Axion Dark Matter Search with the HAYSTAC Experiment

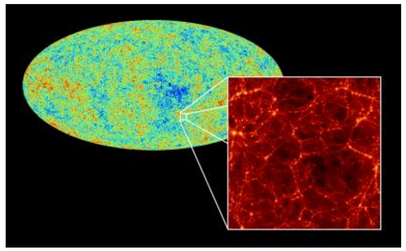
Reina Maruyama
Yale University

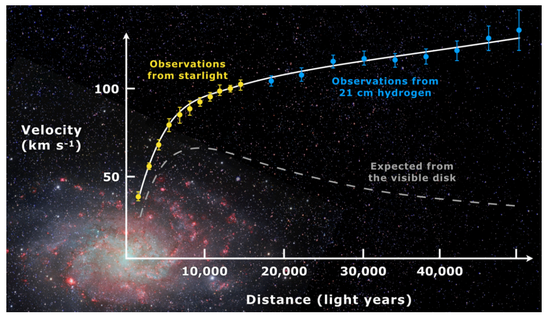
20th Patras Workshop on Axions, WIMP, and WISPs
22–26 September, 2025

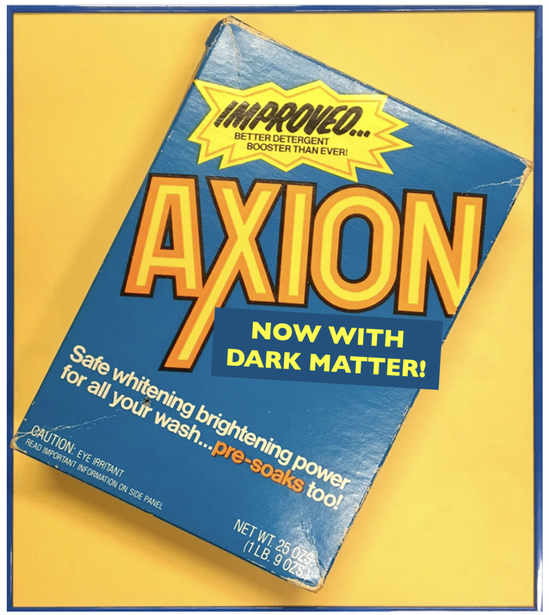
Axions: A Solution

Dark Matter

Astrophysical measurements of gravitational interaction

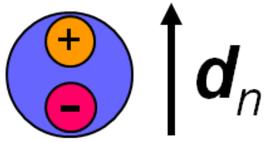


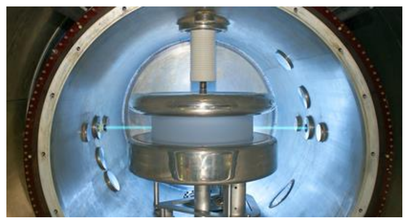


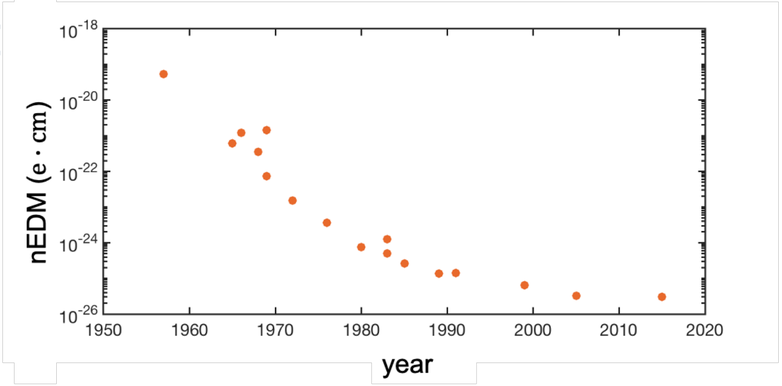


Strong CP Problem

No neutron electric dipole moment





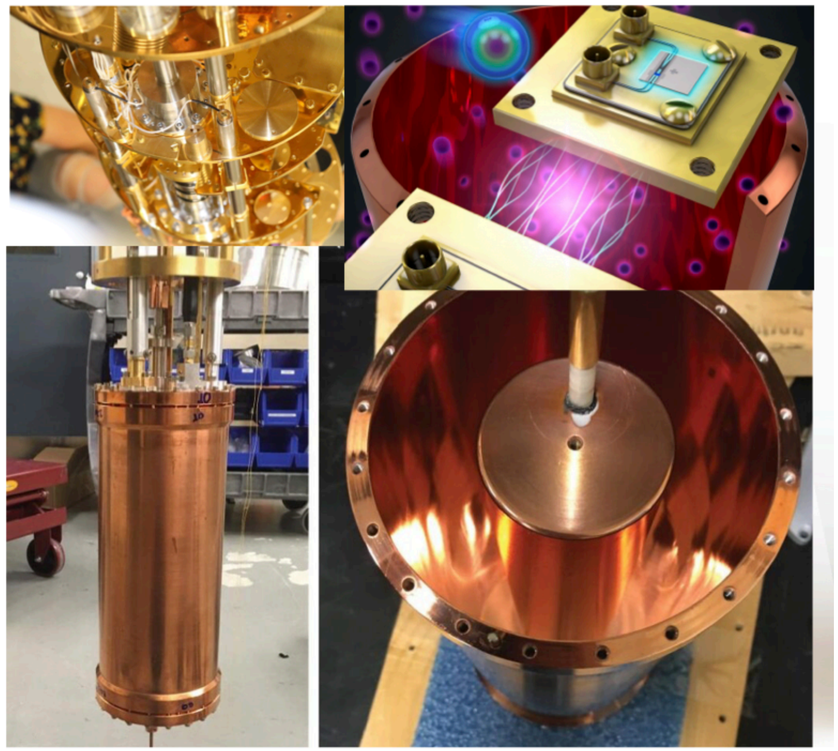


Solution to “clean up” both problems

Axion Searches at Yale

https://axion-dm.yale.edu/

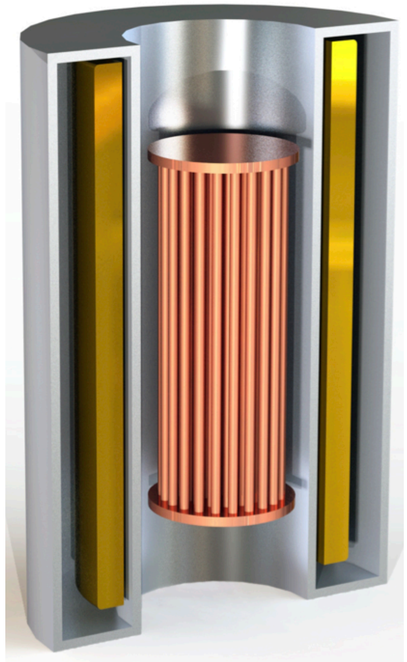
Haystac



Nature **590**, 238–242 (2021)
PRD **107** 072007 (2023)
PRL **134**, 151006 (2025)

This talk

alpha Phase1

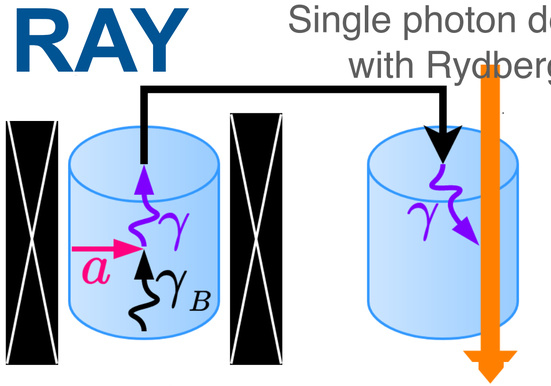


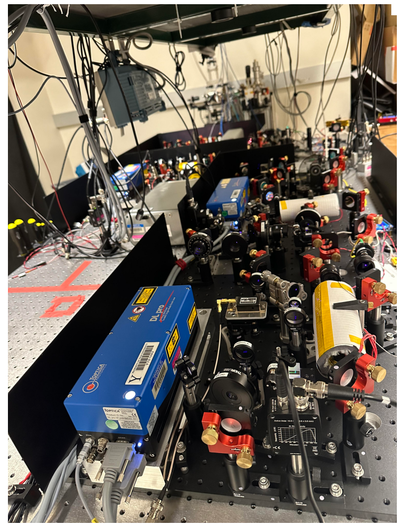
PRL **123**, 141802 (2019)
PRD **107**, 055013 (2023)

Talks/Poster: Max Silva-Feaver, Junu Jeong, Jacob Lindahl

RAY

Single photon detection with Rydberg atoms





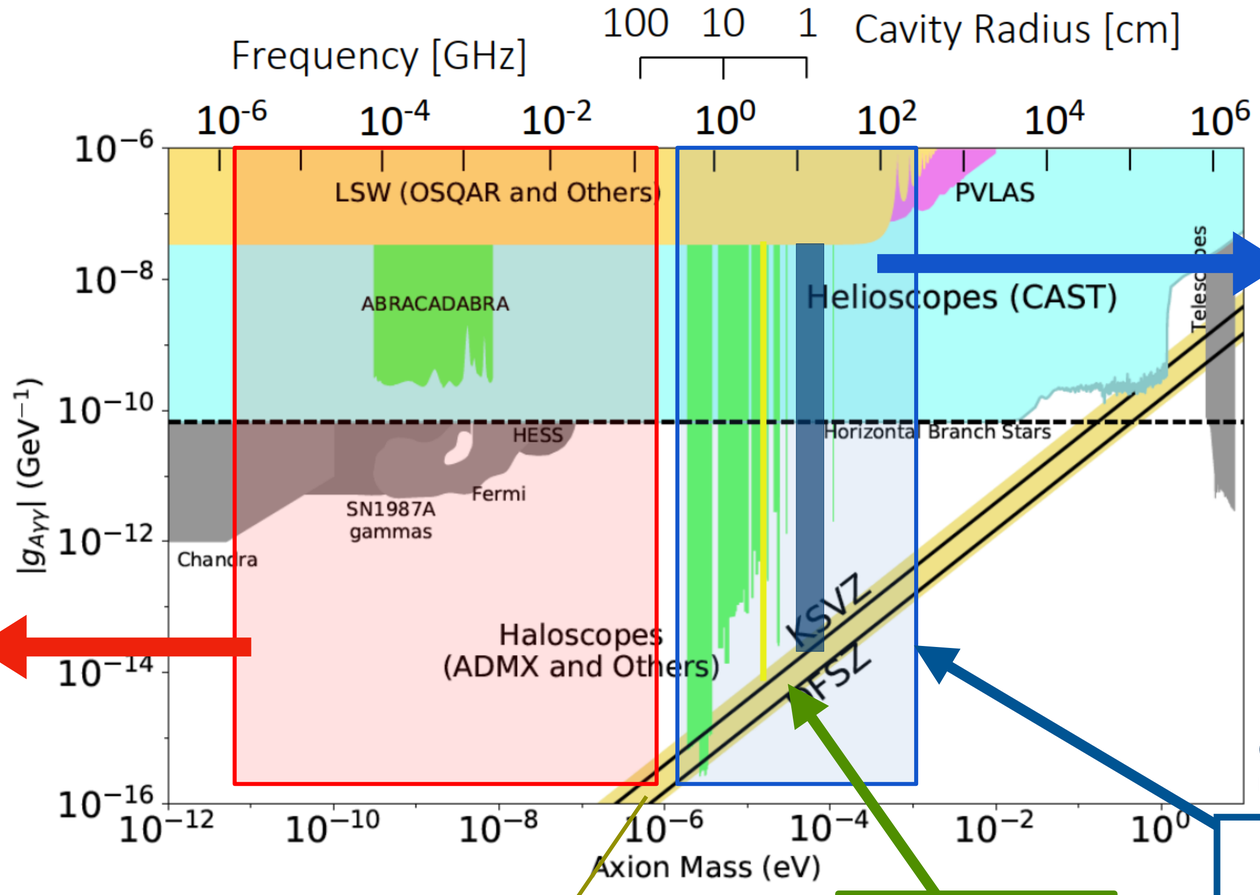
Phys. Rev. D **109**, 032009 (2024)

Standby for future talks

Axions' Pre- vs. Post-Inflation Production

Pre-inflation axion –
wide range of viable masses.
"GUT-scale" axion.

Mass: below 1 μeV
Typical Measurement:
Lumped element detectors



Credit: Particle Data Group 2020 review of axion particle physics

Post-inflation axion –
theoretically calculable from string production mechanisms.

