Advancements on CAPP's Axion Research

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Center for Axion and Precision Physics Research (CAPP)
Institute for Basic Science (IBS)

19th Patras Workshop on Axions, WIMPs and WISPs

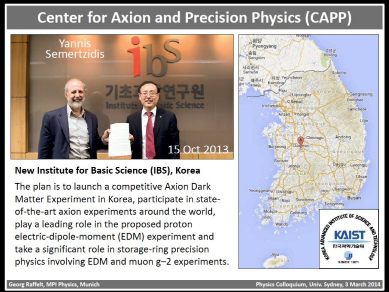
IBS-CAPP in 10 years

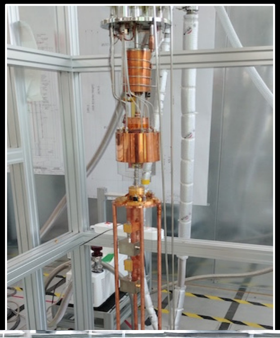
- Last 10 years, CAPP has grown to be one of the best axion search facilities in the world
  - CAPP-MAX: the most sensitive axion experiment (when NT is right…)
- Whole axion community has grown much more than before
- However, there are “WIDE” range of frequencies waiting to be explored. If you want to do it in your lifetime, you need serious R&Ds (Improvements/Innovations)
  - Powerful, big bore Magnet
  - Quantum noise-limited JPA / Single Photon Detector
  - HTS superconducting cavities
  - Higher frequency w/o sacrificing volume
- CAPP is phasing out at the end of 2024
  - We may continue in other form, which we don’t know yet

CAPP's First 10 years…

ibs Institute for Basic Science
CAPP
Center for Axion and Precision Physics Research

Founded in 2013 (Oct16th.)





2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

- Procuring equipment, testing cavities, cryo-RF @KAIST (2014–2016)
- Constructing 7 LVPs @KAIST Munji campus (2016–2023)
- BF3 & BF4 installed (2016)
- BF5 & BF6 installed (2017)
- Janis (He³) installed (2019)
- 12T Oxford Magnet & Leiden installed (2020–2021)

Collecting Axion DM Physics Data

- CAPP-PACE-HEMT
- CAPP-PACE-JPA
- CAPP-PACE-JPA-6cell
- CAPP-PACE-JPA-SC
- CAPP-PACE-SHeT-SC
- CAPP-8TB-HEMT
- CAPP-8TB-JPA-8cell
- CAPP-8TB-AQN-SC
- CAPP-HF-2cell
- CAPP-12TB-commissioning
- CAPP-12TB-JPA
- CAPP-12T-HF-JPA-3cell

CAPP's First 10 years…

Founded in 2013 (Oct16th.)


Center for Axion and Precision Physics (CAPP)

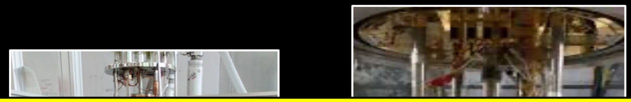
Yannis Semertzidis

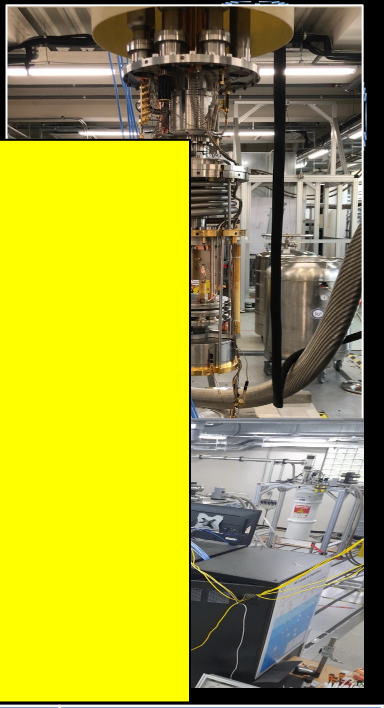
15 Oct 2013

New Institute for Basic Science (IBS), Korea

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.

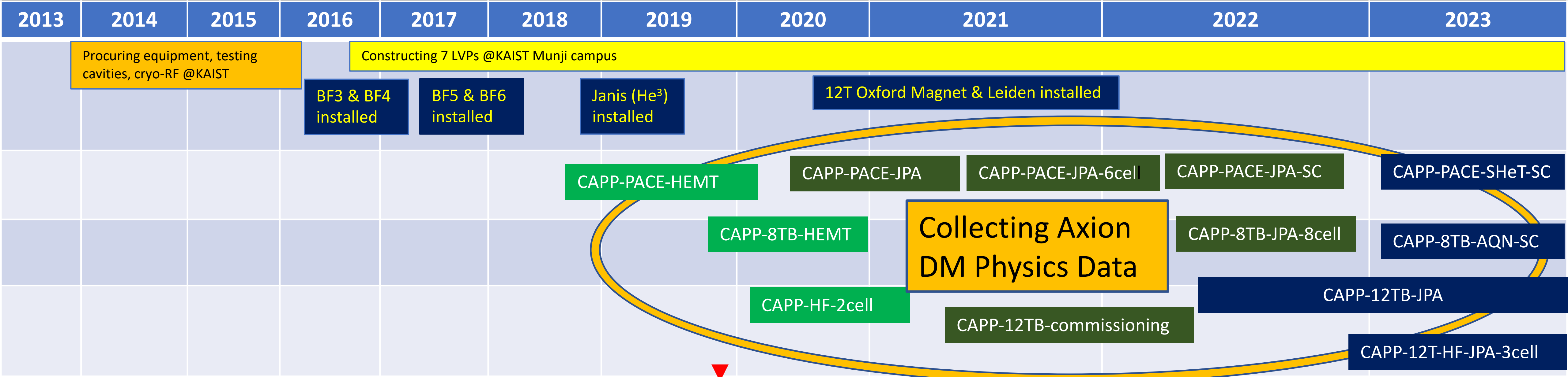
Georg Raffelt, MPI Physics, Munich



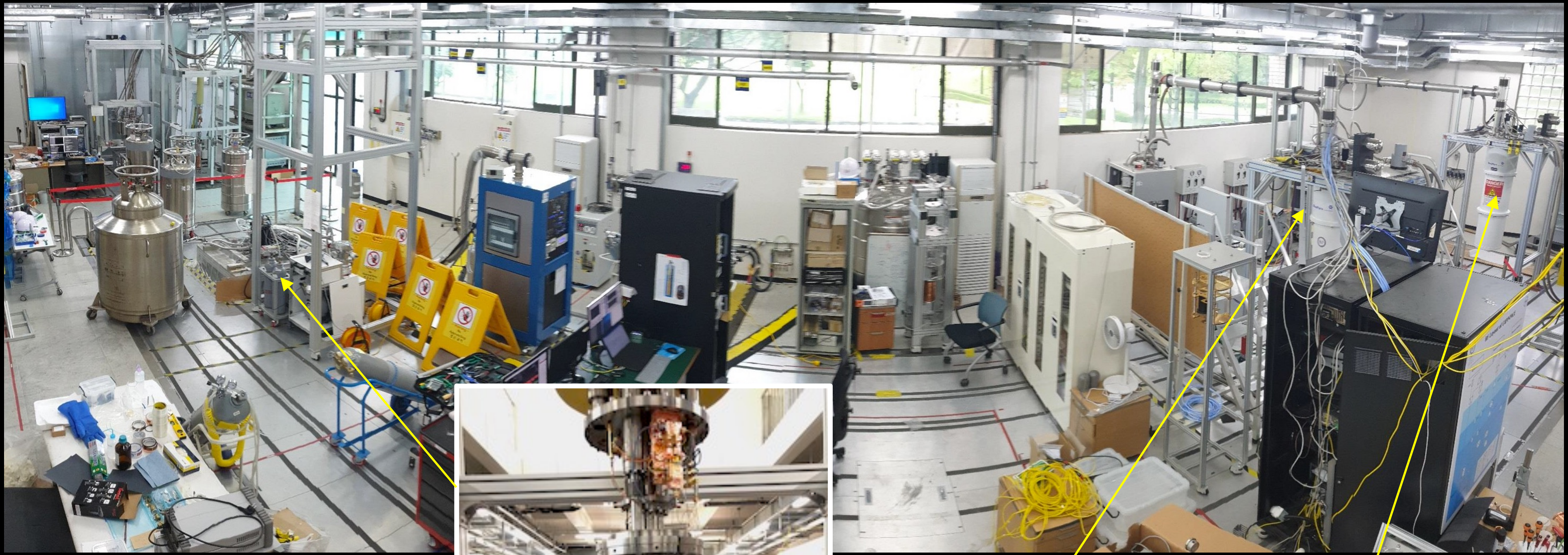


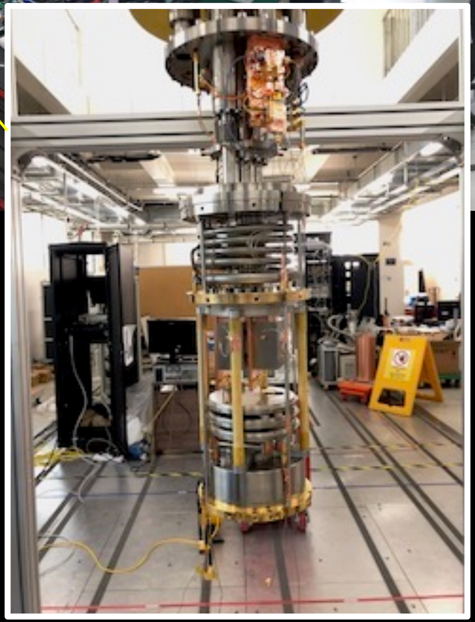
2016: Dilution Fridges installation (w/ LVP)
2018: First Axion DM Data
2020: First Axion DM Data w/ JPA
2022: First Axion DM Data w/ JPA + SC cavity
2022: First Axion DM Data w/ JPA (DFSZ sensitivity)

Now: Four Axion DM Exps are running…



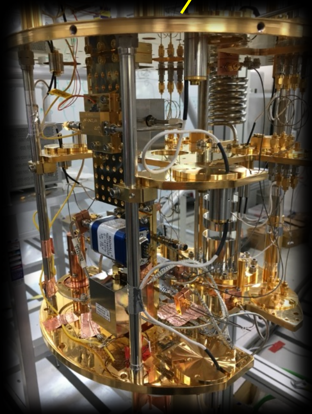
CAPP Experimental Hall (LVP)





CAPP-HF

CAPP-MAX



CAPP-HeSC

CAPP-AQN

Status of CULTASK at CAPP

Refrigerators						SC Magnets					Experiments		
Vendor	Model	BaseT	Power	Type	Install	B field	Bore	Mat.	Vendor	Install	Exp.	Status	Freq (GHz)
Leiden	DRS1000	10 mK	1.3mW@120mK	wet	2020	12T	32cm	Nb_3Sn	Oxford	2020	CAPP-MAX	Running	1.0~1.5
BlueFors (BF3)	LD400	10 mK	580uW@100mK	dry	2016	12T	10cm	Nb_3Sn	AMI	2021	CAPP-HF	Running	4.0~10.0
BlueFors (BF4)	LD400	10 mK	580uW@100mK	dry	2016						CAPP-QNA	Testing	JPA test
BlueFors (BF5)	LD400	10 mK	580uW@100mK	dry	2017	8T	12cm	NbTi	AMI	2016	CAPP-PACE	Running	2.0~3.0 (5.6-5.9)
BlueFors (BF6)	LD400	10 mK	580uW@100mK	dry	2017	8T	16.5cm	NbTi	AMI	2017	CAPP-8TB	Running	1.5~2.0 (5.8-6.0)
Janis	He3	300 mK	25uW@300mK	wet	2017	9T	12cm	NbTi	Cryo-Magnetics	2017	CAPP-HF	Installing	3.5~4.5 (~10.0)
Oxford	Kelvinox	30 mK	400uW@120mK	wet	2017	18T	7cm	GdBCO	SuNAM	2017	CAPP-18T	upgrading	4.5~6.0

