June 26, 2025

A comprehensive plan to resolve the axion dark matter problem with high sensitivity experiments

Yannis K. Semertzidis, KAIST
Particle physics seminar, BNL

- "Cosmic Axions Revealed via Amplified Modulation of Ellipticity of Laser (CARAMEL)," with Hooman Davoudiasl and YkS, will be submitted to the arXiv shortly.
- Talk suggested by Hong Ma; work encouraged by Dmitri Denisov, thank you!

- A new approach to reading out axion haloscopes could increase the axion frequency scanning rate by more than an order of magnitude, enabling its detection or exclusion in less than five years.

Cosmic Axions Revealed via Amplified Modulation of Ellipticity of Laser (CARAMEL)

Hooman Davoudiasl[1] and Yannis K. Semertzidis[2,*]

Dark matter

Dark Matter and Isaac Newton (1642-1726)

Isaac Newton unified the Physics phenomena:
falling of an apple with the planet/moon/star/sattelite/comet motions, under Gravity! Needed Calculus for it.

He clarified the view of Heavens for Humanity!

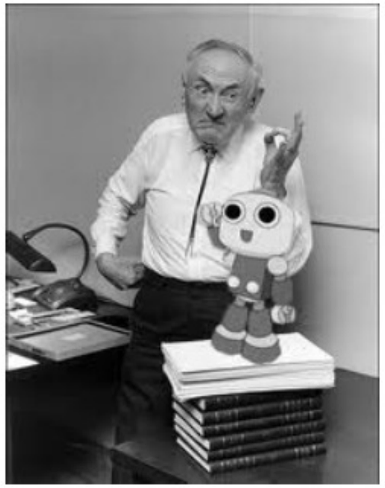
He also gave us the ability to see what cannot be seen with ordinary methods. Looking for deviations from his rules we are able to sense the presence of Dark Matter.

The axion dark matter community is now close to be able to answer in a definitive way whether axions, one of the leading DM candidates, is behind it all. Not close enough!

For gravitational attraction, n equals −1 and the average kinetic energy equals half of the average negative potential energy

$$\langle T \rangle_\tau = -\frac{1}{2} \langle V_{\mathrm{TOT}} \rangle_\tau .$$

Origins of dark-matter: Zwicky (Coma cluster) & Smith (Virgo cluster)



Coma Cluster

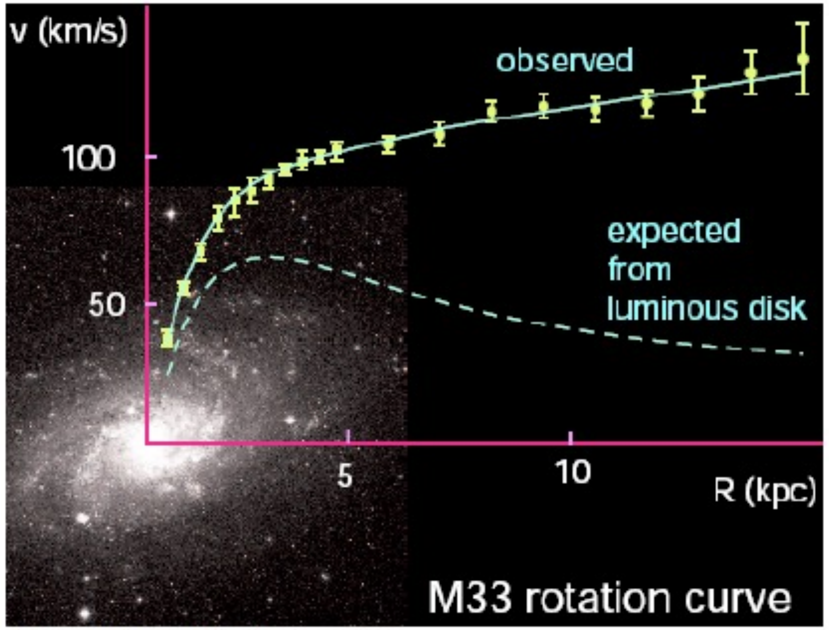
Virial motions within galaxy clusters:

"The difference between this result and Hubble's value for the average mass of a nebula must remain unexplained until further information becomes available."

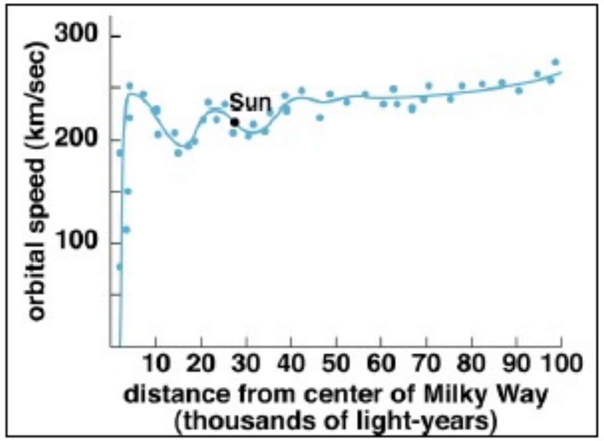
The "dunkelmaterie" of Zwicky 1936

Origins of dark matter: Rubin, Gallagher, Faber et al.

Flat galactic rotation curves
Rubin, "1970's: The decade of seeing is believing."



Paolo Saluchi



Vera Rubin

- Her findings were cross checked and found to be correct.
- More galaxies were checked, most of them found to be part of extended halos
- Vera Rubin started a field in Astronomy that firmly established the idea of DM.

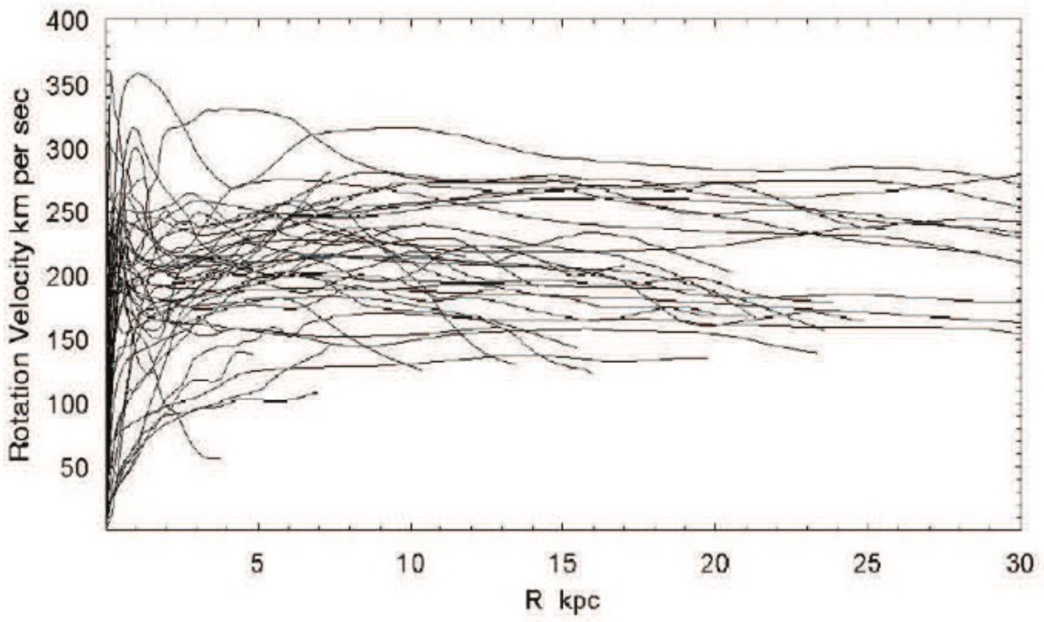


Figure 4: Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999).

[https://www.nature.com/articles/nature25767].

A Galaxy without Dark Matter, effectively confirming Dark Matter.

Active research on the topic is on-going.

It's critical to show that galaxies without DM exist!

A Galaxy Without Dark Matter

Press Release - Source: Yale University   Posted March 28, 2018 10:34 PM   0 Comments

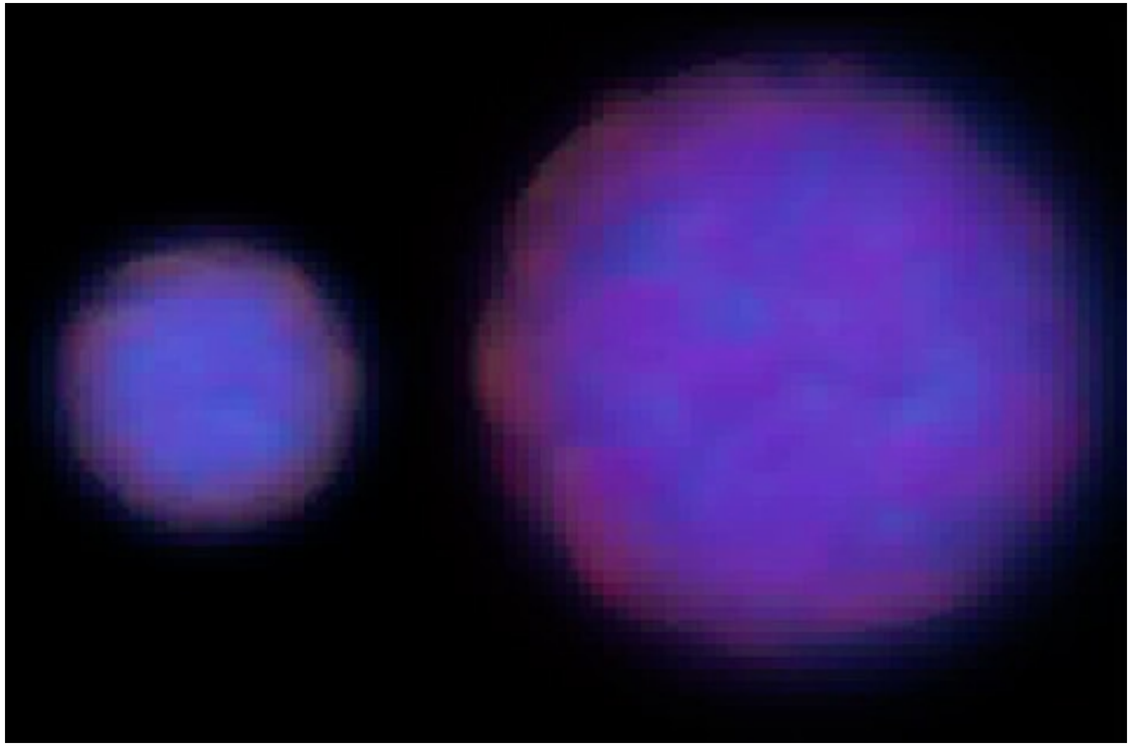
NGC 1052-DF2   ©YALE/NASA

A Yale-led research team has discovered a galaxy that contains no dark matter -- a finding that confirms the possibility of dark matter as a separate material elsewhere in the universe.

The discovery has broad implications for astrophysics, the researchers said. It shows for the first time that dark matter is not always associated with traditional matter on a galactic scale, ruling out several current theories that dark matter is not a substance but merely a manifestation of the laws of gravity on cosmic scales.

Dark Matter's smoking gun

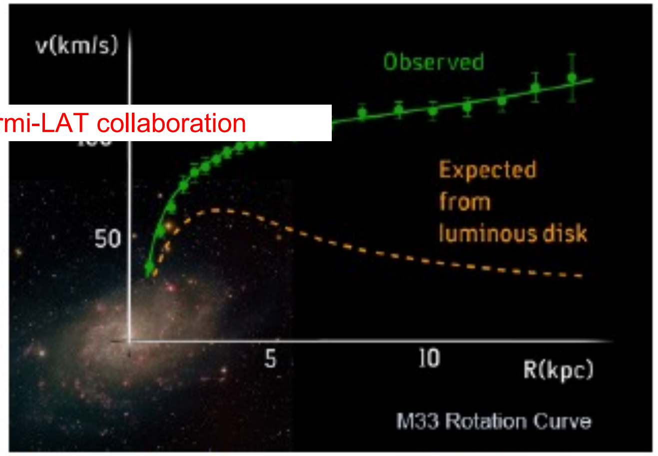
- Two cluster galaxies colliding
- The regular matter (red) interacts, i.e., collides (friction) with each other
- The dark matter (blue) moves unaffected…



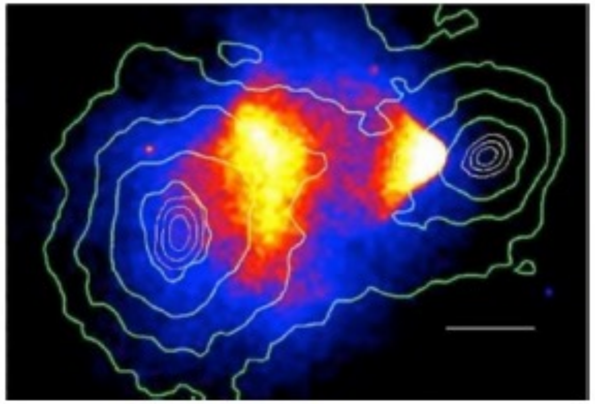
Evidence for / Salient Features of Dark Matter

Eric Charles, Fermi-LAT collaboration

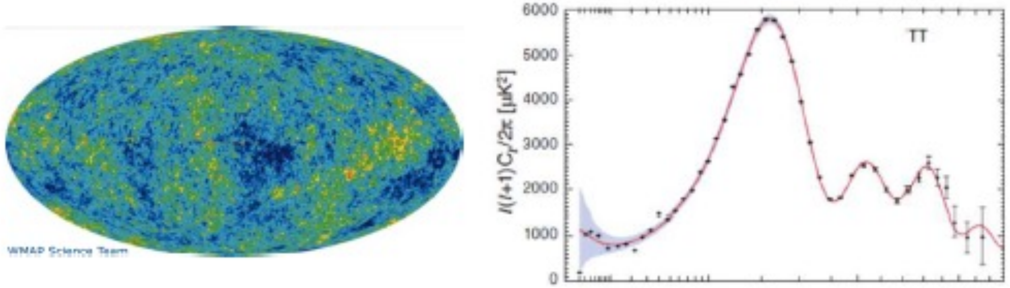
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)



*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)

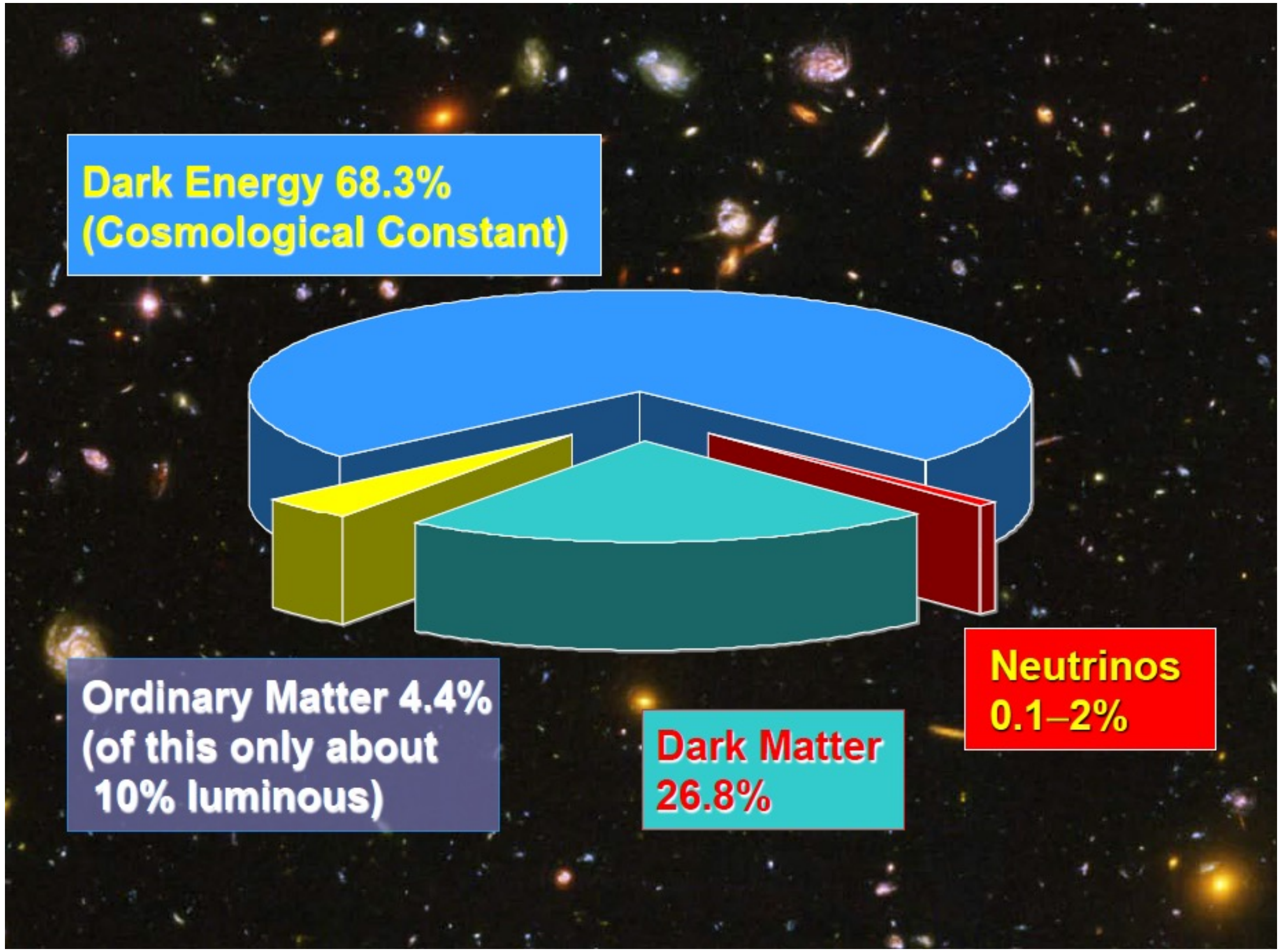


*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

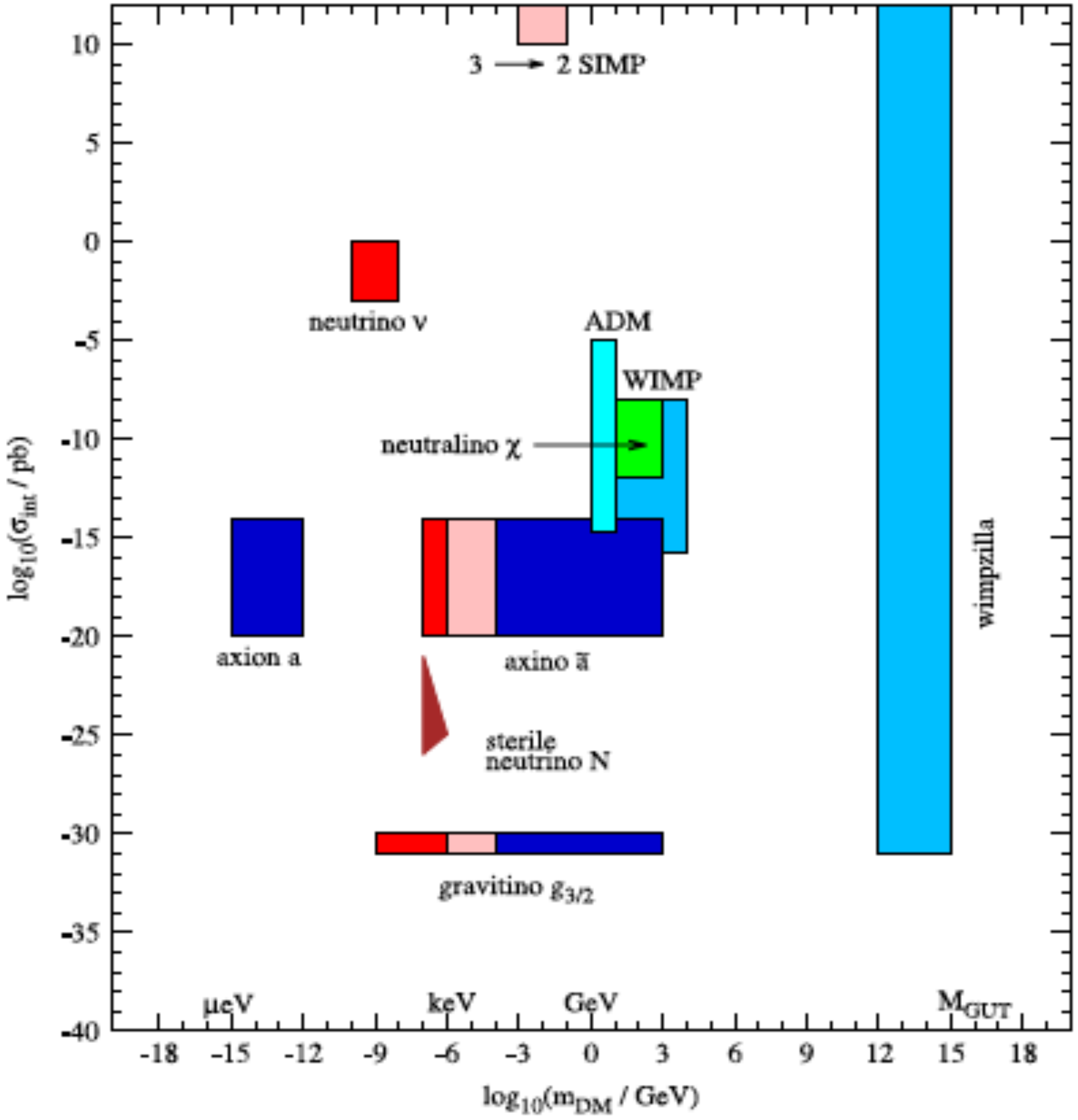
Cosmological inventory



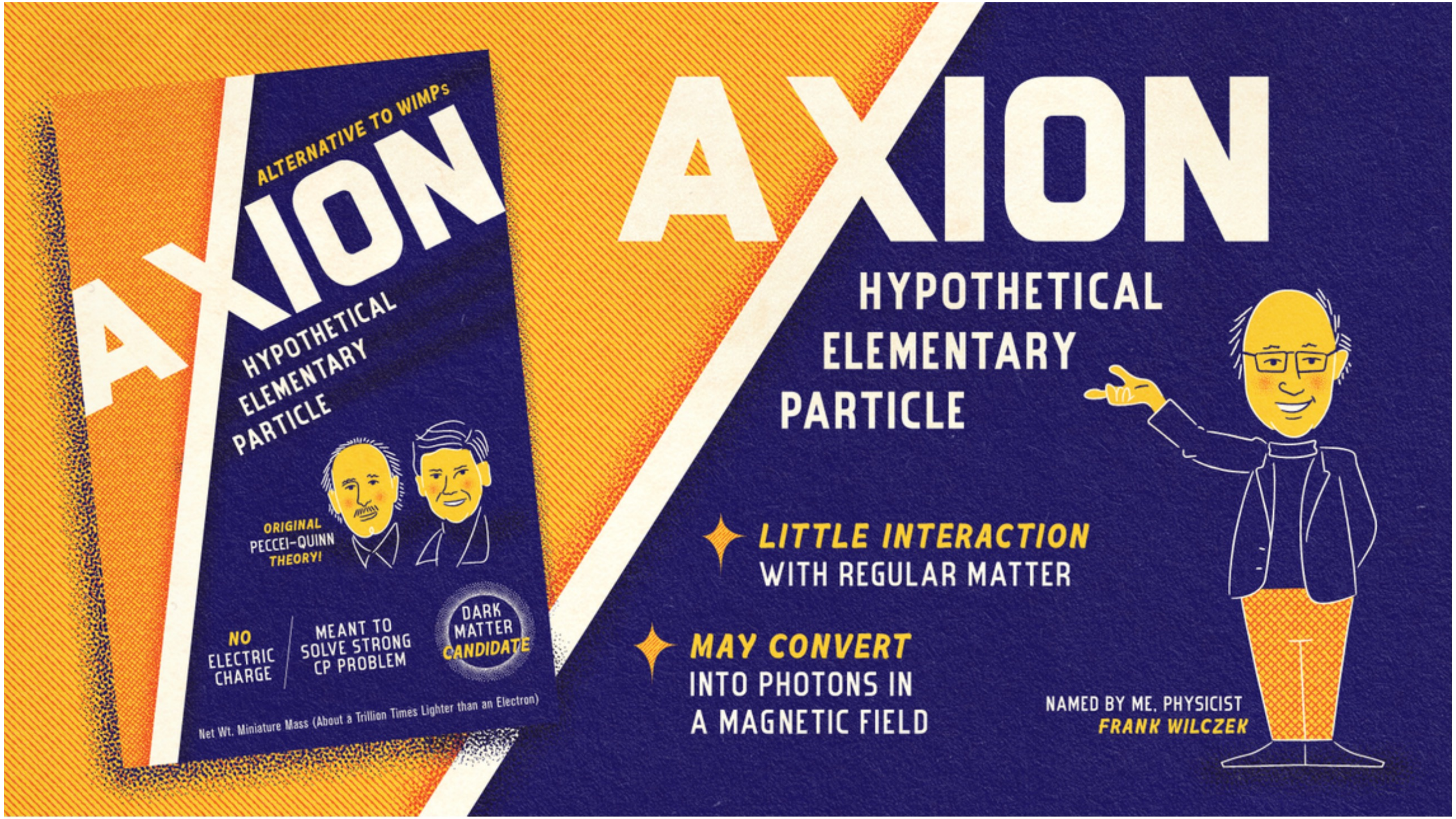
We Have Discovered Dark Matter!

