CAPP
Center for Axion and Precision Physics Research

RIKEN QUANTUM COMPUTING

APPLIED PHYSICS THE UNIVERSITY OF TOKYO

The incredible journey of IBS-CAPP to DFSZ sensitivity since its establishment on October 16, 2013

Yannis K. Semertzidis, IBS/CAPP & KAIST

Georg Raffelt celebration, MPP, November 10, 2022

- I know Georg's name since I got involved with axions in 1987. His papers are a reference for us all and I'm honored to be here to celebrate with him and colleagues.

- All the interesting axion frequencies will be probed globally in the next 10-20 years

CAPP-Physics: strong CP-problem and axion dark matter

- Dark Matter is one of the top ten most important Particle Physics questions

Strong CP-problem: why Strong interactions don't violate CP-symmetry?

- The coupling is feeble, it requires the effective application of latest state of the art technology and lots of ingenuity (high-risk, high-physics-potential)

- CAPP (est. October 16, 2013) has acquired the equipment and has developed the technology, know-how, and infra-structure to effectively probe the 1-8 GHz in the next five years at DFSZ sensitivity.

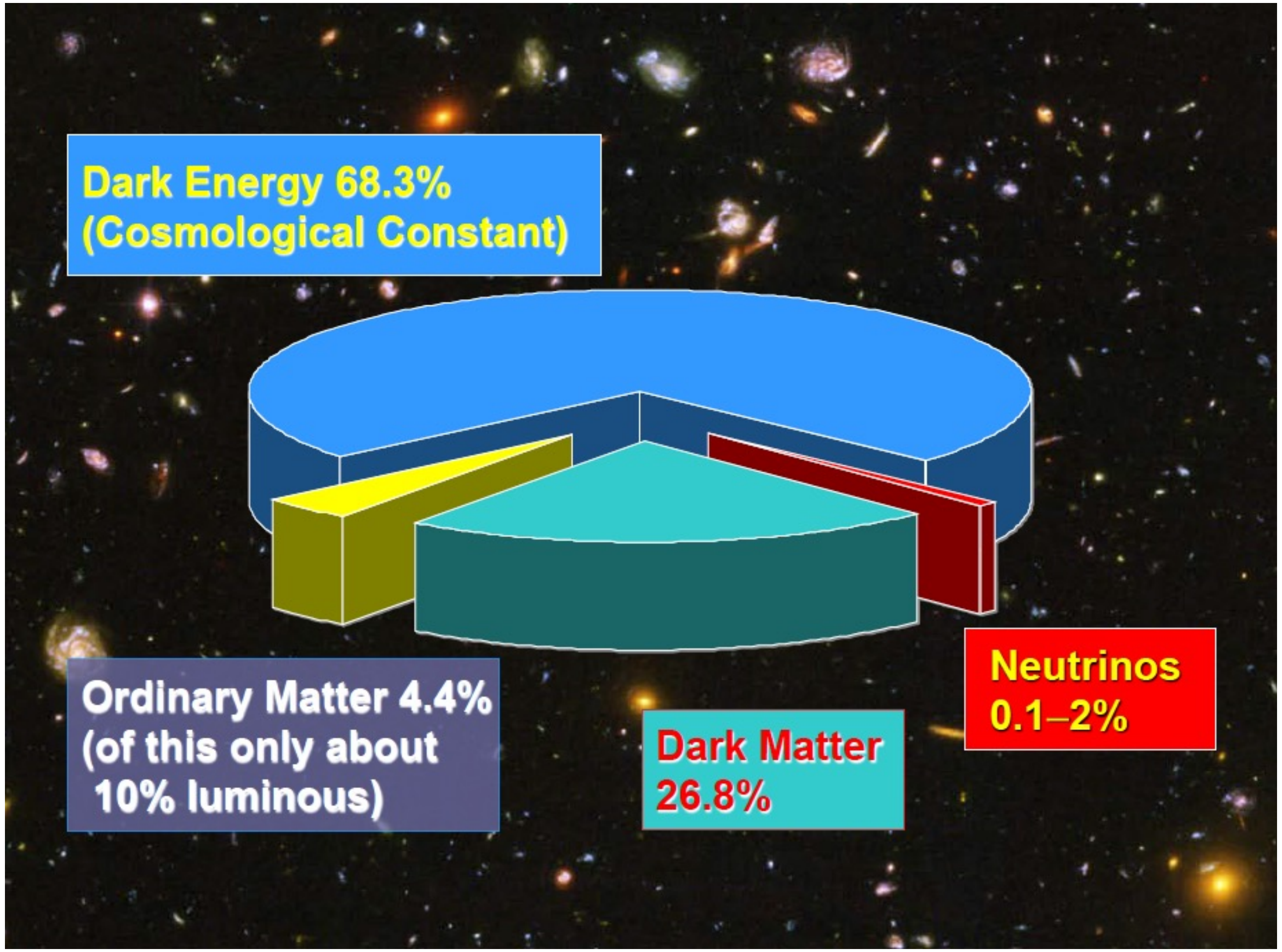
Dark Matter and Isaac Newton (1642-1726)

Isaac Newton unified the Physics phenomena: falling of an apple with the planet, moon, star, sattelite, comet motions, under Gravity!

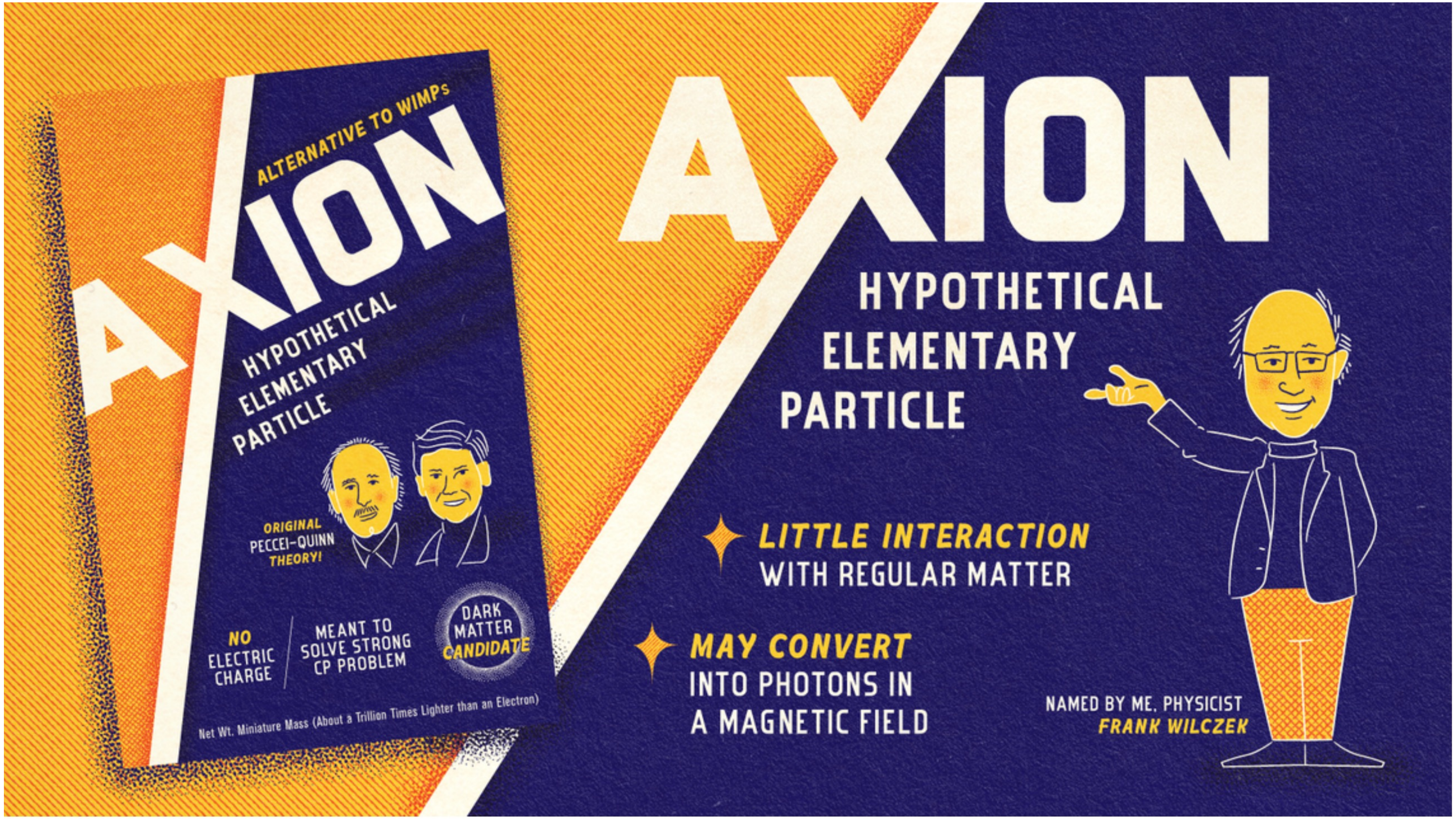
He clarified the view of Heavens for Humanity!

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

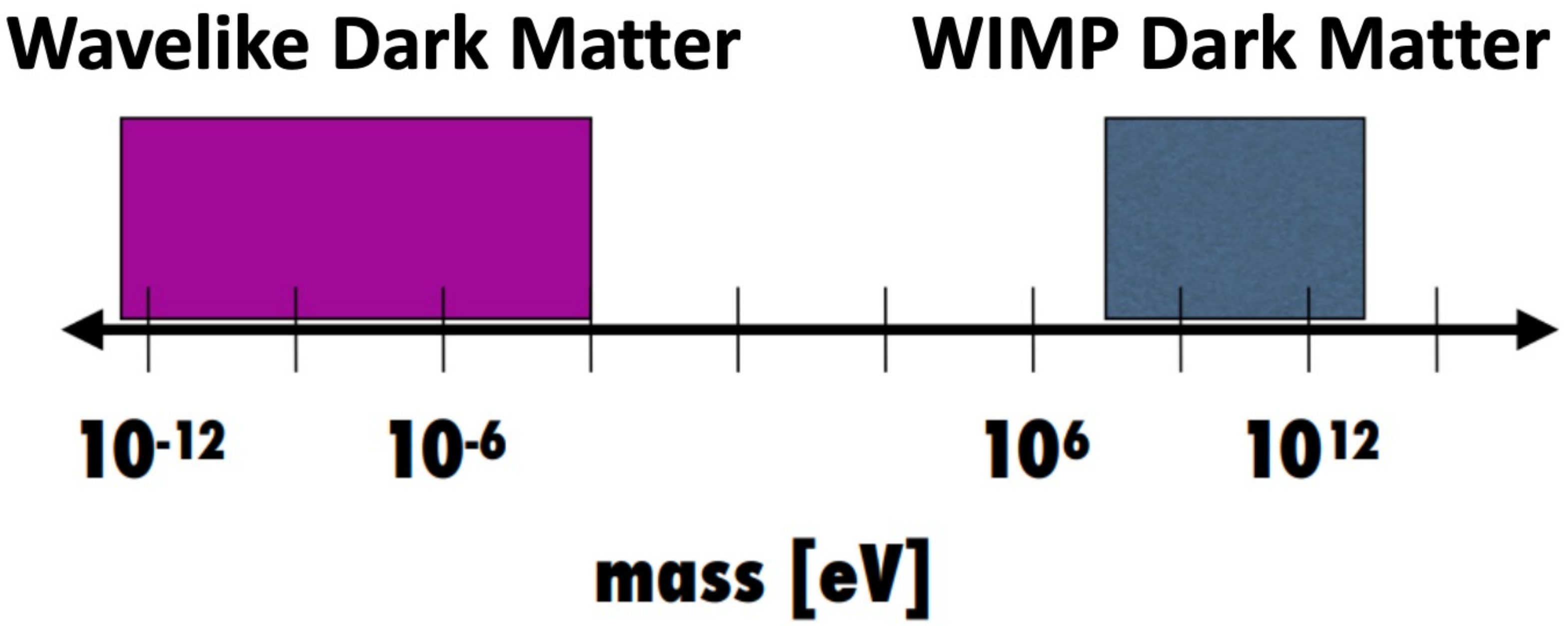
Cosmological inventory



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

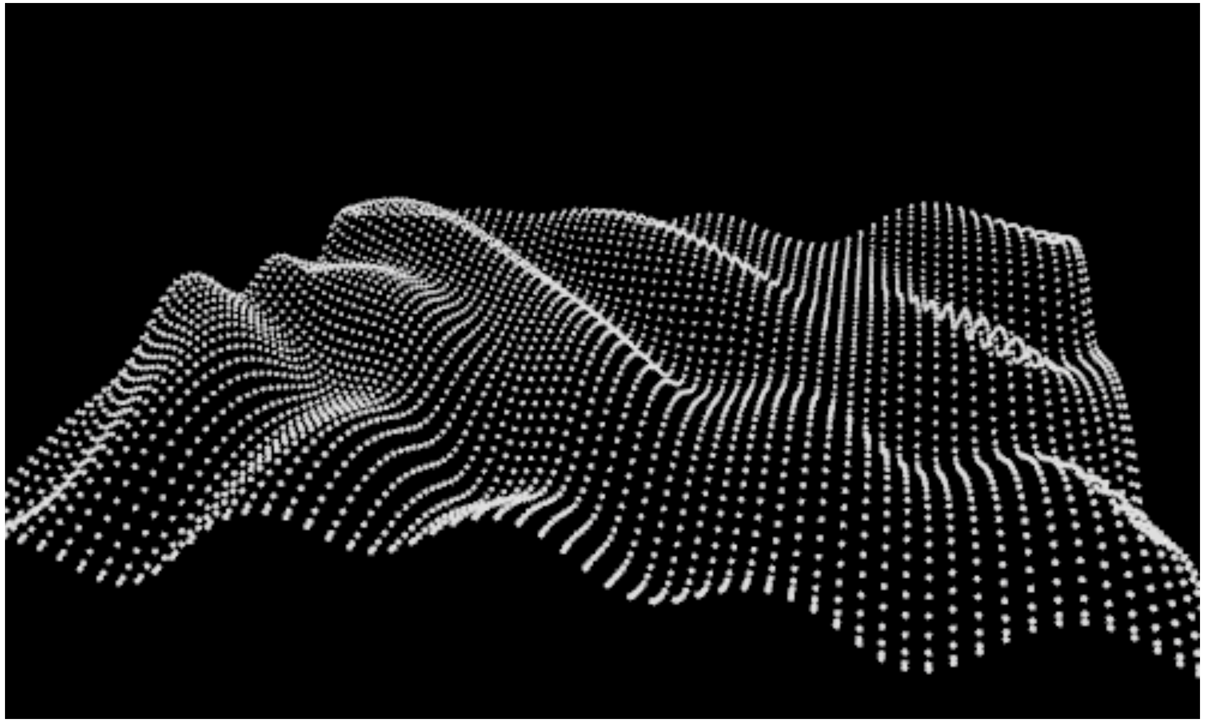
Adapted from B. Safdi

Axion Dark Matter: a Cosmic MASER

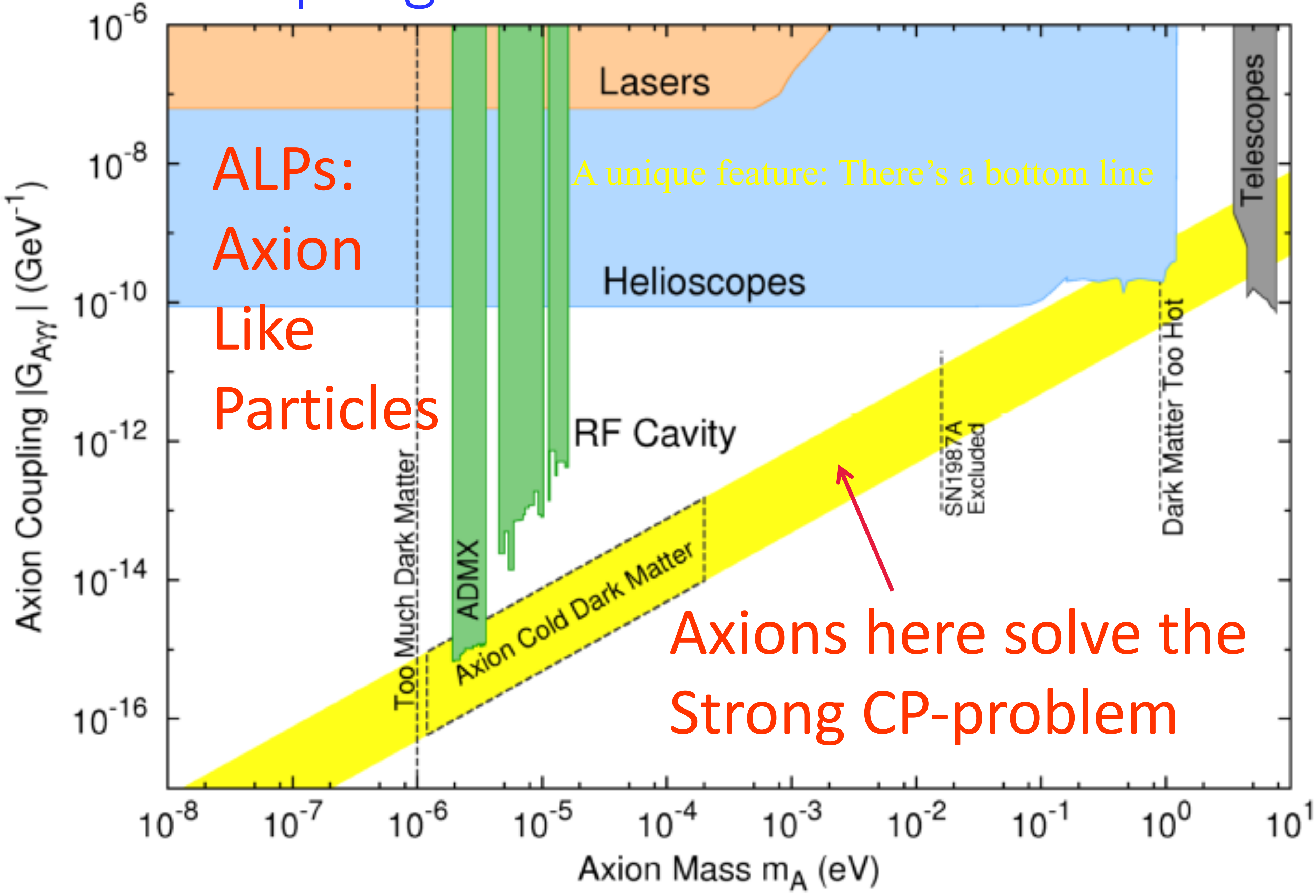
De Broglie wavelength of axions

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

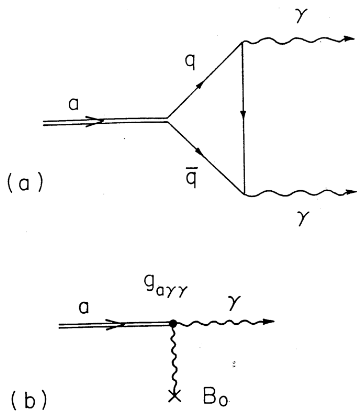
$$\lambda \approx 300\mathrm{m} \times \left(\frac{1\mu\mathrm{eV}}{m_a}\right)$$



Axion coupling vs. axion mass



Axion Couplings



- Gauge fields:
  - Electromagnetic fields $$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$
  -
  - Gluon Fields (Oscillating EDM,…)

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

- Fermions (coupling with axion field gradient, pseudomagnetic field)

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

IBS CAPP Center for Axion and Precision Physics Research

Axion Detection Scheme (Haloscope)

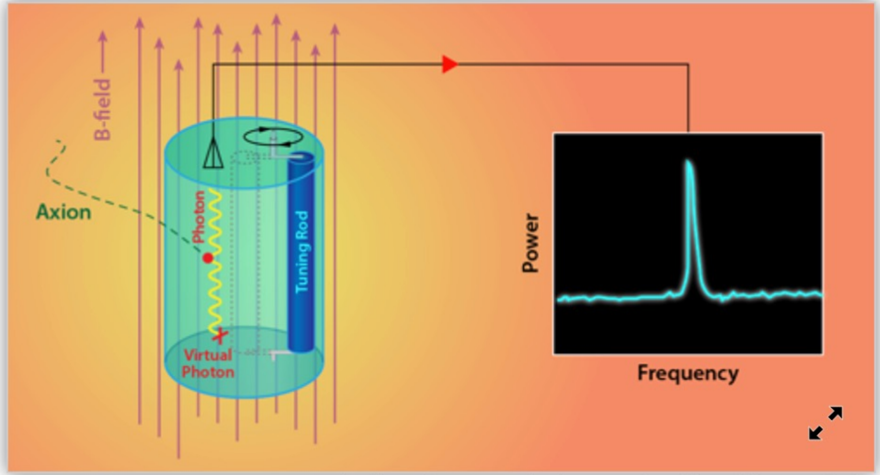
KAIST 1971

- Conventional axion haloscope technique consists of a high-Q microwave cavity inside a homogeneous magnetic field to trigger the conversion of DM axions into photons.

