Seismic Isolation of Advanced Virgo+

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The Virgo Collaboration

Virgo is a European collaboration with more than 700 members

Participating countries are
France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

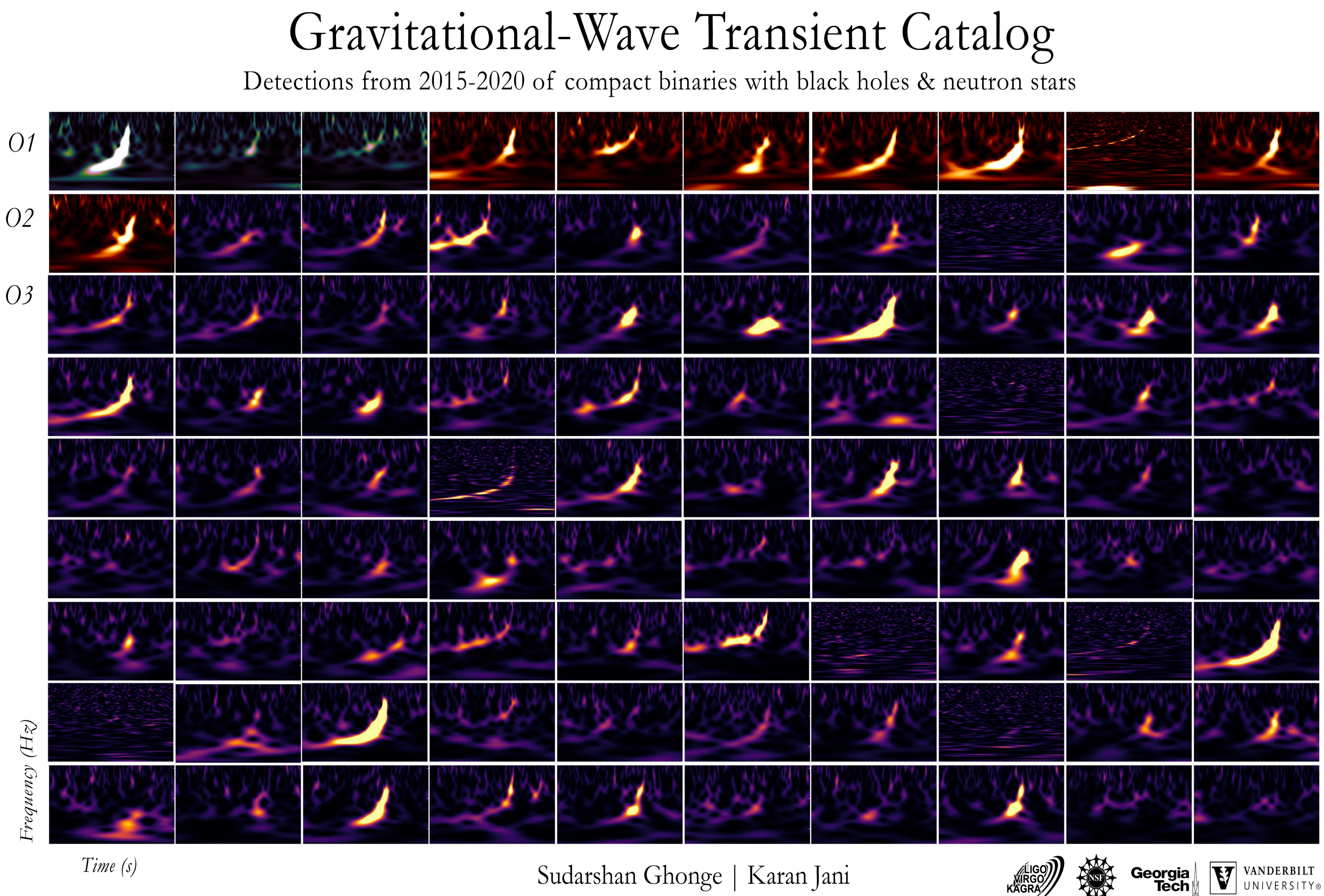
With a total of 25 laboratories

− APC Paris − ARTEMIS Nice − EGO Cascina − IFAE − 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 − UCLouvain − ULiège − Univ. of Barcelona − Univ. of Valencia − University of Jena

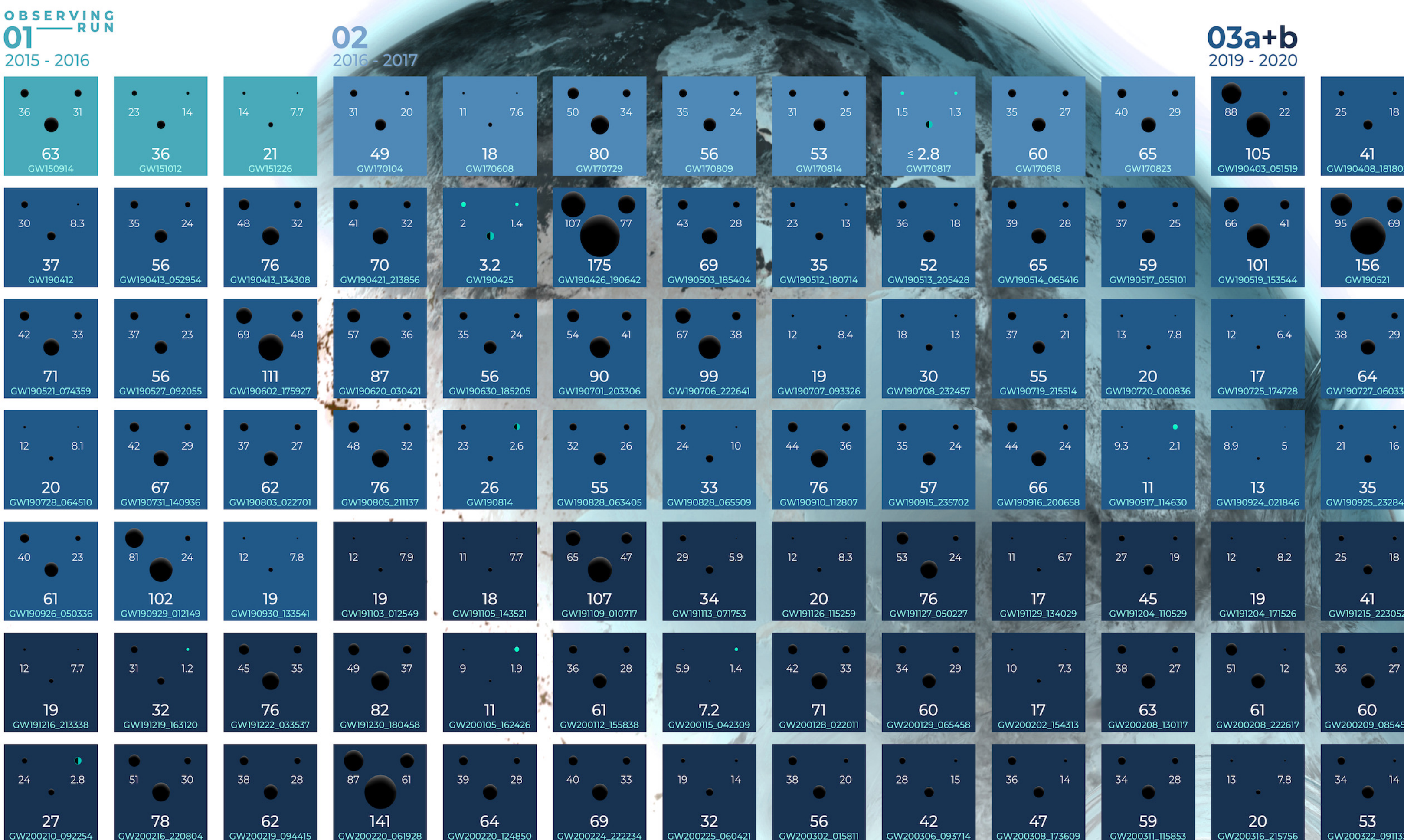
The birth of gravitational wave astronomy

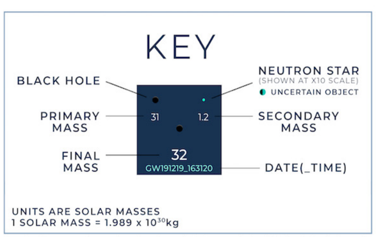
17^{th} August 2017 at 14:41:04 CET

♫ Madamina, il catalogo è questo… ♫



GRAVITATIONAL WAVE MERGER DETECTIONS SINCE 2015





Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

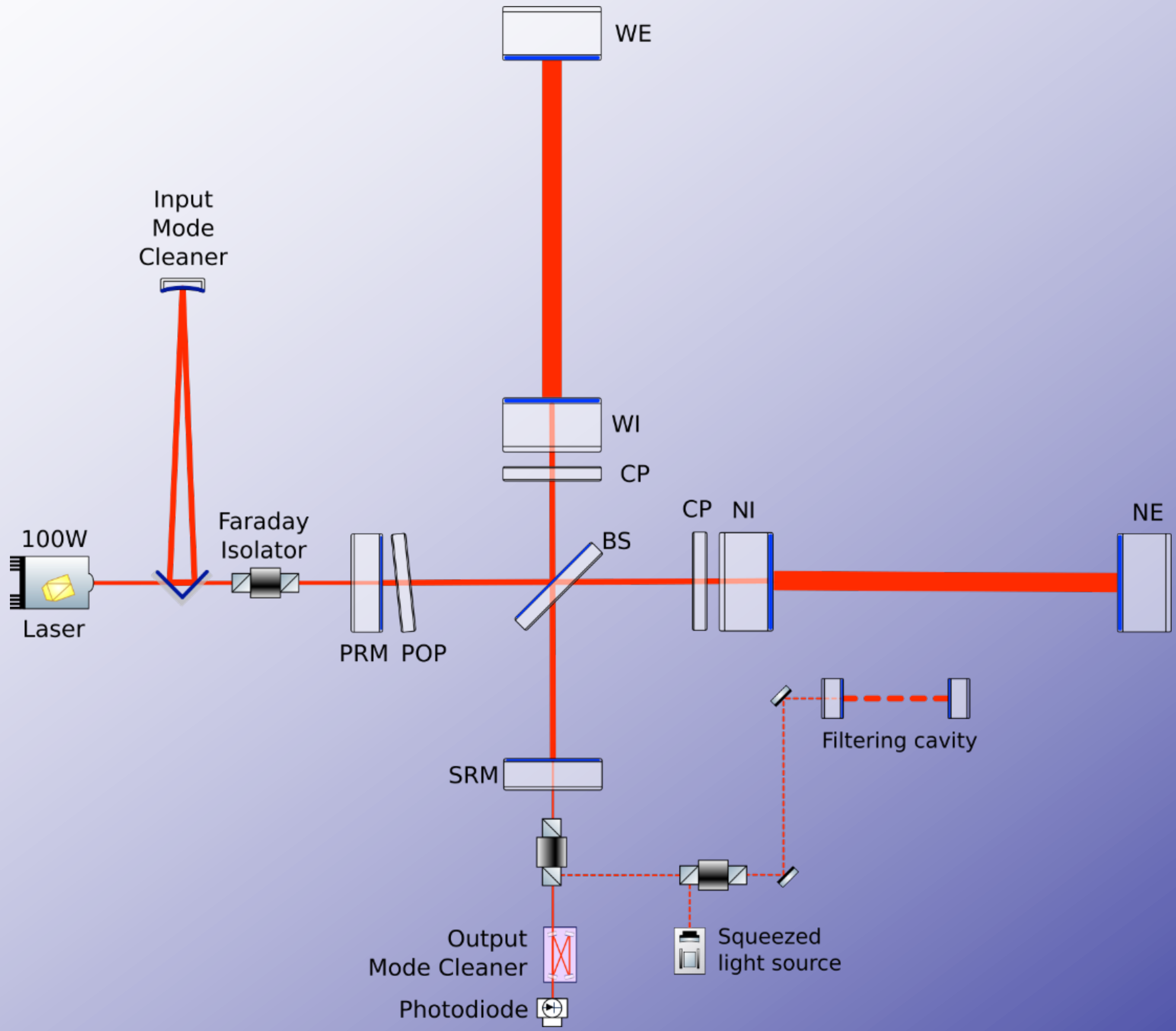
OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

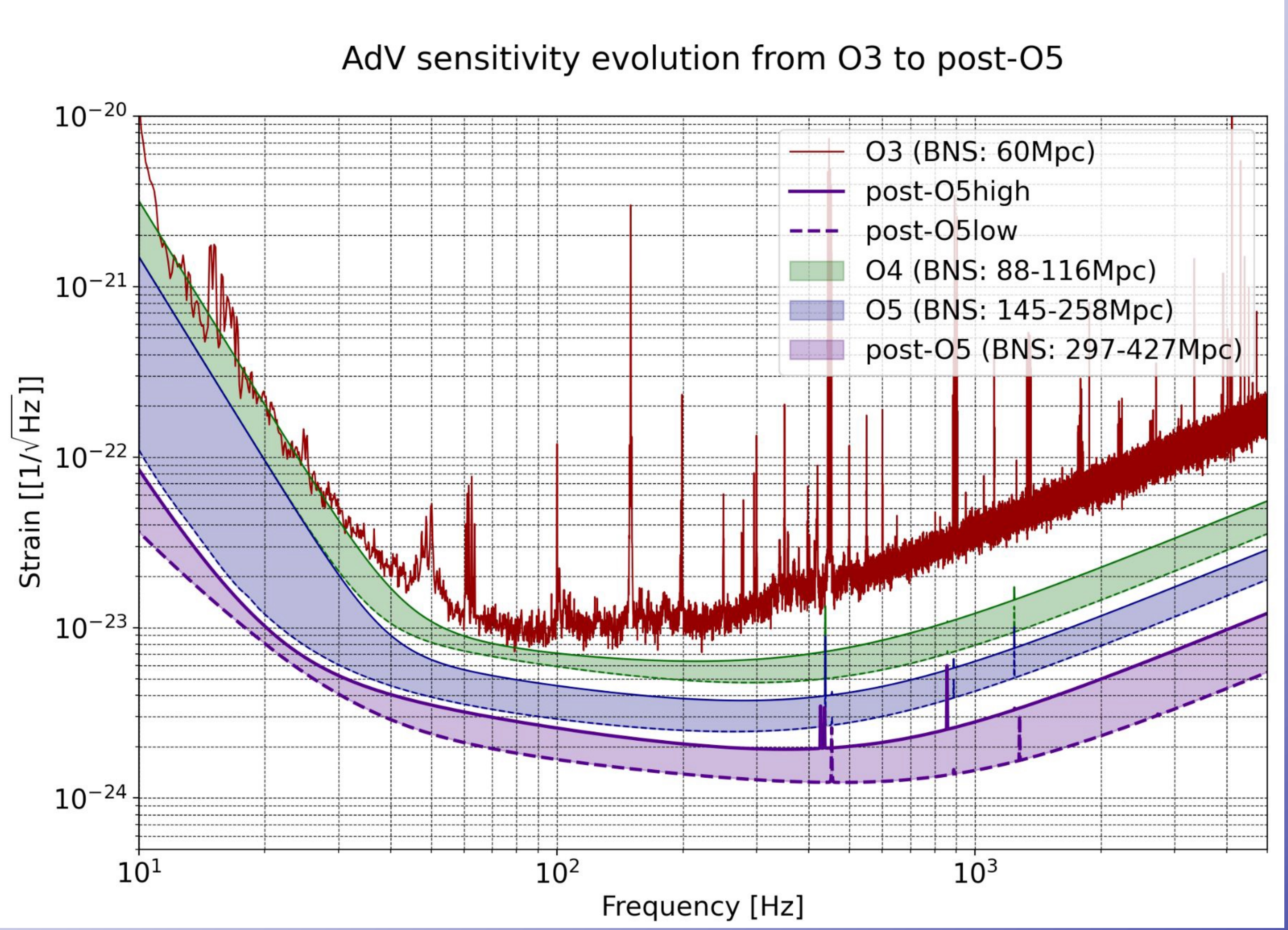
LIGO VIRGO KAGRA

Optical Design

AdVirgo+ Phase I Baseline

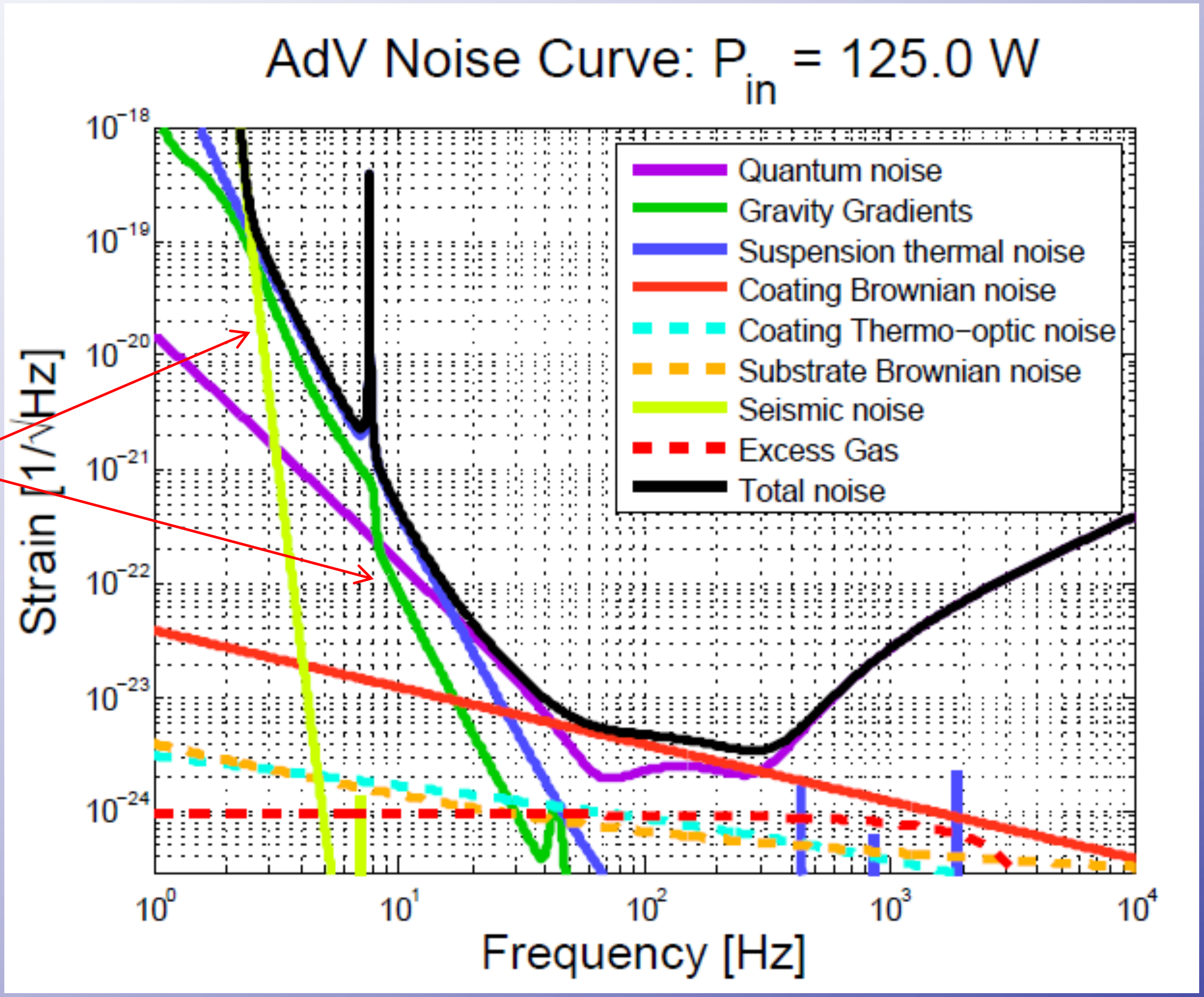


AdVirgo/AdVirgo+ sensitivity



AdVirgo Noise budget

Newtonian and Seismic noise dominate at low frequency

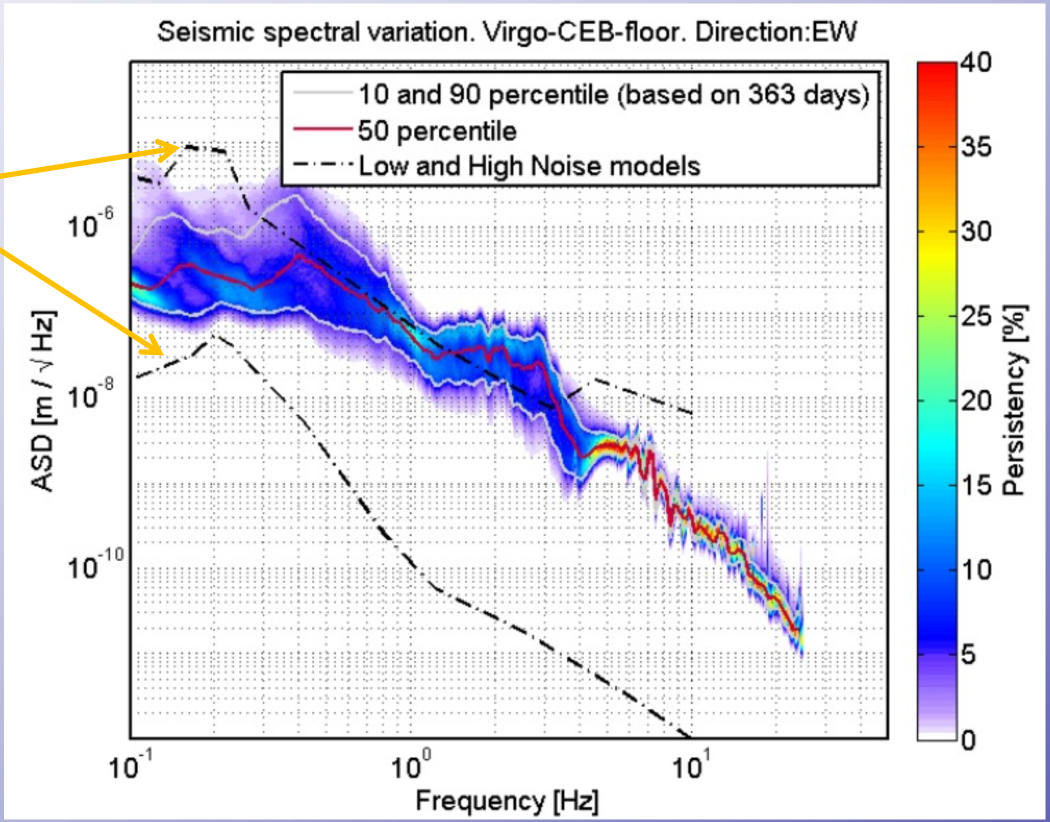


Introduction
Seismic Noise on Earth

- Seismic noise has both natural and human origins and can vary by few orders of magnitude from site to site.
- Al ground motion displacement spectra observed worldwide share some common characteristics: they have essentially the same amplitude in all three orthogonal space directions, and they exhibit a low pass behavior that follows the empirical law for f > 0.1 Hz

$$x(f) \sim A\,(1\ \mathrm{Hz}/\mathrm{f})^2 \ \text{m/sqrt(Hz)}$$

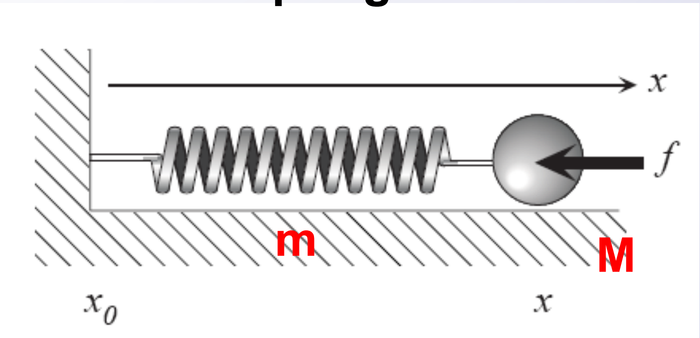
Peterson's High and Low Noise Models



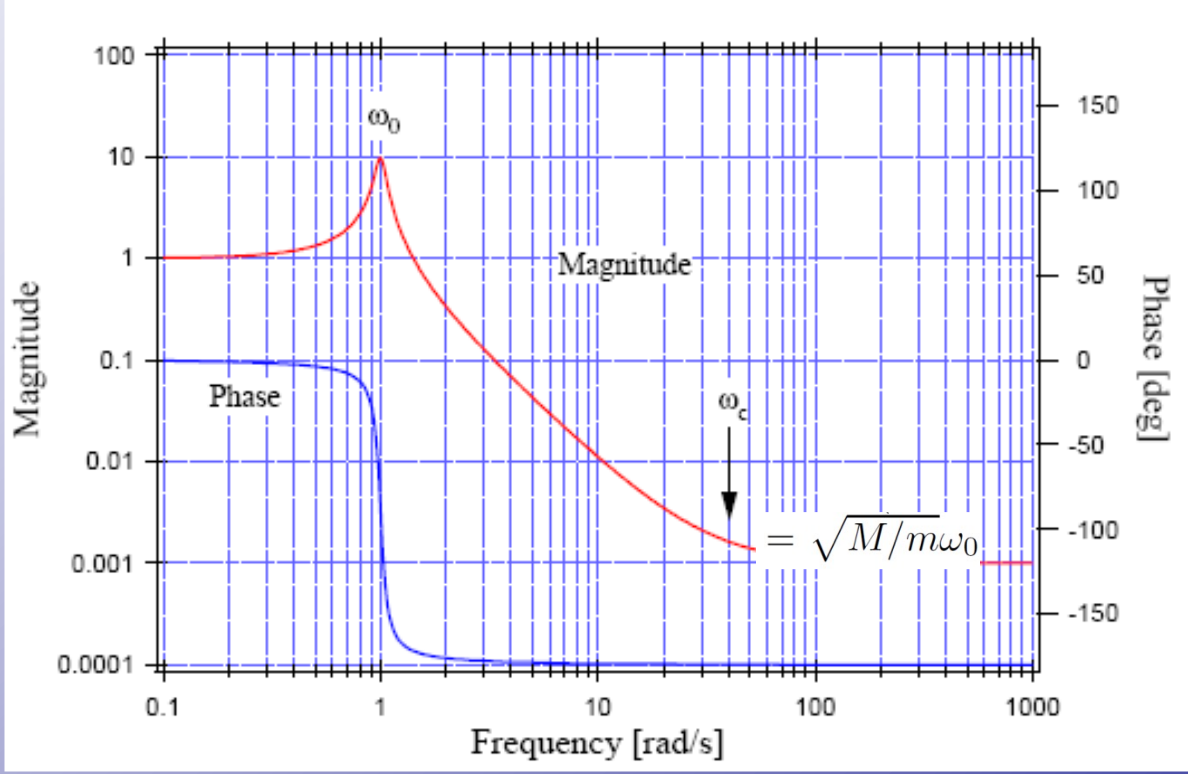
Introduction
Harmonic Oscillators as Mechanical filters

At frequencies higher than the oscillator resonance, the transfer function of an harmonic oscillator is equivalent to a second-order low pass filter.

Massive Spring



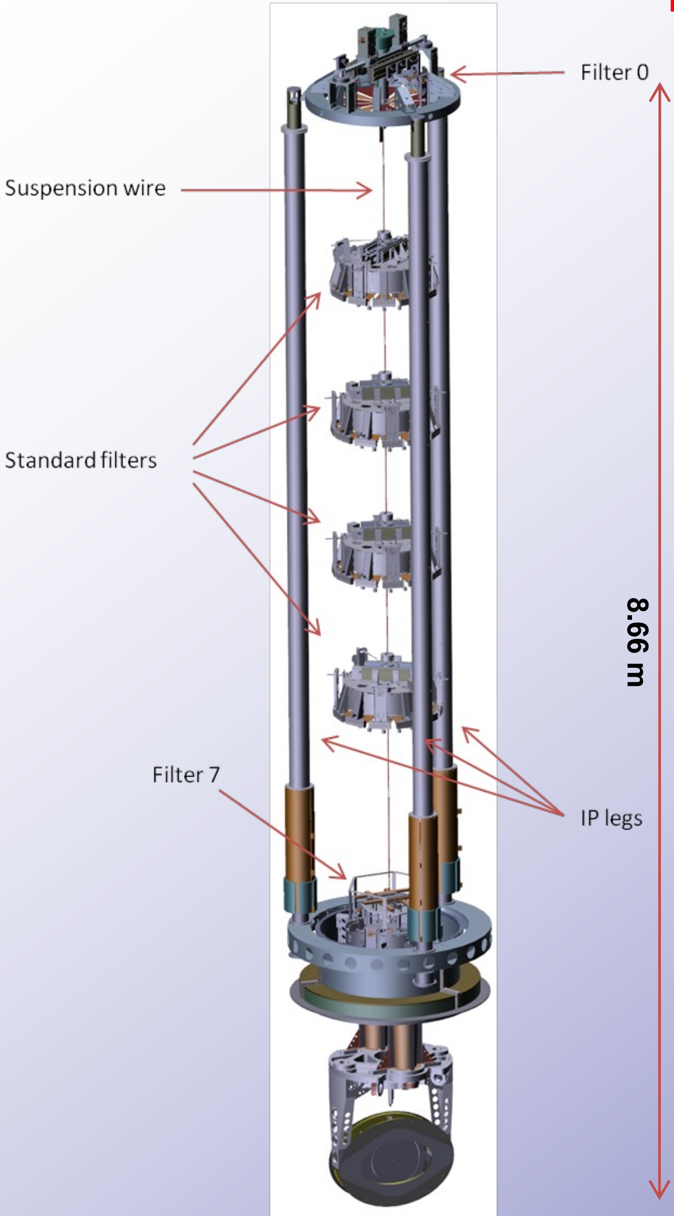
Transfer Function



$$H_X = \frac{\omega_0^2(1+i\phi) + \frac{m}{M}\omega^2}{\omega_0^2(1+i\phi) - \omega^2 + i\frac{\gamma}{M}\omega}$$

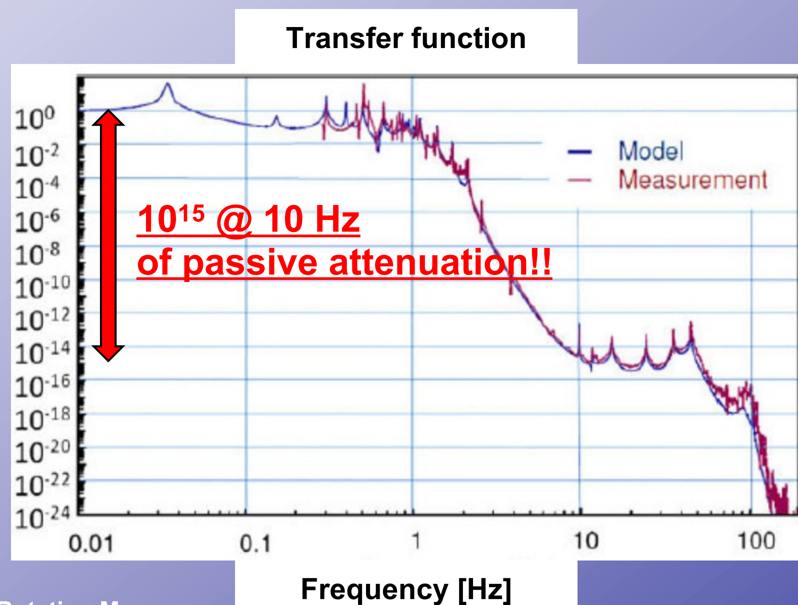
AdVirgo Superattenuator

The superattenuator (SA)



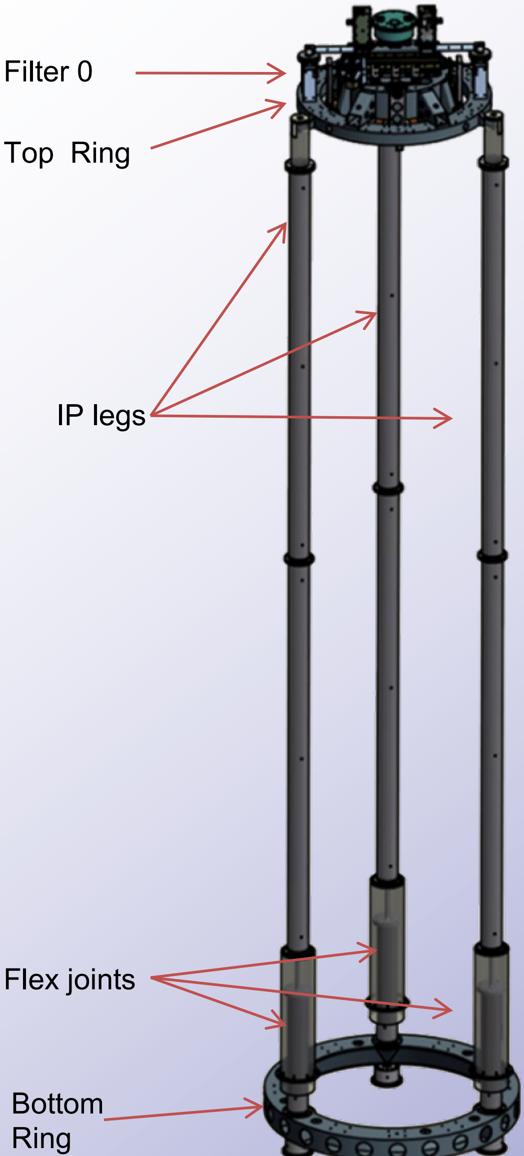
The AdVirgo superattenuator (SA) is a complex mechanical device capable of providing more than 10 orders of magnitude of passive seismic isolation in all six degrees of freedom above a few Hz

- The SA is a passive mechanical system constituted by a 5 stage pendulum supported by a 3-leg elastic pre-isolator called inverted pendulum (IP).
- All the normal mode resonance frequencies of the SA are kept below 2 Hz.
- The SA mechanical structure, consists of three fundamental parts: the inverted pendulum, the chain of standard filters, the payload.
- Mechanical design for AdVirgo is essentially the same of Virgo except for the payload.



AdVirgo Superattenuator

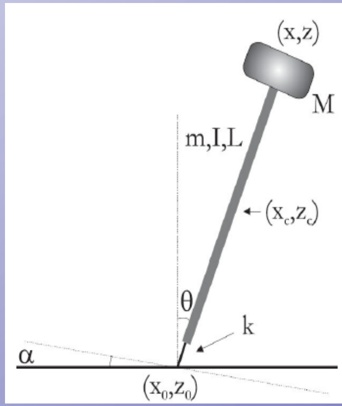
The inverted pendulum



- A low frequency pre-isolator constituted of three 6 m-long hollow legs, each one connected to the ground through a flexible joint and supporting an interconnecting structure (the top ring) on its top.

- The structure horizontal normal modes are tuned at about 30-40 mHz.

- A simple mechanical model such as this



Gravitational Anti-spring

gives

$$\omega_0 = \frac{k - (M + m/2)g/L}{M + m/4 + I/L^2}$$

- Since the system is very soft, it requires very low forces to be moved:

for f<<f0 $F \simeq M{\omega_0}^2 x$

- The top ring is a mechanical support for an additional seismic filter, called filter 0, similar to those used in the chain.

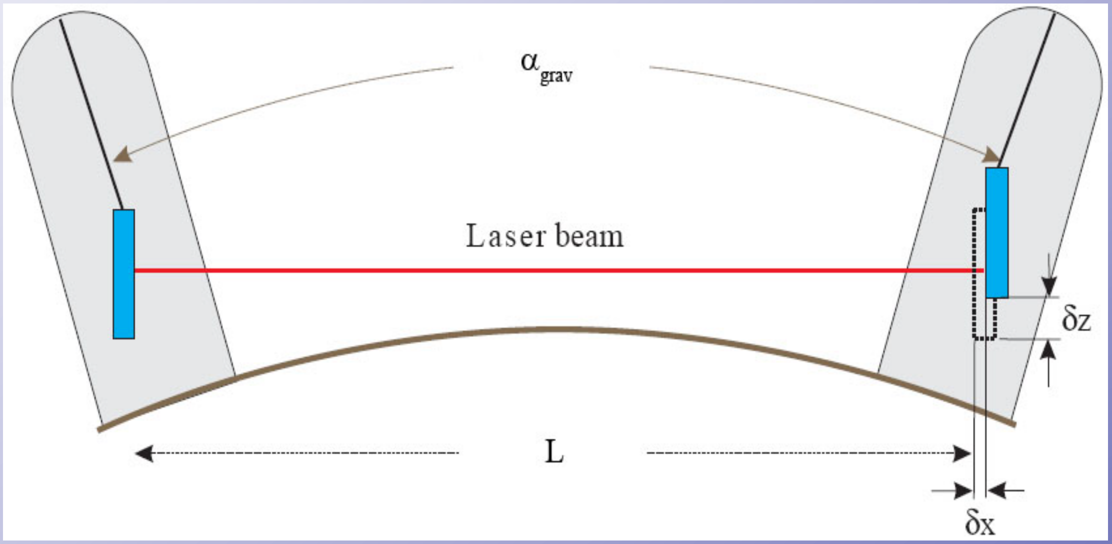
- The filter 0 is equipped with a set of sensors and actuators, placed in a pinwheel configuration, that are used to actively damp the IP resonance modes.

AdVirgo Superattenuator

Why vertical attenuation ?

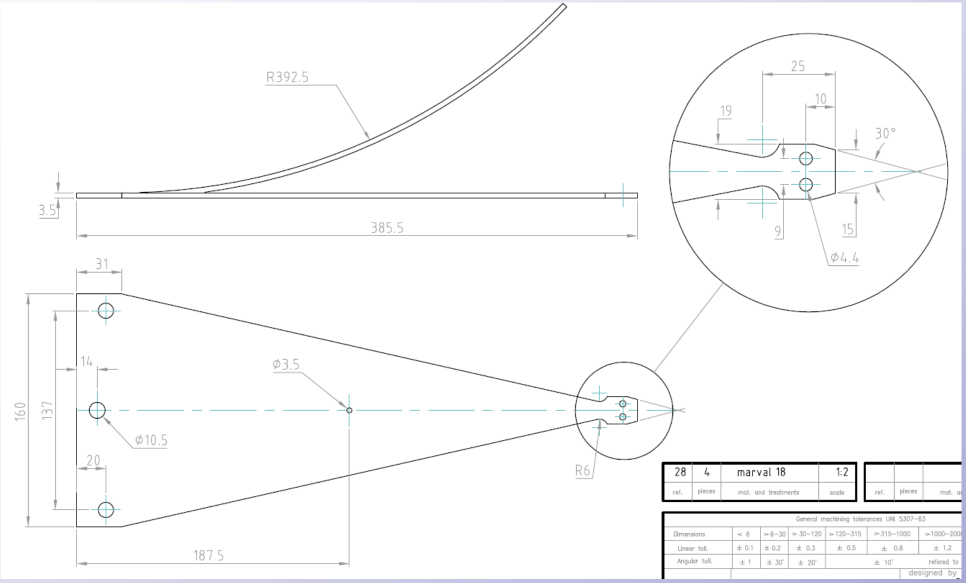
- The input and output mirrors of a Fabry-Perot cavity form an angle alpha_grav = L/r = 5*10^{-4} rad (where L = 3 km is the cavity length and r is the Earth radius) with the global vertical direction. Therefore vertical displacement Δz has effect along the beam direction, producing a variation alpha_grav*Δz of the optical path.

- The suspension system causes even larger mechanical couplings (1%), due to structural reasons.



AdVirgo Superattenuator

Vertical attenuation: Blades



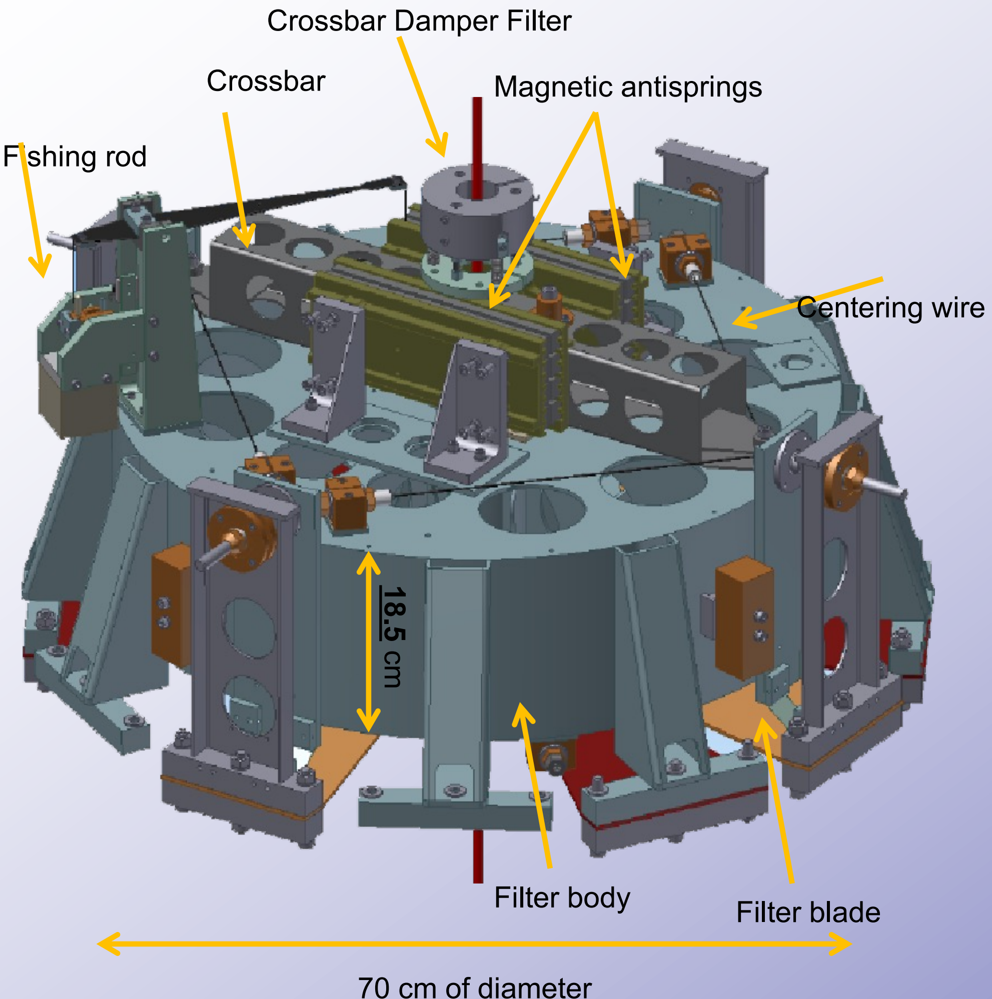
- All the maraging steel blades have a thickness of 3.5 mm, a length of 385.5 mm, while the width of the triangular base changes according with the load to be supported.

- The number of blades ranges from 12 (in the first filter of the chain) to 4 (in the filter 7) according to the suspended load. A total of 52 blades is needed for a long tower.

- The load M depends by the base width b, by the thickness t and length l with this law

$$M = \frac{Ebt^3}{12R_c g l}$$

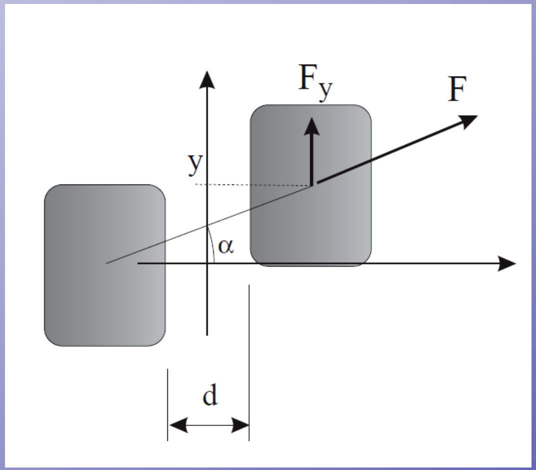
AdVirgo Superattenuator
Vertical Attenuation: Standard filters



The first four pendulum stages of the SA are denominated Standard Filters (SFs).

The SF is essentially a rigid steel cylinder supporting a set of maraging steel cantilevered triangular blades clamped along the outer surface of the filter body.

A magnetic anti-spring system, assembled on each filter, is designed to reduce its fundamental vertical frequency from about 1.5 Hz down below 0.5 Hz.

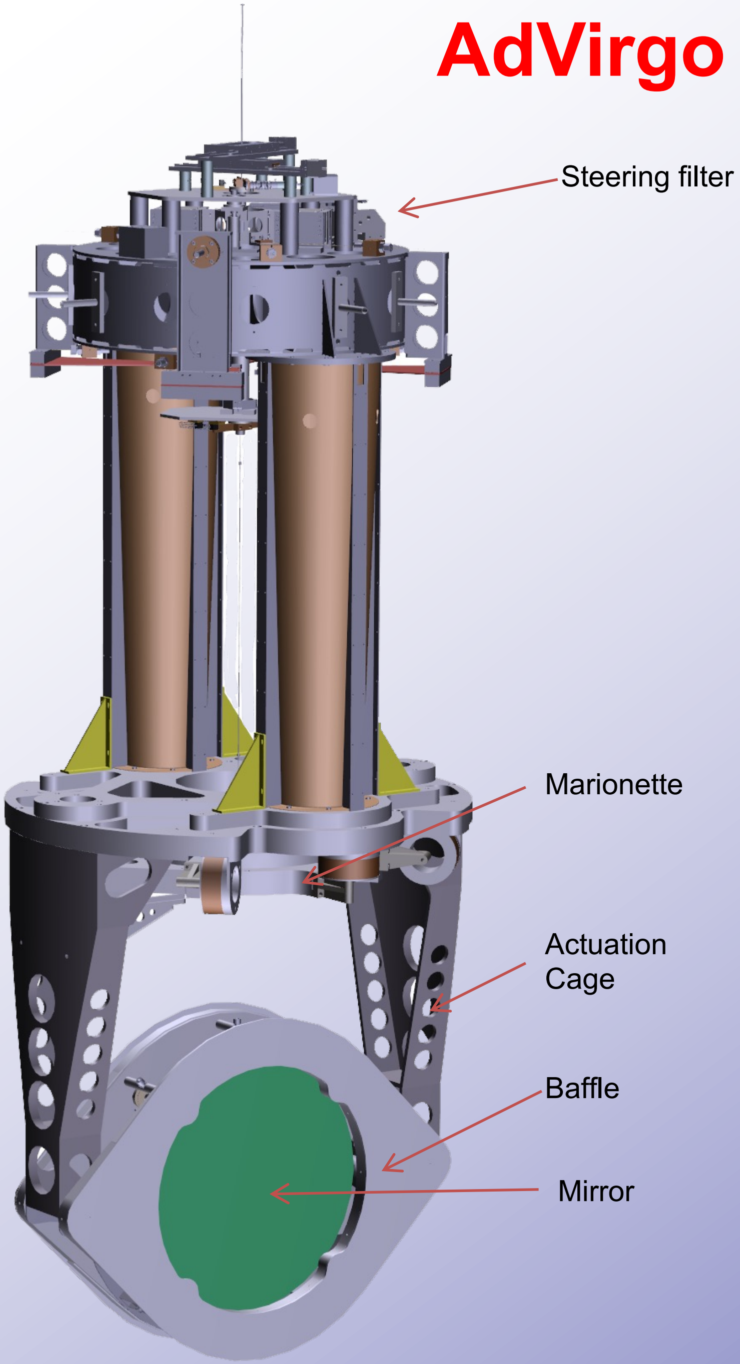


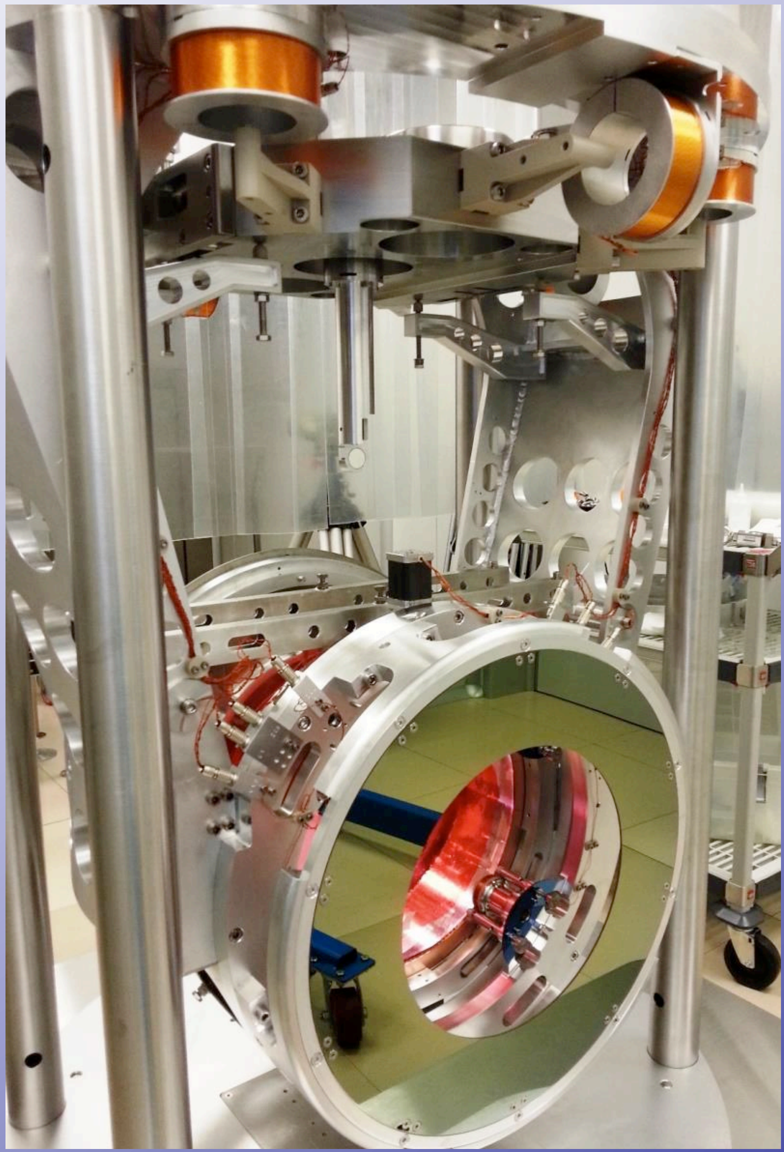
Magnetic antispring working principle

10^2 for *f* > 2 Hz of passive attenuation in both horizontal and vertical direction !!

AdVirgo Superattenuator

The payload

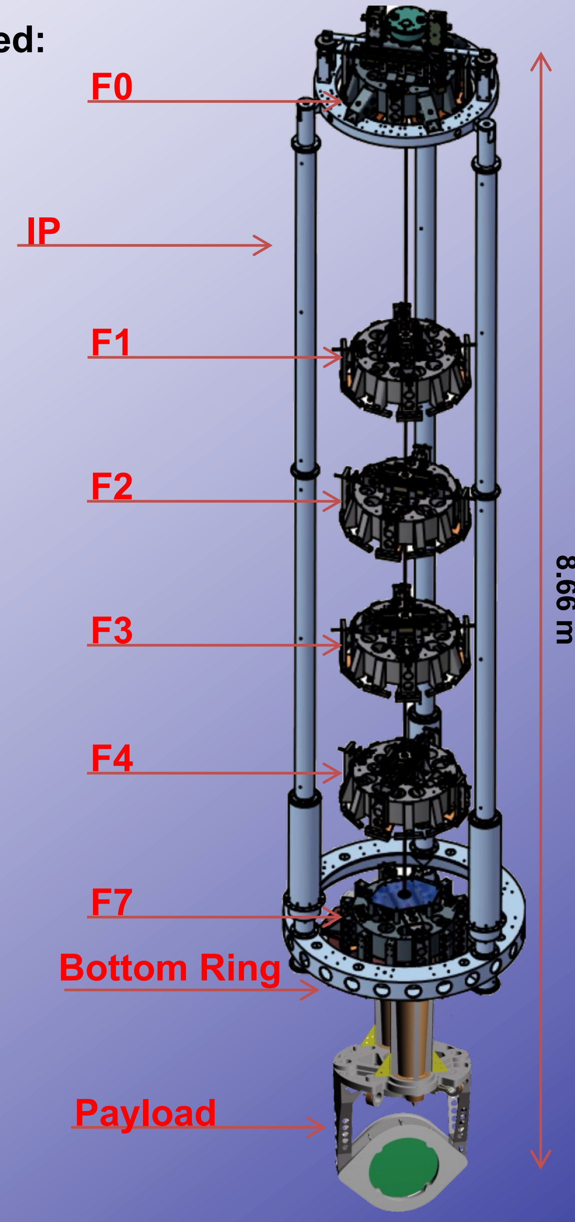




AdVirgo Superattenuator
Control system setup

On long superattenuators (BS, NI, NE, WI, WE, PR, SR) are installed:

- **18 LVDTs** of 3 different types
    - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
    - 3 F0 Horizontal LVDT
    - 6 F7 LVDTs
- **5 Accelerometers** of 2 different types installed on F0:
    - 3 Horizontal Accs
    - 2 Vertical Accs
- **23 Coils** of 4 different types
    - 5 F0 Coils
    - 6 F7 Coils
    - 8 Marionette coils
    - 4 Mirror coils
- **3 Piezos** on bottom ring
- **21 Motors**
    - 1 Top screw F0 vertical motor
    - 3 F0 trolley motors
    - 6 Fishing rod motors
    - 2 Marionette motors
    - 4 F7 motors
    - 5 Accelerometer motors



AdVirgo Superattenuator

Control sytem hardware

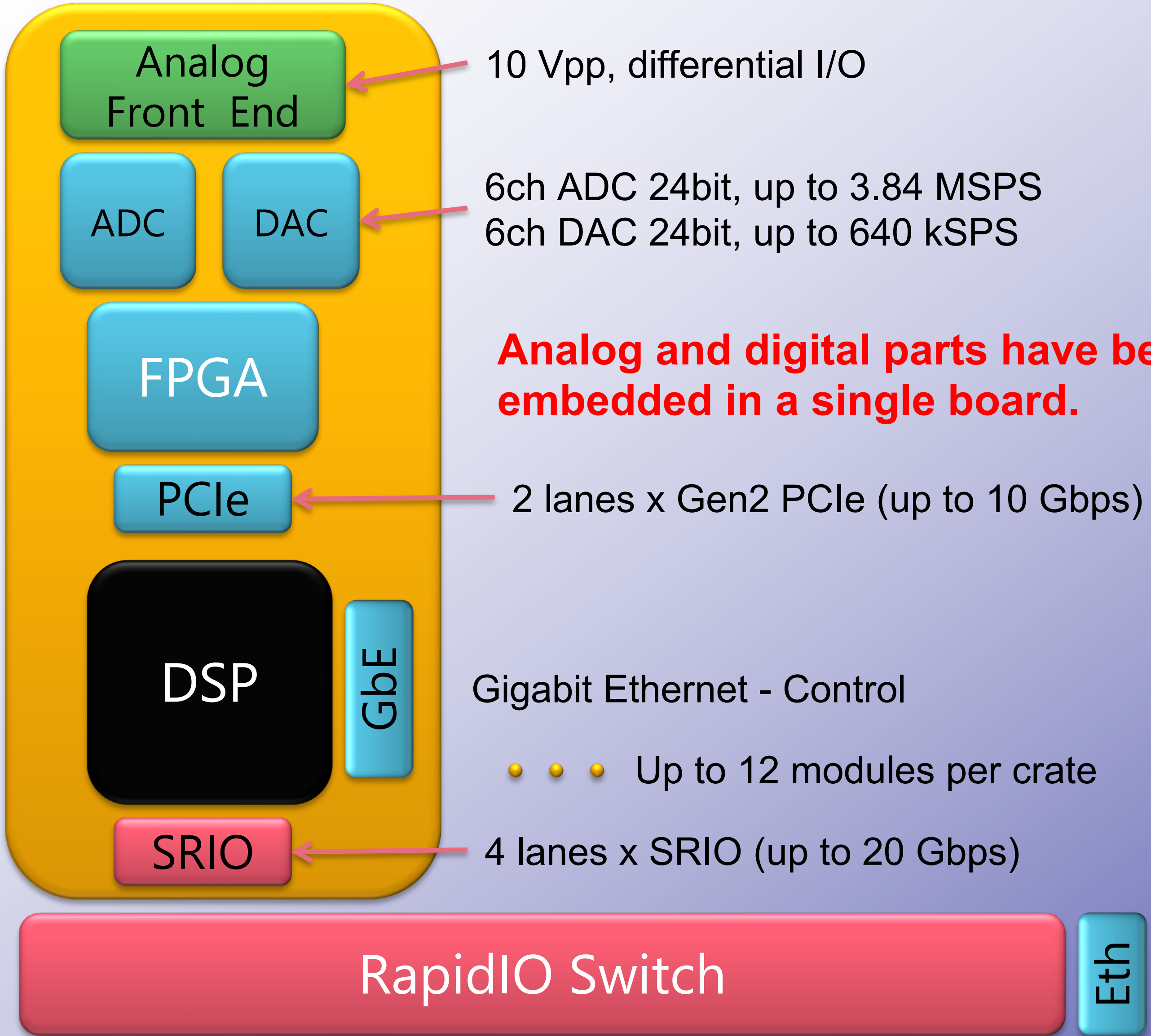
- **Electronics Design based on Texas Instruments DSP**
  - TMS320C6678
    - Eight TMS320C66x DSP Core Subsystems
    - 320 GMAC/160 GFLOP @ 1.25GHz
    - Four Lanes of SRIO 2.1 - 5 Gbaud Per Lane Full Duplex
    - Two Lanes PCIe Gen2 - 5 Gbaud Per Lane Full Duplex
    - Ethernet MAC Subsystem - Two SGMII Ports w/ 10/100/1000 Mbps operation
    - 64-Bit DDR3 Interface (DDR3-1600)

Computing power of a high-end GPU but extremely energy efficient and specifically designed for hard real-time applications

Platform		Effective Time to complete 1024 complex to complex FFT (single precision) μs	Power (Watts)	Energy per FFT (μJ)
GPU	nVidia Tesla C2070	0.16	225	36
GPU	nVidia Tesla C1060	0.3	188	56.4
GPP	Intel Xeon Core Duo @ 3 GHz	1.8	95	171
GPP	Intel Nehalam Quad Core @ 3.2 GHz	1.2	130	156
DSP	TI C6678 @ 1.2 GHz	0.86	10	8.6

AdVirgo Superattenuator

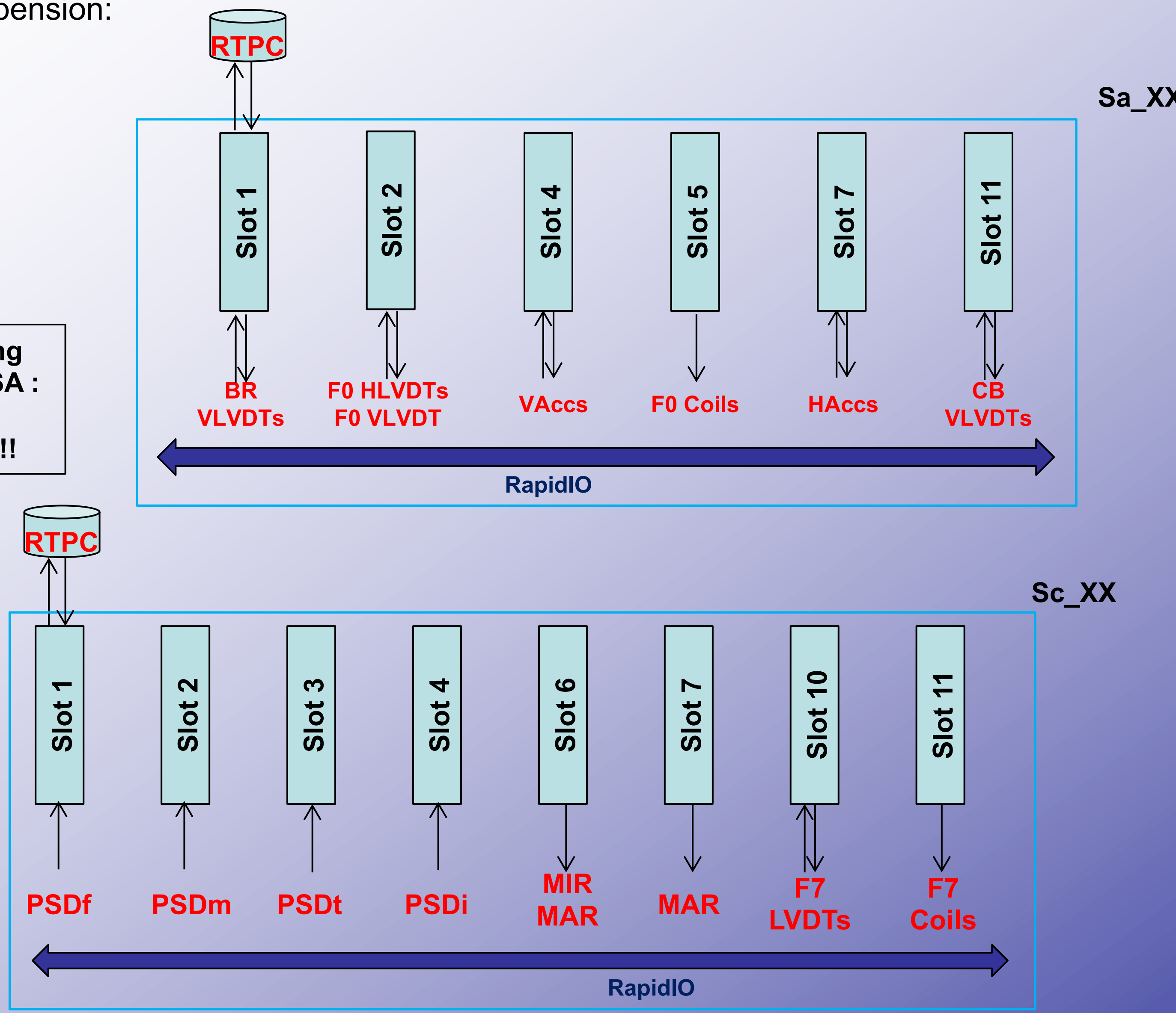
Control system hardware



Analog and digital parts have been embedded in a single board.

AdVirgo Superattenuator
Control system hardware

- A total of 14 boards, each one equipped with an 8-core TMS320C6678 DSP, are connected to each long suspension:



Total computing power of each SA :

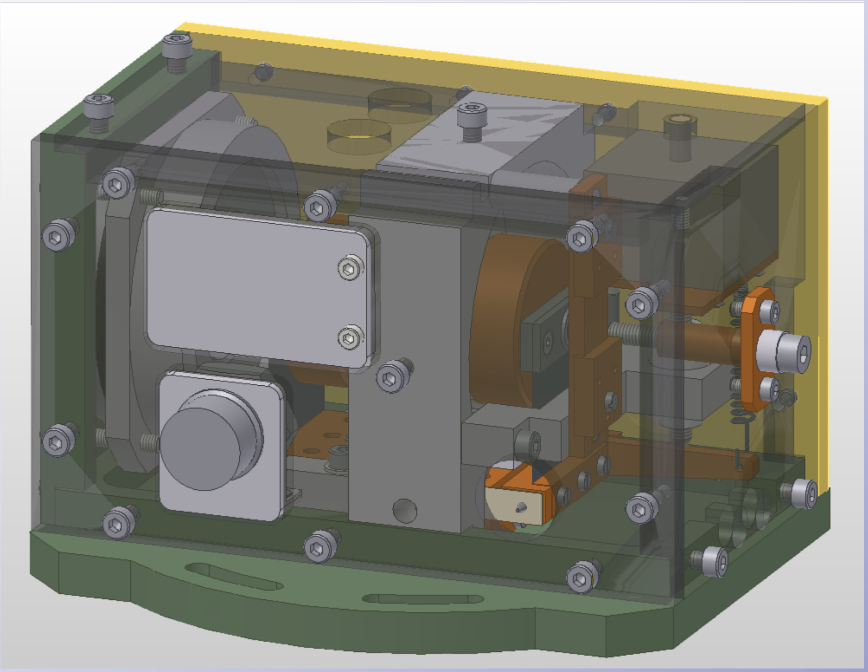
> 2.2 TFLOPs !!

AdVirgo Superattenuator
Sensors

• There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types with sensitivity of about $3*10^{-10}$ m/s^2/sqrt(Hz) for f < 3 Hz

• There are 18 LVDTs installed on long tower suspensions of 3 different types with a sensitivity of about 10^{-8} m/sqrt(Hz) for f > 0.1 Hz

• All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency

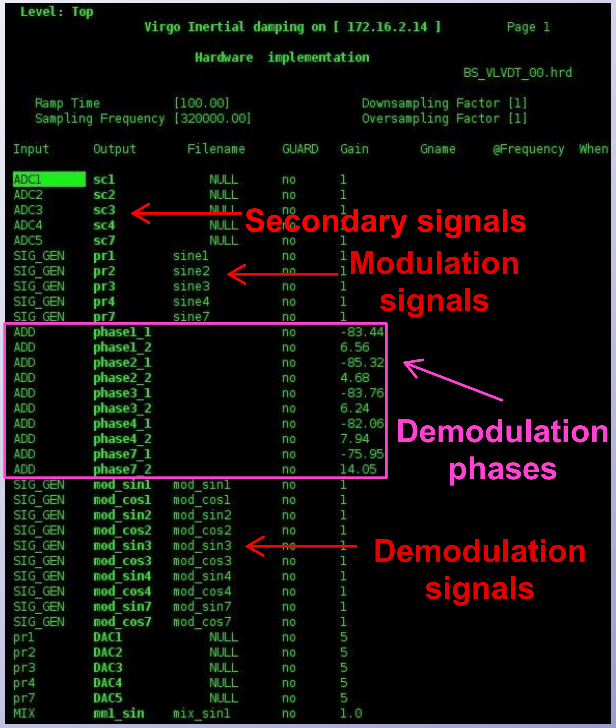


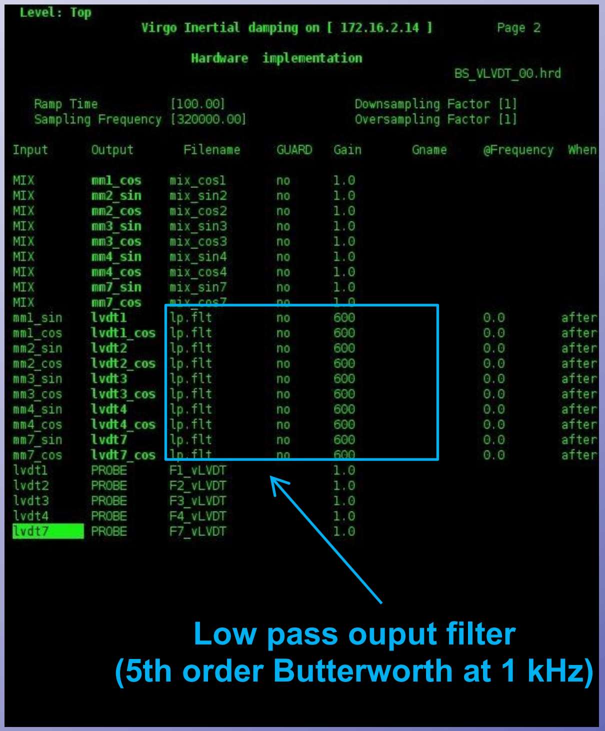
AdVirgo Superattenuator
Sensors

- There are 18 LVDTs installed on long tower suspensions of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs

- Each sensors have been characterized and calibrated

- All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency:

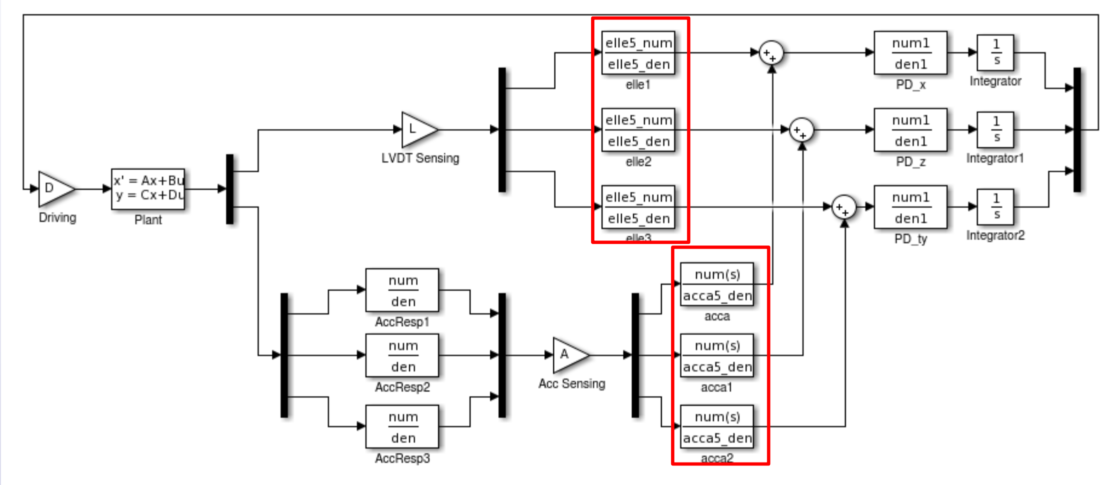




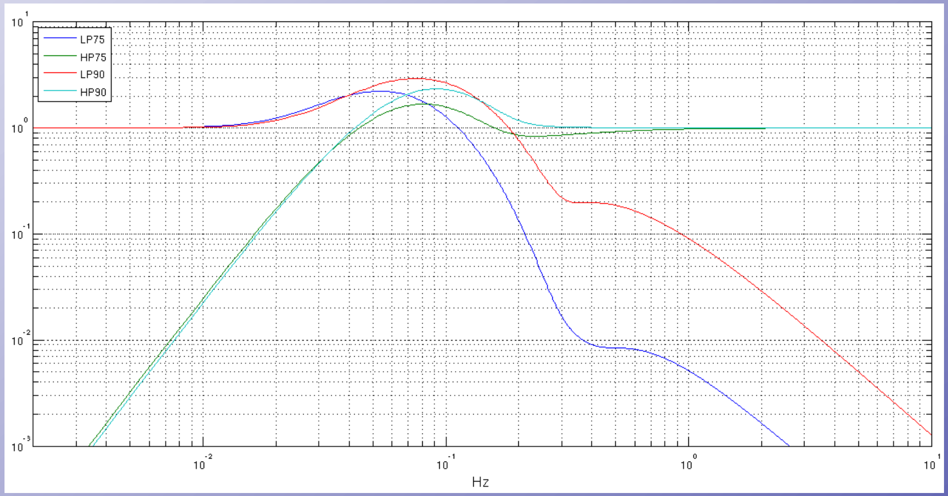
AdVirgo Superattenuator
Inertial Damping

Two Accelerometer-LVDT blending filters are used (High Pass for Accs and Low Pass for LVDTs)

- 75 mHz crossover frequency used for standard operation
- 90 mHz crossover frequency for robustness (High microseism or windy conditions)



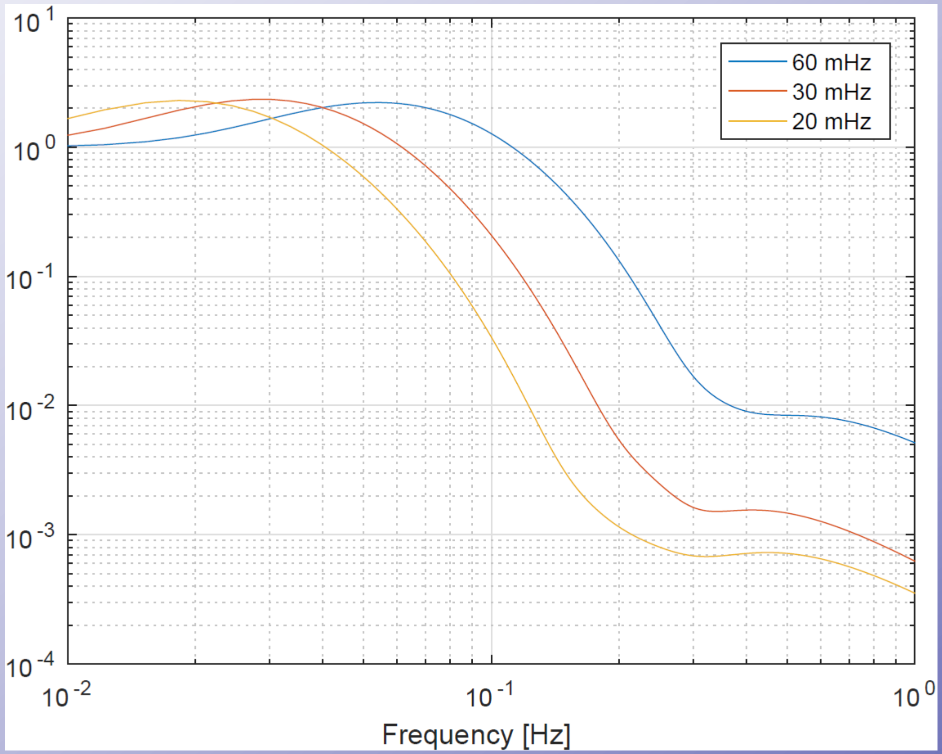
Standard Blending filters



Inertial Damping
GIPC

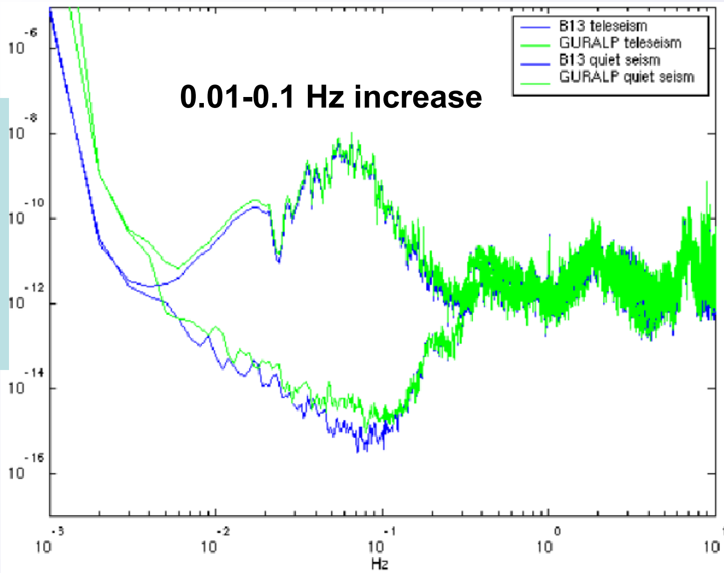
- Global Inverted Pendulum Control (GIPC) is a technique already used in VIRGO in which common and differential error signals are used to control the IP top stage instead of the local LVDTs and Accelerometers
- Using this strategy, the crossover frequency of the blending filters can be lowered (20 mHz, 30 mHz) without losing robustness improving the rejection of microseism.

Accelerometer low-pass filter comparison

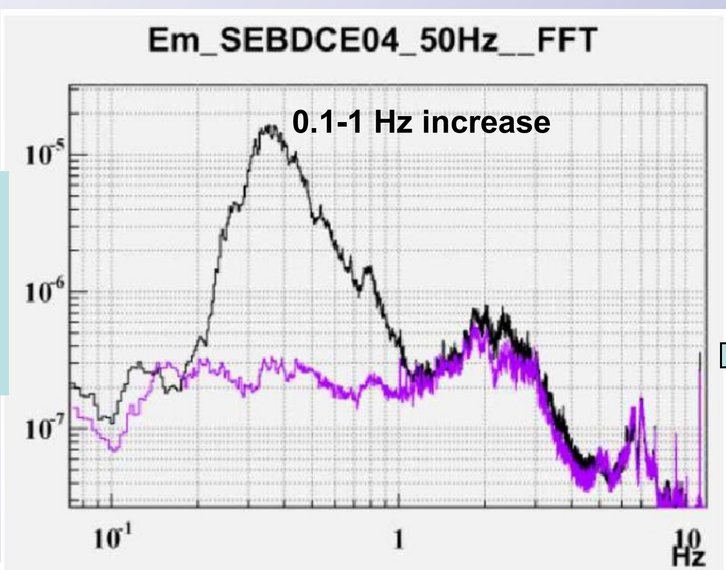


AdVirgo Superattenuator
Tilt Control Problem

Earthquake effect on seismic noise



Wind effect on seismic noise



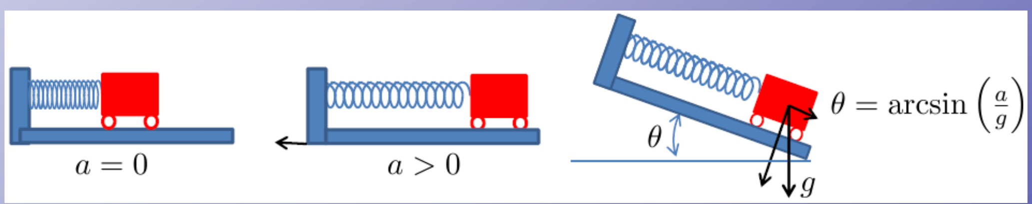
Experimentally, due to earthquakes or bad weather conditions, seismic noise grows up to 2 or 3 orders of magnitude in 100 mHz -1 Hz band with its maximum between 400 and 500 mHz (micro-seismic peak).

How to compensate the noise increase?

- **Piezo actuators are installed on bottom ring**

We need to know how much of the noise increase is tilt since

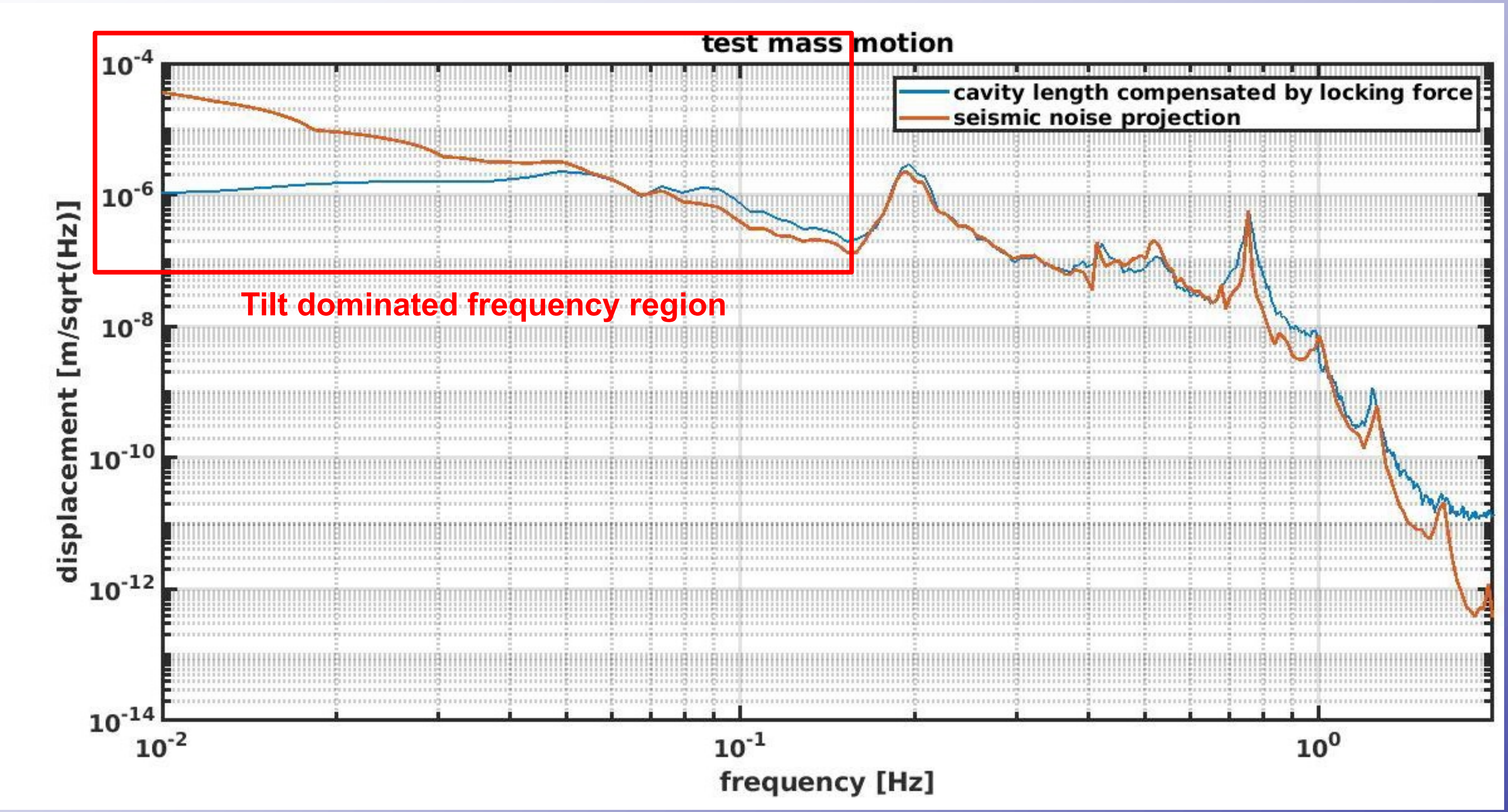
- Ground tilt is transmitted to Superattenuator (SA) top stage without any attenuation.
- Accelerometers on SA top stage are sensitive both to tilt and acceleration



A pure-tilt inertial sensor would be beneficial to increase the duty-cycle of the interferometer

AdVirgo Superattenuator
Tilt Control Problem

- An estimate of the noise re-introduced by the accelerometers due to tilt can be calculated comparing the cavity length obtained by the IFO correction signals and the projection of the seismic noise on the closed loop models oh the suspension.
- **We get about 0.4 nrad/sqrt(Hz) @ 0.01 Hz**



Plot by Paolo Ruggi (EGO)

AdVirgo Superattenuator
Tilt sensors: g-sensitivity

Since at low frequency the accelerometers provide already an output proportional to angles, a very low crosscoupling between acceleration and angular velocity is essential for tilt control.

Fourier – transformed Accelerometer output:

$$\tilde{A} = \tilde{x}(\omega)\omega^2 - g\tilde{\theta}(\omega)$$

Fourier – transformed Tiltmeter output:

$$\tilde{T} = k\tilde{x}(\omega)\omega^2 - \tilde{\theta}(\omega)\omega$$

In order to have linearly independent outputs for f>1 mHz we need to have the crosscoupling between angular velocity and acceleration

k < w/g ~ 2*pi*10^-4 s/m

↓

CC < 10^-4/f s^2/m

Angle Crosscoupling

AdVirgo Superattenuator
Tilt sensors: HRGs

Hemispherical Resonator Gyros (HRGs) are the de facto standard gyroscopes used in the inertial guidance of space missions (launched aboard more than 100 spacecrafts).

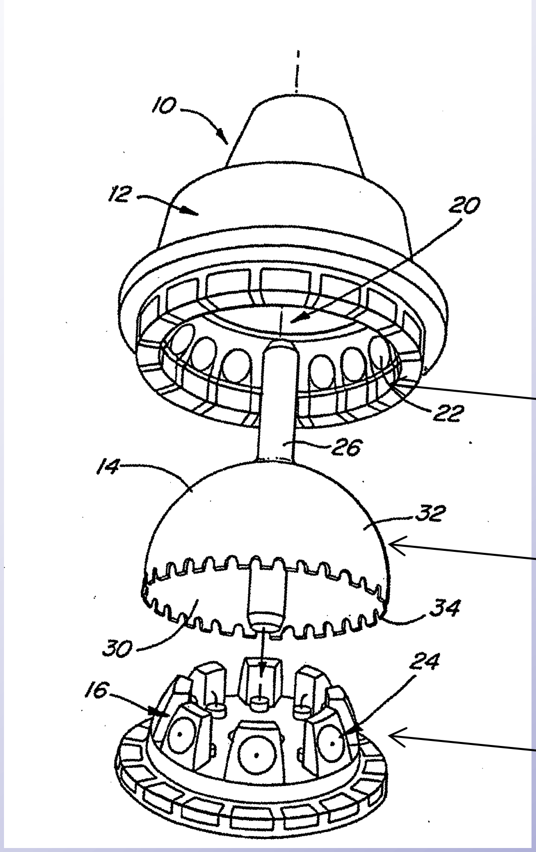
Advantages:

- No moving parts
- Small and light
- Very long operation and reliability

(25 millions of hour of operation in space without failure!)

Problems:

- Designed for high angular velocity sensing
- Long term drift



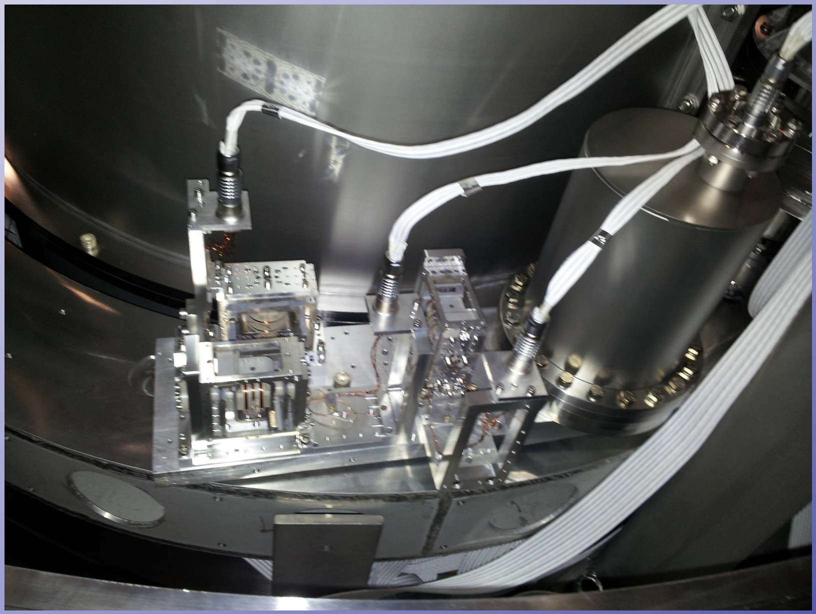
Control Electrodes

High-Q Fused-Quartz Wine Glass Resonator
(Key component, typically produced using ion beam etching)

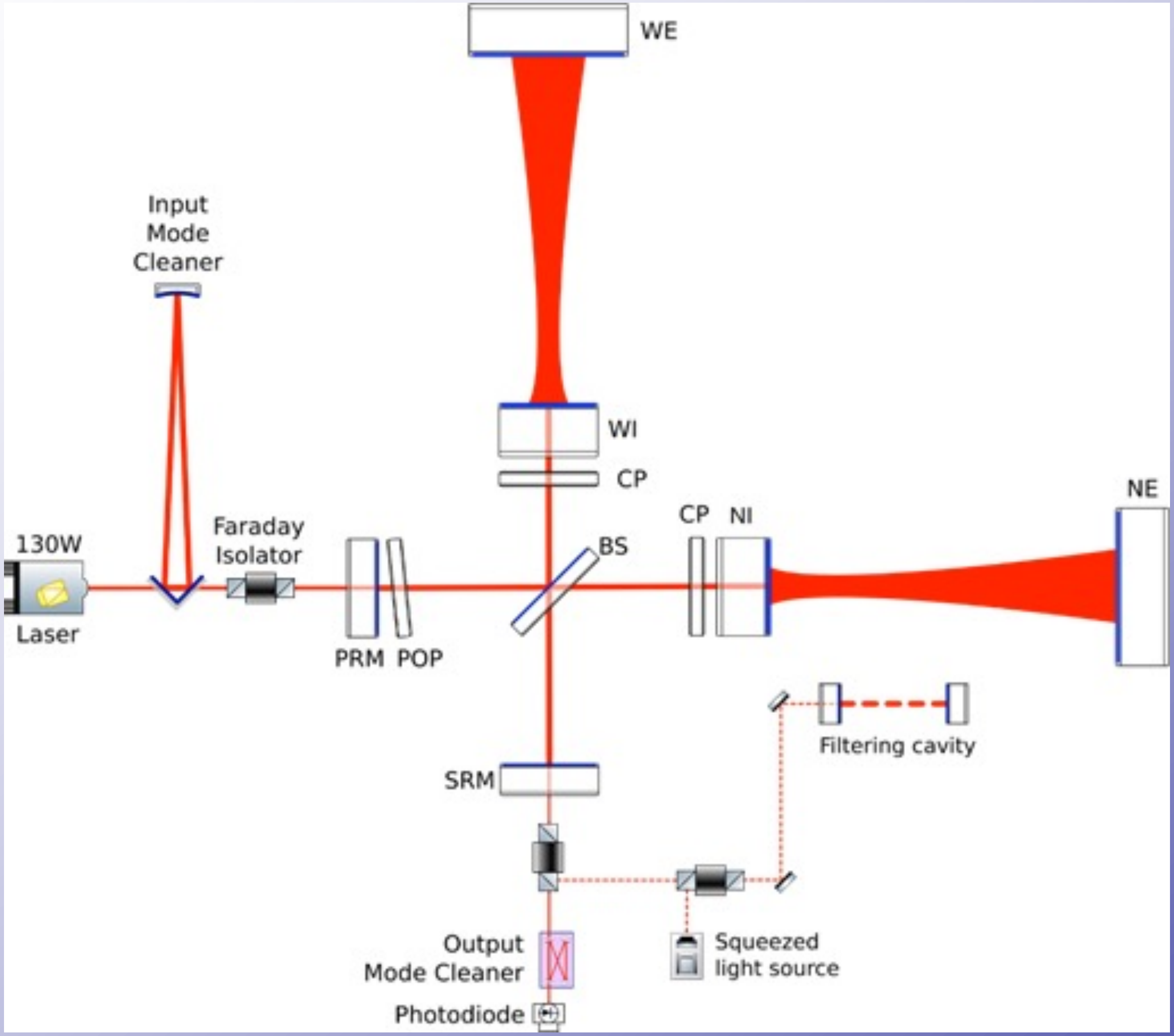
Pickoff Electrodes

AdVirgo Superattenuator
Tilt sensors: CVGs

- A custom-made Coriolis Vibratory Gyroscope made by the Irish firm Innalabs was tested and installed on the bottom ring of SR back in 2018.
- Each sensing element consists of a metallic cylindrical resonator which has two flexural second order resonant modes which occur at the same frequency.
- The device (still in operation) has a sensitivity of a few hundreds of nrad/sqrt(Hz) below 0.1 Hz. We hoped it could provide an upper limit of the motion in bad weather conditions.



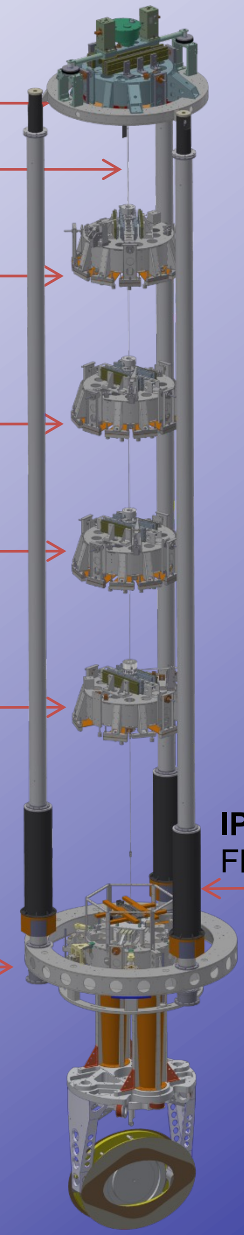
The future of gravitational wave astronomy
AdVirgo+ Phase II Baseline



The future of gravitational wave astronomy
SA updates for LMs

Here is a summary of the mechanical design updates foreseen for Phase II

- IP flex joints and all wires will be thicker
- F0 and F1 filters will have thicker blades (3.7 mm)
- Current F1 filter will be used as F2
- Current F2 filter will be used as F3
- F4 and F7 will have more blades (from 6 and 4 to 8 and 6 respectively) with current thickness (3.5 mm)
- All filters except F7 are expected to keep current Magnetic Antispring configurations
- F0, F1 and F2 will host updated movable blades support



The future of gravitational wave astronomy
Virgo Next

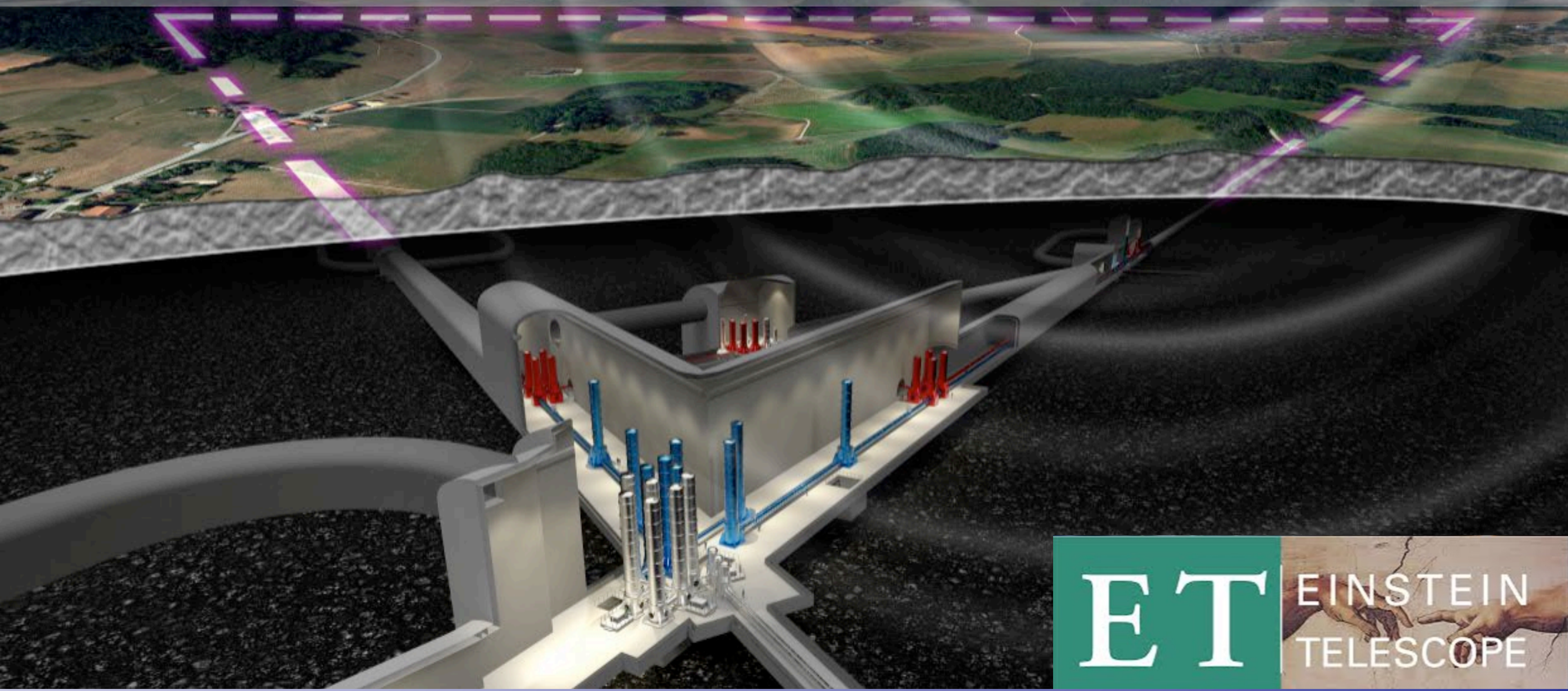
Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6
Newtonian noise reduction	None	1/3	1/3	1/5	1/5
Technical noise	“Late high”	“Late low”	“Late low”	None	None
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc

The future of gravitational wave astronomy

Einstein Telescope

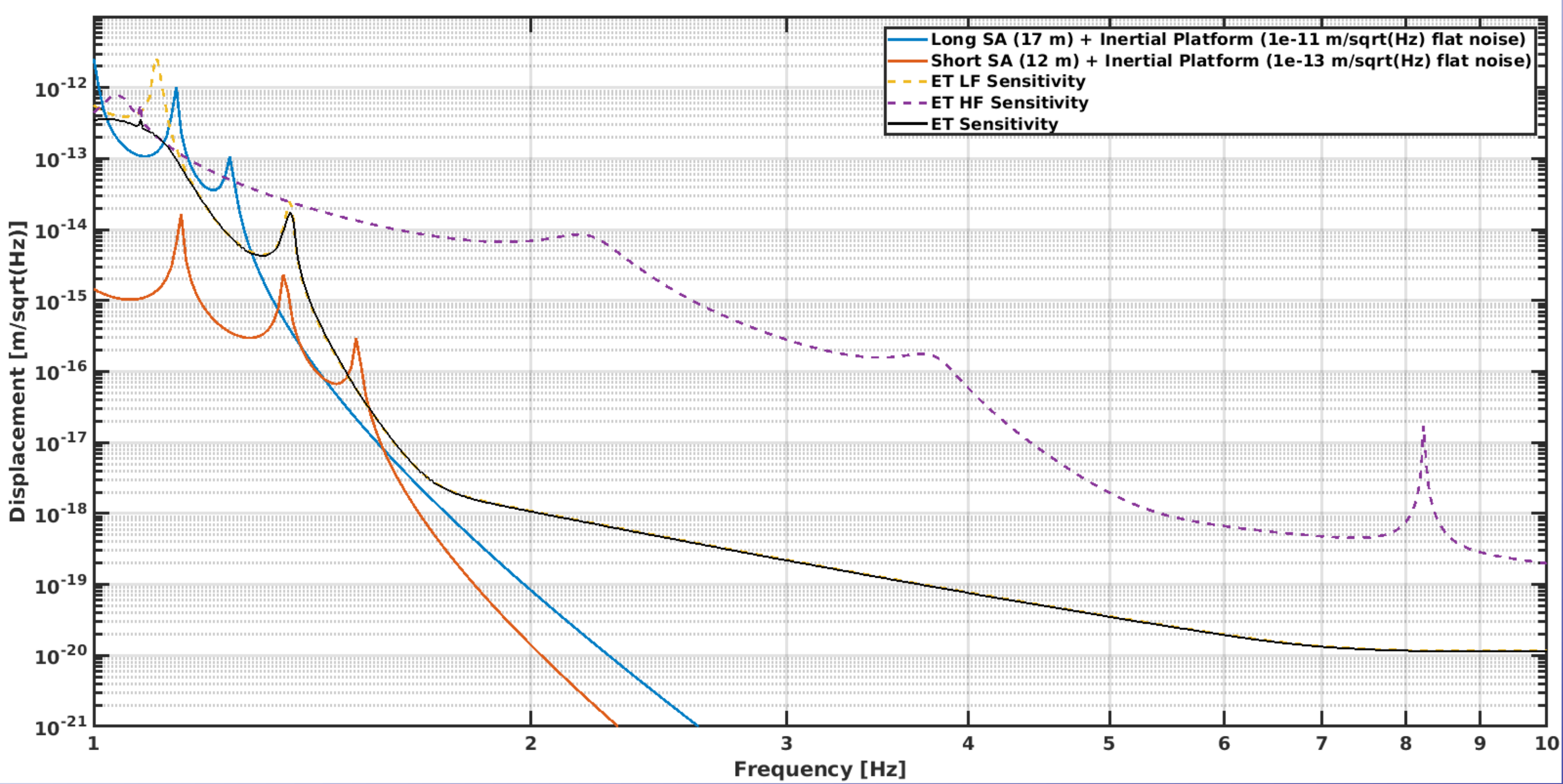
- Einstein Telescope (ET) is expected to have a triangular configuration, with 10 km of length for each side, in order to host two detectors with different bandwidths, and, to drastically reduce the effects of ground motion, will be built underground, making the needed infrastructural works very complex and expensive.

- In Europe three candidate sites have been identified for ET: an area in the Nuoro province, in Sardinia, Italy, the Meuse-Rhine euroregion at the border between Netherlands, Belgium and Germany, and a location in Saxony, Germany.



Einstein Telescope
Seismic isolation

- The gravitational-wave interferometers of next generation, Einstein and Cosmic Explorer, aim at gaining a factor of 10 in noise level, respect to Virgo and LIGO, but also extending at low frequency their detection band.
- Even in a site with very low seismicity, the sensitivity increase in the low frequency region will put challenging constraints on the suppression of seismic noise: **new designs should be studied**.



ET Design Update (ET-0007B-20)

BHETSA

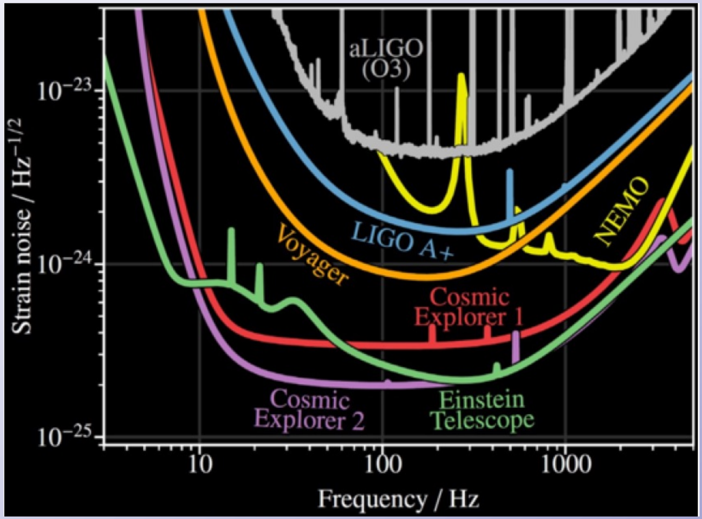
A seismic isolation system for the test masses of the Einstein Telescope

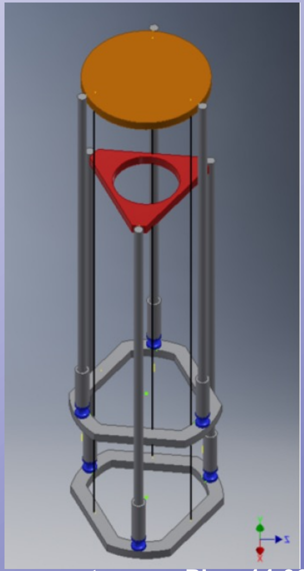
- Black Holes for ET SArdinia (BHETSA) is a 3-year project funded by the PRIN2020 MIUR call.
- Its goal is the design of a suspension system that isolates seismically the test masses of the Einstein Telescope at frequencies above 2 Hz with a height of about 10 m, like the one of the Virgo Superattenuator (SA).
- To test the new design a prototype will constructed, tested and validated.

Achieving detections of **low frequency gravitational waves** is crucial for the science program of the Einstein Telescope

While based on current VIRGO SA, the mechanical solutions proposed envisaged both an upgrade of the standard filters and of the inverted pendulum pre-isolator.

The prototype will be tested in Sardinia at the **SOS Enattos** candidate site for ET





Thank you for your attention!!