Mass: above 1 μeV
Typical Measurement:
Cavity haloscopes

Coupling for QCD Axion

HAYSTAC (This talk)

ALPHA Phase 1 (See Max Silva-Feaver, Monday)

Adapted from Max Silva-Feaver

The Axion Haloscope

- Axions modify Maxwell's equation and produce an **effective AC current,** which couples Axions to EM.
- **High Q-factor** cavity to capture photons produced through axion-photon conversion
- Measuring our local dark matter halo = "Haloscope"

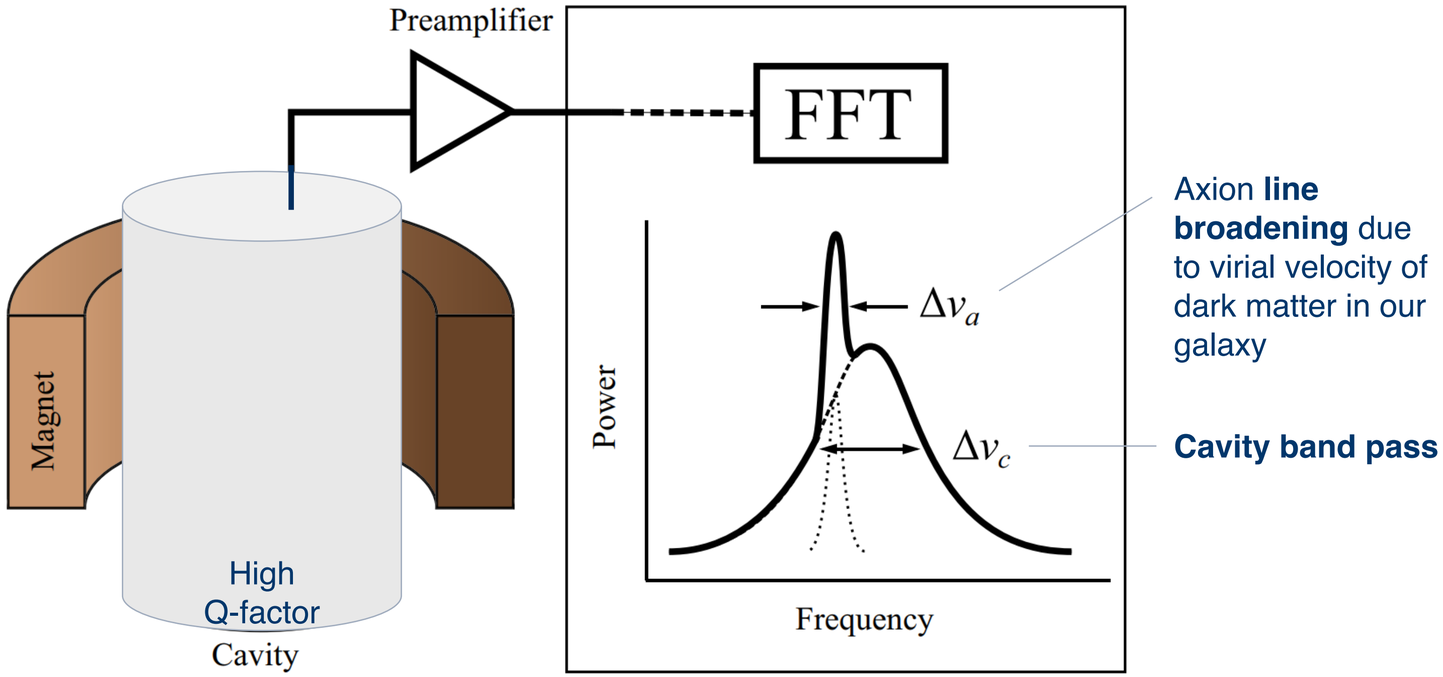


Figure: Kowitt, Balafendiev et al. (2023) *Tunable wire metamaterials for an axion haloscope*

Haloscope principle: P. Sikivie, *Phys. Rev. Lett.,* **51**, 1415 (1983)

Detecting Axions

Signal Power:

$$P \propto B^2 C V Q \simeq 10^{-24}\mathrm{W}$$

B = External field

V = Cavity Volume

Q = Quality Factor

C = Overlap of cavity mode & magnetic field

System Noise:

$$k_b T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_b T} - 1} + \frac{1}{2} \right) + k_b T_A$$

T_{sys} = System temp.

T = Cavity temperature

T_A = Amp. noise temp.

Requirements: Low temp. & signal amplification

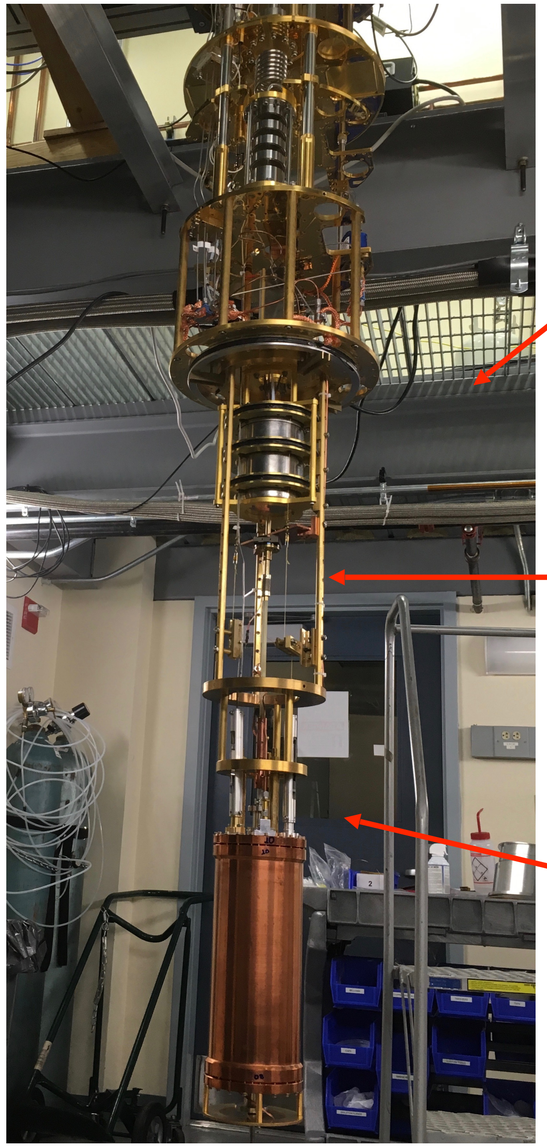
Figure of Merit:

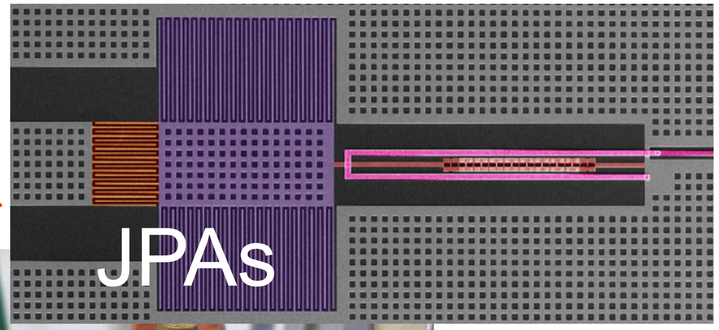
(FOM)

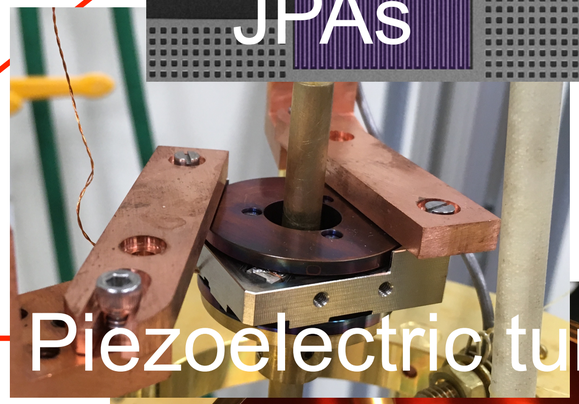
$$\frac{d\nu}{dt} \propto \frac{V^2 B^4 C^2 Q}{T_{sys}^2}$$

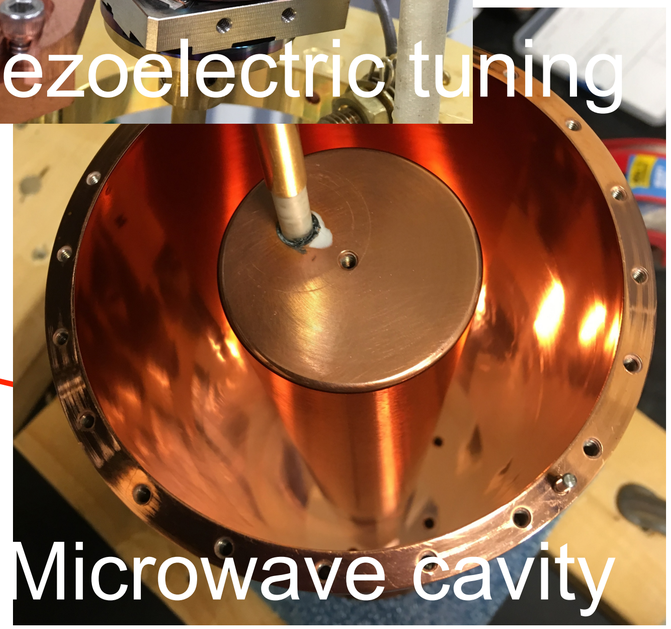
Challenge: Do experiments in human timescales!

HAYSTAC Experiment







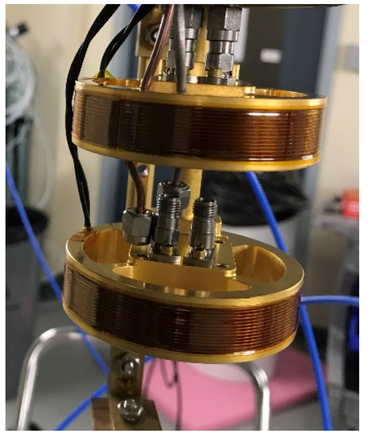


Brubaker et al., PRL 118 061302 (2017)

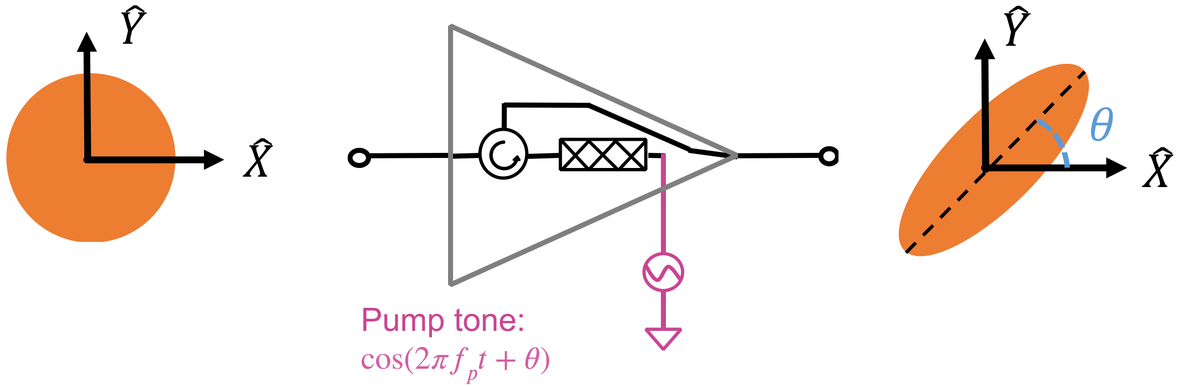
HAYSTAC Innovations: Phase 1

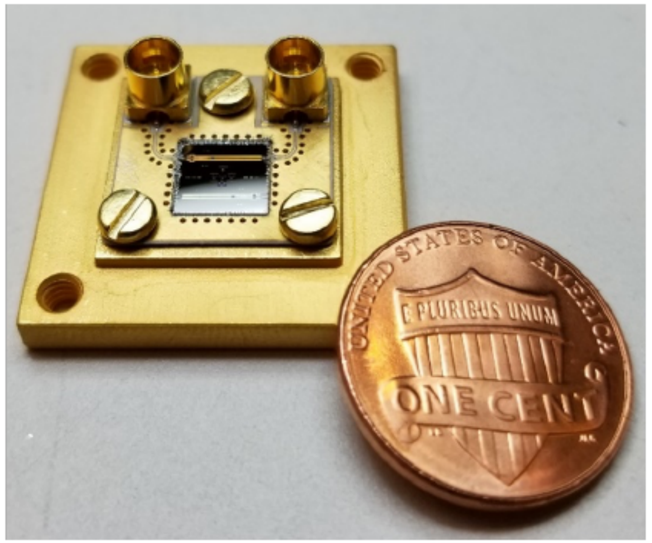
Josephson Parametric Amplifier (JPA)

