Experimental challenges in ground-based gravitational-wave detectors

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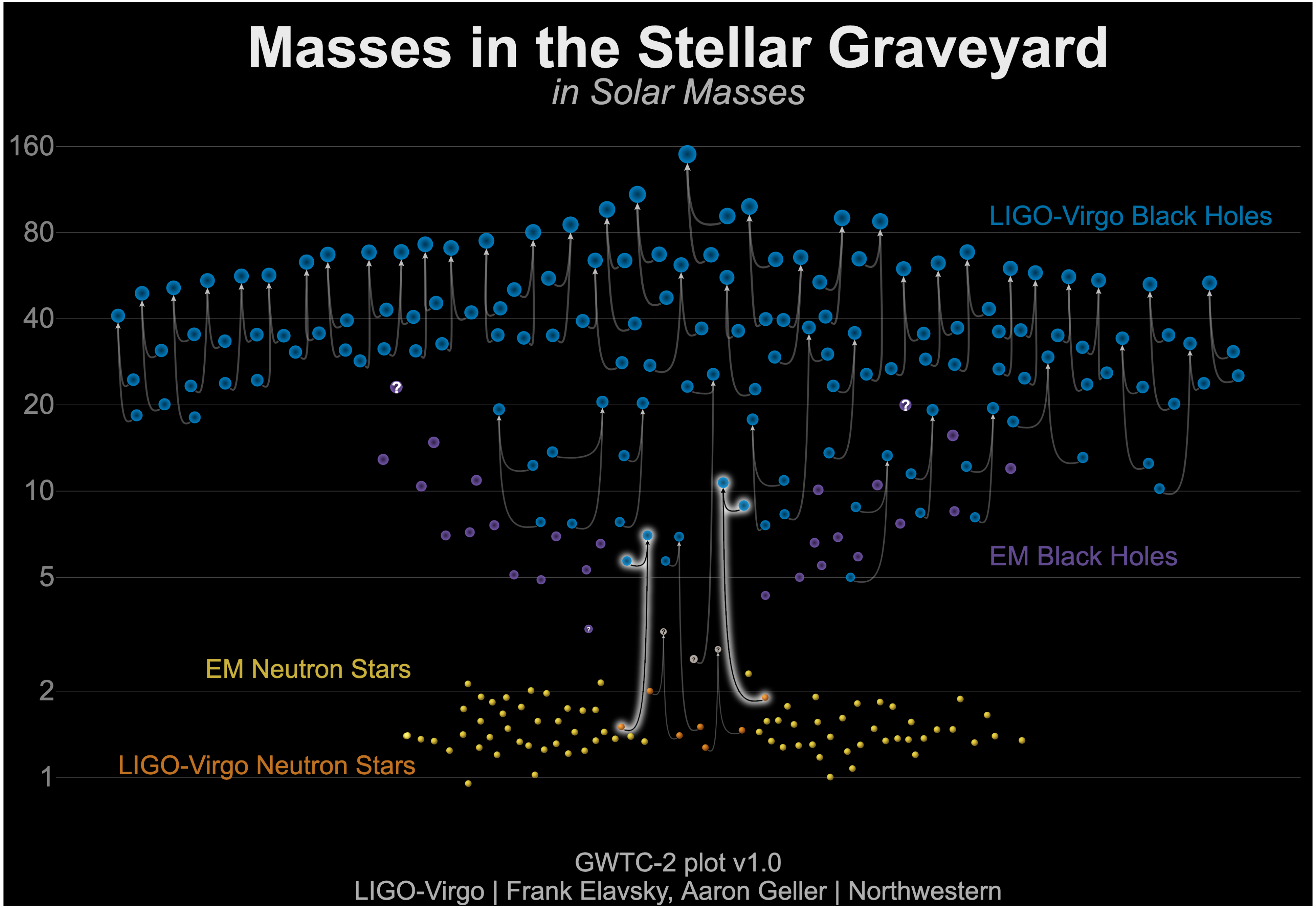
CNRS/IN2P3 – Astroparticule et Cosmologie

Thanks to colleagues working in LIGO,Virgo and KAGRA, Einstein Telescope and Cosmic Explorer

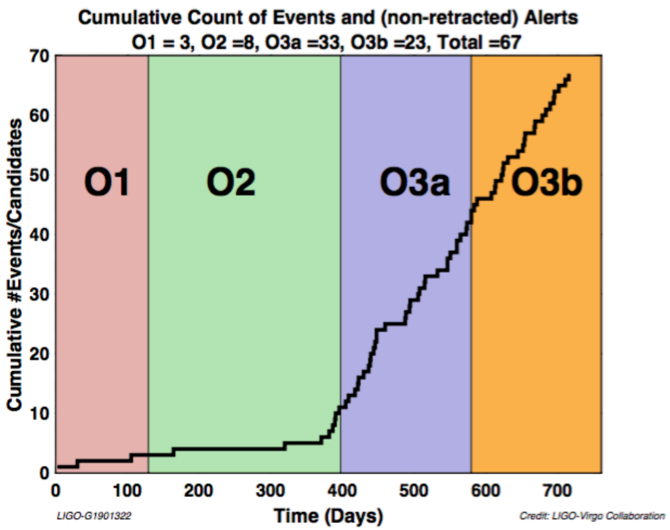
Outline

- Context and background
  - Science with GW detectors
  - Performances of Virgo and LIGO during O3
- The next data takings (O4 and O5)
- The gap between O5 and third generation detectors
- The third generation detectors

LIGO/Virgo observations



O3 results so far
(analysis not concluded)



- 6 new *exceptionall* astrophysical systems published
- More distant sources (z ~ 0.5 → ~ 0.8)
- New tests of general relativity (i.e. harmonics of the GW signal)

- A drastic change in slope in the number of sources
- Statistics on black-hole populations

- Upper limits on several sources and physical effects (i.e. GW background, lensing, specific dark matter candidates)

O3 scientific results: 6 new « exceptional » events

- GW190412: BBH merger with component masses ~ $8M_\odot$ and ~ $3M_\odot$
    - Mass asymmetry → observable GW beyond the leading quadrupolar order

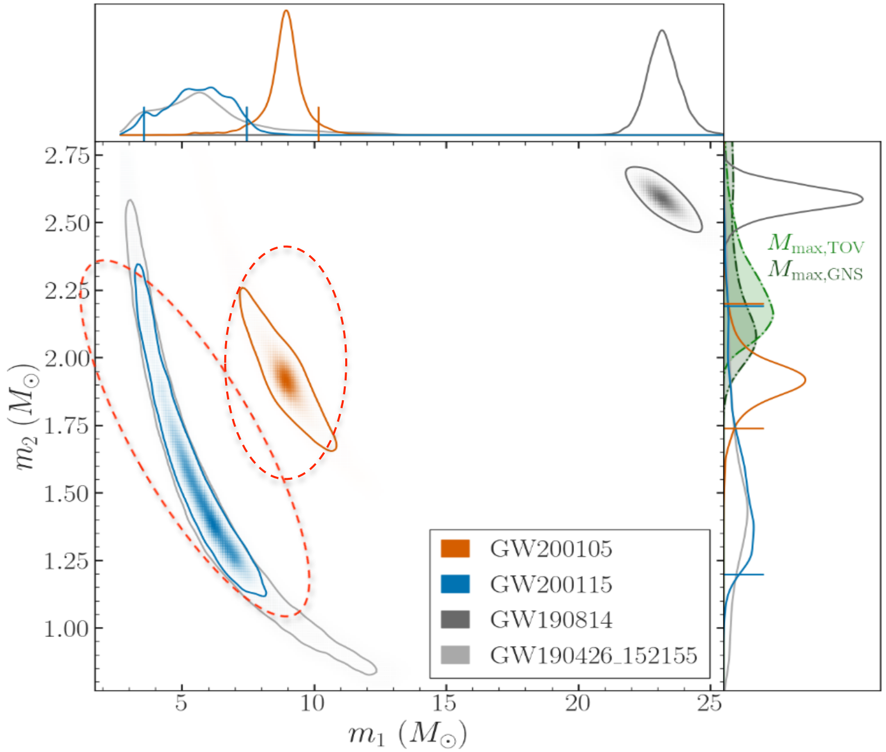
- GW190814: compact object merger, with component masses ~ $23M_\odot$ (BH) and ~ $3M_\odot$
    - ~ $3M_\odot$ object: the lightest BH or the heaviest NS ever observed ?

- GW190425: BNS merger, with a total mass of ~ $3.4M_\odot$
    - Total mass significantly larger than any of the other known BNS systems

- GW190521: BBH merger with component masses ~ $66M_\odot$ and ~ $85M_\odot$. The final BH is 142 $M_\odot$
    - A recent global analysis of IMBH in O3 confirmed the event with higher significance (paper published on June 2021)

- GW200105 and GW200115: first two NS-BH systems
    - Announced 6 days ago

GW200105 and GW200115



Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences, LIGO/Virgo/KAGRA Collaborations
The Astrophysical Journal Letters, Volume 915, Number 1 (2021)

First observations of NSBH system

- GW200105 - 8.9 and 1.9 solar masses
- GW200115 – 5.7 and 1.5 solar masses

O3 results
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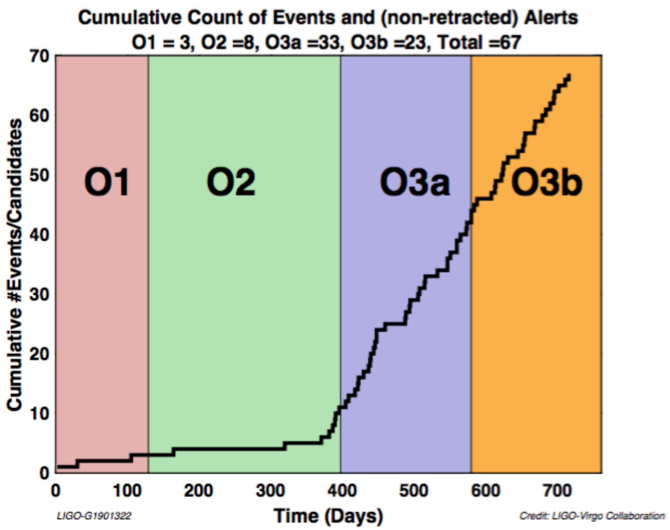

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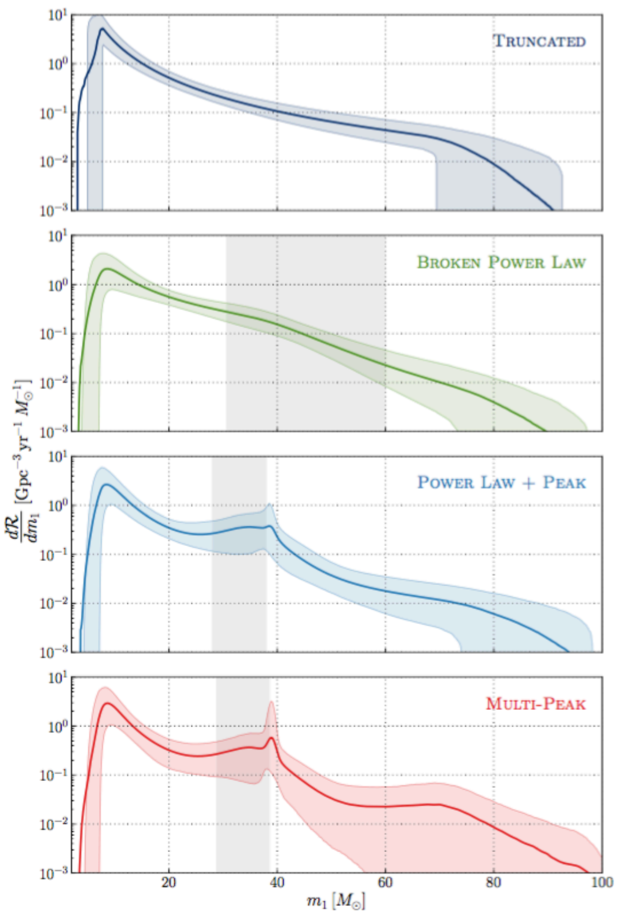
GWTC-2: Statistics, population properties



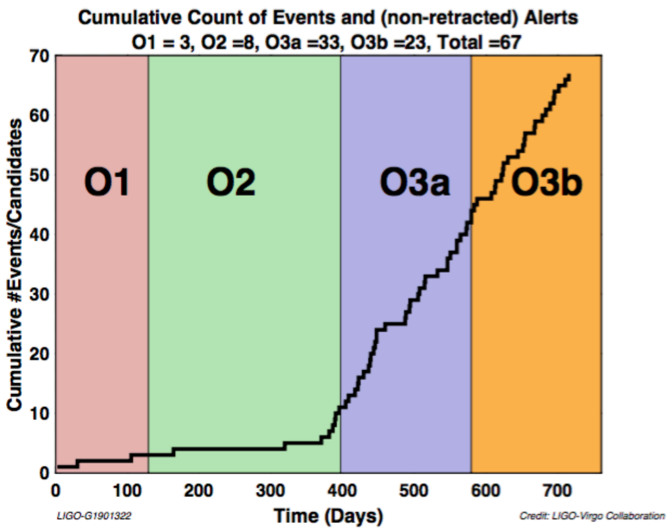
- What is the minimum mass of a BH?
- Does the merger rate evolve with z?
- Are there structures in the distribution of masses ?

