Integrity 2024

Yuta Michimura
RESCEU, University of Tokyo

Who am I?

- PhD in 2015 from Tsubono → Ando Group
  - Lorentz invariance test
- July 2014 – March 2022
  - Assistant Professor at Ando Group
- April 2022 – March 2024
  - Research Scientist at LIGO Caltech
- April 2024 –
  - Associate Professor at RESCEU (THE UNIVERSITY OF TOKYO, RESEARCH CENTER FOR THE EARLY UNIVERSE)

理学部4号館6階1615号室

Contents

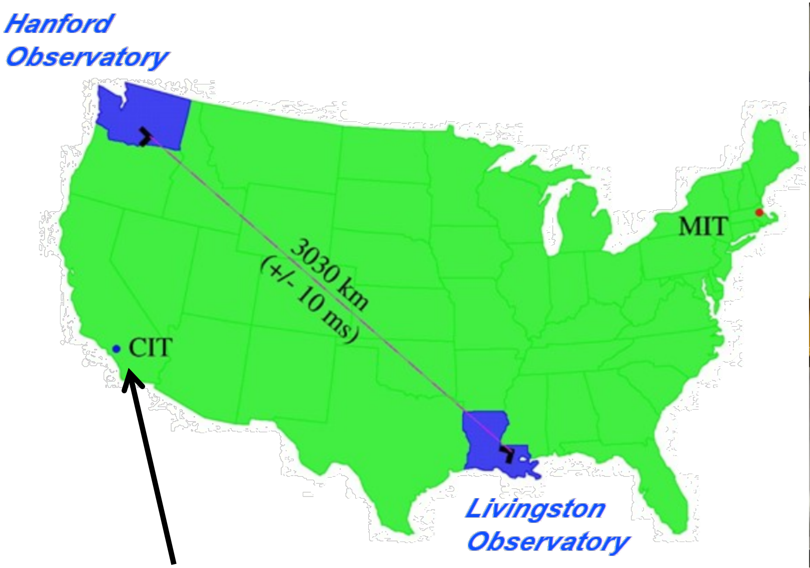
- **Who am I?**
- **How am I doing at Caltech?**
- **What do I want to do in 2024?**
- **Interesting papers**
  - Gravity sensing with levitated oscillators
  - Quantum gravity test near measurement events

My Two Years at Caltech

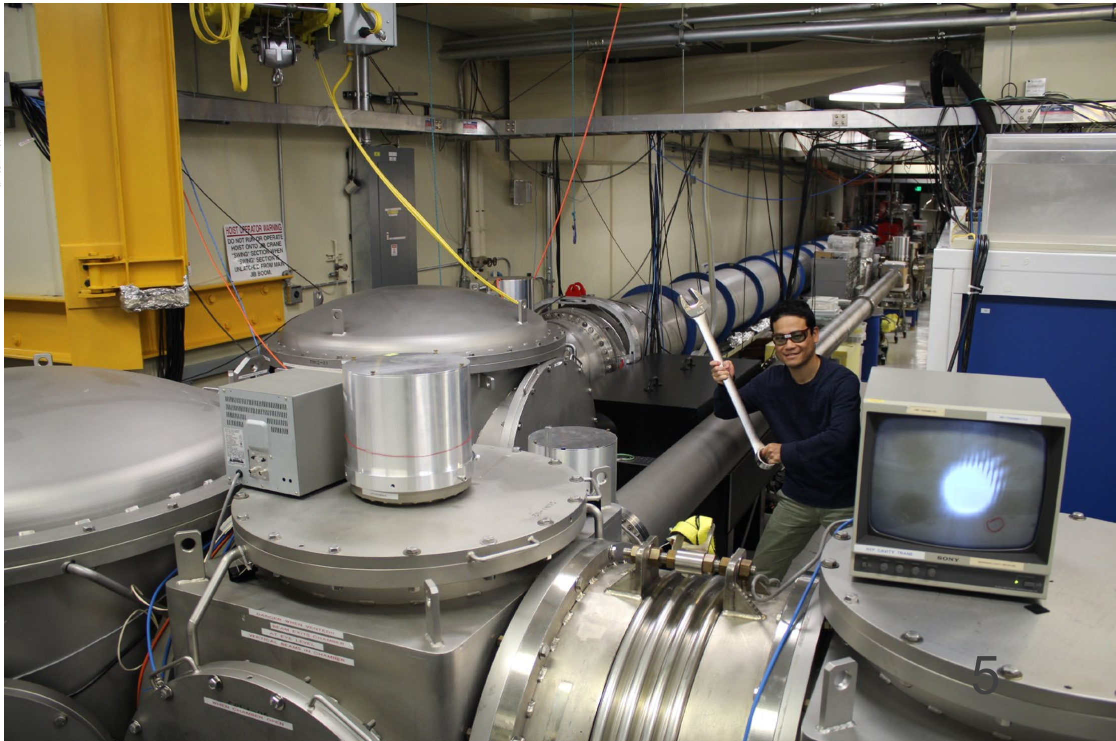
- Balanced homodyne readout experiment at 40m prototype
- Planning for LIGO Voyager and Mariner 40m
  - Cryogenic silicon upgrade
  - Birefringence noise
- Dark matter related
  - Axion with 40m BHD setup
  - Phonon-photon conversion to improve sensitivity
  - First DM search papers released
- Quantum gravity related
  - Geontropic fluctuations
  - Unstable optical levitation

Caltech 40m Prototype

- 40 m version of 4 km LIGO
- Demonstration of balanced homodyne readout (BHR) for LIGO O5
  - Quantum non-demolition technique
  - What and why? Ask me later!

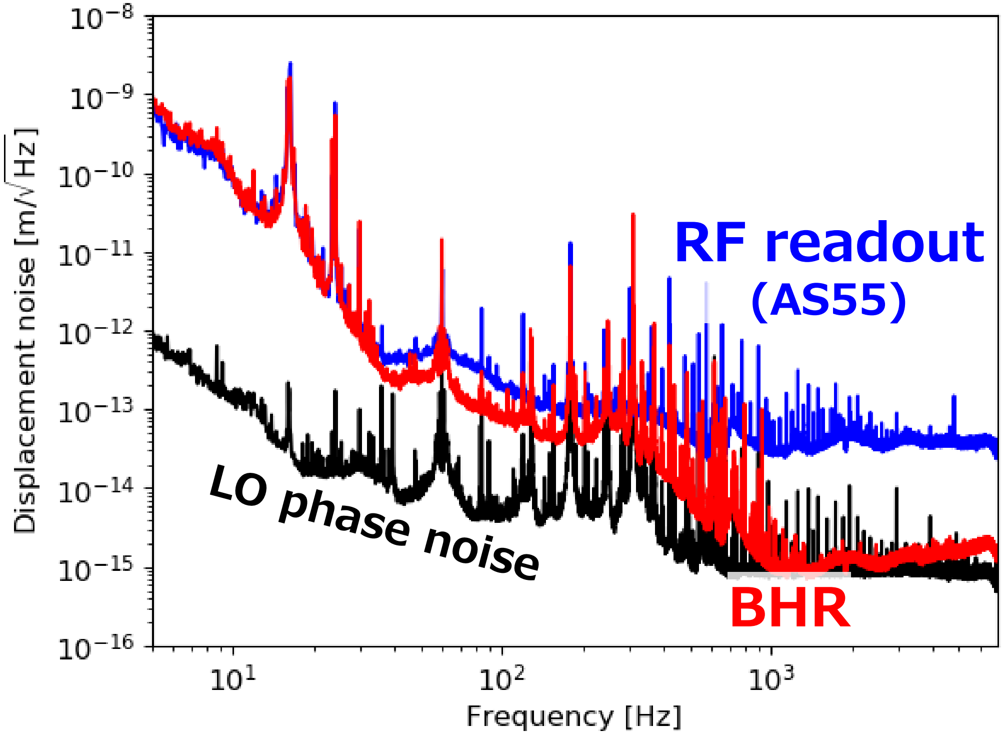


Pasadena in Los Angeles County

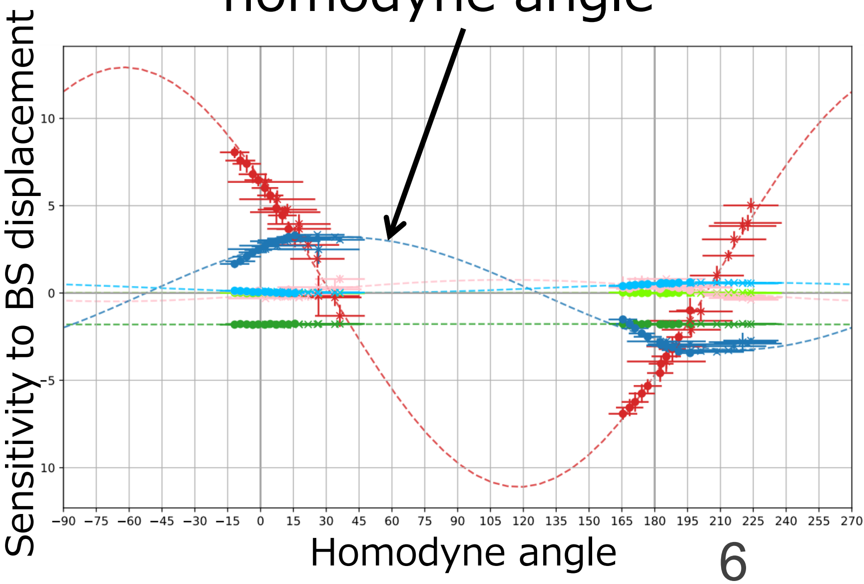


40m BHR Experiment

- Lock demonstrated under MI, FPMI and PRMI configurations, but not PRFPMI yet
- Still not very stable to do detailed measurements

