CAPP's Axion Dark Matter Experiment and R&D's

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

For

IBS Conference on Dark World

OUTLINE

- Introduction
  - IBS/CAPP
  - Dark Matter Axion
- CAPP-PACE (Pilot Axion Cavity Exp.)
  - CULTASK (CAPP's Ultra Low Temperature Axion Search in Korea)
  - First complete axion experiment in Korea
  - Physics data (10*KSVZ and KSVZ runs) in 2018
- Improvements
  - High Field Magnets
  - Quantum Amplifiers
  - High Q-factor (superconducting) cavity
- Summary

Center for Axion and Precision Physics Research (CAPP)

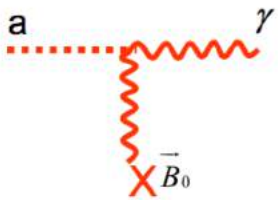
Funded by the Institute for Basic Science (IBS)

- 6 years old in Oct.
- Led by Director, Yannis Semertzidis (first gen. axion hunter)
- Physics at CAPP:
  - Dark Matter Axion Search (Cosmic Frontier)
  - Storage Ring Proton EDM (Strong CP Problem, BAU)
  - Muon g-2, J-PARC, COMET, CAST, ARIADNE
- Located at and working with KAIST (Korea Advanced Institute of Science and Technology)
- ~50 members

DM and Axions

- Peccei and Quinn (1977) postulated an elegant solution by adding a new global symmetry to resolve the Strong CP Problem in Standard Model

- Axion is an excellent (and attractive) dark matter candidate
  - Pseudo Goldstone Boson
  - Small Mass ($1\mu eV < m_a < 10 meV$)
  - Extremely Weakly Interacting
  - Local Halo Density of 0.45 GeV/cm^3
  - $\beta \sim 10^{-3} \rightarrow Q_a \sim 10^6$

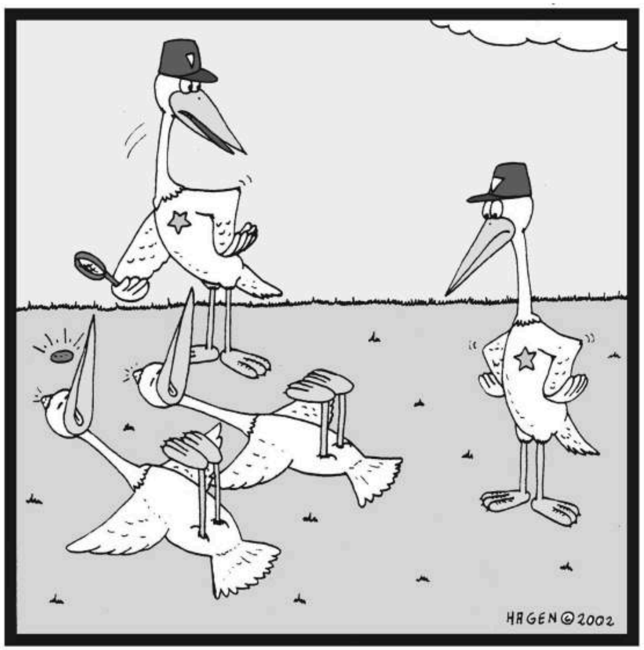


$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

- Detection scheme by P. Sikivie (PRL 51:1415 1983) : Haloscopy
  - Axions will convert to photons in a strong magnetic field

DM and Axions

Killing Two Birds With One Stone



Unbelievable! It looks like they've
both been killed by the same stone...

Peccei-Quinn mechanism
- Solves strong CP problem
- Provides dark matter in the form of axions

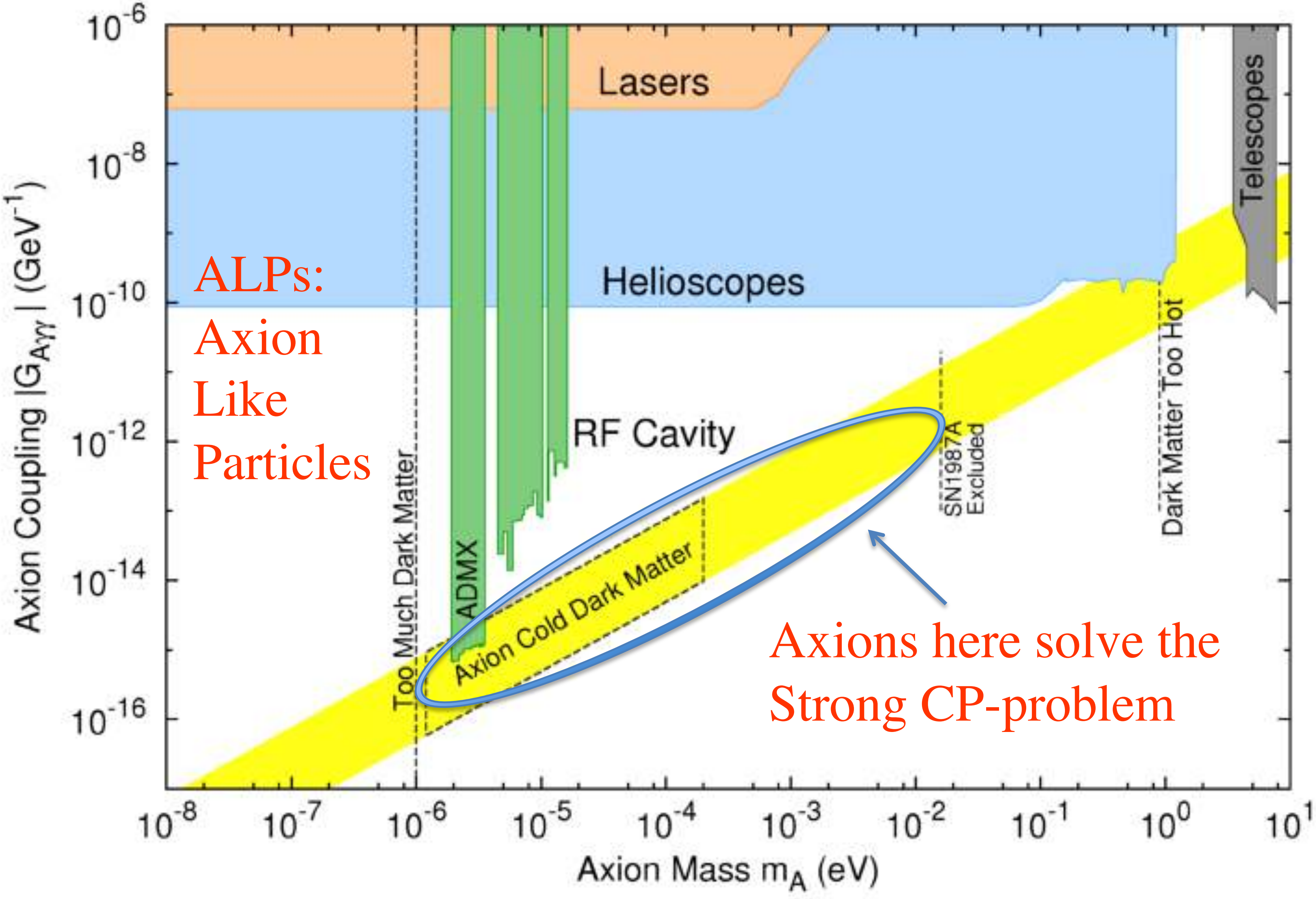
Georg Raffelt, MPI Physics, Munich — Physics Colloquium, Univ. Sydney, 3 March 2014

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 talk to it.

Axion Landscape



Major Axion Activities

Axion Search Experiments

- Cosmic Axion Search
  - Haloscopes (Microwave Cavity) ← Most sensitive so far
  - Dish Antenna
  - Dielectric Haloscope
  - LC Circuit
  - NMR techniques
  - Atomic Transitions
- Solar axion search
  - Axion Helioscopes
  - Bragg Diffraction Scattering
  - Geomagnetic Conversion
- Laboratory Axion Search
  - Light Shining through Wall
  - Polarization Experiment
  - 5^{th} Force

Cosmic Axion Search

Name	Type	Mass range	Location	Status	Reference
ADMX G2	cavity	10^{-6} to 10^{-5} eV	Seattle	Running	Phys. Rev. Lett. 120, 151301
HAYSTAC	cavity	10^{-5} to 10^{-4} eV	Yale	Running	https://arxiv.org/abs/1803.03690
CULTASK	cavity	10^{-5} to 10^{-4} eV	IBS/CAPP	Running	https://capp.ibs.re.kr/html/capp_en/
KLASH	cavity	2 x 10^{-7} eV	INFN	Proposed	https://arxiv.org/abs/1707.06010
ORGAN	cavity	10^{-4} eV	UWA	Prototype	https://arxiv.org/abs/1706.00209
RADES	cavity	3.5 x 10^{-5} eV	CERN	Prototype	https://arxiv.org/abs/1803.01243
BEAST	capacitive	10^{-11} eV	UWA	Tests	https://arxiv.org/abs/1803.07755
FUNK	dish	(hidden γ search)	KIT	Running	https://arxiv.org/abs/1711.02961
BRASS	dish	10^{-5} to 10^{-2} eV	Hamberg	Proposed	

ADMX (Haloscope)

CAPP
Center for Axion and Precision Physics Research

The ADMX Program

ADMX
AXION DARK MATTER EXPERIMENT

Pacific Northwest NATIONAL LABORATORY

ADMX G2 at U. Washington
Scientific American, 2015

Goal: Find Dark Matter axions, or exclude them at high confidence

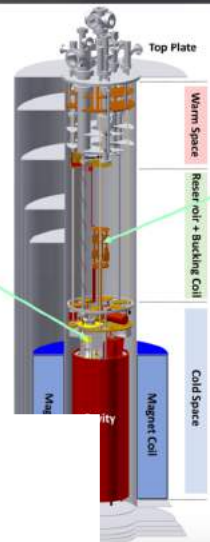
Collaborating Institutions:
UW, UFL, PNNL
FNAL, UCB, LLNL
LANL, NRAO, WU, Sheffield

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, DE-SC0010296, DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-AC03-76SF00098.

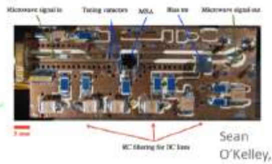
ADMX Design: Reducing Noise

Pacific Northwest NATIONAL LABORATORY

Dilution Refrigerator



ADMX Tunable MSA



Sean O'Kelley, Clarke Group, UC Berkeley

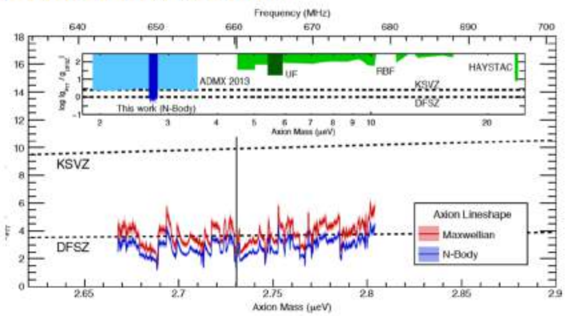
ADMX JPA

Yanjie Qiu, Siddiqi Group, UC Berkeley

Figures from 2nd Workshop of Microwave Cavities and Detectors for Axion Research

February 21, 2018 | 13

ADMX Exclusion Limits 2017



We didn't find an axion over this narrow range. More importantly, we could have. This is the first exploration into the plausible DFSZ coupling in the prime mass range for Dark Matter. A discovery could come at any time.

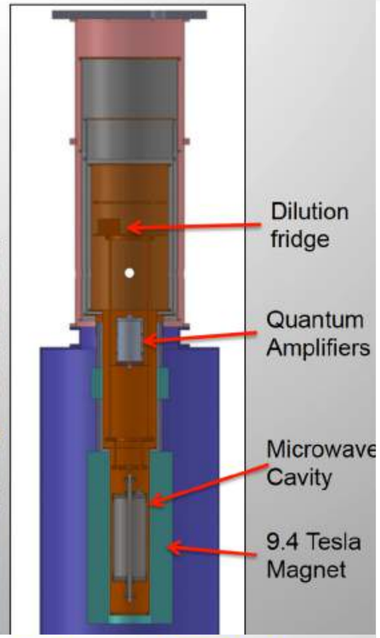
13 Rybka - ICHEP July 2018

CAPP

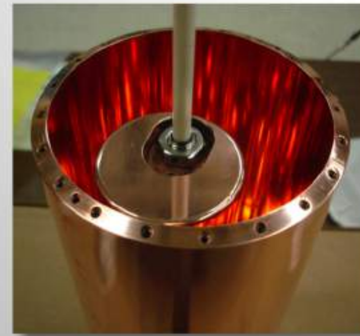
HAYSTAC (Haloscope)

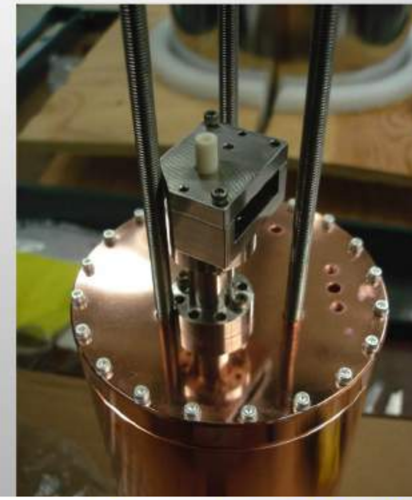
Purchased new magnet from Cryo-Magnetic Instruments.
- *9 Tesla / 170 H coil*
- *5" diameter bore*
- *Persistent with bucking region*
- *Designed with highly parallel field (Br < 50 G)*
- *Cryogen free*



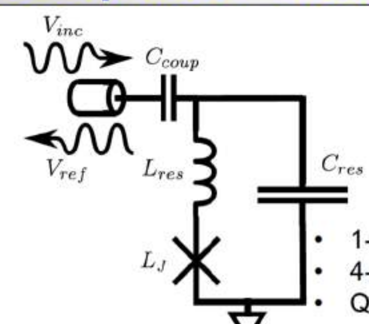


Cavity #2a – Single rod ("internal pivot") design





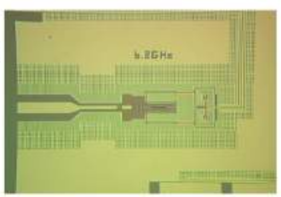
Josephson Parametric Amplifiers (JPAs)



Josephson Junction - a nonlinear inductor

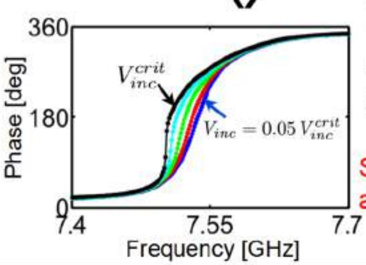
$$L_J = L_{J0} + L_{J2}\left(\frac{I}{I_{crit}}\right)^2$$

Nonlinear LC circuit
- 1-10 MHz band
- 4-8 GHz tunable range
- Quantum Limited



$$T_n = \hbar\omega / k_B$$

1 GHz = 50 mK
5 GHz = 250 mK

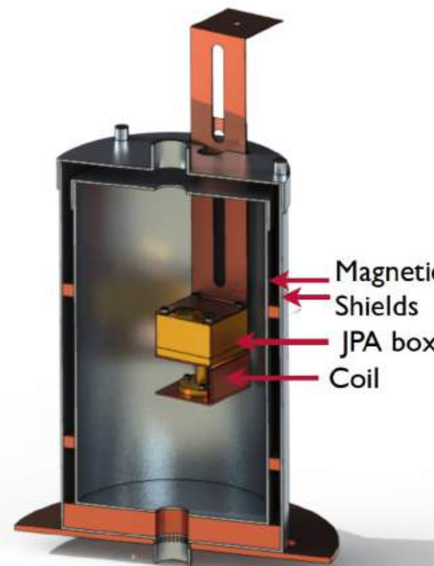


Status: JPA delivered, Installed and Tested to 2 Tesla!