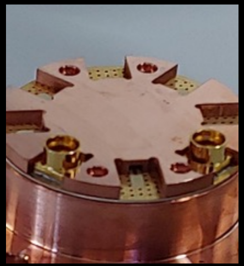
Axion Detection Scheme: Haloscope

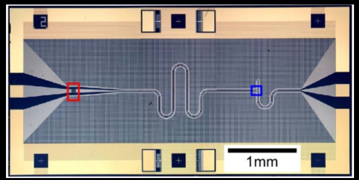
P. Sikivie's Haloscope:

$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

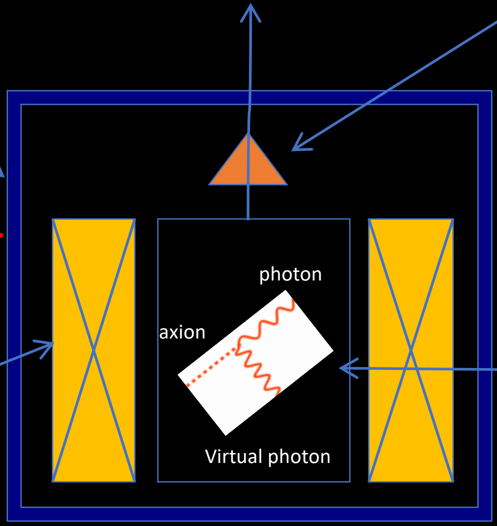
Cryogenics (<40mK)
Dilution Refrigerators

Quantum Amplifier
SQUID and/or JPA (T_N ~ SQL)

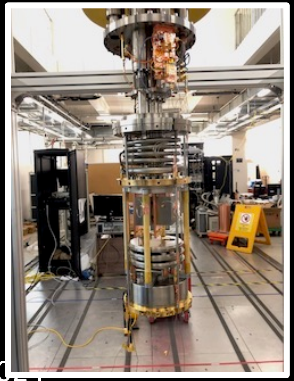




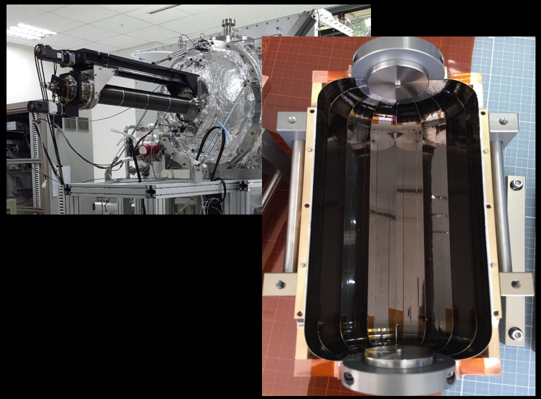
To RF Receiver



High Field & Big bore Magnet
12T LTS Big Bore SC Magnet



High Q Tunable Cavity
Superconducting tapes

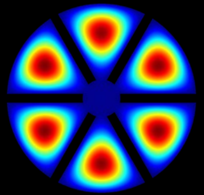


How much can you improve?

- Maximize Signal (B^2VQ)
  - 12T 32cm bore LTS magnet by Oxford — > x100 faster scan (than 8T-10cm)
  - Improve Q-factor of cavity – SC cavity — x10-100 faster scan than Cu

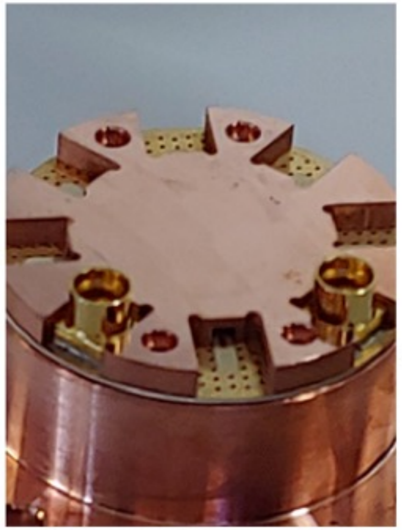
- Minimize Noise ($T_{system} = T_{physical} + T_{amp}$) — ~ x50 faster scan compared to HEMTs
  - Quantum noise-limited amplifier – JPA
  - Optimize cryo-RF receiver chain (SQL)
  - Single photon detector in the future (esp. for high freq.)

- Higher frequencies without sacrificing volume
  - Pizza Cavity
  - Dielectric rings (TM_{030} and TM_{050})
  - Photonic cell cavity
  - Meta material + Superfluid LHe tuning



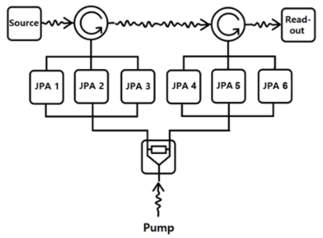
Quantum Noise-Limited Amp (S. Uchaikin)

- Collaboration with Nakamura's group (U. of Tokyo, RIKEN)
  - > 200 JPA chips delivered (1.0 – 6.0) GHz (4 batches) + Packaged at CAPP
  - 1.0 GHz
    - DAQ running ~ 1.0 GHz data in CAPP-MAX (DFSZ)
  - 2.3 GHz
    - Excellent Noise Temperature (close to SQL) ~120 mK
    - Completed taking axion dark matter physics data around 2.3 GHz
  - 6.0 GHz
    - Wider bandwidth: ~ MHz (covers ~ 300 MHz of frequencies)
    - Taken 5.5-6.0 GHz physics data using 6 & 8 cell Pizza Cavity (two DRs)
    - Shows excellent NT: ~ 250 mK
  - 6 JPAs bundled to give wider coverage
- Wideband (1~15 GHz) TJWPA (INFN) and TWJPA (Lancaster)
- Single photon detector for higher frequency in progress
  - Collaboration with Aalto U., INFN and U. of Hamberg



- Quantum-limited noise
- Noise Squeezing
- $T_N \leq$ 167 mK @5.6 GHz
- SQL at 5.6GHz 260 mK

Split-band (Dulcimer) Amplifier (up to 6 JPAs)

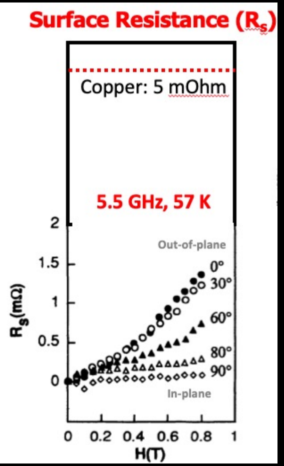


Uchaikin S.V. et al. Front. Phys., v.12-2024
https://doi.org/10.3389/fphy.2024.1437680

HTS Superconducting Cavity (OJ Kwon)

- SC Resonant Cavity in Axion Haloscope Exp.
  - ✓ Could improve axion to photon conversion power: enhancing scanning speed (> x10)
  - ✓ Requirement: should sustain high enough Q-factor in high magnetic field (up to 43 T?)

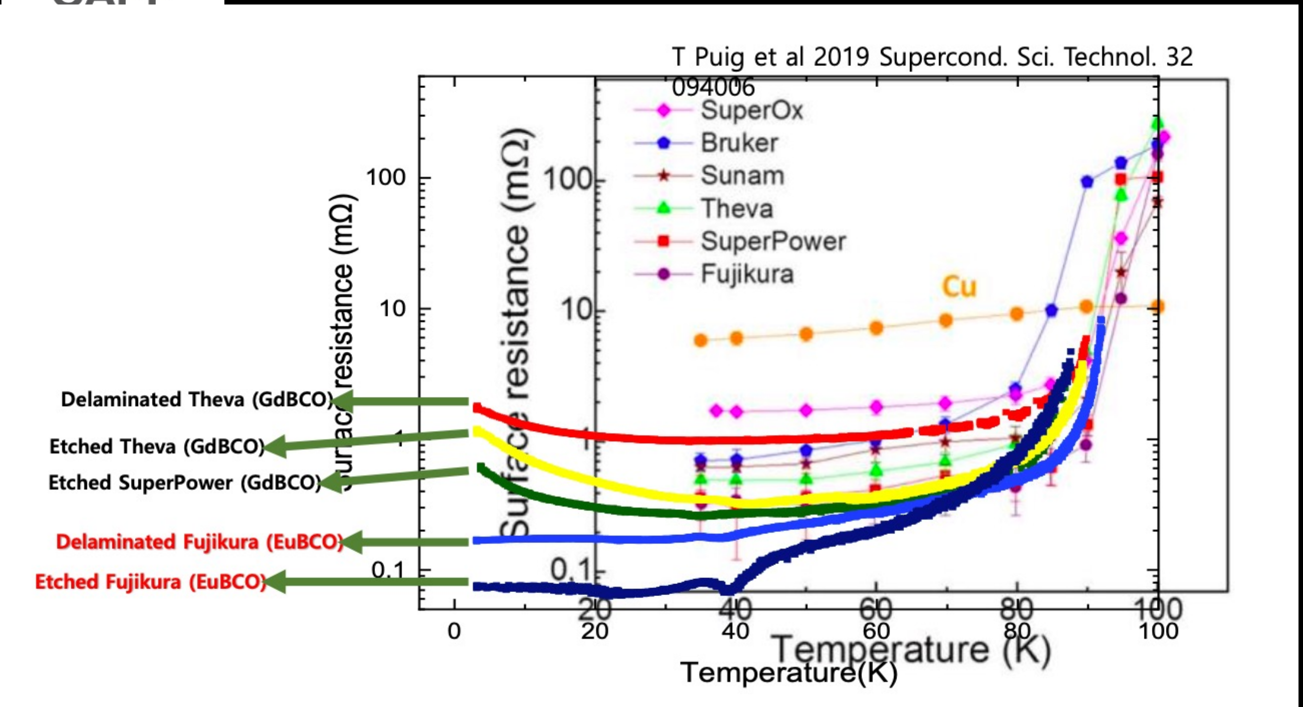
- Choice of SC at CAPP: well-known ReBCO
  - ✓ Reasonably low surface resistance
  - ✓ Very high Hc2 (~100 T) and high depinning frequency (~100 GHz)
  - ✓ "biaxially textured"
    - ✓ Technically challenging to grow on 3D surface
    - ✓ But, many "grain aligned" high quality tapes are commercially available.



