Future development plan of Torsion-bar antenna

Tomofumi Shimoda

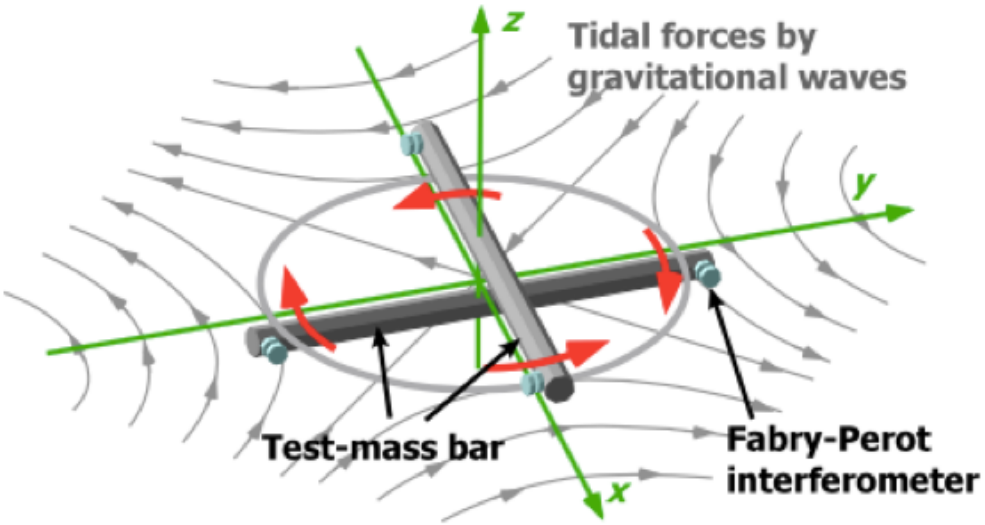
Ando lab. midterm seminar (2018/5/8)

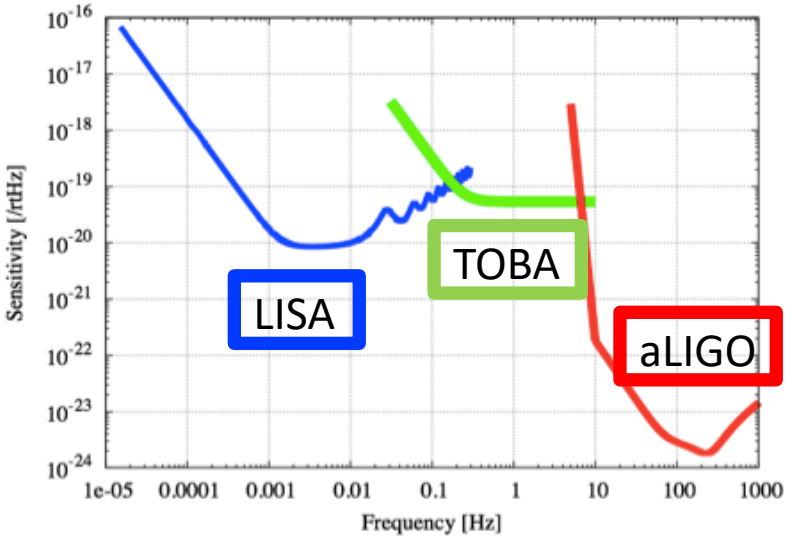
contents

- overview of TOBA
- protypes : what is done so far
  - cross-coupling reduction
  - technical noise investigation
- next plan : for Phase-III TOBA
  - cryogenic suspension
  - vibration isolation
  - angular sensing
- summary of TOBA development plan

TOrsion-Bar Antenna

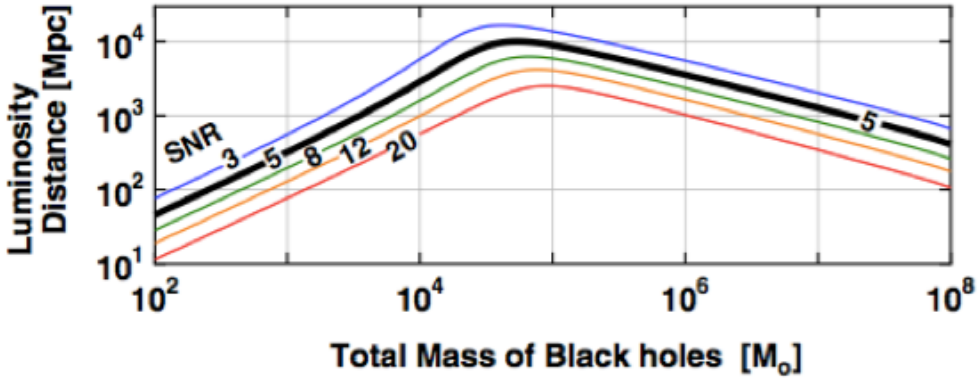
- TOBA = a gravitational wave detector using a torsion pendulum
- sensitive to low-frequency GWs because of **low resonant frequency** (~mHz) of Yaw rotation
- target sensitivity : **10^{-19} /rtHz @0.1Hz** with 10m bar





scientific targets of TOBA

- **low-frequency GWs**
  - intermediate mass blackholes (~10^5 M_{sun})

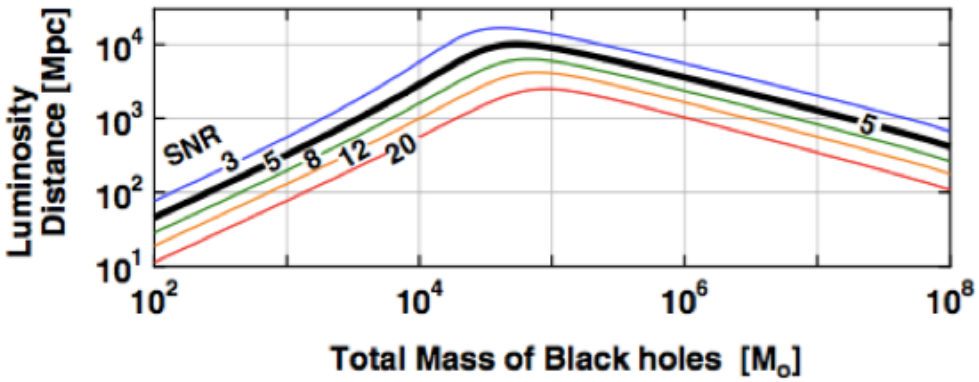


PhysRevLett. 105.161101

- **Earthquke early warning** with gravity signal
  - M6.0 earthquakes are detectable in 10sec from 100km away
- **Newtonian noise**
  - test noise models for the next generation GW detectors

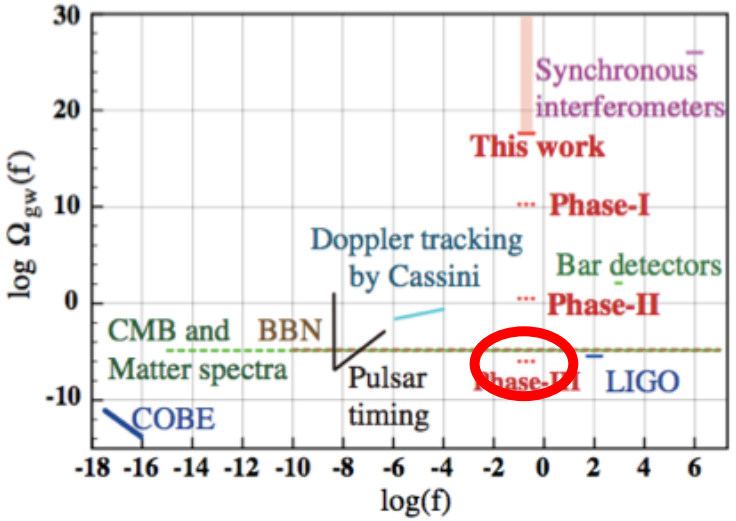
low frequency GWs

- Intermediate mass black holes
  - **<u>10 Gpc</u>** for 10^5 M_{sun} IMBHs



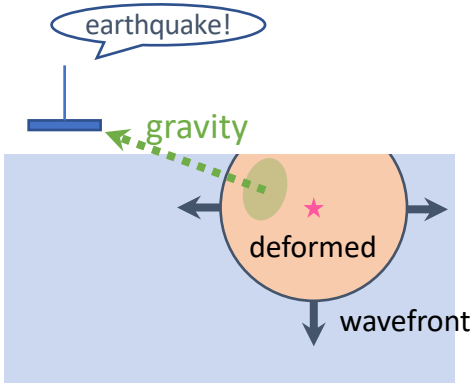
PhysRevLett. 105.161101

- stochastic GW background
  - beyond BBN bound



Phys. Rev. Lett. 106.161101

earthquake early warning



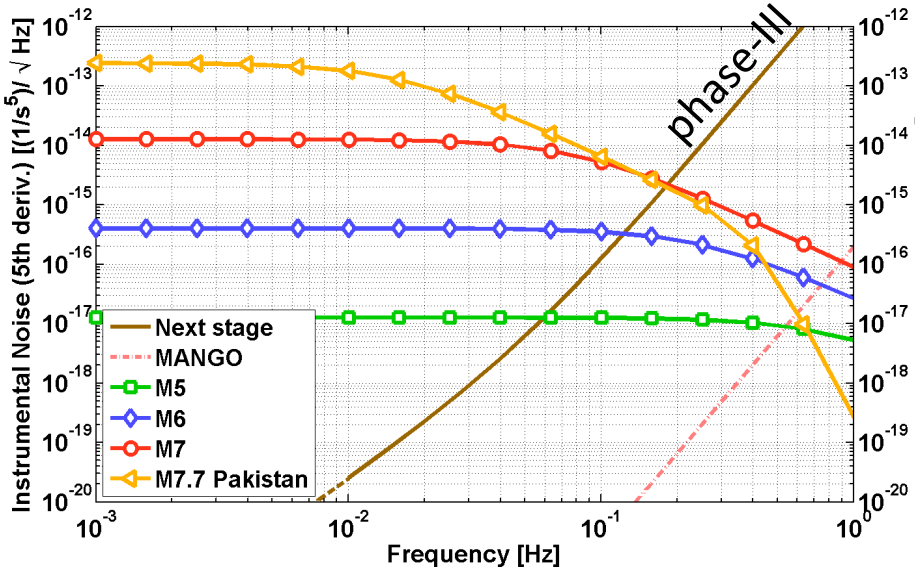
- ground deformation by earthquakes

  → Newtonian gravity perturbation

- gravitational signal propagates at the <u>speed of light</u>

  faster than seismic waves

- M6.0 earthquakes are detectable in 10sec from 100km away with smaller scale (~1m) TOBA



