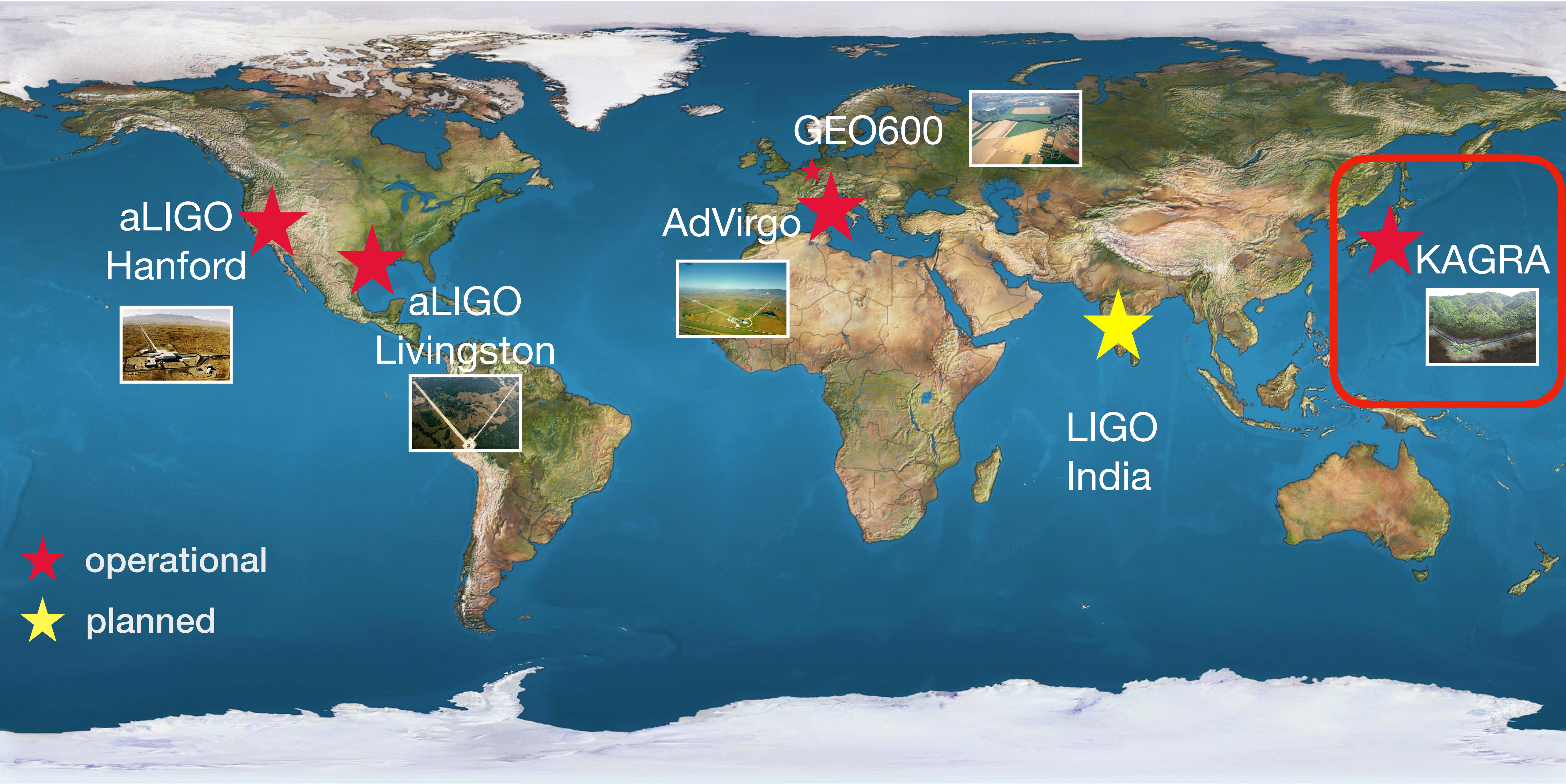
KAGRA physics and technology

Eleonora Capocasa

June 10th 2021

KAGRA Collaboration / Rey.Hori

Second generation GW detector network



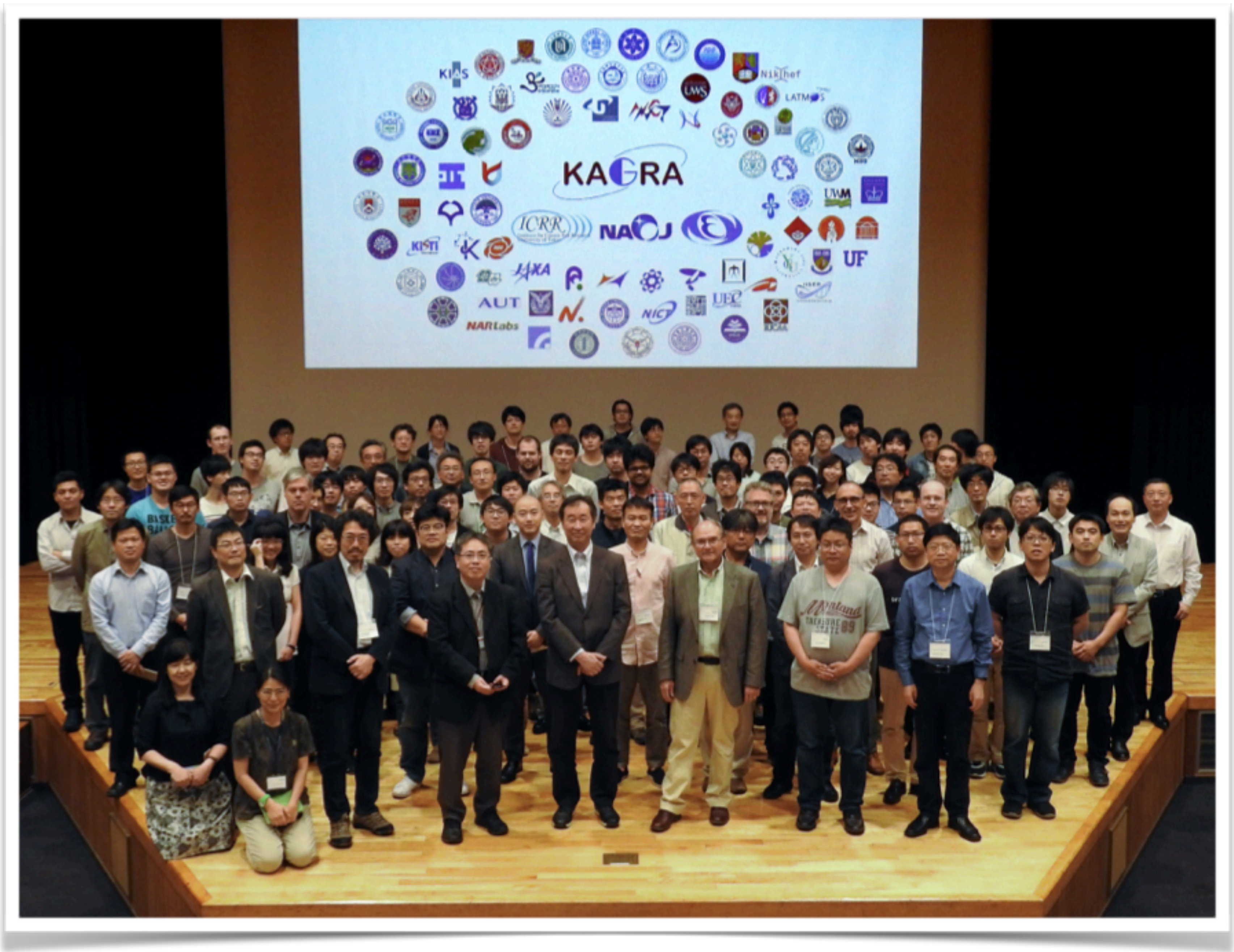
Outline

- General introduction about KAGRA
- Underground operation
- Cryogenic operation

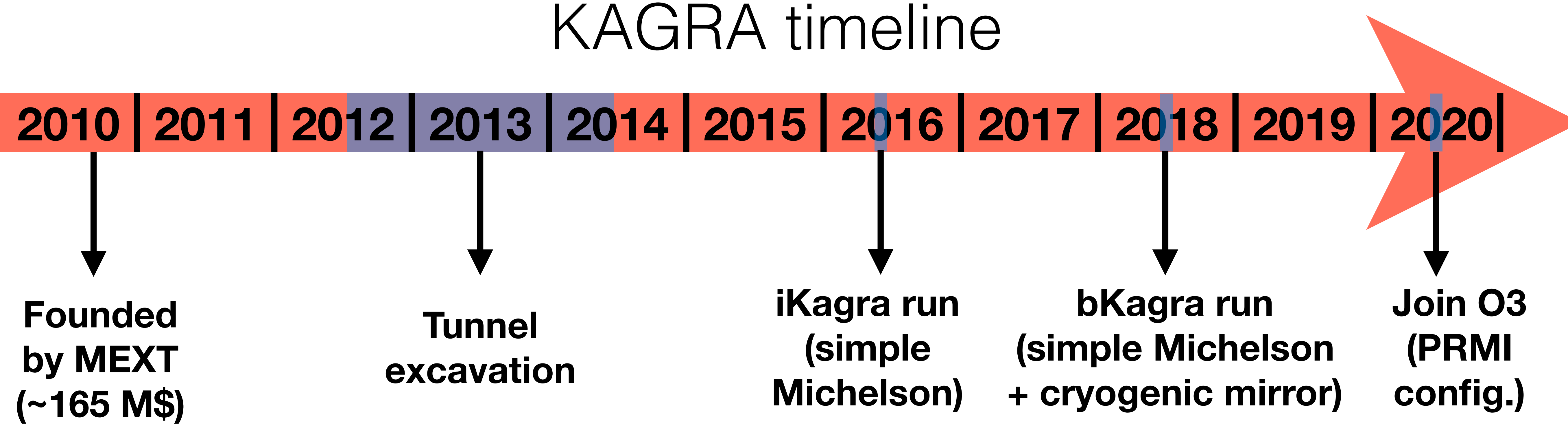
KAGRA gravitational wave detector

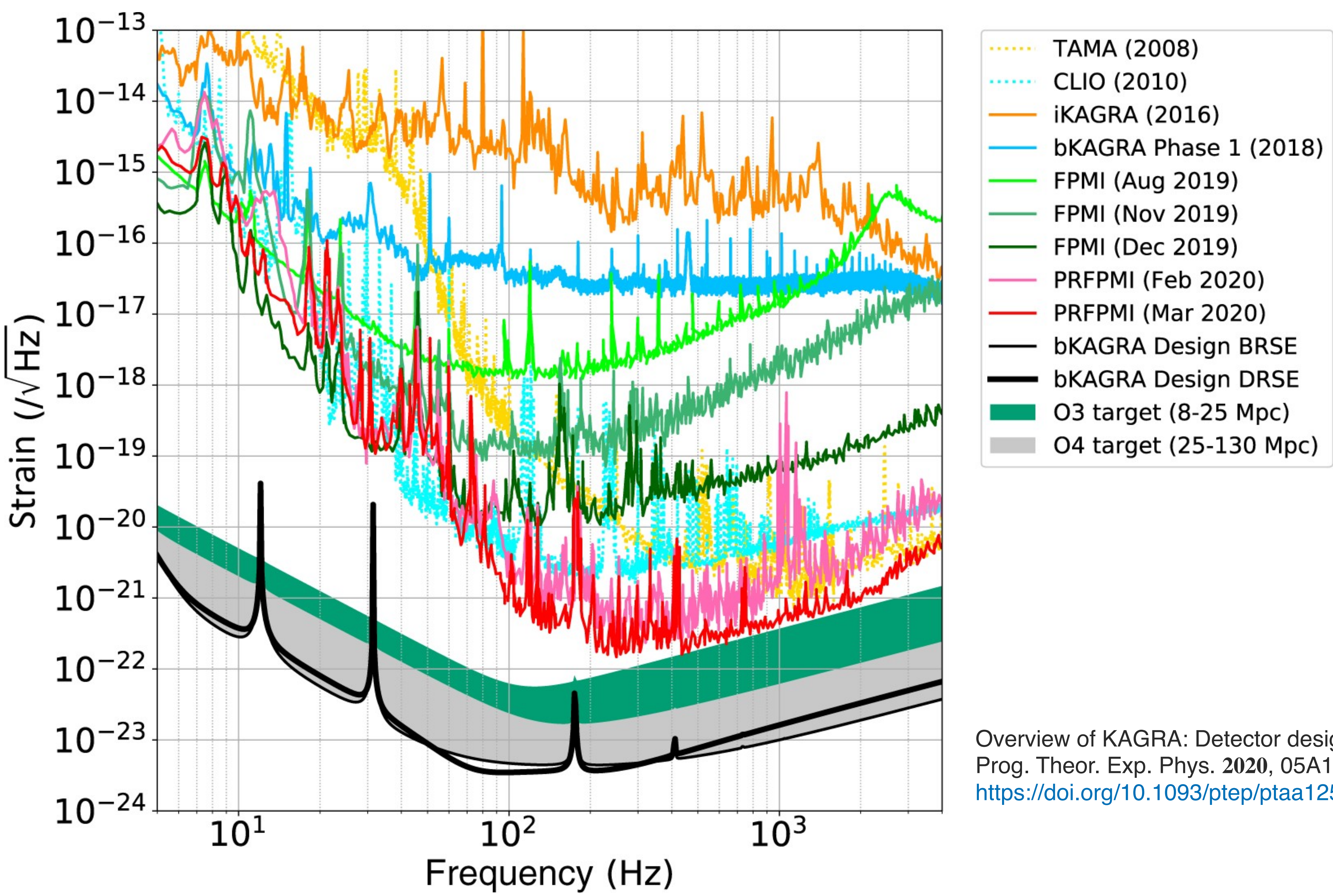
The KAGRA collaboration

- Host institution: ICRR, Co-Host: NAOJ and KEK
- 103 institutions from more than 10 countries
- ~470 collaborators



KAGRA timeline

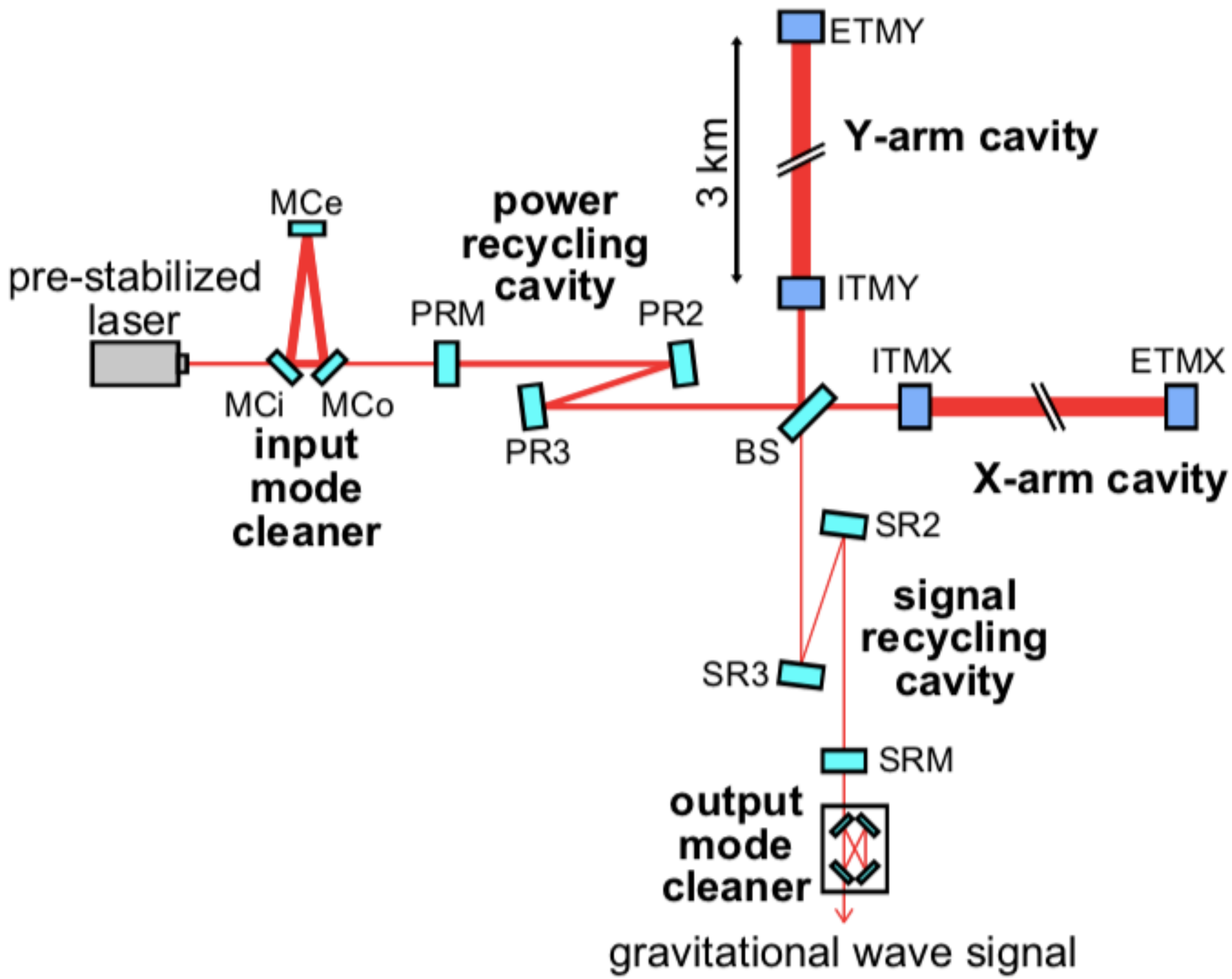


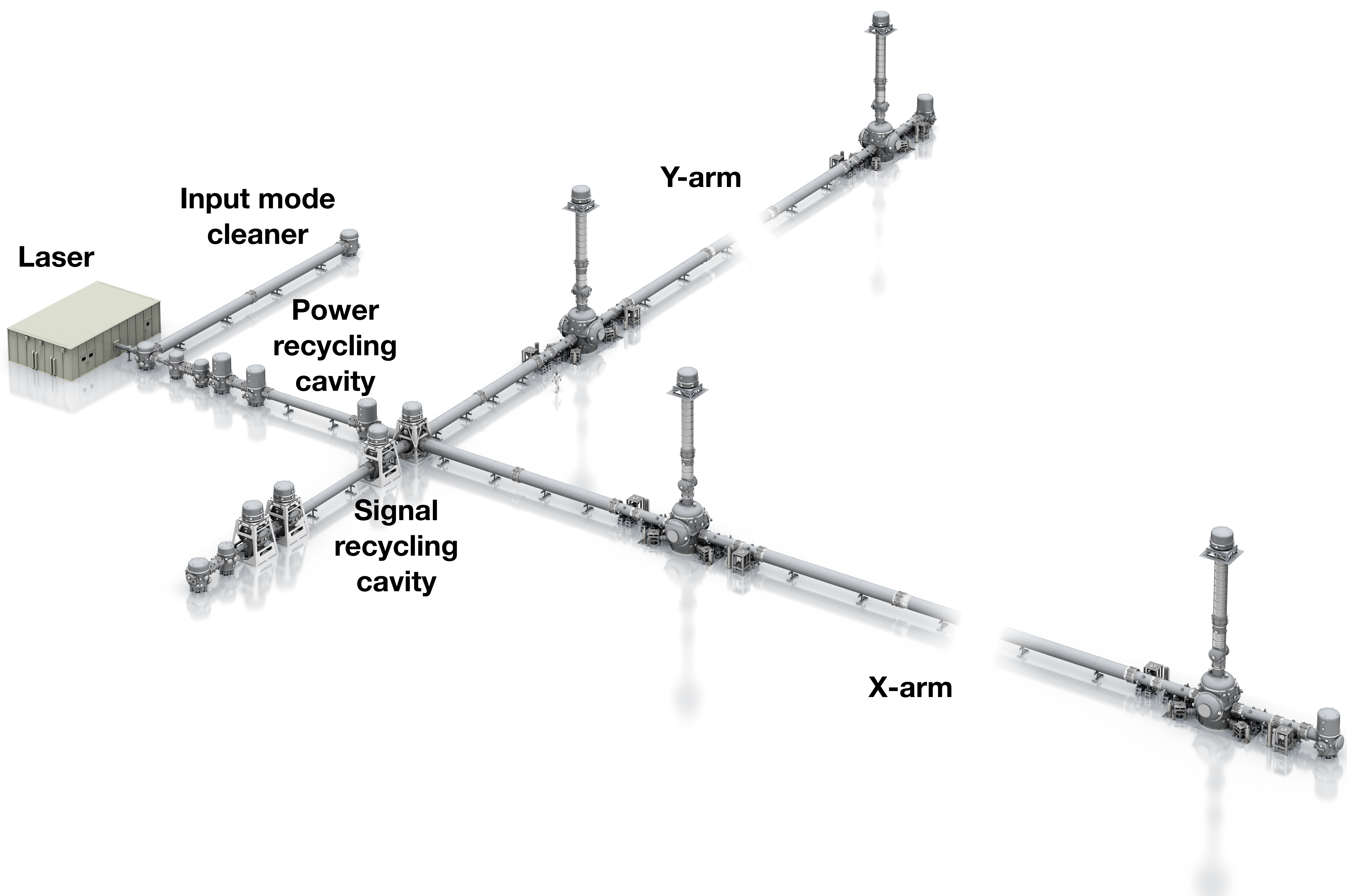


Overview of KAGRA: Detector design and construction history, Prog. Theor. Exp. Phys. **2020**, 05A101
https://doi.org/10.1093/ptep/ptaa125

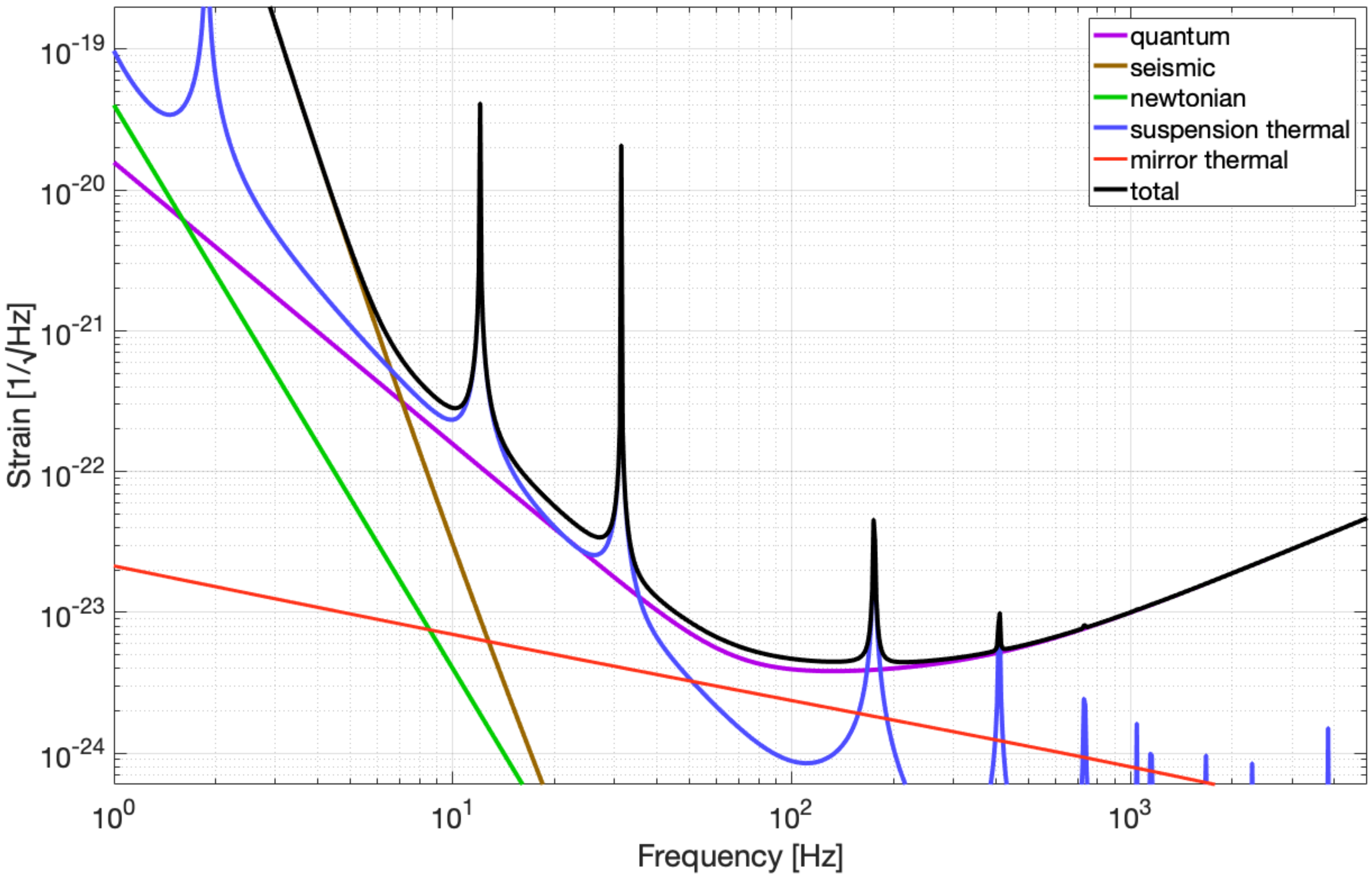
KAGRA optical scheme

- Very similar to LIGO with 3 km cavities

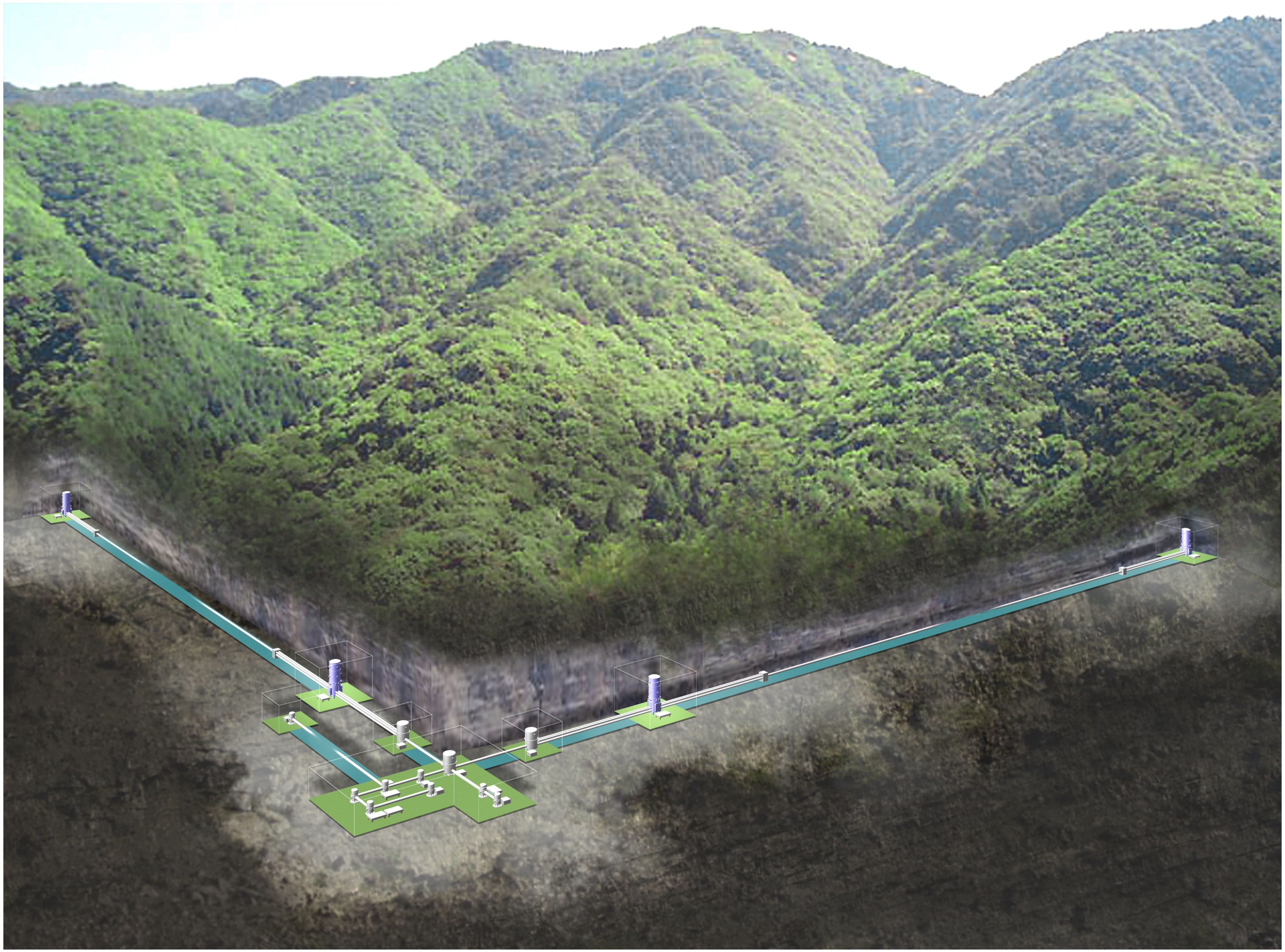



Laser
Input mode cleaner
Power recycling cavity
Y-arm
Signal recycling cavity
X-arm

