2nd General Meeting of COST Action COSMIC WISPers (CA21106)

Funded by the European Union

CAPP

Center for Axion and Precision Physics Research

Tuesday, September 3, 2024 - Friday, September 6, 2024

Istinye University, Istanbul (TR)

Status and prospects of the search for hadronic axions in the 1-8 GHz frequency range at IBS-CAPP in South Korea

Yannis K. Semertzidis, IBS-CAPP & KAIST

- 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

The power of Science

John Ellis, Serkant Cetin, Nick Samios, YkS,
ICPP, Istanbul, 2008

- A basic feature of human activity is to identify the group we belong to.
- Exciting science unites us like no other human activity.
- Funding good science is one of the best ways to bring the world together!

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)

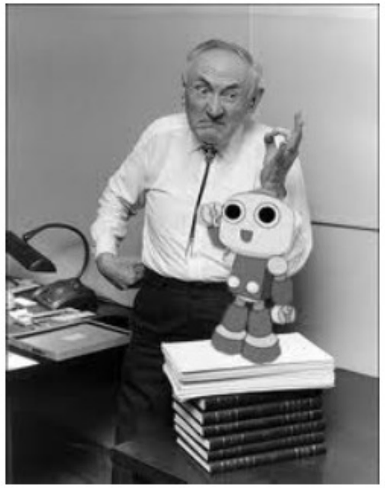
What is known about DM?

- 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.

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

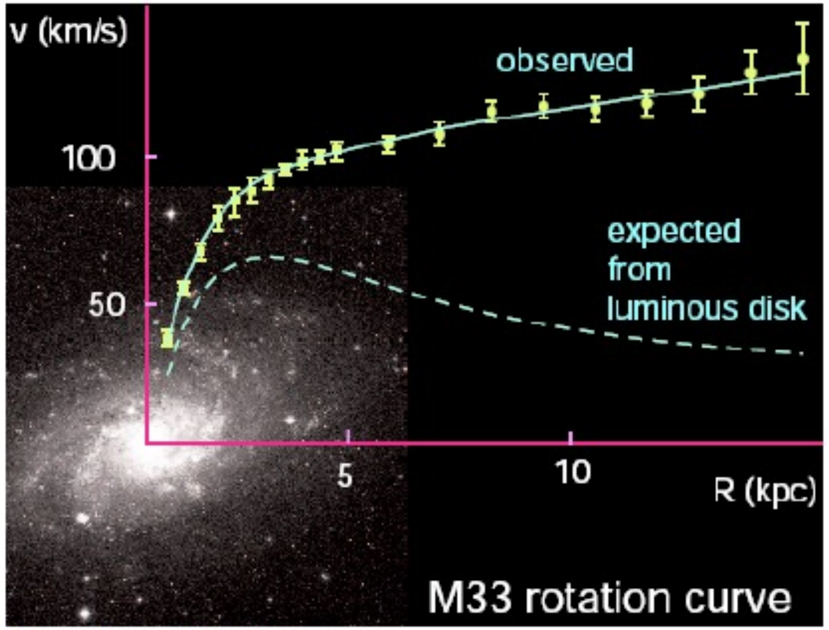
Virial motions within galaxy clusters:

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

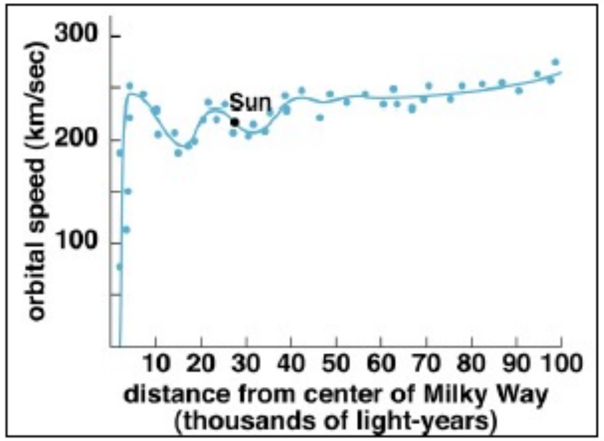
The "dunkelmaterie" of Zwicky 1936

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.

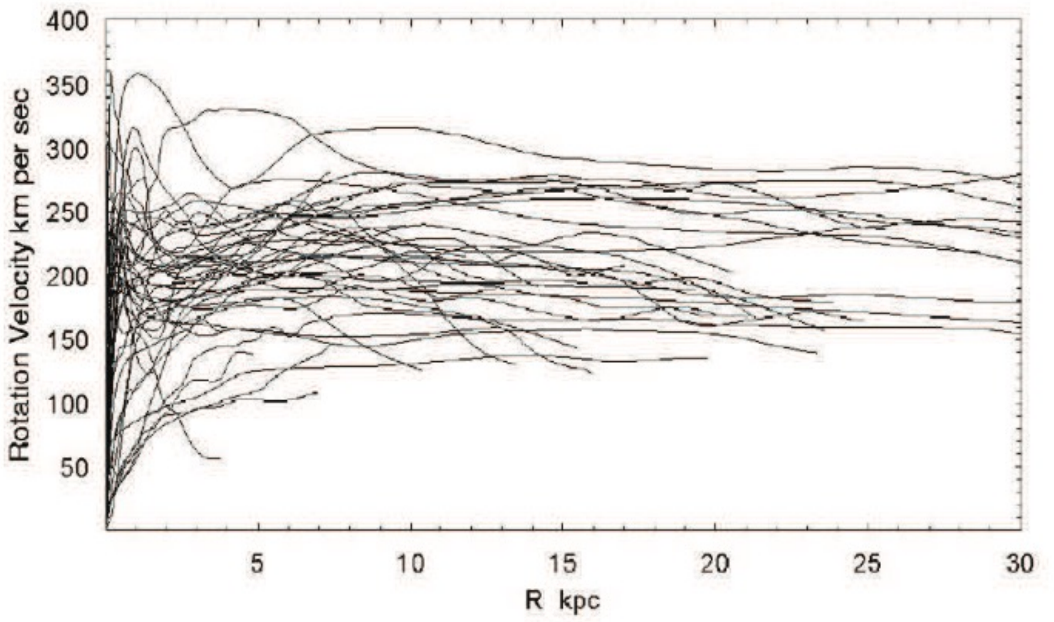


Figure 4: Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999).

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

A Galaxy without Dark Matter, effectively confirming Dark Matter!

(This "discovery" is critical to be confirmed!)

Review talk from this field?

A Galaxy Without Dark Matter

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

NGC 1052-DF2 ©YALE/NASA

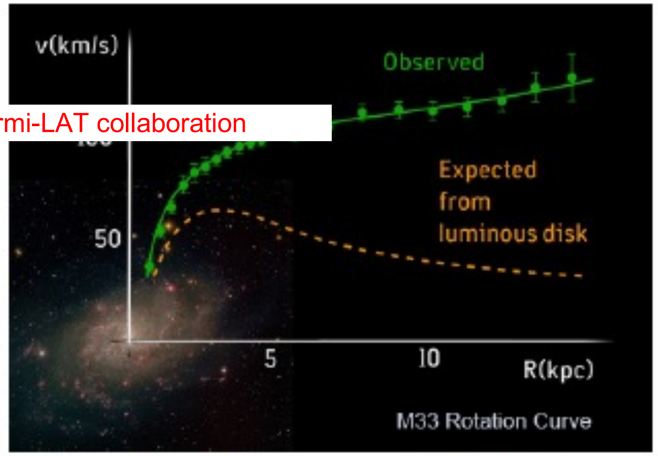
A Yale-led research team has discovered a galaxy that contains no dark matter -- a finding that confirms the possibility of dark matter as a separate material elsewhere in the universe.

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.

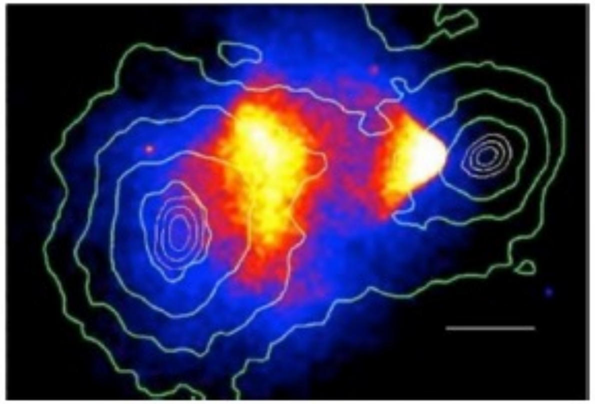
Evidence for / Salient Features of Dark Matter

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

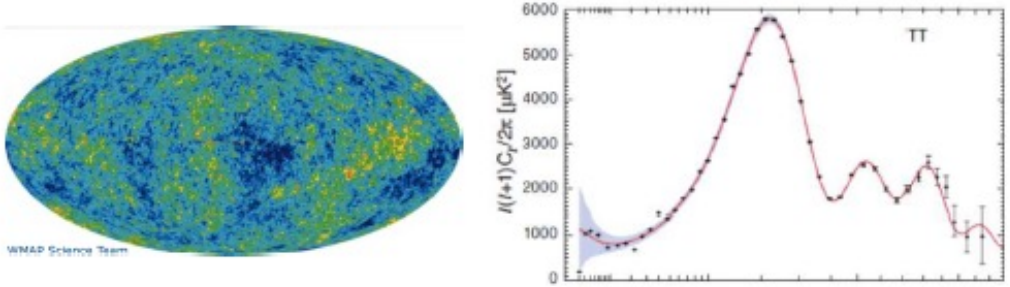
Eric Charles, Fermi-LAT collaboration



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



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



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

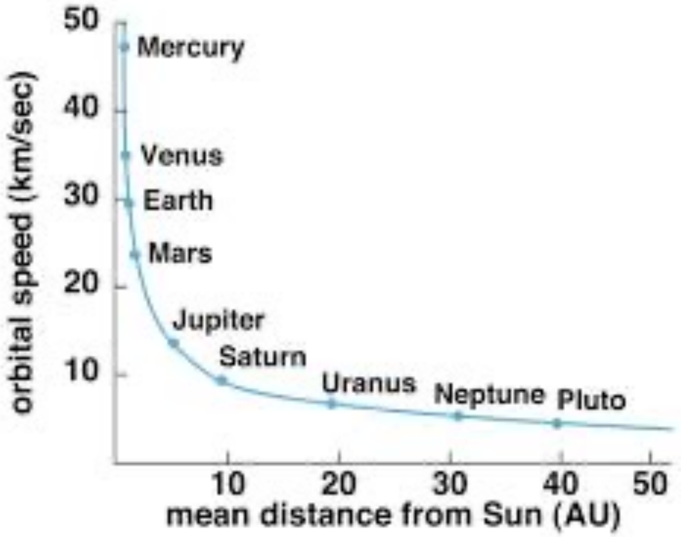
Newton's laws: "observing" the unseen

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

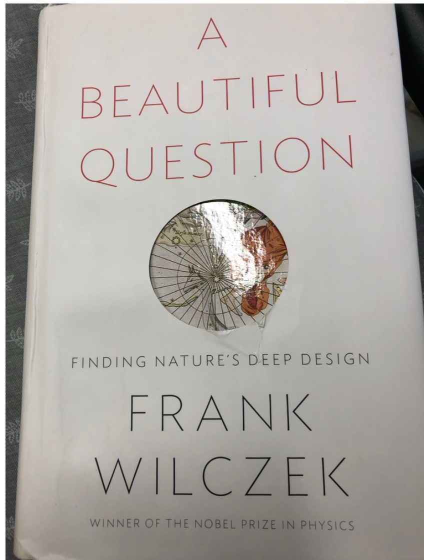
$$F = \frac{GM_{\odot}m}{r^2} = \frac{mv^2}{r}$$

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

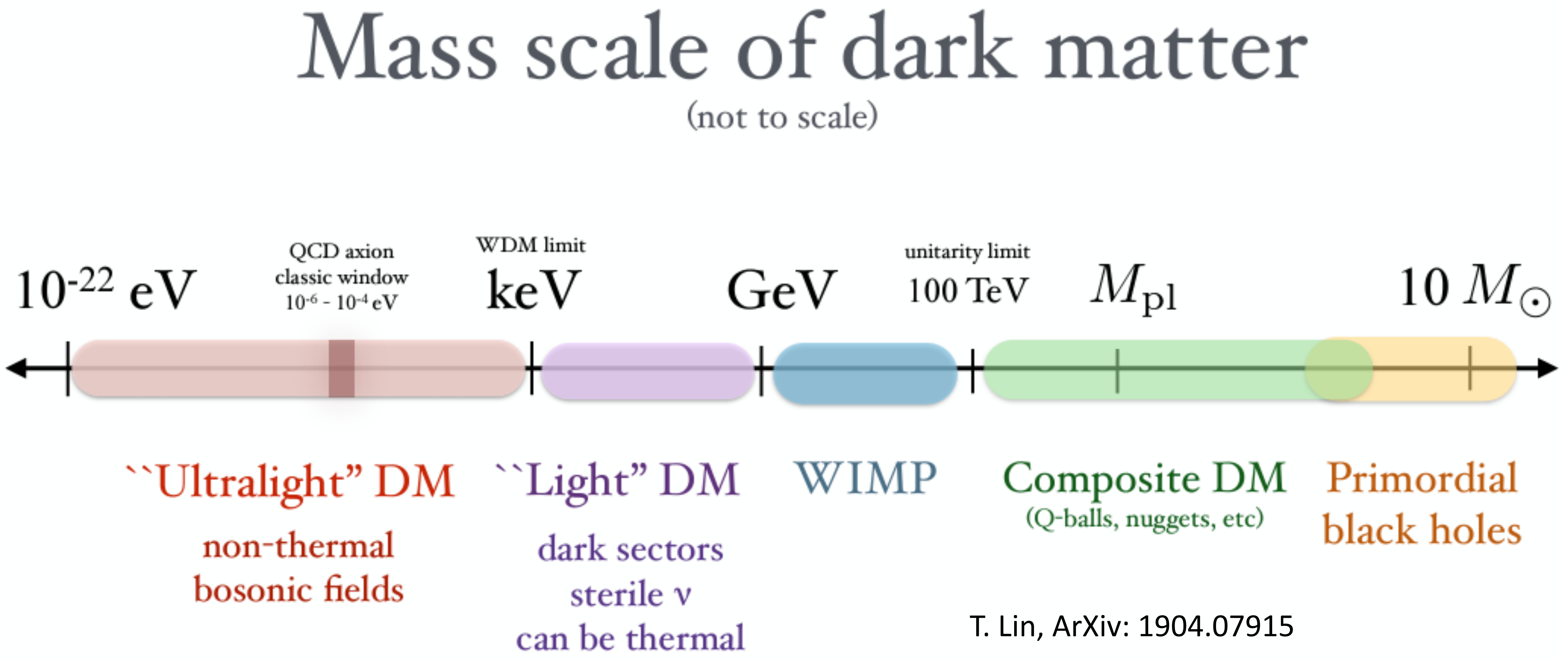
1915, Einstein's General Relativity
Resolved the issue with Mercury's precession



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

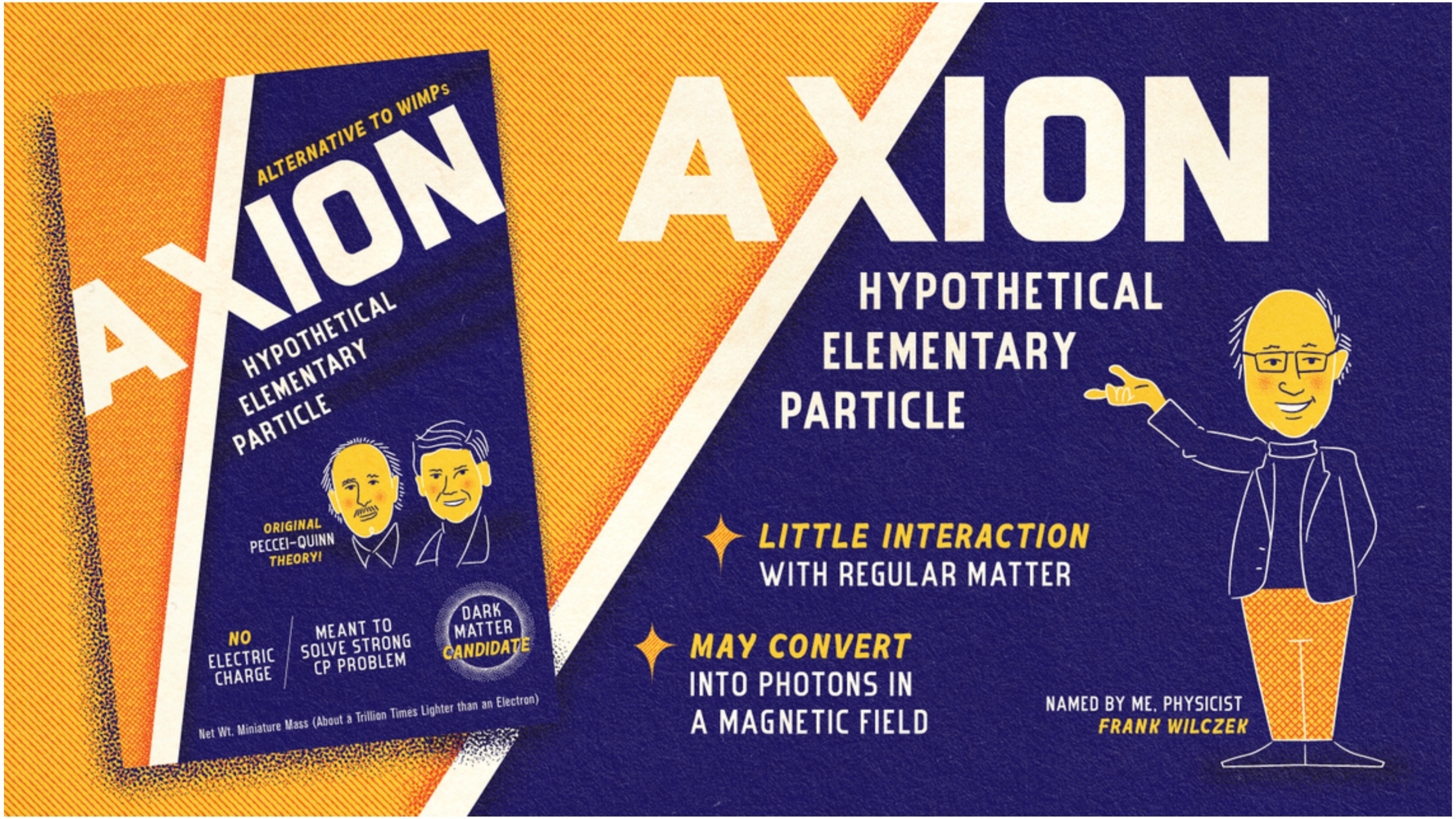


Vast range

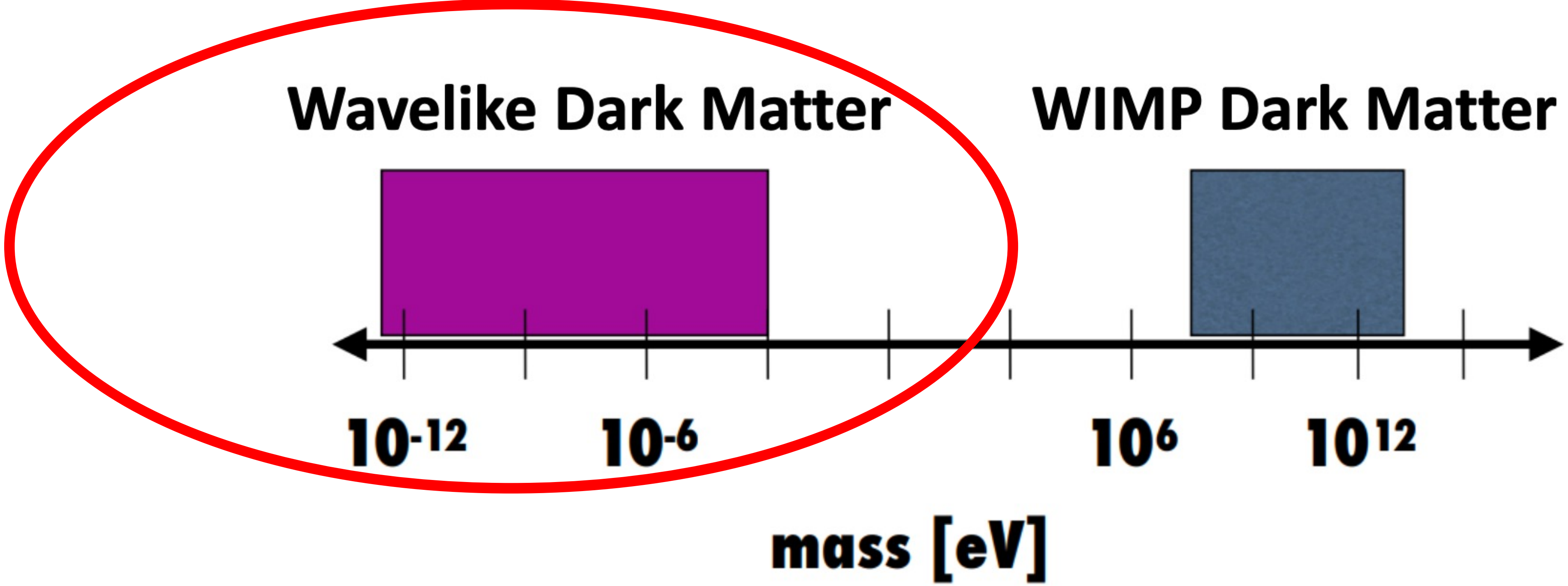


T. Lin, ArXiv: 1904.07915

Axions: A leading Dark Matter Candidate



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



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

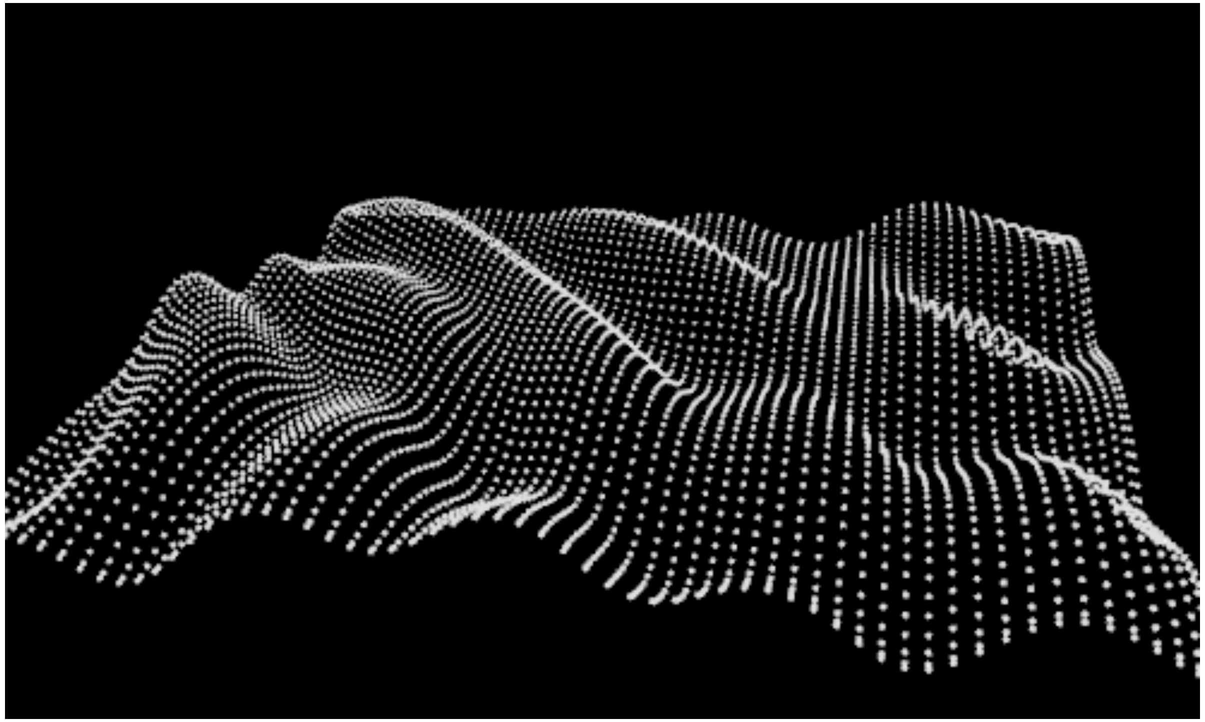
Adapted from B. Safdi

Axion Dark Matter: a Cosmic MASER

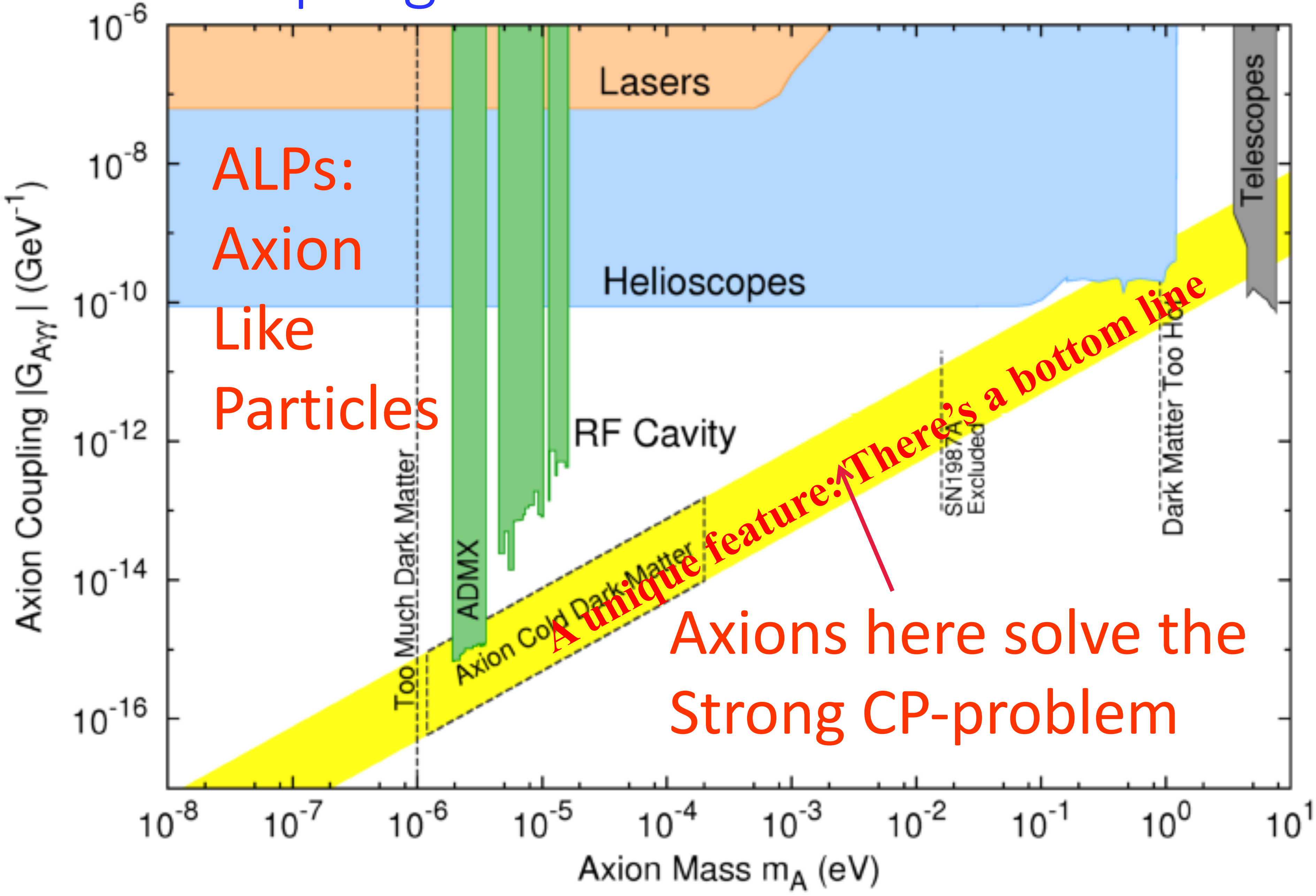
De Broglie wavelength of axions

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

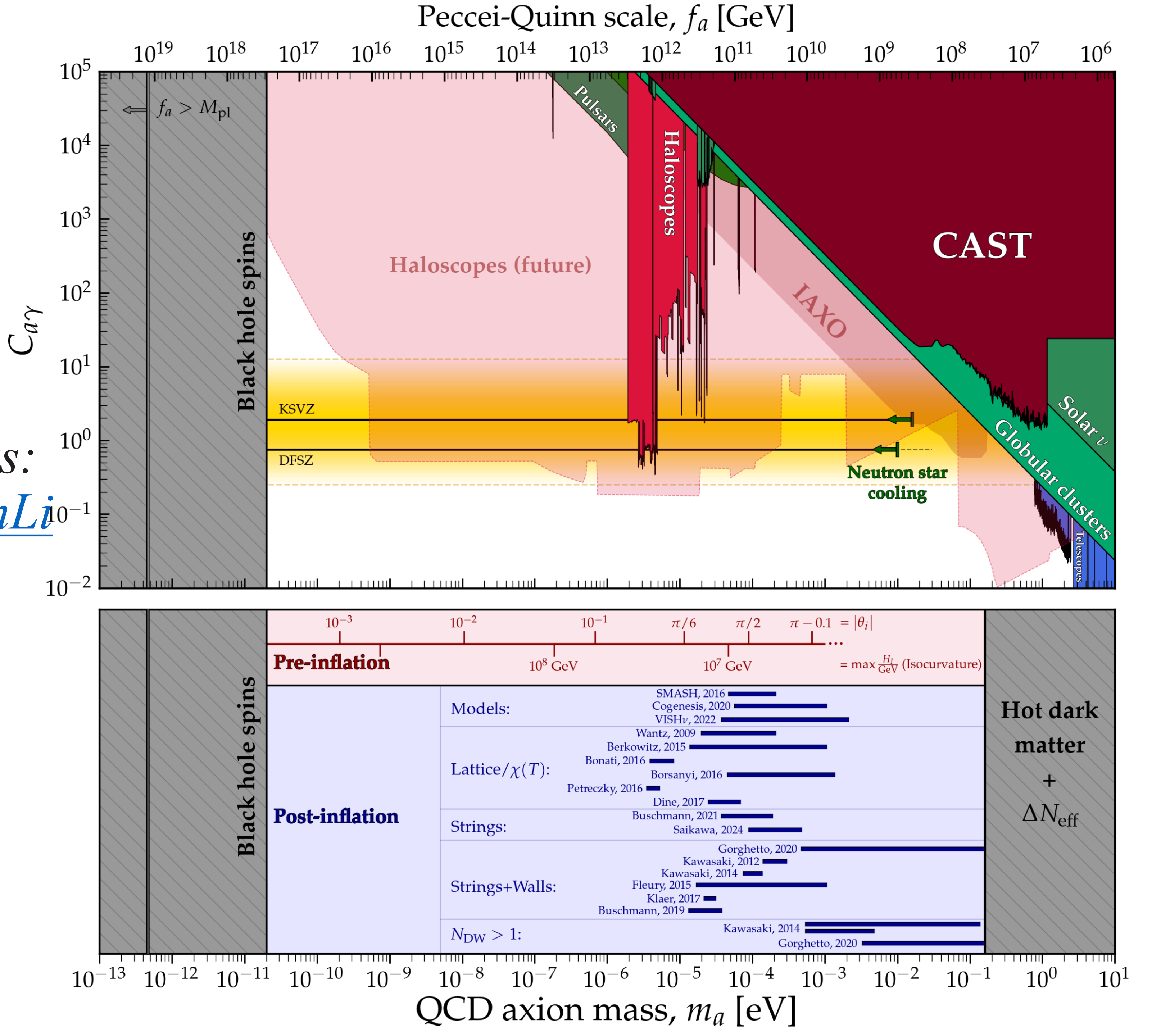
$$\lambda \approx 300\text{m} \times \left(\frac{1\mu\text{eV}}{m_a}\right)$$



