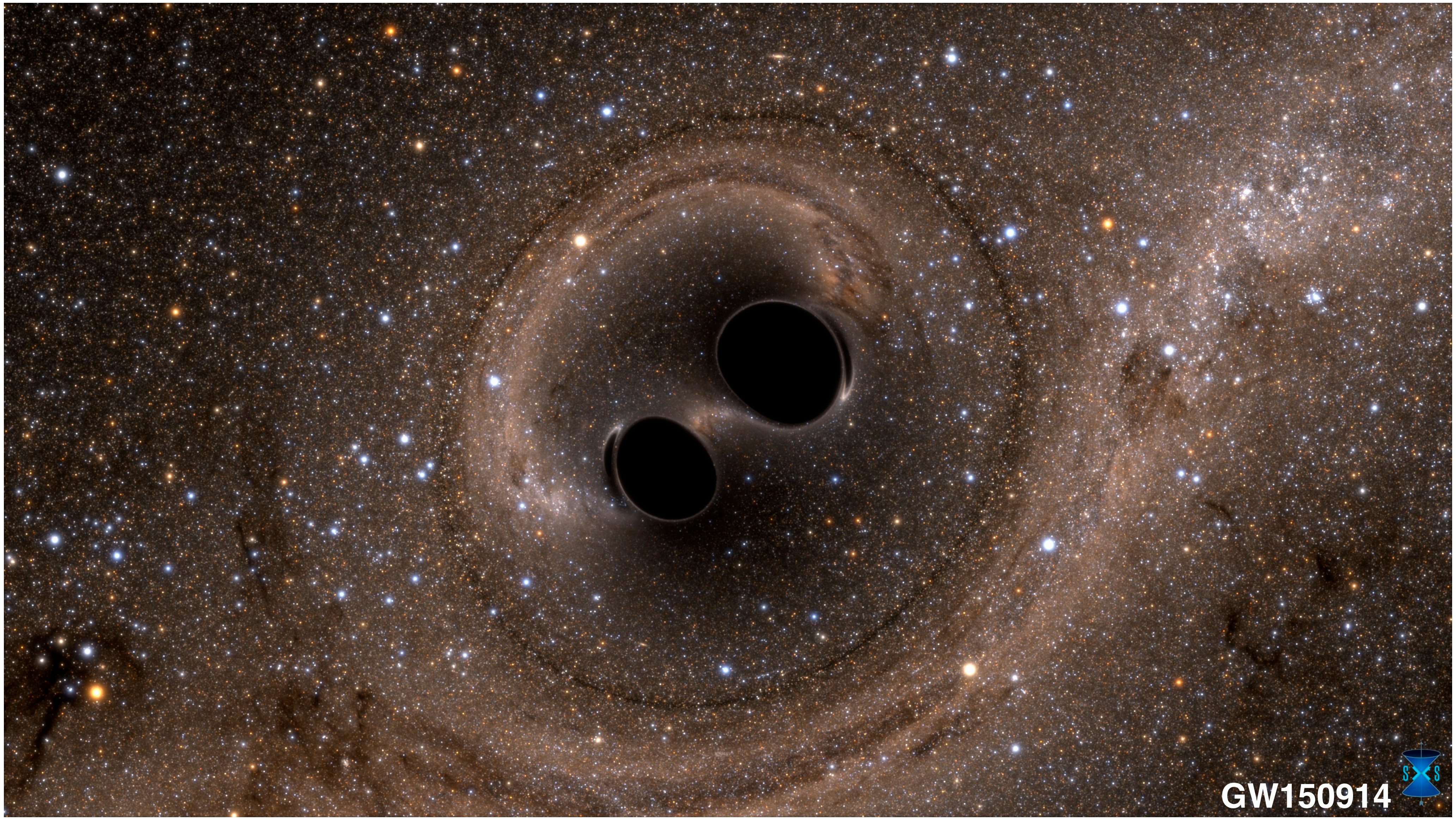
Study and improvement of torsion damping for the signal recycling mirrors of KAGRA

Rikako Hatoya
Supervisor: Professor. Aso Yoichi
Position: 1st Year, Undergraduate
Affiliation: Lawrence Berkeley National Laboratory (LBNL)

Introduction to GW

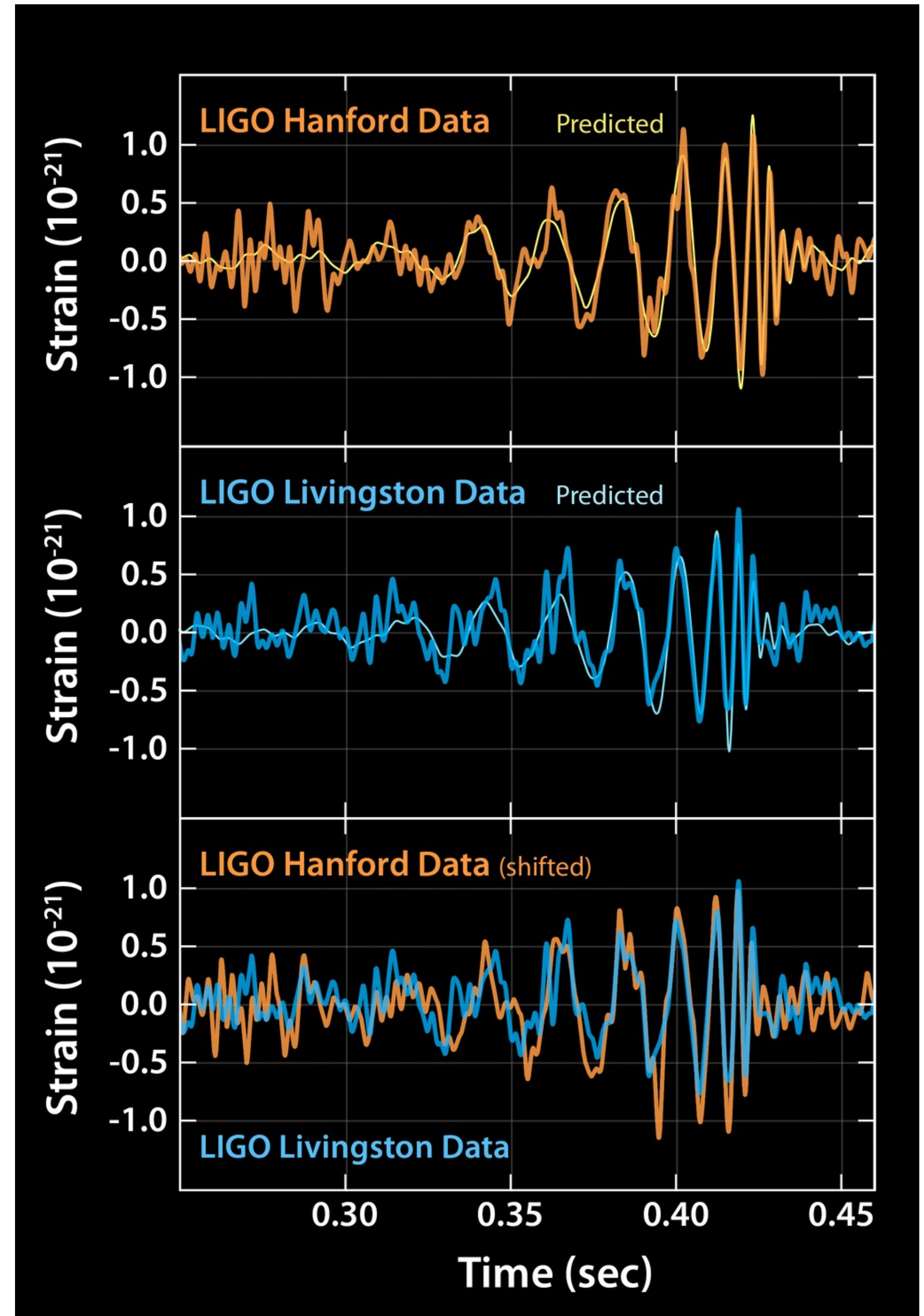
What are Gravitational Waves (GW)?

- Ripples in spacetime created by the motion of heavy objects.
- Prediction of GR (General Relativity)



Achievements in Gravitational Physics

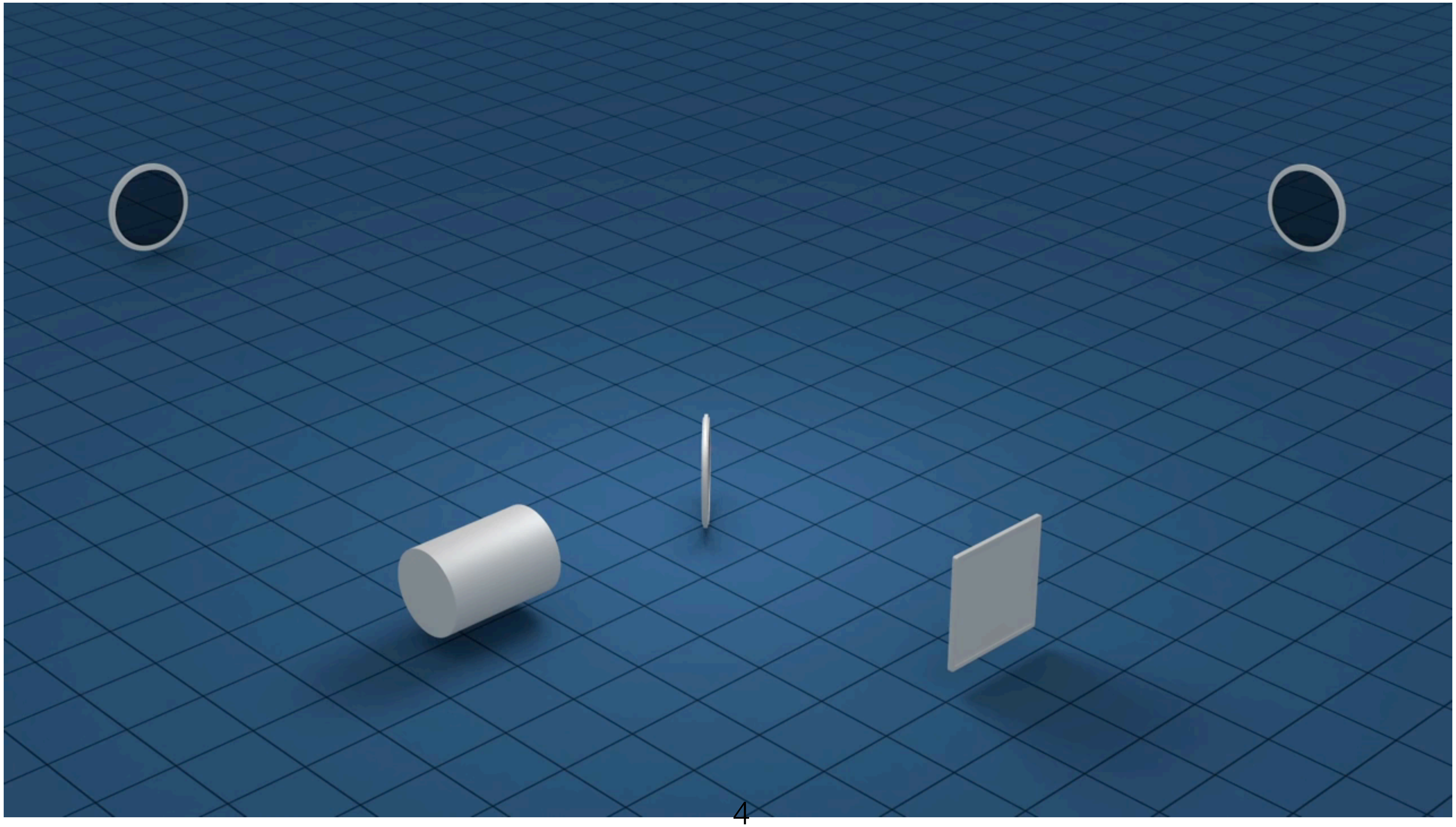
- General Theory of Relativity (1915)
- Hulse-Taylor (**PSR B1913+16**)
- LIGO, **GW150914** (BH-BH)
- VIRGO joined last 3 weeks of O2
- LIGO and VIRGO, **GW170817** (NS-NS)
- Other telescopes observed cosmic rays in the event of GW170817 as well



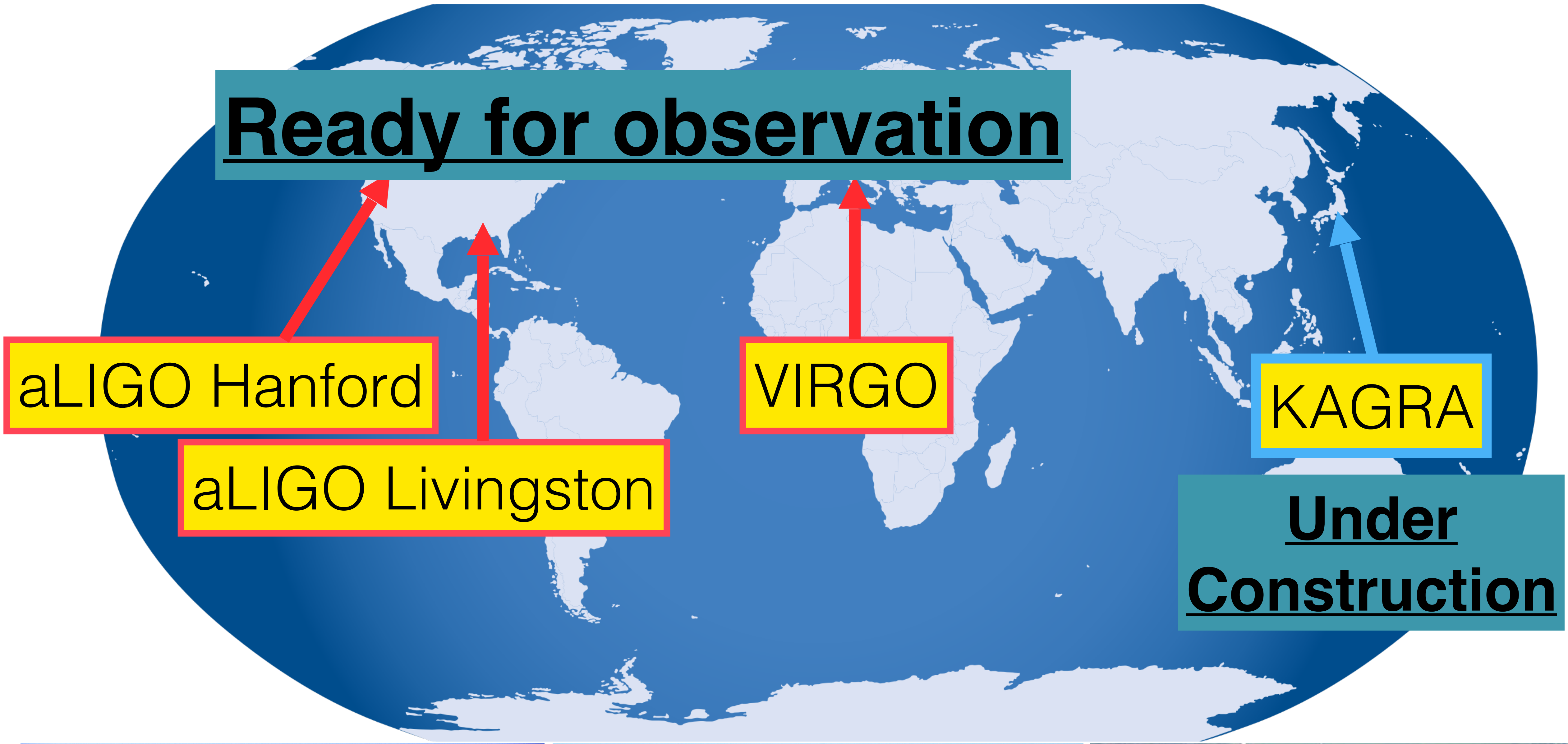
Detecting GW

GWs have “plus polarization” and “cross polarization”