P. Sikivie, \Experimental tests of the invisible axion,"
Phys. Rev. Lett. 51 (1983) 1415 . 6 , 53 , 61 , 63

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

Woohyun Chung's slide



C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker

Running Axion Experiments (Haloscope)

ADMX
HAYSTAC
CAPP

Axion haloscope method by Pierre Sikivie

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

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

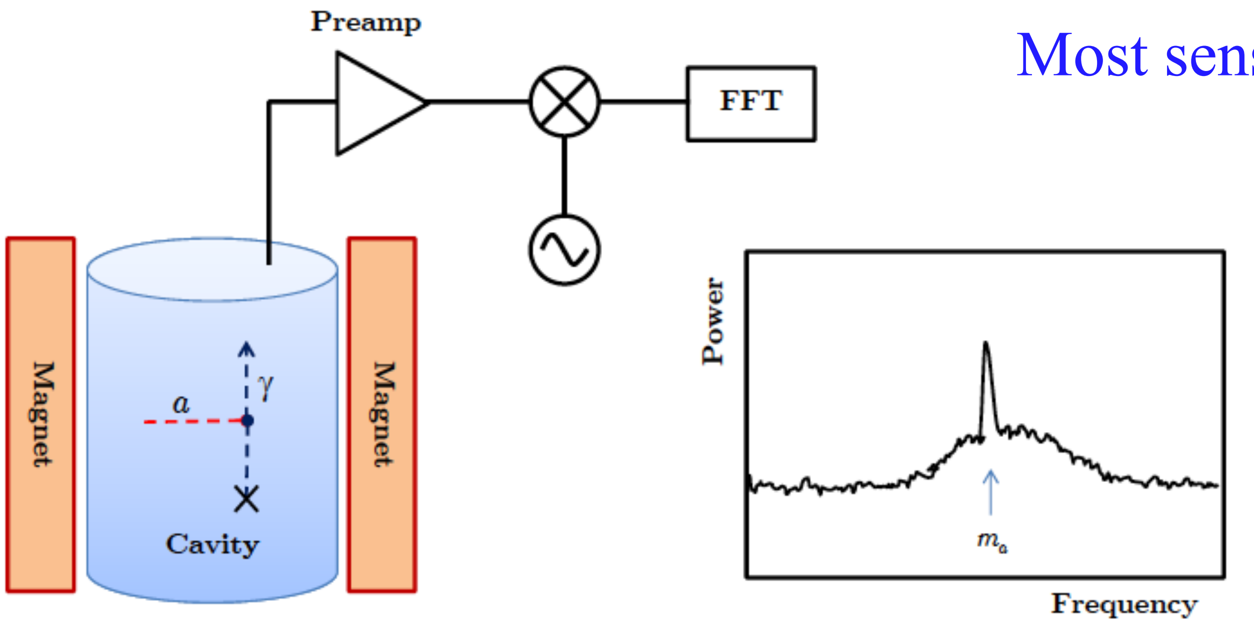


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Most sensitive method

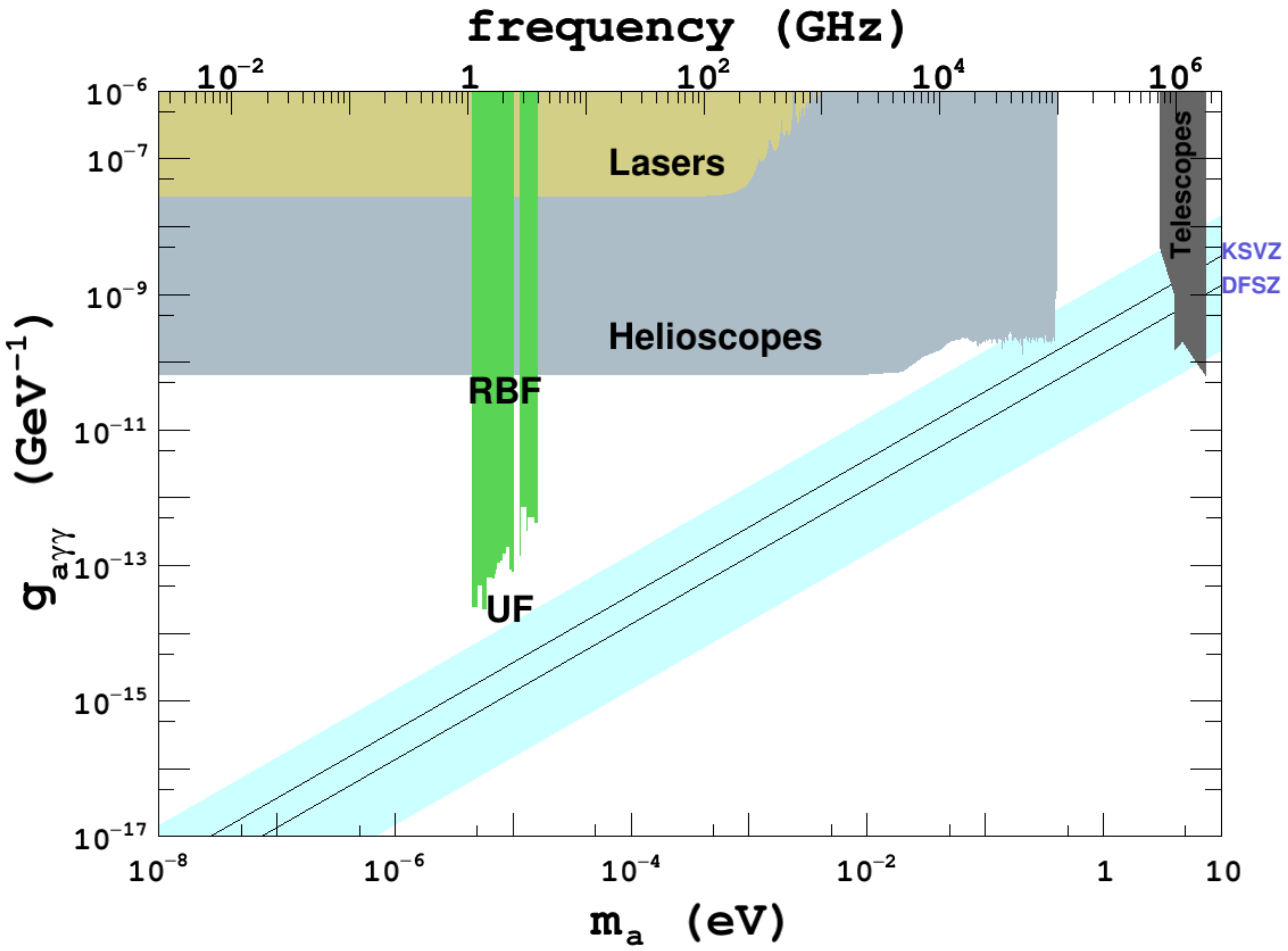
Running Haloscope Experiments:
CAPP
ADMX
HAYSTAC

Rochester Brookhaven Fermilab axion dark matter search

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

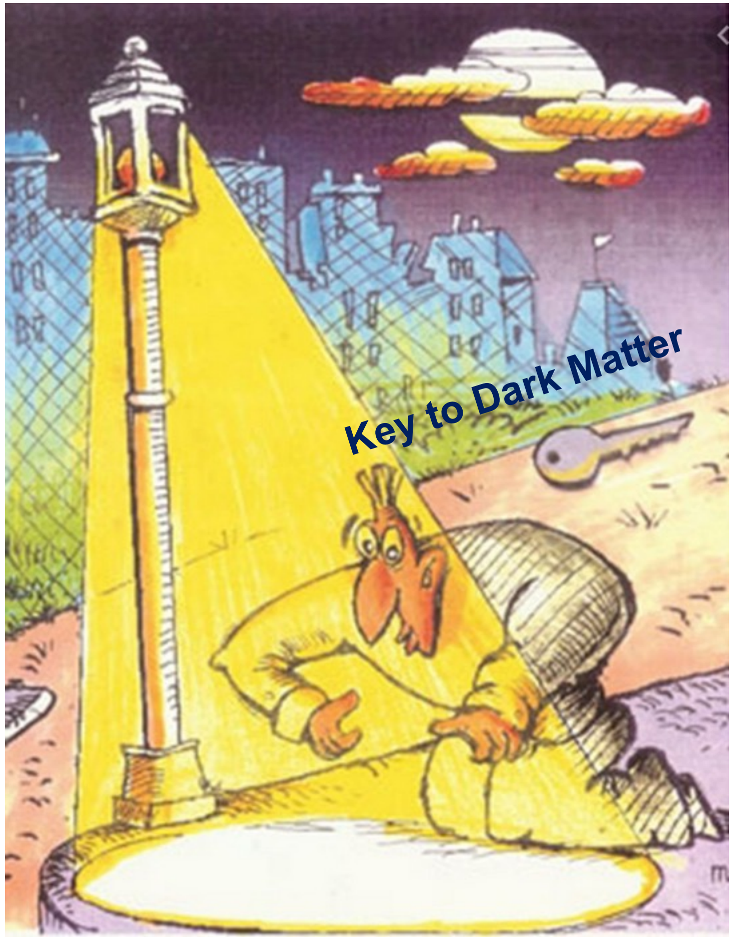
First haloscope limits: Rochester, Brookhaven, Fermilab.

Then University of Florida



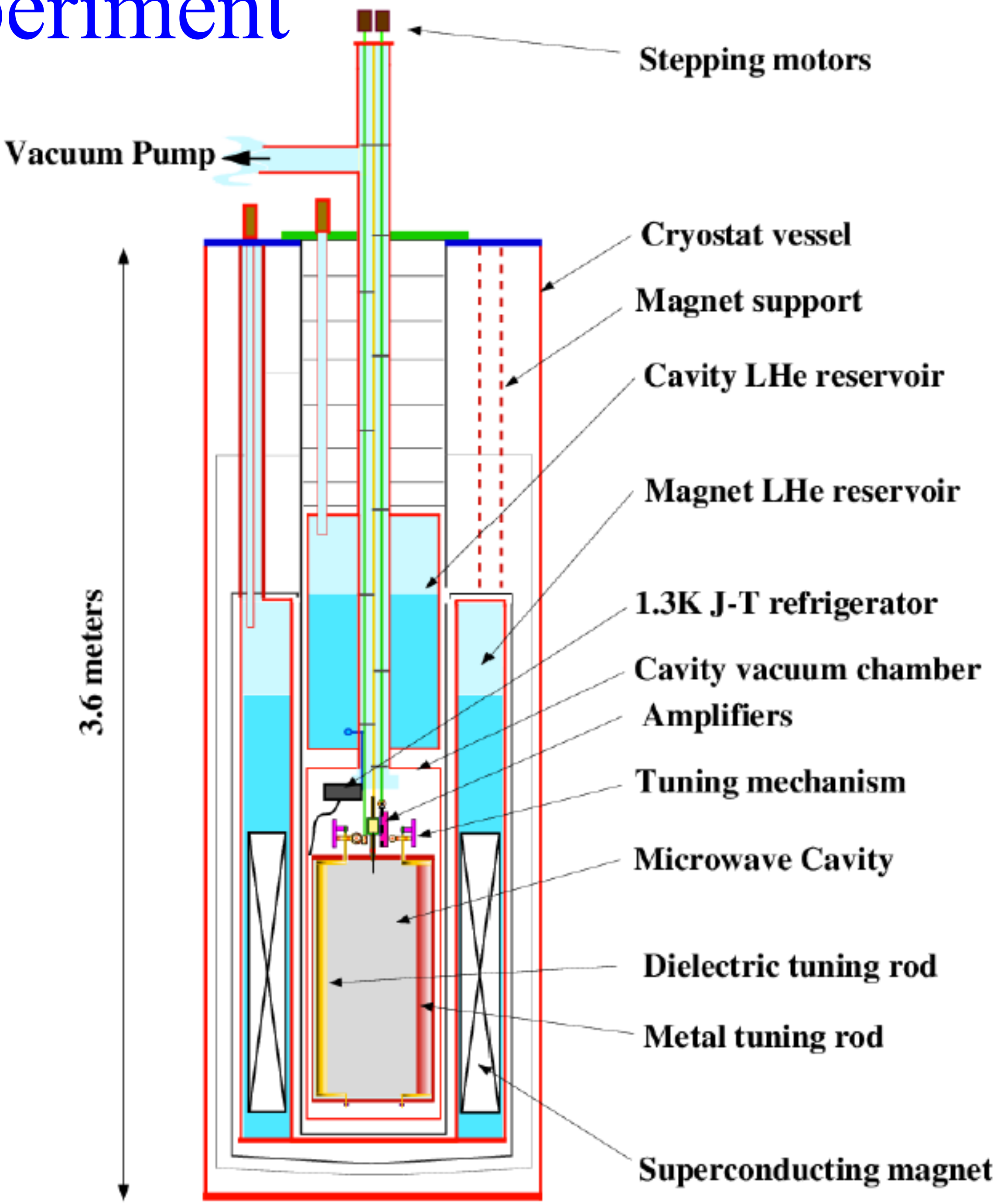
Where to look? ADMX established in 1990.

- Below 1 GHz there is a “sweet” spot chosen by ADMX:
- Large volume, with large B^2V including a low-cost low temperature superconducting (LTS) magnet.
- Low noise Microstrip SQUID Amplifier (MSA)
- Dilution refrigerators became readily available (reducing labor cost)

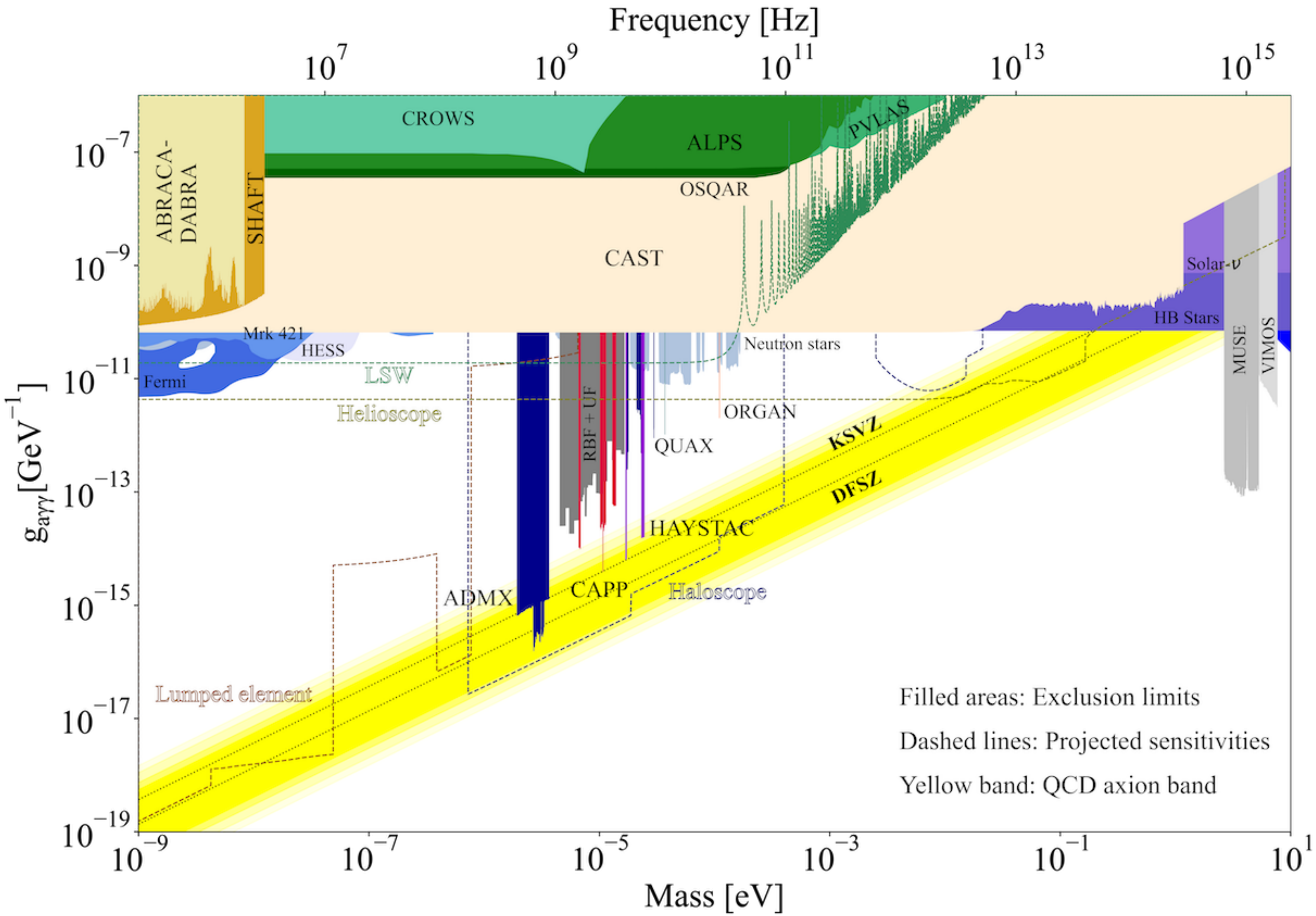


Axion Dark Matter eXperiment

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

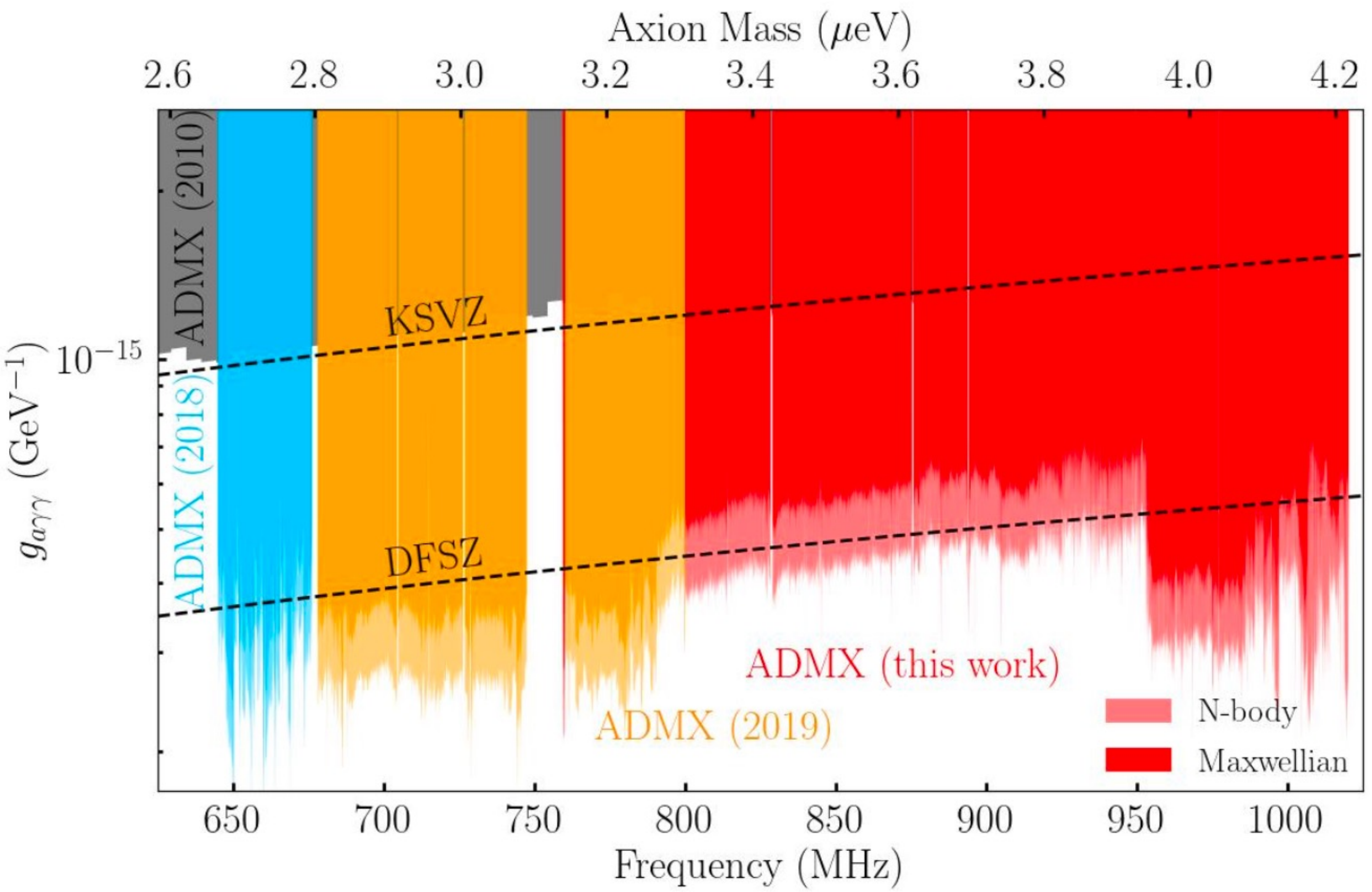


ADMX reached KSVZ sensitivity in 2010; DFSZ in 2018. Patience paid off



ADMX 2021 Exclusion

Gray Rybka's slide (ADMX)



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

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

Editors' Suggestion | Featured in Physics

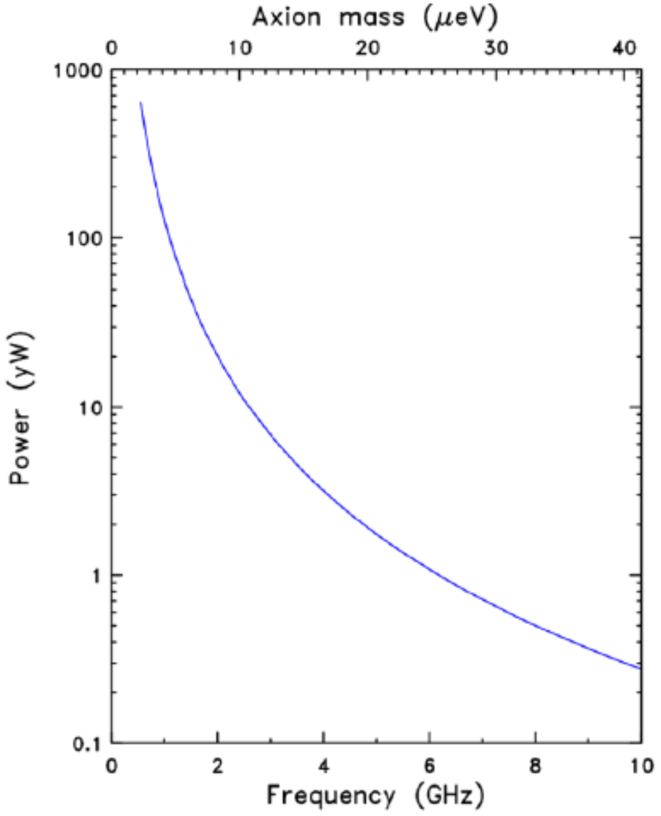
Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range

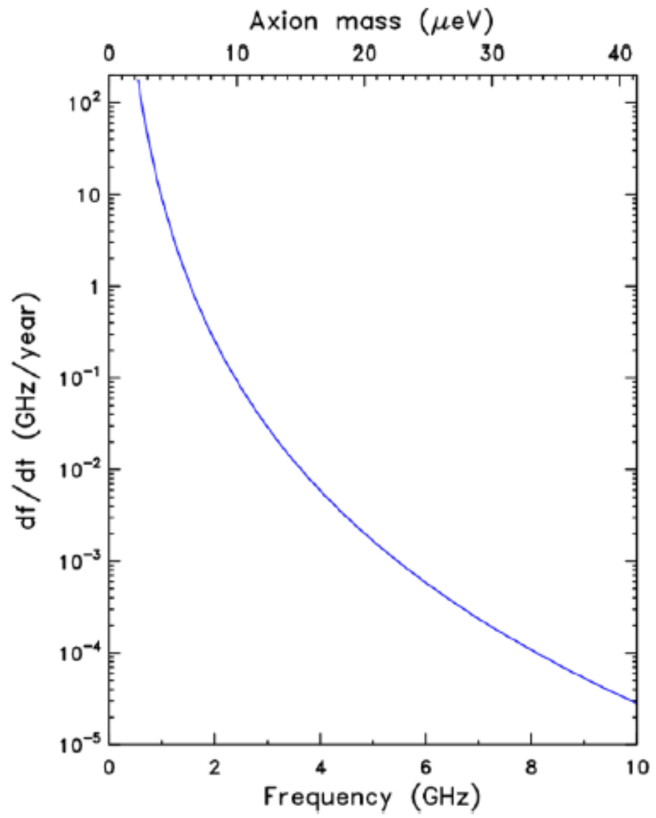
C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S.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

(ADMX Collaboration)

David Tanner, Univ. of Florida

Strawman 2: Single cavity





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

Patras 18

IBS-CAPP recruitment time, making clear: Axion research is like a Marathon, not a short-term effort

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

IBS President Oh, Se Jeong at my recruitment time (I was the first foreign-born IBS-Director): "Just show promise…" when I stated 10-years as too short for axion dark matter research to leave my Senior-Scientist-Tenured position at BNL for it. He gave me a very supportive contract to enable the effective operation of the Center. CAPP was established October 16, 2013.