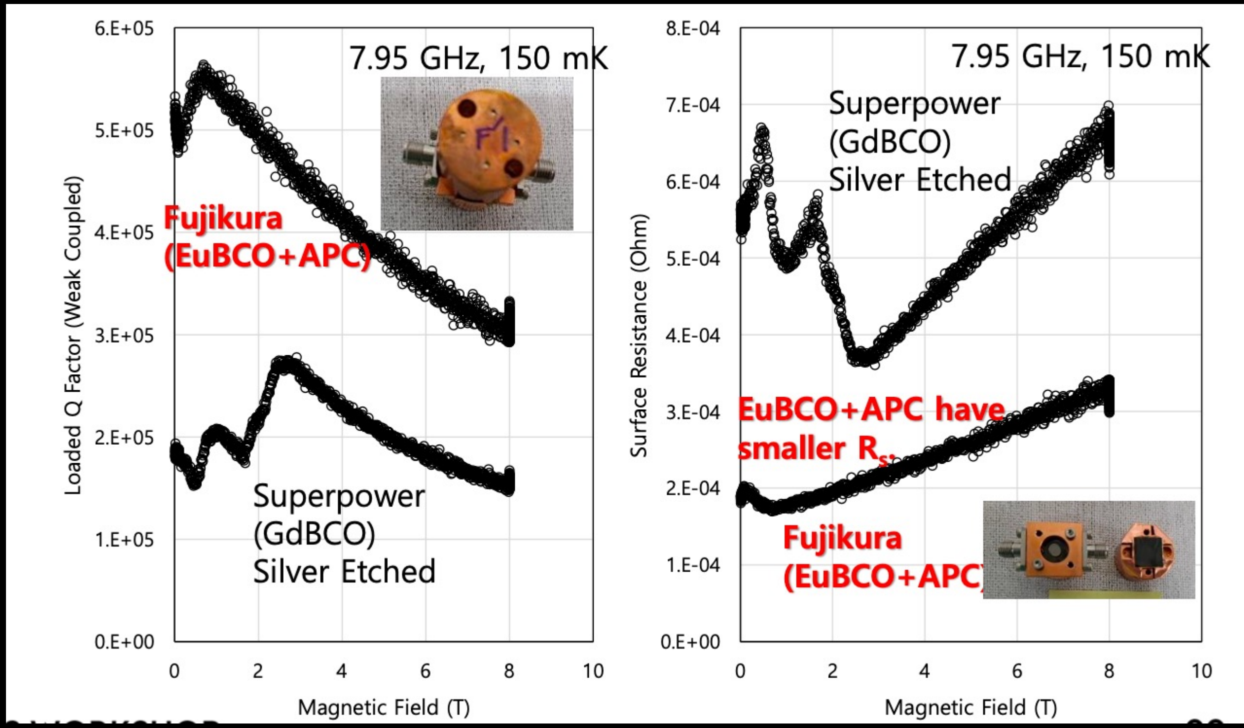
- How can we attach those tapes on the inner surface of resonant cavity?
  - ✓ 3D surface with planar objects: polygon cavity based on TM010 mode (called "melon cut")
- Excellent results (Q>500,000) even up to 8 T (further improvement in progress)
- Physics data run w/ 0.5M Q-factor is complete: will publish soon

- Much higher Q-factor (>10,000,000) achieved
- Bigger HTS superconducting cavity?

HTS Superconducting Cavity (tapes)



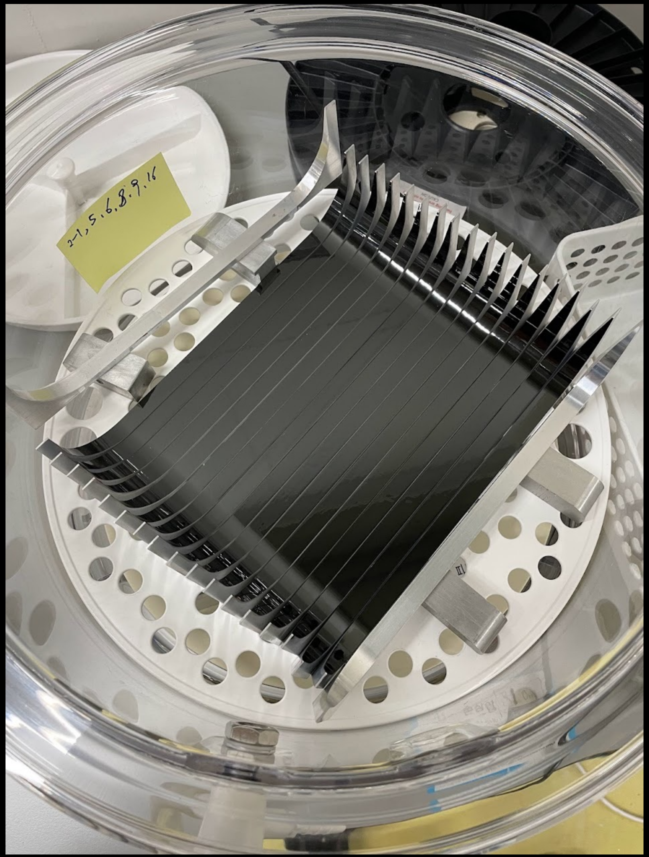
Test cavity (w/ rutile in the middle)
Comparing Fujikura w/superpower @150 mK



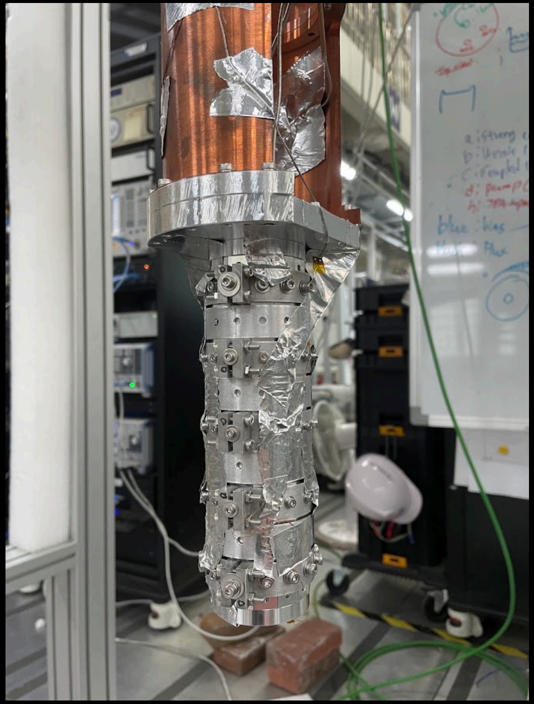
Overlaying test results over existing data
Extend to lower temp. (mK)

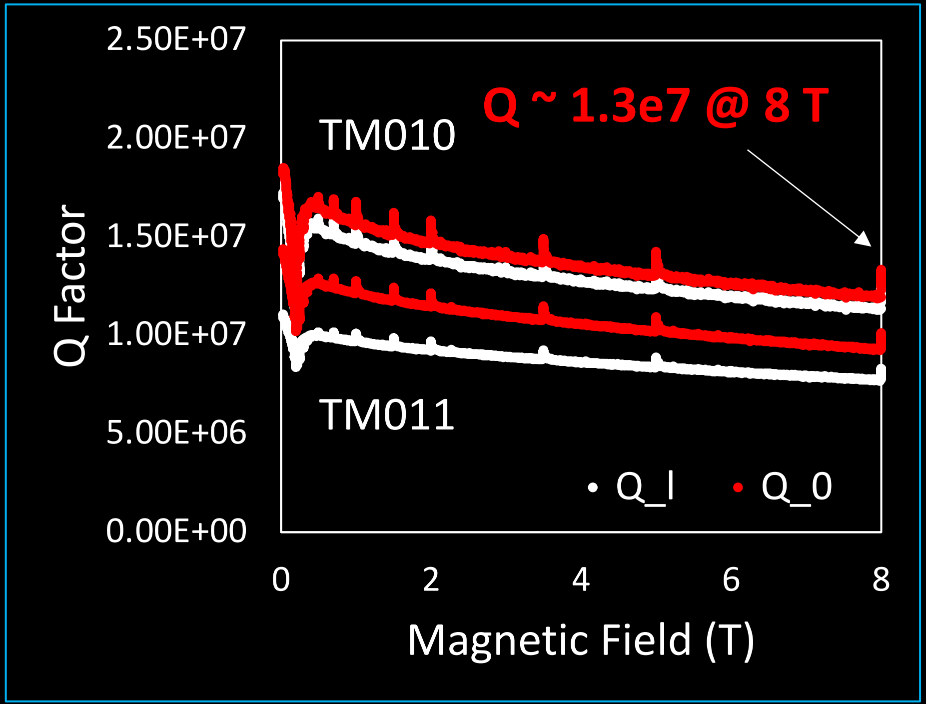
HTS Superconducting Cavity

Eliminating edge defects
Reaches Q ~ 3.7M, first time $Q > Q_{axion}$

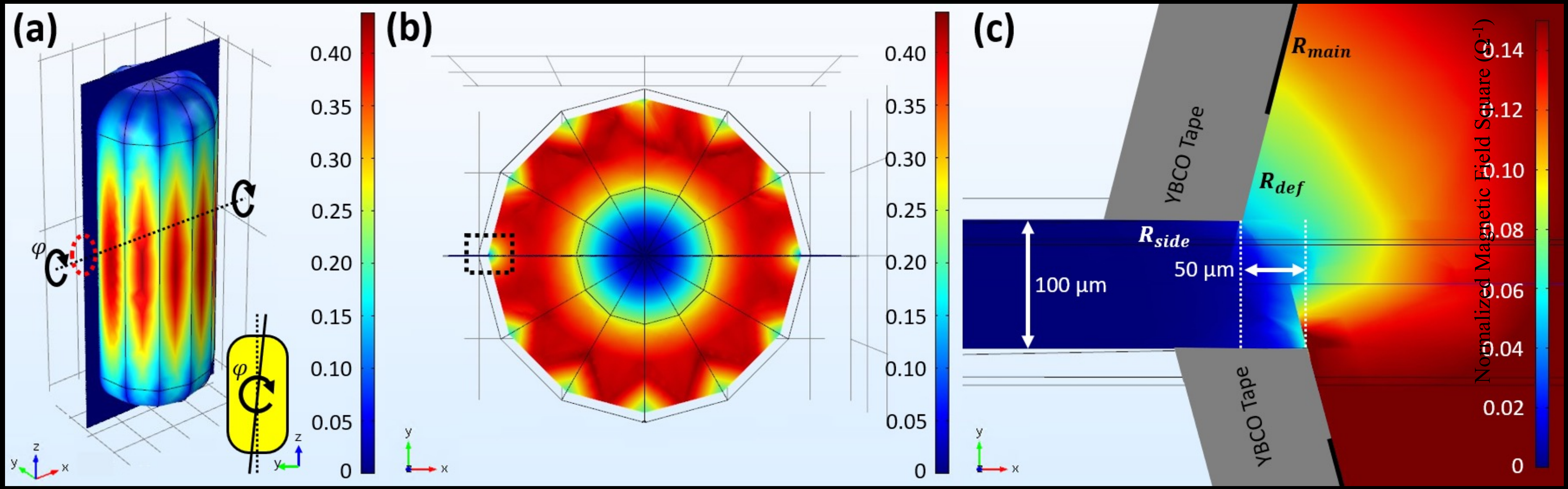

13 million Q-factor HTS Cavity





- HTS cavity Q-factor can be more than 10 times larger than axion's (~ 10^6)
- The scan rate could be enhanced two orders of magnitude compared to using copper cavities