- Stretches in spacetime observed by orthogonal arms
- Michelson Interferometer



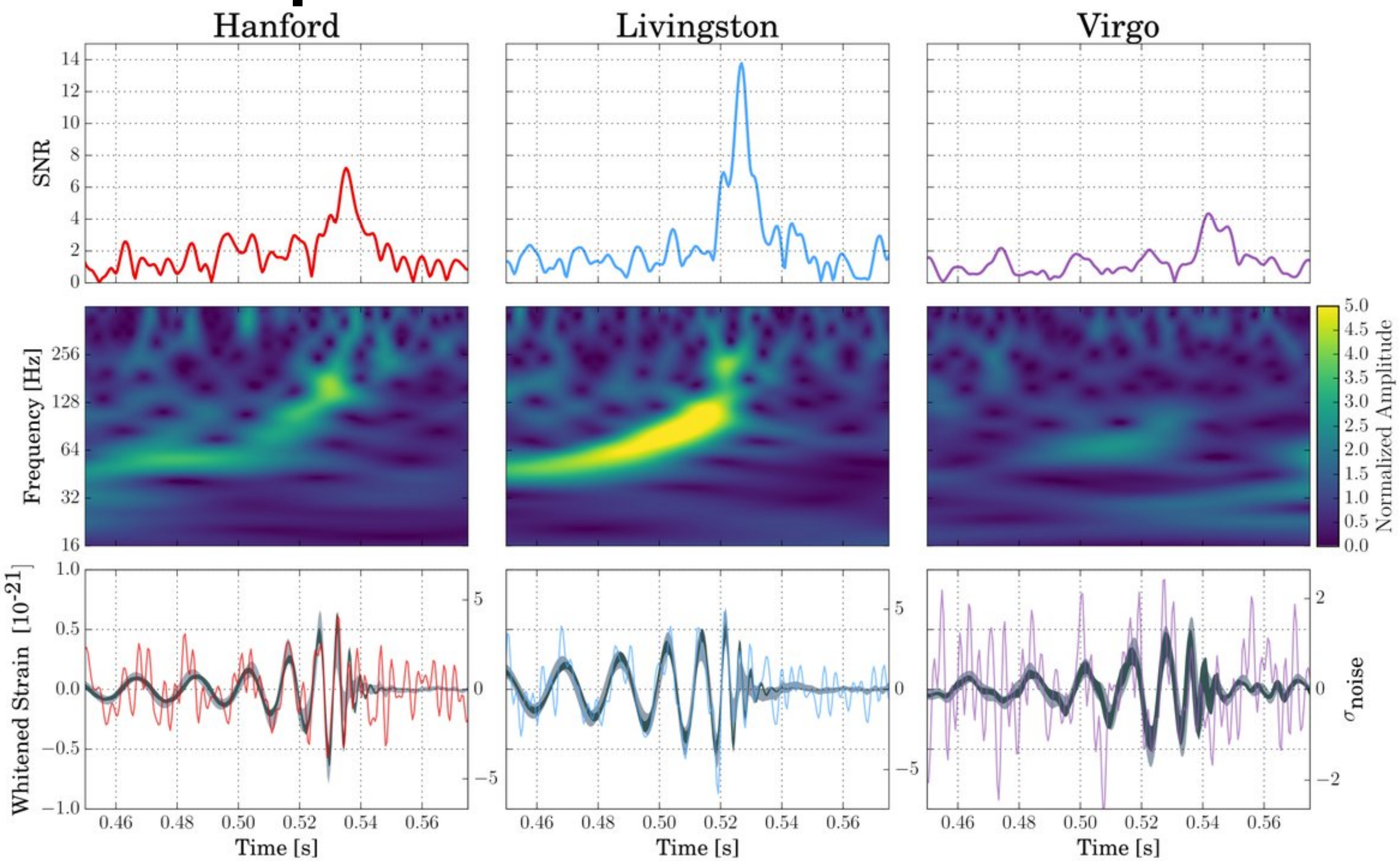
GW Detector Network



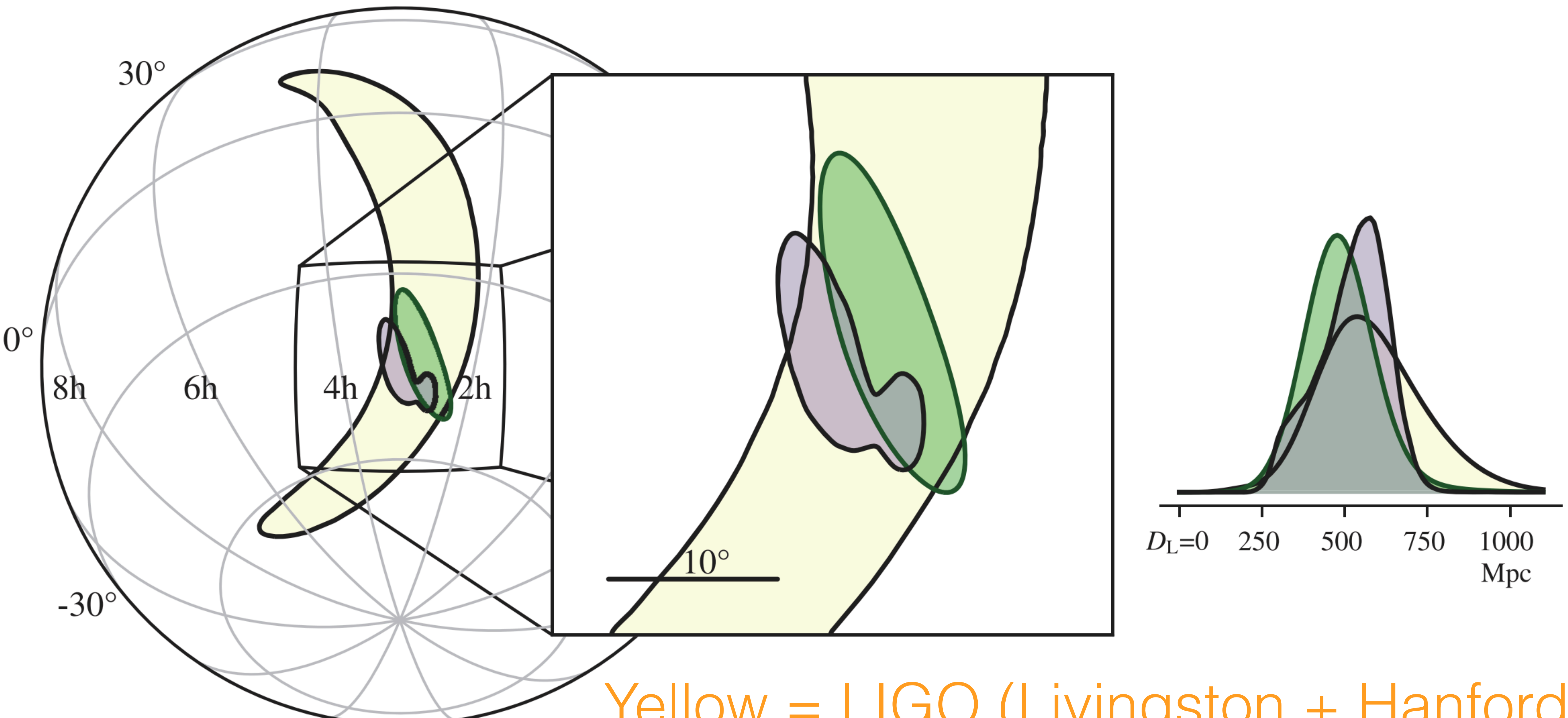
Motivations for the network of GW detectors

- Antenna patterns
- Smaller Localization Errors

Triple Detection of GW170817

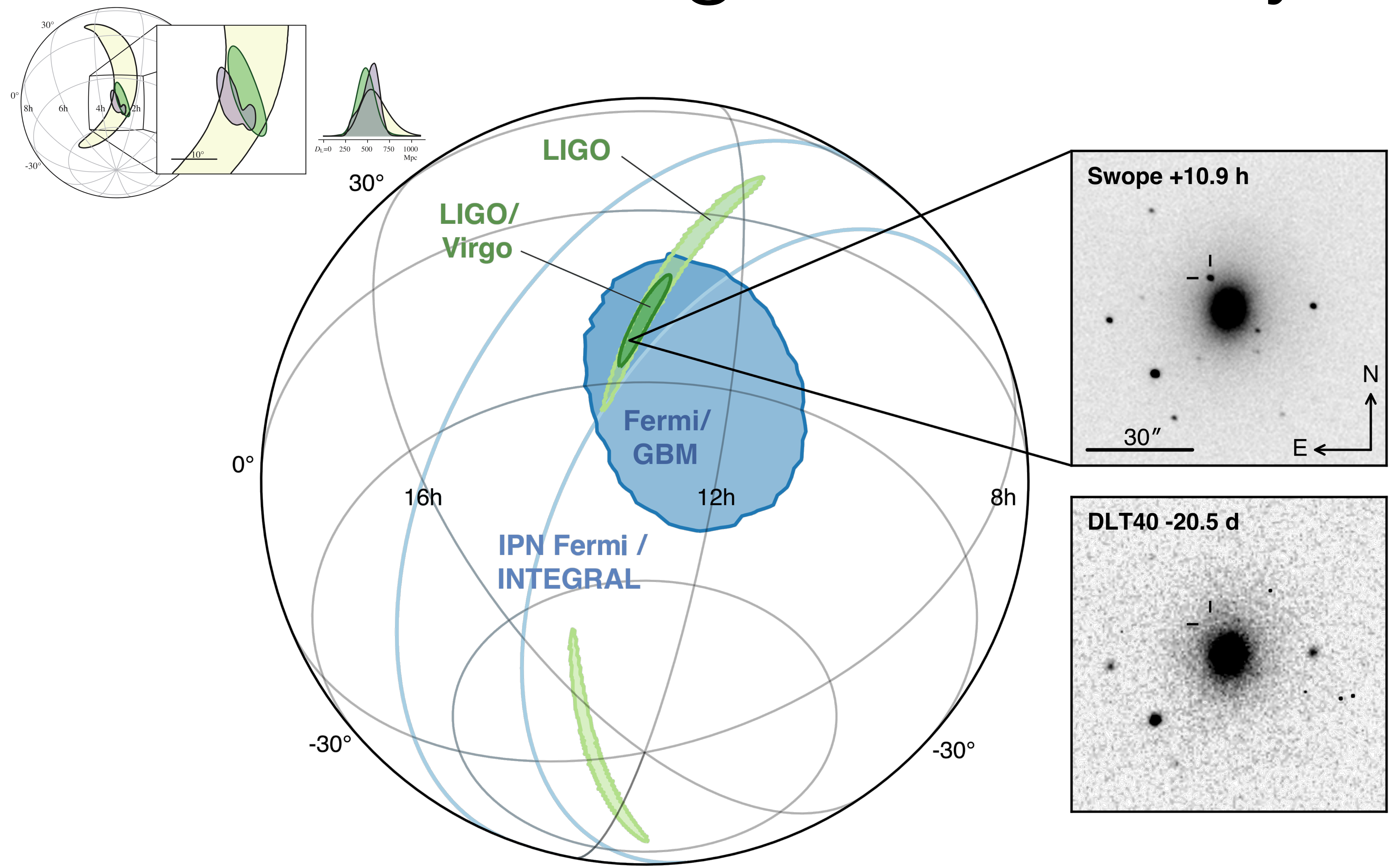


Motivations for the network of GW detectors

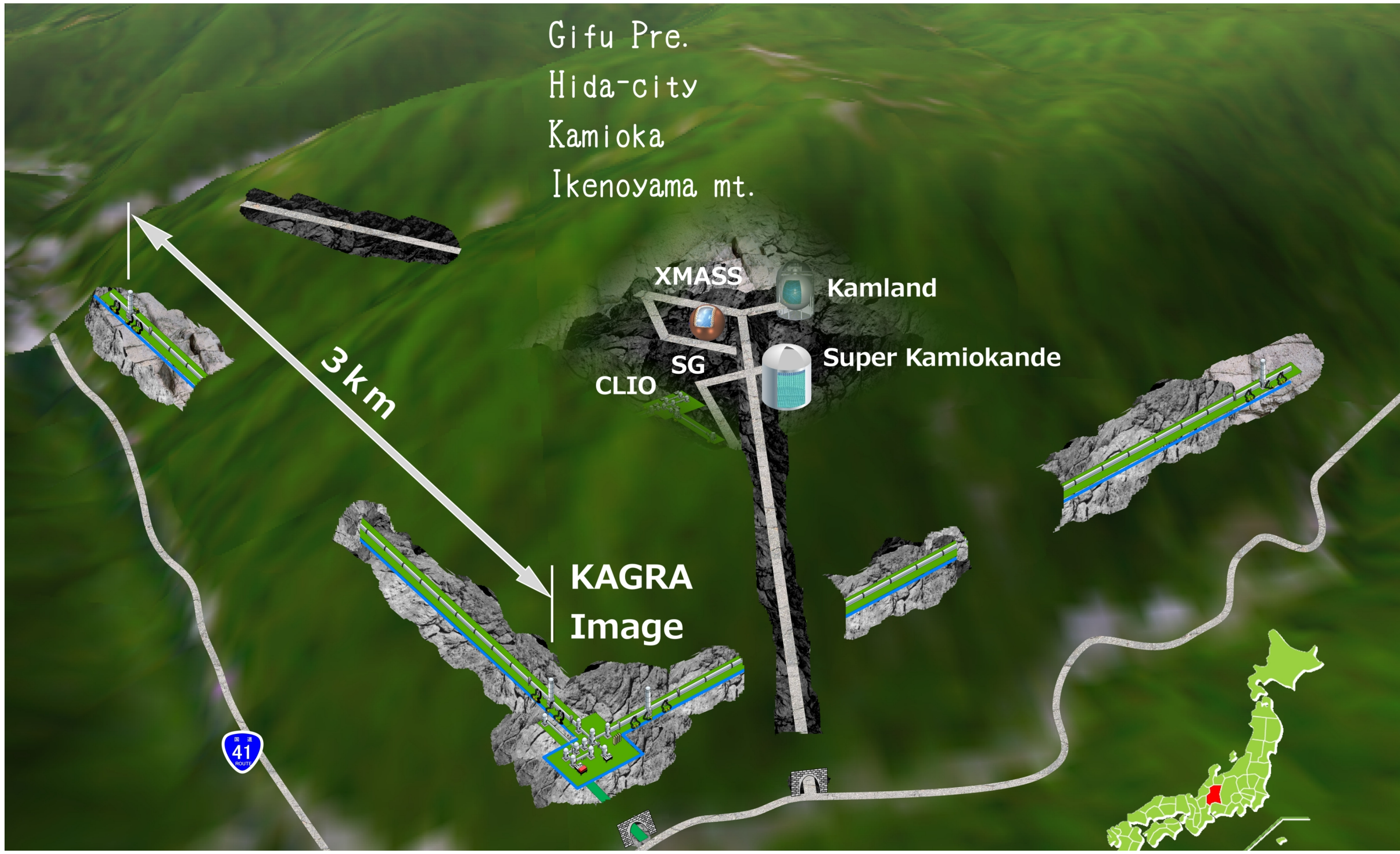


Yellow = LIGO (Livingston + Hanford)
Green = LIGO + VIRGO
Purple = Full Bayesian Localization

Multi-messenger Astronomy



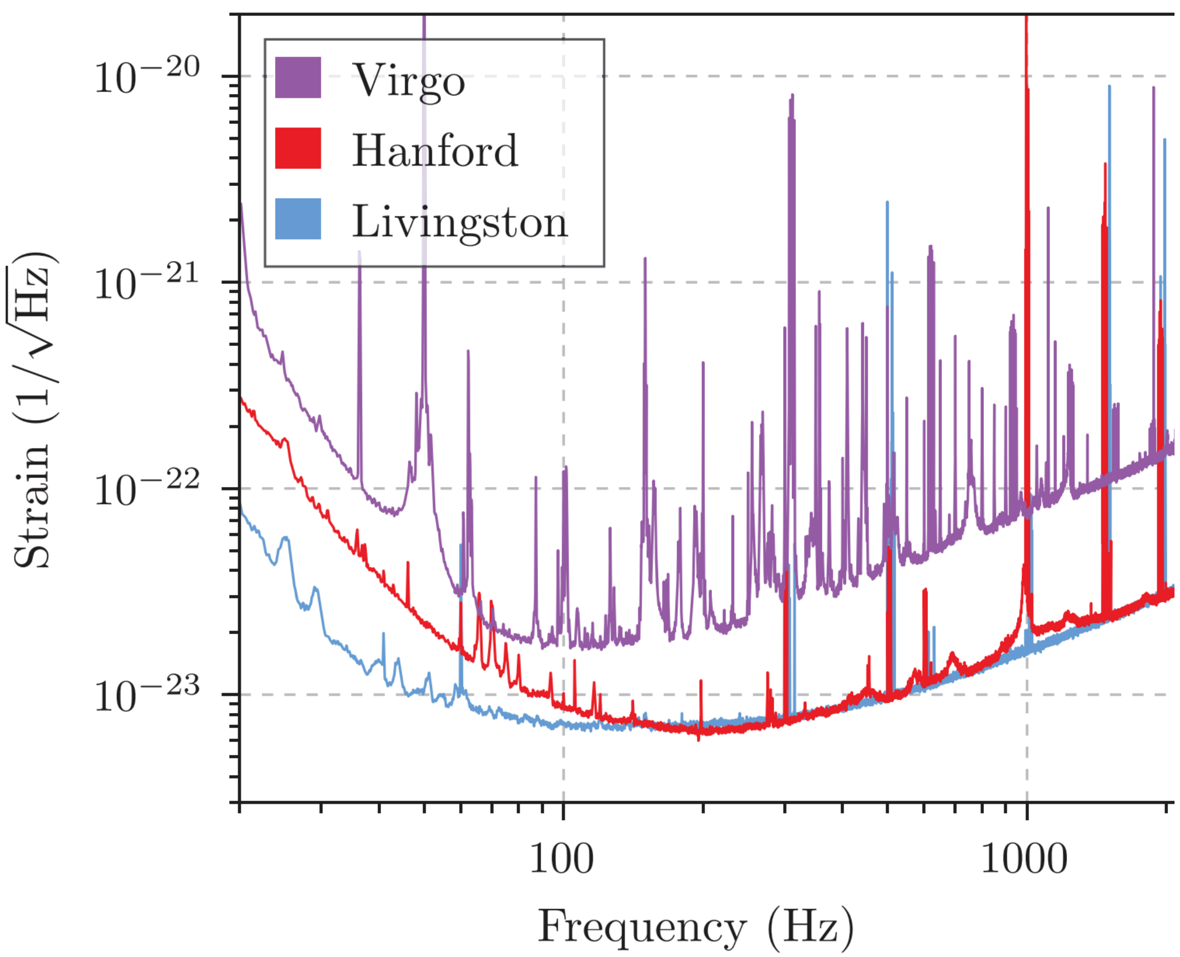
Introduction to KAGRA



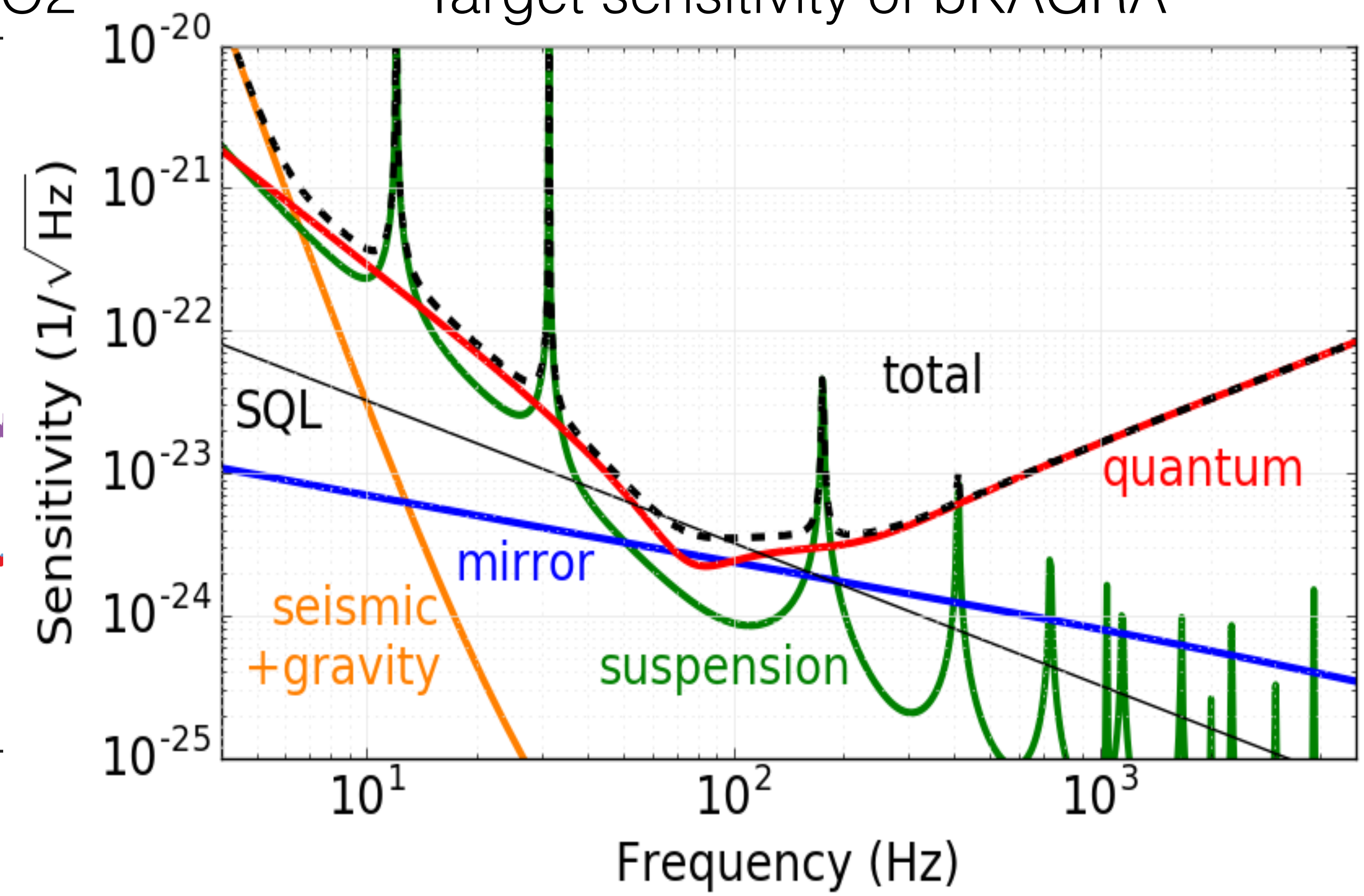
- 3km Arm Length
- Gifu Prefecture, Japan
- Underground, 1km from the mountain top
- Cryogenic (Very low temperatures)

What's so special about KAGRA?

