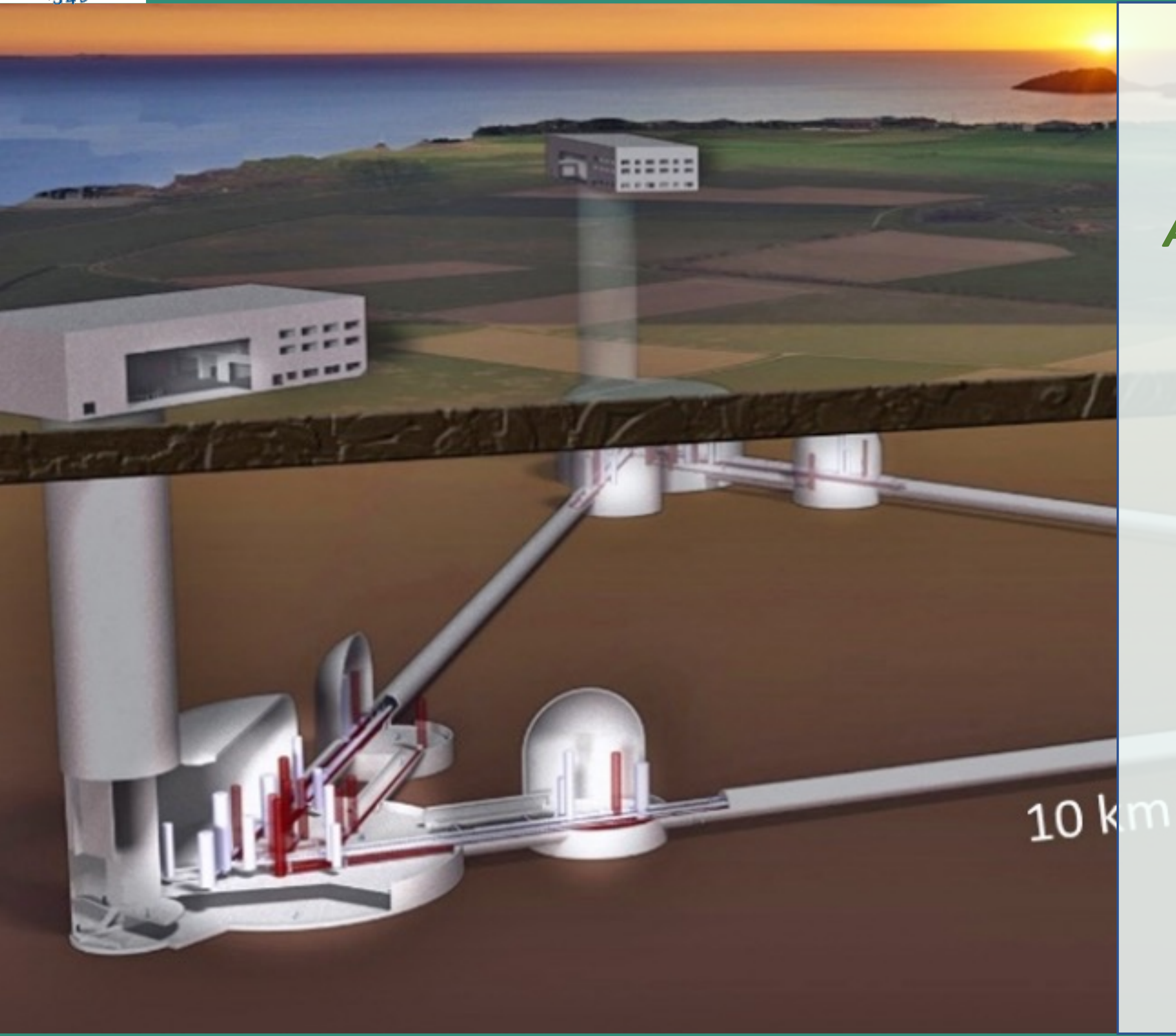


Improving Low-frequency sensitivity of GW detectors:

A new compact seismic attenuation system for the Einstein Telescope

M. Razzano, F. Fidecaro, M. Baratti, L. Bellizzi, A. Fiori, F. De Santi, L. Muccillo, M. A. Palaia, L. Papalini, M. Vacatello