…but what is it?

Dark matter candidates



Axions: A leading Dark Matter Candidate



(https://www.symmetrymagazine.org/sites/default/files/images/standard/Inline_1_Axion.png)

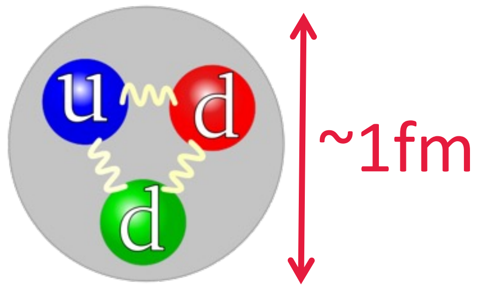
Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

The QCD Lagrangian contains a theta-term violating <u>both</u> P-parity and T-time reversal symmetries.

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\,\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n(\bar{\theta}) \sim \bar{\theta}\,\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n(\bar{\theta}) \approx -d_p(\bar{\theta}) \approx 3.6\times10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm}$$

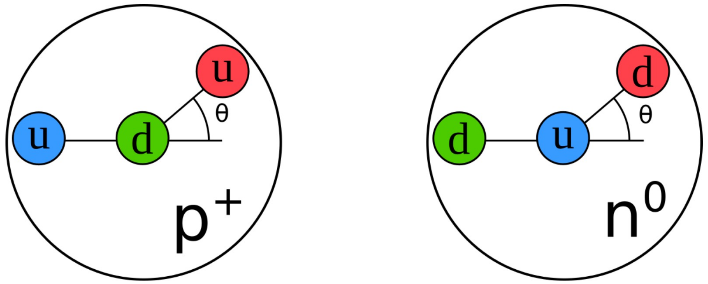
M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

$$\text{Exp.: } d_n < 3\times10^{-26} e\cdot \mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

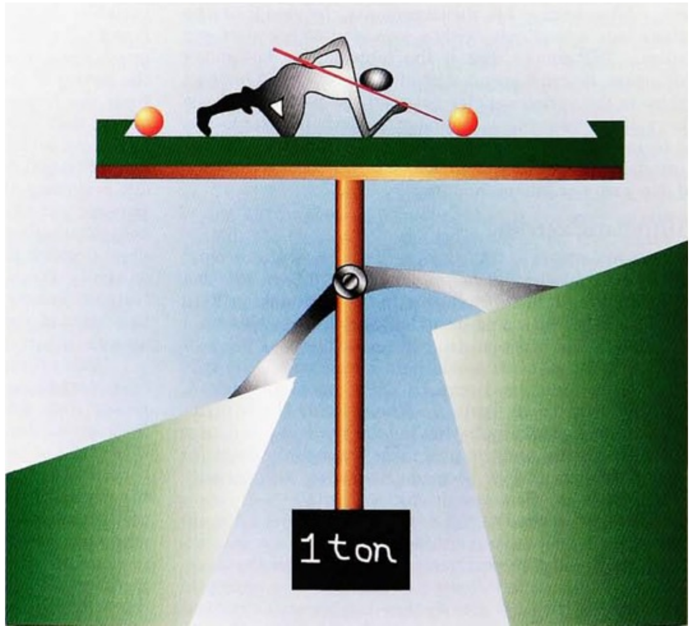
In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

Strong CP-problem: why is the neutron EDM unnaturally small?

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally
- Weinberg and Wilczek pointed out that a new particle must exist, axion.

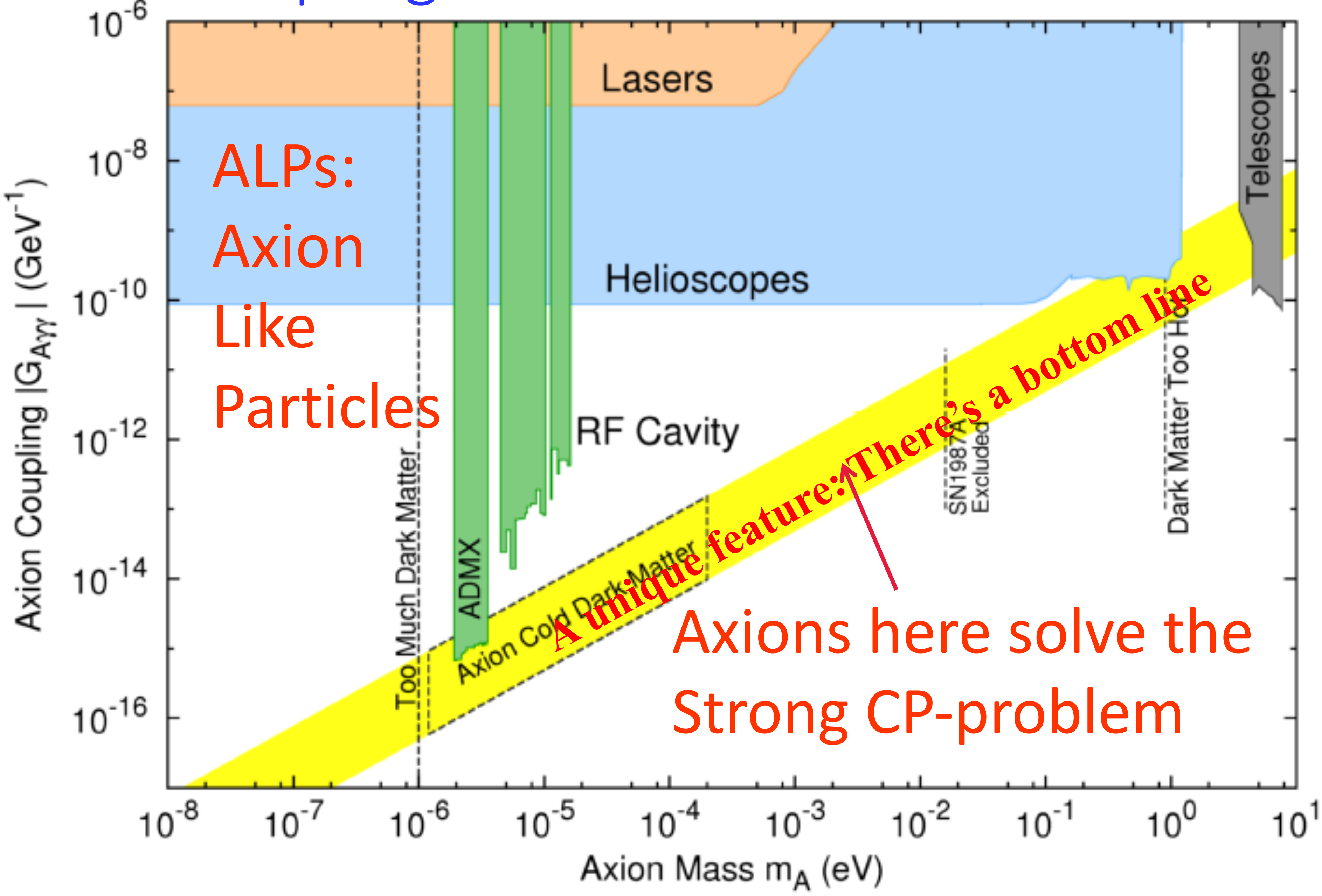


$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

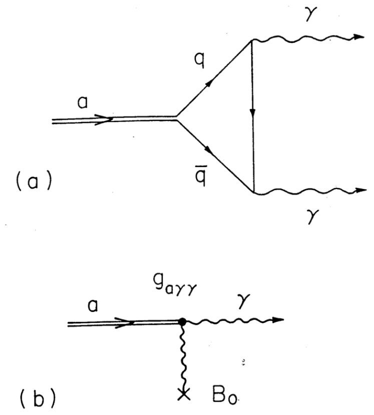


The Pool-Table Analogy with Axion Physics, Pierre Sikivie
Physics Today **49**(12), 22 (1996);
http://dx.doi.org/10.1063/1.881573

Axion coupling vs. axion mass



Axion Couplings



- Gauge fields:
  - Electromagnetic fields (microwave cavities: CAPP, ADMX,…)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

  -
  - Gluon Fields (Oscillating EDM: CASPEr, storage ring EDM)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field, CASPEr-Electric, ARIADNE; GNOME)

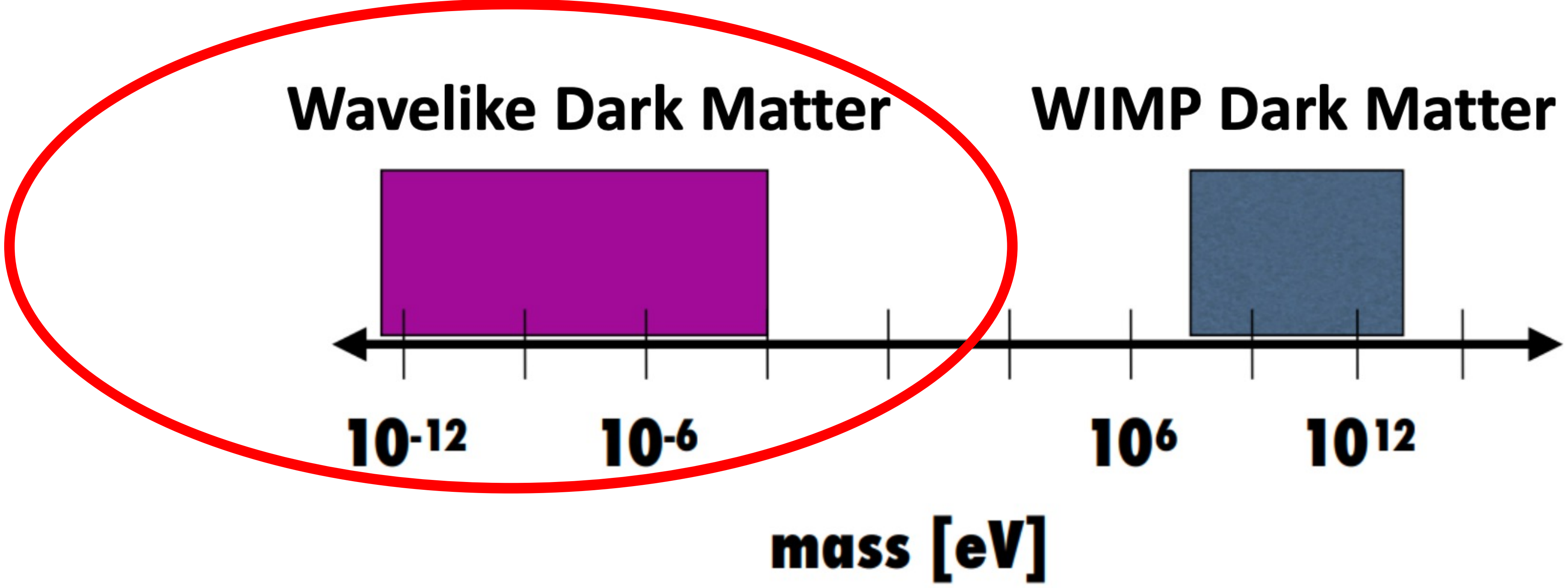
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Axion couplings and effects, using 0.45 GeV/cm^3 as local DM density

1. Magnetic fields (DC) induce a mixing of the axion field (at axion frequency) and electric field (at axion frequency), e.g., 10T magnetic field creates about 0.5pV/m, f=25 GHz, at DFSZ level of axion to photon coupling.

2. Gluon oscillations induce about 10^{-34} $e\cdot$cm of electric dipole oscillation (EDM) for the proton and the neutron at any axion frequency.

3. Nuclear mass is the source of an axion field that interacts with fermion spins. It acts like a (pseudo)magnetic field, but it cannot be shielded by superconductors



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$

Occupancy Number - $N \approx \frac{\rho_{DM}}{m} \lambda_{dB}^3$

- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4$ GeV/cm^3

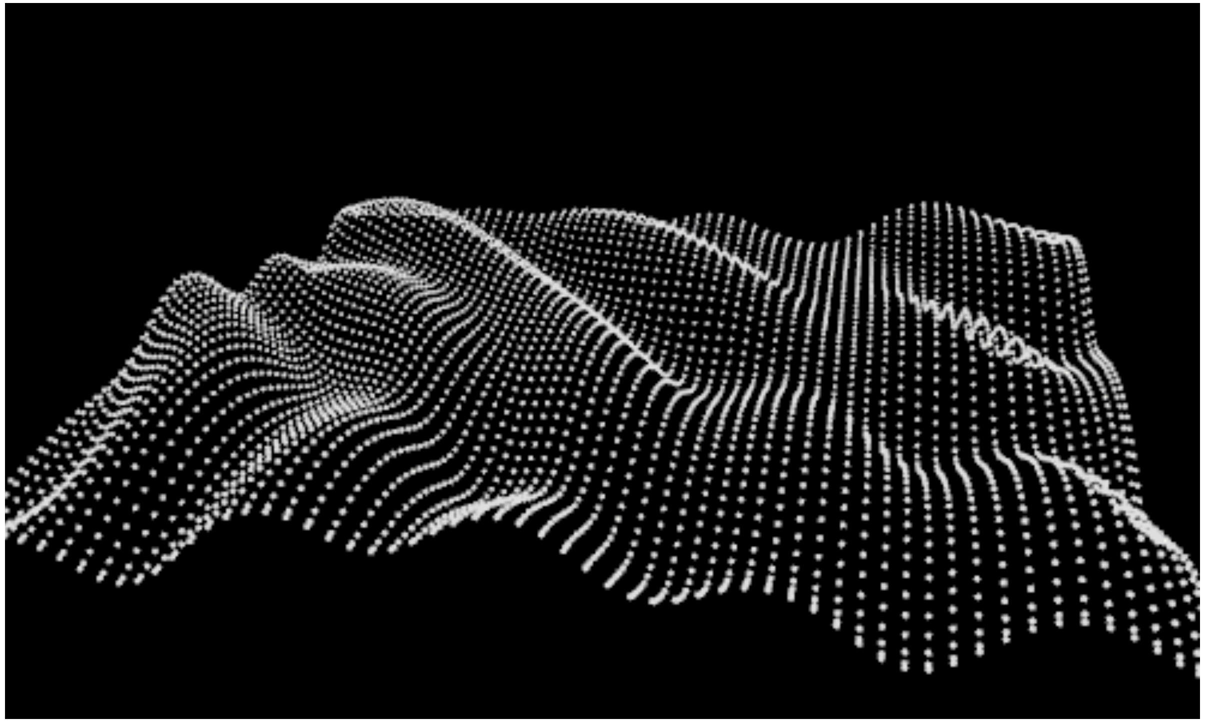
Adapted from B. Safdi

Axion Dark Matter: a Cosmic MASER

De Broglie wavelength of axions

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$\lambda \approx 300\text{m} \times \left(\frac{1\mu\text{eV}}{m_a}\right)$$



Axion dark matter overview

Axion dark matter review articles, theory and experiment

- Axion dark matter: What is it and why now?

By Francesca Chadha-Day, John Ellis, David J.E. Marsh, *Sci. Adv.* **8**, eabj3618 (2022)

- Axion dark matter: How to see it?

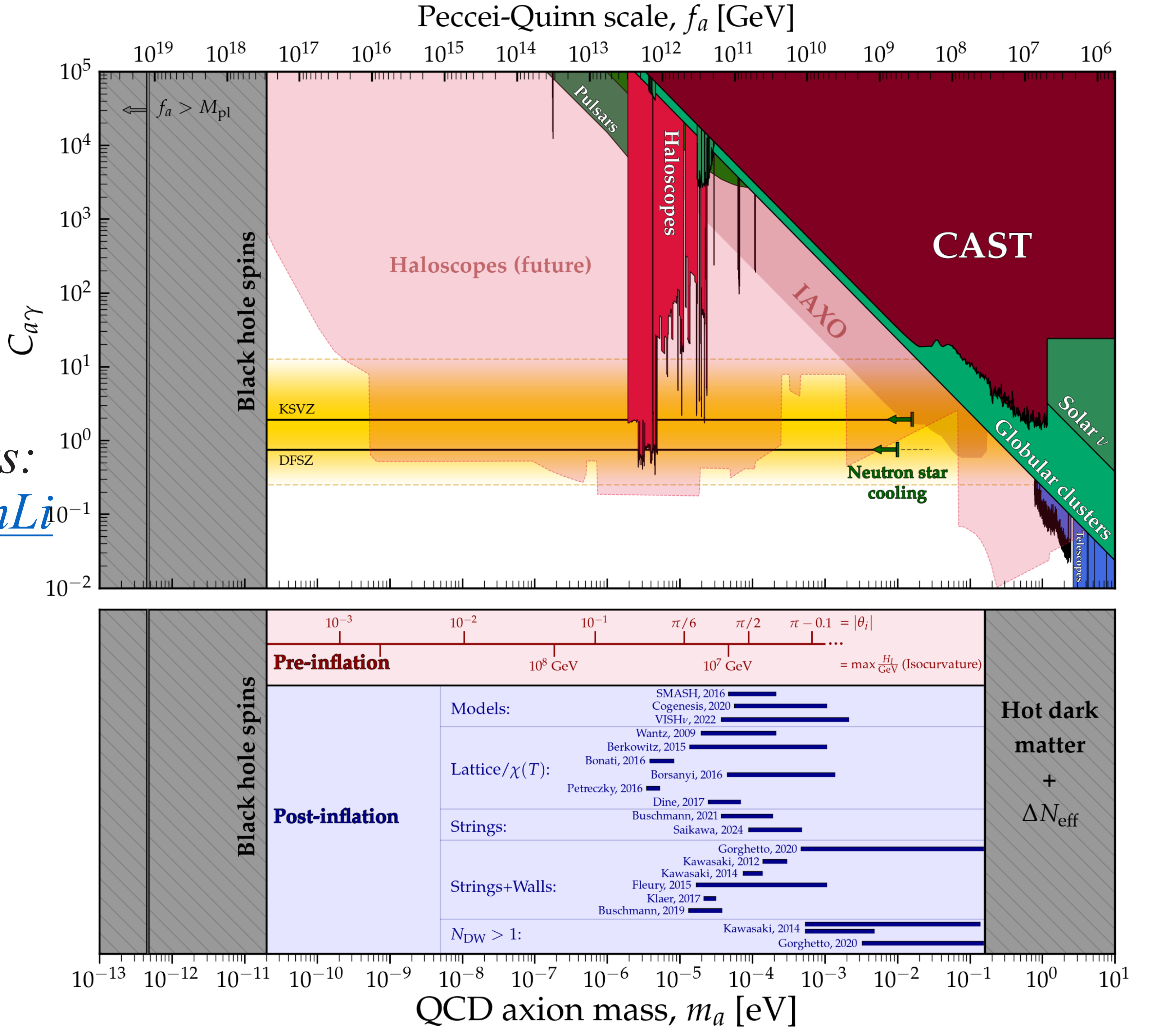
By YkS and SungWoo Youn, *Sci. Adv.* **8**, eabm9928 (2022)

What is known about DM?