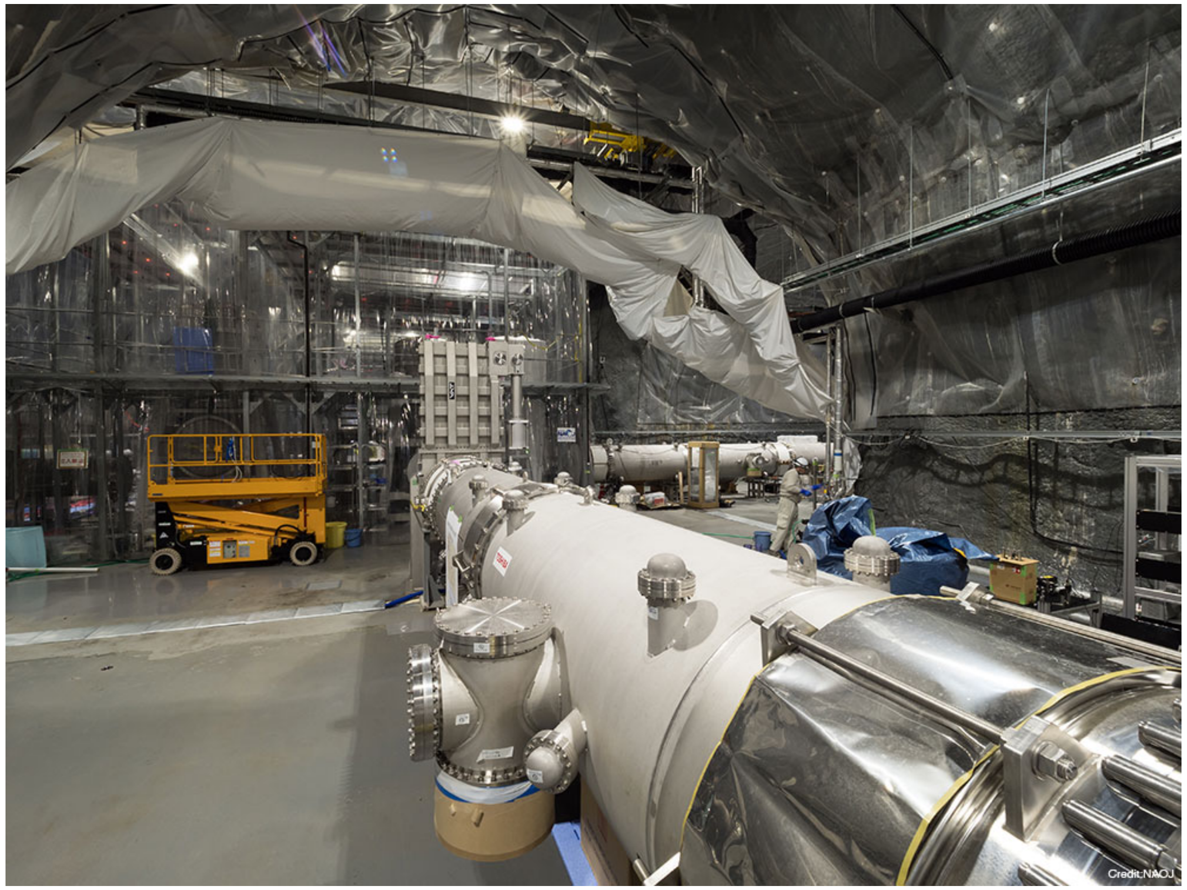
Design sensitivity



KAGRA: un underground GW detector



KAGRA: un underground detector



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

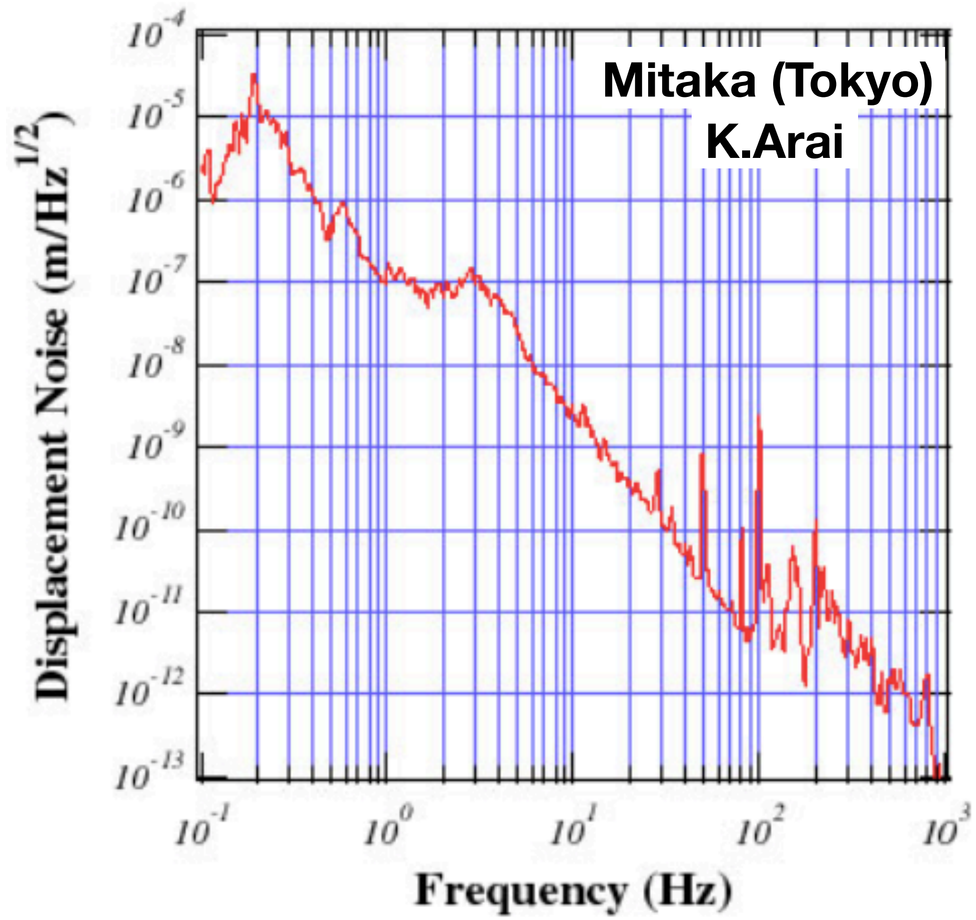
- Low frequency: ($f < 1$ Hz): oceanic and sea origin. Depends on large-scale meteorological conditions
- Mid frequency: ($f \sim 1$ Hz): local meteorological condition
- High frequency: ($f > 1$ Hz): human activities

Seismic noise amplitude

- Amplitude spectral density (above few Hz) approximated by

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

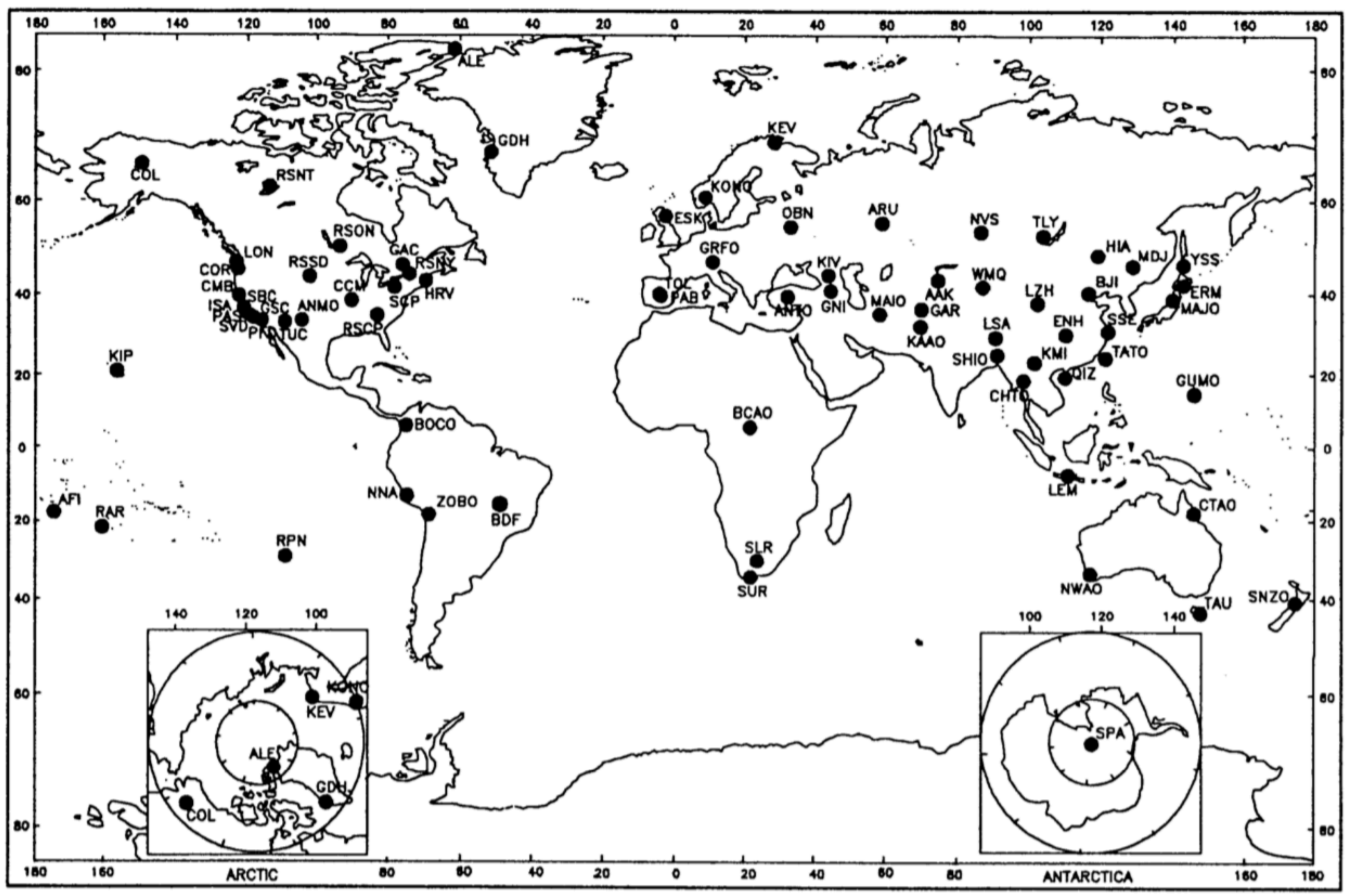
$$A \simeq 10^{-6} - 10^{-9}$$



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

Seismic noise characterisation

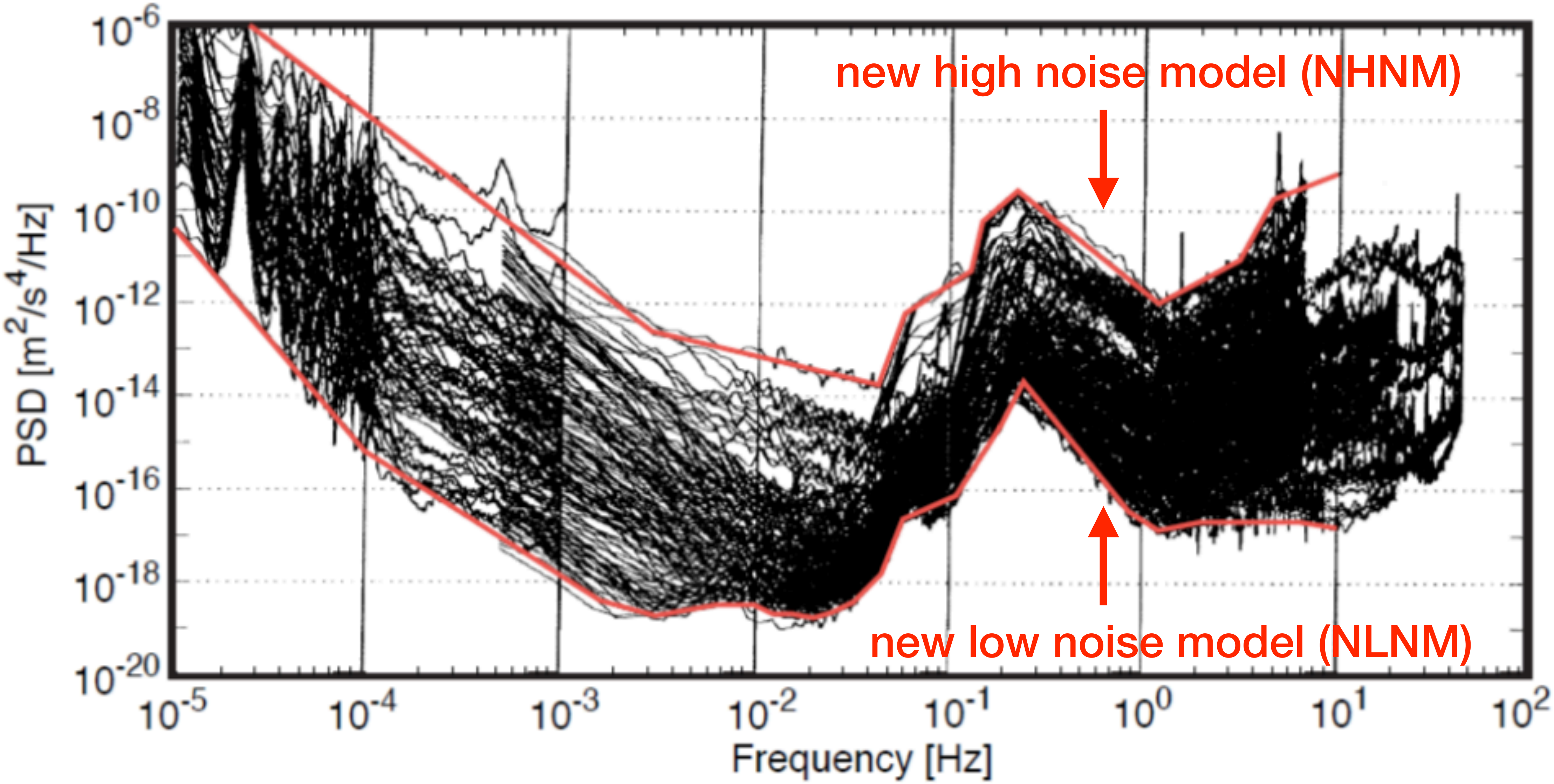
- Peterson measurement from a worldwide seismometer network composed of 75 stations (in surface and underground)



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

Seismic noise characterisation

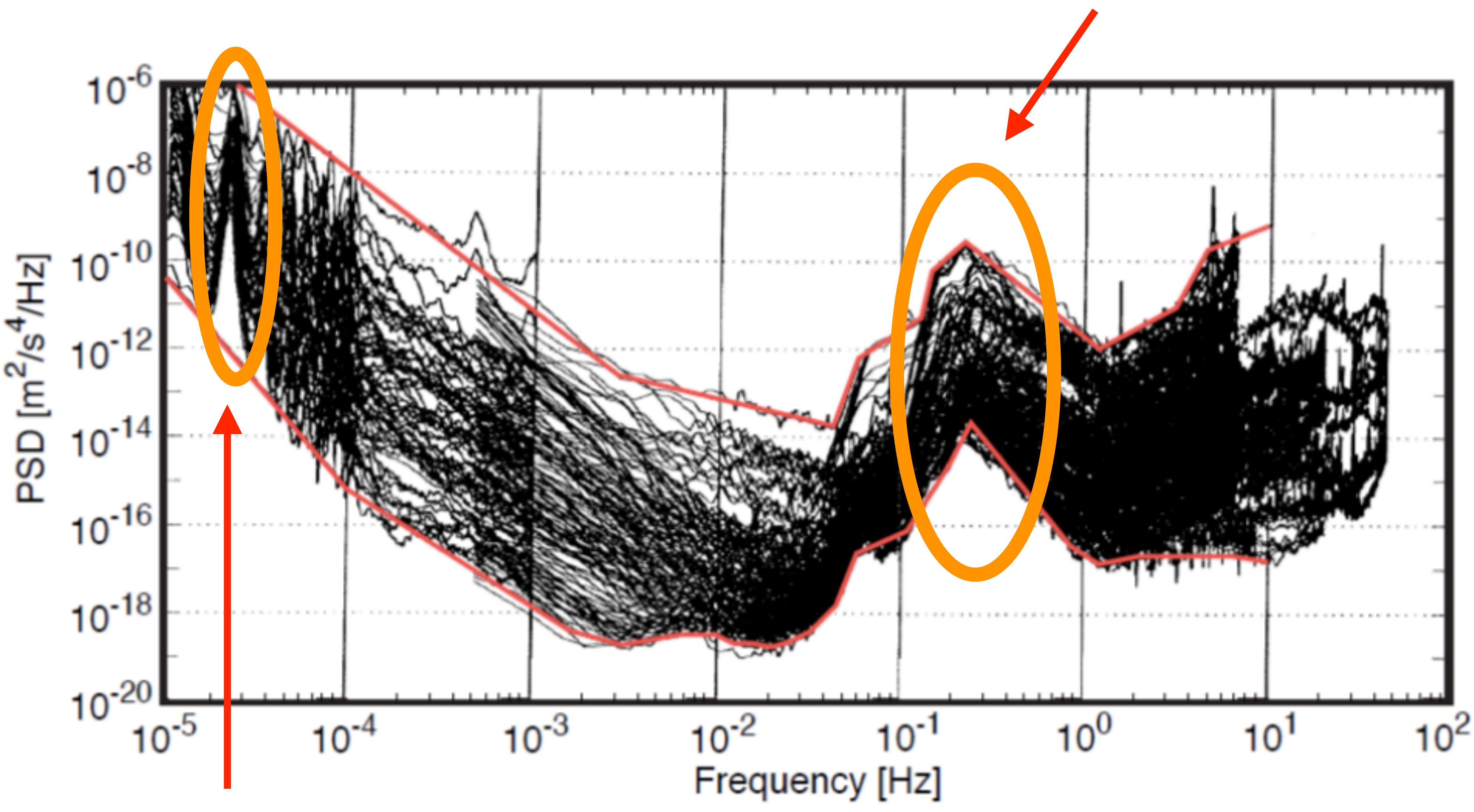
- Measurement between 10^{-5} and 50 Hz



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

Seismic noise characterisation

Micoseism: generated by sea waves



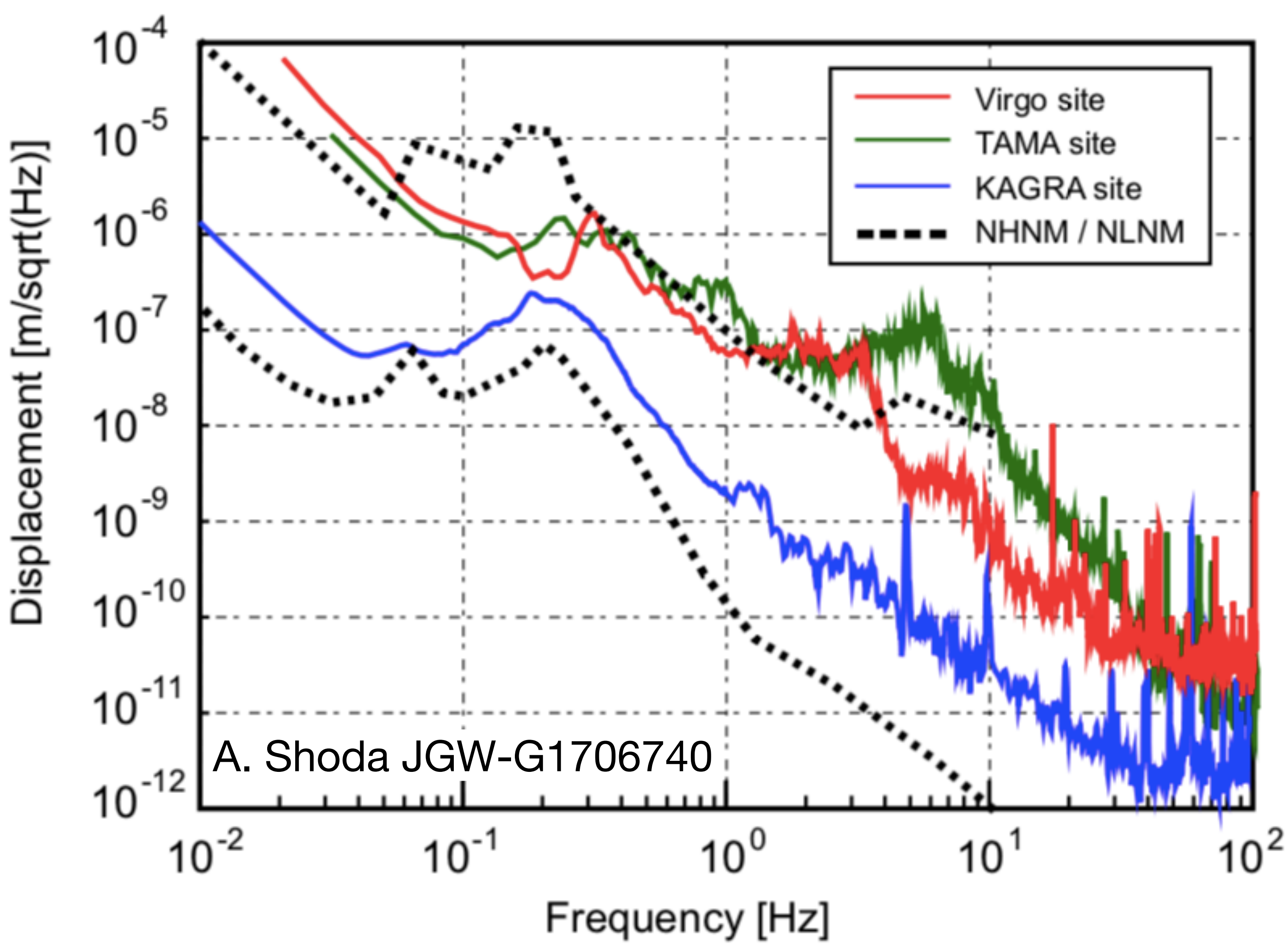
Earth tide:displacement of the solid earth's surface caused by the gravity of the Moon and Sun

Depth dependence

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

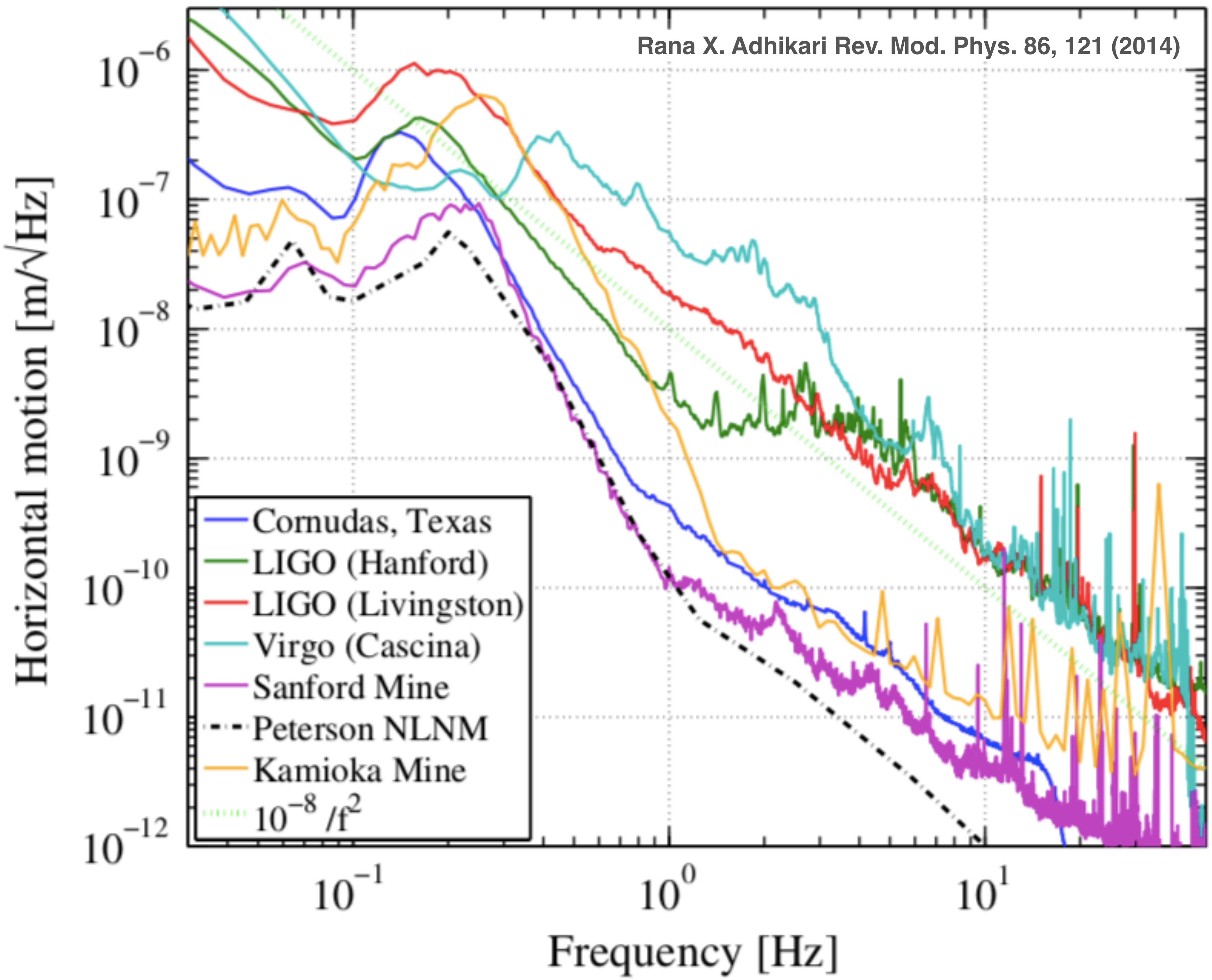
$$\frac{\tilde{x}_{seism}(f,d)}{\tilde{x}_{seism}(f,d=0)} \propto e^{-4\frac{d}{\lambda}}$$

d = depth
λ = seismic wavelength



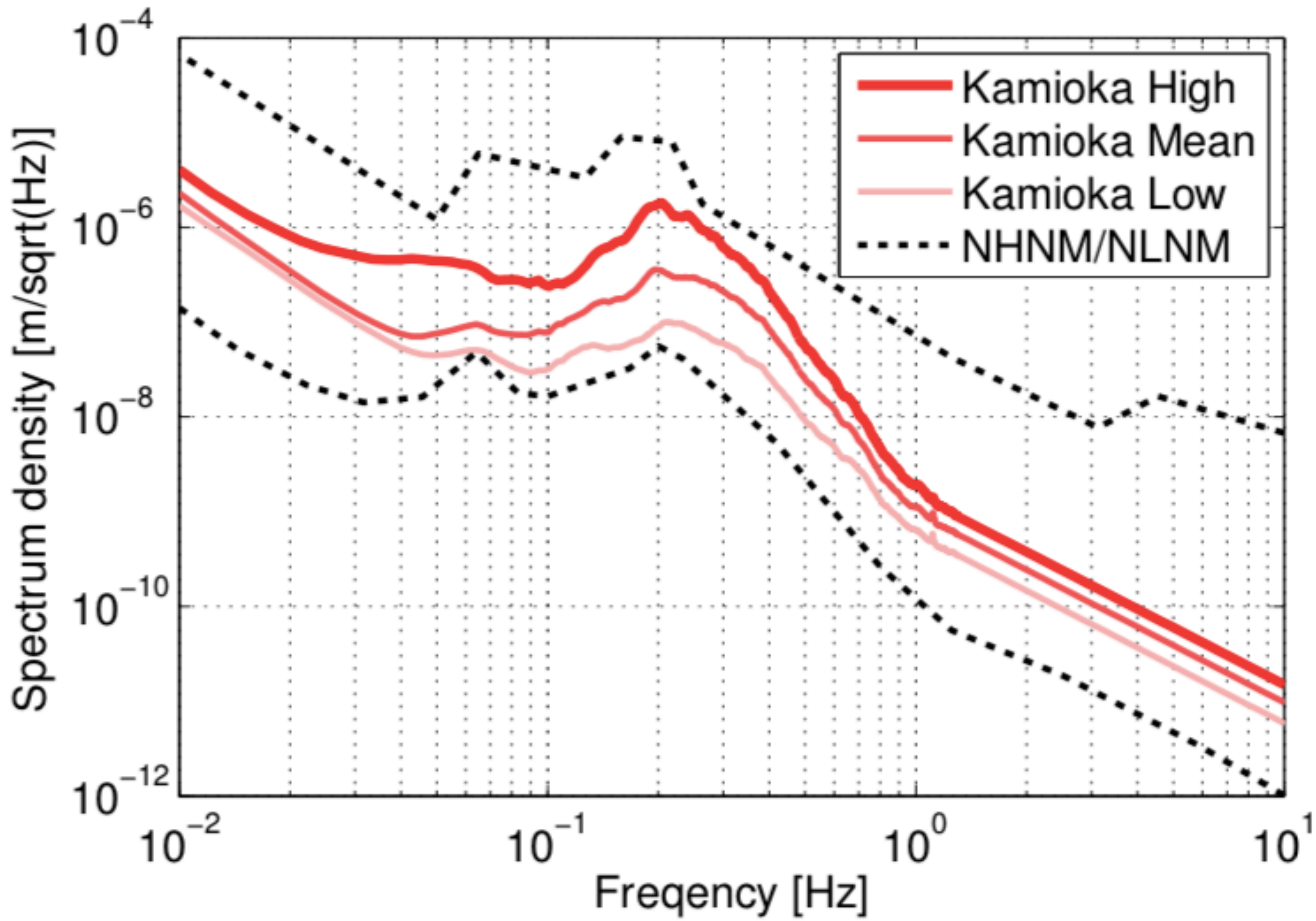
Factor ~100 between VIRGO and KAGRA site

Seismic noise at different detector sites



Seismic noise in KAGRA

- Large variation according to the atmospherical condition

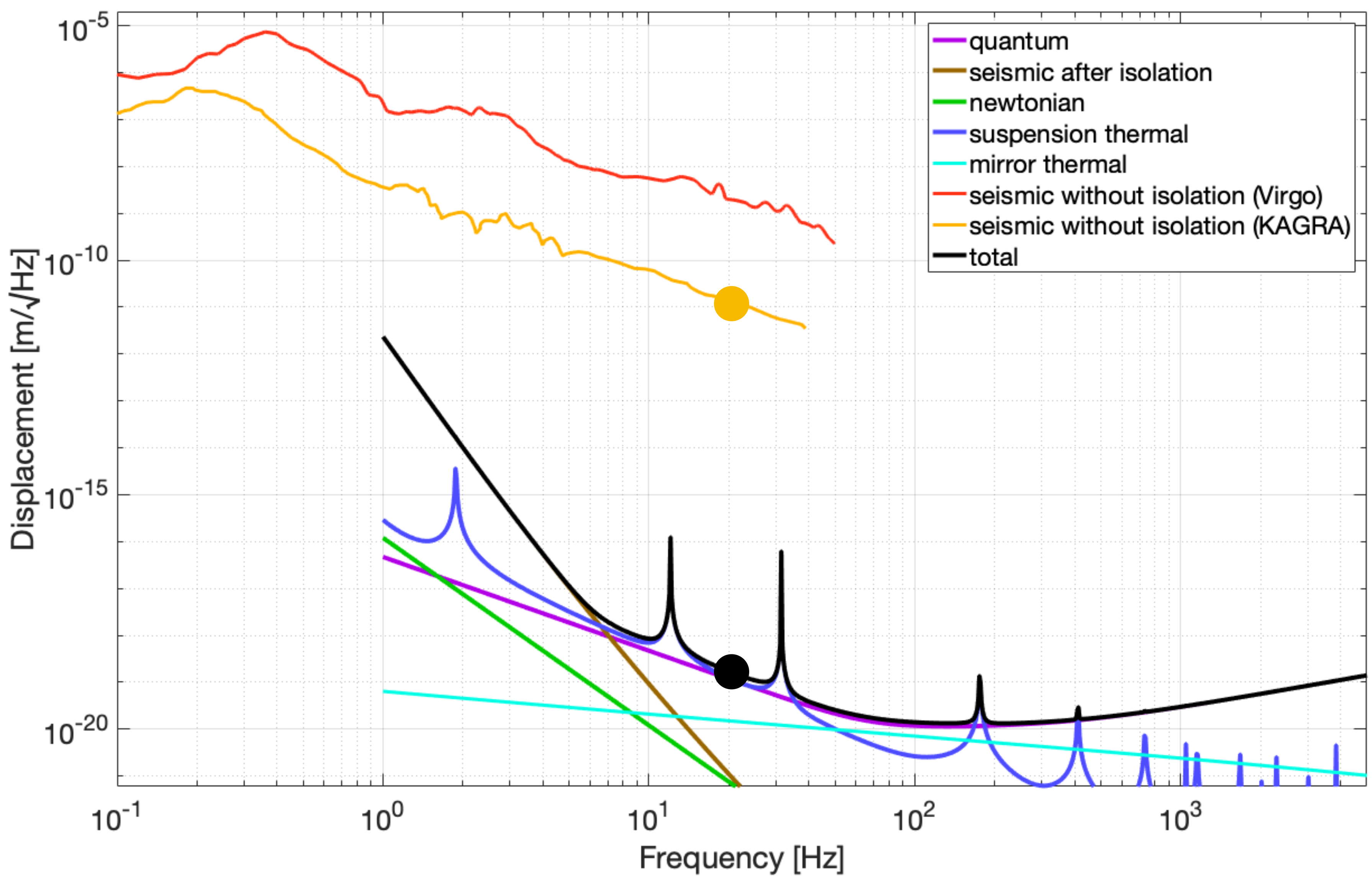


T. Sekiguchi. A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors. Phd thesis

Vibration isolation

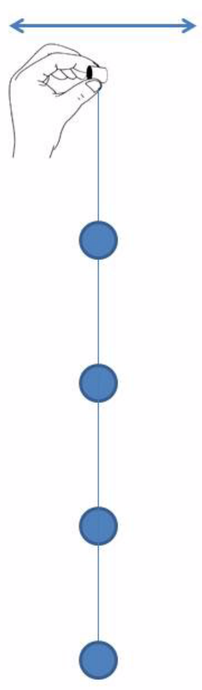
- Seismic motion at ~10 Hz: ~ 10^{-11} m/√Hz
- Required mirror motion at ~10 Hz: ~ 10^{-19} m/√Hz