Population Properties of Compact Objects from the Second LIGO–Virgo Gravitational-Wave Transient Catalog, LIGO and Virgo Collaborations , The Astrophysical Journal Letters, Vol 913, n. 1 (2021)

Next data takings:

~ hundreds of events in O4
~ 1000 events for O5

O3 results
(analysis not concluded)



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Other searches (a few examples)

- Constraints on **dark photon dark matter** using data from LIGO's and Virgo's third observing run, https://arxiv.org/abs/2105.13085
- Constraints **on cosmic strings** using data from the third Advanced LIGO-Virgo observing run, arXiv: 2101.12248
- Search **for lensing signatures** in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run, https://arxiv.org/abs/2105.06384,
- Search for **anisotropic gravitational-wave backgrounds** using data from Advanced LIGO's and Advanced Virgo's first three observing runs, https://arxiv.org/abs/2103.08520
- Upper Limits on the **isotropic Gravitational-Wave Background** from Advanced LIGO's and Advanced Virgo's First Three Observing Runs, https://arxiv.org/abs/2101.12130,
- Searches for **continuous gravitational waves** from young supernova remnants in the early third observing run of Advanced LIGO and Virgo, https://arxiv.org/abs/2105.11641
- All-sky search in early O3 LIGO data for **continuous gravitational-wave signals** from unknown neutron stars in binary systems, https://arxiv.org/abs/2012.12128
- **Diving below the spin-down limit**: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910, https://arxiv.org/abs/2012.12926,

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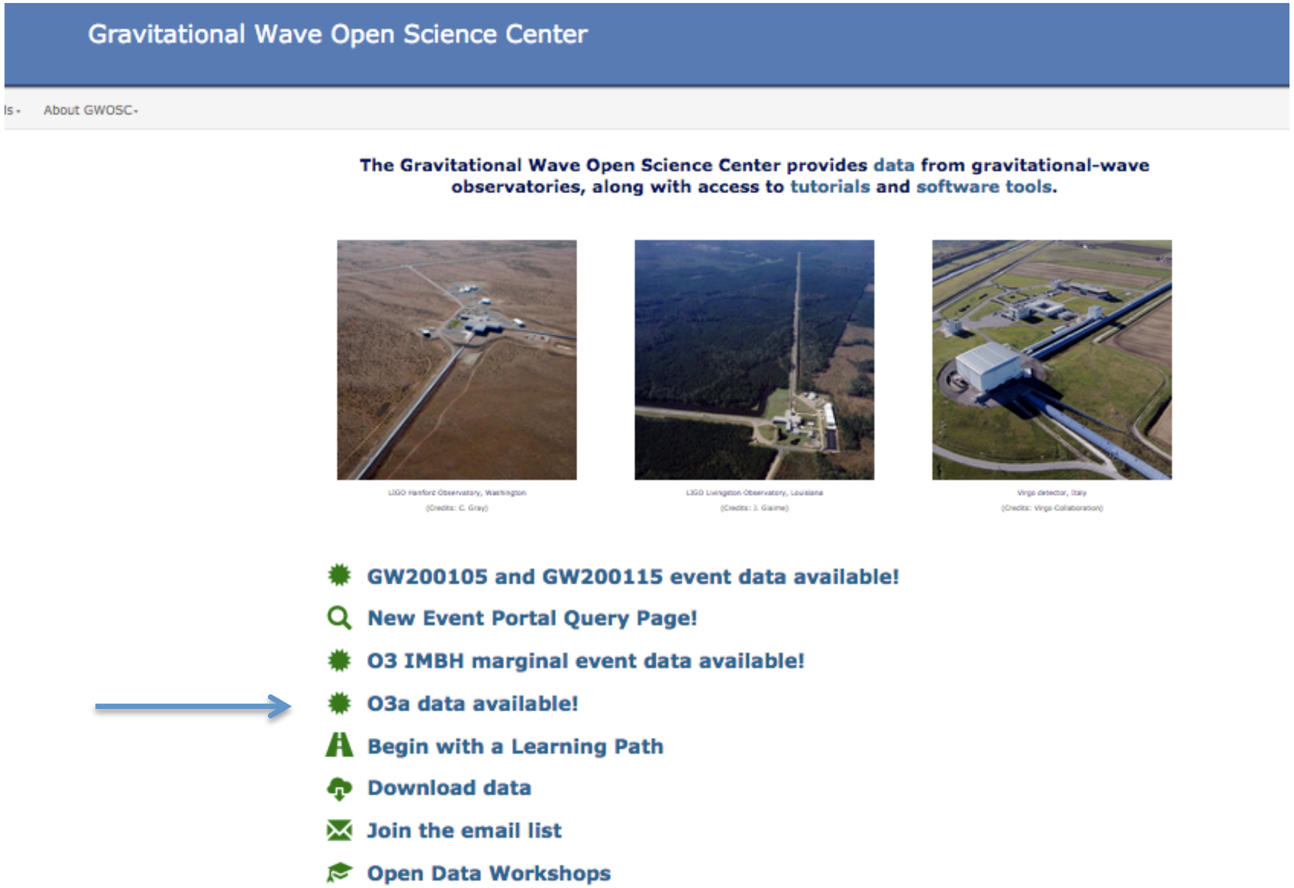
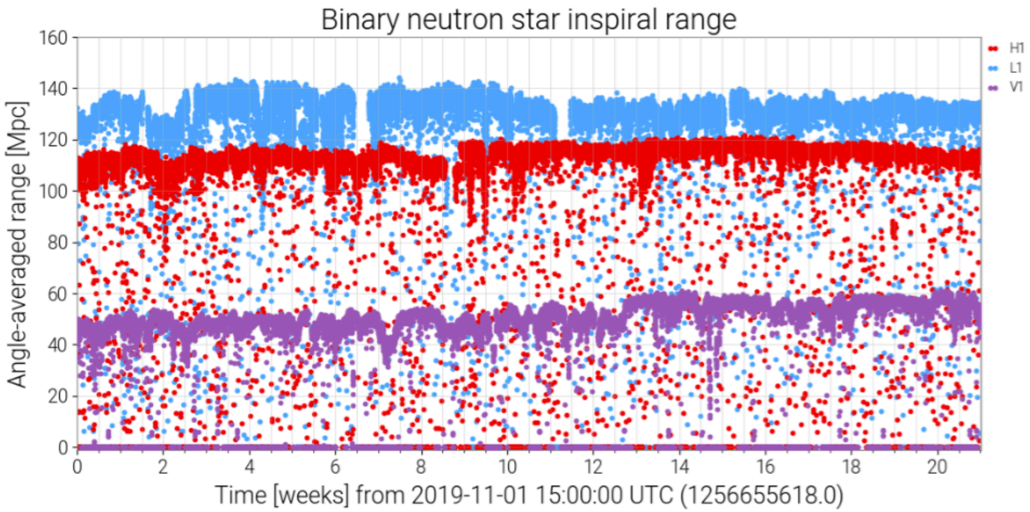
Open data
www.gw-openscience.org

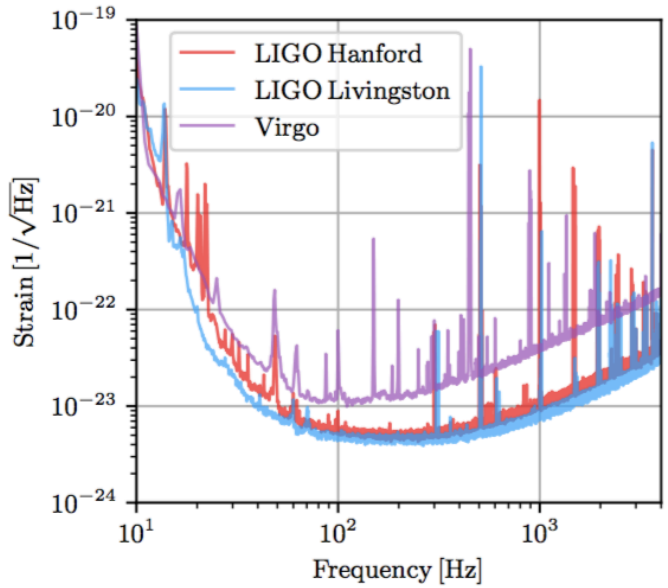


Open data from the first and secondo observing runs of Advanced Virgo and Advanced LIGO, Software X, SoftwareX 13 (2021) 10065

O3 :
LIGO/Virgo performances

- April 2019→March 2020 (1 month before the expected date because of the the COVID pandemic)