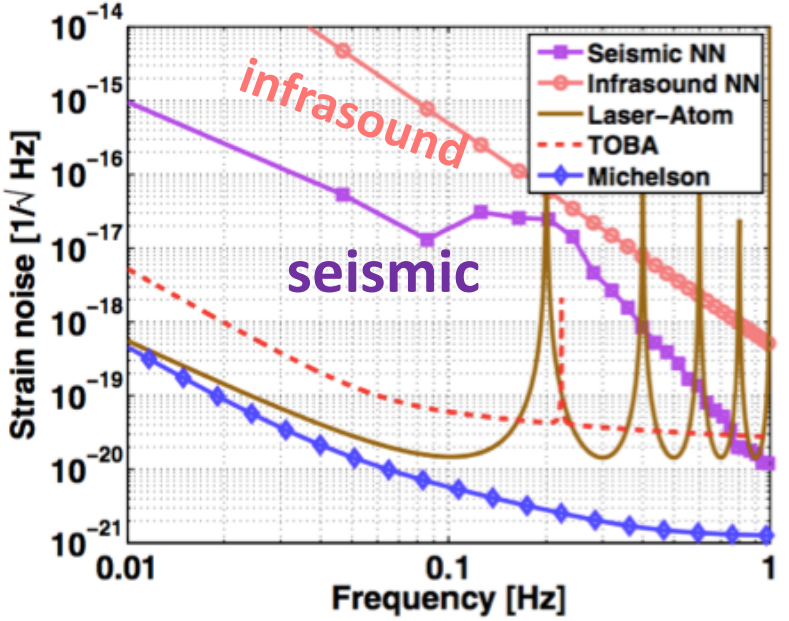
(from 70km)

by Pablo Ampuero

Newtonian noise

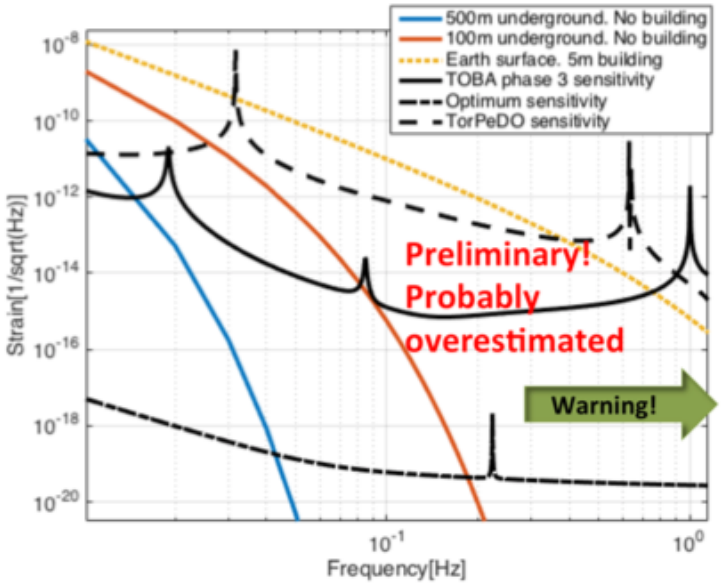
- density perturbation of the ground and the atmosphere
- measurement at low-frequency can help understanding the nature of the noise (for next generation detectors)

seismic & infrasound(pressure)



(J.Harms et al., 2013)

temperature (atmosphere)



calculated by D. Fiorucci

development plan

- prototypes → **phase-III** → final

	prototypes	**Phase-III**	Final
features	~20cm bar	40cm bar **cryogenic**	10m bar cryogenic
sensitivity	10^{-8} /$Hz^{1/2}$ @0.1Hz	**~10^{-15} /$Hz^{1/2}$ @0.1Hz**	10^{-19} /$Hz^{1/2}$ @0.1Hz
	✓ proof of concept ✓ noise hunting	✓ **noise reduction** ✓ IMBHs in Milky-way galaxy ✓ Earthquake detection ✓ NN measurement	**GW observation**

now here

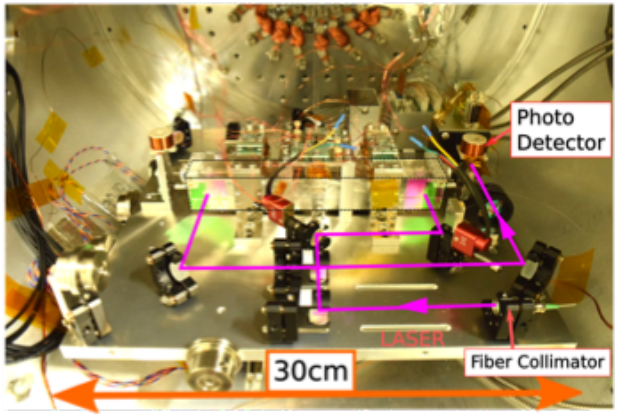
what do we have to do for phase-III ?

