The Dark Side of the Universe - DSU2024

SEPTEMBER 8 - 14, 2024

KAIST

CAPP
Center for Axion and Precision Physics Research

Exploring the Axion Dark Matter Landscape: Current Experiments and Future Directions

Yannis K. Semertzidis, IBS-CAPP and KAIST

Axion field made enormous progress in last decade

- Theoretical models on couplings, structures, methods,…
- ADMX, CAPP, HAYSTAC, QUAX, … are either nearing or better than KSVZ/DFSZ sensitivity
- Haloscopes: Conquering the 1-8 GHz region, expanding up to 25 GHz and down to ~100 MHz
- Great promise above 25 GHz and below ~100 MHz with new approaches
- Progress in technology of *magnets, cavities, SC cavities in strong B-fields, and quantum-level readout electronics* promise to reach 1-8 GHz within the next five years, 0.1 GHz – 25GHz in ten years and within the next two decades the whole Axion parameter space

Dark matter

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.

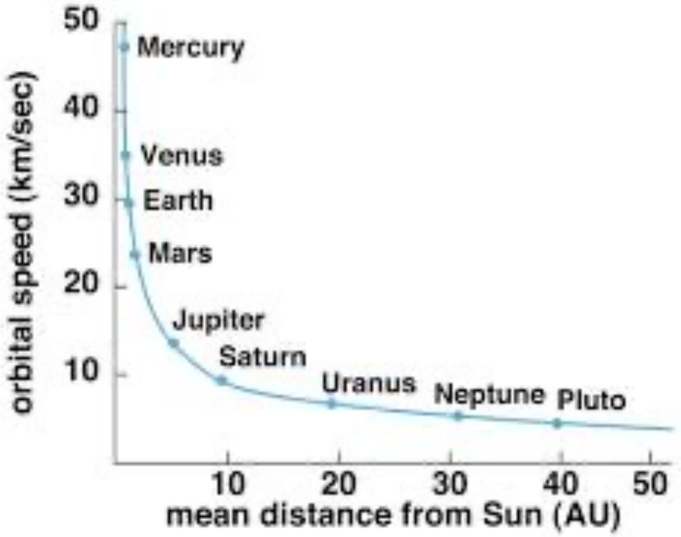
Newton's laws: "observing" the unseen

- Gravitational law applied to the planets: by measuring the planet velocity and its distance from the center, we can estimate the enclosed mass.

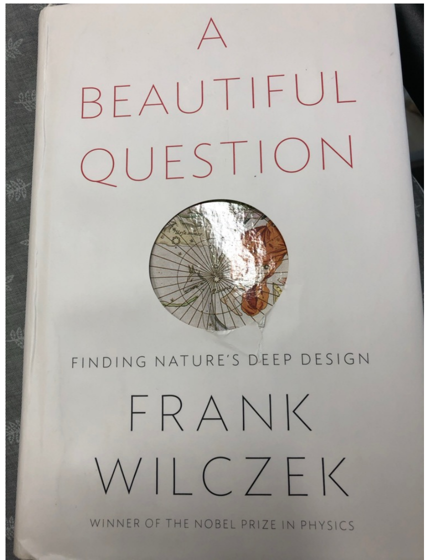
$$F = \frac{GM_\odot m}{r^2} = \frac{mv^2}{r}$$

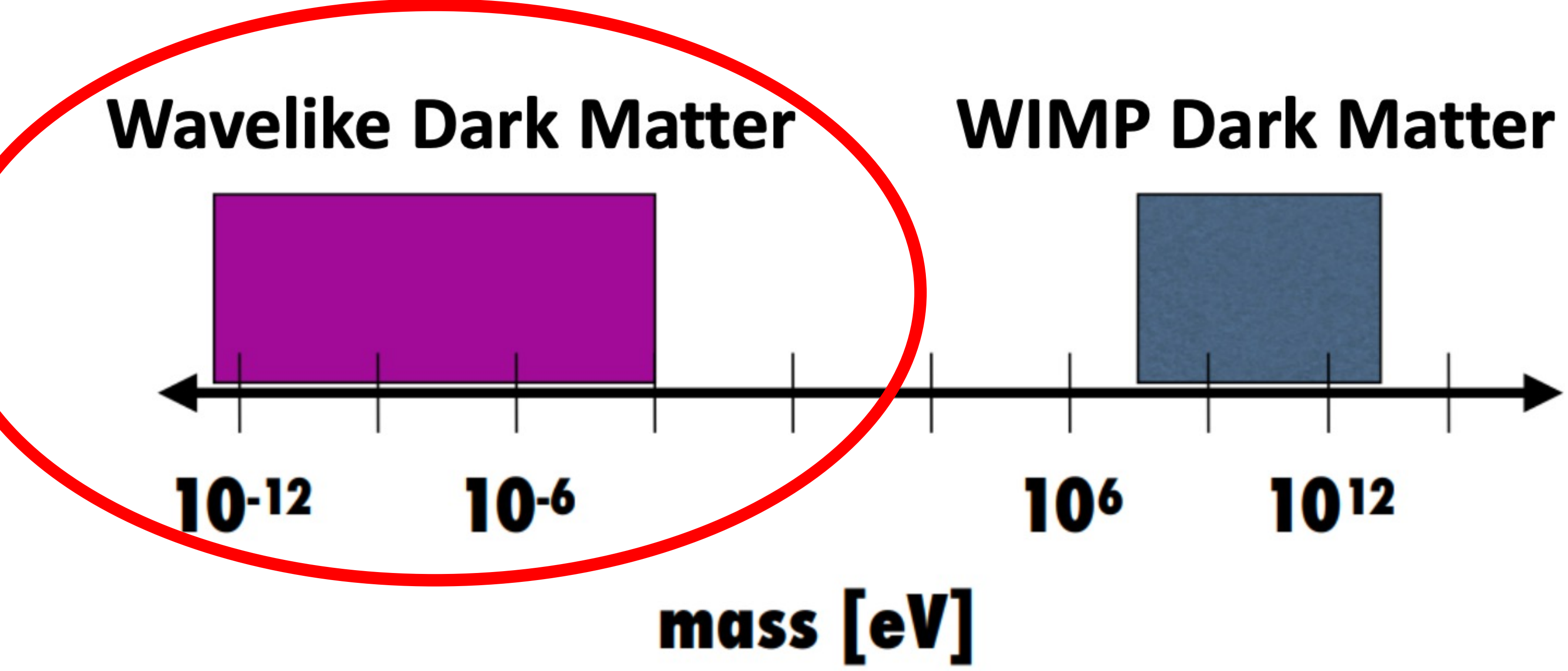
$$v = \sqrt{\left(\frac{GM_\odot}{r}\right)}$$

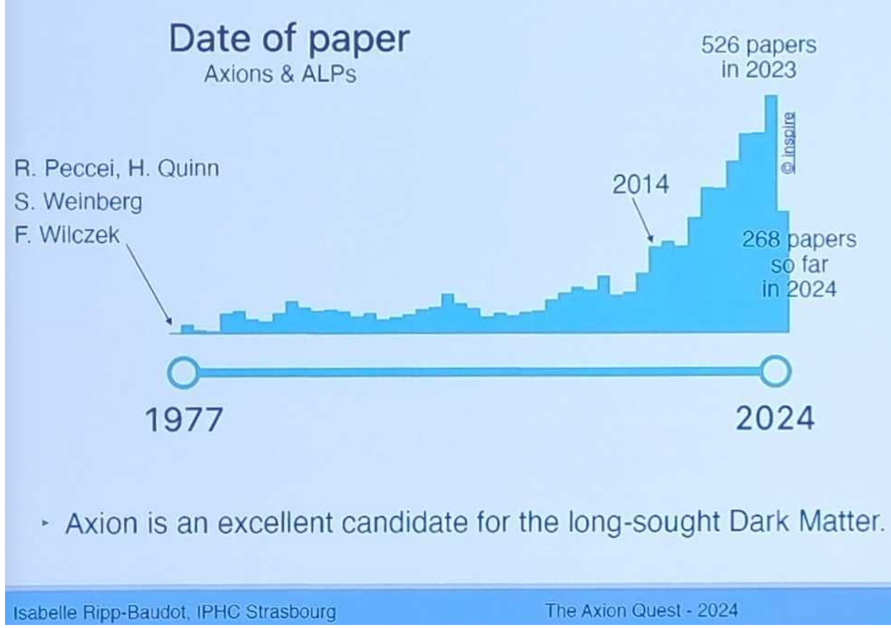
1915, Einstein's General Relativity
Resolved the issue with Mercury's precession



1846, Adams and Le Verrier suggested the existence of Neptune: First discovery of "Dark Matter". Frank Wilczek in "A Beautiful Question"







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

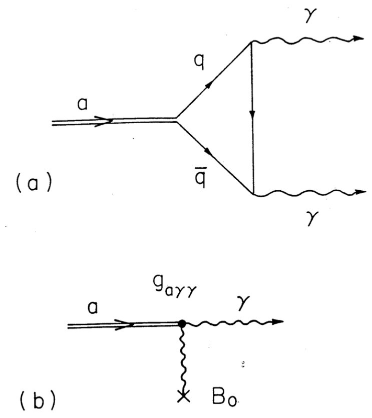
Occupancy Number - $N \approx \frac{\rho_{DM}}{m} \lambda_{dB}^3$

- 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 Couplings



- Gauge fields:
  - Electromagnetic fields (microwave cavities)
  - $$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$
  - 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, QUAX, ARIADNE, GNOME)

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

Major activities (not complete!)

- 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

Major activities

- CASPEr electric (Boston Univ.)
- CASPEr axion-wind (MAINZ)
- QUAX (INFN, spin coupling)
- Oscillating neutron-EDM (PSI)
- Axion-EDM (Storage ring EDM)

Major activities

- GNOME (Axion domain walls, stars; International network)
- ARIADNE (Axion-mediated long-range forces; No dark matter needed)

World map of current experiments on wavy dark matter

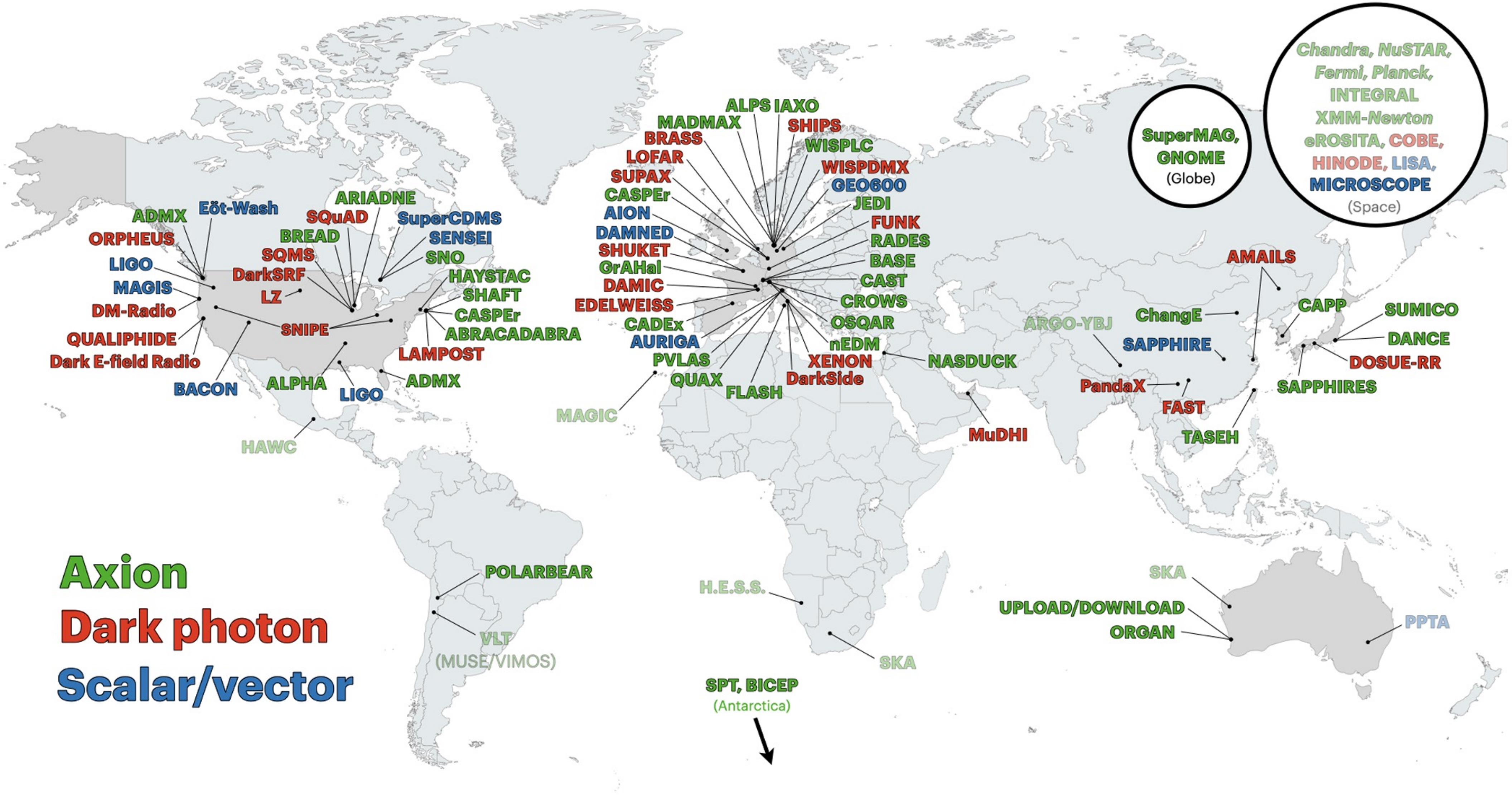


Figure 6: World map displaying current experiments searching for wavy dark matter [9].

Axion haloscope method by Pierre Sikivie

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

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

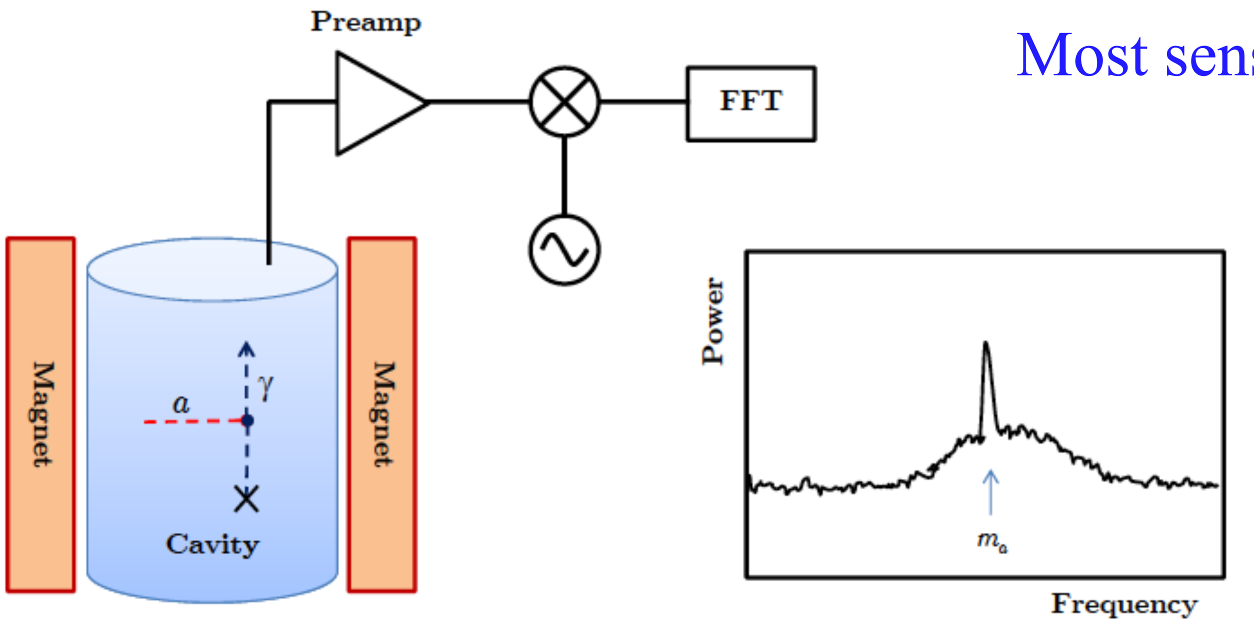


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Most sensitive method

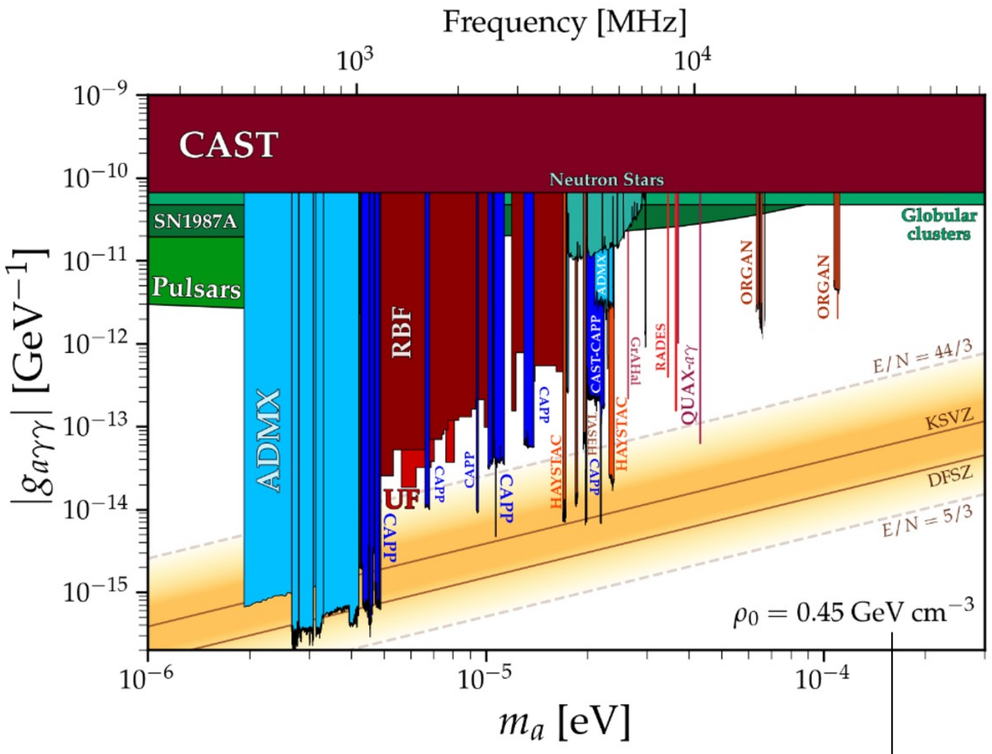
Running Haloscope Experiments:
CAPP
ADMX
HAYSTAC
…

Recent limits in medium axion frequencies

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

← Exclusion limit of Axion haloscope

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

- **Two axion models**

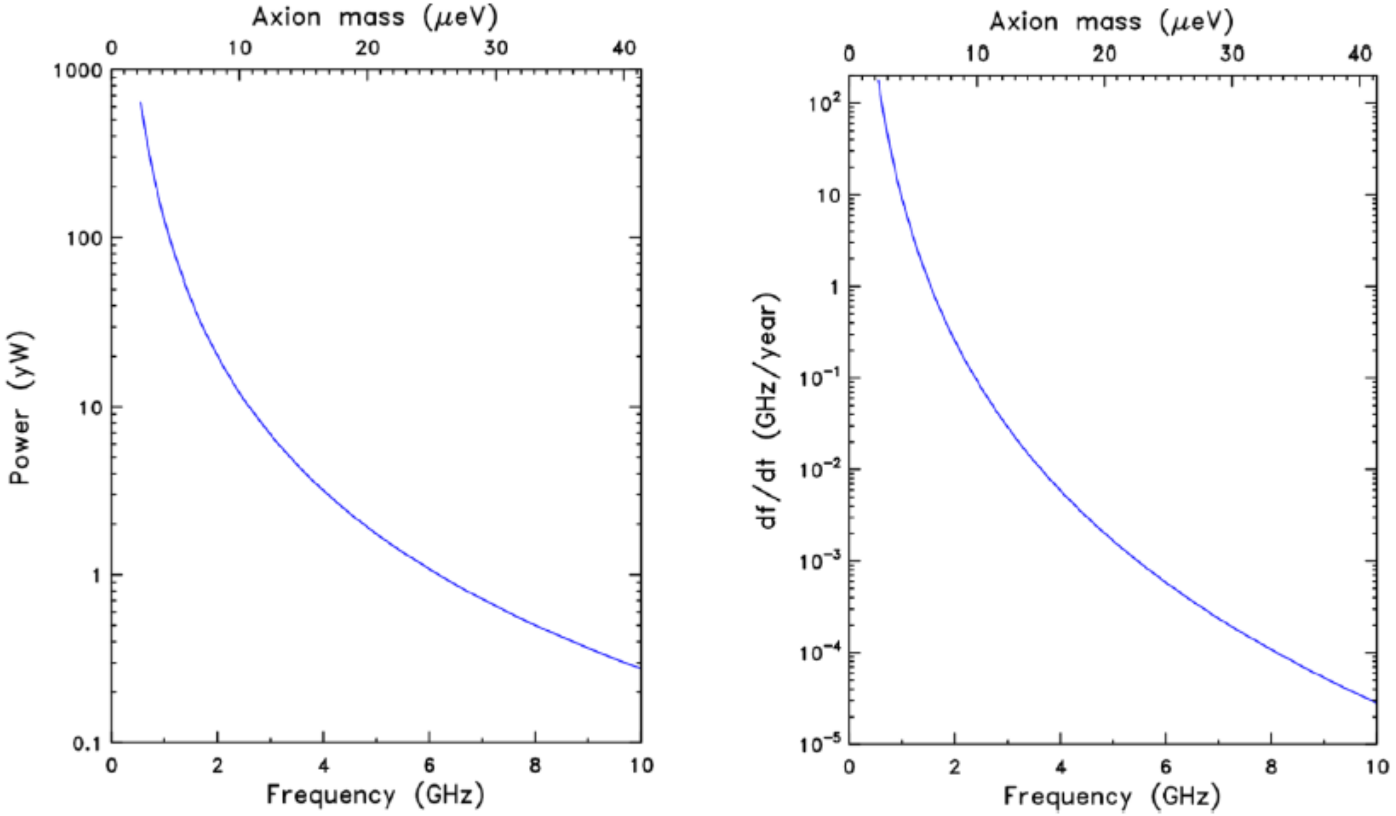
- Kim-Shifman-Vainshtein-Zakharov (**KSVZ**) $g_\gamma = -0.97$
- Dine-Fischler-Srednicki-Zhitnitskii (**DFSZ**) $g_\gamma = 0.36$

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

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

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

Building up CAPP

Axion research is like a Marathon requiring hard work, high-risk, high-potential choices, and lots of patience

IBS President Oh, Se Jeong at my recruitment time (as first foreign-born IBS-Director): "Just show promise…"

CAPP was established October 16, 2013, first major investment on axion research and it has helped bring in the critical mass to the field.

Center for Axion and Precision Physics Research: CAPP/IBS at KAIST, Korea

Se-Jung Oh (right), the president of the Institute for Basic Science (IBS) in Korea, and Yannis Semertzidis, after signing the first contract between IBS and a foreign-born IBS institute director. On 15 October, Semertzidis became the director of the Center for Axion and Precision Physics Research, which will be located at the Korea Advanced Institute of Science and Technology in Daejeon. The plan is to launch a competitive Axion Dark Matter Experiment in Korea, participate in state-of-the-art axion experiments around the world, play a leading role in the proposed proton electric-dipole-moment (EDM) experiment and take a significant role in storage-ring precision physics involving EDM and muon g-2 experiments. (Image credit: Ahram Kim IBS.)

CERN Courier, Dec. 2013

- Completely new (green-field) Center dedicated to Axion Dark Matter Research and Storage Ring EDMs/g-2. KAIST campus.

KAIST
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1971

IBS-CAPP looked at all possible parameters

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$$P_{a\gamma\gamma} = 8.7 \times 10^{-23}\,\mathrm{W} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\,\mathrm{GeV/cm^3}}\right) \left(\frac{\nu_a}{1.1\,\mathrm{GHz}}\right) \left(\frac{B_0}{10.3\,\mathrm{T}}\right)^2 \left(\frac{V}{37\,\mathrm{L}}\right) \left(\frac{G}{0.6}\right) \left(\frac{Q_c}{10^5}\right)$$

This corresponds to 120 photons/s in the cavity without external coupling and to 30 photons/s with optimum coupling (β=2).

1. *B*-field, maximum value of magnetic field (8T, 9T, 12T, 18T, and perhaps up to 25T)
2. Cavity volume, *V*, especially for high-frequencies (37*l*,12T)
3. Cavity quality factor, Q_0 (our record so far: 13×10^6, 1M “easy”)
4. System noise temperature, *T* (~200 mK, 1.1 GHz, measured in situ)
5. Geometrical factor, *C* (keep it high >0.6 with special techniques)

CAPP/IBS axion target plan

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \text{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\text{GeV}\right)^4\left(\frac{5\ \text{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \text{K}}{T}\right)^2$$

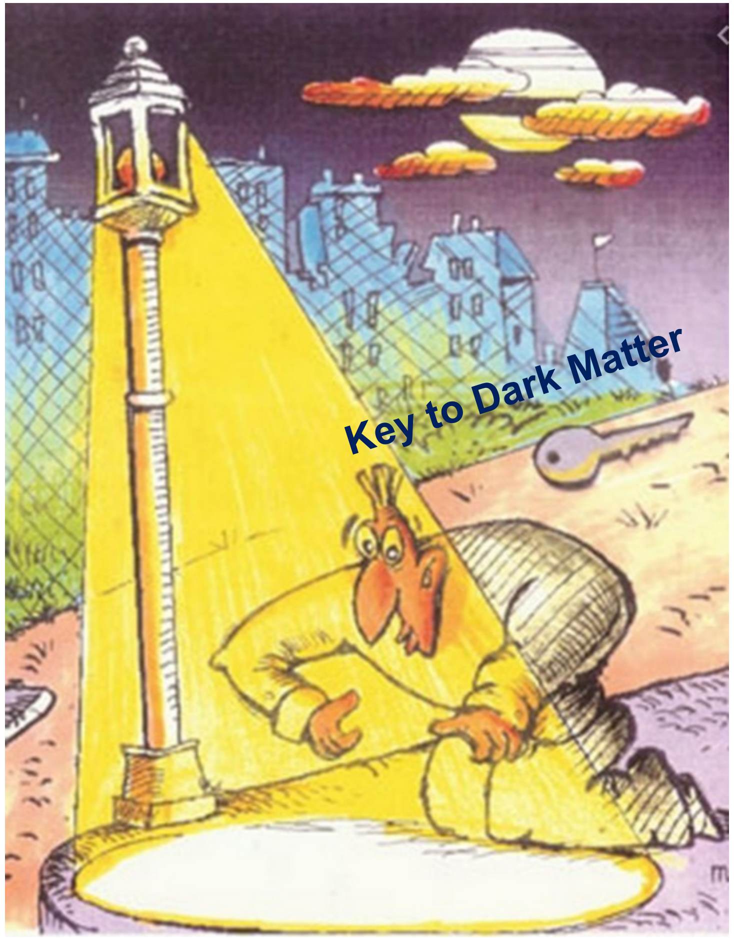
$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

- Major improvement elements:
  - High field solenoid magnets: B
  - High volume magnets/cavities: V
  - High quality factor of cavity: Q
  - Low noise amplifiers: T_N
  - Low physical temperature: T_{ph}

$$T = T_N + T_{ph}$$

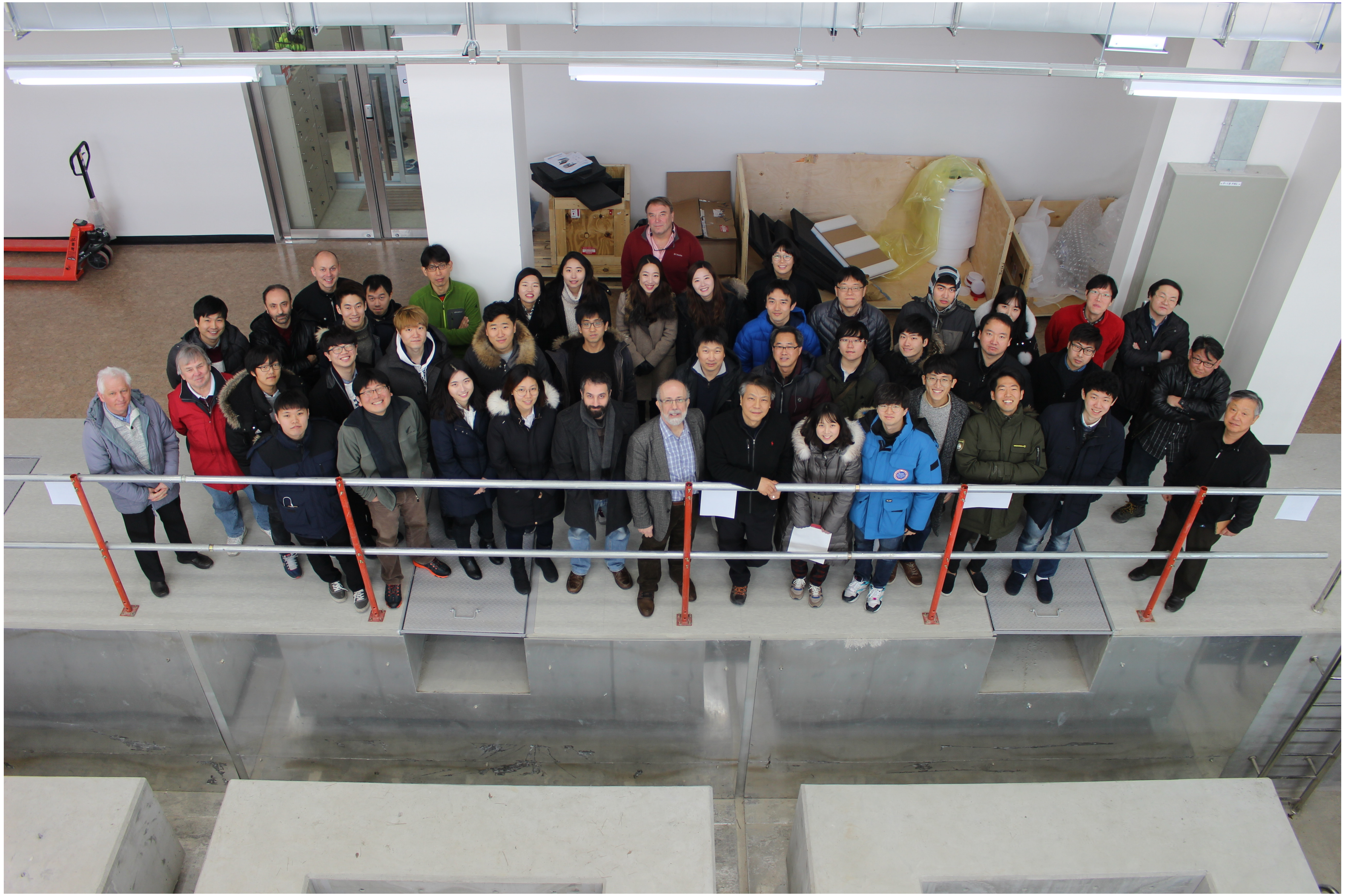
Strategy at CAPP: best infra-structure and know-how

- Under (a brighter) lamp-post with microwave resonators
  - LTS-12T/320mm, Nb_3Sn magnet: for 1-8 GHz
  - 12T for large volume cavities: 37 liters

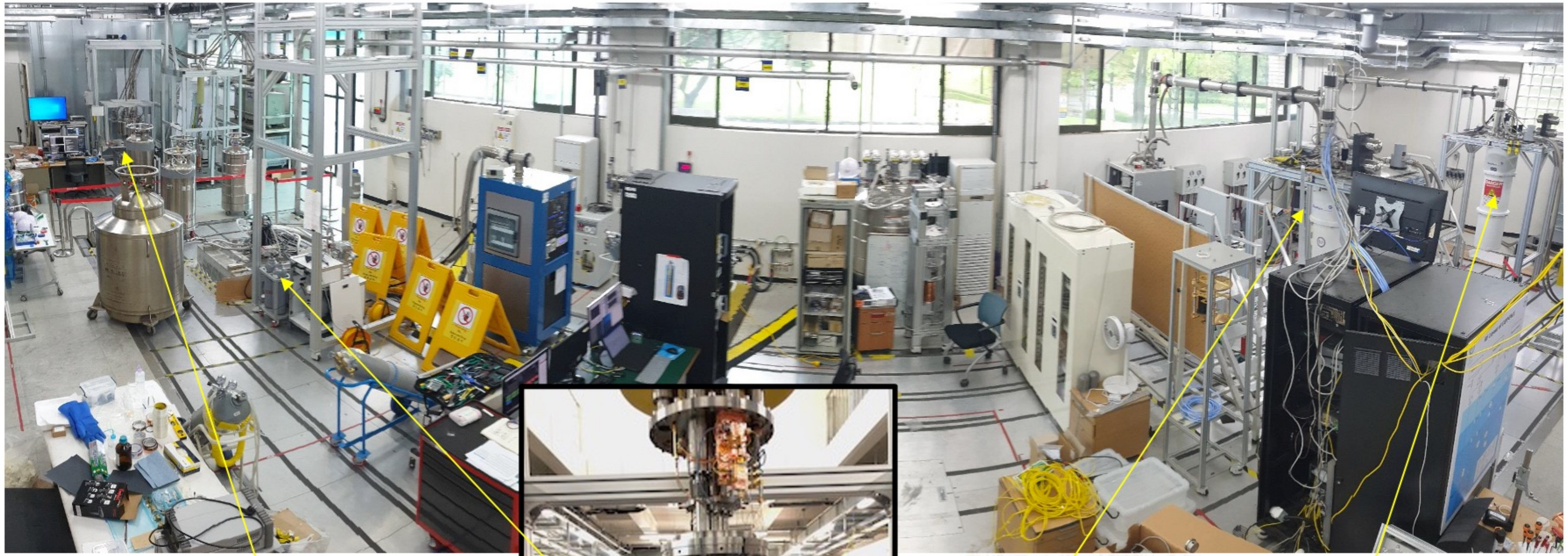


- Powerful dilution refrigerator: ~5mK base temp.
  - 25mK for the top plate of the 37 liter cavity
- State of the art quantum amplifiers (JPAs)
  - Best noise for wide frequencies: 1-6 GHz
- High-frequency, efficient, high-Q microwave cavities (best in the world)

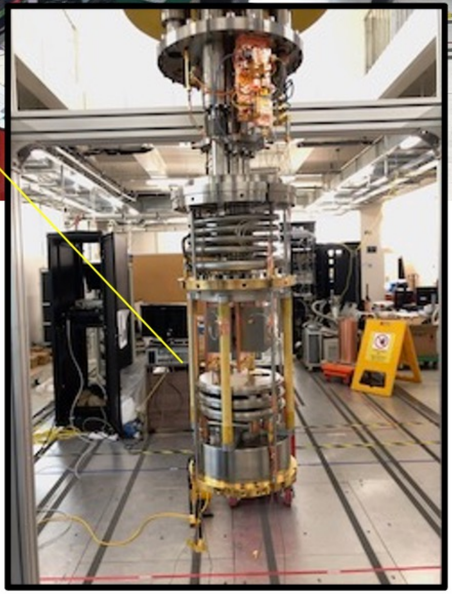
IBS-CAPP at Munji Campus, KAIST, January 2017.