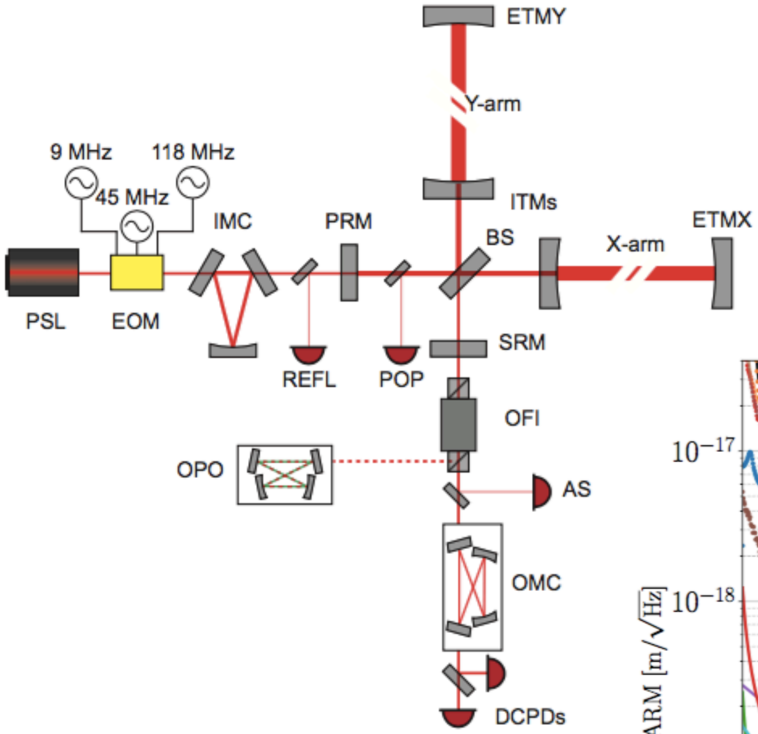
L1: 120-140 Mpc
H1: 110-120 Mpc

Virgo: 50 to 60 Mpc

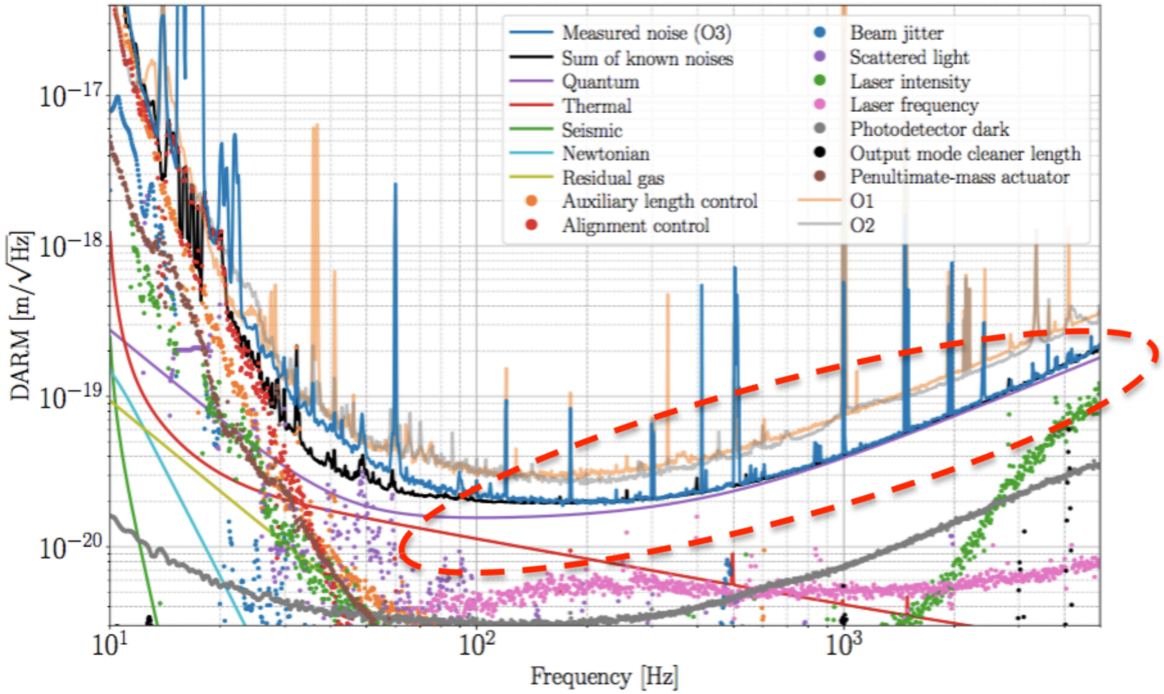
Duty cycle

47% of the time 3 detectors
83% of the time at least 2 detectors

Advanced LIGO configuration and sensitivity during O3



Sensitivity and performance of the Advanced LIGO detectors in the third observing run, A. Buikema *et al.*
Phys. Rev. D 102, 062003 (2020)



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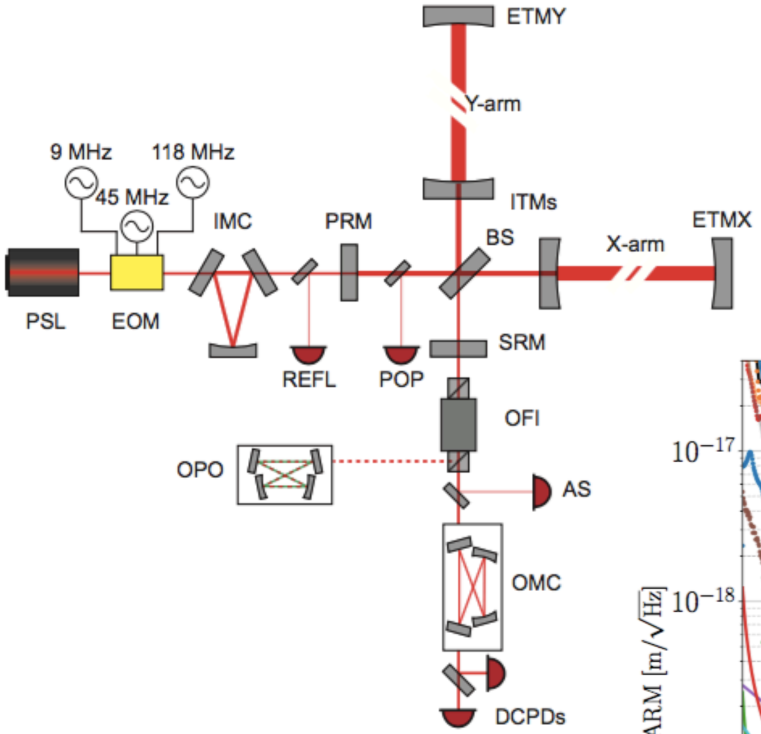

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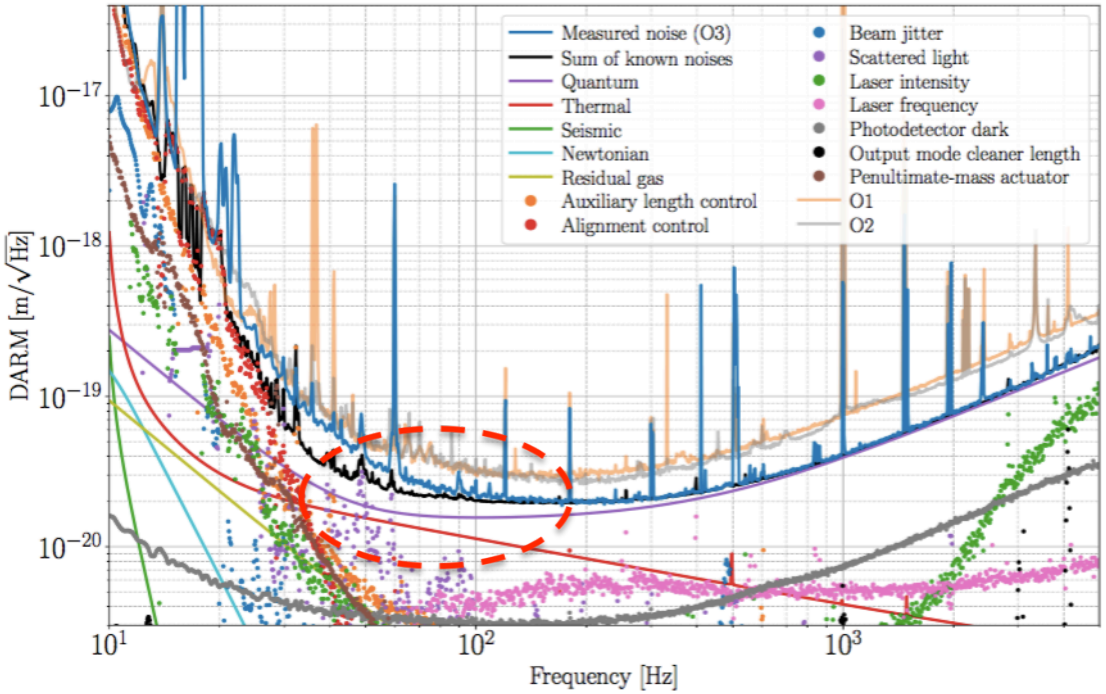

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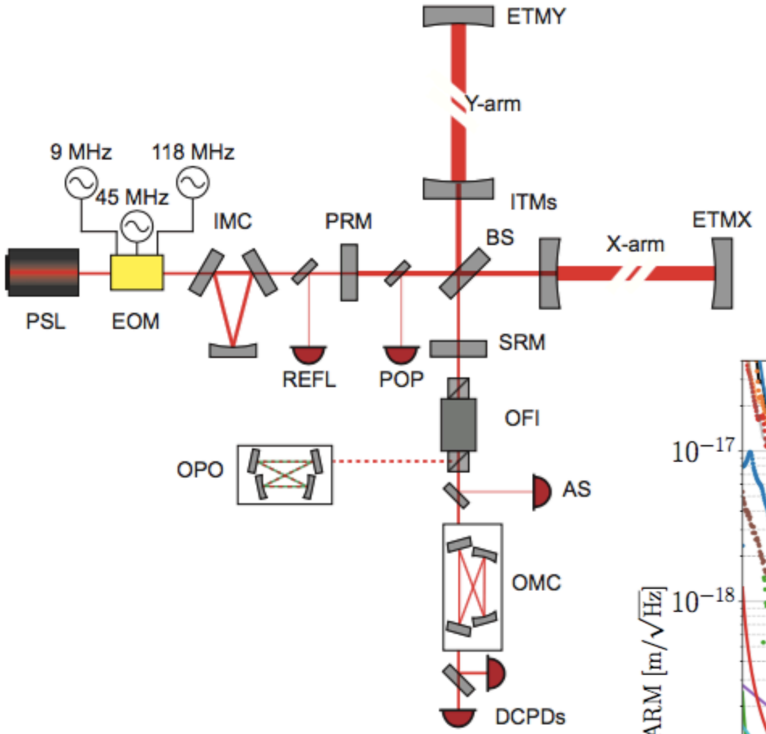

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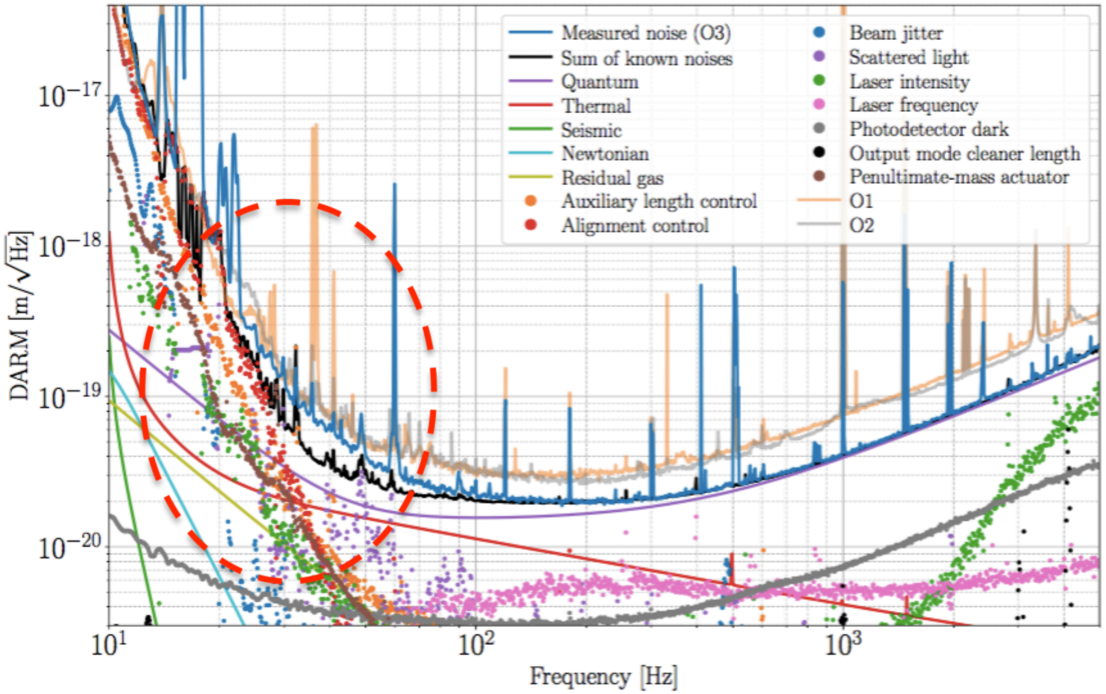
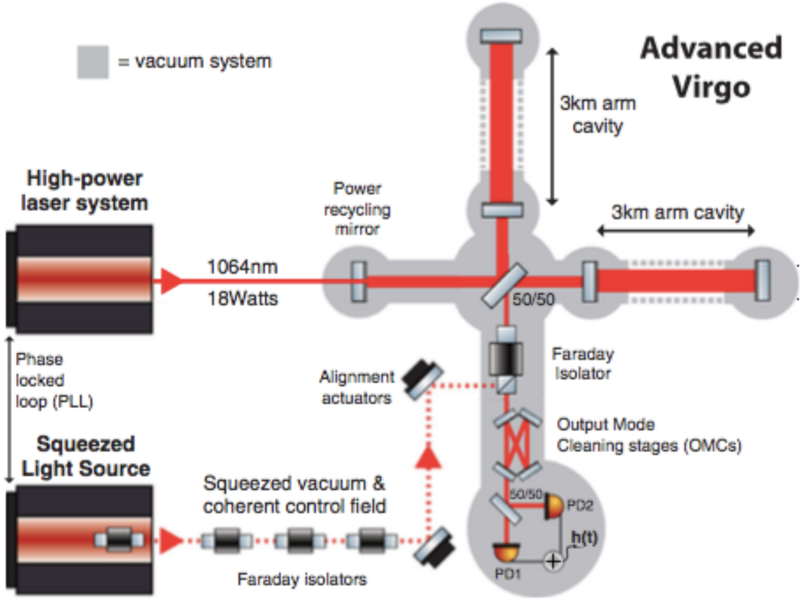
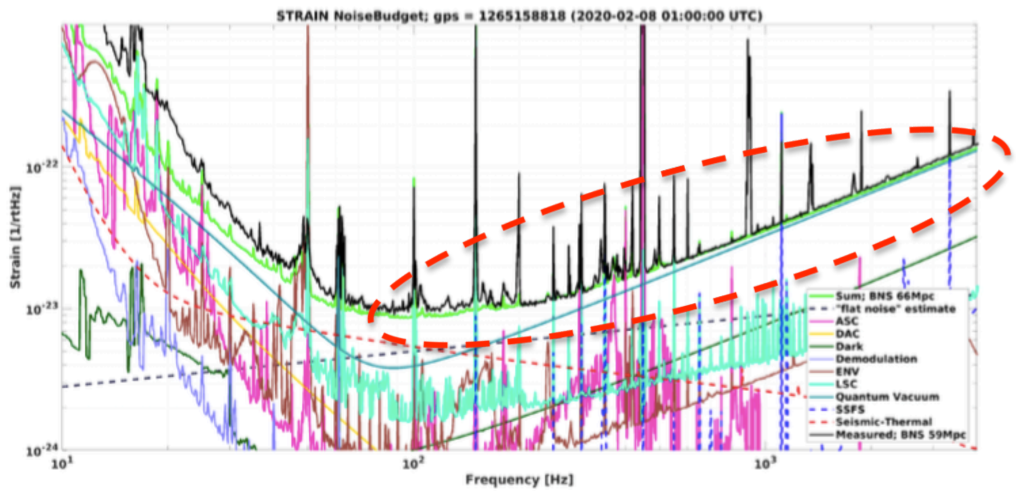