Axion coupling vs. axion mass



Axion coupling vs. axion mass



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

World map of current experiments on wavy dark matter

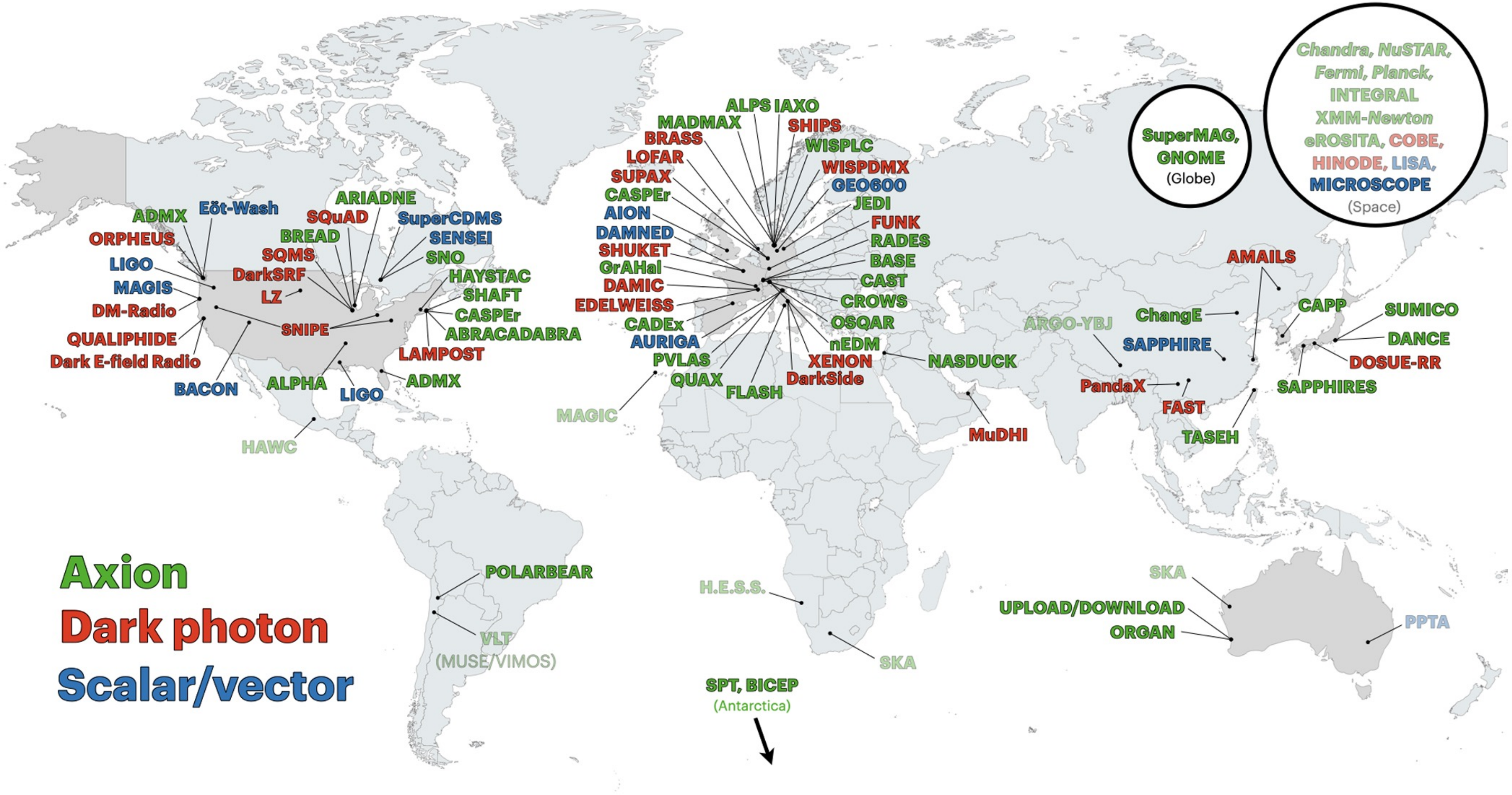


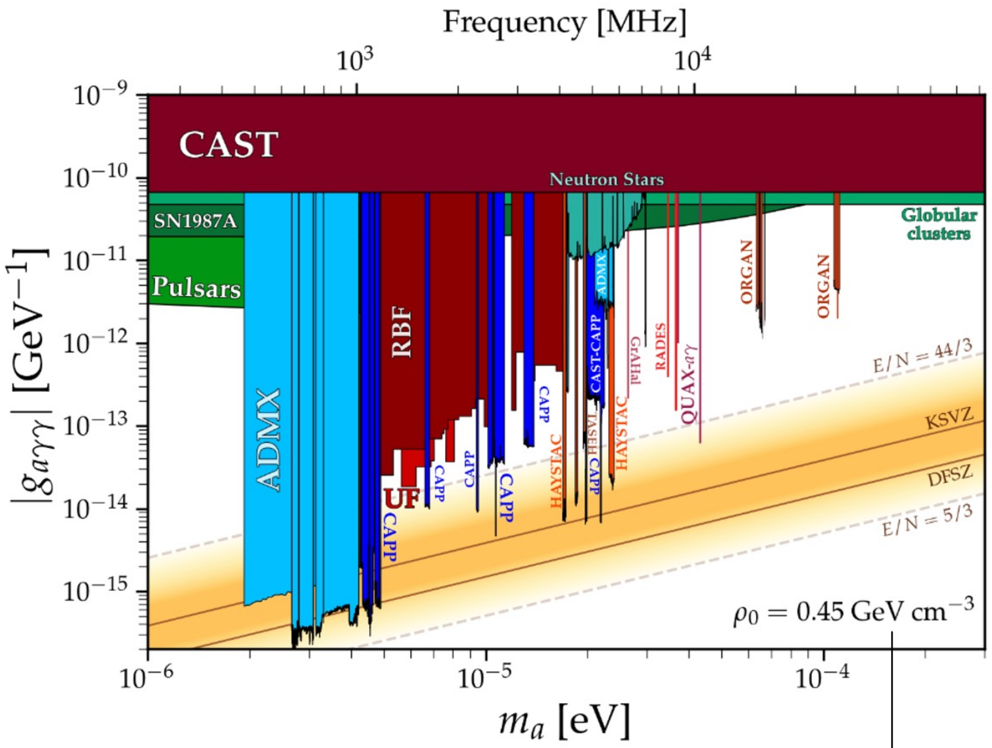
Figure 6: World map displaying current experiments searching for wavy dark matter [9].

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

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

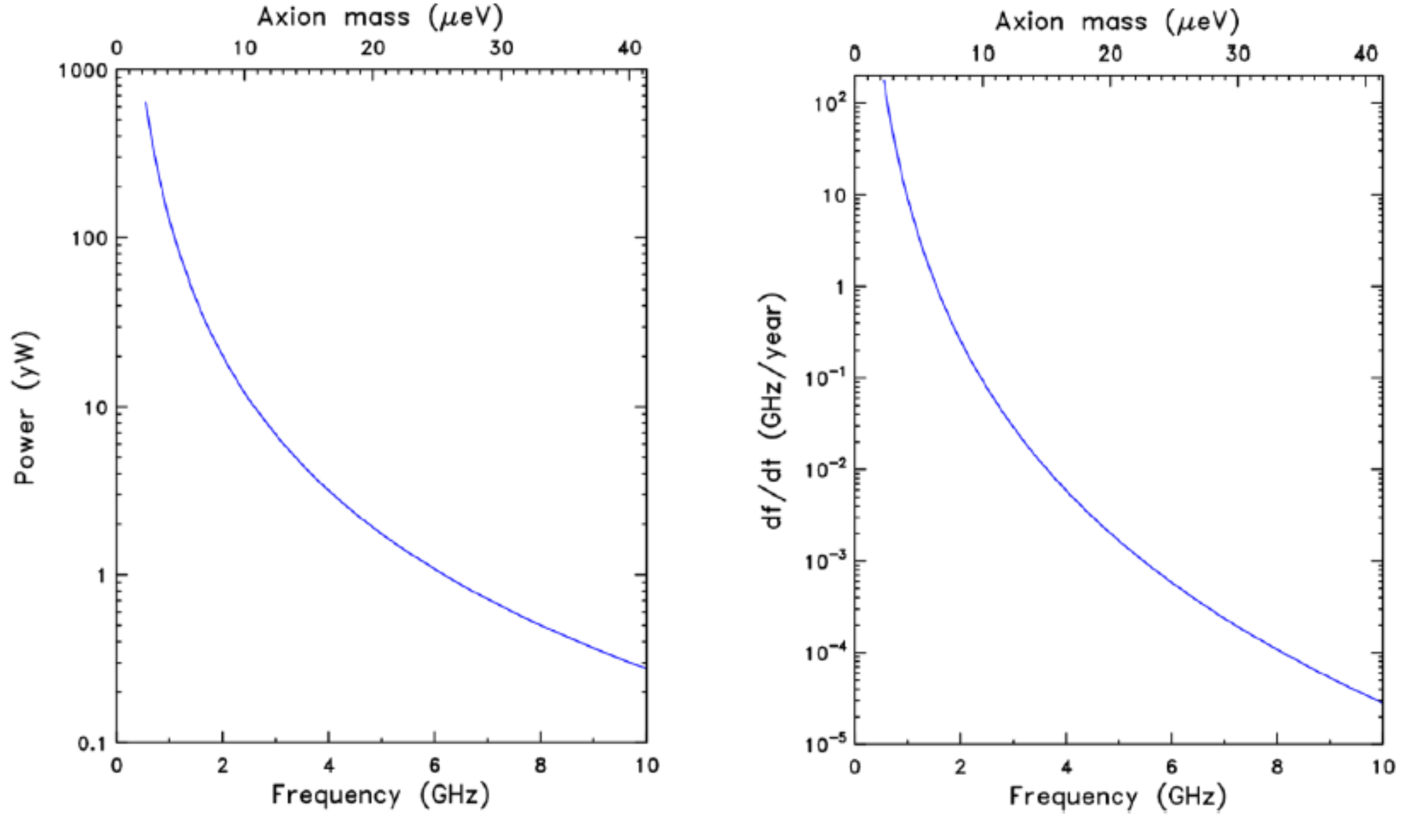
← Exclusion limit of Axion haloscope

- 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**) $g_\gamma = 0.36$

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

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 the Center

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.

IBS-CAPP looked at all possible parameters

KAIST 1971

CAPP
Center for Axion and Precision Physics Research

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

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:

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

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

- 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}

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

Axion dark matter hunters

Recent (CAPP axion-dark matter group, 2014)

Slide from recruiting tours

Hired two more Research Fellows and more are joining soon…

Strong visitor program:
Bring your ideas,
Teaching skills,
Your attitude!

Center for Axion and Precision Physics (CAPP)

http://capp.ibs.re.kr/html/capp_en/

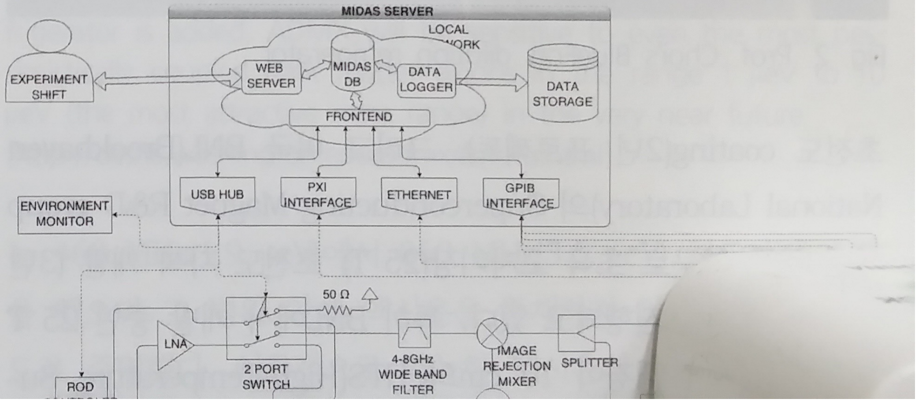

CAPP / IBS, May 2015

CAPP/IBS RF-Training

Fig. 4. Participants of the rf lab measurements. The lecturer, Dr. Fritz Caspers (CERN) and people from CAPP, RISP and PAL are discussing and learning the rf measurement using network analyzer.

전도를 잘 다스리면 공진기의 온도는 50 mK을 넘지 않으리라는 게 냉동기 전문가인 최형순 교수의 예측이다. 여지껏 2 K를 웃돌던 액시온 공진기의 온도가 기록적으로 떨어지지 않을까

Fig. 5. The lecturer, Dr. Fritz Caspers (CERN), and Dr. Young-Im Kim at CAPP/IBS who organized and prepared the entire rf training courses.



Developing collaborating skills

KUSP
KOREA
UNDERGRADUATE/GRADUATE/H.S.
SCIENCE PROGRAM

Importance and Promise of Electric Dipole Moments

Frank Wilczek

January 22, 2014

Support letter to P5 for the proton EDM

The additional symmetry has another remarkable consequence. It predicts the existence of a new very light, very weakly interacting spin 0 particle, the *axion*. The possible existence of axions raises the stakes around these ideas, because it entails major cosmological consequences. Indeed, if axions exist at all, they must provide much of the astronomical "dark matter", and quite plausibly most of it.

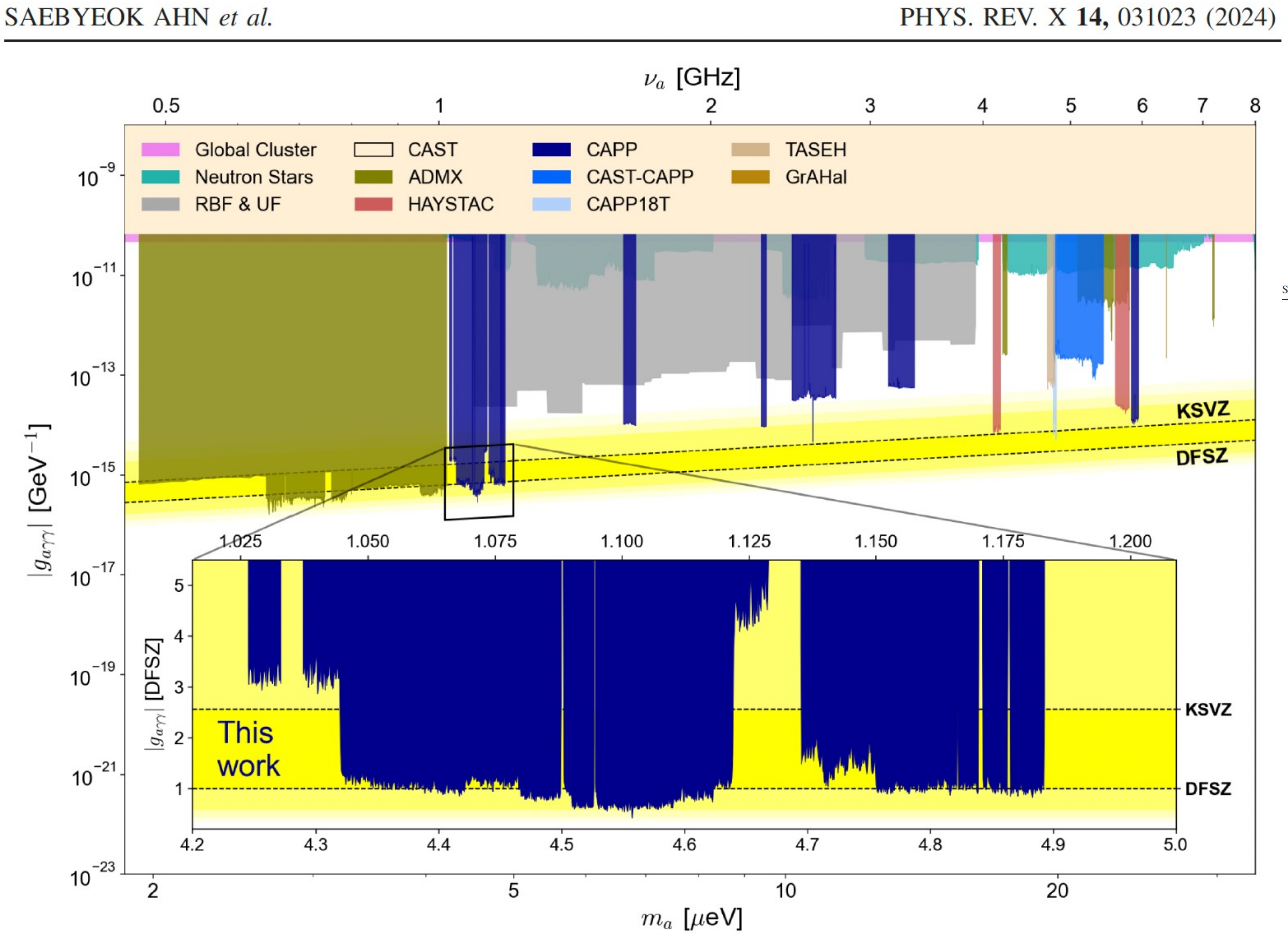
Better bounds on θ, or especially an actual determination of its value, would allow us to sharpen these considerations considerably. Better measurements of fundamental electric dipole moments are the most promising path to such bounds, or measurement.

CAPP Axion dark matter hunters, students and faculty

Prof. Selcuk Haciomeroglu, Storage ring EDM, now at Istinye Univ., Istanbul

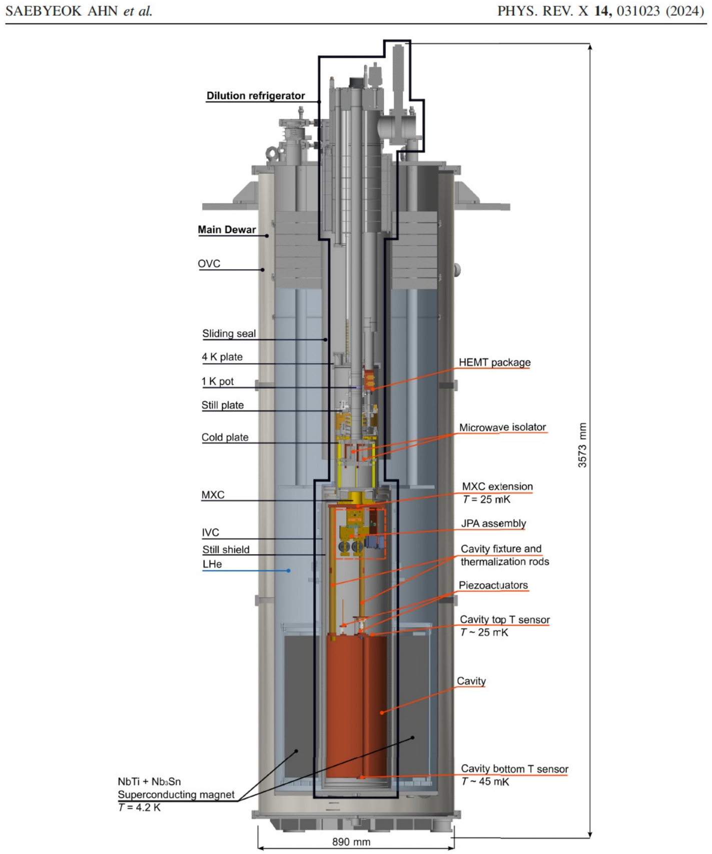
Students from KAIST and IBS-CAPP: Junu Jeong (Stockholm), Andrew Yi (SLAC), YoungGeun Kim (Mainz, Humboldt fellow)

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

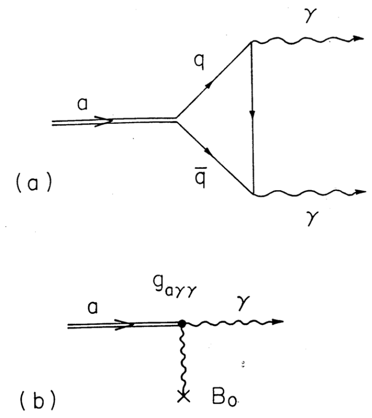


S. Ahn et al., PRX (2024) from CAPP.

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



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, ARIADNE; GNOME)

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

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: $10^5 \rightarrow 10^6$

  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

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

KAIST 1971

ibs CAPP Center for Axion and Precision Physics Research

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

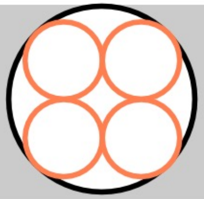
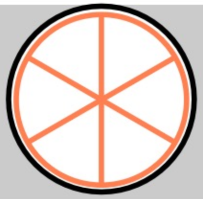
Parameter	**B-field**	**Volume**	**Quality factor**	**Temp.**	**Readout electronics**
df/dt	$\sim B^4$ From 8T to 12T, 18T, 25T, … Any gain in B is a gain in the coupling	V^2 Pizza-cavities: 3-4x, dielectric: 5x	Q HTS cavities: 1-2 orders gain achieved	T^{-2} Near quantum noise	HEMT, JPA Probing method (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!

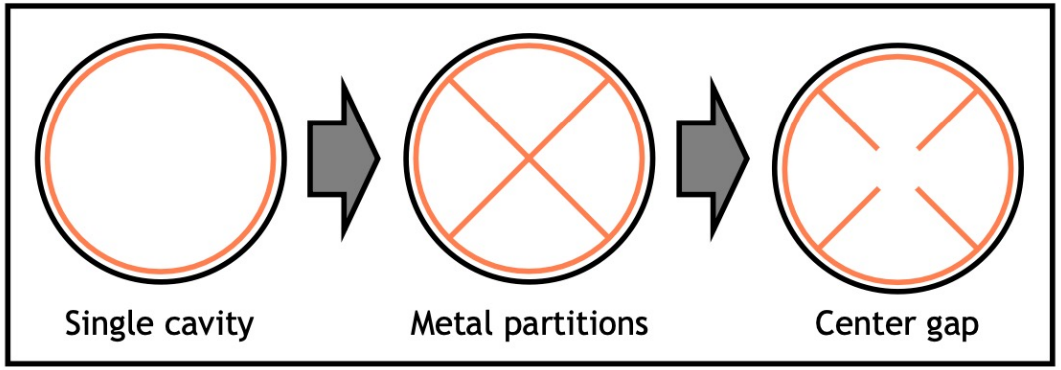
Higher frequency than the “natural” one

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

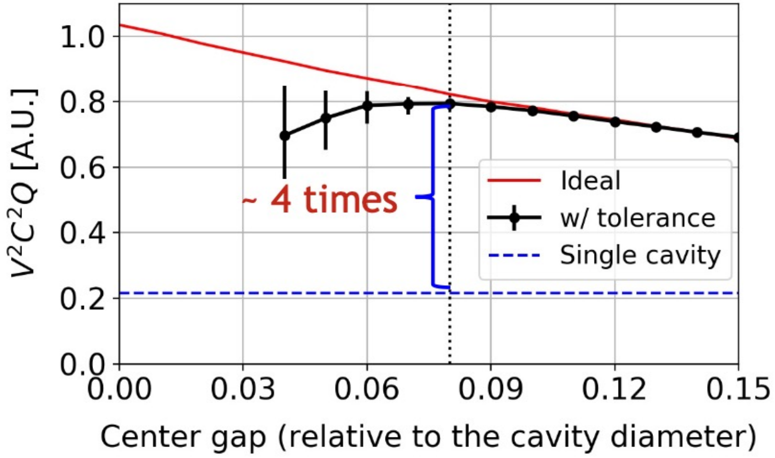
Multiple-cell cavity
- ➢ Almost no volume loss
- ➢ Single antenna & no combiner
- ➢ Robust against tolerance

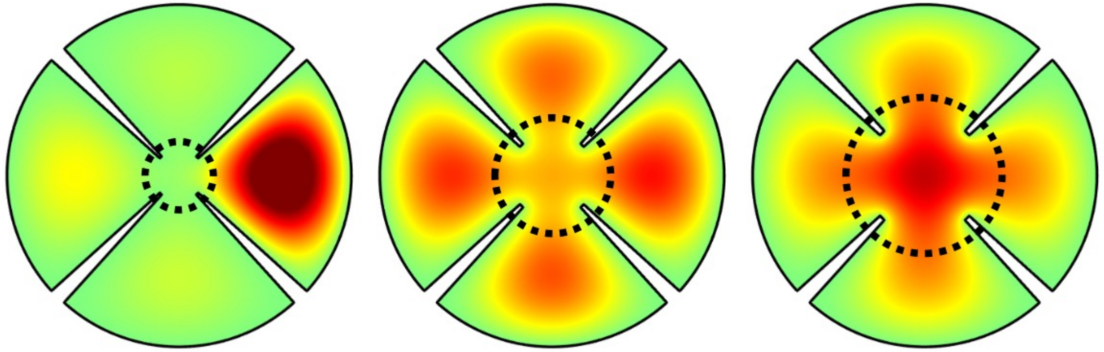
Slide by Junu Jeong, SungWoo Youn et al.

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

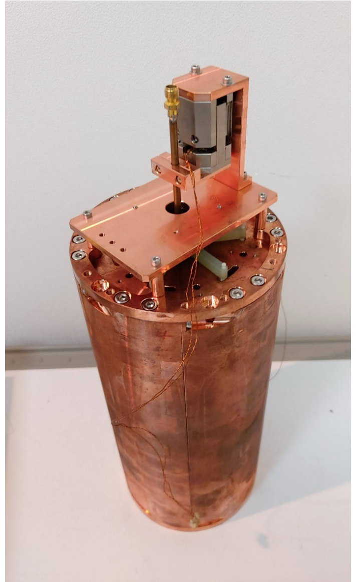
Large center gap low quality factor

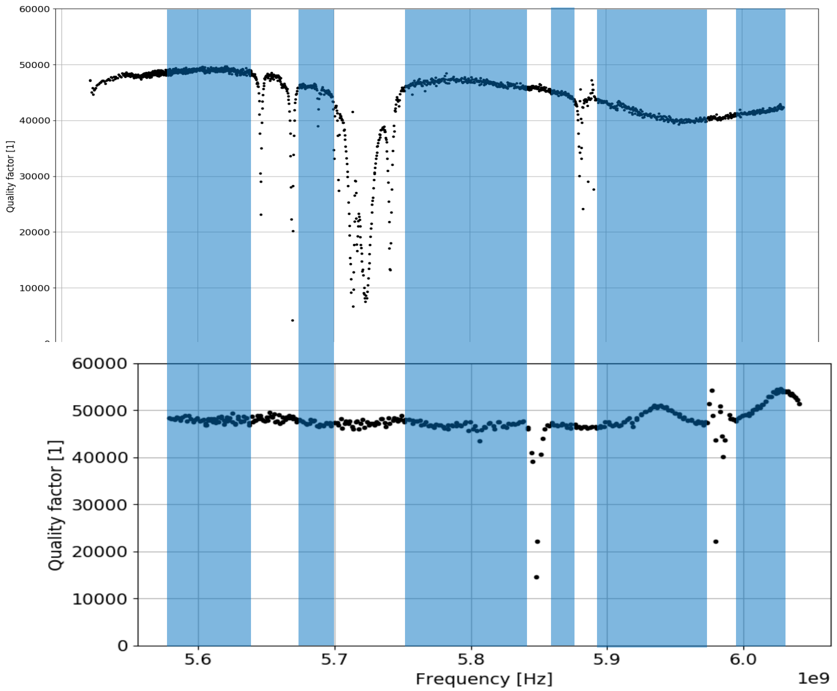
Multiple-cell (pizza) cavity

- *First axion search with a double-cell cavity*
  - *3.14 ~ 3.36 GHz (13.0 ~ 13.9 μeV)*

PRL 125, 221302 (2020)

- *Sextuple-cell and Octuple-cell cavities*
  - *5.5 ~ 6.0 GHz (23 ~ 25 μeV)*
  - *Phase-matching*

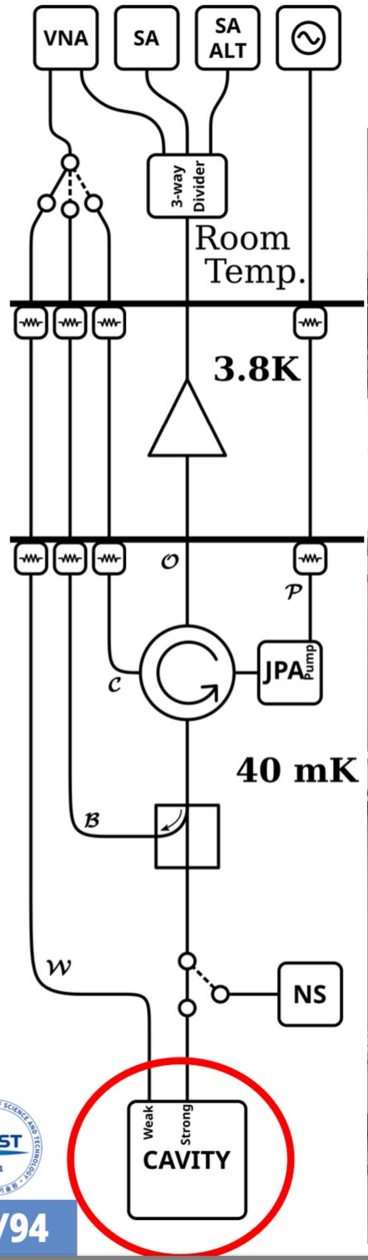


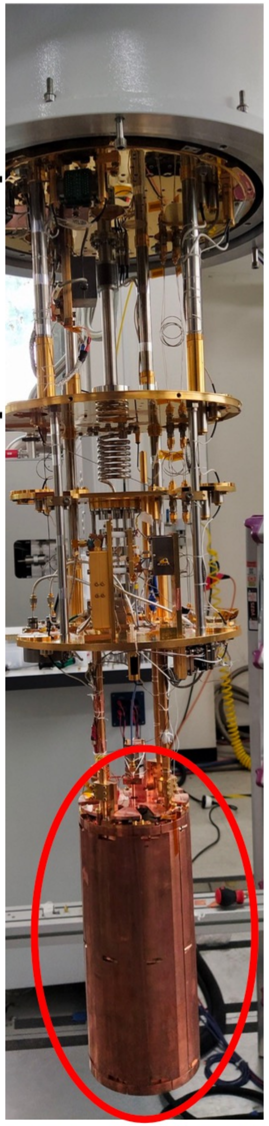


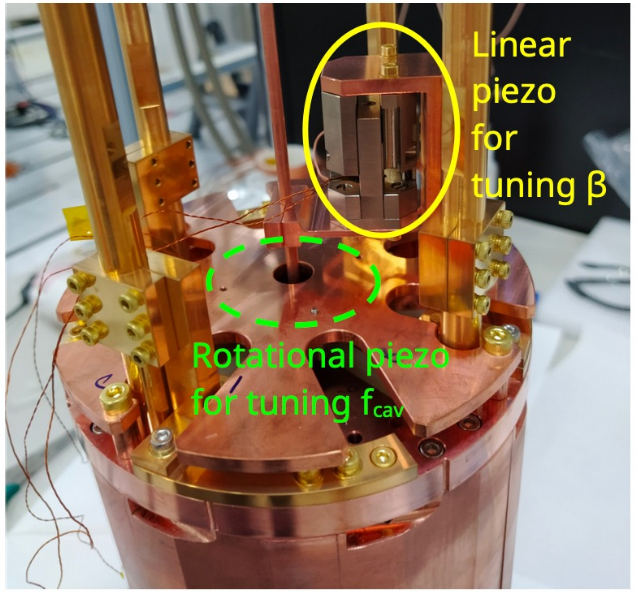
8-cell
(BF6)

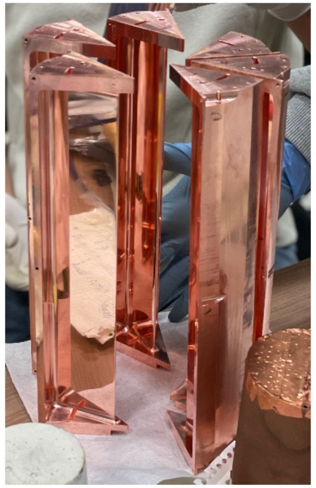
6-cell
(BF5)

CAPP8TB-6G: The 8-cell cavity

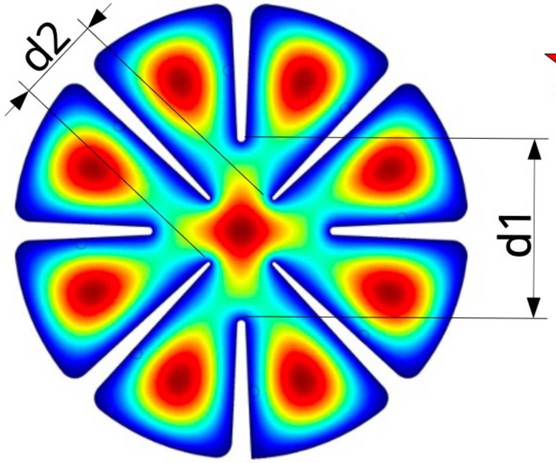








"Carousel" tuning rods



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

★ d1 and d2 are optimized for machining tolerance.

