Experimental Search for Axion Dark Matter at IBS-DMAG

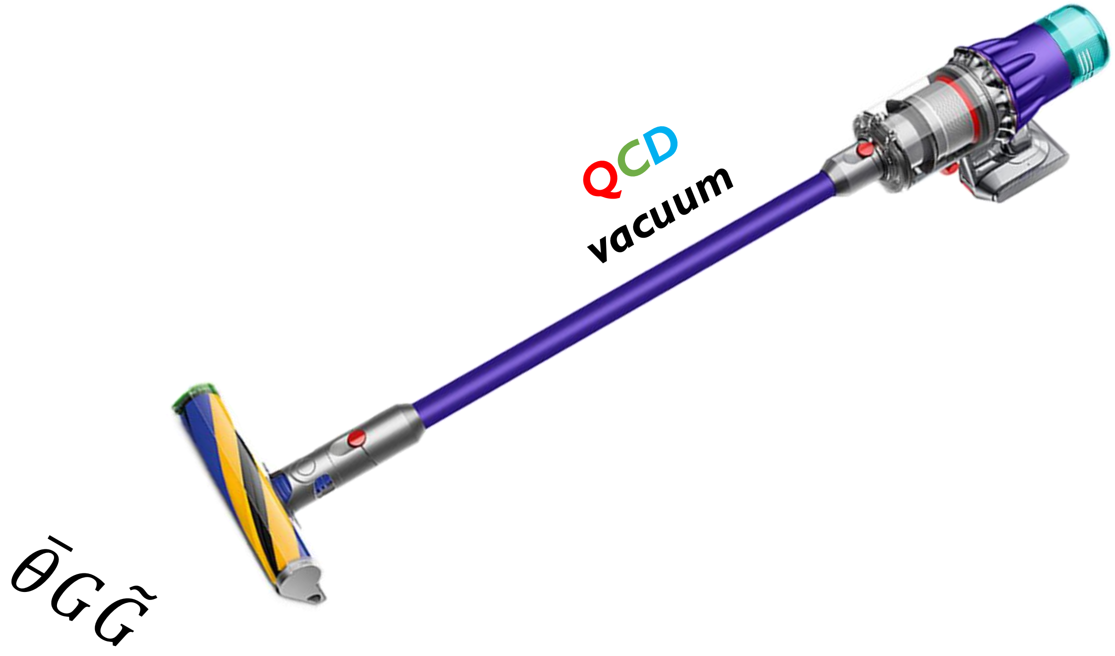
Saebyeok Ahn

Senior researcher

Institute for Basic Science (IBS) / Dark Matter Axion Group (DMAG)

Strong CP problem

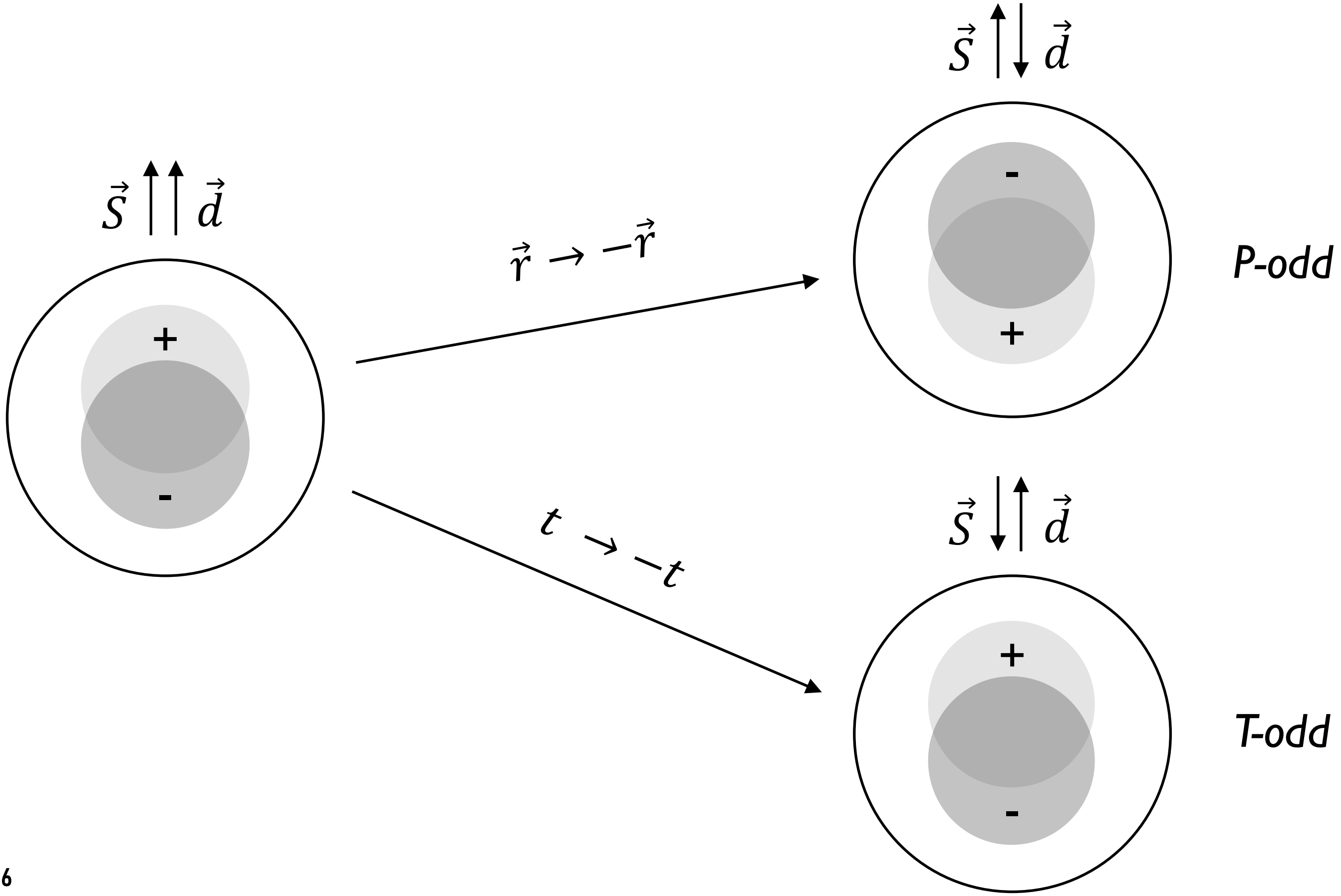
- QCD and CP symmetry



Idea from https://indico.cern.ch/event/663474/contributions/3062438/attachments/1681668/2702690/Tom_Cohen_Crete.pdf

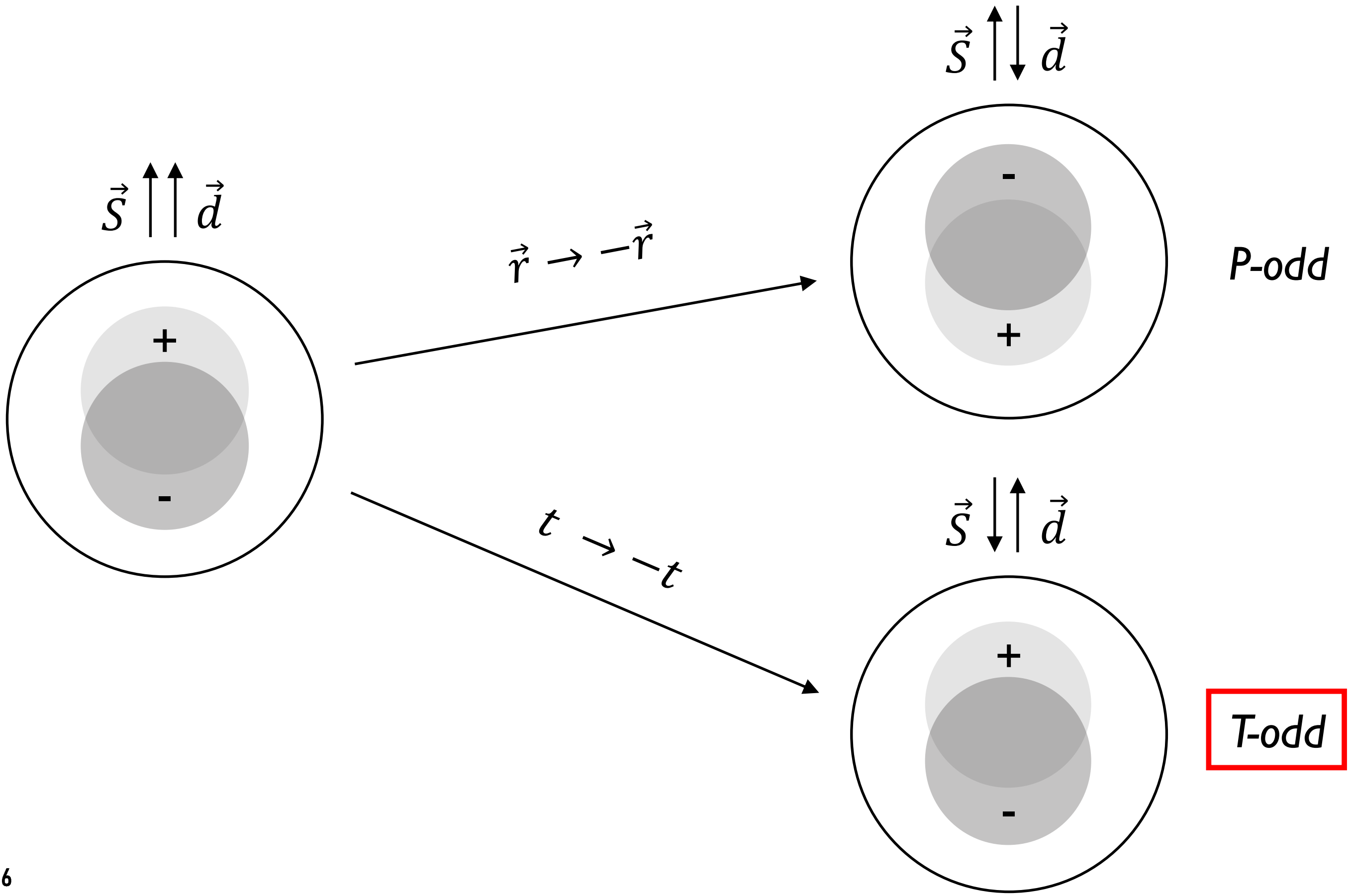
Strong CP problem

- QCD and CP symmetry
- How can we see it?
    - Neutron electric dipole moment (nEDM)



Strong CP problem

- QCD and CP symmetry
- How can we see it?
  - Neutron electric dipole moment (nEDM)



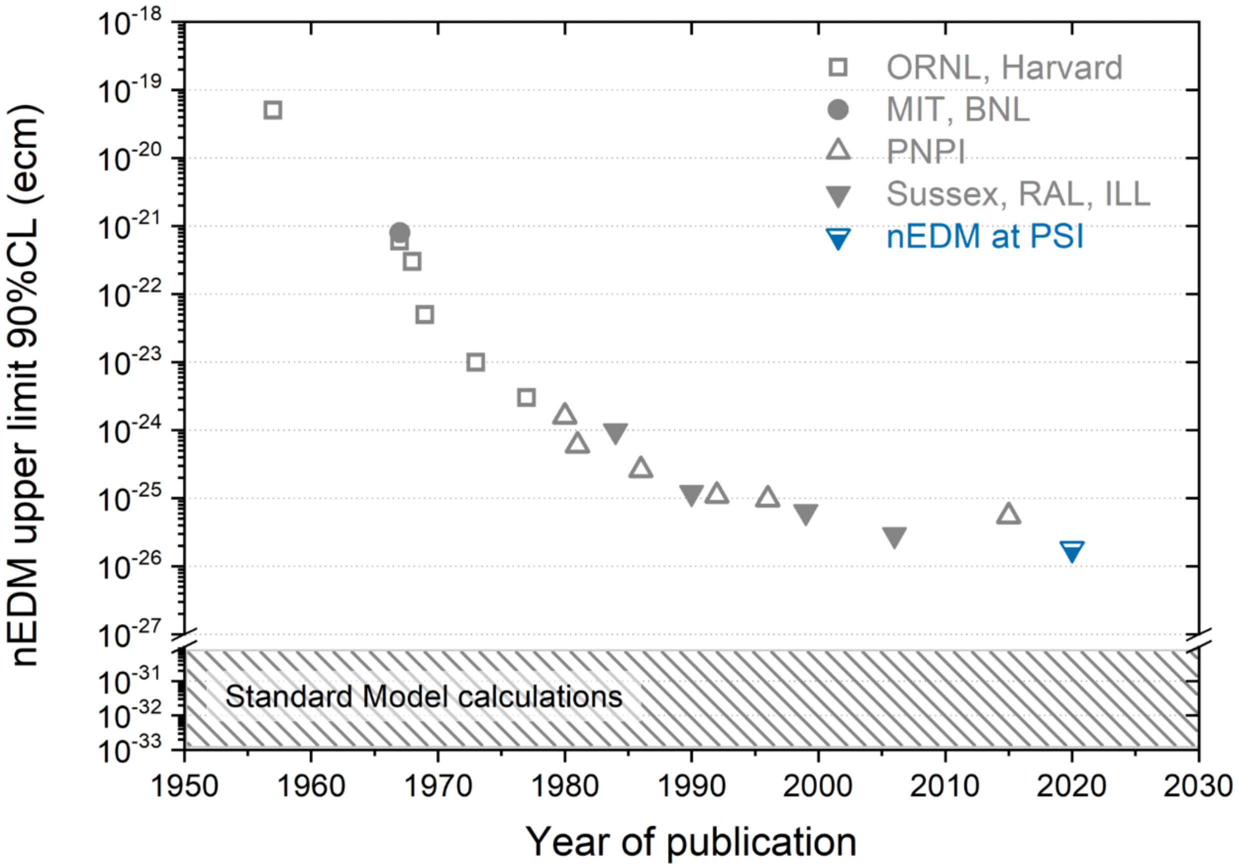
If Neutron EDM exists, the physics that governs it must be CP-odd

KSHEP spring meeting, 2026

Strong CP problem

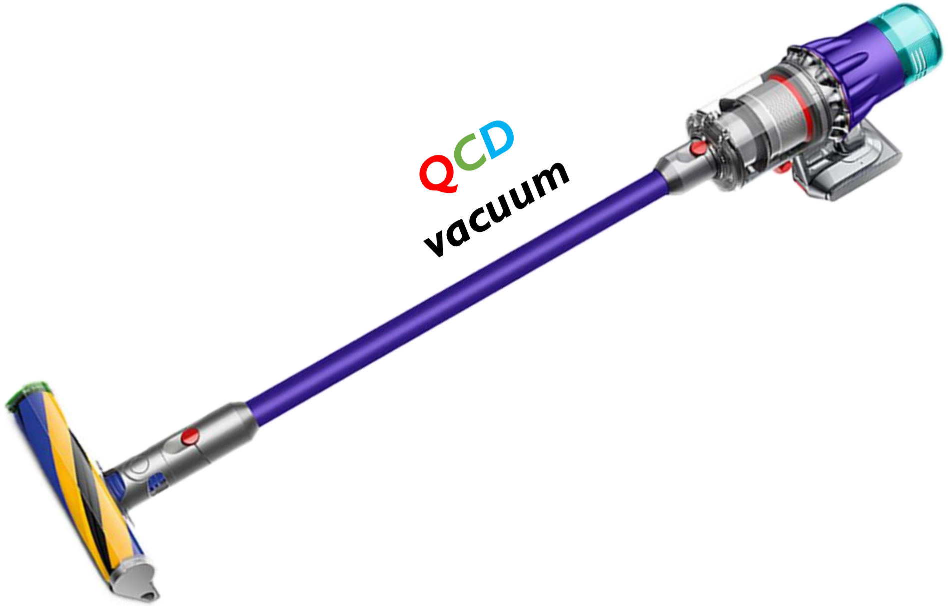
- QCD and CP symmetry
- How can we see it?
    - Neutron electric dipole moment (nEDM)
- Current upper limit: $d_n < \ 10^{-26}\ e \cdot \mathrm{cm}\ (90\%\ \mathrm{C.L.})$
    - $\bar{\theta} < 10^{-10}$
- Why is $\bar{\theta}$ so small???