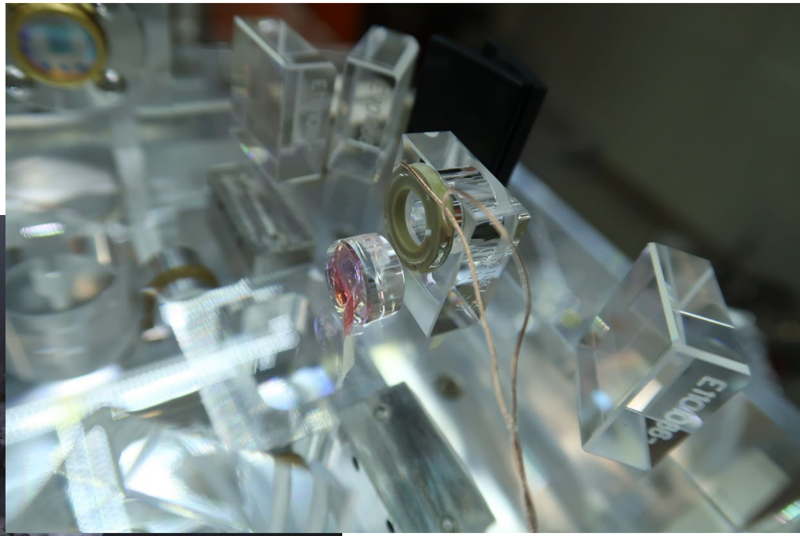


Response changes as a function of homodyne angle

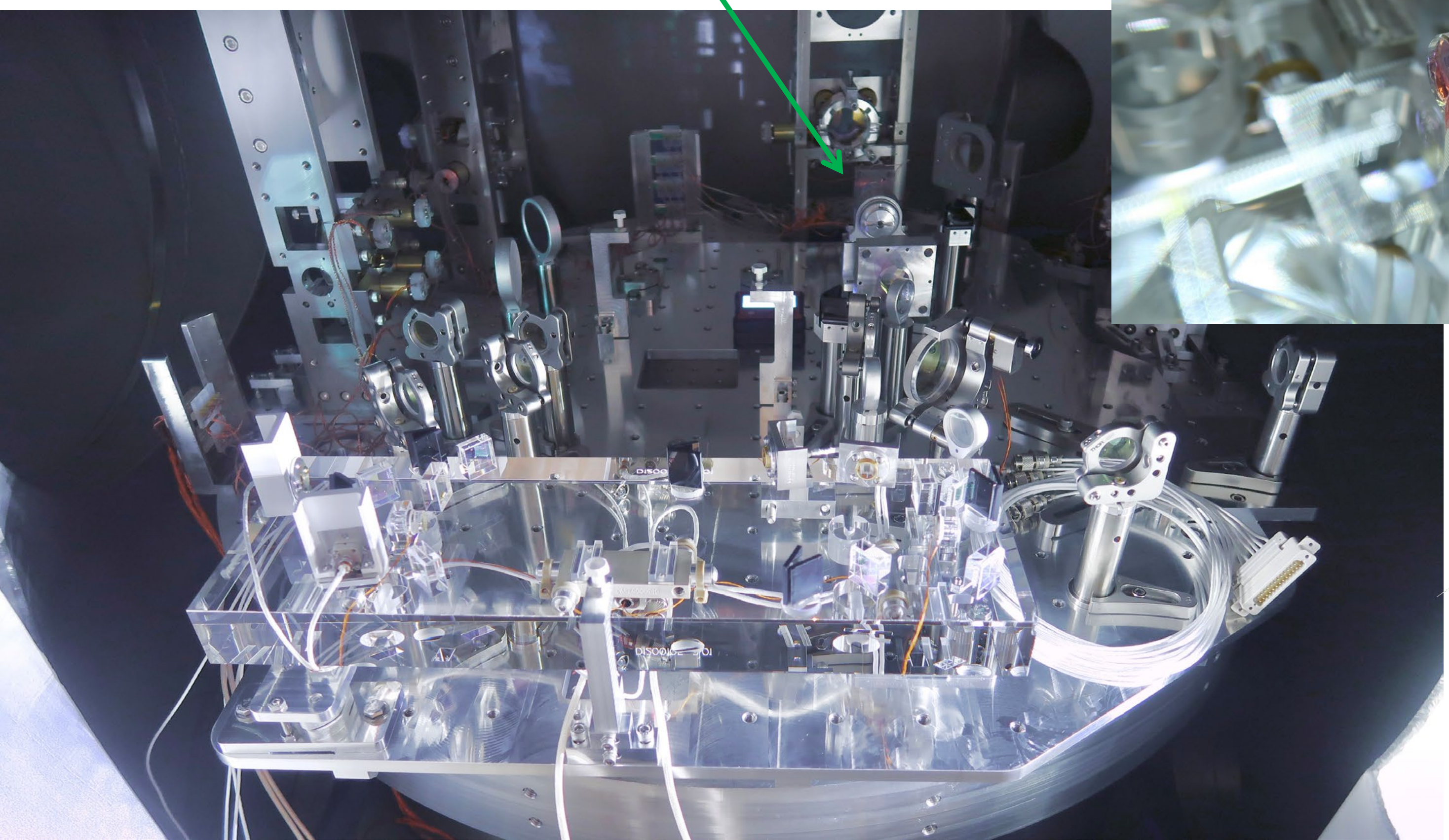


OMC for 40m BHR

- Installed in Dec 2023, but the one for LHO broken, so taken out to ship it to LHO



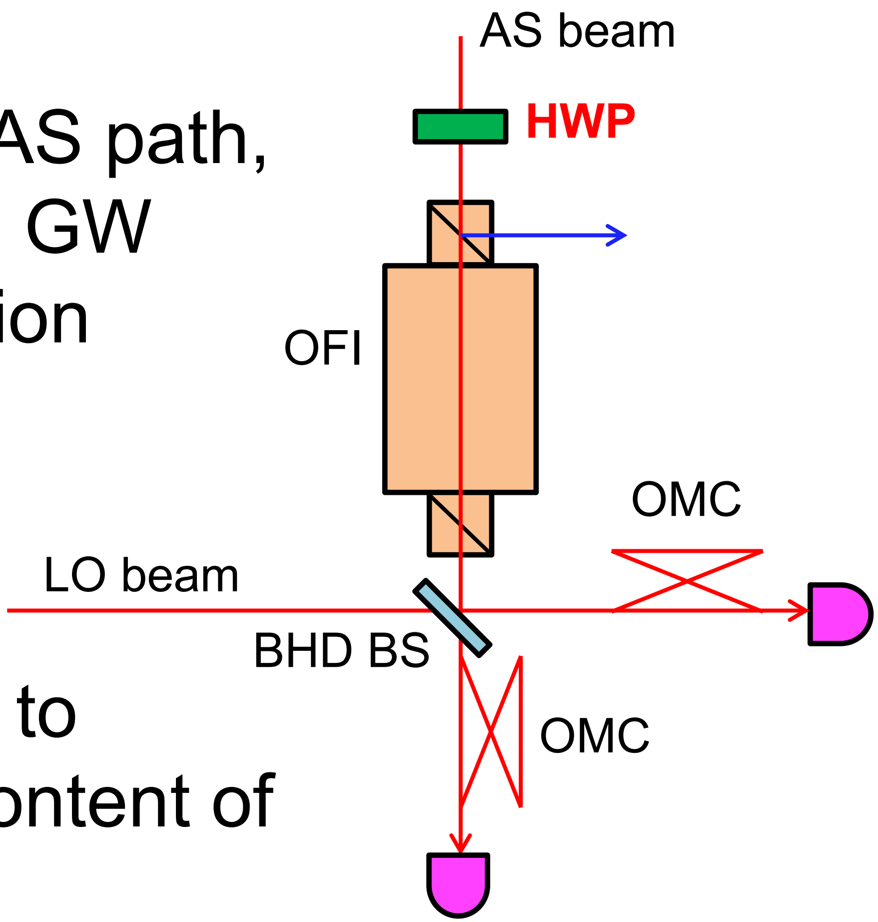
HWP for axion search (birefringence noise search)



さきがけ
PRESTO

BHR is also Convenient for Axions

- At AS port, amount of LO for axion signal depend on IFO polarization state, which is not well understood
- By installing a HWP in AS path, we can switch between GW detection mode and axion search mode
- LO beam can be used for both
- OMC can also be used to investigate the mode content of orthogonal polarization



Geontropic Fluctuations

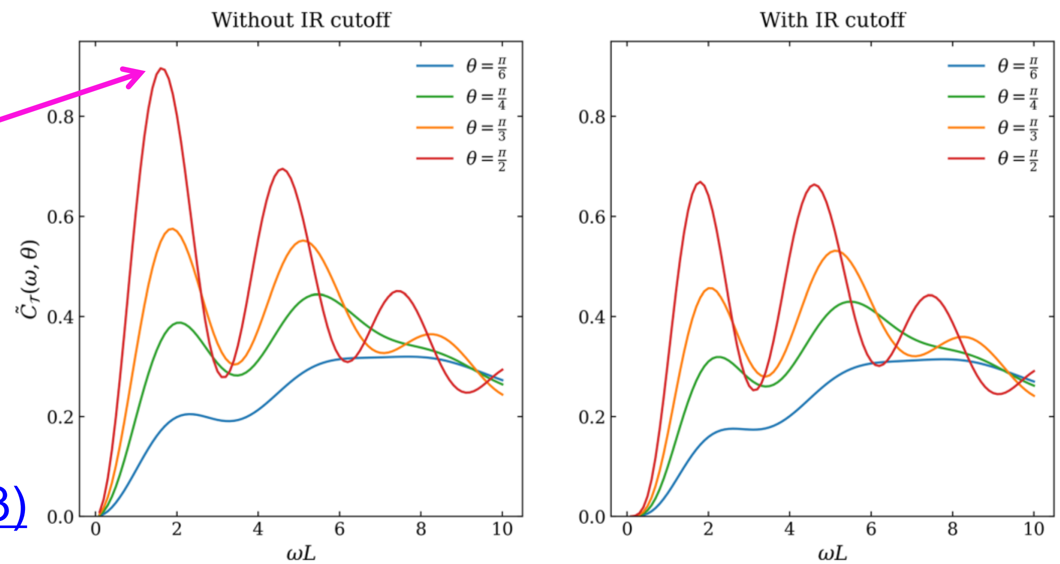
- Spacetime vacuum fluctuations in quantum gravity with a scalar field
- Observable

$$\left\langle \left(\frac{\Delta L}{L}\right)^2 \right\rangle \sim \frac{l_\mathrm{p}}{L}$$

Planck length

- Parametrized by the power of noise α (Natural benchmark $\alpha \sim 1$)

