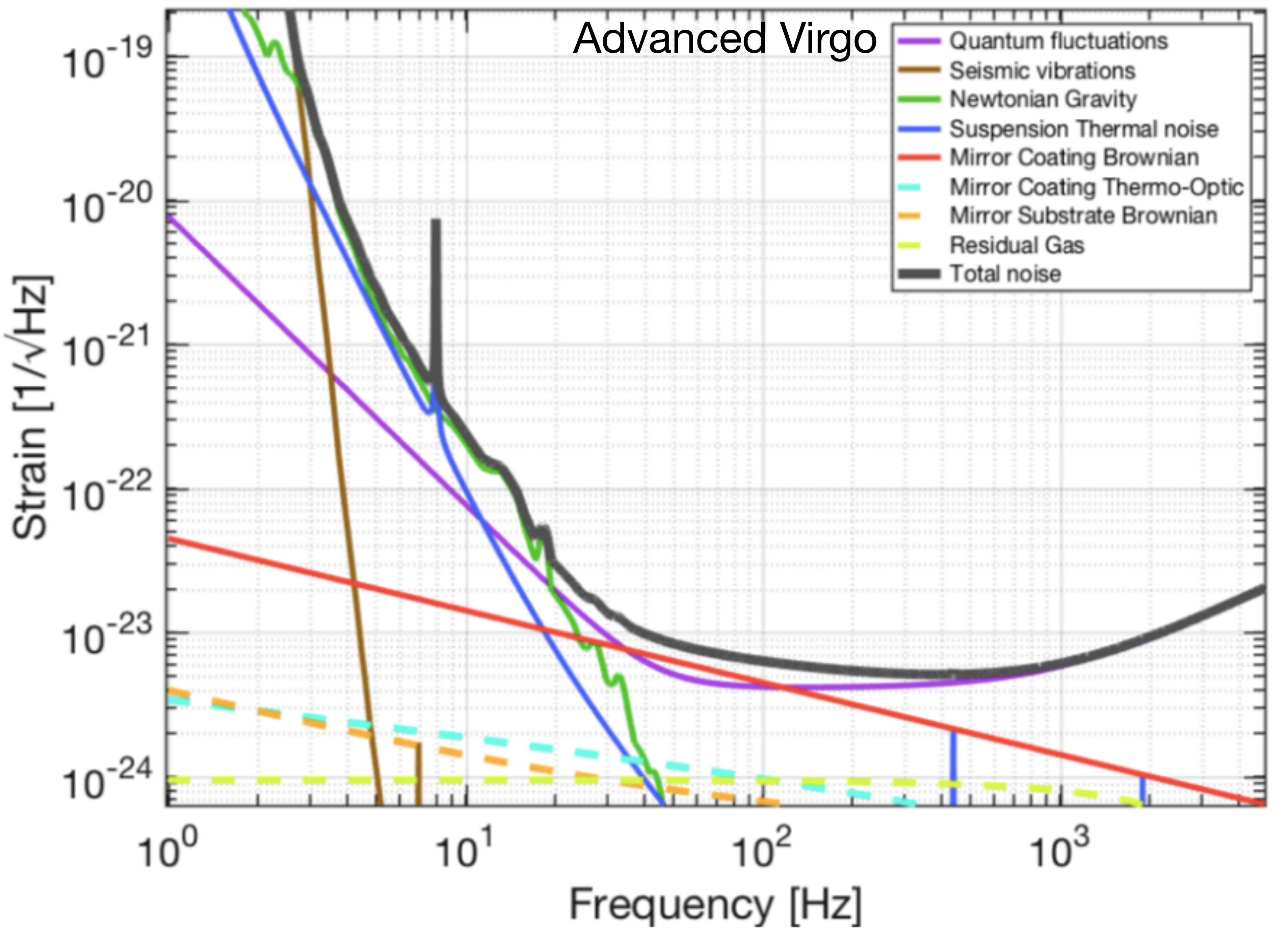

External injection bench


Detection bench (during the assembly)

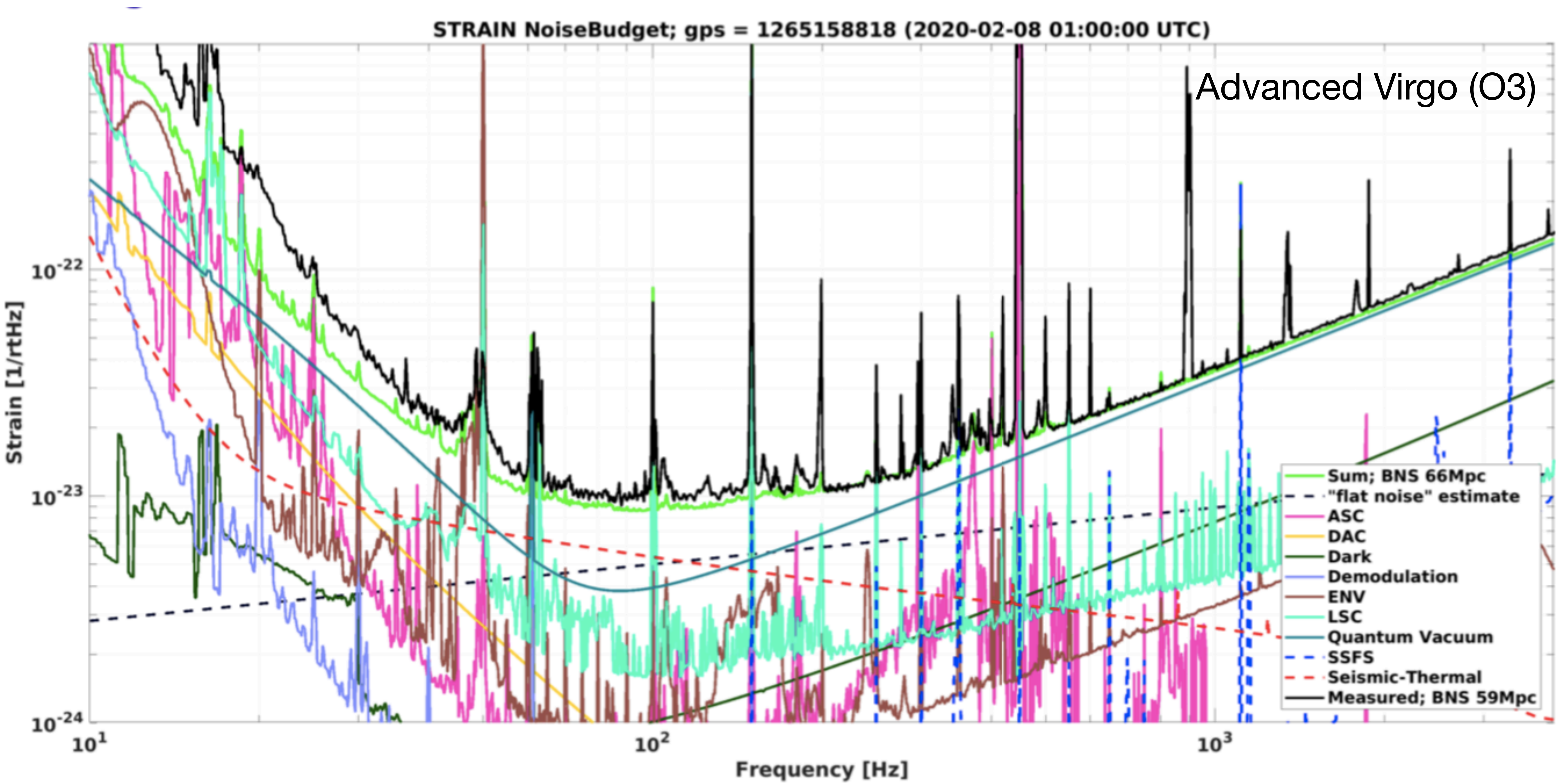

Suspended optical benches

GW detector noise budget (design)

- Only fundamental noises considered here



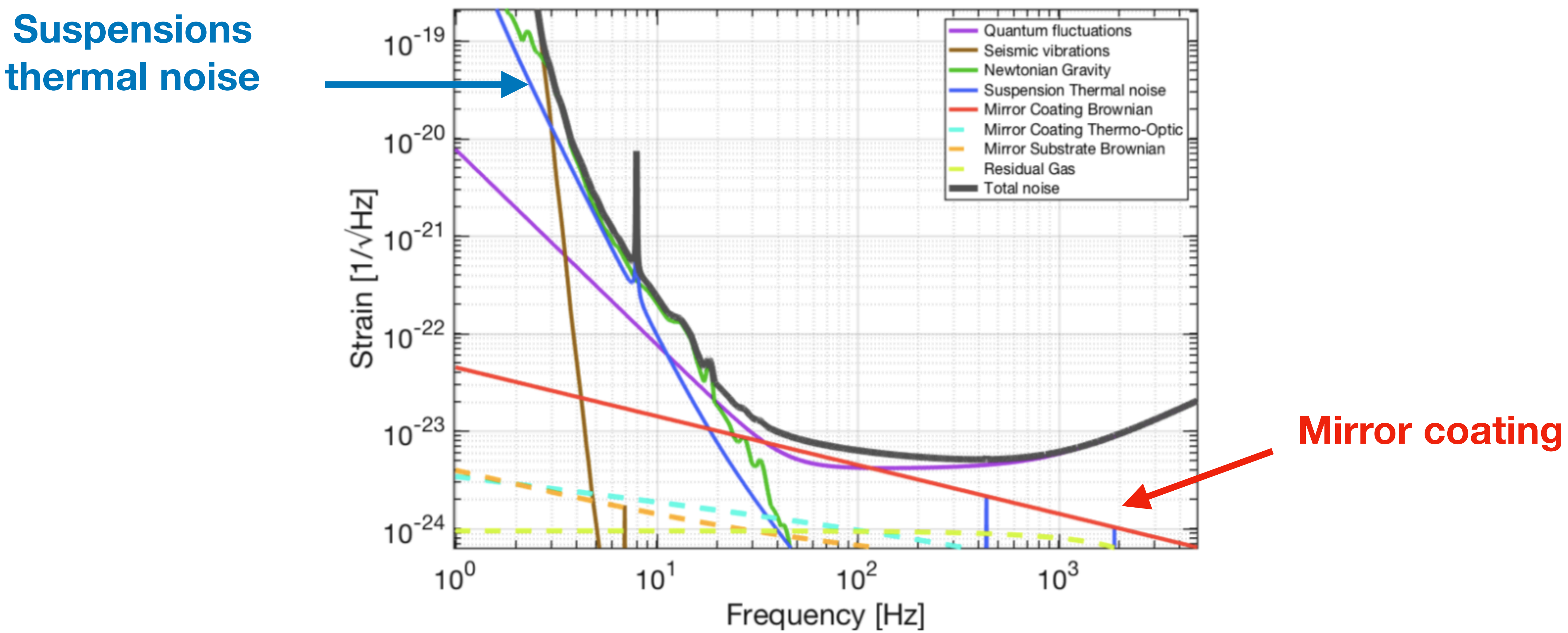
GW detector **real** noise budget



Thermal noise

- Thermal fluctuation of a atoms and molecules of mirrors and suspensions sets a limit on the rest condition of the test masses

- How are these fluctuations distributed in frequency?



Quantum noise

- Quantum noise is originated by vacuum fluctuation entering the dark port

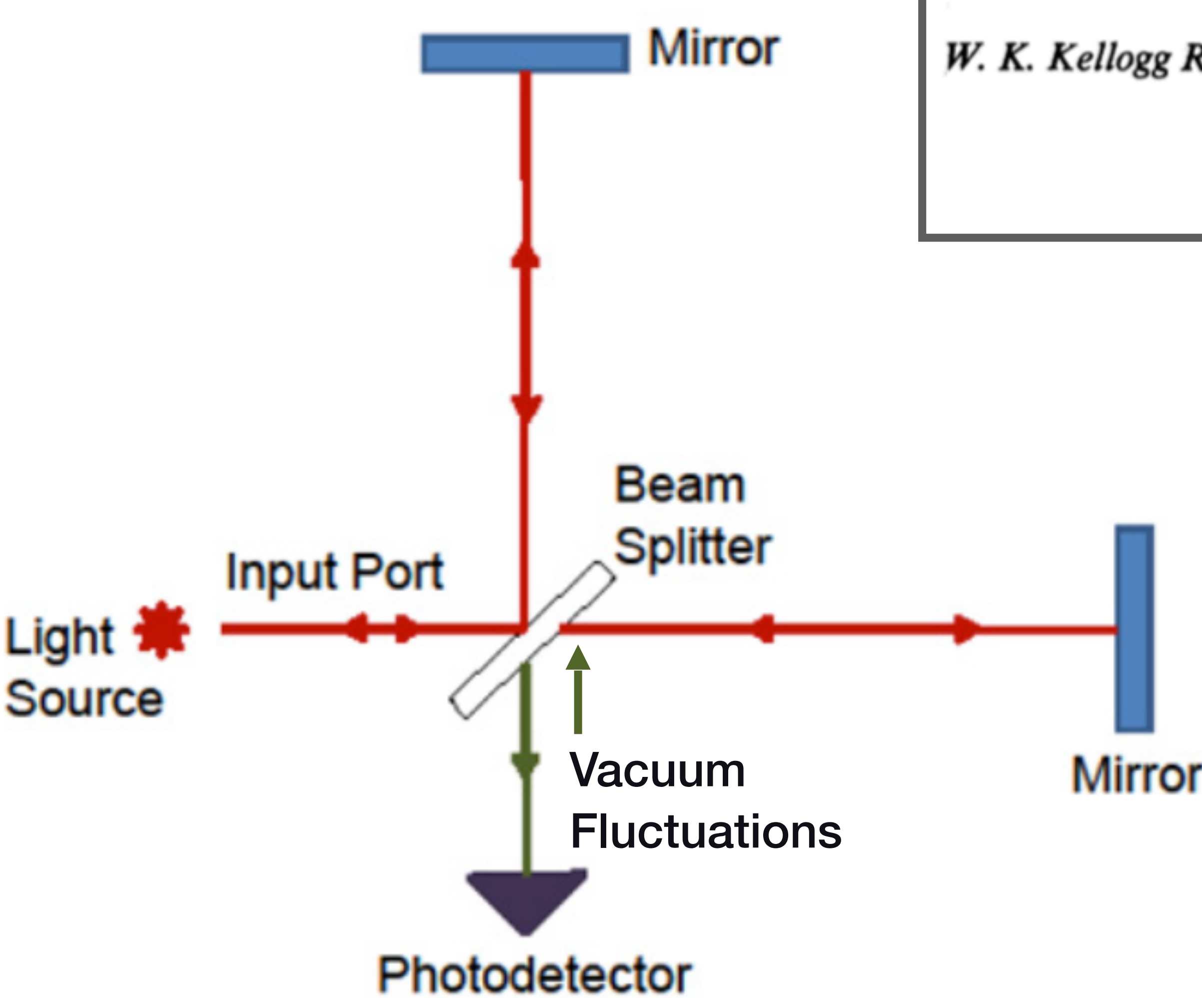
PHYSICAL REVIEW D — 15 APRIL 1981

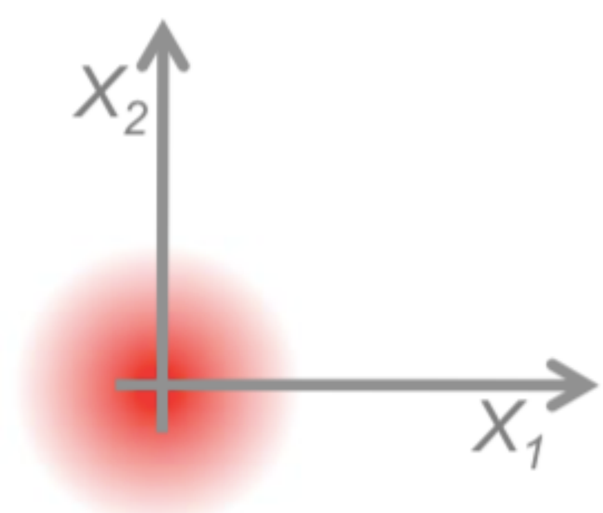
Quantum-mechanical noise in an interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