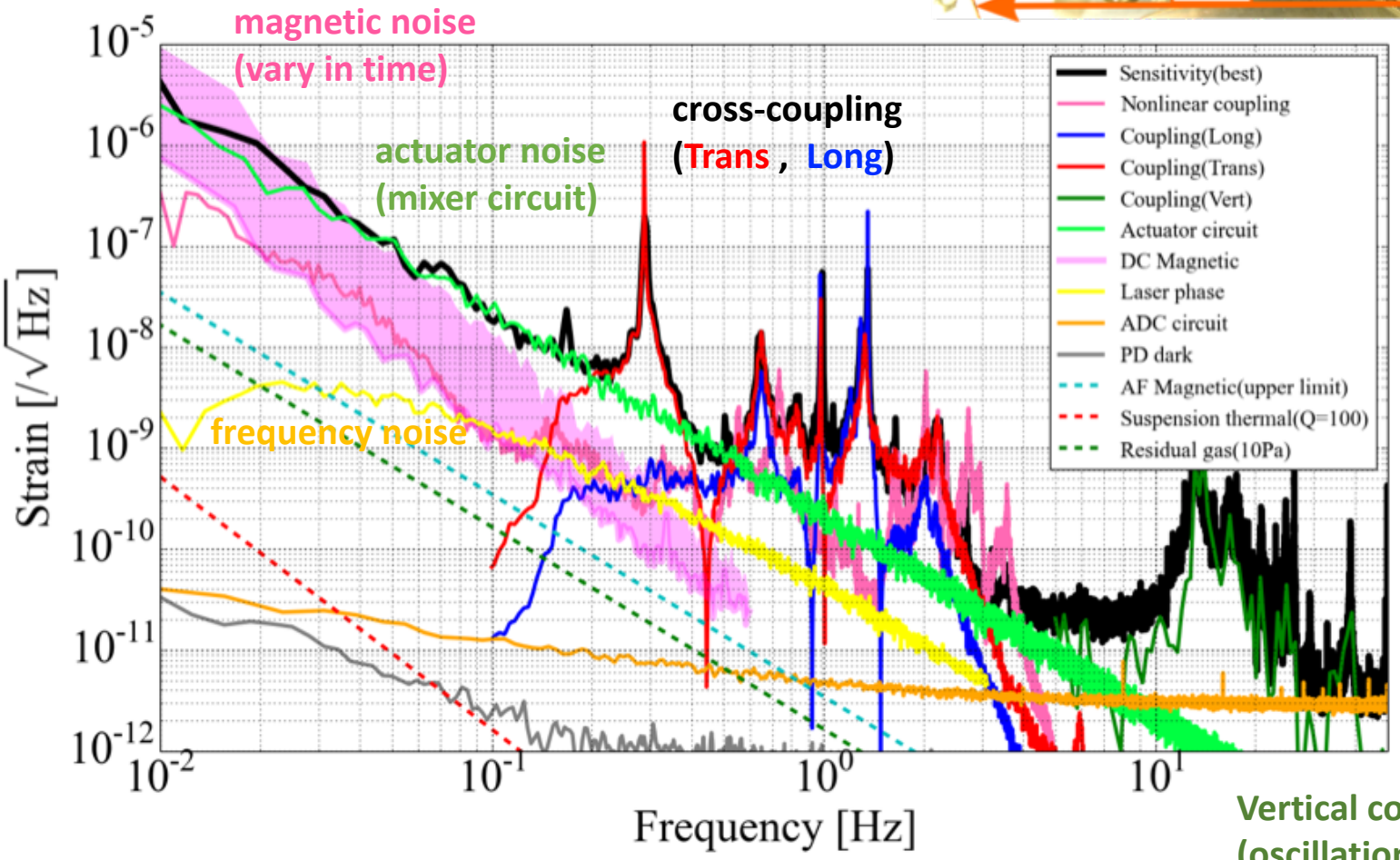
prototypes

what is done so far

current prototype

- 2×10^{-8} /rtHz @ 0.1Hz

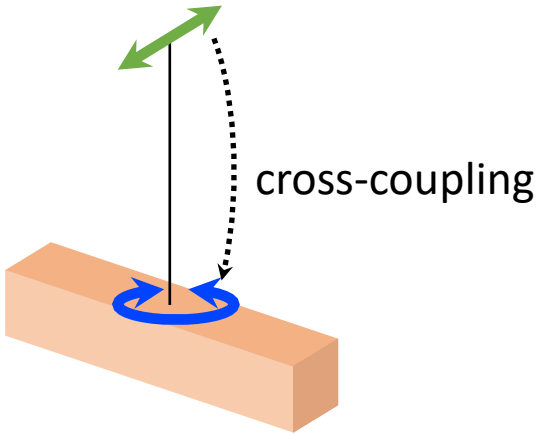


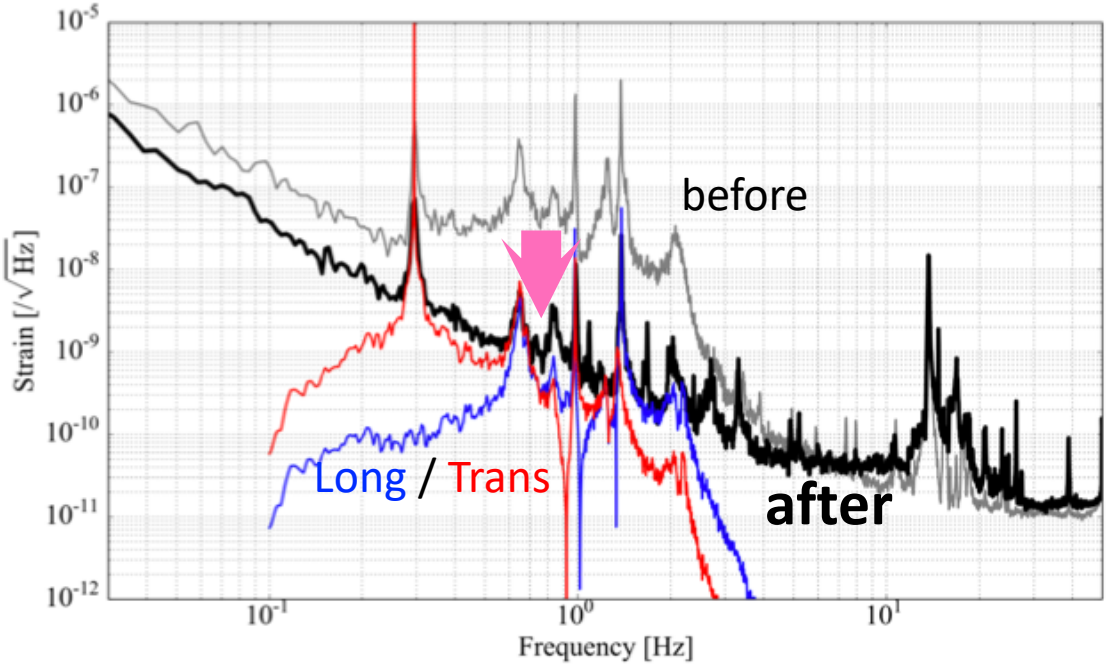


tilt adjustment for cross-coupling reduction

significant noise in TOBA

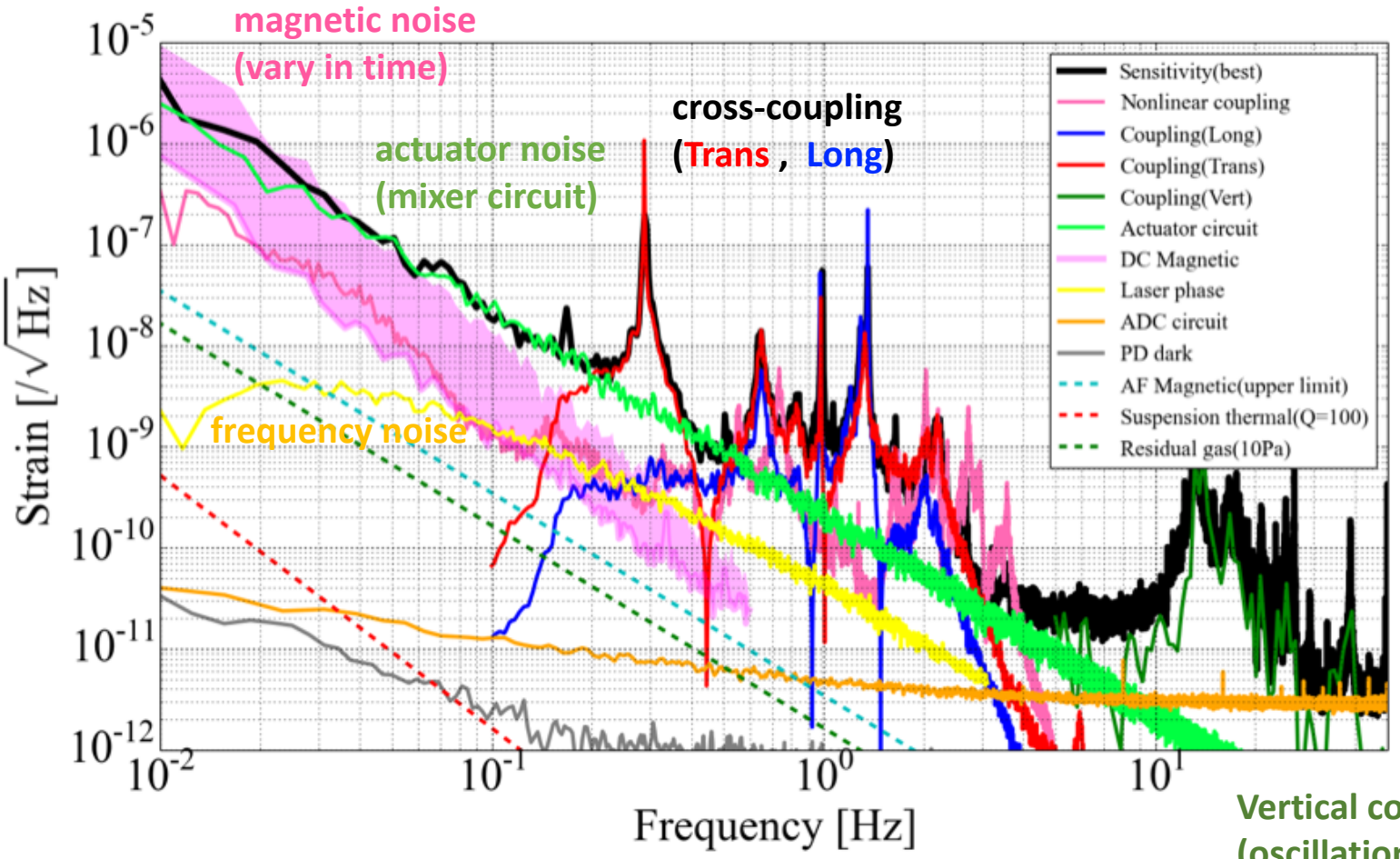
- translation of the ground can be transferred to the rotation of the bar via asymmetries of the system (cross-coupling)
- **tilt** is the main asymmetry which introduces coupling
- after adjustment : **~10^{-5} rad/m @0.1Hz**





technical noise investigation

- **noise sources are well identified**



next : Phase-III

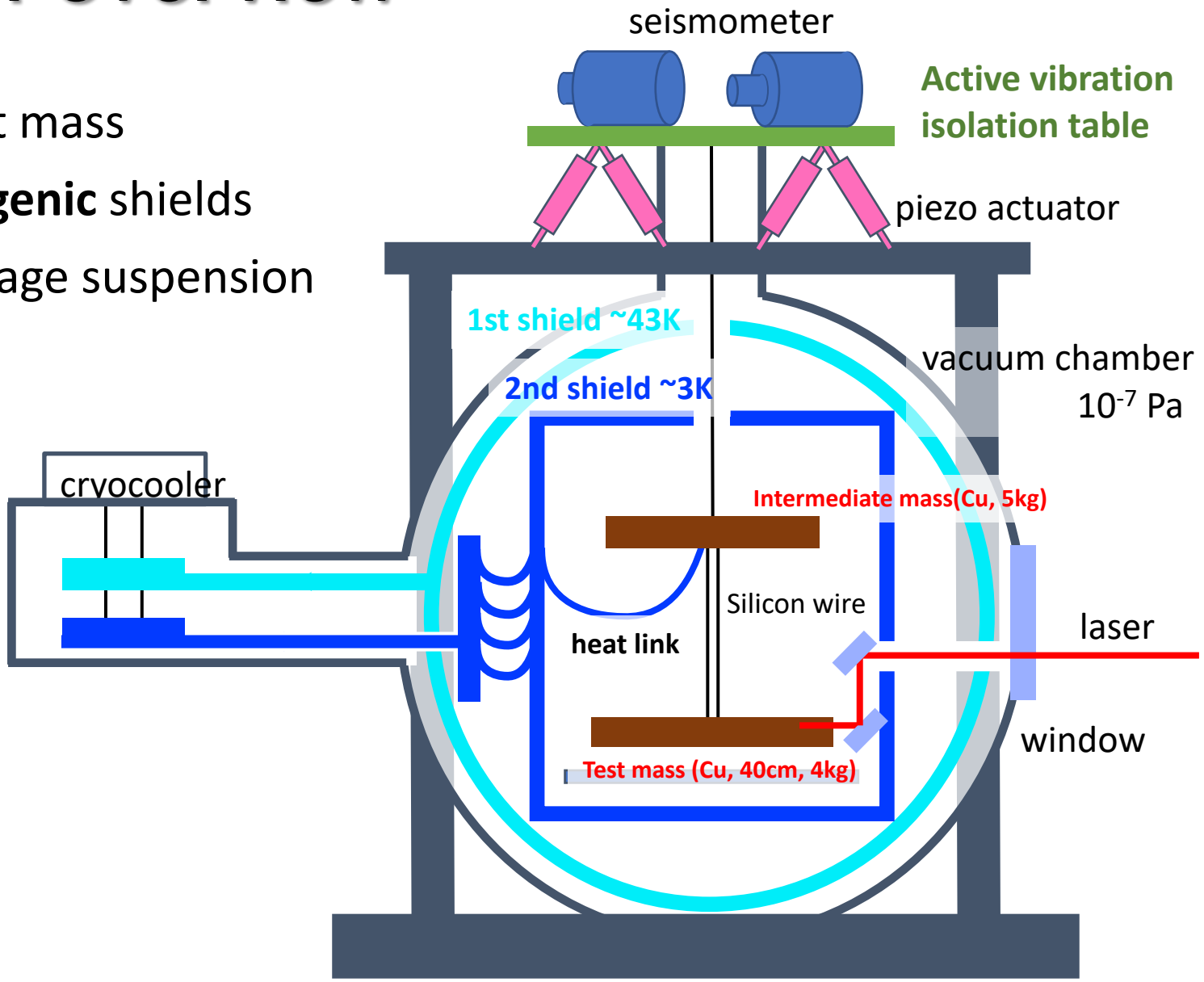
phase-III TOBA

- **~10^{-15} /rtHz @0.1Hz** with small scale (~40cm) bar
  - demonstration of noise reduction for final (10m) TOBA

- Scientific targets of Phase-III
  - search IMBHs inside the Milky-way galaxy (~ 1 Mpc)
  - earthquake early warning (M6.0 in 10s from 100km)
  - Newtonian noise investigation (cancellation demonstration)

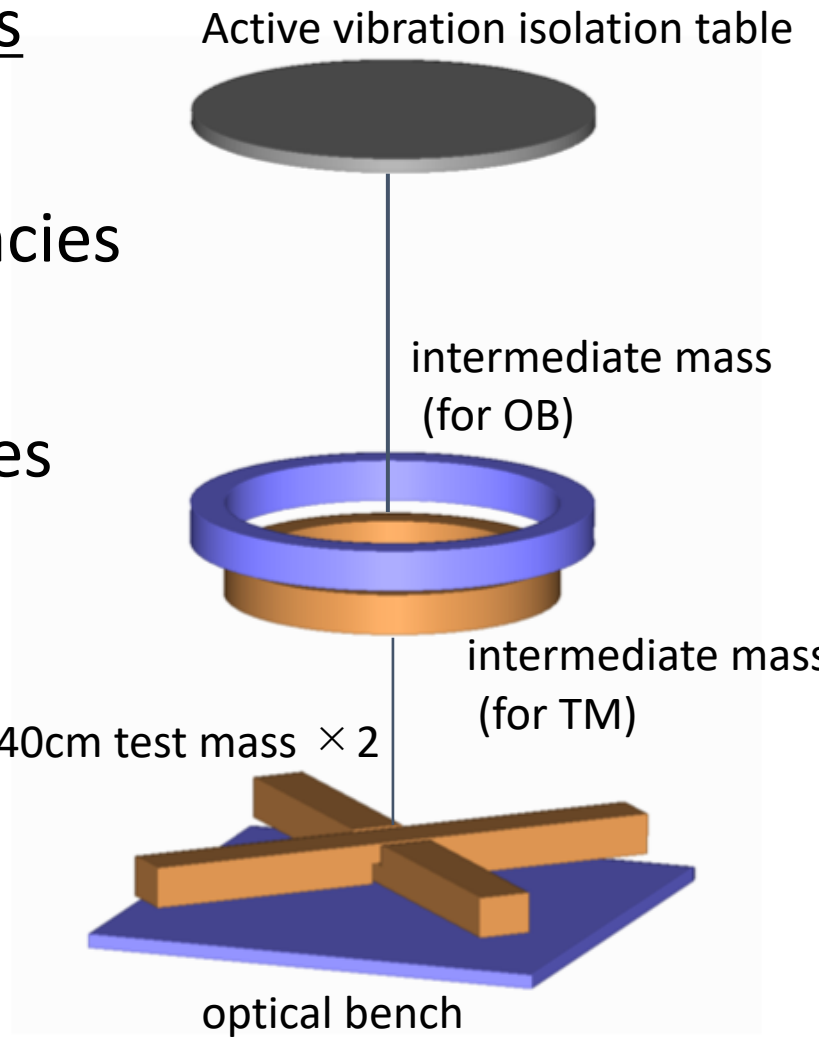
design overview

- 40cm test mass
- two **cryogenic** shields
- double stage suspension



suspension design

- two individual suspension series
  (TM susp. & OB susp.)
- matching Yaw resonant frequencies
  for common-mode rejection
- damping on intermediate masses
  (not shown in the figure)