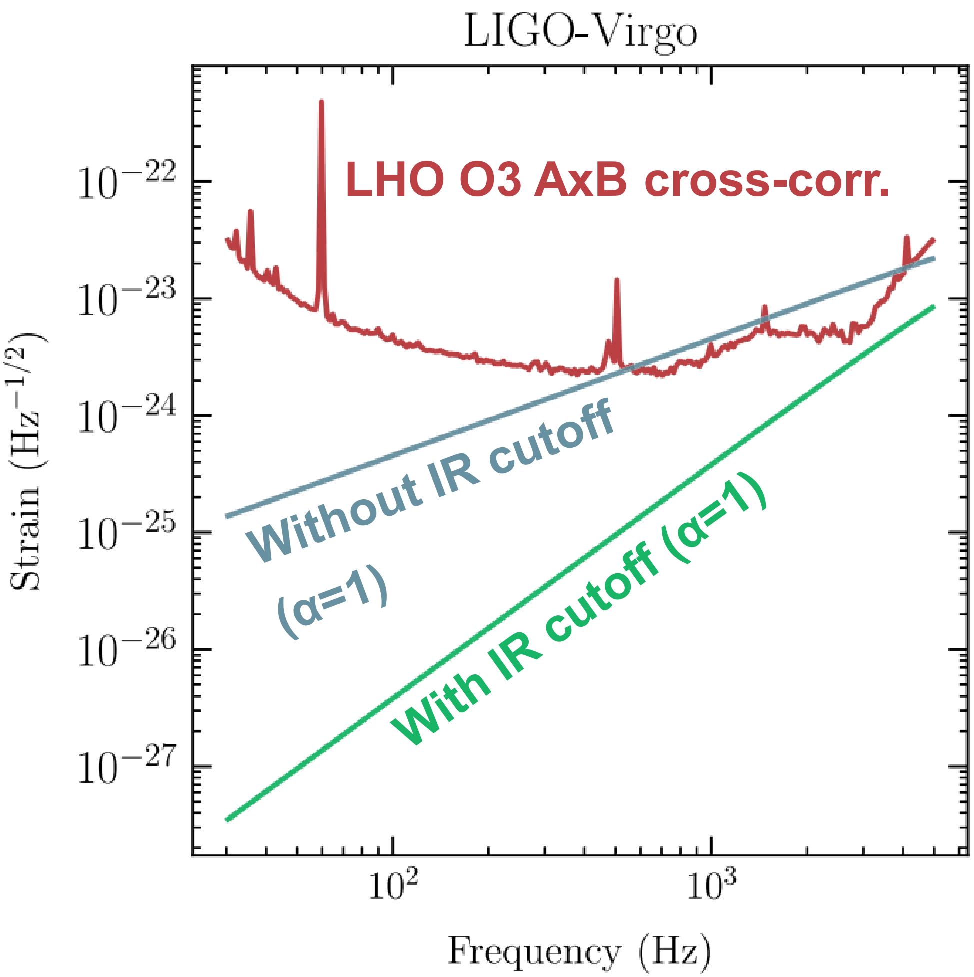
Displacement noise peaks at odd x FSR/2



D. Li+, PRD 107, 024002 (2023)

Limit from O3

- Roughly $\alpha \lesssim 0.1$ and $\alpha \lesssim 3$ (with IR cutoff) at 3σ



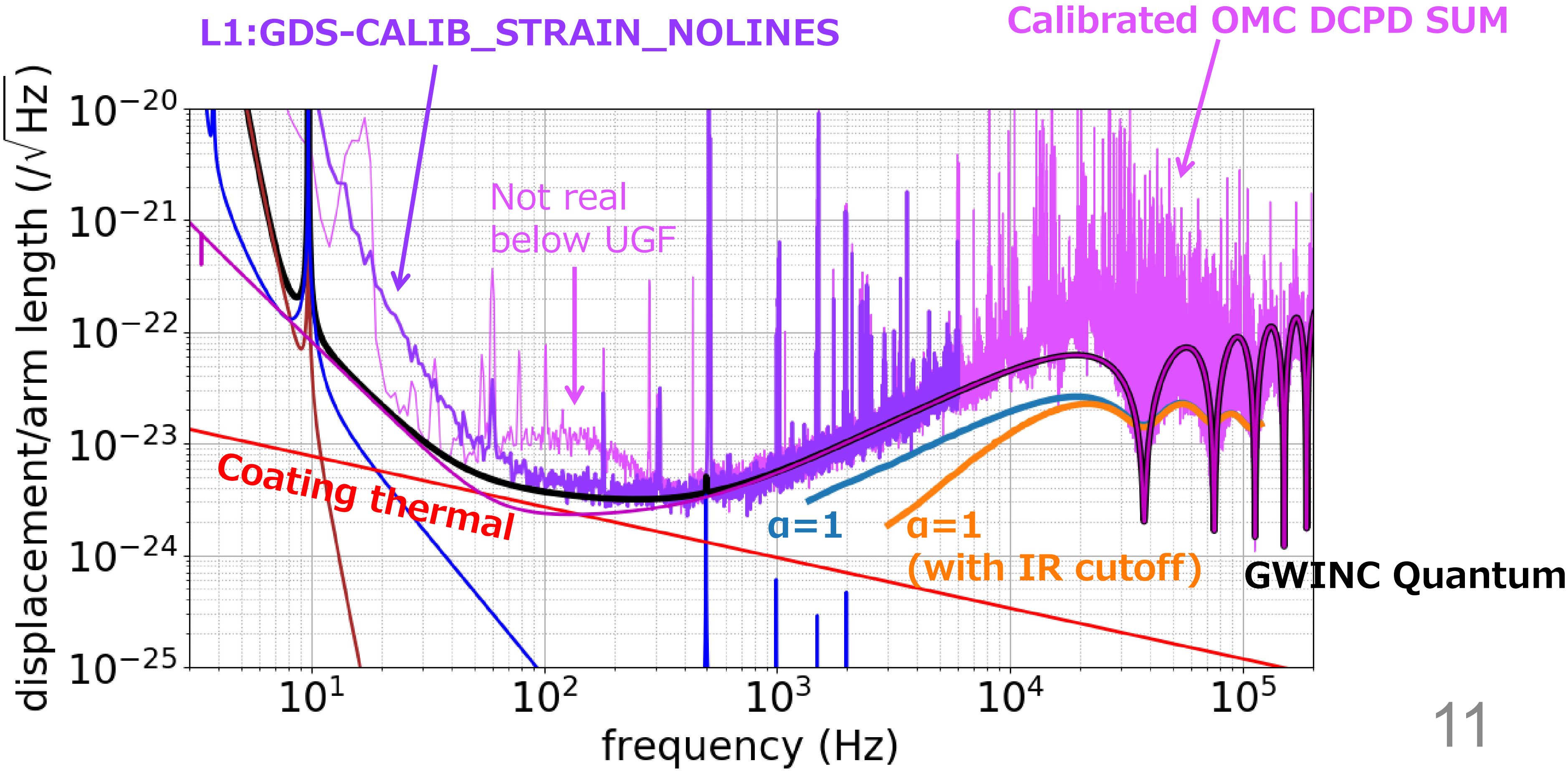
From O4, 512 KHz ADC is available.
We can search at FSRs!

D. Li+, [PRD 107, 024002 (2023)]

Calibrated O4 HF data

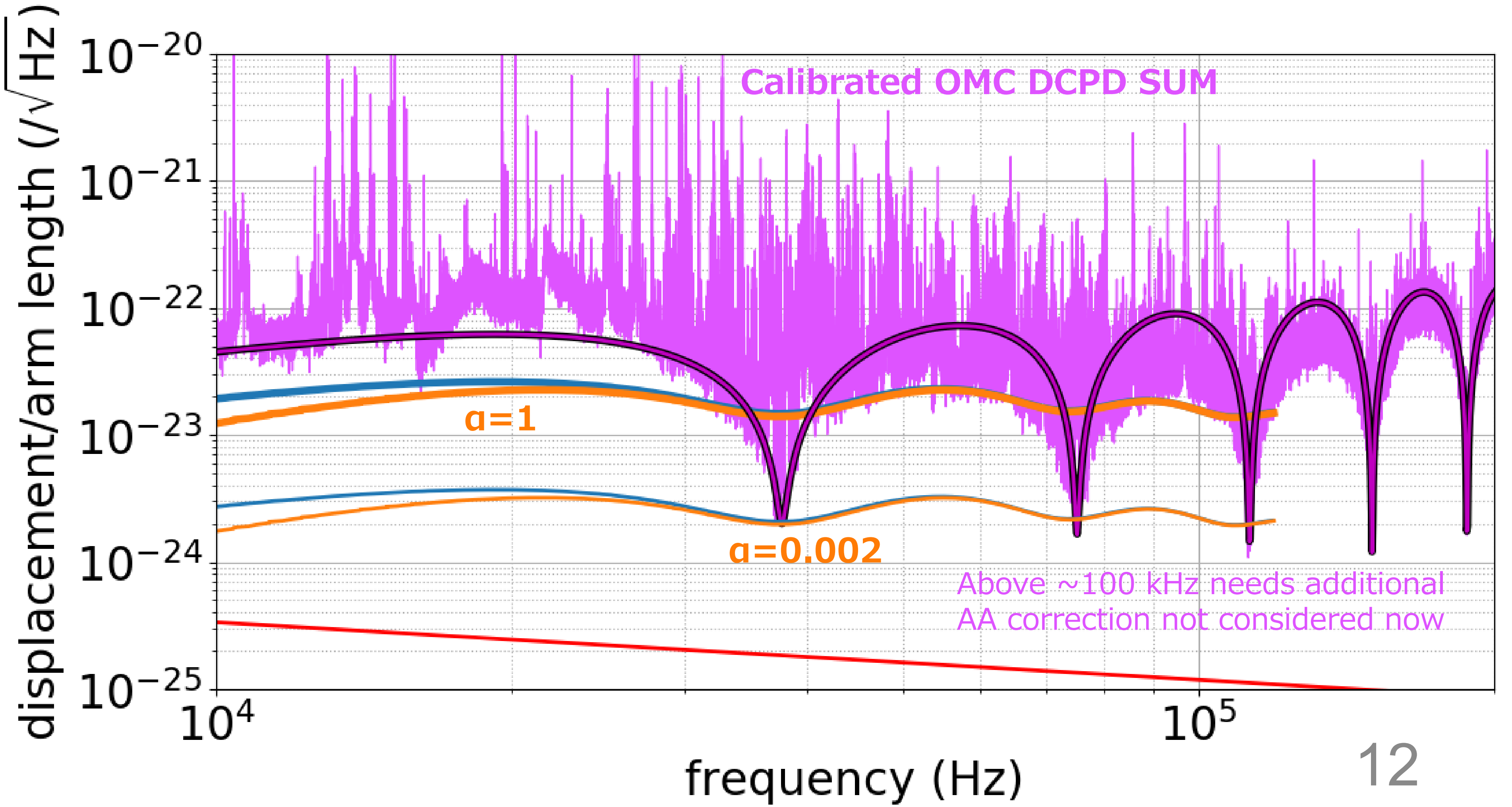
- Data from LLO (GPS: 1367978358 May 13, 2023, 01:59:00 UTC)
- With freq. dep squeezing (-5dB at 2 kHz)

