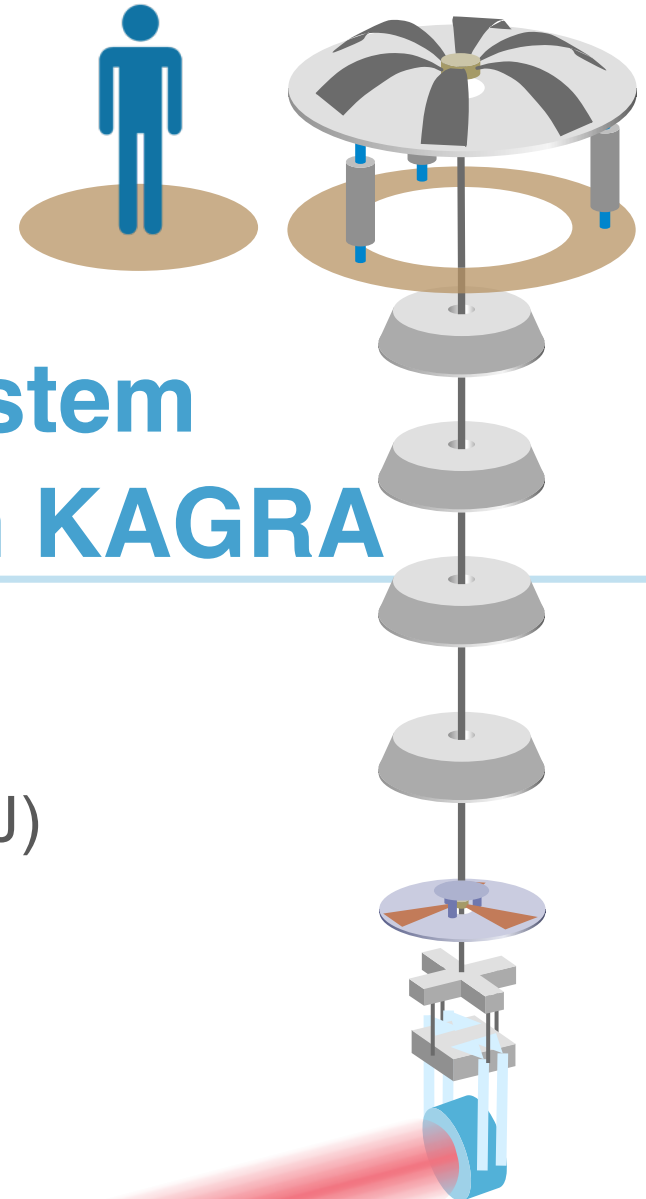


Development of 13.5-meter-tall Vibration Isolation System for the Main Mirrors in KAGRA



Koki Okutomi (Sokendai, NAOJ)

Dec 6, 2018

KAGRA F2F meeting @NAOJ Mitaka

Poster: Overview of My Work

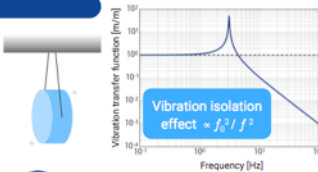
Development of 13.5-meter-tall Vibration Isolation System for the Main Mirrors in KAGRA

K. Okutomi¹, R. Takahashi, N. Sato, H. Ishizaki, T. Miyamoto, A. Shoda, Y. Fujii, K. Miyo, T. Yamamoto, K. Izumi, O. Miyakawa, M. Kamlizumi, T. Tomura, Y. Inoue, N. Kimura, T. Sekiguchi, M. Barton, R. DeSalvo, T. Akutsu, Y. Aso
 Sokendai (GUAS), NAQJ, ICRR, Dept. of Astronomy, Univ. of Tokyo, NCU, KEK, Univ. Sannio



Introduction

Terrestrial gravitational wave detectors suffer from seismic disturbances which fluctuate the mirrors of the interferometer. The vibration transmits to the mirrors can be attenuated by suspending the optics like a pendulum. The vibration isolation systems used in KAGRA are multi-stage suspension systems with local sensors and actuators; the suspension systems provide not only seismic attenuation but also controllability of the mirrors. Here we present the performance test of the vibration isolation system for the main mirrors (test masses) in KAGRA, called *Type-A suspension*.



What's Type-A suspension?

- 13.5 m tall, 9-stage multi-stage suspension (*right fig.*)
- For 4 test masses in 3 km arm cavities

Tower: upper 5 stages

- Room temperature (~ 300 K)
- Key components for vibration isolation performance implemented (listed below)
- **Main target of this study:**
To evaluate the performance of the Type-A tower

Inverted pendulum (IP)
 Horizontal low-frequency oscillator
 ♦ Pre-isolation stage: $f_0 \sim 70$ mHz
 ♦ Static positioning of the suspension point

Geometric anti-spring (GAS) filter
 Vertical low-frequency oscillator
 ♦ 5 stage chain: $f_0 \sim 300$ mHz
 ♦ Vertical fluctuation couples cavity length variation

Payload: bottom 4 stages

- Cryogenic temperature (~ 20 K)
- Key components for vibration isolation performance implemented (listed below)
- Out of scope in this study

Installation & Test setup

- Type-A tower installed at the X-end is tested
- Tower and payload are separately installed into the vacuum chamber then integrated later
- Performance test of the Type-A tower is done before integration with the payload
- A dummy payload with equivalent weight is suspended during installation and the test

Dummy payload: 203 kg

Tests & Results

Transfer function measurement

- Frequency response
- Compared with model prediction
- Gross behavior is as expected

Torsion mode damping

- Yaw resonant modes are damped with **bottom filter control**
- RMS ~ 230 nrad ✓
- Decay time < 1 min ✓

Modal damping in GAS chain

- Coupled mode decomposition ✓
- Functionality ✓
- Independent mode damping ✓

Vibration isolation ratio measurement

- Using MICH signal in phase-1 operation
- Measured data + model extrapolation
- Estimated: 10^{21} ✓

Conclusion

- We constructed Type-A suspension satisfying the basic requirements for vibration isolation
- Modal damping is implemented and validated
- Full Type-A suspension will be tested and commissioned

• Details: Thesis coming soon!

• Stay tuned!

• Poster: SE09



Contents

- Type-A suspension
- Modal damping for GAS vertical modes

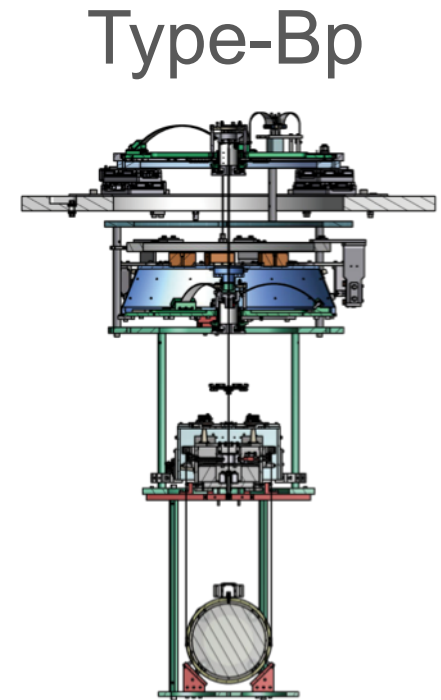
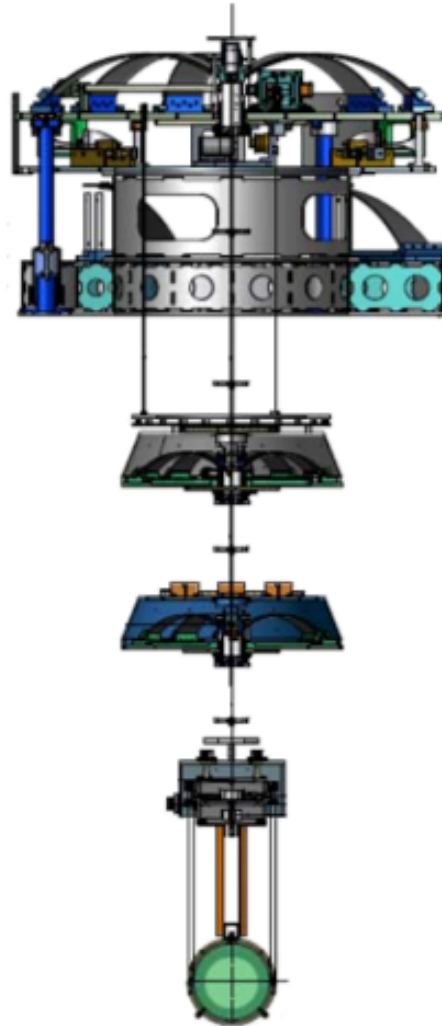
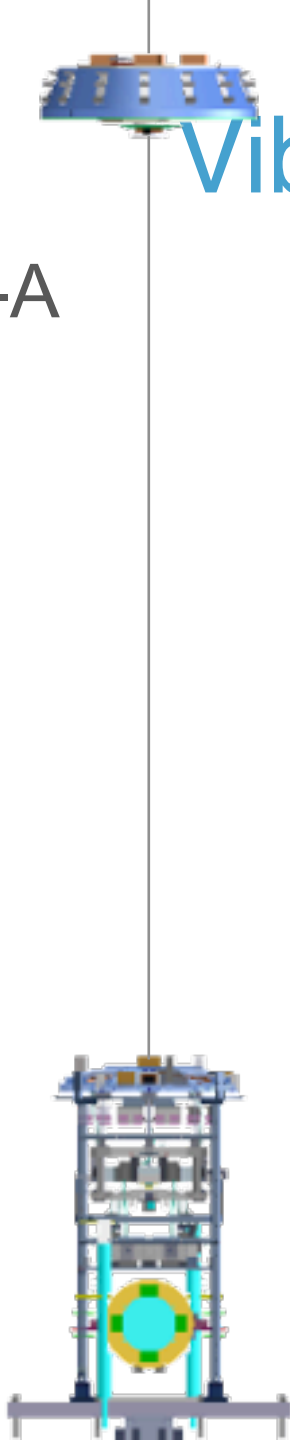
Type-A Suspension

Vibration Isolation Systems in KAGRA

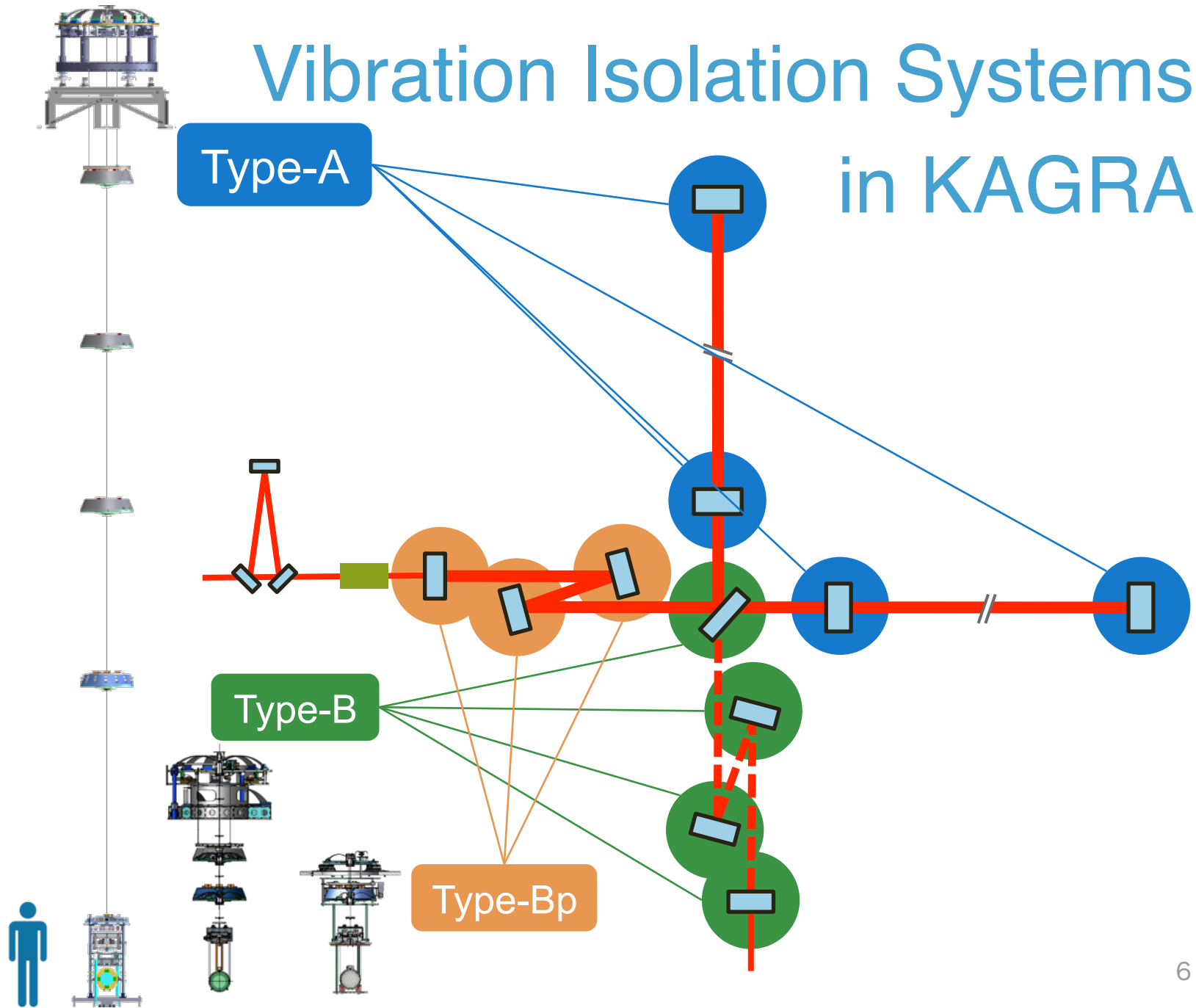
Type-A

Type-B

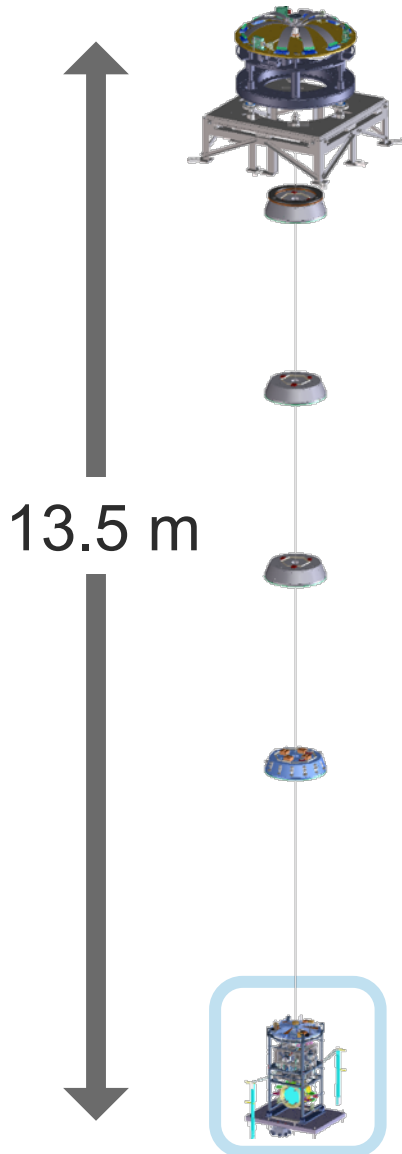
in KAGRA



Vibration Isolation Systems in KAGRA



Type-A Suspension

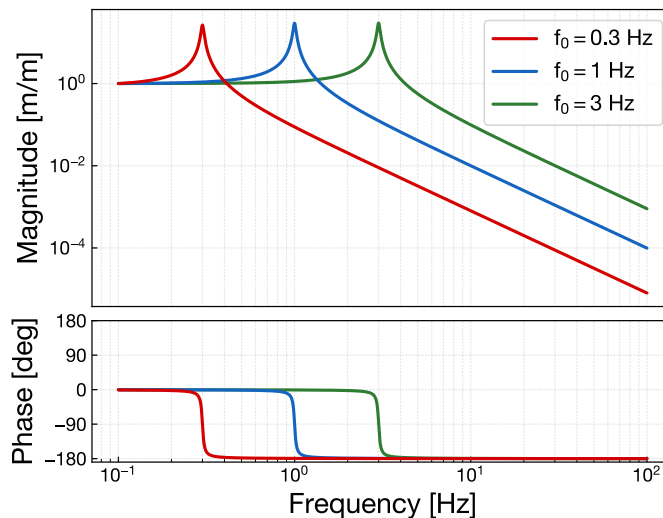


9-stage multiple pendulum

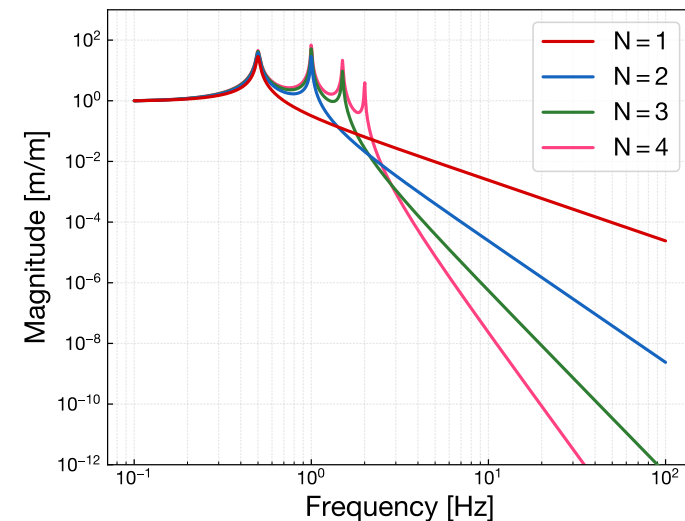
- Top 5 stages: Tower (~300 K)
- Bottom 4 stages : Payload (~20 K)

➤ For high vibration-isolation performance...

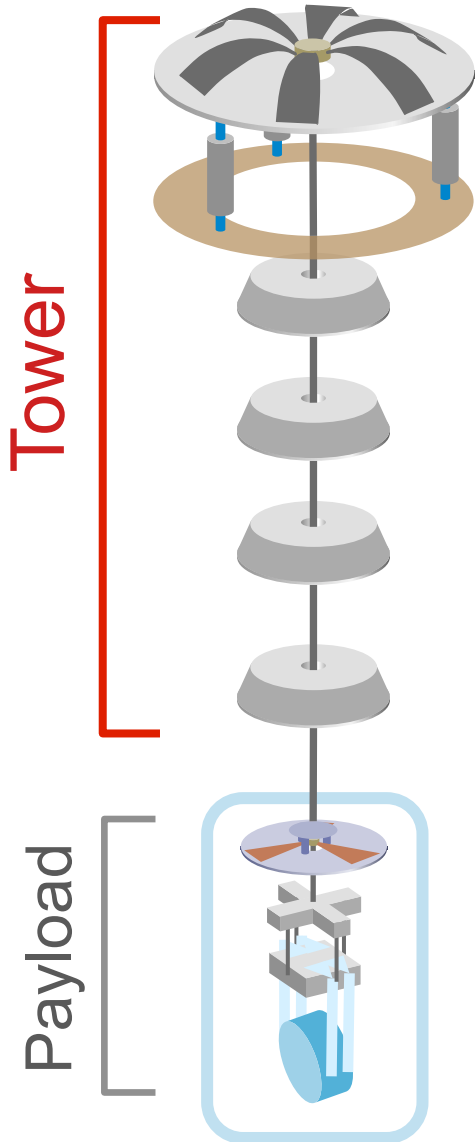
Lowering resonant freq.



Cascading



Scope of This Study



Tower: VIS

Payload : CRY

- Hardware installation
- System characterization
- Real-time control model construction
- Modeling
- Damping control

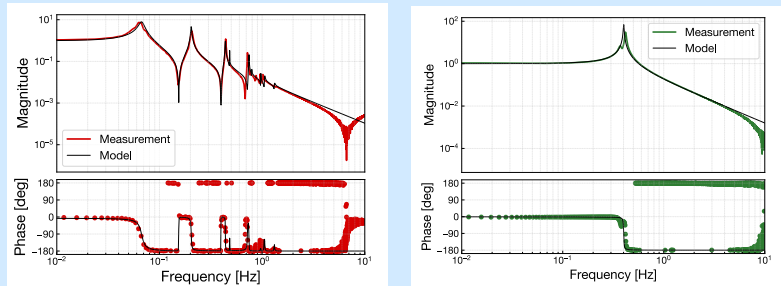


TARGET

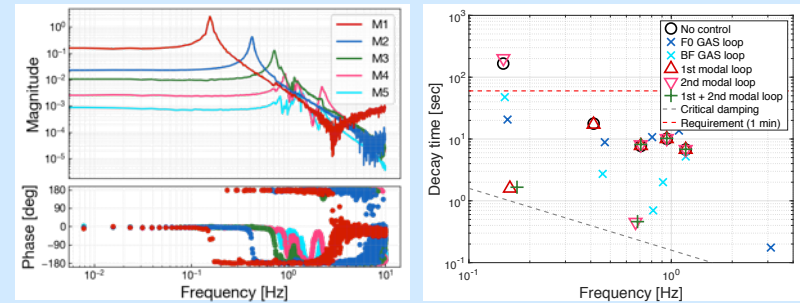
To construct a Type-A tower satisfying the basic requirements

What I Did

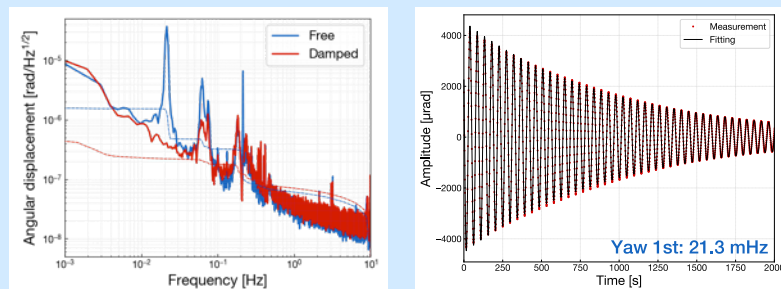
Transfer function measurement



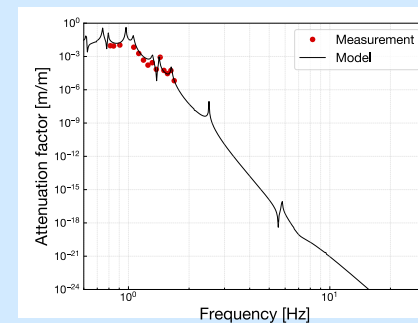
Modal Damping in GAS chain



Torsion mode damping



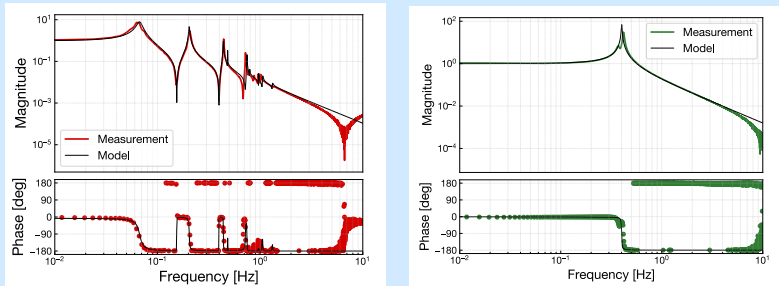
Vibration isolation ratio measurement (full suspension)



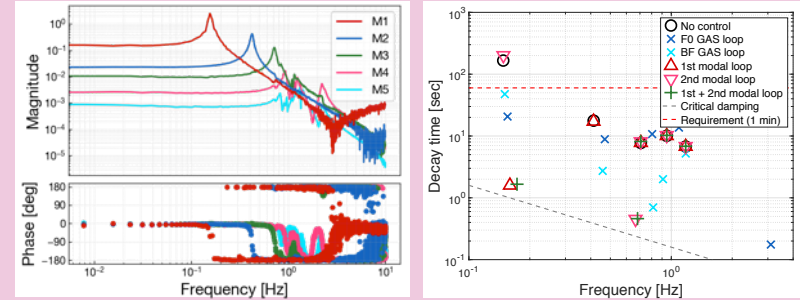
Topic of this talk!