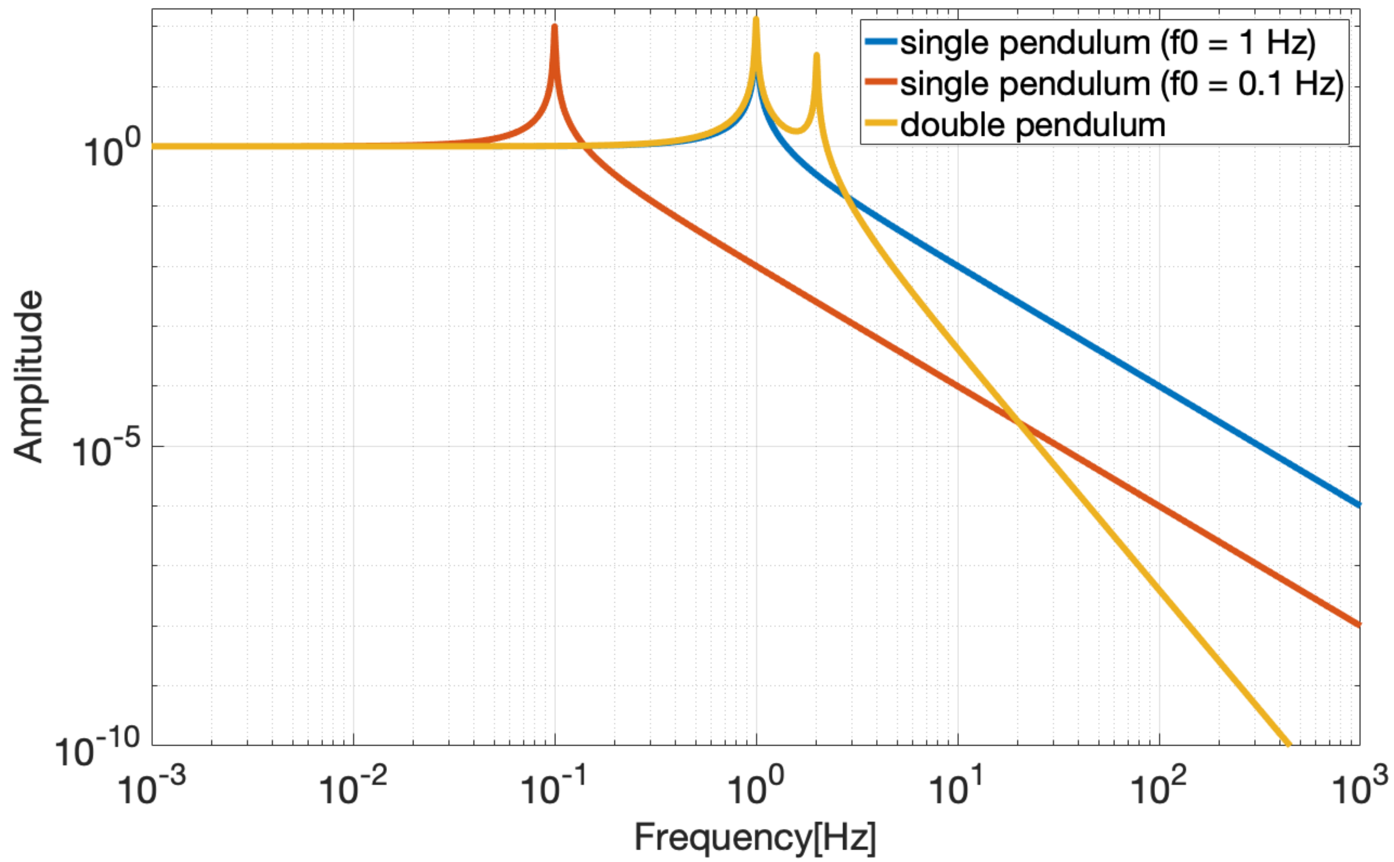
A high performance vibration isolation system is still required (at least 8 order of magnitudes)



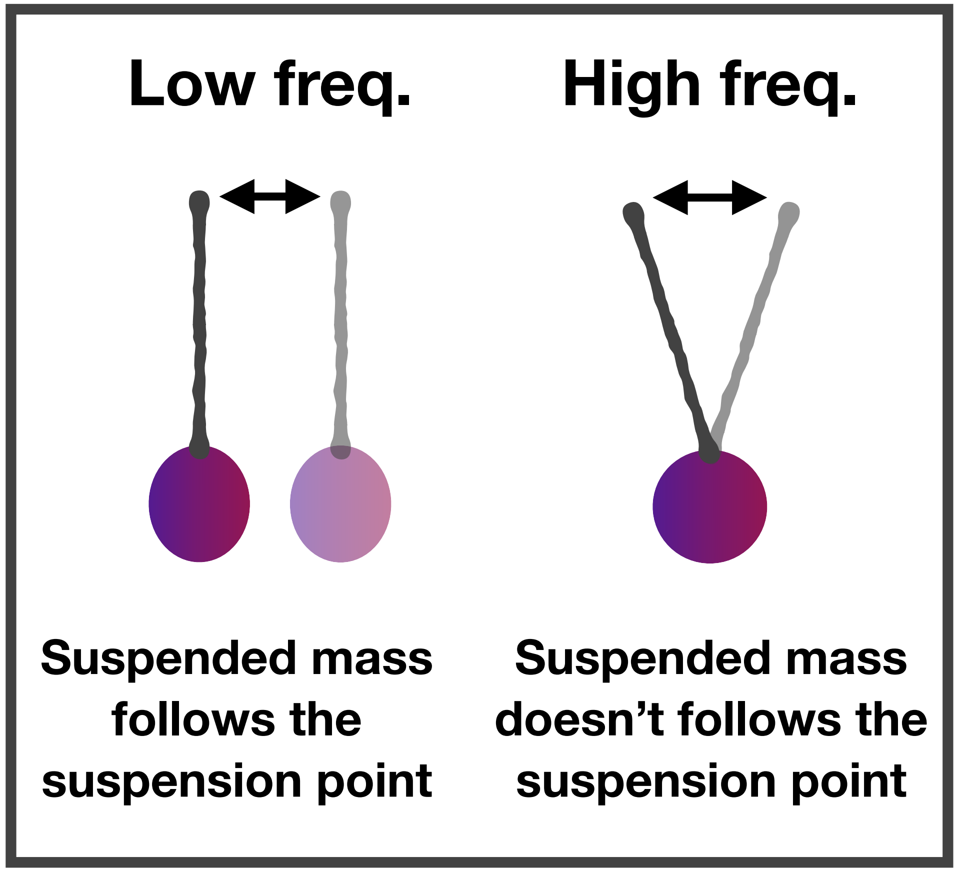
Vibration isolation system

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



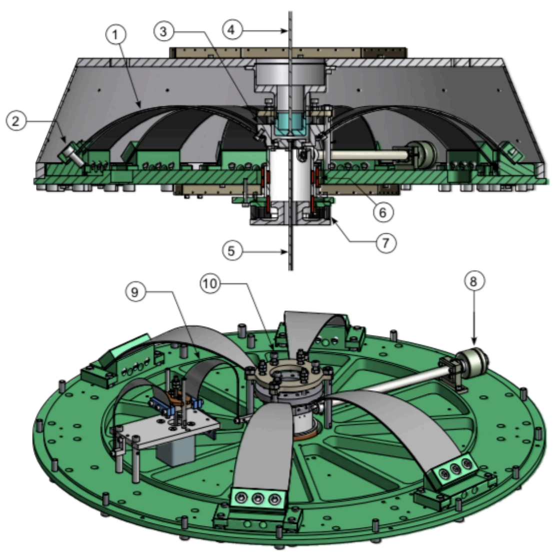


Transfer function: motion of mirror/motion of support

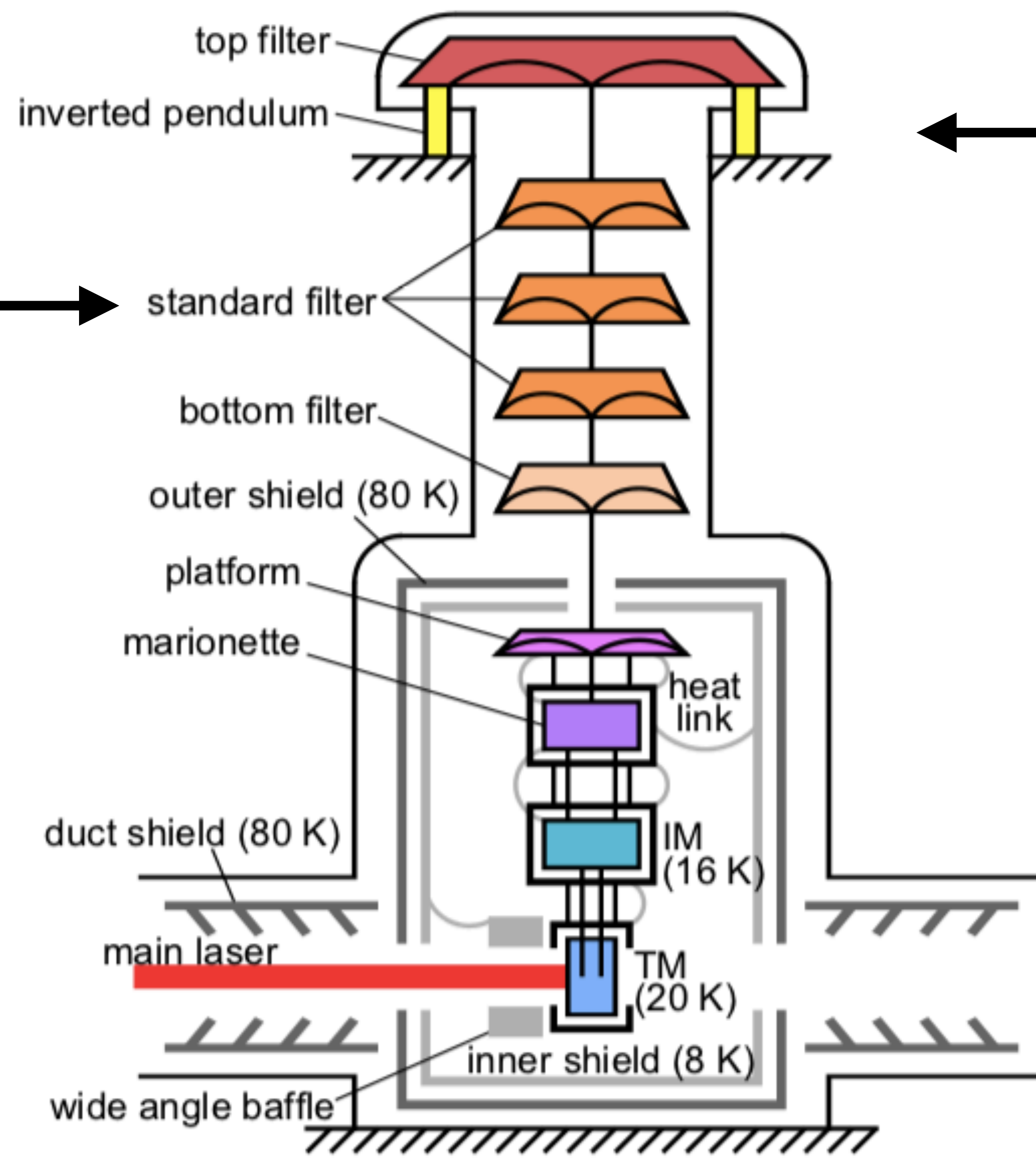


Vibration isolation system

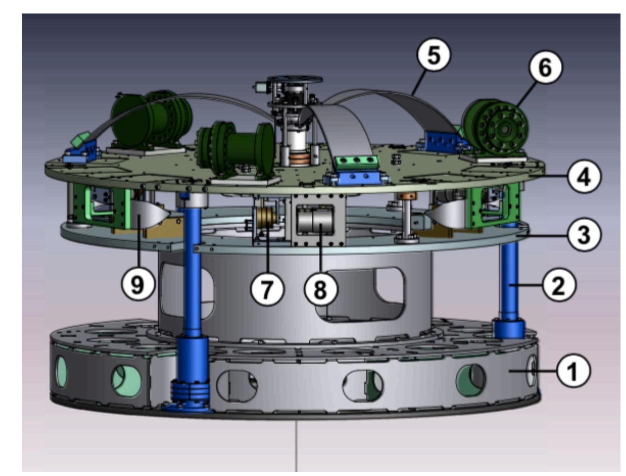
- KAGRA vibration isolations (as Virgo) uses a chain of pendulums and vertical (GAS) spring to attenuate seismic vibration in all the degrees of freedom



Geometrical antispring (GAS) filter

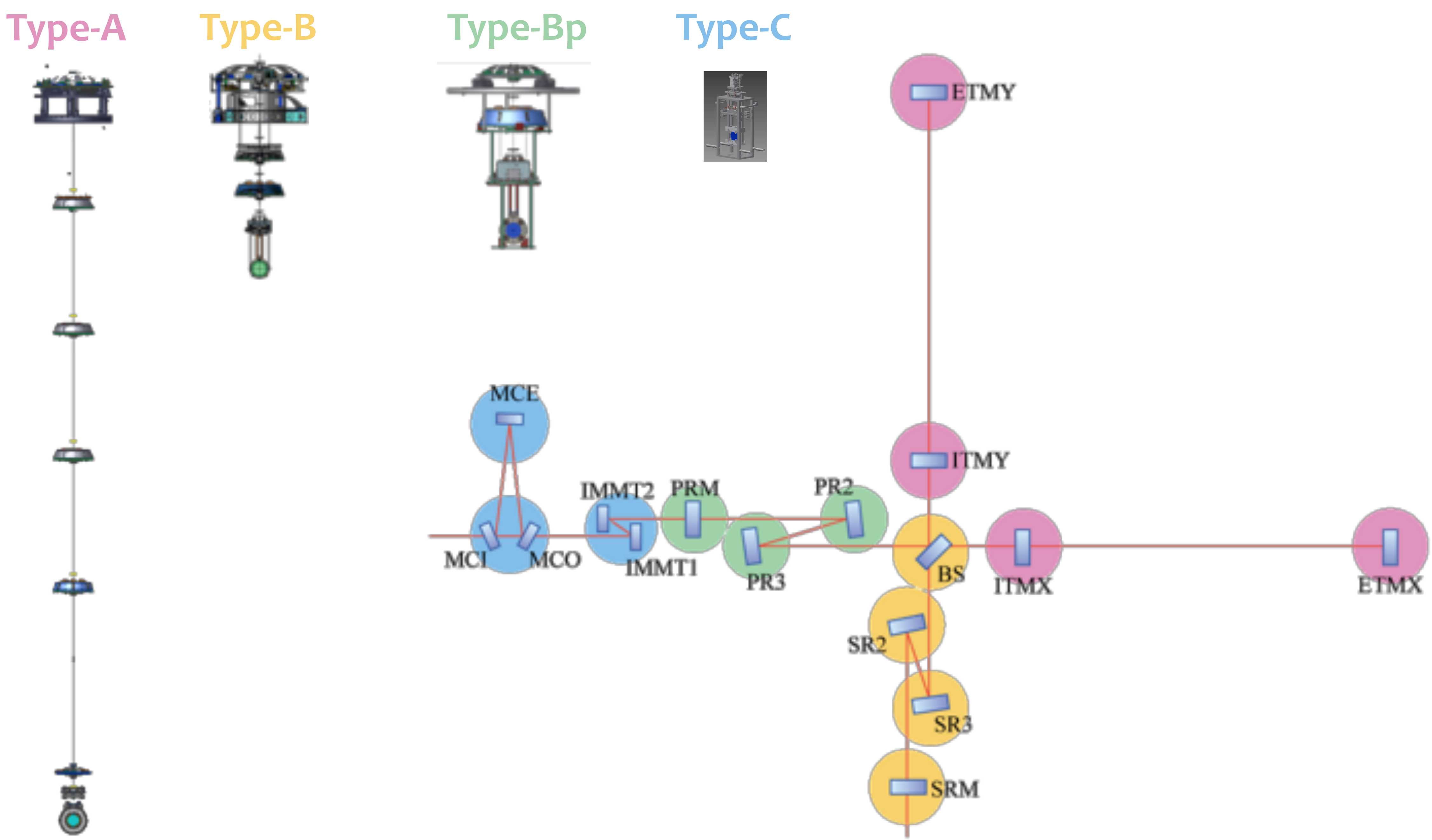


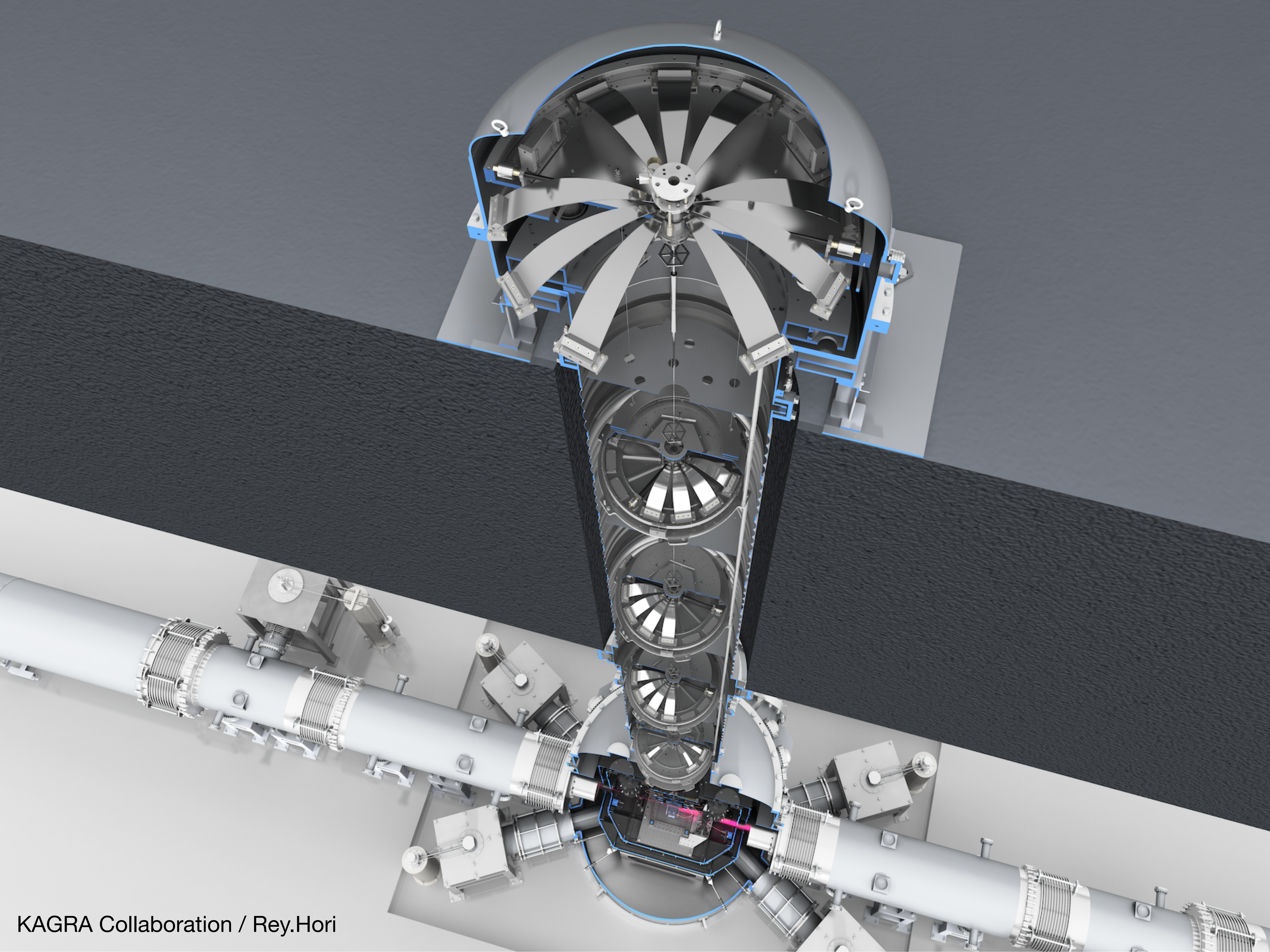
Preisolation stage with inverted pendulum



Vibration isolation system

- Different optics have different requirements for vibration isolation

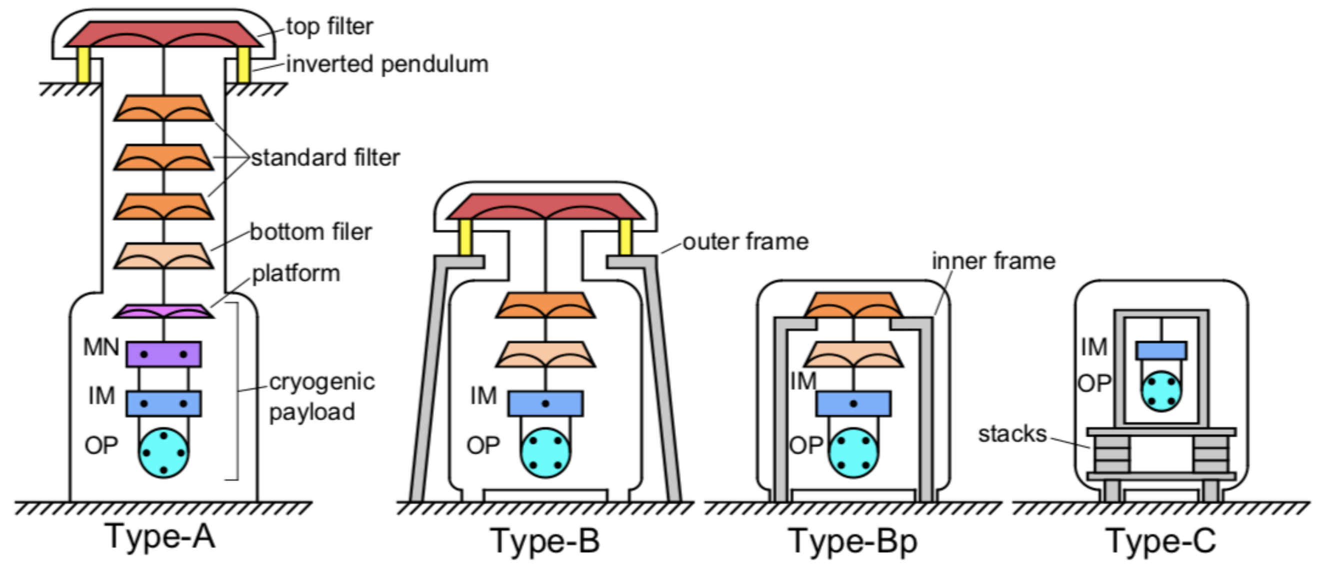


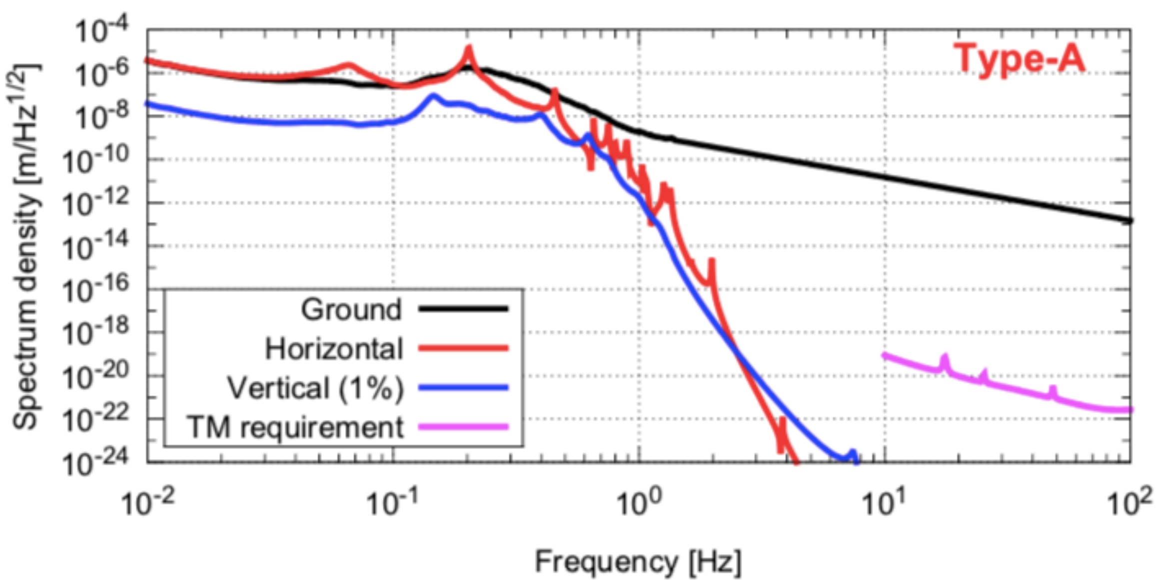


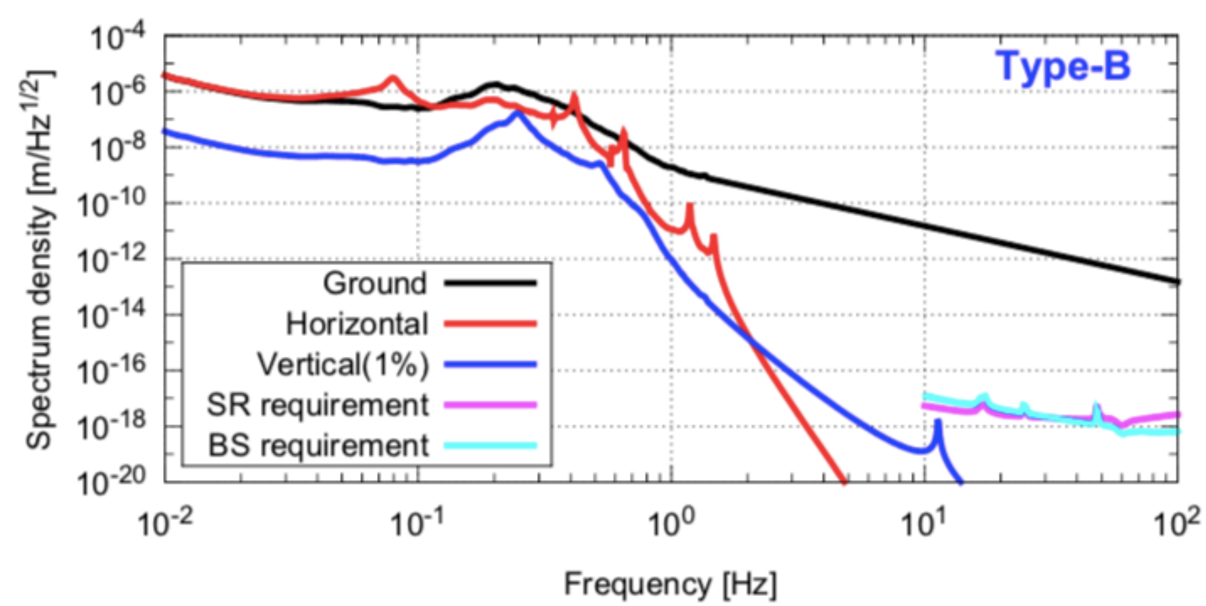
KAGRA Collaboration / Rey.Hori

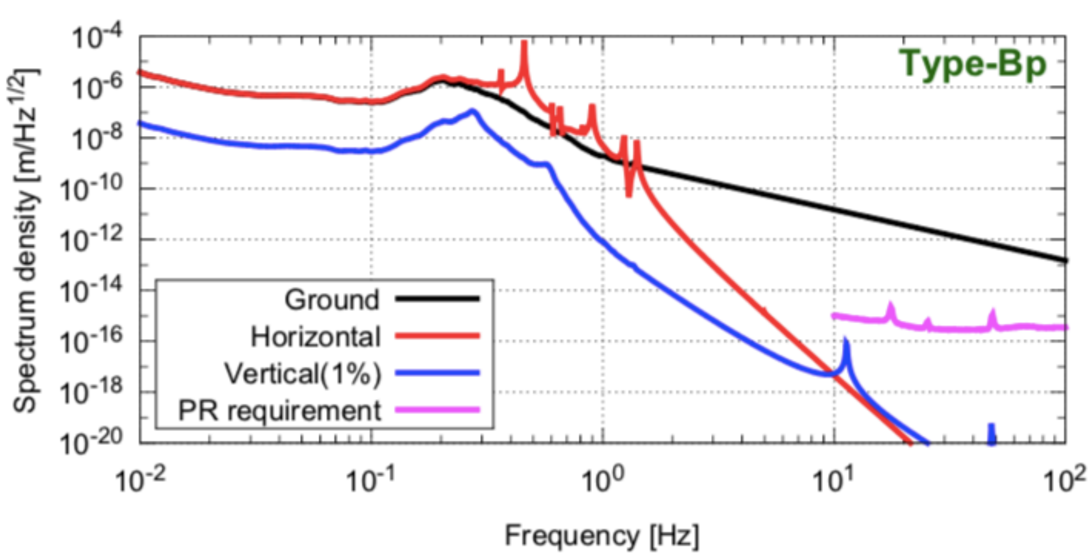
Suspension installation

Vibration isolation system performances





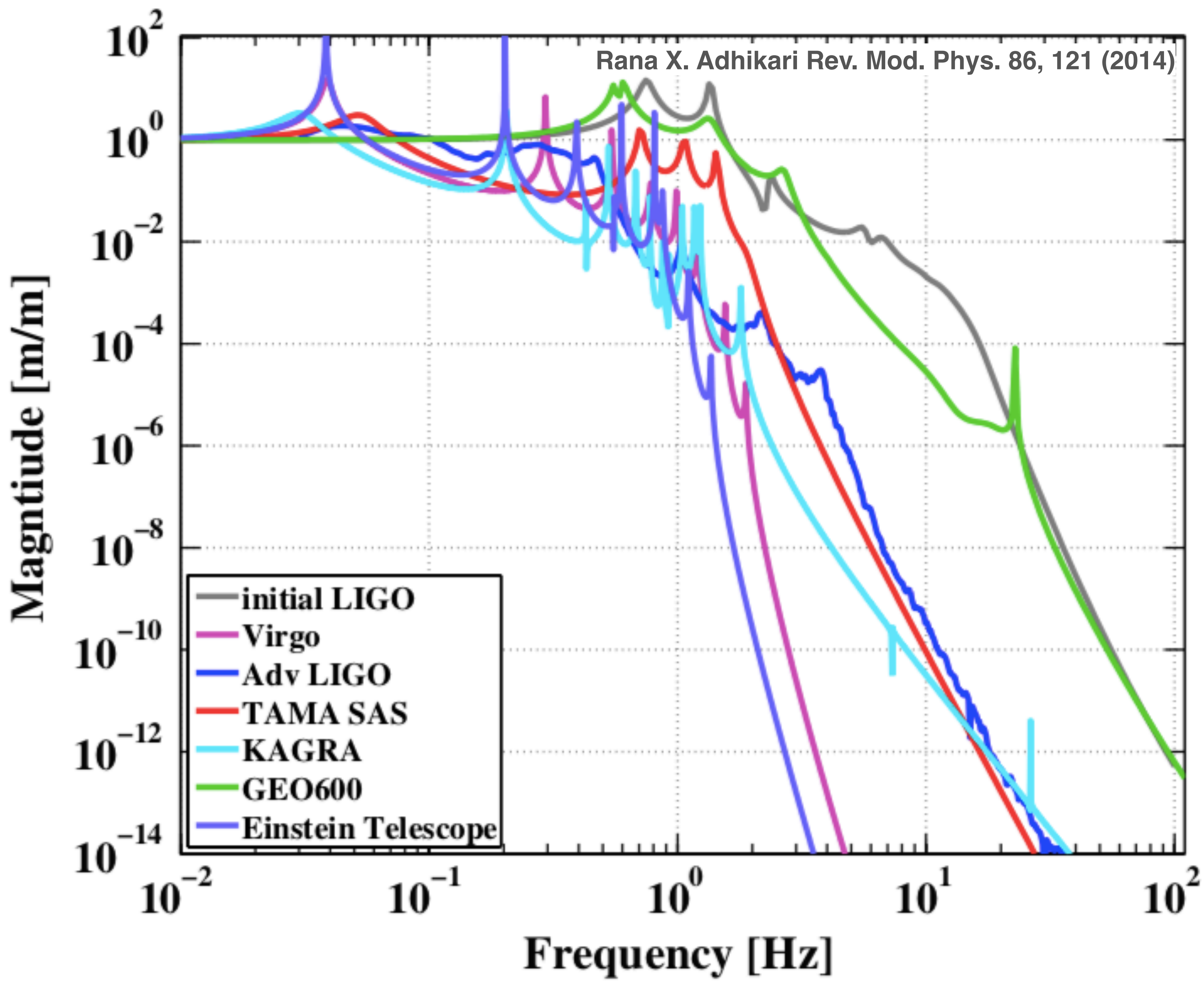




T. Sekiguchi. A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors. Phd thesis

Vibration isolation system

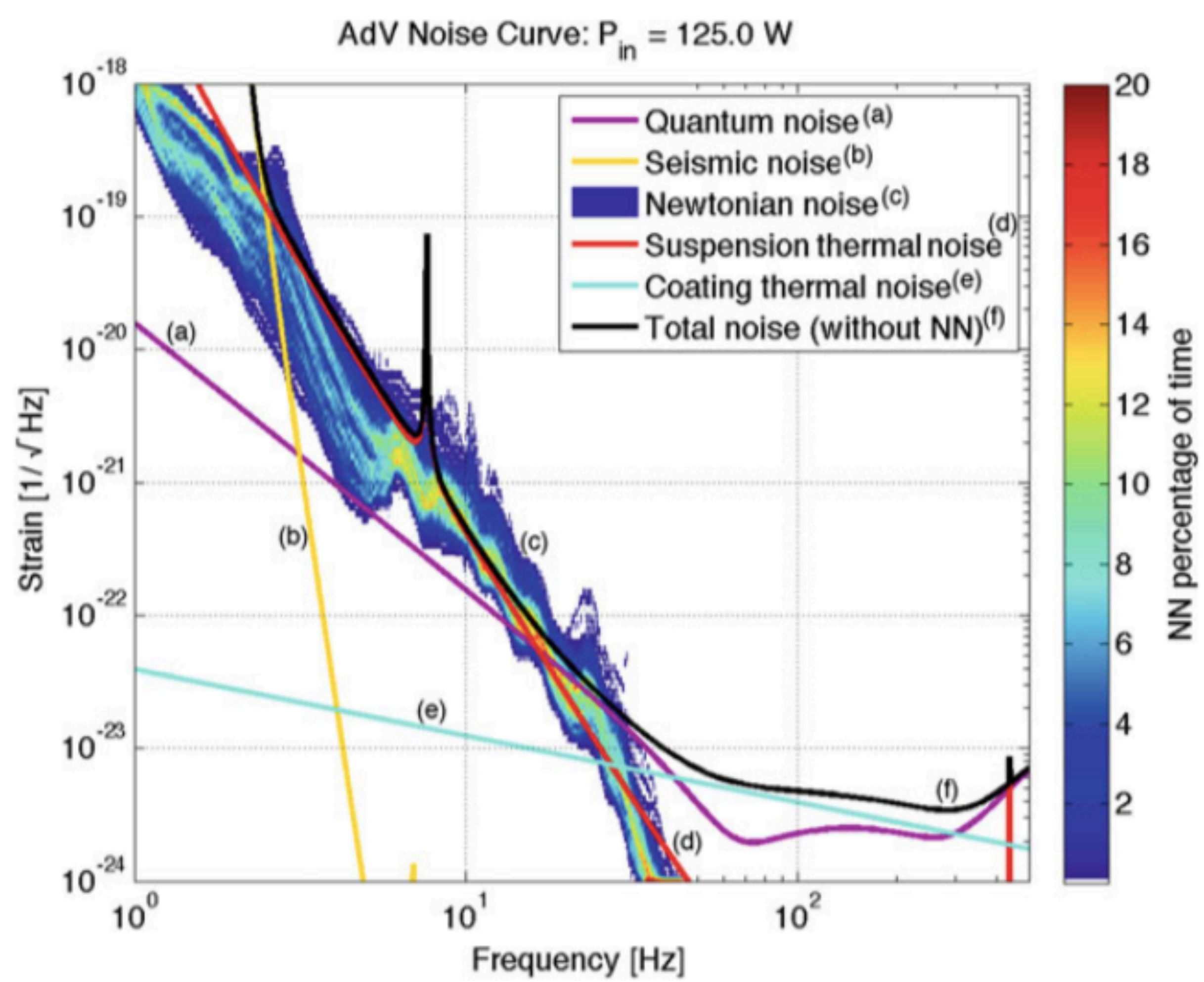
- Comparison of the performances of different detector suspension



