Advanced Virgo detector: the path from O2 to O3

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on the behalf of the Virgo collaboration

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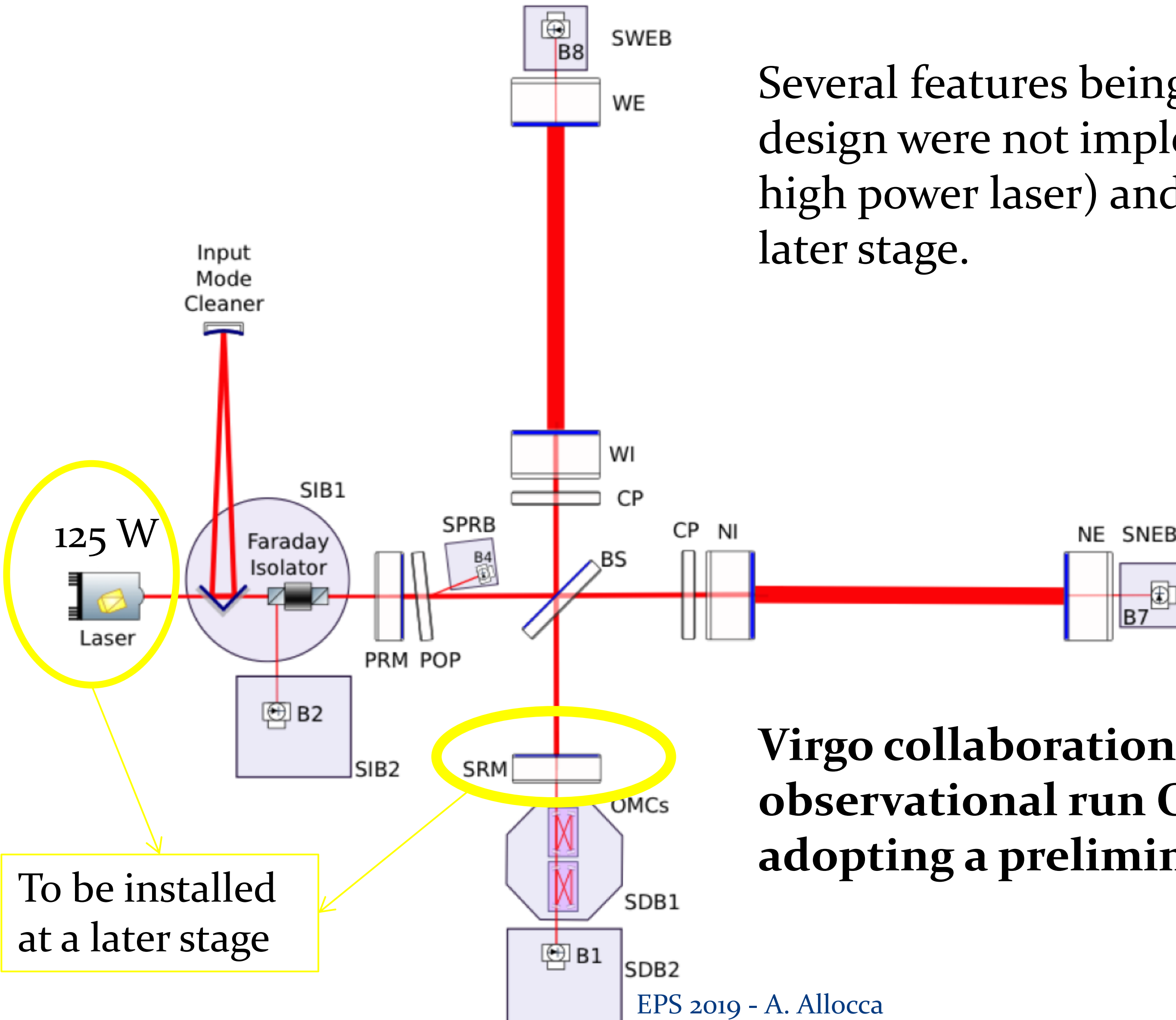
“Sapienza” Rome University

Advanced Virgo optical scheme – O2 configuration

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



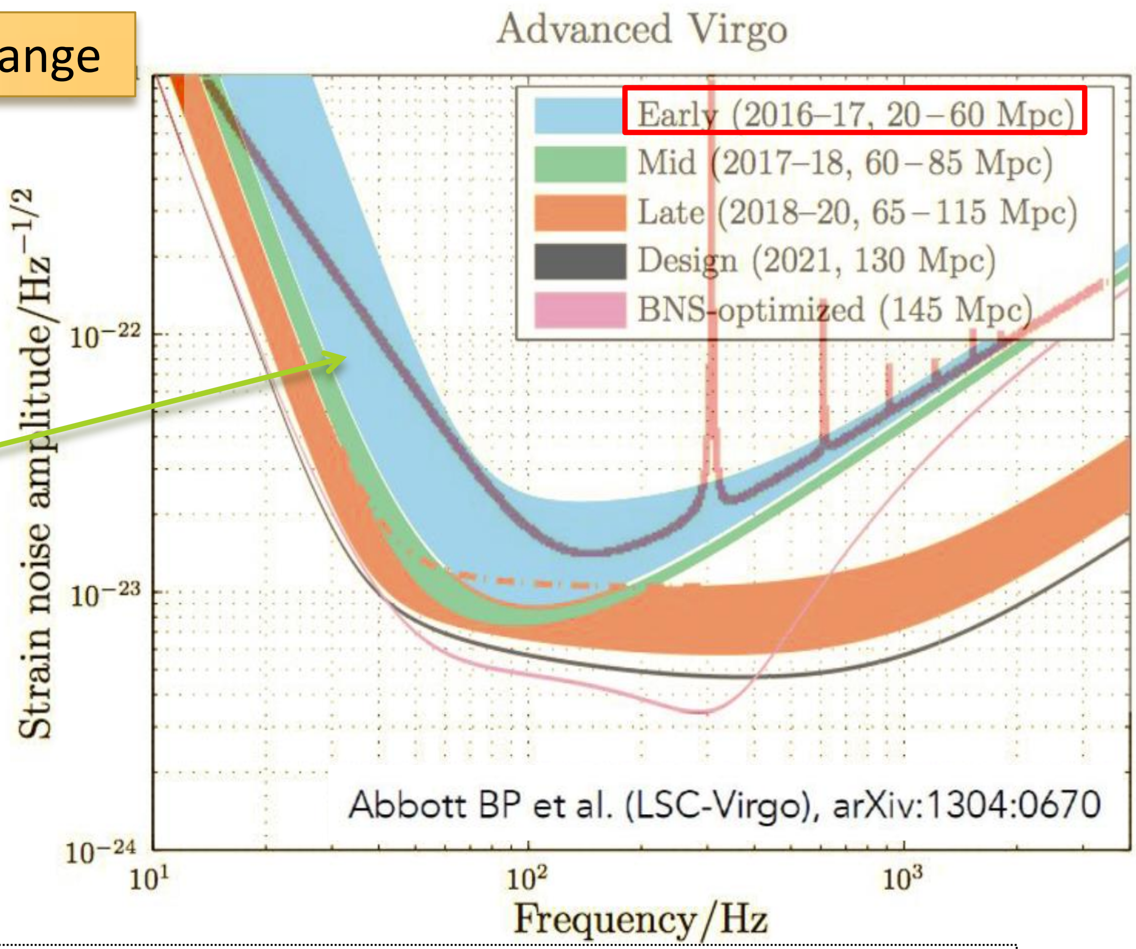
Virgo collaboration rushed to join observational run O2, August 2017, adopting a preliminary configuration

Advanced Virgo performance during O2

After the failure of monolithic suspensions, the four test masses were suspended through steel wires

Early scenario: 20-60Mpc BNS range

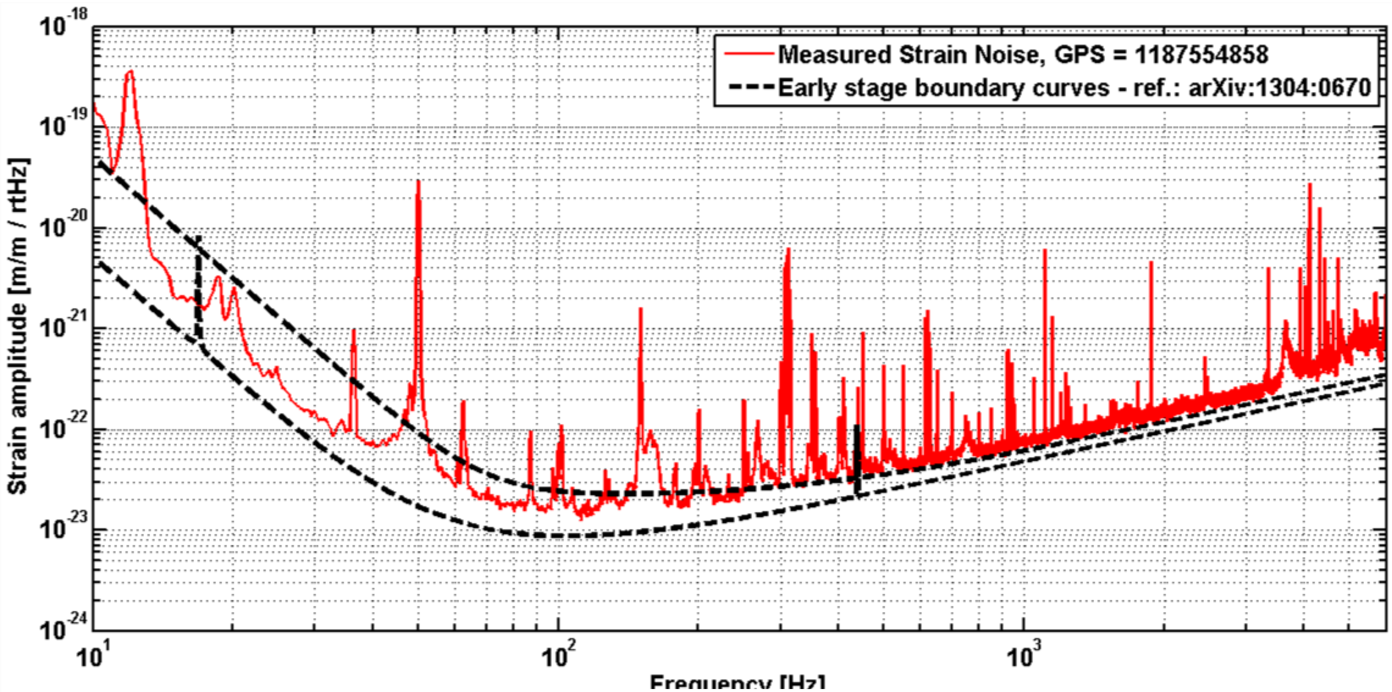
Sensitivity with steel wires still compatible with the goal for the early phase