- Near quantum-limited noise
- Tunable LC resonators
- Phase-sensitive amplifier

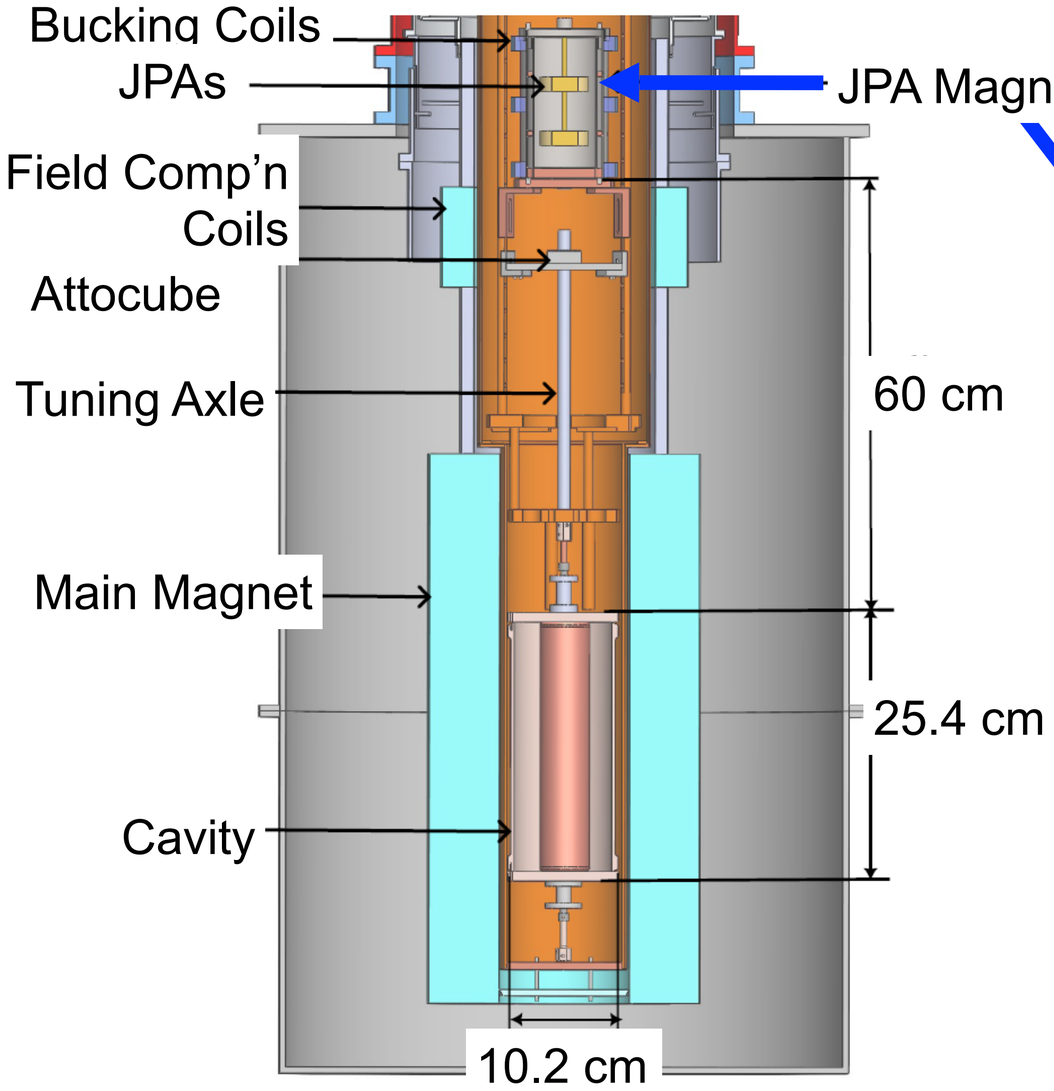


Ben Brubaker
(Tanaka Dissertation Award)

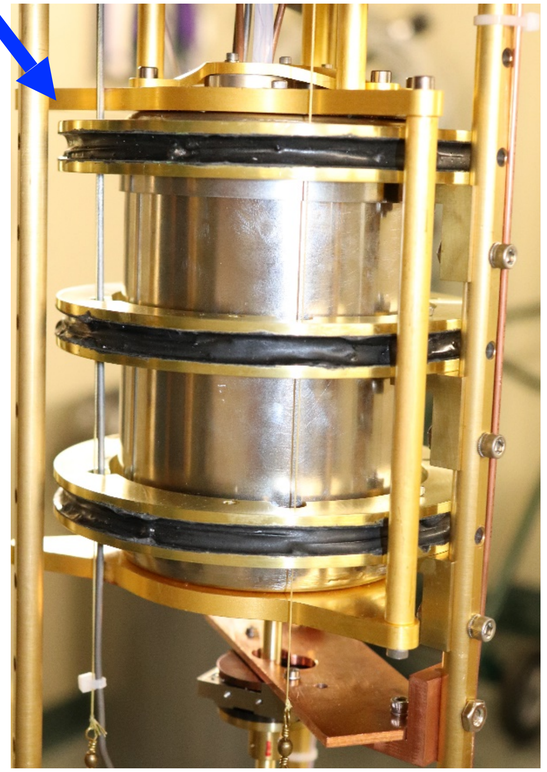




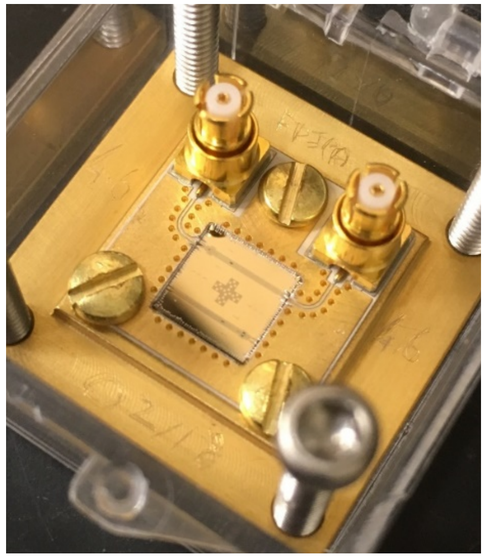
JPAs in HAYSTAC



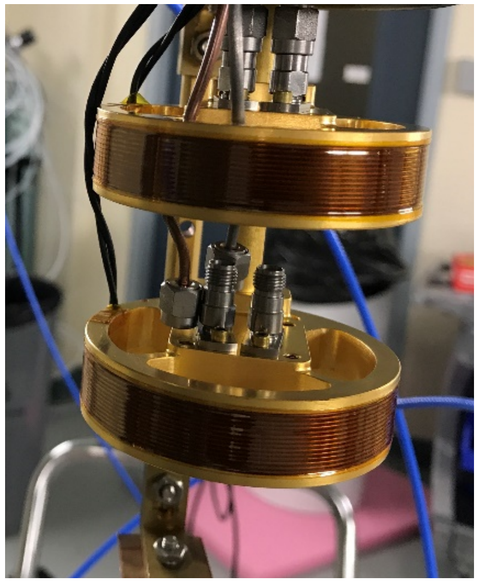
JPA Magnetic Shield



JPA Magnetic Shielding



JPA



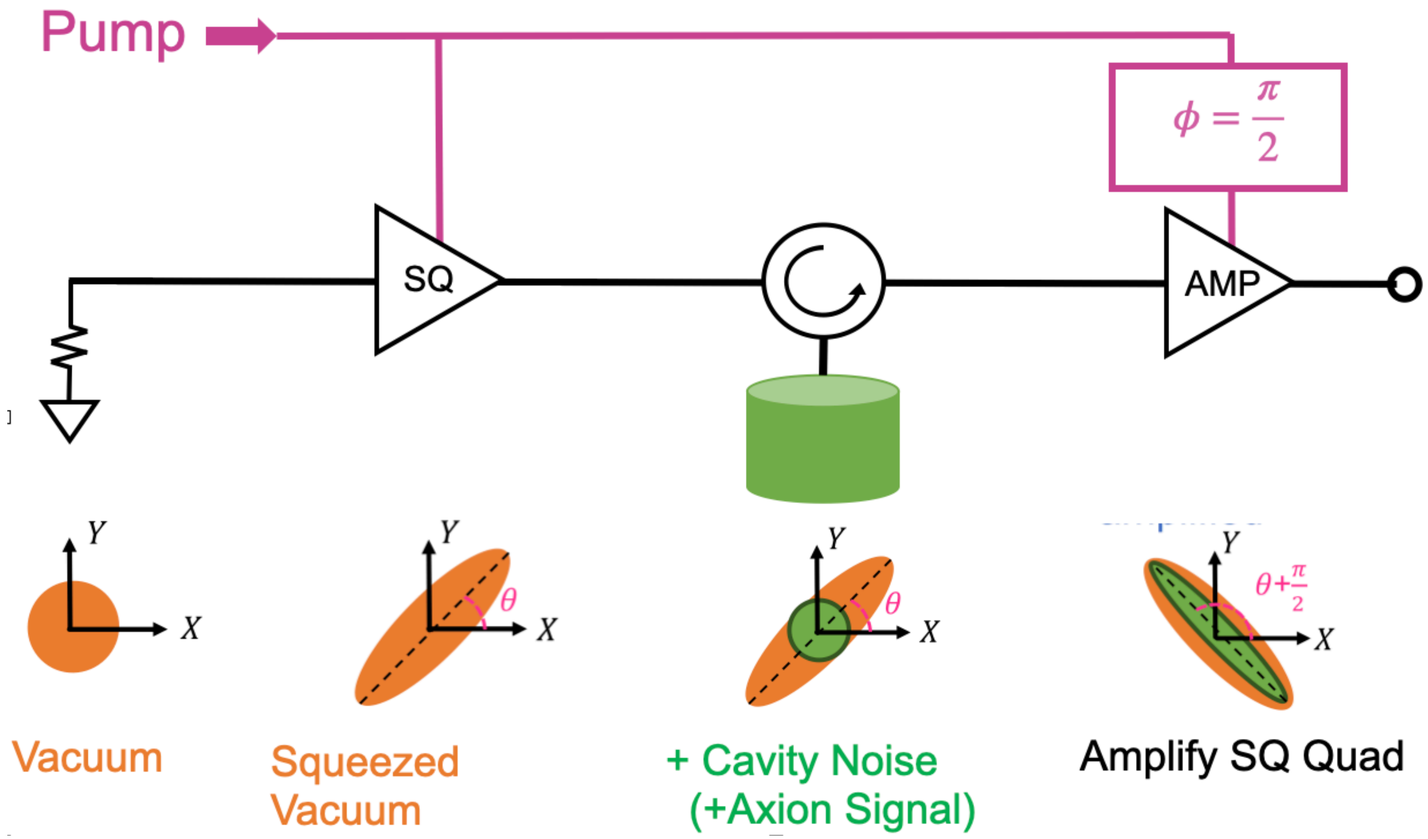
JPA Coils

Malnou et al., Phys. Rev. X 9, 021023 (2019)

HAYSTAC Innovation: Phase 2

Squeezed State Receiver (SSR)

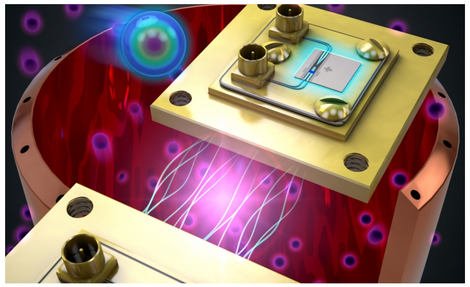
- 2 JPAs in tandem to beat the quantum limit

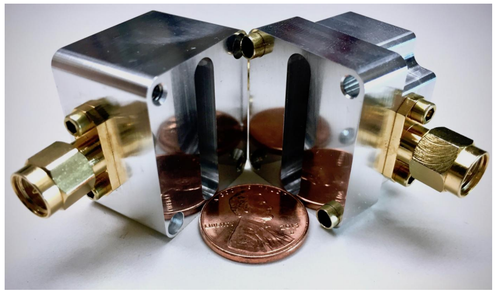


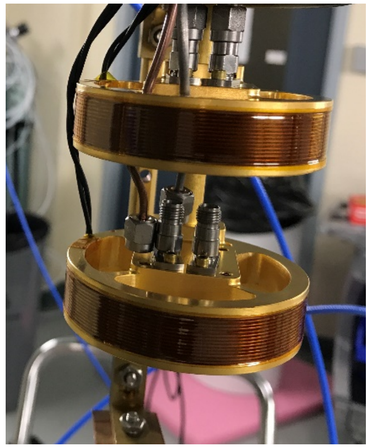
HAYSTAC: Phase 2

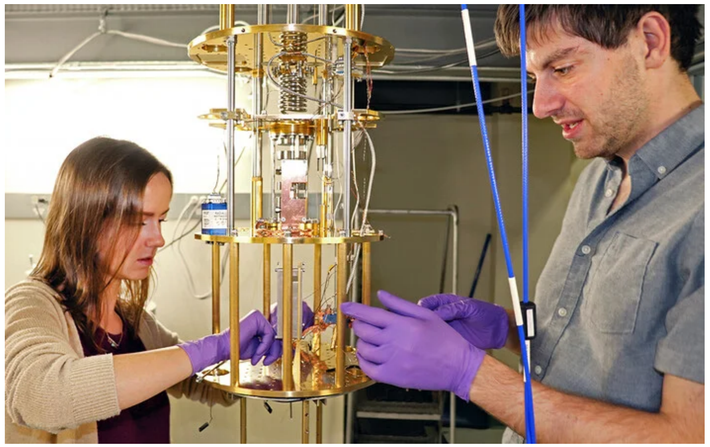
Malnou et al., Phys. Rev. X 9, 021023 (2019)
Backes et al., Nature, **590,** 238 (2021)

