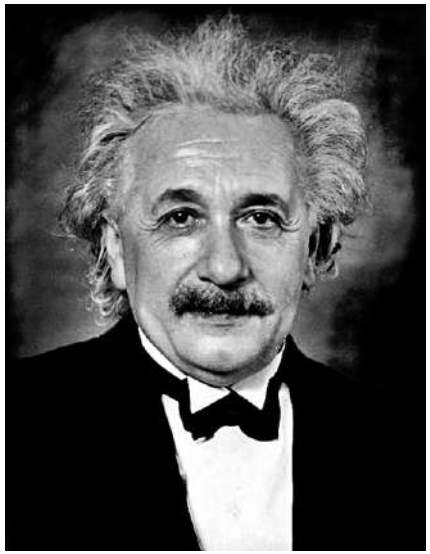
Conception mécanique des détecteurs d'ondes gravitationnelles:

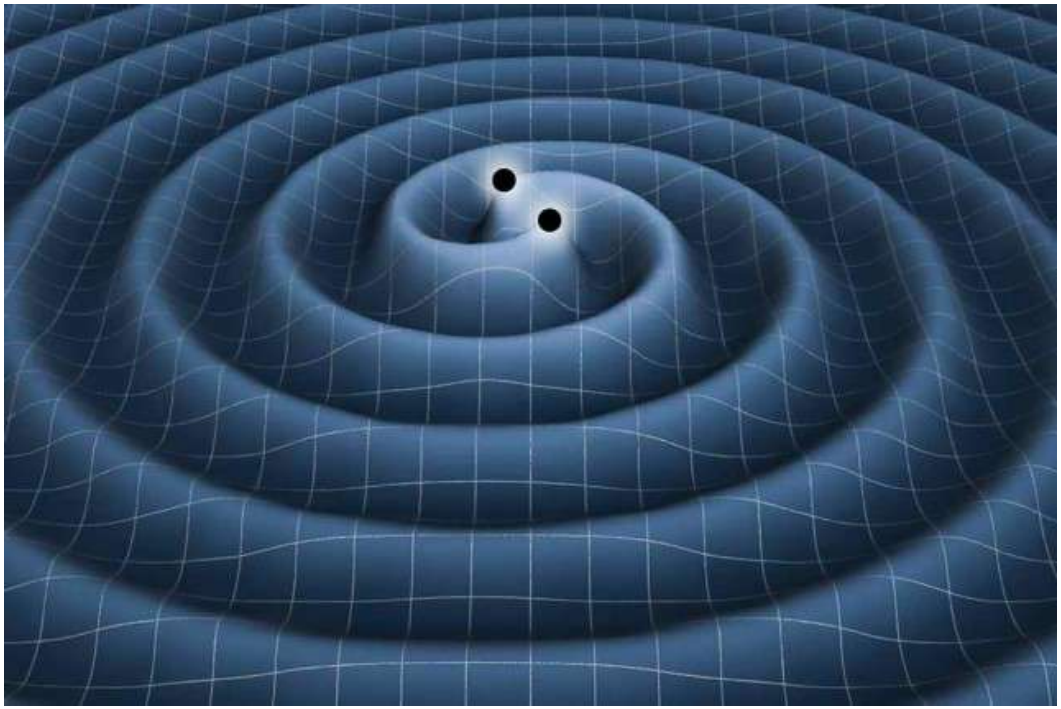
Performances actuelles et challenges pour les détecteurs de 3ème génération

Christophe Collette

Precision Mechatronics Laboratory

1916: Théorie de la relativité générale

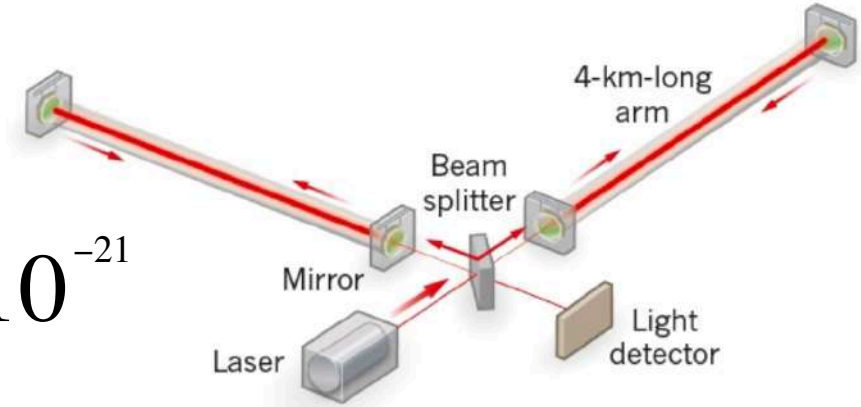




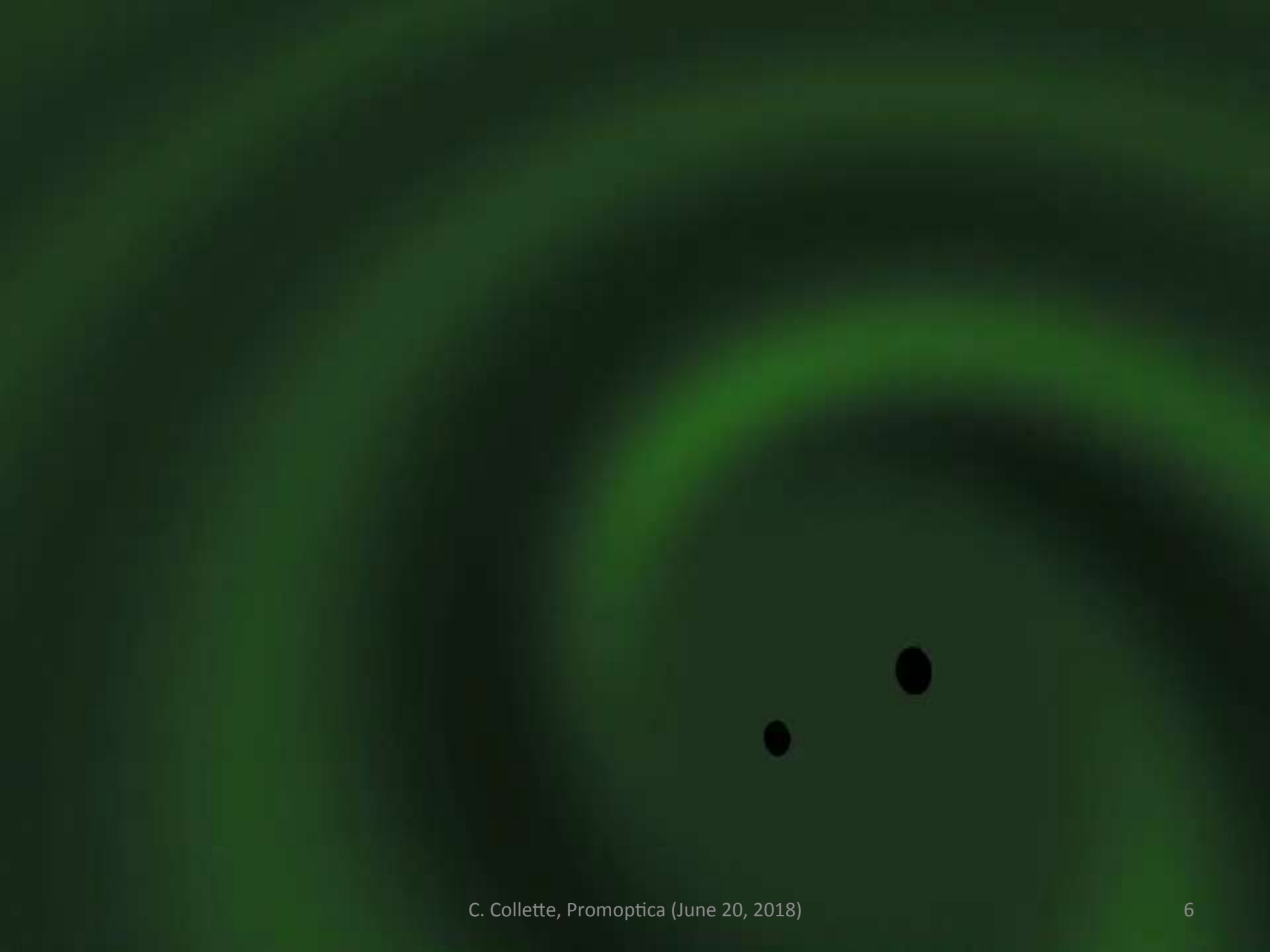
La fusion d'objets massifs (trous noirs) génère des déformations de l'espace, créant des déplacements de 10^{-18} m entre deux objets situés à 1 km de distance.

Observatoires existants

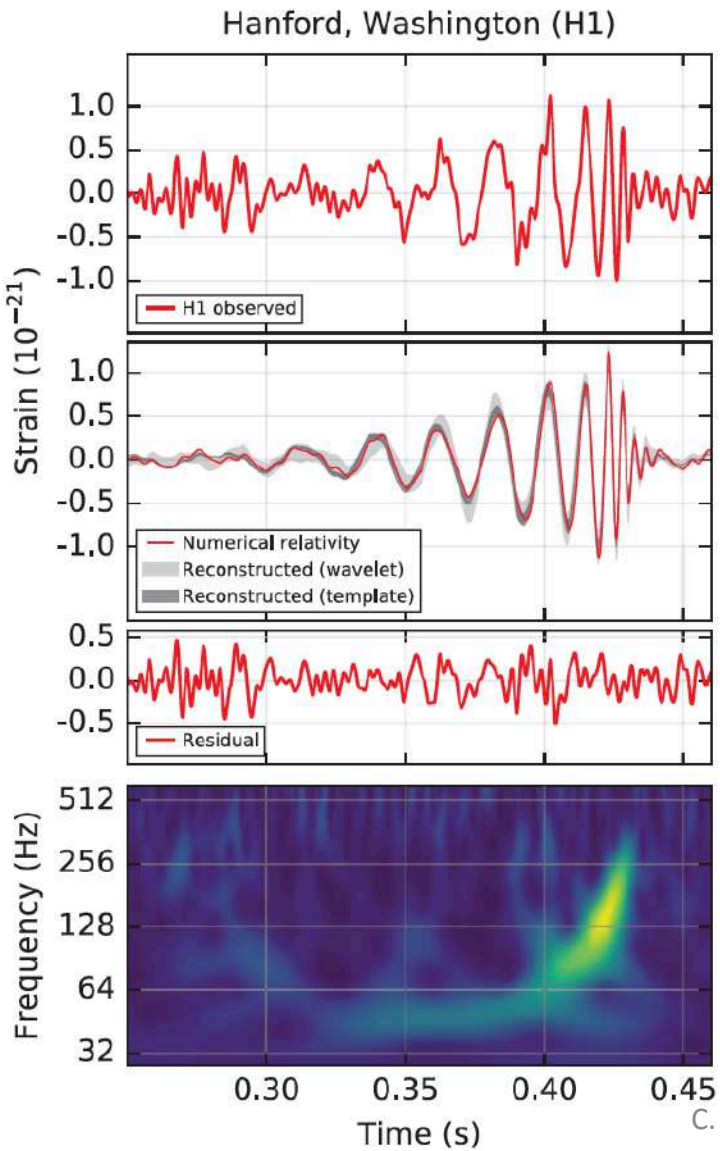
$$h \approx \frac{\Delta L}{L} = 10^{-21}$$

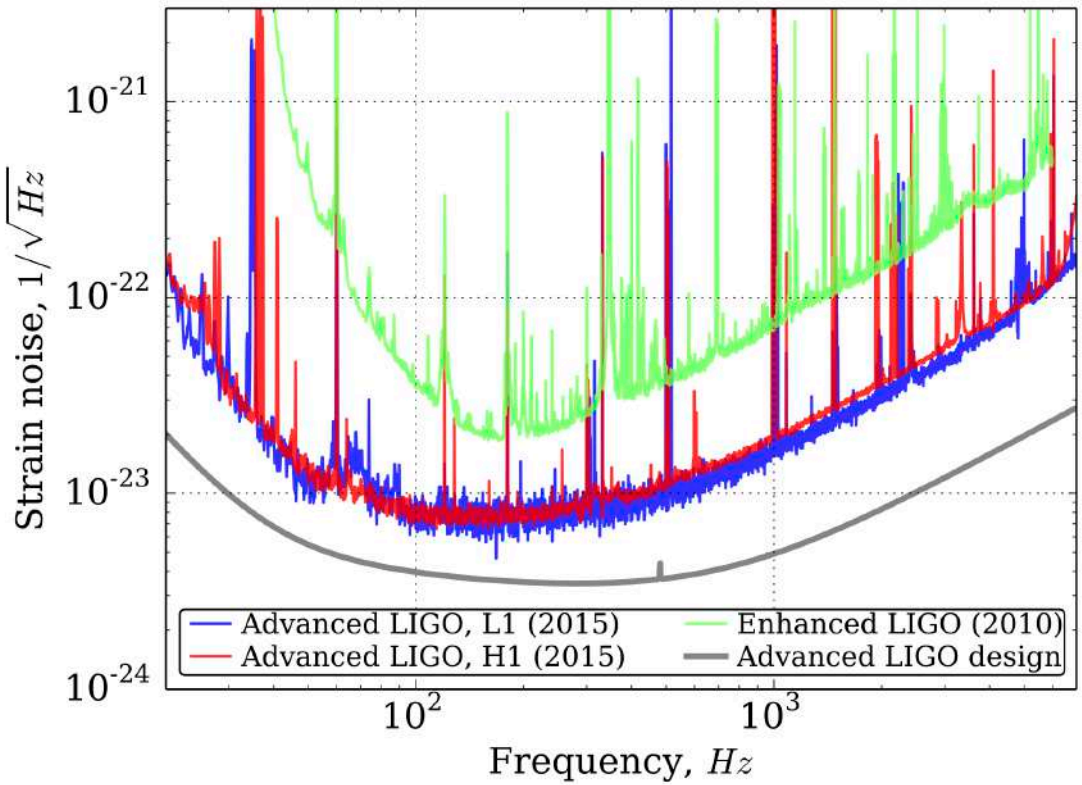


On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal.