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



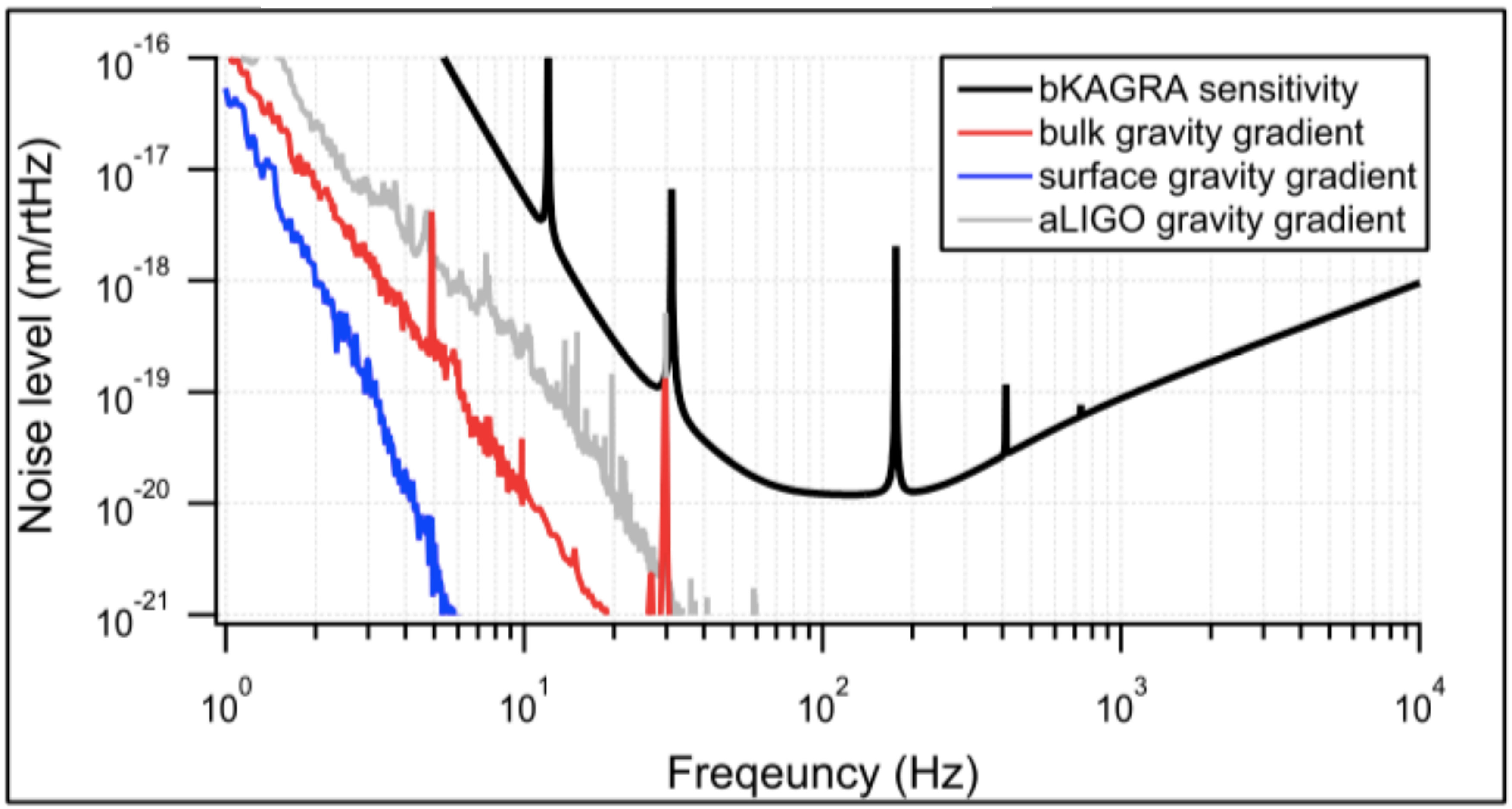
ET design study

Newtonian noise: depth dependance

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

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

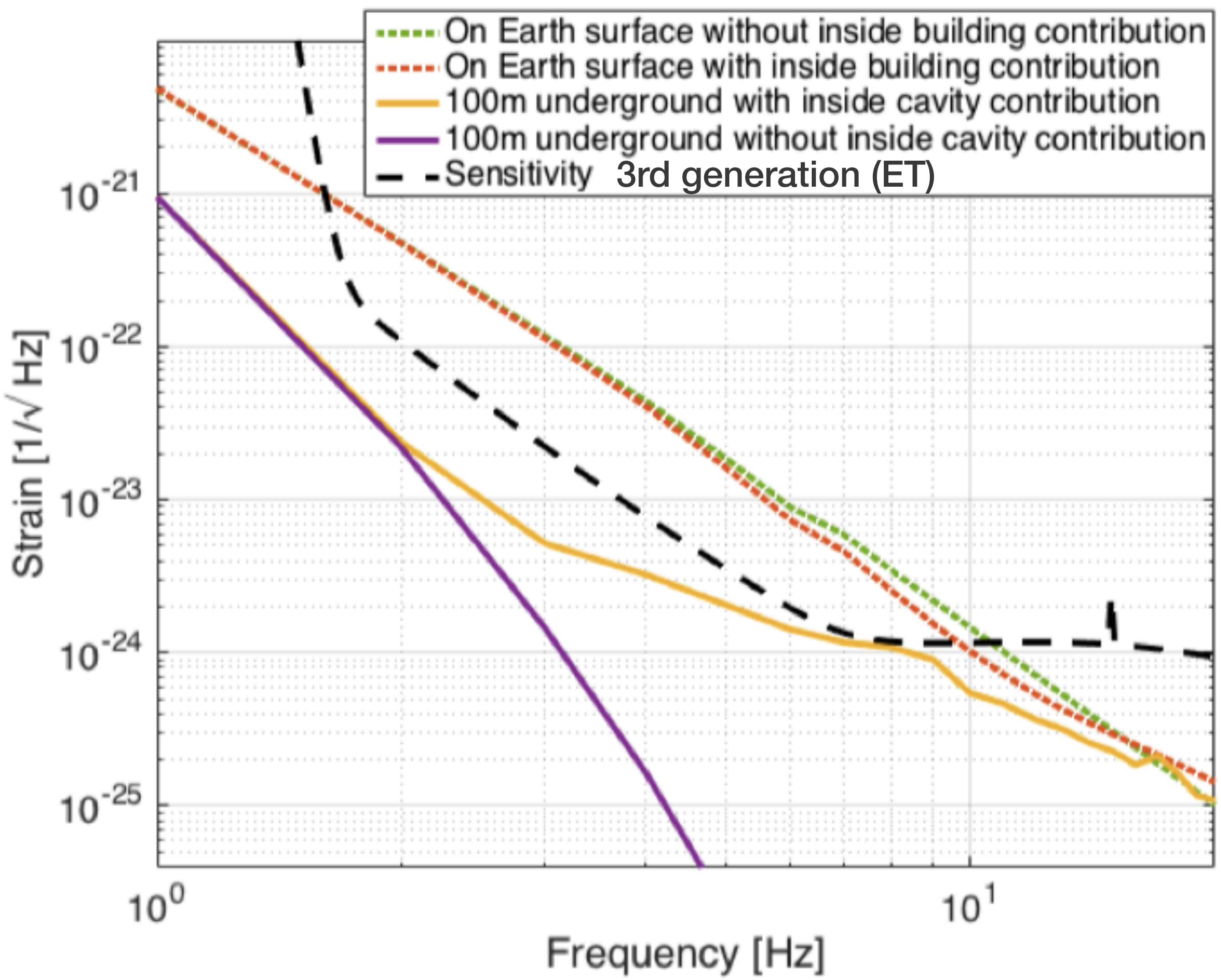
P Saulson
Phys. Rev. D 30, 732



Construction of KAGRA: an underground gravitational-wave observatory,
https://doi.org/10.1093/ptep/ptx180

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

Why to reduce seismic disturbance?

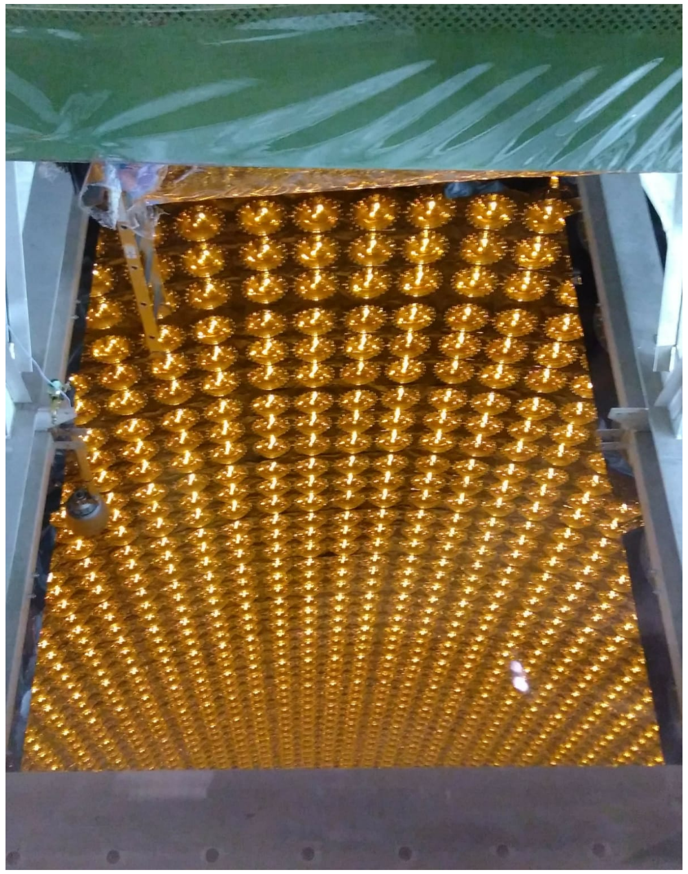
- Reduce Newtonian Noise
- Reduced low-frequency motion of mirrors
- Lower gain of control loops → lower control noise in-band
- Reduce technical noise coupled to seismic (i.e scattered light)
- Stability

Underground challenges

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

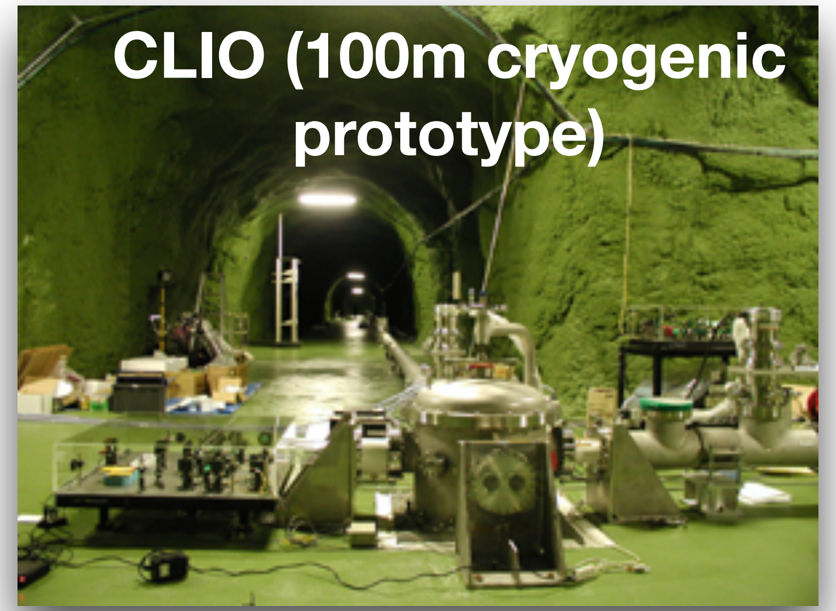
Kamioka Mine

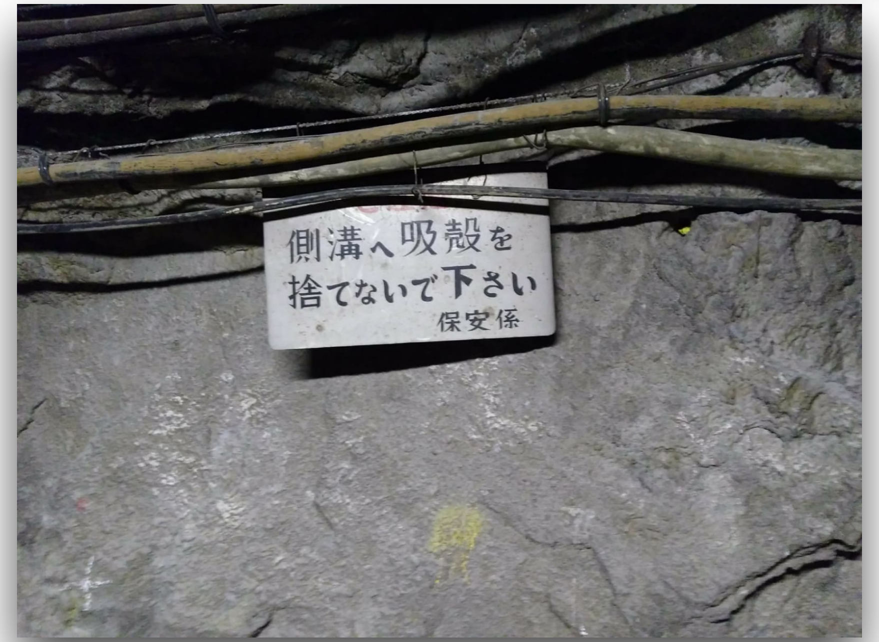
- Very old and well known mine
- It host neutrinos and dark matter experiment facilities (SK, XMASS)



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

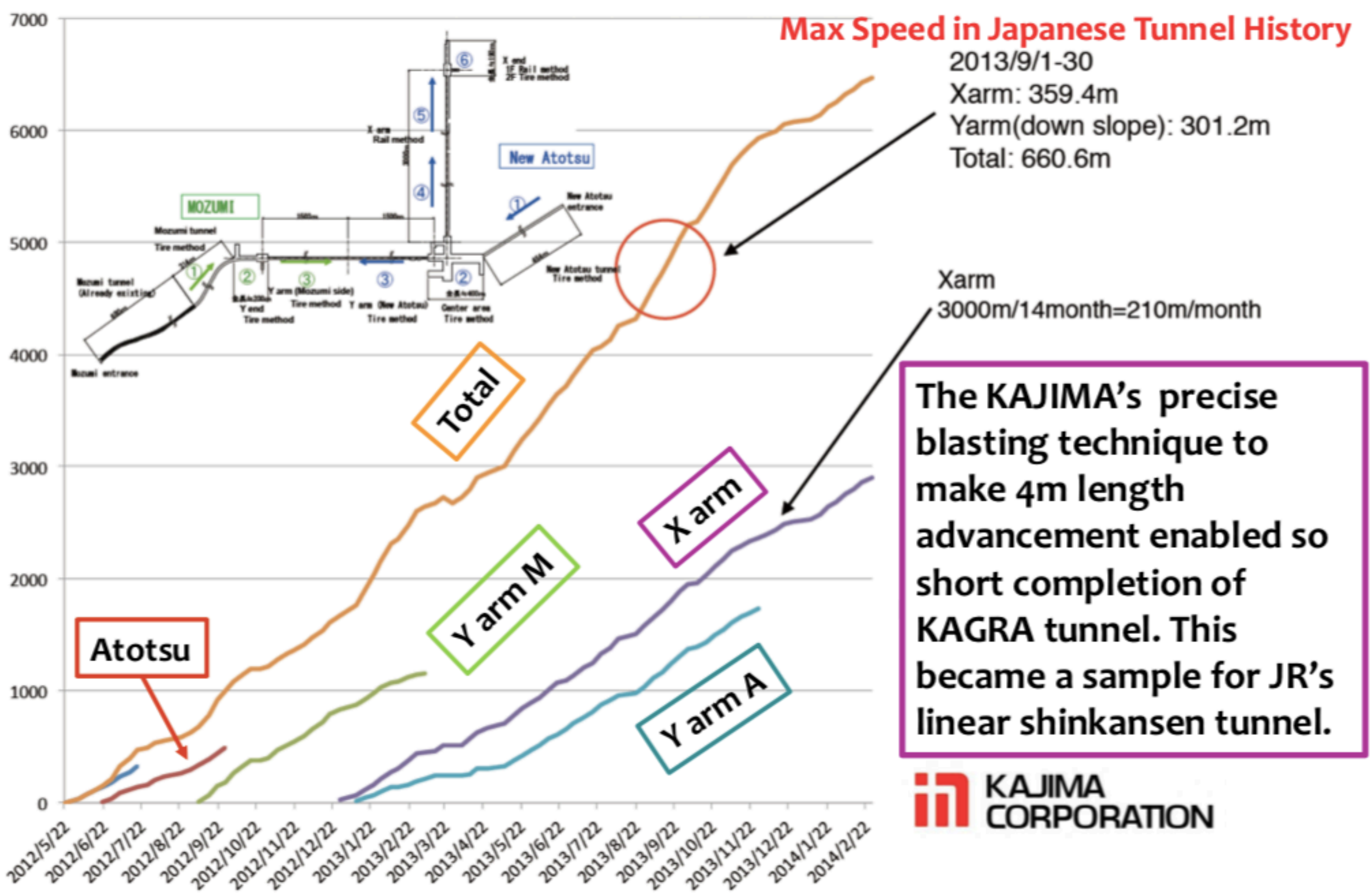
- Total cost of the tunnel: 24 MUSD (original) + 3.5 MUSD (additional cost)

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
- Neutralisation of alkalised spring water caused by concrete

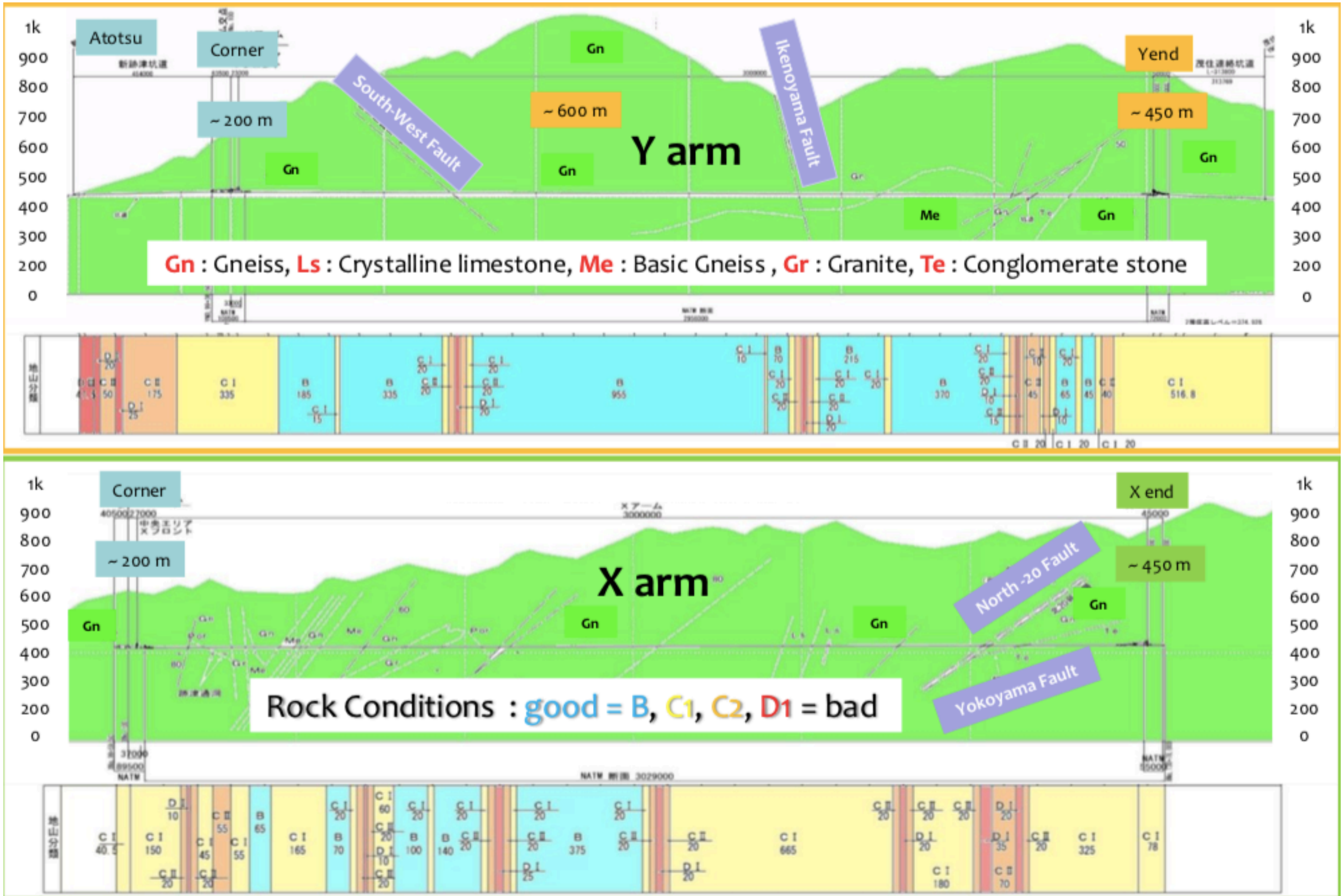
S. Miyoki *"Experience with underground facilities for KAGRA site"* GWADW 2018

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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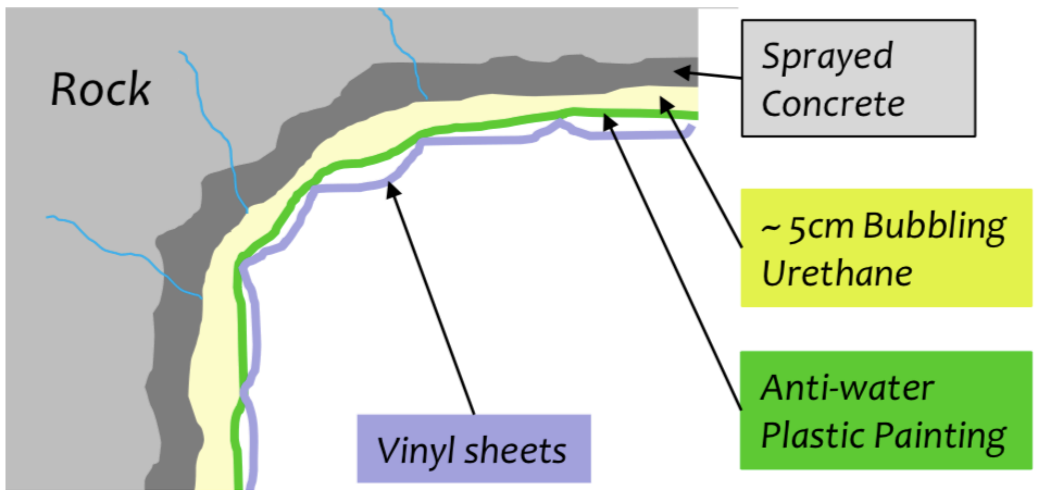
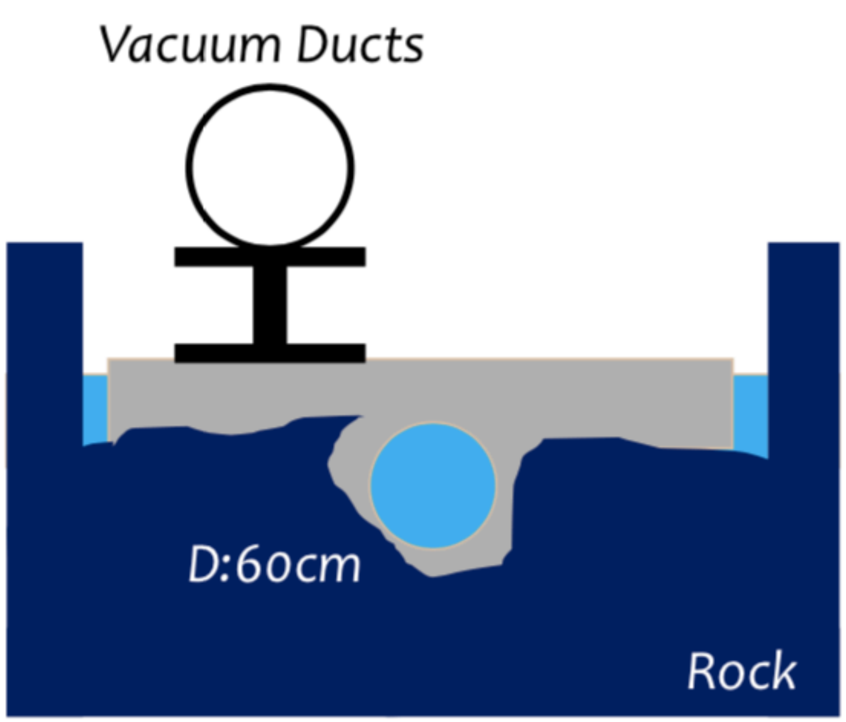
Spring water in the tunnel



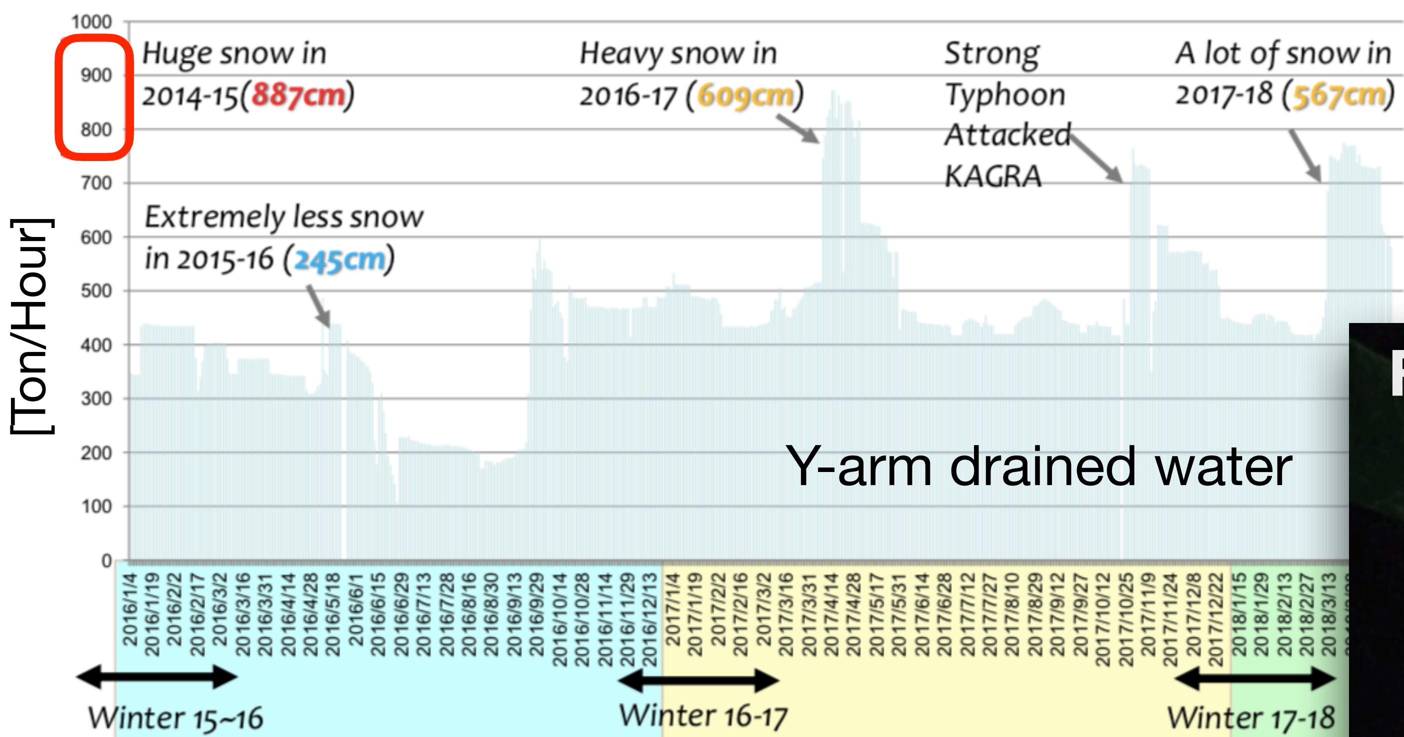


- Underestimated problem
- Many levels of isolation required for the walls
- 1/300 slope for the tunnel floor
- Ditch and pumps and water pipe installed to drain the water

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

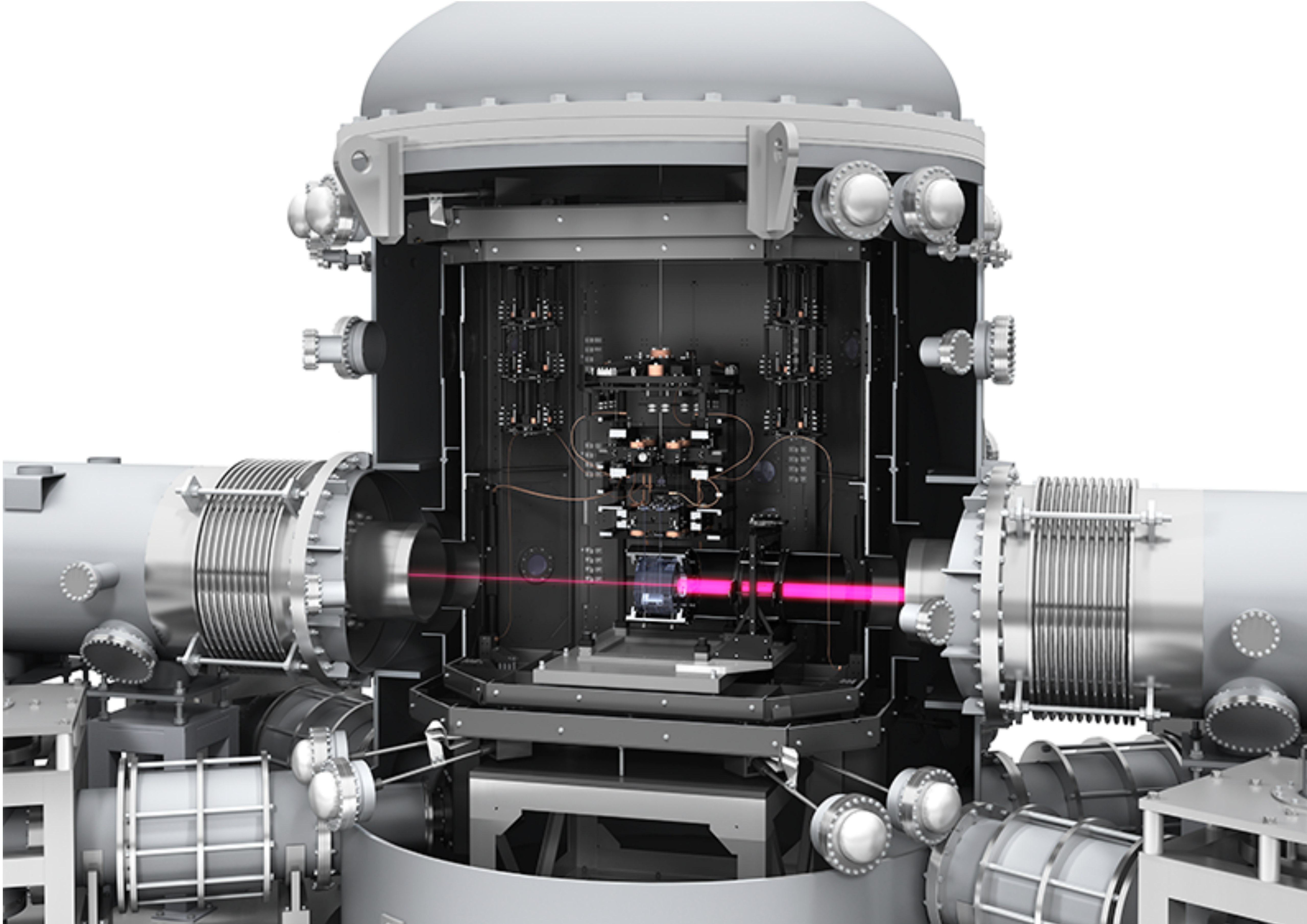
Many “small” issues..