noise sources & requirements

- **suspension thermal nosie**
  - cooling : **4K** @ suspension wire
  - high-Q suspension wire : **$Q = 10^8$** (silicon or sapphire)
- **seismic noise** (cross-coupling from translation)
  - cross-coupling : **10^{-9} rad/m @0.1Hz**
  - active vibration isolation : **10^{-7} m/rtHz @0.1Hz** (~10^{-2} isolation)
  - rotational passive isolation : **10^{-6} rad/rad @ 0.1Hz**
- **sensing noise**
  - **5×10^{-16} rad/rtHz @0.1Hz**
  - (new angular sensor, monolithic optics)
- **Newtonian noise**
- technical noise

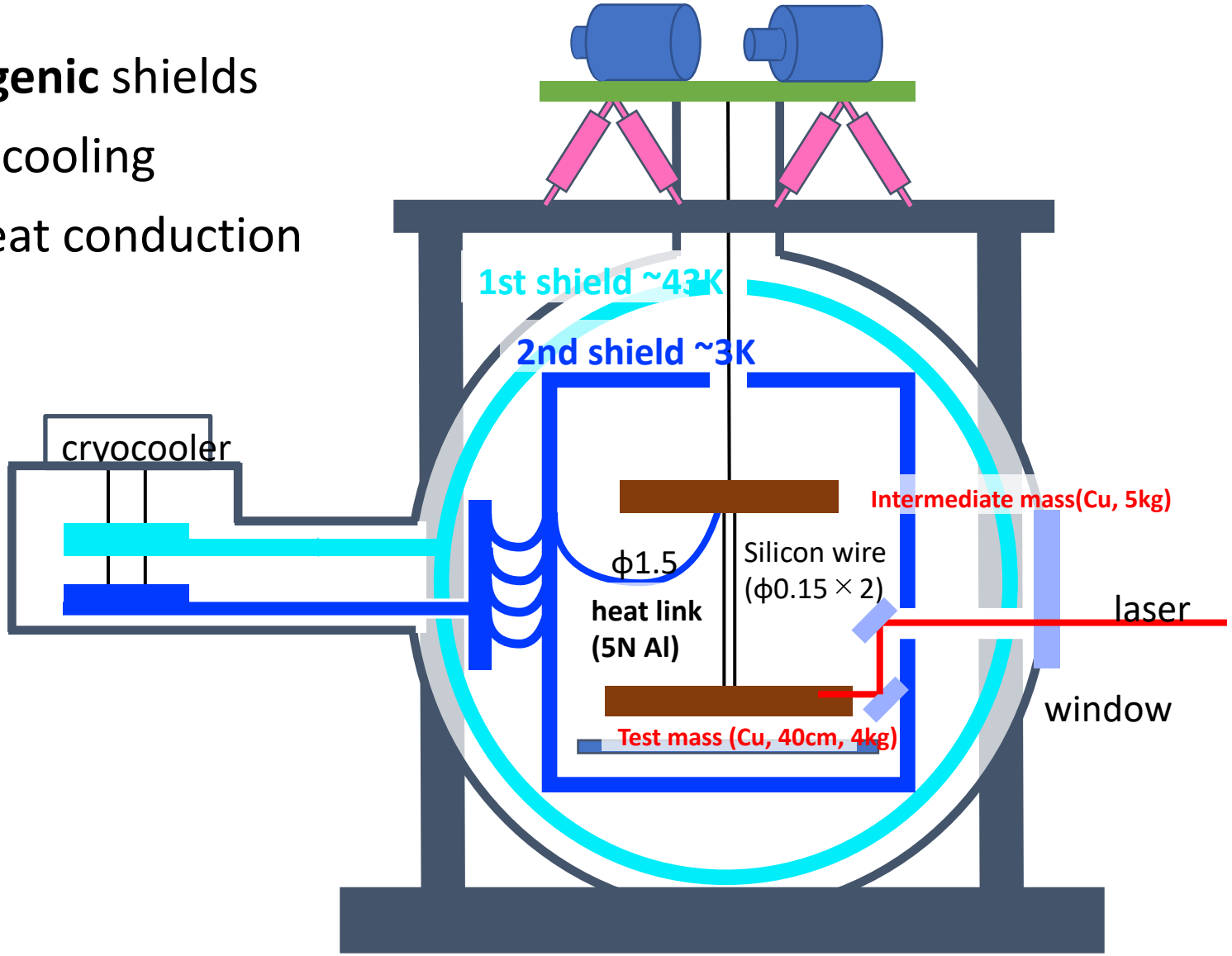
noise sources & requirements

- **suspension thermal nosie**
  - cooling : **4K** @ suspension wire
  - high-Q suspension wire : **$Q = 10^8$** (silicon or sapphire)
- **seismic noise** (cross-coupling from translation)
  - cross-coupling : **10^{-9} rad/m @0.1Hz**
  - active vibration isolation : **10^{-7} m/rtHz @0.1Hz** (~10^{-2} isolation)
  - rotational passive isolation : **10^{-6} rad/rad @ 0.1Hz**
- **sensing noise**
  - **5×10^{-16} rad/rtHz @0.1Hz**
  - (new angular sensor, monolithic optics)
- **Newtonian noise**
- technical noise

cryogenic configuration

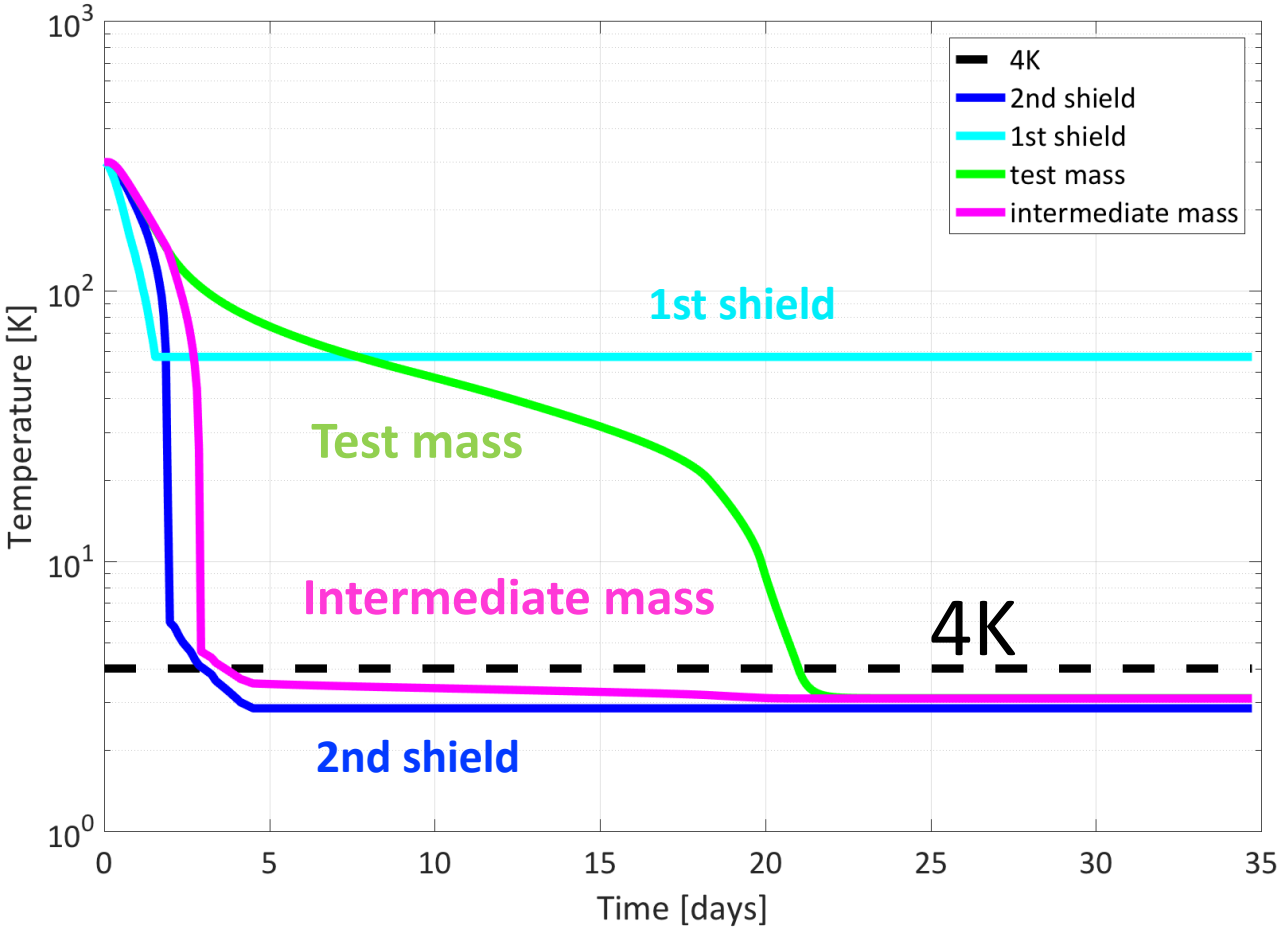
- two **cryogenic** shields
- radiation cooling