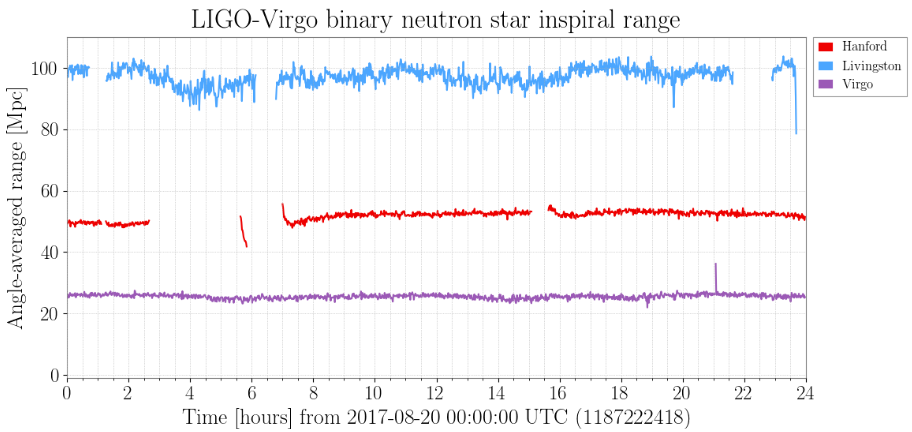
BNS range: Standard figure of merit for the sensitivity of the interferometer

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

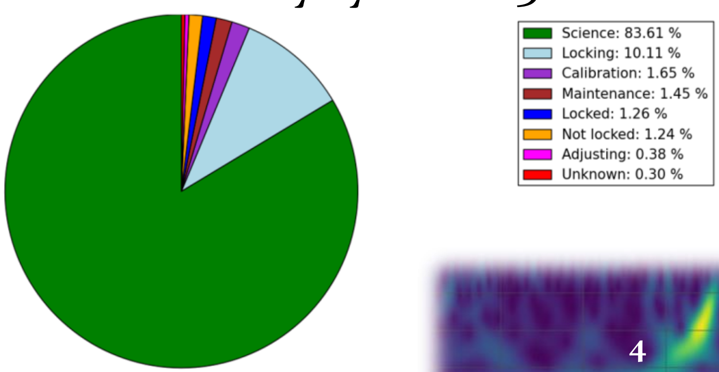
AdV measured sensitivity compared to early stage boundaries



BNS range up to 28 Mpc during O2



AdV Duty cycle of 83%

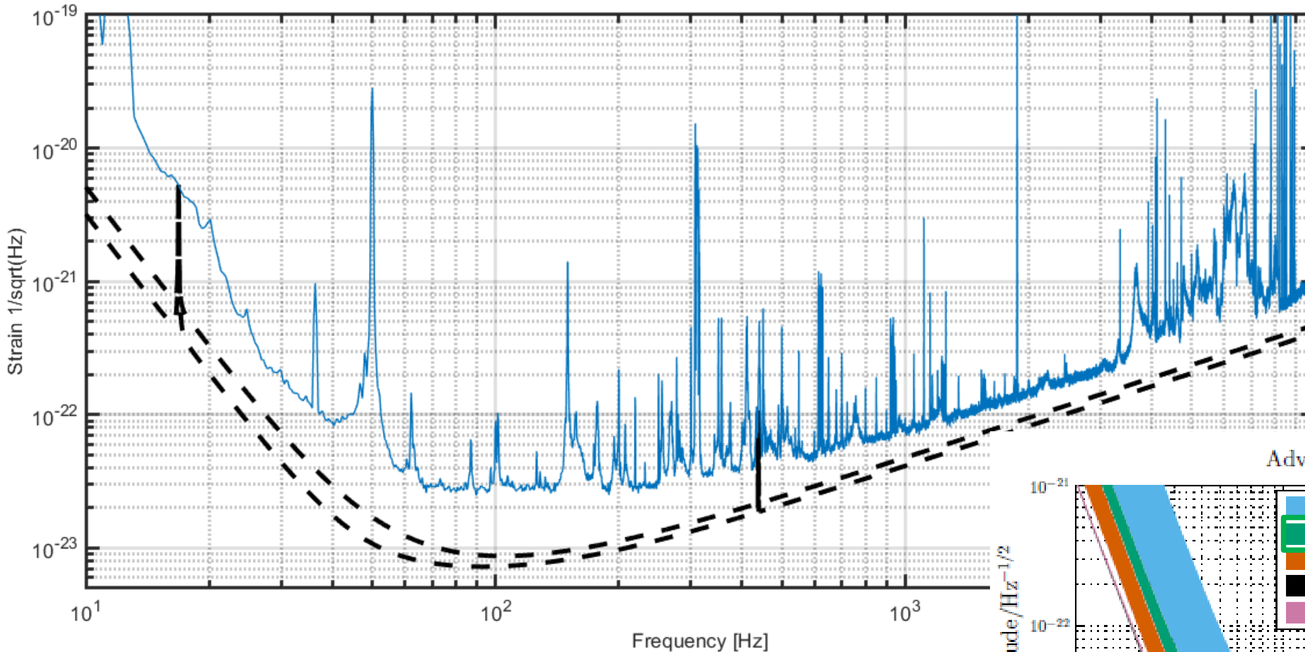


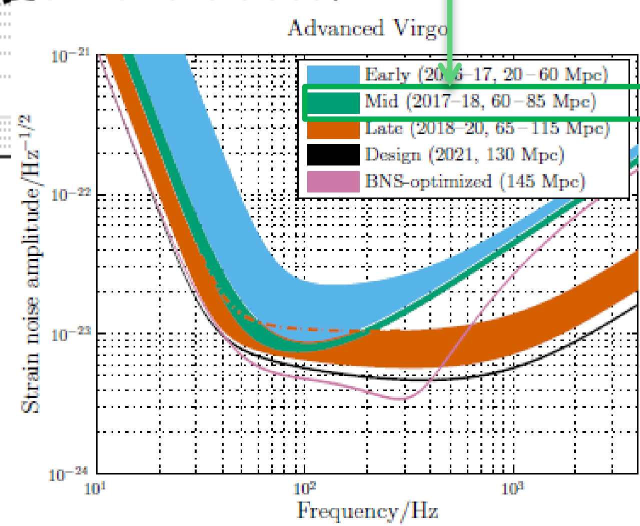
See G. Losurdo's presentation for more details

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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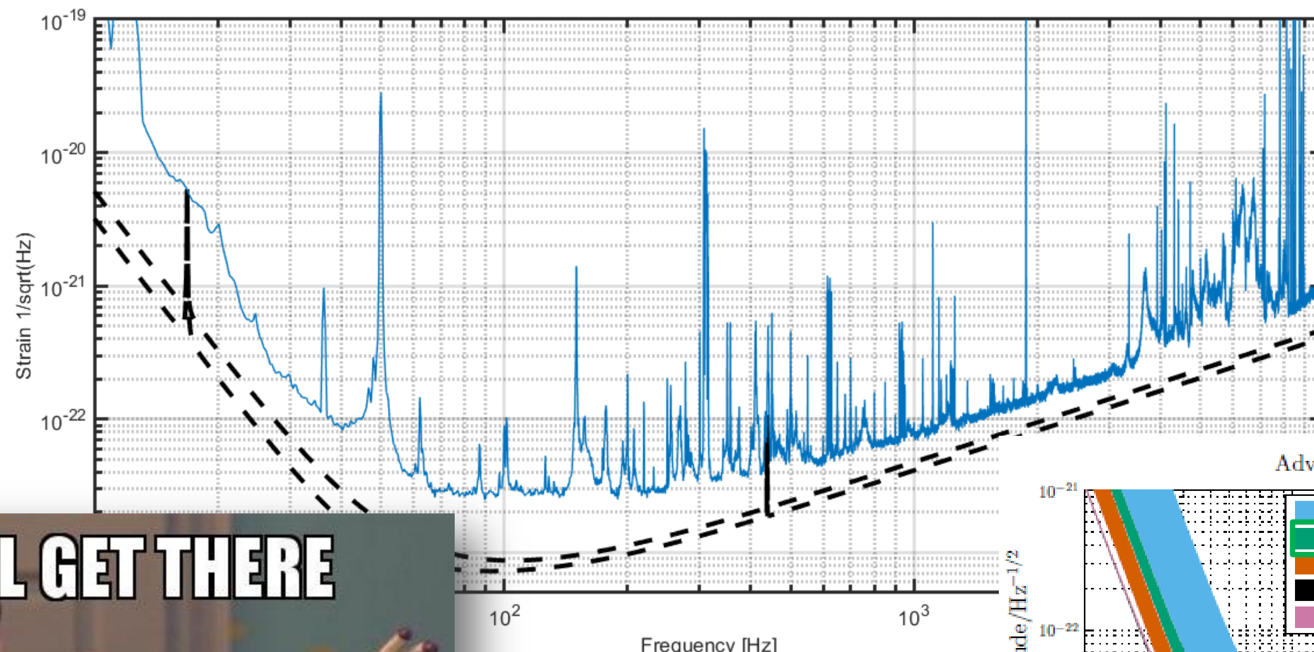
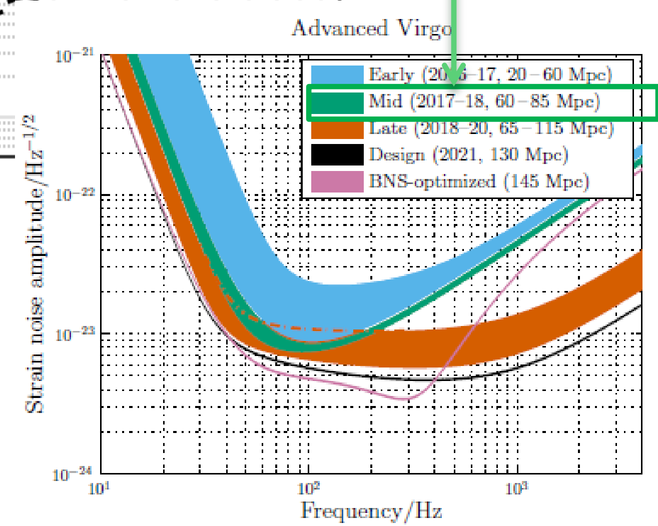
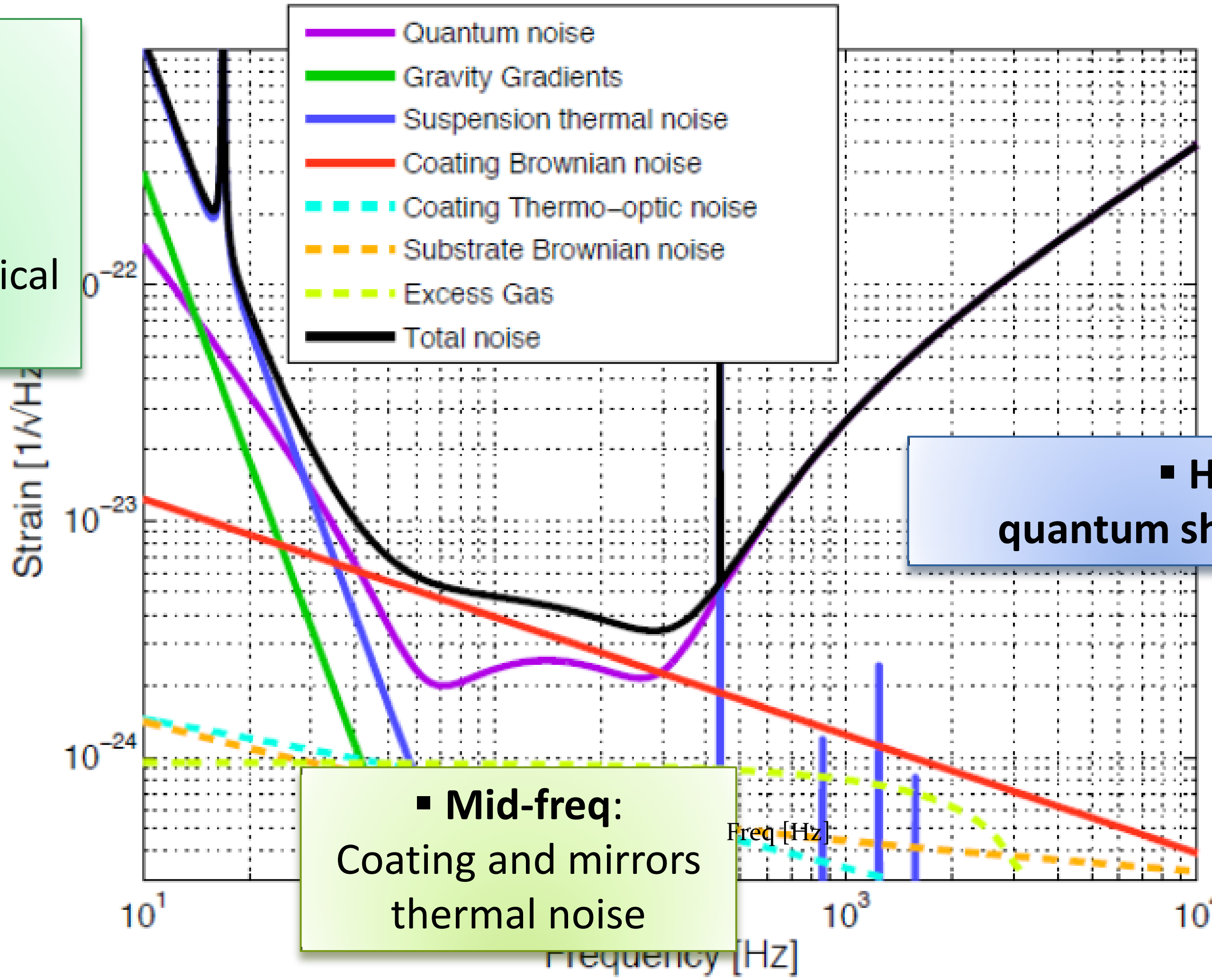