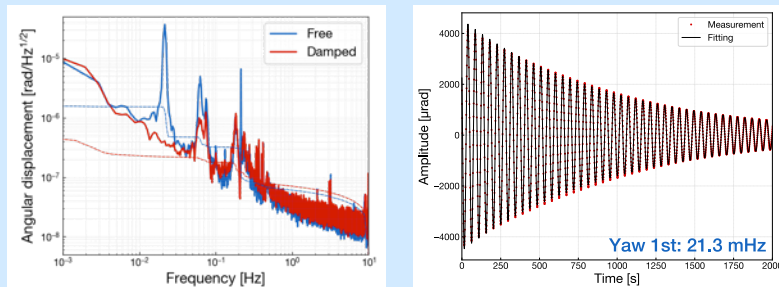
Transfer function measurement



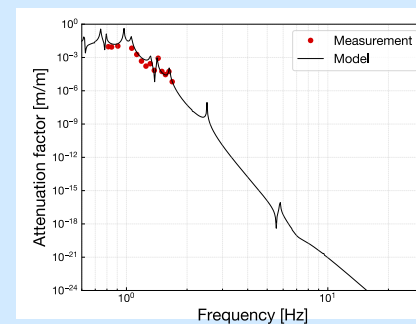
Modal Damping in GAS chain



Torsion mode damping

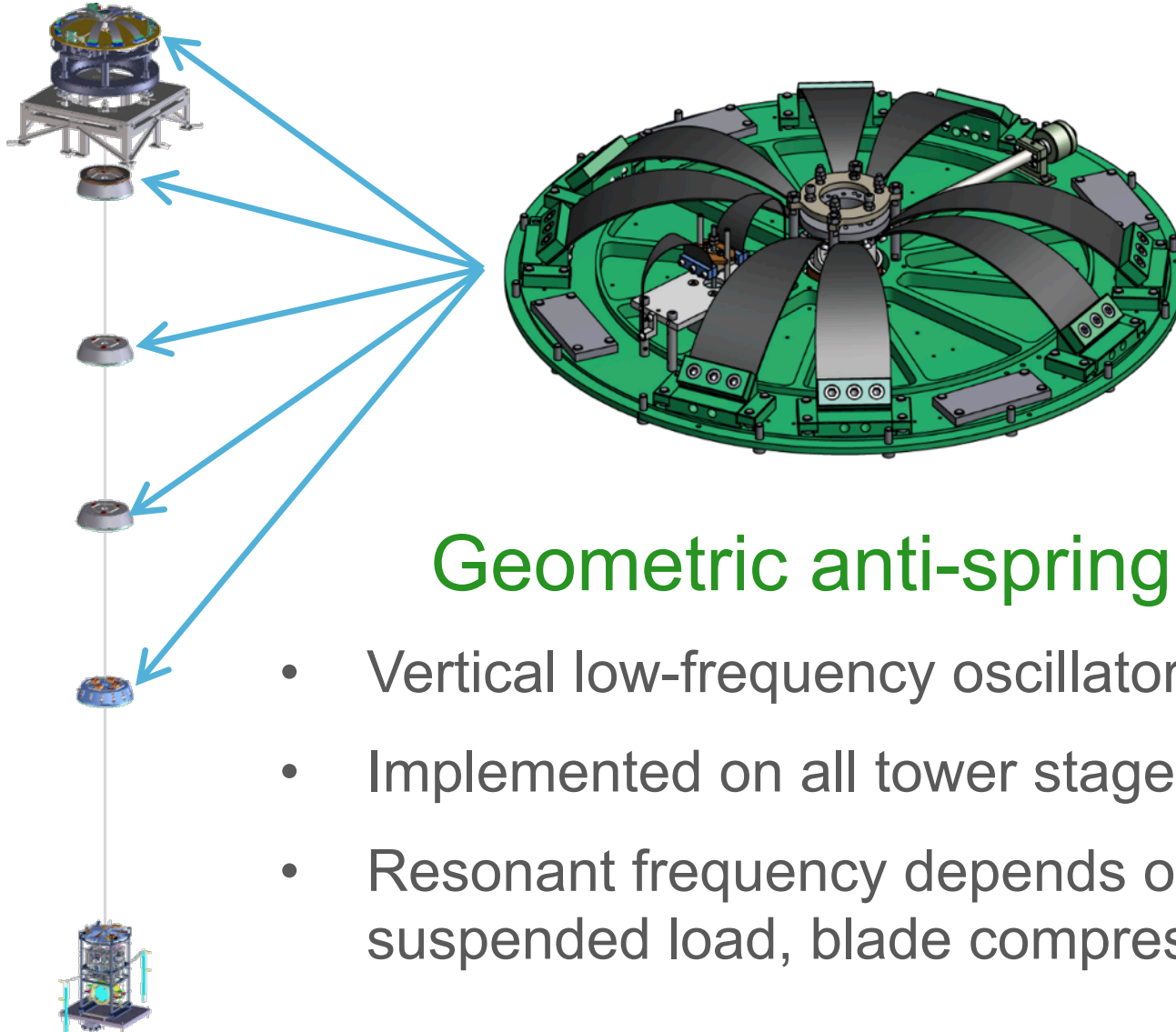


Vibration isolation ratio measurement (full suspension)



Modal damping in GAS vertical modes

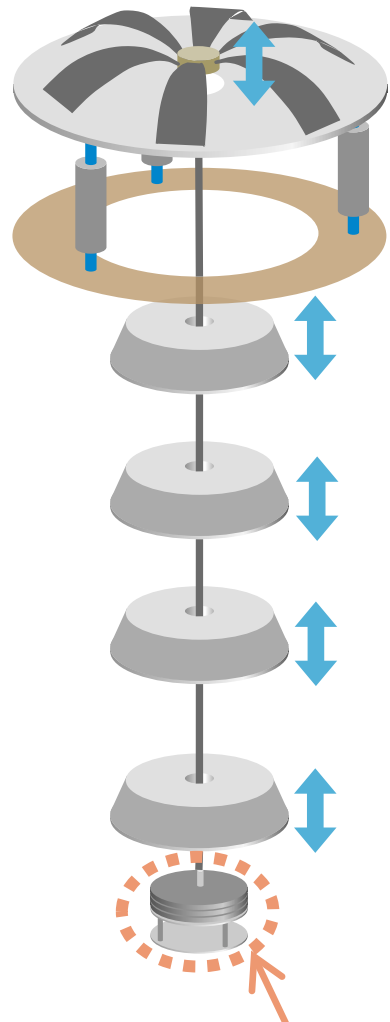
GAS Filter



Geometric anti-spring filter

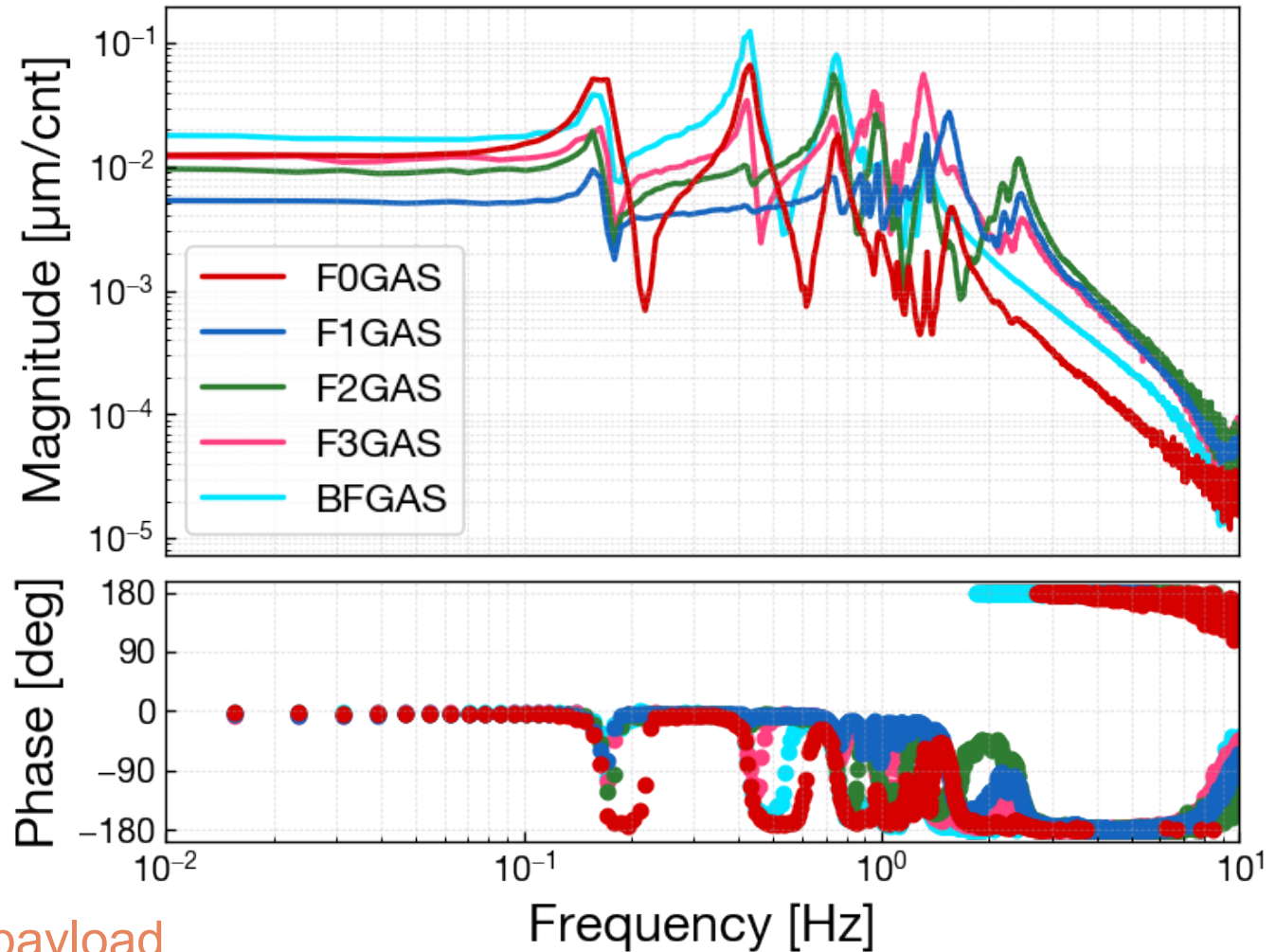
- Vertical low-frequency oscillator
- Implemented on all tower stages
- Resonant frequency depends on suspended load, blade compression, etc...

GAS Vertical Control

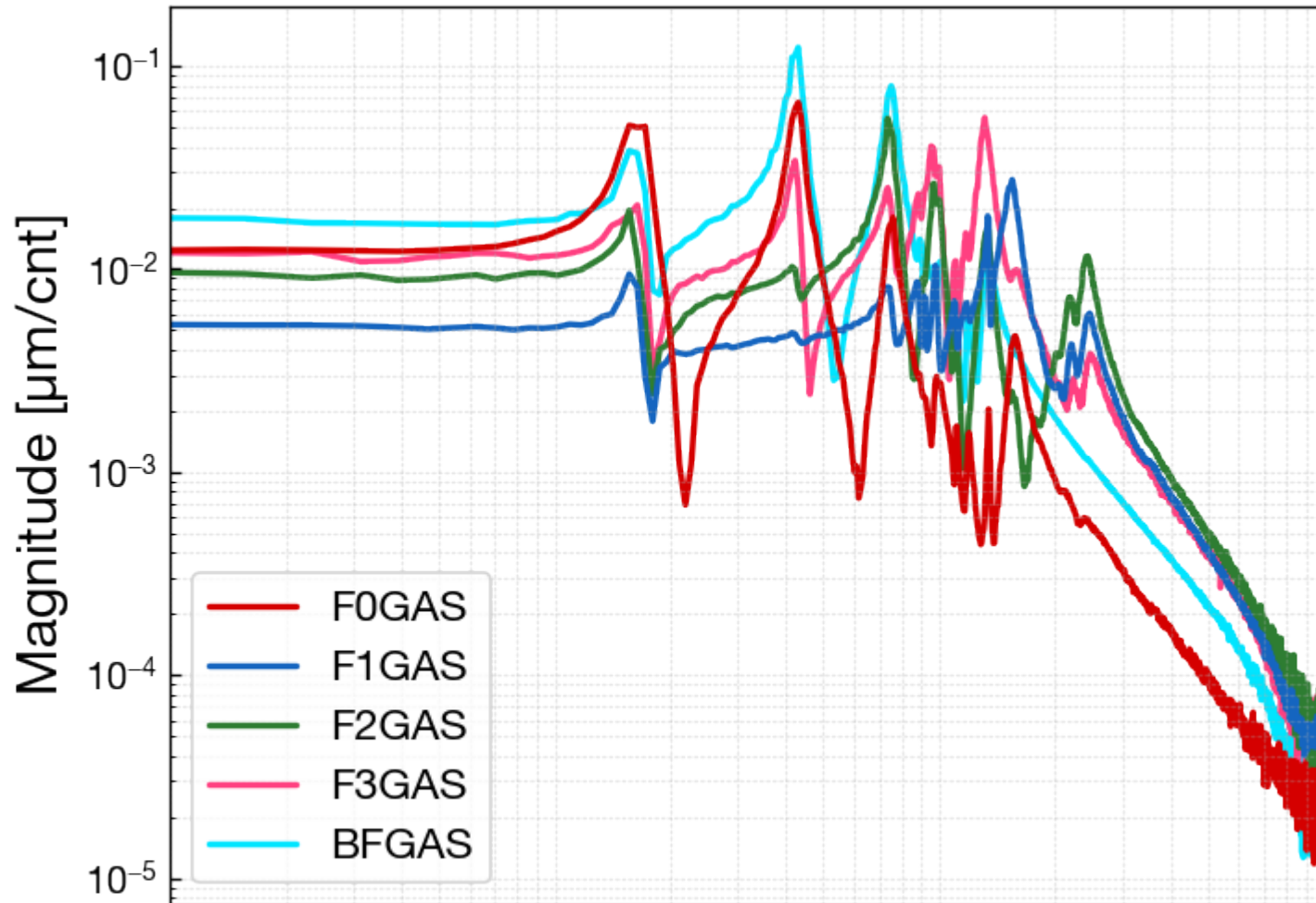


Dummy payload

GAS response in stages



GAS Frequency Responses



周波数 [Hz]

GAS Frequency Response

2nd: 0.43 Hz

1st: 0.17 Hz

3rd: 0.74 Hz

Lower-order modes

▶ 😊 we want to damp

Magnitude

10^{-3}

10^{-4}

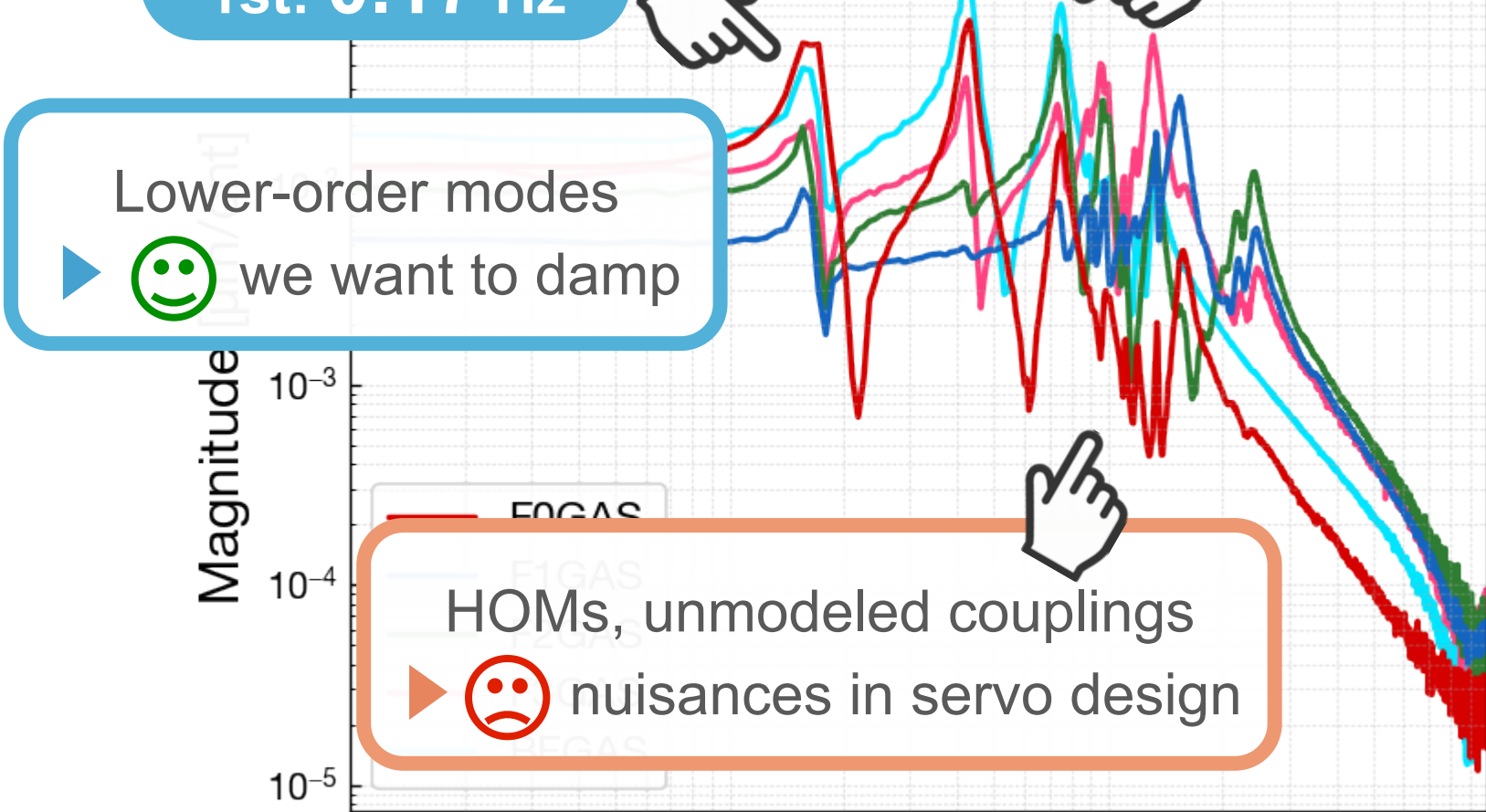
10^{-5}

HOMs, unmodeled couplings

▶ 😞 nuisances in servo design

周波数 [Hz]

F0GAS
F1GAS
F2GAS
F3GAS

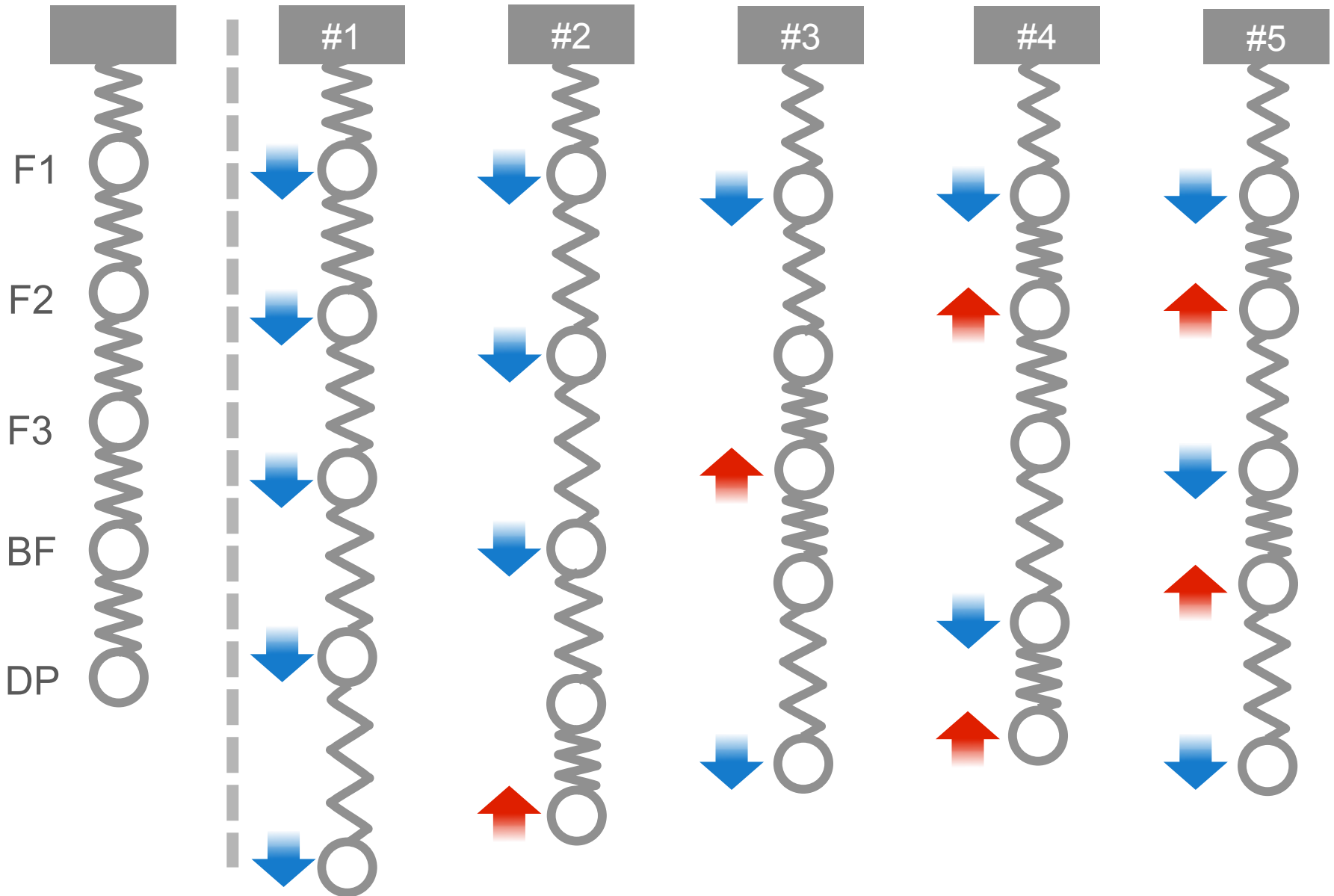


Can we damp specific modes independently...?

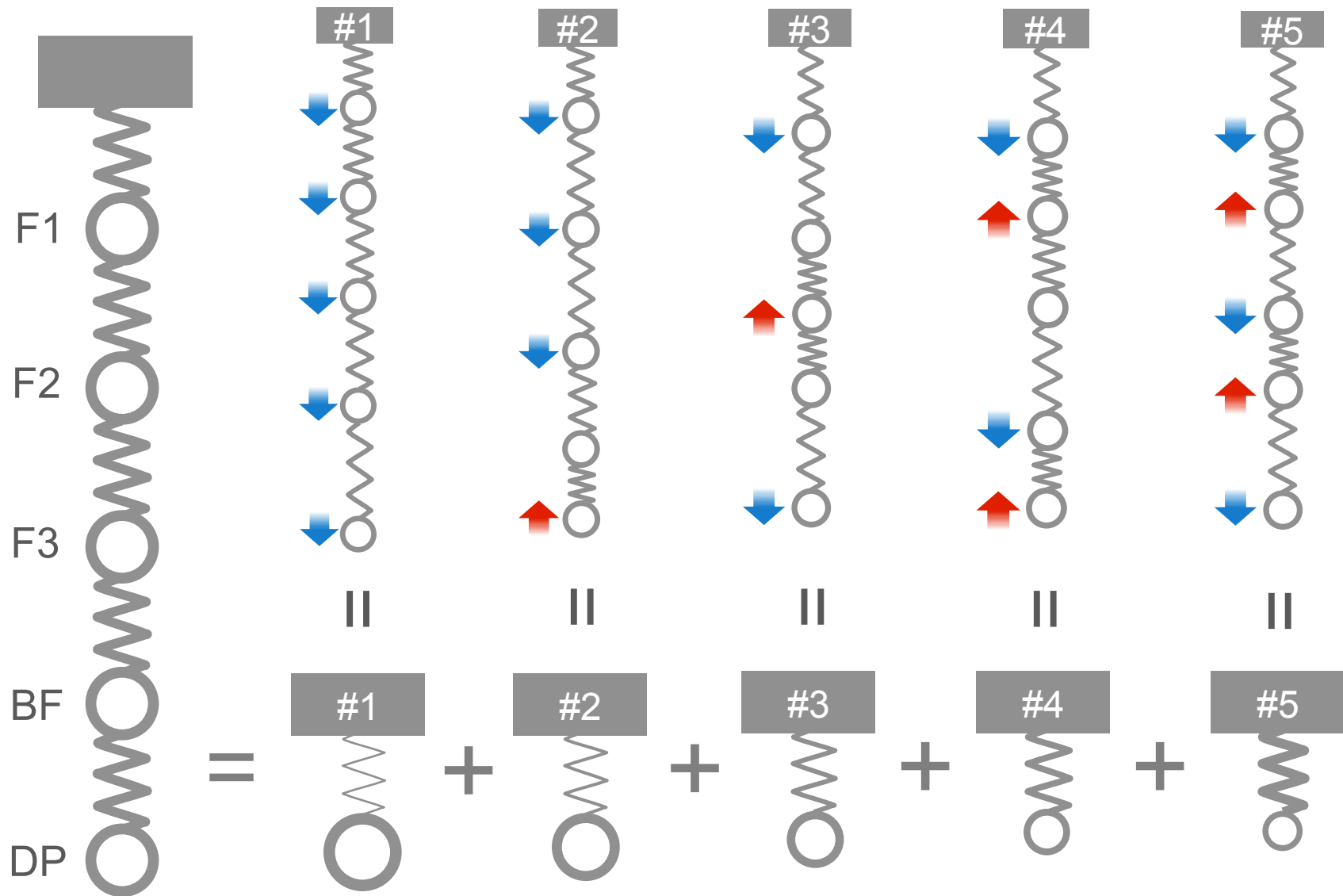


Modal damping

Mode shapes in GAS



Concept of Modal Decomposition



Modal Decomposition

$$\begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix} = \mathbf{\Phi}^{-1} \mathbf{M} \begin{bmatrix} V_{F0GAS} \\ V_{F1GAS} \\ V_{F2GAS} \\ V_{F3GAS} \\ V_{BFGAS} \end{bmatrix}$$

Modal basis

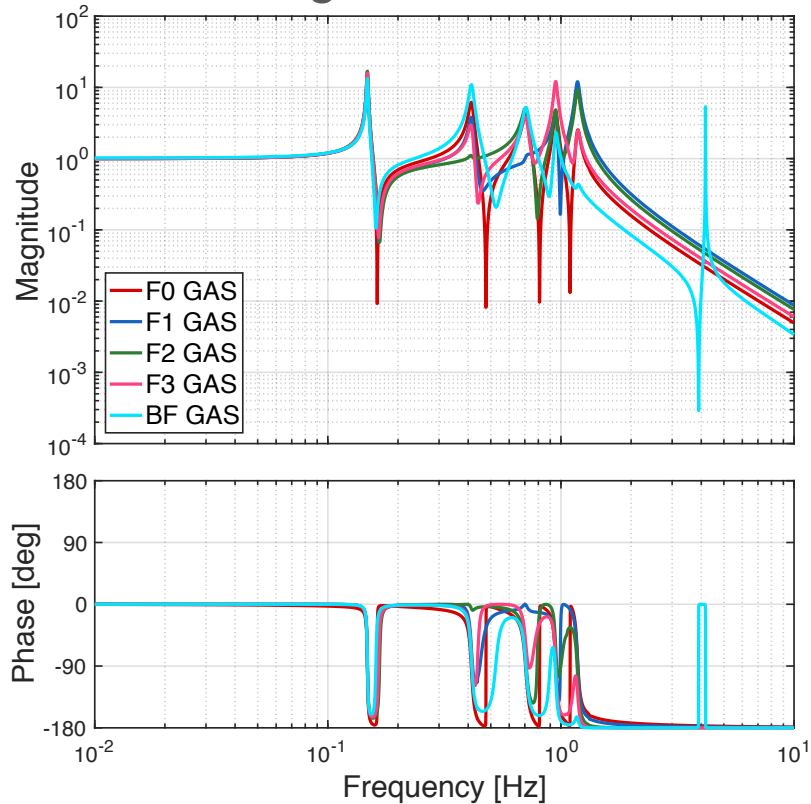
Sensor basis

$\mathbf{\Phi}$: **Eigenmode matrix** (modal basis \rightarrow Cartesian basis)
calculated from 3D rigid-body model