K. Lenhert's group
U. of Colorado/JILA

Status – Magnetic Shielding

JPA
- works at ~1Gauss
- ADMX-HF stray field ~100 Gauss

Axion Detection Scheme (CULTASK)

P. Sikivie's Haloscope:

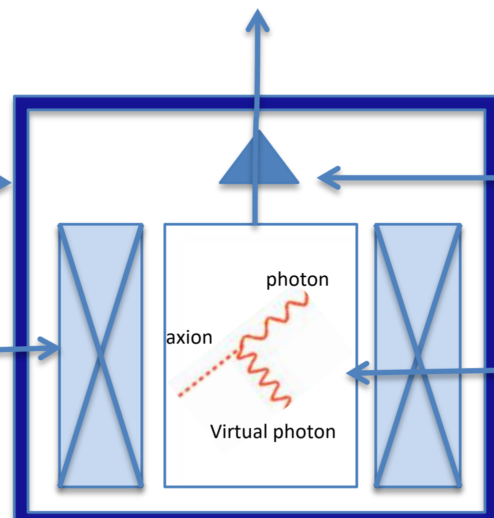
Axion Conversion Power ($\sim 10^{-24}$W): $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

Signal to Noise Ratio: $SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$

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

Cryogenics (<50mK)

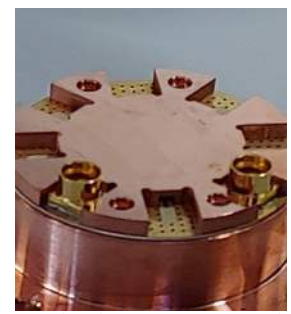
To RF Receiver



Quantum Amplifier

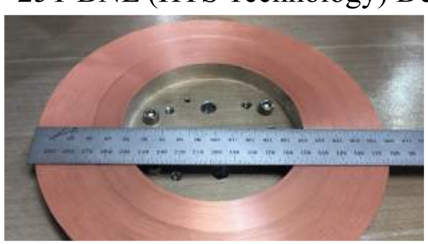
SQUID and/or JPA

Dr. Matlashov and Uchaikin



High Field SC Magnet

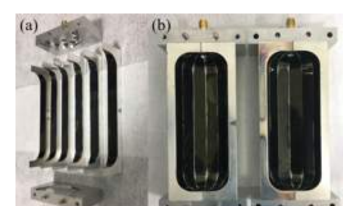
25T BNL (HTS Technology) Design



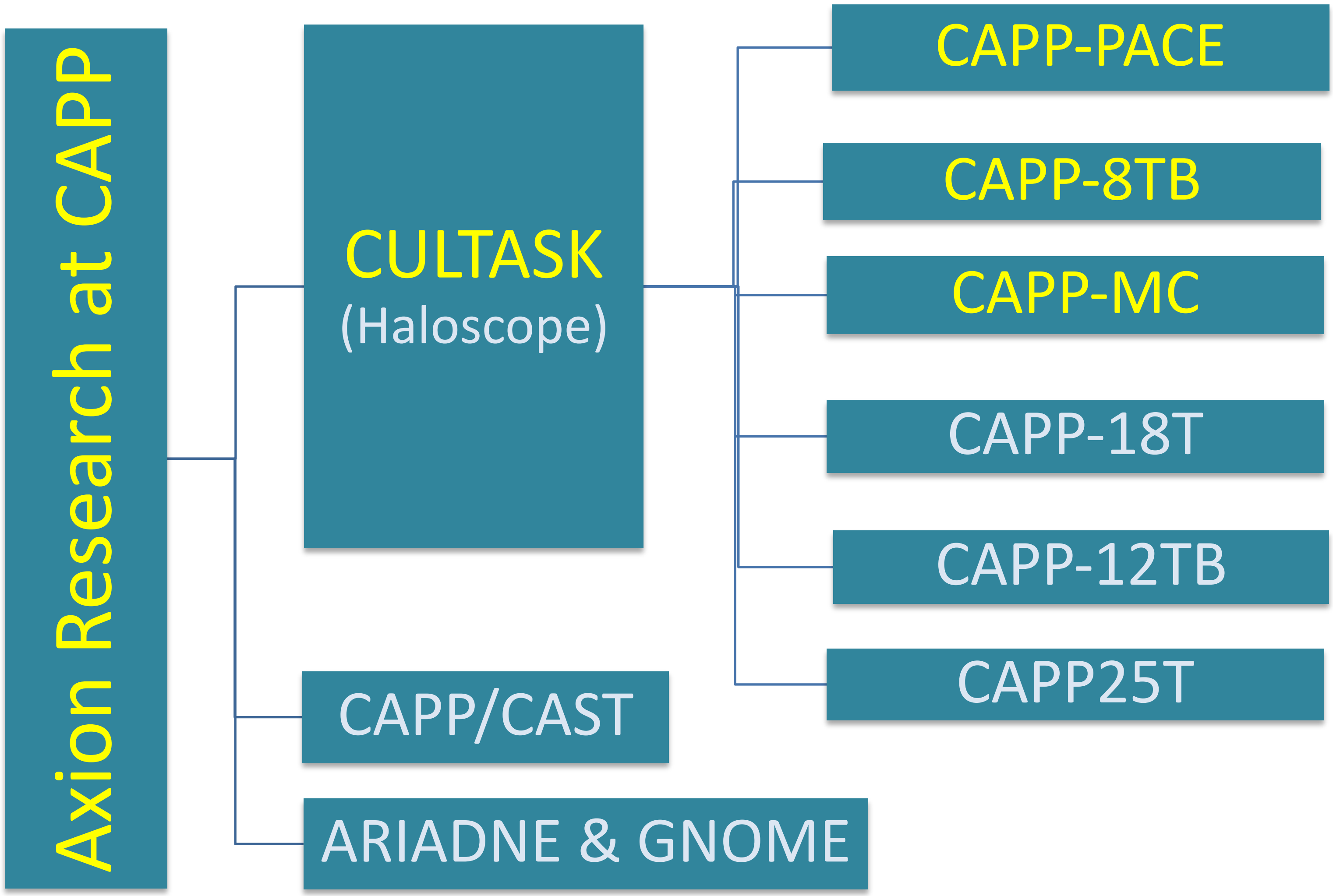
High Q Tunable Cavity

Superconducting Coating

Prof. Dojun Youm



CAPP's Axion Research



First 5 years…

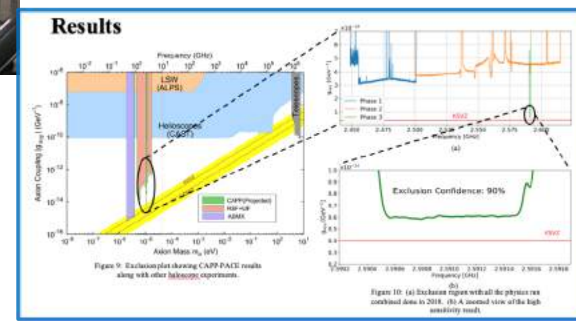
Axion Laboratory with 7 Low Vibration Pads in KAIST Munji campus

Founded in 2013 (Oct.)

BF5 & BF6

BF3 & BF4

First Axion DM data!



LVP

2013	2014	2015	2016	2017	2018	2019

CAPP Experimental Hall (LVP) in 2018

Refrigerators and Magnets

Testbeds

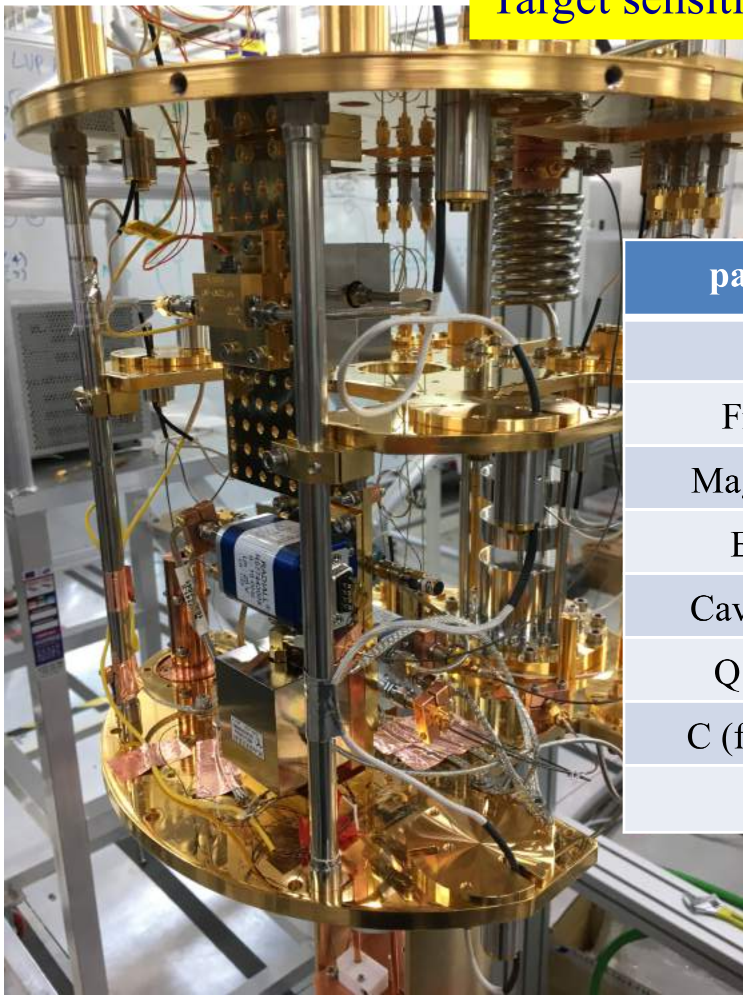
Refrigerators					Magnets					EXP
Vendor	Model	Base T (mK)	Cooling power	Install	B field	Bore (cm)	Material	Vendor	Delivery	
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016	26T	3.5	HTS	SUNAM	2016	BF3 & BF4 for testing RF, QA and cavities
BlueFors	LD400	10	18μW@20mK	2016	18T	7	HTS	SUNAM	2017	
Janis	HE3	300	25μW@300mK	2017	9T	12	NbTi	Cryo-Magnetics	2017	CAPP-MC
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100mK	**2017**	**8T**	**12**	**NbTi**	**AMI**	**2016**	CAPP-PACE
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100mK	2017	8T	16.5	NbTi	AMI	2017	CAPP-8TB
Oxford	Kelvinox	<30	400μW@120mK	2017	25T	10	HTS	BNL/CAPP	~~2020~~	Preparing for CAPP-12TB and CAPP-25T
Leiden	DRS1000	100	1.3mW @120mK	2019	12T	32	Nb_3Sn	Oxford	2020	

CAPP-PACE (Pilot Axion Cavity Experiment)

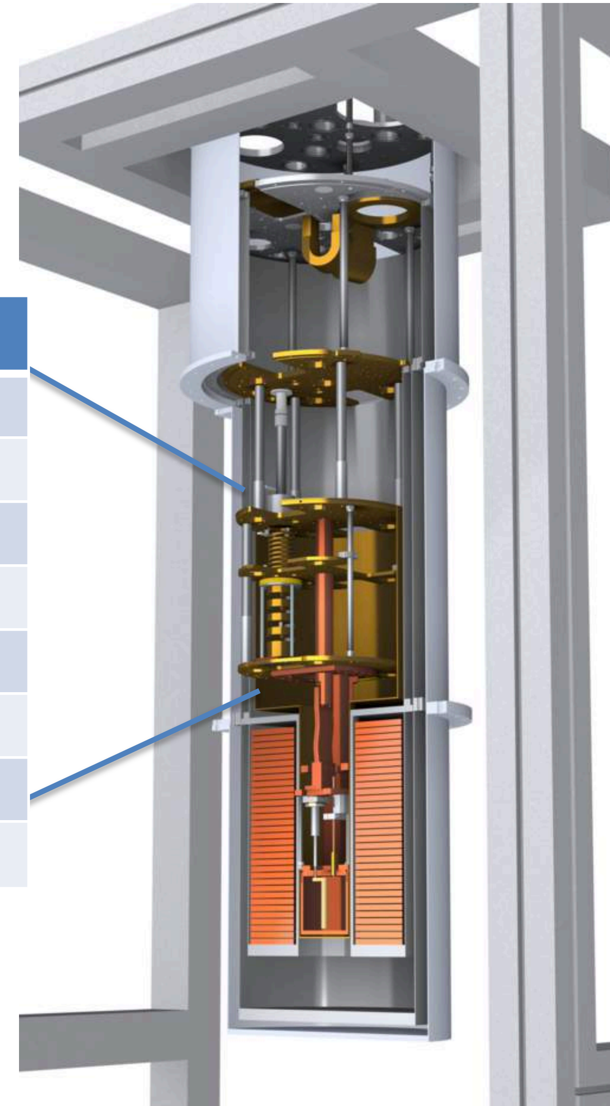
- Originally, R&D Project and testbed for
  - Cryogenics (dry-type dilution refrigerator)
  - Cavity development
  - Frequency Tuning System (FTS)
  - Low noise cryo-RF receiver (Optimization)
  - DAQ and Controls
- Has grown into the first complete axion experiment in Korea
  - Achieved cavity physical temperature below 40 mK
  - Flawless operation of FTS w/ Piezo actuators (sapphire and Cu rod)
  - System noise temperature below 1.2 K
  - Complete DAQ and Controls including automatic Safety Warnings
- Physics Data in 2018
  - 10*KSVZ runs: 2.45 – 2.70 GHz scanned
  - KSVZ run: around 2.59 GHz, ~ 1 MHz scanned

CAPP-PACE

Target sensitivity: 10*KSVZ, KSVZ

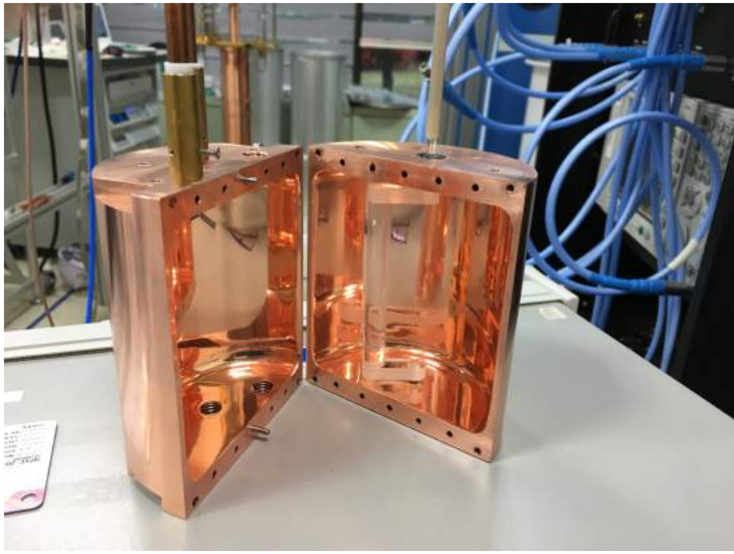


parameters	value
T_{cavity}	**<40mK (WR)**
Frequency	**2.45~2.70GHz**
Magnetic field	**7.2 T**
Bore size	**11.8 cm**
Cavity volume	**1.12 L**
Q unloaded	**~ 100,000**
C (form factor)	**~ 0.55**
T_{system}	**< 1.2 K**



