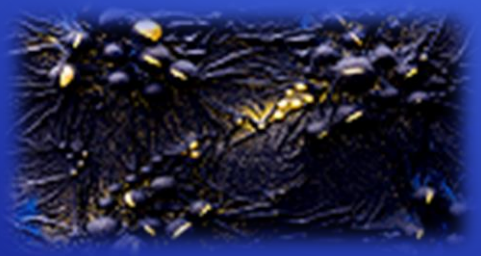
Advanced Virgo status

A. Allocca

on the behalf of the Virgo collaboration



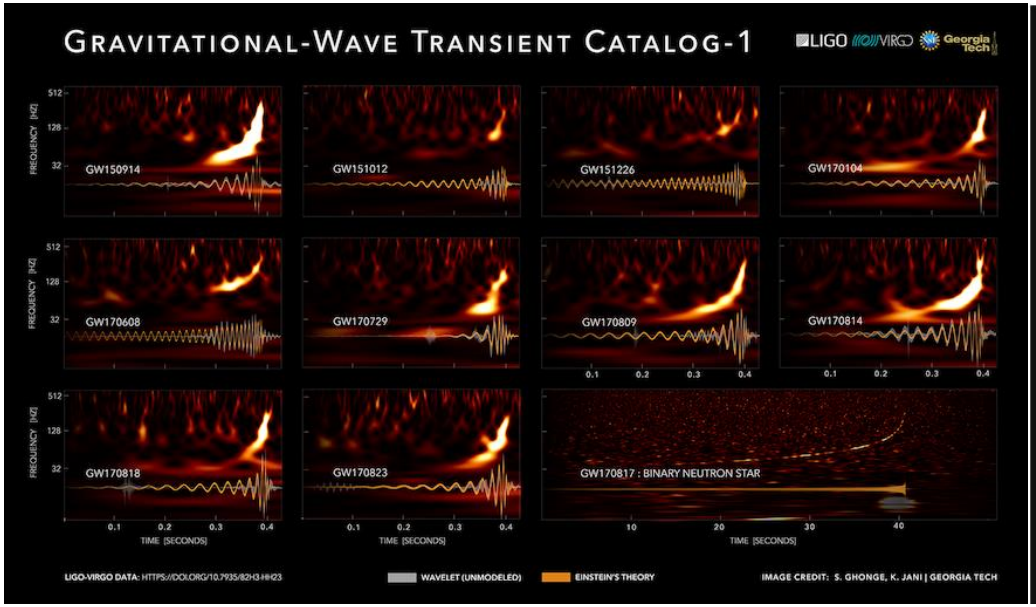
28th April – 3rd May
Orosei

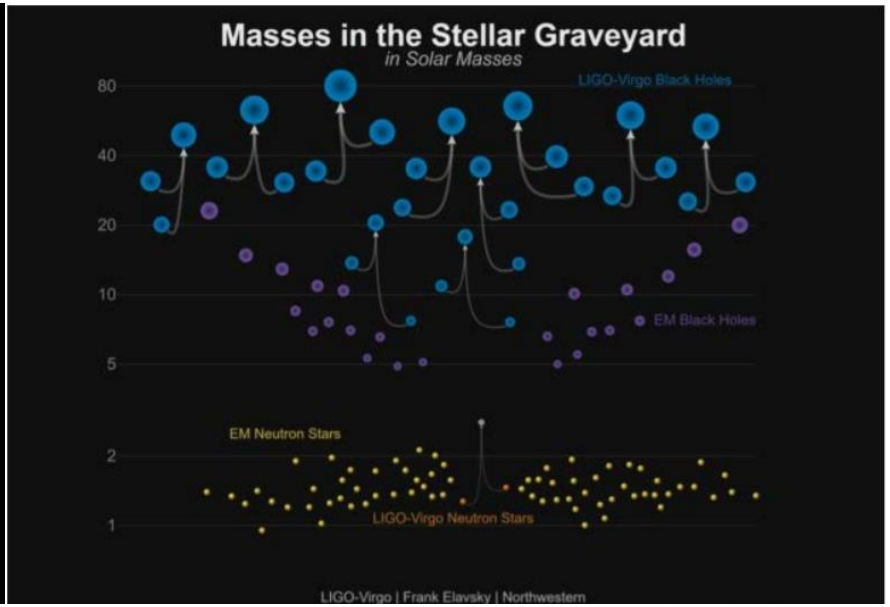
Birth of Gravitational Wave Astronomy

10 BBH and 1 BNS GWs observed between O1 and O2

- GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs arxiv.1811.12907

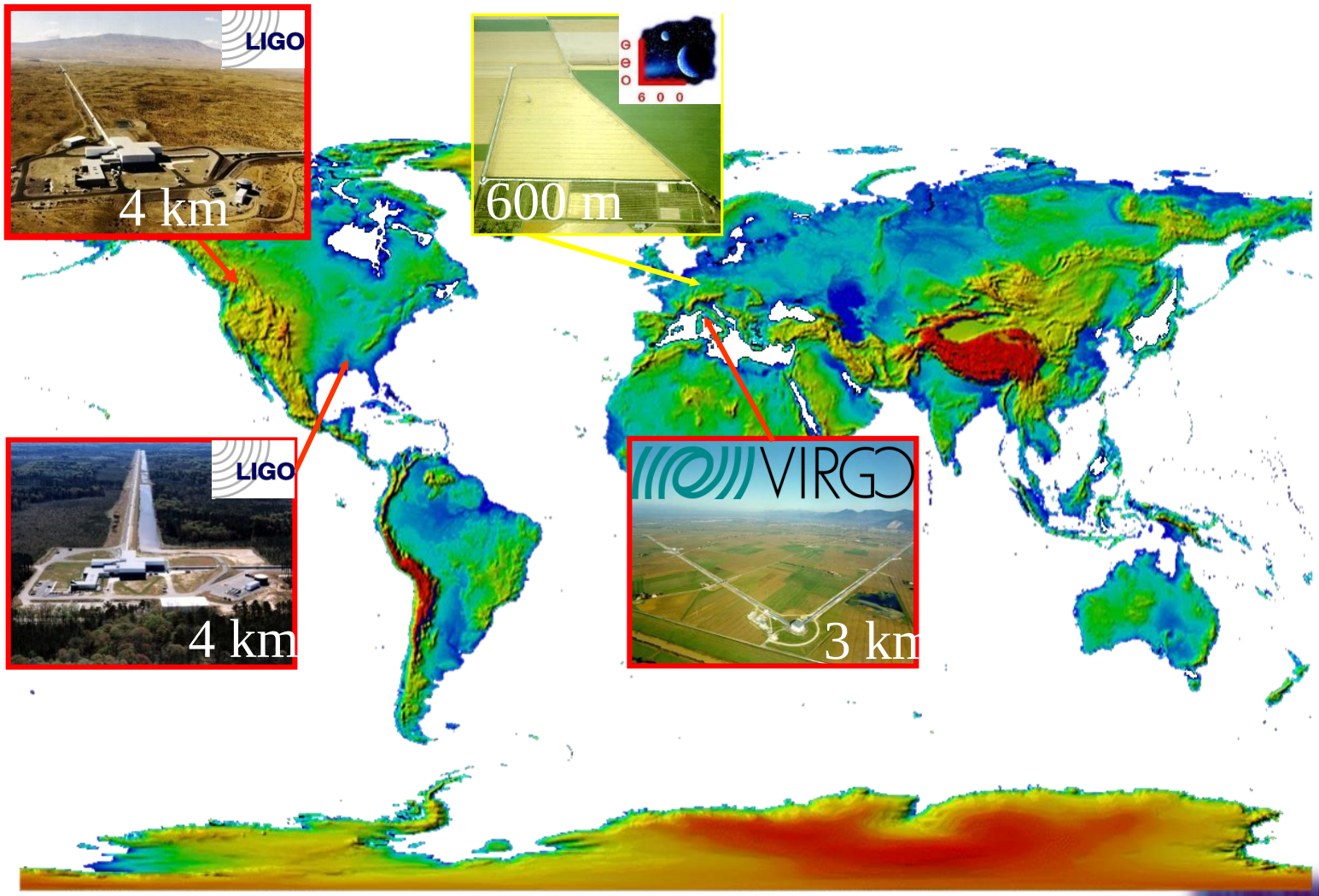
- Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo arxiv.1811.12940





GW worldwide detectors network

Observe together as a network of GW detectors. LVC have integrated their data analysis



Outline

- Advanced Virgo design
- Advanced Virgo performance during O2
- The path from O2 to O3
- Current status of O3
- Future perspectives: Advanced Virgo +

Outline

- **Advanced Virgo design**
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The Advanced VIRGO project (AdV)

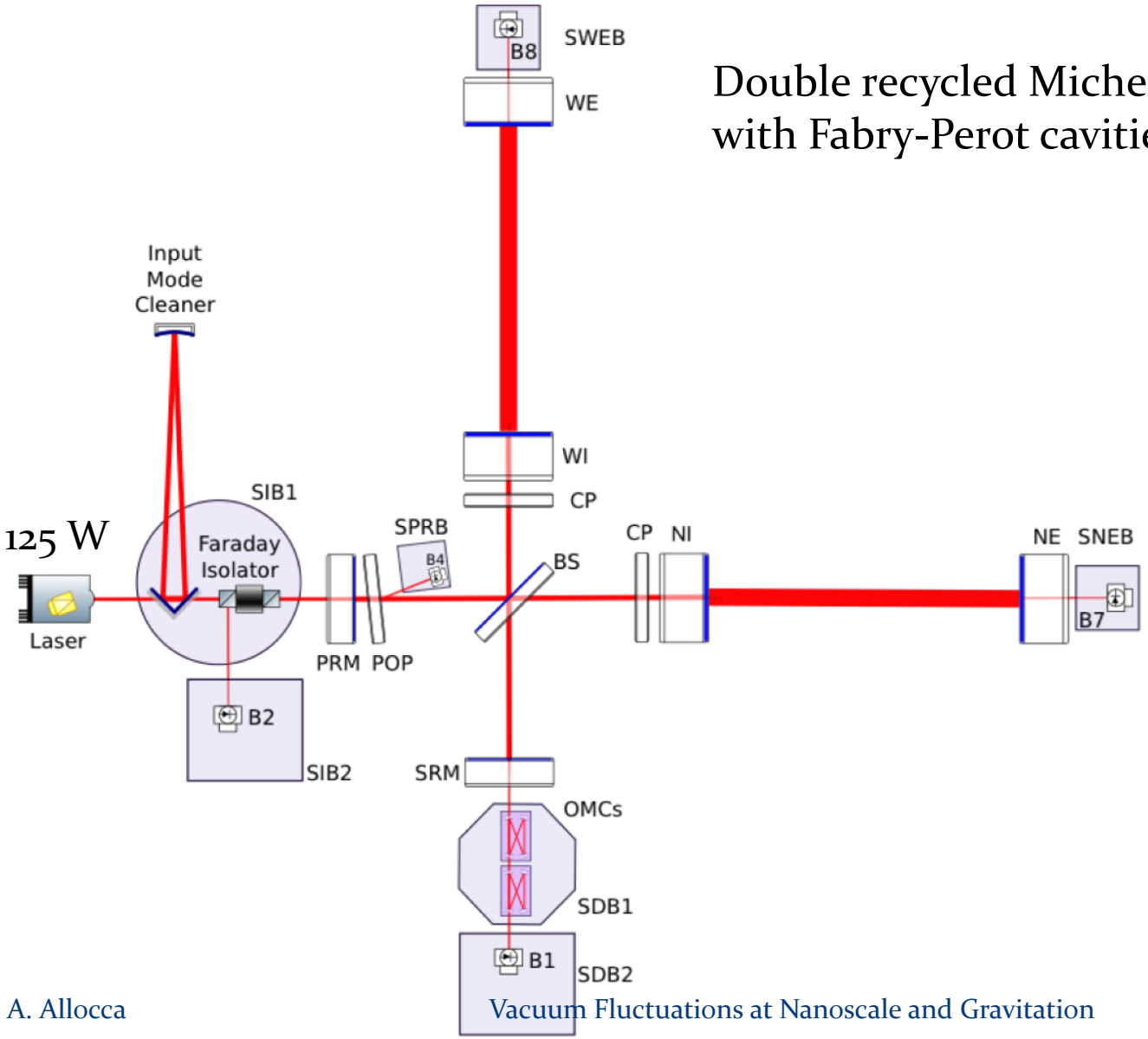
The Advanced VIRGO project (AdV)

- Upgrade of the Virgo interferometric detector
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Hungary, Poland, Spain, Belgium, Germany
- Part of International network (MoU with LIGO and GEO600)

8 European countries
70 Institutes, ~300 authors

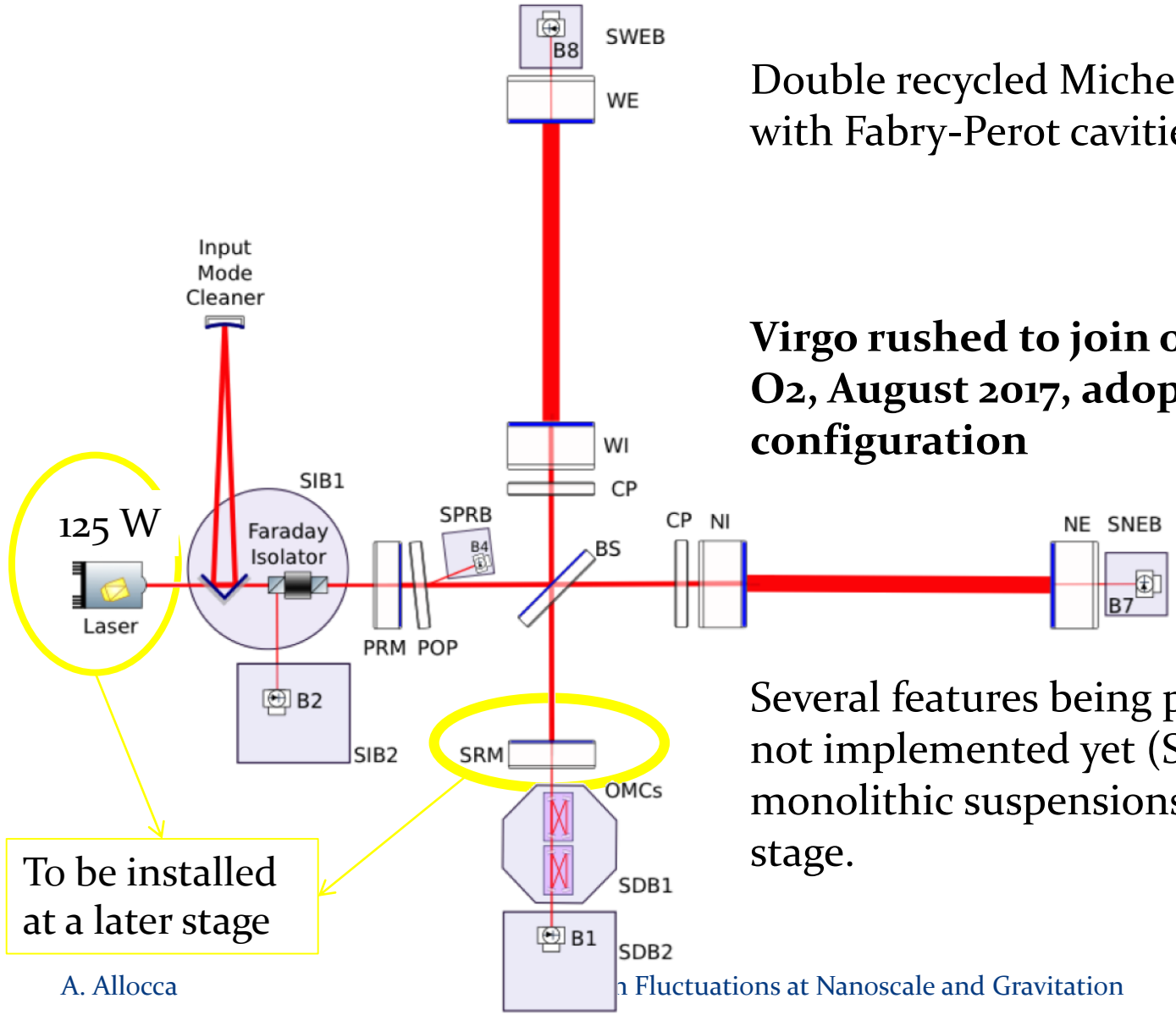
- APC Paris
- ARTEMIS Nice
- IFAE Barcelona
- EGO Cascina
- INFN Firenze-Urbino
- INFN Genova
- INFN Napoli
- INFN Perugia
- INFN Pisa
- INFN Roma La Sapienza
- INFN Roma Tor Vergata
- INFN Trento-Padova
- LAL Orsay – ESPCI Paris
- LAPP Annecy
- LKB Paris
- LMA Lyon
- NIKHEF Amsterdam
- POLGRAW(Poland)
- RADBOUD Uni. Nijmegen
- RMKI Budapest
- Univ. Of Valencia
- UCLouvain, ULiege
- Univ. of Barcelona
- University of Sannio
- University of Jena

Advanced Virgo optical scheme



Double recycled Michelson interferometer with Fabry-Perot cavities in each arm

Advanced Virgo optical scheme – O2 configuration



Double recycled Michelson interferometer with Fabry-Perot cavities in each arm.