AdV design

Limiting noises at different frequency ranges:

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



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

- **Mid-freq**: Coating and mirrors thermal noise

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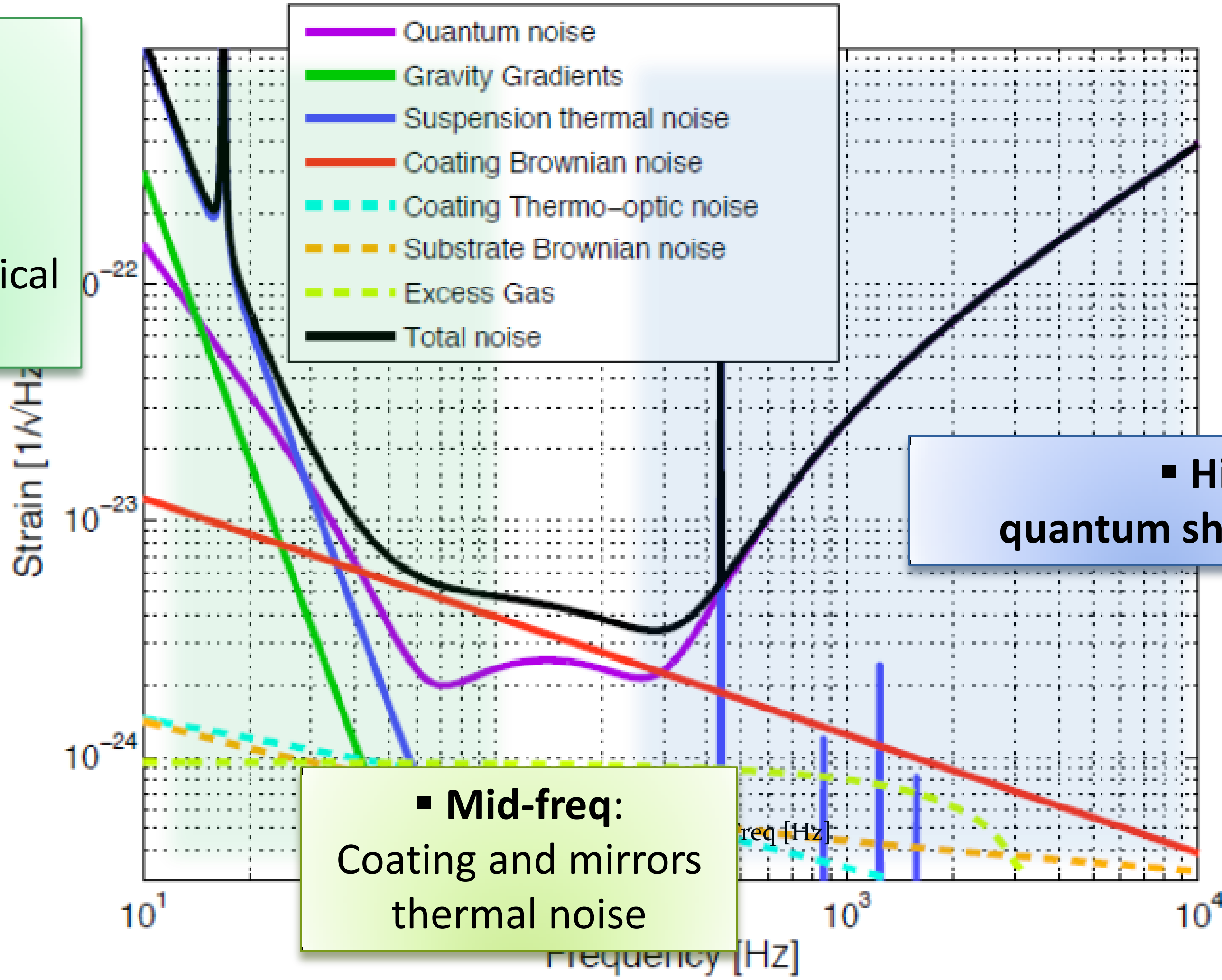

- **High-freq**: quantum shot-noise

- **Mid-freq**: Coating and mirrors thermal noise

Getting ready for O3

- Major upgrades
  - Reducing suspension thermal noise: monolithic suspensions installation
  - Reducing quantum noise: input power increase and squeezing installation
- Noise hunting activities and stray light mitigation

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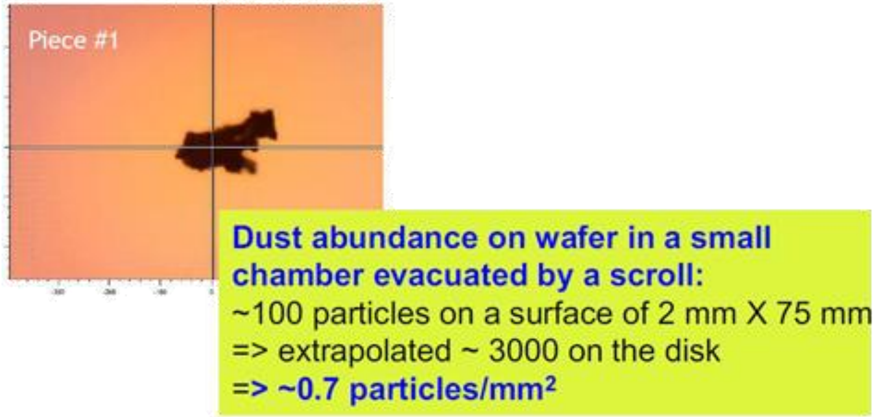
Monolithic suspensions

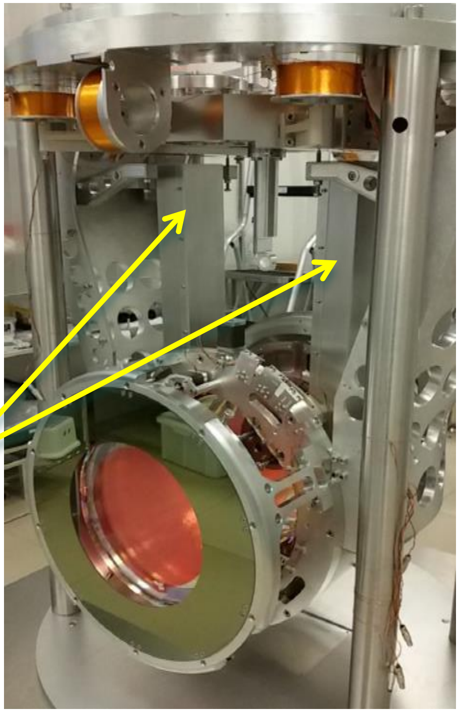
SiO2 fibers **400μm** in diameter used to suspend SiO2 mirrors **42kg** in weight

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



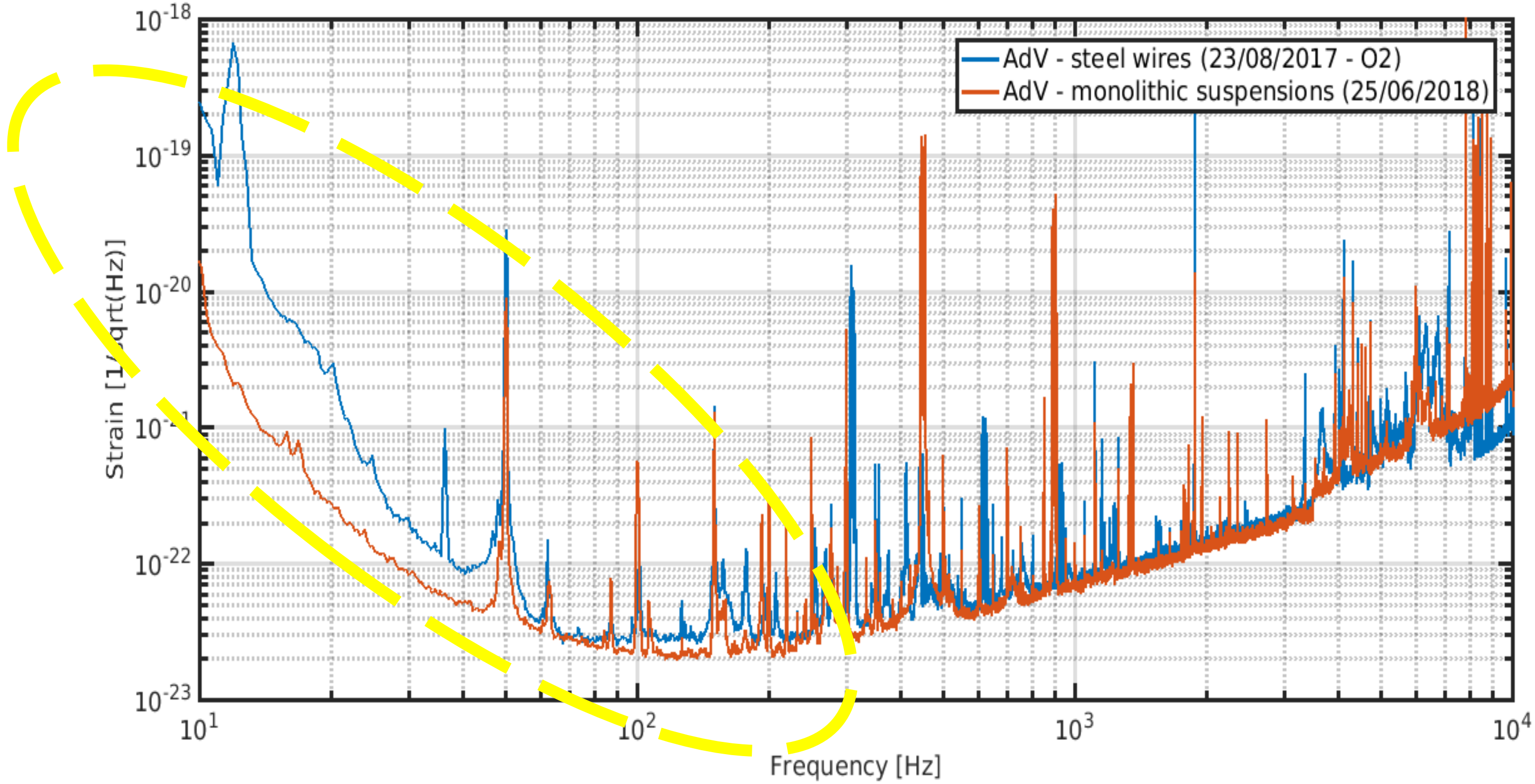
Fiber guards as additional protections against dust impact