- Dark matter search enhanced by quantum squeezing
  - LIGO - the other experiment that uses squeezing to enhance signal
- -4dB noise reduction
- x2 speedup

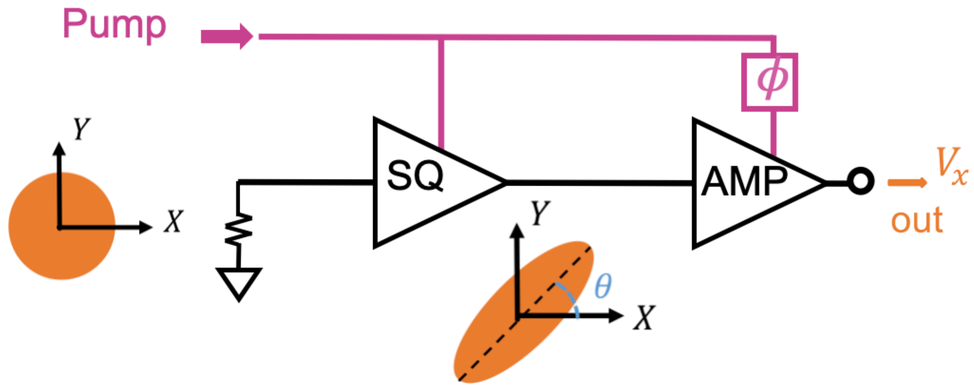


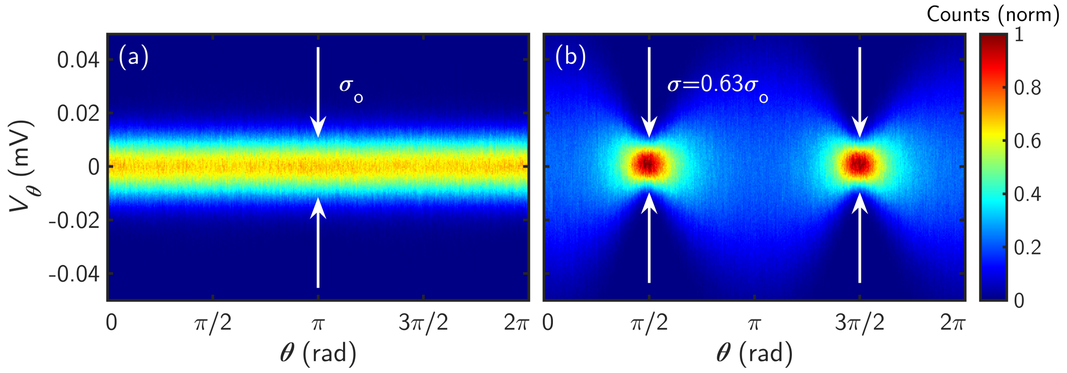






Kelly Backes Dan Palken



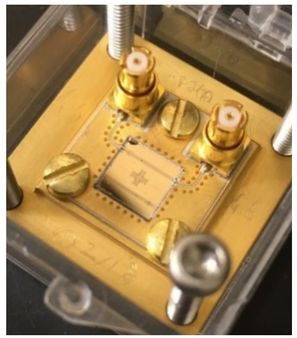


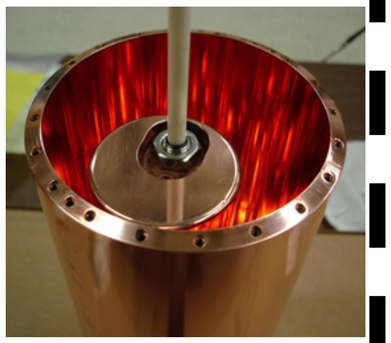
Design/Construction

Phase I (Single JPA)

Phase II (SSR)

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025





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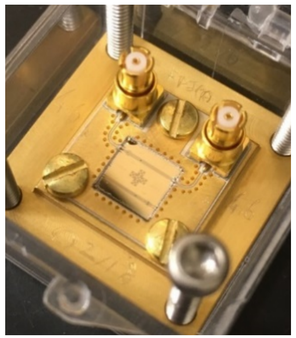
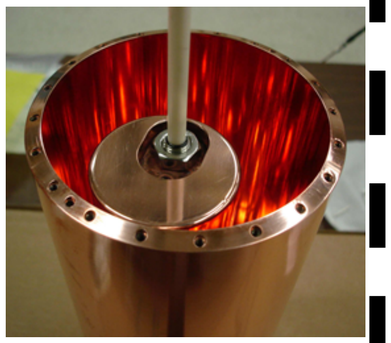
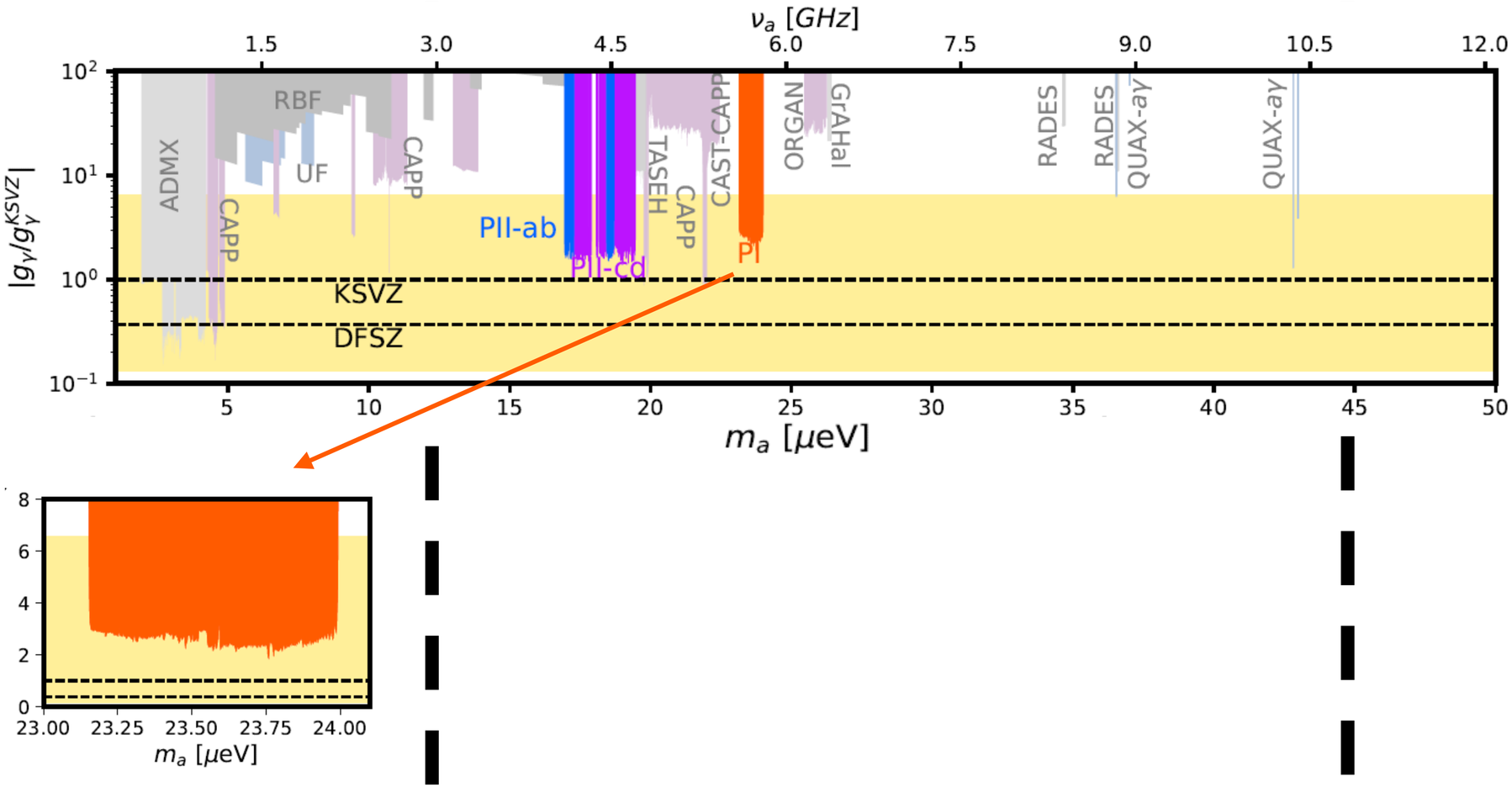






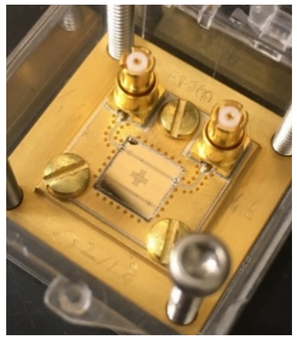
PRL 118 (2017)
PRD 97 (2018)

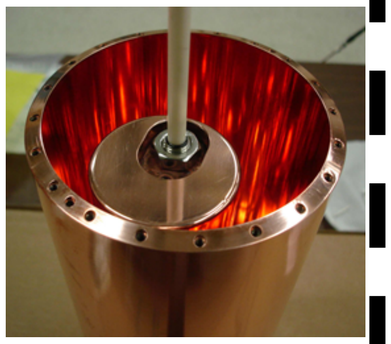
Design/Construction

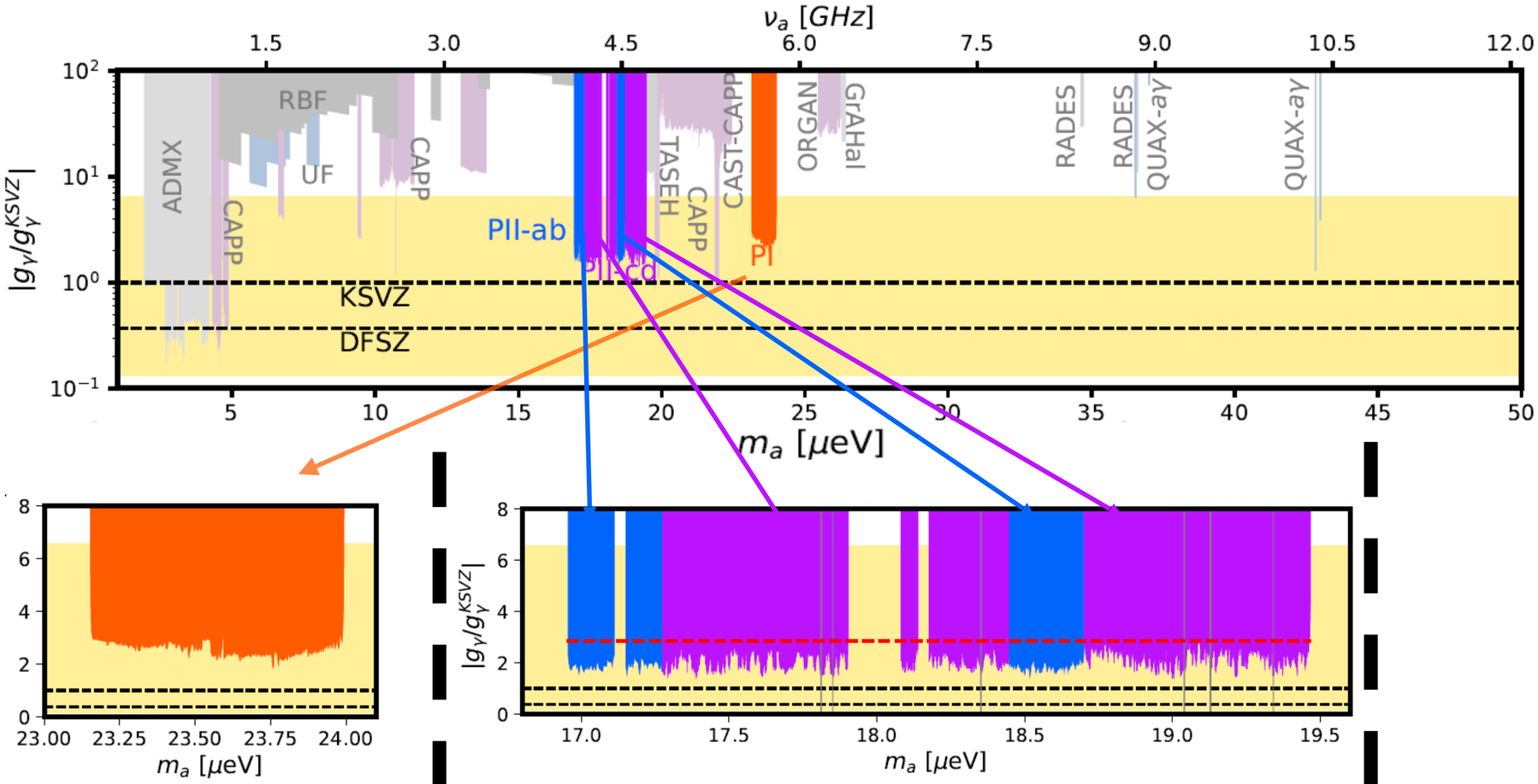
Phase I (Single JPA)