HTS Microwave Cavity Design Simulation



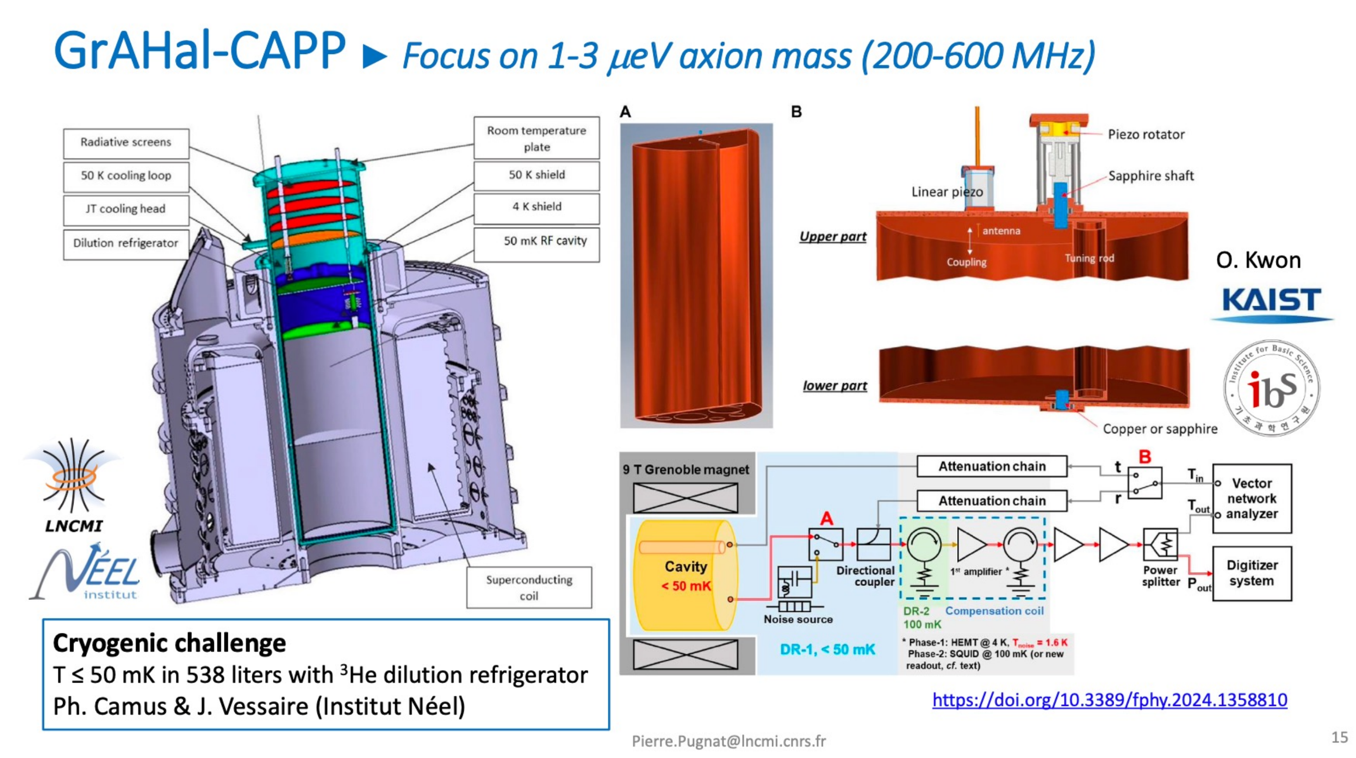
We learned…

- HTS tape surface quality matters
- Gaps between tapes has to be minimized
- Mechanical considerations
- Tape alignment

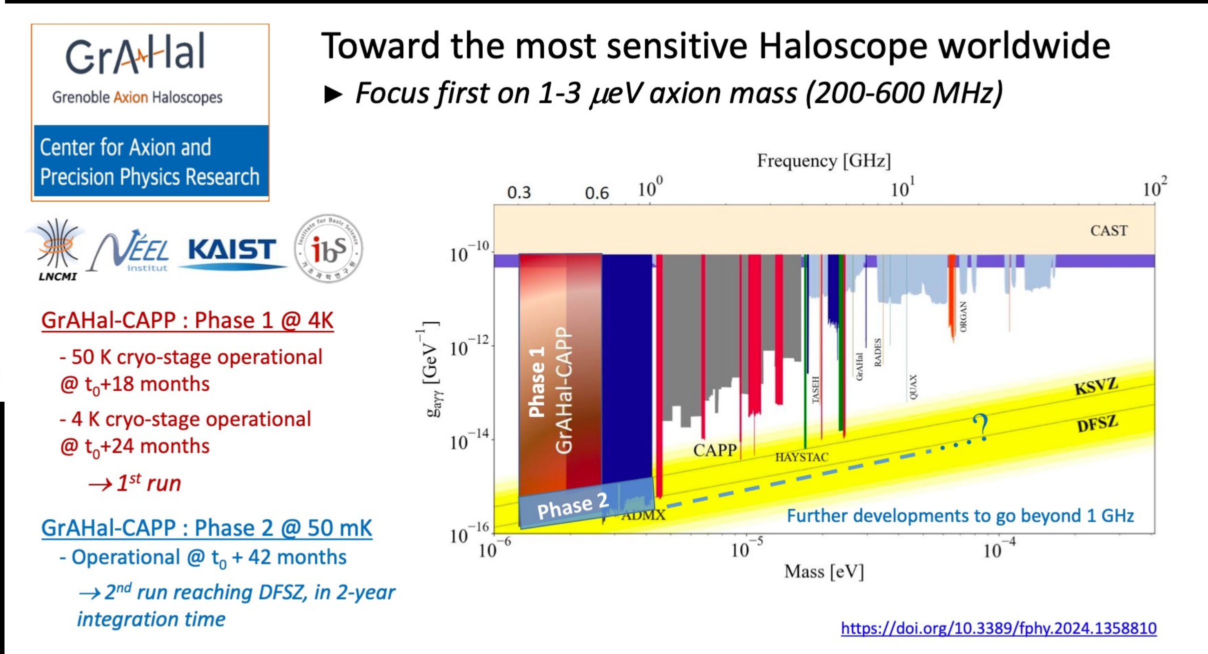
Axion Experiments at CAPP

	CAPP-PACE	CAPP-8TB	CAPP-HF	CAPP-PACE-JPA	CAPP-PACE-JPA-6cell	CAPP-8TB-JPA-8cell	CAPP-PACE-JPA-SC	CAPP-MAX-1.0	CAPP-AQN-SC	CAPP-HeT-SC	CAPP-12T-HF-3cell	CAPP-MAX-1.2
Year	2018	2019	2019	2020	2021	2021	2021	2021	2023	2023	2023	2024
Magnet [T]	8	8	9	8	8	8	8	12	8	8	12	12
m_a [GHz]	~2.5	~1.6	~4.0	~2.3	~5.6	~5.8	~2.3	1.0 ~ 1.2	~2.3	~5.4	~5.3	1.2 ~ 1.5
Δm_a [MHz]	250	200	250	30	80	>100	30	~20	-	> 50	~30	~ 150
Sensitivity	10*KSVZ +KSVZ	4*KSVZ	10*KSVZ	2*KSVZ	3*KSVZ	KSVZ	KSVZ	DFSZ	DFSZ	KSVZ	KSVZ	DFSZ
T_{phy} [K]	< 0.05	< 0.05	~2	~0.05	~0.05	~0.03	~0.04	~30 mK	60 mK	30 mK	30 mK	~30 mK
T_{sys} [K, mK]	~1 K	~1 K	~2 K	~200 mK	<300 mK	<300 mK	<200 mK	<300 mK	~200 mK	~400 mK	~400 mK	<300 mK
Comments	R&D machine: First physics run (coldest axion data)	First result published by CAPP	First multi-cell cavity result	First run with JPA	First run with JPA+6-cell	First run with JPA+8-cell	First run with JPA+SC	CAPP's main axion detector with JPA	Axion Quark Nugget + SC cavity (Q~1.6M)	First run with He tuning + SC cavity (Q~10M)	3-cell with 12T mag + JPA SC cavity (future)	CAPP's main axion detector with JPA
Publication	Published in PRL	Published in PRL	Published in PRL	Published in PRL	--	Will publish	Will publish	Published in PRL	Will publish	--	Published in PRL	Published in PRX

GrAHal-CAPP



P. Pugnat's presentation on Tue.



- Challenging task of fabricating 538 liter cavity
- SC cavity for > 35 T environment

CAPP-MAX

- CAPP's main flagship experiment
- Powerful 12 Tesla Nb3Sn superconducting magnet with big 32 cm bore
- Achieved DFSZ sensitiviity around 1 GHz
- Total T_{sys} reaches 100 ~ 200 mK
- Physical temp. of cavity (30 mK)

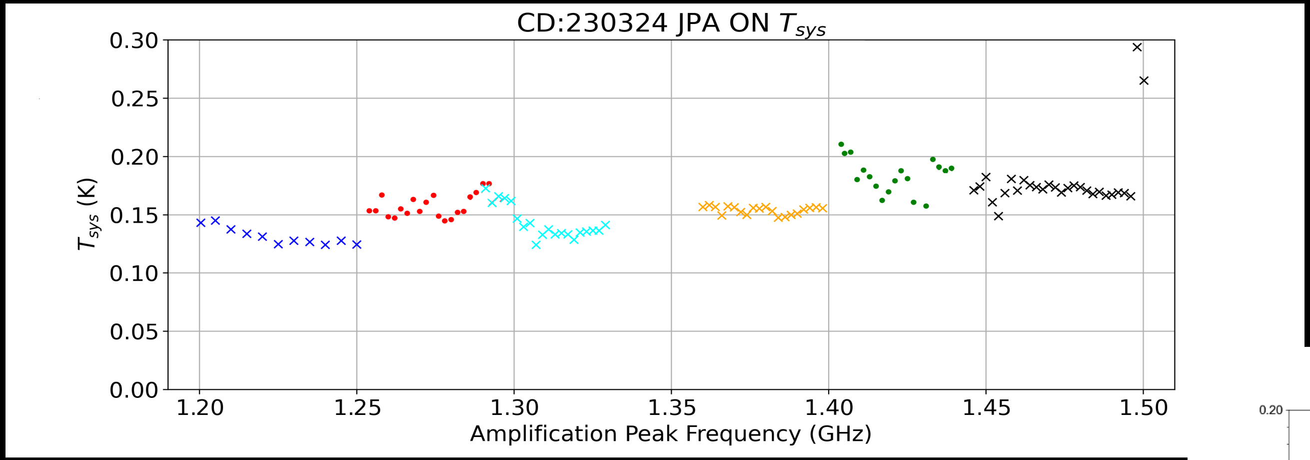
- First scan: ~20 MHz (4.51~4.59 μeV) Published in PRL
- Second + Third scan: ~58 + 150 MHz scan ~@1 GHz: complete, published in PRX

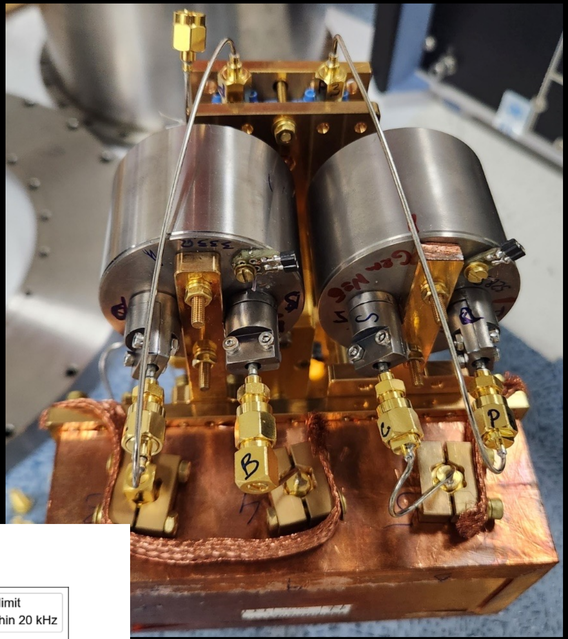
CAPP-MAX

- Fourth scan: ~300 MHz scan (1.200 – 1.500 GHz) next
  - Target physical temperature of cavity T_{phy} < 30 mK
  - Bundled 6 JPAs : T_{sys} < 200 mK → > 3 MHz / day
  - Adding SC cavity:
    - Speed up more: 36 liter 100% SC cavity is implemented
    - Q-factor > 1M will speed up the search ~ 10 times
  - Engineering Run in progress