Rough calibration done with Masayuki Nakano and Joe Betzwieser



Calibrated O4 HF data

- Better SNR at FSRs ($\alpha \sim 10^{-2}$ should be feasible)
- A and B cross-corr. might give better result if no squeezing



Exciting high frequency GWs

- Can also be used to do other HF physics
  - Stochastic, PBH, BH superradiance …
- Calibration at HF (arm asymmetry?), antenna pattern function, squeezing characterization … are also fun for 3G

A. Arvanitaki & A. A. Geraci, PRL **110**, 071105 (2013)

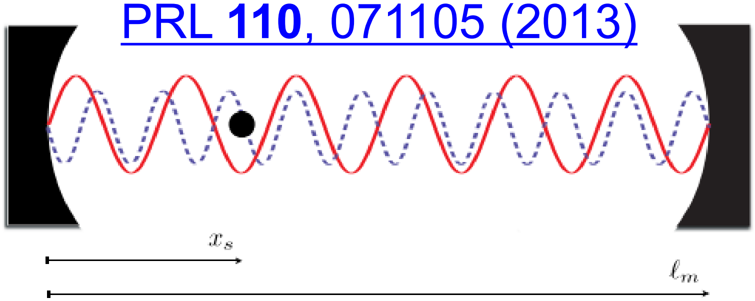


FIG. 1 (color online). A dielectric nanosphere or microdisk is optically trapped in an antinode (solid red line) of a cavity of length ℓ_m at position x_s. A second light field with two different frequency components (dashed blue line) is used to cool and read out the axial position of the levitated object, respectively. Two additional beams perpendicular to the cavity axis (not shown) are used to cool the transverse motion of the sensor. A passing gravitational wave at frequency ω_{GW} displaces the sensor from its equilibrium position in the optical trap and imparts a force as described in text. The resulting displacement is resonantly enhanced when ω_{GW} coincides with the trap frequency ω_0.

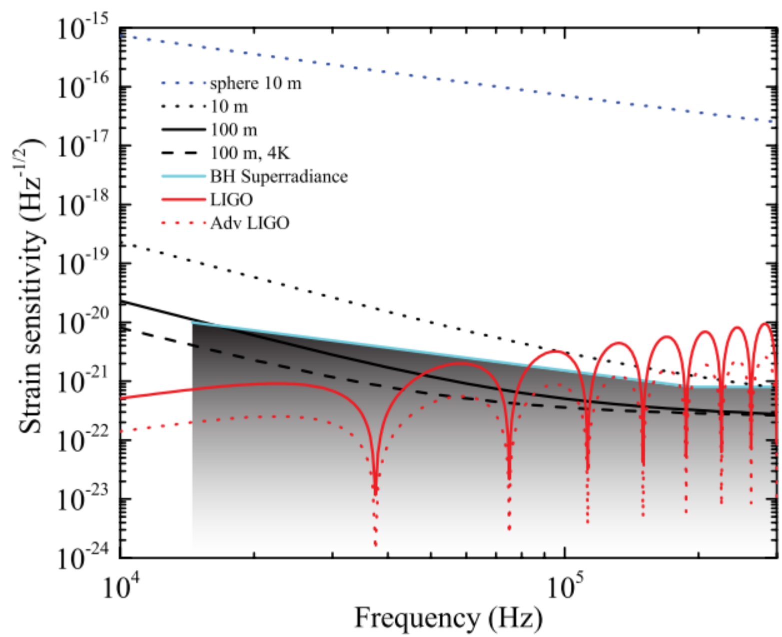


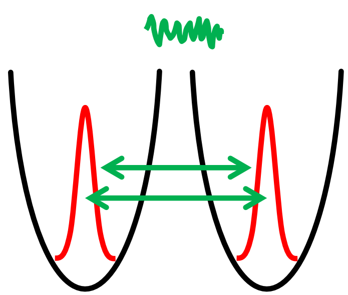
FIG. 2 (color online). Strain sensitivity for optically levitated microdisks (black dashed line) or spheres (blue dashed line) for experimental parameters described in the text. For comparison, also shown are the LIGO and predicted Advanced LIGO sensitivity in the frequency range of 10–300 kHz [25,28]. The shaded region denotes predicted signals due to black hole superradiance.

Another Test of Quantum Gravity

- Is gravity quantum?
- As a first step, we can verify if quantum entanglement can be induced by Newtonian gravity
- We found that anti-spring is useful because it will broaden wavefunctions faster

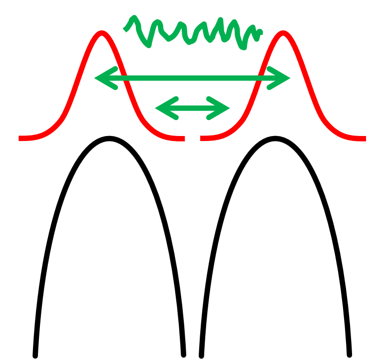
T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552

during Tomo's visit to Caltech



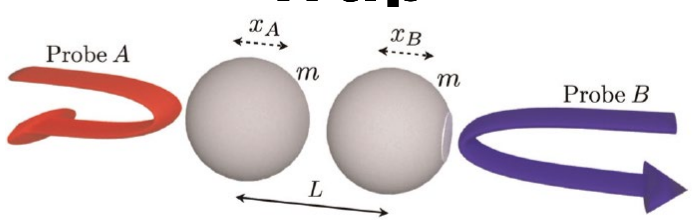
Small Entanglement

Trap



Large Entanglement

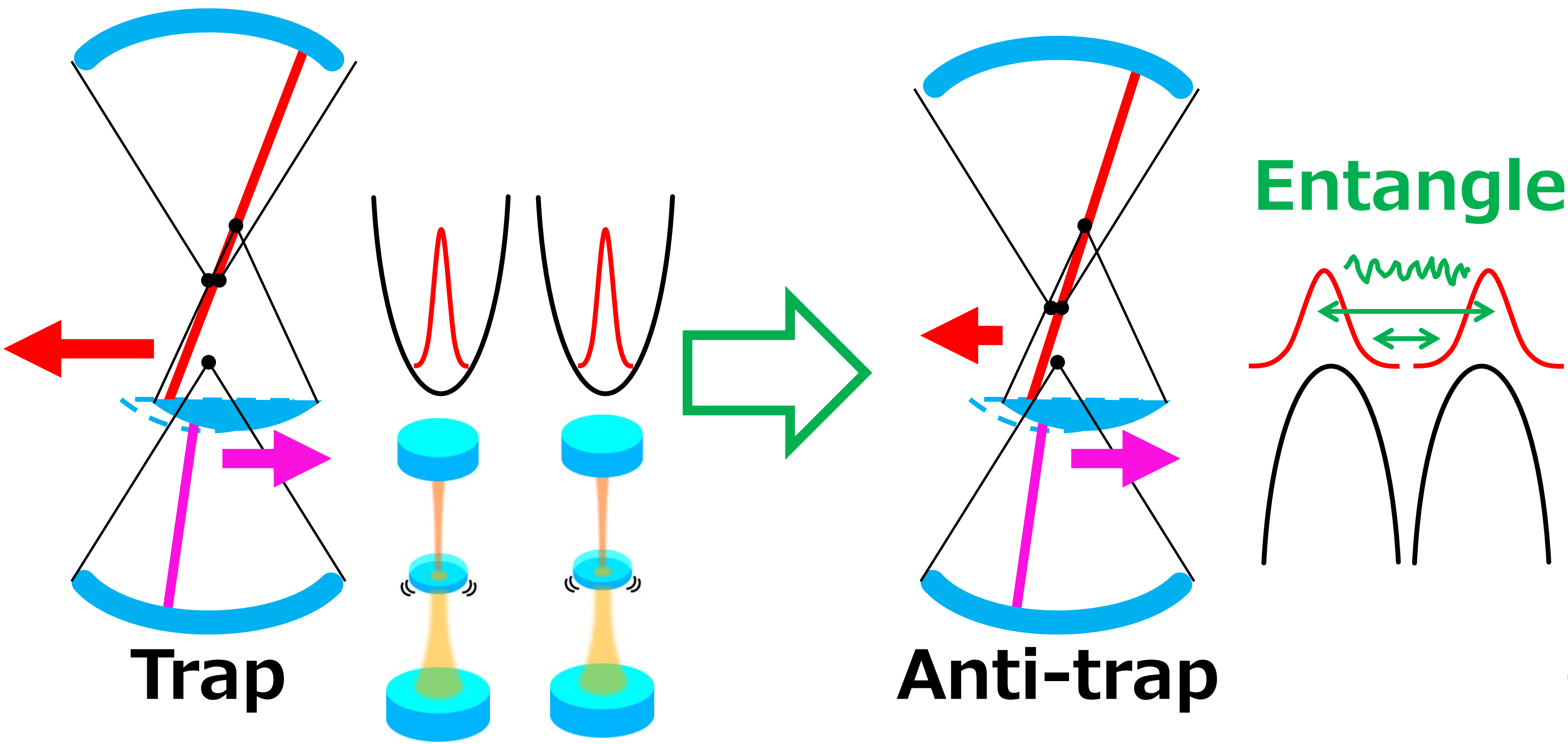
Anti-trap



T. Krisnanda+, npj Quantum Information **6**, 12 (2020)

Can be Done with Optical Levitation

- First, trap strongly to prepare narrow wavefunctions
- And then switch to anti-trap to broaden the wavefunction fast (this can be done by effectively switching the cavity geometry)