VOLUME 23, NUMBER 8





Quantum noise

- Replace standard fluctuation with **squeezed vacuum fluctuation**

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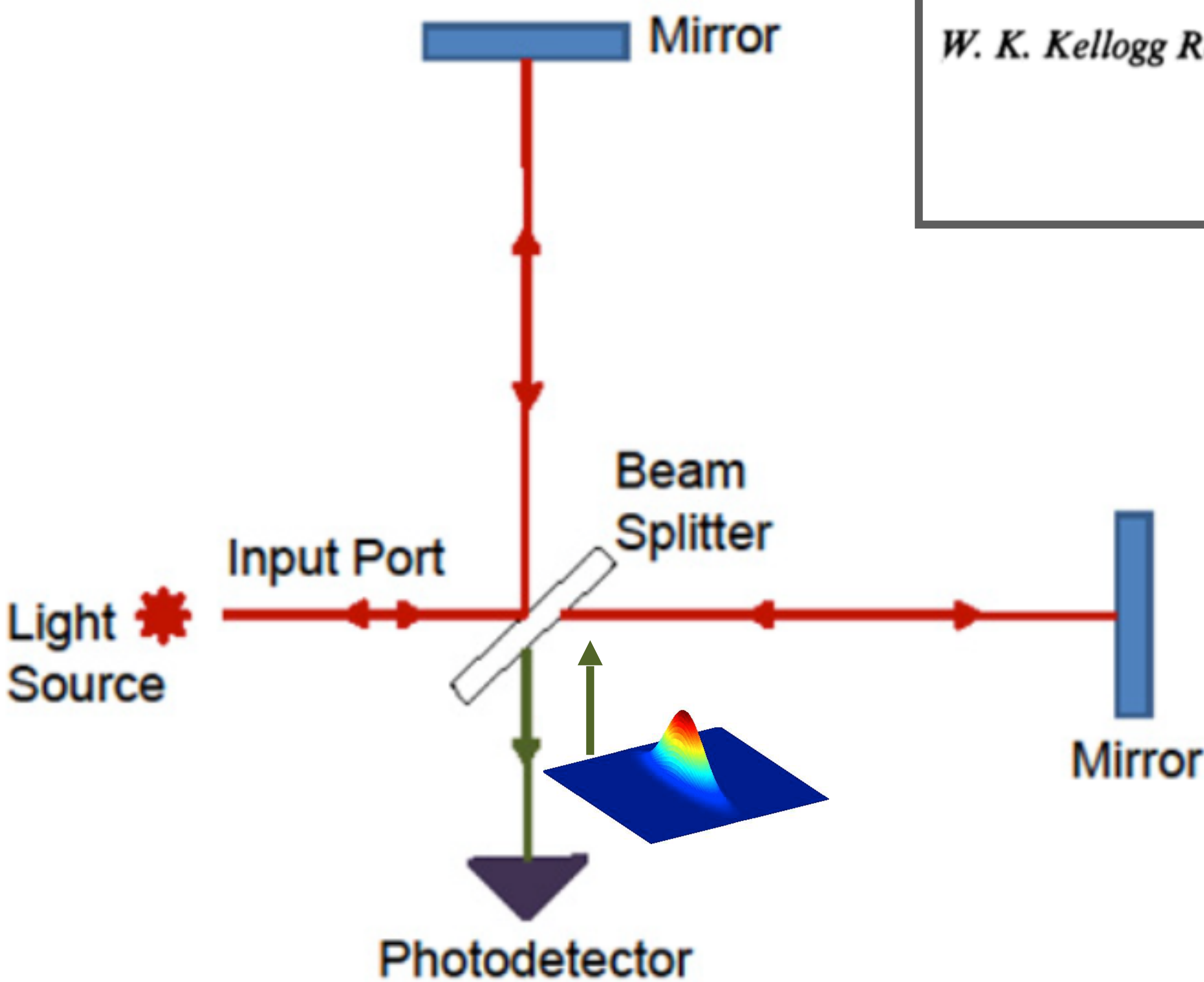
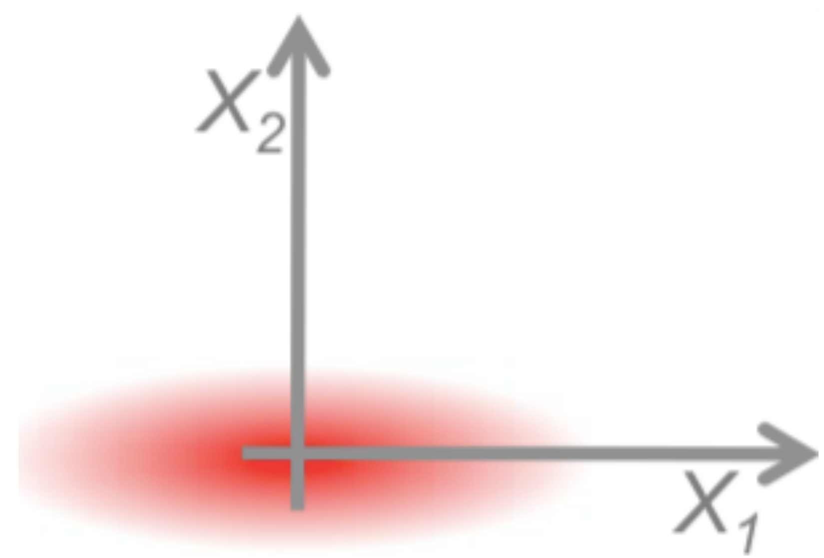
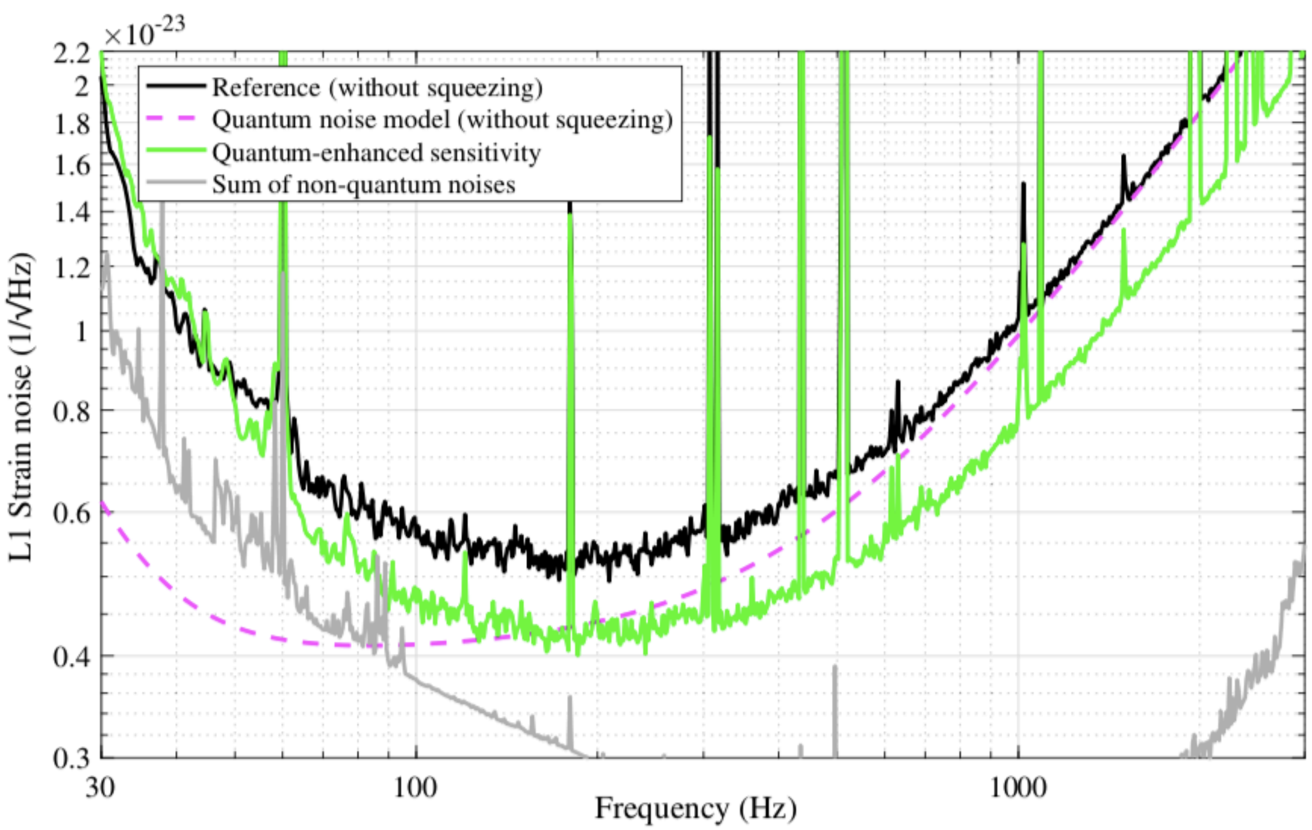




Successful application to 2G detectors since O3

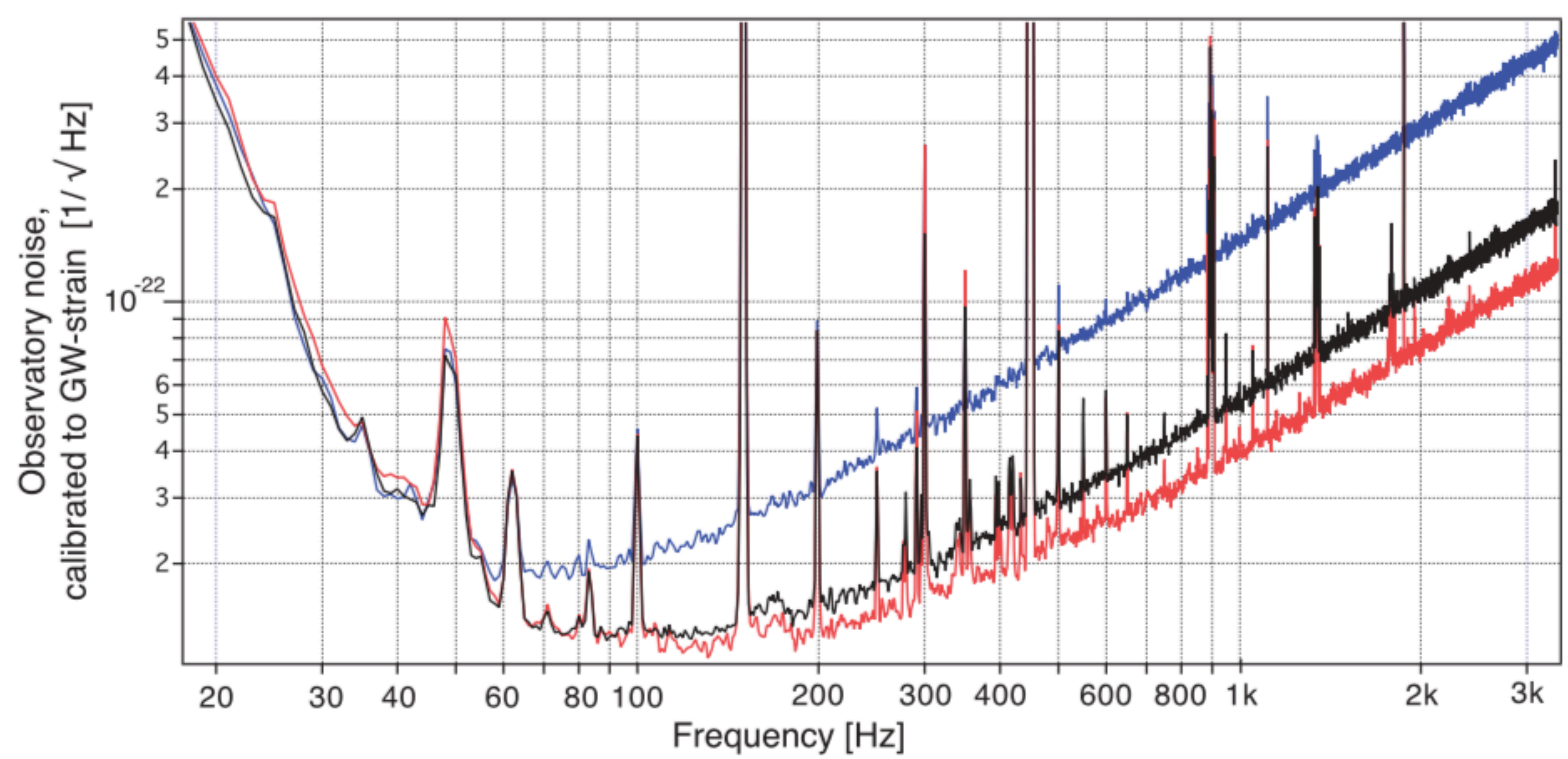


Advanced LIGO

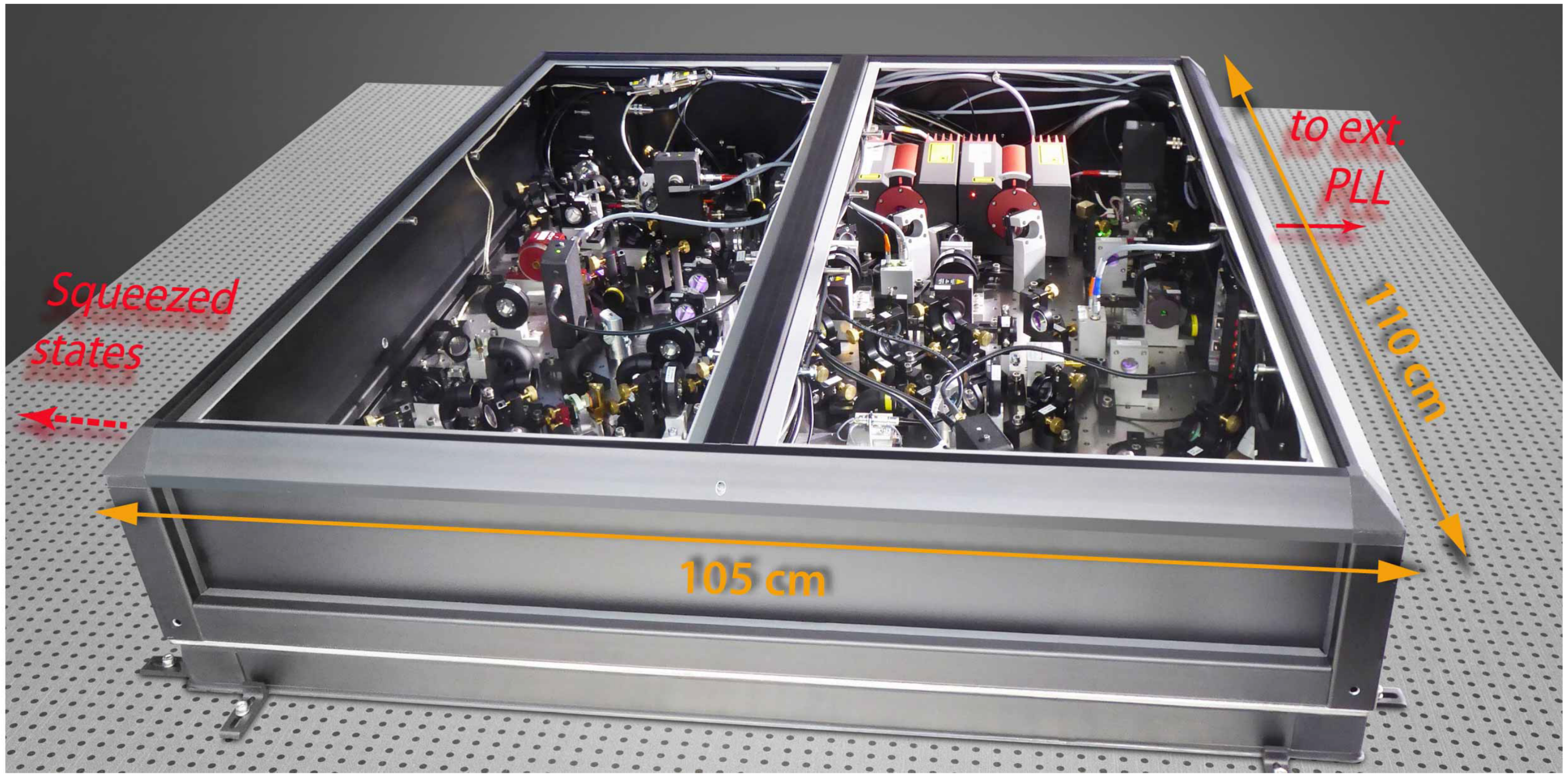
- Best measured ~3 dB
- BNS Range improvement: 14%
- Detection rate improvement: 50%

Advanced Virgo

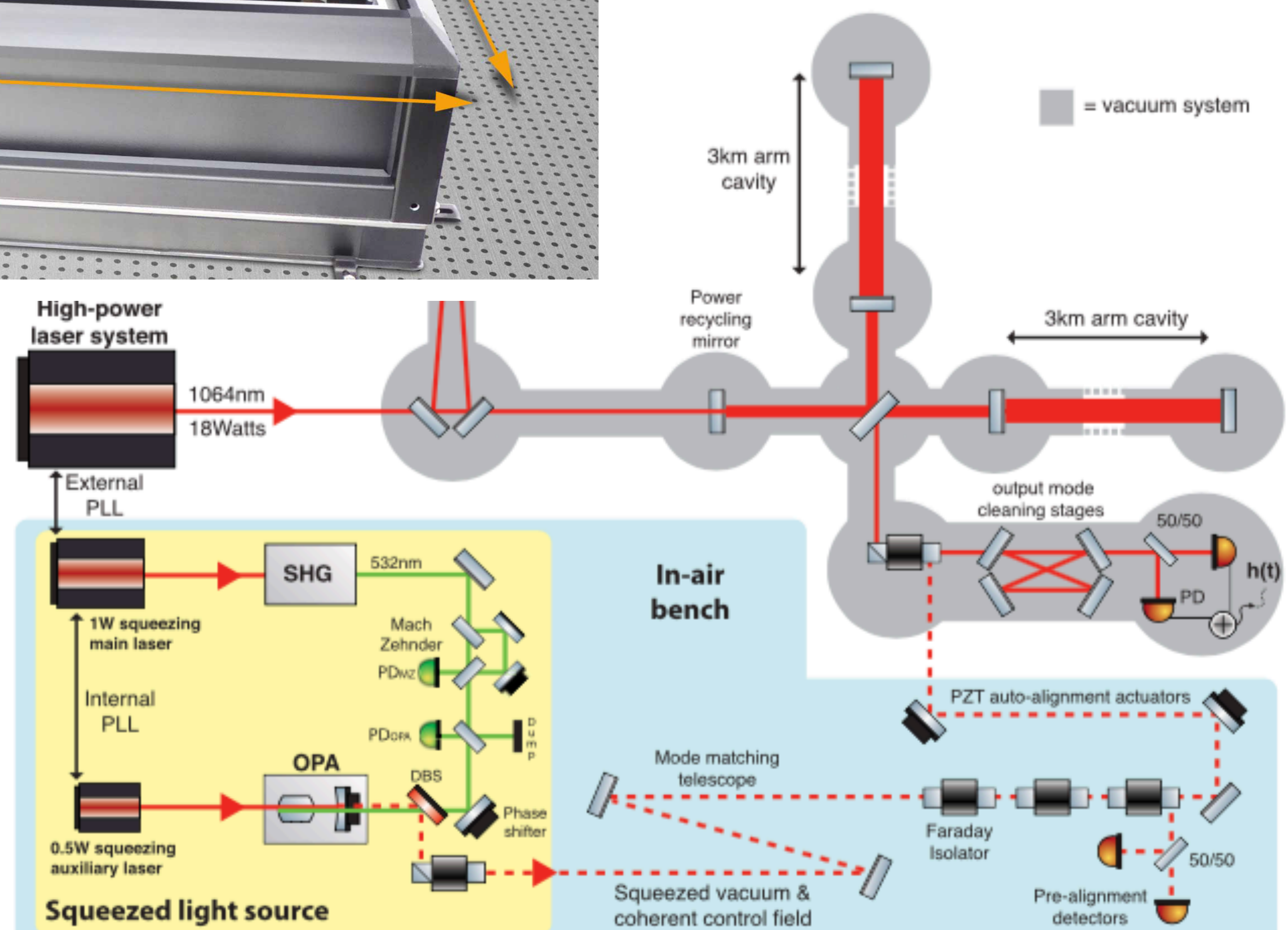
- Best measured ~3 dB
- BNS Range improvement: 5%-8%
- Detection rate improvement: 16-26%



