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Preparing for O3 – the Virgo perspective

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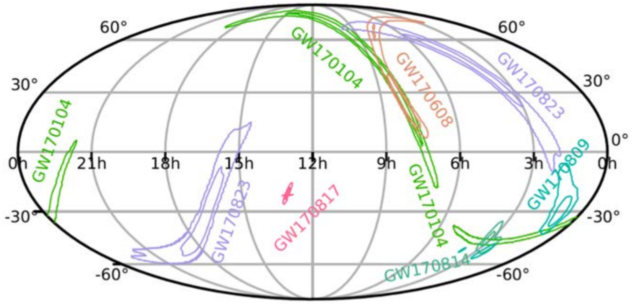
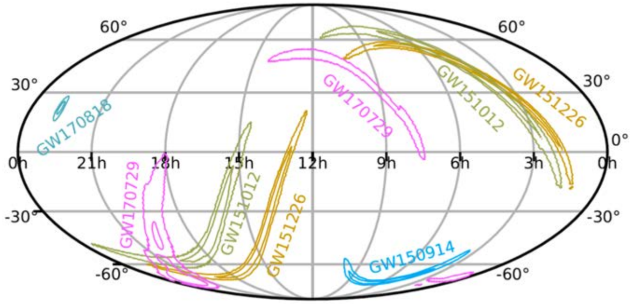
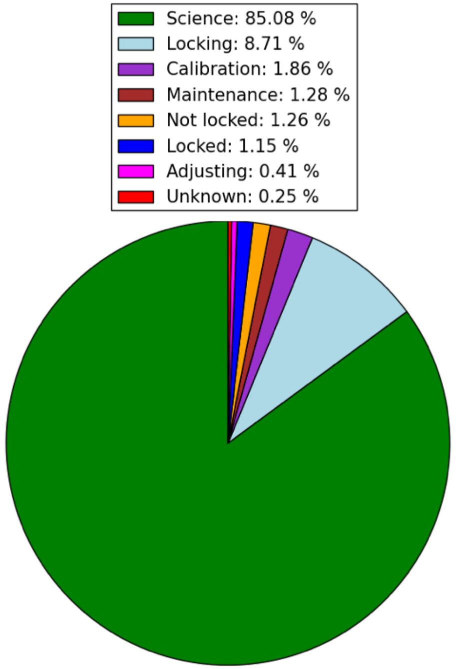
7 Dec 2018 | OzGrav retreat | Perth

O2: 25-30 Mpc BNS range and important for sky localisation

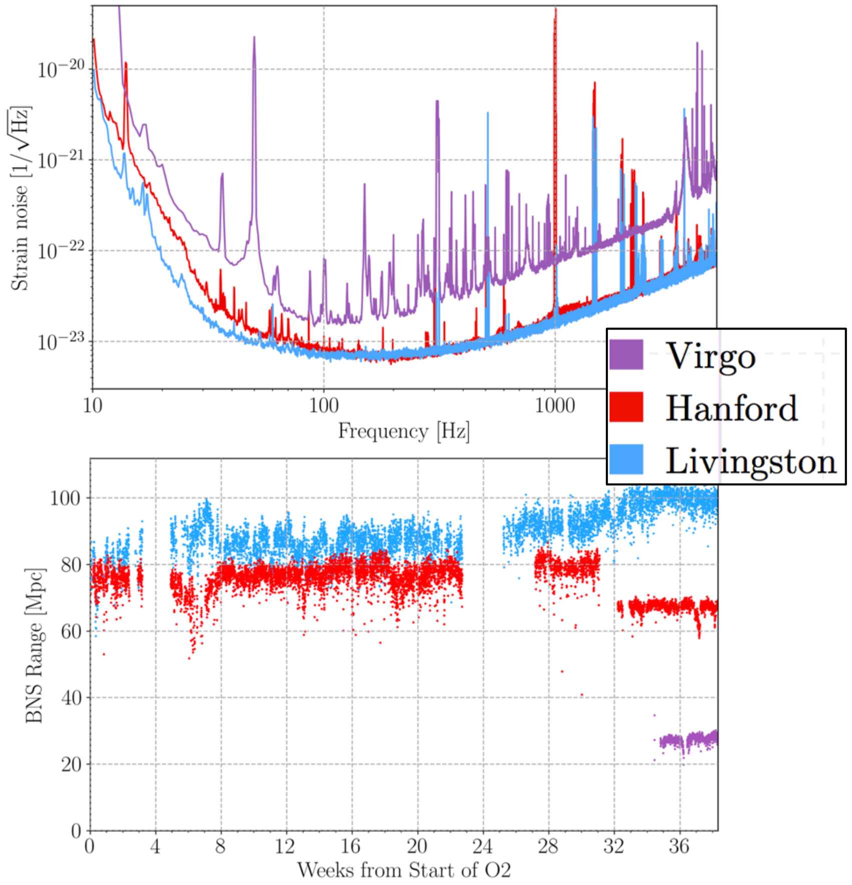
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651







Duty cycle of Virgo in O2



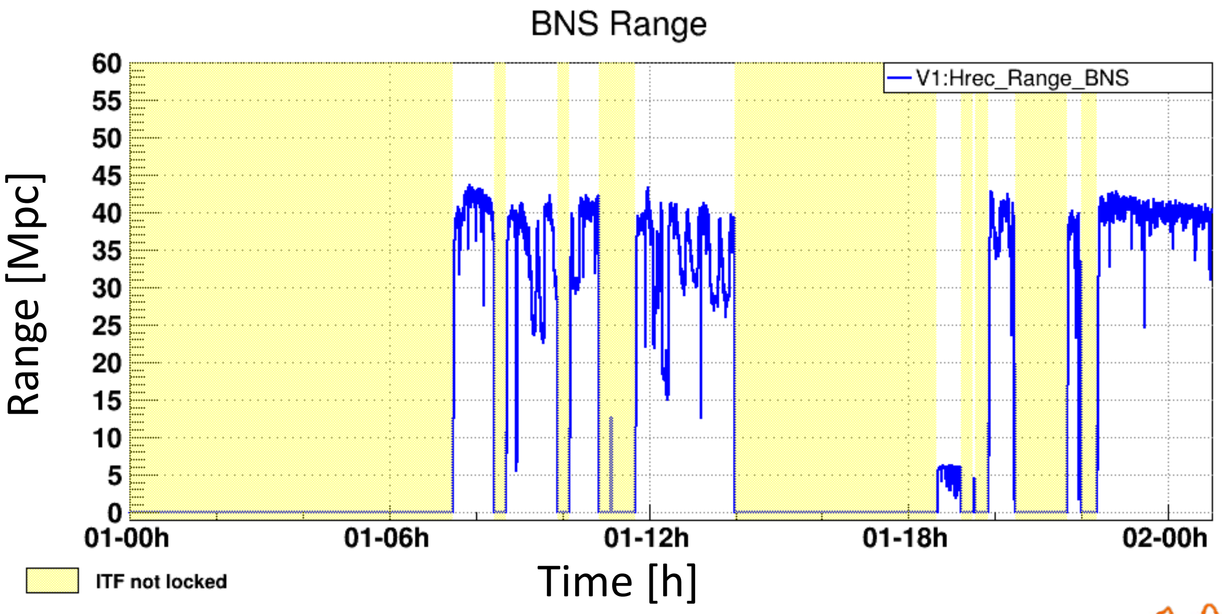
For O3, Virgo has promised* to deliver > 65 Mpc BNS range

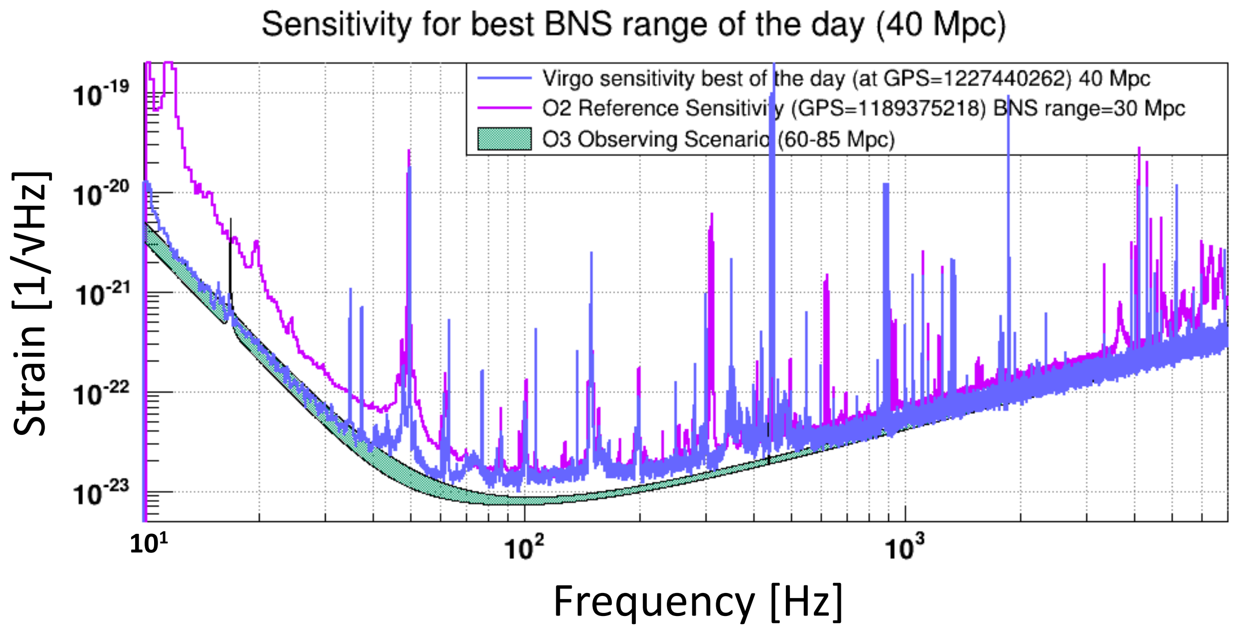
*Prospects for Observing [...] with [...] Advanced Virgo [...], Living. Rev. Relativ. 21:3 (2018)

sources: J. van den Brand, "Status of Virgo", Nov 2018 and LVC, "GWTC-1,[..]" (2018)

How is Advanced Virgo performing now?