  + heat conduction



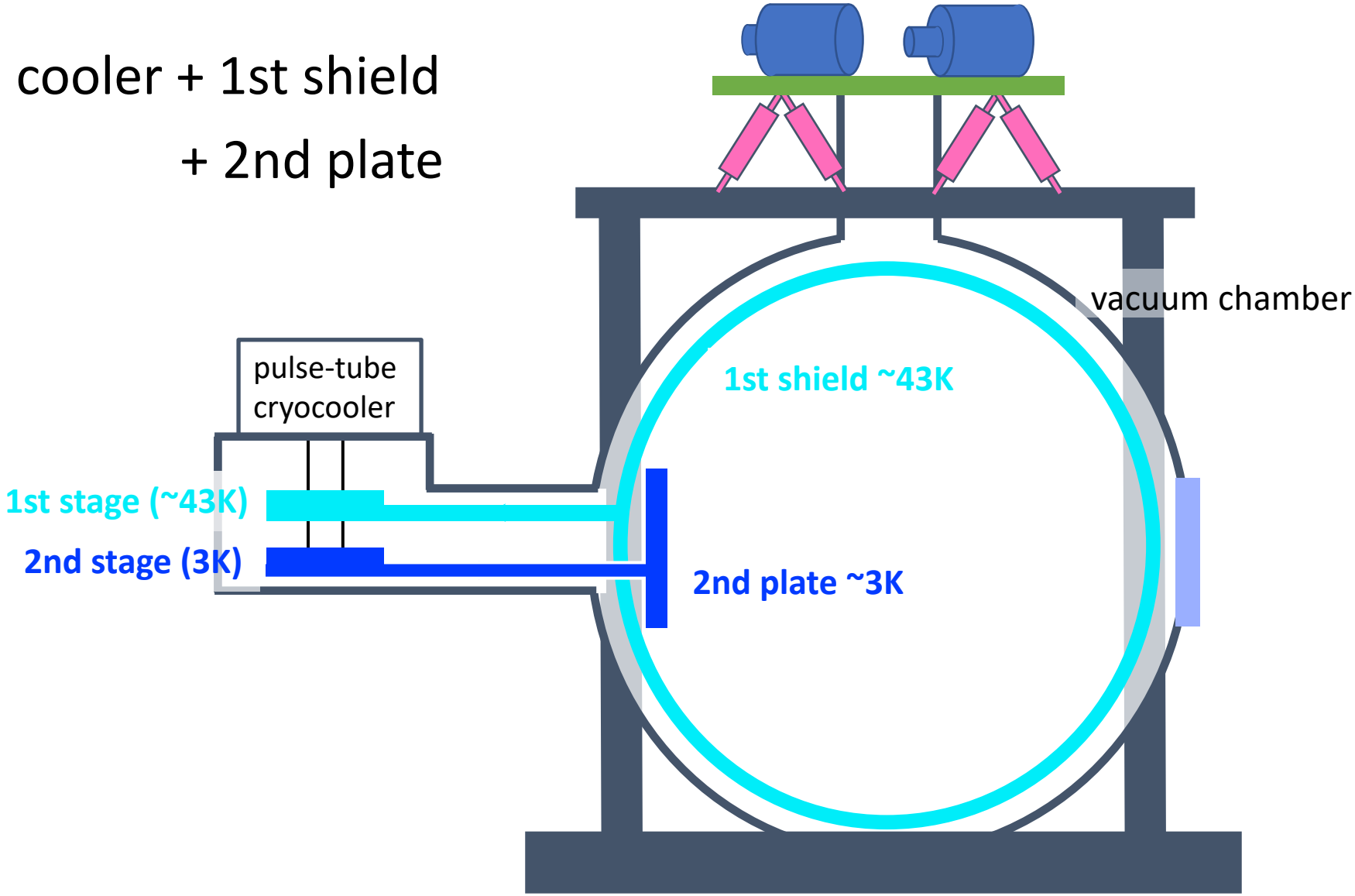
cooling time of the suspension

- calculation shows the wire reaches **3.1K in 21 days**

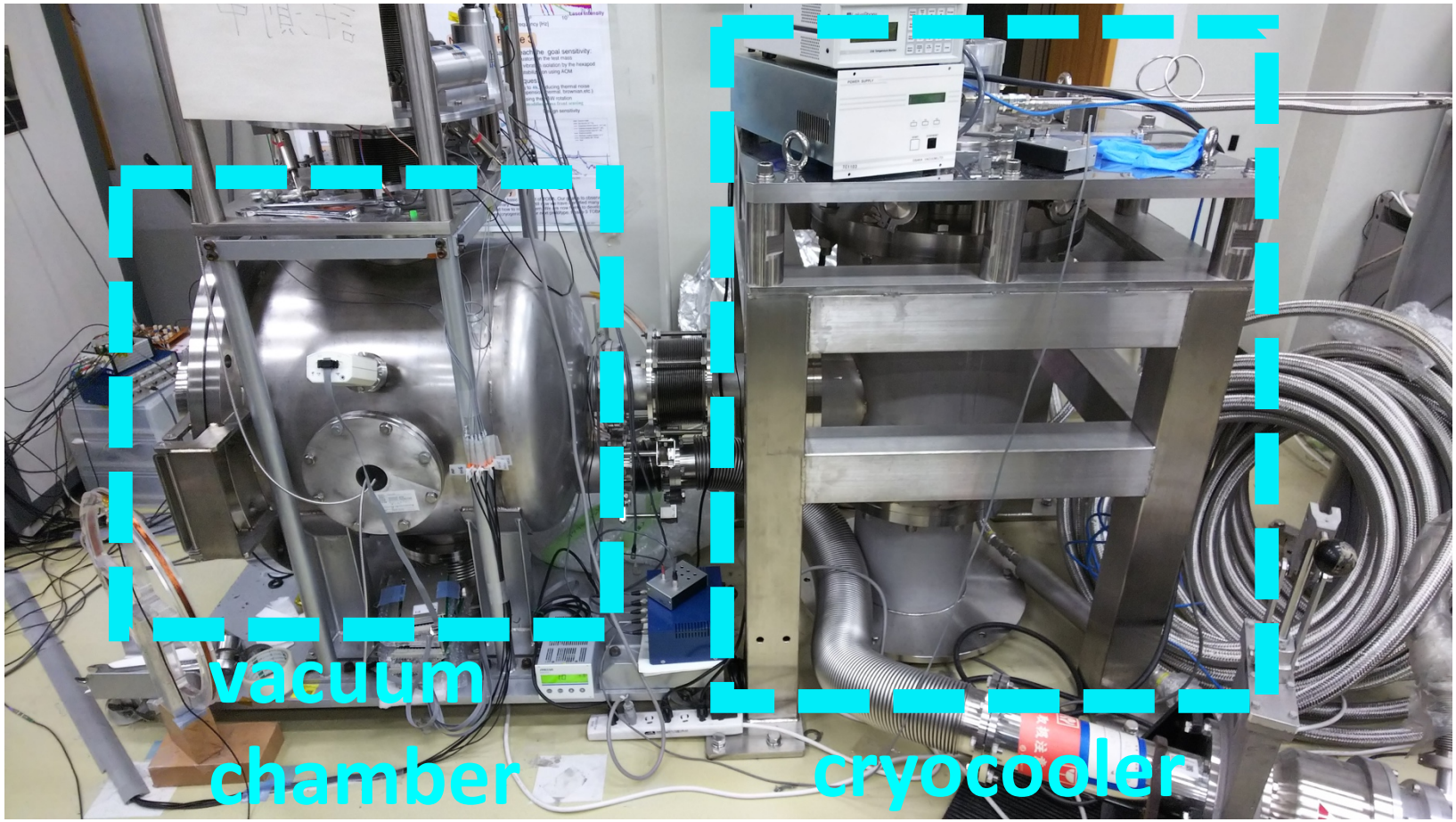


cryocooler is already installed

- cooler + 1st shield
  + 2nd plate

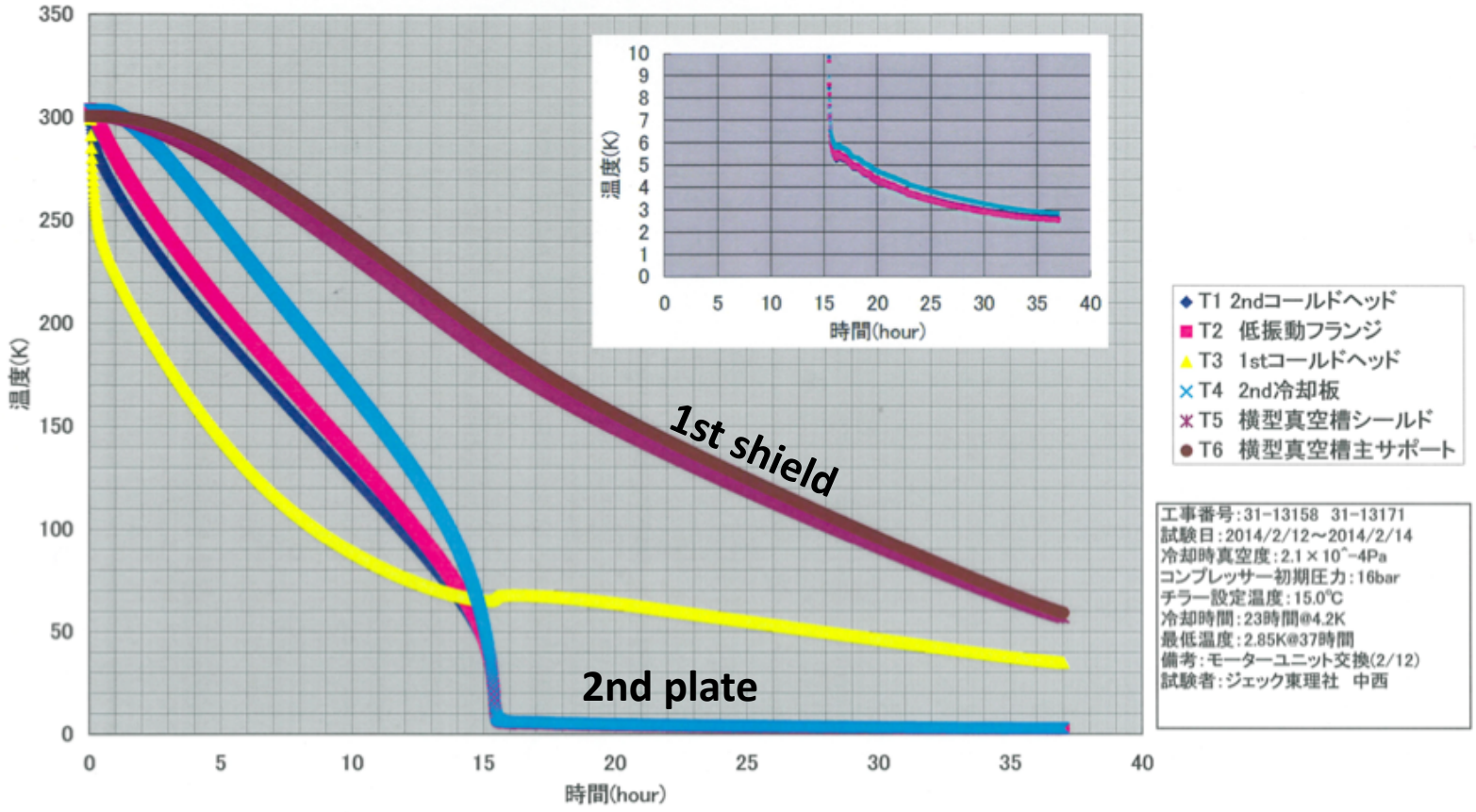


cryocooler + vacuum chamber



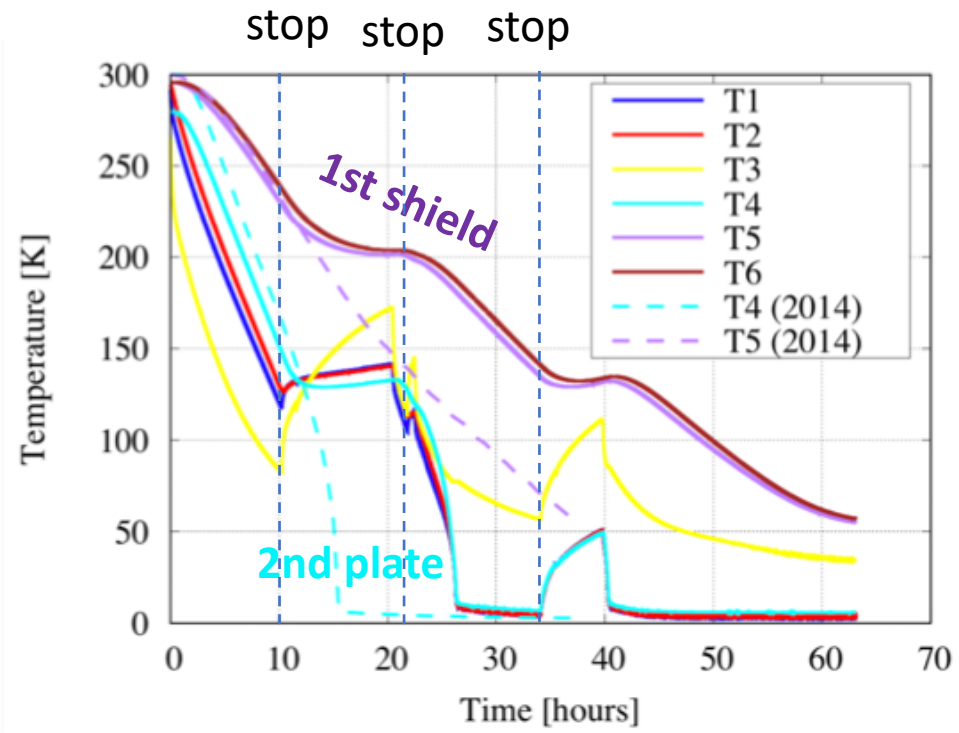
cooling test of cryocooler (2014)

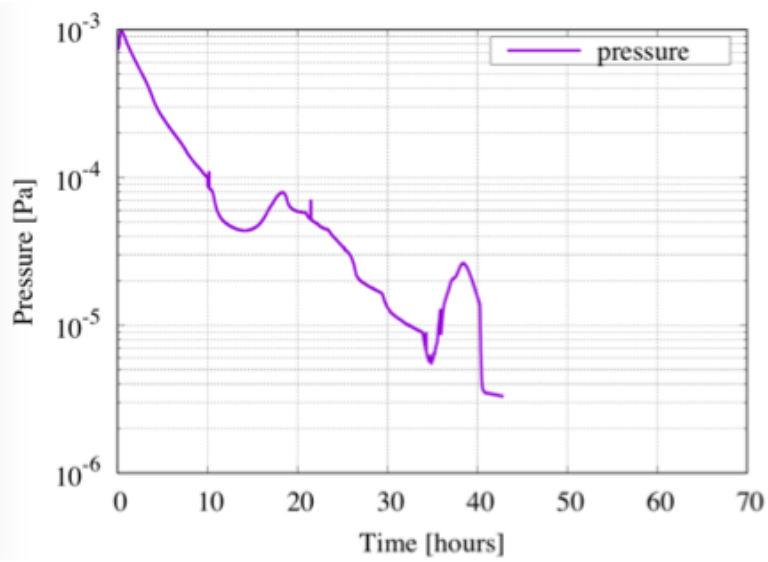
- worked well (reached 3K in 25 hours)



cooling test of cryocooler (2018)

- sometimes stops due to errors of the chiller
- reached to 5.8 K (cooling ability decreased?)
- cryo pump : 7×10^{-4} Pa (300K) → 2×10^{-6} Pa (5.8K)

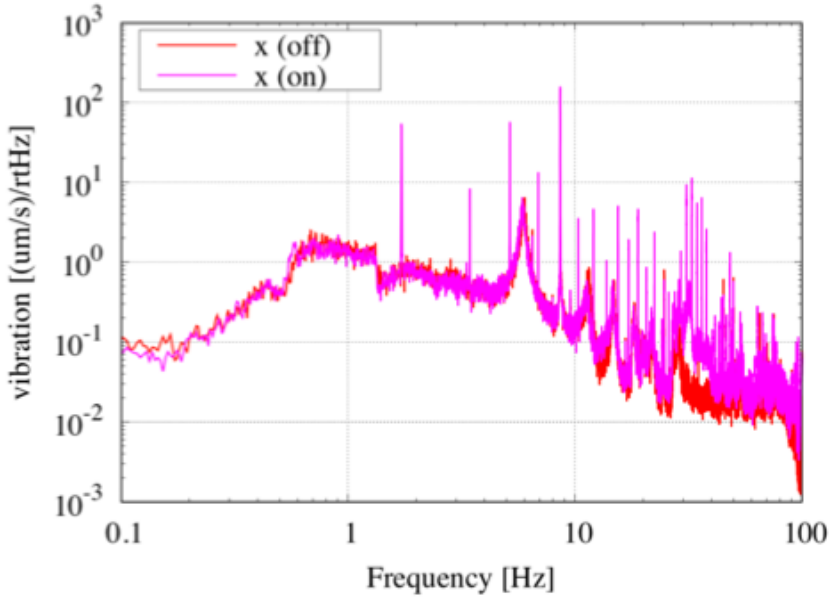


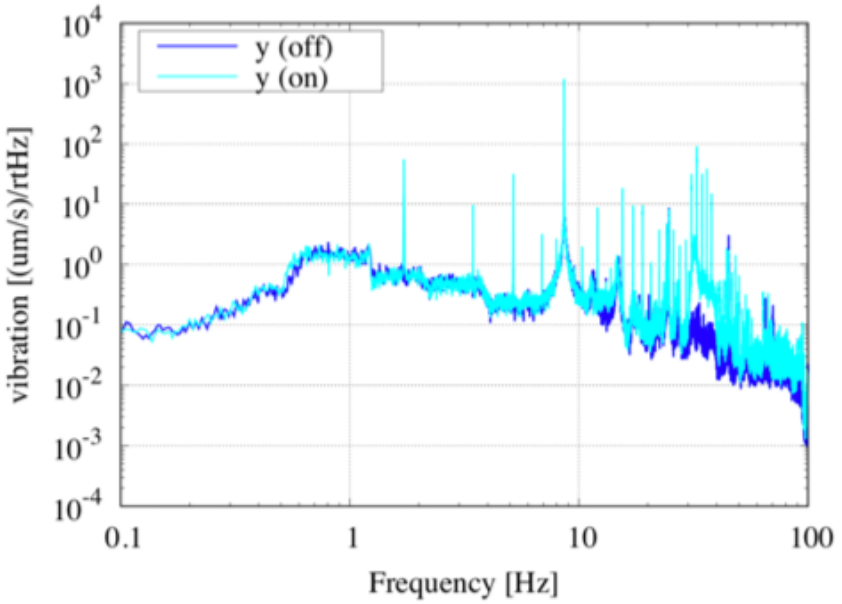


large vibration

- peaks at 1.7Hz and its harmonics (2-3 orders excess)
- seismometers saturate
- where do the vibration come from?