LIGO, VIRGO Sensitivity Curve from O2



Target sensitivity of bKAGRA



Limitations: Seismic Noise in ~10e02 [Hz], Shot Noise in 10e03~ [Hz]

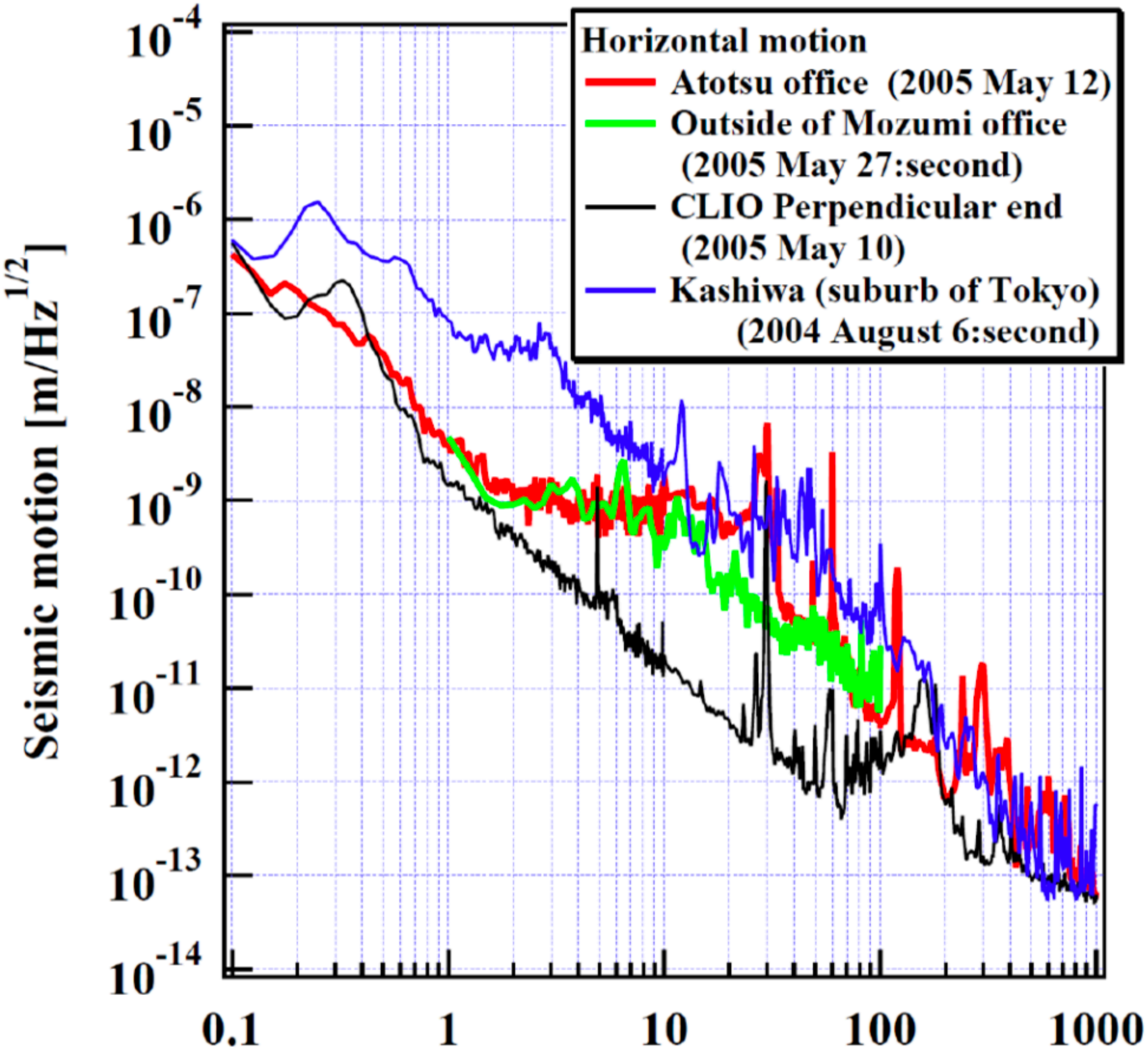
KAGRA is different from LIGO and VIRGO because it is:

Underground and **Cryogenic**

which means, KAGRA reduces 2 important sources of noise:

Seismic Noise and Thermal Noise

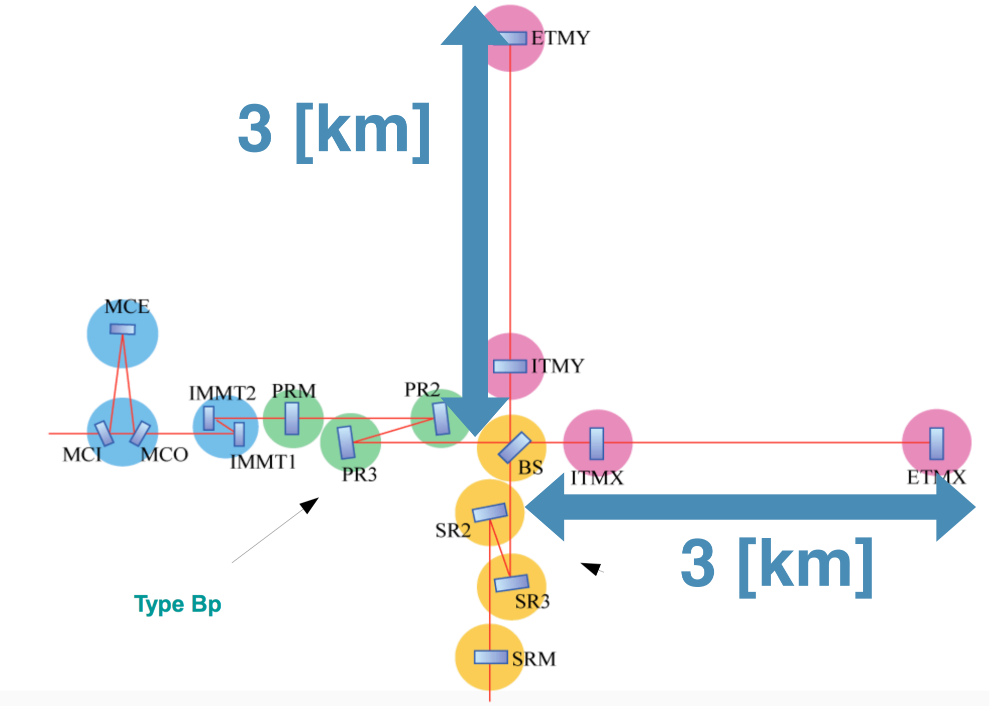
VIS (Vibration Isolation System)



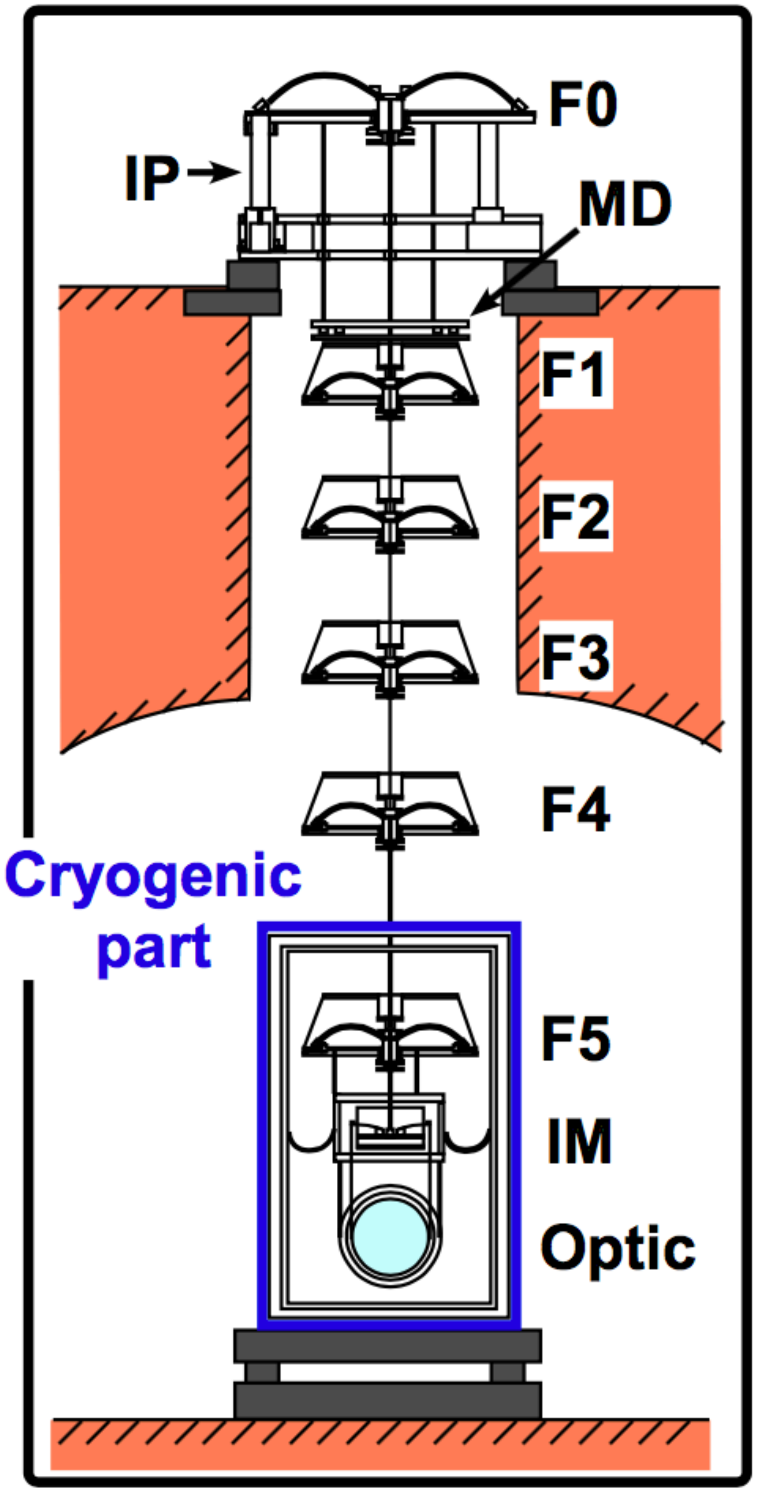
Implementation of the Vibration Isolation System:

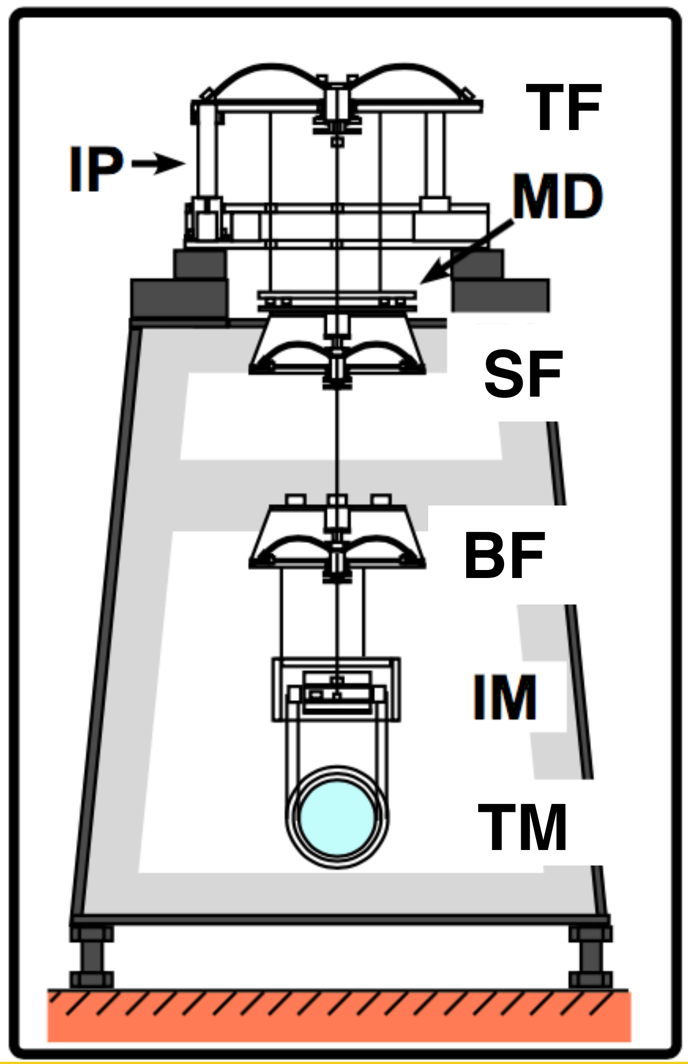
- Free-falling TM (Test Mass)
- Isolation from Seismic Noise

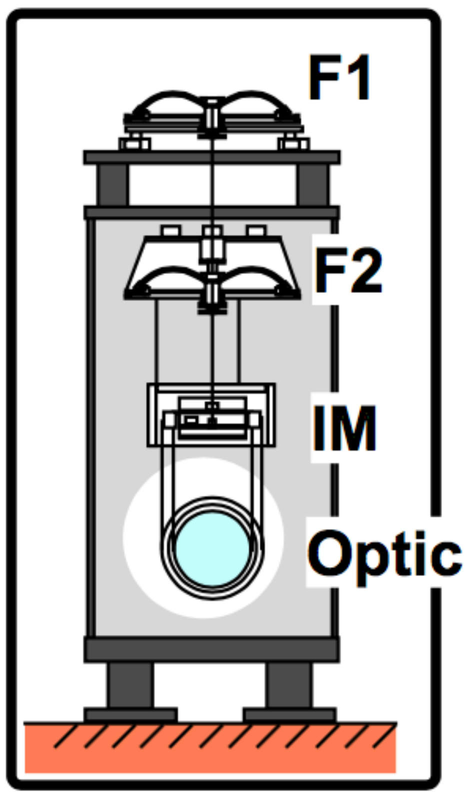
Usage of Different VIS Suspension Systems

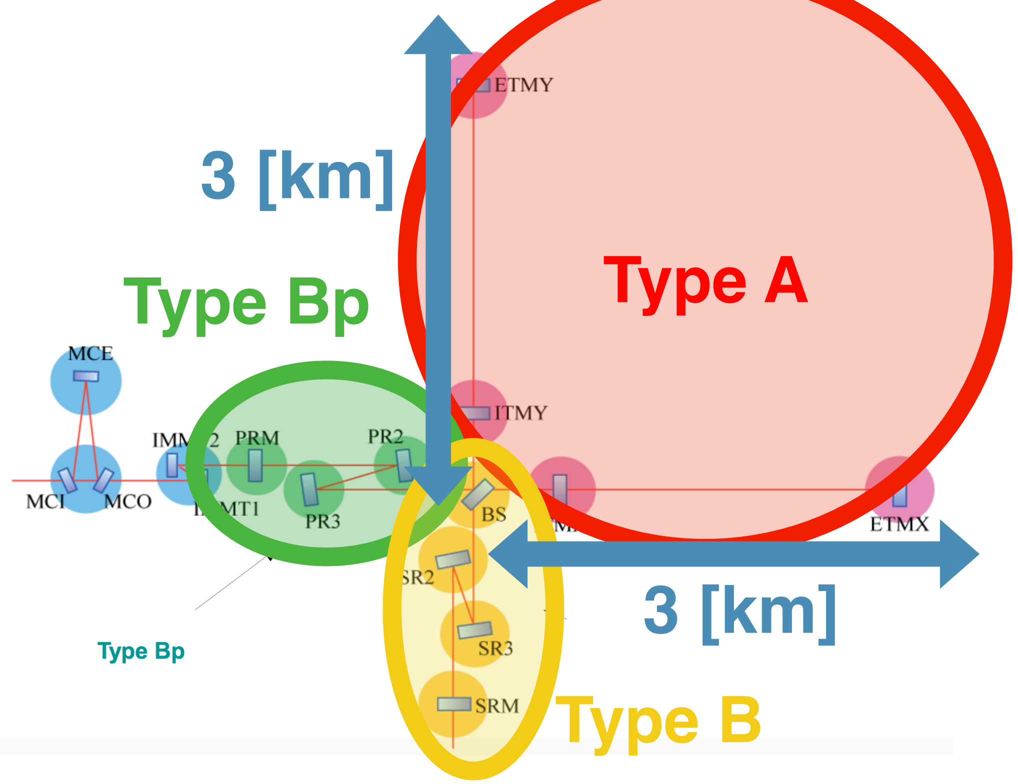


Usage of Different VIS Suspension Systems









Structure of Type-B Suspension System

3.1 [m]

Top Filter (TF)

Inverted Pendulum (IP)

Magnetic Damper (MD)

Standard Filter (SF)