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

Landscape

October 16, 2013 CAPP is established. No particle or nuclear exp. physics present at KAIST

2014-2017. Setting up infrastructure, purchasing expensive equipment. Started hiring "high-energy", dynamic people.

2017-2020. Set R&D goals, work in parallel to achieve results fast. First setup and runs of prototype experiments.

2020-present. Combine achievements to create competitive axion dark matter experiments

Some points to consider:

1. No axion dark matter experimental activity in Korea prior to CAPP.

2. The prospects of reaching theoretically interesting sensitivities above 1 GHz seemed remote.

3. IBS was a newly established institution. Not long Basic Science tradition in Korea. Nonetheless, it was possible to make it happen since Korea learns fast.

IBS-CAPP period timeline, established Oct. 16, 2013

- 2013-2015, exhausting recruitment effort, not a single "axion expert" came to Korea. We needed to develop all expertise in-house. A time of great growth and infra-structure setup.

- 2016-2019, turbulent period for IBS, budget was drastically reduced. All my contract provisions were fully ignored by the second IBS administration. Building up of CAPP prototype experiments and developing know-how.

- 2020-May 2022, returned to stability with thriving innovation period. Breakthrough results from CAPP pouring out. Most budget cuts remained.

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 and tested.

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

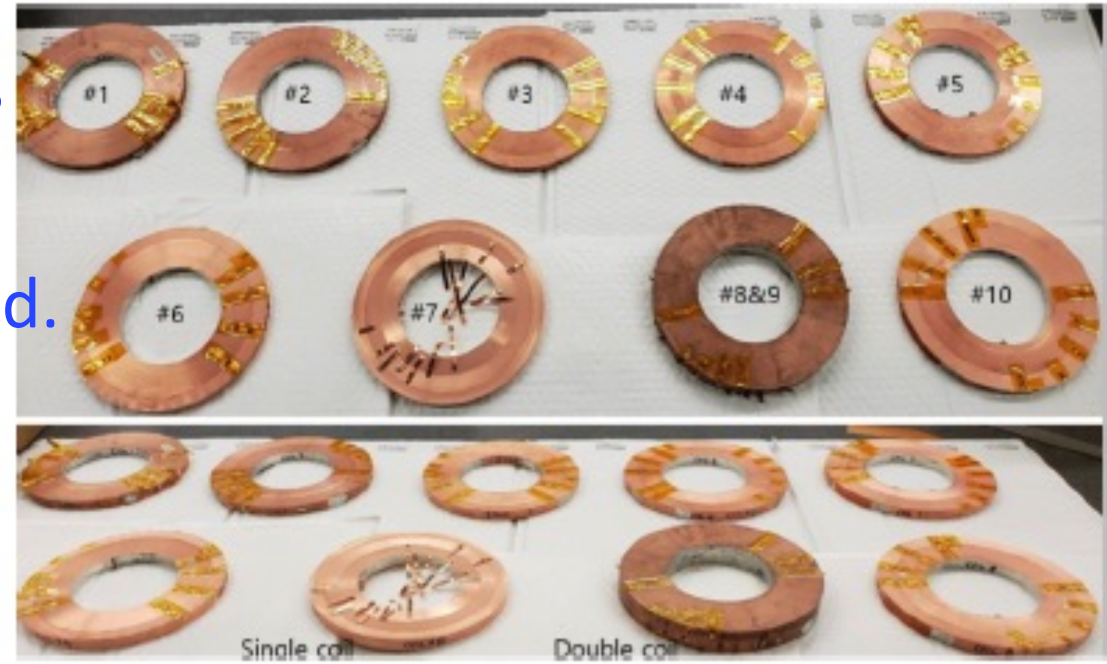
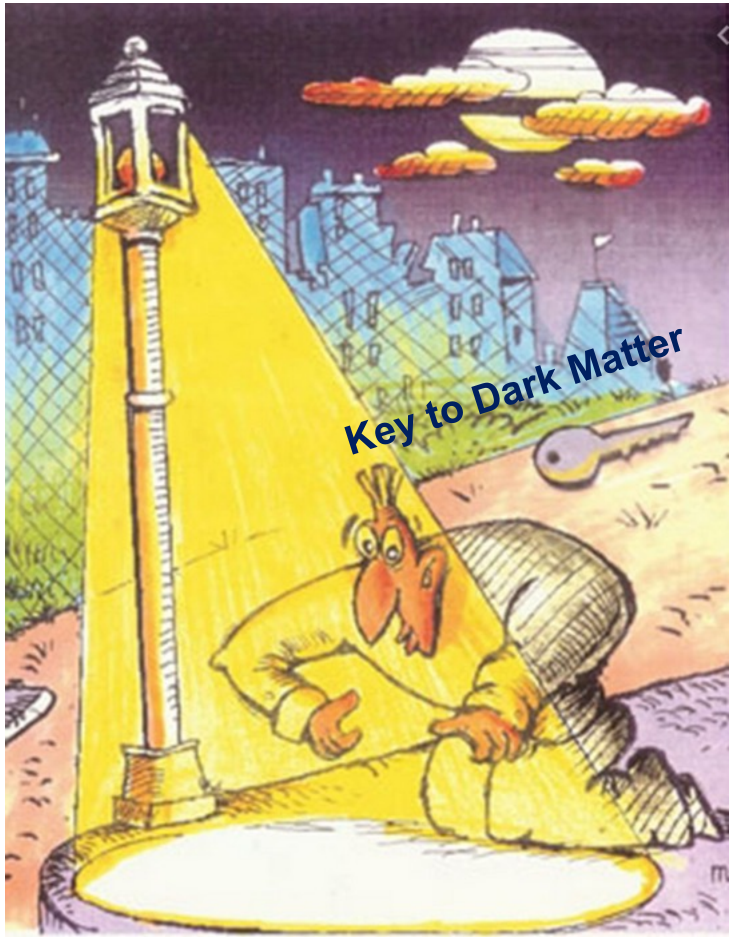


Figure 2.67: Manufacturing process (10 HTS coils).

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 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)

CAPP started from scratch in 2013.
Lab space at KAIST, 2014

Another room at KAIST.
We had to buy even screwdrivers.

CAPP had to create a miracle

Had to change everything:

- Several parallel R&D efforts

- High-risk projects with high-potential payout

- Developing state of the art infrastructure at the same time.

Main CAPP tactics, targeting axions of 1-10 GHz

- Develop infra-structure
- Develop in-house expertise
- Collaborate with the best around the world on amplifiers (long lead-time) and others as needed

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

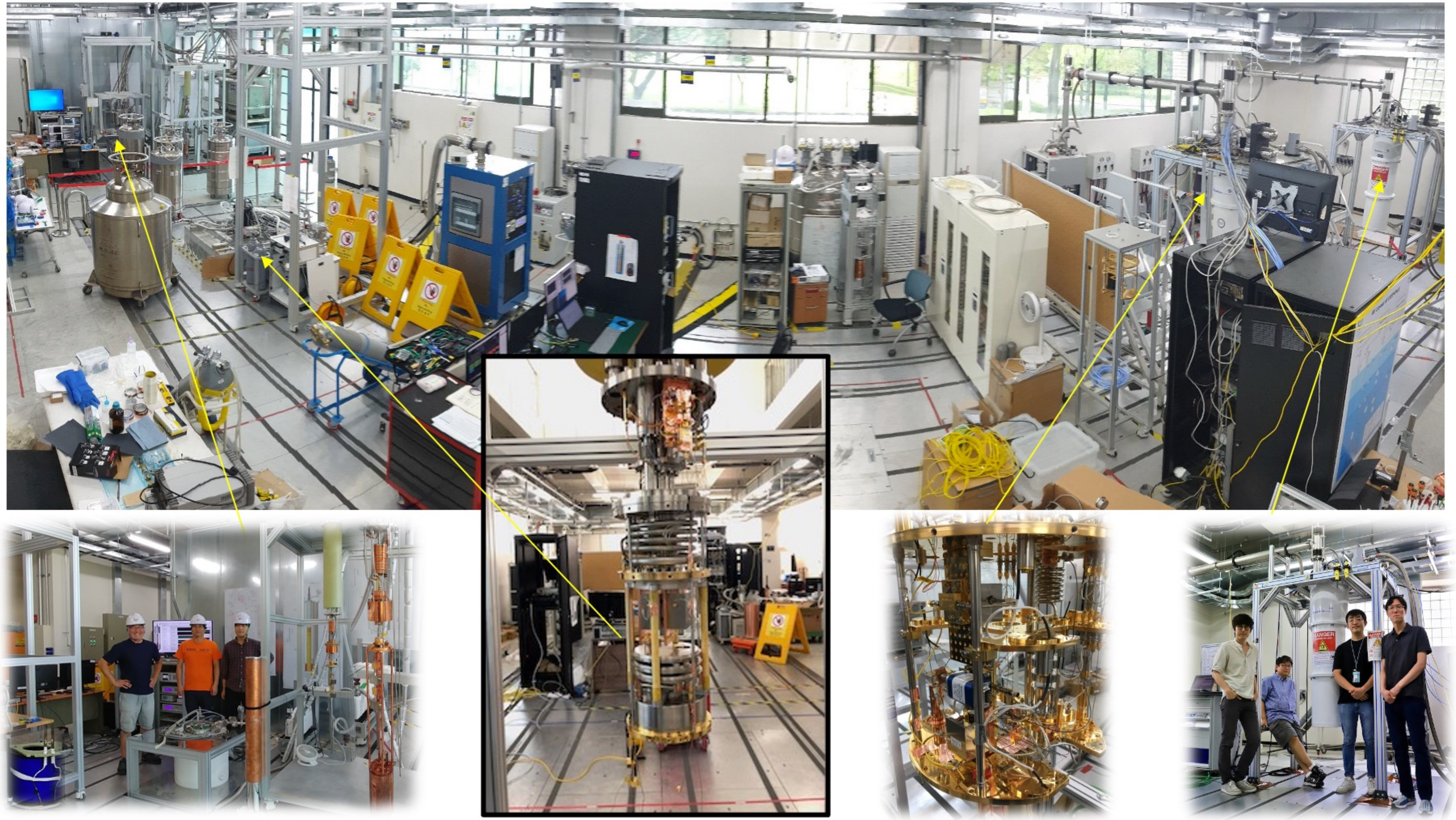
Created a state-of-the-art RF-lab at an existing bldg. (Creation Hall at Munji Campus of KAIST)

Operation model:

- Reward risk taking with high-physics potential R&D efforts
- Created a can-do environment with competent and confident scientists.
- Fast pace, the Korean clock running three times faster than regular clocks!

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 (LVP) in 2021



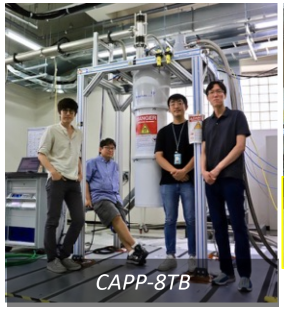
CAPP-HF CAPP-12TB CAPP-PACE CAPP-8TB

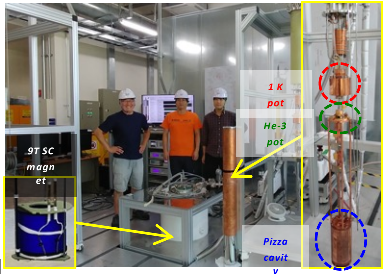
IBS-CAPP at eight-years and beyond

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

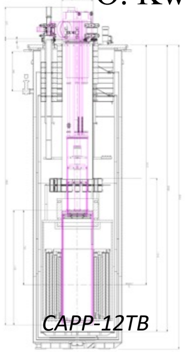
J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020).

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



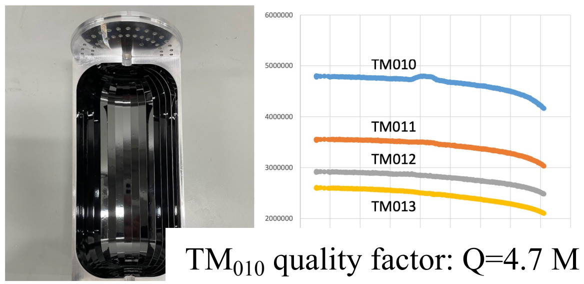


CAPP-9T MC

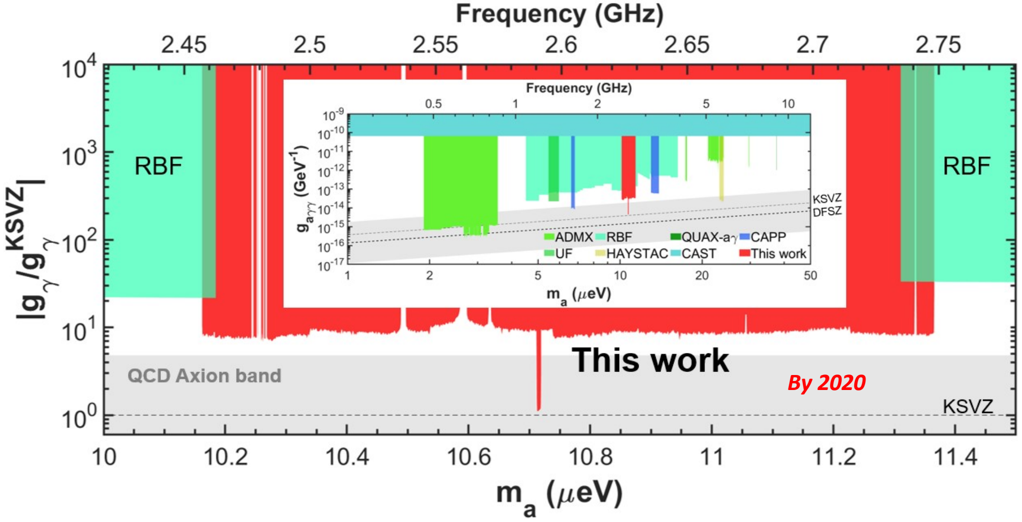


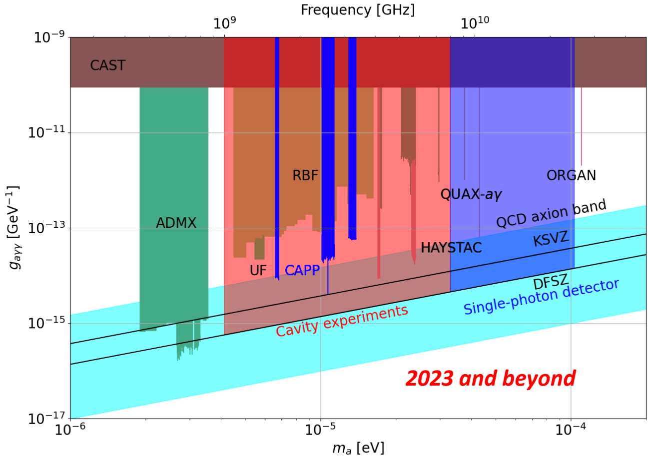
CAPP-12TB

Melon 34 Cavity Q Factor Measurement



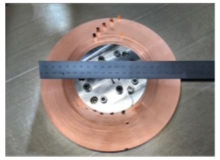
TM_{010} quality factor: Q=4.7 M



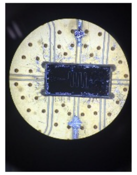


- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

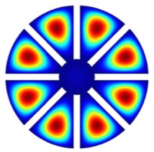
CAPP-25T



+



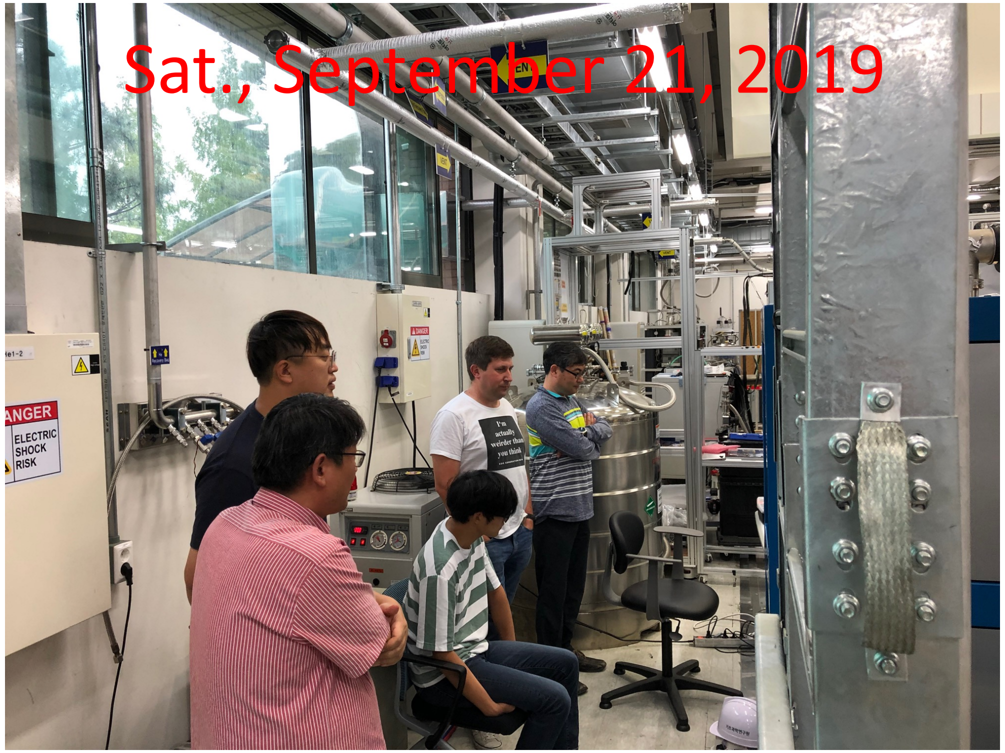
+



We have succeeded in all our R&D goals. 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!

LTS-12T/320mm from Oxford Instruments

- ByeongRok Ko, Team leader of CAPP-12TB including the Nb_3Sn, LTS-12T/320mm magnet. Here, with his team testing the Leiden system.



LTS-12T/320mm magnet (12TB experiment)

- Nb_3Sn + NbTi, LTS-12T/320mm from Oxford Instr., delivered March 2020, commissioned in August-December 2020.