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

AdV sensitivity with monolithic suspensions

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



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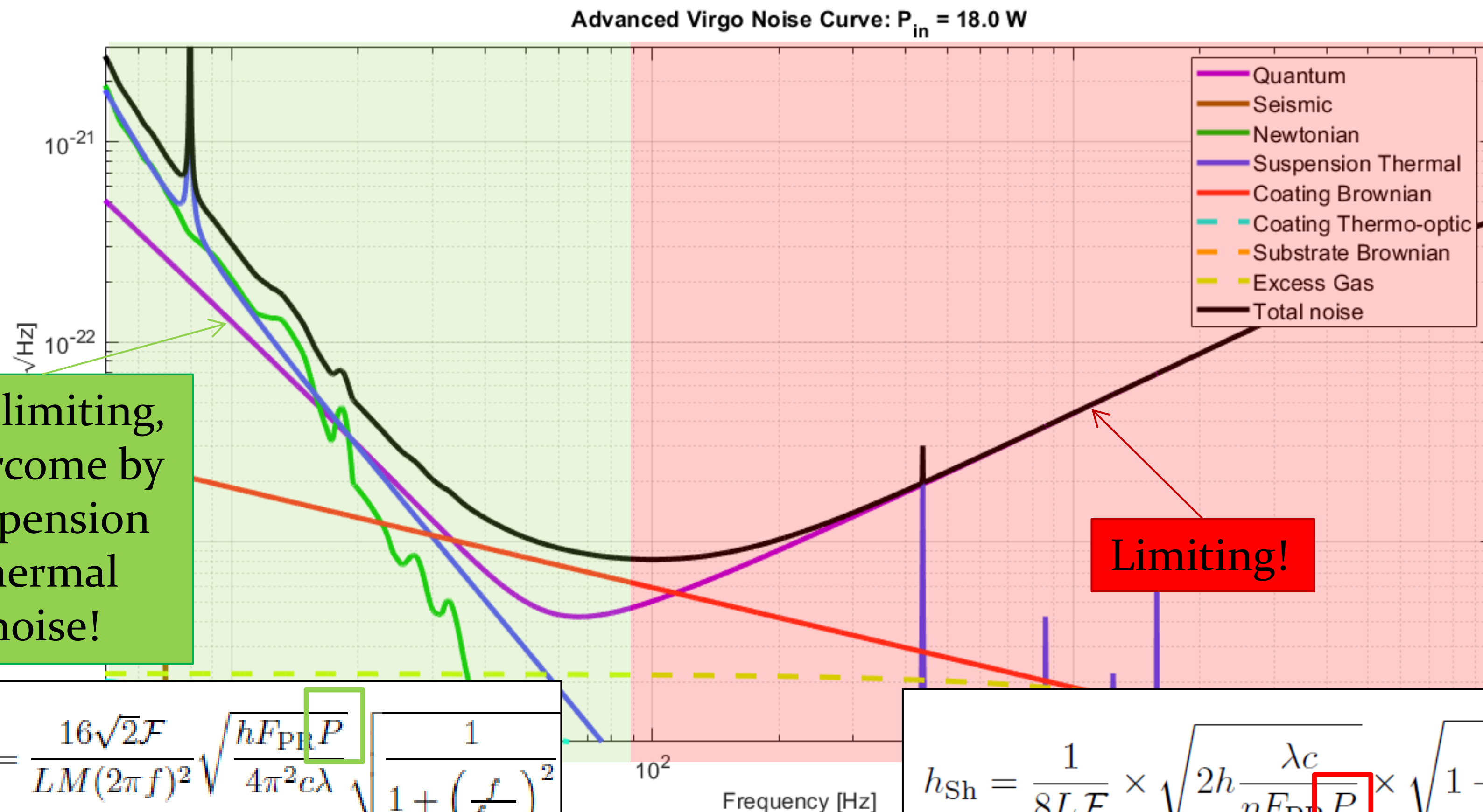
Quantum noise

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



Not limiting, overcome by suspension thermal noise!

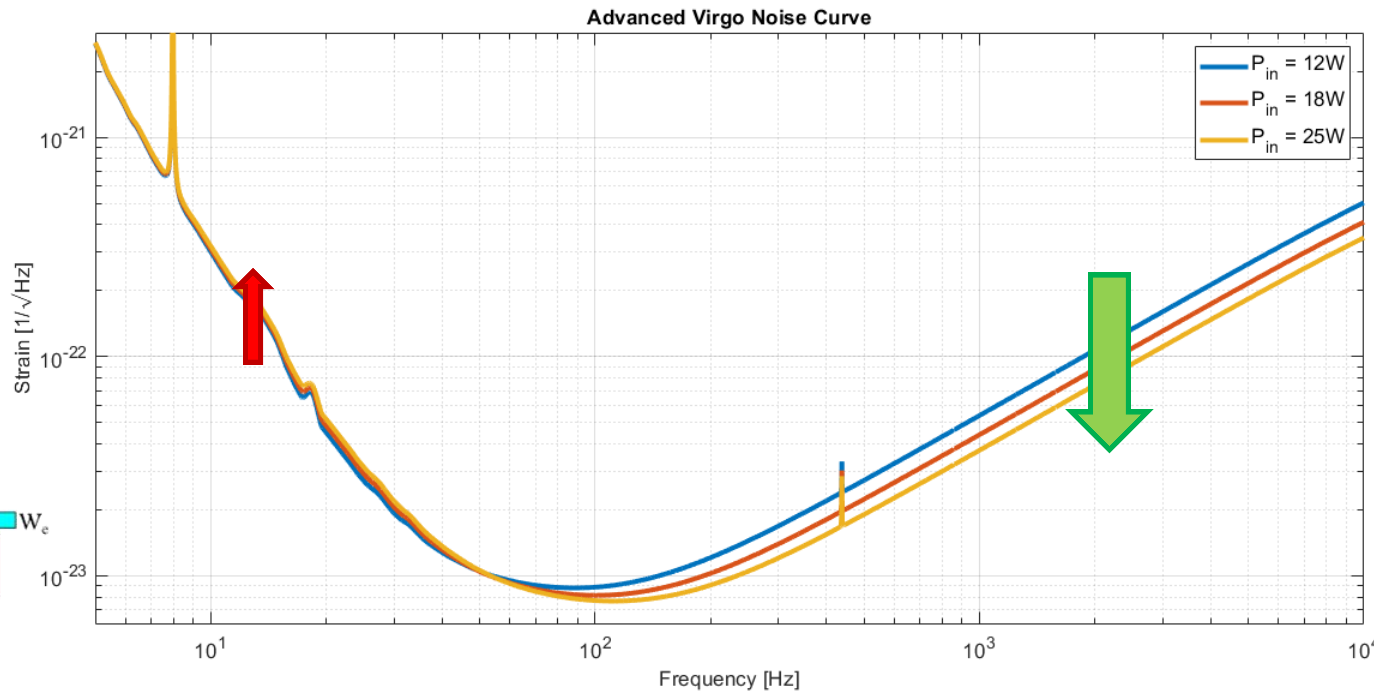
Limiting!

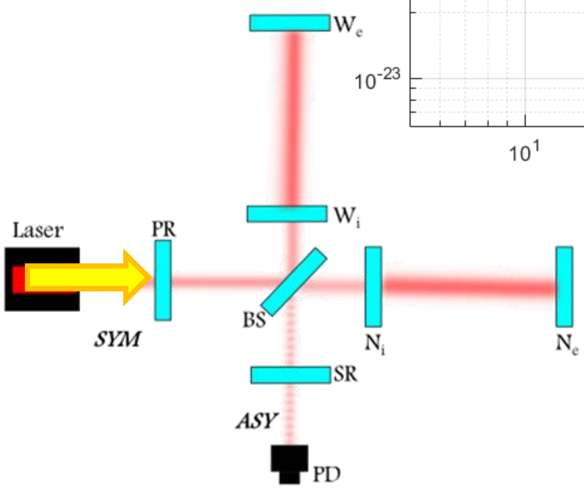
$$h_{\mathrm{RP}} = \frac{16\sqrt{2}\mathcal{F}}{LM(2\pi f)^2}\sqrt{\frac{hF_{\mathrm{PR}}\boxed{P}}{4\pi^2 c\lambda}}\sqrt{\frac{1}{1+\left(\frac{f}{f_{\mathrm{FP}}}\right)^2}}$$

$$h_{\mathrm{Sh}} = \frac{1}{8L\mathcal{F}} \times \sqrt{2h\frac{\lambda c}{\eta F_{\mathrm{PR}}\boxed{P}}} \times \sqrt{1+\left(\frac{f}{f_{\mathrm{FP}}}\right)^2}$$