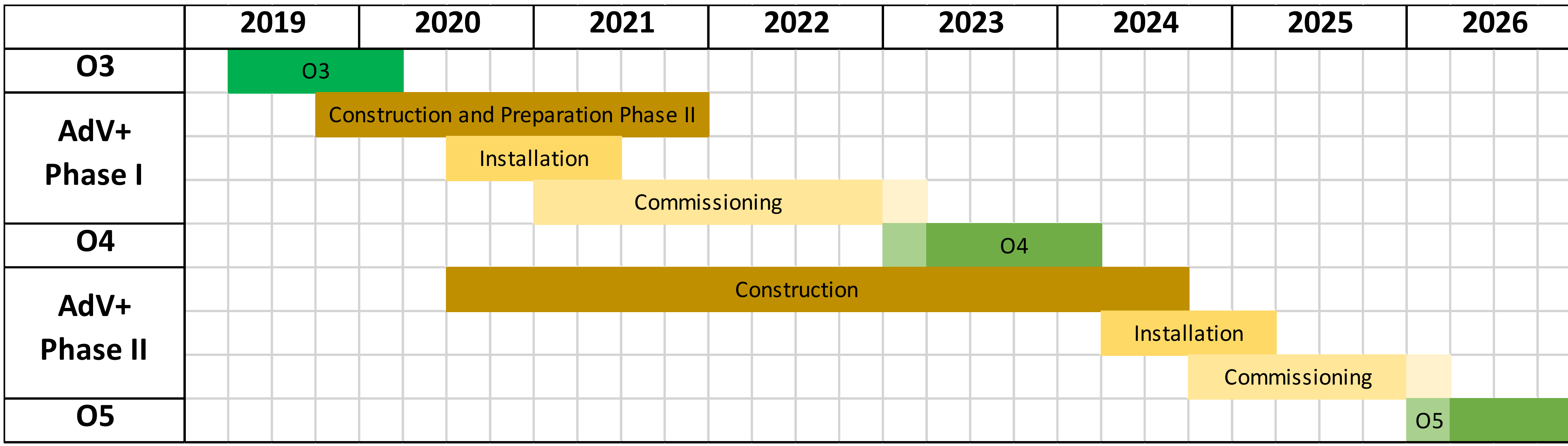
AdVirgo vacuum squeezed source



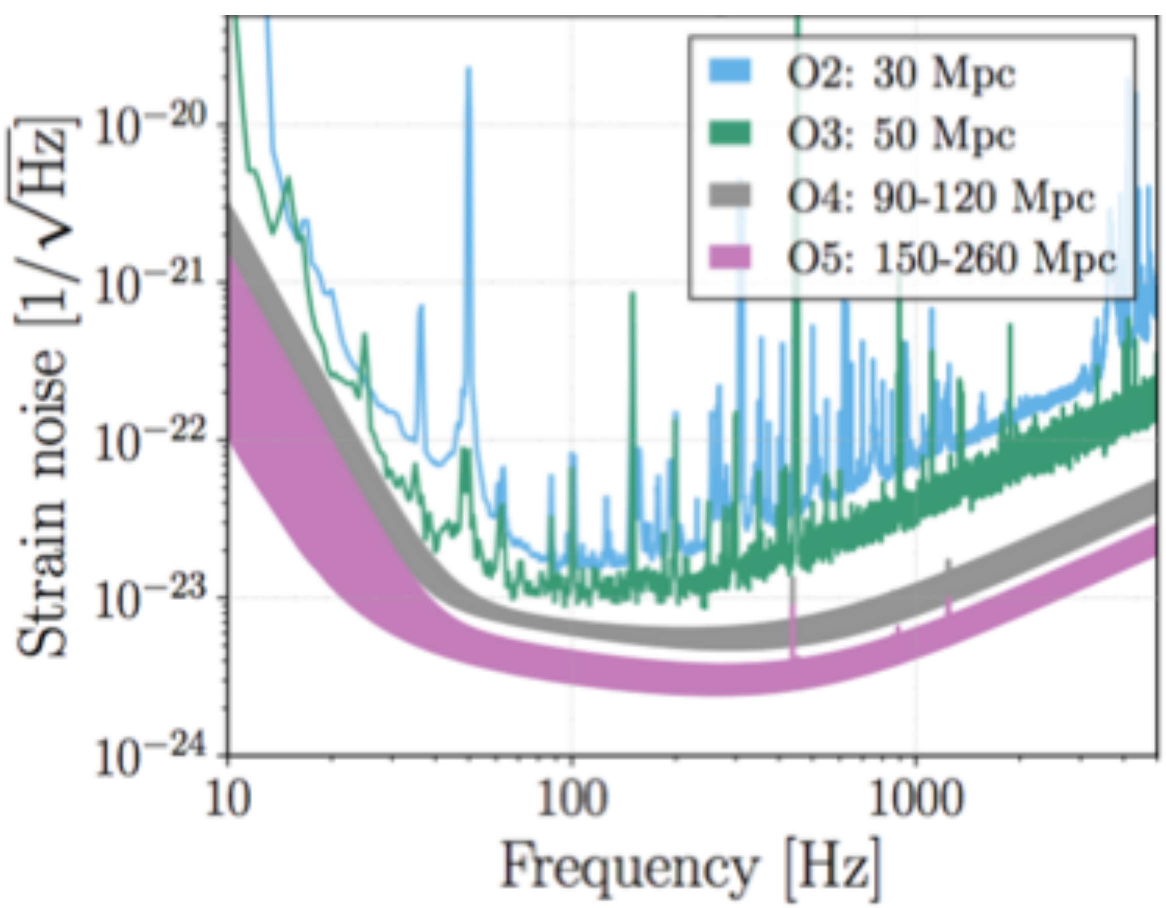
F. Arcenese, et al. (Virgo Collaboration), *Increasin*
Reach of the Advanced Virgo Detector via the A
Squeezed Vacuum States of Light, Phys. Rev. Lett.



Advanced Virgo+



Now



PHASE I (O4) ⇒ Target ~100 Mpc

Quantum noise reduction

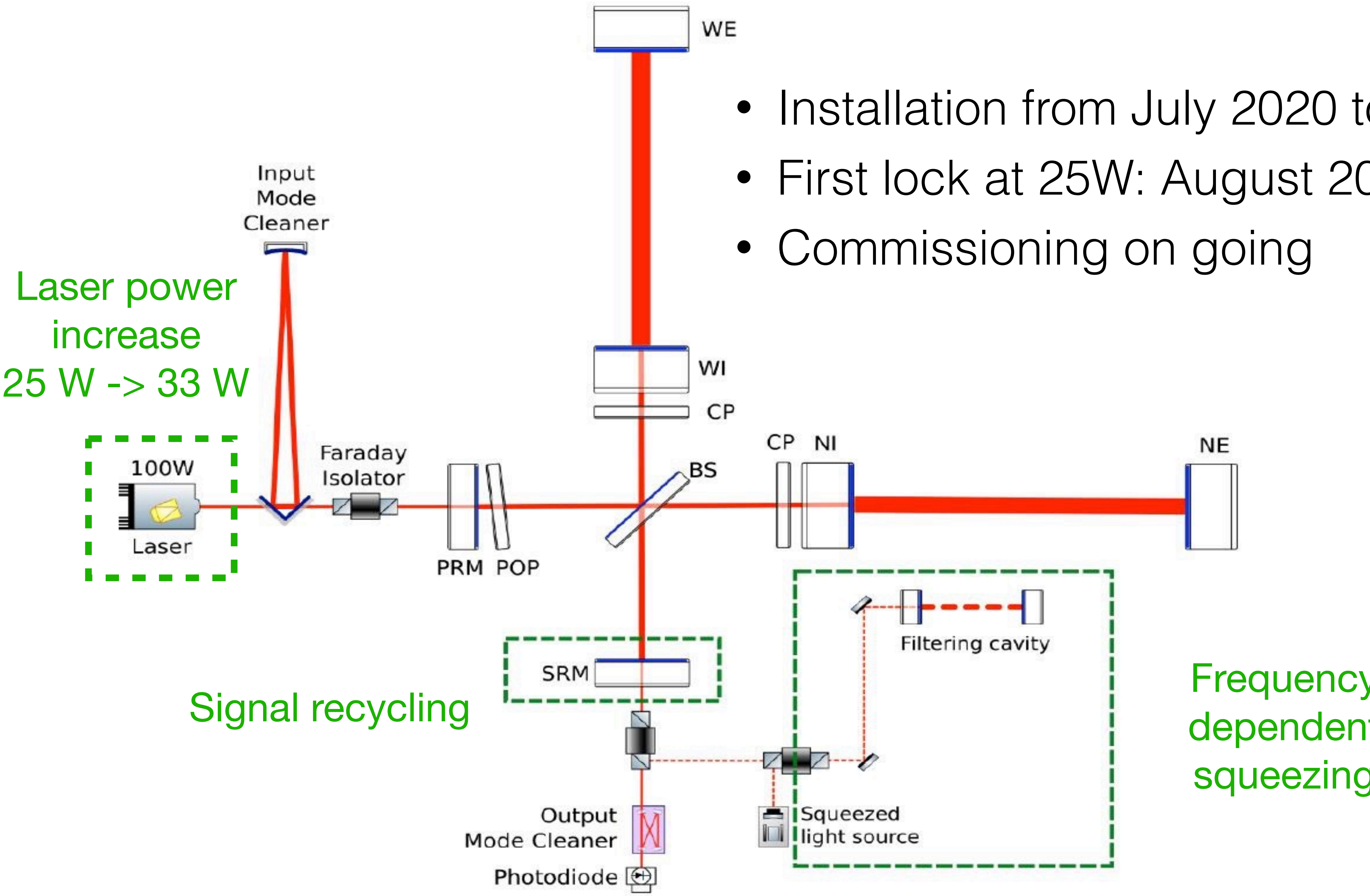
PHASE II (O5) ⇒ Target ~200 Mpc

Thermal noise reduction

Advanced Virgo+ Phase I

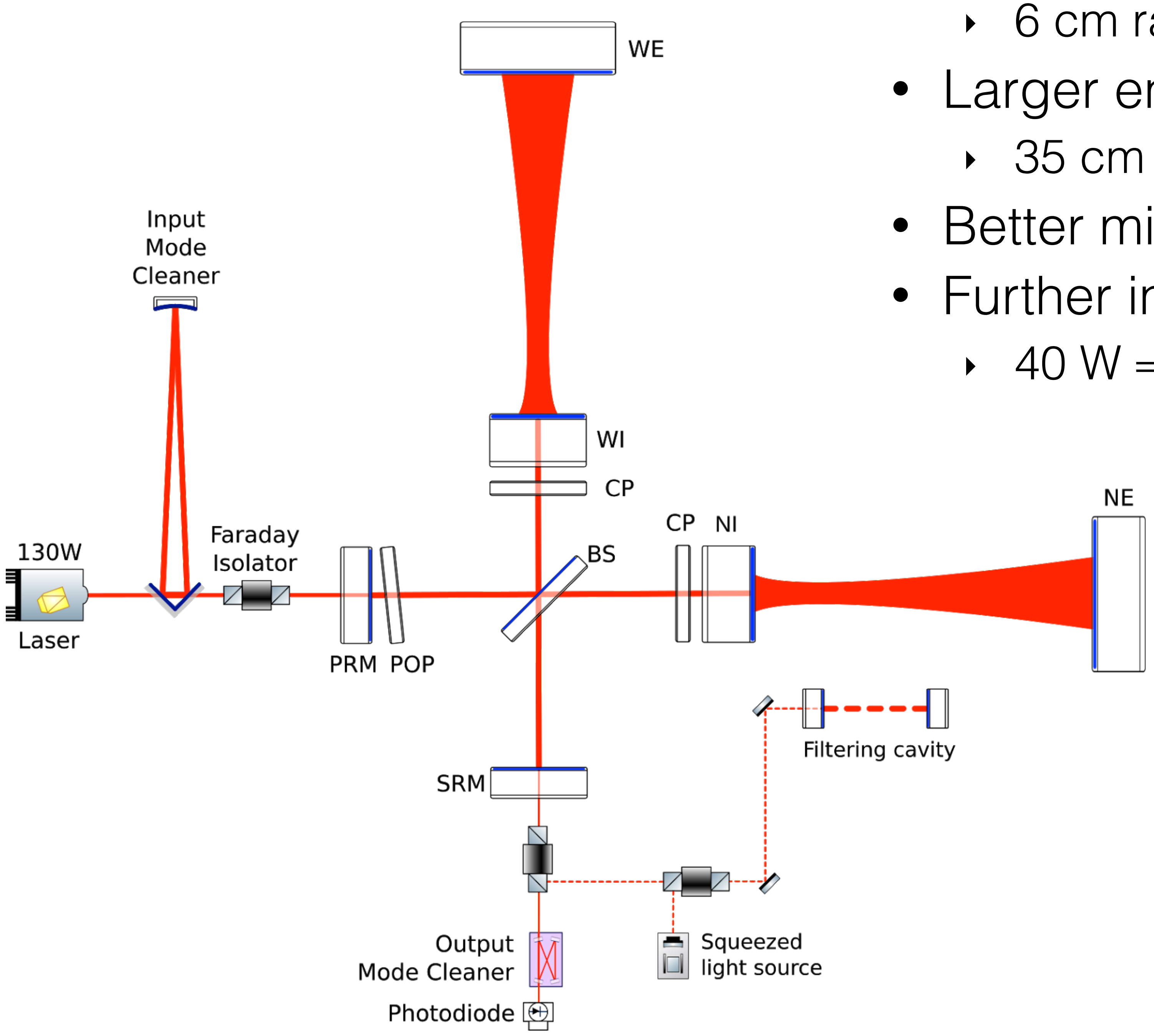
- **Main target: quantum noise reduction ⇒ ~100 Mpc**

- Installation from July 2020 to April 2021
- First lock at 25W: August 2021
- Commissioning on going



Advanced Virgo+ Phase II

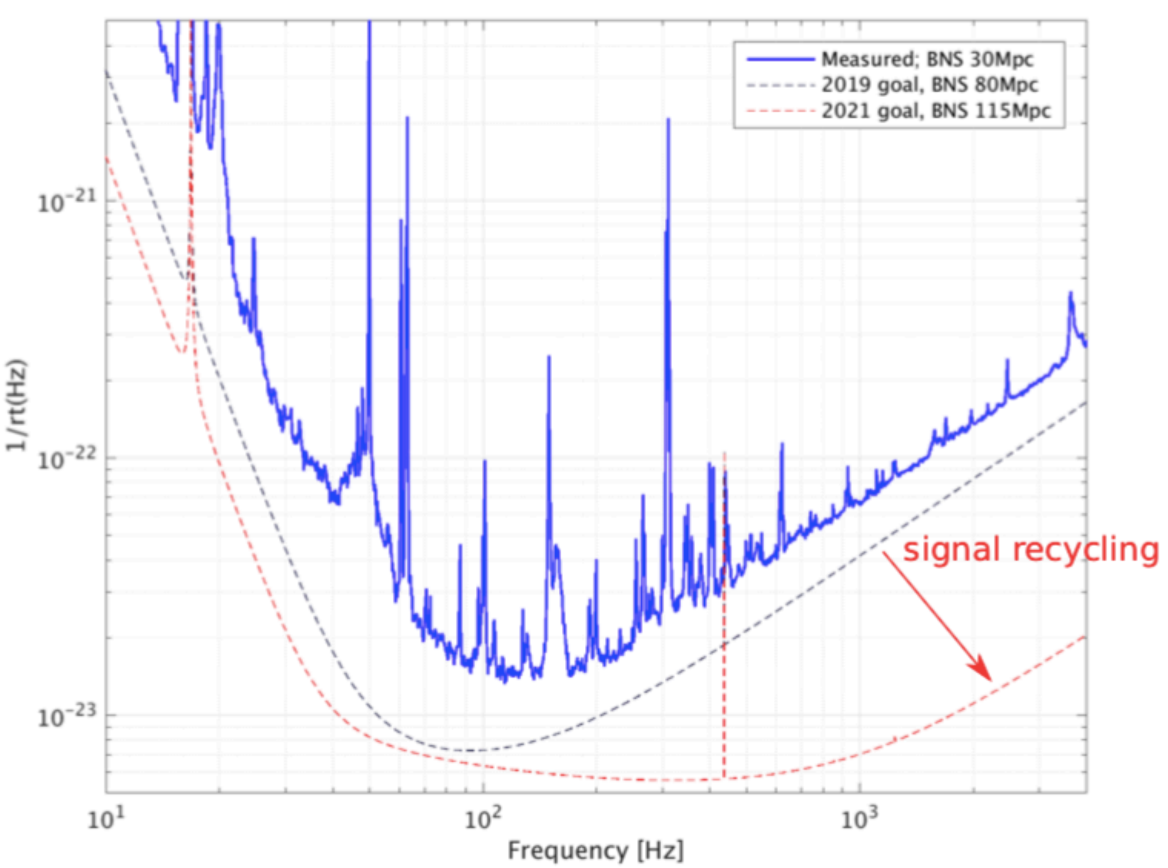
- **Main target: thermal noise reduction ⇒ ~200 Mpc**