- 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

Underground operation: summary

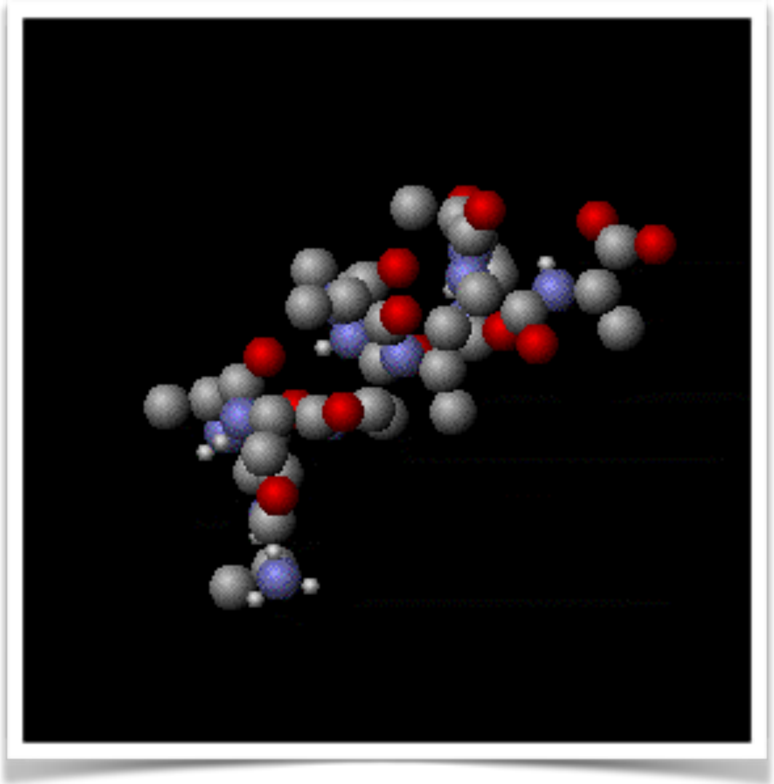
- Underground operation can reduce significantly seismic noise (about a factor ~100)
- Lower seismic noise relaxes the requirement on vibration isolation possibly reducing technical noise in the observation bandwidth
- Newtonian noise is also reduced
- Many “underground” issues had to be tackled → valuable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

KAGRA: un cryogenic GW detector



Where does thermal noise come from?

- Thermal fluctuation of atoms and molecules related to their temperature



- **Equipartition theorem**: total thermal energy of each degree of freedom is

$$E = \frac{1}{2}KT$$

- This sets a limit on the rest condition of an harmonic oscillator

- The vibration amplitude of the mechanical mode of a microscopic object (e.g a 20 kg mirror) is ~ 10^{-15} m

How are these fluctuations distributed in frequency?
What is its spectrum?

Fluctuation-dissipation theorem

If a system is affected by a dissipation process (i.e energy turned into heat), there is a reverse process which induces a fluctuation of its position, related to the temperature:

- **Brownian noise** and **drag**: objects is moving through a fluid, it experiences drag (kinetic energy into heat). In turn the object does not sit still, but rather moves kicked by molecules in the fluid. (heat energy into kinetic energy)

- **Johnson noise** and **resistance**: Resistance dissipates electrical energy, turning it into heat (Joule heating). In turn a wire loop with a resistor in it has a fluctuating current caused by the thermal fluctuations of the electrons and atoms in the resistor (heat energy into electrical energy)

Fluctuation-dissipation theorem

Relation between the response of the system when it is driven by an external force and the fluctuations of its position when it is not excited by any external force [Callen et al. 1975]

Boltzmann constant:
1.38*10^{-23} m^{2} kg s^{-2} K^{-1}

Temperature

Position fluctuation spectrum

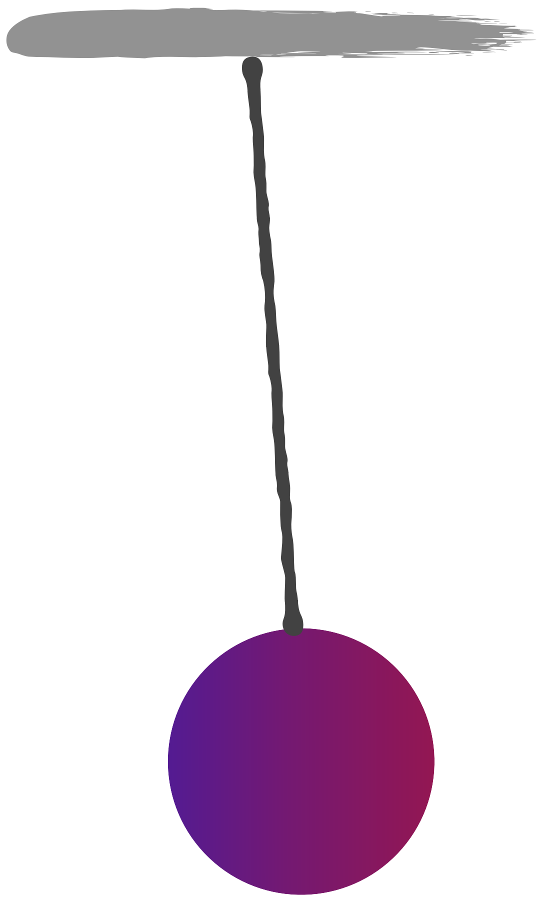
$$x_{th}^2(\omega) = \frac{4kT}{\omega^2} Re\left(Z^{-1}(\omega)\right)$$

Mechanical impedance

$$Z(\omega) = \frac{F_{\text{driving}}(\omega)}{v(\omega)}$$

Resistance of a system to acquire a speed under the application of a driving force

FDT: application to a damped harmonic oscillator



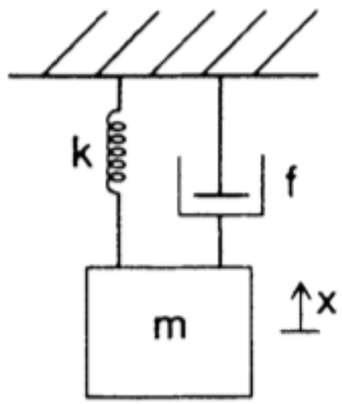
Equation of motion (depends on the type of damping)

$$Z(\omega) = \frac{F_{\text{driving}}(\omega)}{v(\omega)}$$

$$x_{th}^2(\omega) = \frac{4kT}{\omega^2} Re\left(Z^{-1}(\omega)\right)$$

Different types of damping

Viscous damping

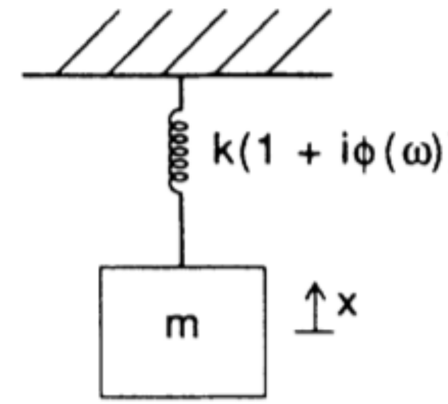


$$m\ddot{x} + f\dot{x} + kx = F$$

- Eg. Residual air, eddy currents

$$x^2(\omega) = \frac{4kTf}{(k - m\omega^2)^2 + \omega^2 f^2}$$

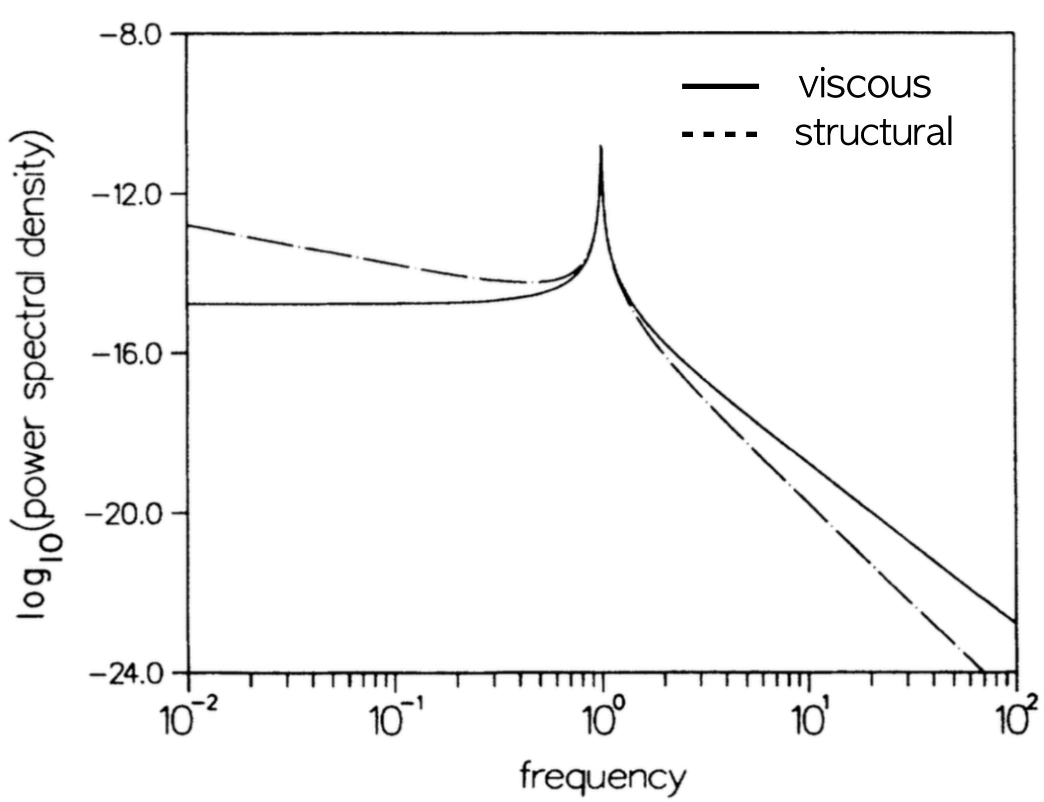
Structural damping



$$m\ddot{x} + k(1 + i\phi)x = F$$

- Due to anelasticity. Lag between force and displacement

$$x^2(\omega) = \frac{4kT\phi(\omega)}{\omega[(k - m\omega^2)^2 + k^2\phi^2]}$$



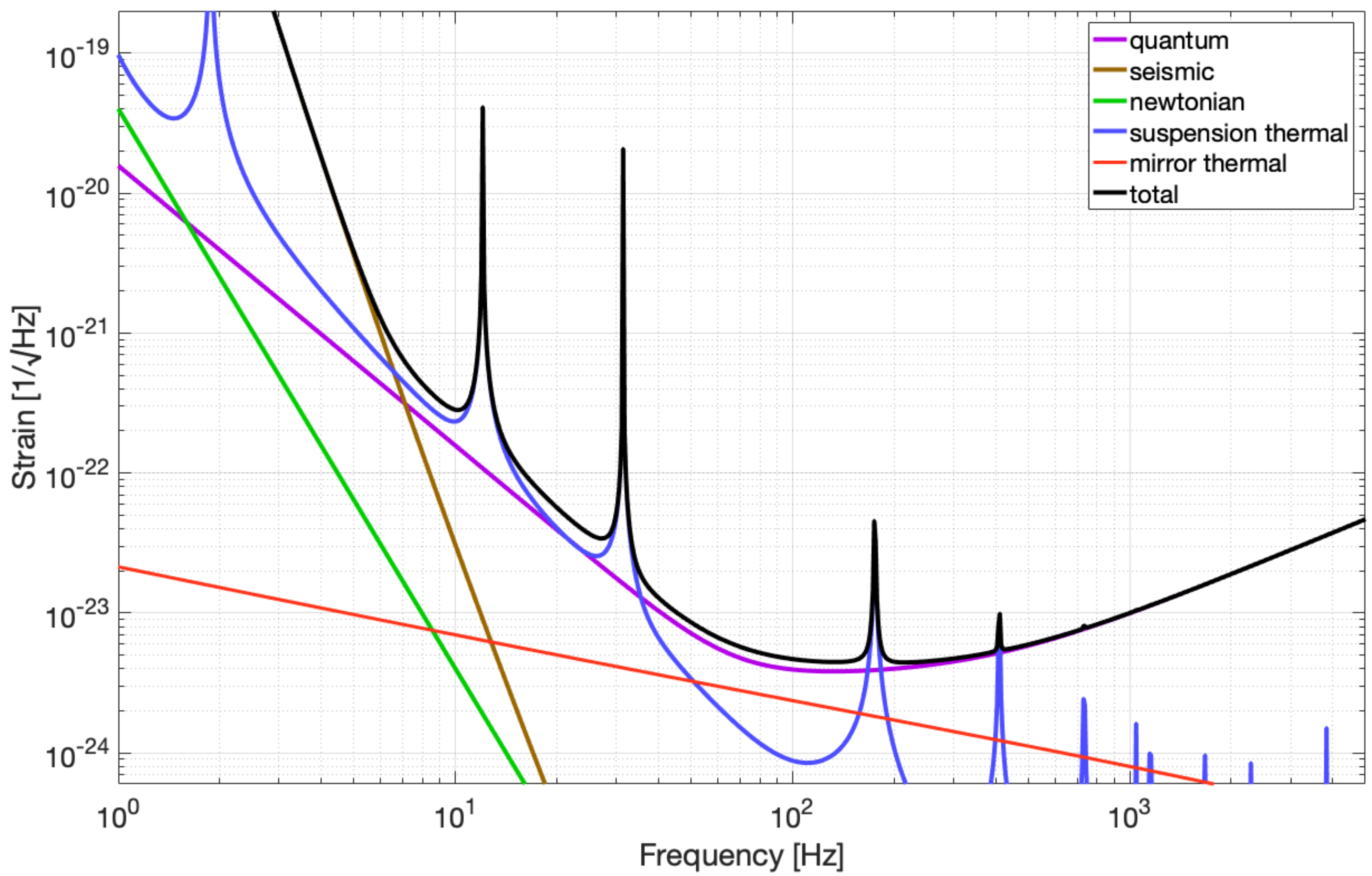
Thermal noise in mechanical experiments
Peter R. Saulson
Phys. Rev. D **42**, 2437 (1990)

The lower the losses (f, ϕ) the lower the amount of fluctuations out of resonance

What we learnt about the spectrum of thermal fluctuation

- It can be computed using fluctuation-dissipation theorem
- It depends on the damping mechanism
- Structural damping is the dominating effect in our case
- It reduces out of resonance for lower losses
- It reduces at all the frequencies for lower temperature

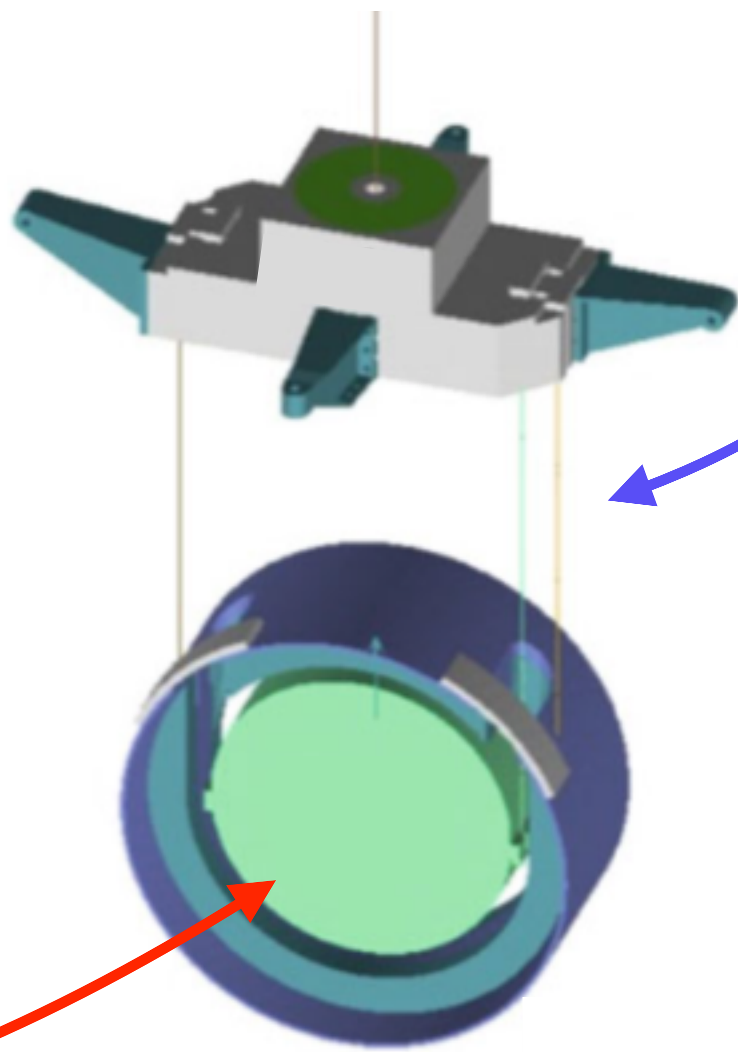
Thermal noise components in GW detectors



Suspension thermal noise

(w_0 ~ few Hz)

Relevant fluctuations above resonance



Mirror thermal noise

(w_0 ~ few KHz)

Relevant fluctuations below resonance

Pendulum thermal noise

- Restoring force mainly provided by **gravity**, which is **lossless**
- Small contribution by **wire elasticity**, which is **affected by losses**
- Total elastic constant of the pendulum is the sum of the two

$$k = k_g + k_{el}(1 + i\phi_w) = \frac{Mg}{L} + \frac{N\sqrt{TEI}}{2L^2}(1 + i\phi_w)$$

N = number of wire
T = wire tension
E = Young modulus
I = momentum of Inertia

Pendulum thermal noise

$$k \simeq k_g(1 + \frac{k_{el}}{k_g} i\phi_w)$$

- The losses due to the wires are diluted by the factor $\frac{k_{el}}{k_g}$
- The pendulum loss angle is $\phi_p = \frac{N\sqrt{TEI}}{2LMg}\phi_w$
- The associated power spectrum (from dissipation fluctuation theorem)

$$x_{th}^2(\omega) = \frac{4kT\phi_p}{M\omega_0^2}\omega^{-5}$$

We consider only the part above the resonance, which is at ~1 Hz

How to reduce pendulum thermal noise?

$$x_{th}^2(\omega) = \frac{4kT\phi_p}{M\omega_0^2}\omega^{-5} \qquad \phi_p \sim \frac{\sqrt{M}}{L}\phi_w$$

$$\downarrow$$

$$\boxed{x_{th}^2(\omega) \sim \frac{T\phi_w}{\sqrt{ML}}}$$

- Increase mirrors mass
- Increase wires length
- Reduce wire losses
- Reduce temperature

Mirror thermal noise: substrate

- Substrate thermal noise

$$x_{th}^2(\omega) = \frac{4k_B T}{\omega^2} \frac{1-\sigma^2}{\sqrt{\pi} E_0 w} \phi(\omega)$$

σ = poisson modulus

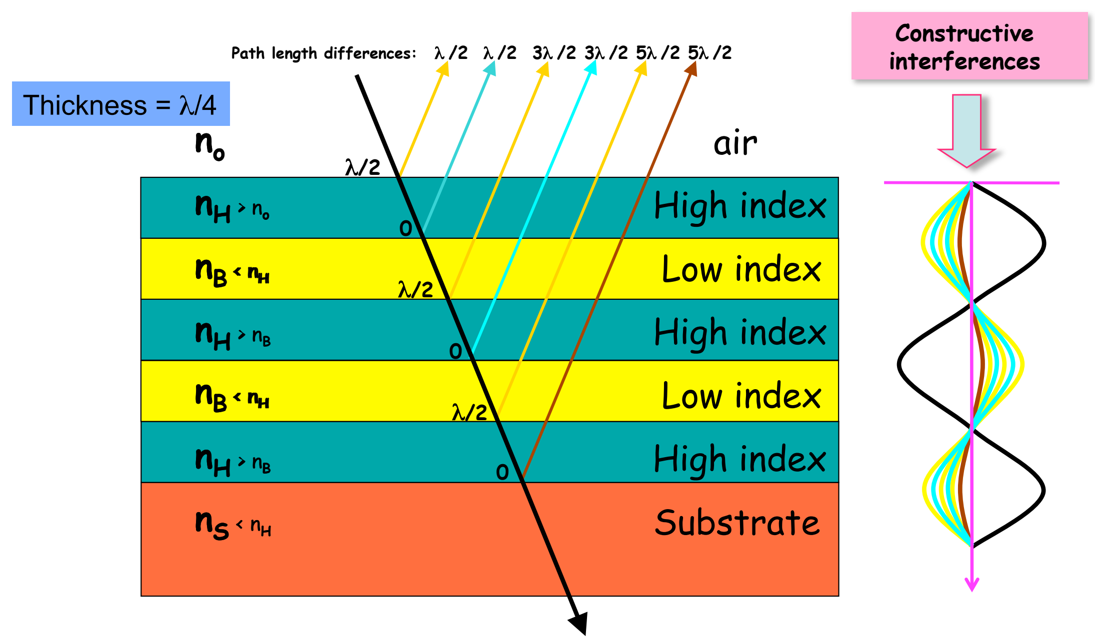
E_0 = mirror Young modulus

w = laser beam radius

- Fused silica shows very good performances at room temperature
  - low loss angle ~ 10^{-9}
  - low absorption < 1ppm
  - high homogeneity

Mirror thermal noise: coating

- Mirror coating: multilayer of alternating low and high refraction index material in order to obtain the required reflectivity



Numbers of layers between 15 and 40

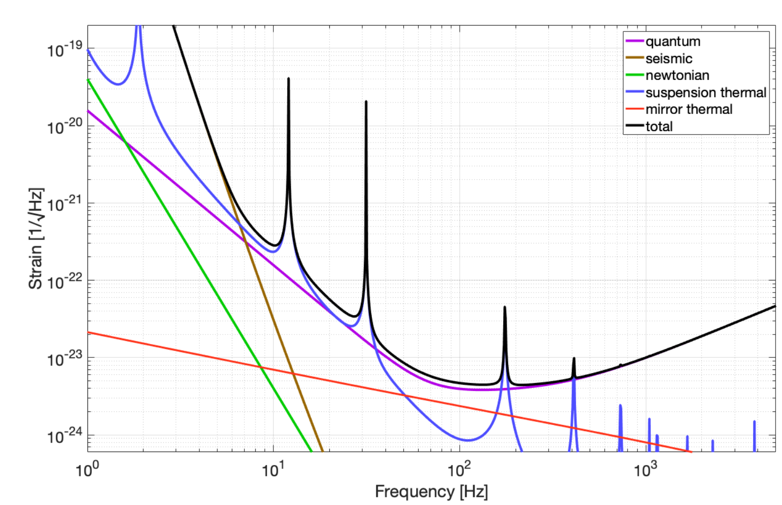
$$x^2(\omega) = \frac{8k_bT}{\omega}\frac{(1+\sigma)(1-2\sigma)t}{\pi E_0 w^2}\phi_{coat}$$

	Silica	Tantala
Refraction index	~1.45	~2
Loss angle	~10^{-5}	**~10^{-4}**

- Total loss angle dominated by Tantala losses

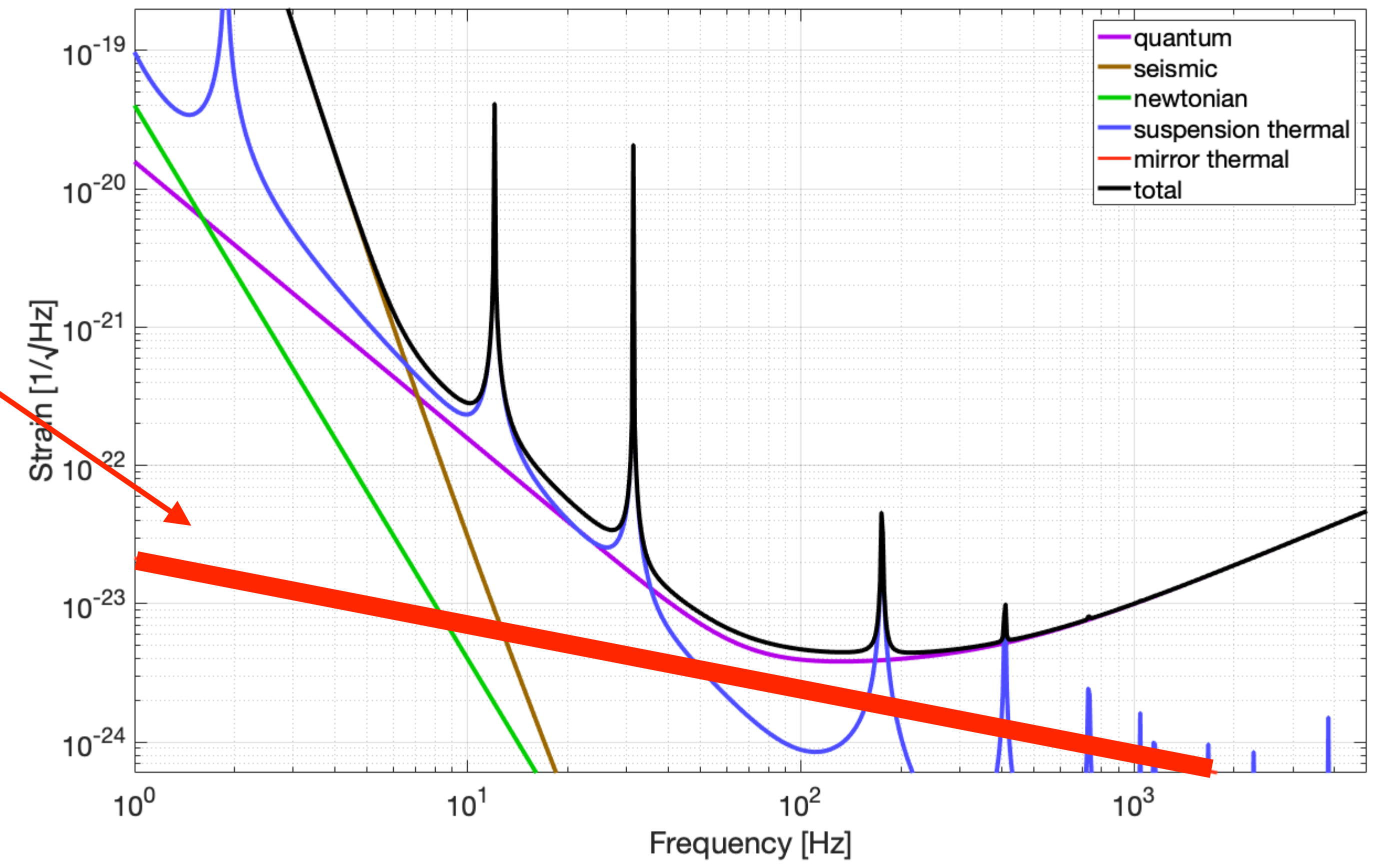
$$\phi_{coat} \sim 10^{-4}$$

Dominating source of thermal noise



Coating thermal noise

- Mirror thermal noise is dominated by coating thermal noise



- How to reduce it?