Phase II (SSR)

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025







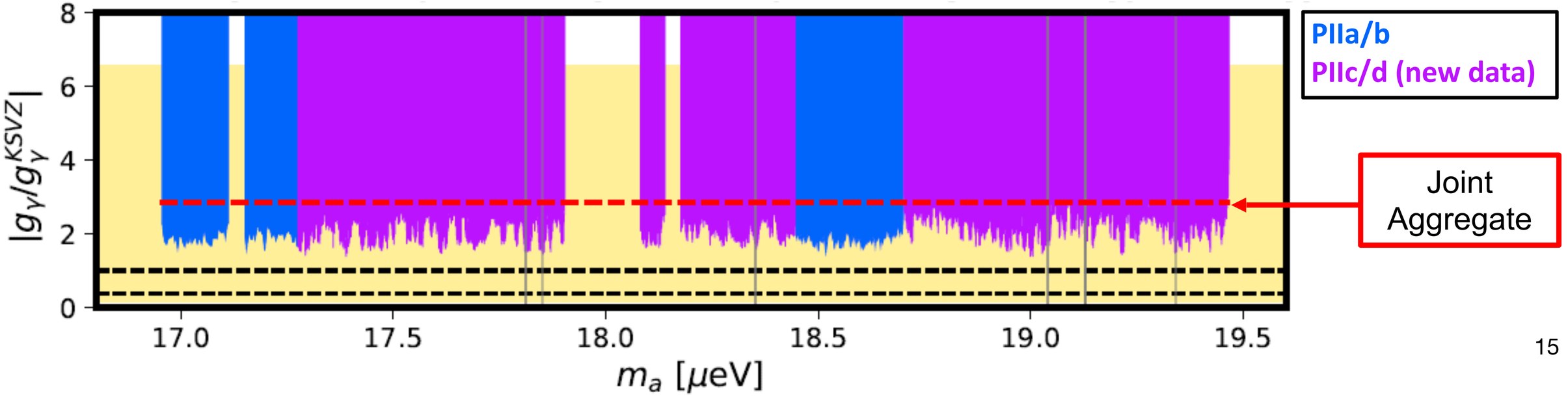
PRL 118 (2017)
PRD 97 (2018)

Nature **590**, 238–242 (2021)
PRD **107** 072007 (2023)
PRL **134**, 151006 (2025) *Editors' Suggestion*

Results from Phase II

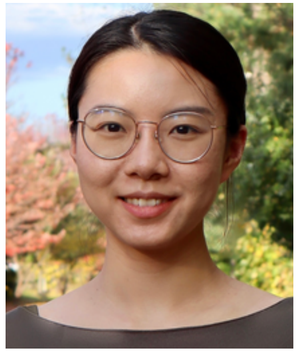
X. Bai *et al.*, PRL **134**, 151006 (2025)

- Phase II covered 550MHz of unexplored parameter space
  - Gaps = mode crossings
- No evidence of an axion signal
- 90% Aggregate exclusion $|g_\gamma| > 2.86\ |g_\gamma^{KSVZ}|$ over all Phase II



HAYSTAC Phase I & II

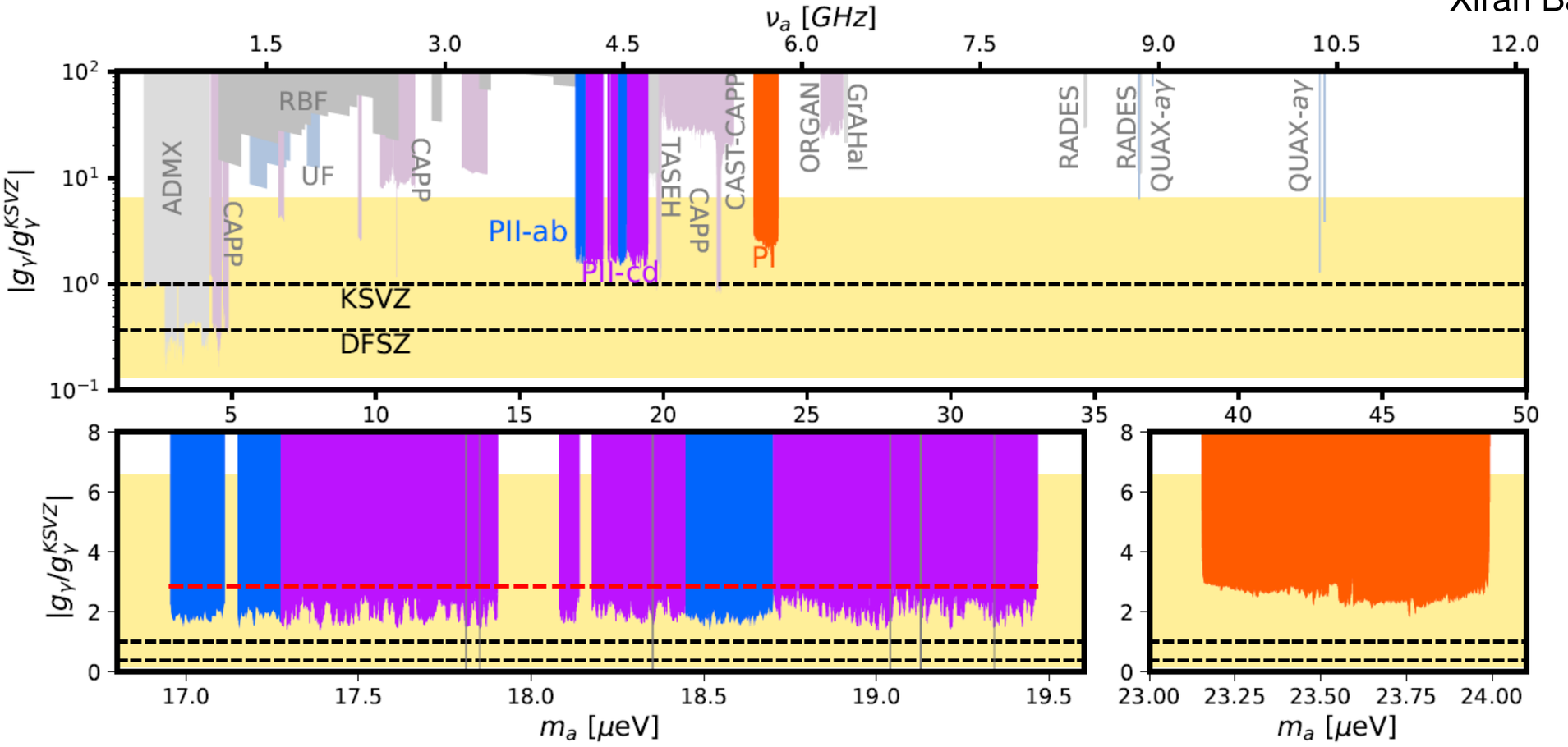
Bai, Jewell, *et al.,* PRL **134**, 151006 (2025)



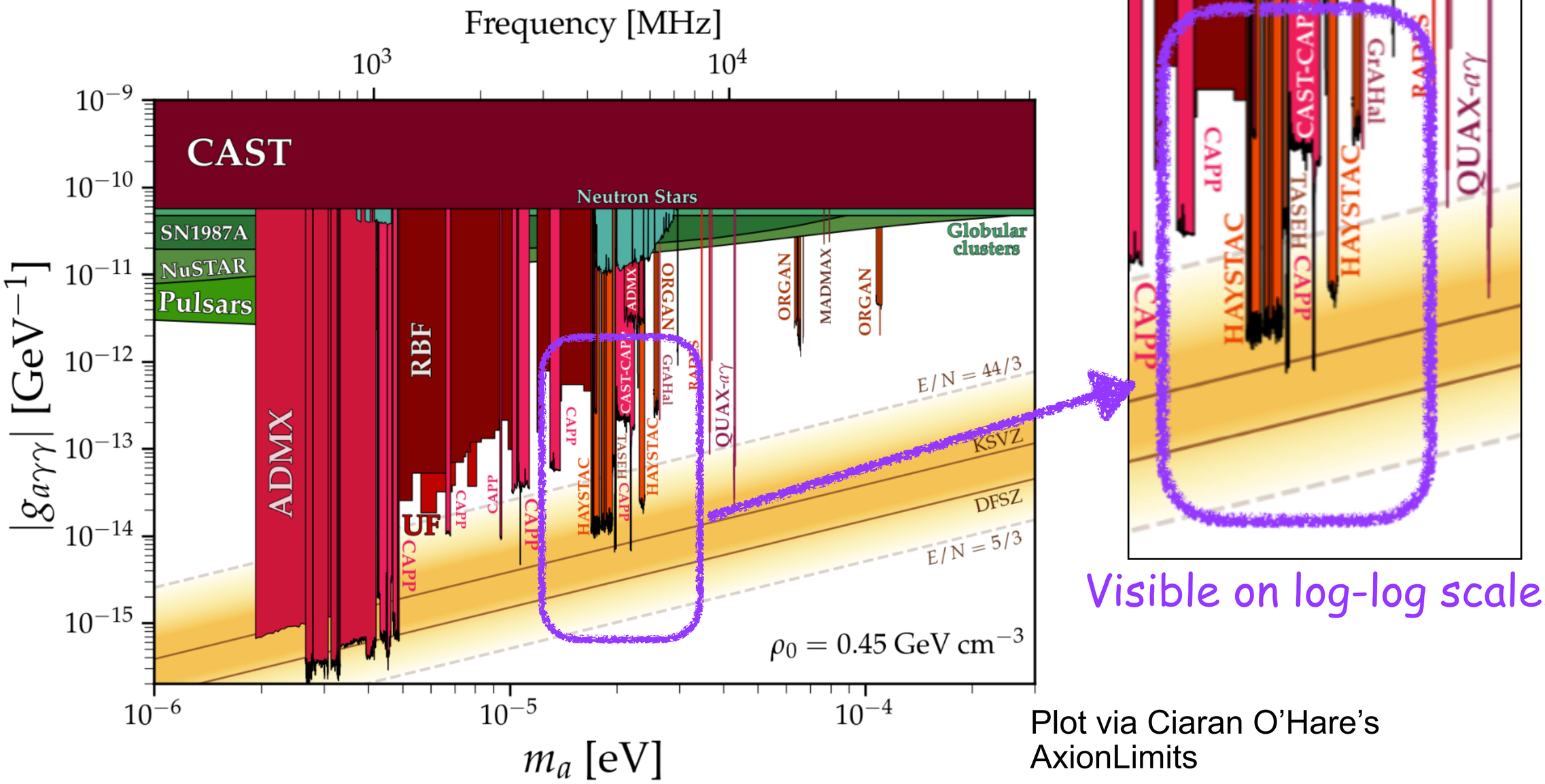
Xiran Bai

Mike Jewell

- Phase I & II ~750 MHz covered between 4 – 6GHz



HAYSTAC in 2025



Visible on log-log scale!