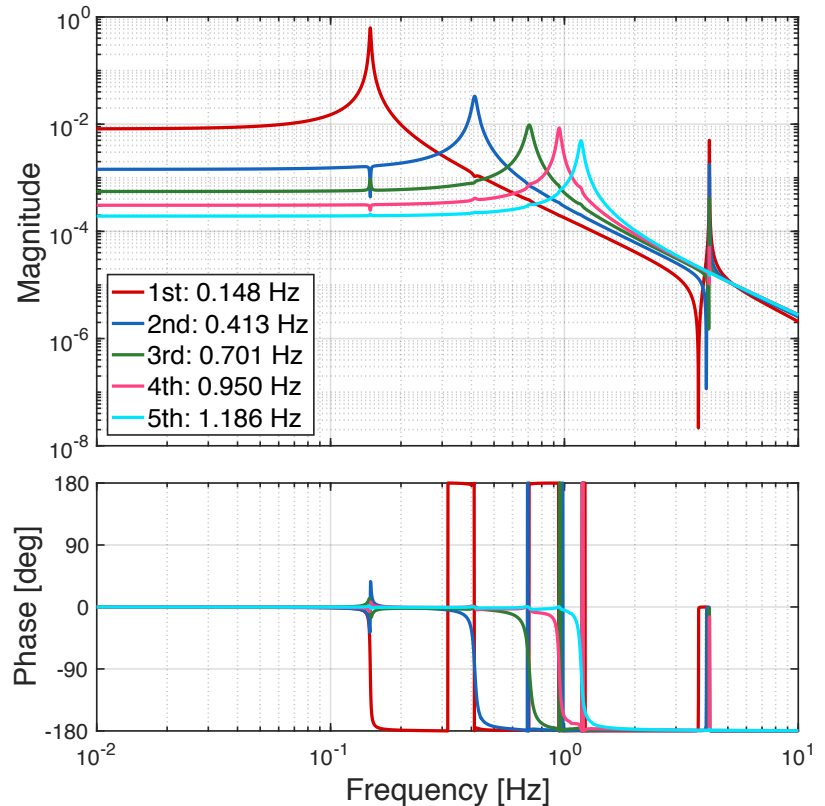
\mathbf{M} : Sensing matrix

Modal Decomposition in Model

Stage-based TF



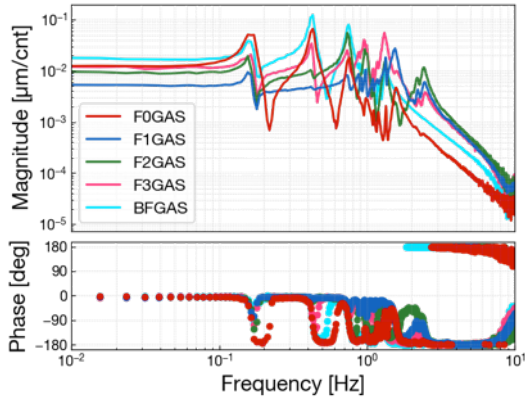
Modal-based TF



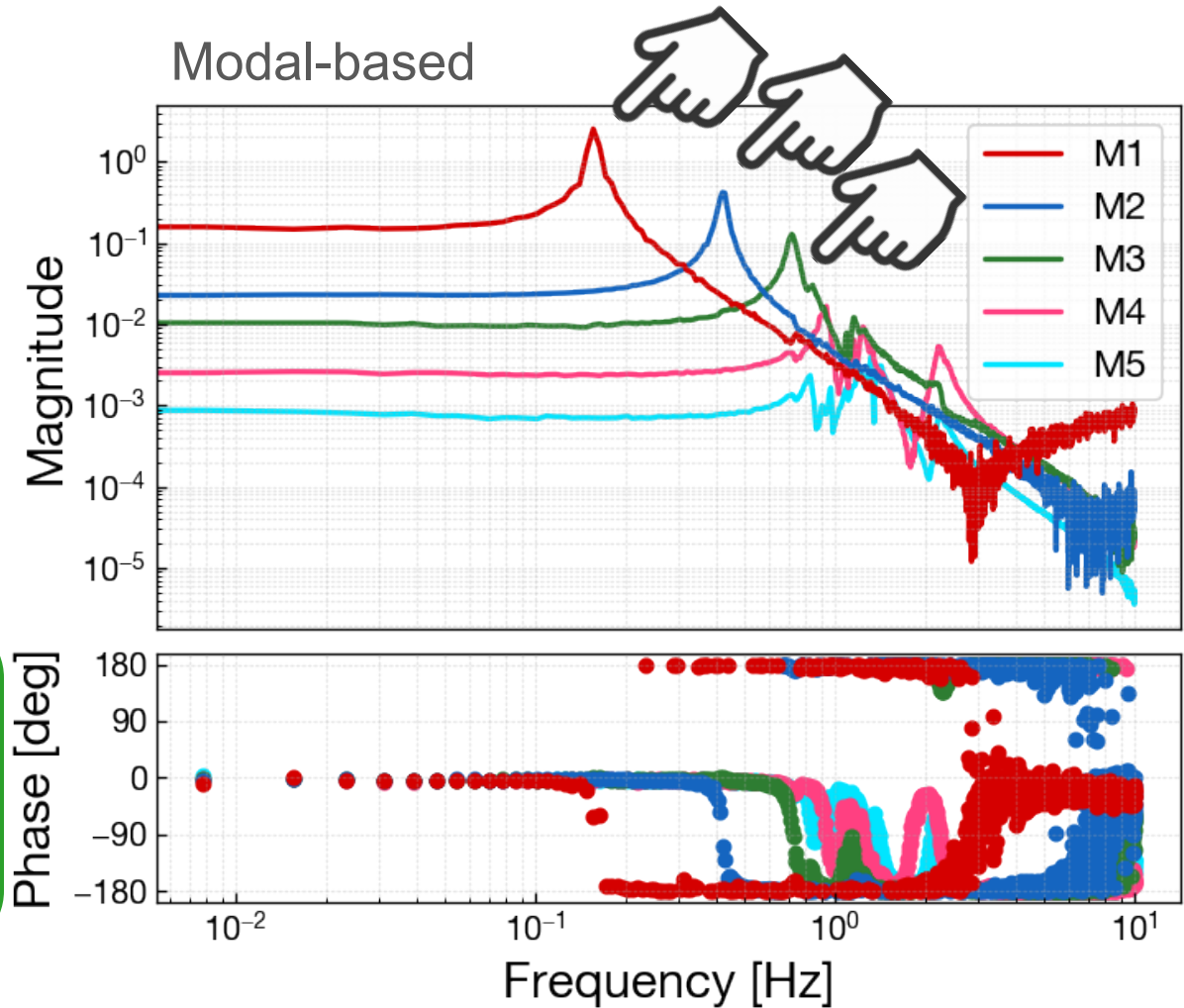
Decoupled into a set of single pendulum responses

Measured Modal Decomposition

Stage-based

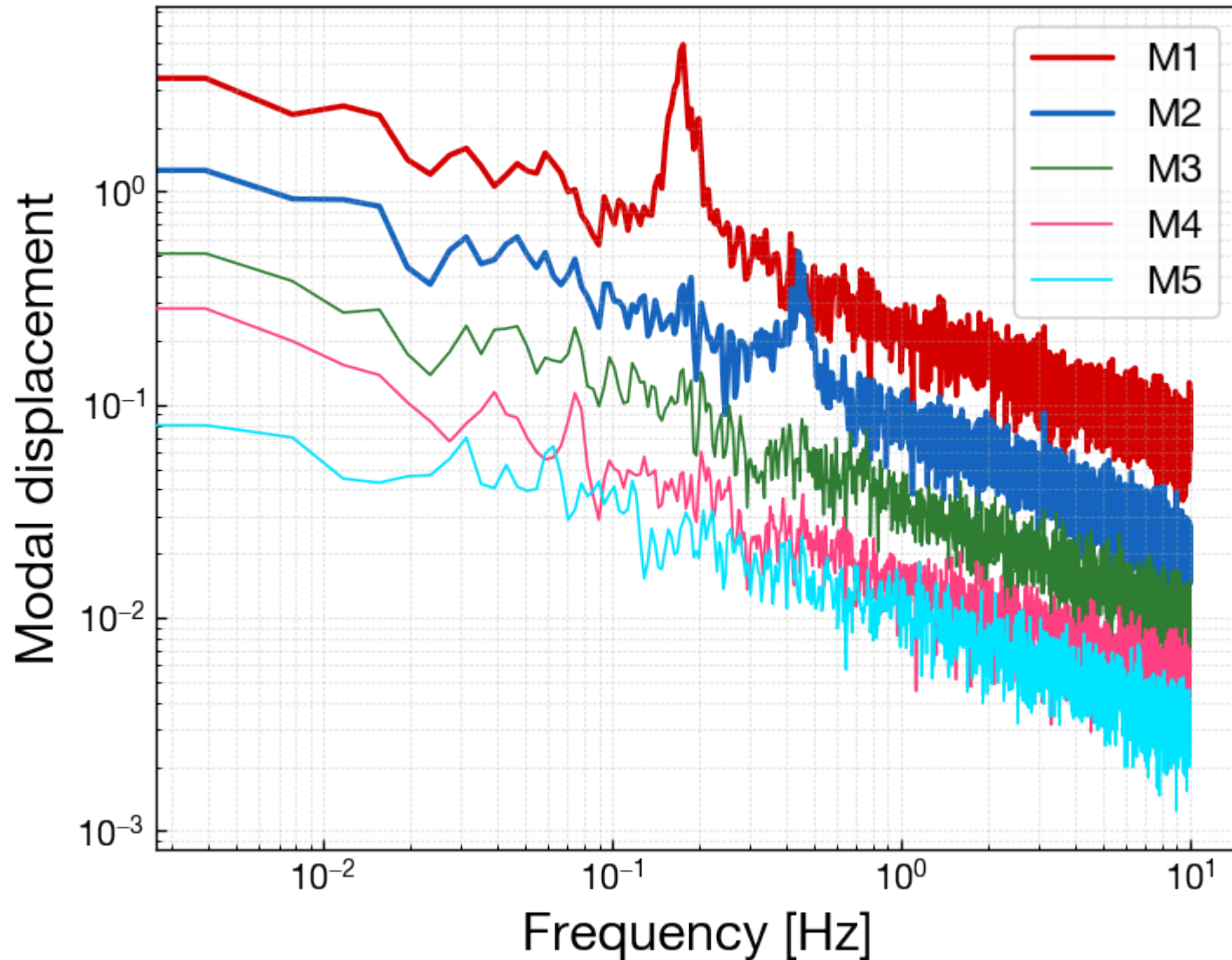


Modal-based

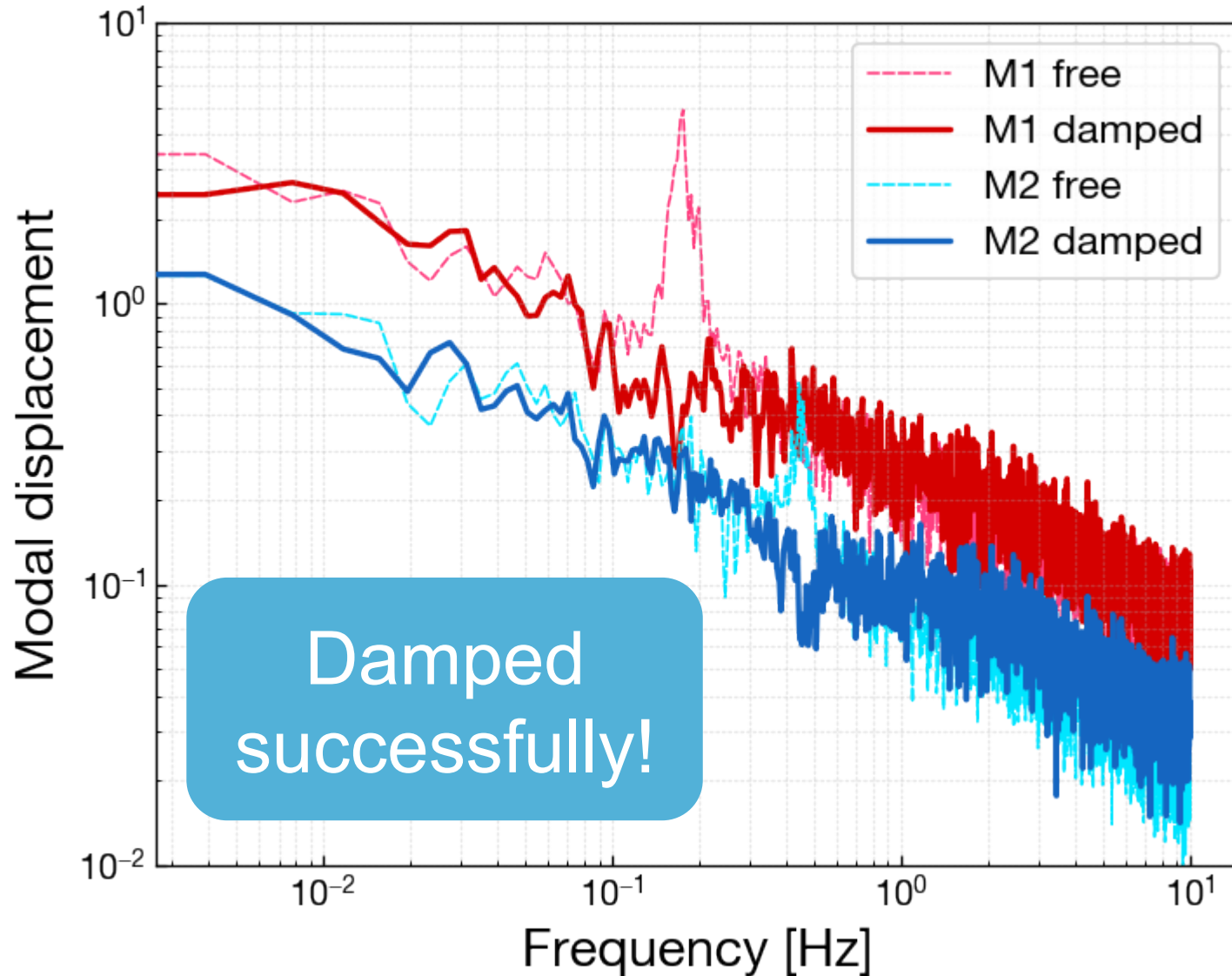


Lower-order modes well decomposed

GAS Modal Spectrum (No Control)





1st + 2nd Modal Loop Closed






Other Topics



Transfer function measurement

-  Gross behavior is as expected (IP, BF)
-  GAS mode shape mismatch




Modal Damping in GAS chain

-  Lower-order modes decoupled
-  Modal damping worked
-  Decay time performance: to be checked

Torsion mode damping

-  RMS ~ 230 nrad $<$ req.
-  Yaw decay time $<$ 1 min.

Vibration isolation ratio measurement (full suspension)

-  Estimated: 10^{-21} $<$ req.
-  Model vs measurement mismatch
-  Only longitudinal, vertical also to be measured

Summary

- The installed Type-A tower satisfies basic requirements for vibration isolation
- Modal damping is implemented and validated in GAS vertical mode control
- The Type-A suspension integrated with cryogenic payload is in commission

KAGRA

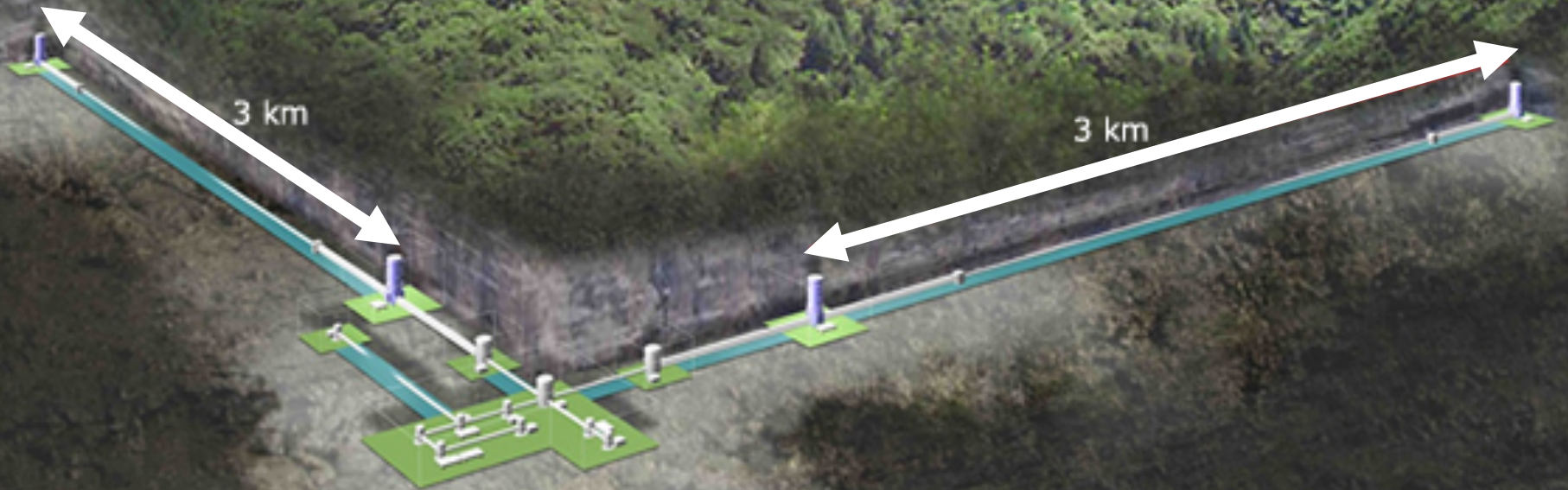
2.5th generation laser interferometer

Underground site

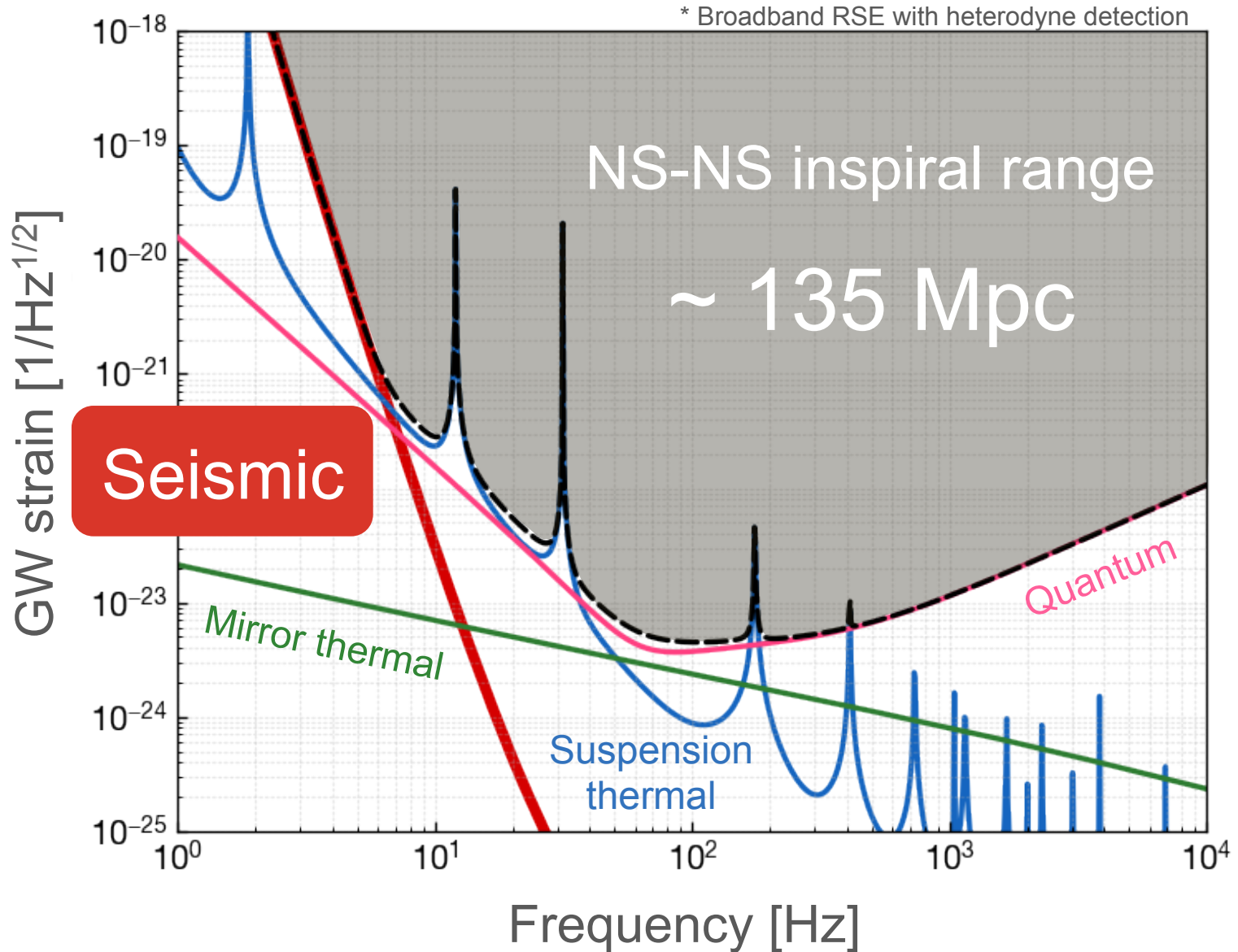
▶ Low seismic noise

Cryogenic sapphire mirror

▶ Low thermal noise



KAGRA Noise Breakdown



KAGRAの現状

2017年1月 ~ 2018年3月

大型防振システムのインストール・試験

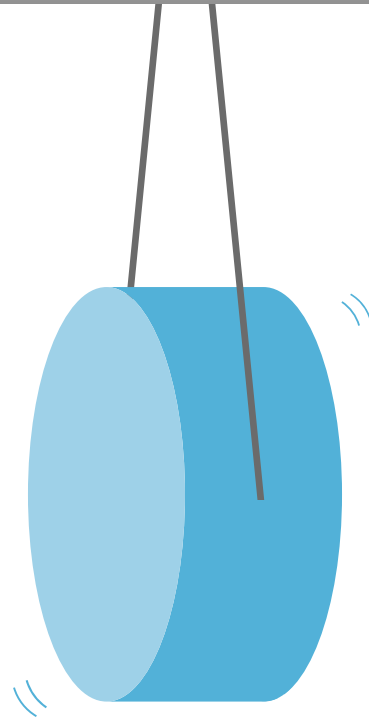
2018年4月28日 ~ 5月7日

低温Michelson干渉計でのengineering run

現在~2019年

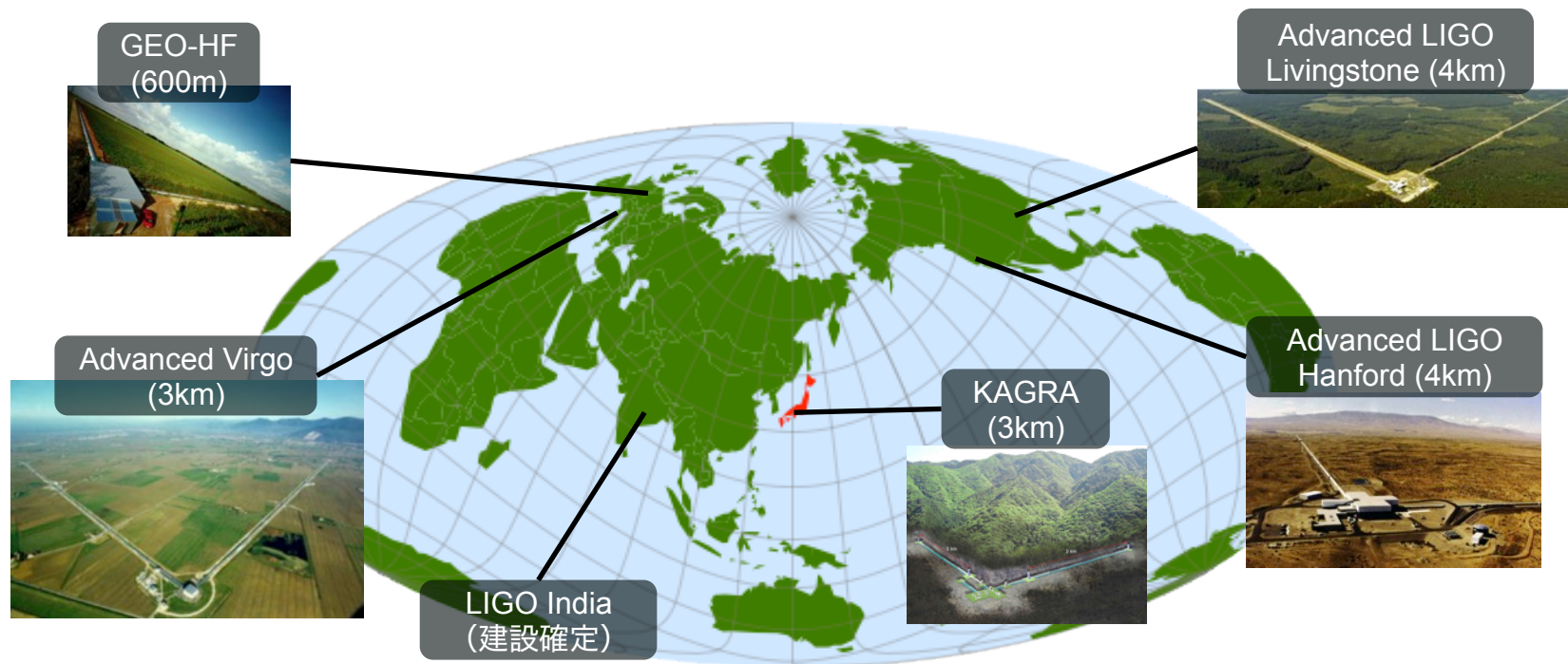
LIGO + Virgo observation run-3 (O3) 参加に向けて感度向上のためのアップグレード中

振り子による受動防振



地面から鏡へ伝わる振動 $\propto f_0^2 / f^2$

KAGRAの位置付け

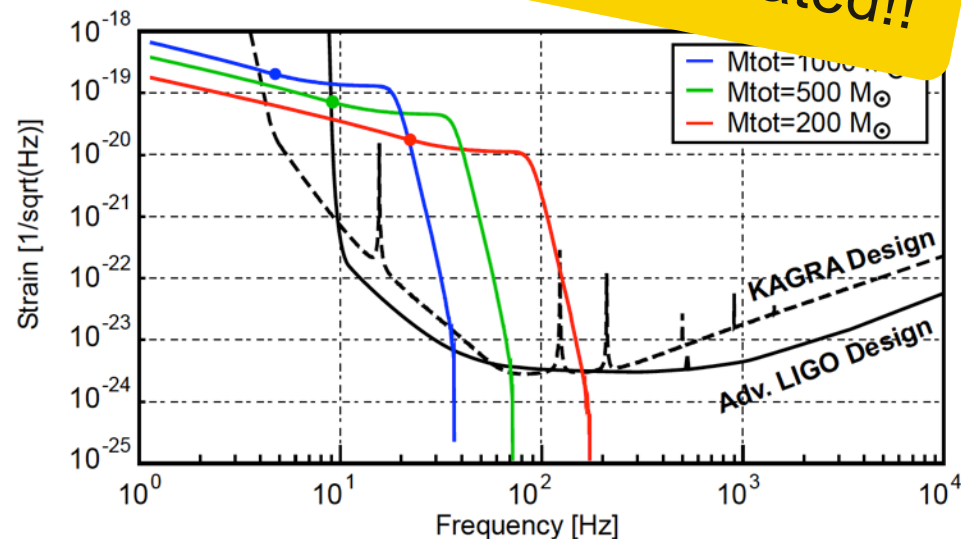
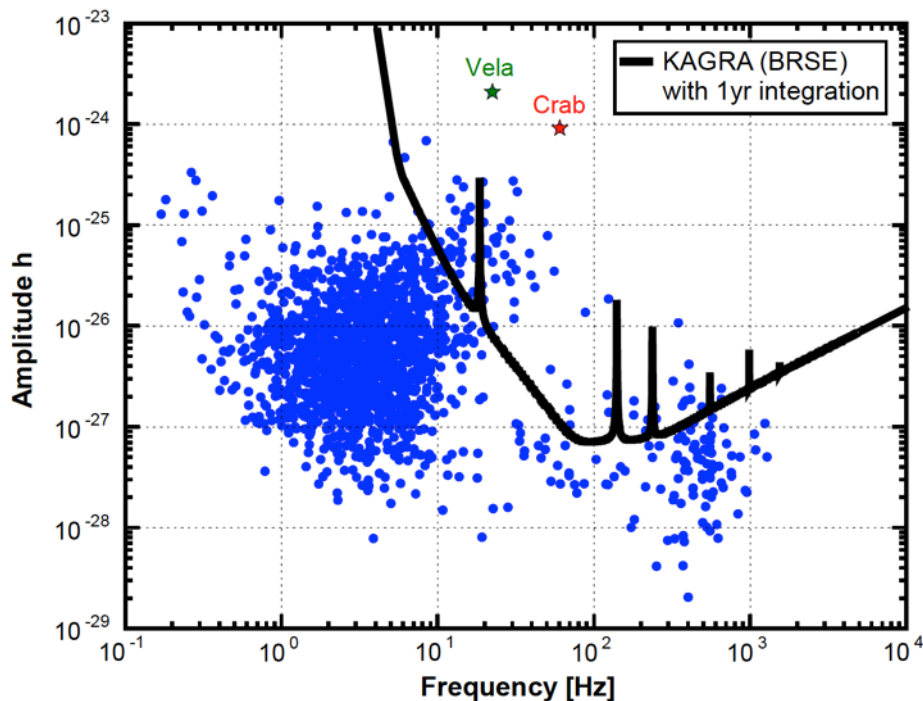


- Adv. LIGO + Adv. Virgo + KAGRA での同時観測シナリオを計画中、一刻も早い本格稼働が望まれている
- 地下環境 + 低温技術 ▶ 第3世代望遠鏡への応用

低周波帯における感度改善の意義

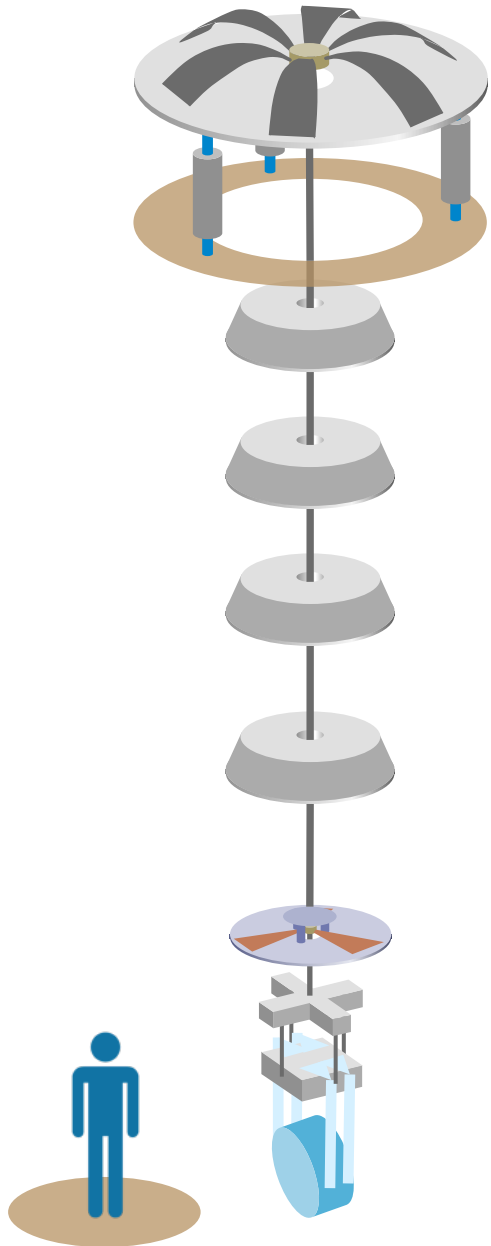
- コンパクト連星合体のパラメータ決定推定精度の向上
- 非対称な中性子星の自転
- 中間質量ブラックホール連星の合体

and more...