Example Setup

- To prepare 1 kHz anti-spring for 0.1 mg mirror

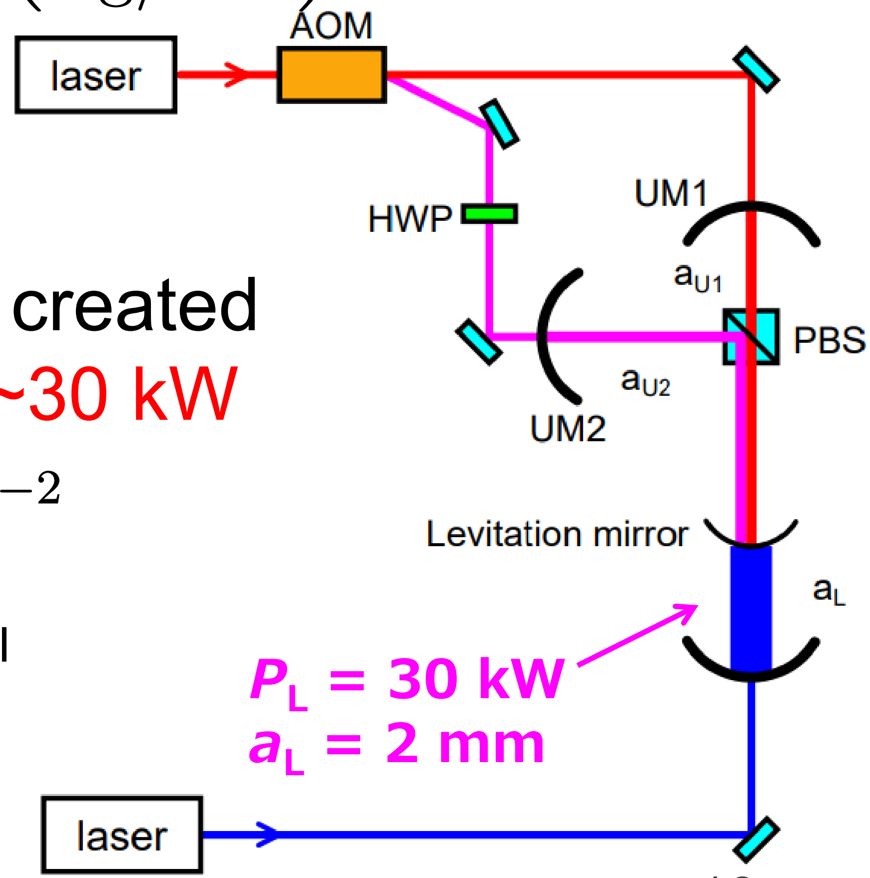
$$\mu << \eta = 2.7 \times 10^{-13} \omega_{\mathrm{kHz}} \left(\frac{m/d^3}{2\,\mathrm{g/cm^3}} \right)$$

- Requires T < ~1 K and P < ~10^{-17} Pa (as usual)
- ~1 kHz anti-spring can be created with intra-cavity power of ~30 kW
- Time to generate $E_N = 10^{-2}$

$$\tau_{\mathrm{ent}} = 4.2 \omega_{\mathrm{kHz}}^{-1/3}\,\mathrm{sec}$$ for free-fall

300 times faster

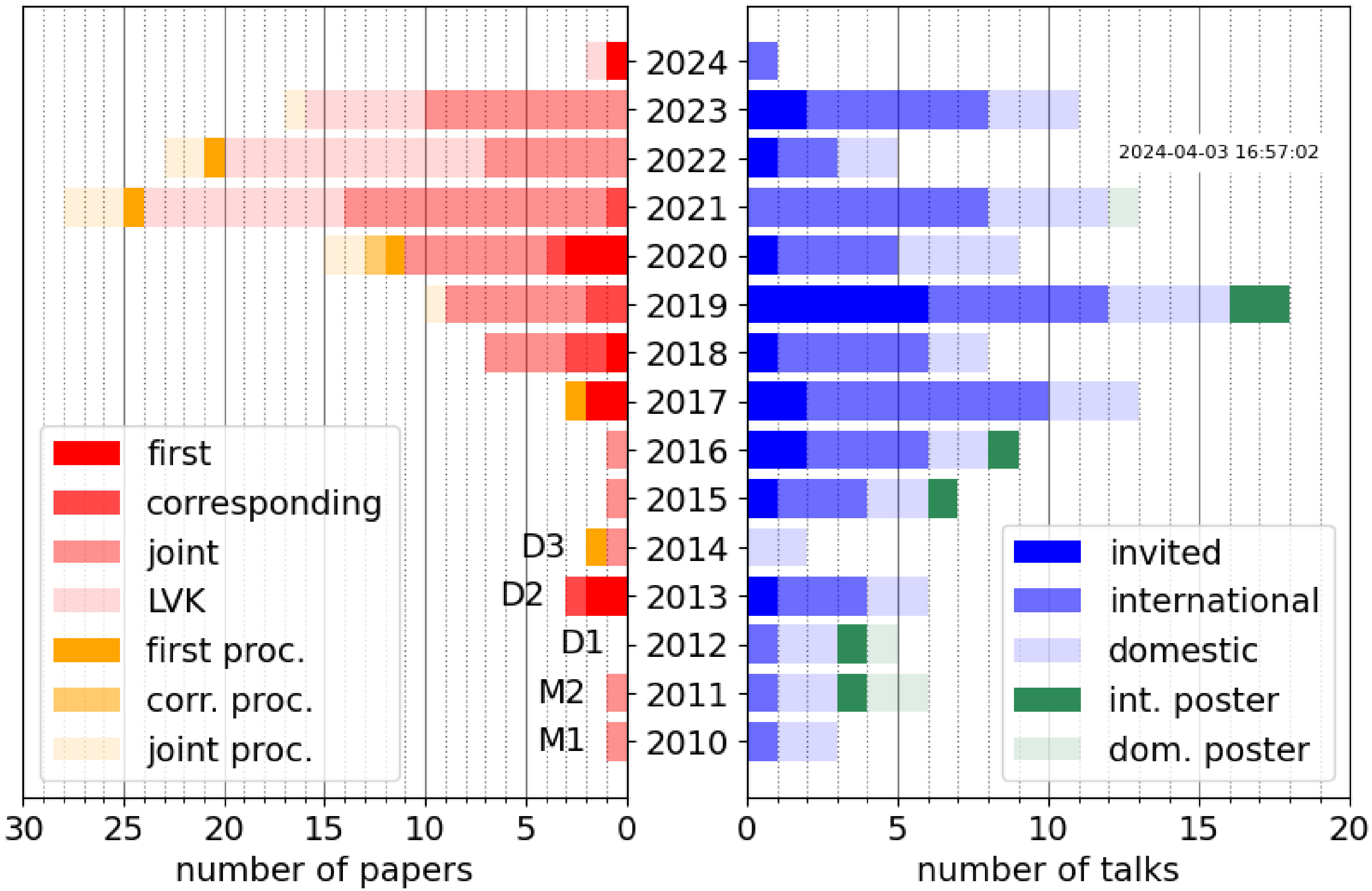
$$\tau_{\mathrm{ent}} = 1.3 \times 10^{-2} \omega_{\mathrm{kHz}}^{-1/3}\,\mathrm{sec}$$ for inverted




LASER RADIATION

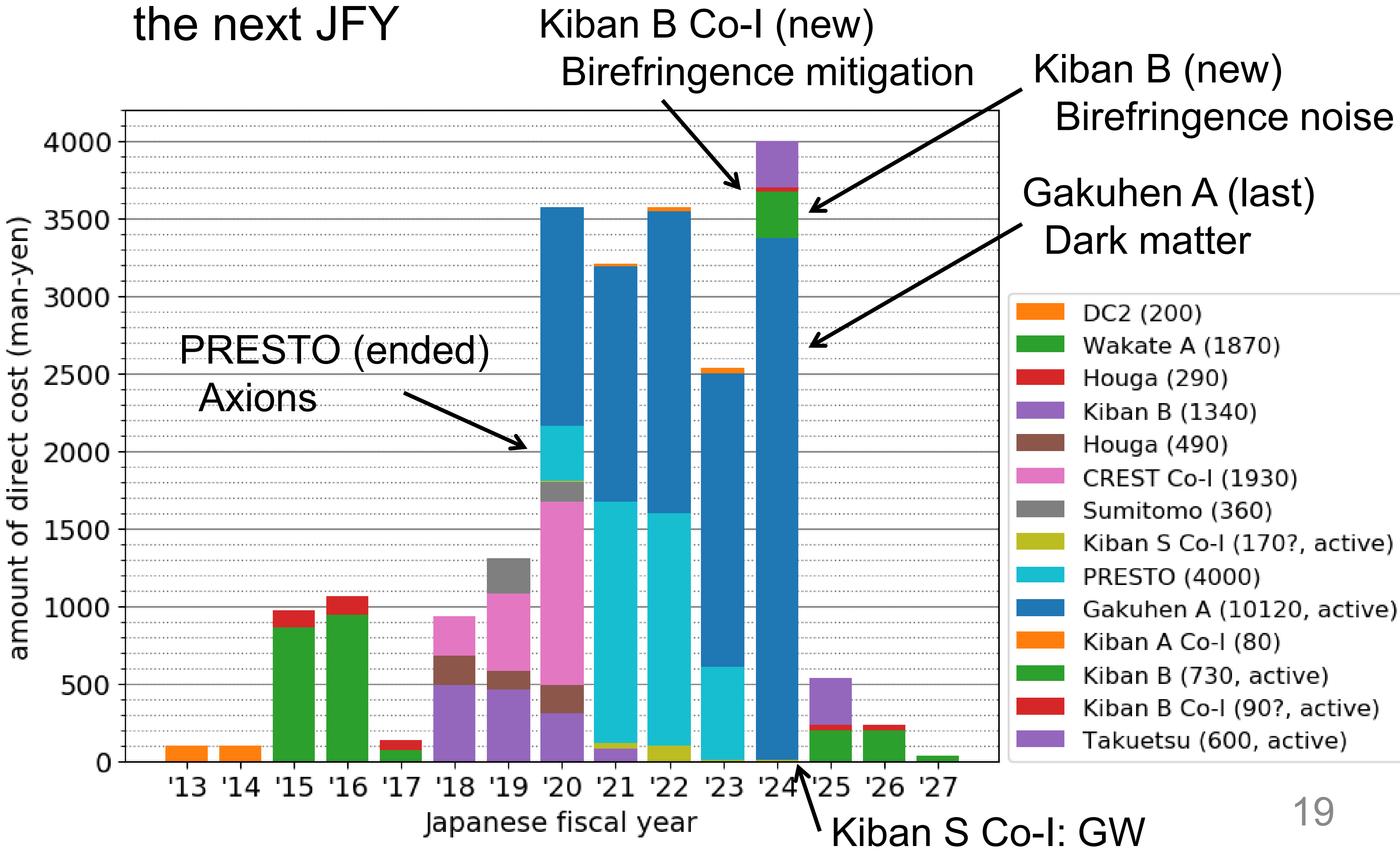
Productivity

- I need to increase the productivity (as always!)



