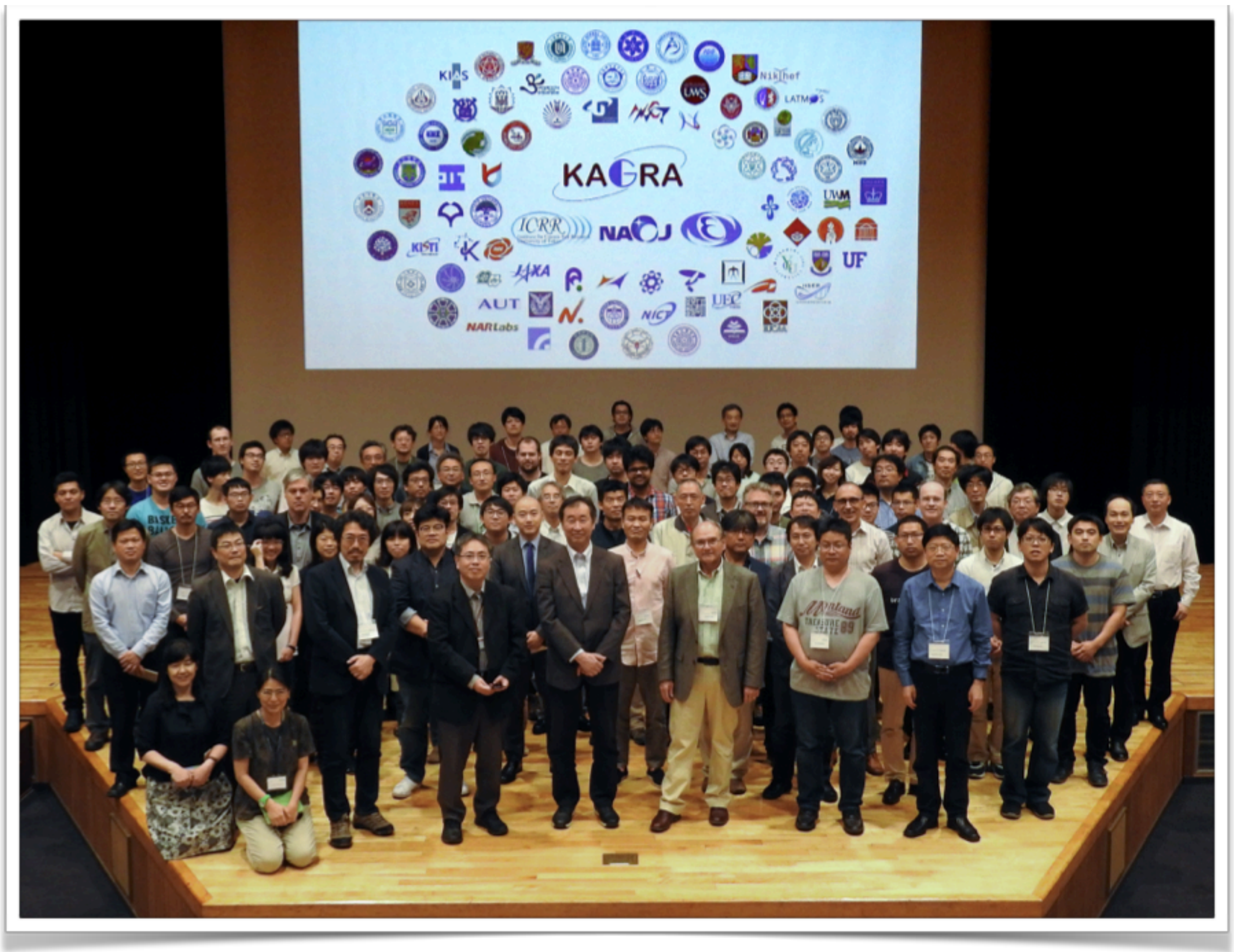
Reducing the seismic disturbances: an underground detector

Eleonora Capocasa

KAGRA gravitational wave detector

The KAGRA collaboration

- Host institution: ICRR   Co-Host: NAOJ and KEK
- More than 90 institutions from Japan and abroad (~280 collaborators)



KAGRA timeline

2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020

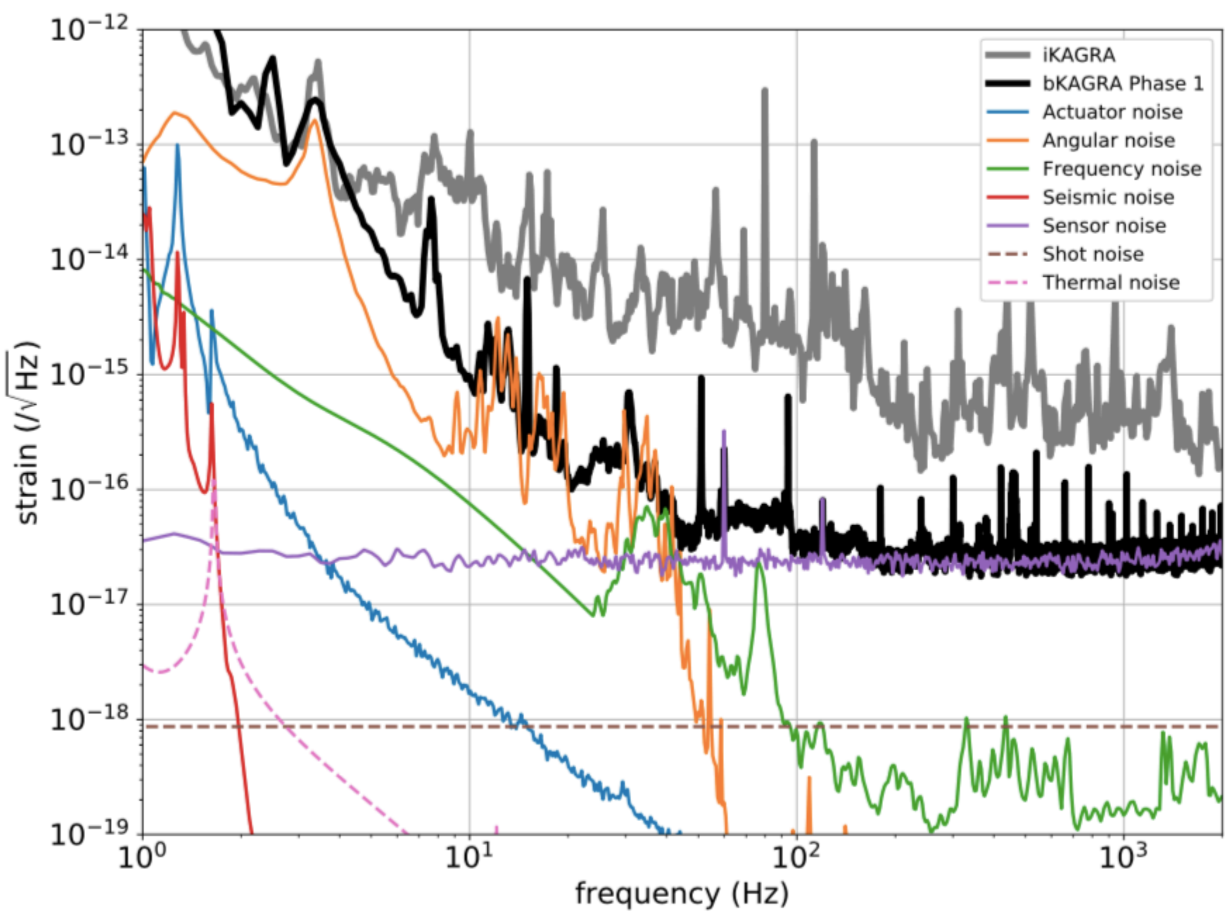
Founded by MEXT (~165 M$)

Tunnel excavation

iKagra run (simple Michelson)

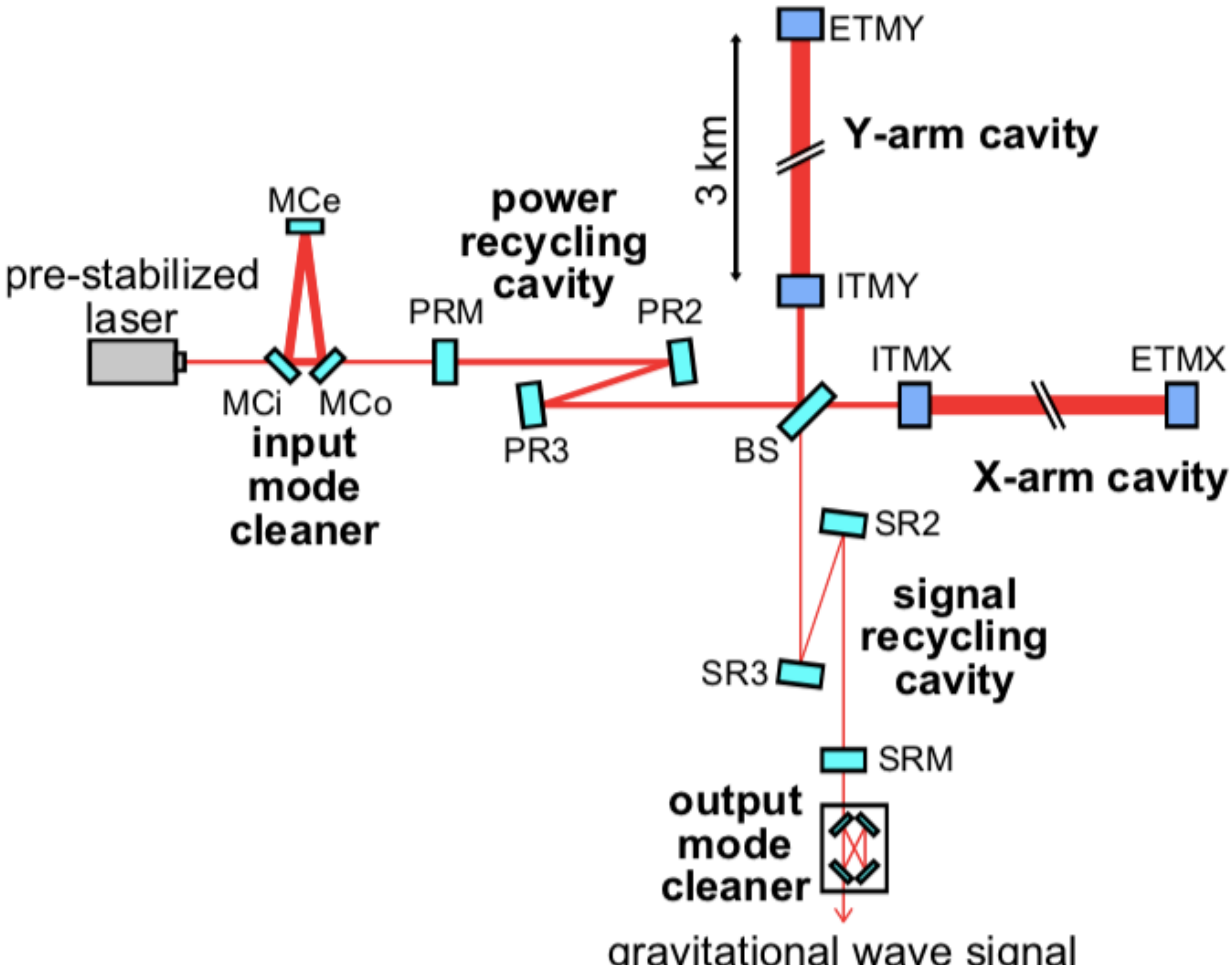
bKagra run (simple Michelson + cryogenic mirror)

Join O3



arXiv:1901.03569

KAGRA optical scheme



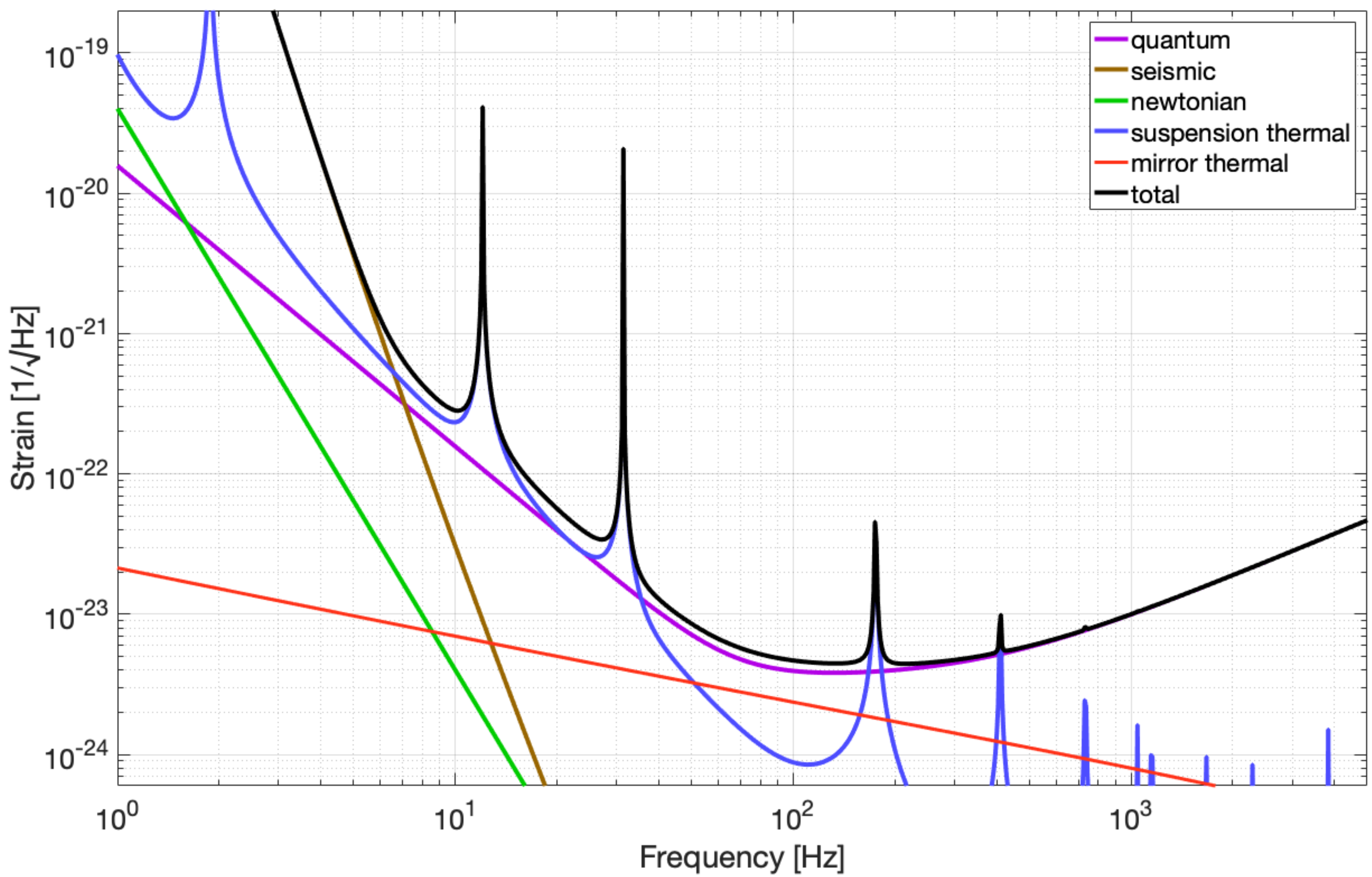
Status of KAGRA

- Injection system installed and commissioned
- All the suspensions have been installed in they vacuum chamber
- All the mirrors are suspended (including the cryogenic ones)
- X arm has been stably locked (more than 1 day of continuous lock)

..next steps..

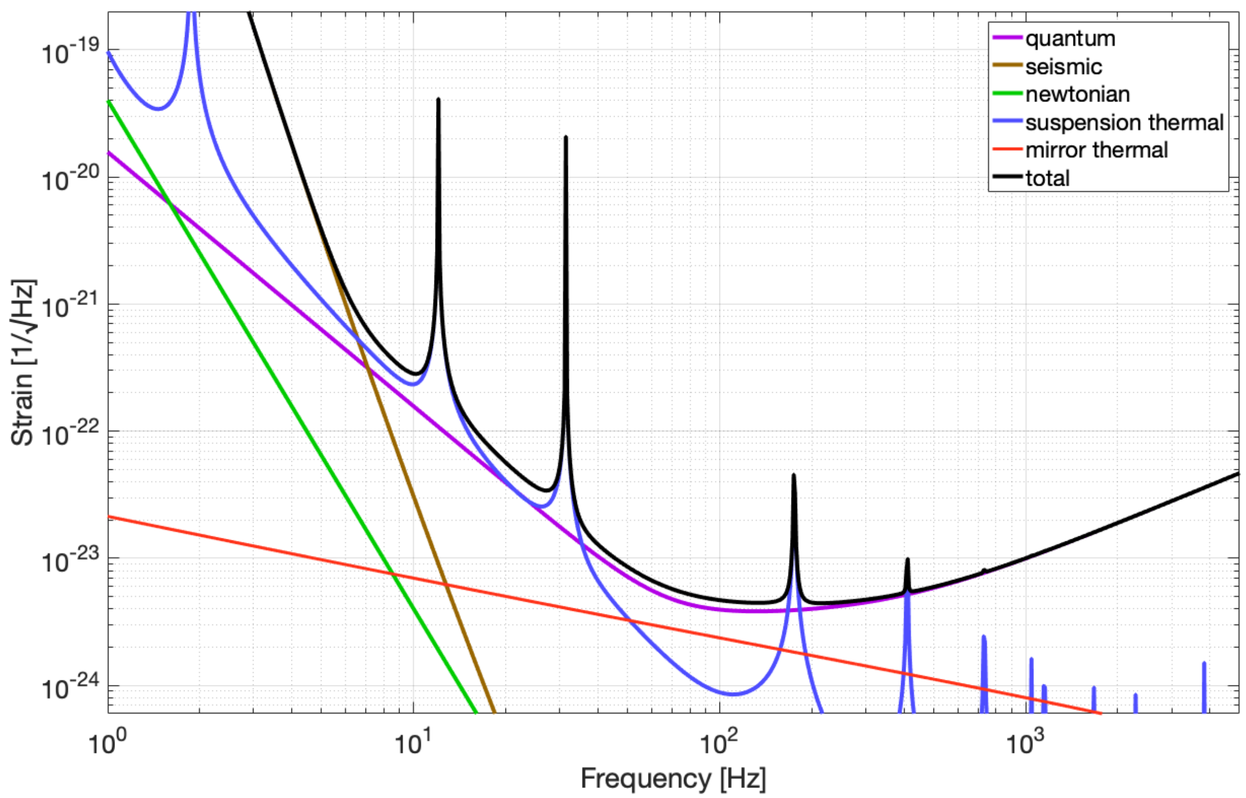
- Lock of the Y arm
- Lock of the full dual recycling interferometer
- Intense commissioning activity to join the network before the end of O3

Expected sensitivity

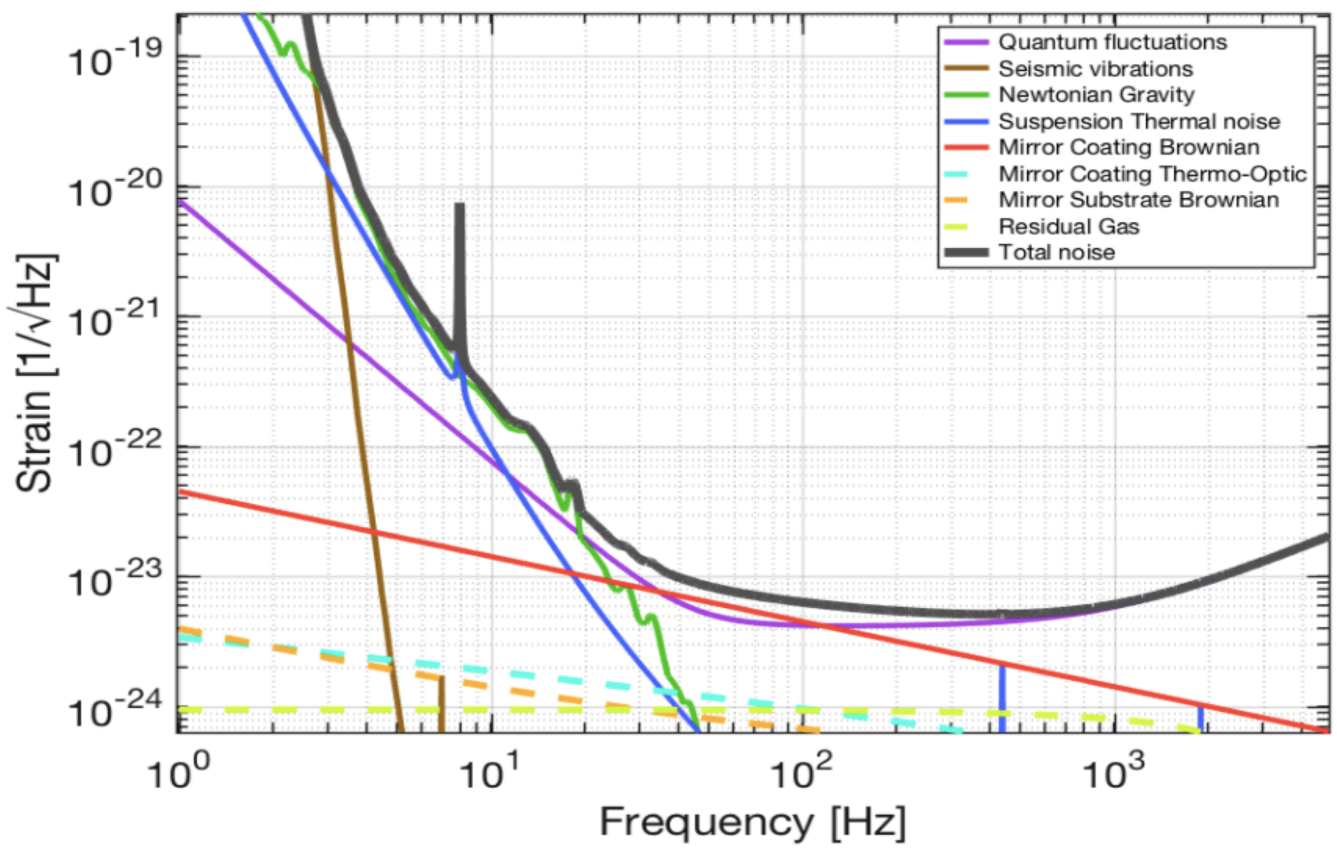


Expected sensitivity

KAGRA



VIRGO



- Seismic noise (and Newtonian noise) limit the low frequency sensitivity

Why to reduce seismic disturbance?