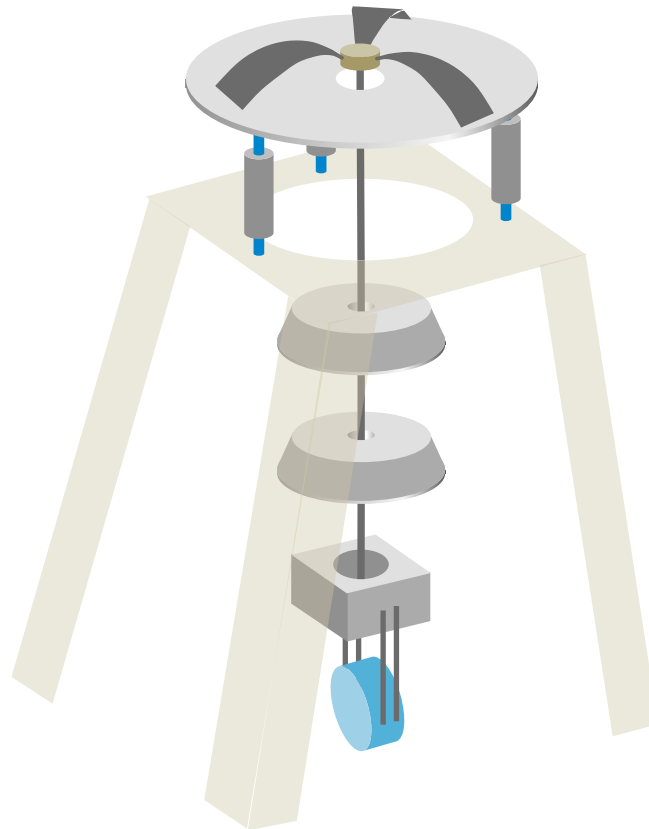


KAGRAの防振懸架系

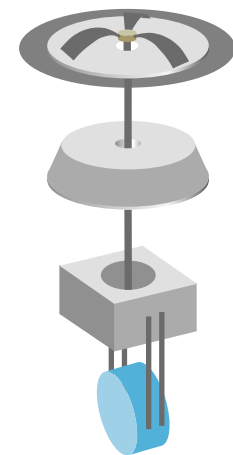
Type-A



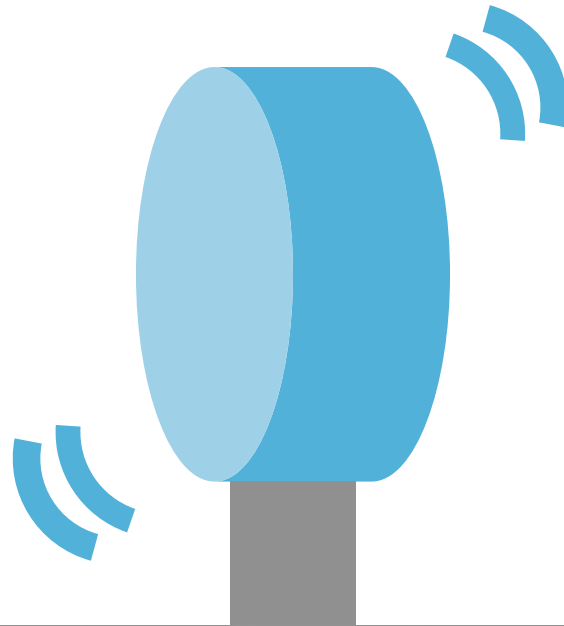
Type-B



Type-Bp

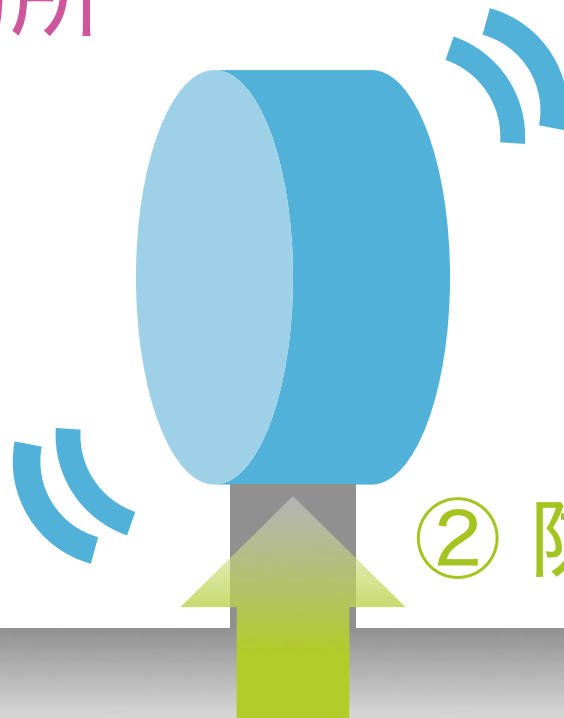
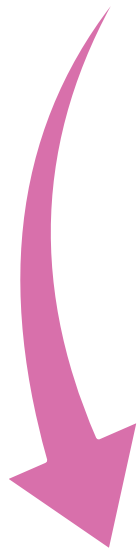


地面振動雑音とは



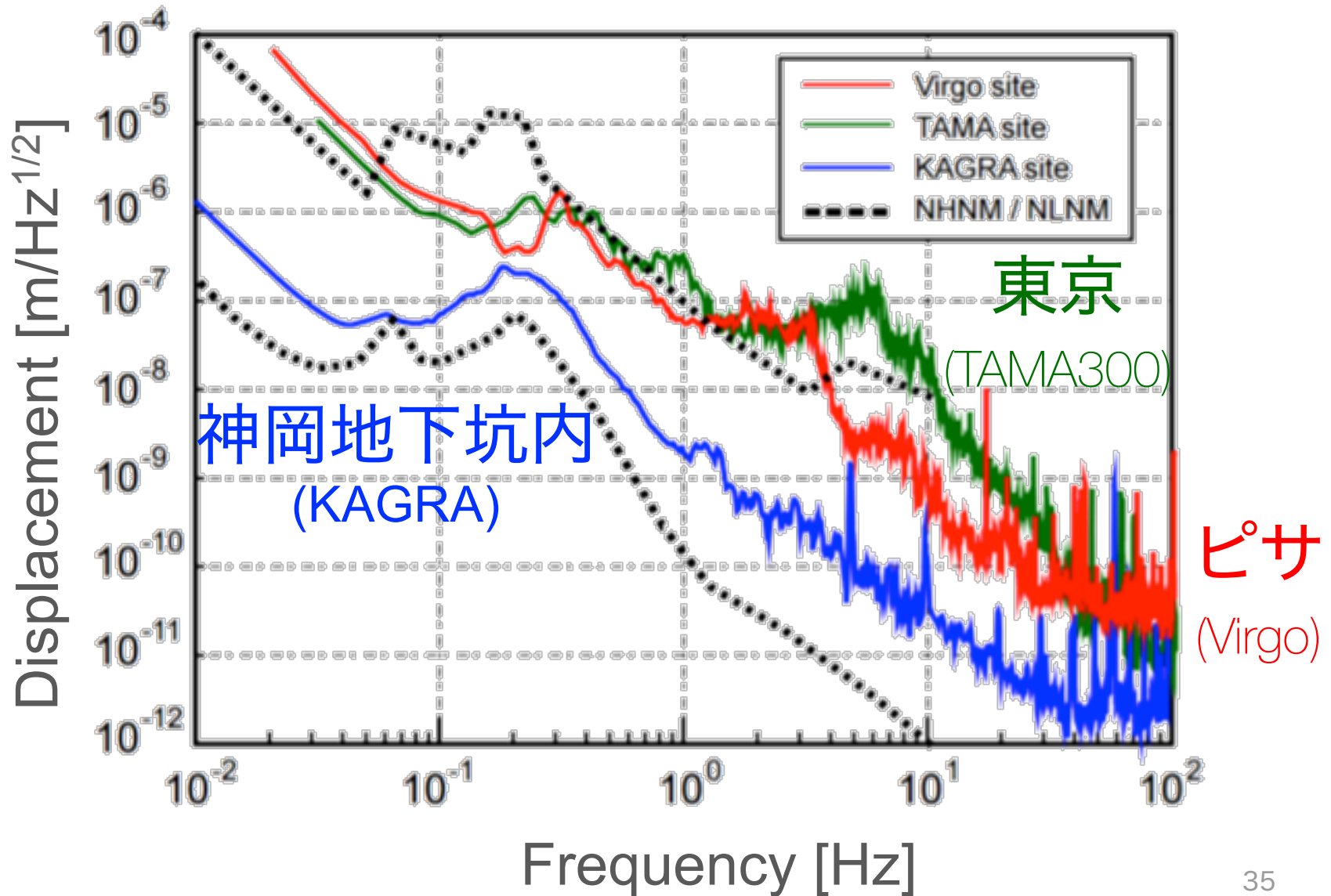
地面振動雑音を減らすには？

① 静かな場所

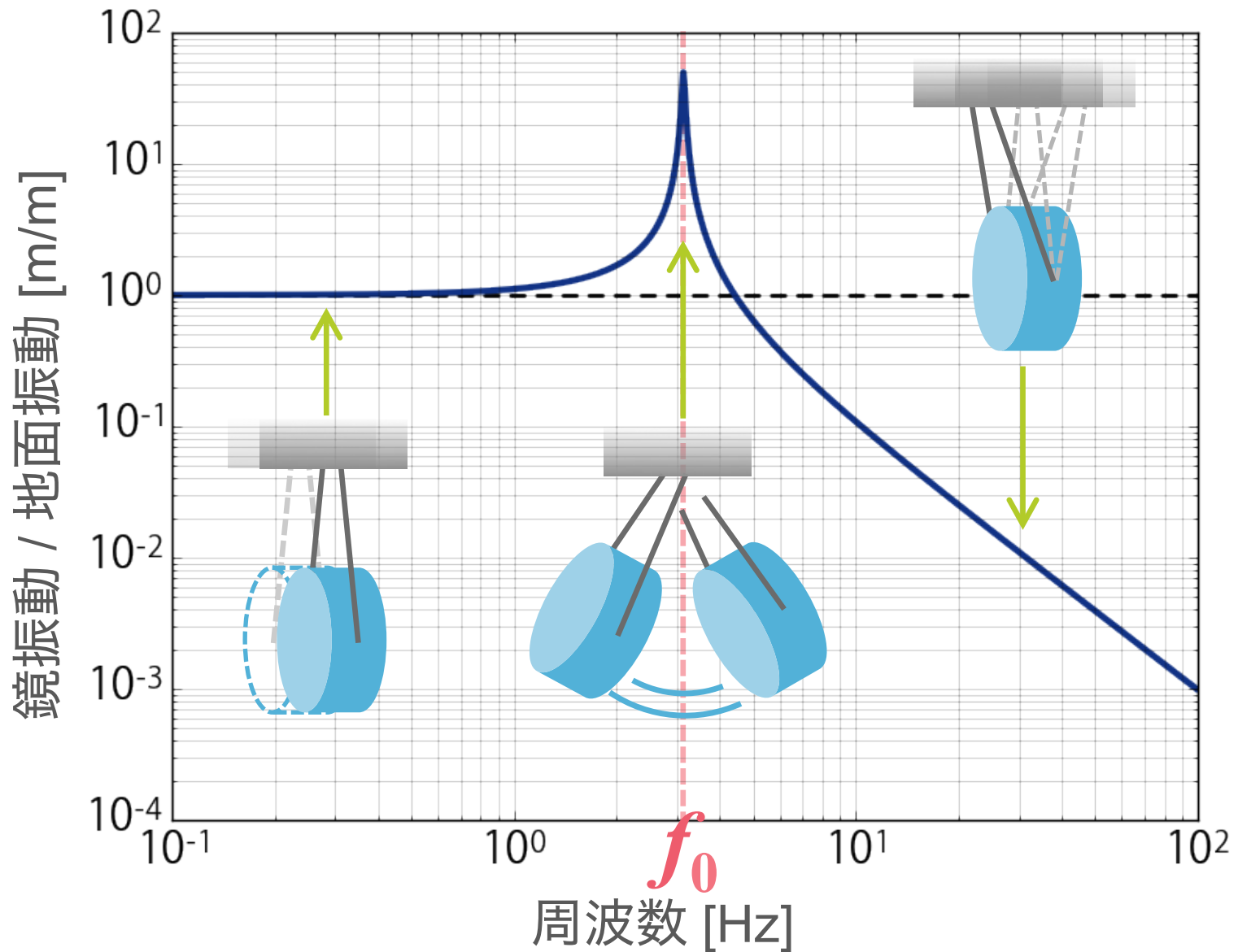


② 防振

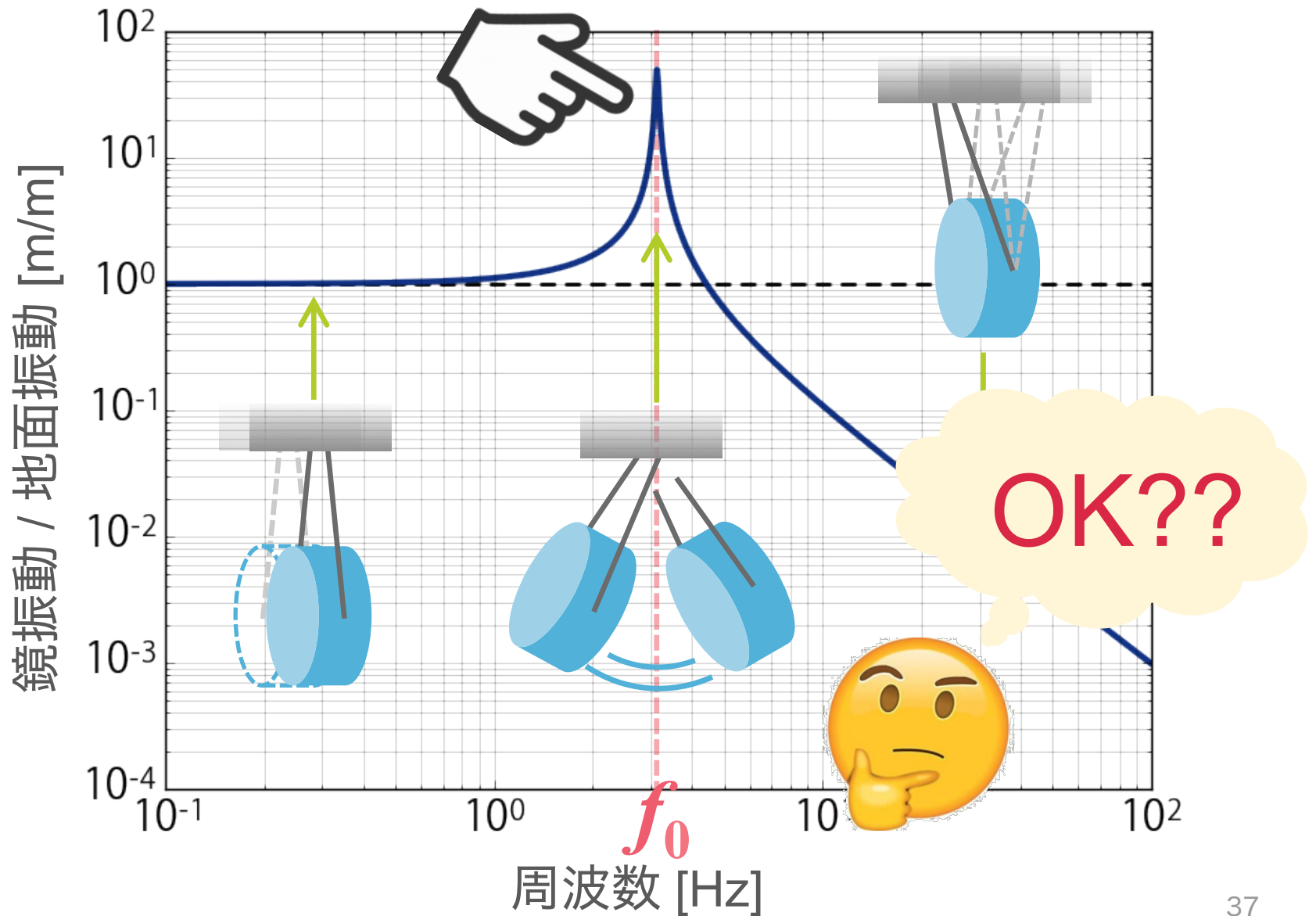
① 地下は静か



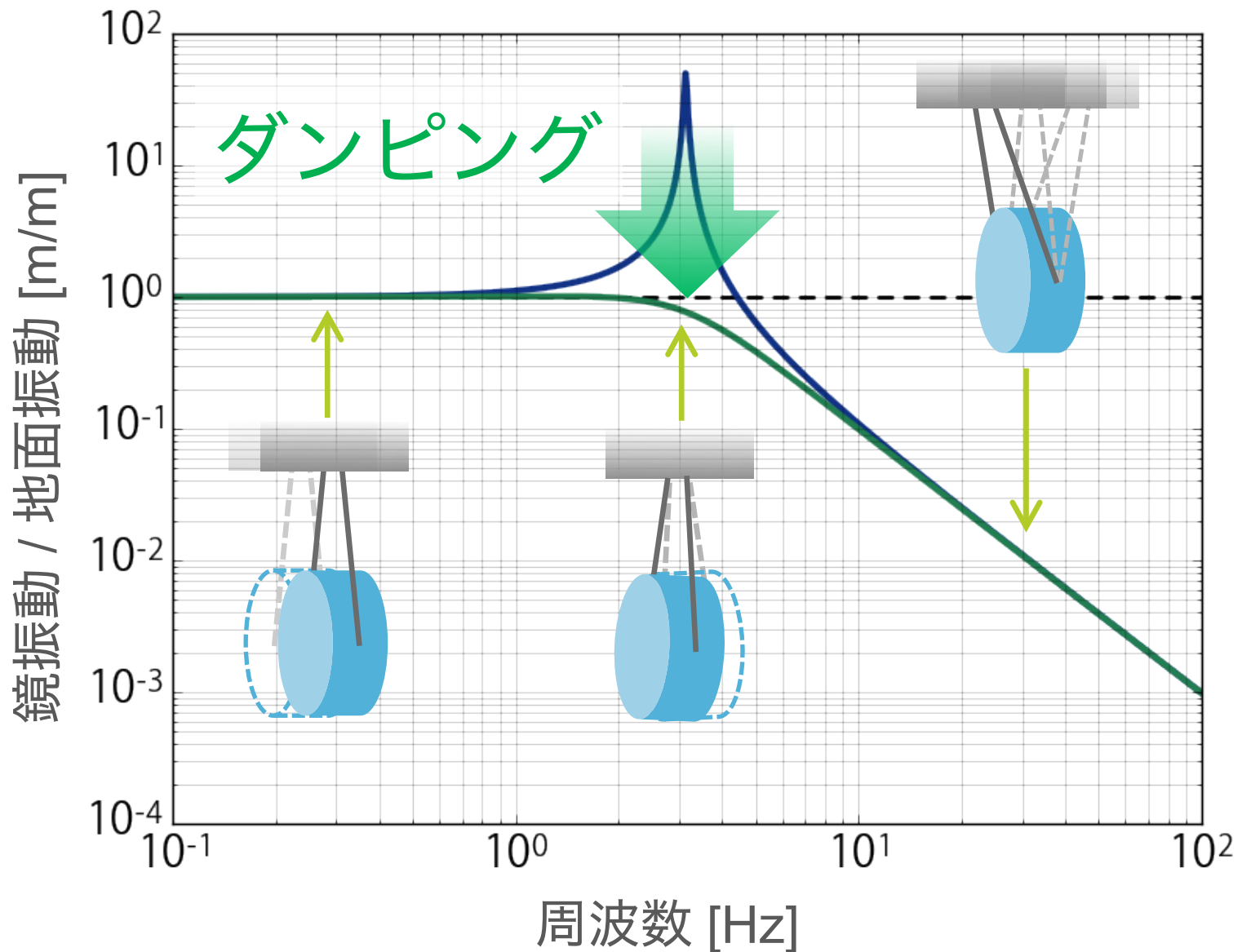
振り子の周波数応答



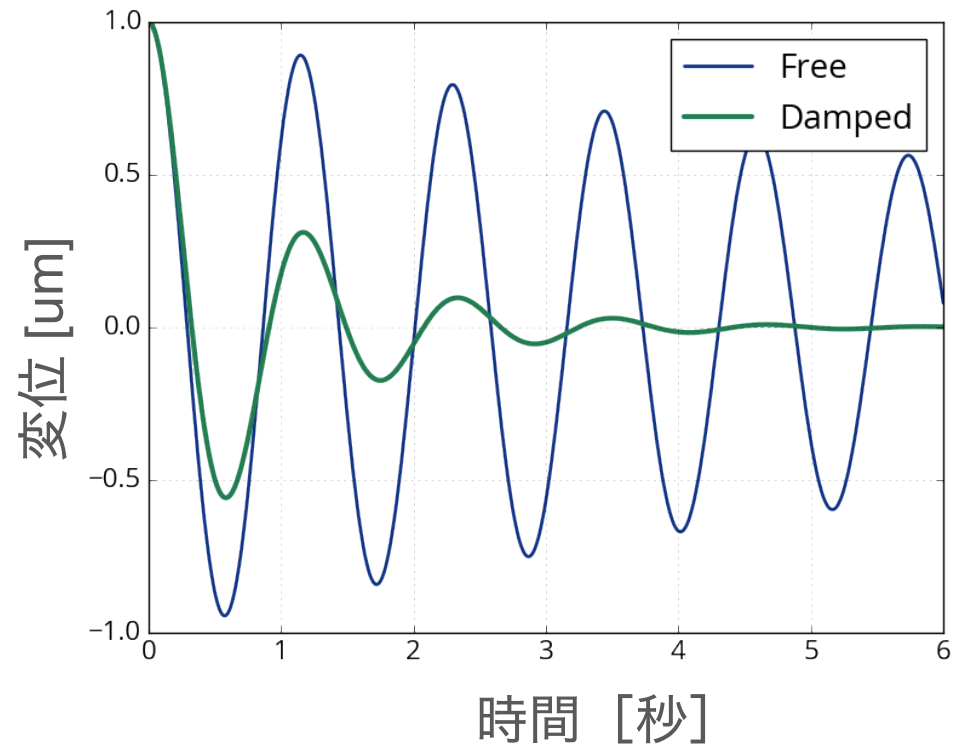
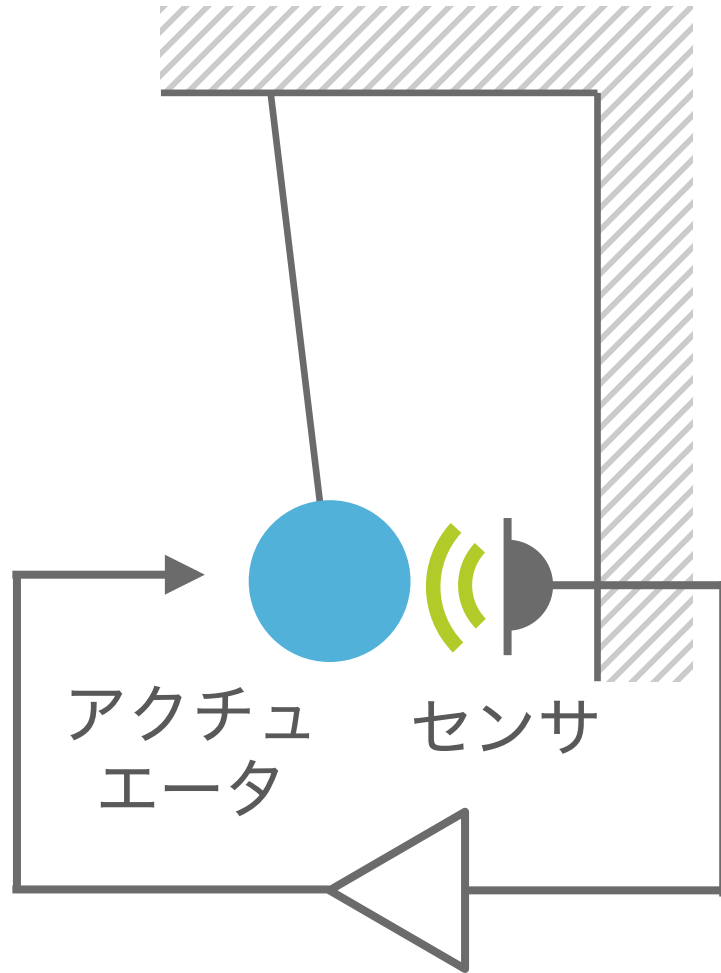
振り子の周波数応答



共振を抑制するには...