CAPP Experimental Hall (LVP) in 2021

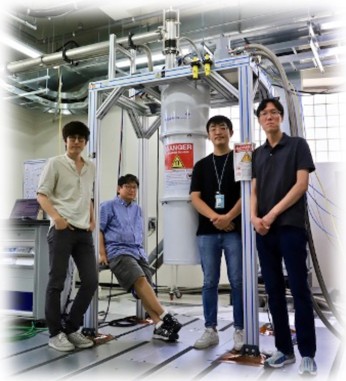


CAPP-HF



CAPP-12TB

CAPP-PACE



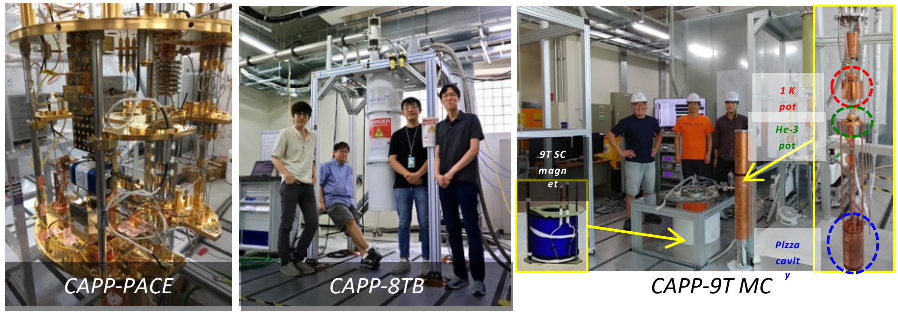
CAPP-8TB

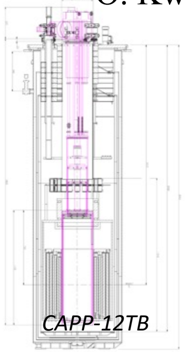
IBS-CAPP at eight-years and beyond

- S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)

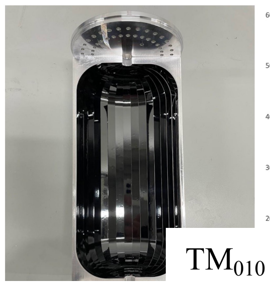
J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020).

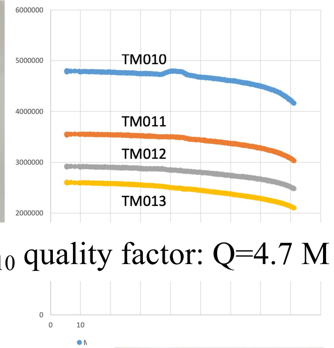
O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 (2021)



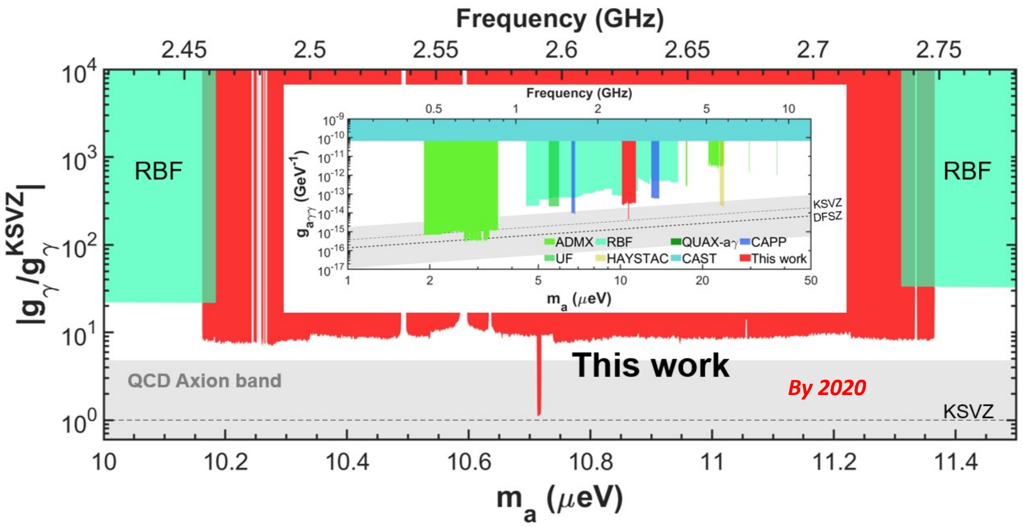


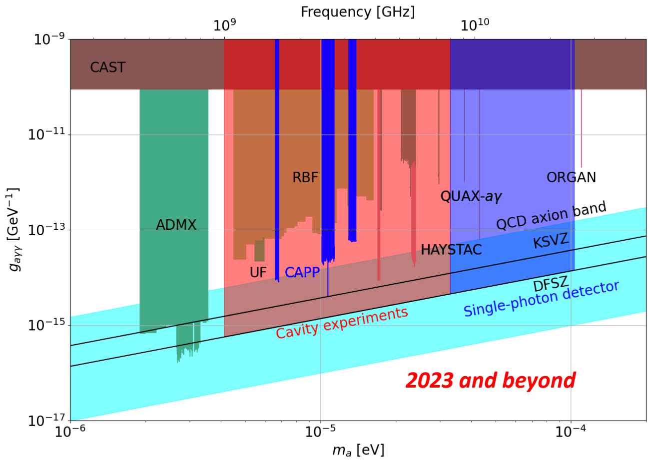
Melon 34 Cavity Q Factor Measurement



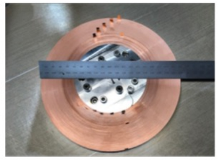


TM_{010} quality factor: Q=4.7 M





CAPP-25T



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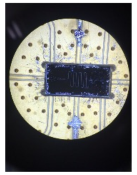

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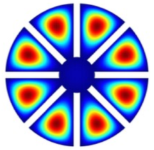


- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

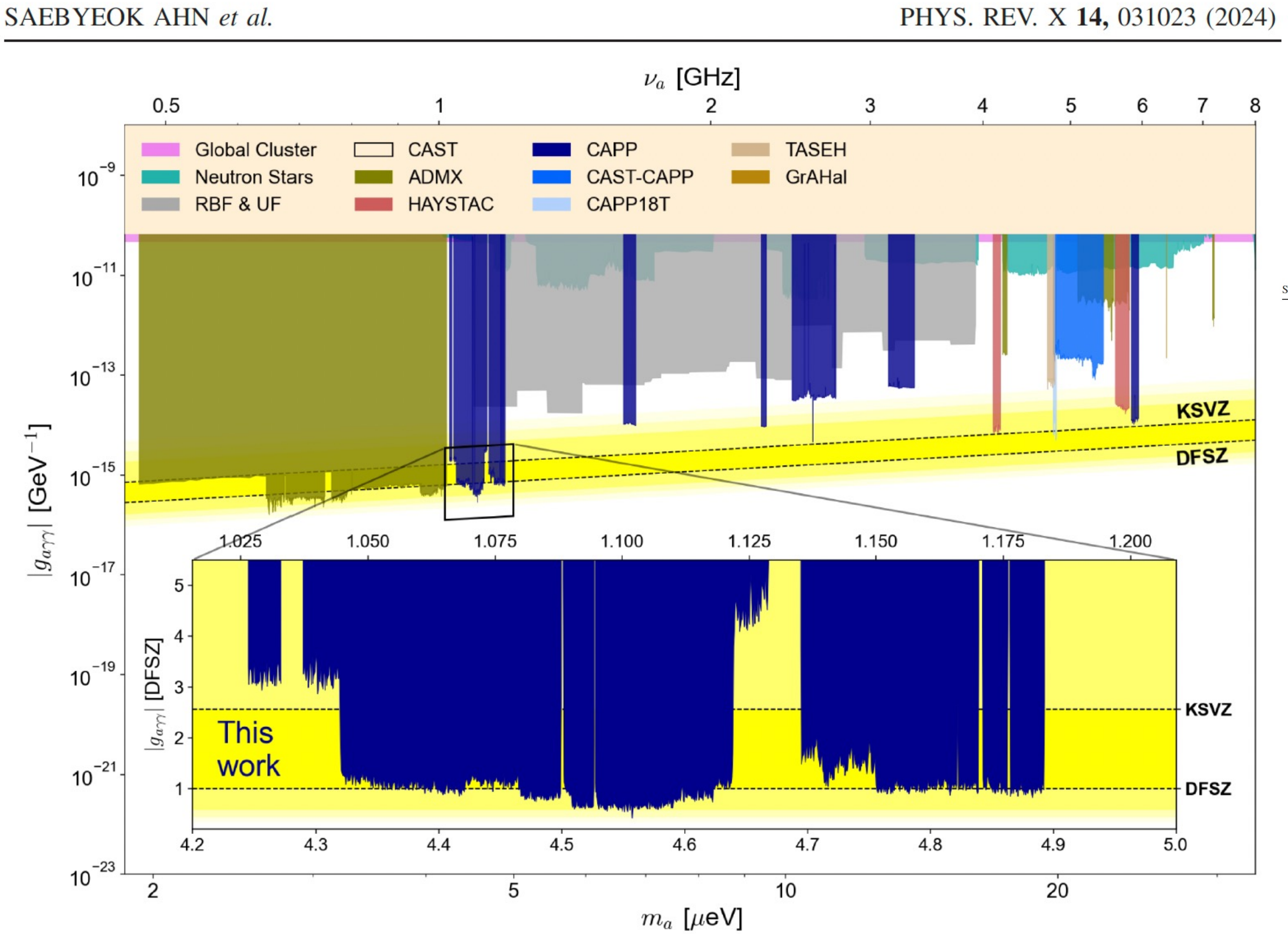
We expect to reach DFSZ sensitivity even for a fraction of axion content in the local dark matter halo. Target sensitivity: 10% axions in DM halo.

IBS-CAPP did R&D in a massive parallel mode in a typical approach for an important Particle Physics experiment.

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \left[\frac{1.2\ \text{GHz}}{\text{year}}\right] \times \left[\frac{g_\gamma}{0.36}\right]^4 \left[\frac{1.1\ \text{GHz}}{\nu_a}\right]^2 \left[\frac{5}{SNR}\right]^2 \left[\frac{0.25\ \text{K}}{T}\right]^2 \left[\frac{B}{10.3\ \text{T}}\right]^4 \times \left[\frac{C}{0.6}\right]^2 \left[\frac{\rho_a}{0.45\ \text{GeV/cc}}\right]^2 \left[\frac{V}{37\ l}\right]^2 \left[\frac{Q_0}{10^5}\right] \left[\frac{Q_a}{10^6}\right] \left[\frac{\beta}{1+\beta}\right]^2$$

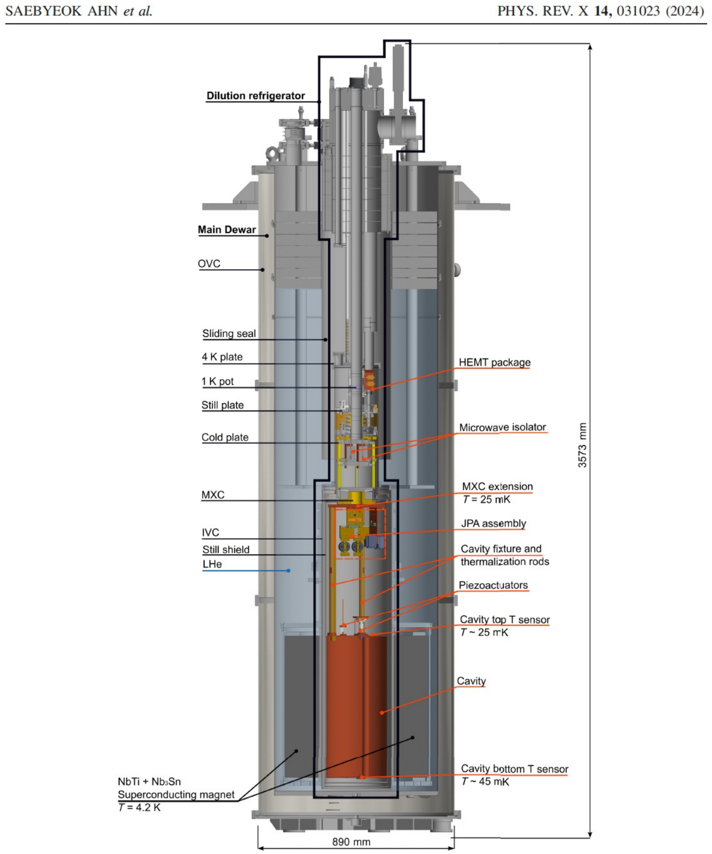
Parameter	**B-field**	**Volume**	**Quality factor**	**Temp.**	**Readout electronics**
df/dt	$\sim B^4$ From 8T to 12T, 18T, 25T, … Any gain in B is a gain in the coupling	V^2 Pizza-cavities: 3-4x, dielectric: 5x	Q HTS cavities: 1-2 orders gain achieved	T^{-2} Near quantum noise	HEMT, JPA Probing method (variance). Single photon det.
Comments, Challenges	HTS, still expensive, SC tape might pill-off when quenching. Fixed. Nb_3Sn more robust	Pizza-cavities: simple, robust, functional. Dielectric, same.	HTS based SC cavities: they work!	Careful design can bring the cavity below 30mK	Our JPAs best noise in the world, low temp. Single photon det. on its way!

IBS-CAPP at DFSZ sensitivity, scanning 1-8 GHz



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

A 32 page reference paper on how to achieve DFSZ sensitivity. No secrets…

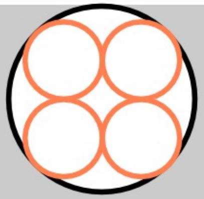
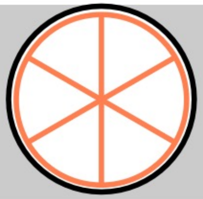


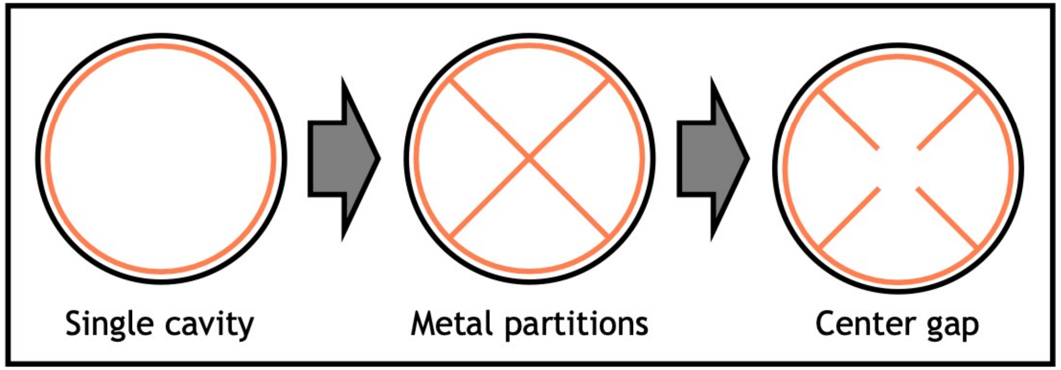
Higher frequency than the “natural” one

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

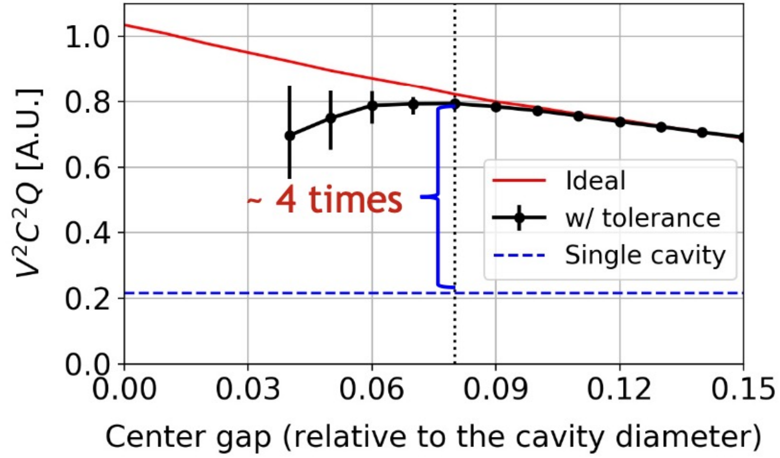
Multiple-cell cavity
- ➢ Almost no volume loss
- ➢ Single antenna & no combiner
- ➢ Robust against tolerance

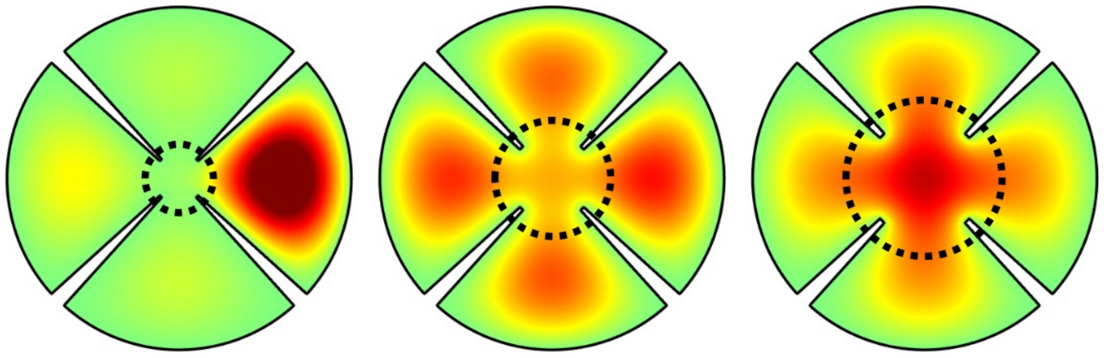
Slide by Junu Jeong, SungWoo Youn et al.

Tolerance for the field localization

Slide by Junu Jeong

- Field localization
  - Asymmetric geometry
    ⇒ Asymmetric field distribution
    ⇒ Reduction in the form factor
- Tolerance
  - Larger center gap ⇒ No localization
  - Too large center gap ⇒ No merit of multiple-cell cavity
  - There is an optimal center gap
- Monte Carlo simulation (optimization)
  - A double-cell cavity with 110 mm diameter
  1. For each center gaps
  2. Random variates dimension (100 um)
  3. Calculate scan rate
  4. Found the optimal center gap

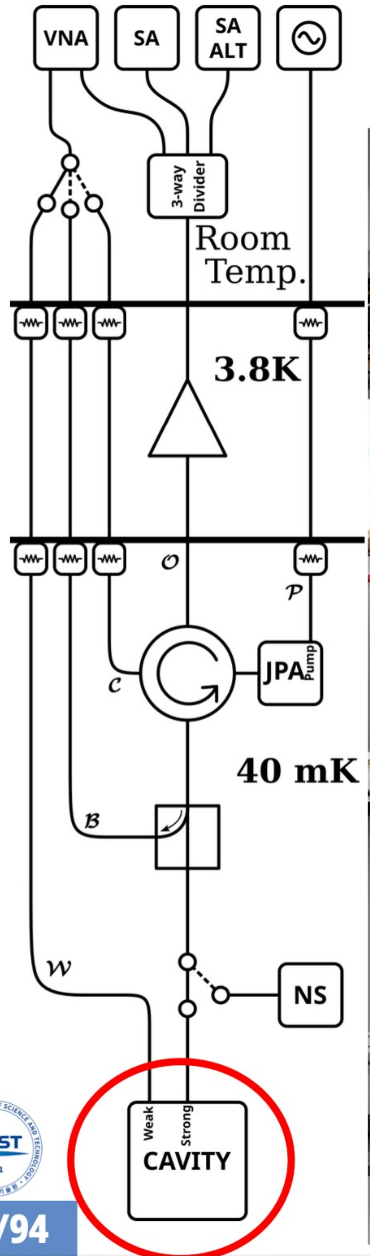


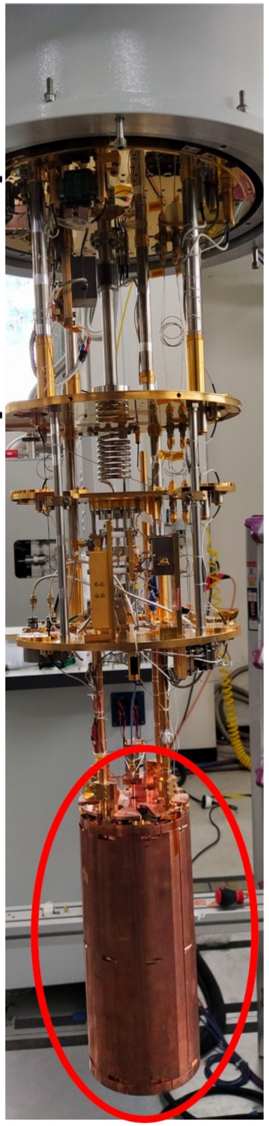


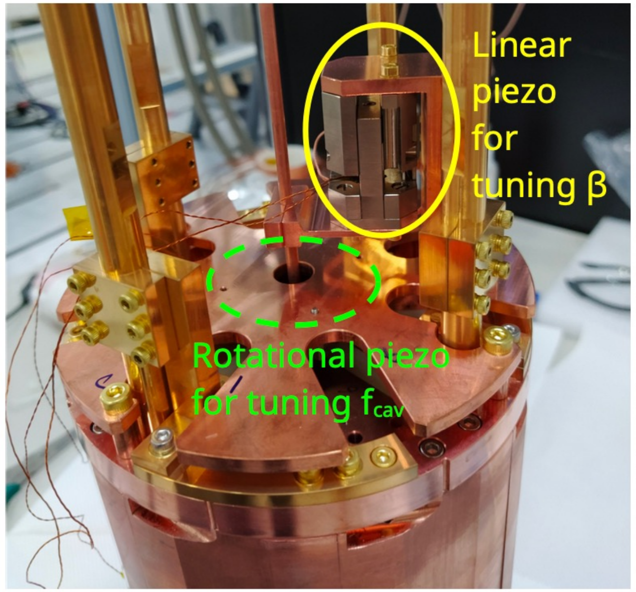
Small center gap localization | Optimal center gap | Large center gap low quality factor

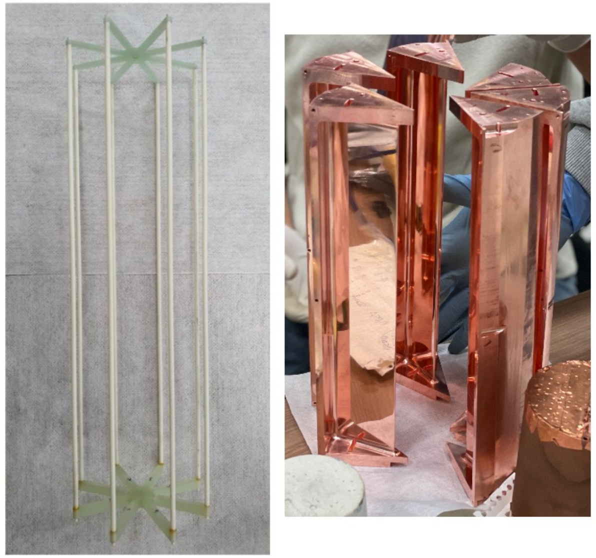
CAPP8TB-6G: The 8-cell cavity

Caglar Kutlu’s slide

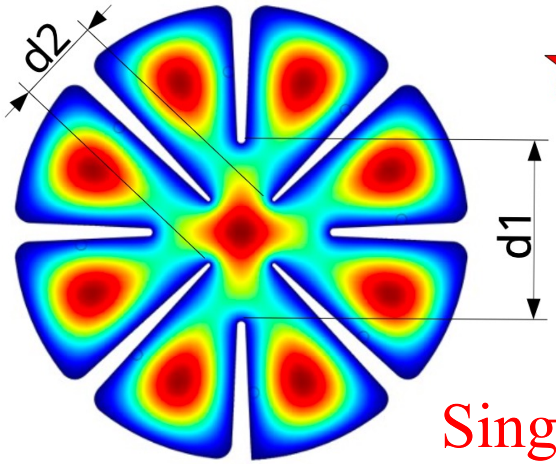








“Carousel” tuning rods



E-field strength of the axion sensitive TM_{010}-like mode

★ d1 and d2 are optimized for machining tolerance.

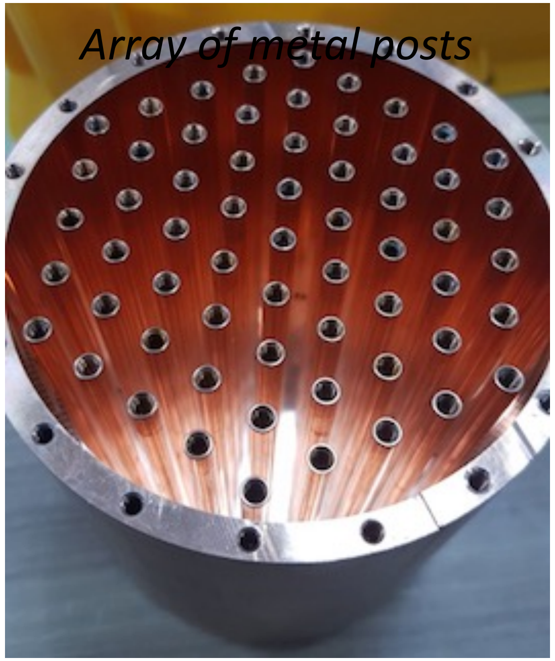
Single readout system!

CAPP
Center for Axion and Precision Physics Research

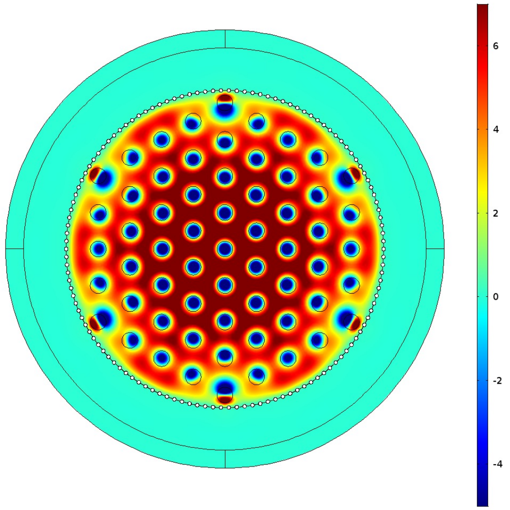
Metal wire vs. post vs. dielectric

Array of wires

Array of metal posts



Array of dielectric posts

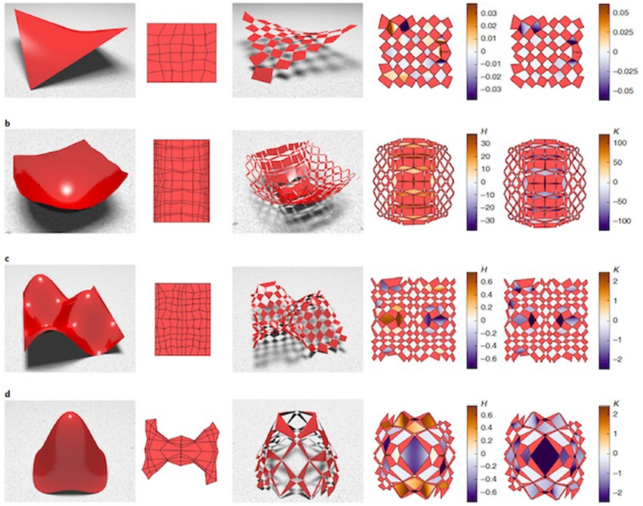


Metal wires	Metal posts	Dielectric posts
C = 0.81	*C* = 0.76	*C* = 0.23 (TM_{020}-like)
Q = 9.6 × 10^3	*Q* = 1.7 × 10^4	*Q* = 1.8 × 10^5
D = ~3 wires/cm^2	*D* = ~1 posts/cm^2	*D* = ~1 posts/cm^2
Very challenging	Less challenging	More reliable
Tuning (variing s) not trivial	LHe tuning (?)	Various tuning mechanisms