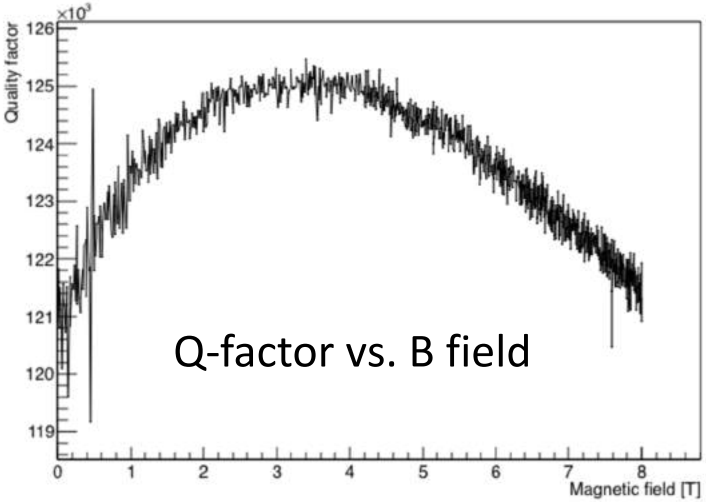
CAPP-PACE (innovations)

Cavity: OFHC Cu “split” type
Unloaded Q-factor of ~100,000



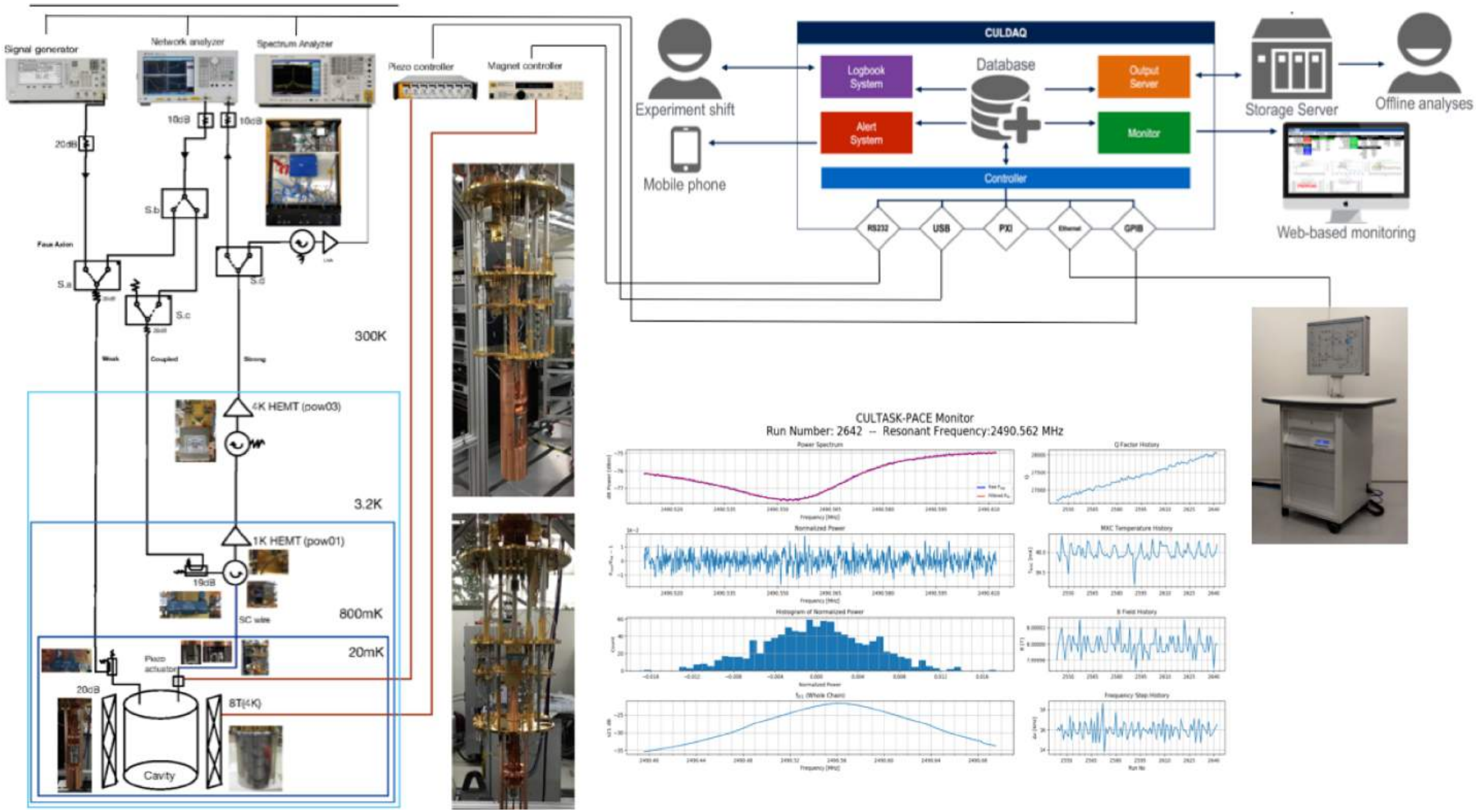
Tuning: Piezoelectric actuators (Attocube)
Thermal link to 1K plate
Sapphire rod to cavity by cryo bearing
Rotator resolution of 1/1000 deg → 16 kHz/step
Vibration free: w/ ball and spring

Linear and Rotational Piezo Actuators



CAPP-PACE (RF receiver chain)

RF read-out chain & Controls



CAPP-PACE (Online Monitor)

CAPP-PACE axion data

In 2018

	10*KSVZ (1)	10*KSVZ (2)	10*KSVZ (3)	KSVZ	10*KSVZ (4)
Date	1/19 – 2/13	7/23 – 8/01	8/14 – 8/23	9/01 – 10/26	11/1 – 11/24
Frequency [GHz]	2.450 – 2.500	2.500 – 2.548	2.547 – 2.613	2.5905 – 2.5915	2.613 – 2.710
Volume [liter]	0.59	0.59	1.12	1.12	1.12
T_{system} [K]	1.05	1.05	1.14	1.16	1.16
$\langle B_0 \rangle$ [T]	7.0	7.0	7.2	7.2	7.2
coupling	1.9	1.9	2.0	1.9	2.0
C (form factor)	.50	.50	0.55	0.66	0.55

CAPP-PACE results

Results (Mr. Caglar Kutlu's)

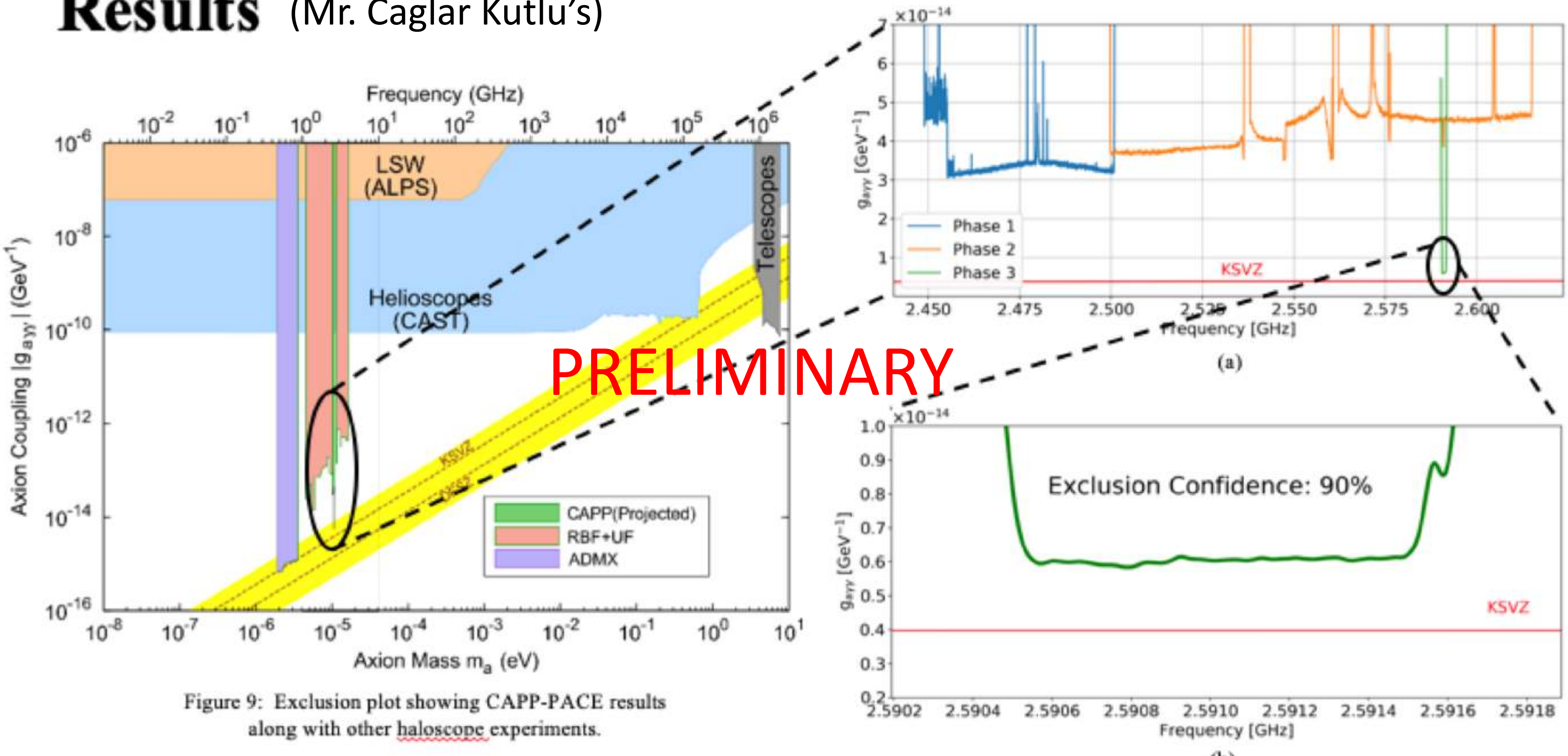


Figure 9: Exclusion plot showing CAPP-PACE results along with other haloscope experiments.

Figure 10: (a) Exclusion region with all the physics run combined done in 2018. (b) A zoomed view of the high sensitivity result.

Axion Detection Scheme (CULTASK)

P. Sikivie's Haloscope:

Axion Conversion Power (~10^{-24}W): $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

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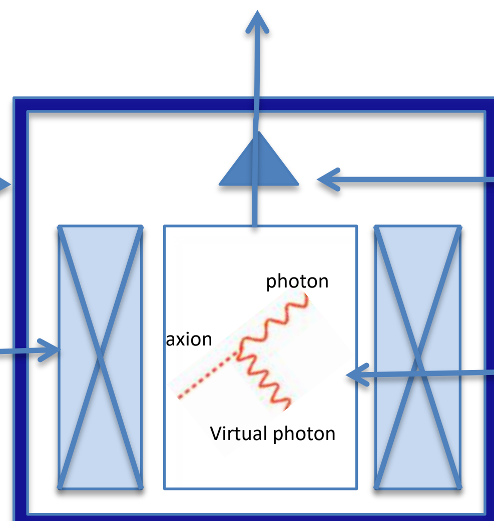
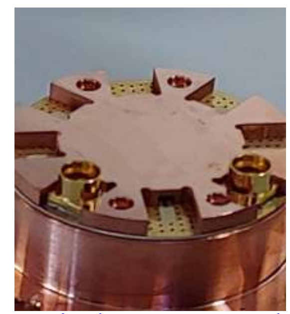
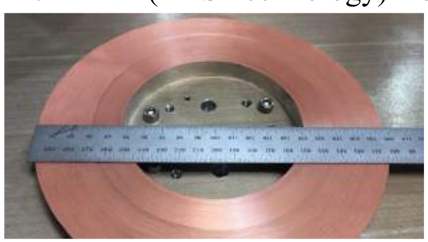
To RF Receiver



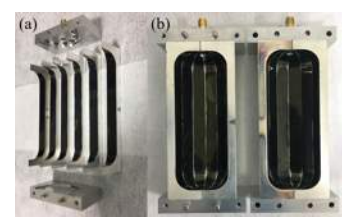
Quantum Amplifier
SQUID and/or JPA
Dr. Matlashov and Uchaikin



High Field SC Magnet
25T BNL (HTS Technology) Design



High Q Tunable Cavity
Superconducting Coating
Prof. Dojun Youm



How to improve?