<u>Strong CP problem</u>



Axion

- Peccei-Quinn mechanism: a new anomalous global U(1) symmetry



$$\bar{\theta} G\tilde{G}$$

$$\frac{a}{f_a} G\tilde{G}$$

Axion

- Peccei-Quinn mechanism: a new anomalous global U(1) symmetry

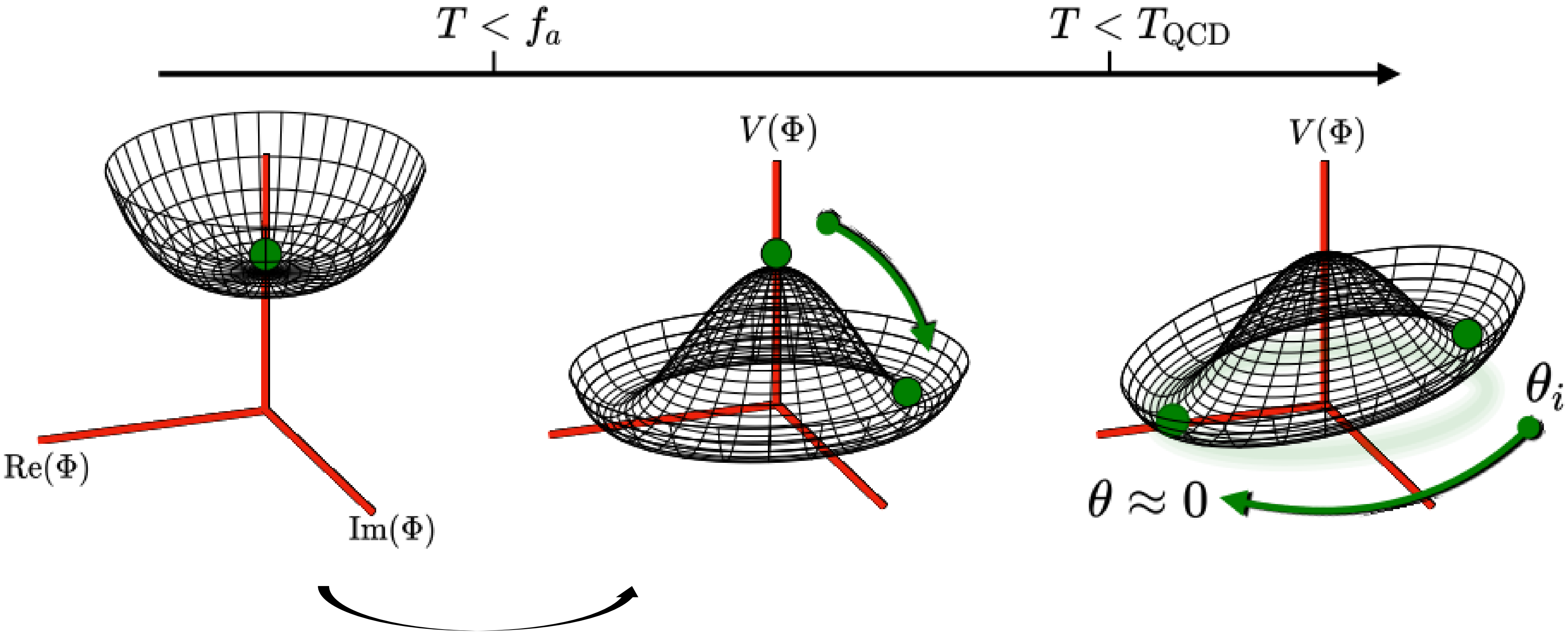
Axion field

$$\theta_{\text{eff}} G\tilde{G} \rightarrow \left(\bar{\theta} + \frac{a}{f}\right) G\tilde{G}$$

Scale constant

Axion

- Peccei-Quinn mechanism: a new anomalous global U(1) symmetry

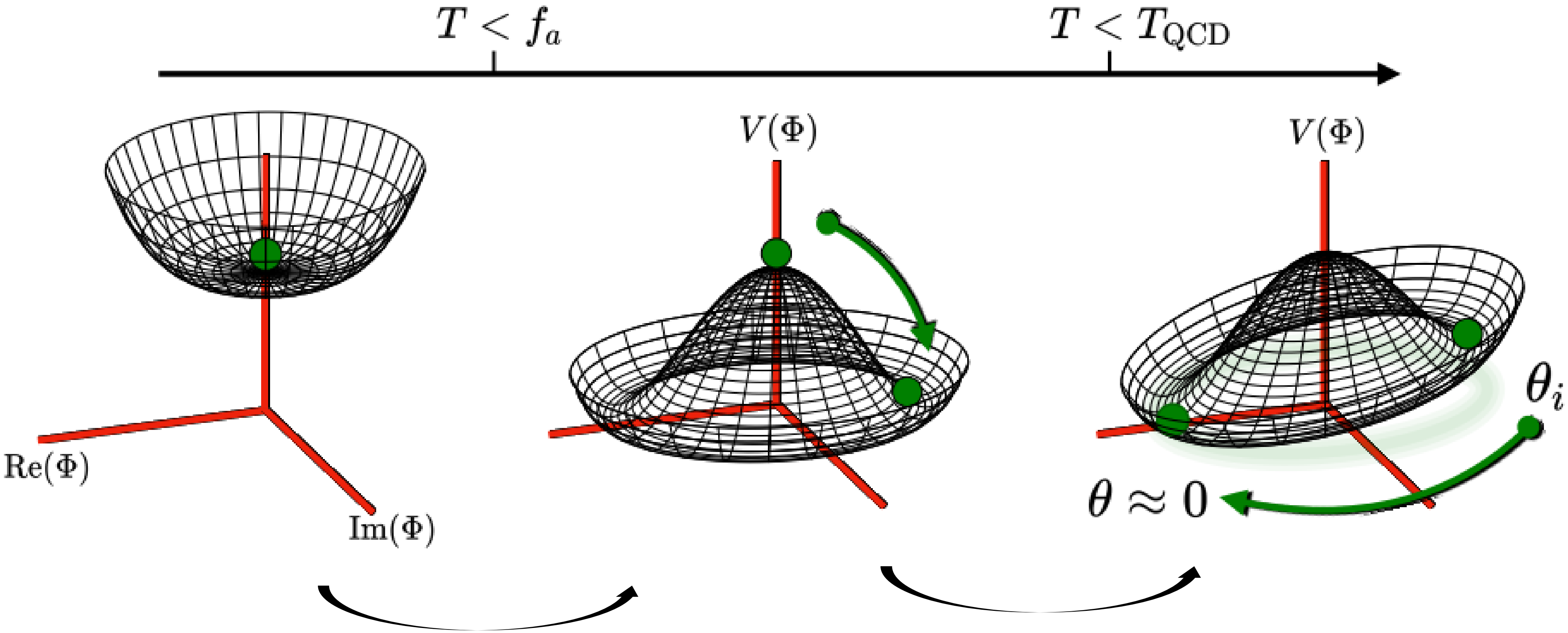


Spontaneous symmetry breaking

Ciaran A.J. O'hare, arXiv:2403.17697v2

Axion

- Peccei-Quinn mechanism: a new anomalous global U(1) symmetry



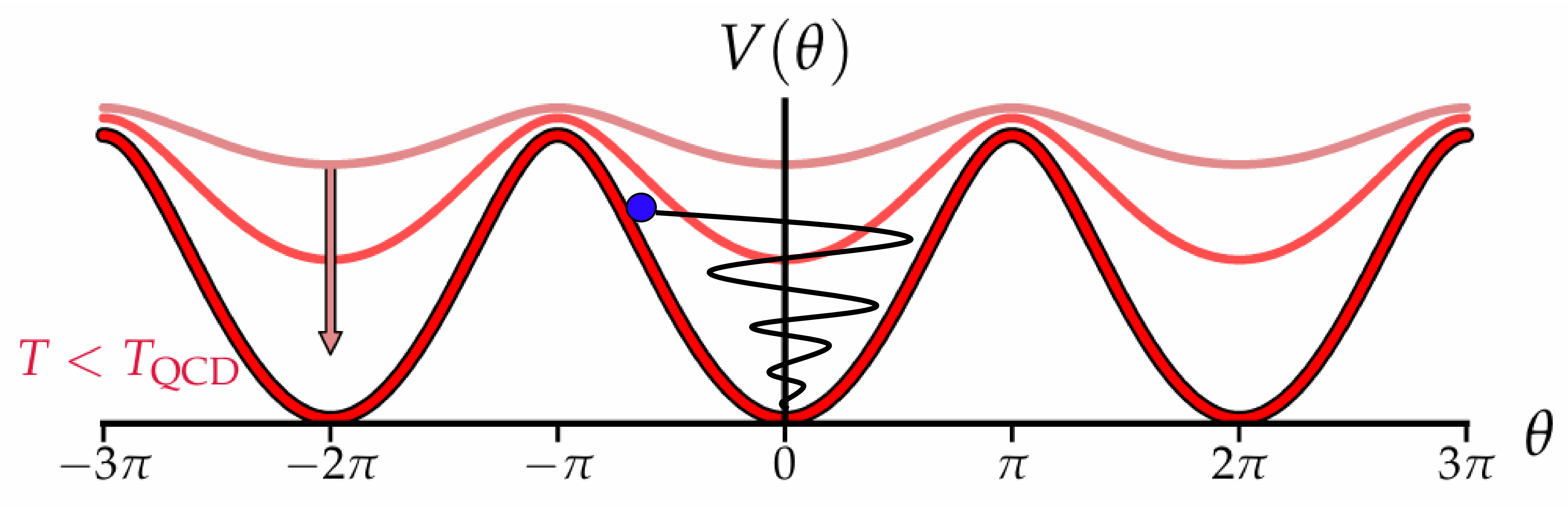
Spontaneous symmetry breaking

Explicit breaking Axion gets mass

Ciaran A.J. O'hare, arXiv:2403.17697v2

Axion

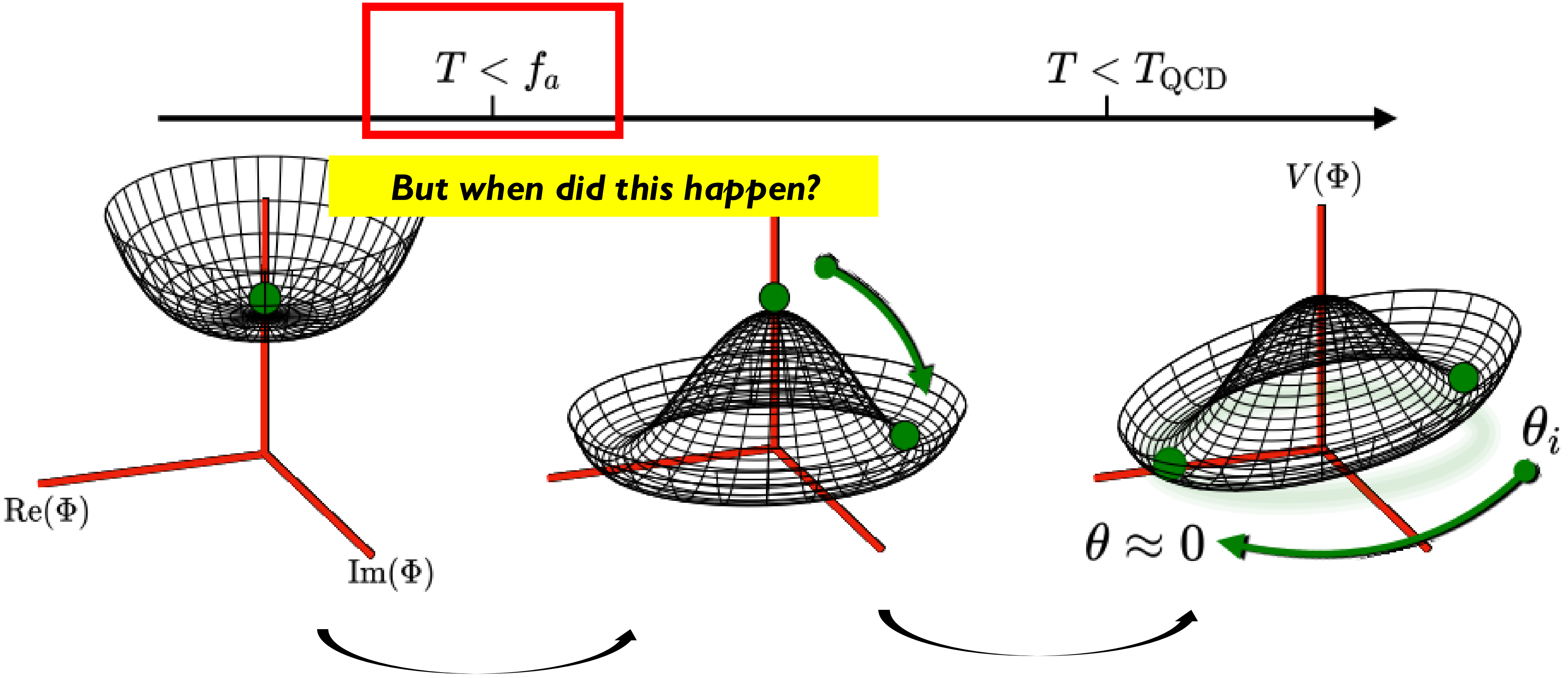
- Below QCD scale: axion gets mass!



Ciaran A.J. O'hare, arXiv:2403.17697v2

Axion

- Peccei-Quinn mechanism: a new anomalous global U(1) symmetry



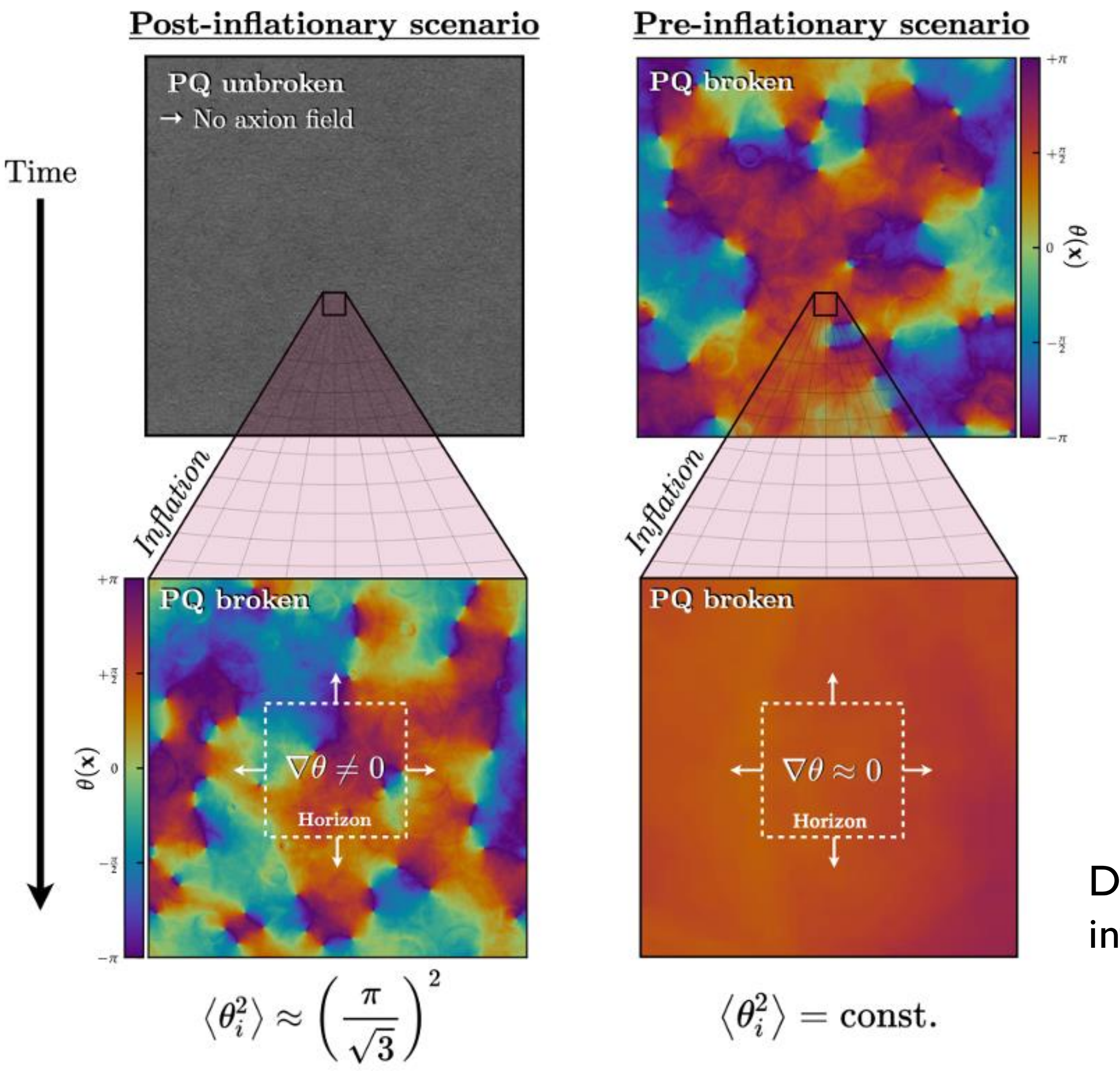
But when did this happen?