Since Wed 20 November, Virgo reaches BNS ranges ≳ 40 Mpc

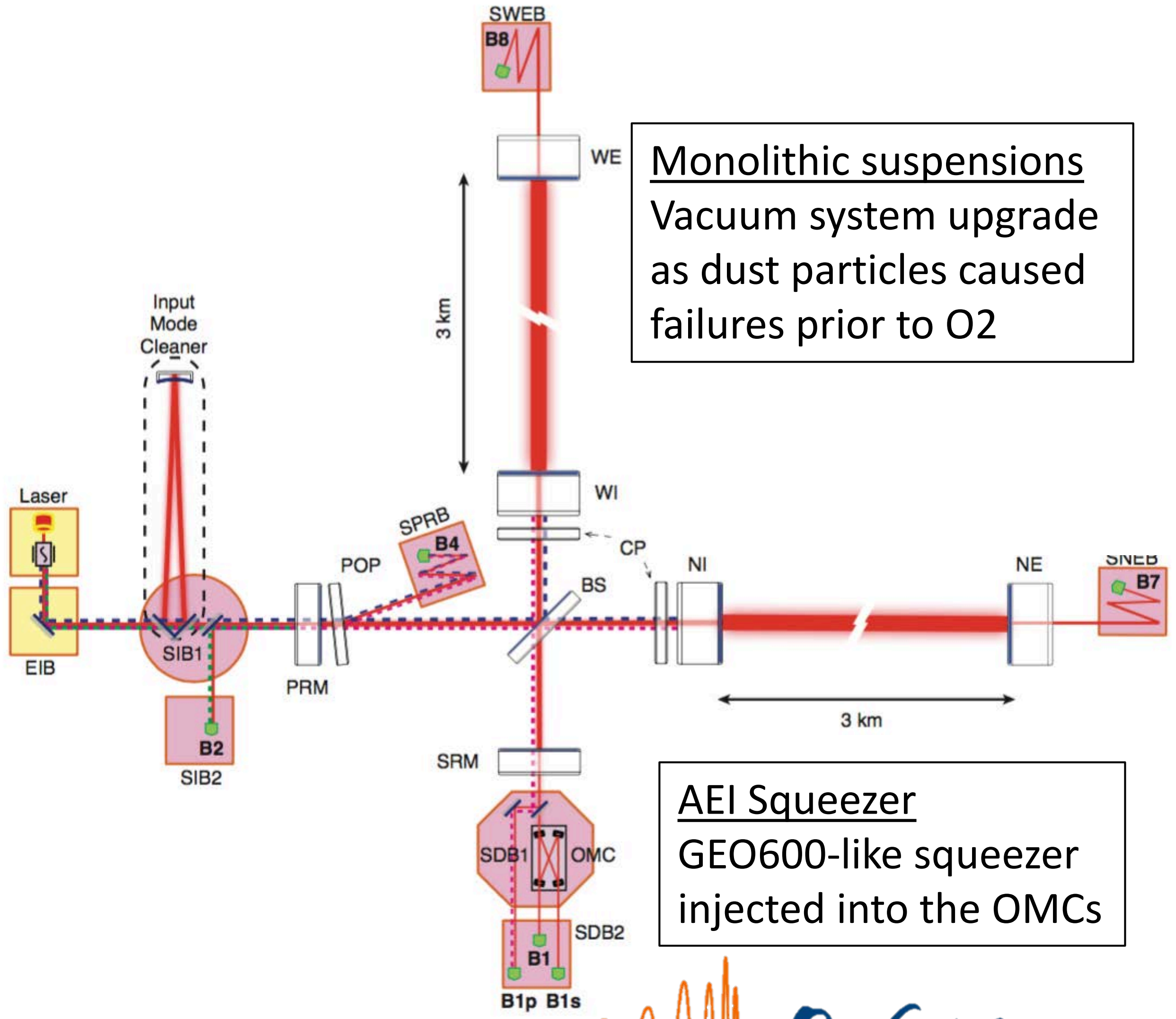




Already in the *promised land* between 10 – 40 Hz and above 800 Hz

source: Virgo summary webpage, https://vim.virgo-gw.eu

Quick overview of Virgo and the O2-to-O3 updates



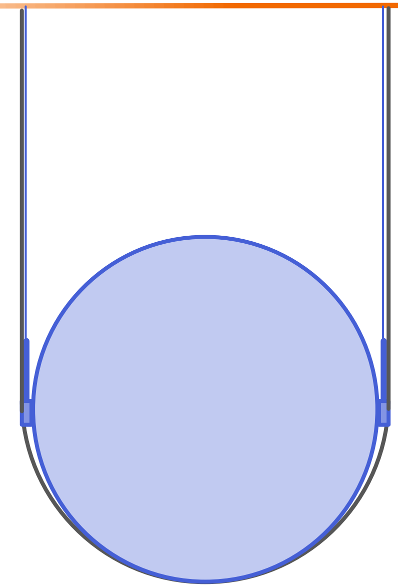
<u>Monolithic suspensions</u>
Vacuum system upgrade as dust particles caused failures prior to O2

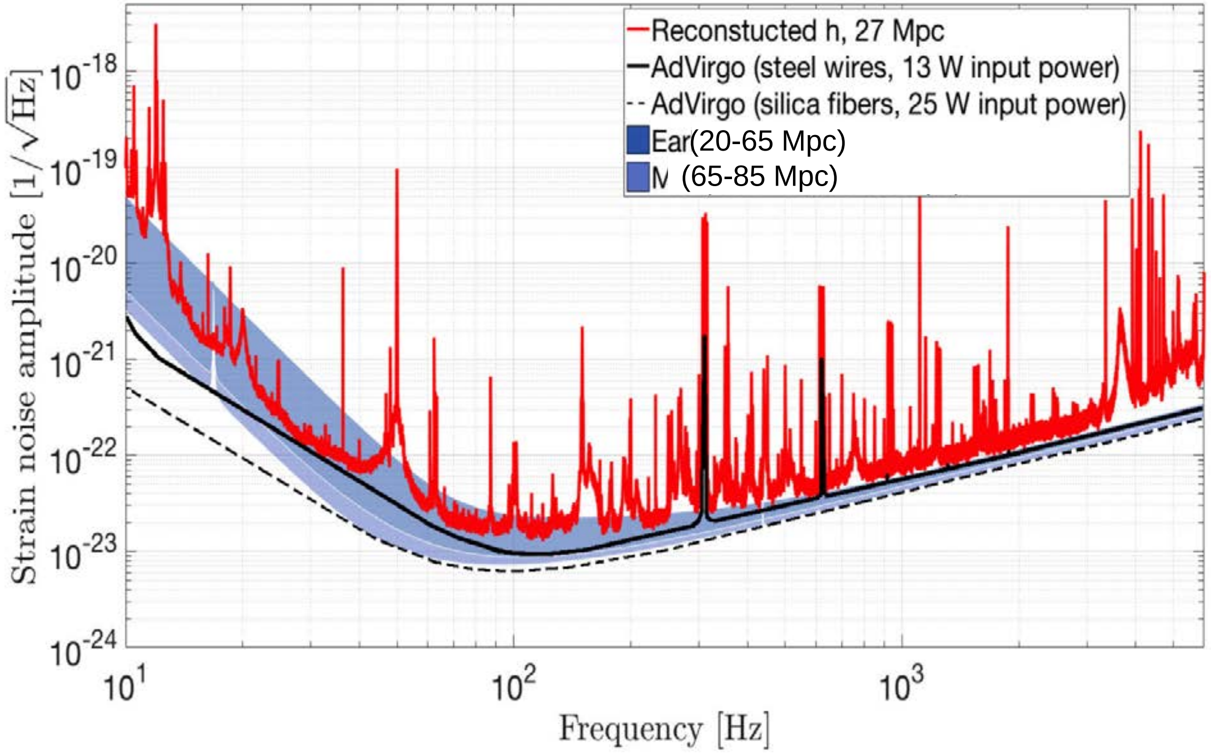
<u>New 100 W laser</u>
Now delivering 18 W power at the PR mirror

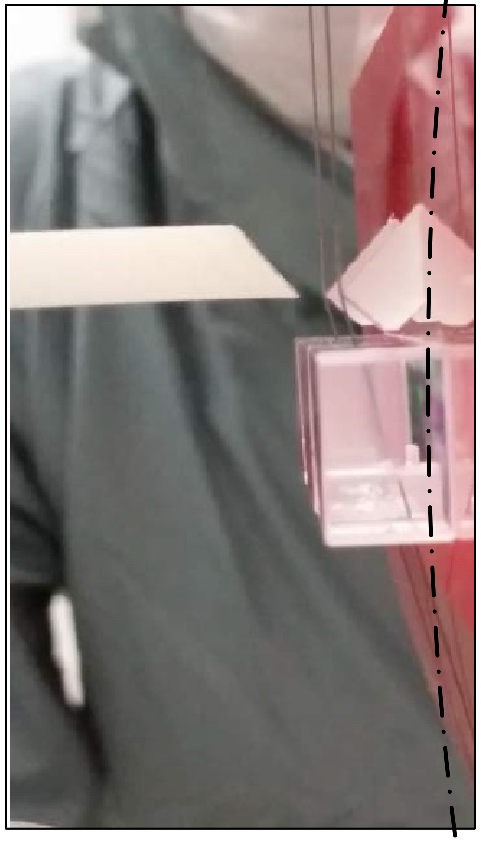
<u>Newtonian Noise (NN)</u>
NN subtraction test array around end test masses

<u>AEI Squeezer</u>
GEO600-like squeezer injected into the OMCs

Many monolithic suspensions failures prior to O2





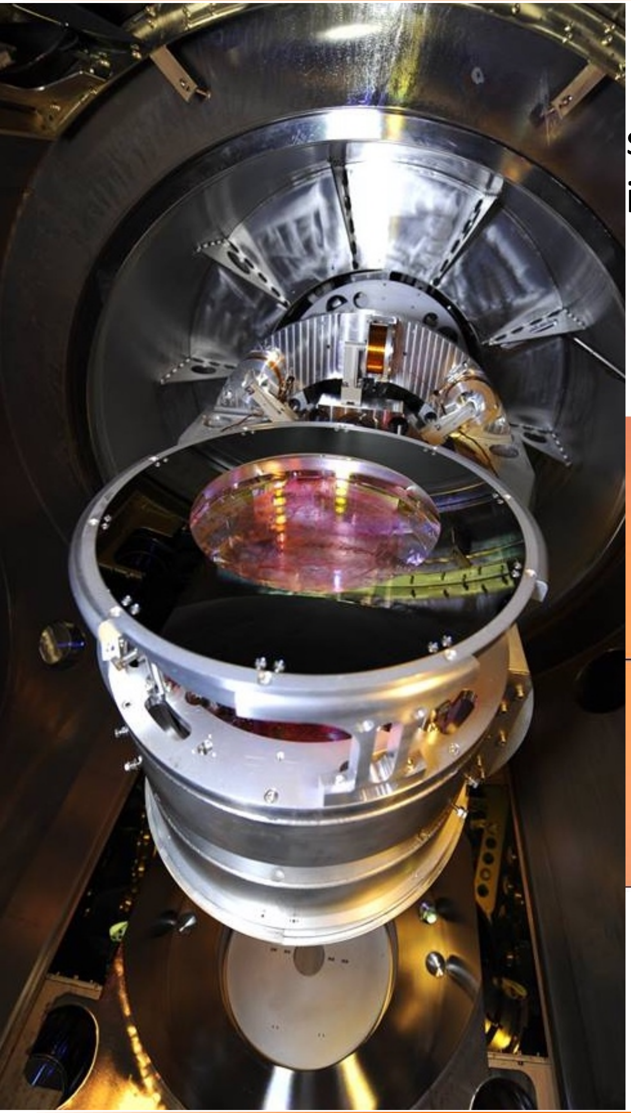


Fallback solution: steel wires

High loss angle caused dramatic fall in (theoretical) range (< 45 Mpc) for the design sensitivity

source: "From O2 to O3", H. Heitmann, LVC meeting, CERN, August 2017

Failures were due to dust particles colliding with fibers

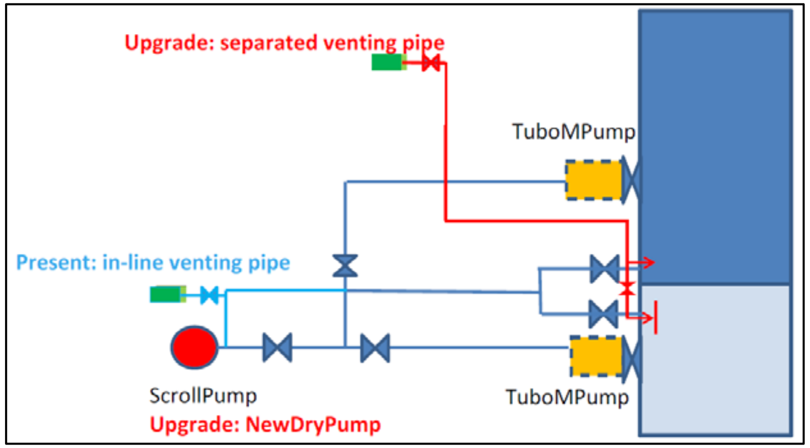


stigation,
ined to be

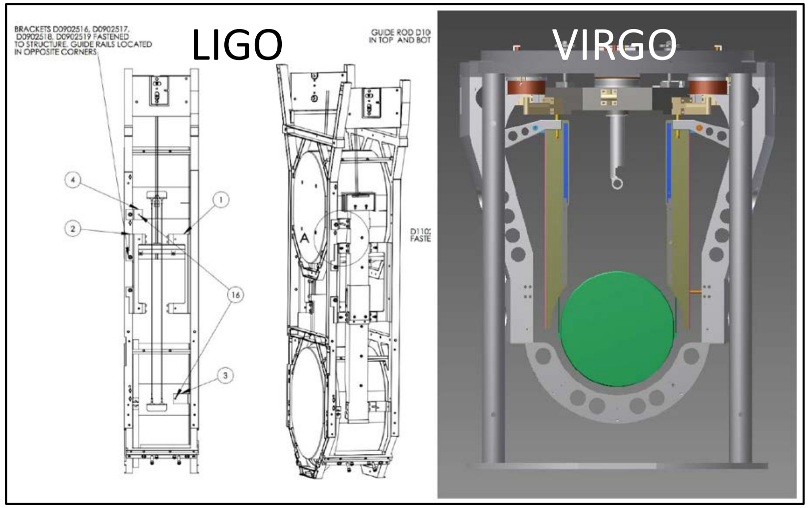
All four monolithic suspensions are installed and stay intact since begin 2018