Advanced Virgo sensitivity during O3





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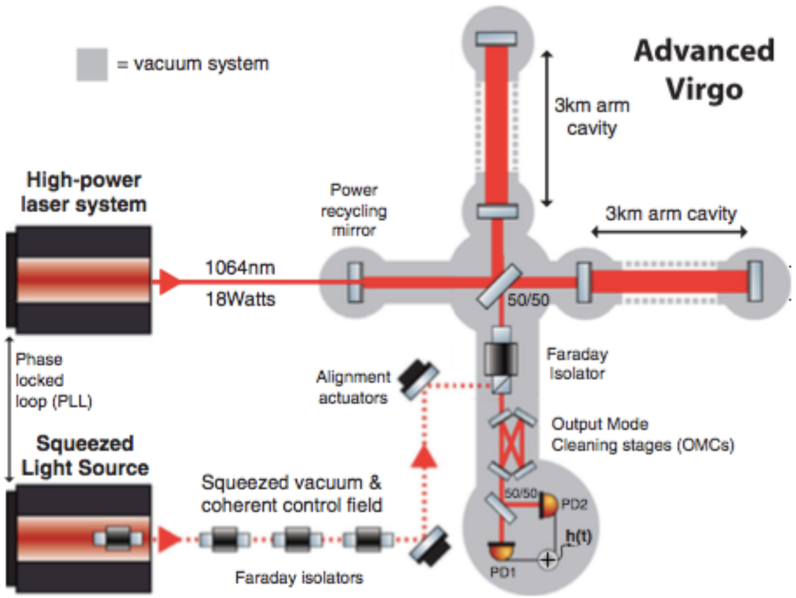

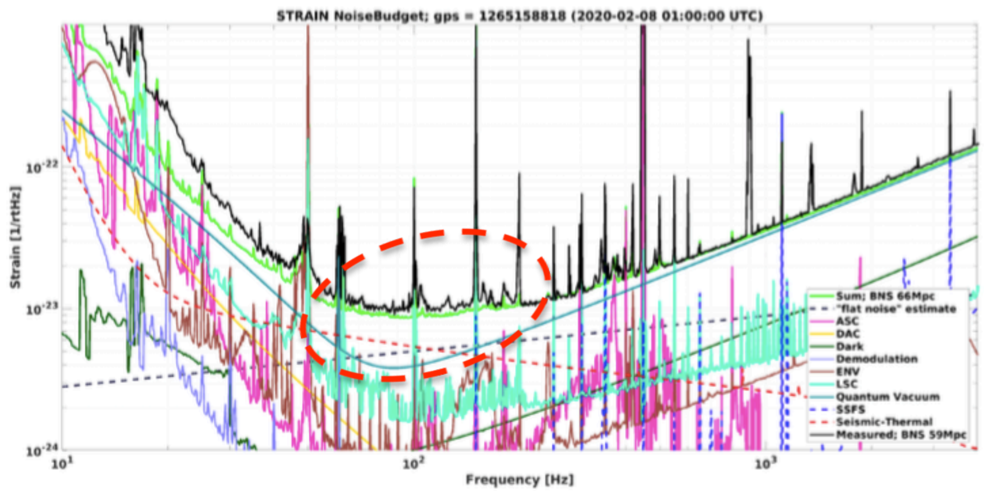

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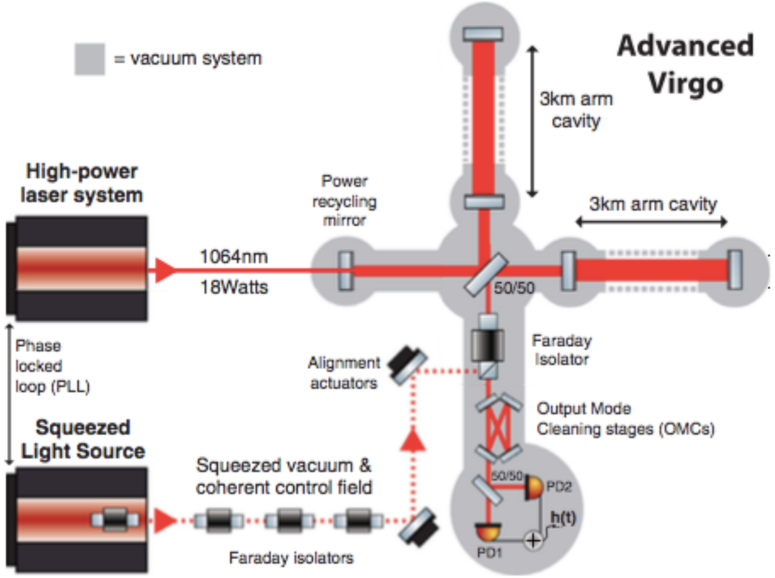
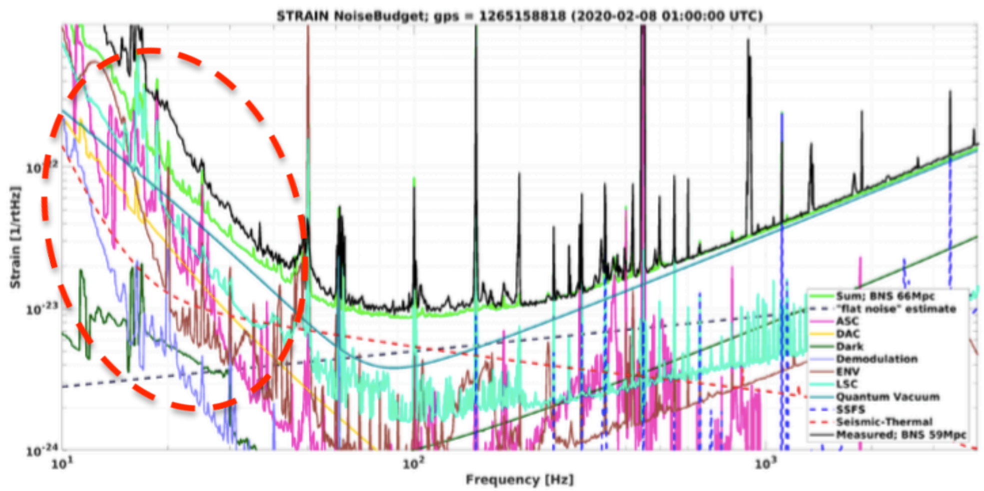
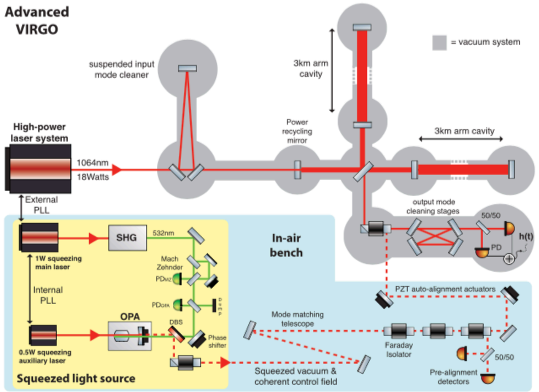


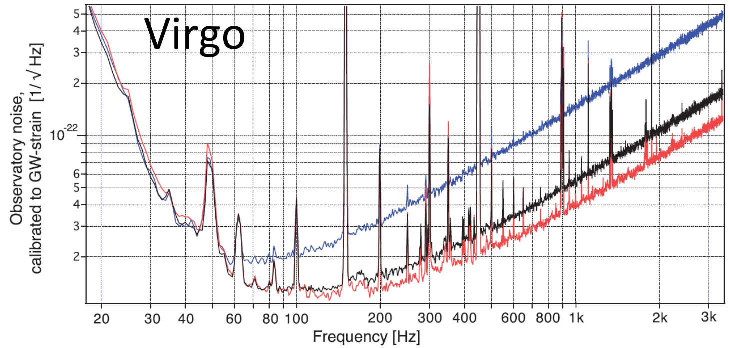


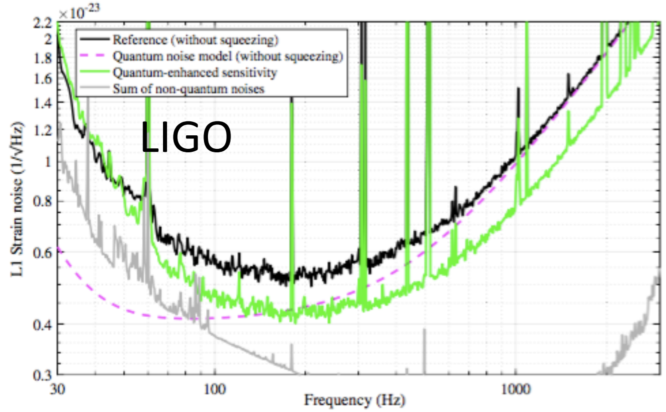
Squeezing in Virgo and LIGO during O3

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)

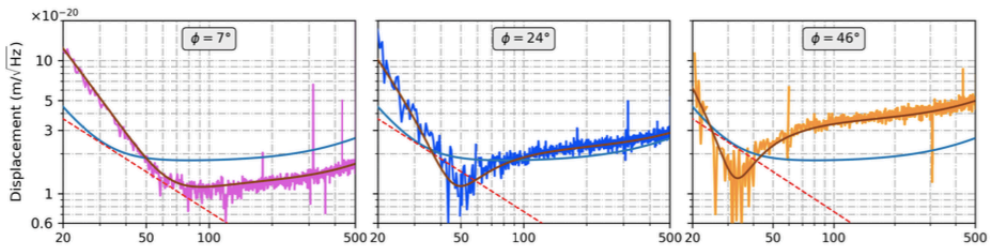
M. Tse *et al.*, Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy, Phys. Rev. Lett. 123, 231107 (2019)







Quantum correlations between light and kilogram-mass mirrors of LIGO, H.Yu et al *Nature* volume 583, pages 43–47 (2020)