Plot via Ciaran O'Hare's AxionLimits

Dark Photon Search with TASEH Data

- Claim for tentative dark photon signal @ 4.7σ by Y-H Chang et al., on reanalysis of TASEH's 2022 results
- Two authors in common (Y.-H. Chang and H.T. Doan)

PRL 129, 111802 (2022)

First Results from the Taiwan Axion Search Experiment with Haloscope at 19.6 μeV

Hsin Chang,[1] Jing-Yang Chang,[1] Yi-Chieh Chang,[2] Yu-Han Chang,[3] Yuan-Hann Chang,[4,5] Chien-Han Chen,[4] Ching-Fang Chen,[1] Kuan-Yu Chen,[1] Yung-Fu Chen,[1,*] Wei-Yuan Chiang,[2] Wei-Chen Chien,[3] Hien Thi Doan,[4] Wei-Cheng Hung,[1,4] Watson Kuo,[3] Shou-Bai Lai,[1] Han-Wen Liu,[1] Min-Wei OuYang,[1] Ping-I Wu,[1] and Shin-Shan Yu[1,5,†]
(TASEH Collaboration)

arXiv:2507.00784 (July 2025)

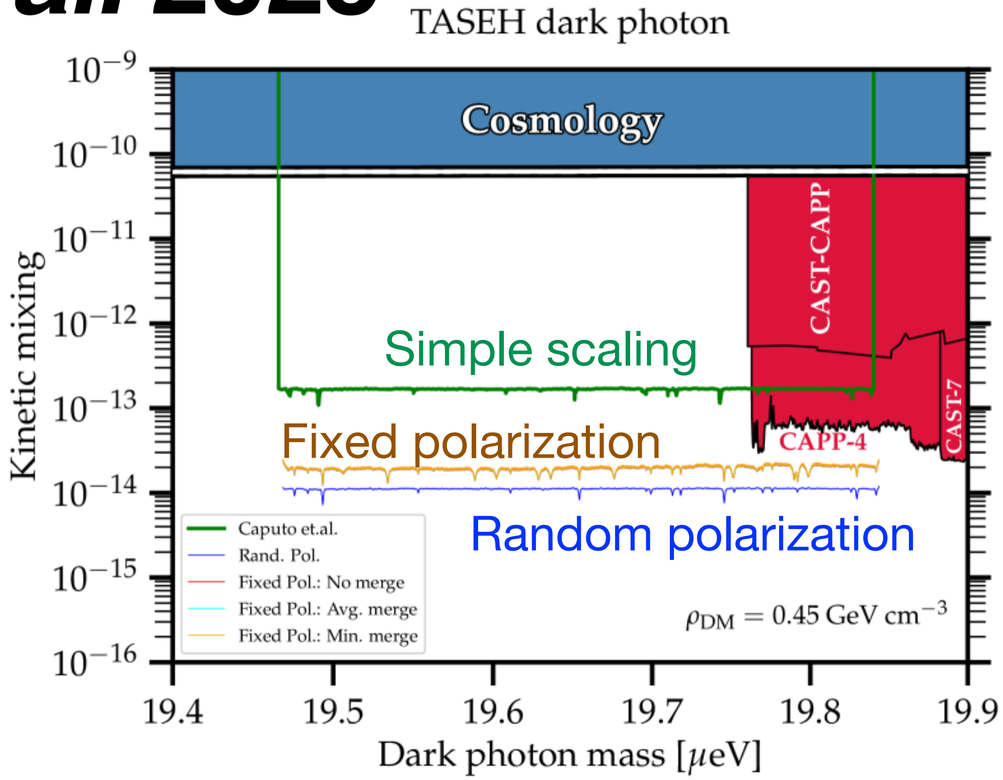
Dark photon dark matter constraints and a tentative signal at the TASEH experiment

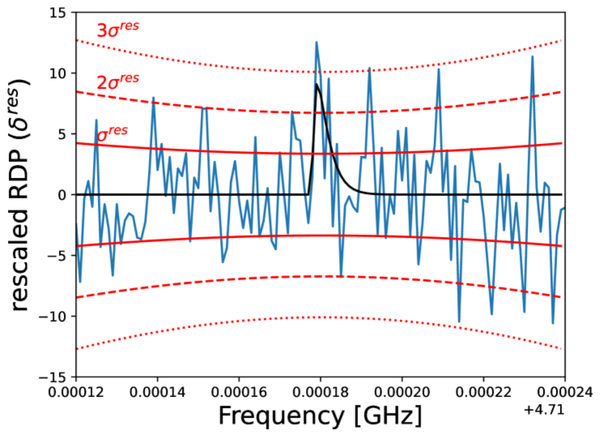
Yuan-Hann Chang,[1,2,*] Cheng-Wei Chiang,[3,4,†] Hien Thi Doan,[5,‡] Nick Houston,[6,§] Jinmian Li,[7,¶] Tianjun Li,[8,9,10,**] Lina Wu,[11,††] and Xin Zhang[12,13,‡‡]
[1]*Center for High Energy and High Field Physics,*
National Central University, Taoyuan City 320317, Taiwan

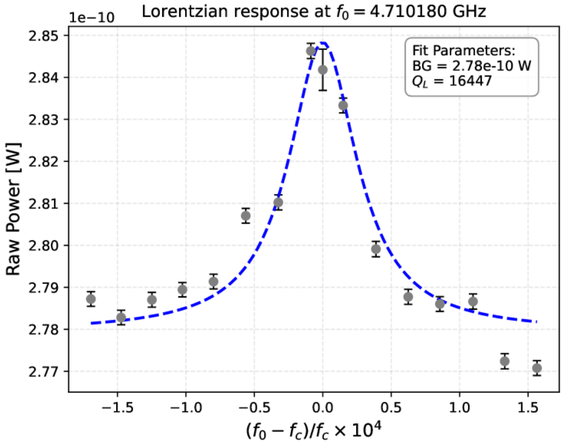
(See also Ben McAllister's talk on ORGAN's follow-up on this from Monday)

Dark Photon Y.-H. Chang *et al.* 2025

- Two TASEH authors + theorists published a re-analysis for dark photon
- Exclude $|\epsilon| > 2 \times 10^{-14}$ from 19.46–19.84 μeV
- Reported dark photon signal at 4.71018 GHz.
- Local significance: 4.7σ
- Global significance: 1.7σ
- Scan 28 times:
  - persists with magnet off
  - not present in ambient RFI detector

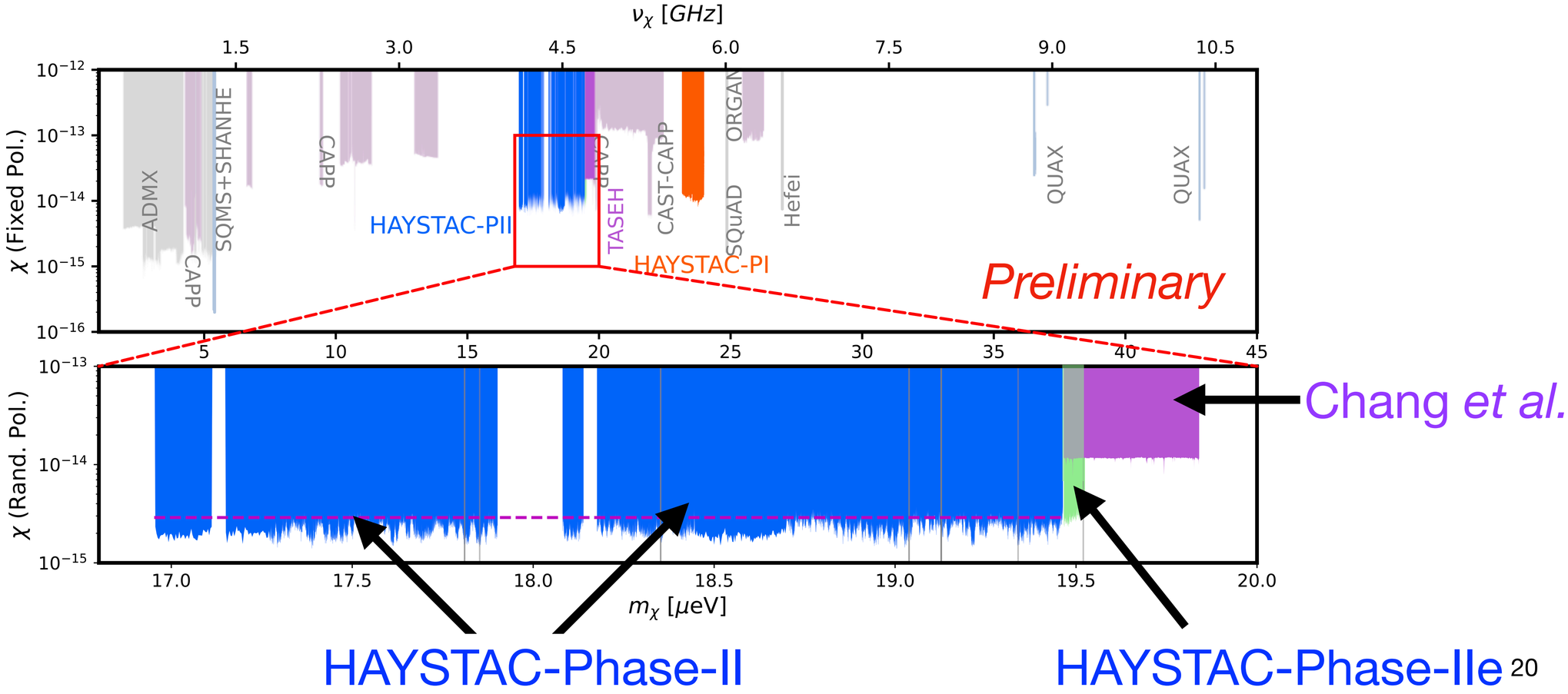






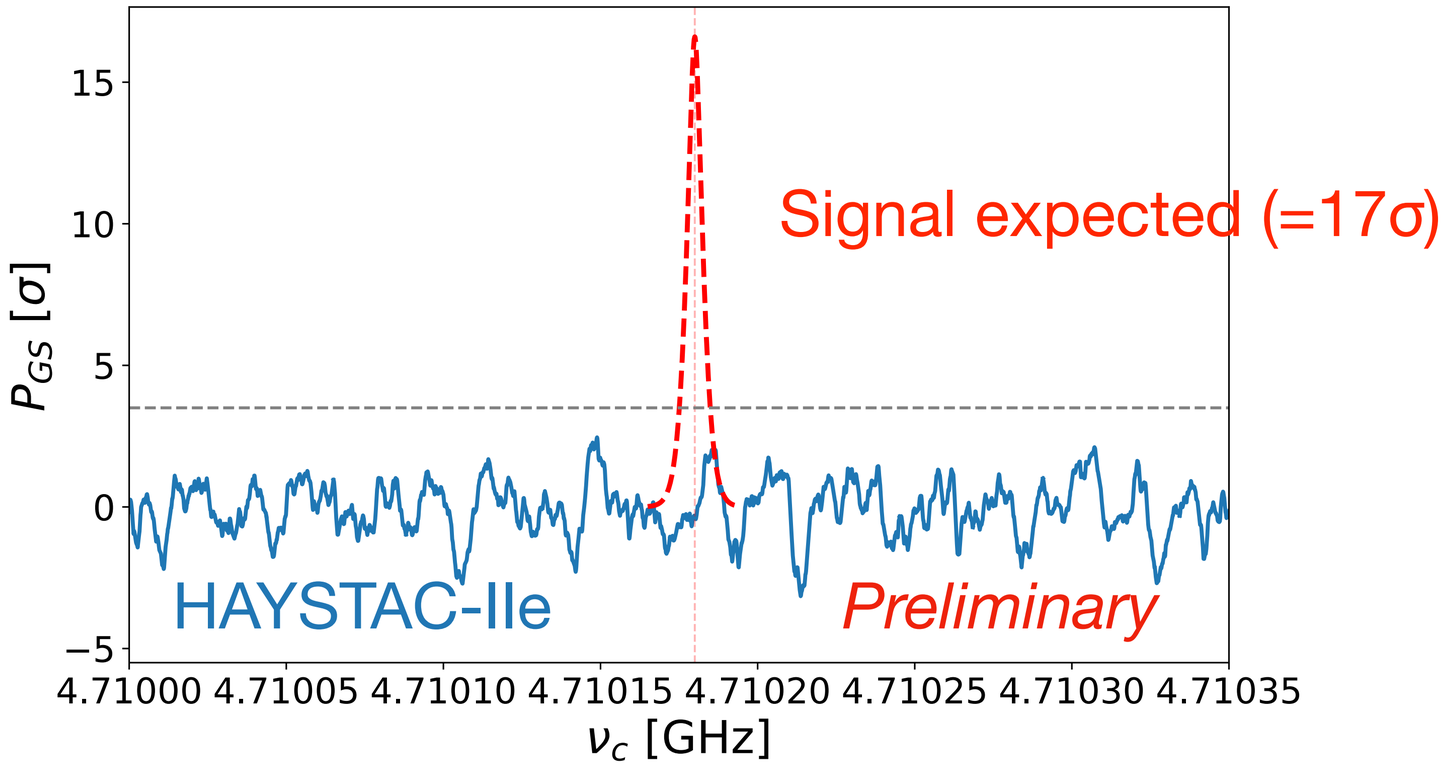
Dark Photon Search with HAYSTAC Phase-IIe

- Search in unpublished data from 7/13/22 - 8/10/22
- Data previously omitted from analysis due to uncertainty in the position of the tuning rod