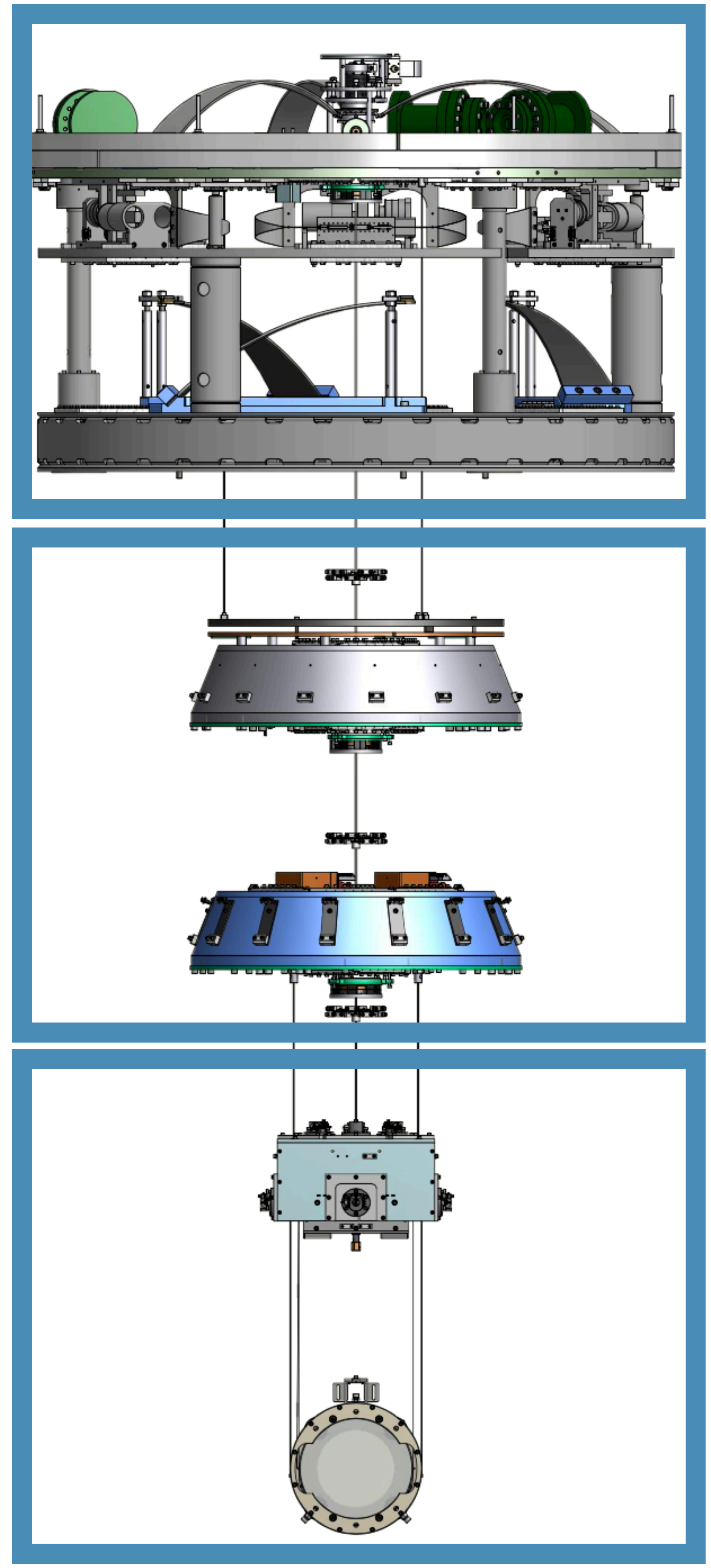
Bottom Filter (BF)

Intermediate Mass (IM)

Intermediate Recoil Mass (IRM)

Test Mass (TM)

Recoil Mass (RM)



Pre-Isolator (PI)

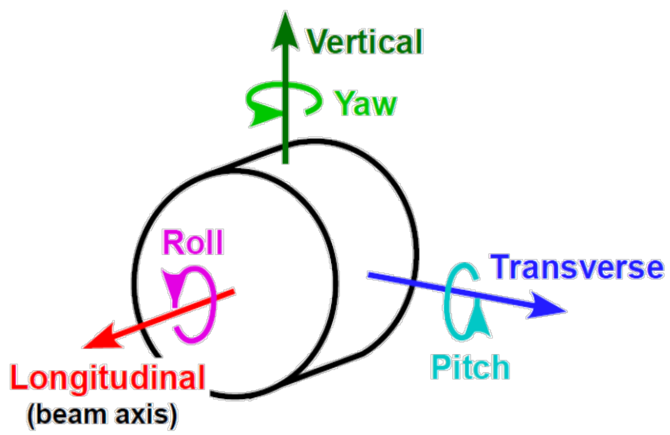
GAS Filter (Geometric Anti-Spring)

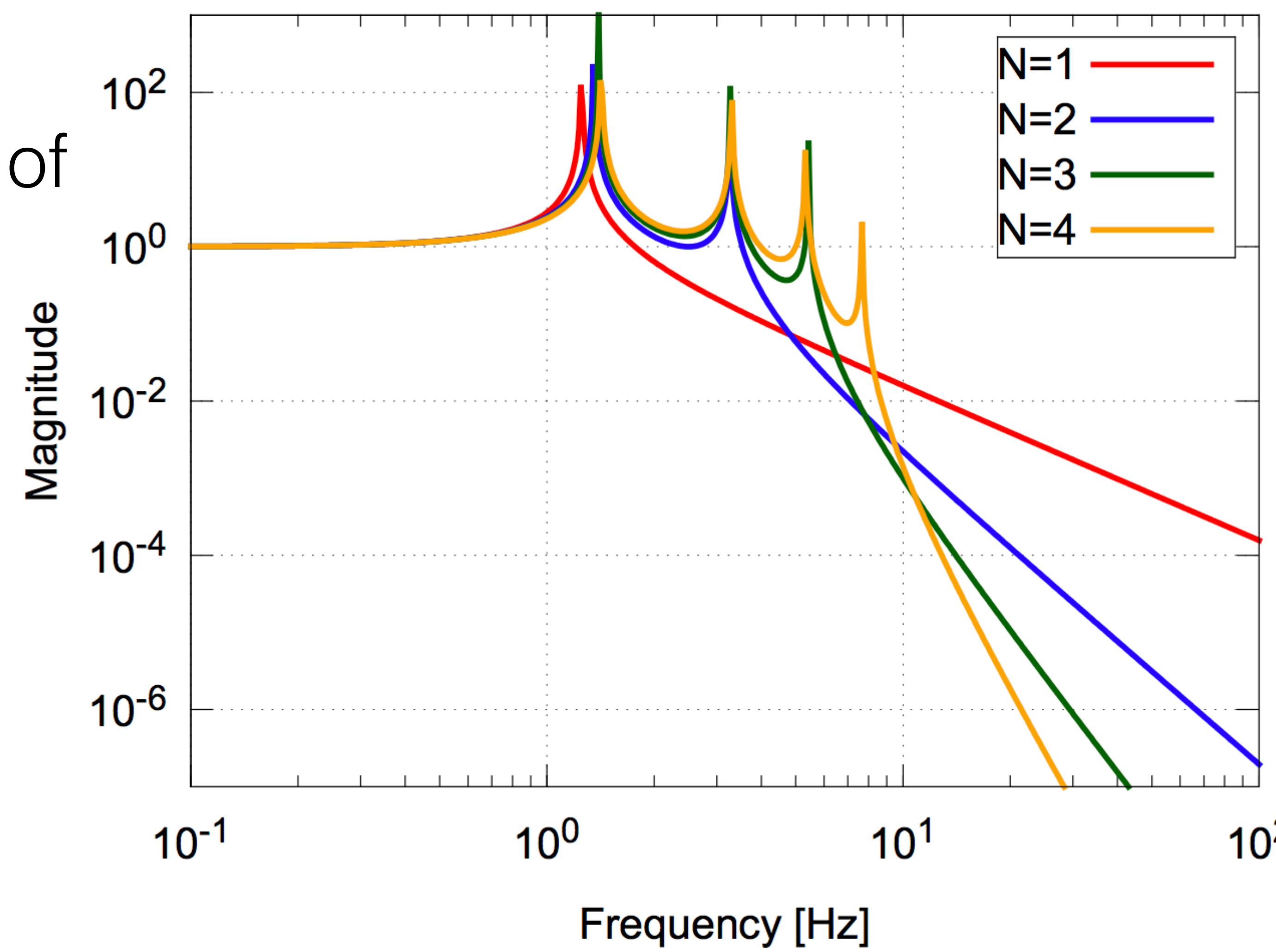
Payload

Structure of Type-B Suspension System

Suspension systems oscillate at resonance frequency.

- Torsion mode of the chain produces large yaw motion of the suspended Mirror.

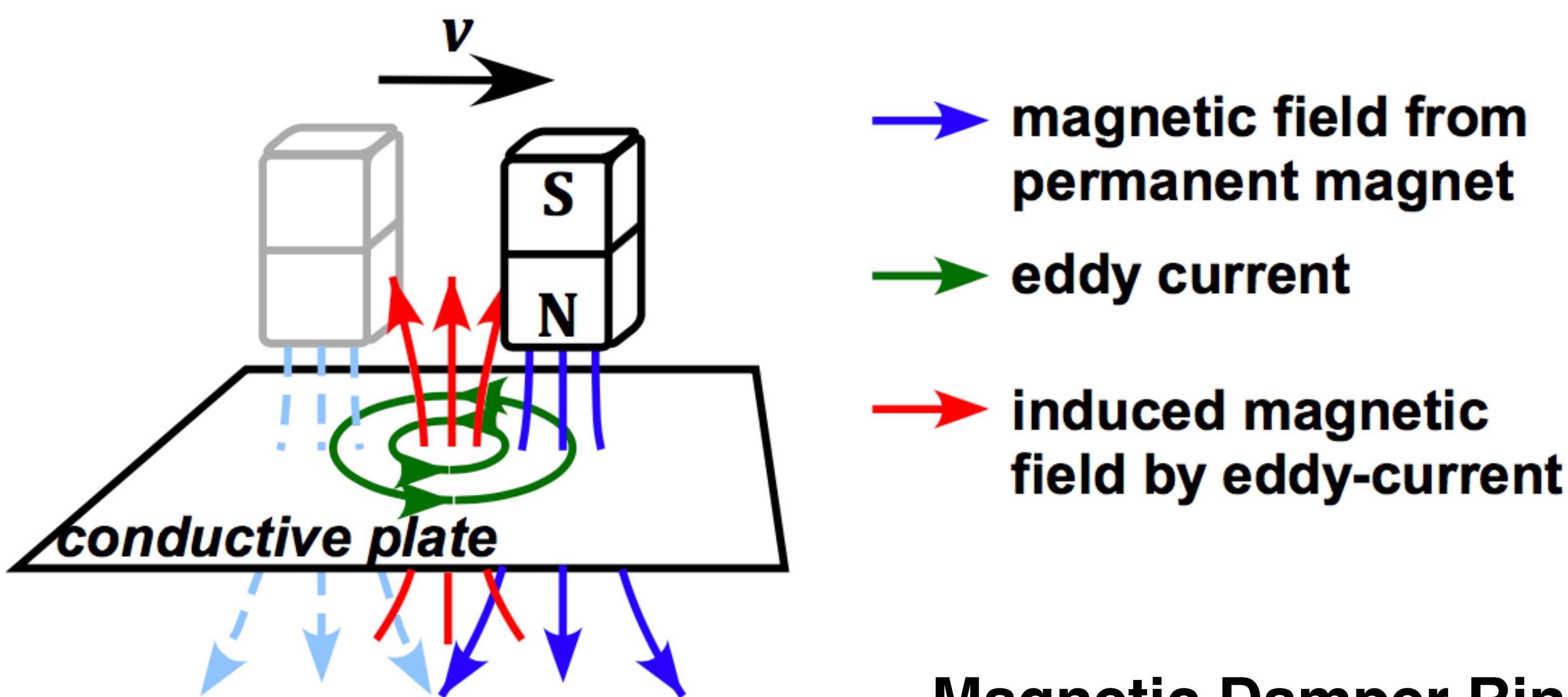


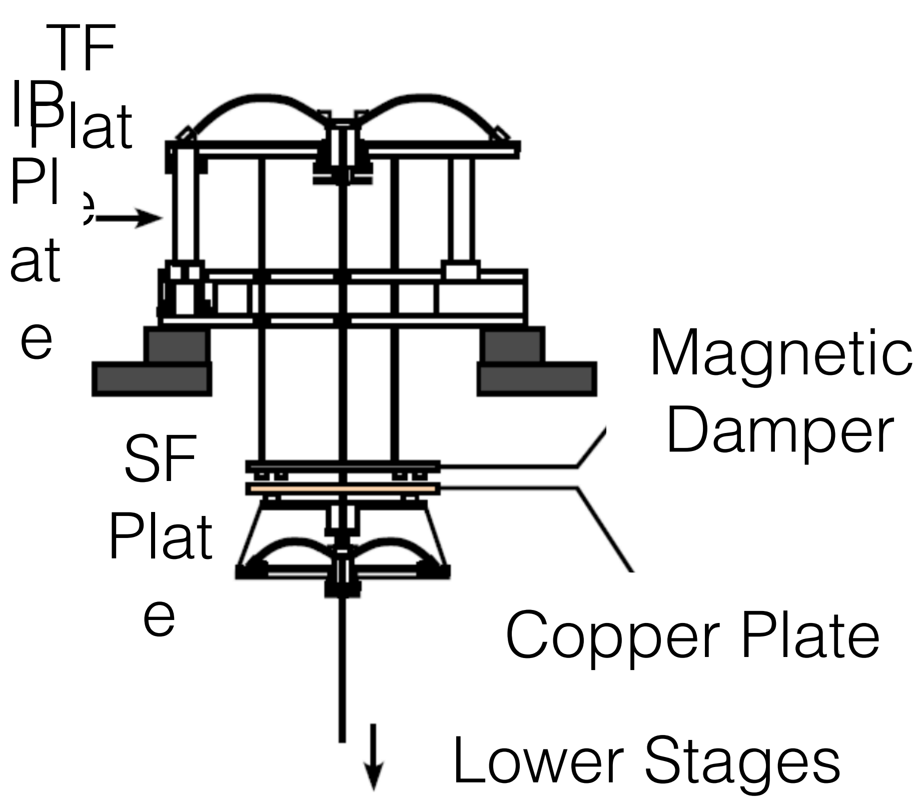


Magnetic Dampers (MD) are the key to success!