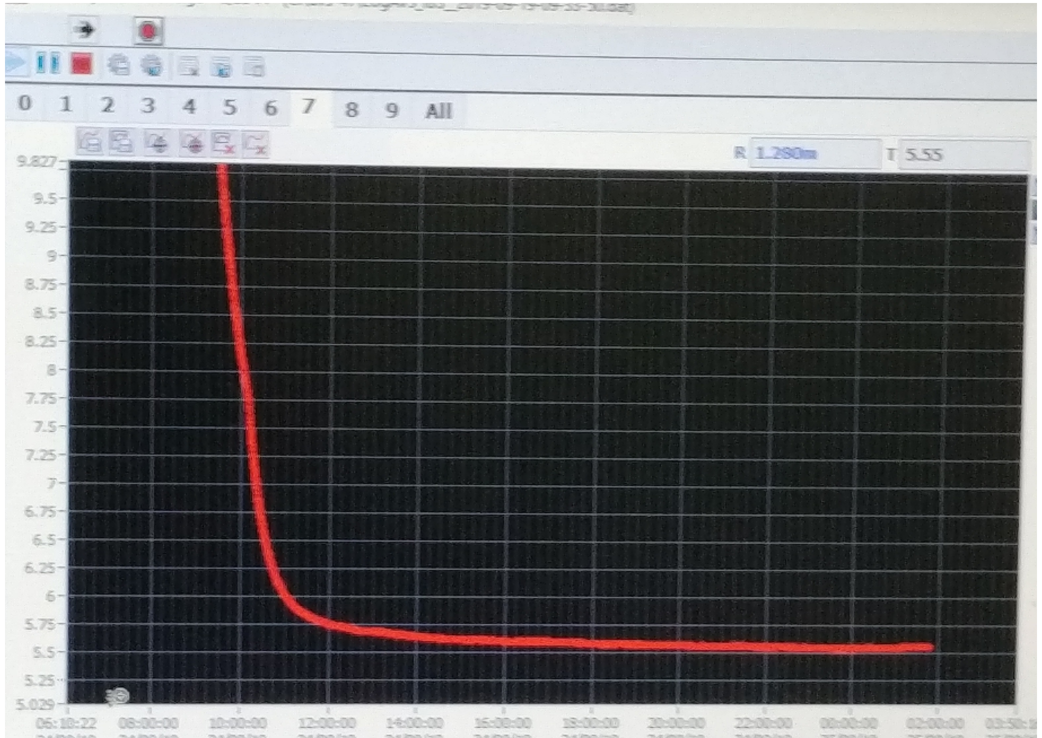
- This system can reach DFSZ level sensitivity in the 1-8 GHz, with present technology. Using SC cavities probe more…

- Wet system,

  Leiden dilution system:

  1.3mW at 120mK,

  achieved 5.6mK.



LTS-12T/320mm from Oxfrod Instruments

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

LTS-12T/320mm from Oxfrod Instruments

- Based on Nb_3Sn and NbTi, new challenging technology, 12T. Persistent mode switch
- Project delayed by a year due to COVID-19
- The largest Nb_3Sn magnet system in axion dark matter search.
- Cavity: ~37 liter, ultra-light cavity, 25mK
- The main activity at IBS-CAPP, integrating all experience from small experiments

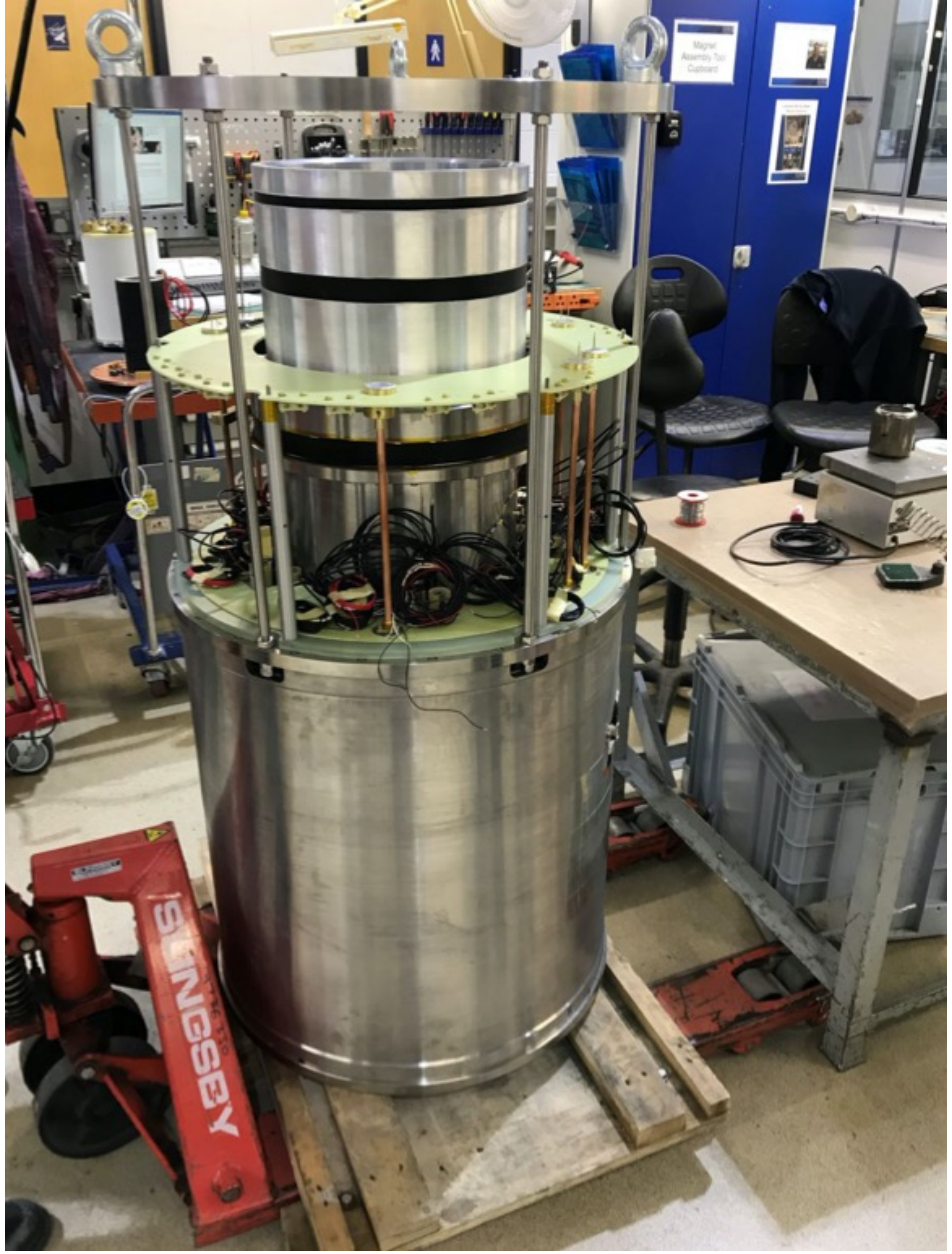


Figure 6. Recent picture of the LTS-12T/320mm magnet in its final form at the Oxford Instruments laboratory. Its total energy content is 5.652 MJ, a powerful magnet that requires respect and caution when energized. The system is to undergo its final tests before its scheduled shipment to IBS-CAPP by March 2020.

The CAPP-12TB, 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)

The CAPP-12TB, 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, $Q_0=2\times10^6$
  - DFSZ: 2 GHz/year for 20% of dark matter as axions

The Josephson parametric amplifiers (JPA) from Tokyo/RIKEN are quantum-noise limited. Best integrated system in the world.

- Collaboration with University of Tokyo/RIKEN, providing us with the chips, while we provide feedback for noise improvement.

- Currently we have the lowest noise temperature JPAs in the world at:

  1GHz, 2 GHz, and 6 GHz.

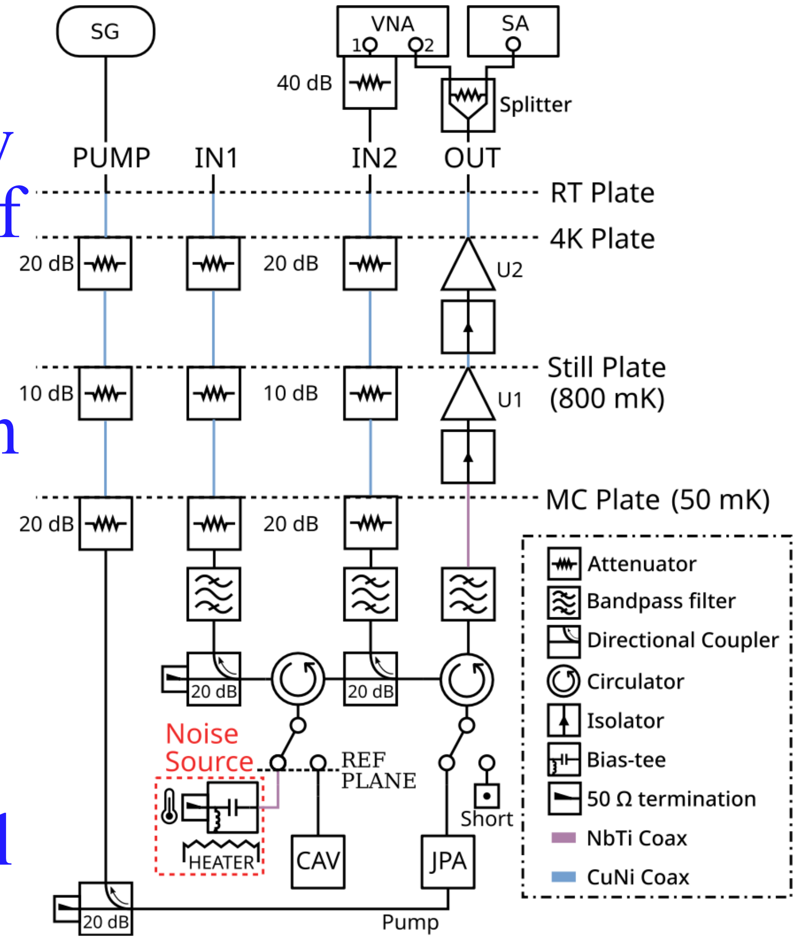
Cryogenics, RF-chain & JPAs

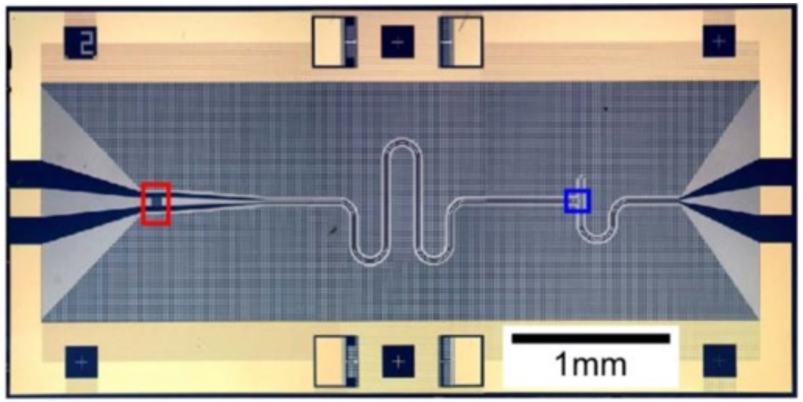
- Caglar Kutlu, JinMyeong Kim, Saebyeok Ahn, Andrew Yi, … KAIST graduate students under the leadership of Sergey Uchaikin on JPAs created the best performing quantum-noise-limited amplifiers. Chips/expertise from RIKEN/Univ. of Tokyo, Prof. Y. Nakamura, Arjan F van Loo.

- Ultra-light-cavity (37 liter) and cryogenics, OhJoon Kwon, Woohyun Chang, Heesu Byun, Sergey Uchaikin, Boris Ivanov achieved 25mK cavity physical temperature. The best in the world.

- Total system noise <200mK, measured with Noise Source at 1 GHz. Best in the world.

Ç Kutlu *et al*

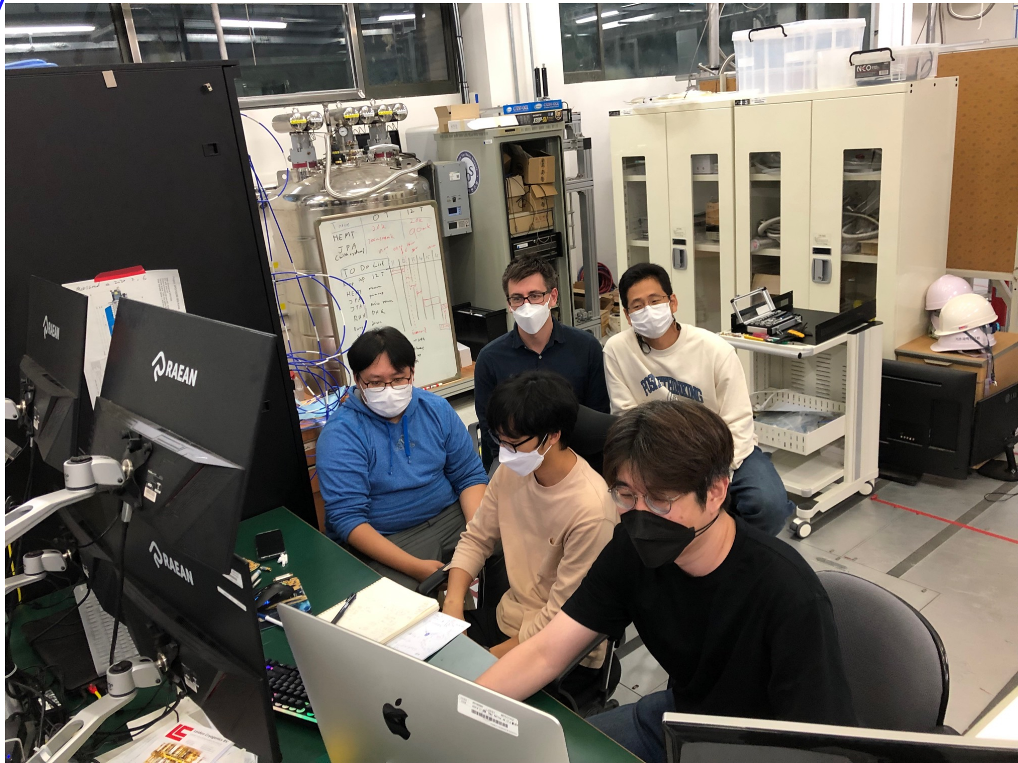




CAPP status in spring 2022

- We have two small systems taking data at KSVZ sensitivity:
  - BF6: Around 5.8 GHz, ~1 MHz/day, scanned: ~100 MHz, "Pizza" cavity, first and still best in the world
  - BF5: Around 2.3 GHz, ~1 MHz/day, first goal: 25 MHz, superconducting cavity, first and still best in the world

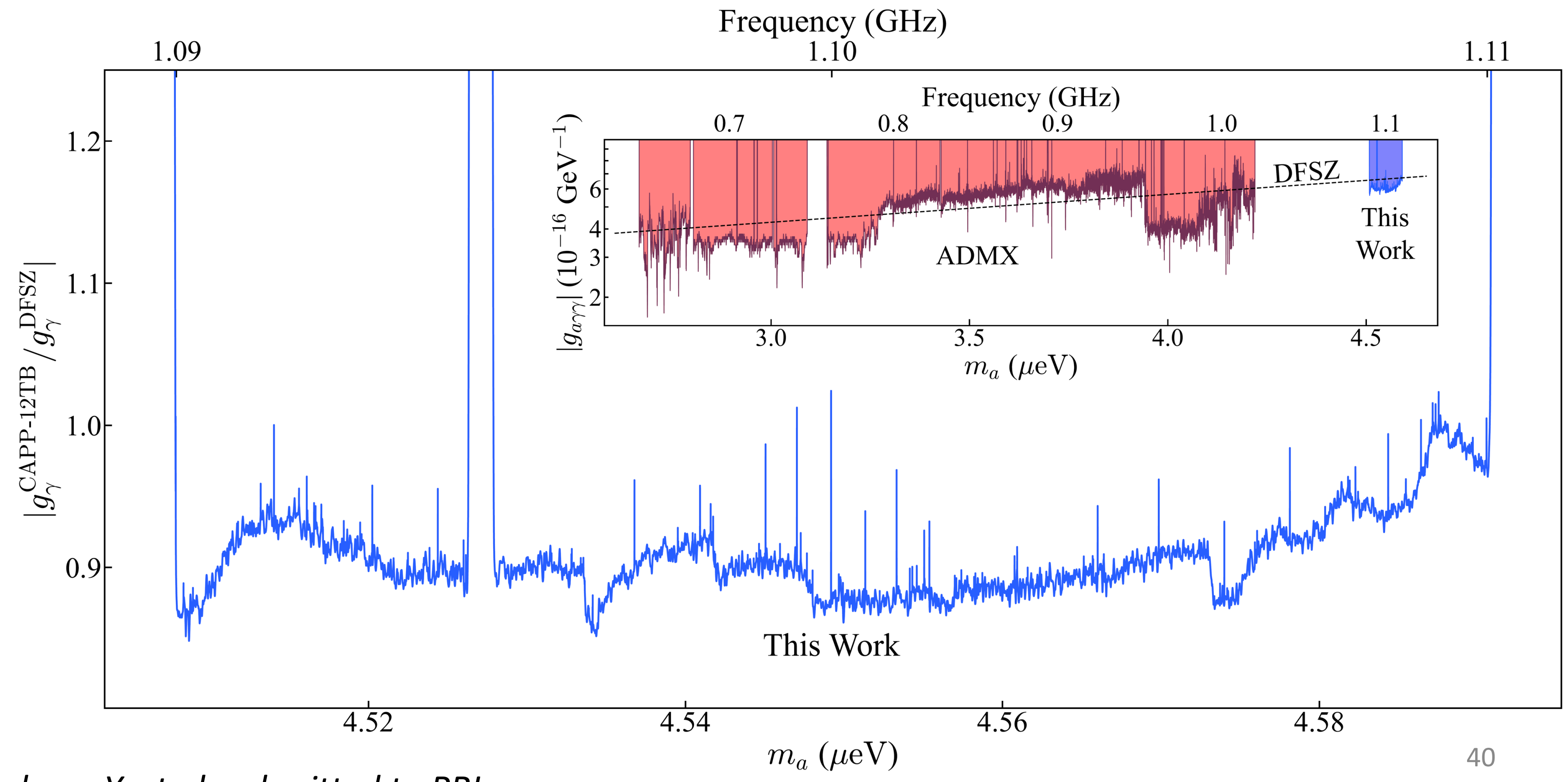
- LTS-12T/320mm, after the heroic job by so many
  - Taking axion dark matter data at DFSZ sensitivity at 1.1 GHz with ~1.4 MHz/day



- In preparation:
- HTS-18T/70mm, with SC cavity, 6 GHz
- BF3, at 7 GHz
- JANIS high Freq. at ~10 GHz

CAPP-12TB RUN4, engineering run, spring 2022

Goal : axion search around 4.55 μeV (1.09 – 1.11 GHz) with DFSZ sensitivity, scanning at 1.4MHz/day



Andrew. Y. et al, submitted to PRL

CAPP-12TB RUN4, engineering run, spring 2022

Andrew. Y. et al, submitted to PRL

DFSZ Axion Dark Matter Search around 4.55 μeV

Andrew K. Yi,[1,2] Saebyeok Ahn,[1,2] Çağlar Kutlu,[1,2] JinMyeong Kim,[1,2] Byeong Rok Ko,[2,*] Boris I. Ivanov,[2] HeeSu Byun,[2] Arjan F. van Loo,[3,4] SeongTae Park,[2] Junu Jeong,[2] Ohjoon Kwon,[2] Yasunobu Nakamura,[3,4] Sergey V. Uchaikin,[2] Jihoon Choi,[2,†] Soohyung Lee,[2] MyeongJae Lee,[2,‡] Yun Chang Shin,[2] Jinsu Kim,[1,2] Doyu Lee,[2,§] Danho Ahn,[1,2] SungJae Bae,[1,2] Jiwon Lee,[1,2] Younggeun Kim,[2] Violeta Gkika,[2] Ki Woong Lee,[2] Seonjeong Oh,[2] Taehyeon Seong,[2] DongMin Kim,[2] Woohyun Chung,[2] Andrei Matlashov,[2] SungWoo Youn,[2] and Yannis K. Semertzidis[2,1]

[1]Dept. of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea
[2]Center for Axion and Precision Physics Research,
Institute for Basic Science, Daejeon 34051, Republic of Korea
[3]RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan
[4]Dept. of Applied Physics, Graduate School of Engineering,
The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan

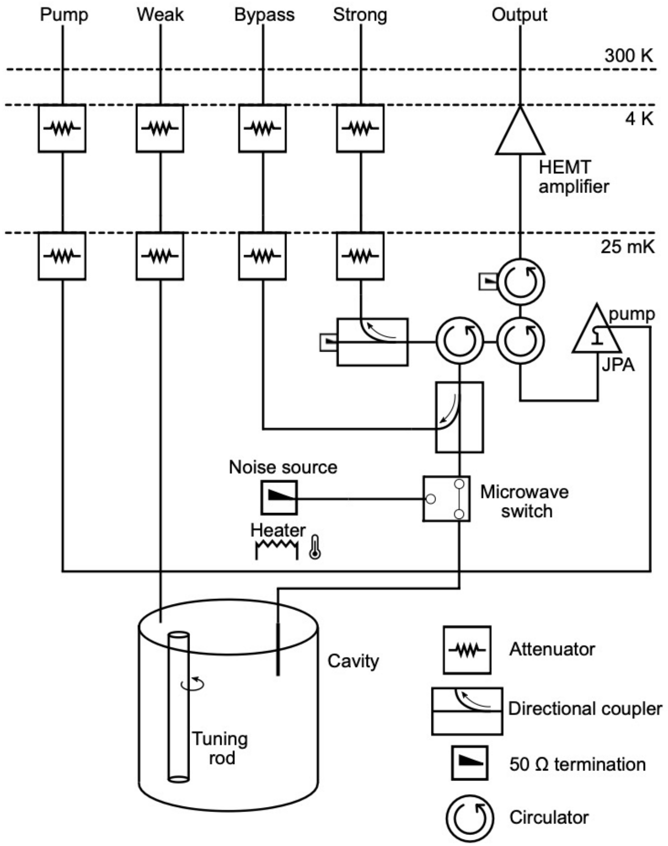
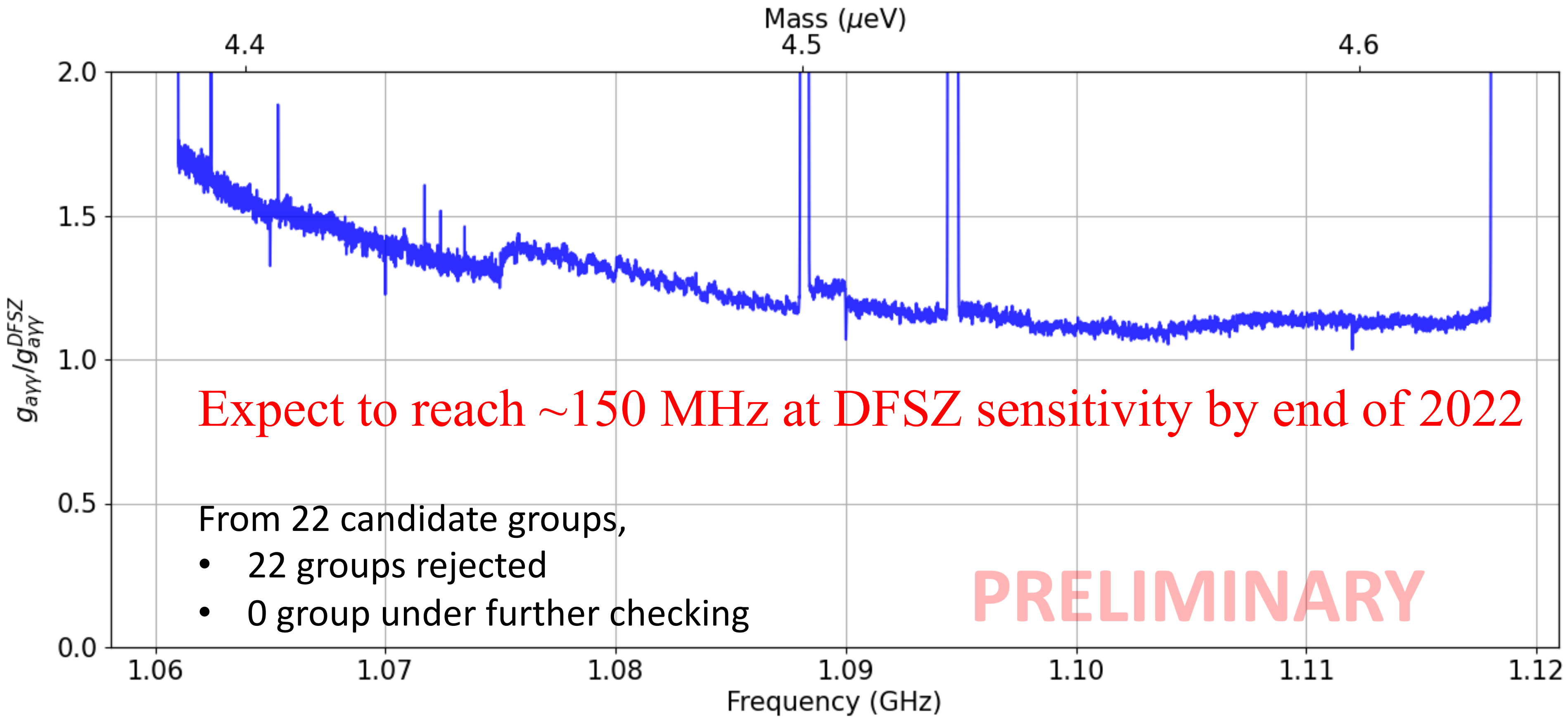


FIG. 2: CAPP-12TB receiver diagram.

New data: CAPP-12TB RUN5C, since September 2022

Achieved already sensitivity (preliminary), scanning at 4MHz/day

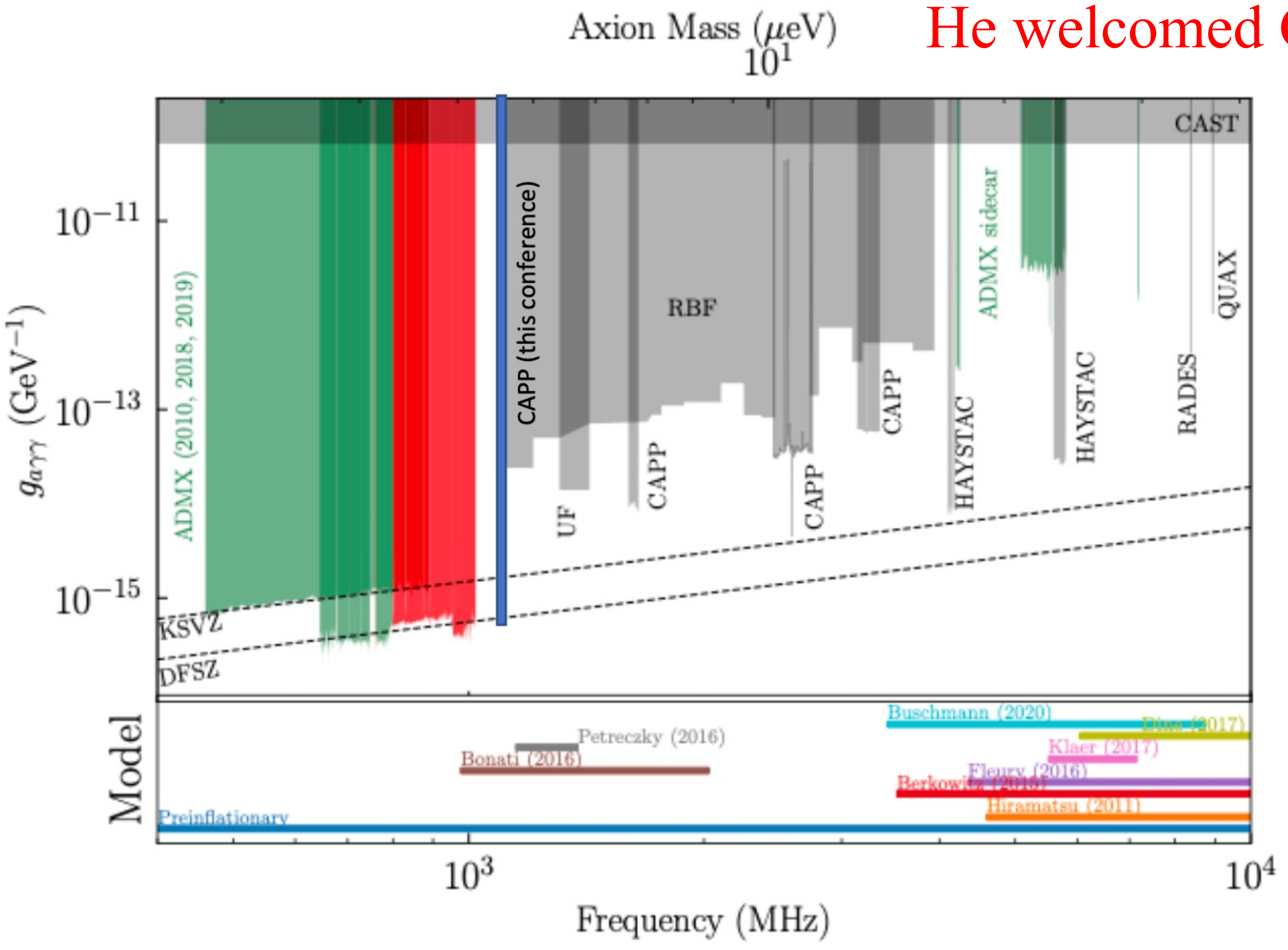


60 MHz

Rybka's slide from Patras, August 2022

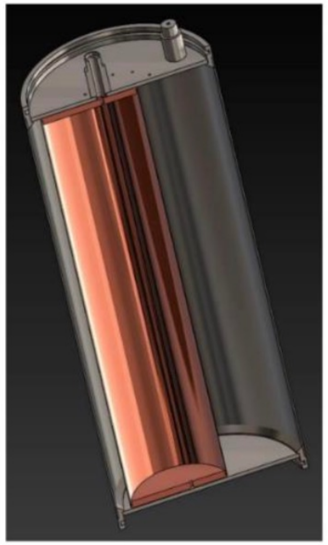
ADMX 2021 Exclusion - Context

He welcomed CAPP to the DFSZ club!

