Towards observational run O3 with Virgo detector

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Outline

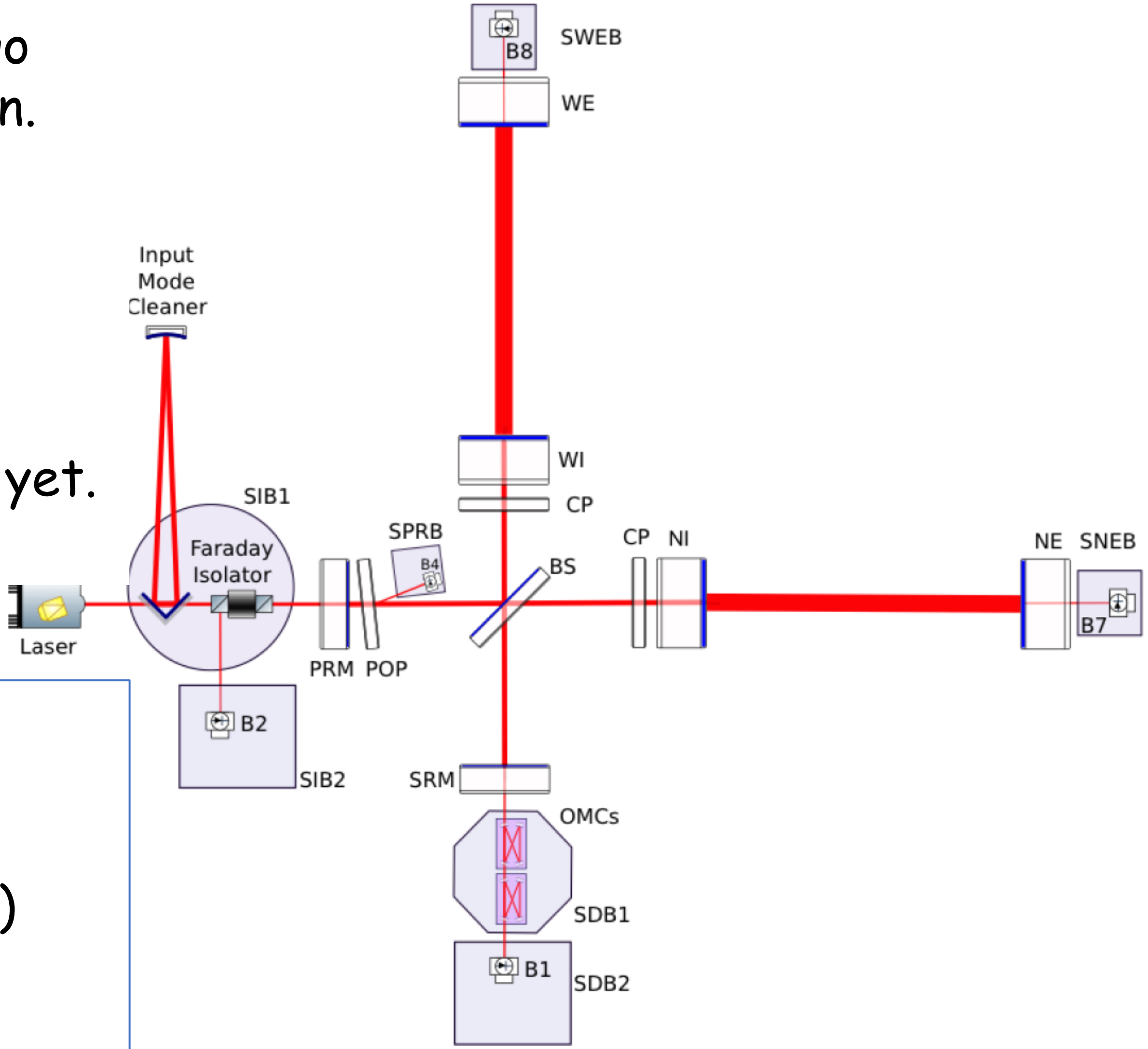
I. Advanced Virgo Status VS O2

II. Pending works, towards O3

III. Very short sight beyond O3

Advanced Virgo layout VS O2 configuration

- Rushing to join observational run O2 (2017), Virgo collaboration, adopted a preliminary configuration.
- Comparing AdV/Virgo, main features comparing were: **a)** adoption of a new optical layout and **b)** heavier test masses
- Many minor AdV features were not implemented yet.



O2

- x2 Mass of 3km FP cavity mirrors
- x2.5 larger beams
- Higher quality substrates (<0.5 nm Roughness)
- Improved coatings (<0.5 ppm, scattering <10ppm)
- x3 Higher Finesse
- Improved Thermal Compensation System
- Improved Stray Light reduction

Advanced Virgo layout

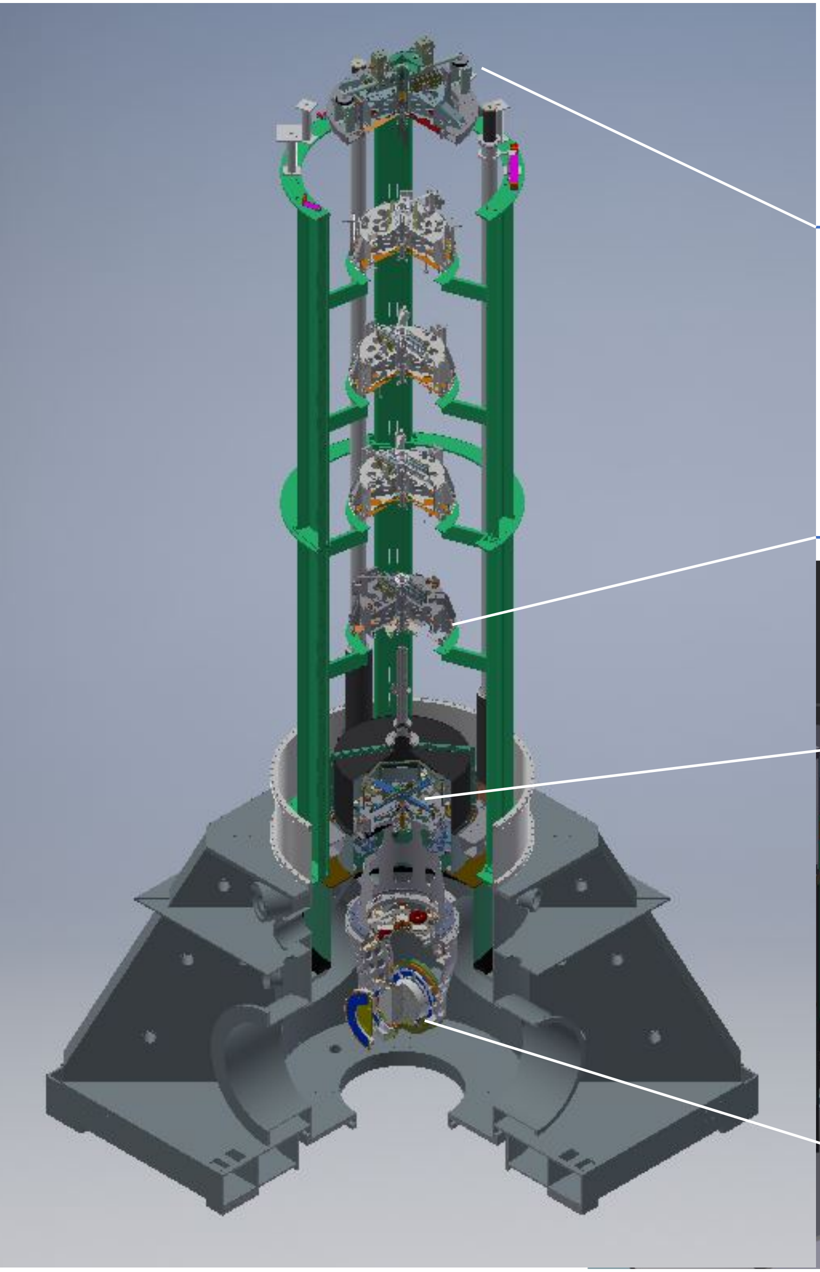
Main characteristics

- **SiO2 mirrors**, **350 mm** in diameter, **200 mm** thick, with residual roughness **< 0,5 x 10^{-9} m**.
- ***Marginally stable cavities***.
- ***Monolithic suspensions:*** SiO2 fibers **400 μm** in diameter to suspend mirrors ***42 kg in weight***.

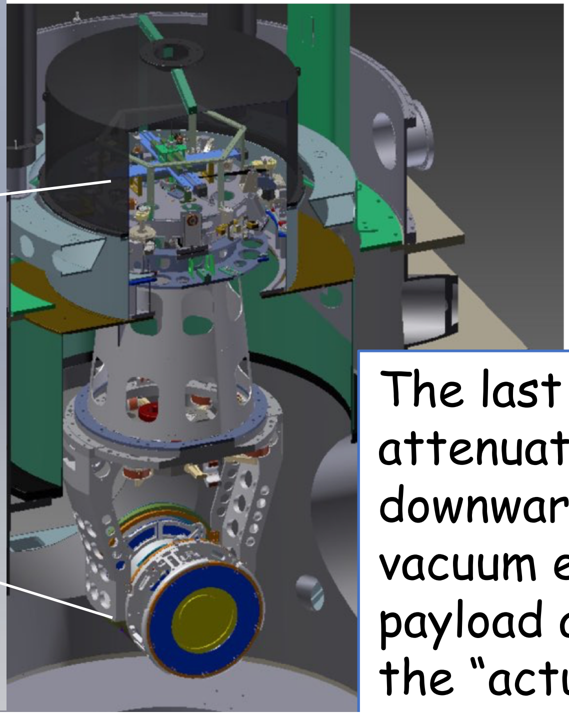
Also…

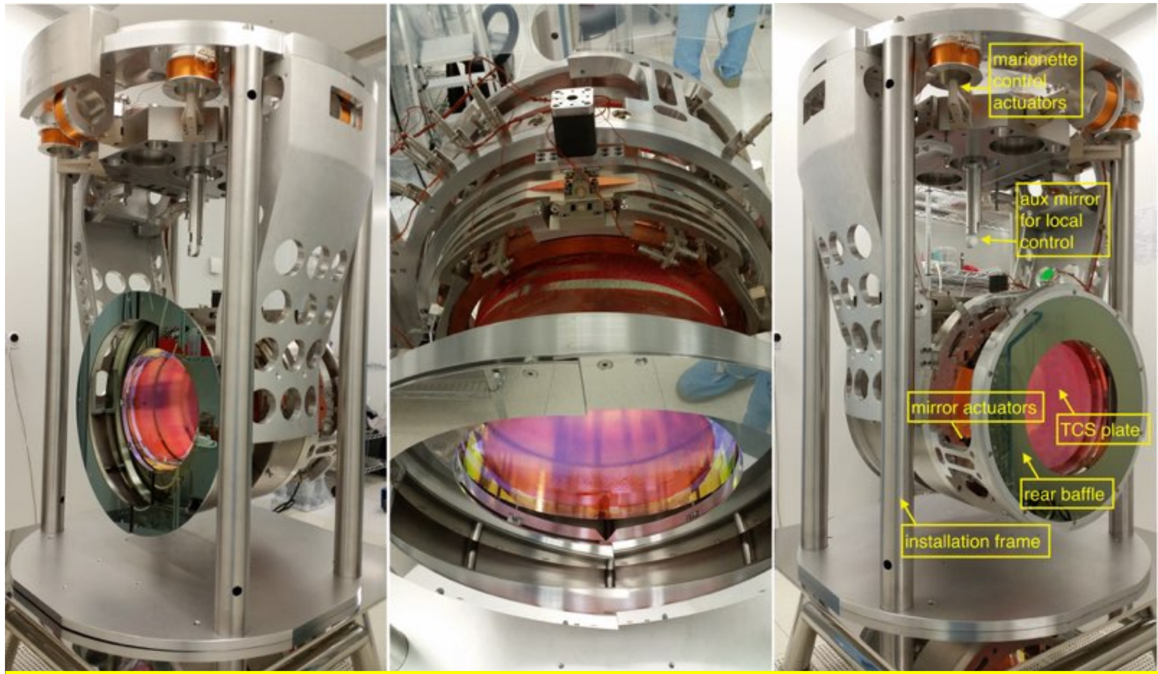
- Improved **Stray Light Control** suspended baffles
- Improved Thermal Compensation System
- ….

Test mass suspensions and seismic isolator: *overall system*



In AdV the first 5 stages of the Super-Attenuator (horizontal and vertical) are the same as in initial Virgo.





AdV quasi-monolithic suspensions, same successful design adopted since 2009, broke several times and a deep investigation was needed

The last filter of the Super attenuator, prolonged downwards, is in the same vacuum environment of the payload and surrounds it: the "actuation cage".

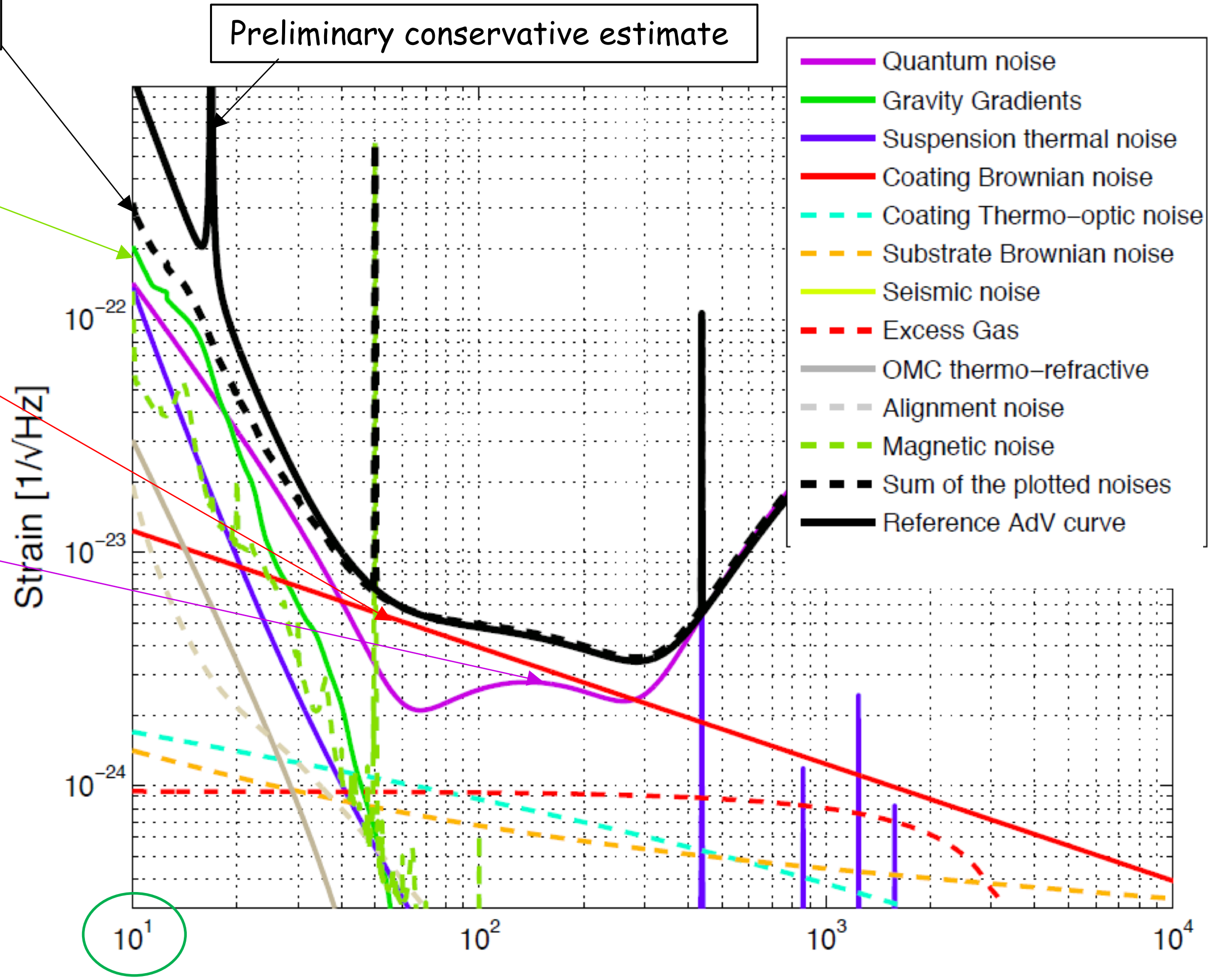
Target sensitivity

OVERALL

Low F:
Gravity Noise (Newtonian/Seismic)

Middle F:
Thermal Noise (mirror coating thermal noise)

High F:
Quantum Noise



Class. Quantum Grav. 32 (2015) 024001

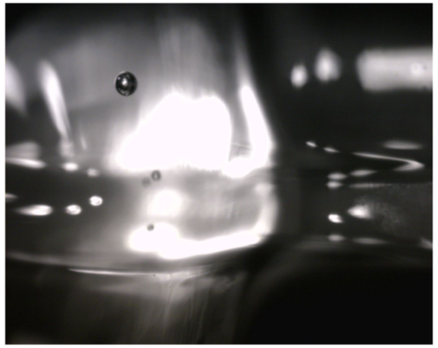
After O2 (i.e. after the first detection + further observations using Virgo)

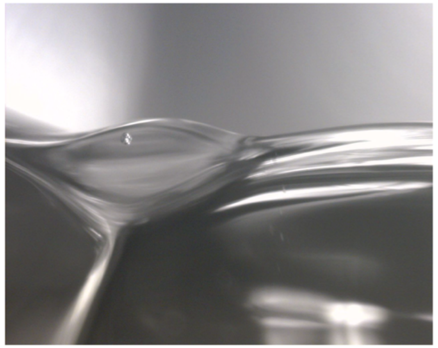
we worked to recover robustness, pending implementations, noise hunting & characterization … commissioning

Monolithic fused silica suspension

breaking failures nightmare:

typically weeks after installation, at rest, under vacuum





Evidences of isolated bubbles in 3/8 cases

Tests conducted through an intensive collaborative effort conducted also outside Virgo collaboration (e.g. Glasgow, ext. companies and research institution)

- Small bubbles in SiO2 (seemed the most promising)
- Quality of welding
- Mechanical impacts inside the payload structure
- Stress FEA studies
- Cleanliness and assembly procedures
- ……..
- Existence of a radioactivity near the payload (the most exotic)

Null identification of critical parameters

Investigation tools integrated in the procedure

Implementation of **non-critical improvements**

Monolithic fused silica suspension

On October 13th, 2016, just after the last fused silica suspension breaking, *we realized the event was clearly correlated with vacuum operations*

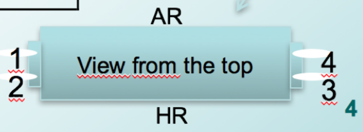
Material investigation study assessed that all the breakings failures started at the level of the fiber and not at the clamp/welding

Table of Payload Failures, *updated to Oct. 12 2016*

Failed Mirror	Failure date	Time in air	Time in vacuum	Failed Fiber	Anchor type	Likely cause
WI (1st assembly)	Nov 18th, 2015	5 months	9 days	3	old	Anchor collapse
NI (1st assembly)	Dec 18th, 2015	4.5 months	5 days	2	old	Fiber/welding failure
NI (2nd assembly)	Mar 1st, 2016	1 week	5 days	2	new	Fiber/rod failure
NE	Oct.12 2016	6 months	4 months (currently	TBD	new	TBD
WI dummy (1st assembly)	Apr 25th, 2016	1 week	11 days	1	mixed old	Anchor collapse
WI dummy	No failure	2 days	2 weeks		mixed old	No failure
WI (2nd assembly)	June 25th, 2016	1 month	30 days	3	new	Fiber/welding failure
WE (1st assembly)	Jun 28th, 2016	7 months	18 days	3	new	Fiber/welding failure

New identification of failed fiber, after revision of Aug.2016

Mirror Reference System



…from the report to the STAC, October 18th 2016

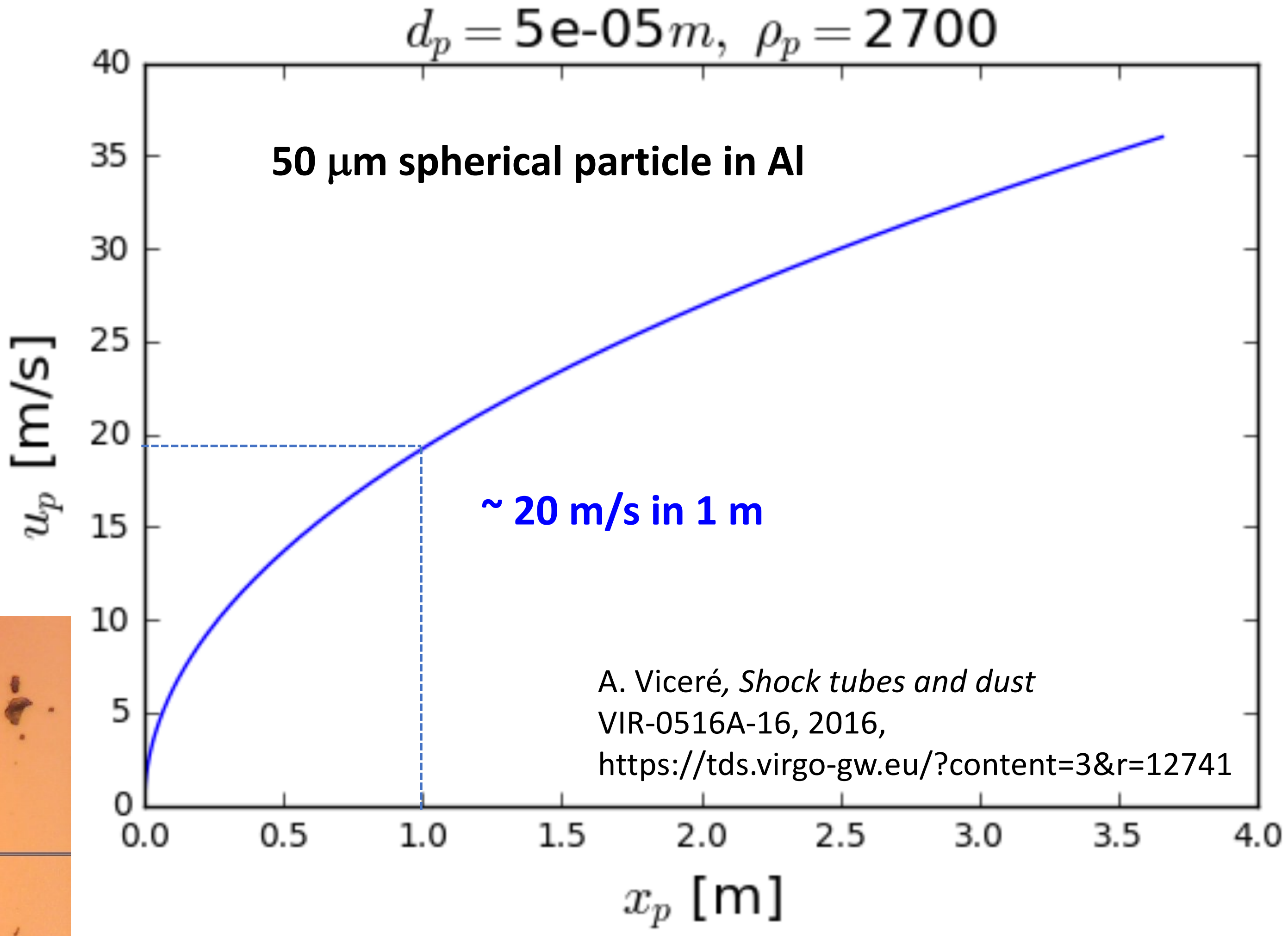
Piero Rapagnani – Virgo Week January 24th 2017

Breakdown causes finally identified as arising from vacuum/venting inlets at least in 7/8 cases.

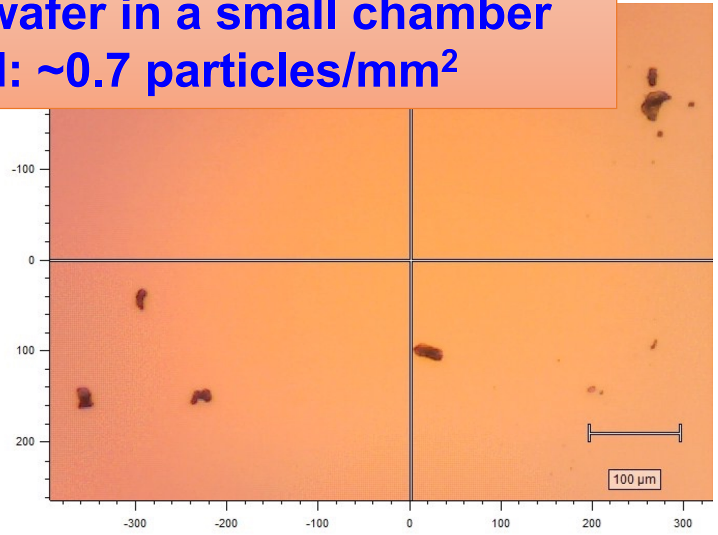
Vacuum: *dust bullets VS monolithic suspension*

During venting, air shock waves can accelerate 50-100 μm particles at rest up to 20-50 m/s over a 2 m travel.

The kinetic energy of these particles is large enough to break a fiber under stress.