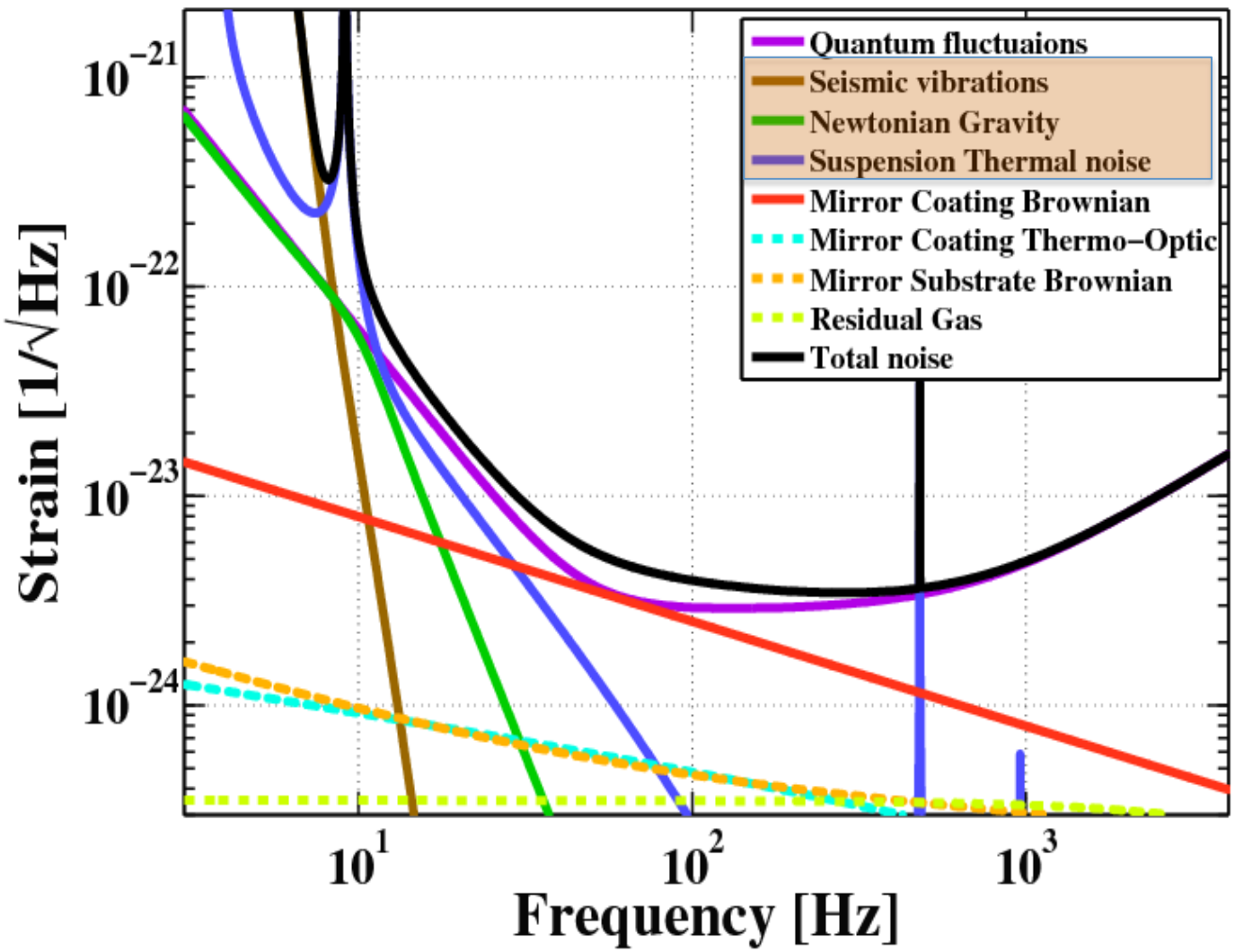
Sensitivity



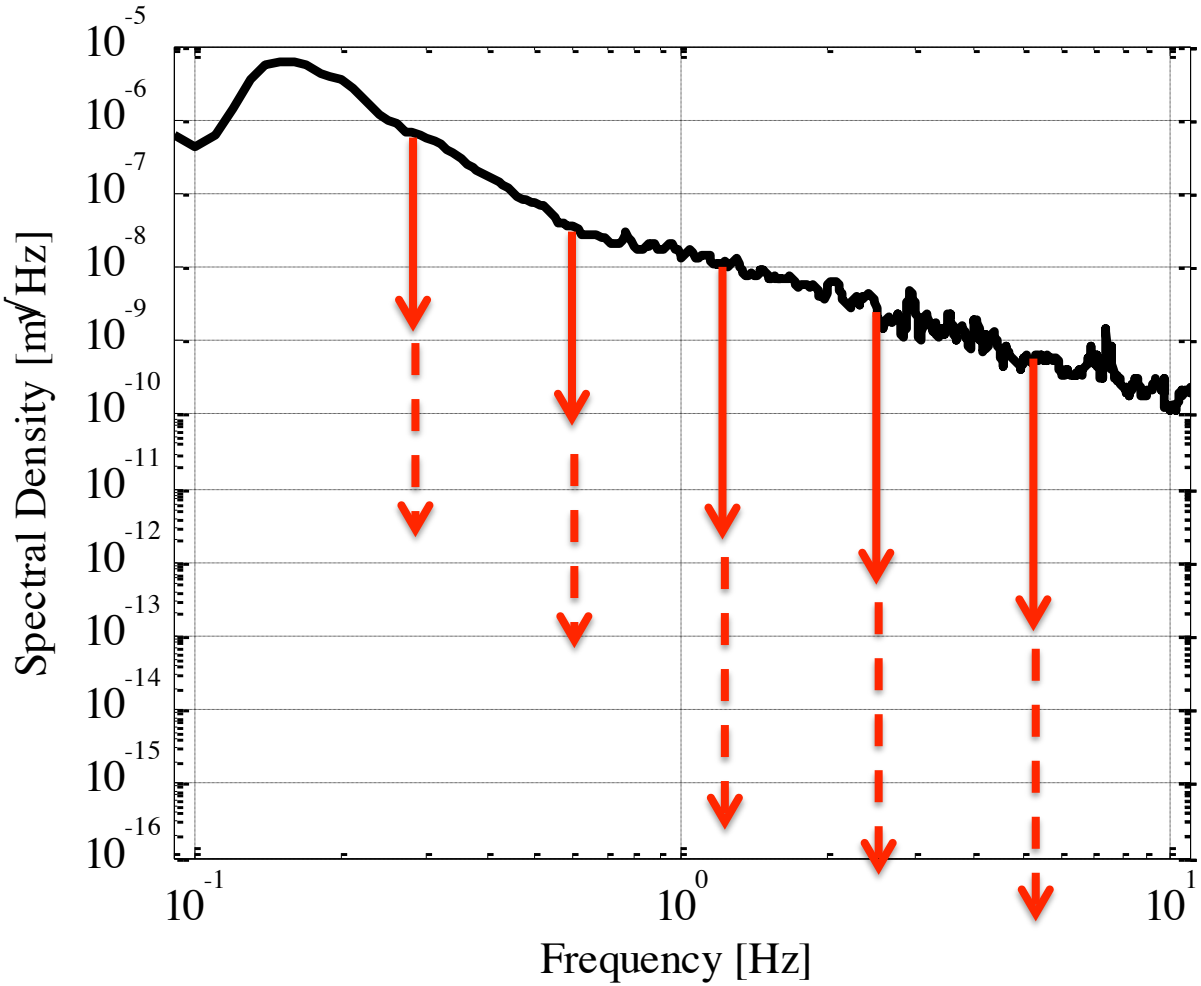


How is it possible ?

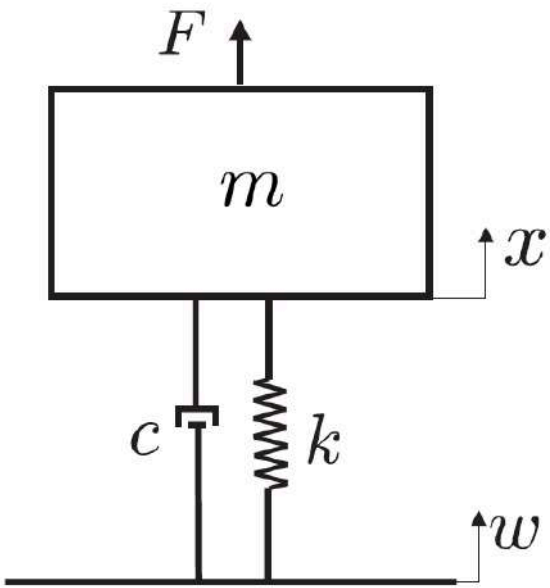
aLIGO noise budget

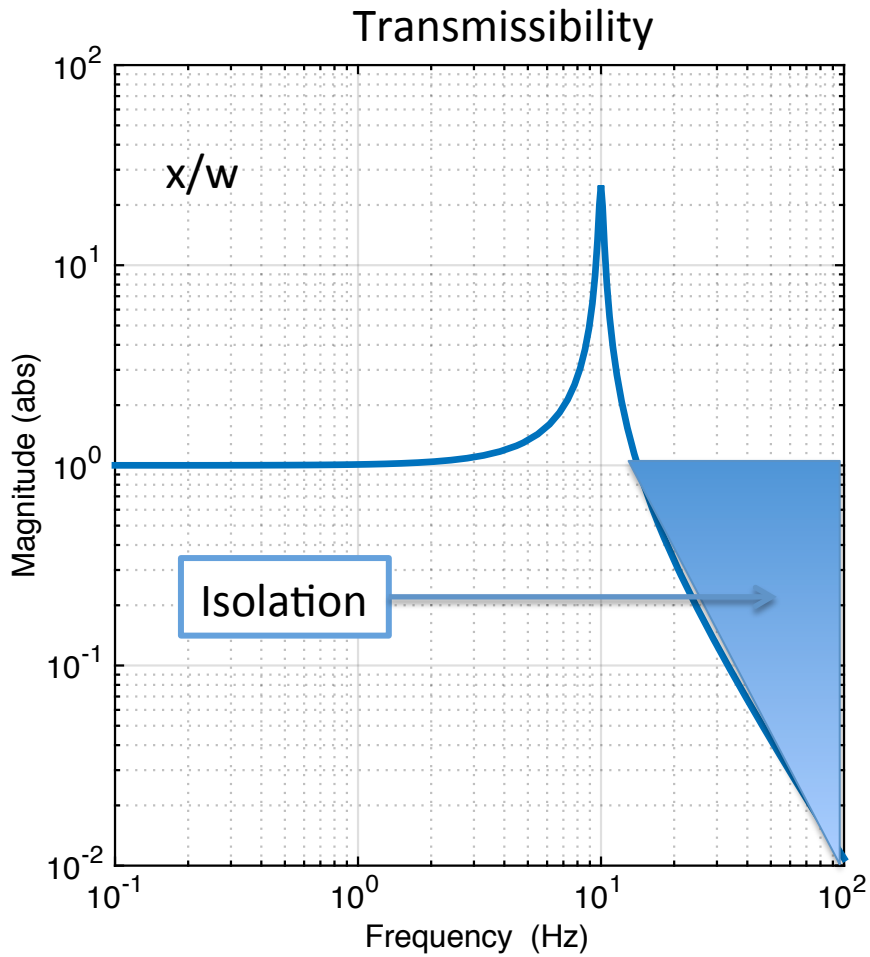


Seismic isolation requirements

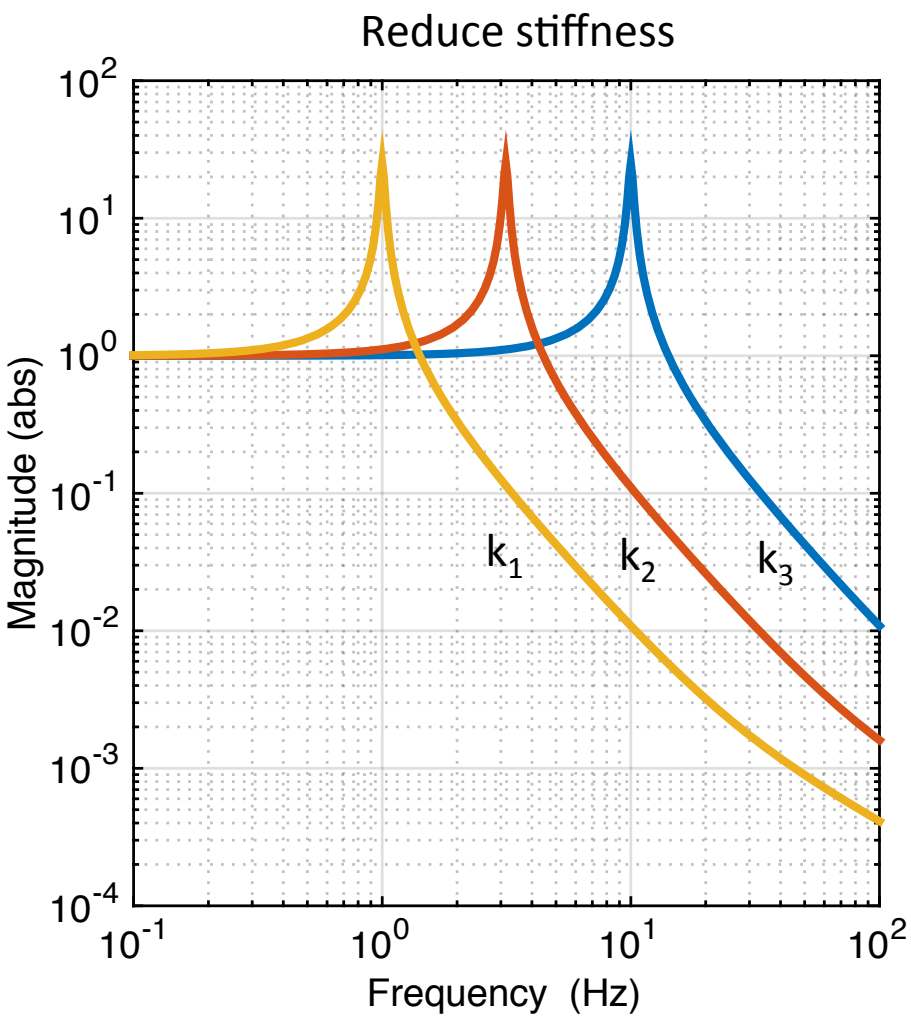


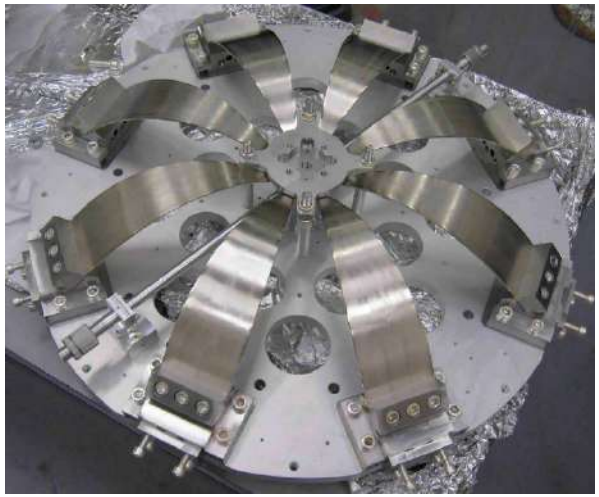
Seismic isolation principle

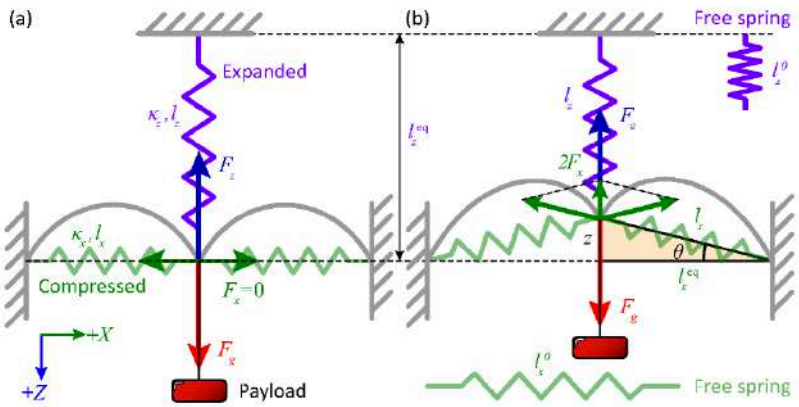




Strategy 1: Passive isolation





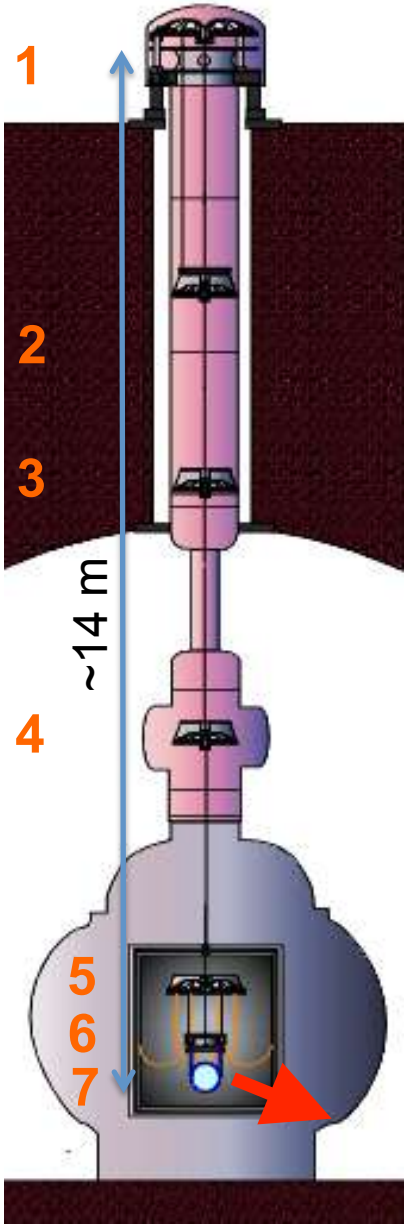


Wanner PhD thesis (2013)