Spontaneous symmetry breaking

Explicit breaking Axion gets mass

Ciaran A.J. O'hare, arXiv:2403.17697v2

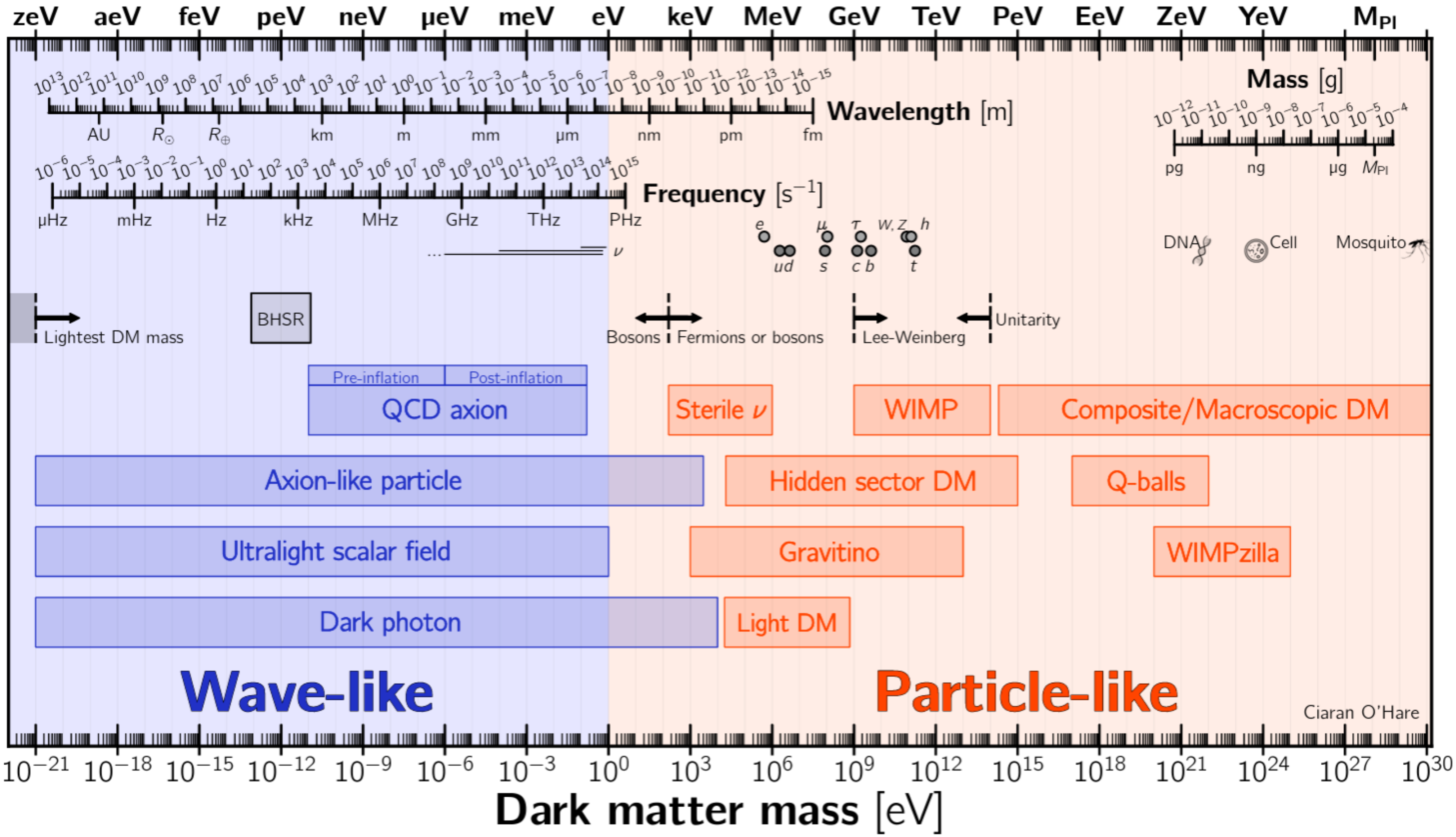
Axion



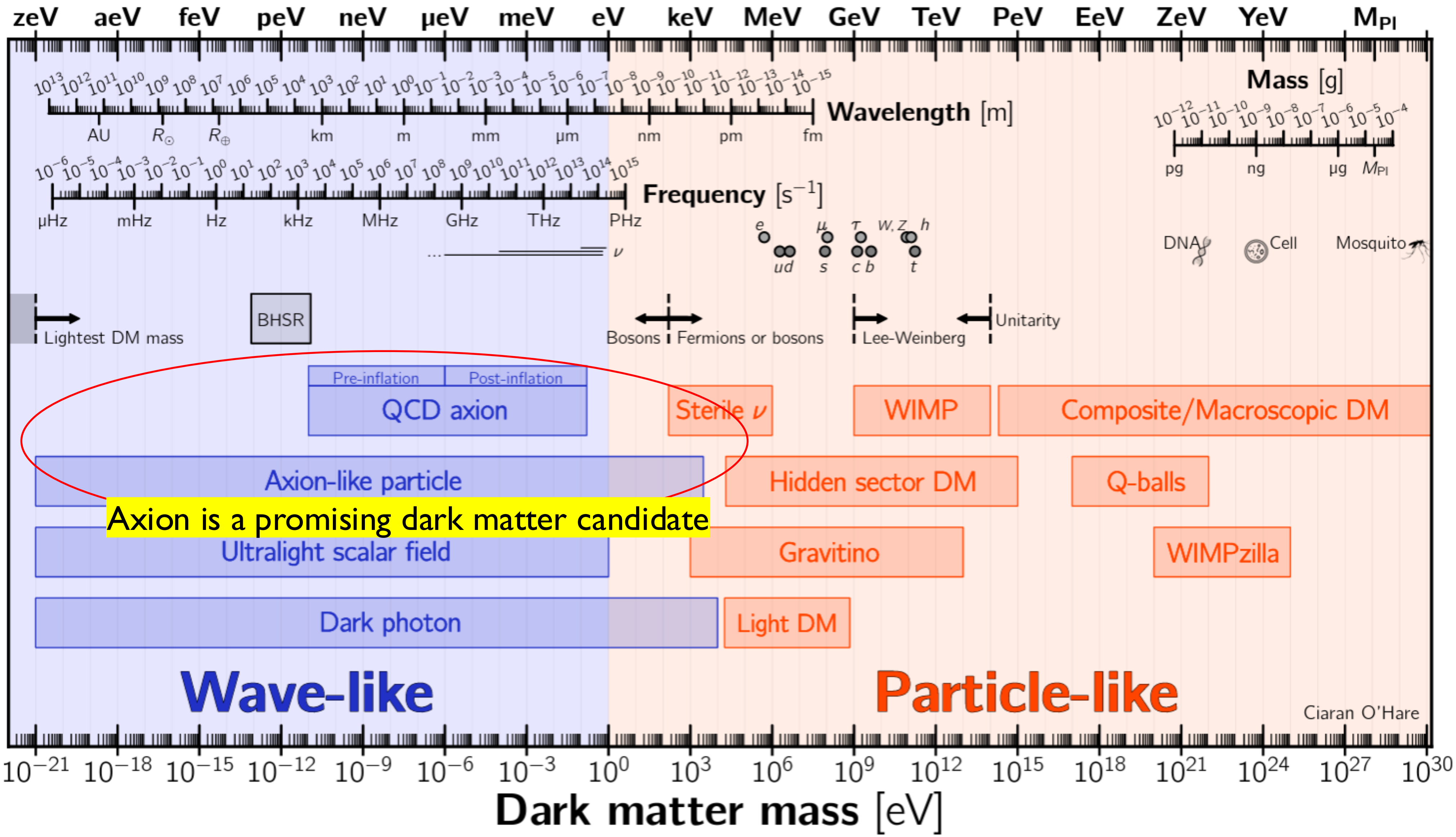
Depending on the PQ and inflation scales…

Ciaran A.J. O'hare, arXiv:2403.17697v2

Axion is a promising DM candidate



Axion is a promising DM candidate



Axion is a promising dark matter candidate

Axion haloscope

Axion-photon coupling

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Model dependent coupling (KSVZ, DFSZ)

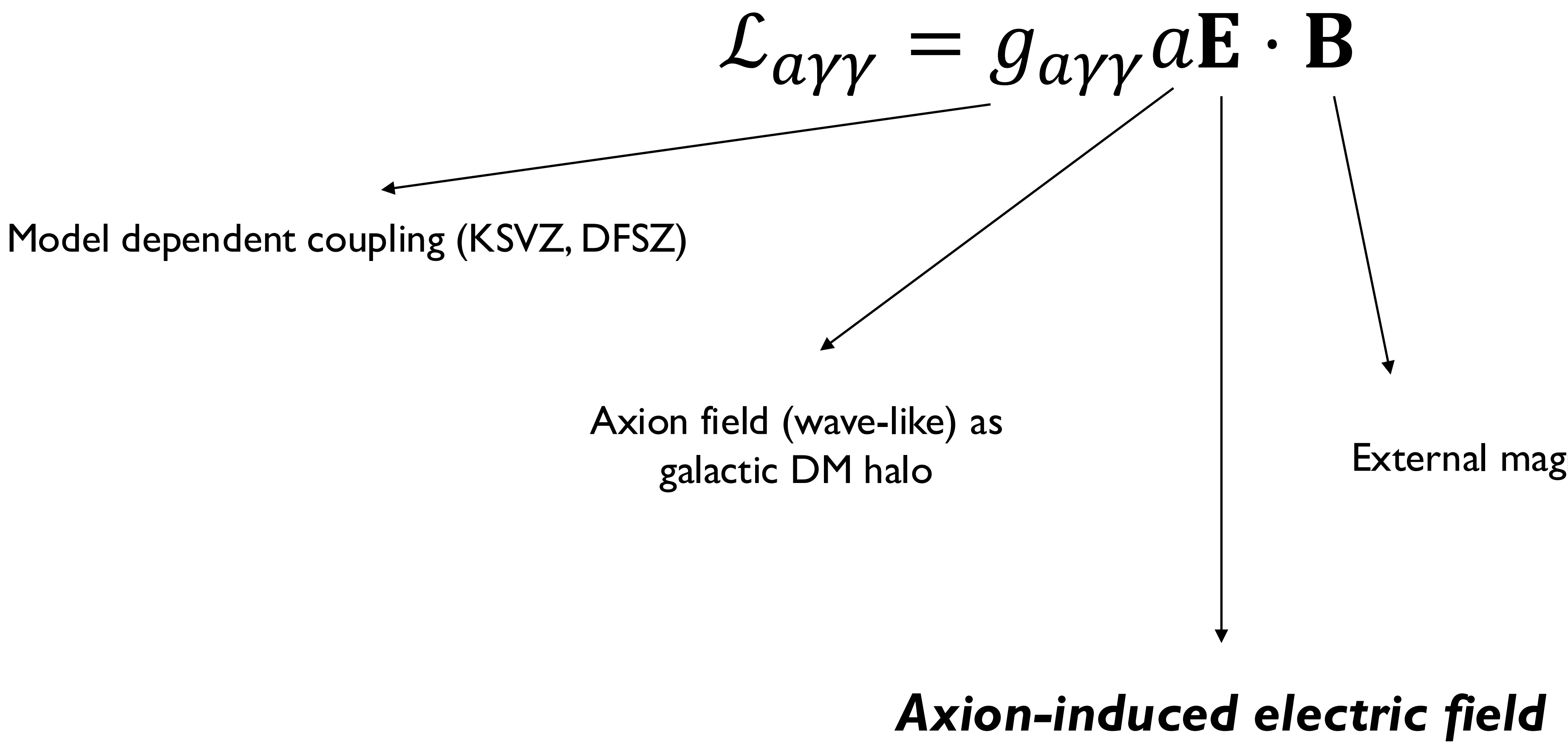
Axion-photon coupling

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Model dependent coupling (KSVZ, DFSZ)

Axion field (wave-like) as
galactic DM halo

Axion-photon coupling



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\, a\mathbf{E} \cdot \mathbf{B}$$

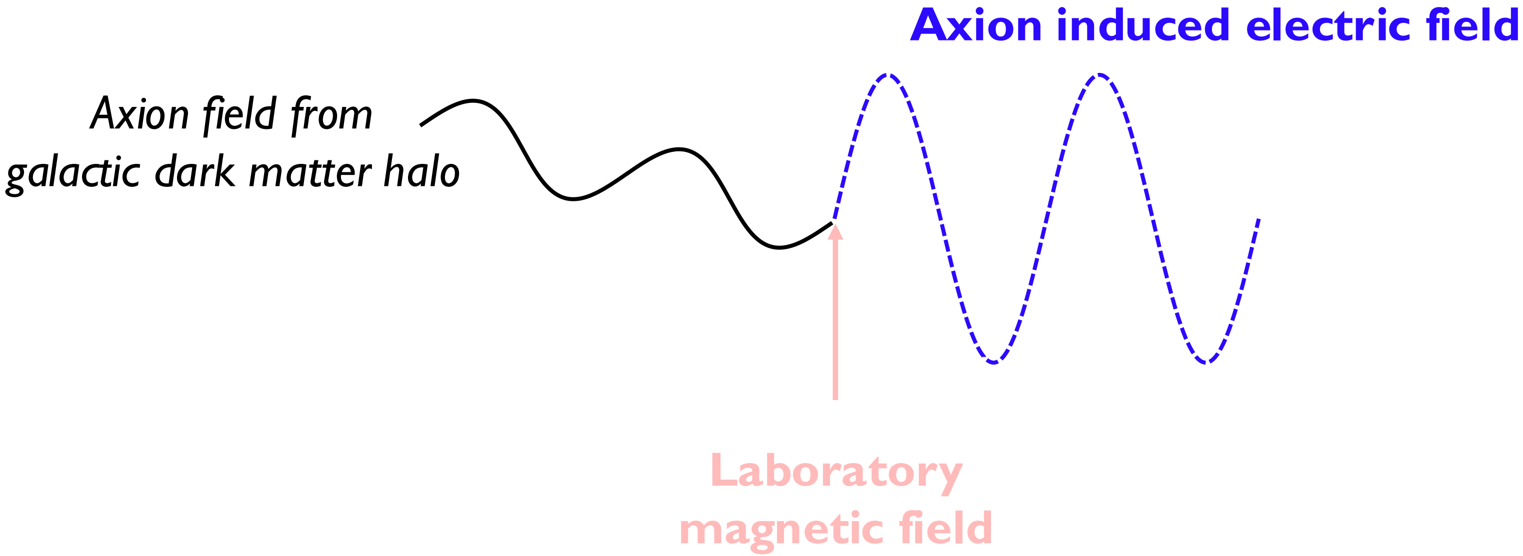
Model dependent coupling (KSVZ, DFSZ)

Axion field (wave-like) as
galactic DM halo

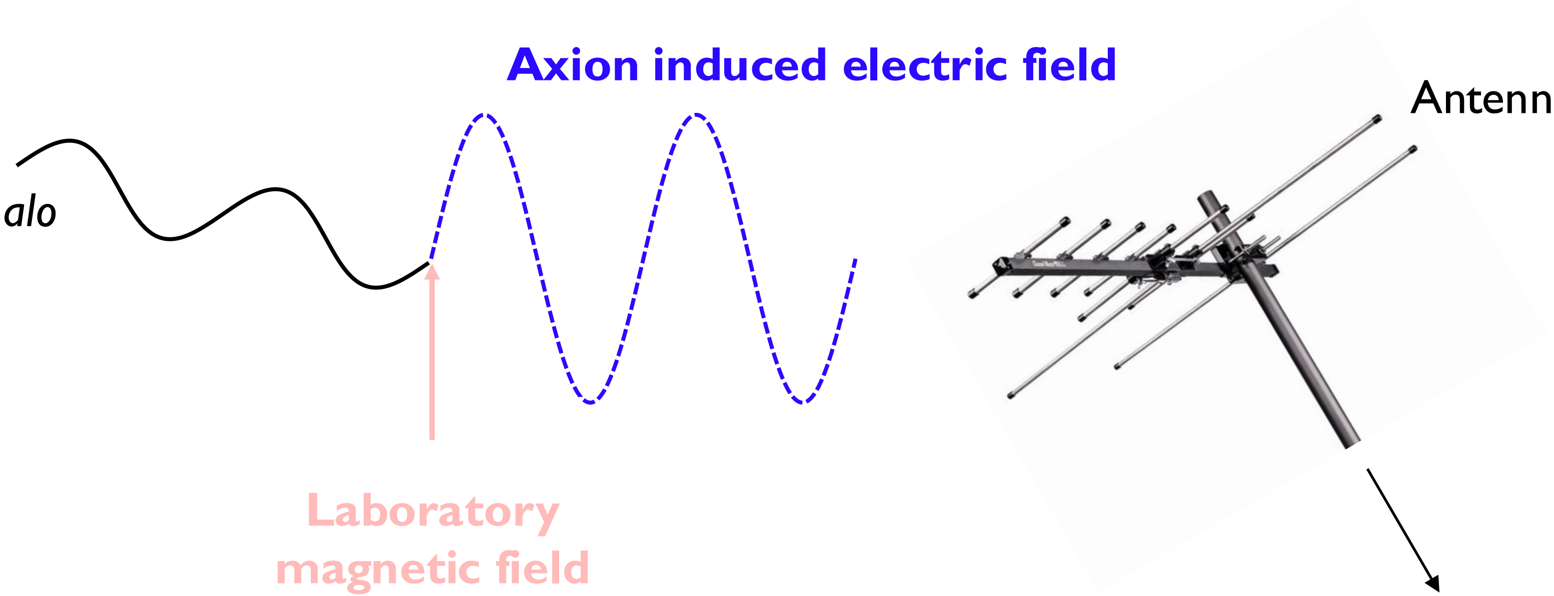
External magnetic field (virtual photon)

Axion-induced electric field

Axion-photon coupling



Axion-photon coupling



Axion field from galactic dark matter halo

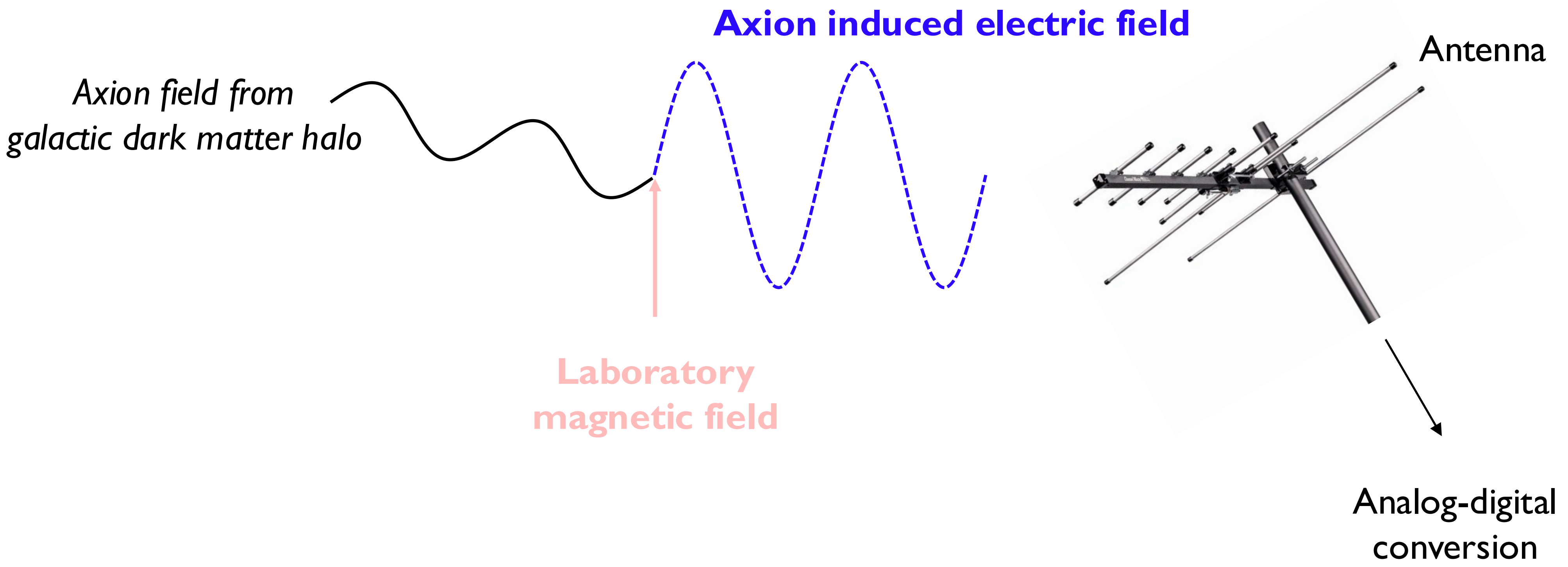
Axion induced electric field

Laboratory magnetic field

Antenna

Analog-digital conversion

Axion-photon coupling



Axion field from galactic dark matter halo

Axion induced electric field

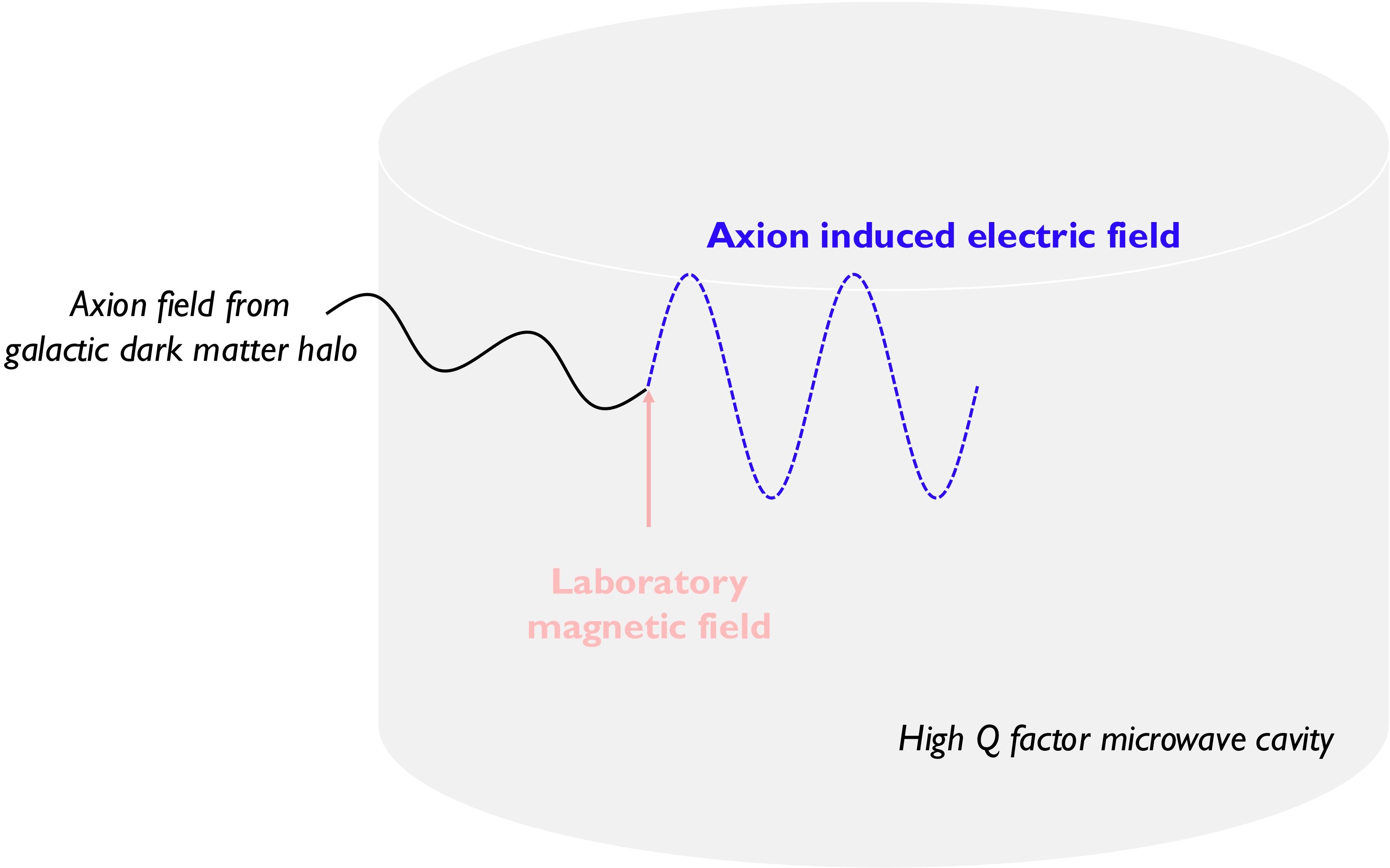
Laboratory magnetic field

Antenna

Analog-digital conversion

Can we do it better?