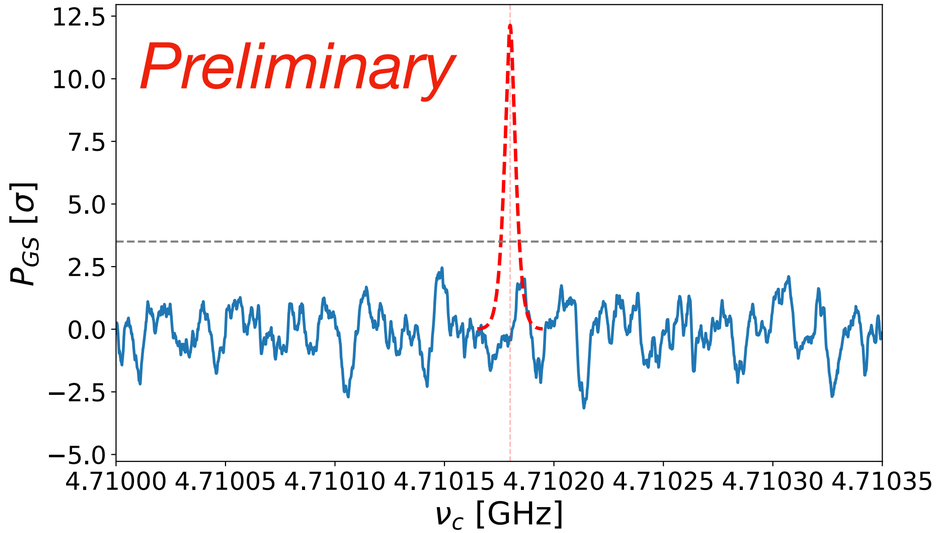
HAYSTAC Phase-IIe

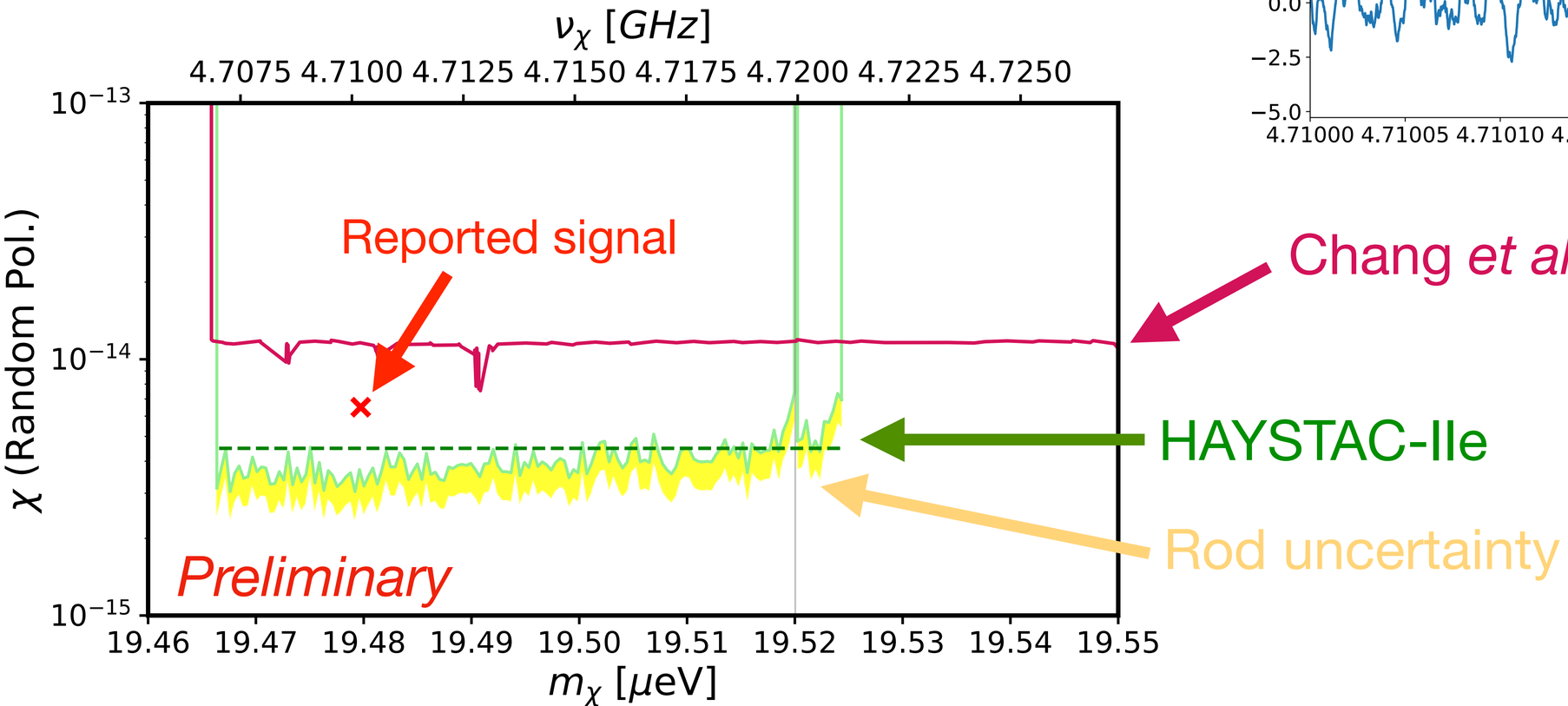
- Search in unpublished data from 7/13/22 - 8/10/22
- Dark photon excluded at ~3.5 x 10^{-15}
- No signal observed at 19.479727 μeV



HAYSTAC Phase-IIe

- Search in unpublished data from 7/13/22 - 8/10/22
- Dark photon excluded at ~3.5 x 10^{-15}
- No signal observed at 19.479727 μeV



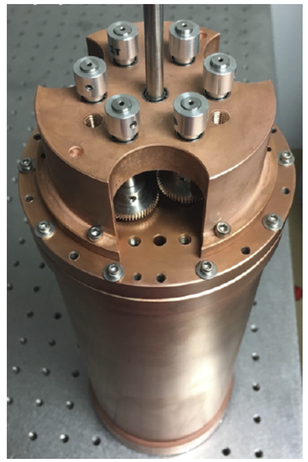


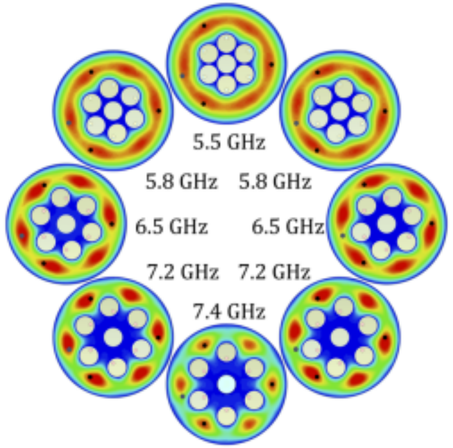
Paper soon

Pushing the Frontiers: New Techniques

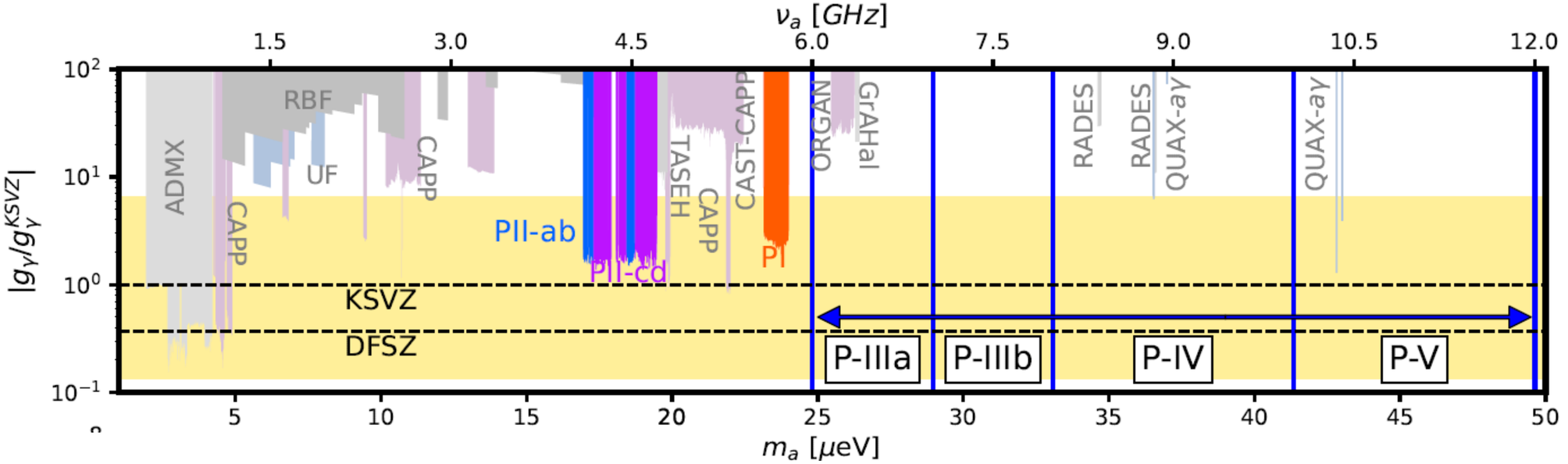
HAYSTAC: Phase IIIa

P-IIIa



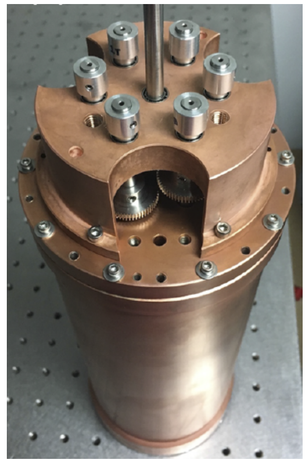


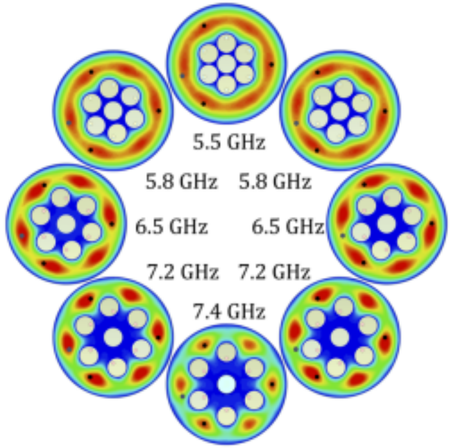
Rev.Sci.Instrum. ***92*** *(2021)*



HAYSTAC: Phase IIIb

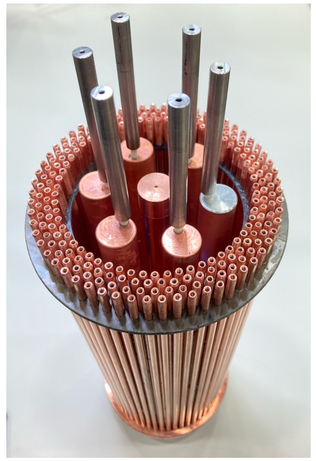
P-IIIa



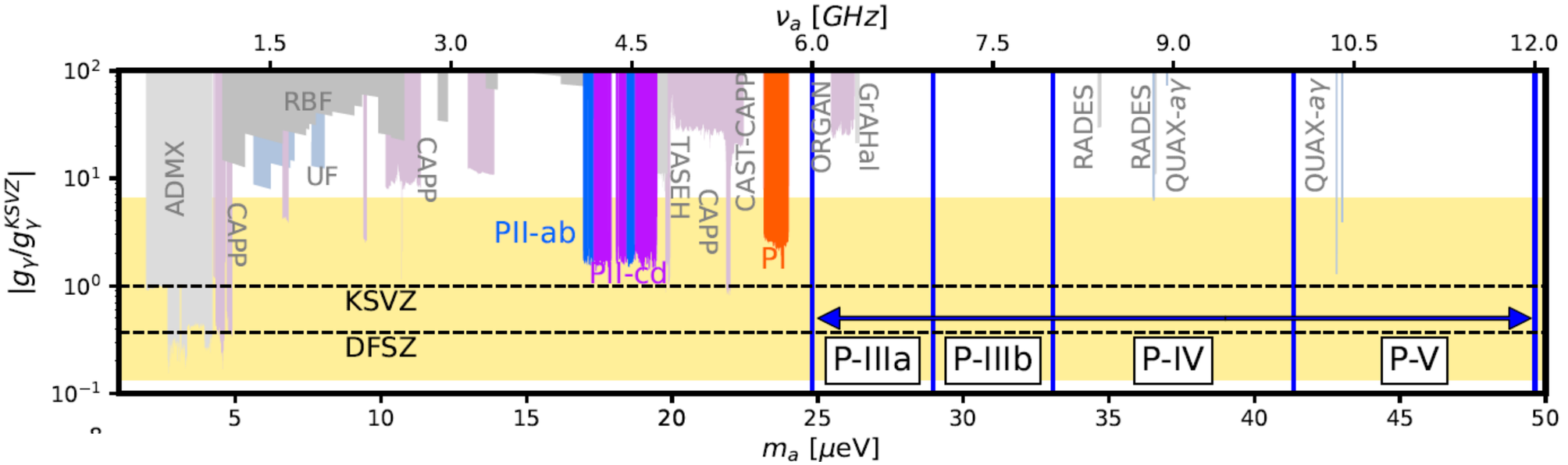


Rev.Sci.Instrum. ***92*** *(2021)*

P-IIIb

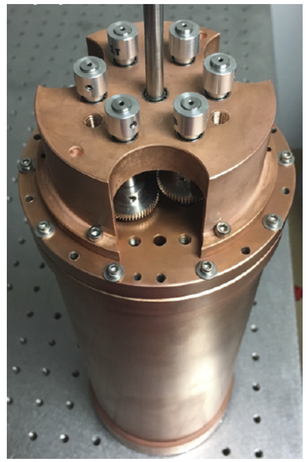


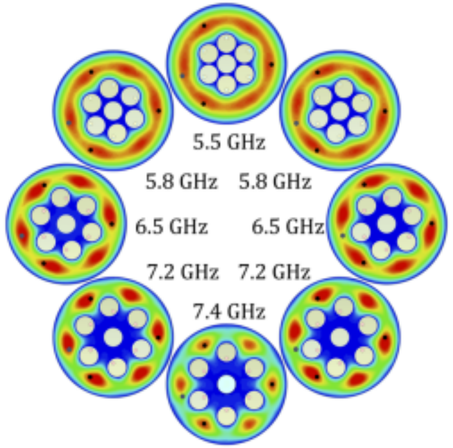
Rev.Sci.Instrum. **96** (2025)