- Reduce Newtonian Noise
- Reduced low-frequency motion of mirrors
- Lower gain of control loops → lower control noise in-band
- Reduce technical noise coupled to seismic (i.e scattered light)
- Stability

Seismic noise

A persistent vibration of the ground generated by natural and human activities

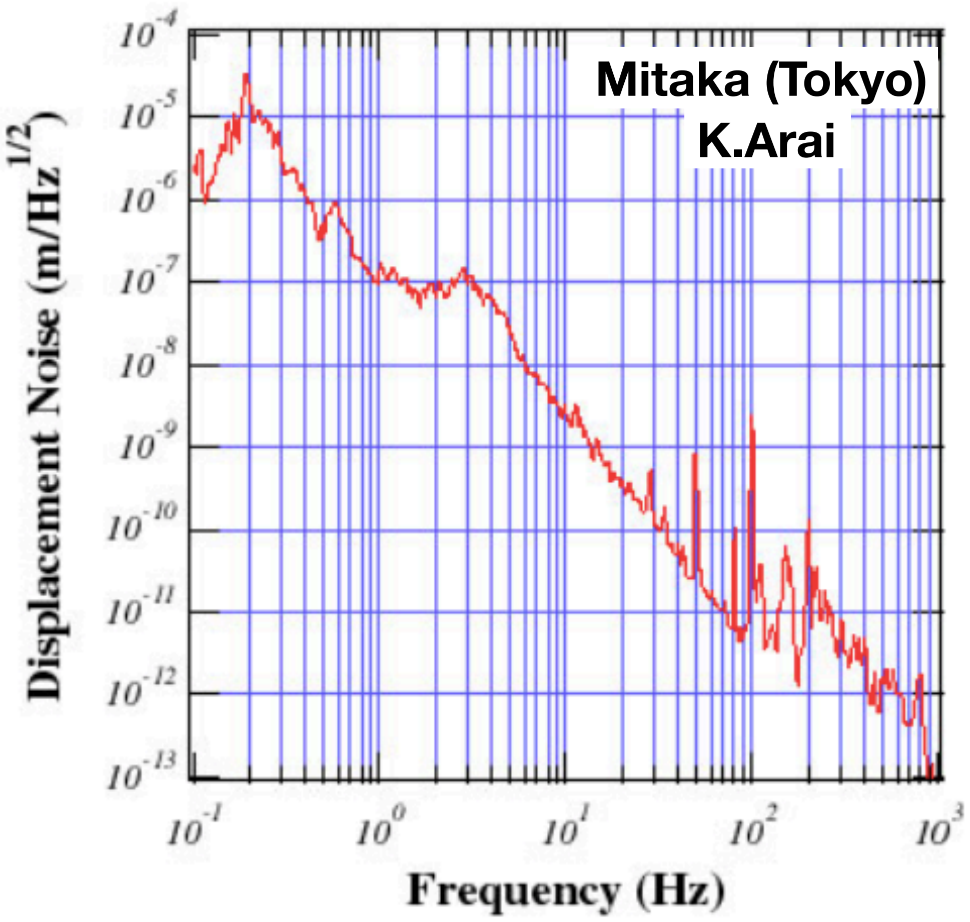
- Low frequency: ($f < 1$ Hz): oceanic and sea origin. Depends on large-scale meteorological conditions
- Mid frequency: ($f \sim 1$ Hz): local meteorological condition
- High frequency: ($f > 1$ Hz): human activities

Seismic noise amplitude

- Amplitude spectral density (above few Hz) approximated by

$$\tilde{x} = A \times \left[\frac{1\mathrm{Hz}}{f^2}\right] \; [\mathrm{m}/\sqrt{\mathrm{Hz}}]$$

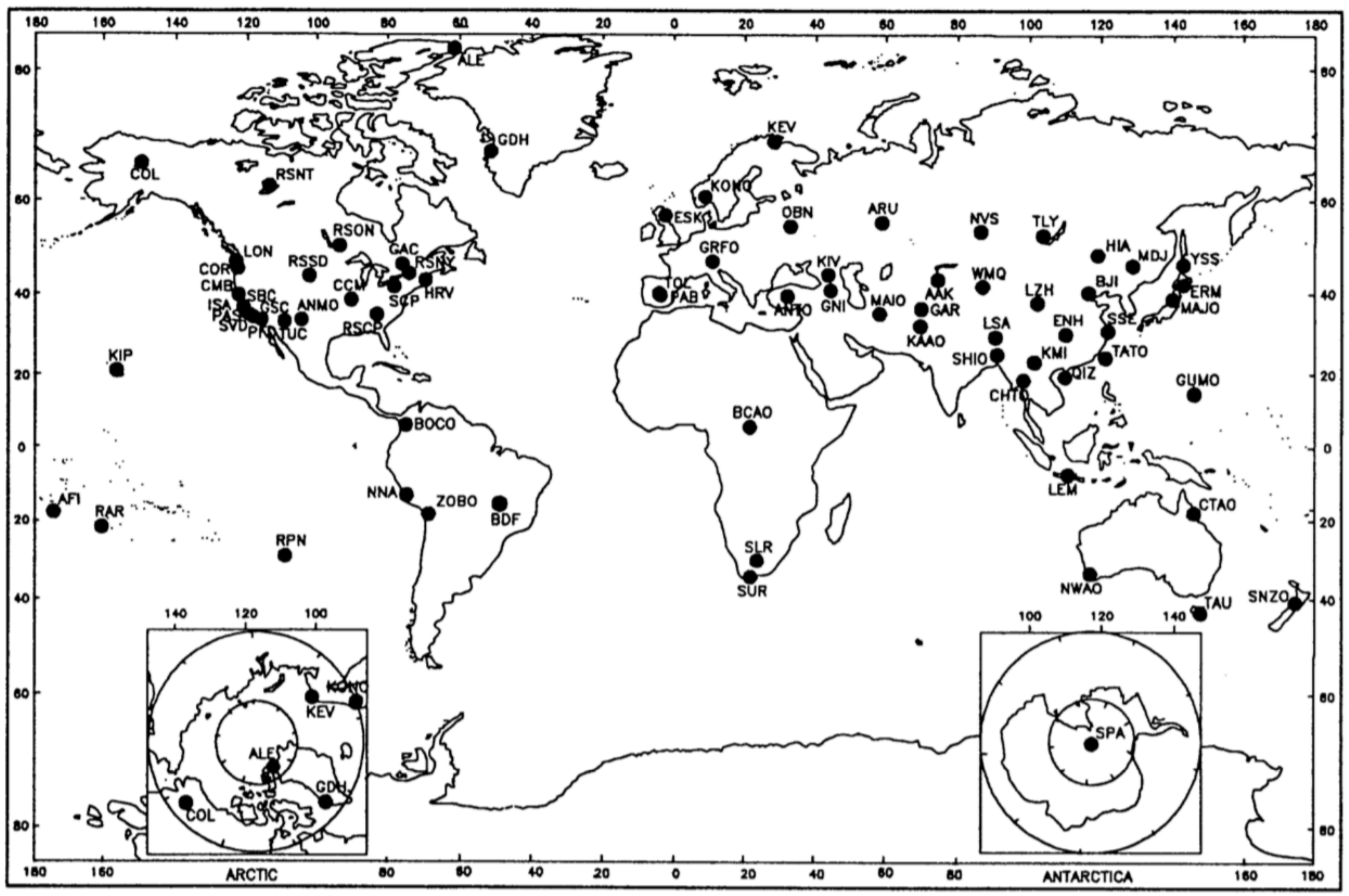
$$A \simeq 10^{-6} - 10^{-9}$$



- It can vary depending on the human and natural activity
- Similar amplitude in the three directions

Seismic noise characterization

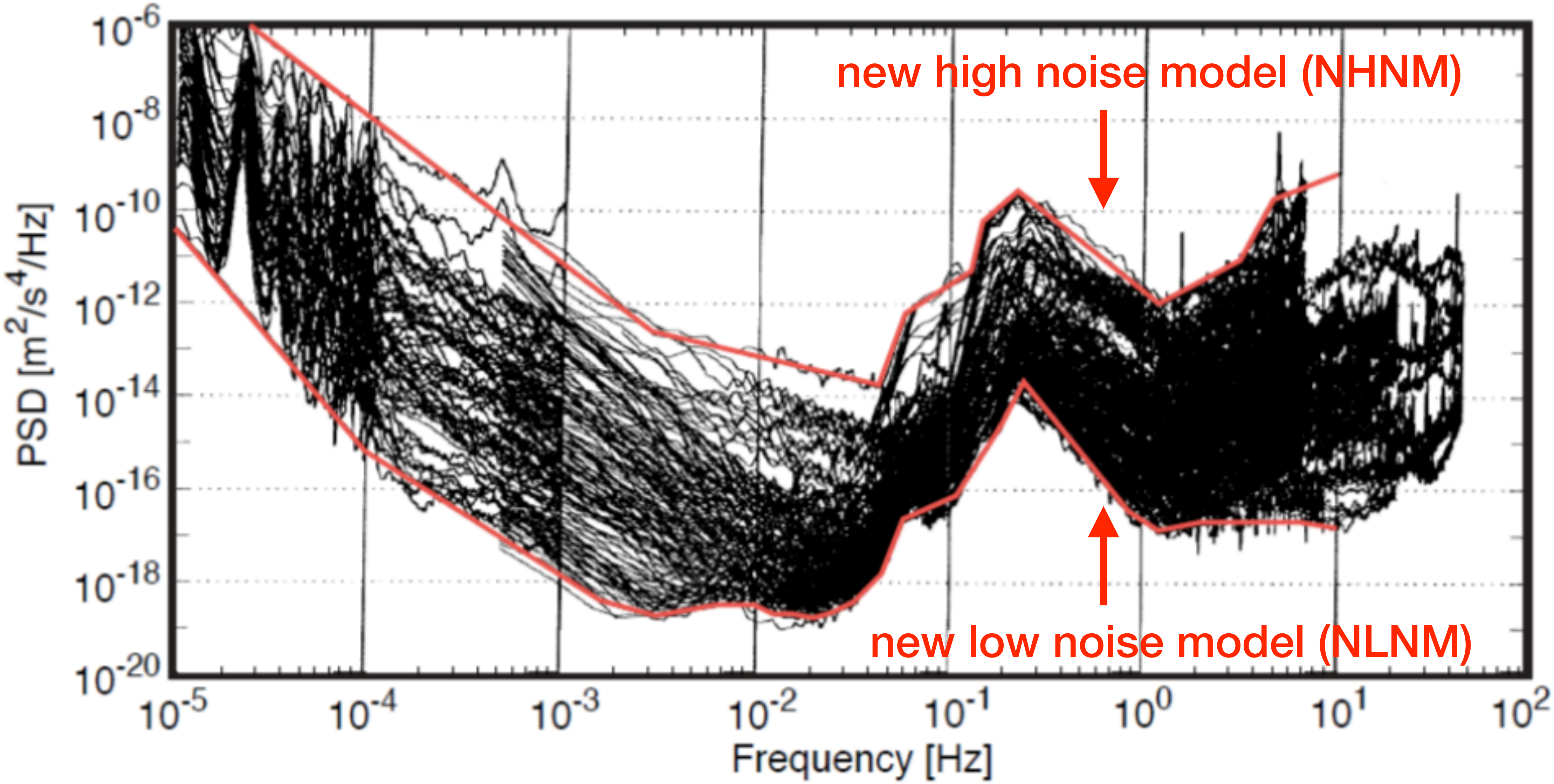
- Peterson measurement from a worldwide seismometer network composed of 75 stations (in surface and underground)



Peterson (1993), *Observation and modeling of seismic background noise*.
U.S. Geological Survey Technical Report 93-322, pages 1–95.

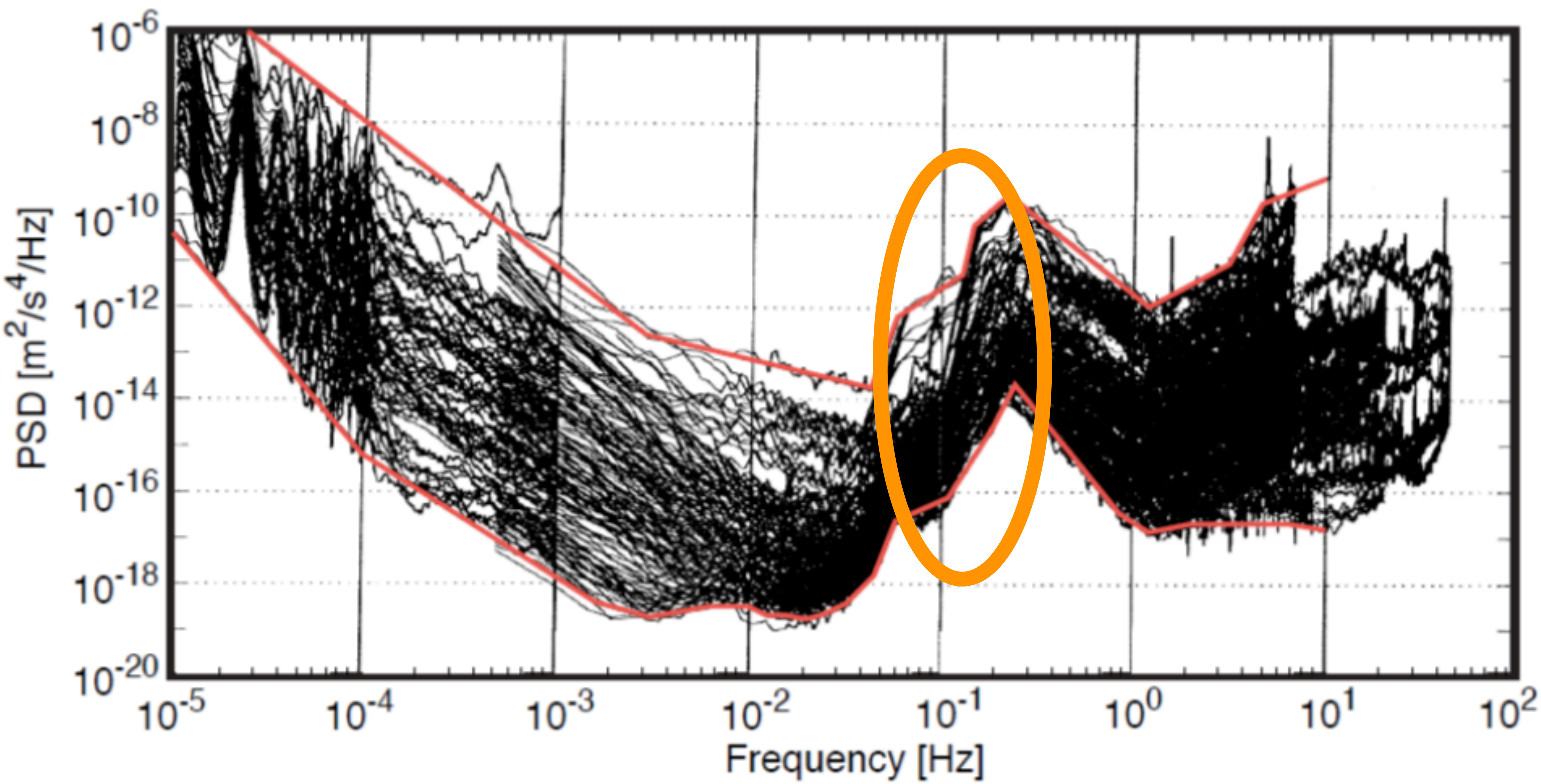
Seismic noise characterization

- Measurement between 10^{-5} and 50 Hz



Peterson (1993), *Observation and modeling of seismic background noise*.
U.S. Geological Survey Technical Report 93-322, pages 1–95.