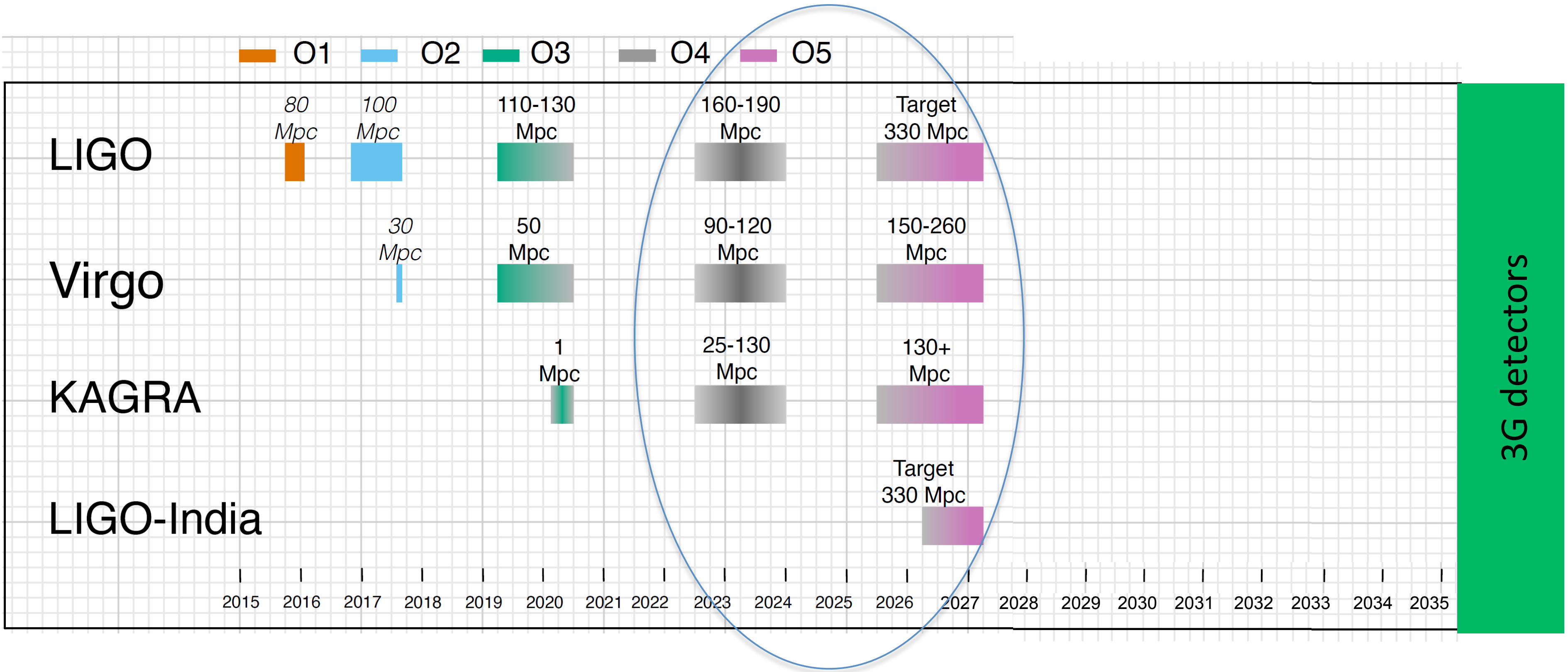
LIGO/Virgo sensitivities during O3

- Quantum noise at high frequency
    - squeezing technologies more and more important
    - thermal effects
    - optomechanical effects
    - parametric instabilities

- Coating and quantum noise in the 100 Hz region
    - coatings research crucial to increase the sensitivity

- A forest of noises at low frequency - detector behavior not completely understood
    - Control noises – auxiliary degrees of freedom
    - Actuation noises
    - scattered light mitigation
    - ...

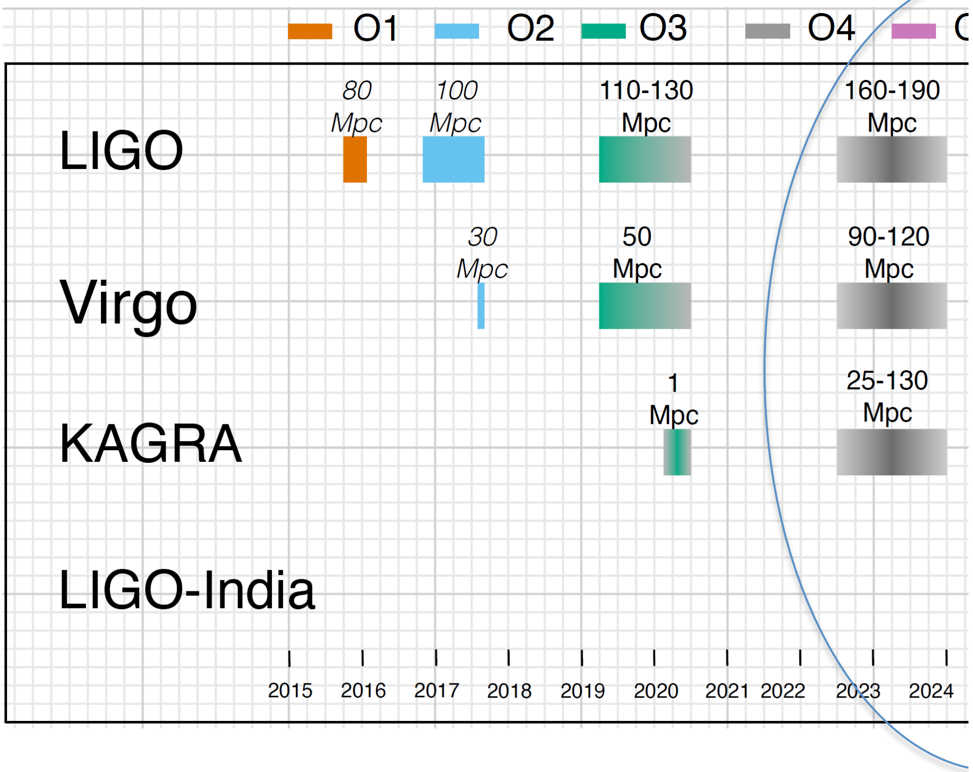
Plans until 2027

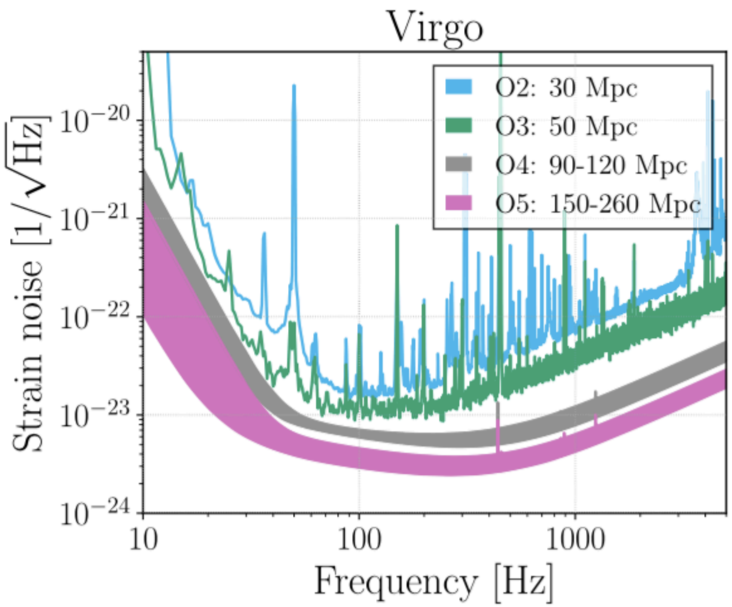


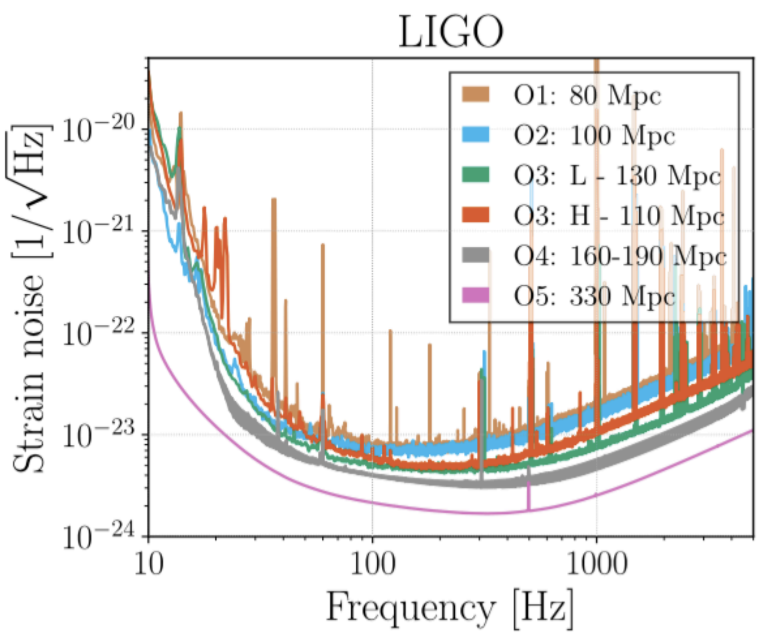
Advanced Virgo
Advanced LIGO
KAGRA

Advanced Virgo +
Advanced LIGO+
KAGRA

Plans u

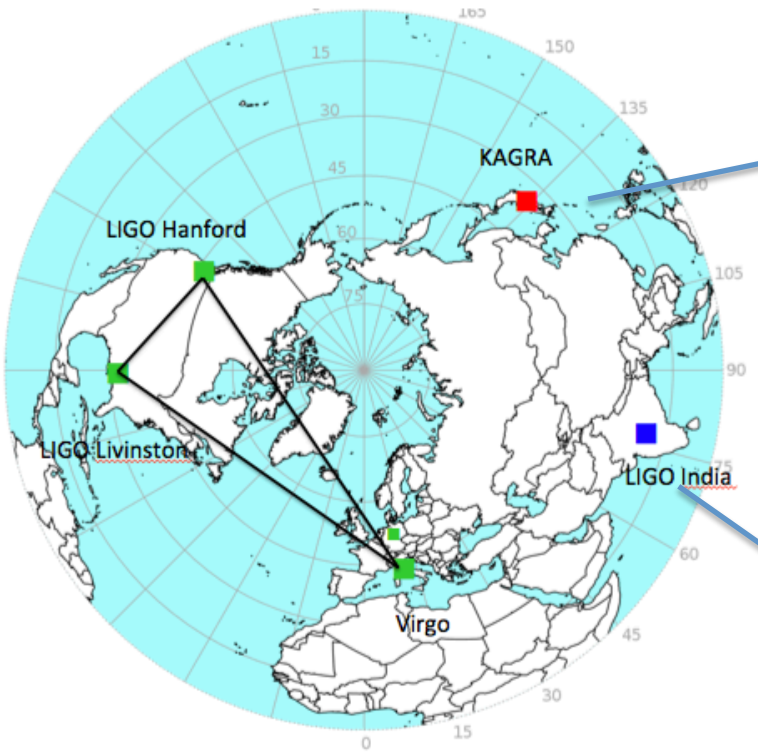






Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, LIGO/Virgo/KAGRA Collaborations arXiv:1304.0670