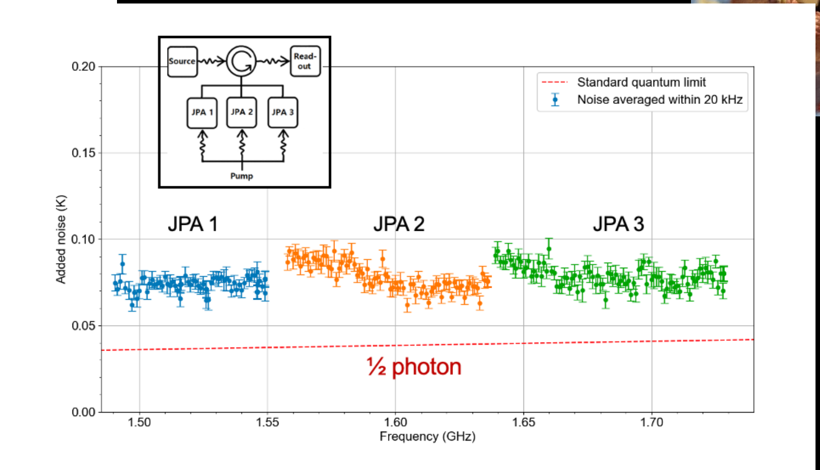
CAPP-MAX

- Fourth scan: ~300 MHz (1.2 – 1.5 GHz)
  - Preparing 6 JPAs : T_{sys} < 200 mK → > 3 MHz / day





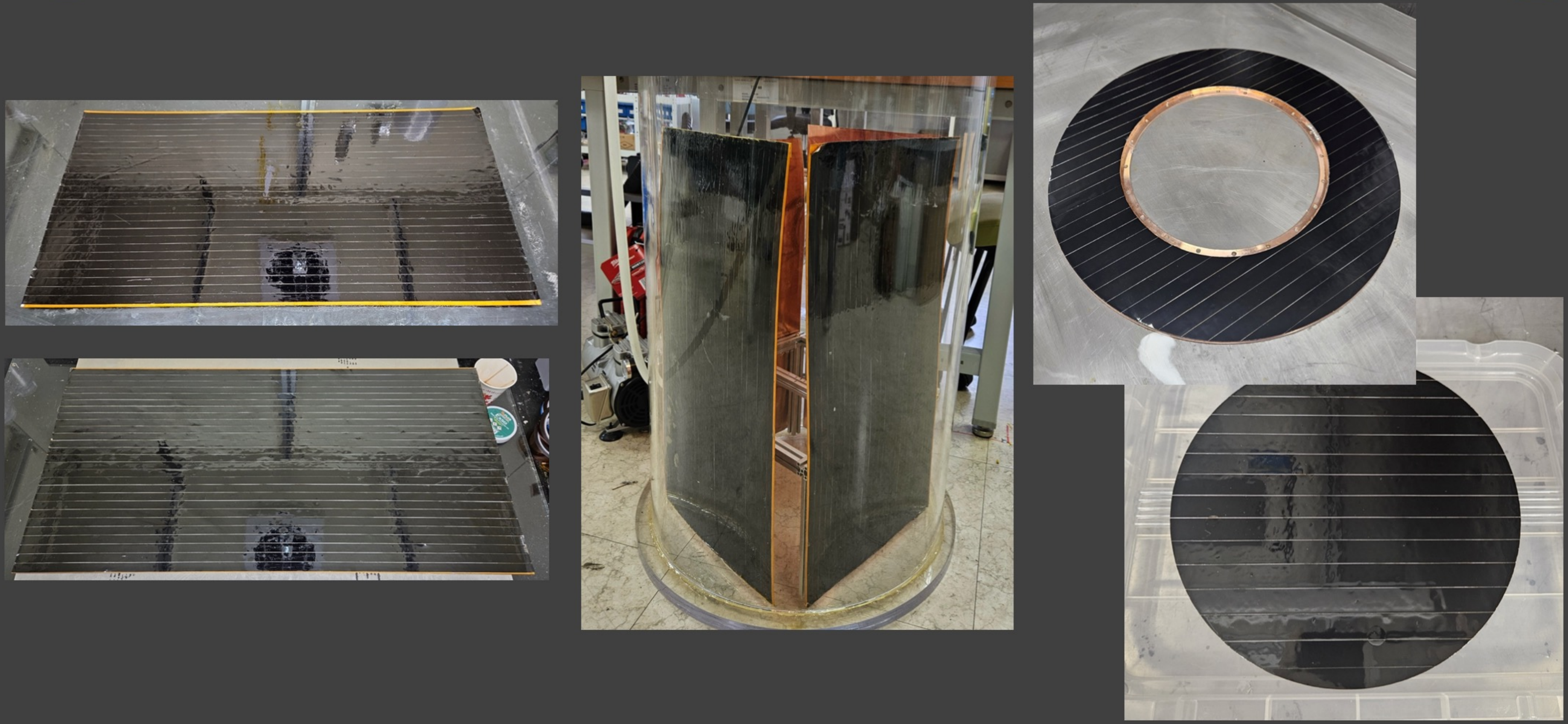
- 5th scan: ~250 MHz (1.50 – 1.75 GHz)



CAPP-MAX

From O. Kwon's presentation

All the parts are ready to assemble

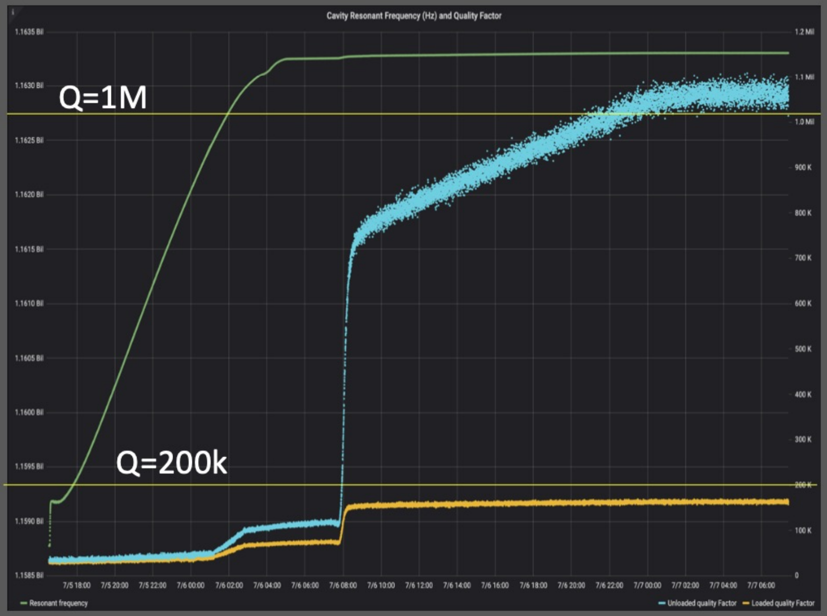


CAPP-MAX

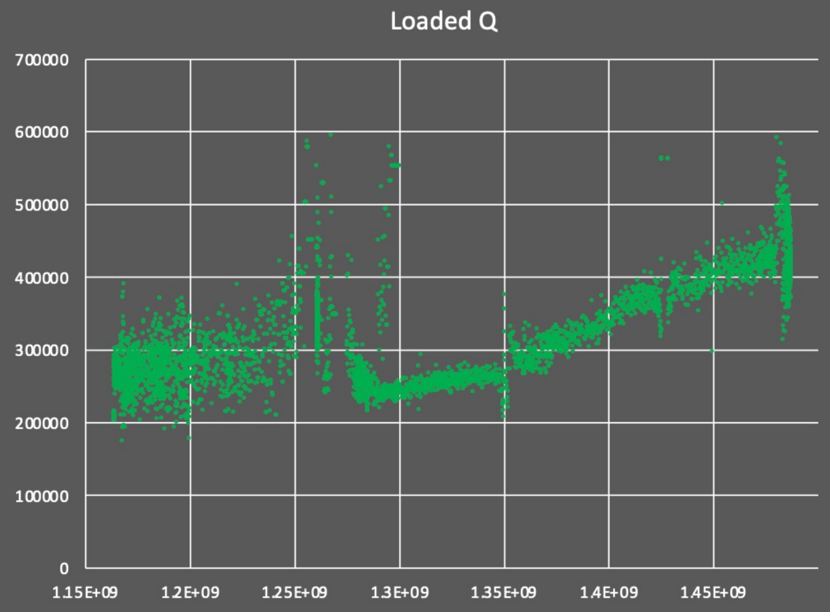
From O. Kwon’s presentation

Q-factor measurement (0 field)

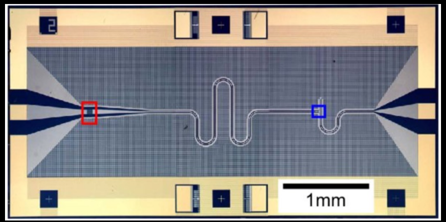
During cooling down @1.163 GHz

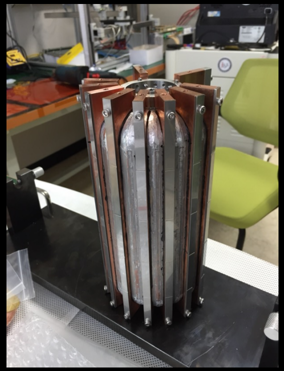


w/ frequency tuning



Axion Experiments at CAPP

+ 

+ 

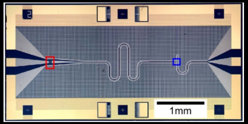
+ HF

CAPP-MAX + JPA + SC cavity + HF

- 12T LTS magnet working as expected
- Physics data (w/ 6 JPAs)
- Δf ~ 300 MHz for DFSZ sensitivity
- Ultra-light 100% Superconducting Cavity (36 liters)
- High frequency R&D in progress for next freq. range

Axion Experiments at CAPP

In PRX (Aug. 2024)