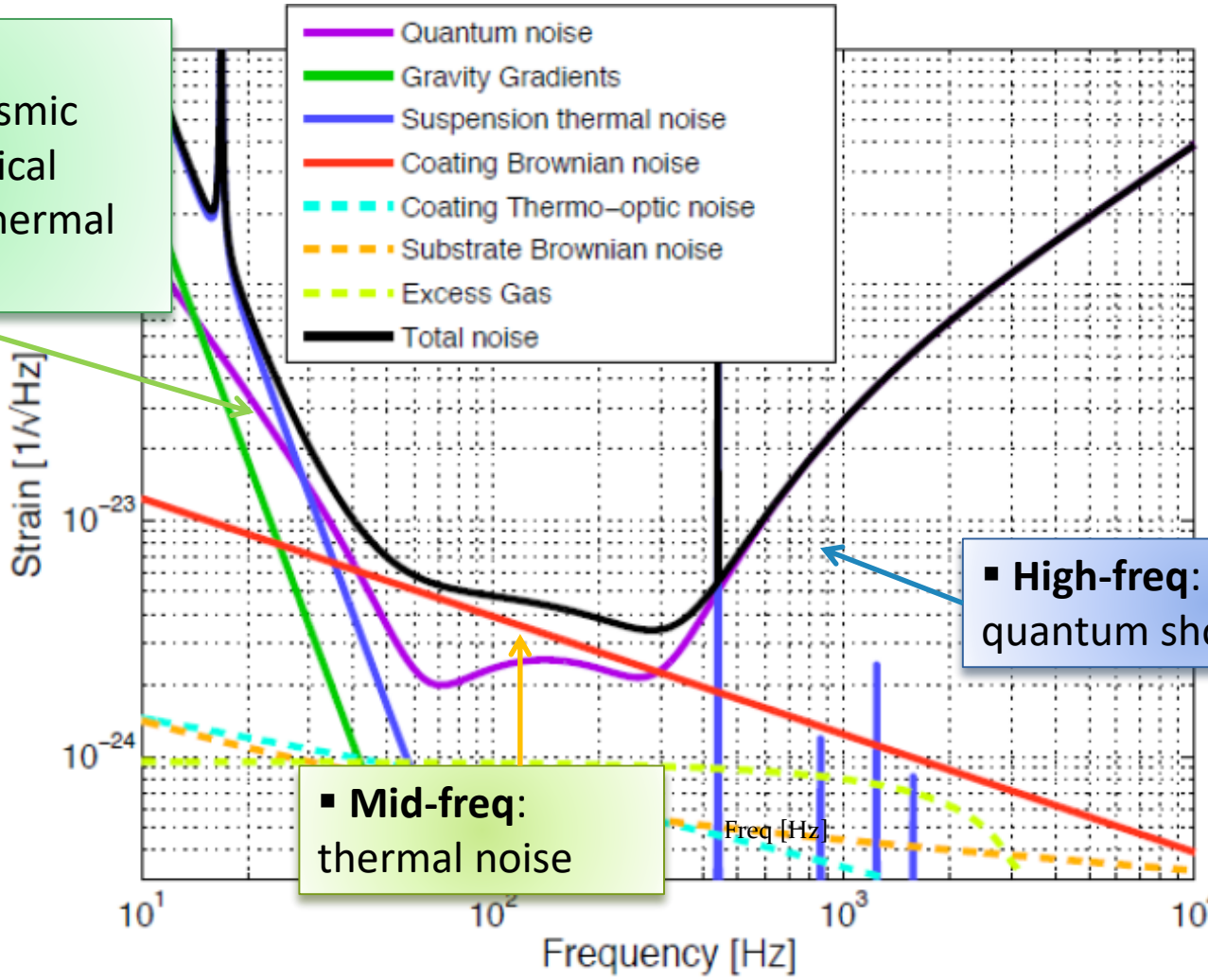
Virgo rushed to join observational run O2, August 2017, adopting a preliminary configuration

Several features being part of the AdV design not implemented yet (SRM, high power laser, monolithic suspensions), installed at a later stage.

AdV design

Limiting noises at different frequency ranges:

- **Low-freq**: newtonian noise, seismic noise, residual technical noises, suspension thermal noise



- **High-freq**: quantum shot-noise

- **Mid-freq**: thermal noise

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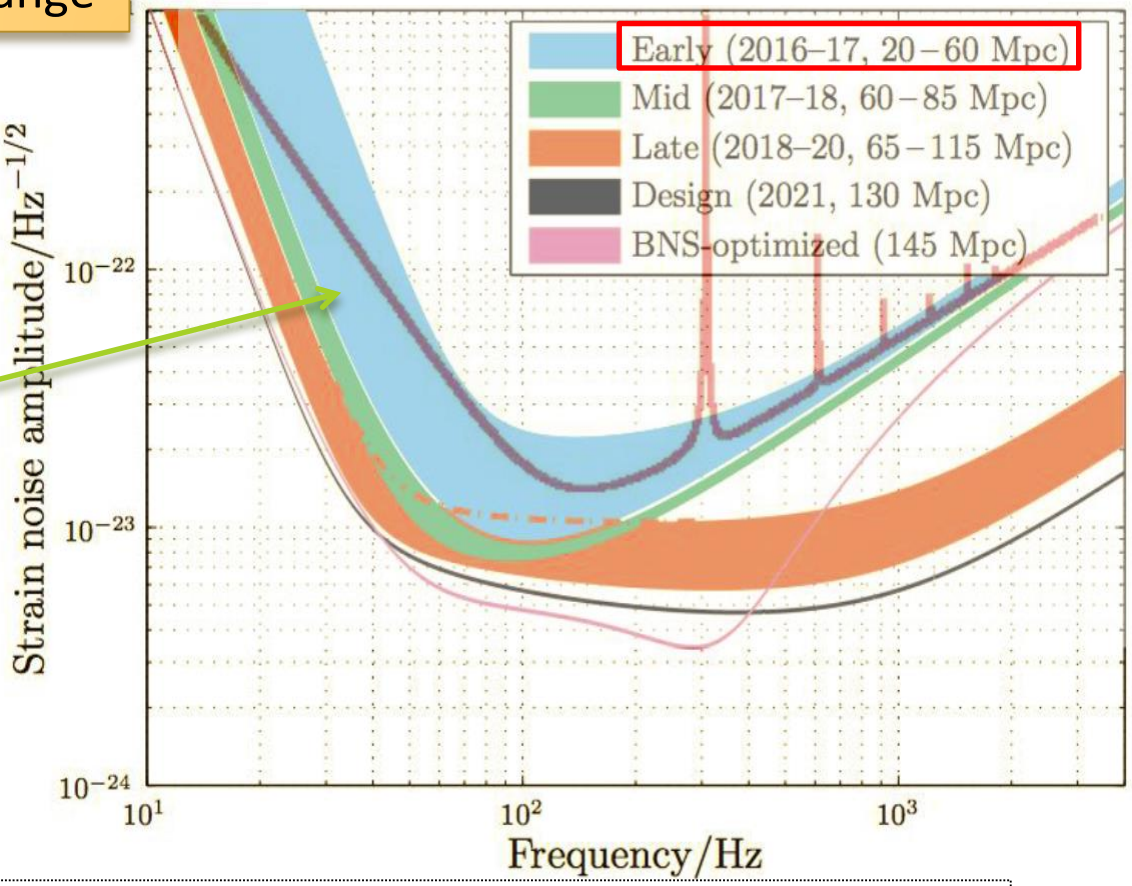
Advanced Virgo performance during O2

Failure of monolithic suspensions → the four test masses were suspended through steel wires

Early scenario: 20-60Mpc BNS range

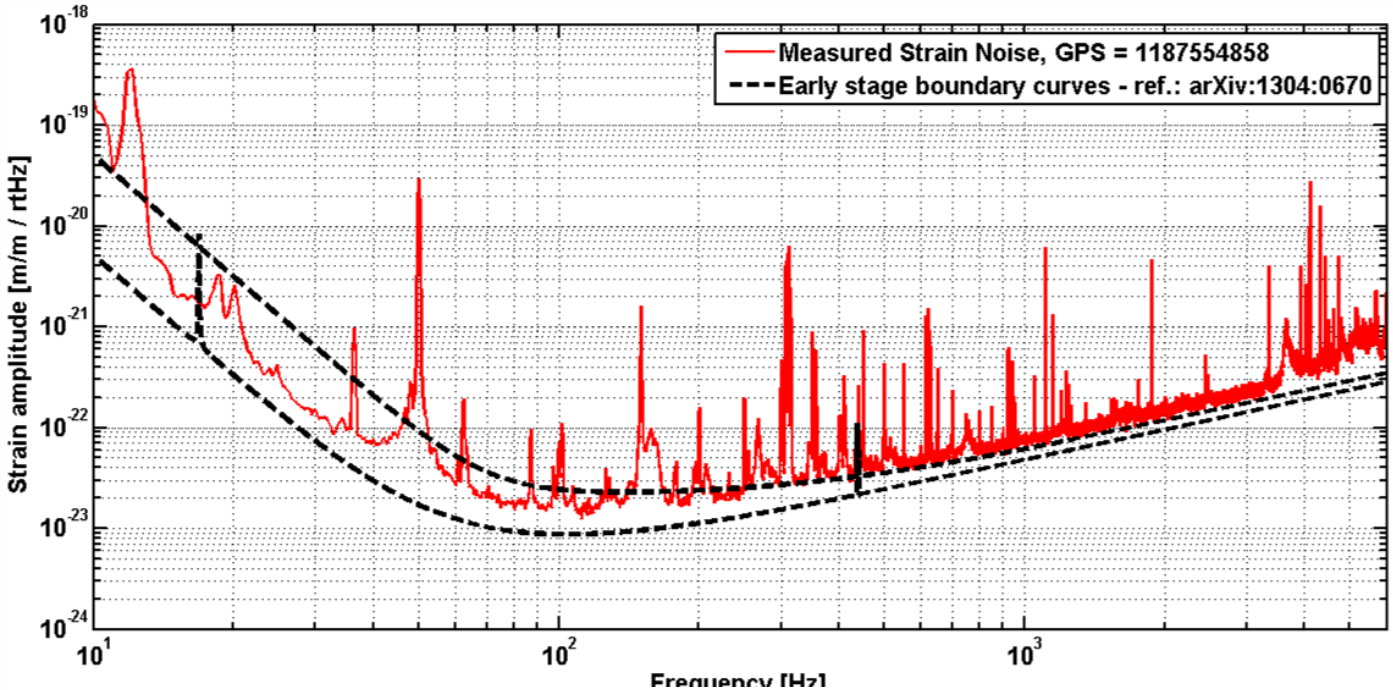
Sensitivity with steel wires still compatible with the goal for the early phase

Advanced Virgo observing scenario

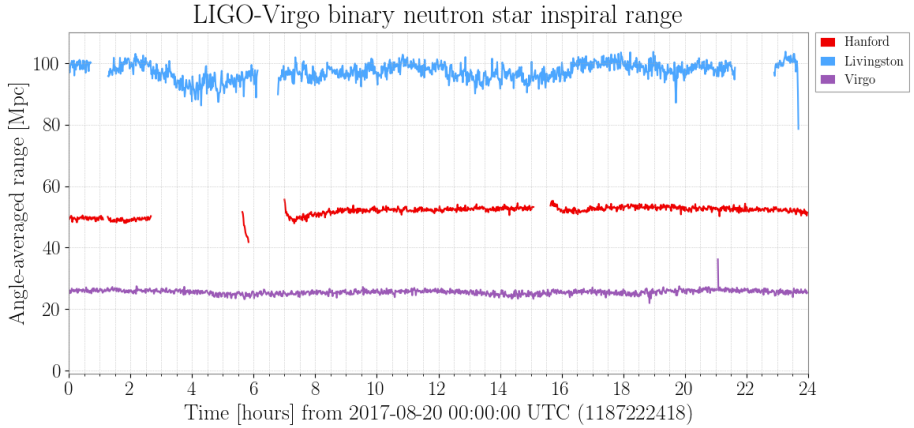


BNS range: Standard figure of merit for the sensitivity of the interferometer
Volume- and orientation-averaged distance at which a compact binary coalescence consisting of two 1.4 $M_\odot$ neutron stars gives a matched filter SNR of 8 in a single detector

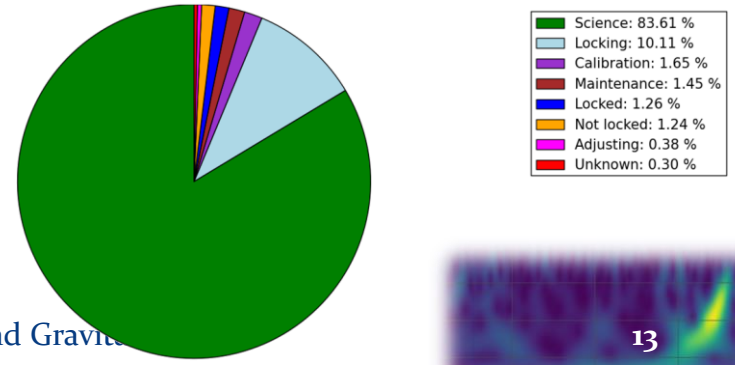
AdV measured sensitivity compared to early stage boundaries



BNS range up to 28 Mpc during O2



AdV Duty cycle of 83%



Outline

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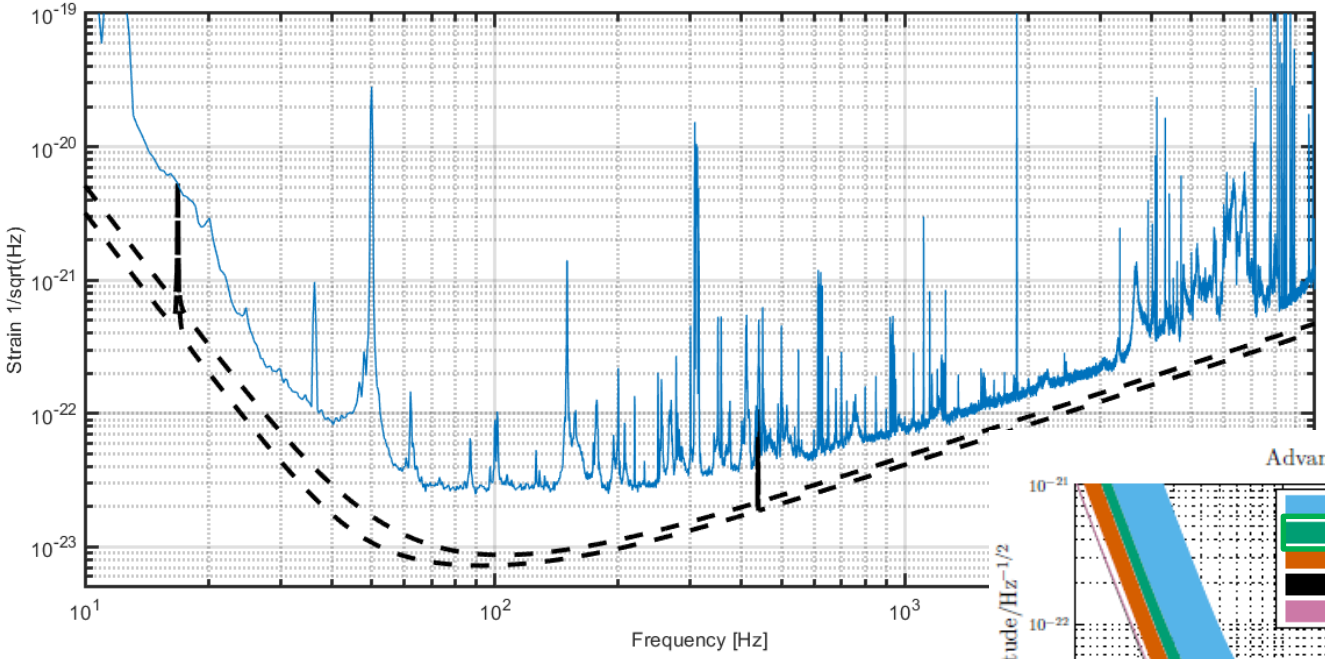
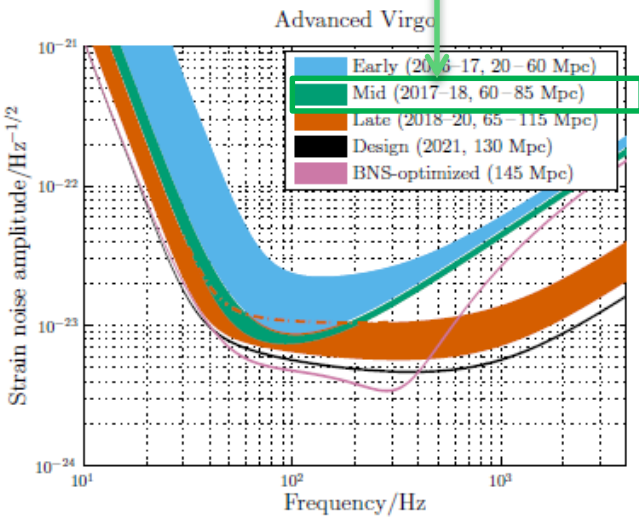
How do we increase the sensitivity?