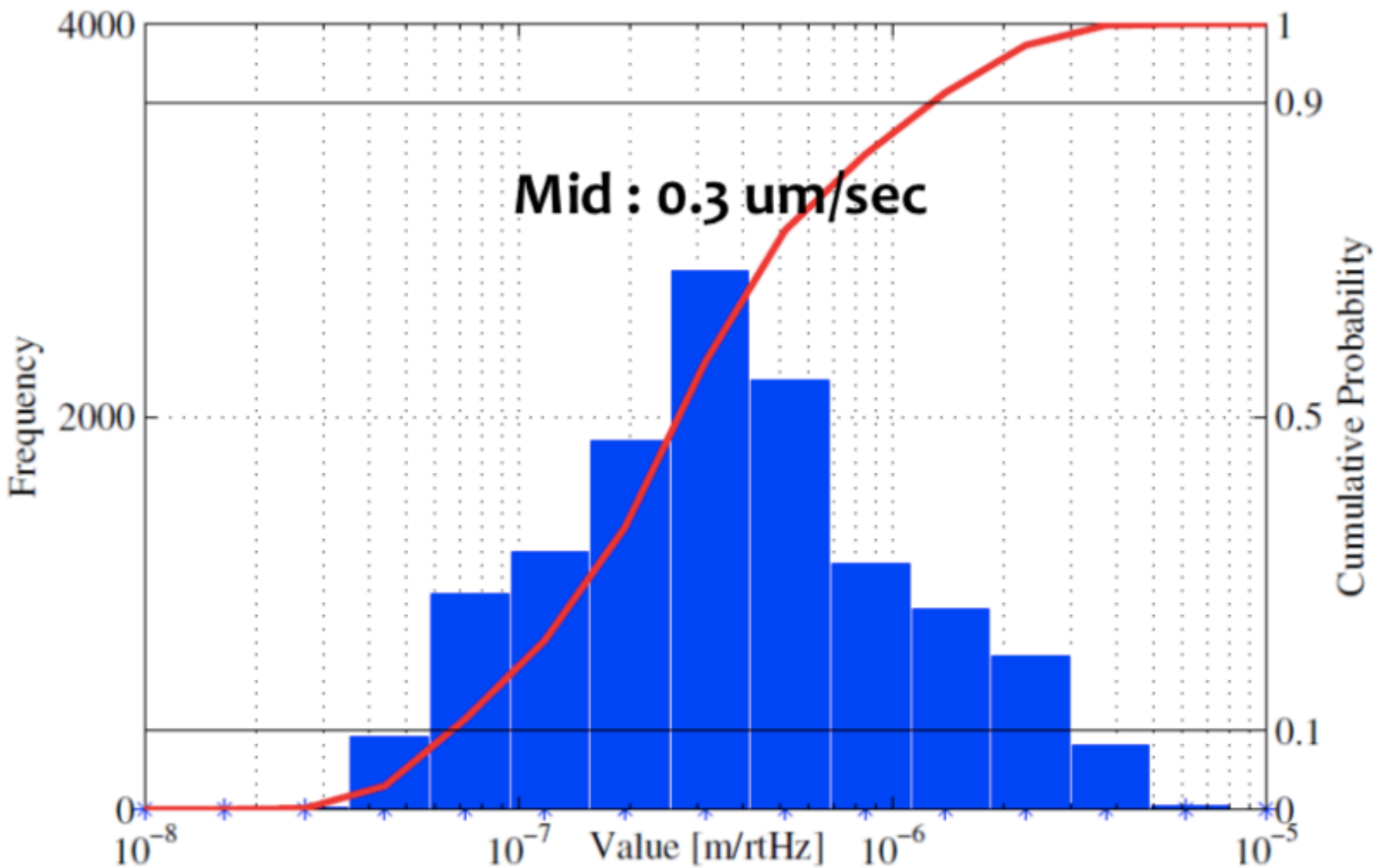
Microseism



- PRIMARY (~ 0.06 – 0.1 Hz): generated only in shallow waters next to the coast
- SECONDARY (~0.2 Hz): generated by pairs of ocean wave trains of opposing propagation directions with half the seismic frequency -> more harmful

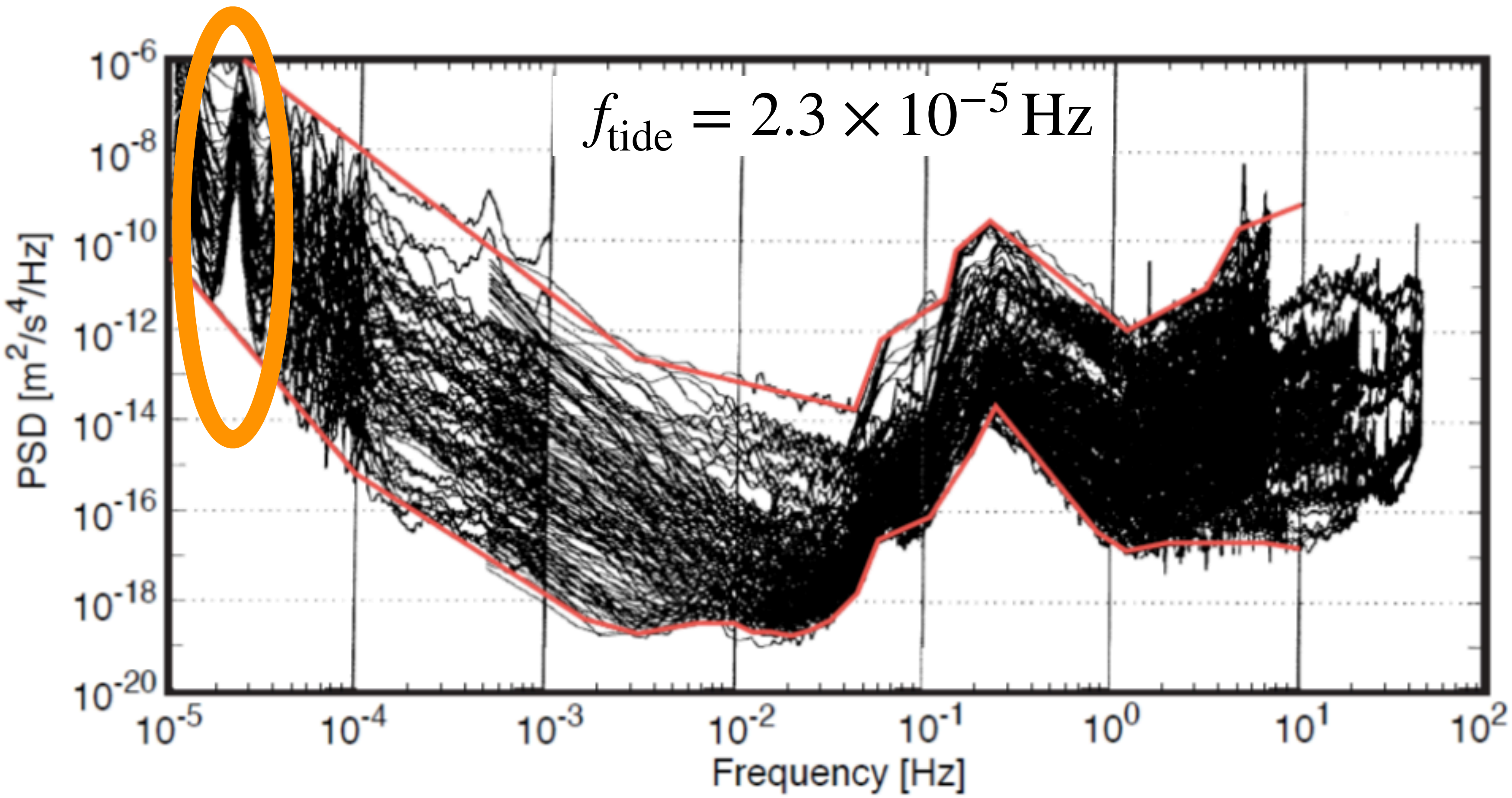
Microseism in KAGRA

Histogram of displacement at 0.2 Hz (Sept. 2009 ~ Feb. 2011)



T.Sekiguchi

Earth tide



- Effect of the gravitational interaction with the Moon and Sun
- Strain of ~ 100 um for the kilometric interferometer
- Test mass move coherently and the effect can be predicted and compensated → not a limitation for the sensitivity

1500 m strain meter in Kamioka mine

Araya *et al. Earth, Planets and Space* (2017) 69:77
DOI 10.1186/s40623-017-0660-0

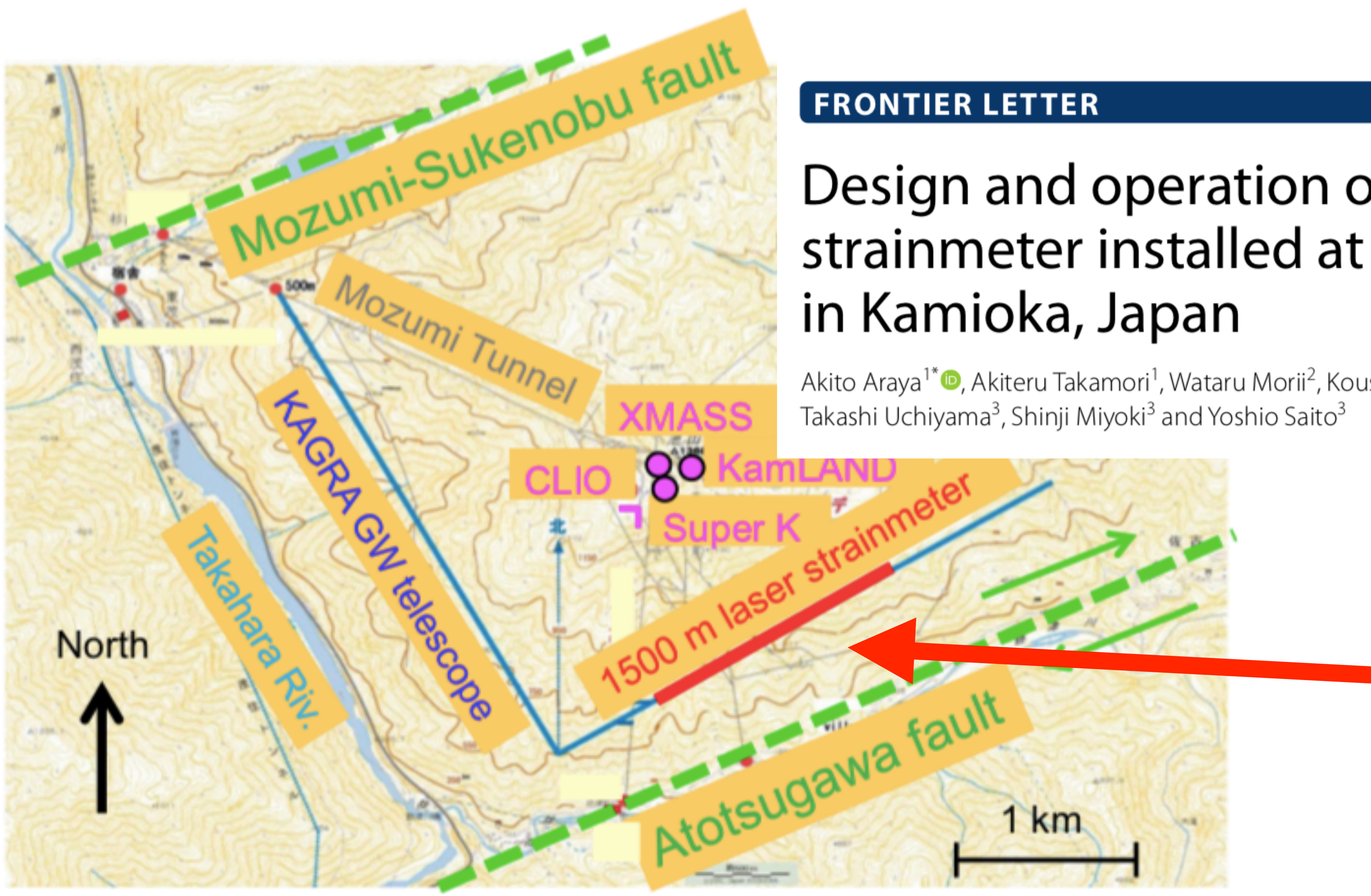
Earth, Planets and Space

FRONTIER LETTER Open Access

CrossMark

Design and operation of a 1500-m laser strainmeter installed at an underground site in Kamioka, Japan

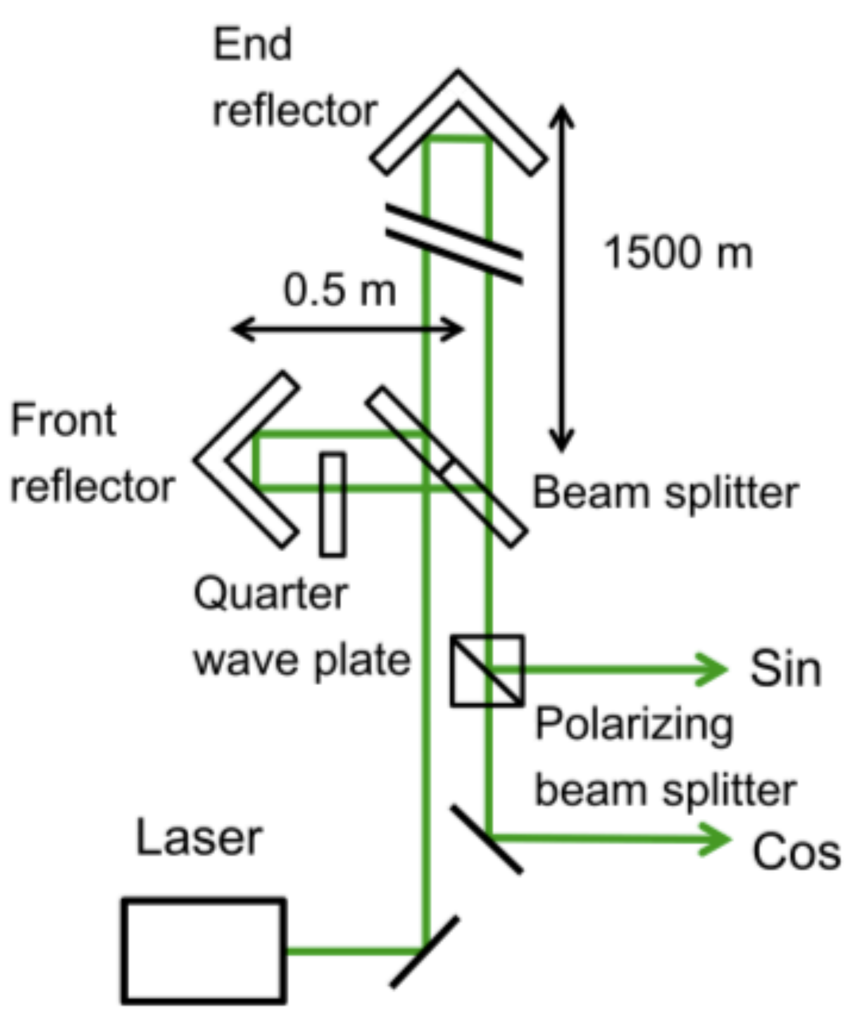
Akito Araya[1*], Akiteru Takamori[1], Wataru Morii[2], Kouseki Miyo[3], Masatake Ohashi[3], Kazuhiro Hayama[3], Takashi Uchiyama[3], Shinji Miyoki[3] and Yoshio Saito[3]

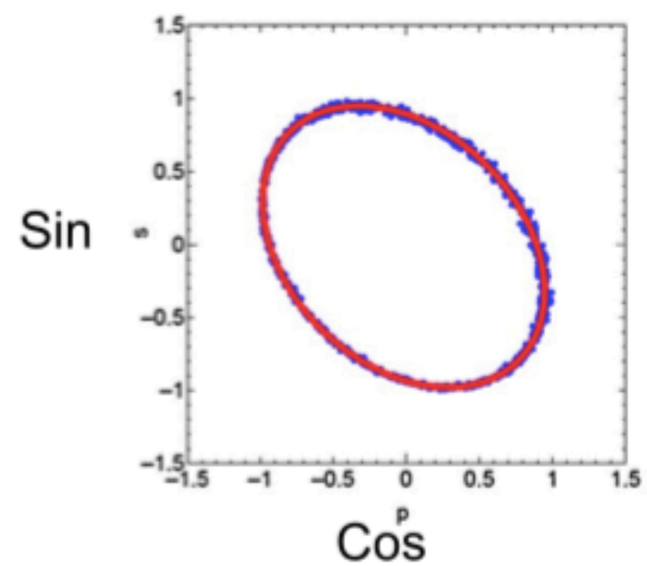


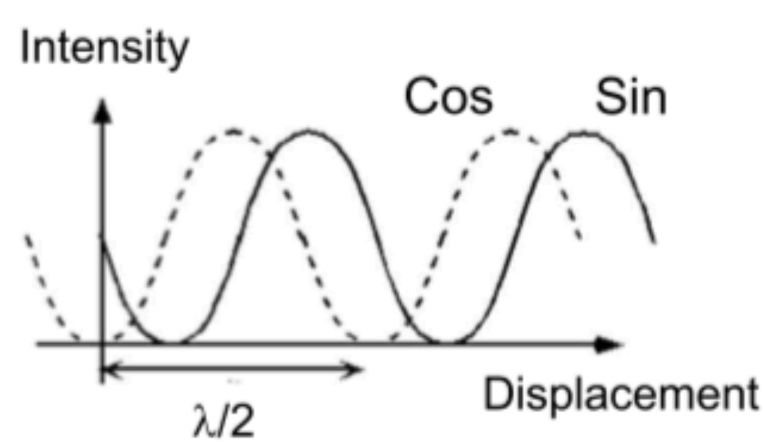
- Asymmetric Michelson interferometer to measure strain at low frequency

1500 m strain meter: operation

- Mirrors are fixed to the ground with granite blocks
- High frequency stabilized laser





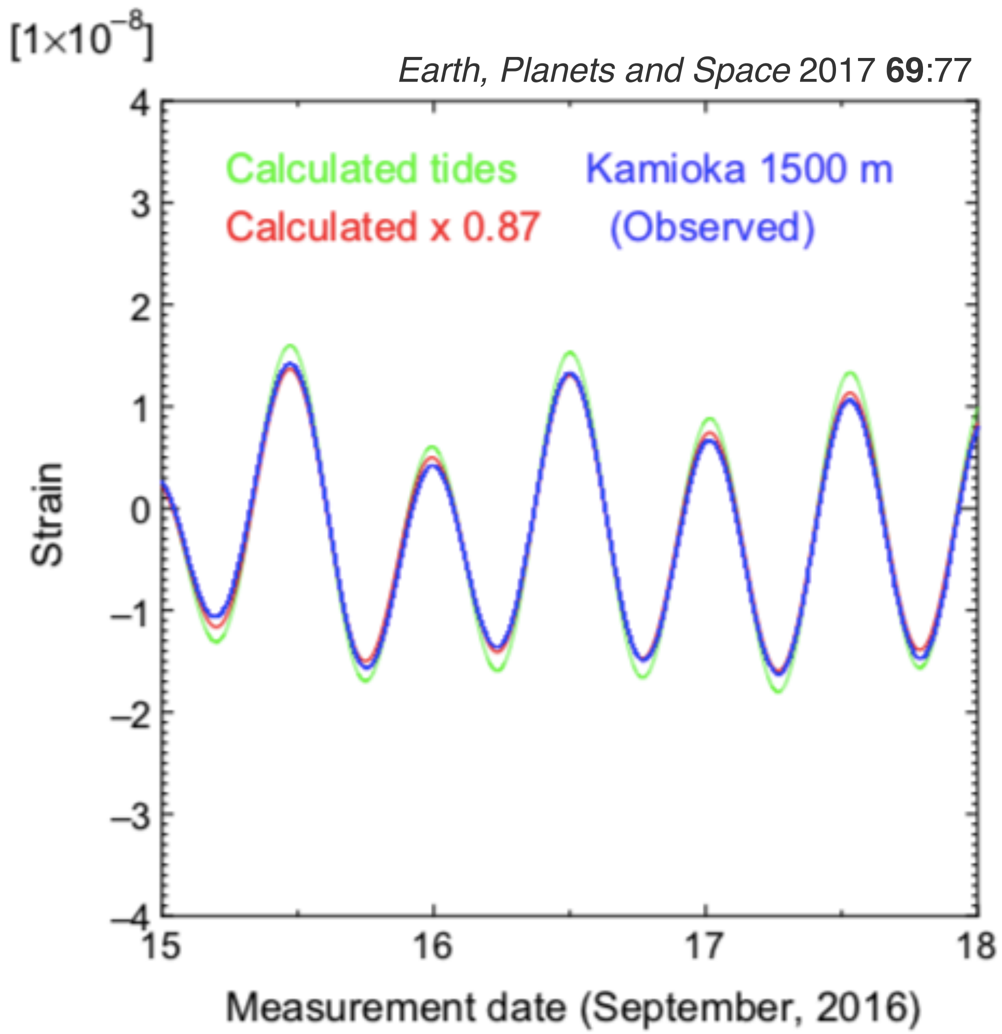


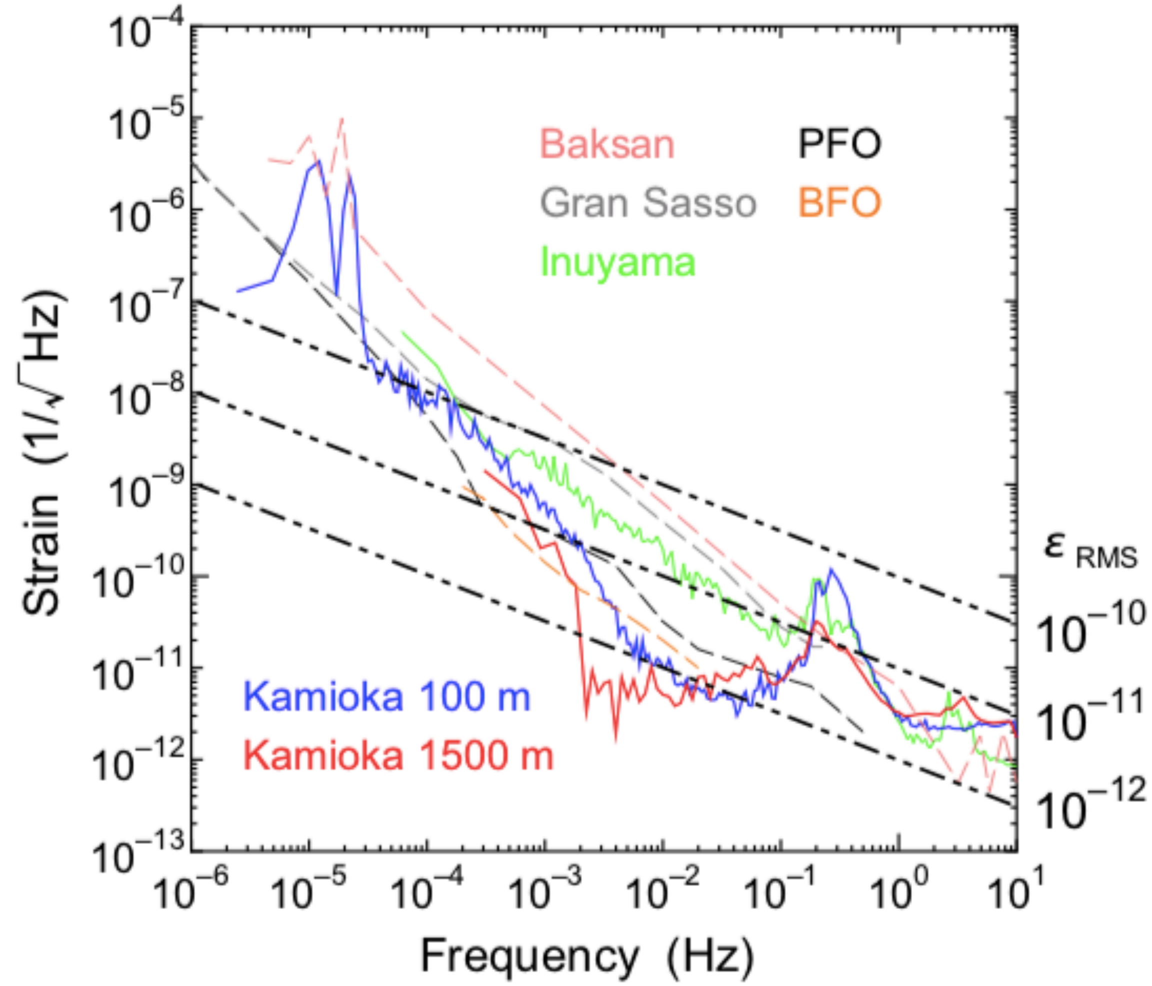
Quadrature interferometer

- A quarter-wave plate produces a 90° phase shift between S and P polarizations.
- The intensities of the interference beams separated by the polarizing beam splitter complementarily change as sine and cosine (bottom right)
- By normalizing the observed elliptic Lissajous curve (top right) into a circular one, mirror motion can be determined from the phase angle