Axion-photon coupling

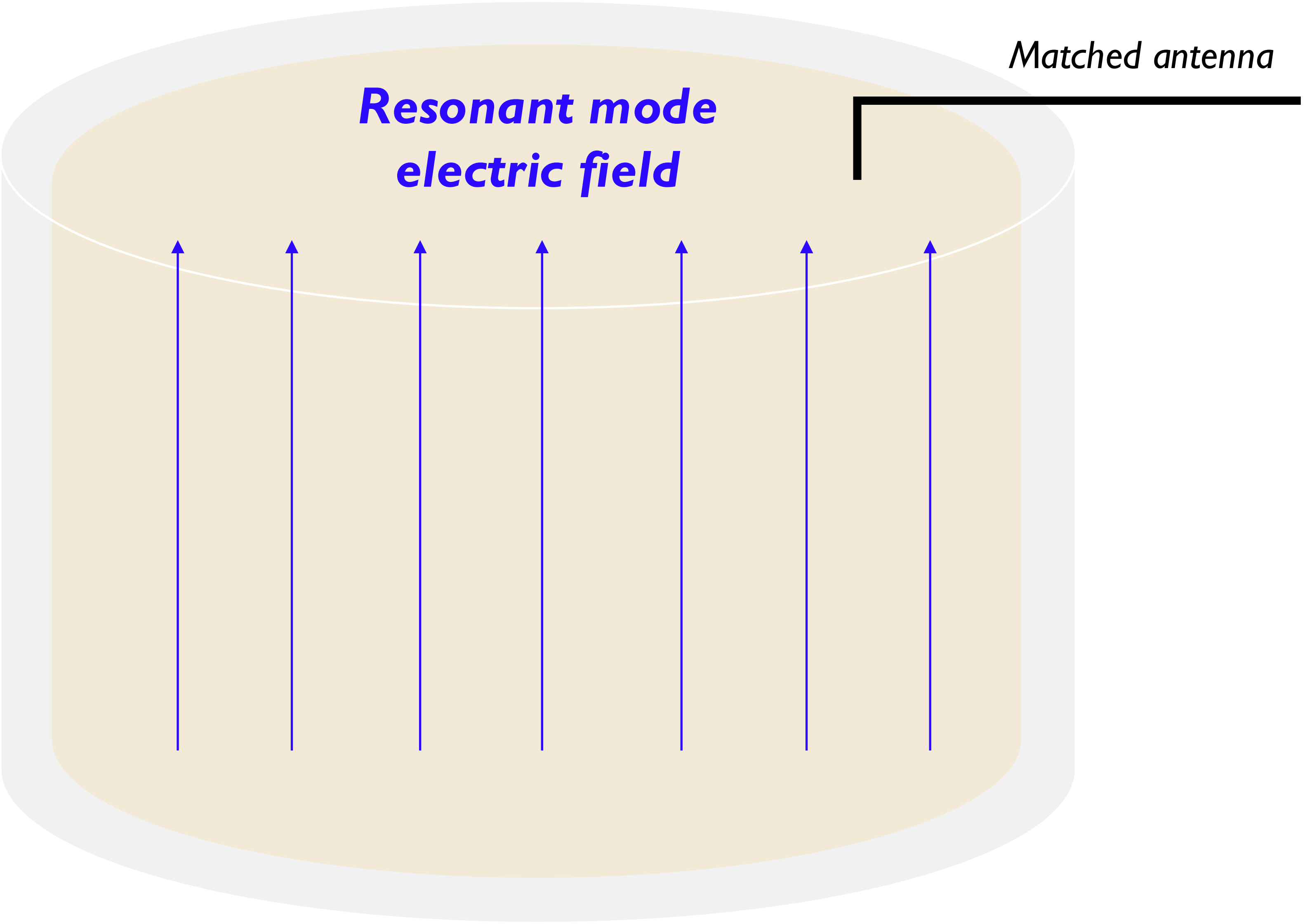


Axion-photon coupling

P_{arr} boosted by cavity Q!

($P \propto Q$)

- *Sikivie's "haloscope"*
- *With matched antenna, maximum pickup rate*
- ***<u>So far the best sensitivity</u>***



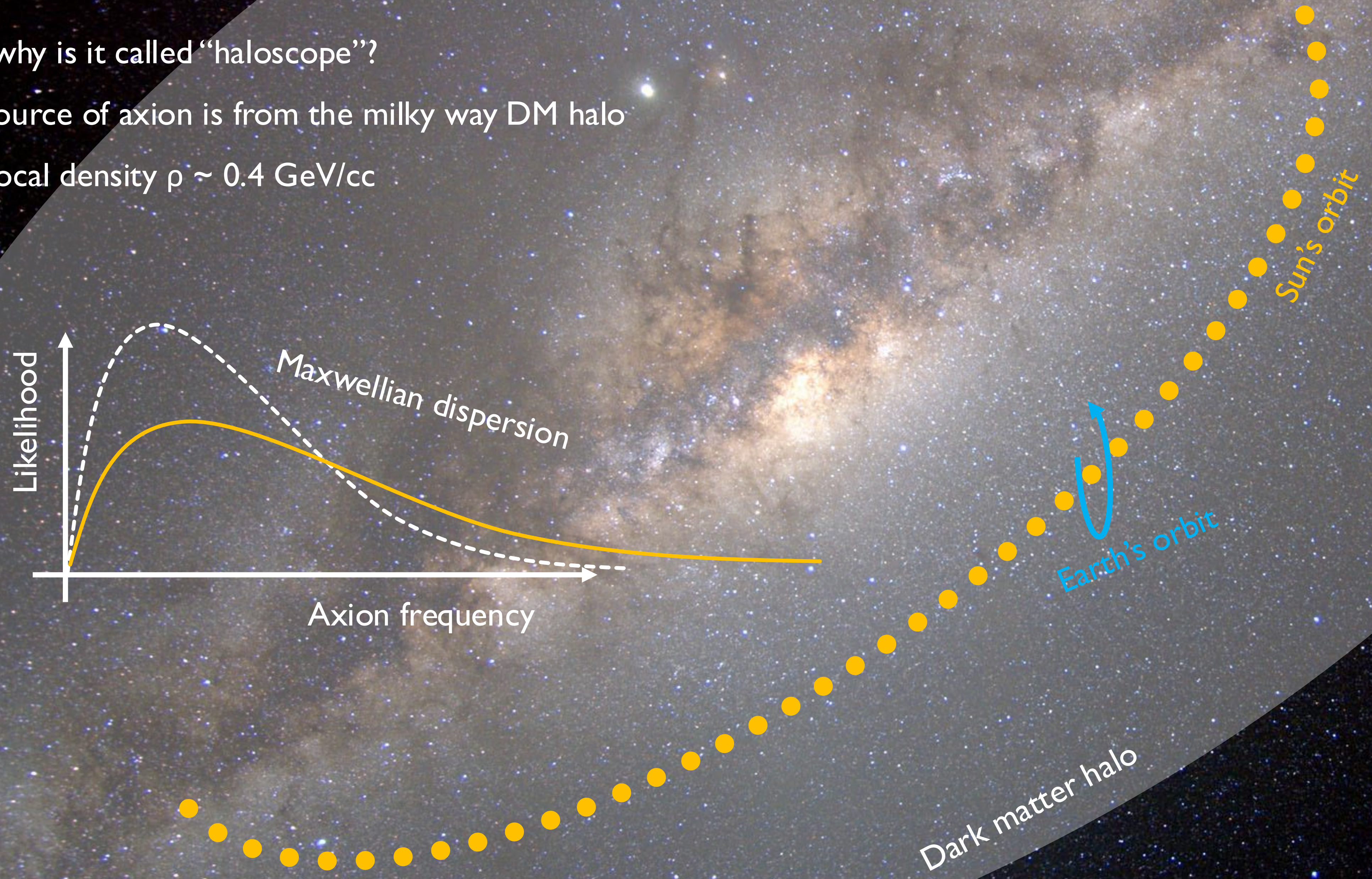
High Q factor microwave cavity

Axion-photon coupling

Turner, Phys. Rev. D **42**, 3572 (1990)

But why is it called “haloscope”?

- Source of axion is from the milky way DM halo
- Local density ρ ~ 0.4 GeV/cc



Axion conversion power

$$P_{\text{signal}} = 22.51\ \text{yW} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{B_{\text{avg}}}{10.31\ \text{T}}\right)^2 \left(\frac{V}{36.85\ \text{L}}\right) \left(\frac{C}{0.6}\right) \left(\frac{Q_L}{35000}\right) \left(\frac{\nu}{1.1\ \text{GHz}}\right) \left(\frac{\rho_a}{0.45\ \text{GeV/cc}}\right)$$

Parameters taken from DMAG's main axion experiment (DMAG-12TB)

To increase the signal power,

- *Higher external magnetic field*
- *Larger volume of the cavity*
- *Higher Q factor of the cavity*

S.Ahn et al., Phys. Rev. X ***14****, 031023*

Axion conversion power

$$P_{\text{signal}} = 22.51\ \text{yW} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{B_{\text{avg}}}{10.31\ \text{T}}\right)^2 \left(\frac{V}{36.85\ \text{L}}\right) \left(\frac{C}{0.6}\right) \left(\frac{Q_L}{35000}\right) \left(\frac{\nu}{1.1\ \text{GHz}}\right) \left(\frac{\rho_a}{0.45\ \text{GeV/cc}}\right)$$

Parameters taken from DMAG's main axion experiment (DMAG-12TB)

To increase the signal power,

- *Higher external magnetic field*
- *Larger volume of the cavity*
- *Higher Q factor of the cavity*

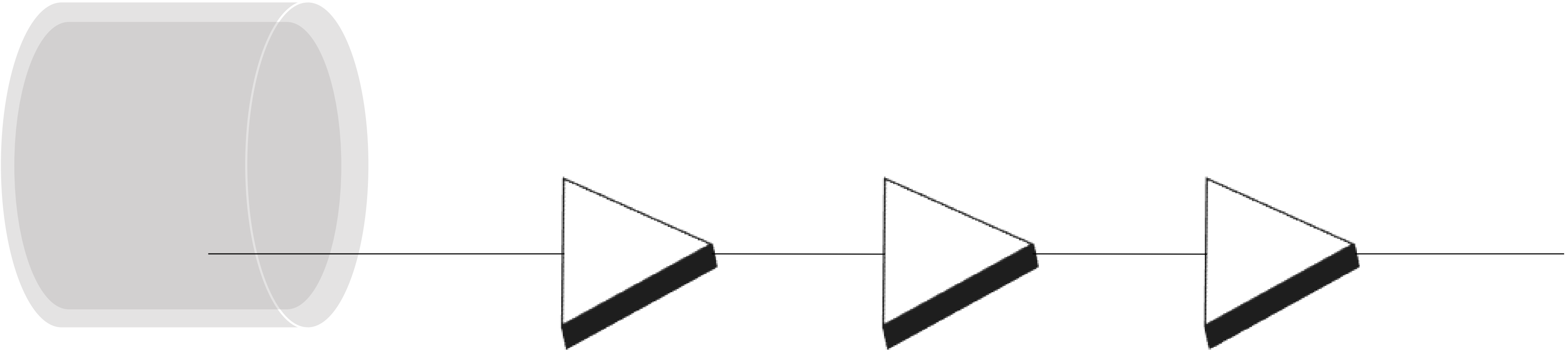
With the state-of-the-art apparatus, the signal is still too weak. (10^{-23} W)

S.Ahn et al., Phys. Rev. X ***14****, 031023*

Background: thermal noise

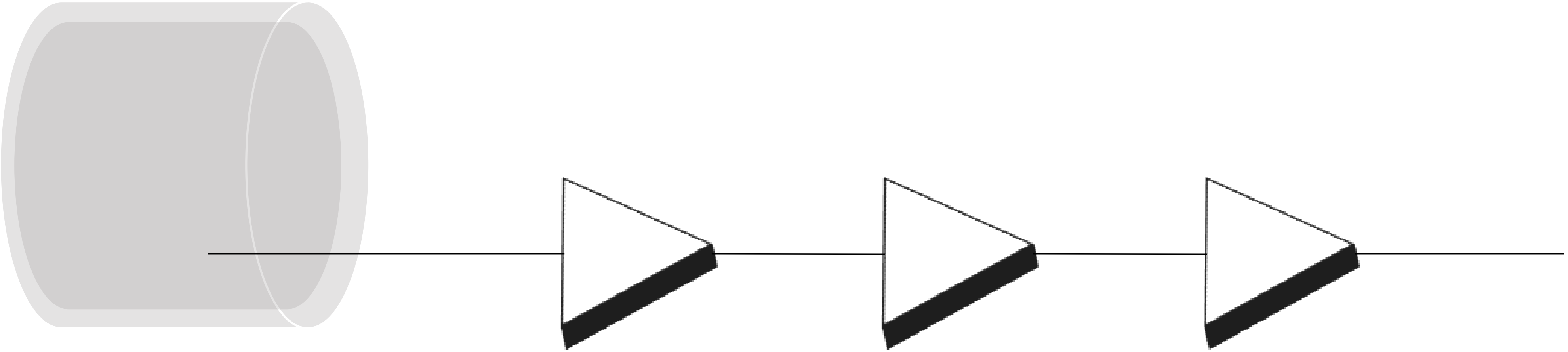
$$E(T,f) = hf\left(\underbrace{\frac{1}{e^{\frac{hf}{k_B T}}-1}}_{\text{Thermal noise (Nyquist, Johnson, Planck)}} + \underbrace{\frac{1}{2}}_{\text{Standard Quantum limit (SQL)}}\right)$$

Noise in haloscopes



Signal + thermal noise

Noise in haloscopes

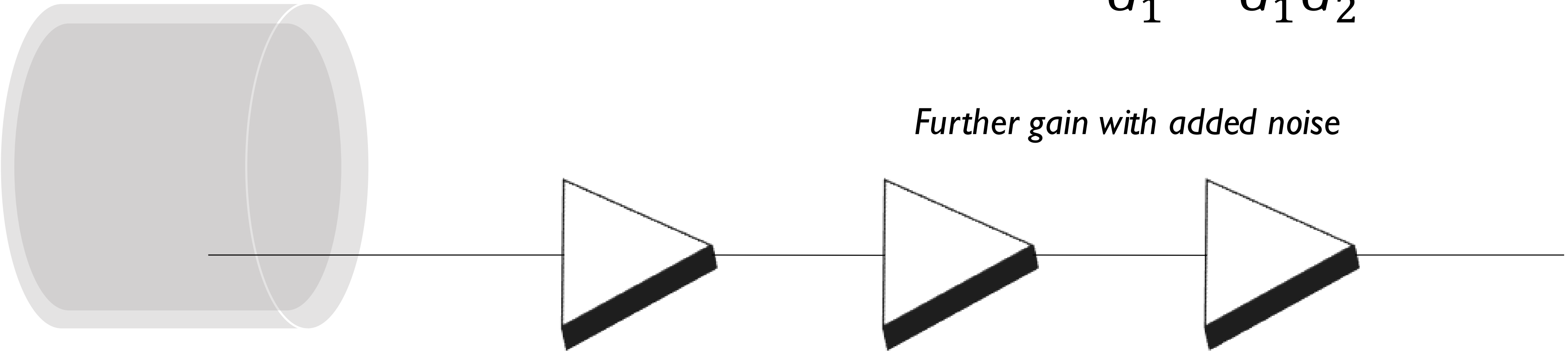


(Signal
+ thermal noise
+ amplifier noise)

x gain $(10^2 - 10^3)$

Noise in haloscopes

$$T_{\text{sys}} = T_{\text{thermal}} + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$