KAIST

CAPP Center for Axion and Precision Physics Research

Dec 8, 2022

Caglar Kutlu's slide

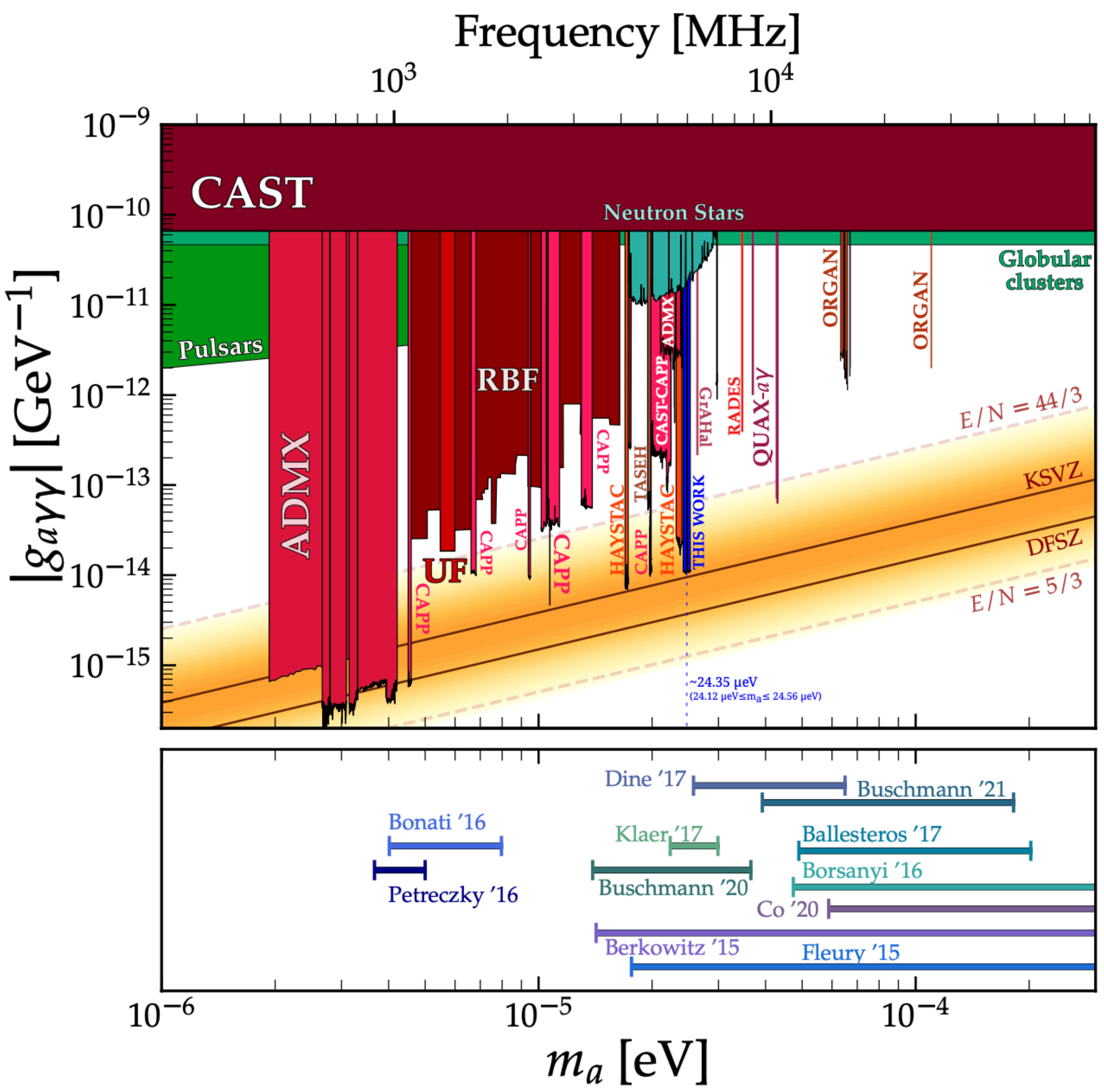
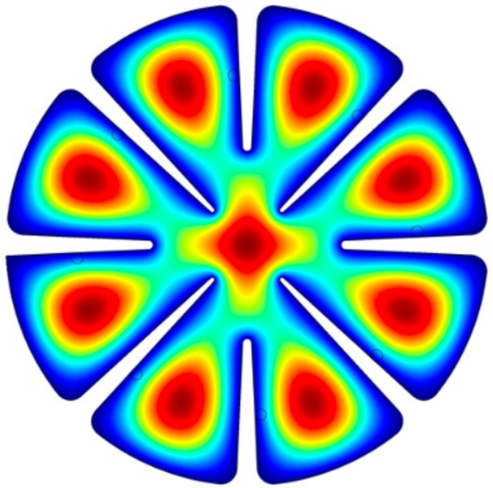


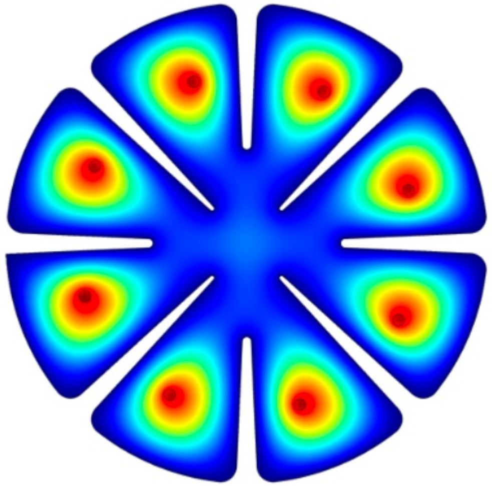
Figure 1.9: (Upper) Mass exclusion plot for the $g_{a\gamma\gamma}$ in the mass window discussed in the text. The results of this work are shown here for convenience. (Bottom) Axion mass ranges favored by various axion dark matter simulation studies. Figures are adapted from [76]

[76] C. O'Hare, "cajohareaxionlimits: Axionlimits," https://cajohare.github.io/AxionLimits/ (2020).

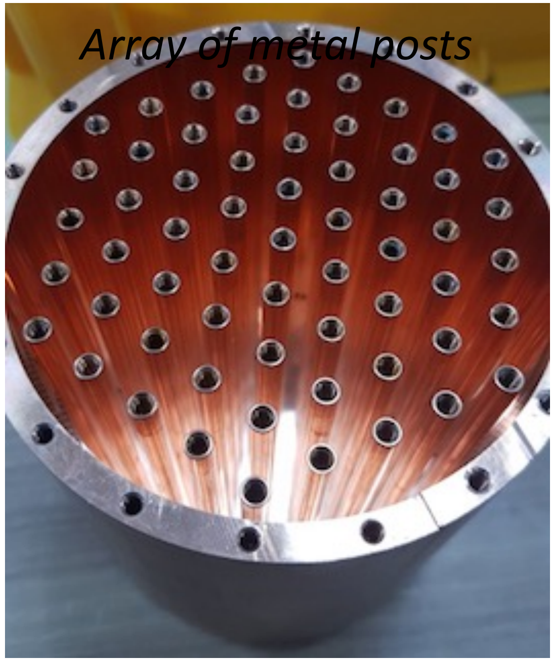
From Caglar Kutlu's PhD thesis, KAIST



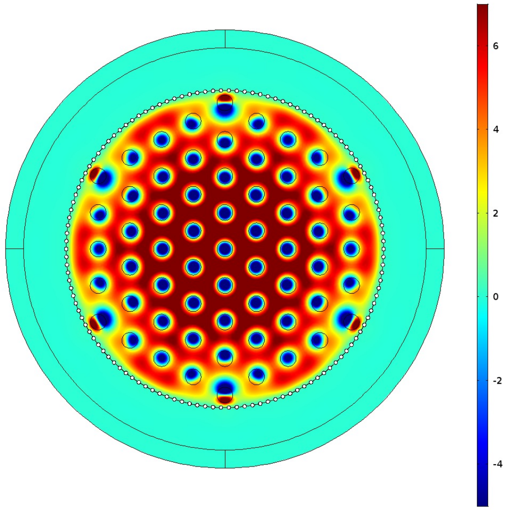
"Carousel" tuning rods in different positions



Metal wire vs. post vs. dielectric



Array of dielectric posts

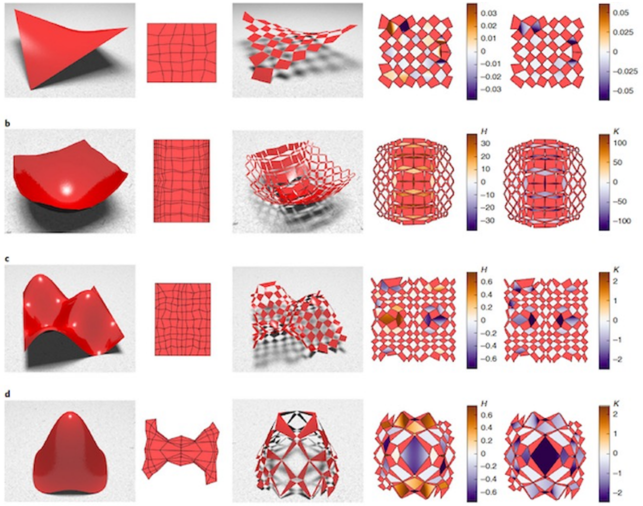


Metal wires	*Metal posts*	*Dielectric posts*
C = 0.81	*C = 0.76*	*C = 0.23 (TM_{020}-like)*
$Q = 9.6 \times 10^3$	*$Q = 1.7 \times 10^4$*	*$Q = 1.8 \times 10^5$*
D = ~3 wires/cm^2	*D = ~1 posts/cm^2*	*D = ~1 posts/cm^2*
Very challenging	*Less challenging*	*More reliable*
Tuning (variing s) not trivial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

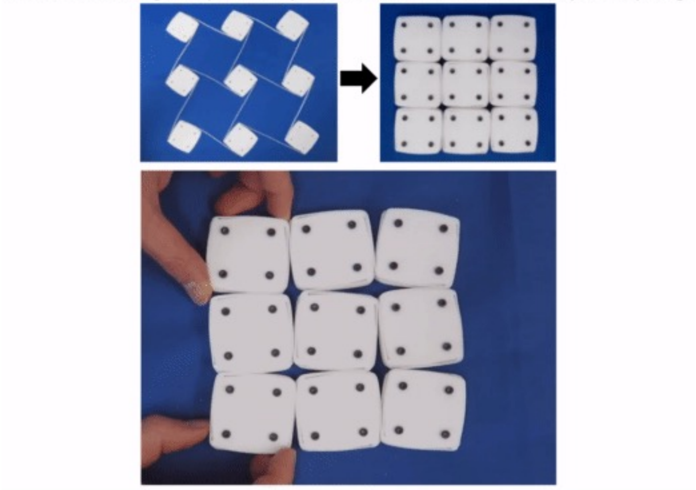
Kirigami tessellations

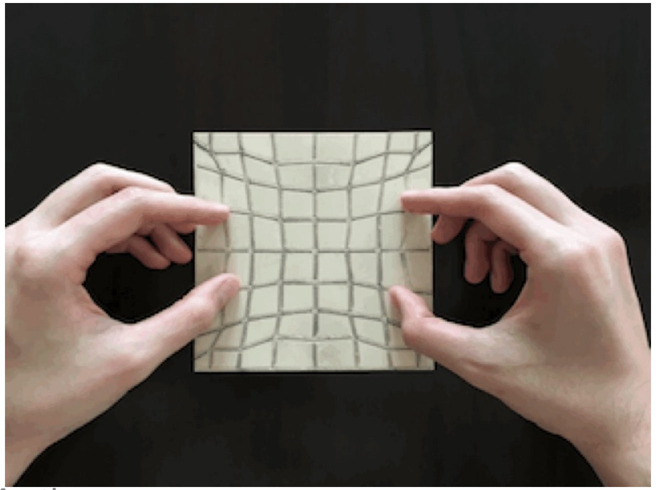
Kirigami

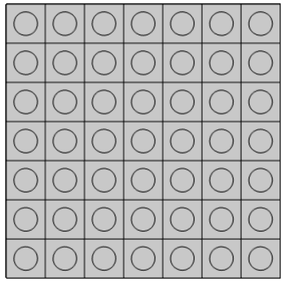
Nature material ***18****, 999*

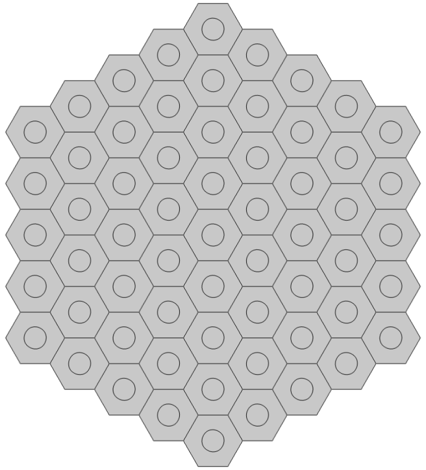


Nature communication ***9****, 4594*



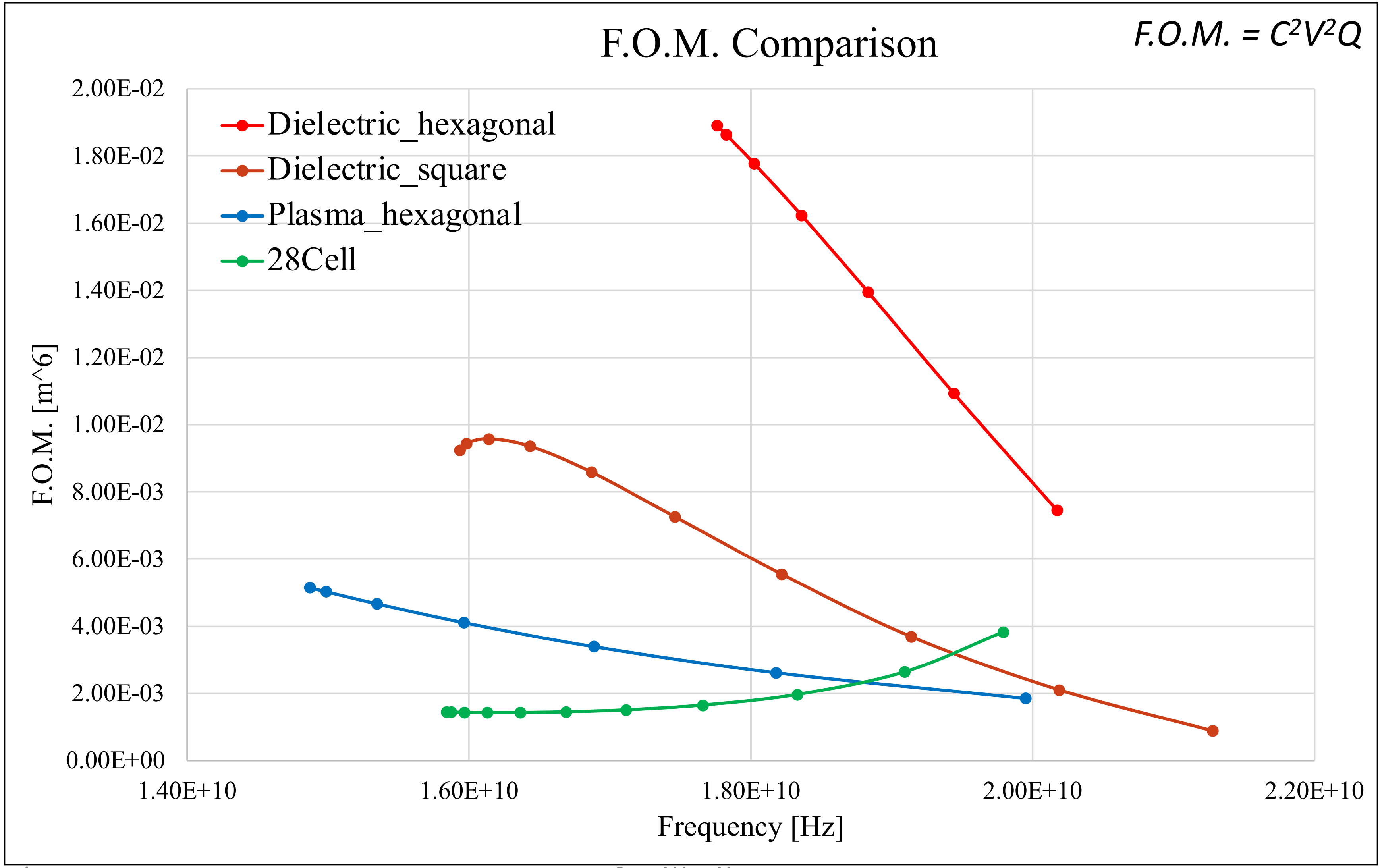






Performance comparison

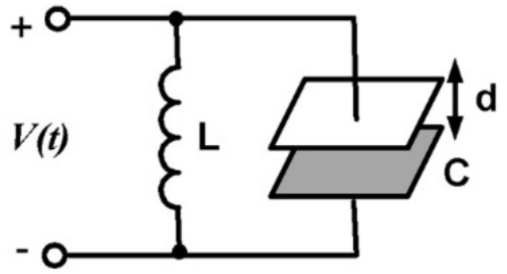
Physical Review D Vol. 107, No. 1, 015012-1-015012-8(2023)

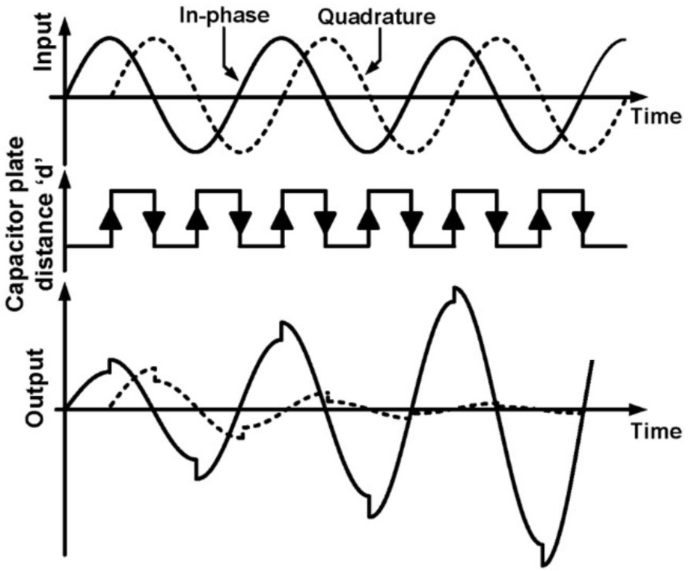


Quantum-based readout electronics

JPA Principle

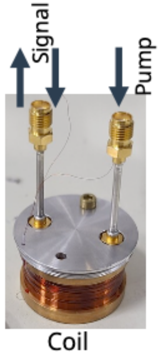
(Caglar Kutlu's slide, Sergey Uchaikin et al.)



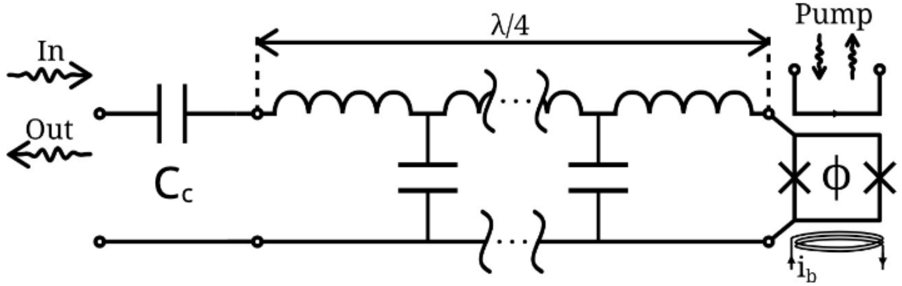


JPA Principle

(no resistors)

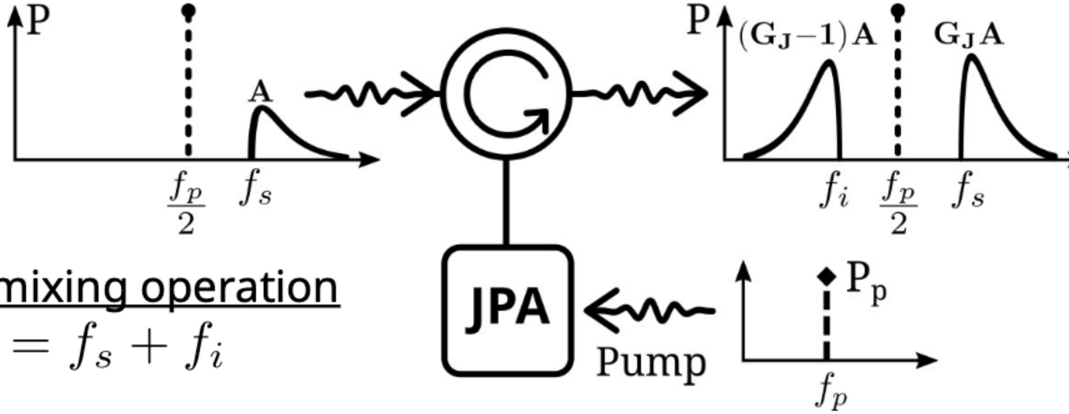


Flux-driven Josephson Parametric Amplifier



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

- 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.



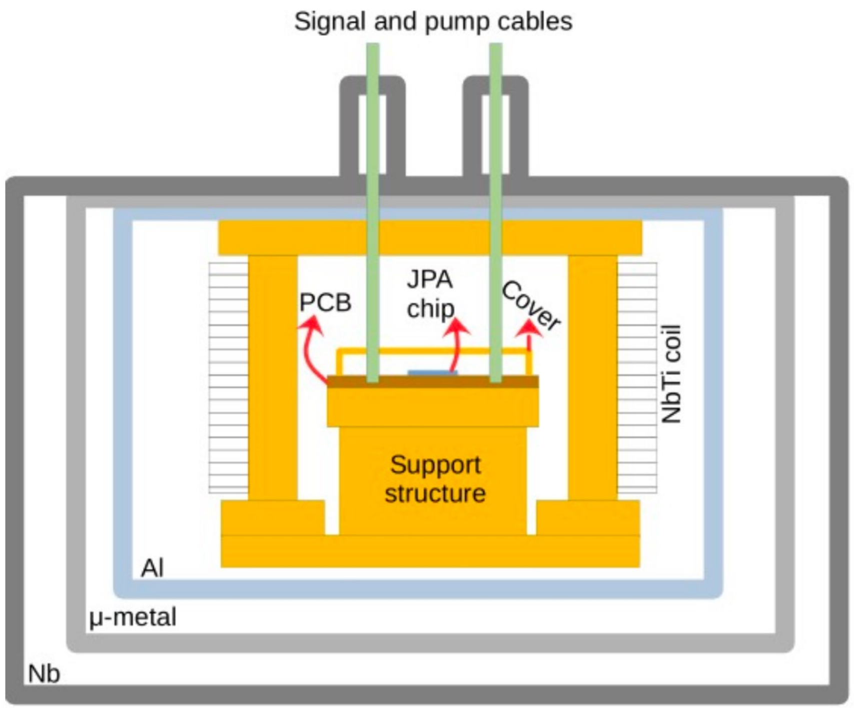
3 wave mixing operation

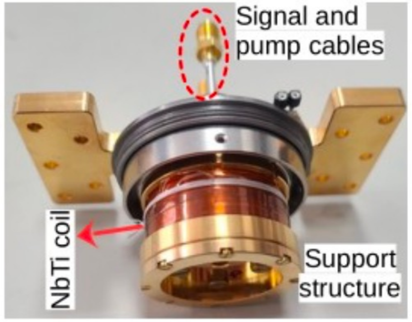
$$f_p = f_s + f_i$$

Caglar is now with a quantum computing startup in Switzerland

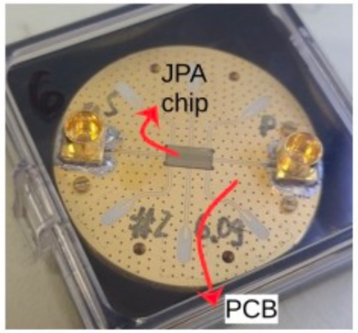
[1] W. Lee and E. Afshari, "A CMOS Noise-Squeezing Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 2, pp. 329-339, Feb. 2012

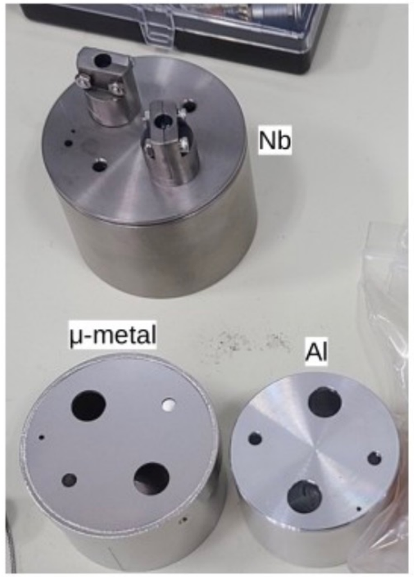
JPA implementation



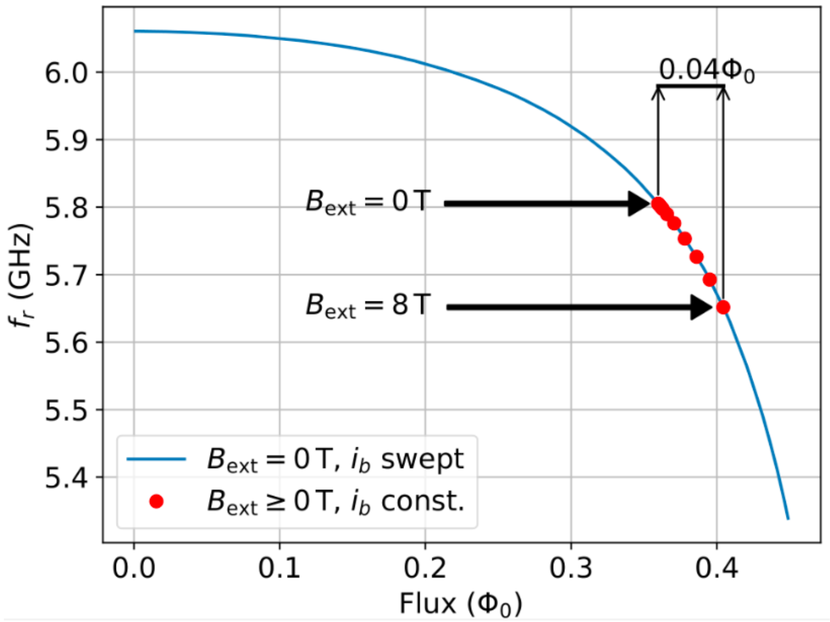


JPA packaging design: Sergey Uchaikin

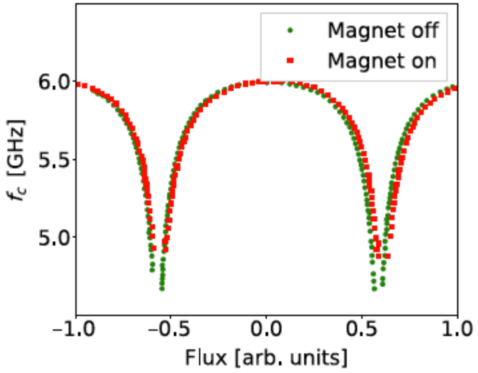




Chips designed and manufactured in Univ. of Tokyo (Arjan van Loo)
Packaging and shielding designed by Sergey Uchaikin (CAPP)



Caglar Kutlu's slide



RIKEN QUANTUM COMPUTING

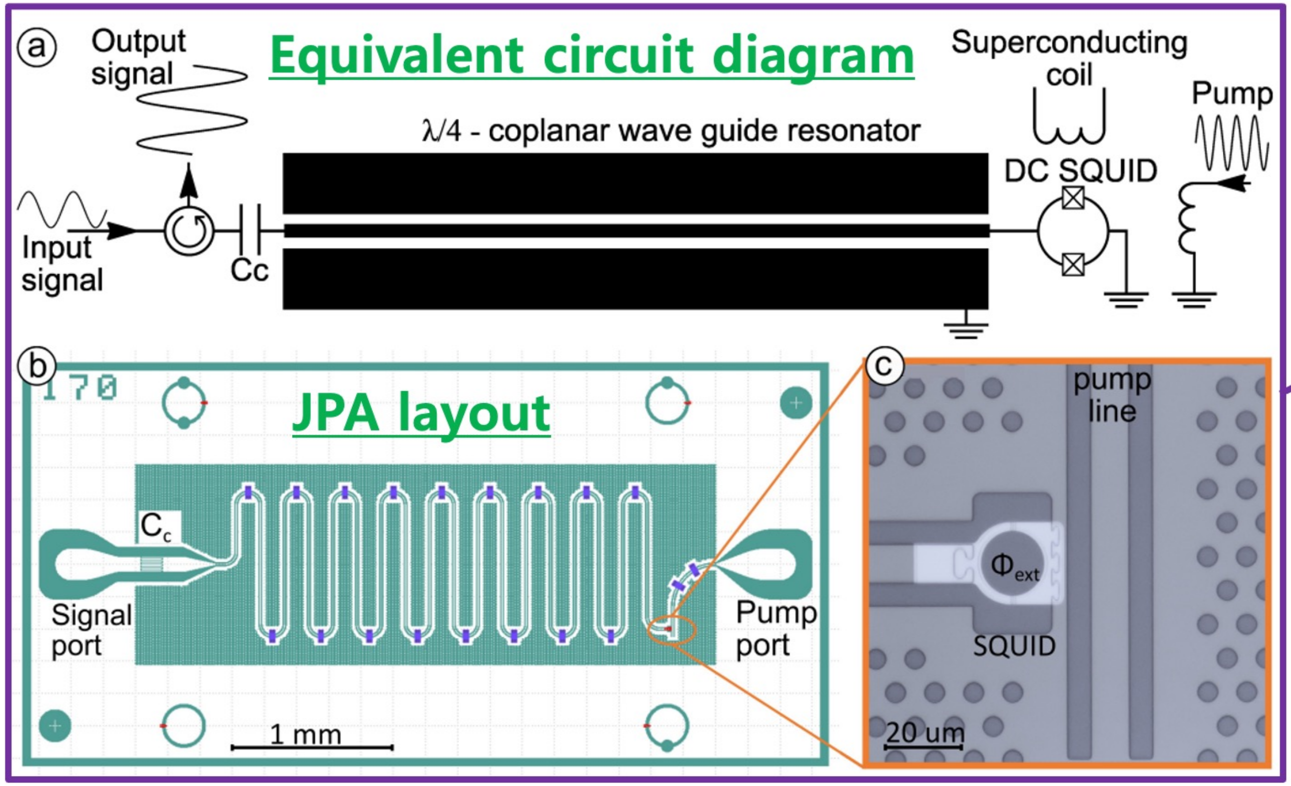
Collaboration with Yasunobu Nakamura
They made chips and IBS-CAPP packed them.