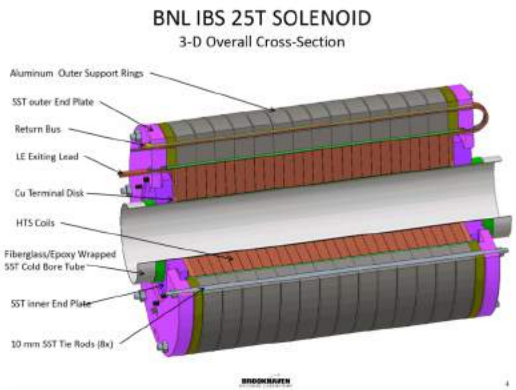
- Maximize Signal (B^2VQ)
  - 25T 10cm bore HTS magnet by BNL (?) ~ x100 faster scan
  - 12T 32cm bore LTS magnet by Oxford (2020) > x100 faster scan
    - Higher frequencies without shrinking volume
      - Pizza Cavity (S. Youn)
      - Dielectric rings (TM_{030} and TM_{050}) (O. Kwon)
  - Improving Q-factor of cavity – YBCO cavity (D. Ahn) > x20 faster scan

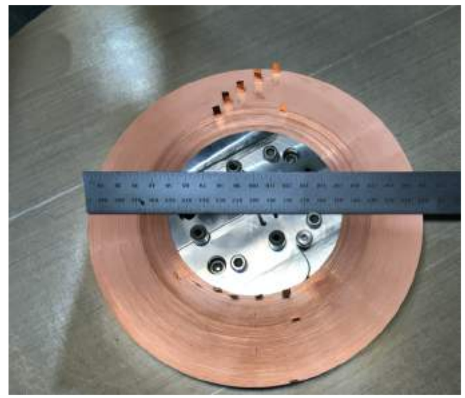
- Minimize Noise ($T_{system} = T_{physical} + T_{amp}$) > x100 faster scan
  - Quantum Amplifier - SQUID and/or JPA
  - Optimize cryo-RF receiver chain

- Others (DAQ efficiency)
  - Dead-time-less DAQ

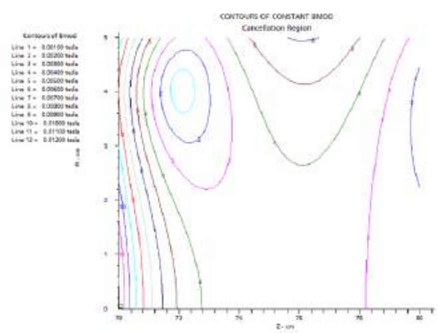
High Field & Big Bore Magnets

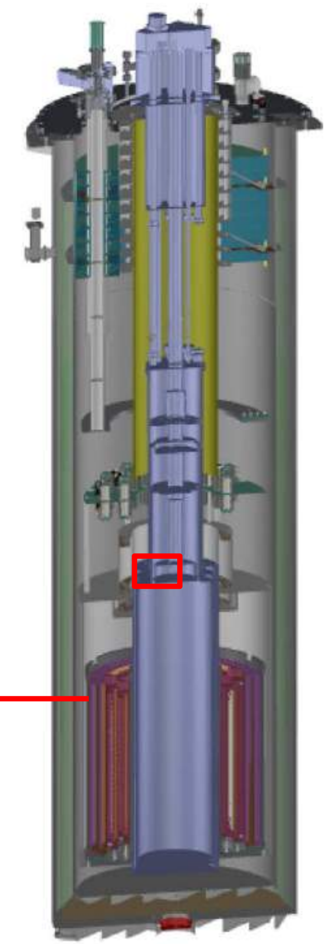
- 25T 10cm bore HTS magnet by BNL (2021) – Funding limited!
  - ➢ The first 16 (of 24) pancakes wound!
  - ➢ No-insulation coil design (ReBCO tapes)
  - ➢ 5 km of SC tape will be delivered





- 12 T 32 cm bore LTS magnet by Oxford Inst. (end of 2019)
  - ➢ Nb_3Sn
  - ➢ Powerful Leiden DRS1000

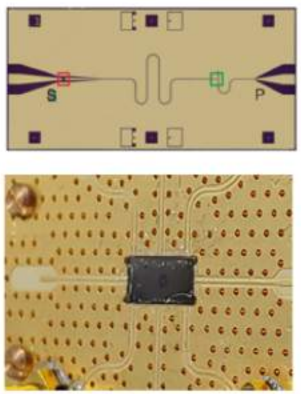


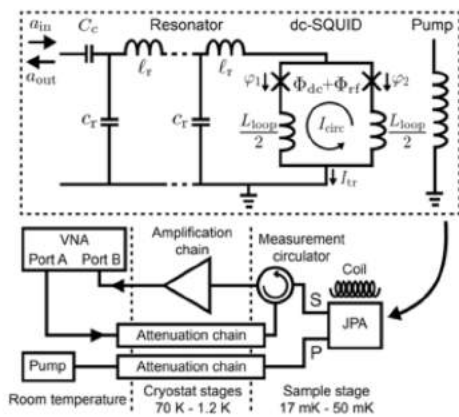


R&D Projects (JPA)

- Led by A. Matlashov (from Los Alamos) and S. Uchaikin (from D-Wave)
- First batch of JPA’s for PACE frequency range (2.4 GHz) from U. of Tokyo (Nakamura’s group): taking adv. of their know-hows

JPAs: Collaboration with University of Tokyo and RIKEN





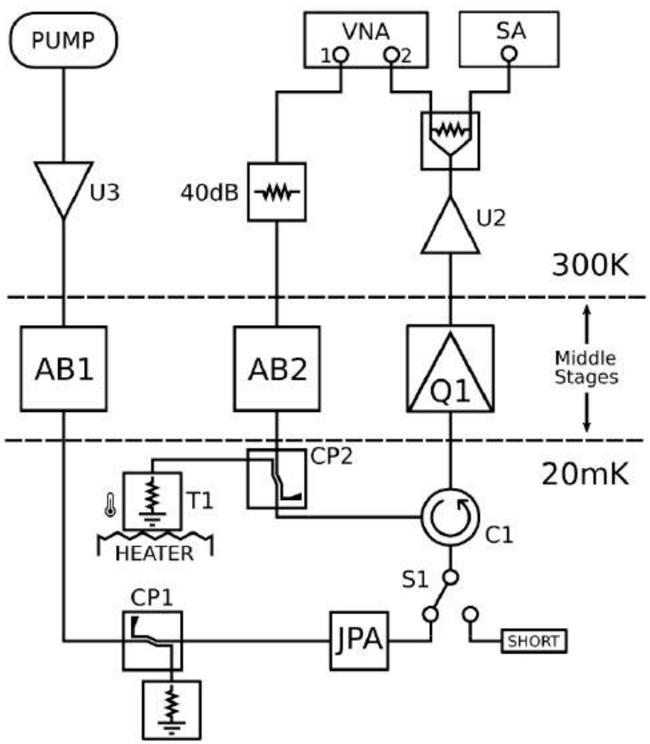
From Andrei Matlashov

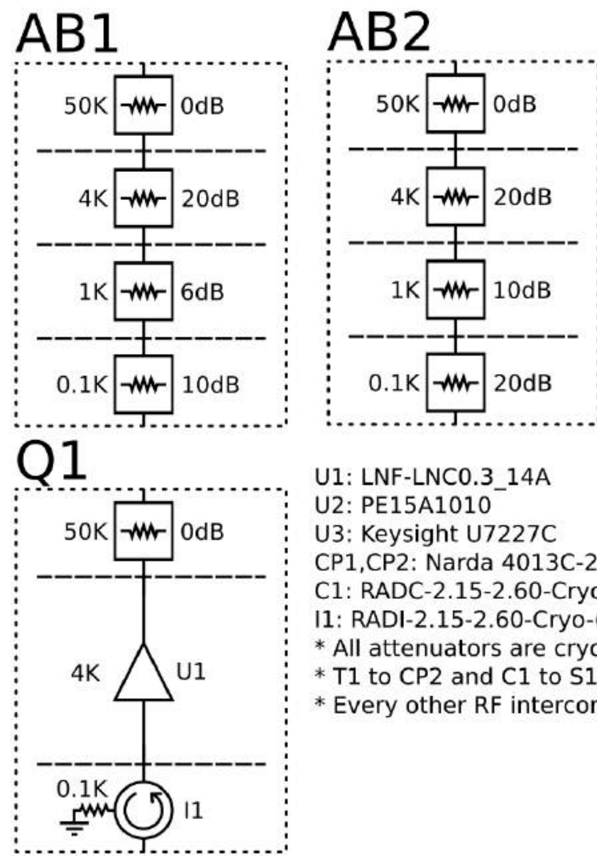
RIKEN, University of Tokyo

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

R&D Projects (JPA)

- Test Setup





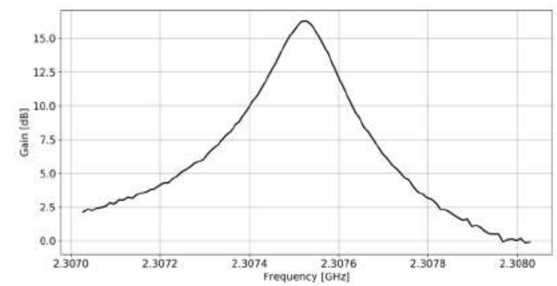
U1: LNF-LNC0.3_14A
U2: PE15A1010
U3: Keysight U7227C
CP1,CP2: Narda 4013C-20
C1: RADC-2.15-2.60-Cryo-(0.01-4K)-S23-1WR-MS-b
I1: RADI-2.15-2.60-Cryo-(4-77K)-S3-1WR-MS-b
* All attenuators are cryogenic type from XMA.
* T1 to CP2 and C1 to S1 is NbTi-NbTi
* Every other RF interconnect is SCuNi-CuNi.

From Caglar Kutlu

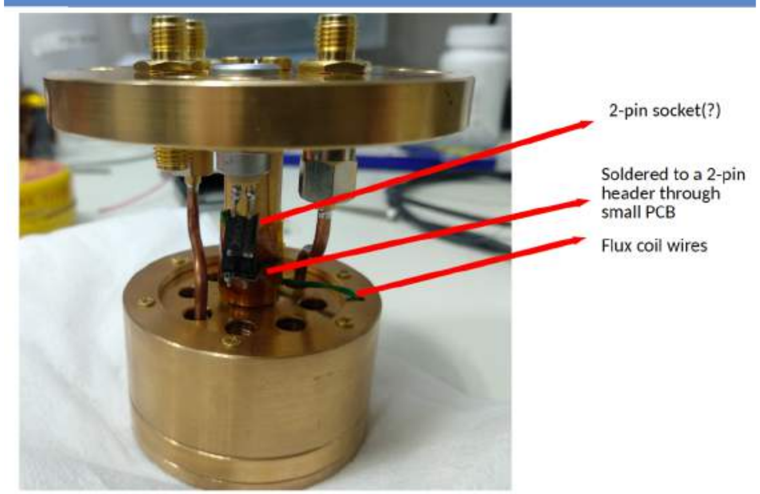
R&D Projects (JPA)

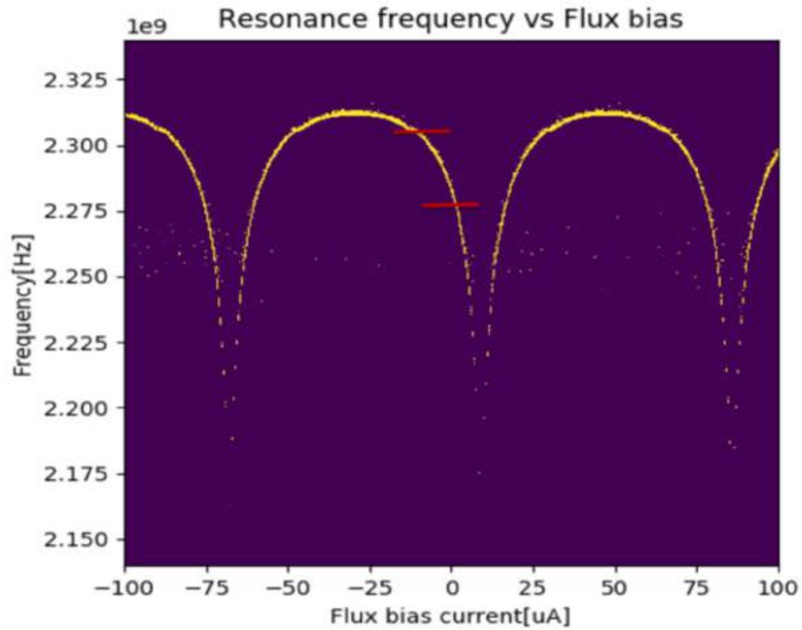
- Second batch of JPA's for 1.6, 4.0 and 6.9 GHz arrived
- 2.3 GHz JPA implemented into CAPP-PACE in Aug. (2019)
- Noise measurement measured < 125 mK: close to QNL
- Crucial to speed up the search (20~100 times) w/ squeezing
- Almost ready to take data with JPA

Gain vs frequency



ASSEMBLY



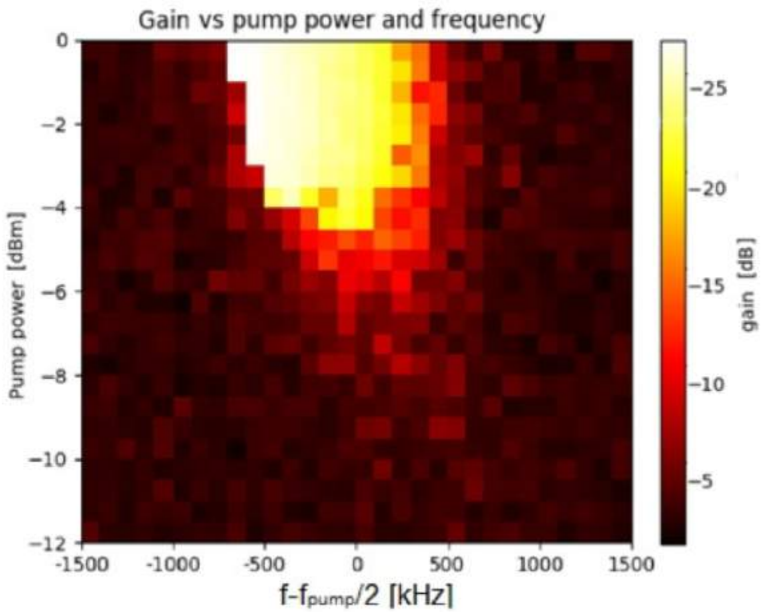


Operating range about 30 MHz

6

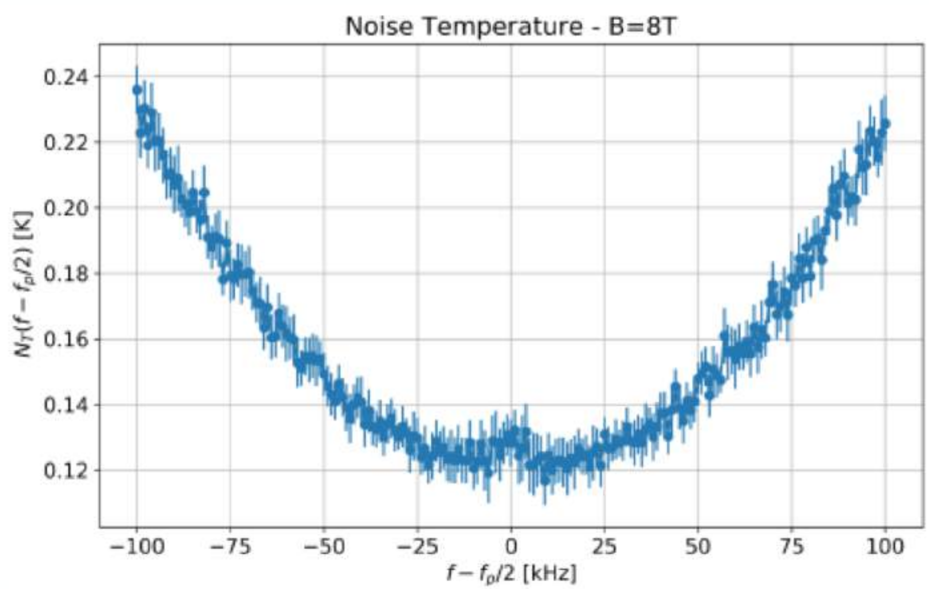
R&D Projects (JPA)

Gain vs. pump power and frequency



Maximum Gain > 25dB (0 dBm corresponds to -60 dBm at JPA pump inpu

Noise Temperature vs Frequency



R&D Projects (Superconducting cavity)

➤ SC Resonant Cavity in high magnetic field

- ✓ No significant progress last 15 years
- ✓ Improve conversion power: 50k (typical Cu) to 1M(possibly...)
- ✓ Usual SC material loses superconductivity even at small amount of magnetic field
- ✓ Choice of material: HTS → REBCO (Rare Earth)
- ✓ Help from KAIST: superconductor expert Prof. Dojun Youm
- ✓ Polygon cavity with YBCO tape attached (texture aligned): 6.9 GHz
- ✓ Sustain superconductivity (high Q-factor) even up to 8 Tesla!
- ✓ arXiv:1904.05111
- ✓ Room for improvement further
- ✓ Bigger structure designed

det] 10 Apr 2019

Maintaining high Q-factor of superconducting $YBa_2Cu_3O_{7-x}$ microwave cavity in a high magnetic field

Danho Ahn,[1,2] Ohjoon Kwon,[1] Woohyun Chung,[1,*] Wonjun Jang,[3] Doyu Lee,[1,2] Jhinhwan Lee,[4] Sung Woo Youn,[1] Dojun Youm,[2] and Yannis K. Semertzidis[1,2]
[1]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[2]*Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, 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*
(Dated: April 11, 2019)

A high Q-factor microwave resonator in a high magnetic field could be of great use in a wide range of fields, from accelerator design to axion dark matter search. The natural choice of material for the superconducting cavity to be placed in a high field is a high temperature superconductor (HTS) with a high critical field. The deposition, however, of a high-quality, grain-aligned HTS film on a three-dimensional surface is technically challenging. We have fabricated a polygon-shaped resonant cavity with commercial $YBa_2Cu_3O_{7-x}$ (YBCO) tapes covering the entire inner wall and measured the Q-factor at 4 K at 6.93 GHz as a function of an external DC magnetic field. We demonstrated that the high Q-factor of the superconducting YBCO cavity showed no significant degradation from 1 T up to 8 T. This is the first indication of the possible applications of HTS technology to the research areas requiring a strong magnetic field at high radio frequencies.