Further gain with added noise

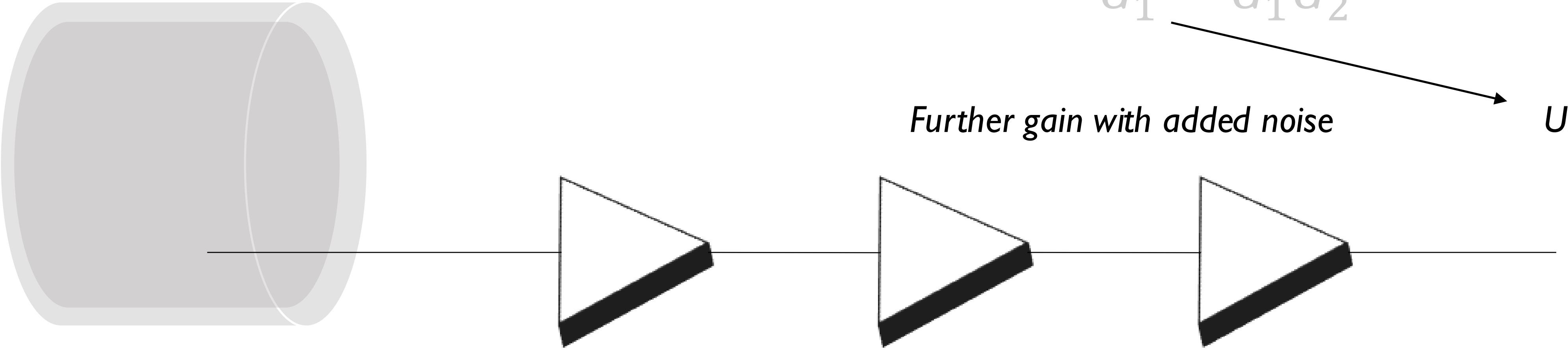
(Signal
+ thermal noise
+ amplifier noise)

x gain ($10^2 - 10^3$)

KSHEP spring meeting, 2026

Noise in haloscopes

$$T_{\mathrm{sys}} = T_{\mathrm{thermal}} + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$



Further gain with added noise

Usually, > 100

(Signal
+ ***thermal noise***
+ ***amplifier noise***)

x gain ($10^2 - 10^3$)

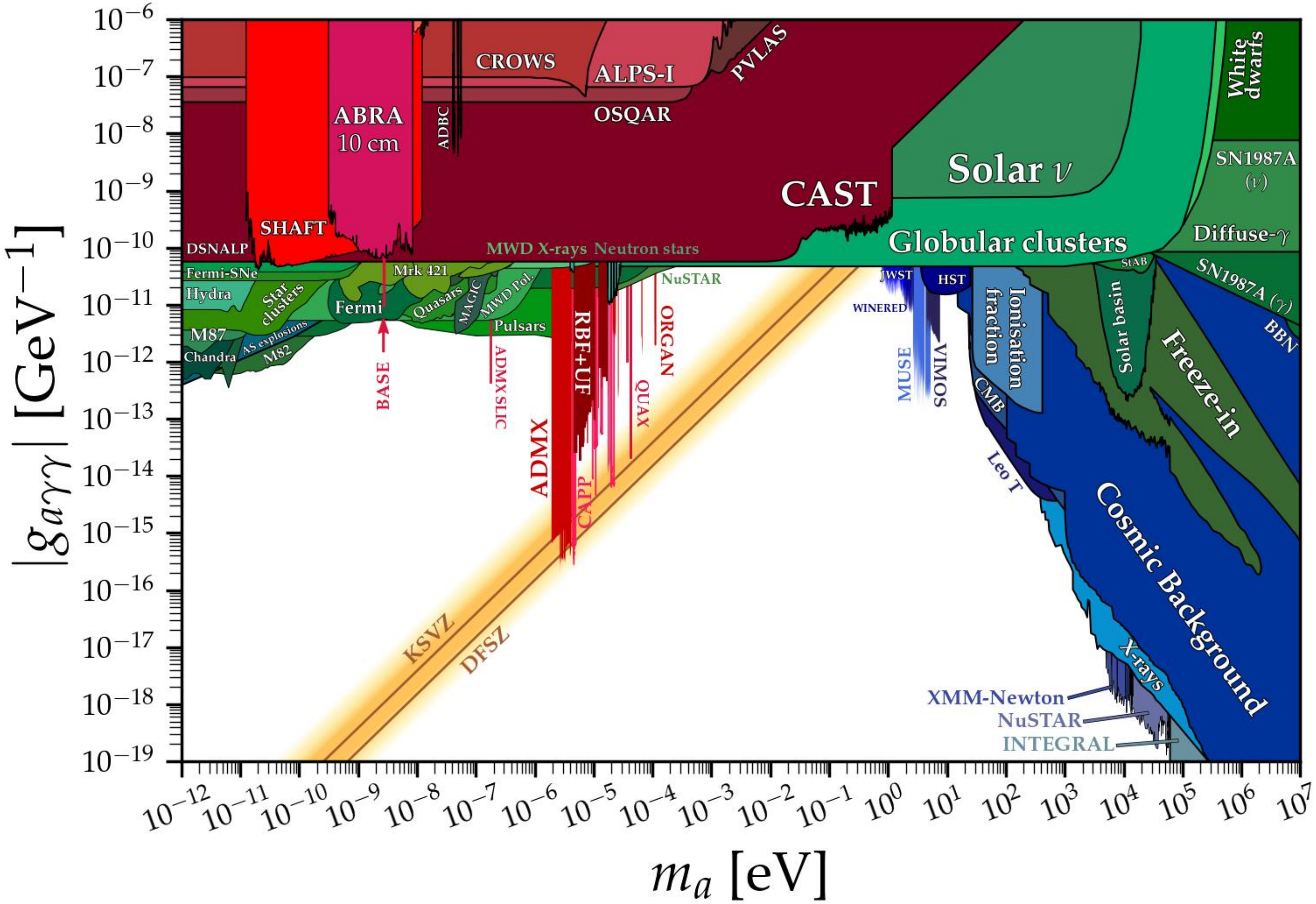
The system noise is mostly determined by the first amplifier or detector

Challenges

Challenges

DM axion mass: 10^{-6} – 10^{-3} eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity



Challenges

DM axion mass: 10^{-6} – 10^{-3} eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

High frequency is usually more challenging

- Cavity needs to be smaller
- Surface loss gets larger
- Higher thermal noise

Challenges

DM axion mass: $10^{-6} – 10^{-3}$ eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

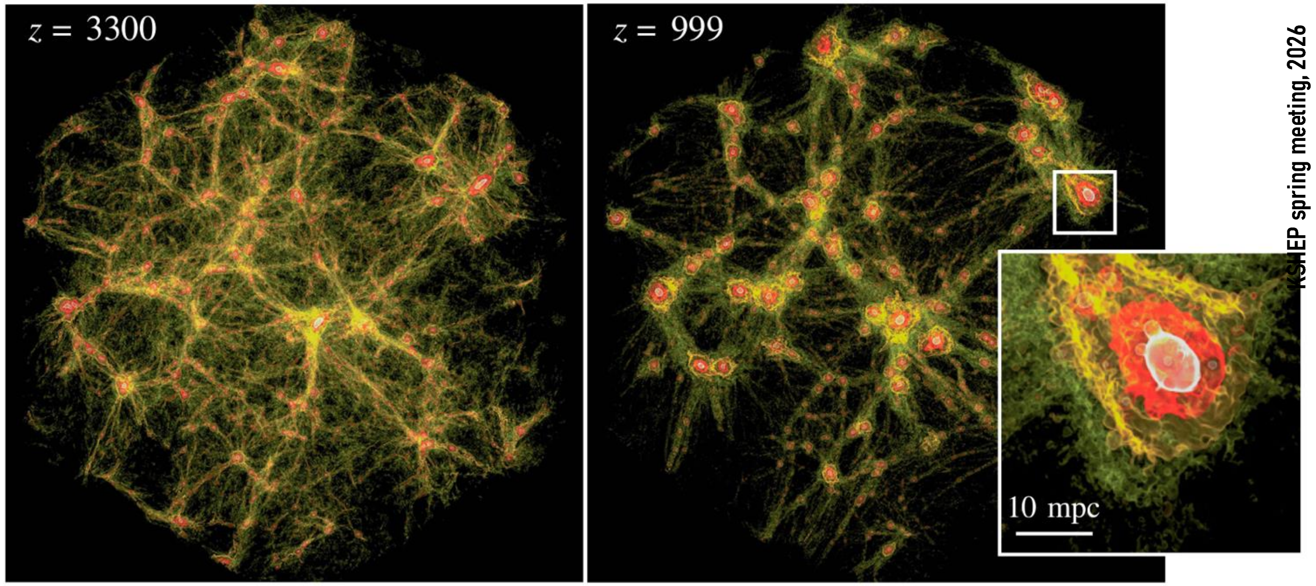
High frequency is usually more challenging

- Cavity needs to be smaller
- Surface loss gets larger
- Higher thermal noise

Dark matter structure

- Local density fluctuation: minicluster and minivoids

In the post-inflationary scenario,



ENEDIKT EGGEMEIER et al. PHYS. REV. D 107, 083510 (2023)

Challenges

DM axion mass: 10^{-6} – 10^{-3} eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

High frequency is usually more challenging

- Cavity needs to be smaller → *Multi-cell cavity, metamaterial cavity*
- Surface loss gets larger
- Higher thermal noise

Dark matter structure

- Local density fluctuation: minicluster and minivoids

Challenges

DM axion mass: $10^{-6} – 10^{-3}$ eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

High frequency is usually more challenging

- Cavity needs to be smaller → *Multi-cell cavity, metamaterial cavity*
- Surface loss gets larger → *Superconducting cavity*
- Higher thermal noise

Dark matter structure

- Local density fluctuation: minicluster and minivoids

Challenges

DM axion mass: $10^{-6} – 10^{-3}$ eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

High frequency is usually more challenging

- Cavity needs to be smaller → *Multi-cell cavity, metamaterial cavity*
- Surface loss gets larger → *Superconducting cavity*
- Higher thermal noise → *Quantum-sensing*

Dark matter structure

- Local density fluctuation: minicluster and minivoids

Challenges

DM axion mass: 10^{-6} – 10^{-3} eV → frequency range of MHz to THz

- Still takes a lot of time to cover all the mass range with reasonable sensitivity

High frequency is usually more challenging

- Cavity needs to be smaller → *Multi-cell cavity, metamaterial cavity,*
- Surface loss gets larger → *Superconducting cavity*
- Higher thermal noise → *Single photon detector*

Dark matter structure

- Local density fluctuation: minicluster and minivoids → ***HIGHER SENSITIVITY!***

Dark Matter Axion Group (IBS-DMAG)

Dark Matter Axion Group (former CAPP)

Former CAPP, now Dark Matter Axion Group (DMAG)

Cavity-based dark matter axion experiments

SungWoo Youn *the group leader (Chief Investigator)*

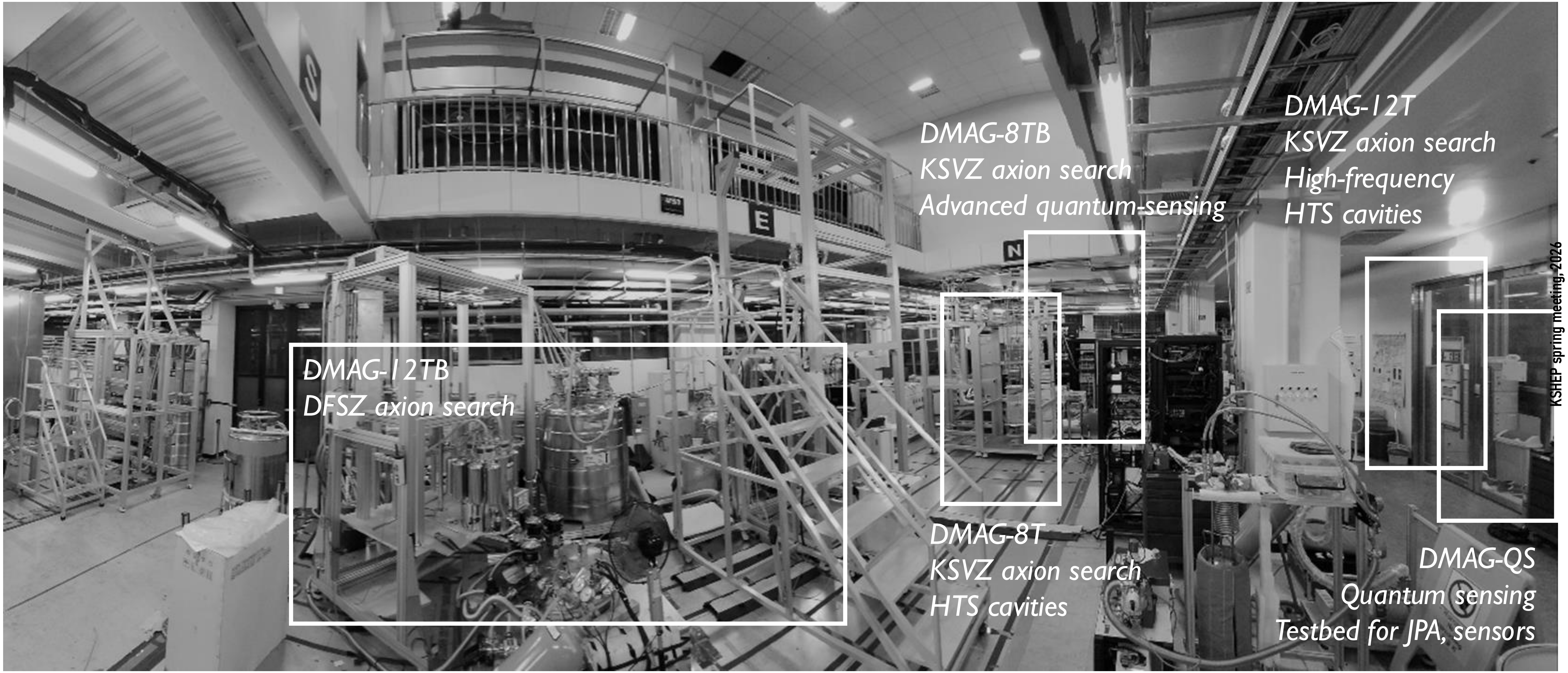
- *3 (dry) + 1 (wet) fridges with superconducting magnets (8 T, 12 T) as axion haloscopes*
- *A dry fridge for quantum sensor testbed*

- *5 researchers/fellows, 2 students, 4 research engineers, a visiting professor (emeritus of KAIST)*
- ***High frequency techniques / High Q cavities with HTS films / Quantum sensing***

Dark Matter Axion Group (former CAPP)

Dark Matter Axion Group (former CAPP)

Dark Matter Axion Group (former CAPP)



DMAG-12TB
DFSZ axion search

DMAG-8TB
KSVZ axion search
Advanced quantum-sensing

DMAG-8T
KSVZ axion search
HTS cavities

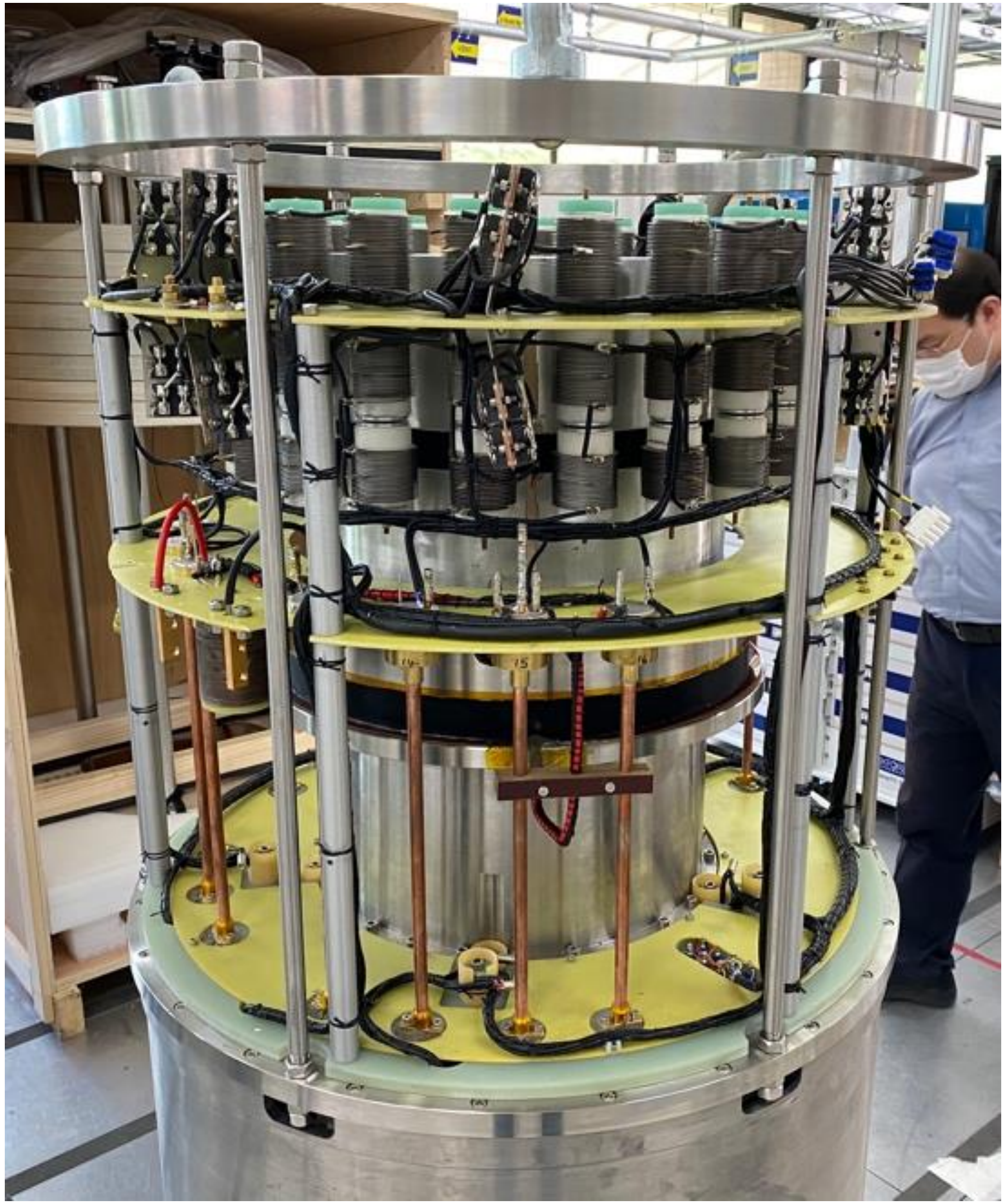
DMAG-12T
KSVZ axion search
High-frequency
HTS cavities