KAGRA and LIGO India

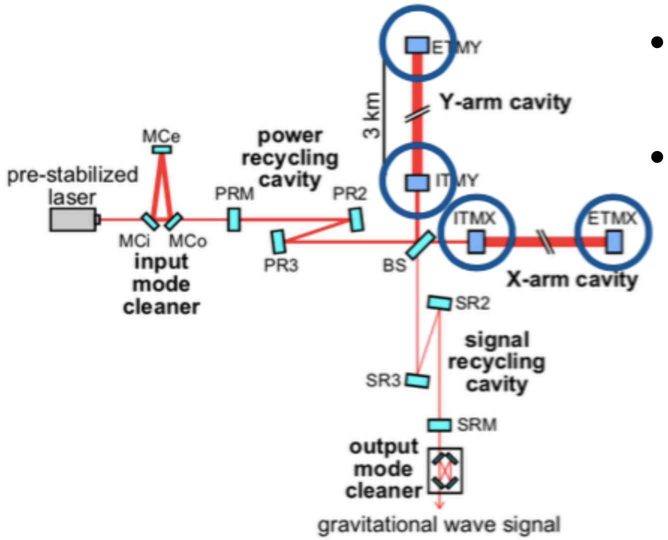


KAGRA

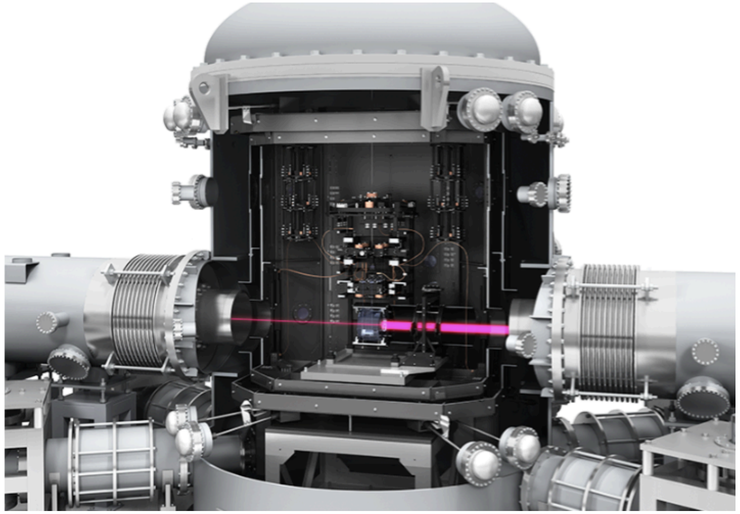
https://gwcenter.icrr.u-tokyo.ac.jp/en/

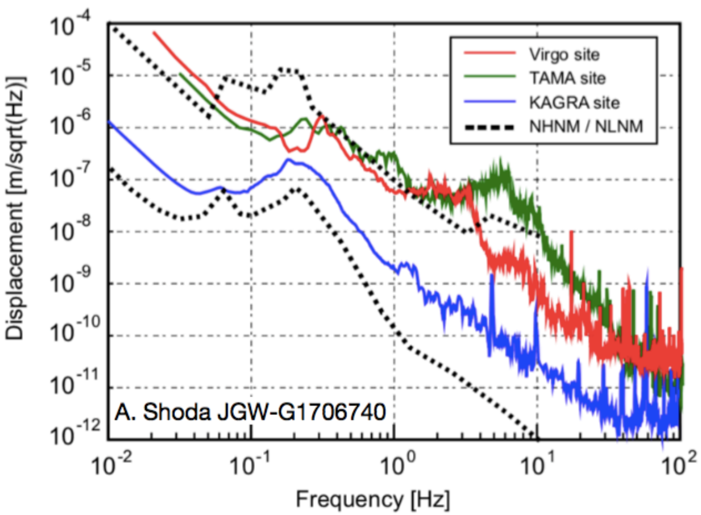
LIGO India

KAGRA



- Sapphire mirrors
- 20 K





Credit : E.Capocasa, lecture at the 2021 ISAPP School

Advanced Virgo +: *phase 1*

Quantum noise reduction

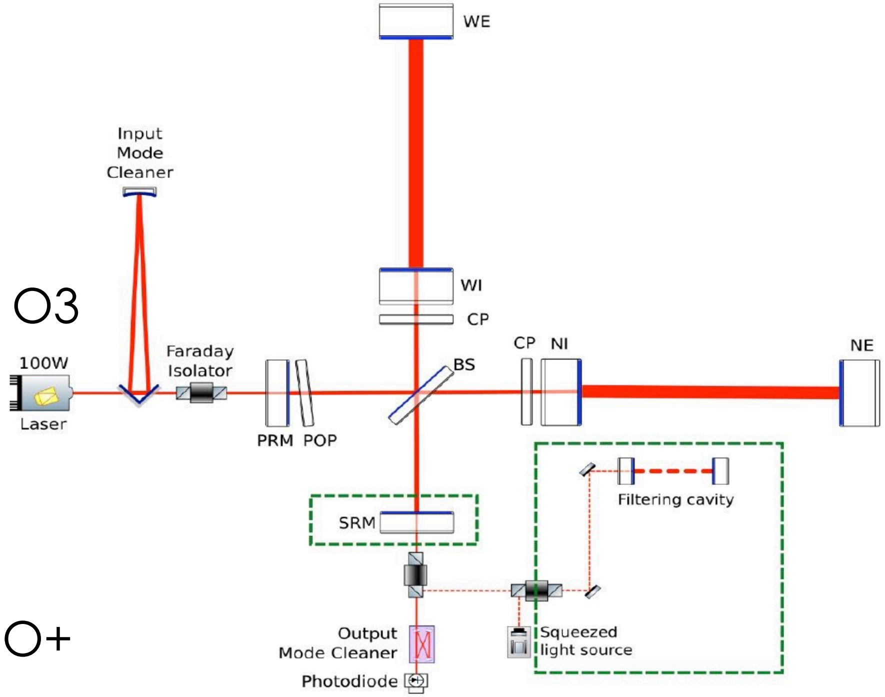
- Signal recycling
- Laser power increase

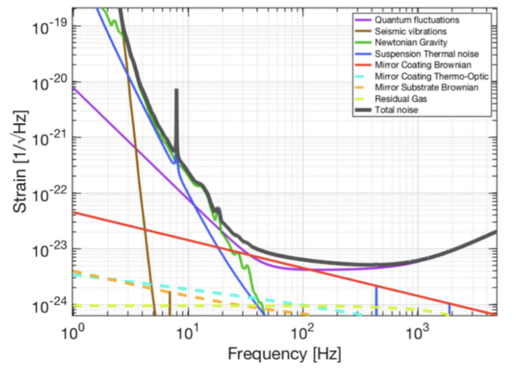
(26 W→40 W)