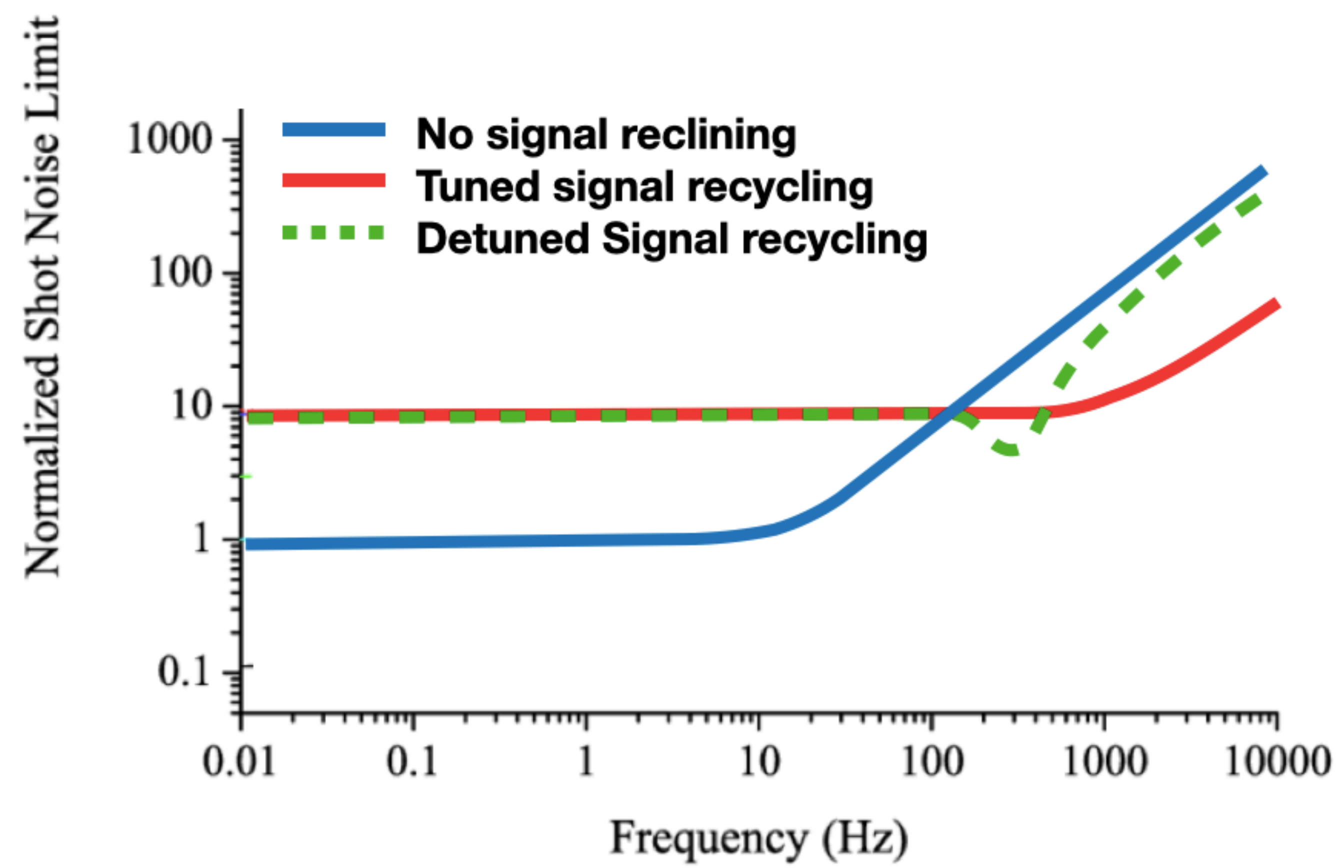


- Larger beams on end test masses
  - 6 cm radius ⇒ 10 cm radius
- Larger end mirrors
  - 35 cm diameter ⇒ 55 cm diameter
- Better mirror coatings
- Further increase of laser power
  - 40 W ⇒ 60 W ⇒ 80 W

O4 commissioning challenges: signal recycling

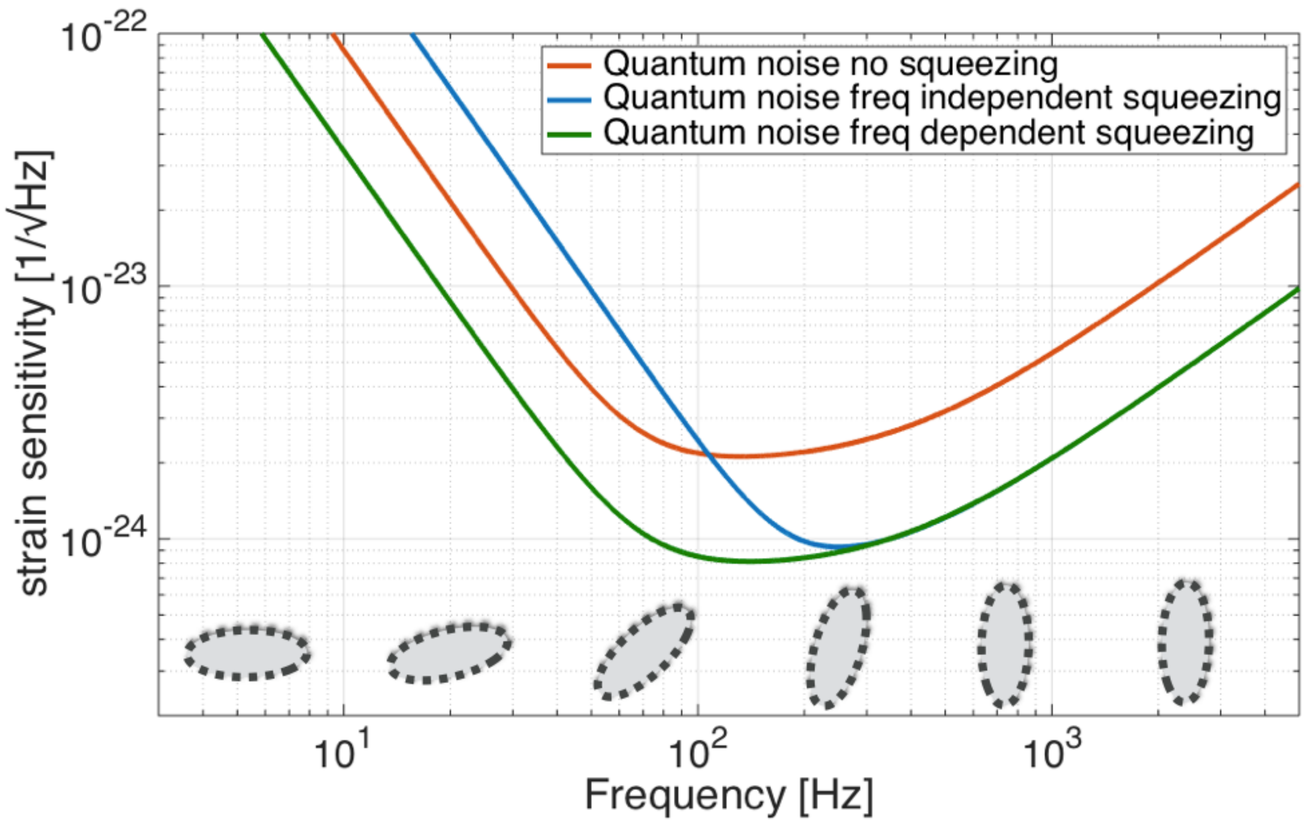
- Goal: enlarge the detection bandwidth
- Issues:
  - ITF responses not as expected (optical spring)
  - Need for additional thermal actuator for compensating optical defect (realised in April -> slow down progress up to June 22)
  - No good angular control signal for SR found so far

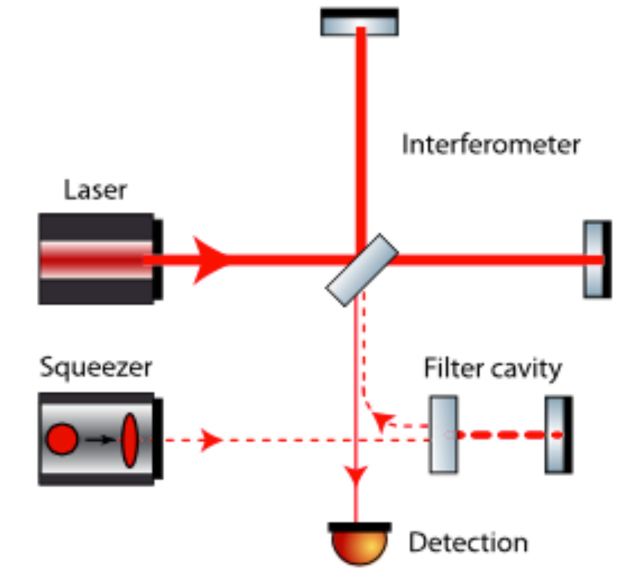




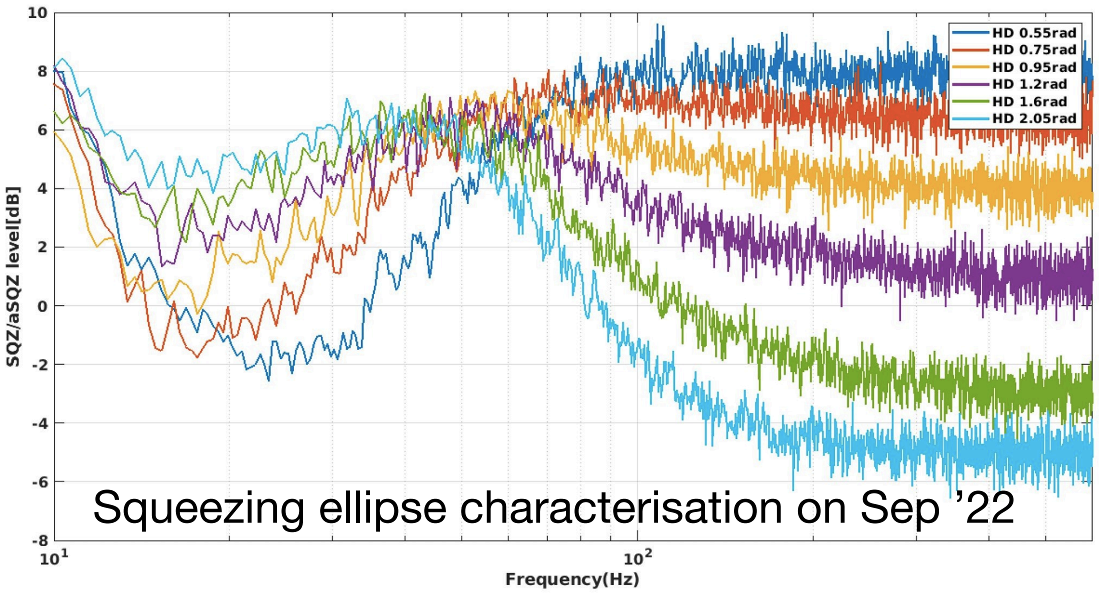
Frequency dependent squeezing ready for injection in ITF

- Goal: quantum noise reduction even at low frequency





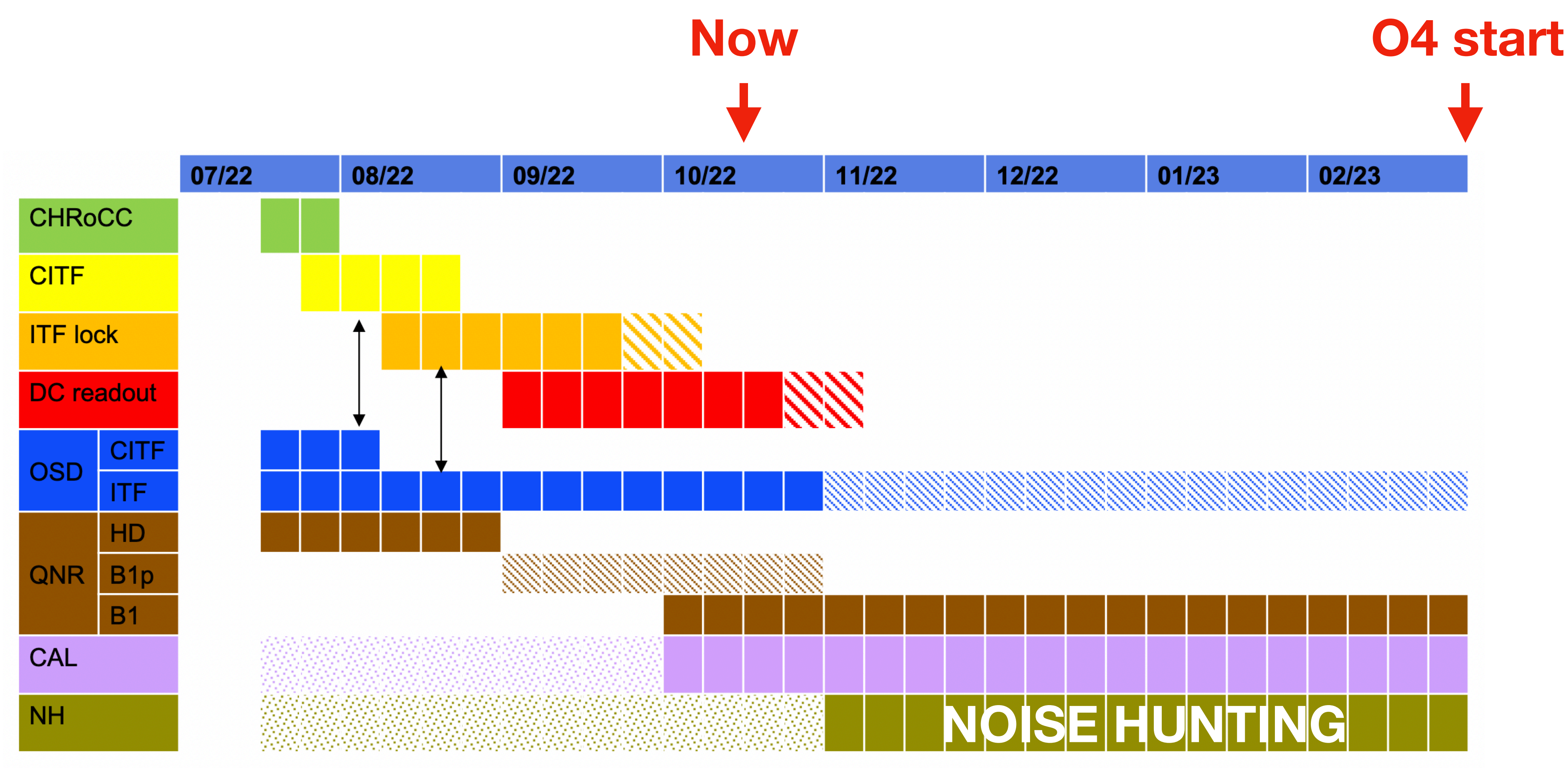
- Standalone squeezing measurement performed with the required rotation angle (25 Hz)
- On-going work to improve stability



Squeezing ellipse characterisation on Sep ’22

Virgo commissioning toward O4 summary

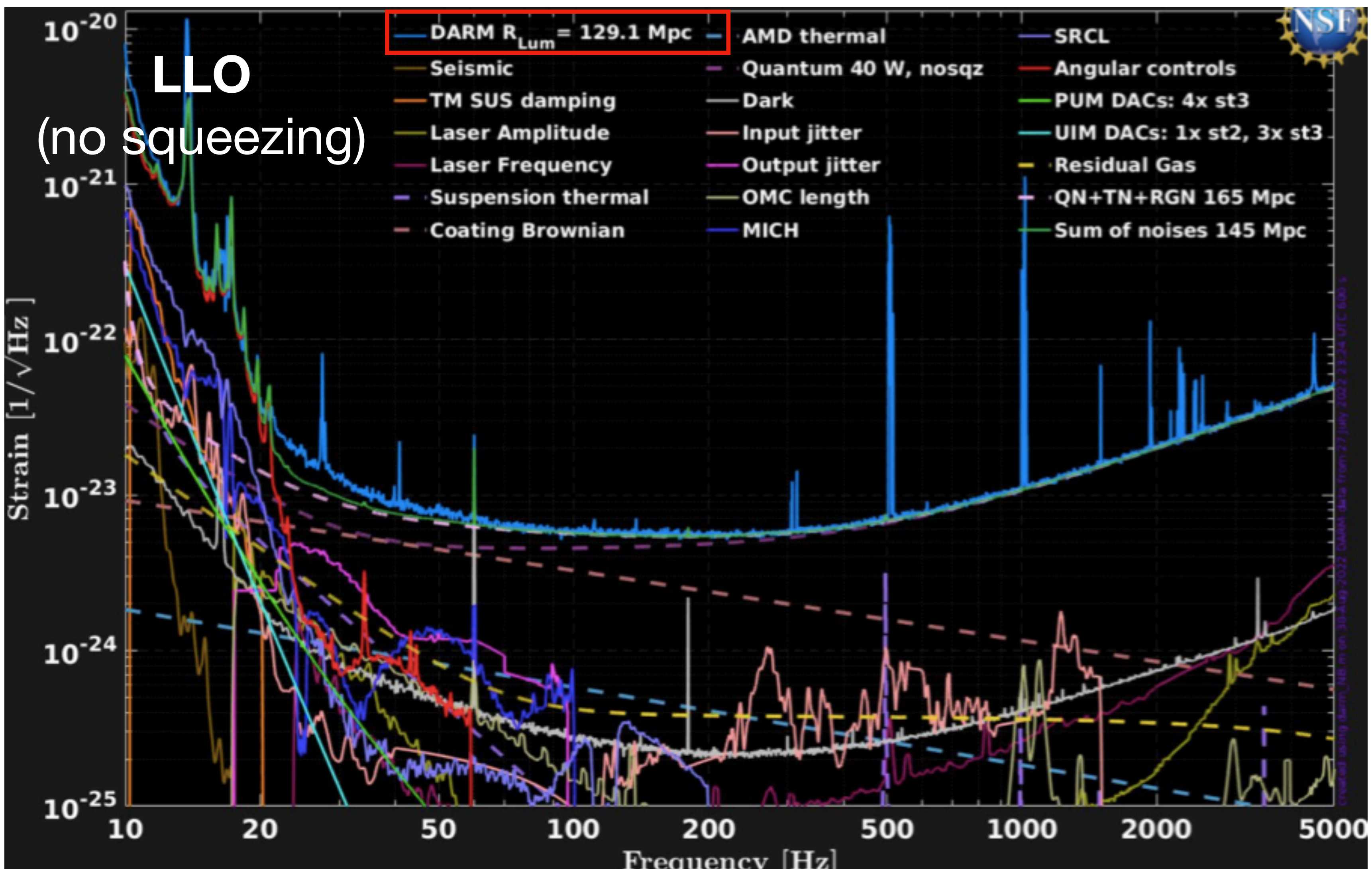
- Issue with control stability solved in July
    - Installation of a new thermal actuators
- On going: optimisation of thermal and alignment working point
    - Looking for SR alignment signal
- Soon: sensitivity measurement, noise hunting and squeezing injection