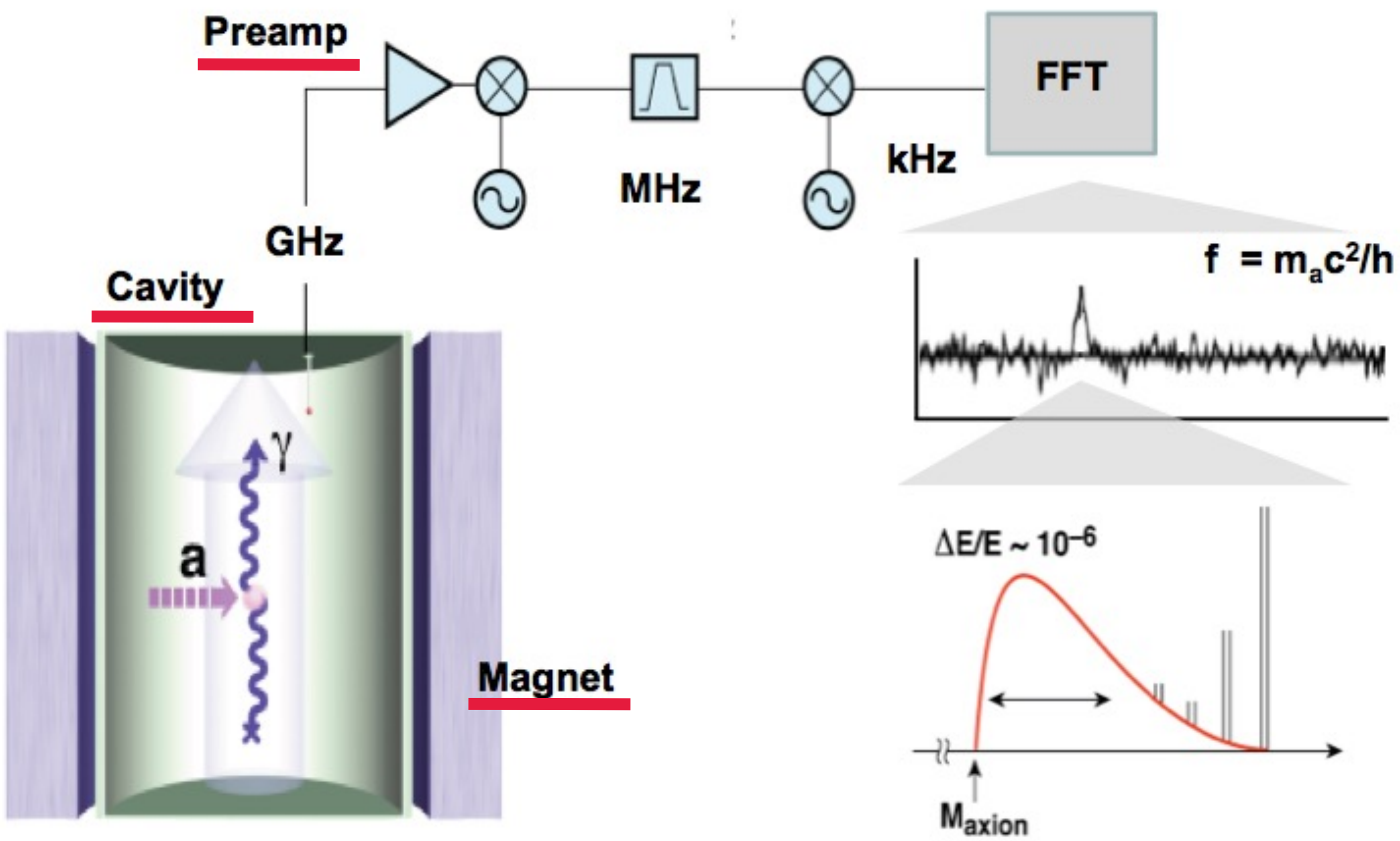
- Cosmic density [strong evidence: CMB anisotropies (*13*)]. Expressed as a fraction of the total density of the universe, DM makes up 26% of the universe, compared to 6% in ordinary matter and 68% in vacuum energy.
- Local density (strong evidence: Milky Way stellar motions). The local density of DM is around 0.3 to 0.4 GeV cm^{-3}, equivalent to one proton every few cubic centimeters or one solar mass per cubic lightyear. The density is measured, on average, over a relatively large fraction of the galaxy. The actual density at the precise location of Earth could be substantially different. This is particularly relevant to axions, as discussed below. The local density is around 10^5 times the average cosmic density.
- Local velocity dispersion (strong evidence: Milky Way stellar motions). The velocity dispersion of DM is around $\sigma_v = 200\,km\,s^{-1}$, and our local motion with respect to the galactic rest frame is in the direction of the constellation Cygnus.
- No preferred galactic length scale (strong evidence: galaxy clustering and evolution). DM must be nonrelativistic ($v \sim c$ would allow DM to move significant distances during galaxy formation) and have negligible pressure (which would imprint sound waves during galaxy formation). This discounts standard model neutrinos and other "hot" or "warm" DM. For bosons, the de Broglie wavelength (which can be modeled as an effective pressure) must be small compared to the galaxy clustering scale.
- Early appearance of DM (strong evidence: galaxy clustering). DM had to be present, as well as gravitating, in the universe long before the CMB formed, and its gravitational influence began before the universe was 1 year old. For light bosonic DM (such as the axion), this corresponds to the latest epoch of particle creation (t_{cold} in Fig.4).
- Lack of significant interactions [strong evidence: the "Bullet Cluster" (*17*)]. DM cannot interact with itself or ordinary matter too strongly.

Axion mass predictions

C. O'Hare, cajohare/axionlimits: *https://cajohare.github.io/AxionLimits/*



Haloscope method method suggested by Pierre Sikivie (1983)



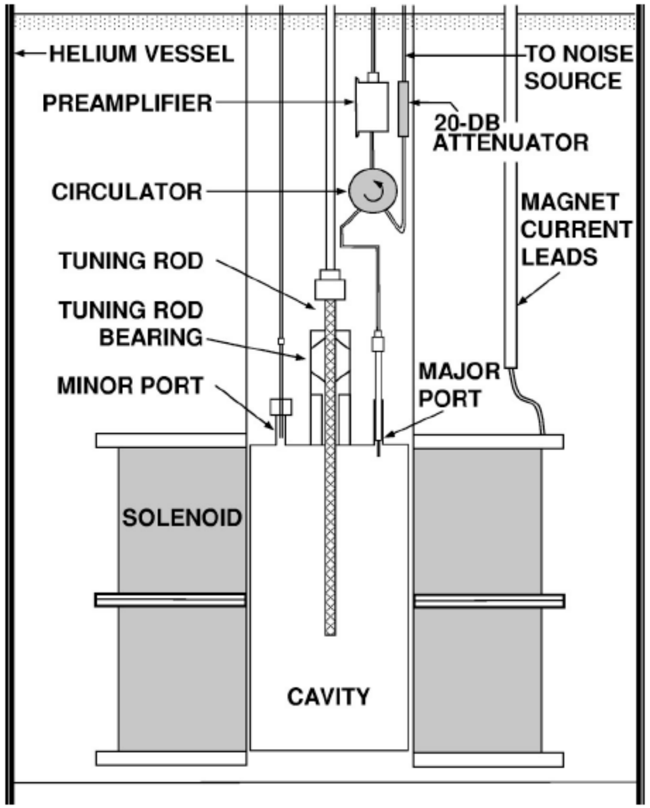
$$P_{sig} \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23}\,W \qquad s/n = \frac{P_{sig}}{kT_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$

Rochester Brookhaven Fermilab axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Under the leadership of Adrian C. Melissinos (Rochester), 1929-2022, a daring pioneer, full of energy, a great teacher.

The first-generation axion-dark-matter experiment
Rochester Brookhaven Fermilab, at BNL – 1980's

W. Wuensch *et al.*, Phys. Rev. D40 (1989) 3153



First PhD Thesis
Joe Rogers
(1957-2004)

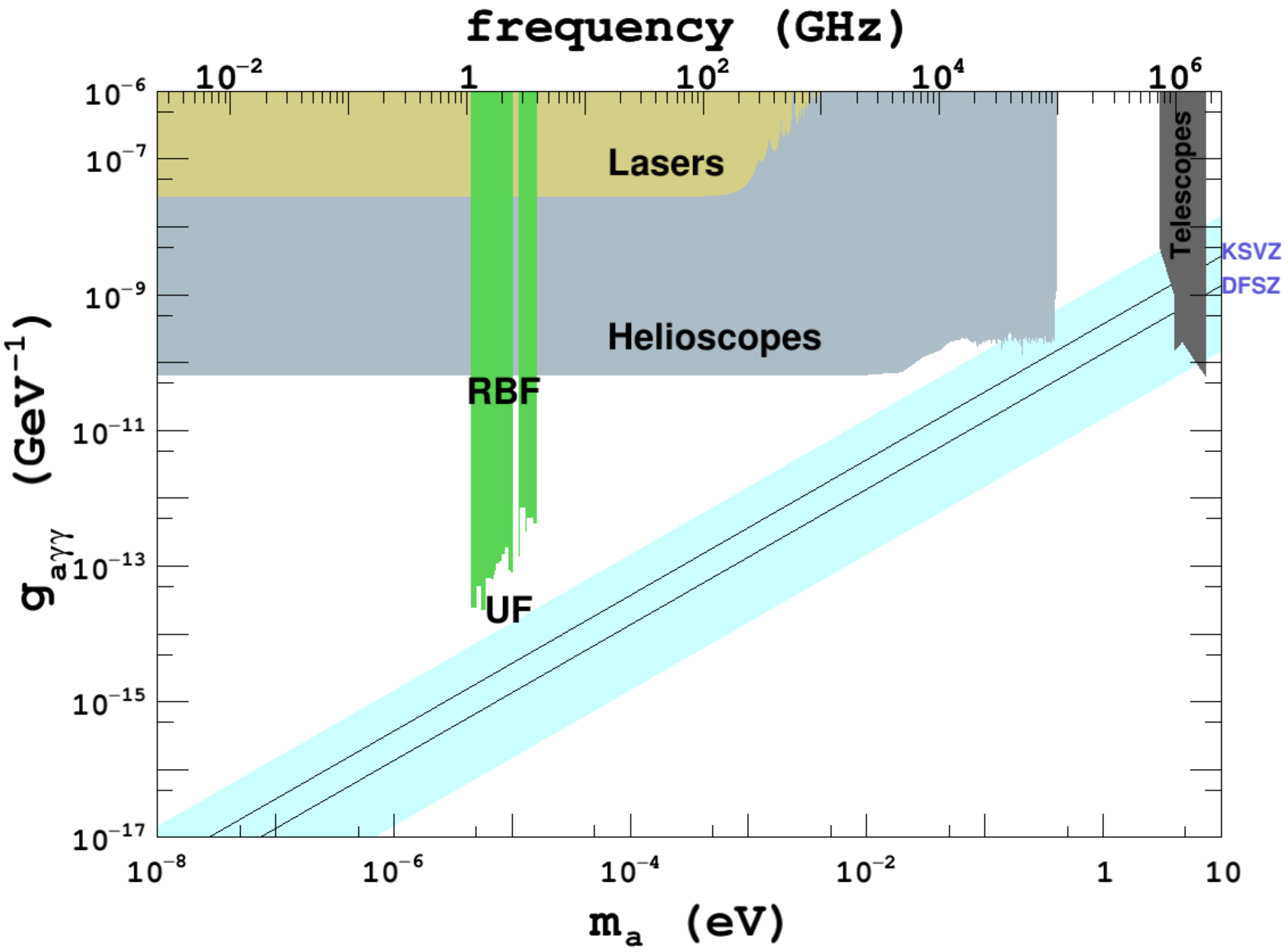
~1.5-liter cavity

8 T magnetic field

12 K total system noise temperature

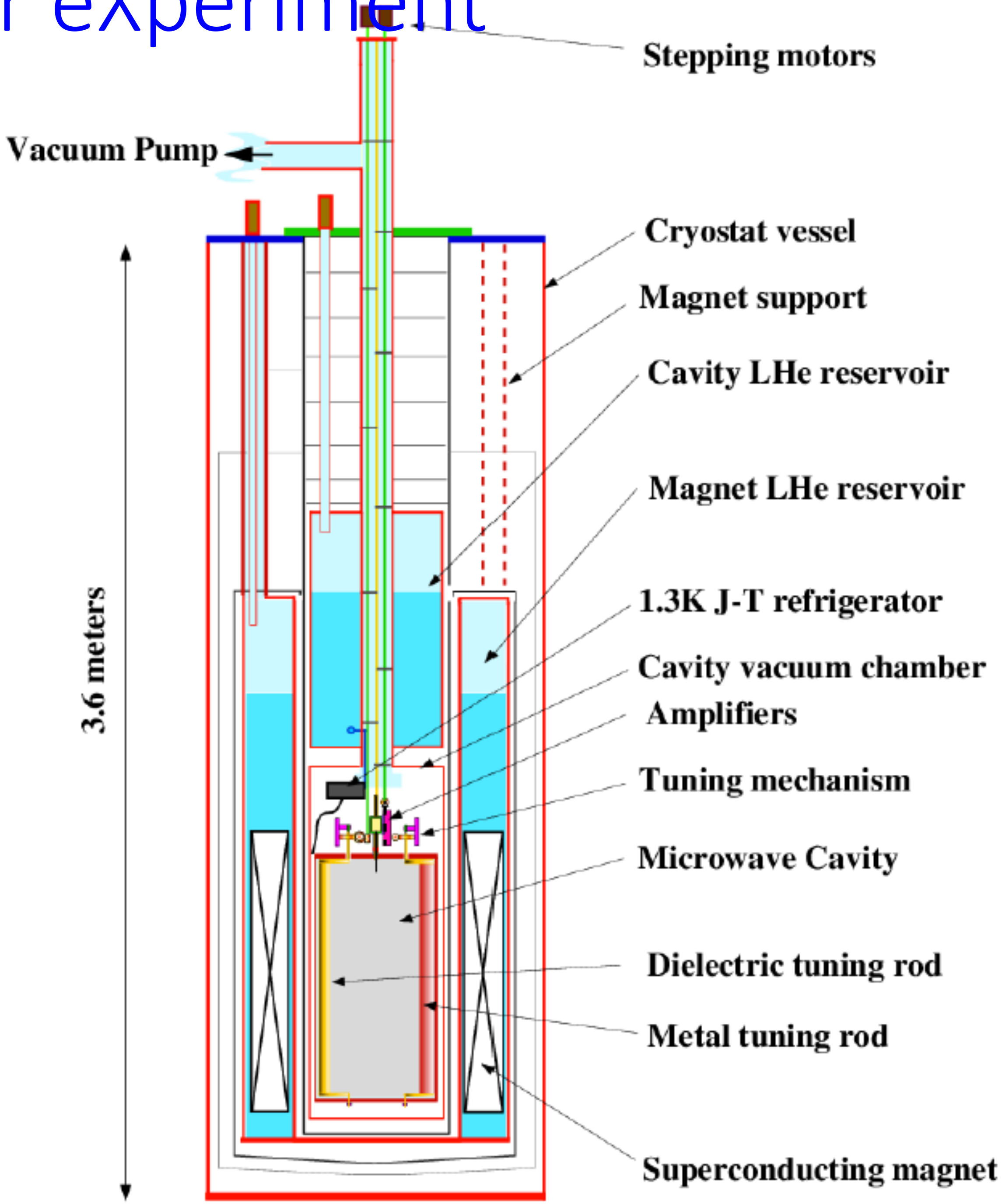
First haloscope limits:
Rochester,
Brookhaven,
Fermilab.

Then
University of
Florida



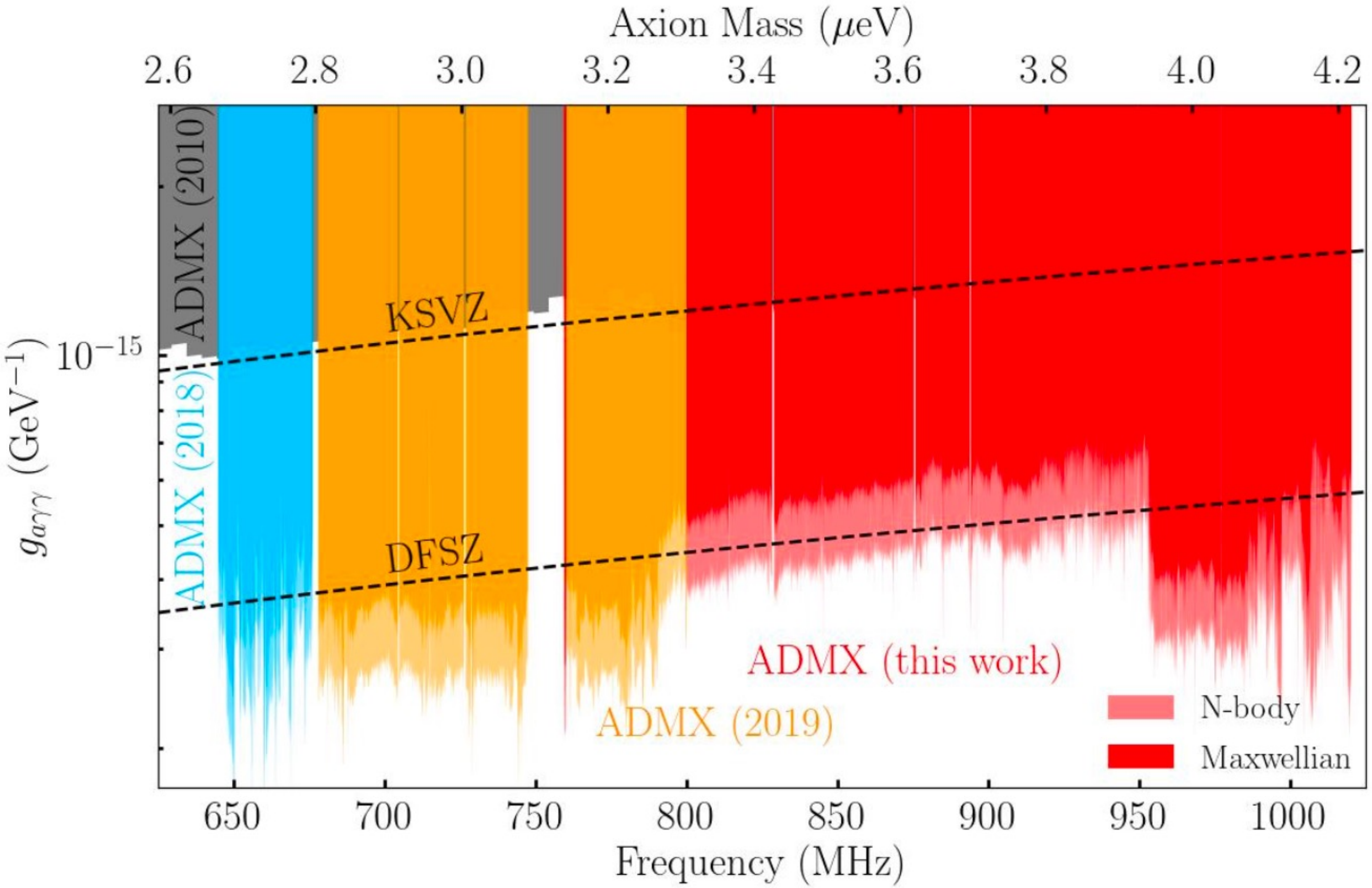
Axion Dark Matter eXperiment

- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity (140*l*)
- Low noise amplifiers
  - From 12K to 1K
  - Currently SQUID and JPA (<1K)



ADMX 2021 Exclusion

Gray Rybka's slide



As we found no axion signals, we can exclude an even wider mass range.

PHYSICAL REVIEW LETTERS **127,** 261803 (2021)

Editors' Suggestion   Featured in Physics

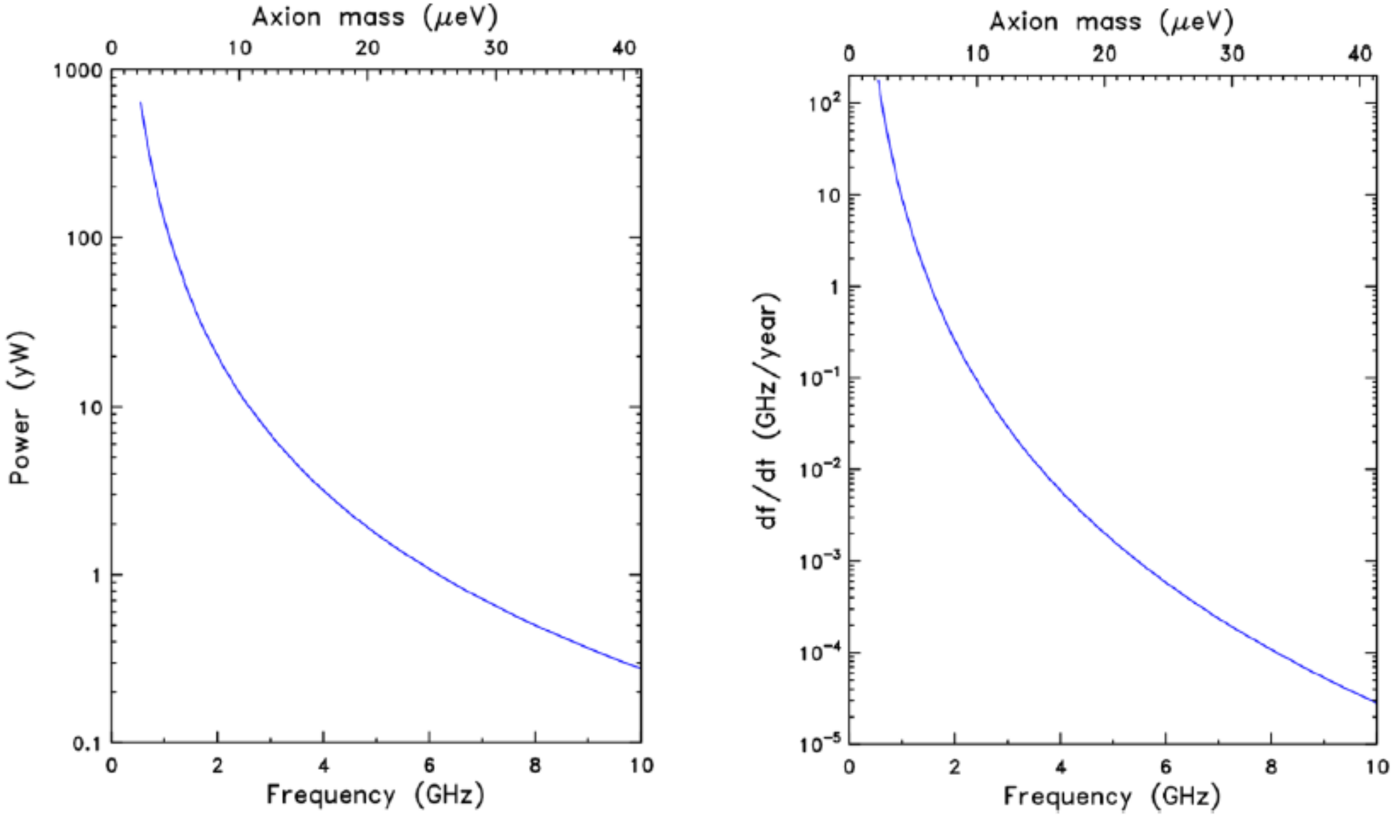
Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range

C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L.J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] S. Jois,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] E. Lentz,[6] R. Khatiwada,[7,4] G. Carosi,[8] N. Robertson,[8] N. Woollett,[8] L. D. Duffy,[9] C. Boutan,[10] M. Jones,[10] B. H. LaRoque,[10] N. S. Oblath,[10] M. S. Taubman,[10] E. J. Daw,[11] M. G. Perry,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. W. Murch,[12] M. Goryachev,[13] B. T. McAllister,[13] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]

(ADMX Collaboration)

David Tanner, Univ. of Florida

Strawman 2: Single cavity



- Power and scan rate decrease as frequency goes up ☹
- Just the opposite of what we want.

