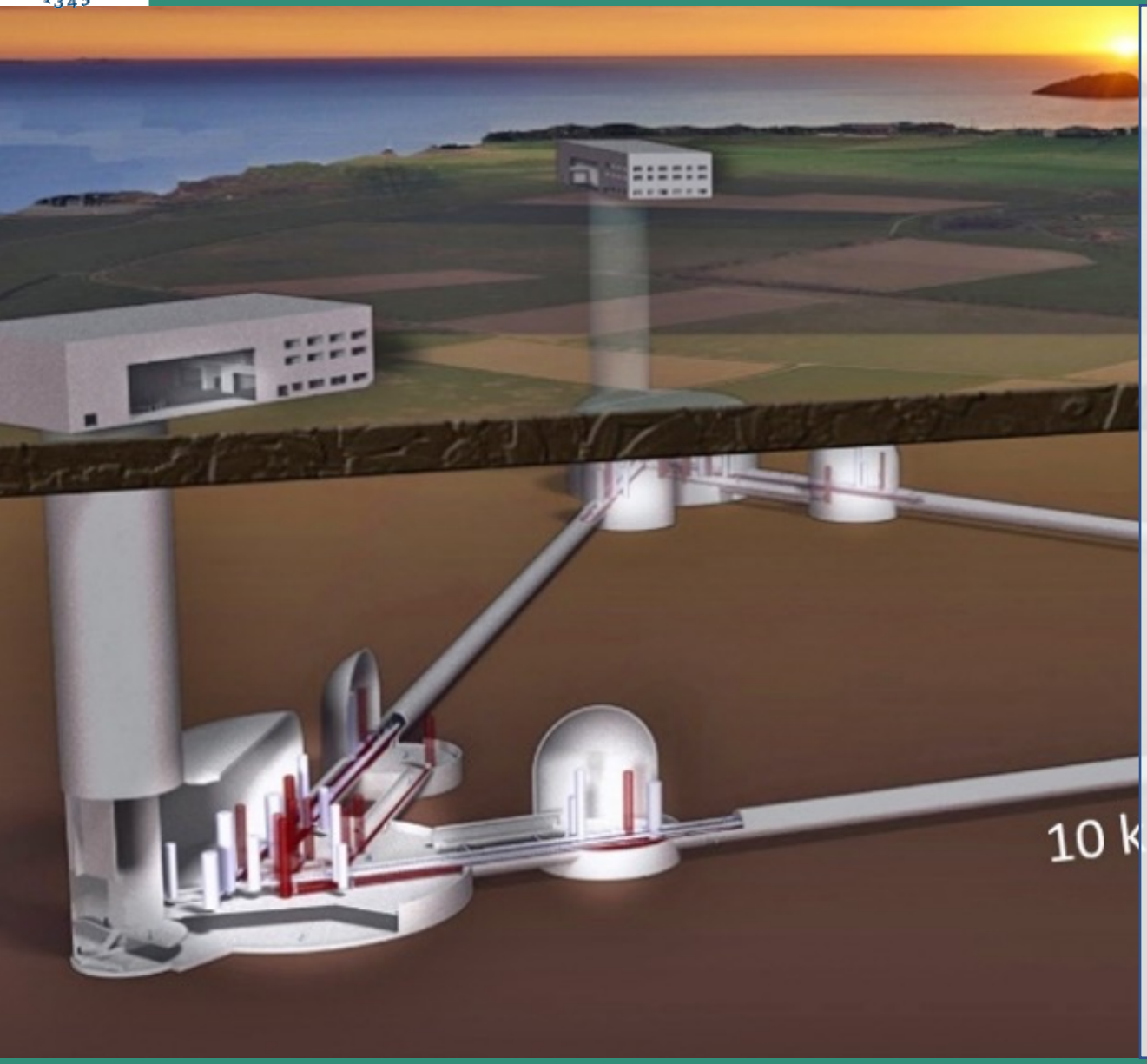


A new concept for compact seysmic attenuation systems

to improve low-frequency sensitivity of gravitational wave detectors

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

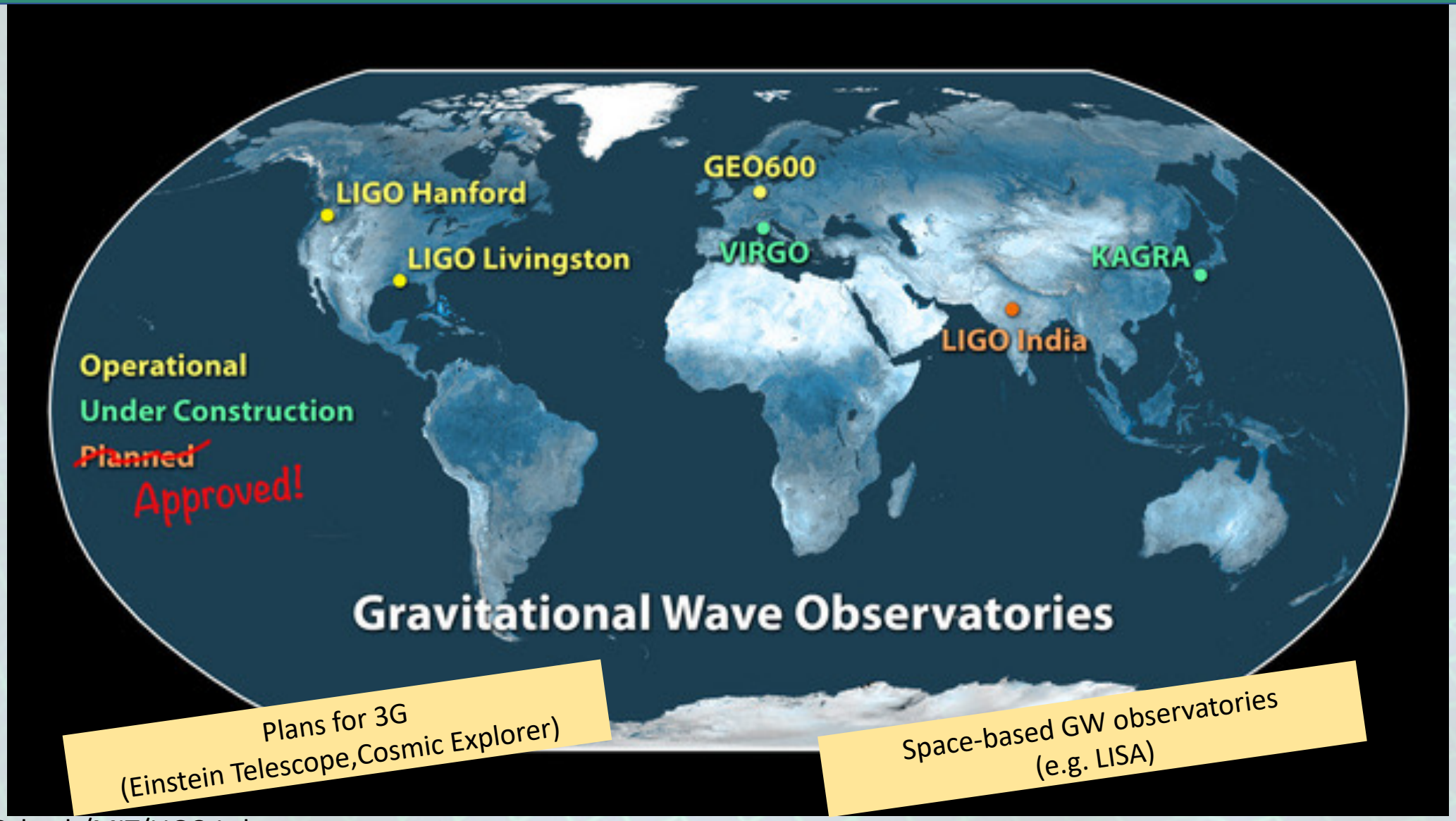
University of Pisa & INFN-Pisa

RICAP 2024

Frascati, 23 – 27 September 2024