R&D Projects (Superconducting cavity)

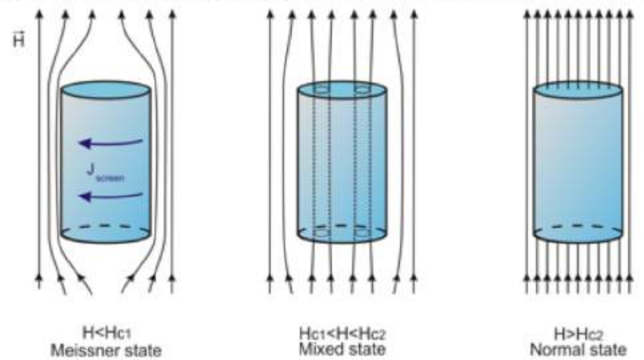
CAPP
Center for Axion and Precision Physics Research

KAIST

Superconductivity in DC Magnetic Field

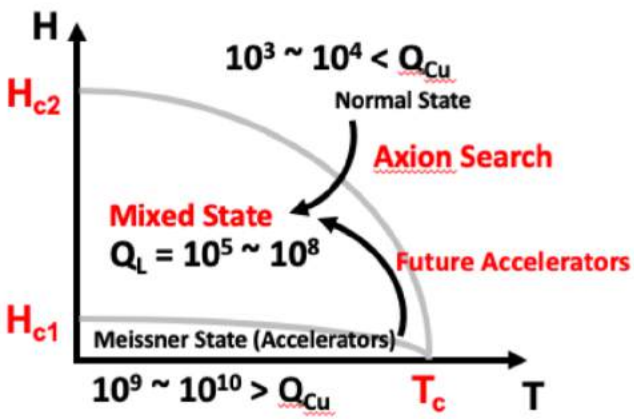
Three Phases of Type II Superconductor

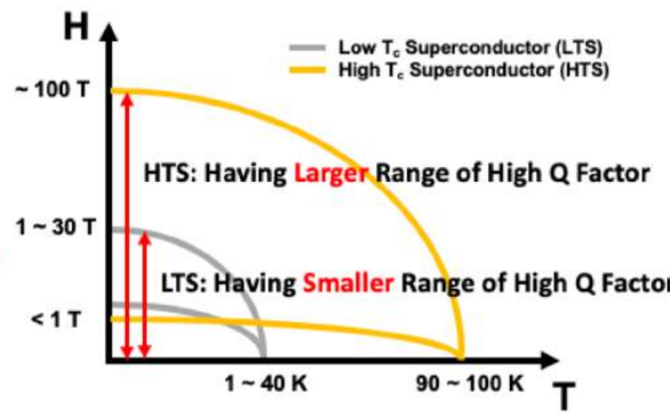
https://www.cee.elektro.dtu.dk/news/nyhed?id=E6796539-A36B-4CA5-BC31-CBDBBCA335D8



Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)
Nb_3Sn	A15 cubic	Negligible	18	27 T (4 K)
MgB_2	*P6/mmm* hexagonal	2–2.7	39	15 T (4 K)
YBCO	Orthorhombic layered perovskite	7	92	>100 T (4 K)
Bi-2223	Tetragonal layered perovskite	~50–100	108	>100 T (4 K)

D. C. Larbalastier *et al*, "High-T_c superconducting materials for electric power applications," Nature (2001).



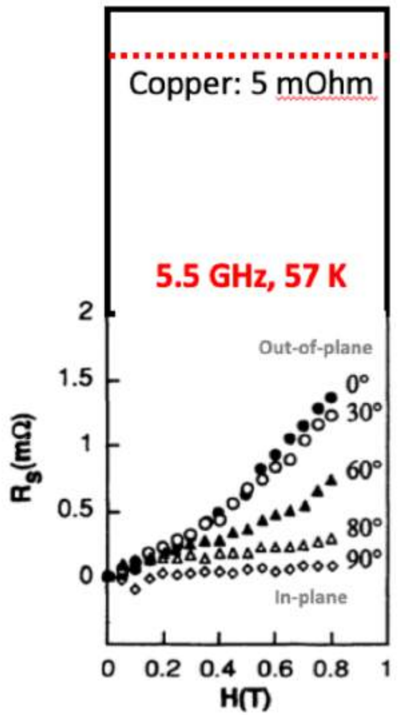


From Danho Ahn

R&D Projects (Superconducting cavity)

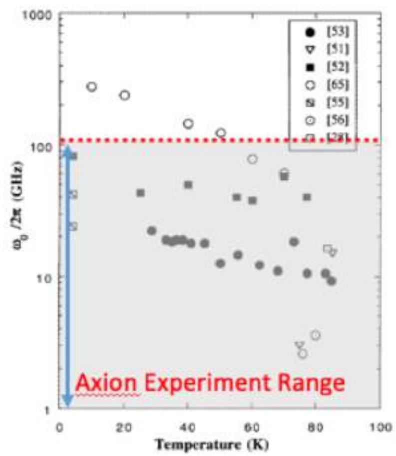
Are $YBa_2Cu_3O_{7-x}$ Films Good for Axion Search?

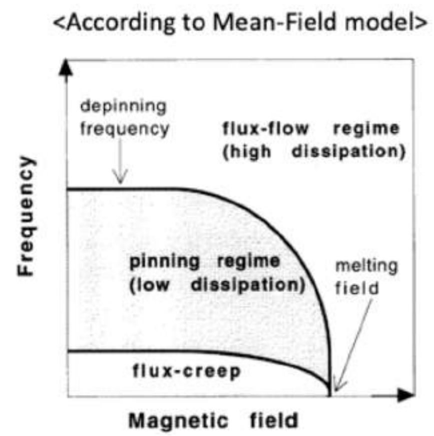
Surface Resistance (R_s)



M. Golosovsky *et al*, "Vortex depinning frequency in YBCO superconducting thin films," Phys. Rev. B (1994).

Depinning Frequency





M. Golosovsky *et al*, "High-frequency vortex dynamics in YBCO," Supercond. Sci. Technol. (1996).

The experiments say 'YES'

Why there is no practical YBCO microwave cavity?

From Danho Ahn

R&D Projects (Superconducting cavity)

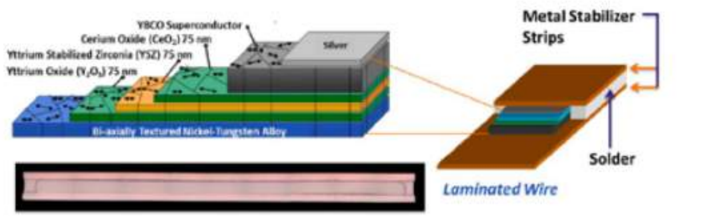
Impossibility of Biaxially Textured Cavity Surface

There is no method to implement biaxially textured film on the curved geometry.

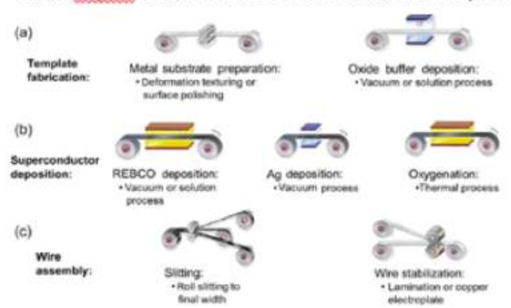
- Biaxially textured = Grains are aligned
  a, b crystal direction

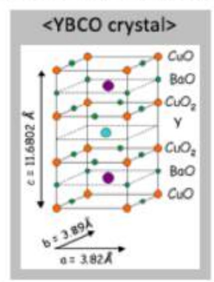
- ✓ RABiTs: YBCO, AMSC, 10mm width
- ✓ IBAD: ReBCO, Superpower

<Rolling-Assisted, Biaxially Textured Substrate (RABiTS) Method>



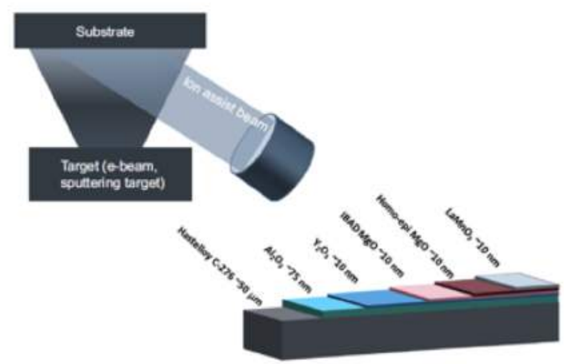
M. W. Rupich *et al*, "Second Generation Wire Development at AMSC," IEEE (2013).





C. Rey *et al*, "Superconductors in the Power Grid," Woodhead Publishing (2015).

<Ion Beam-Assisted Deposition (IBAD) Method>



C. Rey *et al*, "Superconductors in the Power Grid," Woodhead Publishing (2015).

From Danho Ahn

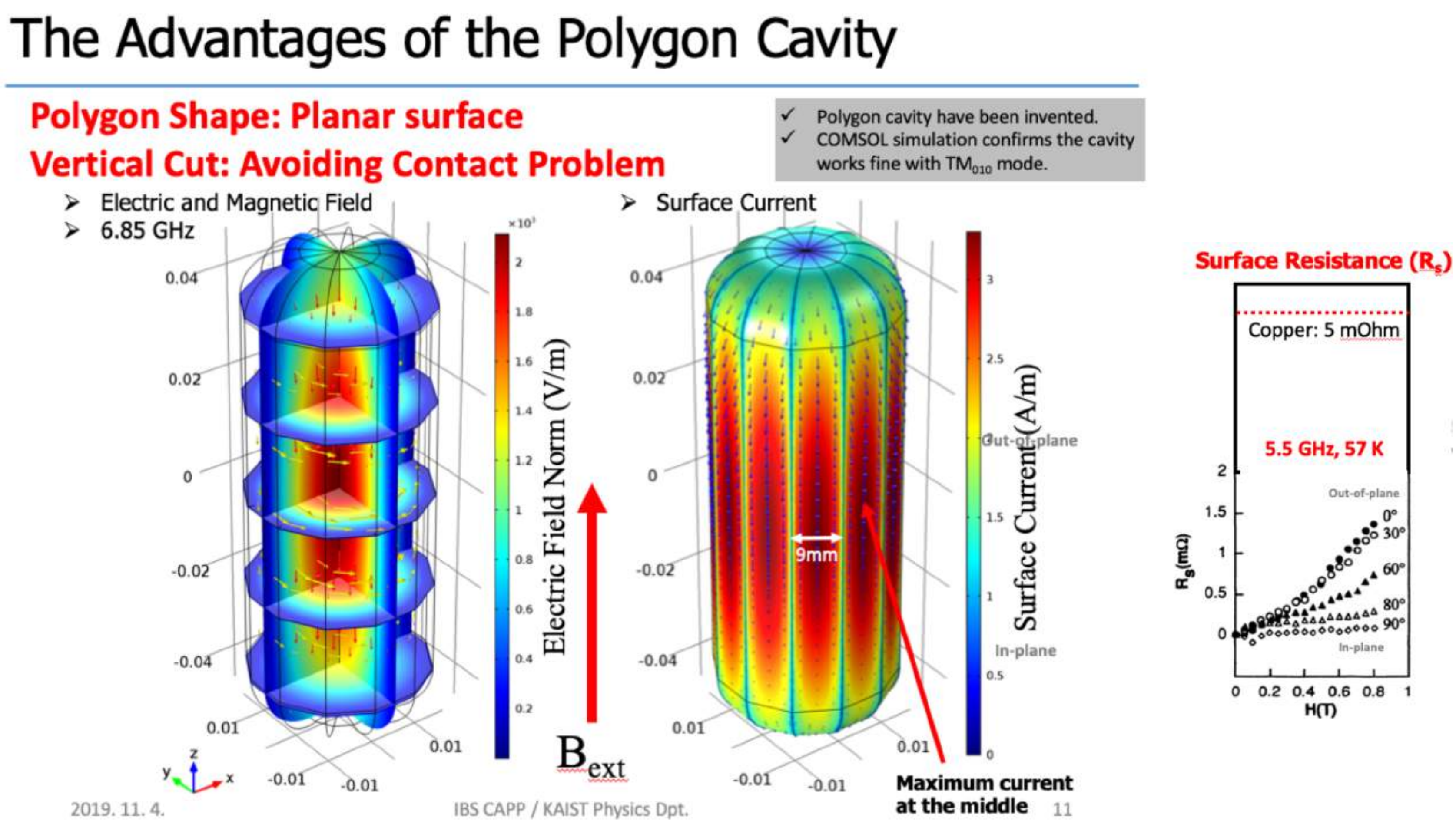
R&D Projects (Superconducting cavity)

CAPP's Solution:

- ➢ Bulk or deposition of HTS SC on cavity is almost impossible
  - ✓ Growing well-textured HTS film on 3D surface is not available
- ➢ Many commercial HTS tapes are available.
  - ✓ RABiTs: YBCO, AMSC, 10mm width
  - ✓ IBAD: ReBCO, Superpower
- ➢ How can we attach tape on the cavity inner surface?
  - ✓ **How can we make 3D surface with planar objects?**
  - ✓ **What about "melon cut"?**

From Danho Ahn

R&D Projects (Superconducting cavity)