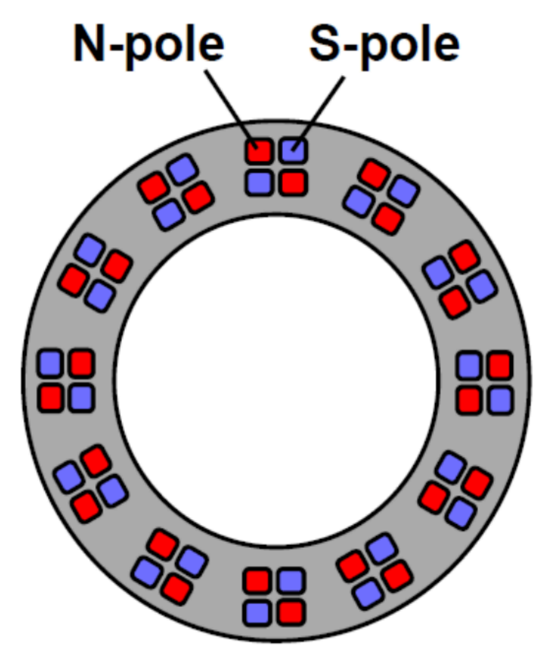
One of the most difficult tasks…

Eddy Current Damping Filter

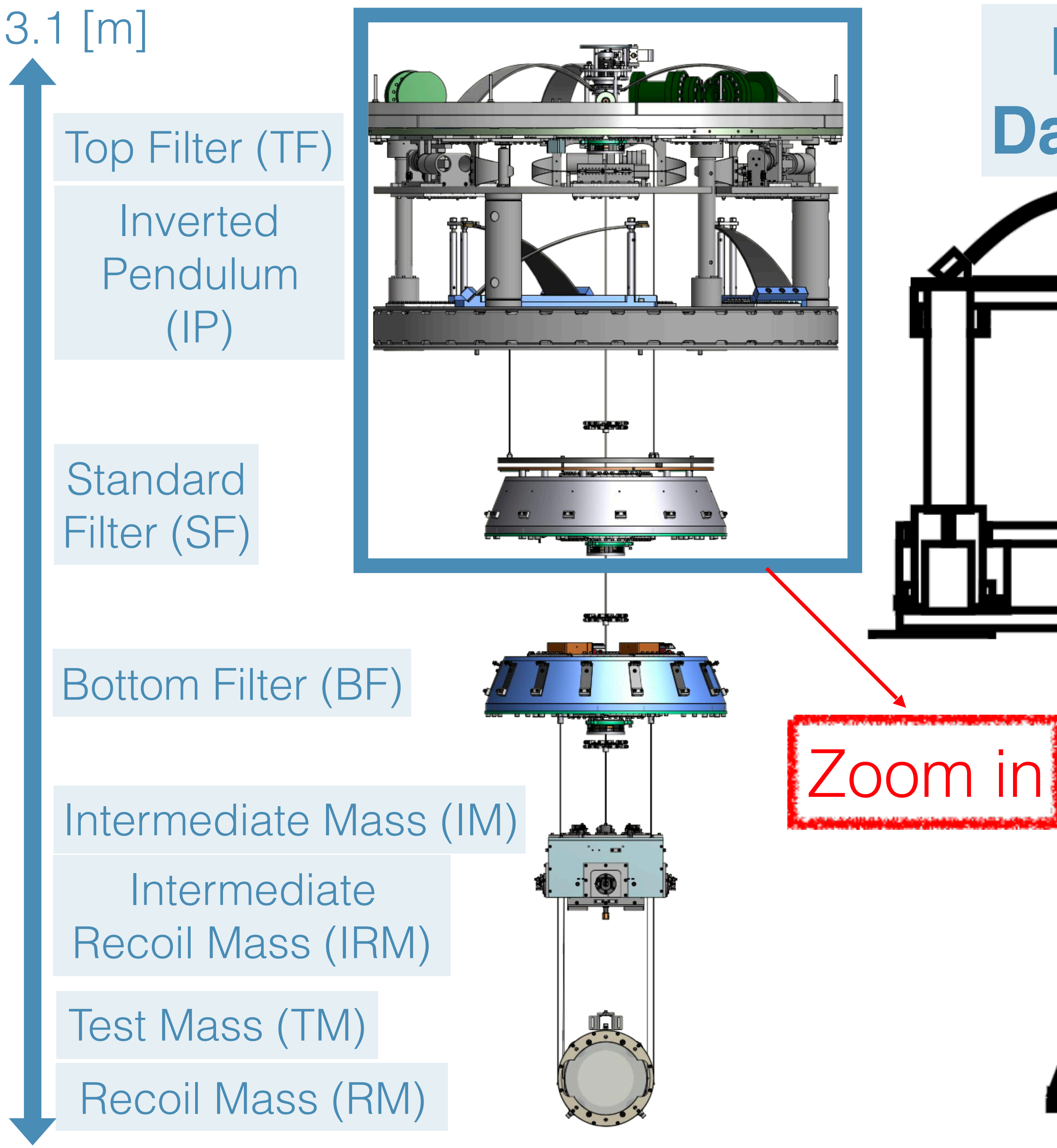




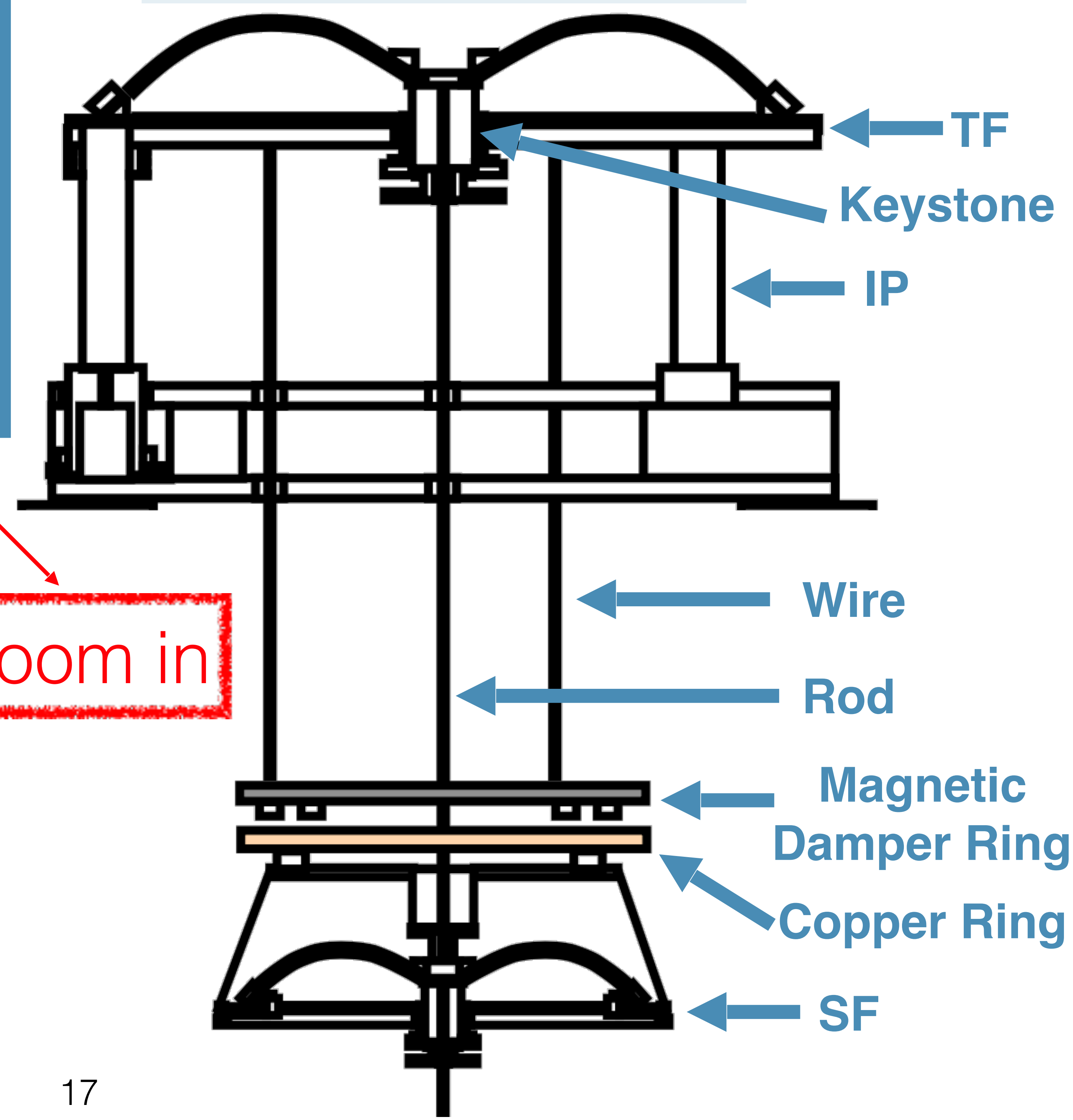
Magnetic Damper Ring



Structure of Type-B Suspension System



Eddy Current Damping System



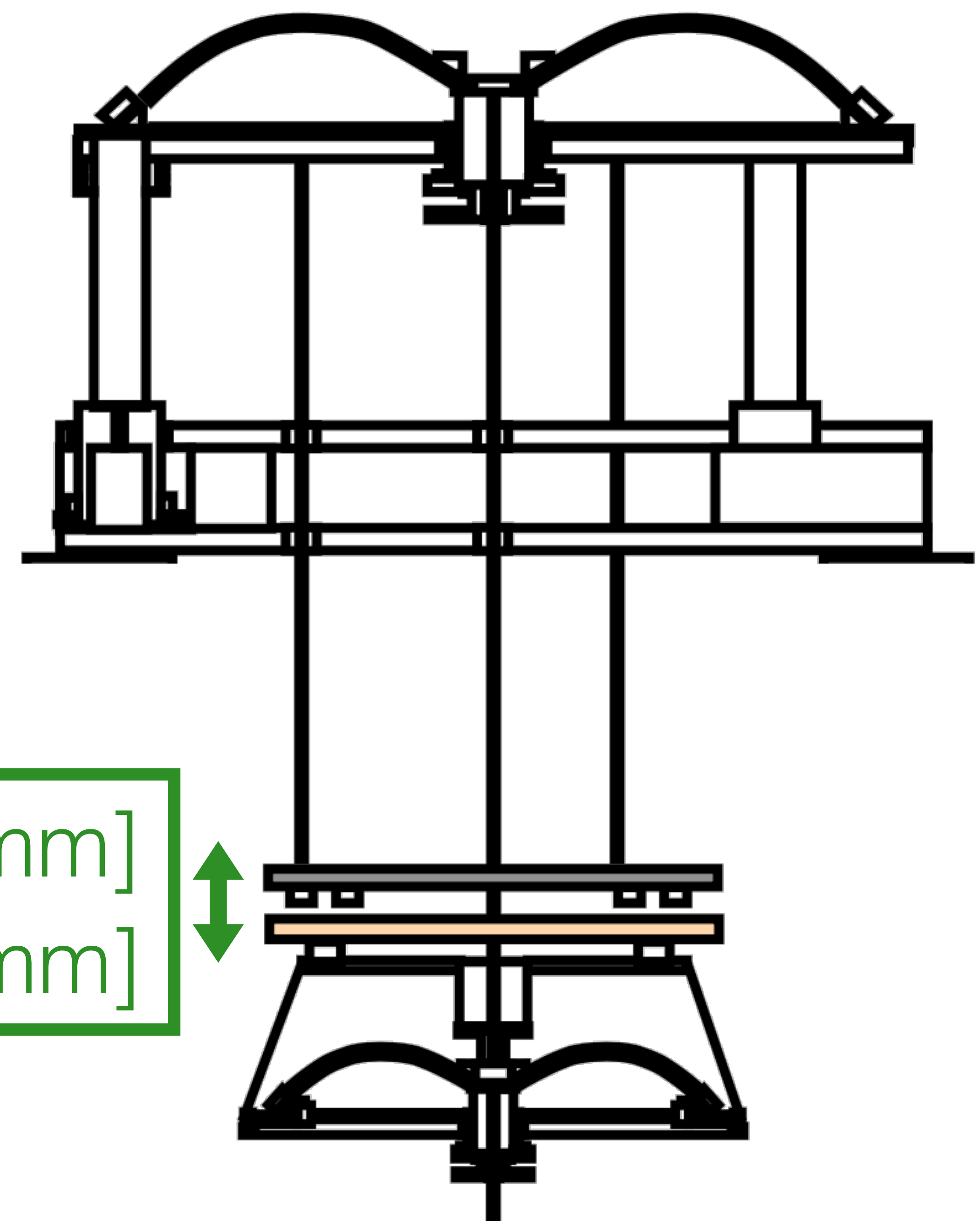
Objectives

Main Objective: Efficient Damping

- Distance too small ⟹ Contribution of seismic noise
- Distance too large ⟹ Amount of damping not sufficient

Goal:

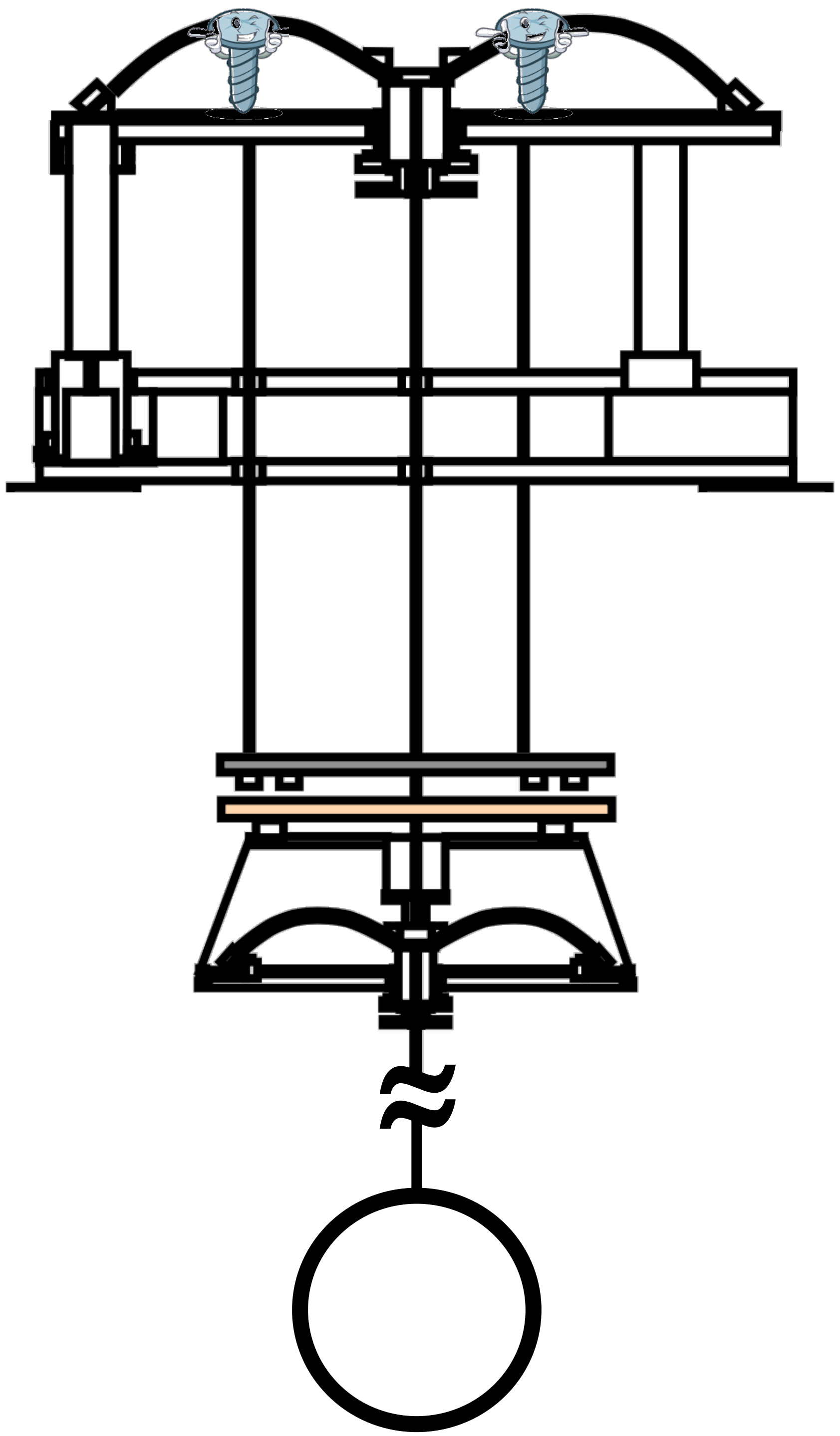
Best distance between MD and Cu Ring???



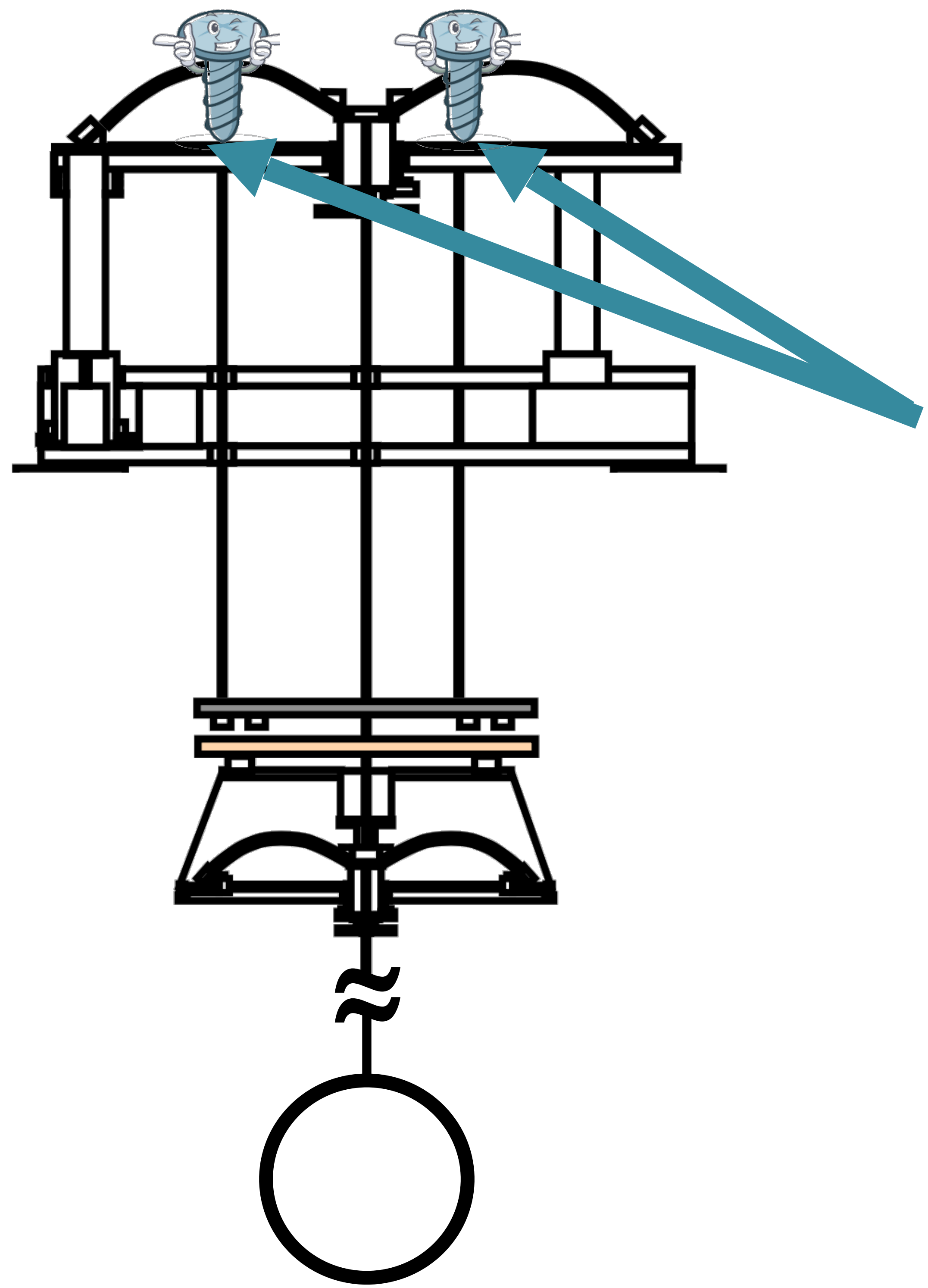
Nominal position ≡ 0 [mm] when distance is 3.5 [mm]