Flux-driven Josephson Parametric Amplifier

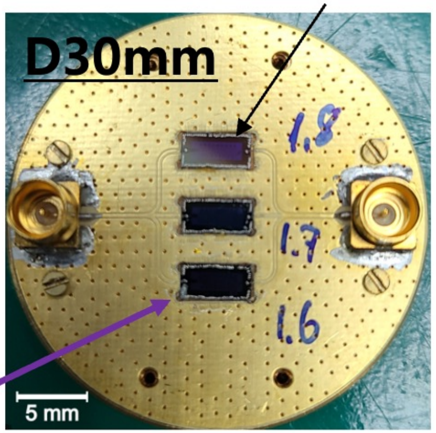
Uchaikin, et al, "Josephson Parametric Amplifier based Quantum Noise Limited Amplifier Development for Axion Search Experiments in CAPP," Frontiers in Physics **12**, 1437680 (2022).

Quantum noise limited amplifier

⊠: Josephson junction

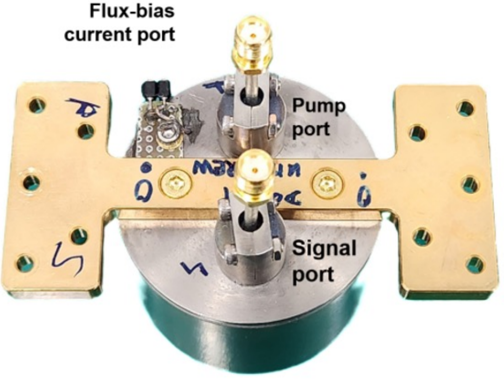


$\mathbf{2.5 \times 5\ mm^2}$



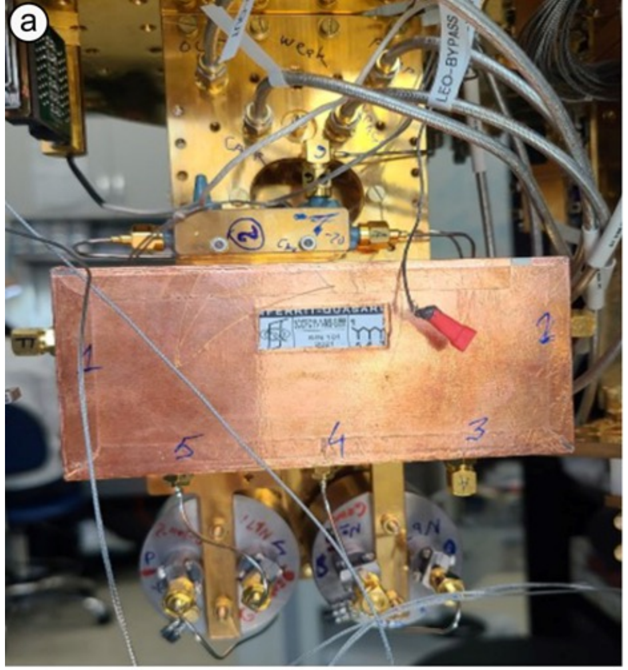
Jiwon Lee's slide

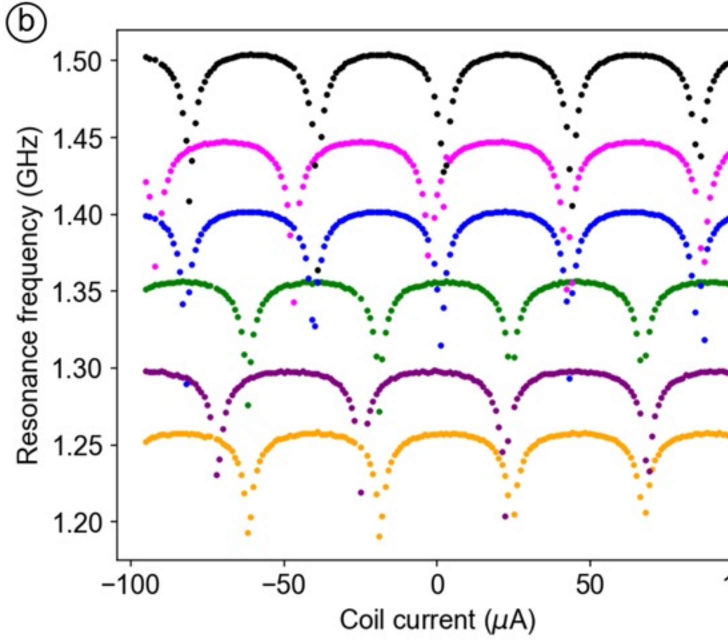
Top view of the gold-plated PCB with JPA chips bonded.

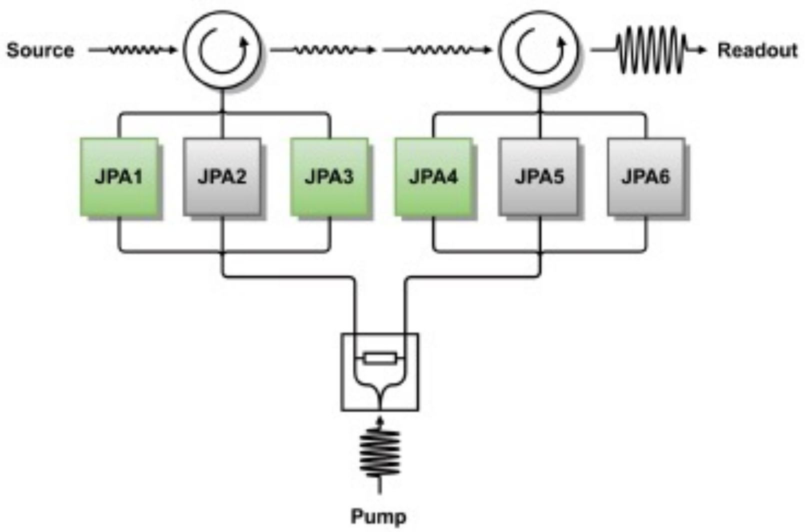


The assembly with the SMA connectors

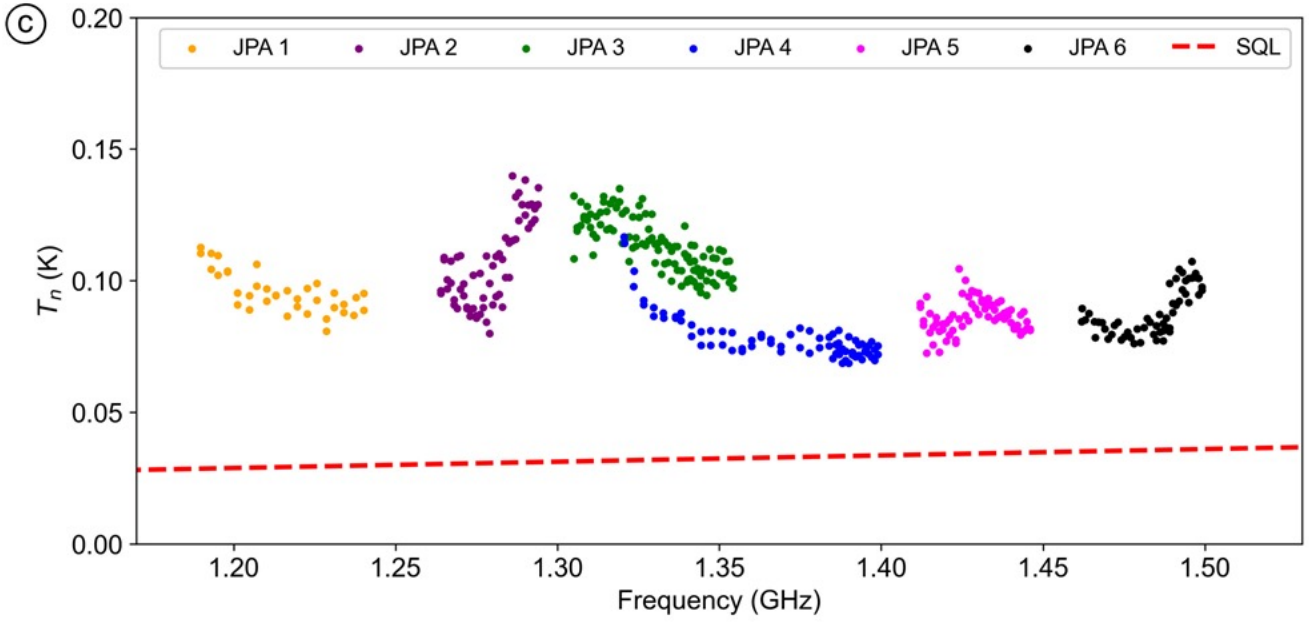
CAPP-MAX, JPA-bundle development testing
Added system noise (JPA+ HEMT noise).
Chips by Tokyo (Nakamura et al.)
Development at CAPP: Sergey Uchaikin et al.







(b)



Expect to finishscanning 1.2 - 1.5 GHz at better than DFSZ within next 2 months

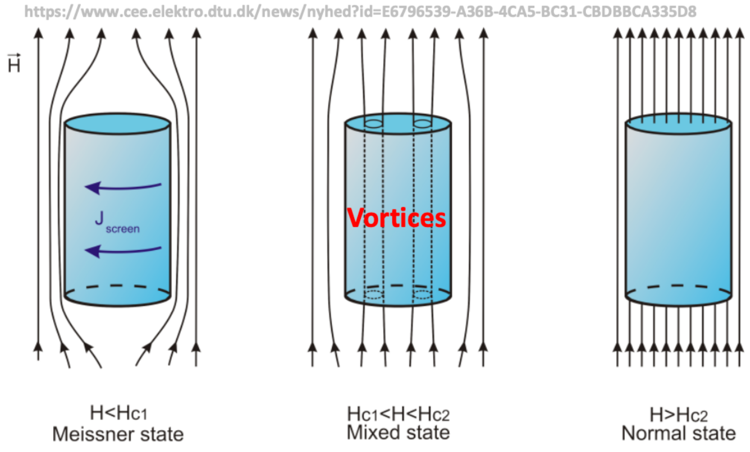
Superconducting cavities in strong B-fields

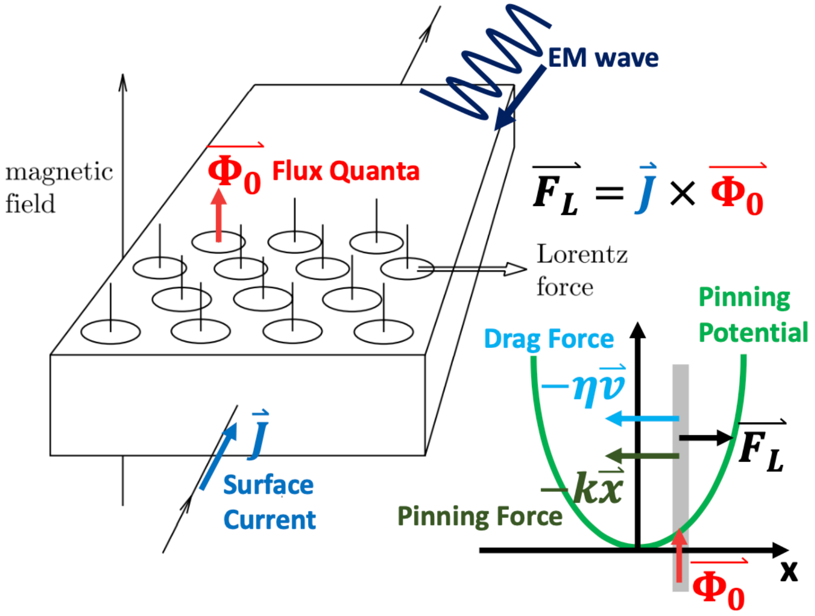
Superconducting (SC) cavities

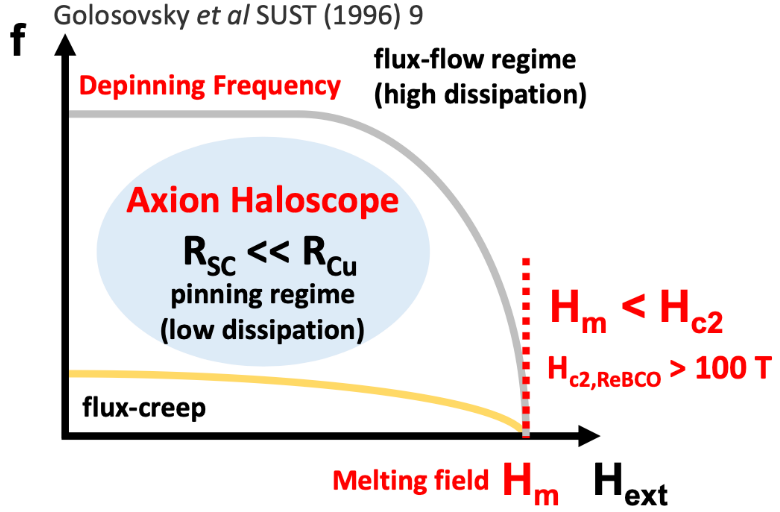
Danho Ahn's slide,
Woohyun Chung et al.

Vortex Pinning is Important for Low R_s

Three Phases of Type II Superconductor



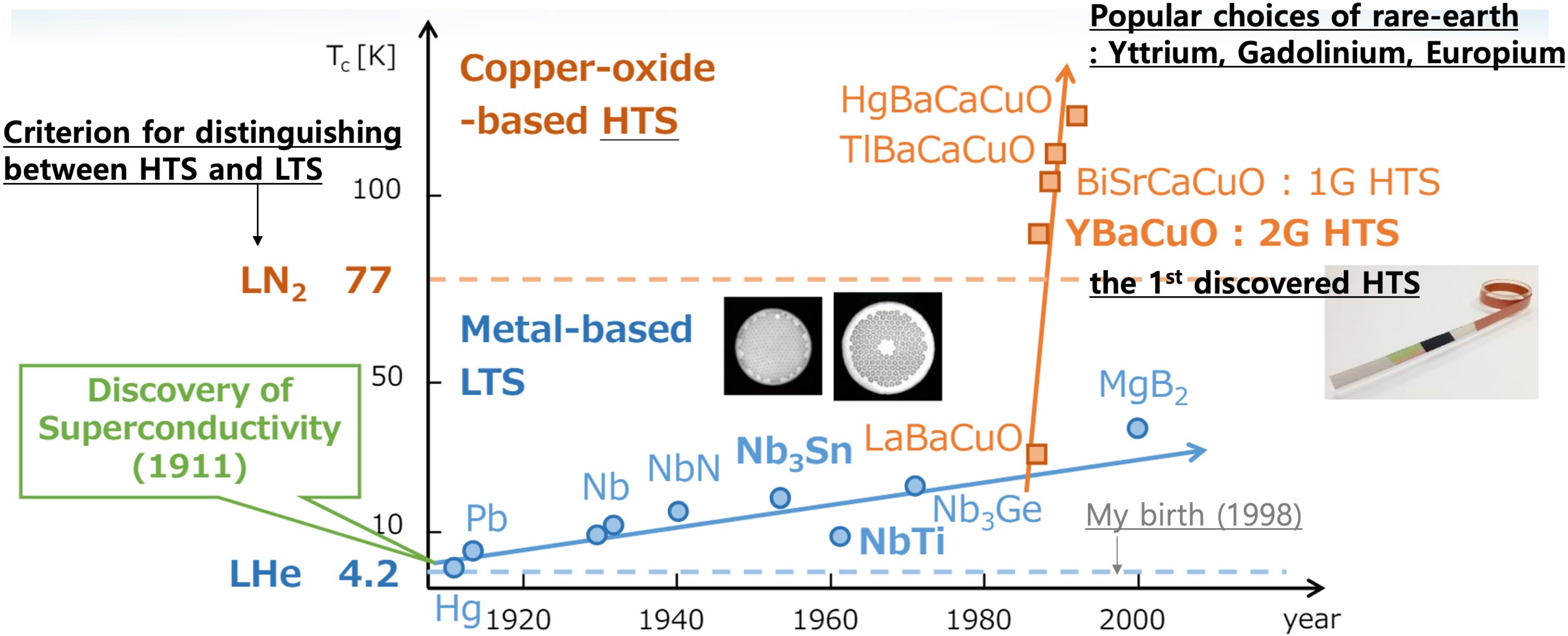




- Two criteria for evaluating materials
  - ✓ Large upper critical field ($H_{c2} > 30$ T)
    - Lower Vortex Density
  - ✓ High depinning frequency ($\omega_0 > 1$ GHz)
    - $\omega_0 = k / \eta$
    - $\omega \gg \omega_0$ (Drag force ≫ Pinning force)

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

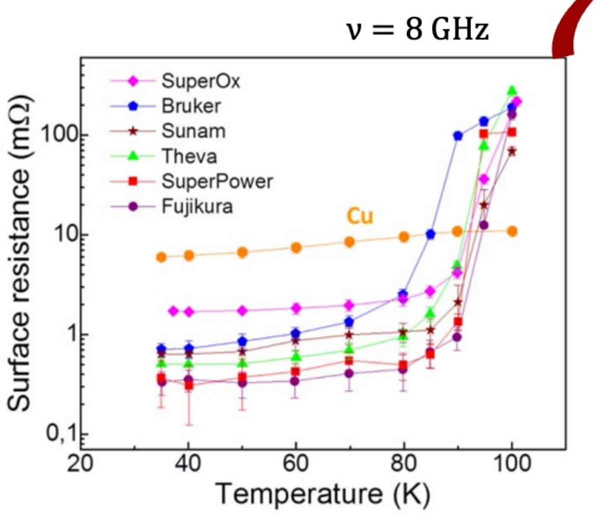
R_S(ReBCO) I did these measurements with Dr. Danho Ahn.

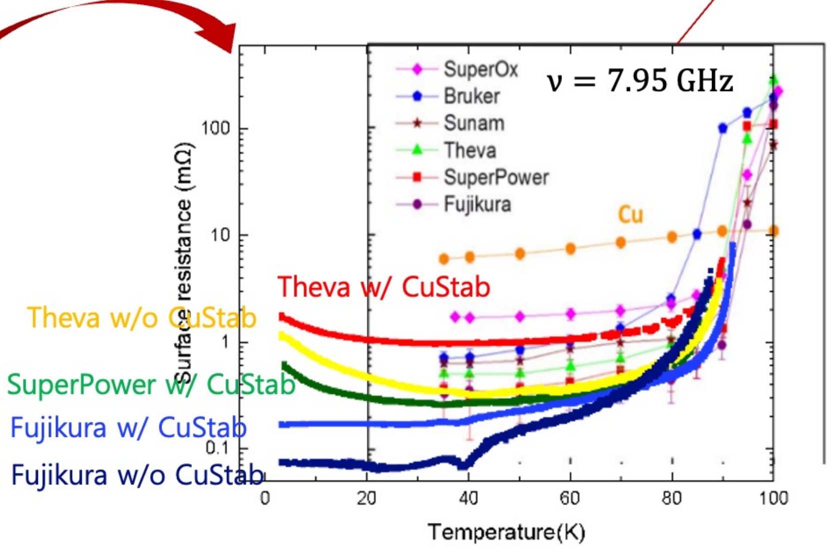
Theva	GdBCO
Superpower	GdBCO
Fujikura	EuBCO

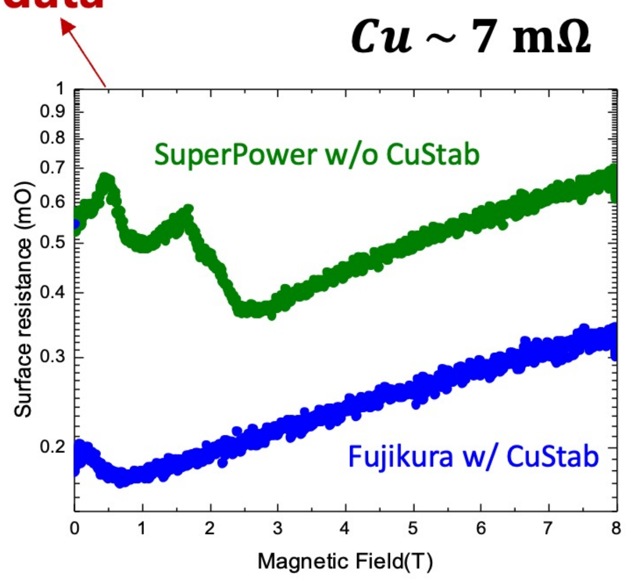
- Measured R_S of the ReBCO including research at IBS-CAPP

Overlapping on top of it

Measured data







Currently in use

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).

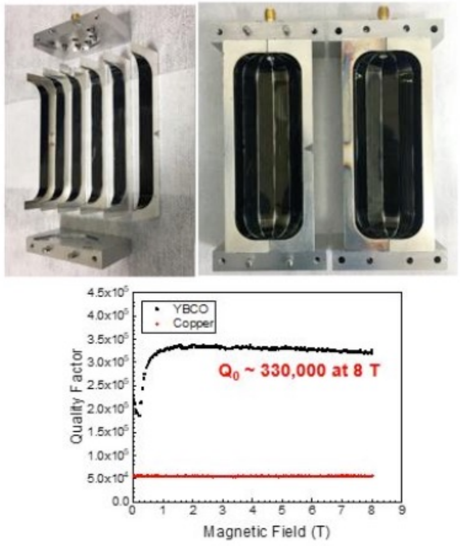
Even up to 8 T,
the R_s did not deteriorate much.

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

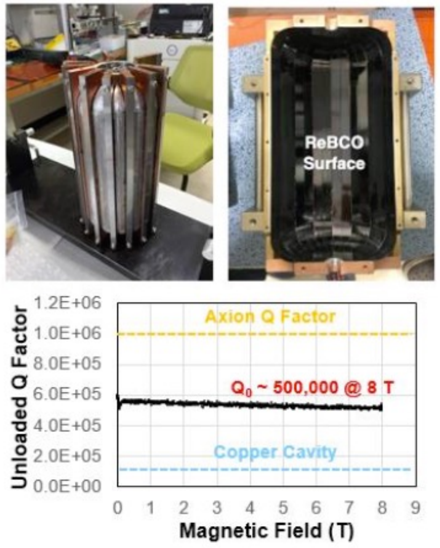
Danho Ahn's slide

History of HTS Cavity Development @ CAPP

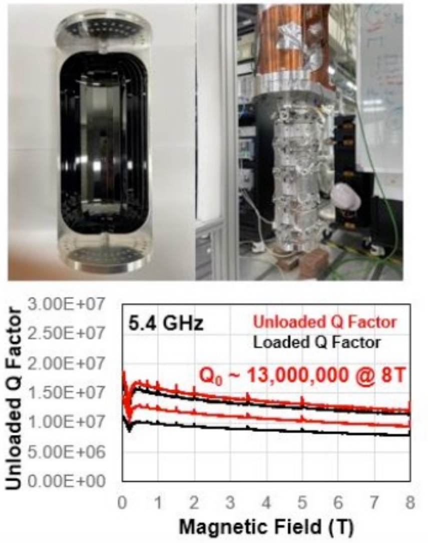
First Gen. (6.9 GHz)



Second Gen. (2.3 GHz)



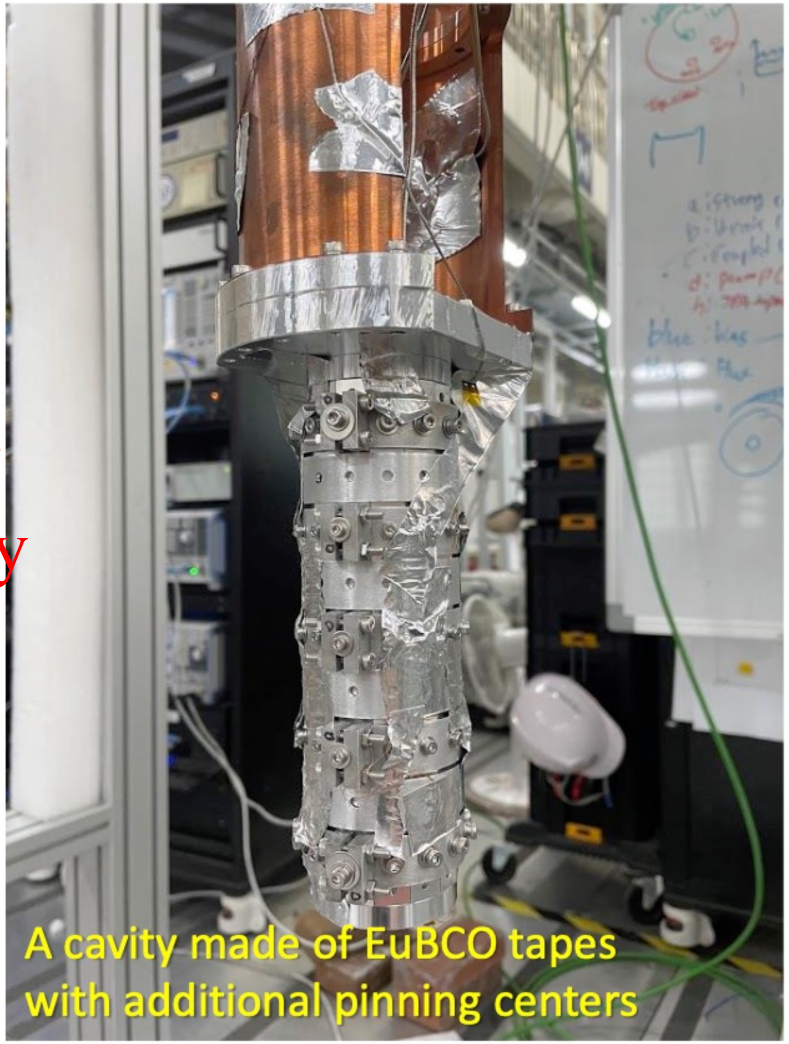
Third Gen. (2.2 GHz & 5.4 GHz)