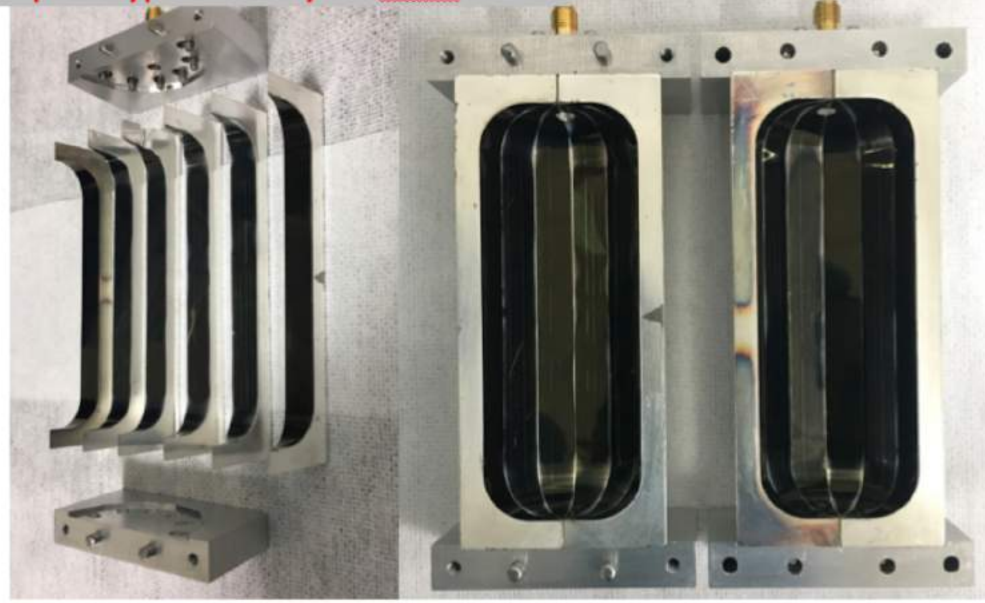


From Danho Ahn

R&D Projects (Superconducting cavity)

Prototype Cavity

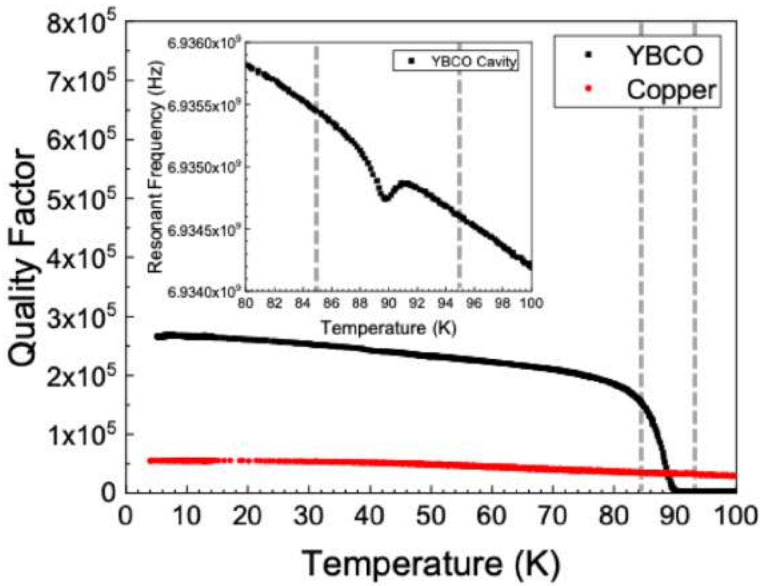
1st prototype SC cavity for axion search



- Attach YBCO tape on the cavity inner surface with epoxy.
- Cut edges exposed on the sides and polish the sides.
- Remove the silver protective layer.
- Sputter silver on the side of the tape. (Ni-9W may cause large loss)

From Danho Ahn

Cavity Characterization (1): Temperature



- Transition temperature = 90 K
- Anomalous resonance frequency drop at 90 K
- Q factor of YBCO Cavity (4 K) = 267,000.
- Q factor of Copper Cavity (4 K) = 56,500.

M. Golosovsky *et al*, "Vortex depinning frequency in YBCO superconducting thin films," Phys. Rev. B (1994).

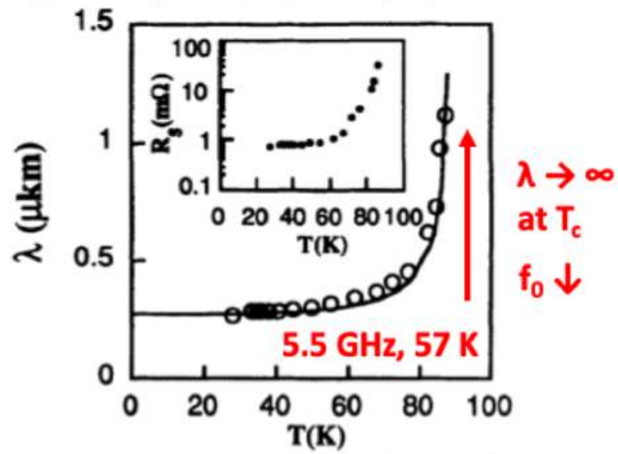
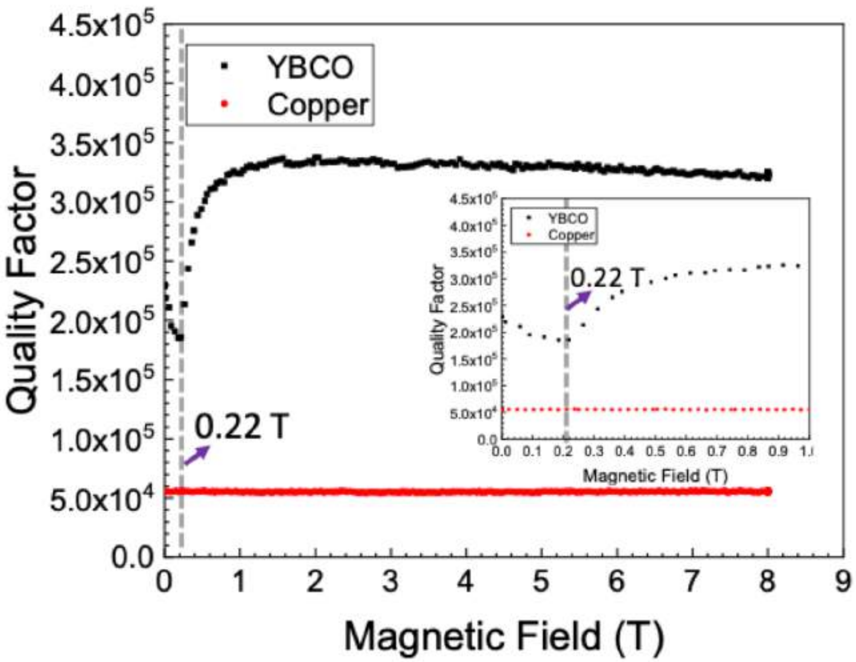


FIG. 2. Temperature dependence of the penetration depth λ of a pair of laser-ablated $YBa_2Cu_3O_{7-x}$ films at $f=5.4$ GHz calculated from Eq. (6). The solid line is the two-fluid dependence $\lambda=\lambda_0[1-(T/T_c)^4]^{-1/2}$ with $T_c=89$ K and $\lambda_0=0.27$ μkm. Inset shows temperature dependence of the surface resistance R_s.

From Danho Ahn

Cavity Characterization (2): Magnetic Field



- Q factor at 0.23 T = 56,000
- Maximum Q at 3.5 T = 337,000
- $Q_{YBCO} \sim 6 \times Q_{Cu}$

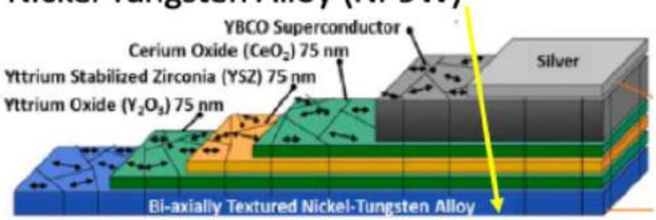
Why the quality factor increased suddenly?

$$\frac{1}{Q} = \frac{P_{YBCO\ film} + P_{etc}}{\omega U_{tot}}$$

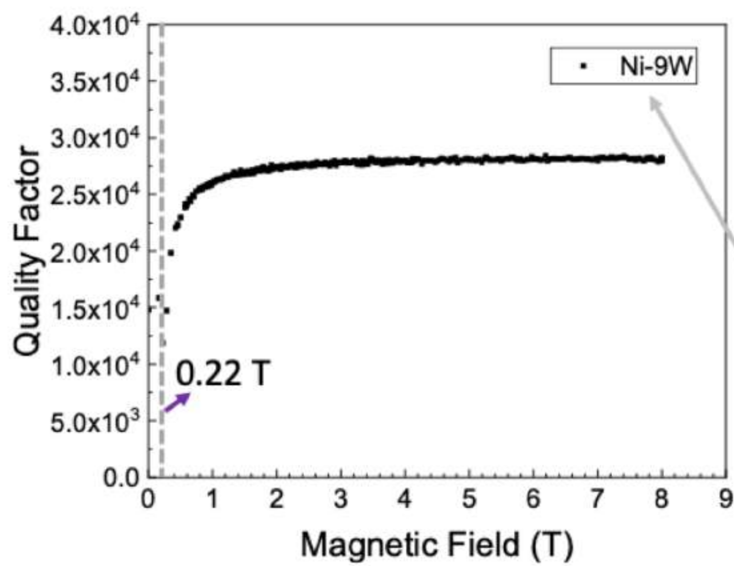
From Danho Ahn

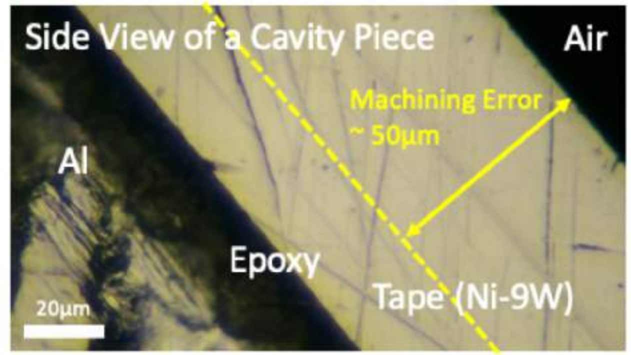
Magnetic Property of Nickel Tungsten Alloy

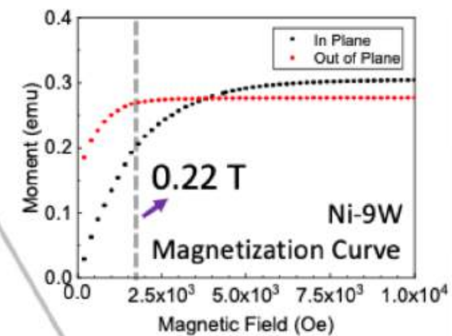
Nickel Tungsten Alloy (Ni-9W)

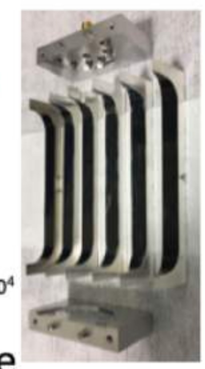


M. W. Rupich *et al*, "Second Generation Wire Development at AMSC," IEEE (2013).







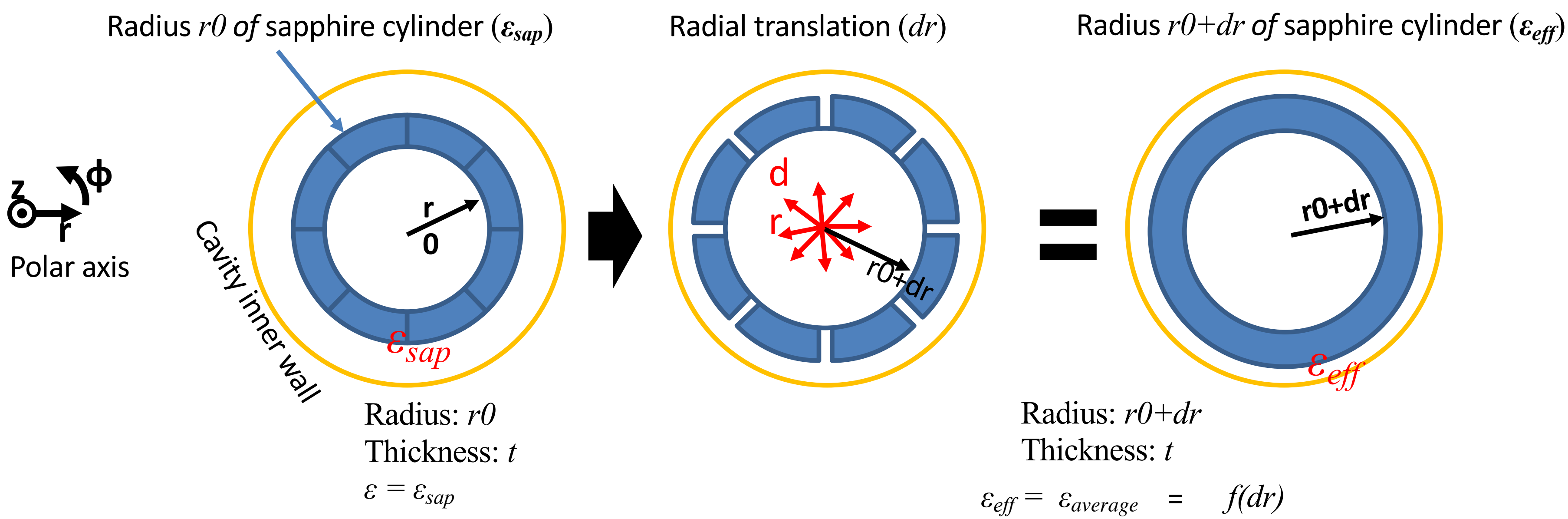


- 1/12 of Ni-9W surface
- Q factor kink appears at 0.22 T (Same as full YBCO cavity)

From Danho Ahn

R&D Projects (Dielectric Meta-material)

Higher order mode axion search w/ dielectric *meta-material*

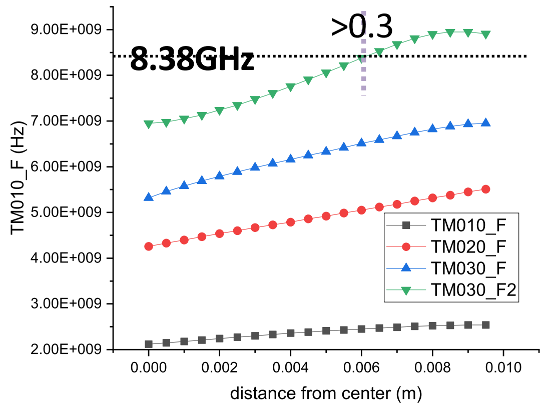


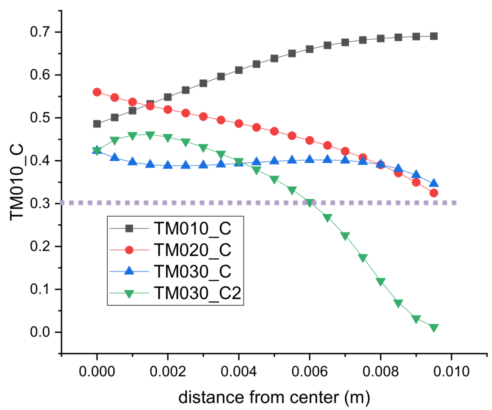
Radial translation of dielectric pieces effectively changes inner radius as well as effective dielectric constant