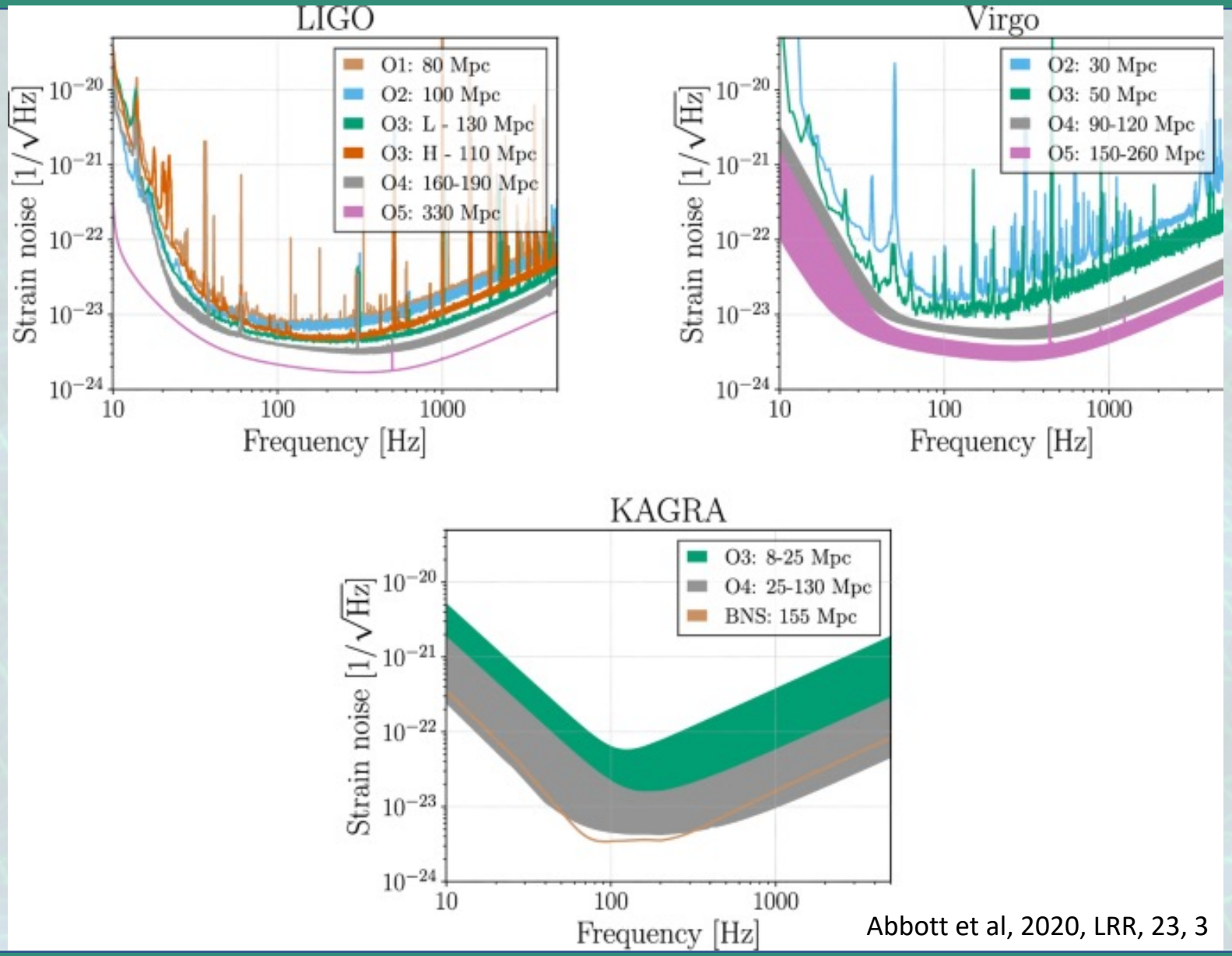
BHETSA
Black Holes for ET in SArdinia

The era of gravitational waves



Credits: Caltech/MIT/LIGO Lab

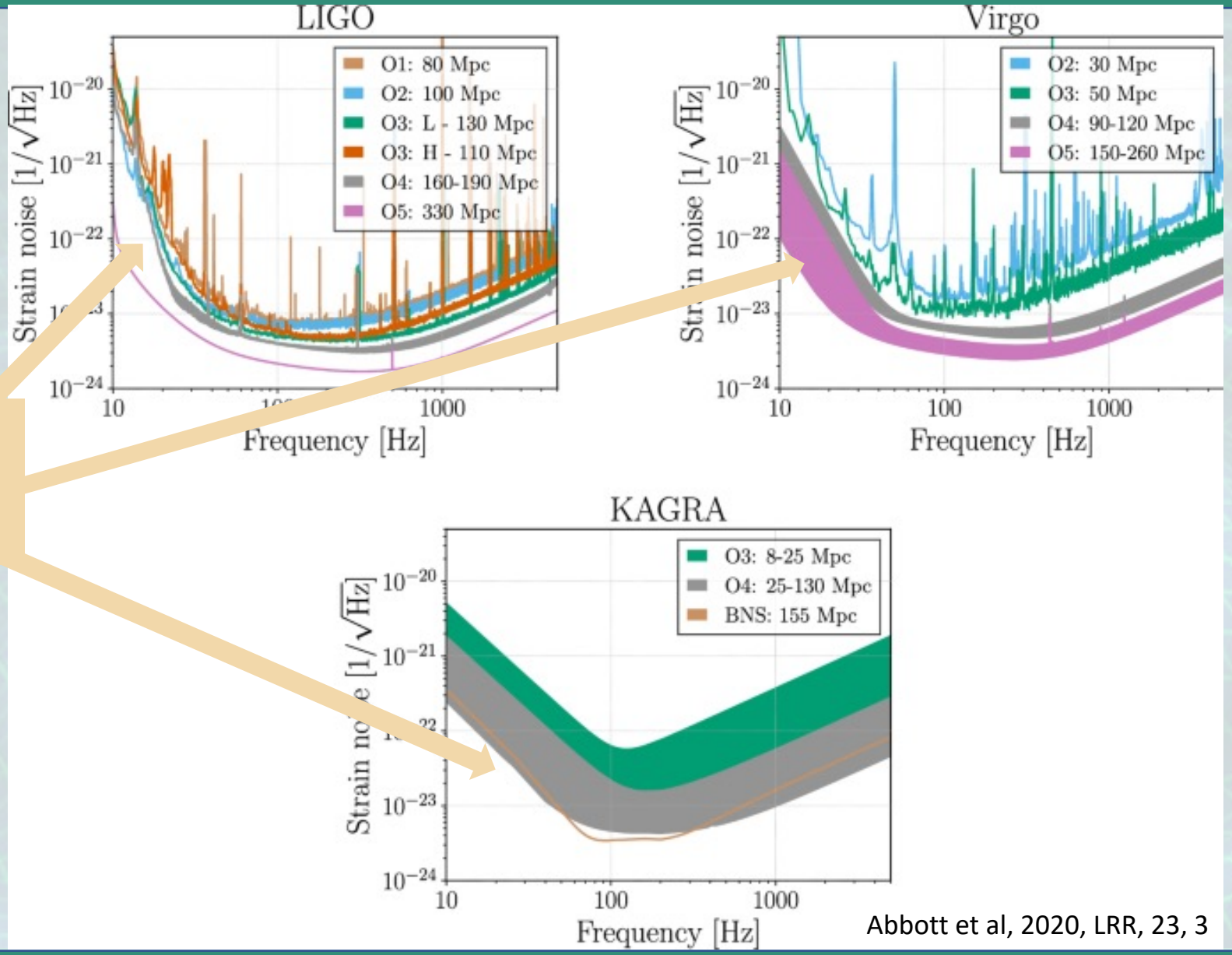
Sensitivity curves



Abbott et al, 2020, LRR, 23, 3

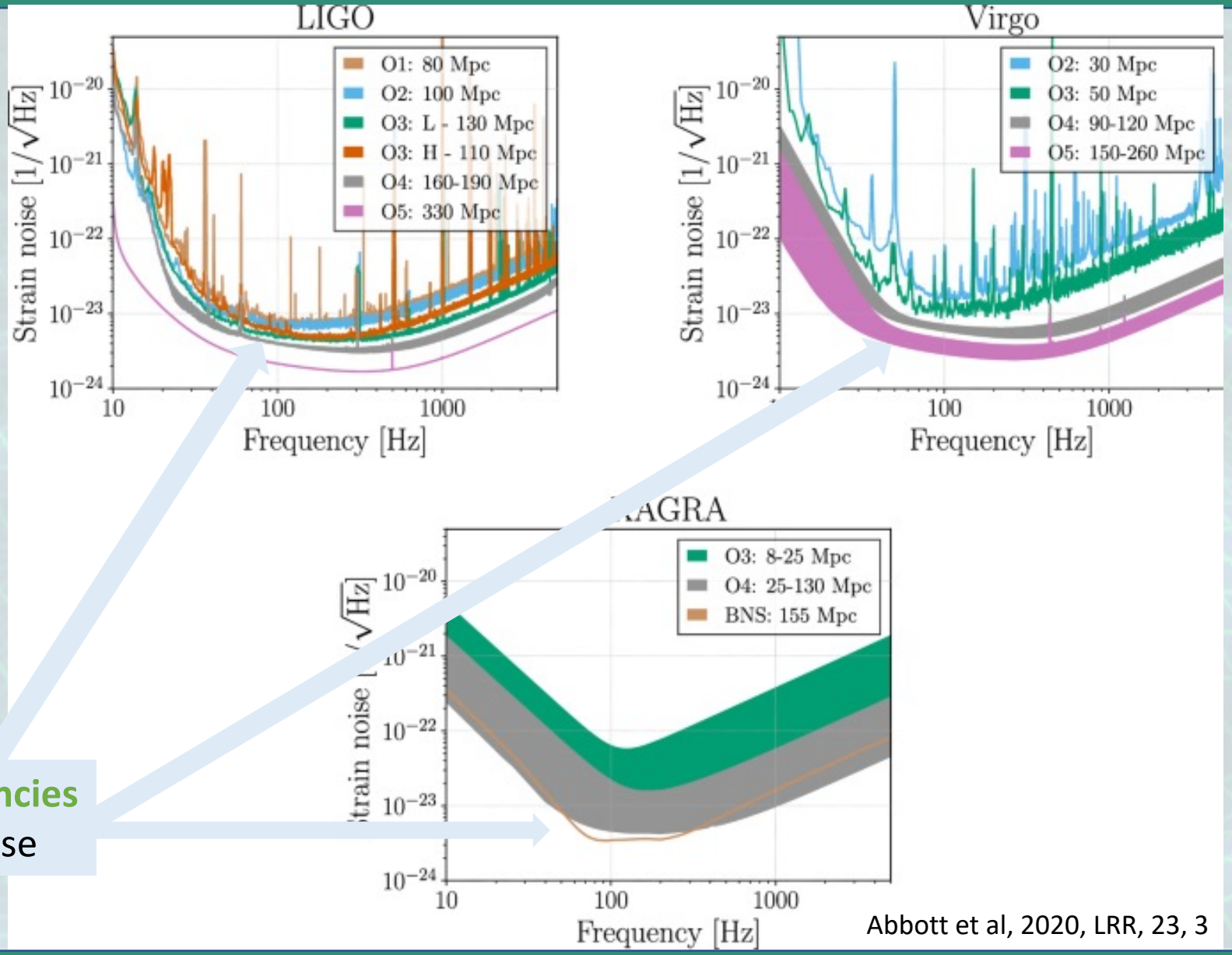
Sensitivity curves

Low Frequencies
Seismic & Newtonian Noise



Abbott et al, 2020, LRR, 23, 3