Two solutions:

1. Upgrade in vacuum system



2. Passive protection of the fibers



New 100 W laser installed providing 40 W at the IMC for O3

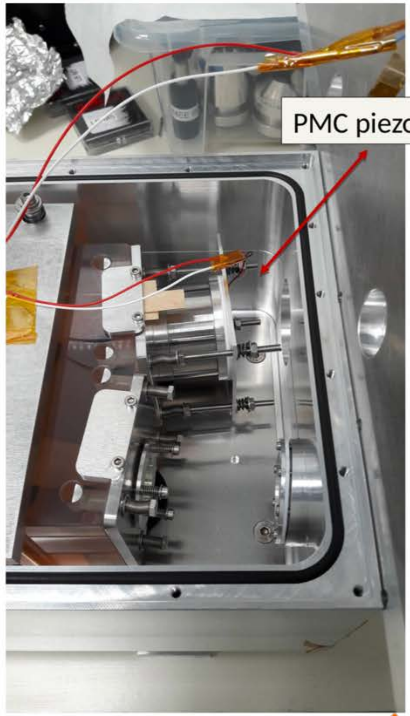
Solid State Laser: NeoVan 4S HP

It will provide > 50 W power at IMC (≥ O4)

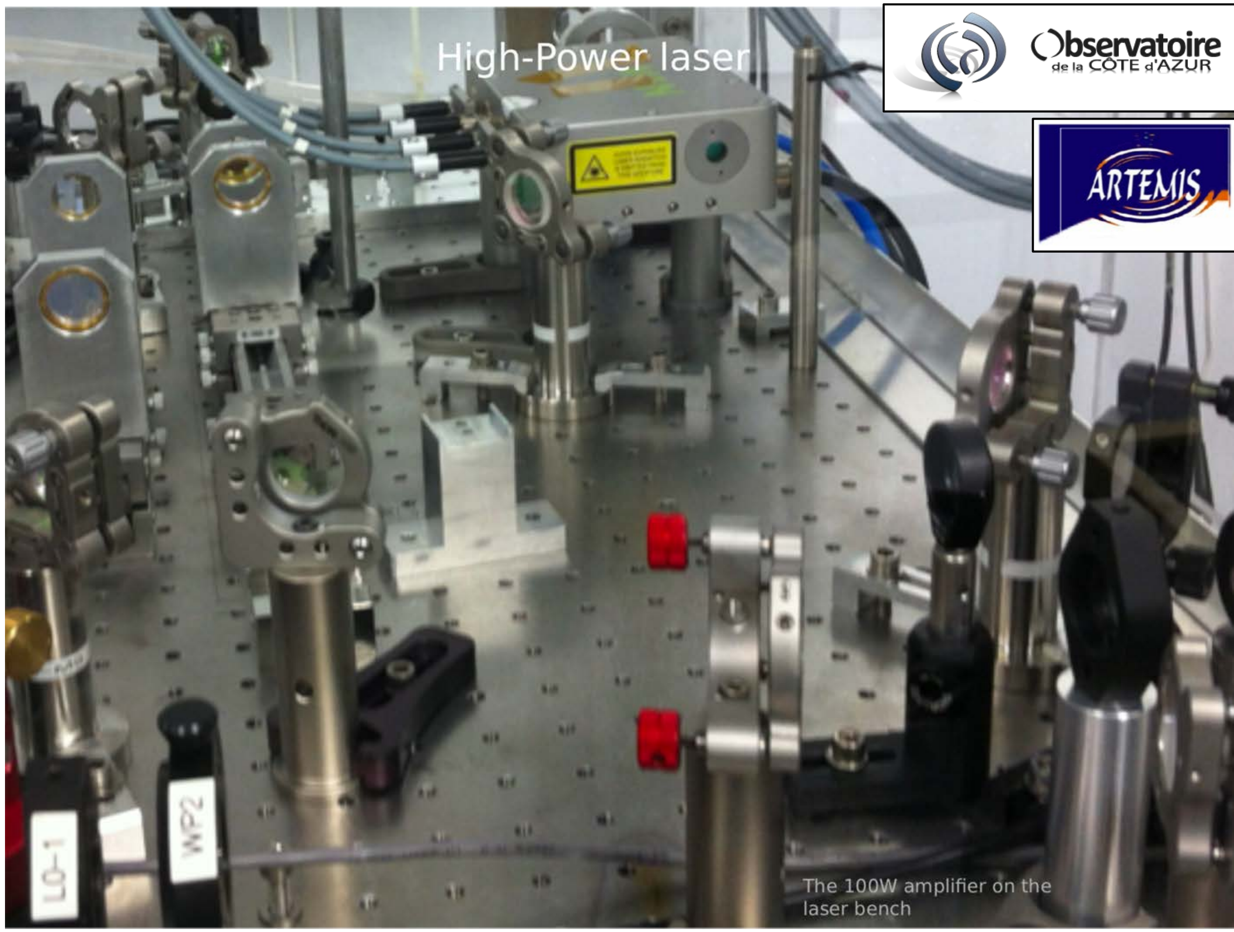
New Zerodur pre-mode cleaner (PMC)

PMC zerodur spacer

PMC enclosure



PMC piezo mount



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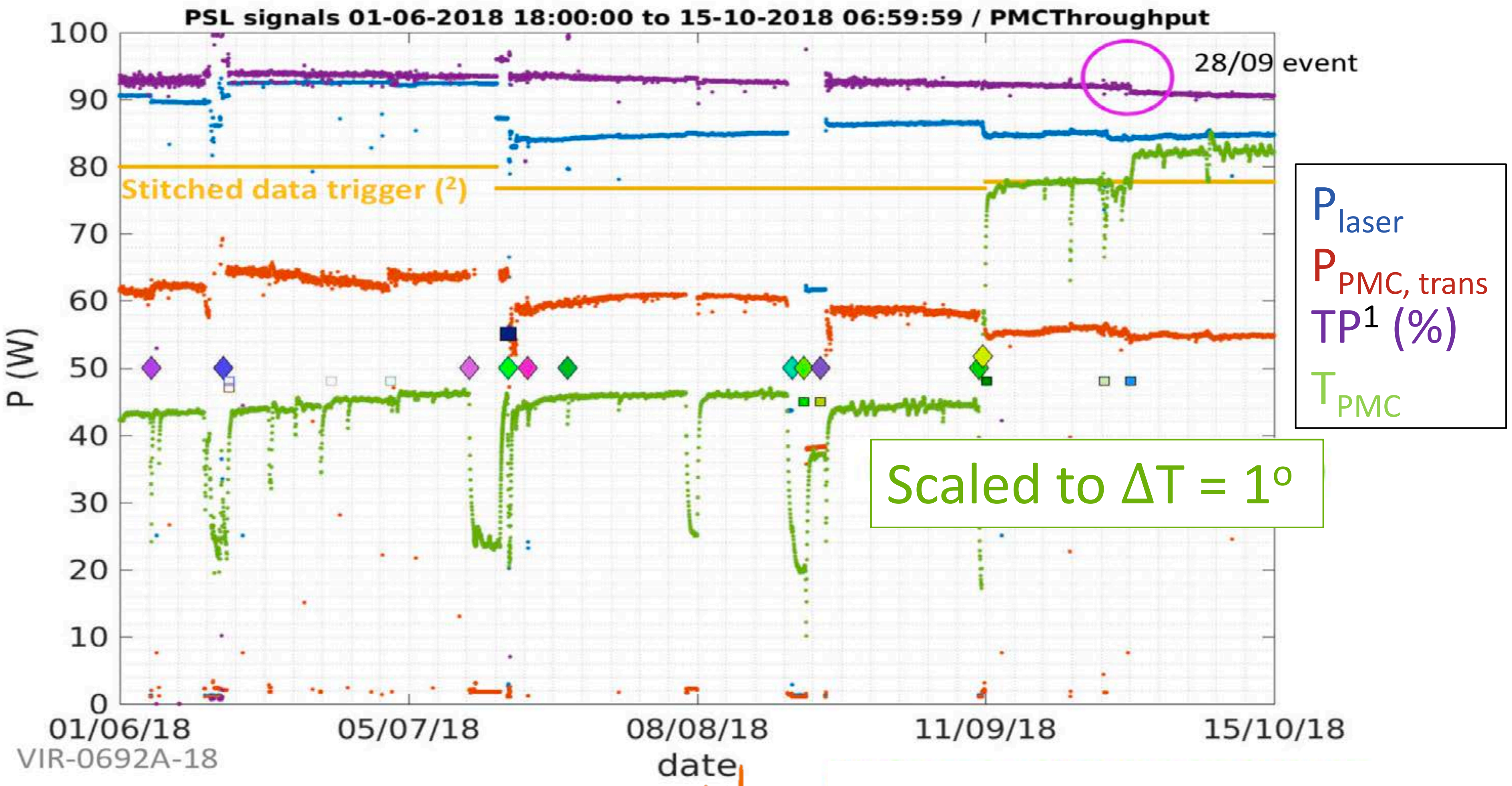
source: “Advanced Virgo High Power Laser Status”, N. Christensen *et al.*, Virgo Week, Jan 2018