Lower temperature

Better material

$$x^2(\omega) = \frac{8k_bT}{\omega}\frac{(1+\sigma)(1-2\sigma)t}{\pi E_0 w^2}\phi_{coat}$$

Larger beam

How to reduce mirror thermal noise/3

Use of larger beam

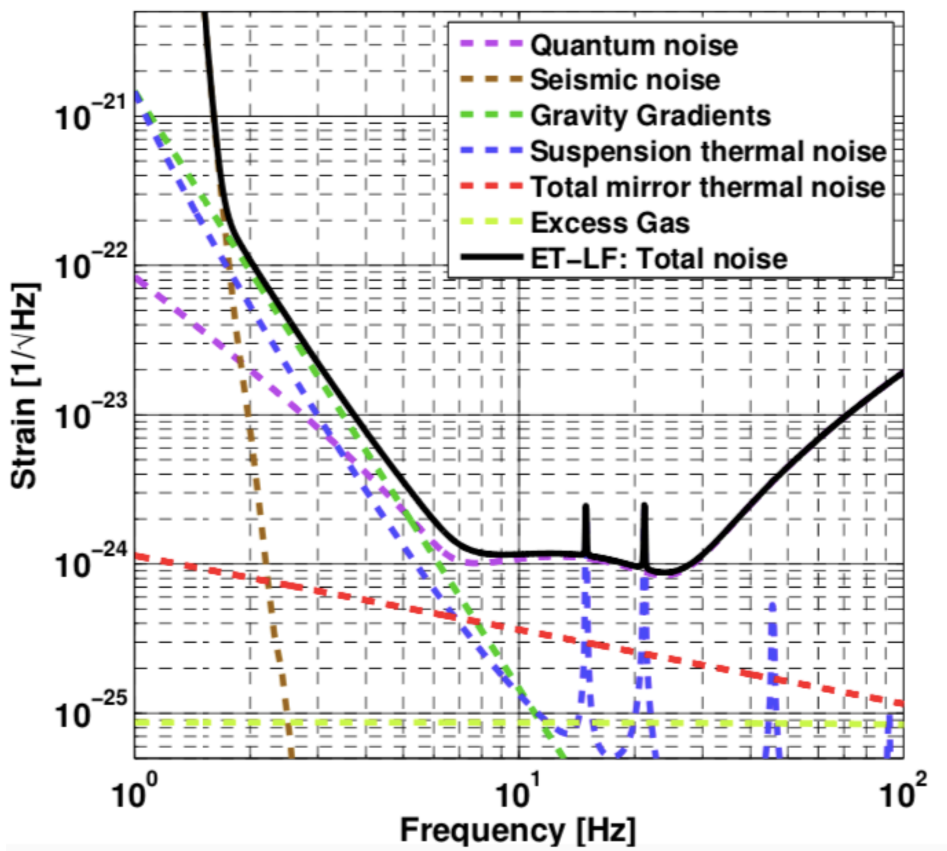
- Need beam ~ 1 m to get a factor 10 improvement
- Limited by the stability of the cavities
- Difficulties to realize mirrors large enough

$$x^2(\omega) = \frac{8k_bT}{\omega}\frac{(1+\sigma)(1-2\sigma)t}{\pi E_0 w^2}\phi_{coat}$$

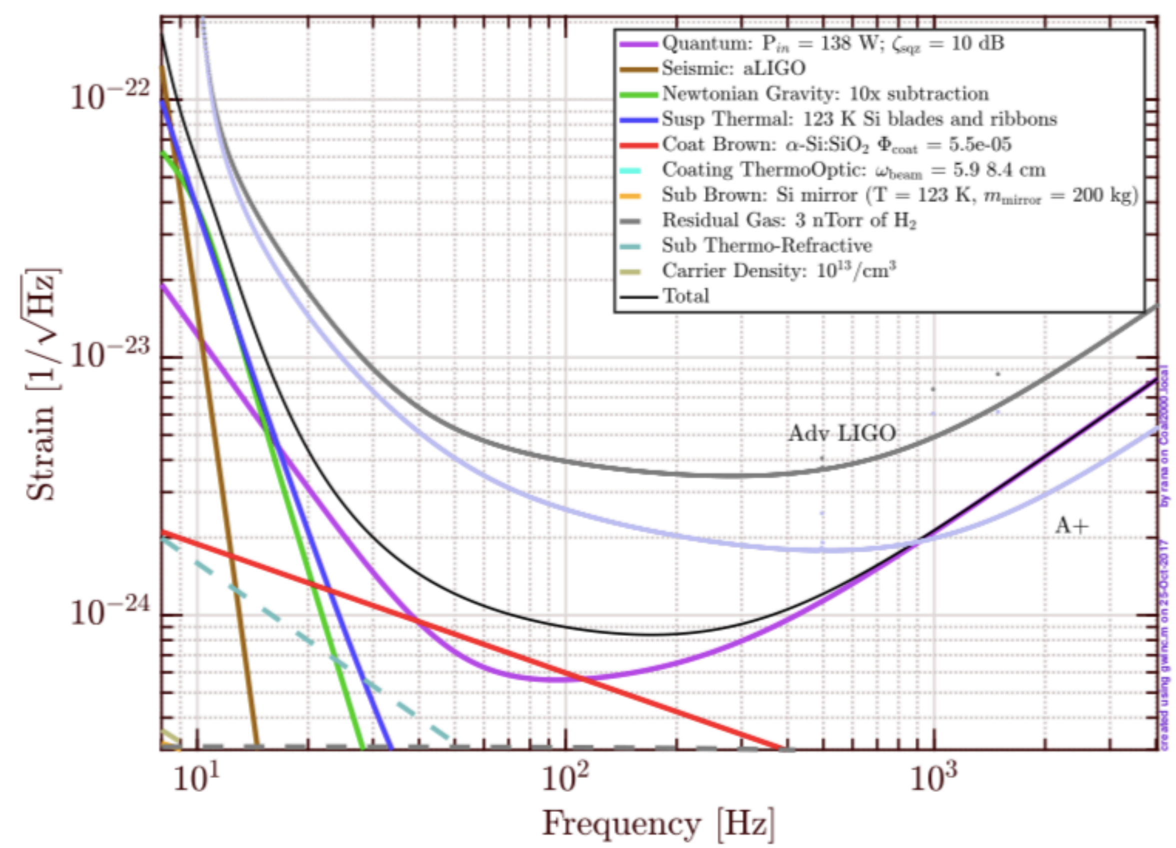
Cryogenics in future detectors

- 3rd generation detectors are designed to operate at cryogenic temperature

ET - LF



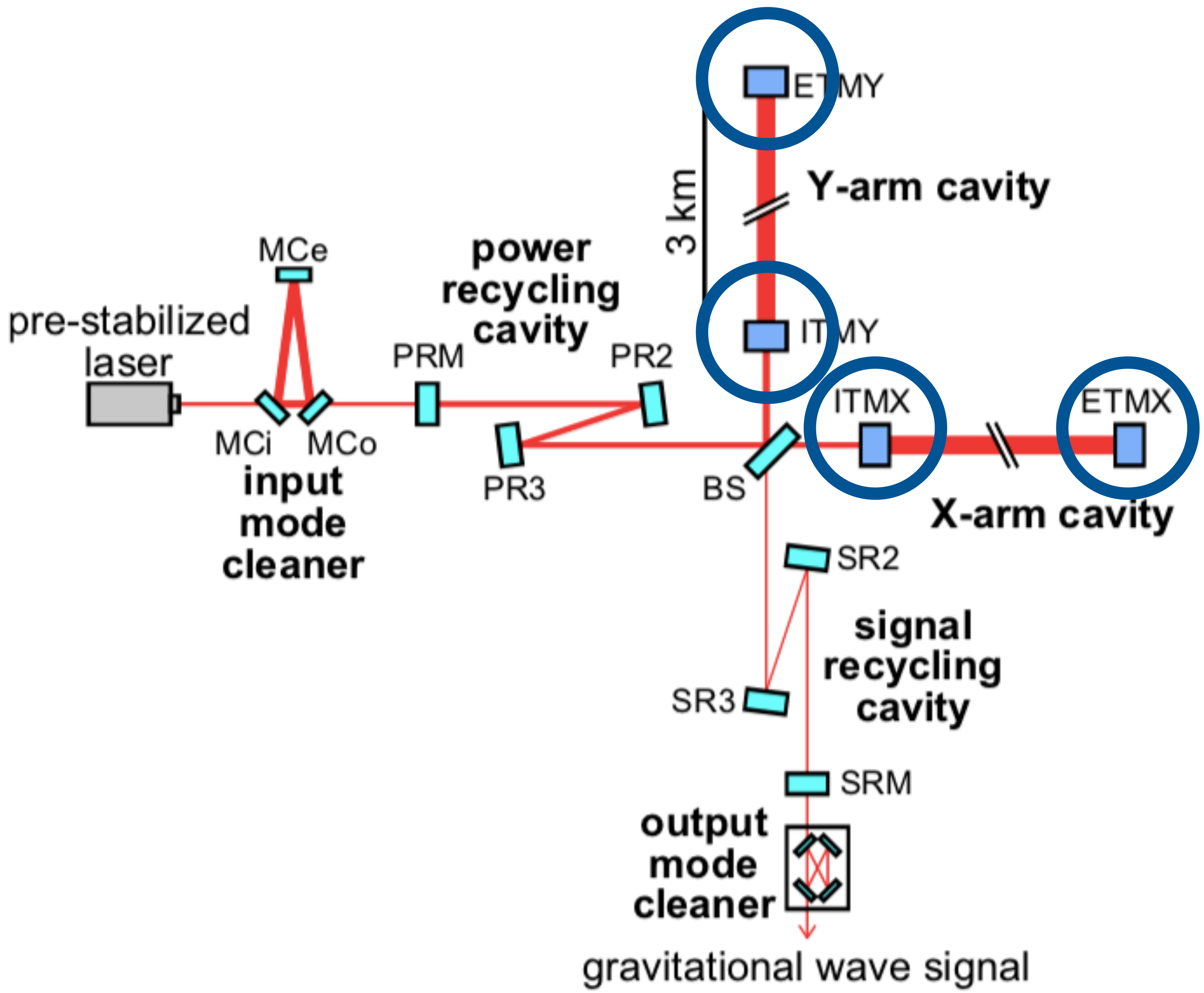
Voyager



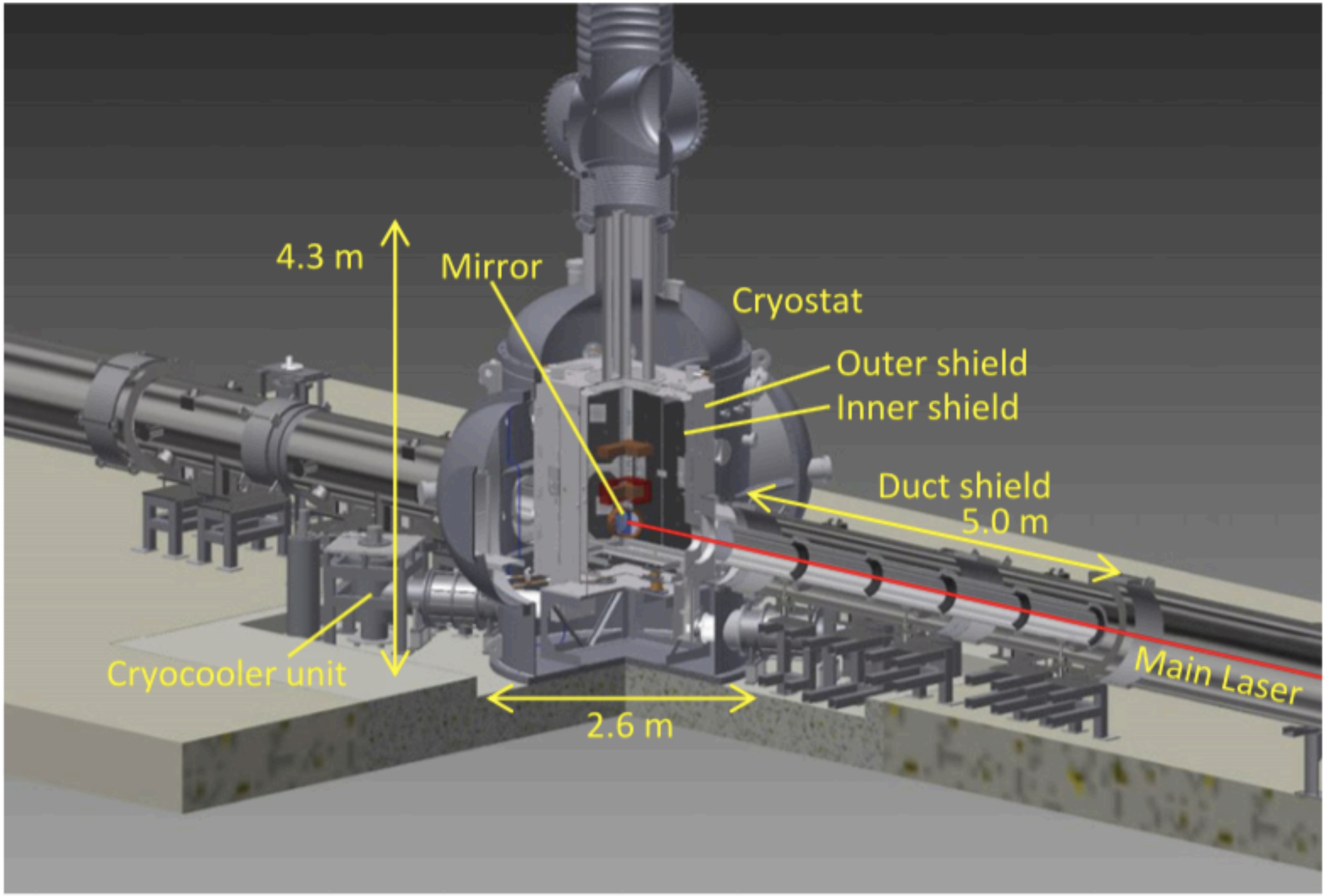
- KAGRA will open the path to test this technique on large scale detectors

KAGRA: cryogenic operation

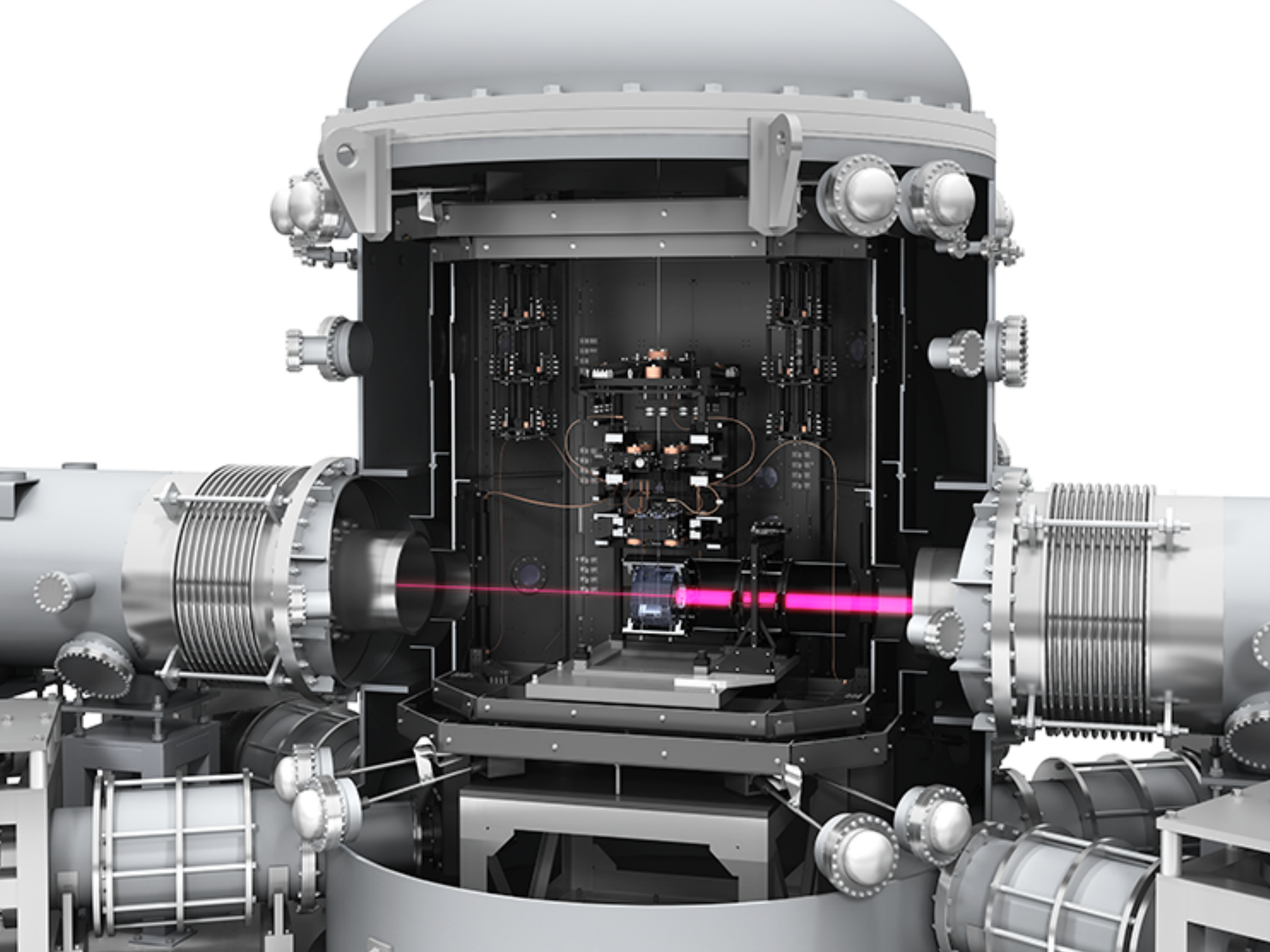
- **Sapphire** test masses cooled down at **20 K**



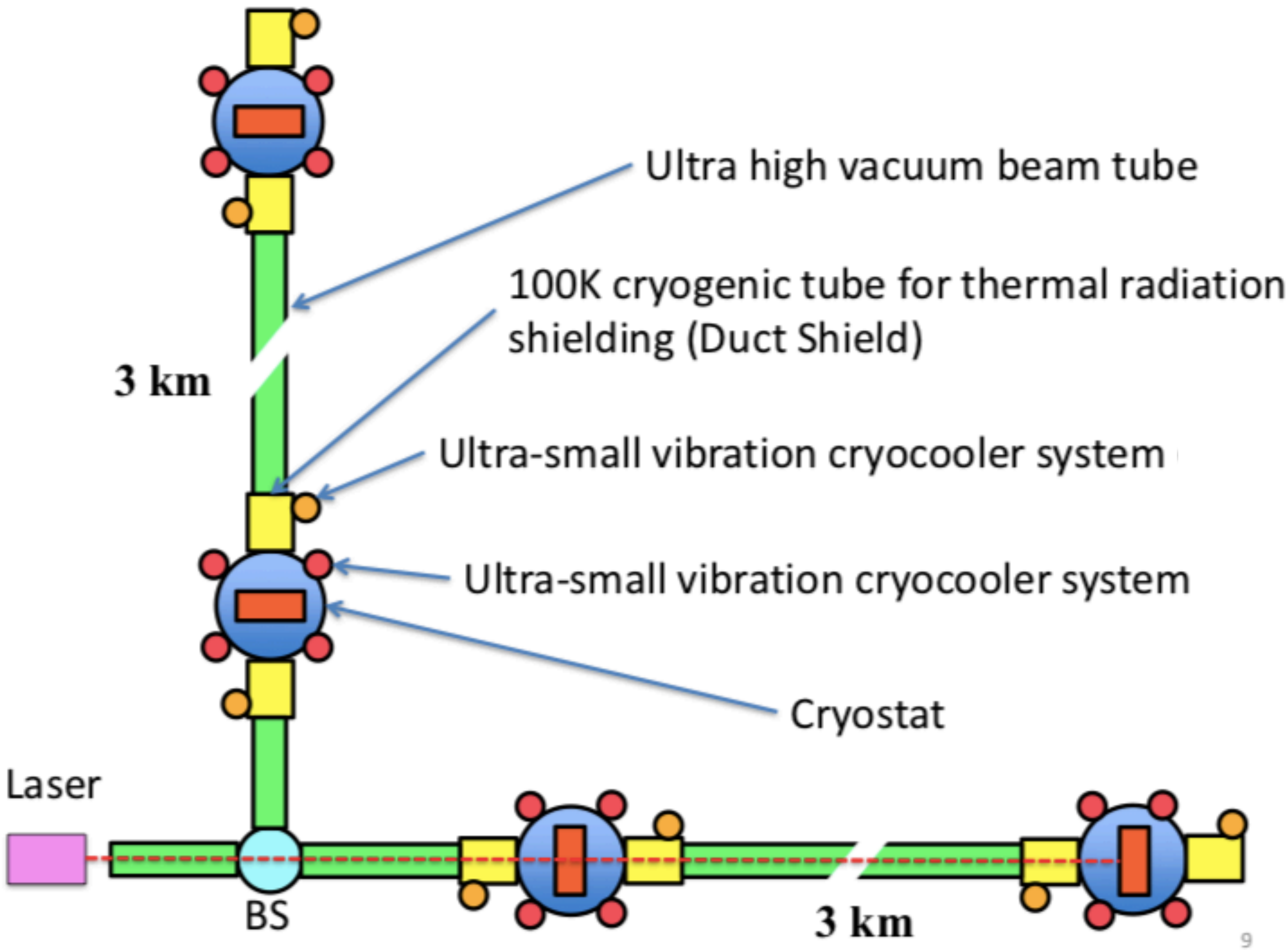
KAGRA cooling system



Yusuke Sakakibara *et al* 2014 *Class. Quantum Grav.* **31** 224003



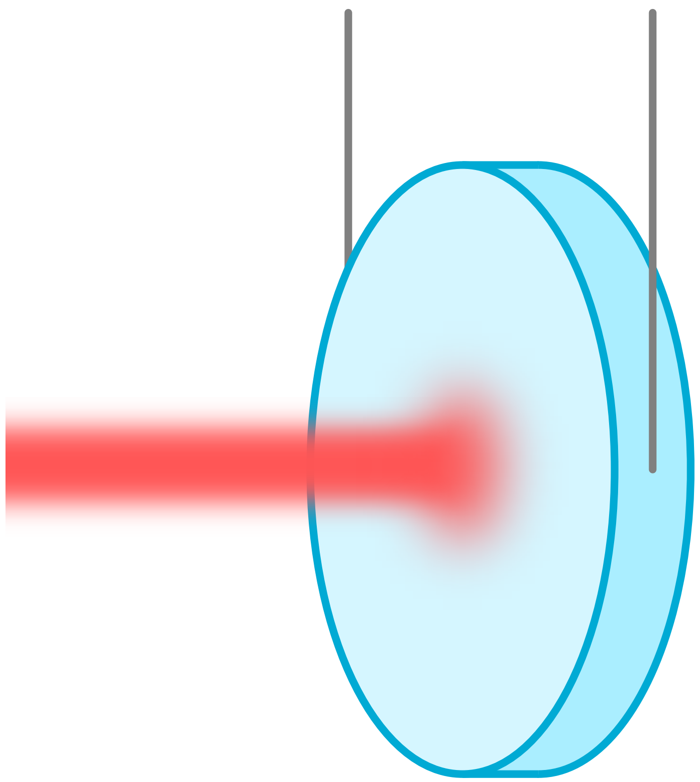
KAGRA cooling system layout



T.Tomaru- “ cryogenics in KAGRA” Joint Gravitational Waves and CERN Meeting- 09/17
https://indico.cern.ch/event/660772/

How much heat do we need to extract?

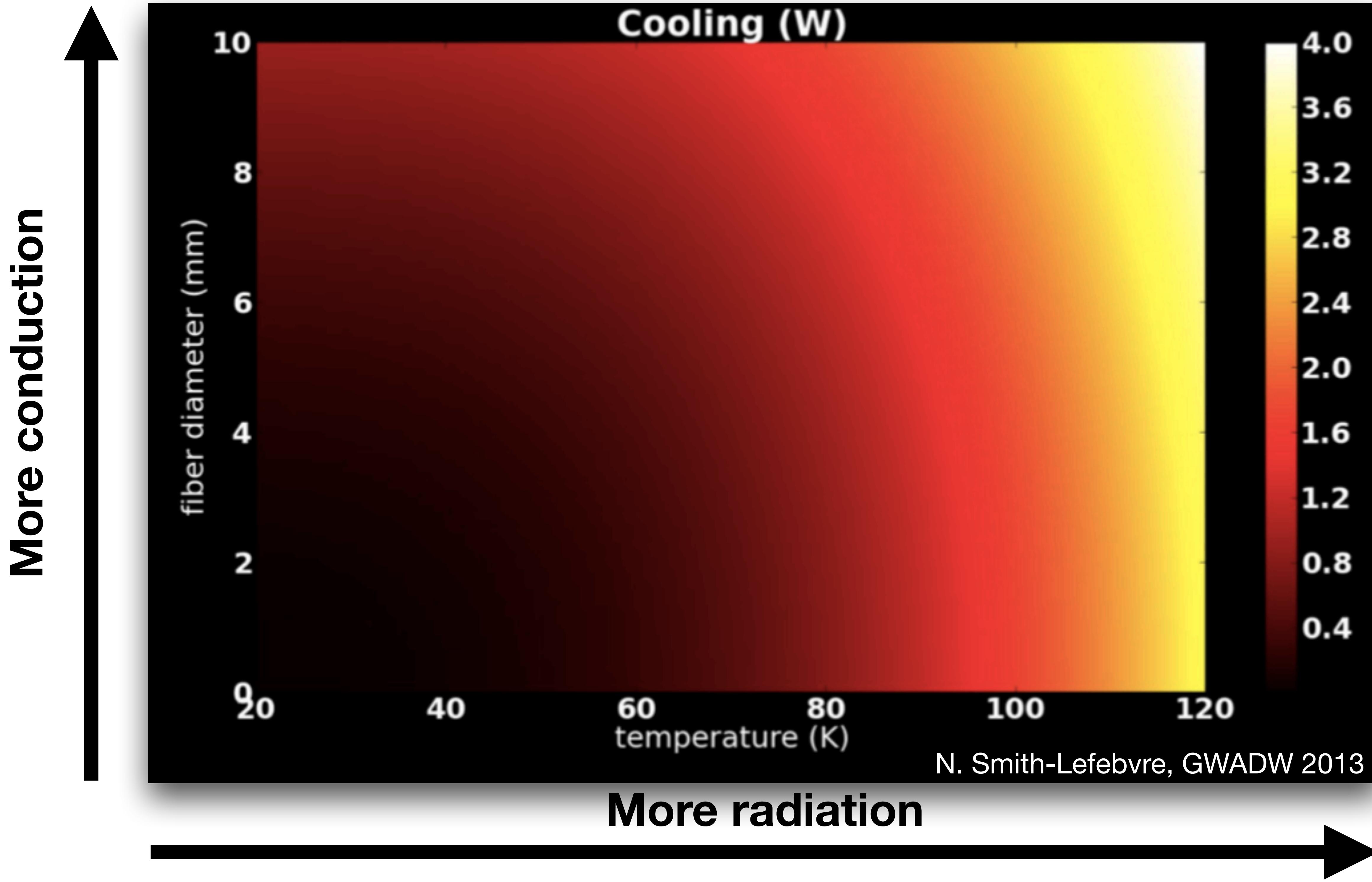
- ~1 W absorbed by sapphire substrate and coating (~400 kW of circulating power)
- ~ 200 mW introduced through the radiation from the apertures and the viewports



Total = 1.2 W

Cooling mechanism

- Conduction
- Radiation

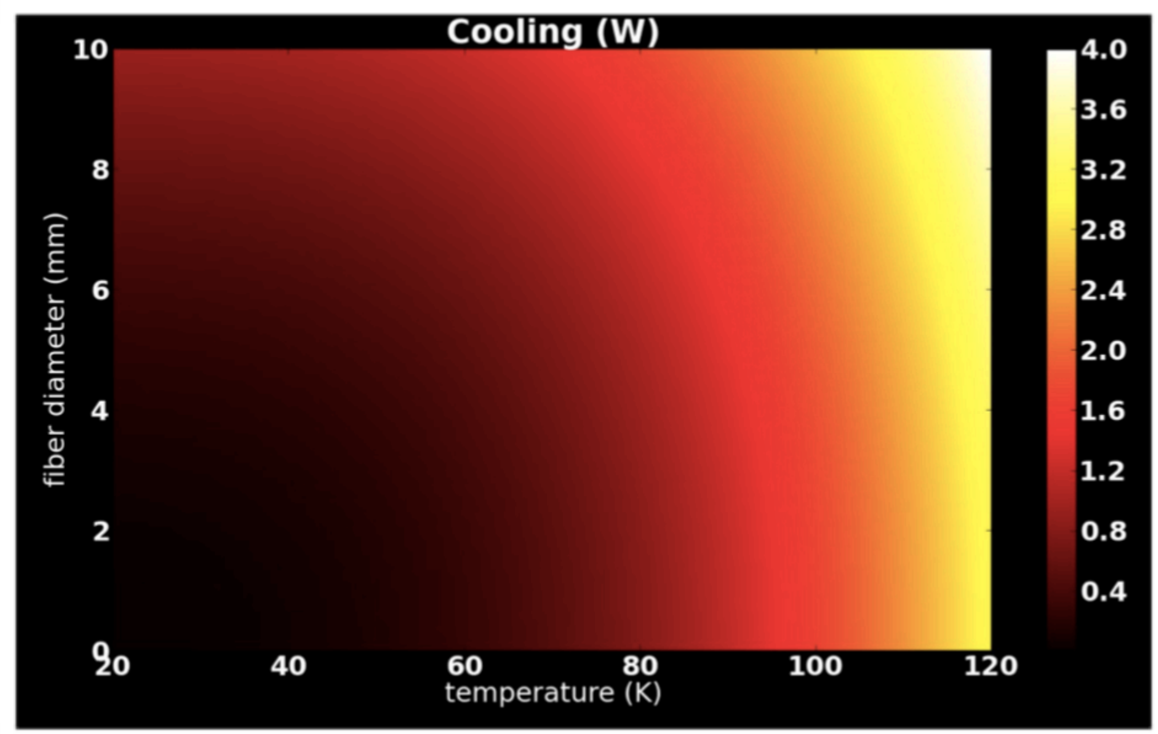


Temperature and cooling trade-off

- Thermal noise increases with temperature and fiber diameter

- Cooling is fixed by the detector configuration (power, mirror absorption)

- Lower temperature requires thicker fibers



Need to compromise between lower temperature and fiber thickness

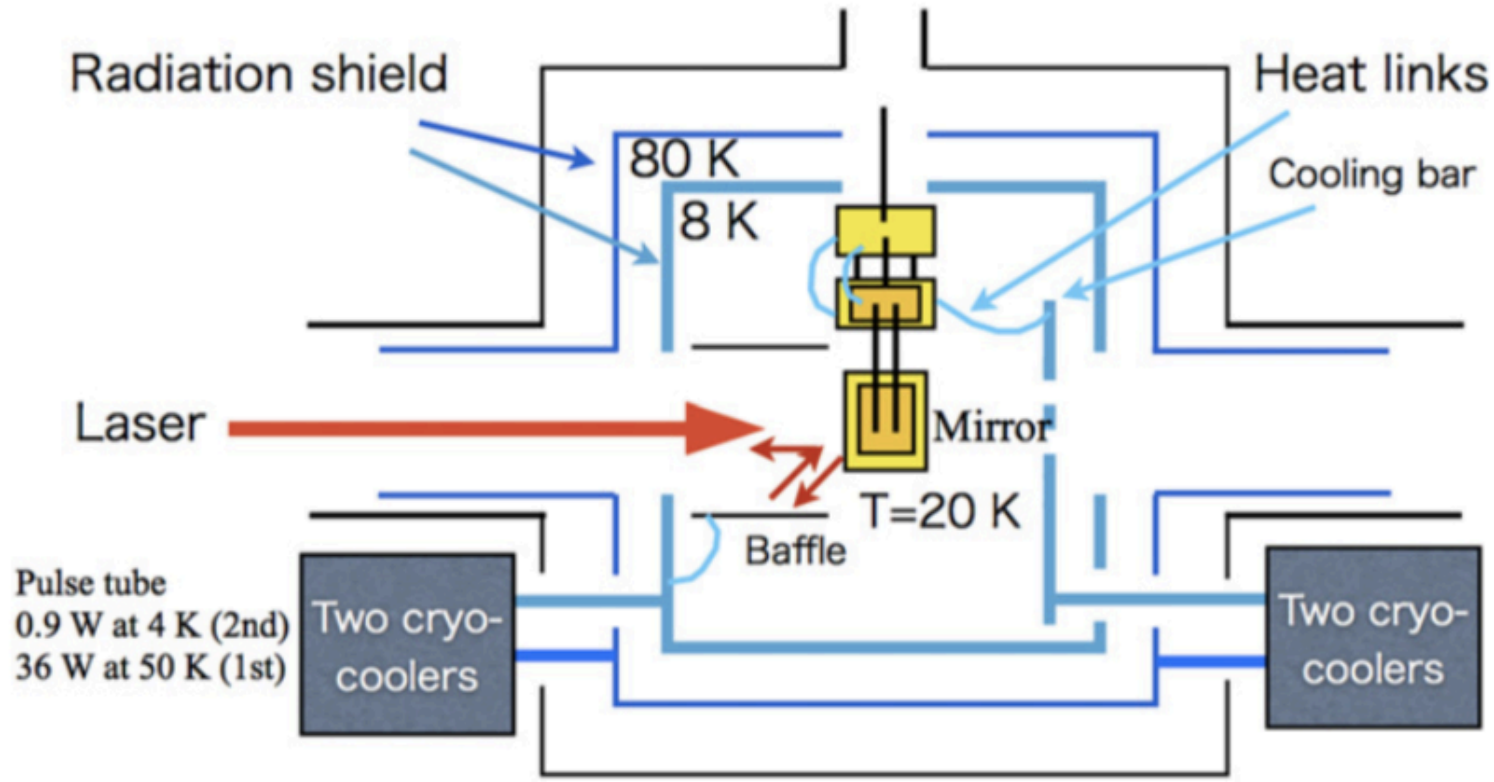
Temperature and cooling trade-off

- Material shows temperature dependent properties
- Suitable materials for cryogenic operation can require configuration changing (eg. Silicon not transparent for the current wavelength 1064nm)
- Different compromises can be done:
  - KAGRA sapphire 20 K (thicker fiber)
  - ET Sapphire 20 K (low power → lower cooling)
  - LIGO voyager Silicon 120 K (radiation cooling)