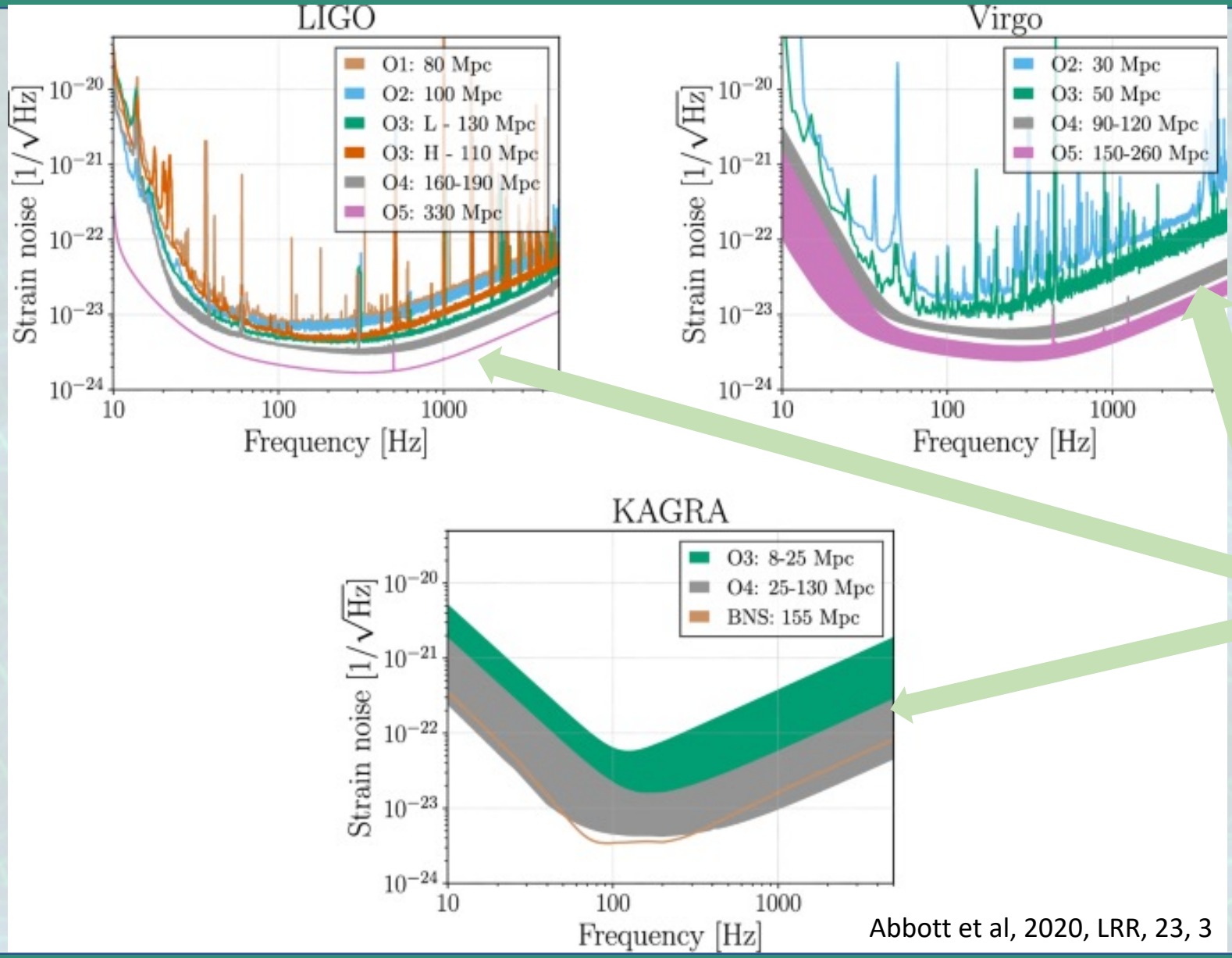
Sensitivity curves



Mid Frequencies
Thermal Noise

Abbott et al, 2020, LRR, 23, 3

Sensitivity curves

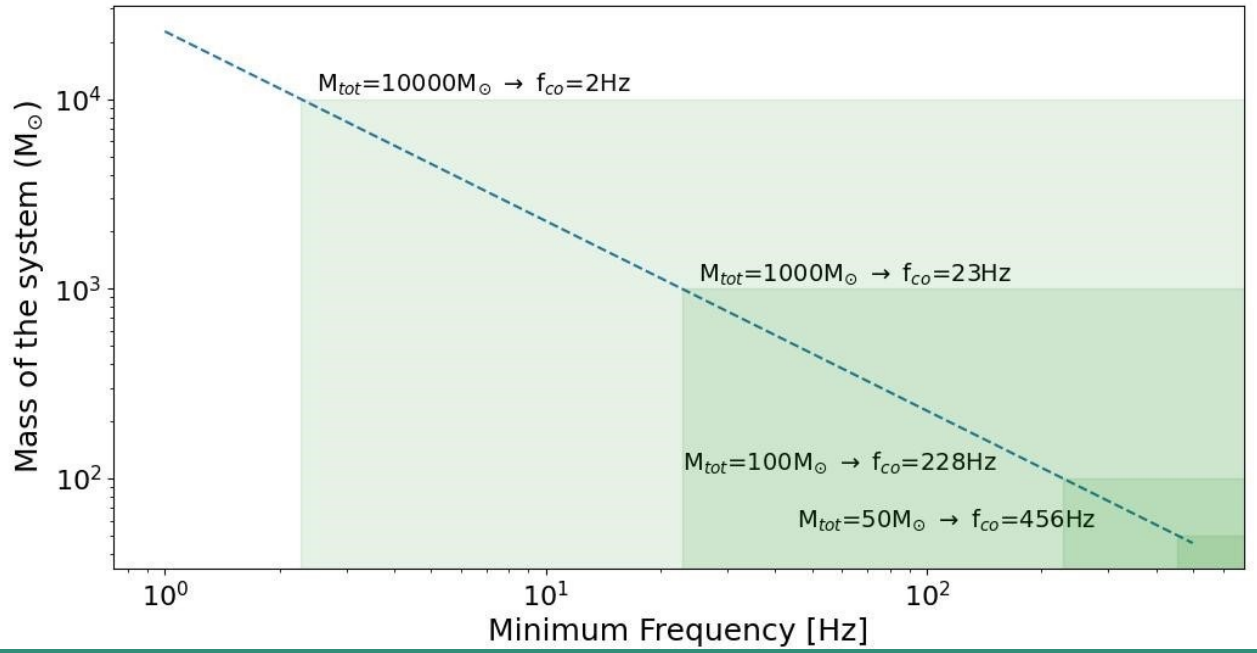


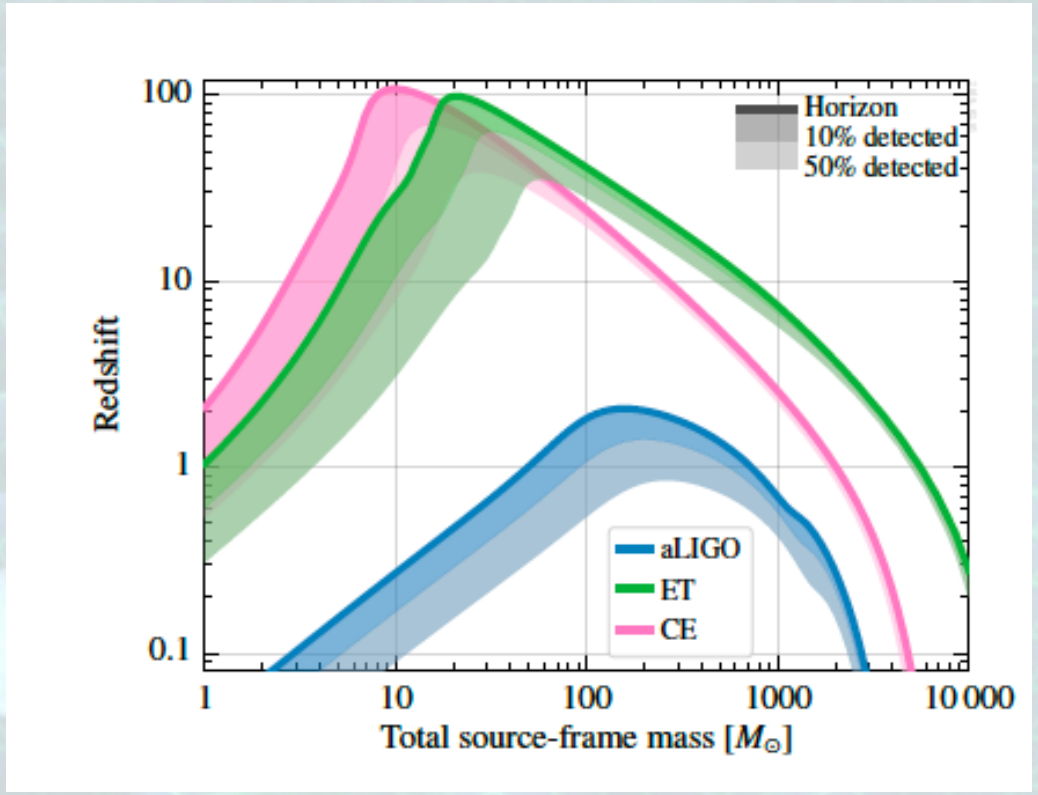
High Frequencies
Quantum Noise

Abbott et al, 2020, LRR, 23, 3

Low-Frequency science: high-mass black holes