University of Pisa & INFN-Pisa

17th Marcel Grossmann Meeting

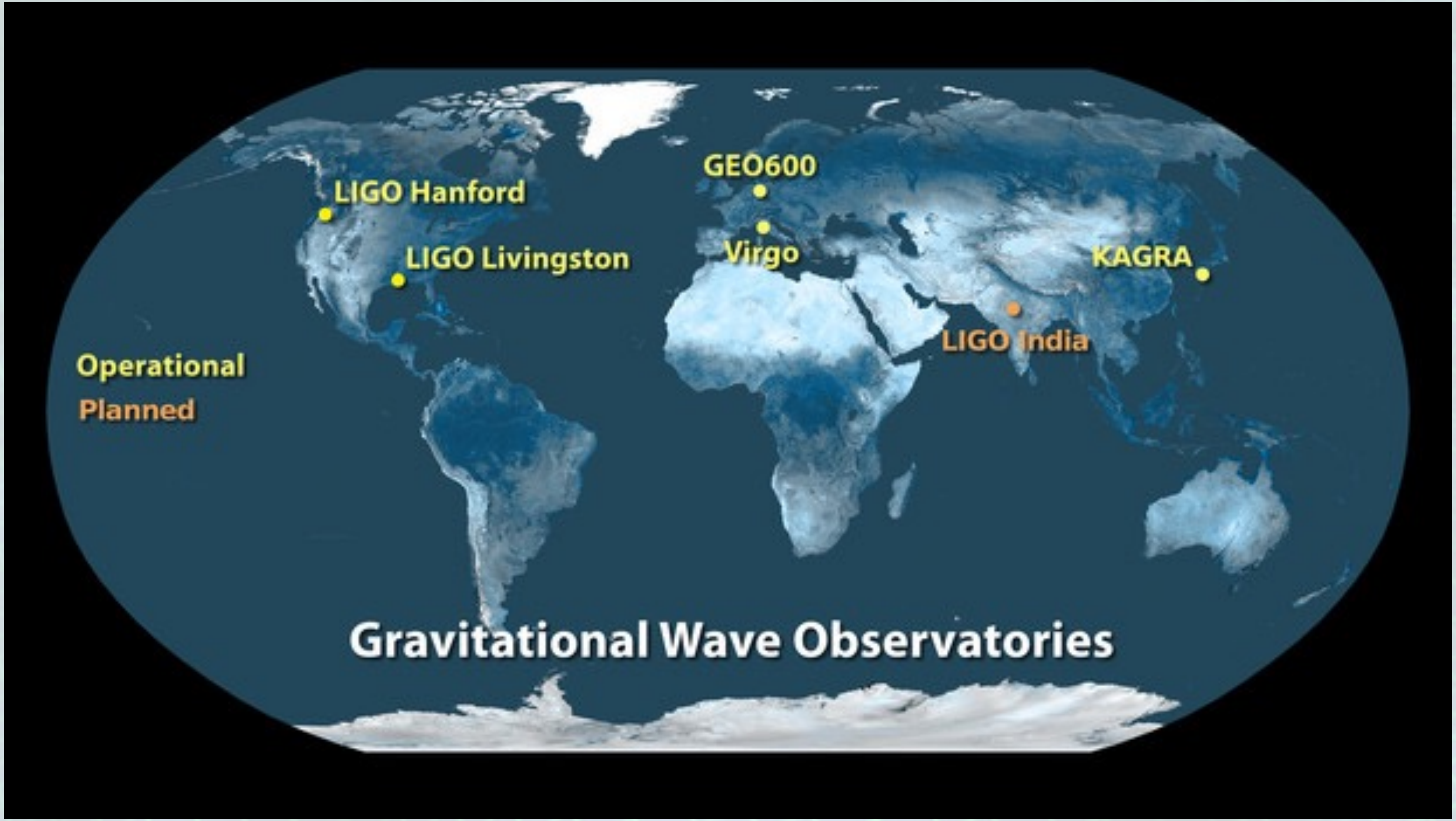
Pescara, 7 -12 July 2024

BHETSA

Black Holes for ET in SArdinia

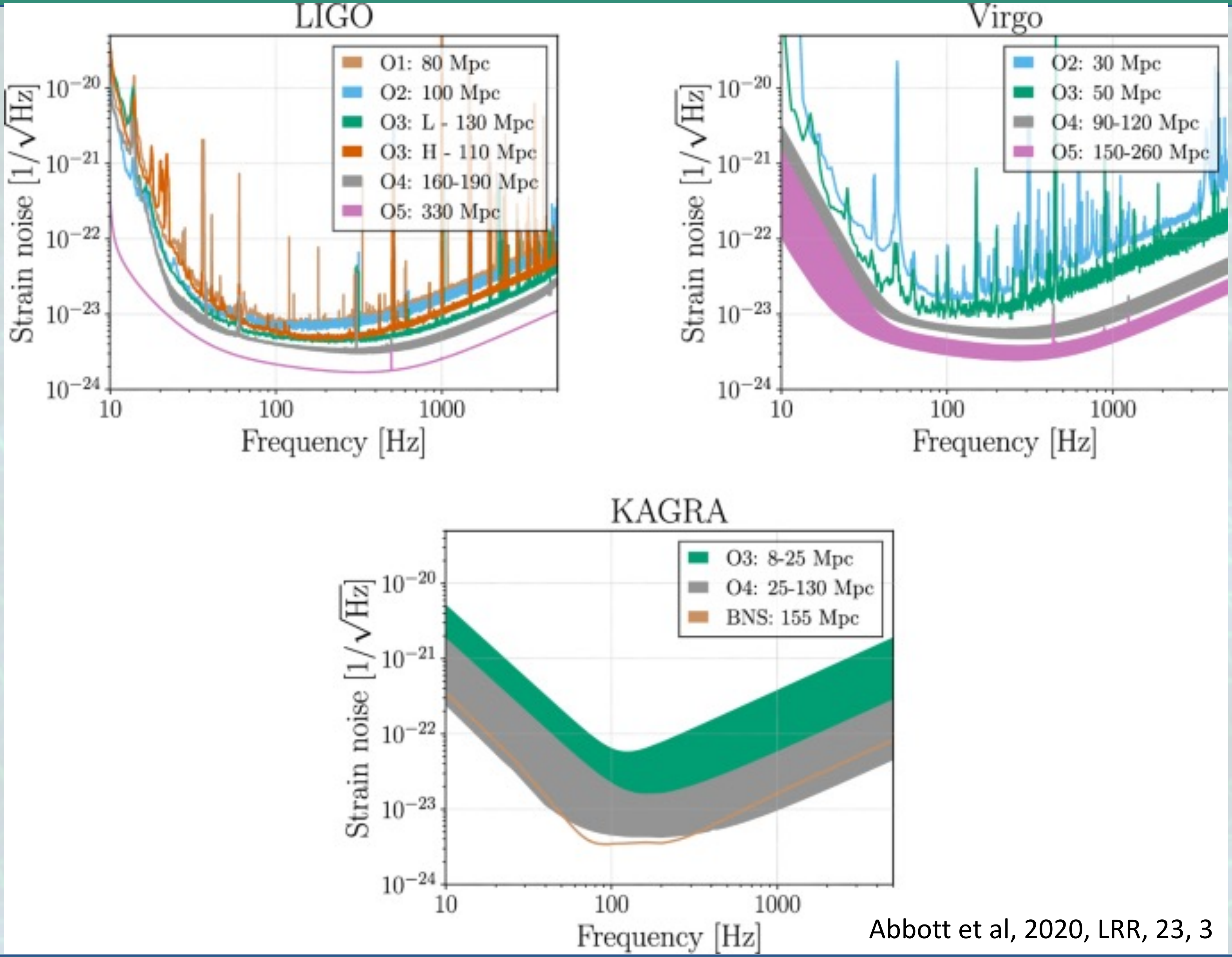
Istituto Nazionale di Fisica Nucleare

The era of gravitational waves



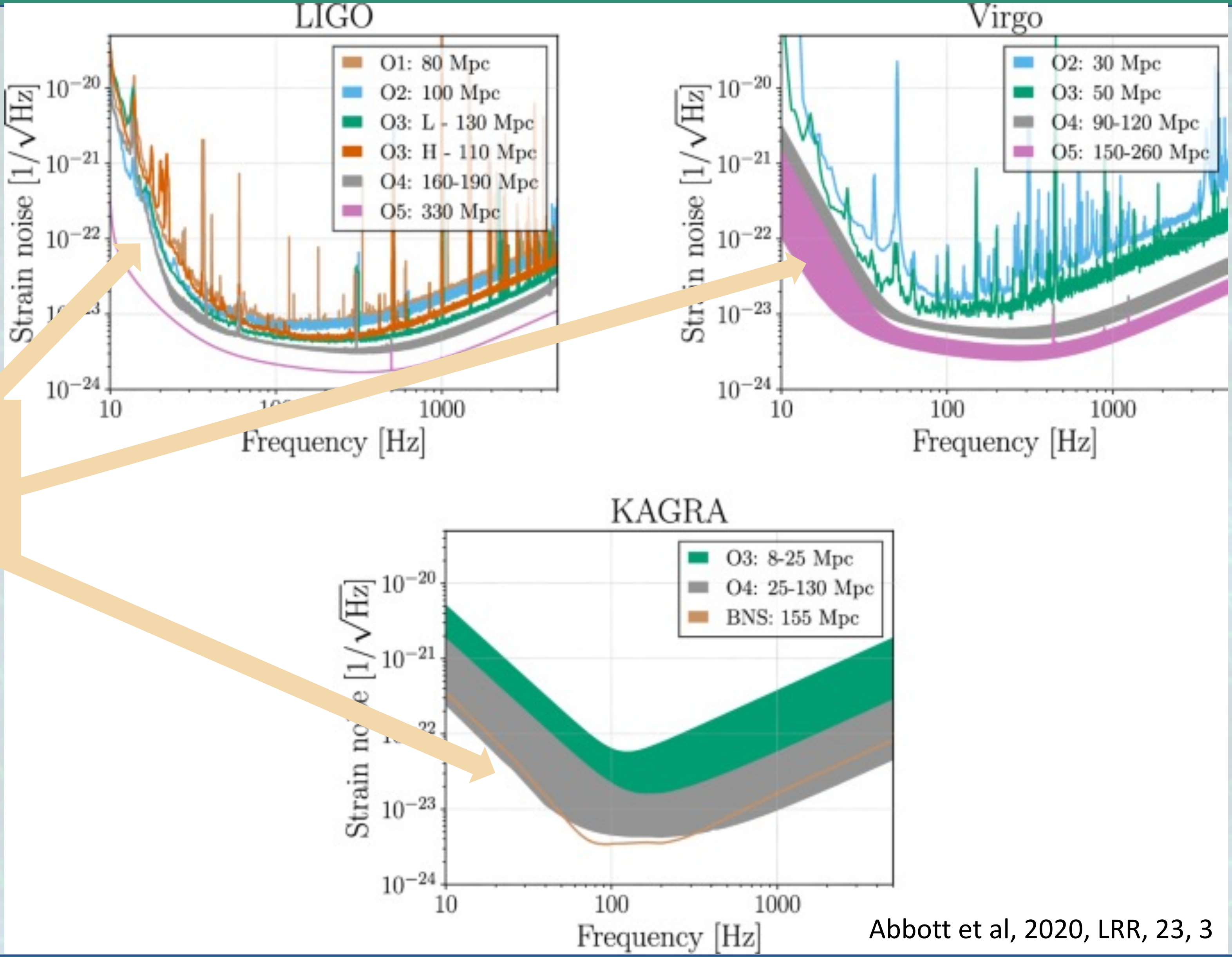
Credits: Caltech/MIT/LIGO Lab

Sensitivity curve



Abbott et al, 2020, LRR, 23, 3

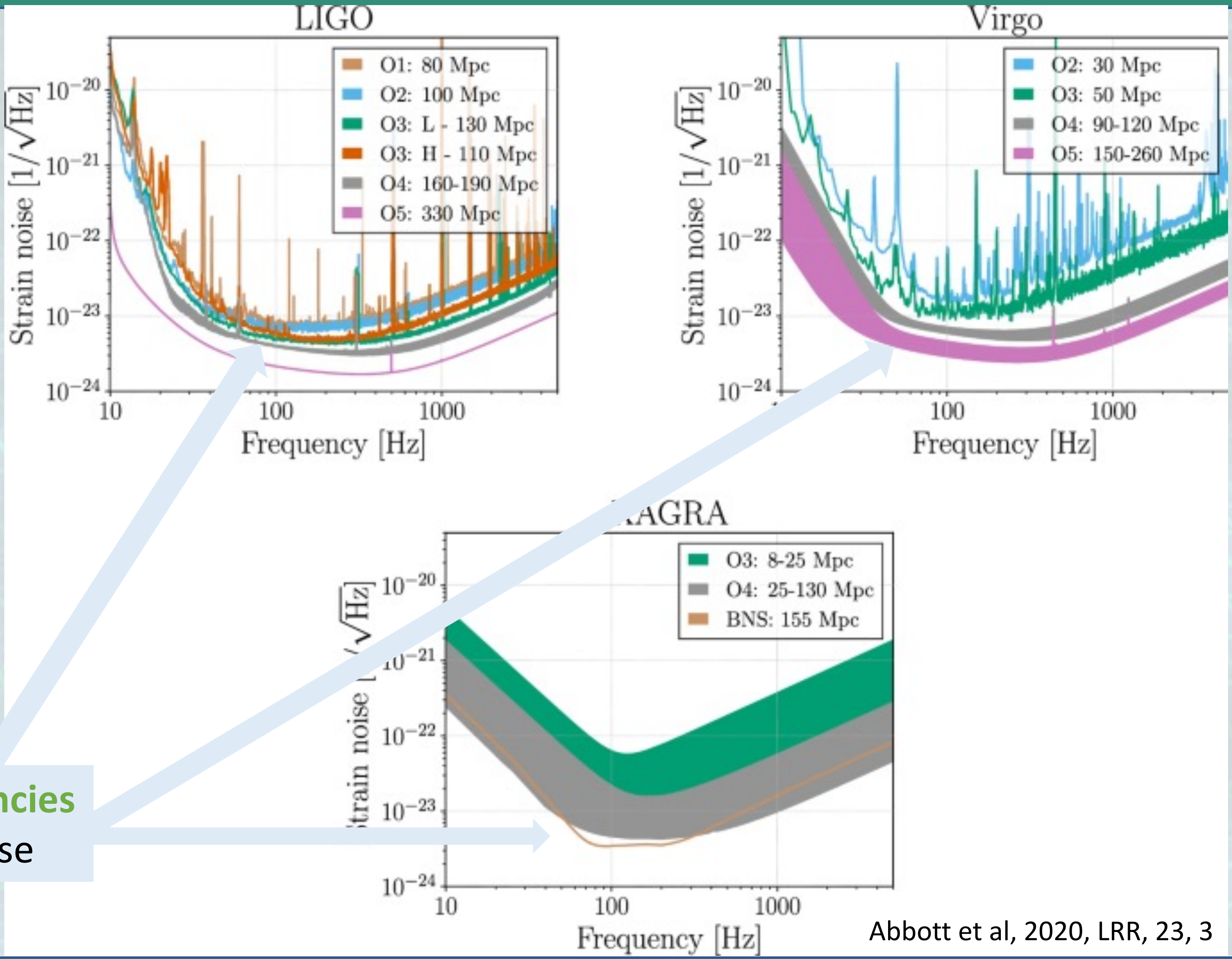
Sensitivity curve



Low Frequencies
Seismic & Newtonian Noise