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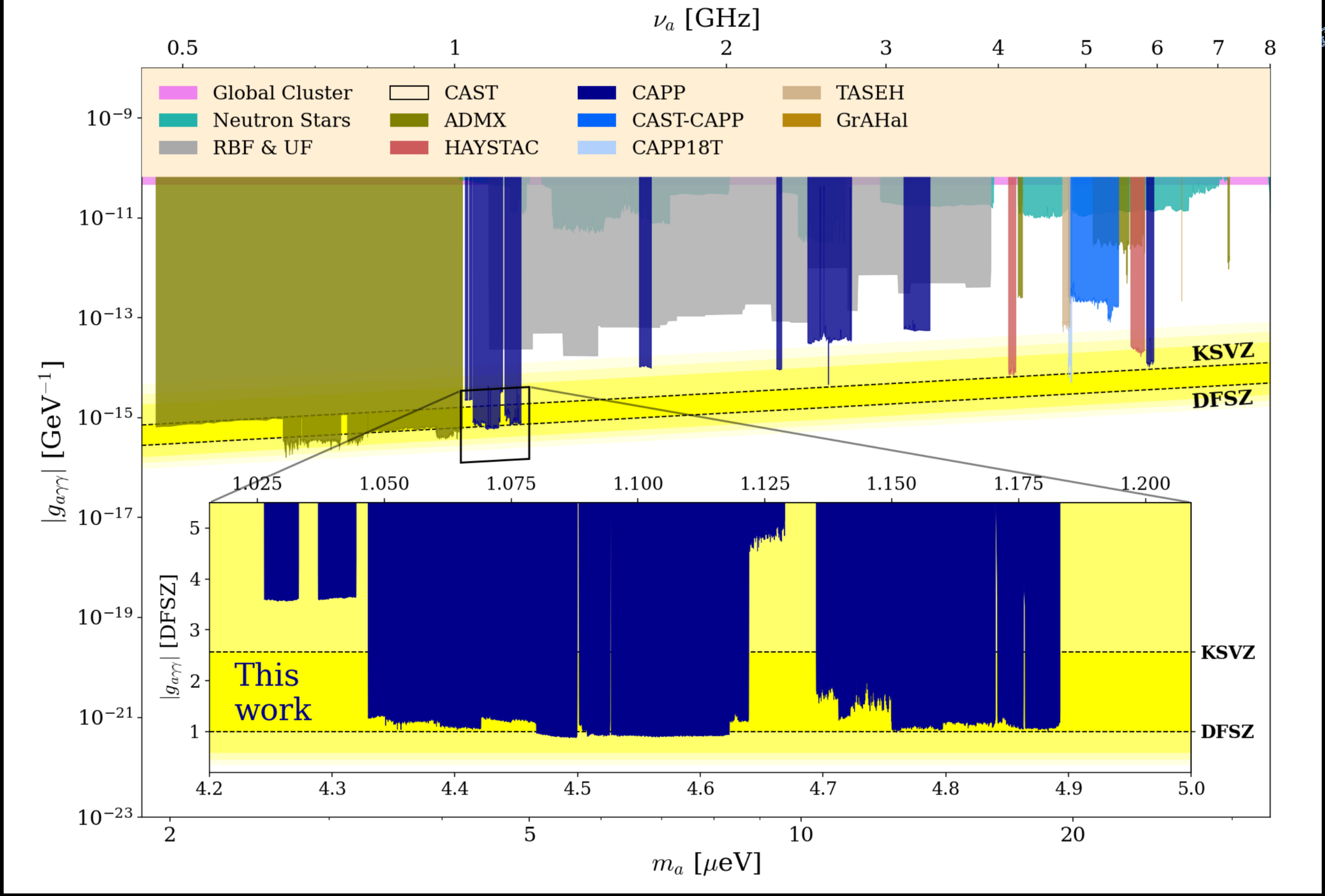
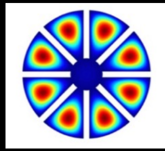


September 19th 2024

Axion Experiments at CAPP

Beyond 2024

CAPP
Center for Axion and Precision Physics Research



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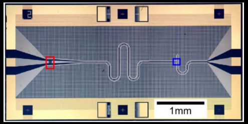

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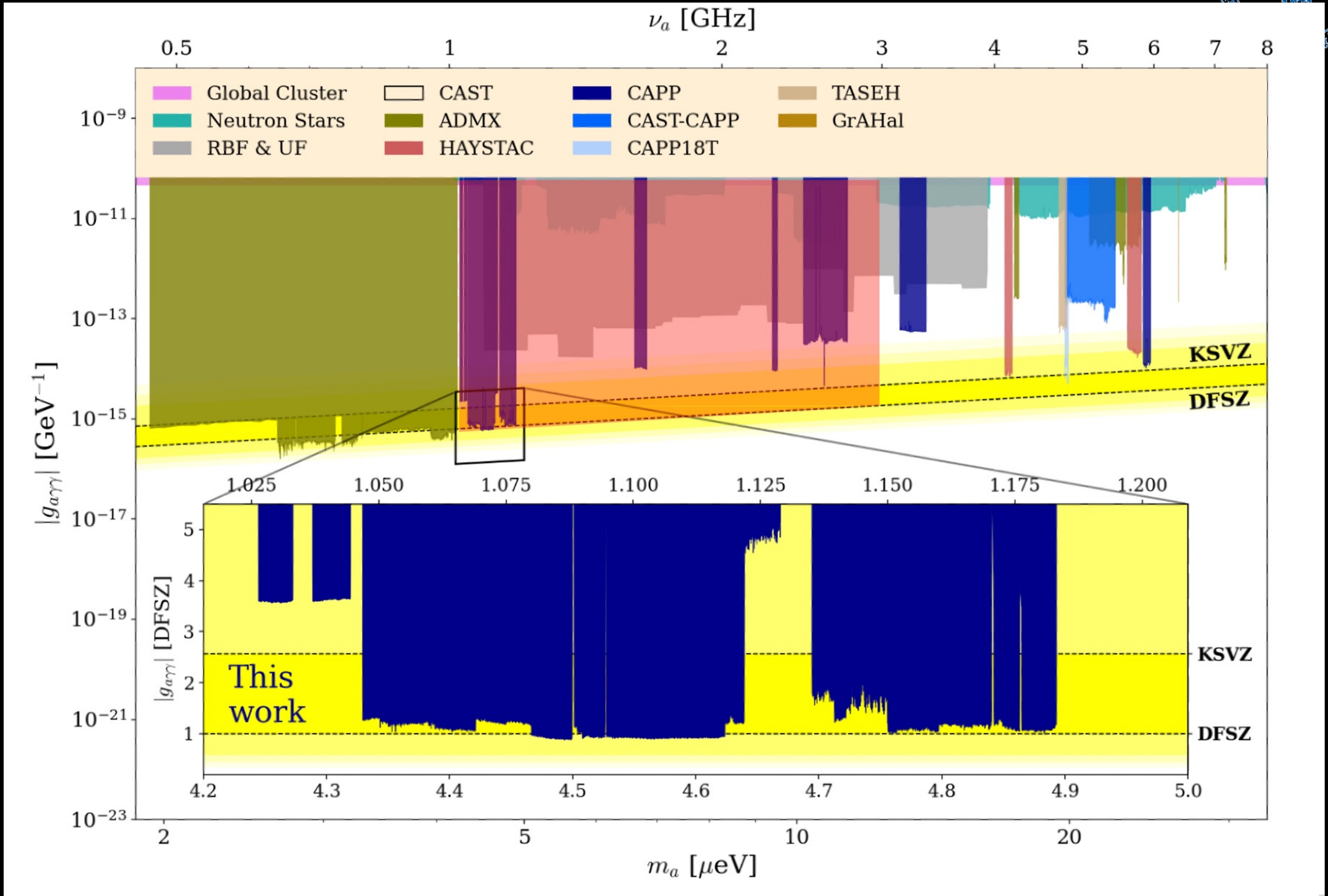


September 19th 2024

CAPP's Winning Strategy

- Objective: pinpointing axion mass (discovery) in mass range 1-10 (near future) and 10-100 GHz (requires more R&D)
- Scanning Speed is the key to cover the possible axion mass range, asap
- Required Technology: cryogenics + big & powerful magnet, quantum noise limited amplifiers and high Q-factor superconducting cavity
- CAPP is equipped with everything required now (plus multiple fridges) and ready to race!

CAPP's advantage:

- Powerful Flagship exp. w/ 12T-32cm SC magnet + 4 dry dilution refrigerators
- Achieved the lowest system noise temperature (< 200 mK) among existing experiments
- Physics data w/ HTS superconducting cavities (> 10 times boost)
  (new gen. SC cavity shows >10M Q-factor even under 8T field)

Summary

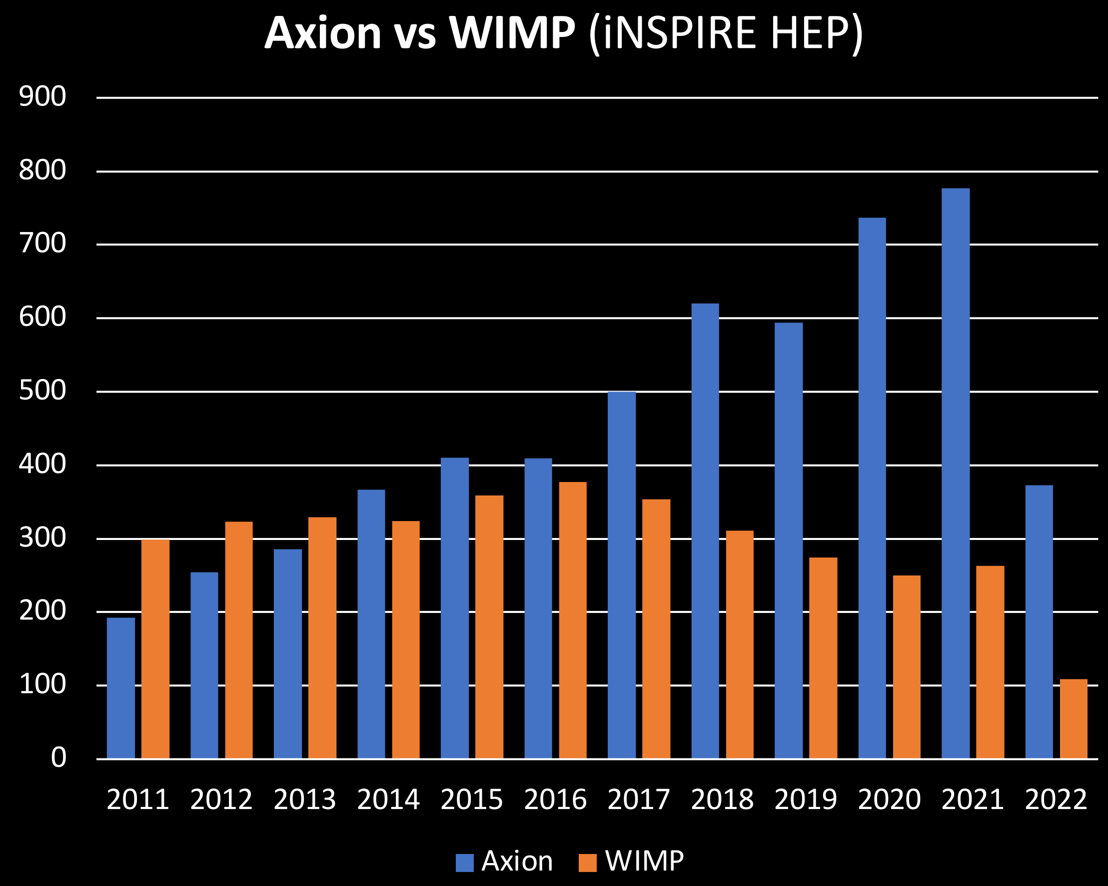
- CAPP has successfully established multiple haloscope axion dark matter experiments in Korea, the best axion research facility in the world
- Through R&Ds we are ready to speed up our axion search and presently, we are collecting data with DFSZ sensiitiivity for axion dark matter search in our flagship experiment, CAPP-MAX
- HTS SC cavity in all our Haloscope
- Major improvement is expected with CAPP-MAX for next 5 years

  QA + SC + HF (1-10 GHz)
- Stay tuned!

Thank You For Your Attention!