- **Black hole population**
  - BBH rate with ET $O(10^5\text{-}10^6)$ yr^{-1}
  - High-mass binary black holes $\propto f^{-1}$
  - High-z black holes
  - Higher Signal-to-noise ratio



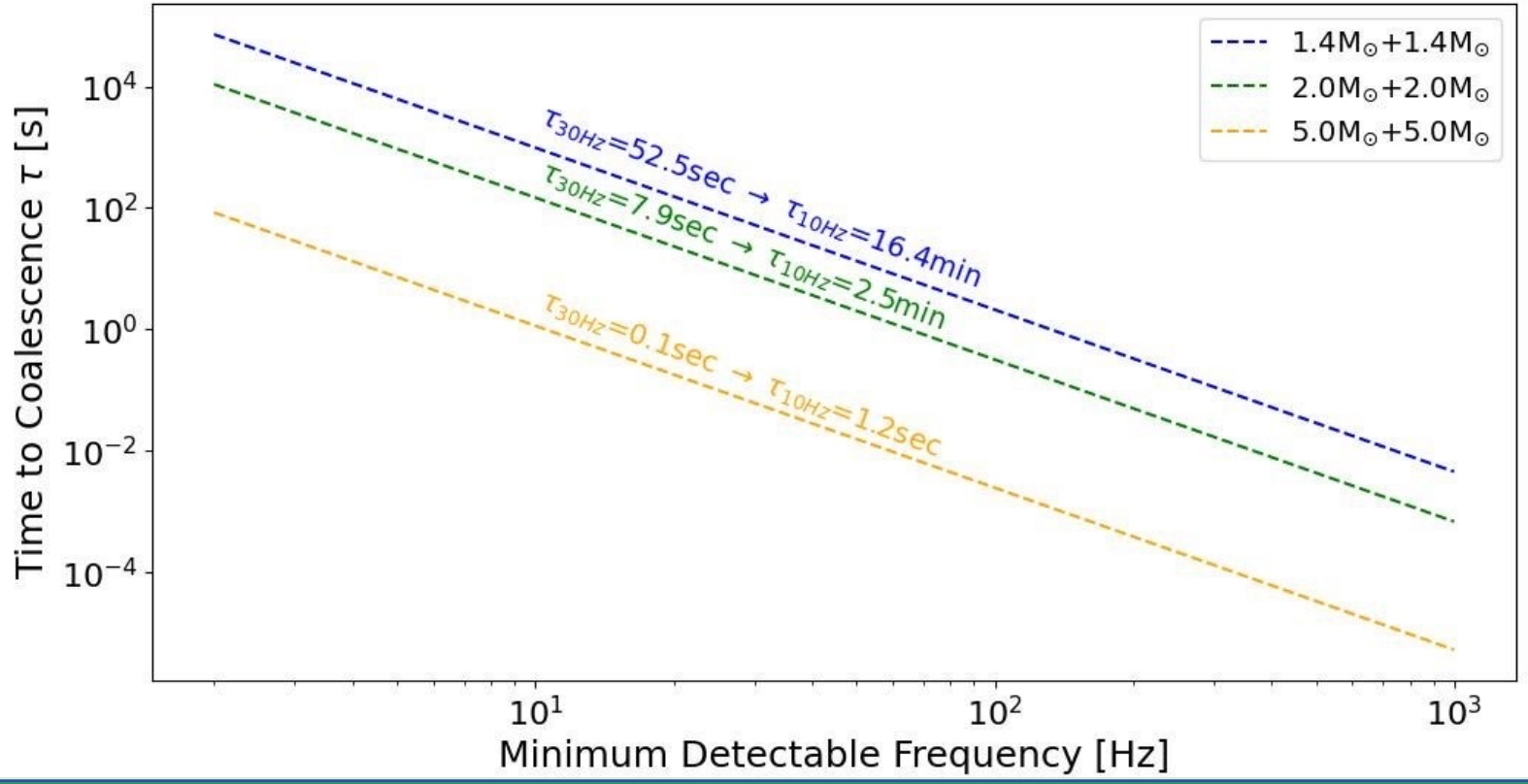


Maggiore et al, 2020, JCAP, 03, 50

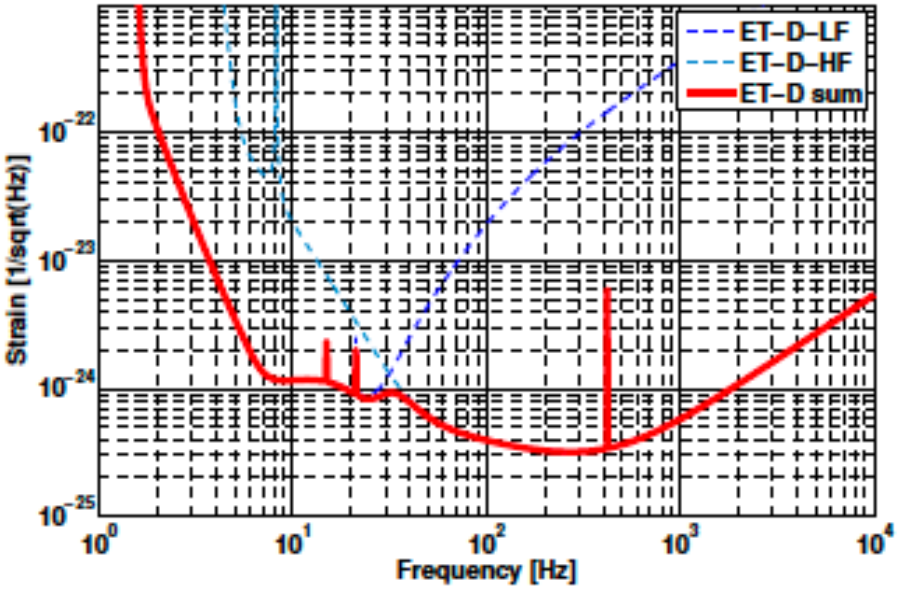
Low-Frequency science: high-mass black holes