Hybrid Systems

J. Kissel, GWADW, May 17 2012
G1200556-v1

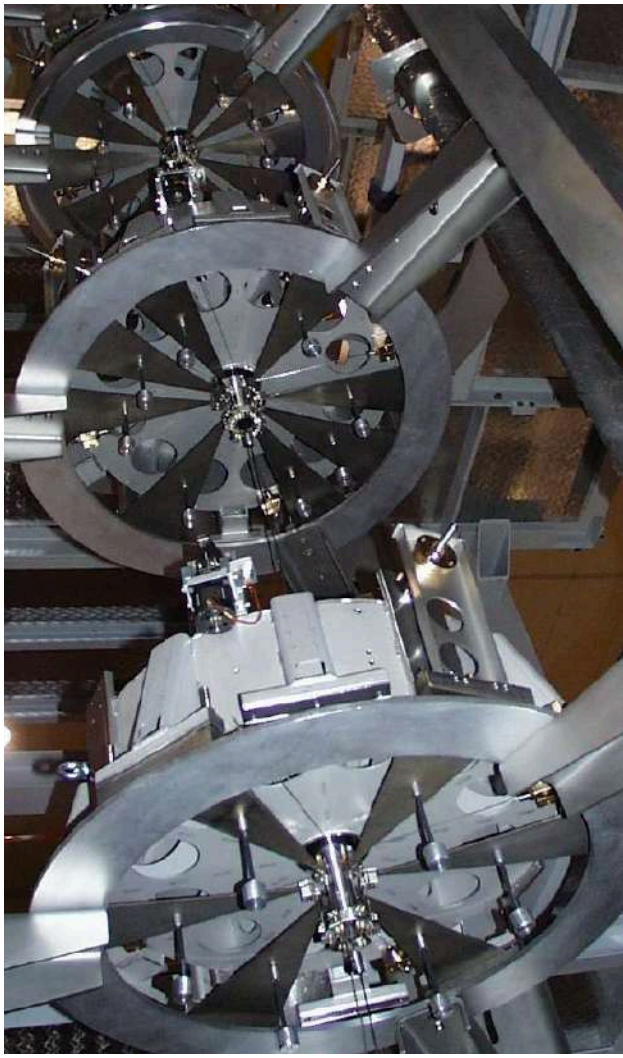
Advanced VIRGO, Kagra, ET – The Design

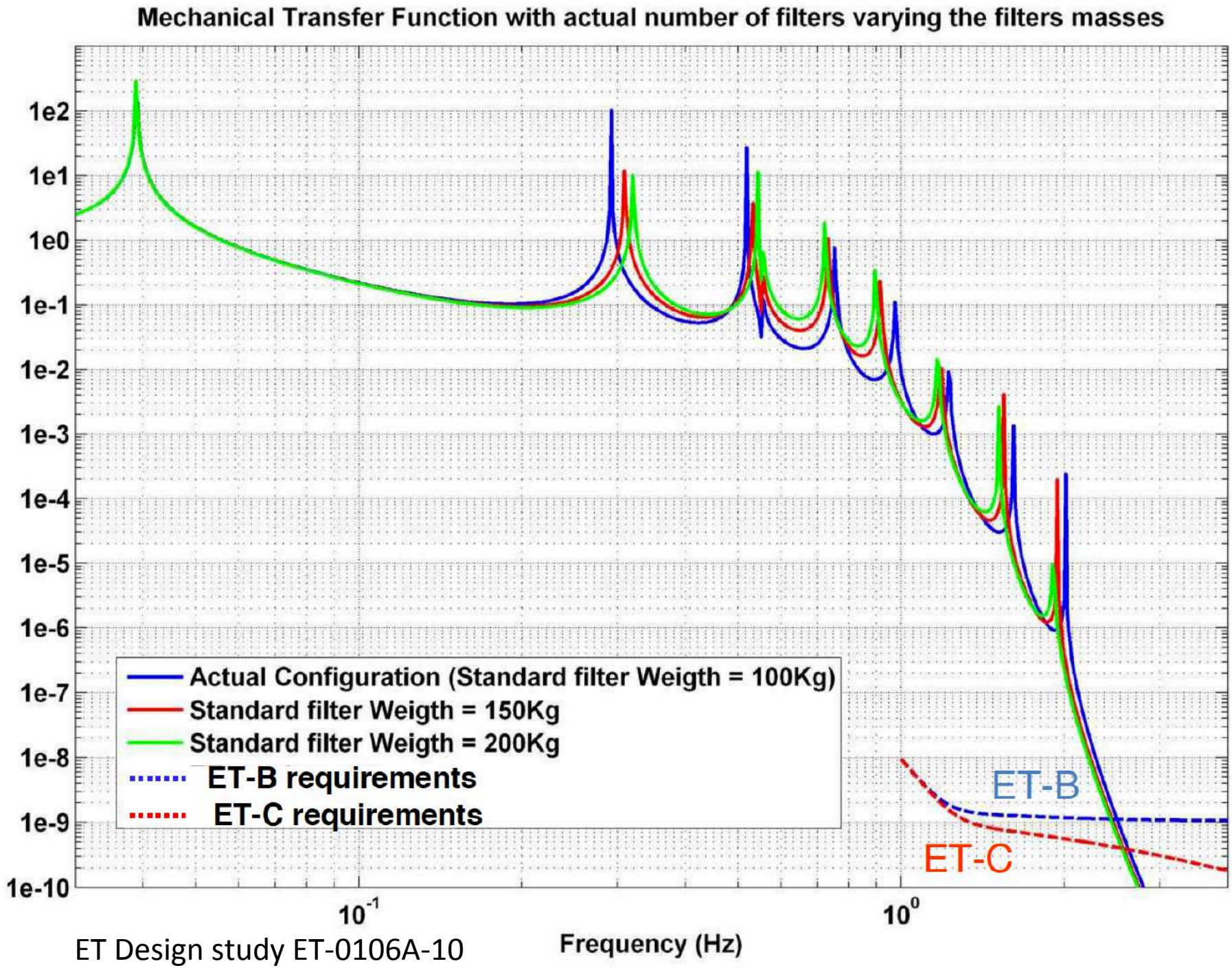


- 7 Stages of Isolation
  - Inverted Pendula Pre-isolation stages (Horz. only)
  - Blade springs and tunable anti-spring vertical pendula (geometric, magnetic)
- Sensors and actuators for 6 DOFs of 6th stage, 4 DOFs (Long., Vert., Pitch, Yaw) at 1st stage
- (4 + 6 + 3) = 13 out of 42 Trans./Rot. resonant modes sensed and controlled

Performance limited by

- **direct transmission of ground motion**
- **Length of the stages**
- **Ultra-soft system: 1N on 1 ton creates a motion of 1cm**

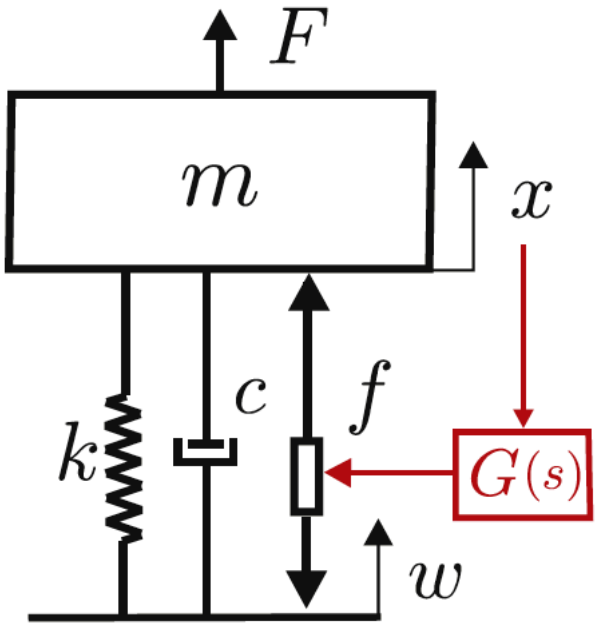


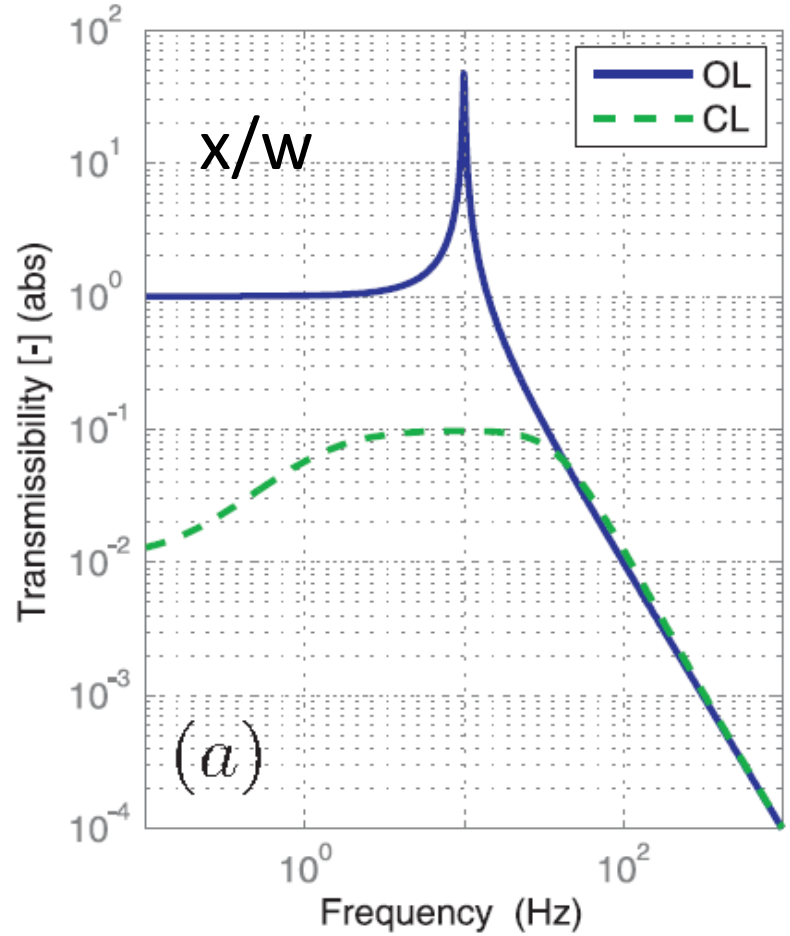


ET Design study ET-0106A-10

Strategy 2: Active isolation

Inertial control

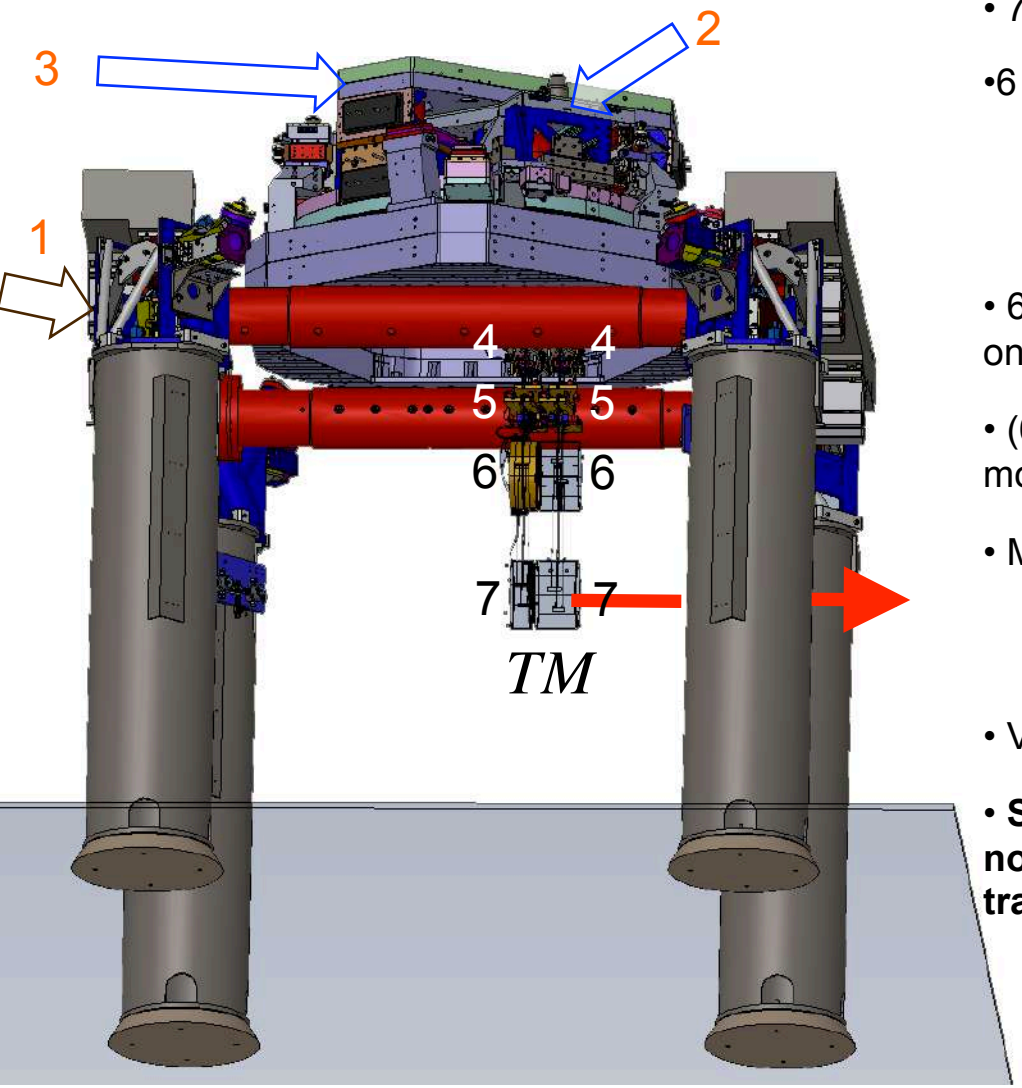




Hybrid Systems

J. Kissel, GWADW, May 17 2012
G1200556-v1

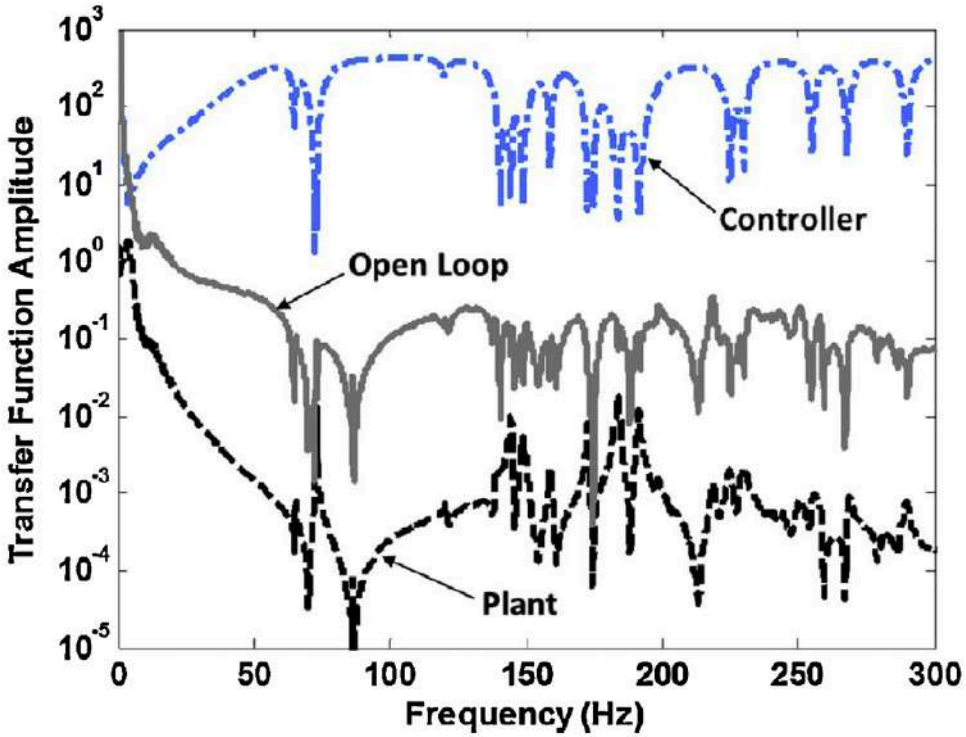
Advanced LIGO - The Design



- 7 Stages of Isolation
- 6 DOF sensing on stages 1 – 4, 3 DOF on 5 – 6
  - Inertial and displacement on stages 1-3
  - Displacement only on stages 4 - 6
- 6 DOF DC - 1kHz actuation on Stages 1 – 4, 3 DOF on 5 - 7
- (6+6+6+[3*6+4]) = 40 out of 42 Trans./Rot. resonant modes sensed and controlled
- Many-control-loop system
  - Sensor blending, Feed back, Feed forward, Sensor Correction, Heirarchical control
- Versatile 800 kg payload
- **Stage 1 – 3 "Performance limited by sensor noise," Stage 4 – 7 "Performance limited by direct transmission of platform motion"**