Earth, Planets and Space 2017 **69**:77

1500 m strain meter: results



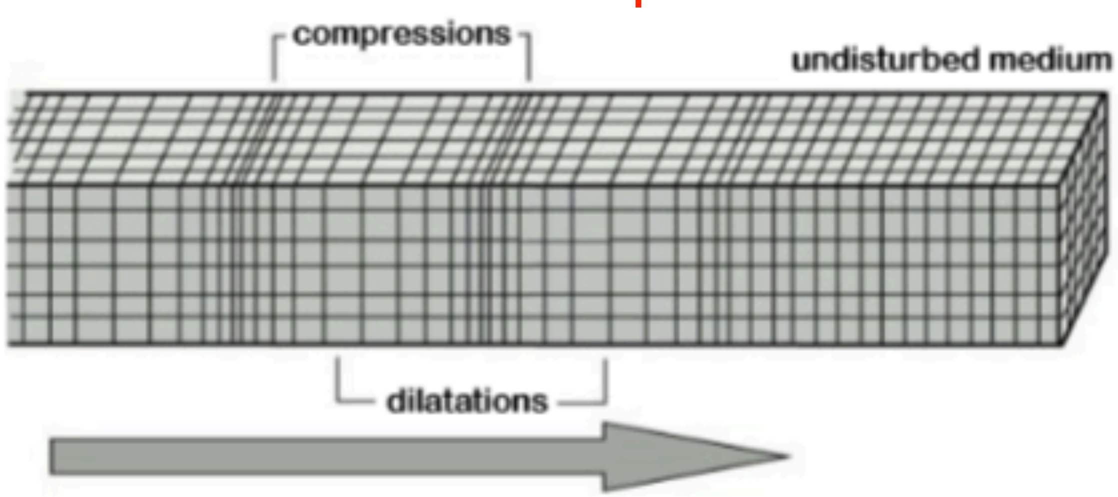


- The observed tidal waveform shows good agreement with the theoretical waveform
- Strain spectra show lower background noise than those obtained from other strain meters at 2–20 mHz

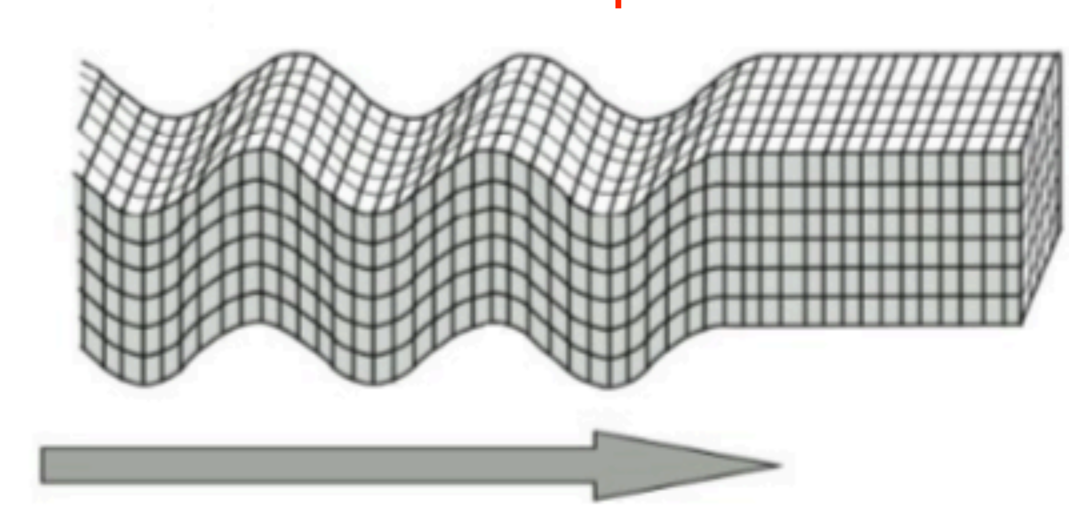
Seismic waves

Body waves

Speed : 0.5 - 8 km/s



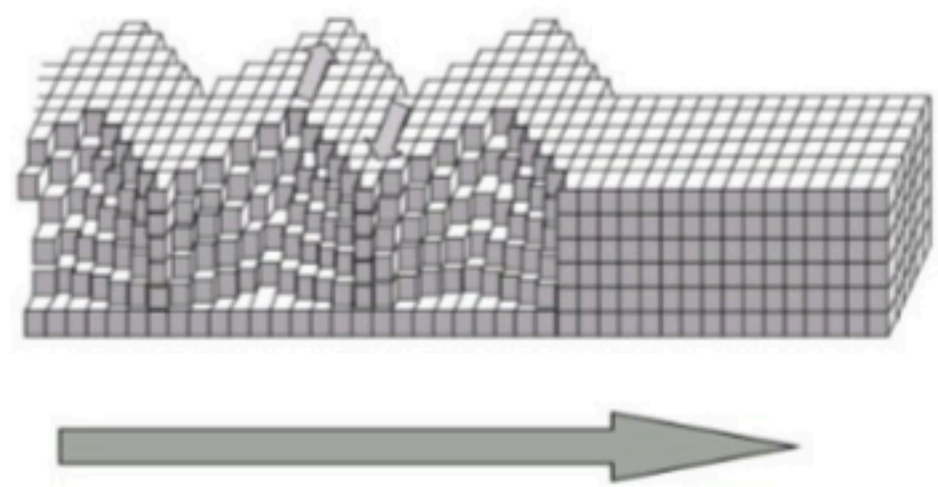
Speed : 0.25 - 4 km/s



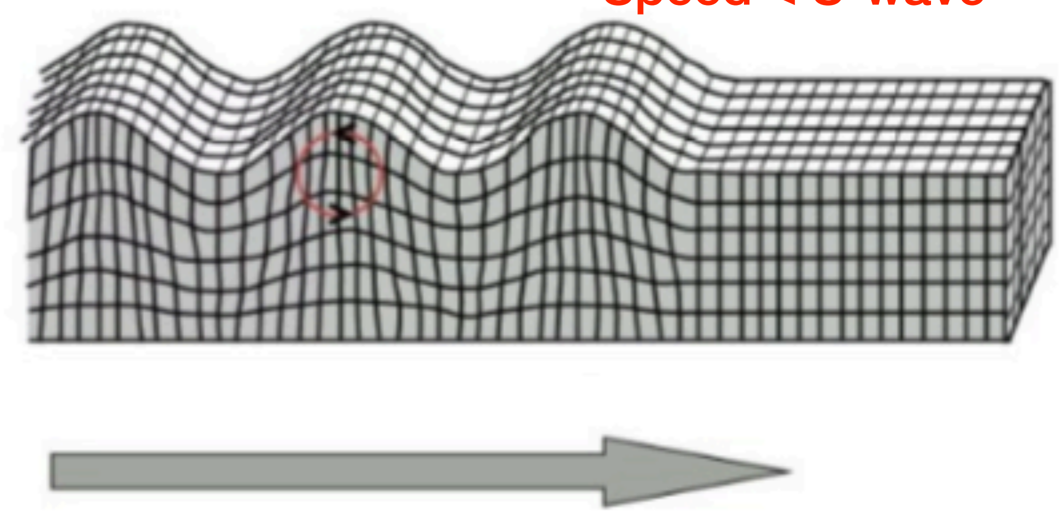
L. Naticchioni - *Low Frequency Noise Suppression for the Development of Gravitational Astronomy*. PhD Thesis.

Surface waves

Speed : < S-waves



Speed < S-wave



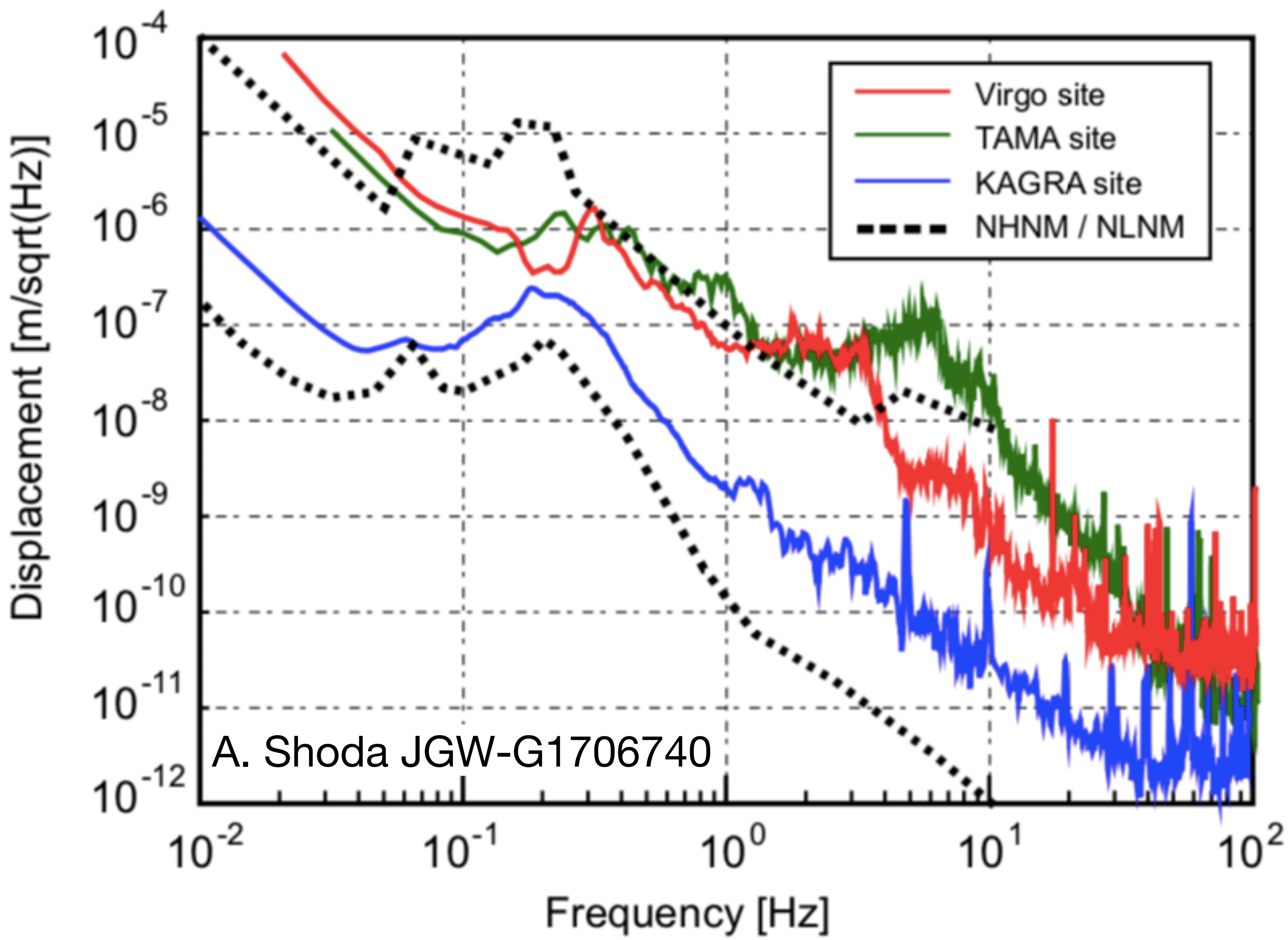
- *Lower frequency and larger amplitude*
- *Exponential decay with depth*

Depth dependence

- Seismic wave either by natural or anthropic sources, are attenuated exponentially in an underground environment

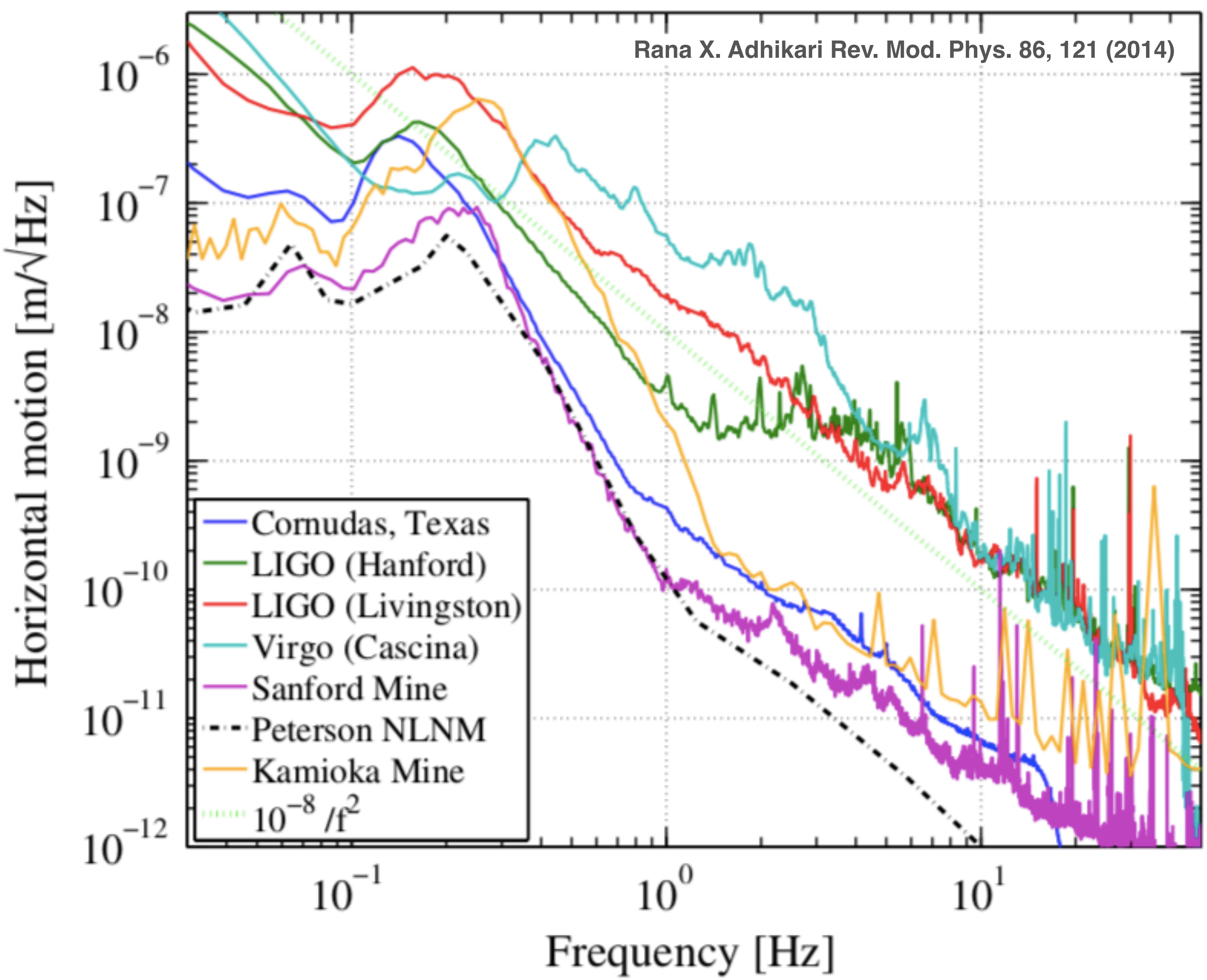
$$\frac{\tilde{x}_{seism}(f,d)}{\tilde{x}_{seism}(f,d=0)} \propto e^{-4\frac{d}{\lambda}}$$

d = depth
λ = seismic wavelength



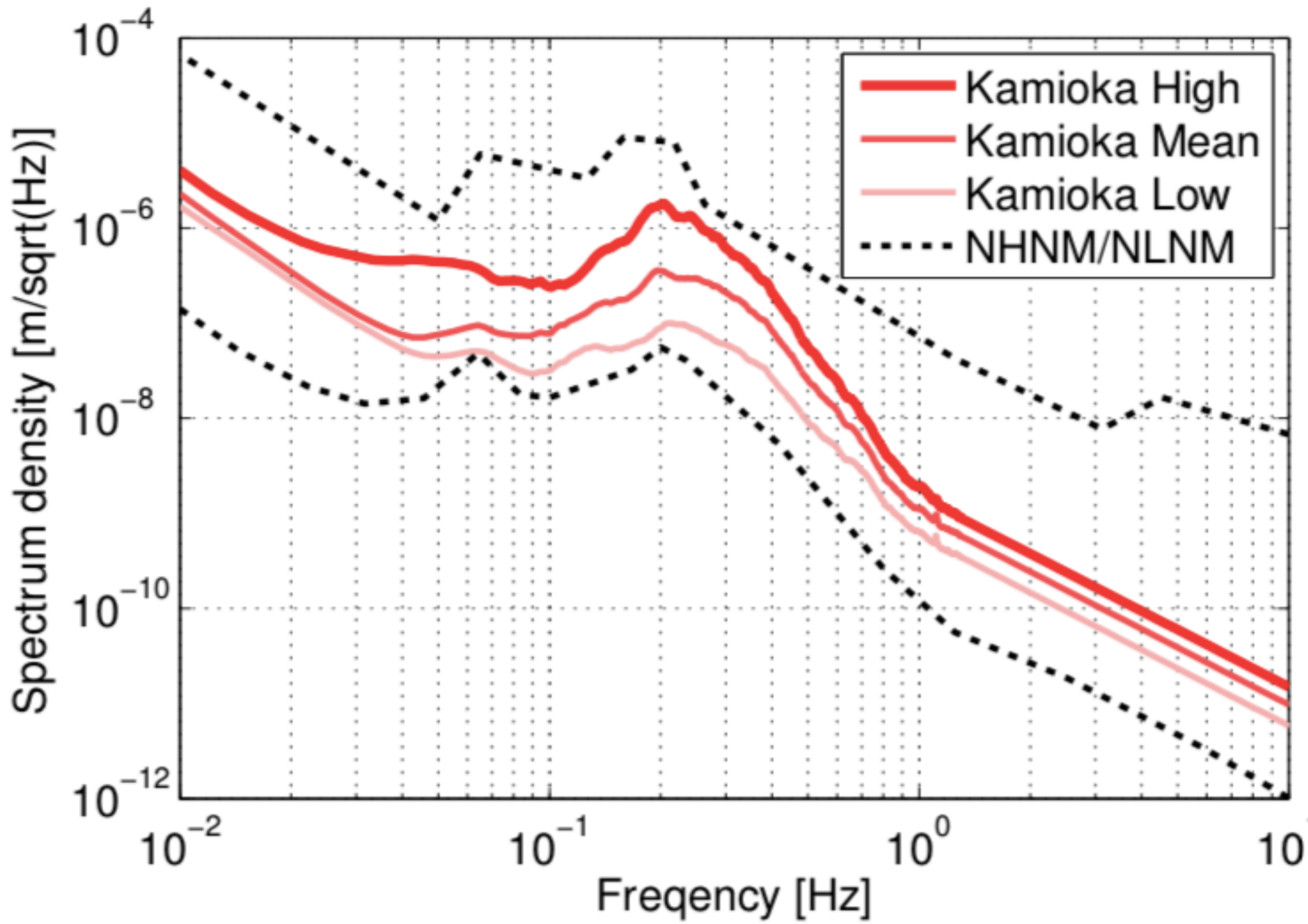
Factor ~100 between VIRGO and KAGRA site