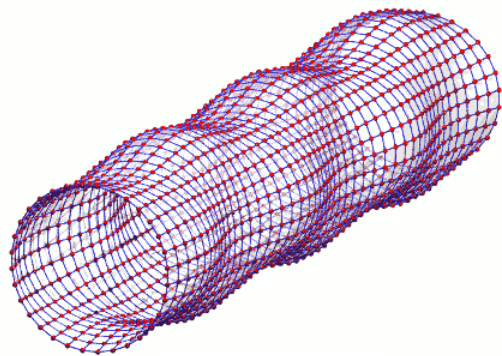


ダンピング制御

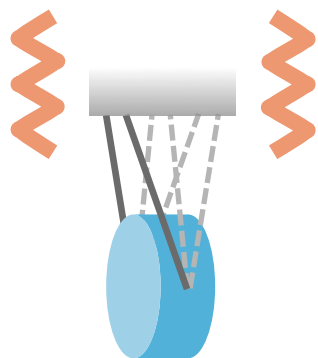


フィードバックされる力 \propto マスの変位

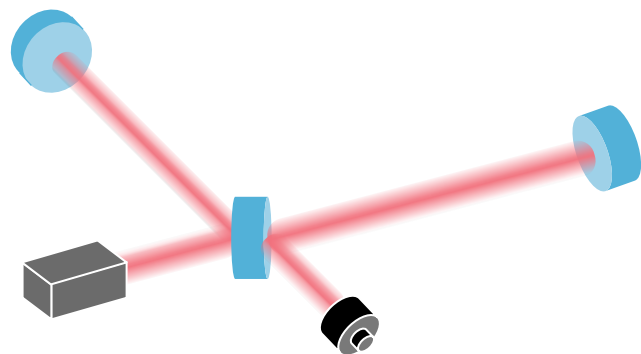
防振懸架系の役割



1. 重力波に対する
自由落下応答

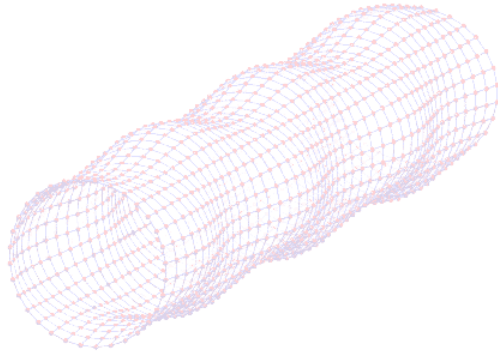


2. 地面振動からの防振

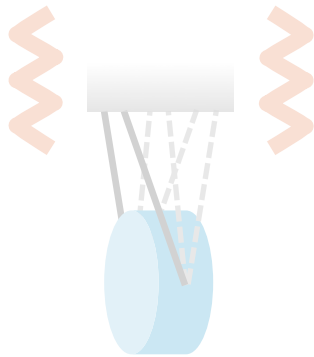


3. 干渉計の制御性能

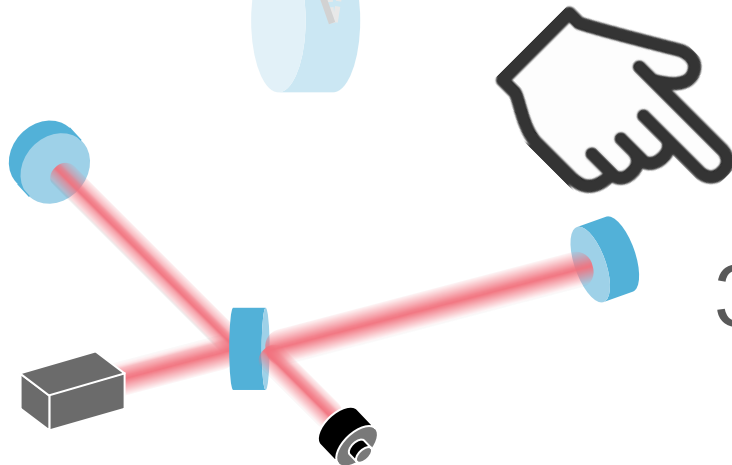
Why Are Mirrors Suspended?



1. Geodesic (free-falling) response to GW

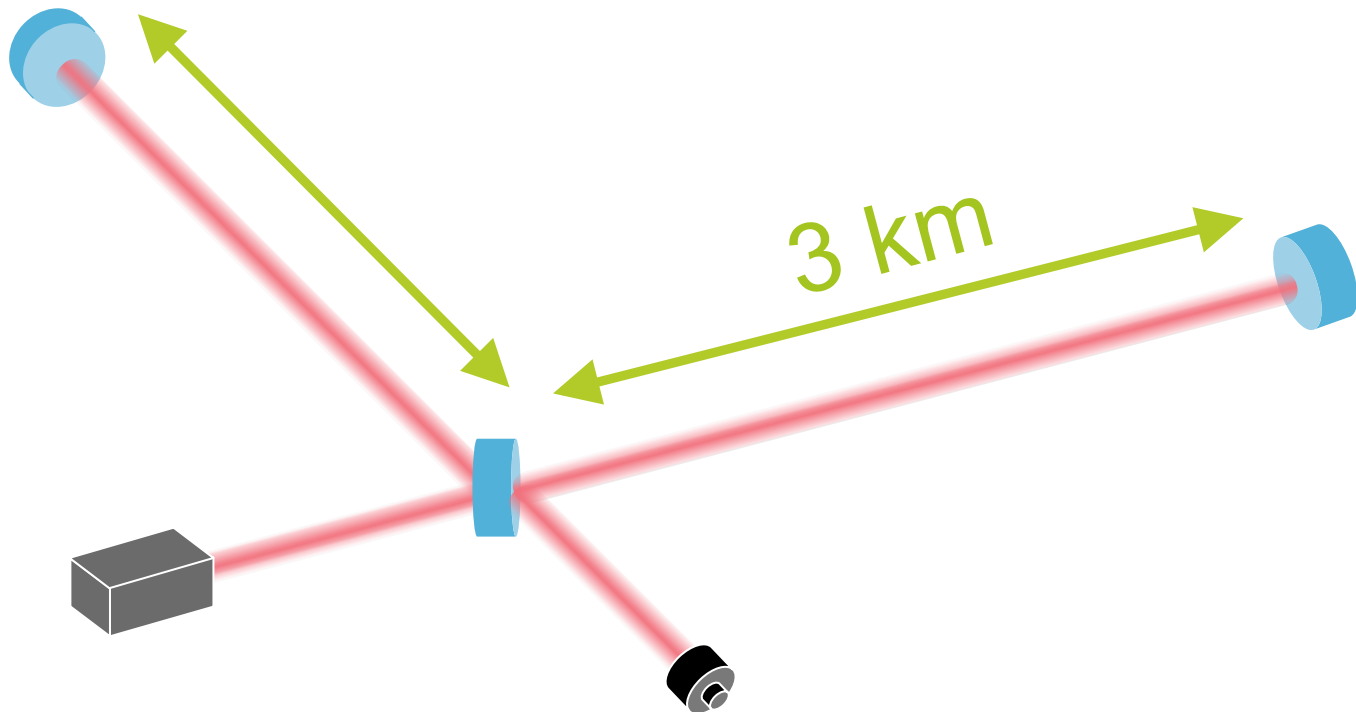


2. Vibration isolation

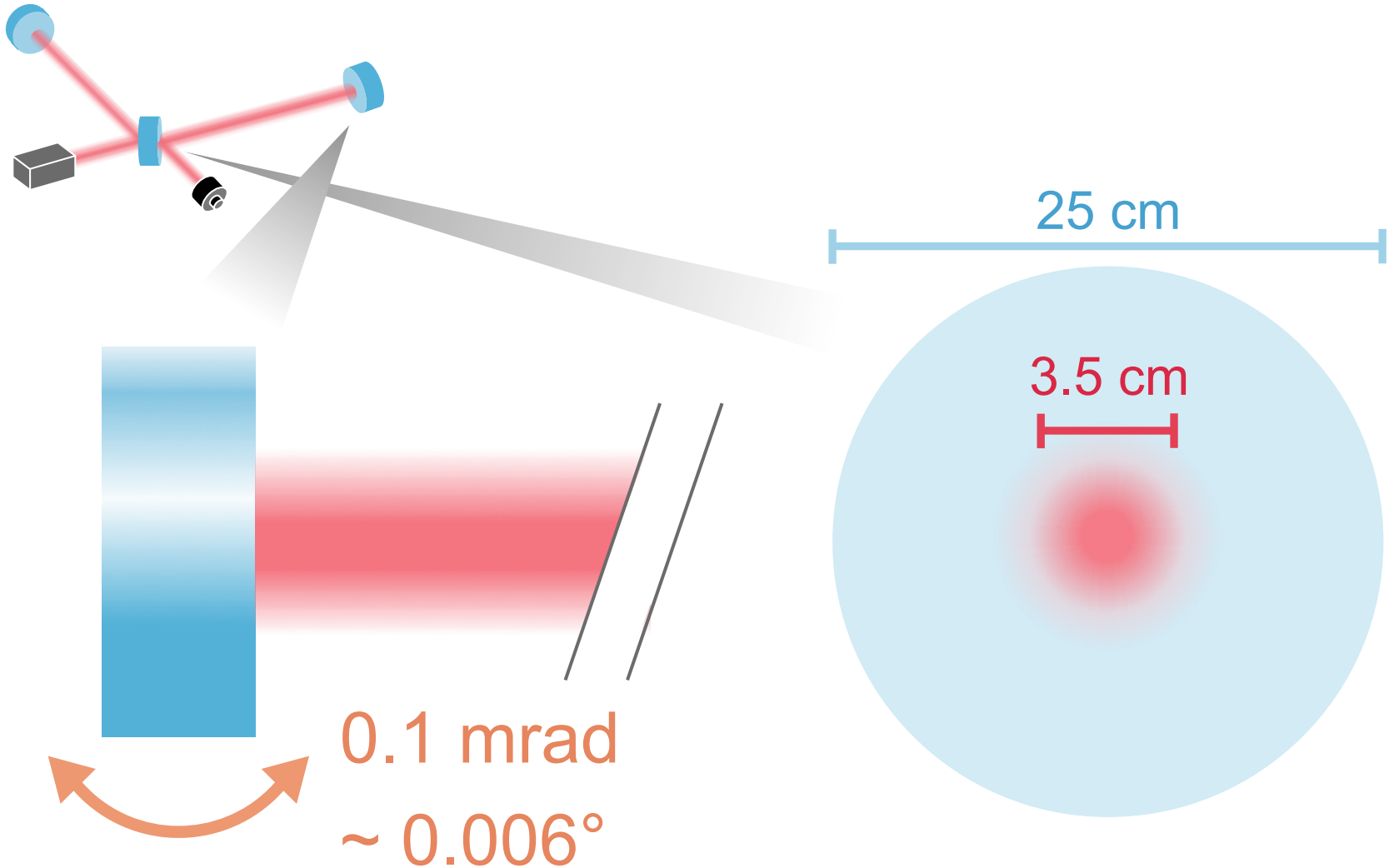


3. Interferometer control

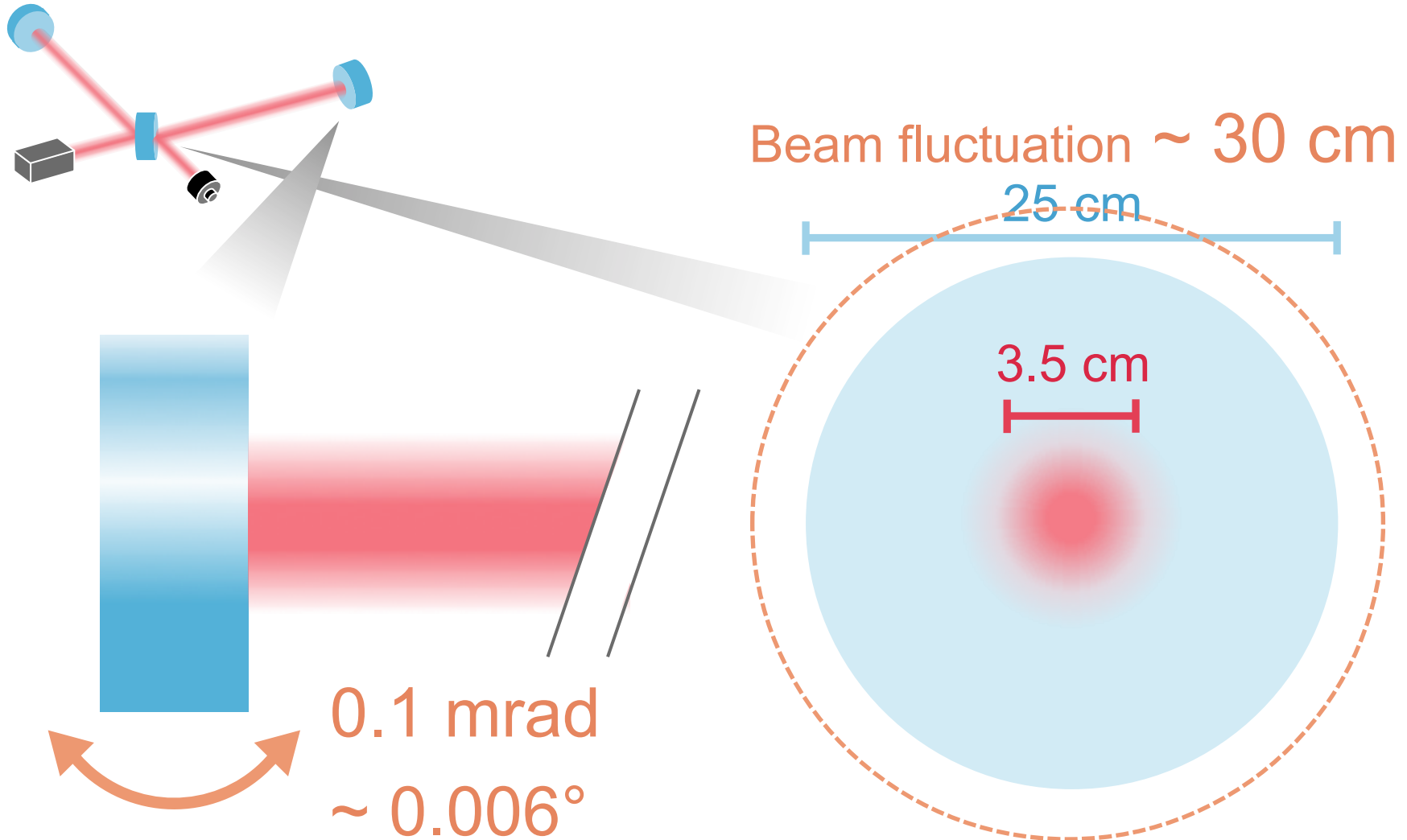
Michelson Interferometer



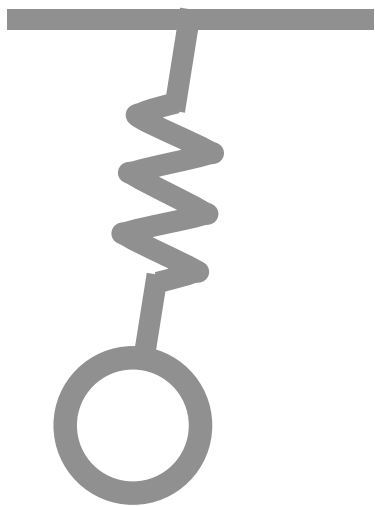
Mirror Alignment



Mirror Alignment

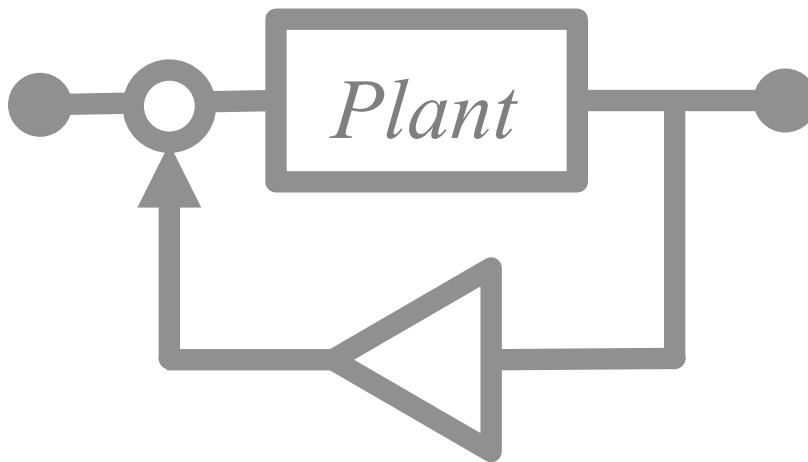


防振懸架系の性能評価



機械的パラメータ
の同定

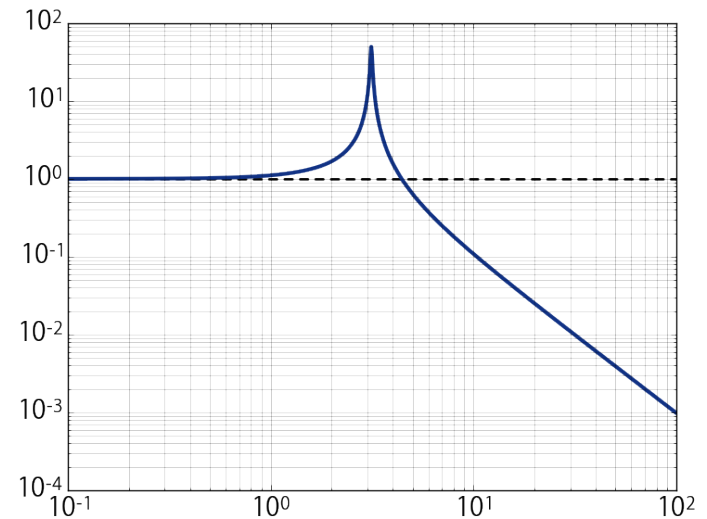
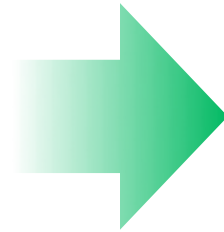
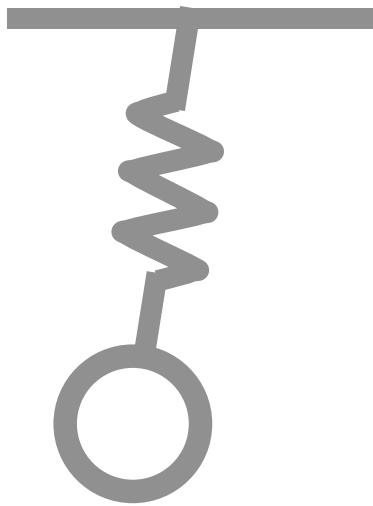
▶ 防振性能



制御系設計

▶ 制御性能

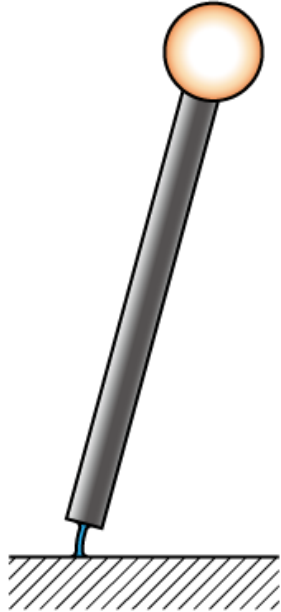
機械的パラメータの同定



- 固有振動モード
周波数
- 振動のQ値

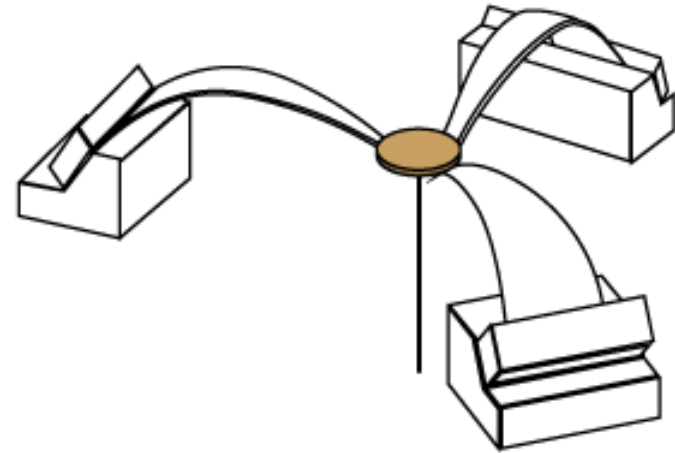
- 伝達関数の測定
- 3D剛体モデルシミュレーションとの比較

Anti-spring Mechanisms



Inverted pendulum
(IP)

~ 0.07 Hz in horizontal

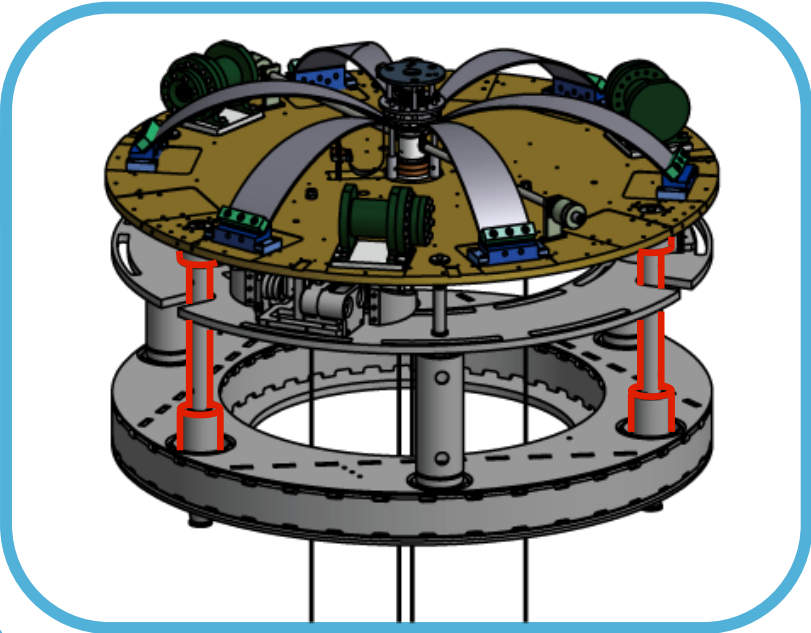
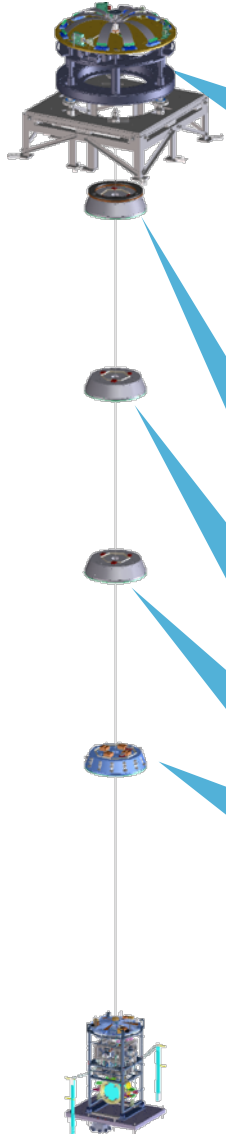


Geometric anti-spring
(GAS)

~ 0.3 Hz in vertical

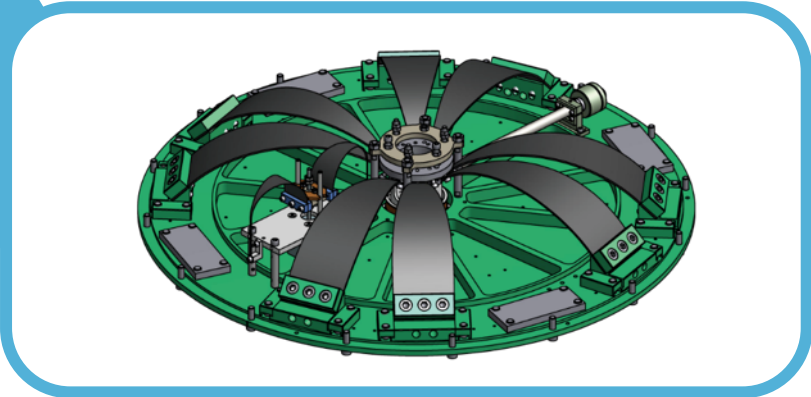
► Adjustable resonant frequency

Anti-spring Mechanisms



IP

Top stage

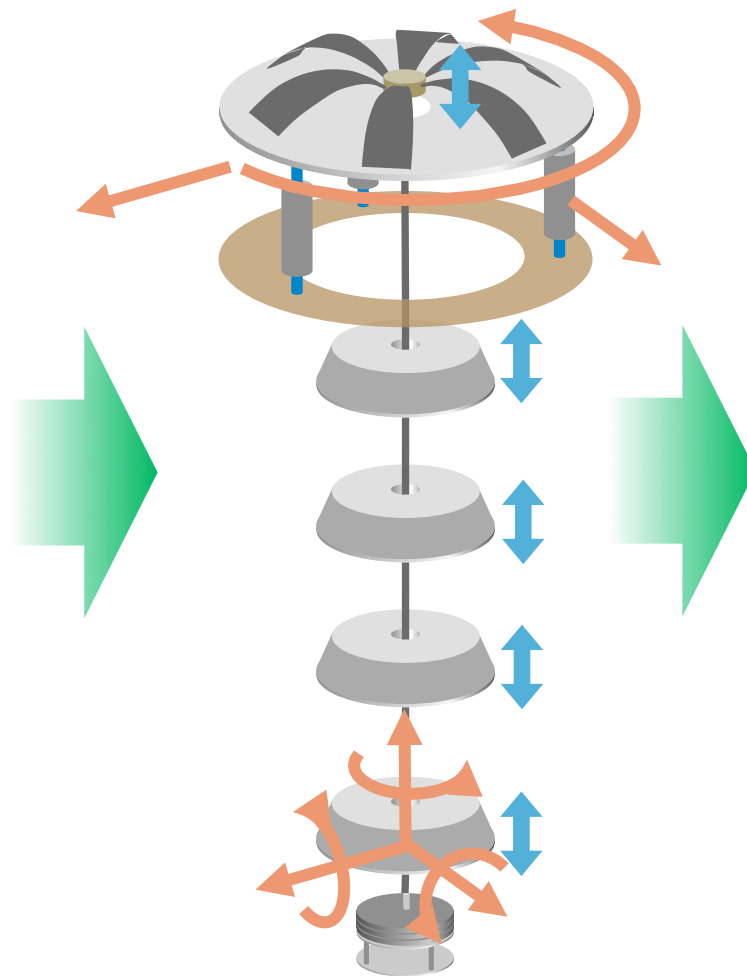


GAS

All tower stages

伝達関数の測定

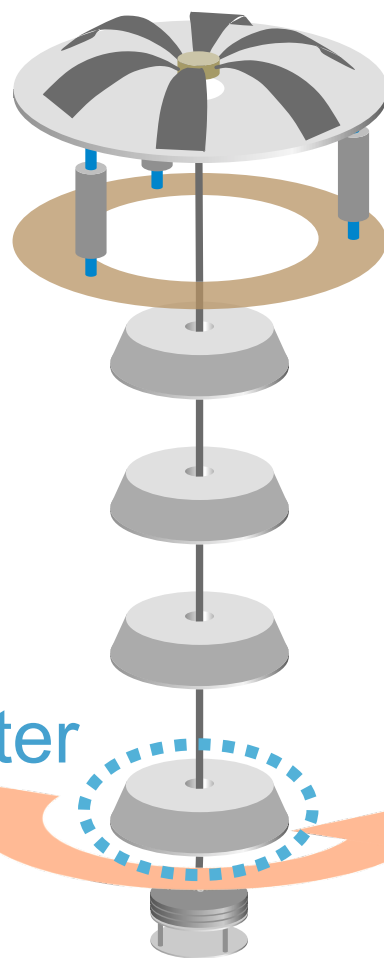
力
or
トルク



並進変位
or
角度変位

伝達関数の測定

力
or
トルク



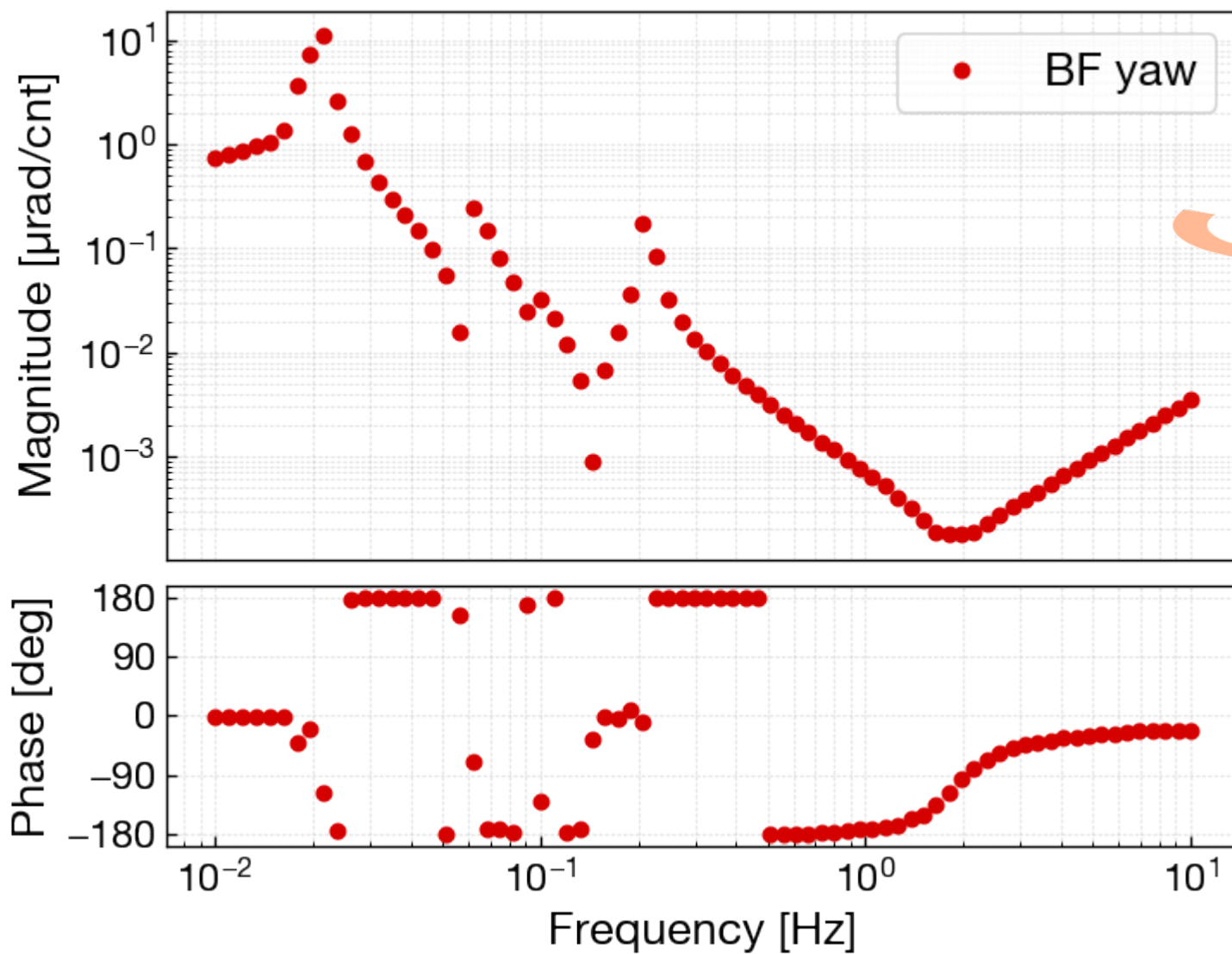
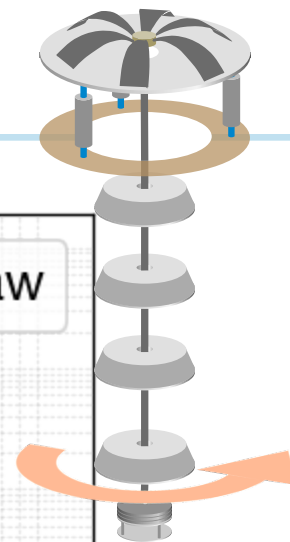
Bottom Filter
(BF)