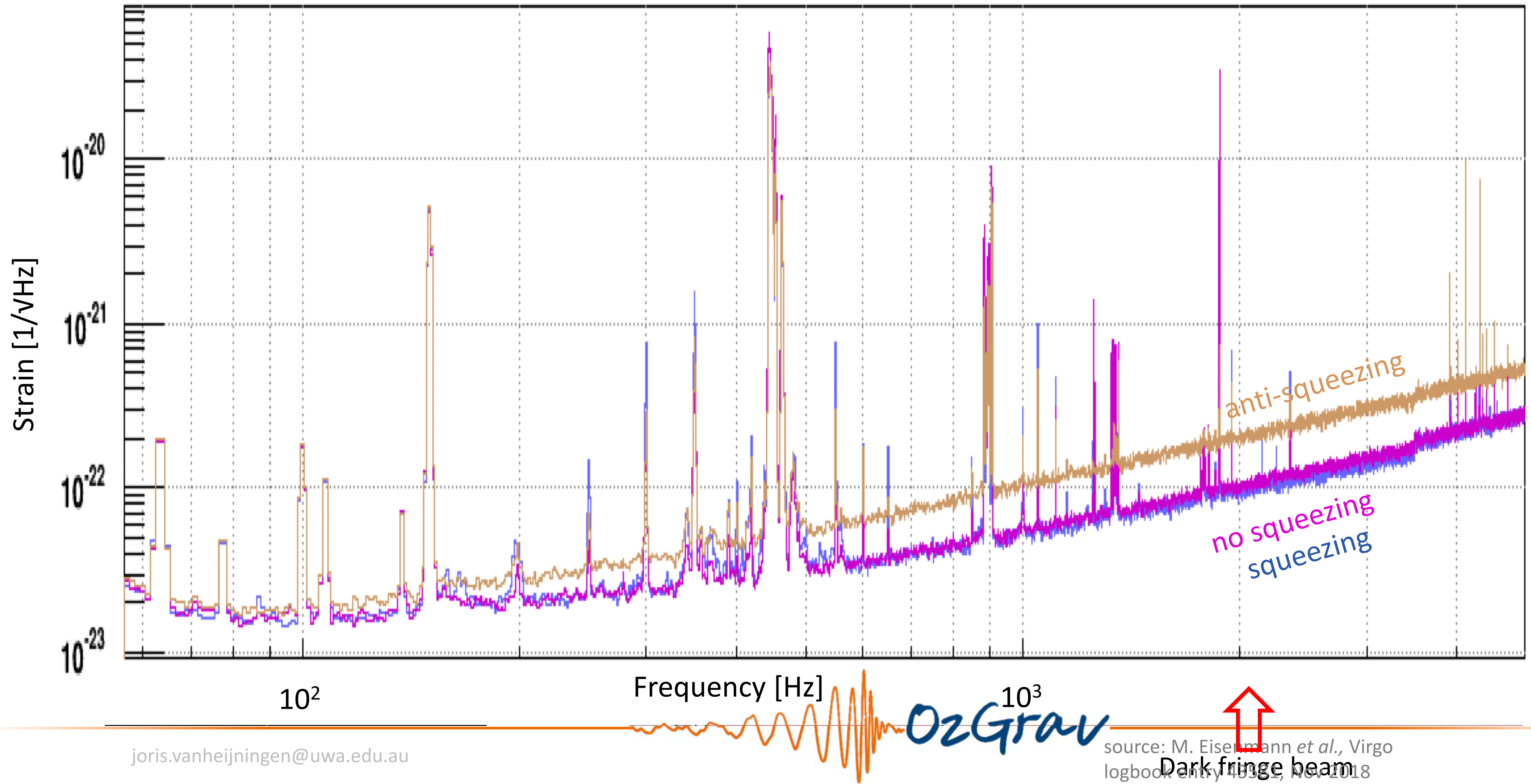
Laser power and PMC temperature over 4½ months



[1] ThroughPut = $(P_{PMC, trans} + P_{PMC, refl}) / P_{PMC, in}$

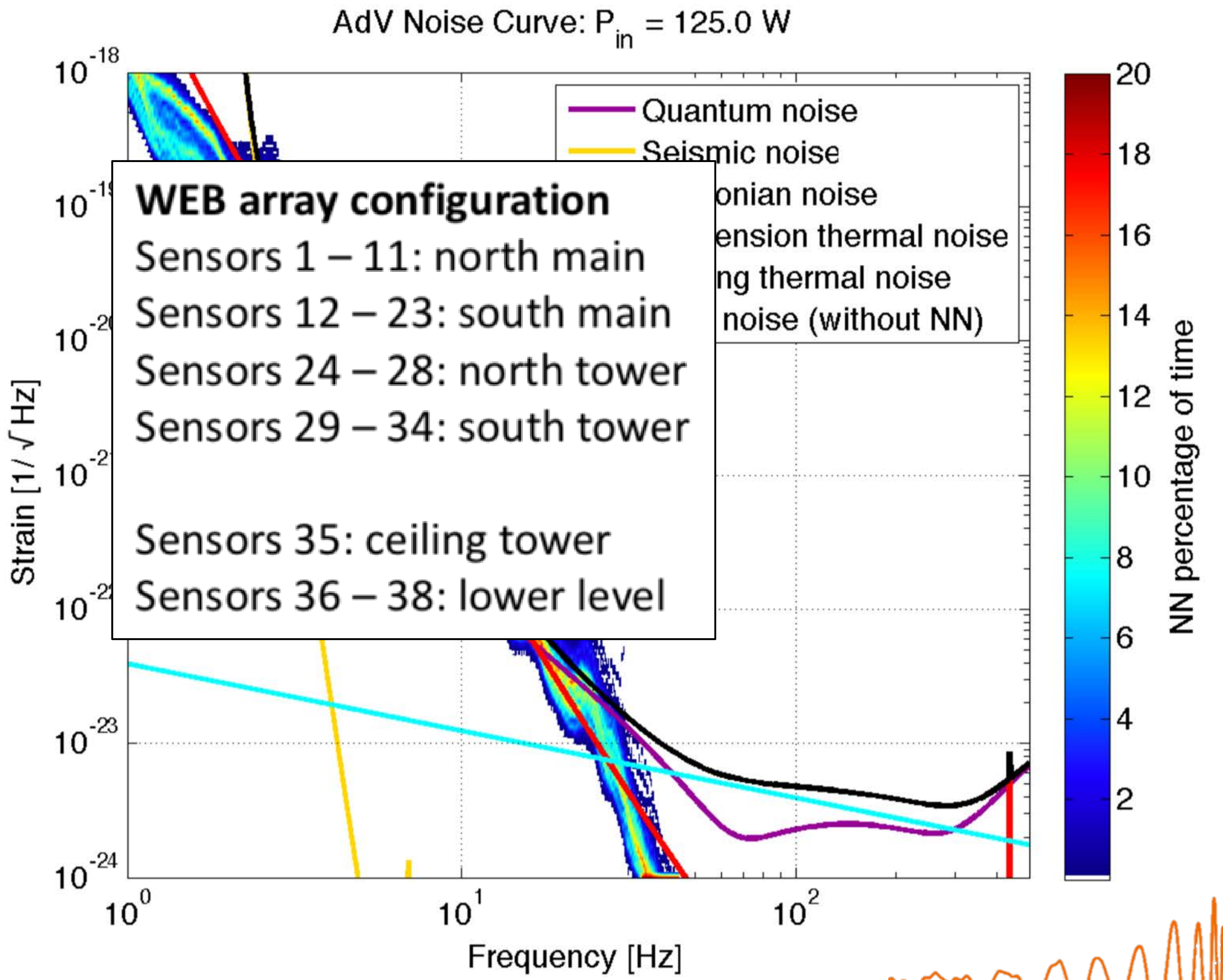
source: "Laser and Injection system (ISYS) status", E. Genin *et al.*, Virgo Week, Nov 2018

AEI installed their latest squeezer in Virgo



source: M. Eisenmann *et al.*, Virgo logbook entry 43581, Nov 2018

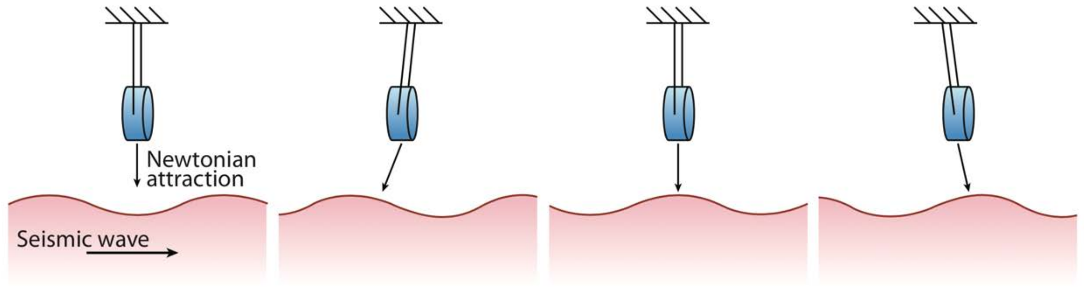
Newtonian noise subtraction test array at end stations



WEB array configuration

Sensors 1 – 11: north main
Sensors 12 – 23: south main
Sensors 24 – 28: north tower
Sensors 29 – 34: south tower

Sensors 35: ceiling tower
Sensors 36 – 38: lower level



Newtonian attraction from varying mass distribution below test mass

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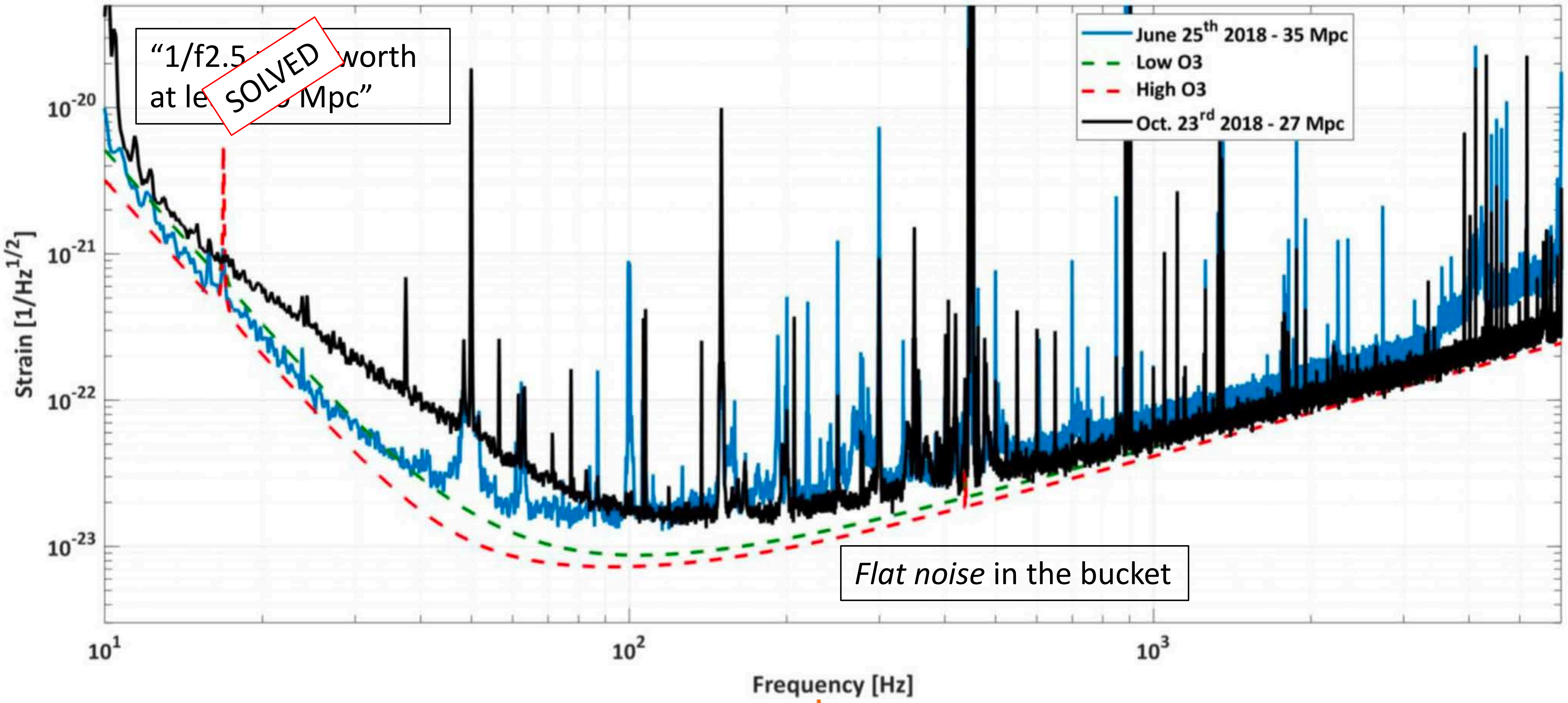
source: J. Harms *et al.* "Update from the NN working group", Virgo week, Nov 2018

The situation until 20 Nov 2018



Low frequency sensitivity was limited by $1/f^{2.5}$ noise

Tests done (during 3 months) before problem was found

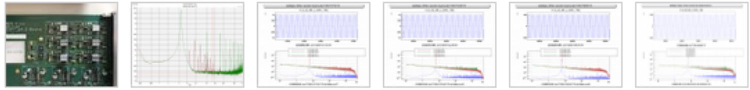
AdV-SAT (Suspension control upgrade)

Boschi, Magazzu, Passuello, Ruggi - 20:01, Tuesday 17 July 2018 (42141)

End Mirrors Low Noise Boards modified, installed and tested

The shaping filters of the end mirrors DSP boards have been modified as shown in VIR-0486-A18 using polyester capacitors of 4.7 uF (see photo). The (red) and after (green) the shaping filter modification. The distortion level measured on the 3rd harmonics is less than -115 dB. The boards have then b with 92 Hz pole and 4.1 Hz zero). The same test described in entry #41816 have been performed again on the new boards both in LN1 (figure 2 and 3) -70 dB.