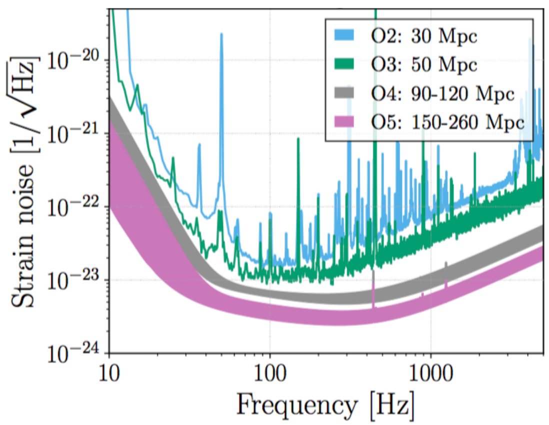
Already in Advanced LIGO O3

- **Frequency dependent squeezing**

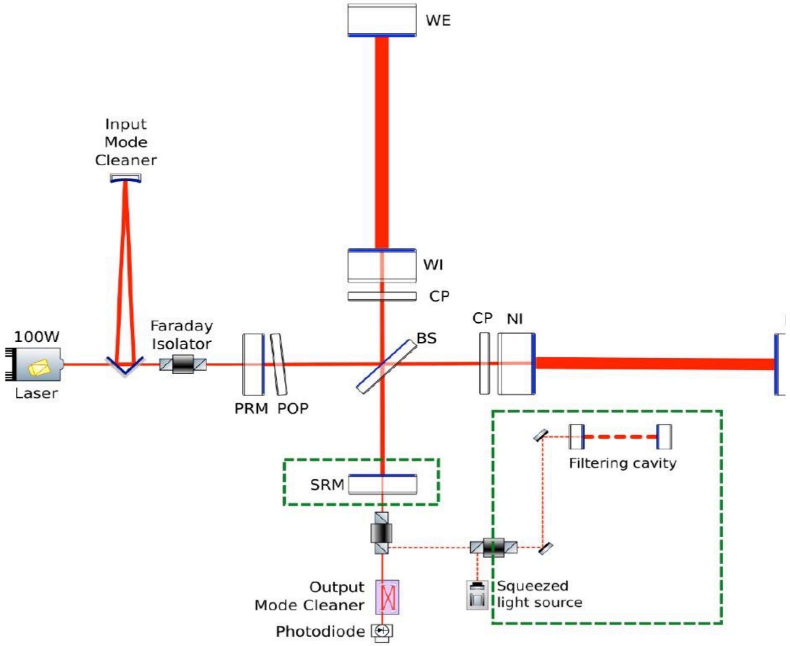
Also used in Advanced LIGO+

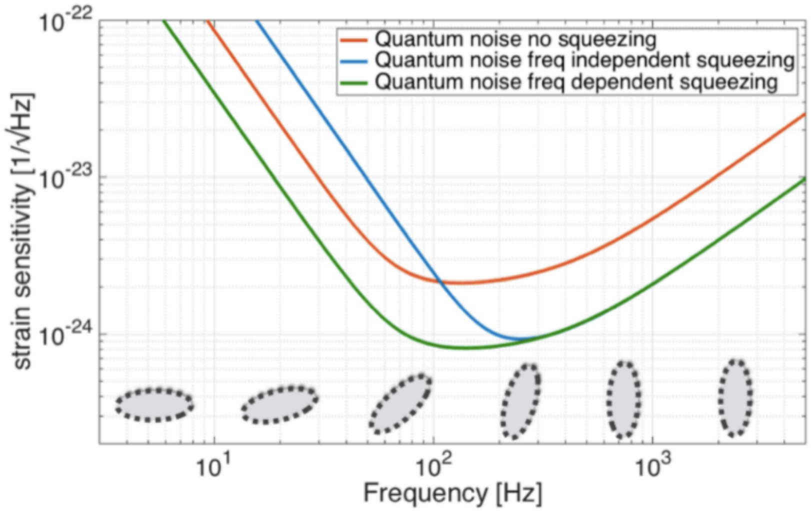


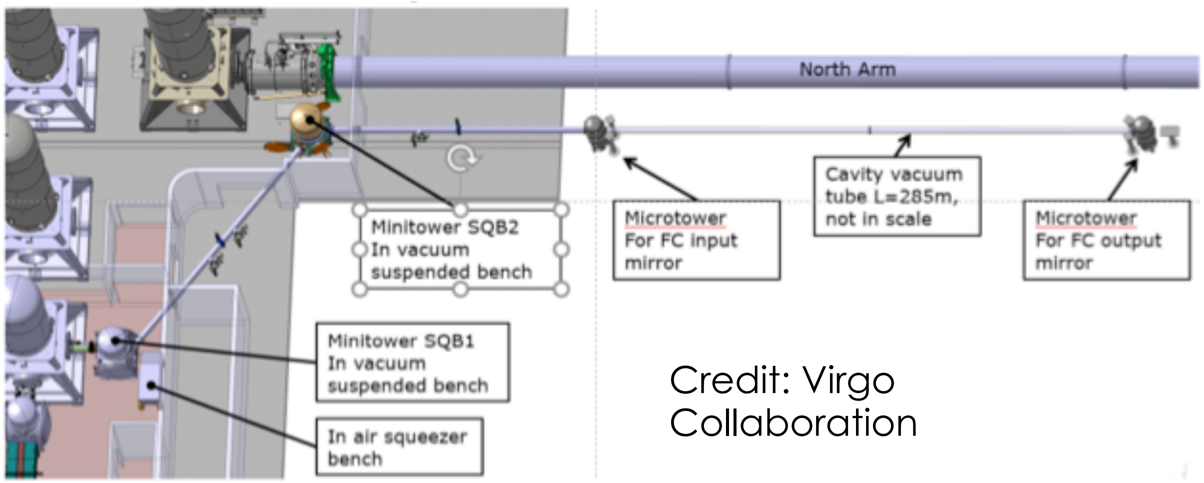




Frequency dependent squeezing

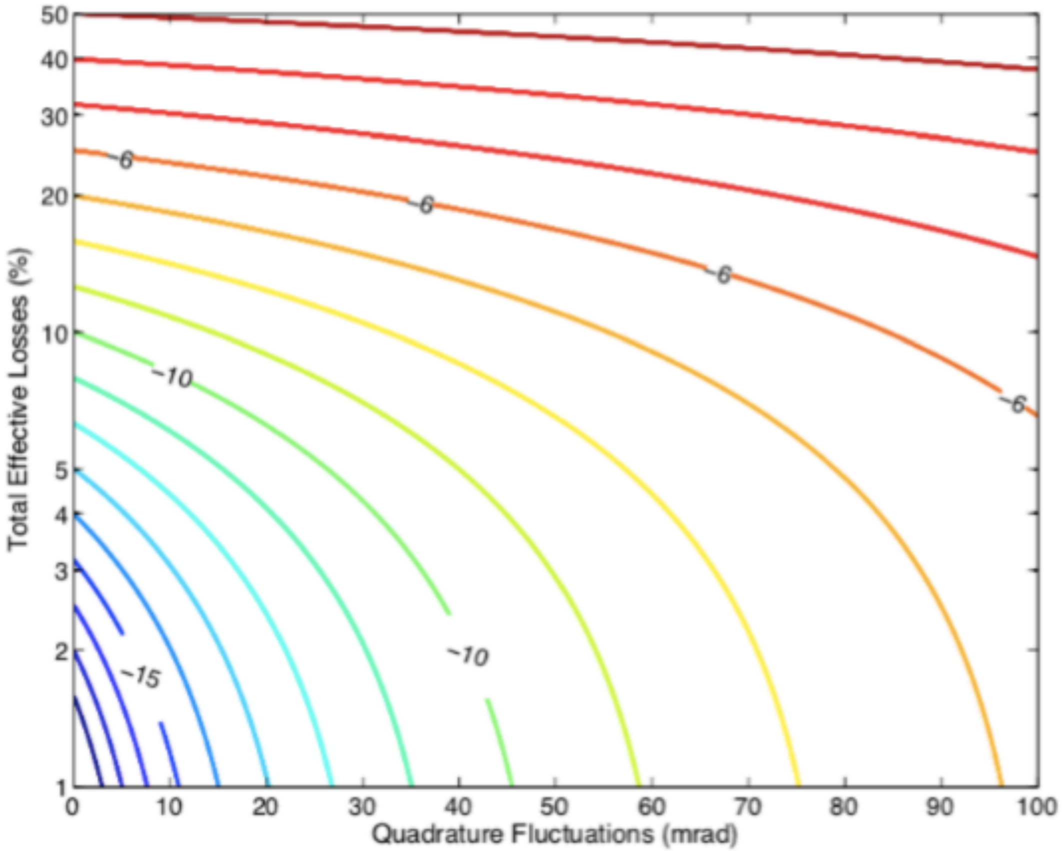






Credit: Virgo
Collaboration

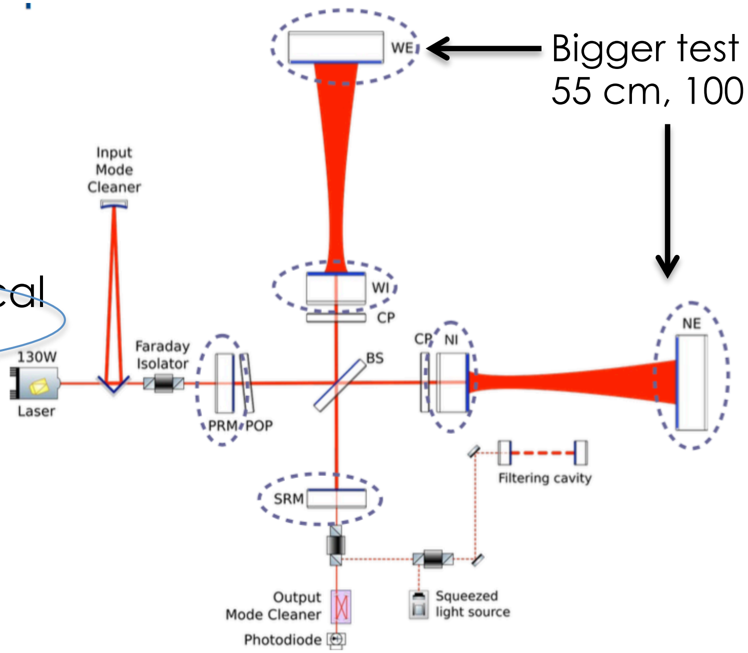
Squeezing and losses

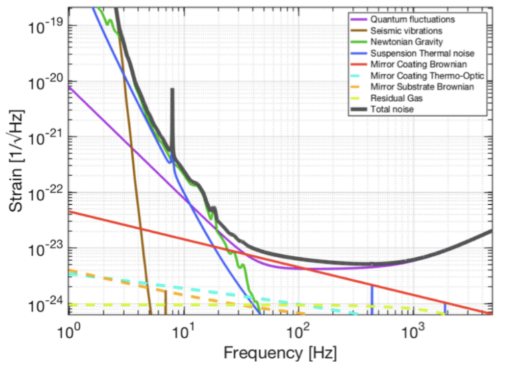


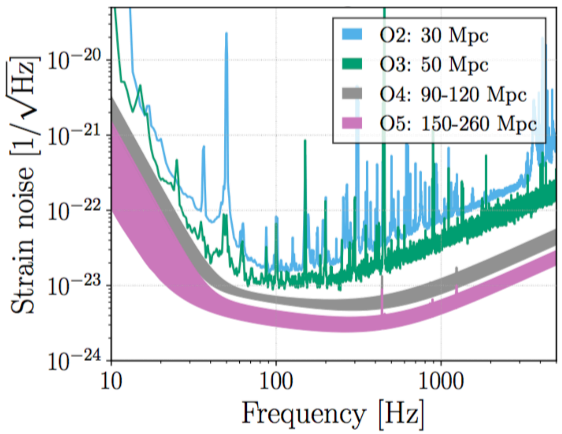
Squeezed vacuum states of light for gravitational wave detectors
L. Barsotti, J. Harms and R. Schnabel
Reports on Progress in Physics, Volume 82, Number 1 (2018)

Advanced Virgo+: phase 2

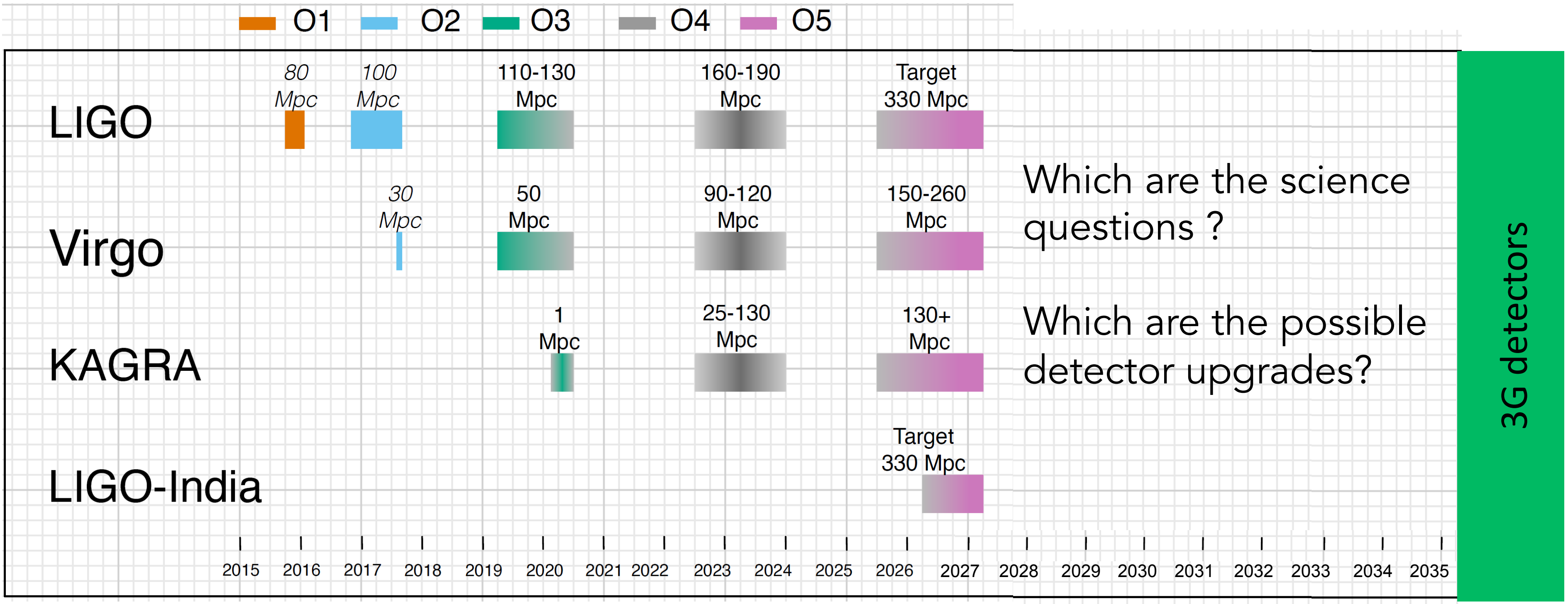
- **Thermal noise reduction :**
  - Beam size increase on end test masses
  - R&D on coating mechanical and optical properties
- Quantum noise reduction
  - Laser power increase (40 W → 80 W)







Plans for the future



Which are the science questions ?

Which are the possible detector upgrades?

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

Plans for a cryogenic detector (123 K) in the LIGO infrastructure
Voyager

Possible upgrades during the post-O5 era 2027-2036

- Higher input power
- Improved thermal compensation system
- Improved frequency dependent squeezing (losses, control of the filter cavity)
- Changes in the signal recycling (tuning, reflectivity)

quantum technologies, losses, configurations

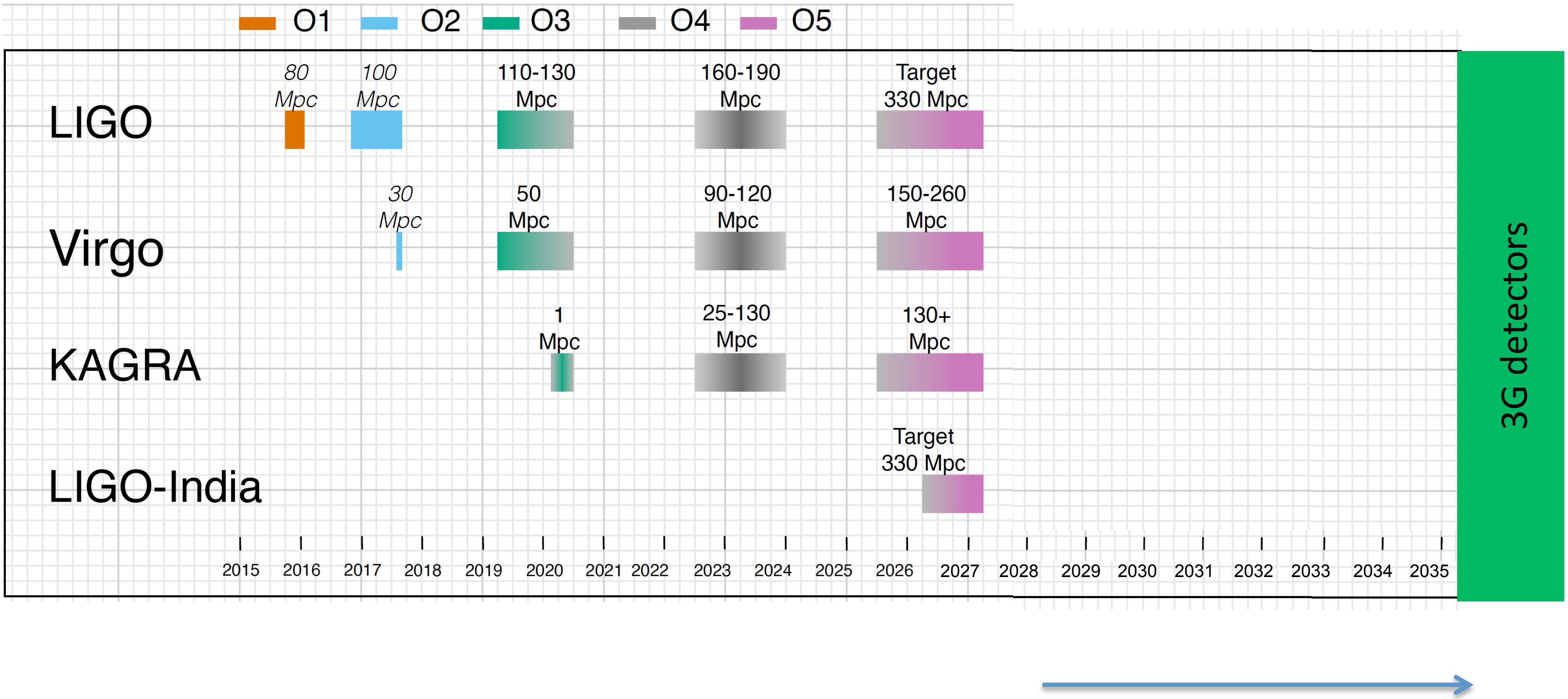
- New coatings
- Large mirrors/beams on all test masses

materials, stability of the cavities, technology of mirrors

- Control noise improvements
- Enhanced Newtonian noise subtraction
- Suspensions upgrades
- Scattered light mitigation