O2 sensitivity as compared to the mid stage scenario (60-85Mpc)

From 2013 Observing scenario, arXive:1304:0670. We projected at least 60Mpc for 2018





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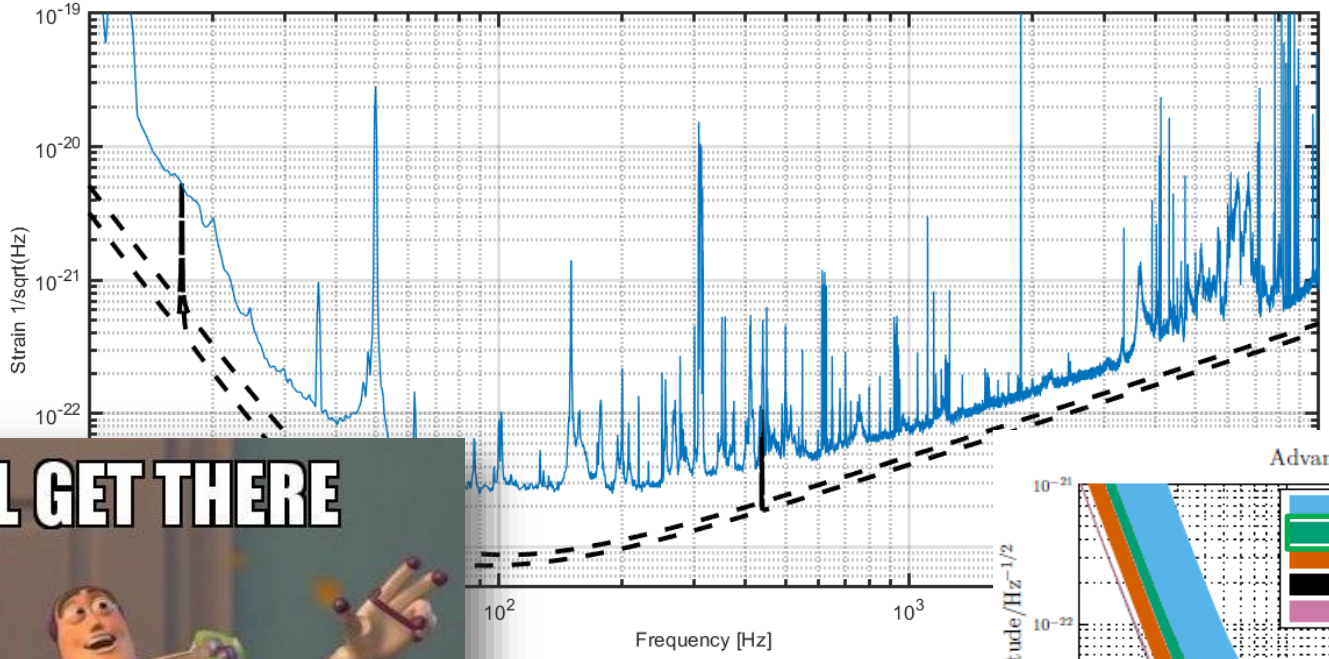
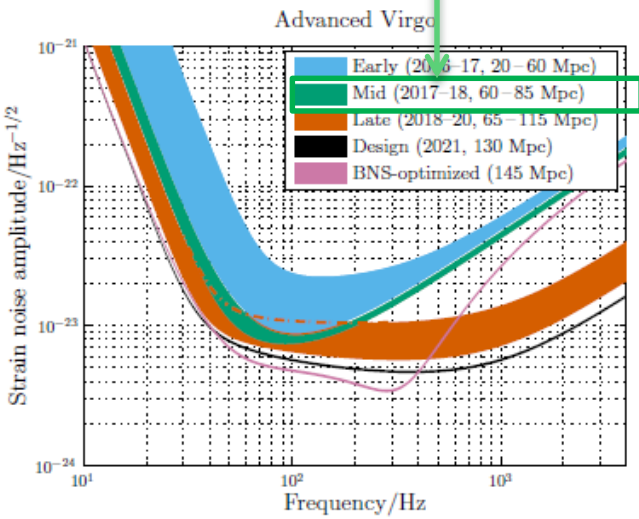
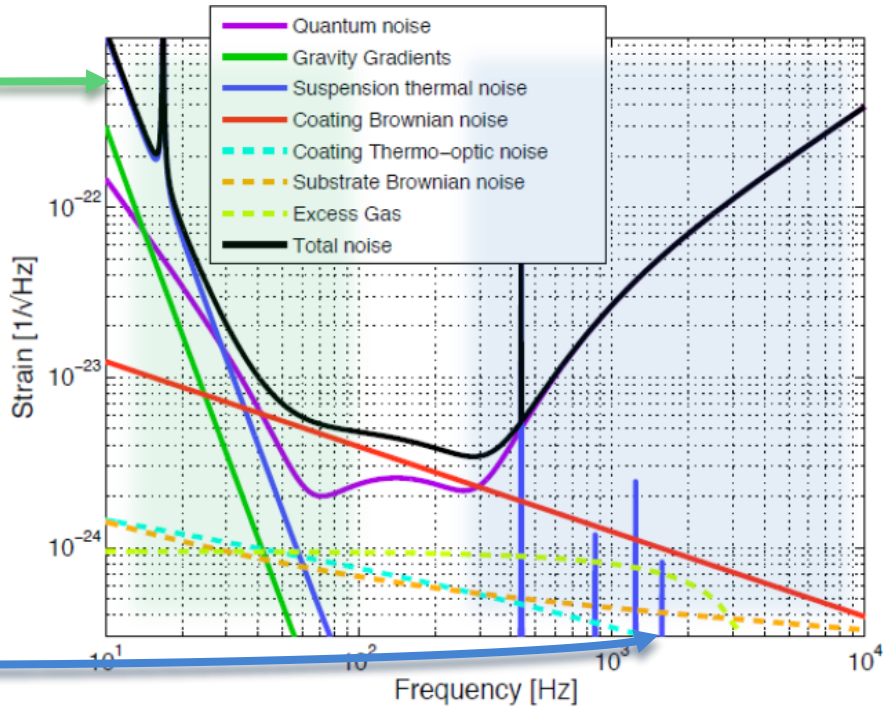




Getting ready for O3

- Major upgrades
  - Reducing suspension thermal noise: monolithic suspension installation
  - Reducing quantum noise: input power increase and squeezing installation



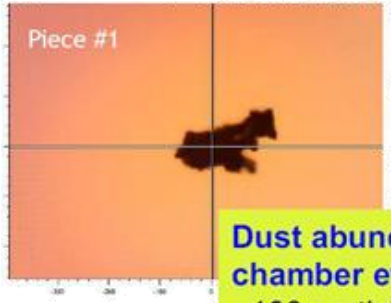
- Noise hunting activities and stray light mitigation

Monolithic suspensions

SiO_2 fibers 400 µm in diameter to suspend mirrors 42 kg in weight

Already installed during Virgo+. However, many cases of breaking fibers during the installation of Advanced Virgo occurred, and we decided to install steel wires in order to join O2, while investigating the problem

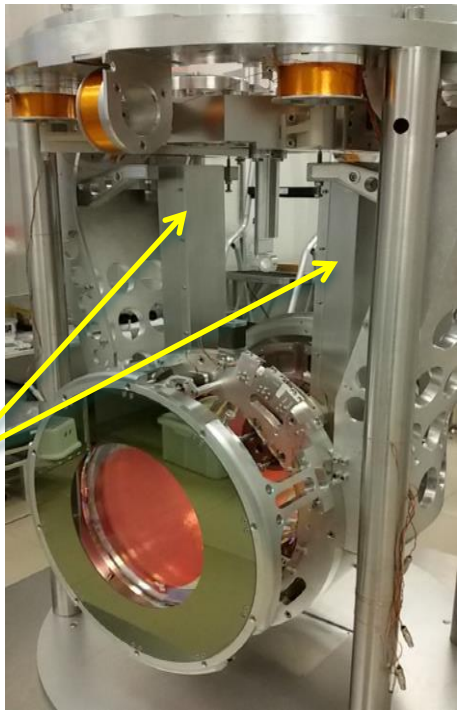
After the O2 run, a deep investigation was carried out, and finally found out the problem



Dust abundance on wafer in a small chamber evacuated by a scroll:
~100 particles on a surface of 2 mm X 75 mm
=> extrapolated ~ 3000 on the disk
=> ~0.7 particles/mm²

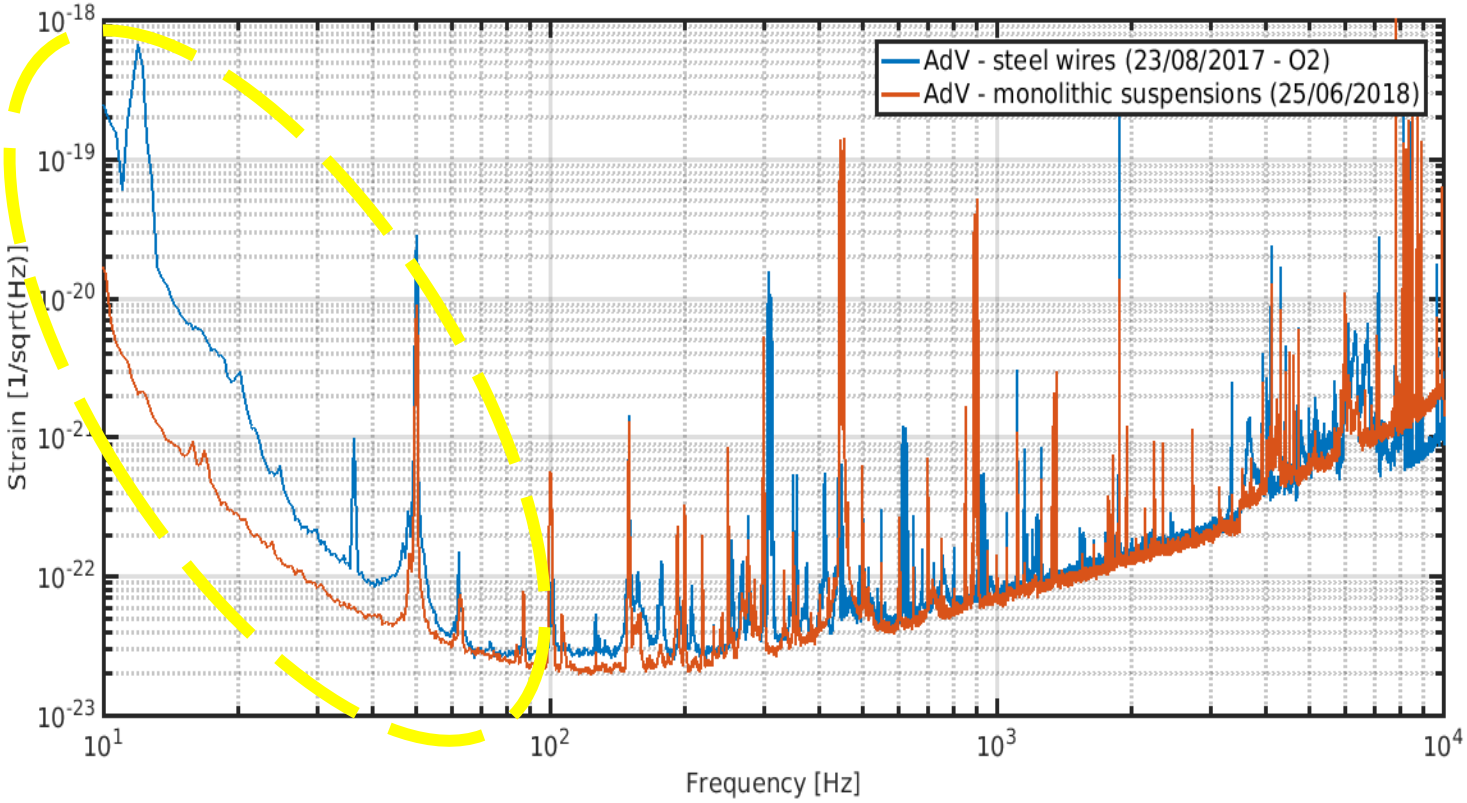
- Careful cleaning of the vacuum system
- Improved dust diagnostics
- Installation of separated venting pipe and of a new dry pump

Fiber guards as additional protections against dust impact



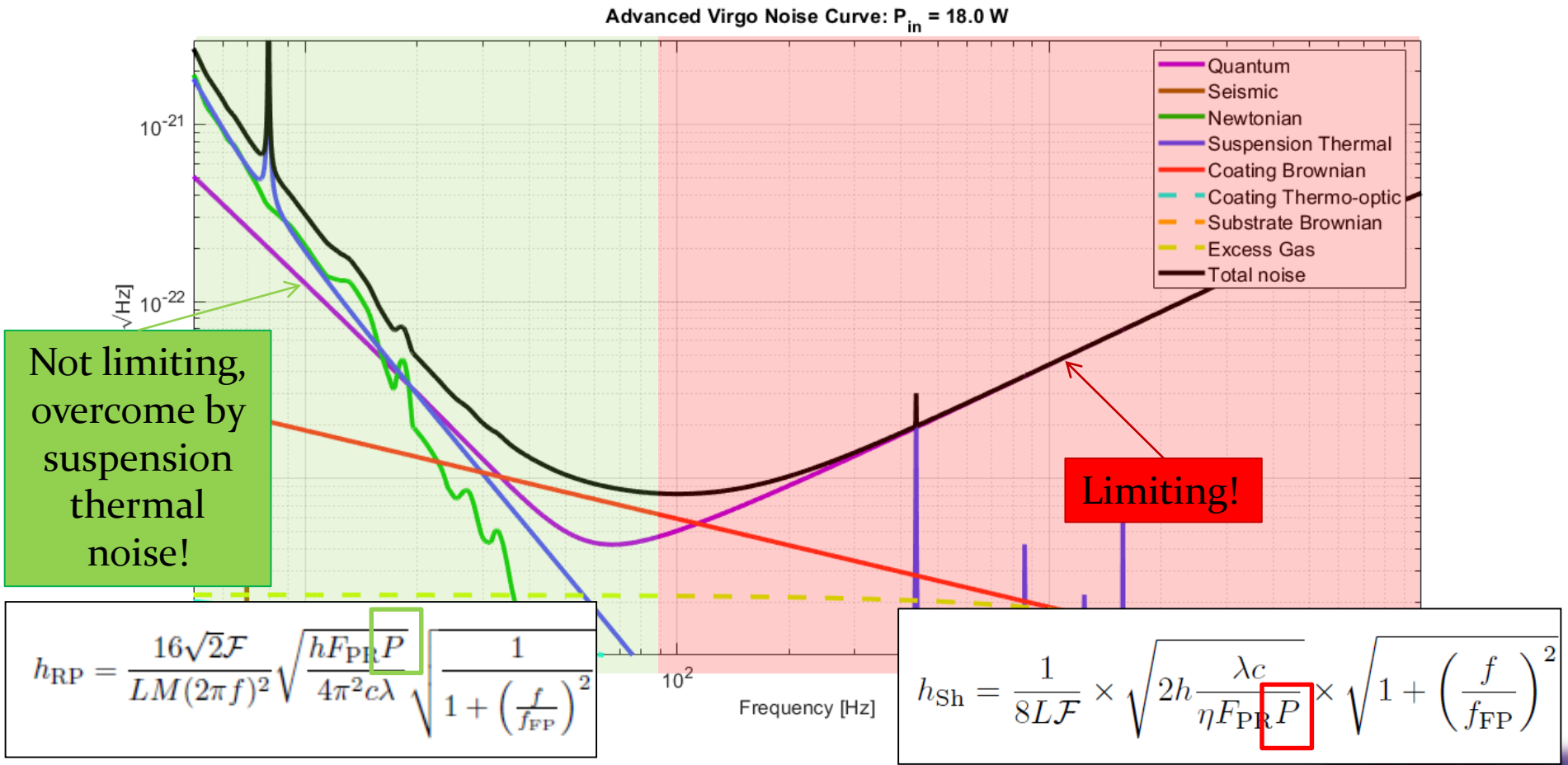
AdV sensitivity with monolithic suspensions

Improvement in the low-mid frequency region because of lower suspension thermal noise: about 10 Mpc gained



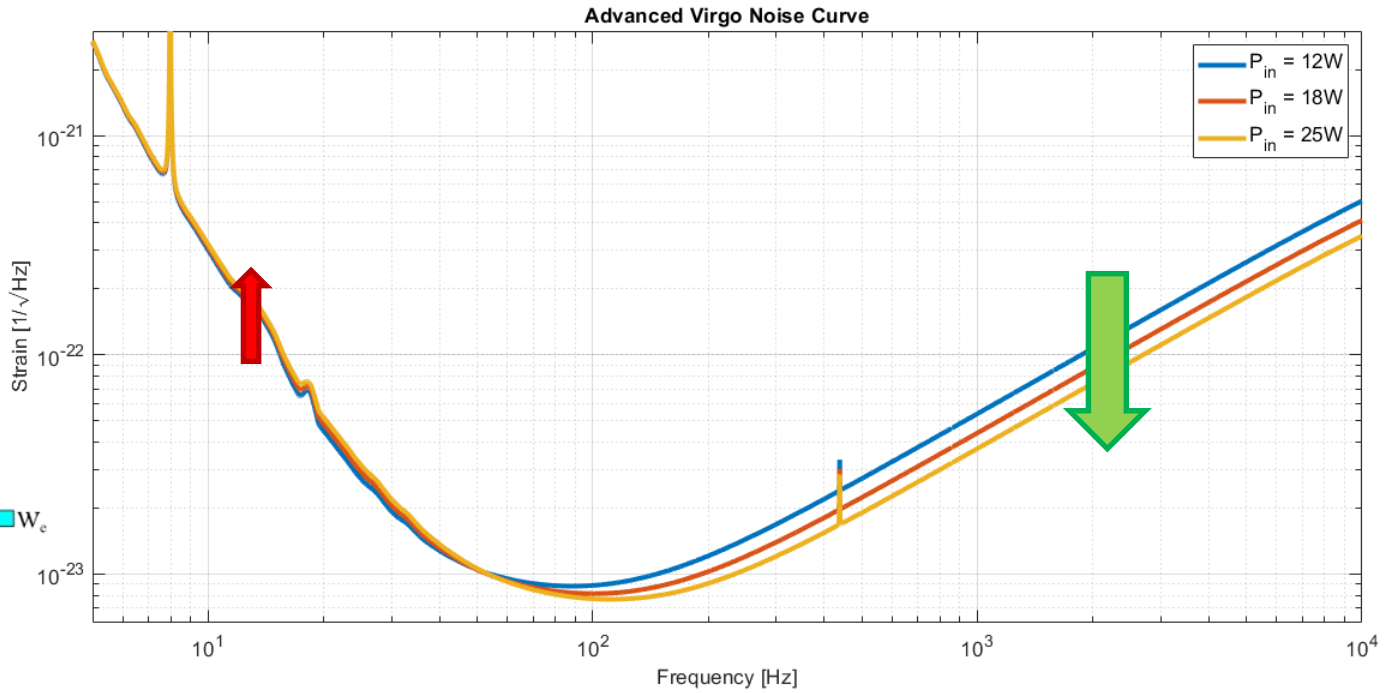
Quantum noise

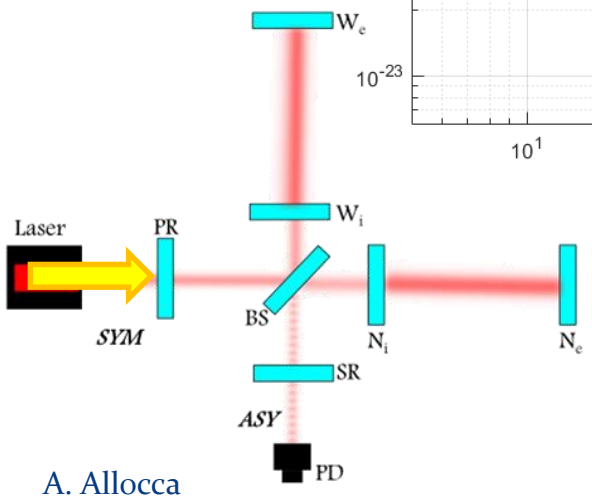
Statistical fluctuations in the number of detected photons (shot noise) and radiation pressure fluctuations on test masses.