Patras 18

State of the art axion haloscopes

The ability to scan fast depends on B-field, Volume, Temperature, and Q_0

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

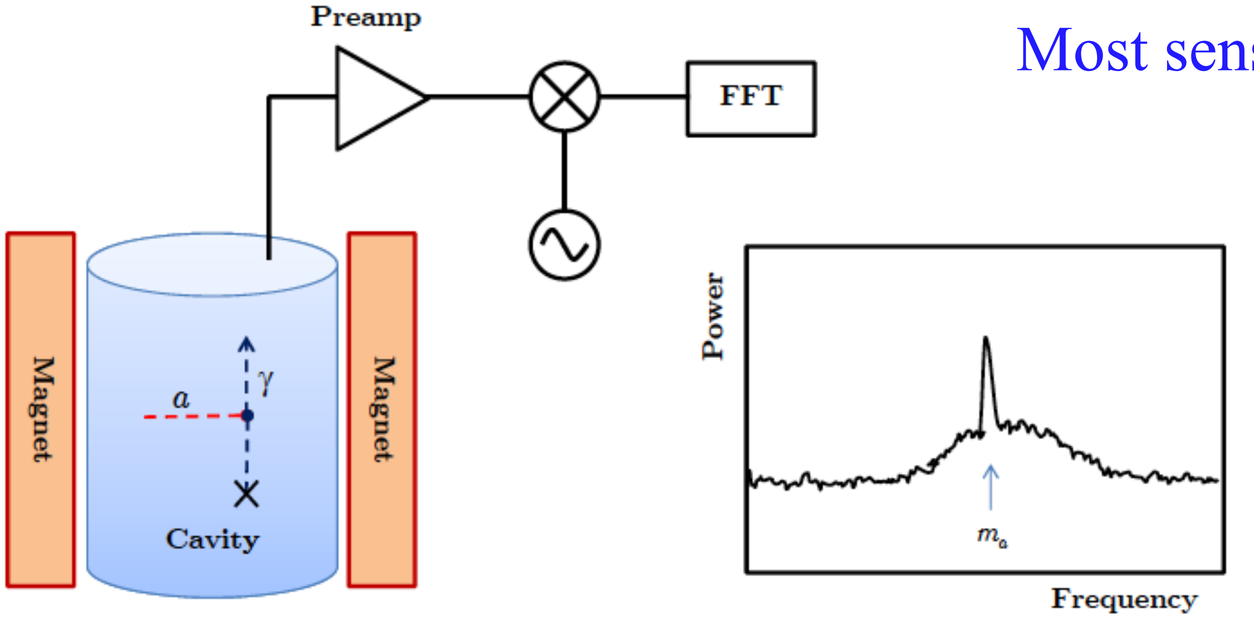


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Most sensitive method

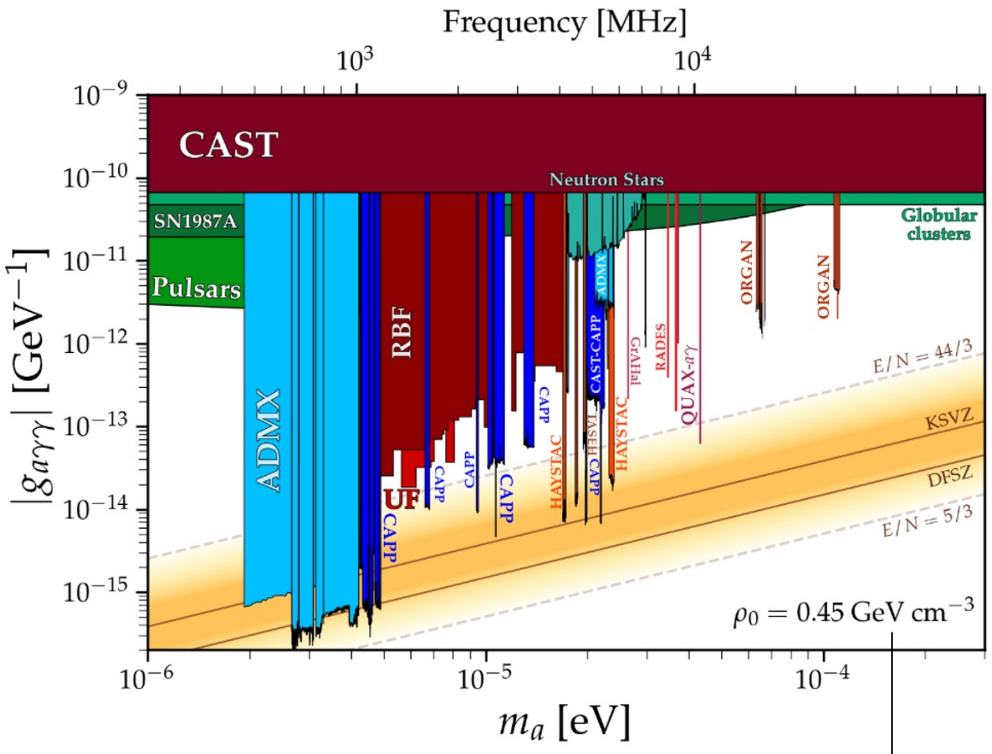
Running Haloscope Experiments:
CAPP
ADMX
HAYSTAC

Limits in medium axion frequencies (up to 2024)

Axion haloscope

Slide by Jiwon Lee,
KAIST, PhD work (ongoing)

- The most sensitive method for searching axion dark matter



https://cajohare.github.io/AxionLimits/docs/ap.html

We have assumed axion makes up 100% of the local dark matter density.

← Exclusion limit of Axion haloscope

- Many experiments (CAPP, ADMX, ...) have been conducted worldwide.

- **Two axion models**

- Kim-Shifman-Vainshtein-Zakharov (**KSVZ**) $g_\gamma = -0.97$
- Dine-Fischler-Srednicki-Zhitnitskii (**DFSZ**) $g_\gamma = 0.36$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Major activities

- ADMX (UW, microwave cavity)
- HAYSTAC (Yale, microwave cavity)
- IBS/CAPP (CULTASK, multiple microwave cavities)
- ORGAN (UWA, high frequency)
- QUAX (INFN, microwave cavity)
- KLASH (Large volume magnet in Frascati, microwave cavity)
- MADMAX (DESY, dielectric interfaces)
- ALPHA (Sweden, plasmonic resonance)
- BabyIAXO (DESY, axion helioscope)
- ALPs (DESY, coupled FP resonators)
- CAST-CAPP (CERN, rectangular cavities-TE modes)
- Dark Matter RADIO

World map of current experiments on wavy dark matter

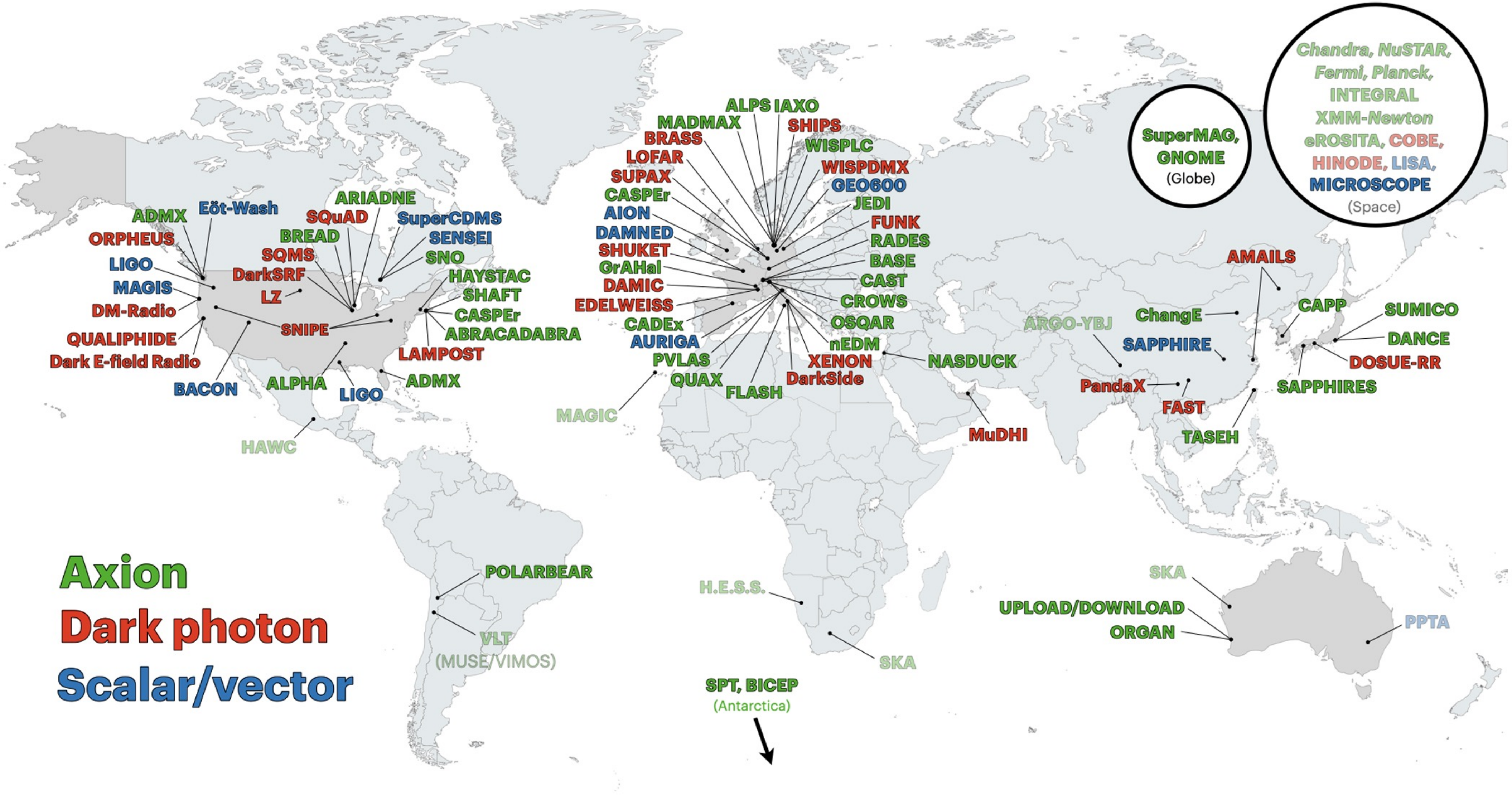


Figure 6: World map displaying current experiments searching for wavy dark matter [9].

There are two major issues with axion research and possibly one solution

- Breakthrough advances are not being openly shared within the community.
- Achieving quantum level sensitivity continues to elude every experiment.

- In order to cover from f_{min}=0.5 GHz to f_{max}=50 GHz and assuming a frequency step of half the axion width (Q_a=10^6) we would need to cover $N = 2Q_a \int_{f_{min}}^{f_{max}} \frac{df}{f} = 2Q_a \ln \frac{f_{max}}{f_{min}} \approx 10^7$ separate steps! (Looking for a radio station in 10million channels.)
- Most current experiments spend/need more than 100s integration time per step for DFSZ sensitivity. That's 30 years at 100% running time efficiency.

- With CARAMEL, we aim to reach better than DFSZ sensitivity with less than 3s integration time per step. A DOE lab can cover the whole region in <5 years, with less than $10M total budget.

Axion dark matter search

- The axion mass is unknown, like any number in a phone book in New York. The way we look for it:

- Once it's discovered, anyone will be able to dial in… and listen to it.

Axion dark matter search

- Once it's discovered, anyone will be able to dial in… and listen to it.

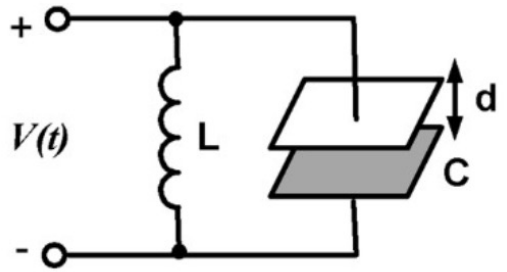
Axion dark matter search

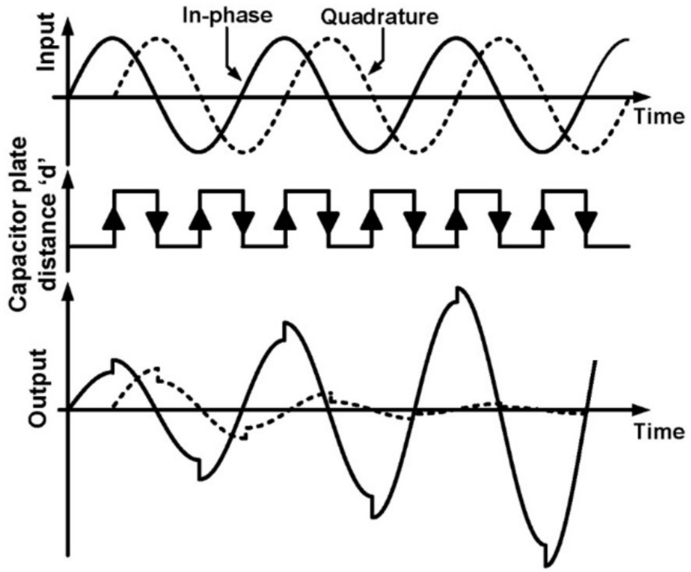
- We need to speed up the dial by developing new, simpler technologies/know-how.

The currently best readout system: Josephson parametric amplifiers (JPA)

JPA Principle

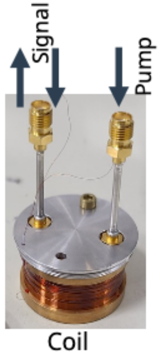
(Caglar Kutlu's slide, Sergey Uchaikin et al.)



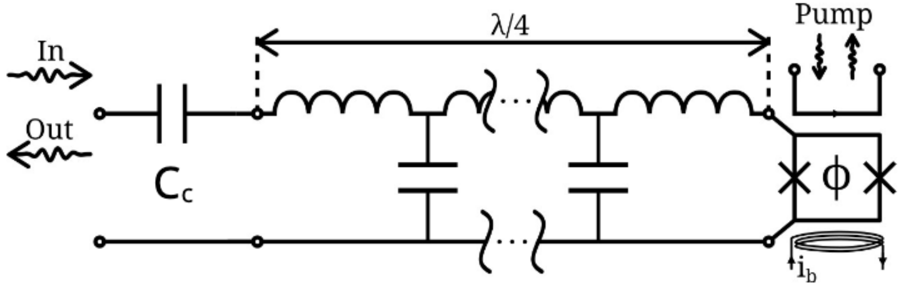


JPA Principle

(no resistors)

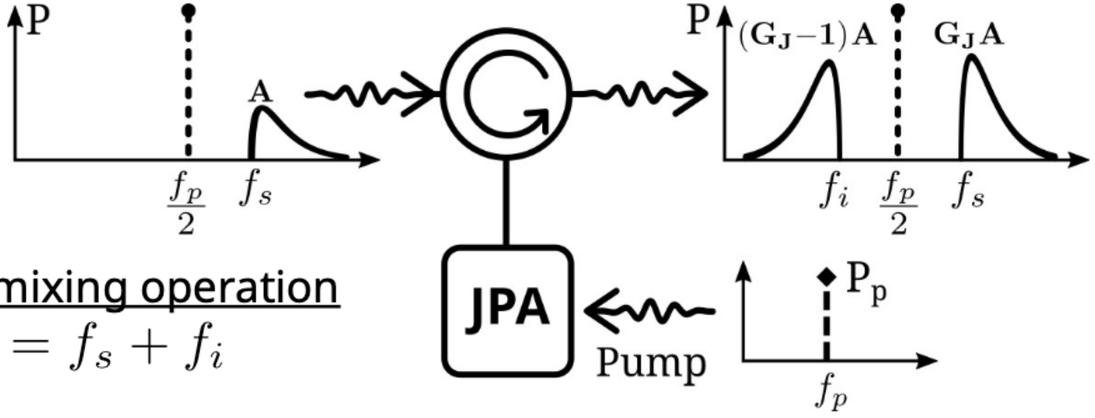


Flux-driven Josephson Parametric Amplifier



$$L_s = \frac{\Phi_0}{2\pi I_c} \frac{1}{\left|\cos\left(\pi \frac{\Phi}{\Phi_0}\right)\right|}$$

- The "parameter" is the effective inductance of the SQUID.
- With $\phi = \phi_{DC}(i_b) + \phi_{AC}(P_p, f_p)$, the ϕ_{DC} controls bare resonance frequency f_r.
- When the pump tone is present, its amplitude P_p, and frequency f_p determine the dynamics of the system for a certain f_r.



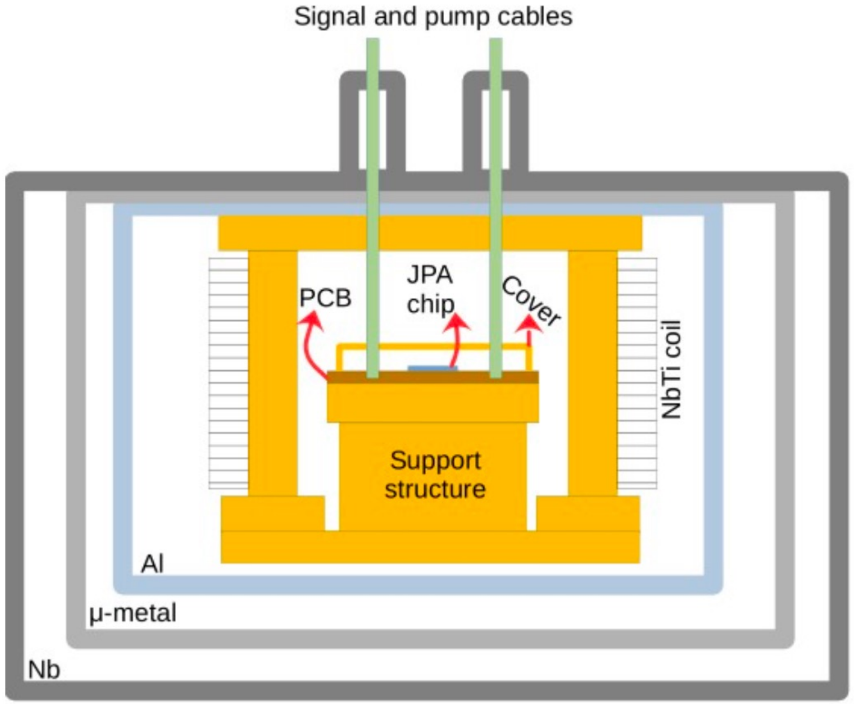
3 wave mixing operation

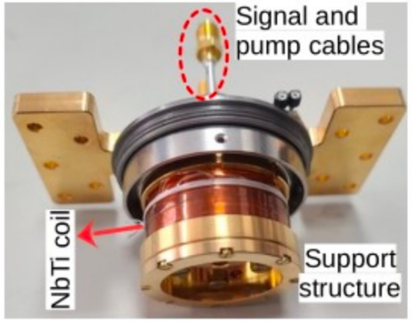
$$f_p = f_s + f_i$$

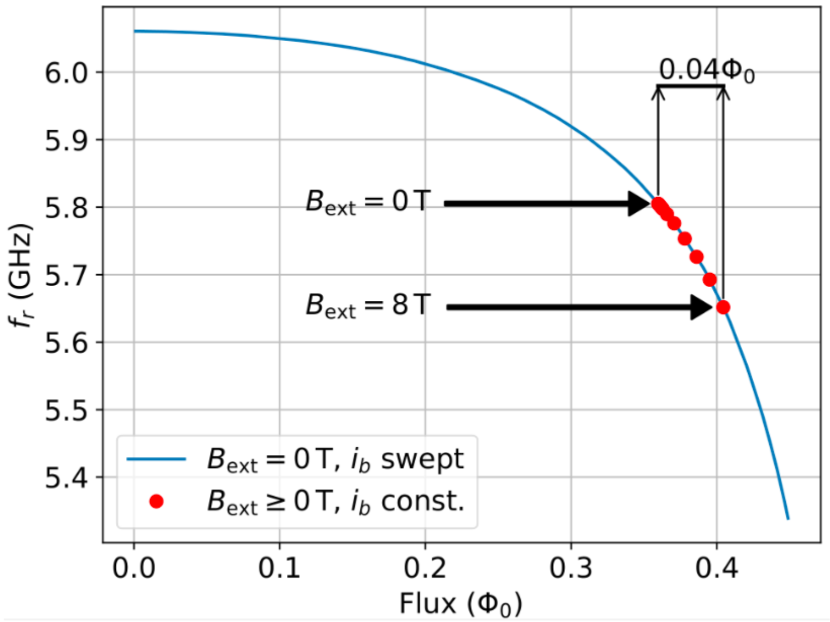
Caglar is now with a quantum computing startup in Switzerland

[1] W. Lee and E. Afshari, "A CMOS Noise-Squeezing Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 2, pp. 329-339, Feb. 2012

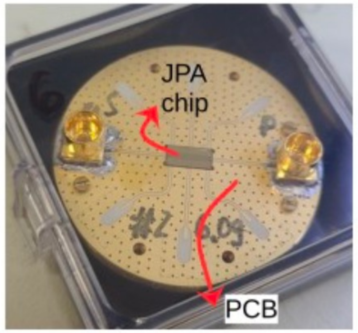
JPA implementation

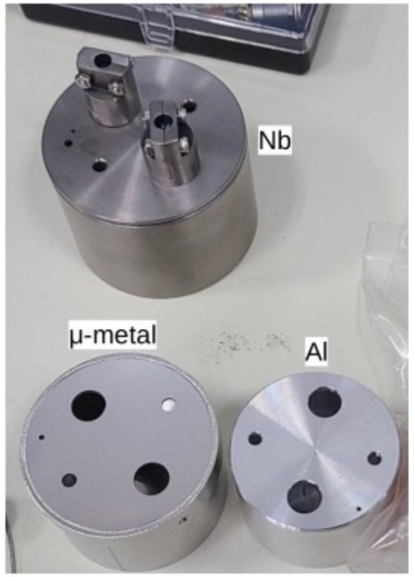




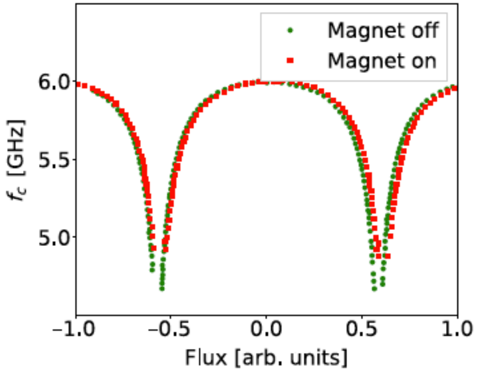


JPA packaging design: Sergey Uchaikin





Caglar Kutlu's slide



Chips designed and manufactured in Univ. of Tokyo (Arjan van Loo)
Packaging and shielding designed by Sergey Uchaikin (CAPP)

RIKEN QUANTUM COMPUTING

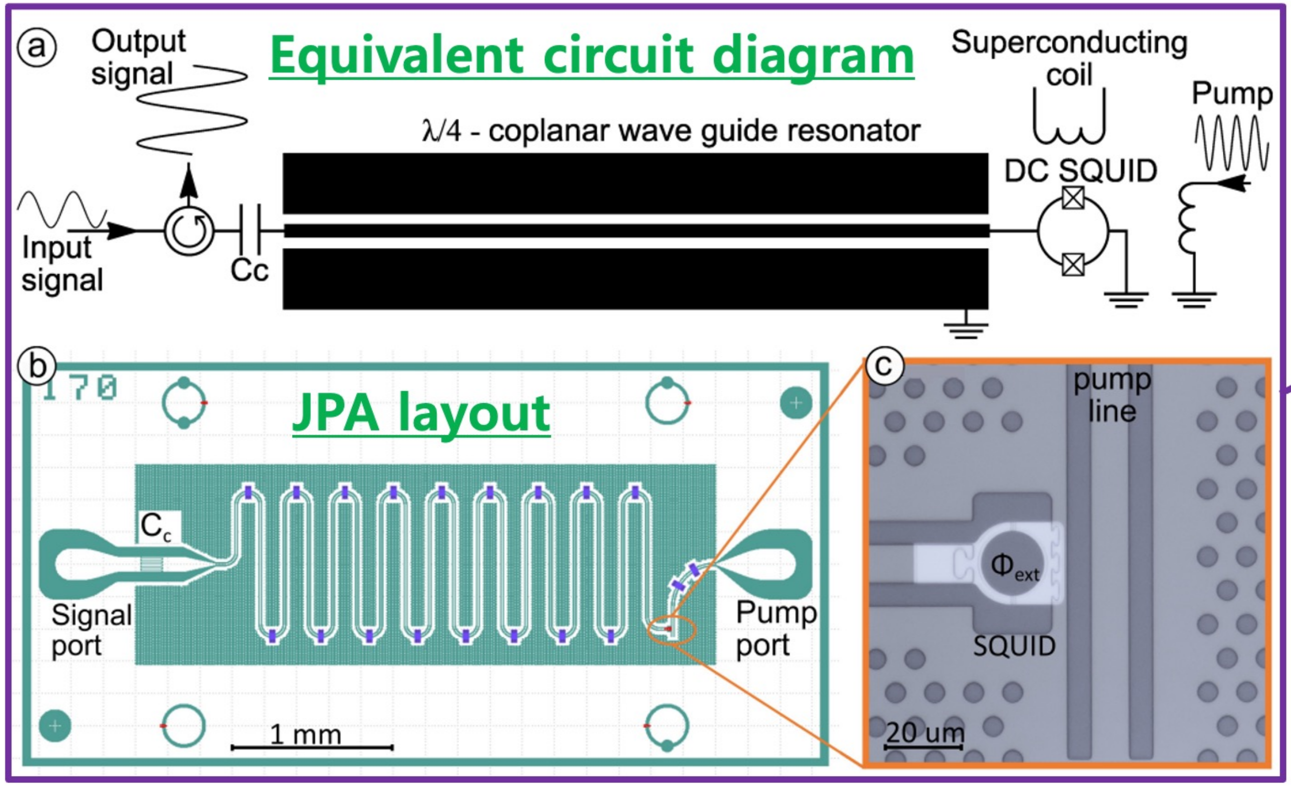
Collaboration with Yasunobu Nakamura
They made chips and IBS-CAPP packed them.