Abbott et al, 2020, LRR, 23, 3

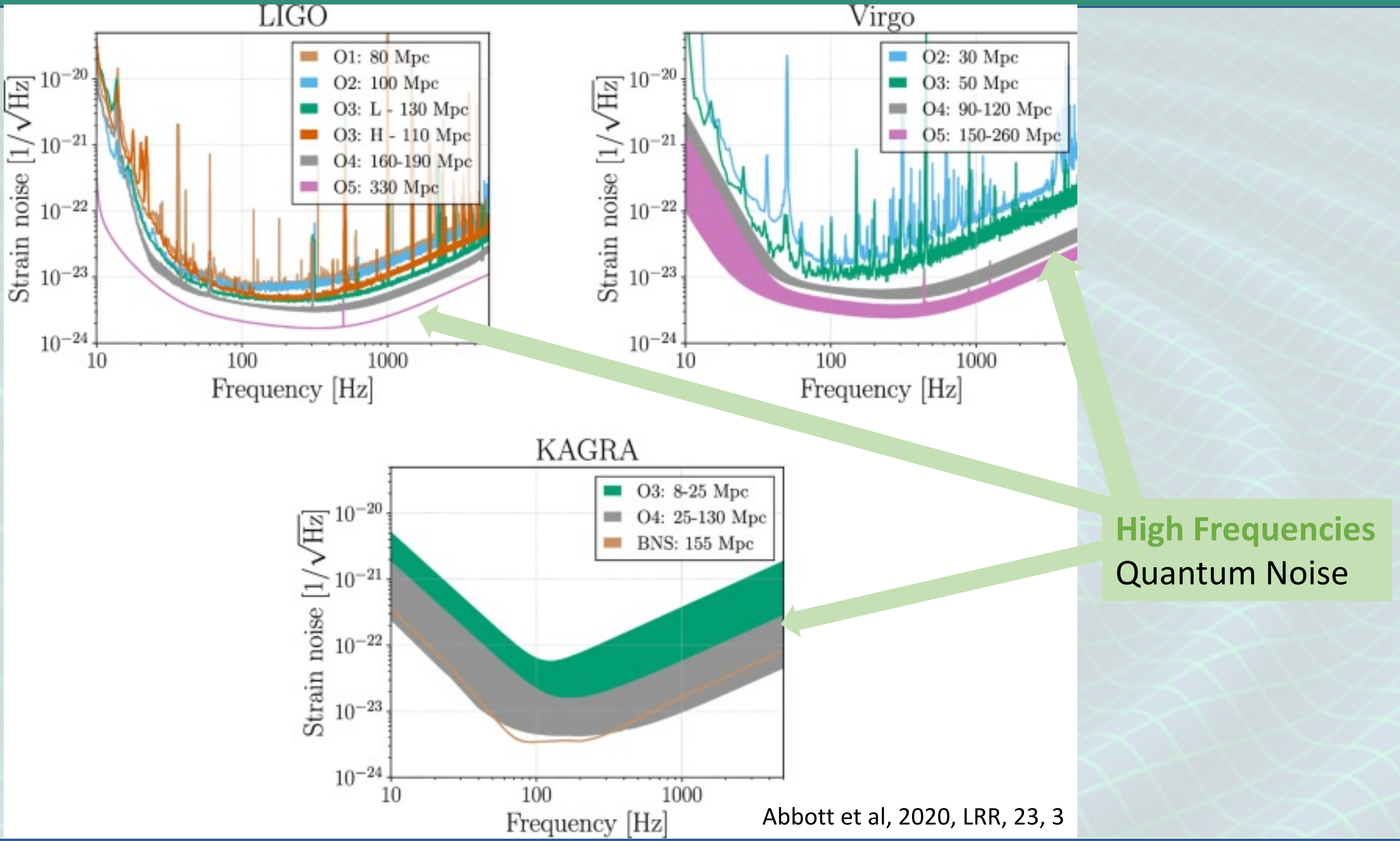
Sensitivity curve



Abbott et al, 2020, LRR, 23, 3

Mid Frequencies
Thermal Noise

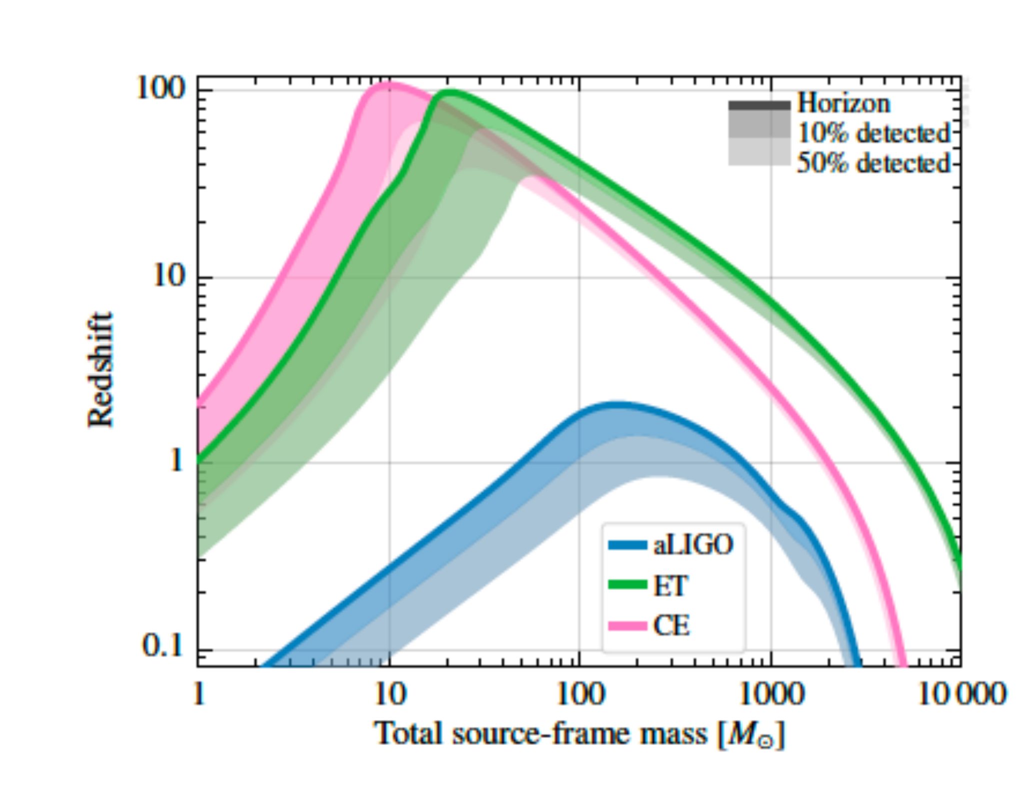
Sensitivity curve



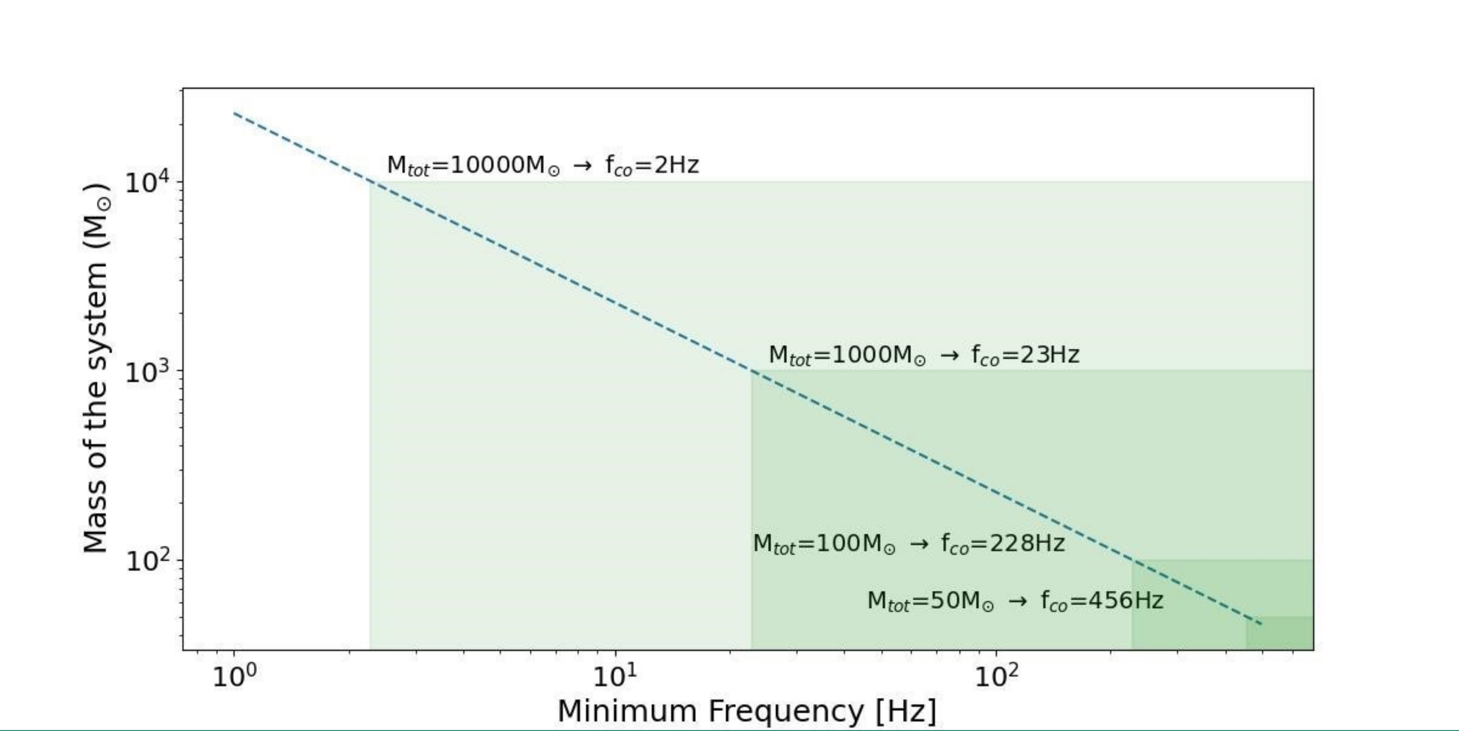
Abbott et al, 2020, LRR, 23, 3

LF science cases: high-mass black holes

- **Black hole physics**
  - High-mass binary black holes **∝ f^{-1}**
  - $M_{obs} = (1+z)M_{src}$ → high-z black holes
  - Higher Signal-to-noise ratio
  - Characterize the BH population