vibration at the chamber





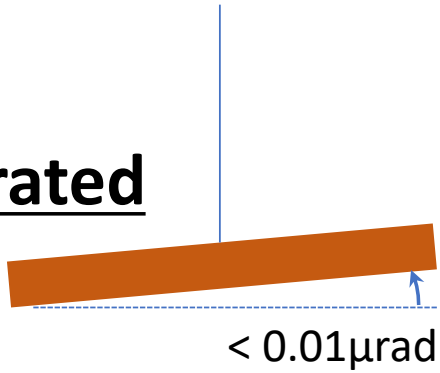
noise sources & requirements

- **suspension thermal nosie**
  - cooling : **4K** @ suspension wire
  - high-Q suspension wire : **$Q = 10^8$** (silicon or sapphire)
- **seismic noise** (cross-coupling from translation)
  - cross-coupling : **10^{-9} rad/m @0.1Hz**
  - active vibration isolation : **10^{-7} m/rtHz @0.1Hz** (~10^{-2} isolation)
  - rotational passive isolation : **10^{-6} rad/rad @ 0.1Hz**
- **sensing noise**
  - **5×10^{-16} rad/rtHz @0.1Hz**
  - (new angular sensor, monolithic optics)
- **Newtonian noise**
- technical noise

cross-coupling reduction

- basic reduction scheme is **already demonstrated**
- requirement : 10^{-9} rad/m @0.1Hz

  ⇔ tilt adjustment in precision of **0.01 µrad**



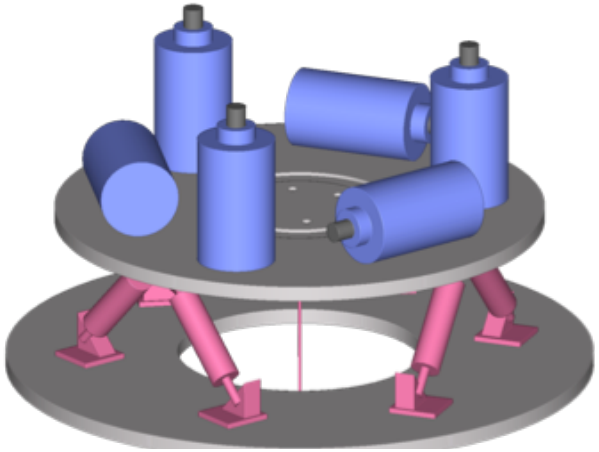
seismically indeced RMS ~ **10-100 µrad**