Flux-driven Josephson Parametric Amplifier

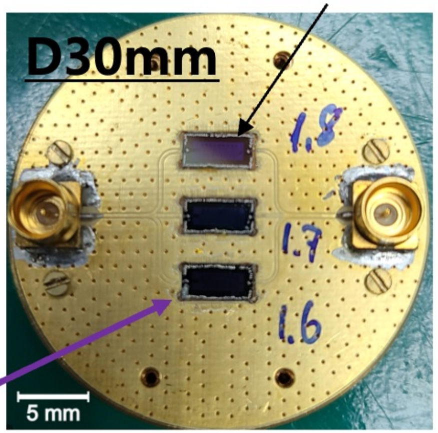
Uchaikin, et al, "Josephson Parametric Amplifier based Quantum Noise Limited Amplifier Development for Axion Search Experiments in CAPP," Frontiers in Physics **12**, 1437680 (2022).

Quantum noise limited amplifier

☒: Josephson junction

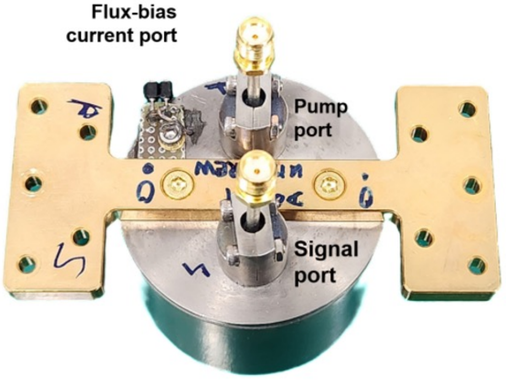


$\mathbf{2.5 \times 5\ mm^2}$



Jiwon Lee's slide

Top view of the gold-plated PCB with JPA chips bonded.



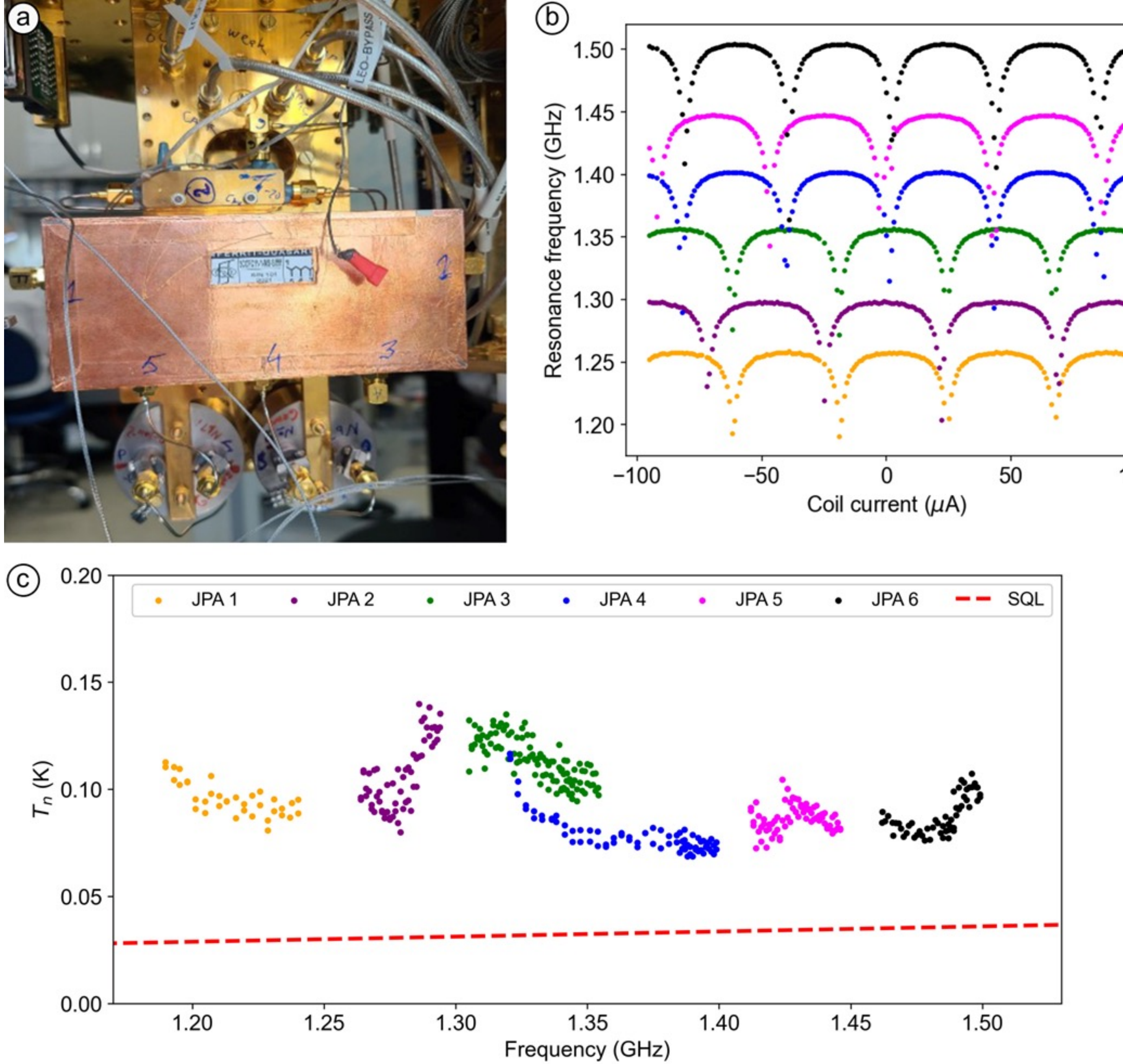
The assembly with the SMA connectors

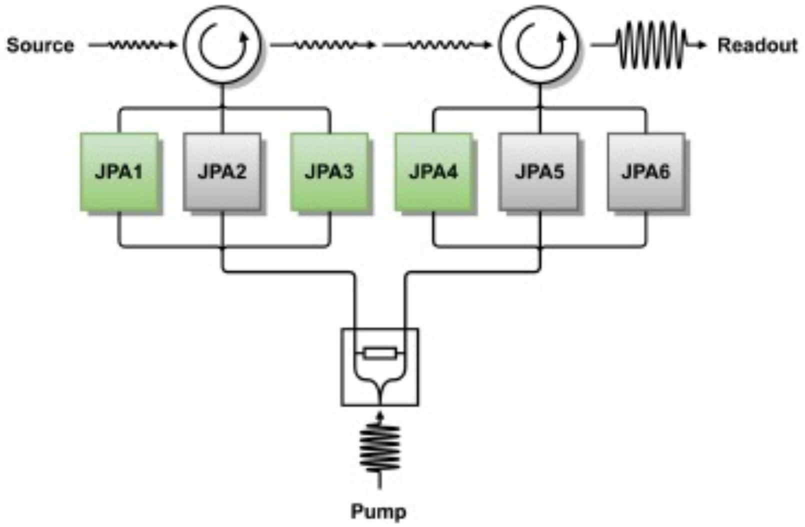
CAPP-MAX, JPA-bundle development testing

Added system noise (JPA+ HEMT noise).

Chips by Tokyo (Nakamura et al.)

Development at CAPP: Sergey Uchaikin et al.

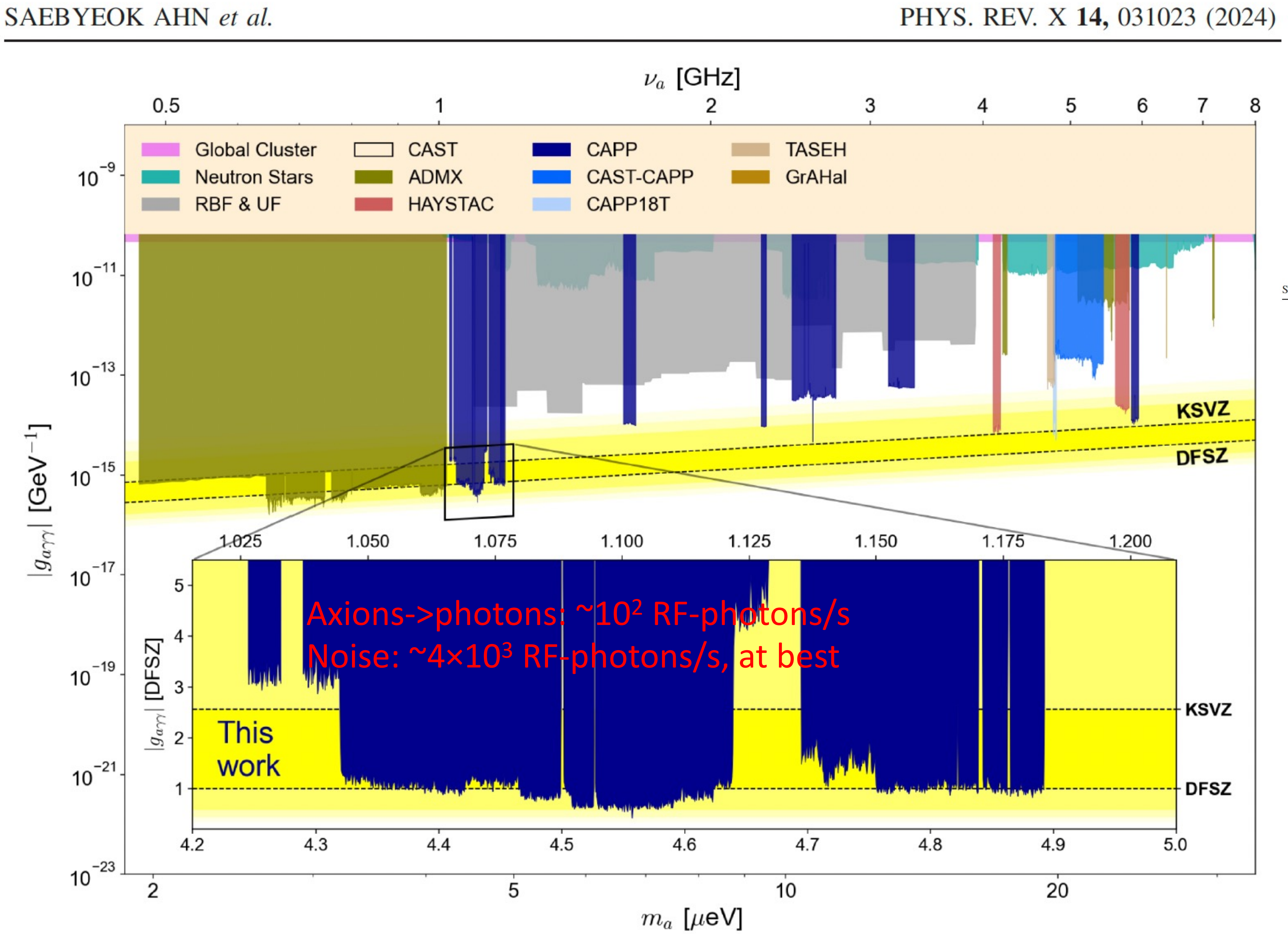




(b)

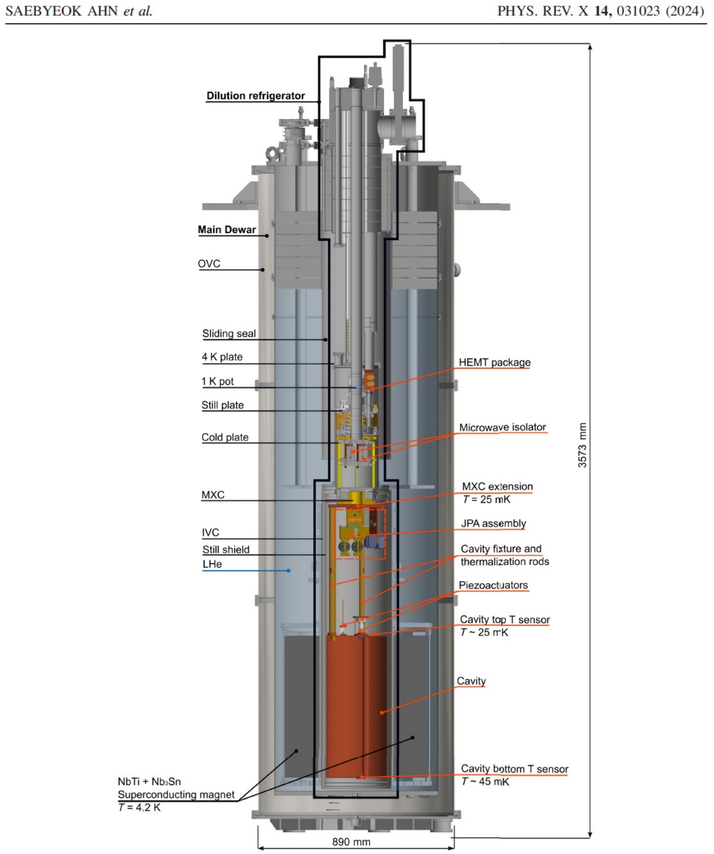
Combining JPAs to achieve high sensitivity in 1.2 - 1.5 GHz, running at low temperature <30mK

IBS-CAPP at DFSZ sensitivity, scanning 1-4 GHz



S. Ahn et al., PRX (2024) from CAPP.

A 32 page reference paper on how to achieve DFSZ sensitivity.



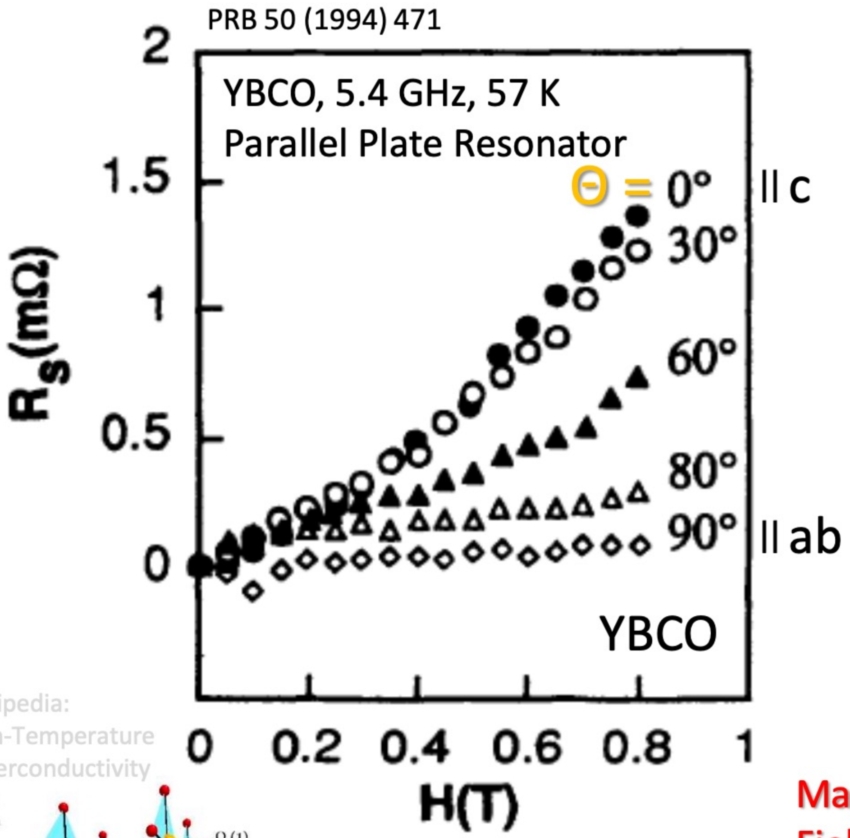
The best JPAs today

- Their average noise is between 3-5 times the quantum noise level
- Their frequency BW is limited, and they are labor intensive
- Require < 50mK cooling for best performance (at CAPP we had a best physical temp. ~22mK, with more common 25-40mK). The total system noise was ~220mK, requiring >100 s of integration time over the axion BW.

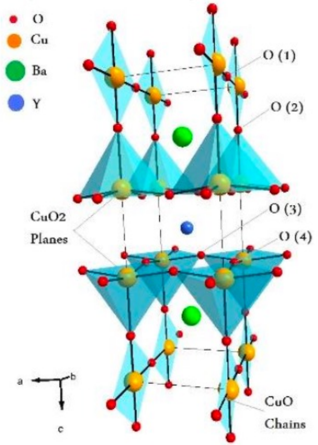
Cavities made of High Temperature Superconducting (HTS) tapes

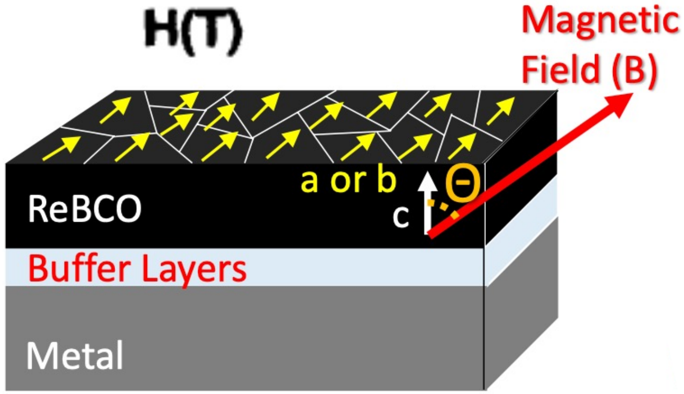
Biaxially Textured ReBCO Tape

Danho Ahn's slide



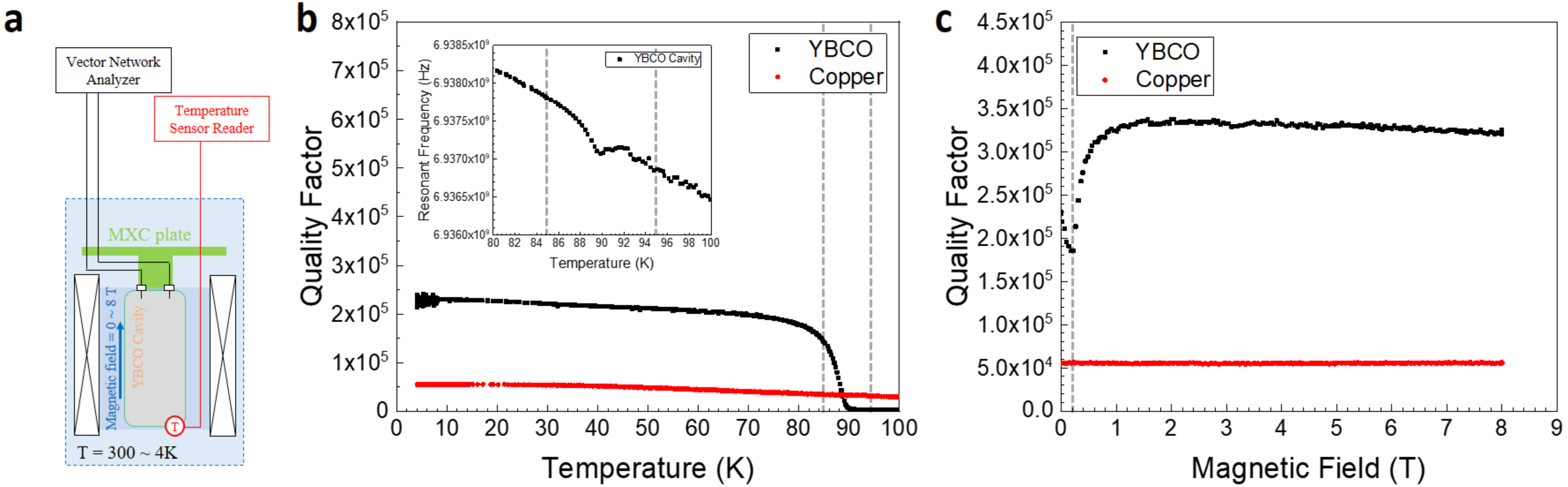
Wikipedia:
High-Temperature
Superconductivity





- Biaxially-Textured ReBCO films have anisotropy of surface resistance due to their crystal structure.
- The surface resistance of a film is maximized when the c axis of a crystal and the direction of an external magnetic field is parallel to each other.
- Directions of a ReBCO crystal should be considered to design a cavity.

HTS superconducting cavity in large B-field!



First and best in the world!

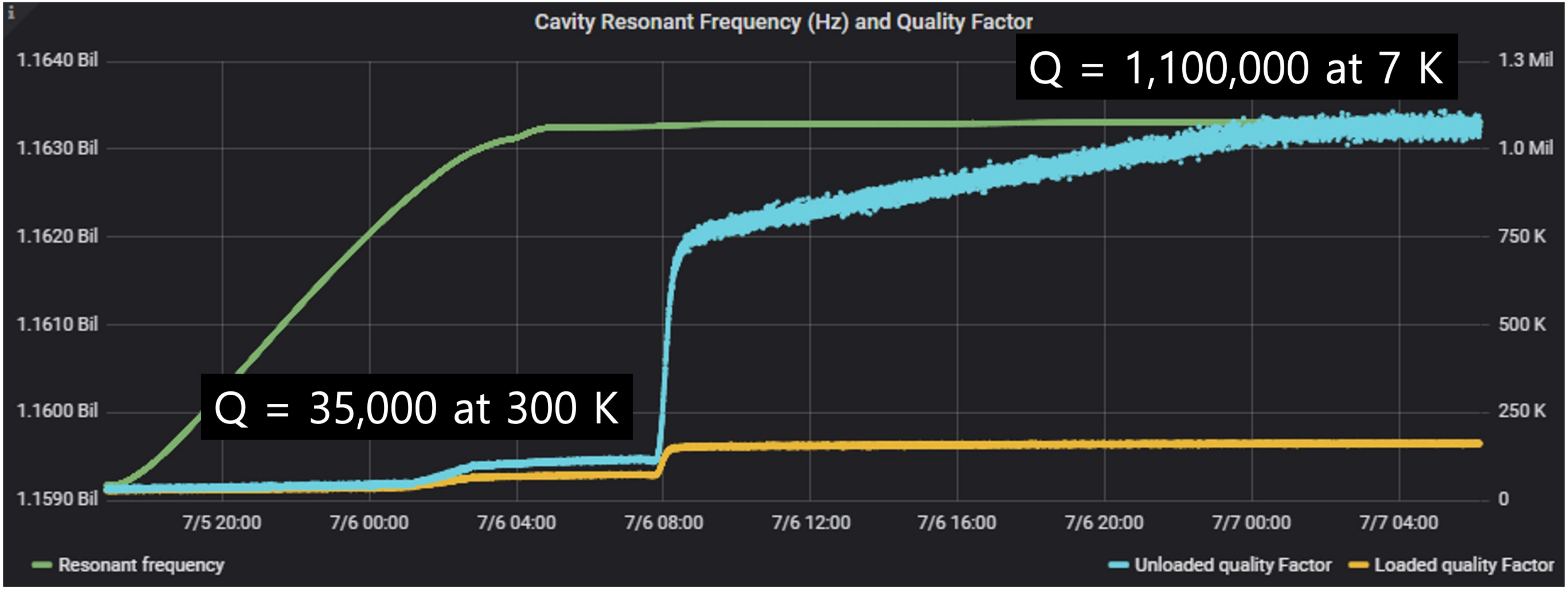
Phys. Rev. Applied **17**, L061005 – Published 28 June 2022

CAPP summer 2024, unique achievement, 34 liter cavity!