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

- **Not just these science cases**
  - Continuous waves from pulsars
  - Cosmology
  - …



Low frequencies and 3G detectors



Maggiore et al, 2020, JCAP, 03, 50

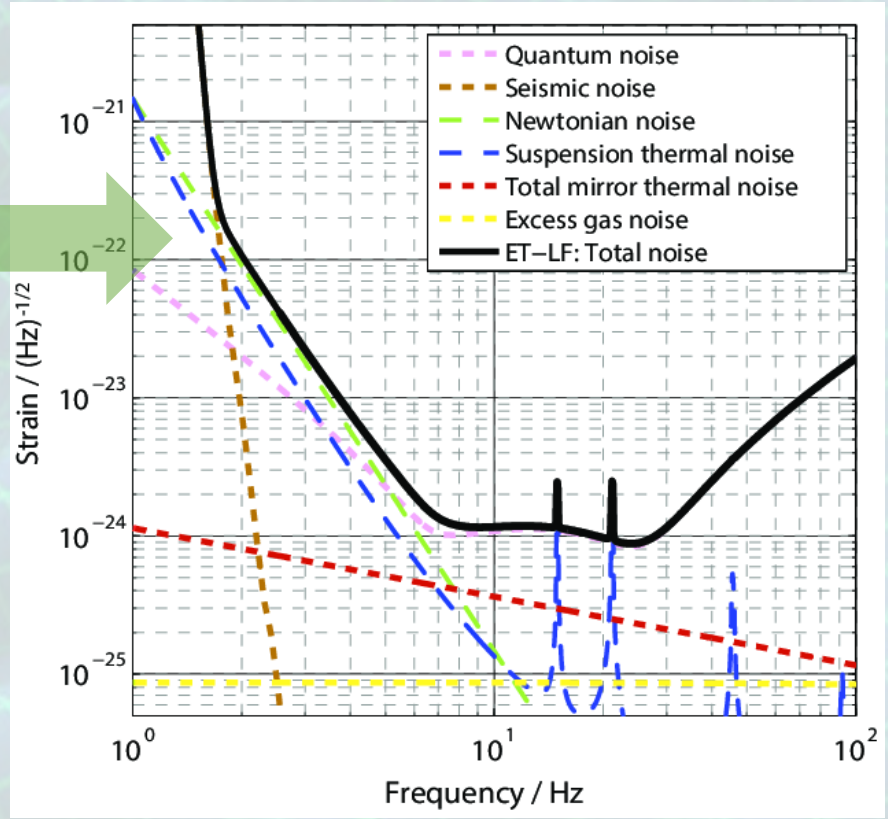
- **Main Components**
  - Micro seismic noise
  - Gravity gradient (Newtonian Noise)
  - Control noise

See also M. Mantovani talk

Newtonian noise crossing point

2×10^{-22} $Hz^{-1/2}$ @1.8 Hz

(3.2Hz@AdVirgo)



ET Conceptual Study, 2011

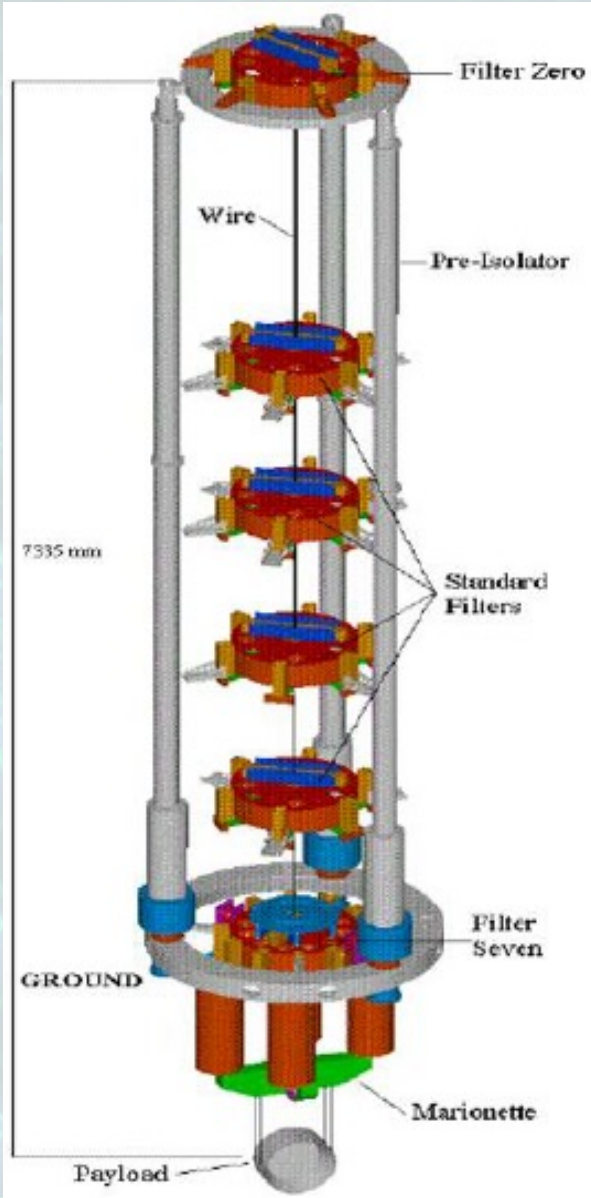
- **Einstein Telescope seismic attenuation system**
  - Baseline design: 17m high (e.g. ET Conceptual study)
  - Superattenuator concept like Virgo
  - **→Reducing height will reduce excavation costs**

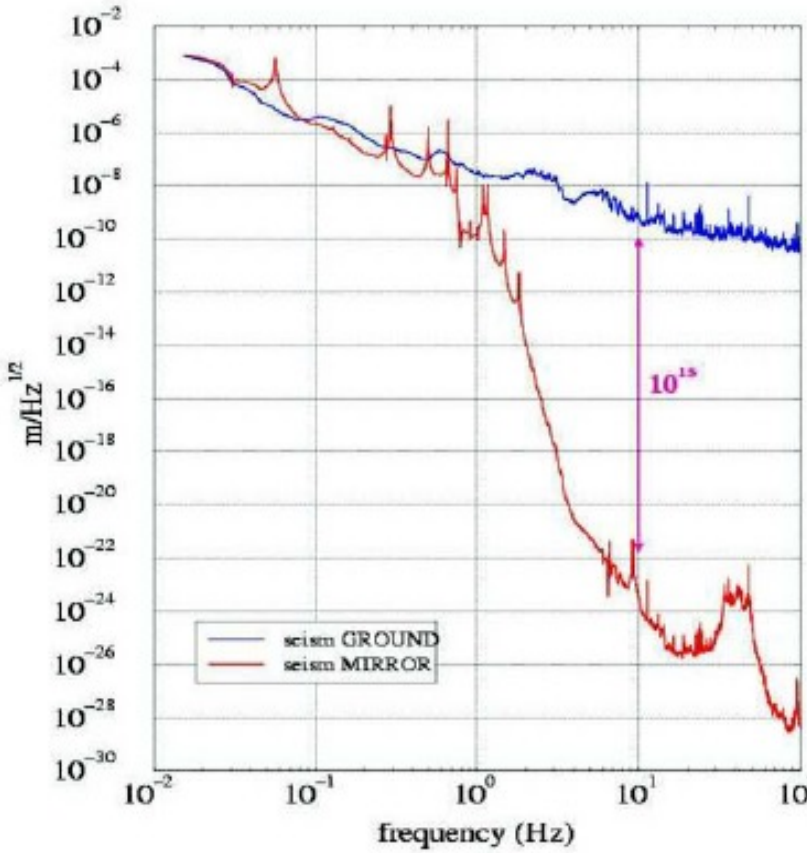
The SuperAttenuator concept

- **Key ideas**
  - Implement passive attenuation
  - Active attenuation to damp resonances
  - Sensing and control to mantain components in working point (See A. Gennai talk)