Limitation 1: Mechanical design

Initial prototype (2008)

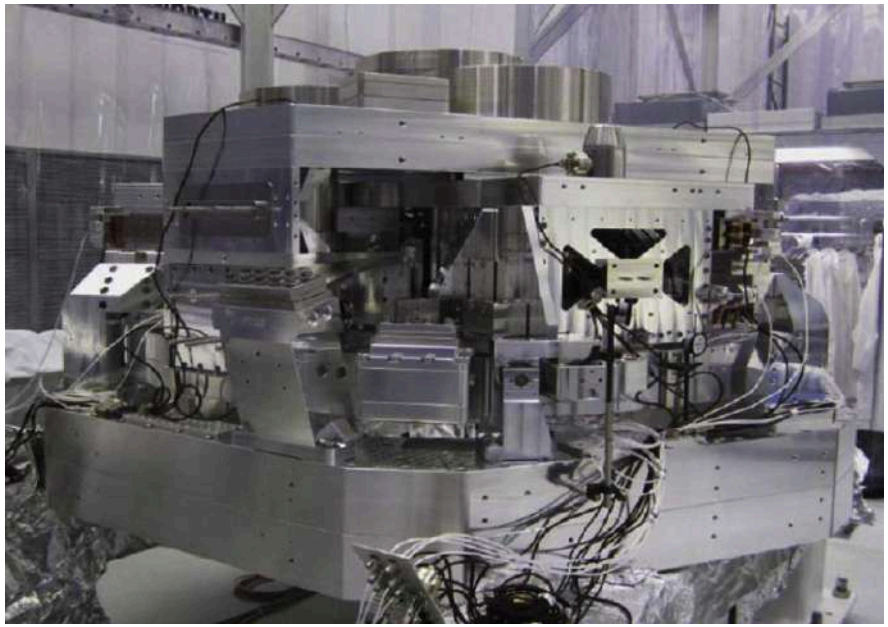


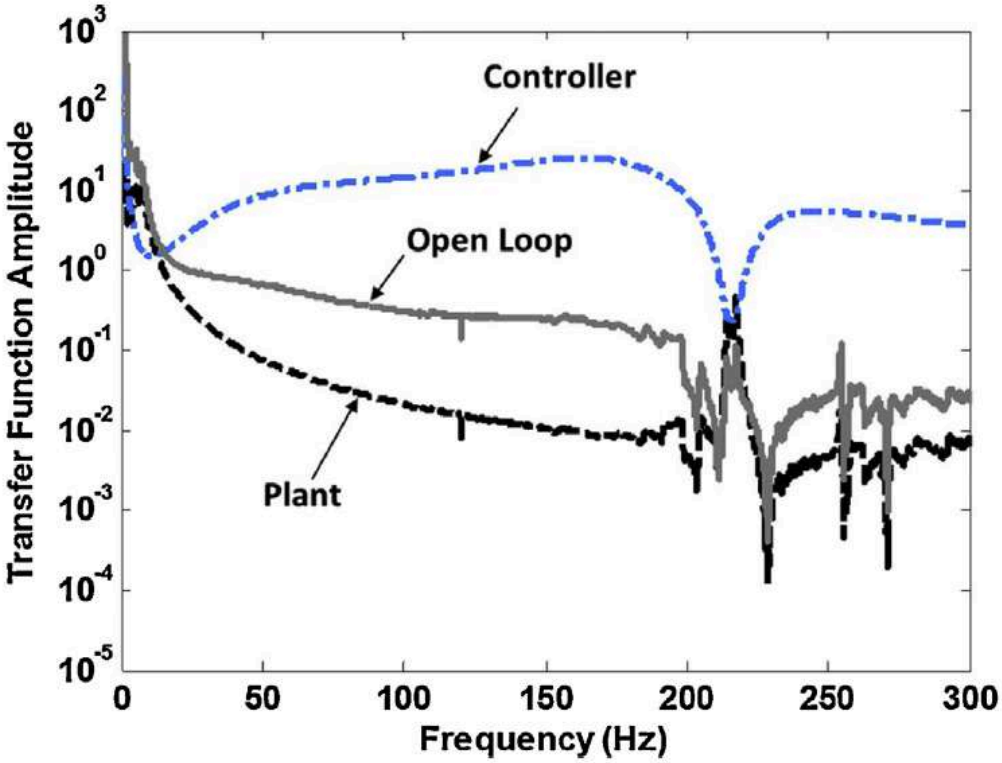
F. Matichard, Precision engineering, 40 (2015), 287-297

Compensator was made of 104 poles and zeros.

Limitation 1: Mechanical design

Final Design (2011)

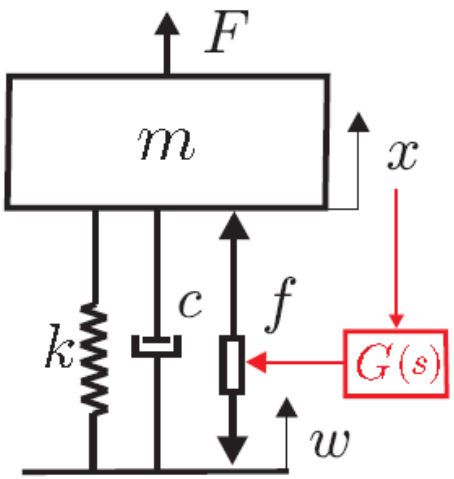


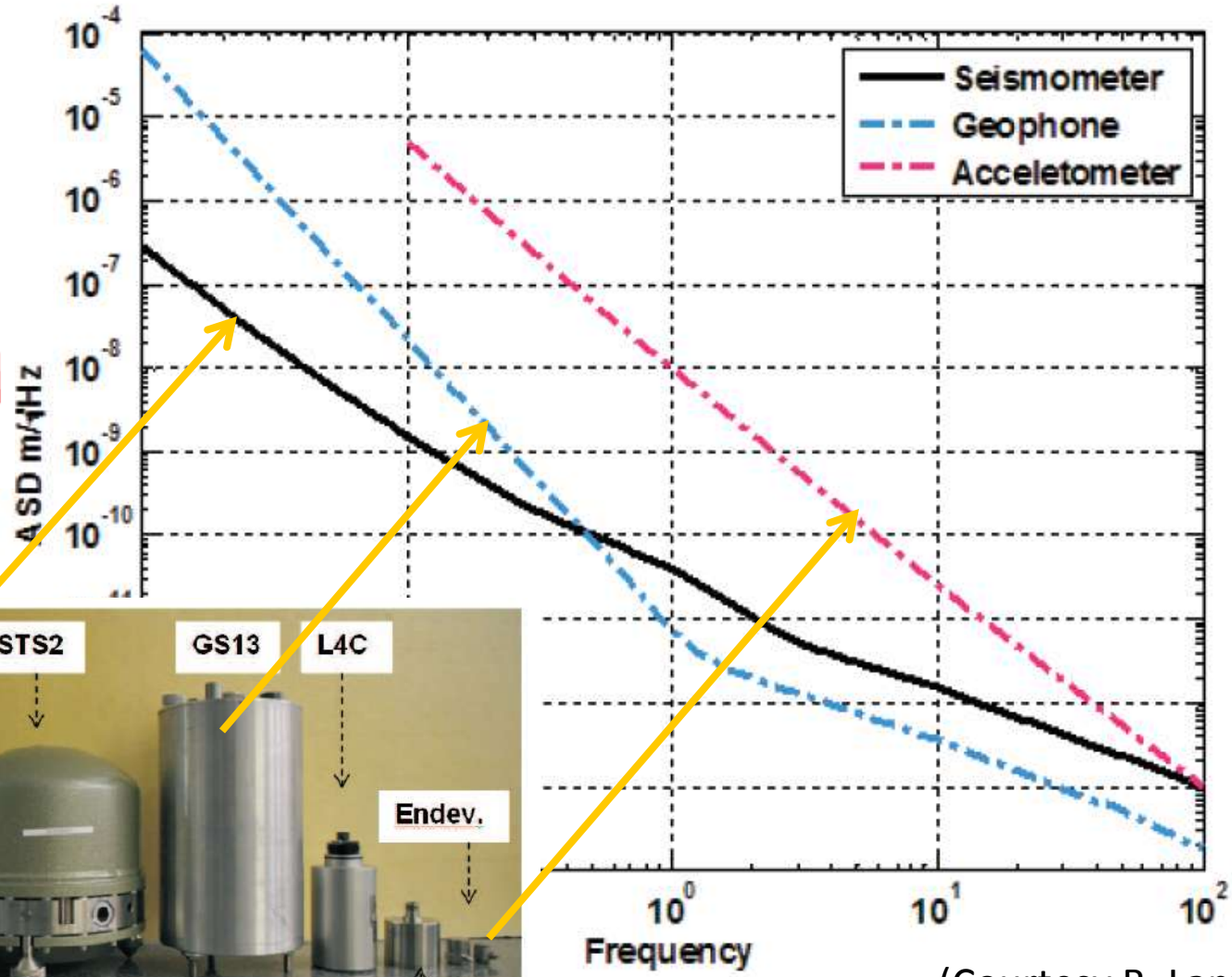


F. Matichard, Precision engineering, 40 (2015), 287-297

22 poles and zeros !

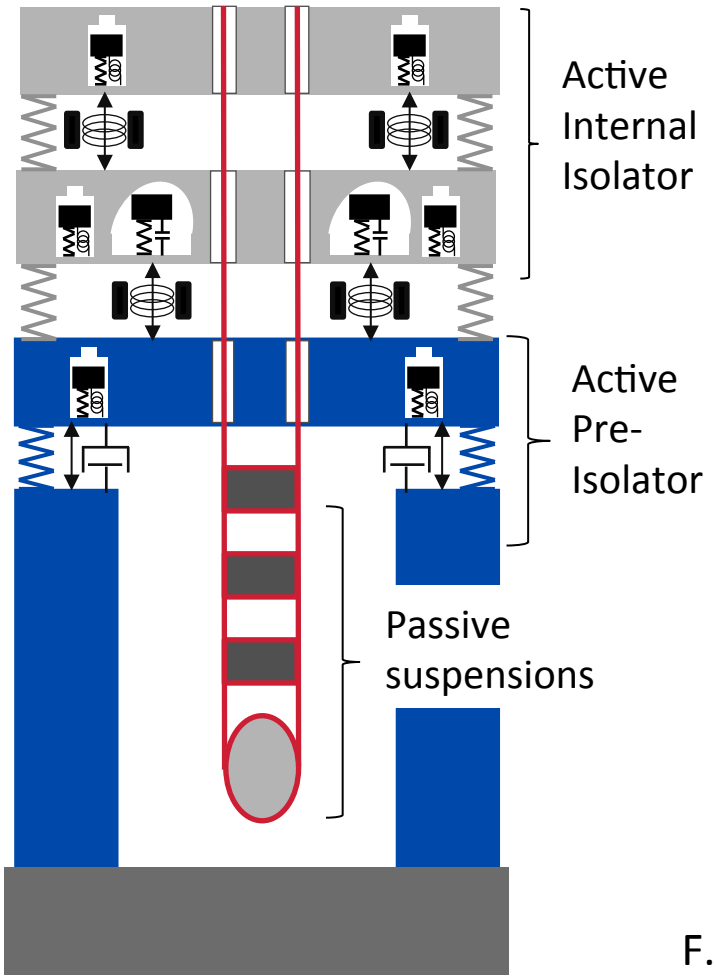
Limitation 2: Sensor noise

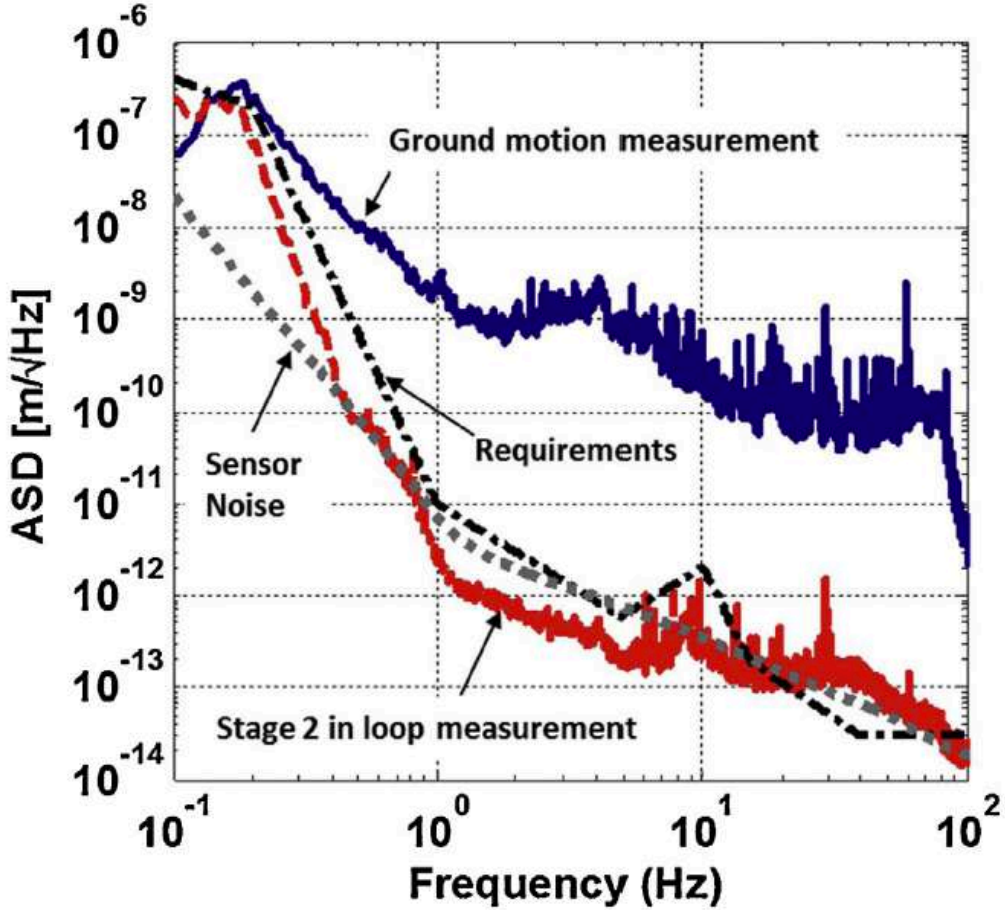




(Courtesy B. Lantz)