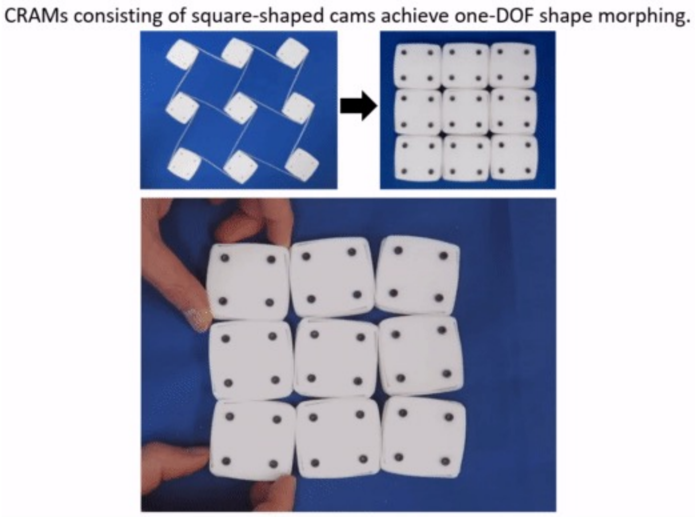
Kirigami tessellations

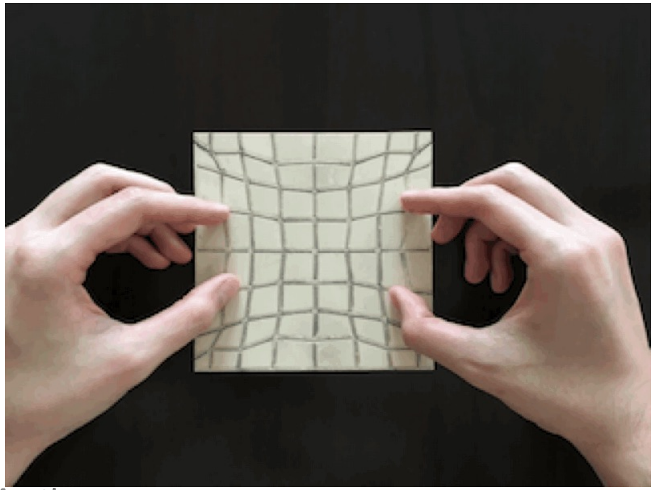
Kirigami

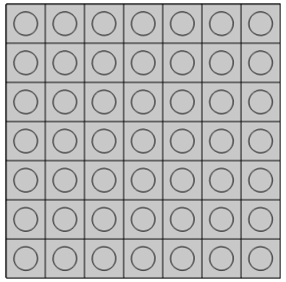
Nature material ***18***, *999*

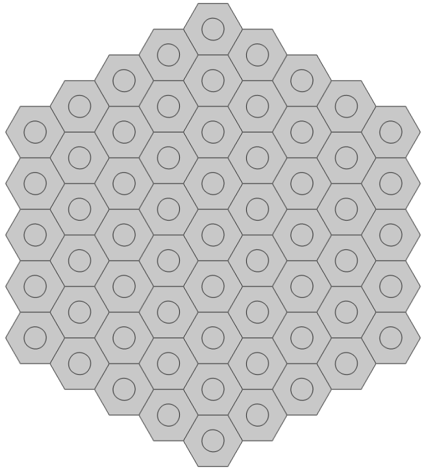


Nature communication ***9***, *4594*



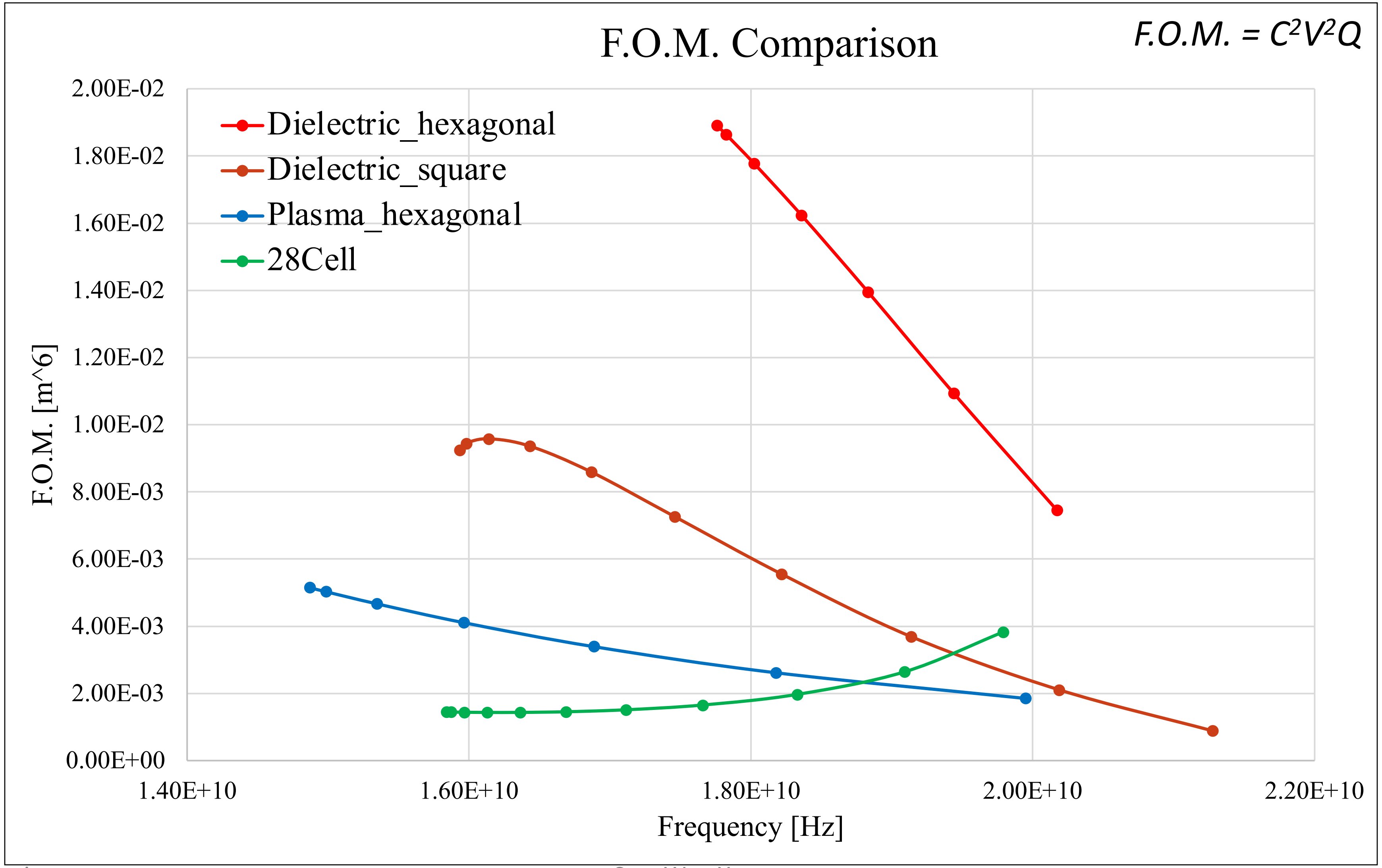






Performance comparison

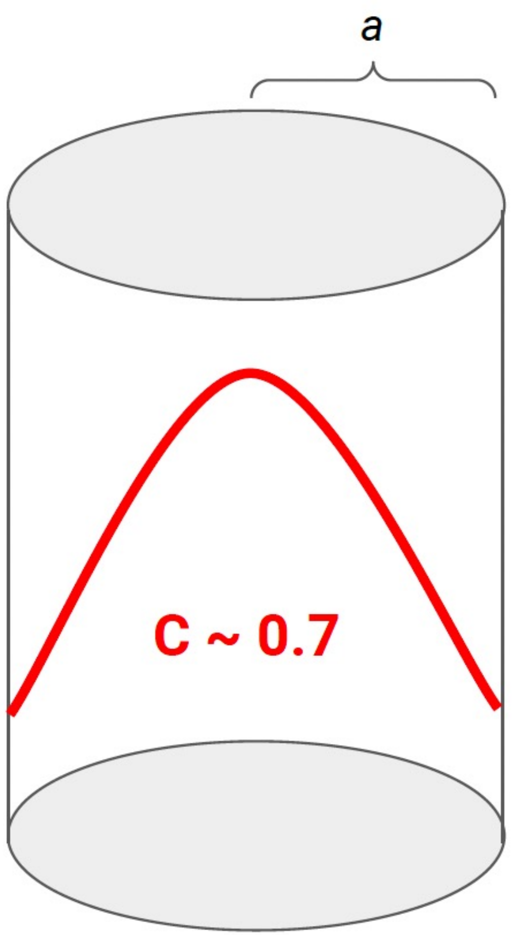
Physical Review D Vol. 107, No. 1, 015012-1-015012-8(2023)



Alpha collaboration

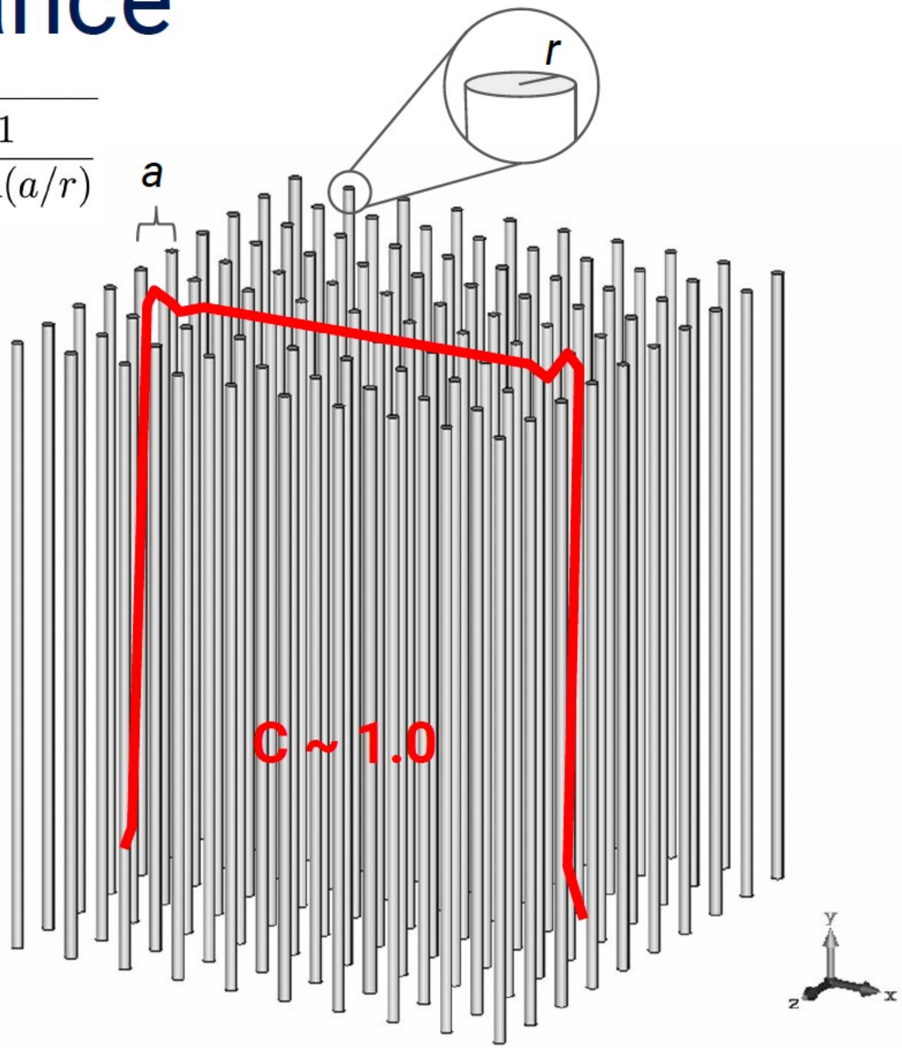
Solution: plasmonic resonance

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



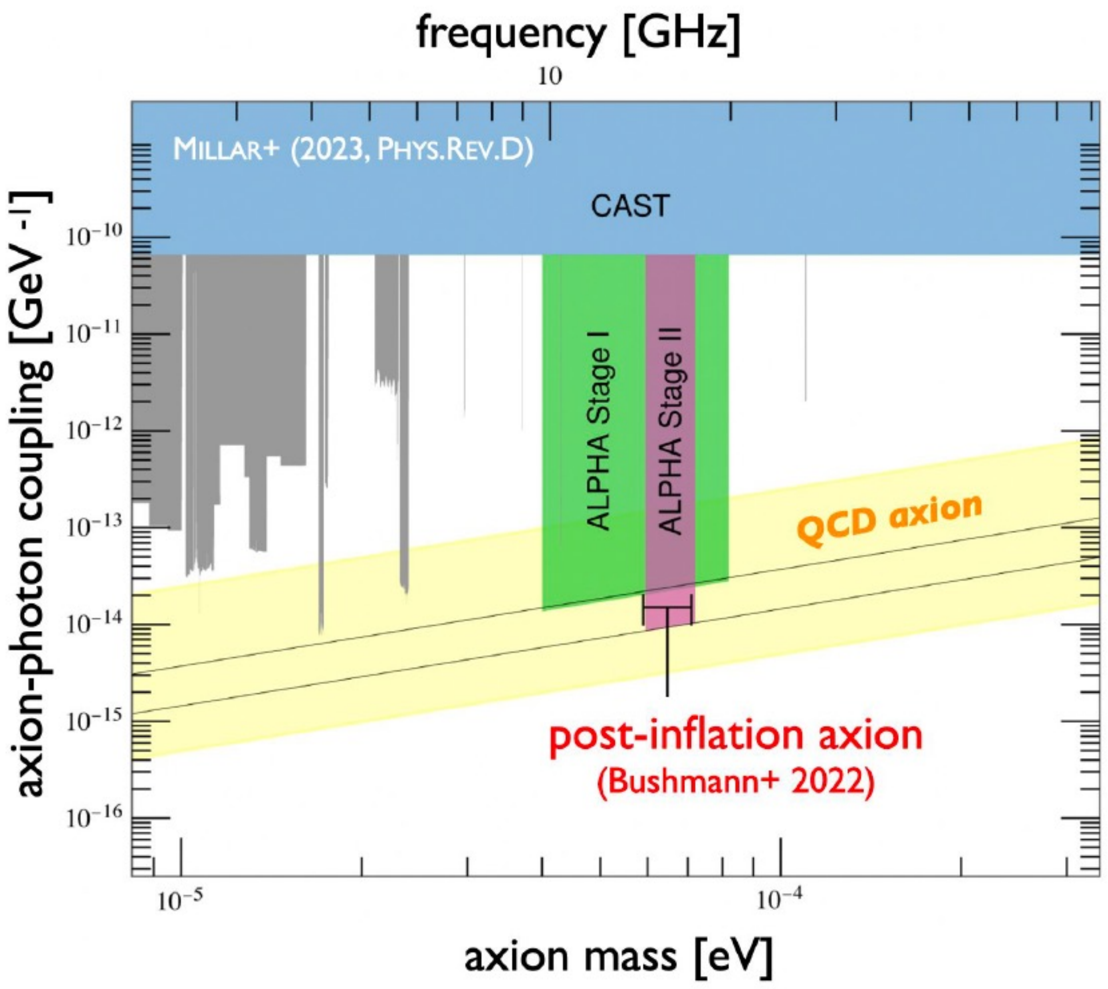
Sikivie (1983), PRL

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



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

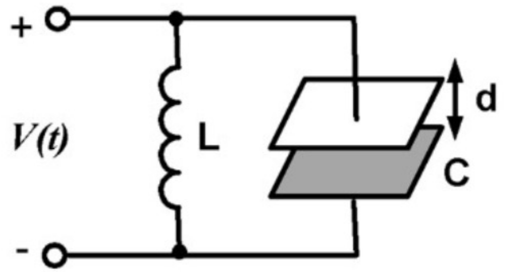
Quantum-based readout electronics

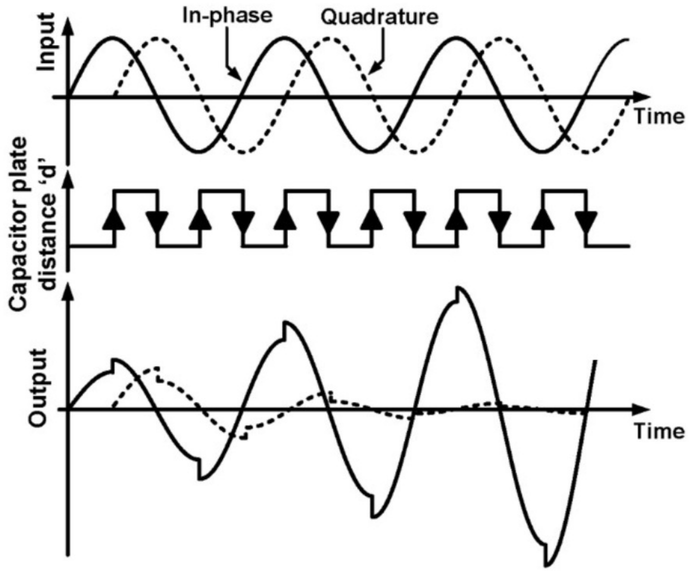
JPA Principle

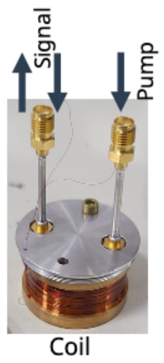
(no resistors)

JPA Principle

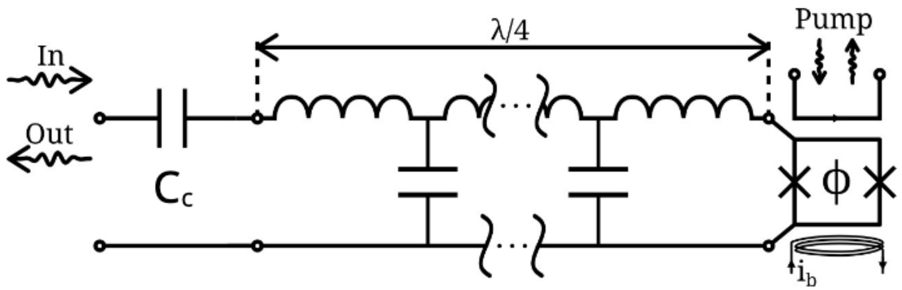
(Caglar Kutlu's slide, Sergey Uchaikin et al.)





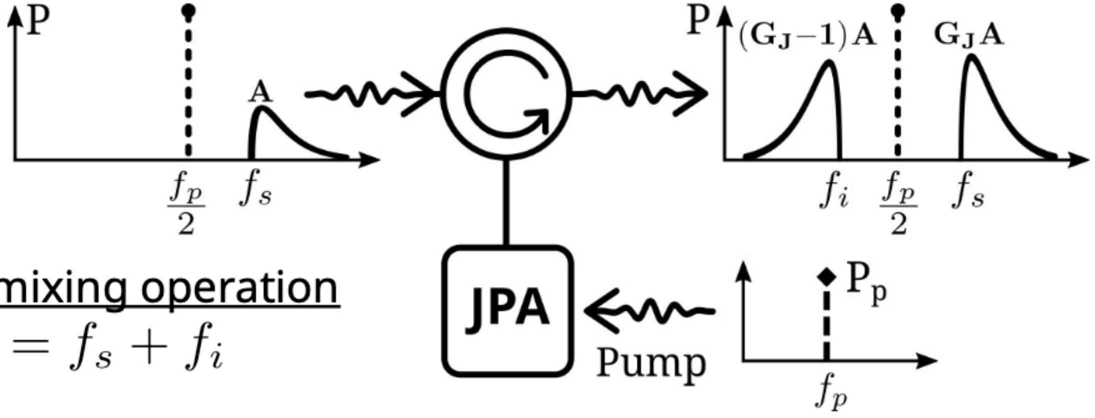


Flux-driven Josephson Parametric Amplifier



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

- 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.

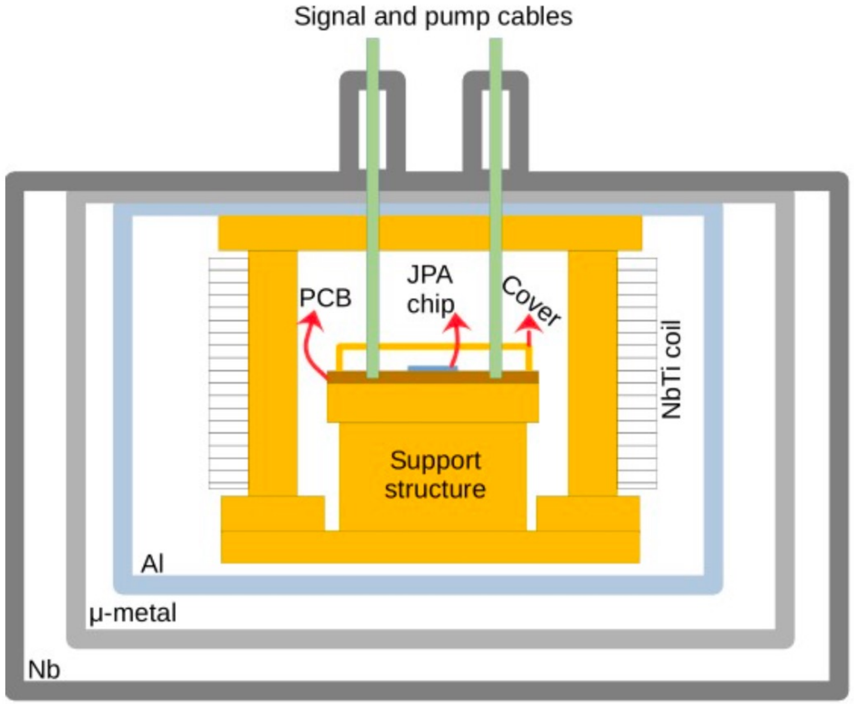


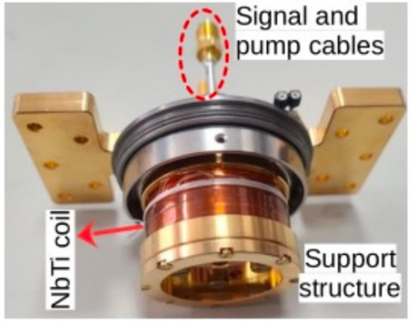
3 wave mixing operation

$$f_p = f_s + f_i$$

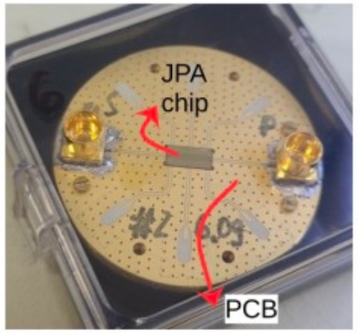
[1] W. Lee and E. Afshari, "A CMOS Noise-Squeezing Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 2, pp. 329-339, Feb. 2012

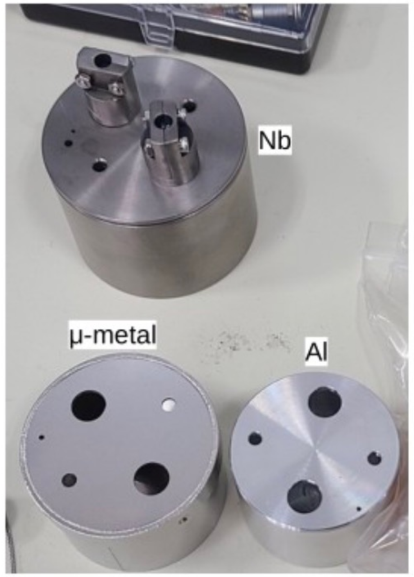
JPA implementation

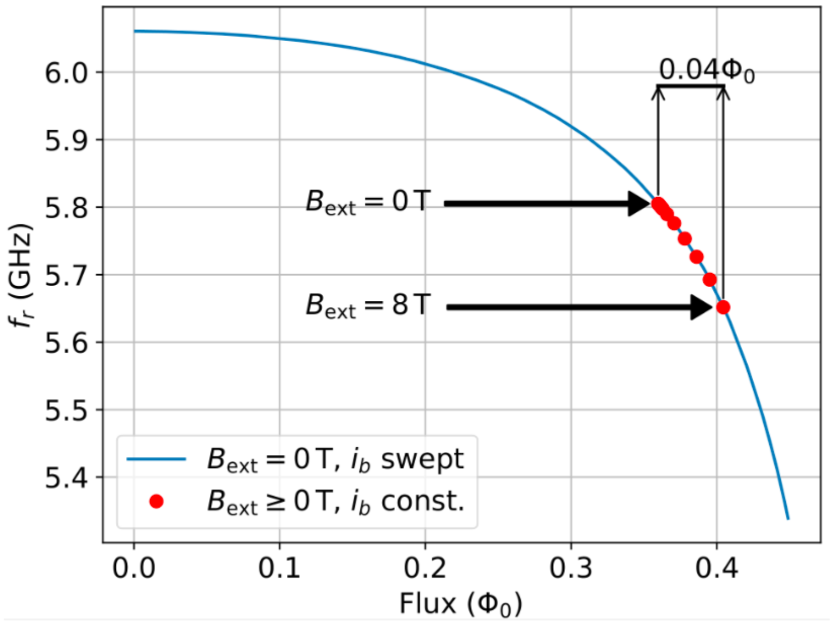




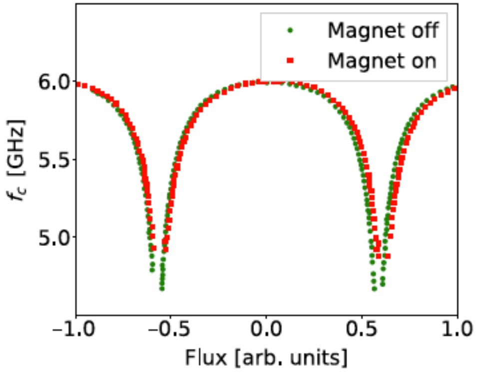
JPA packaging design: Sergey Uchaikin







Caglar Kutlu’s slide



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

CAPP
Center for Axion and Precision Physics Research

RIKEN QUANTUM COMPUTING

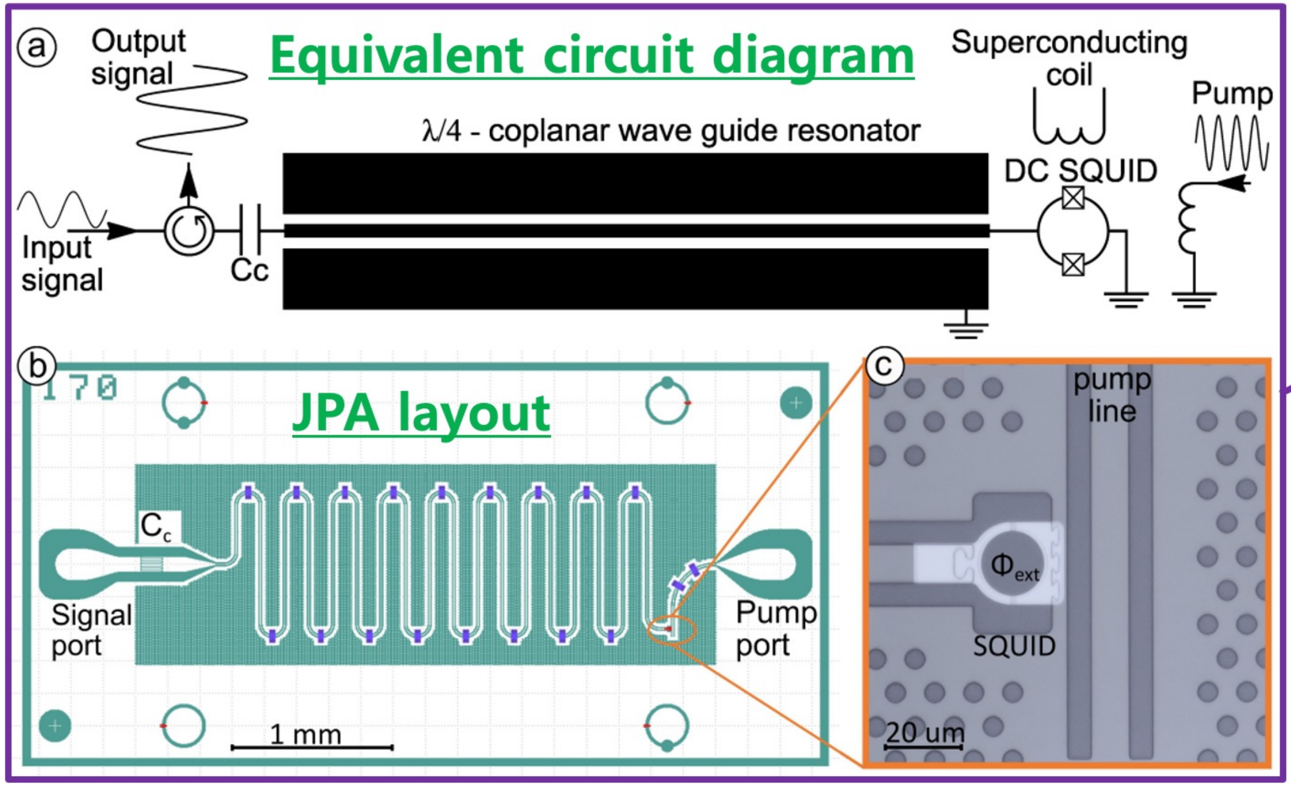
Collaboration with Yasunobu Nakamura
They made chips and IBS-CAPP packed them.

Flux-driven Josephson Parametric Amplifier

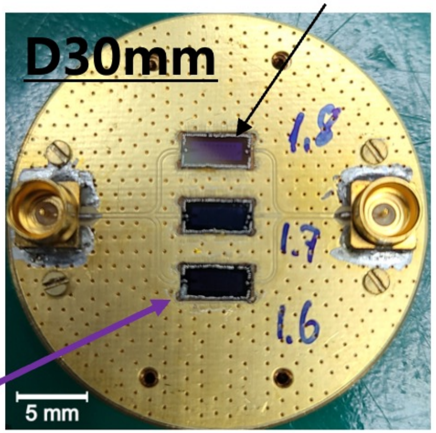
Uchaikin, et al, "Josephson Parametric Amplifier based Quantum Noise Limited Amplifier Development for Axion Search Experiments in CAPP," Frontiers in Physics **12**, 1437680 (2022).

Quantum noise limited amplifier

☒: Josephson junction

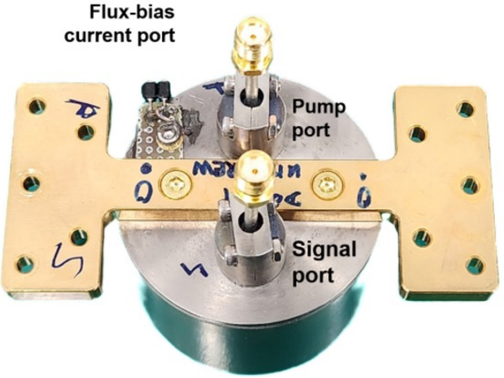


$\mathbf{2.5 \times 5\ mm^2}$



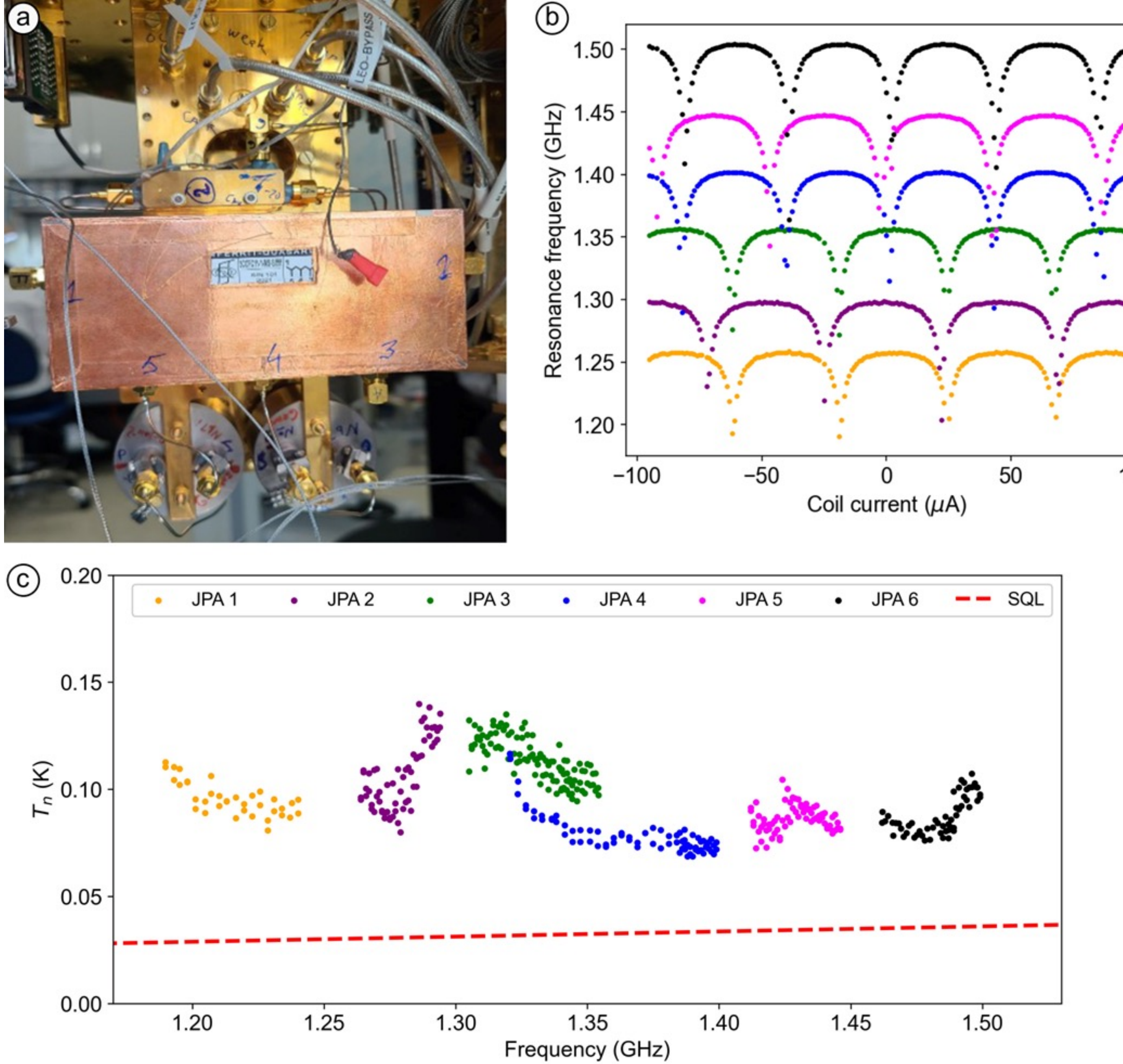
Jiwon Lee's slide

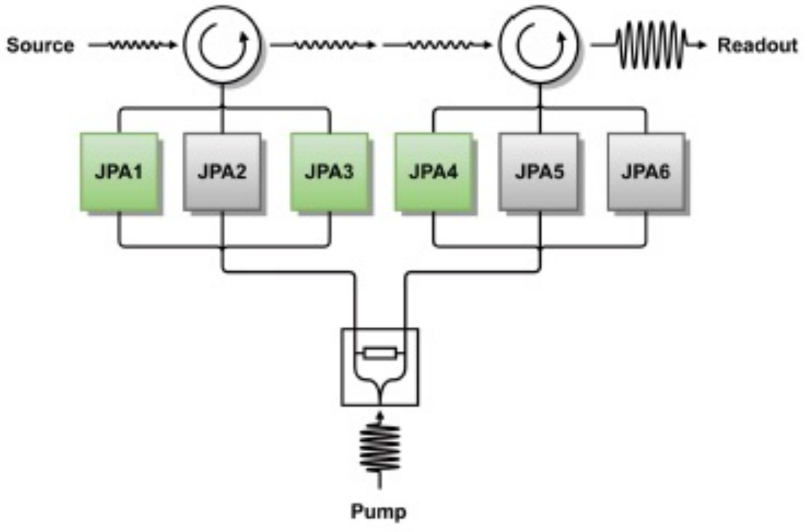
Top view of the gold-plated PCB with JPA chips bonded.



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)

Expect to scan 1.2 - 1.5 GHz at better than DFSZ, currently under commission.

Superconducting cavities in strong B-fields

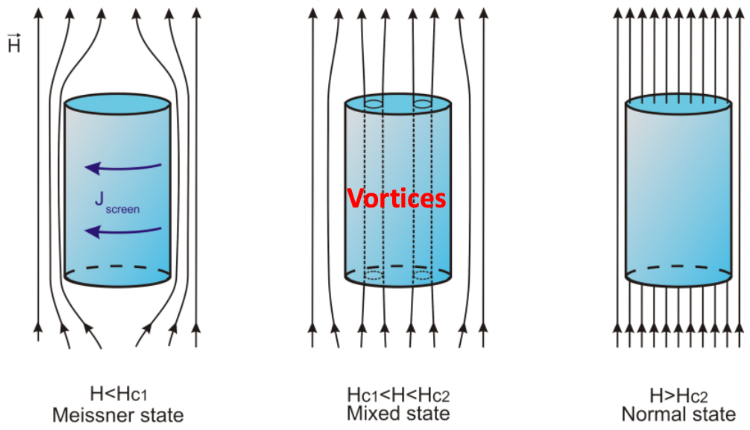
Superconducting (SC) cavities

Danho Ahn's slide,
Woohyun Chung et al.