Yaw

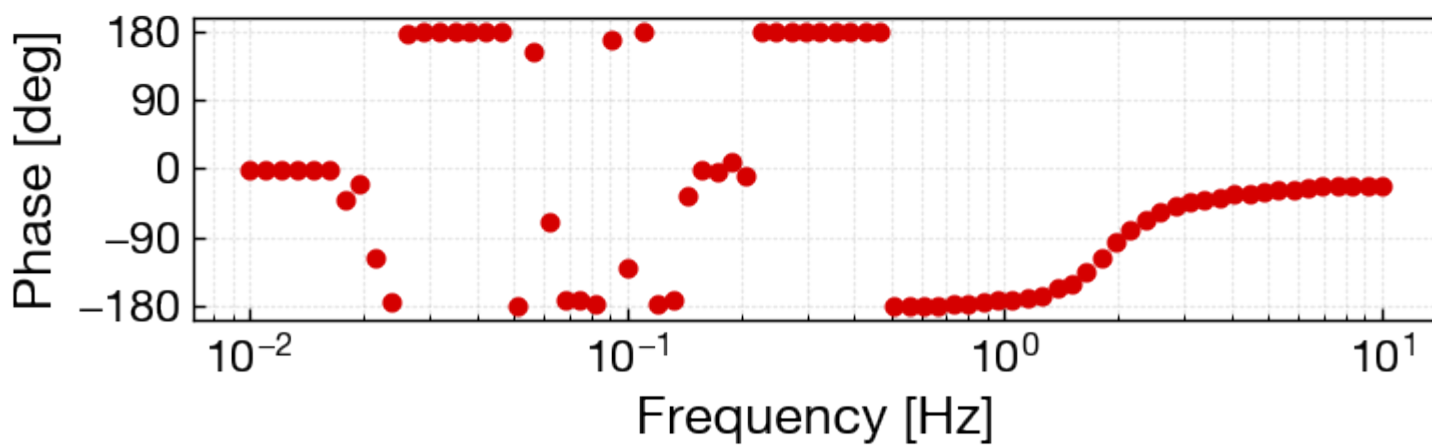
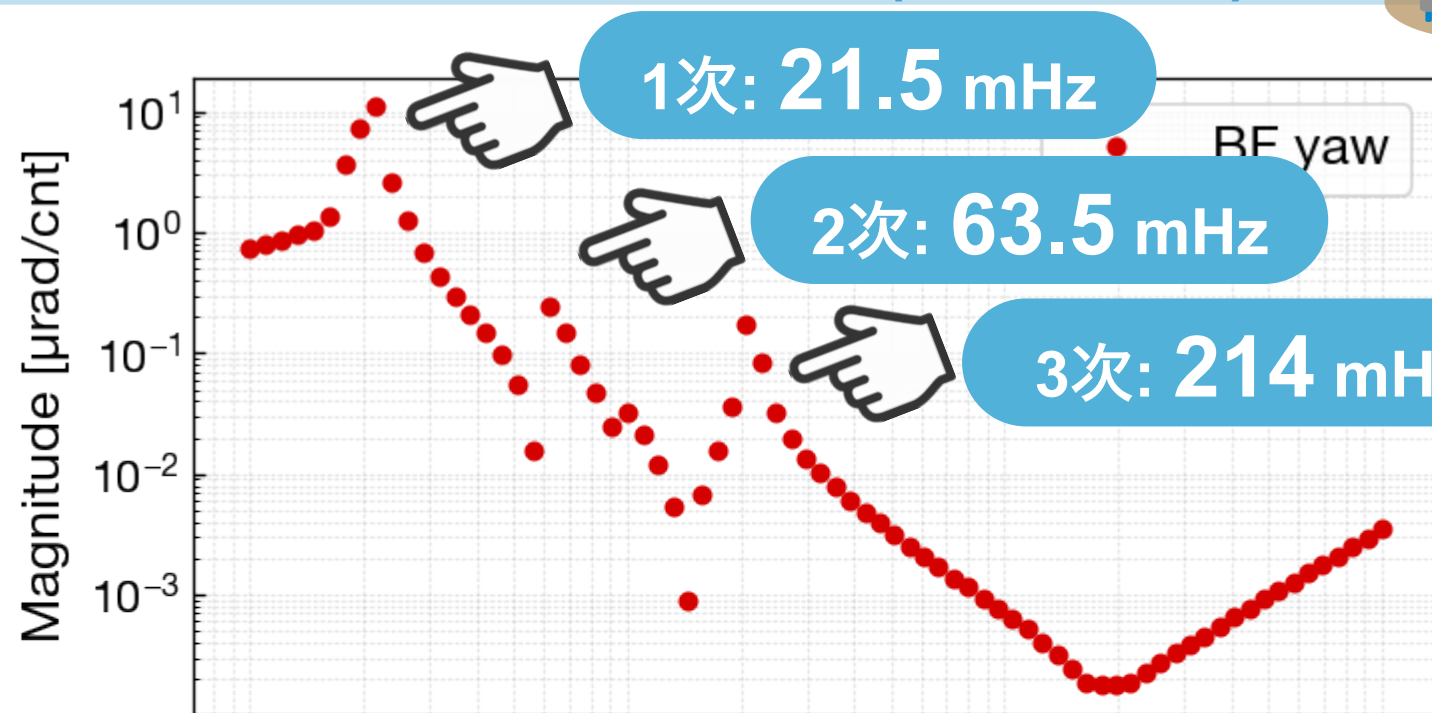
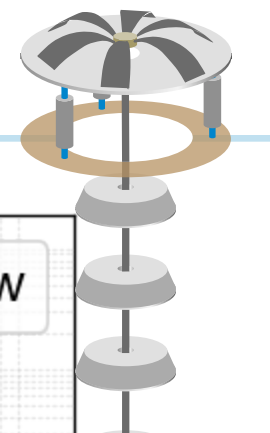


並進変位
or
角度変位

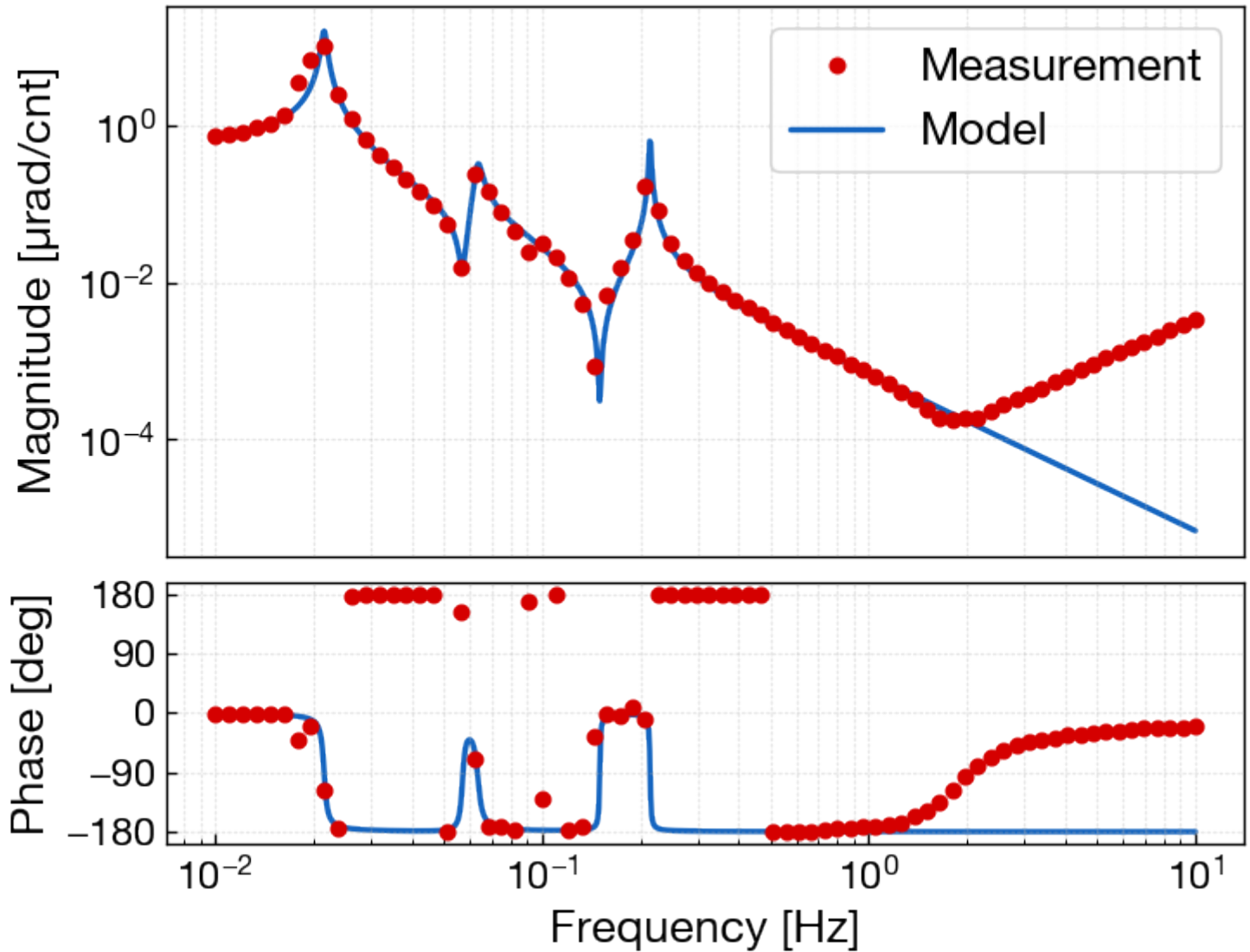
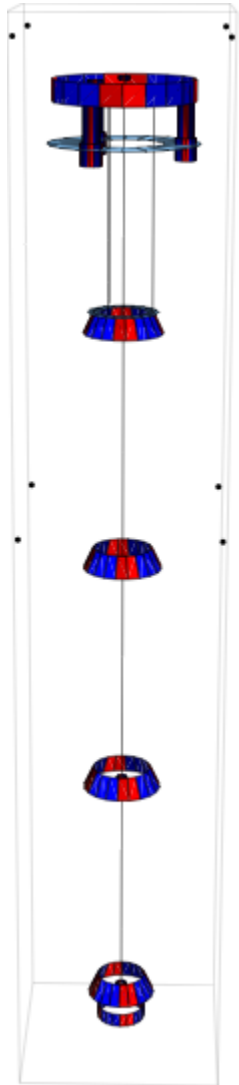
トルク角度伝達関数 (BF Yaw)



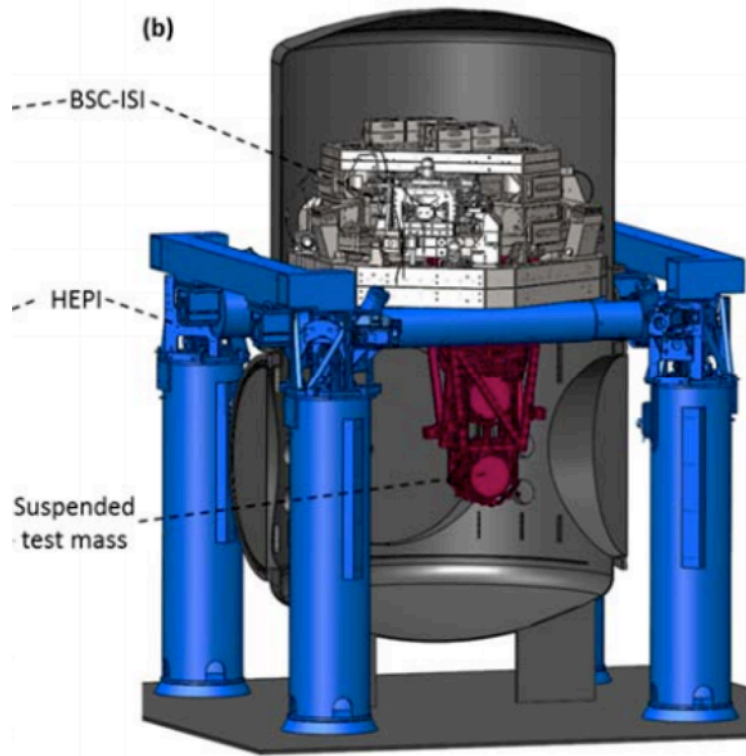
トルク角度伝達関数 (BF Yaw)



モデルとの比較

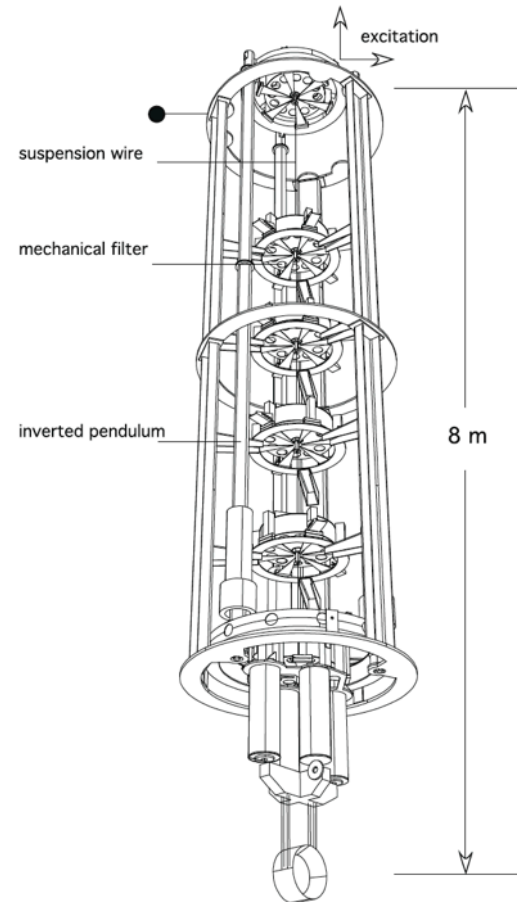


重力波分野における防振システム



LIGO: Quad suspension

$\sim 10^{-12} \text{ m/Hz}^{1/2} @ 10 \text{ Hz}$



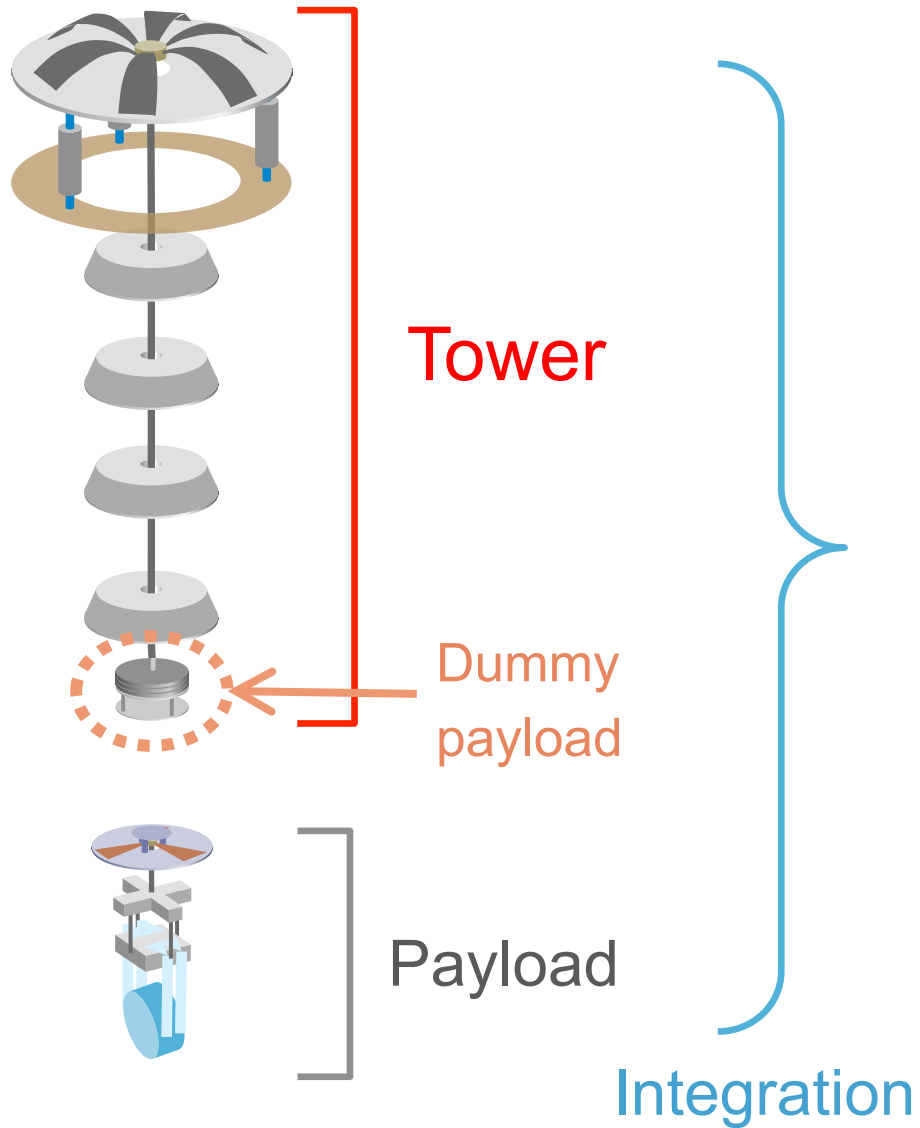
Virgo: Superattenuator

$\sim 10^{-23} \text{ m/Hz}^{1/2} @ 10 \text{ Hz}$

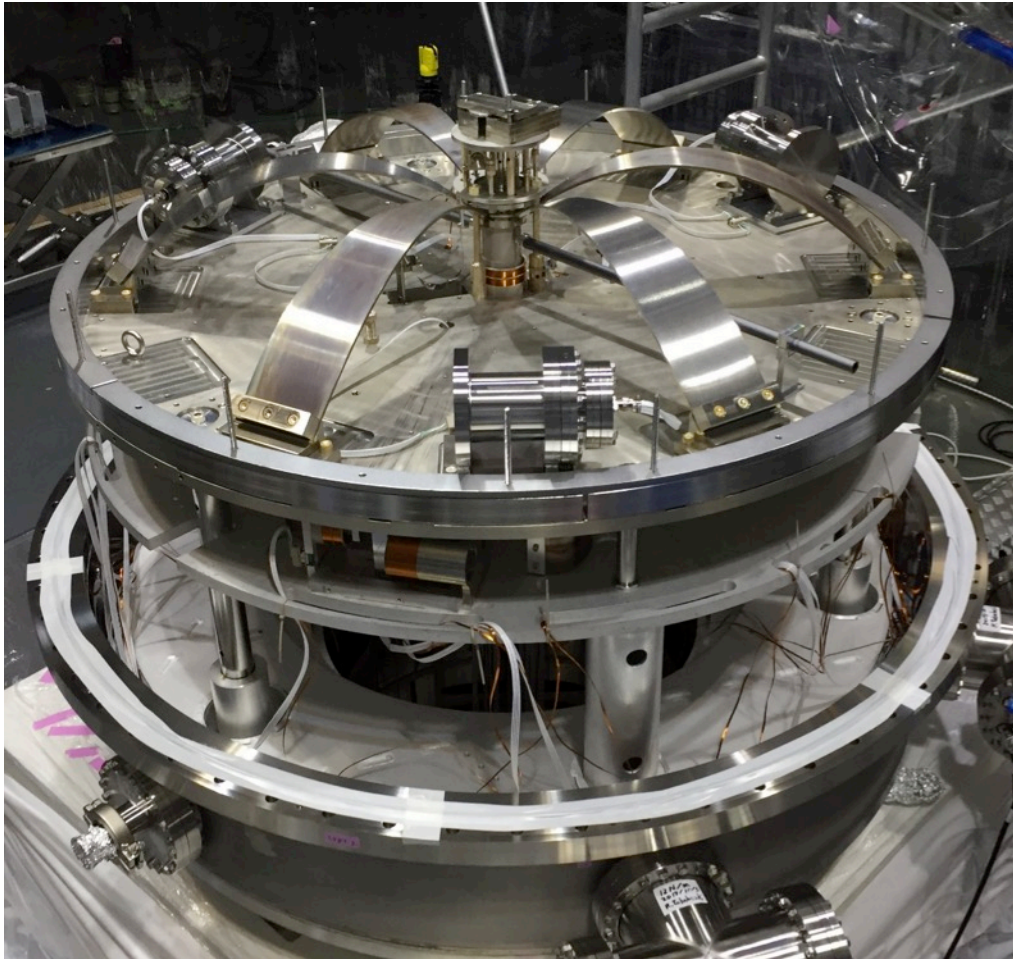
Requirements for Type-A Suspension

		Value	Notes
Mech.	Displacement noise (long.)	$< 8 \times 10^{-20} \text{ m/Hz}^{1/2}$	@ 10 Hz, x10 margined
	Displacement noise (vert.)	$< 8 \times 10^{-18} \text{ m/Hz}^{1/2}$	@ 10 Hz, x10 margined
Control	1/e decay time	$< 60 \text{ sec}$	
	RMS velocity (long.)	$< 0.01 \text{ } \mu\text{m}$	
	RMS displacement	$< 1 \text{ mm}$	
	RMS angle (pitch, yaw)	$< 0.3 \text{ } \mu\text{rad}$	
	Control noise (long.)	$< 1 \times 10^{-19} \text{ m/Hz}^{1/2}$	