Advanced LIGO+ commissioning status

Main actions toward O4

- Test mass replacement to remove point absorber
- Frequency dependent squeezing (filter cavity to be commissioned)
- Double power in the arm (from 200 kW to 400 kW)
- Techical noise reduction



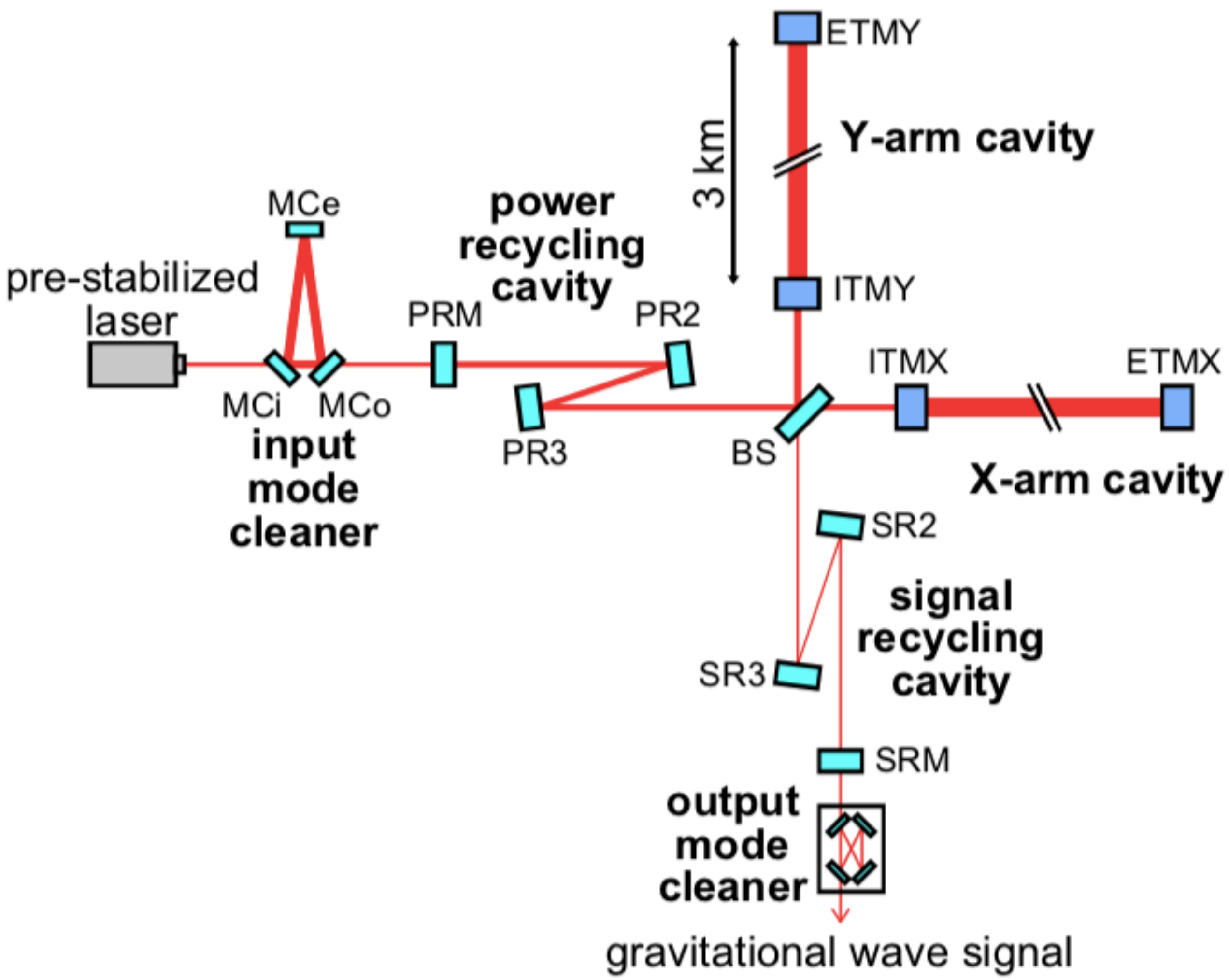
Target 175 Mpc

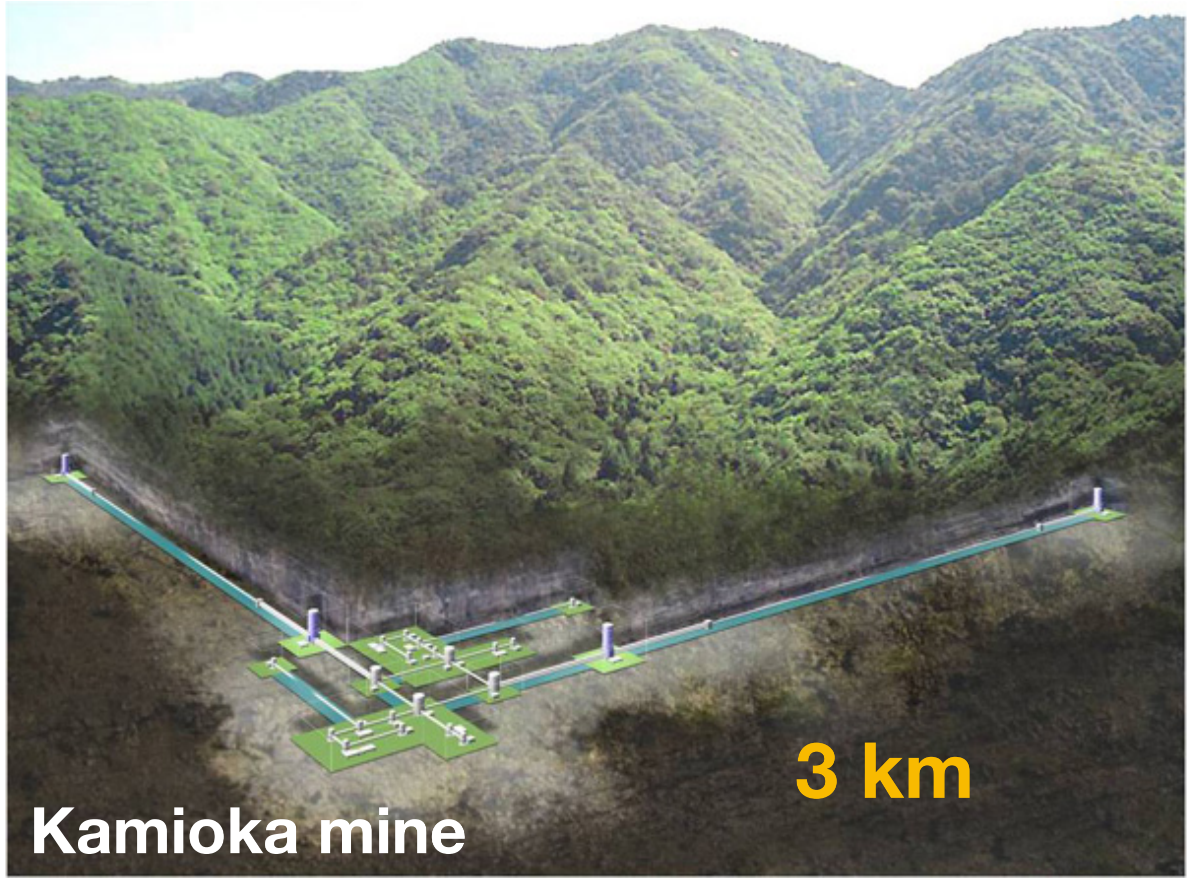
https://dcc.ligo.org/LIGO-G2201504

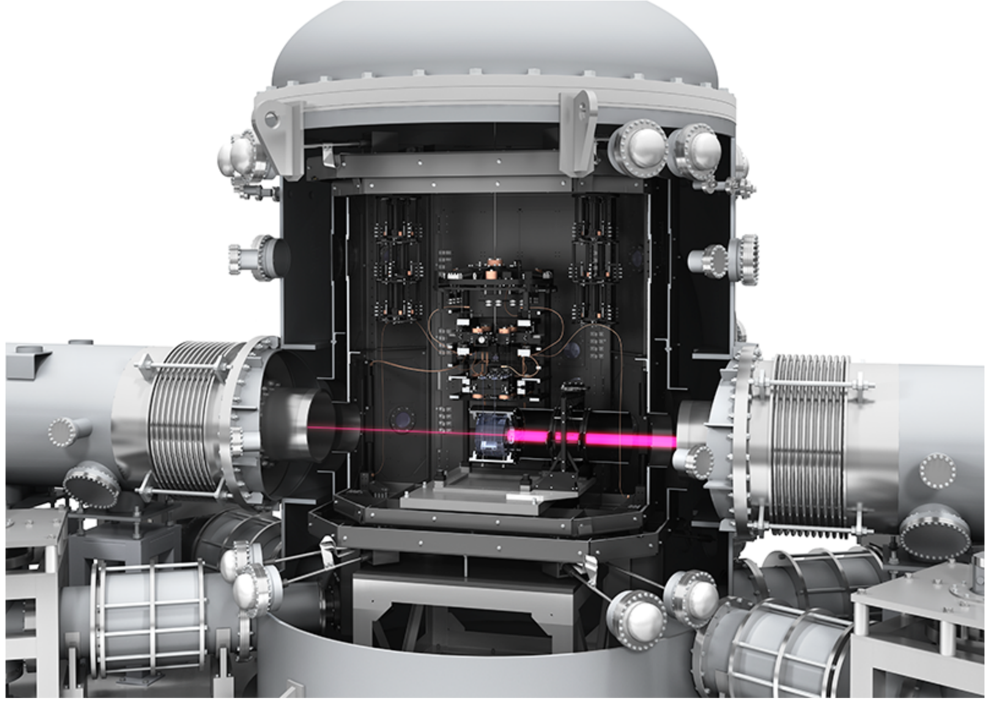
KAGRA status

Japanese 2.5 generation detector

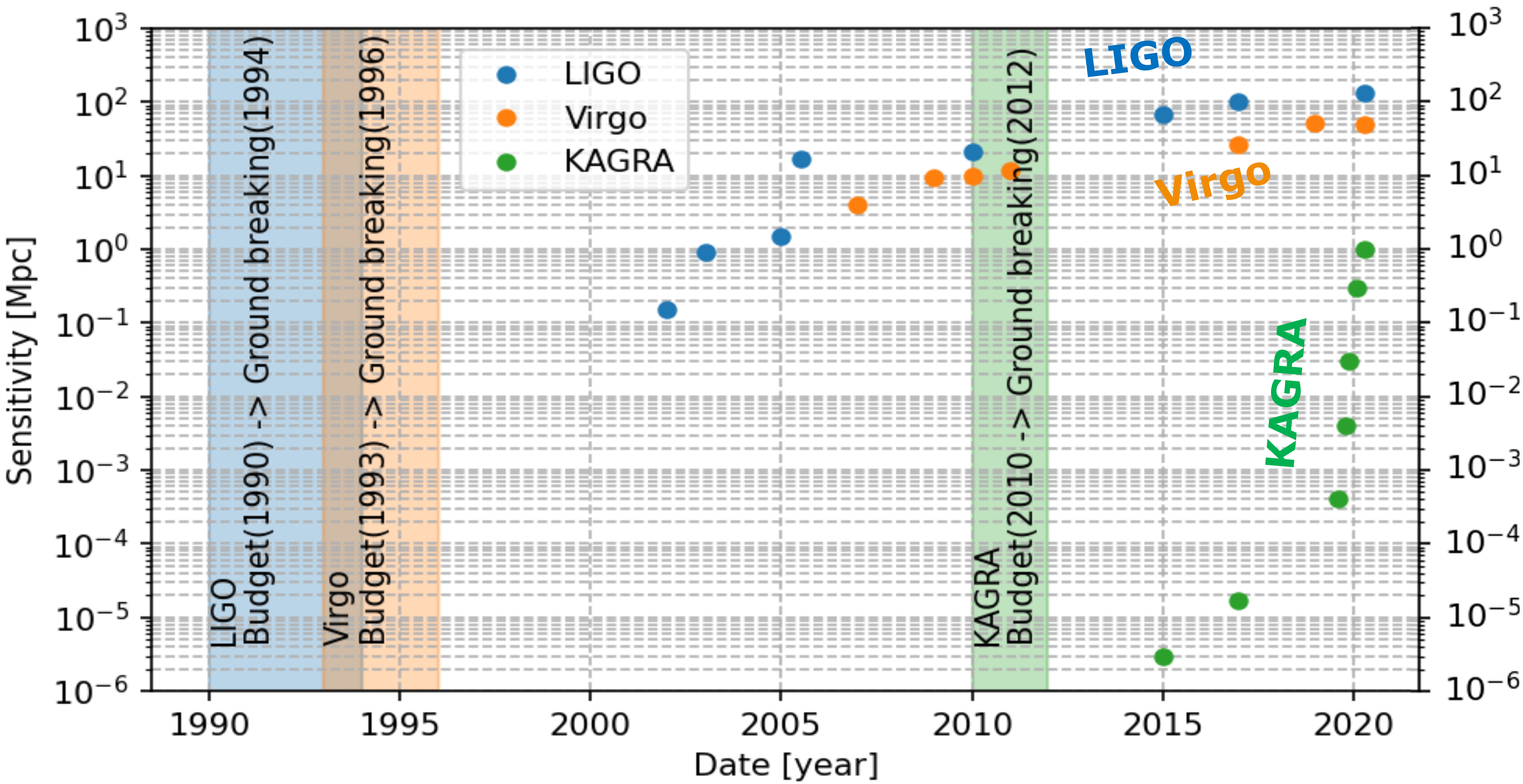
- Undeground
- Cryogenic







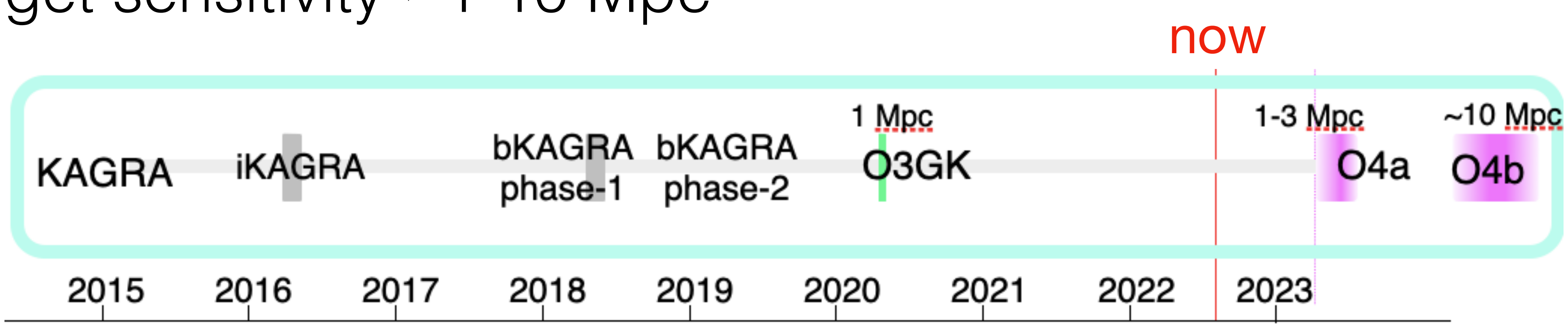
BNS range evolution comparison



J.Yokohama, "status of KAGRA" LVK meeting 09/22

KAGRA configuration for O4

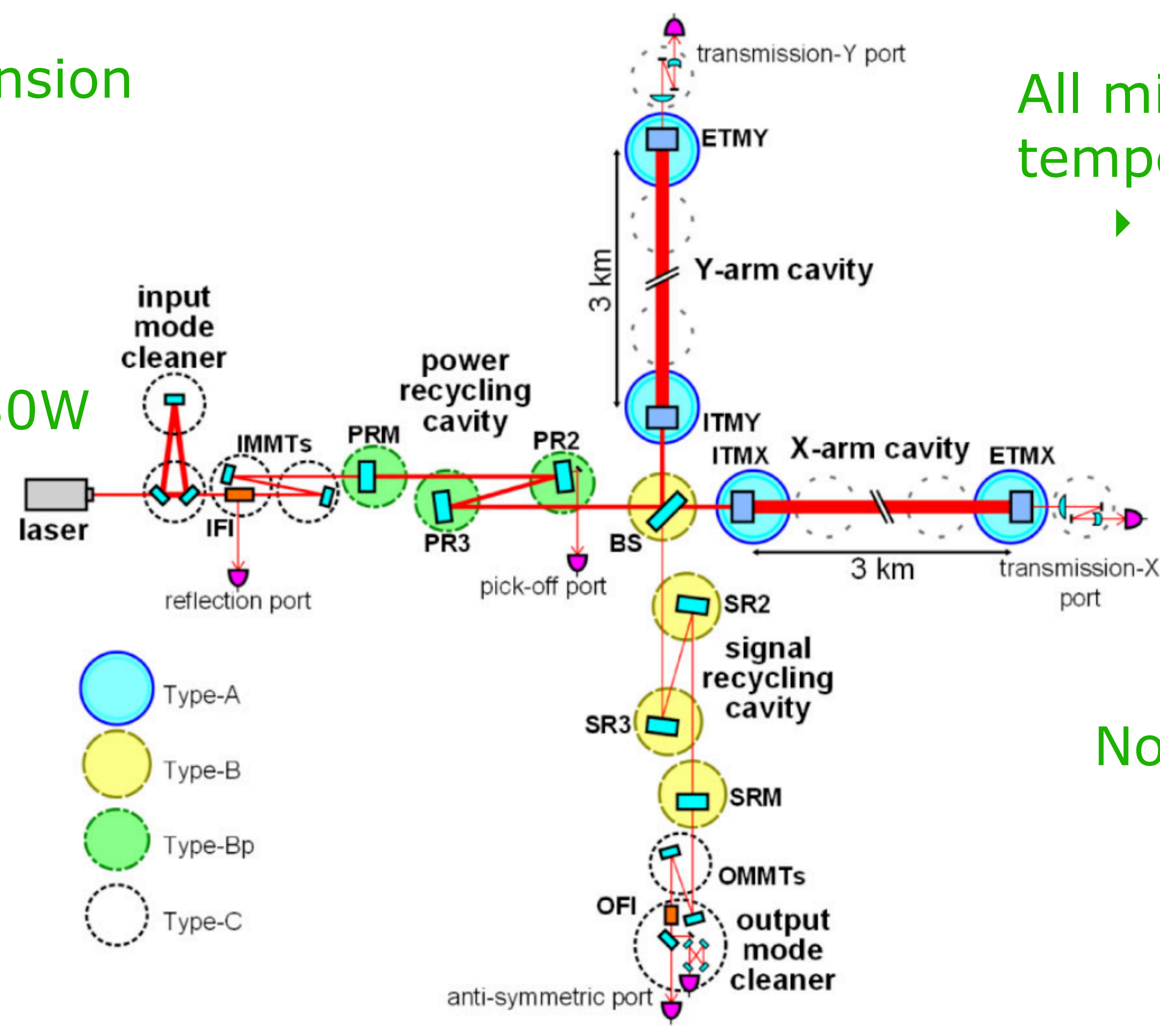
- Target sensitivity ~1-10 Mpc



Improved suspension performances

All mirrors at cryogenic temperature (O4b)
- frosting issue solved

~30W



Scattered light reduction

No signal recycling
- Few time for commissioning
- Sapphire birefringence issue

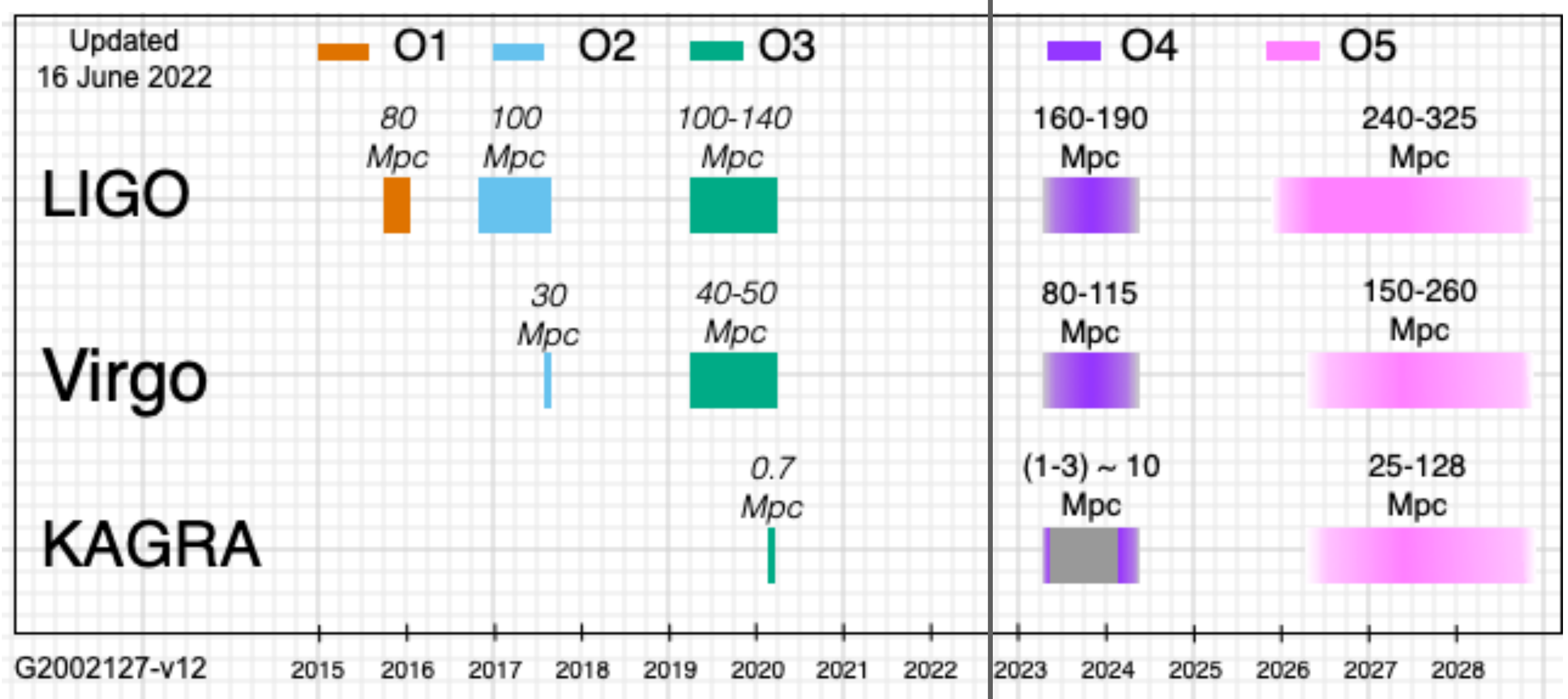
- Fabry-Perot Michelson controlled on September

Possible future roadmap for ground base detectors