Grants

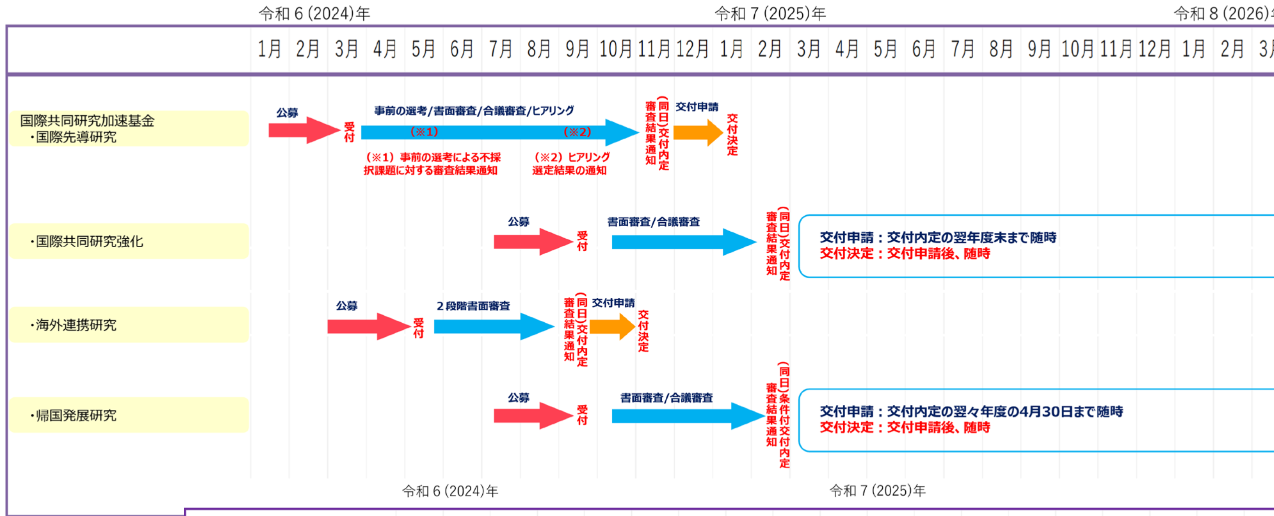
- Applying for 3 (probably +2 more) to prepare for the next JFY

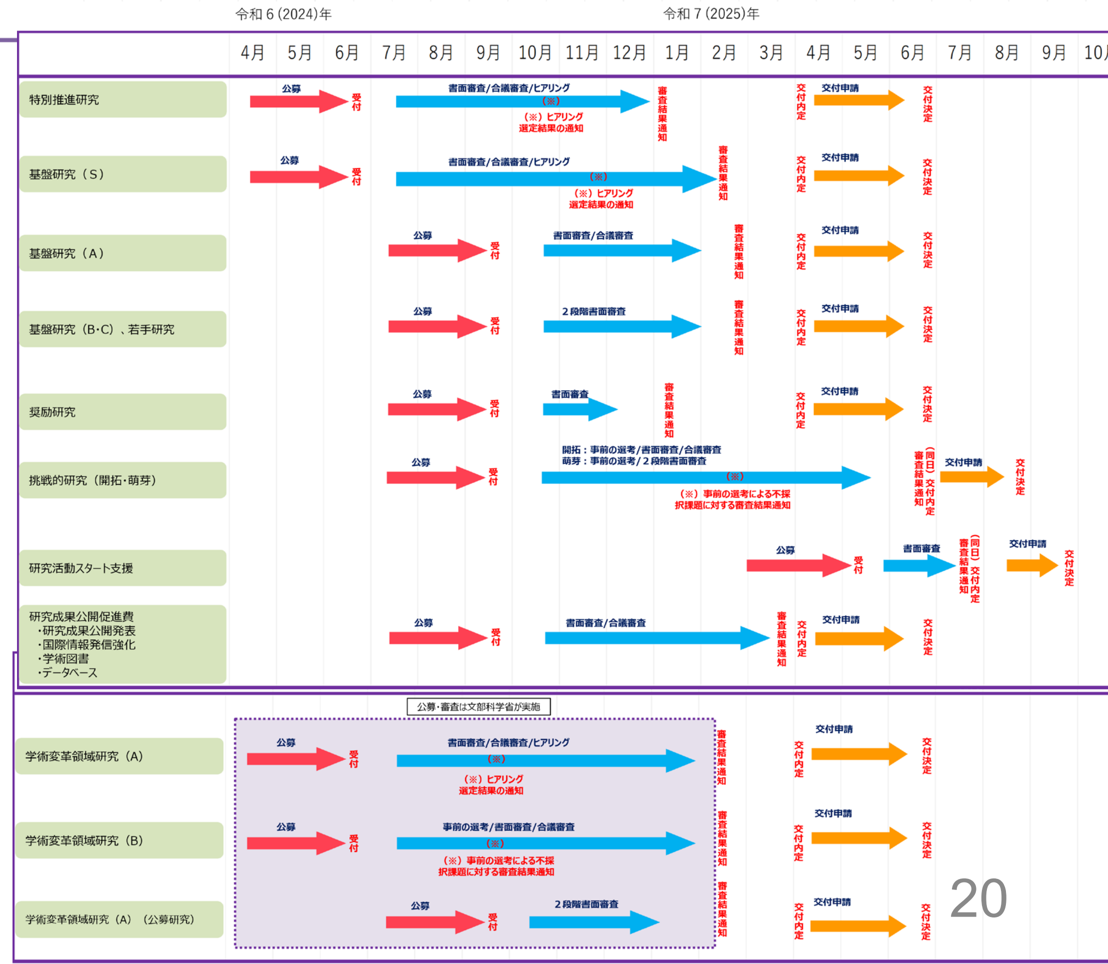


KAKENHI Schedule

Always application season

(and CREST, さきがけ(PRESTO), 創発(FOREST), other foundations …)





My Plans for 2024

- Achieve 10 Mpc sensitivity with KAGRA

  Let's visit Kamioka together!

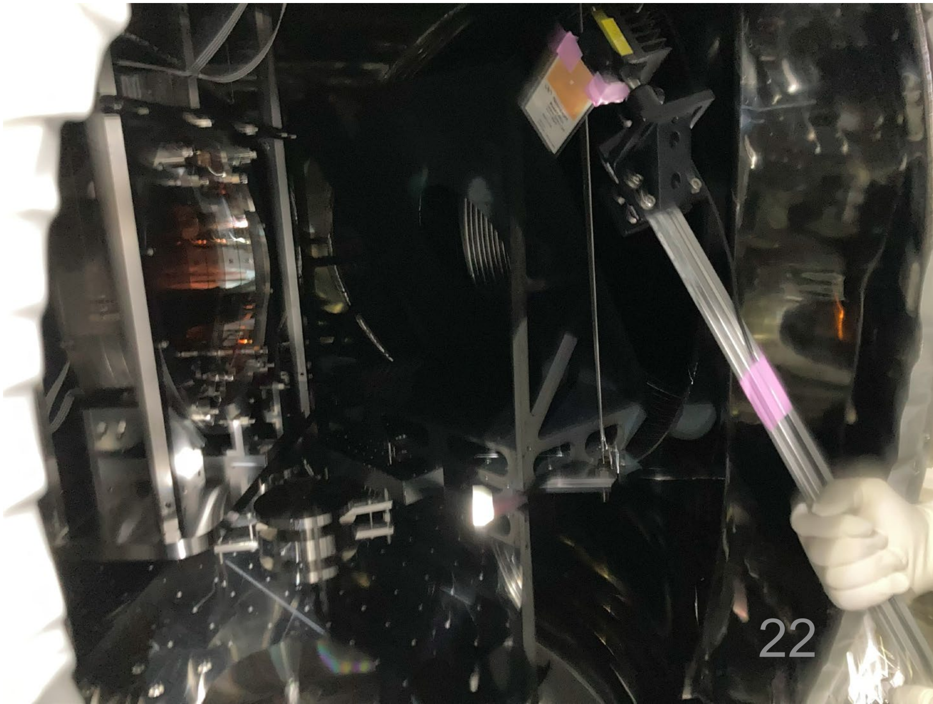
- Re-organize KAGRA future discussions
- In-vac PD and QPD for KAGRA

- Possibly following or at least think about them
  - Silicon birefringence fluctuation measurements
  - Characterization of optical levitation mirrors
    (in collaboration with ANU)
  - Quantum nature of gravity experiments
  - Search for various signals in LIGO HF data at FSRs
  - Axion optomechanics, long SRC, GW tests of GR …

Volunteers welcomed!

KAGRA Visit Last Week

- Measured BS transmission & reflectivity for s/p-pol
- To better understand p-pol effects
- Result (klog 29284):
  Ts=51.9 +/- 0.2 (stat.) +/- 0.2 (sys.) % for s-pol
  Rs=47.7 +/- 0.2 (stat.) +/- 0.2 (sys.) % for s-pol
  Tp=77.7 +/- 0.6 (stat.) +/- 0.2 (sys.) % for p-pol
  Rp=21.8 +/- 0.2 (stat.) +/- 0.2 (sys.) % for p-pol
- To be measured again with better alignment
- Measured together with Takumi Shimasue (M2 student from Hotokezaka Group)



KAGRA 観測再開祈願

無二無三 耐える。

復活

再開早く!!

ガンバレ!!

ガンバレ!!

早期再開

頑張ろう

ガンバレ!!

頑張れ!!

ガンバレ!!

頑張ろう!