DMAG-QS
Quantum sensing
Testbed for JPA, sensors

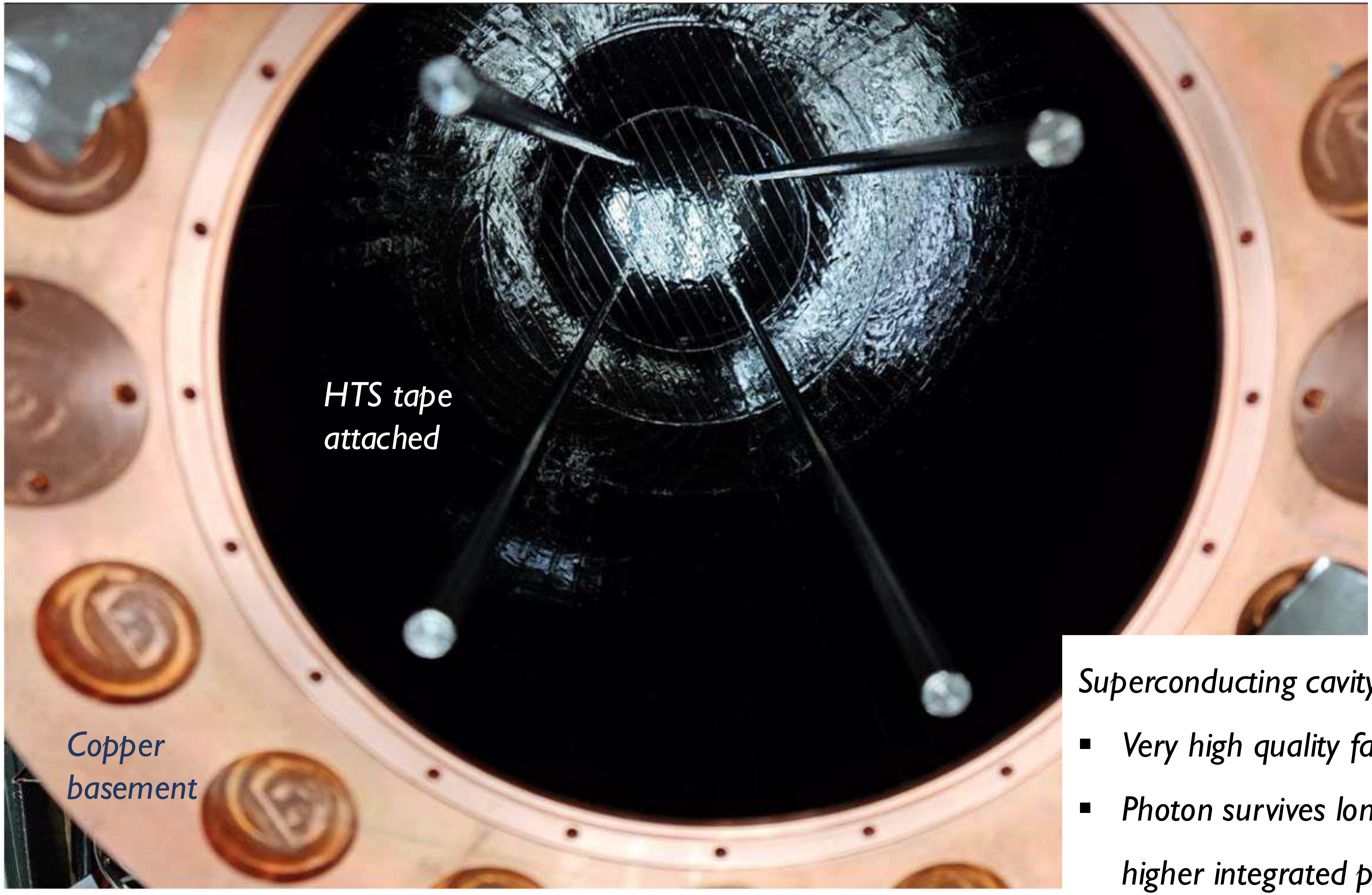
DMAG’s approach

Superconducting magnet

- *12 T peak field with Nb_2Sn_3*



DMAG's approach

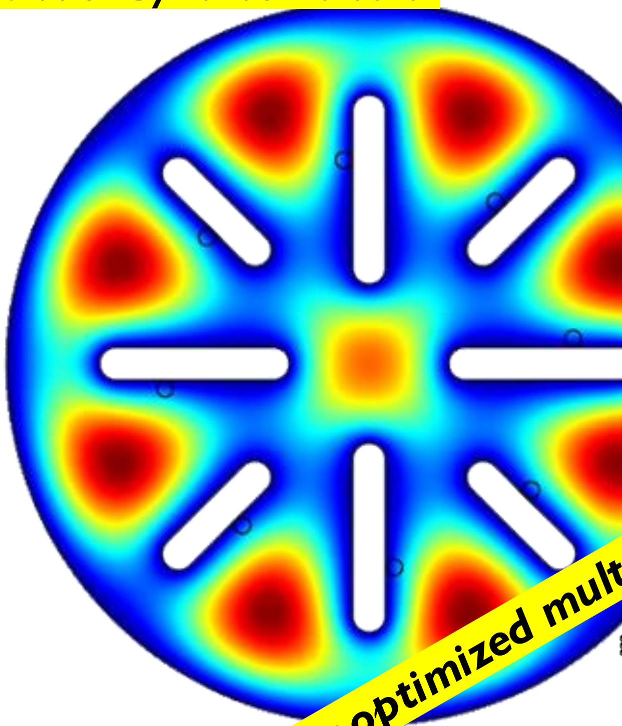


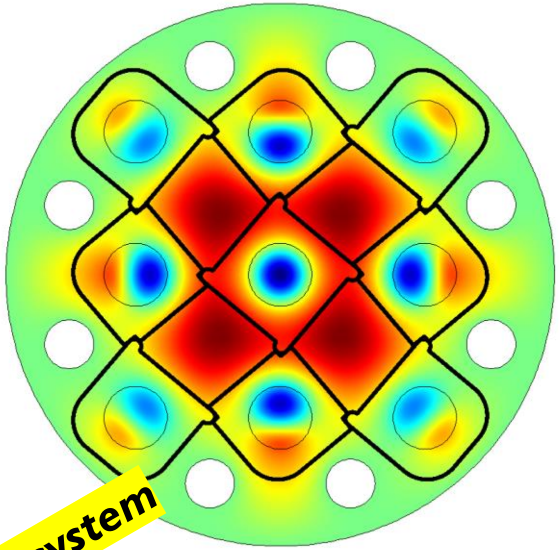
Superconducting cavity

- *Very high quality factor*
- *Photon survives longer, higher integrated power*

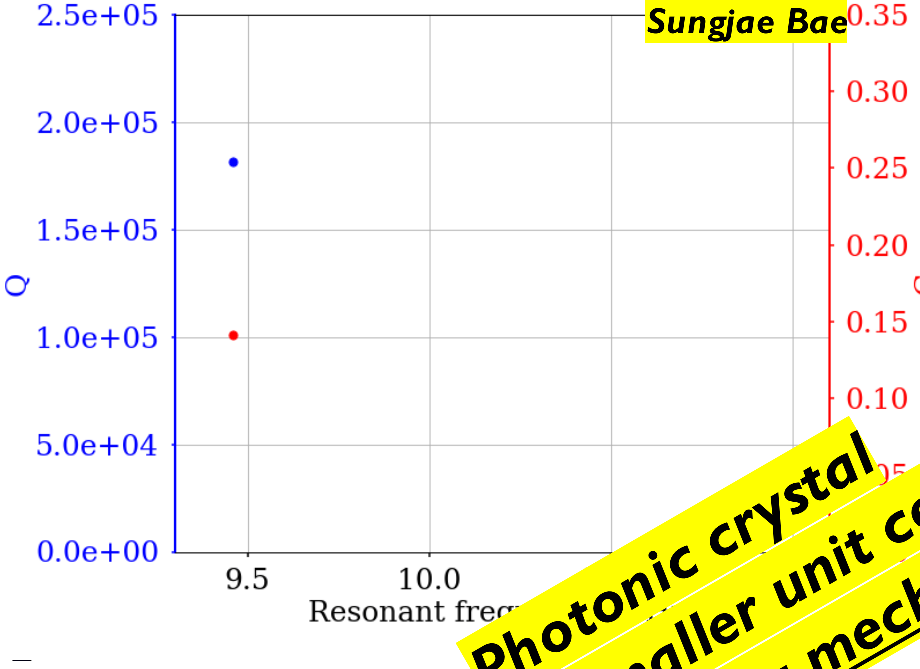
DMAG’s approach

Simulation by Pallavi Parashar





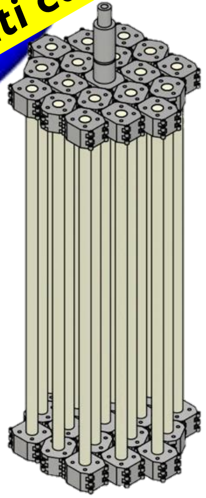
Pizza / Kiwi cavity: optimized multi cavity system

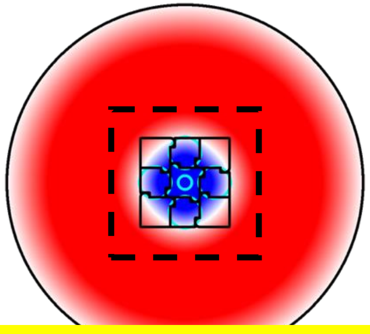


Photonic crystal

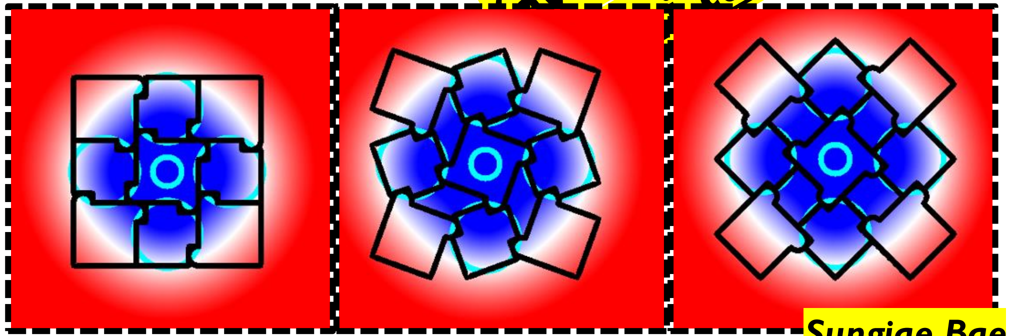
(even smaller unit cell)

tuning mechanism



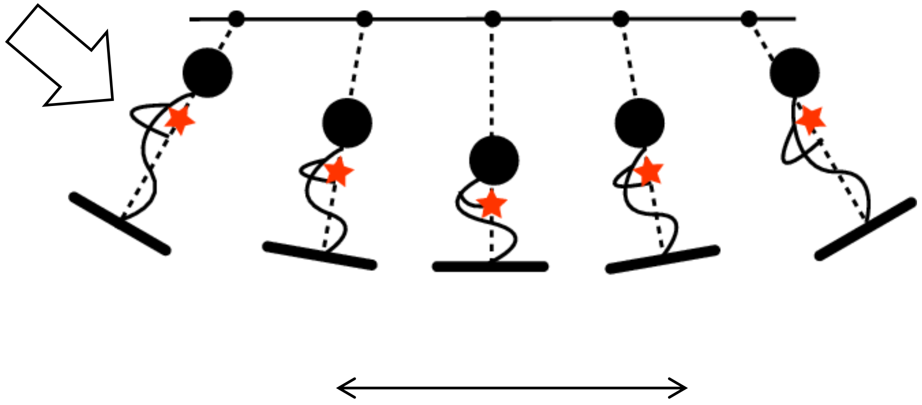


TM$_{020}$ cavity



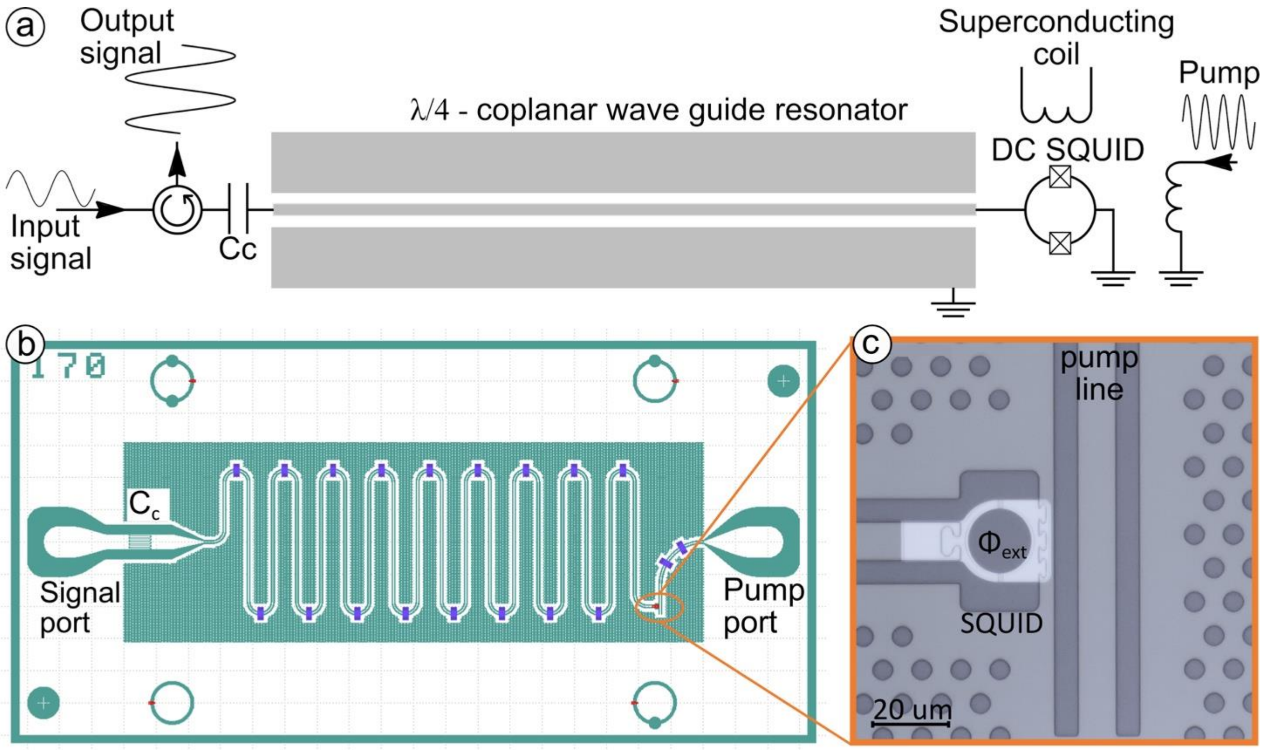
Sungjae Bae

DMAG’s approach



Pump (2f_s)

Signal amplitude (f_s)

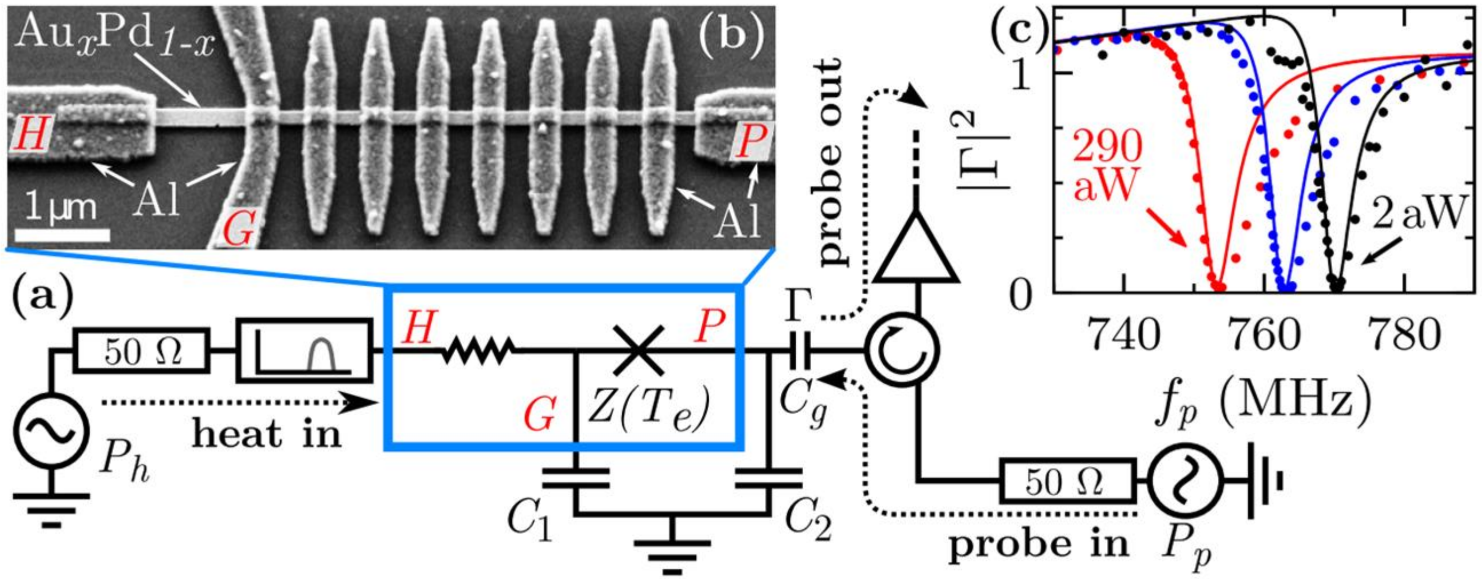


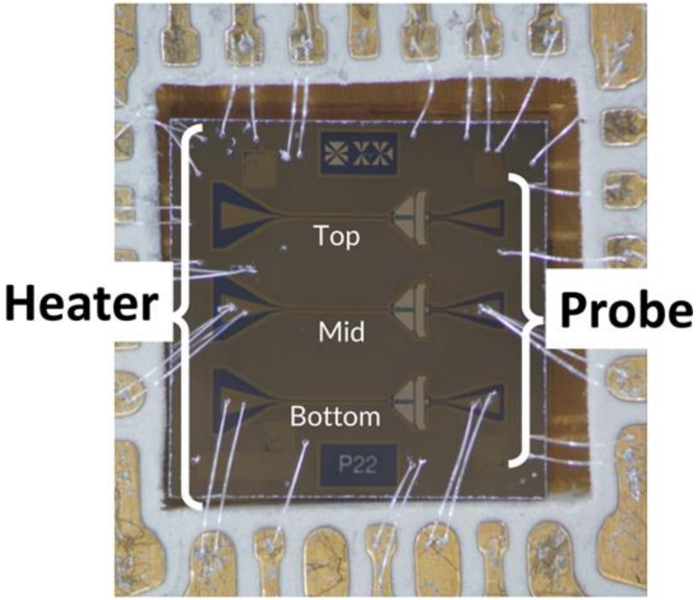
Josephson parametric amplifier (JPA)