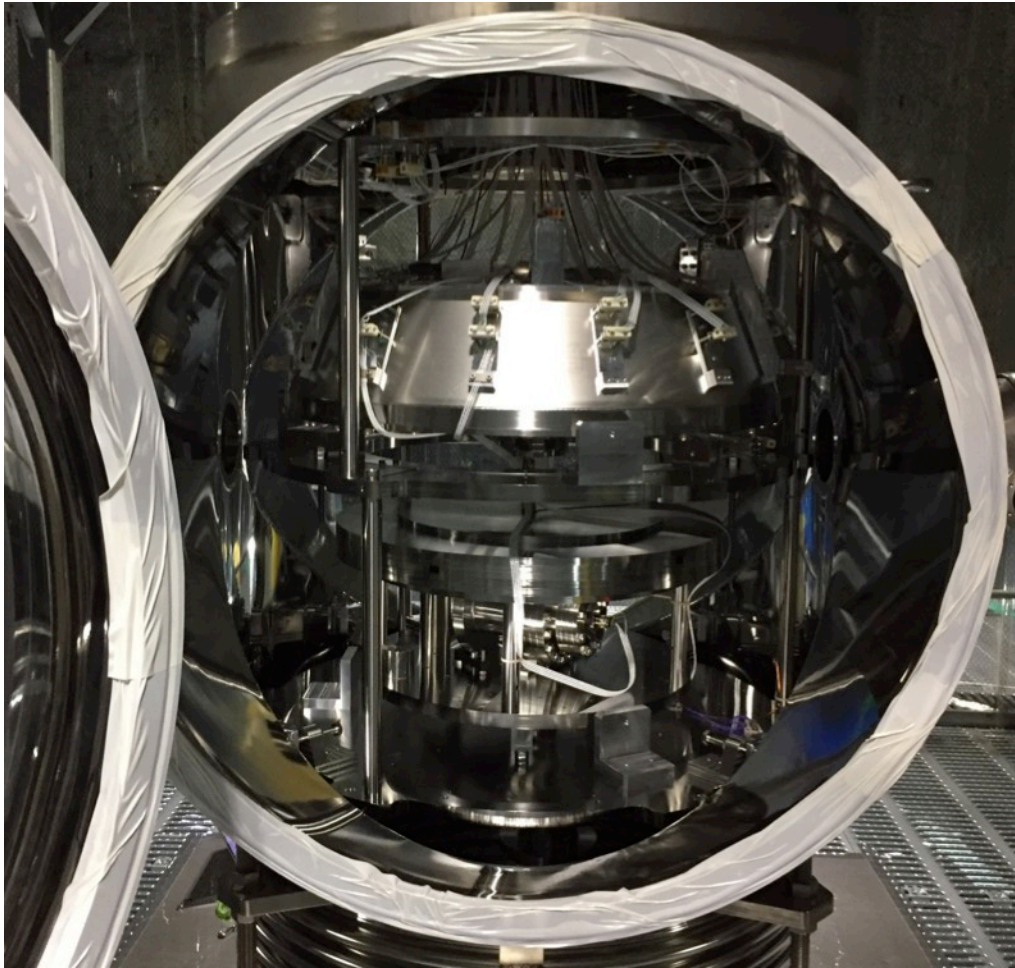
Installation



Installation

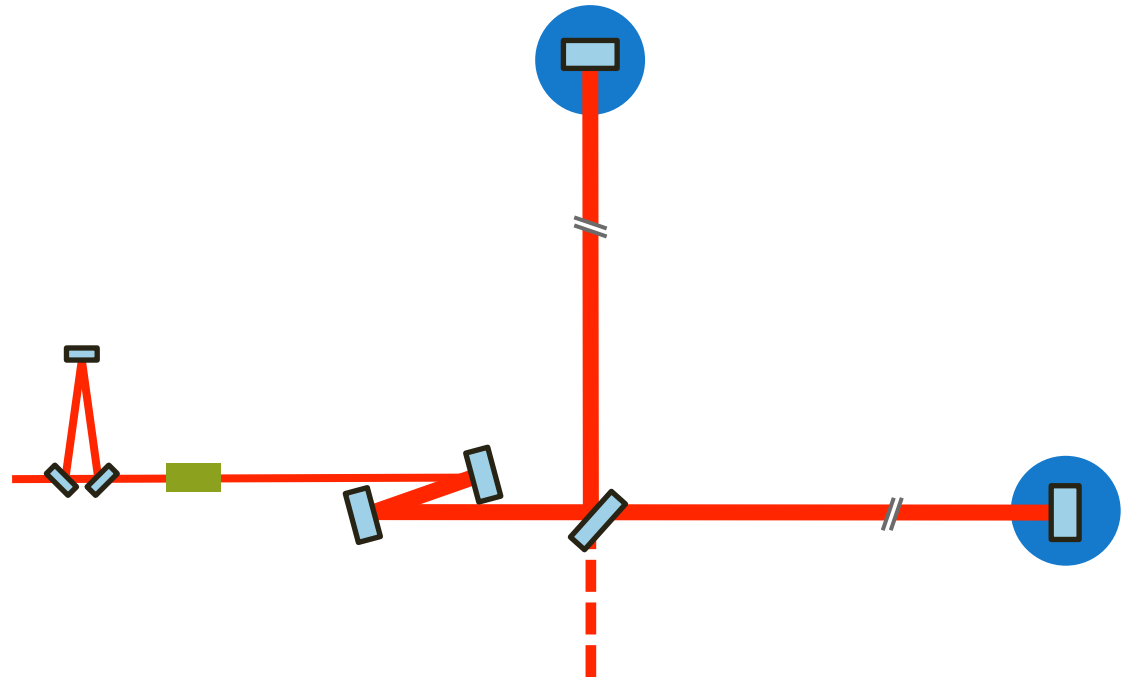
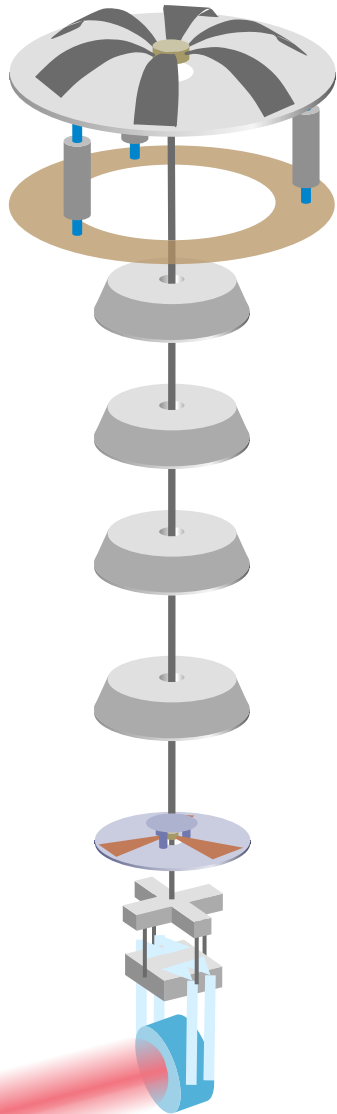


Installation



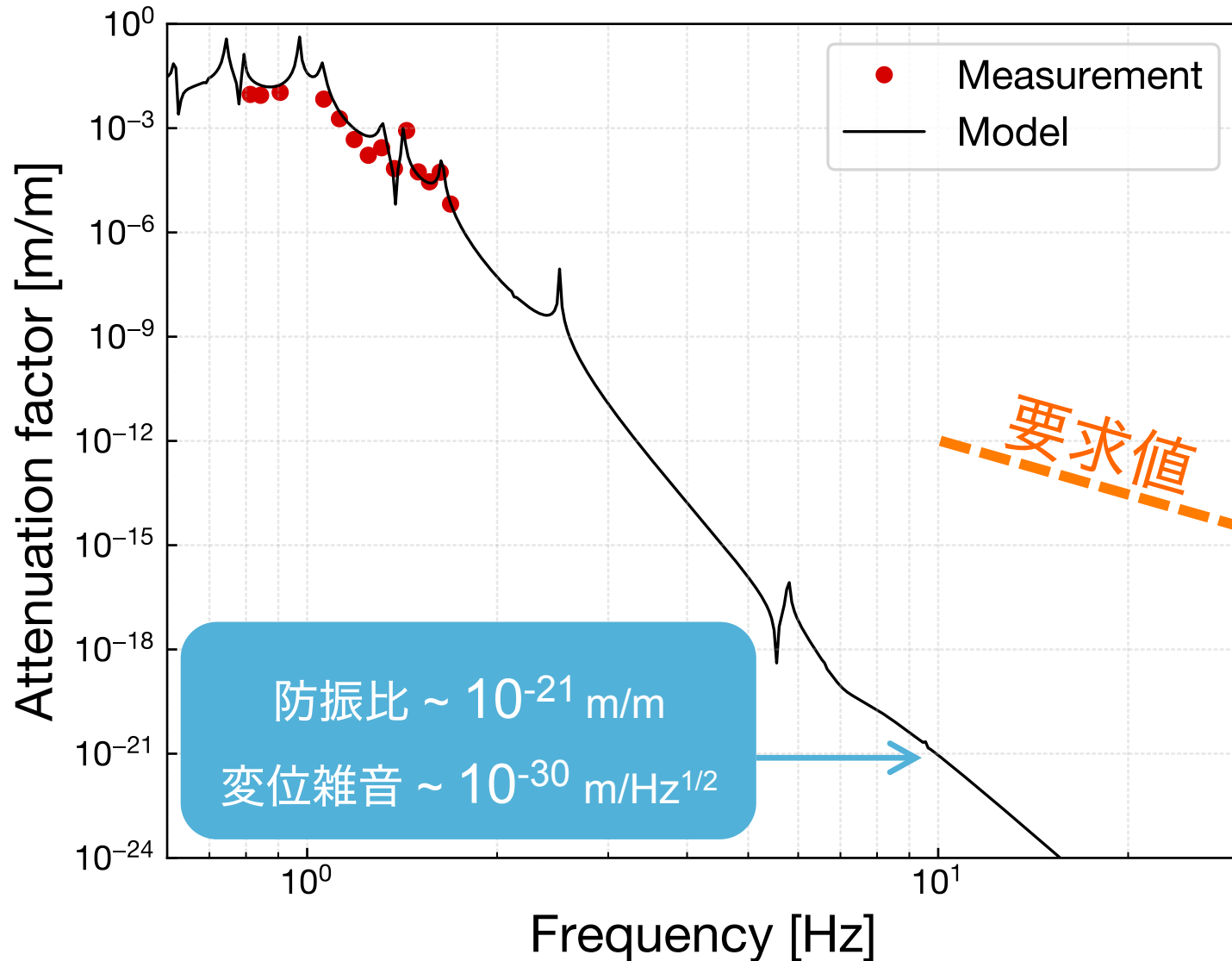
防振性能の評価

Seismic Attenuation Measurement

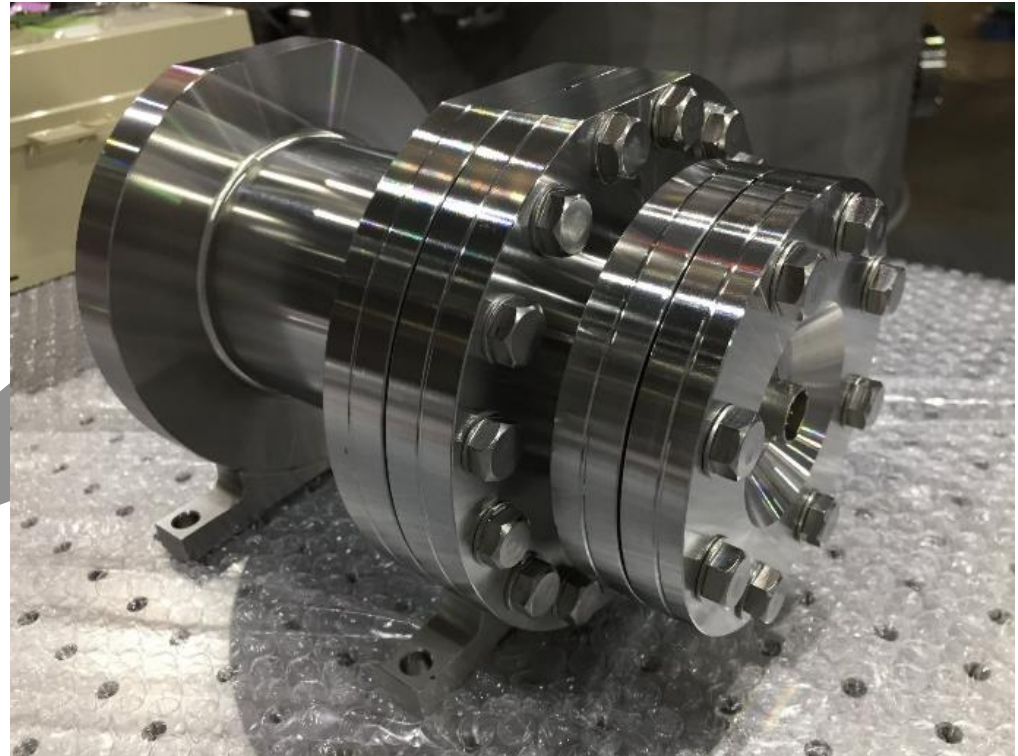
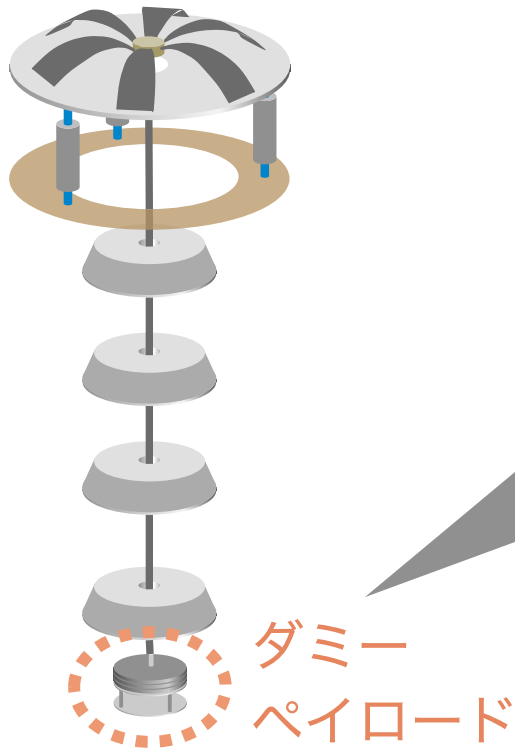


低温Michelson干渉計で防振比の測定
一部帯域で測定 ▶ モデルから全帯域を推定

防振比の測定結果

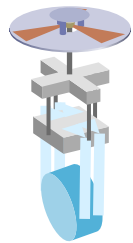


ダミーペイロードでの残留RMS

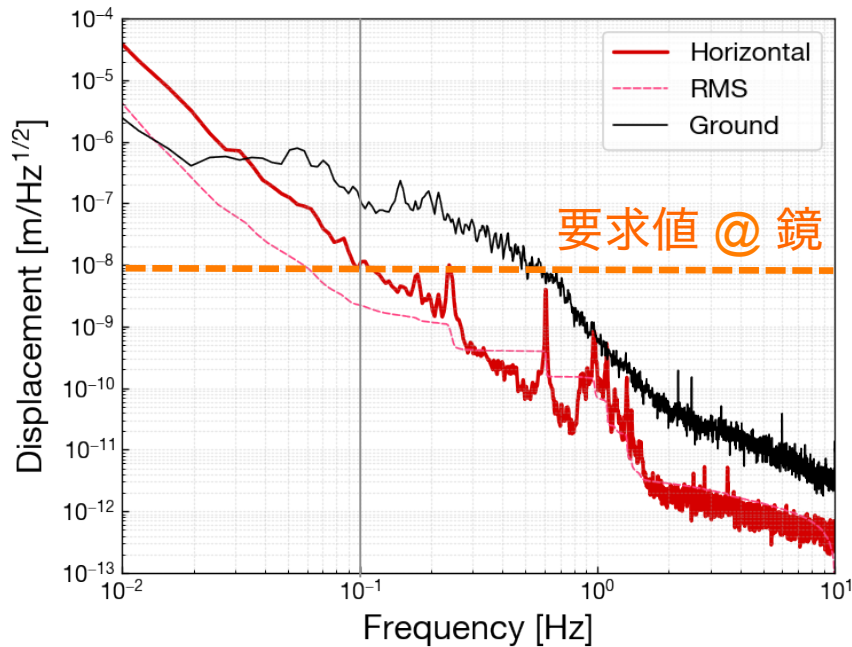


Geophone (速度センサ) x2

▶ 水平方向と鉛直方向のRMSを評価

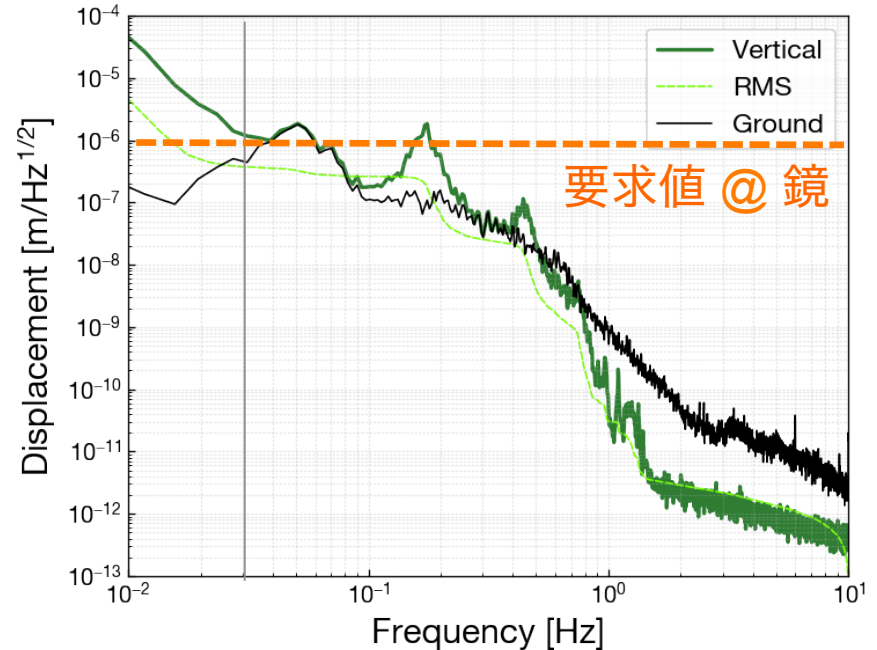


RMS Residual Motion @ DP



Horizontal

$2.2 \times 10^{-9} \text{ m } (> 0.1 \text{ Hz})$

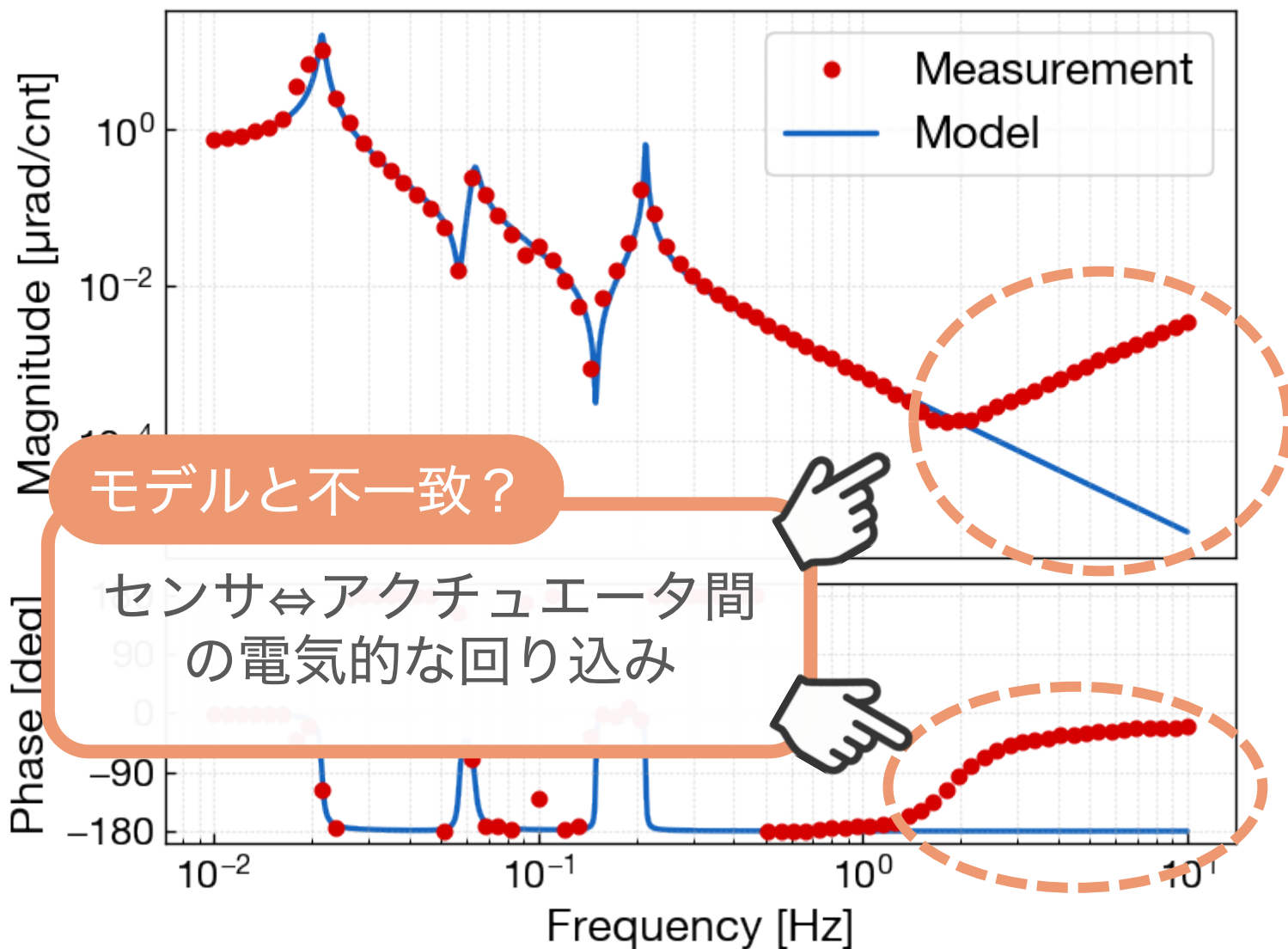
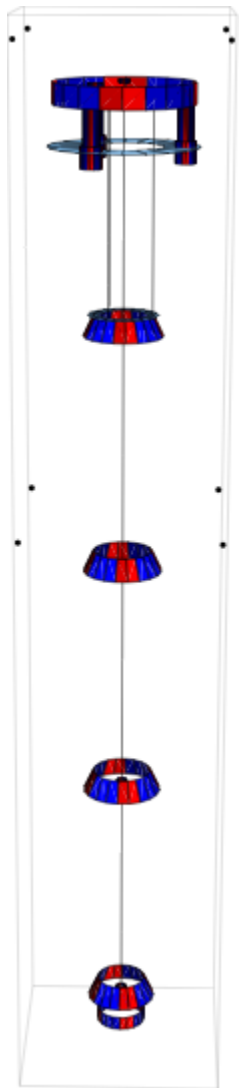


Vertical

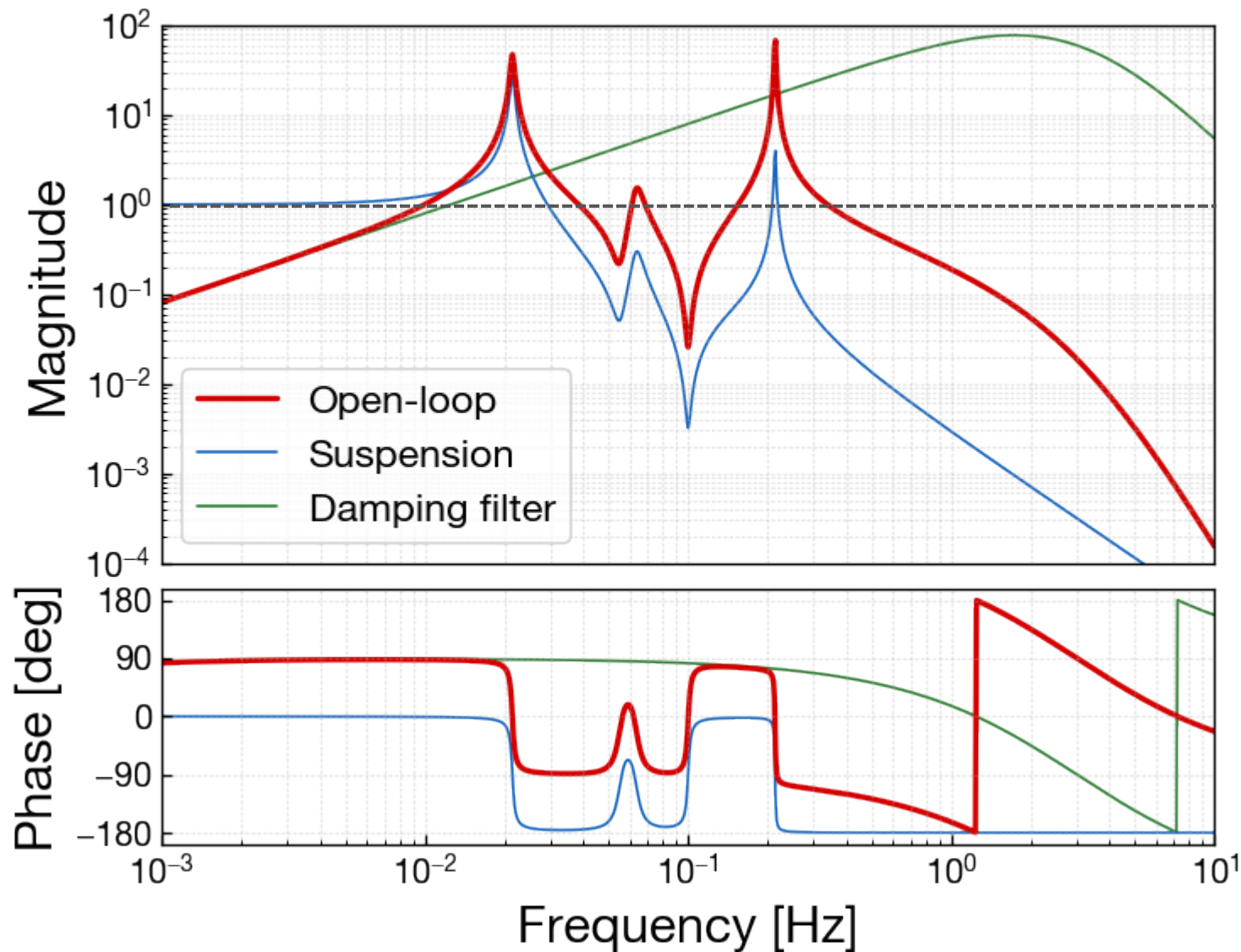
$3.9 \times 10^{-7} \text{ m } (> 0.03 \text{ Hz})$

タワー部の性能としては **OK** ▶ ペイロード接続後再評価

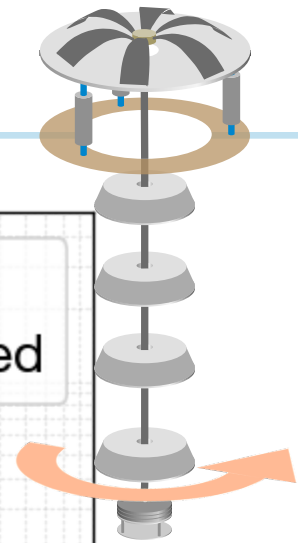
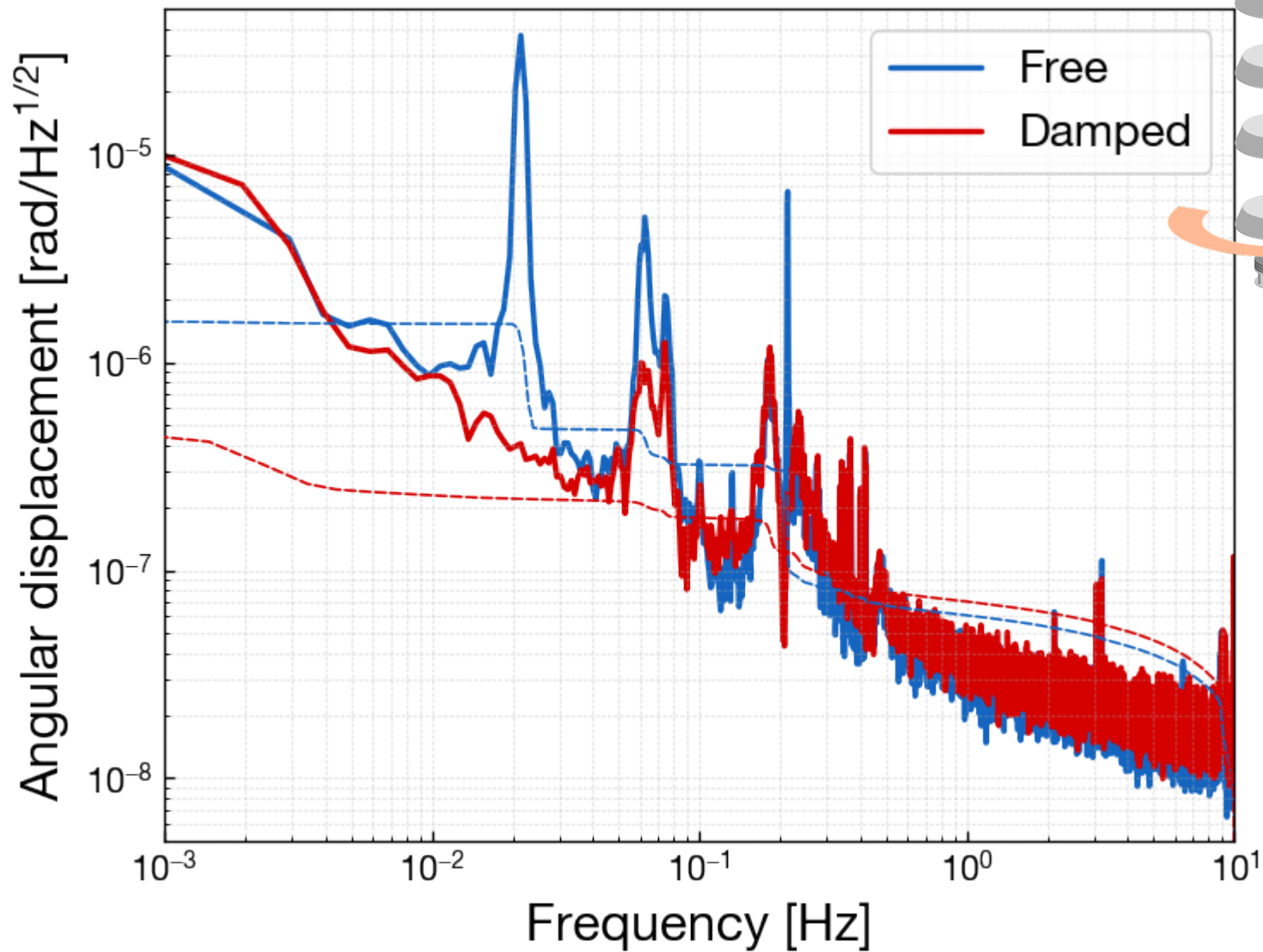
モデルとの比較