Frequency tuning of TM_{0n0} mode

From Ohjoon Kwon

Wide Frequency tuning w/ DM





Preliminary

mode	Original method TM010	TM020	TM030-1	TM030-2	TM040	TM050
F (GHz) **(12T used)**	2.45-2.5 **~0.9**	4.26-5.51 **1.5~1.9**	5.3-6.95 **1.8~2.4**	6.95-8.38 **2.4~2.9**	8.4~10 **2.9~3.5**	11.1~12.8 **3.9~4.5**
C (average)	0.6 – 0.64 **~0.62**	0.56 – 0.33 **~0.45**	0.43– 0.35 **~0.4**	0.46– 0.3 **~0.4**	**~0.24**	**~0.18**
Normalized scan rate	1	**2.3**	**2.6**	**3.9**	**2.4**	**2.3**

4.26 - 8.38GHz tuning available w/ same tuning mechanism

1.5~2.9 **(1~1.5GHz can be covered with conventional method)**

+ α w/ TM_{040}, TM_{050}

From Ohjoon Kwon

Improvements

P. Sikivie's Haloscope:

Axion Conversion Power (~10^{-24}W): $$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

Signal to Noise Ratio: $$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{\text{int}}}{\Delta f_a}}$$

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

Cryogenics

Physical temp of cavity
2018: 38 mK

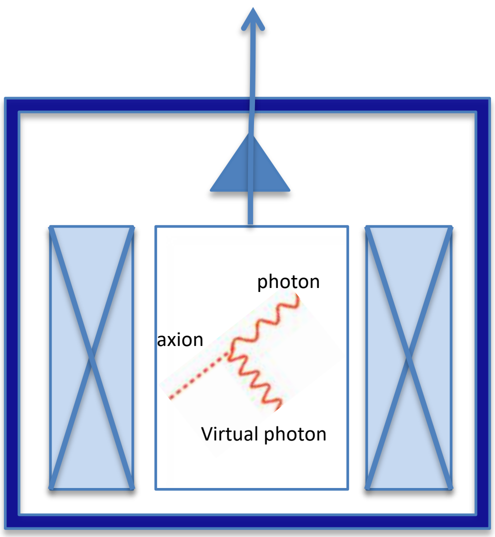
Quantum Amplifier

JPA noise temp: T_N<125 mK@2.3 GHz
Other (switches, circulators, cables): ~30 mK

Total system noise temp:

$T_{syst} = T_{Tphy} + T_{RF}$
2018: 1.2 K
2019: < 200 mK, x36 faster scan

To RF Receiver



High Field SC Magnet

B^4V^2:

8T (1 *liter*): x1
8T (2 *liters*): x4
12T (30 *liters*): ~ x100
25T (4 *liters*): ~ x400

High Q Tunable Cavity

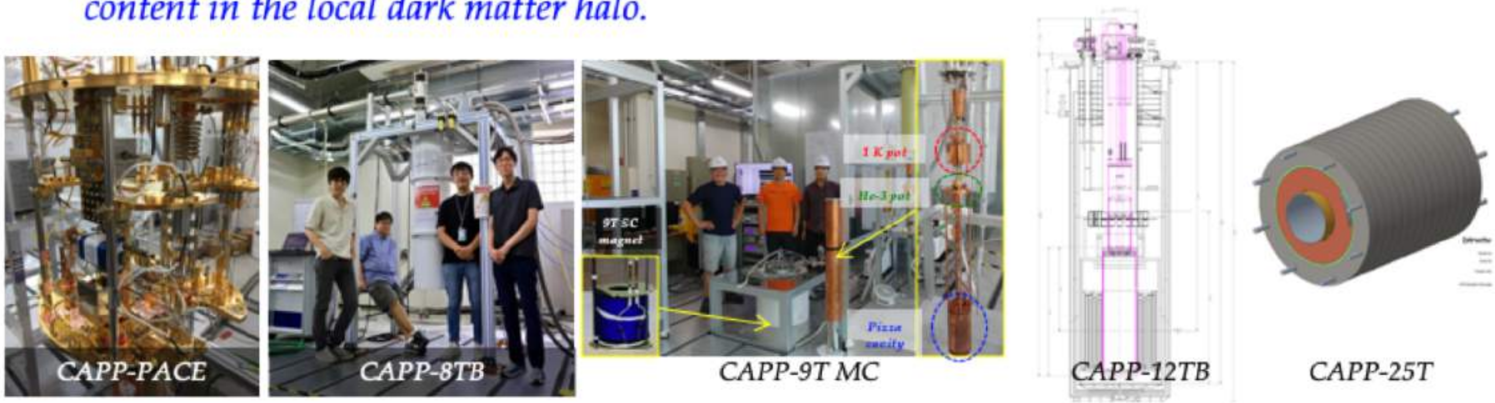
YBCO taping
Q-factor: > x6 better than Cu already
> x20 possible

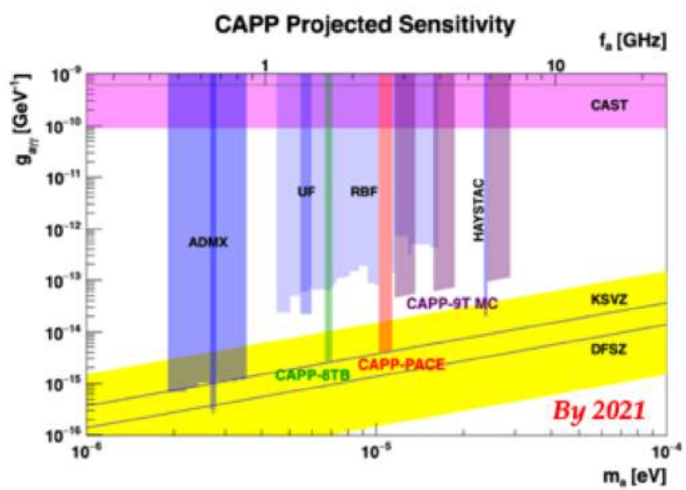
Plans/Goals (Optimistic)

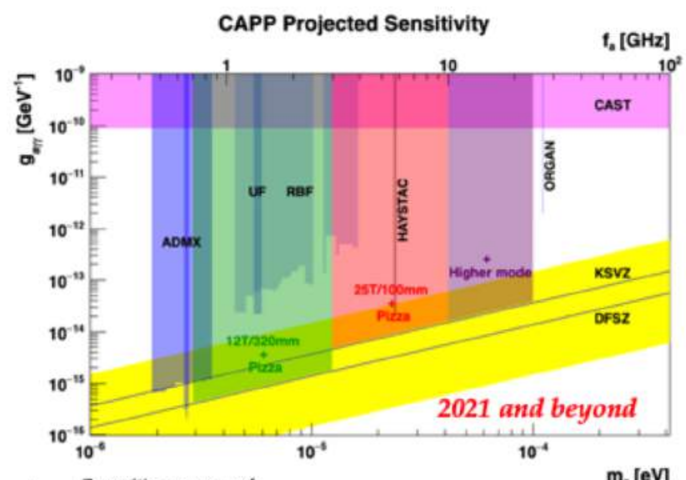
- In 2018 CAPP-PACE's KSVZ run (2 months) scanned 1 MHz (6 MHz/year)
  - ✓ System noise temperature of ~1.2 K
  - ✓ Cavity $Q_L \sim 30{,}000$ ($Q_0 \sim 90{,}000$)
  - ✓ Cavity volume: 1 liter
- Physics run with JPA will start soon (before the end of 2019)
  - ✓ System NT < 200 mK (x36)
  - ✓ Cavity volume: 2 liters (x4)
  - ✓ Scanning rate: > x100 → ~ 500 MHz/year
- In 2020, taking data with JPA and SC cavity
  - ✓ Scanning rate: 0.5 x (Q_{sc}/Q_0) GHz
  - ✓ Qsc ~ 10^6, then we should be able to scan ~ 5 GHz/year (very optimistic!!)
- JPA and SC cavity should be applied to CAPP-12TB with high frequency R&D
  - ✓ x100 enhancement from B^4V^2 → 1~10 GHz DFSZ scan in a year (Hmmm)

CULTASK Prospects

- *All the ingredients together, we will reach the DFSZ sensitivity even for 10% axion content in the local dark matter halo.*







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

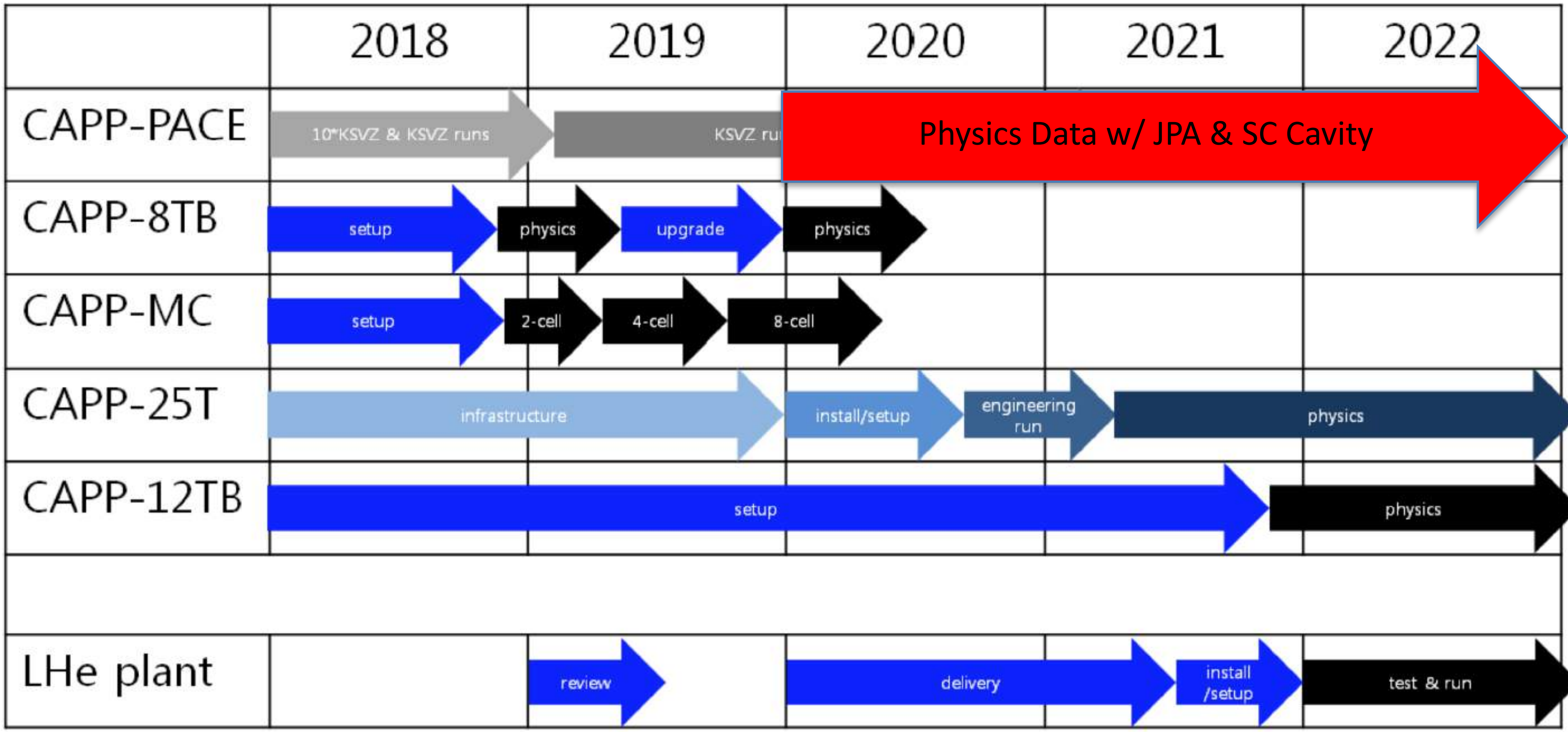
Summary

- CAPP has successfully established multiple haloscope axion dark matter experiments in Korea.
- CAPP's pilot experiment, CAPP-PACE started to take physics data in 2018 (10*KSVZ and KSVZ runs).
- 2 more experiments, CAPP-8TB and CAPP-MC, are ready to take data soon.
- R&D on superconducting cavity looks promising!
- Major improvement is expected with big bore (12 T, 32 cm bore) magnet (end of 2019) and high frequency regime.
- CAPP will start physics runs with quantum amplifier + superconducting cavity for axion dark matter search in 2020.

Thank You For Your Attention!

Timeline

CAPP Axion Dark Matter Search Timeline



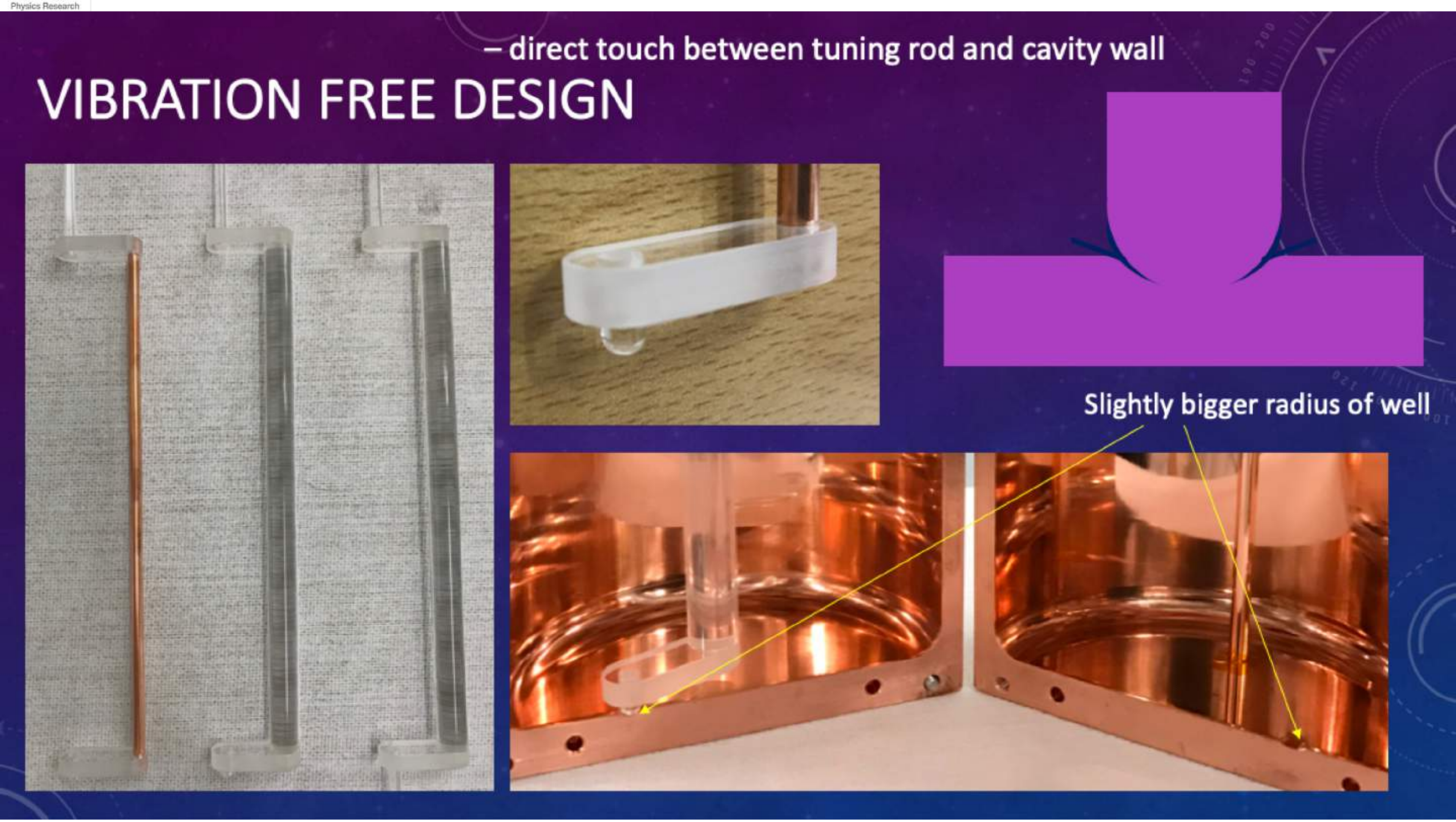
Upcoming Publications in 2019

- **Design and Operation of a Microwave Cavity Axion Detector for the 10 – 20 μeV**
  For PRD
- **First results from the CAPP-PACE microwave cavity axion experiment**
  For Physical Review Letters
- **A superconducting microwave cavity made of YBCO tapes in a high magnetic field**
  For Nature (rapid communication) or PRR