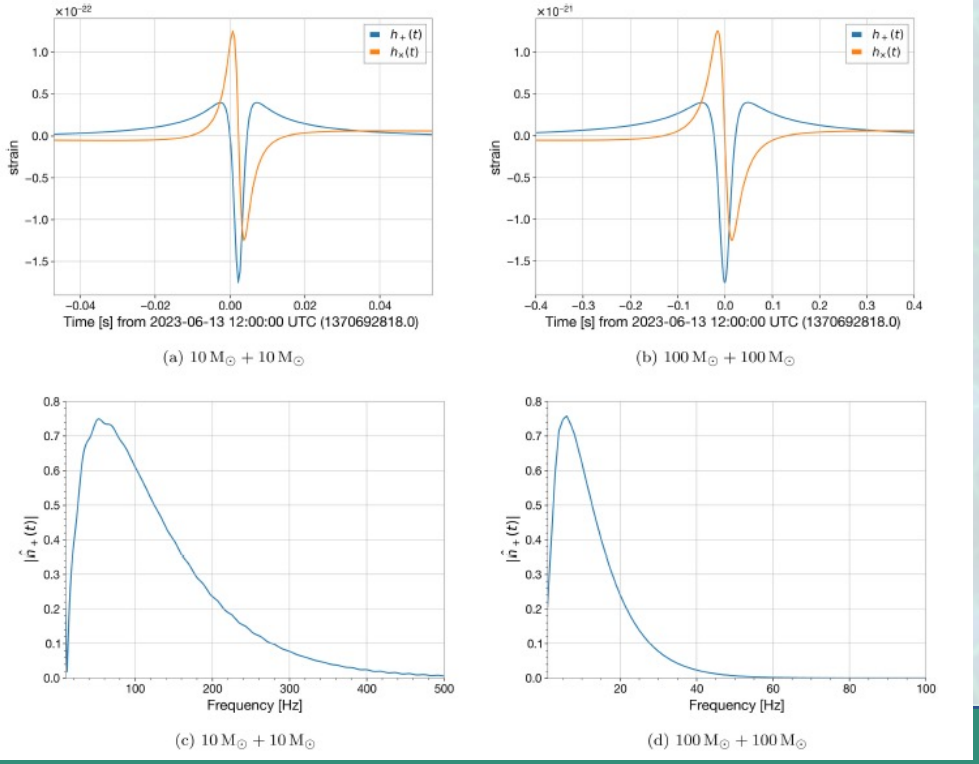
Maggiore et al, 2020, JCAP, 03, 50

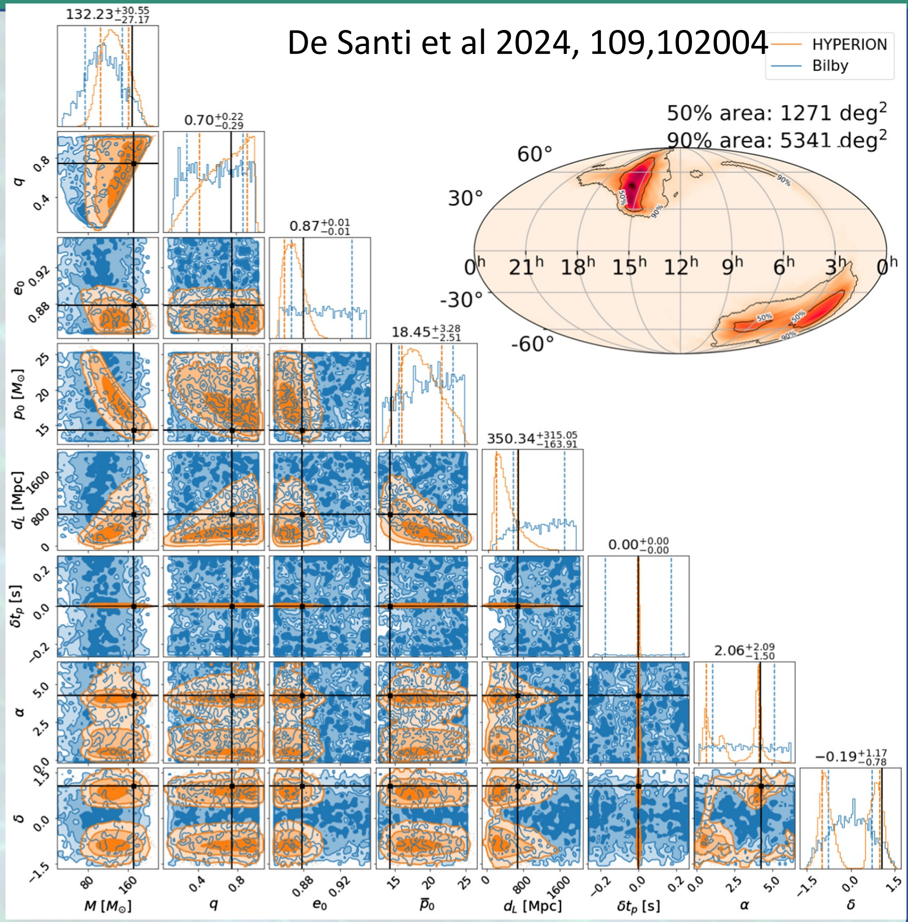


LF science case: close encounters

- **Main Features**
  - Hints of a dynamical formation channel
  - N-body interactions
  - F-modes excitations in neutron stars: EoS studies
  - Single or multi-burst expected emission

De Santi et al 2024, 109,102004

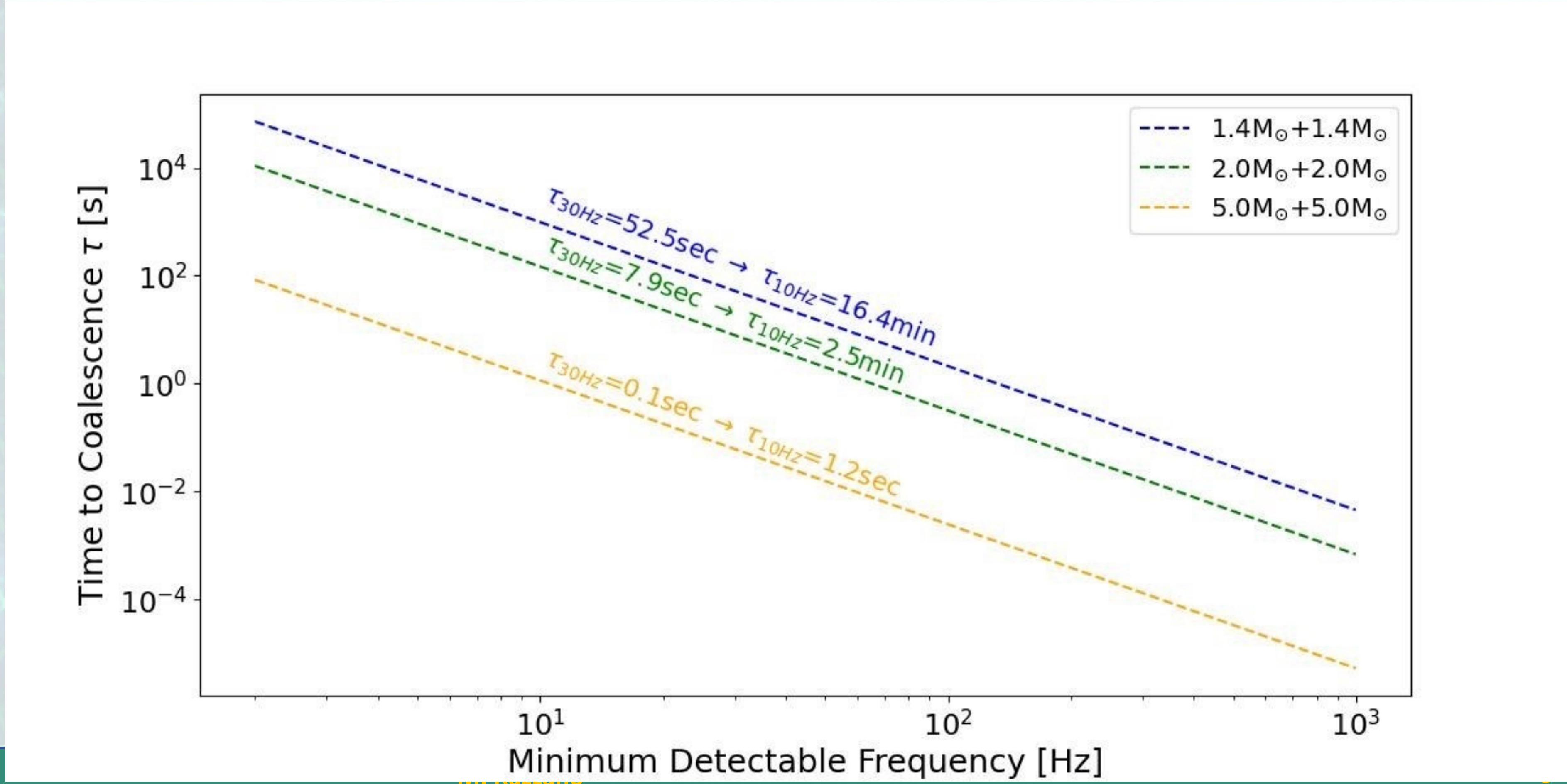




- **New methods for CE: Deep Learning**
  - Normalizing Flows for fast parameter estimation
  - From 10h (5x10^3 samples) to 0.5s (5x10^4 samples)
  - More details in De Santi et al PRD,109,102044, (2024)