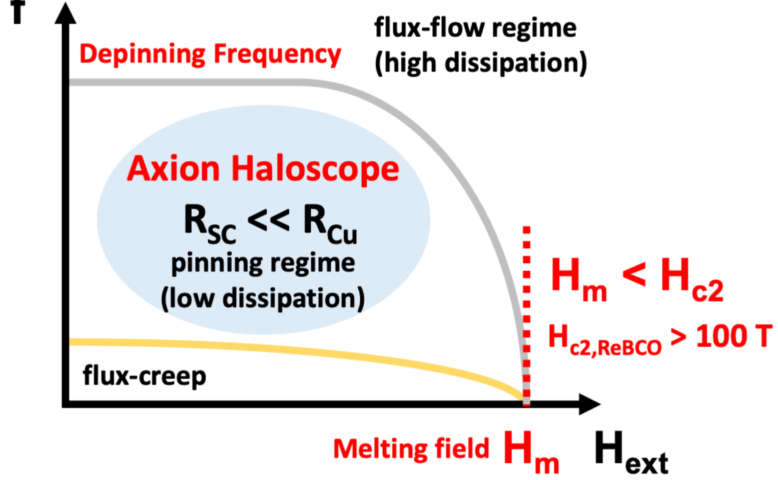
Vortex Pinning is Important for Low R_s

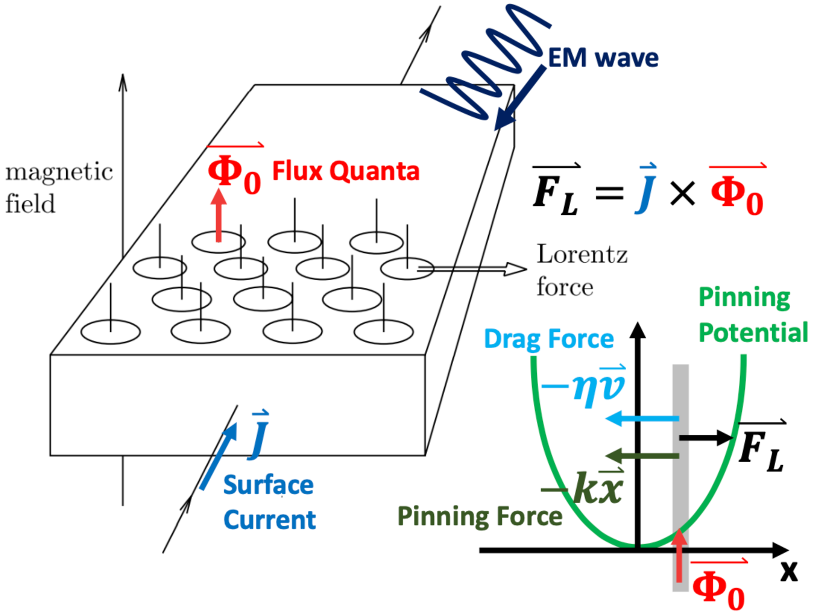
Three Phases of Type II Superconductor

https://www.cee.elektro.dtu.dk/news/nyhed?id=E6796539-A36B-4CA5-BC31-CBDBBCA335D8



Golosovsky *et al* SUST (1996) 9

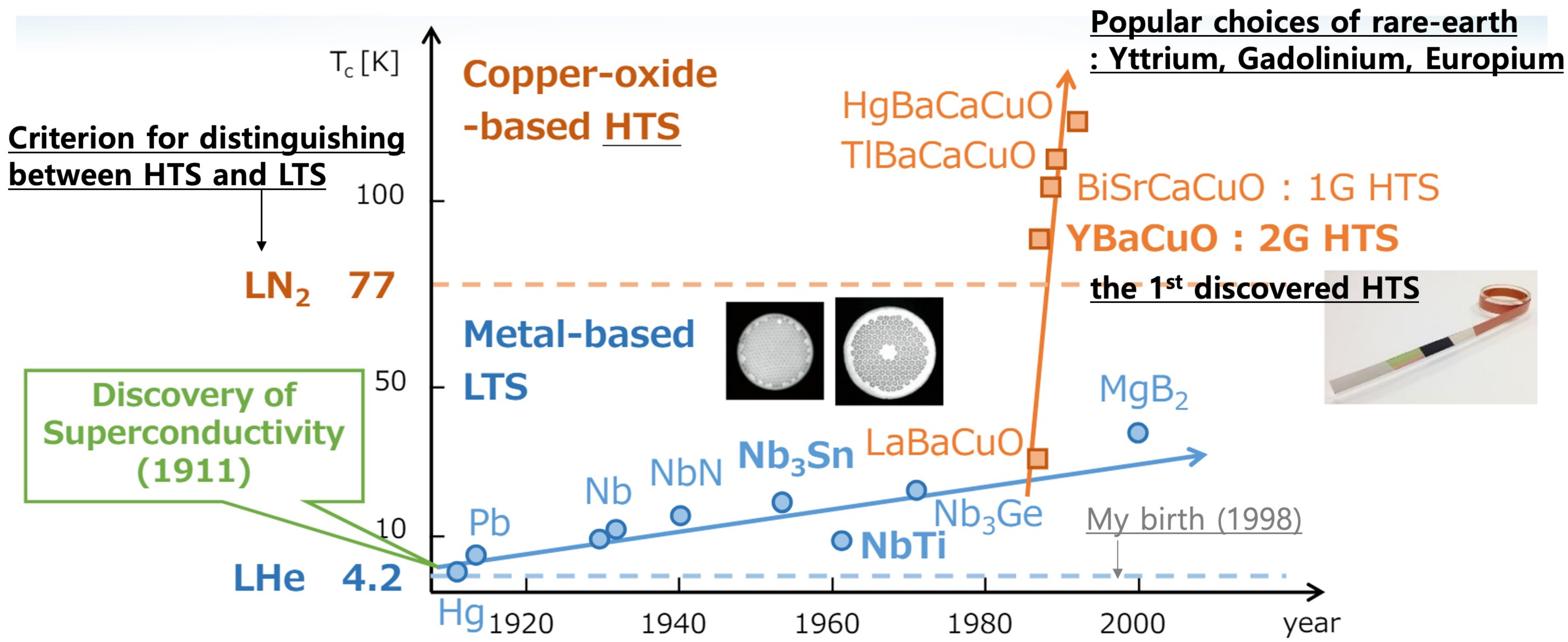




- Two criteria for evaluating materials
  - ✓ Large upper critical field (H_{c2} > 30 T)
    - Lower Vortex Density
  - ✓ High depinning frequency (ω_0 > 1 GHz)
    - $\omega_0 = k / \eta$
    - $\omega \gg \omega_0$ (Drag force ≫ Pinning force)

Jiwon Lee’s slide

Rare-earth barium copper oxide



Material Evaluation

Danho Ahn's slide

100 mK 8 GHz	R_s (B = 0 T) (Ohm)	R_s (B = 8 T, ∥c) (Ohm)	Critical Field (H_{c2})	Depinning Frequency
OFHC Cu (Metal)	~ 7E-3	~ 7E-3	None	None
Low Temperature Superconductors (LTS)				
NbTi (LTS) Gatti *et al.* PRD(2019)	~ 1E-6	~ 4e-3	Small ~ 13 T	~ 45 GHz
Nb_3Sn (LTS) Alimenti *et al.* SUST(2020)	~ 1E-6	?	~ 25 T	Small ~ 6 GHz
High Temperature Superconductors (HTS)				
Bi-2212 (HTS) Bi-2223 (HTS)	~ 1E-5	?	> 100 T (∥ab) Larbalestier *et al.* Nature(2001)	Weak Pinning ?
Tl-1223 (HTS)	~ 1E-5	~ 1e-4 Calatroni *et al.* SUST(2017)	> 100 T (∥ab) Larbalestier *et al.* Nature(2001)	12 – 480 MHz Calatroni *et al.* SUST(2017)
ReBCO (HTS)	~ 1E-5 Ormeno *et al.* PRB(2001)	**~ 1e-4** Romanov *et al.* Scientific Reports(2020)	**> 100 T (∥ab)** Larbalestier *et al.* Nature(2001)	Strong Pinning **10 – 100 GHz** Romanov *et al.* Scientific Reports(2020)

Jiwon Lee's slide

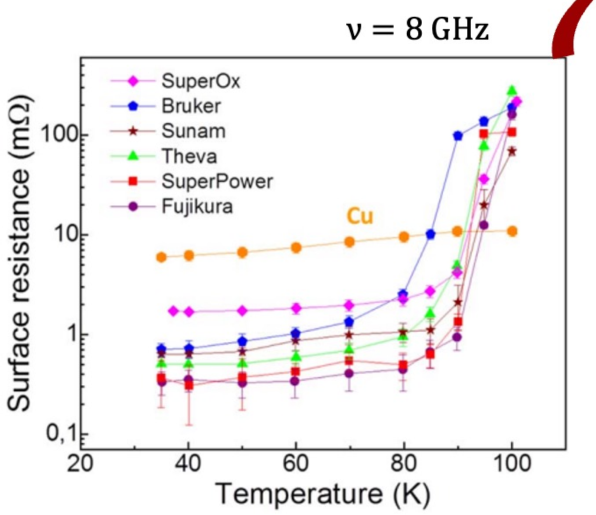
R_S(ReBCO) I did these measurements with Dr. Danho Ahn.

Theva	GdBCO
Superpower	GdBCO
Fujikura	EuBCO

- Measured R_S of the ReBCO including research at IBS-CAPP

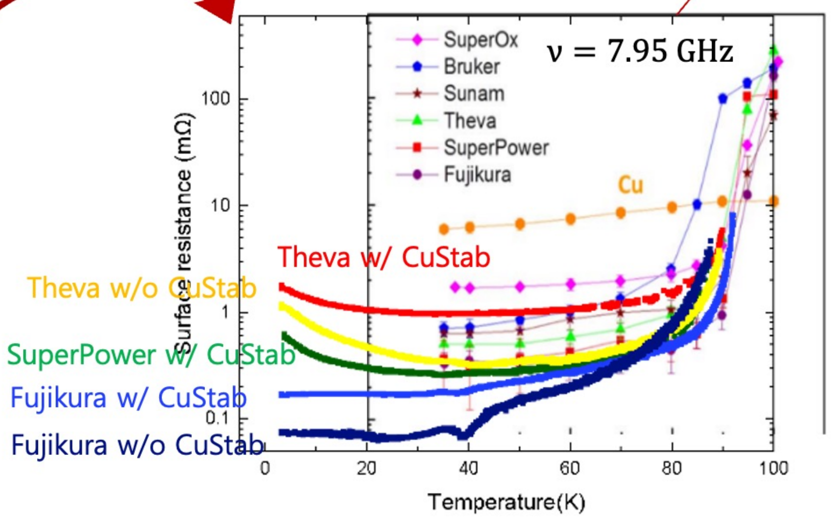
Overlapping on top of it

Measured data



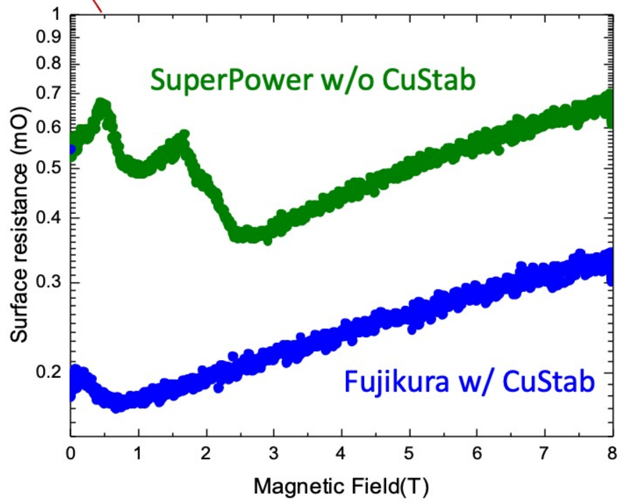
Date of the **existing** paper

T. Puig, et al, "Coated conductor technology for the beamscreen chamber of future high energy circular colliders," Superconductor Science and Technology/Superconductor Science & Technology **32**(9), 094006–094006 (2019).



When $H = 0$,
Fujikura (EuBCO) performed best (about 100× better than Cu).

$Cu \sim 7\ m\Omega$



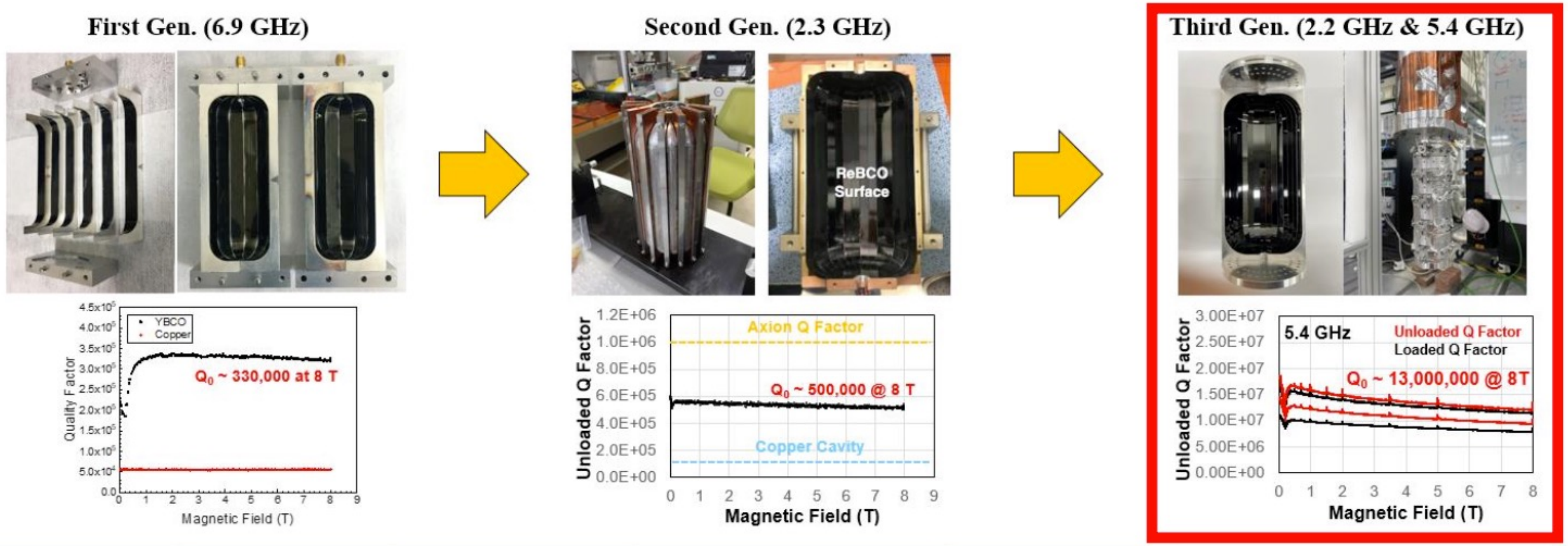
Currently in use

Even up to 8 T, the R_s did not deteriorate much.

HTS tapes: Superconducting cavities in large B-field for first time.

Danho Ahn's slide

History of HTS Cavity Development @ CAPP

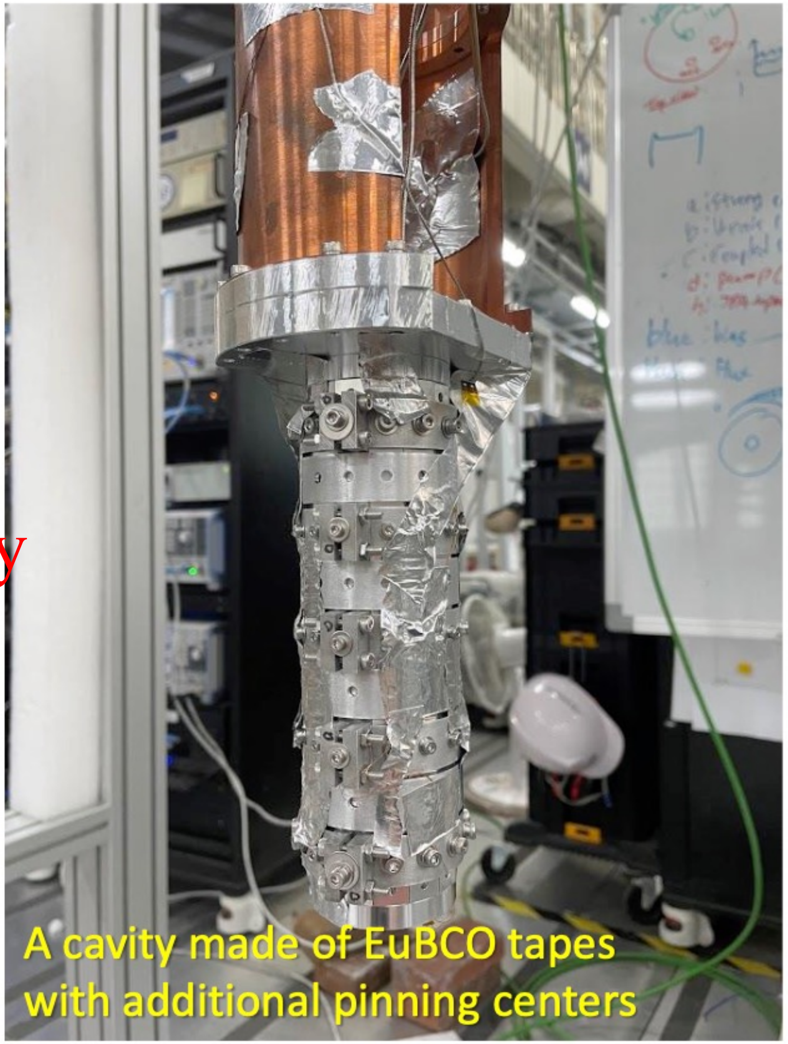


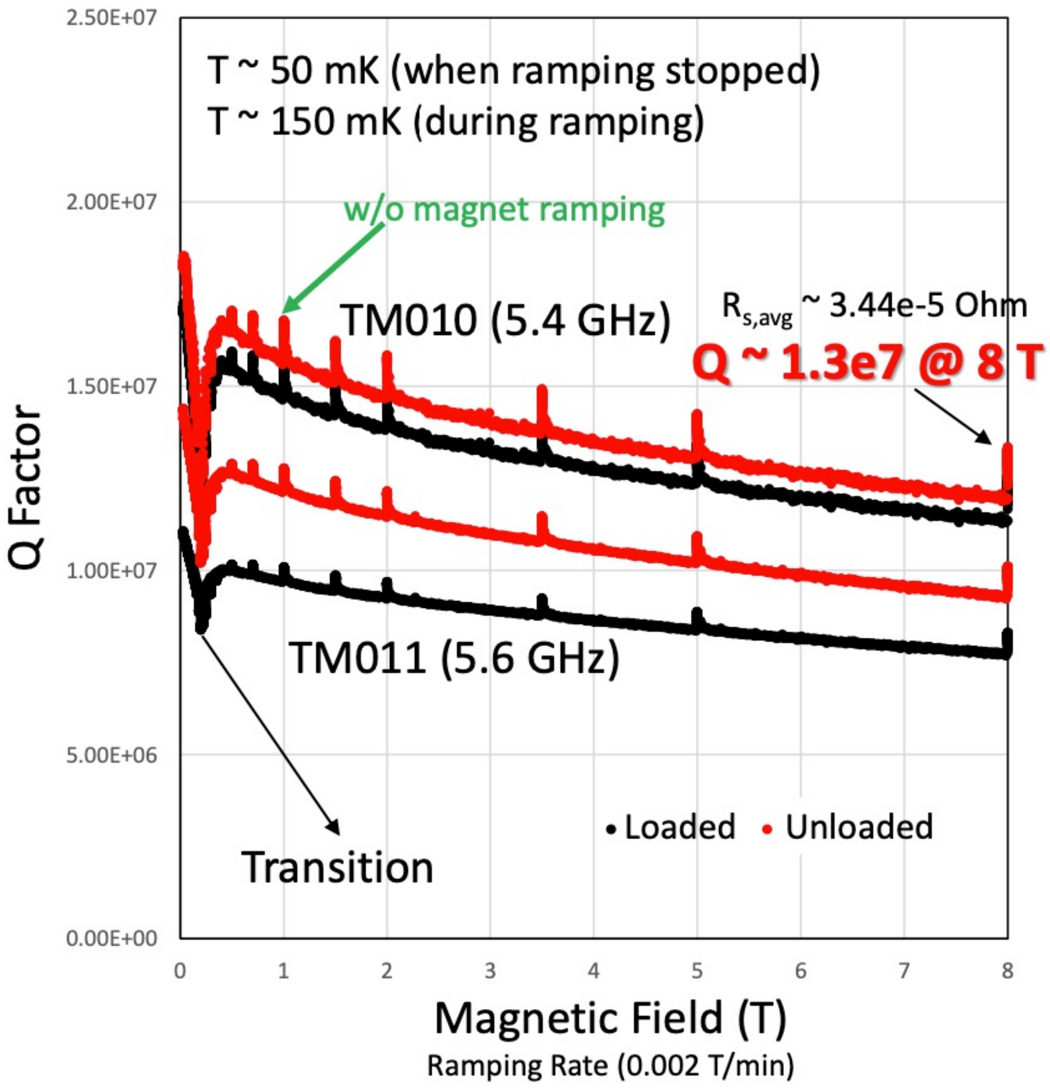
Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

Superconducting cavity with Q=13M in large B-field.

3rd Generation Cavity using EuBCO Tapes

CAPP is now running with a 34 *l* HTS cavity and 12T!



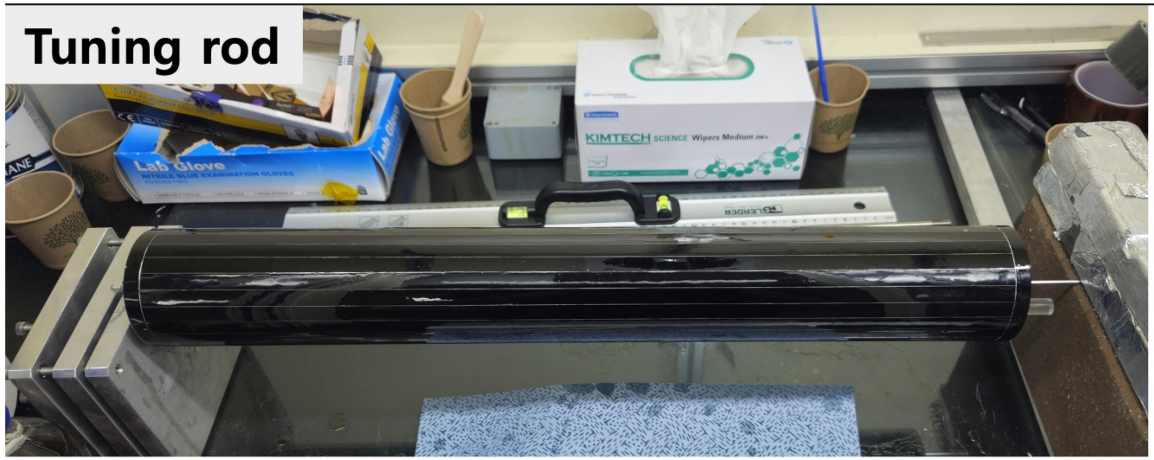


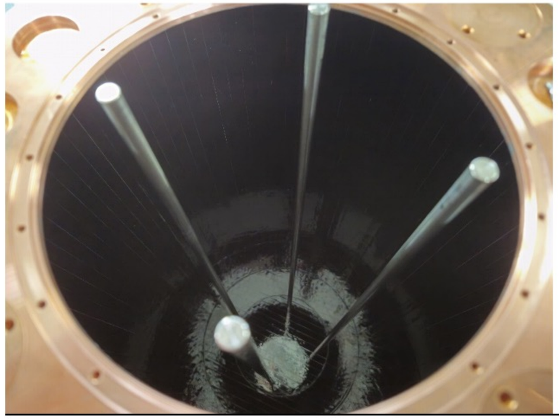
Jiwon Lee's slide

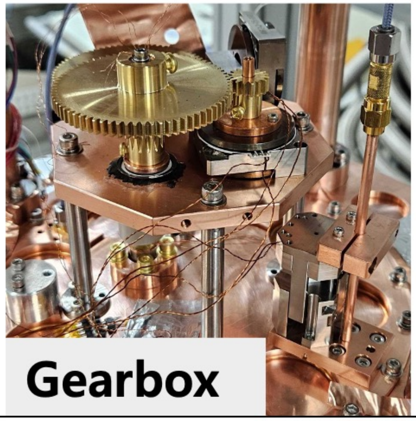
Q-factor is about 14 times better than Full Cu ULC.

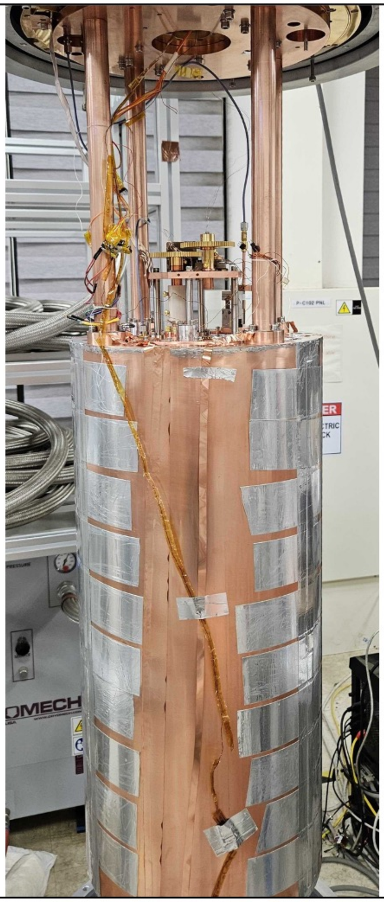
Full-HTS-ULC fabrication process

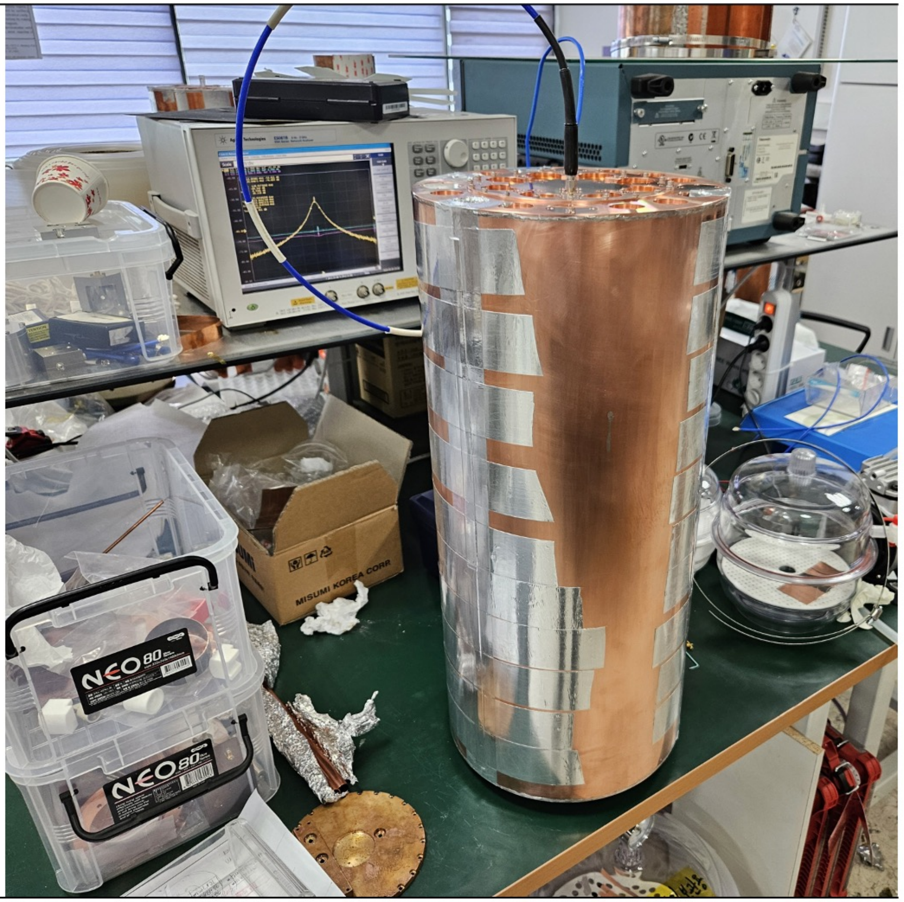
RF measurement w/ HTS tuning rod







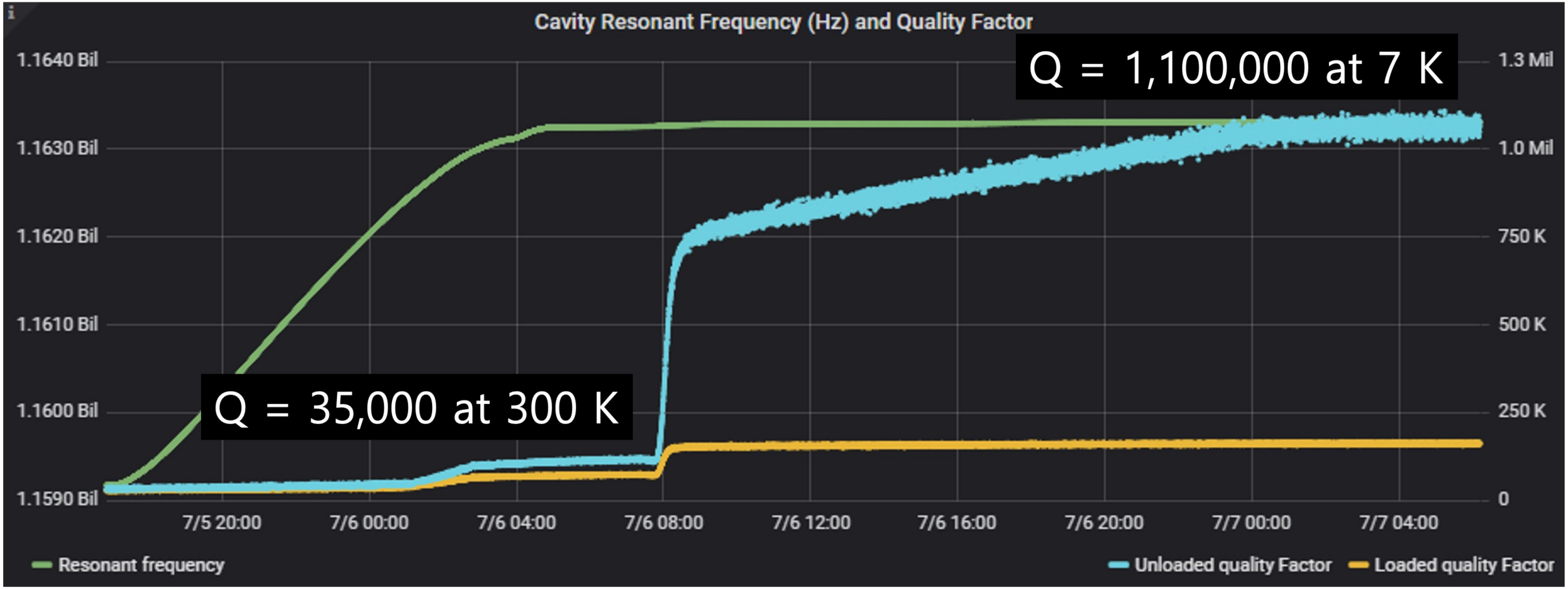




Jiwon Lee's slide

Full-HTS-ULC fabrication process

RF measurement w/ HTS tuning rod



CAPP-PACE Detector

HTS cavities speed up scanning rates

	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** arXiv:2207.13597, PRL (in process) (Mr. Jinsu Kim *et al.*)	**SC Run** In process
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	**1.5 L**
Quality Factor (Q_0)	100,000	100,000	**500,000**
Geometrical Factor (C)	0.51 – 0.66	0.45	0.51 – 0.65
System Noise (T_{sys})	~ 1.1 K	**~ 200 mK**	**~ 180 mK**
Scan Rate (Norm.) $\propto B^4V^2C^2Q_0/T_{sys}^2$	**1**	**18**	**310**

Higher B-field magnets

LTS-12T/320mm from Oxfrod Instruments

Magnet delivered early March 2020 but couldn't be comissioned due to COVID-19

- Fully commissioned end of 2020 delivering 12T max field (5.6MJ)

The CAPP-MAX, our flagship experiment

based on the LTS-12T/320mm magnet

- Axion to photon conversion power at 1.15 GHz
  - KSVZ: 6.2×10^{-22} W or ~10^3 photons/s generated
  - DFSZ: 0.9×10^{-22} W or ~10^2 photons/s generated

- With total system noise of 300mK, $Q_0=10^5$, eff. = 0.80
  - KSVZ: 25 GHz/year
  - DFSZ: 0.5 GHz/year
- With total system noise of 200mK, $Q_0=10^5$
  - KSVZ: 50 GHz/year
  - DFSZ: 1 GHz/year Published work (PRX 2024)
- With total system noise of 100mK (150mK), $Q_0=10^5$
  - KSVZ: 200 GHz/year (90 GHz/year)
  - DFSZ: 4 GHz/year (1.7 GHz/year)

The CAPP-MAX, our flagship experiment
based on the LTS-12T/320mm magnet

- Axion to photon conversion power at 1.15 GHz
  - KSVZ: 6.2×10^{-22} W or $\sim10^{3}$ photons/s generated
  - DFSZ: 0.9×10^{-22} W or $\sim10^{2}$ photons/s generated

- With total system noise of 300mK, $Q_0=10^5$, eff. = 0.80
  - KSVZ: 25 GHz/year
  - DFSZ: 0.5 GHz/year
- With total system noise of 200mK, $Q_0=10^5$
  - KSVZ: 50 GHz/year
  - DFSZ: 1 GHz/year
- With total system noise of 125mK, $Q_0=1\times10^6$
  - DFSZ: 1-2 GHz/year for 20% of dark matter as axions
  - DFSZ: 2-4 GHz/year, 4-8 GHz/year, 20% ADM

Current work

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

- IBS-CAPP is scanning at DFSZ sensitivity for axions over 1 GHz in 2022, first time.

- Currently, we have a 34liter HTS cavity in 12T, with much better than DFSZ sensitivity and >3MHz/day scanning rate.

- IBS-CAPP has demonstrated that the original IBS idea was correct: target a great science subject, fund it properly, and allow independence.