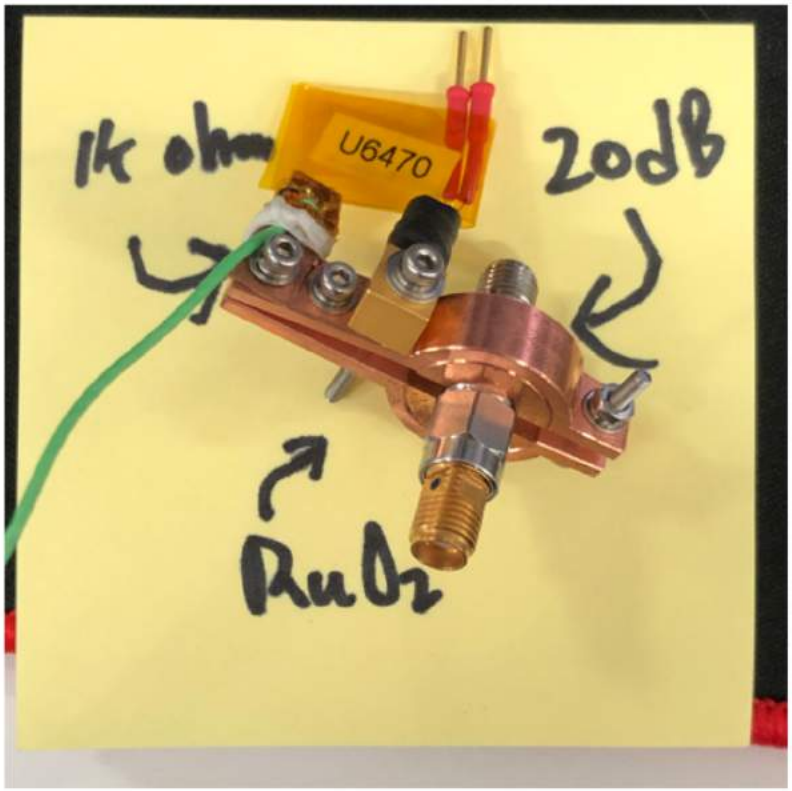
- **And Many More on…**
  - **SQUID and/or JPA test results**
  - **LVP**
  - **Physics results from CAPP-8TB**
  - **Results from CAPP-MC**
  - **Another from SC cavity development**
  - **Dielectric cavity for high frequency results**
  - **….**

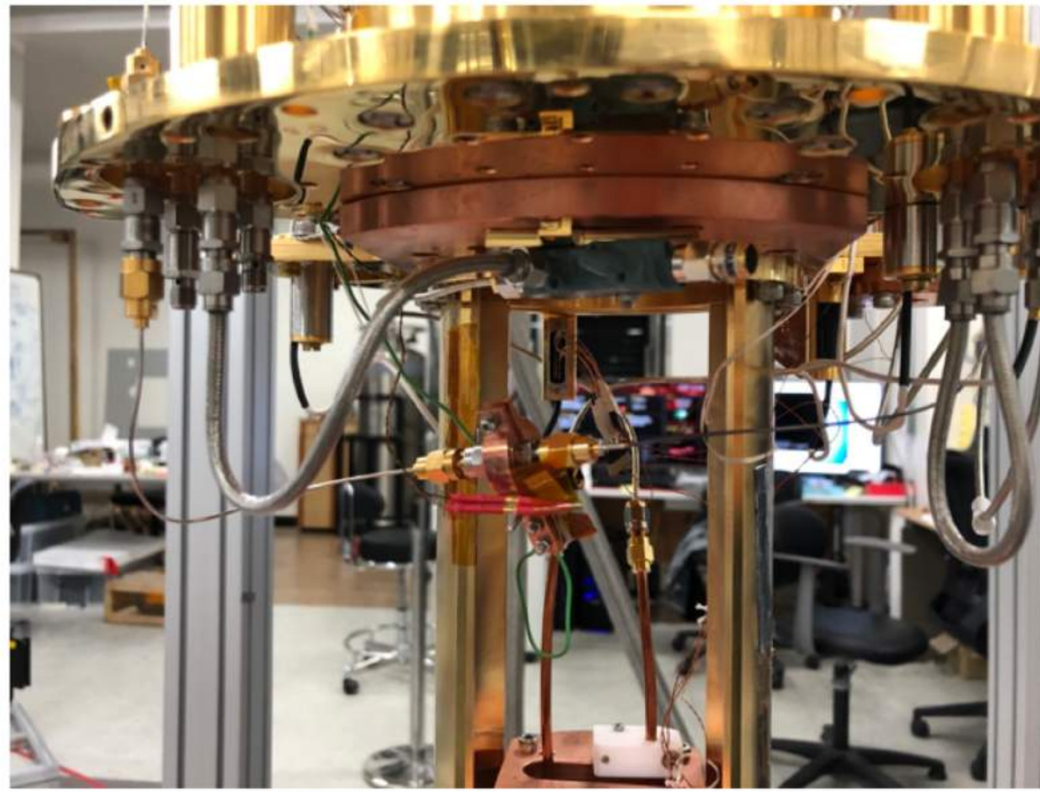
Backup Slides

Backup Slides



Setup - Photos

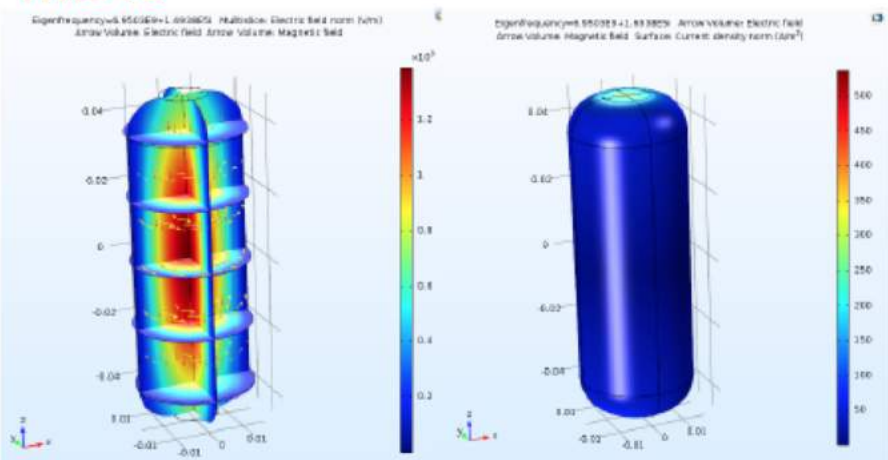




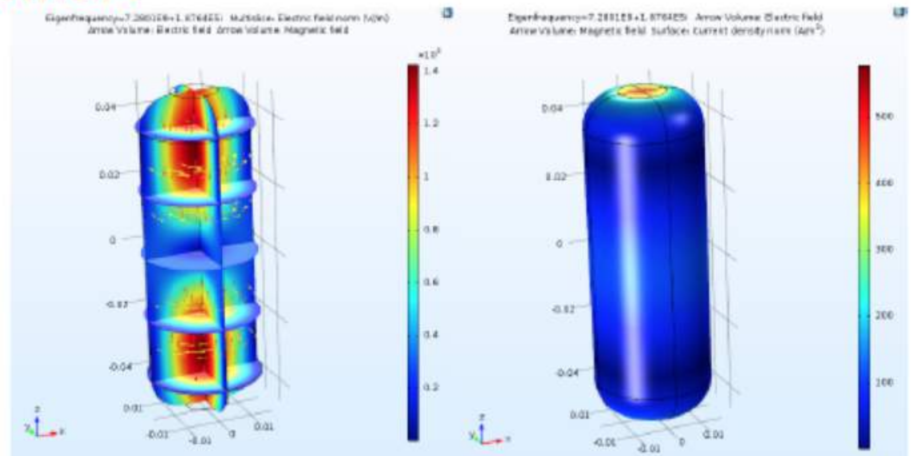
Backup Slides(YBCO Cavity)

TM010 & TM011 modes

TM010



TM011



- TM010: Current density is large at the middle wall.
- TM011: Current density is large at the top and bottom.

Backup Slides(YBCO Cavity)

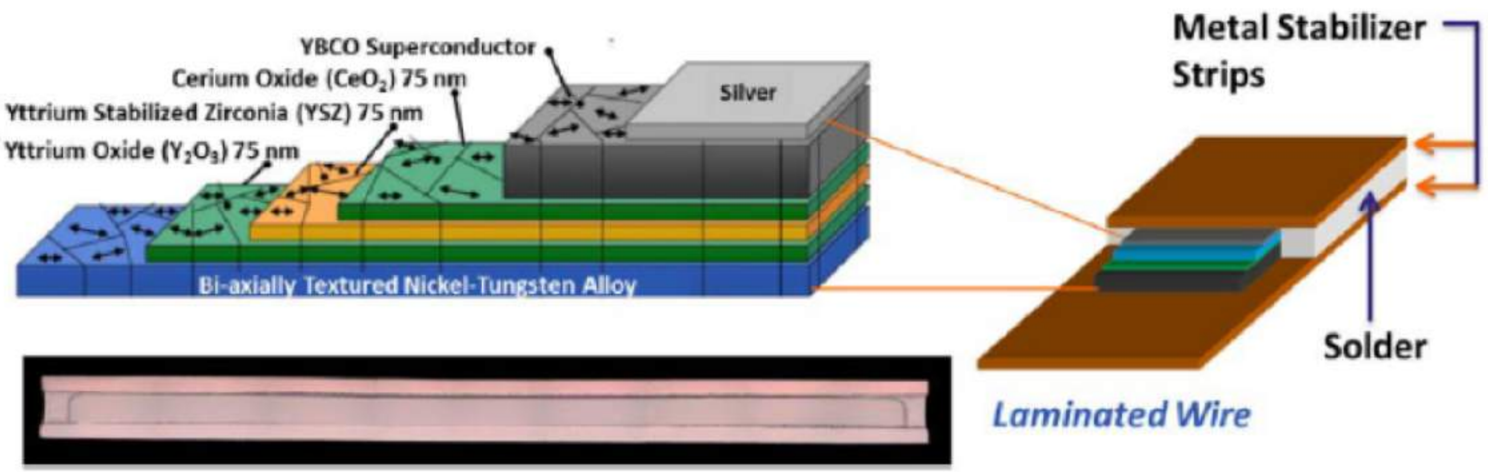


Figure 1 The architecture of the AMSC tape [19]

Backup Slides(YBCO Cavity)

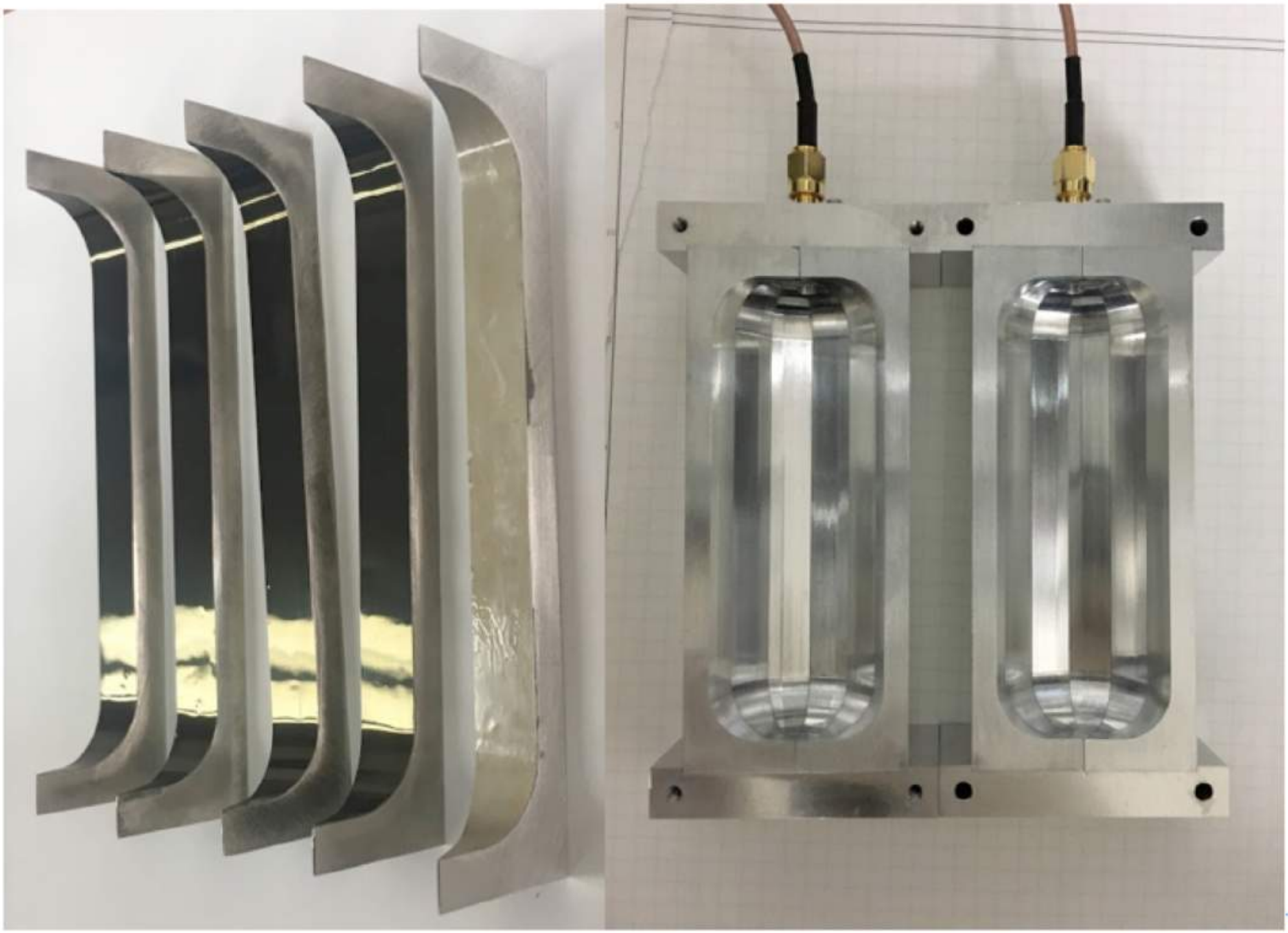


Figure 2 The structure of polygon cavity.