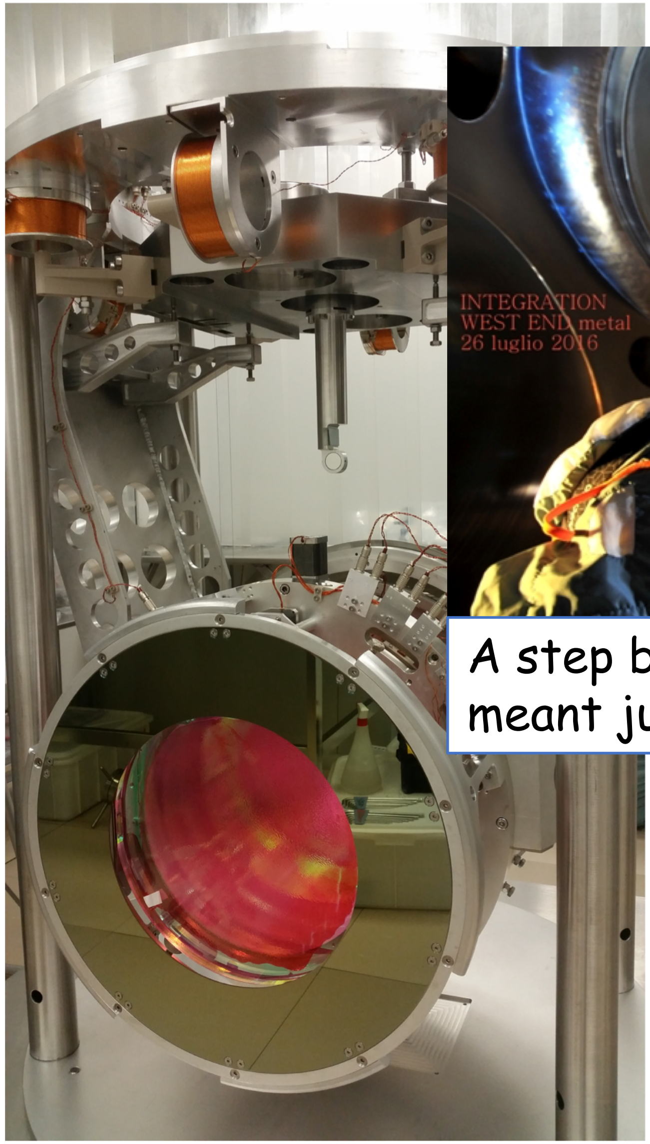


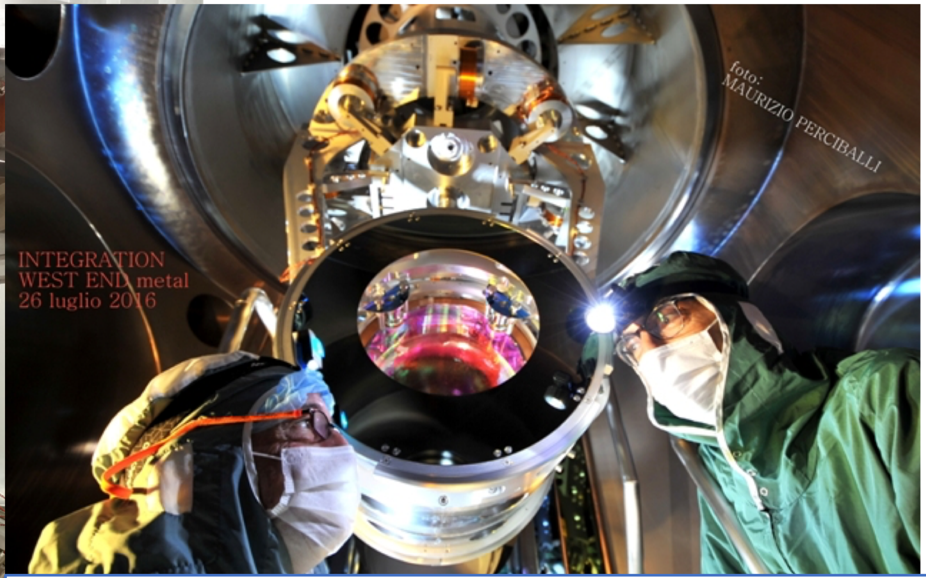
Dust abundance on wafer in a small chamber evacuated by a scroll: ~0.7 particles/mm²



Breaking through dust bullets experimentally verified

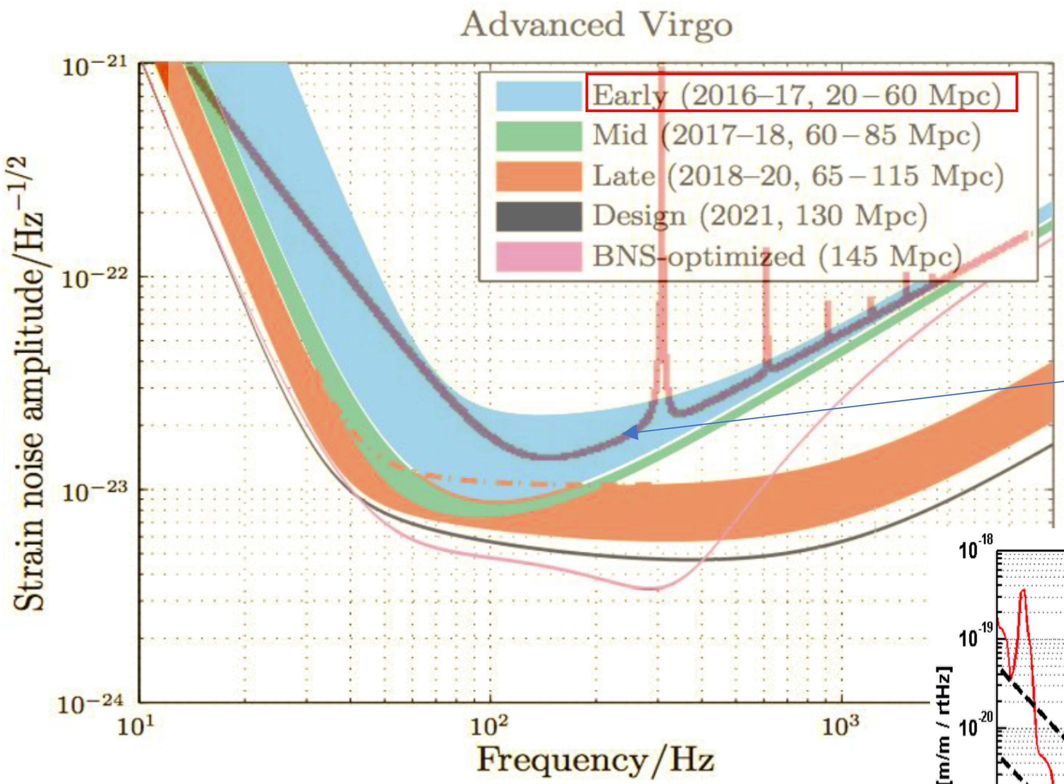
Backup solution: *readapting payload to steel wires to join O2*



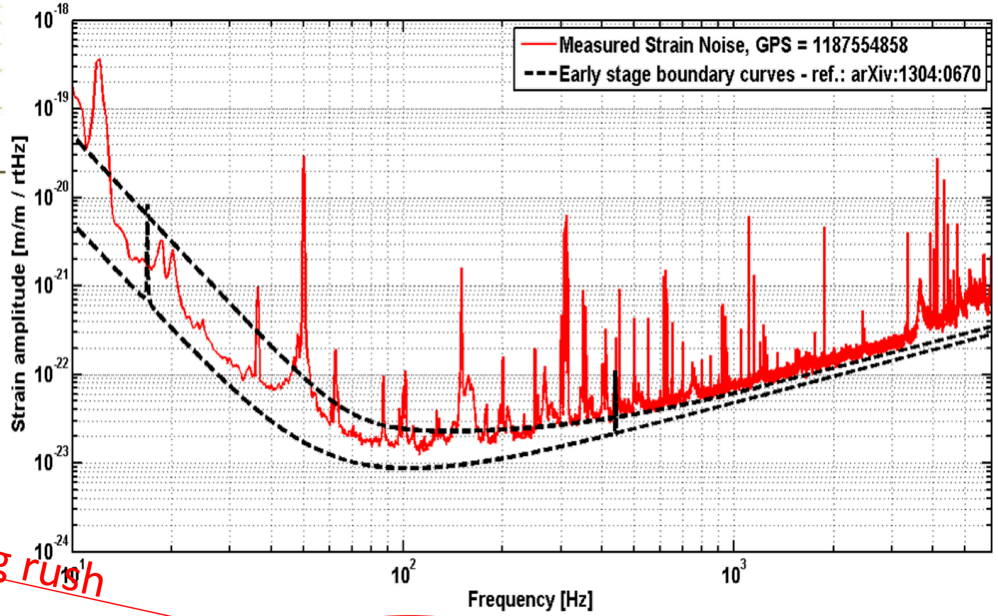


A step backwards (…before V+, 2011 !),
meant just to allow AdV commissioning

Monolithic suspensions: *Sensitivity VS steel-wire backup*



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



Steel ***(*** ϕ ***=10^{-3})***

Horizon NS-NS - 45 Mpc

Horizon BH-BH - 202 Mpc

Monolithic

Horizon NS-NS - 101 Mpc

Horizon BH-BH - 985 Mpc

Through a very fast commissioning rush

BNS range → 28 Mpc → **ready to join O2!**

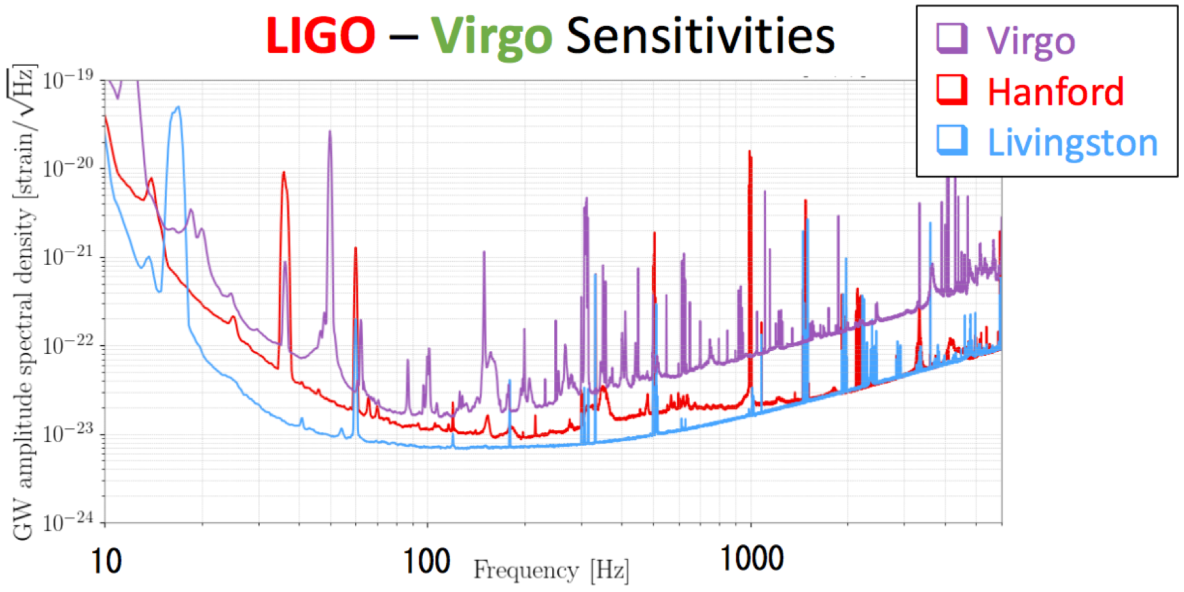
SUMMARY

- **O1** ~49 ***days*** of coincident **LIGO** data
- **O2** ~120 ***days*** of coincident **LIGO** data
  ~16 ***days*** of coincidence with **Virgo** data
  10 GW alerts for EM follow-up

Averaged distances to which Binary Neutron Star could be detected

VIRGO : 26 Mpc
HANFORD : 55 Mpc
LIVINGSTON : 100 Mpc

LIGO – Virgo Sensitivities



❑ observations 2015-17 vs 2010:
averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events

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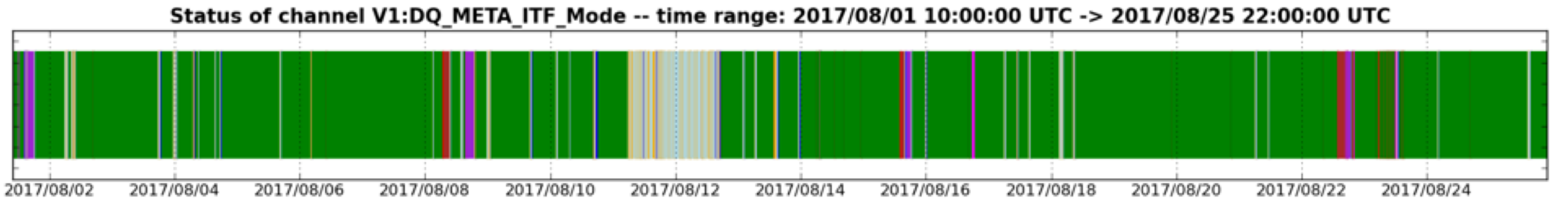
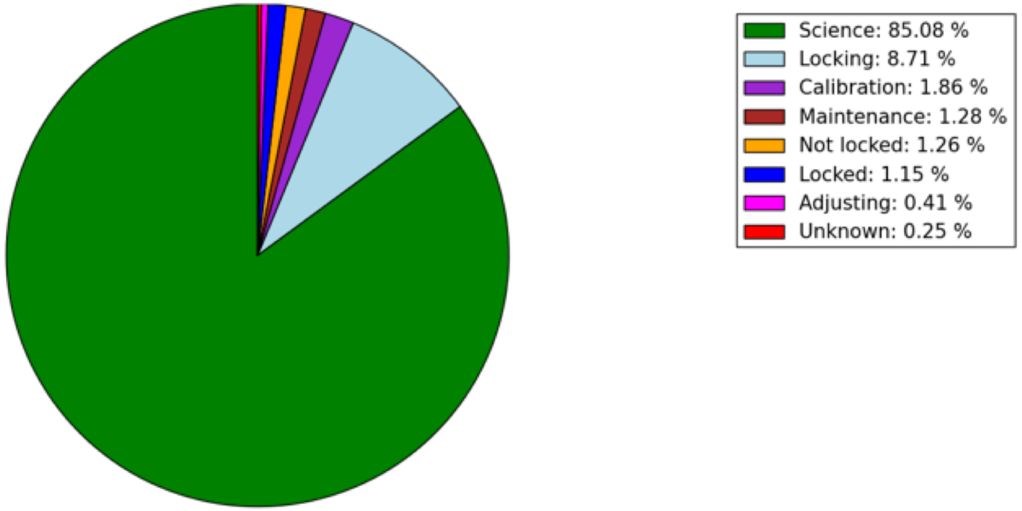
O2



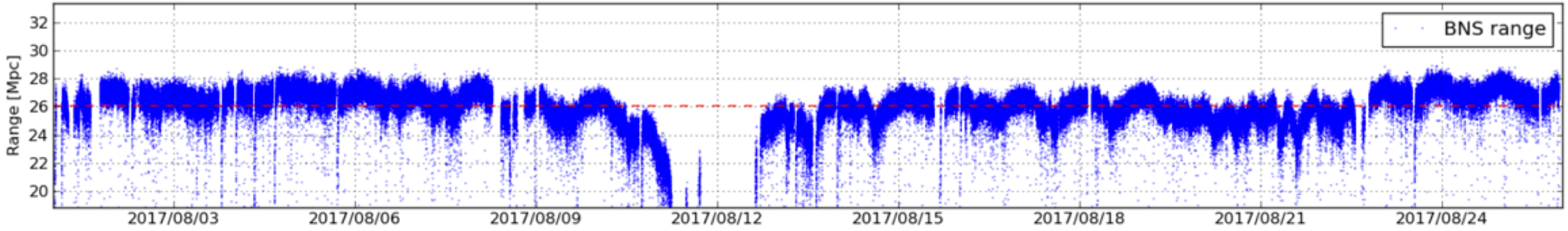
Quiet weather conditions (summer)
Good duty cycle (85.5% in spite of some technical bug)



Highest BNS range: 28.2 Mpc

Average ranges: BNS 26 - BBH_{10} 134 - BBH_{30} 314 Mpc

Short duration
Glitchness to be reduced
Automatic Alignment accuracy to be improved

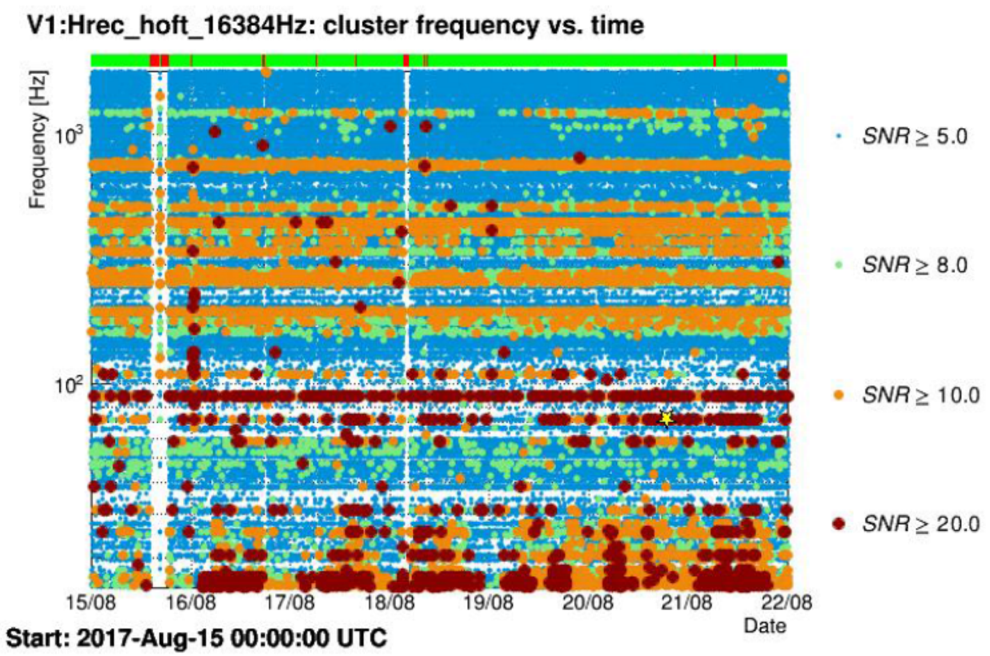


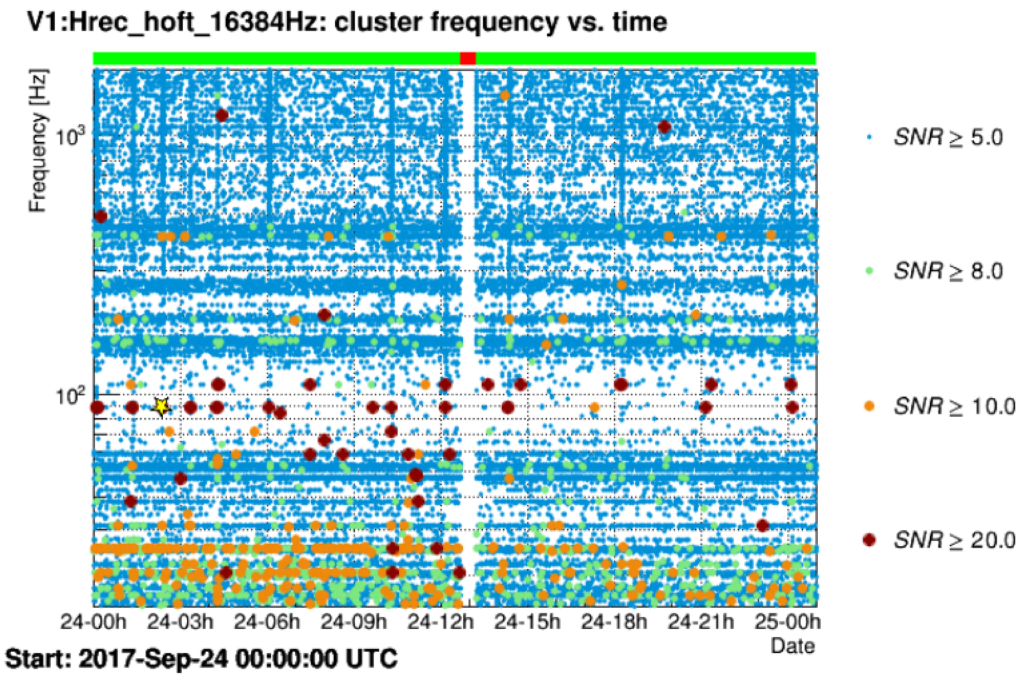
Two well know events detected through LIGO-Virgo network

Post-O2 commissioning (fall 2017),
to tackle most relevant pending issues

Limited BNS range improvement
Maximum value reached around 30 Mpc, Mean O2 range: 26.5 Mpc

Glitch rate significantly reduced (autoalignment, Global Inverted Pendulum Control…)





Still a significant difference with respect to the max performance achievable with steel suspension

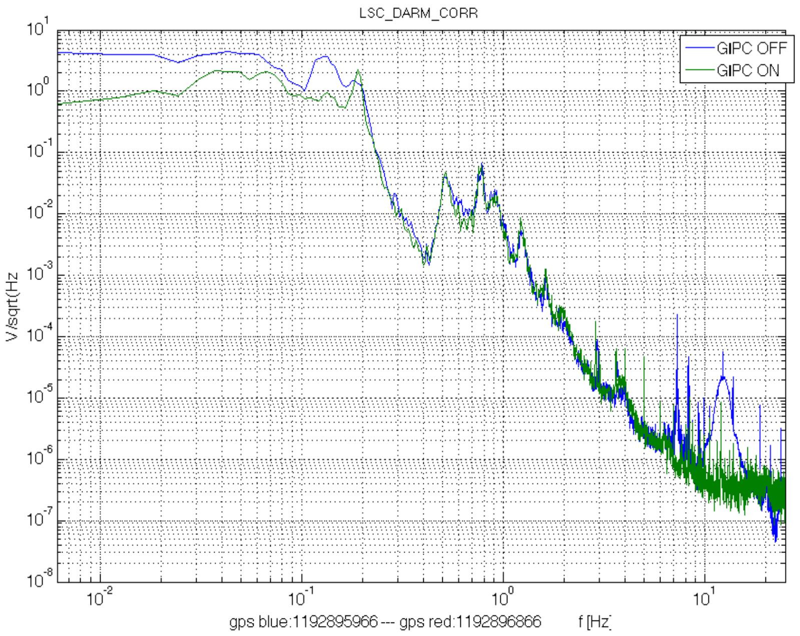
Nevertheless, go ahead with upgrades

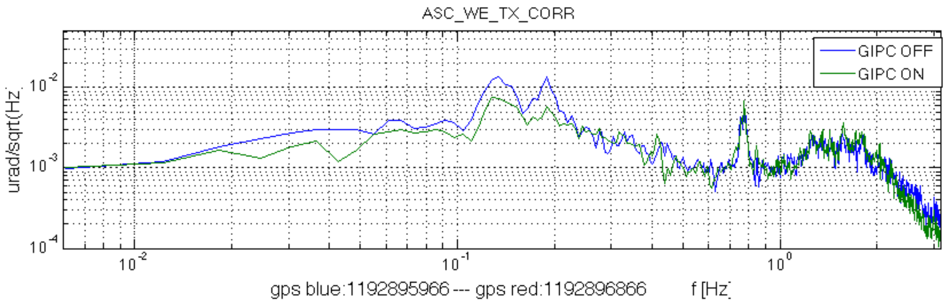
Overall suspension improvement

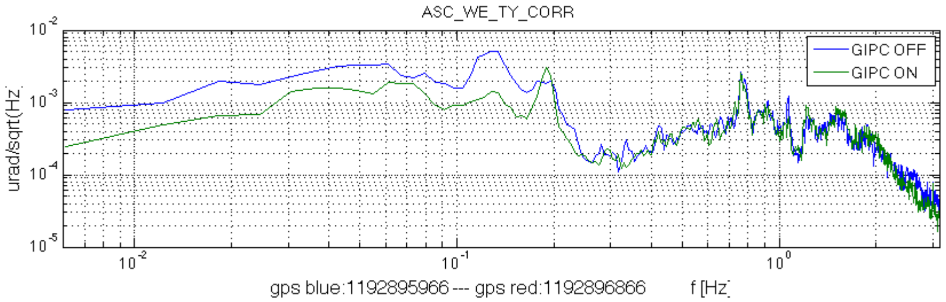
- Global Inverted Pendulum Control (GIPC) is a technique already used in VIRGO in which common and differential error signals are built-up to control the seismic suspension top-stages.