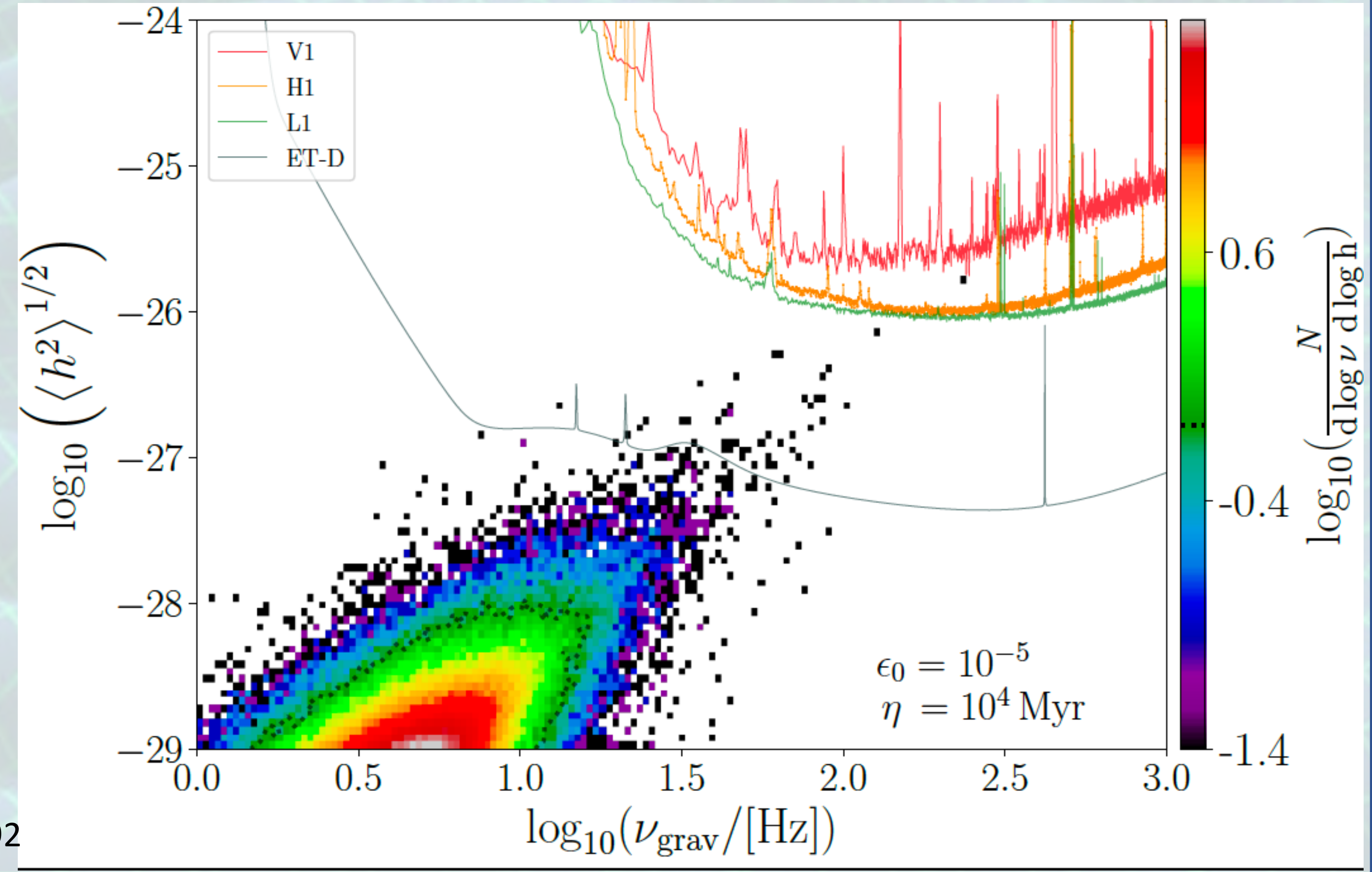
LF science case: BNS early warning

- **Early warning**
  - Time to coalescence increase with lower frequencies
  - Better waveform measurement and parameter estimation
  - Prealert→ Enabling real-time/simultaneous electromagnetic observations



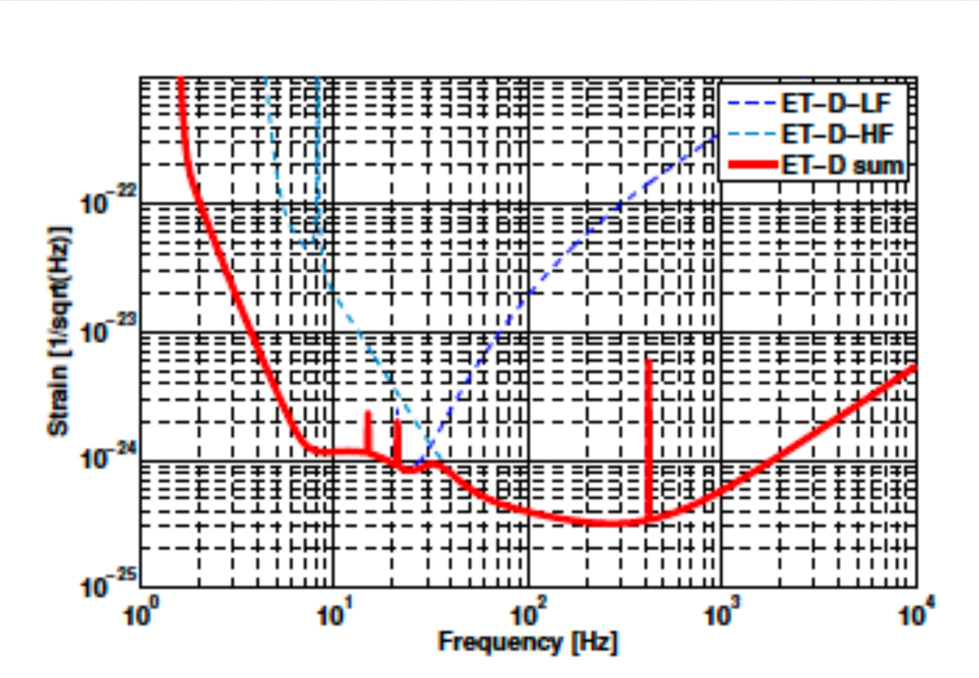
LF science case: pulsars

- **Isolated neutron stars**
  - Expected continuous, periodic GW emission (not yet detected!)
  - Depending on asymmetries in the neutron star structure
  - f_{GW} at twice the neutron star spin frequency



Cieslar et al 2021, A&A, 649,92

Low frequencies and ET



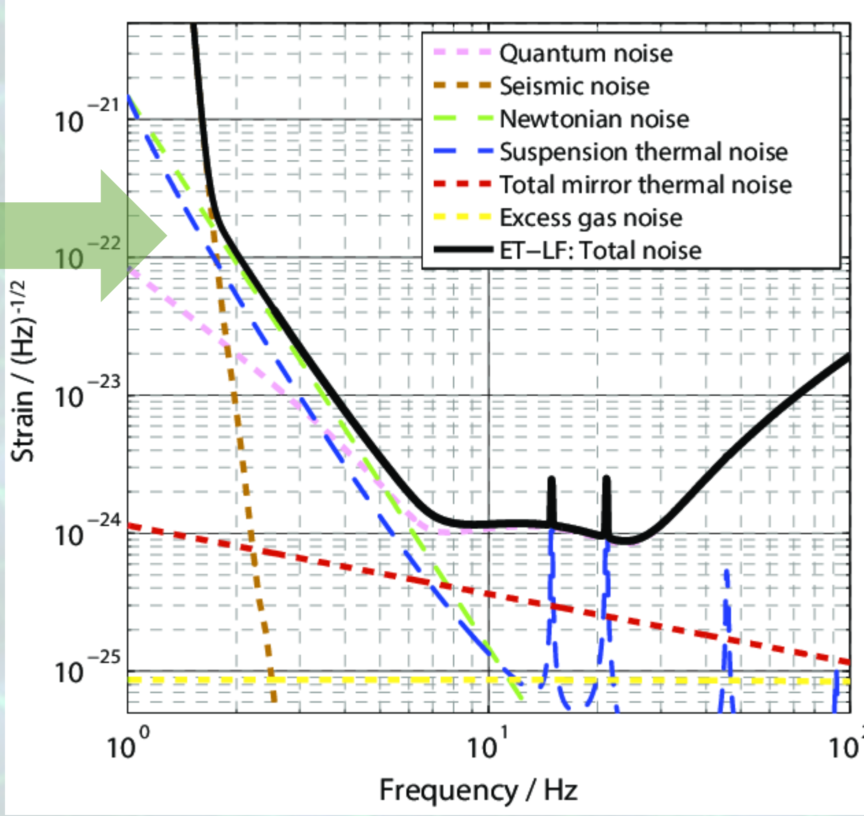
Maggiore et al, 2020, JCAP, 03, 50

- **Main Components**
  - Micro seismic noise
  - Gravity gradient (Newtonian Noise)
  - Control noise
  - Residual noise

Newtonian noise crossing point

2×10^{-22} Hz$^{-1/2}$ @1.8 Hz

(3.2Hz@AdVirgo)