Seismic noise at different detector sites



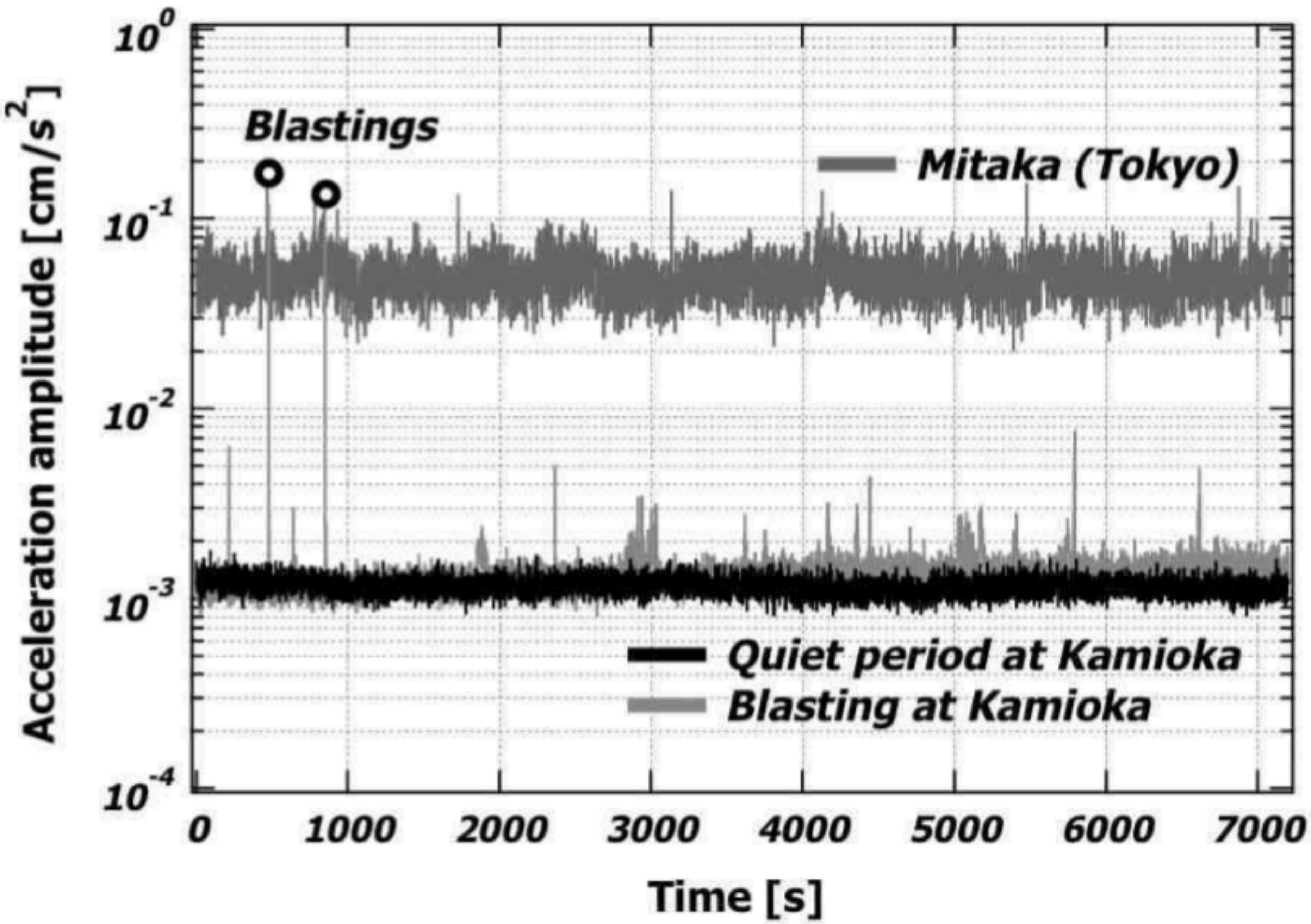
Seismic noise at different sites

- Large variation according to the atmospherical condition



T. Sekiguchi. A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors. Phd thesis

Seismic noise: time series

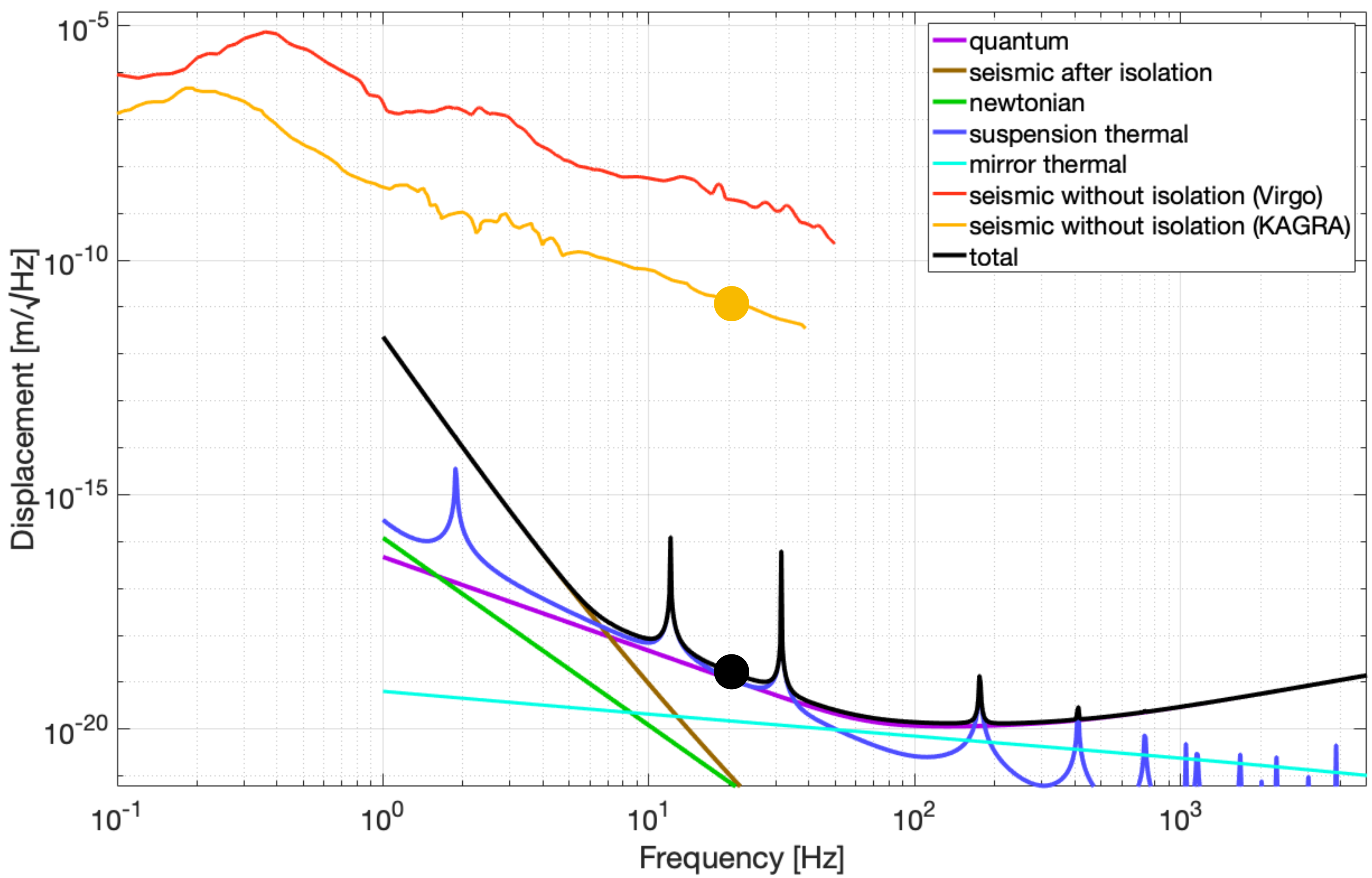


Ultrastable performance of an underground-based laser interferometer observatory for gravitational waves
LISM Collaboration
Phys. Rev. D **69**, 102005 – Published 28 May 2004.

Vibration isolation

- Seismic motion at ~10 Hz: ~ 10^{-11} m/√Hz
- Required mirror motion at ~10 Hz: ~ 10^{-19} m/√Hz

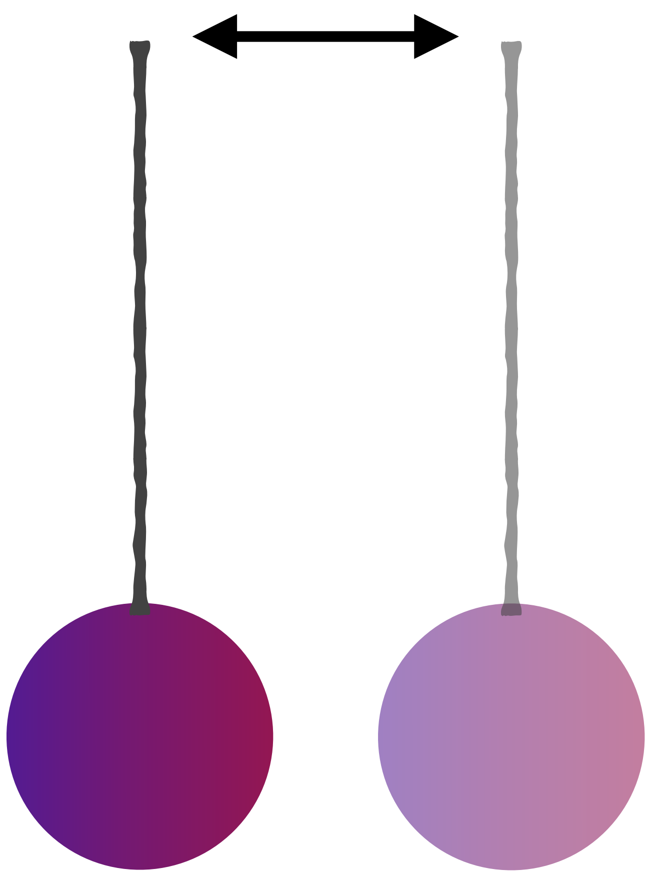
A high performance vibration isolation system is still required (at least 8 order of magnitudes)



Vibration isolation system

- Pendulum transfer function

slow motion



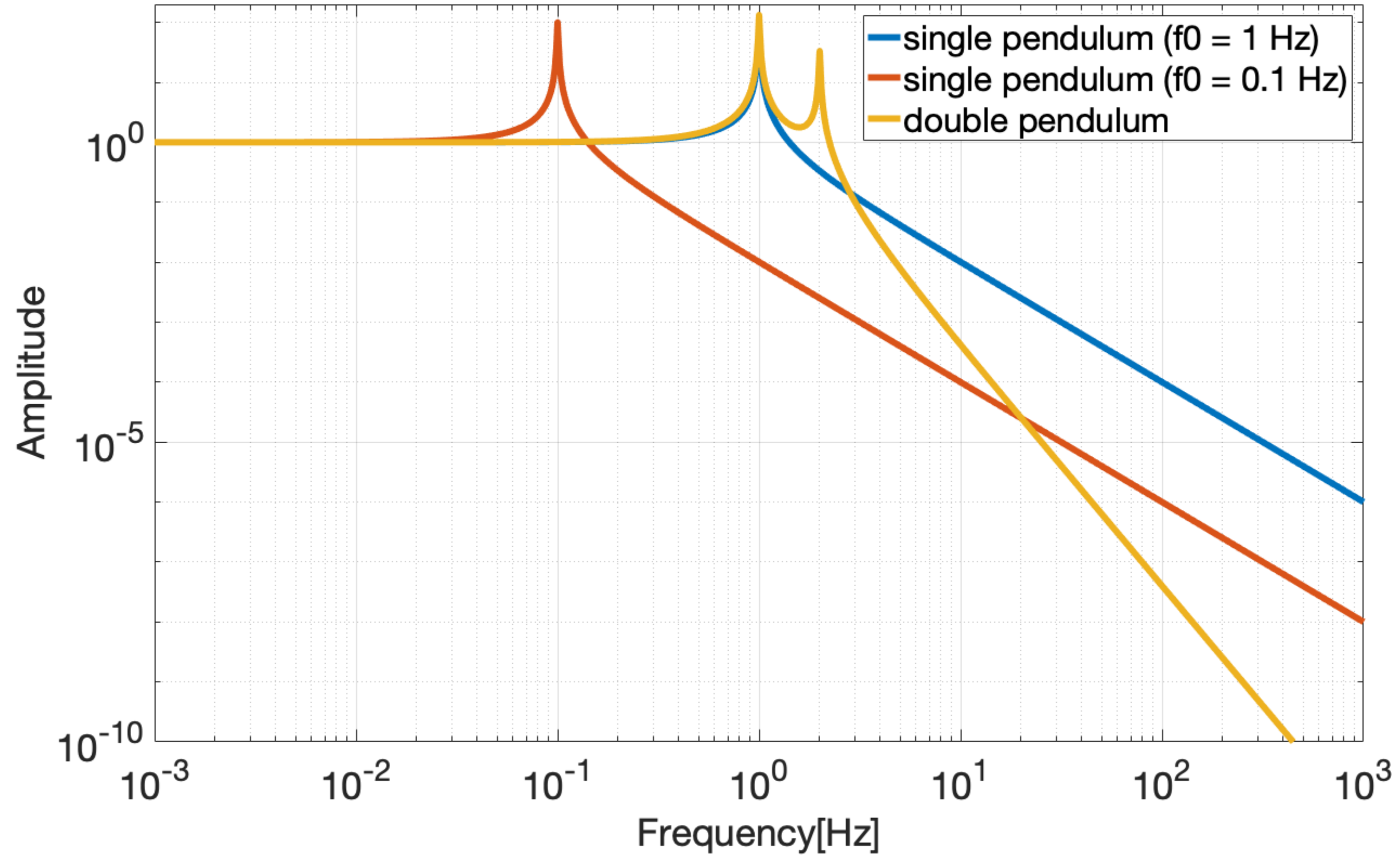
The suspended mass follows the suspension point

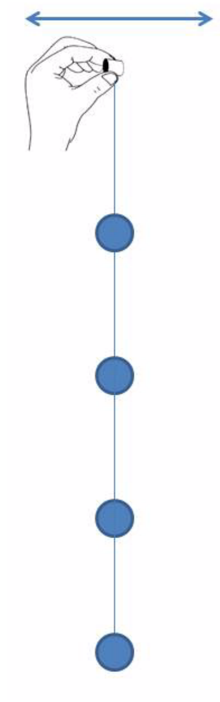
rapid motion

The suspended mass doesn't follows the suspension point

Vibration isolation system

- Usual system based on a chain of pendulums to isolate the test mass from the vibration of their suspension point

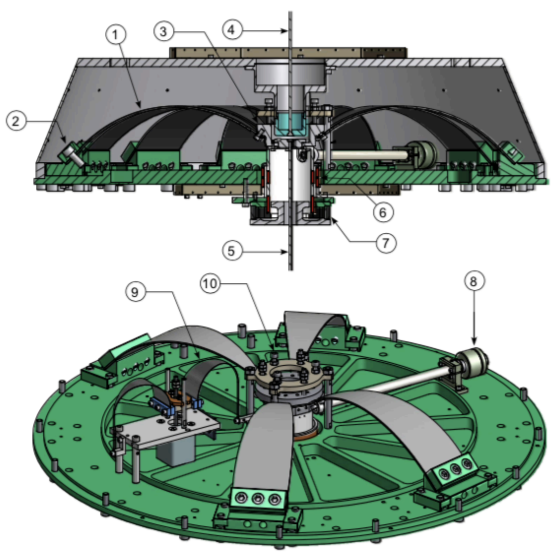




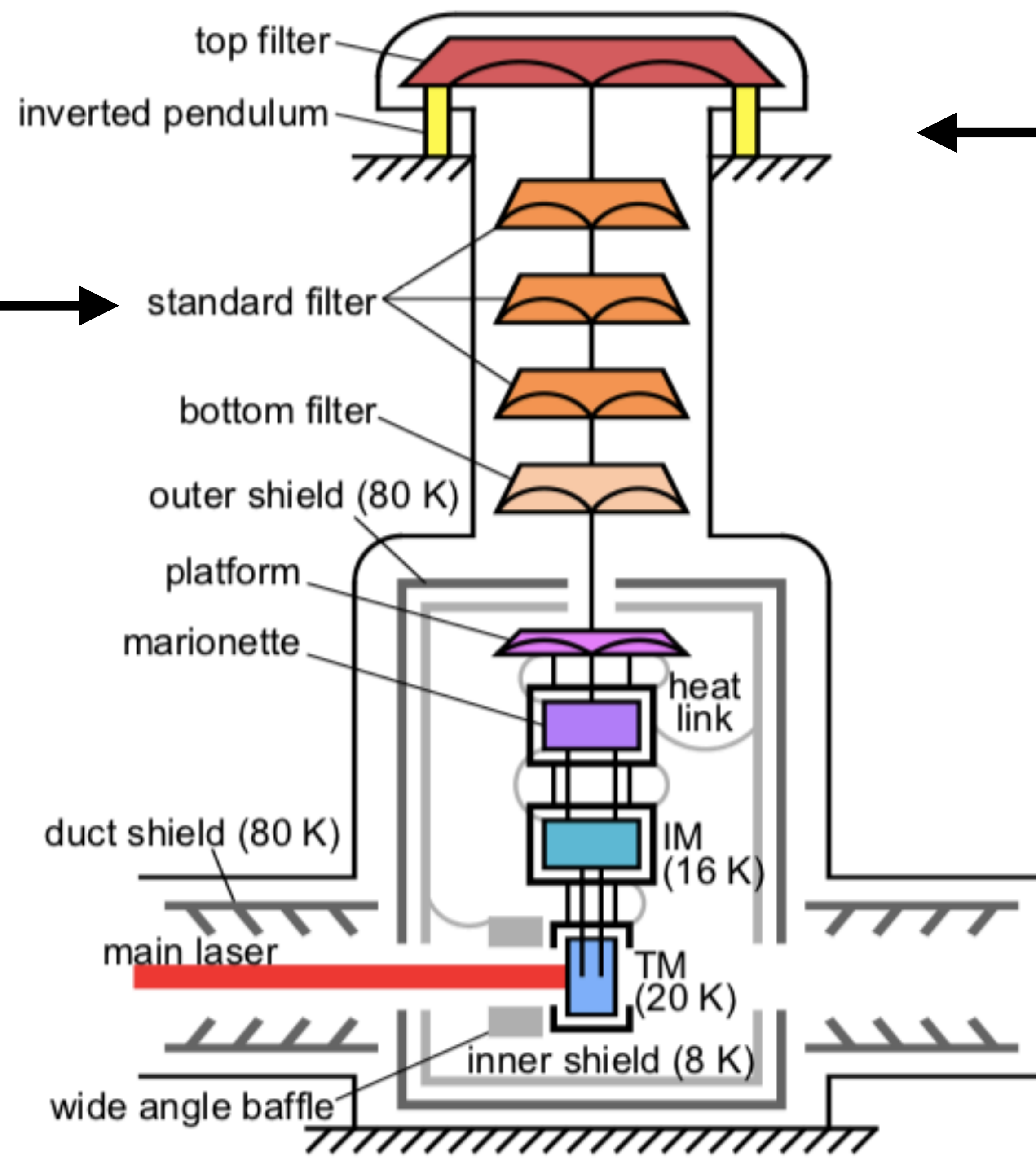
Transfer function: motion of mirror/motion of support

Vibration isolation system

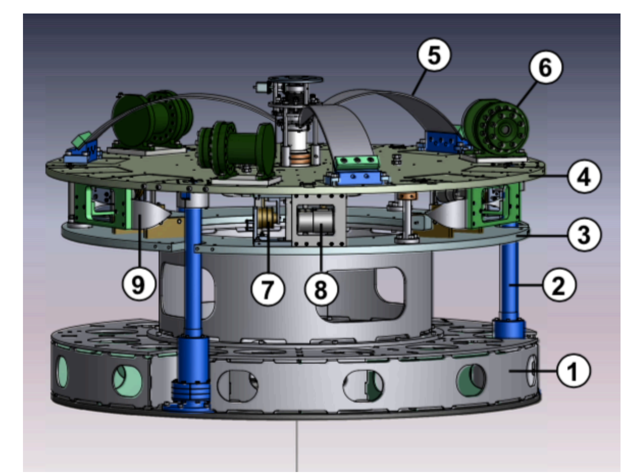
- KAGRA vibration isolations (as Virgo and TAMA) uses a chain of pendulums and vertical (GAS) spring to attenuate seismic vibration in all the degrees of freedom