- *Parametrically amplification of weak signals*
- *Added noise (1/2 photon) → **total system noise down to ~ single quanta (quantum-limited)***
- ***Strong collaboration with U. of Tokyo, RIKEN (Nakamura’s group)***

DMAG's approach

Bolometer and heterodyne detection



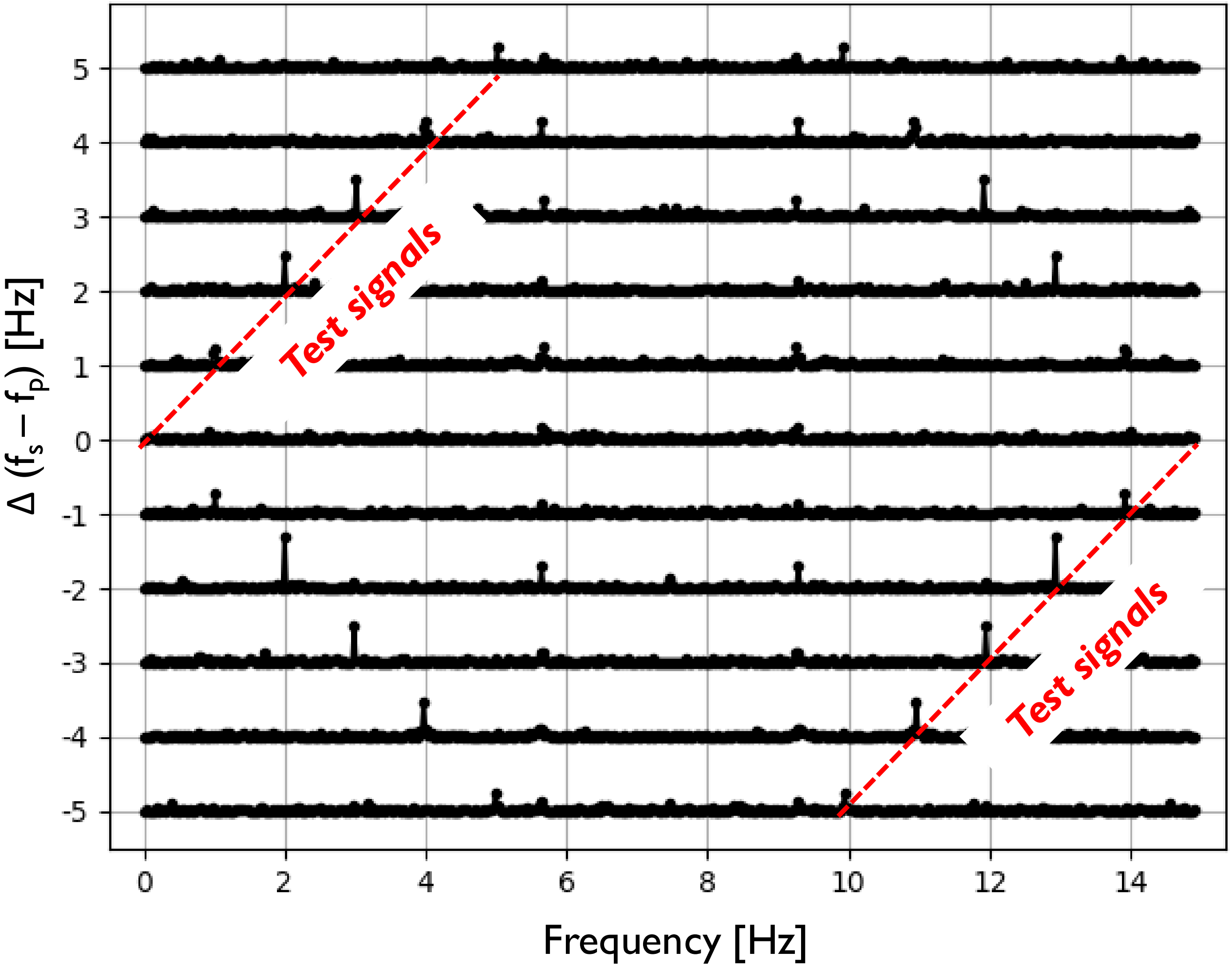


Zeptojoule nanobolometer (Aalto university)

- *Non-linear power detector*
- *Detecting heat dissipation on the film*
    - *With JJ-terminated resonator*

DMAG's approach

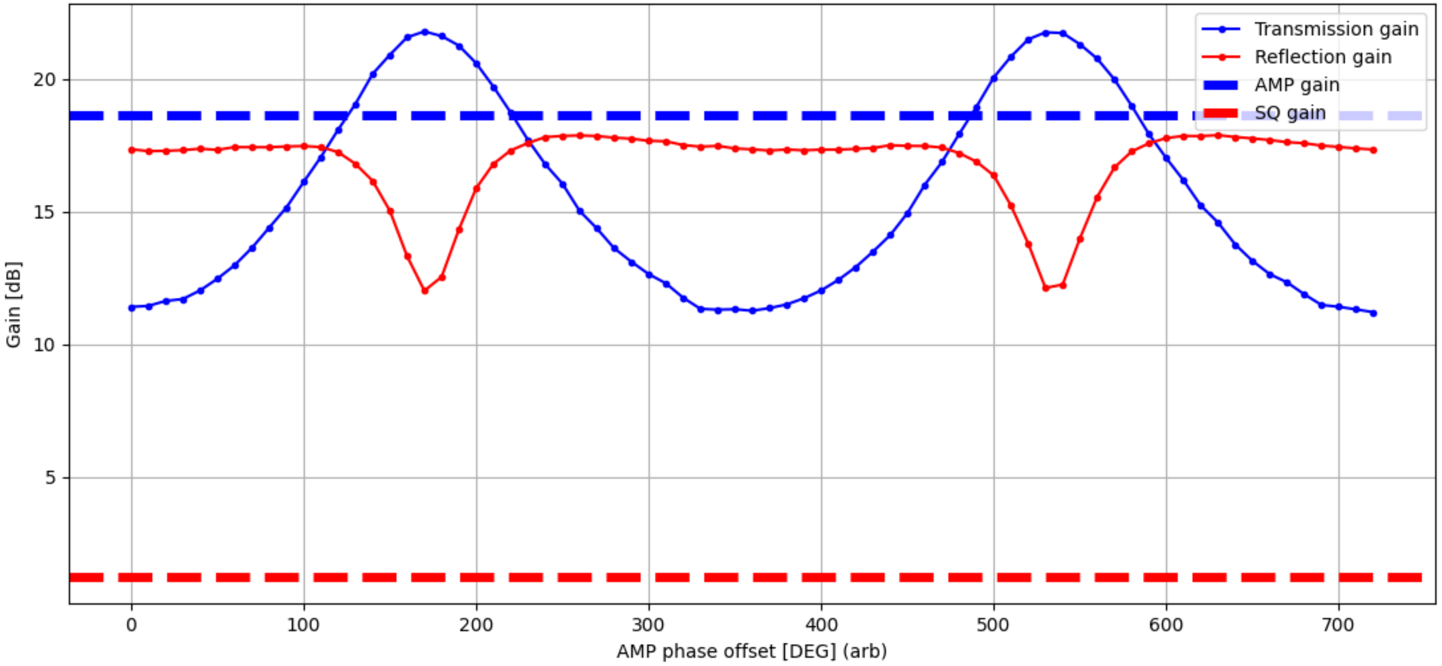
Bolometer and heterodyne detection



- *Signal offset [-5, 5] Hz with 1 Hz step*
- *Downmixing happens at the bolometer*
- ***Beating signal detected at higher amplitudes***

KSHEP spring meeting, 2026

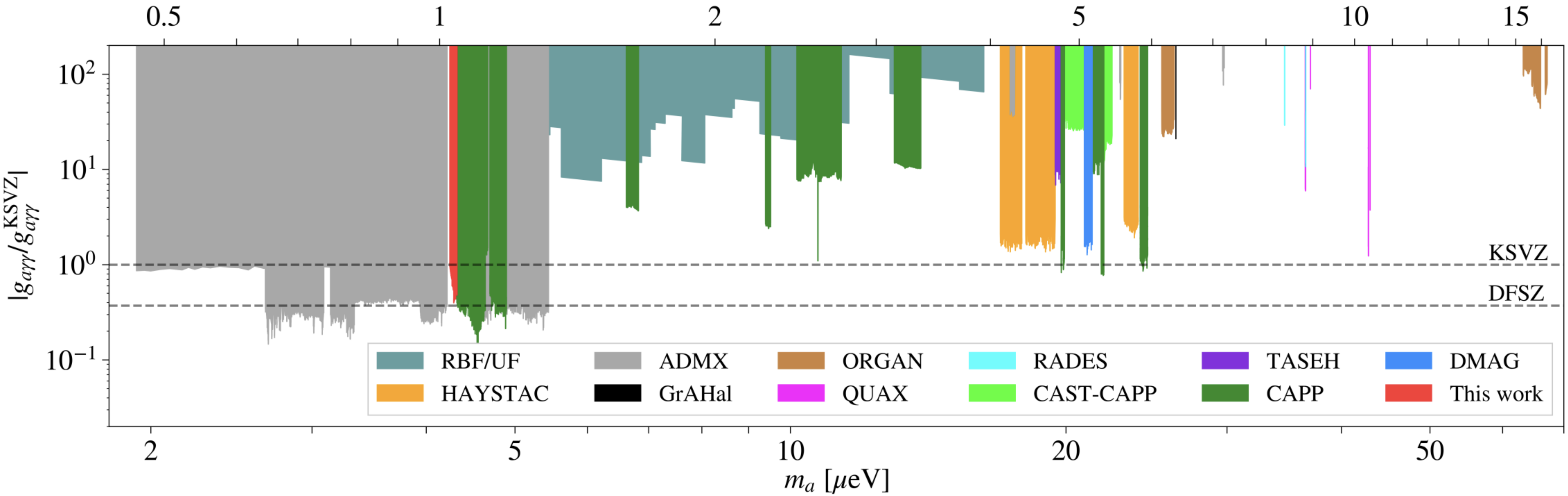
DMAG's approach



Quantum squeezing

- *JPA: phase-selective amplification*
- *Two JPAs: one for amplification, one for phase-offset of one quadrature*

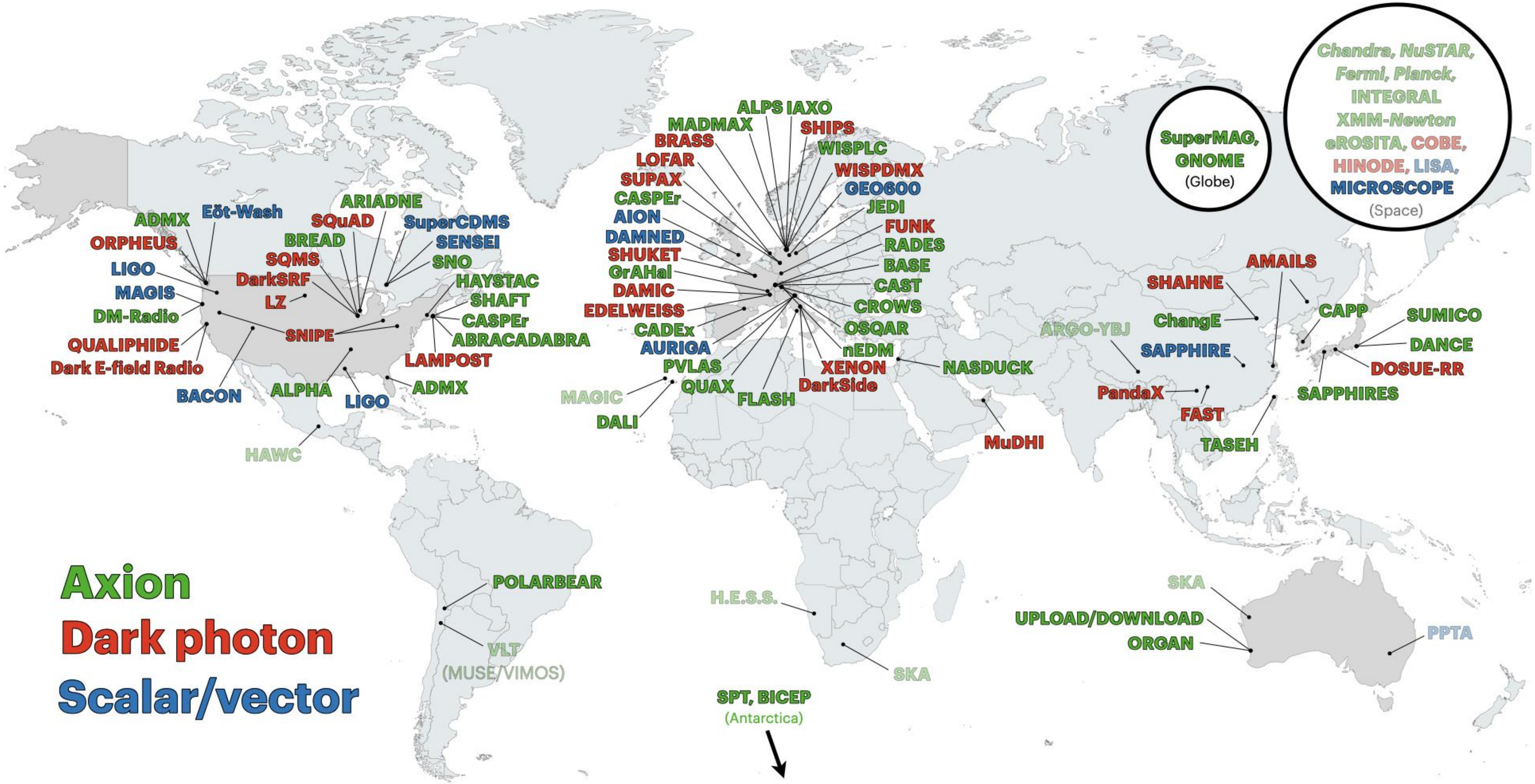
Haloscope results



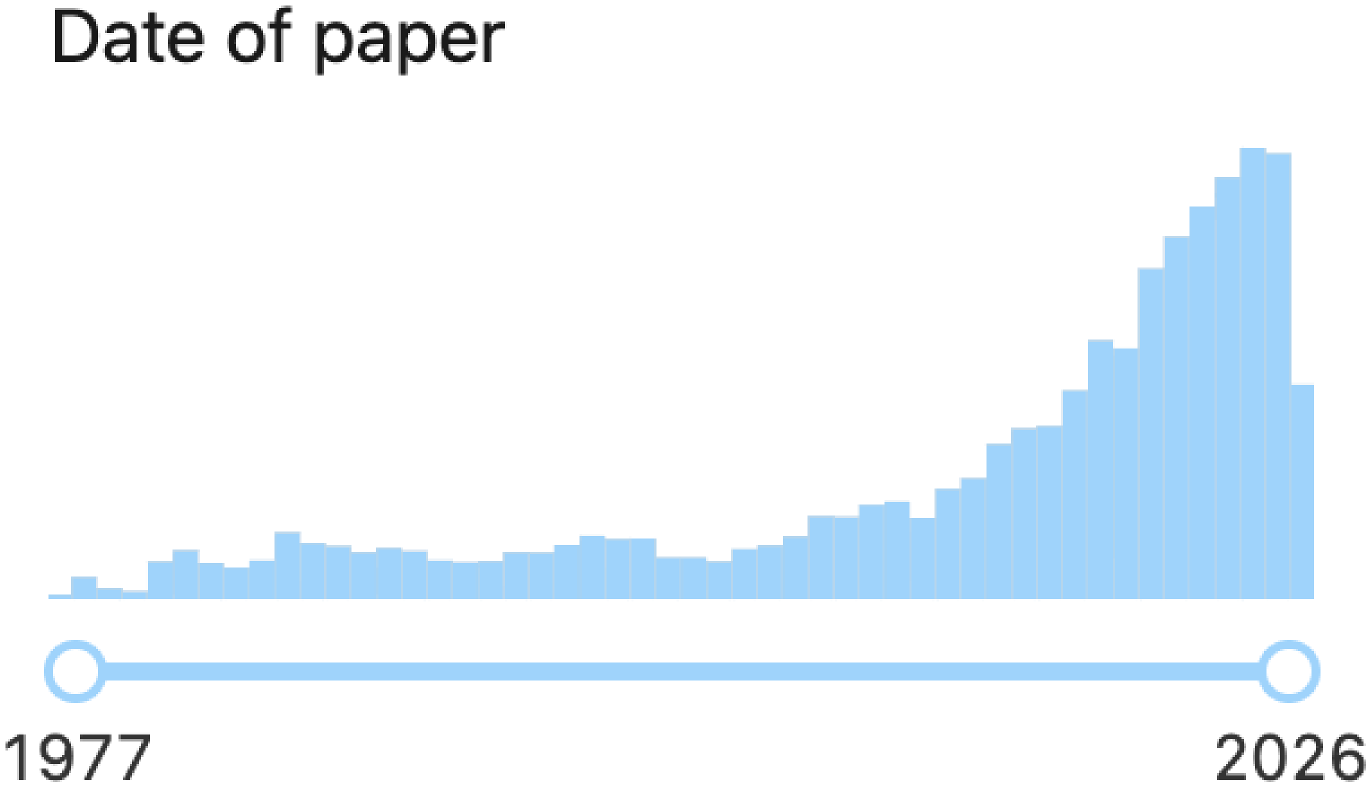
KSHEP spring meeting, 2026

Axion community is growing fast

Worldwide projects for axion-like particles



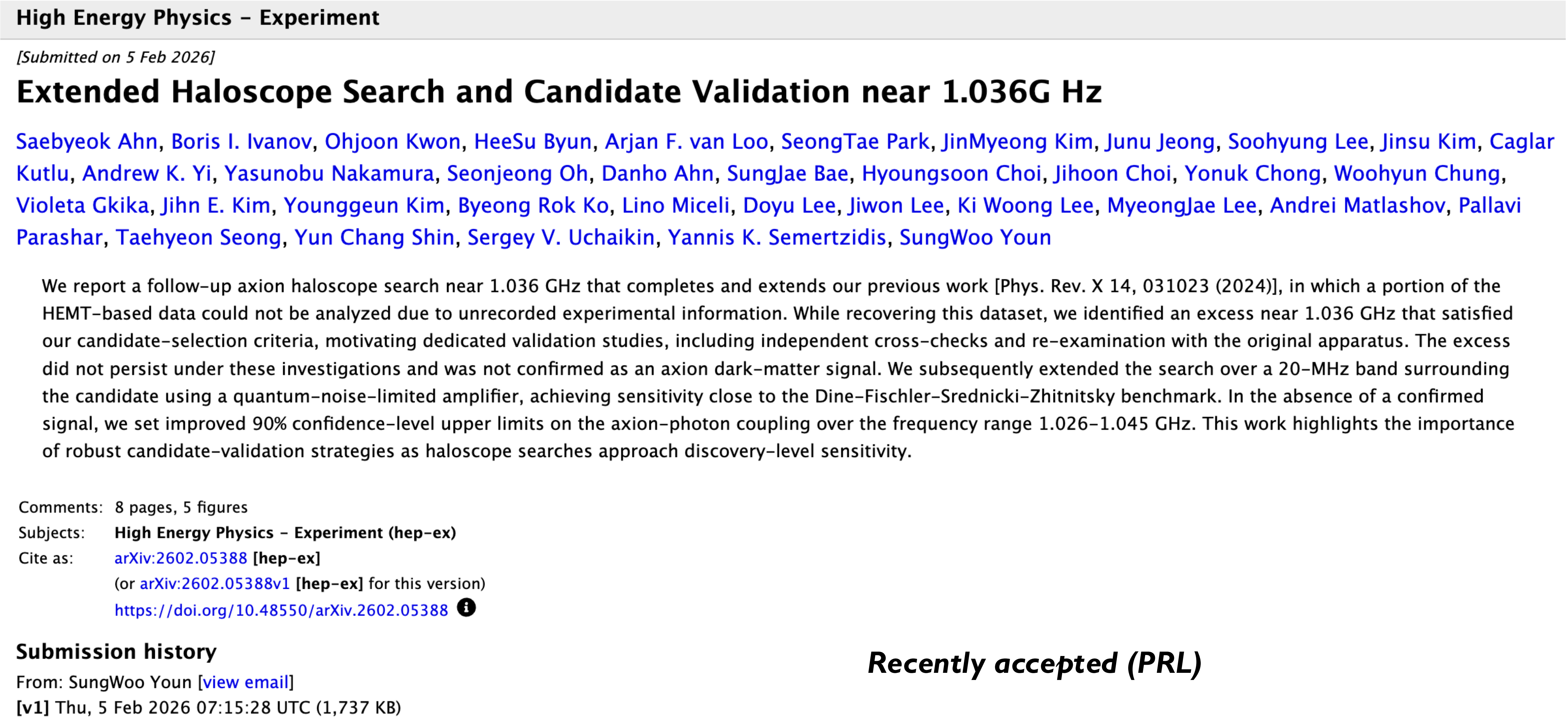
Axion community is growing fast



# of published papers about Axion and axion-like particles

INSPIRED-HEP

Axion?