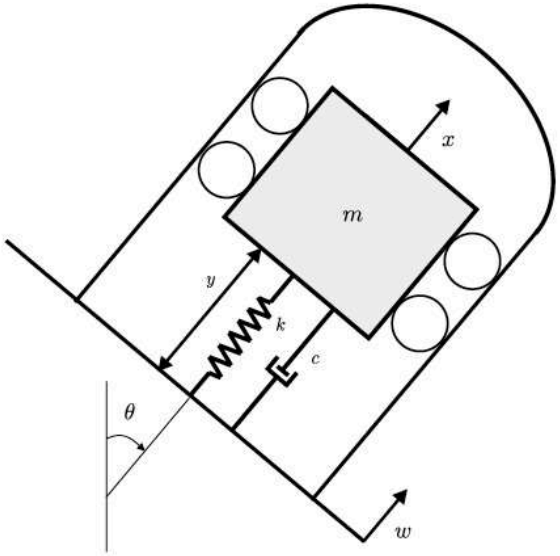
Two-stage active seismic isolation





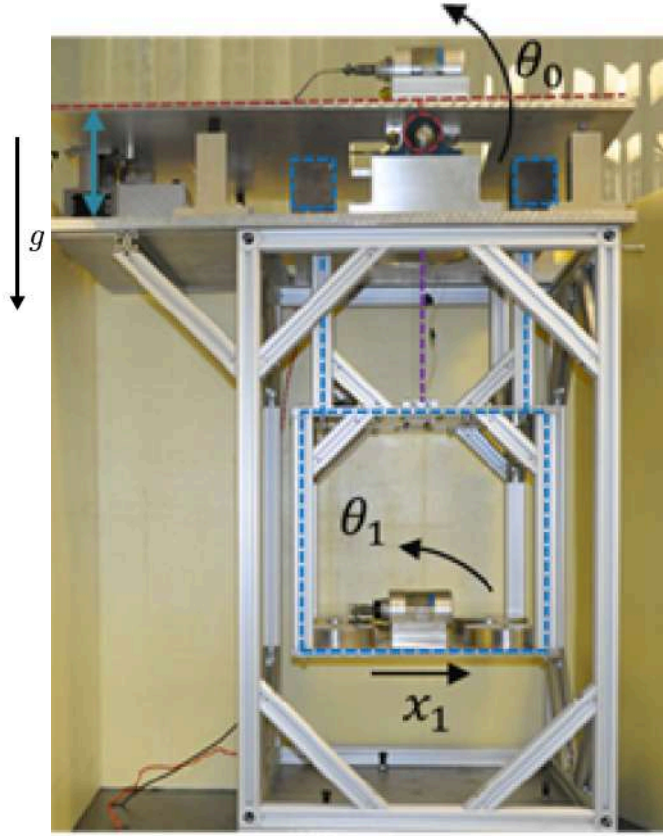
F. Matichard, Precision engineering, 40 (2015), 287-297

Limitation 3: Tilt-horizontal coupling



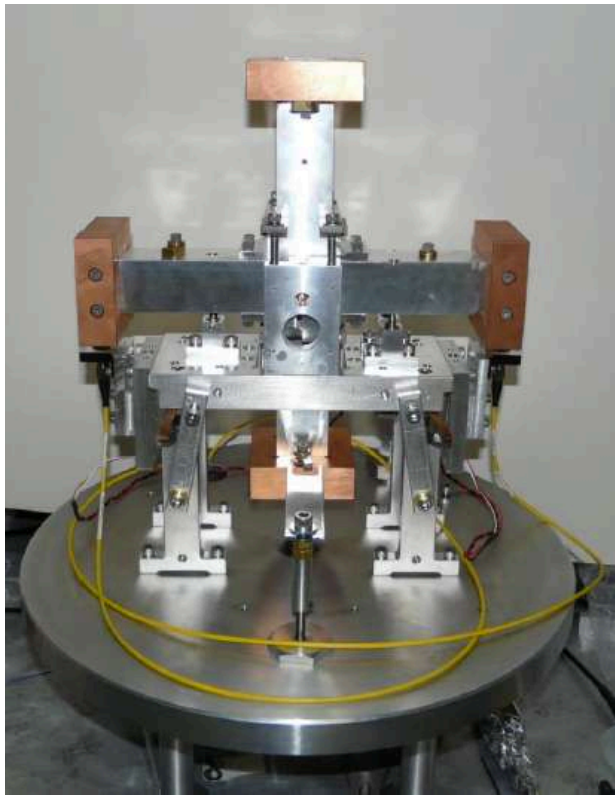
At low frequency, inertial sensor cannot make the difference between support acceleration and rotation

1. Suspended seismometer



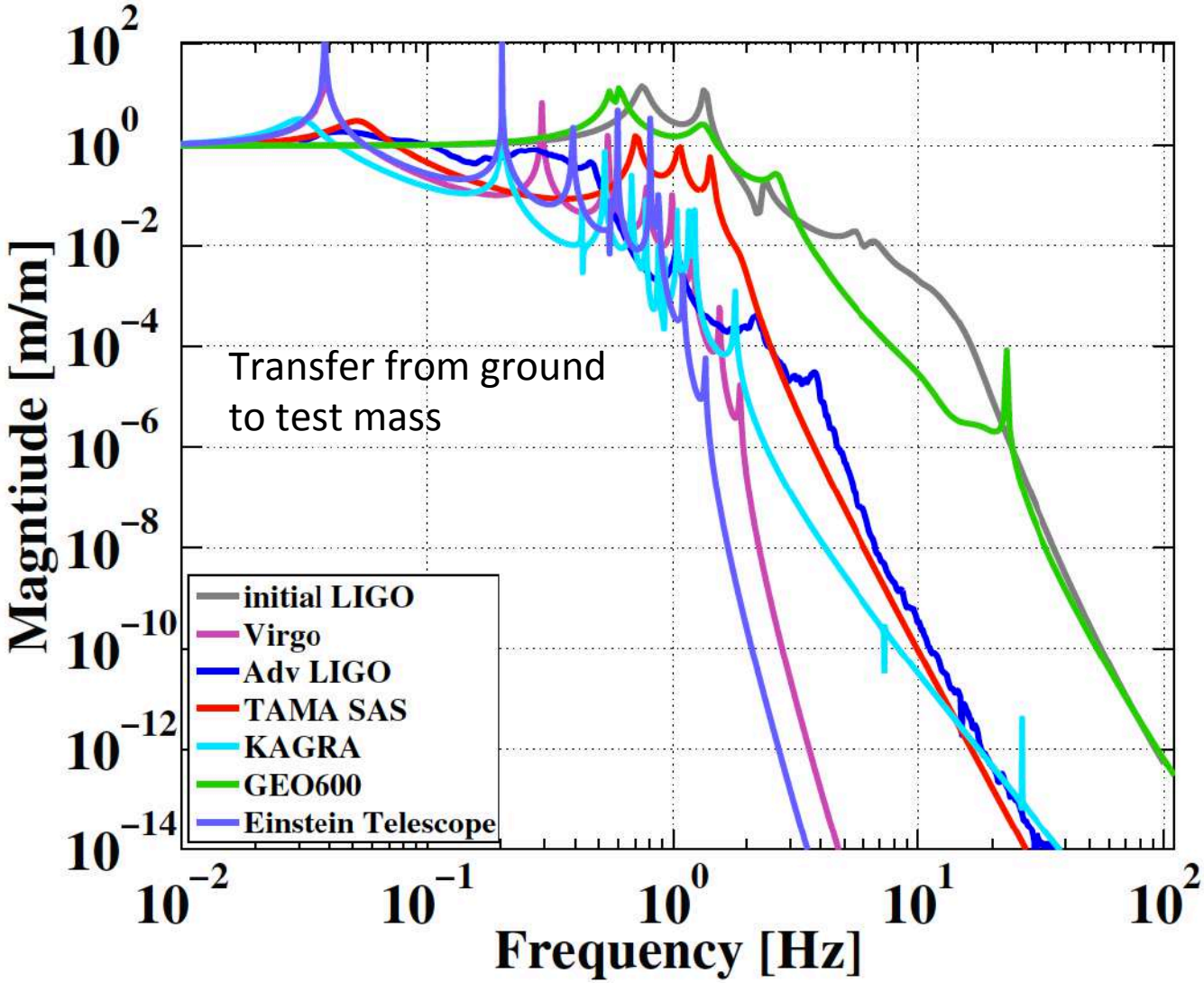
Fabrice Matichard, LIGO P1400061

2. Tilt substraction



Krishna Venkateswara, BSSA 107(3) 2017

Transfer function comparison



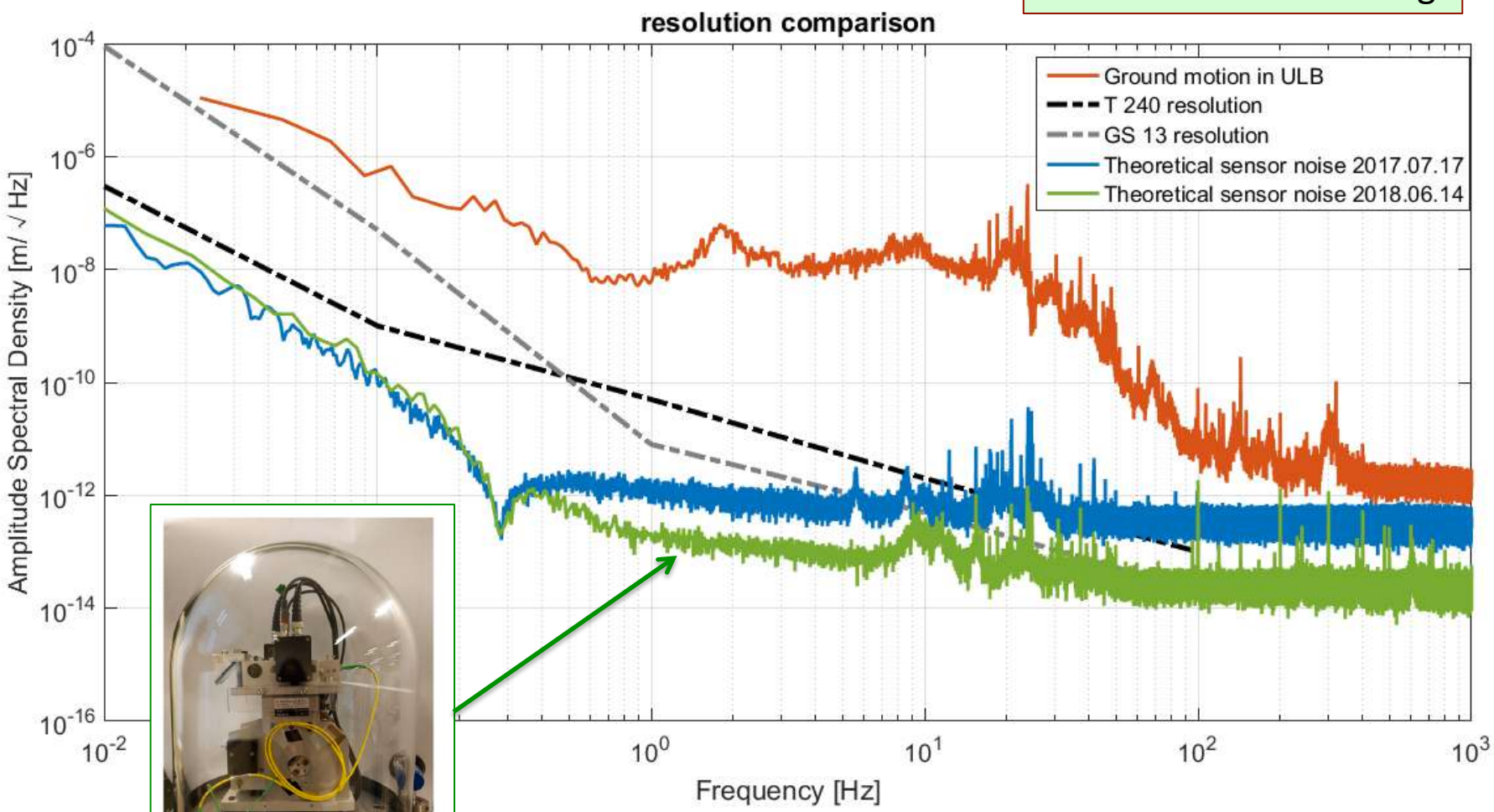
R. Adhikari, Gravitational Radiation Detection with Laser Interferometry (2014).