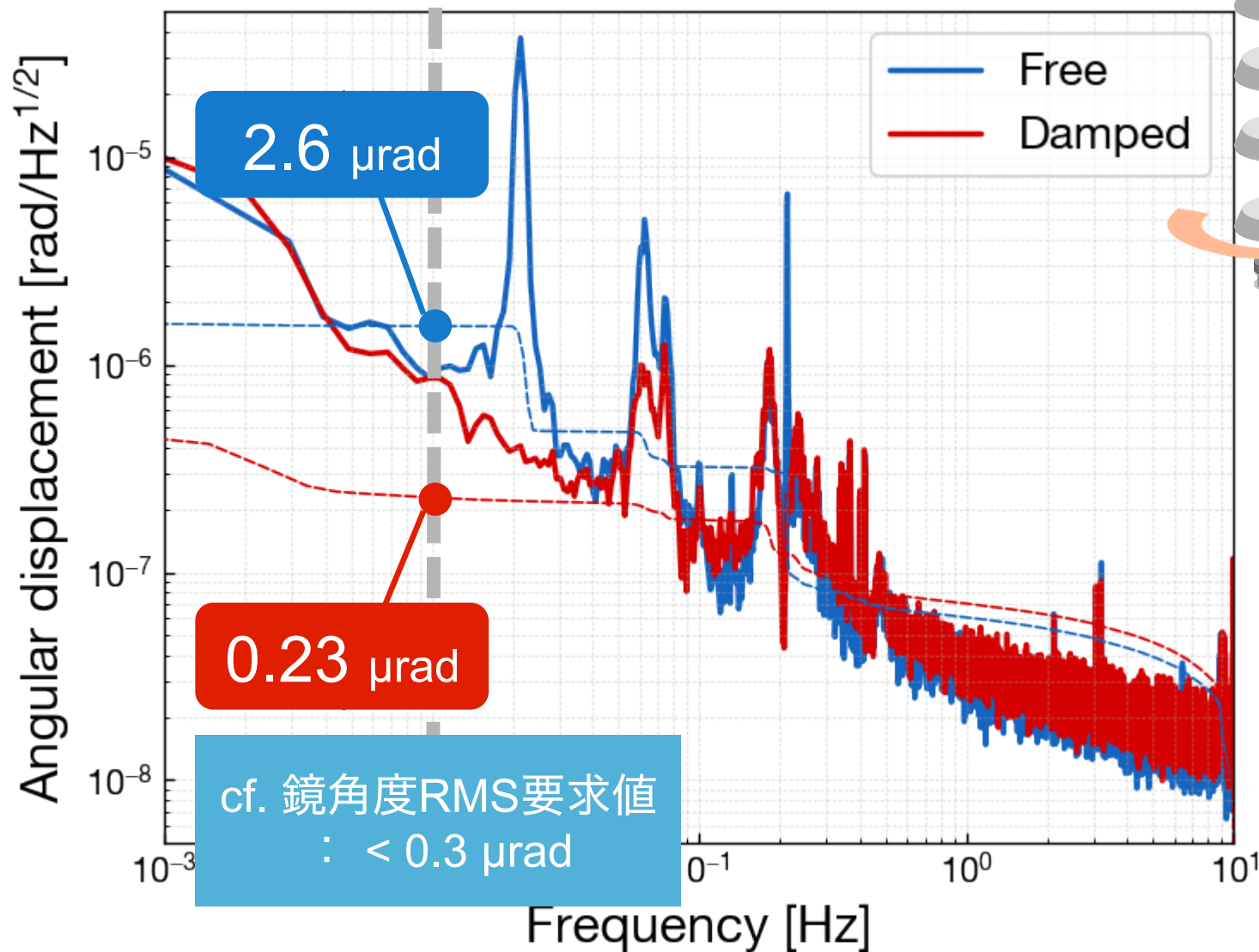
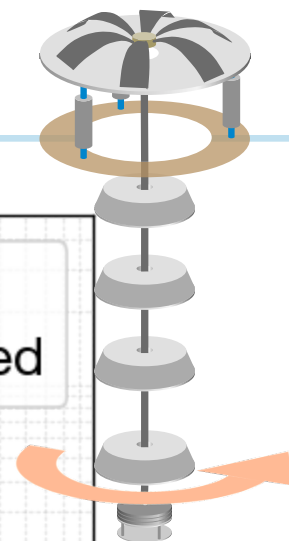
ダンピング制御 - 開ループ伝達関数



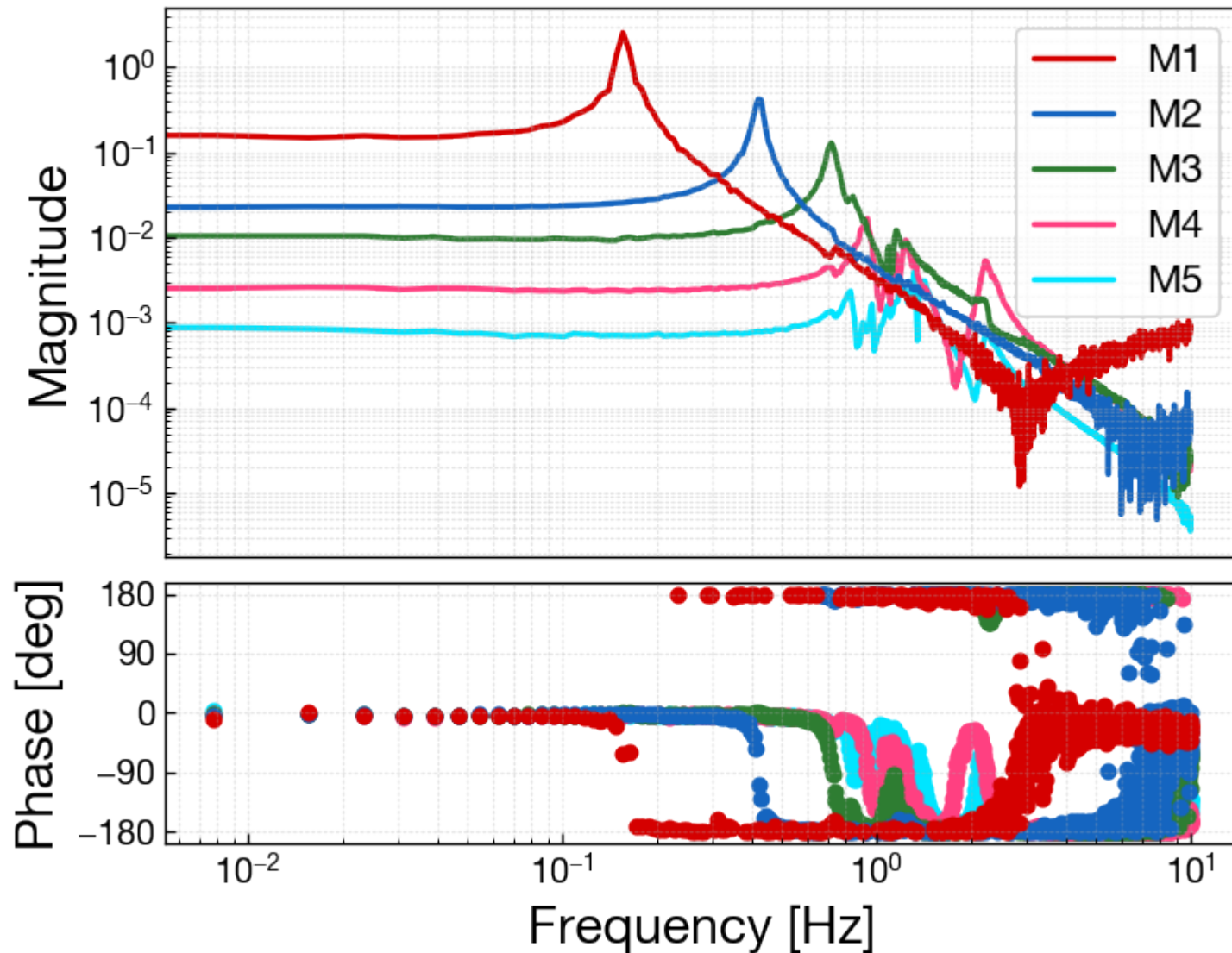
ダンピング制御の結果



ダンピング制御の結果

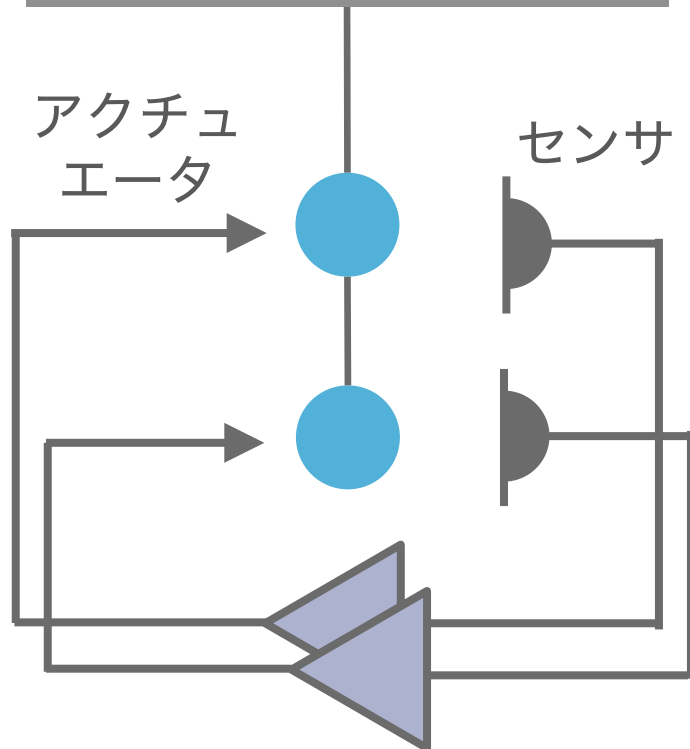


モード座標系での力変位伝達関数



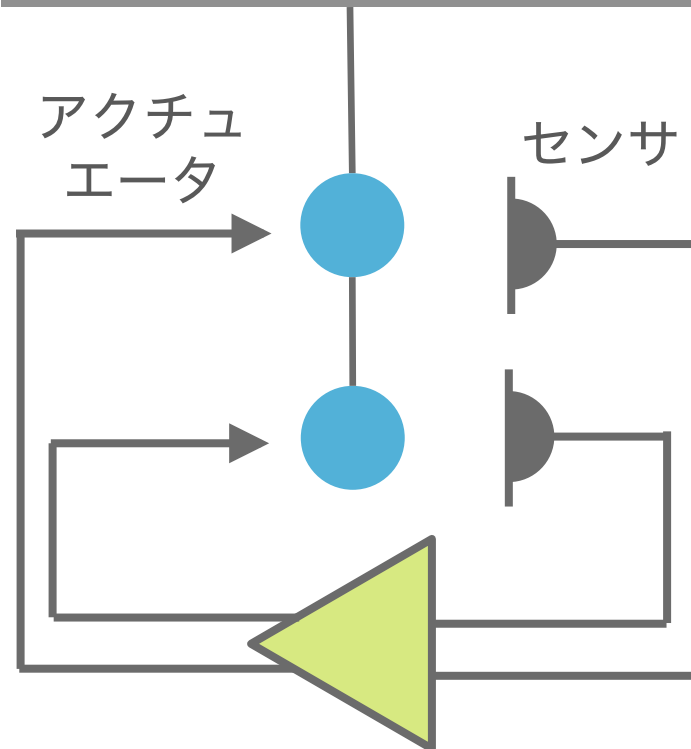
多入力多出力(MIMO)制御とは？

一入力一出力制御



- センサ信号をそれぞれの段のアクチュエータにフィードバック
- 測定した伝達関数をベースにPIDフィルタを設計

多入力多出力制御



- 各段のセンサ信号をまとめて処理してフィードバック信号を分配
- 状態空間モデルと評価関数をベースに最適レギュレータを設計

最適制御

状態空間モデル

$$\dot{\mathbf{x}}(t) = \underline{A}\mathbf{x}(t) + \underline{B}\mathbf{u}(t)$$

$$\mathbf{y}(t) = \underline{C}\mathbf{x}(t) + \underline{D}\mathbf{u}(t)$$

状態変数

入力

評価関数 $J = \int_0^{t_f} [\mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t)] dt$

重み付け行列

➤ 最適フィードバックゲイン

$$\mathbf{u}(t) = -\mathbf{F}\mathbf{x}(t), \quad \mathbf{F} = \mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}$$

MIMO制御の長所と短所

- 多段フィードバックを自動的に計算
 - KAGRAの防振システムのような多自由度連成振動系の制御に適する
- モデルをベースとした制御
 - 物理パラメータの時間変化やロバスト性などを定量的に考慮できる（応用）
- × 性能がモデリング精度に依存
 - 実システムとモデルの誤差を減らす必要

重力波分野における現代制御

T. Accadia et al., Rev. Sci. Instrum. **82**, 094052 (2011)

- KalmanフィルタによるVirgo倒立振り子の状態推定

M. Beker et al., Rev. Sci. Instrum. **85**, 034501 (2014)

- Virgo external optical benchの最適制御

B. Shapiro PhD Thesis (2012)

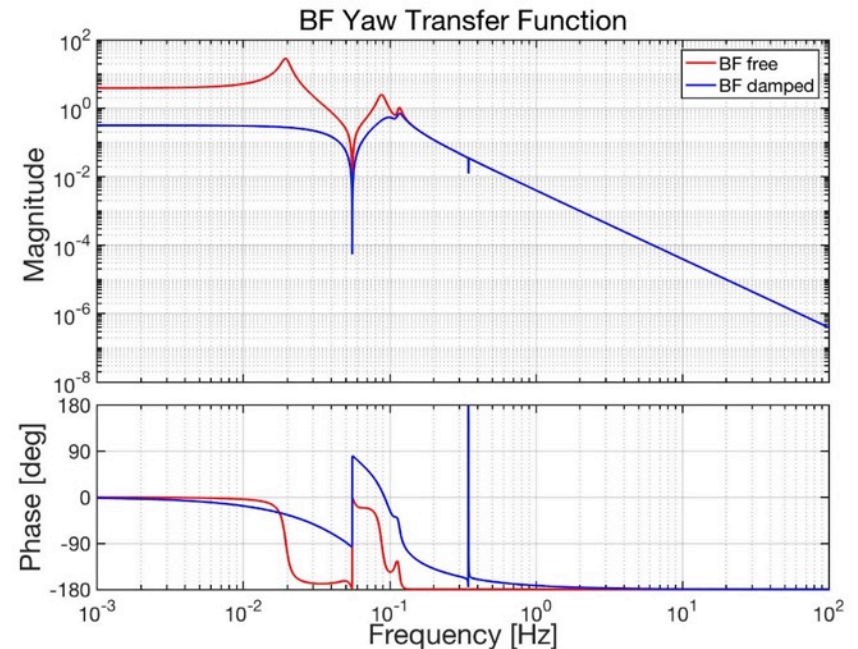
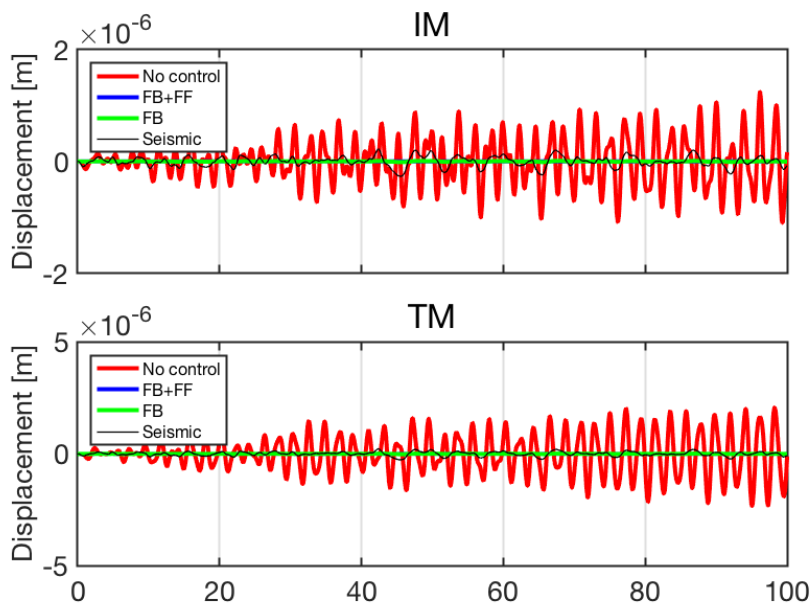
- LIGO quad suspensionの適応モーダルダンピング

D. Martynov PhD Thesis (2015)

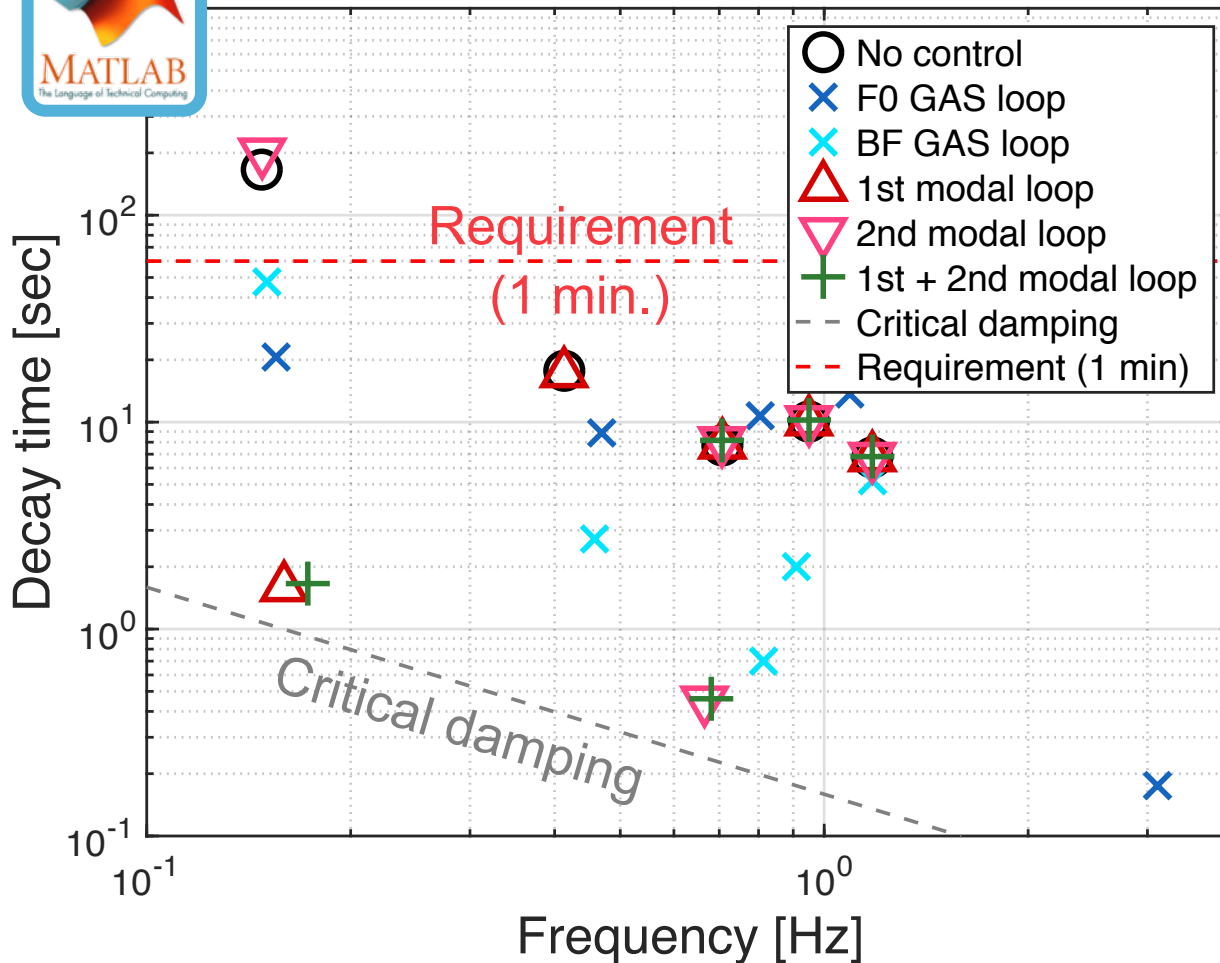
- LIGO quad suspensionの光てこ制御における H_{∞} 制御

最適制御の実装に向けて

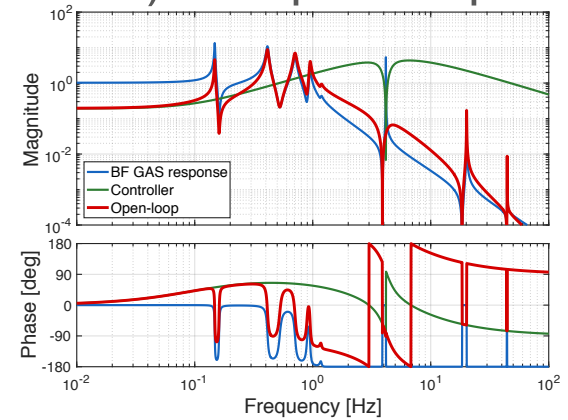
- ✓ 2段振り子トイモデルによる検証
- ✓ Type-Aモデルを用いたGASモーダルダンピング
- Type-Aモデルでの最適制御の調整
- KAGRAデジタルシステムへ実装・性能評価



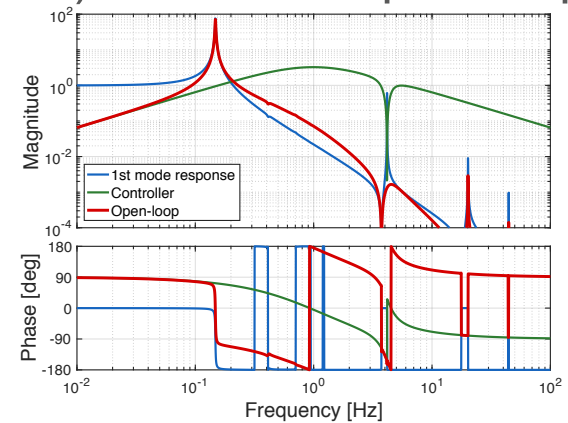
Decay Time with Damping Simulation



ex) BF open-loop



ex) 1st modal open-loop



Implementation

$$\begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix} = \underbrace{\Phi^{-1}}_{\text{Eigenmode matrix}} \mathbf{M} \begin{bmatrix} V_{F0GAS} \\ V_{F1GAS} \\ V_{F2GAS} \\ V_{F3GAS} \\ V_{BFGAS} \end{bmatrix}$$

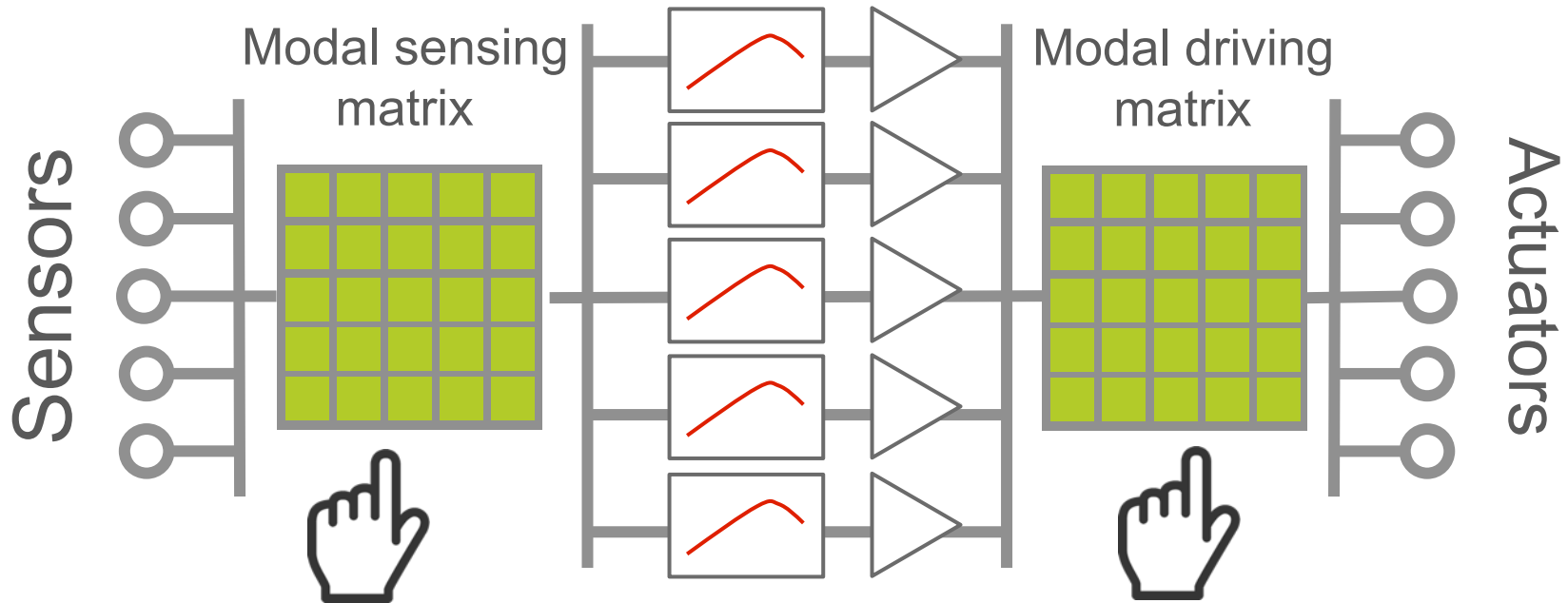
$\Phi_{\text{model}} \longleftrightarrow \Phi_{\text{real}}$
Mismatch



Imperfect
mode decoupling

➤ 😊 Let's do Diagonalization!

Sensor & Actuator Diagonalization



Excited at each mode frequency

DC gain in modal transfer functions

Update the matrix to cancel coupling elements