Geometrical antispring (GAS) filter

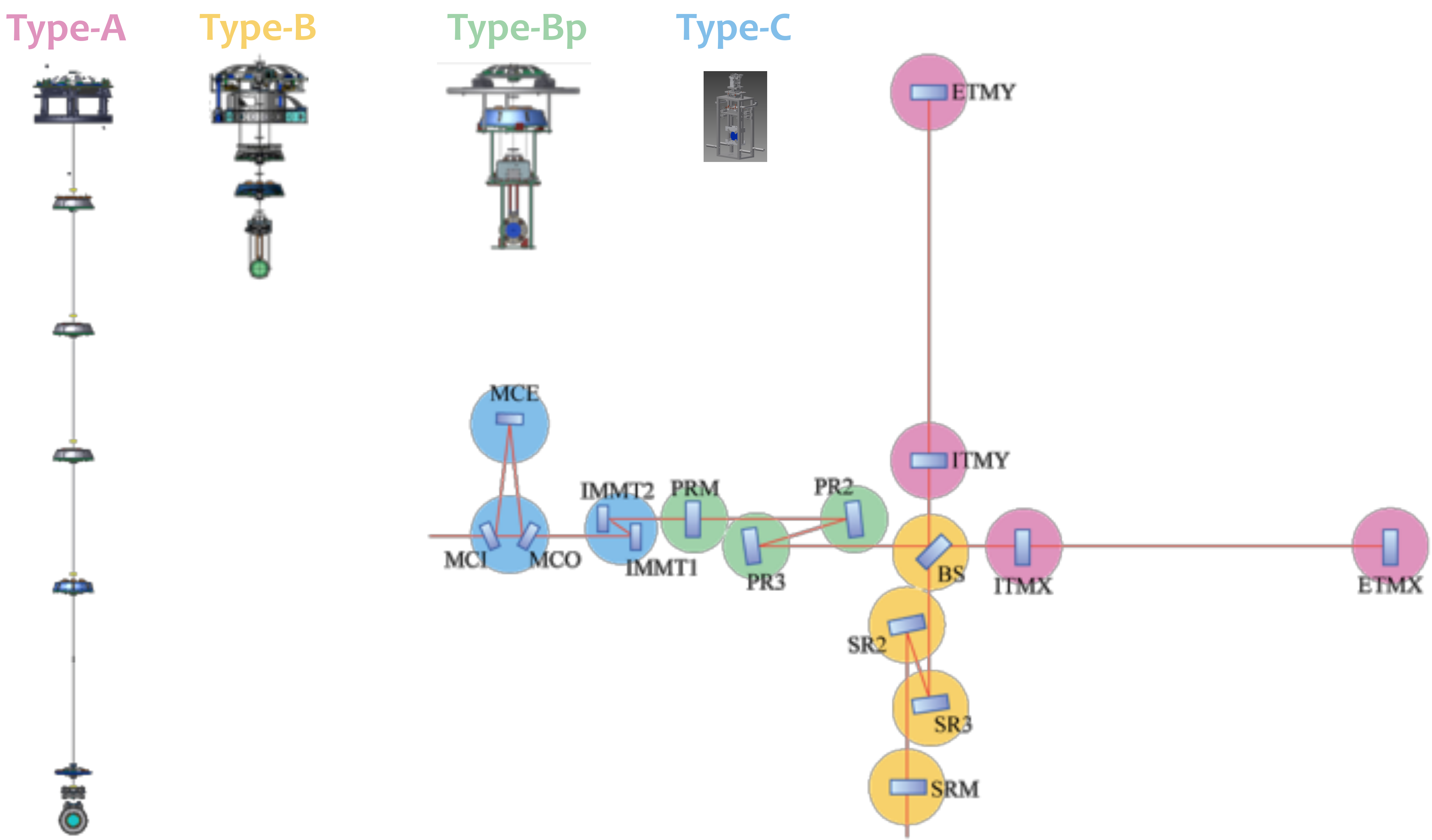


Preisolation stage with inverted pendulum

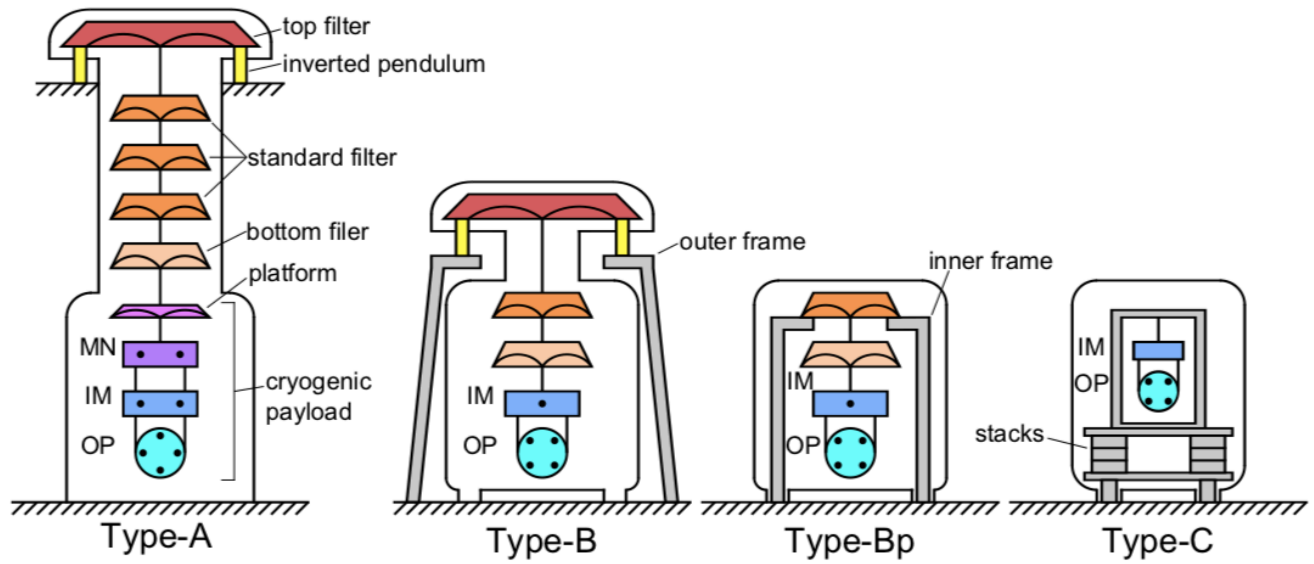


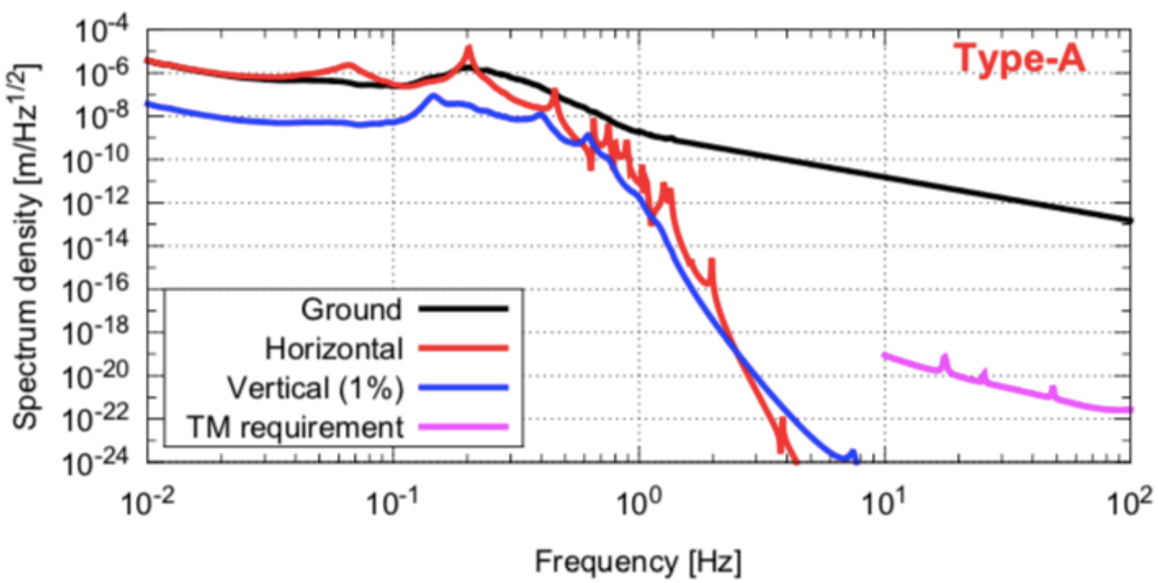
Vibration isolation system

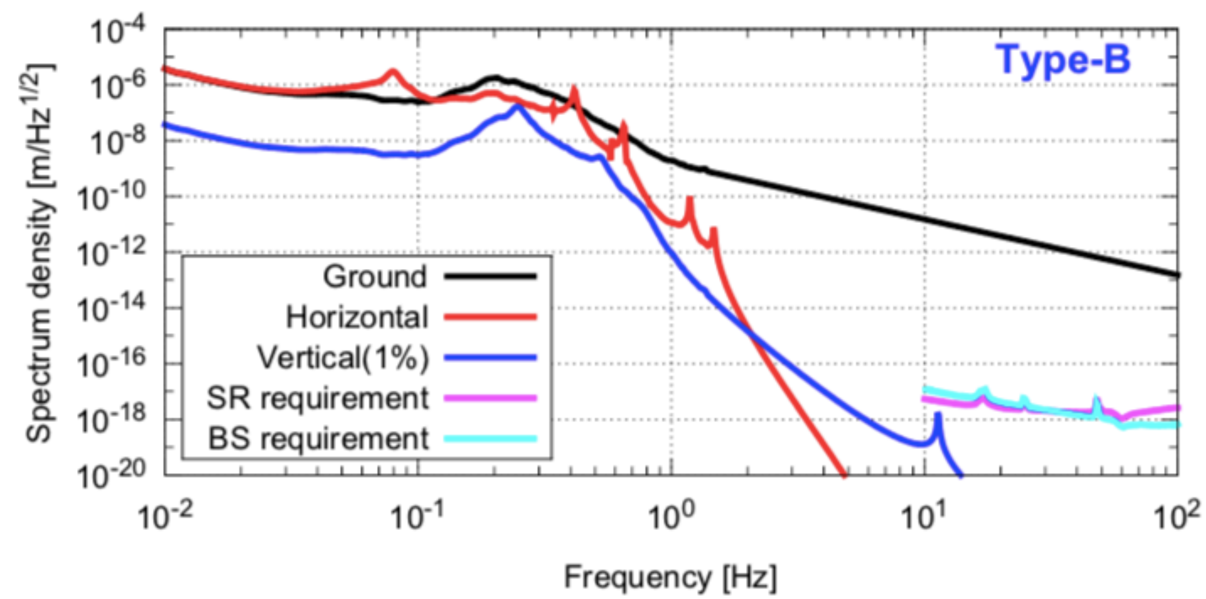
- Different optics have different requirements for vibration isolation

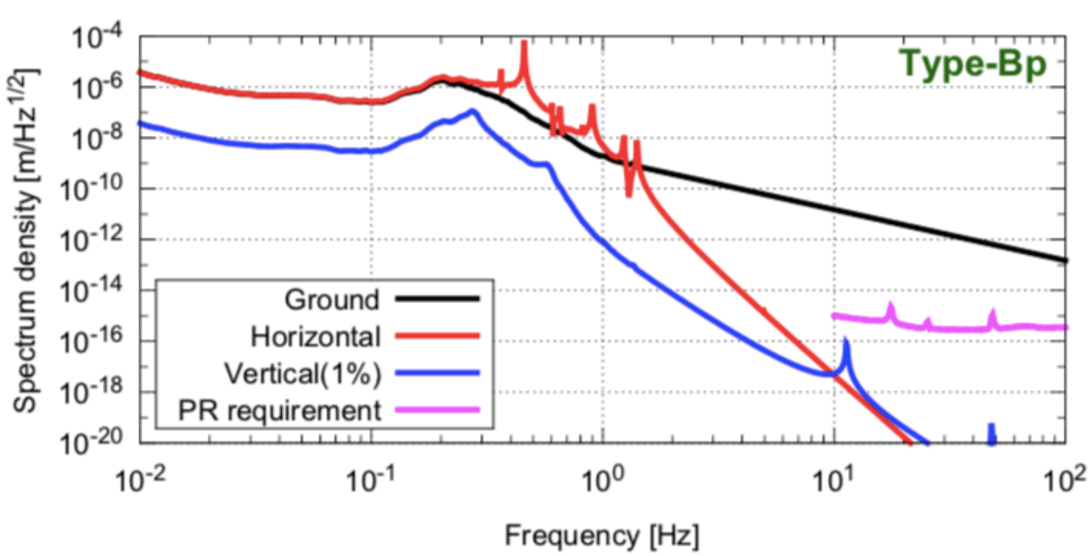


Vibration isolation system performances





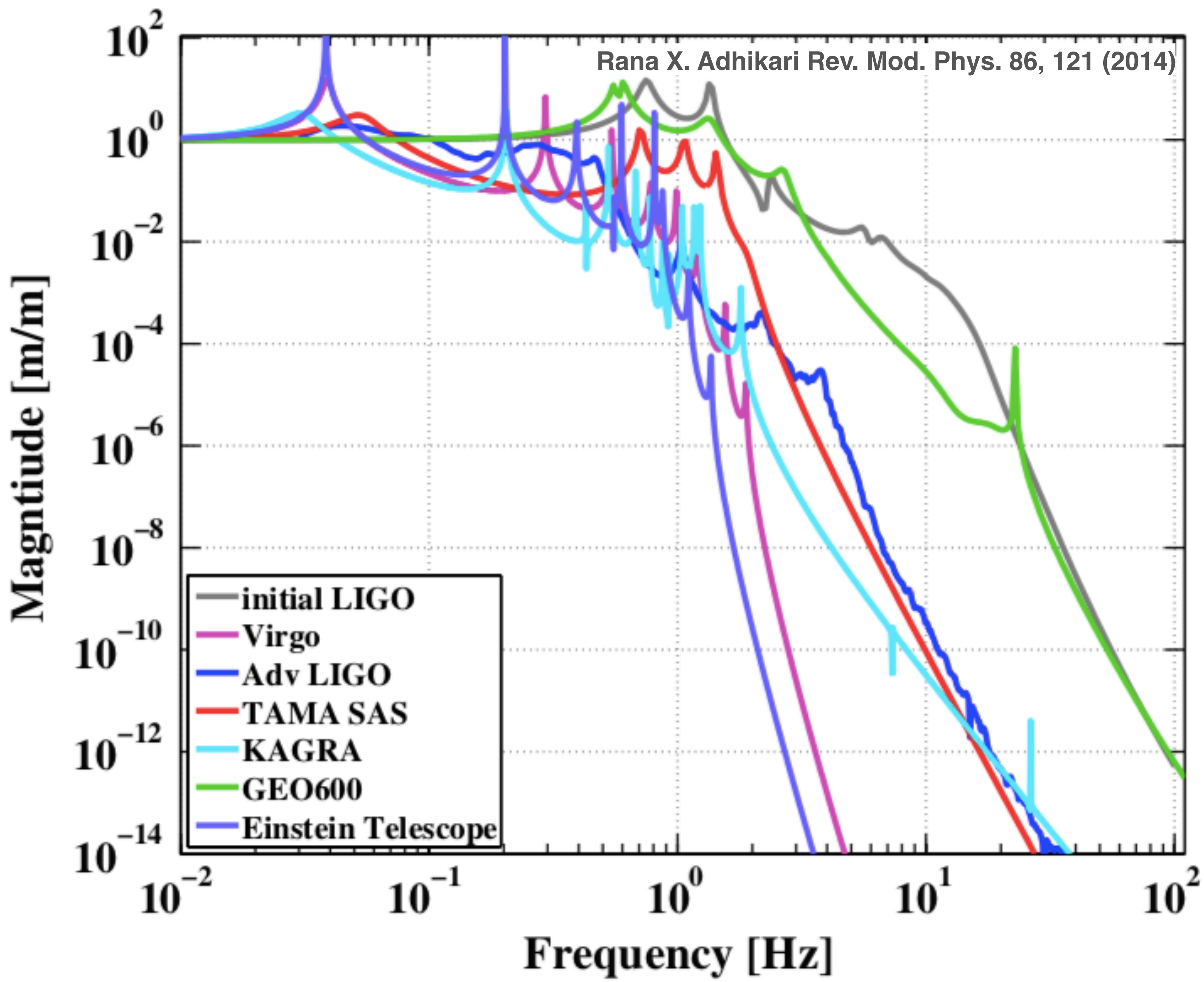




T. Sekiguchi. A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors. Phd thesis

Vibration isolation system

- Comparison of the performances of different detector suspension

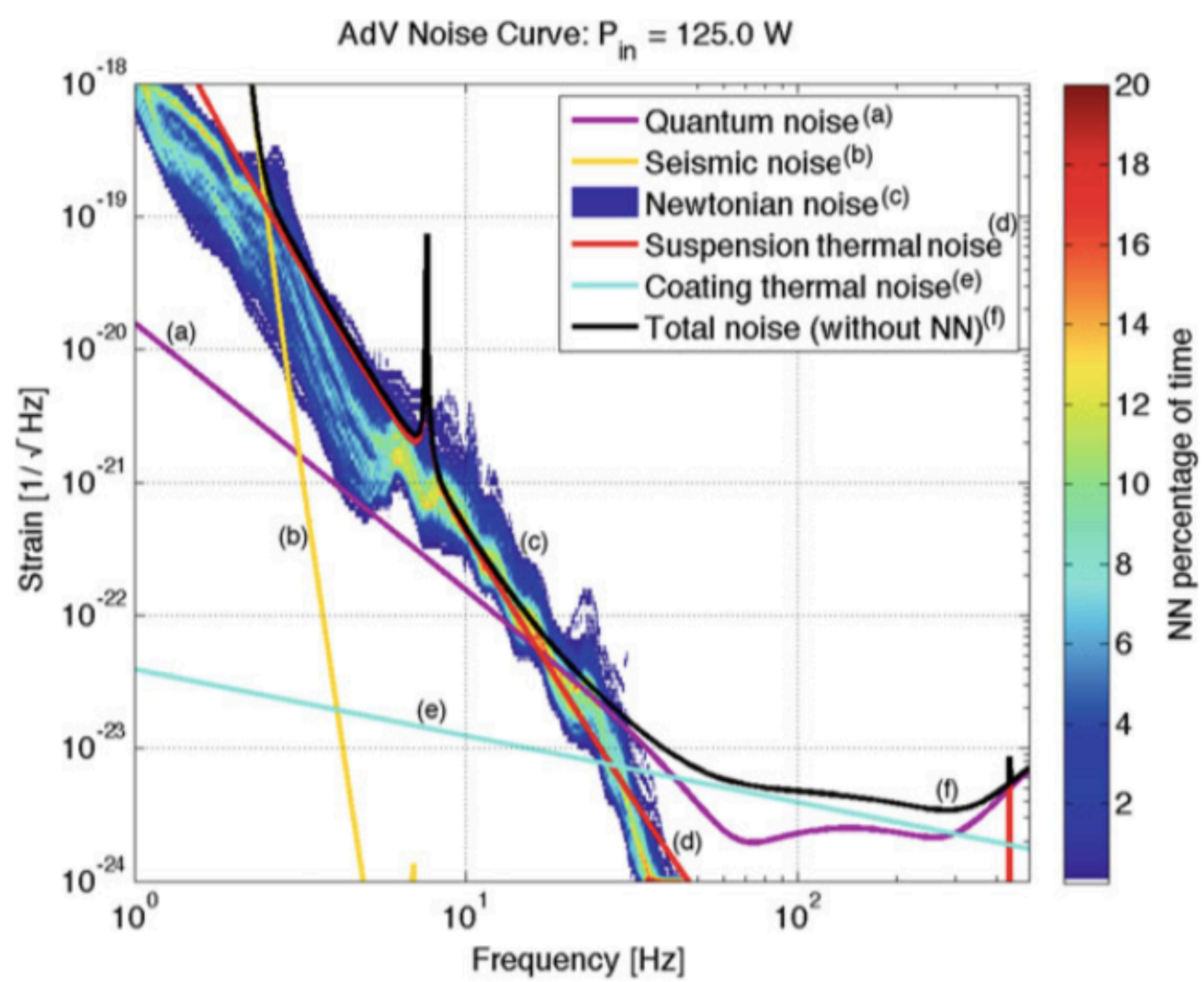


Newtonian noise

Due to fluctuations of the terrestrial gravity field

- Mainly produced by density perturbation in the atmosphere or from seismic field
- It couples directly to the mirrors, bypassing any isolation system
- It is expected to limit low frequency sensitivity