OBSERVATOIRE ROYAL
DE BELGIQUE
Séismologie-Gravimétrie

Dr. M. Van Camp

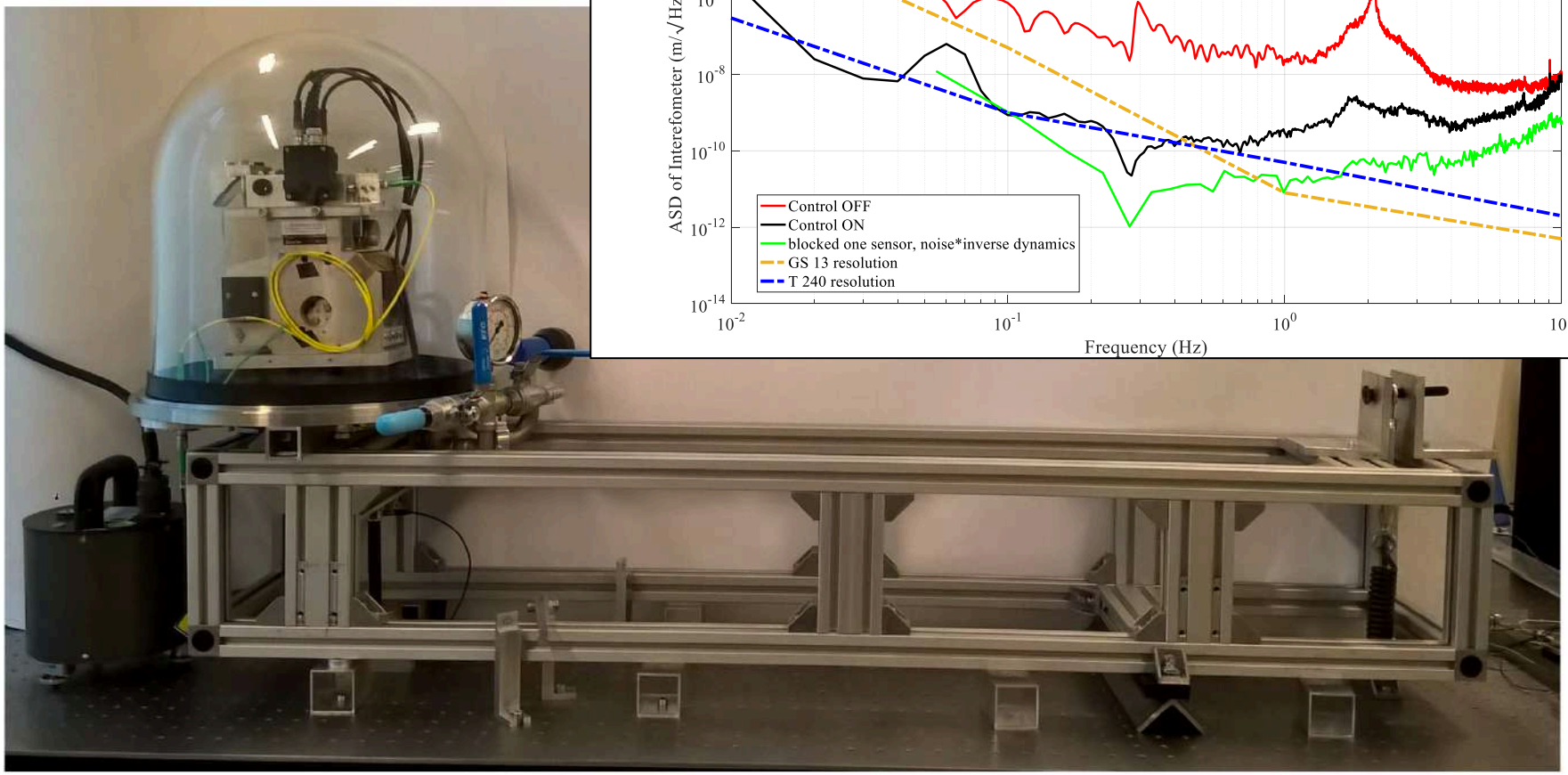
Optical inertial Sensor

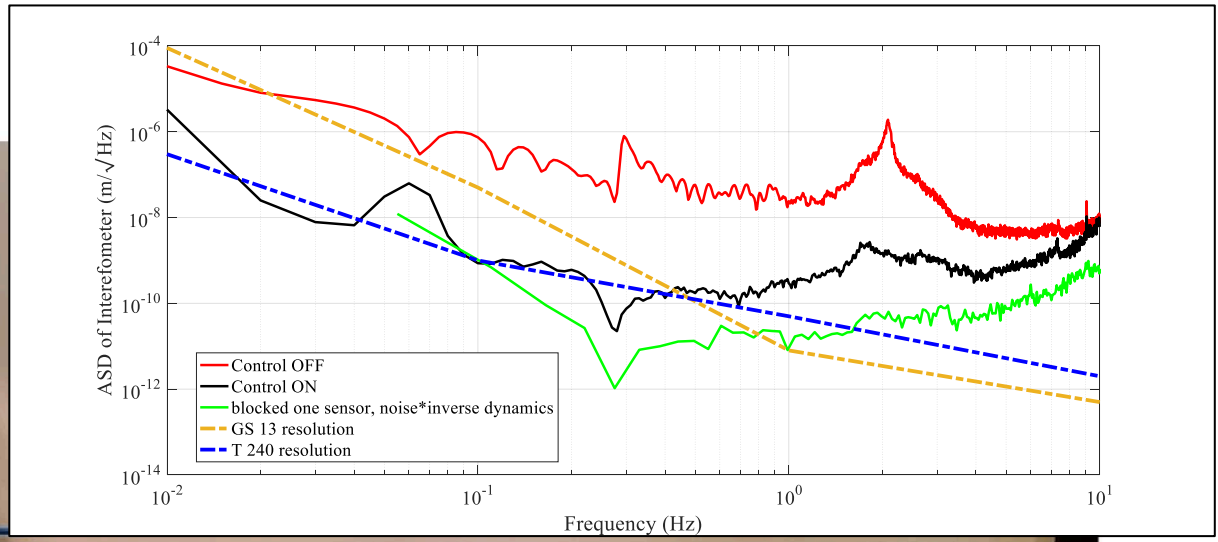
PhD thesis of Binlei Ding



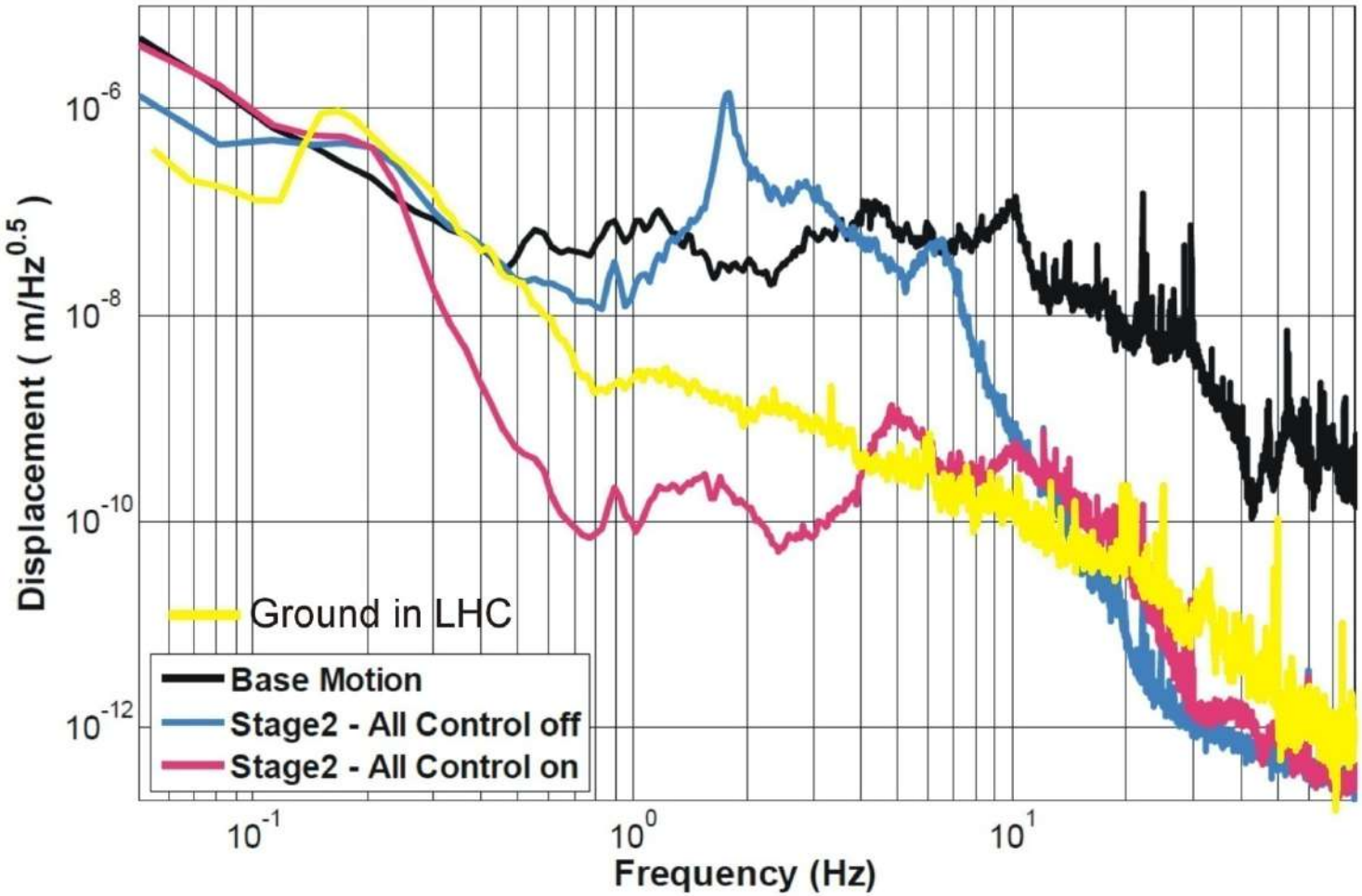
Active vibration isolation system

Guoying Zhao, Jennifer Watchi

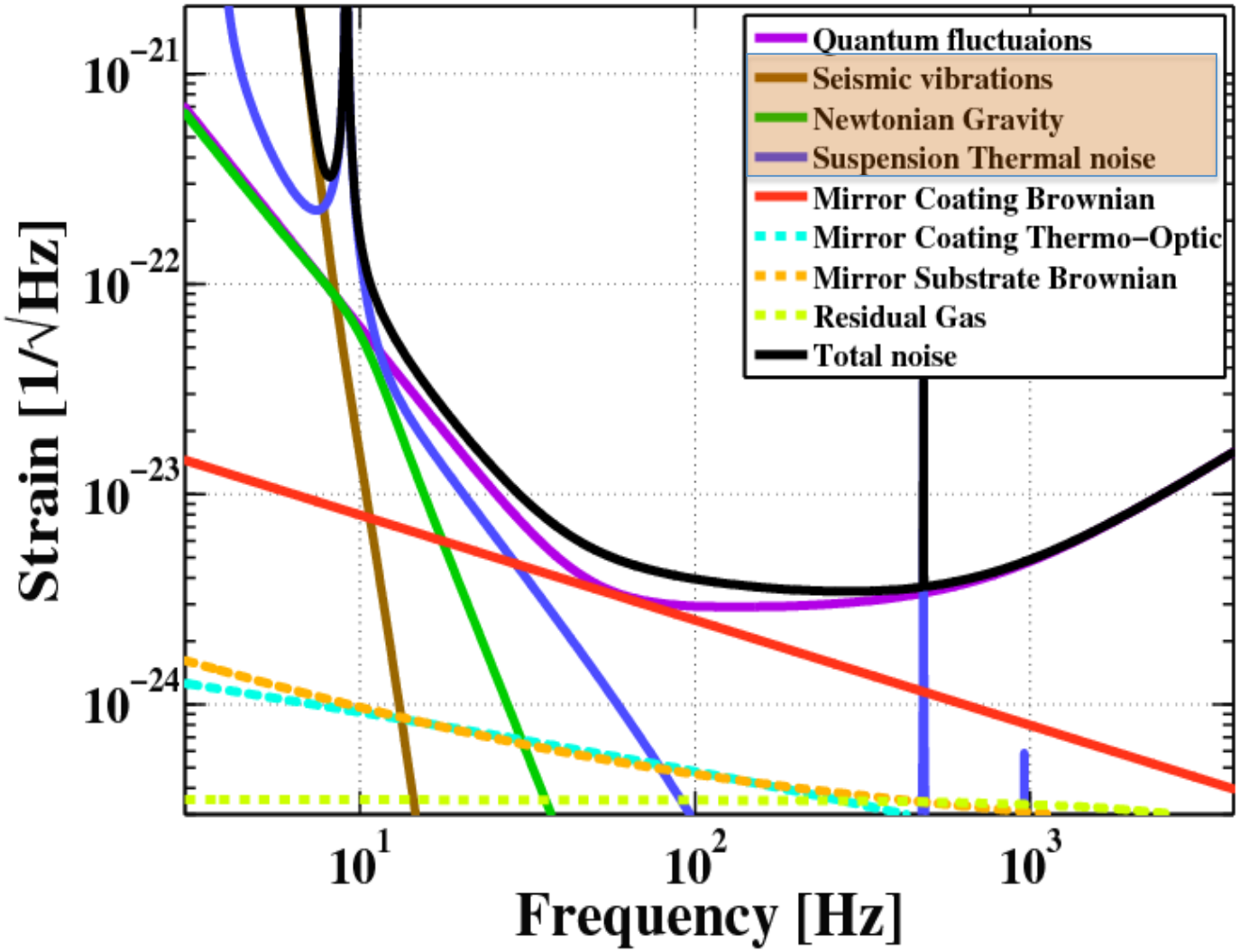




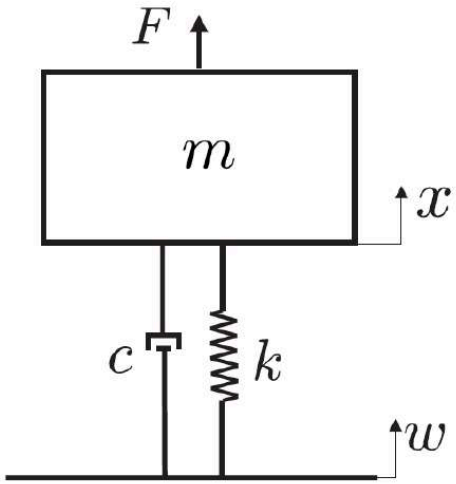
LIGO / LHC comparison



aLIGO noise budget



Thermal noise



Can be modelled by a random force whose spectral density is :

$$\Phi_F(f) = 4k_B T c (N^2/\mathrm{Hz})$$

Power spectral density of suspended mass acceleration:

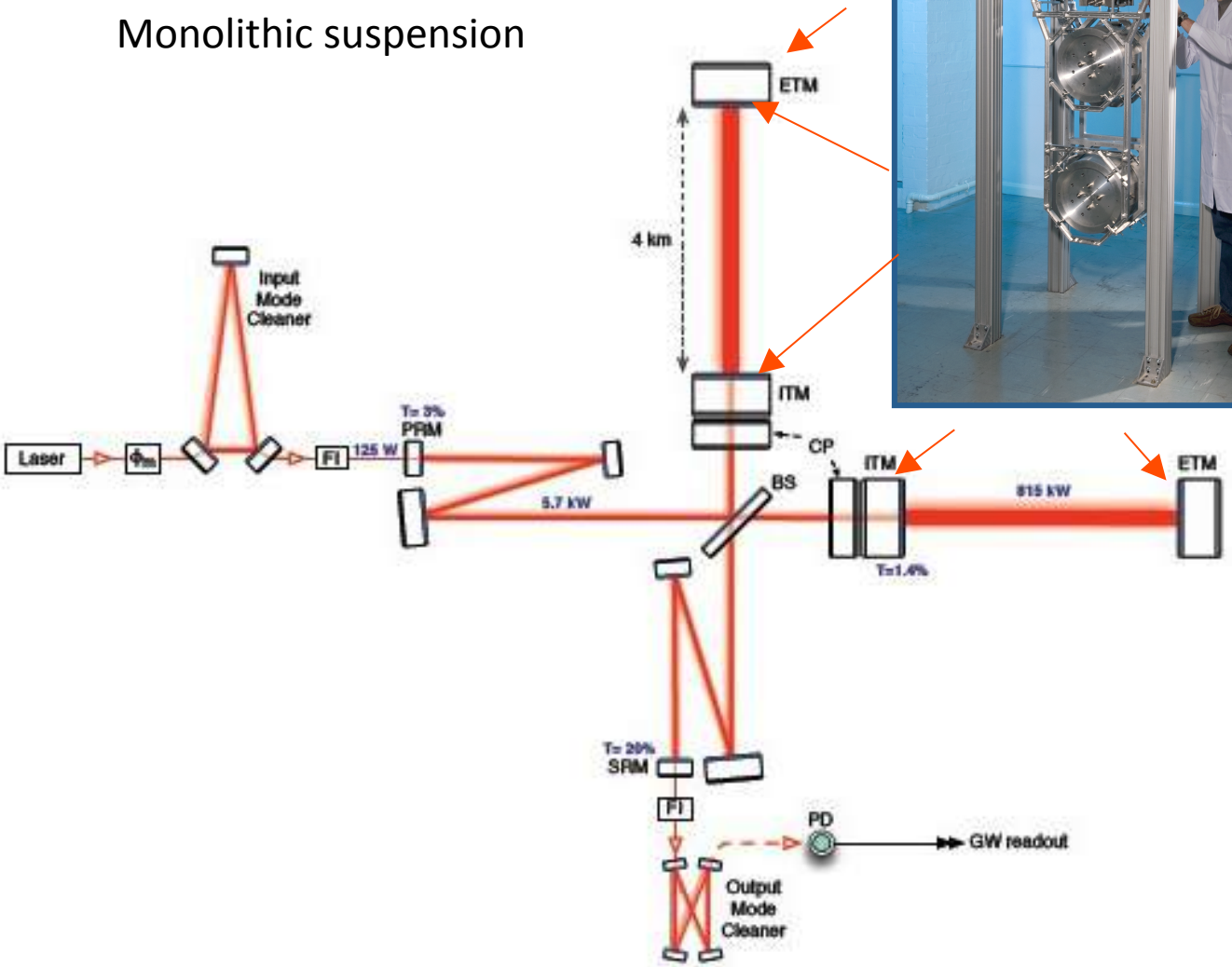
$$\Phi_B(f) = \frac{f^4}{(f_0^2 - f^2)^2 + (2\xi f_0 f)^2} \frac{16\pi k_B T \xi f_0}{m} (\mathrm{m/s^2})^2/\mathrm{Hz}$$

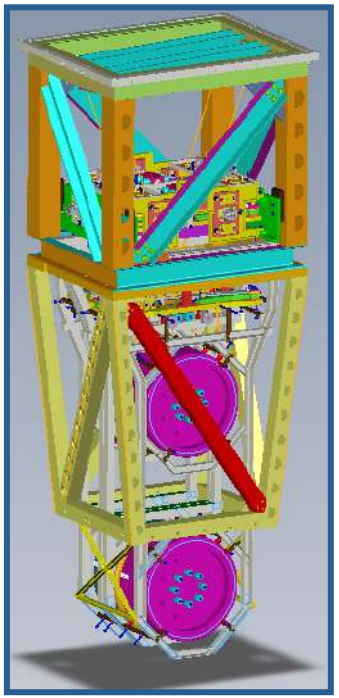
For example, taking $\xi = 0.7$, $T = 300$ k, $M = 10$ gr, $f_0 = 1$ Hz

$\Phi_B(f) = 7.3 \times 10^{-17} (\mathrm{m/s^2})^2/\mathrm{Hz}$ RMS value : 0.02 nm !