HAYSTAC: Phase IV

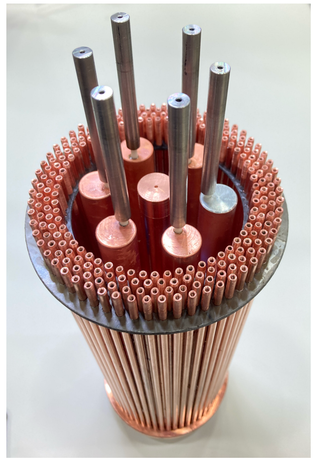
P-IIIa





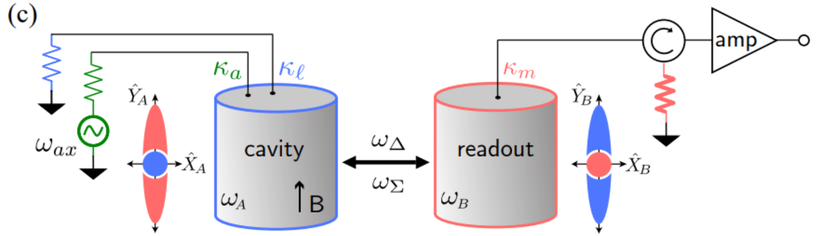
Rev.Sci.Instrum. ***92*** *(2021)*

P-IIIb

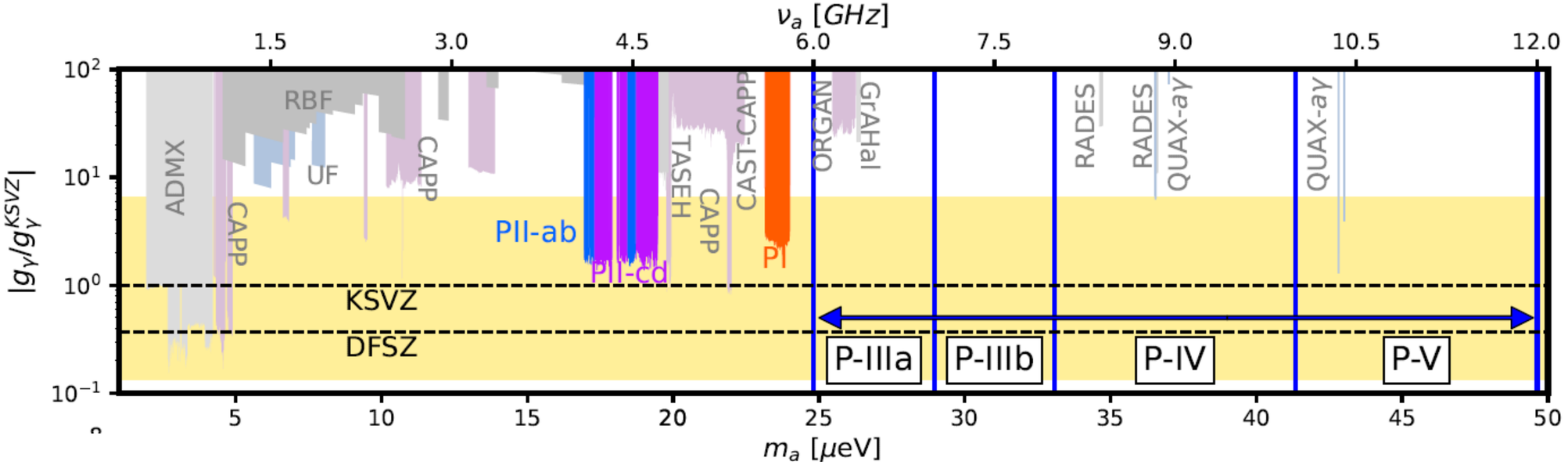


Rev.Sci.Instrum. **96** (2025)

P-IV

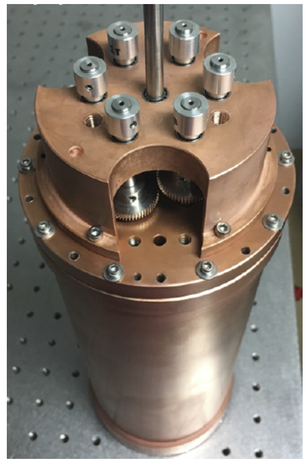


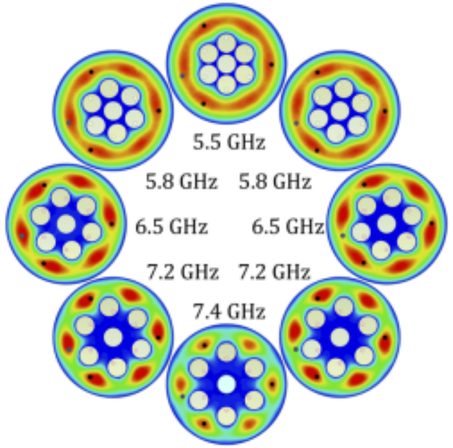
Y. Jiang et al., PRX Quantum ***4*** *(2024)*



HAYSTAC: Phase V

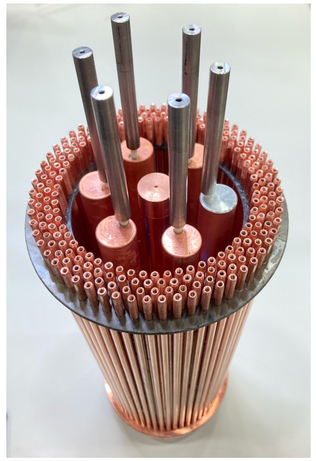
P-IIIa





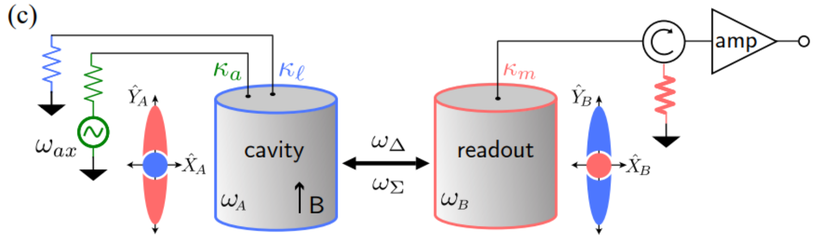
Rev.Sci.Instrum. ***92*** *(2021)*

P-IIIb



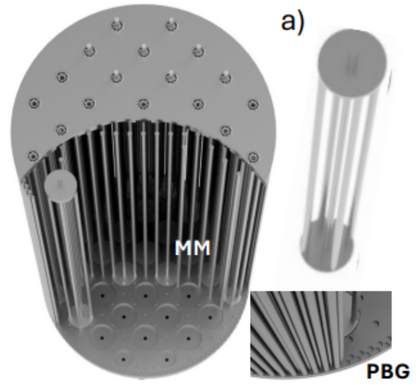
Rev.Sci.Instrum. **96** (2025)

P-IV

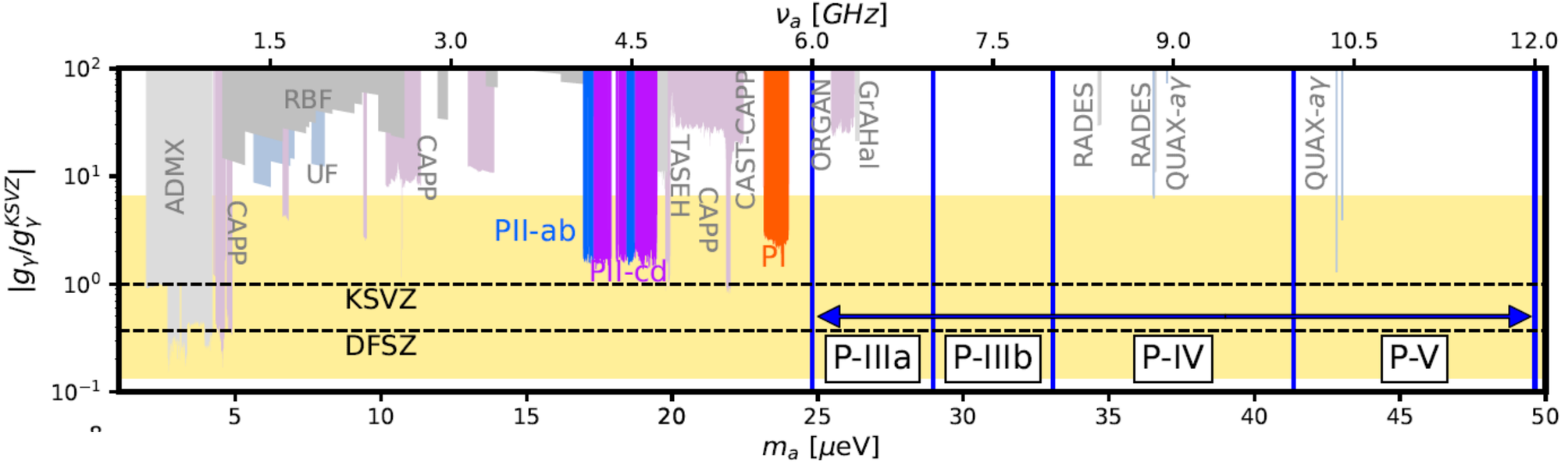


Y. Jiang et al., PRX Quantum ***4*** *(2024)*

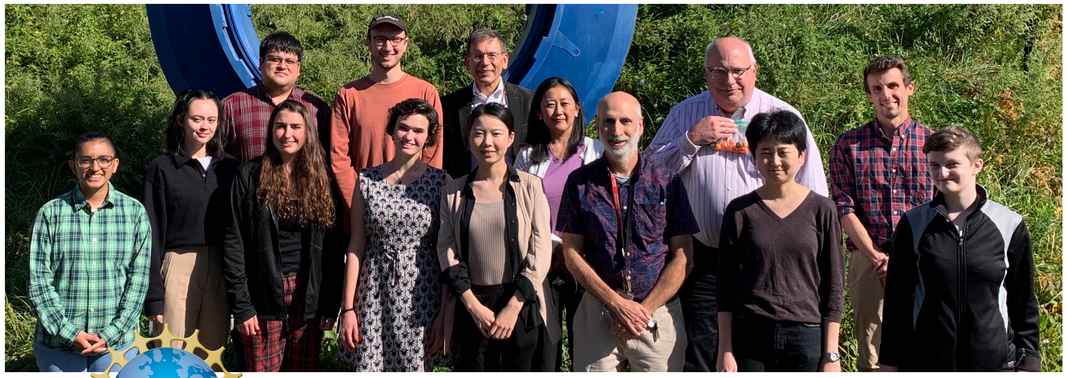
P-V



Rev.Sci.Instrum. **96** (2025)

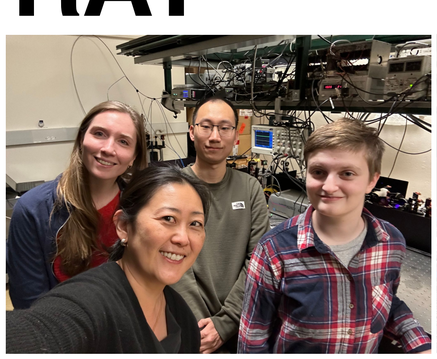


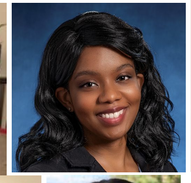
Haystac



YALE (HOST), UC BERKELEY, JOHNS HOPKINS

RAY





YALE (HOST) & JOHNS HOPKINS

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Wright Laboratory, Yale

Summary & Outlook

- Axions are a great dark matter candidate and solve the strong-CP problem
- HAYSTAC as a test-bed for new technologies
- No QCD axions down to ~2x KSVZ ~17–19.5 μev, ~550 MHz
  - HAYSTAC visible in log-log plots
- Stay tuned!