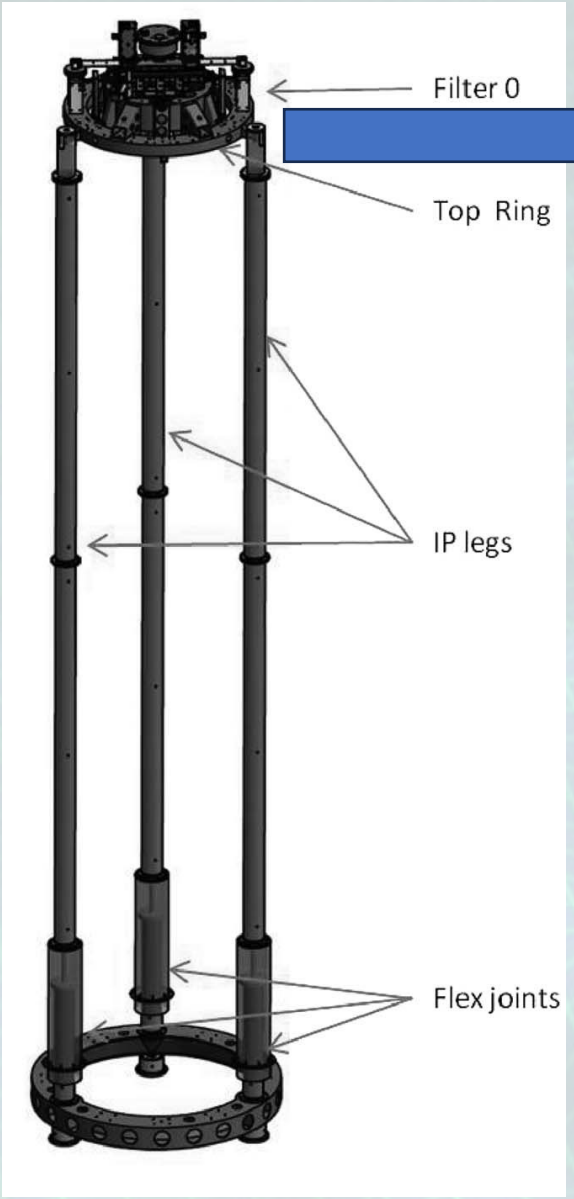
- **Virgo superattenuator**
  - Inverted Pendulum as pre-isolator stage
  - Standard filters
  - Payload
  - Normal mode resonance frequencies < 2 Hz
  - Total height 8.66 m

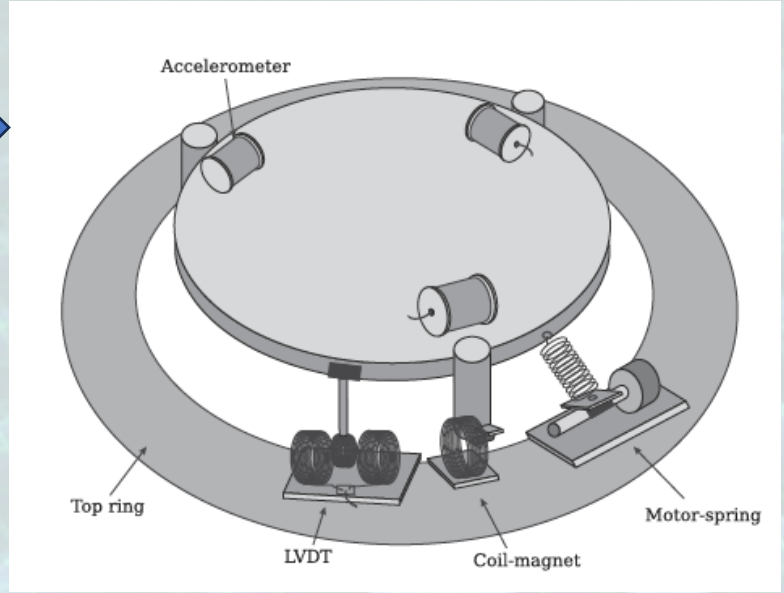
Accadia et al 2012, CQG





The inverted Pendulum



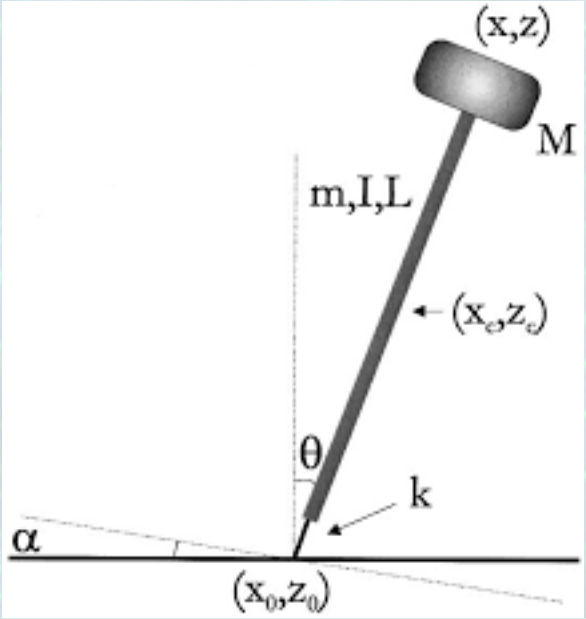


- **Main components**
  - Three 6-m hollow legs
  - Top ring + Filter 0
  - Horizontal normal modes tuned at 30-40 mHz
  - Filter 0 equipped with sensors and actuators to damp resonances