Input power increase

A quantum noise reduction can either be obtained by increasing the input power…

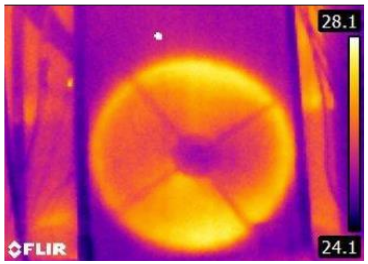


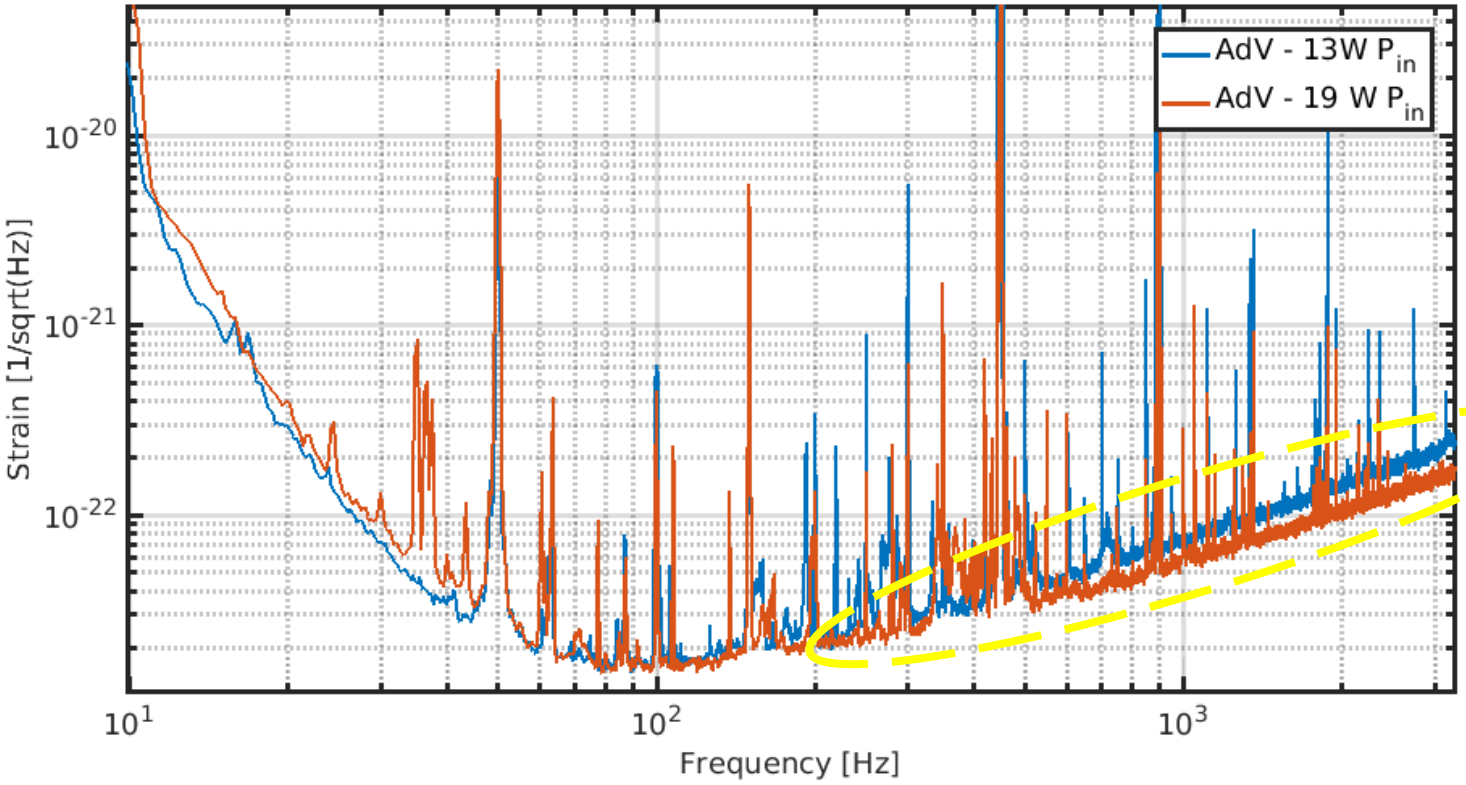


Input power increase

The increase of input power induces an improvement of the high frequency sensitivity, as the shot noise is proportional to $1/\sqrt{P_{in}}$.

Thermal Compensation System properly tuned to mitigate the increasing YAG thermal effects

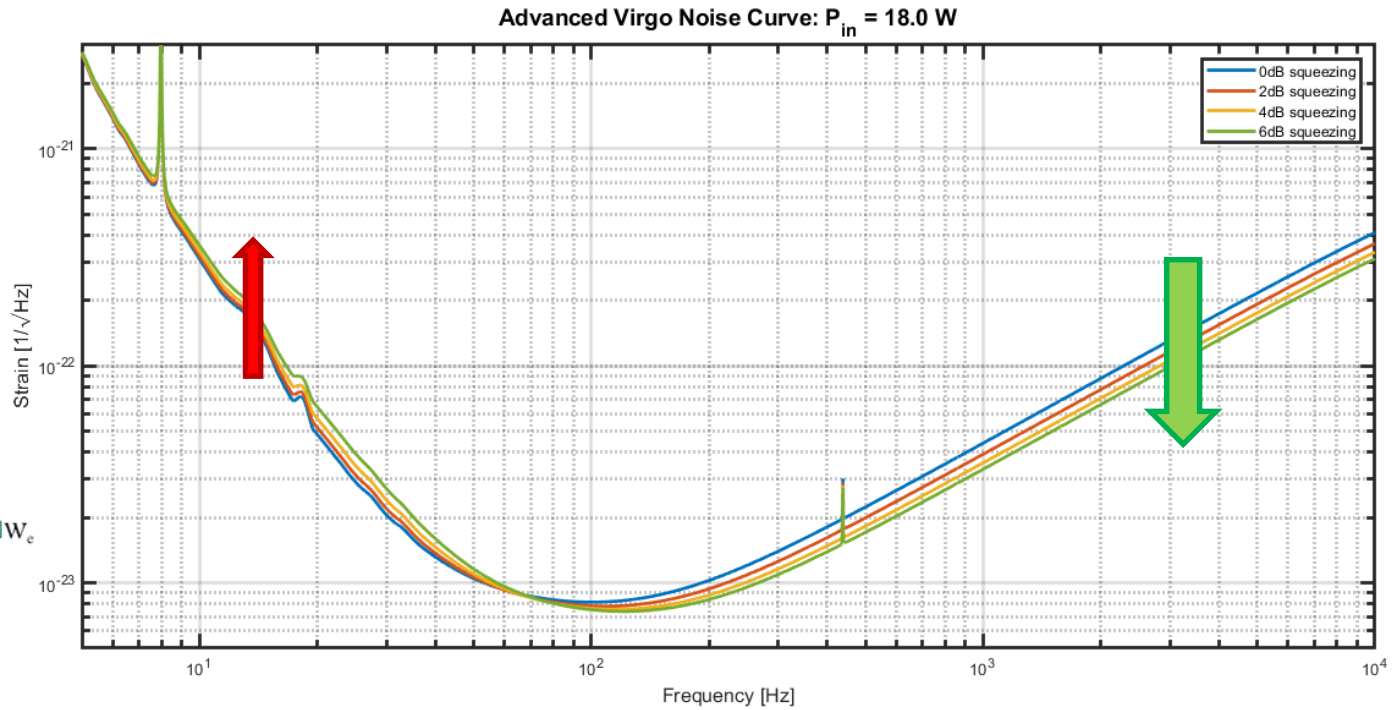


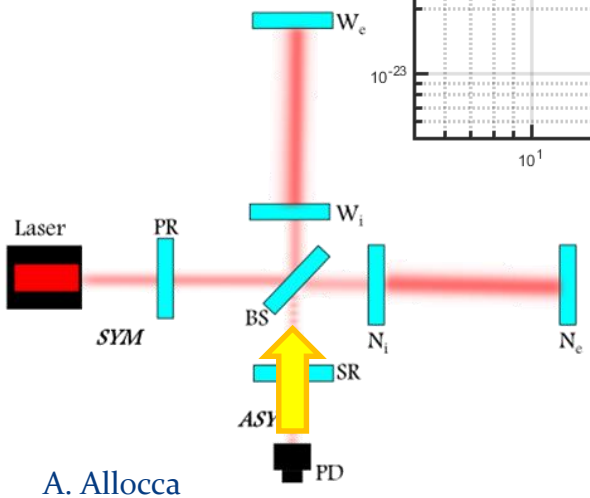


Factor ~0,8 lower noise at high frequency

The Frequency Independent Squeezing

...or injecting squeezed vacuum



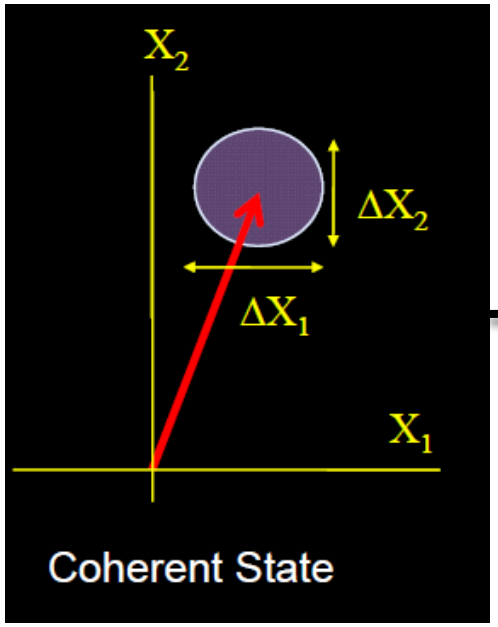


The squeezing principle

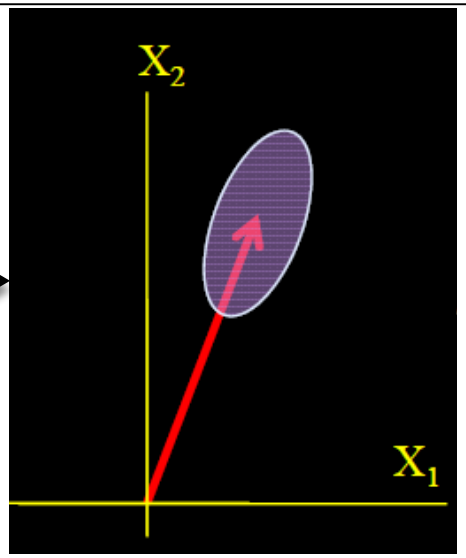
Vacuum fluctuations entering from the dark port cause quantum noise in interferometers. Squeezing was proposed as a solution over 30 years ago. [*Caves, Phys. Rev. D (1981)*]

For a coherent state, the uncertainty principle holds

$$\Delta X_1 \, \Delta X_2 \geq 1$$



There is a minimum uncertainty product, but the area can be re-distributed



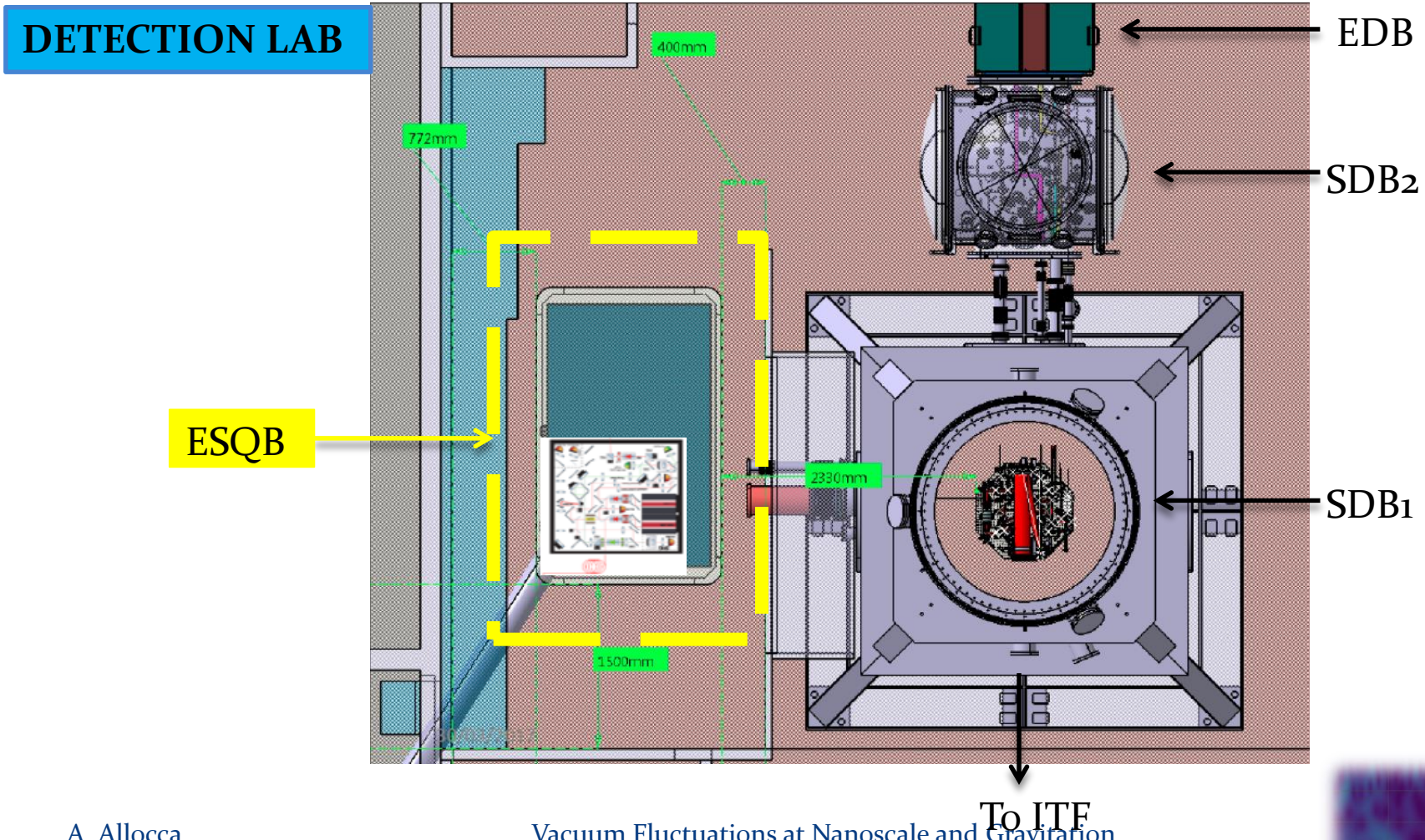
Phase squeezed
Amplitude anti-squeezed

Squeezing the field entering the dark port reduces the noise on the gravitational waves readout

See more in M. De Laurentis, L.Naticchioni and V. Sequino's talks

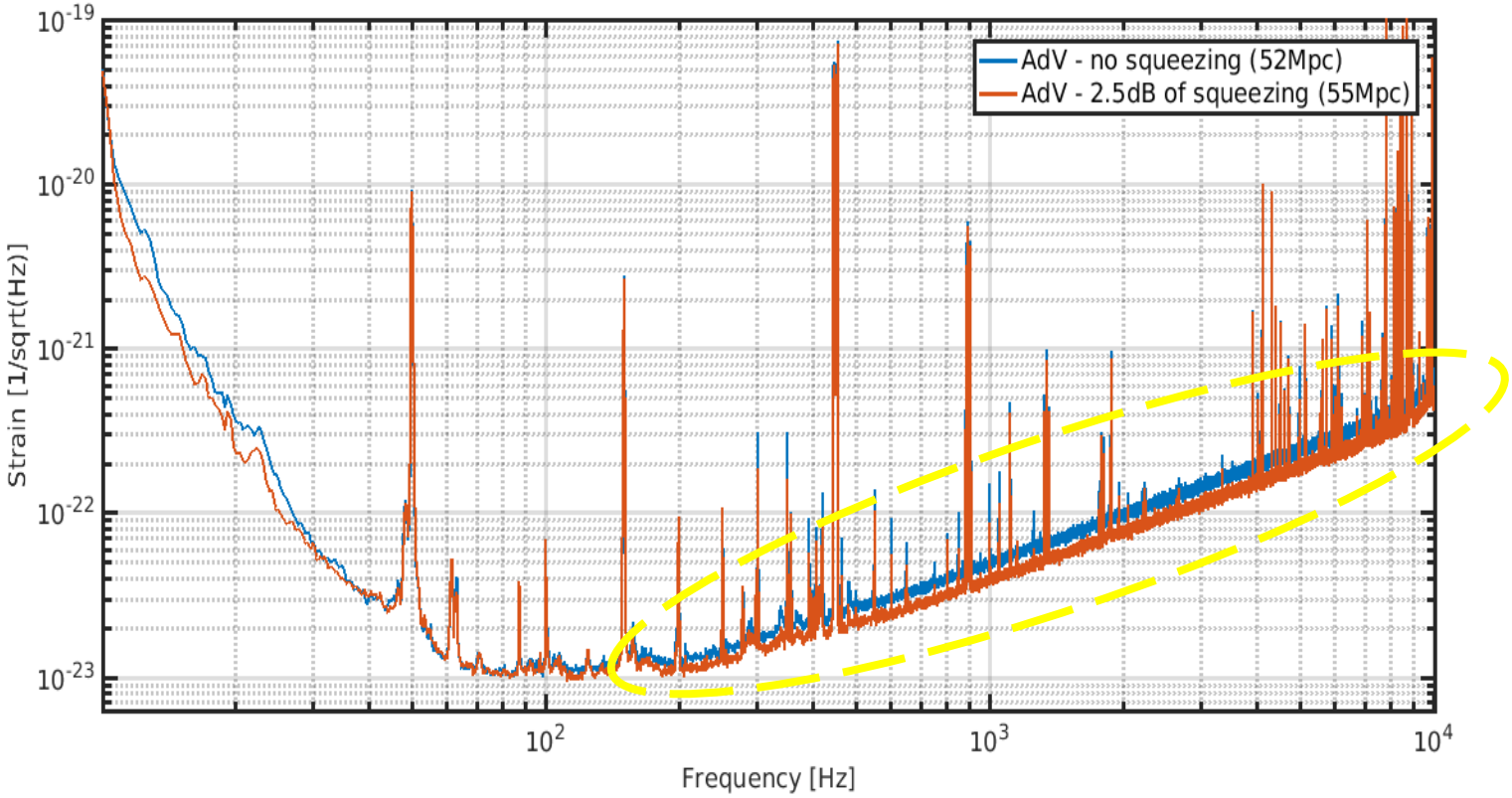
The squeezer installation

Thanks to a collaboration agreement with the Max Plank institute AEI, they installed the last generation of their frequency independent squeezer in Virgo.