希望

頑張ろう KAGRA

神岡商工会議所
Kamioka Chamber of Commerce and Industry

祈完全復活！世界に羽ばたけ！
飛騨市長 都竹淳也

夢と希望の場所KAGRA再開へ！
岐阜県議会議員 布俣正也

感謝してます！頑張ろう！
飛騨市議会議長 井端浩二

よみがえれ KAGRAの鼓動

岐阜県立飛騨神岡高等学校
生徒代表 倉住夏音

NPO法人 宇宙まるごと創生塾飛騨アカデミー

KAGRAの地震被害衷心よりお見舞い申し上げます。地元の唯一無二の宝でもありますKAGRAの一日も早い復旧と観測再開を地元神楽を通して祈念しております。
理事長 川上佳洋

地震に負けず重力波を捕まえてください。全力で応援しています。
理事

KAGRA 日本の希望 私たちの夢
ユニバース

ひだ宇宙科学館 カミオカラボ

富山市科学館博物館でKAGRAのお話を聞きました。とても面白かったです。ぼくは将来うちゅうのおしごとをしてみたいです。KAGRAが早く元気になれるように応えんしています！
小2

がんばれ♥ がんばれ♥
匿名

研究者の皆さん応援してます 大変だけど頑張ってください！
eureka

FIGHT!

復興後に新しい成果が出るのを楽しみにしております。
島本真帆子

ガンo(`・ω・´)oバレ
ガンo(`・ω・´)oバレ
KAGRA
(・3・)ﾌﾟｪ〜

がんばれ!

飛騨市民から研究者の皆様へ

時空の歪みで宇宙を暴く
大型低温重力波望遠鏡

KAGRA
かぐら

観測再開祈願応援メッセージ

天文観測につながる設備が復旧したら見学に行きたいです。応援しています。

世界が注目しているKAGRAが早く復活することを願っています。神岡の希望です。

震災に負けない、強いKAGRA。KAGRAの復活は、震災からの復興の光です。応援しています!!

神岡中学校

地元神岡のチームメンバーとしてKAGRAプロジェクトの皆様へ、心より応援のメッセージを送ります。

地震という予期せぬ自然災害によって、長年にわたる努力と準備が一時的に影を潜める形となりましたが、この難局を乗り越え、プロジェクトが再び前に進むことを強く信じています。
重力波検出という宇宙の謎を解き明かすための貴重な試みは、人類の知の探究にとって非常に価値のあるものであると同時に、私たち地元メンバーにとっても、大きな誇りとなっています。
私たちは、KAGRAプロジェクトの活動をどんな時も支え続ける応援団であることをお約束するとともに、KAGRAプロジェクトが深遠なる重力波を検出する日を心待ちにしています。

GEO SPACE ADVENTURE
ジオスペースアドベンチャー実行委員会
及びボランティアスタッフ 一同

地震に負けるな！KAGRA
復活の日を皆で待っている
飛騨市役所職員一同

KAGRA による重力波天文学の進展を応援しています
岐阜県立古城高等学校

頑張ろうKAGRA！
さらなる進化を遂げた復活を!!
神岡振興事務所職員一同

(Non-Quantum) Research Topics

- Better suspension controls
- Better length and alignment sensing and controls
- Better arm length stabilization
- Laser frequency stabilization
- Investigate the mechanism for acoustic noises
- Investigate effects from birefringence
- Measure birefringence noise in sapphire for the first time
- Birefringence mitigation schemes
- Sapphire Q-value investigations
- Magnets and glues for cryogenic
- Parametric instability
- Underground Newtonian noise
- Machine learning based controls

Projects Led by Students

- Thermal noise in non-equilibrium steady-state
  K. Komori, Y. Enomoto, H. Takeda, YM+ PRD **97**, 102001 (2018)
- GW polarization test using KAGRA
  H. Takeda, A. Nishizawa, YM+, PRD **98**, 022008 (2018)
- New laser amplitude/phase modulation scheme
  K. Yamamoto, K. Kokeyama, YM+ CQG **36**, 205009 (2019)
- Control scheme using second harmonic beam
  KAGRA Collab. (by Y. Enomoto) CQG **37**, 035004 (2020)
  日本物理学会若手奨励賞
- Input optics during O3GK
  KAGRA Collab. (by M. Nakano & K. Kokeyama) PTEP **2023**, 023F01 (2023)
- Vector dark matter search with KAGRA data
  LIGO-Virgo-KAGRA Collab. (written by J. Kume) arXiv:2403.03004

Various research opportunities for students!

※ Just the ones I'm involved are listed. Some are submitted/published after graduation

Gravity Sensing with Levitation

- Measurement of the Earth Tides with a Diamagnetic-Levitated Micro-Oscillator at Room Temperature
    Y. Leng+, [PRL 132, 123601 (2024)]

PHYSICAL REVIEW LETTERS **132,** 123601 (2024)

Editors' Suggestion **Featured in Physics**

Measurement of the Earth Tides with a Diamagnetic-Levitated Micro-Oscillator at Room Temperature

Yingchun Leng,[1] Yiming Chen,[1] Rui Li,[2,3,4] Lihua Wang,[1] Hao Wang,[1] Lei Wang,[1] Han Xie,[1] Chang-Kui Duan,[2,3,4] Pu Huang,[1,*] and Jiangfeng Du[2,3,4,5,†]

[1]*National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China*

[2]*CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China*

[3]*CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

[4]*Hefei National Laboratory, Hefei 230088, China*

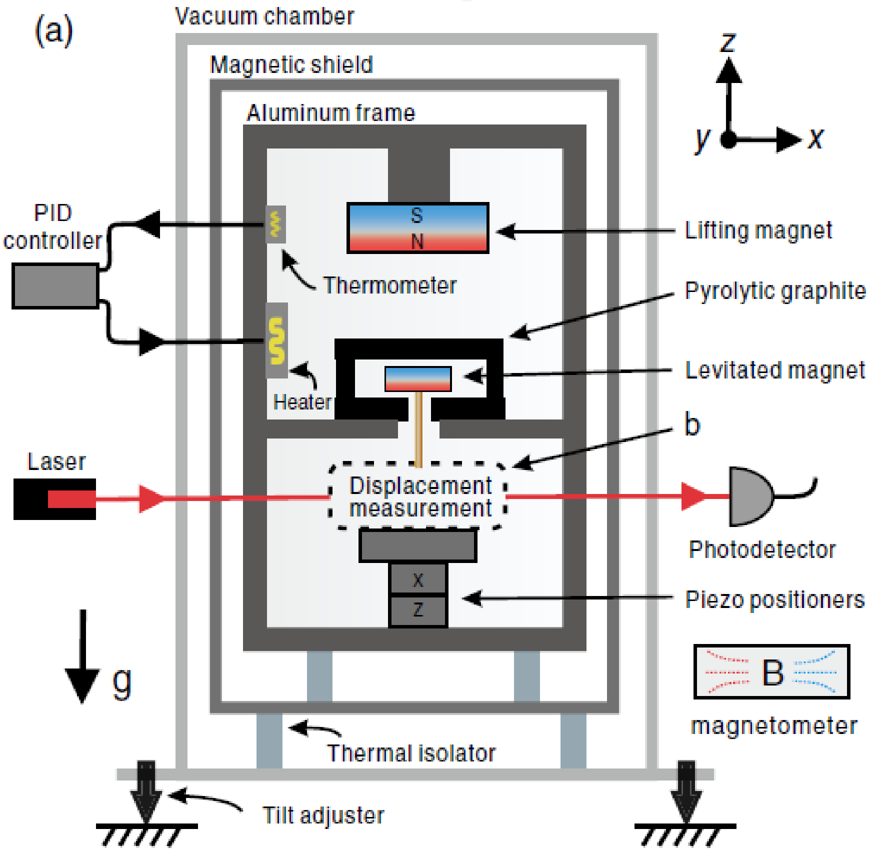
[5]*Institute of Quantum Sensing and School of Physics, Zhejiang University, Hangzhou 310027, China*

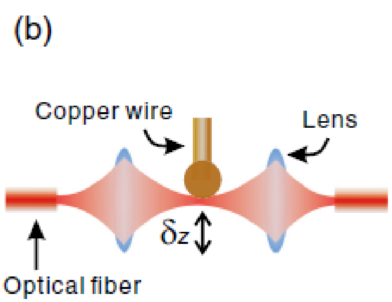
(Received 28 September 2023; revised 19 December 2023; accepted 7 February 2024; published 22 March 2024)

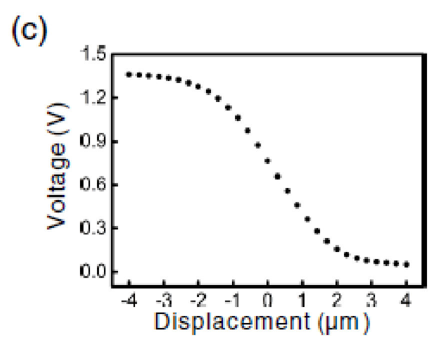
The precise measurement of the gravity of Earth plays a pivotal role in various fundamental research and application fields. Although a few gravimeters have been reported to achieve this goal, miniaturization of high-precision gravimetry remains a challenge. In this work, we have proposed and demonstrated a miniaturized gravimetry operating at room temperature based on a diamagnetic levitated micro-oscillator with a proof mass of only 215 mg. Compared with the latest reported miniaturized gravimeters based on microelectromechanical systems, the performance of our gravimetry has substantial improvements in that an acceleration sensitivity of 15 $\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$ and a drift as low as 61 μGal per day have been reached. Based on this diamagnetic levitation gravimetry, we observed Earth tides, and the correlation coefficient between the experimental data and theoretical data reached 0.97. Some moderate foreseeable improvements can develop this diamagnetic levitation gravimetry into a chip size device, making it suitable for mobile platforms such as drones. Our advancement in gravimetry is expected to facilitate a multitude of applications, including underground density surveying and the forecasting of natural hazards.

DOI: 10.1103/PhysRevLett.132.123601

Simple and Cool (operated at room temp.)