Images attached to this report

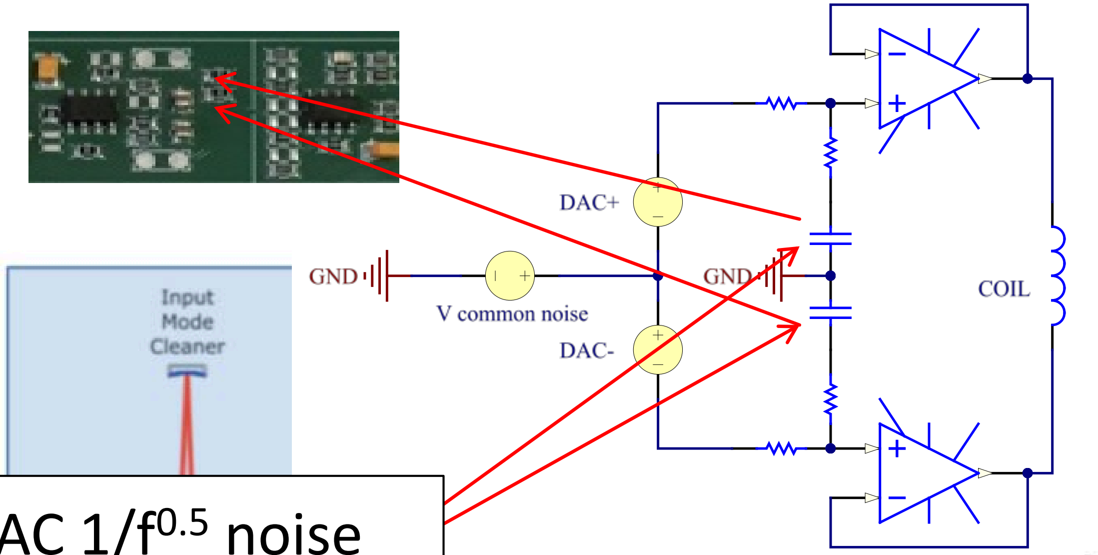


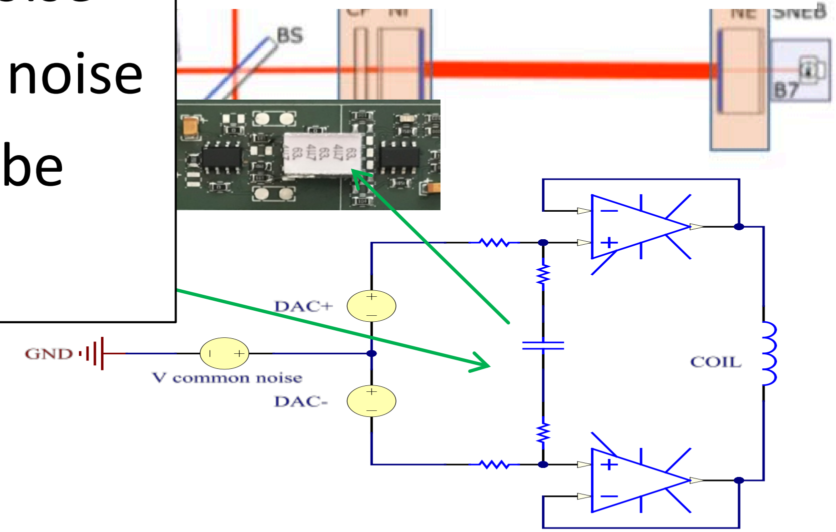
- PCal Switch-Off T
- Measurement of C
- Comparisons from
- Quick Investigatio
- Correlation betwe
- 1/f^2.5 noise vs DARM accuracy - #43303
- Check of 1/f^2.5 noise stability over C... #43305
- Relative displacement of the cage and mirror ... #43360
- Switch off test of towers coil cathode ... #43395

Solved
(distorti

Problem arose from a (common mode) DAC $1/f^{0.5}$ noise source, filtered via the pendulum TF, gave the $1/f^{2.5}$ noise Virgo was facing. The mirror is charged (it seems to be the case), the electrostatic actuation was very high

Problem: a ground reference was removed, and the shaping filter became effective for the differential signal ONLY, **not for the common noise!**

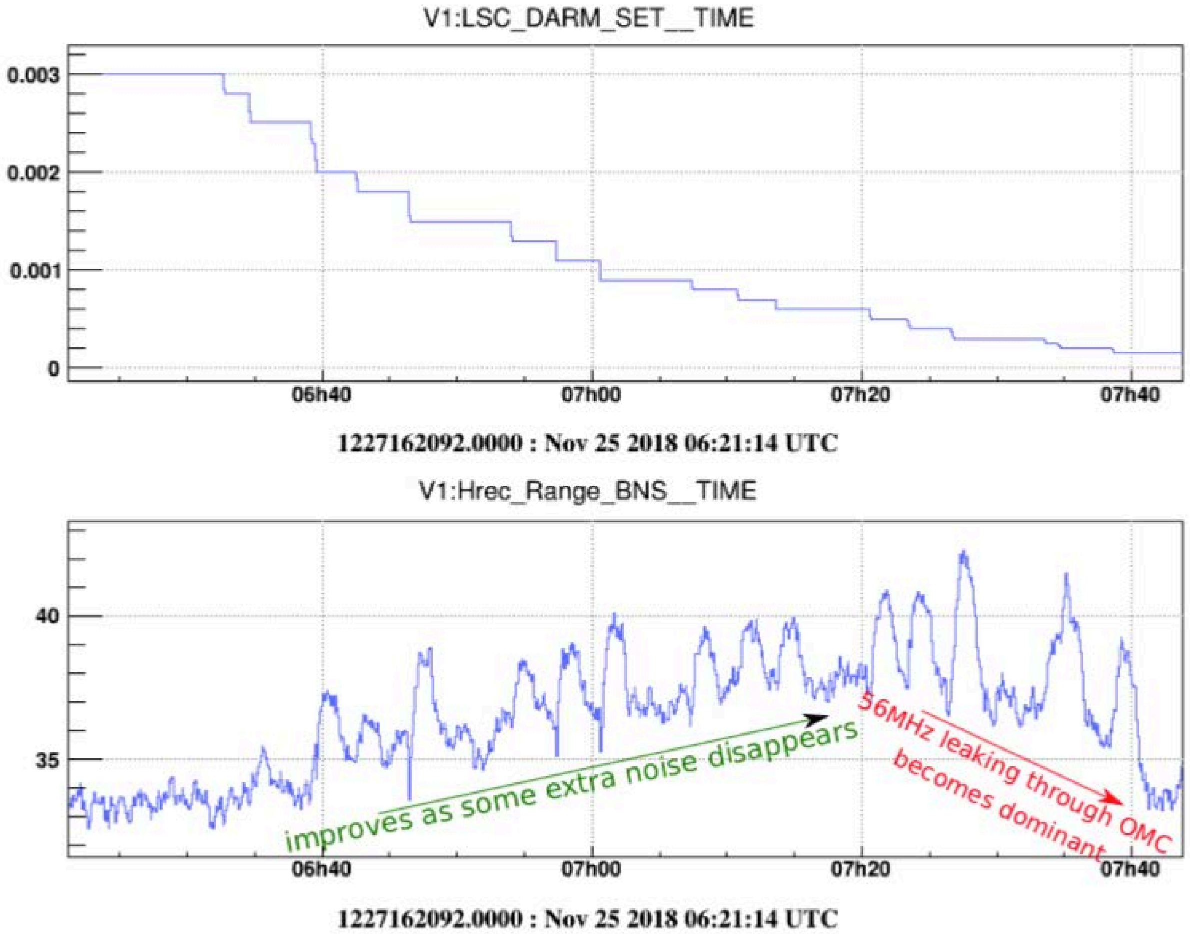




source: F. Paoletti *et al.*, "The (in)famous $1/f^{2.5}$ noise: latest update", VIR-0805A-18, Nov 2018

Noise hunting continues in the bucket

- h(t) is calibrated using *optical gain* (100 sec avg) 2 minutes after step h(t) should be correct again;
- Sensitivity improves as (still unknown) noise is removed; then it starts to worsen as 56MHz leakage becomes dominant;
- Optimum at ~4 mW for B1; better sensitivity everywhere between 80 Hz and 300 Hz.

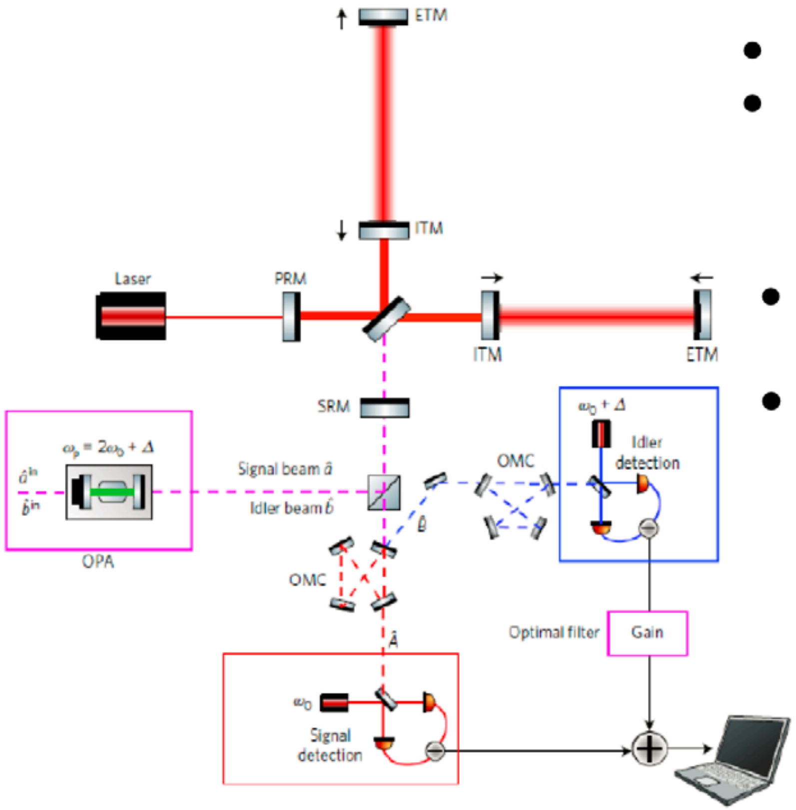


source: M. Was, “Dark fringe offset reducing flat noise”, VIR-0857A-18, 27 Nov 2018

The future is now!

EPR

F. Sorrentino and J. Harms VIR-0705A-17



Y. Ma et al., Nature Physics 13, 776 (2017)

Disadvantages

- There is an overall 3dB penalty
- Loss at the output port counts twice

Advantages

- Not required new infrastructures
- High fexibility

Starting from 2018: Demonstrator under development at 1500W Lab

- Just as with aLIGO, frequency dependent squeezing is coming (O4);
- "Here, we show that the need for such a filter cavity can be eliminated, by exploiting Einstein–Podolsky–Rosen (EPR)-entangled signals and idler beams."