ET design study

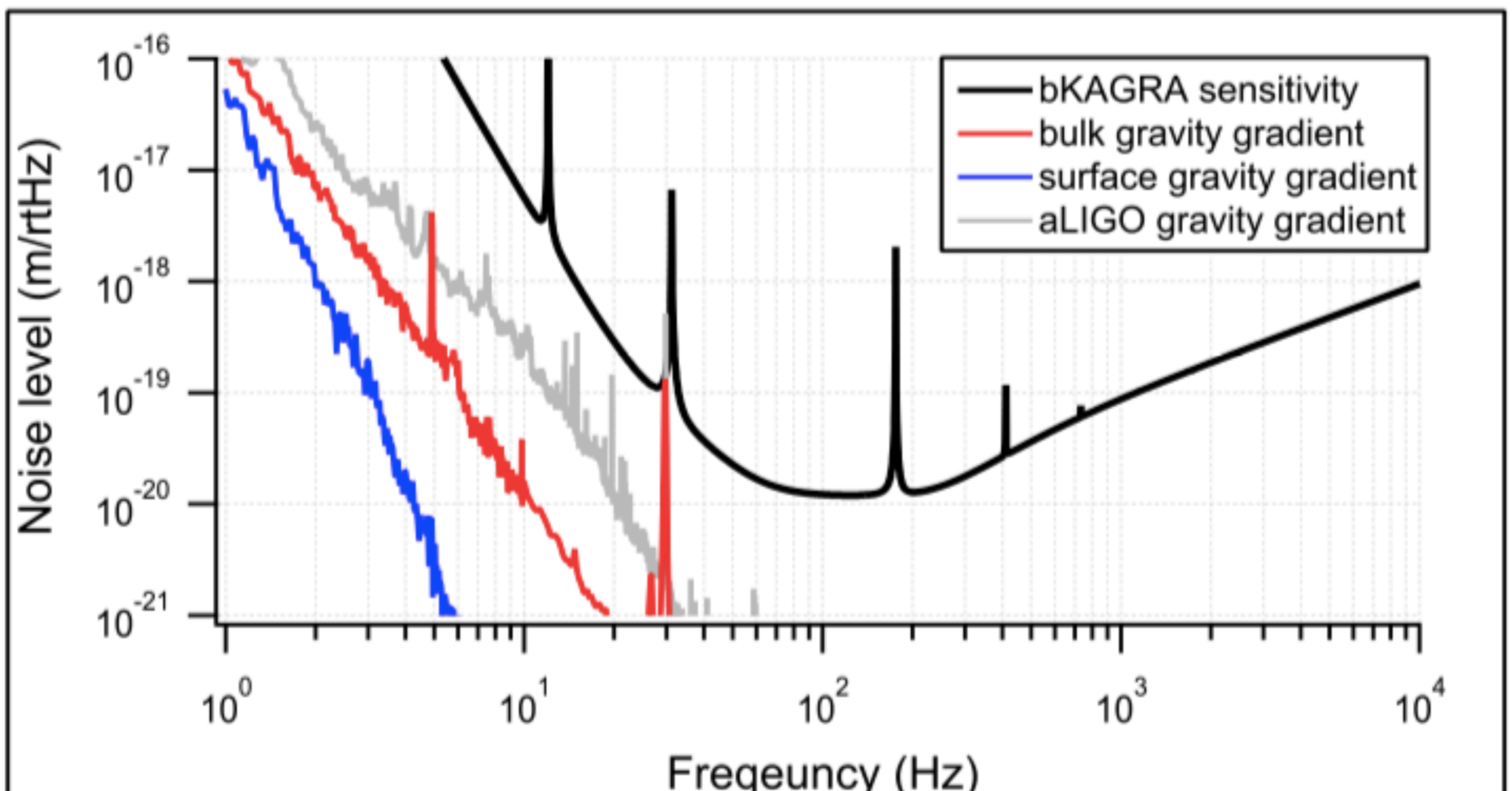


Newtonian noise: depth dependance

- Seismic NN effect it is proportional to the ground motion, so it reduces with depth

$$h_{\mathrm{nn}} = \frac{G}{\sqrt{3}\pi} \frac{\rho}{L} \frac{x_g}{f^2}$$

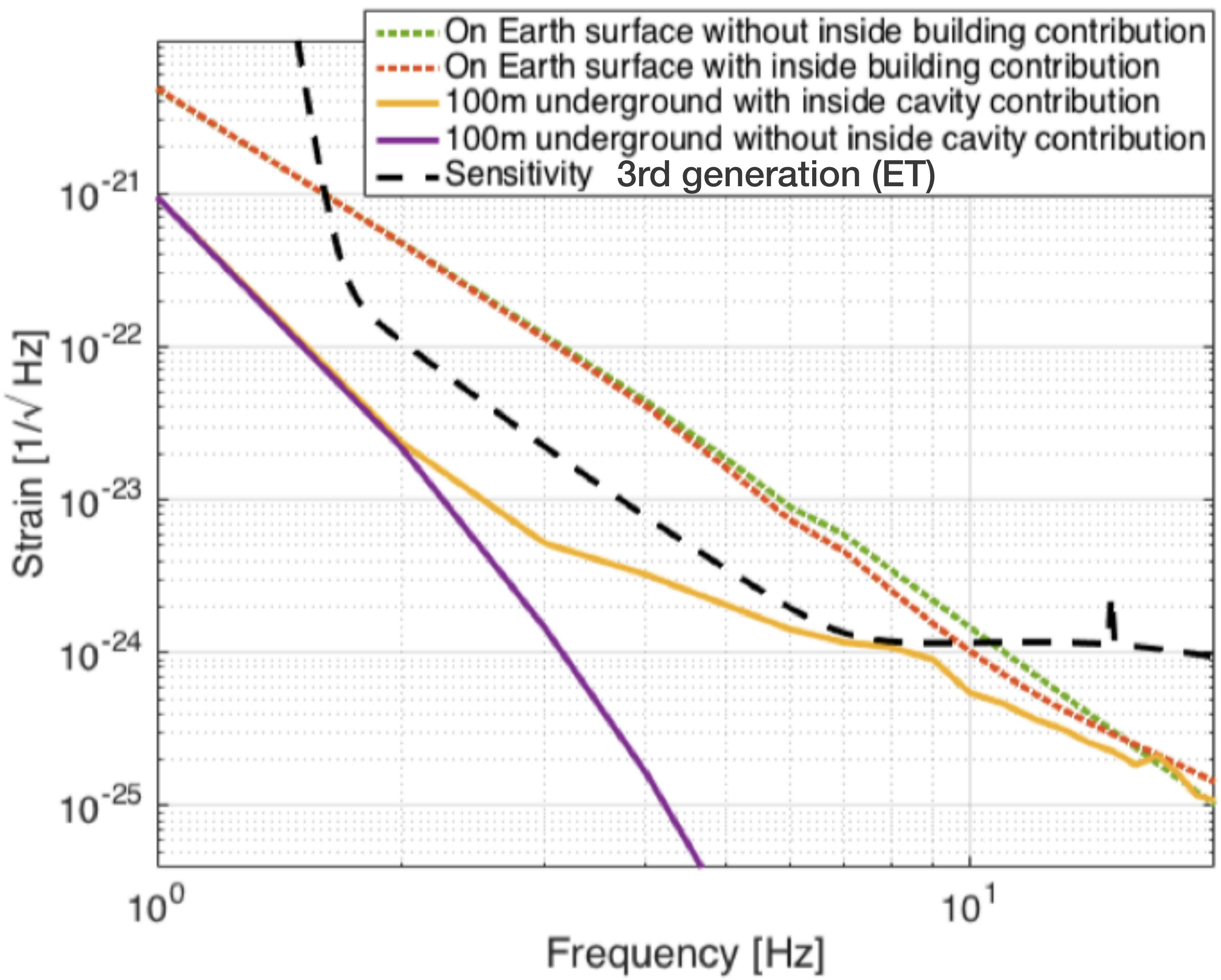
P Saulson
Phys. Rev. D 30, 732



arXiv:1712.00148

Newtonian noise: depth dependance

- Other sources of NN noise (human activity, atmospheric) are also reduced underground

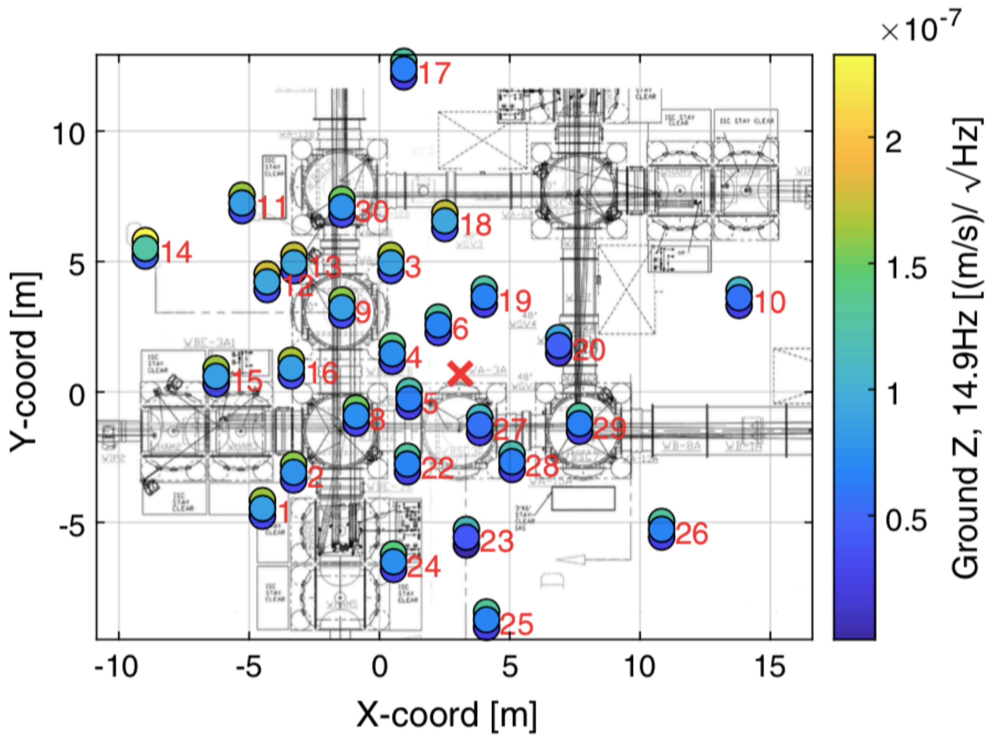


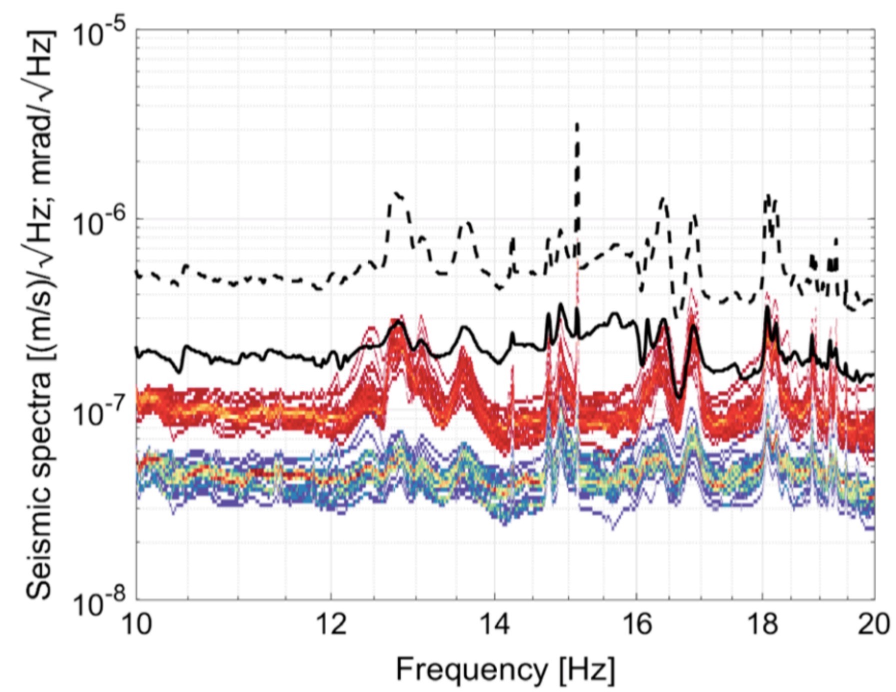
Impact of infrasound atmospheric noise on gravity detectors used for astrophysical and geophysical applications

Donatella Fiorucci, Jan Harms, Matteo Barsuglia, Irene Fiori, and Federico Paoletti
Phys. Rev. D **97**, 062003 – Published 30 March 2018

Newtonian noise: cancellation

- Seismic sensors surrounding the detector to obtain the correlation between seismic signal and detector data
- Use the information to subtract the noise





- Tested but not yet used for science data

PHYSICAL REVIEW LETTERS **121,** 221104 (2018)

Implications of Dedicated Seismometer Measurements on Newtonian-Noise Cancellation for Advanced LIGO

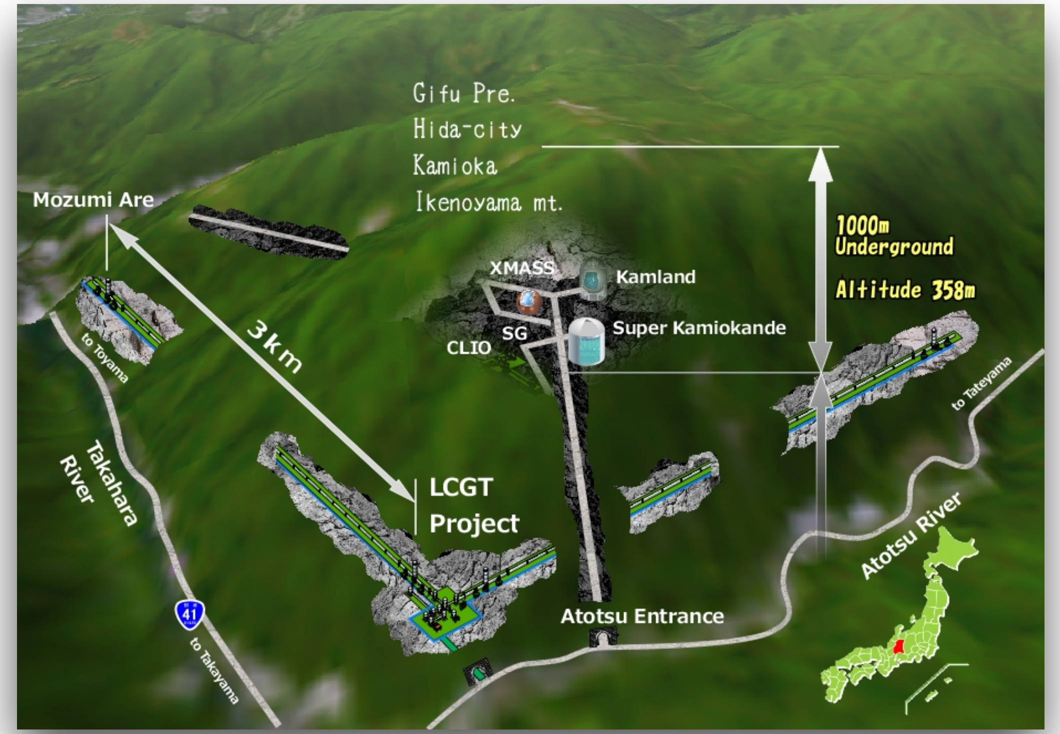
M. W. Coughlin,[1] J. Harms,[2,3] J. Driggers,[4] D. J. McManus,[5] N. Mukund,[6] M. P. Ross,[7]
B. J. J. Slagmolen,[5] and K. Venkateswara[7]

(Received 18 July 2018; revised manuscript received 20 August 2018; published 28 November 2018)

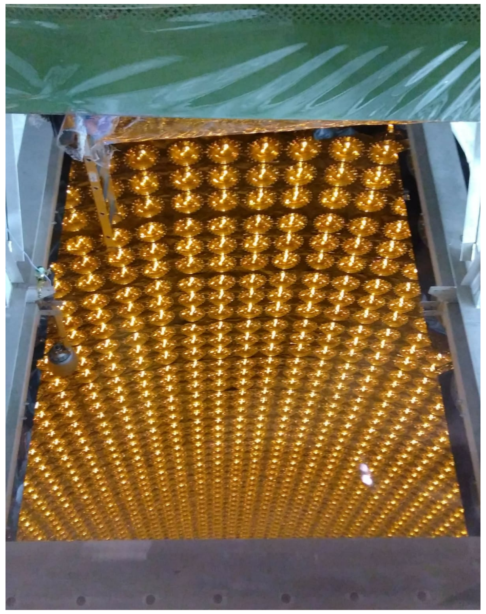
Underground challenges

- Tunnel excavation
- Underground environmental issues
- Daily work and safety

Kamioka Mine

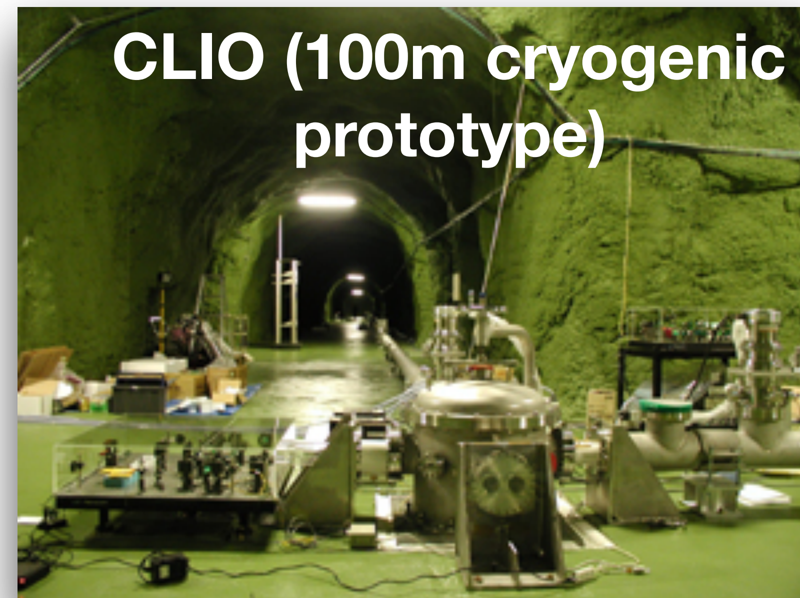


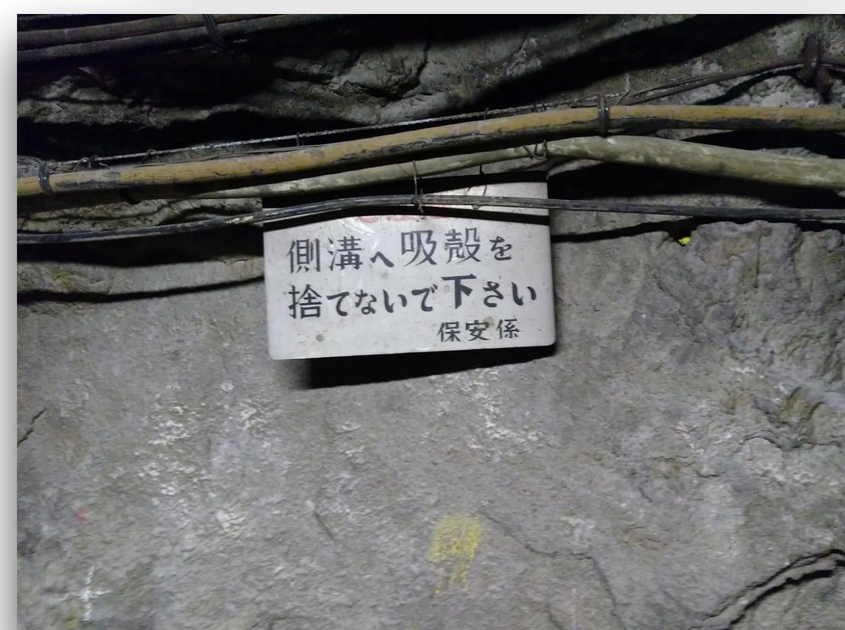
- Very old and well known mine
- It host neutrinos and dark matter experiment facilities (SK, XMASS)



Kamioka mine

- It already hosted two GW detector prototypers of 20 m and 100 m respectively





Tunnel excavation

- Delayed due to the 2011 earthquake
- Started in May 2012
- Completed in 22 months