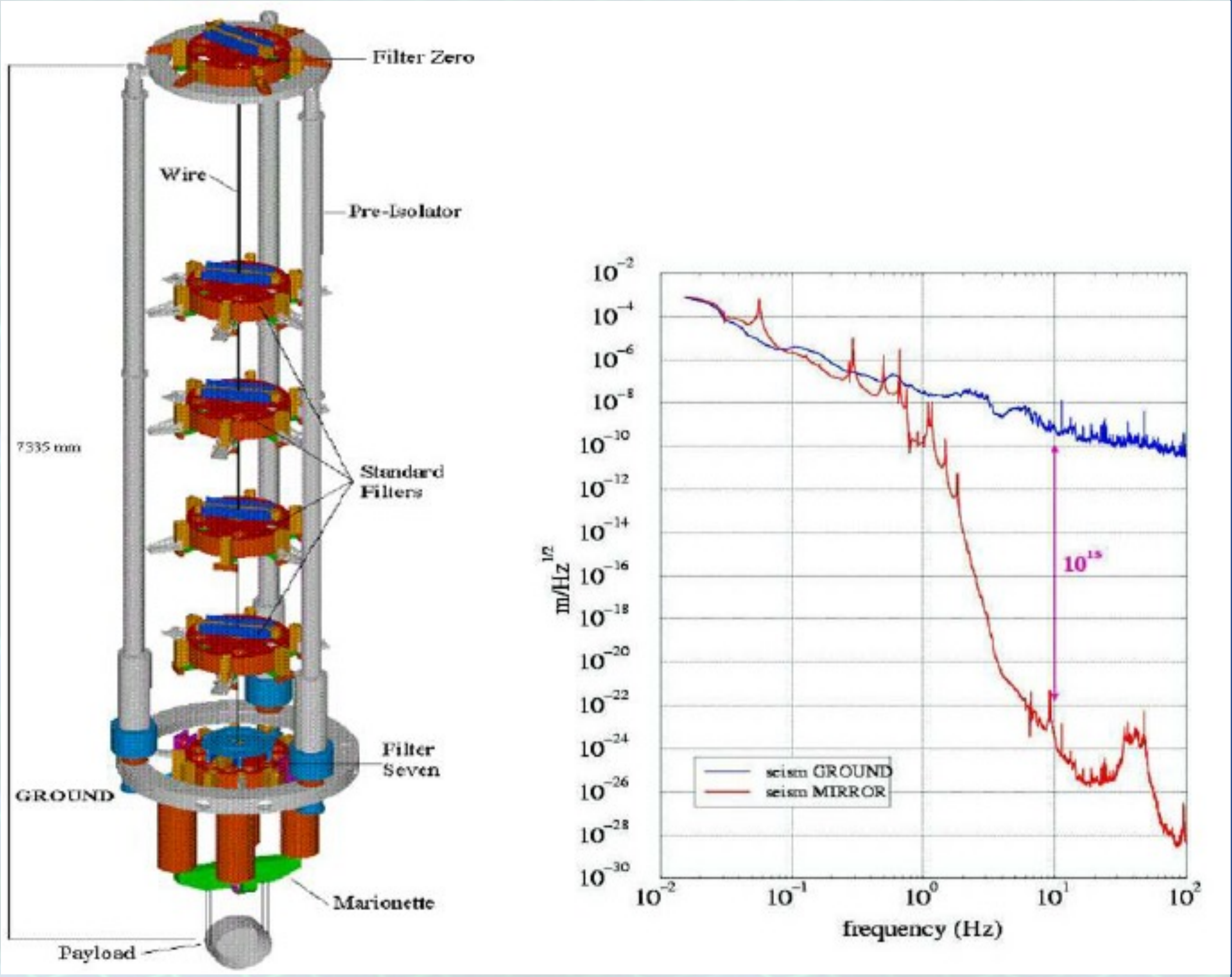
ET Conceptual Study, 2011

- **ET seismic attenuation system**
  - Baseline design: 17m high
  - Superattenuator concept like Virgo
  - **→Reducing height will reduce excavation costs**

The SuperAttenuator concept

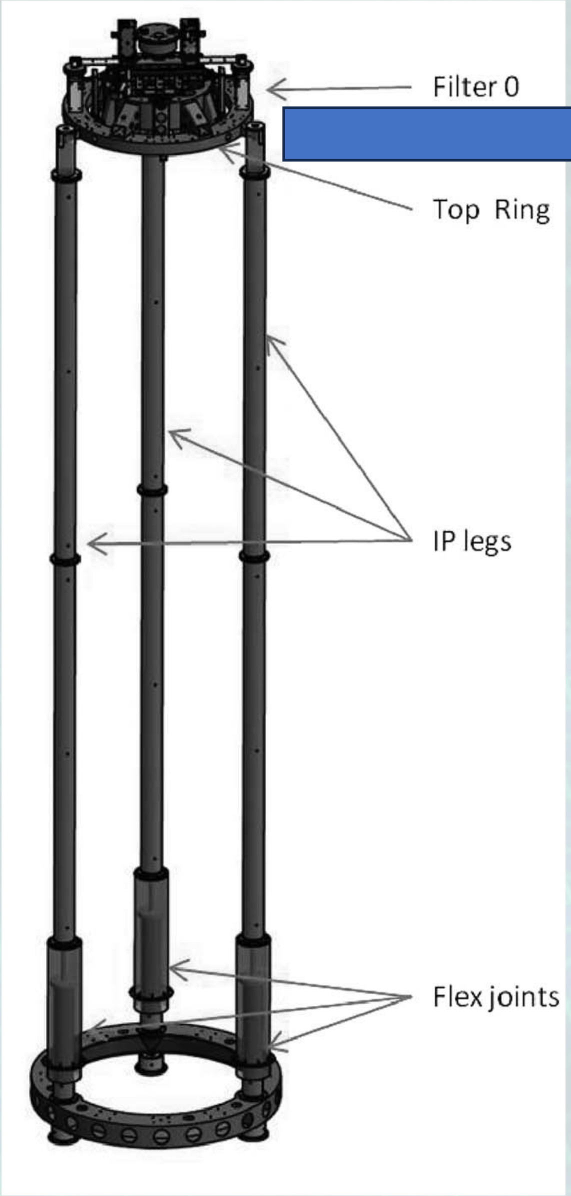
- **Key ideas**
  - Implement passive attenuation
  - Active attenuation to damp resonances
  - Sensing and control to mantain components in working point

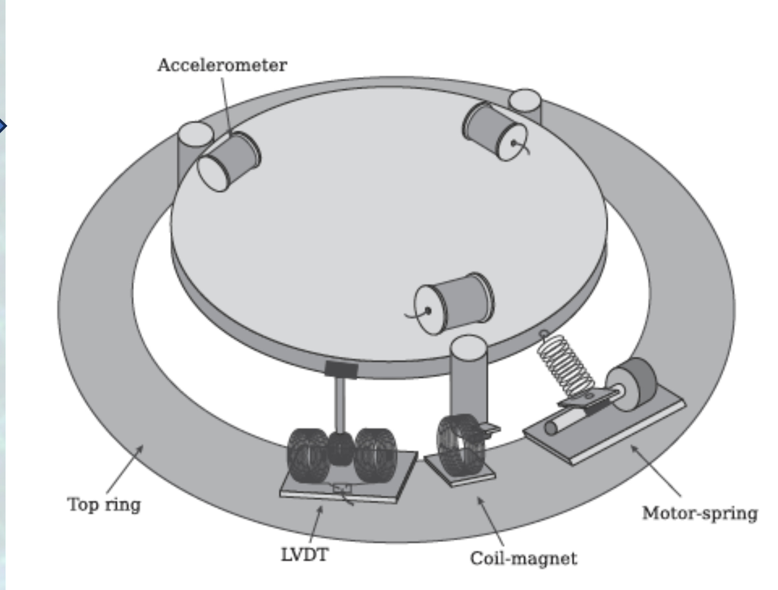
- **Virgo superattenuator**
  - Inverted Pendulum as pre-isolator
  - Standard filters
  - Payload
  - Normal mode resonance frequencies < 2 Hz
  - Total height 8.66 m



Accadia et al 2012, CQG

The inverted Pendulum



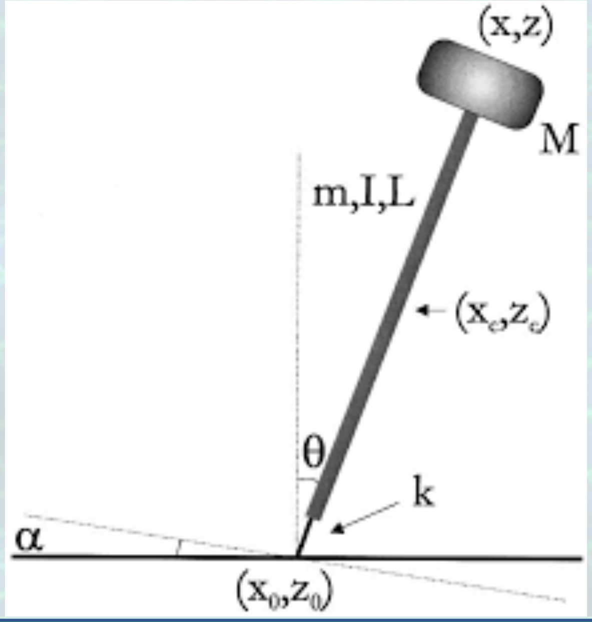


- **Main components**
  - Three 6-m hollow legs
  - Top ring + Filter 0
  - Horizontal normal modes tuned at 30-40 mHz
  - Filter 0 equipped with sensors and actuators to damp resonances