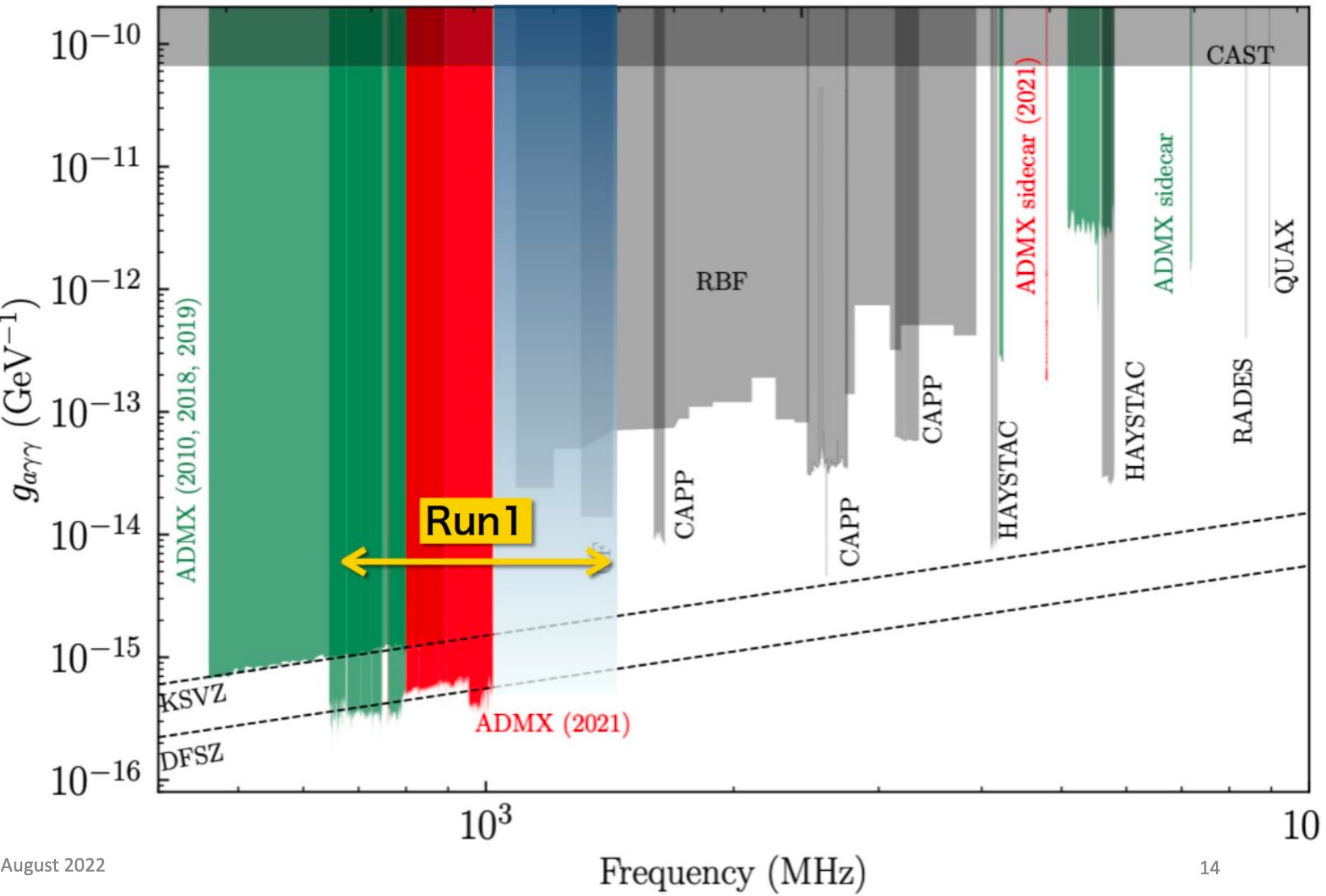


Rybka's slide from Patras, August 2022

Future Plans



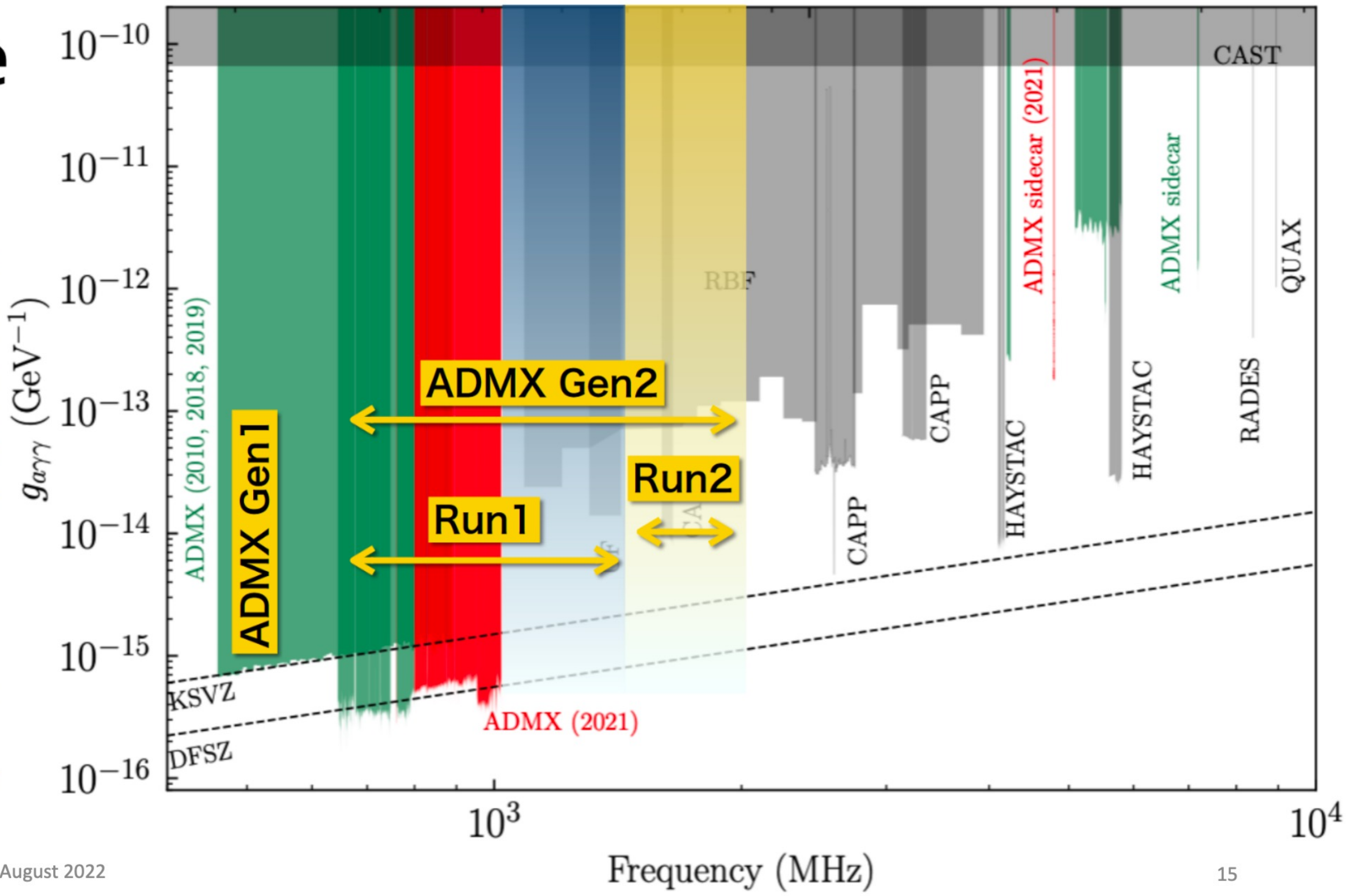
Bigger tuning rod



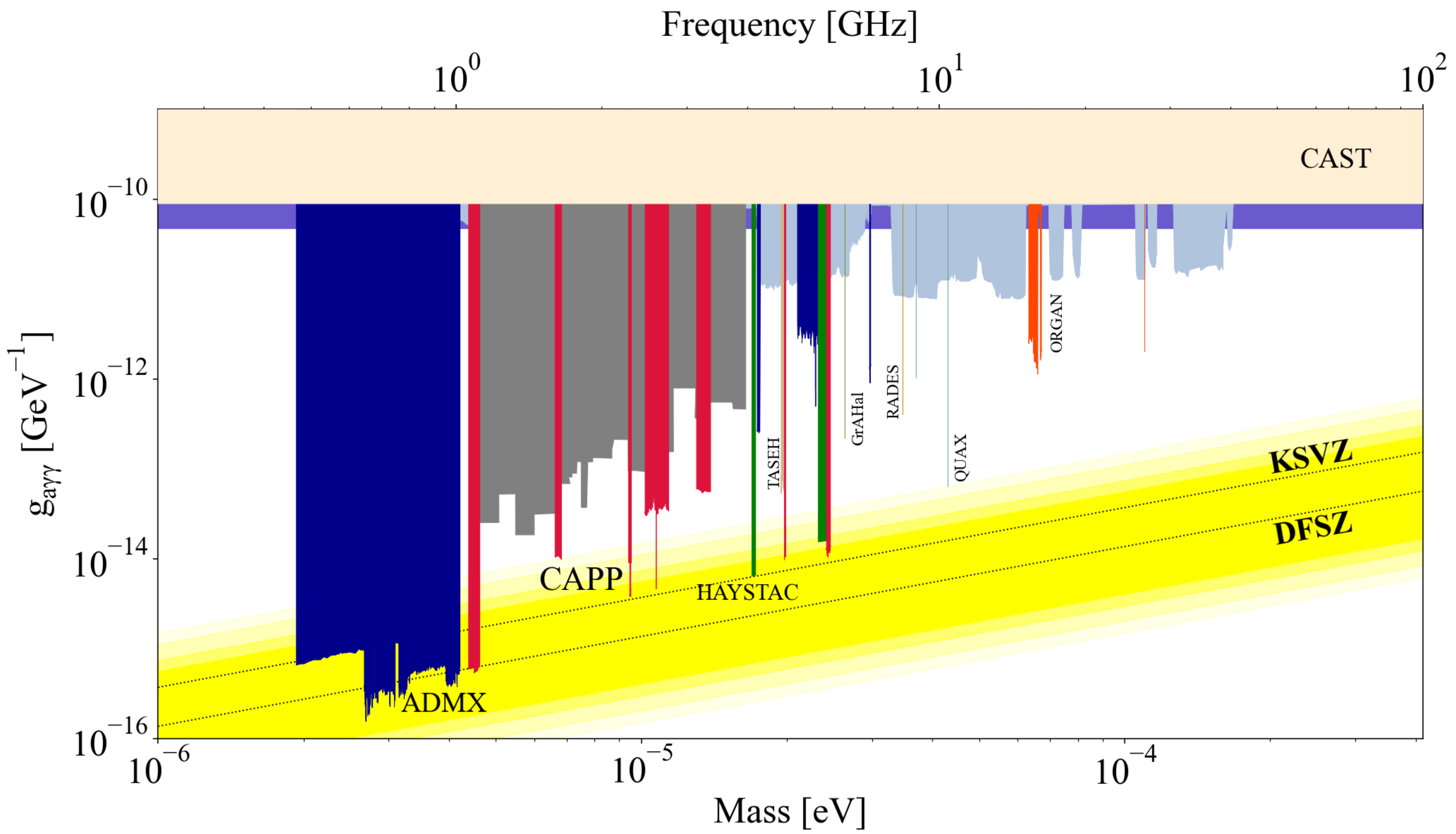
Rybka's slide from Patras, August 2022

Future Plans

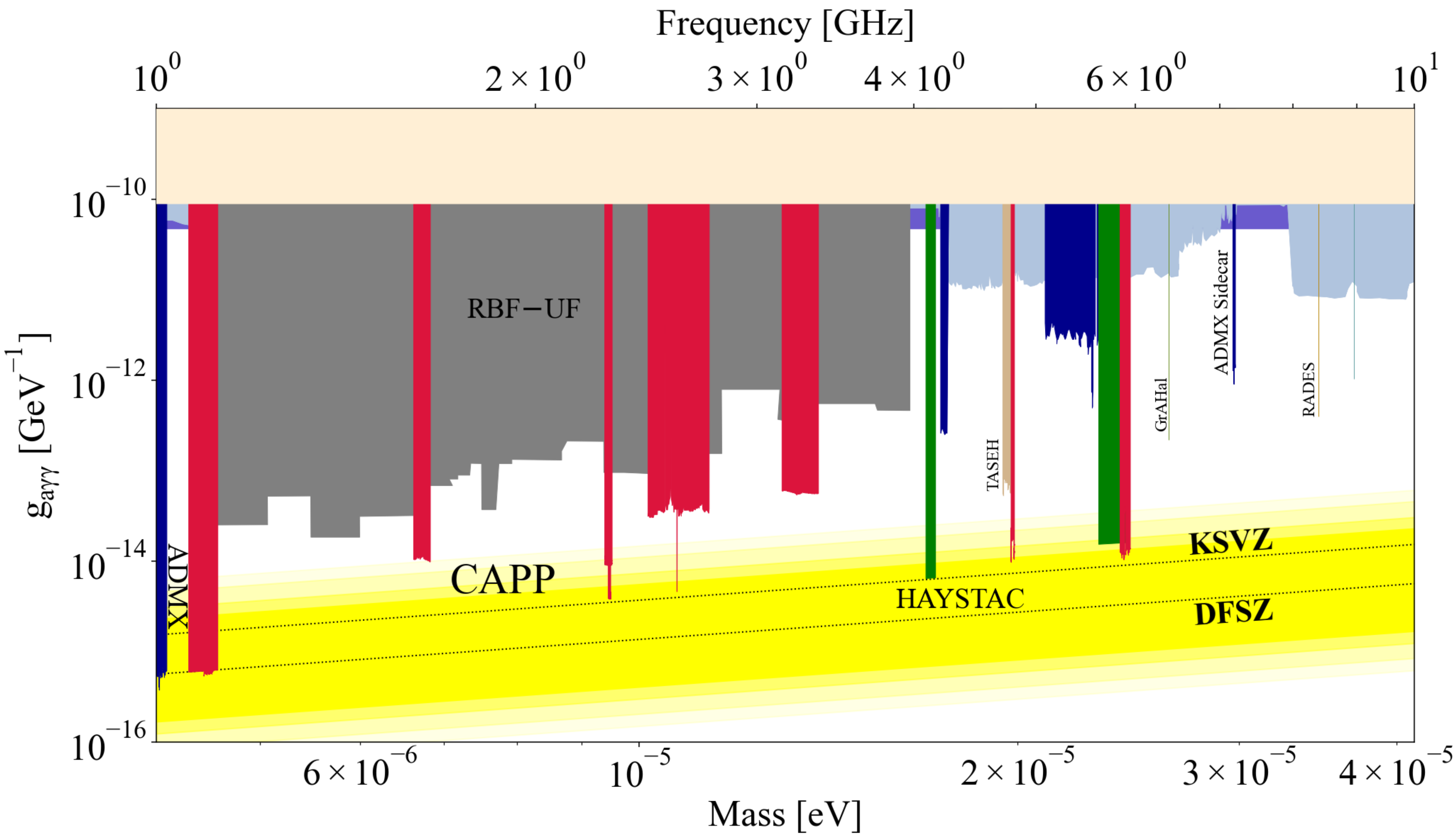
4-cavity array



Our place in the world, CAPP in red, now

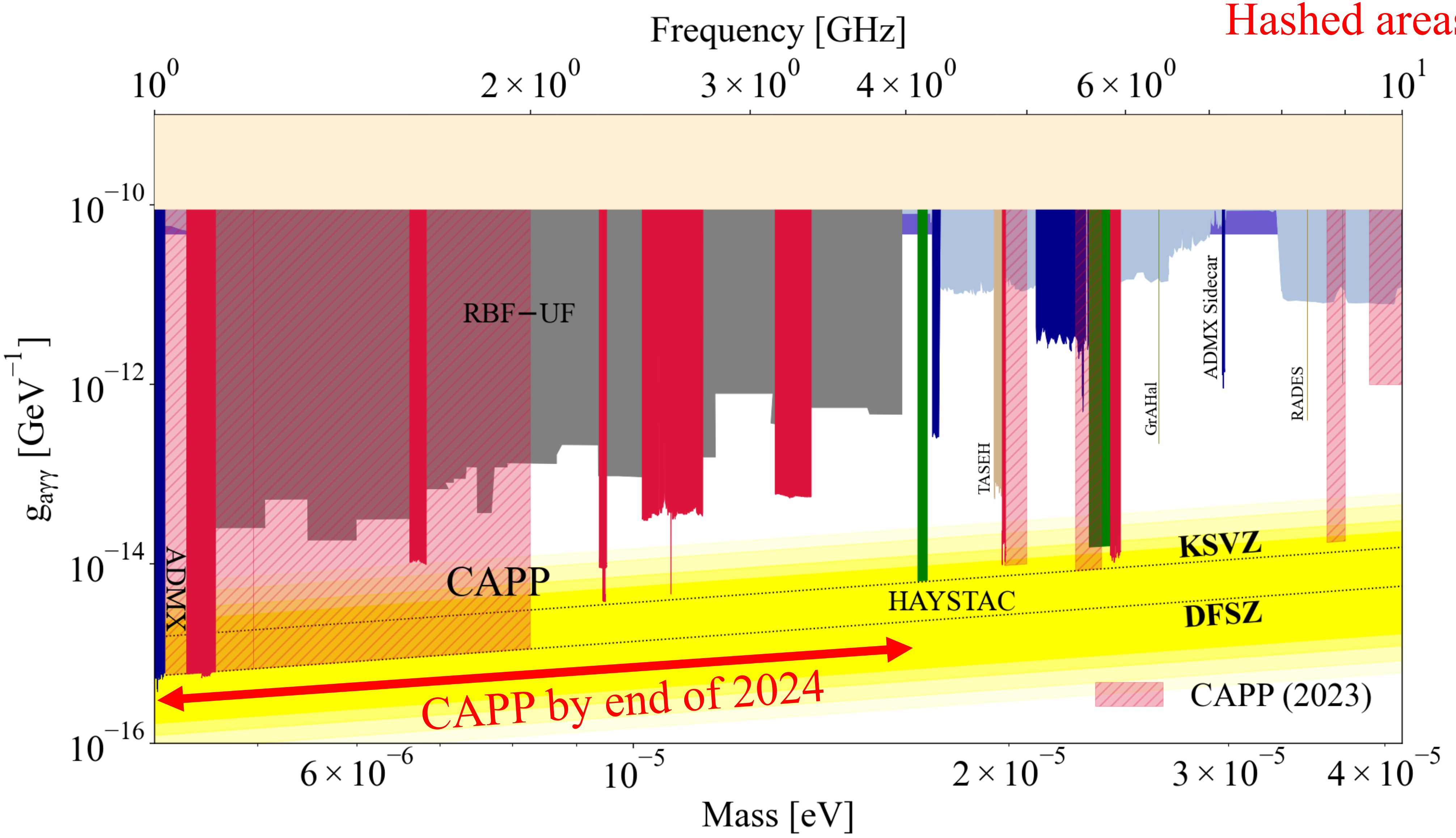


Our place in the world, CAPP in red, now



CAPP's target for 2023, 1-10 GHz

CAPP's scans in solid red
Hashed areas within 2023



Superconducting cavity in large B-field!

YBCO tapes on cavity walls

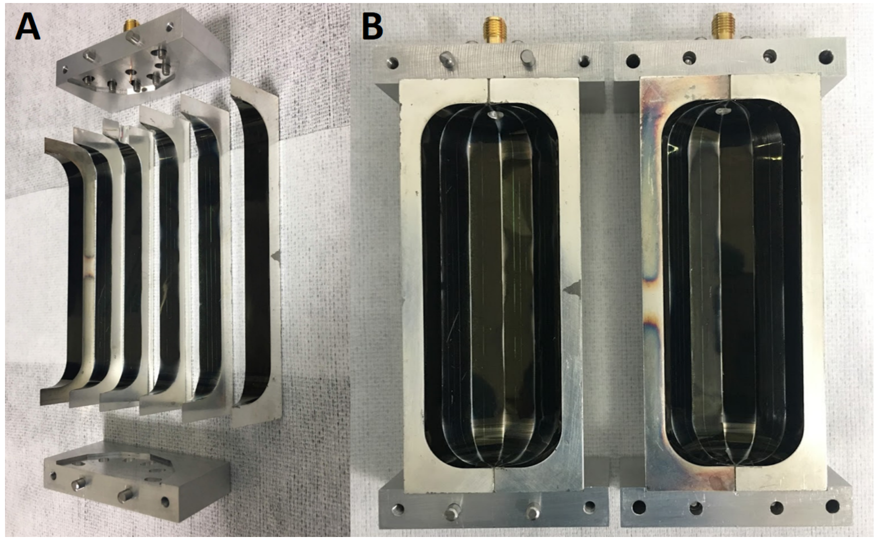
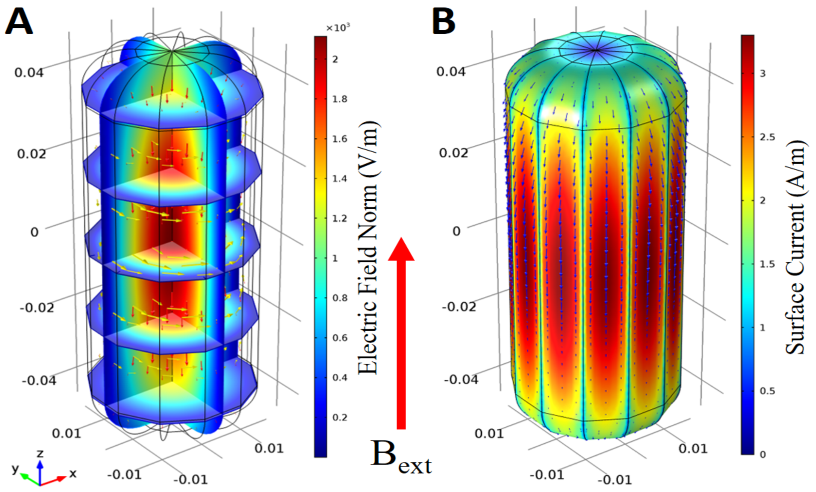


FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

TM_{010} mode



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,‡] Jinhwan Lee,[4] Sung Woo Youn,[2] HeeSu Byun,[2] Dojun Youm,[1] and Yannis K. Semertzidis[1,2]

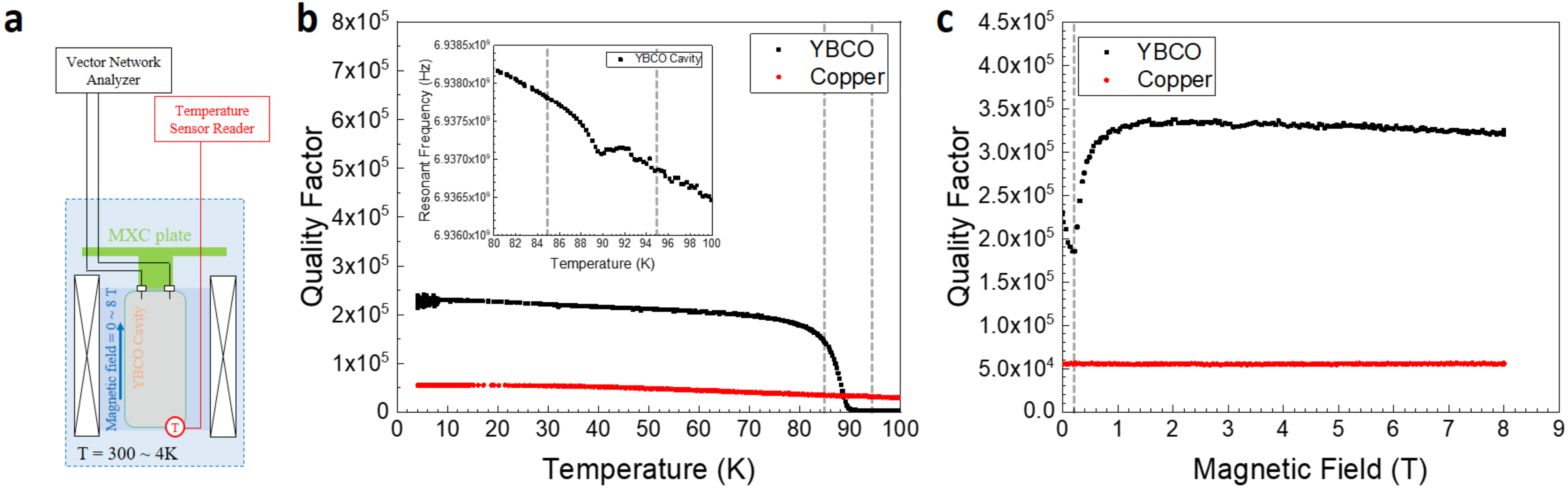
[1] *Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea*

[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*

Superconducting cavity in large B-field!



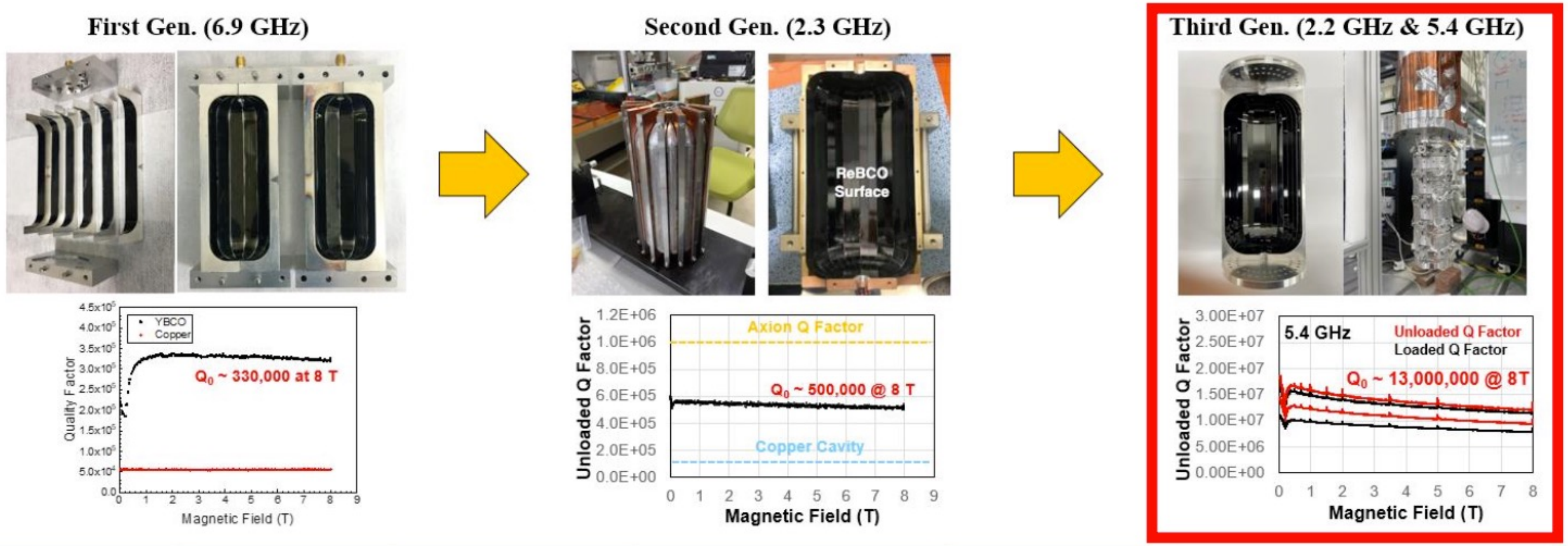
Best in the world!

Phys. Rev. Applied **17**, L061005

Superconducting cavities in large B-field!

Great interest from CERN and FNAL on our results.

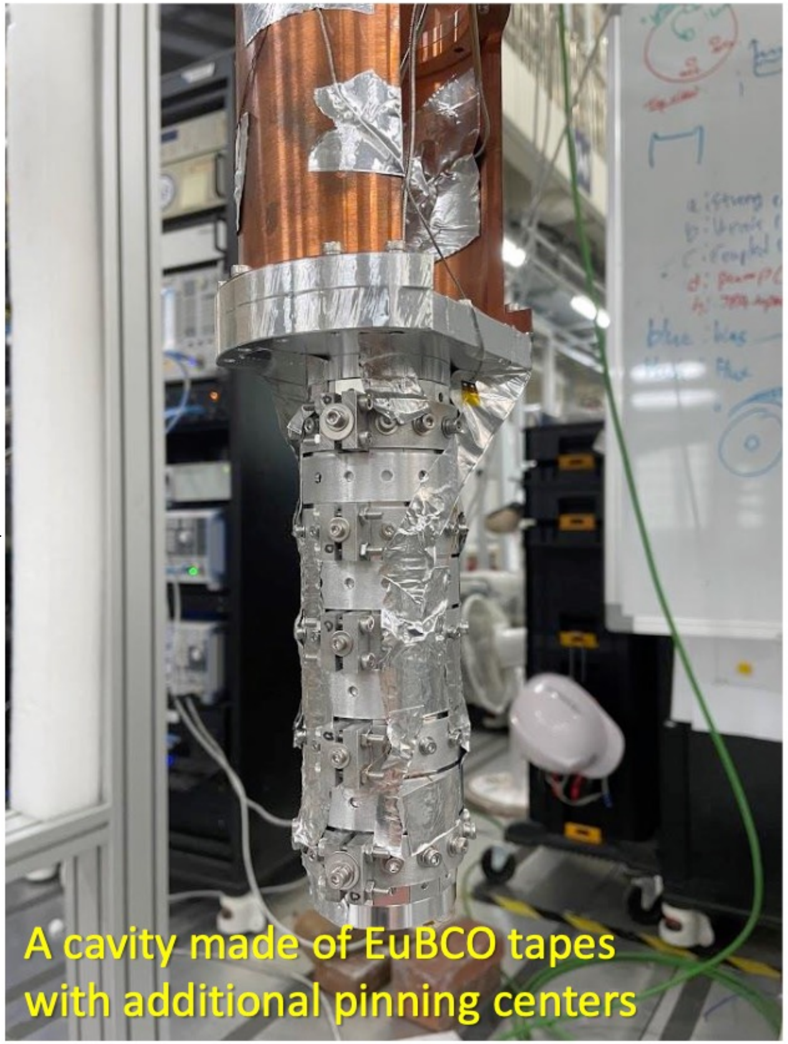
History of HTS Cavity Development @ CAPP

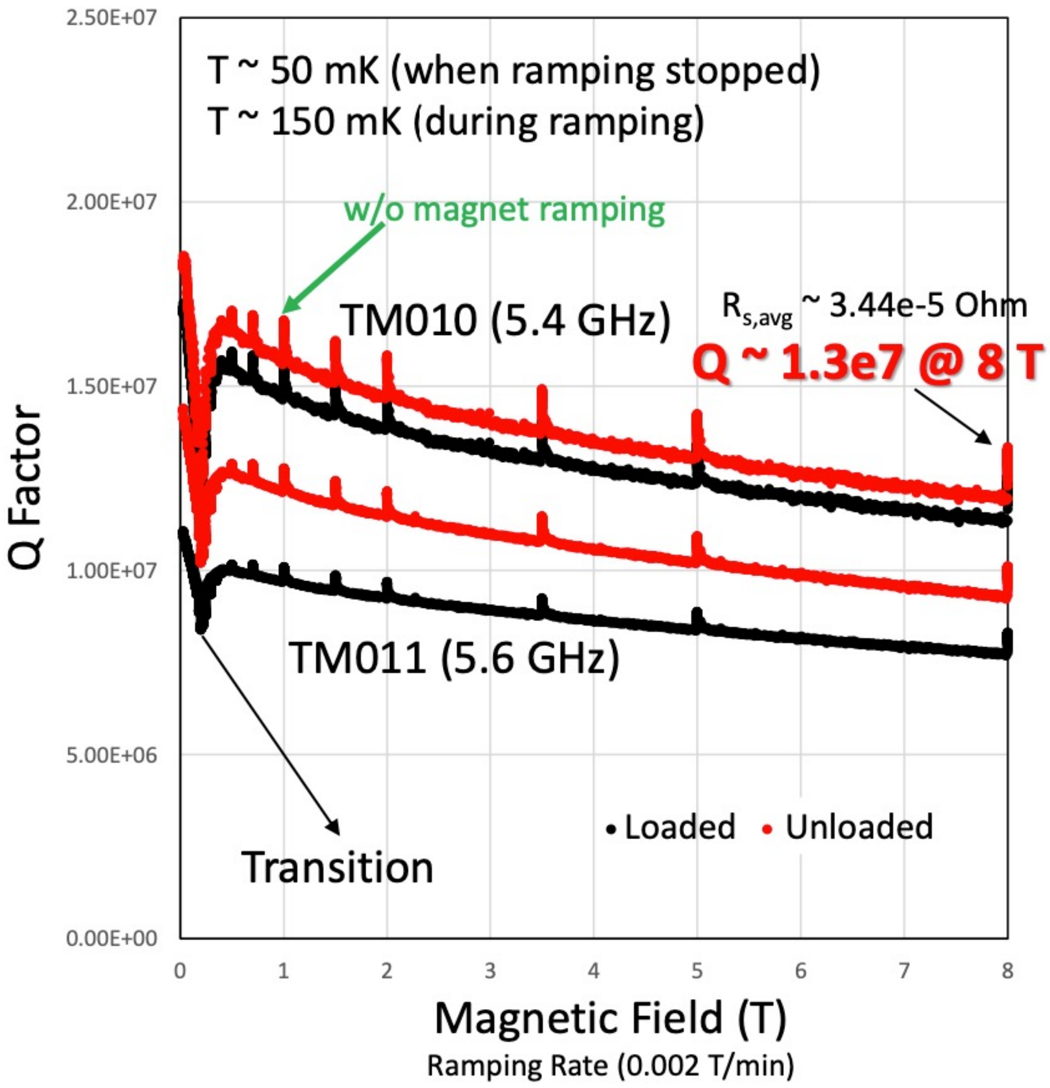


Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Waiting for Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

Superconducting cavity in large B-field!