Current infrastructures

New infrastructures

Advanced Virgo+
Advanced LIGO+



- Virgo_nEXT
- A#

~ 2030-2035

- Einstein Telescope
- Cosmic Explorer

> 2036

Already founded

- See E.Tournefier talk about Virgo_nEXT tomorrow

Expected detection rates

- O3 ⇒ O4

  ~ x 3 BBH (almost ~1 per day, total ~250/year)

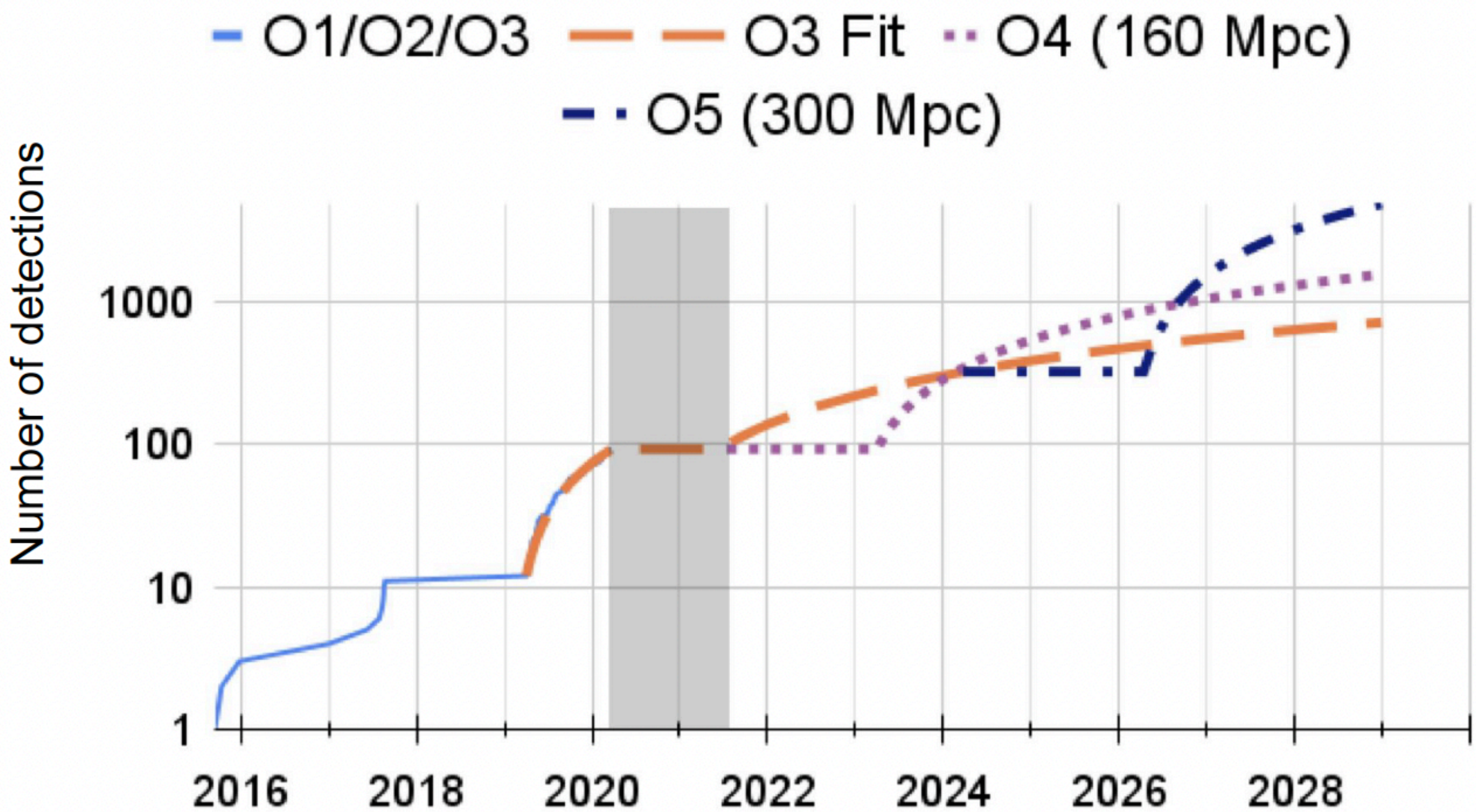
- O3 ⇒ O5

  ~x 10 BBH (a few per day, total ~1000/year)

- ~ 5-10 BNS in O4

- O4 average BNS localization: ~hundreds deg^2
  Kagra sensitivity few Mpc

Alternation of observing/upgrades periods



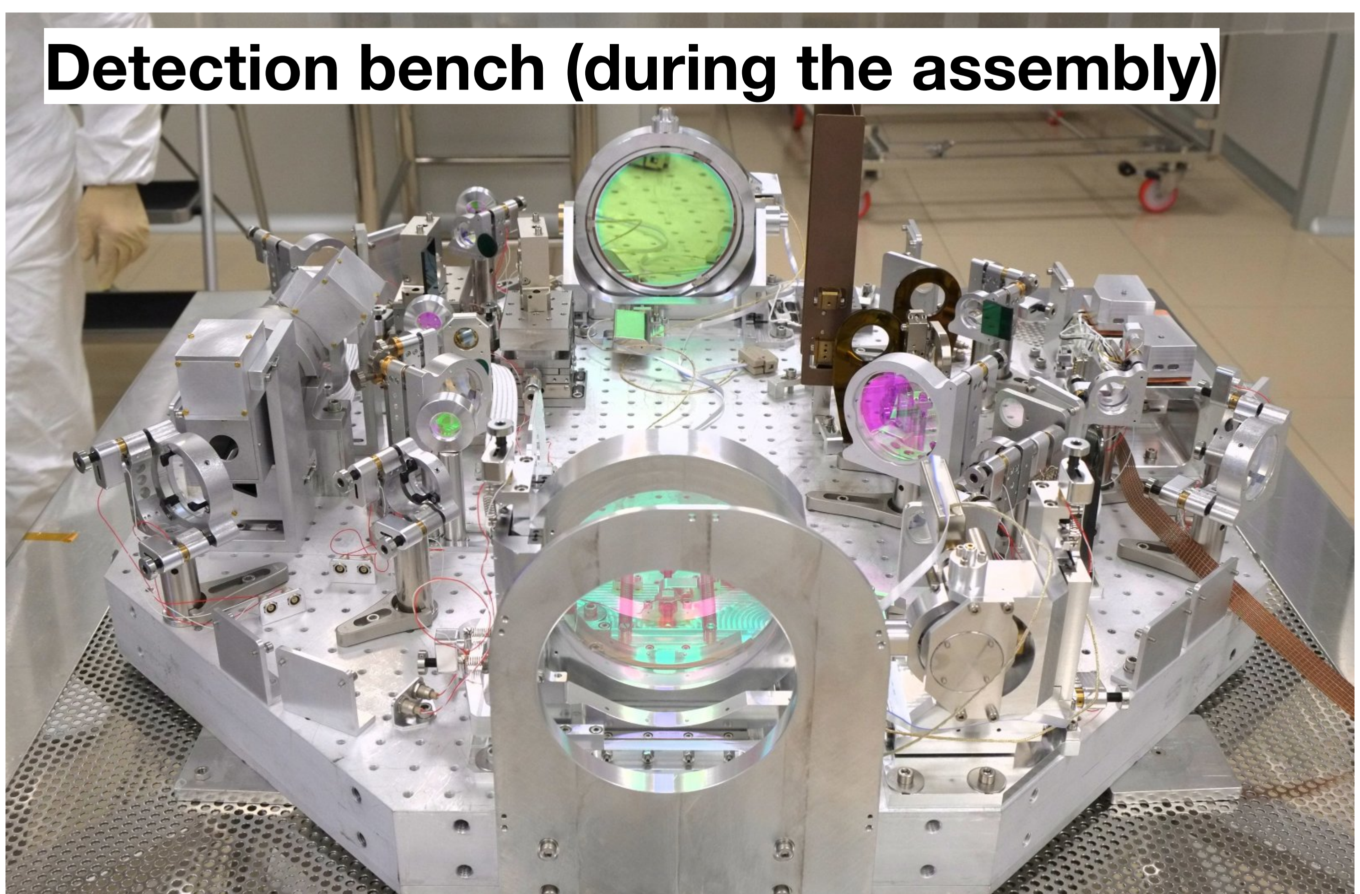
Credit: P.Brady

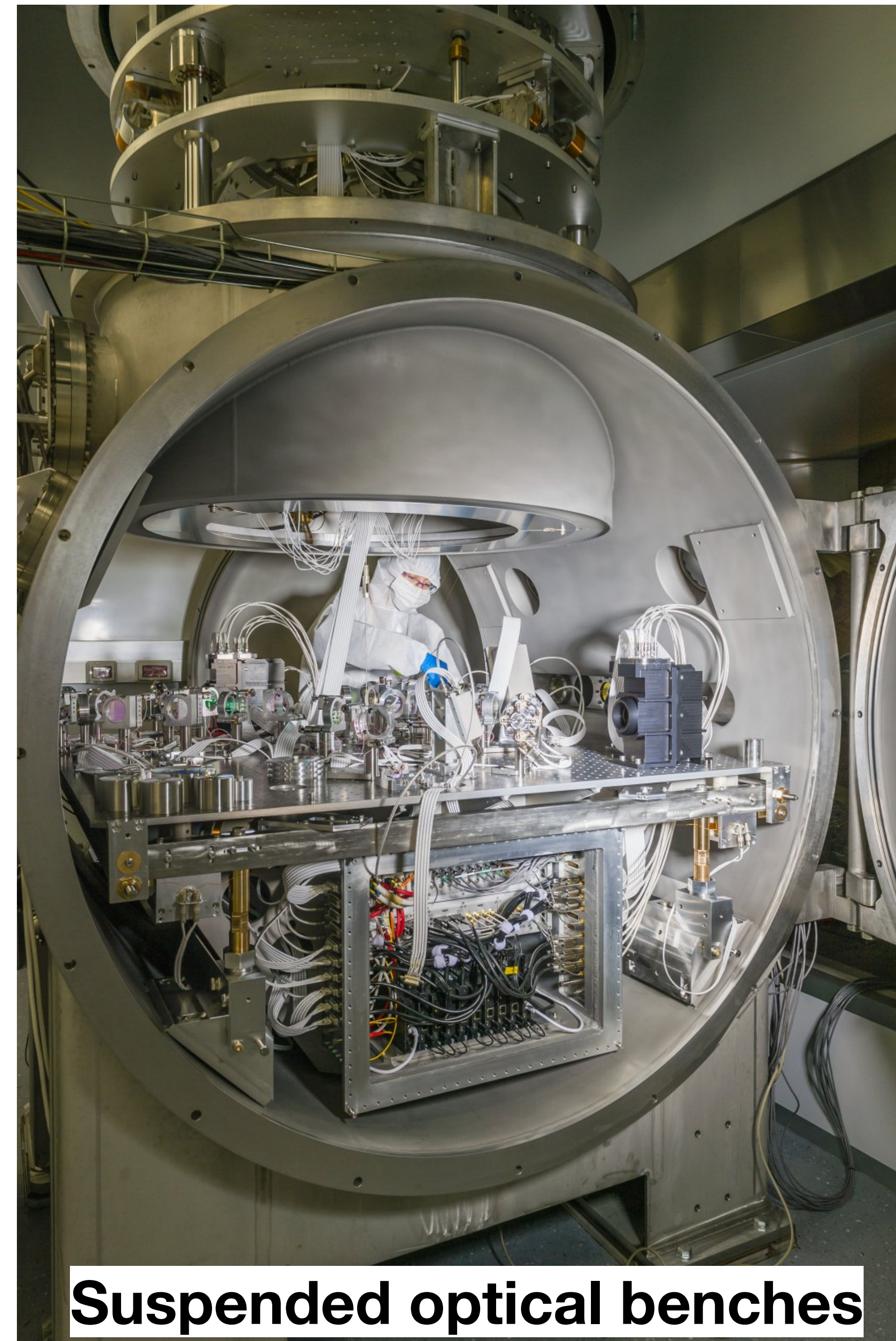
Summary

- Network of 2G ground GW detectors operating since 2015 provided many detections (~90) and a lot of science
- They are now on a commissioning phase in view of O4 (March 2023)
- Observation plan scheduled up to 2028 (O5 upgrades already funded)
  - O4 -> almost 1 detection per day
  - O5 -> 3-4 detections per day
- Post-O5 plans under discussion (concept study released)
  - Sensitivity limit of the infrastructures not yet reached
  - Fill the gap between 2G and 3G