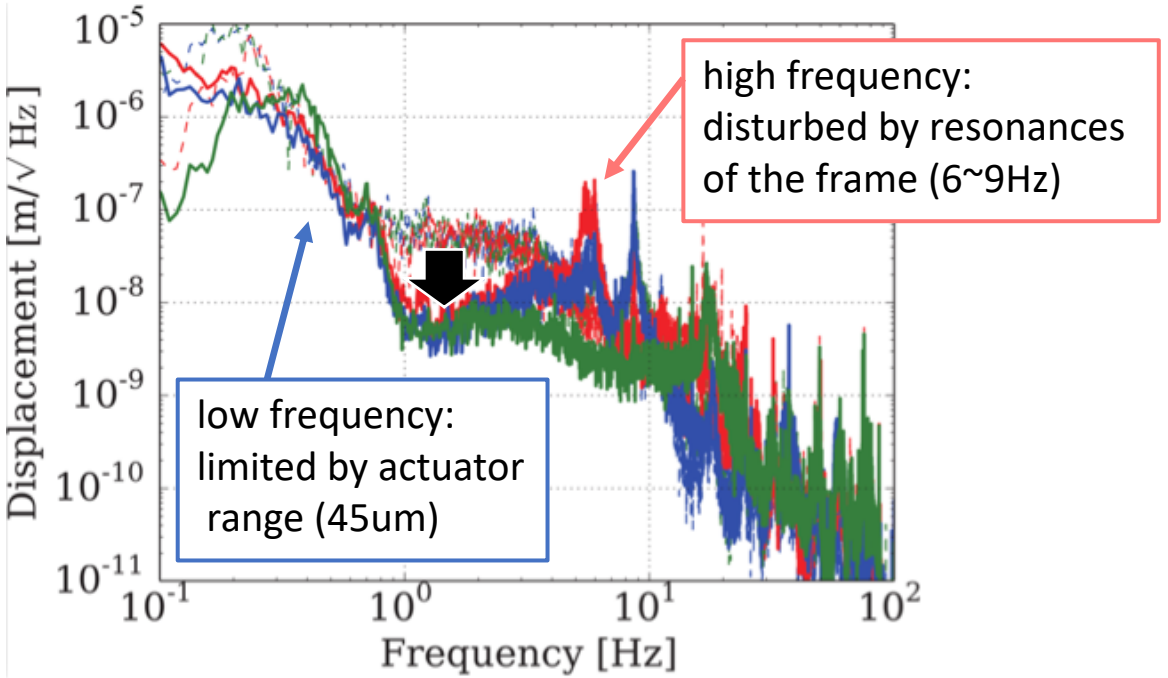
- **stabilize the tilt** with auxiliary sensors (optical lever) and actuators (coil-coil) then **adjust its DC position**

- automatic reduction idea
  1. excite suspension point motion at a single frequency
  2. measure coupling transfer function at the frequency
     (coupling TF is proportional to the tilt)
  3. feedback to the tilt actuator of the mass

active vibration isolation

- requirement : 10^{-2} isolation @0.1Hz
- **10^{-1}** isolation at 1 Hz is **already achieved** (by A. Shoda)





- use longer range PZTs (150um)
- make the frame stiffer and lower-Q

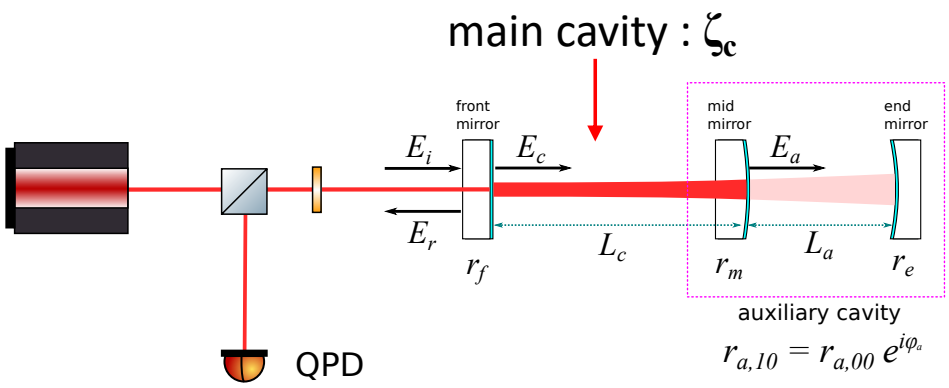
} broader band isolation

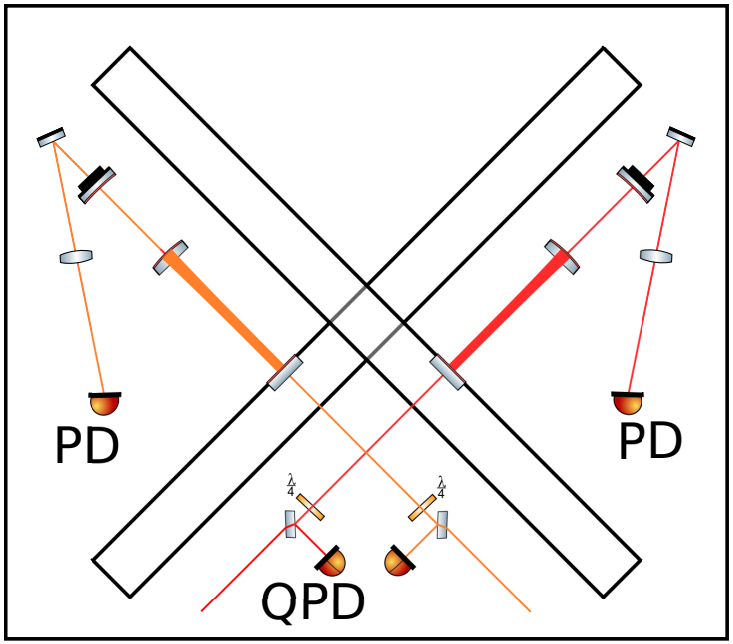
noise sources & requirements

- **suspension thermal nosie**
  - cooling : **4K** @ suspension wire
  - high-Q suspension wire : **$Q = 10^8$** (silicon or sapphire)
- **seismic noise** (cross-coupling from translation)
  - cross-coupling : **10^{-9} rad/m @0.1Hz**
  - active vibration isolation : **10^{-7} m/rtHz @0.1Hz** (~10^{-2} isolation)
  - rotational passive isolation : **10^{-6} rad/rad @ 0.1Hz**
- **sensing noise**
  - **5×10^{-16} rad/rtHz @0.1Hz**
  - (new angular sensor, monolithic optics)
- **Newtonian noise**
- technical noise

optical configuration

- improved type of wave front sensor (<u>new</u>)
  - enhance angular signal (HG_{10} mode) using an auxiliary cavity





$\zeta_c = -\varphi_a$ (detuned auxiliary cavity)

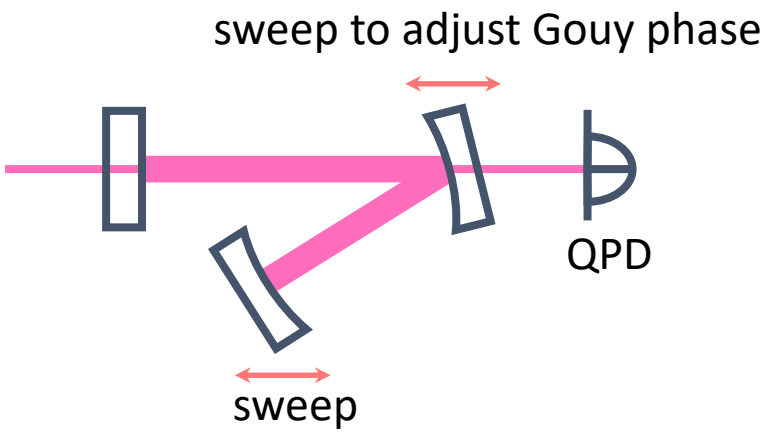
⇒ HG_{00} and HG_{10} **resonate at the same time**

⇒ angular signal (HG_{10}) enhanced

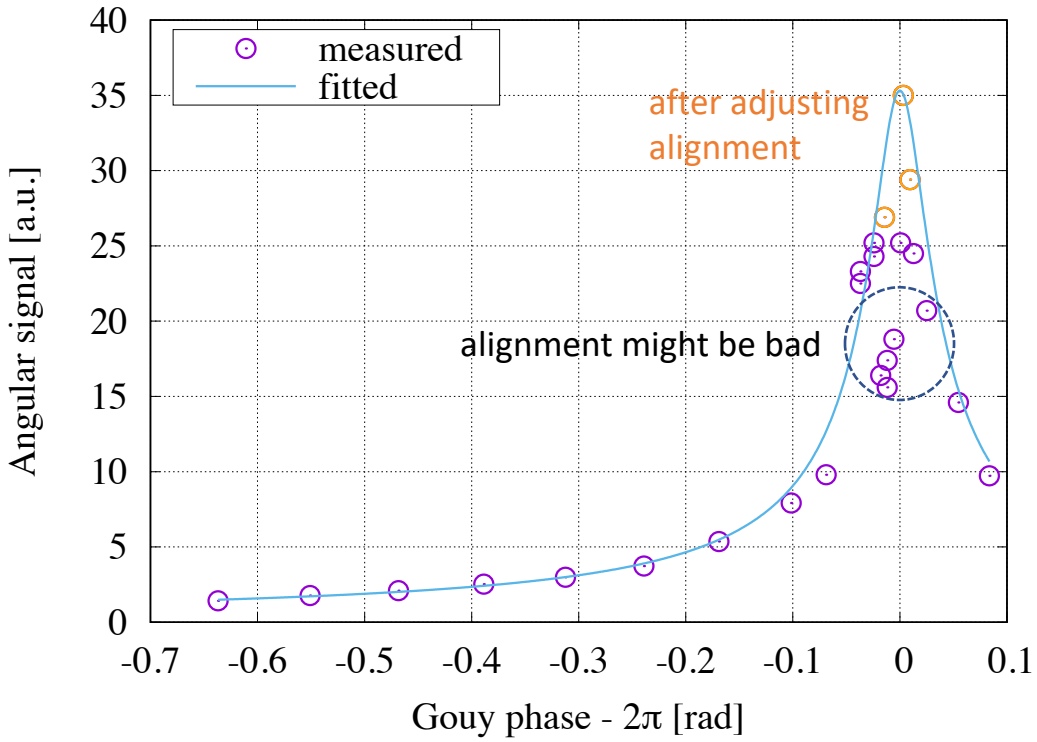
low shot noise, no frequency noise

demonstration of angular sensor

- angular signal enhancement was measured with another possible configuration (folded)
- not completed yet