Summary and outlook

- Advanced Virgo was between 25-30 Mpc BNS range during that “spectacular month in August” at 85% duty cycle;

- Currently they are $\gtrsim$ 40 Mpc after introduction of monolithic suspensions and noise hunting effort, but aim to be > 65 Mpc in March 2019;

- The future is here! Frequency dependent squeezing is “around the corner” and a clever EPR scheme is being investigated.

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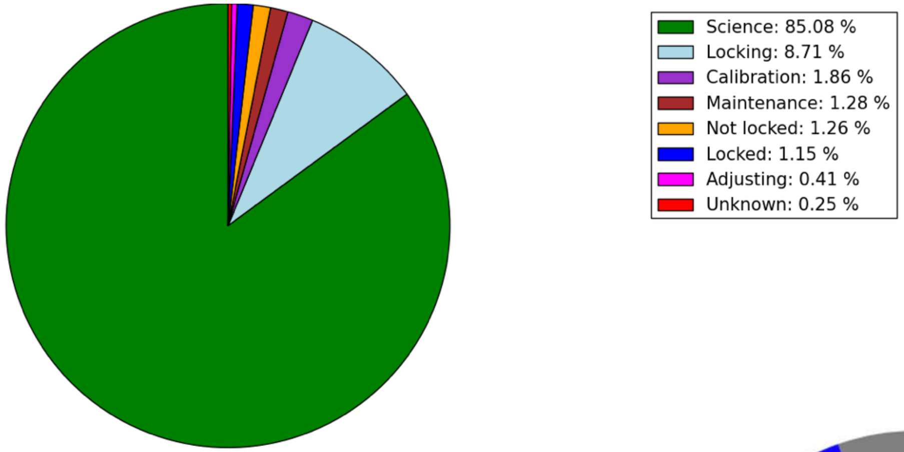
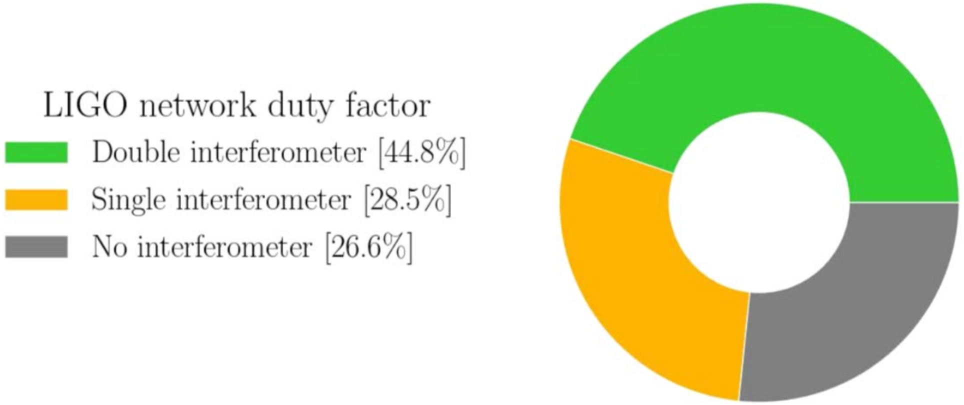
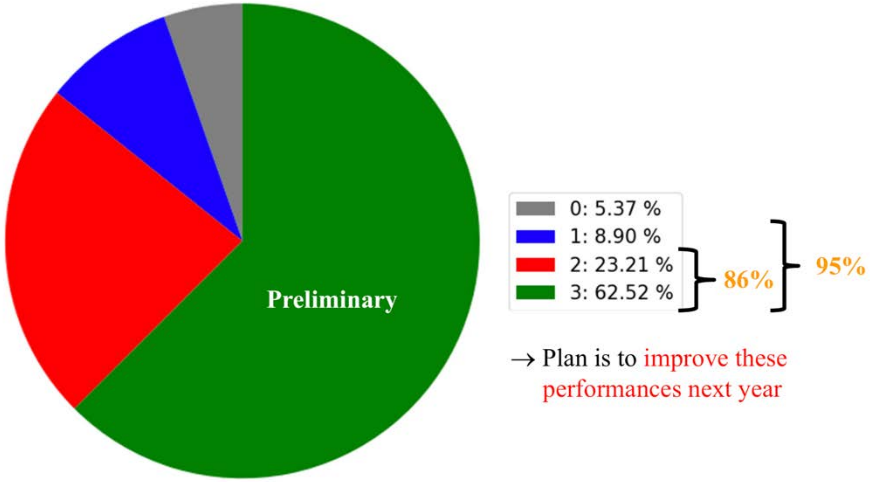
Duty cycle O2 breakdown in pie-charts



Virgo in O2



LIGO in O2



Combined uptime in O2

Lines in the Virgo spectrum during O2 (graph on slide 19)

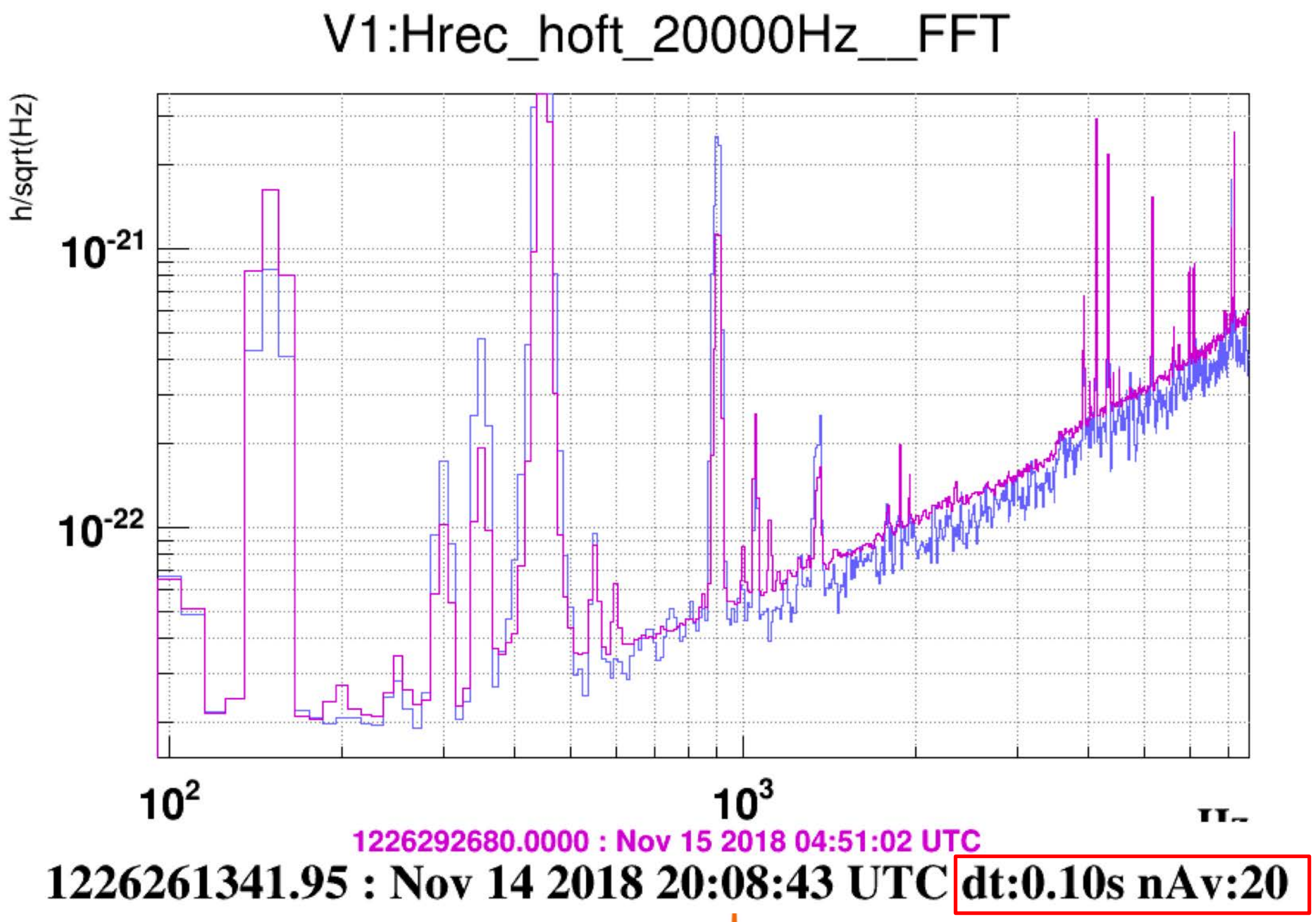
The typical shape of GW detector spectra is clearly visible, but structures and lines can be found over the entire frequency range. The structures below 30 Hz are believed to be control noise stemming from timing issues in the digital system [120]. The lines around 10.5 Hz, 12.5 Hz, 16.3 Hz, 35 Hz, 45 Hz, 60 Hz, 90 Hz and 350 Hz are calibration lines. The line at 18.6 Hz and 24.6 Hz is associated with air conditioners in the central building clean room and the DAQ room, respectively.

The broad line at 20 Hz is a mechanical mode of the locked EIB-SAS suspension. The mains power line is at 50 Hz. The broad line at 100 Hz is a mechanical mode of the West input test mass suspension. Current understanding is that the structures and lines between 100 Hz and 1 kHz are associated with SDB1, e.g. ringing optic mounts or (violin) modes of the suspension [122]. The broad line at 207 Hz is a mechanical mode of M6 mirror mount on the external injection bench, which is not yet isolated by EIB-SAS. The line at 315 Hz is the violin mode of the (steel) test mass suspensions (also visible in the solid black curve). Harmonics of this mode are seen at multiples of this frequency value.