Input power increase

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

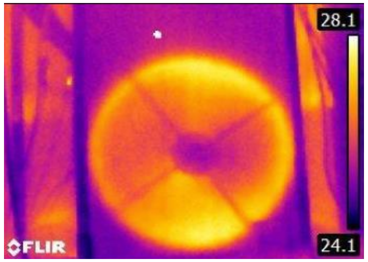


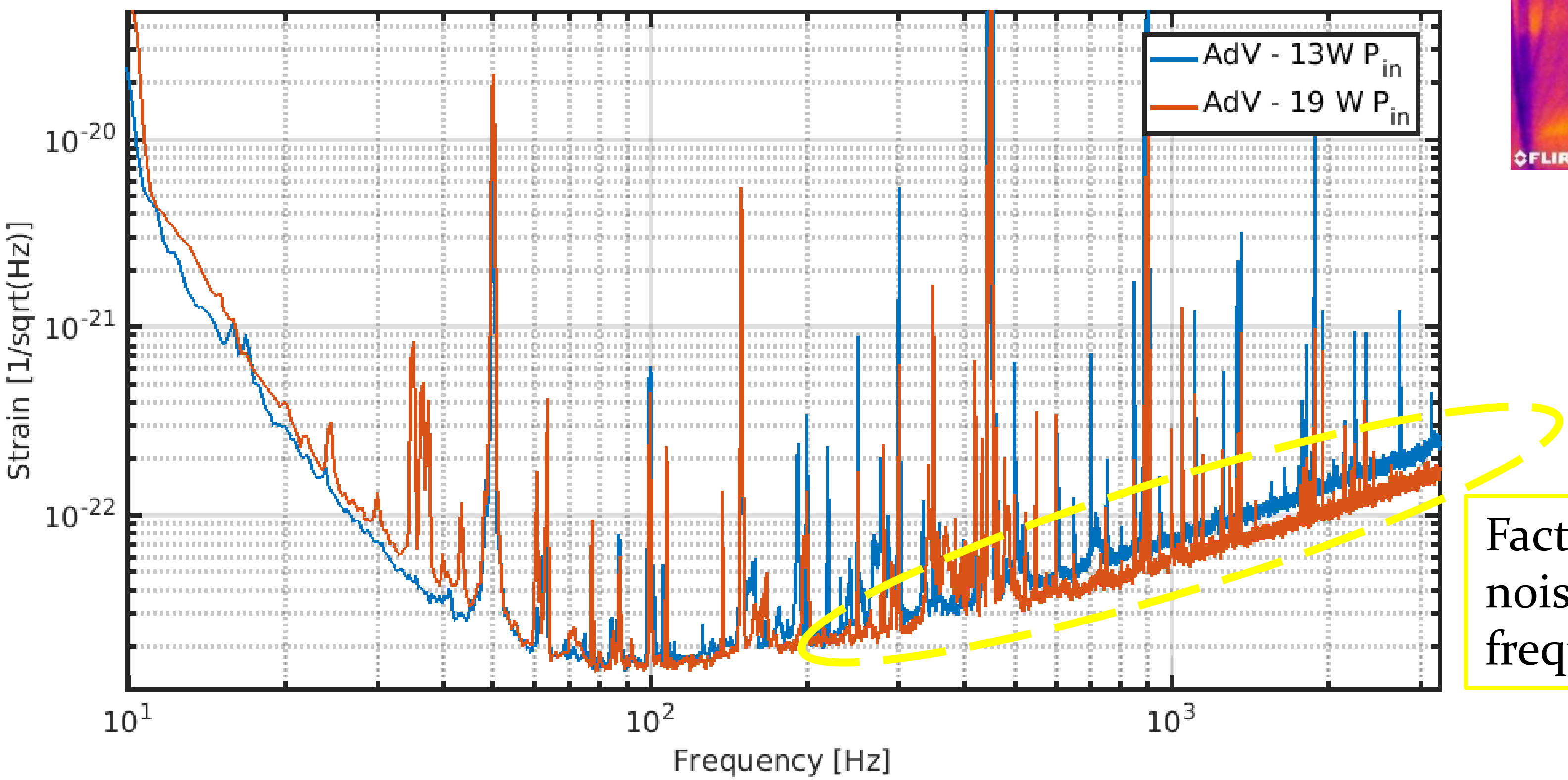


Input power increase

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

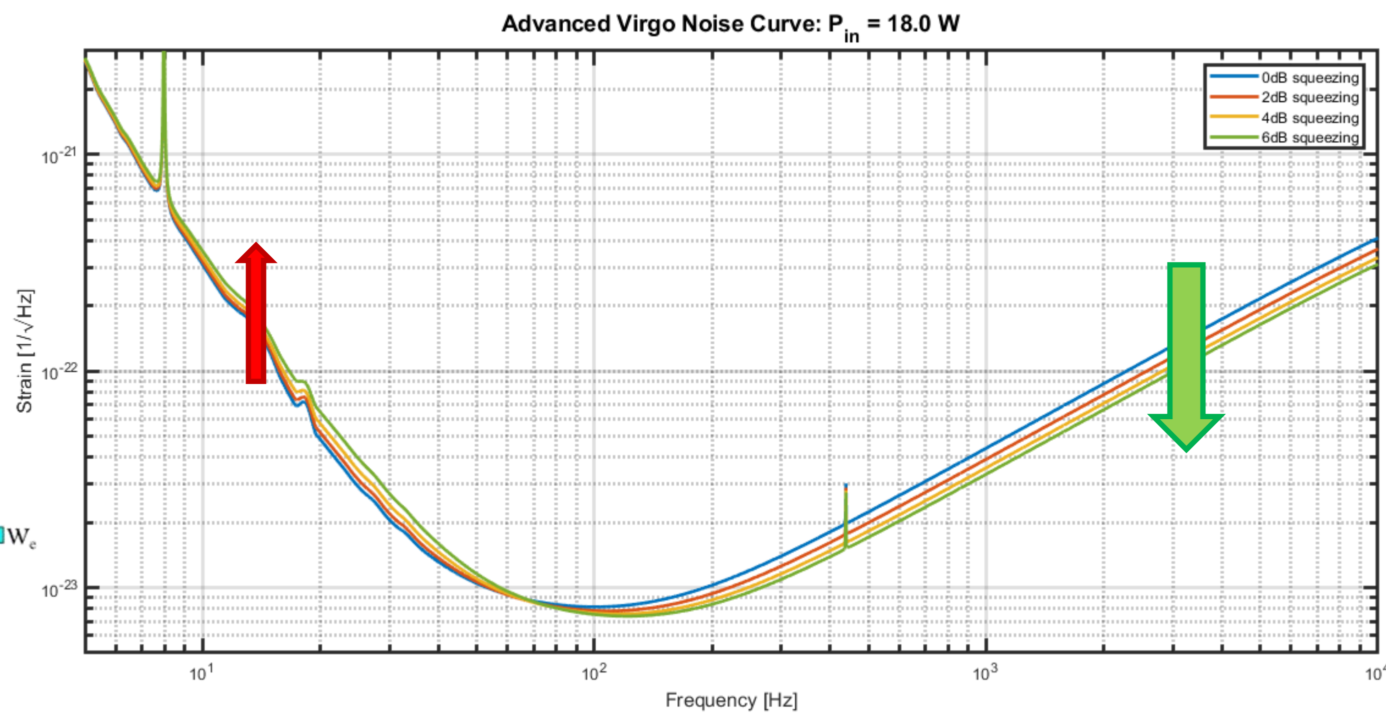


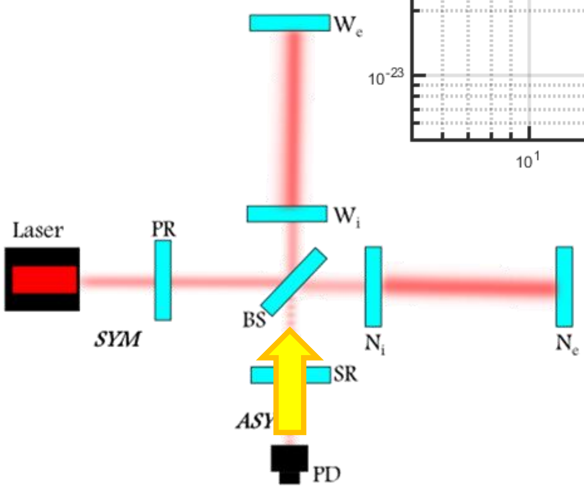


Factor ~0,8 lower noise at high frequency

The Frequency Independent Squeezing

…or injecting squeezed vacuum



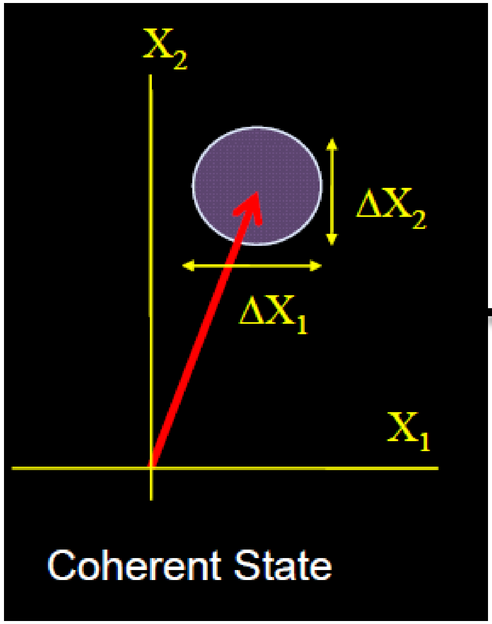


The squeezing principle

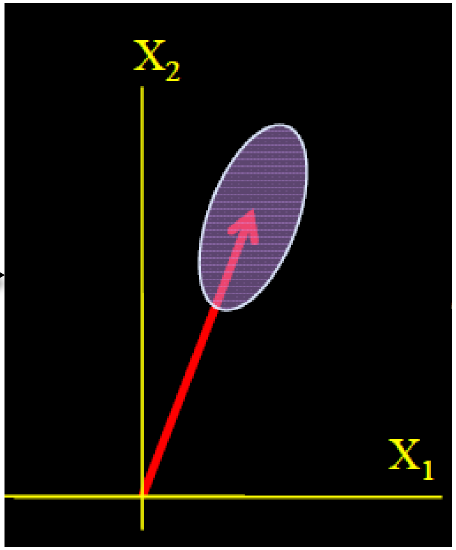
Vacuum fluctuations entering from the dark port cause quantum noise in interferometers. Squeezing was proposed as a solution over 30 years ago. [*Caves, Phys. Rev. D (1981)*]