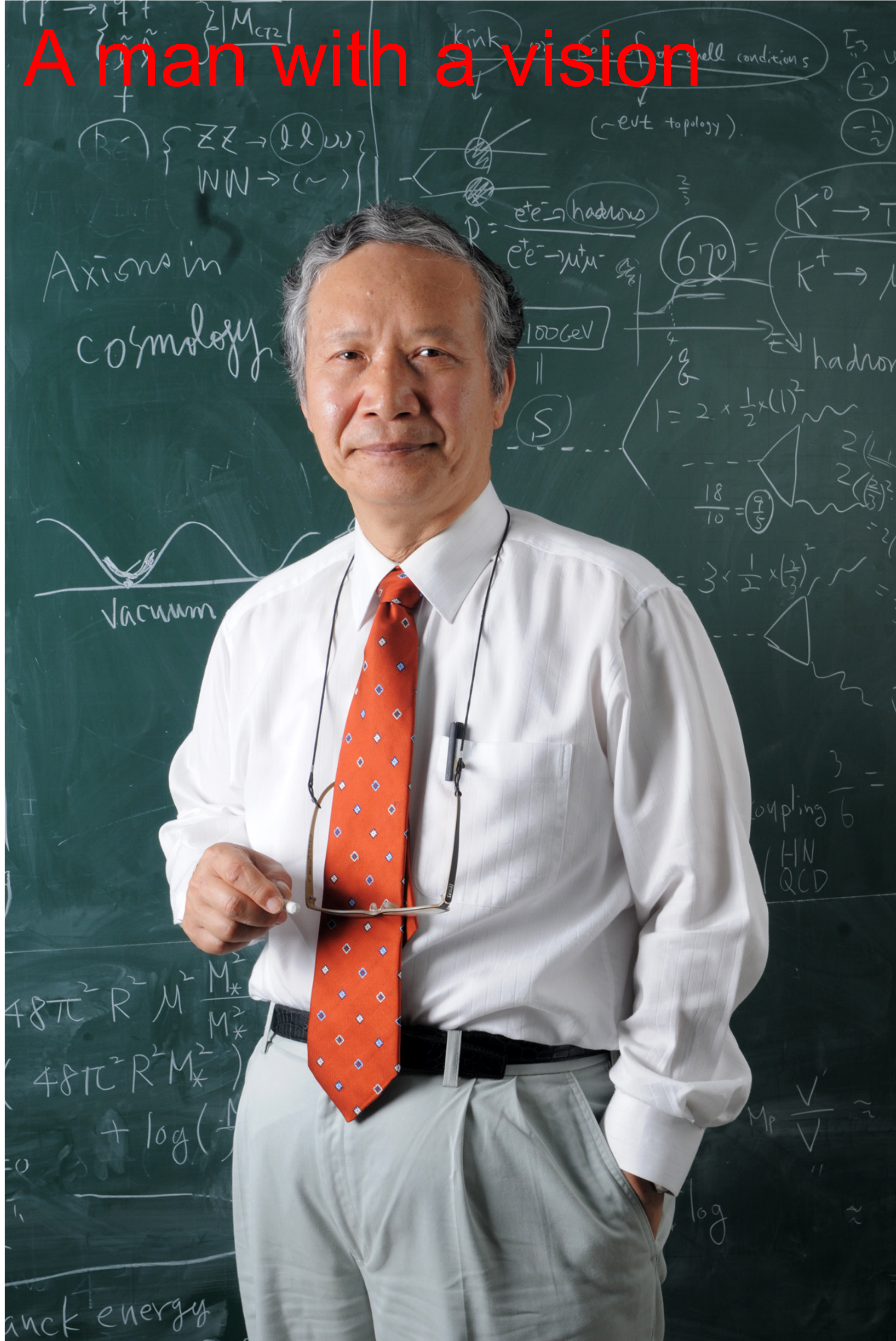
Photo: KAIST Munji Campus, January 2023

Professor Jihn E. Kim

He worked hard to establish IBS-CAPP to make axions Visible.

We (IBS-CAPP) honored our commitment, and we proved the original IBS idea to be correct.

IBS-CAPP science will continue after December 2024 at KAIST. IBS and KAIST agreed to collaborate closely (IBS's involvement level to be finalized in November, 2024).



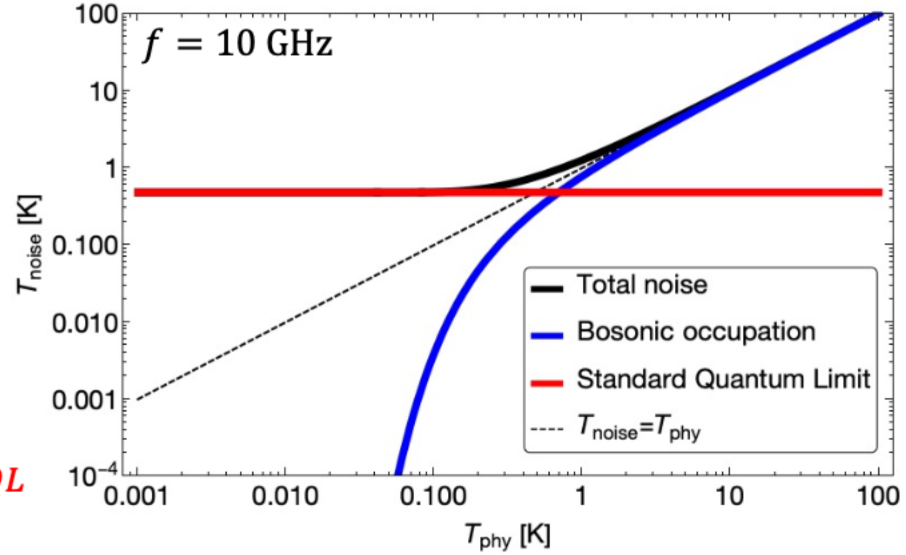
Equivalent noise temperature

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 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 (quality factor $>10^6$) pave the path to the high frequency. It's getting very close to a major running system.

QUAX, INFN

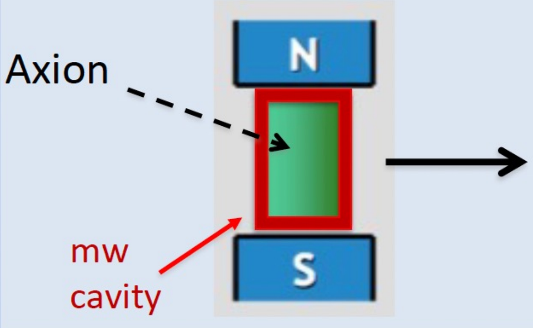
QUAX experiment in Italy

Using innovation and quantum RF-readout to make progress

QUAX – QUaerere AXion

Main Activity

- **Photon coupling: Due to the motion of the solar system in the galaxy, Dark Matter axions** are converted into **rf photons** inside a **resonant cavity** immersed in a **strong magnetic field**

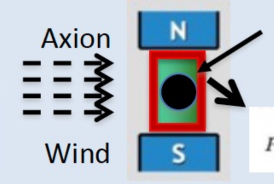


Expected rf power

$$P_a = 1.85 \times 10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2 \times \left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

R&D Activity

- **Electron coupling:** the axion DM cloud acts as an **effective RF magnetic field** on electron spin exciting magnetic transitions in a magnetized sample and **producing rf photons**



Expected rf power

$$P_{\mathrm{out}} = \frac{P_{\mathrm{in}}}{2} = 8 \times 10^{-26}\left(\frac{m_a}{2\cdot 10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{V_s}{1\ \mathrm{liter}}\right)\left(\frac{n_S}{10^{28}/\mathrm{m}^3}\right)\left(\frac{\tau_{\min}}{10^{-6}\,\mathrm{s}}\right)\mathrm{W},$$

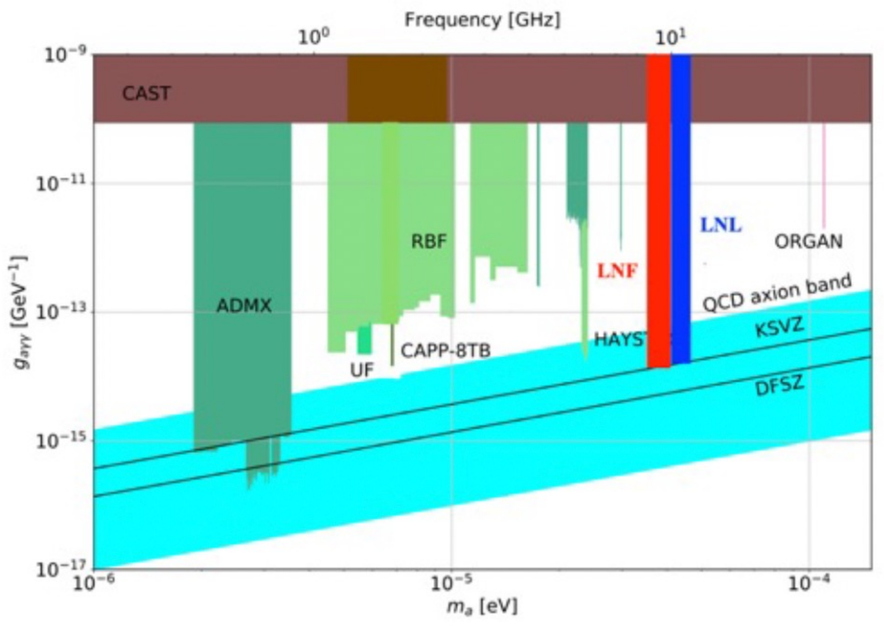
QUAX

Projection at 8.5 -11 GHz

QUAX Experiment

- The **INFN has approved the QUAX experiment** to run an observatory for searching axion via the **axion-photon coupling**
- The R&D activity on the axion – electron coupling will proceed with low priority
- **Two haloscopes** will be built: one in **Legnaro** and the other in **LNF**

	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	7⊗0.15 liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK



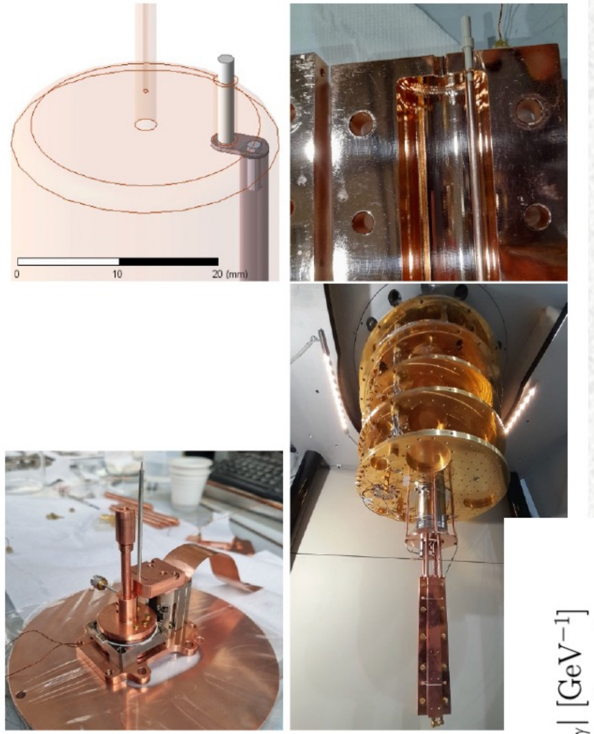
Quax 2025 projection: 2 GHz scan to the KSVZ line

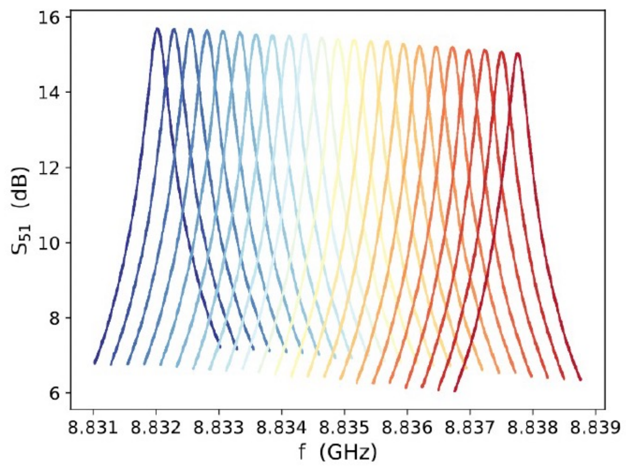
- The **LNL haloscope** will be based on dielectric cavities, travelling wave parametric amplifiers and 14 T magnet
- Cryogenic system: Dilution Refrigerator to work below 60 mK

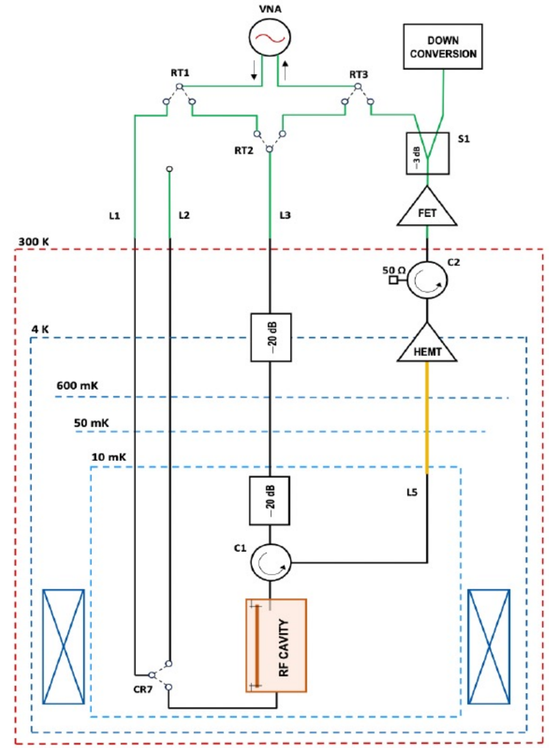
QUAX

Current status at 8.5 -11 GHz

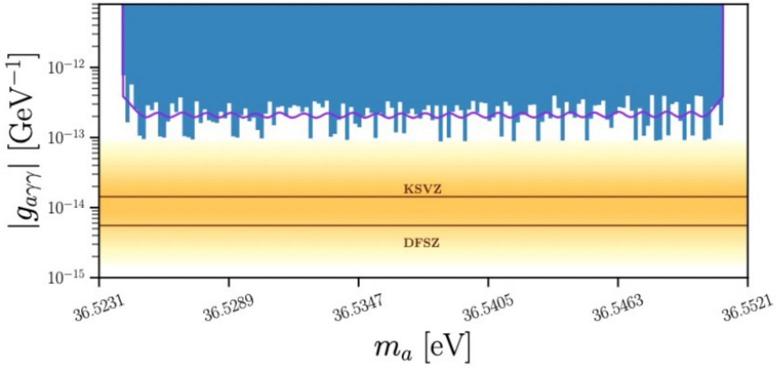
Search for Axion dark matter with the QUAX–LNF Tunable Haloscope

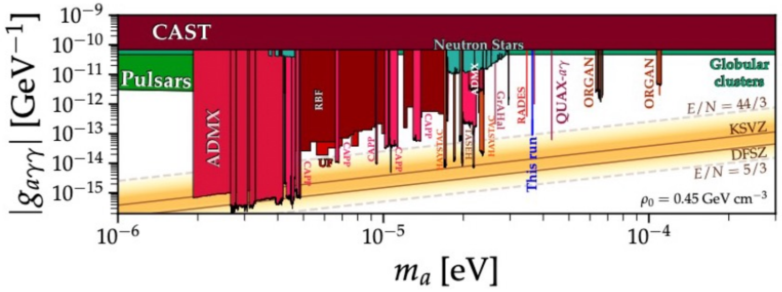






Autumn Run with JPA





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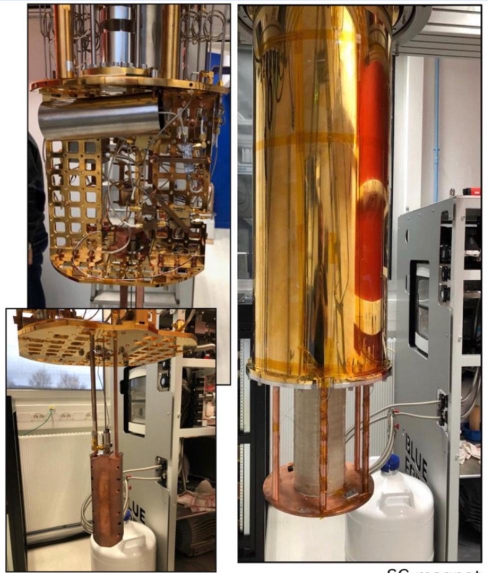
QUAX experiment in Italy

Significant progress in single photon detection

Single Photon Detection – First Test @ Saclay

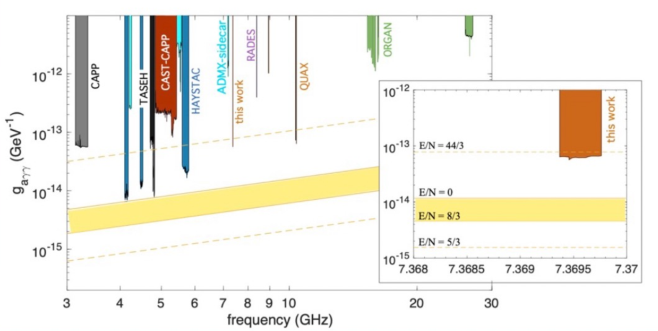


SMPD (top) and cavity

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



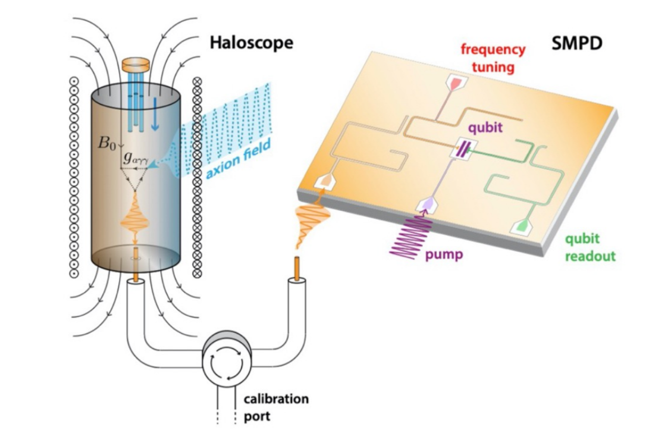
https://arxiv.org/abs/2403.02321

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

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

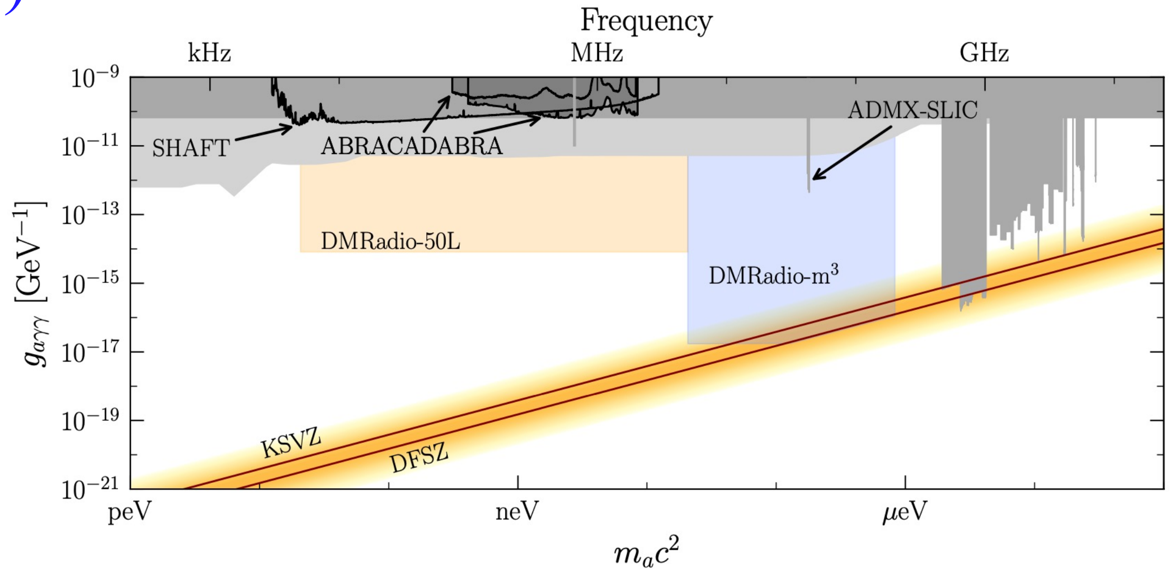
Improvement in scanning speed with SMPD

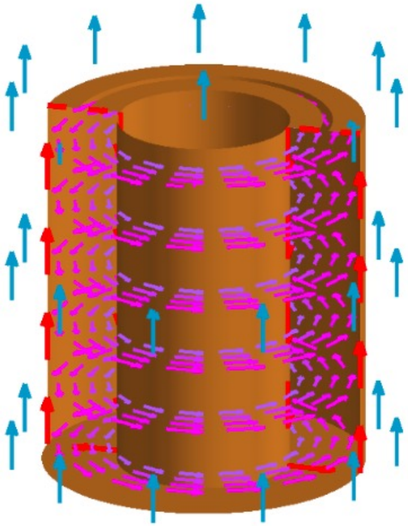
$$\eta^2 \frac{\Delta\nu_a}{\Gamma_{\mathrm{dc}}}$$

The low-frequency domain

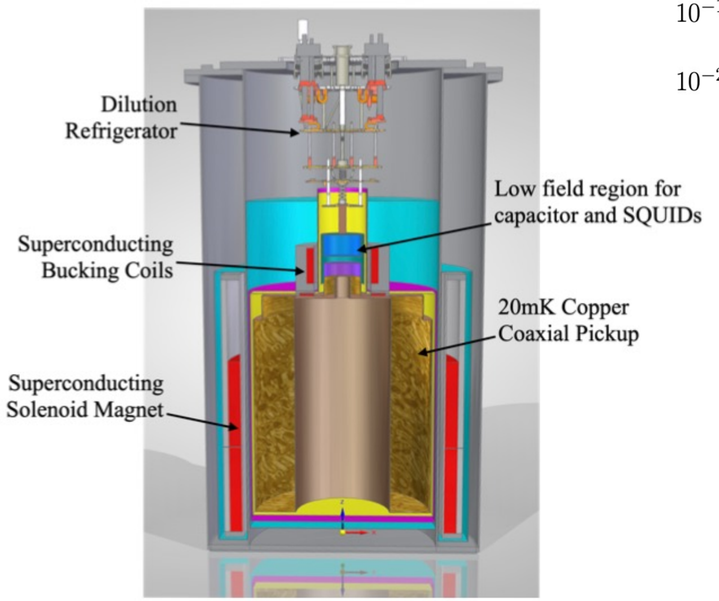
Dark-Matter Radio, probing the low frequency axions at SLAC/USA

Low frequencies (long Compton wavelength) favor induction coil detection



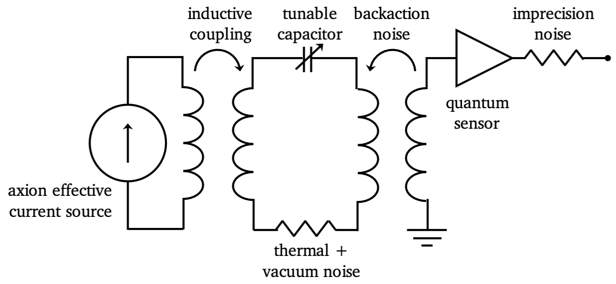


(a)



(b)

Dark Matter Radio, 2203.11246



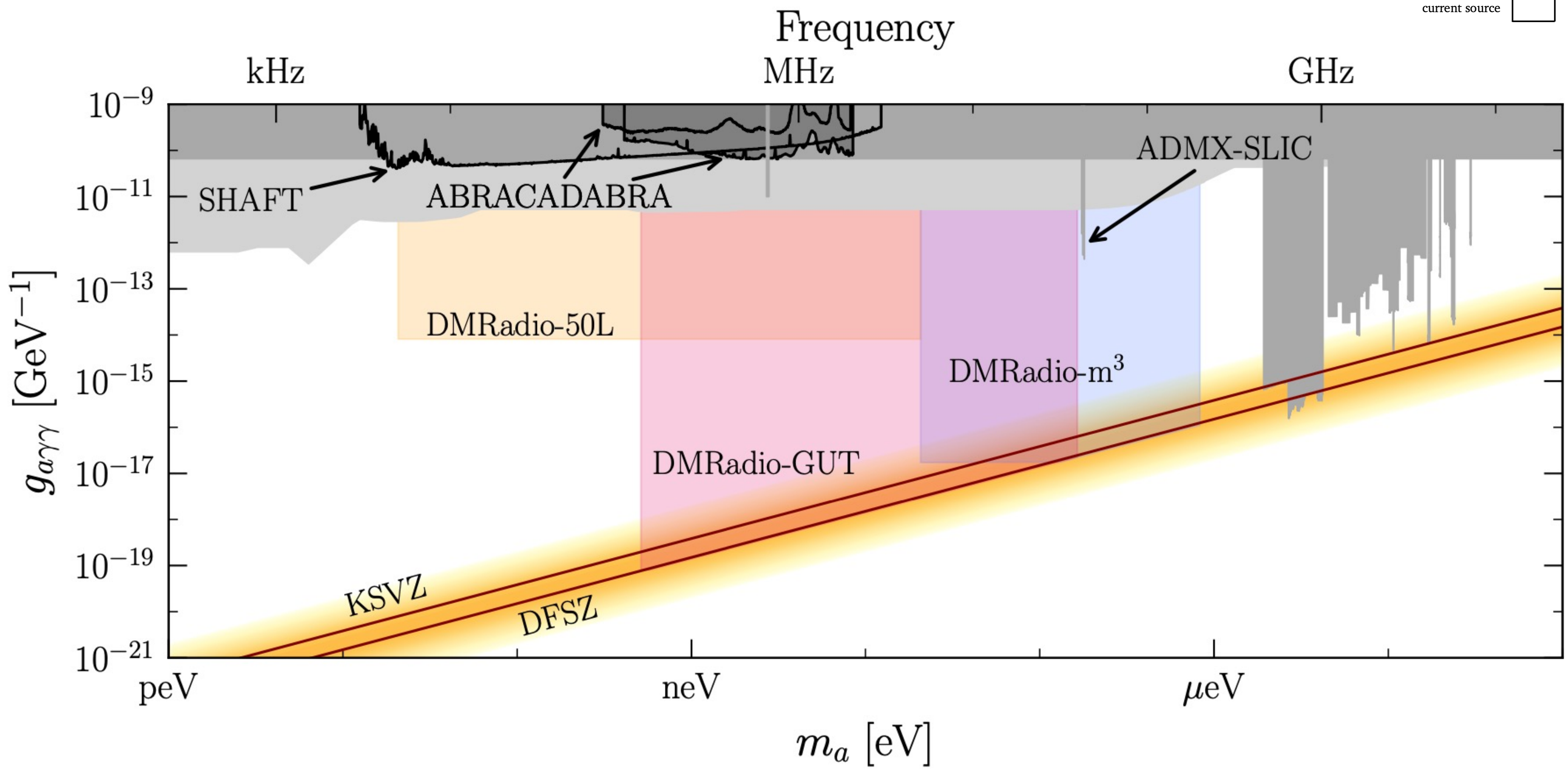


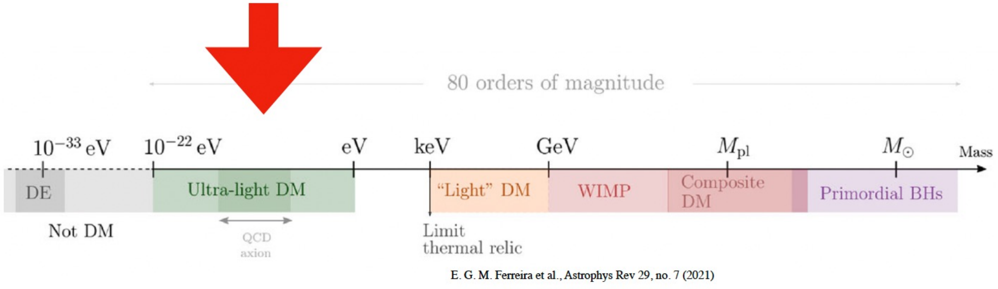
FIG. 4. Projected sensitivity for DMRadio-GUT in pink. The total scan time to cover this reach is ∼ 6 years, depending on R&D outcomes. Various scenarios are outlined in Table II. Existing limits are shown in grey.

Haloscopes using spins

Cosmic Axion Spin Precession Experiment (CASPEr)

Slide material from Arian Dogan, Mainz, 2024

CASPEr-Gradient



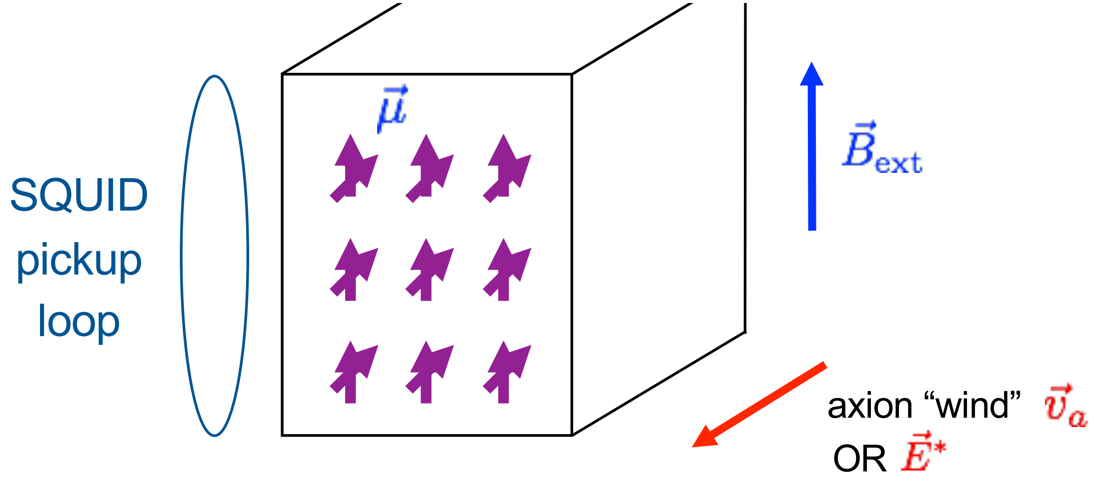
Axionlike Particles (ALPs)

- Coupling to nuclear spin $\vec{I}$
- $H = g_{aNN} \vec{\nabla} a(t) \cdot \vec{I}$
- The ALP-gradient $\vec{\nabla} a$ acts as a pseudo-magnetic field
- g_{aNN} as coupling constant and $a(t) = a_0 \cos(\omega \cdot t)$
- The Compton frequency $\omega = \frac{m c^2}{\hbar}$

Couplings between Axionlike Particles (ALPs) and Standard Model particles in CASPEr:

1) ALPs - gluon coupling -> CASPEr-Electric

2) ALPs - fermion coupling -> CASPEr-Gradient



Larmor frequency = axion mass ➔ resonant enhancement

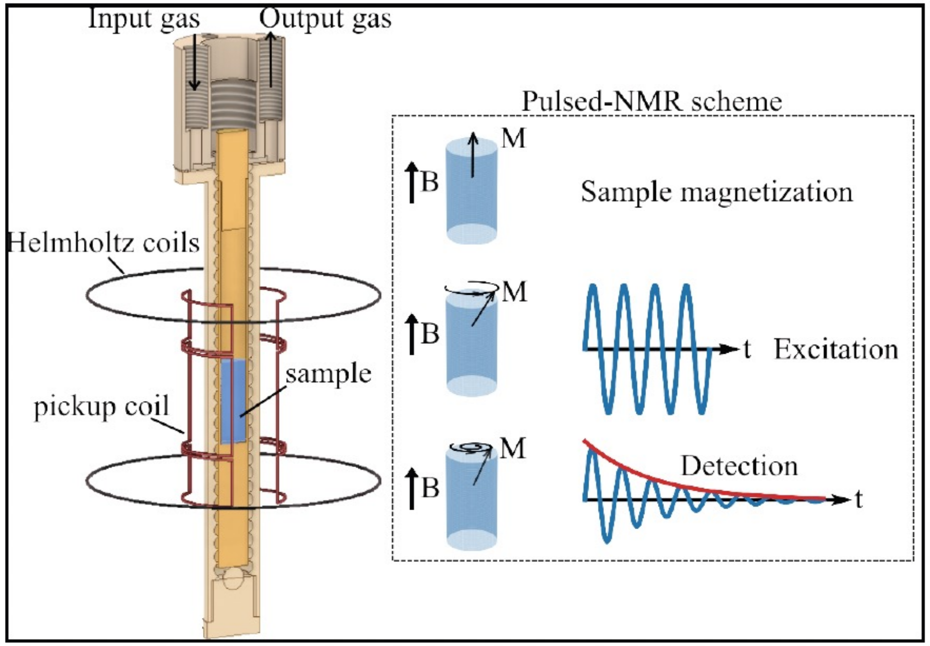
SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