Cryogenic challenges

- Heat evacuation in vacuum
- Vibration isolation
- Choose of appropriate materials for cryogenic operation

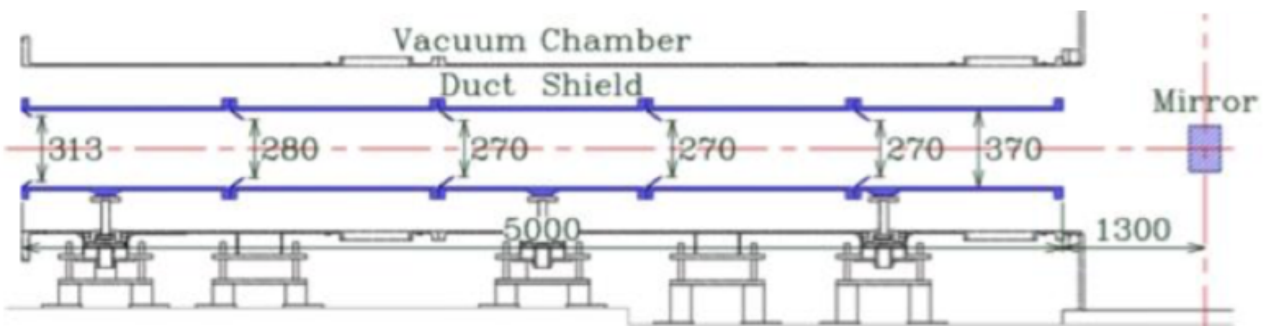
Heat evacuation: the cryostat

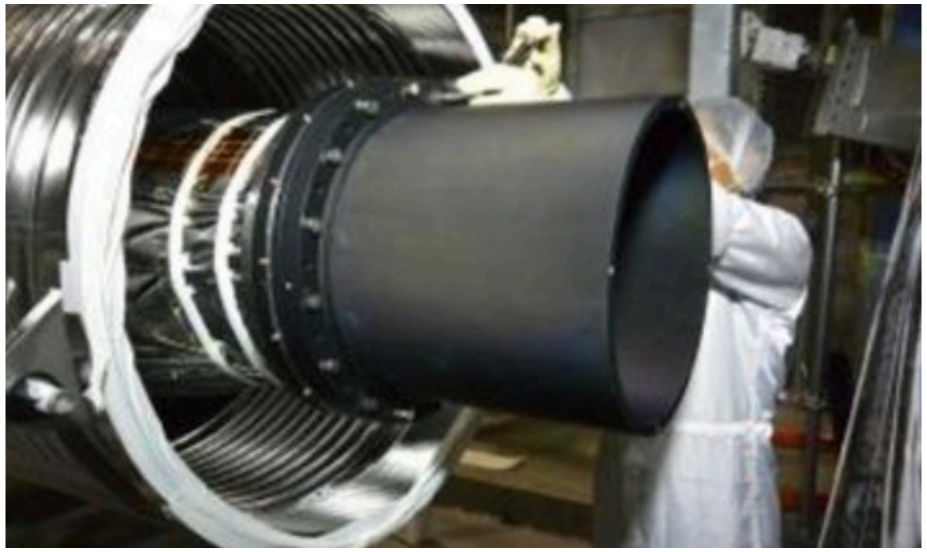


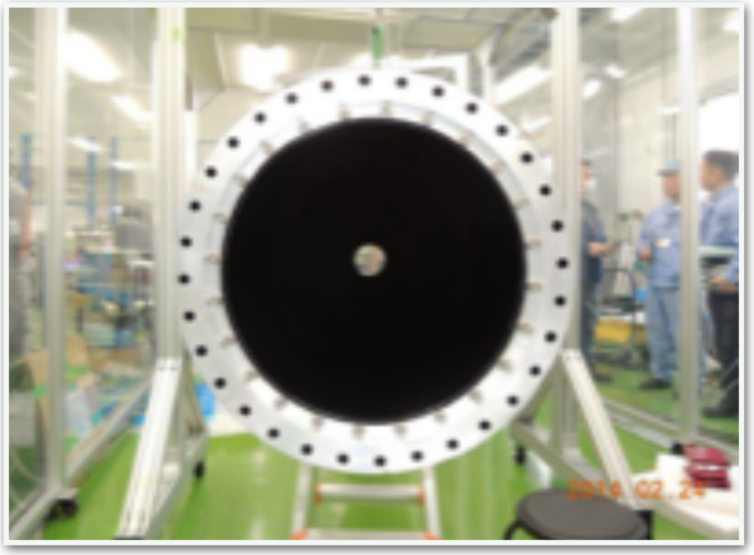
- Payload surrounded by inner (8K) and outer shield (80K)
- Four low vibration double-stage pulse-tube cryocoolers for each cryostat
- Inner shield coated with the diamond-like carbon (DLC) to reduce to cool down time (large absorption of radiated heat)
- Different kinds of baffles to absorb stray light

Duct shield

- Duct shields for absorbing thermal radiation from room temperature ducts
- ~17 m long at 100K, with black coating and baffles
- Two cryocoolers
- Reduce about ~1000 times thermal radiation heat from room temperature pipe

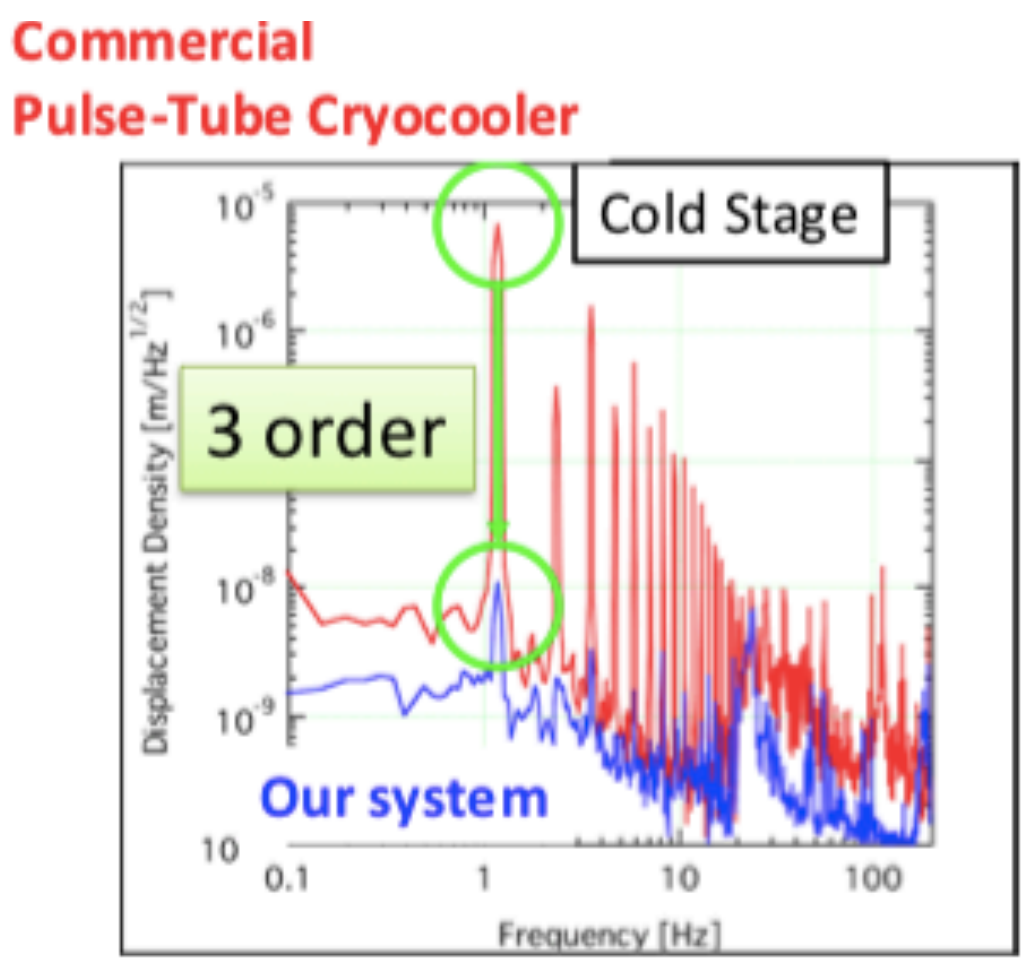


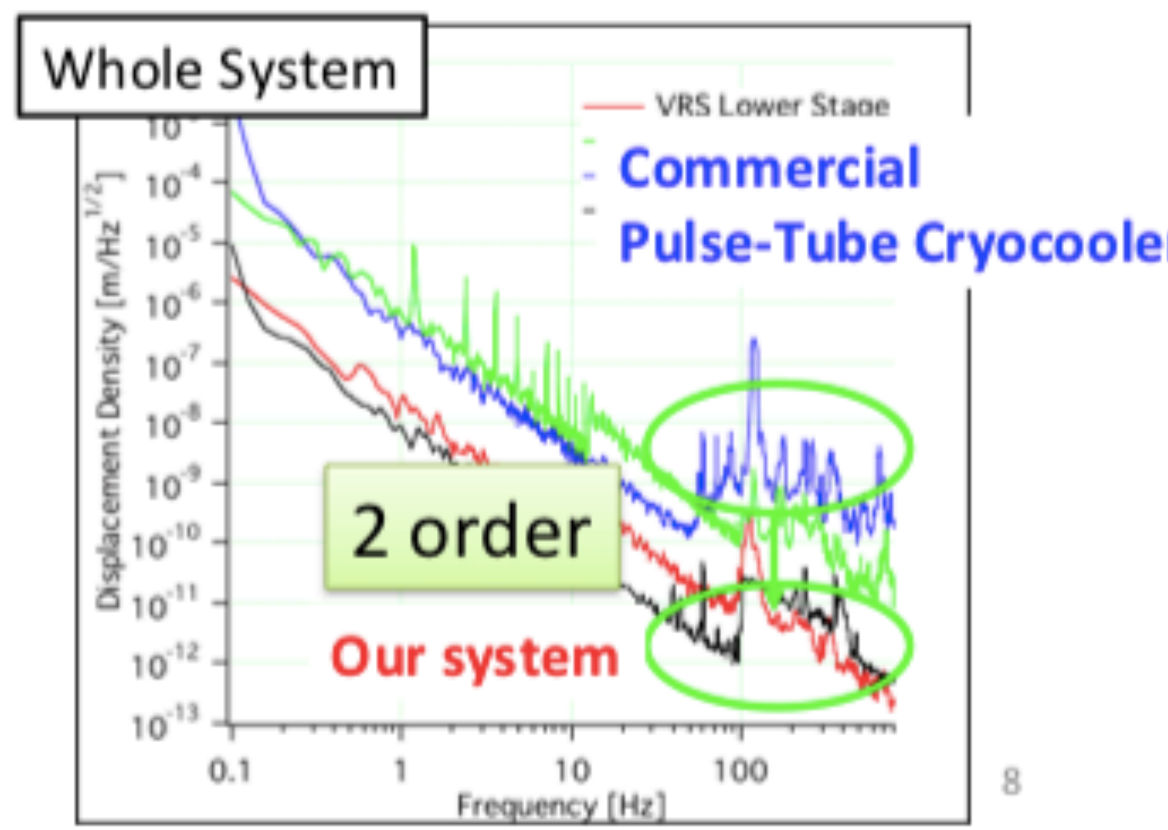




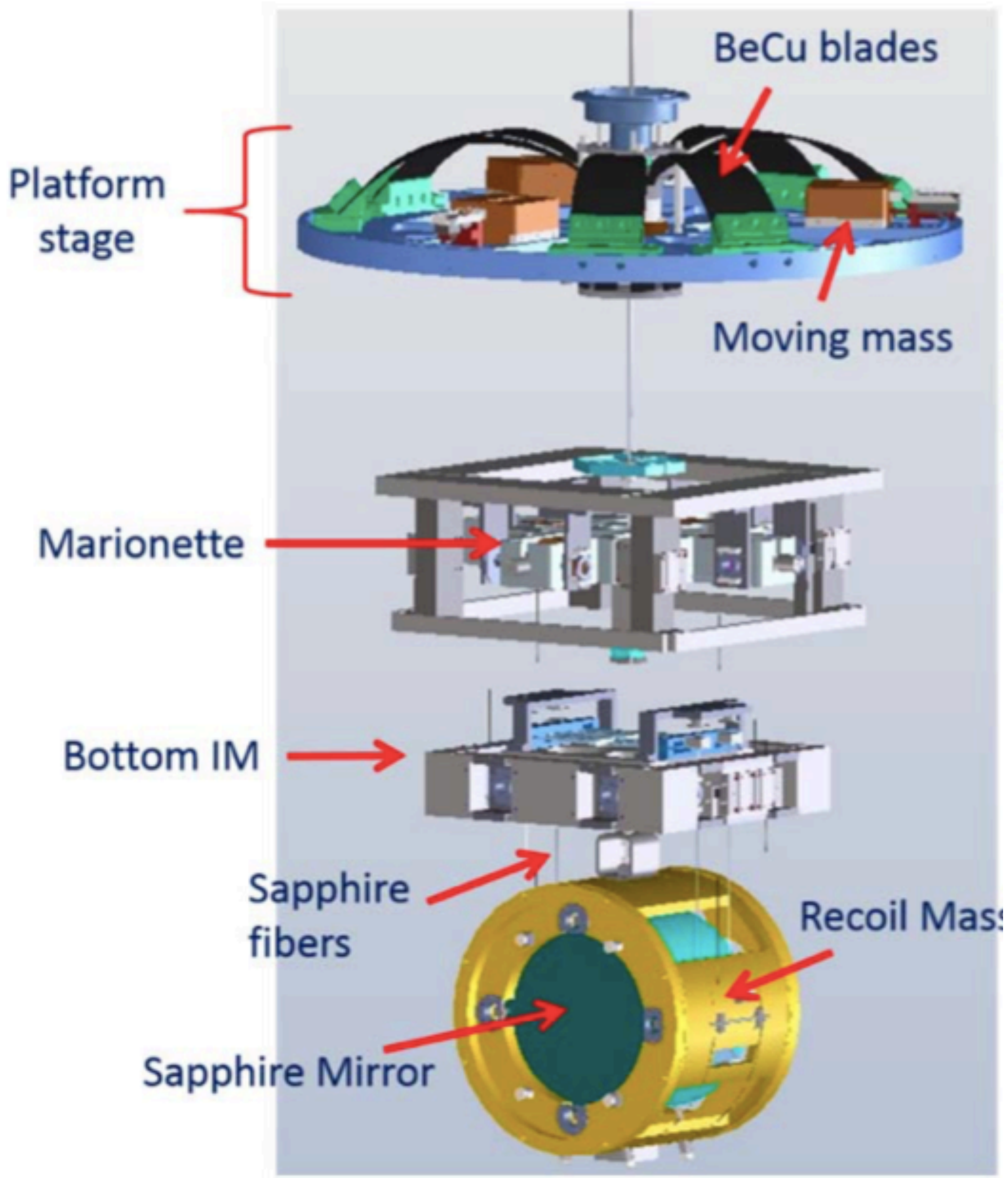
The pulse tube cryocoolers

- Developed for CLIO prototype
  (T.Tomaru et al CQG, Vol 21, N 5)
- ~nm vibration at cold stage
- Vibration level of whole system comparable with Kamioka seismic vibration





The cryogenic payload



R Kumar et al 2016 J. Phys.: Conf. Ser. 716 012017

- 4 stages
- Marionette is suspended from the platform with a single maraging steel wire.
- Intermediate mass is suspended from the marionette with four CuBe fibers.
- high purity aluminum heat link to evacuate heath

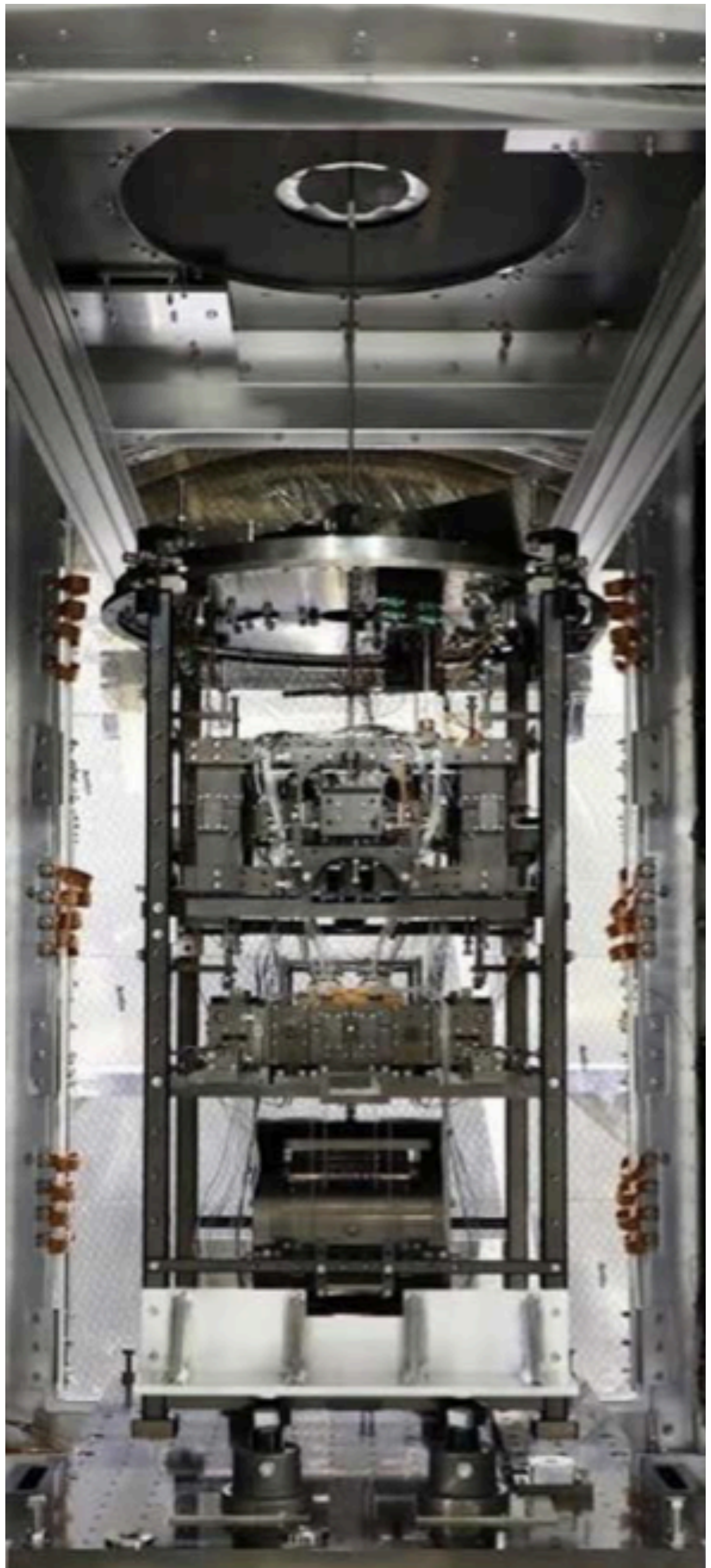
KEK Inter-University Research Institute Corporation High Energy Accelerator Research Organization