Thermal noise

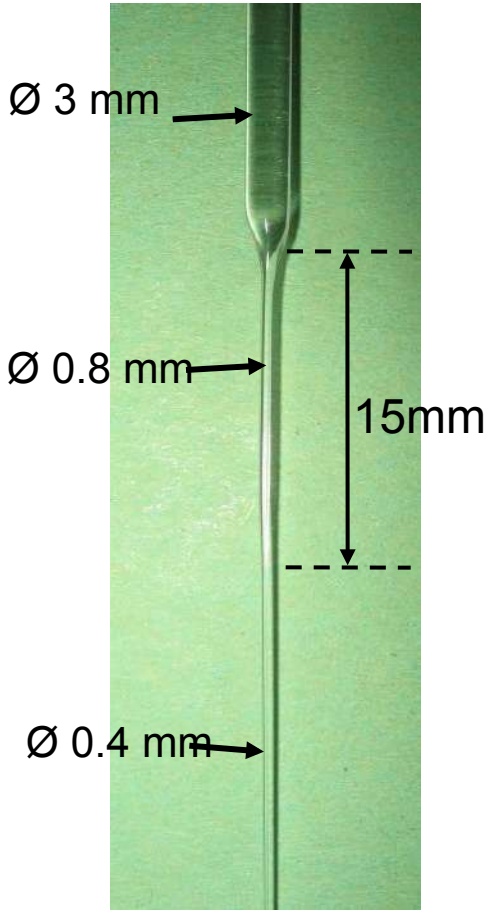
Monolithic suspension



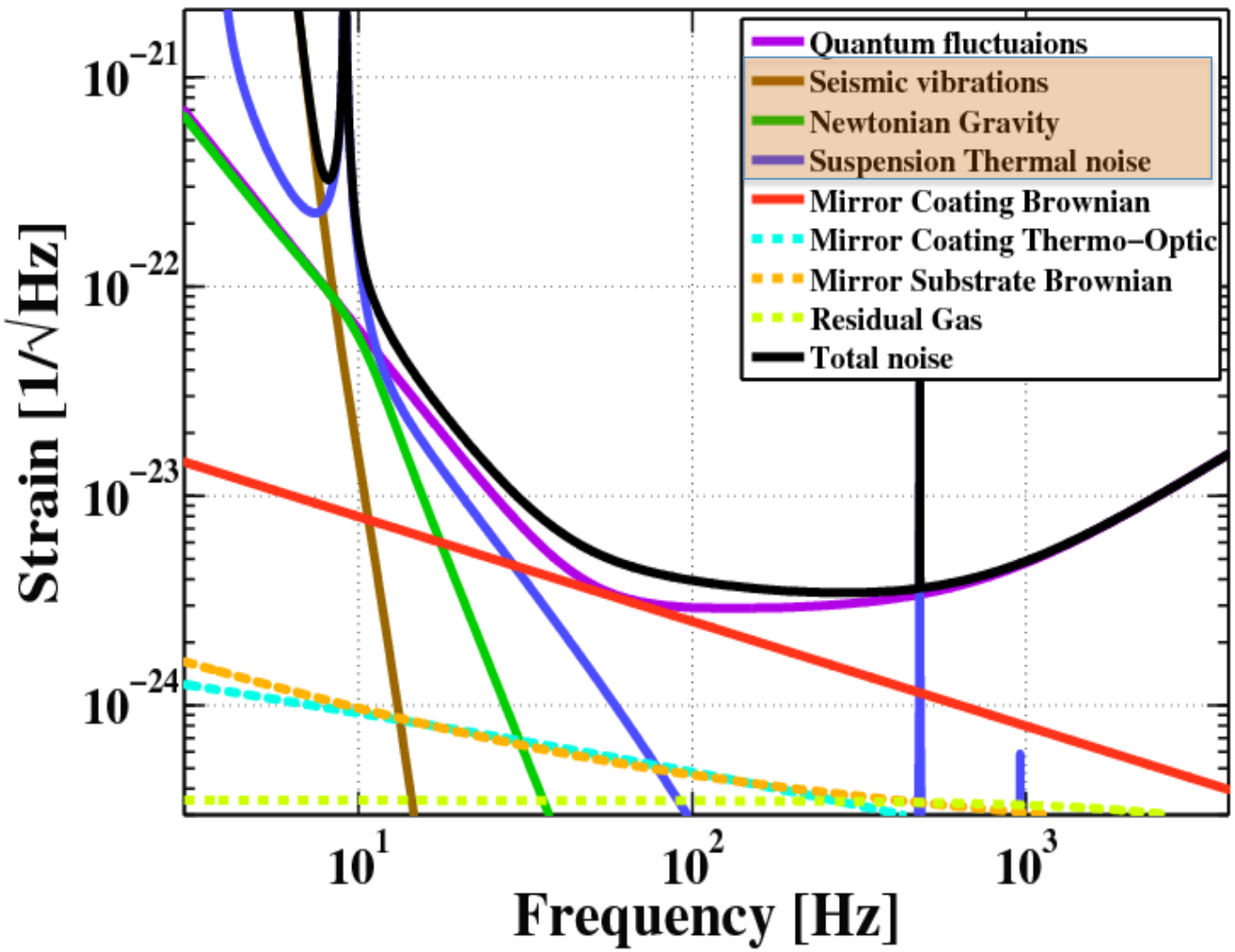


Thermal noise

- Thermal noise reduction: monolithic fused silica suspension as final stage
- - low pendulum thermal noise and preservation of high mirror quality factor :
  - *silica fibre loss angle ~ $3 \cdot 10^{-7}$,*
  - *c.f. steel ~$2 \cdot 10^{-4}$*

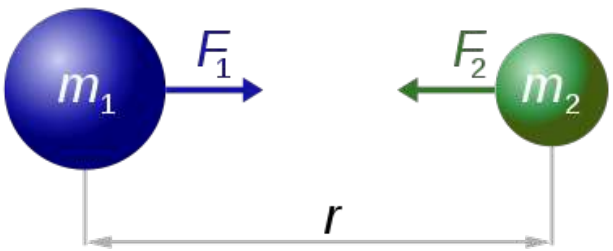


aLIGO noise budget



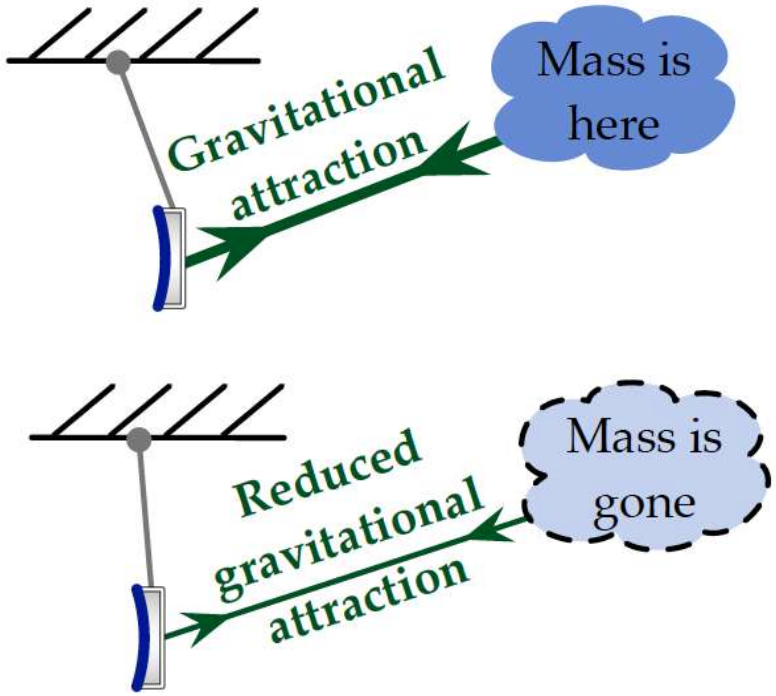
Newtonian noise

Universal law of gravitation :

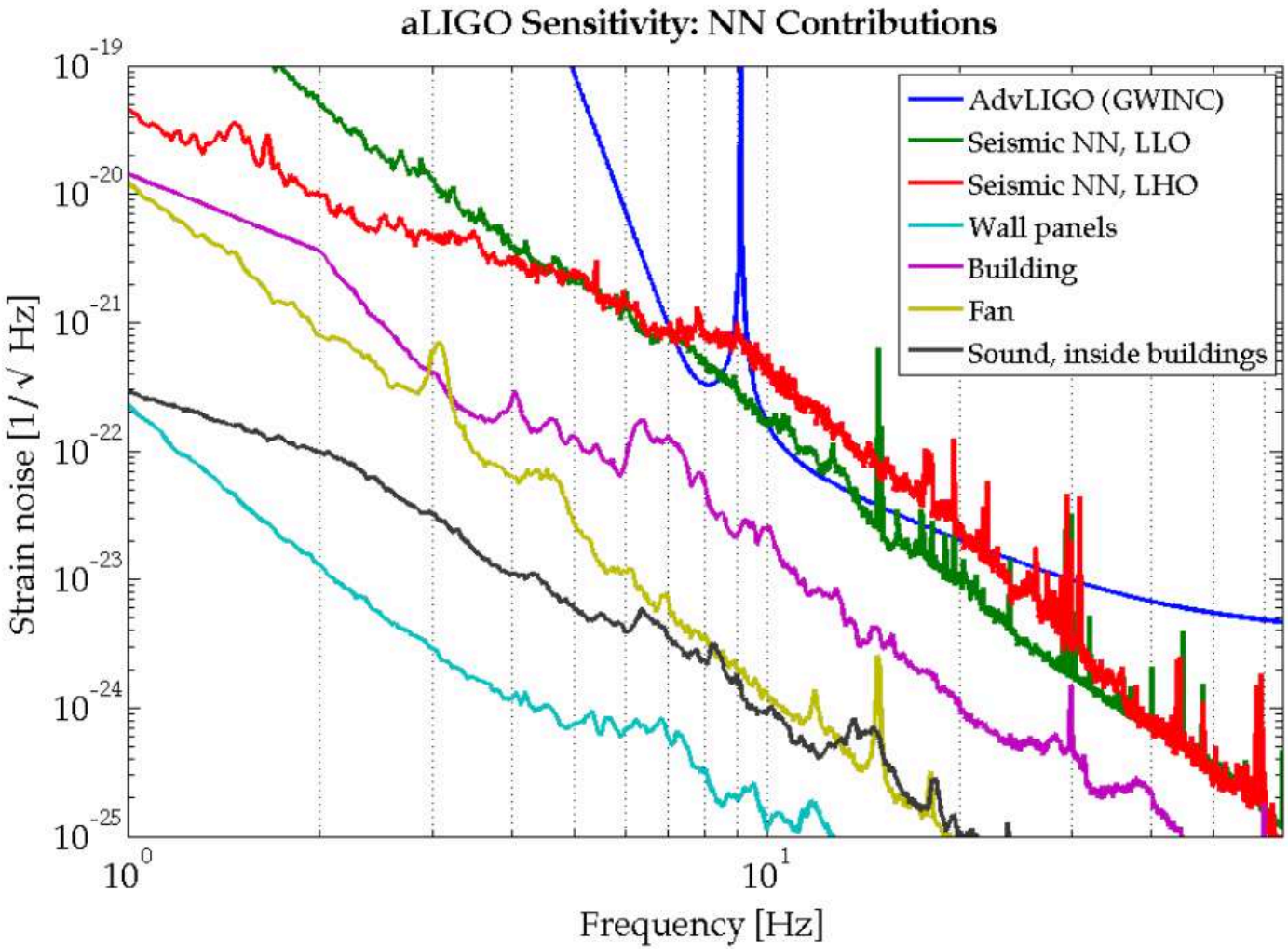


$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

G=6.67 10^{-11} N.(m/kg)^2



Newtonian noise

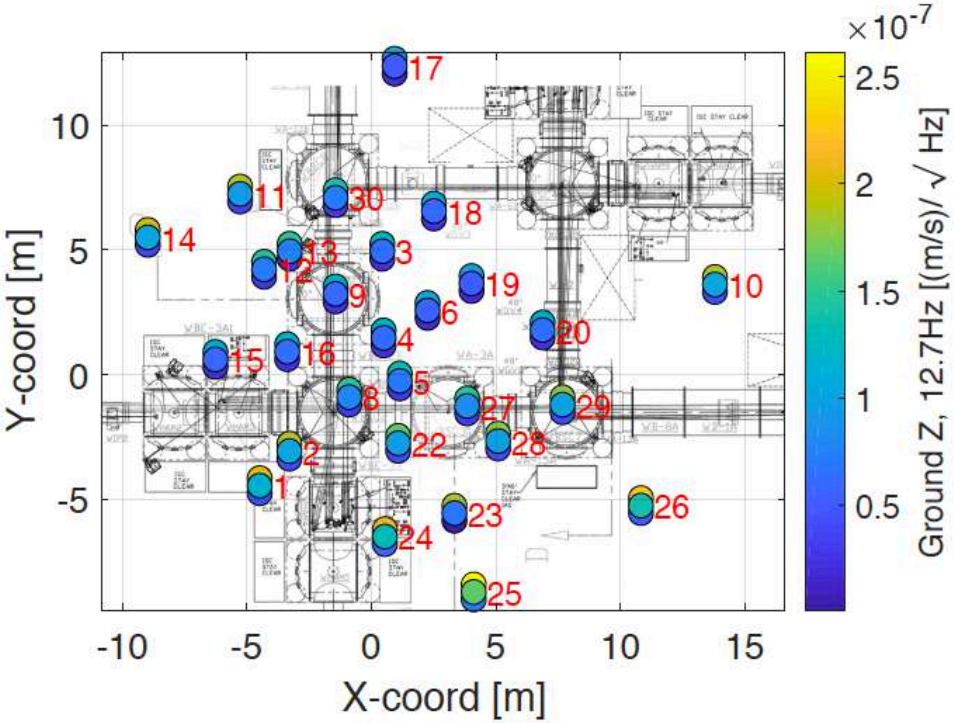


Impossible to “shield” !