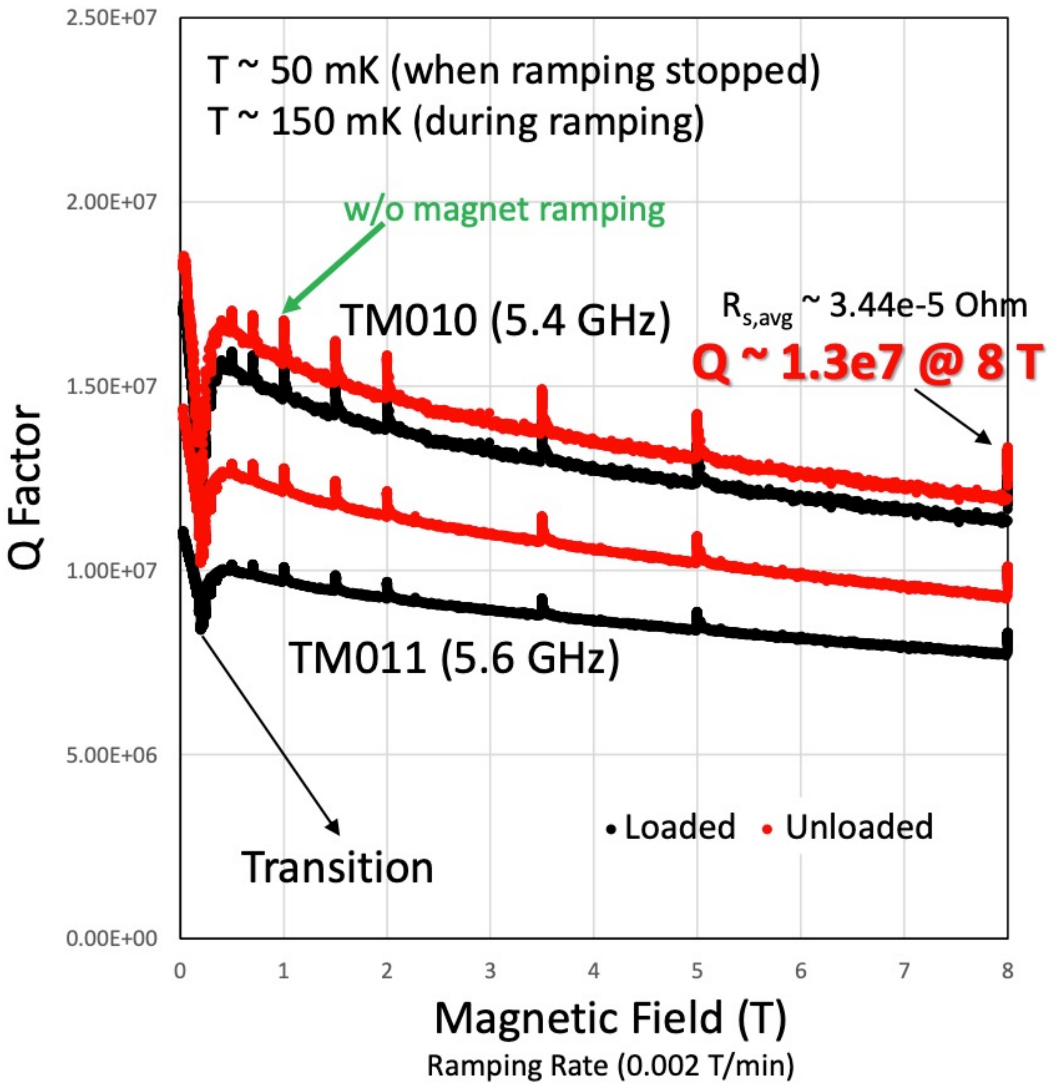


Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T [redacted] Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

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

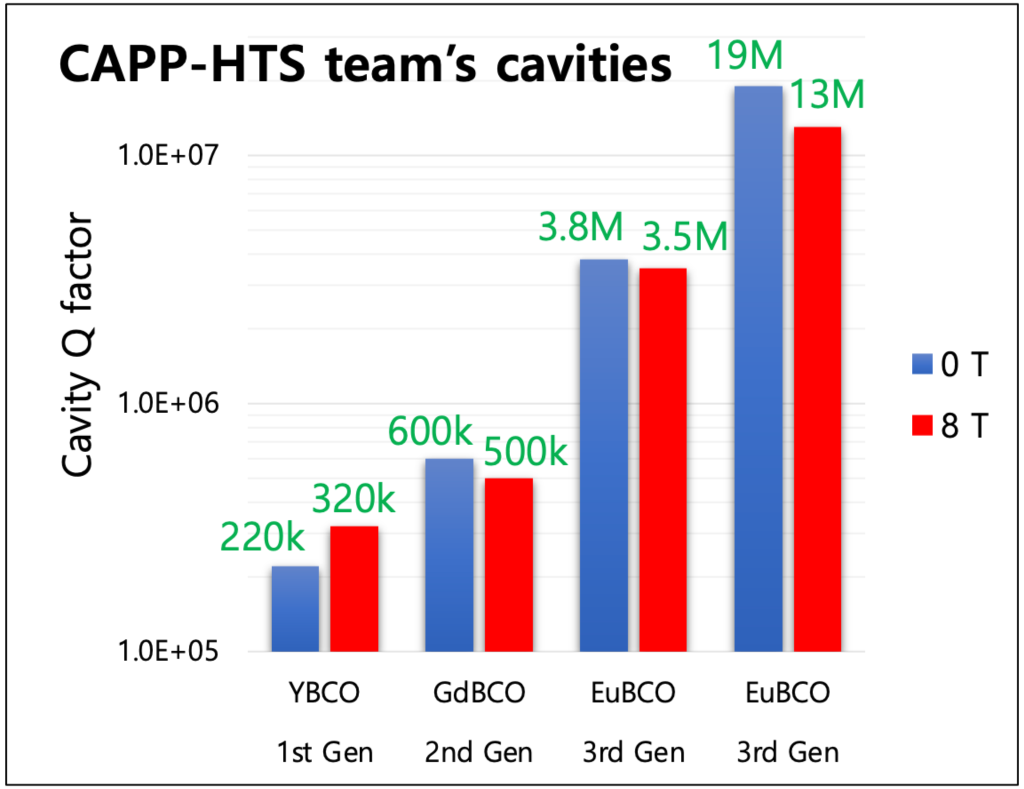
CAPP-PACE Detector

HTS cavities speed up scanning rates

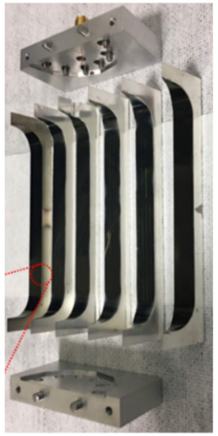
	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** arXiv:2207.13597, PRL (in process) (Mr. Jinsu Kim *et al.*)	**SC Run** In process
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	**1.5 L**
Quality Factor (Q_0)	100,000	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**

Jiwon Lee's slide

History of HTS cavities development

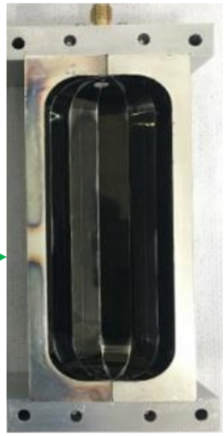


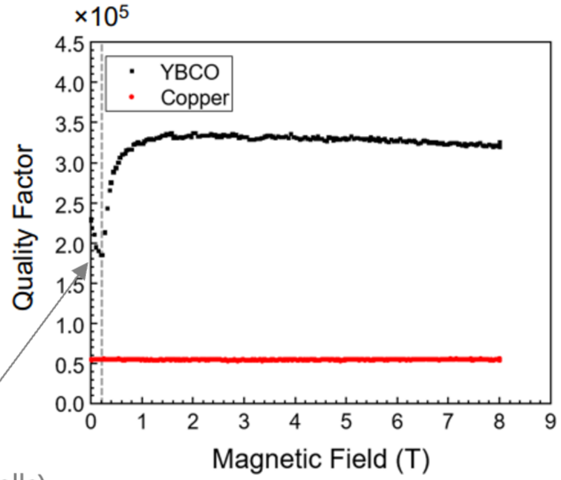
Due to the magnetic saturation of the Ni-9W layer behind the YBCO layer
(the atomic spins become more rigid due to the reduction of the magnetic domain walls)
(from Doctor Danho Ahn's thesis)



First HTS cavity

Attach tapes to melon-shaped wedges and combine them





300k Q-factor
(6 times better than Cu)

PHYSICAL REVIEW APPLIED 17, L061005 (2022)

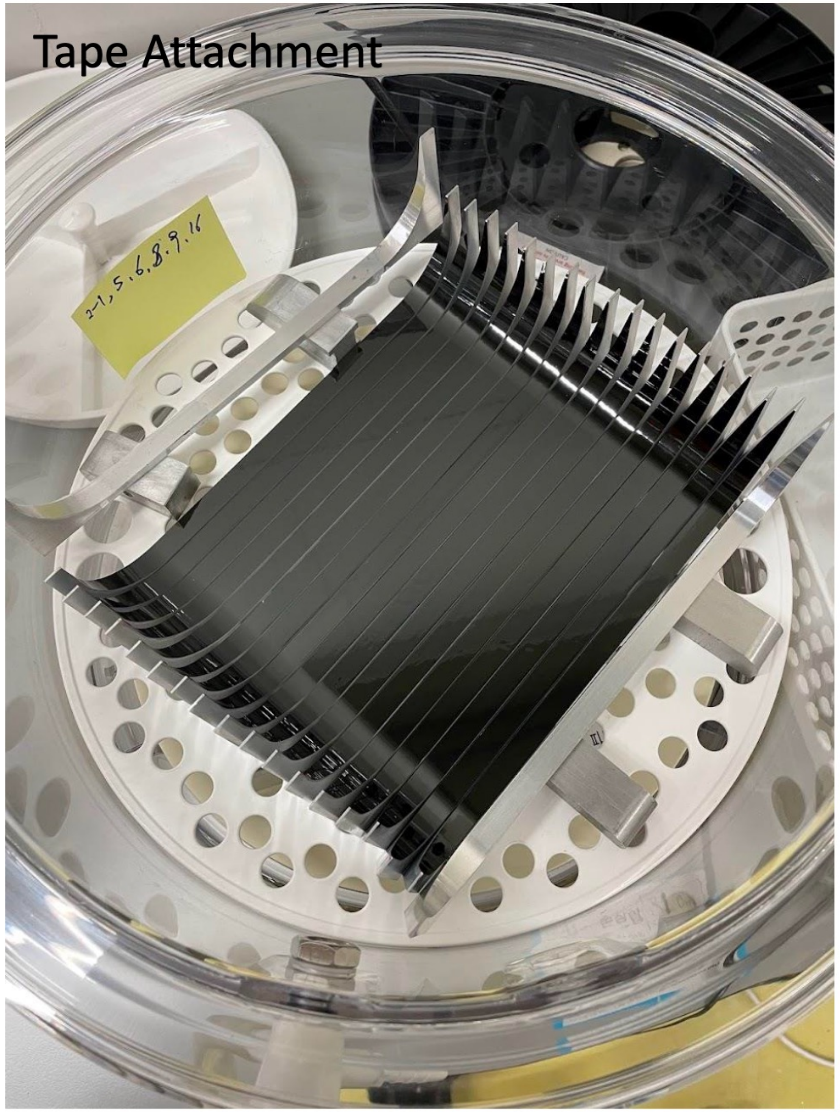
Letter

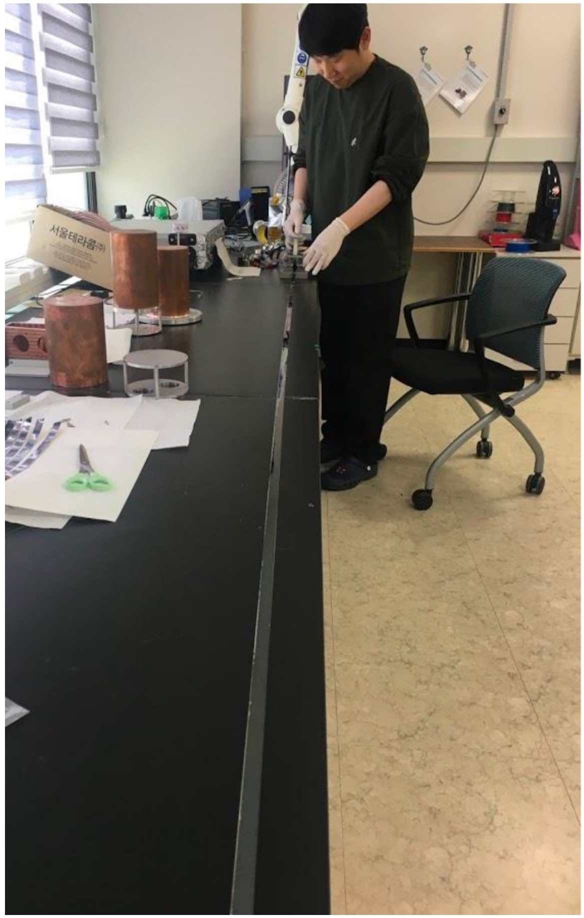
Biaxially Textured $YBa_2Cu_3O_{7-x}$ Microwave Cavity in a High Magnetic Field for a Dark-Matter Axion Search

Danho Ahn,[1,2] Ohjoon Kwon,[2] Woohyun Chung,[2,*] Wonjun Jang,[3,†] Doyu Lee,[2,‡] Jhinhwan Lee,[4] Sung Woo Youn,[2] HeeSu Byun,[2] Dojun Youm,[1] and Yannis K. Semertzidis[1,2]

[1] Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea
[2] Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea
[3] Center for Quantum Nanoscience, Institute for Basic Science, Seoul 33760, Republic of Korea
[4] Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang 37673, Republic of Korea

3rd Generation Cavity using EuBCO Tapes (1)



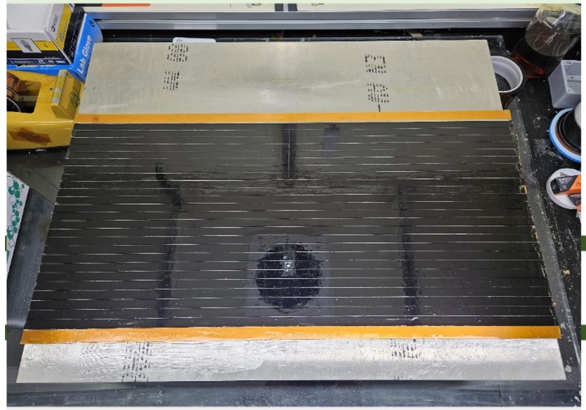


Dr. Danho Ahn, IBS-CAPP

Jiwon Lee's slide

Full-HTS-ULC fabrication process

Tuning rod - Sidewall

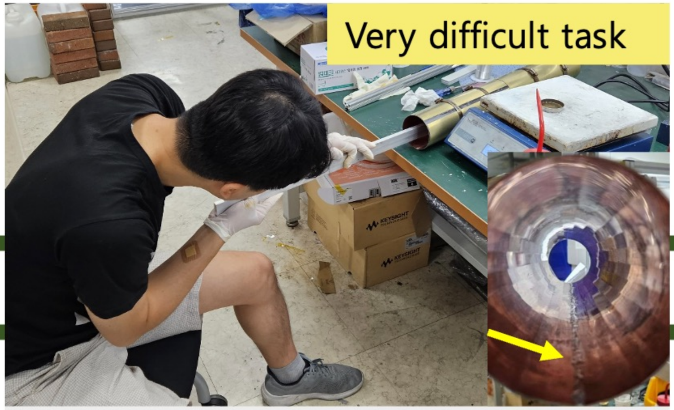


It is the same process as the sidewall of the cavity body

I made this jig.

Roll it up and tighten it with a clamping jig

Very difficult task



Indium cold welding by Dr. Ohjoon Kwon

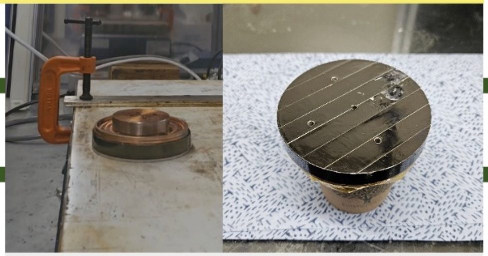
Connection

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)



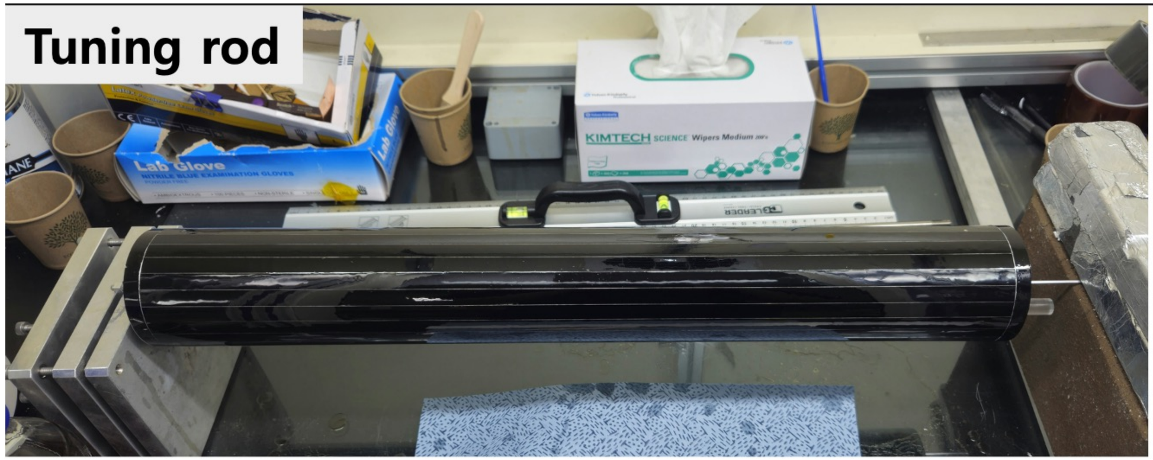
2nd soldering (the side)

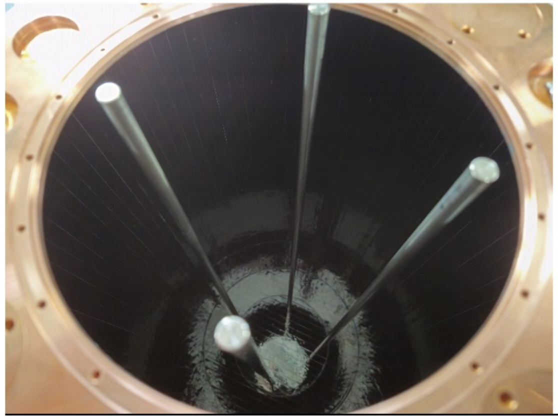
Jiwon Lee's slide

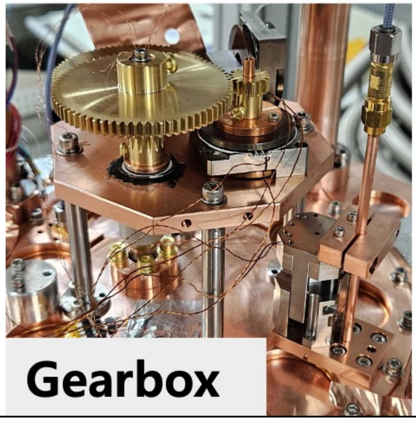
Q-factor is about 14 times better than Full Cu ULC.

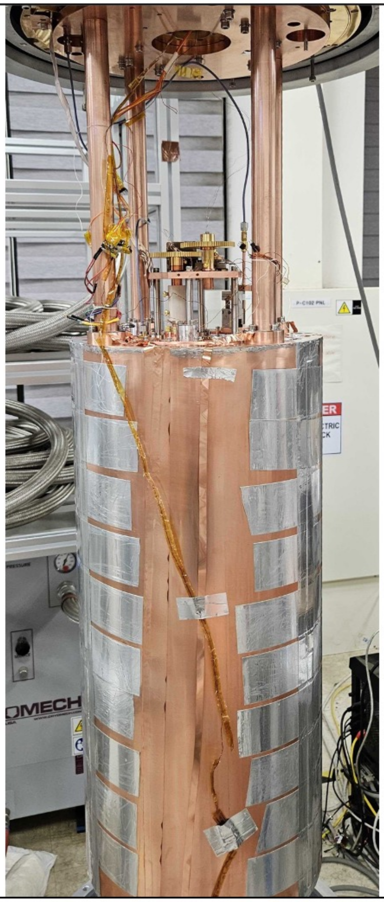
Full-HTS-ULC fabrication process

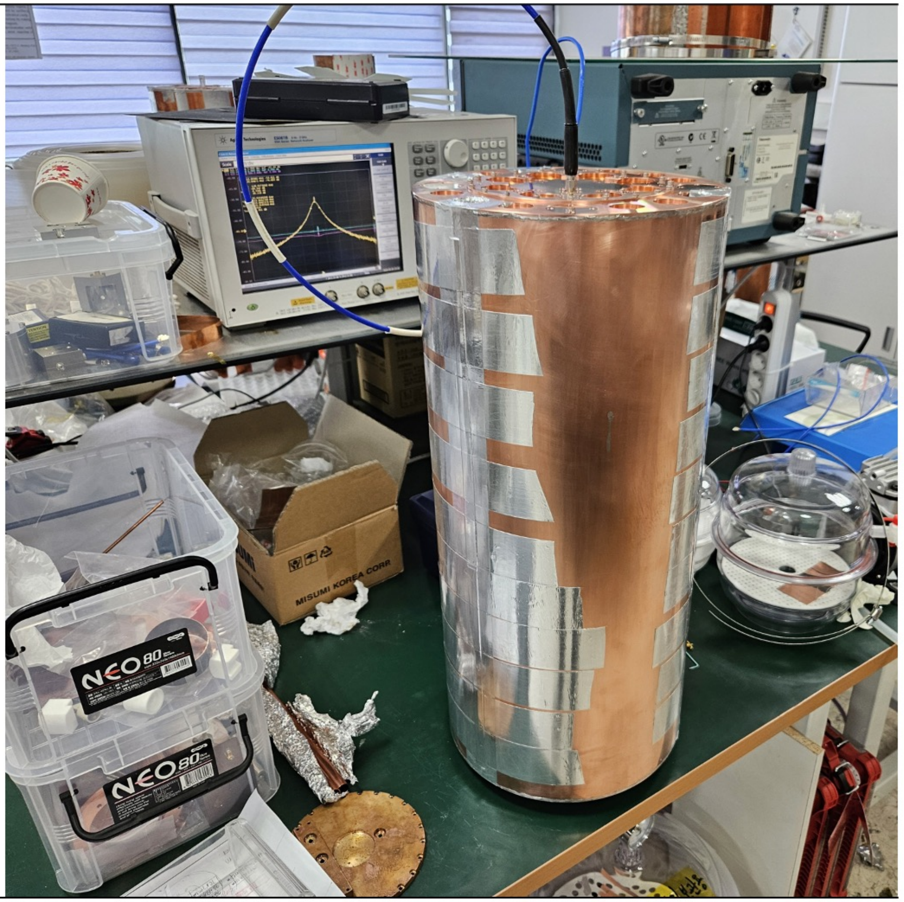
RF measurement w/ HTS tuning rod







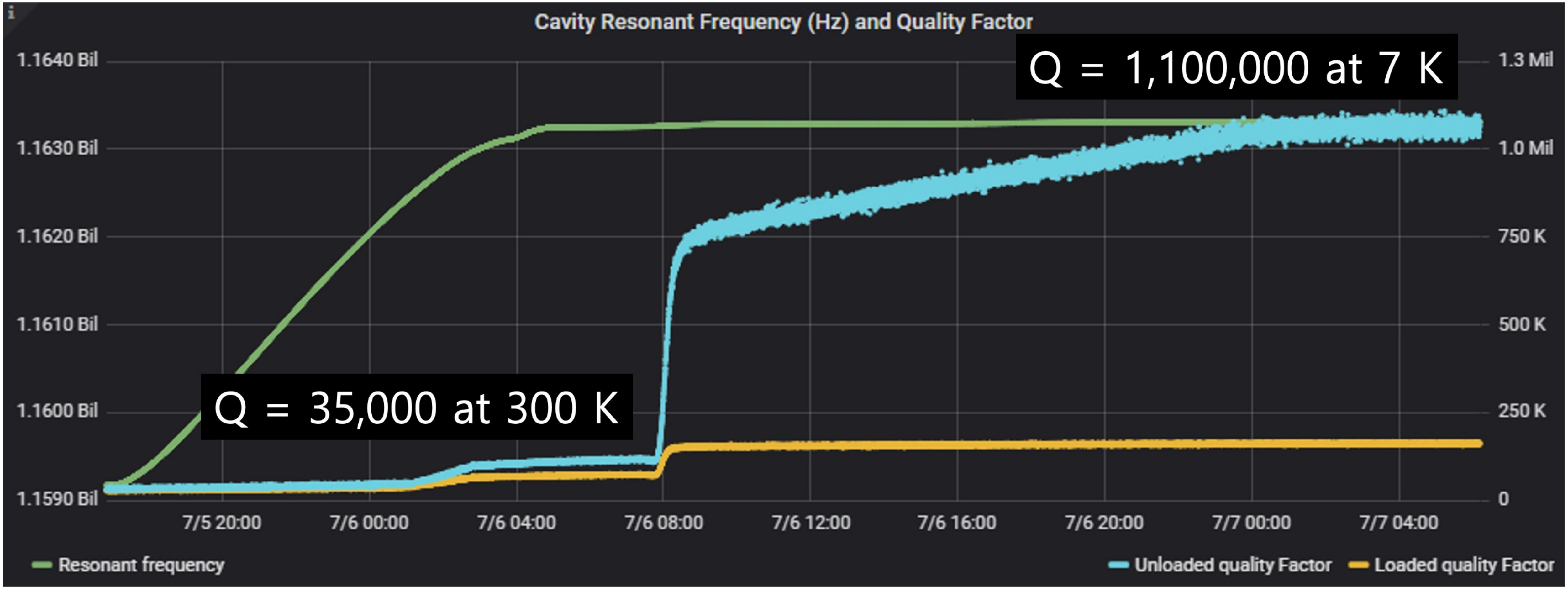




Jiwon Lee's slide

Full-HTS-ULC fabrication process

RF measurement w/ HTS tuning rod



Higher B-field magnets

Superconducting cables

Material Name	Class	Critical Temperature (K)	Critical Field B_{c2}	Critical Field@2.2 K	Geometry
NbTi	LTS	9.8	9.5 T @ 4.2 K	11.5 T	Multi-filamentary round & rectangular wire
Nb_3Sn	LTS	18.1	20 T @ 4.2 K	23 T	Multi-filamentary round wire
MgB_2	MTS	39	5–10 T @ 4.2 K 1–3 T @ 10 K	N/A	Multi-filamentary round wire
Bi–2212	HTS	90–110	40 T @ 4.2 K 10 T @ 12 K	N/A	Multi-filamentary round wire
Bi–2213	HTS	90–110	40 T @ 4.2 K 8 T @ 20 K 4 T @ 65 K	N/A	Tape
YBCO	HTS	92–135	45 T @ 4.2 K 12 T @ 20 K 8 T @ 65 K	N/A	Tape

Table 8. Superconducting materials. LTS, MTS, and HTS stand for low-, medium-, and hight-temperature superconductors. N/A means that these materials as are typically not used below 4.2 K. They can operate at lower temperatures but without particular advantage.

Superconducting materials

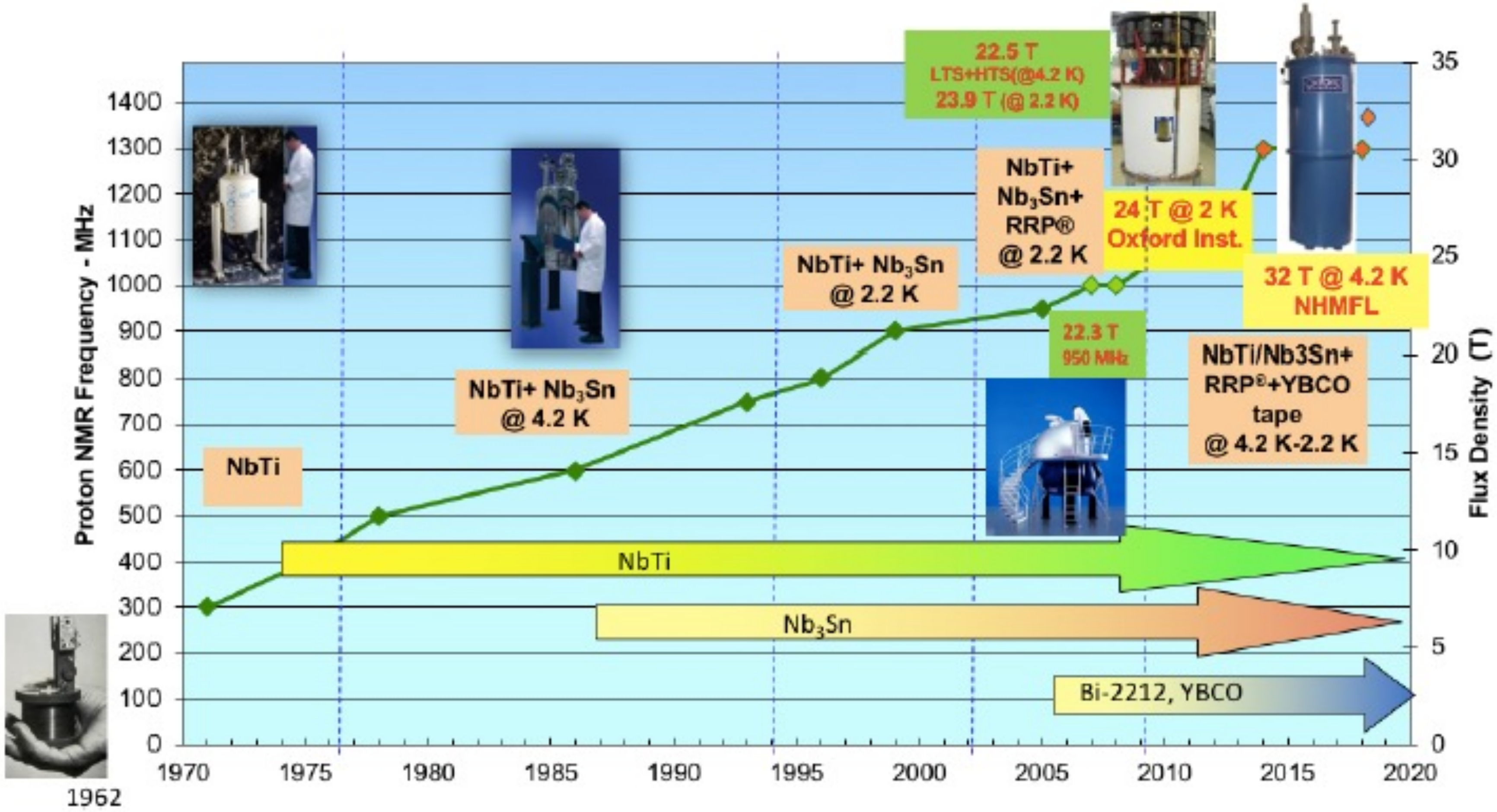
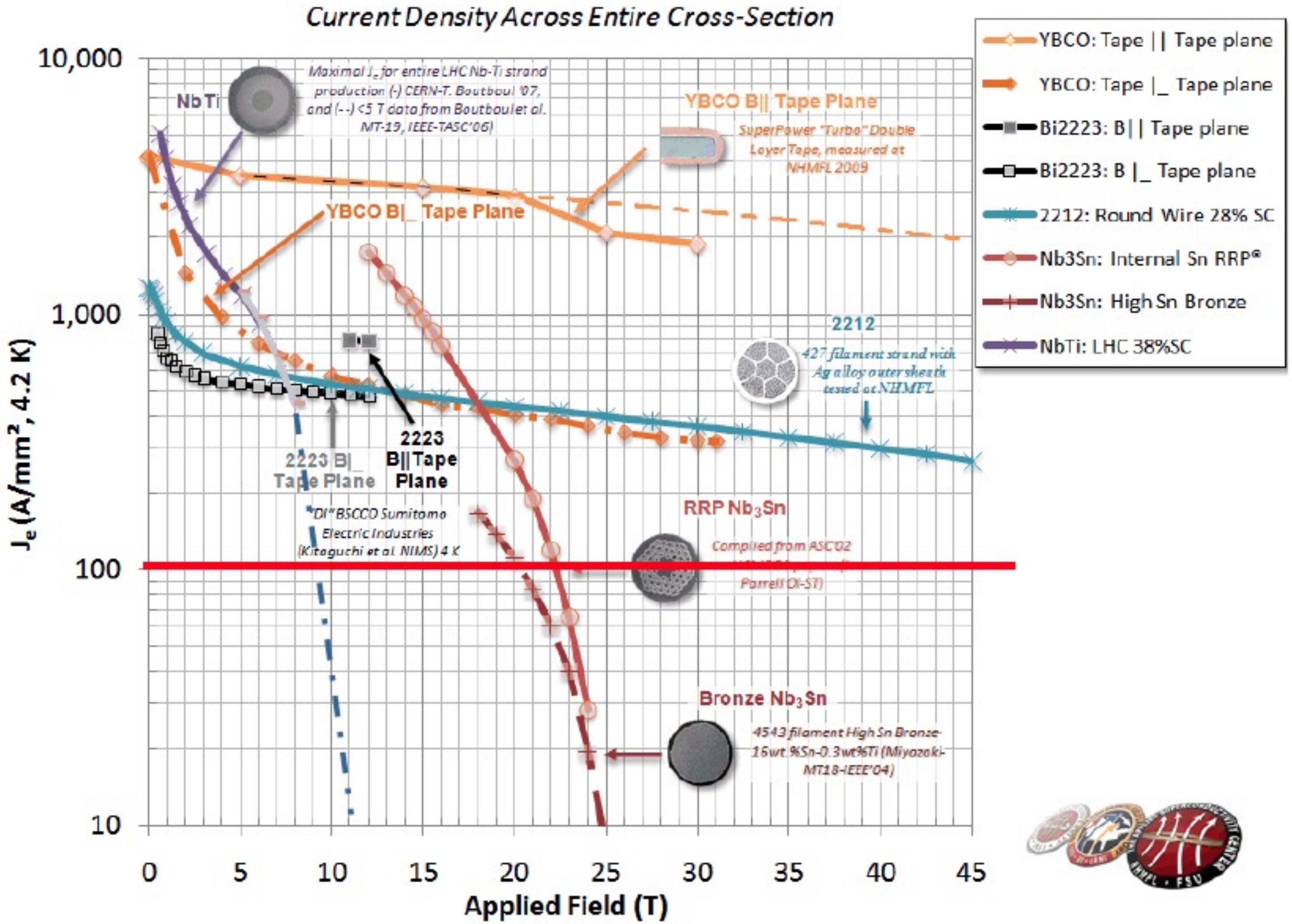


Fig. 22. Solenoid magnets for NMR as a representative example of the progress in magnet technology. NHMFL: National High Magnetic Field Laboratory, Tallahassee, Florida.