KAGRA

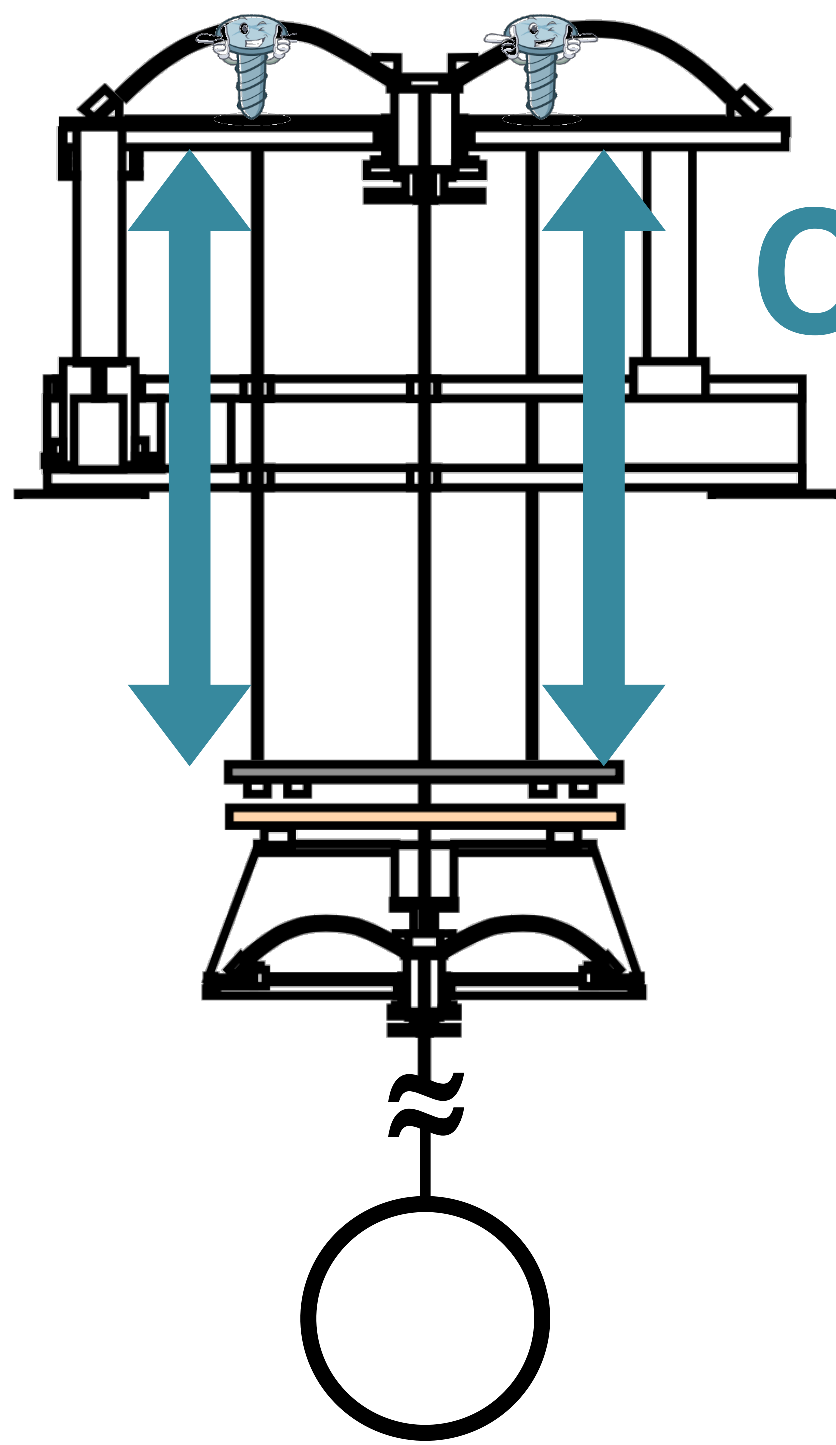
Procedures for obtaining measurements



Procedures for obtaining measurements

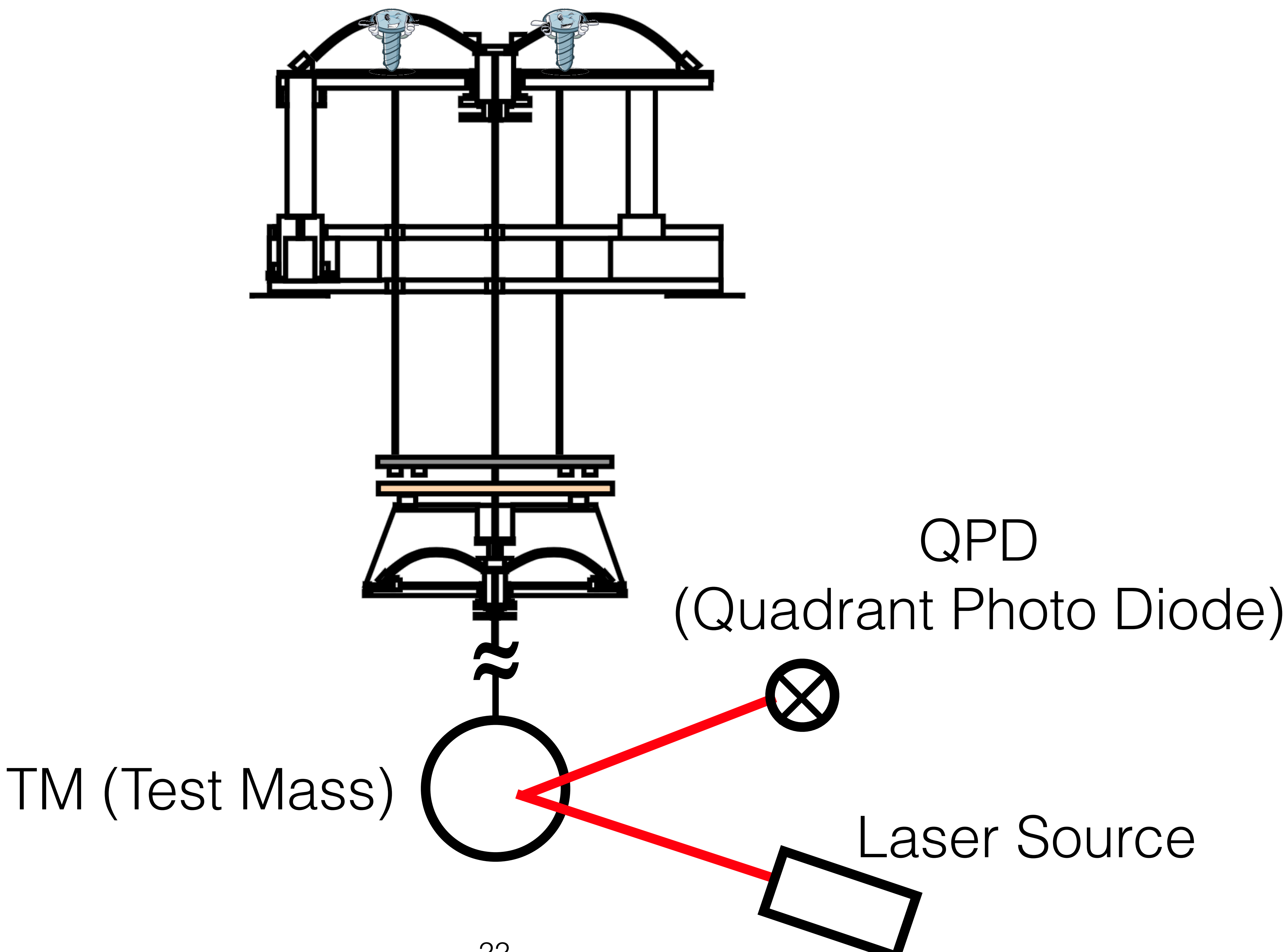


Procedures for obtaining measurements

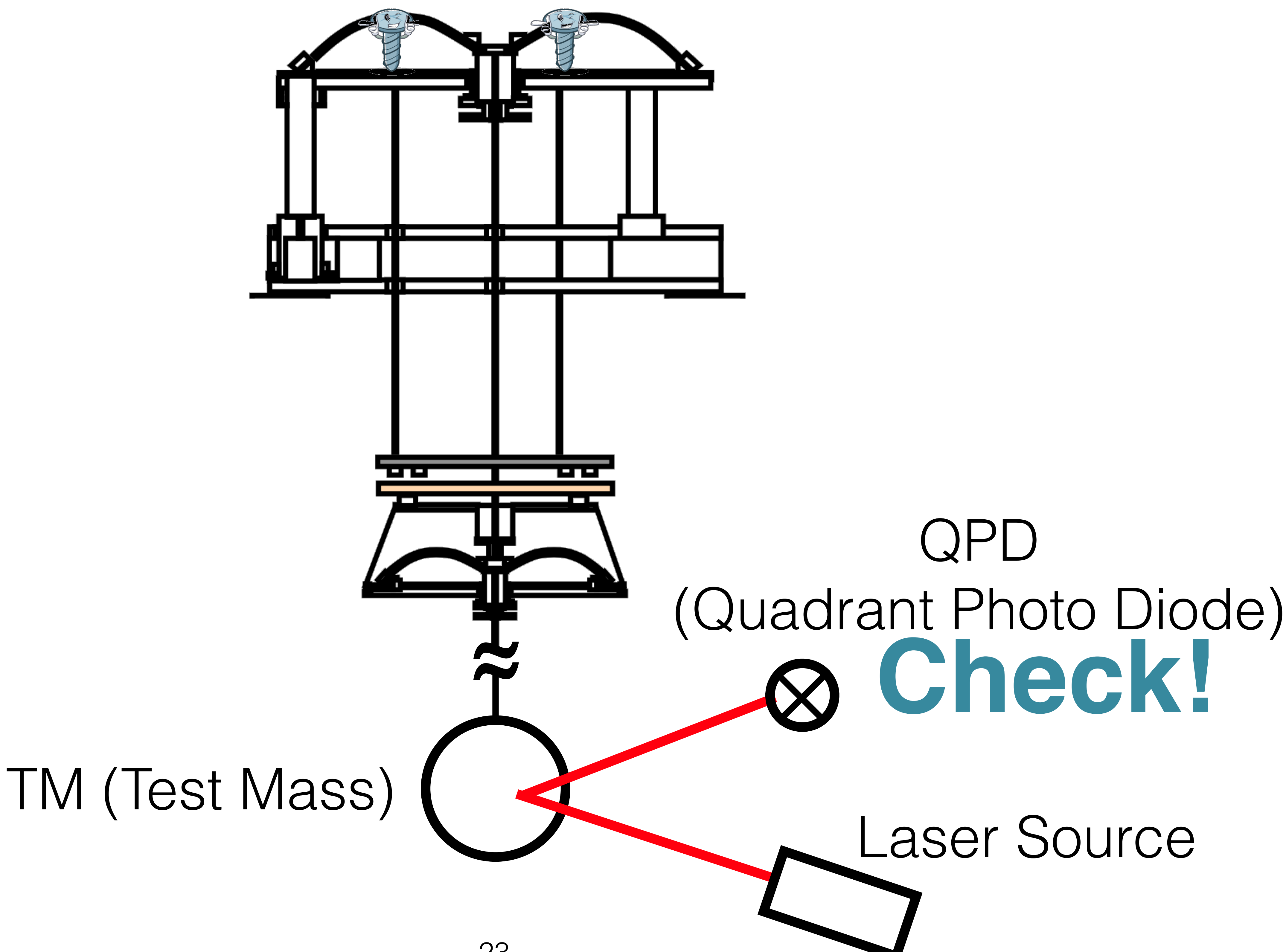


Change this distance

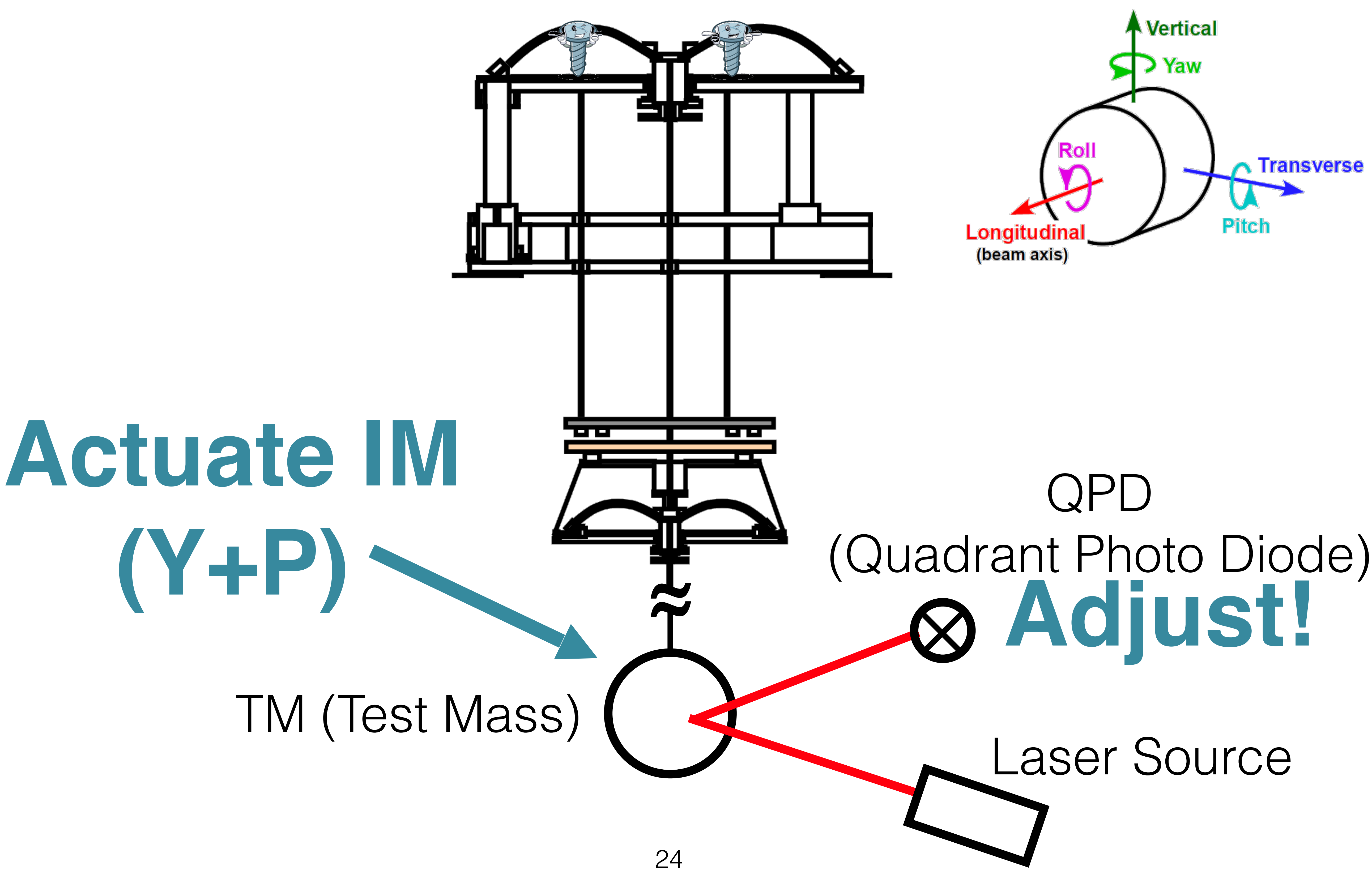
Procedures for obtaining measurements



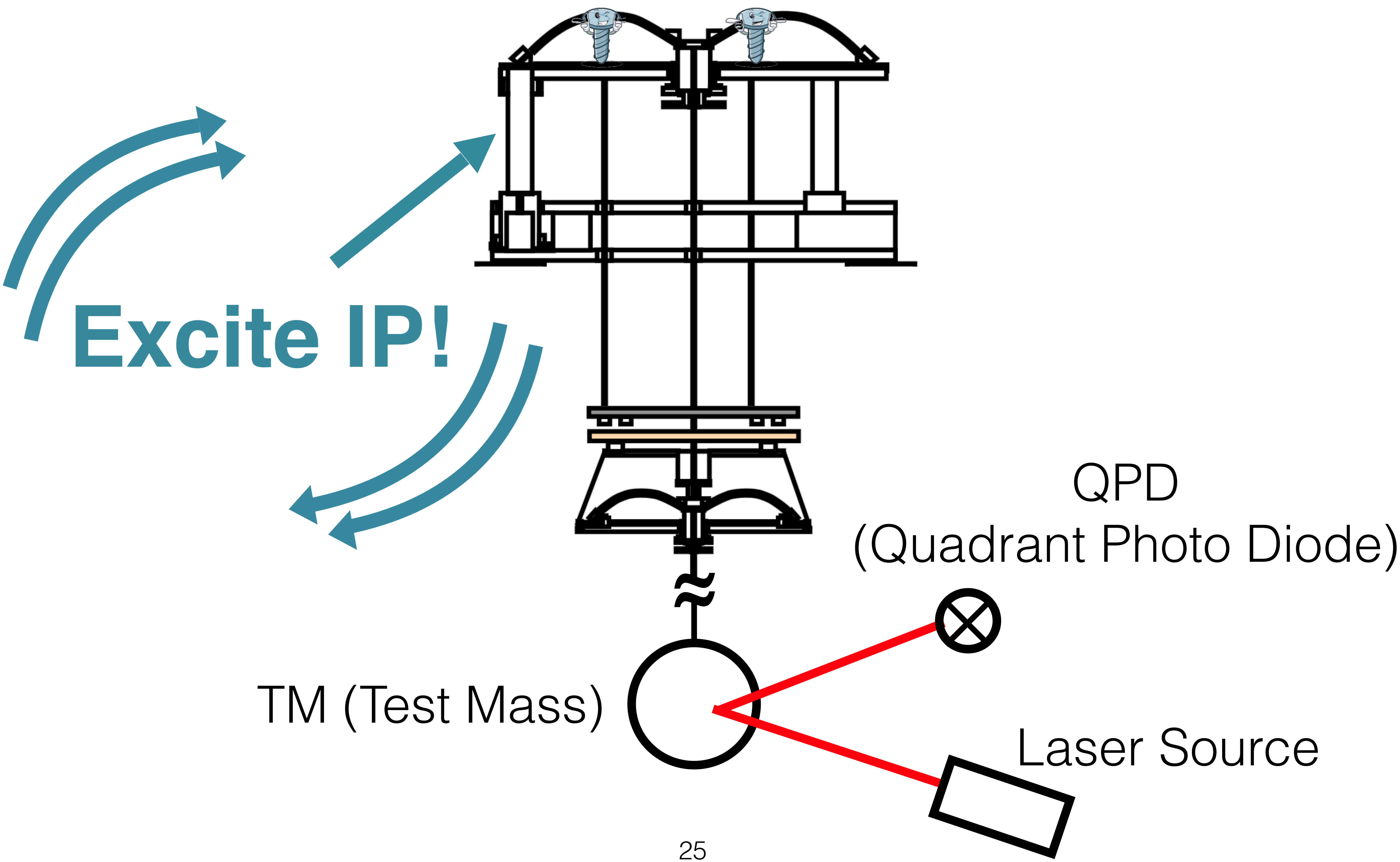
Procedures for obtaining measurements



Procedures for obtaining measurements

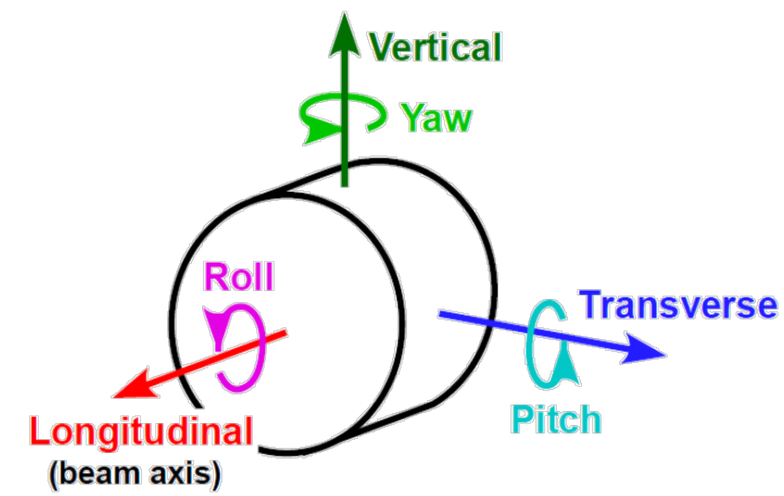


Procedures for obtaining measurements

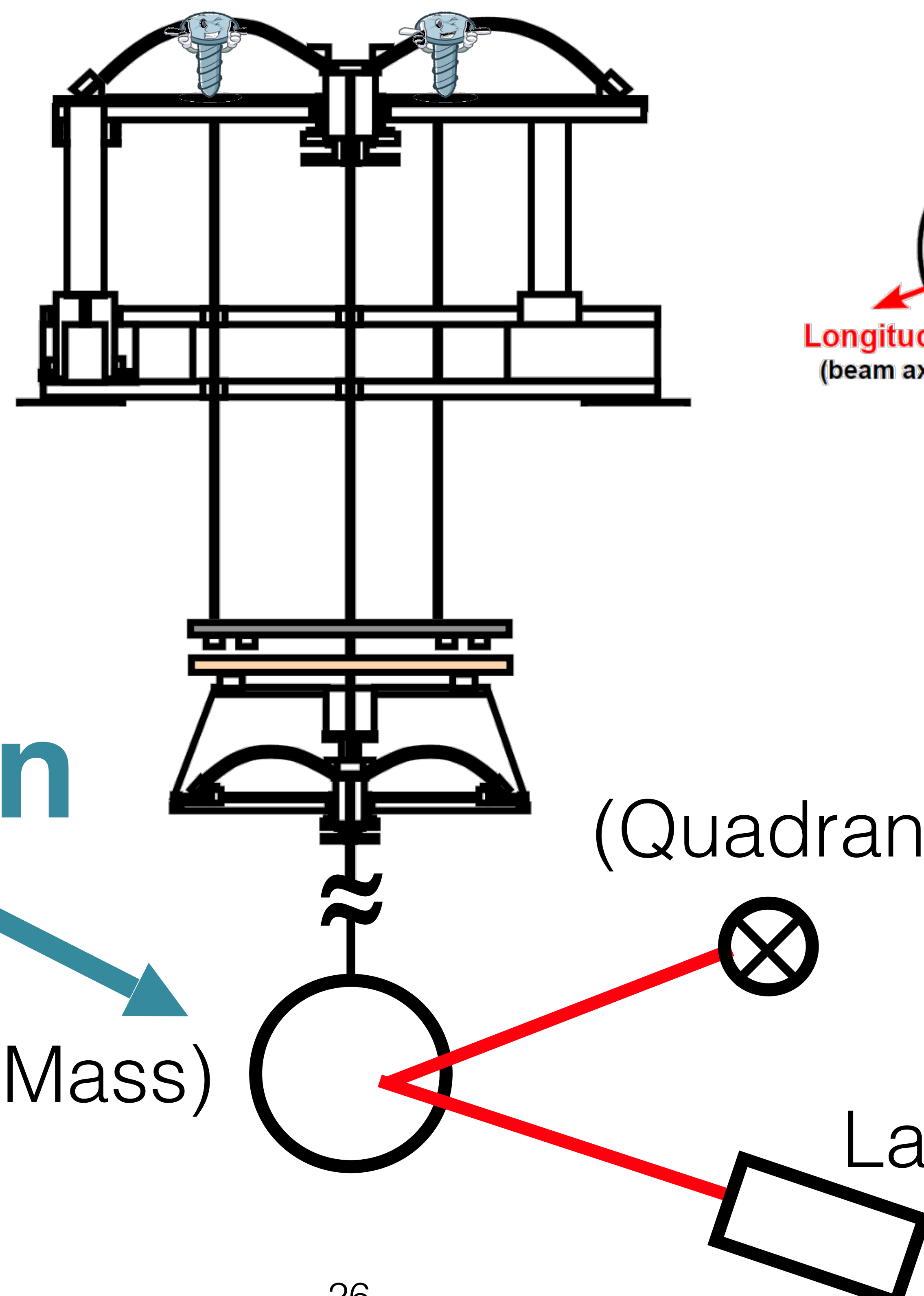


KAGRA

Procedures for obtaining measurements