Squeezing effect on the interferometer

Injecting frequency independent squeezing we could improve the sensitivity from 52Mpc to 55Mpc!



Getting ready for O3

- Major upgrades
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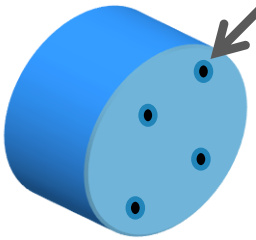
  - Reducing quantum noise: input power increase and squeezing installation
- **Noise hunting activities and stray light mitigation**

Noise hunting and stray light mitigation

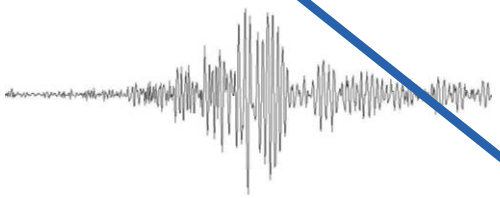
Noise injections are performed in order to spot possible coupling between the noise source and the detector and, therefore, mitigate it.

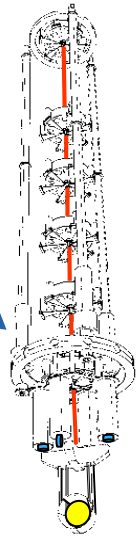
Radio waves
(6MHz, 8MHz, 56MHz)
Photodiodes RF modulated
used for angular and longitudinal controls

Electro Magnetic fields
Act on mirror MAGNETS, possible electrostatic charges on the mirror



Slow ground motion





Excite mechanical modes of mirrors and optical benches suspensions

Seism & Sounds

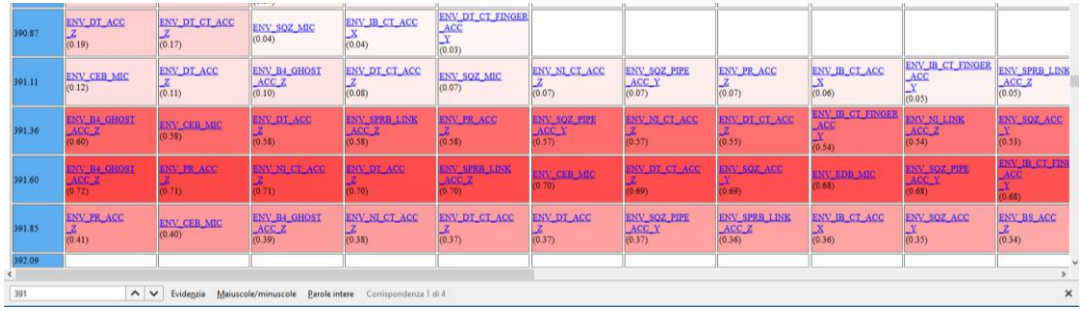
- Excite vibrations of vacuum pipes and tanks, optics on in-air benches
- Imprint phase noise on spurious scattered light beams

Analysis

- "Brute force" coherence tool (BruCo)

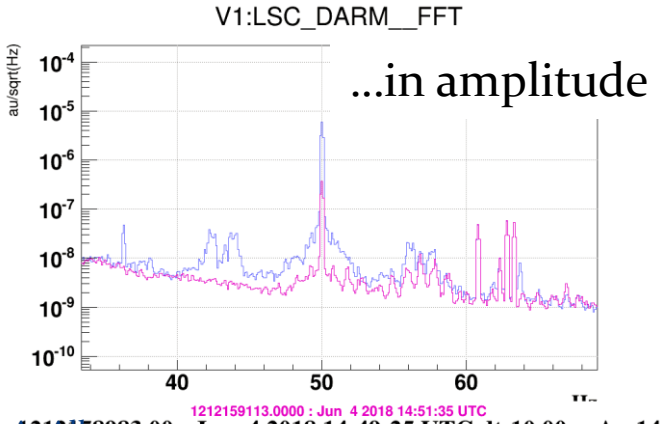
– *computes and ranks Coherence* between Hrec and all AUXILIARY channels (G.Vajente, https://dcc.ligo.org/LIGO-G1500230)

"brute force" approach = search for noise correlation in ALL (not obvious) channels (i.e. O(10000 channels)!)

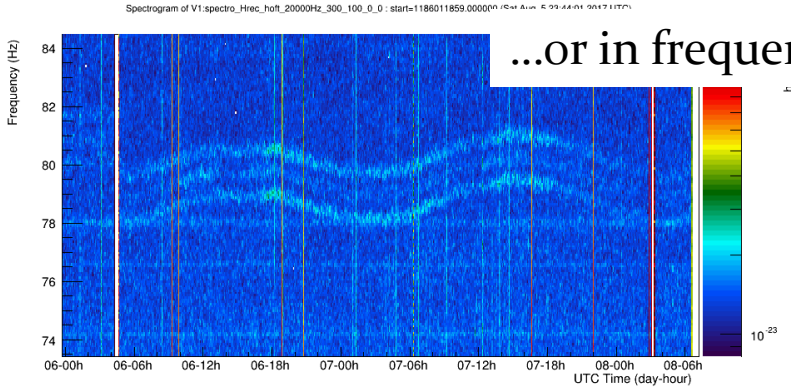


- Non-stationary Noise Analysis (NonNA)

- Brute force correlation for noises which are non-stationary…



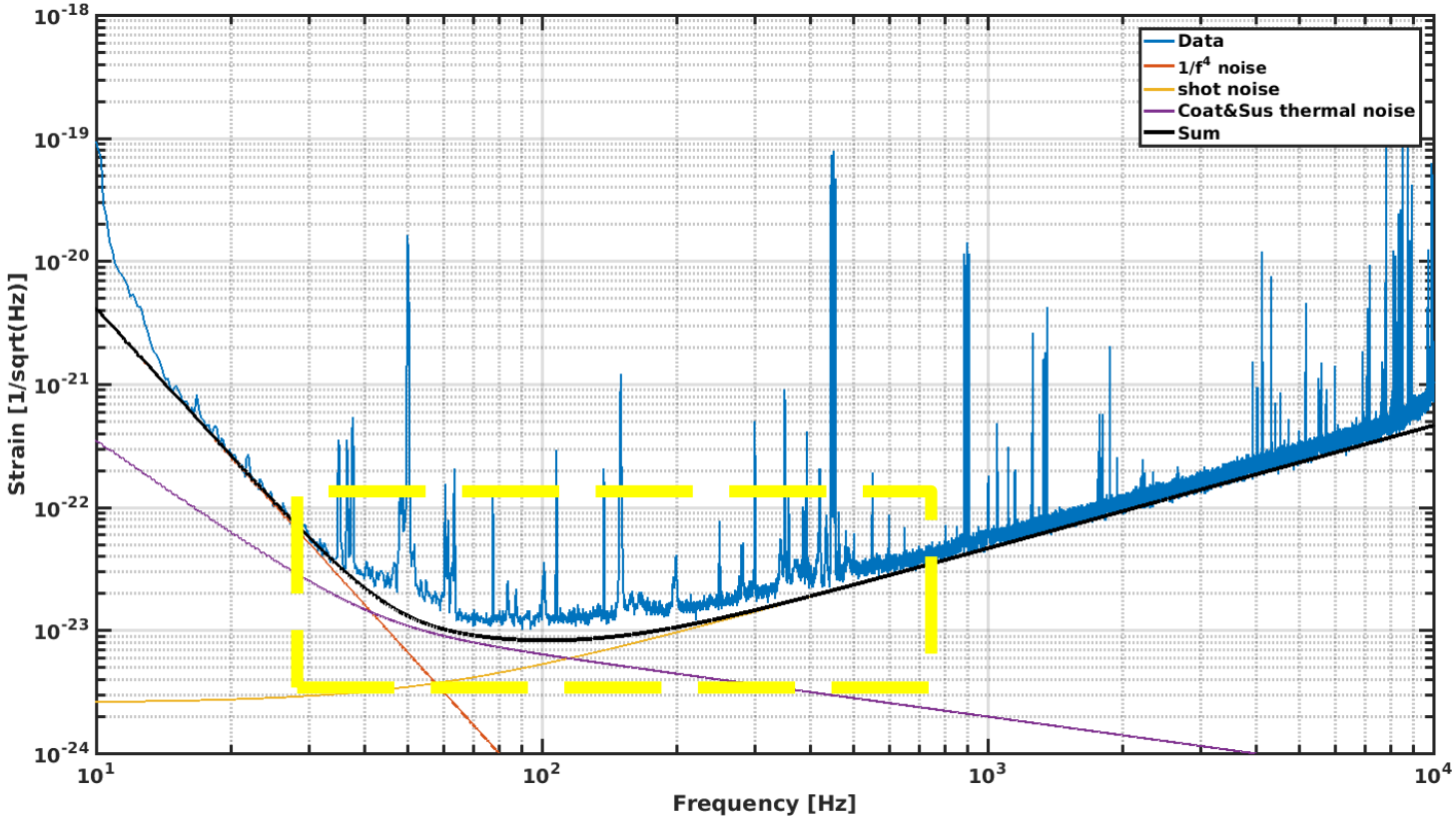
…in amplitude



…or in frequency

The “flat” noise

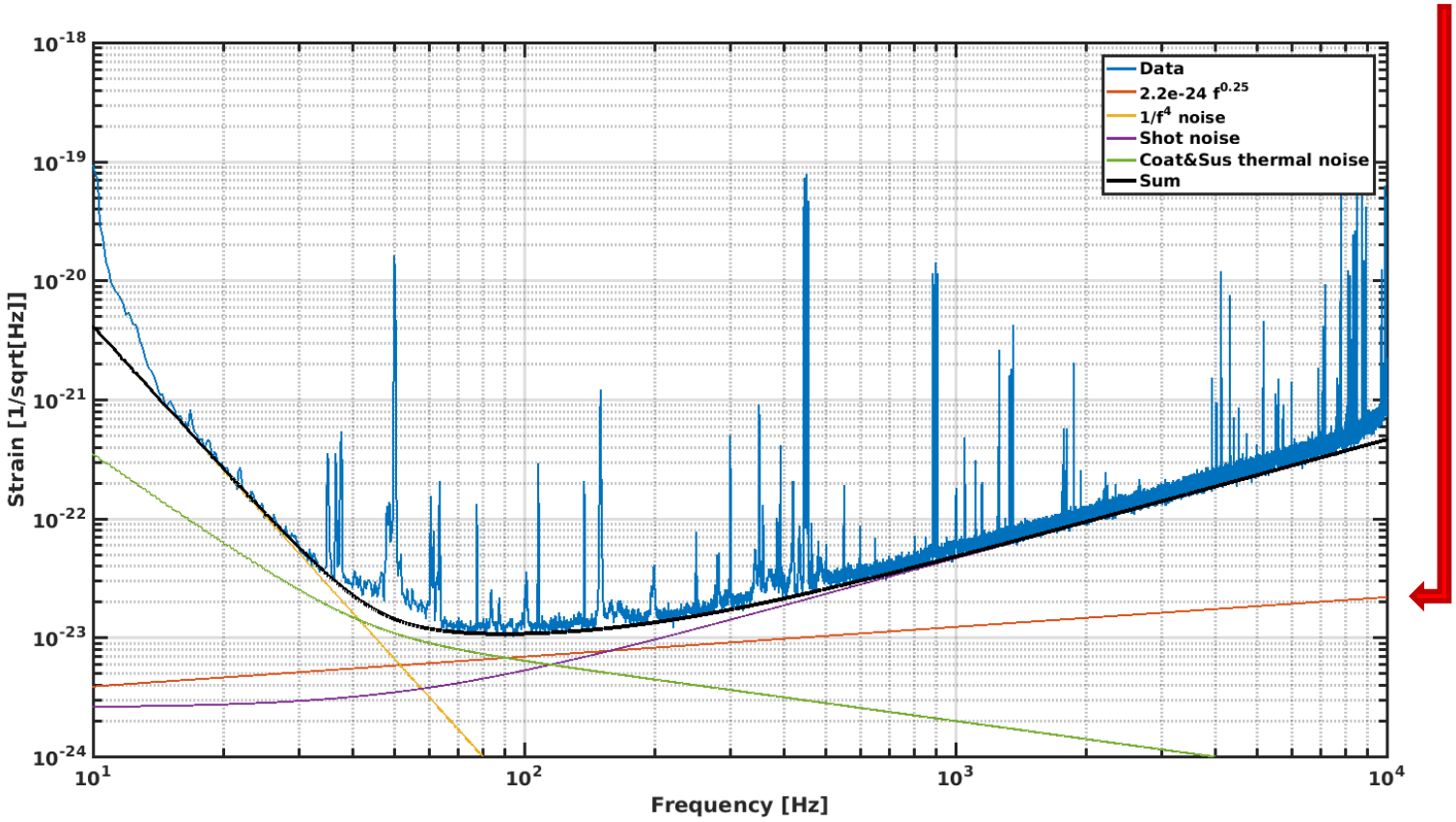
Main culprit preventing us from reaching 60 Mpc



The noise budget accounts for all the known technical noises, but cannot account for the noise “in the bucket”, in the region between 40Hz and 400Hz. This is what we call the “flat” noise

“Flat” noise

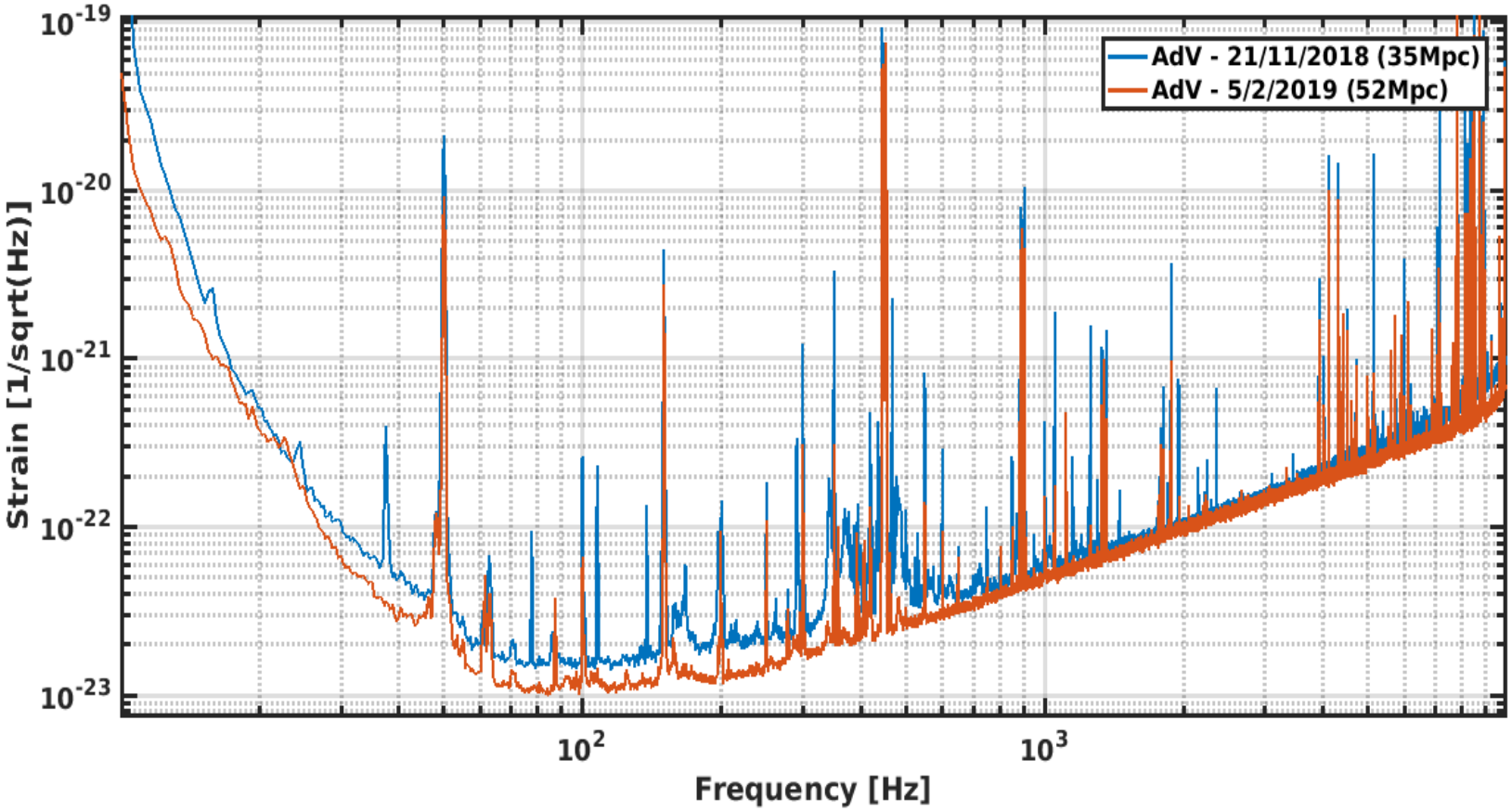
It fits better the sensitivity curve between 60Hz and 300 Hz if it has a small slope (~$f^{0,25}$)



Still not completely clear what is the mechanism giving rise to this noise, but it was reduced after a stray light mitigation intervention