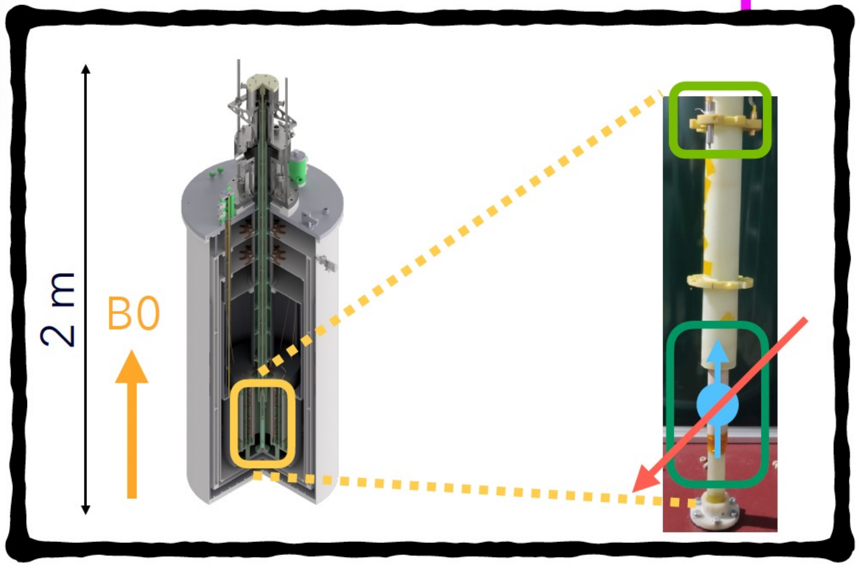
Slide material from Arian Dogan, Mainz, 2024

- **Transfer HP Xe to Low field setup (0.1 T)**
  -> Will increase sensitivity by 6 orders of magnitude
  -> As an alternative higher thermally polarized sample
- **Transport of hyperpolarized Xe to the High field setup (14 T) or using other candidates**

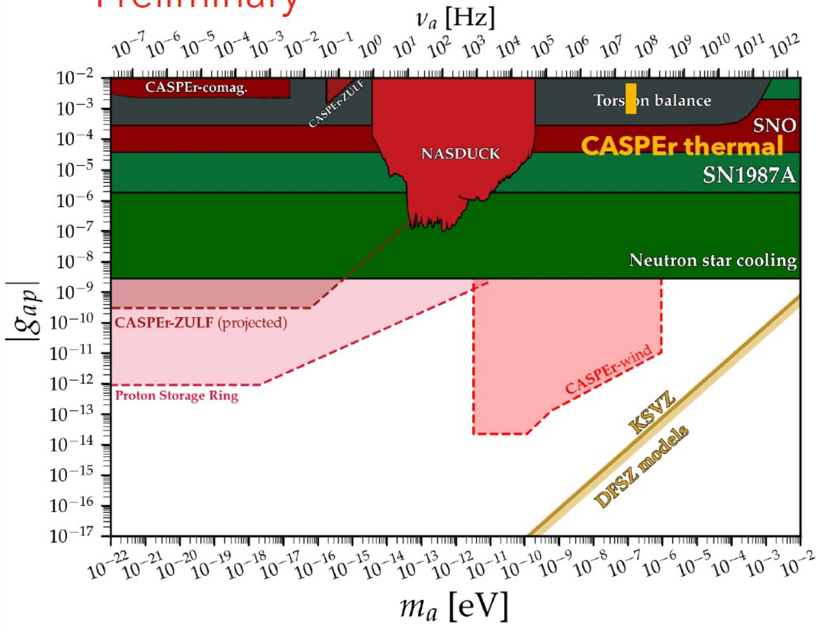
Liquify Xenon



ALP detection setup



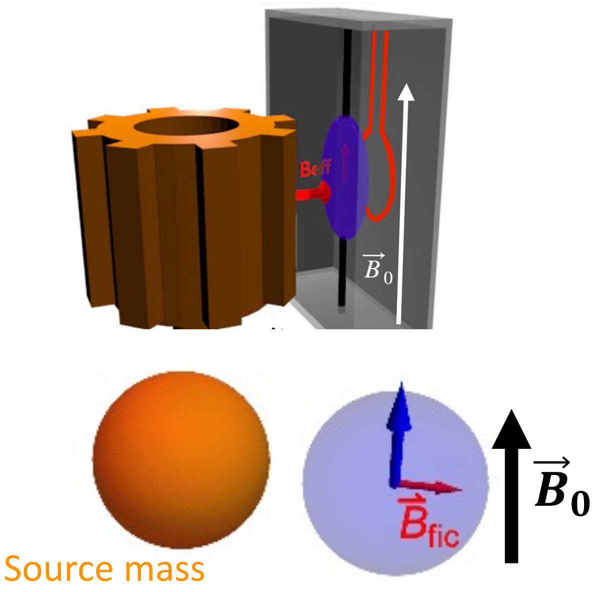
Preliminary



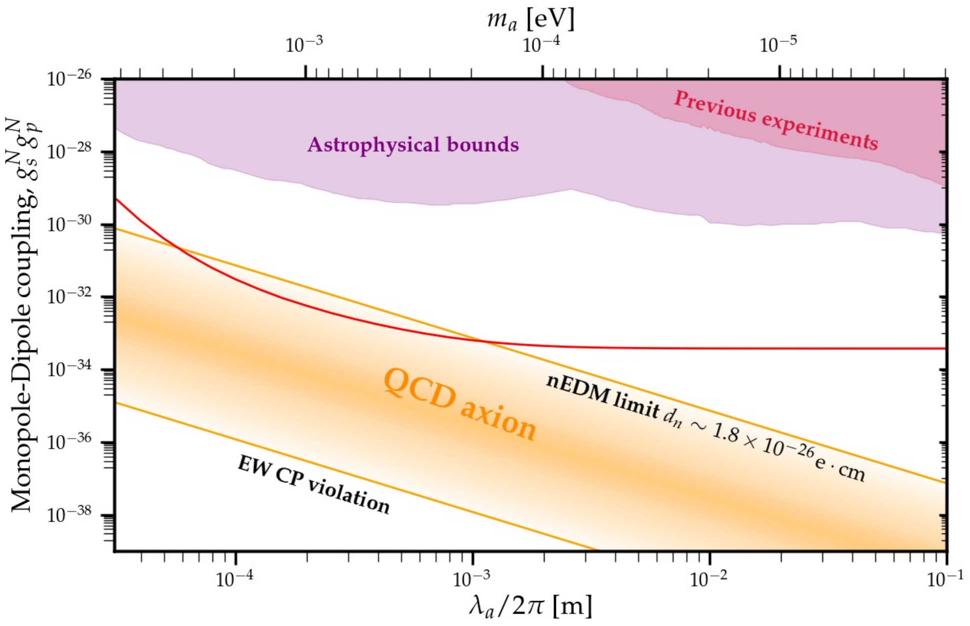
1) Low field setup: frequency range KHz - MHz
2) High field setup: frequency range - 600 MHz
3) DM search & analysis works for a 240 Hz frequency range

ARIADNE

Axion source: nuclear mass. The axion field gradient acts on fermion spins



Experimental scheme



Projected Sensitivity (first phase)

- Fictitious magnetic field B_{fic}:

$$\vec{B}_{\text{fic}} = \frac{\hbar g_s g_p}{8\pi\gamma_p M_p}(\vec{\sigma}\cdot\hat{r})\left(\frac{2\pi}{\lambda_a r}+\frac{1}{r^2}\right)e^{-2\pi r/\lambda_a}\hat{r}$$

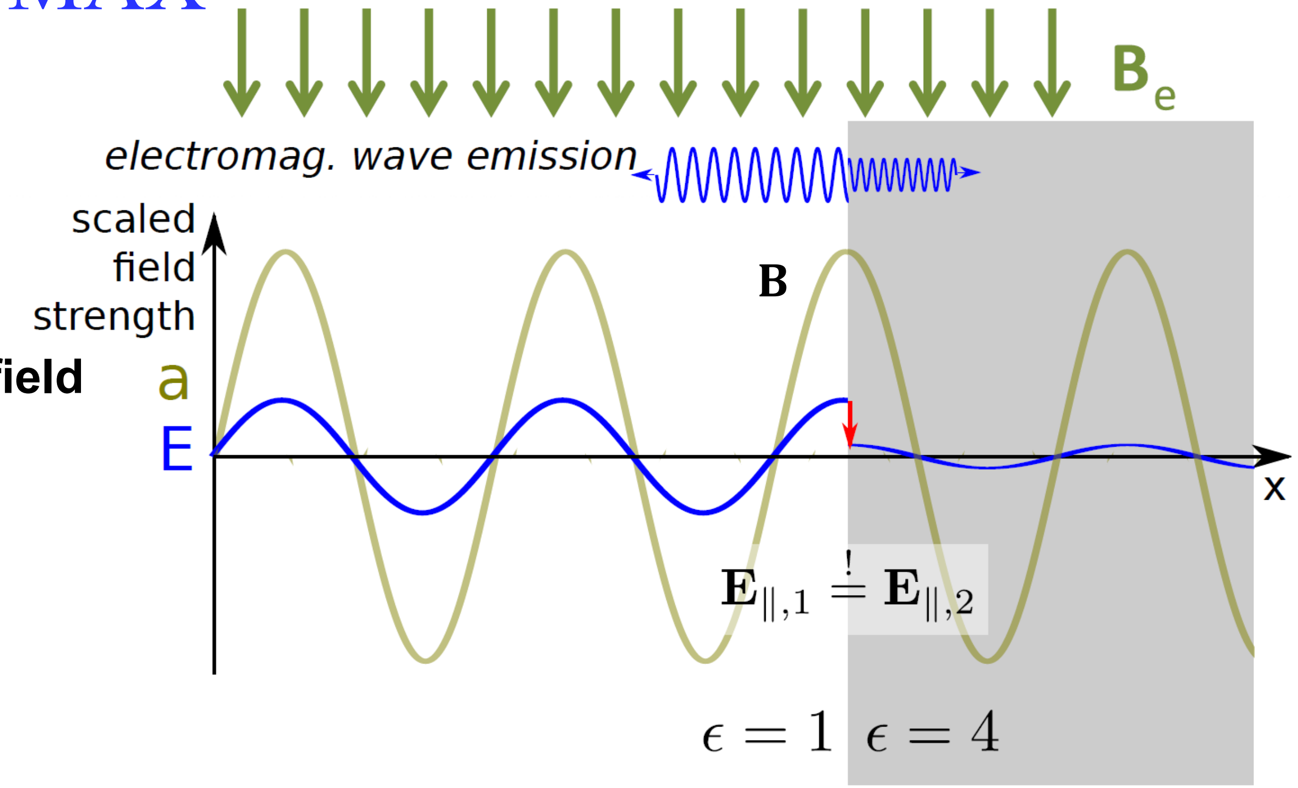
- Spin system resonantly enhance B_{fic}
- Scan broad axion mass range from one measurement.

Plan

- Now in R&D of sub-components
- First Prototype measurement in 2022
- Full scale exp. In 2024

Haloscopes with dielectrics

MADMAX

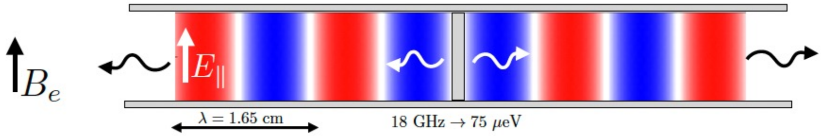


Mixing of axion with photon in extrenal B-field
→ Sources oscillating E-field
At surfaces with transition of ε: Discontinuity of E-field
→ Emission of photons

Dielectric haloscope principle

The 2D toy haloscope

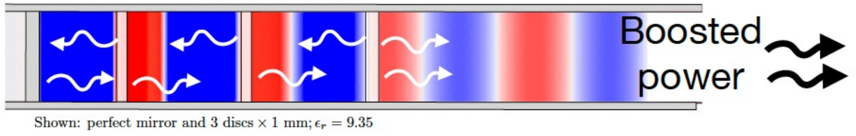
Emission from a perfect mirror



Tiny output power even for a high B-field and a large mirror:

$$P_{sig} = 2.2 \cdot 10^{-27} \mathrm{W} \left(\frac{A}{1\mathrm{m}^2}\right)\left(\frac{B_e}{10\mathrm{T}}\right)^2 \left(\frac{g_{a\gamma}}{m_a}\right)^2$$

Emission from a booster



Output power boosted relative to the mirror emission:

$$P_{sig} = 2.2 \cdot 10^{-27} \mathrm{W} \left(\frac{A}{1\mathrm{m}^2}\right)\left(\frac{B_e}{10\mathrm{T}}\right)^2 \left(\frac{g_{a\gamma}}{m_a}\right)^2 \beta^2$$

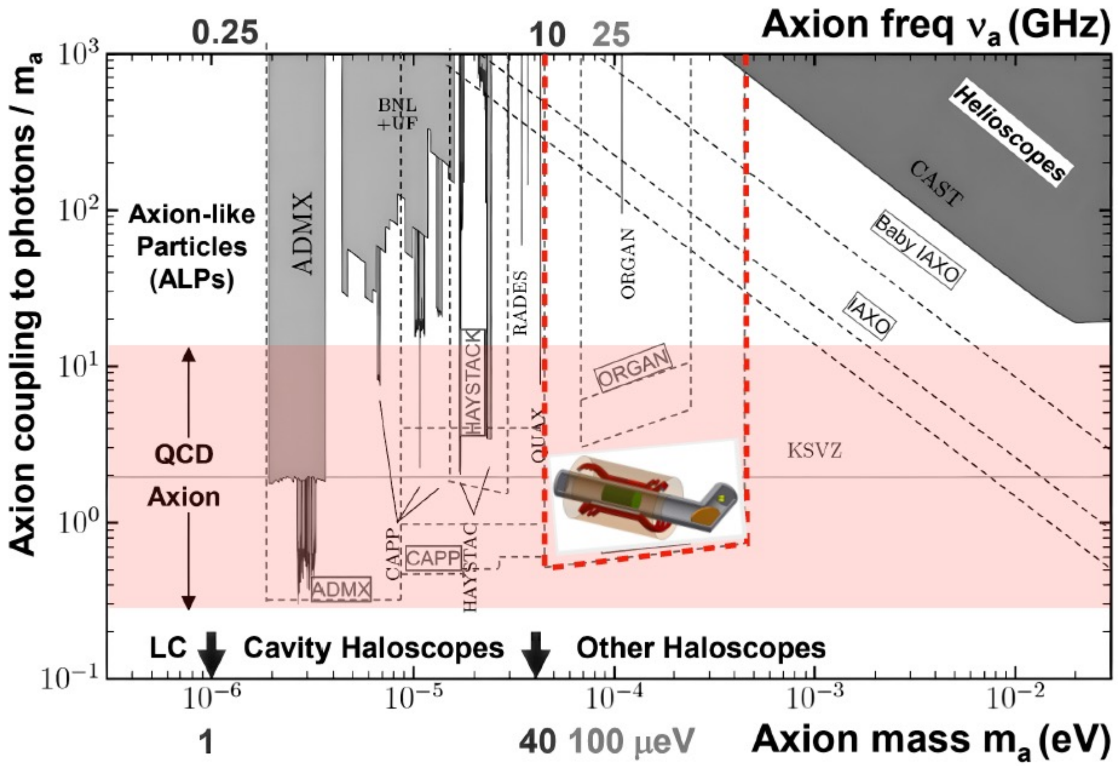
Power "Boost factor" β^2

$$\beta^2 = \frac{P_{booster}}{P_{mirror\ only}}$$

Currently running a prototype experiment using the Morpurgo magnet at CERN

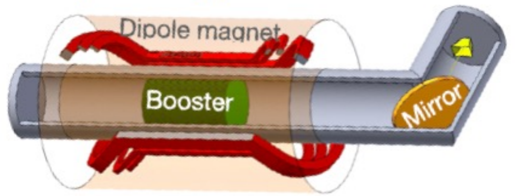
Magnetized Disc and Mirror Axion experiment

Goal and exciting developments of MADMAX



Goal: Tunable dielectric haloscope

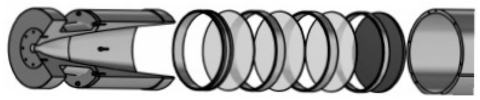
- Aimed at QCD and Post-inflationary[1] range
- 40-400 μeV or 10-100 GHz
- Many discs of 1 m^2
- T_{sys} = 8 K and B_e = 9 T



First axion search at CERN 2024

200 mm prototype

100 mm prototype



Solar axions

At DESY

BabyIAXO

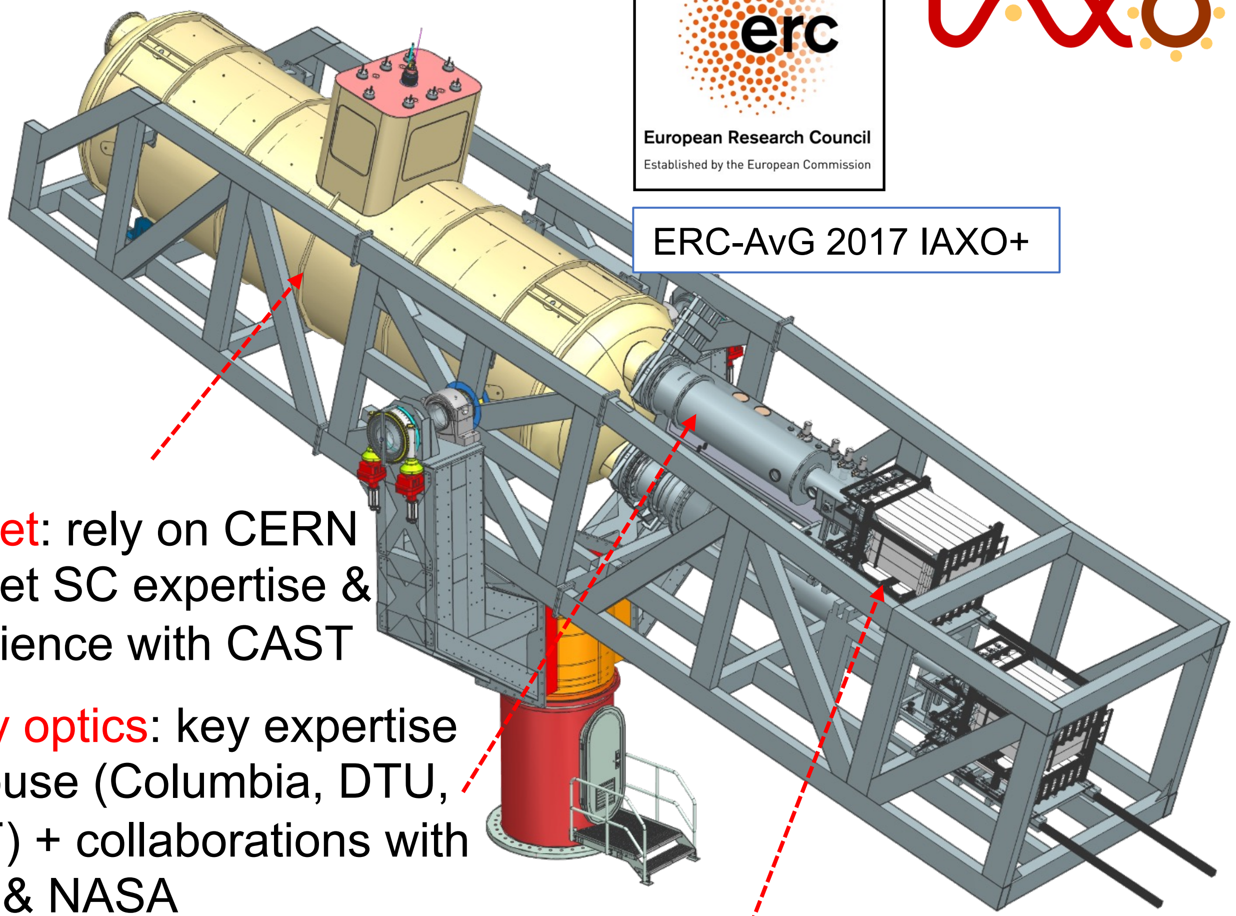
- Prototype: Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO
- Physics: will also produce relevant physics outcome

  (~100 times larger FOM than CAST)

BabyIAXO conceptual design
JHEP 05 (2021) 137

European Research Council
Established by the European Commission

ERC-AvG 2017 IAXO+

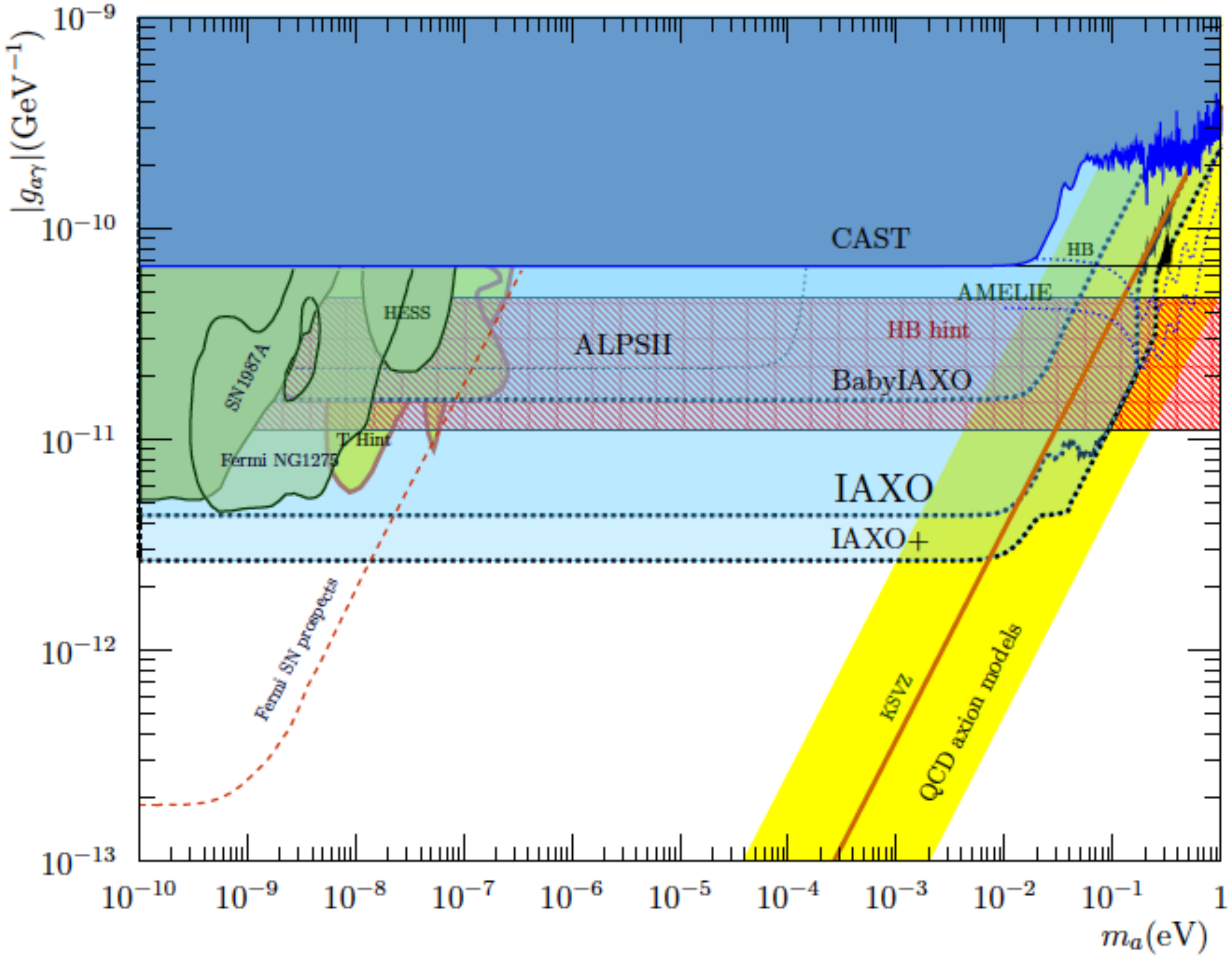


- Magnet: rely on CERN magnet SC expertise & experience with CAST
- X-ray optics: key expertise in-house (Columbia, DTU, INAF) + collaborations with ESA & NASA
- X-ray detectors: Baseline technology (Micro megas) + diverse multitechnology R&D program. Low background (radipuriy,shielding) expertise in-house

BabyIAXO status

- Current status: construction of most parts started
  - Baseline detectors + beamlines being built.
  - Optics: one existing load secured from ESA, 2nd optics under construction
- DESY host of experiment (formal approval in 2019). Technical coordination. Site preparation.
- Magnet construction critical item.
  - Substantially delayed due to SC cable procurement problem and need to update costs/funding. Good progress now in both fronts. Construction now expected by 2028
  - Meanwhile magnet-less operation considered (hidden photons + early commissioning).
- Physics beyond baseline being continuously enriched:
  - Other solar axion channels: ABC axions, axion-nucleon, plasmon-axion, …
  - Other astrophysical sources: Supernova axions
  - BabyIAXO magnet to also host DM axion setups (RADES, MADMAX). Connection with quantum sensor development (DarkQuantum ERC-SyG recently awarded)
  - Post-discovery precision physics (axion mass & model determination)
  - Other WISPs: hidden photons, scalars/chameleons.
  - HF Gravitational waves

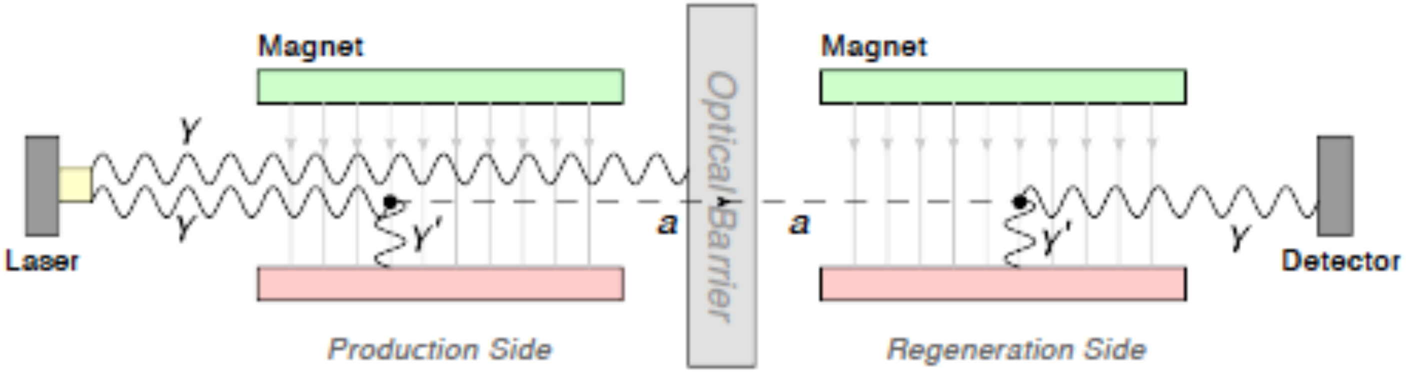
CAST and planned axion Helioscopes



Shining through the wall using axions

ALPS

ALPSII is running at DESY



$$P_{\gamma\to a\to\gamma} = \frac{1}{16}(g_{a\gamma\gamma}BL)^4 = 6\cdot 10^{-38}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\frac{B}{1\,\mathrm{T}}\frac{L}{10\,\mathrm{m}}\right)^4,$$

For sufficiently small axion mass

Experiment	Reference	Photon energy [eV]	Laser power	Power buildup	Magnetic field strength B[T]	Magnetic field length L[m]	$(BL)^4$ [Tm]^4
ALPS	[66]	2.33	4 W	$P_p = 300$	5	4.3	$2\cdot 10^5$
BRFT	[21]	2.47	3 W	$P_p = 100$	3.7	4.4	$7\cdot 10^4$
BMV	[67]	1.17 (14 pulses)	$8\cdot 10^{21}\gamma$/pulse	-	12.3	0.4	$6\cdot 10^2$
GammeV	[68]	2.33 (3600 pulses)	$4\cdot 10^{17}\gamma$/pulse	-	5	3	$6\cdot 10^4$
OSQAR	[69]	2.33	18.5W	-	9	14.3	$3\cdot 10^8$
ALPS-II	[70]	1.16	30W	$P_p = 5000$ $P_r = 40000$	5	100	$6\cdot 10^{10}$
LSW with X-Rays	[71]	50200 90700	10 mW 0.1 mW	-	3	0.150 and 0.097	0.017
LSW with Pulsed Magnets and Synchrotron X Rays	[72]	9500	46 mW	-	8.3 T and 5.7 T pulsed (duration 1ms)	0.8	10^3

Table 5. Overview of experimental parameters of previous and future LSW experiments: the photon energy, the initial laser power, the power-buildup in the production and regeneration side (P_p and P_r), as well as the magnetic field strength and length in production and regeneration sides (B_P, B_R, L_P, L_R). For all the cases, $B = B_p = B_r$ and $L = L_p = L_r$.

Rémy Battesti *et al.*/ Physics Reports (2018)

ALPS II at DESY, Started data taking with production cavity

ALPS II Optical System

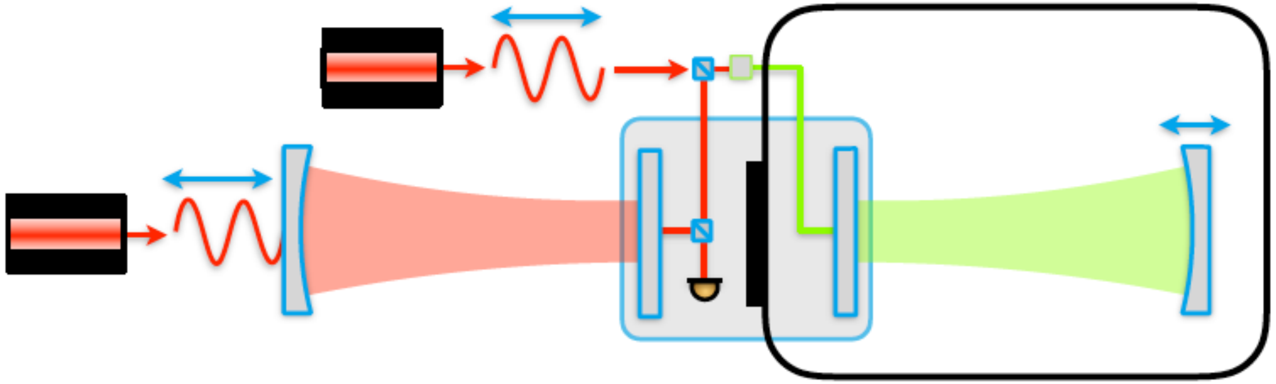
A unique set of challenges

Two 100 m optical resonators

- 30 W amplified NPRO input laser
- PC: 150 kW circulating power
- RC: 120,000 finesse

Challenges

- Maintenance of dual resonance
- Maintenance of spatial overlap
- Light tightness 1 photon / 2 weeks



ALPS

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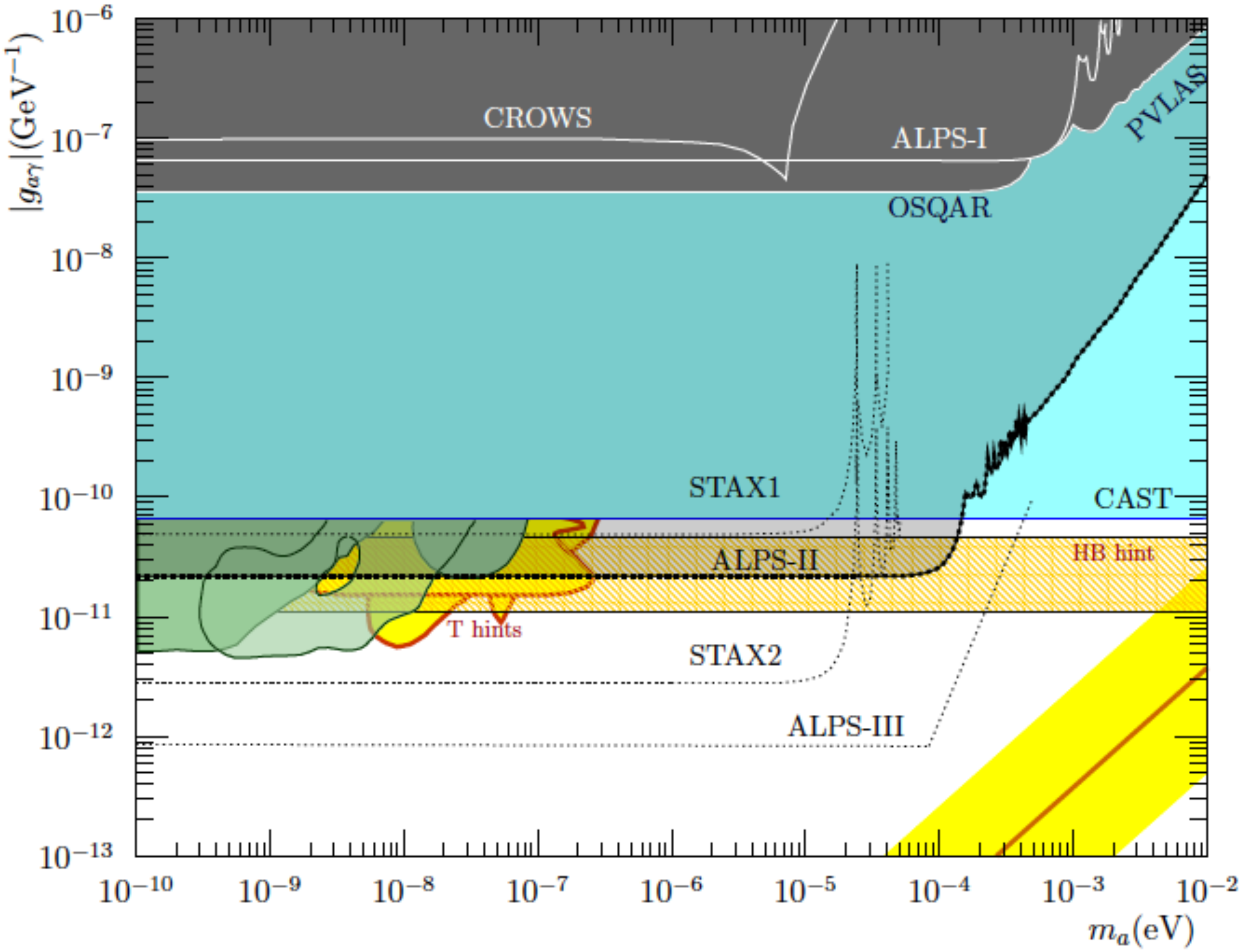
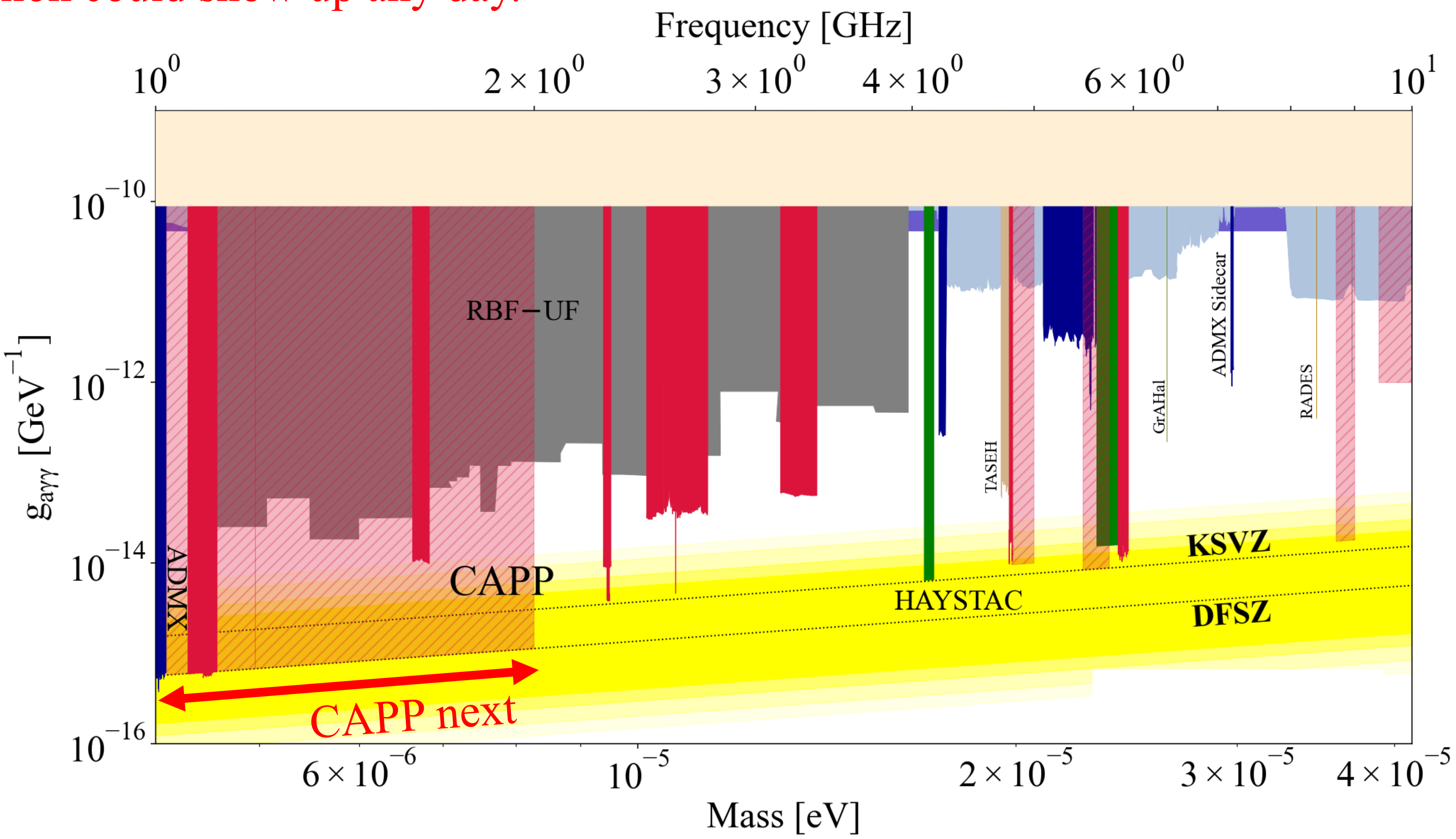


Near future

CAPP's immediate target 1-2 GHz

The axion could show up any day.