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

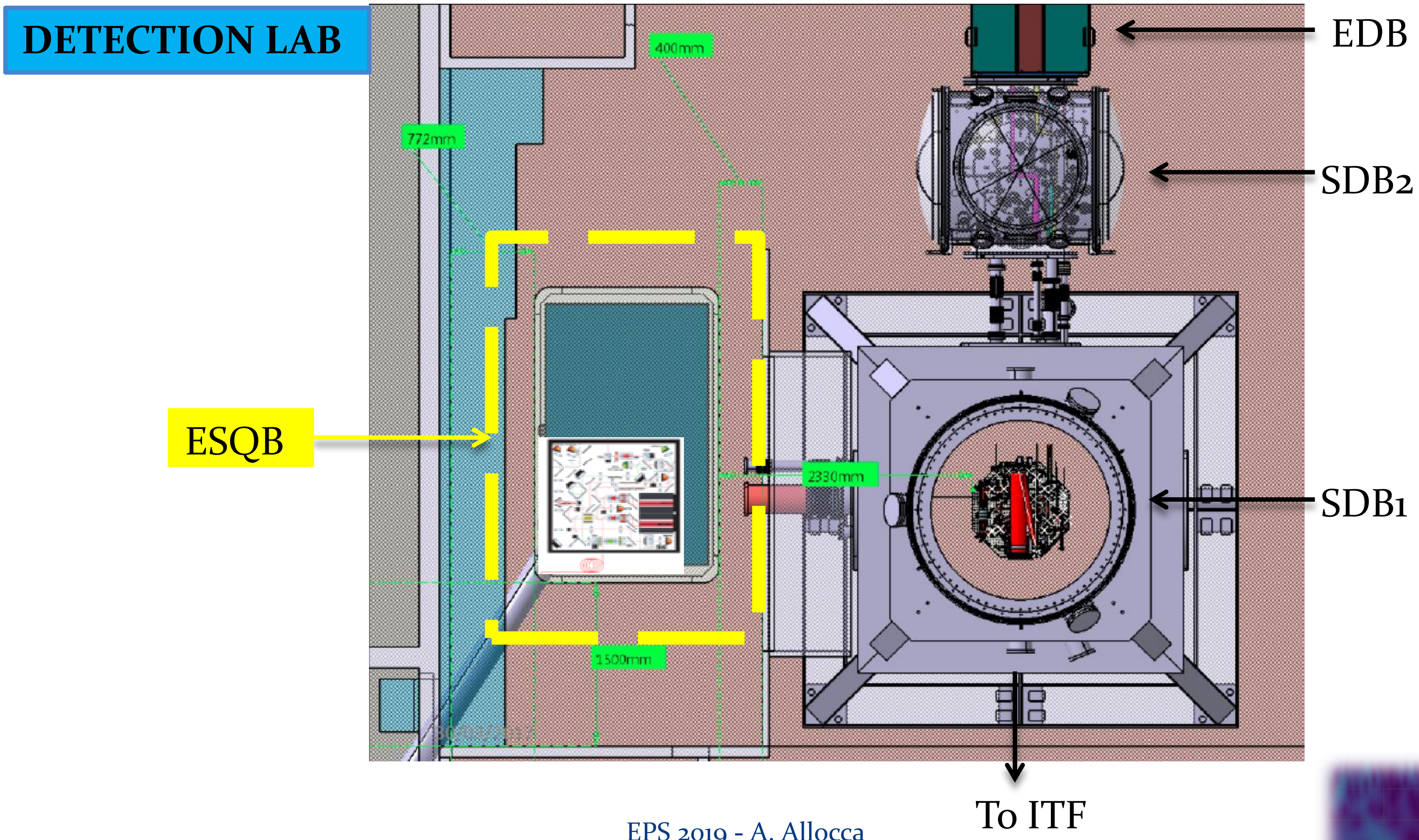


Phase squeezed
Amplitude anti-squeezed

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

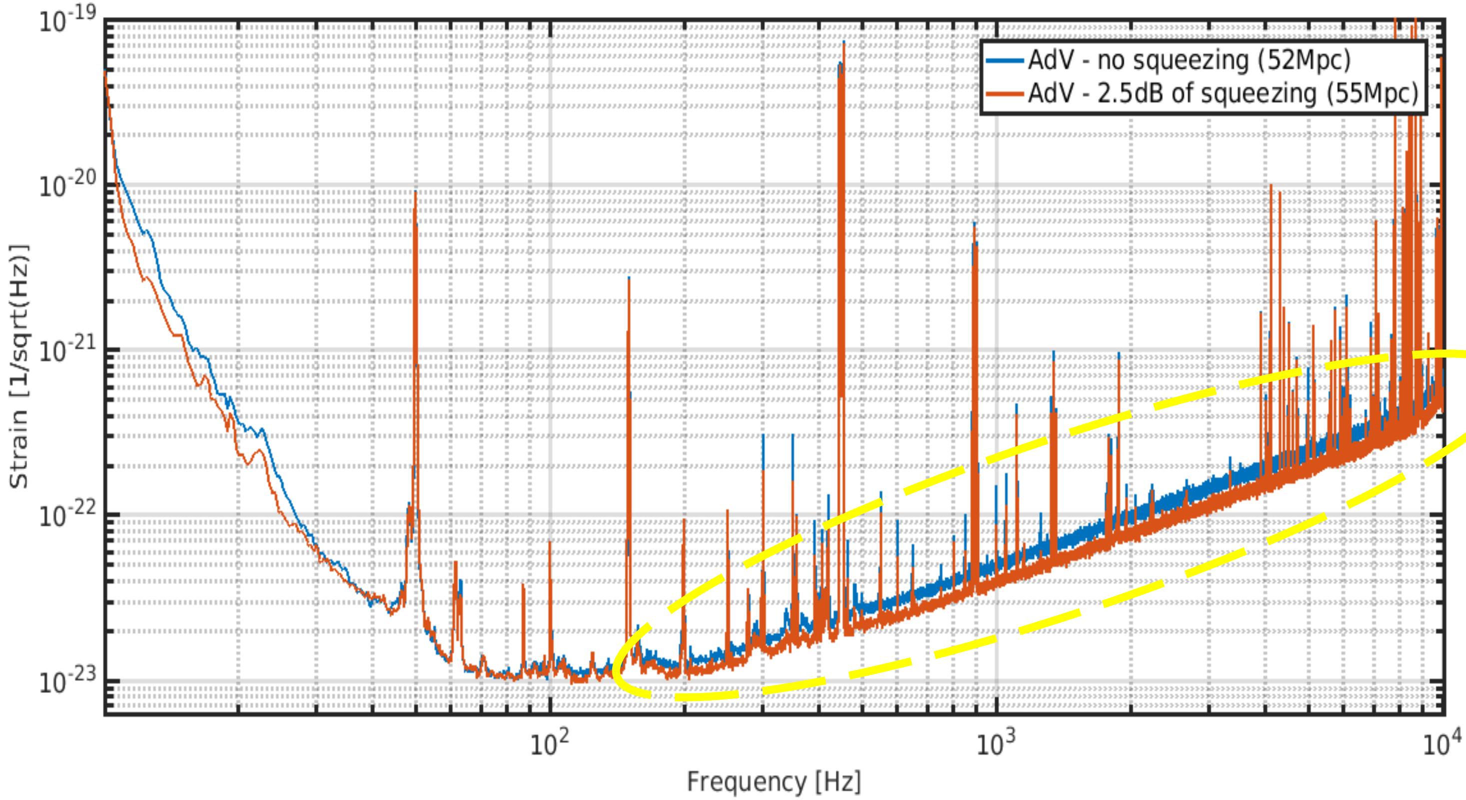
The squeezer installation

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!



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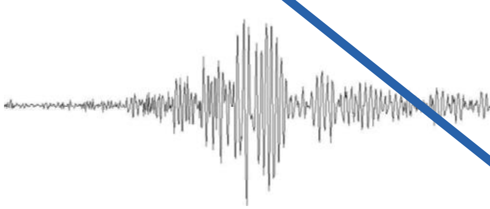
Noise hunting and stray light mitigation

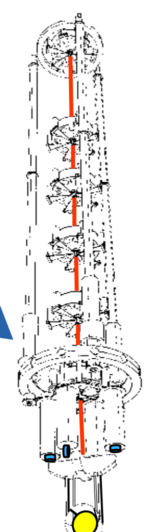
Noise injections are performed in order to spot possible coupling between the noise source and the detector and, therefore, mitigate it.

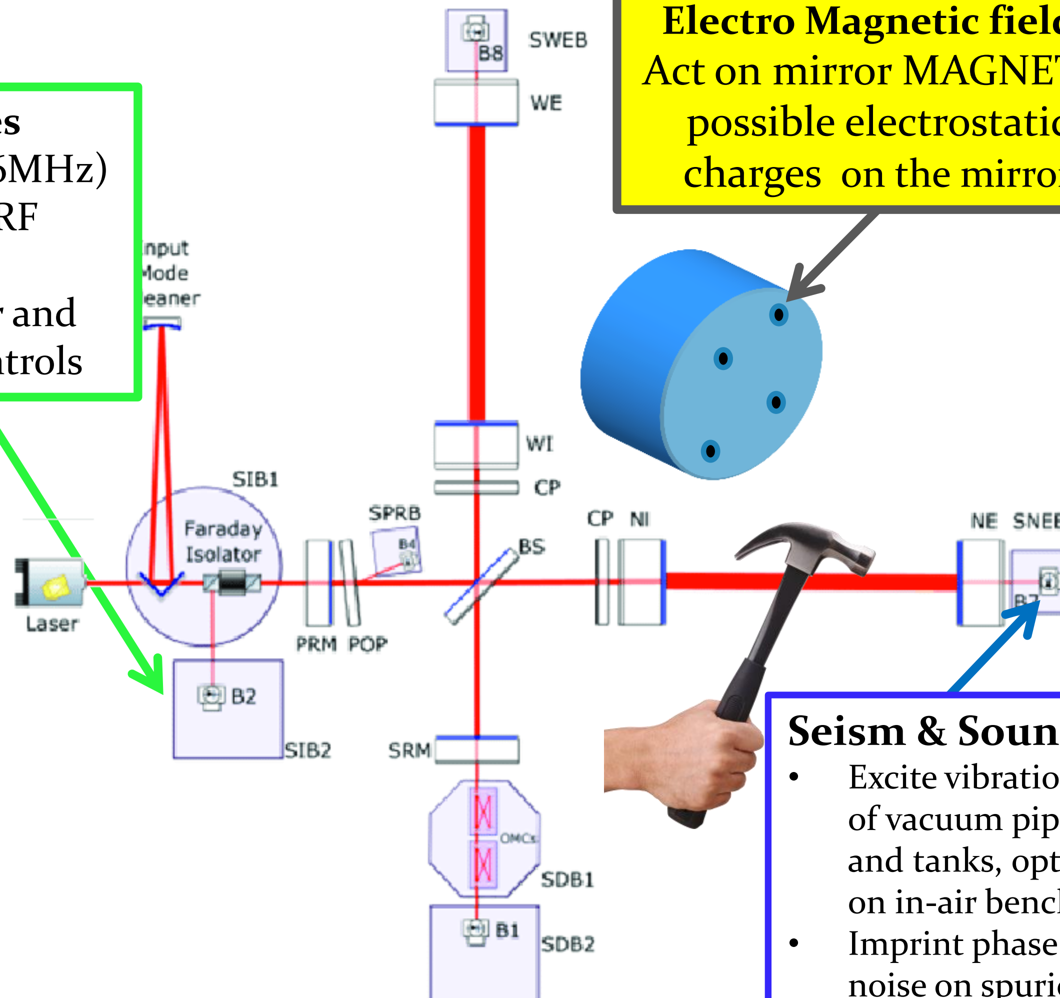
Electro Magnetic fields
Act on mirror MAGNETS, possible electrostatic charges on the mirror

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



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)

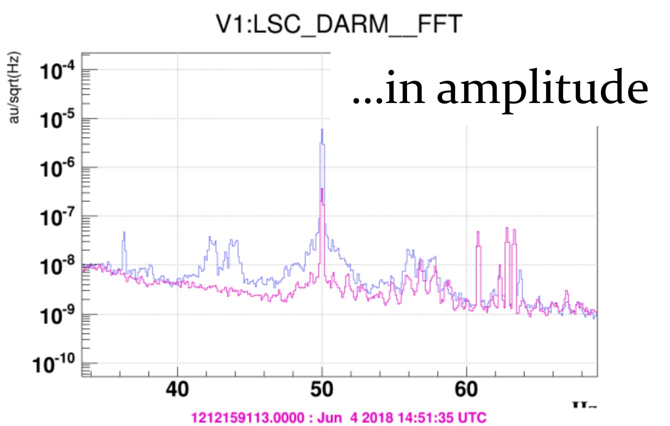
“brute force” approach = search for noise correlation in ALL (not obvious) channels (i.e. O(10000 channels)!)