BACK UP SLIDES


External injection bench


Detection bench (during the assembly)

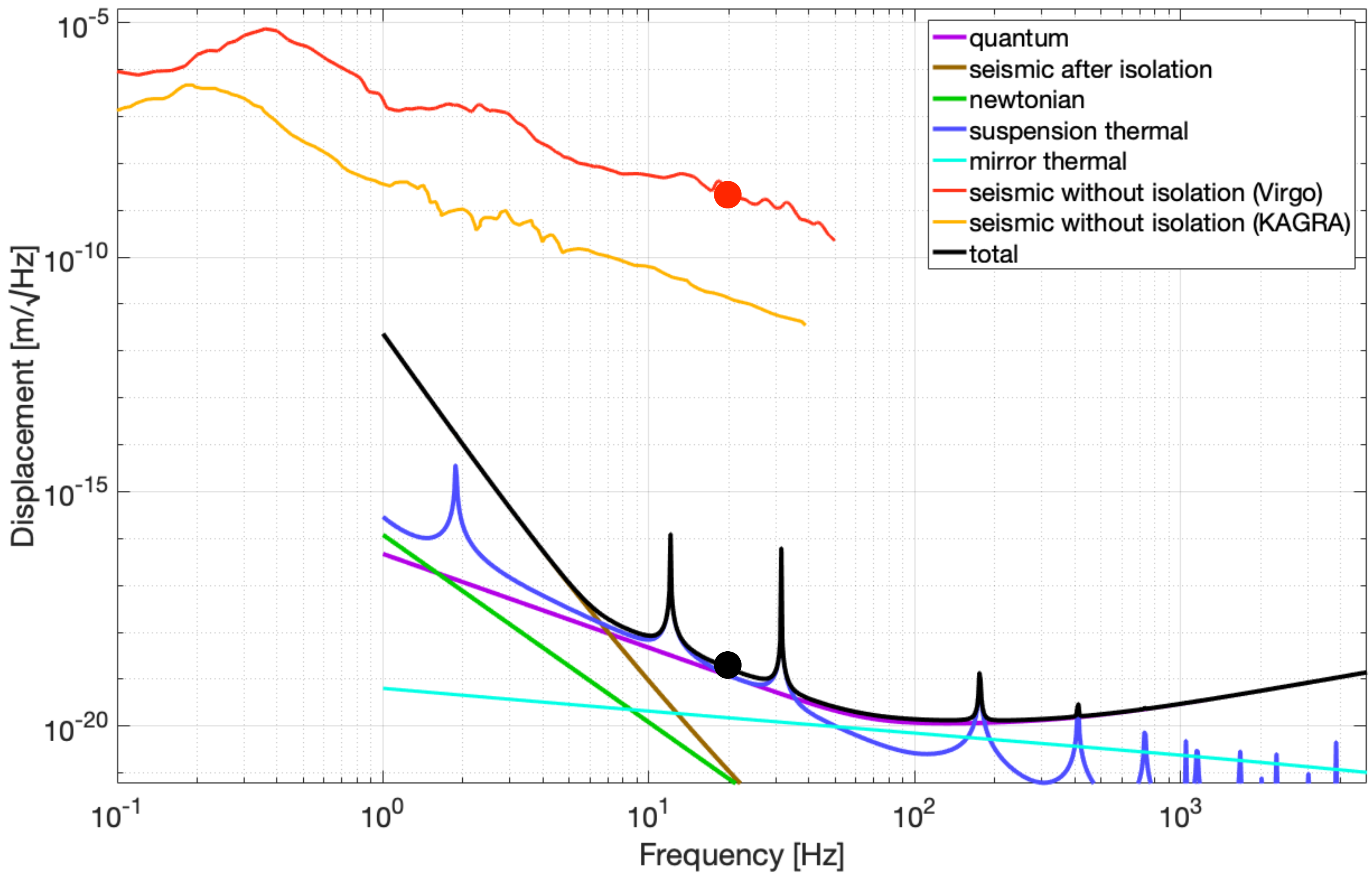

Suspended optical benches

Seismic noise isolation requirement

- Seismic motion at ~10 Hz: ~ 10^{-9} m/√Hz
- Required mirror motion at ~10 Hz: ~ 10^{-19} m/√Hz

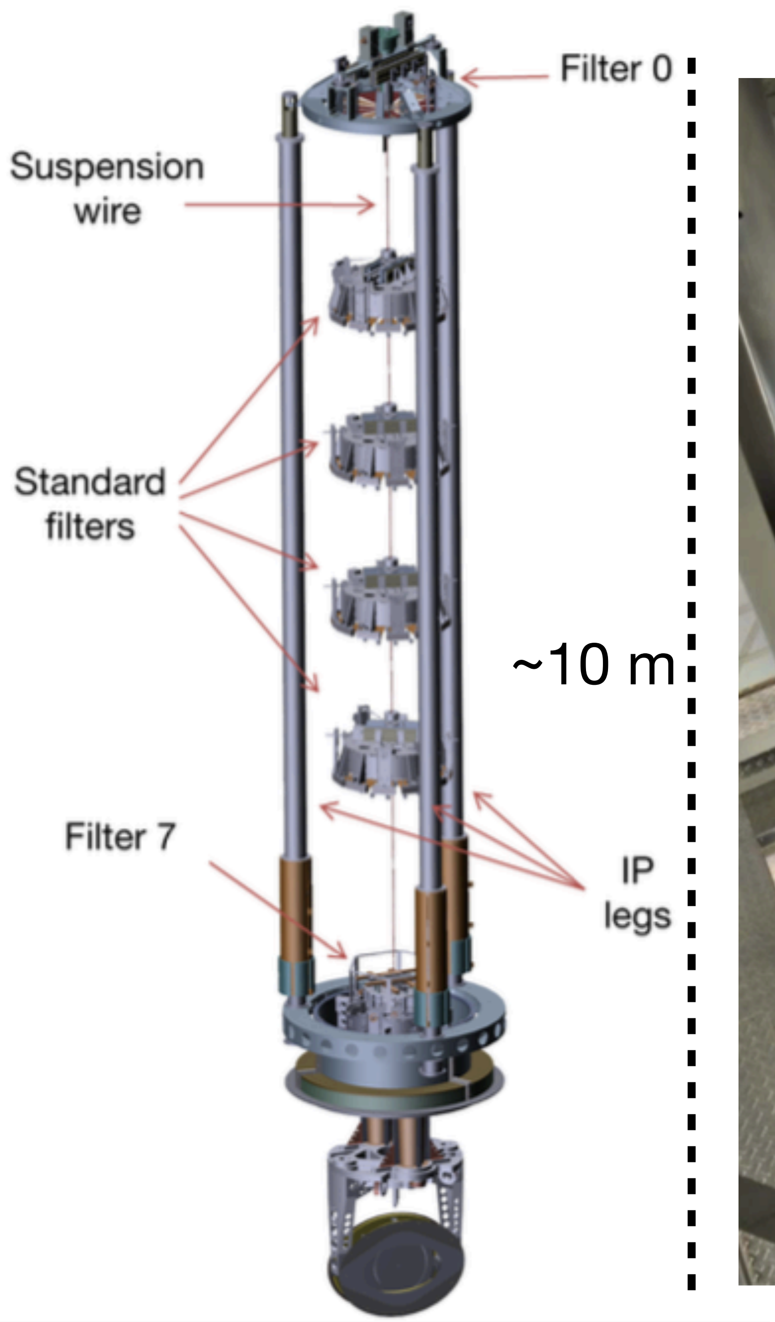
↓

Need for high performance vibration isolation system (at least 10 order of magnitudes)

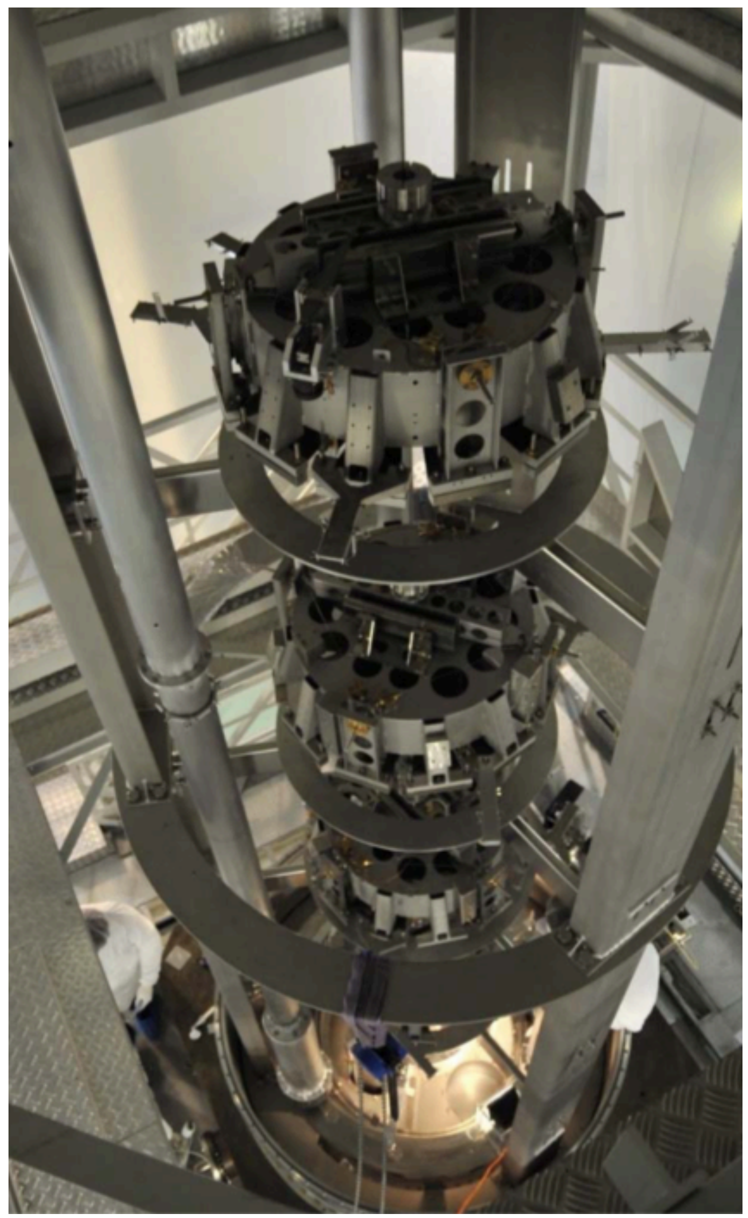


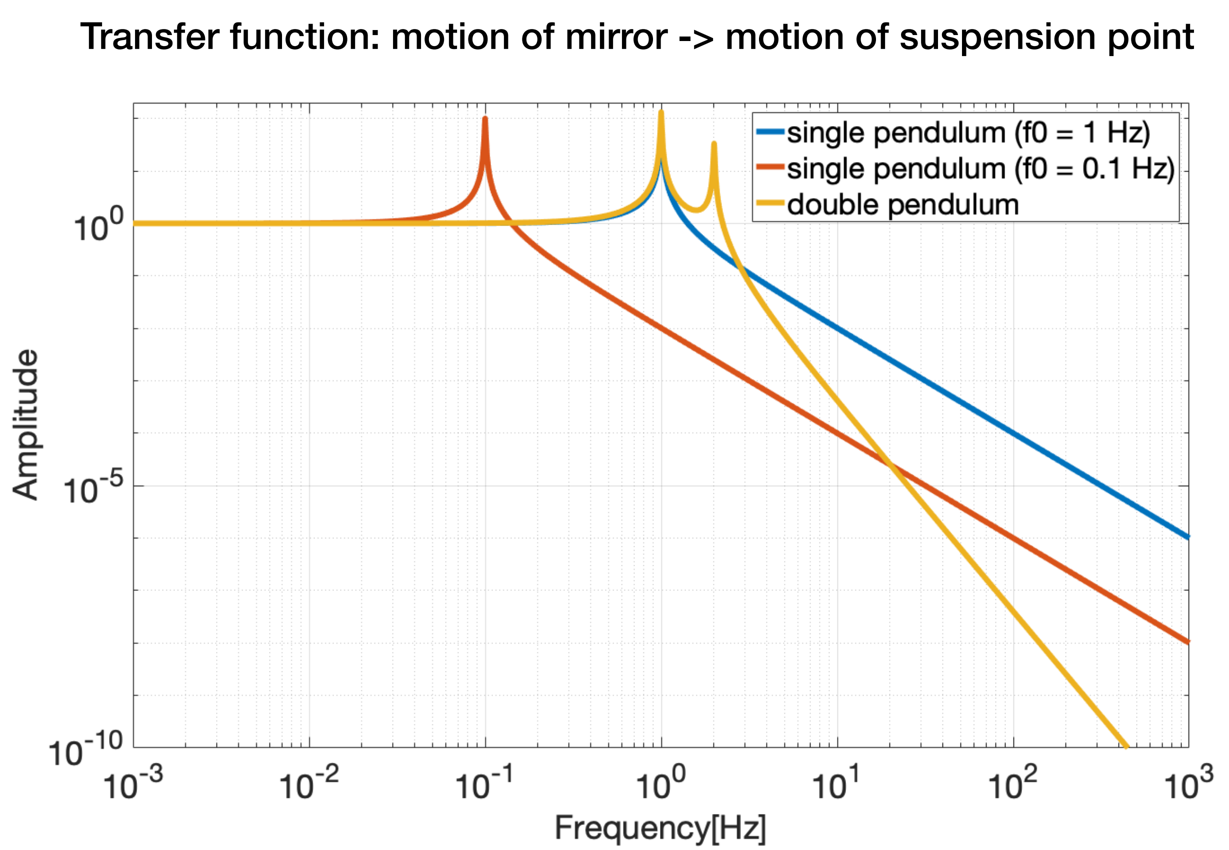
How to isolate mirrors from ground vibrations?