A new haloscope at Grenoble: GrAHal

New experimental effort!

B^2V wins (GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ)

9 T in 810 mm warm bore

$\langle B^2V \rangle$ at 9 T central field	Q at 4.4 K	C_{010}	Noise T	$g_{A\gamma\gamma}$
34.4 T^2m^3	1-2 10^5	0.63-0.69	1.6 K	DFSZ

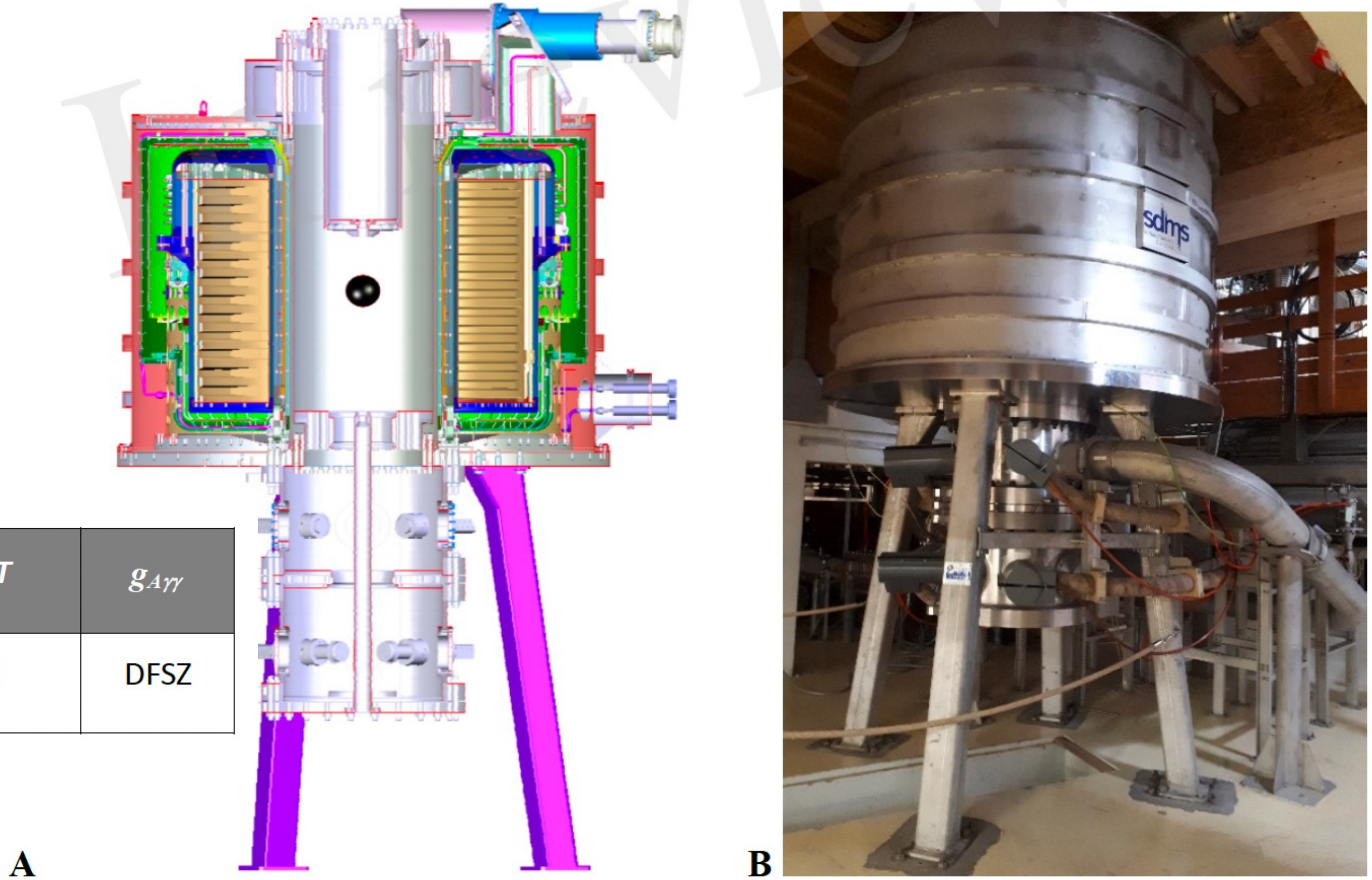
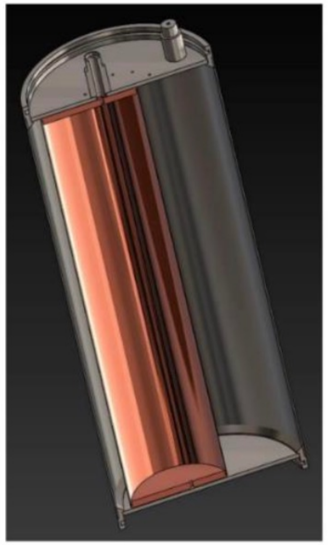


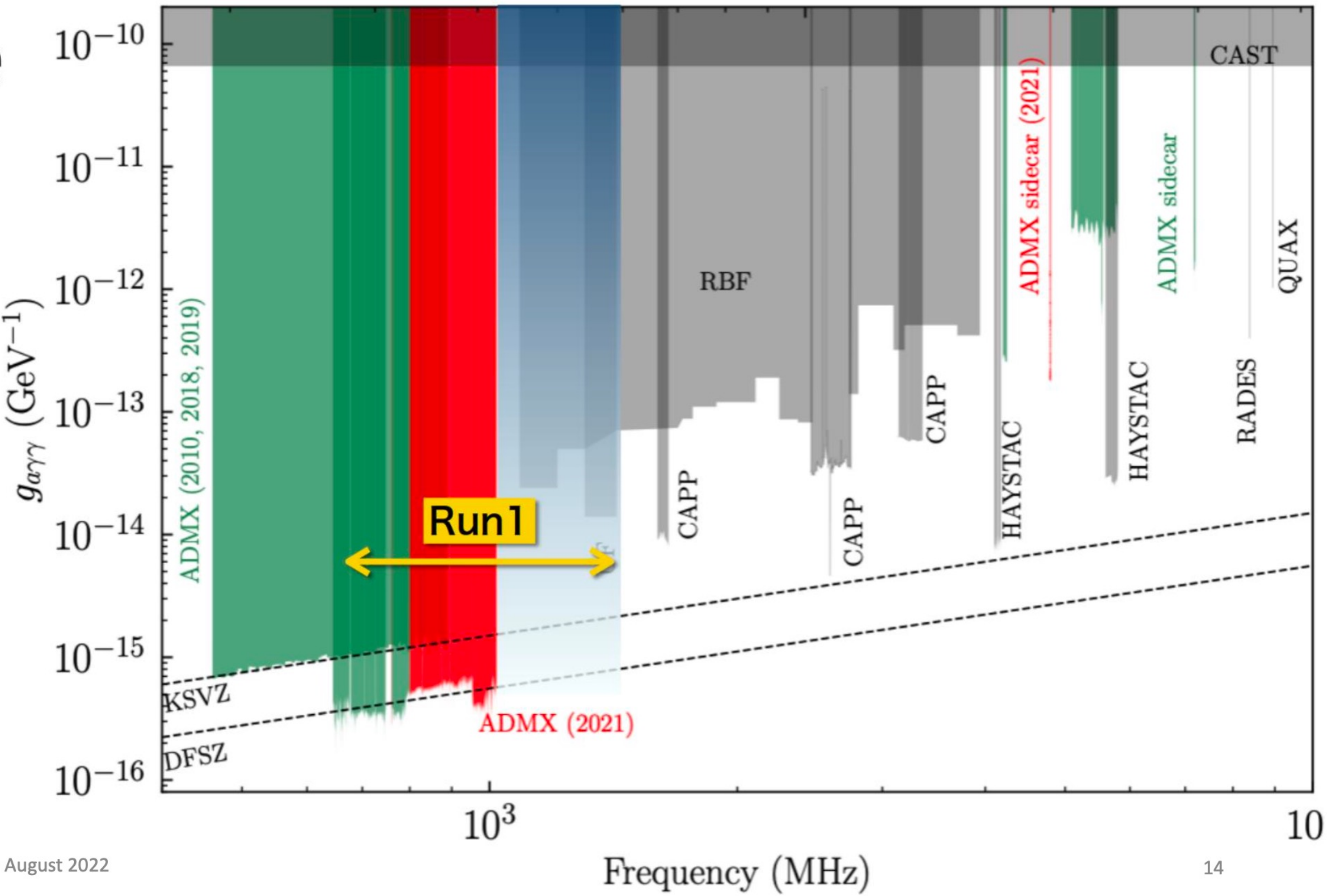
FIGURE 1
A) Cut view of the cryostat and large bore superconducting outsert of the Grenoble hybrid magnet.
B) The magnet as built in operation at LNCMI-Grenoble. The total height is about 5.4 m for a total weight of about 52 tons. Mechanical structures above and below the magnet aperture are water cooling boxes for the 24 MW resistive inserts used to reach higher magnetic fields. They will not be used for the GrAHal-CAPP haloscope described in this article.

ADMX plan

Future Plans



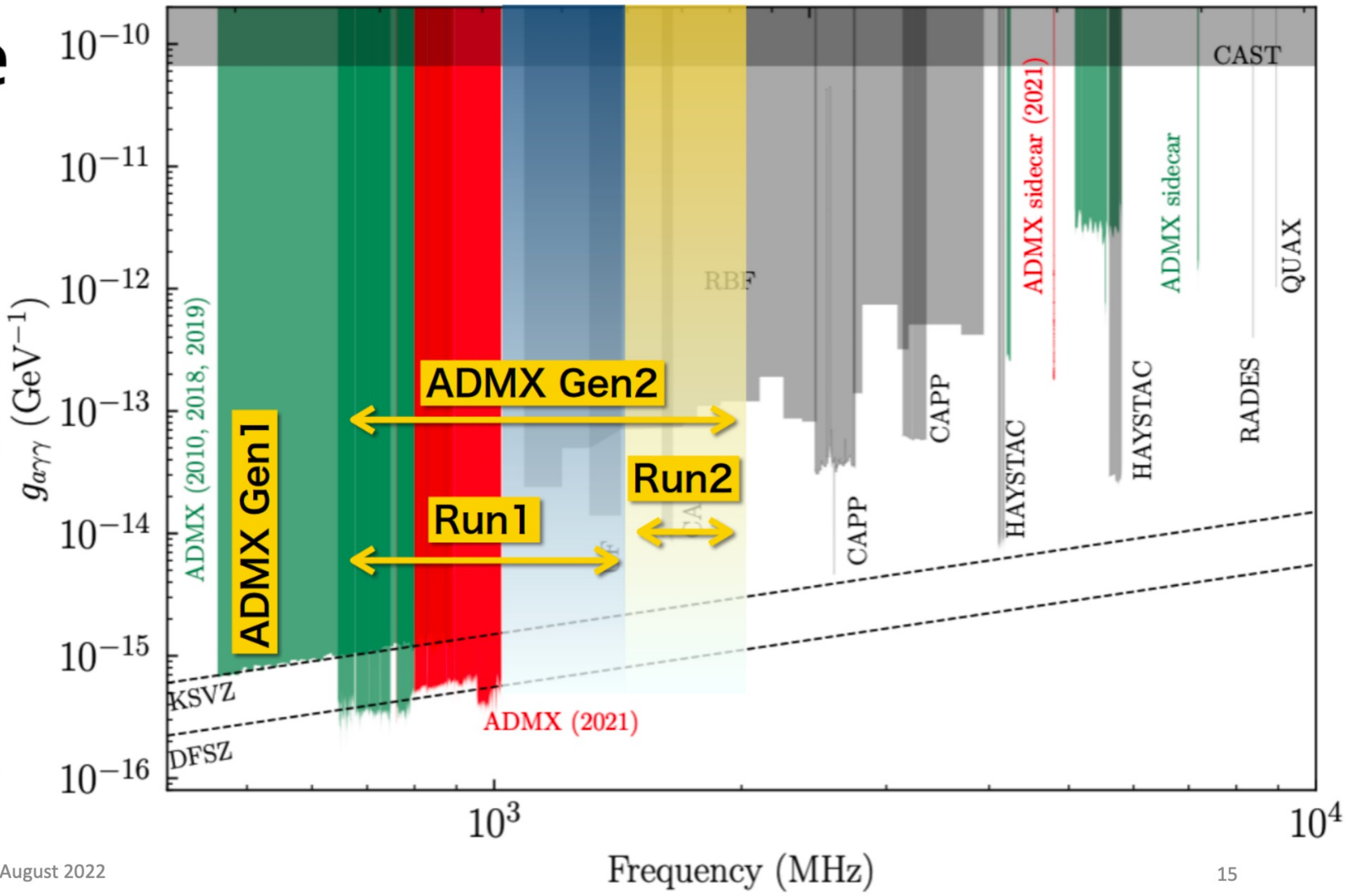
Bigger tuning rod



ADMX plan

Future Plans

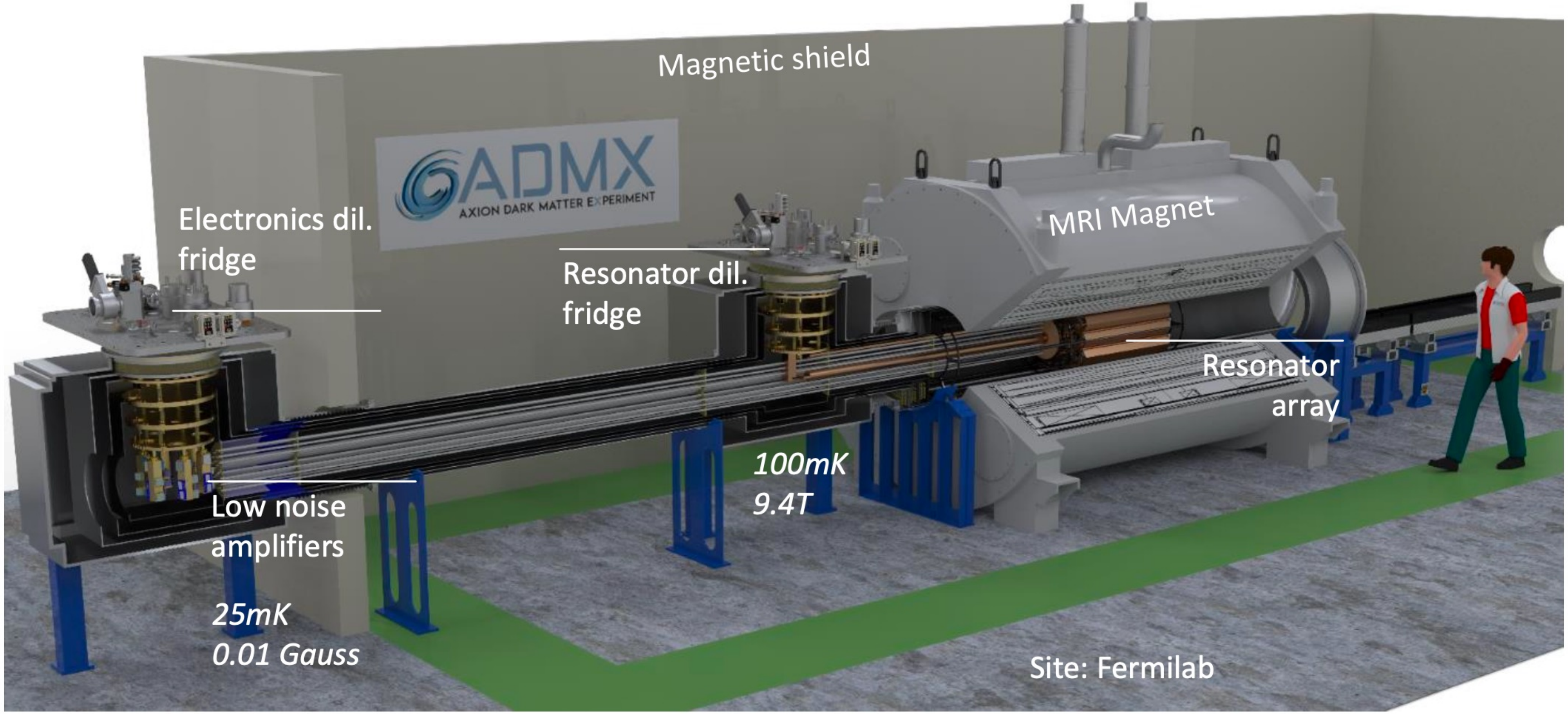
4-cavity array



ADMX: Rybka, August 2022

ADMX-EFR – Design Overview

Existing MRI magnet moved to Fermilab, 2024



~ 5 × scan speed of current ADMX

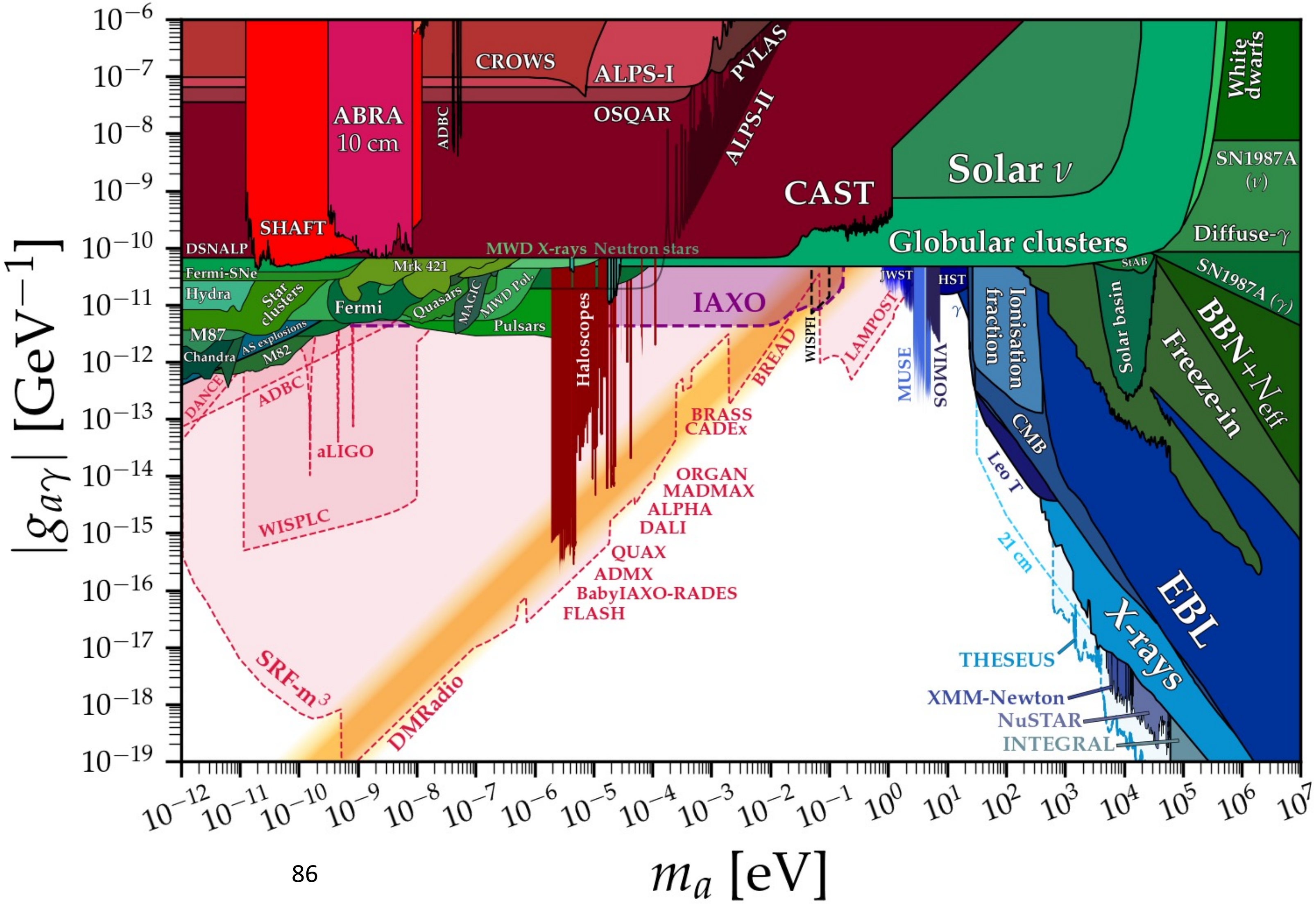
Axion-photon with projections

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

CAPP plans to scan 1-8 GHz at better than DFSZ

GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ, using existing magnets, know-how.

ARIADNE will reach high mass axions (no dark matter required)



Summary

- ALPHA, ADMX, CAPP, GrAHal, HAYSTAC, QUAX,… now could cover:
  - 0.2-4 GHz axion freq. in the next 2-years (DFSZ)
  - 4-8 GHz within the next 5-years from now (DFSZ)
  - 0.2-25 GHz within <2 decades, even for 20% of axions as dark matter

- HTS-based cavities and single photon detectors can bring a phase-transition in high-frequency axion cavity searches. Heterodyne-variance method is a bridge…
- Large volume dielectric/metamaterial microwave cavities are sensitive and able to reach the high frequency axions
- The international effort is intensified, promising to cover all the available axion dark matter parameter space within the next 10-20 years.
- The low frequency (<0.1 GHz), with DM-Radio and CASPER is on path to great success, the high frequency (>25 GHz) started developing sensitive experiments

Extra slides

Heterodyne-variance method, Omarov, Jeong, YkS, 2209.07022

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

System Noise Temperature

Adapted from Junu Jeong's slides

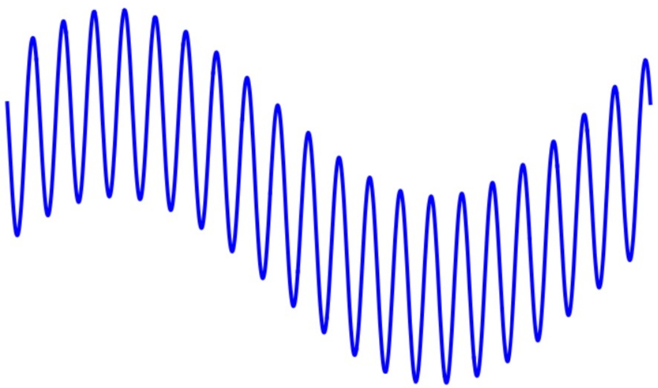
- **Noise Sources**

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

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]

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

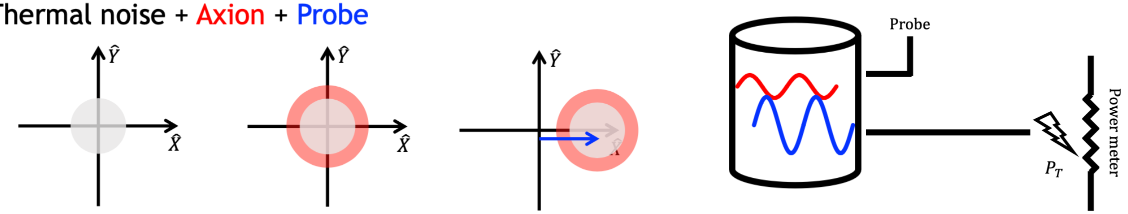
- **Heterodyne**

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*

Heterodyne-variance method, 2209.07022

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: $\dot{N} \equiv N \times f_s$

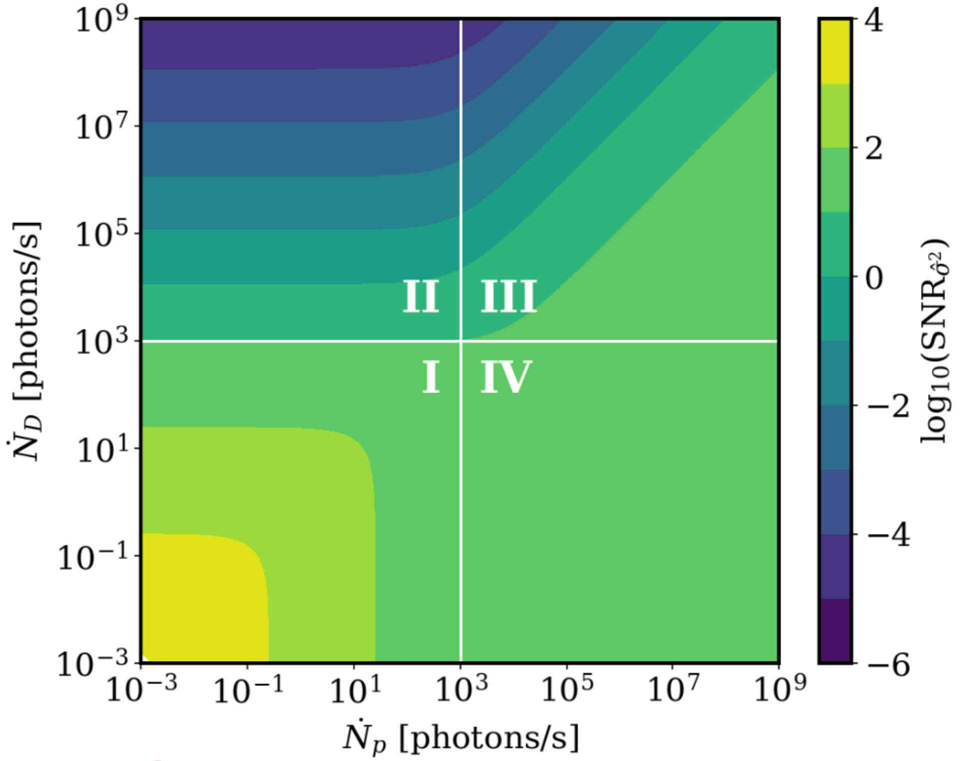
$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s (1 + \dot{N}_p / f_s)\sqrt{f_s \Delta t}}{(\dot{N}_D + \dot{N}_p)\sqrt{2 + f_s/(\dot{N}_D + \dot{N}_p)}} \rightarrow \frac{\dot{N}_s}{\sqrt{2 f_s}}\sqrt{\Delta t}$$

$\dot{N}_p \gg f_s$

- **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 $\dot{N}_D|_{eff} \rightarrow 2 f_s$
- **Region IV:** $\dot{N}_D < f_s,\ \dot{N}_p > f_s$

  Injecting prboe reduces the SNR



Heterodyne-variance method, 2209.07022

Intermediate method before low-noise single photon detection

Comparisons

Junu Jeong's slide

- **SNR comparison with Single Photon Detector**

$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s}{\sqrt{2f_s}}\sqrt{\Delta t} \qquad \mathrm{S/N}_{\mu} \approx \frac{\dot{N}_s}{\sqrt{\dot{N}_{\mathrm{th.}} + \dot{N}_D}}\sqrt{\Delta t}$$

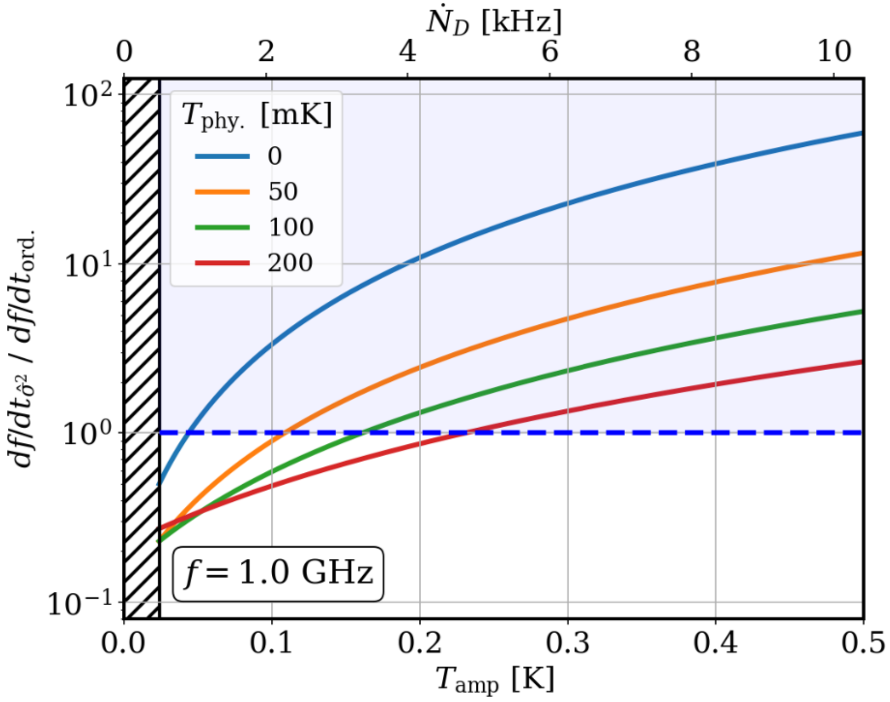
  - The denominator changes from $\sqrt{2f_s}$ to $\sqrt{\dot{N}_{\mathrm{th.}} + \dot{N}_D}$
  - In the case that $\dot{N}_D > 2f_s$, $\mathrm{S/N}_{\sigma^2} > \mathrm{S/N}_{\mu}$

- **Scan rate comparison with Ordinary Method**

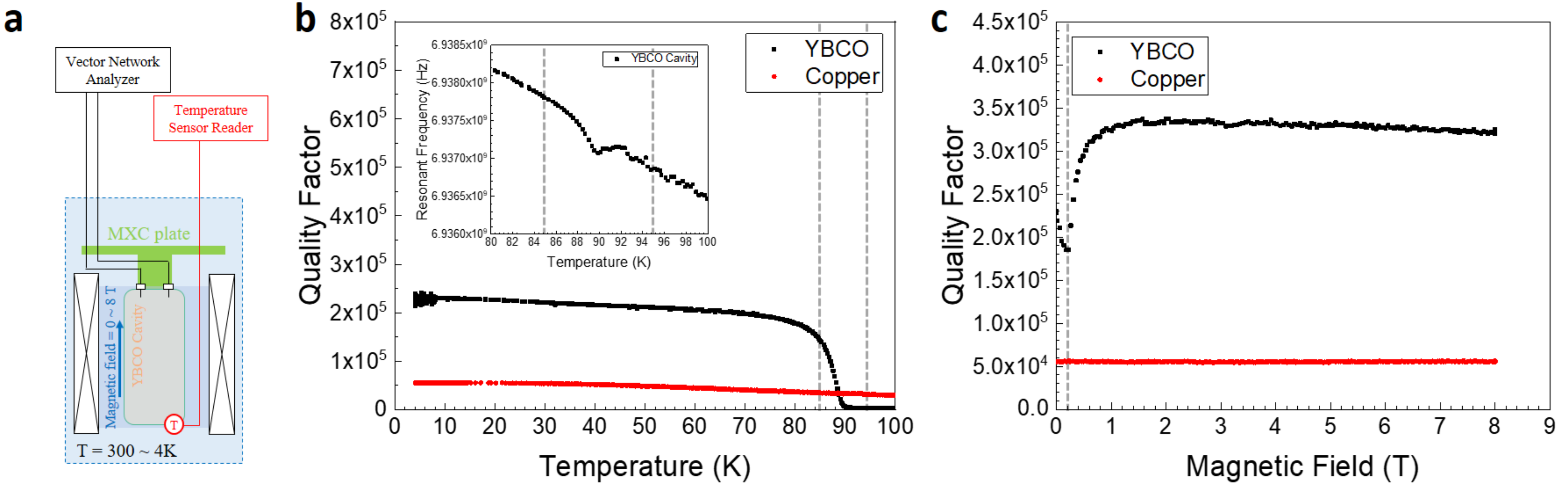
$$\left.\frac{df}{dt}\right|_{\sigma^2} \approx \frac{\Delta f_c}{\Delta t} = \frac{\dot{N}_s^2}{\mathrm{S/N}_{\sigma^2}} \frac{\Delta f_c}{2\Delta f_a}$$

$$\left.\frac{df}{dt}\right|_{\mathrm{ord}} \approx \frac{\Delta f_c}{\Delta t} = \frac{1}{\mathrm{S/N}_{\mu}}\left(\frac{P_s}{k_B T}\right)^2 \frac{Q_a}{Q_l}$$

- $T_{\mathrm{amp}} \sim T_{\mathrm{QL}} = hf$: Ordinary method is fast
- $T_{\mathrm{amp}} \gtrsim 2T_{\mathrm{QL}} = 2hf$: Variance method is fast



HTS superconducting cavity in large B-field!