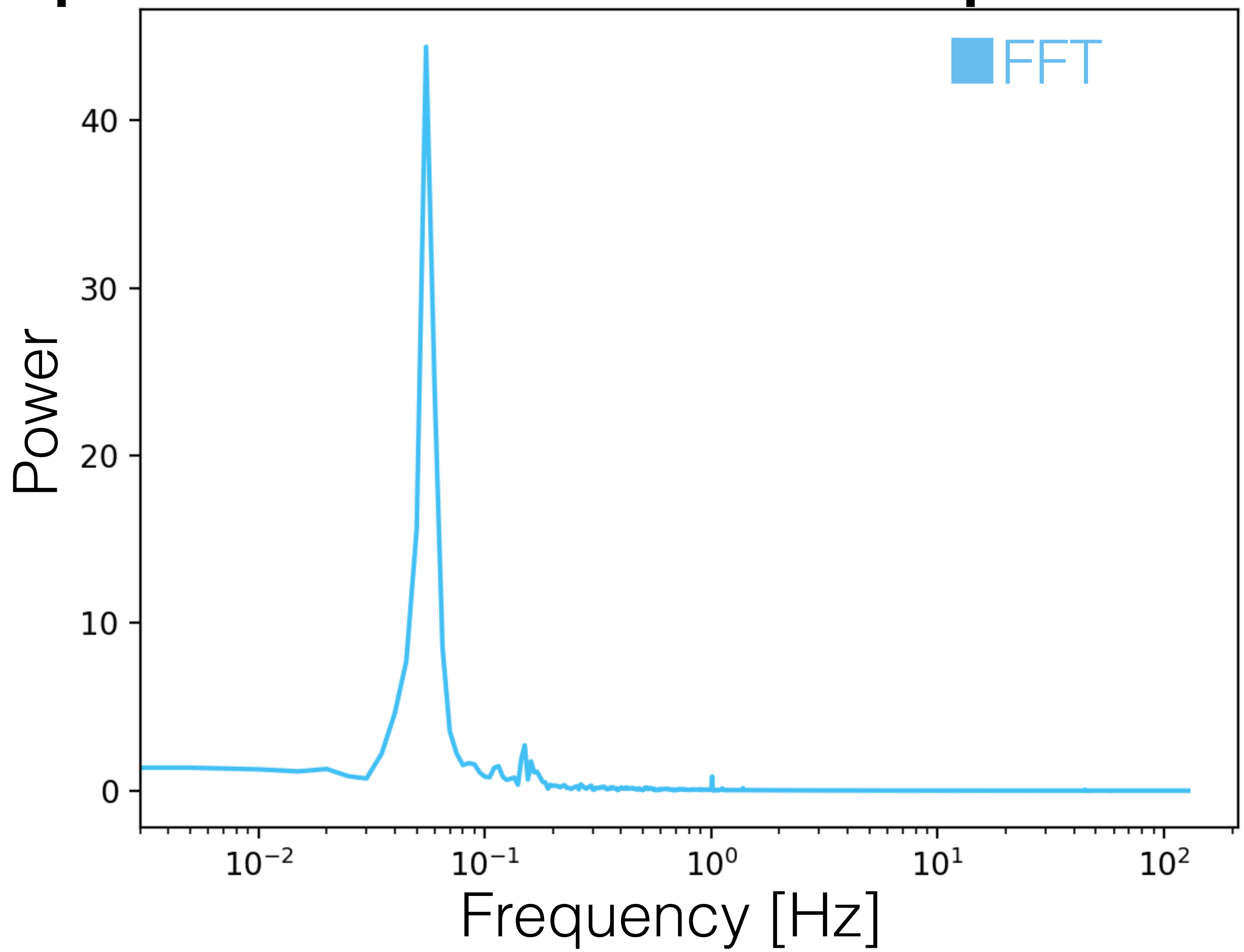


Observe Yaw Motion



Procedures for Data Analysis

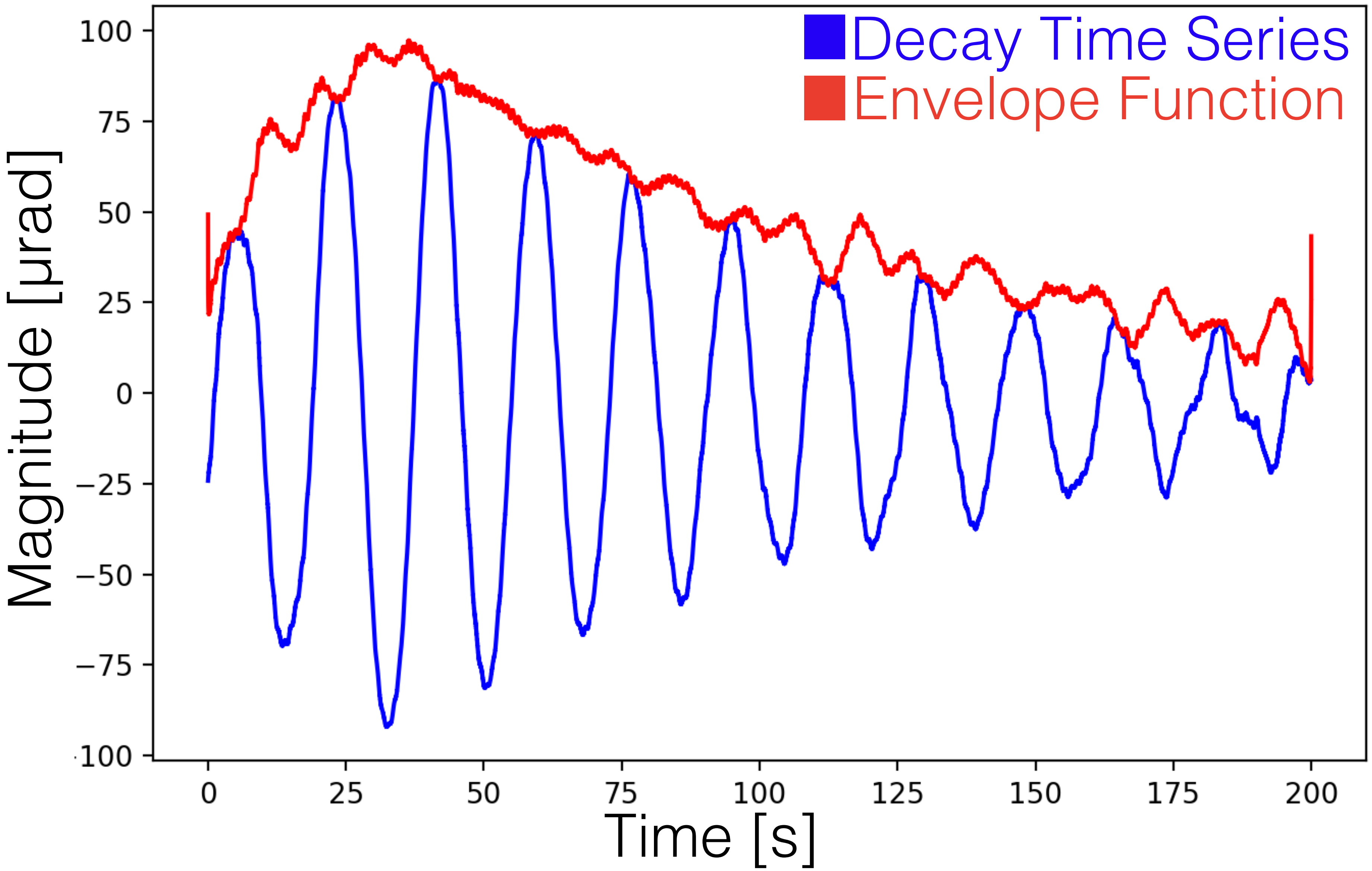
Fast Fourier Transformation of decay time series when displacement of MD from nominal position is 5 [mm]



1. Estimate resonance frequency of the Torsion mode of the system.

Procedures for Data Analysis

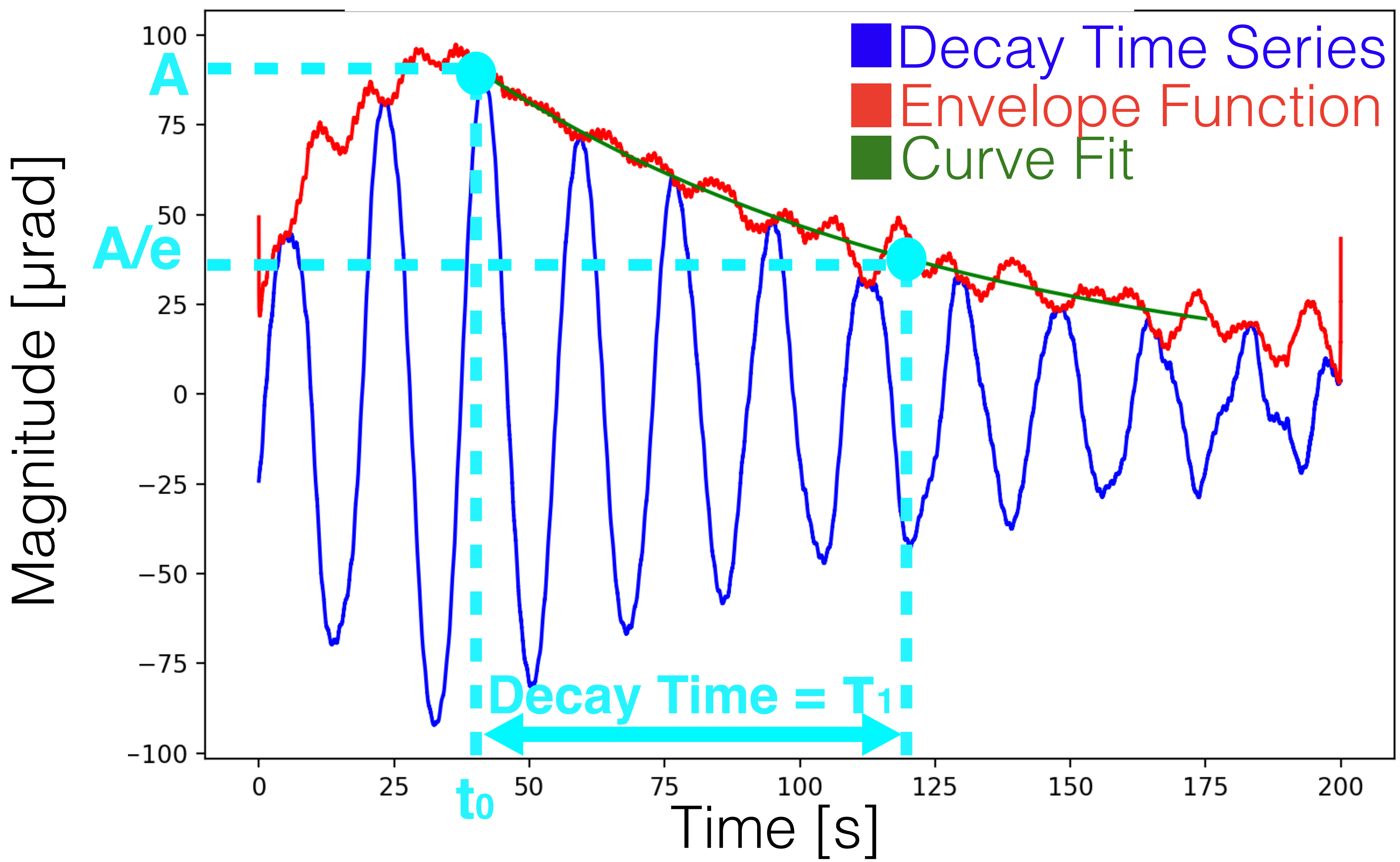
Decay Time Series when displacement of MD from nominal position is 5 [mm]



2. Obtain “Envelope Function” using Hilbert Transformation.

Procedures for Data Analysis

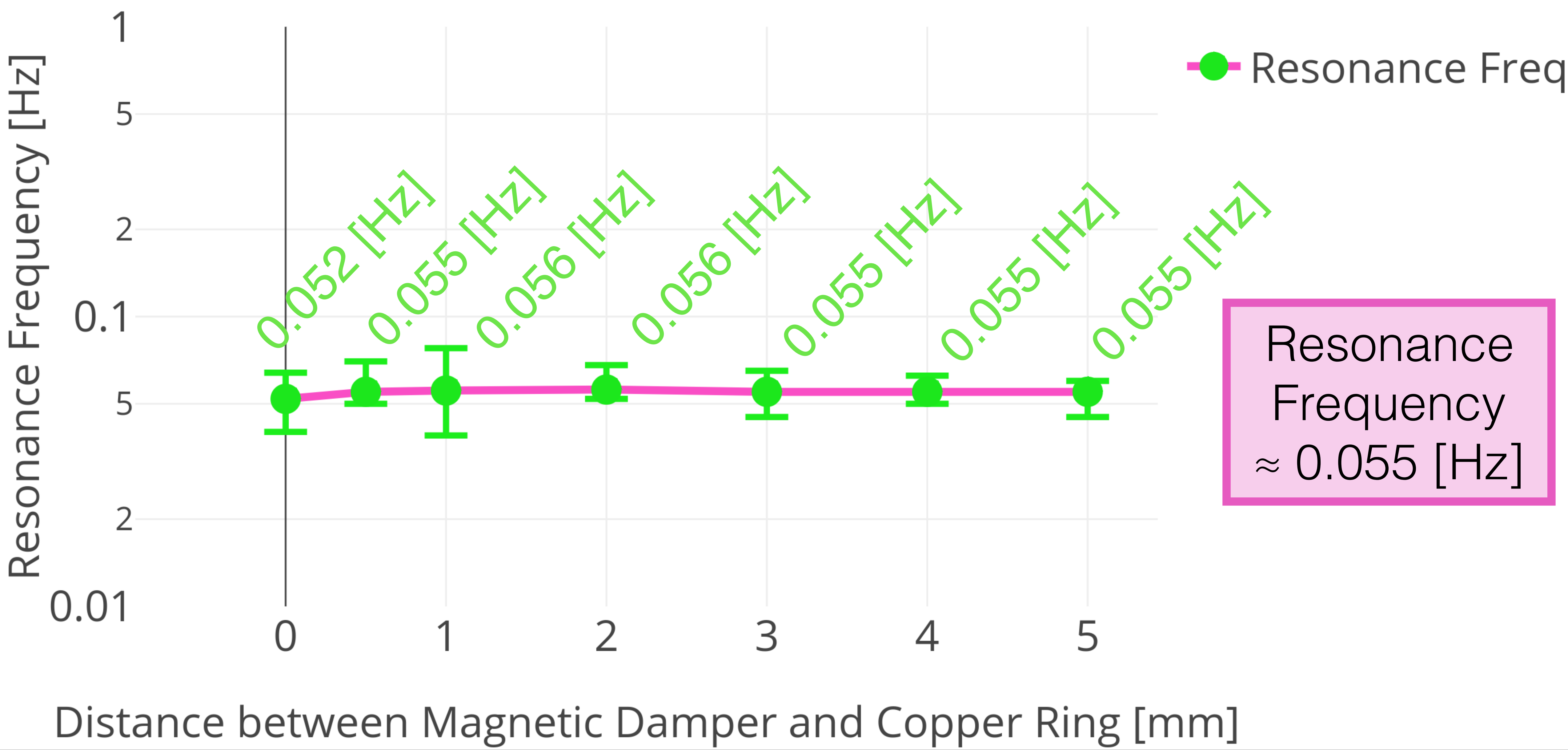
Decay Time Series when displacement of MD from nominal position is 5 [mm]