390.87	ENV_DT_ACC_Z (0.19)	ENV_DT_CT_ACC_Z (0.17)	ENV_SQZ_MIC (0.04)	ENV_IB_CT_ACC_X (0.04)	ENV_DT_CT_FINGER_ACC_Y (0.03)						
391.11	ENV_CEB_MIC (0.12)	ENV_DT_ACC_Z (0.11)	ENV_B4_GHOST_ACC_Z (0.10)	ENV_DT_CT_ACC_Z (0.08)	ENV_SQZ_MIC (0.07)	ENV_NI_CT_ACC_Z (0.07)	ENV_SQZ_PIPE_ACC_Y (0.07)	ENV_PR_ACC_Z (0.07)	ENV_IB_CT_ACC_X (0.06)	ENV_IB_CT_FINGER_ACC_Y (0.05)	ENV_SPRB_LINK_ACC_Z (0.05)
391.36	ENV_B4_GHOST_ACC_Z (0.60)	ENV_CEB_MIC (0.58)	ENV_DT_ACC_Z (0.58)	ENV_SPRB_LINK_ACC_Z (0.58)	ENV_PR_ACC_Z (0.58)	ENV_SQZ_PIPE_ACC_Y (0.57)	ENV_NI_CT_ACC_Z (0.57)	ENV_DT_CT_ACC_Z (0.55)	ENV_IB_CT_FINGER_ACC_Y (0.54)	ENV_NI_LINK_ACC_Z (0.54)	ENV_SQZ_ACC_Y (0.53)
391.60	ENV_B4_GHOST_ACC_Z (0.72)	ENV_PR_ACC_Z (0.71)	ENV_NI_CT_ACC_Z (0.71)	ENV_DT_ACC_Z (0.70)	ENV_SPRB_LINK_ACC_Z (0.70)	ENV_CEB_MIC (0.70)	ENV_DT_CT_ACC_Z (0.69)	ENV_SQZ_ACC_Y (0.69)	ENV_EDB_MIC (0.68)	ENV_SQZ_PIPE_ACC_Y (0.68)	ENV_IB_CT_FIN_ACC_Y (0.68)
391.85	ENV_PR_ACC_Z (0.41)	ENV_CEB_MIC (0.40)	ENV_B4_GHOST_ACC_Z (0.39)	ENV_NI_CT_ACC_Z (0.38)	ENV_DT_CT_ACC_Z (0.37)	ENV_DT_ACC_Z (0.37)	ENV_SQZ_PIPE_ACC_Y (0.37)	ENV_SPRB_LINK_ACC_Z (0.36)	ENV_IB_CT_ACC_X (0.36)	ENV_SQZ_ACC_Y (0.35)	ENV_BS_ACC_Z (0.34)
392.09											

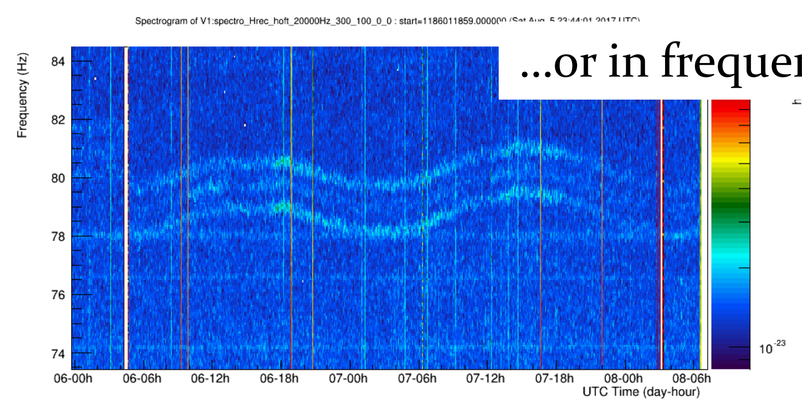
391 Evidenzia Maiuscole/minuscole Parole intere Corrispondenza 1 di 4

- Non-stationary Noise Analysis (NonNA)

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

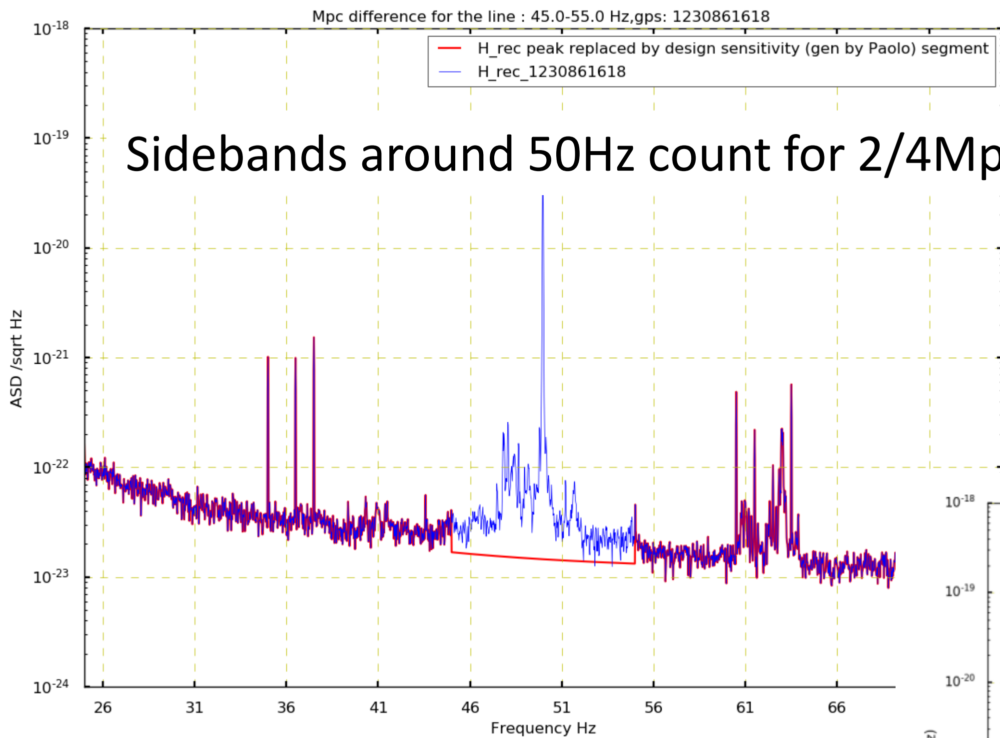


…in amplitude

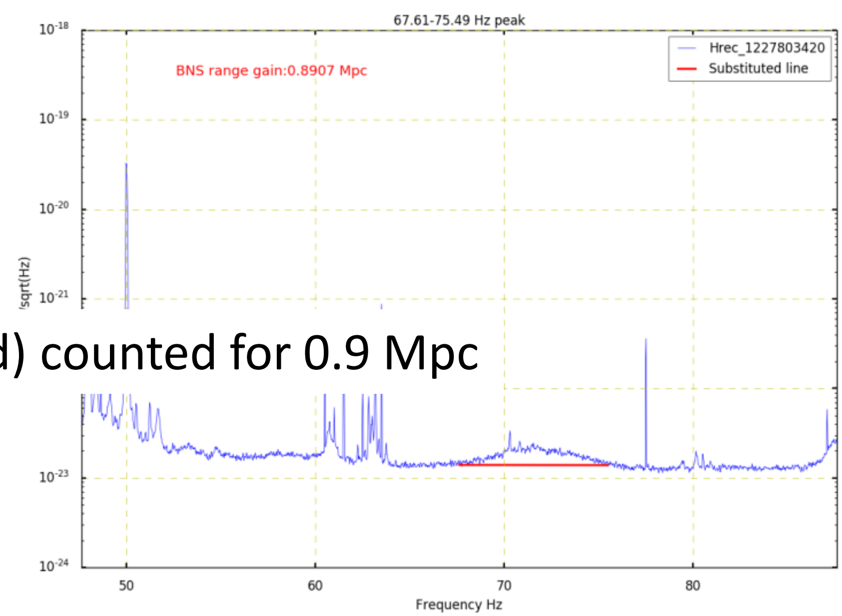


…or in frequency

How many Mpc do the structures “eat”?