folded configuraton



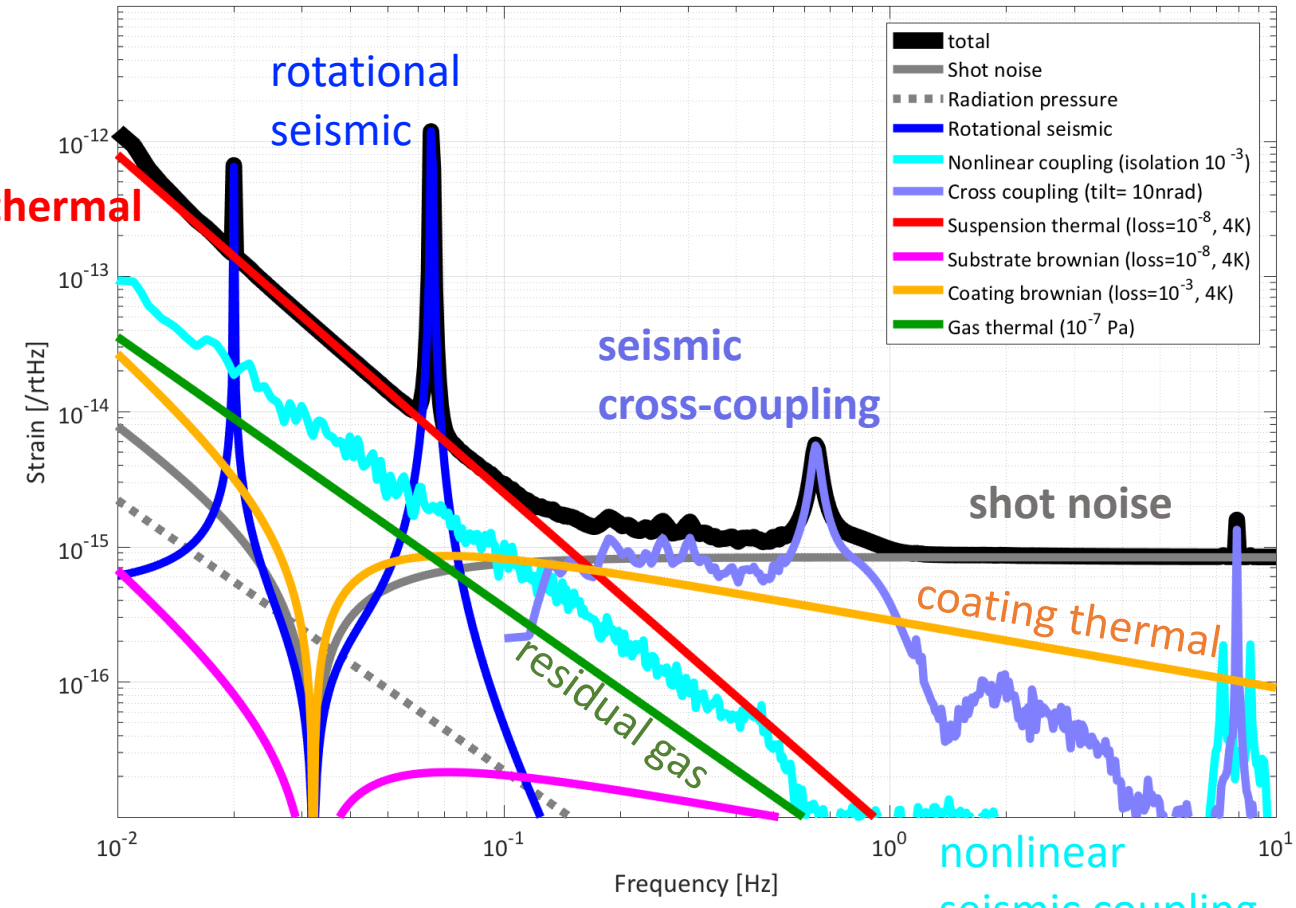
summary of noise reduction plan

- cryogenic systems
  - design : cooling to 4K by radiation & conduction
  - cryocooler is already installed

- seismic noise reduction
  - 10^{-9} rad/m cross-coupling : tilt stabilization → adjusting
  - 10^{-2} active isolation : longer range actuator & stiffer frame

- sensing noise
  - improved wave front sensor (resonating HG_{10})
  - proof-of-concept experiment is ongoing

design sensitivity

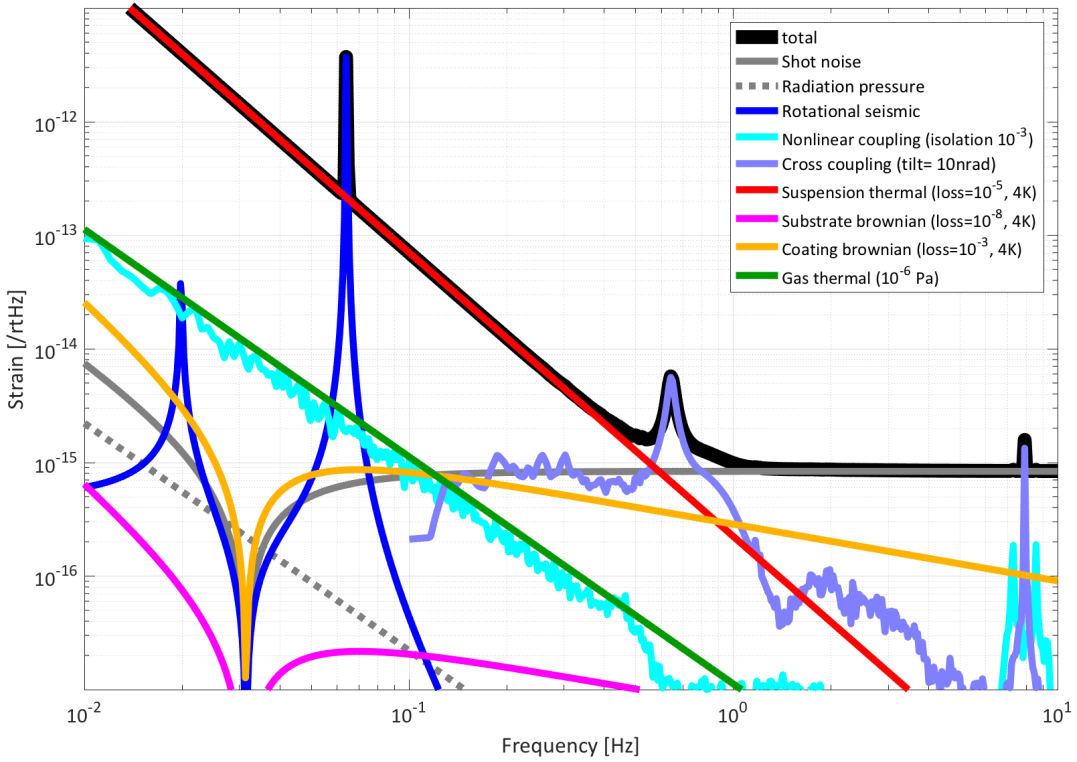


suspension thermal

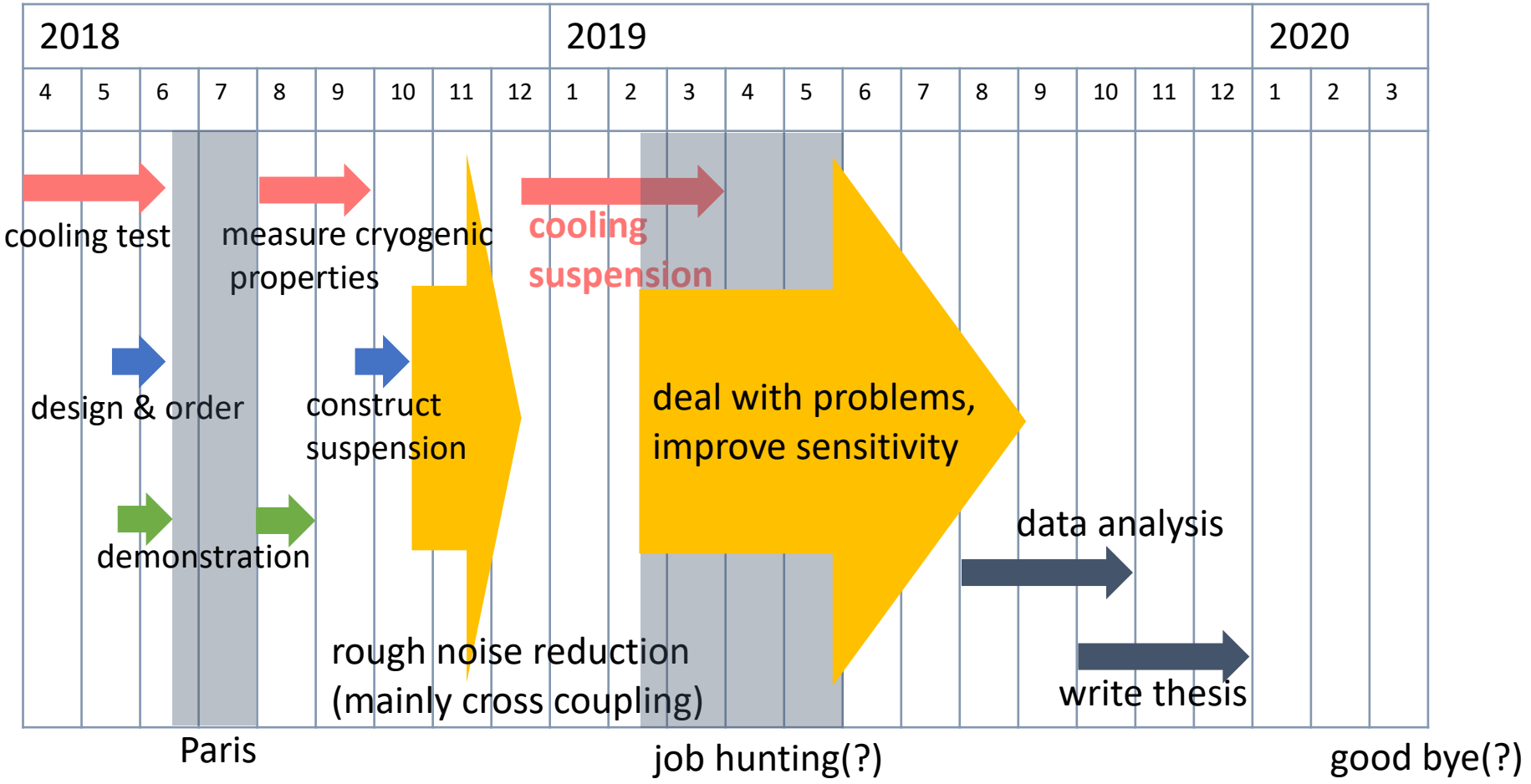
10^{-15}

pre-Phase-III(??) TOBA

- using **CuBe ($Q=10^5$)** suspension wire
  - until high-Q(Silicon?) wire development is completed
- other configurations are almost same as phase-III



schedule



- I can get an additional year if DC2 application is approved

Summary

summary of phase-III

- **phase-III** is an important demonstration of TOBA

- cryogenic systems
  - design : cooling to 4K by radiation & conduction
  - cryocooler is already installed
- seismic noise reduction
  - 10^{-9} rad/m cross-coupling : tilt stabilization → adjusting
  - 10^{-2} active isolation : longer range actuator & stiffer frame
- sensing noise
  - improved wave front sensor (resonating HG_{10})
  - proof-of-concept experiment is ongoing

- cooling will start from the end of 2018

End !!