3. Find decay time (τ_1) from curve fit: $y = Ae^{-(t-t_0)/\tau_1} + b$

Results

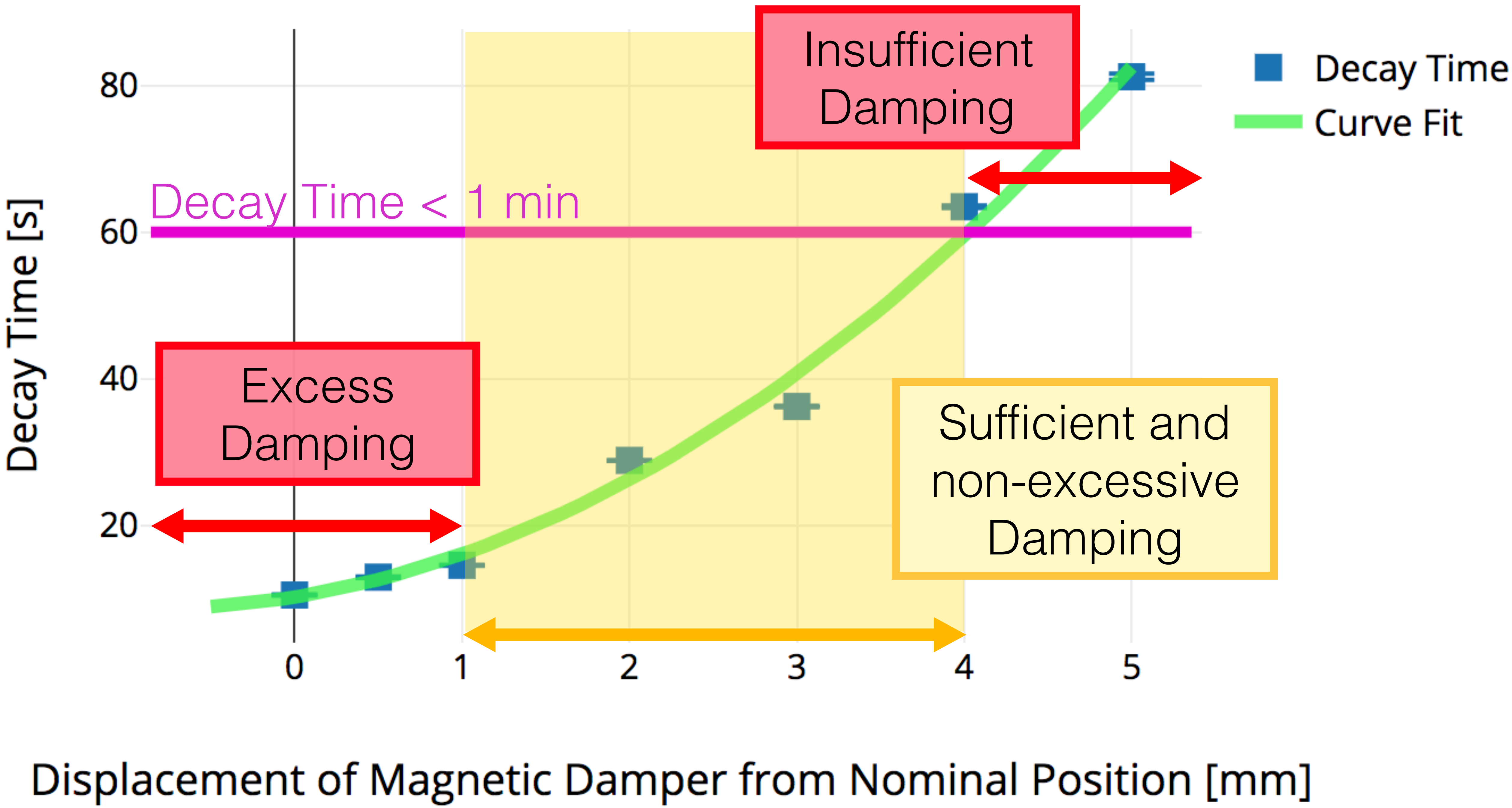
Resonance Frequency vs. Displacement between Magnetic Damper and Copper Plate



Resonance Frequency ≈ 0.055 [Hz]

Results

Decay Time vs. Displacement between Magnetic Damper and Copper Plate



Conclusion

- Sufficient and non-excessive damping occurs between 1.0~4.0 [mm].
- Want the shortest decay time possible.
- Damping excessively will affect the performance of the suspension to suppress the seismic noise.

→ Best tuning is to have the MD displaced from its nominal position by 2.5 [mm]

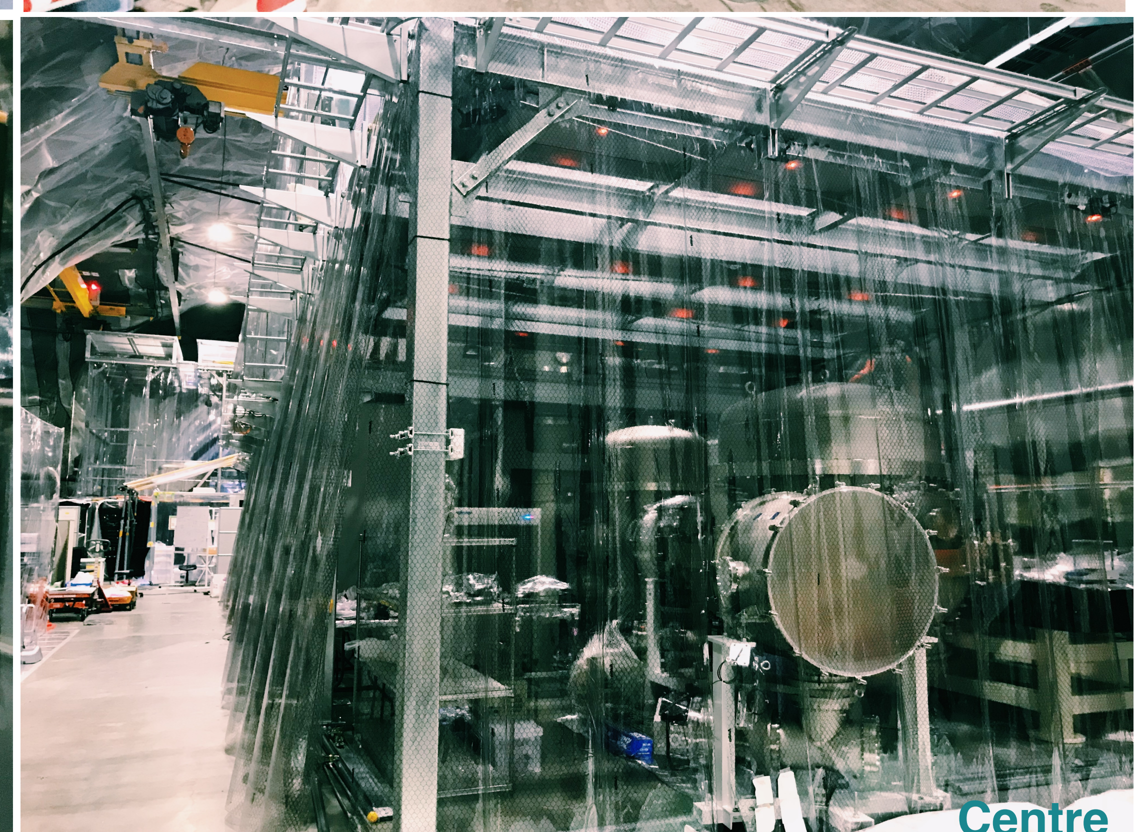
Life at KAGRA

Inside the Mine

Bicycles to get to the Centre

Cycling inside the Mine

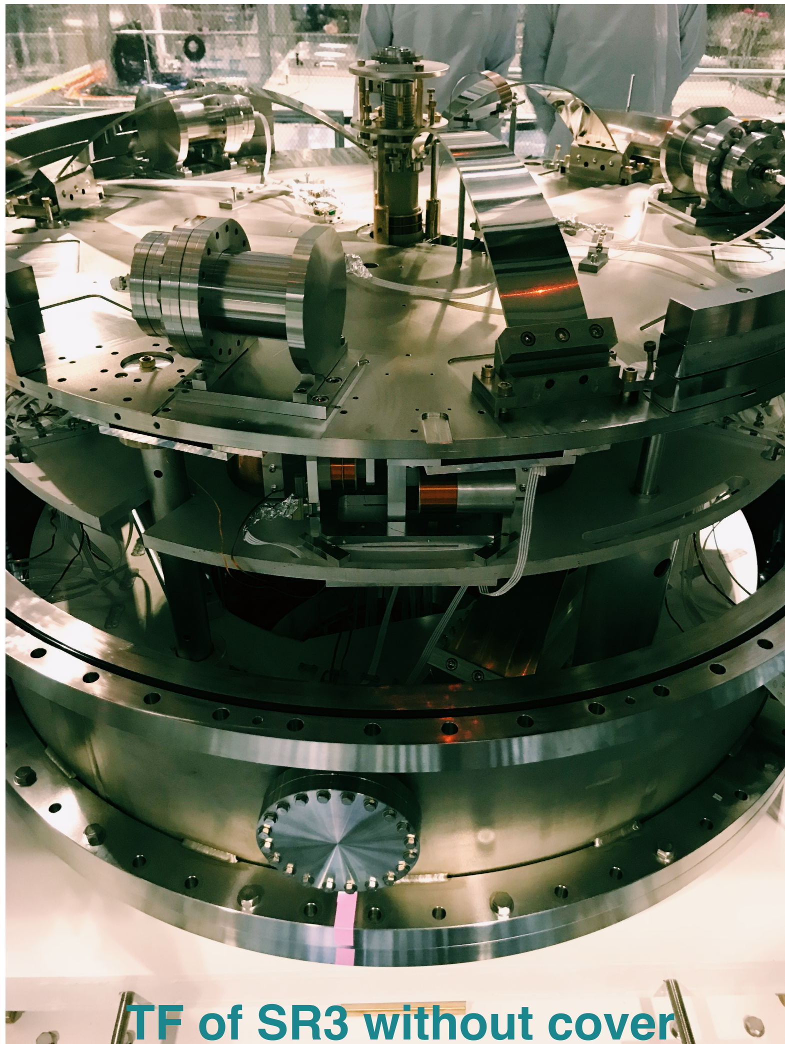
Before entering the clean booth

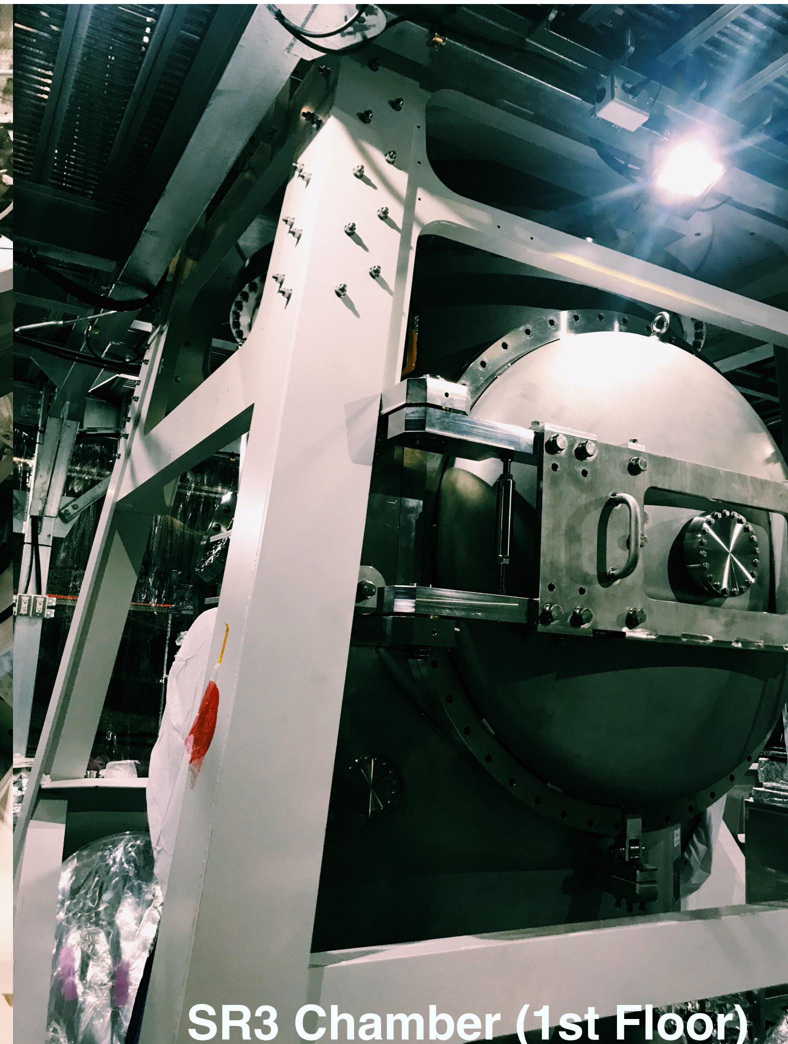


Centre

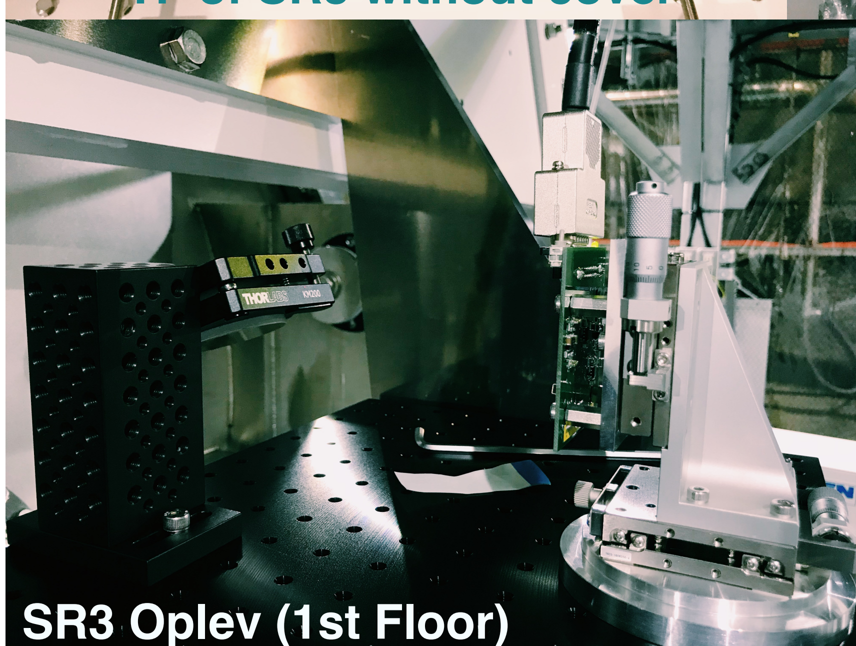
KAGRA

Inside the Mine


TF of SR3 without cover


SR3 Chamber (1st Floor)


Control Room at Mozumi


SR3 Oplev (1st Floor)

In front of SR3

Type-B team in front of Atotsu Entrance

References

Sekiguchi, T. “A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors.” *A Study of Low Frequency Vibration Isolation System for Large Scale Gravitational Wave Detectors*, Dec. 2015, gwdoc.icrr.u-tokyo.ac.jp/DocDB/0041/P1504155/015/tseki_PhDThesis_main.pdf.

B.P. Abbott, et al. (2017) “GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Colaescence”. *Physical Review Letters, 119, 141101.*

KAGRA

Acknowledgements

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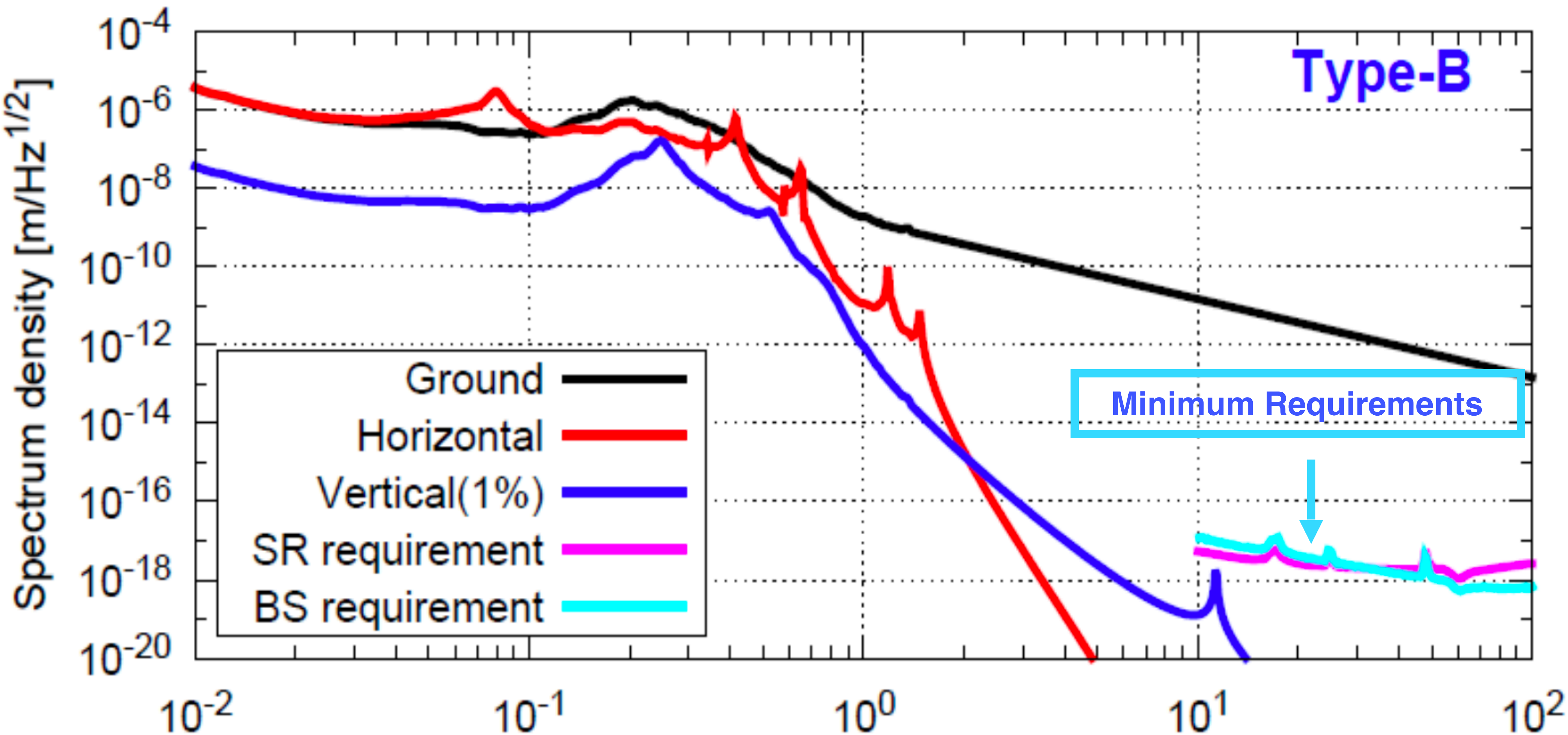
This work was partially supported by Summer Student Program (2018)
National Astronomical Observatory of Japan and the Department of Astronomical Science, SOKENDAI (the Graduate University for Advanced Studies).

Back Up

Structures of Suspension Systems

Different numbers of filters depending on the minimum requirements.



Results

Displacement of MD from Nominal Position [mm]	Decay Time [s]	Decay Time Error (±) [s]	Q-factor
0	10.47	0.08	1.80
0.5	12.91	0.10	2.22
1	14.53	0.05	2.50
2	28.85	0.06	4.97
3	36.21	0.08	6.23
4	63.47	0.16	10.93
5	81.21	0.44	13.98

Averaged Resonance Frequency: 0.055 [Hz]

Mass Budget Problem

The most optimal way of setting up the eddy current damper is to have more surface area for the copper plate. However, due to the "mass budget" problem, the initial plan for the SR2 copper plate had to be changed from 3 plates to 2 plates to reduce mass. There was no longer any point in having an array of magnets across the area where there is no contact with the copper ring. So to reduce weight of the magnetic damper, some of the magnets were also removed. For the commissioning phase 1 of KAGRA, it was difficult to damp the torsion modes.