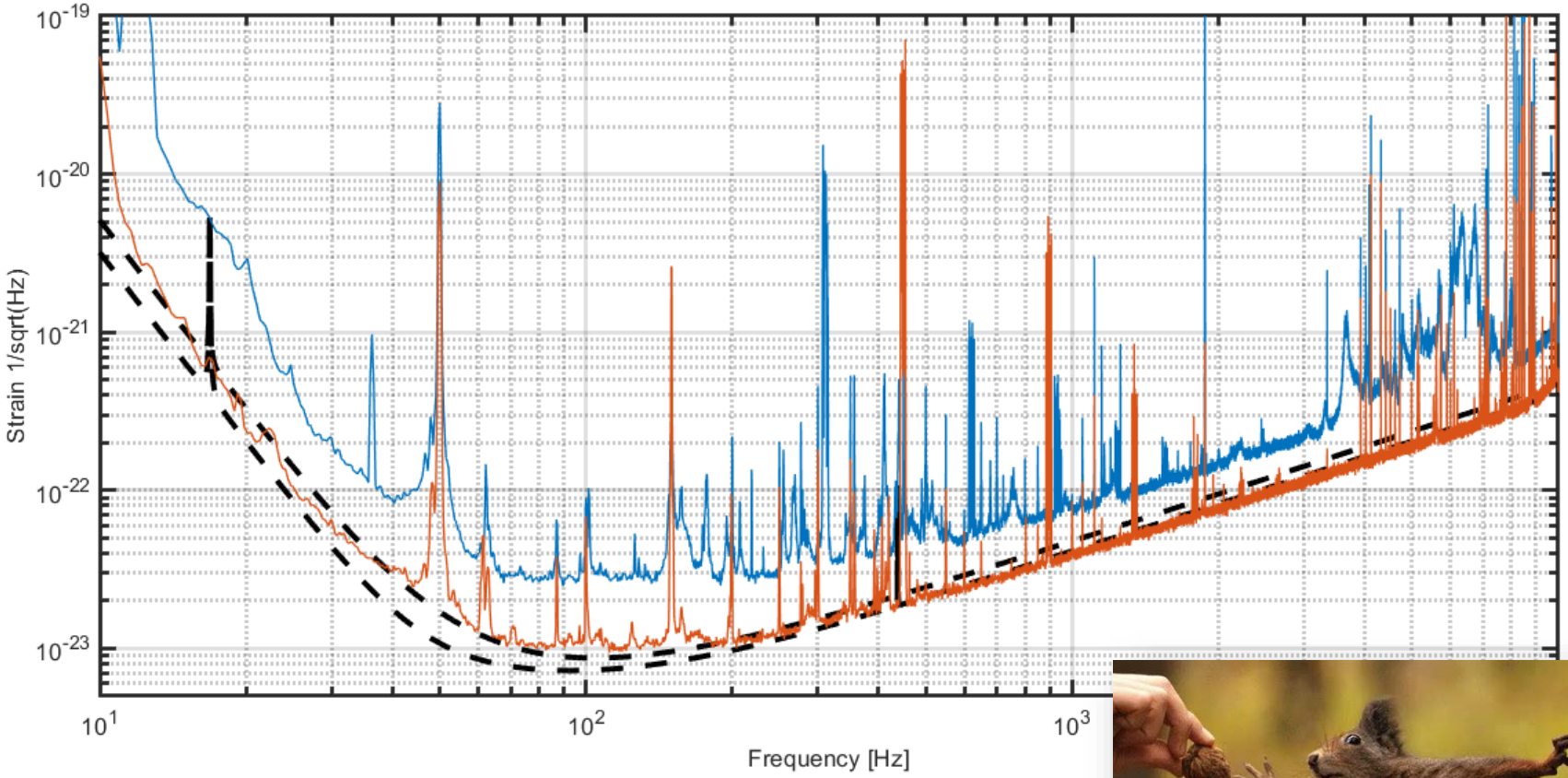
“Flat” noise mitigation

Huge improvement in the mid frequency range after the flat noise was reduced



...in the end, we got almost there!

AdV, Feb 5° 2019 → 55 Mpc



Ready to join O3!

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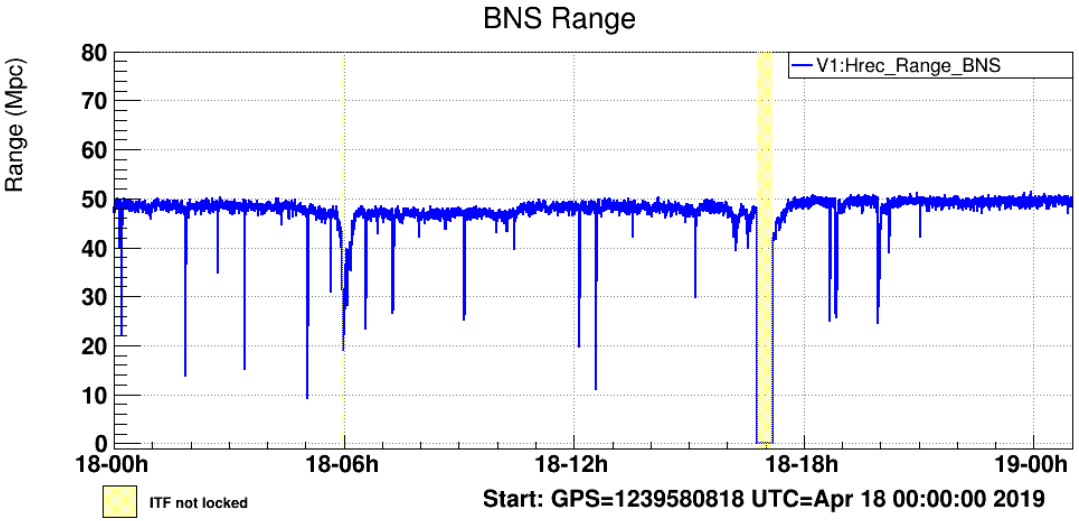
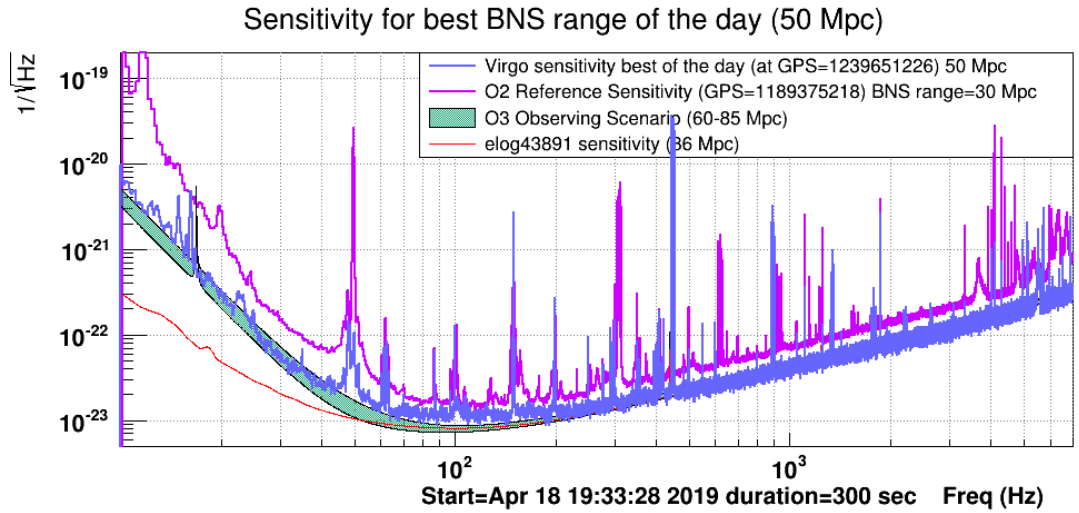
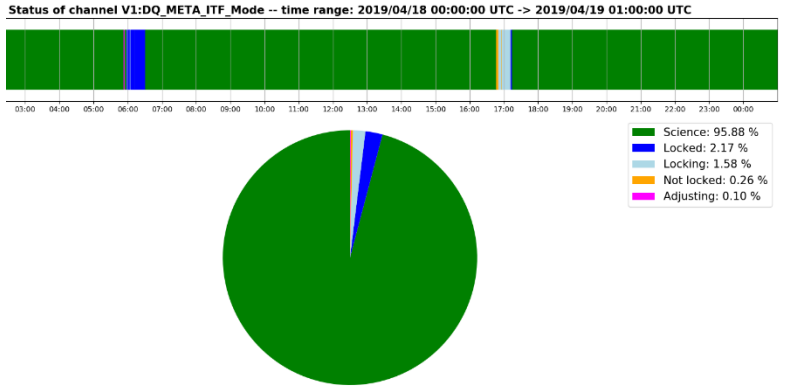
O3 Advanced Virgo performance

The third joint observation run (O3) started on April 1°, after one month of engineering run



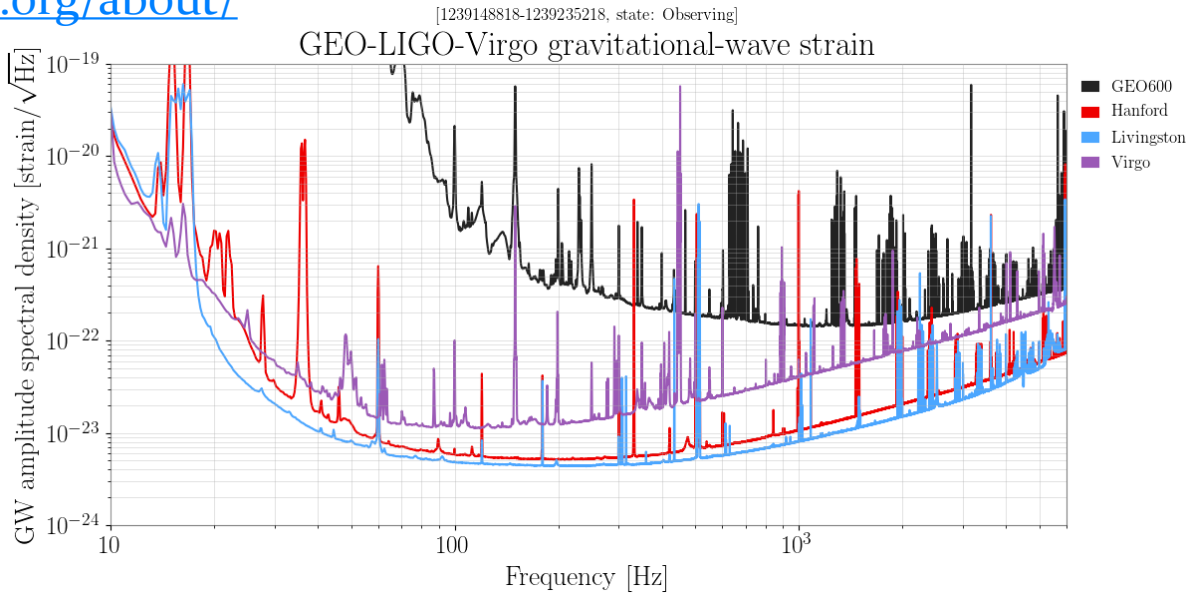


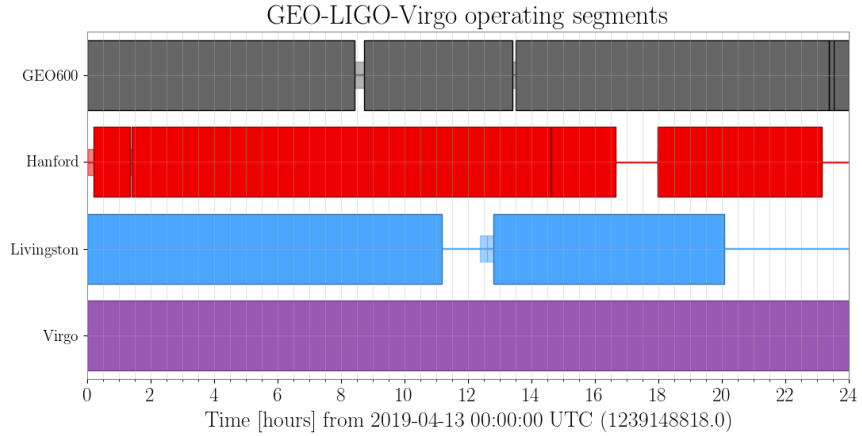
High duty cycle (more than 90%) with a sensitivity of ~50 Mpc BNS range (almost x2 higher than O2)

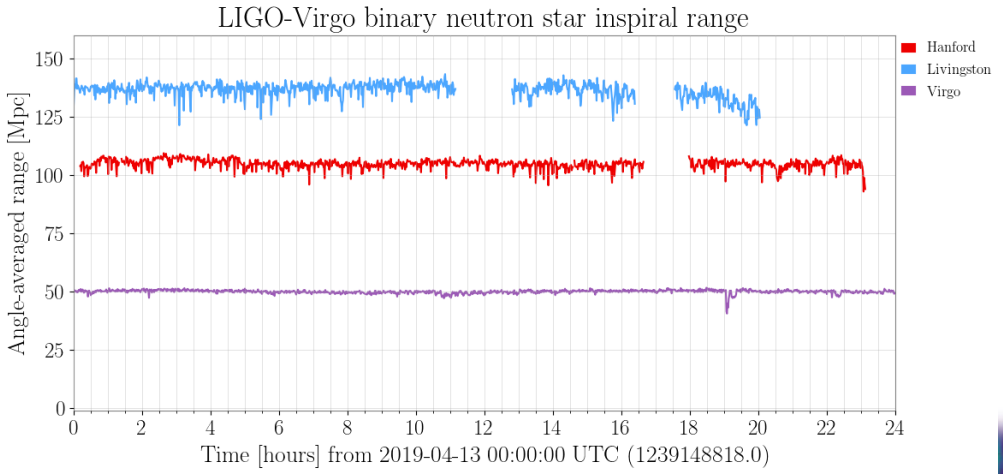


O3 LIGO-Virgo performance

https://www.gw-openscience.org/about/



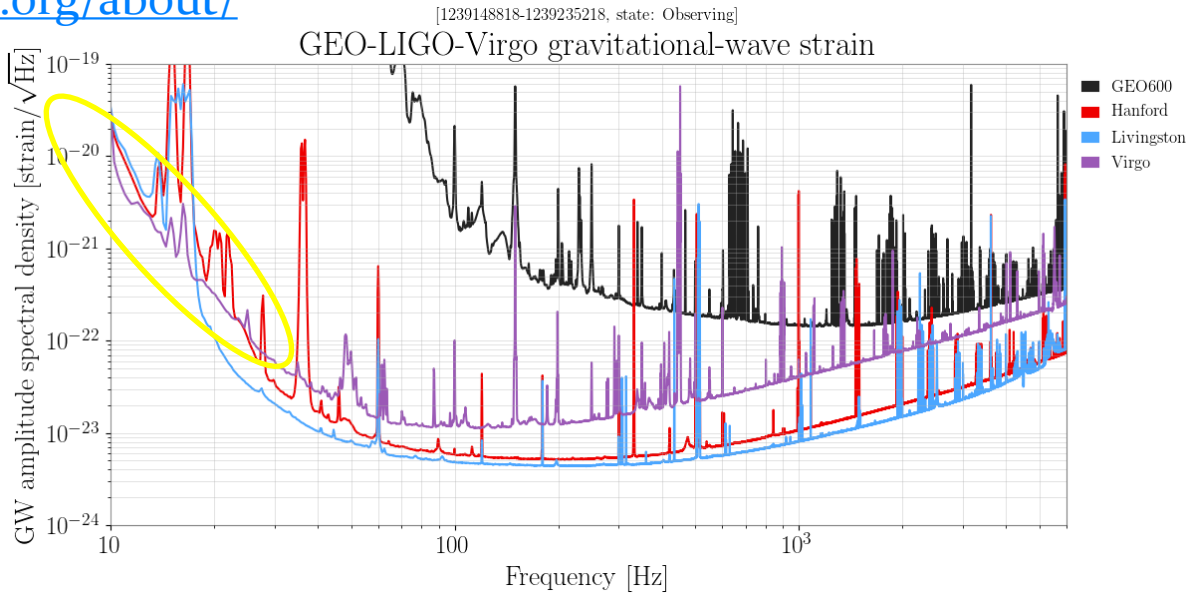


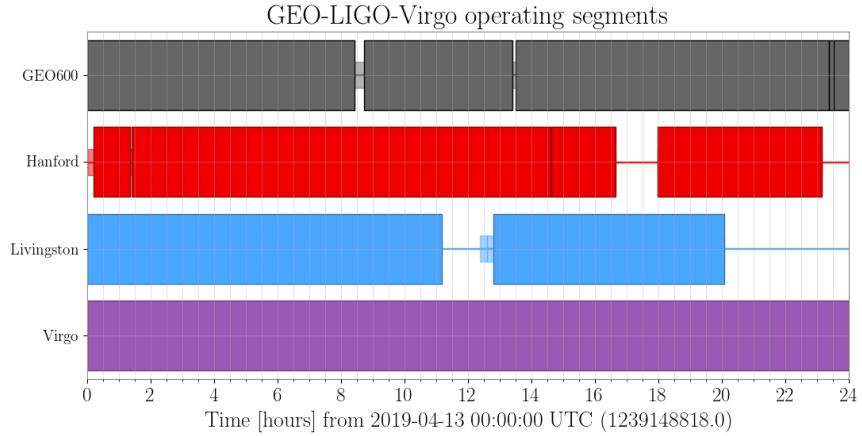


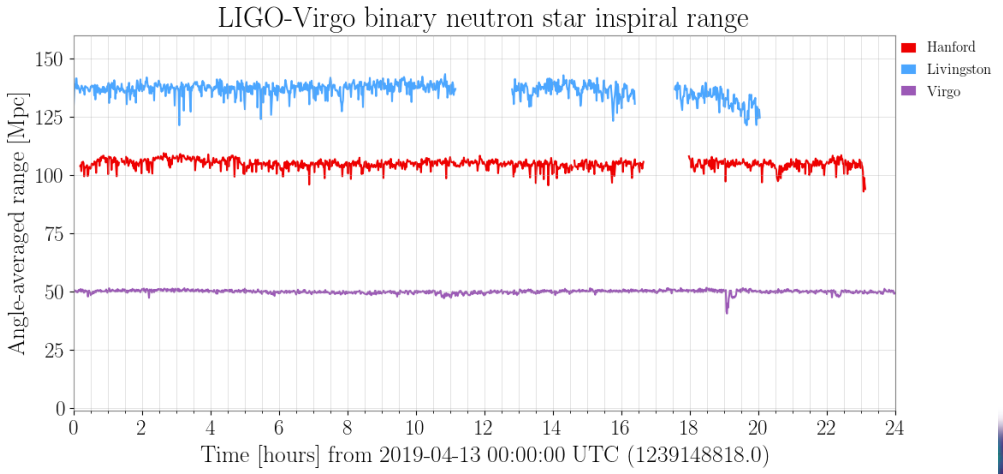
O3 LIGO-Virgo performance

https://www.gw-openscience.org/about/

Thanks to the seismic attenuation system performances, Advanced Virgo sensitivity is comparable or even better than LIGO at low frequency (<20 Hz)