Discovered by WC in Bogota, Colombia (Sep. 14th, 2018)

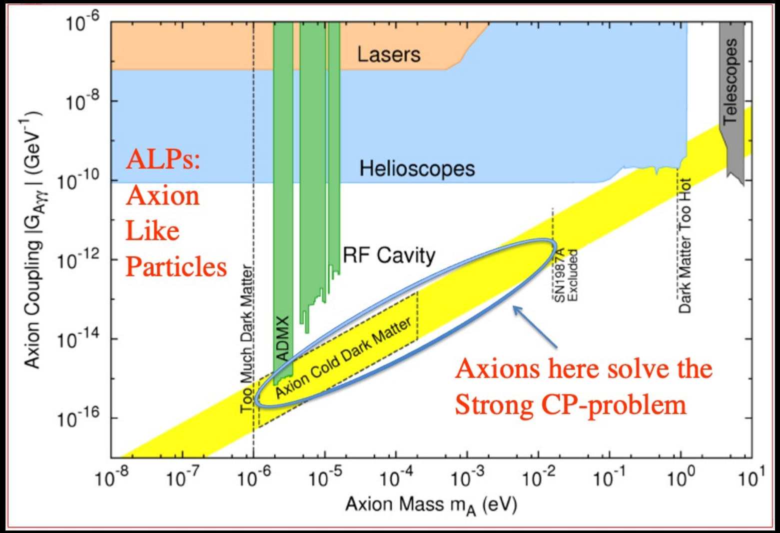
Global Trend in Axion Research



- Axion solves both strong CP problem and a dark matter puzzle
- Two most popular dark matter candidates: Axion and WIMP, but axion is gaining momentum compared to WIMP
- Presently, there are >30 axion experiments worldwide with front-runners including

Axion Detection (experimentalist's view)

- Haloscope: the most sensitive method known today, but
- Still very wide range of mass to scan…

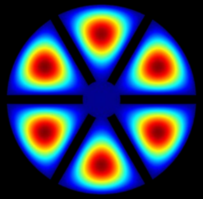


- Needs innovations/breakthroughs to speed up the search!
- Taking advantage of the advancement of Superconductor technology (quantum noise-limited amp + superconducting tapes)

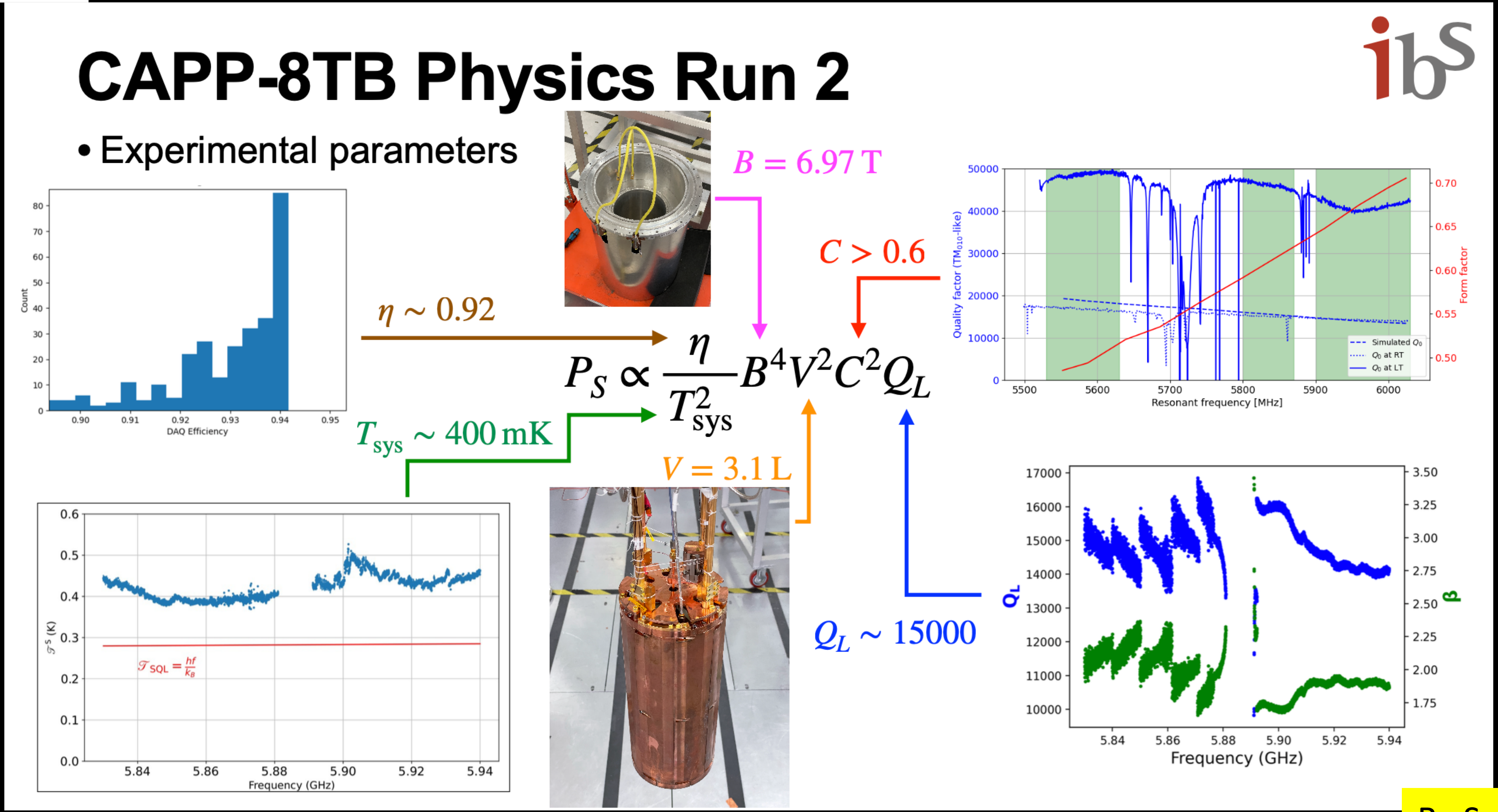
CAPP's R&D

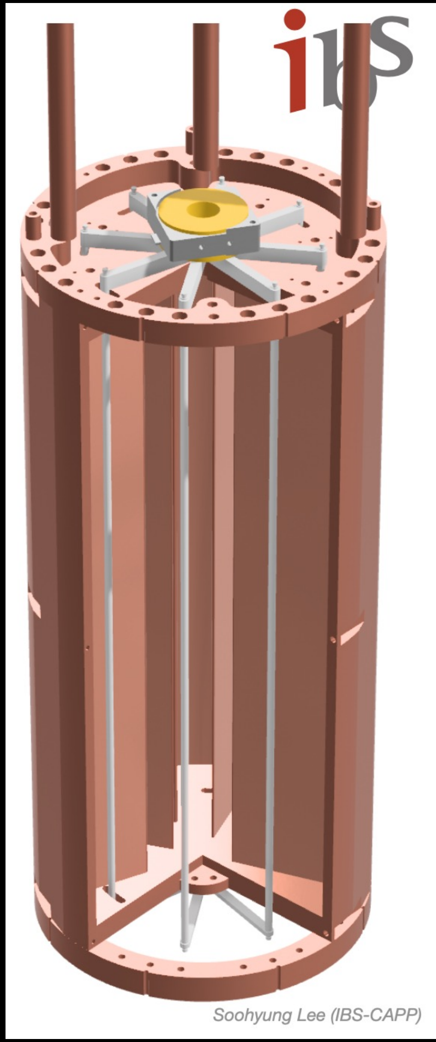
- What we achieved
  - 7 refrigerators (6 magnets) operational at CAPP
  - 4 (better than KSVZ sensitivity) experiments running…

- R&Ds needed to search 1~10 GHz in 5 years
  - Optimizing cryo-RF receiver with quantum amplifiers (JPA) at or near SQL
    - ✓ Ultra-low physical temperature (< 25 mK)
    - ✓ Reduce the total noise ~ 120 mK @ 1 GHz
    - ✓ >5 MHz /day scanning speed
  - Developing Superconducting Cavity under High Magnetic Field
    - ✓ HTS cavity could enhance the scan speed > 10 times
  - Developing High-Frequency Cavities
    - ✓ Avoid sacrificing volume of the cavity
    - ✓ Multi-cavity, dielectric cavity and photonic gap crystal
    - ✓ Superfluid He tuning



Multi-cell (8) cavity + JPA (6 GHz) (S. Lee)

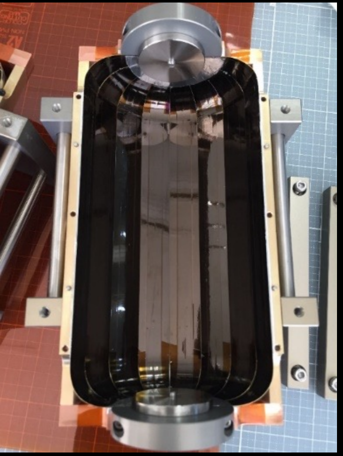


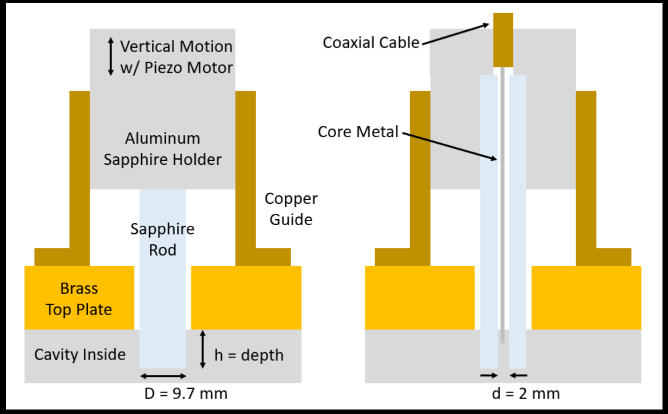


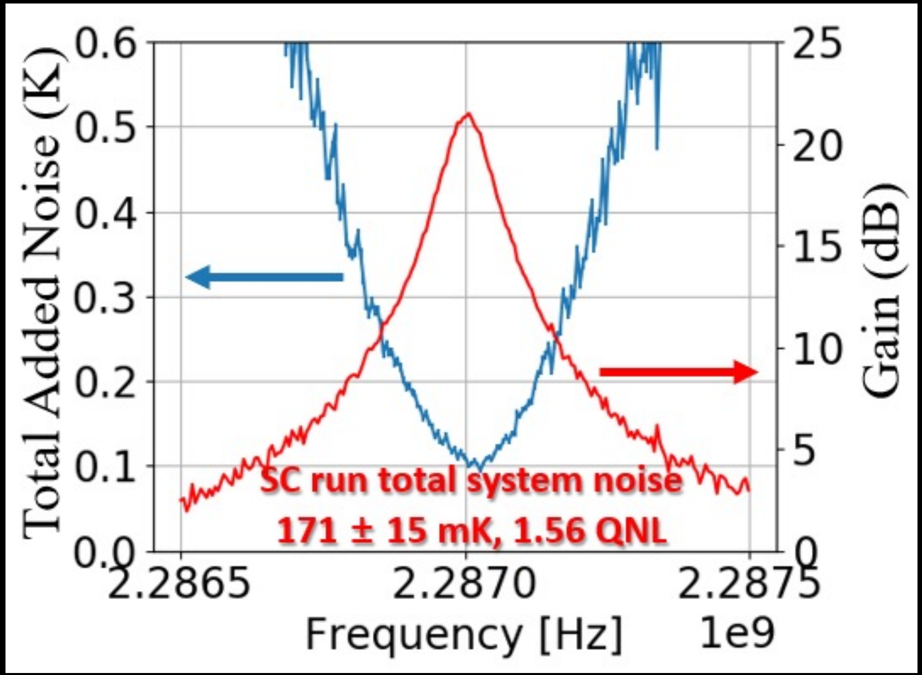
By S. Lee

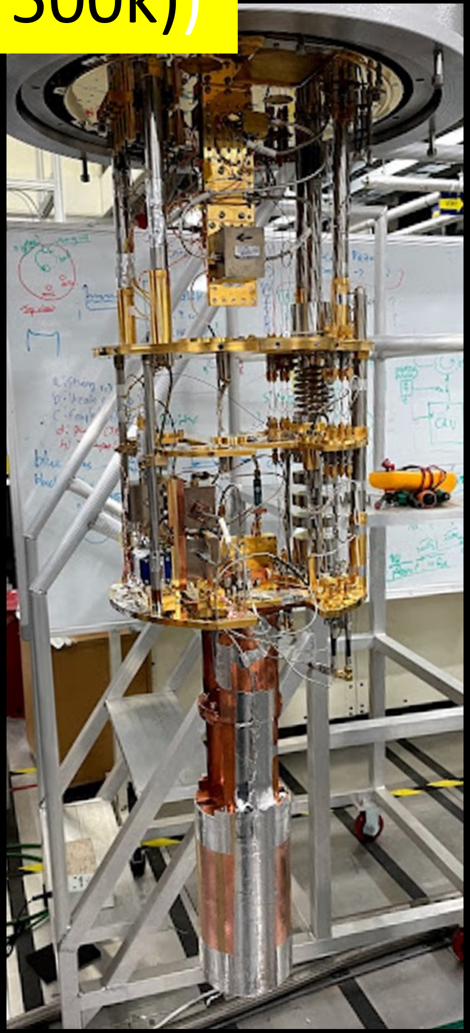
Axion Search w/ SC Cavity (D. Ahn)