3rd Generation Cavity using EuBCO Tapes





CAPP plans to make a 36-liter HTS cavity for CAPP-12TB

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 near DFSZ sensitivity in September 2022, at 4 MHz/day

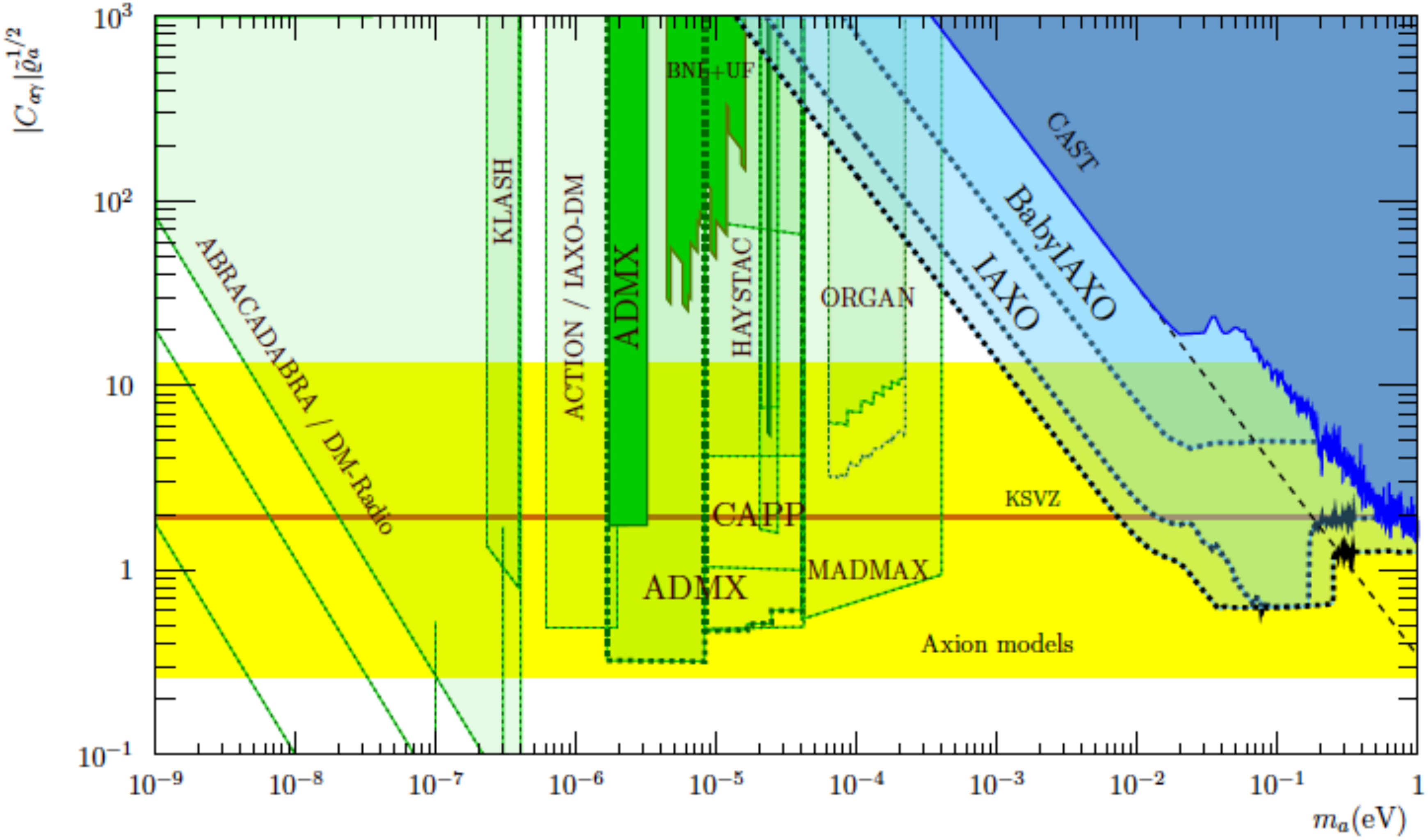
- Target 100 MHz by the end of 2022 at 4 MHz/day and 1 GHz by end of 2023.

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

CAPP's smaller experiments

- Covered 20 MHz near 2.3 GHz at KSVZ sensitivity using an HTS superconducting cavity (Q_0~0.5M) and low-noise JPA, scanning at ~1 MHz/day.
- Covered 100 MHz at KSVZ sensitivity at 5.8 GHz with ~1MHz/day
- Target 0.4-1 GHz/year at KSVZ sensitivity between 4-8 GHz
- Develop prototype experiments for the 8-25 GHz range.

Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

>>100 participants, 12th Patras Workshop on AXIONs, WIMPs, and WISPs, Jeju Island/Korea, 20-24 June 2016.

>150 participants, 17th Patras Workshop on AXIONs, WIMPs, and WISPs, Mainz, Germany, 8-12 August 2022.

Axion dark matter results using an LHC dipole magnet at CERN

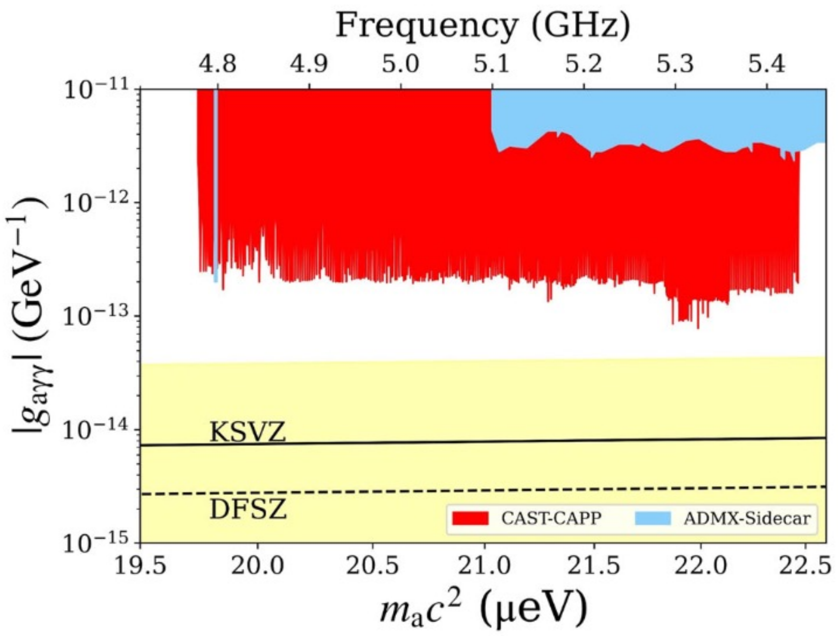


Fig. 5 | CAST-CAPP exclusion limit on the axion-photon coupling as a function of axion mass at 90% confidence level (left), and compared to other axion search results[10,25,30,34–41] within the mass range 1–25 μeV (right). The higher

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

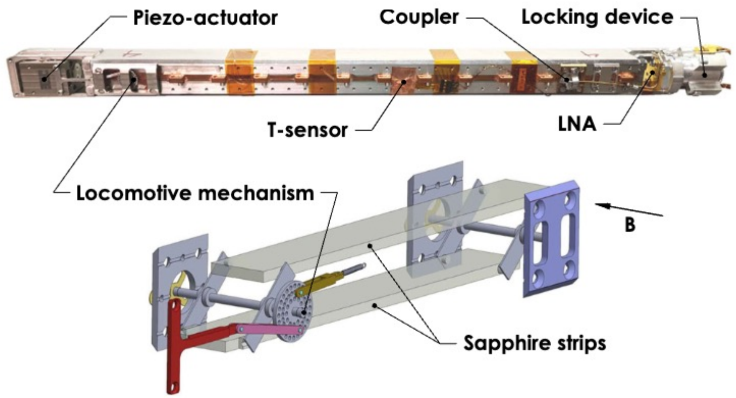


Fig. 1 | A photograph of the elements of a single cavity assembly (top) and a technical drawing of CAST-CAPP tuning mechanism with the two sapphire strips (bottom). The static B-field is shown by the arrow and is parallel to the two axes of the tuning mechanism.

Summary

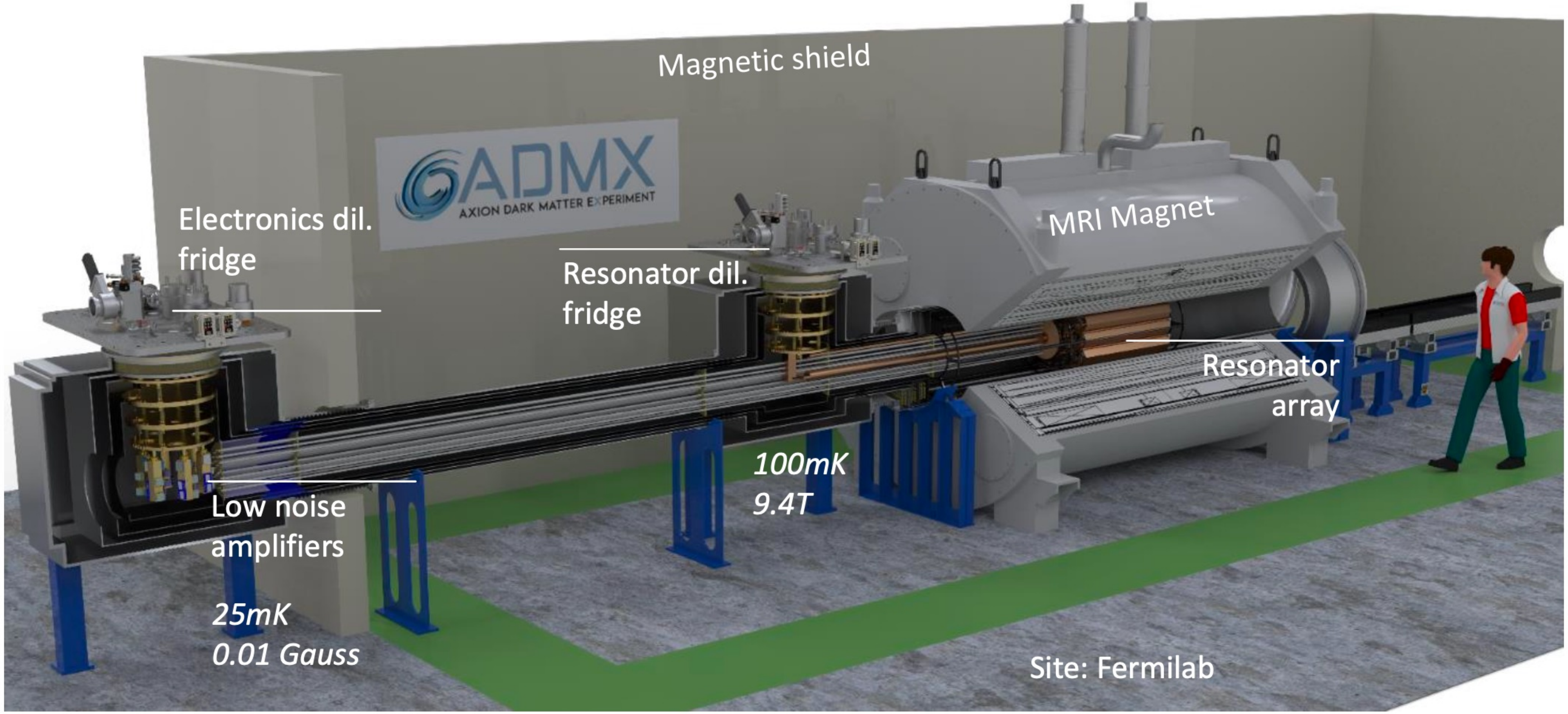
- IBS-CAPP has achieved all its R&D goals and now it’s covering
  - 1-4 GHz axion freq. in the next 2-years (DFSZ)
  - 4-8 GHz within the next 5-years (DFSZ)
  - 8-25 GHz within the next 10 years
- IBS-CAPP proved the original IBS idea correct! The human capacity for innovation is amazing and it is possible to achieve it. We have achieved all our R&D goals!
- The international effort is intensified, promising to cover all the available axion dark matter parameter space within the next 10-20 years.
- Georg, have a great retirement and enjoy life!

Extra slides

Rybka's slide from Patras, August 2022

Proposal to DOE

ADMX-EFR – Design Overview



~ 5 × scan speed of current ADMX

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?

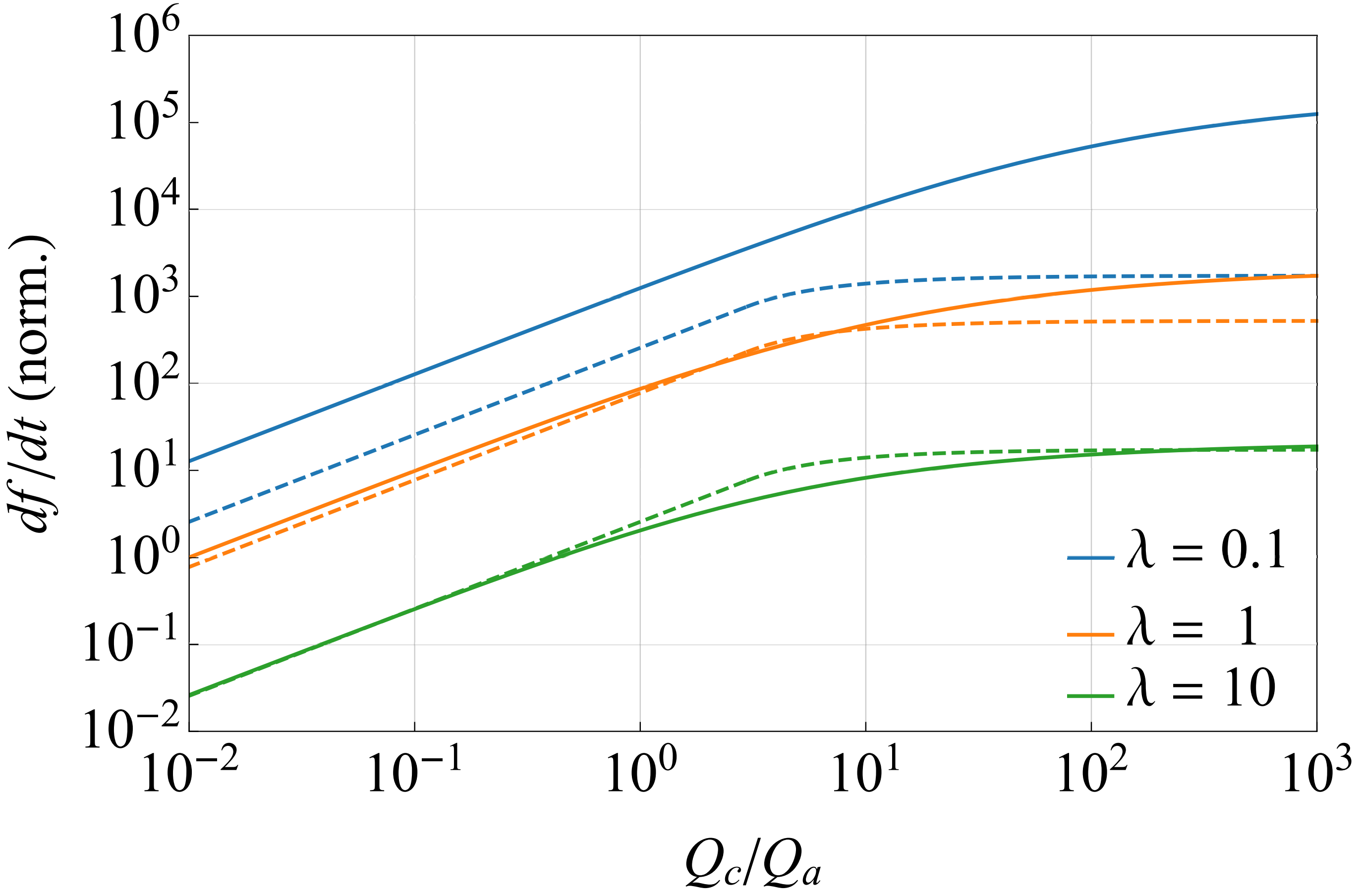


Figure 6. Comparison of the scanning rate between the original (eq. (1.4)) and revised (eq. (5.2)) calculations as a function of normalized cavity quality factor, Q_c/Q_a, for three different values of λ, the relative noise contribution. The former and the latter estimations are represented by dashed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

HTS results from CERN:

Status update: RADES/HTS (input Jessica Golm)

(1) 3 different superconducting cavities realised

HTS tape

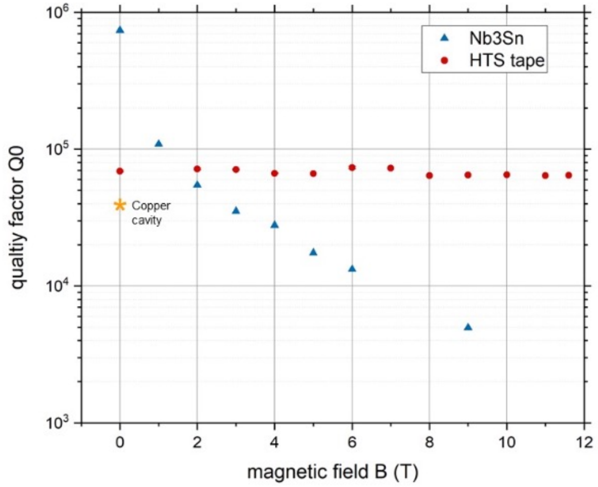
ICMAB
(G. Telles,
N. Lamas,
X. Granados,
T. Puig,
J. Gutierrez)

Nb_3Sn

Coated at
CERN by
G. Rosaz
C. Pereira
Carlos

HTS
coating

Coated by
THEVA and
Ceraco.



(2) HTS tape cavity outperformed the other superconducting and copper coating

(3) ~ 250 h data taking in 11 T magnet with HTS cavity (Q0 of 70000) at 2 K (ARIES at CERN)

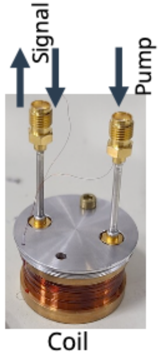
For more details see

'Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter'

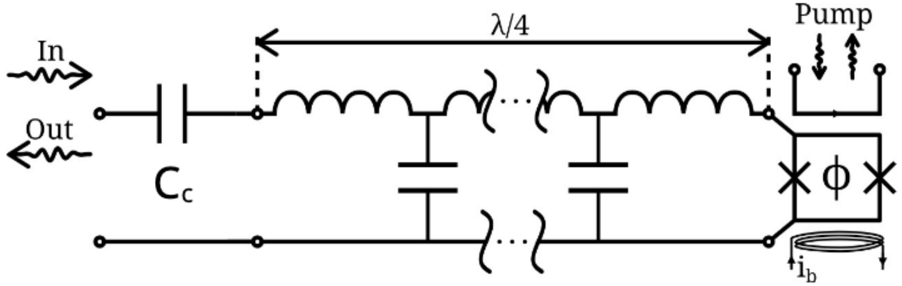
https://arxiv.org/abs/2110.01296

JPA Principle
(Caglar Kutlu's slide)

JPA Principle

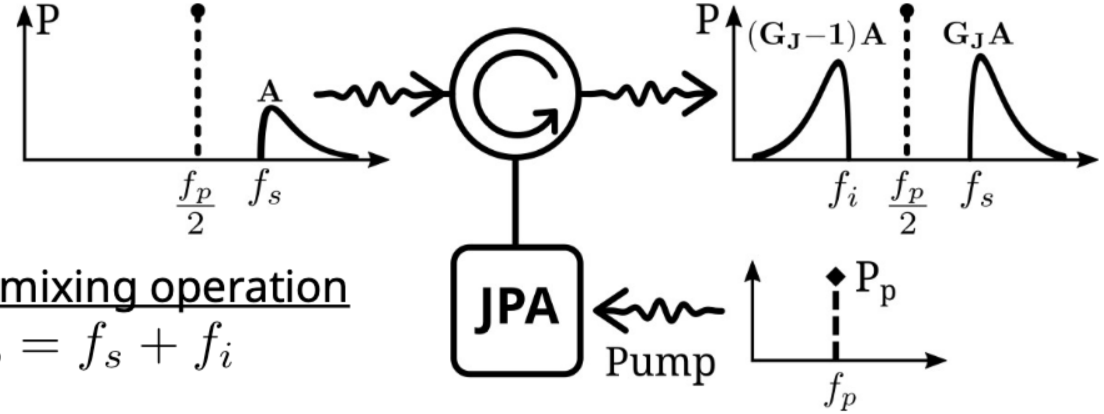


Flux-driven Josephson Parametric Amplifier



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

- 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.