Recap in Inverted Pendulum

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

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

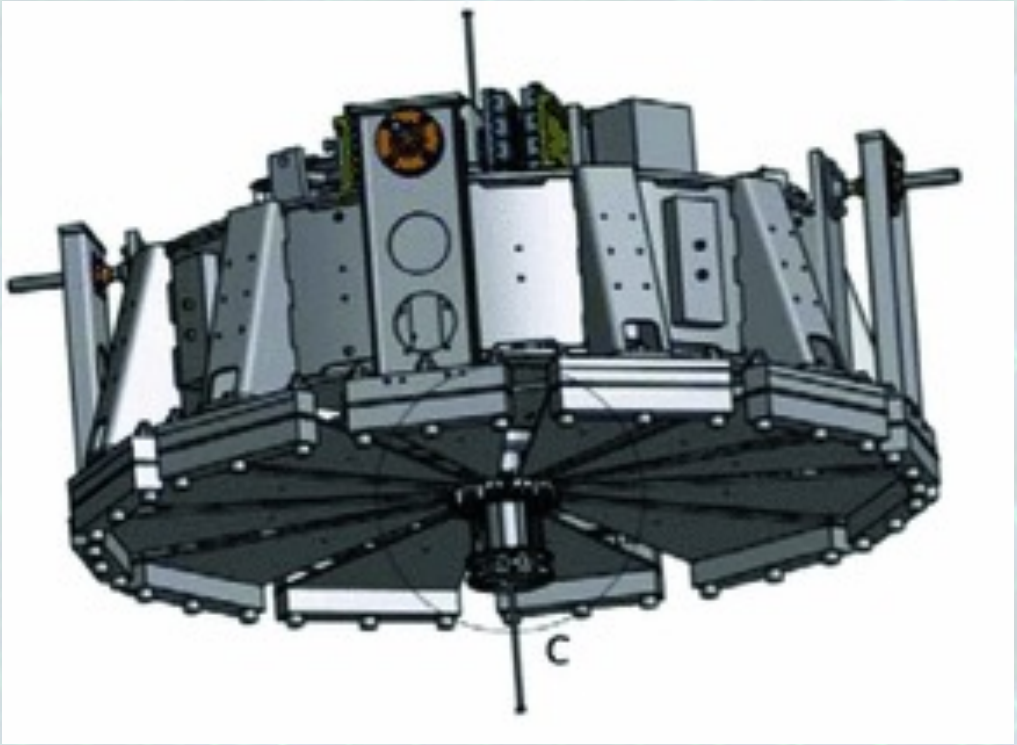


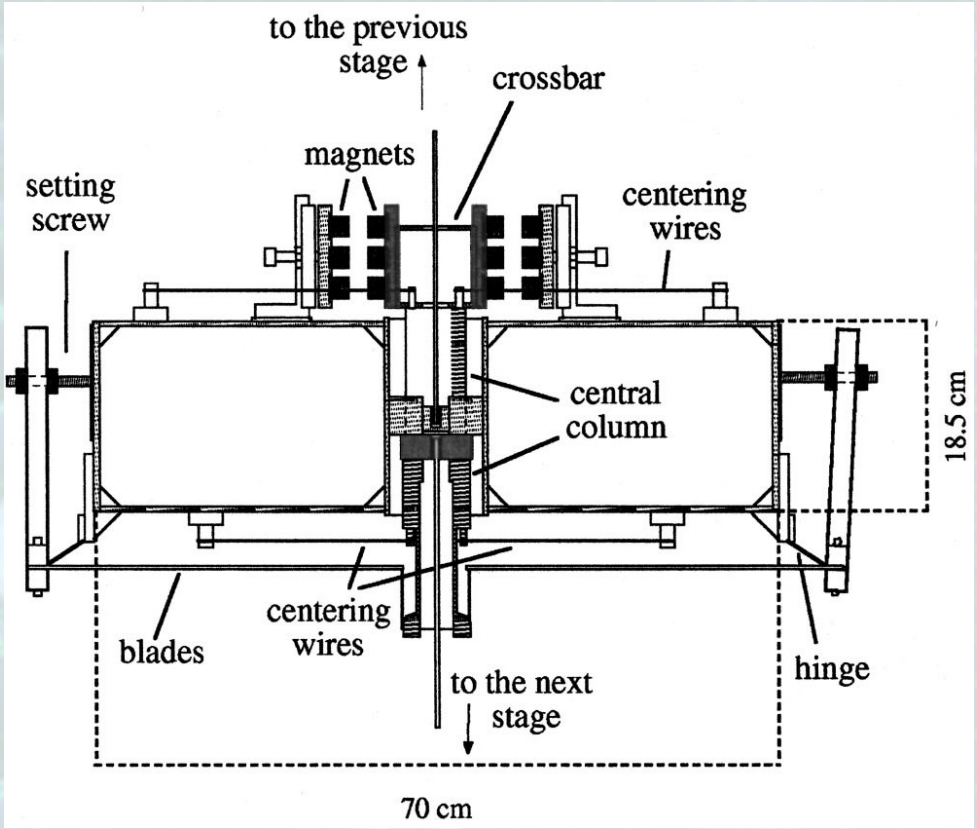
Accadia et al, 2012, RSI,82,094502

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



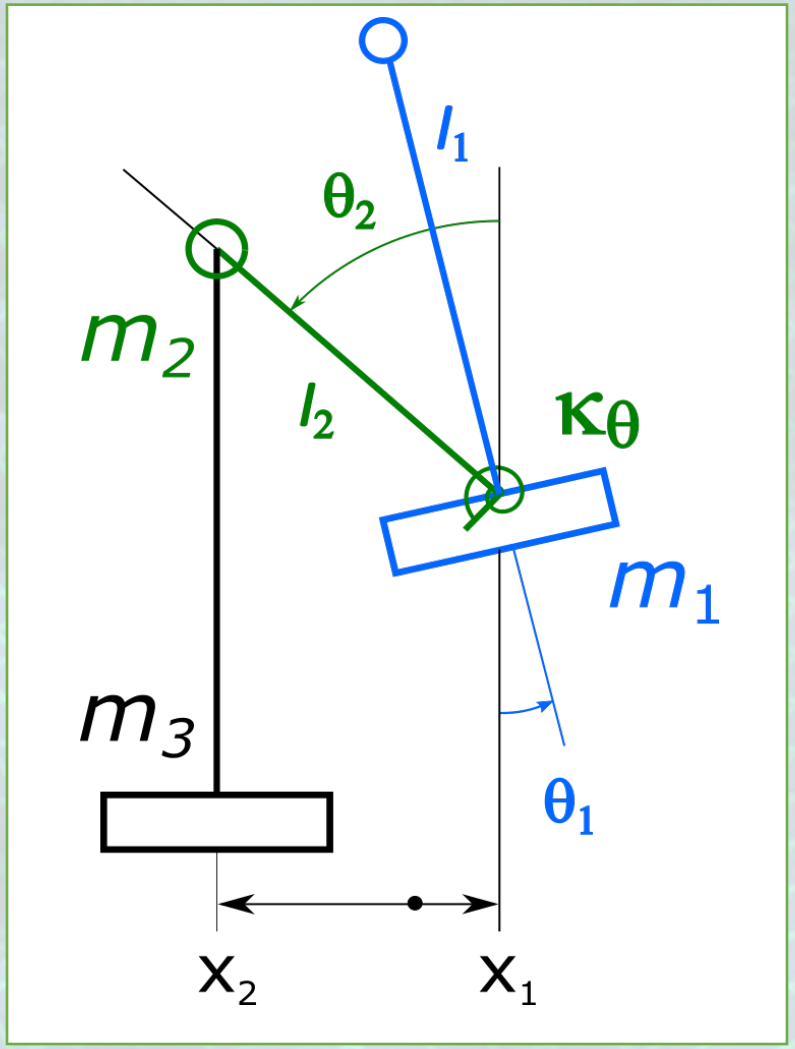


The idea of Pendulum Inverted Pendulum

- **Key Ideas**
  - Seismic attenuation in a compact space
  - Fold a Inverted Pendulum+Pendulum in a single filter
  - System is stable if k stiff (~1700 N m rad^{-1})

Some numbers

Pendulum mass	m_1	80 kg
Pendulum length	l_1	1.5 m
Filter mass	m_2	80 kg
Inverted Pendulum length	l_2	0.5 m
Suspended load	m3	100 kg