Future Solenoids:

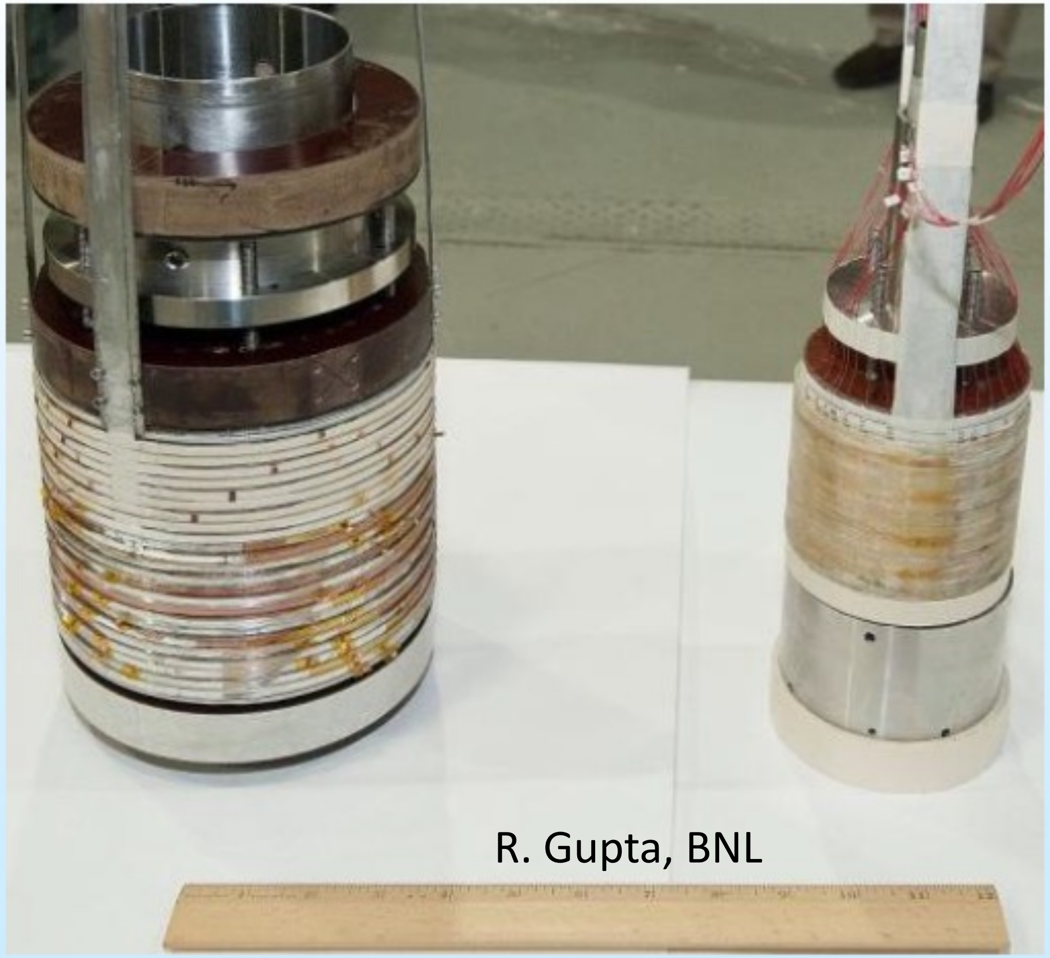
High- Temperature Superconductors



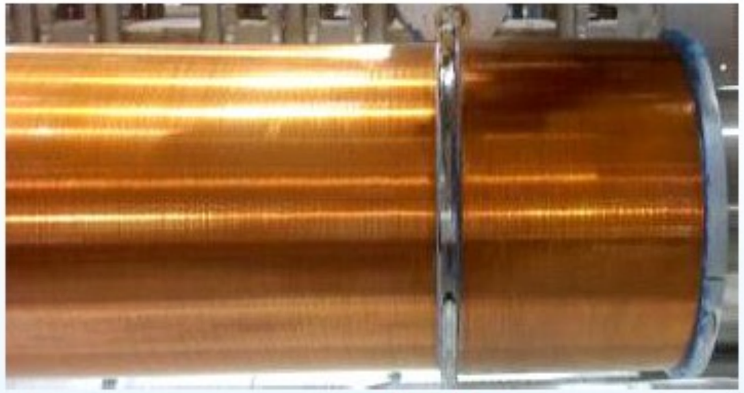
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

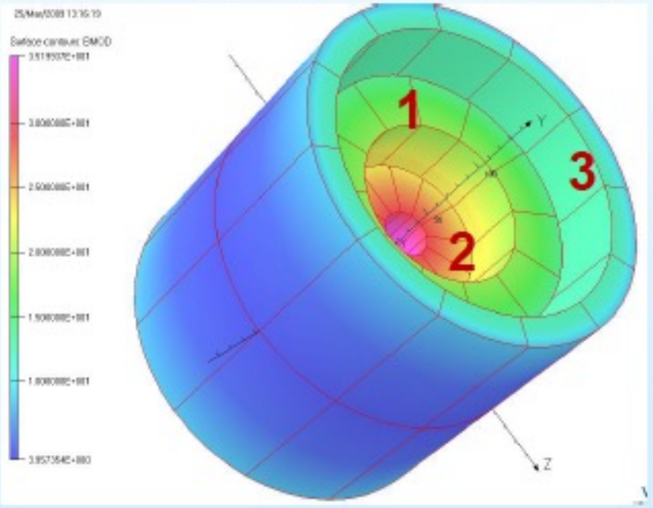
Status of High Field MAP Solenoids

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

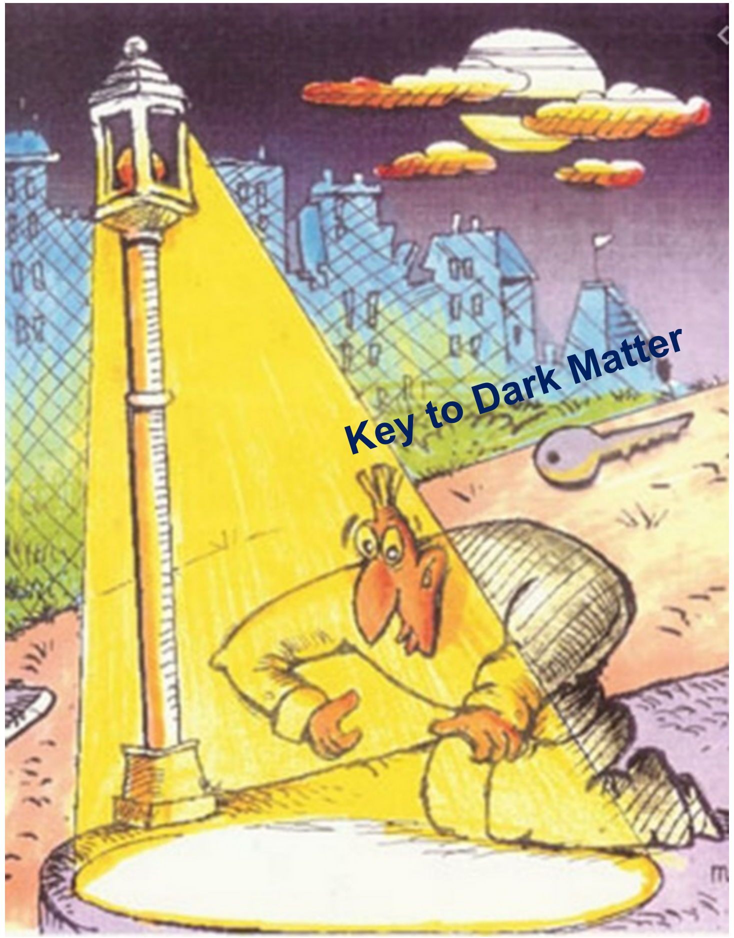
- Magnet construction plan with single layer is sound
- Magnet design with No Insulation making it safe from quenches and structural integrity
- >50% margins in critical current and stresses
- 16 out of 28 pancakes constructed.

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

Figure 2.67: Manufacturing process (10 HTS coils).

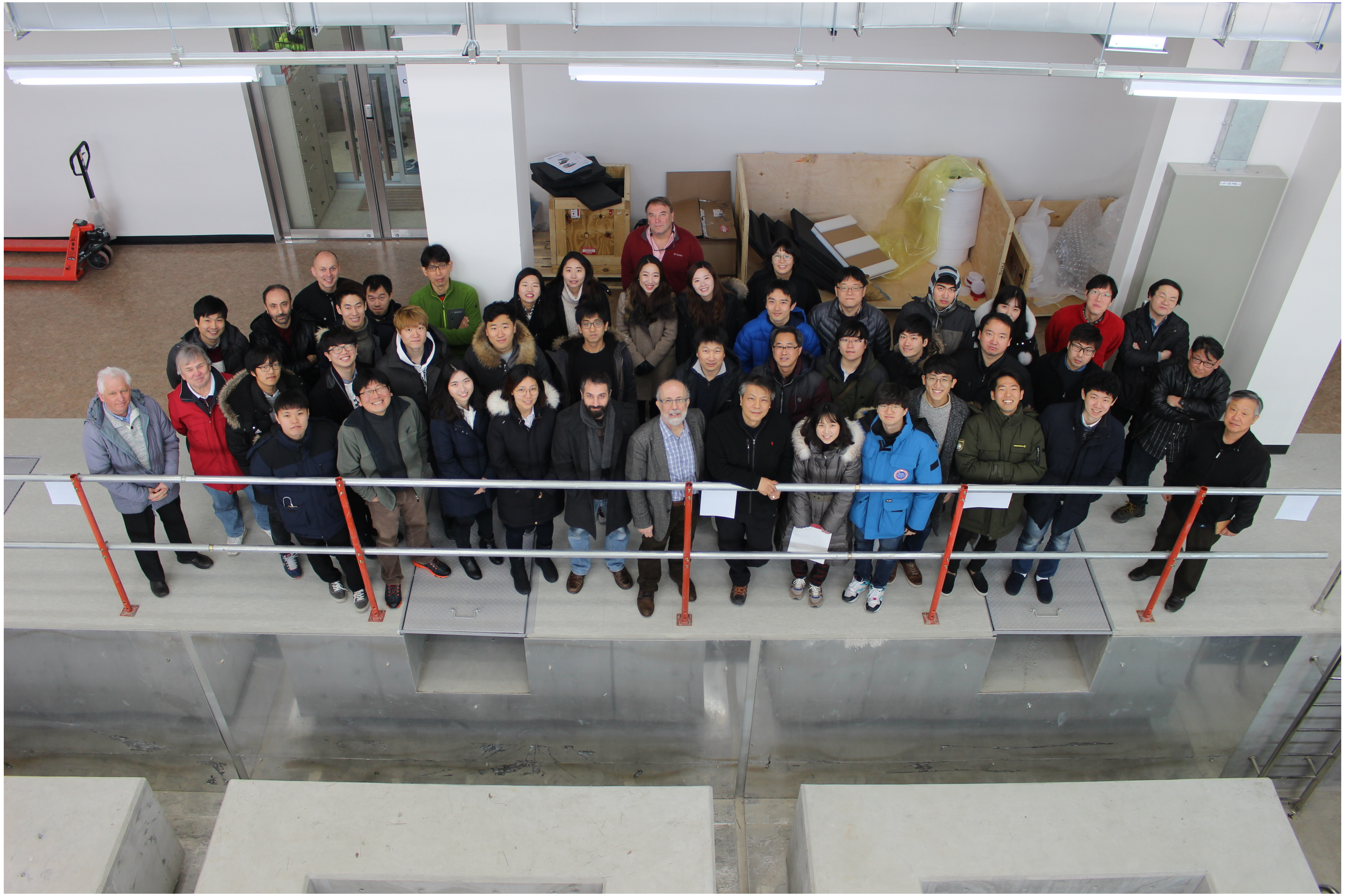
Strategy at CAPP: best infra-structure and know-how

- 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

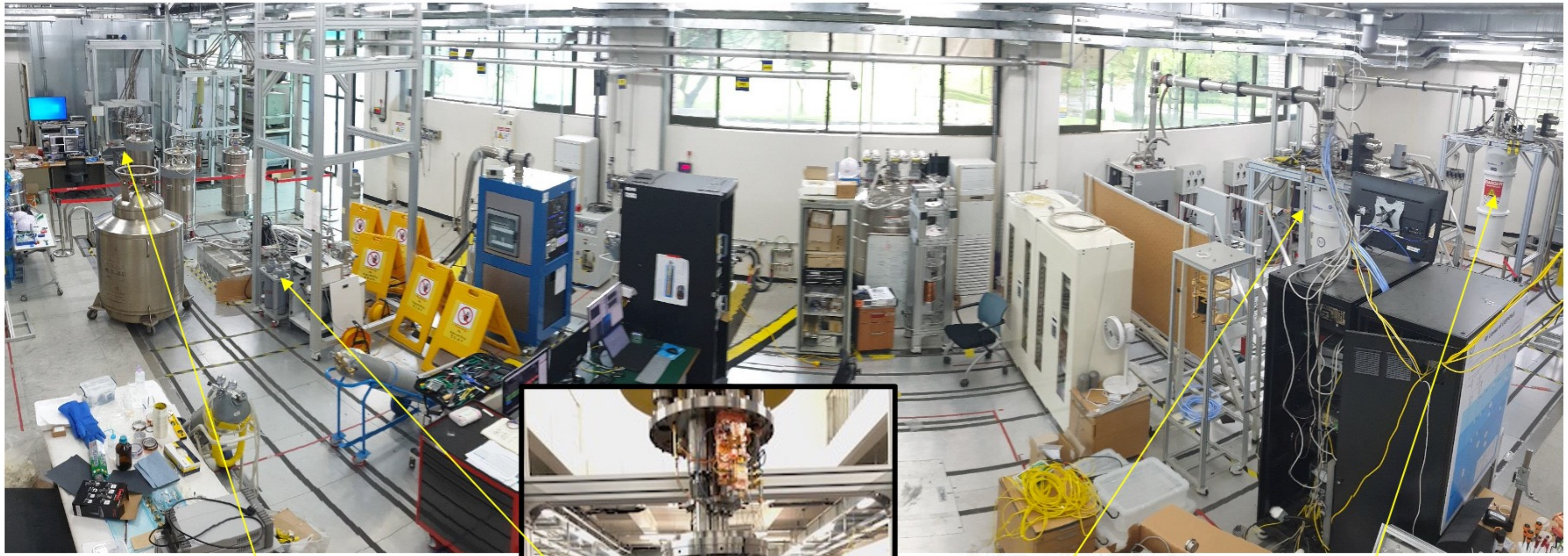


- Powerful dilution refrigerator: ~5mK base temp.
  - 25mK for the top plate of the 37 liter cavity
- State of the art quantum amplifiers (JPAs)
  - Best noise for wide frequencies: 1-6 GHz
- High-frequency, efficient, high-Q microwave cavities (best in the world)

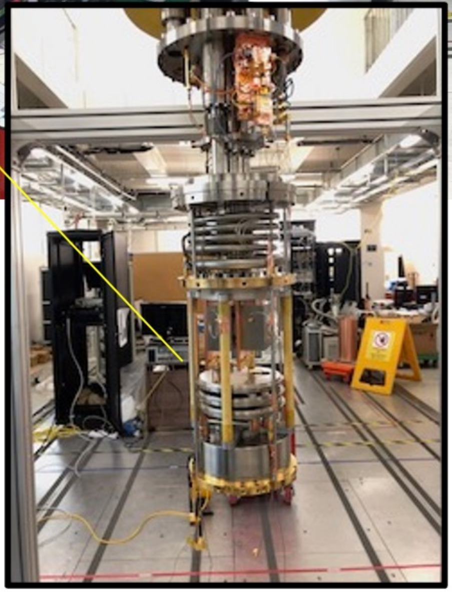
IBS-CAPP at Munji Campus, KAIST, January 2017.



CAPP Experimental Hall (LVP) in 2021

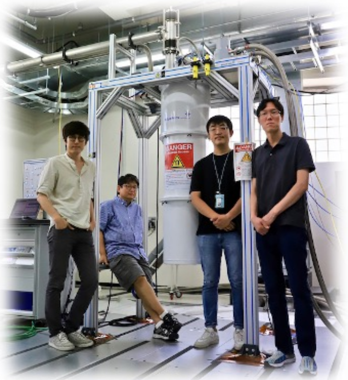


CAPP-HF



CAPP-12TB

CAPP-PACE



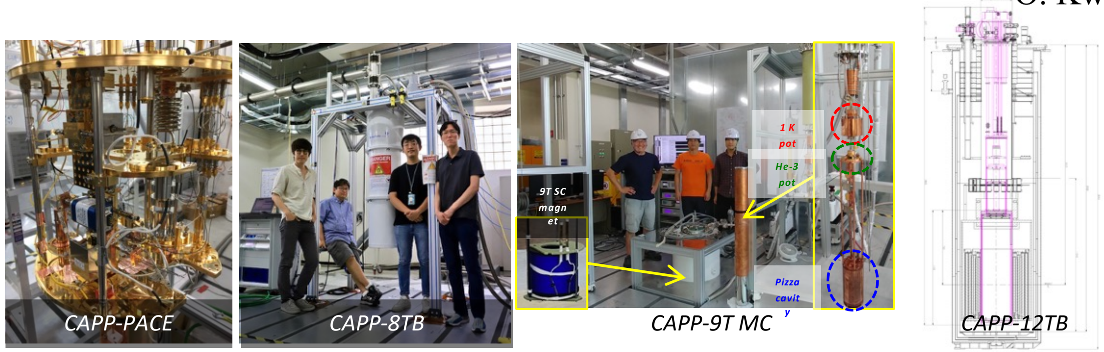
CAPP-8TB

IBS-CAPP at eight-years and beyond

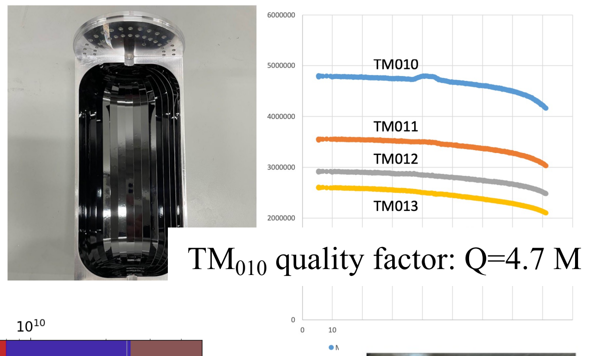
- S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)

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

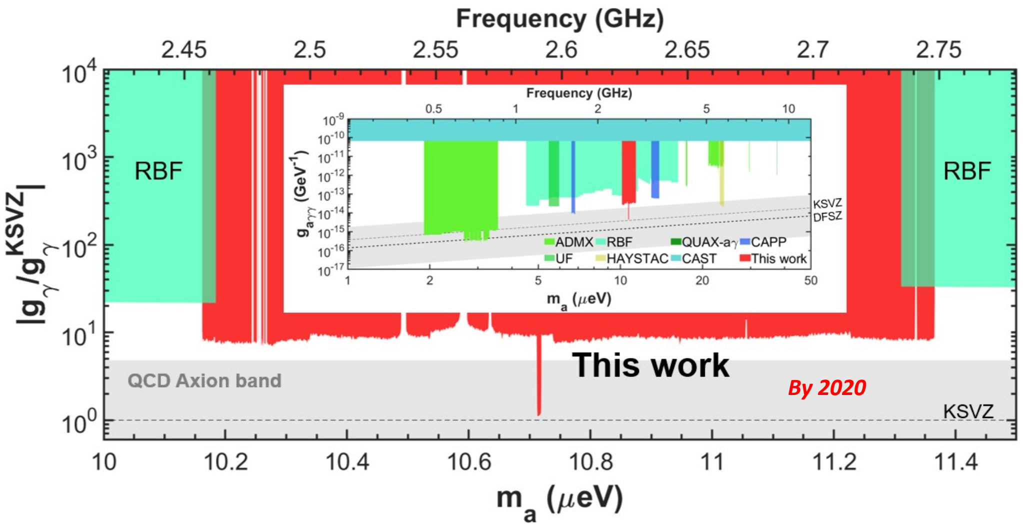
O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 (2021)

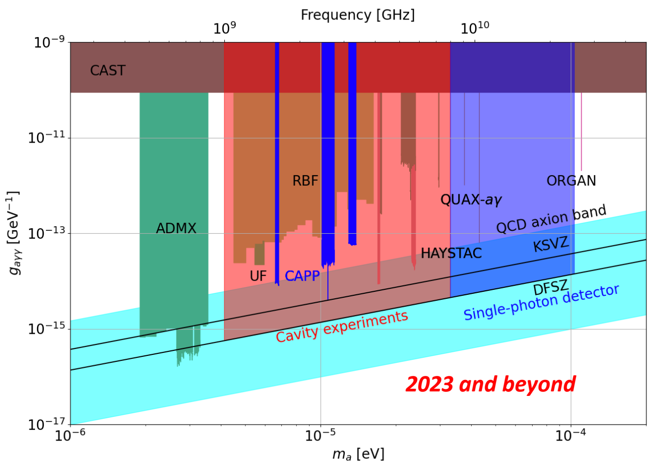


Melon 34 Cavity Q Factor Measurement

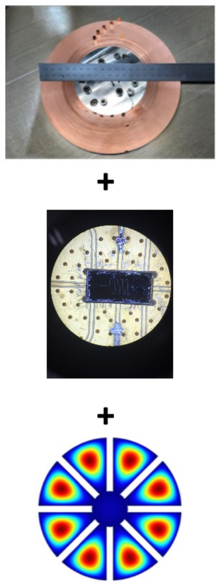


TM_{010} quality factor: Q=4.7 M





CAPP-25T



- *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.

Axion dark matter results using an LHC dipole magnet at CERN

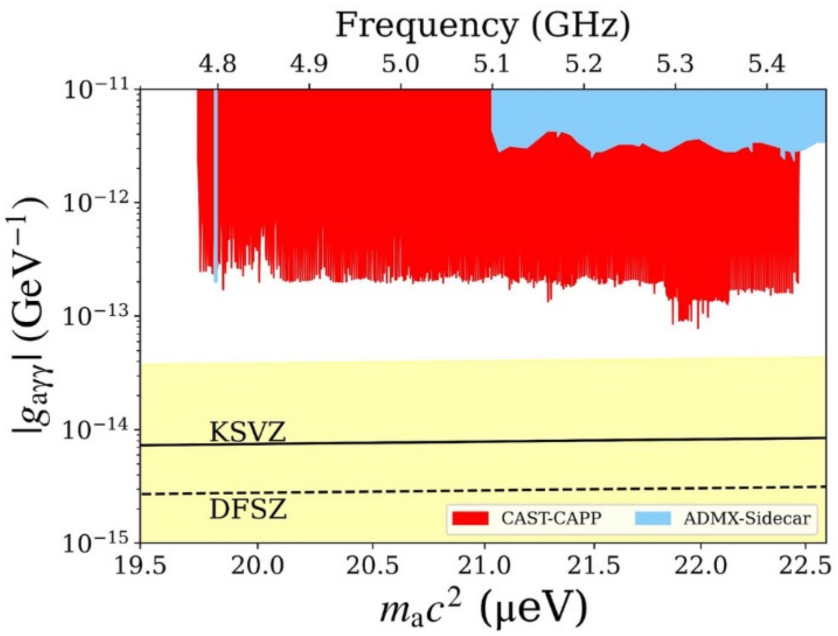


Fig. 5 | CAST-CAPP exclusion limit on the axion-photon coupling as a function of axion mass at 90% confidence level (left), and compared to other axion search results[10,25,30,34–41] **within the mass range 1–25 μeV (right).** The higher

Nature Communications | (2022)13:6180

nature communications

Article https://doi.org/10.1038/s41467-022-33913-6

Search for Dark Matter Axions with CAST-CAPP

Published online: 19 October 2022

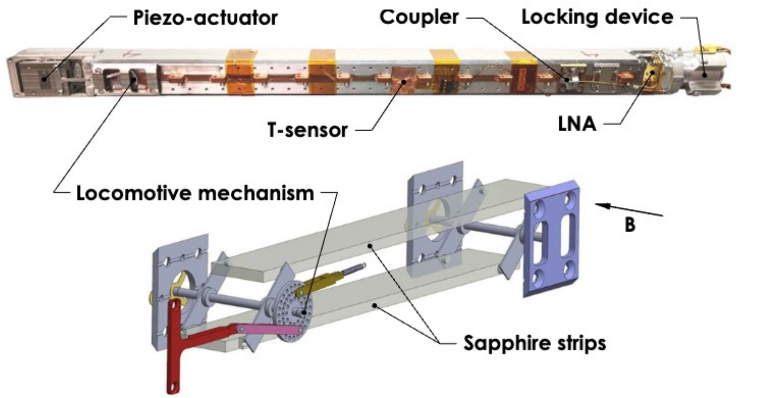


Fig. 1 | A photograph of the elements of a single cavity assembly (top) and a technical drawing of CAST-CAPP tuning mechanism with the two sapphire strips (bottom). The static B-field is shown by the arrow and is parallel to the two axes of the tuning mechanism.

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 (250mK), $Q_0=10^5$
  - KSVZ: 50 GHz/year (35 GHz/year)
  - DFSZ: 1 GHz/year (0.64 GHz/year)
- 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)

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.