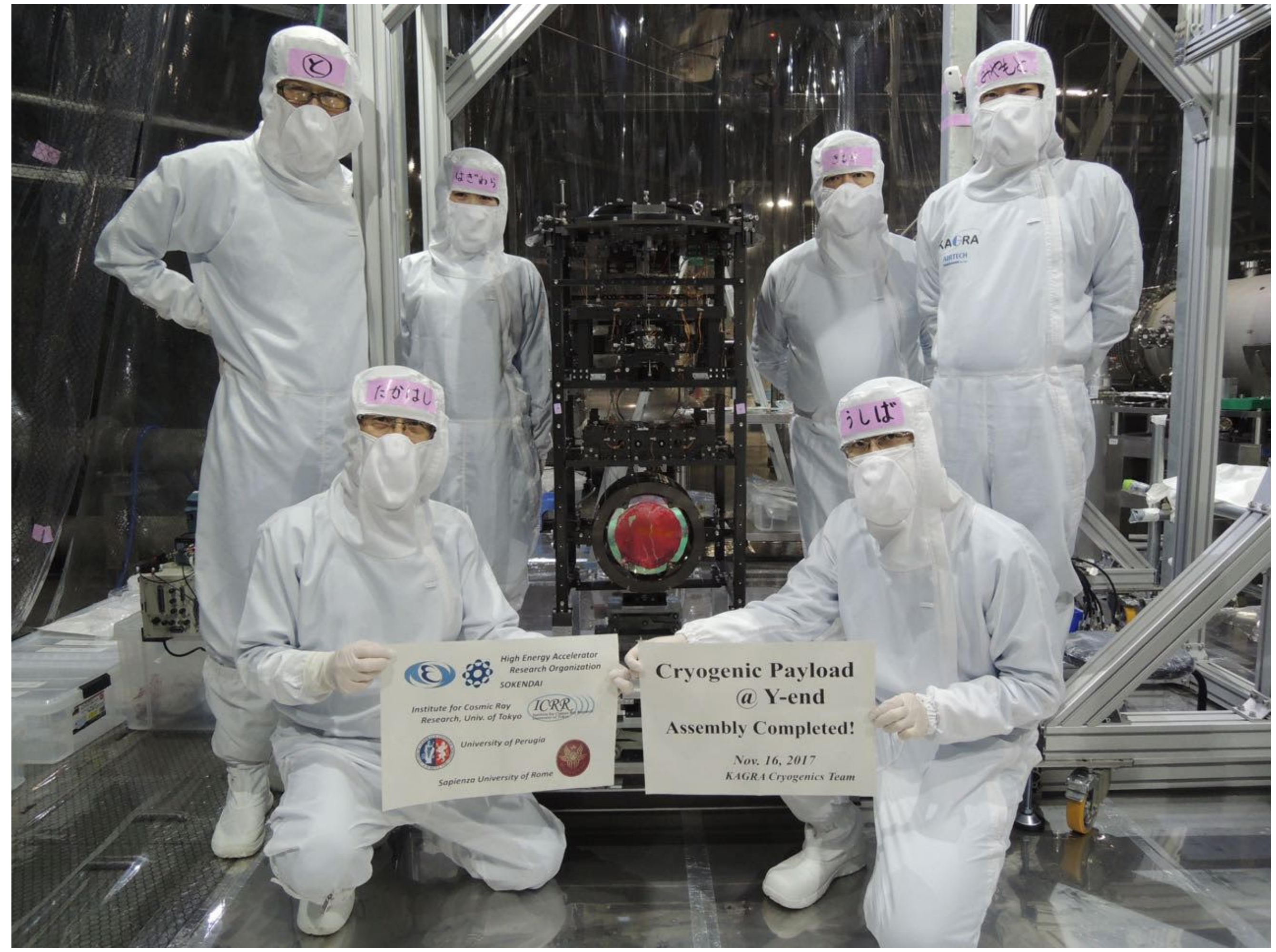
UNIVERSITÀ DEGLI STUDI DI PERUGIA

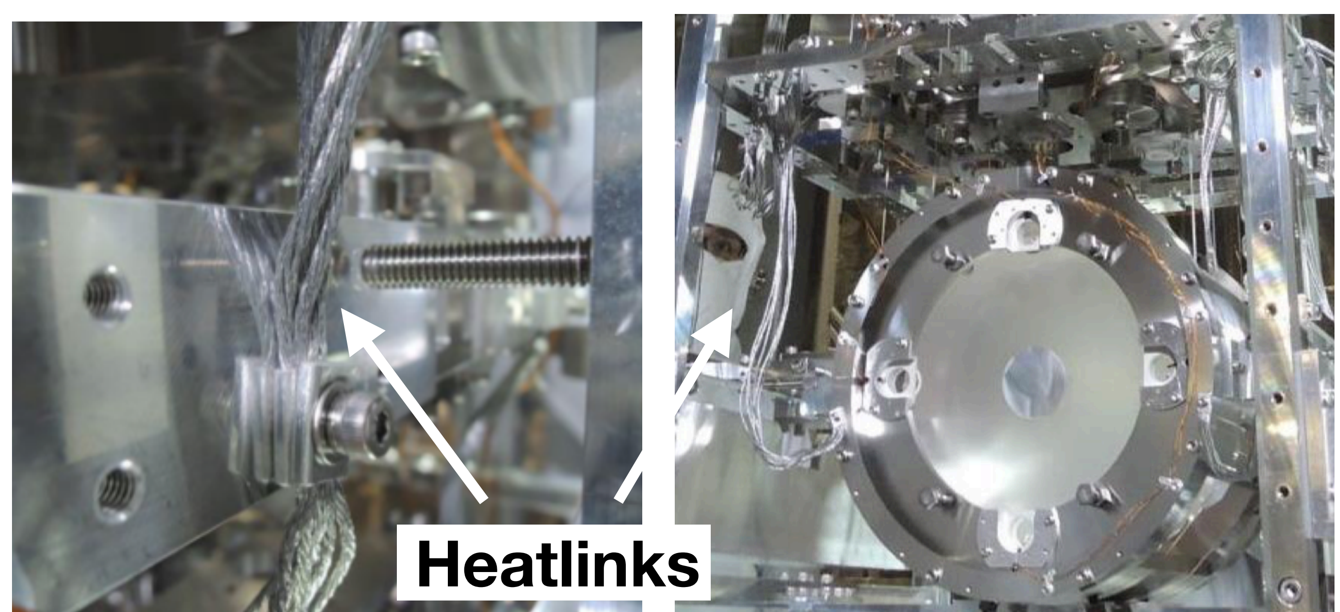
SAPIENZA UNIVERSITÀ DI ROMA

ICRR Institute for Cosmic Ray Research University of Tokyo

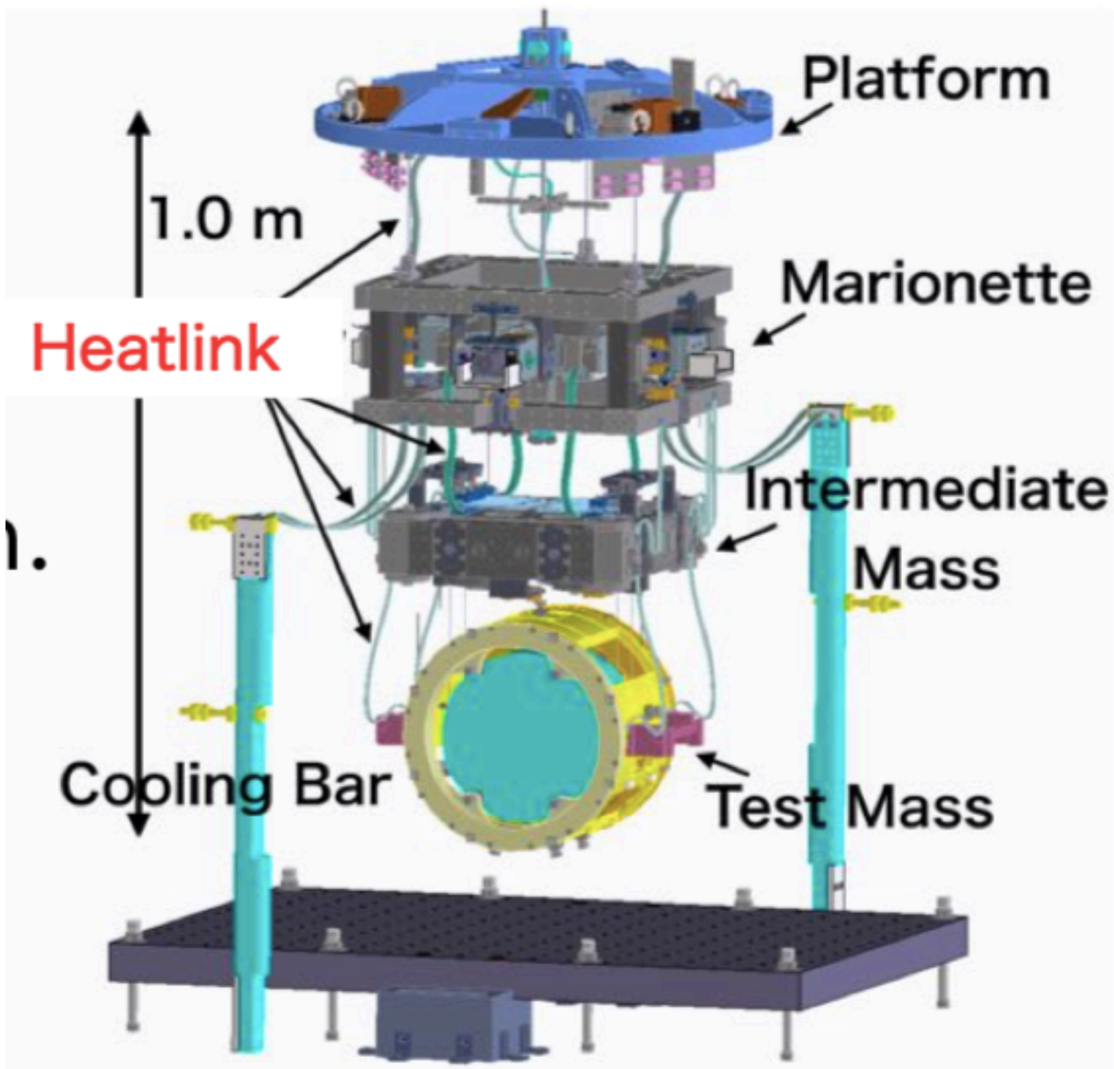
The cryogenic payload





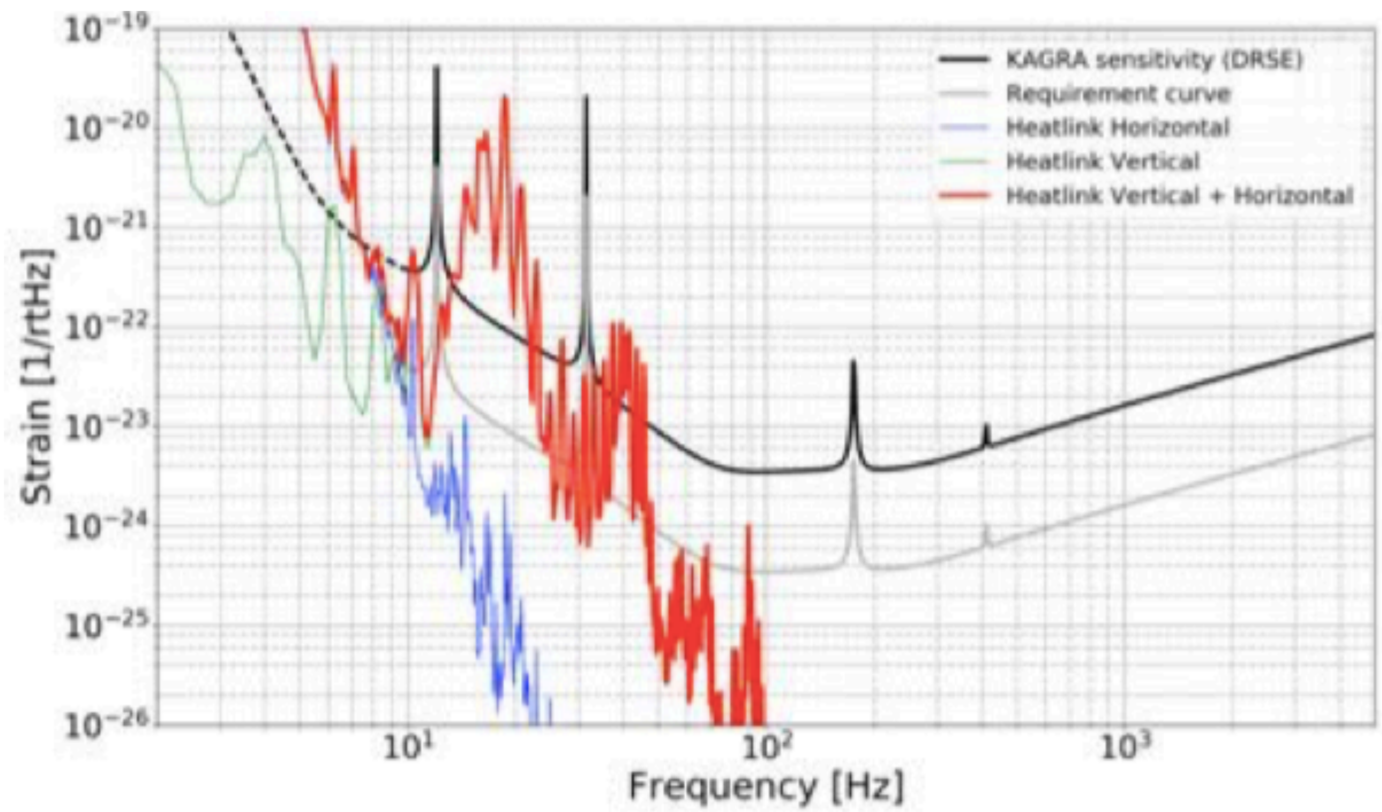


The cryogenic payload: heatlinks



T. Yamada JGW-G1808903
F2F meeting 08-18

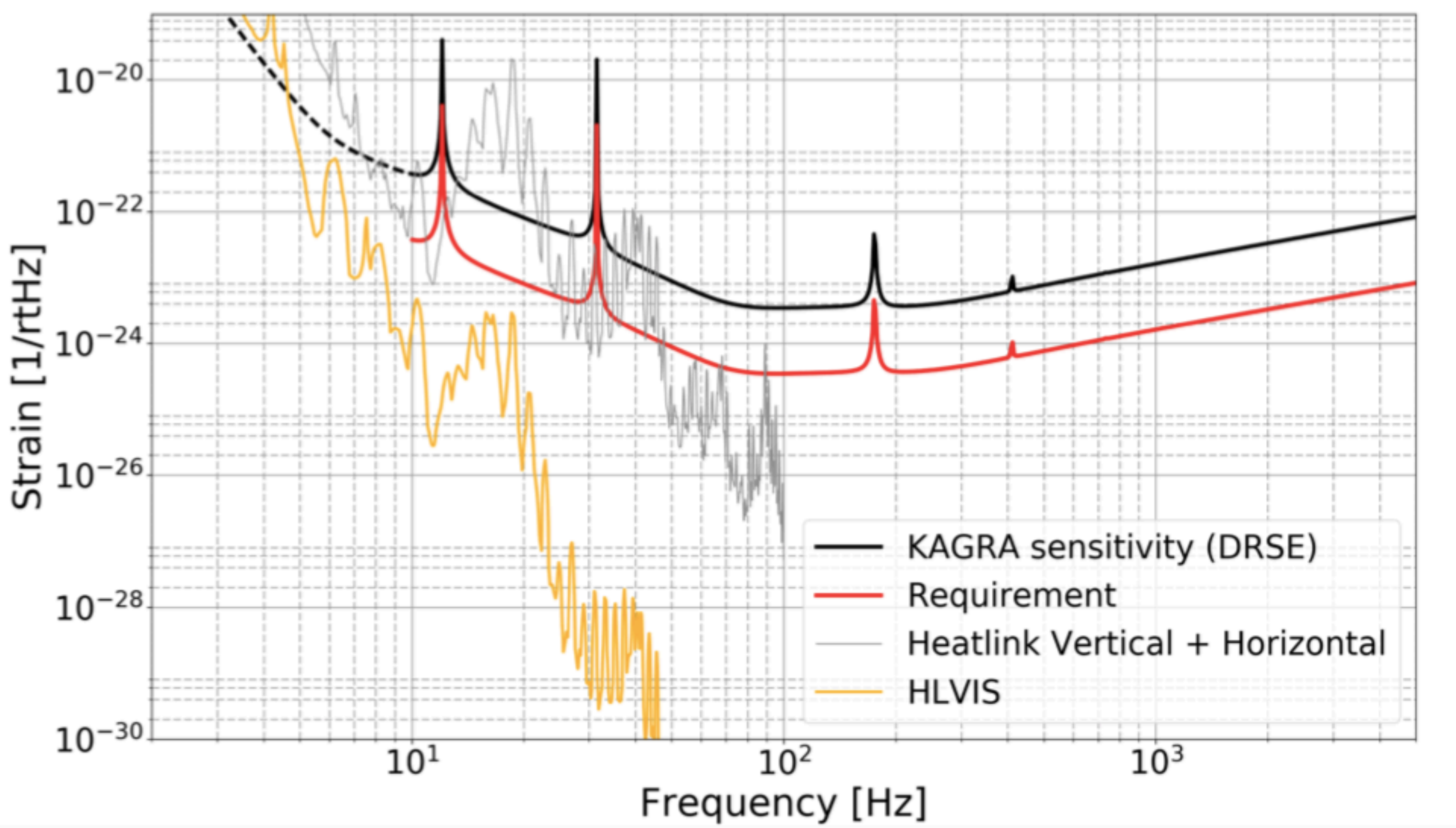
- Heatlink couple too much vibrations and can spoil the sensitivity



- Heatlink-Vibration-Isolation (HLVIS) system was developed and installed to attenuate those vibrations

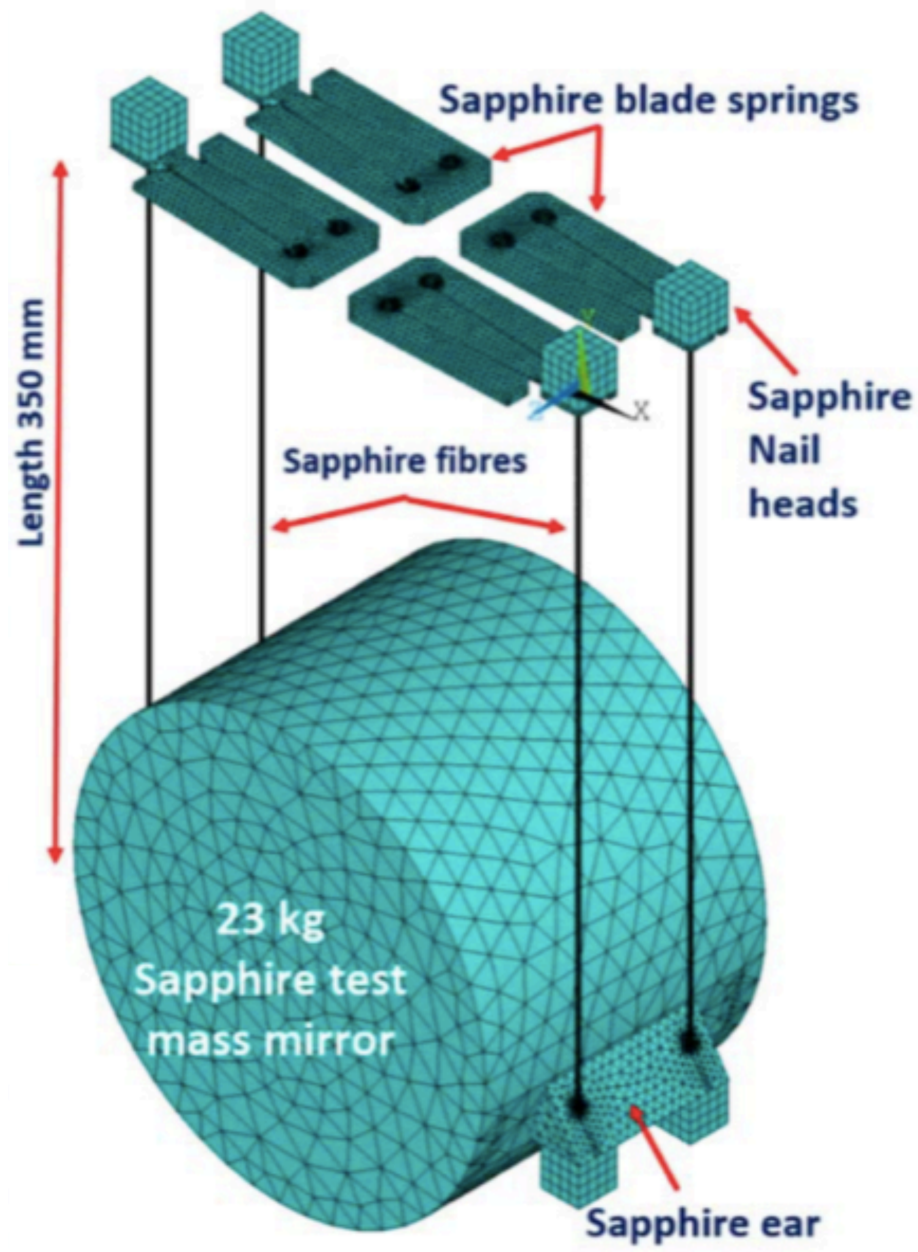
Heatlink vibration isolation

- Heatlink-Vibration-Isolation (HLVIS) system was developed and installed to attenuate those vibrations



T. Yamada JGW-G1808903 F2F meeting 08/18

The cryogenic payload: last stage



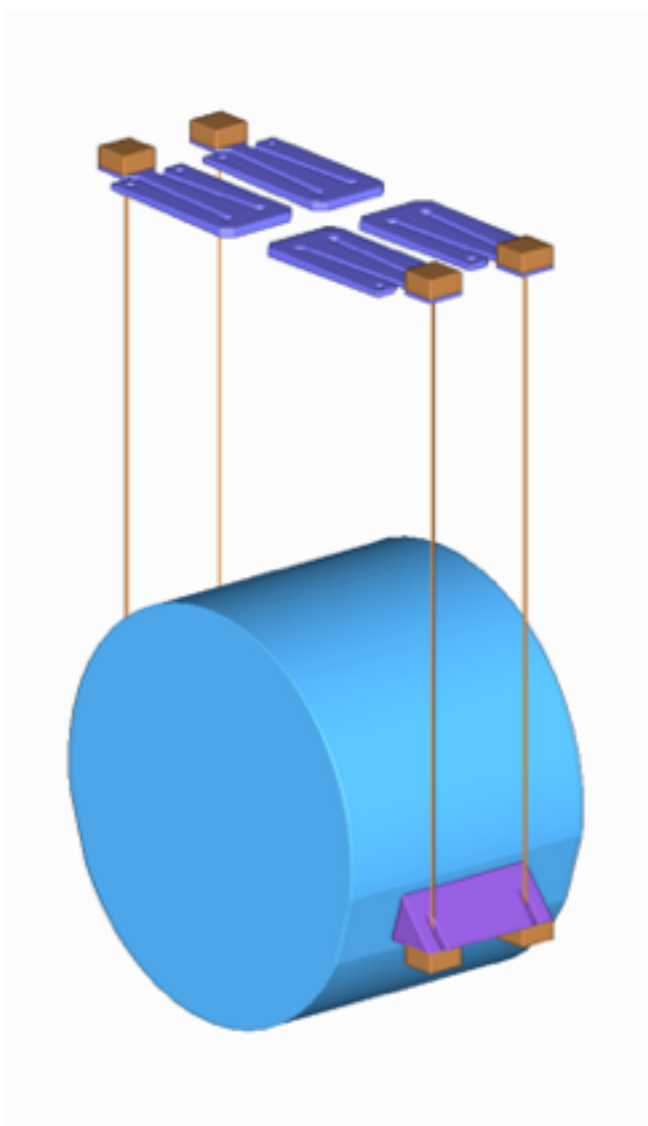
R Kumar et al 2016 J. Phys.: Conf. Ser. 716 012017

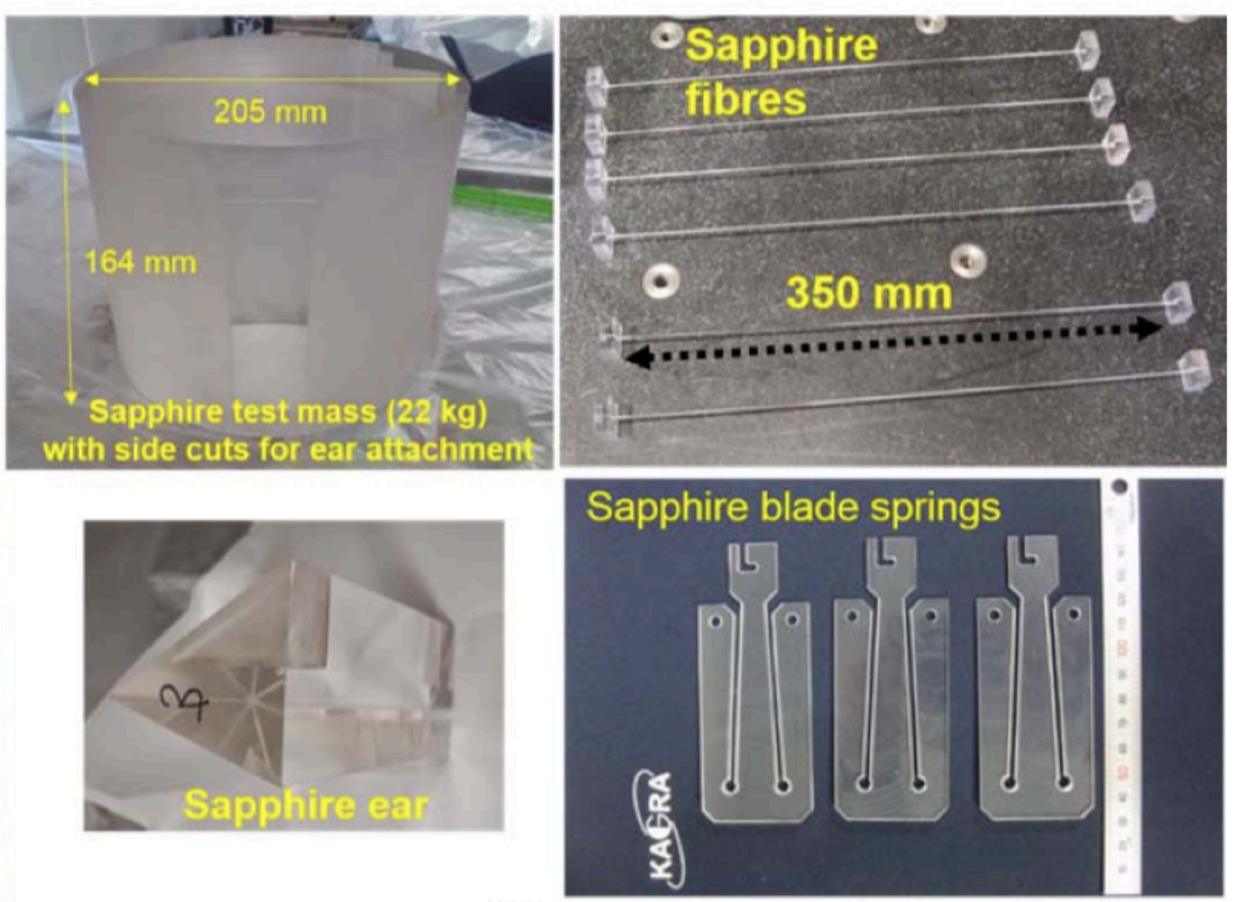
- 4 sapphire fibers of 1.6 mm diameter to extract heath
- Transferable heat

$$K = \int_{T_2}^{T_1} \frac{\pi d_{\text{fiber}}^2}{4\ell_{\text{fiber}}} \kappa_{\text{fiber}}(T) dT$$

Connection between mirror and fibers

- Hydroxide Catalysis Bonding (HCB), based on chemical reaction
- Same used in LIGO and Virgo
- It can be used with sapphire at cryogenic temperature





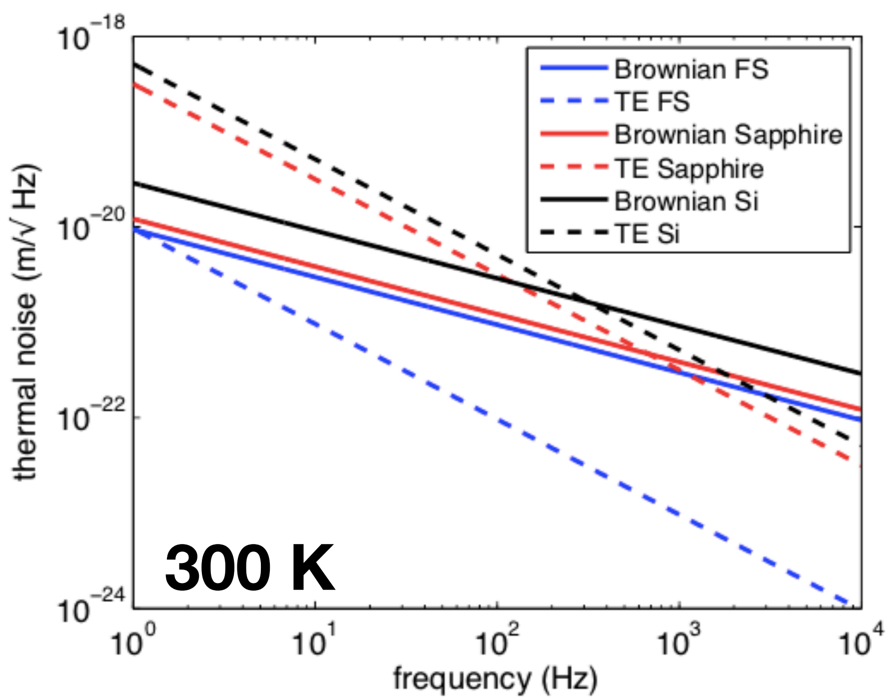
Mechanical loss of a hydroxide catalysis bond between sapphire substrates and its effect on the sensitivity of future gravitational wave detectors

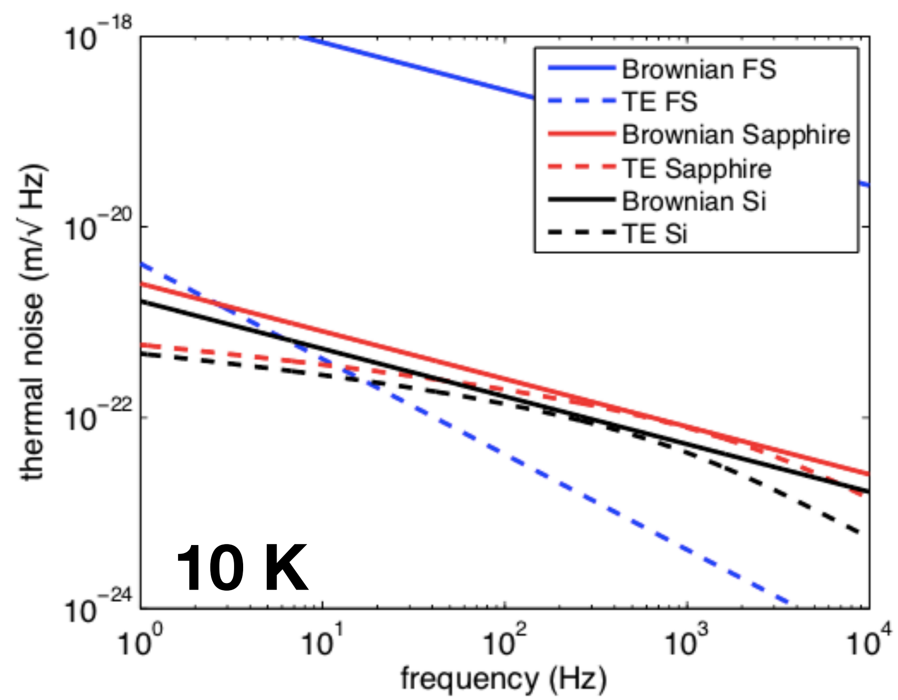
K. Haughian, D. Chen, L. Cunningham, G. Hofmann, J. Hough, P. G. Murray, R. Nawrodt, S. Rowan, A. A. van Veggel, and K. Yamamoto
Phys. Rev. D **94**, 082003 – Published 12 October 2016

Which material for cryogenic operation?

$$S_{TN} \propto \sqrt{T\phi}$$

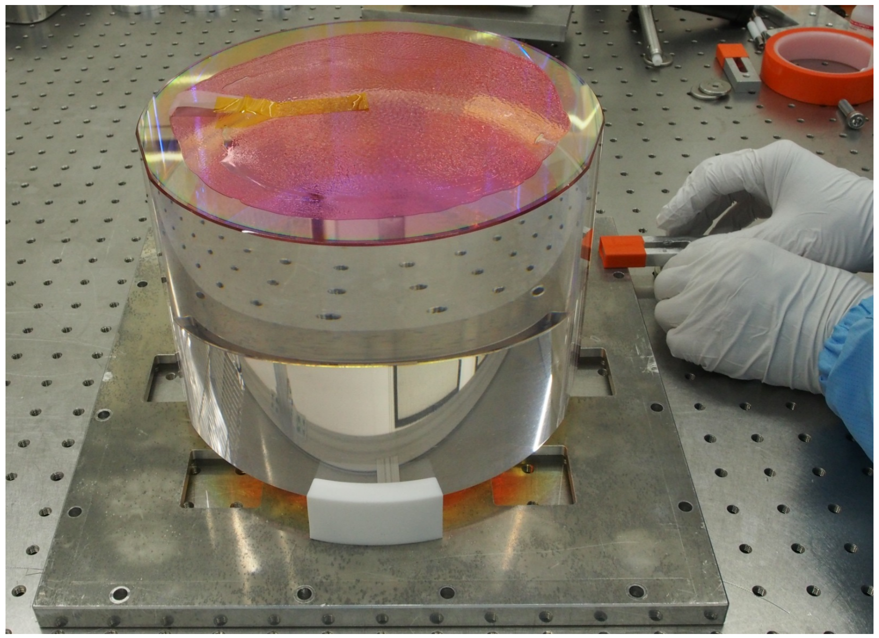
- Silica has larger losses and low thermal conductivity at low temperature
- Silicon have low losses but its not transparent at 1064
- Sapphire have low losses and high thermal conductivity



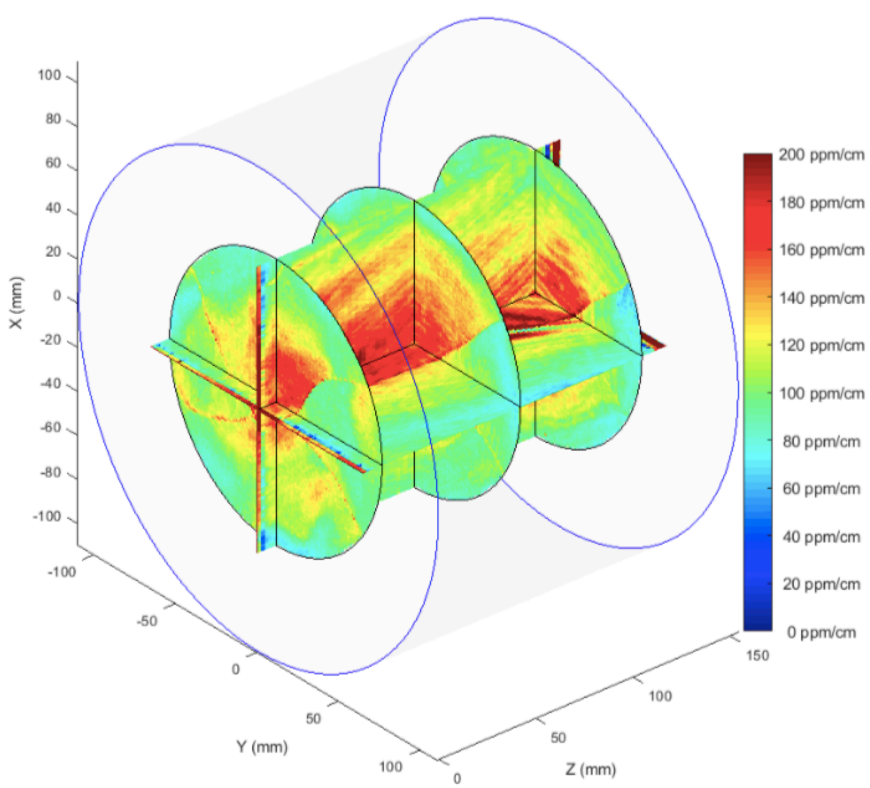


ET design study

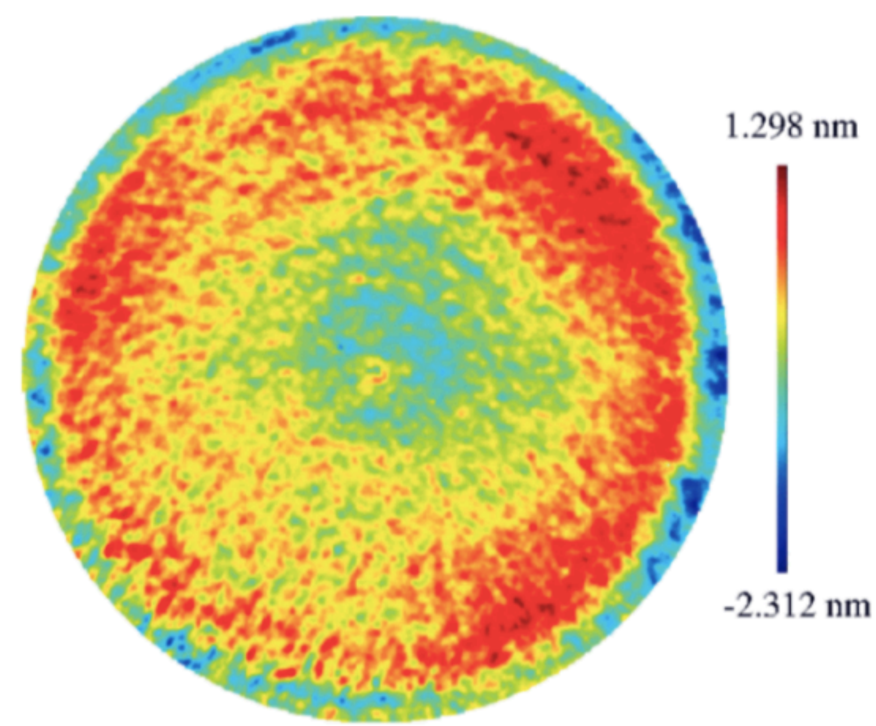
KAGRA cryogenic mirrors



- Sapphire, 23 kg, 22 cm in diameter and 15 cm in thickness
- Less experience than fused silica: **birefringence**, hardness, absorption



Mirror absorption measurement
M. Marchiò et al. Sci Rep 11, 2654 (2021)



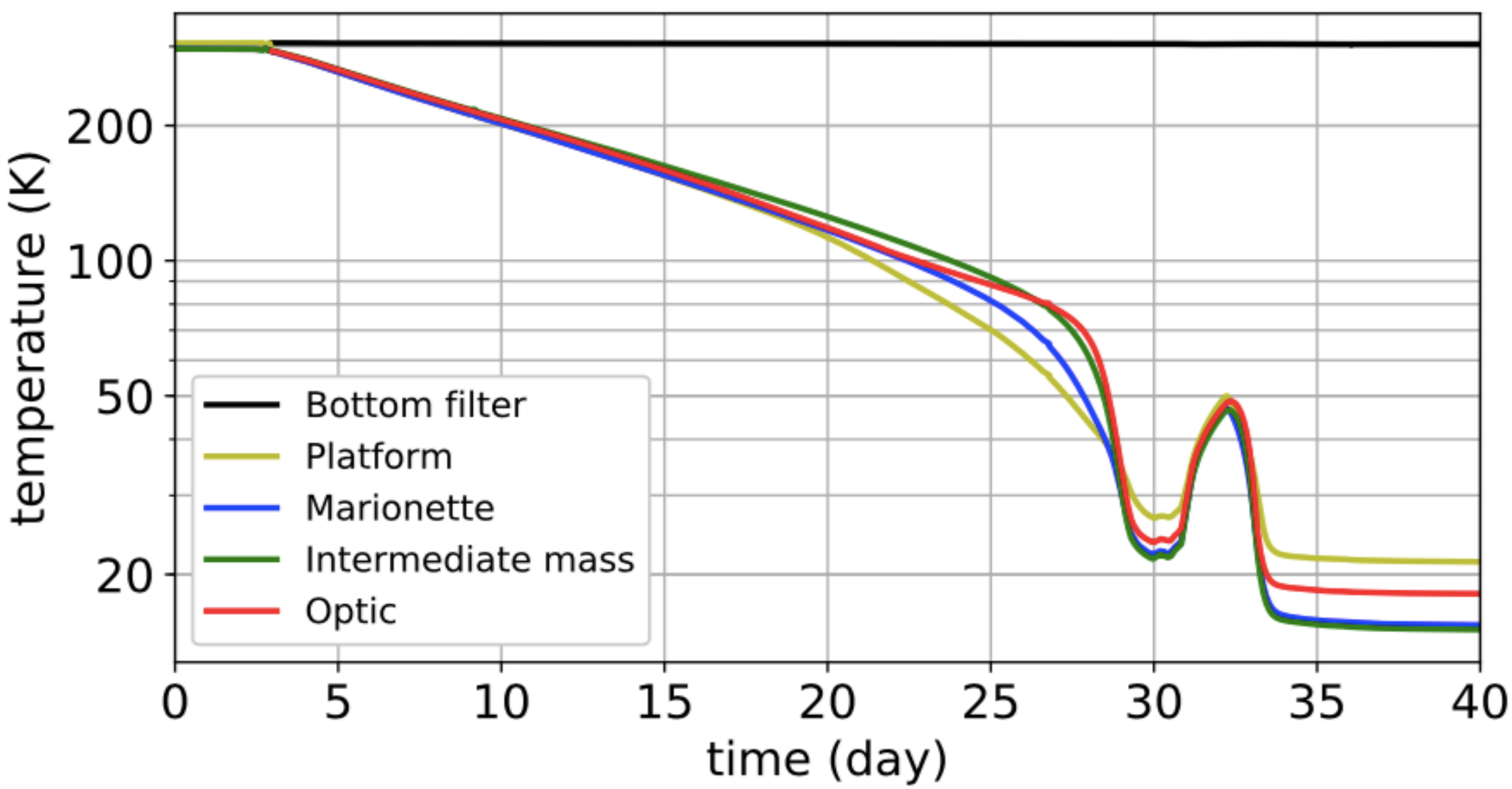
Hirose et al. Phys. Rev. D **89**, 062003

Some issues concerning mirrors

- **Birefringence** of sapphire:
  - Refractive index that depends on the polarization and propagation direction of light -> it can turn s-pol into p-pol
  - Larger than expected: major issue for the stability of the interferometer
- **Ice layers** on the mirrors:
  - Water or other molecules get attached to the cryogenic mirror if the vacuum level is not high enough during the cooling process
  - It modifies the mirror reflectivity
  - Can be avoided by properly cooling the shields

Cooling time

- Radiation is the dominant process for the first 20 days
- Bump due to cryocoolers restart



T.Ushiba et al. Class. Quantum Grav. **38** 085013 (2021)

Cryogenic operation: summary

- Thermal noise of mirror and suspension is one of the main limitation for GW detectors
- Cryogenic operation is a “straightforward" way to reduce thermal noise
- The physics is simple but the technology is challenging
- R&D and prototyping activity for more than 20 year in Japan
- Many lessons learnt for 3rd generation detectors

https://www.youtube.com/watch?v=x7LHXTtGei0

BACK UP SLIDES

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