F. Fidecaro,@GWADW2022

Resonances at @0.68Hz and 0.75Hz

Attenuation Factor

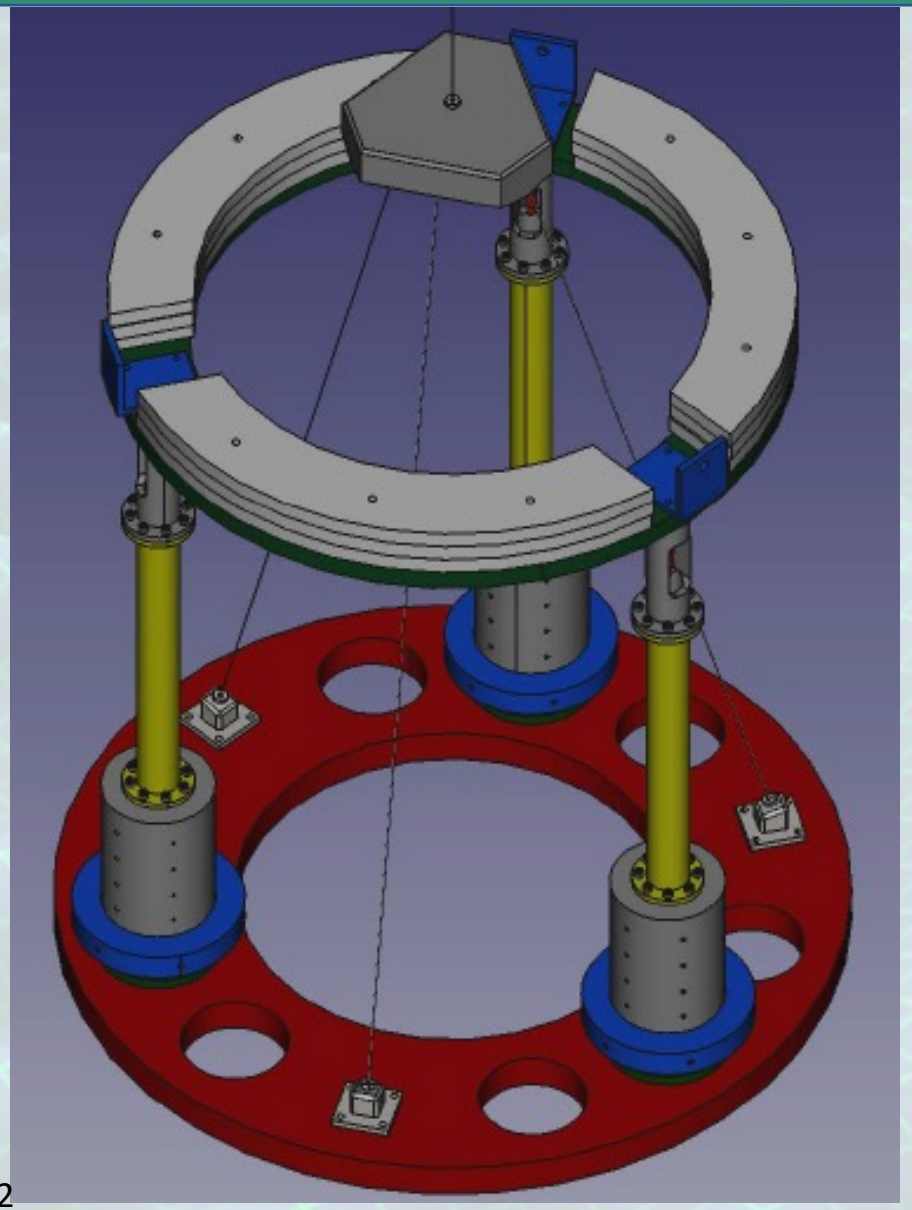
- **Horizontal Attenuation**

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

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}



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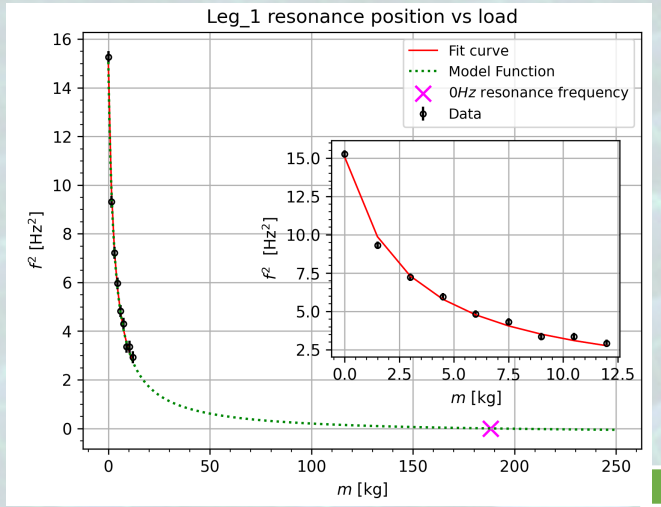
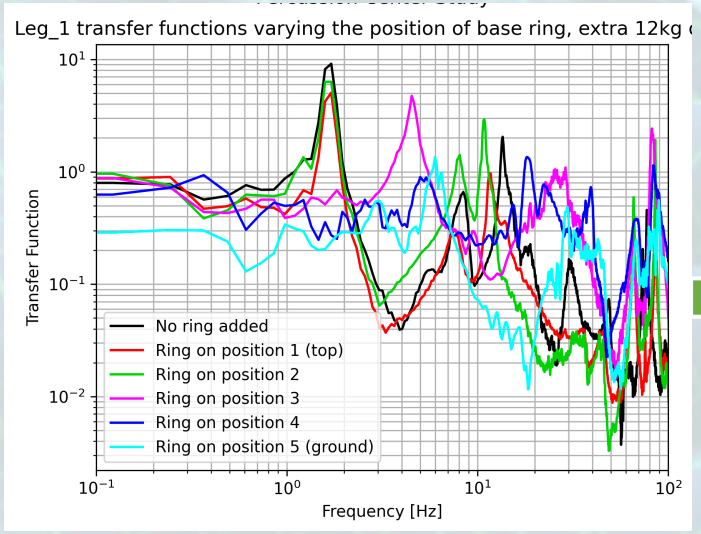
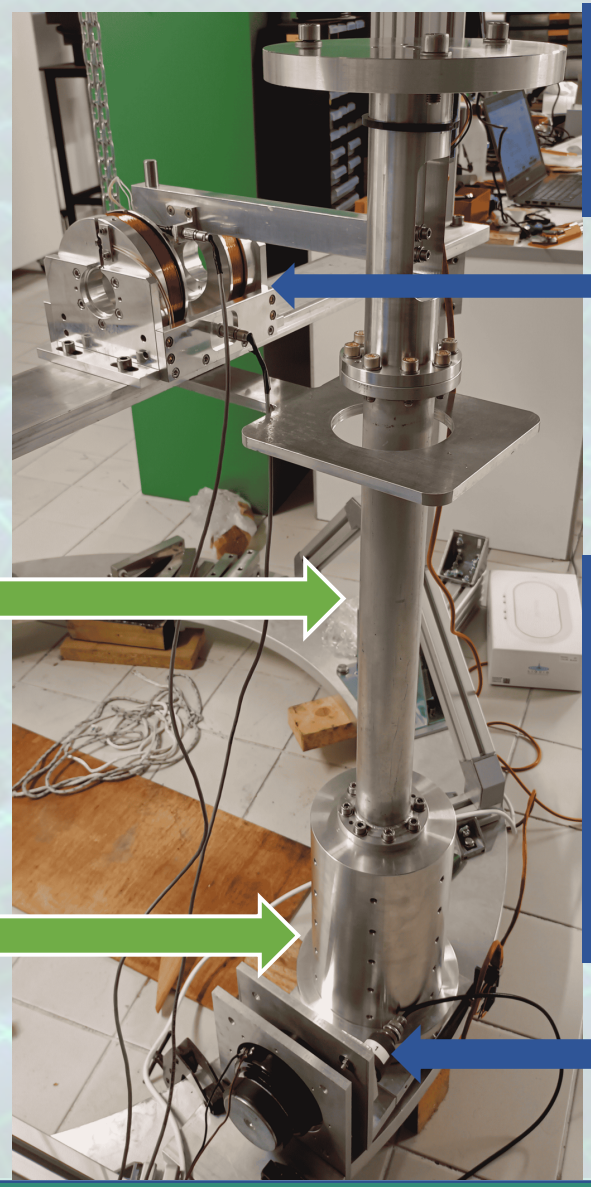
First Characterizations in the Lab

- **First Prototype**
  - First components built and tested at INFN-Pisa Lab
  - Characterized PIP inverted pendulum legs







LVDTs (measuring top motion)

Leg

Counterweights

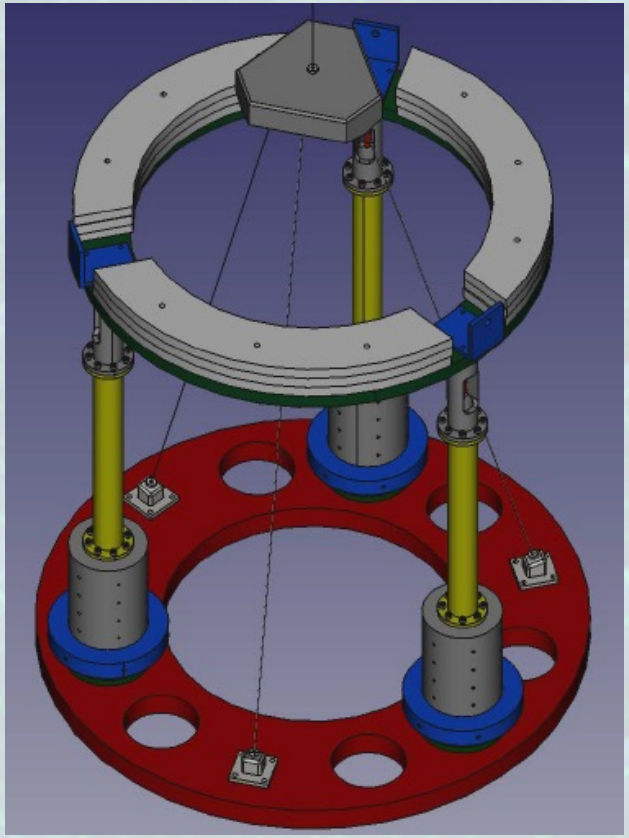
Base actuator + LVDTs (moving & measuring bottom motion)

Testing first PIP prototype

First components built and tested at INFN-Pisa Lab

Prototype assembled and under test

PIP Base+Legs



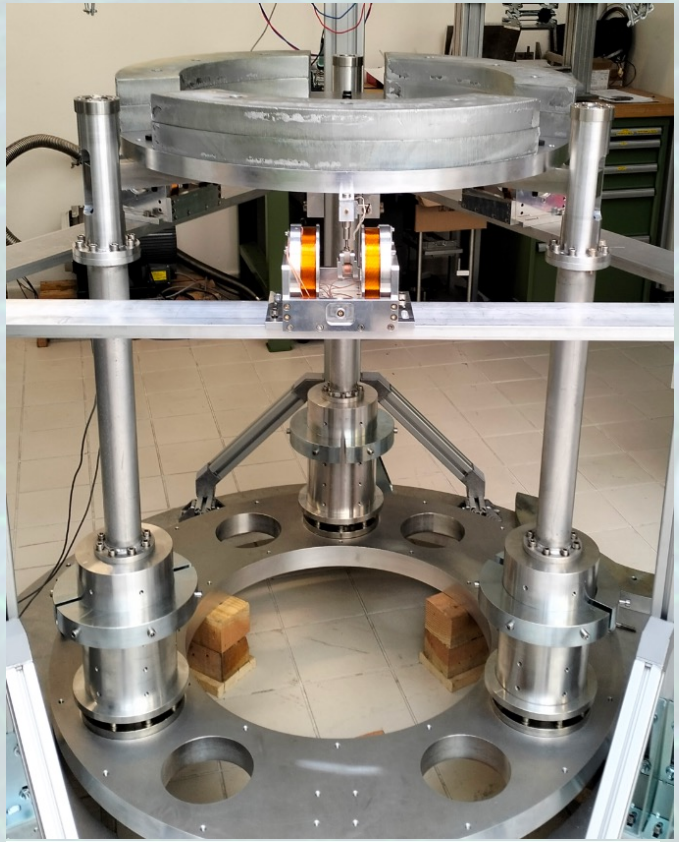
PIP CAD

Testing first PIP prototype

First components built and tested at INFN-Pisa Lab

Prototype assembled and under test

PIP Base+Legs



PIP Inverted pendulum

PIP suspended!
(last week update)

Conclusions

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

- **New ideas for seismic attenuation**
  - Passive+active approach
  - Elaborating 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, now prototype testing