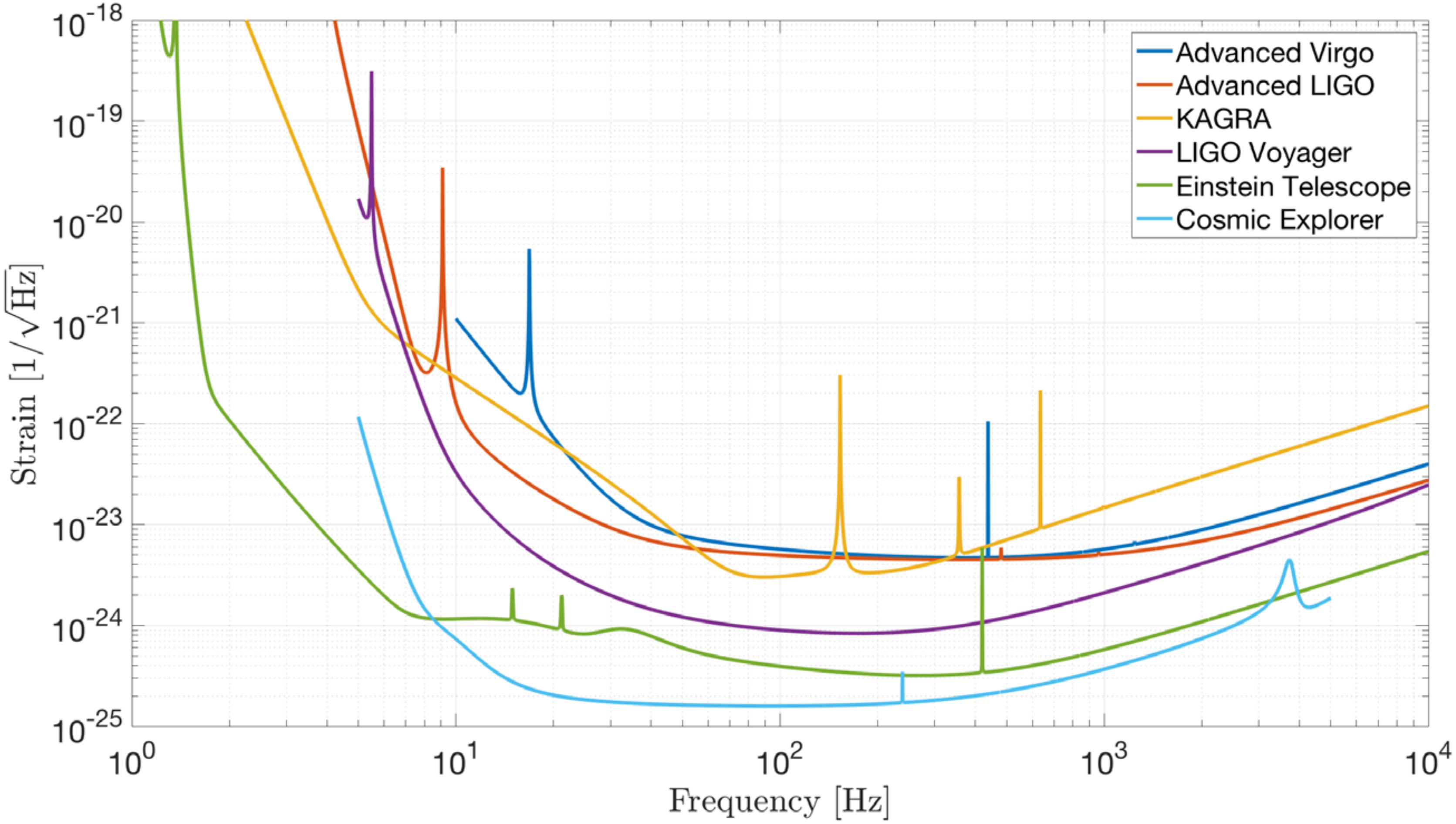
The line around 1.9 kHz is the beamsplitter drum mode, a mechanical mode of the fused silica cylinder. Lastly, the structure around 4 kHz and the lines between 4 kHz and 5 kHz is associated with the demodulation system of the OMCs [120]. It is a beating of the SDB1 local control LVDT lines and OMC demodulation line. The location of these lines are available and regularly updated at the known lines database [123].

source: J.V. van Heijningen, "Low-frequency performance improvement of seismic attenuation systems and vibration sensors for next generation gravitational wave detector", PhD thesis, DCC no. P1800041 (2018)

About 1 second of 10% shot noise reduction

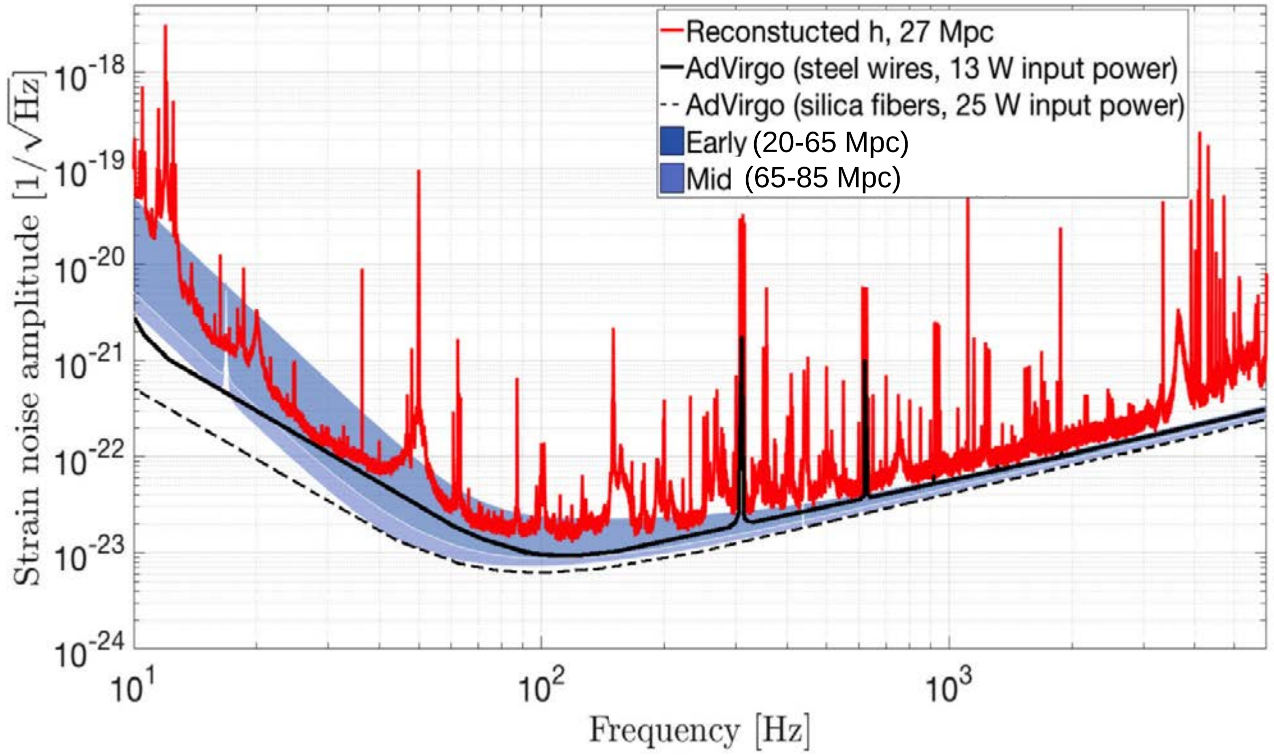


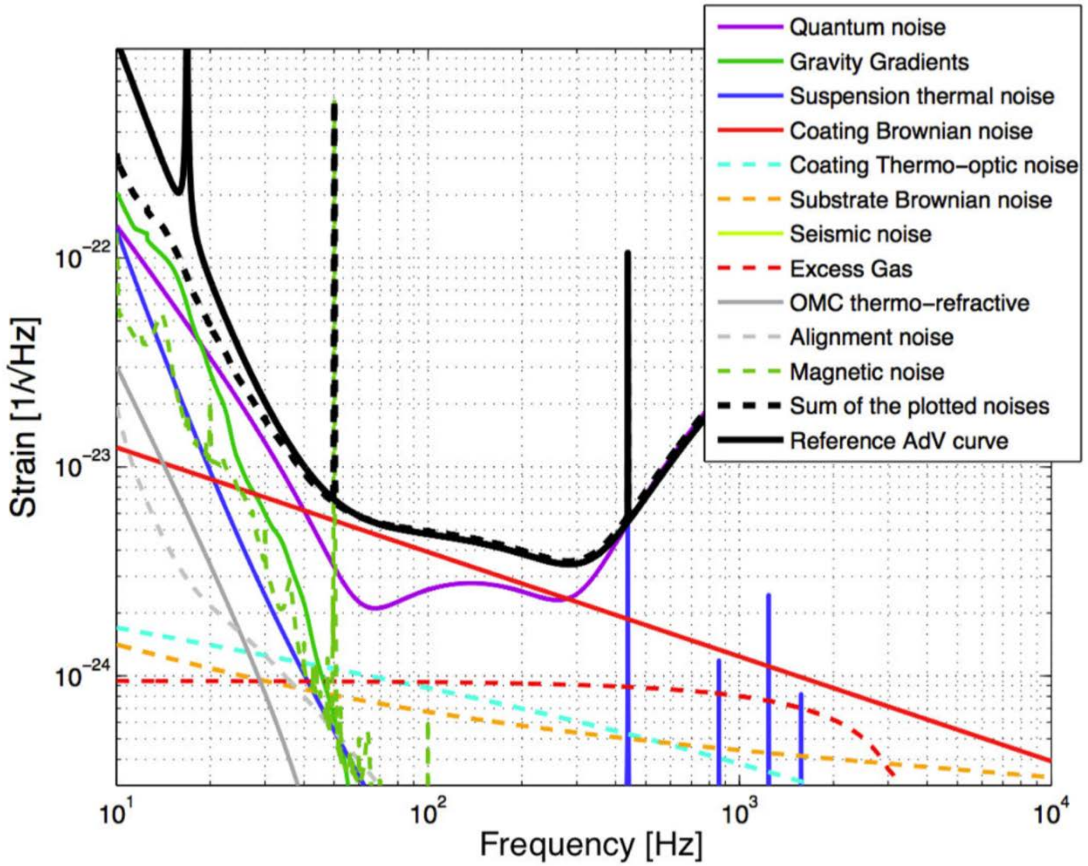
Towards design sensitivities and beyond



Source: M. Evans, "Unofficial sensitivity curves (ASD) for aLIGO, Kagra, Virgo, Voyager, Cosmic Explorer and ET", LIGO DCC document T1500293-v11 (sep 2018)

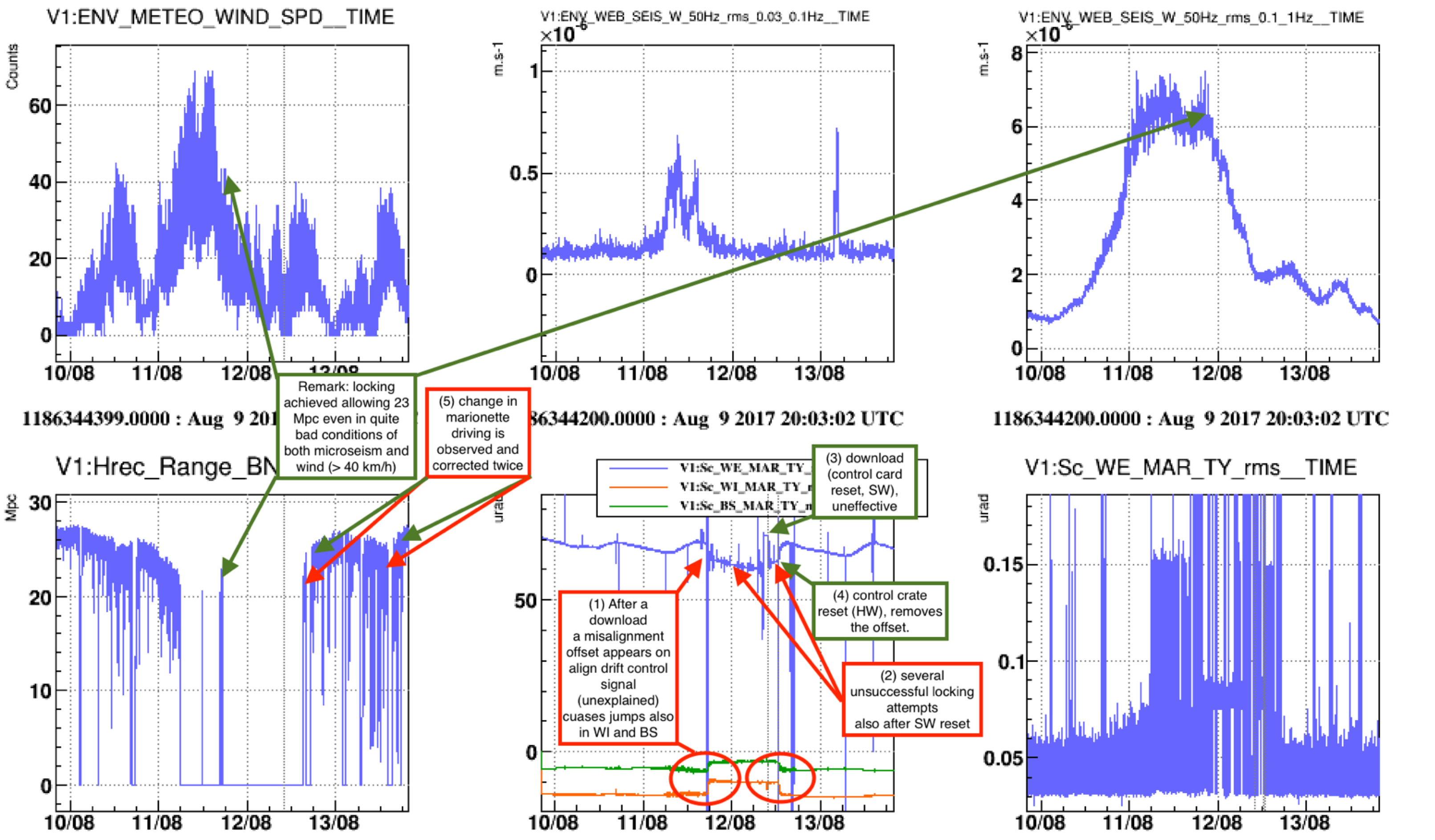
Virgo sensitivity graph is always misrepresented