Tunnel excavation: cost and issues

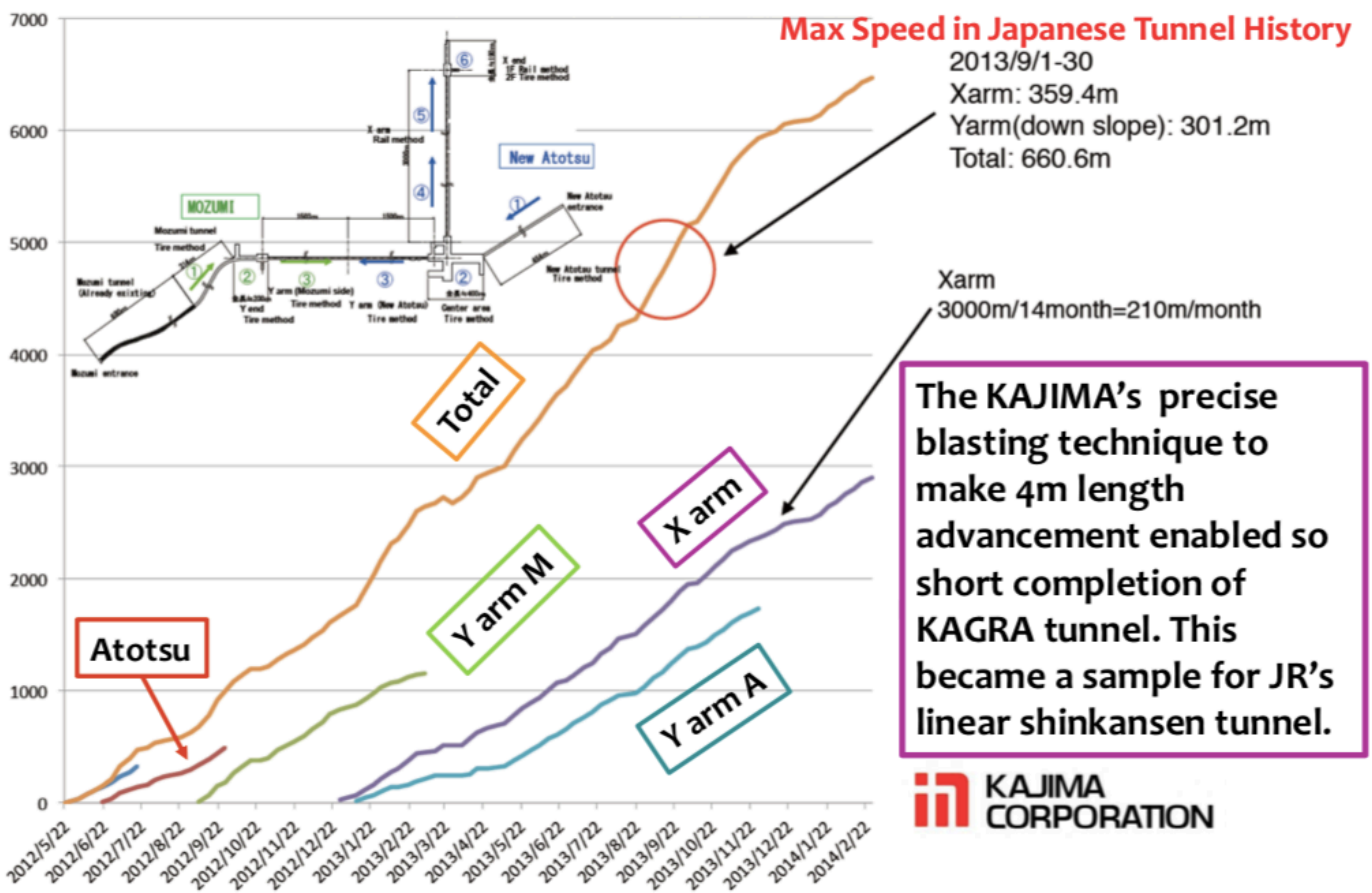
- Total cost of the tunnel: 24 MUSD (original) + 3.5 MUSD (additional cost)

Very Cheap	KAGRA	Highway (Sasago)	Rail Way (Tsugaru)	Subway (in Tokyo)
Size	4m x 4m (~7,770m)	~10m x ~8m (~4,700m)	? (~53,850m)	~6m x ~6m
Cost (USD/m)	3,600	47,900	115,000	283,000 ~167,000
	Only tunnel (NATM)	Including Infrastructure	Including Infrastructure Under Sea	Including Infrastructure (Shield Machine)

- Disposal of heavy metals in the rocks
- Neutralization of alkalized spring water caused by concrete

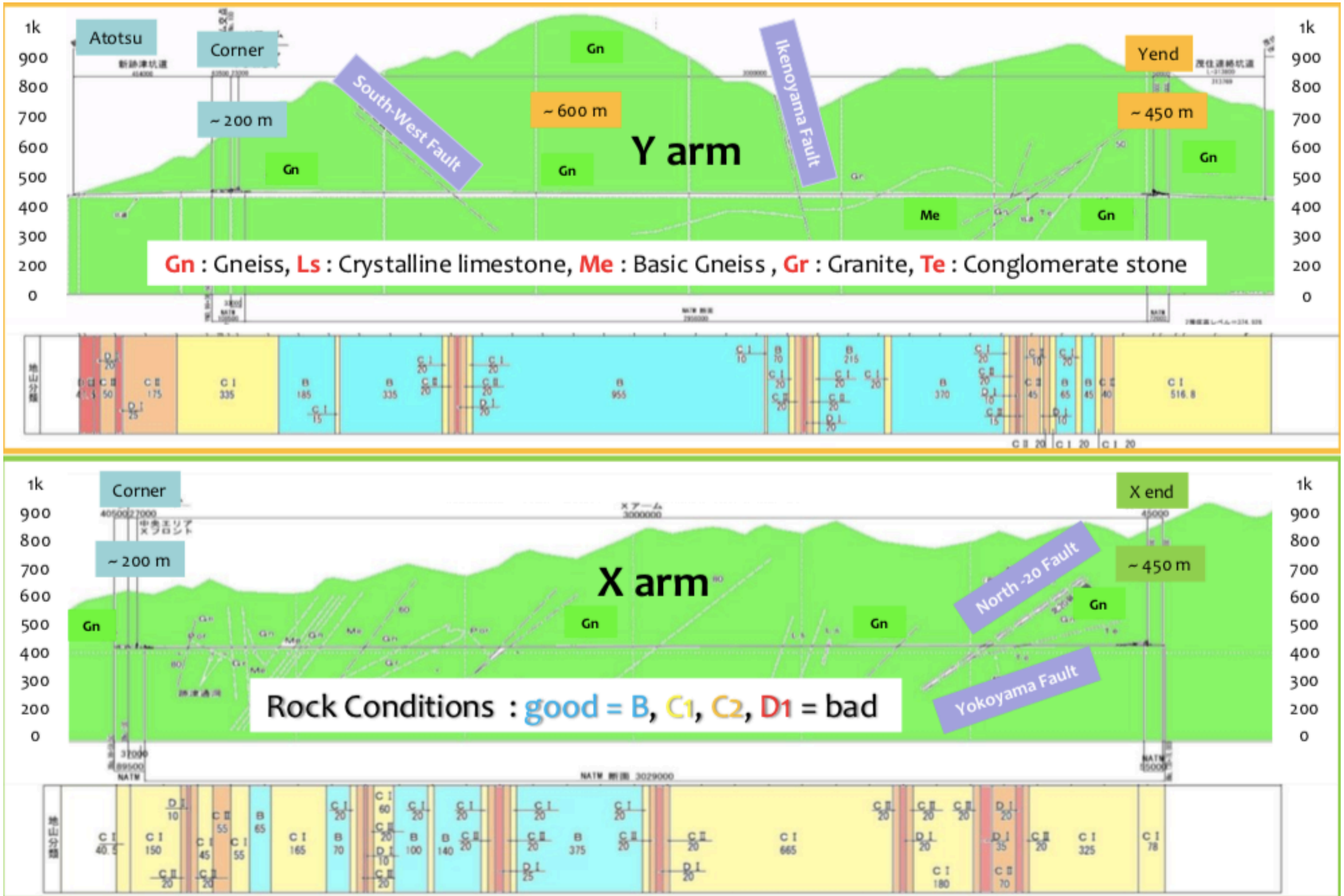
S. Miyoki *"Experience with underground facilities for KAGRA site"* GWADW 2018

Excavation performances: a new record



S. Miyoki *"Experience with underground facilities for KAGRA site"* GWADW 2018

Tunnel depth and rock condition



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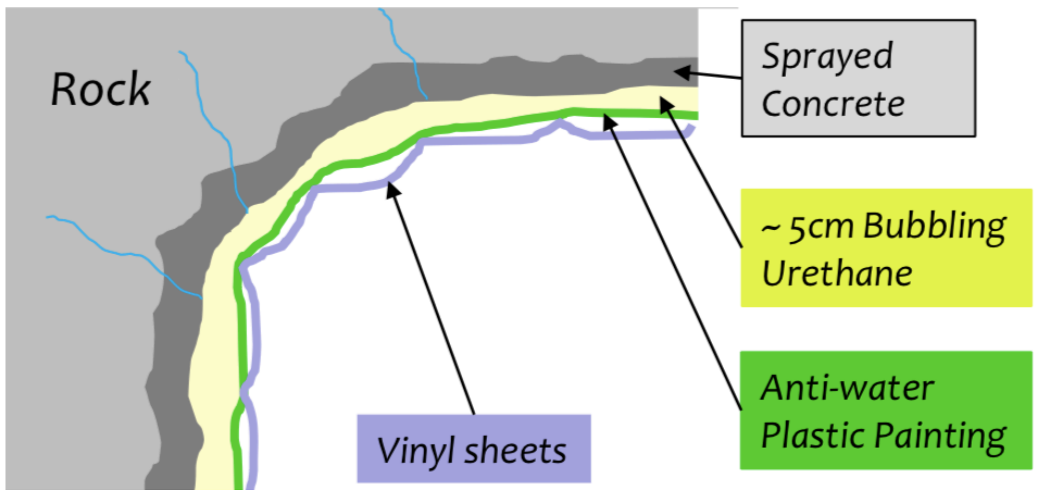
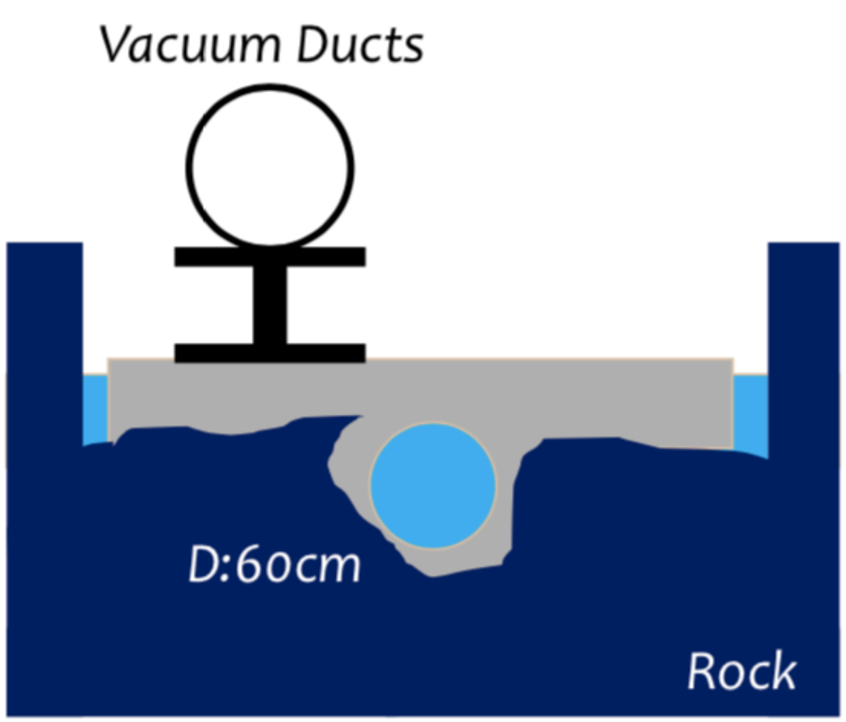
Spring water in the tunnel



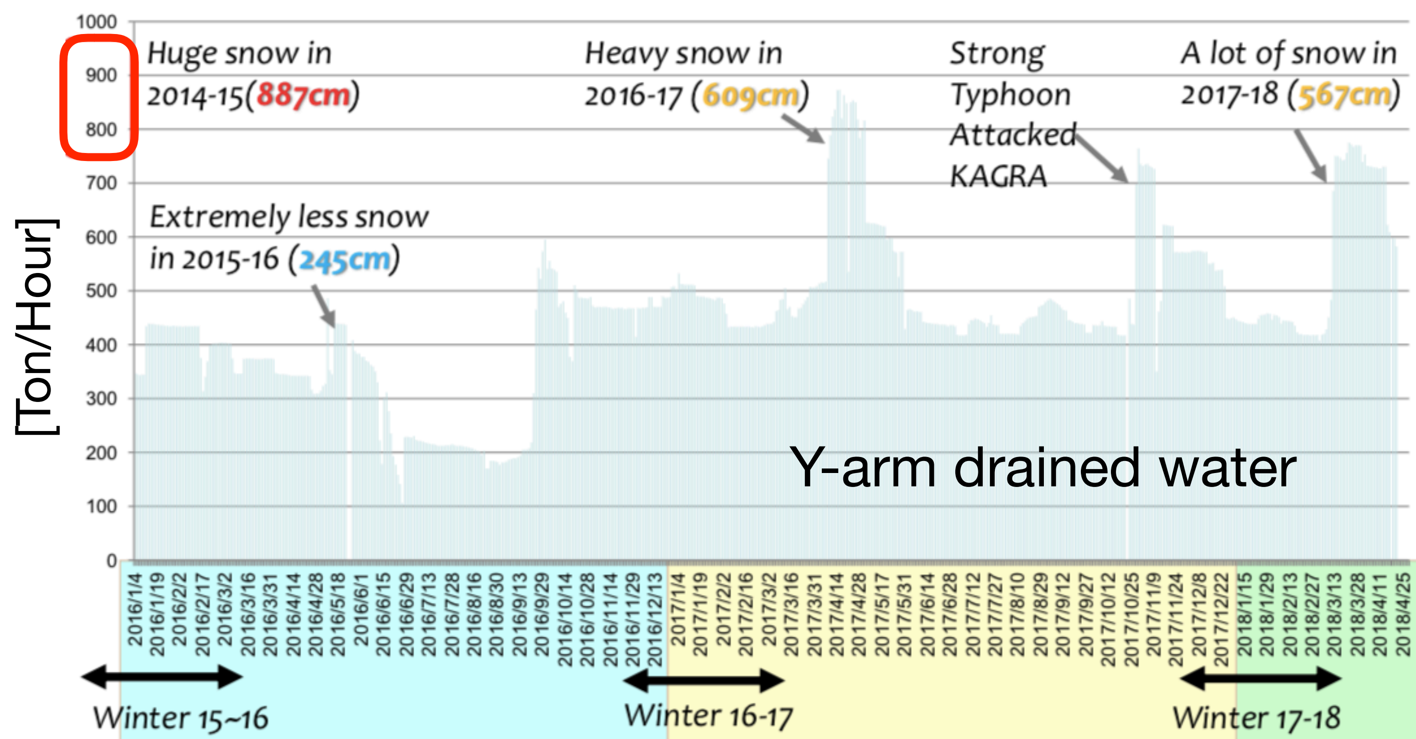


- Underestimated problem
- Many levels of isolation required for the walls
- 1/300 slope for the tunnel floor
- Ditch and pumps and water pipe installed to drain the water

S. Miyoki *"Experience with underground facilities for KAGRA site"* GWADW 2018

Spring water in the tunnel

- Amount of water depends on the amount of winter snow



- Y arm especially affected because of known fault

- Associated Newtonian noise estimated to be negligible

S. Miyoki *"Experience with underground facilities for KAGRA site"* GWADW 2018

Spring water in the tunnel

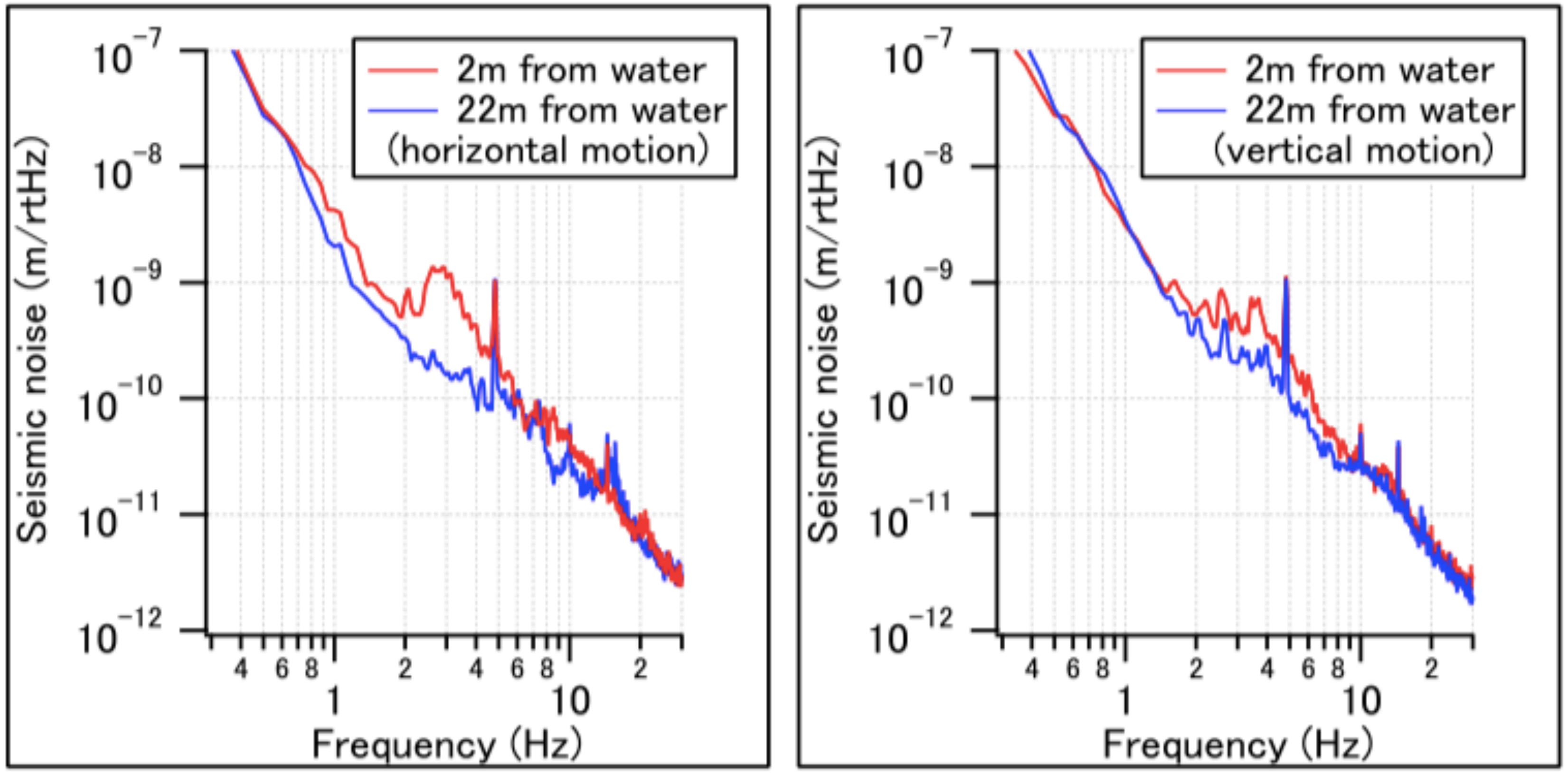


FIG. 15. Seismic noise measured at two locations near the Y-end chamber; one is close to the drain pipe and the other far away from the drain pipe.

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Construction of KAGRA: an underground gravitational-wave observatory

Many “small” issues..

- Provide GPS signal
- Provide power supply and purified water for cryocooler
- CO_2 free vehicle to reach end stations
- Temperature and humidity control
- Air (O_2 CO_2, CO) control and sensors
- Rn gas control
- Clean environment
- Safety

Conclusions

- Underground operation can reduce significantly seismic noise (about a factor ~100)
- Lower seismic noise relaxes the requirement on vibration isolation possibly reducing technical noise in the observation bandwidth
- Newtonian noise is also reduced
- Many “underground” issues had to be tackled → valuable experience for 3rd generation GW detectors