- In particular, FP cavity correction can be used to derive differential signals along each arm

- Using this strategy the crossover frequency of the Position/Acceleration blending filters can be tuned and lowered (20 mHz, 30 mHz), improving the rejection of microseism, and making the system much more robust

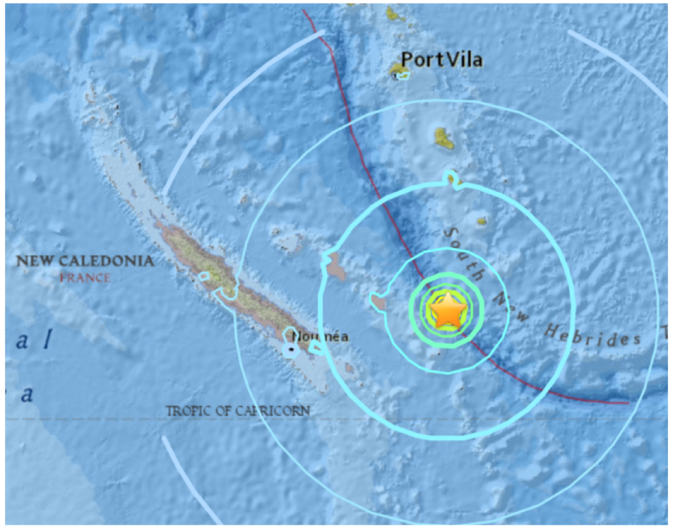




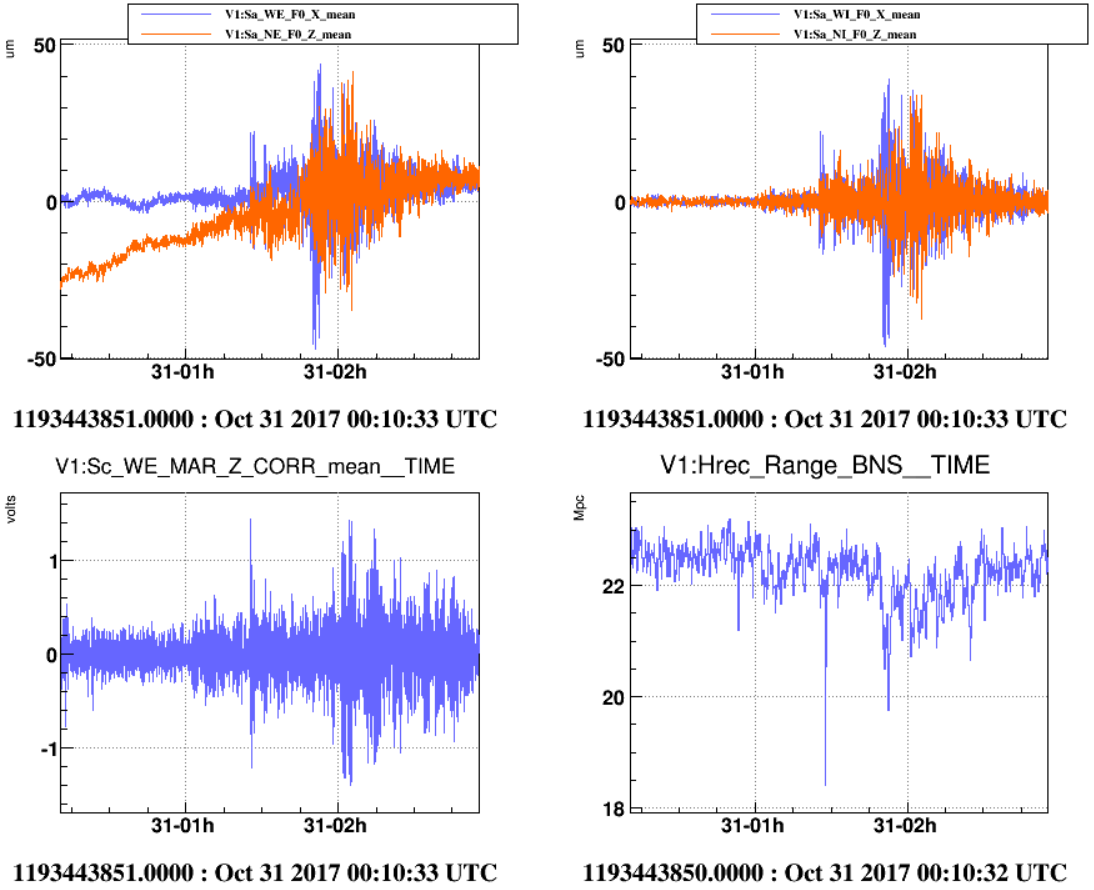


Inertial damping strategy *Global Inverted Pendulum Control (GIPC)*

An example of a strong earthquake that would very likely unlock the IFO without GIPC



M 6.8 - New Caledonia
2017-10-31 00:42:06 UTC
21.660°S 169.203°E
11.1 km depth



Upgrades after O2

- Upgrades before O3

priority

I. Monolithic suspensions

II. Vacuum system modifications

III. Squeezing (AEI)

IV. LASER amplifier integration

V. Integration of seismic sensors deployed around ETM for NN studies (monitor)

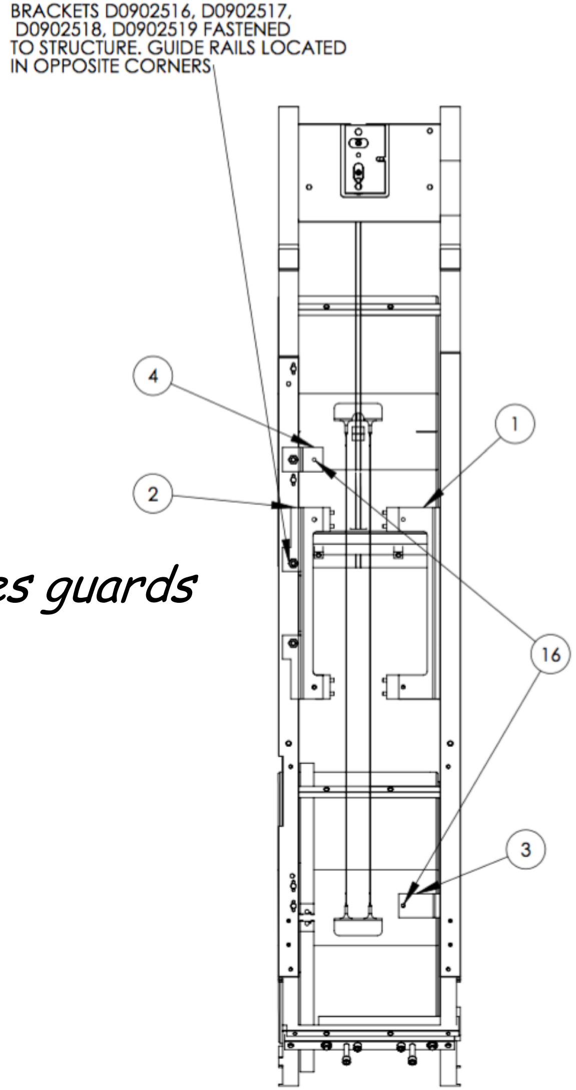
During O2 (GW detection in August 2018) Virgo adopted steel wires in the last stage suspension, as a backup solution

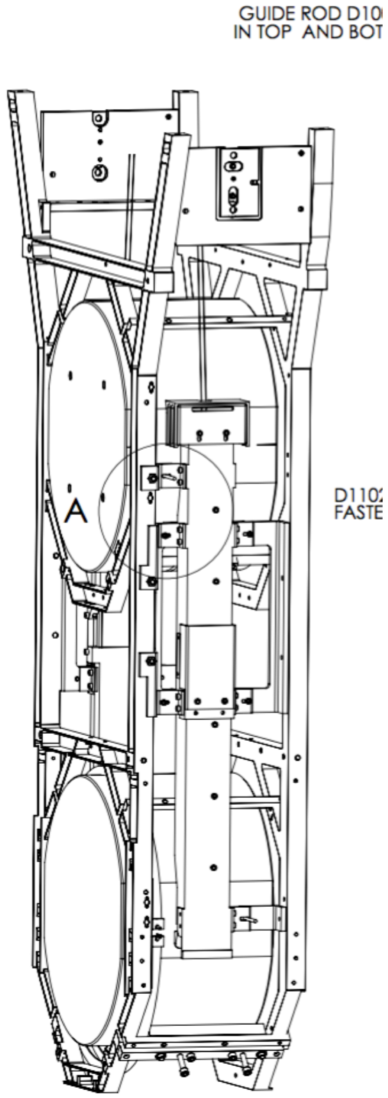
- Upgrades after O3: High Power Laser operation, Squeezing (2° phase)… Signal recycling

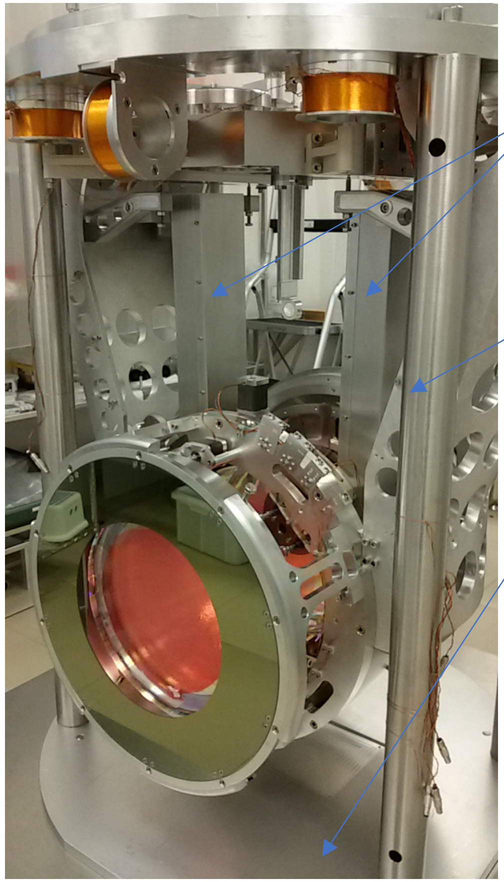
Trouble on Monolithic suspensions, solutions:

fiber guards to protect fibers against any external mechanical agent

Also LIGO uses guards

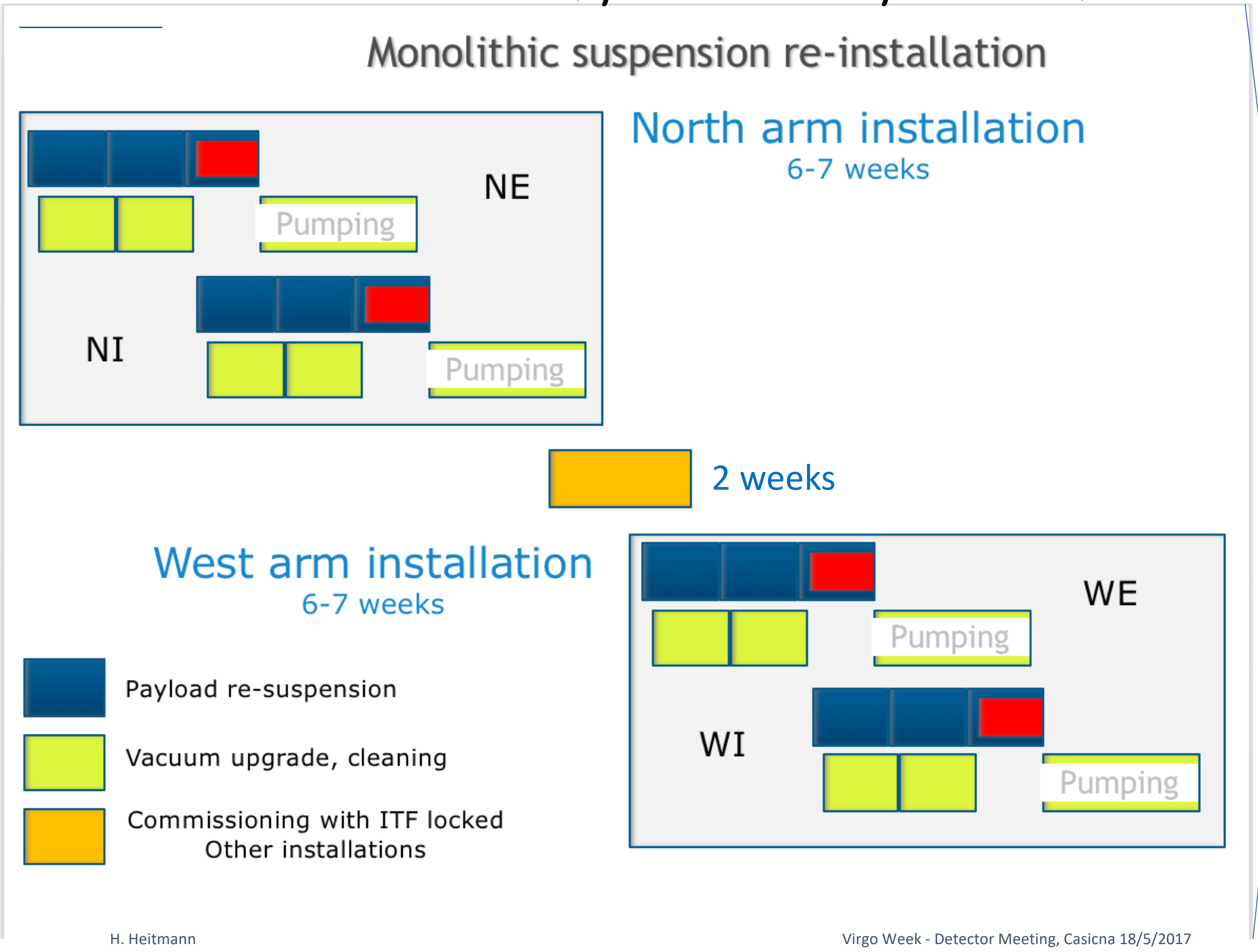






Planning towards O3 assuming to start in fall 2018

rush, parallel compression, accuracy



14-16 weeks

Done in 14 weeks

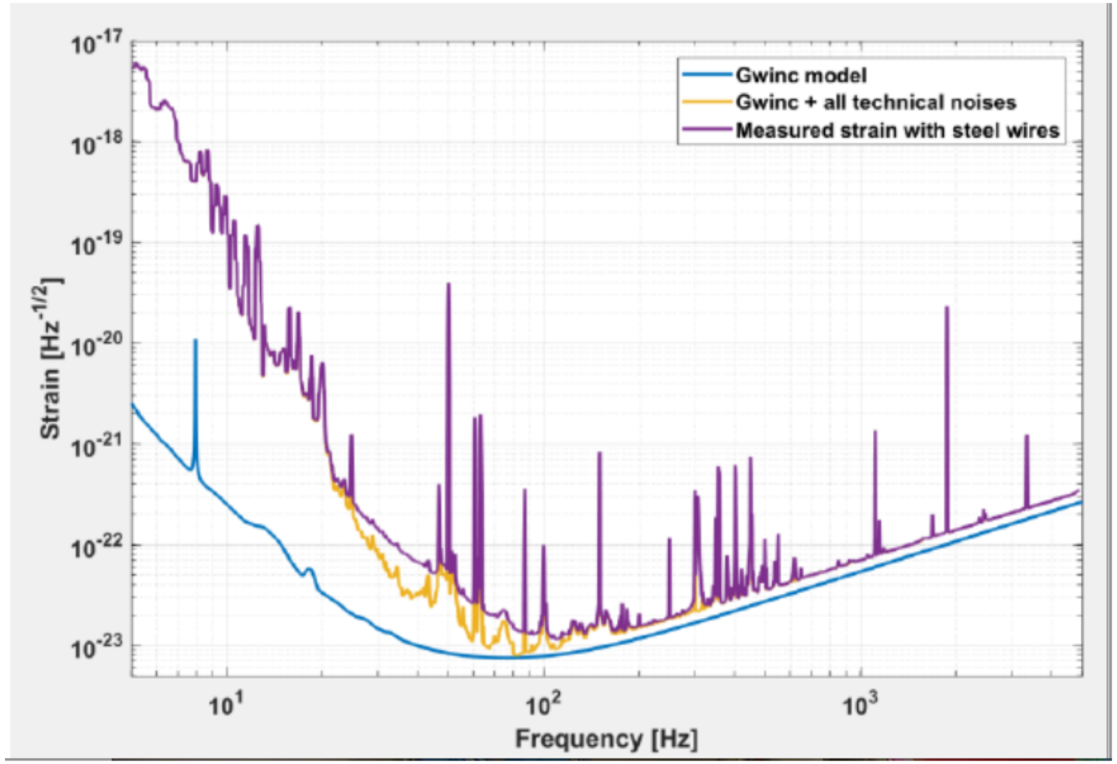
including recovery of four unforeseen issues (2 weeks)

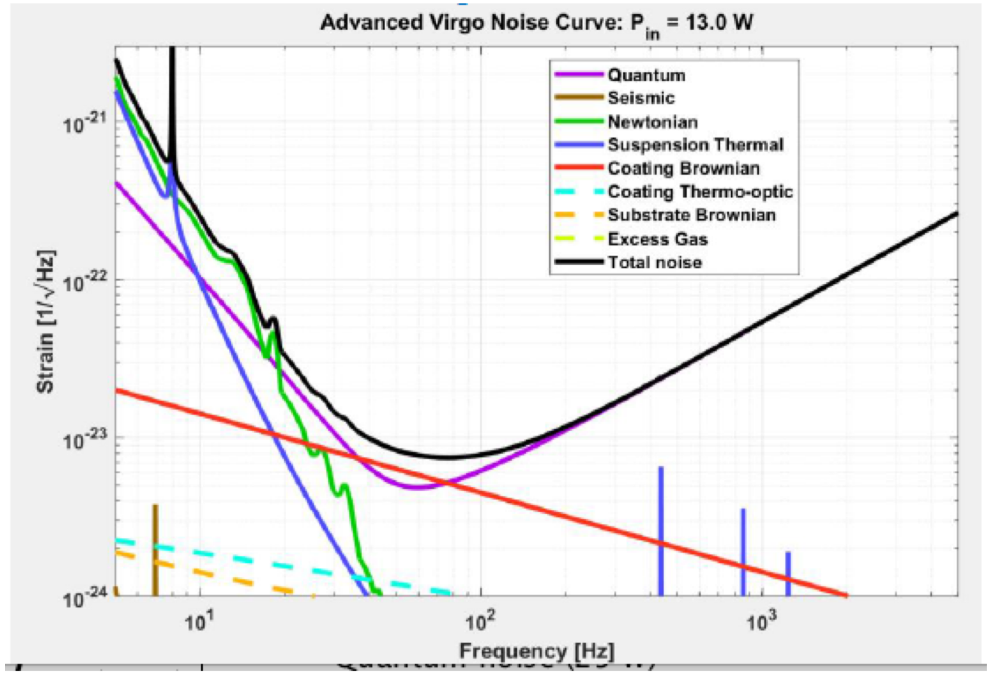
Towards O3 assuming to start in fall 2018

rush, parallel compression, accuracy

Strategy:
- Reserve commissioning time
- Limit the number of upgrades

Target sensitivity for O3: 60 Mpc NSNS std candle
- Main benefit: monolithic suspension as removing the steel wire thermal noise provides a 20 Mpc range increase

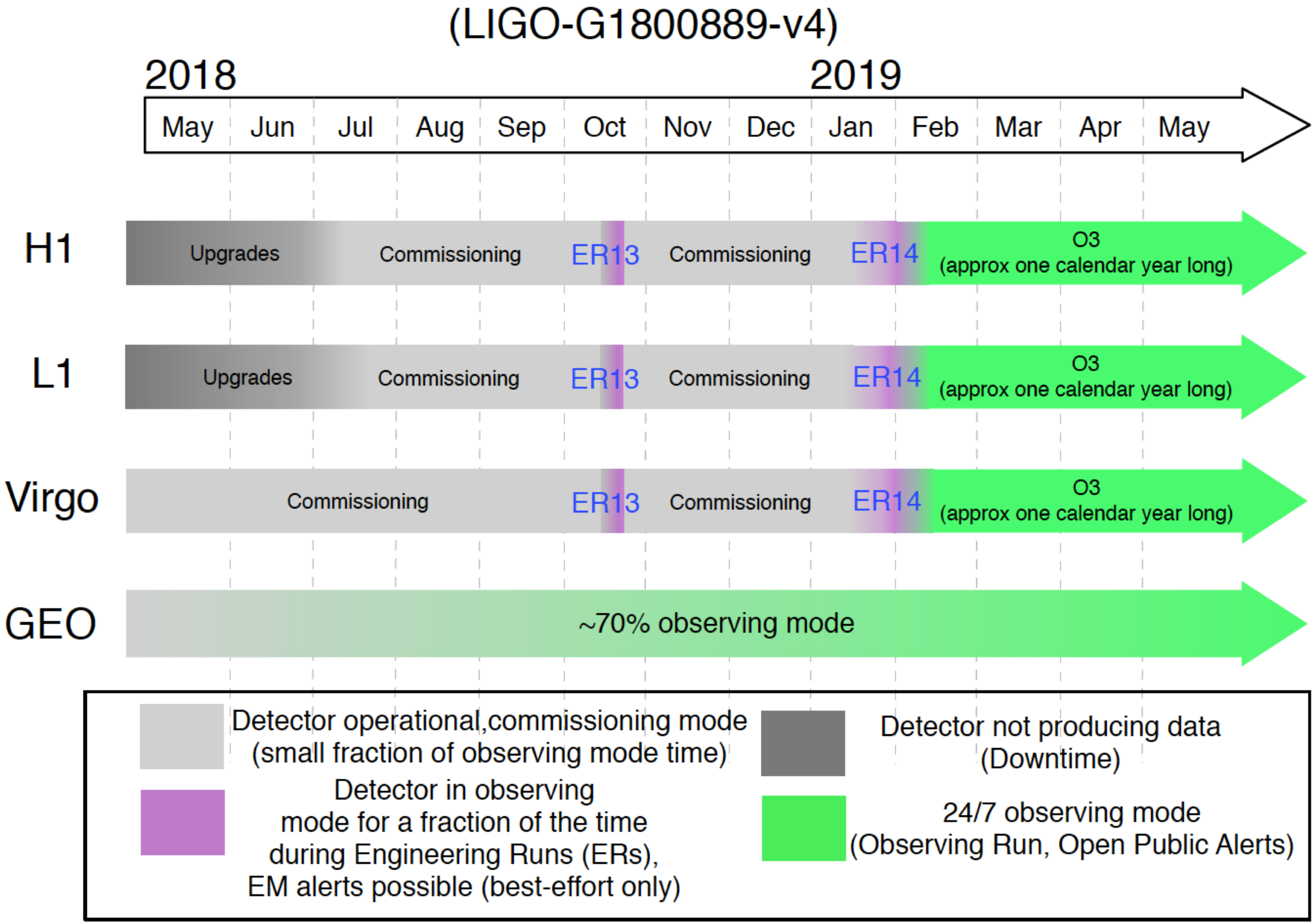




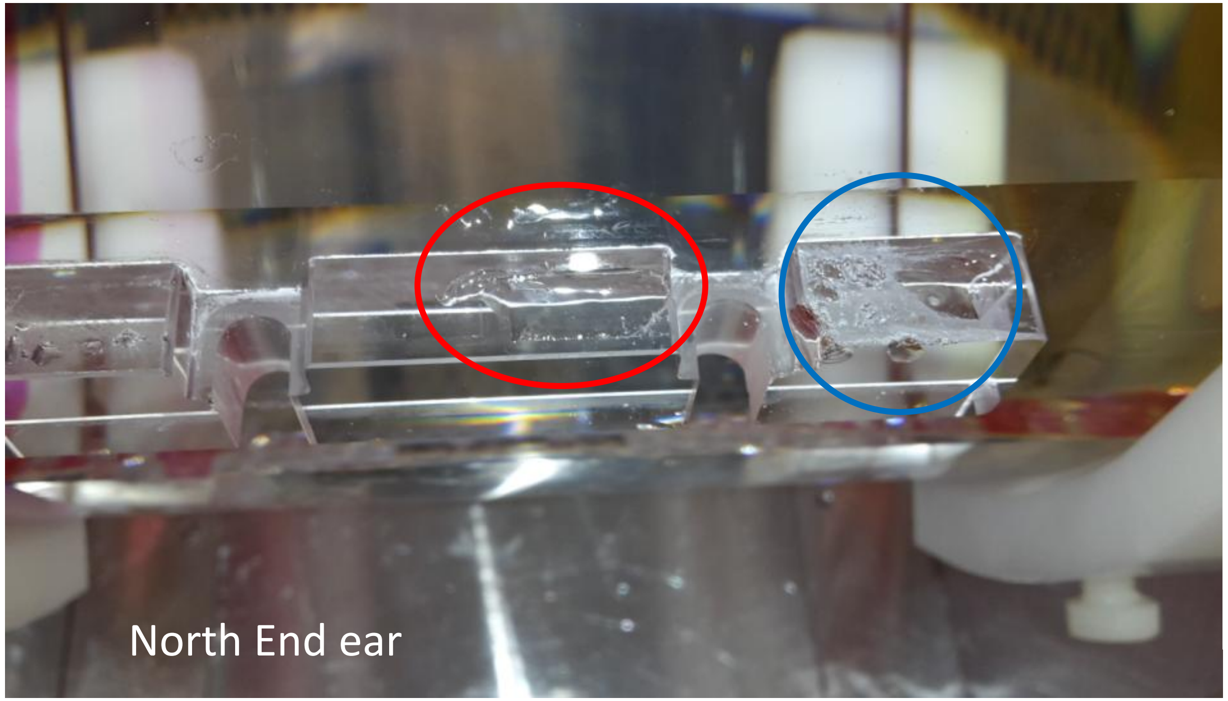
Why a long commisssioning **is** an issue:

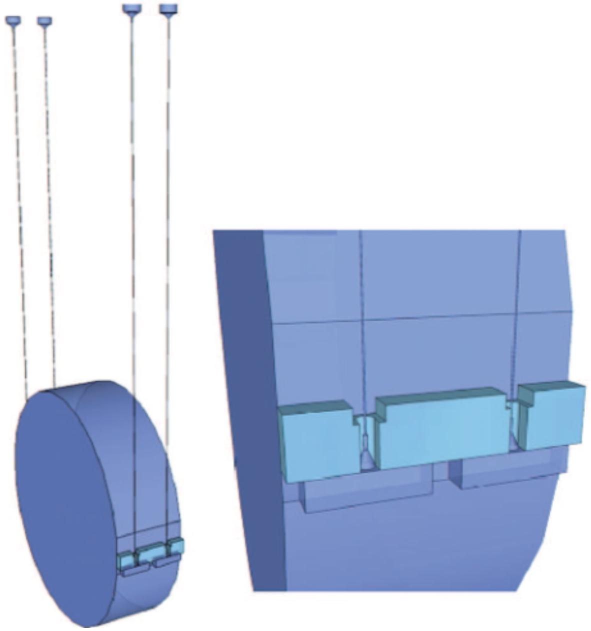
- Significant technical noise to be removed
- Several other (minor, pending) issues in the planning

Updated timeline



Thermal Noise expected improvement:
checking actual implementation



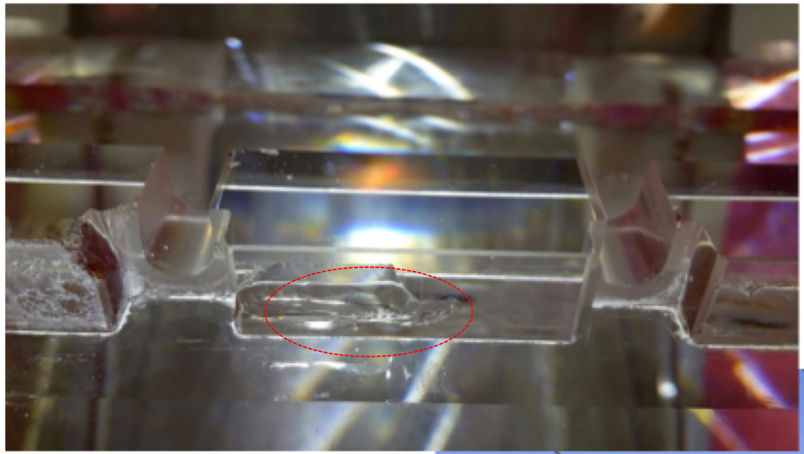


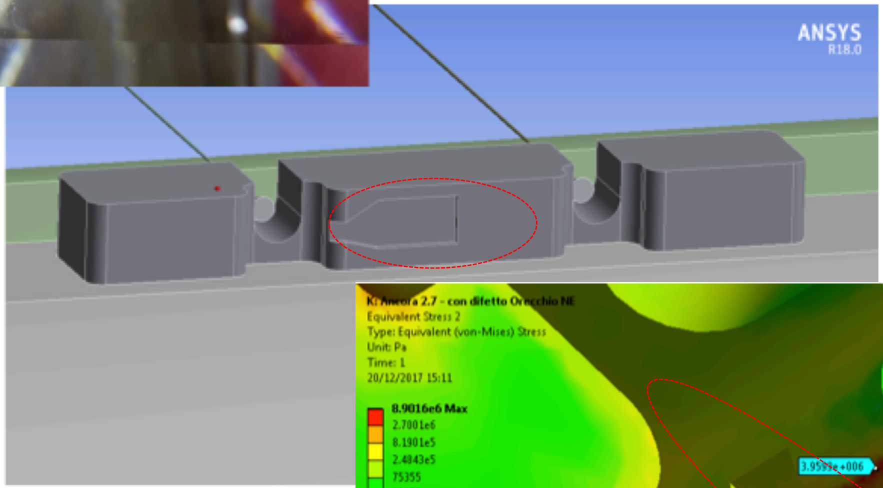
- Breaking of fibers had caused destruction of anchors
- Removal of anchors left holes in ear surface
- Gluing of new anchors to ears was still possible
- But a new failure could make it impossible
- Ears are "hard" bonded to mirror flat – cannot be removed

Actual monolithic suspension:
status of mirror ears after fiber breakings, stress/ thermal noise

Mechanical stress in the damaged ear, after gluing of anchors, is far from breaking strength

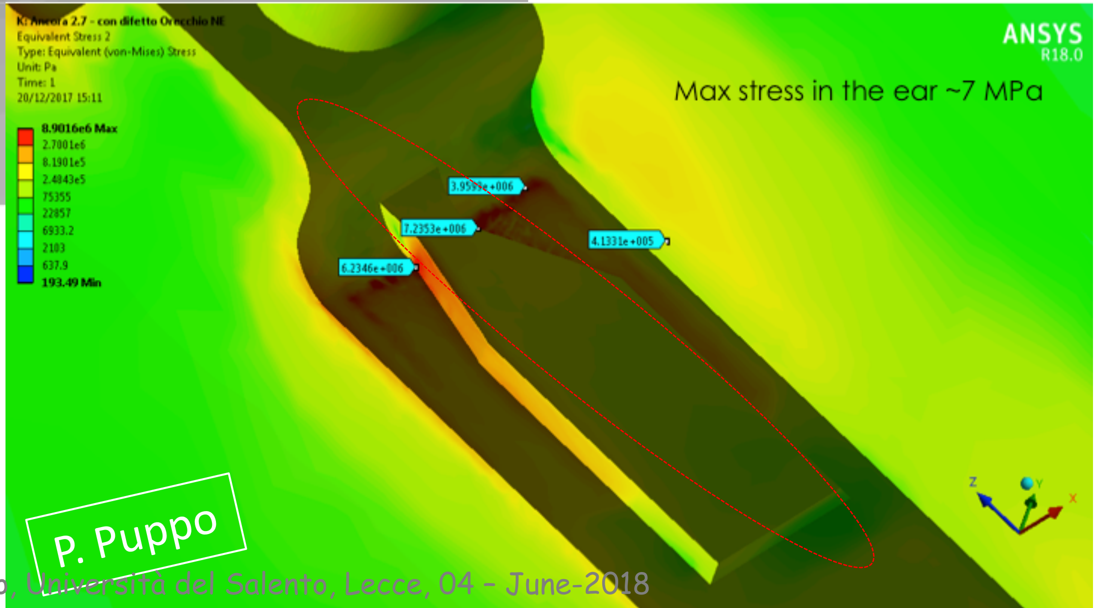
7 MPa vs. 1 GPa in compression





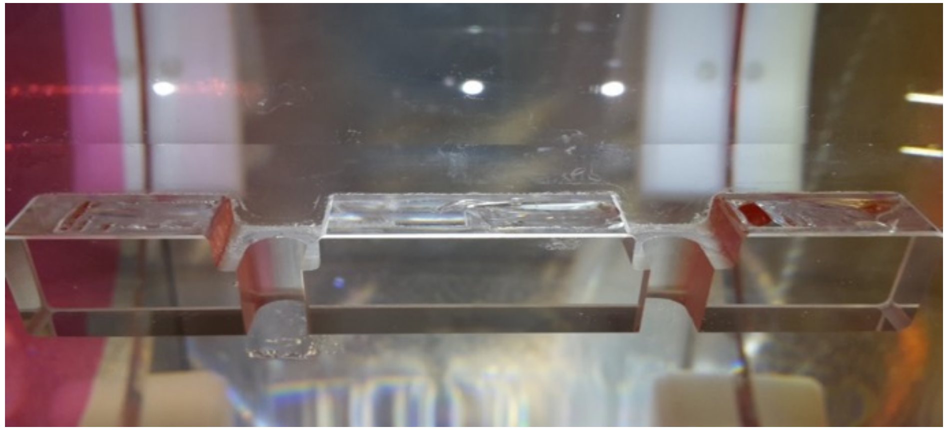
Defect dept 1mm
Area 81 mm^2

Anchor contact area
~2mm width



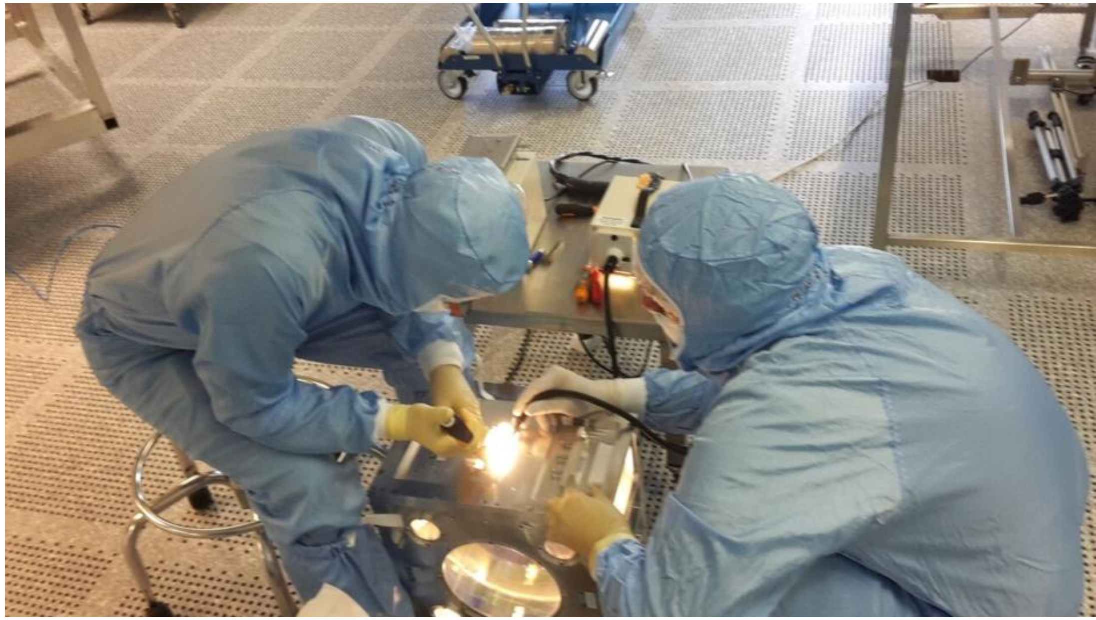
Thermal noise is OK if the ear **holes** are **not** filled with glue
(Talk by L. Naticchioni)

Thermal Noise and risk mitigation: *Spare mirror preparation*



- End mirror spares ready (coated, glued)
- Coating/gluing of input mirrors: all will be ready mid-July

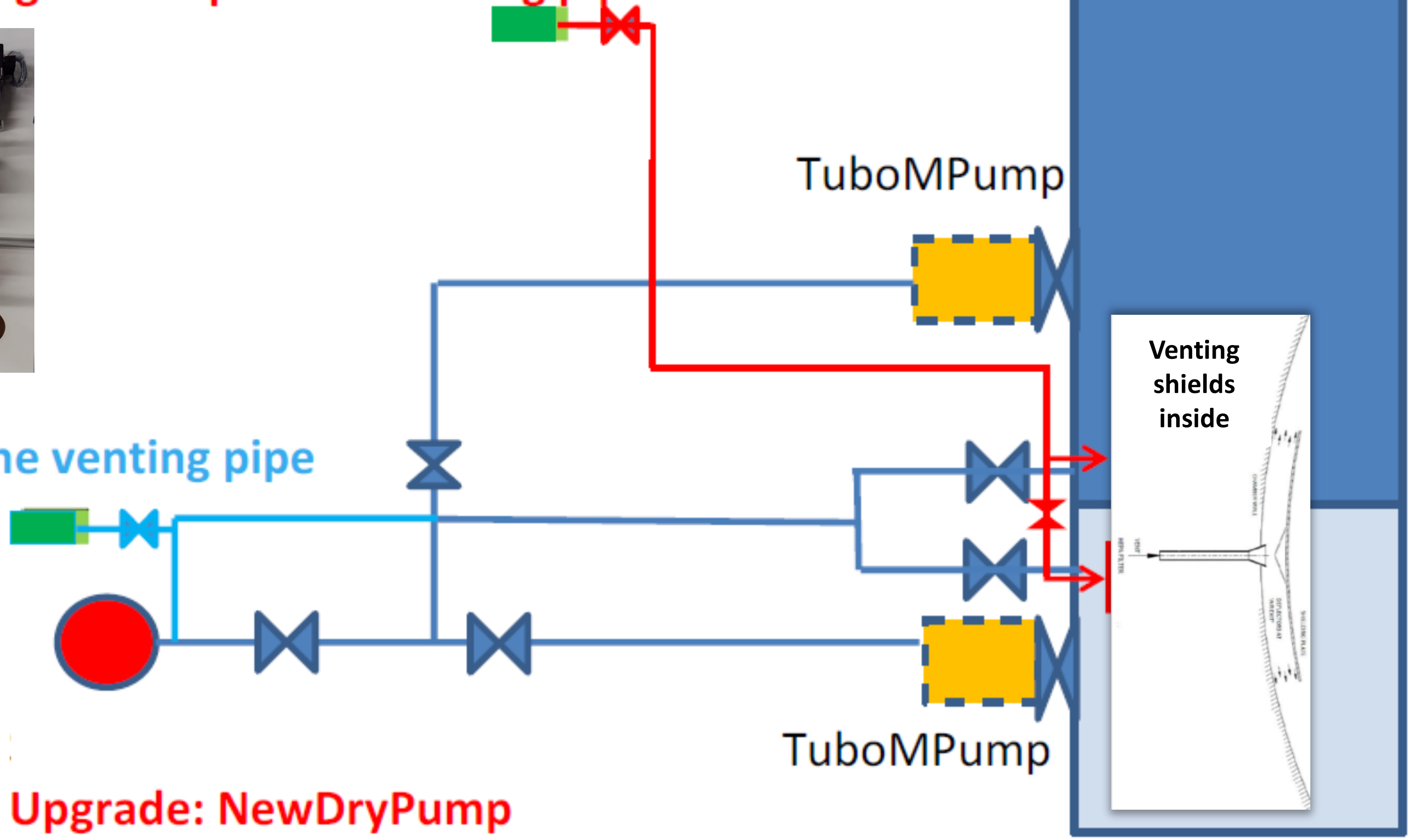
Spare mirrors ready to be suspended will stay in the tray during O3



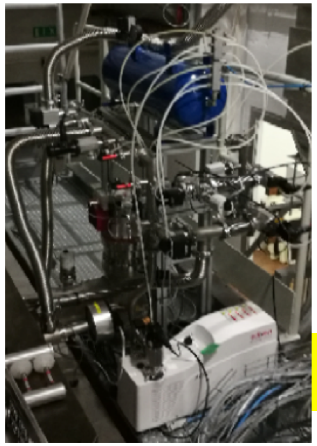
Vacuum modifications

The vacuum system has been modified for eliminating the cause of the fiber problems

Upgrade: separated venting pipe



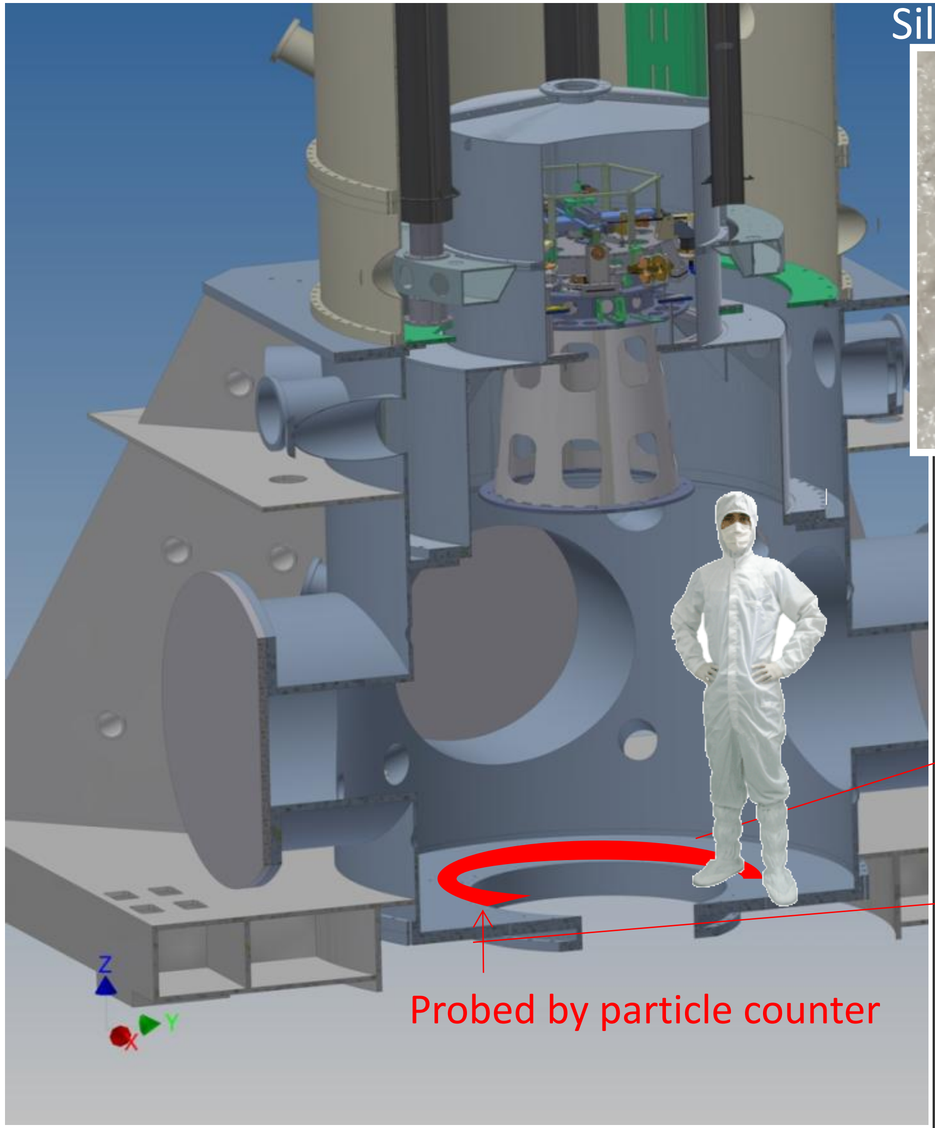
Old : in-line venting pipe



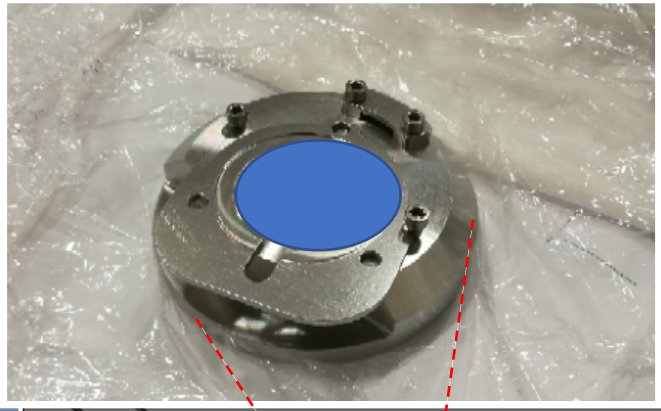
Upgrade: NewDryPump

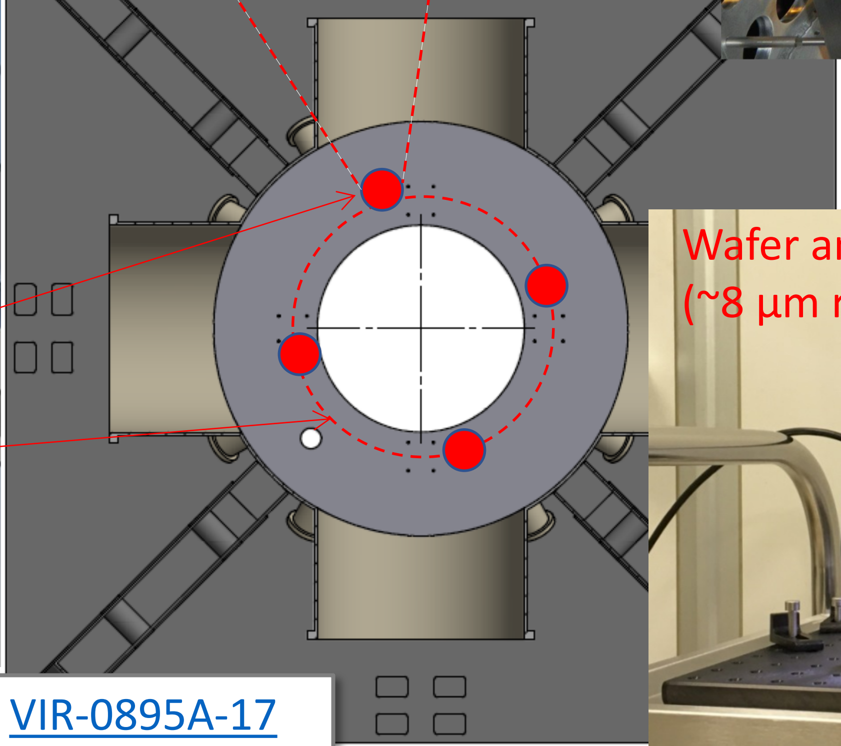
VAC circuit completely renewed, improved dust diagnostics, gate remote control, internal shields

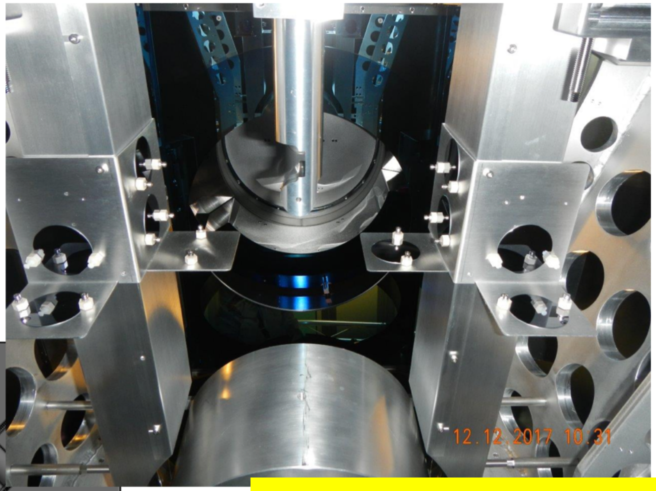
Extraordinary cleaning and dust survey



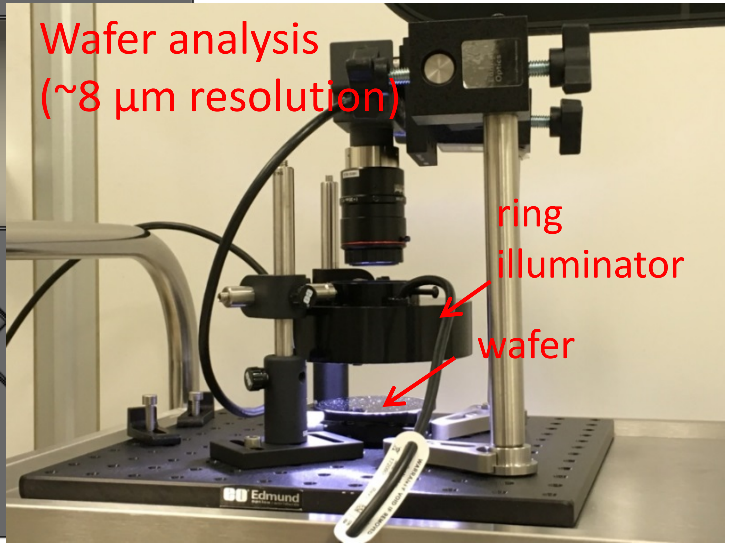
Silicon witness wafer placement







Si wafers everywhere, also on a test payload



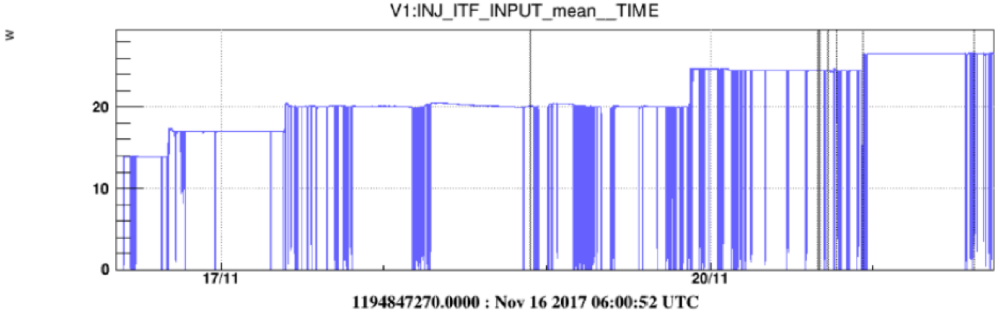
Cleaning procedure document: VIR-0895A-17

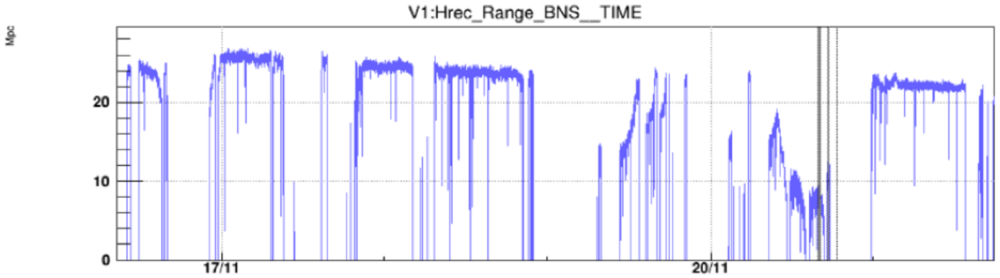
Laser Power &Co…

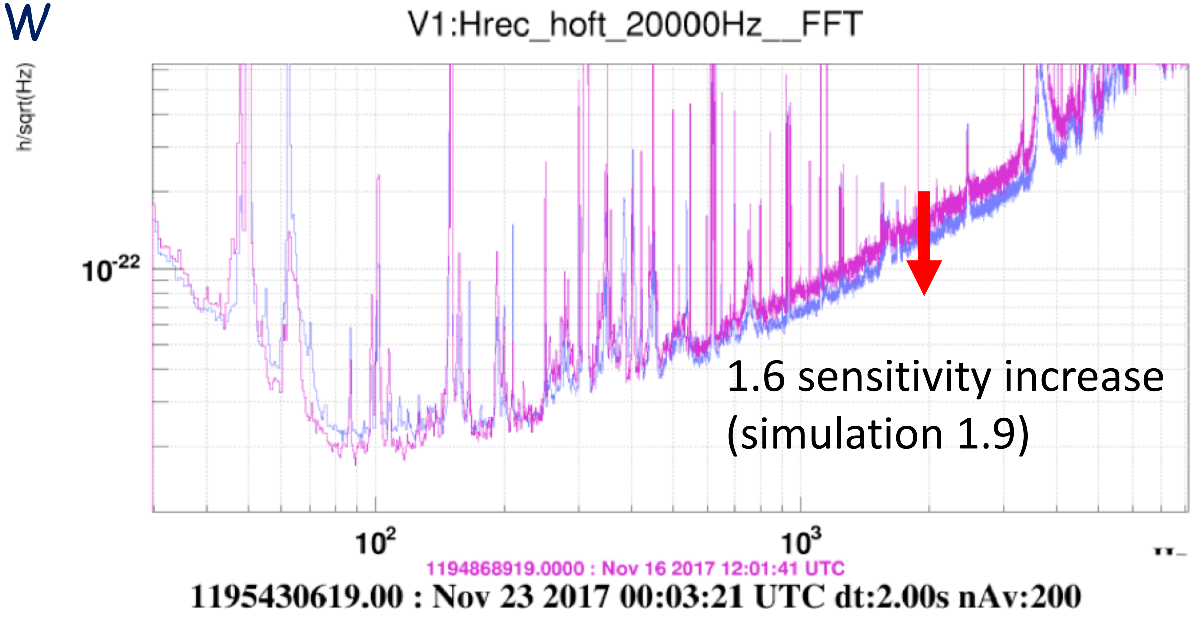
- *O2 configuration towards O3*
- *Further developments towards Nominal AdV power*
- *Thermal Compensation System (TCS)*
- *Parametric Instabilities (PI)*
- *Squeezing implementation*

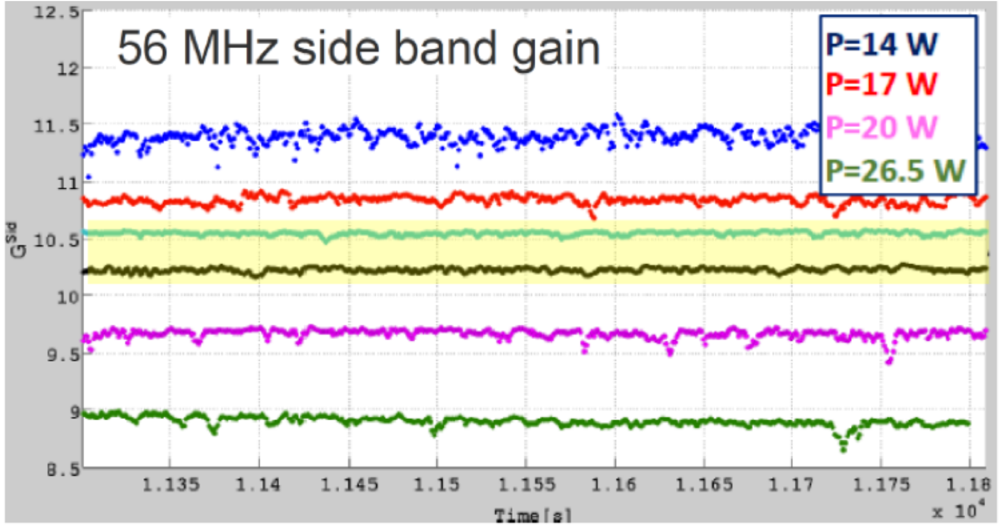
Injected power upgrade: *a trade-off towards O3*

O2 injected set at 13, test later on with 14, 17, 20 and 26 W
No major issues, simulation ~OK
No need to use Thermal Compensation System
Sideband gain reduced
No parametric instabilities









⇒ ITF degrades, TCS needed to further Pin increase
⇒ Parametrin Instability study needed

O3 and beyond, *HP LASER*

4 main activities during last year ARTEMIS

100 W *Fiber LASER*
*(*Azur Light Systems and Alphanov)
- mid-July, long term study finalised.
- Electronics failure

100 W SolidState LASER with 19 W seeder (neoVAN-4S-HP, tested in AEI)
- Seeded using AdV spare slave LASER
- Under test right now

Decision taken, 100 W neoVAN for O3, operated at 50 W

Pre Mode Cleaner
- finalised.

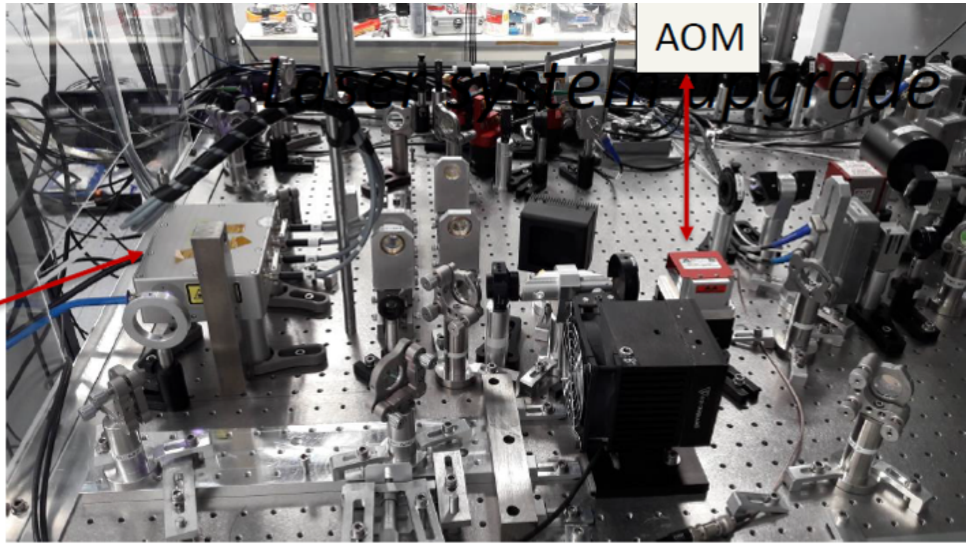
Work completed by summer 2017

Coherent Beam Combination
- Optics Letters Vol. 41, Issue 24, pp. 5817-5820 (2016)
- Meant to attain 200 W LASER

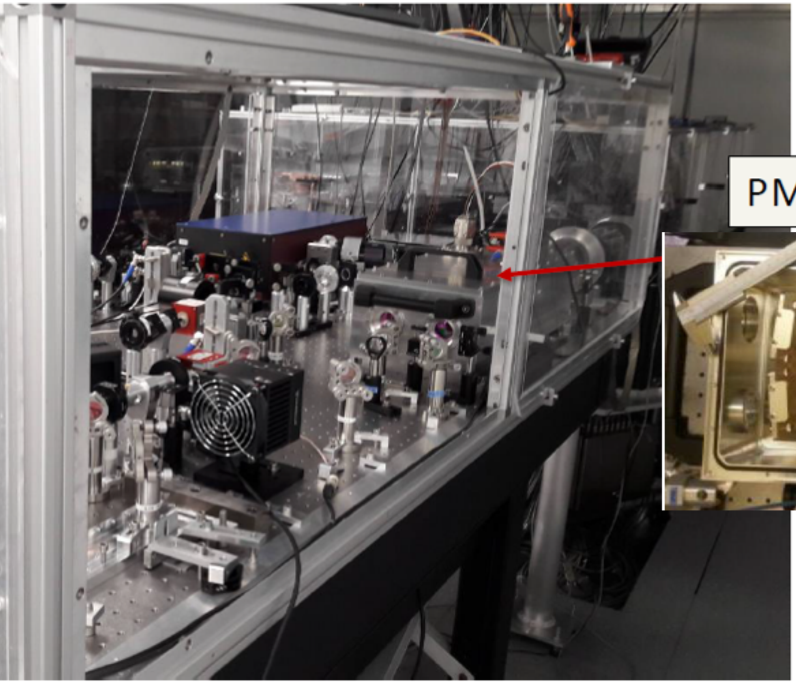
beyond O3: configuration TBD after HP LASER validation

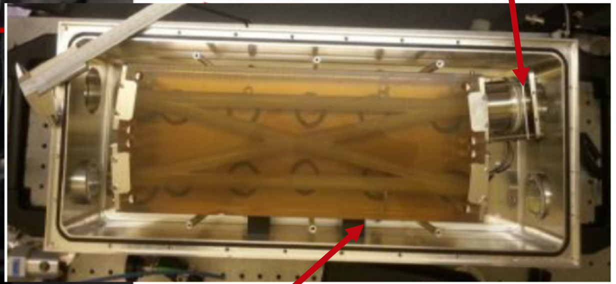
O3, INJECTION SYSTEM: *finalization*

II



- 70 W amplifier replaced by a 100 W
- Max input power in the ITF: around 50 W
- 100 W fiber laser tests ongoing at Nice
- New pre-mode cleaner
- External Injection Bench “suspended”

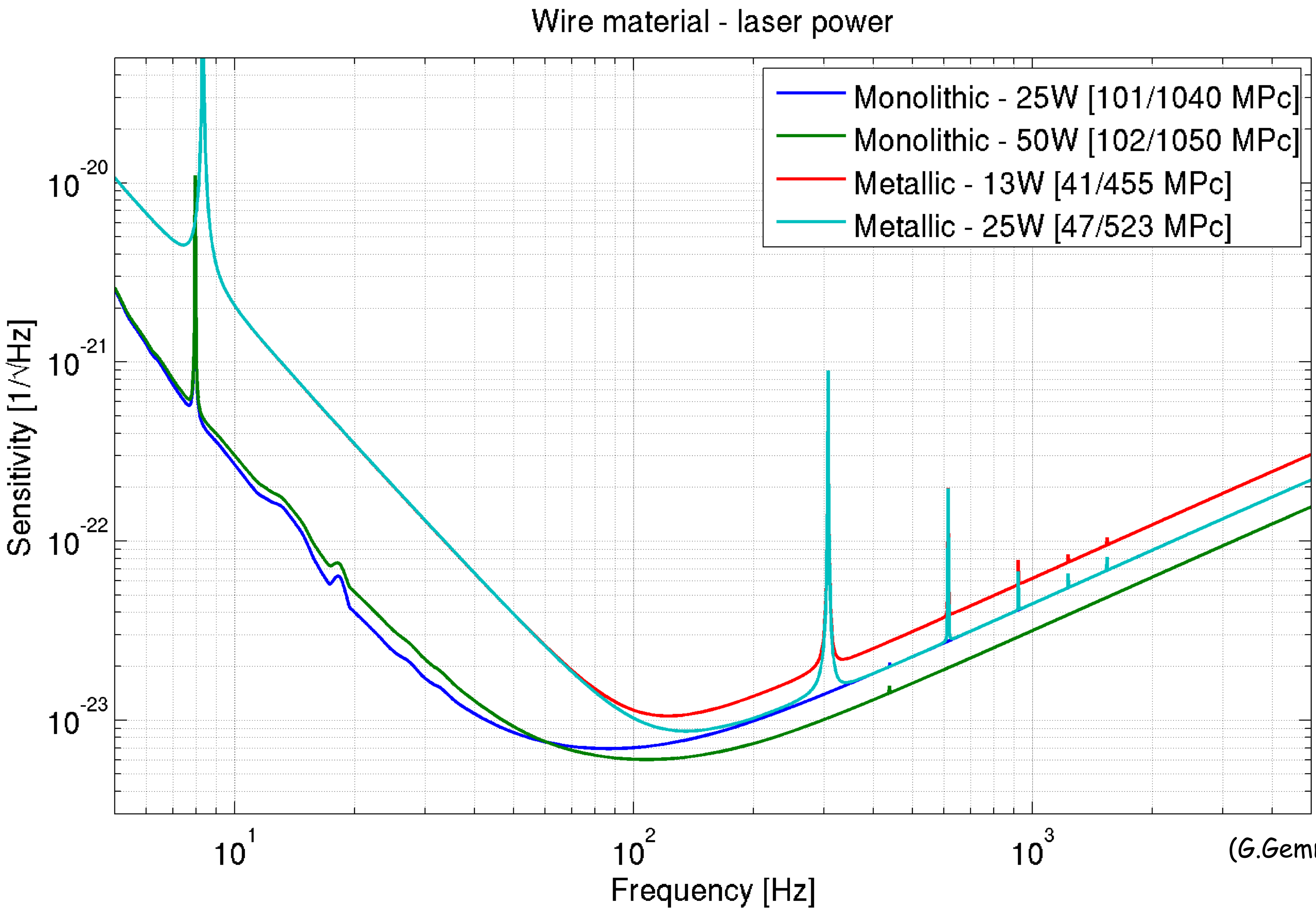




Sensitivity curves: Power/Squeezing/Signal-recycling parameter prediction

Injection Power

BNS/BBH

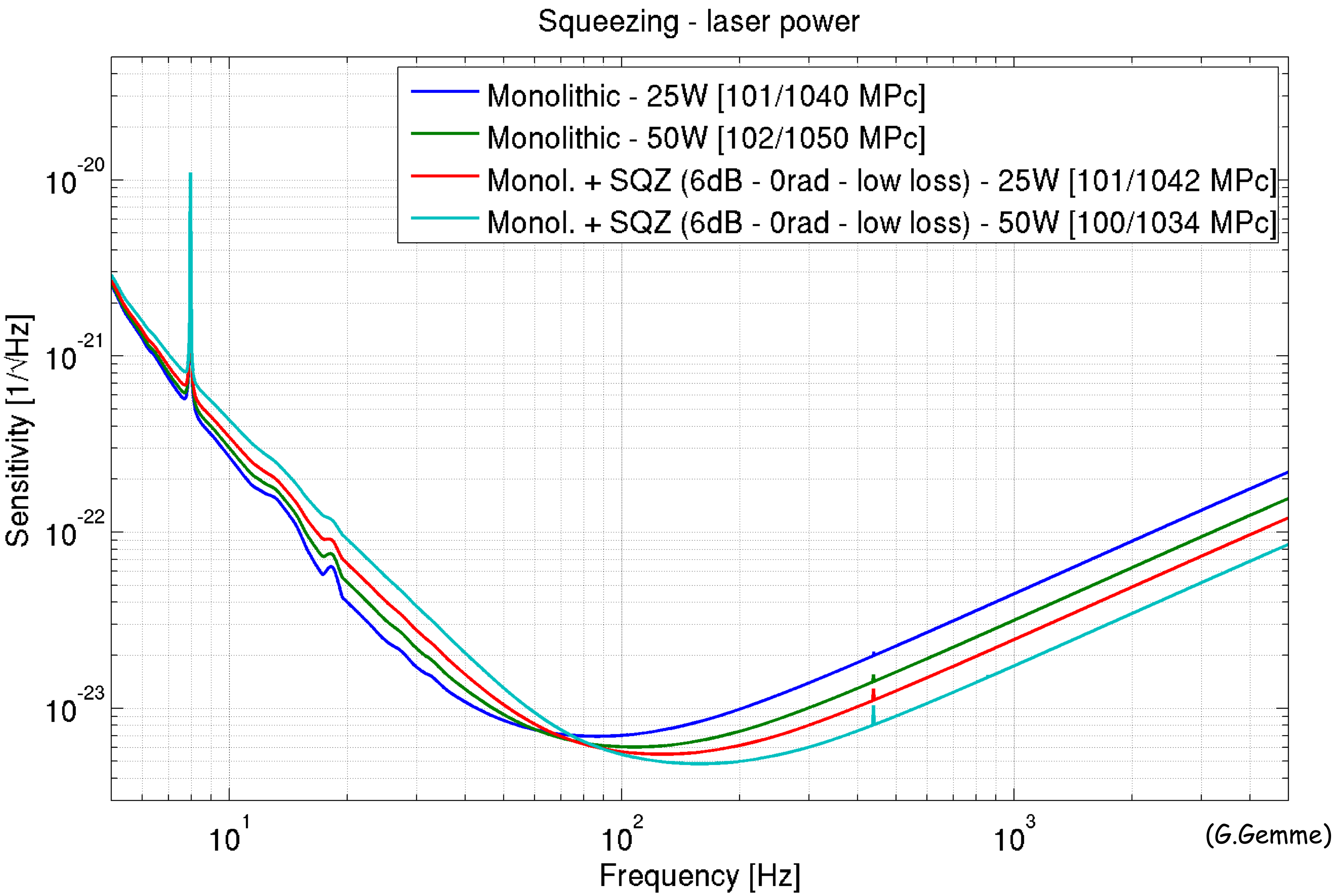


(G.Gemme)

Monolithic suspensions improve factor 8 at LF

Sensitivity curves: Power/Squeezing/Signal-recycling parameter prediction

Injection Power + SQZ

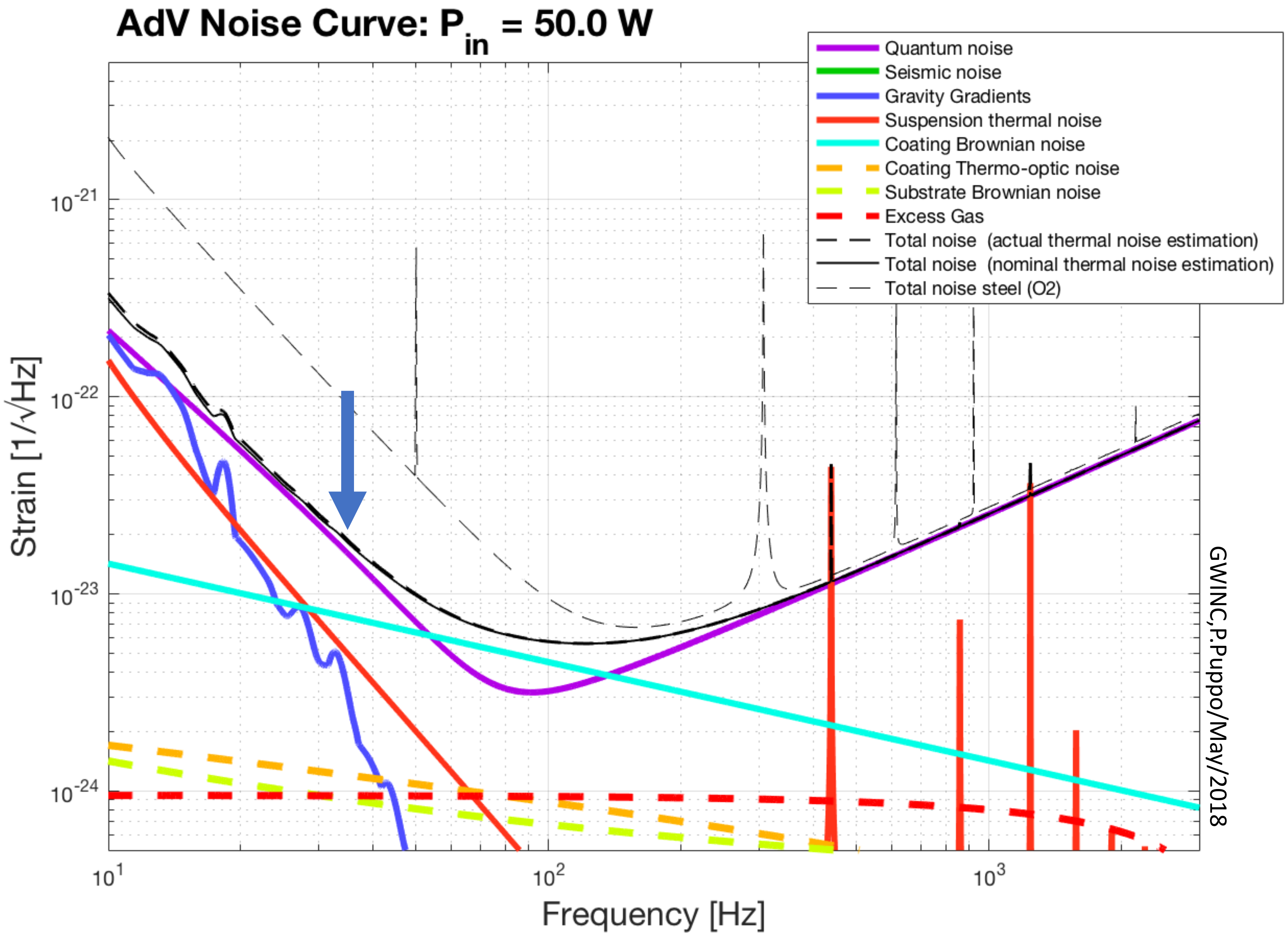


BNS/BBH

- Squeezing angle 0° (not optimized)

Power increase / squeezing improve at HF, lose at LF, **a decision will be taken before summer 2018**

Summary O3 Target

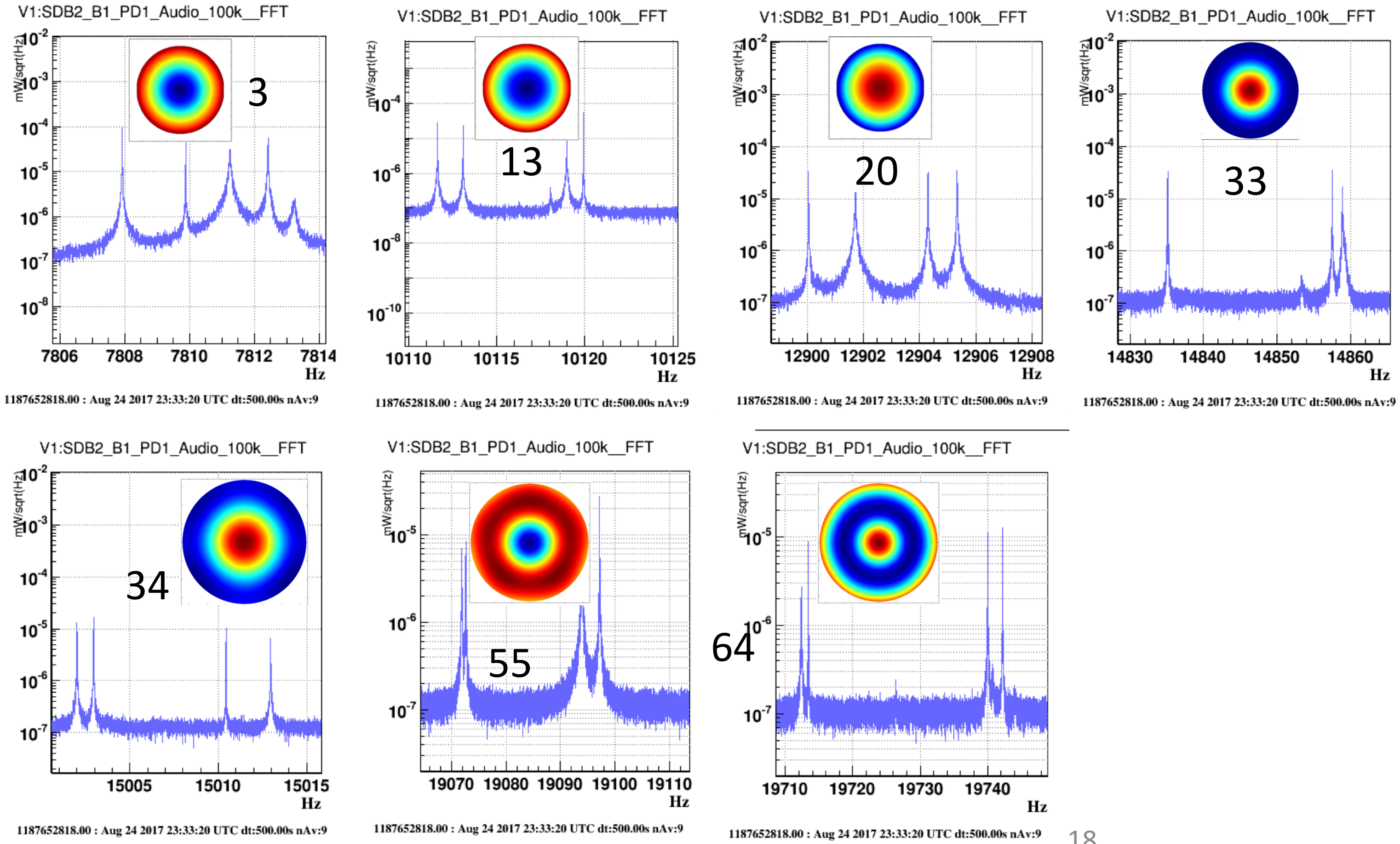


Test Mass internal modes and parametric instabilities

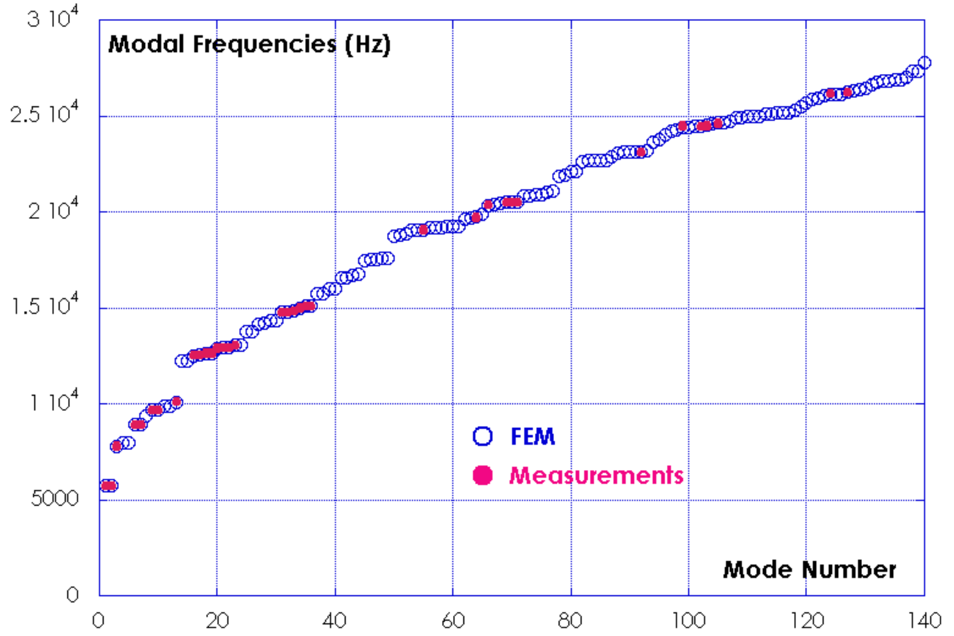
thermal peaks *(axisymmetric modes)*

II

A subset of internal modes computable through FEA might be strongly coupled with cavity E.M. modes and excited, producing instability



4 Peaks identified (NI,NE,WI,WE) during O2,
Axisymmetric modes: drums longitudinal

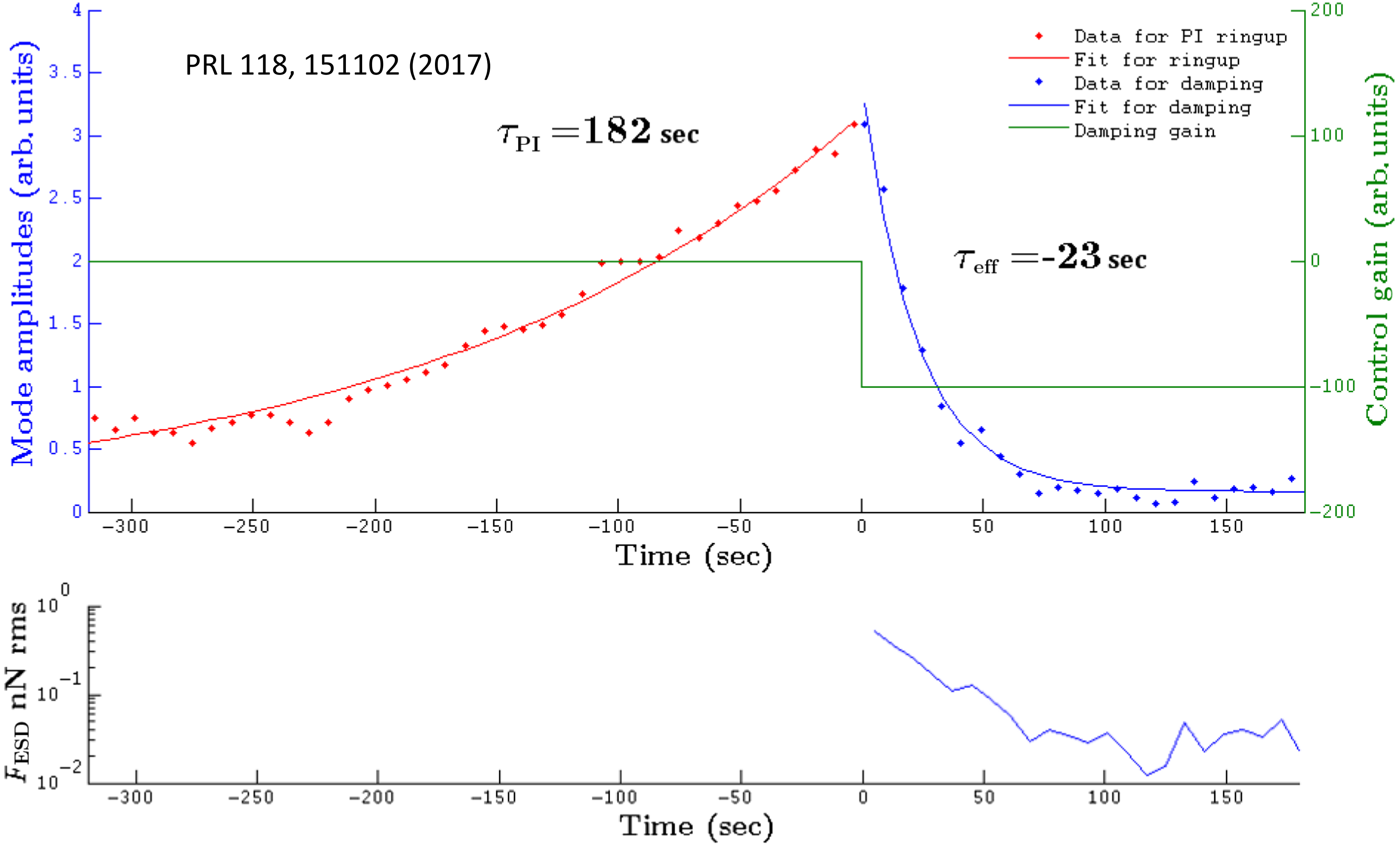


Parametric Instabilities observed in LIGO (O1):
active damping through Electro-Static Drive used for locking

P_{cavity}=100 kW
Q_m= 12 10^6 @ 15.5 kHz

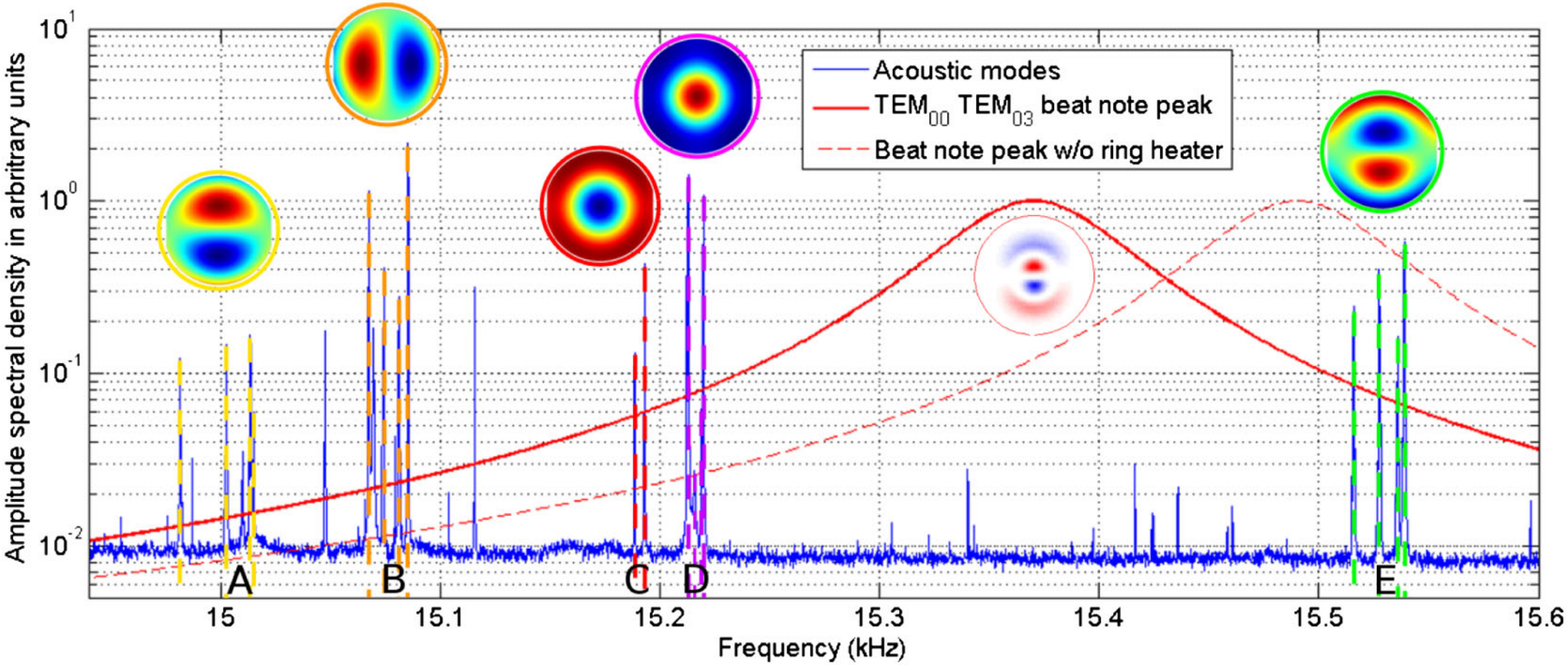
$$\tau_{PI} = \tau_m/(1 - R_m)$$

τ_m: natural time constant of the mechanical mode



Parametric Instabilities observed in LIGO (O1)
deduning through ring heater

Compensation of thermal mirror curvature can be used to attenuate excitation pop-up in specific cases.



Thermal tuning with the RH changes the Mirror radius of curvature and shifts the beating note far from the most critical mode (E)

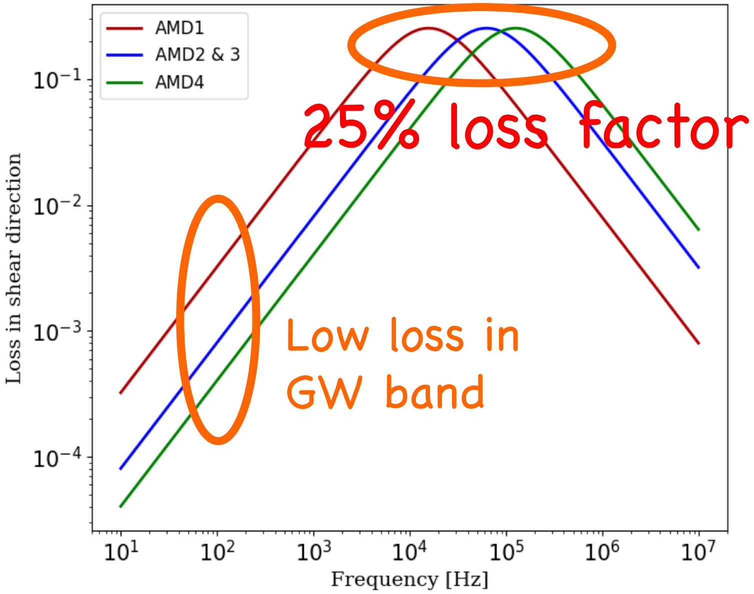
Parametric instabilities passive dampers,
mechanical damper also for Virgo, but after O3

First simulations ongoing with mechanical dampers

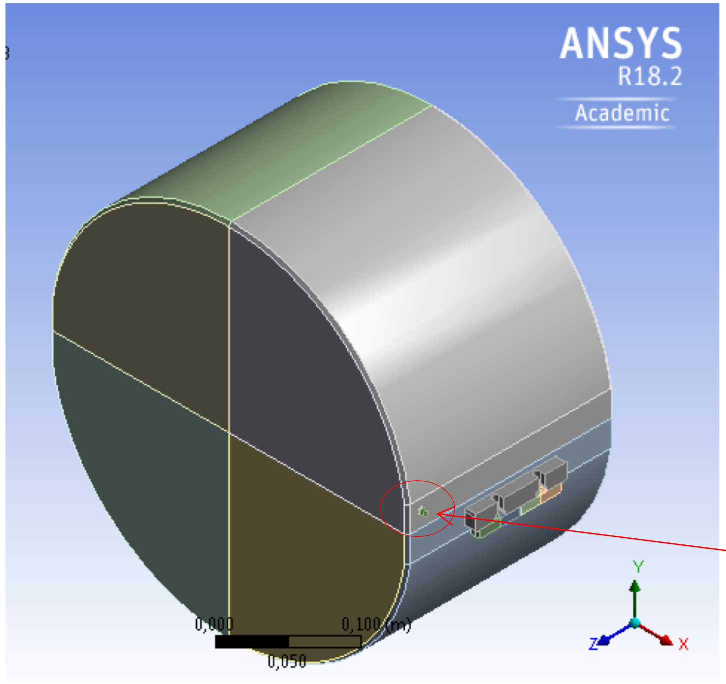
LIGO: the "acoustic mode Damper"
PZT-shunt tuned damper

$$\phi_{shunt} = \frac{\rho k^2}{(1 - k^2) + \rho^2}$$

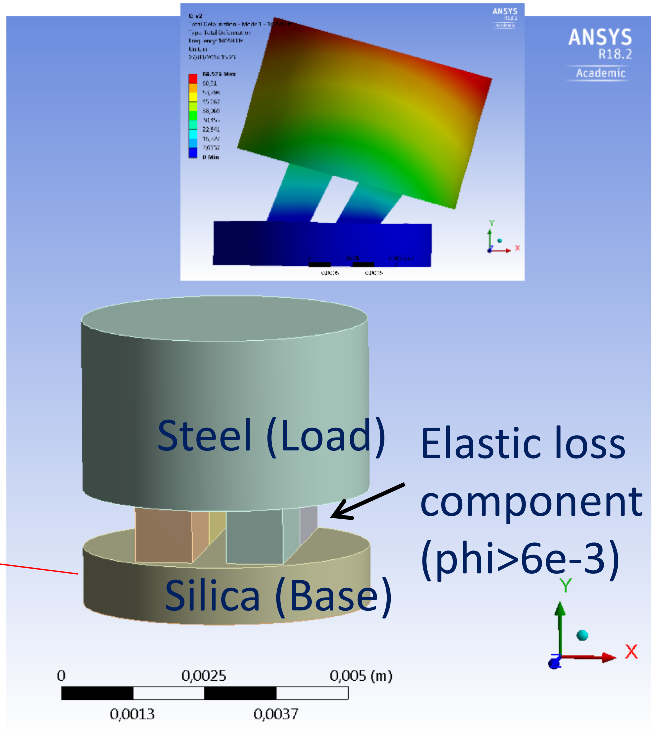
$$\rho = RC\omega$$



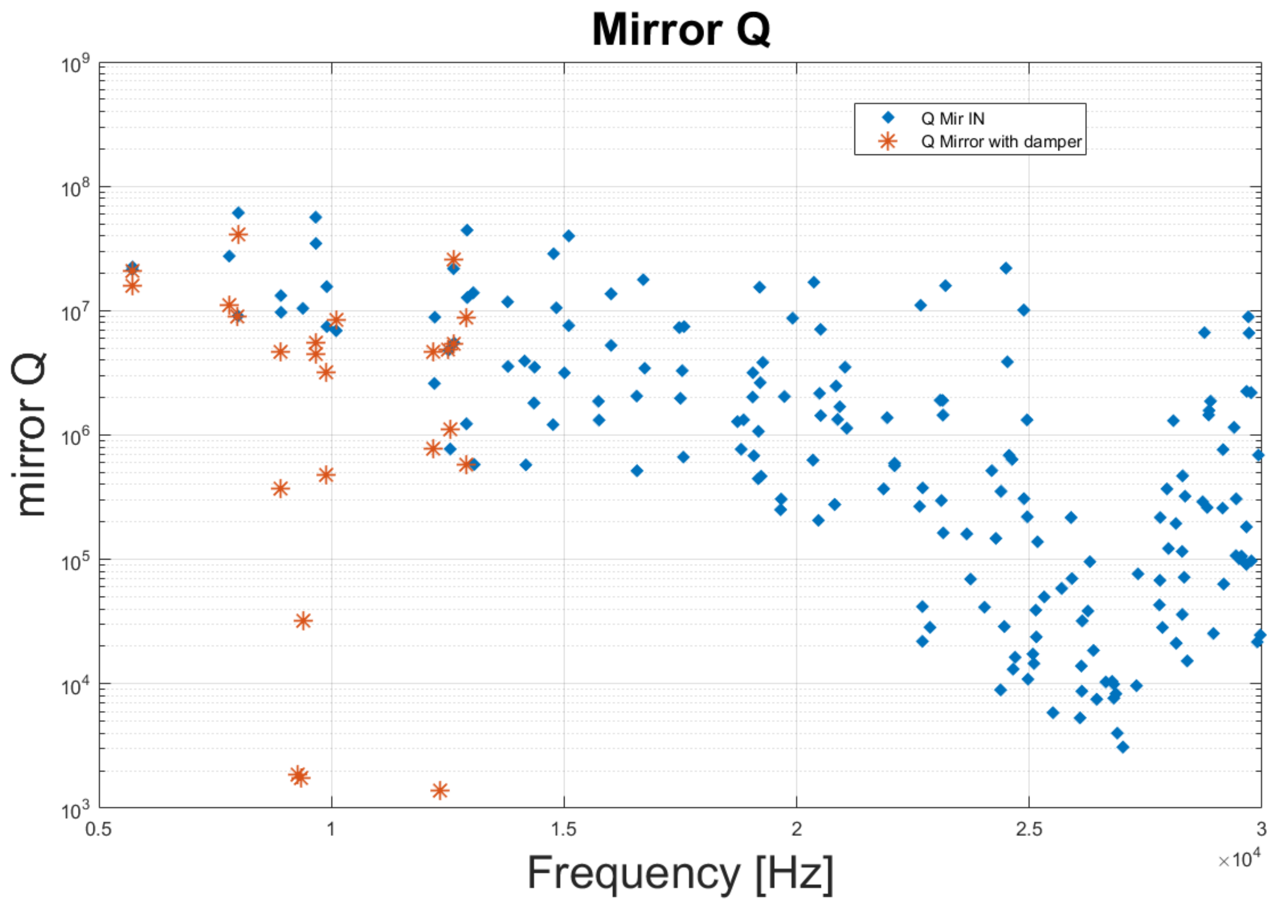
Pure mechanical damping mechanism developed by Virgo, under test using old V+ payload (Rome) and at EGO, through the dummy payload meant to check fused-silica suspension.



HCB to attach the Fused Silica base



Parametric instabilities, *bulk Q using mechanical damper*



P. Puppo

- Coating and FS influence just the first 3-4 modes
- Anchors and ears bonding starts to matter above 9kHz.

Thermal noise terms. [x10^{-22} m/sqrt(Hz)].

TN	Brownian Substrate	Damper	Silicate Bonding Glue	Brownian CTN	Total TM	Increment
ITM	8.7	16	11	52.3	56.4	4%
ETM	8.7	16	11	82.2	84.9	3%

Thermal noise increment a bit high, but the damper materials and resonances can be tuned.

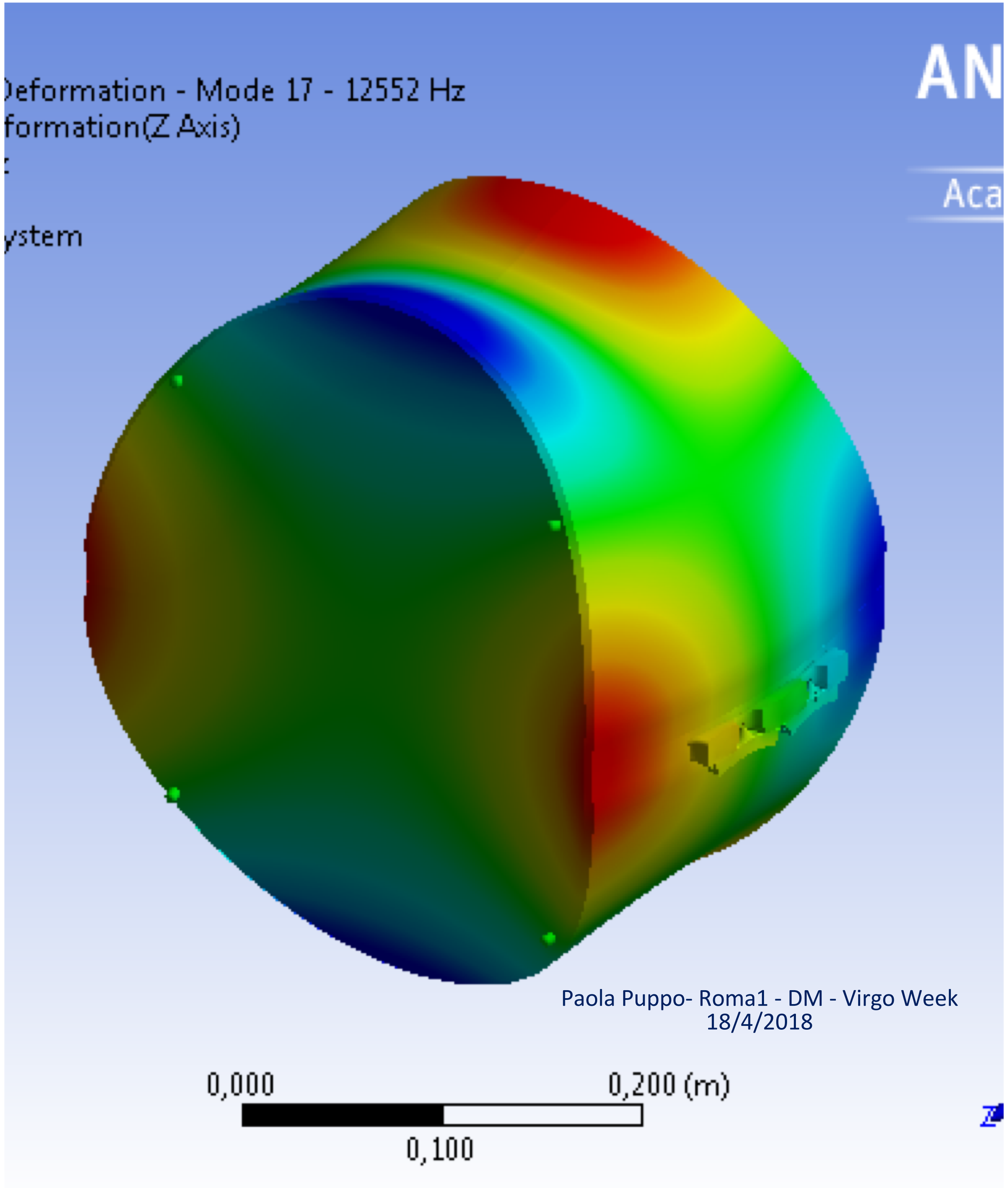
First critical mode

(with the highest PGain)

12.5 kHz – expected Q<1e6 (Rm<<1)

- So far PI study is not completed.
- PI impact might affect O3.
- Then we must use the only handles available:

1. present coil magnet pairs
2. and Ring heater
3. After O3, pure mechanical dampers are, so far, the solution



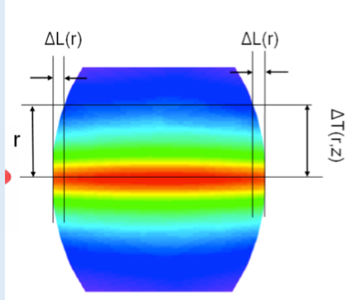
TCS, AdV Thermal Compensation System, *in use during O3 !*

II

✓ High circulating power changes the ITF nominal optical configuration:

✓ Thermal lensing

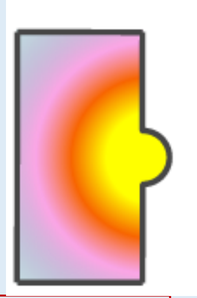
$$\Delta OPL_T = \frac{dn}{dT}\int_S \Delta T ds$$



OPL distortions due to dependence of refractive index from temperature variation

✓ Thermo-elastic effect

$$\Delta u \approx \alpha \int_S \Delta T ds$$



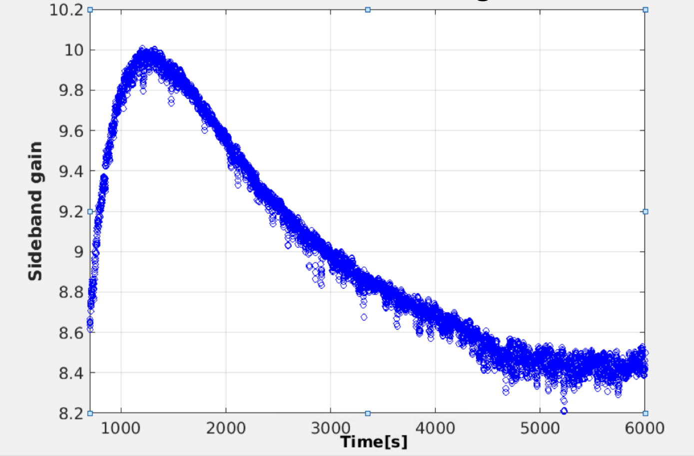
Change of RoC of mirrors due to the absorption of laser power

✓ ITF control signals degradates

✓ Sensitivity decreases

✓ **TCS thermally acts on the ITF optics, restoring the nominal operating point**

Typical behavior of the ITF control sidebands due to the effect of thermal lensing



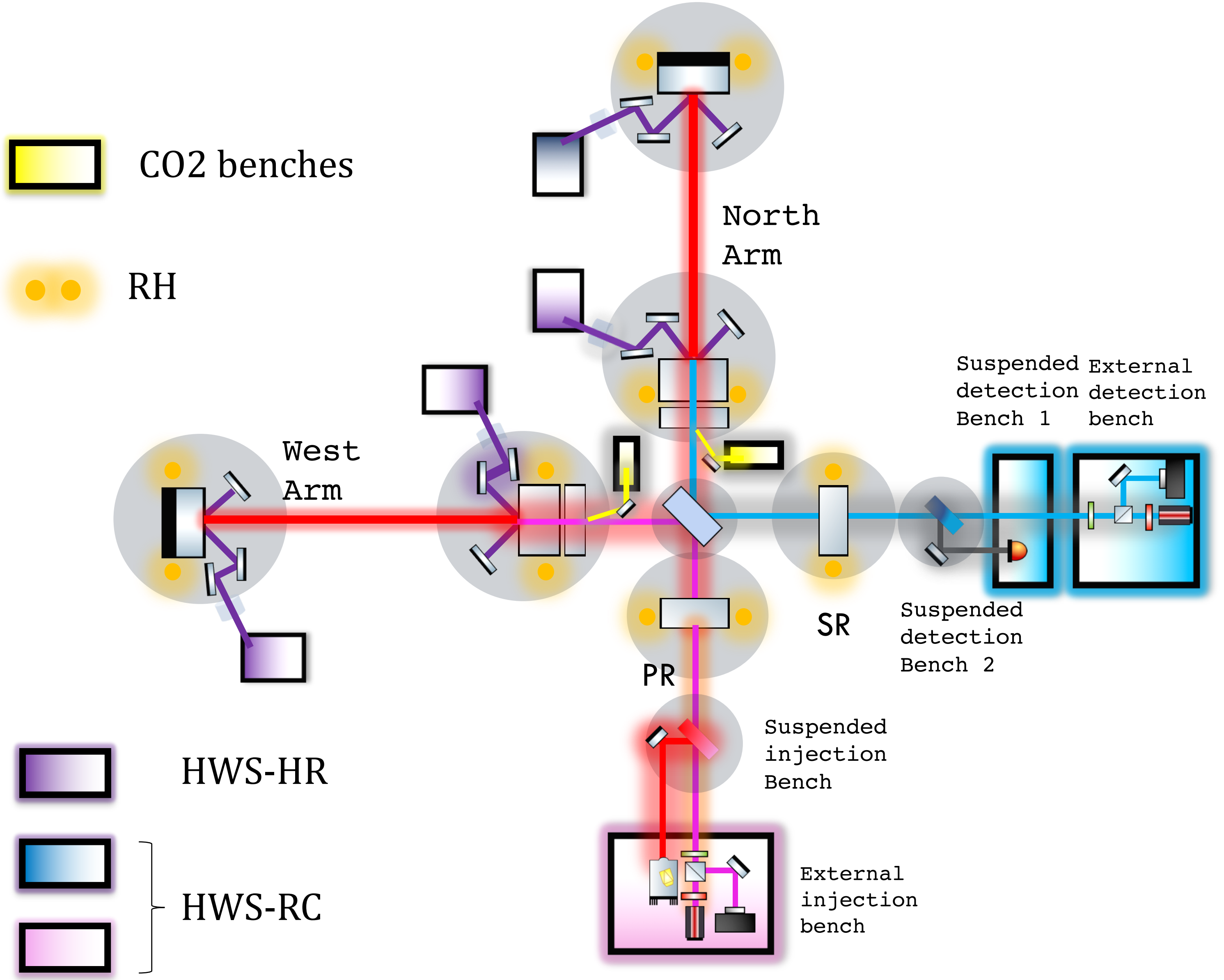
TCS, *layout*

TCS actuators :

- ✓ CO_2 laser projector corrects thermal lensing
- ✓ Ring Heater (RH) acts on the thermoelastic deformation of the HR surface

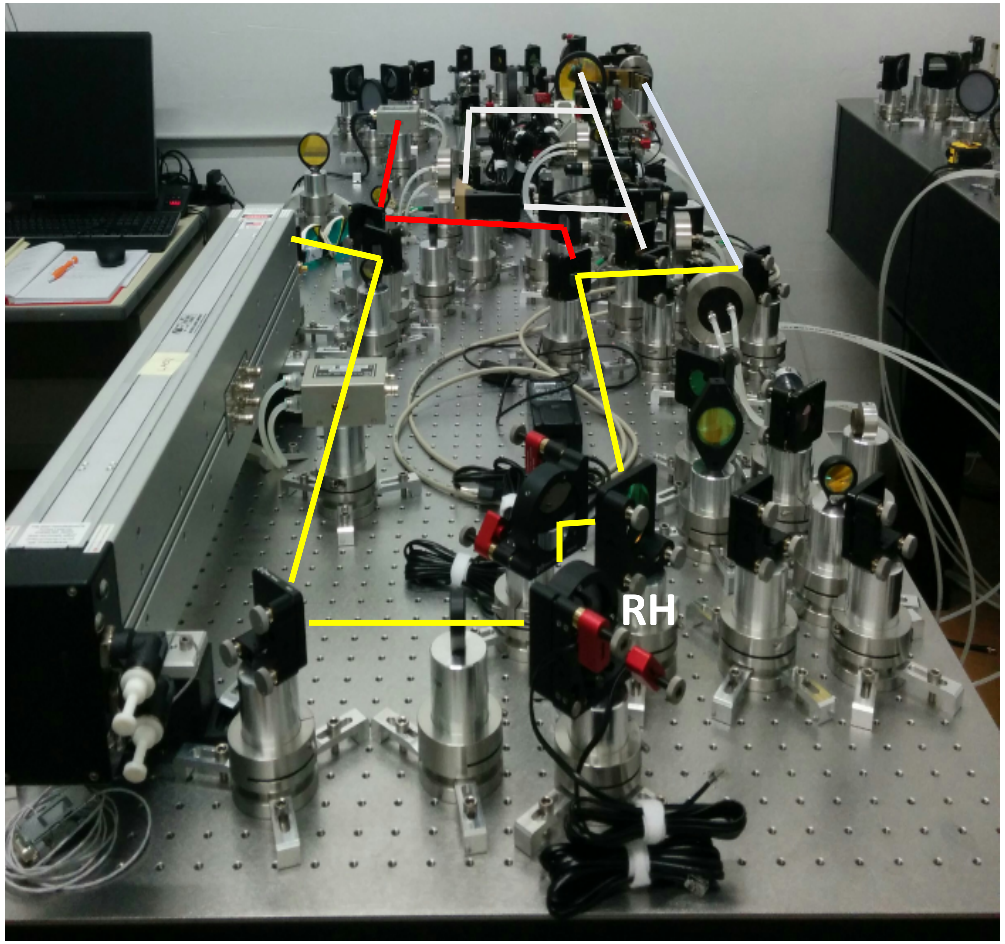
TCS sensing :

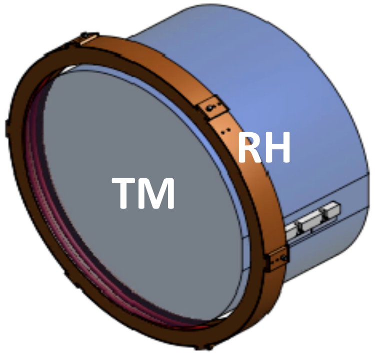
- ✓ Wavefront sensors (HWSs) in the recycling cavity to measure thermal lensing (HWS-RC)
- ✓ HWSs probing each TM surface to measure the thermoelastic effect (HWS-HR)

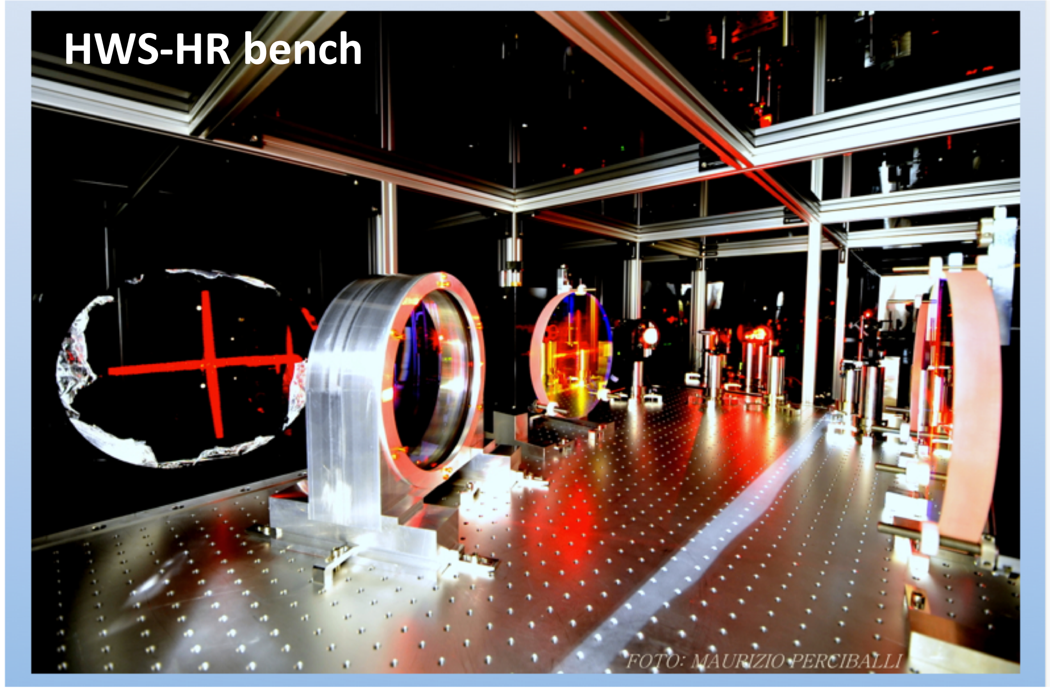


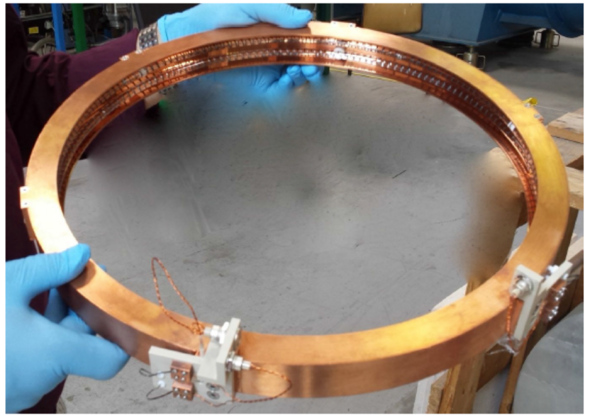
TCS, AdV Thermal Compensation System,
in use during O3 !

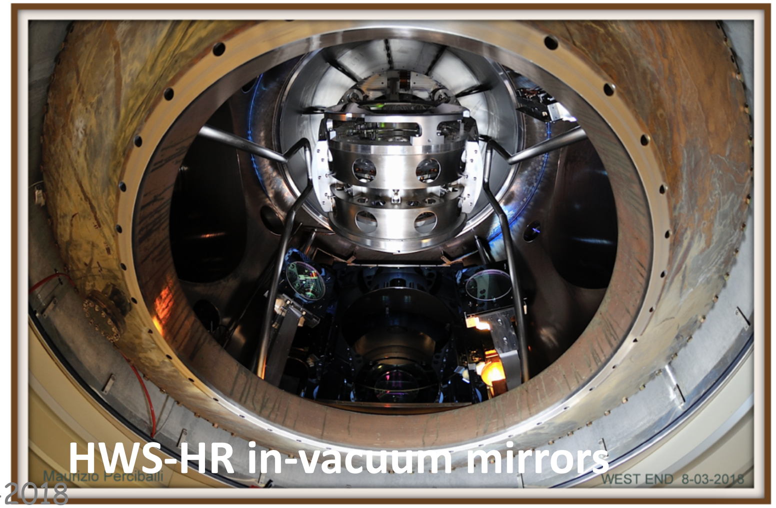
TCS being commissioned to be ready for O3





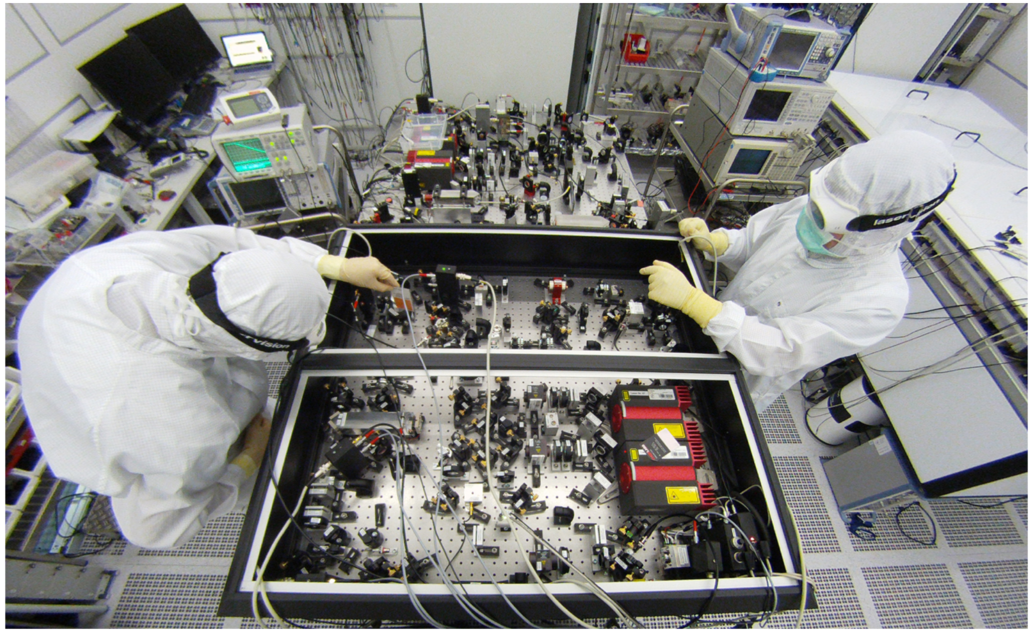






Frequency Independent Squeezing bench *(Max Planck Institute AEI !)* II

In the last two years squeezed light prototype bench took place at the site.
➔ Squeezing observed, local knowledge significantly grown, development facility operative, excellent position to actively collaborate with AEI to integrate **plug&play squeezer bench, presently under commissioning**

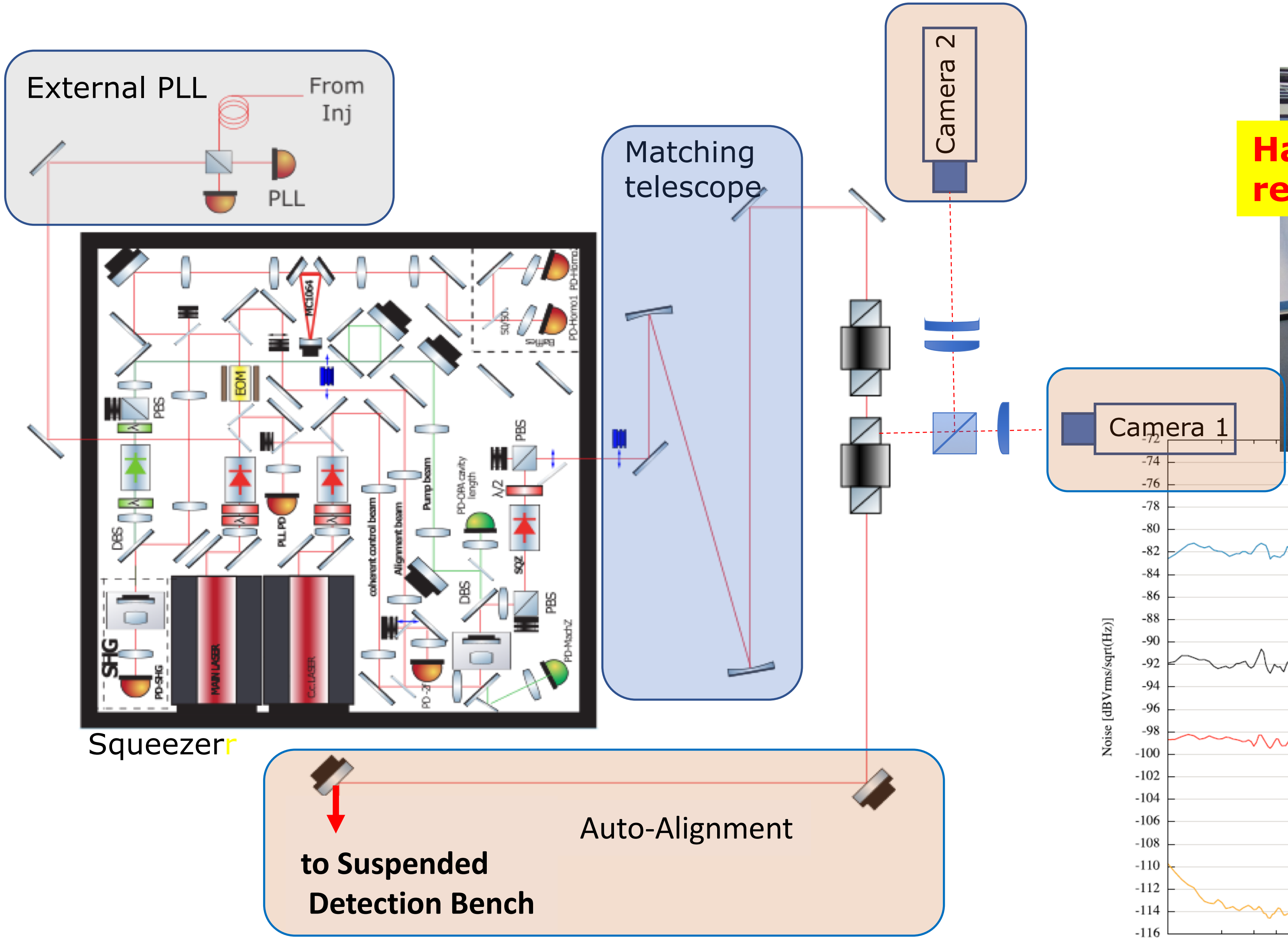


Two identical boxes have been developed, the second one remains in Hannover for debugging

- **3 Faraday isolators**, matching Telescope, autoalignment
- Doubly Resonant OPO (532 and1064 nm).
- **Seismic**: placed on a bench equipped with elastometers
- **Environment**: under laminar clean airflow, DT ~ 0.5 C OK
- AEI **electronics** rack to be integrated in AdV system
- **Digital control HW and SW integrated** with AdV
- **VAC** flange Susp Bench re-adapted
- Squeezer locking on Virgo laser via **OPLL**.

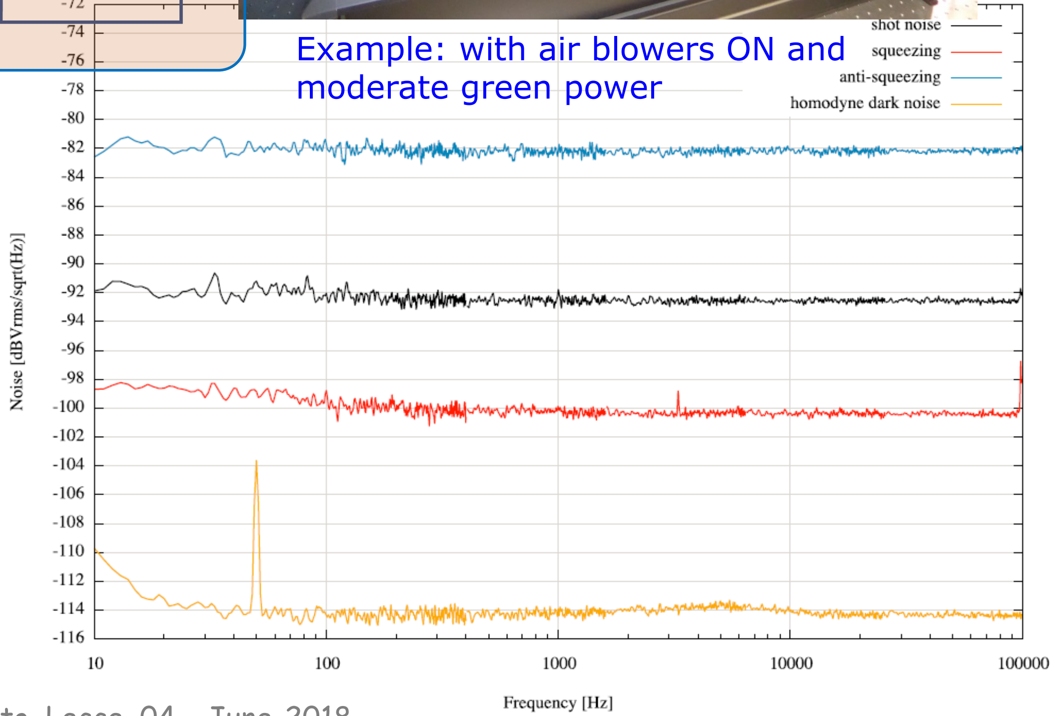
AEI Squeezer integrated in Virgo, commissioned by summer. It will be in operation during O3.

Frequency Independent Squeezing bench, *Integration*



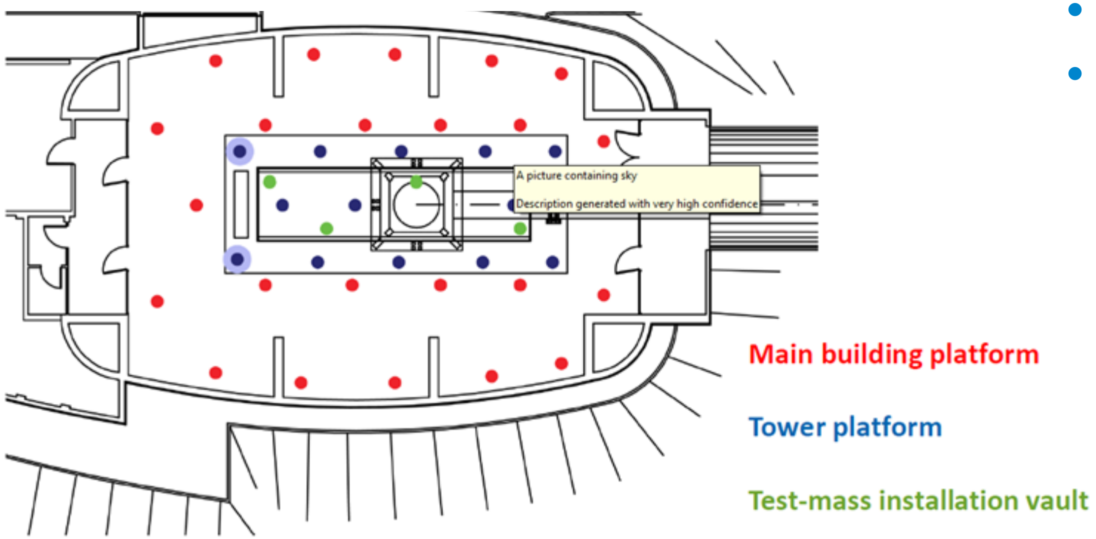
Hannover results reproduced in Cascina

Example: with air blowers ON and moderate green power

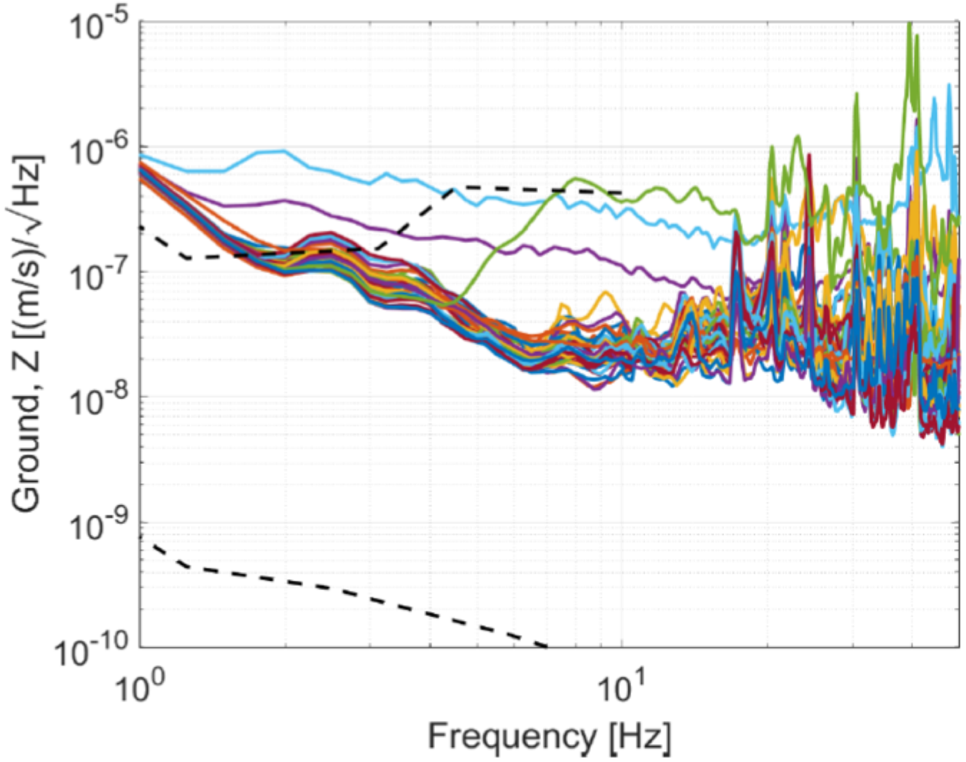


Newtonian Noise subtraction, *preparing post-O3 !*

Terminal Building North

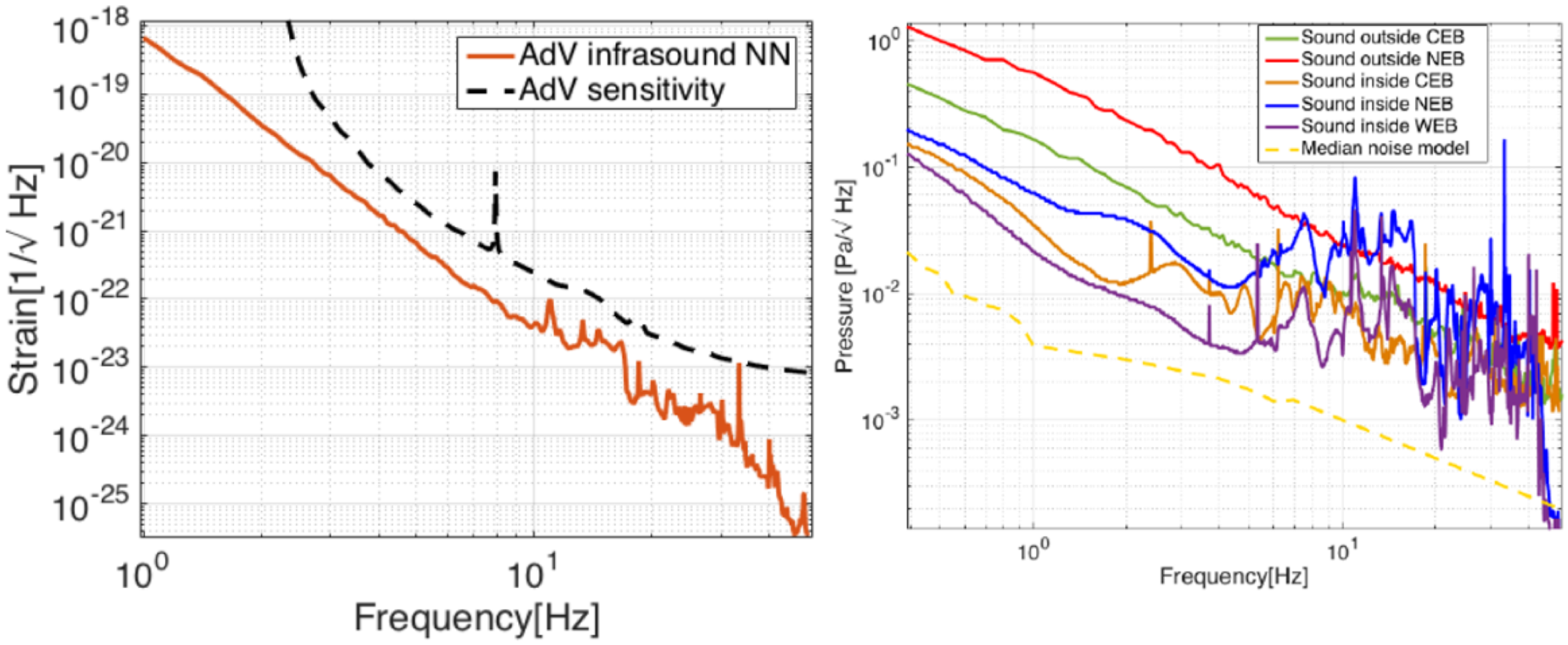


- *About 50 sensors foreseen in each terminal building*
- *Two weeks of data collected in Jan-Feb 2018*
- *Analysis on-going*



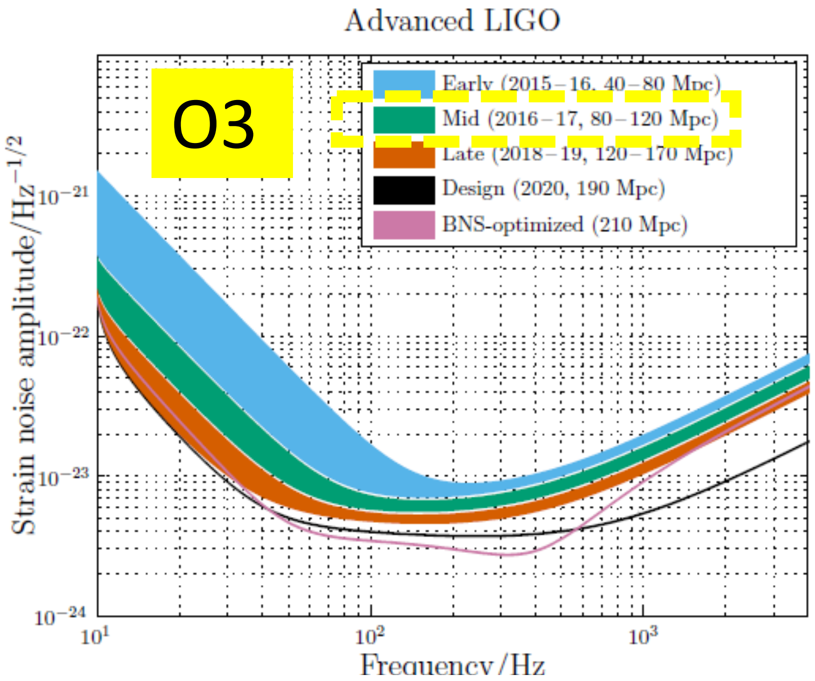
Newtonian Noise subtraction, *preparing post-O3 !*

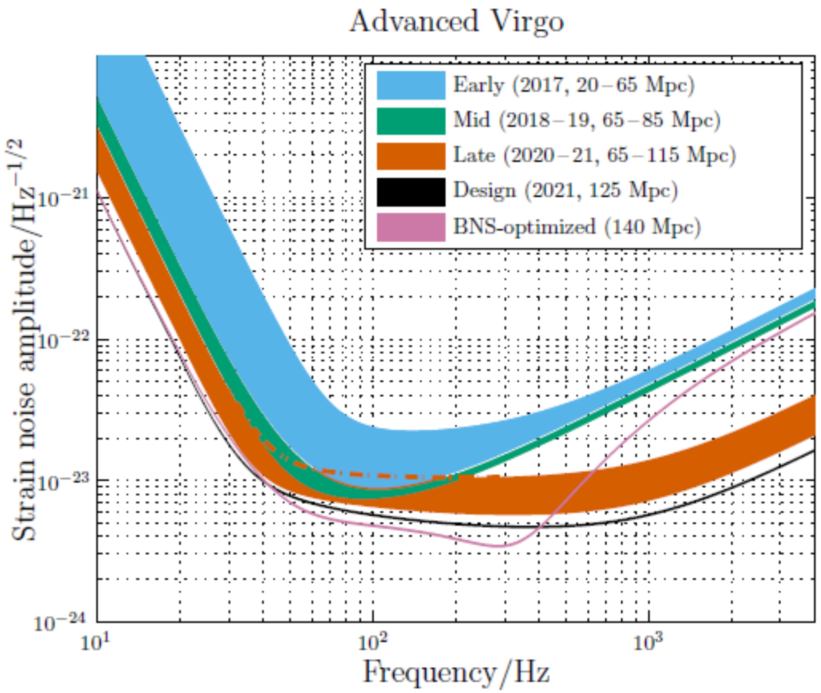
Fiorucci et al, PRD 97, 062003 (2018)

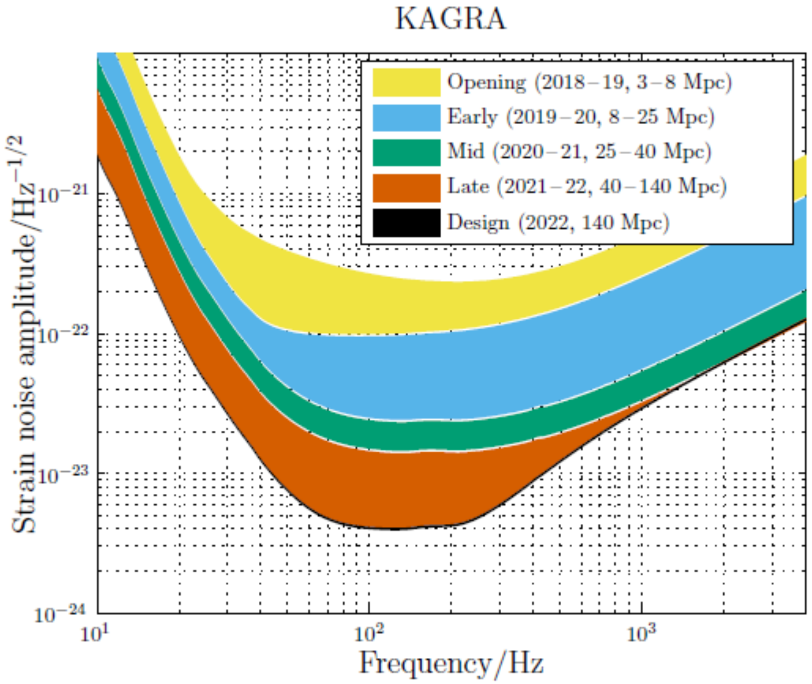


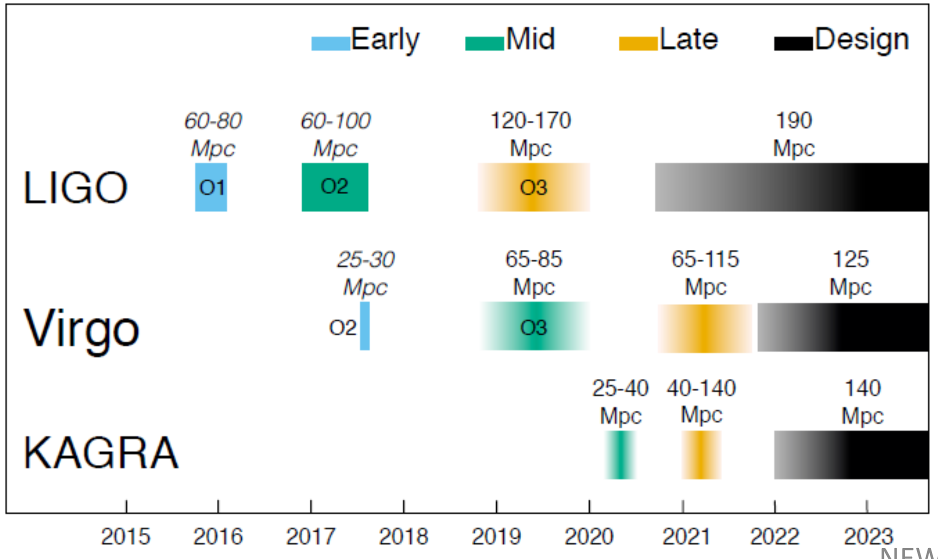
In the range 10-30 Hz sound NN should be at least reduced as it shows a spectrum comparable to seismic NN (!!)

LIGO-Virgo-KAGRA observing scenario









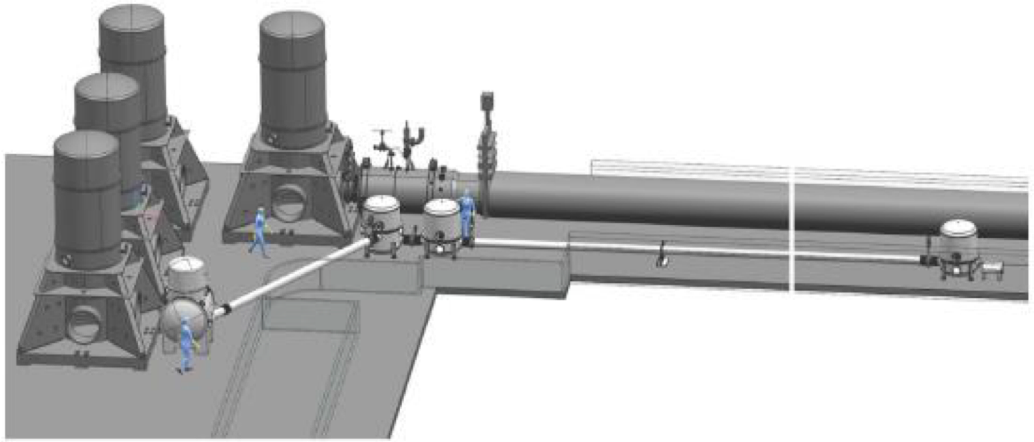
Living Rev. Relativ. (2016) 19: 1

- O3 is a very exciting scenario (including KAGRA, a **seed of 3G detector)**
- What can we do after AdV to exploiting at the best the infrastructure ?
- **AdV+** proposed to the EGO council last December: a two-steps approach, 6-year programme

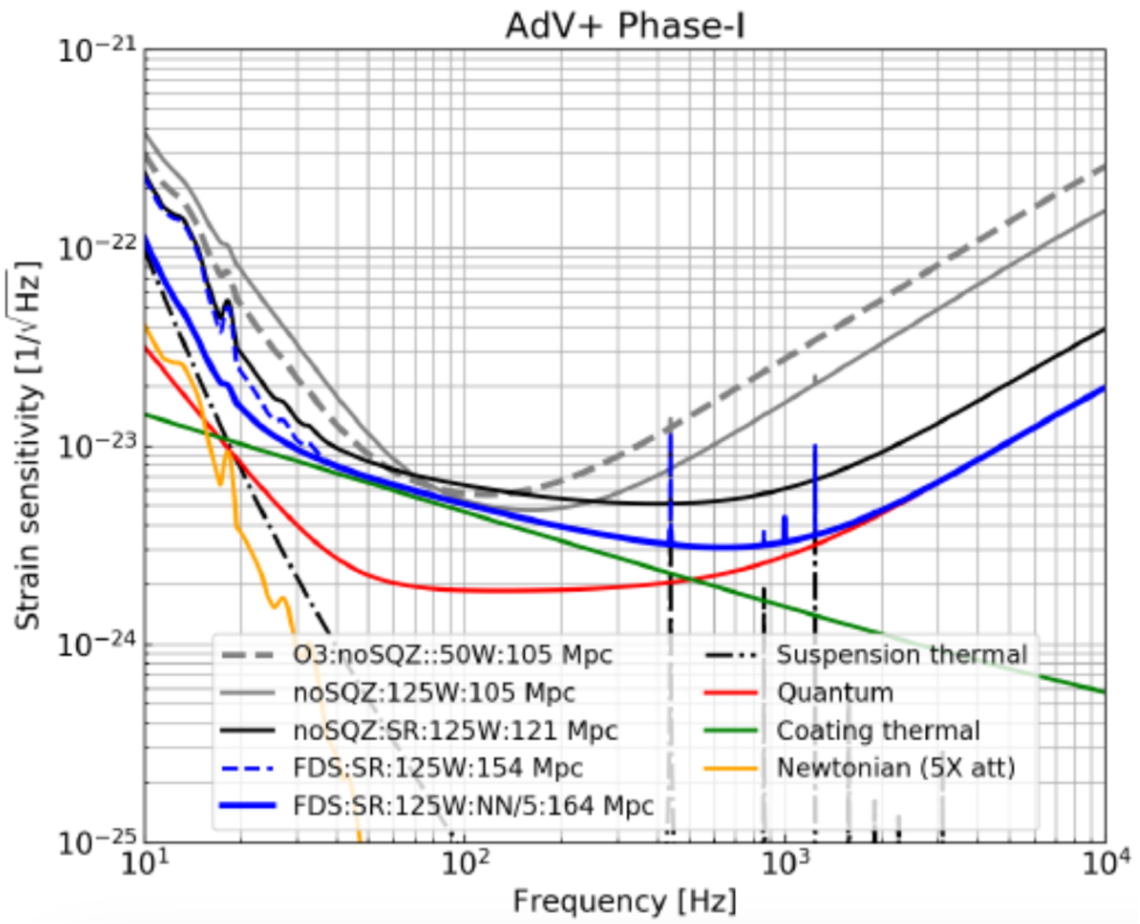
AdV+ phase I: *finally reaching Advanced Virgo full target*

Complete the AdV program:
200 W laser; 125W at the ITF input
Signal recycling → 120 Mpc

Frequency Dependent Squeezing
300 m-long filter cavity →150 Mpc



Newtonian Noise Cancellation →160 Mpc

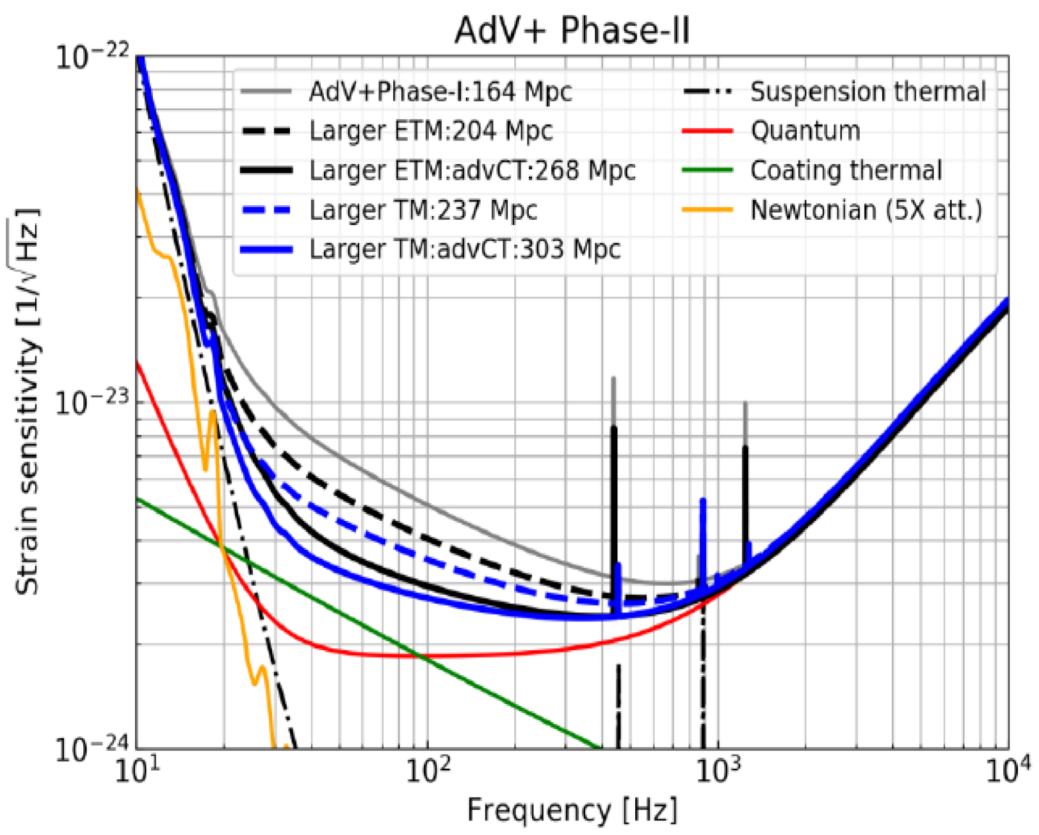


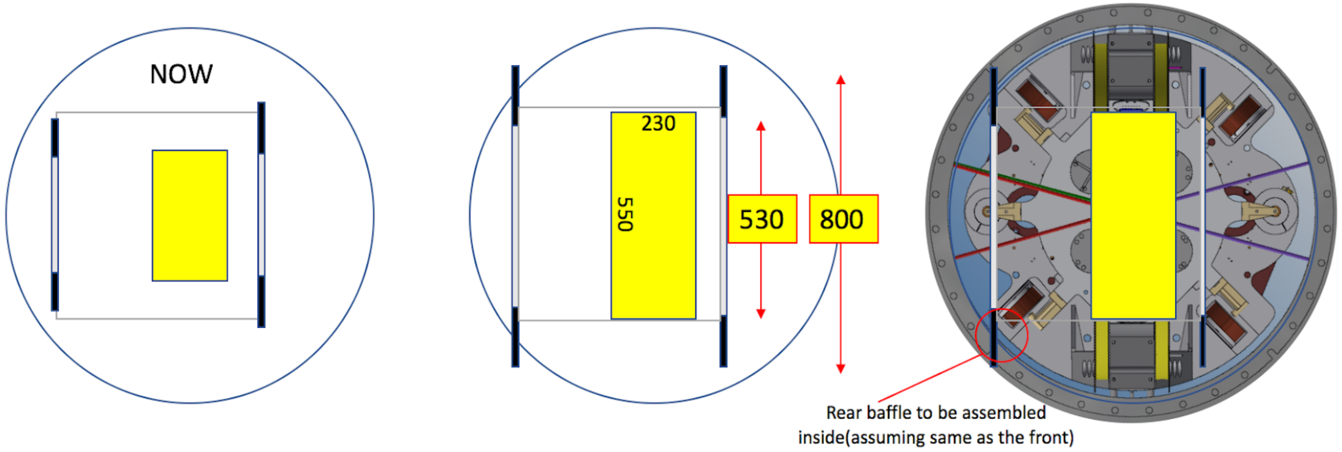
AdV+ phase II: *Thermal noise reduction: large beams*

Larger mirrors
Diameter: 550 mm, thickness: 200 mm, mass: 100-120 kg (?)
Scenario 1: ETM-only → 200 Mpc
Scenario 2: full upgrade → 230 MpcCoating improvements

If factor 3 reduction in **Coating TN**:
Scenario 1: ETM-only → 260 Mpc
Scenario 2: full upgrade → 300 Mpc

Several challenges, feasibility under study





Conclusions

- Virgo upgrades towards O3 done

- Monolithic suspensions
- Laser power increased
- Frequency independent squeezing

- O2 sensitivity just recovered

- Commissioning run with higher sensitivity in fall 2018

- Target 60 Mpc (CBNS) achievable with the HW installed

- **One-year-long organisational and data storage (uncommented here), seriously considered**

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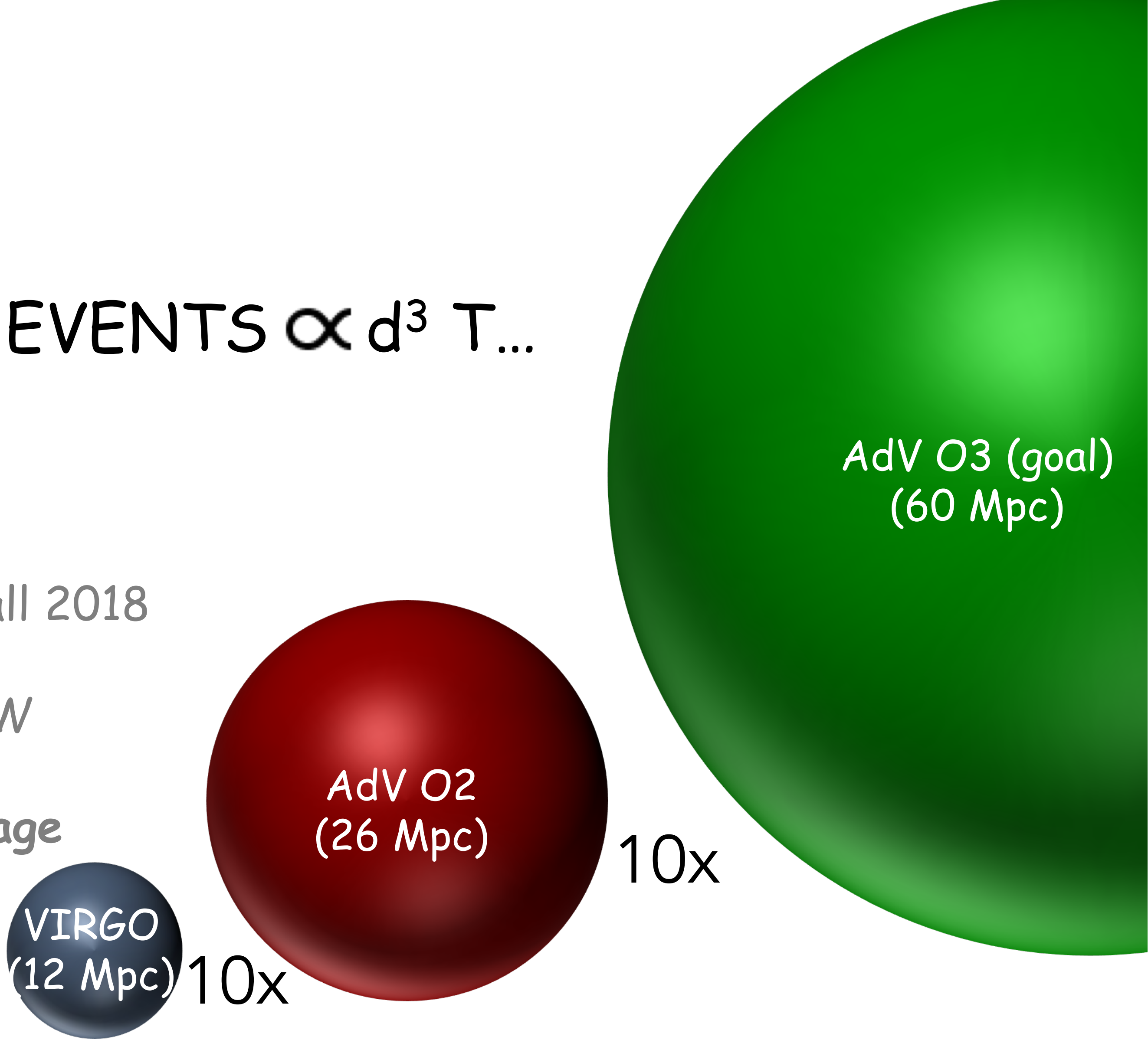

-  *We explore, in parallel, the land beyond O3:* **HIC SVNT LEONES**