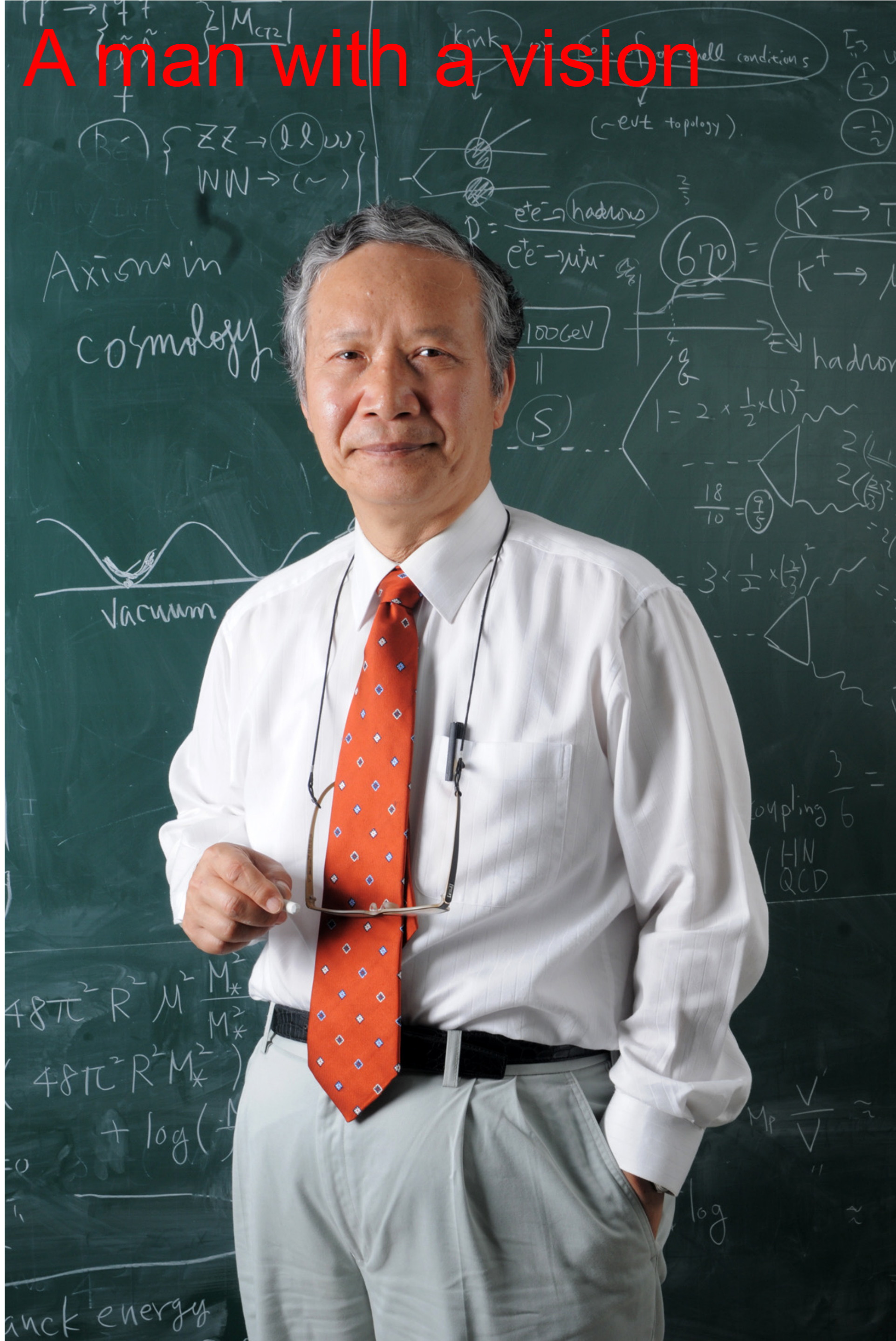
Photo: KAIST Munji Campus, January 2023

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. IBS and KAIST agreed to collaborate closely.



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)

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 (250mK), $Q_0=10^5$
  - KSVZ: 50 GHz/year (35 GHz/year)
  - DFSZ: 1 GHz/year (0.64 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

Equivalent noise temperature

Slide by SungWoo Youn

Noise contributions

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

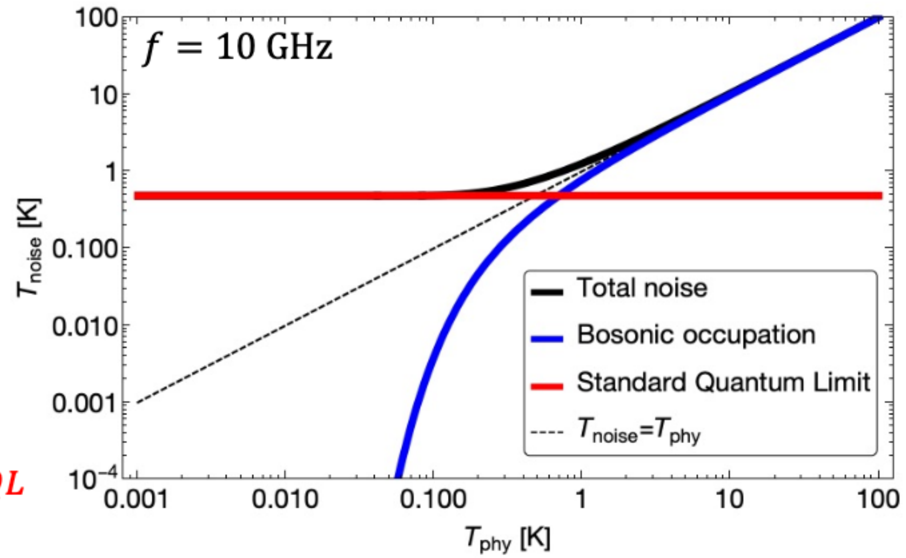
- Thermal noise: bosonic occupation
- Zero-point fluctuations
- Minimum added noise

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!

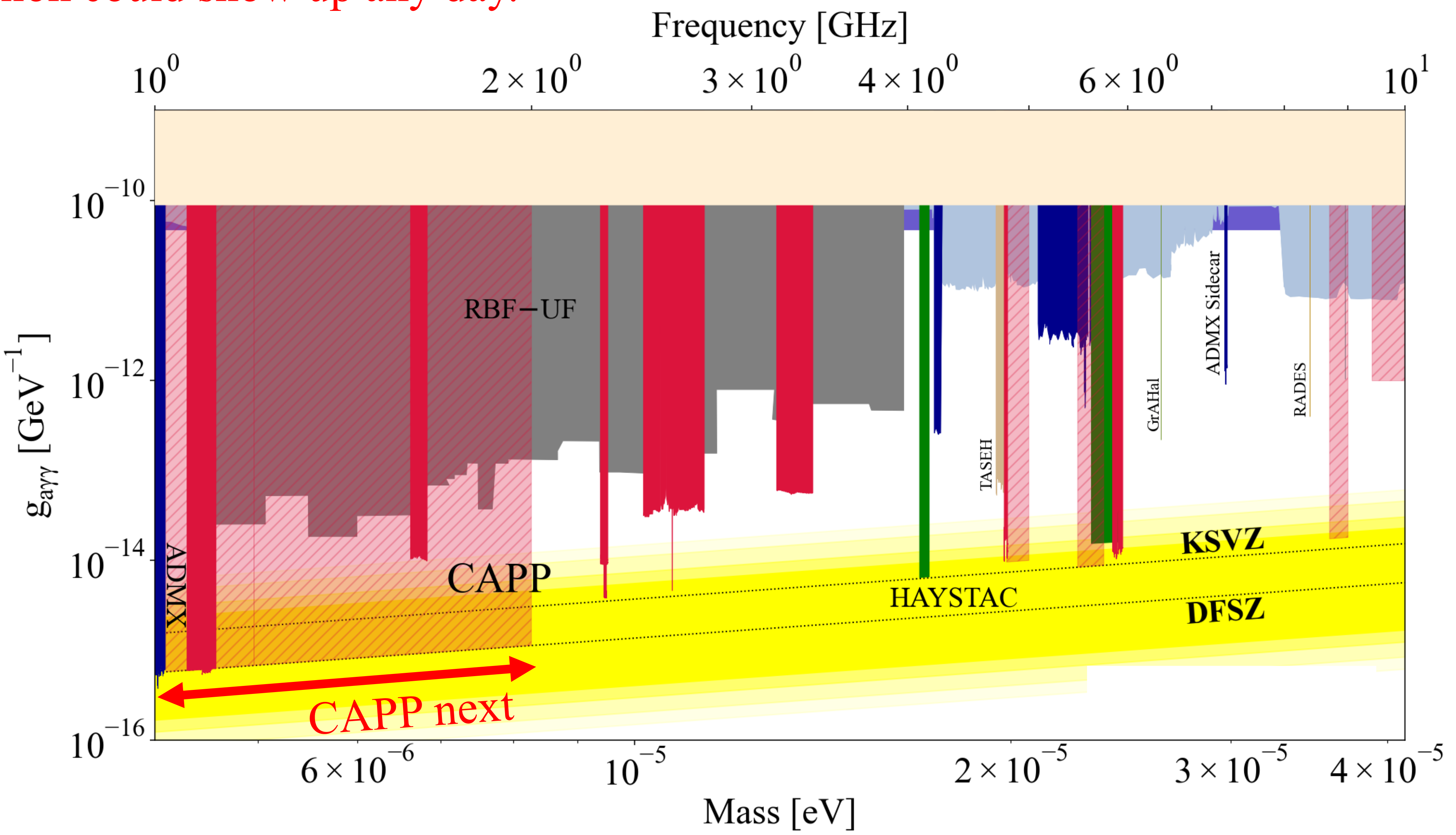
- A dream come true:
  - Lescanne et al., PRX (2020)
  - Albertinale et al., Nature (2021)
  - Wang et al., Nature (2023)

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

Near future

CAPP's immediate target 1-2 GHz

The axion could show up any day.



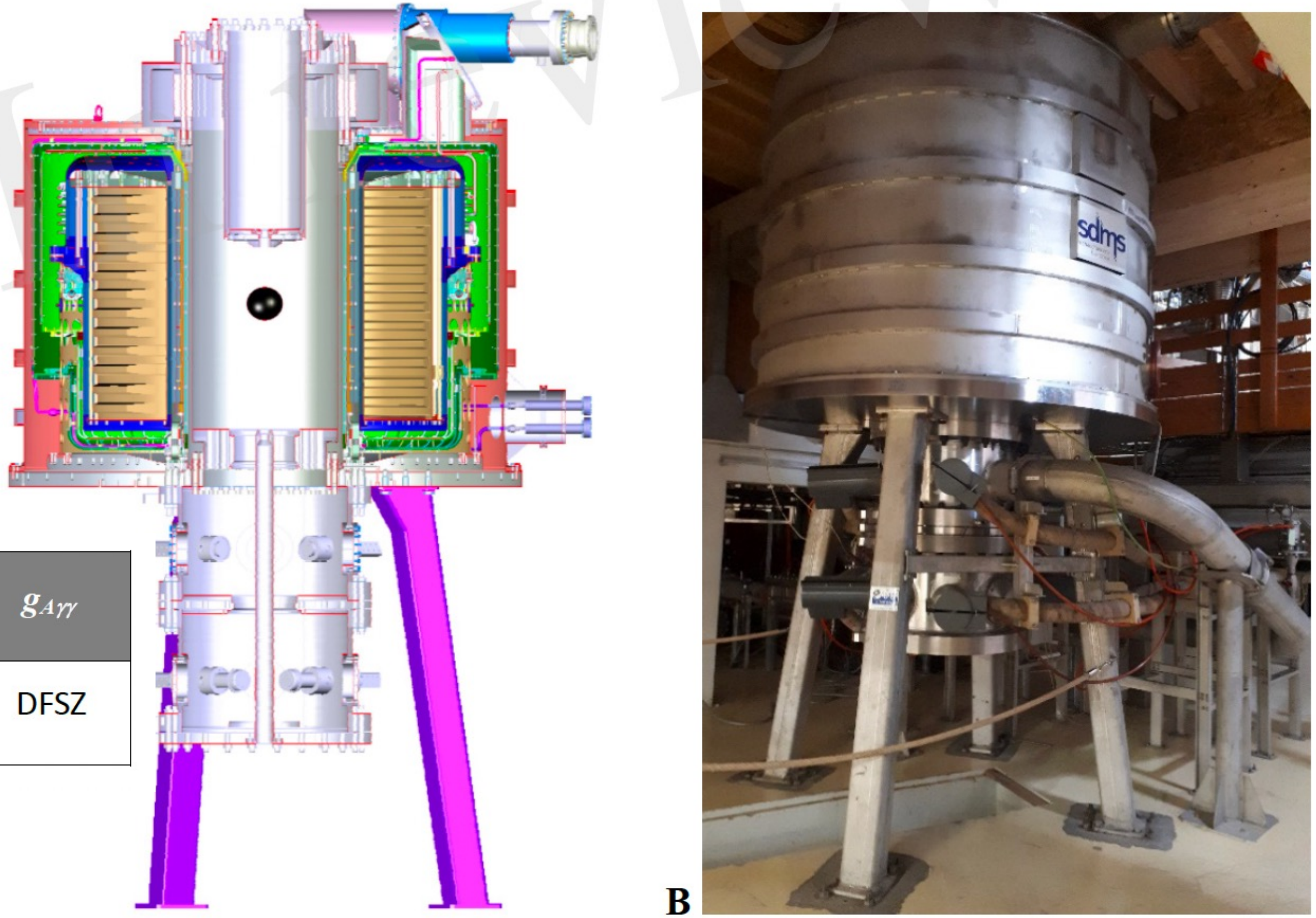
A new haloscope at Grenoble: GrAHal

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



A B

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.

Axion-photon with projections

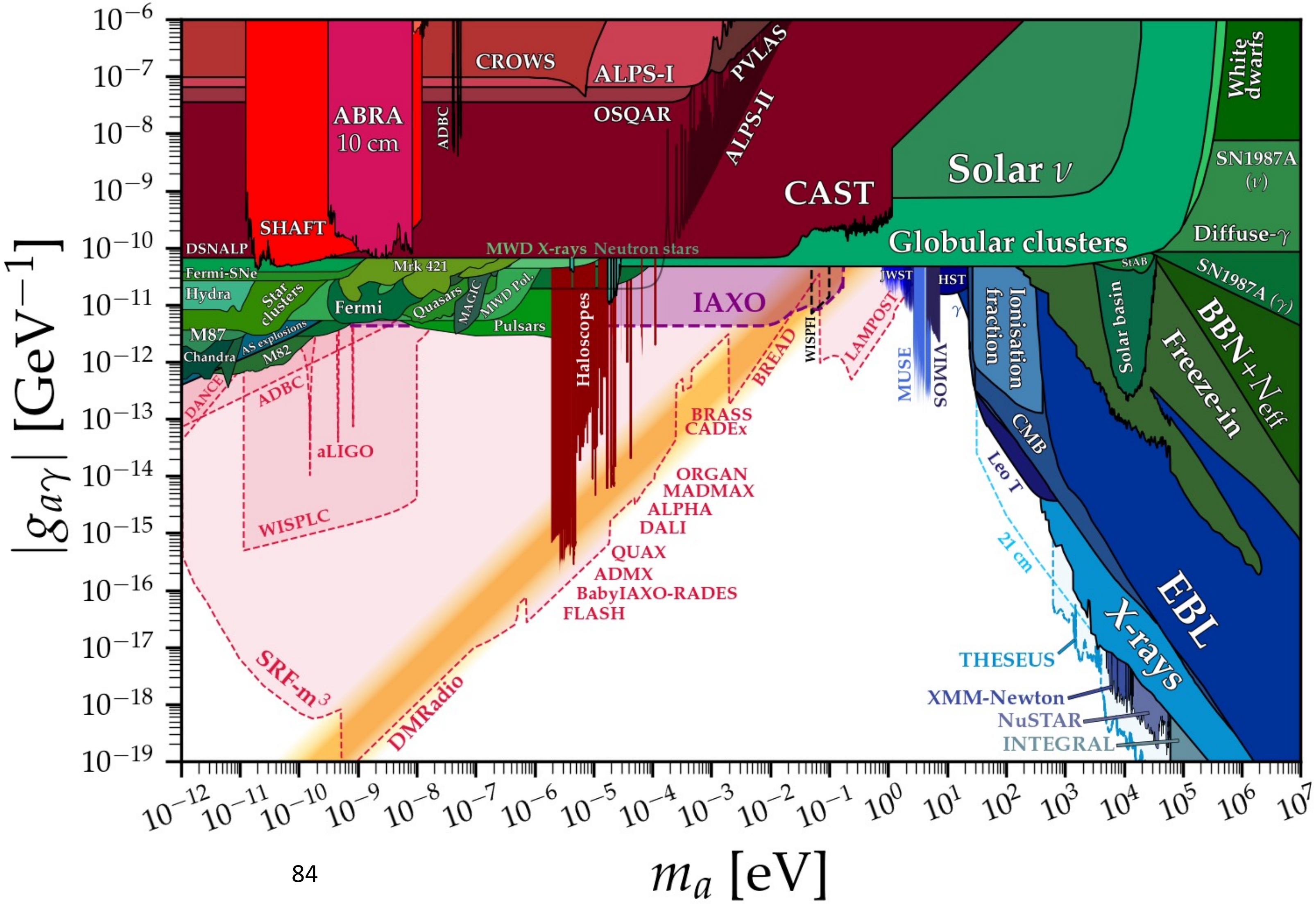
C. O'Hare, cajohare/axionlimits:
https://cajohare.github.io/AxionLimits/

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

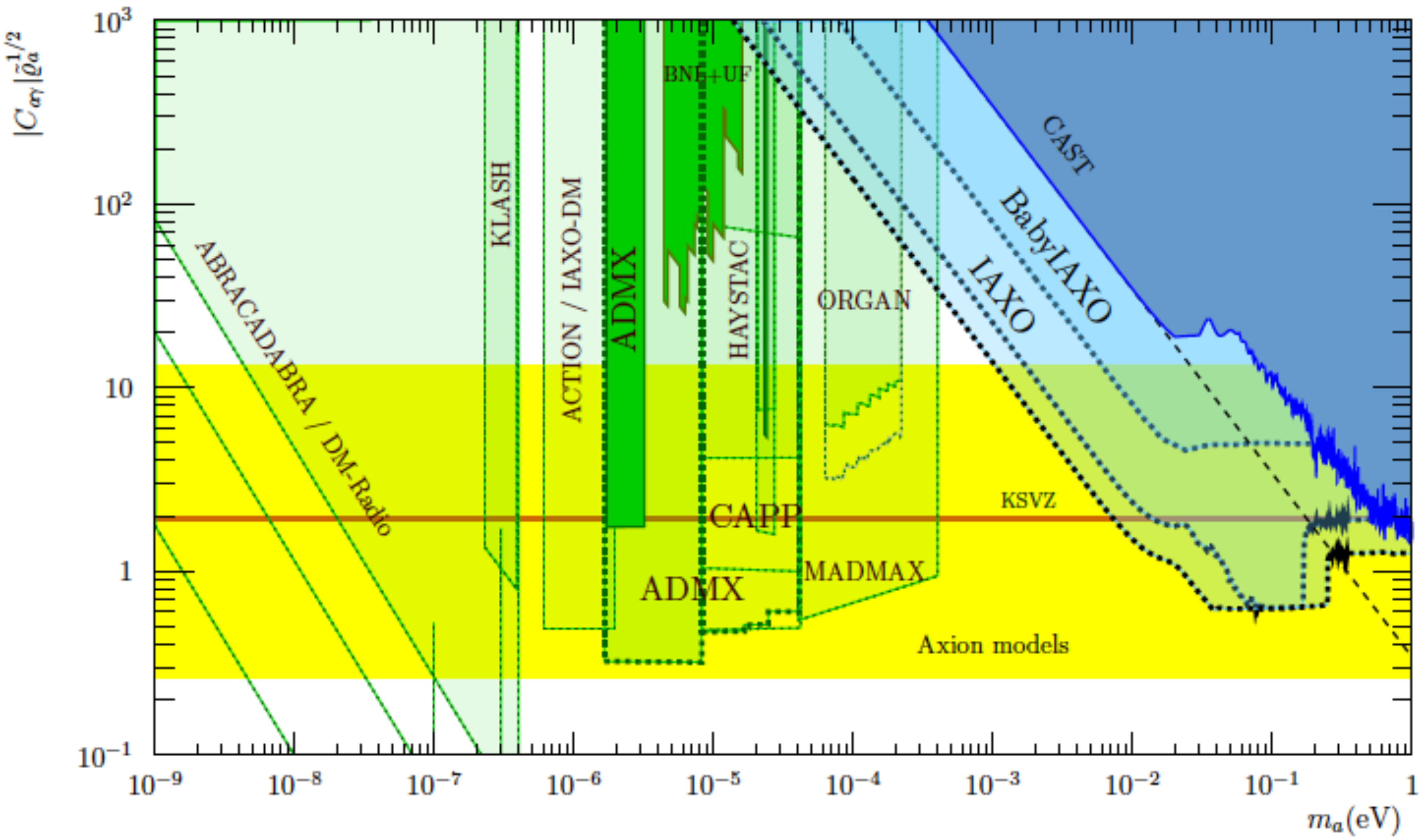
GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ

Using existing magnets, know-how

Collaborating to reach our goals faster



Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

Summary

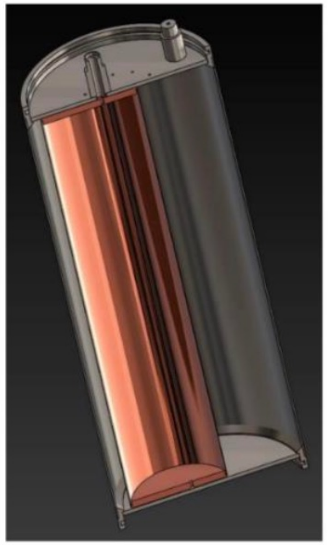
- ADMX, CAPP, GrAHal, HAYSTAC,… now could cover:
  - 0.2-4 GHz axion freq. in the next 2-years (DFSZ)
  - 4-8 GHz within the next 5-years (DFSZ)
  - 0.2-25 GHz within <2 decades, even for 20% of axions as dark matter

- 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

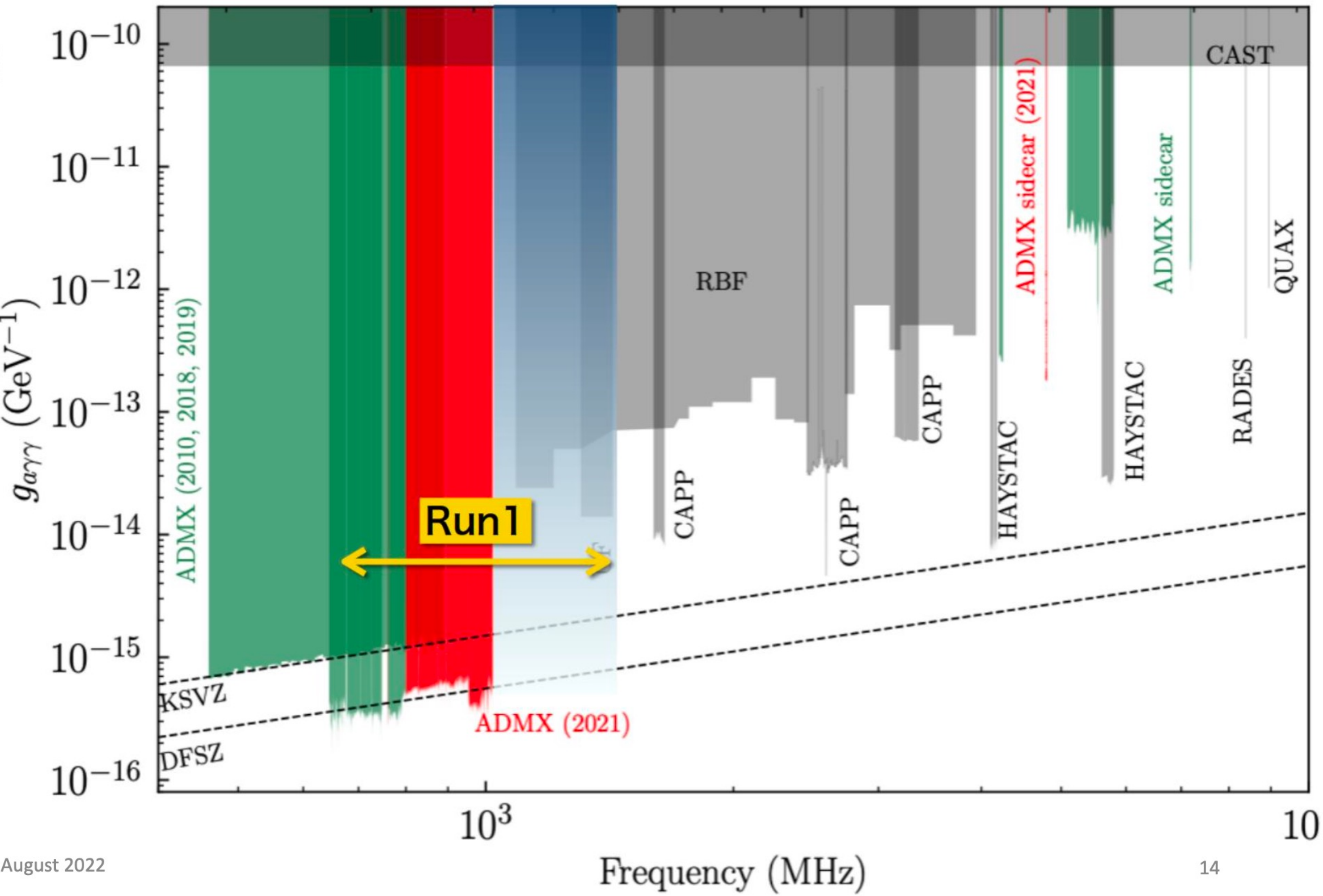
Extra slides

ADMX plan

Future Plans



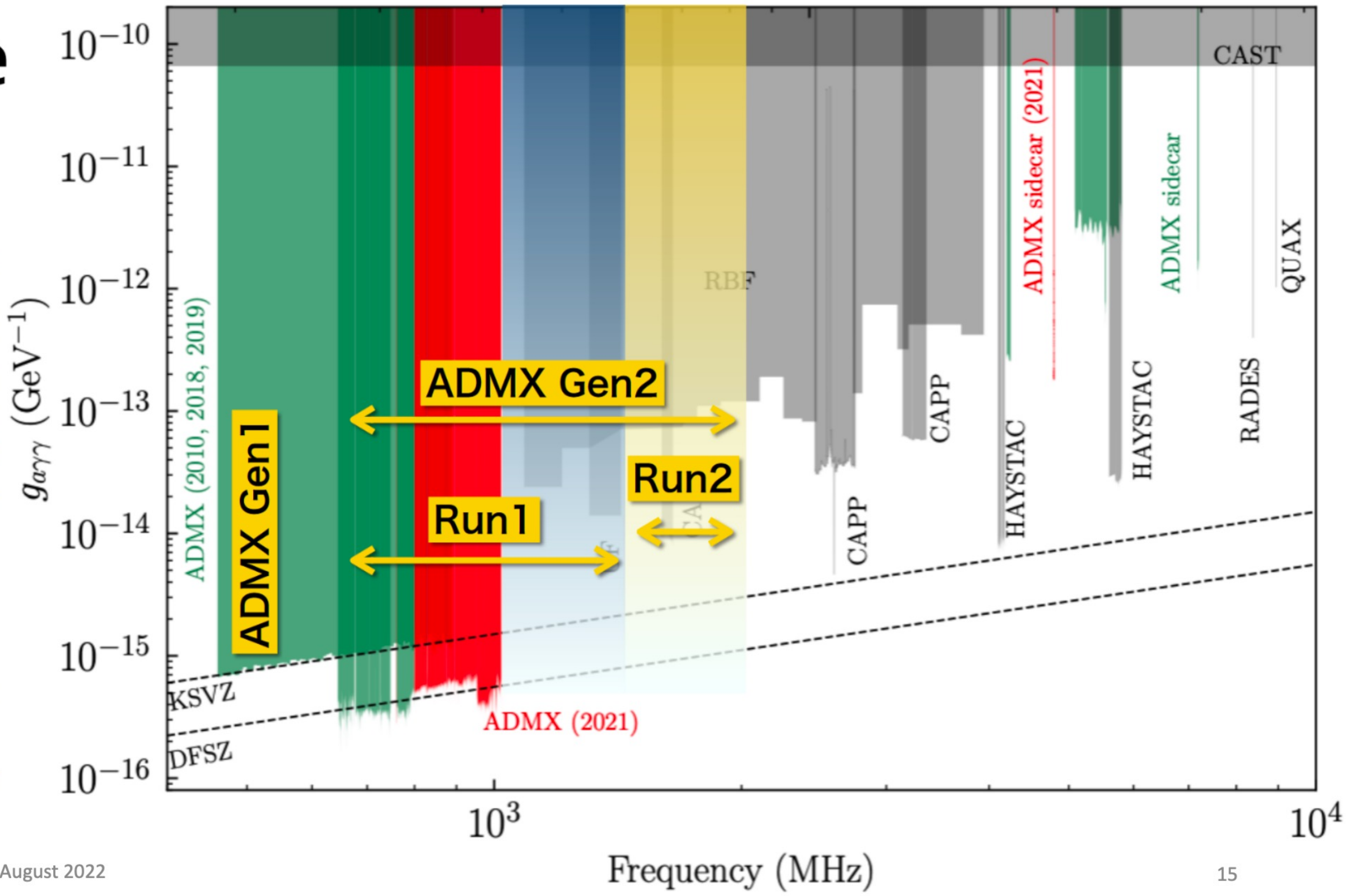
Bigger tuning rod



ADMX plan

Future Plans

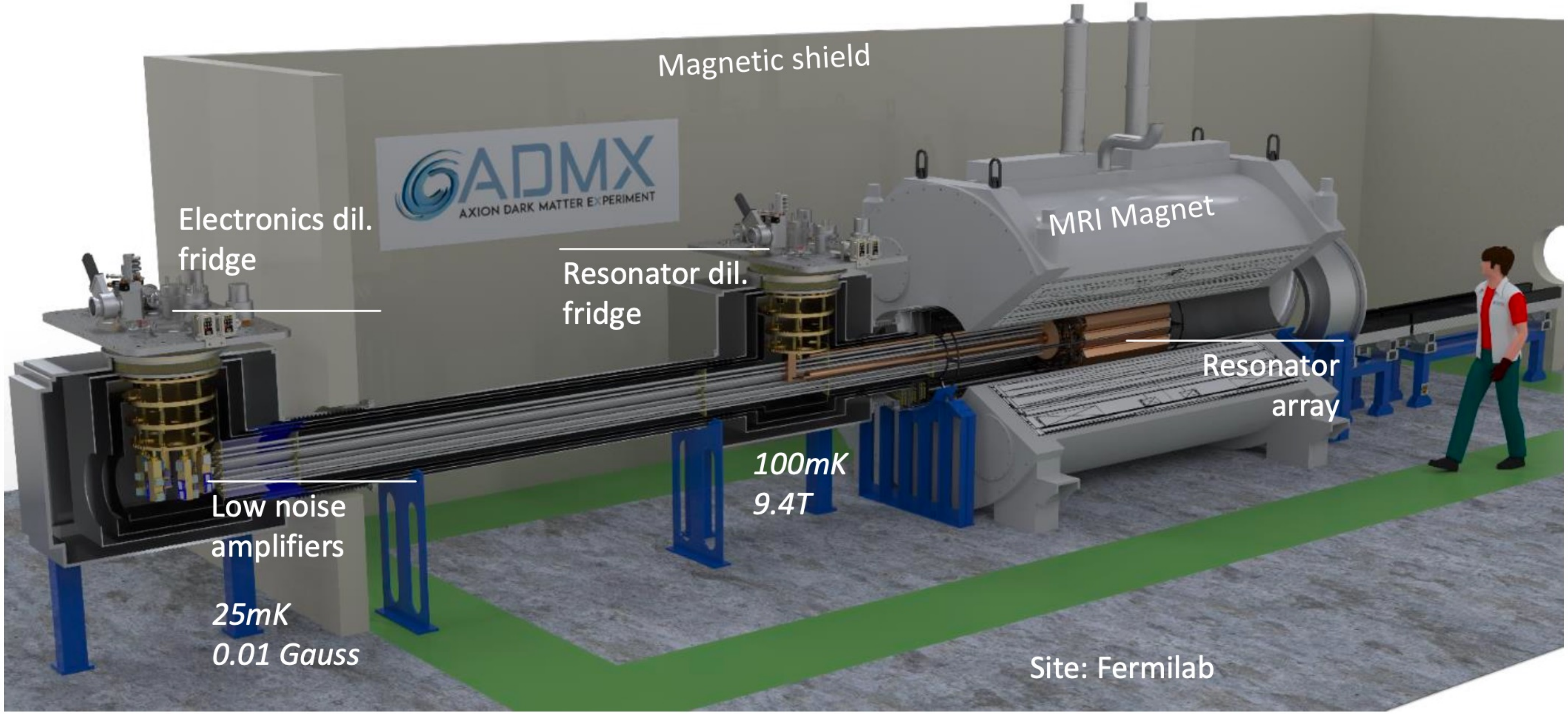
4-cavity array



ADMX: Rybka, August 2022

ADMX-EFR – Design Overview

Existing MRI magnet to be moved to Fermilab



~ 5 × scan speed of current ADMX

CAPP's flagship experiment status and plans

- In spring 2022, covered 20MHz at DFSZ sensitivity, scanning rate at 1.4 MHz/day @ 1.1 GHz with our LTS-12T/320mm magnet from Oxford Instr.