<u>3 wave mixing operation</u>

$$f_p = f_s + f_i$$

[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

CAPP
Center for Axion and Precision Physics Research

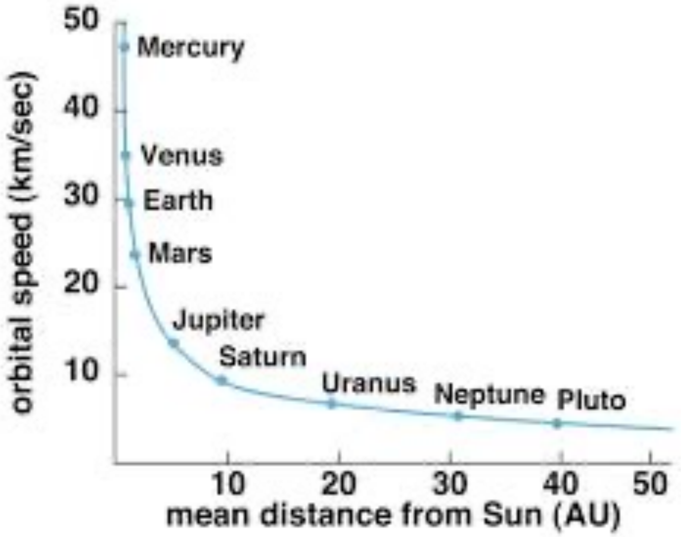
Newton's laws: "observing" the unseen

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

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

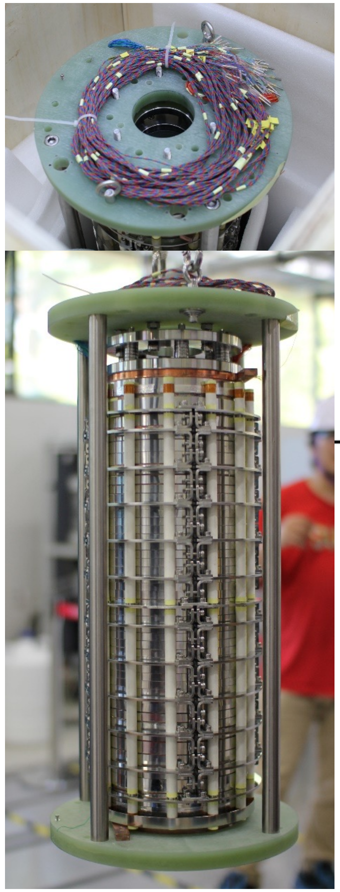
$$v = \sqrt{\left(\frac{GM_\odot}{r}\right)}$$

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

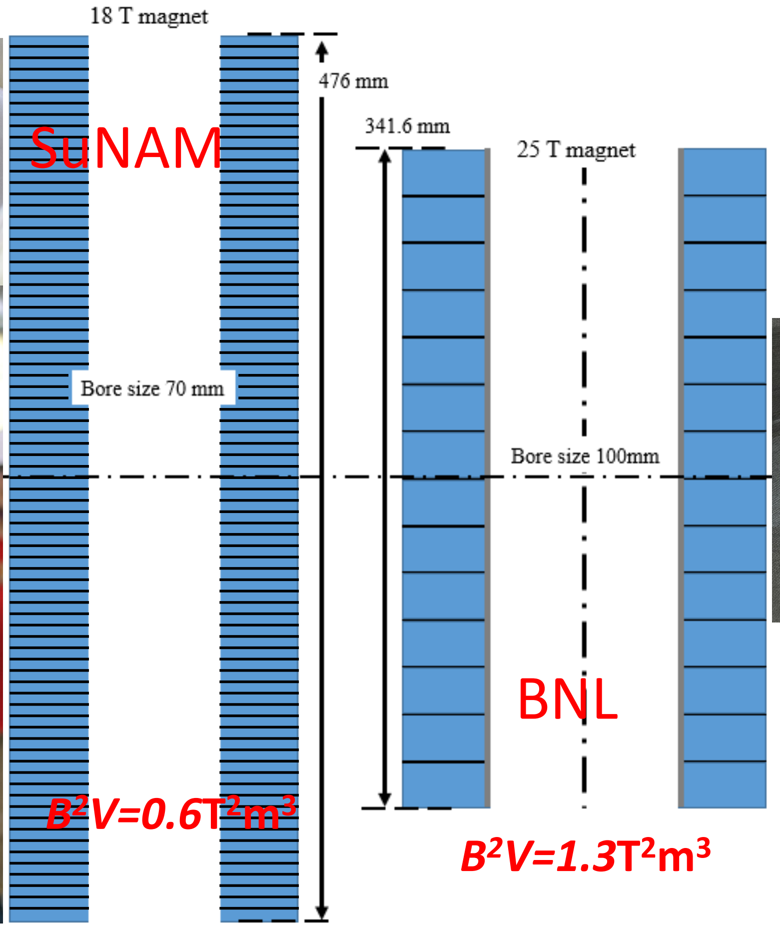


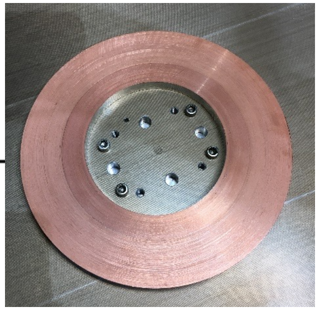
1846, Adams and Le Verrier suggested the existence of Neptune: First discovery of "Dark Matter"

18 T no insulation magnet



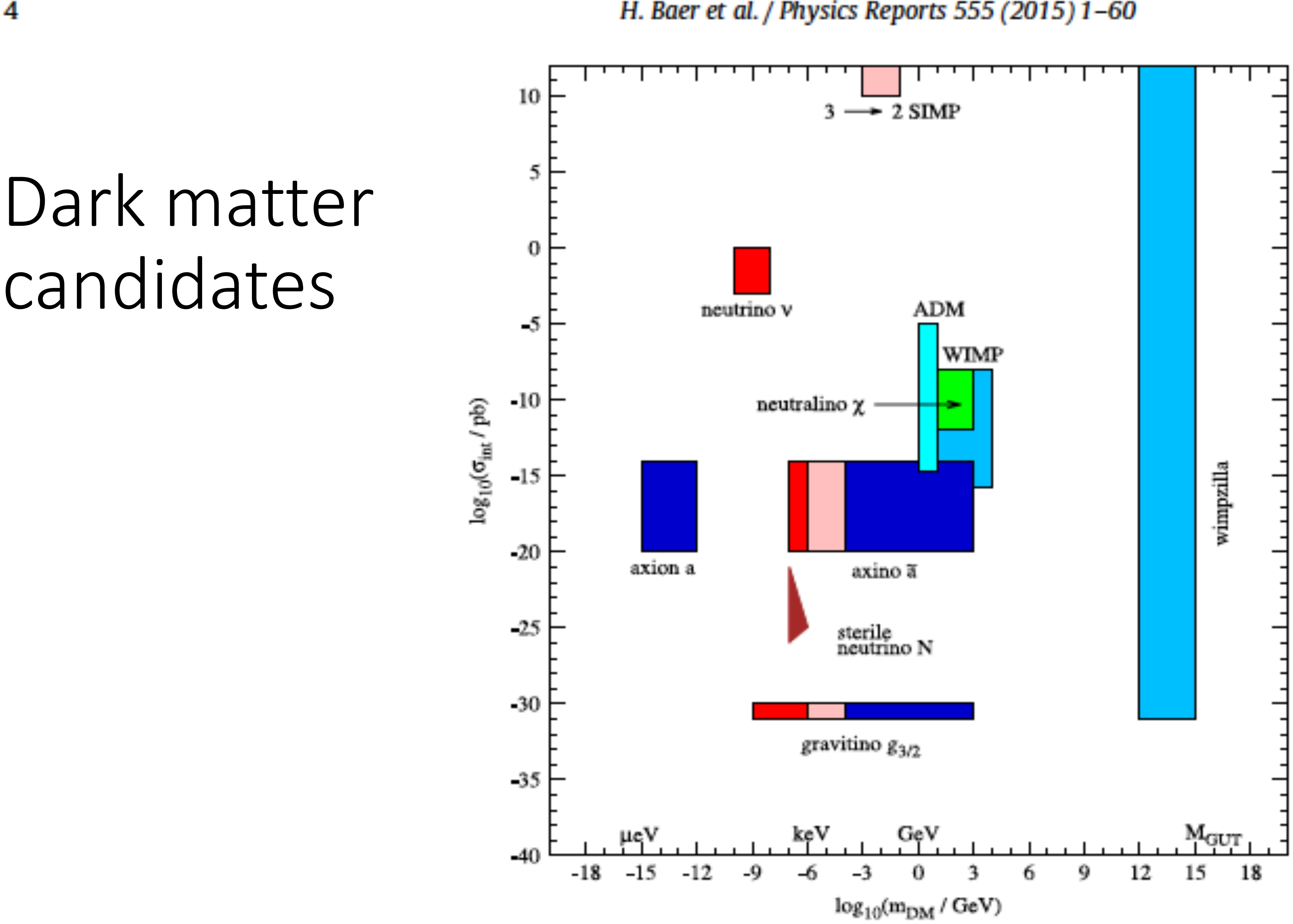
44 double pancake coils



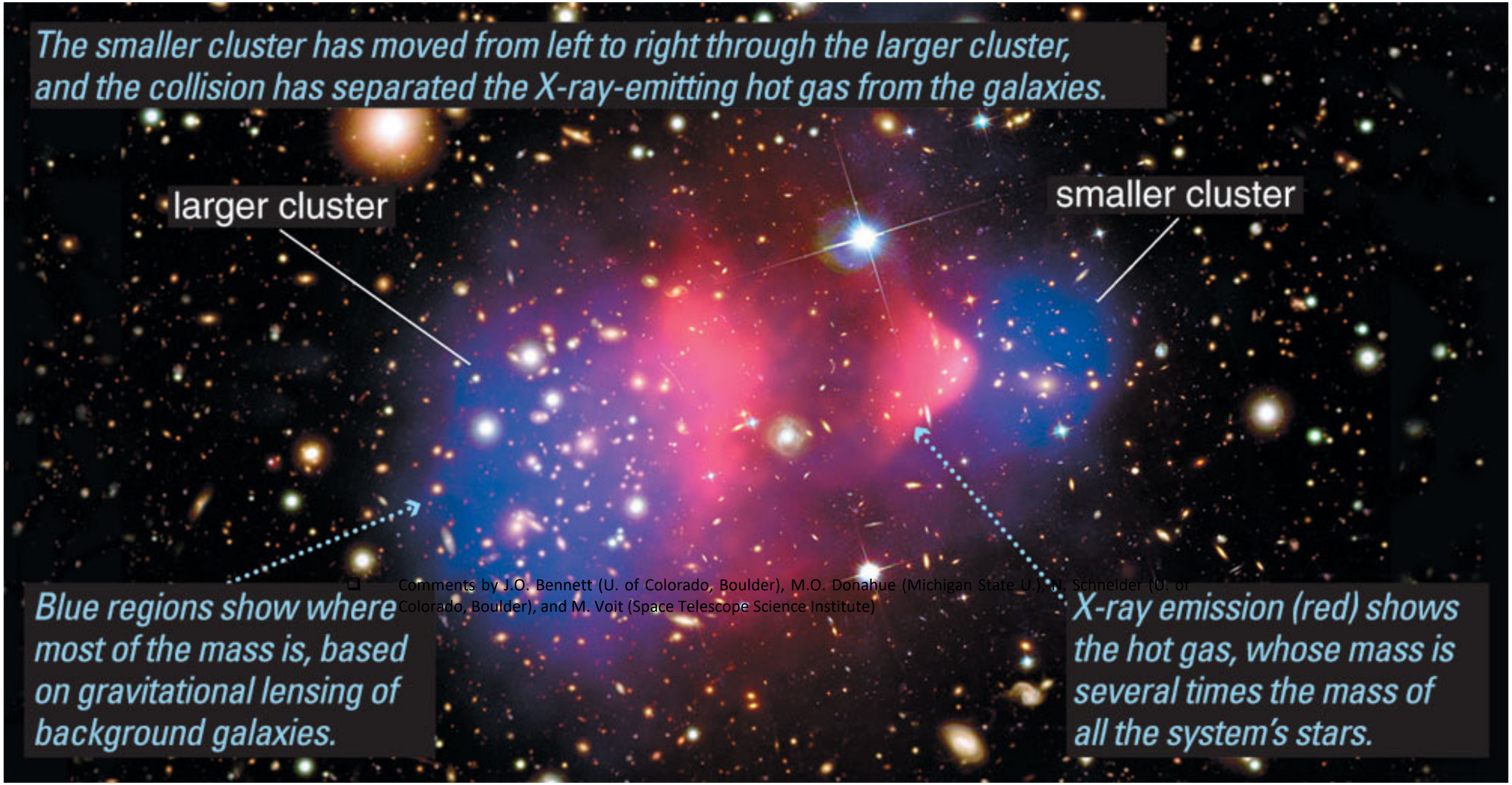


1st coil
for 25 T magnet
1/28

Dark matter candidates



Dark matter: the Bullet Cluster

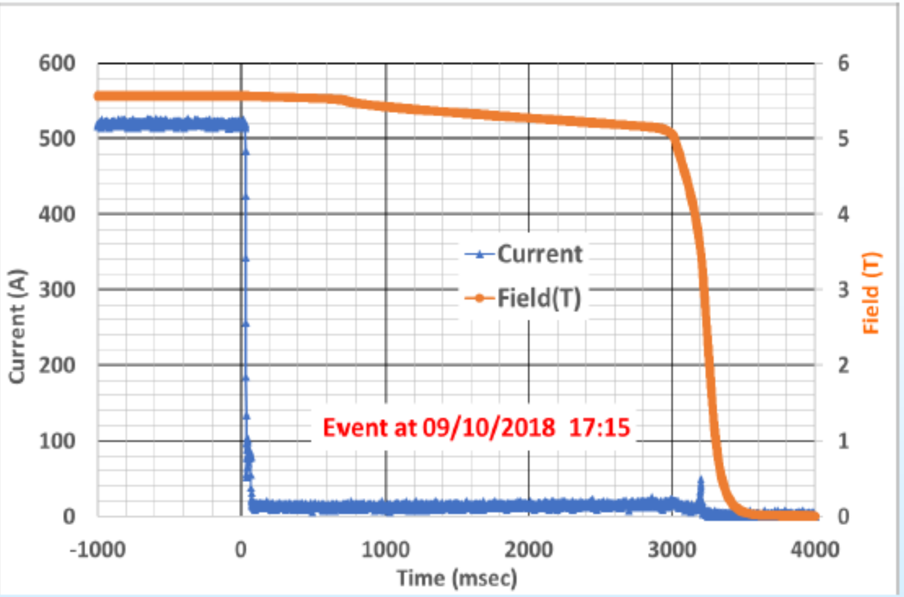


- Comments by J.O. Bennett (U. of Colorado, Boulder), M.O. Donahue (Michigan State U.), N. Schneider (U. of Colorado, Boulder), and M. Voit (Space Telescope Science Institute)

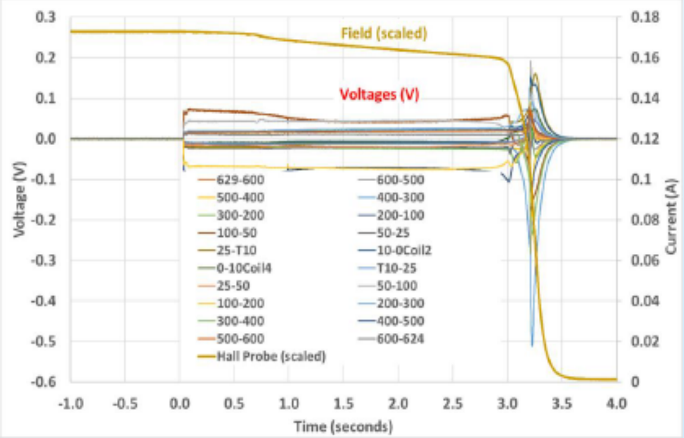
Part of review presentations

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Shut-off Tests in No-insulation Coils (an example @550 A, operating current 450 A)



- No significant energy is extracted during shut-offs or quenches in the no-insulation coils
- Energy is dumped/distributed inside the whole coil with contact resistance between the turns
- Whether coil recovers or runs away depends on how far away it is from critical surface
- Crucial test of inter-connect when it runs-away



550 A example (operating current 450 A):

- Slow internal deposition of energy (3 sec)
- Fast run-away (<0.5 sec), once triggered

This coil recovered (no runaway) up to 400 A

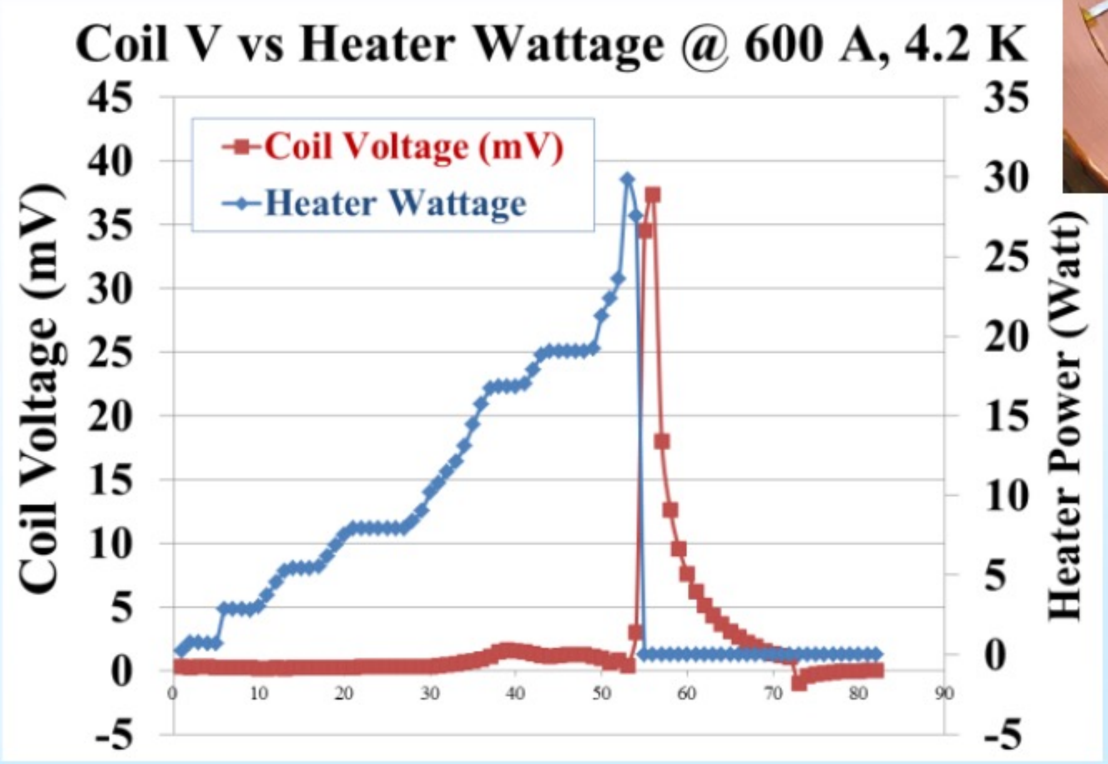
2018 Applied Superconductivity Conference Status of the 25 T, 100 mm HTS Solenoid -Ramesh Gupta, … November 1, 2018 14

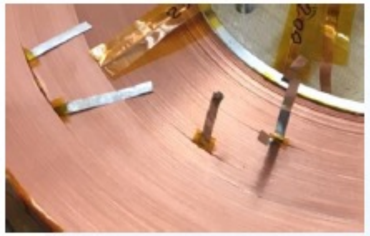
Punishing tests

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Study of Large Local Defects @4.2 K (simulated with heaters up to ~30 W)





No degradation in the coil performance observed

October 22, 2018 25 T Readiness Review Magnet Design and Program Overview -Ramesh Gupta 11

Axion dark matter HTS magnet specs

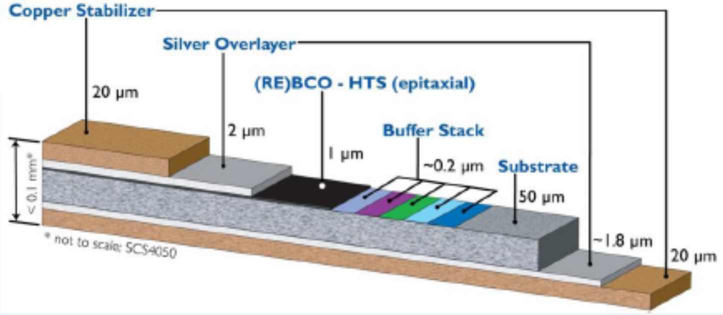
- No Insulation quenches the magnet fast!
- Quenches safely. (Further tests with 3DP, 7DP, 14DP)
- What’s next? Material strength…

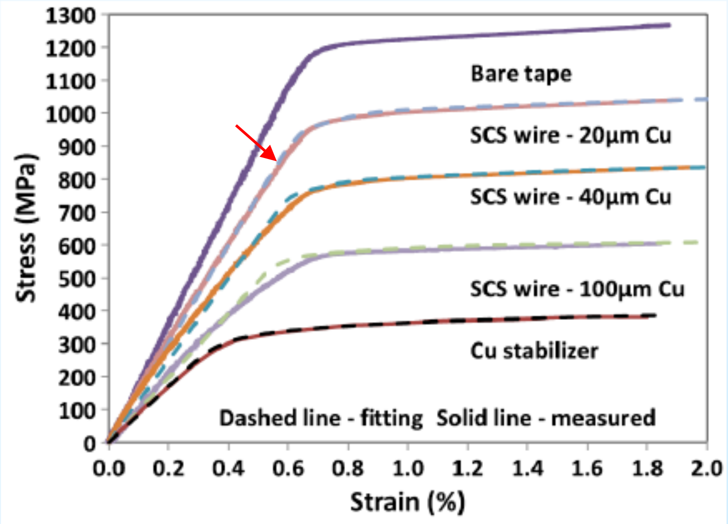
>50% margins

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Choice of Conductor





- Removing insulation increases the current densities in coils
- This creates higher stresses within the coil
- Reducing amount of copper allows us to deal with the higher stresses
- Copper reduced from 40/ 65 microns in SMES to 20 microns in IBS solenoid while keeping the Hastelloy same (50 microns)
- This choice offers >50% margin on hoop stresses

HTS magnet future

- With the new administration at IBS/HQ we need to come up with a plan to finish the project.

- We need support from the community to do this.