Full-HTS-ULC fabrication process

RF measurement w/ HTS tuning rod

Jiwon Lee's slide



Institute for Basic Science, 2011:
Major Investment to Basic Sciences in South Korea.

- IBS-CAPP (est. 2013) scanned at DFSZ sensitivity for axions over 1 GHz in 2022, first time in the world.

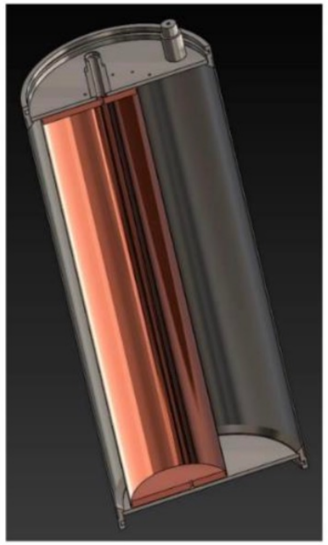
- Since summer 2024, a 34liter HTS cavity in 12T, with better than DFSZ sensitivity and able for >3MHz/day scanning rate.

- IBS-CAPP is now operating under another name: IBS-DMAG using the same equipment, same location at KAIST and same axion science program.

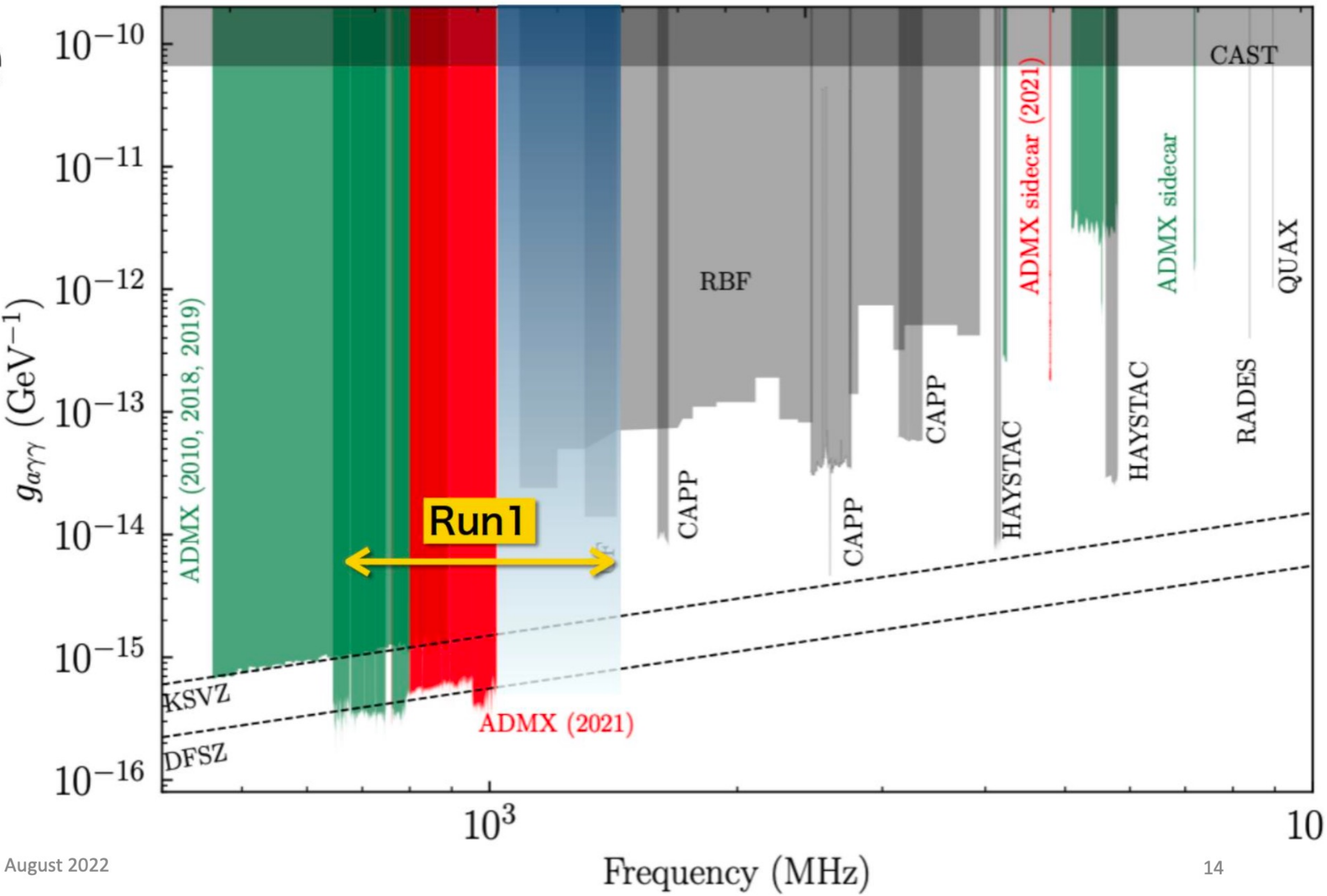
Photo: KAIST Munji Campus, January 2023

ADMX plan

Future Plans



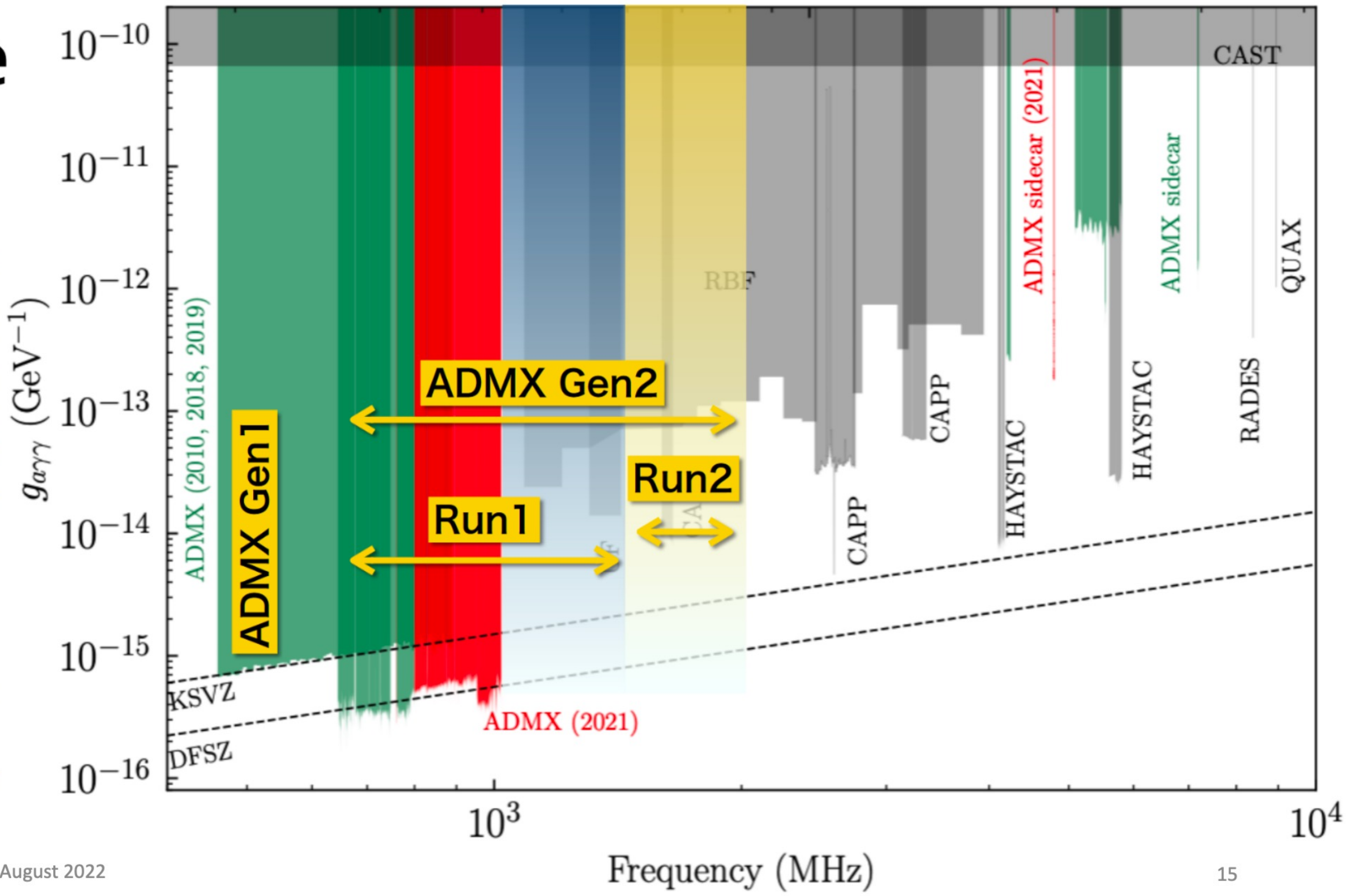
Bigger tuning rod



ADMX plan

Future Plans

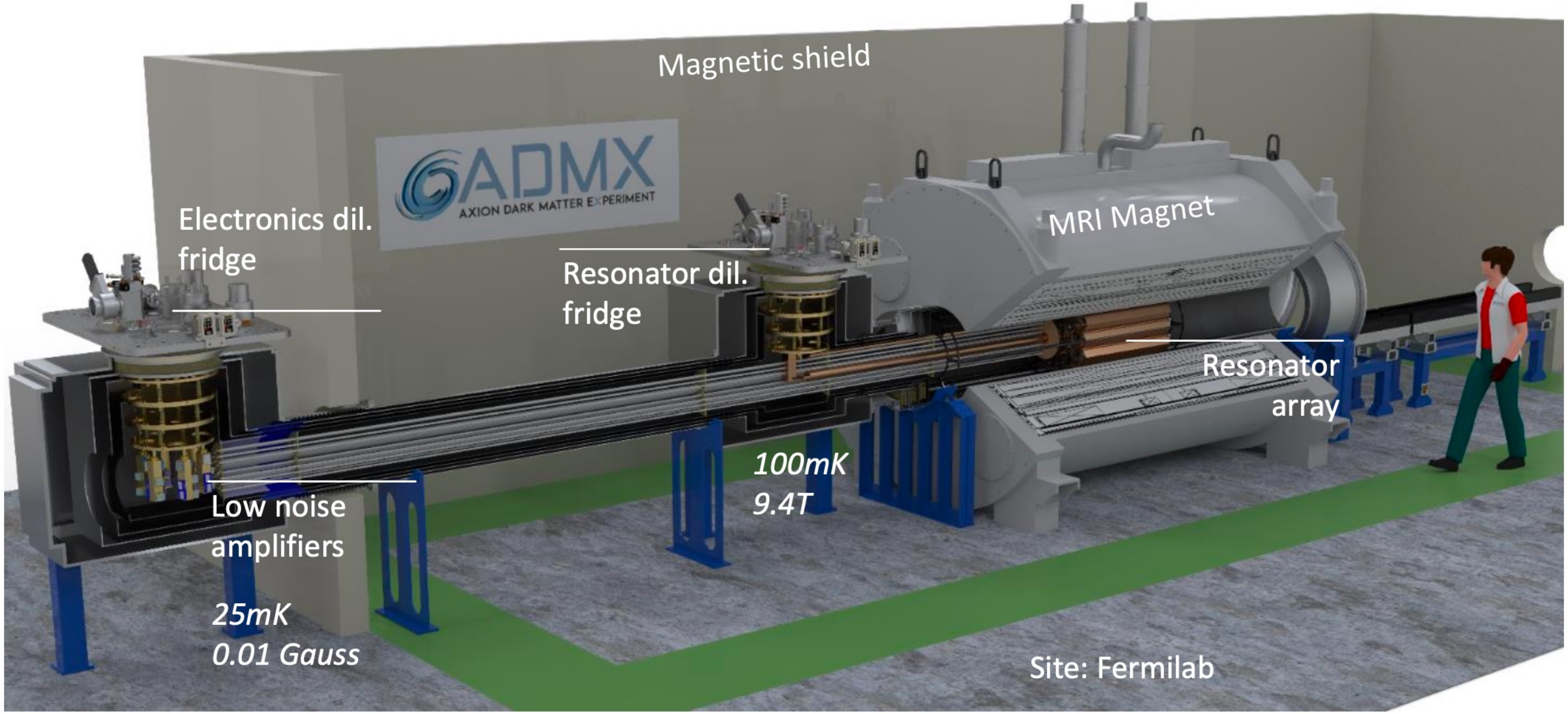
4-cavity array



ADMX: Rybka, August 2022

ADMX-EFR – Design Overview

Large-volume MRI magnet moved to Fermilab



~ 5 × scan speed of current ADMX

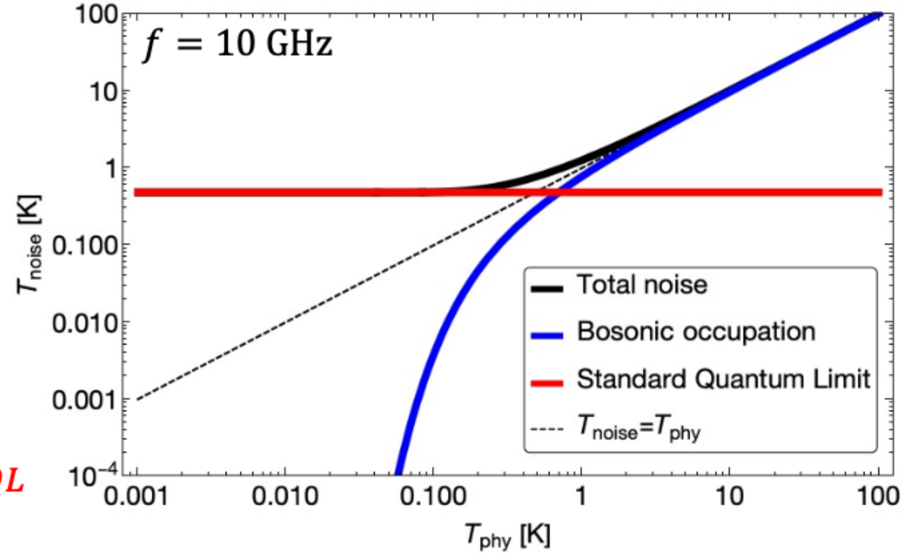
Equivalent noise temperature

Slide by SungWoo Youn

Noise contributions

$$T_{sys} = \frac{hf}{k_B}\left(\frac{1}{\exp\left[\frac{hf}{k_B T_{phy}}\right]-1} + \frac{1}{2} + \frac{G^2-1}{2G^2}\right)$$

- Thermal noise: bosonic occupation
- Zero-point fluctuations
- Minimum added noise



Standard quantum limit (SQL)

- Unavoidable limit by linear amplifiers

$$T_{sys} \geq \frac{hf}{k_B}\left(\frac{1}{2} + \frac{G^2-1}{2G^2}\right) \gtrsim \frac{hf}{k_B} \equiv T_{SQL}$$

- Predominant at high frequencies

1. The uncertainty principle limits the lowest equivalent electronic noise of the system (quantum noise limited amplifiers). Single photon detectors (in blue) would be perfect, but they are still far away from competing.

Single RF-photon detector!

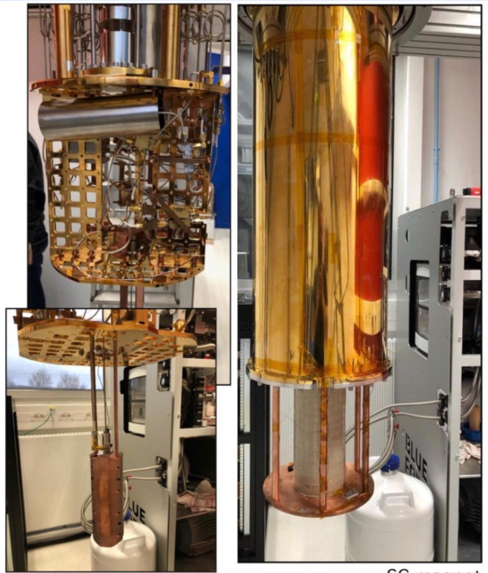
- A dream come true:
  - Lescanne et al., PRX (2020)
  - Albertinale et al., Nature (2021)
  - Wang et al., Nature (2023)

- Qubits or bolometers combined with HTS cavities pave the path to the high frequency. It's getting very close to a major running system.

QUAX experiment in Italy

Significant progress in single photon detection

Single Photon Detection – First Test @ Saclay

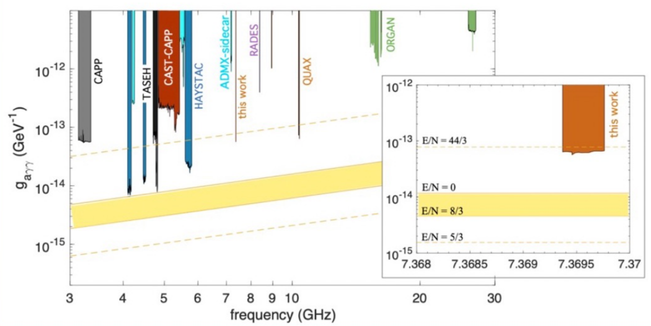


SMPD (top) and cavity

SC magnet

- hybrid (normal-superconducting) cavity 7.37 GHz, tunable, $Q_0 = 9 \times 10^5$
- T=14 mK delfridge base temperature @ Quantronics lab (CEA, Saclay)
- 2 T-field
- triplet of rods controlled by a nanopositioner mounted at the MC stage to probe for different axion masses
- passive protection by the B-field for SMPD and TWPA

- Developed a dedicated protocol
- Dark count at the 100 Hz level
- System stability up to 10 minutes



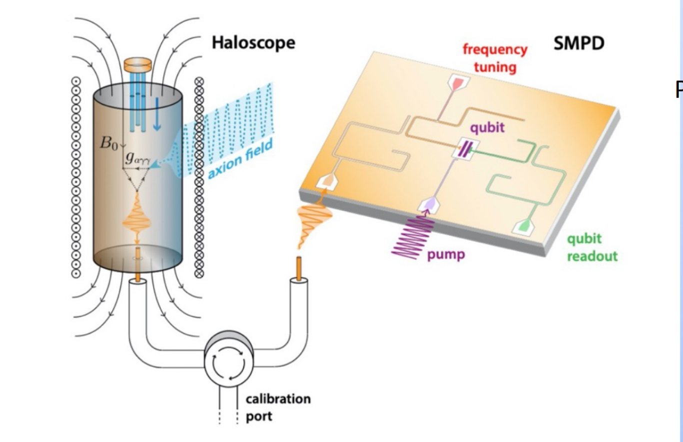
https://arxiv.org/abs/2403.02321

20 Times faster then SQL based Amplifier with a Dark Count @ 10 Hz (new Devices) 100

Next Generation Haloscope – Single Photon Detection

Joint effort between QUAX (LNL, PD), Padova Dept. of Excellence, SQMS, Quantronics Group Saclay

Single Microwave Photon Detector (SMPD) as haloscope receiver



Linear amplifier irreducible limit
Standard Quantum Limit

$$P_{\mathrm{SQL}} = h\nu_a \sqrt{\Delta\nu_a / t}$$

$$\mathrm{SNR}_{\mathrm{SQL}} = \frac{P_a}{h\nu_a}\sqrt{\frac{t}{\Delta\nu_a}}$$

Photon Counter PC limited by **dark count** Γ_{DC} rate and **efficiency** η

$$\mathrm{SNR}_{\mathrm{PC}} \approx \frac{\eta P_a}{h\nu_a}\sqrt{\frac{t}{\Gamma_{\mathrm{dc}}}}$$

Improvement in scanning speed with SMPD

$$\eta^2 \frac{\Delta\nu_a}{\Gamma_{\mathrm{dc}}}$$

From Lattice QCD and requiring axions as dark matter the preferred mass range is: 40-180 μeV

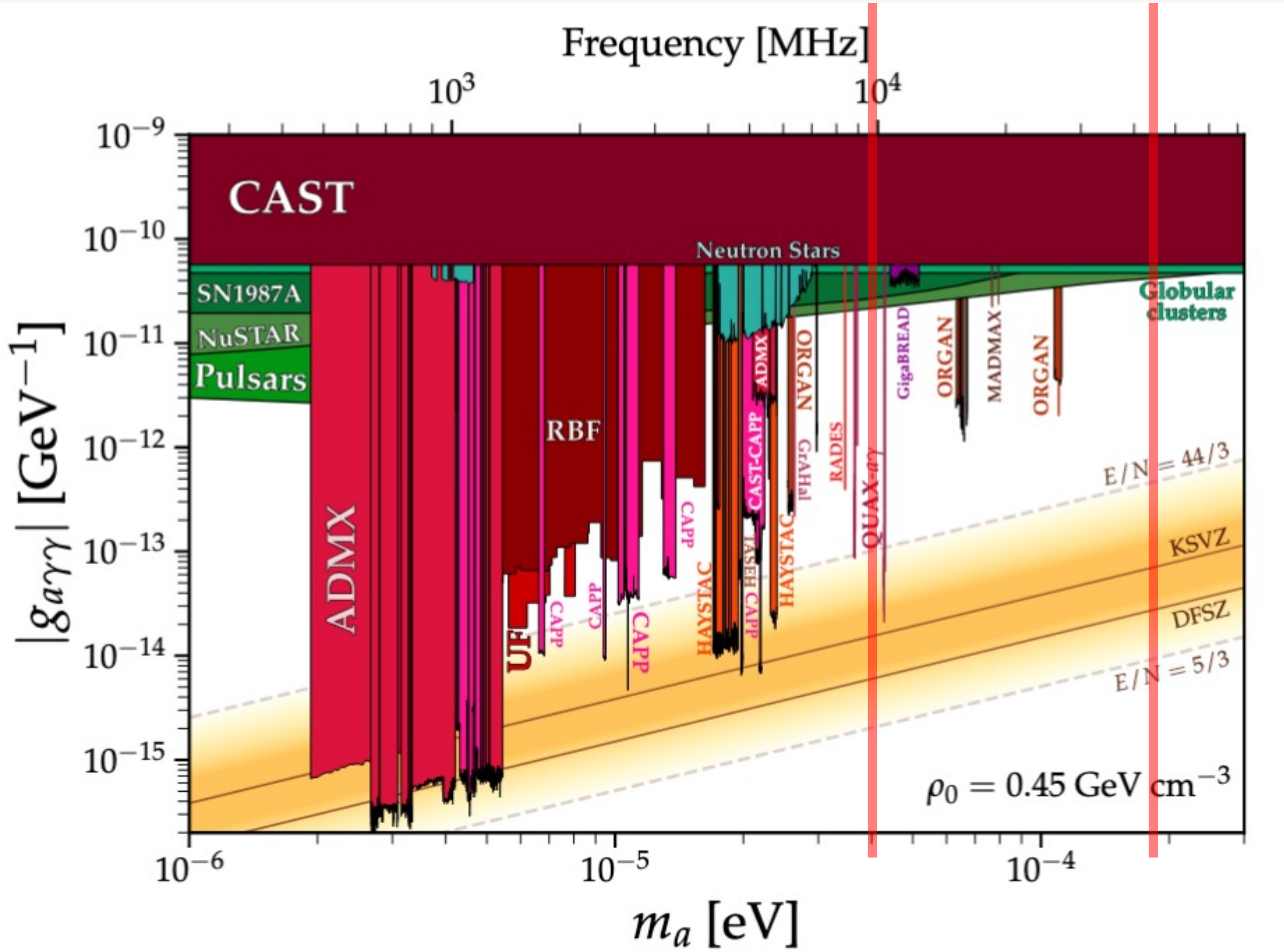


FIG. 1: The current status of the axion to two photon coupling in the mass range 1-300 μeV, corresponding to the frequency range 0.2-70 GHz (from Ref. [23]). CARAMEL aims to facilitate probing the frequency range of 0.5-50 GHz, or ~ (2-200) μeV, with better than DFSZ sensitivity within the next five years. CARAMEL can potentially cover the preferred post-inflationary parameter space, corresponding to 40-180 μeV [17], at better than DFSZ sensitivity, using presently available technical capabilities.