Recap in Inverted Pendulum

- Acting as gravity antispring
- System very soft, low forces to move

$$F \cong M\omega_0^2 x$$

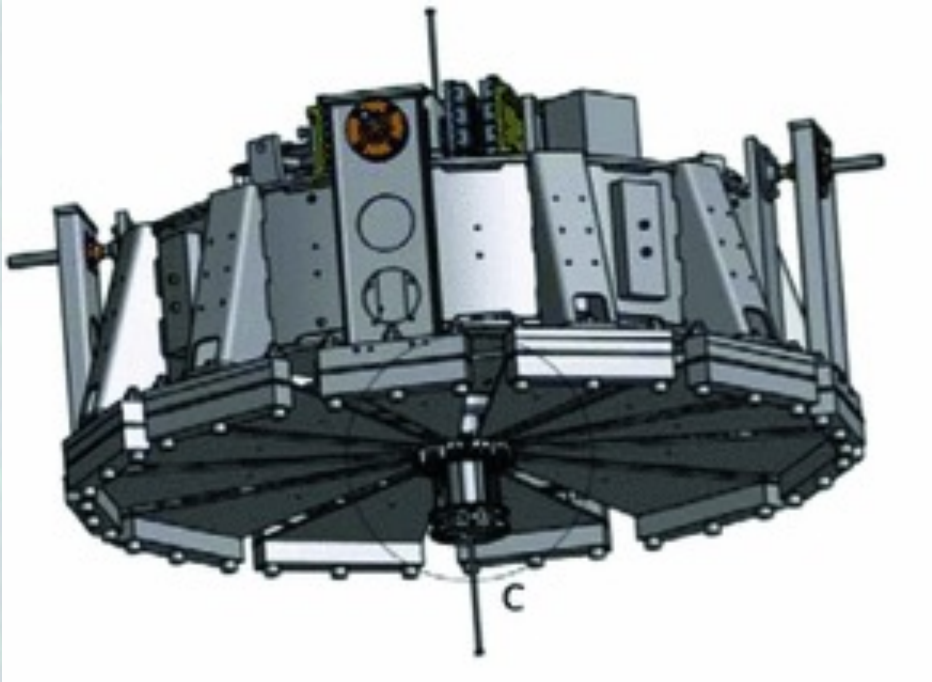


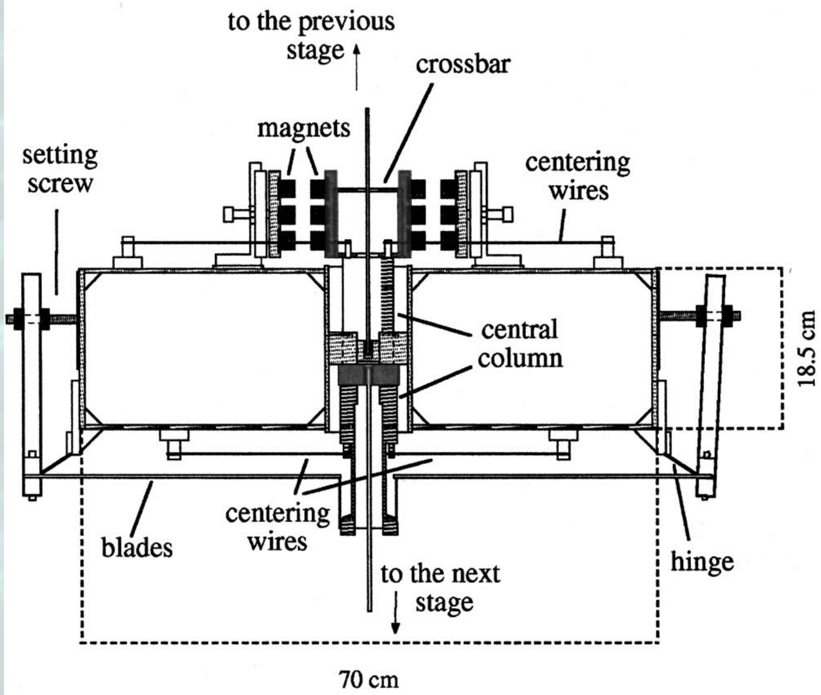
Accadia et al, 2012, RSI,82,094502

Losurdo et al, 1999, RSI,70,2507

Standard Filters

- **Main Body**
  - Rigid, drum-like structure
  - A moving part, attached to lower stages
  - Vertical attenuation by cantilever triangular blades+magnetic antispring

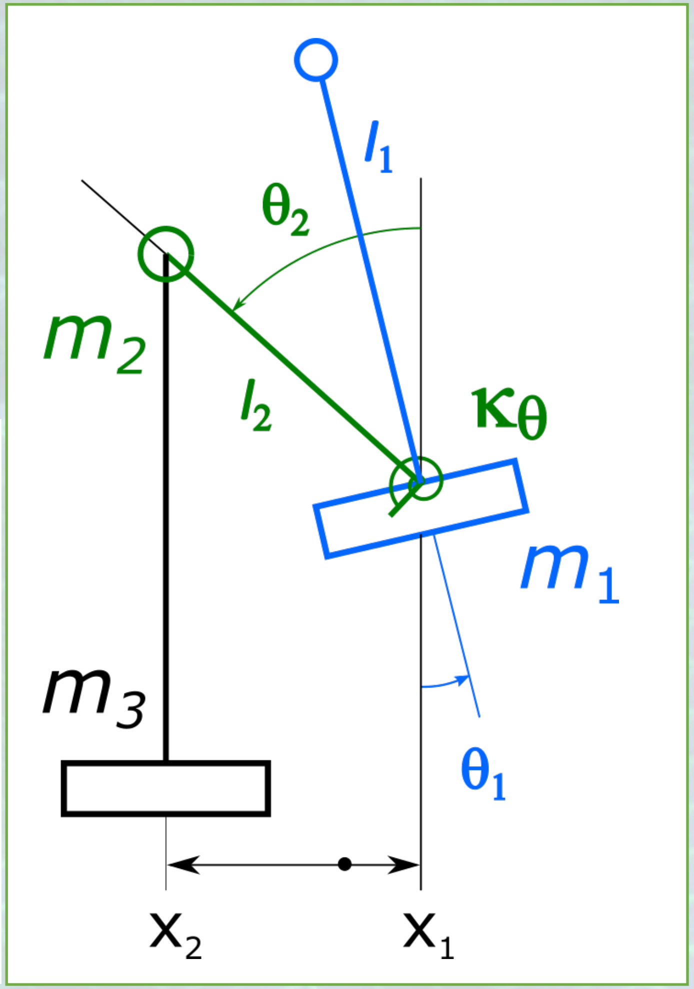




The Pendulum Inverted Pendulum

- **Key Ideas**
  - Seismic attenuation in a compact space
  - Fold a Inverted Pendulum+Pendulum
  - System is stable if k stiff

```
• l1:  1.544, # Pendulum length\
• l2:  0.520, # IP length\
• T1: 2551.0, # Pendulum tension\
• T2: 1766.0, # IP compression\
• m1:   80.0, # Pendulum mass\
• m2:   80.0, # Filter mass\
• m3:  100.0, # Load\
• I1s:  20.0, # Pendulum moment of inertia \
• I2s:   0.8, # IP moment of inertia\
• k:  1700.0, # flex joint elastic constant\
```



F. Fidecaro,@GWADW2022

Normal modes @ 0.68Hz and 0.74Hz

Attenuation Factor

- **Horizontal Attenuation**

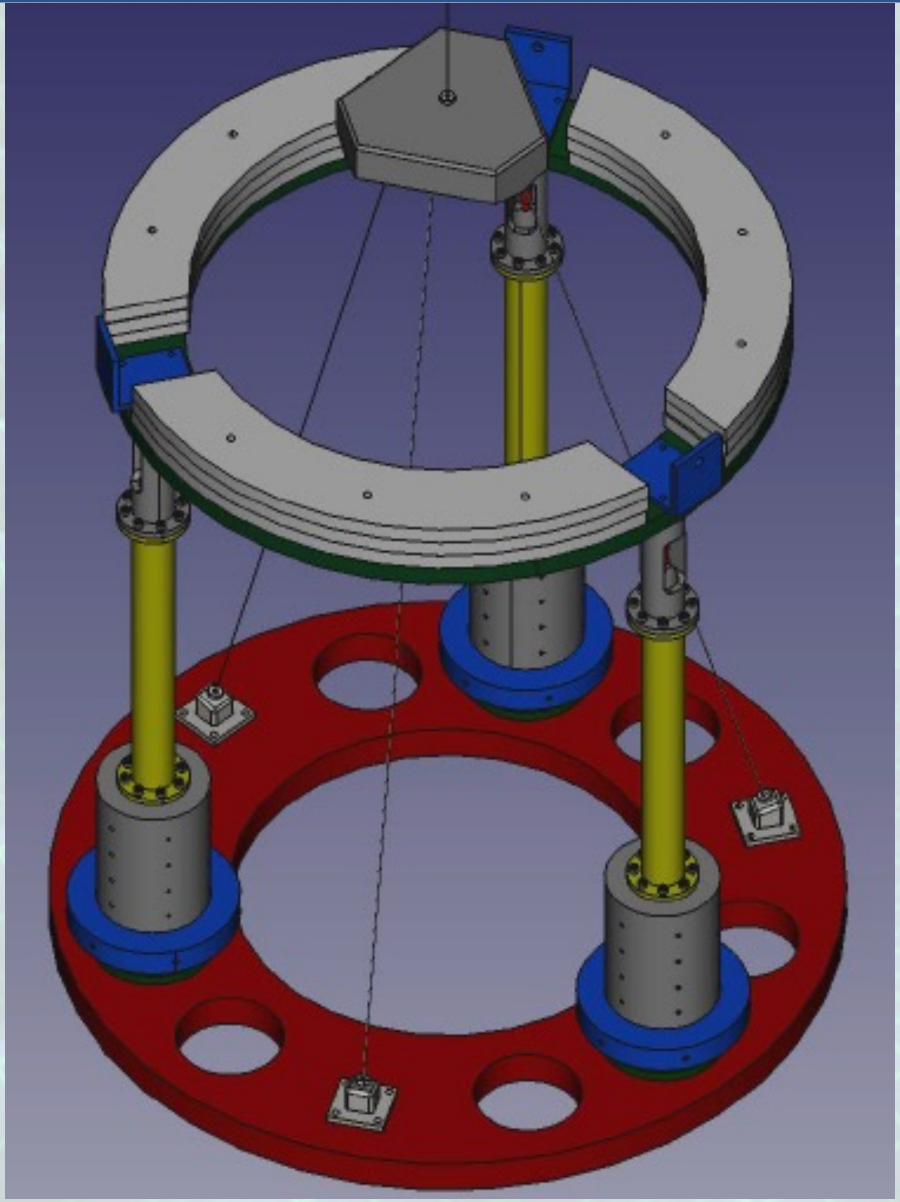
$$A_{f0} = \left(\frac{f_0^2}{f^2 - f_0^2}\right)^2$$