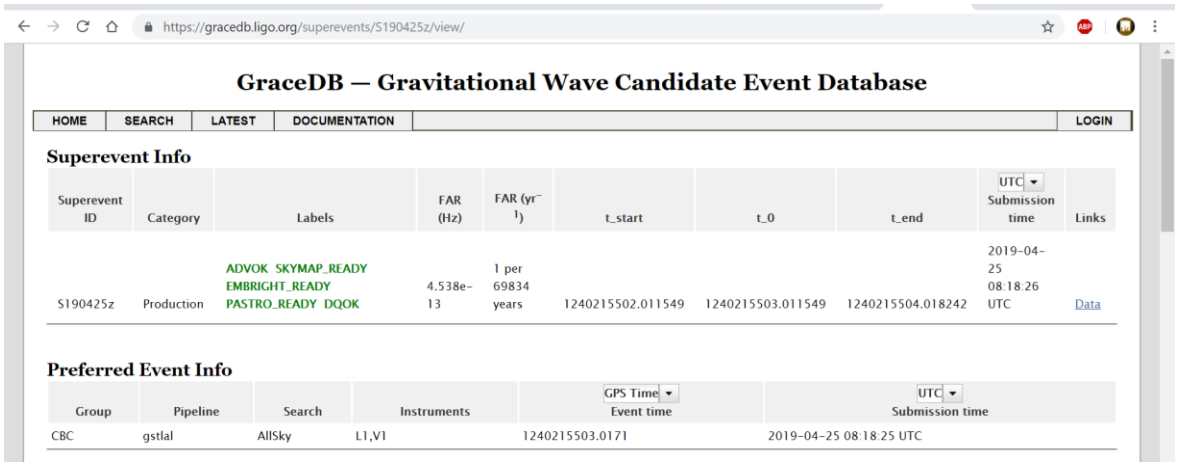


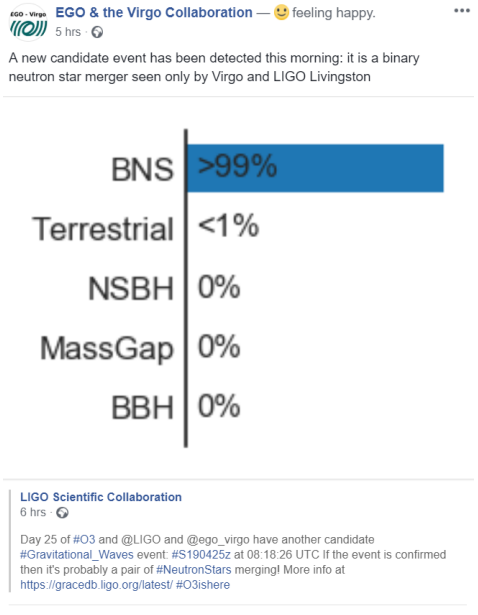




New in O3: open public alerts

- Event candidates will be publicly available in https://gracedb.ligo.org





- About 1 event per week already detected in the first month of run

News spread also on the social networks ☺

- LIGO/Virgo Public Alerts User Guide & Support
  https://emfollow.docs.ligo.org/userguide/index.html
  contact+emfollow/userguide@support.ligo.org

Outline

- Advanced Virgo design
- Advanced Virgo performance during O2
- The path from O2 to O3
- Current status of O3
- **Future perspectives: Advanced Virgo +**

Advanced Virgo +

- Upgrade of Advanced Virgo
- Goal: sensitivity increase from ~100 Mpc to more than 200 Mpc

- **Phase 1** (hitting the thermal noise wall): between O3 and O4
  - Signal recycling installation
  - Input laser power between 40W and 50W (O3 with 18 W)
  - Frequency dependent squeezing (frequency independent squeezing already done in Advanced Virgo)
  - Newtonian noise cancellation
- **Phase 2** (invasive work): between O4 and O5
  - High power laser (200 W)
  - Larger beams → 12cm on end test masses (currently 5cm)
  - 100 Kg test masses → end test masses, TBC on input test masses
  - Better coating: depending on R&D results at the end of Phase I

Advanced Virgo+ anticipated sensitivities

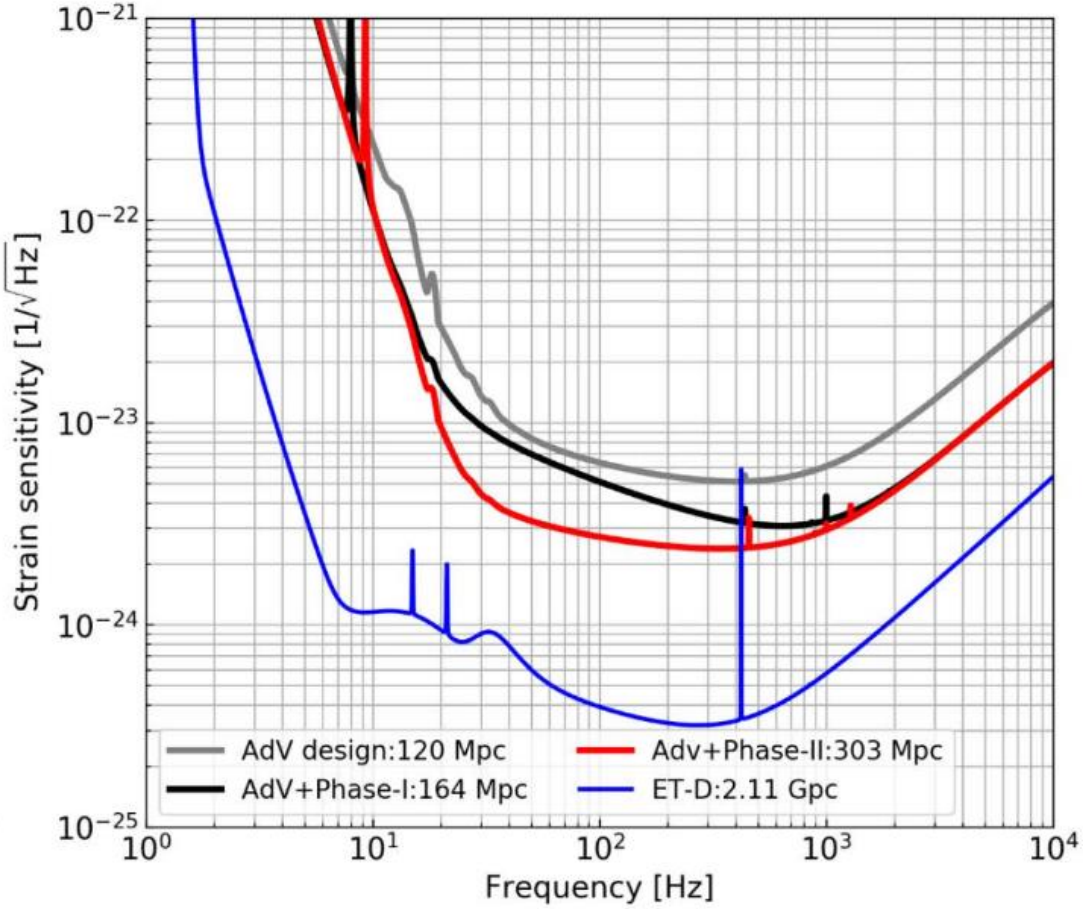
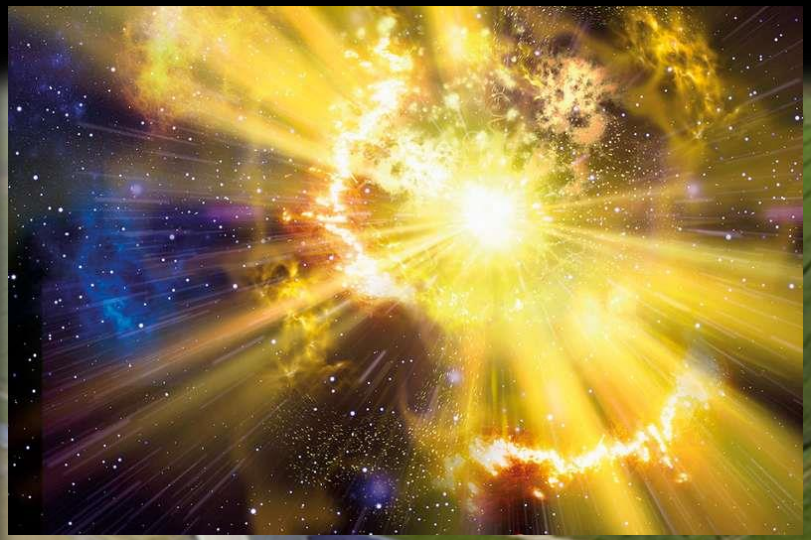
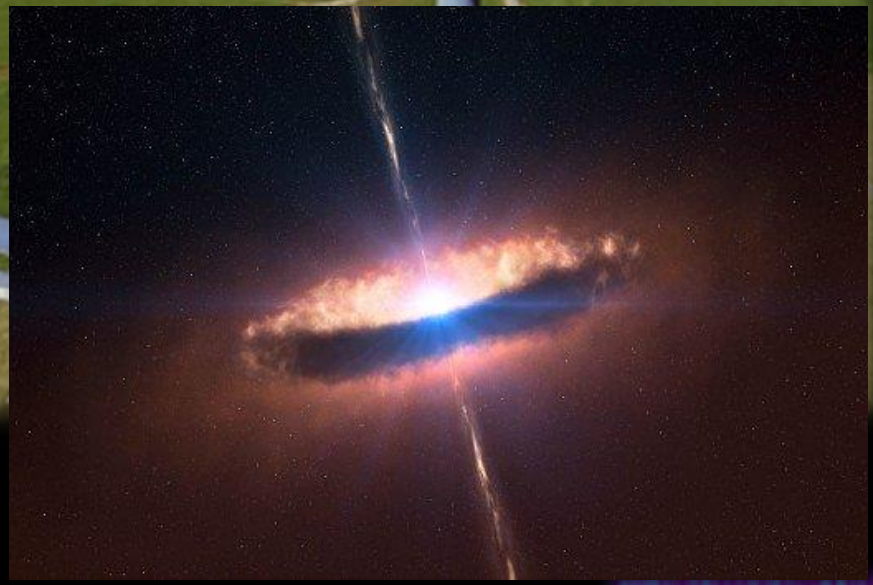


Figure 3.1: *Expected evolution of the Virgo sensitivity, and BNS range, after the completion of the two proposed upgrade phases. The design sensitivities of AdV and Einstein Telescope are also shown for reference.*

Waiting for new exciting events…

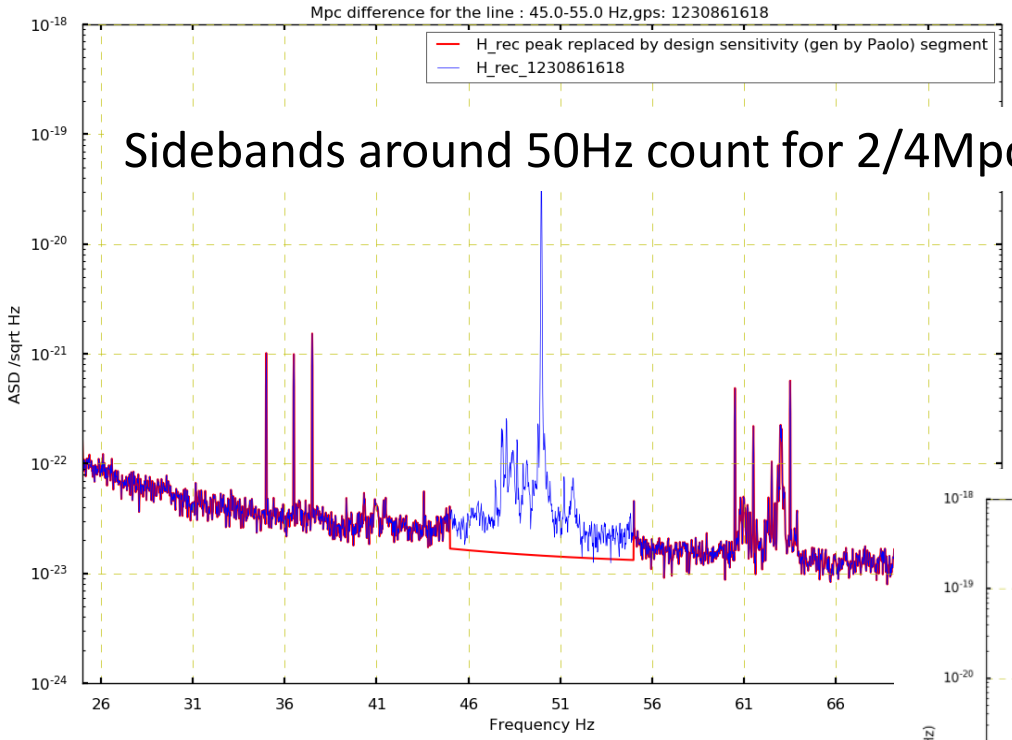




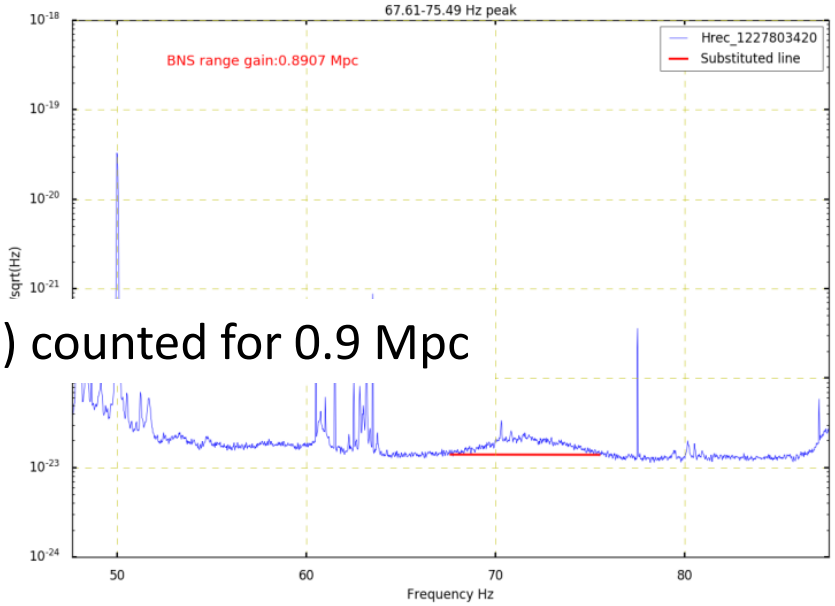
Thank you

Spare slides

How many Mpc do the structures “eat”?



Sidebands around 50Hz count for 2/4Mpc

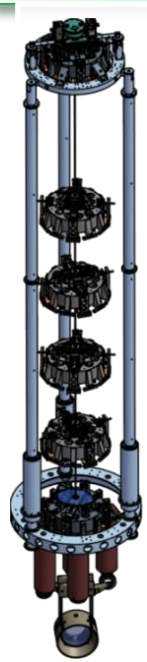


The “bump” around 72Hz (now removed) counted for 0.9 Mpc

AdV design

Limiting noises at different frequency ranges:

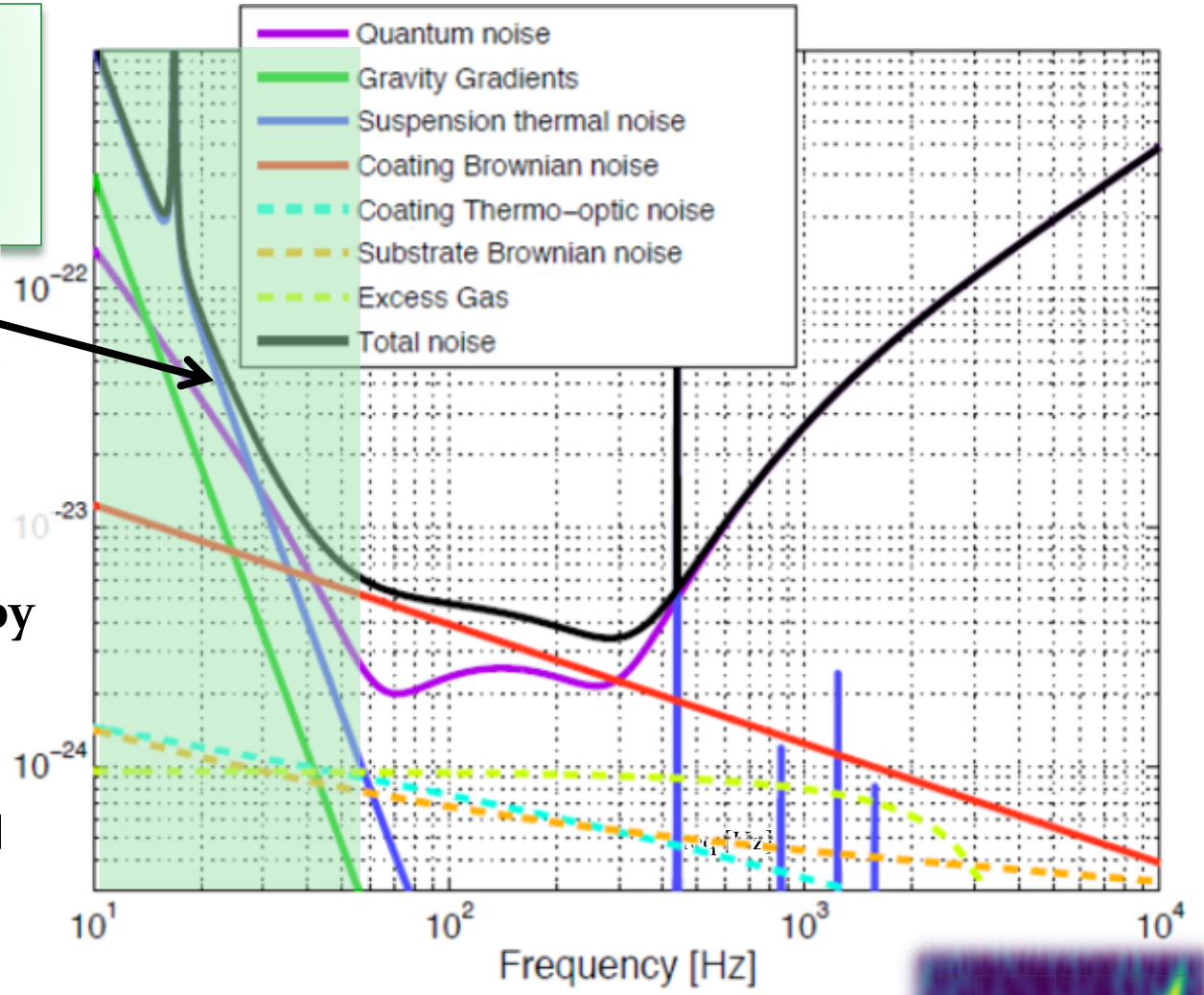
- **Low-freq**:
newtonian noise, seismic noise, residual technical noises, suspension thermal noise