Newtonian noise

Solution 1 : seismic sensor arrays

➔ Measure seismic field
➔ Calculate gravitational field
➔ Estimate the resulting motion
➔ Substract it with feedforward

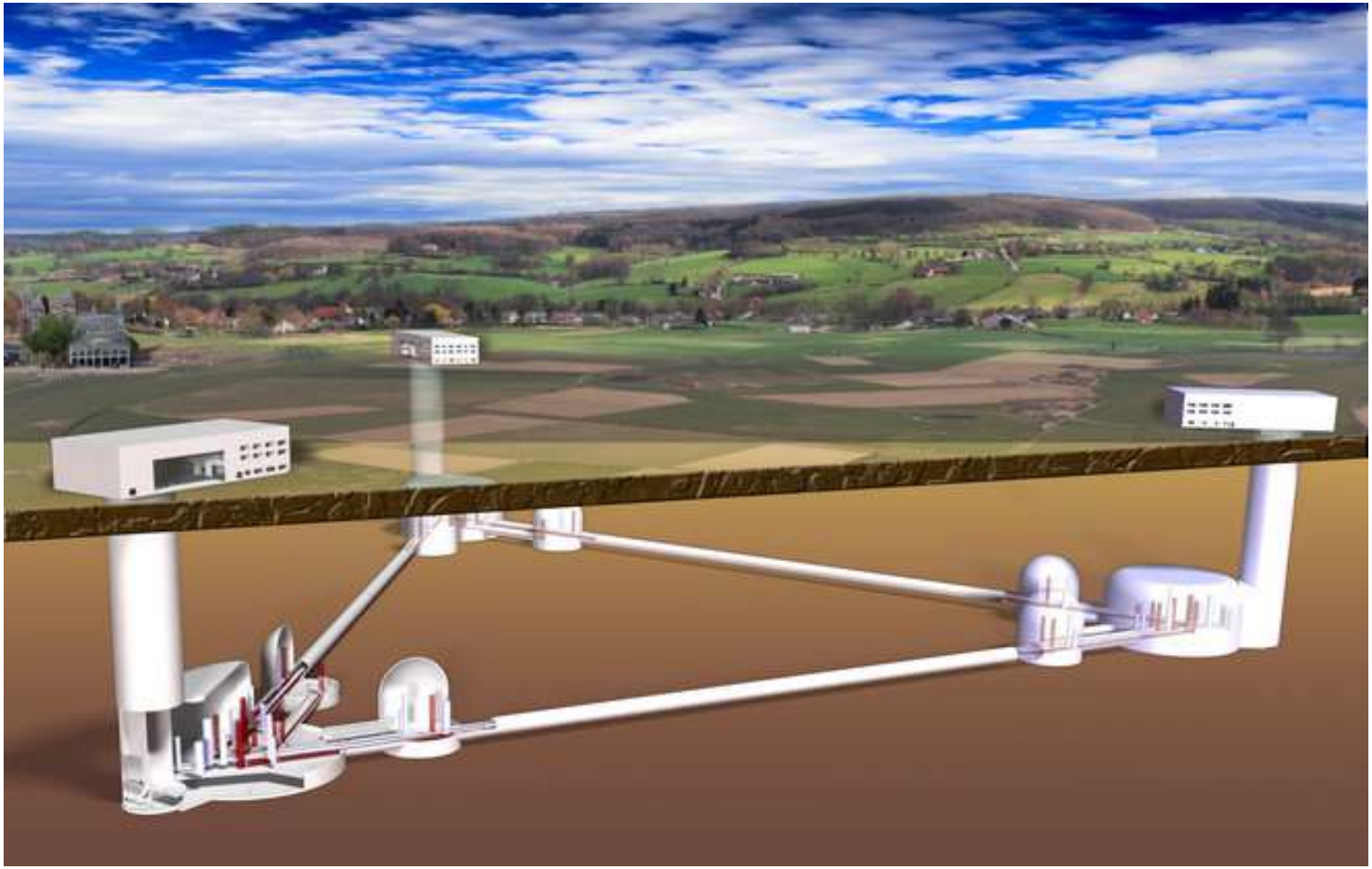


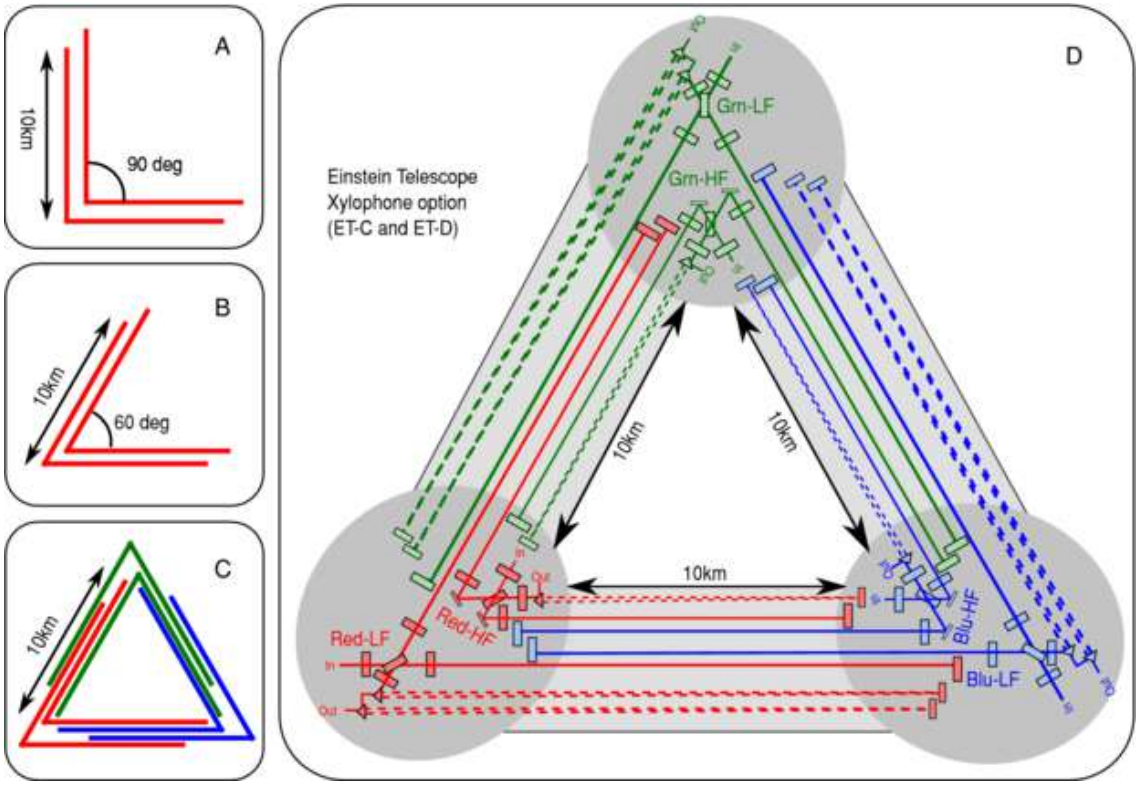
Solution 2: detector underground

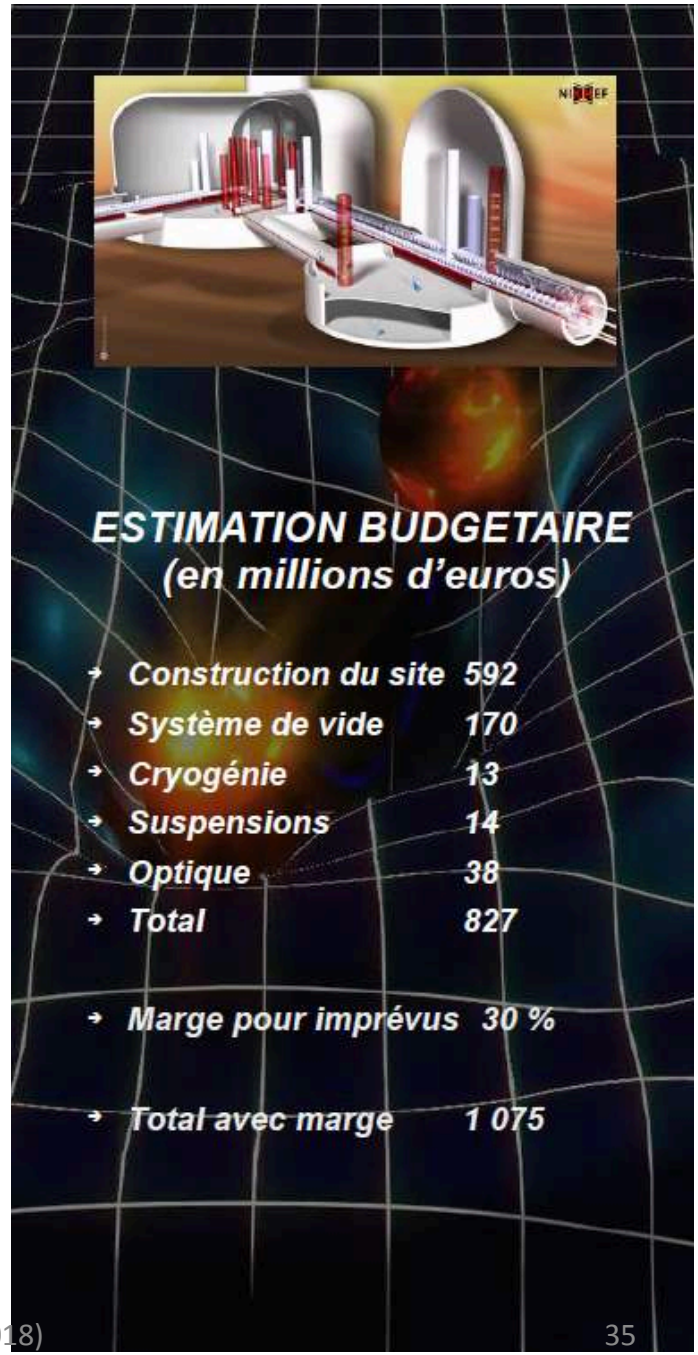
Detectors of 3rd generation :

- Reduce thermal noise
  - Heavy mirror, low dissipation, low frequency
  - Cryogenic temperature
- Improve seismic isolation at low frequency
  - Active seismic isolation
- Newtonian noise reduction
  - Build detector underground
- Increase strain sensitivity
  - Longer arms

Einstein Telescope: 100 000 détections par an !

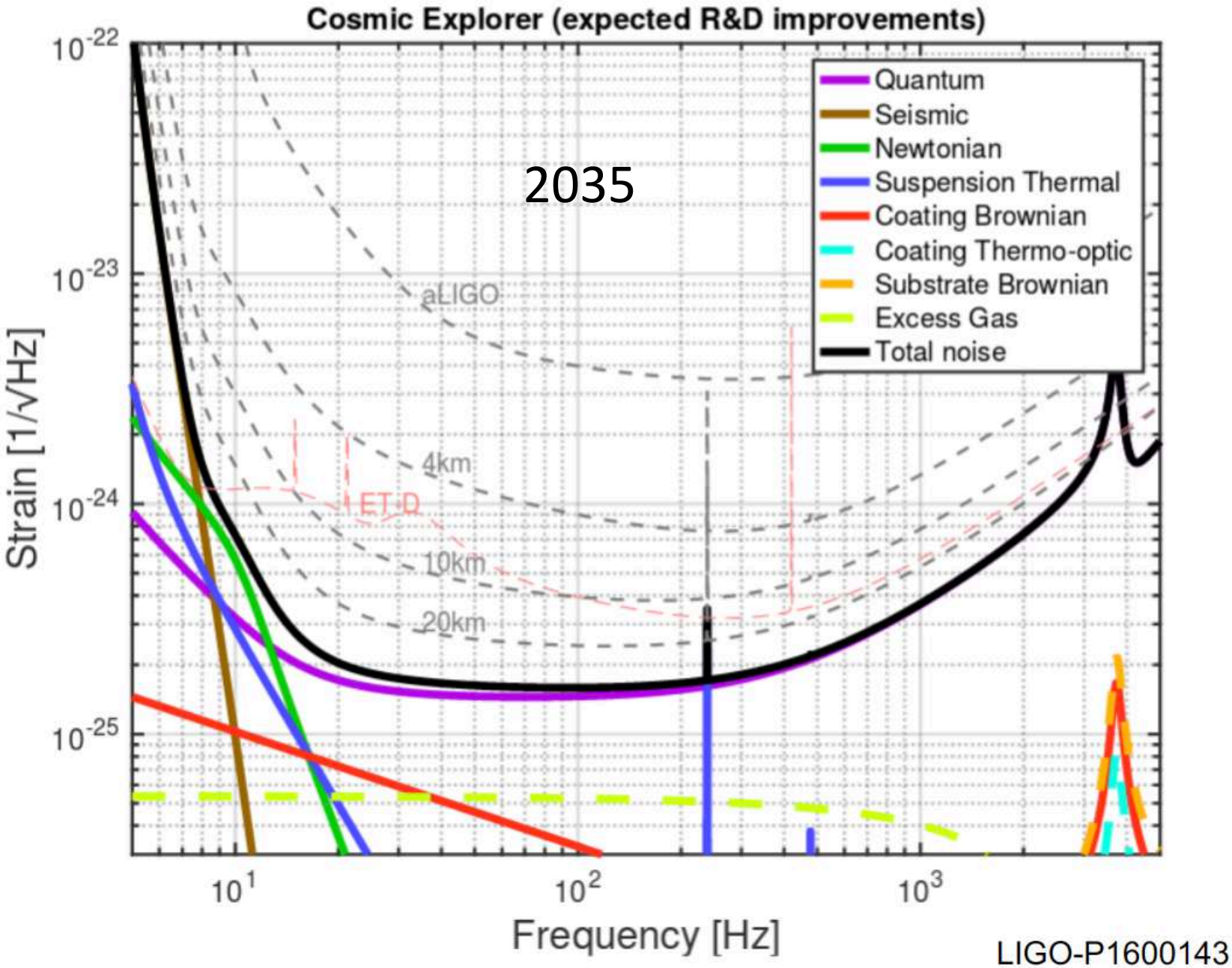






Features:

- 6 interferometers
- 10 km long
- Large mirrors
- Cryogenic temperature


Cosmic Explorer (expected R&D improvements)
2035
Quantum
Seismic
Newtonian
Suspension Thermal
Coating Brownian
Coating Thermo-optic
Substrate Brownian
Excess Gas
Total noise
aLIGO
4km
ET-D
10km
20km
Strain [1/√Hz]
Frequency [Hz]
LIGO-P1600143

3 sites en compétition

Euregio / Sardaigne / Hongrie / …

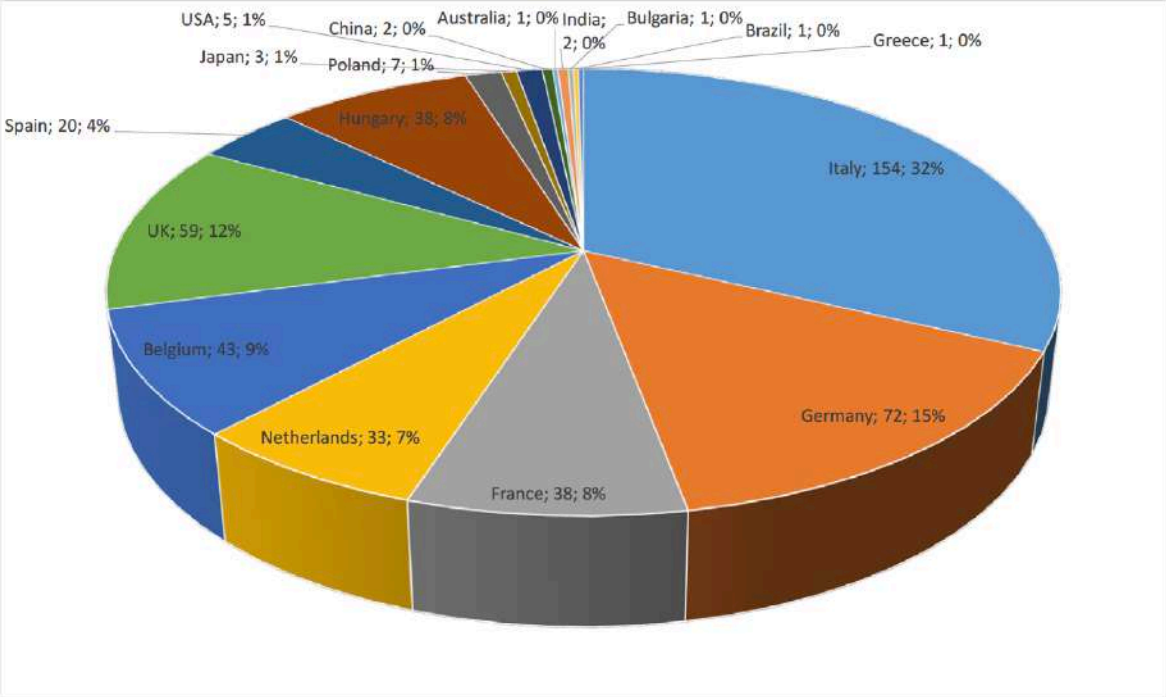
More on Einstein Telescope

- Conceptual Design Report:

https://tds.virgo-gw.eu/?content=3&r=8709

- Letter of intent:

http://www.et-gw.eu/index.php/letter-of-intent



innoviris .brussels
empowering research

fnrs
LA LIBERTÉ DE CHERCHER