For f_0 = 0.75Hz:

# of PIPs	Attenuation @2 Hz
1	2.7×10^{-2}
2	7.2×10^{-4}
3	1.9×10^{-5}

Required Attenuation
For ET ≈ 5×10^{-5}

ca 150 cm



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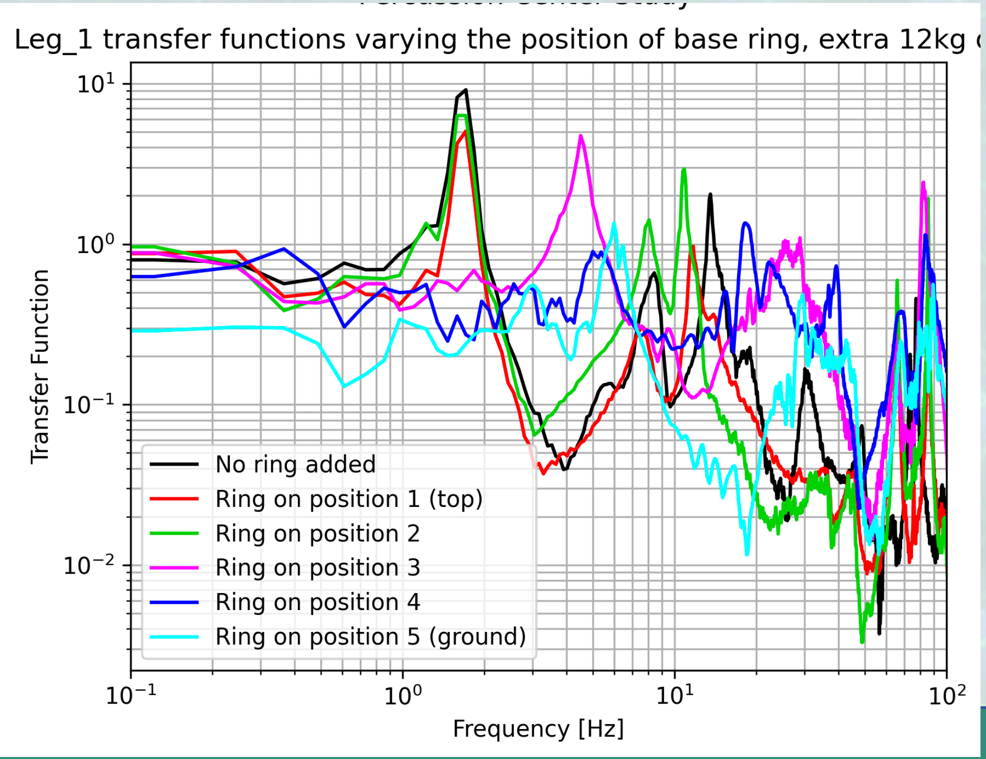
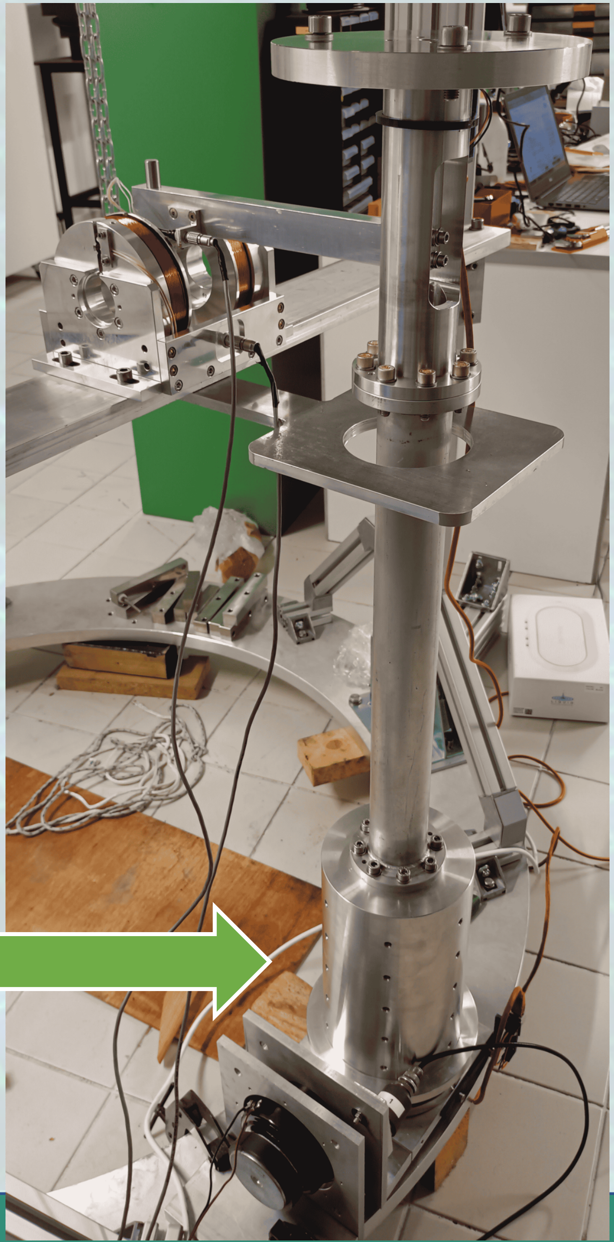
First Characterizations

- **First Prototype**
  - First components built and tested at INFN-Pisa Lab
  - Characterized PIP inverted pendulum legs
  - LVDT sensors on top and bottom of the legs
  - Study transfer function and resonances
  - Full PIP under test



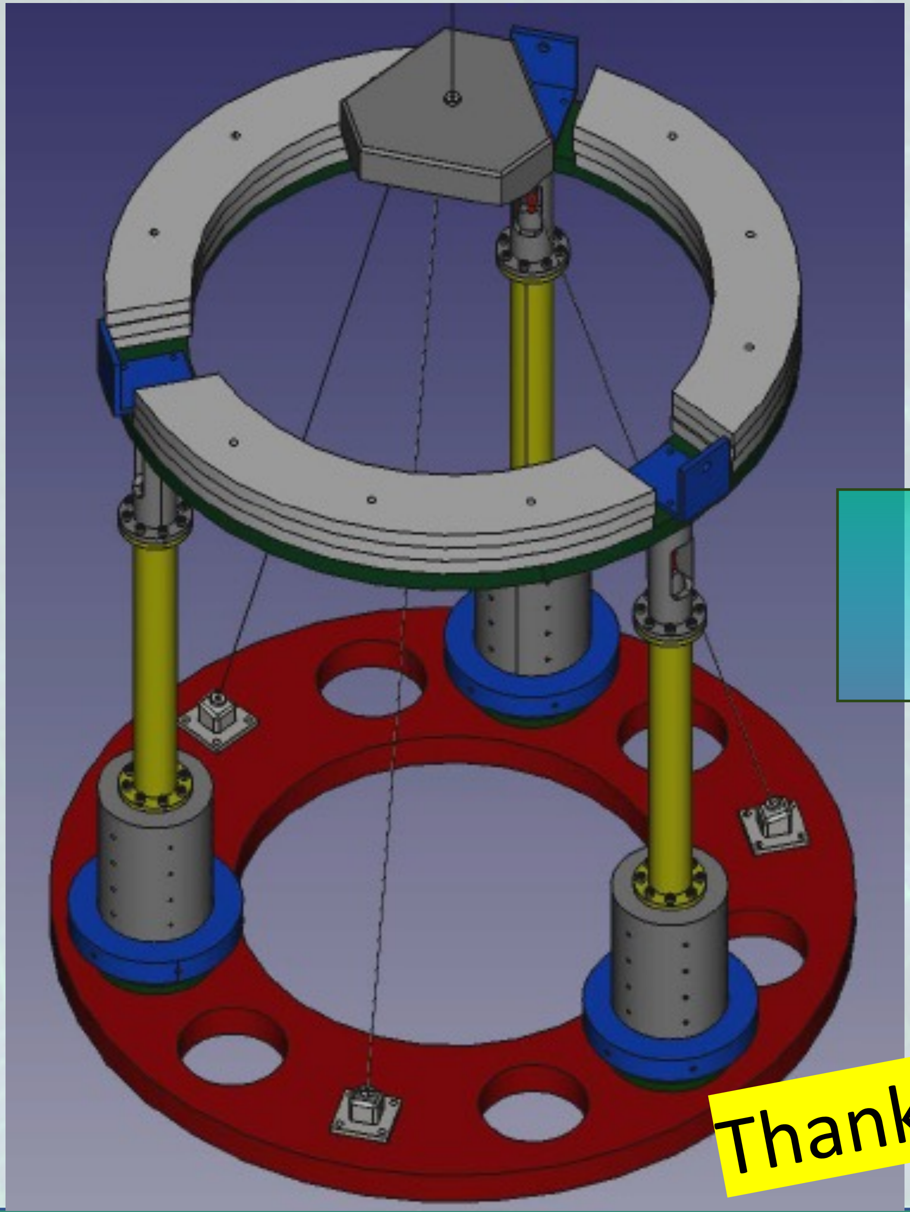
Counterweights



Conclusions

- **Low frequency Science Cases**
  - High-mass black holes (hints: GW190426_190642)
  - Multi-messenger opportunities and early warning (GW170817)
  - Other interesting sources (pulsars, encounters,…)

- **New ideas for seismic attenuation**
  - Passive+active approach
  - Elaborate on SuperAttenuator concept
  - Compact Filter based on Pendulum Inverted Pendulum
  - R&D supported by the project Black Holes for ET in Sardinia (BHETSA), funded by the PRIN2020 call. More details on http://bhetsa.df.unipi.it/
  - PIP Construction and test has been done
  - Not just simulations…



Thanks for your attention!