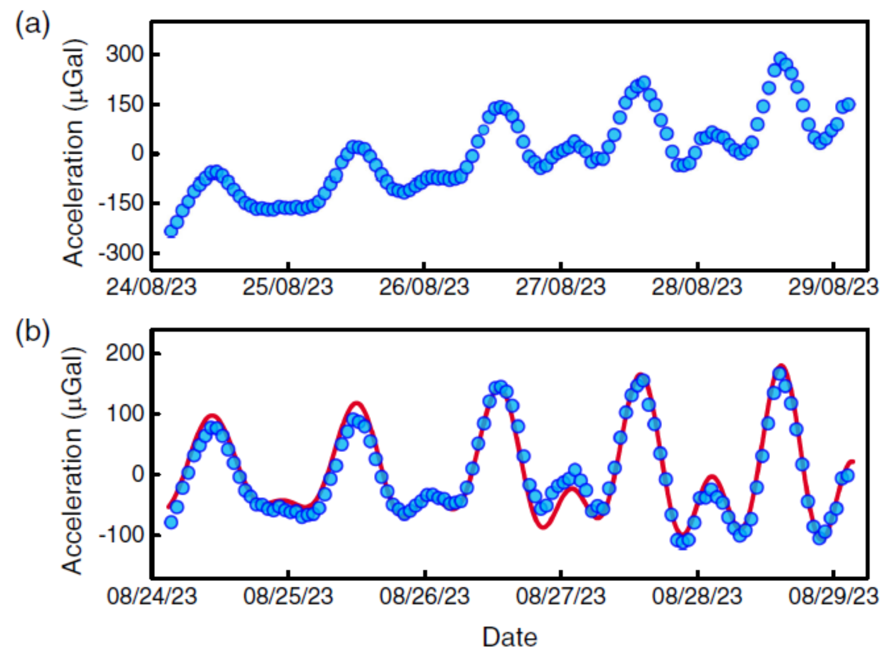
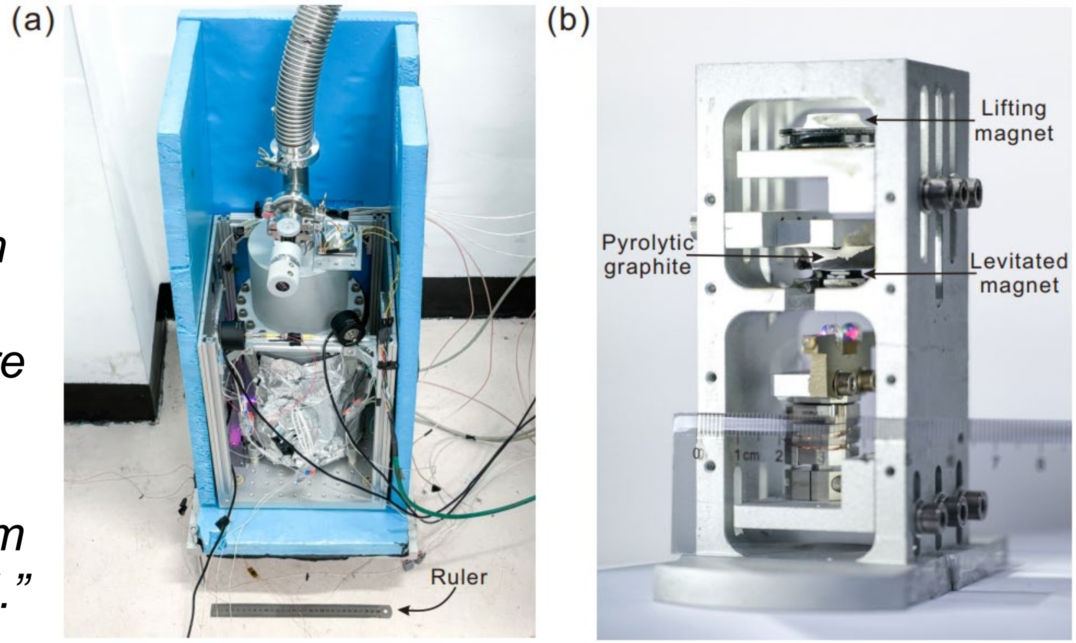


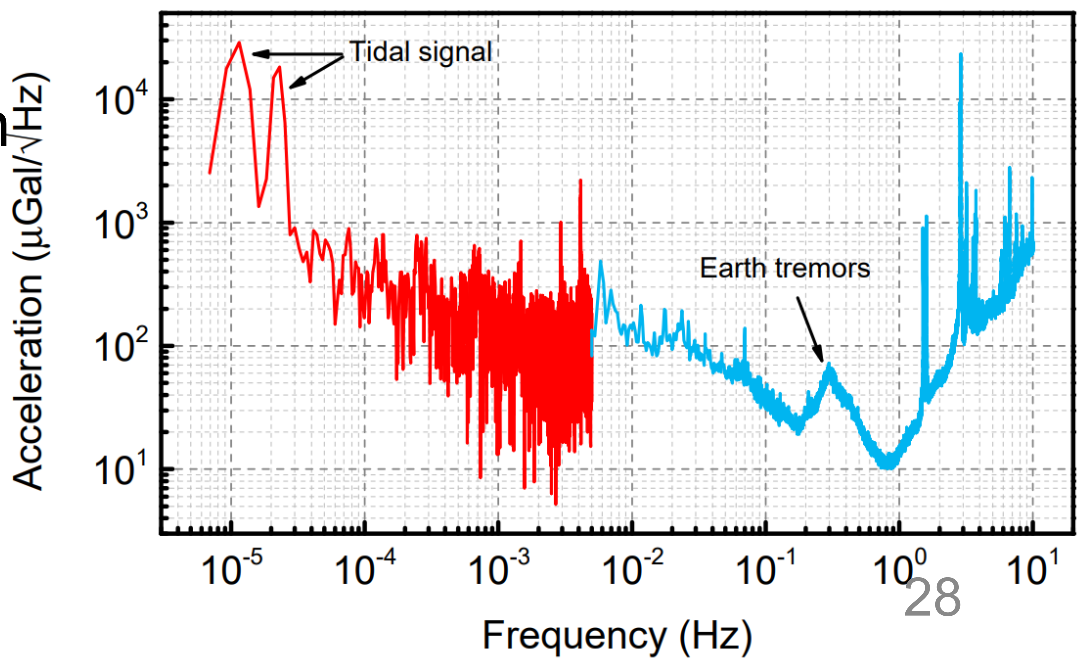
TABLE I. Comparison of key parameters between this work and typical relative gravimeters operating at room temperature.

Gravimeters	Sensitivity ($\mu Gal/\sqrt{Hz}$)	Drift ($\mu Gal/day$)
Scintrex CG-5 [9]	2	500
Glasgow MEMS [10]	40	140
HUST MEMS [11]	8	2400
This Letter	15	61

Sensitivity

- *“To put the current acceleration sensitivity in perspective for density contrast imaging, an ore body with a residual density of 2000 kg/m^3 and a size of 20x20x20 m^3 at a depth of 84 m can be detected in one second.”* (probably iron ore in mind)
- Probably limited by seismic at high freq.
- Can we make this even smaller?
- Optical levitation?
- Earthquake alert?





QG & Measurement Events

- Testing quantum gravity near measurement events
  A. Kent, PRD **103**, 064038 (2021)
- Proposal to test semiclassical gravity

PHYSICAL REVIEW D **103**, 064038 (2021)

Testing quantum gravity near measurement events

Adrian Kent*

Centre for Quantum Information and Foundations, DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, United Kingdom and Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada

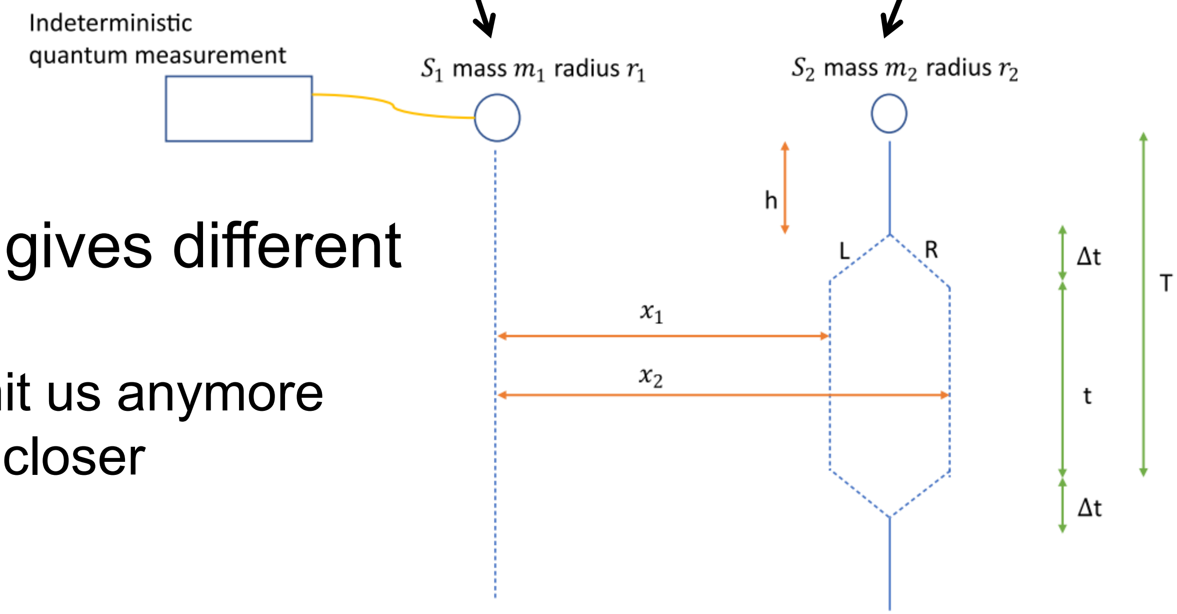
(Received 3 November 2020; accepted 22 February 2021; published 19 March 2021)

Experiments have recently been proposed testing whether quantum-gravitational interactions generate entanglement between adjacent masses in position superposition states. We propose potentially less challenging experiments that test quantum gravity against theories with classical spacetimes defined by postulating semiclassical gravity (or classical effects of similar scale) for mesoscopic systems.

DOI: 10.1103/PhysRevD.103.064038

Quantized or Semiclassical?

Hold or Release　　Left or Right



QG and Semiclassical gives different result even S1 is held

- Casimir effect will not limit us anymore
- S1 and S2 can be much closer

	S1 held	S1 released
Quantized gravity	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}(\lvert L\rangle + \lvert R\rangle)$	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\exp(i\phi_L t)(\lvert L\rangle + \exp(i(\phi_R - \phi_L)t)\lvert R\rangle)$
Semiclassical gravity	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\exp(i\phi_L t/2)(\lvert L\rangle + \exp(i(\phi_R - \phi_L)t/2)\lvert R\rangle)$	

不射之射

- 弓矢の要る中はまだ射之射じゃ。
  不射之射には、烏漆の弓も粛慎の矢もいらぬ。
- Maybe the best is not even doing the measurement

Summary

Let's not do any experiments!