High Energy Physics – Experiment

[Submitted on 5 Feb 2026]

Extended Haloscope Search and Candidate Validation near 1.036G Hz

Saebyeok Ahn, Boris I. Ivanov, Ohjoon Kwon, HeeSu Byun, Arjan F. van Loo, SeongTae Park, JinMyeong Kim, Junu Jeong, Soohyung Lee, Jinsu Kim, Caglar Kutlu, Andrew K. Yi, Yasunobu Nakamura, Seonjeong Oh, Danho Ahn, SungJae Bae, Hyoungsoon Choi, Jihoon Choi, Yonuk Chong, Woohyun Chung, Violeta Gkika, Jihn E. Kim, Younggeun Kim, Byeong Rok Ko, Lino Miceli, Doyu Lee, Jiwon Lee, Ki Woong Lee, MyeongJae Lee, Andrei Matlashov, Pallavi Parashar, Taehyeon Seong, Yun Chang Shin, Sergey V. Uchaikin, Yannis K. Semertzidis, SungWoo Youn

We report a follow-up axion haloscope search near 1.036 GHz that completes and extends our previous work [Phys. Rev. X 14, 031023 (2024)], in which a portion of the HEMT-based data could not be analyzed due to unrecorded experimental information. While recovering this dataset, we identified an excess near 1.036 GHz that satisfied our candidate-selection criteria, motivating dedicated validation studies, including independent cross-checks and re-examination with the original apparatus. The excess did not persist under these investigations and was not confirmed as an axion dark-matter signal. We subsequently extended the search over a 20-MHz band surrounding the candidate using a quantum-noise-limited amplifier, achieving sensitivity close to the Dine-Fischler-Srednicki-Zhitnitsky benchmark. In the absence of a confirmed signal, we set improved 90% confidence-level upper limits on the axion-photon coupling over the frequency range 1.026-1.045 GHz. This work highlights the importance of robust candidate-validation strategies as haloscope searches approach discovery-level sensitivity.

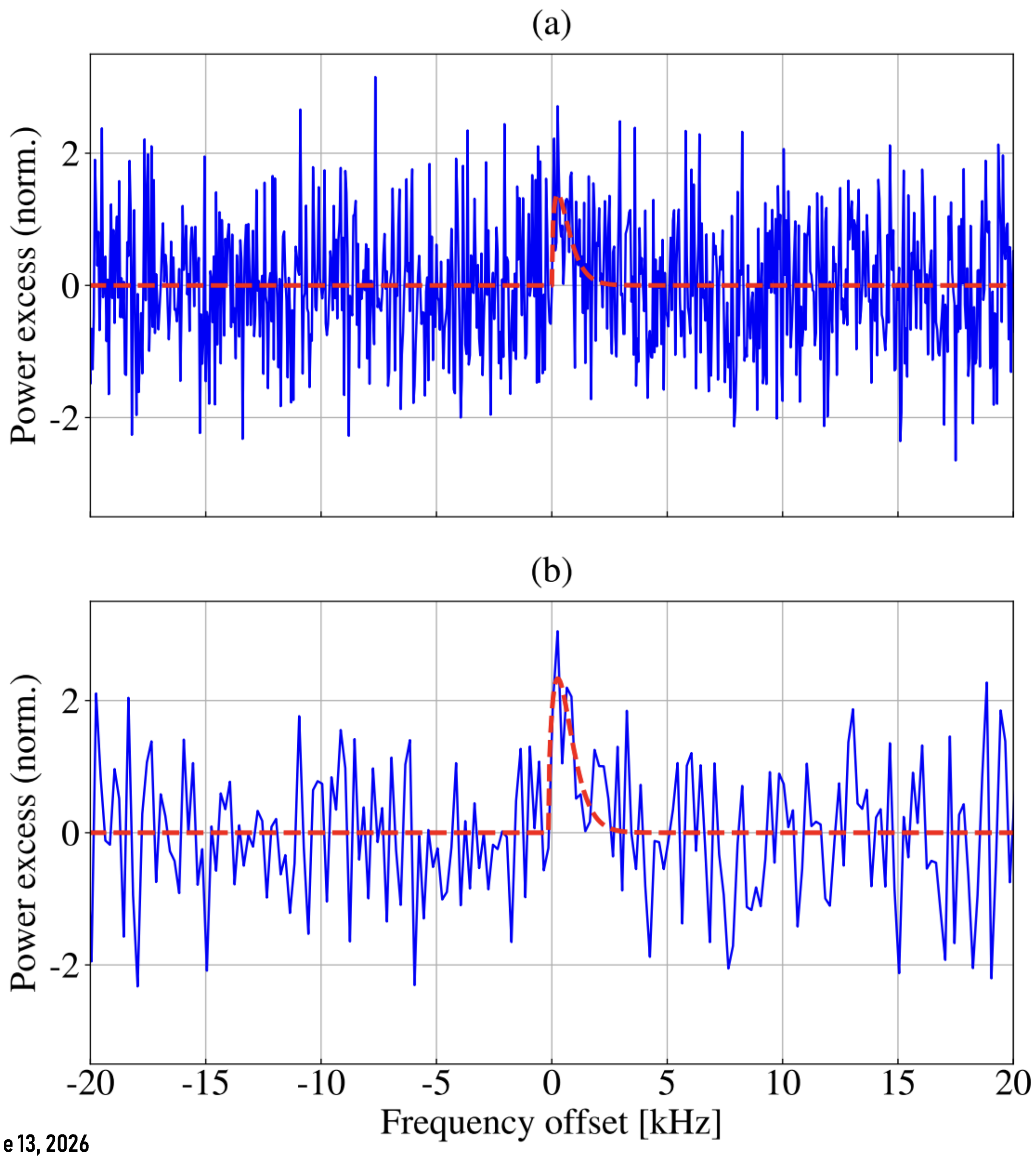
Comments: 8 pages, 5 figures
Subjects: **High Energy Physics – Experiment (hep-ex)**
Cite as: arXiv:2602.05388 **[hep-ex]**
(or arXiv:2602.05388v1 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2602.05388

Submission history

From: SungWoo Youn [view email]
[v1] Thu, 5 Feb 2026 07:15:28 UTC (1,737 KB)

Recently accepted (PRL)

Axion?



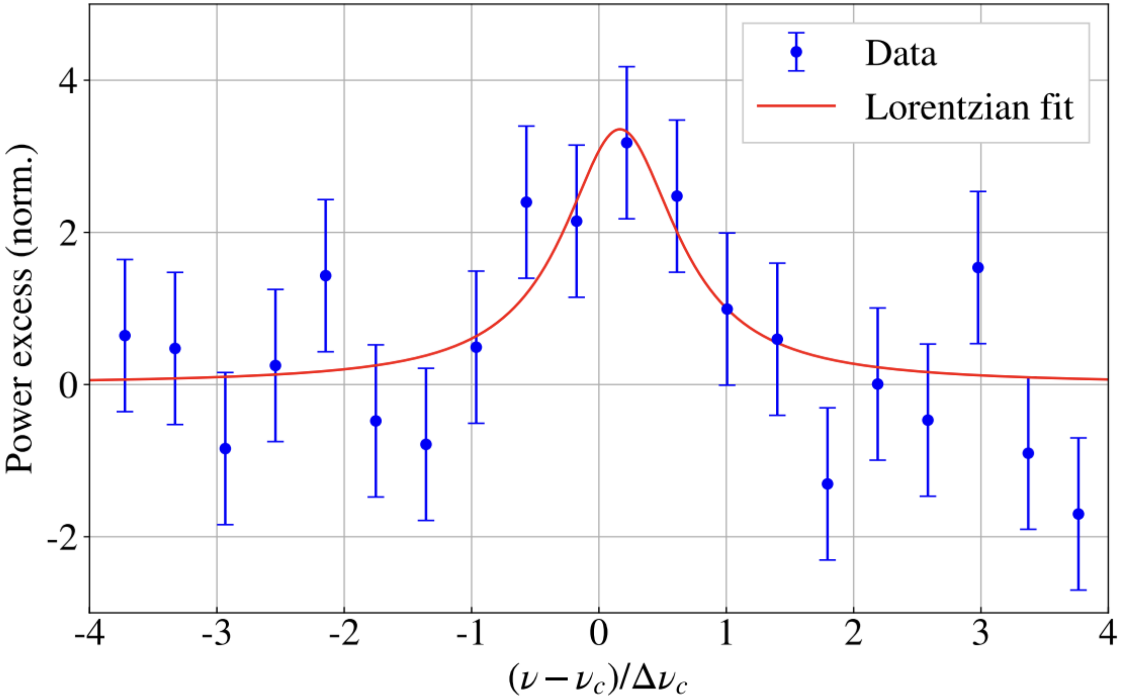
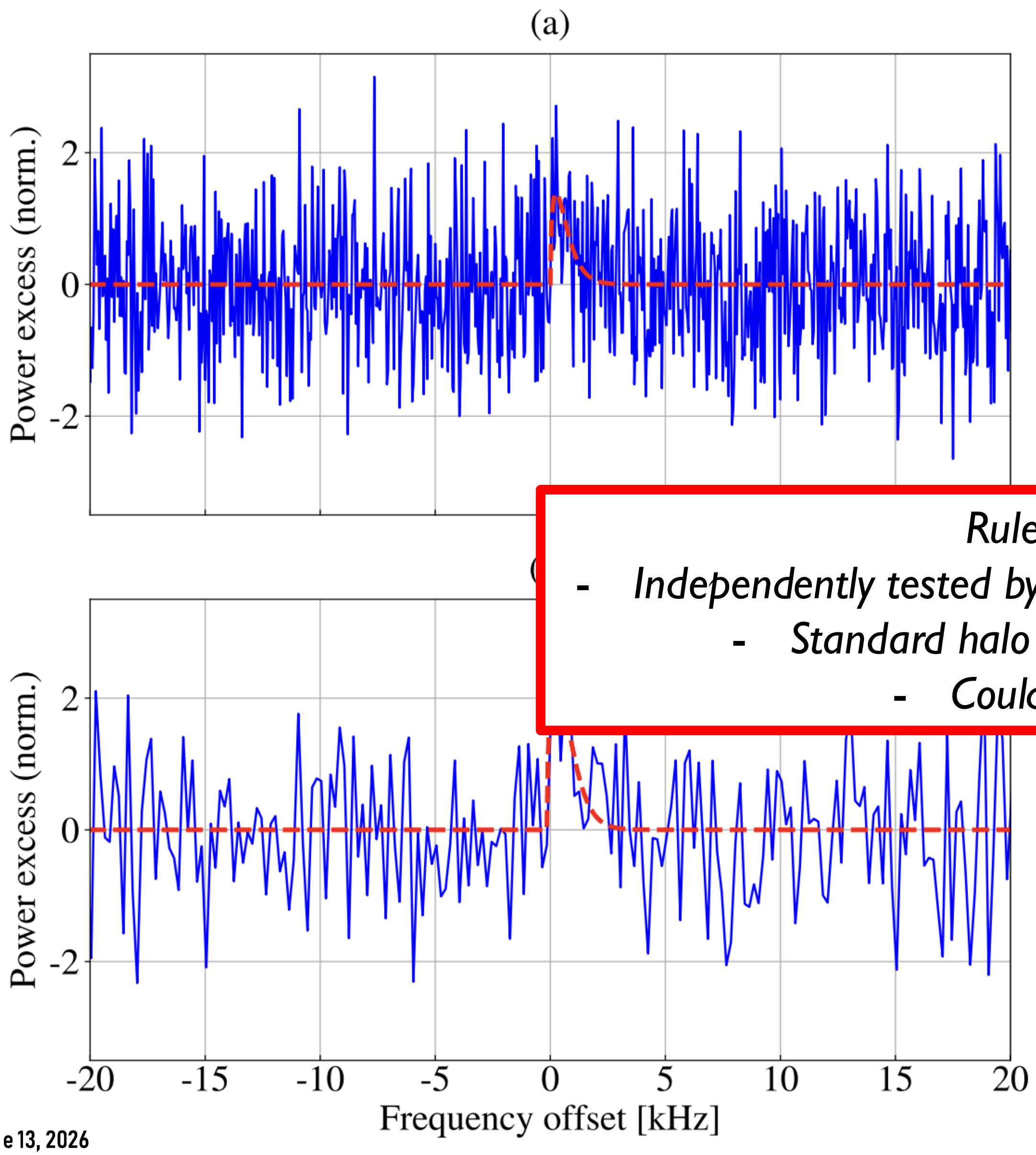


FIG. 3. Signal strength as a function of frequency detuning $\nu - \nu_c$, normalized to the cavity bandwidth ($\Delta\nu_c = 28.25\,\text{kHz}$). The error bars indicate statistical uncertainties. The data are fitted with a Lorentzian profile whose linewidth is consistent with the measured cavity resonance.

Axion?



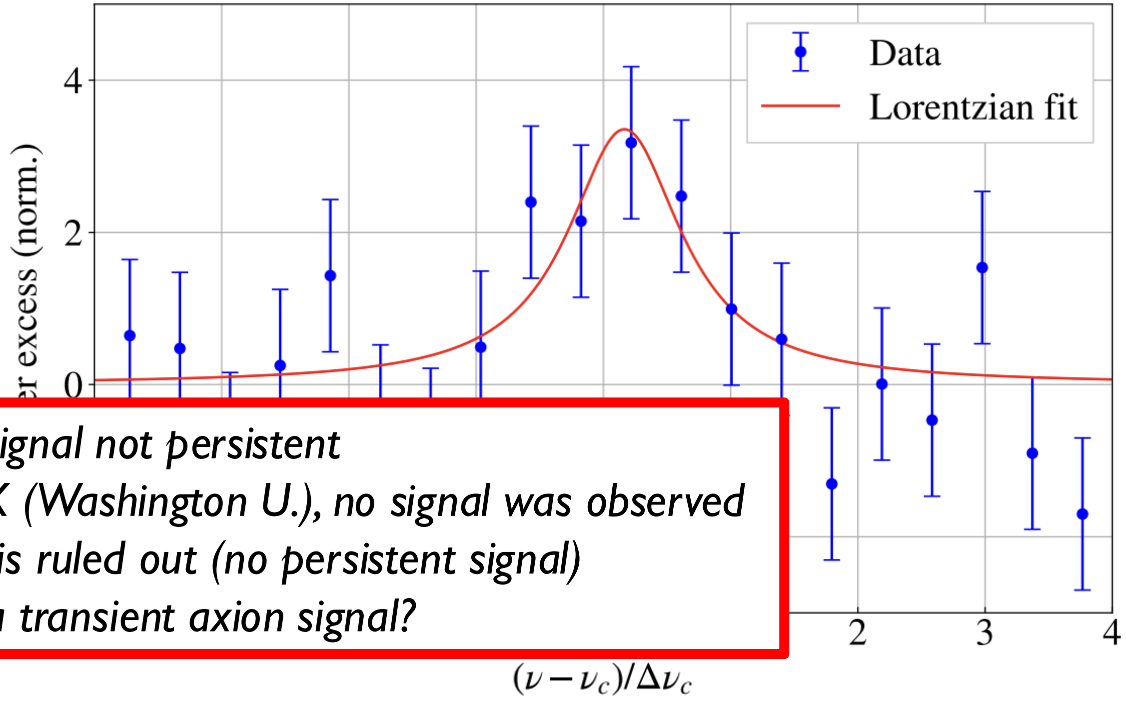


FIG. 3. Signal strength as a function of frequency detuning $\nu-\nu_c$, normalized to the cavity bandwidth ($\Delta\nu_c = 28.25\,\text{kHz}$). The error bars indicate statistical uncertainties. The data are fitted with a Lorentzian profile whose linewidth is consistent with the measured cavity resonance.

Ruled out: signal not persistent

- *Independently tested by ADMX (Washington U.), no signal was observed*
- *Standard halo model is ruled out (no persistent signal)*
- *Could it be a transient axion signal?*

Take home messages

- Axion is a well-motivated solution for two distinct mysteries of our universe
- Axion haloscope is so far the most sensitive method for axion search
- CAPP is at world-best sensitivity with axion haloscopes
- Still many challenges, working hard for the future advancements
- Axion community is growing fast, more and more to come!!

Thank you very much!