First and best in the world!

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

Superconducting materials

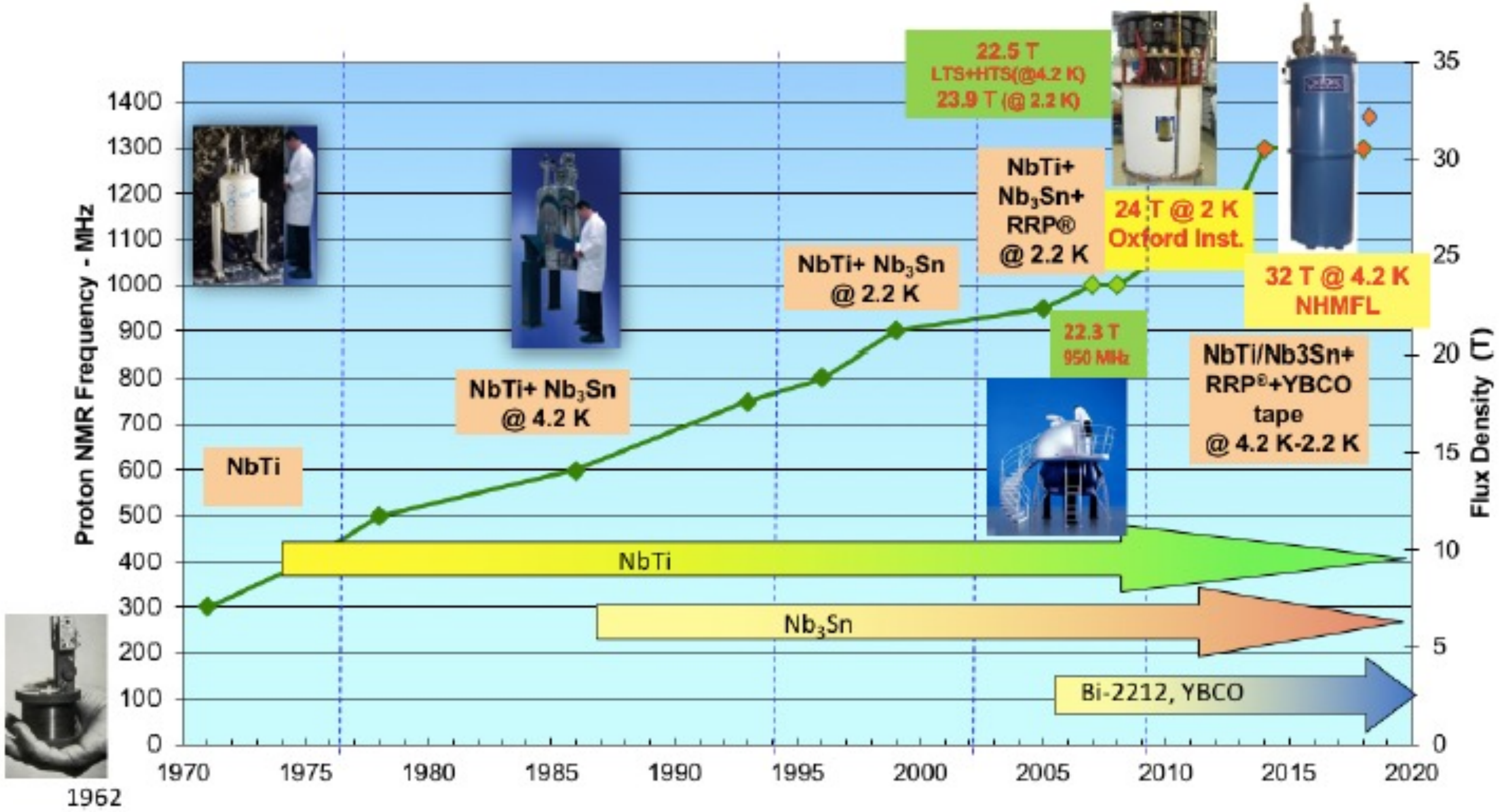
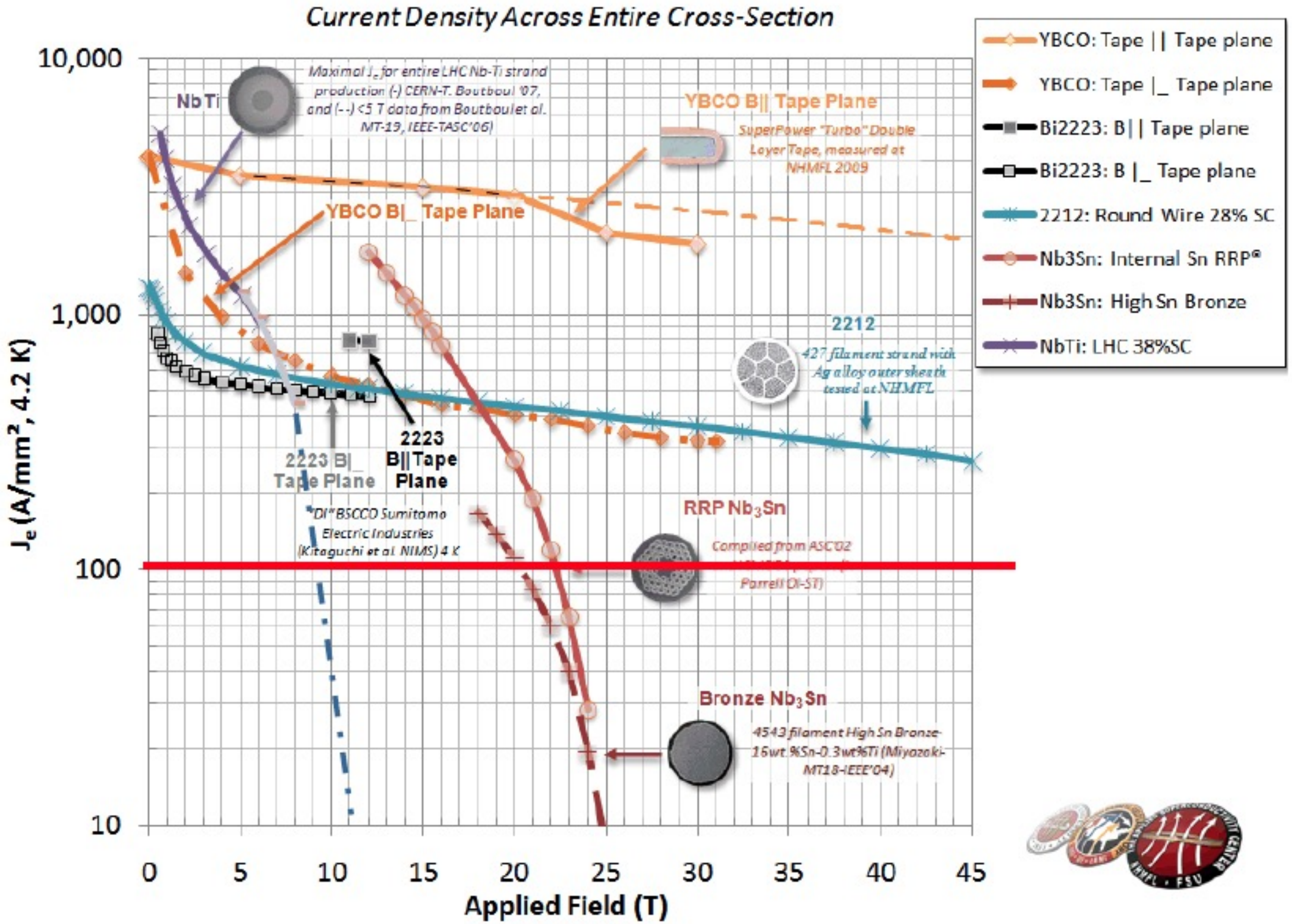


Fig. 22. Solenoid magnets for NMR as a representative example of the progress in magnet technology. NHMFL: National High Magnetic Field Laboratory, Tallahassee, Florida.

Future Solenoids:

High- Temperature Superconductors

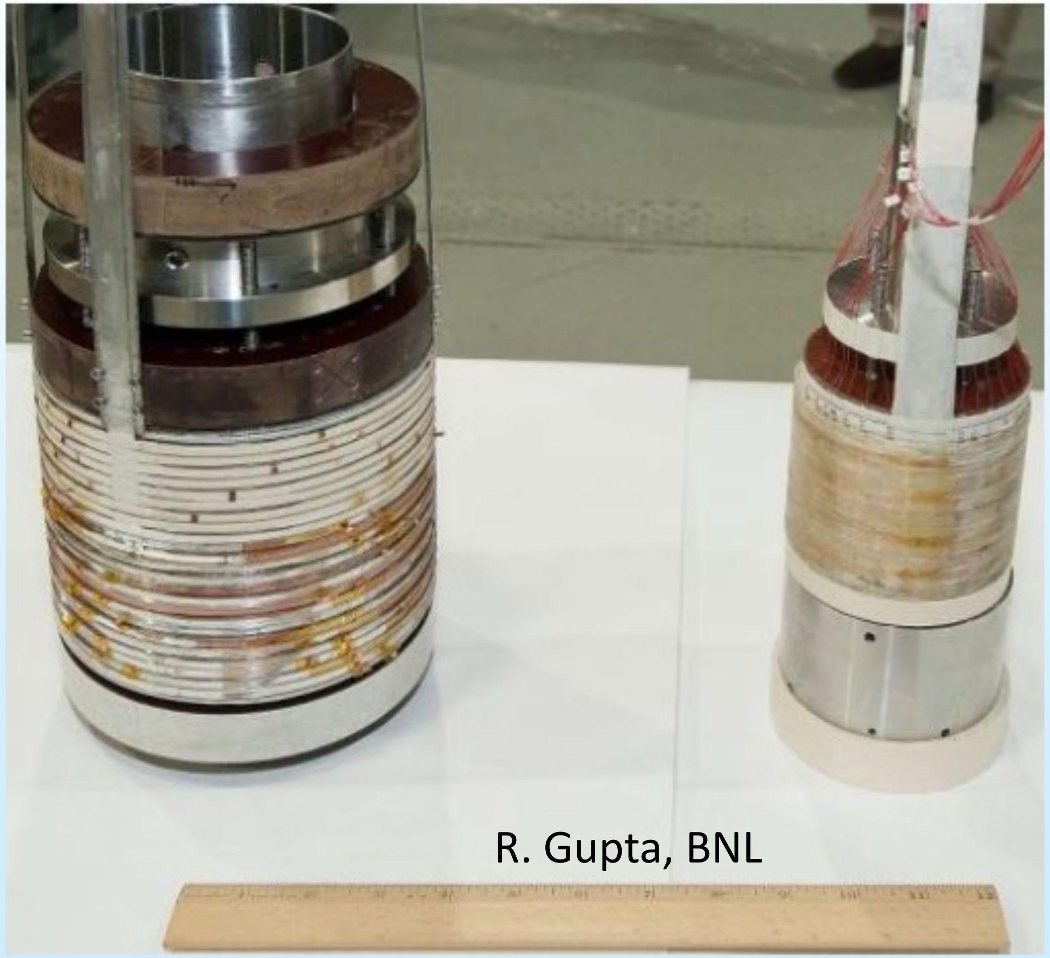


Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

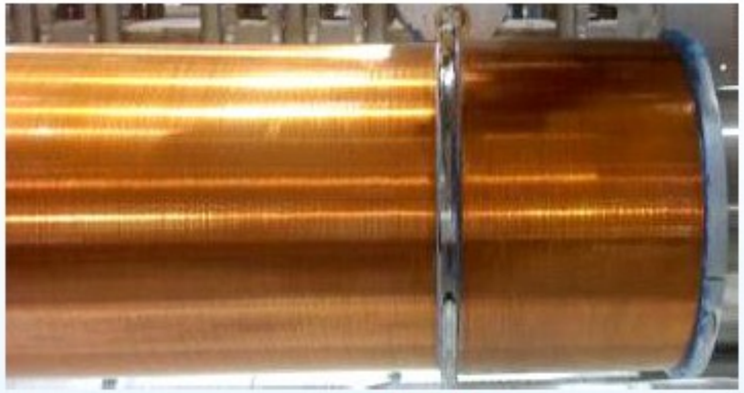
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

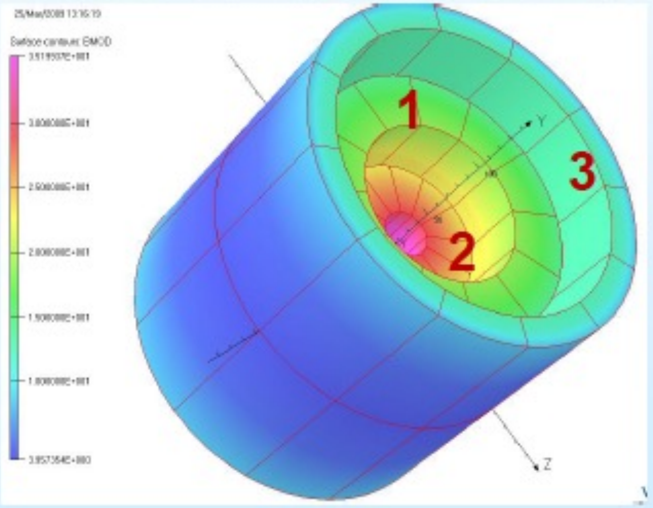
Status of High Field MAP Solenoids

Two HTS coils together made with SuperPower HTS is expected to create 20-25 T, if successful



R. Gupta, BNL





~30 T with NbTi outer
(40 T with Nb_3Sn or more HTS)

BNL 25T/10cm, HTS magnet review

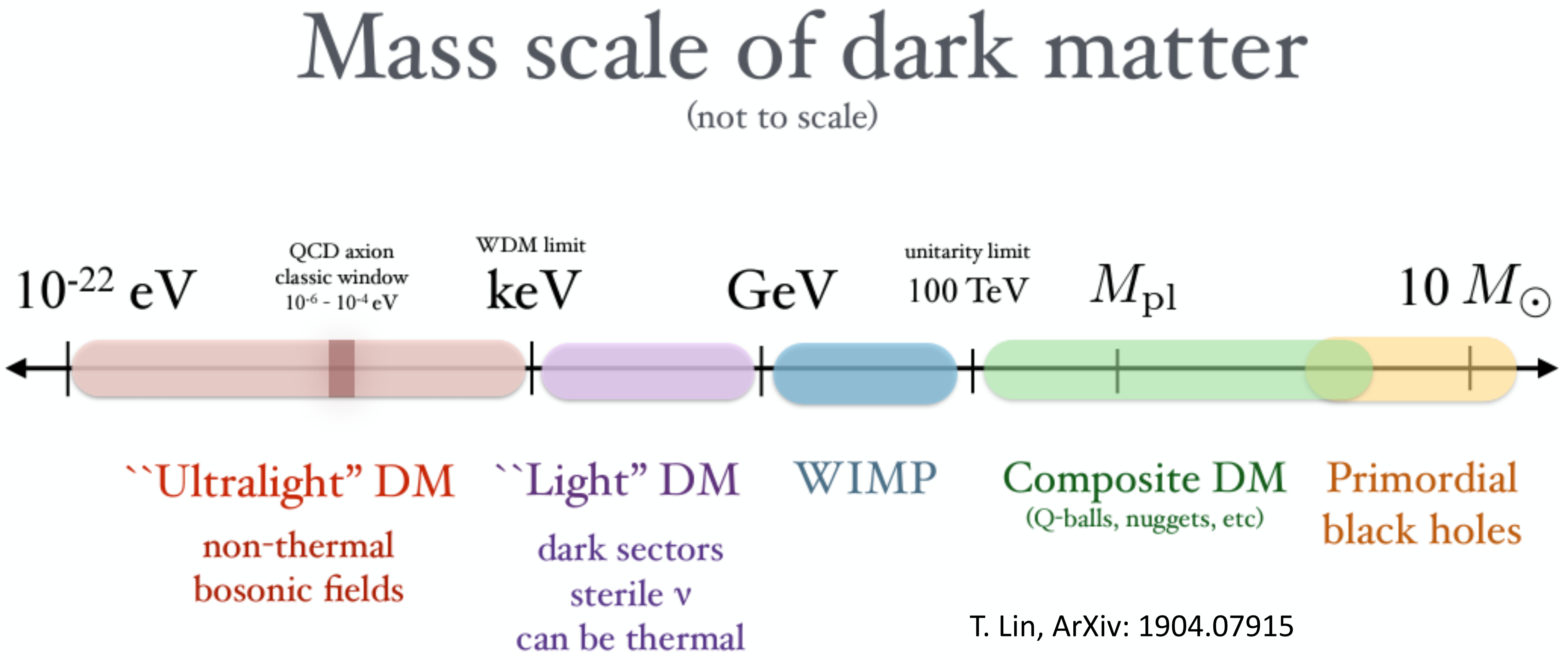
October 22, 2018

- Magnet construction plan with single layer is sound
- Magnet design with No Insulation making it safe from quenches and structural integrity
- >50% margins in critical current and stresses
- 16 out of 28 pancakes constructed.

Canceled by IBS-HQ when IBS's budget was reduced

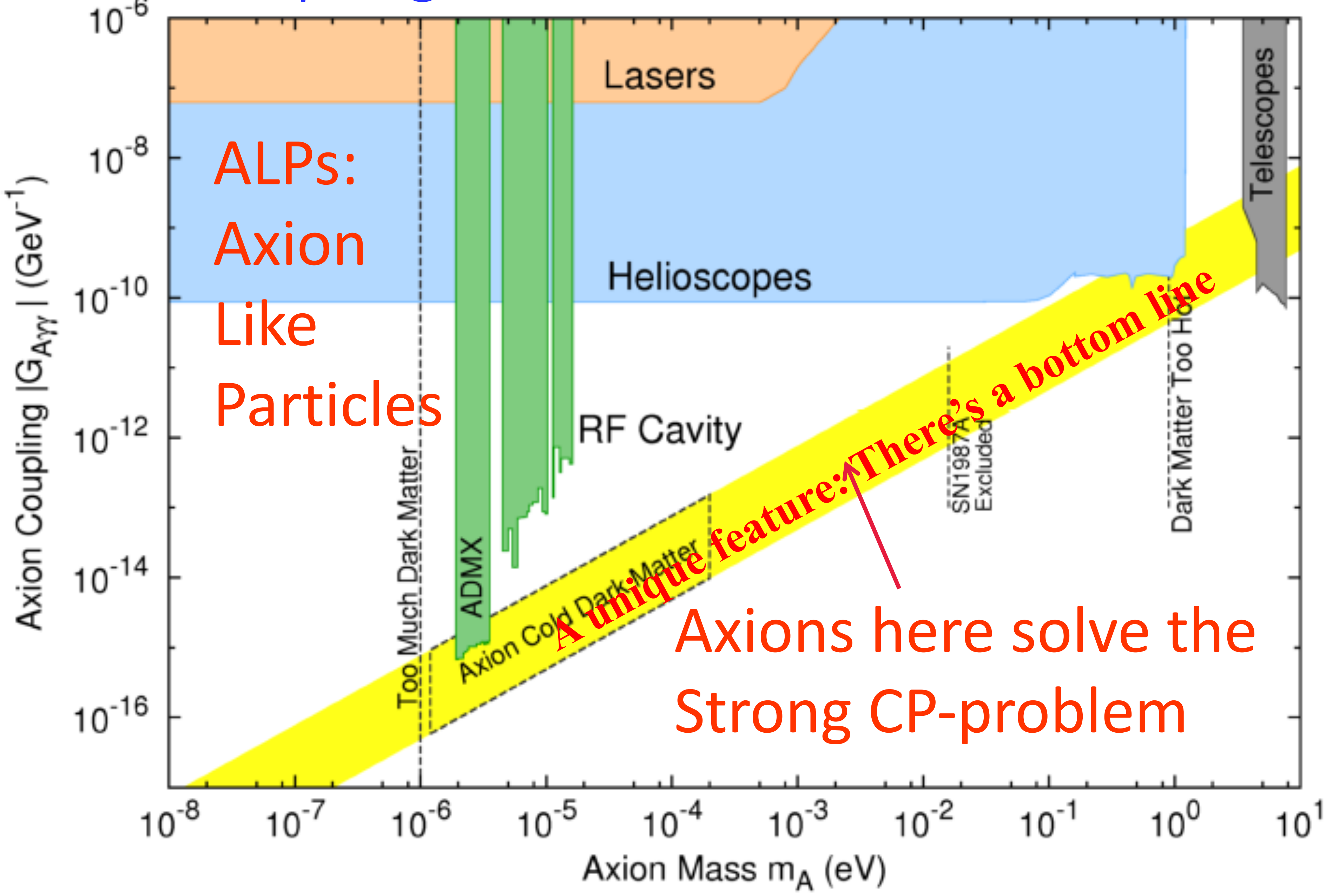
Figure 2.67: Manufacturing process (10 HTS coils).

Vast range



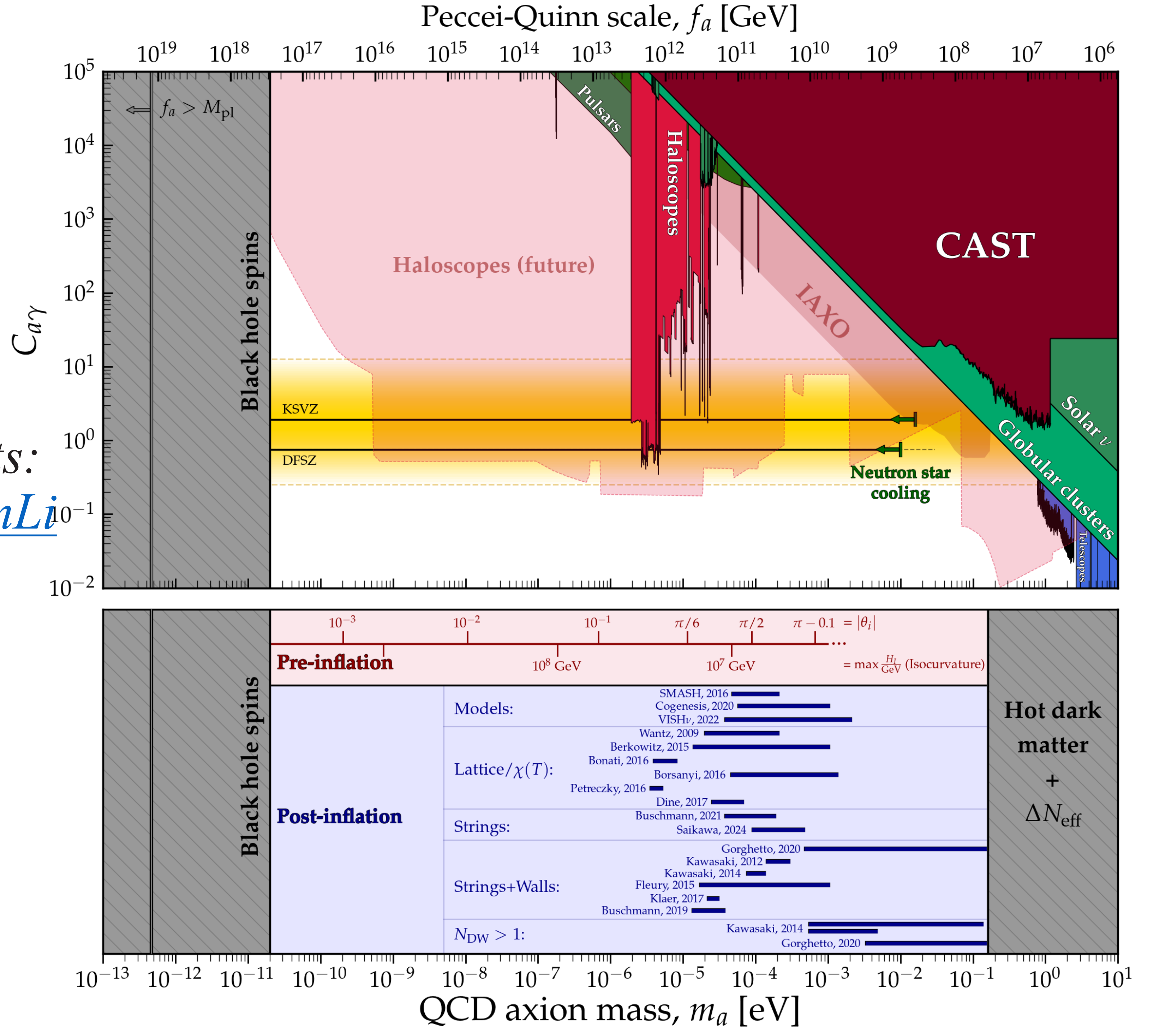
T. Lin, ArXiv: 1904.07915

Axion coupling vs. axion mass



Axion coupling vs. axion mass

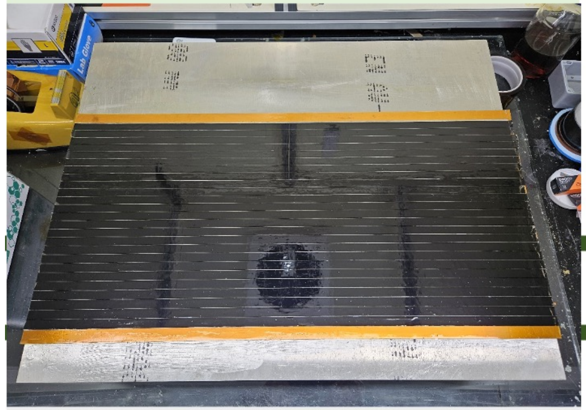
C. O'Hare, cajohare/axionlimits: *https://cajohare.github.io/AxionLimits/*



Jiwon Lee’s slide

Full-HTS-ULC fabrication process

Tuning rod - Sidewall



It is the same process as the sidewall of the cavity body

I made this jig.

Roll it up and tighten it with a clamping jig

Very difficult task

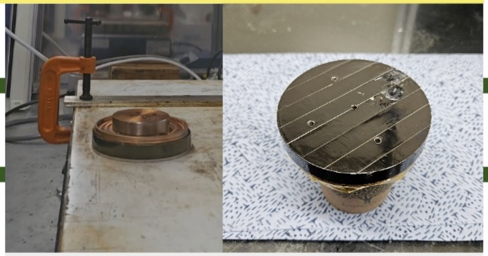
Indium cold welding by Dr. Ohjoon Kwon

Tuning rod - Lids

HTS preparation & Lid masking with Al tapes

I did this soldering in a similar way to the sidewall.

1st soldering (the upper surface)



2nd soldering (the side)

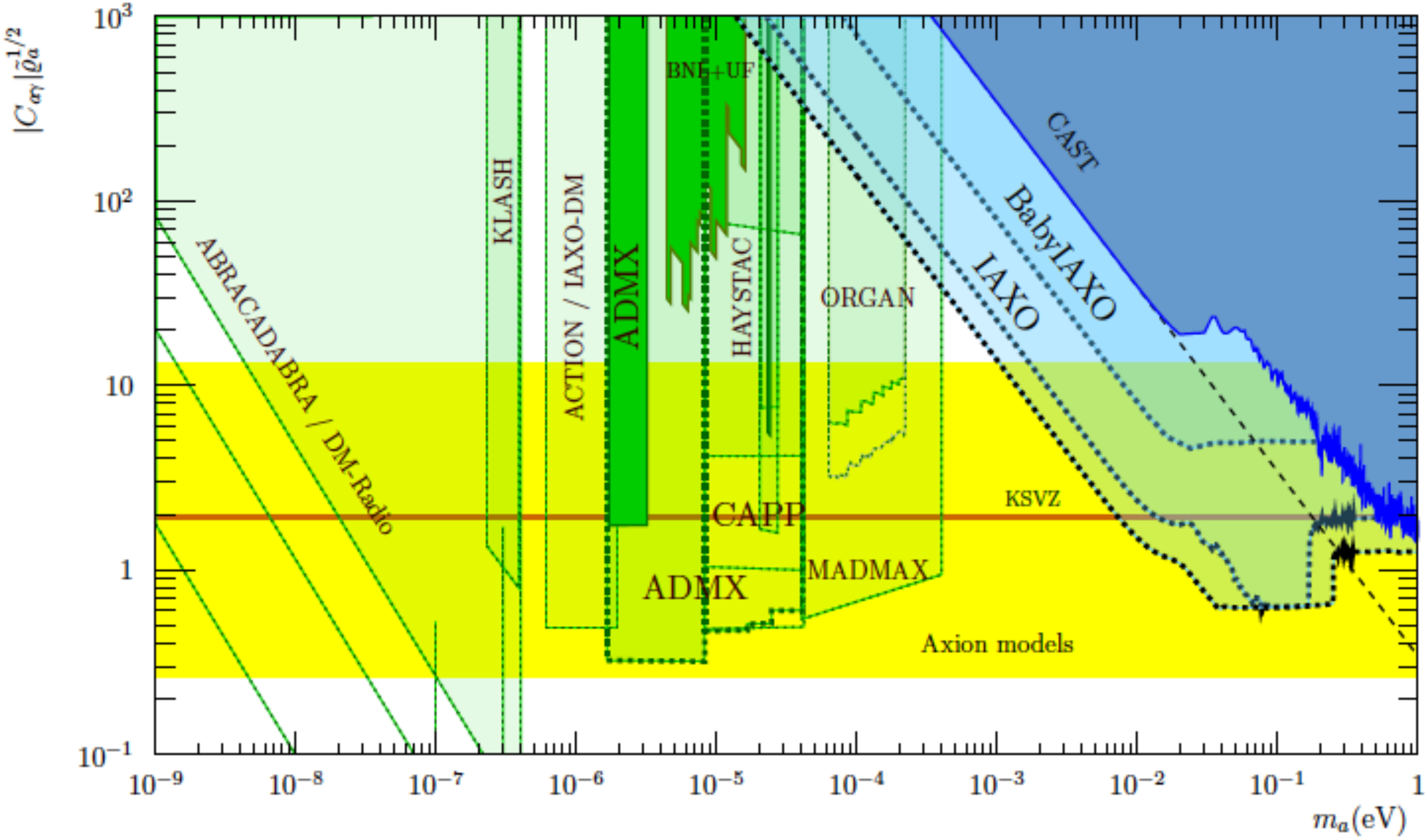
Connection

IBS-CAPP and collaborators

- First efficient high frequency scanning with “pizza” cavities, at KSVZ sensitivity even at >5 GHz. New designs allow us to reach >10 GHz
- Low temperature (<40mK), with large volume ultra-light-cavity, reaching DFSZ sensitivity over 1 GHz and 3MHz/day.
- Best JPA performance for wide frequency cover (international collaboration with Tokyo/RIKEN)
- First HTS cavities with $Q>10^6$ in high magnetic field, reaching >10MHz/day at better than DFSZ

- Critical contributions to ARIADNE, GNOME (international collaborations)
- Active R&D on bolometer, single photon detectors, large volume magnets (international collaborations, Aalto, INFN, Grenoble)

Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

Axion Dark matter

- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s $(100\mu eV / m_a)^5$
- Cold Dark Matter ($v/c \sim 10^{-3}$), Kinetic energy ~$10^{-6} m_a$, very narrow line in spectrum.

Light shining through walls

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}[\mathrm{GeV}^{-1}]$
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	$9.9\times10^{-8}(^*)$
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a. For microwave LSW (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, see Figure 6

Irastorza, Redondo 1801.08127v2

CAPP/IBS axion target plan

- Major improvement elements:

High field solenoid magnets, B: 9T→25T→40T

High volume magnets/cavities, V: 5l→50l

High quality factor of cavity, Q: 10^5→10^6

Low noise amplifiers, T_N: 2K→0.25K

Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6

Improvement in coupling constant: 70