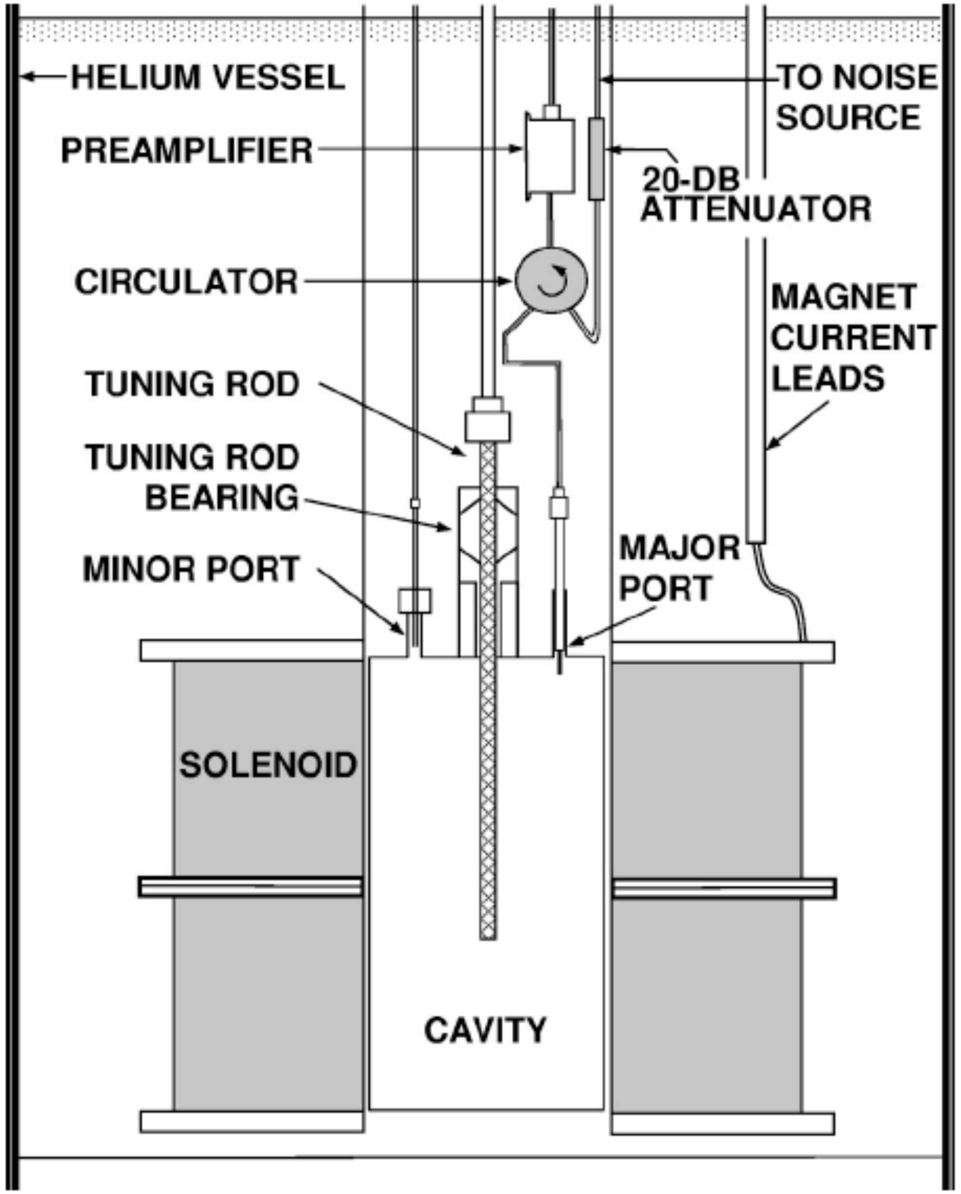
Prospects of scanning the whole axion frequency range

- With current methods we are still looking at several decades before scanning the viable axion frequency (unless it is found sooner out of shear luck).

- With CARAMEL we aim to achieve DFSZ sensitivity in the 40-180 μeV (10-45 GHz) range with a year's running time.

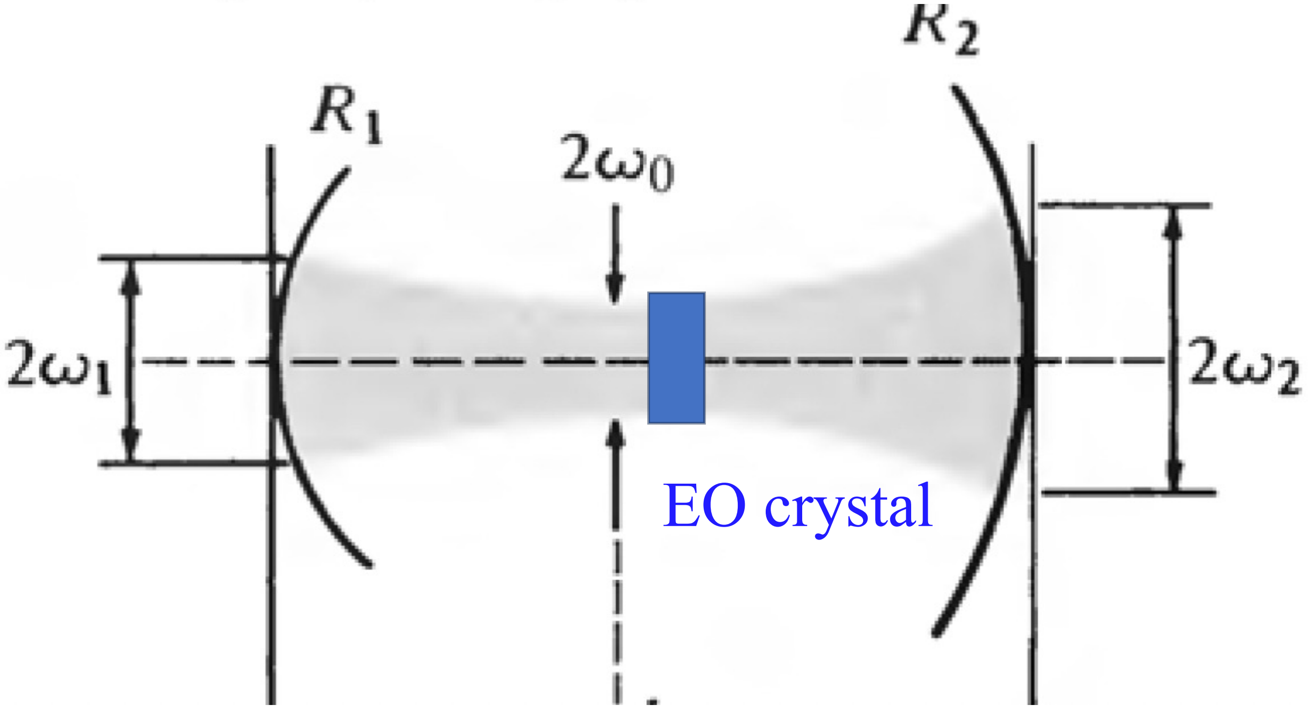
Electro optic detection of the axion induced electric field in microwave cavity

Electro optic (EO) readout using a Fabry Perot resonator plus heterodyning (probing, PRD 107, 103005 (2023)).



Parameter	Value
Laser Power	10 mW
Laser Wavelength	1064 nm
RF Probe Power	2 nW
Microwave Cavity Quality Factor Q_c	10^4
Axion-to-Photon Reference Power P_a ($Q_c = 10^4$)	10^{-23} W
Microwave Cavity Volume	3.7 L
Fabry-Pérot Finesse $\mathcal{F}$	10^4
EO Crystal ($LiNbO_3$) Thickness L	3 mm

TABLE I: Benchmark parameters assumed in this work, for the $\nu_a \sim O(10\text{ GHz})$ regime.



EO measurement using a Fabry-Perot resonator alone

The basis of our proposal is the use of the EO effect, where an electric field $E \equiv |\vec{E}|$ leads to induced ellipticity ψ in a laser beam of wavelength λ (Pockels effect [44, 45]). We have

$$\psi = \frac{\pi}{\lambda} n^3 r_{ij} \, E \, L \,, \qquad (1)$$

where n is refractive index of the EO crystal, r_{ij} is assumed to be the largest element of the EO coefficient tensor, and L is the length of the crystal through which the laser propagates.

$$U_E = \frac{1}{2}\epsilon_0 V E_a^2 = \frac{U}{2} = \frac{P_a Q_c}{2\omega}, \qquad (6)$$

where E_a is the root-mean-square electric field, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the vacuum permittivity, and V is the cavity volume. Solving for E_a we get

$$E_a = \sqrt{\frac{P_a Q_c}{\omega \epsilon_0 V}}, \qquad (7)$$

We will consider using lithium niobate, $LiNbO_3$, of size $L = 3$ mm, as our EO crystal, for which $n \approx 2.2$ and $r_{33} \approx 3.1 \times 10^{-11}$m/V. Let us take $f = 10$ GHz as a representative value. We will consider the benchmark values $P_a = 10^{-23}$ W and $Q_c = 10^4$ for the chosen value of f above. From Eqs.(1) and (7), we get $E_a \approx 7.0 \times 10^{-9}$ V/m and $\psi_a \approx 2 \times 10^{-14}$ rad.

1. Axion induced electric field oscillation amplitude (for Q_c=10^4): E_a=7nV/m.
2. Ellipticity induced for a single pass $\psi \sim 2\times10^{-14}$ rad
3. With a Fabry-Perot and 10^4 finesse $\psi_{FP} \sim 1.3\times10^{-10}$ rad. Laser shot noise: $\psi_{LSN} \sim 3.5\times10^{-9}$ rad (3s integration time)
4. Not quite enough. We can do better…

EO measurement using a Fabry-Perot plus heterodyning (probing)

The axion field is coherent for ~0.1ms, while the laser noise is incoherent.

Next, we will examine implementing the probing method to provide a feasible detection approach, without FP enhancement. We will consider an injected RF power $P = 2\,\mathrm{nW} = 2 \times 10^{-9}$ W. The electric field amplitude, for $\omega = 2\pi \times 10^{10}$ rad Hz, is:

$$E_{\rm probe} = \sqrt{\frac{Q_c P}{\epsilon_0 V \omega}} \approx 0.1\,\mathrm{V/m} \qquad (13)$$

In the probing method, we are interested in detecting the fluctuations of the ellipticity, which are enhanced by the RF injected power. To see this, we note that the total electric field in the cavity is given by

$$E(t) = E_{\rm probe}\cos(\omega t) + E_a \cos(\omega t + \phi(t)), \qquad (14)$$

where $\phi(t)$ is the time-dependent relative phase between the two fields.

The axion field is not perfectly monochromatic; it has a finite spectral width $\Delta\nu_a \sim 10^{-6}\nu$ due to the virialized velocity dispersion of dark matter in the galactic halo. At $\nu = 10\,\mathrm{GHz}$, this corresponds to $\Delta\nu_a \sim 10\mathrm{kHz}$ and a coherence time of

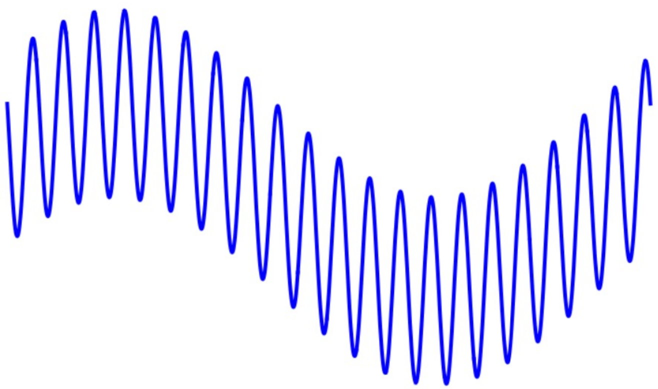
$$\tau_a \sim \frac{1}{\Delta\nu_a} \sim 0.1\,\mathrm{ms}. \qquad (15)$$

Over timescales shorter than τ_a, the axion field behaves like a coherent wave with a well-defined phase. Over longer timescales, this phase $\phi(t)$ drifts randomly, reflecting the stochastic nature of the axion field.

In the probing method, one is interested in measuring the variance of the ellipticity

$$\langle\psi^2\rangle \propto \frac{1}{2}\left[E_{\rm probe}^2 + E_a^2 + 2E_{\rm probe}E_a\langle\cos(\phi(t))\rangle\right], \qquad (16)$$

where $\langle\cos(\phi(t))\rangle$ vanishes over many coherence times, but the variance of the fluctuations is nonzero. To cap-



Heterodyne-variance method, Omarov, Jeong, YkS: PRD107, 103005 (2023)

Injecting photons into the microwave cavity can enhance the axion detection rate

System Noise Temperature

Adapted from Junu Jeong's slides

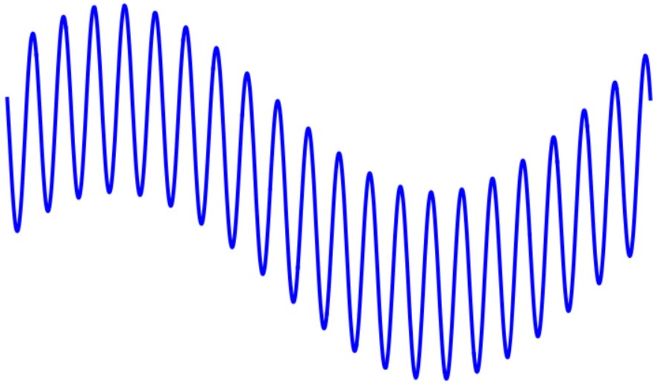
- **Noise Sources**

$$T_{\text{sys}} = \boxed{T_{\text{thermal}}} + \boxed{T_{\text{amplifier}}} = \frac{hf}{k_B}\left(\frac{1}{\exp[hf/k_B T_{\text{phy}}]-1}+\frac{1}{2}\right) + T_{\text{amplifier}}$$

Shot noise (Randomness of Amplification)

Bosonic statistics + Zero-point fluctuation

Dilution Refrigerator sufficiently reduces T_{thermal} *down to the limit* $(0.5\,hf)$



- **Amplifier Noise** [1]

$$T_{\text{amplifier}}^{\text{current best}} \approx 1.2\,hf, \quad T_{\text{amplifier}}^{\text{limit}} = 0.5\,hf$$

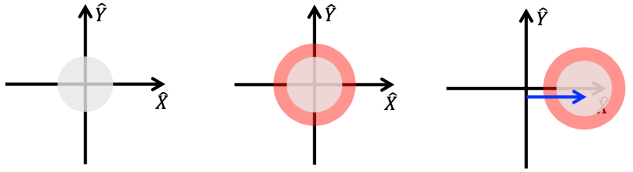
- **Heterodyne**

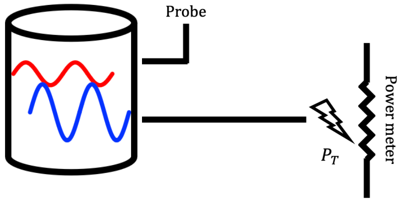
Mixing two frequencies

$$\propto \frac{1}{2}E_{\text{sig}}^2 + \frac{1}{2}E_{\text{LO}}^2 + 2E_{\text{sig}}E_{\text{LO}}\cos(\omega_{\text{sig}}t+\varphi)\cos(\omega_{\text{LO}}t)$$

Heterodyne haloscope

- **Assuming the axion and the probe are** ***the same frequency but random phase***
  - Thermal noise + Axion + Probe





⇒ Injecting the probe simply shifts the signal in IQ plane

⇒ It does not change the signal-to-noise ratio in IQ plane

Instead of the power detector, we propose to use the EO effect and a Fabry-Perot resonator

Heterodyne-variance method: PRD107, 103005 (2023)

Can always reach QNL performance even when the power detectors (bolometers) are noisy

Variance statistics

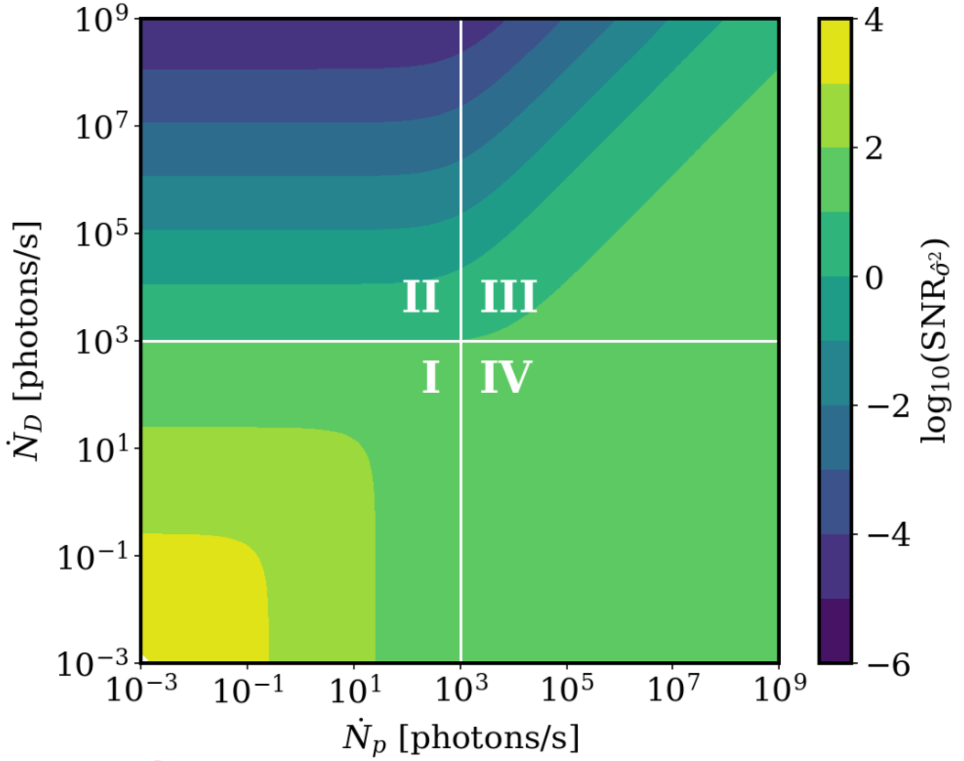
Junu Jeong's slide

- **SNR of the variance estimator**

Detector sampling rate: f_s
Photon rate: $\dot{N} \equiv N \times f_s$

$$S/N_{\sigma^2} \approx \frac{\dot{N}_s (1 + \dot{N}_p/f_s)\sqrt{f_s \Delta t}}{(\dot{N}_D + \dot{N}_p)\sqrt{2 + f_s/(\dot{N}_D + \dot{N}_p)}} \rightarrow \frac{\dot{N}_s}{\sqrt{2 f_s}}\sqrt{\Delta t}$$

$\dot{N}_p \gg f_s$



- **Region I:** $\dot{N}_D < f_s,\ \dot{N}_p < f_s$
- **Region II:** $\dot{N}_D > f_s,\ \dot{N}_p < f_s$
- **Region III:** $\dot{N}_D > f_s,\ \dot{N}_p > f_s$
  Injecting probe increases the SNR, converging to $\dot{N}_D|_{eff} \rightarrow 2f_s$
- **Region IV:** $\dot{N}_D < f_s,\ \dot{N}_p > f_s$
  Injecting prboe reduces the SNR

EO measurement using a Fabry-Perot plus heterodyning (probing)

Next, we will examine implementing the probing method to provide a feasible detection approach, without FP enhancement. We will consider an injected RF power $P = 2\,\mathrm{nW} = 2\times10^{-9}$ W. The electric field amplitude, for $\omega = 2\pi\times10^{10}$ rad Hz, is:

$$E_{\mathrm{probe}} = \sqrt{\frac{Q_c P}{\epsilon_0 V \omega}} \approx 0.1\,\mathrm{V/m} \qquad (13)$$

Given the above discussion, the detected ellipticity scales with the geometric mean of the axion and probe electric fields:

$$\psi_{\mathrm{probe}} = \frac{\pi}{\lambda} n^3 r_{33} \sqrt{E_a E_{\mathrm{probe}}}\, L \qquad (17)$$

Substituting the above benchmark values, we find $\psi_{\mathrm{probe}} \approx 7.7\times10^{-11}$ rad. As before, if we employ a FP cavity with a finesse $\mathcal{F}$, we can enhance the signal

1. Heterodyning (probing) enhances the axion signal by sqrt(E_{probe}/E_a)~3×10^3
2. The axion induced ellipticity is now ~ 5×10^{-7} rad at 10 GHz with 10kHz modulation.
3. We can see this in less than 3s.

$$\psi_{\mathrm{probe}} \to \left(\frac{2\mathcal{F}}{\pi}\right)\psi_{\mathrm{probe}}\,, \qquad (18)$$

which for $\mathcal{F} = 10^4$ will result in $\psi_{\mathrm{probe}} \approx 4.9\times10^{-7}$ rad.

Thus, the SNR for a 10 mW laser power and int ing for 3 s, is :

$$\mathrm{SNR}_{\mathrm{probe-FP}} \approx \frac{(2\mathcal{F}/\pi)\psi_{\mathrm{probe}}}{\delta\psi_{\mathrm{shot}}} \approx \frac{4.9\times10^{-7}}{3.5\times10^{-9}} \approx 140 \qquad (19)$$

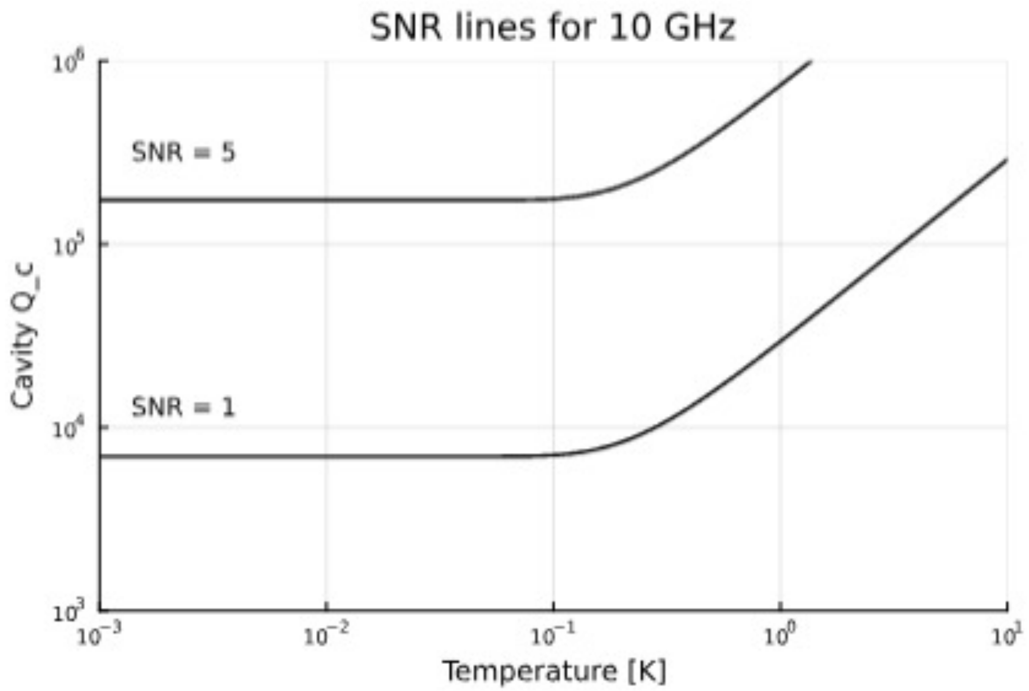


FIG. 2: Signal-to-noise ratio (SNR) as a function of Q_c and T at different operating frequencies. The transition from the quantum regime to the classical regime becomes apparent around 480 mK, where the thermal photon occupation number begins to exceed the vacuum (zero-point) contribution. The cavity volume is kept constant at 3.7 liters. The axion to photon conversion power is kept at 10^{-23} W assuming $Q_c = 10^4$, $t = 3$ s, and scaled appropriately for different cavity quality factor values; see Supplemental Material.