- Seismic isolation: **superattenuators** (same as in iVirgo)

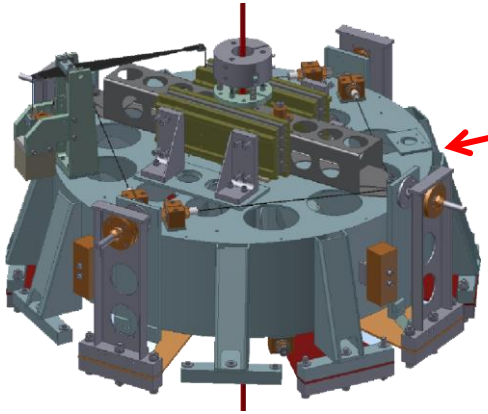
Reduce mirrors seismic vibrations by a factor 10^{11} @10Hz

- Suspension thermal noise: **monolithic suspensions**

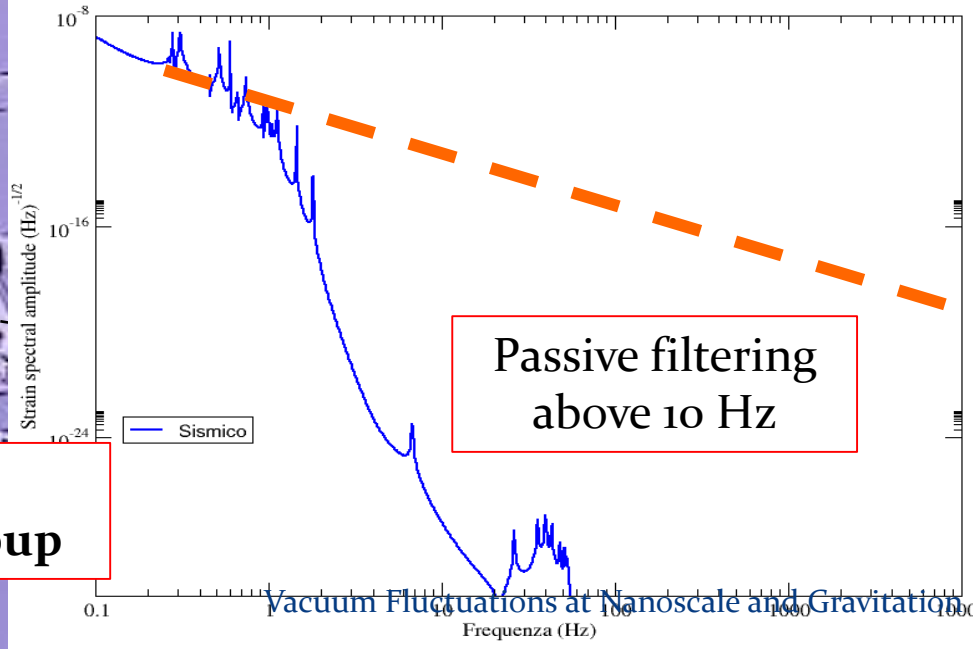


The Superattenuator

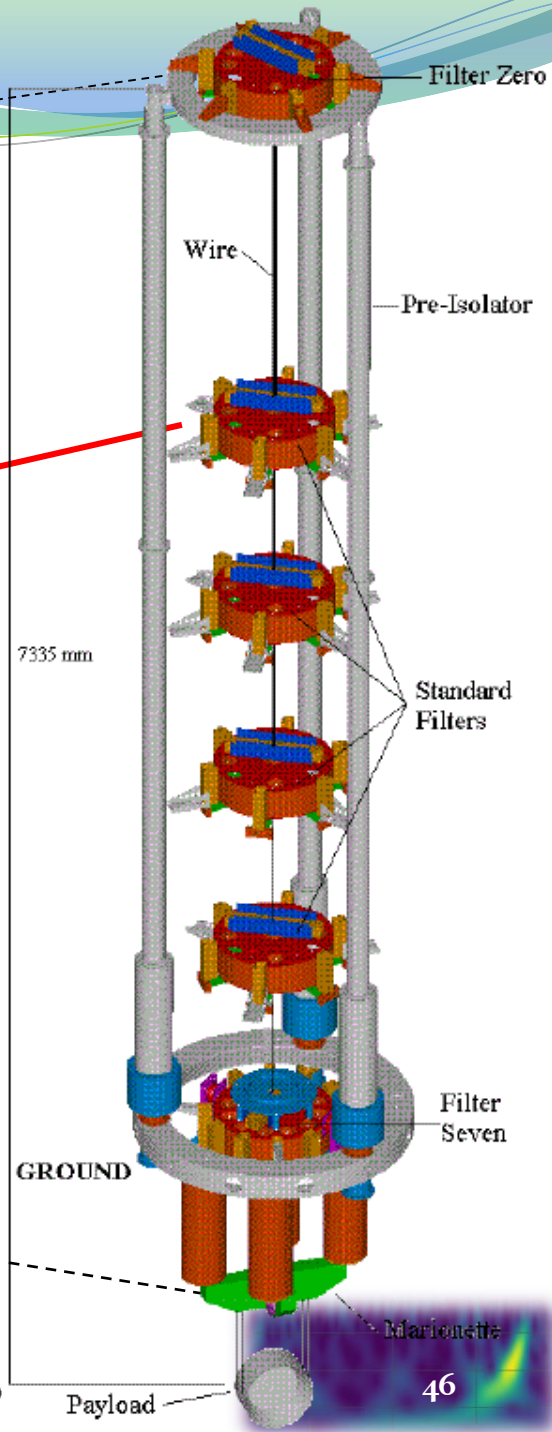
Reduces mirrors seismic vibrations by a factor 10^{11} @10Hz



Standard Filter



Passive filtering above 10 Hz



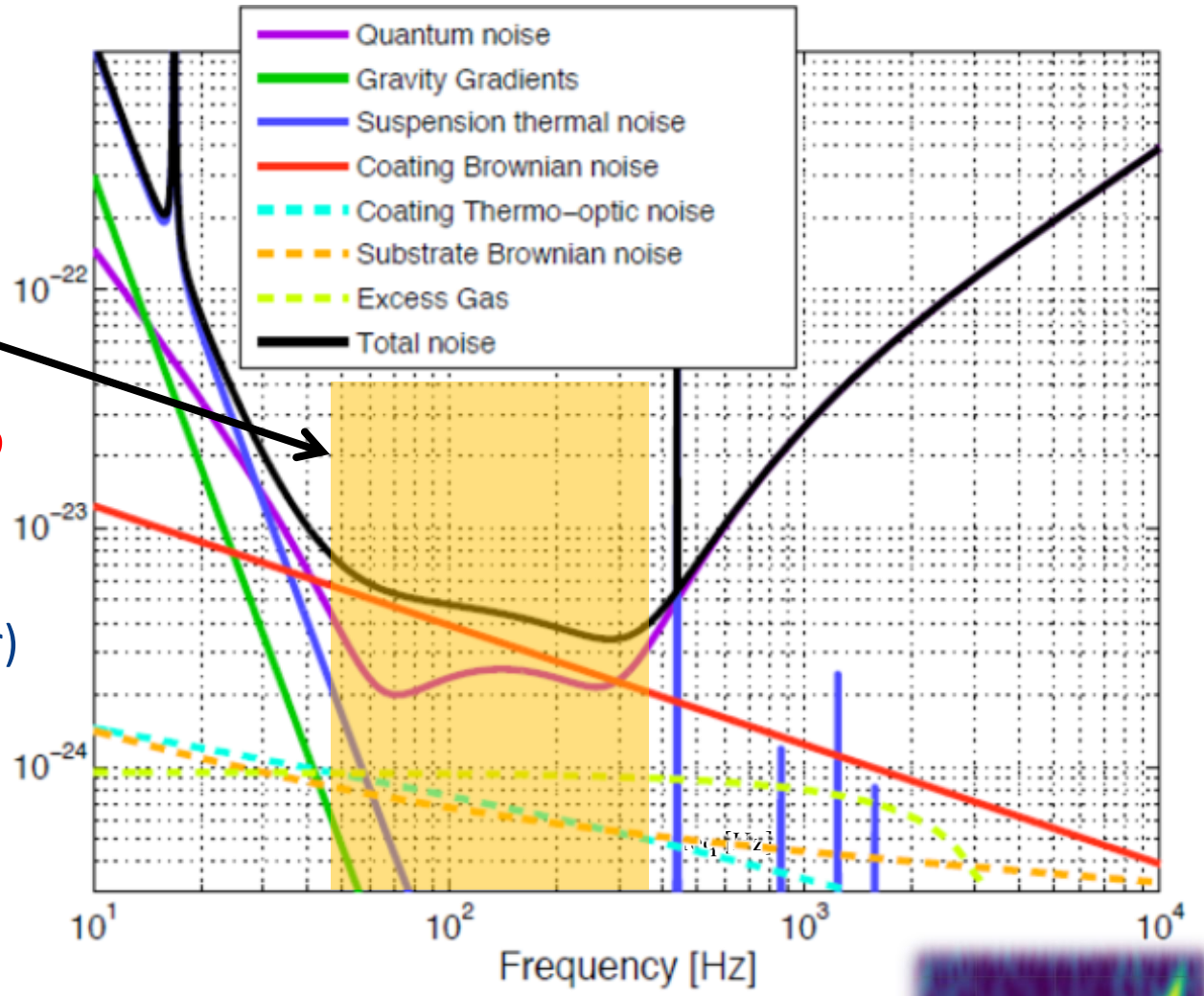
Developed and built by Pisa group

AdV design

Limiting noises at different frequency ranges:

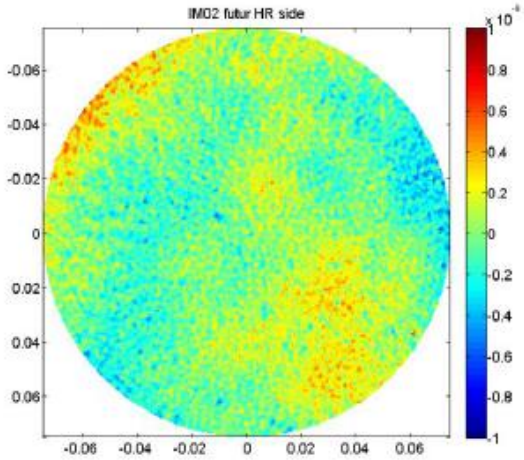
- **Mid-freq**: thermal noise

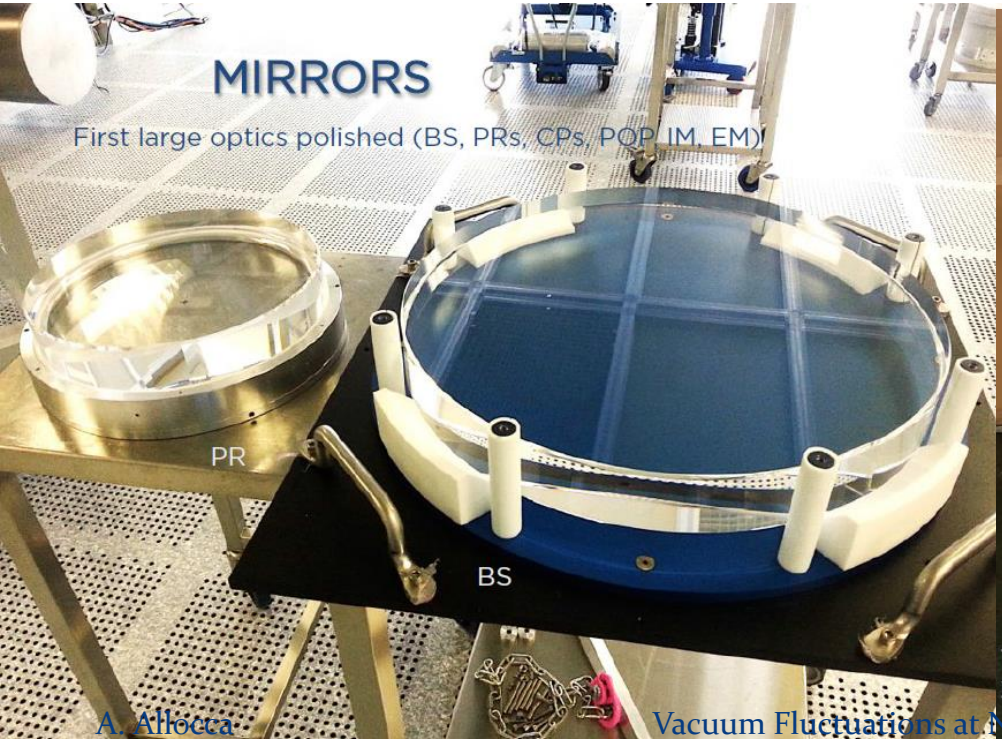
- Reducing thermal noise:
  - **increased beam size @ input TM (2.5 x larger)**
  - Improved coatings for lower losses (7 x better)



The mirrors

- **SiO2 mirrors**, **350 mm** in diameter, **200 mm** thick, with a residual roughness **< 0,5 x 10^{-9} m**.



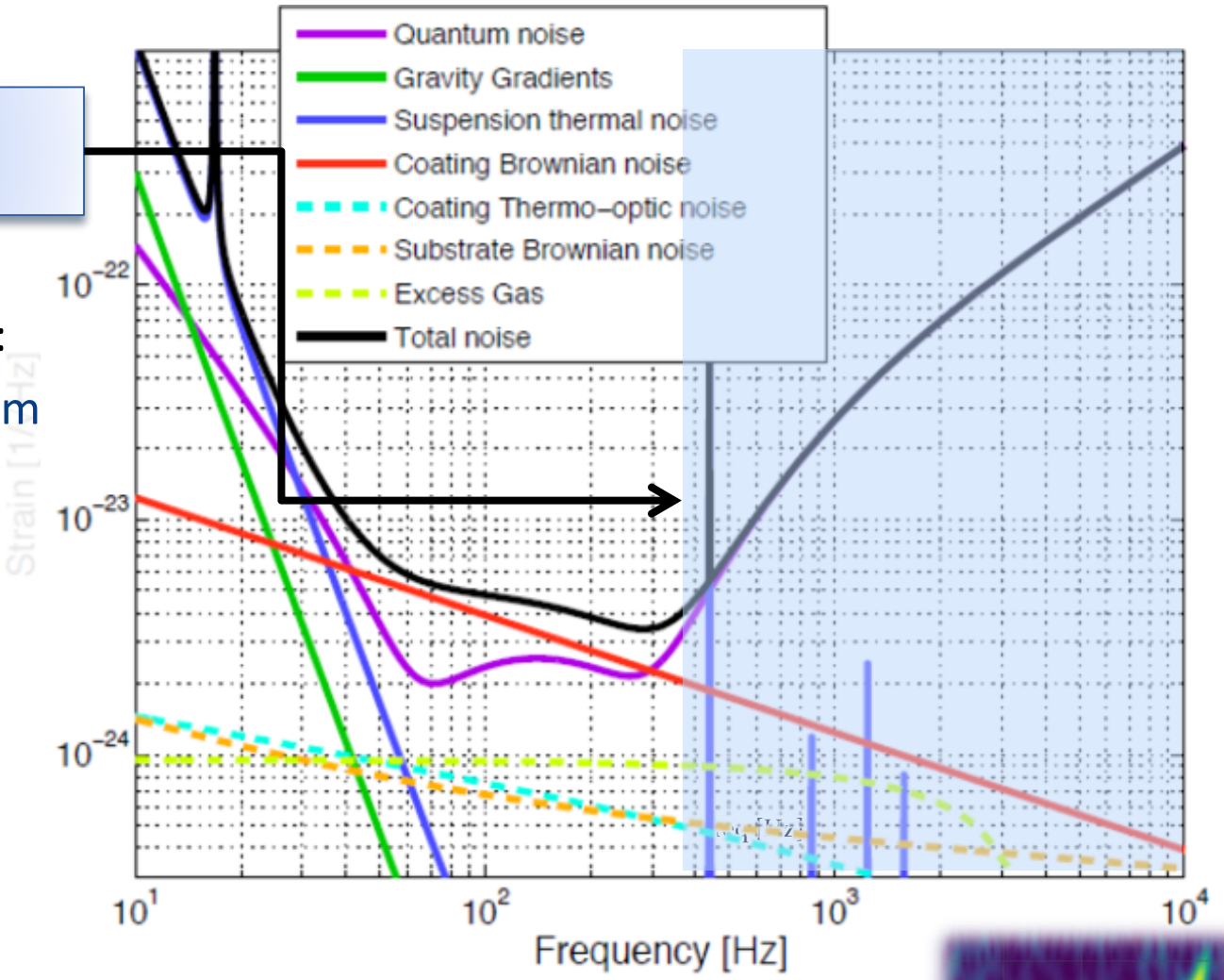


AdV design

Limiting noises at different frequency ranges:

- High-freq:
quantum shot-noise

- Reducing quantum noise:
  - Increased finesse of arm cavities (9x larger than iVirgo, 3x larger than Virgo+)
  - High power laser
  - Squeezing technology



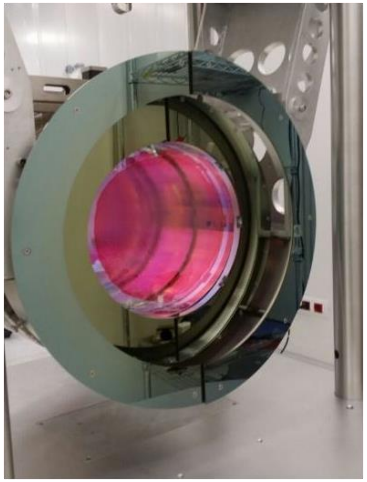
To further reduce the noise all over the frequency band:

- Improved **Thermal Compensation System** to compensate for cold and hot defects on the test masses (100 x higher power on TM)

- Better **vacuum system** with respect to Virgo (10^{-9} mbar instead of 10^{-7})

  with a total volume of 7000 m^3 is the biggest *ultra-high-vacuum* system in Europe

See A. Pasqualetti's talk



- Improved **Stray Light Control**

with suspended optical benches in vacuum and new set of baffles and diaphragms to catch up stray light

See A. Chiummo's talk