controls, geophysics modeling, scattering

Plans for the future

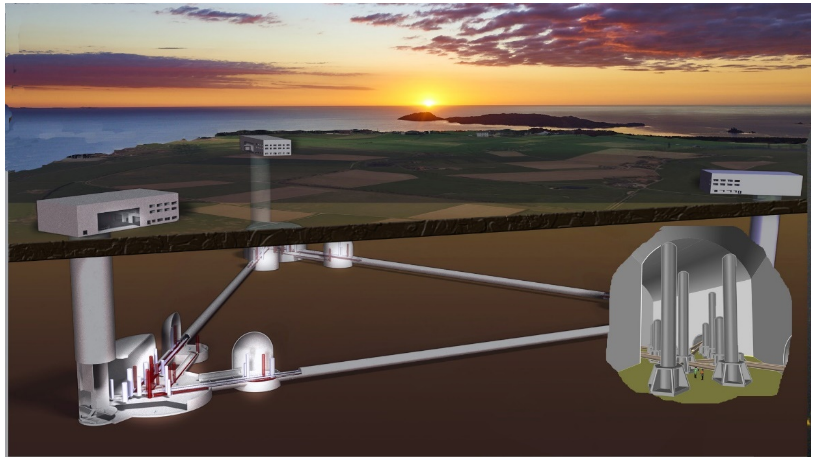


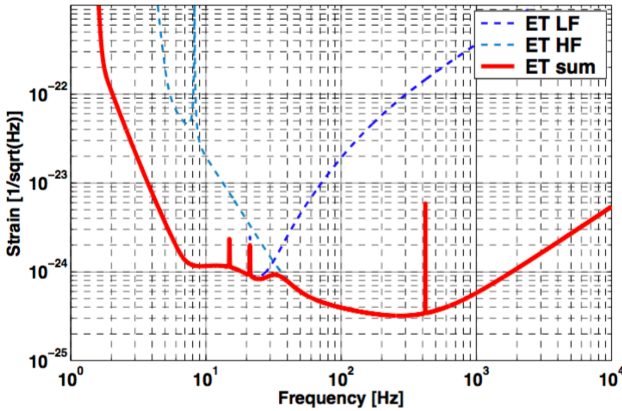
towards the infrastructure limits

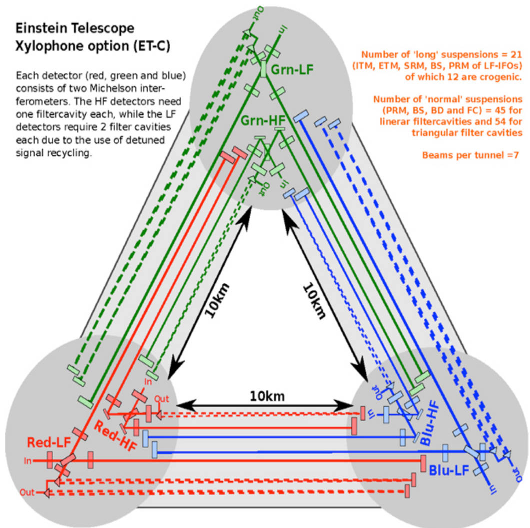
ET design features

- Underground (seismic noise reduction)
- 10- km long arms (signal increase)
- Triangle configuration
- « Xylophone » (two combined detectors) – hot and cold

- ET in ESFRI !



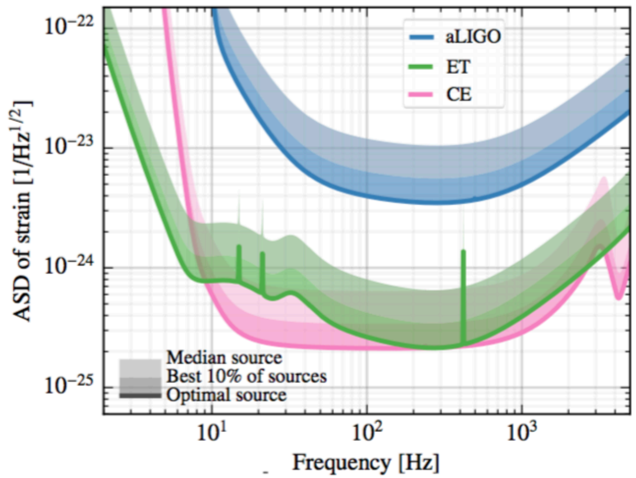


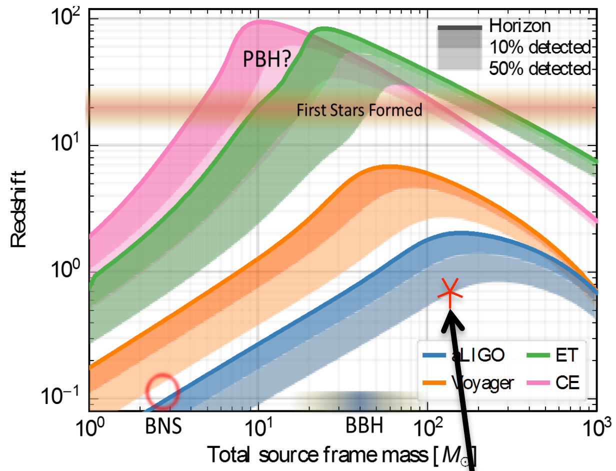


http://www.et-gw.eu/

Einstein Telescope

- Black-holes formation/ population studies
- Fundamental physics / nature of gravitation
- Cosmology / nature of dark energy
- Nuclear physics / ultra-dense matter
- Physics of Supernovae
- Multimessenger astrophysics
- Complementarity and synergies with LISA



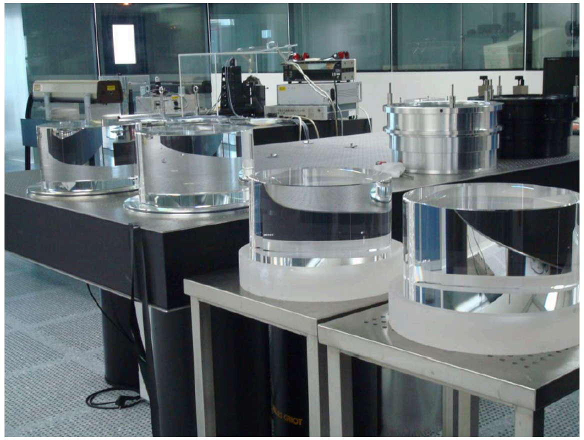


https://arxiv.org/pdf/1912.02622
ET science case

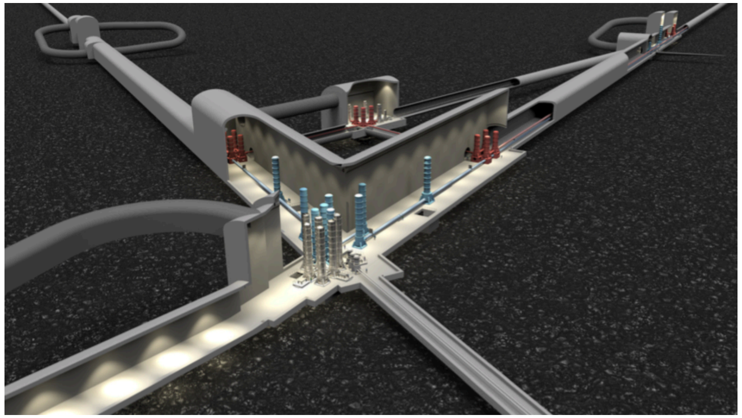
GW190521
z = 0.8, M=150

The ET technologies and challenges

- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Suspension systems

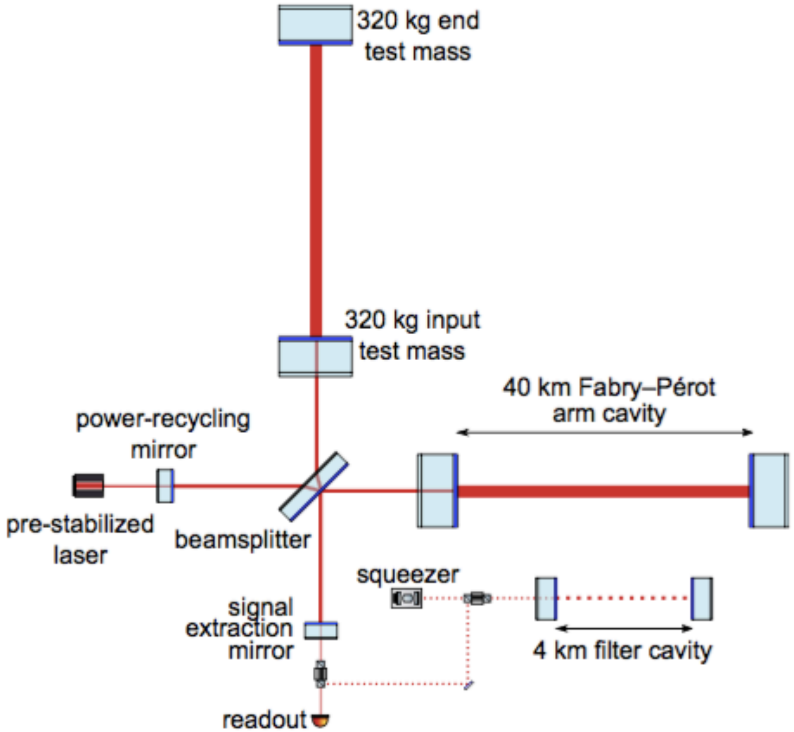


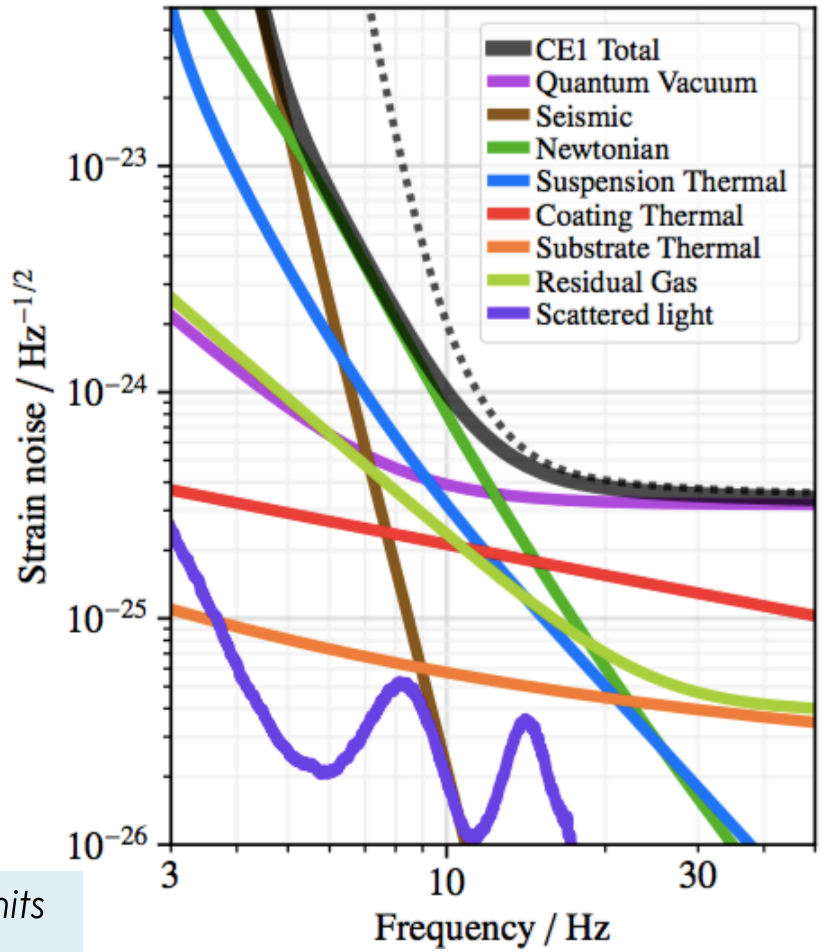
- Technologies not yet tested in Virgo and LIGO - some of them being tested in KAGRA
  - Cryogenics
  - New cryogenic materials
  - New laser wavelengths (1.5 or 2 microns)



Cosmic Explorer

https://cosmicexplorer.org/





Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity
Evan D. Hall et al, Phys. Rev. D 103, 122004 (2021)

Summary

- **Science with GW detectors**
    - 5 exceptional events. First clean detection of 2 NSBH recently announced
    - 52 sources published
    - Statistics on populations

- **O4 and O5**
  - Program of upgrades for Virgo and LIGO established until ~ 2027
  - KAGRA and LIGO India
  - Frequency dependent squeezing and higher power for O4, new coatings for O5

- **Filling the gap between O5 and ET**
  - Incremental upgrades: power, coatings, various technical noises, reaching the sensitivity at low frequency

- **Einstein Telescope is taking off**
  - Great scientific potential, ET in the ESFRI roadmap !
  - 2 interferometers : hot and cold

- **Experimental challenges (not exhaustive list)**
  - Low frequency noises
  - Scattered light
  - Coatings
  - High power - Thermal effects
  - Squeezing (losses, components)
  - Cryogenics (cryogenic operation, new materials, new wavelengths)