The dominant noise

1. Thermal and vacuum (quantum) induced noise.
2. In the current experiments the dominant noise comes from the readout electronics

The axion-induced power is:

$$P_a = P_0 \, Q_{\rm red} , \tag{25}$$

where P_0 is a reference quantity and

$$Q_{\rm red} \equiv \frac{Q_c Q_a}{Q_c + Q_a} . \tag{26}$$

For our benchmark choices $P_0 = 10^{-27}$ W, for $Q_c = 10^4$.

$$\boxed{\mathrm{SNR}(t) = \sqrt{\frac{P_0 Q_{\rm red} t}{\pi \hbar\omega \coth\left(\frac{\hbar\omega}{2k_B T}\right)}}} . \tag{29}$$

This expression smoothly interpolates between the quantum regime at low temperatures (where coth $\to$ 1) and the classical limit at high temperatures (where coth $\to \frac{2k_B T}{\hbar\omega}$).

Frequency dependence

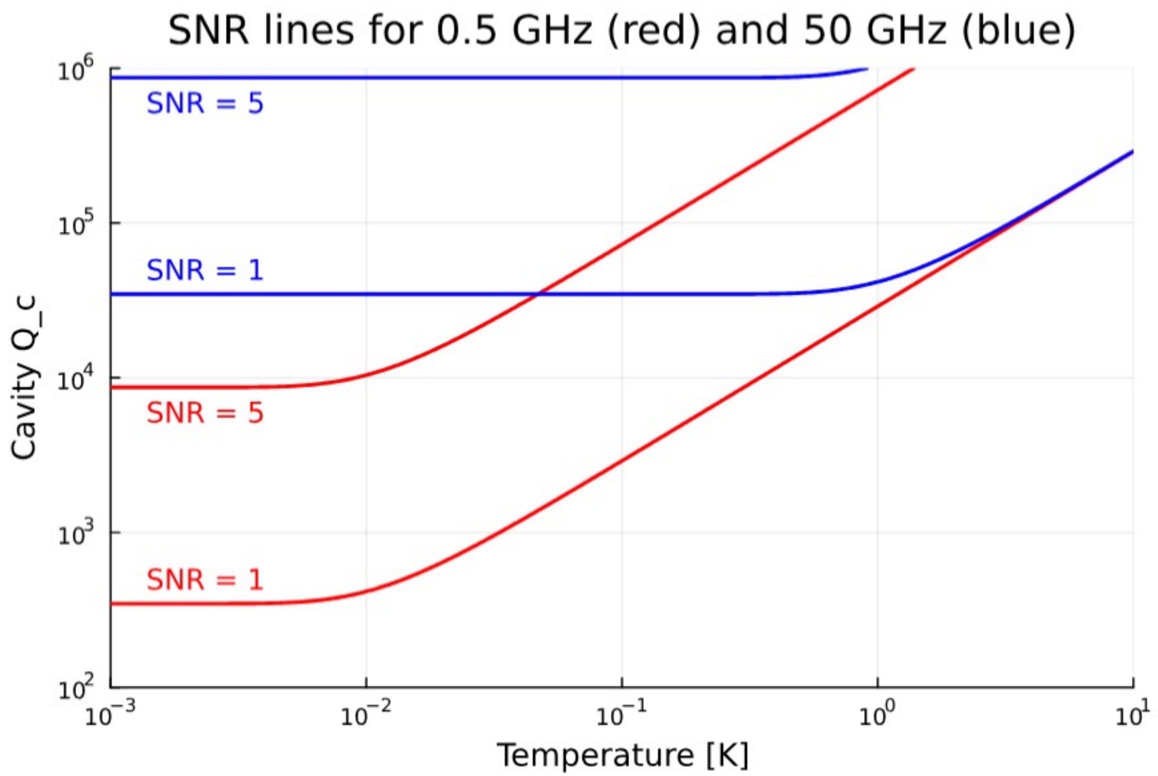


FIG. 3: Signal-to-noise ratio (SNR) as a function of Q_c and T at different operating frequencies. The transition from the quantum regime to the classical regime becomes apparent around 24 mK for 0.5 GHz (red), and 2.4 K for 50 GHz (blue), where the thermal photon occupation number begins to exceed the vacuum (zero-point) contribution. The cavity volume is kept constant at 3.7 liters. The axion to photon conversion power is kept at 10^{-23} W assuming $Q_c = 10^4$ and scaled appropriately for different cavity quality factor values; see text.

1. We can achieve DFSZ sensitivity even for 50 GHz.

2. The frequency range shown includes the favorite range for after inflation PQ scale (10-45 GHz).

Leveraging Axion Spatial Coherence

An immediate and practical extension of the present method would be to deploy a modest array of probing haloscopes operating in parallel. Given that vacuum fluctuations are uncorrelated between separate cavities, while the axion field remains spatially coherent over macroscopic scales, coherently combining the outputs of N detectors leads to a signal that scales as N, while the noise grows only as $\sqrt{N}$. Thus, the overall signal-to-noise ratio improves as

$$\mathrm{SNR}_{\mathrm{total}} \propto \frac{N}{\sqrt{N}} = \sqrt{N} \quad \text{(for fixed total integration time)},$$

or even

$$\mathrm{SNR}_{\mathrm{total}} \propto N \quad \text{(if each detector integrates independently)},$$

offering a clear path to significantly enhanced sensitivity or scanning speed.

This strategy is justified by the fact that the axion field is expected to behave as a classical, spatially coherent oscillation over a characteristic coherence length

$$\ell_{\mathrm{coh}} \sim \frac{2\pi}{m_a v} \sim 100\ \mathrm{m\ to\ 1\,km}, \tag{30}$$

depending on the axion mass m_a (or frequency ν_a) and its virial velocity $v \sim 10^{-3}c$. For example, at $\nu_a = 1\,\mathrm{GHz}$, the coherence length is approximately 200 m, ensuring that ten or more detectors within this radius observe the same axion phase and can be summed coherently.

Can we do even better than quantum noise?

1. Not with a single cavity. Having (N) multiple cavities, the gain in SNR is proportional to N, and in scanning time N^2.

2. The opportunity is indeed great. Using existing technology that can scale up easily.

3. BNL can:
   - Run experiments at the favorite axion frequency range
   - Assist other DOE experiments with their axion signal readout systems

Summary

- ALPHA, ADMX, CAPP, GrAHal, HAYSTAC, QUAX,… are mature experiments, scheduled to complete the full frequency range in a few decades.
- HTS cavities can help, but the readout electronics is still the bottleneck.

- Electro optic readout with Fabry-Perot resonators and heterodyning (probing) can enhance the scanning speed by more than an order of magnitude:
  - Great SNR, quantum noise limitations are mitigated
  - Use a uniform readout system for the favorite frequency range 10 GHz $< f <$ 45 GHz.

- BNL has great in-house expertise in Fabry-Perot resonators (Triveni Rao and Thomas Chang from Instrumentation).
- Joining this experiment for the young and …not so young, who want a major result in less than five years, is a must!

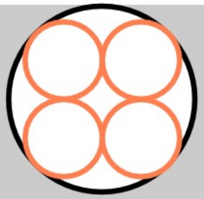
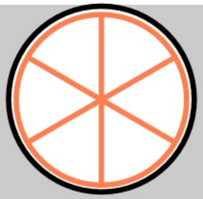
Extra slides

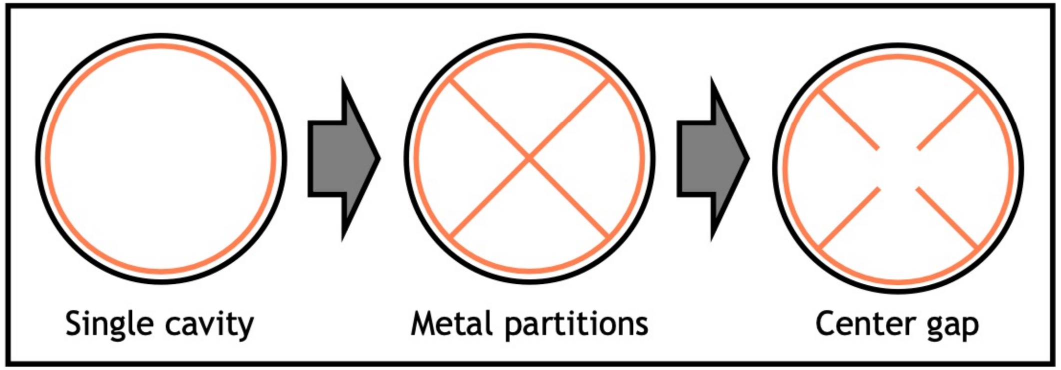
Higher frequency than the “natural” one: CAPP and ALPHA

Doing high frequency efficiently

Multiple-cell cavity

- Multiple-cell cavity
  - New concept developed at CAPP
    1. Single cylindrical cavity fitting into the bore
    2. Split by metal partition with equidistance
    3. A narrow hole at the center

	Quad-cavity	Quad-cell	Sext-cell
Configuration			
Volume [L]	**0.62**	1.08	**1.02**
Frequency [GHz]	7.30	5.89	7.60
Q (room temp.)	19,150	19,100	16,910
Form factor	0.69	0.65	0.63
Conversion power	1.00	1.65	1.32
Scan rate	1.00	2.72	**1.98**



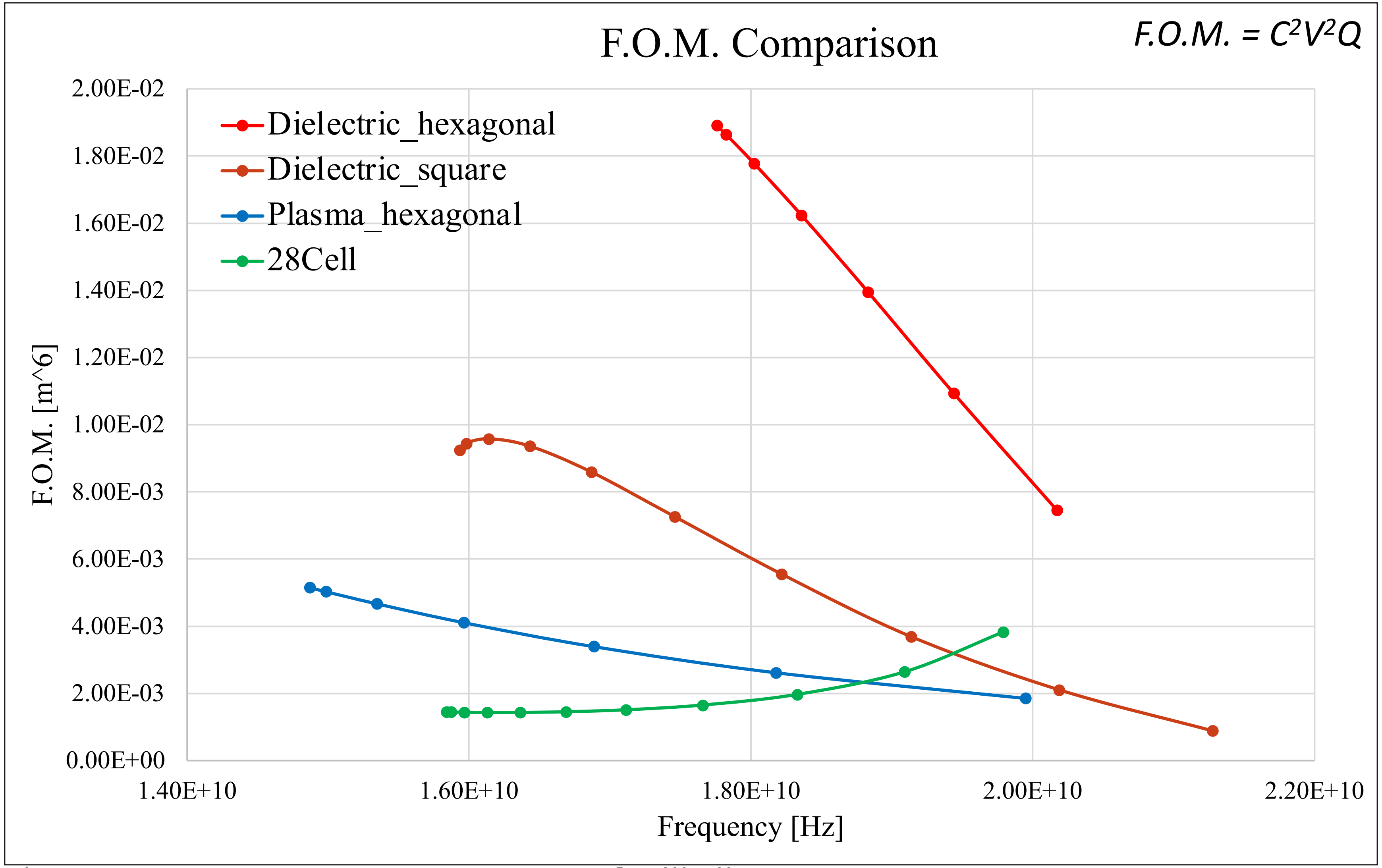
Multiple cavity system
- Inefficient in volume
- Multiple antennae & power combiner
- Frequency matching

Multiple-cell cavity
- Almost no volume loss
- Single antenna & no combiner
- Robust against tolerance

Slide by Junu Jeong, SungWoo Youn et al.

Performance comparison

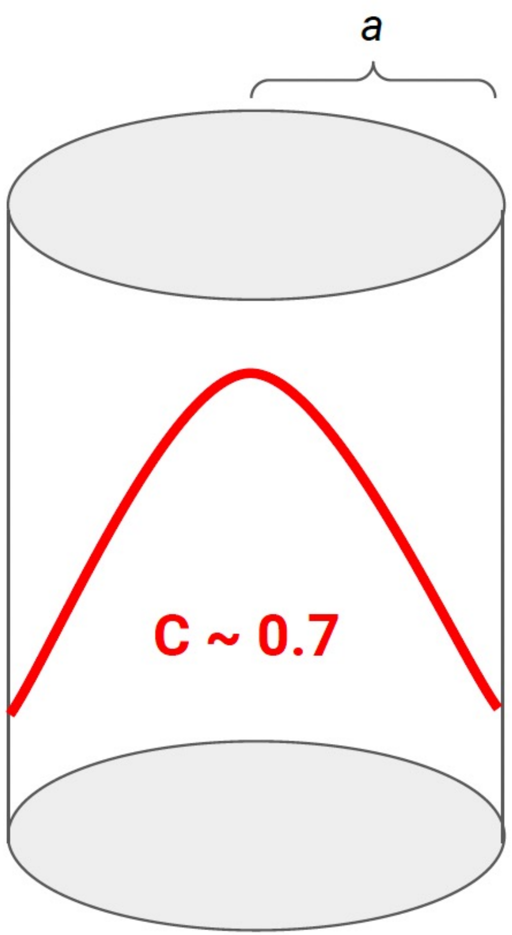
Physical Review D Vol. 107, No. 1, 015012-1-015012-8(2023)



Alpha collaboration

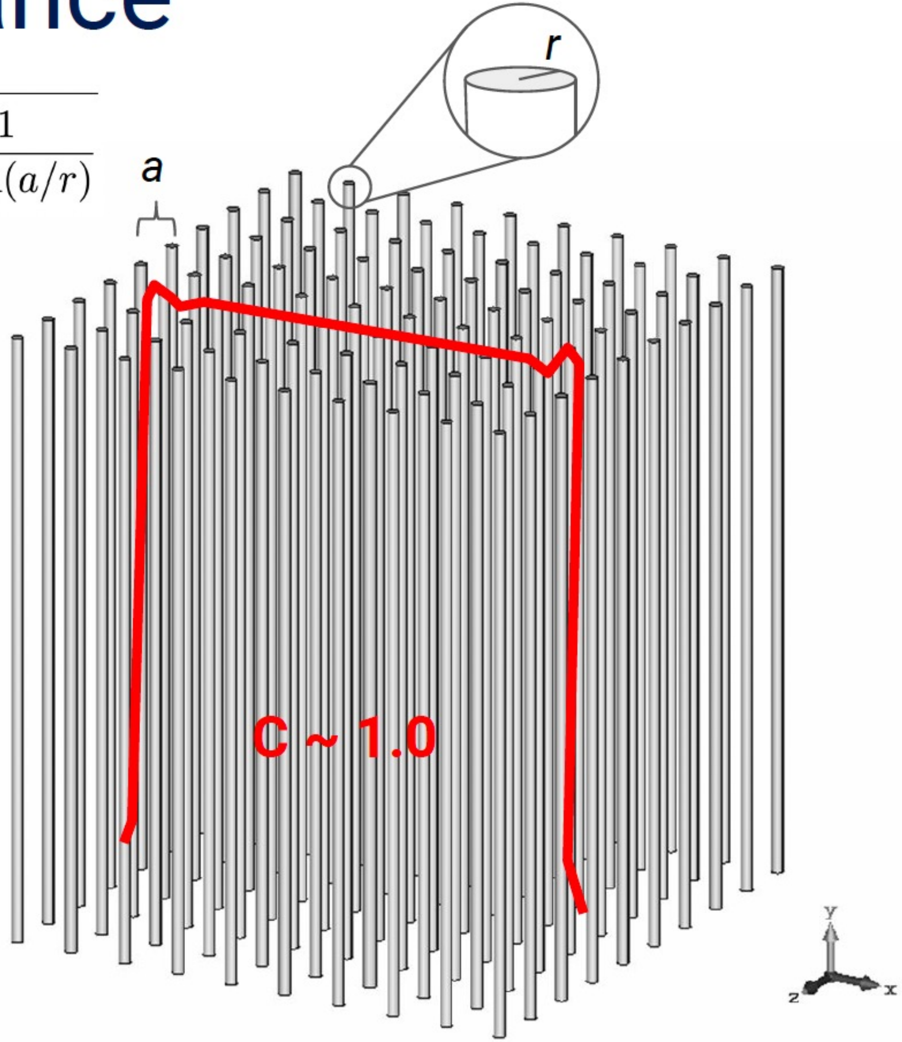
Solution: plasmonic resonance

$$f = \frac{1.202}{\pi}\frac{c}{a}$$



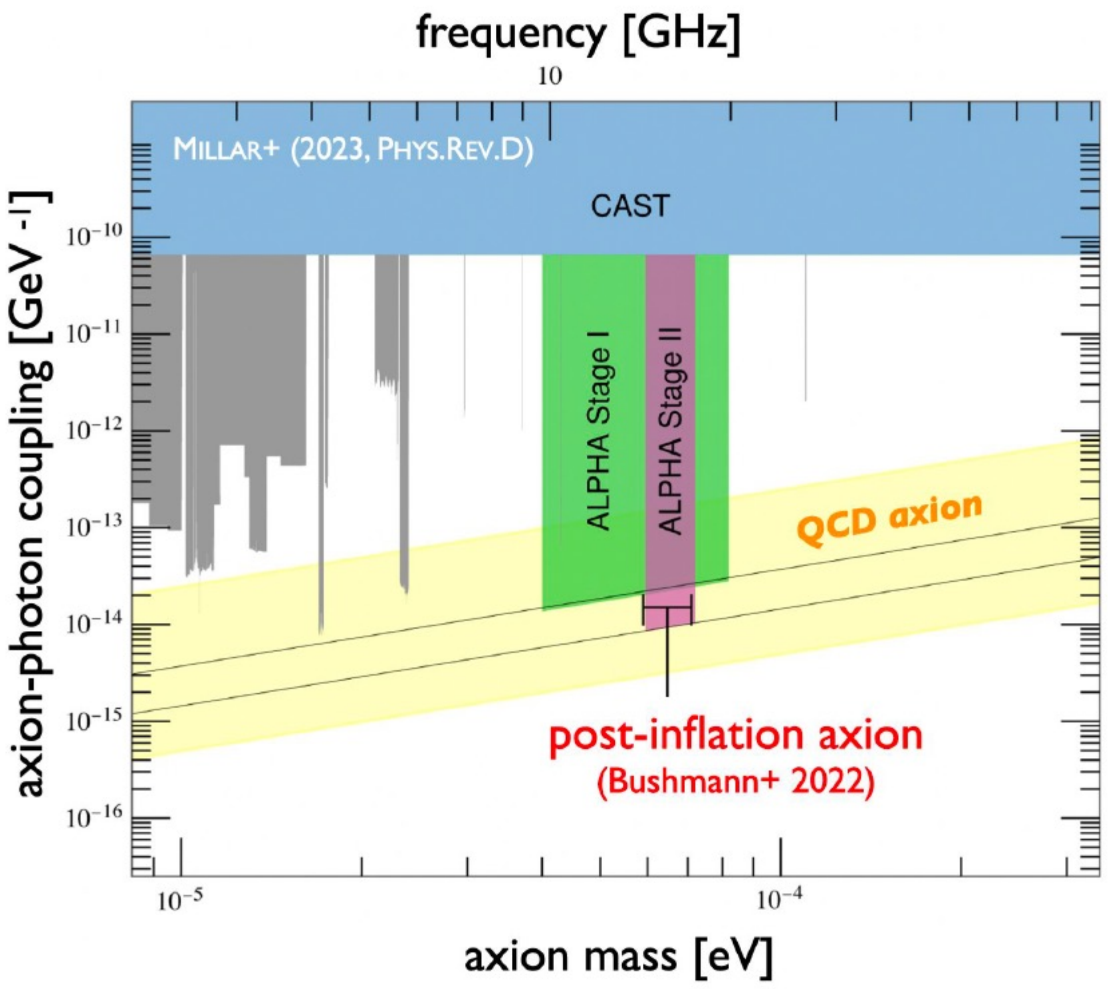
Sikivie (1983), PRL

$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi \ln(a/r)}}$$



Lawson et al. (2019), PRL

Alpha collaboration



Credit: Hiranya Peiris and Alex Millar

- Post-inflation axion one of two well-motivated mass ranges
- Recent calculations: ~15 GHz, 65 μeV (Buschmann et al., 2022)
- Out of reach of conventional haloscopes, but accessible to plasma haloscopes
- ALPHA to focus initially on 40-80 μeV
- Construction of ALPHA under way, experiment hosted at Yale in high-field superconducting magnet (16.4 Tesla)
- Commissioning 2026-27