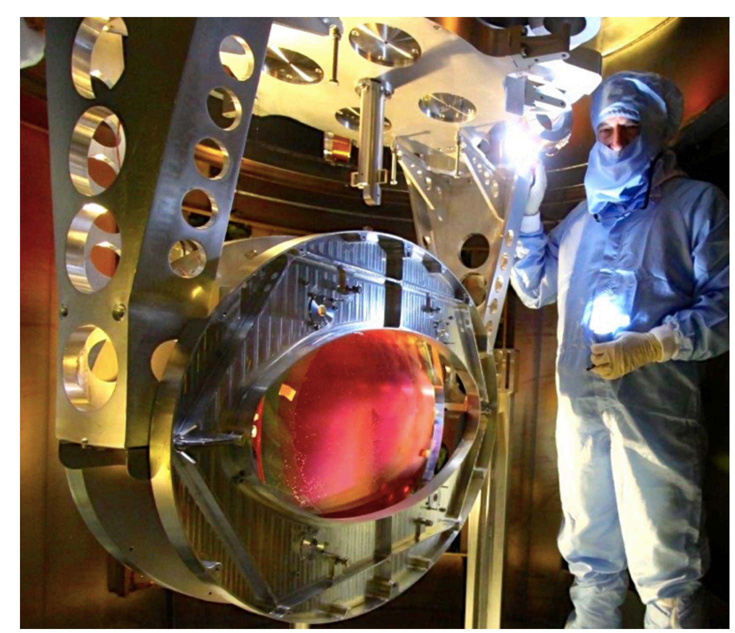
- System based on a chain of pendulums to isolate the test mass from the vibration of their suspension point



AdVirgo

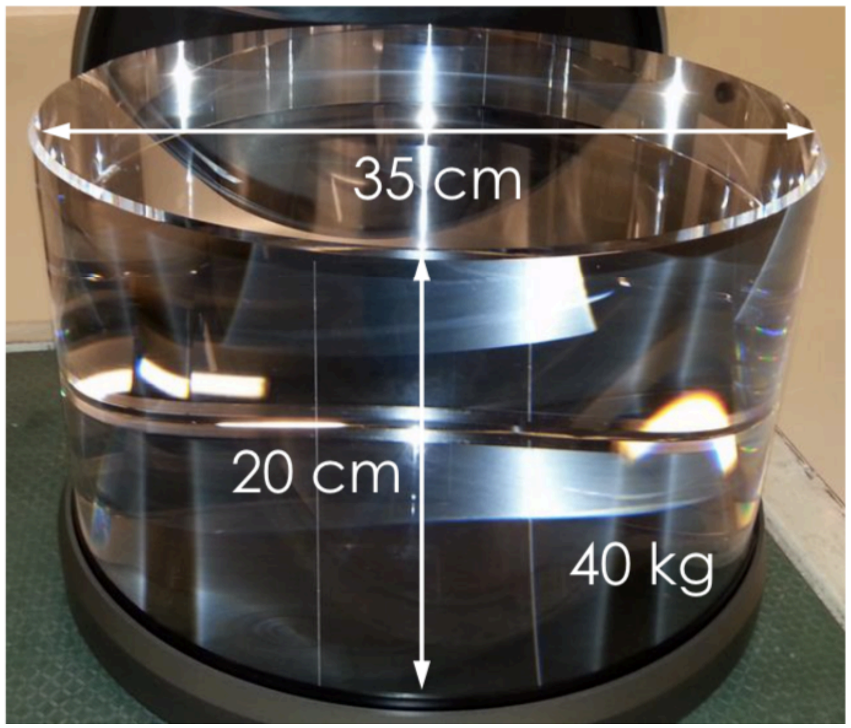






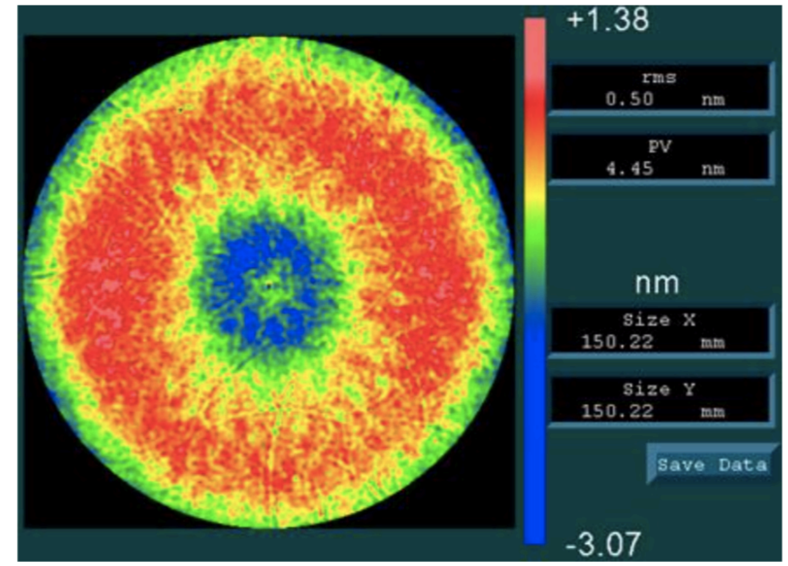
Mirrors

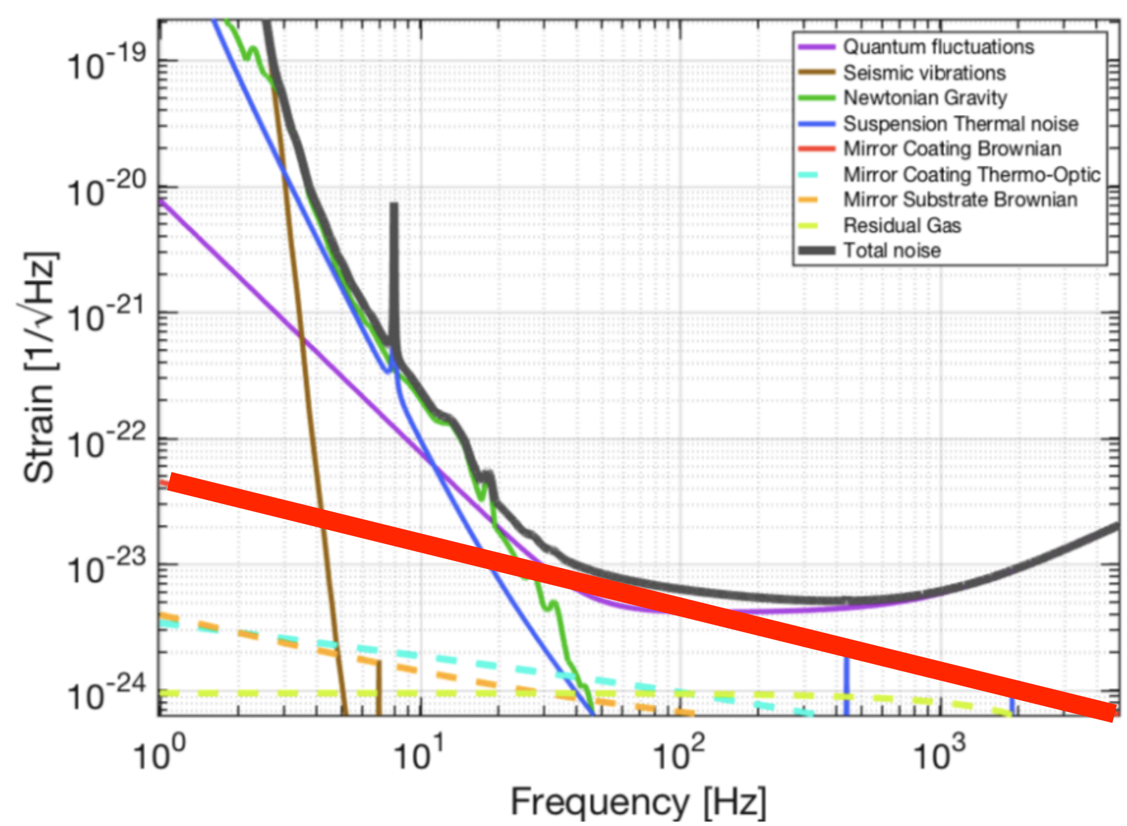
- Substrates: ultra-pure fused silica



- Coatings
  - Multilayers of titania-doped tantala/silica
  - Main responsible for mirror thermal noise
  - Long term effort to find more performant materials

- Extremely small roughness (<0.5 nm rms)

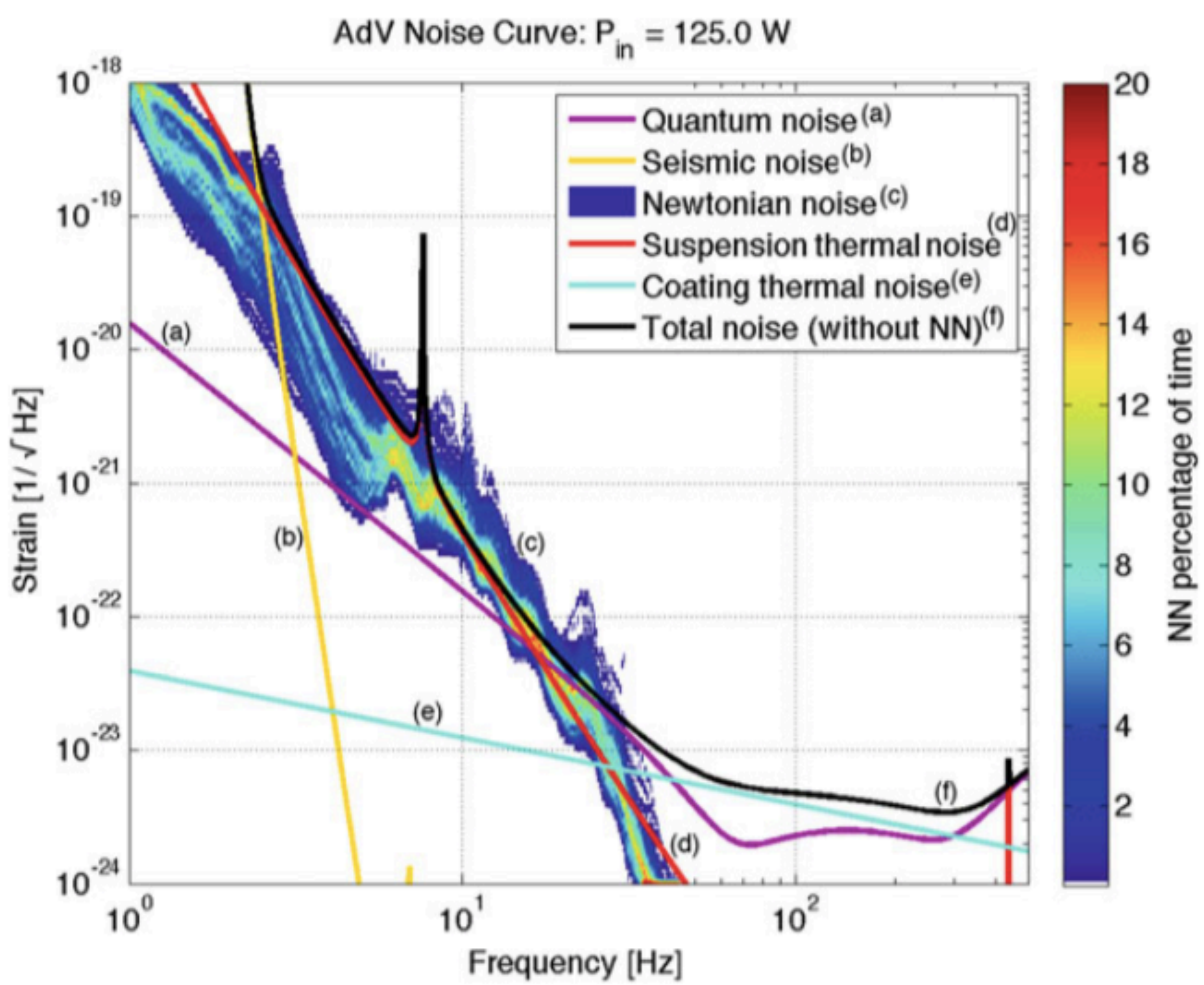




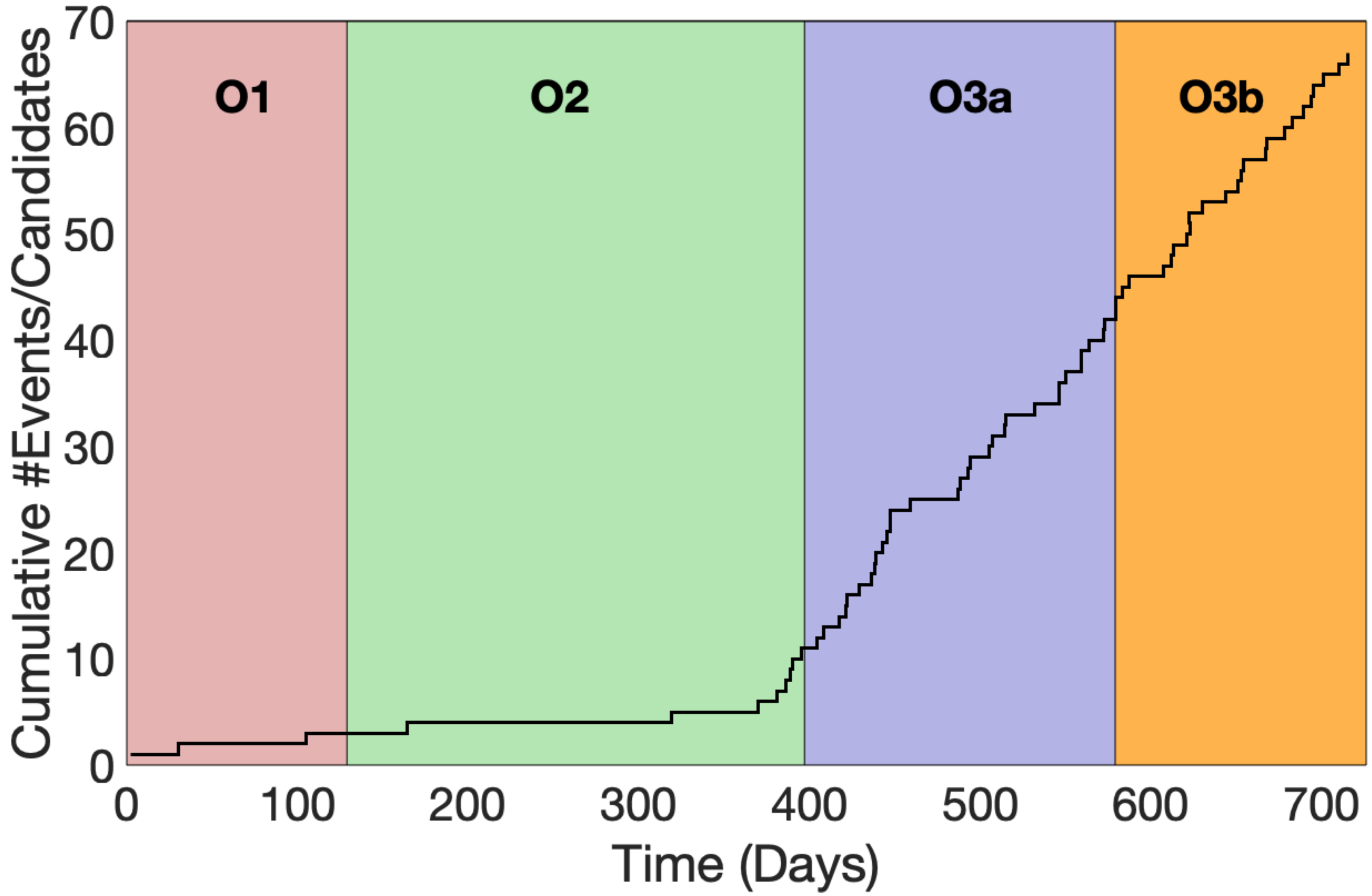
Newtonian noise

Due to fluctuations of the terrestrial gravity field

- Mainly produced by density perturbation in the ground (due to seismic waves) or in the atmosphere
- It couples directly to the mirrors, bypassing any isolation system
- It is expected to limit low frequency sensitivity
- Cancellation techniques under testing



Observations summary



O1-O2 (2015 - 2017)

- 11 detections (10 BBH, 1 BNS)
- GWTC-1 first catalog of GW transient sources (2019)

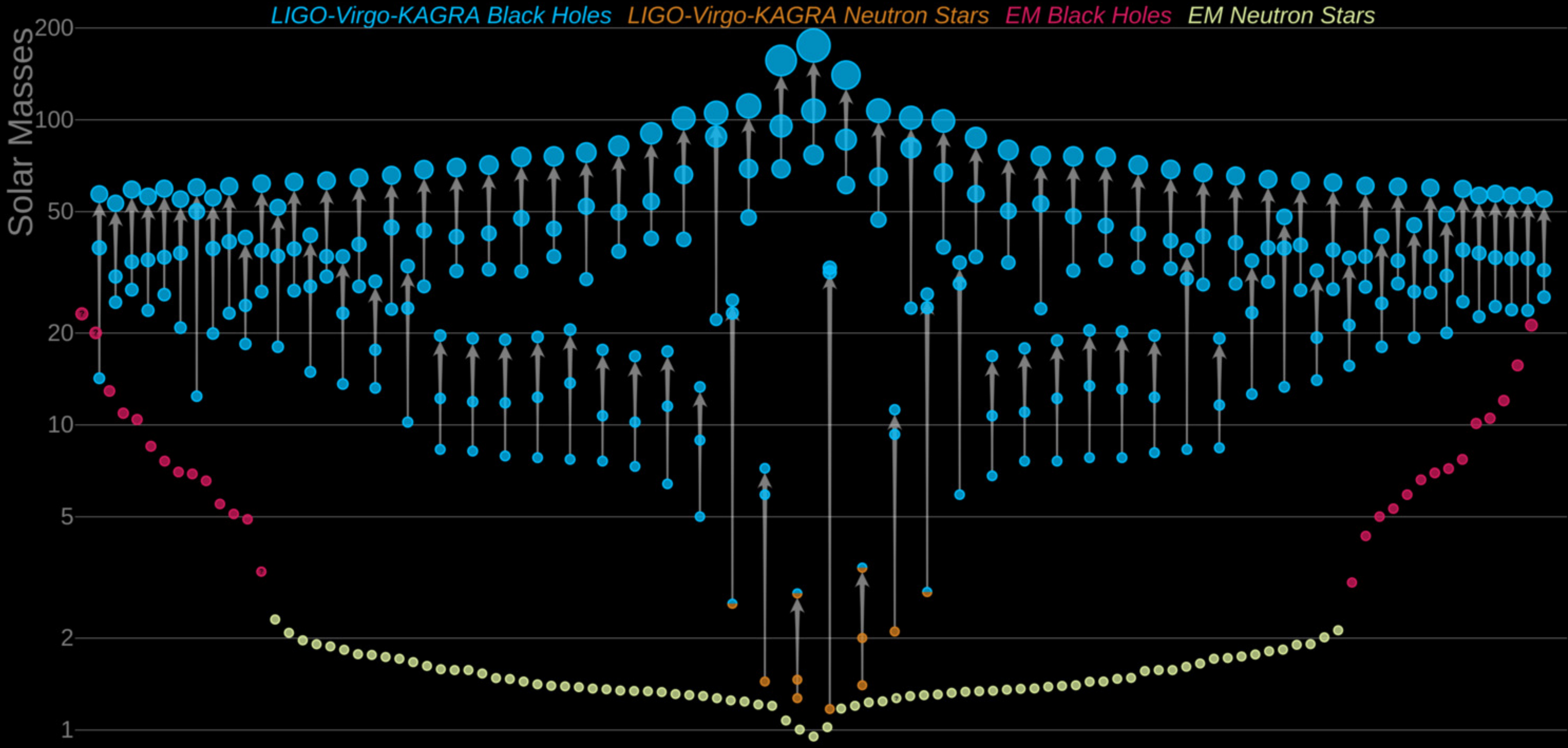
O3a (2019)

- 39 detections
- GWTC-2 second catalog of GW transient sources (2020)

O3b (2019 - 2020)

- 35 detection
- GWTC-3 (2021)

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern