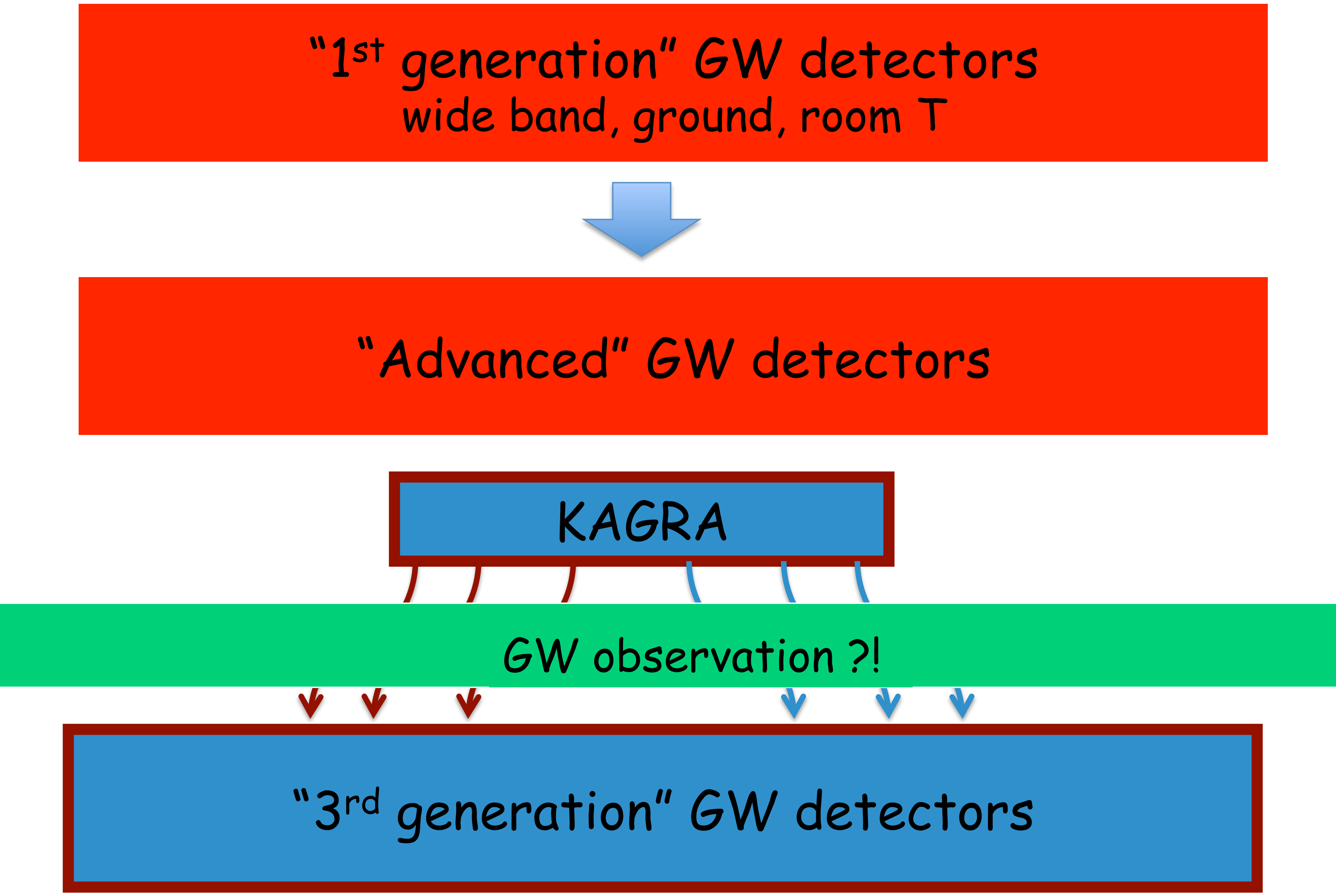
GWADW 2013
Gravitational Wave Detectors for the Next Decade Workshop

Suspensions for future GWDs

E. Majorana

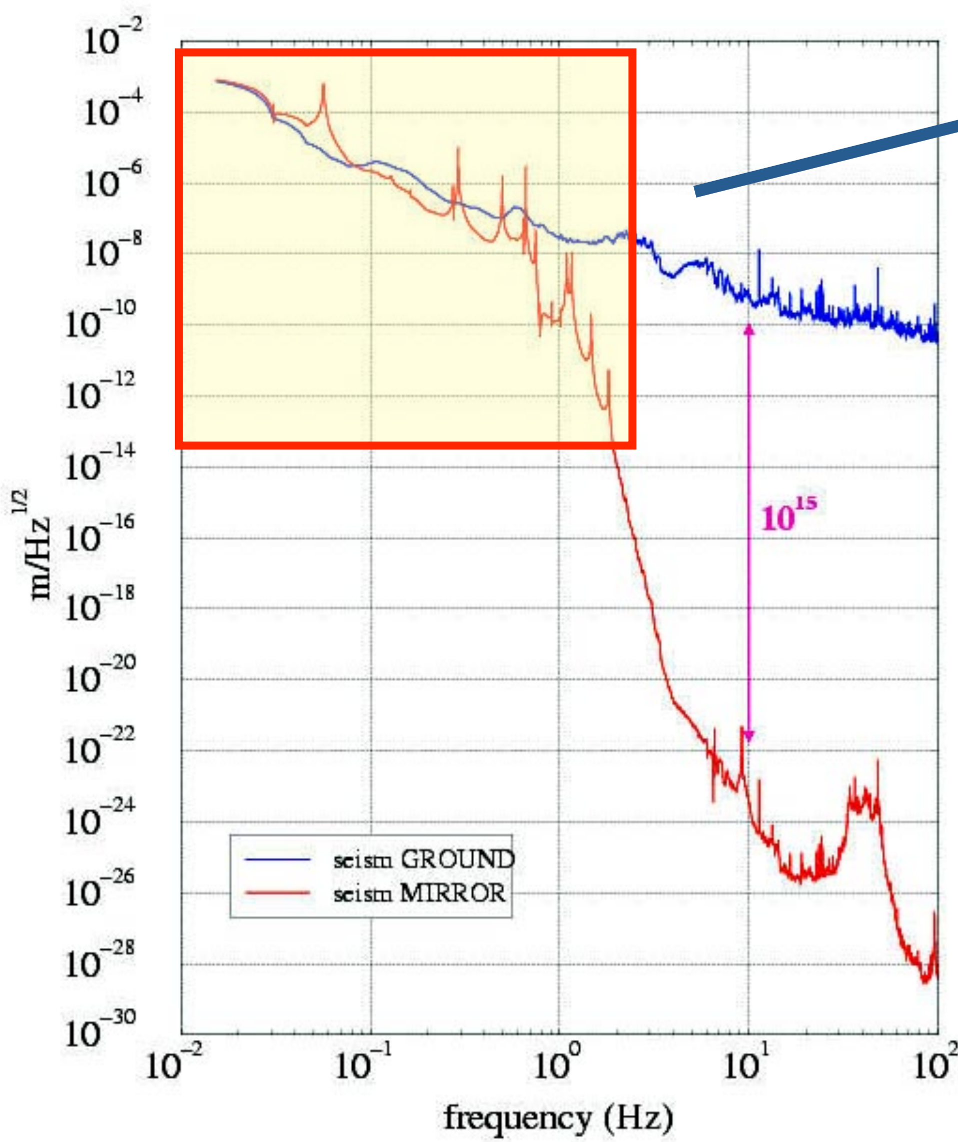
INFN

Isola d'Elba, 19-25 May-2013


"1st generation" GW detectors
wide band, ground, room T
"Advanced" GW detectors
KAGRA
GW observation ?!
"3rd generation" GW detectors

HOW MUCH

The ground



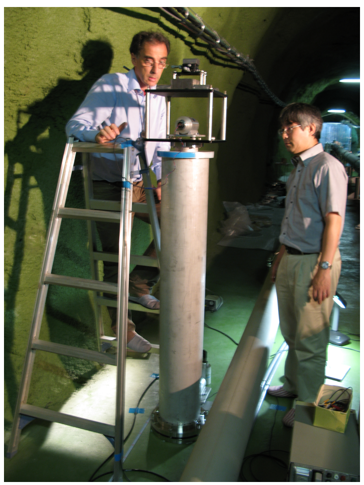
several microns swing

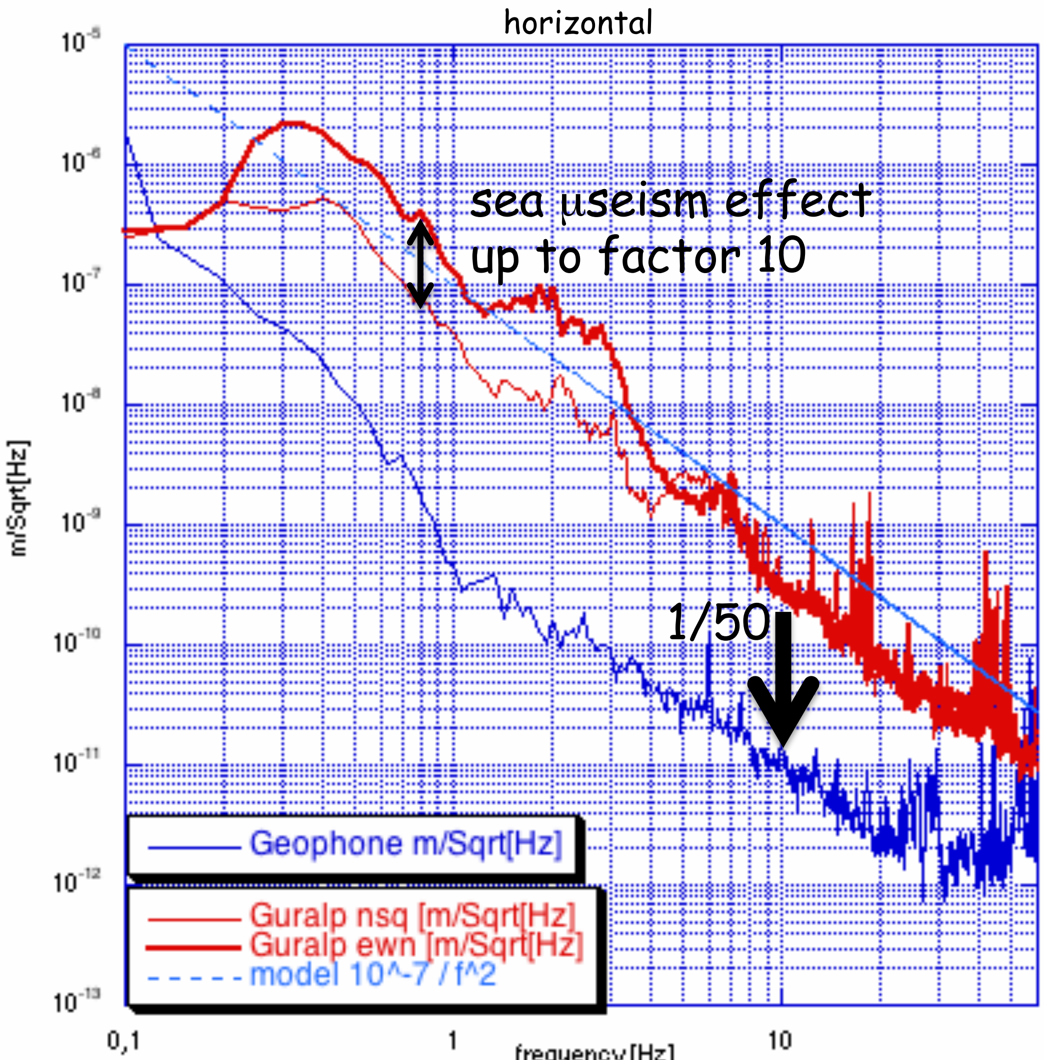
$$S^{1/2}(f) \approx \frac{10^{-7}}{f^2} m/\sqrt{Hz} \quad (f > 1\ Hz)$$

KAGRA

Lat 36° 26′ 7.97″ N
Lon 137° 17′ 21.48″ E
Ht 403.93 m
Lat 36° 25′ 31.19″ N
Lon 137° 20′ 7.07″ E
Ht 424.41 m
Lat 36° 24′ 42.70″ N
Lon 137° 18′ 31.44″ E
Ht 414.18 m
KAGRA X arm, 3 km
宿舎
500m
神岡宇宙素粒子研究施設
茂住坑
池山
カムランド
CLIO
スーパーカミオカンデ
北
跡津坑
高原川
跡津川
village
重力波解析棟(予定)
underground
Japan
Tone River
Tokyo
Yokohama
Nagoya

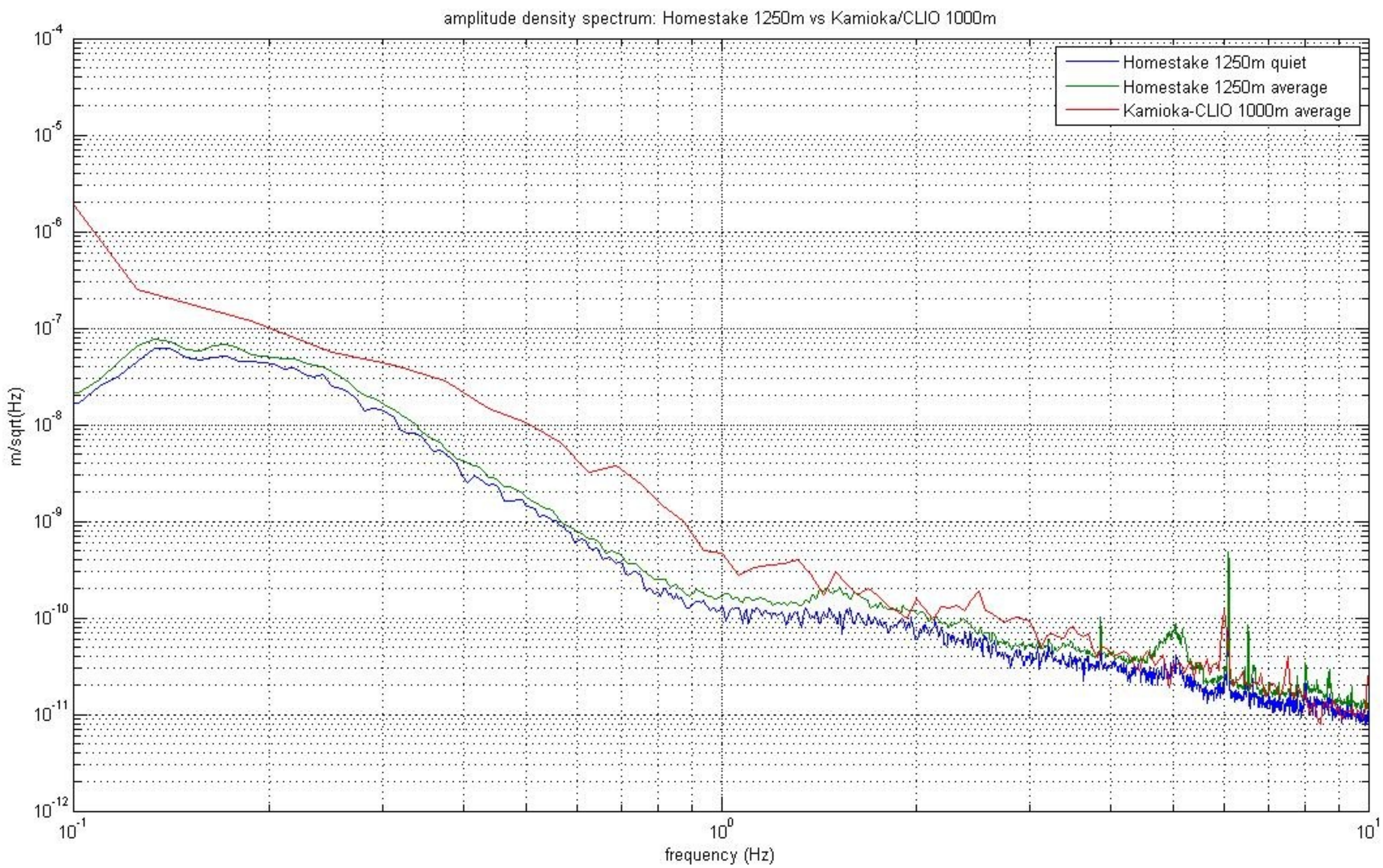
Seismic noise comparison KAGRA/Virgo



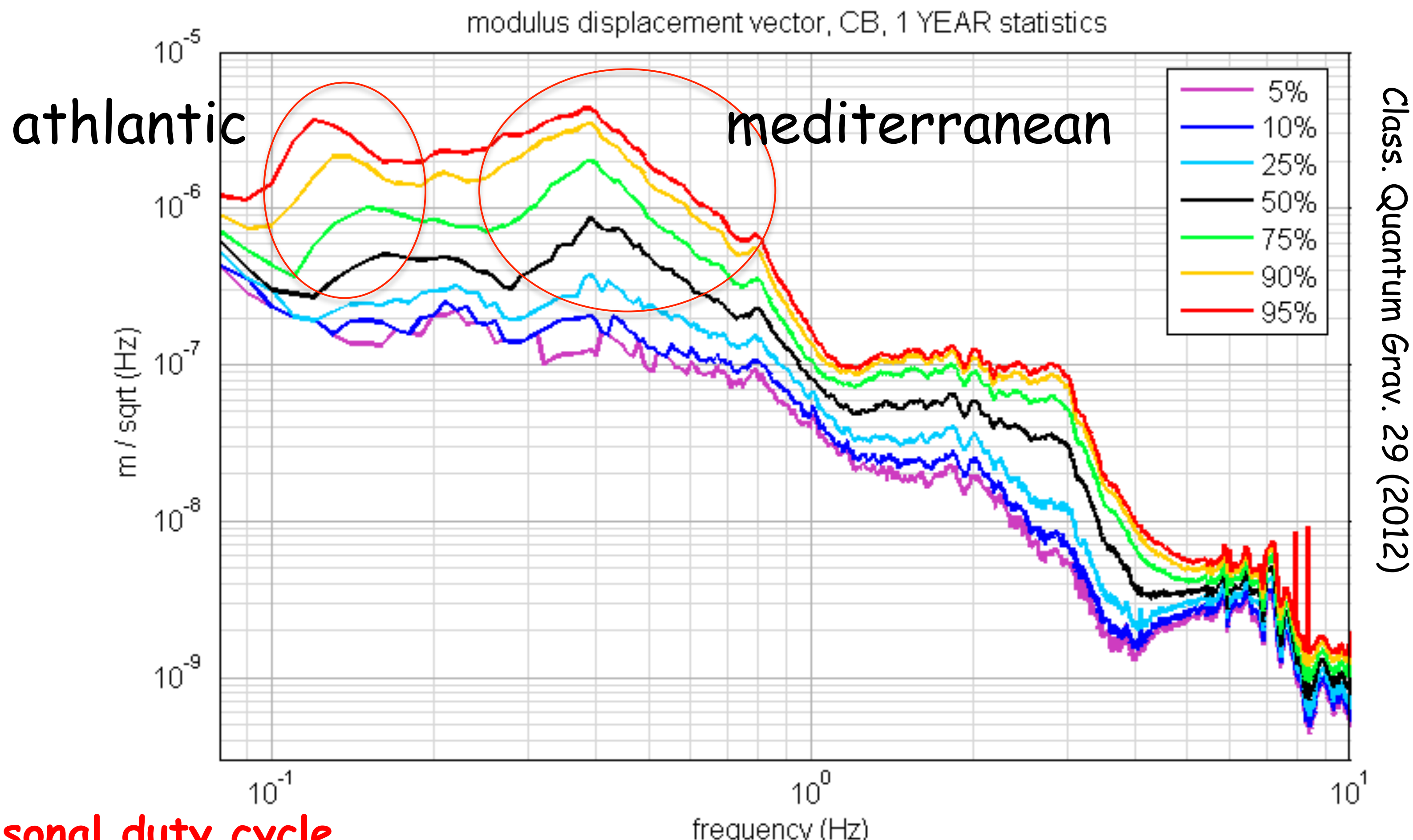


Virgo data from Class. Quantum Grav. 29 (2012)

Seismic noise comparison KAGRA/Homestake



Virgo: ex. of overall seismic disturbance statistics on surface



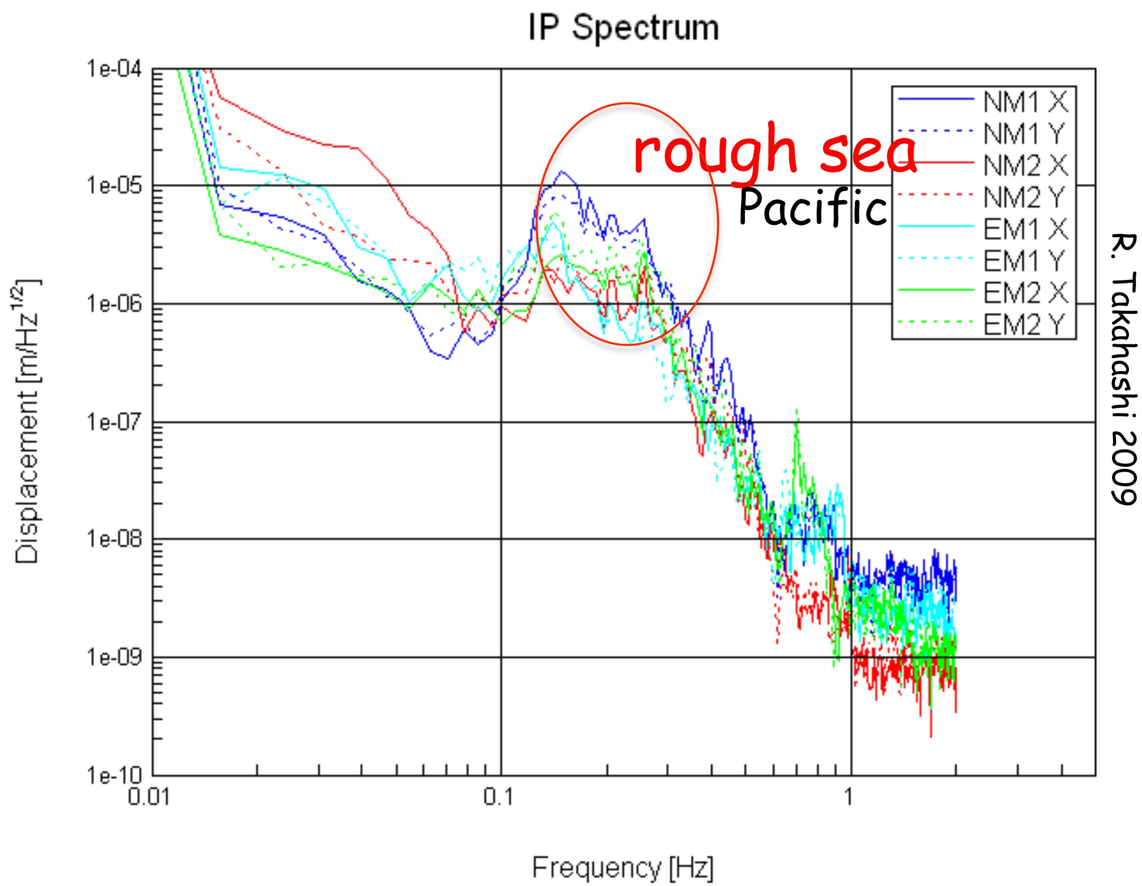
Seasonal duty cycle

- the active section of the suspension control is invoked in the game of sensor pre-filtering/blending (also optimized/adaptive in the future ?)

AND/OR

- the passive attenuation has to perform over-suppression

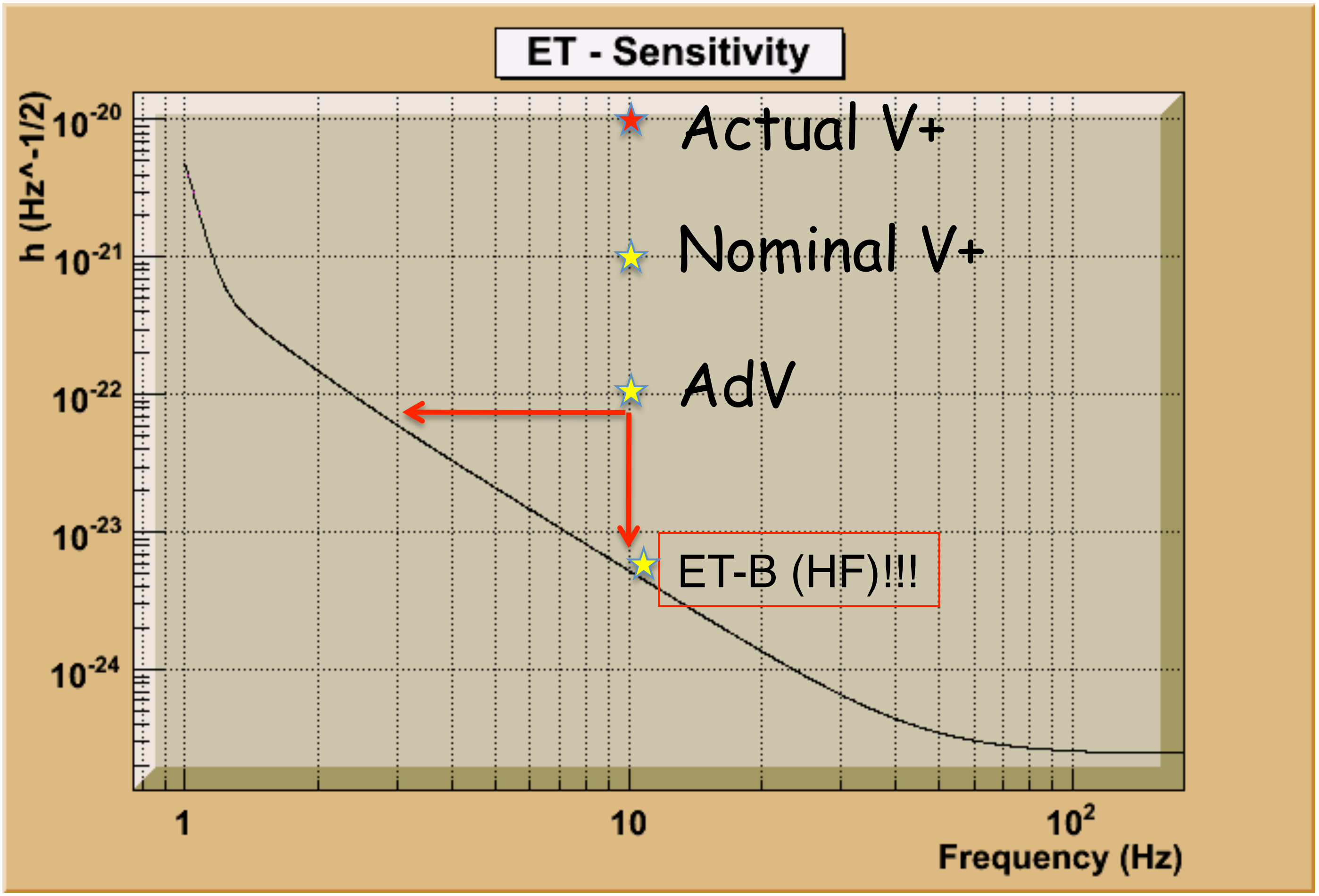
Micro-seismic bump at TAMA site (NAOJ)



On the ground surface microseism noise due to the sea contaminates in-loop position sensors worsening the suspension control.

➔ Building microseism-free error signals is a crucial commissionig activity as the interferometer We expect a lesser impact in underground detectors

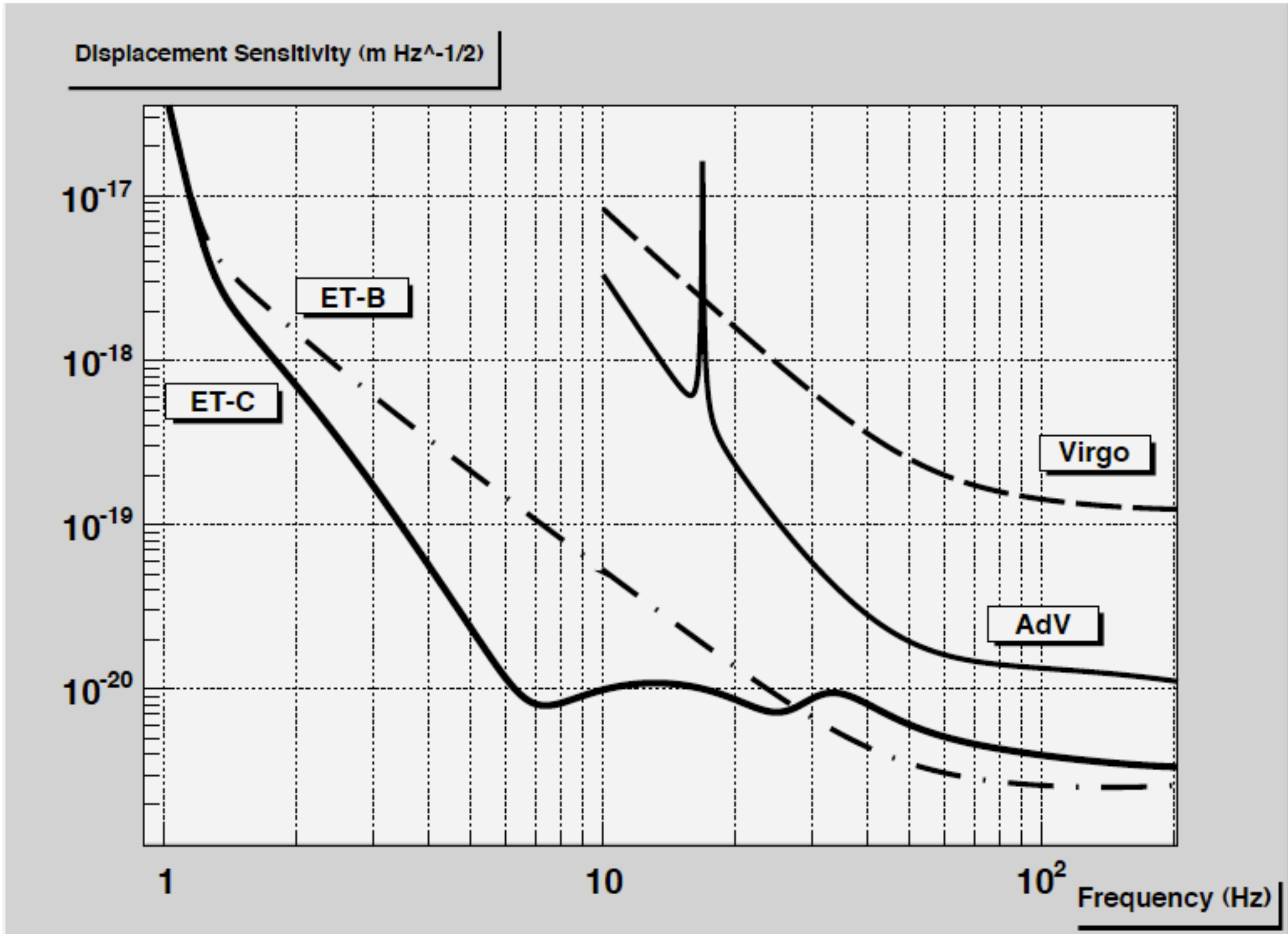
ET Sensitivity Curve (h(f))



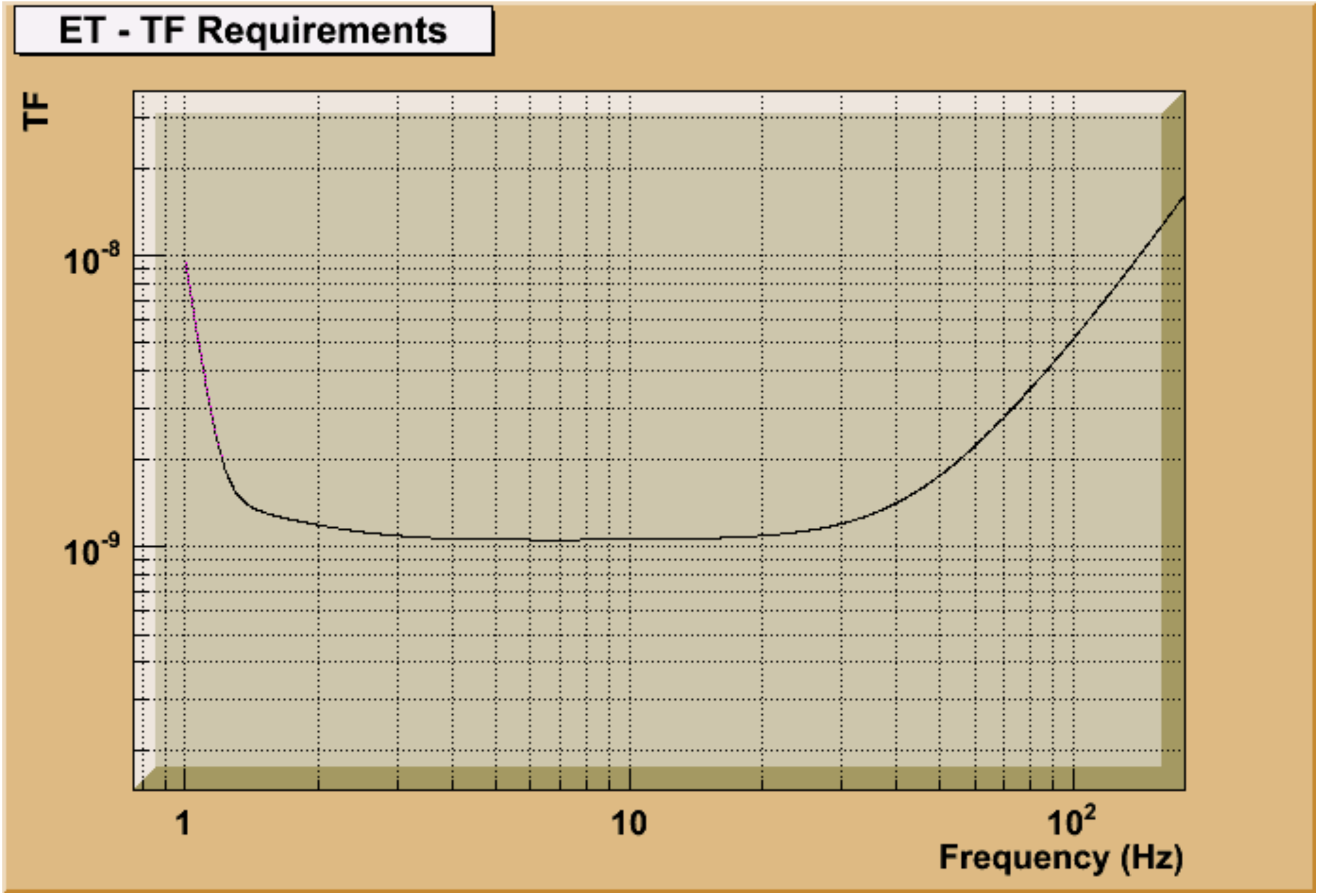
Underground site and Cryogenics are both present

Displacement sensitivity

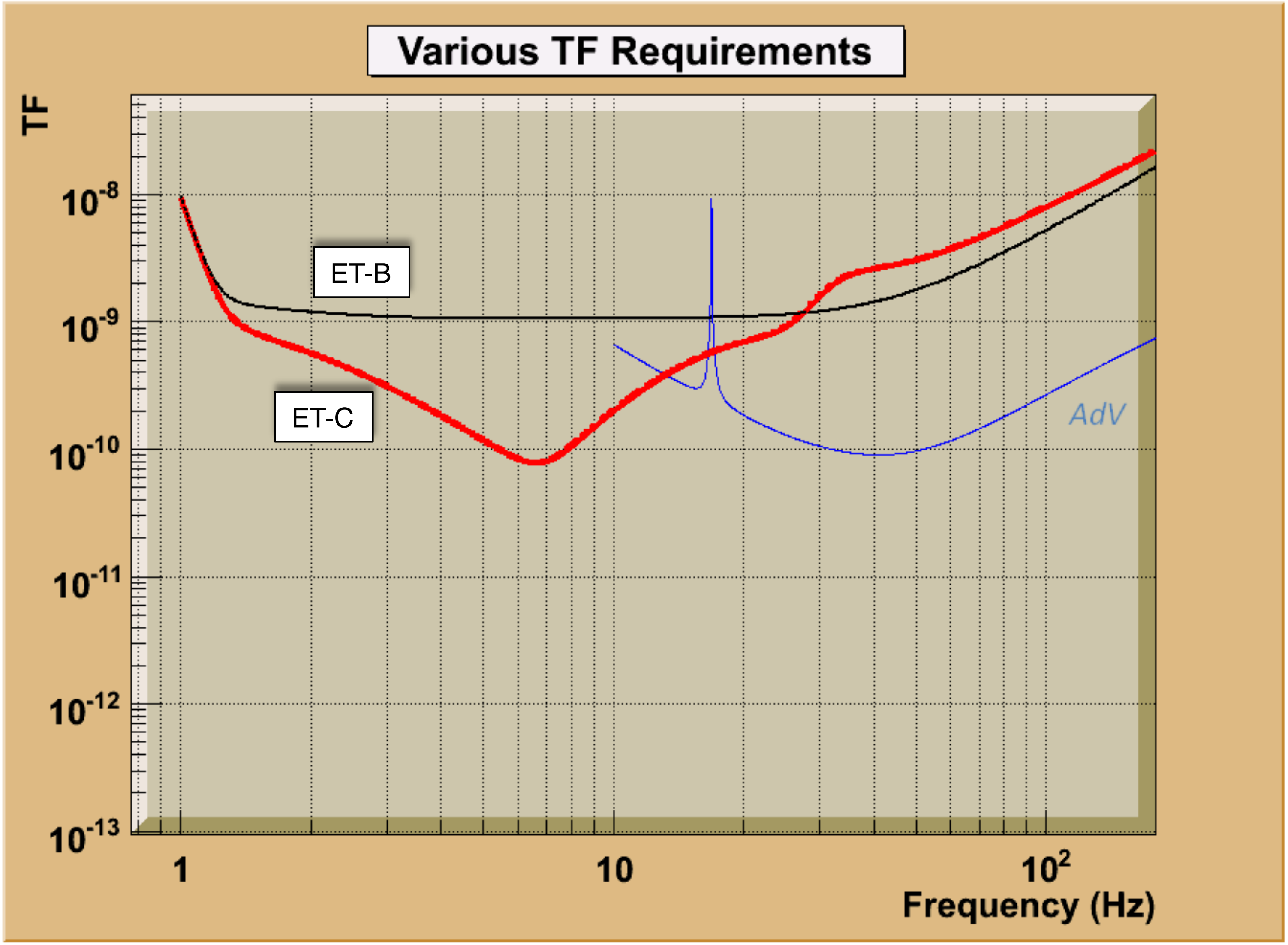
$\Delta L(f) = h(f) \times 10000$ (10 km arms)



$TF_{max} = \Delta L(f) / (\text{Under-Ground Seismic Noise})$



e.g. ground seismic noise (Kamioka) ~ $5 \times 10^{-9} / f^{2}$ (conservative)

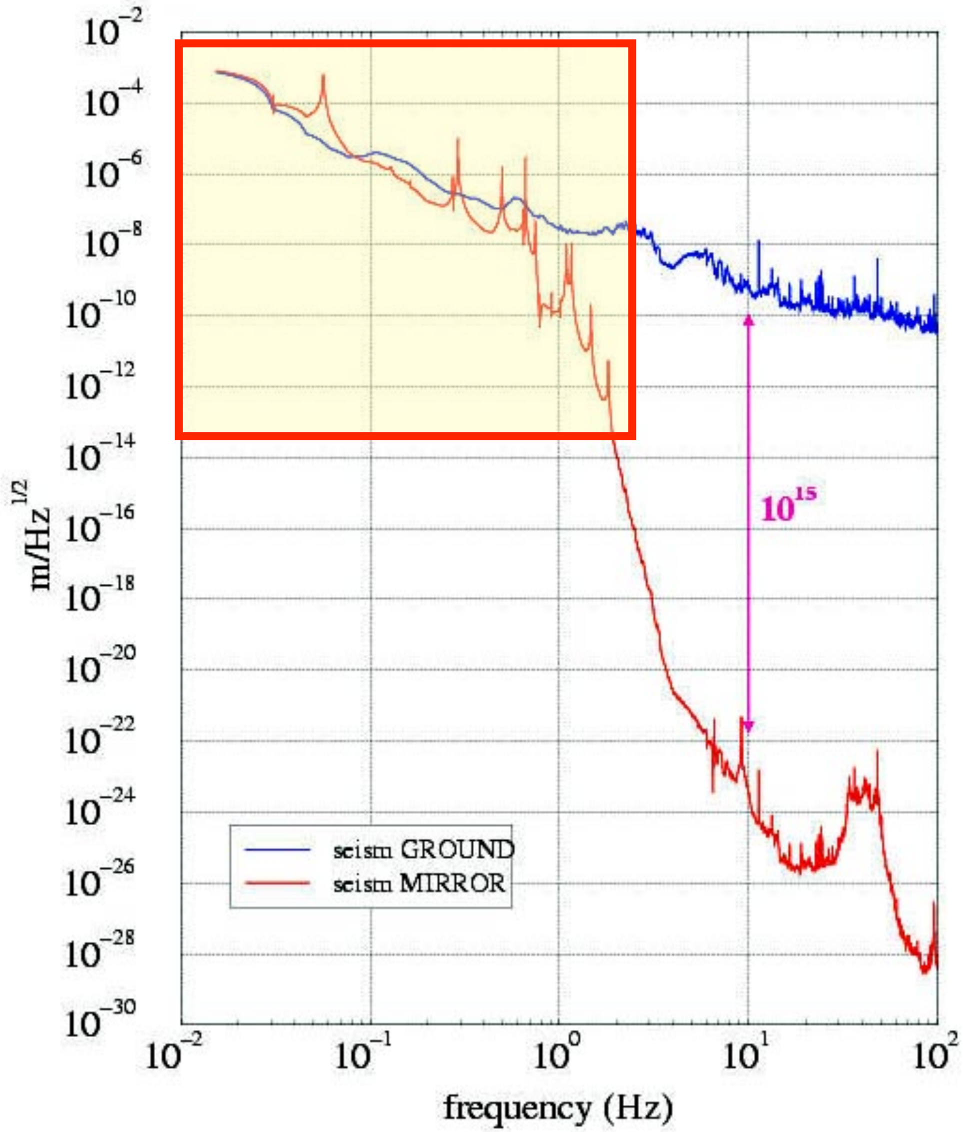


Various TF Requirements
TF
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1
10
10^{2}
Frequency (Hz)
ET-B
ET-C
AdV

STATUS OF ART & DEVELOPMENT

- Conservative (Virgo, “divide et impera”)
- Conservative++ (Virgo-based concept+innovation)
- Full-control (aLIGO)

Passive attenuation + damping + mechanical diagonalization concept



$$S^{1/2}(f) \approx \frac{10^{-7}}{f^2} m/\sqrt{Hz} \quad (f > 1\ Hz)$$

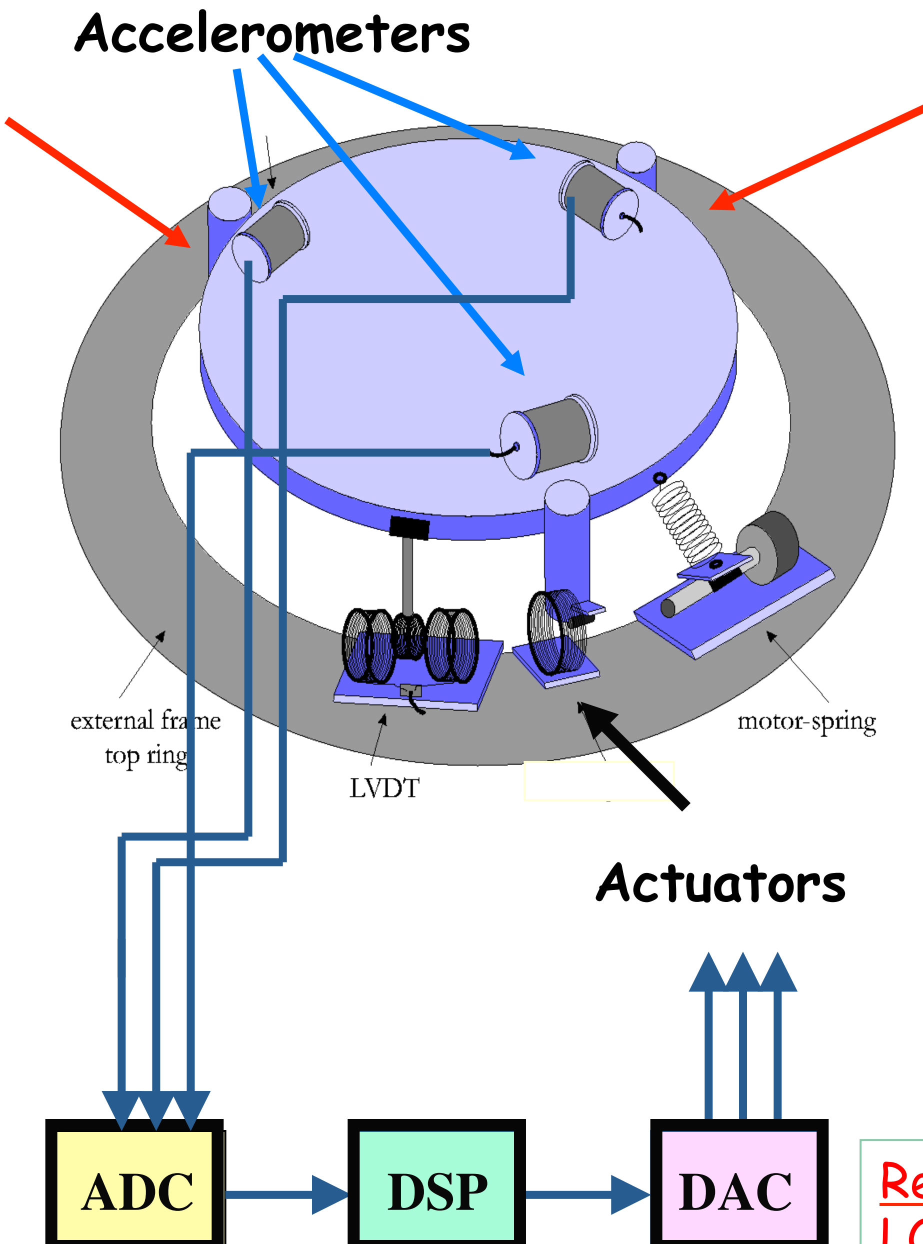
If suspension modes located at LF
➔ more efficient

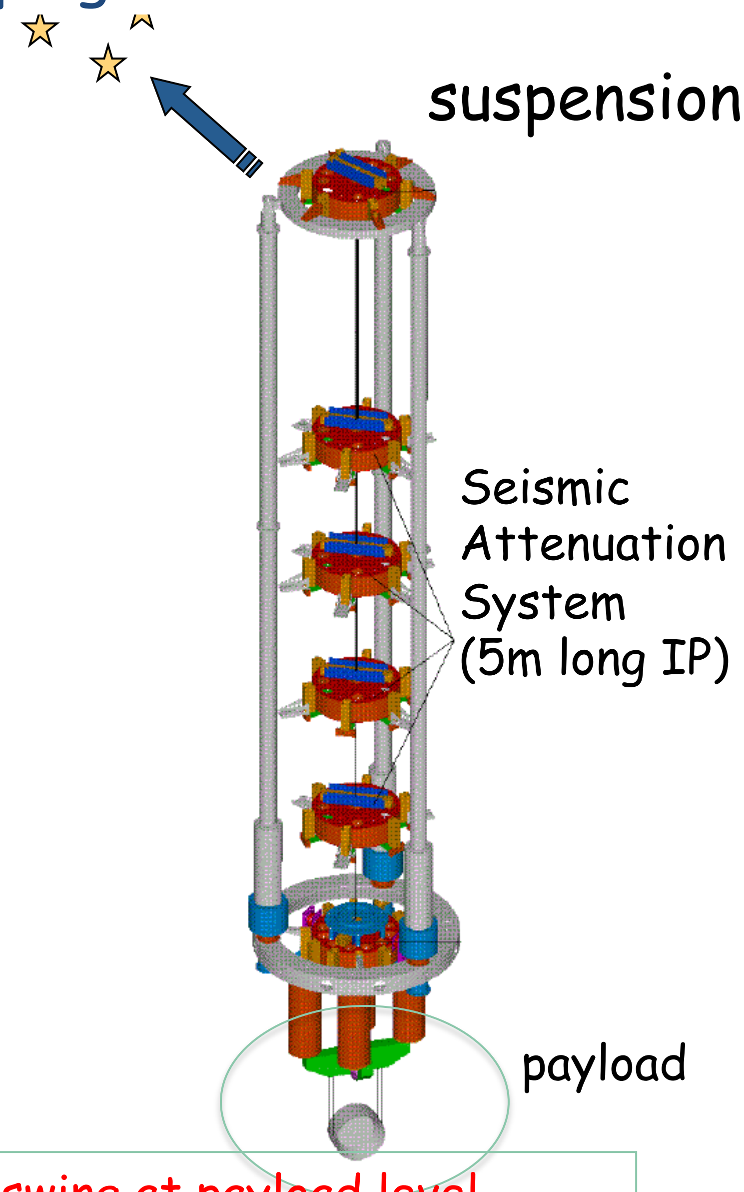
If the modes are at LF the seismic noise induces several-micron RMS

Suspension mode damping needed,
➔ pre-isolation/damping stage

If the pre-isolation stage is soft
➔ ITF setup and tidal control easier

Passive attenuation chain - with damping

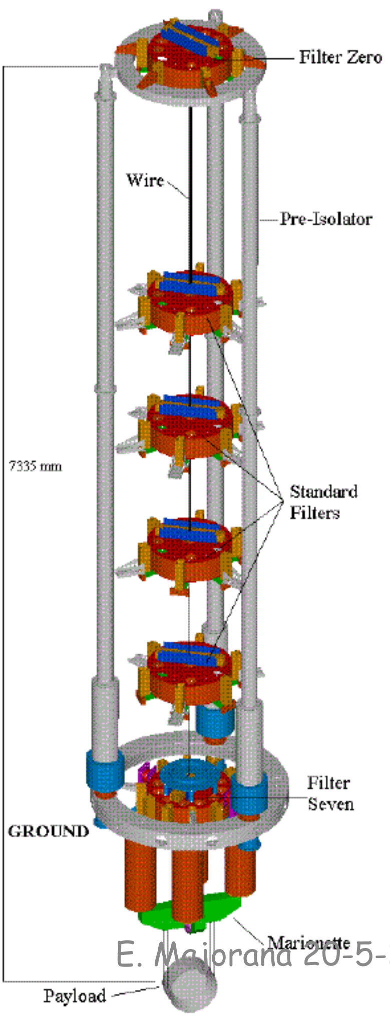




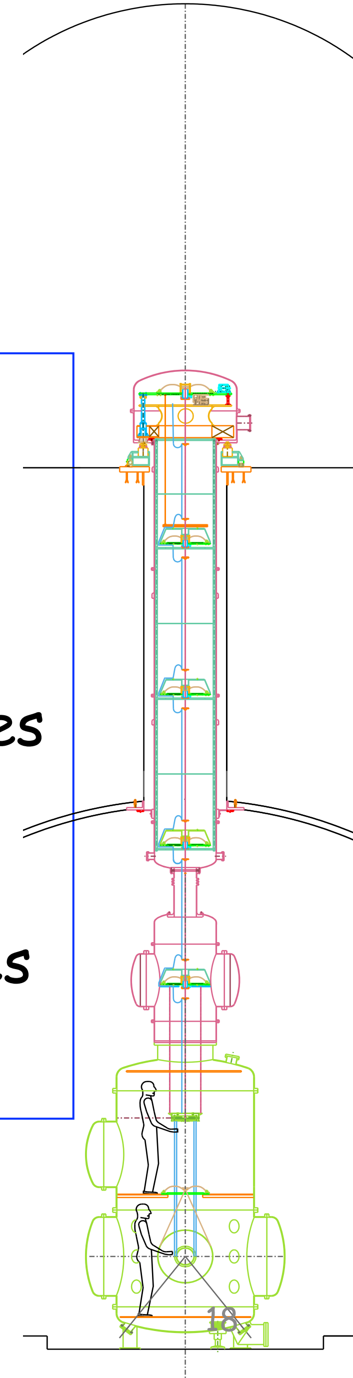
<u>Residual swing at payload level</u>
LONGITUDINAL: around 100 nm pp
ANGLES: fractions of μrad pp

17

The Type-A KAGRA-SAS
(IP+GAS already in TAMA200)



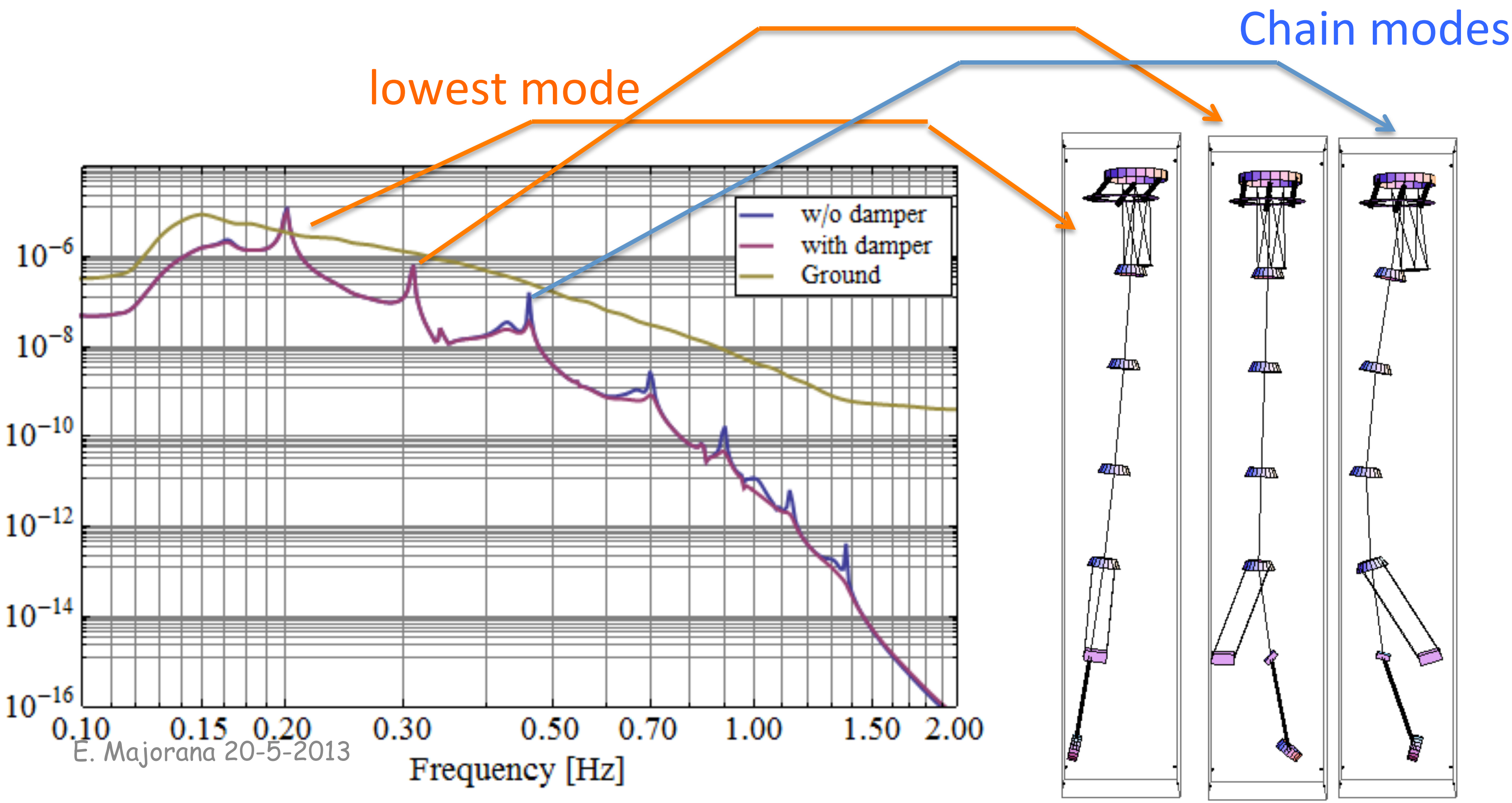
- A "simplified and improved version" of the Virgo Superattenuator
- "Guaranteed" TF performance
- New features:
  - Geometric anti-spring (GAS) replaces magnetic anti-spring (MAS) filters
  - Magnetic damping stage
  - Compact pre-isolator Ver-Hor stages



KAGRA: passive transversal mode damping
(suspension fully modeled by T. Sekiguchi)

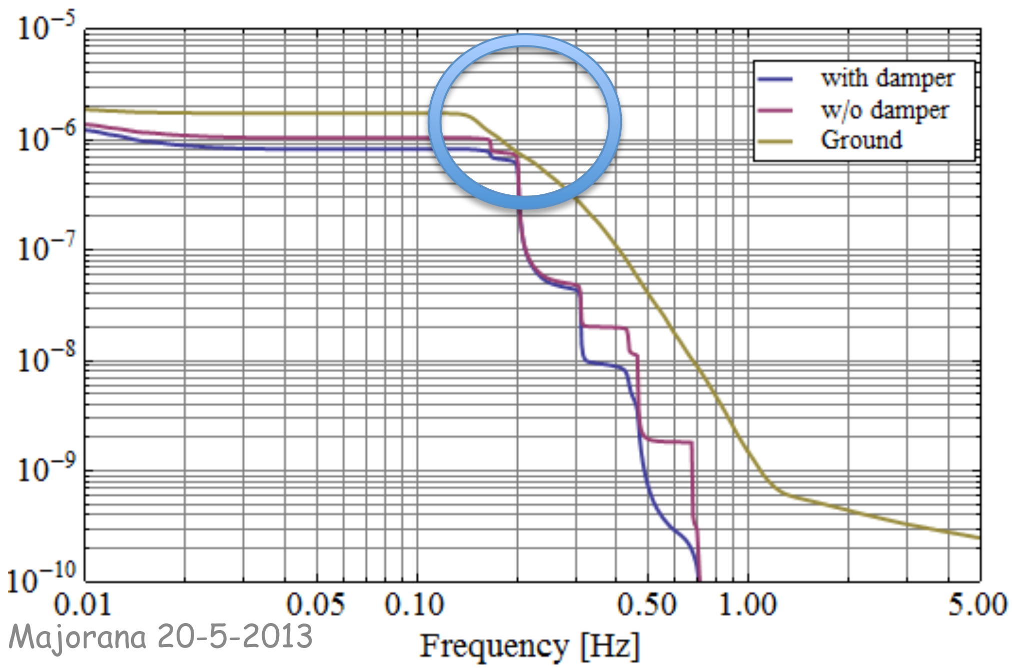
- seismic noise level of TestMass,

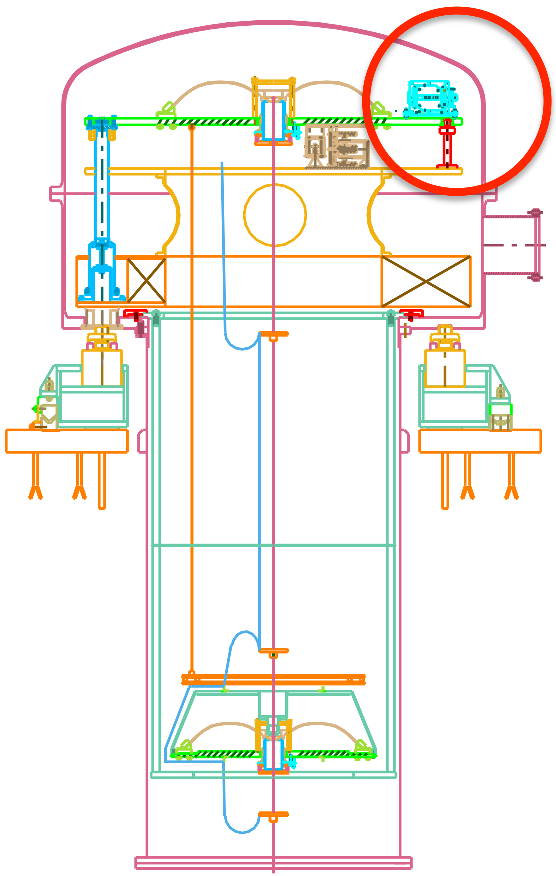
with/without Eddy current damping



Active damping on passive chains

- active seismic attenuation through inertial sensors onboard as in Virgo (and TAMA).
- feed-forward from ground, Kalman flt … new techniques suitable for optimal (adaptive ?) digital prefiltering strategies (premlimary tests performed for AdV @NIKHEF)





KAGRA top stages (the pre-isolator)

Schematic view of Seismic attenuation system (SAS)

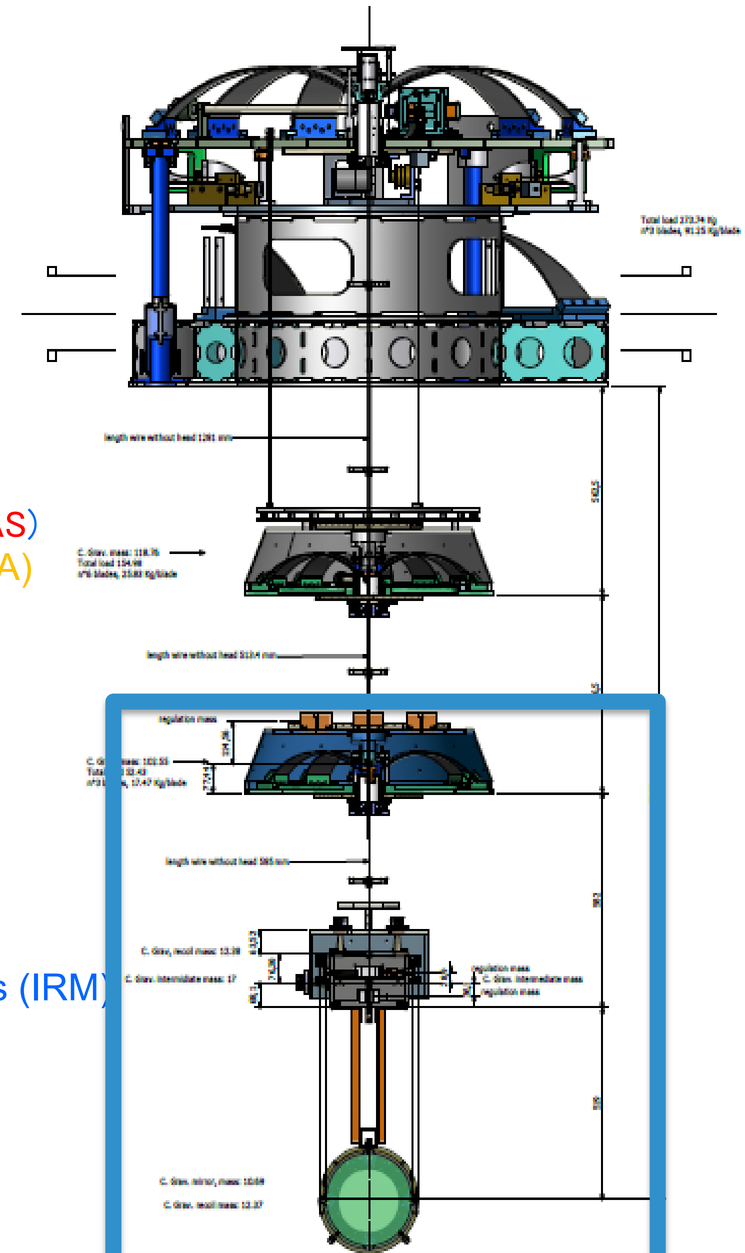
Type-A/B

KAGRA suspension takes into account the implementation of cryogenics and the presence of cryostats (FP)

Pre-isolator
- Top filter [Filter0]
- Inverted Pendulum (IP)

Filter chain
- Geometric Anti-Spring (GAS) Filter1 (Filter1~3 in Type-A)

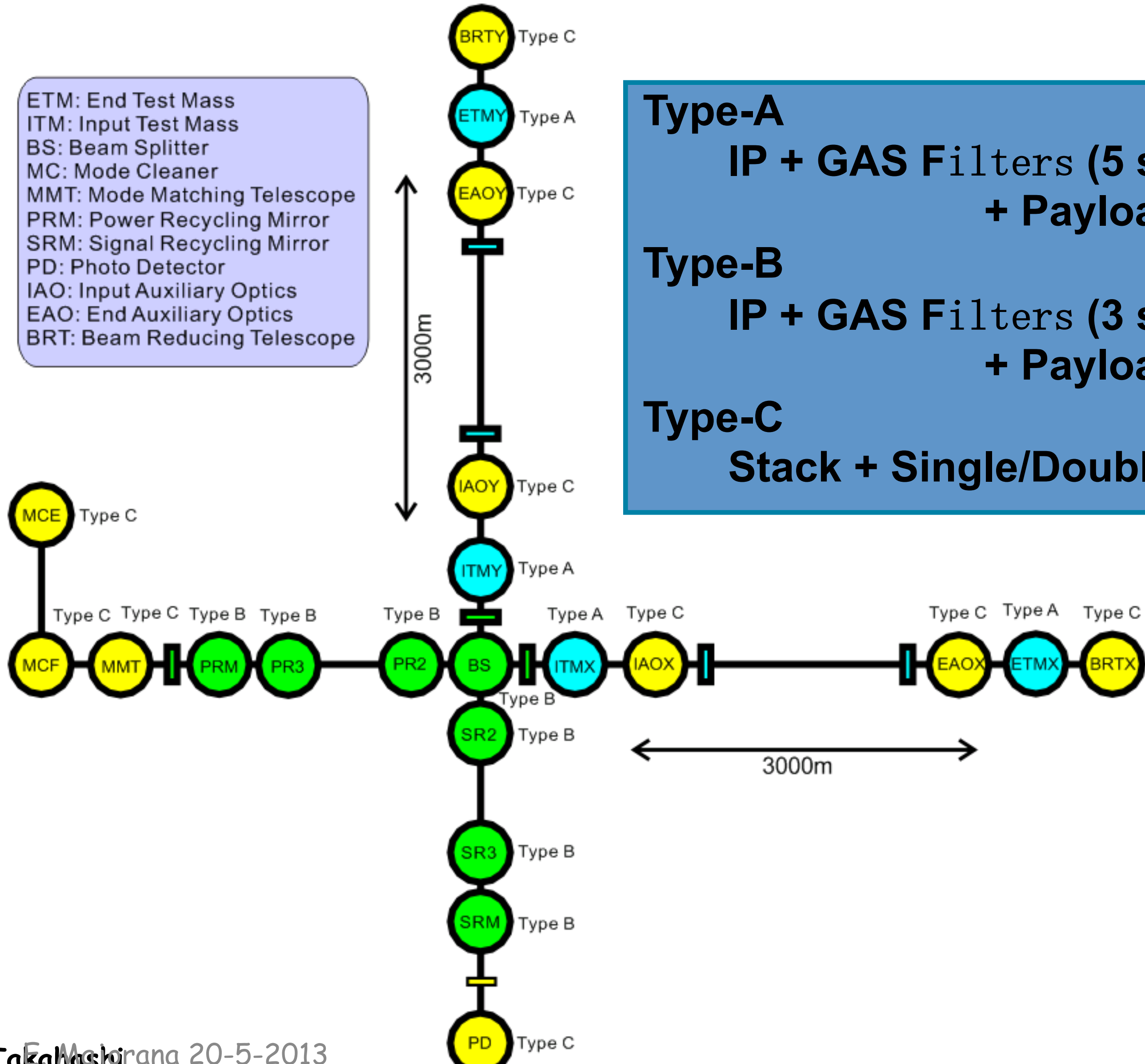
Payload
- Bottom Filter (BF)
- Intermediate Mass (IM) Intermediate Recoil Mass (IRM)
- Test Mass (TM) Recoil Mass (RM)



R. Takahashi,
The 3rd Korea-Japan workshop on KAGRA, Sogang University, Seoul (2012)

Disposition of vibration isolation system

ETM: End Test Mass
ITM: Input Test Mass
BS: Beam Splitter
MC: Mode Cleaner
MMT: Mode Matching Telescope
PRM: Power Recycling Mirror
SRM: Signal Recycling Mirror
PD: Photo Detector
IAO: Input Auxiliary Optics
EAO: End Auxiliary Optics
BRT: Beam Reducing Telescope



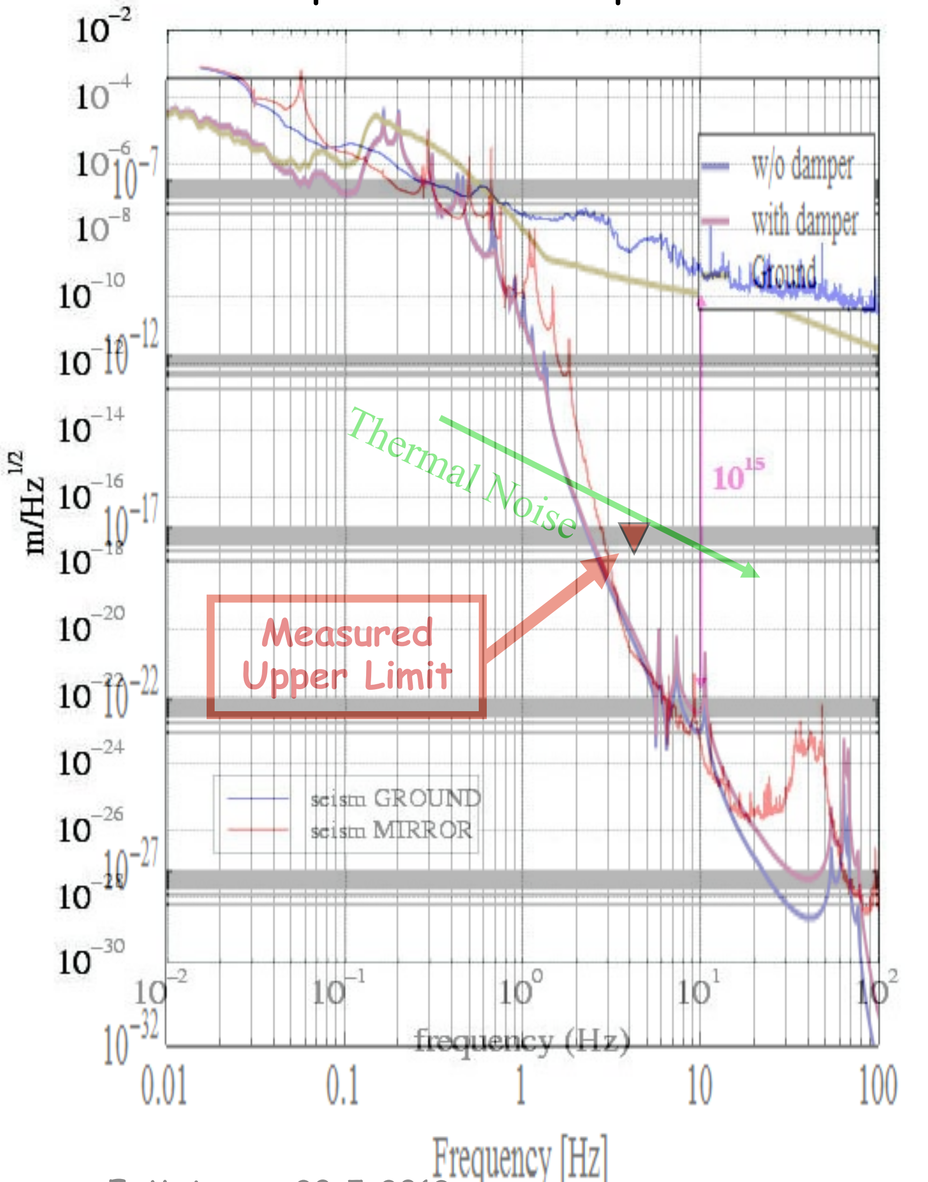
Type-A
IP + GAS Filters (5 stages)
+ Payload (23kg, cryogenic)

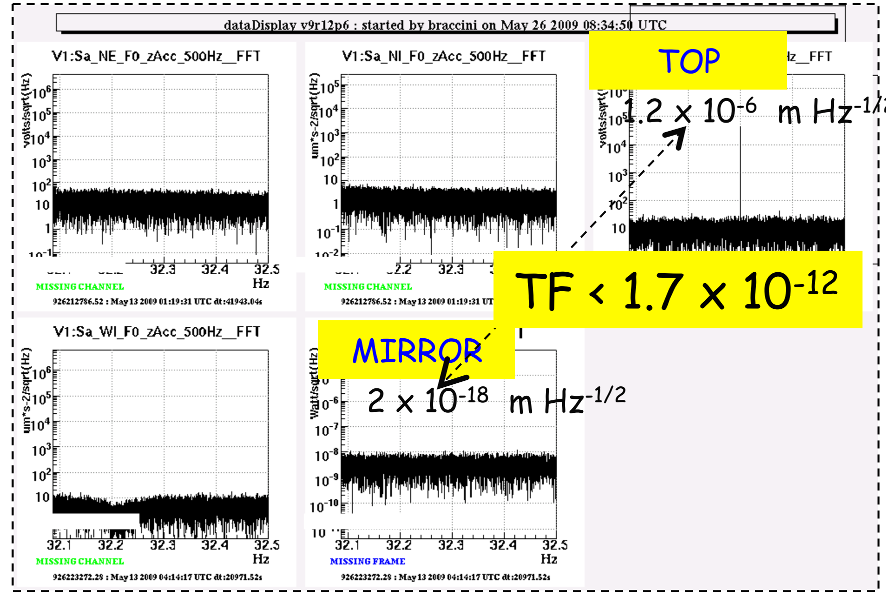
Type-B
IP + GAS Filters (3 stages)
+ Payload (10kg/20kg)

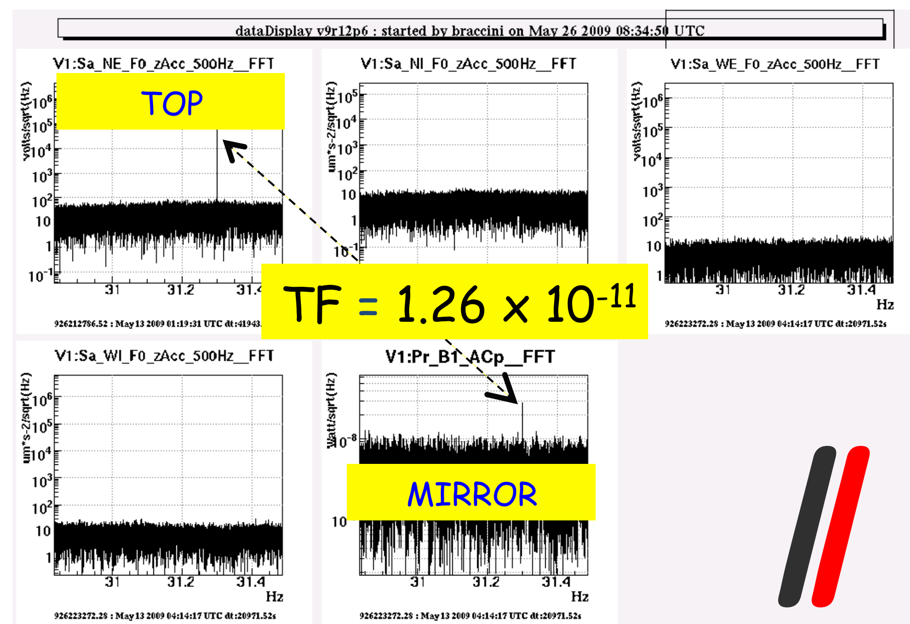
Type-C
Stack + Single/Double-pendulum (~1kg)

R. Takahashi,
The 3rd Korea-Japan workshop on KAGRA, Sogang University, Seoul (2012)

- Virgo: stage-by-stage and integrated TF measurements
- KAGRA: simplified and improved version





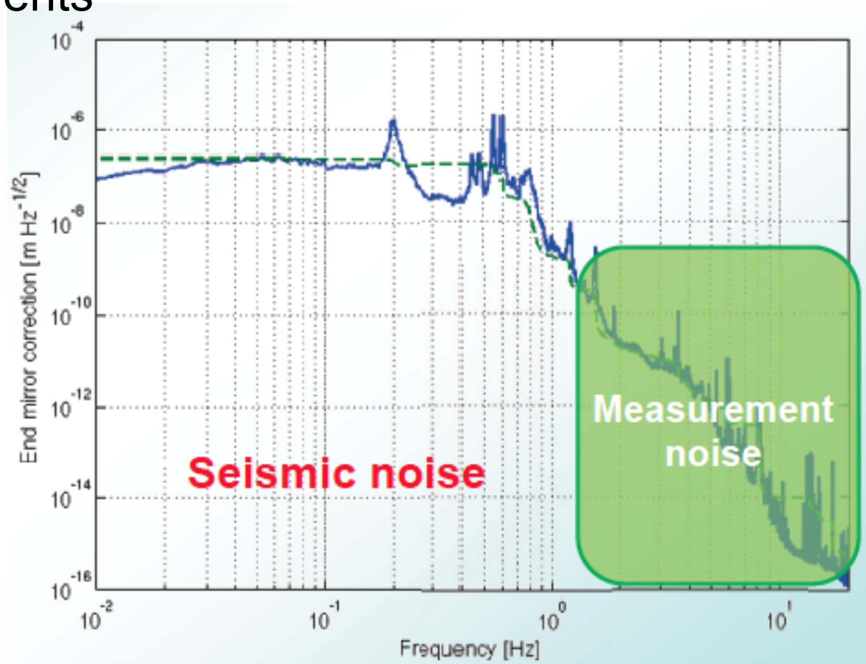


"Virgo+ guaranteed "

From the overall concept view seismic noise is attenuated by Super-Attenuators with performance that fulfills AdV requirements

Mirror motion residual RMS, corrected at the payload level is estimated as **200 nm** (mainly at f<1Hz)

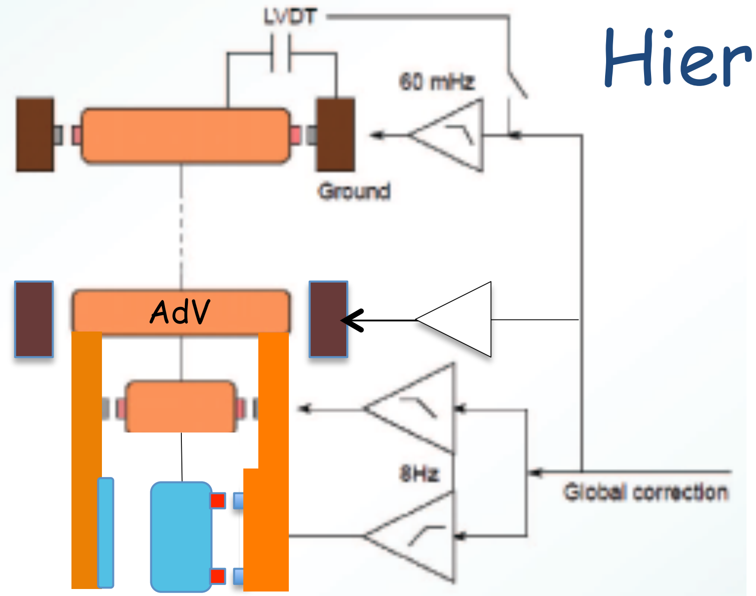
Angular motion residual RMS (due to angular local control) is corrected by wave-front sensing by **100 nrad** (f<few Hz)



In Virgo ITF loops had relatively narrow band-widths and relaxed low frequency gain requirements:

1. MICH ~10 Hz, PRCL ~30 Hz, CARM ~ 2 Hz, DARM ~ 60 Hz
2. Good accuracy&stability in noise subtraction among the noise coupling paths allows small phase margins and narrow locking BWs
3. Angular loops ~ 1.5 Hz (!!!)

Hierarchical control: a common must

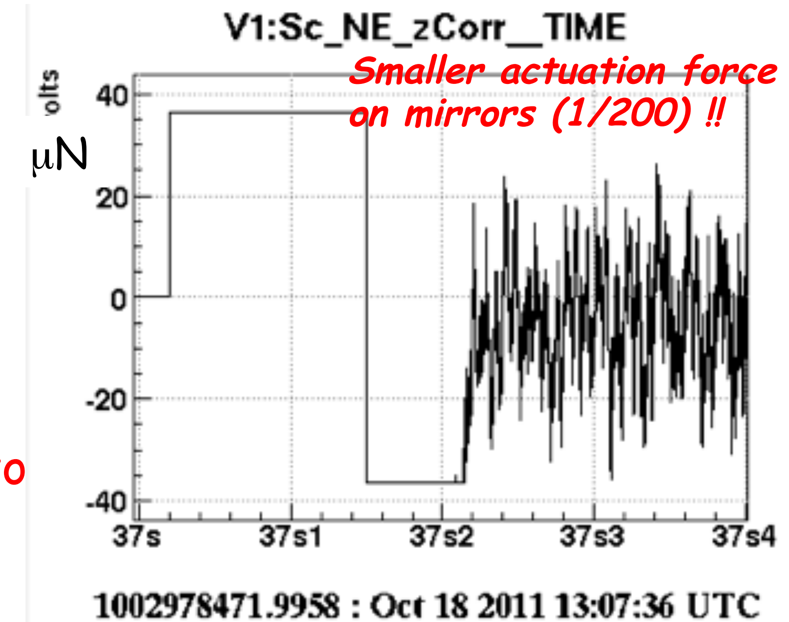


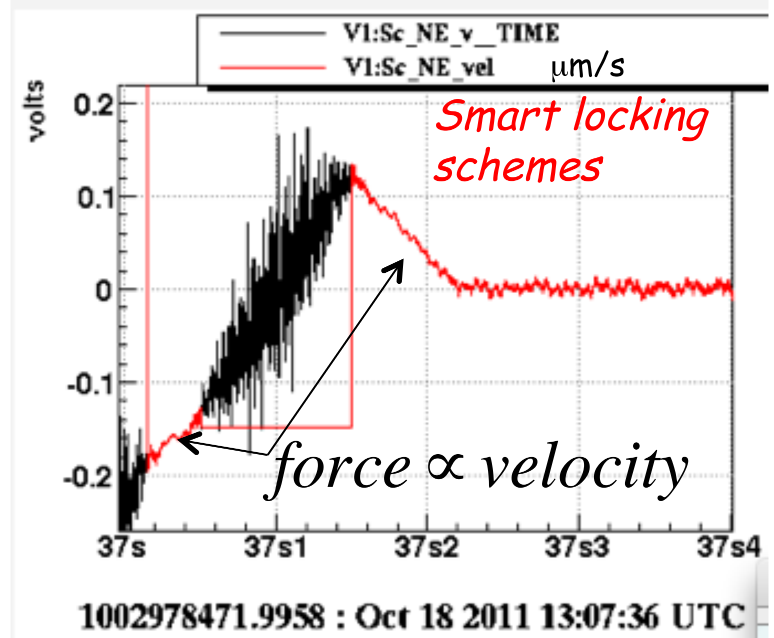
Virgo: reallocation of global control signals allows to

- exploit large actuation dynamics without losing low-noise performance
- build-up cleaner suspension-control signals

Actuation noise is an issue that has also to be attacked at the source:

- DAC conversion noise
- coil driver electronic noise





Ground VS underground

Underground sites:
ultra-stable operation
guaranteed and tested
http://arxiv.org/pdf/gr-qc/0403080v1.pdf

Virgo-based seismic attenuator:
tested in much worse conditions,
on the ground, allows ~85%
stable duty cycle

KAGRA

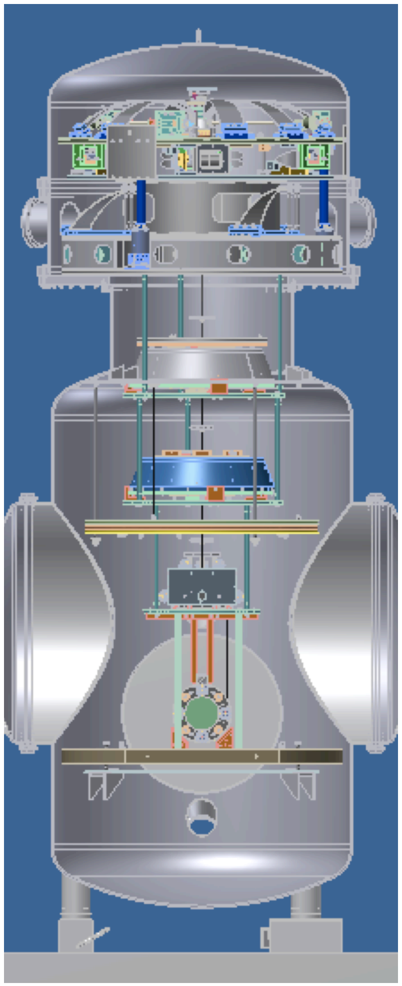
Note: sophisticated strategies, **crucial to operate** Virgo and to stabilize its horizon, in the case of KAGRA will serve **just to refine** LF sensitivity.

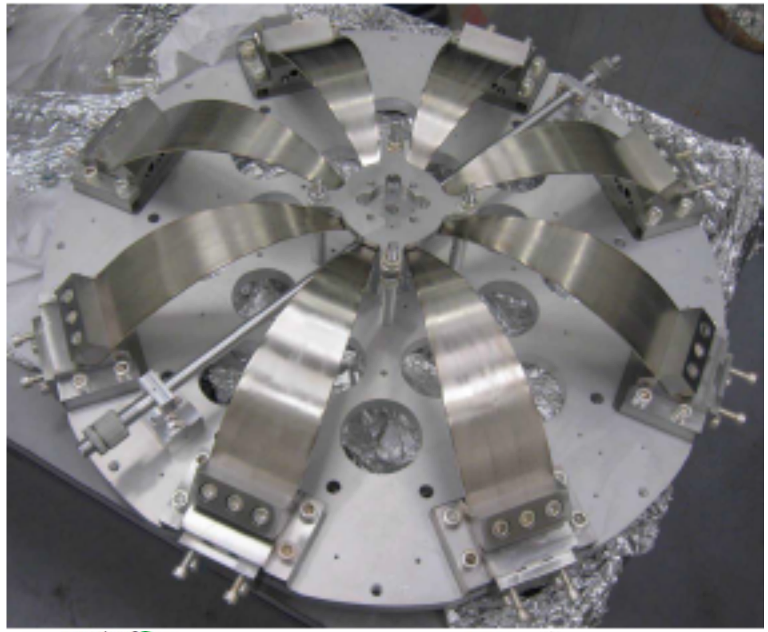
Setting in operation the interferometer at room temperature with SAS might result much faster than expected.

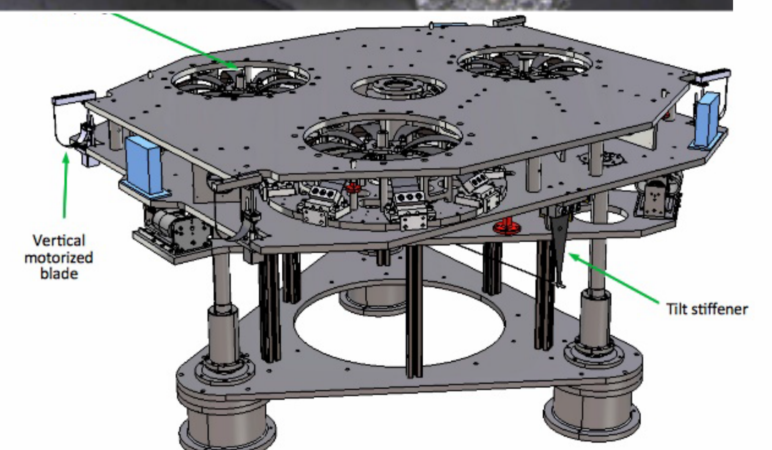
NON-TEST-MASS-ONLY: the current line of development

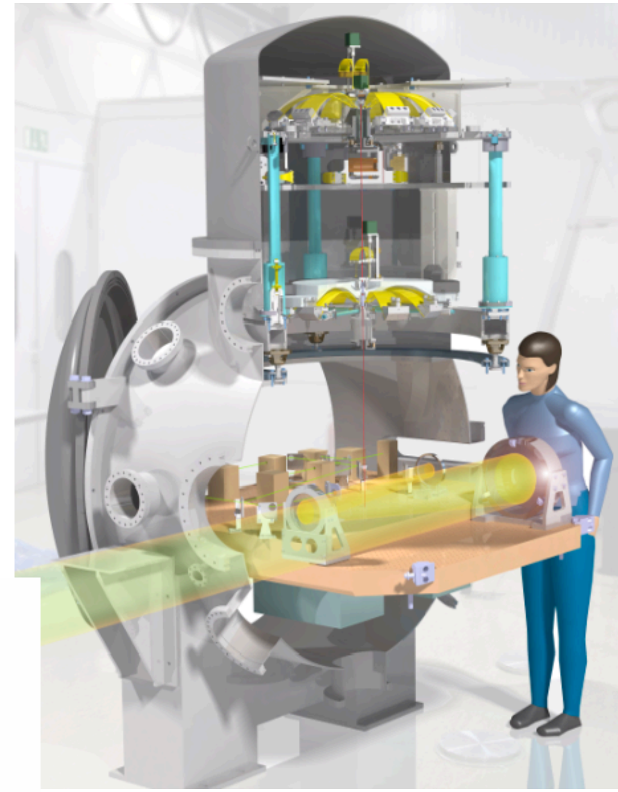
First developed for aLIGO HAM-SAS

➔ implemented in AEI 10 m prototype and Virgo multiSAS/Benches









A. Stochino, Thesis (2007) public JGW Doc Sever JGW-P0900269-v1

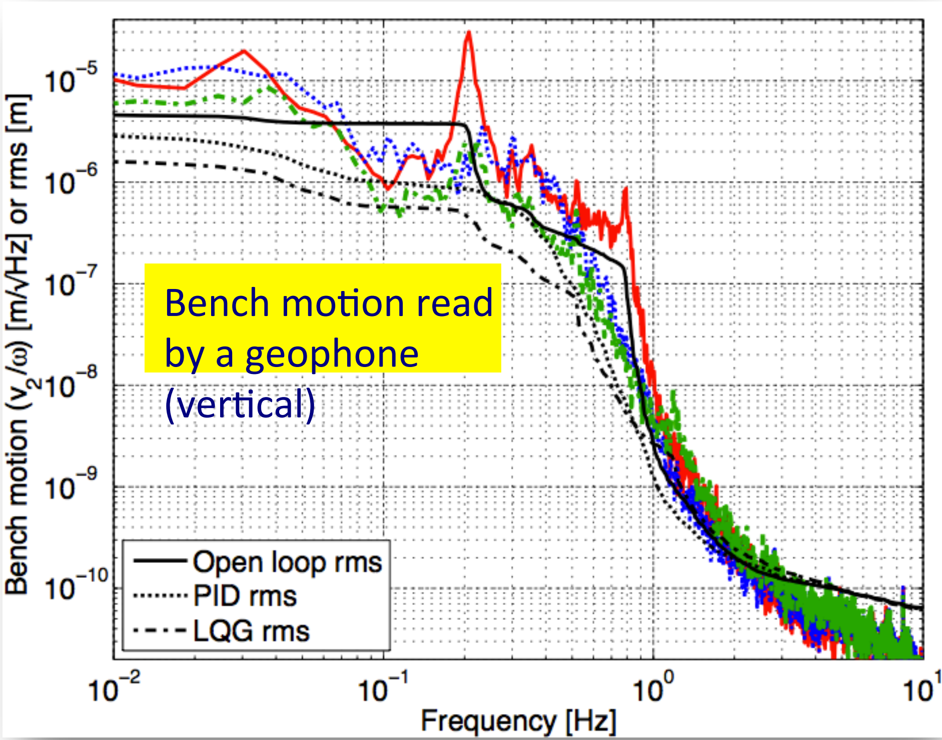
B. http://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0002/P0900269/001/

NON-TEST-MASS-ONLY: the current line of development

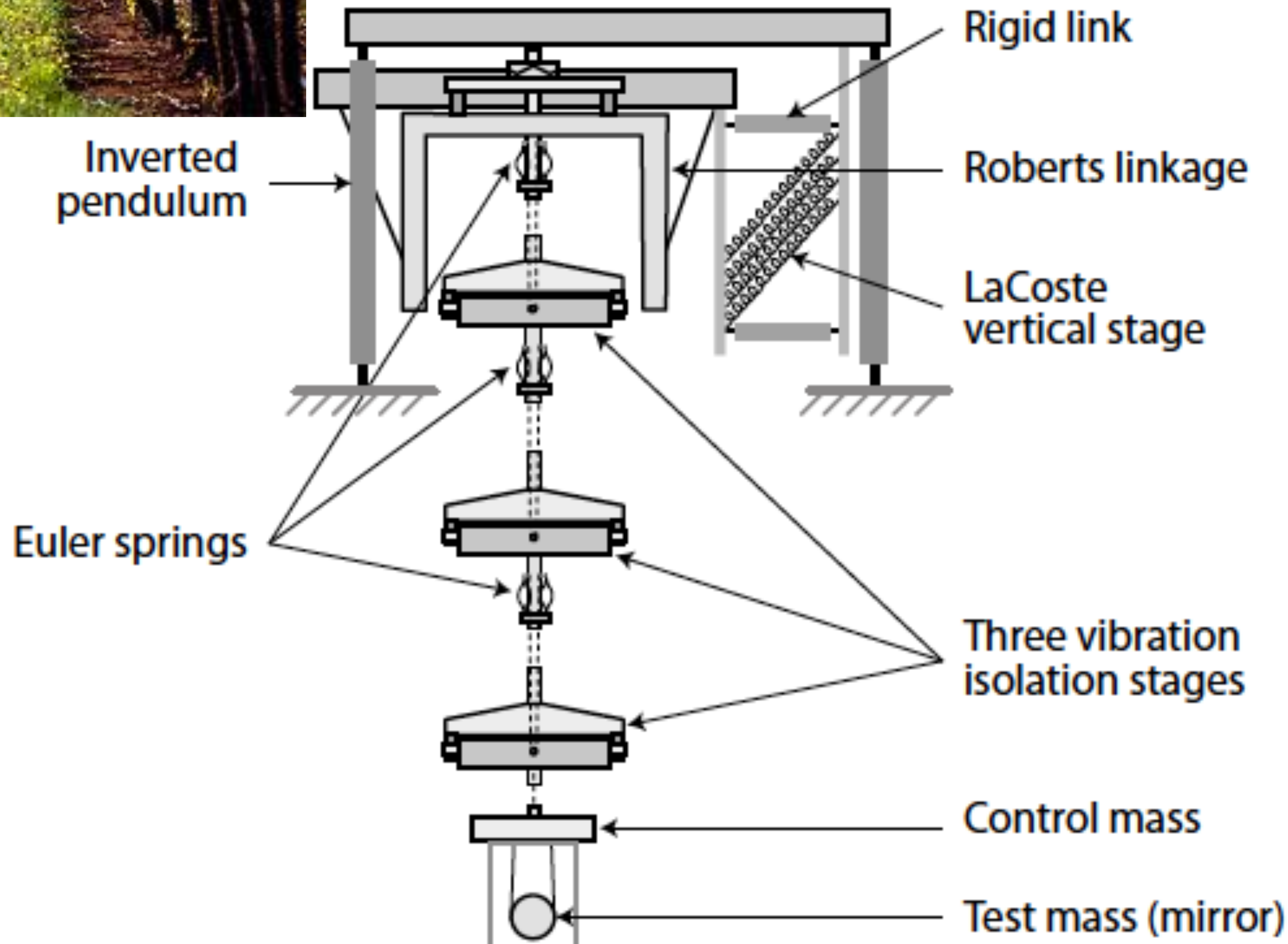
In all GWADs optical elements other than GW test masses adopt in principle the same seismic isolation primary stages and resulted in pilot R&D benchmarks

Example (VirgoSAS, NIKHEF)

MISO control, based on Kalman filtering and optimal regulator successfully tested



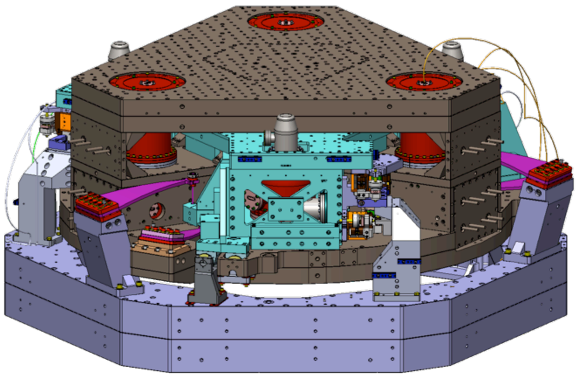
The Australian way (AIGO 80m): an old tradition in original mechanical schemes



aLIGO seismic isolation overview

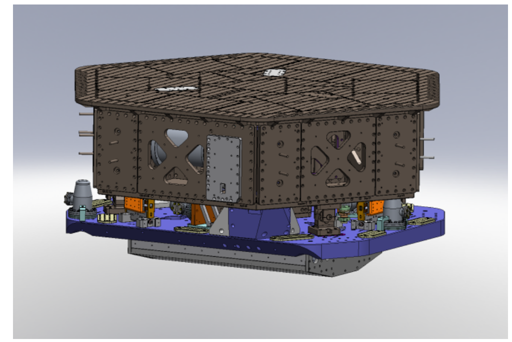
BSC-ISI

Two-Stage Internal Seismic Isolator



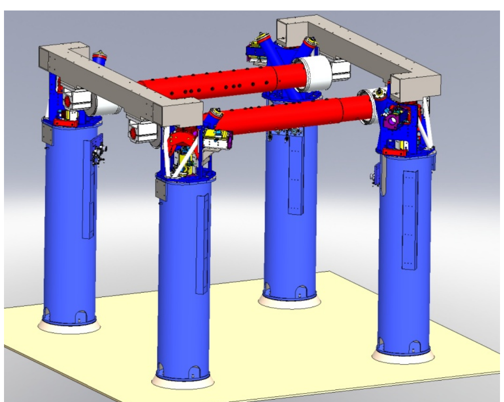
HAM-ISI

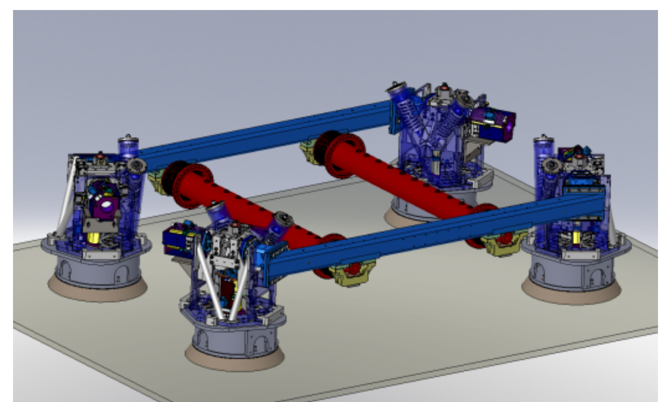
Single Stage Internal Seismic Isolator



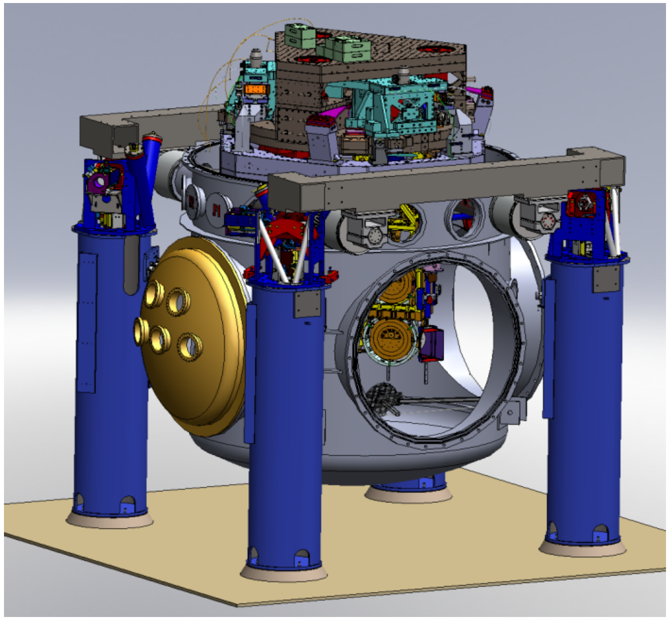
HEPI

Hydraulic External Pre-Isolators (active !)





Advanced LIGO Seismic Isolation Overview

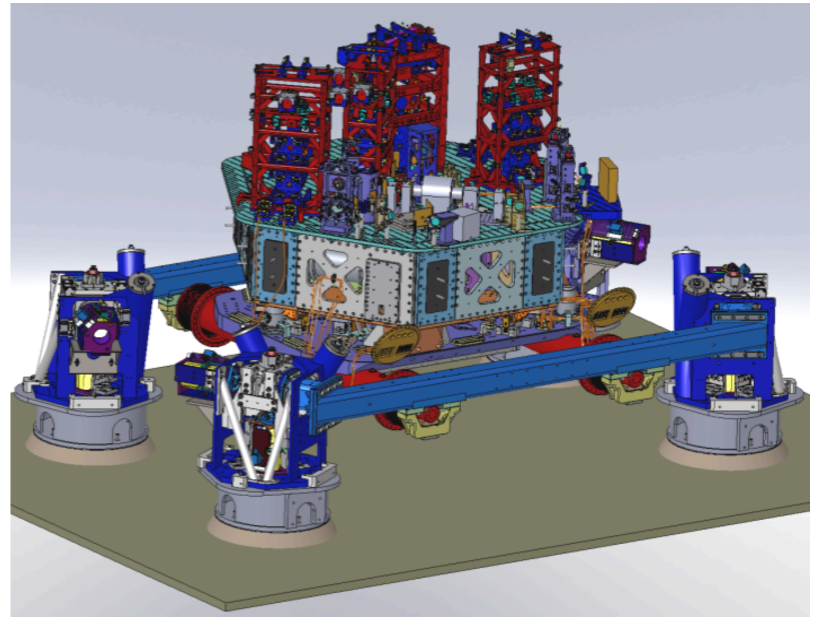


BSC: Up to 7 Stages of Isolation in Series

- HEPI (1 Stage) - SEI subsystem
  Pre-Isolator
  Low frequency positioning
  Isolation from 0.1 to ~5 Hz

- BSC-ISI (2 Stages) - SEI subsystem
  Internal Seismic Isolation
  Isolates above ~0.2 Hz
  Quiet, controlled table

- Quad pendulum (4 Stages) – SUS



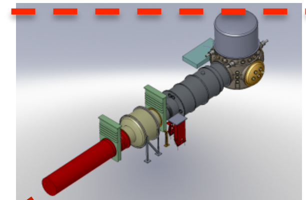
HAM: Up to 5 Stages of Isolation in Series

- HEPI (1 Stage) - SEI subsystem
  Pre-Isolator
  Low frequency positioning
  Isolation from 0.1 to ~5 Hz

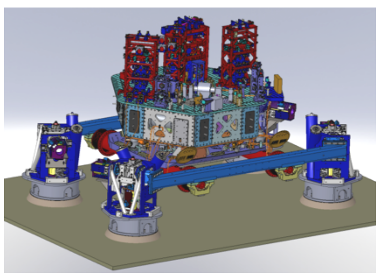
- HAM-ISI (1 Stage) - SEI subsystem
  Internal Seismic Isolation
  Isolates above ~0.2 Hz
  Quiet, controlled table

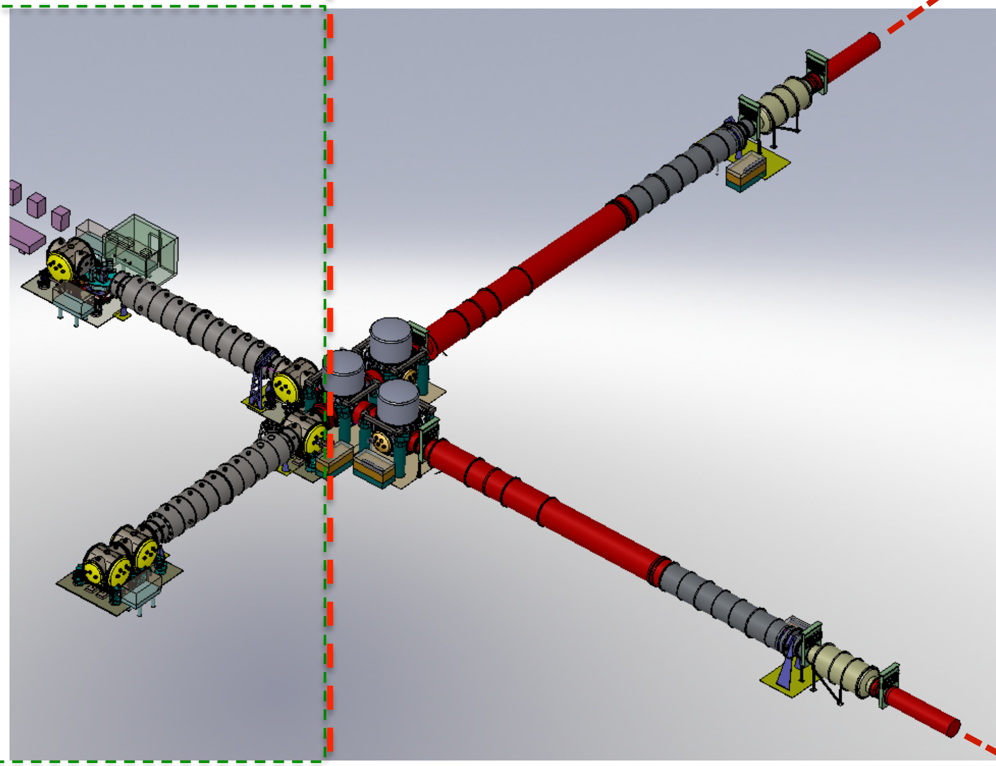
- Triple pendulum (3 Stages) – SUS

Advanced LIGO Seismic Isolation Overview



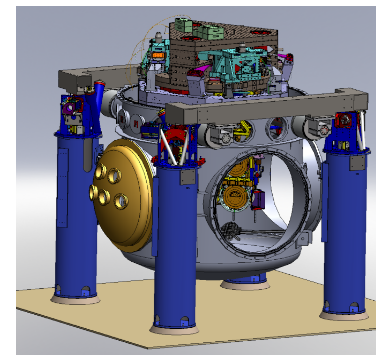
6 HAM chambers:
- 6 HEPI
- 5 ISI

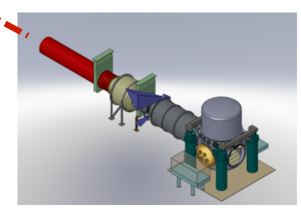




IFO Layout

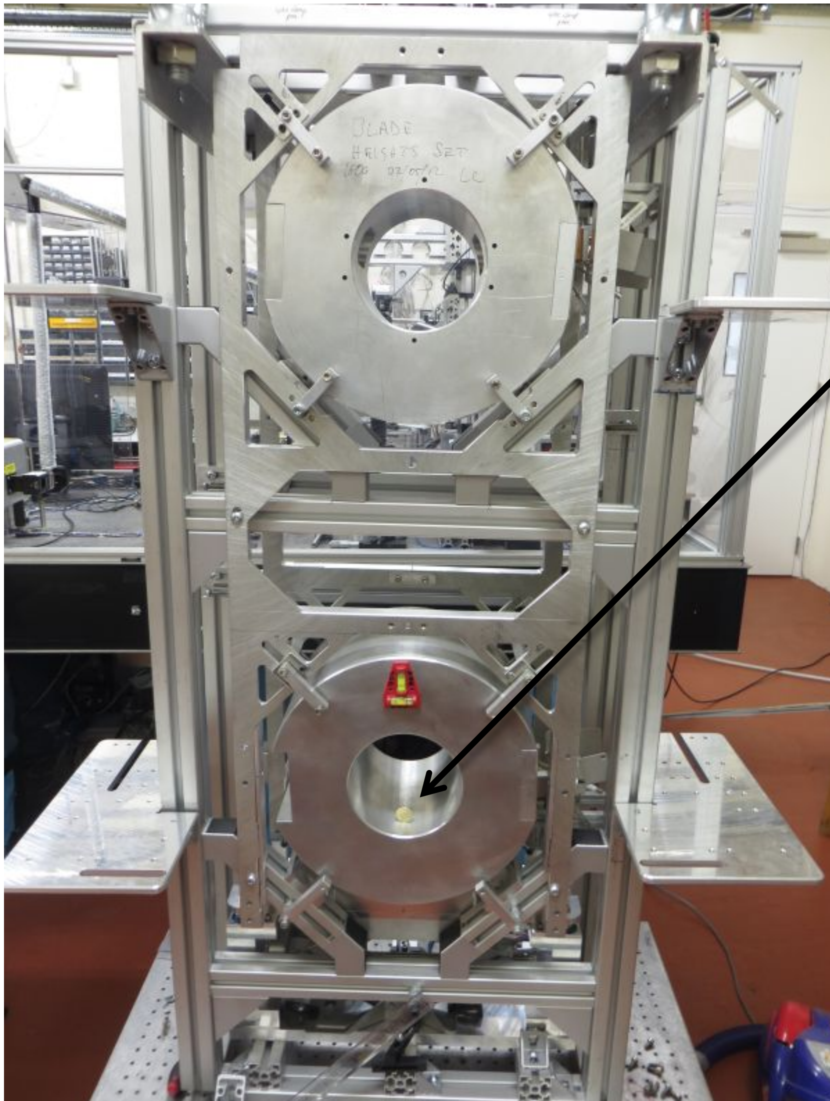
5 BSC Chambers:
- 5 HEPI
- 5 ISI

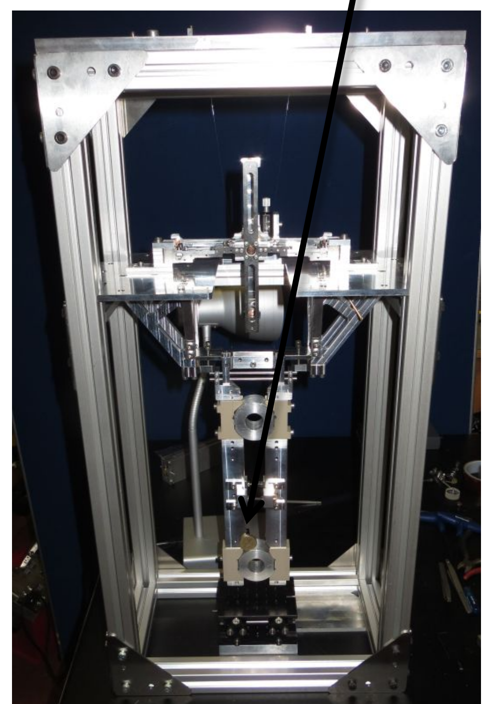




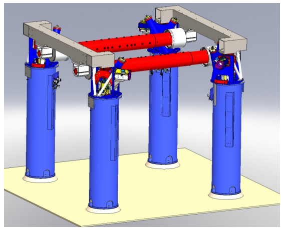
aLIGO vs AEI 10mPrototype

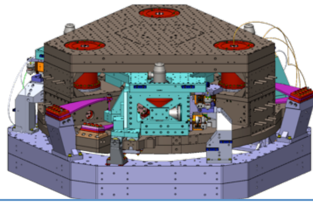
Pound/Euro=1.18 today

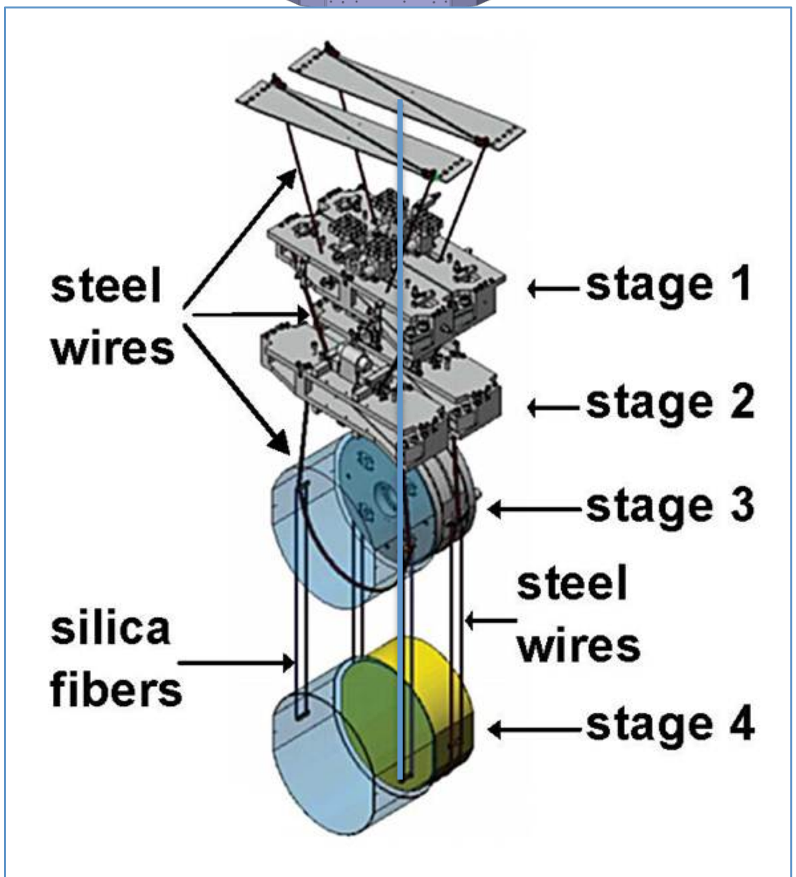


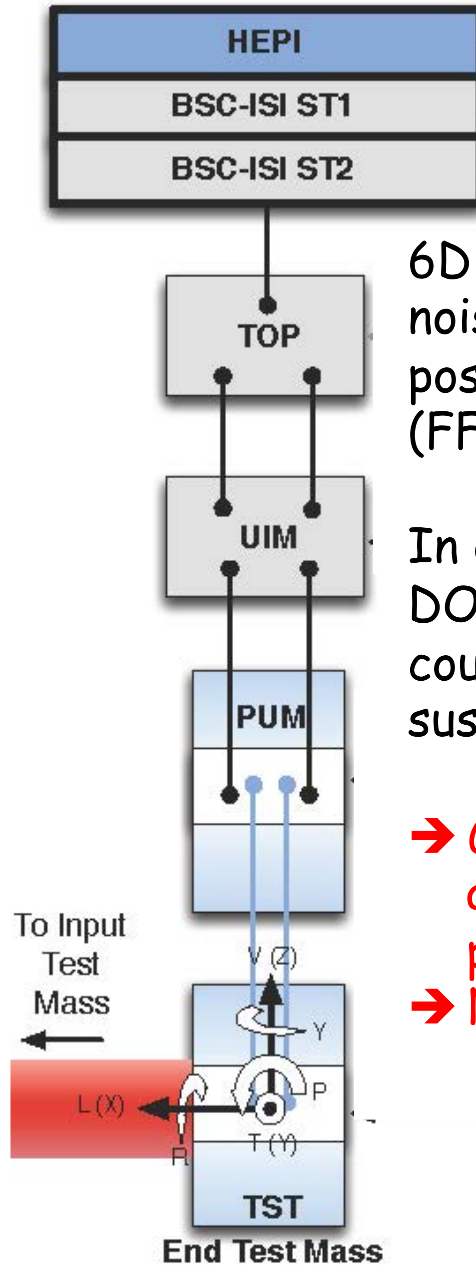


LIGO









Brett Shapiro G1200692

6D controlled and noise-cleaned position of the chain (FF+optimal flt needed)

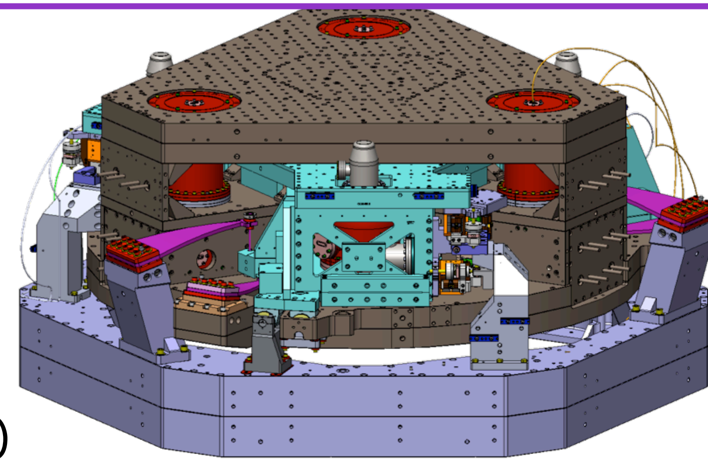
In open-loop mechanical DOFs are significantly coupled, WRT Virgo-like suspension

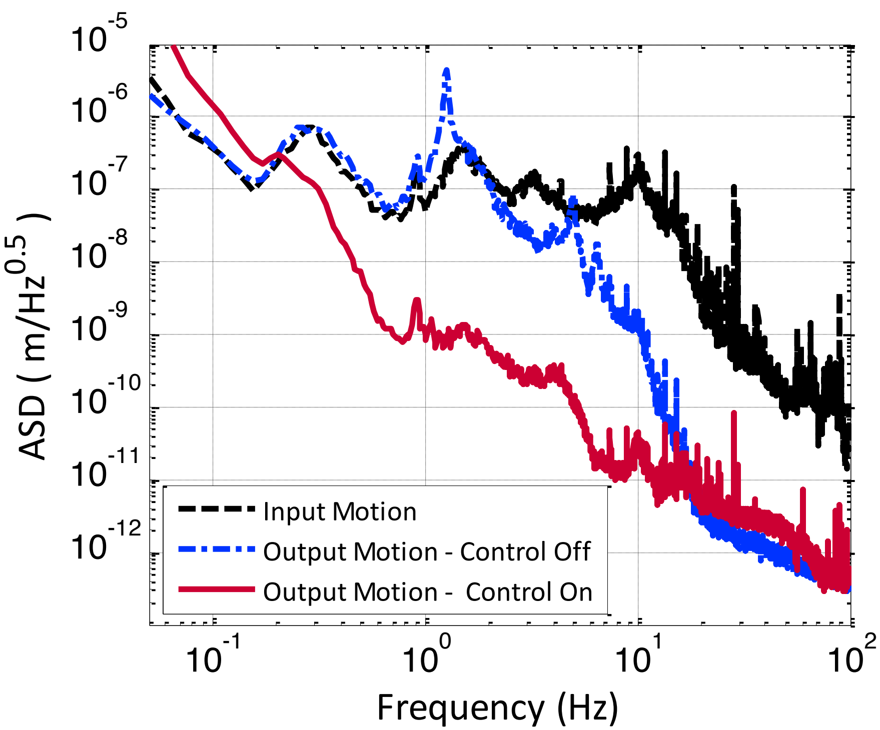
- ➔ Great care spent in on auxiliary sensor performance
- ➔ Novel control strategy

aLIGO: BSC-ISI it hangs the quad payload

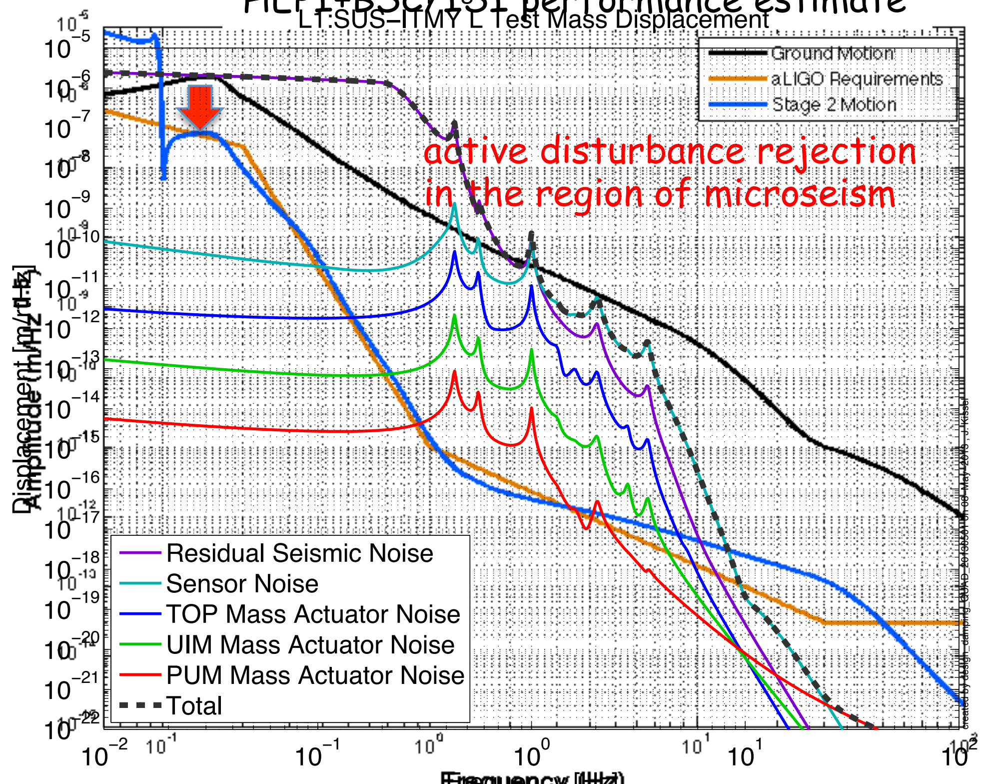
BSC-ISI:

- Two-Stage Isolator
- Internal (In Vacuum)
- 12 Degrees of Freedom
- Positioning and alignment
- Active isolation (0.1 Hz to ~25 Hz)
- Passive Isolation (1/f ^4 from a few Hz to ~100Hz)

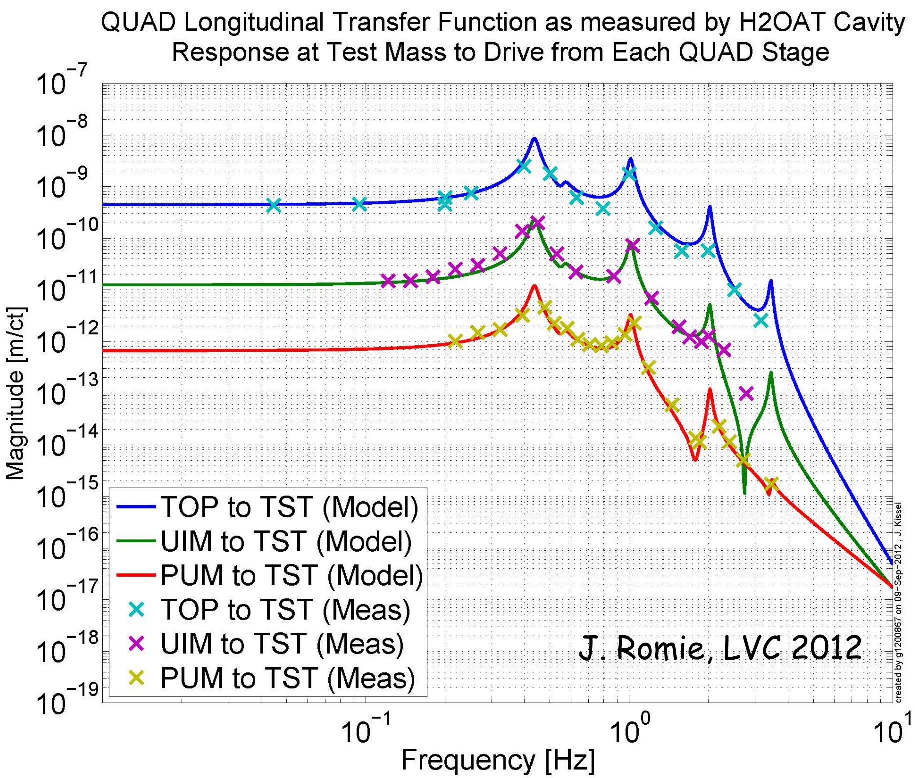


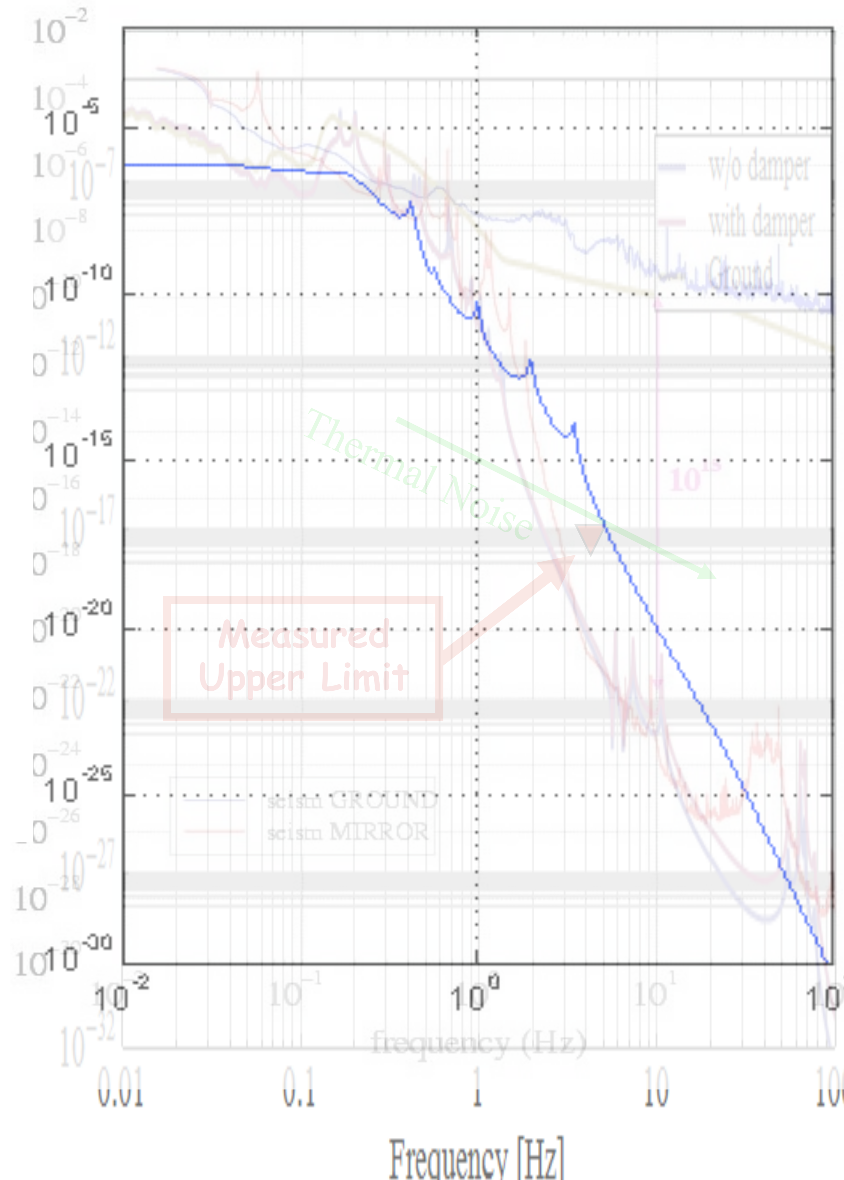


HEPI+BSC/ISI performance estimate



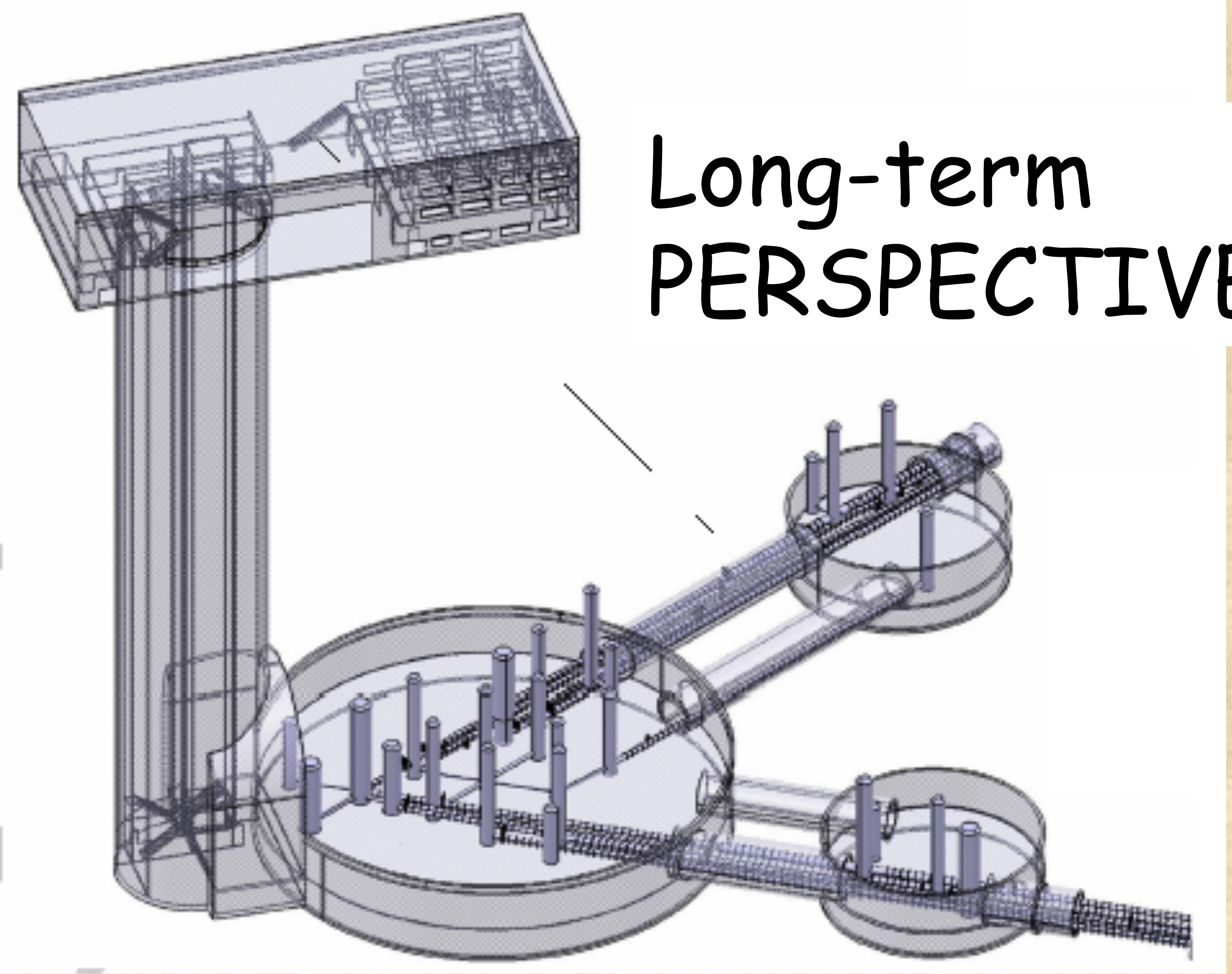
F. Matichard, 5/2013



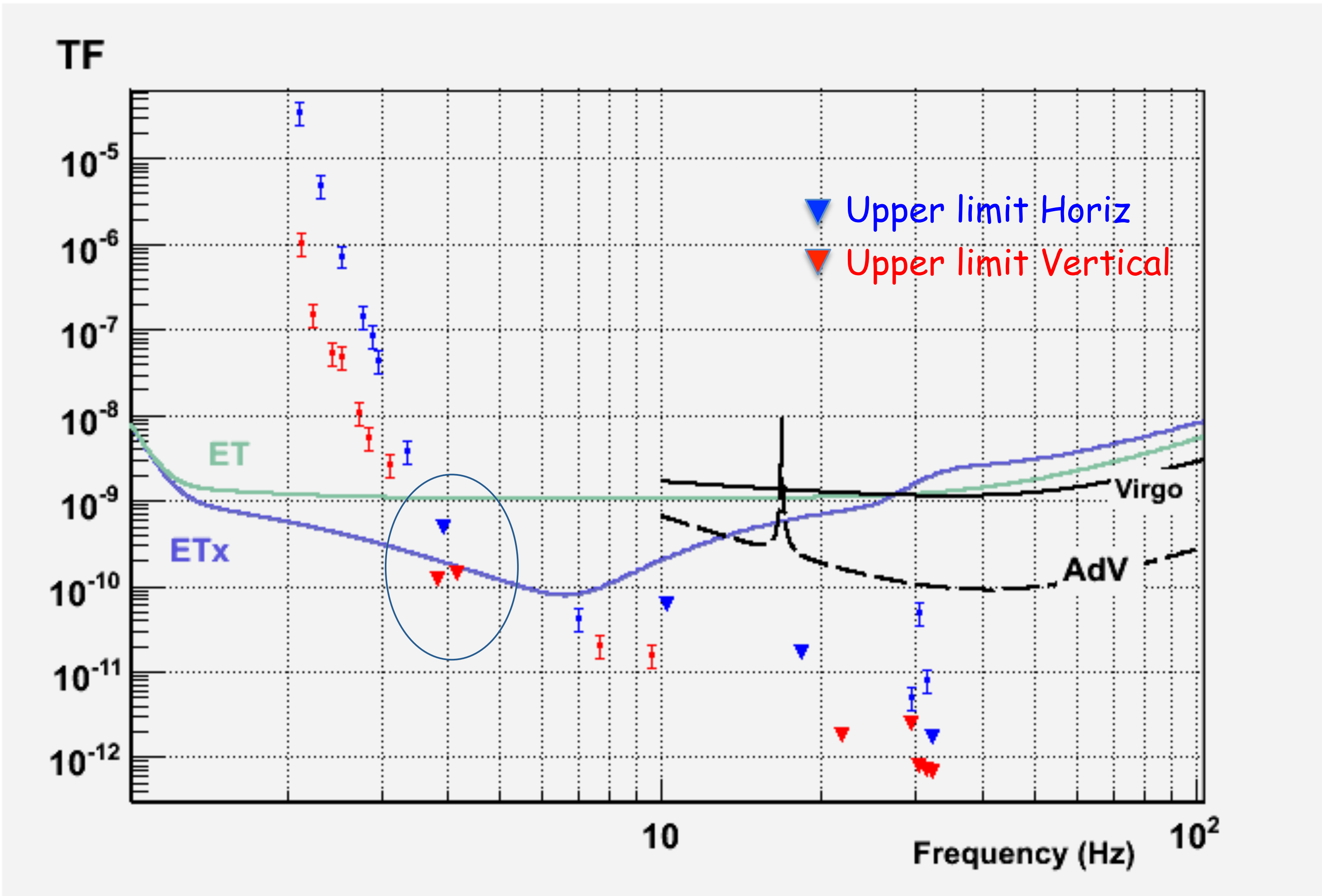


- Virgo
- KAGRA
- aLIGO HEPI-BSC/ISI-QUAD estimate

Long-term PERSPECTIVE



Using the scheme of passive + damping + single point suspension

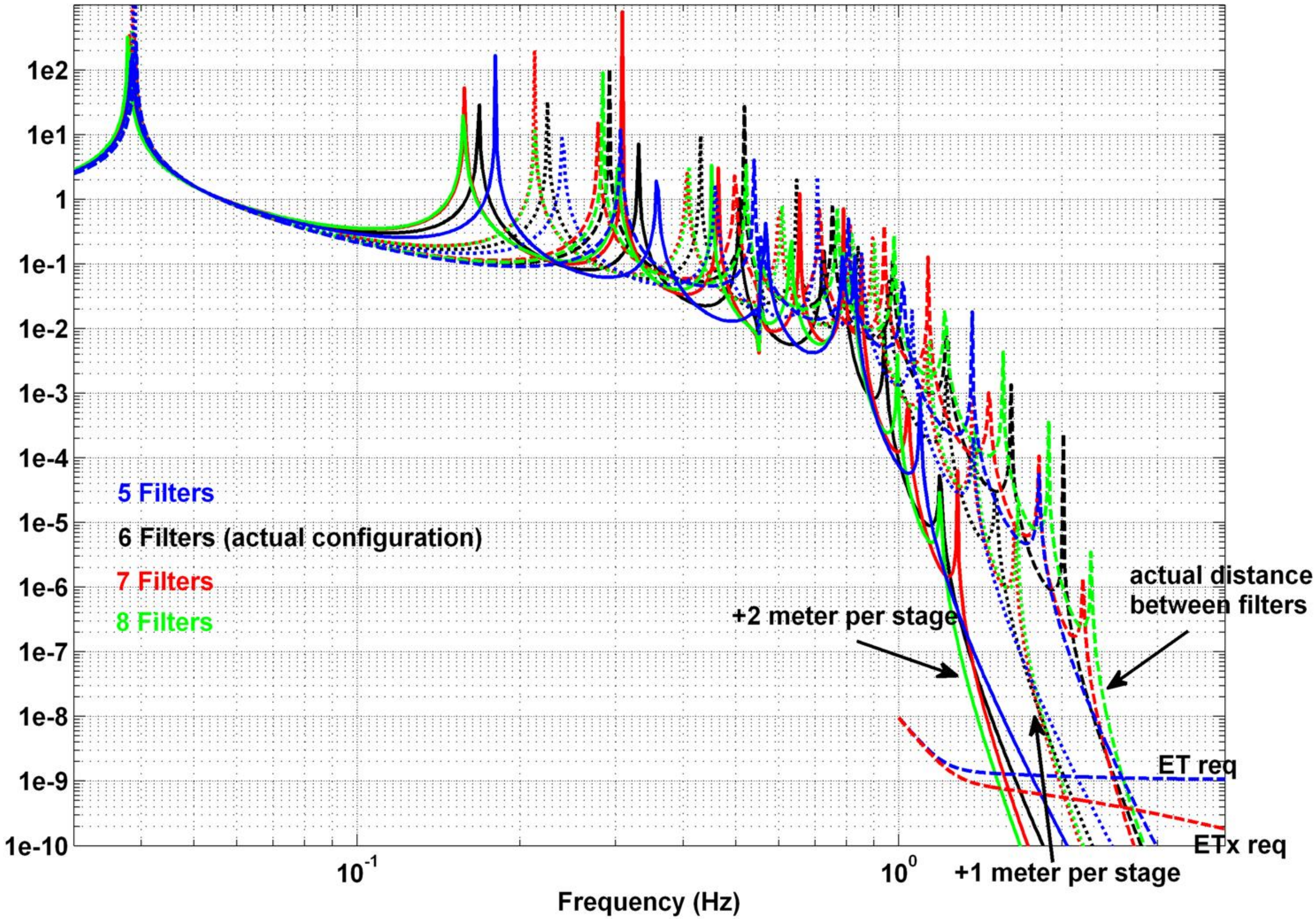


Virgo TF (requirements at p.14) crosses the sentitivity requirement at @ 3-4 Hz

S. Braccini, F. Frasconi
ET Conceptual Design Study (2011)

Changing both the number of filters A/O their distance in order to pull the crossover frequency to lower frequency

TF



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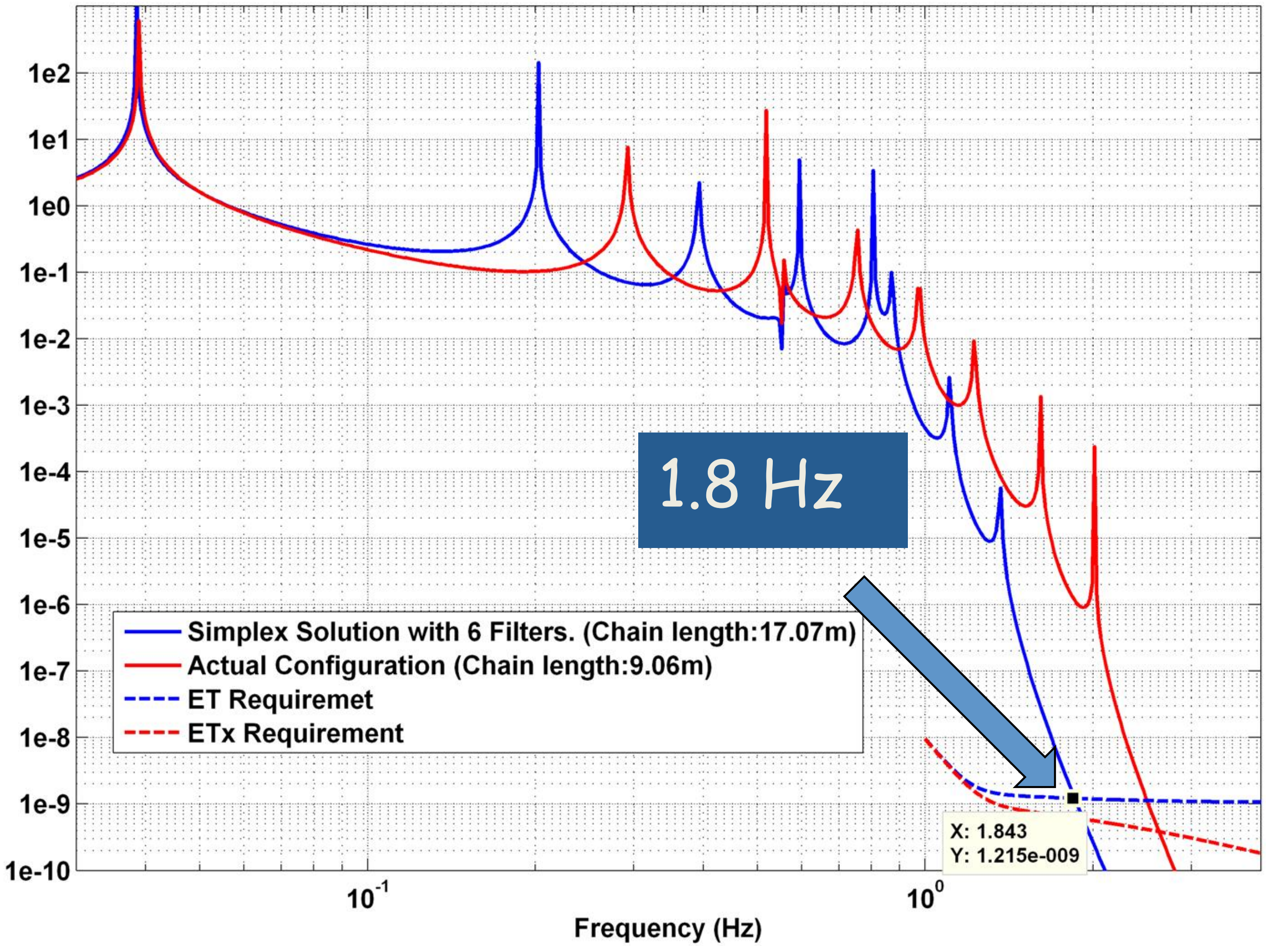
ET Conceptual Design Study (2011)

HORIZONTAL TF

6 filters - 17 m



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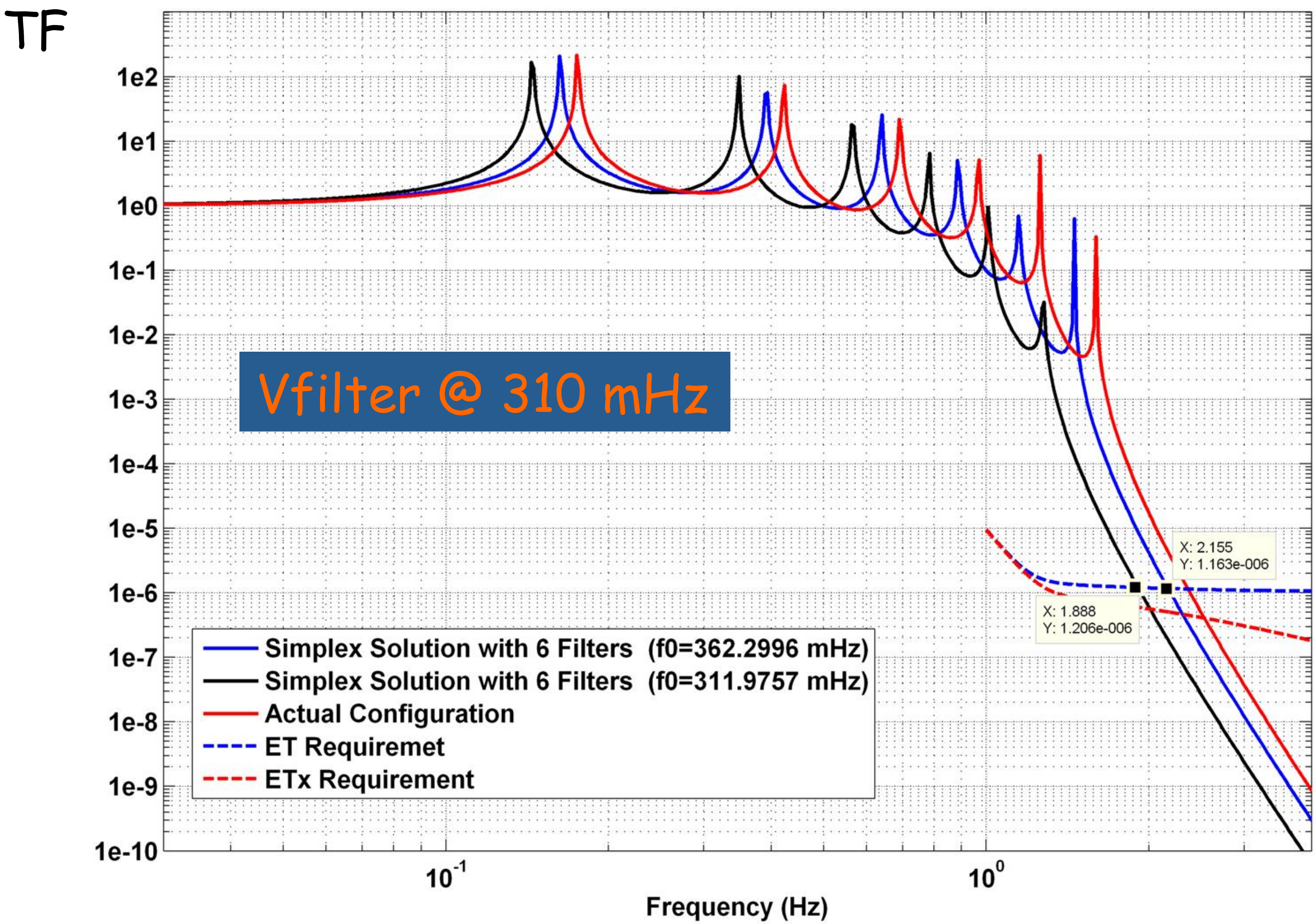
ET Conceptual Design Study (2011)

VERTICAL TF

6 Filters (as now)



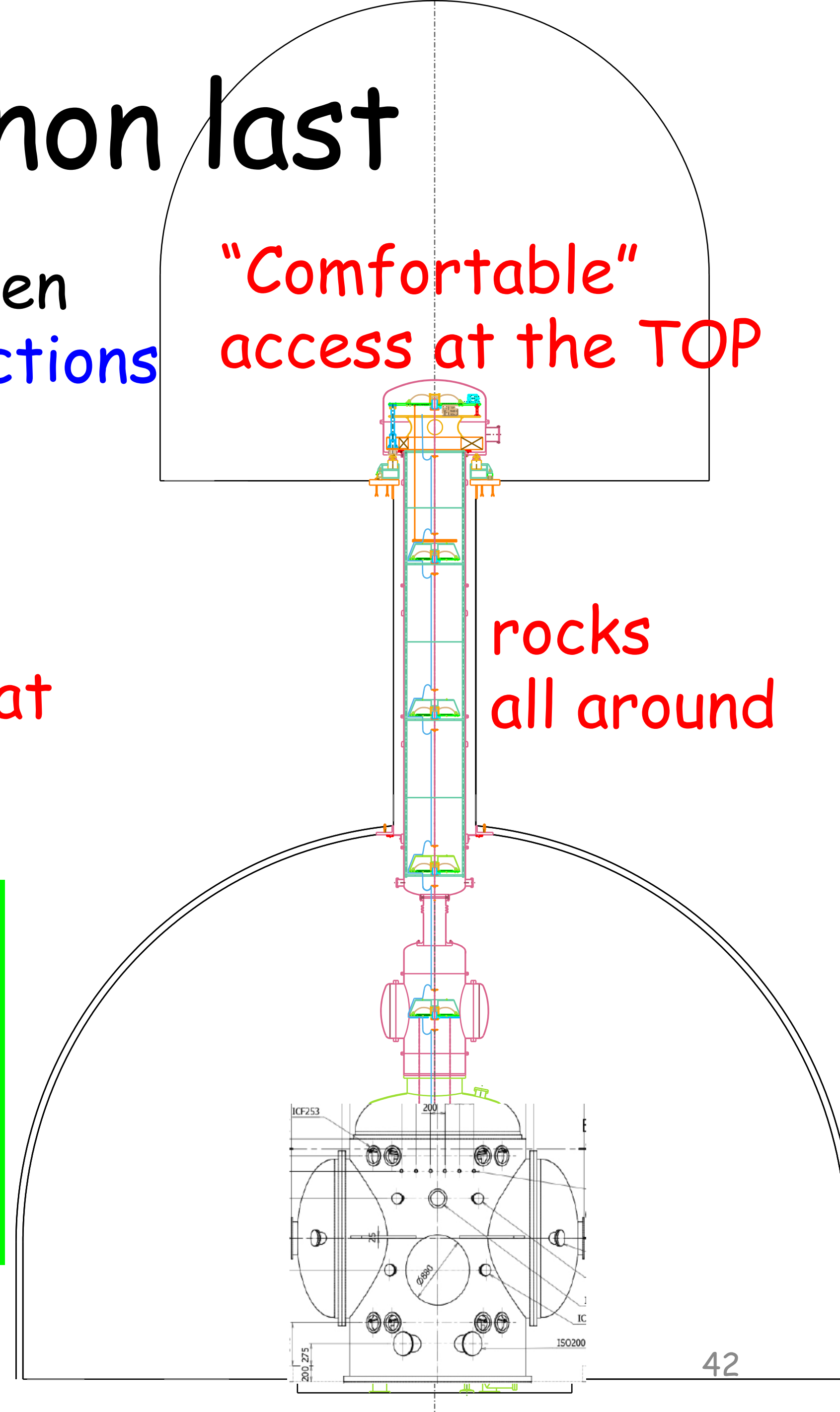
S. Braccini, F. Frasconi
ET Conceptual Design Study (2011)

Least-but-non last

- KAGRA SAS is mounted between two tunnels due to the restrictions of the space reserved for the cryostat

- Free and safe access to cryostat and seismic chain bottom!

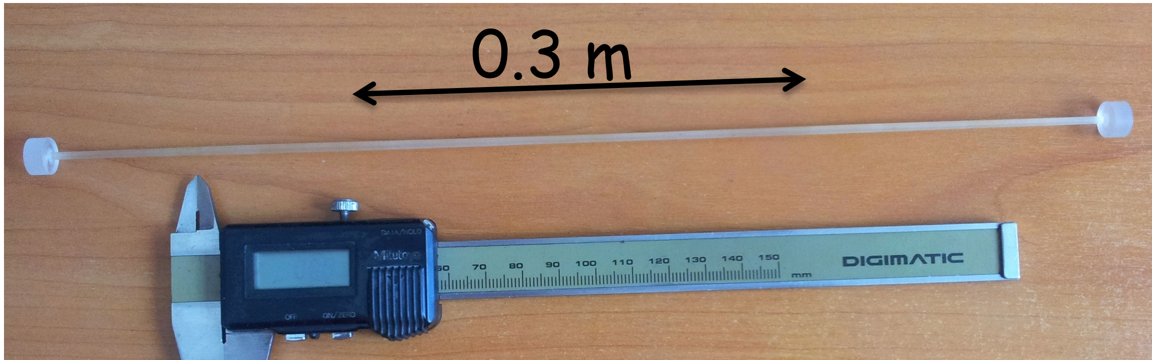
“Comfortable” access at the TOP



rocks all around

Bottom stages/cryogenics: the substantial difference with respect to room-T advanced detectors
(dedicated GWADW13 session on 24/5)

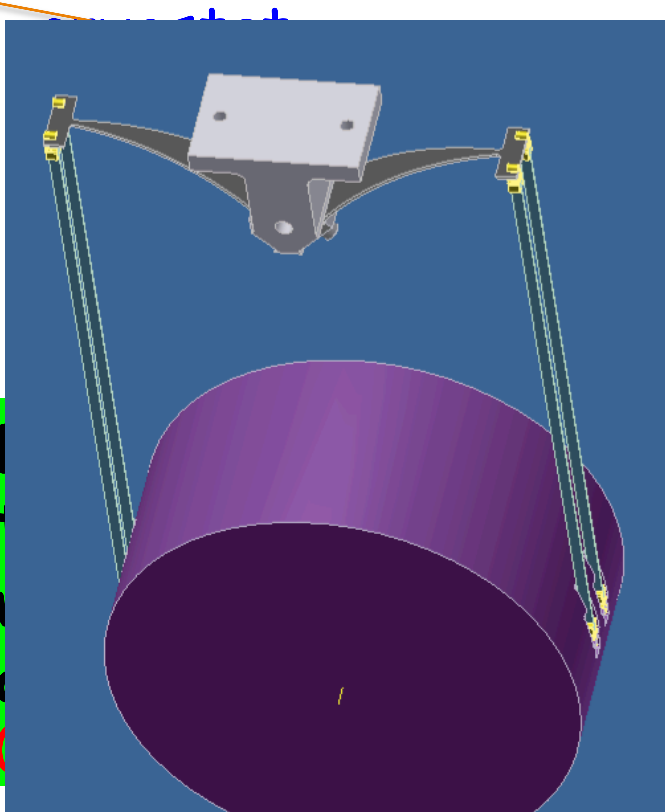
n last



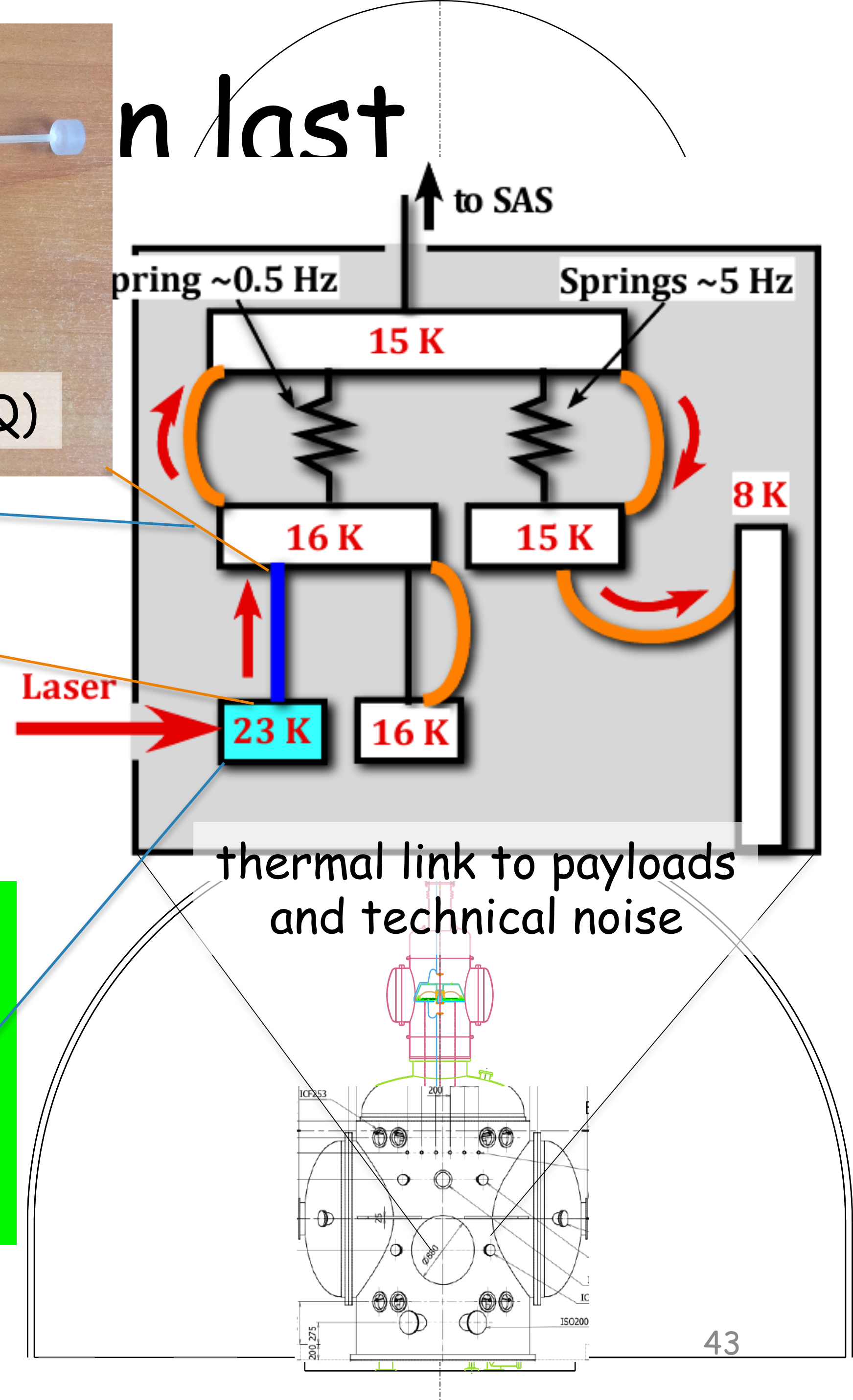
Suspension & thermal conductivity (& high Q)

- to cryos
  tom!

nics:
ence
-T
on on 24/5)



Composite material suspension (ET)



thermal link to payloads
and technical noise

Conclusions

- Fruitful international framework has grown around the upgrades of 1° generation detectors and KAGRA.

- Suspension systems are equipped with sophisticated seismic isolation apparatuses that rely on two main schemes:

A) passive damped preisolation + singe point suspension chain (with mechanical DOF separation) (demonstrated)

B) active preisolation + fullly controlled stages holding parallel passive chains under commissioning (very smooth)

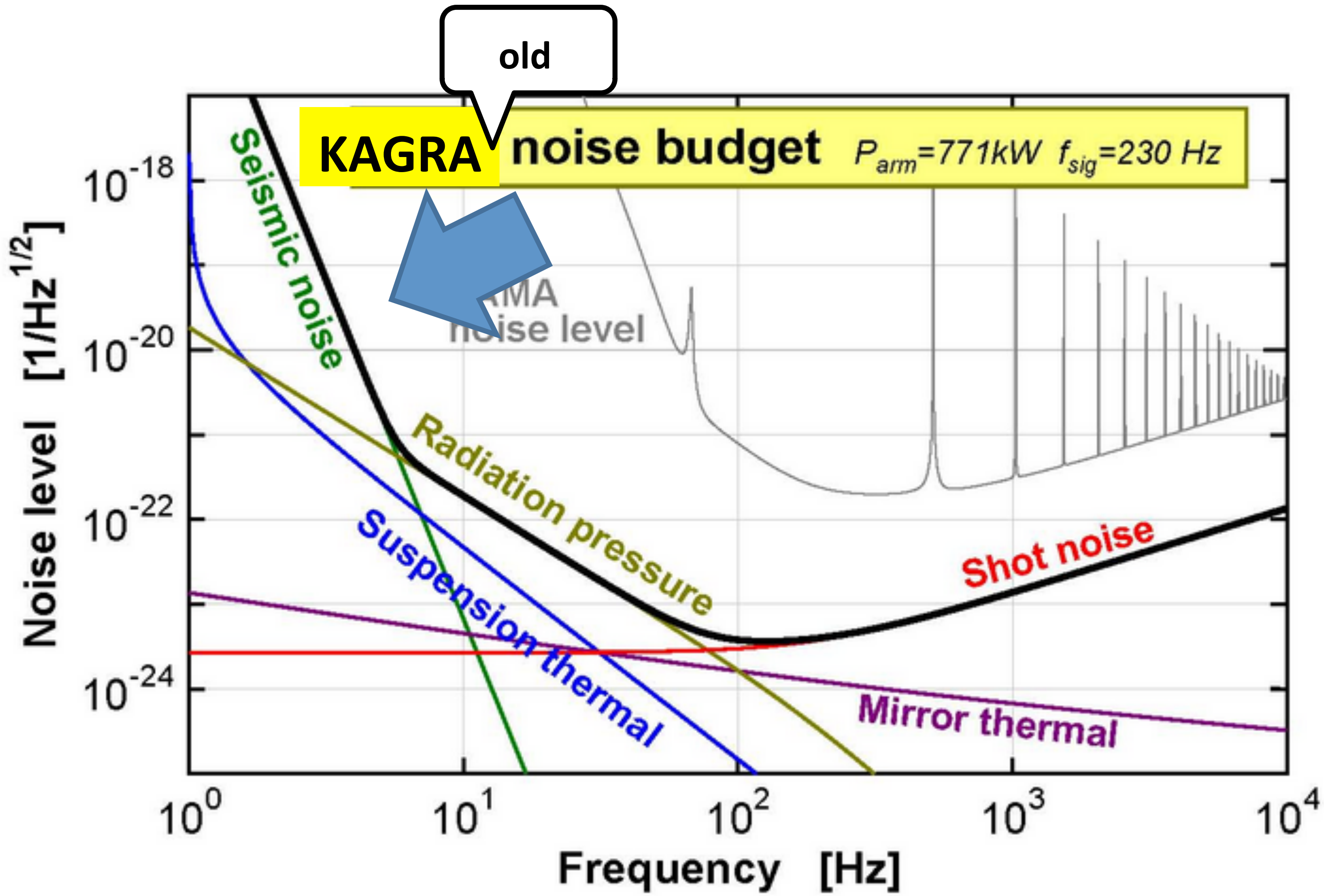
- 3rd GENERATION: it is easy to estimate the adoption of scheme A, so far.

- Major effort is expected, **through KAGRA**, in order to implement cryogenics at the level of suspension last stages and mirror payload.

About SAS

SAS [Seismic Attenuation System]

Seismic isolation starting from ultra low frequency



Composite mirror suspensions

Approach recently pulled out by R. DeSalvo (see JGW-G1201265)

- ❑ Heat transfer and mechanical compliance functions are separated
- ❑ Sapphire ribbons provide heat transport from the mirror to the upper stages
- ❑ Silicon flexures and cantilever blades provide low loss high compliance along the 6 DOF
- ❑ Purely compressive joints
- ❑ No shear stress
- ❑ Could be a viable solution for ET and perhaps of interest also for KAGRA