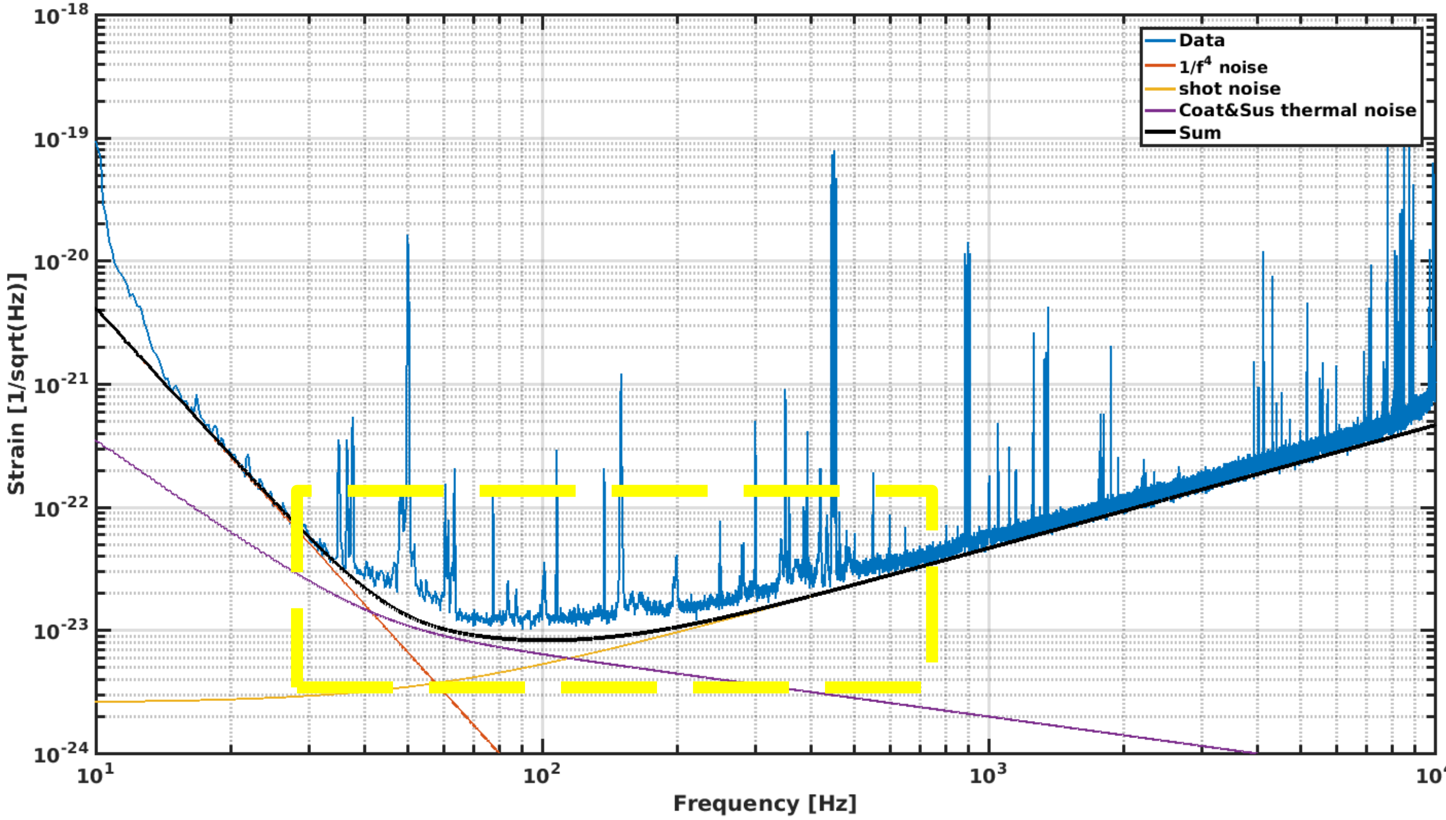
Sidebands around 50Hz count for 2/4Mpc



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

The "flat" noise

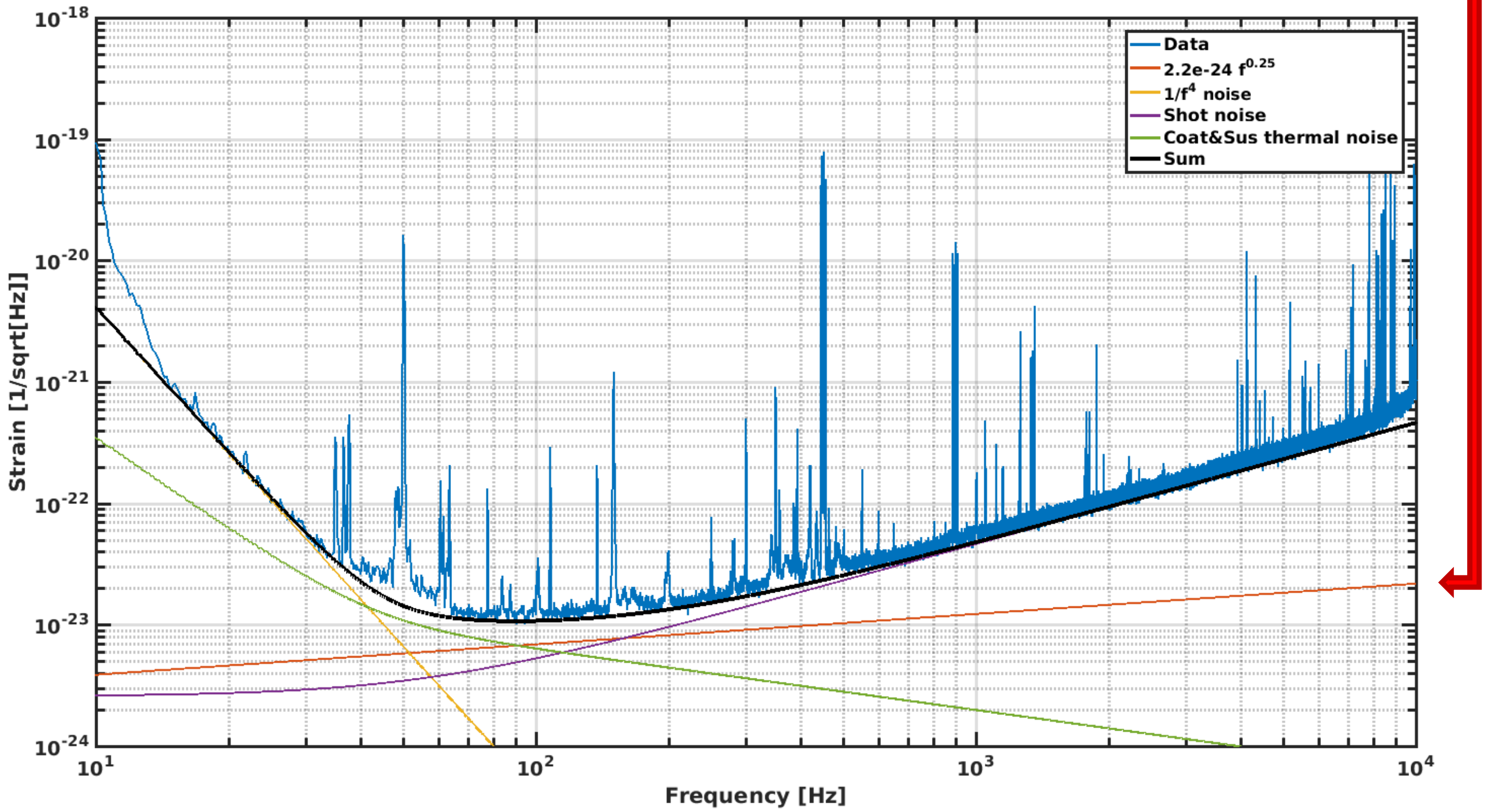
Main culprit preventing us from reaching 60 Mpc



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

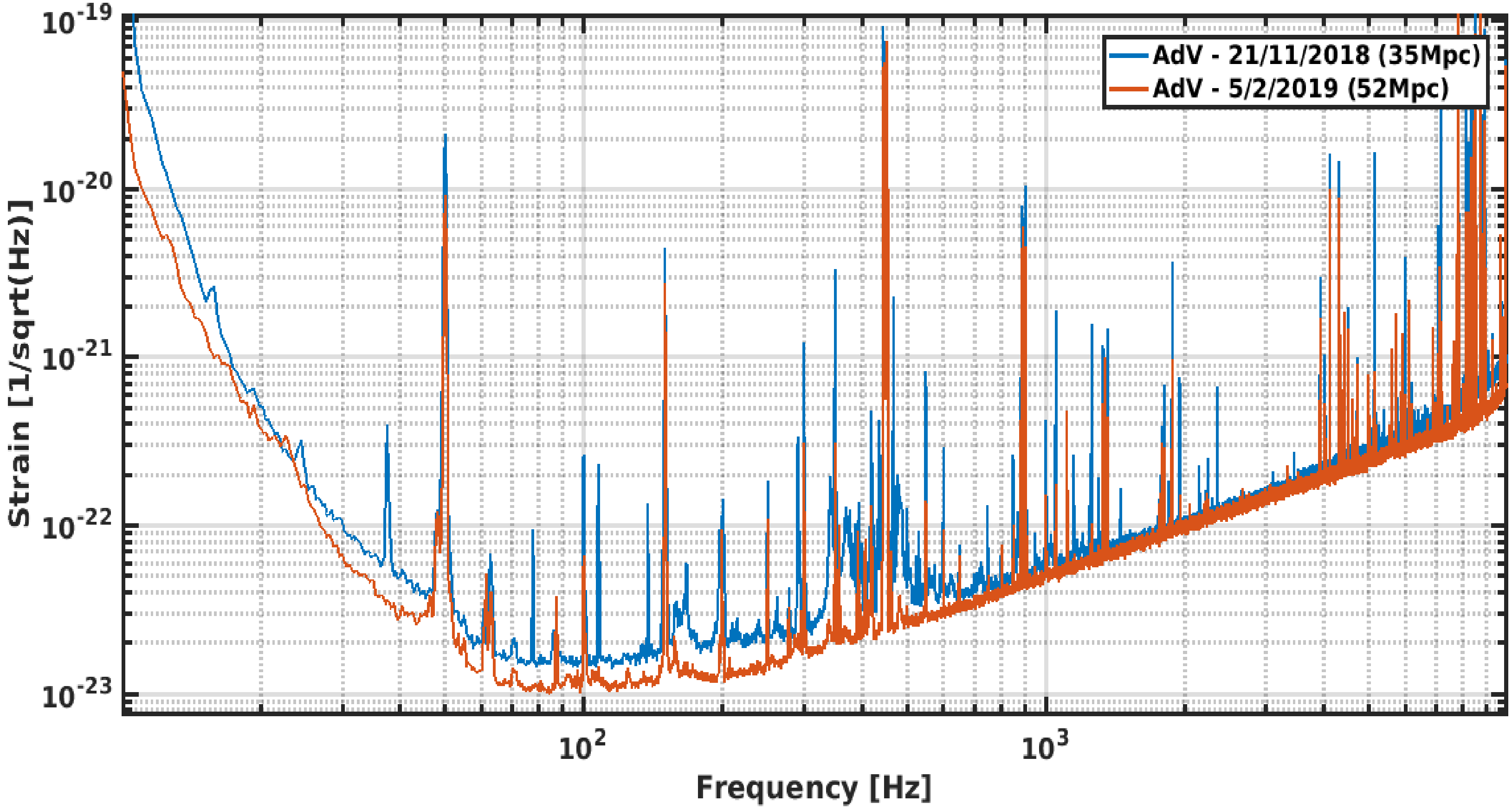
It fits better the sensitivity curve between 60Hz and 300 Hz if it has a small slope ($\sim f^{0,25}$)

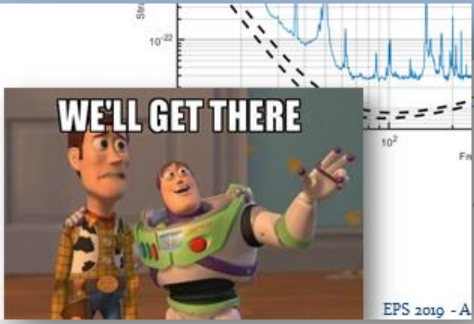


Still not completely clear what is the mechanism giving rise to this noise, but it was reduced after a stray light mitigation intervention

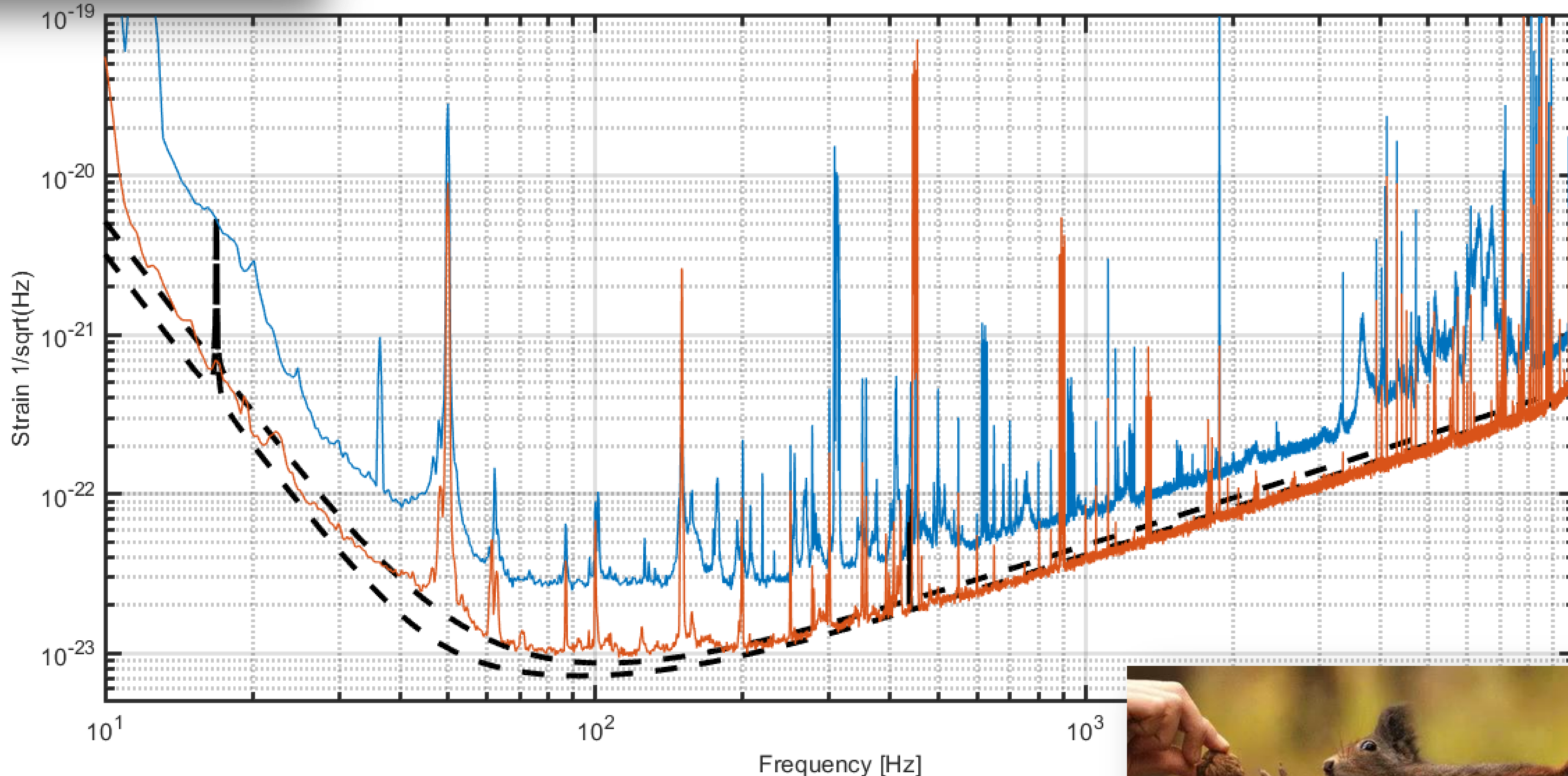
“Flat” noise mitigation

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





...in the end, could we get there?



Ready to join O3!

Thank you