Q (and thus susp. therm. Noise) was overestimated in the Advanced Virgo TDR due to overestimation of the effect of cabling near the TMs

Massive storm around 12 August 2017



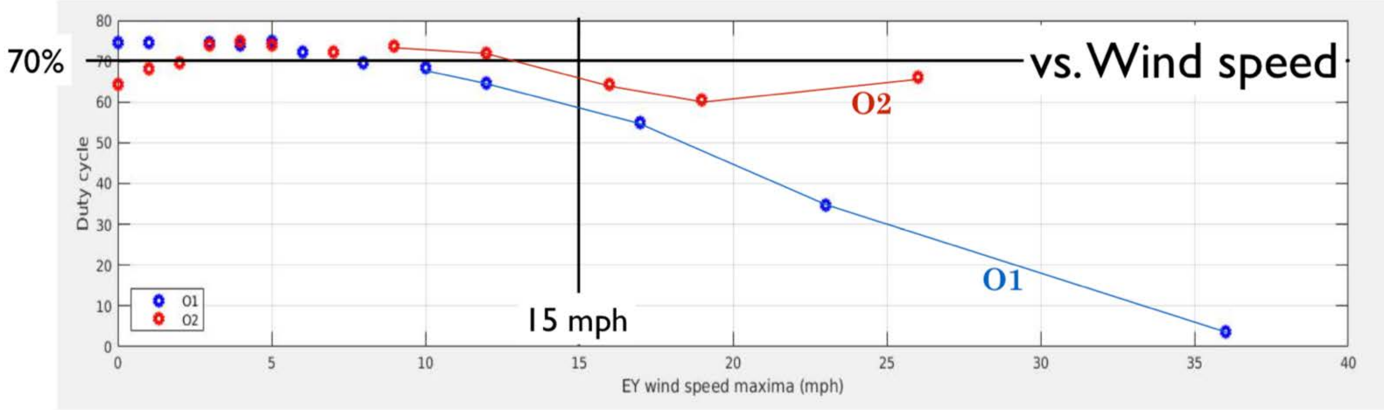
6 µm/s rms microseism

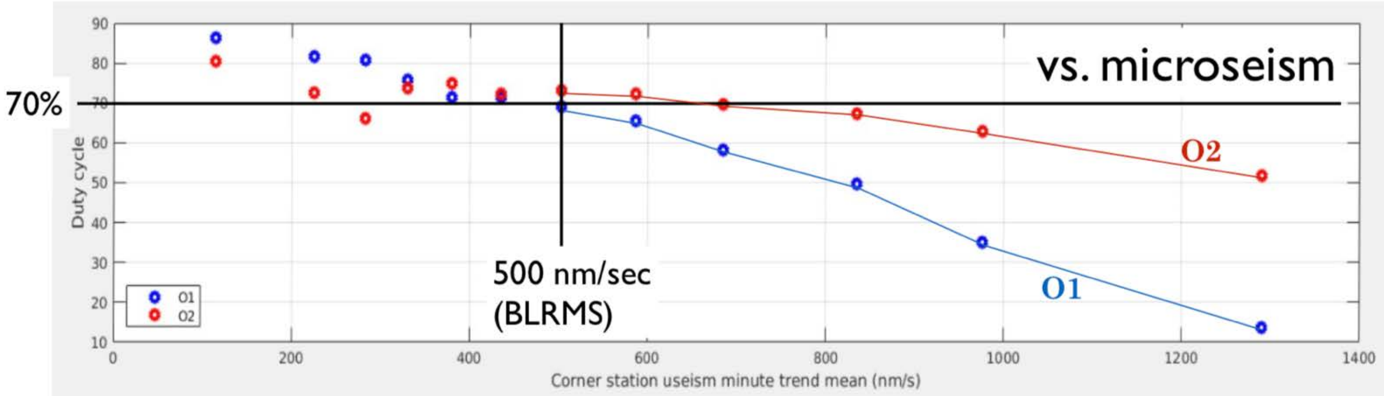
Misalignment offset procuring oscillation as DF operation is achieved; this oscillation, due to unbalanced radiation pressure on the mirror caused fast oscillation of the beam axis (B8) at yaw frequency of the WE mirror and then loss of power and unlock. This problem probably blanketed the other problem, sorted as (5) in the red square on the left side of the plot set. Notice that the problem disappeared only after HW reset of the crate.
Unbalancing in the driving, corrected twice, first as the system was recovered and also one day later in the night.

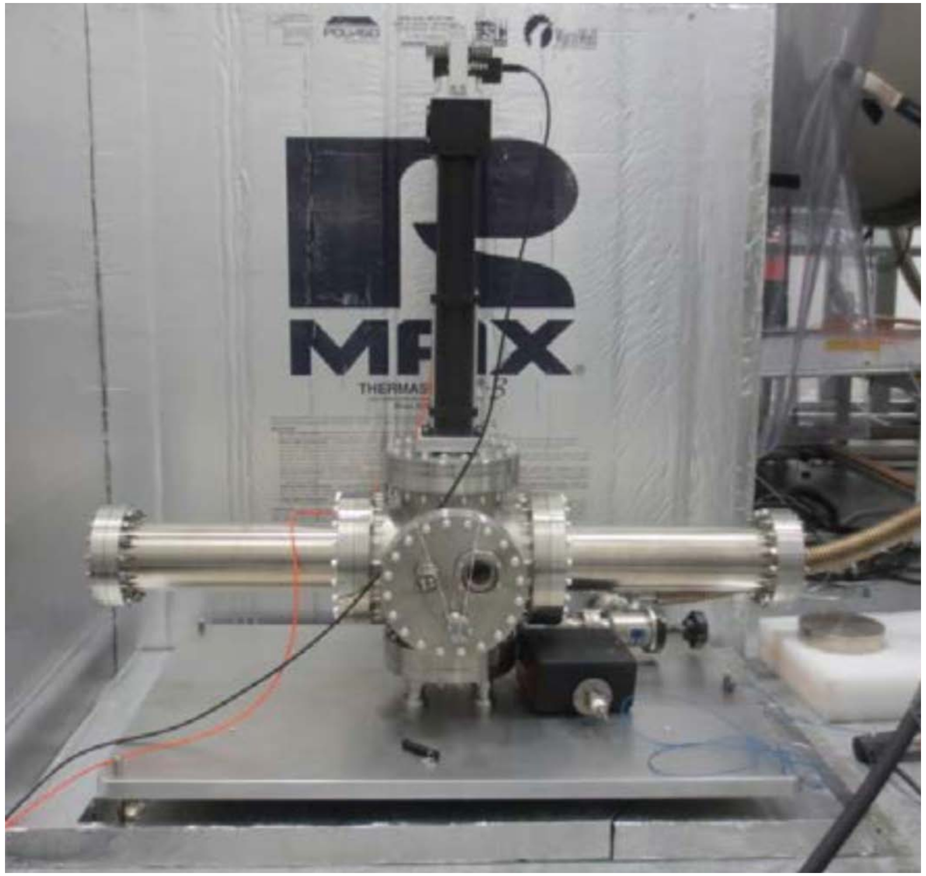
Source: Virgo logbook entry 39228

LIGOs Beam Rotation Sensor improves duty cycle

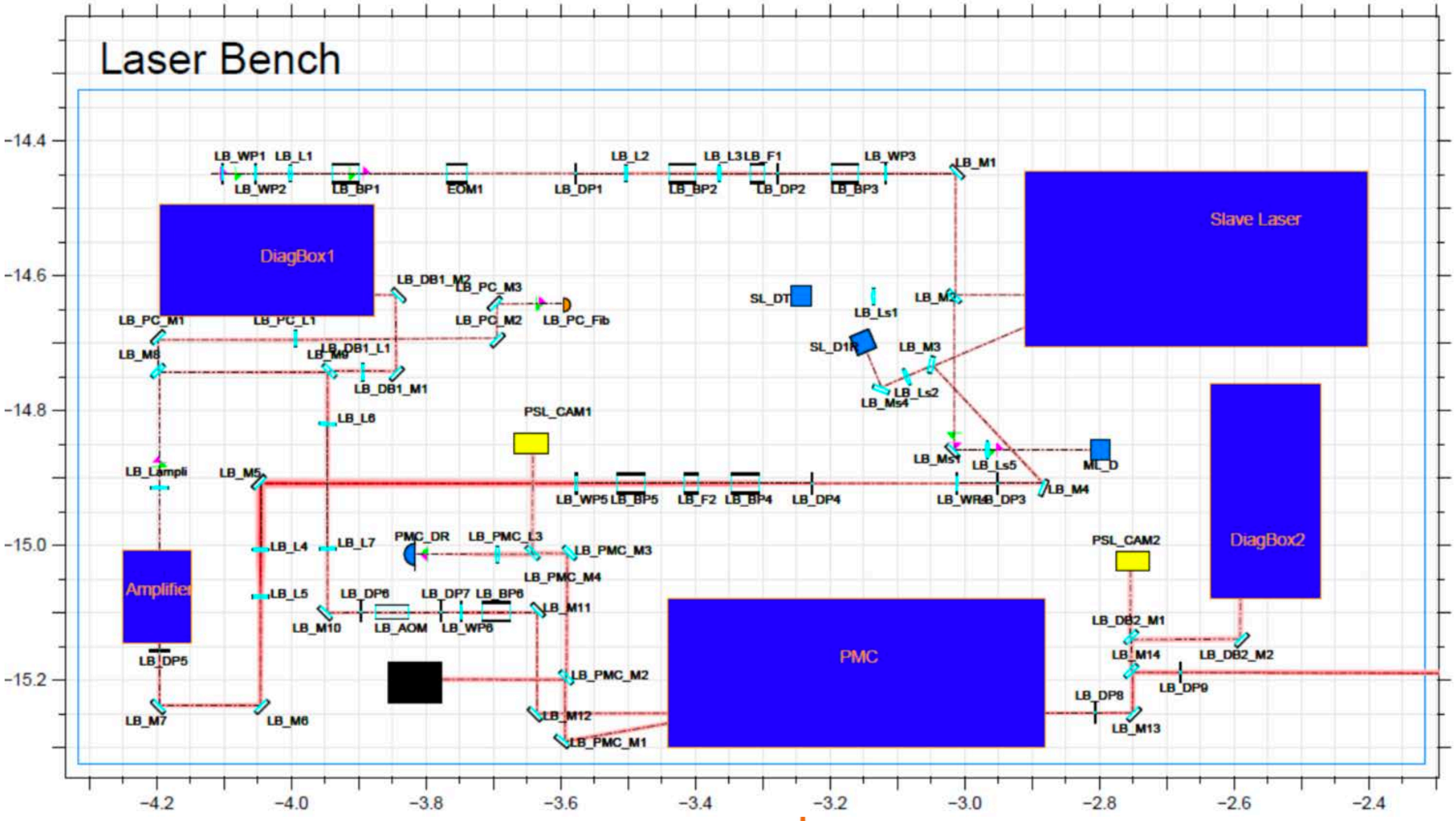
BRS impact at LHO







Laser bench layout during O3



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Frequency dependent squeezing design