- Covered ~60MHz at DFSZ sensitivity in September 2022, scanning at 3 MHz/day

- Target to cover 1-4 GHz within the next two years at DFSZ sensitivity.

Is the axion quality factor (10^6) the limit?

It depends on the noise temperature. For high-frequency, single photon detection is everything!

Revisiting the detection rate for axion haloscopes

To cite this article: Dongok Kim *et al* JCAP03(2020)066

Is the axion quality factor (10^6) the limit?

It depends on the noise parameter: $\lambda \equiv T_{\mathrm{add}}/T_{\mathrm{eff}}$

Single photon detector wins big!

Dongok Kim *et al* JCAP03(2020)066

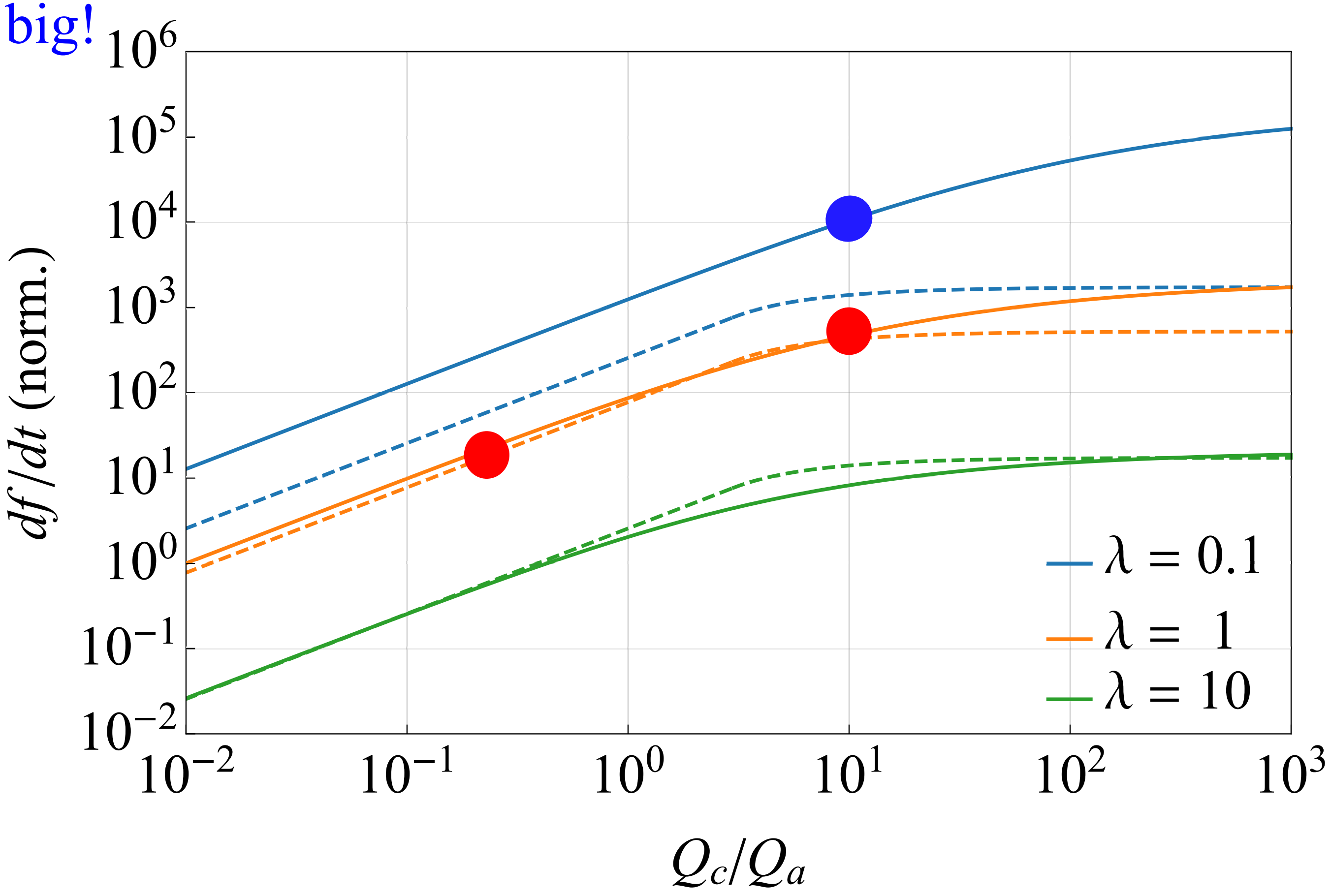


Figure 6. Comparison of the scanning rate between the original (eq. (1.4)) and revised (eq. (5.2)) calculations as a function of normalized cavity quality factor, Q_c/Q_a, for three different values of λ, the relative noise contribution. The former and the latter estimations are represented by dashed and solid lines, respectively.

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

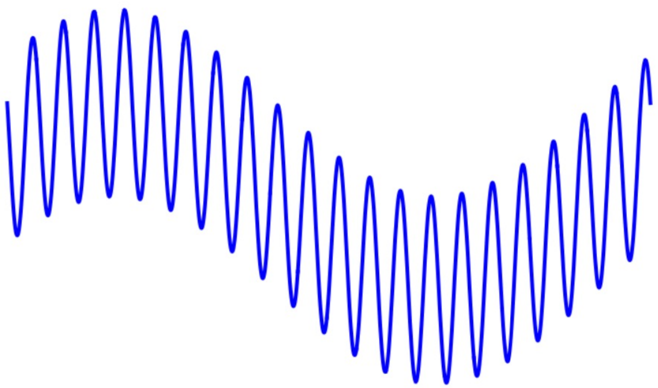
- **Noise Sources**

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

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]

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

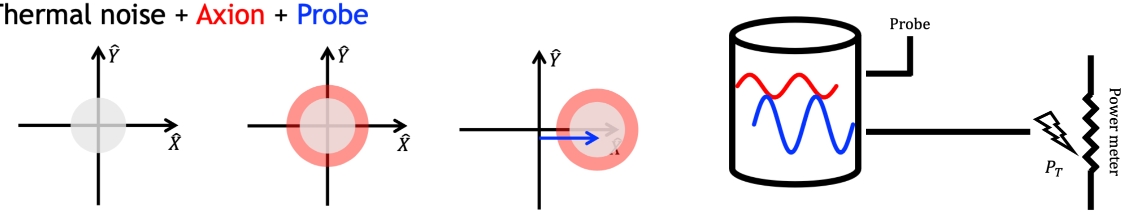
- **Heterodyne**

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

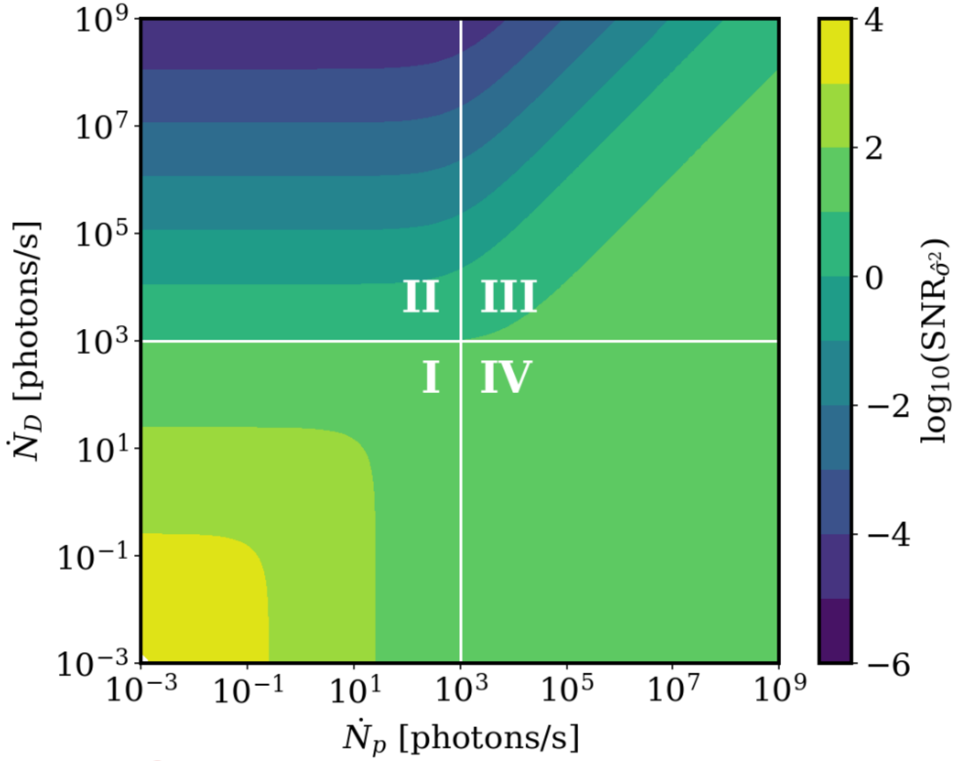
- **SNR of the variance estimator**

Detector sampling rate: f_s

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

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

$\dot{N}_p \gg f_s$



- **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**

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

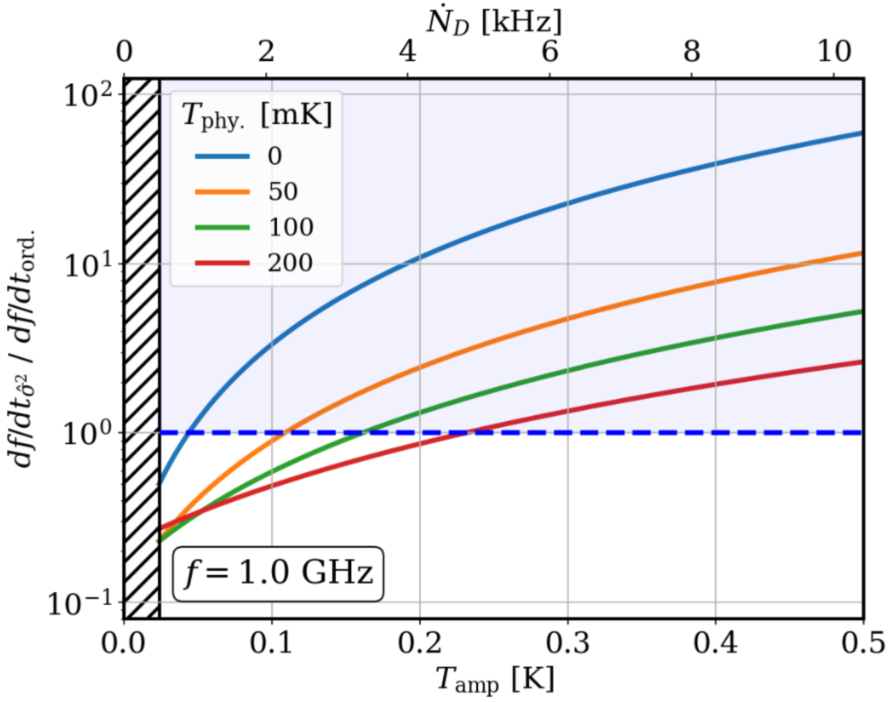
  - The denominator changes from $\sqrt{2f_s}$ to $\sqrt{\dot{N}_{\text{th.}} + \dot{N}_D}$
  - In the case that $\dot{N}_D > 2f_s$, $\mathrm{S/N}_{\sigma^2} > \mathrm{S/N}_{\mu}$

- **Scan rate comparison with Ordinary Method**

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

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

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



HTS superconducting cavity in large B-field!

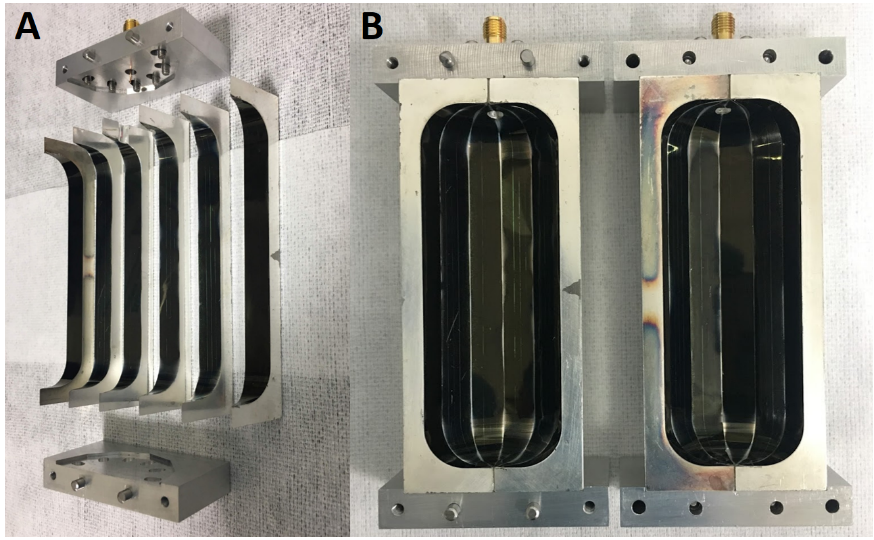
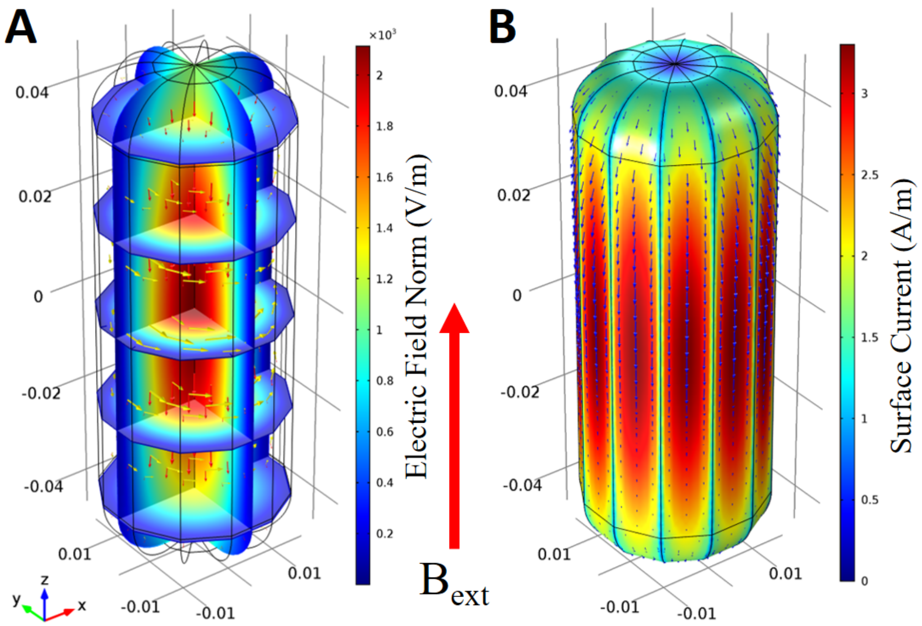


FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

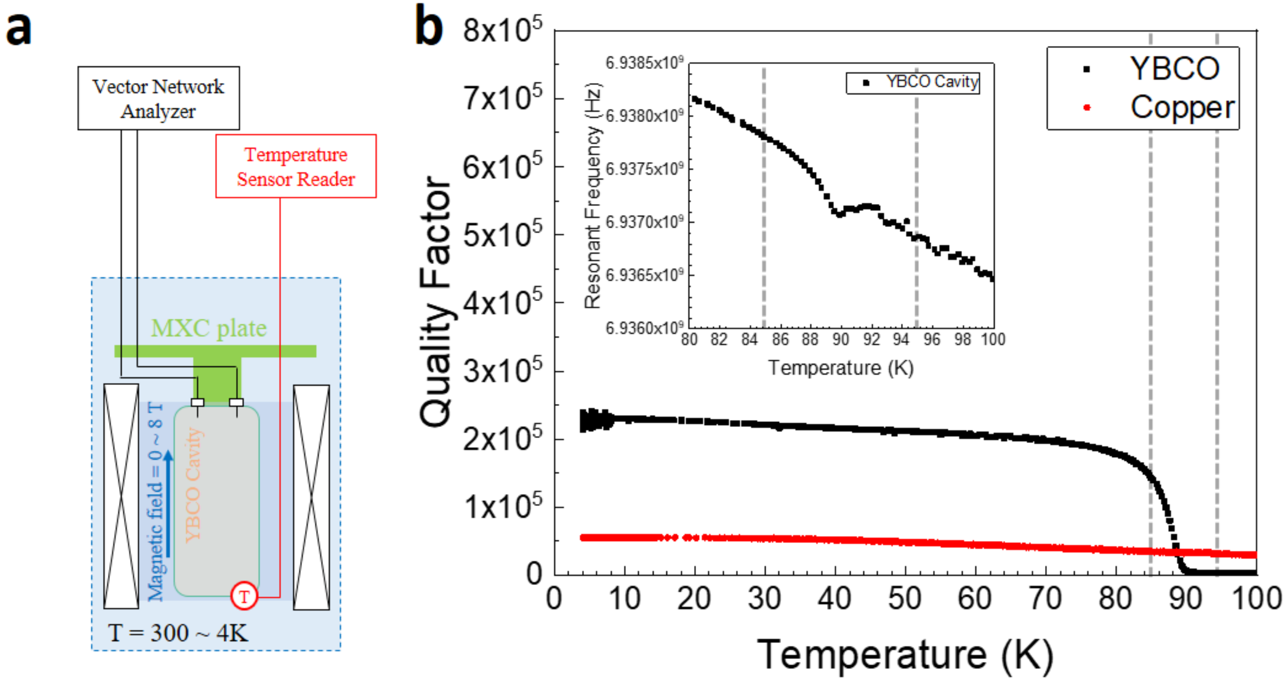
TM_{010} mode



YBCO tapes on cavity walls

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

HTS superconducting cavity in large B-field!



First and best in the world!

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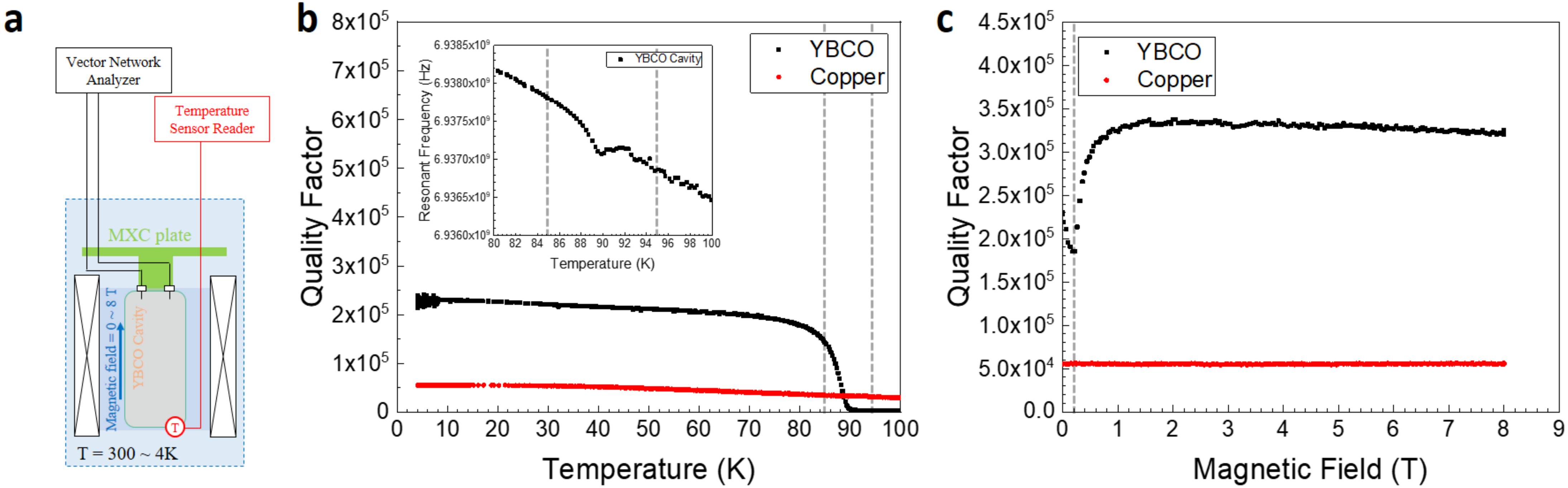
HTS superconducting cavity in large B-field!



First and best in the world!

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

Axion dark matter search

- The axion mass is unknown, like any number in a phone book. 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

- The axion mass is unknown, like any num
  The way we look for it:

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

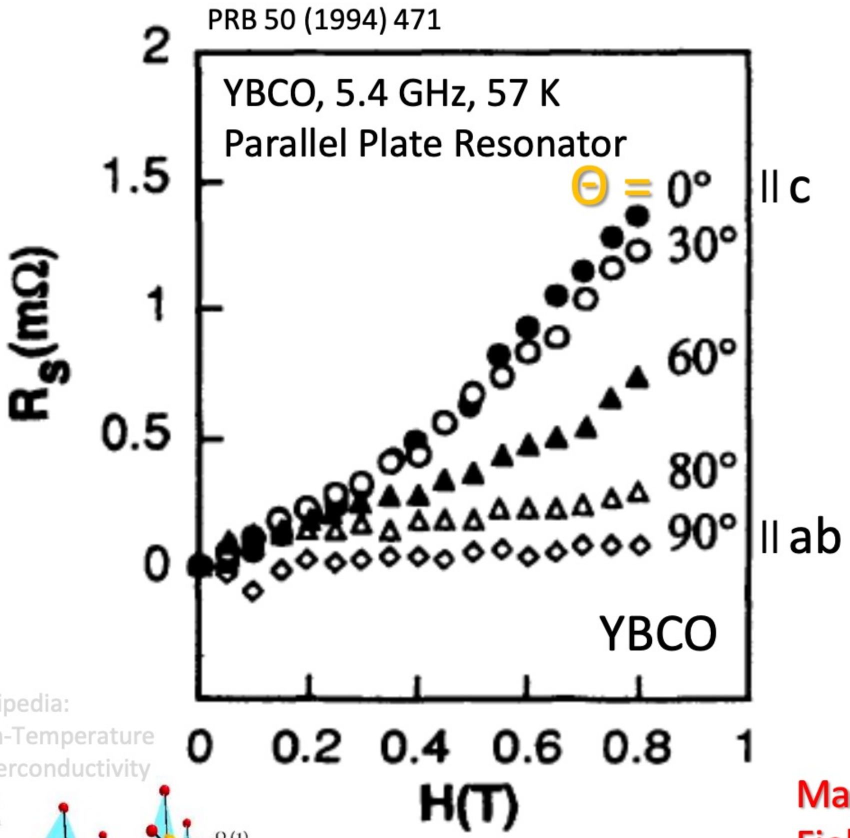
Axion dark matter search

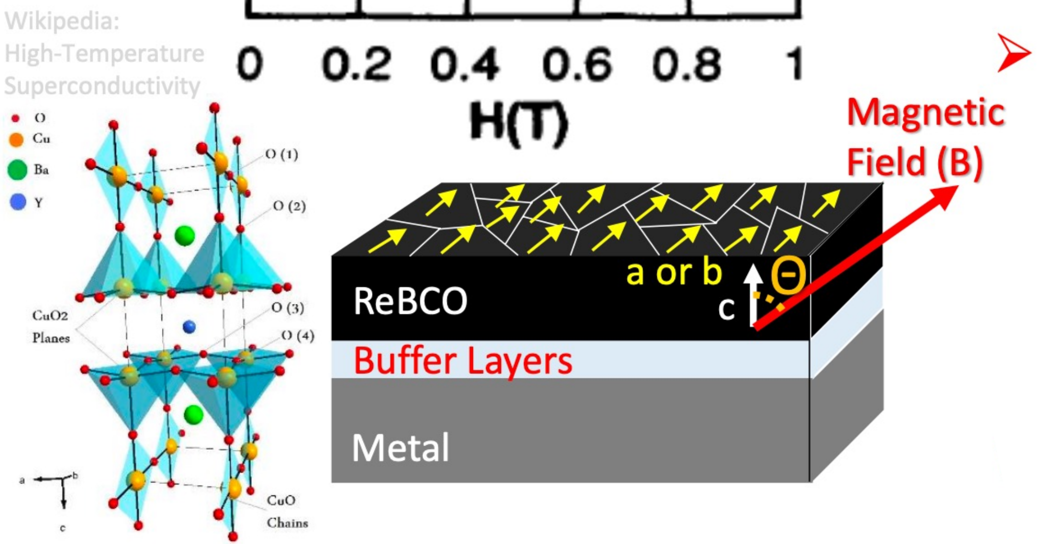
- The axion mass is unknown, like any num
  The way we look for it:

- CAPP's approach was to speed up the dial by developing new technologies/know-how and do it fast.

Biaxially Textured ReBCO Tape

Danho Ahn's slide





- 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.

Center for Axion and Precision Physics Research (IBS-CAPP) at KAIST

- CAPP of Institute for Basic Science (IBS) at KAIST in Korea since October 2013.
- Projects : Axion dark matter, Storage ring proton EDM, Axion mediated long range forces

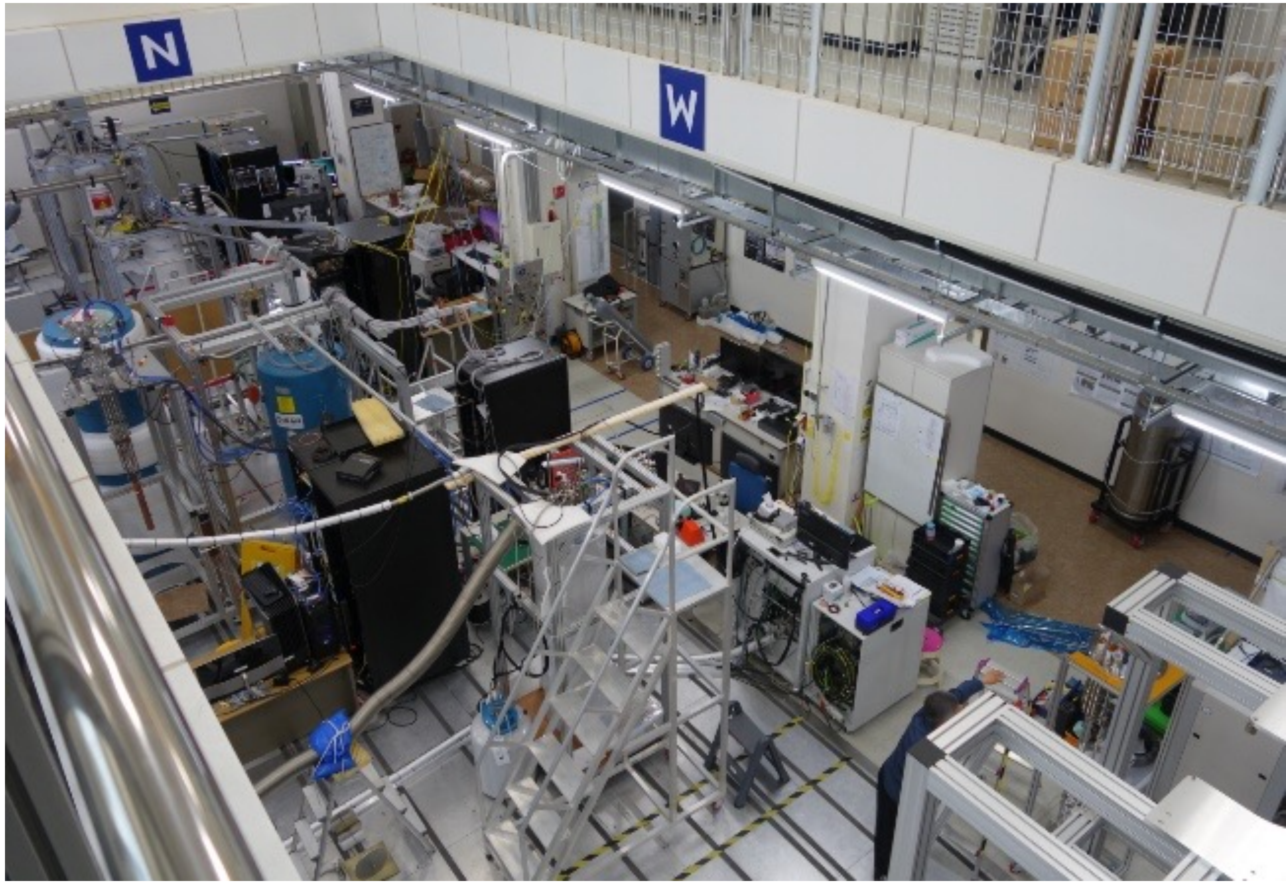
Created a state-of-the-art RF-lab at an existing bldg.

Operation model of parallel R&D

- Several experiments in parallel
- Nb_3Sn based magnet
- High-risk, high physics potential outcome
- Confident scientists with "can-do" attitude.

State of the art infra-structure: 7 low vibration pads for parallel experiments; 6 cryo or dilution refrigerators; high B-field, high volume magnet: 12T, 5.6MJ. Flagship exp.

CAPP experimental hall, top view



David Tanner

Strawman: Single cavity

- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130\ \mathrm{yW} \left(\frac{1\ \mathrm{GHz}}{f} \right)^{2.67}$$

- Volume decreases as f^{-3}, the Q decreases as $f^{-2/3}$ while the mass increases as f

- Length as well as diameter changes because the cavity cannot get too long
  - The longer the cavity, the more TE/TEM modes there are
  - Typically:

$$L \sim 4.4r$$