First axion exp. w/ HTS taped SC cavity (Q ~ 500k))









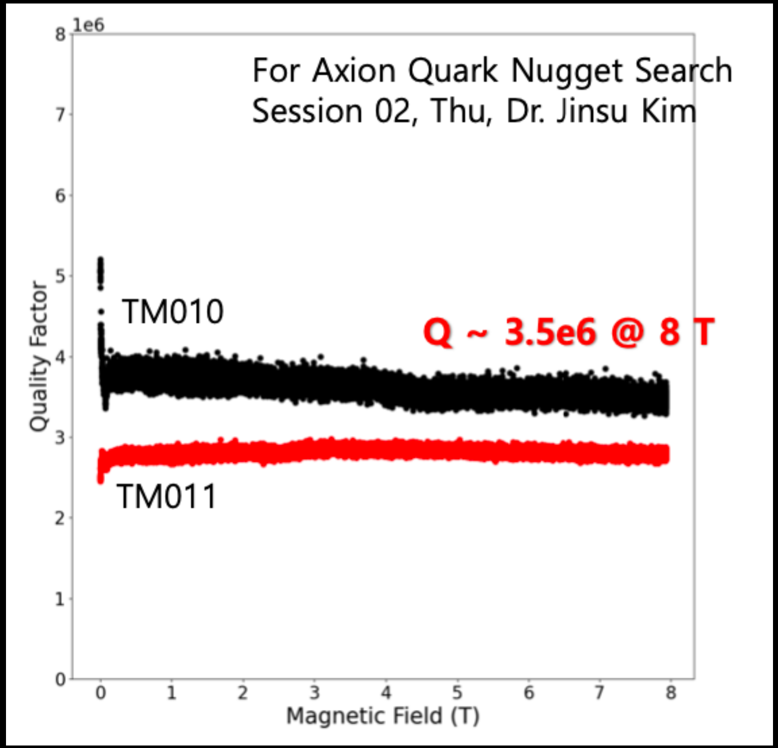
- Cavity Tuning
  - Tunability (2270 – 2295 MHz)
  - Form factor ($C \approx 0.6$)
- Total System Noise ($T_{sys} = T_{eff} + T_{add}$)
  - Josephson Parametric Amplifier + HEMT
  - Effective cavity noise temperature ($T_{eff} \approx$ 60mK)
  - Added noise by the receiver chain ($T_{add} \approx$ 115mK)

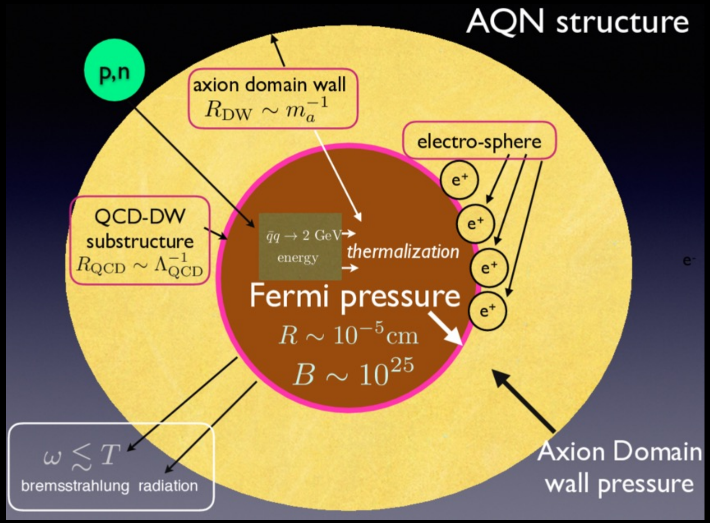
AQN Experiment at CAPP (Jinsu Kim)

- CAPP's first **Axion Quark Nugget experiment w/ haloscope**
- **SC taped cavity** (Q > 1.6 M) is implemented

Demonstrate the ability of analyzing high-Q data

Develop AQN analysis (can be done in parallel using haloaxion data)

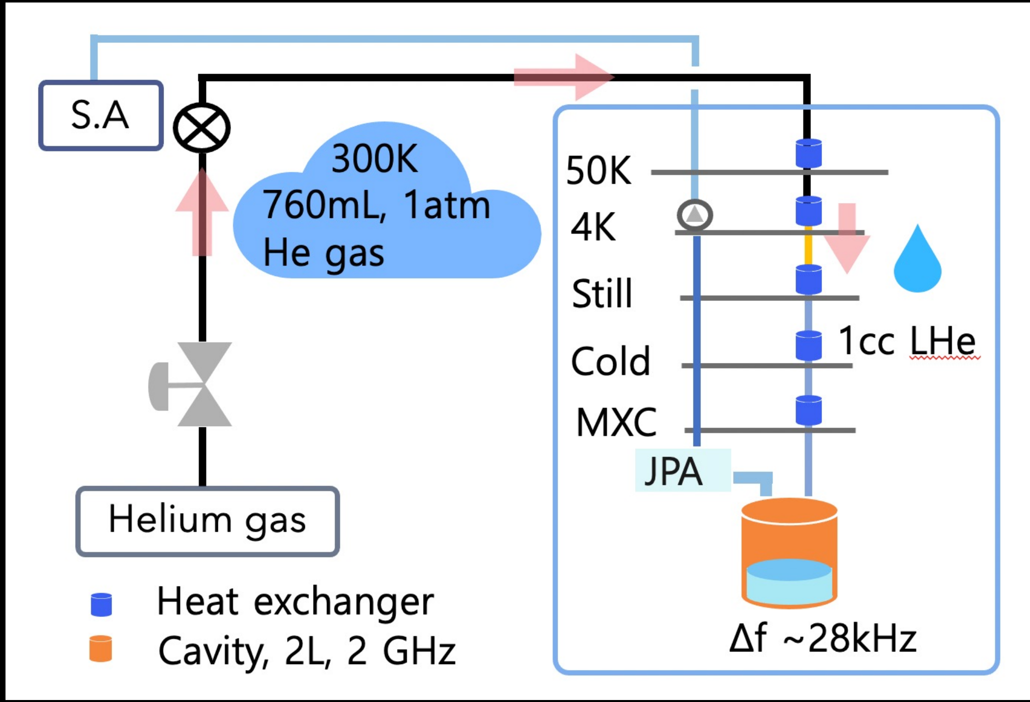




Superfluid Helium Tuning w/ SC cavity (H. Byun)

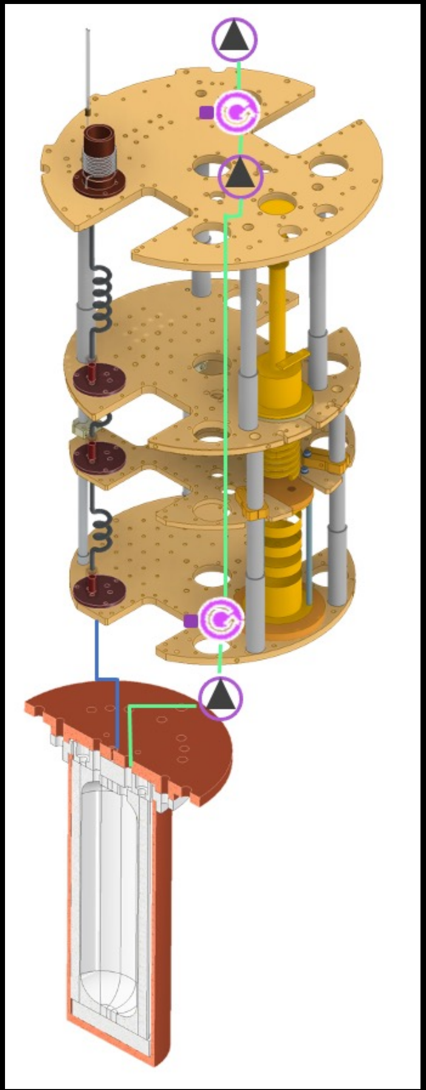
- Applicable to superconductor cavity and metamaterial cavity
- No significant change in field distribution, form factor and Q-factor

DAQ run with JPA + SC cavity (Q~13M) + superHe is in progress

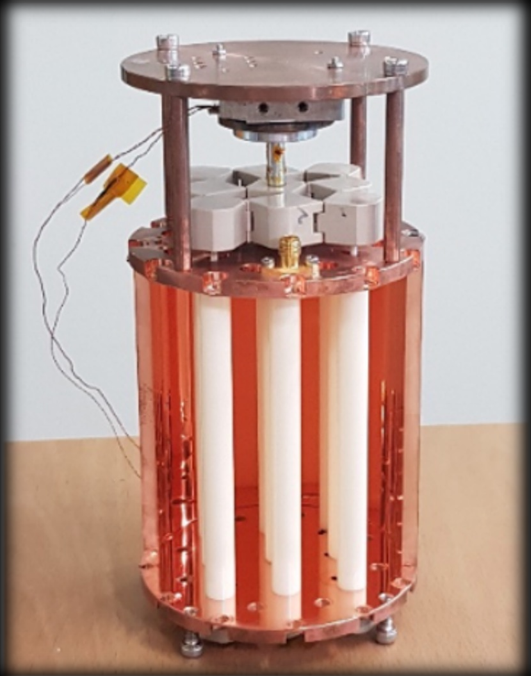


Concept of Superfluid Helium ($\epsilon_r \approx 1.057$) tuning

- $f_{TM010} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\frac{2.405}{R}$
- $\frac{f_{empty} - f_{LHe}}{f_{LHe}} = \sqrt{\epsilon_{LHe}} - 1$
  ≈ 0.028, ***~3 % frequency shift***



High-Frequency Cavity Design (J. Jeong)



High-Frequency Cavity Designs at IBS-CAPP

Multiple-cell Cavity [J. Jeong *et al.*, Phys. Lett. B **777**, 412]

Wheel Tuning Mechanism [J. Kim *et al.*, J. Phys. G: Nucl. Part. Phys. **47**, 035203]

Tunable Photonic Crystal [S. Bae *et al.*, Phys. Rev. D **107**, 015012]