Axion Dark Matter Search at IBS/CAPP

3rd Workshop on Microwave Cavities and Detectors for Axion Research

Aug. 21~24 2018 Lawrence Livermore National Laboratory

SungWoo YOUN

Center for Axion and Precision Physics Research (CAPP)

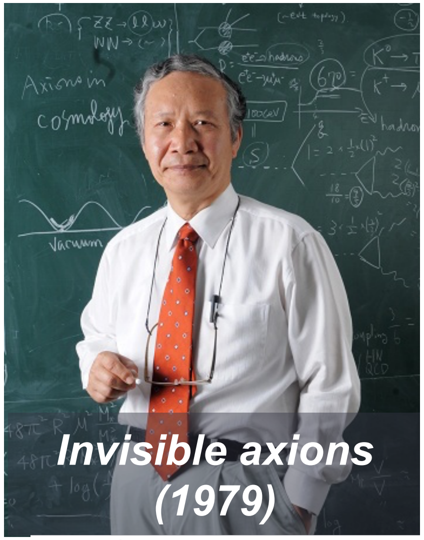
Institute for Basic Science (IBS)

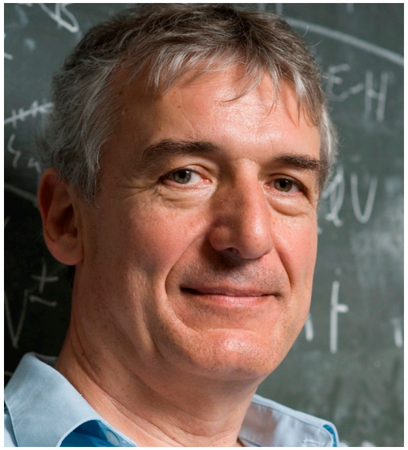
Outline

- *What is the axion dark matter?*
- *What do we have at CAPP?*
  - *Refrigerators / magnets*
- *What are we doing at CAPP?*
  - *Magnets / MSA / high frequency cavities*
- *What experiments are we preparing for at CAPP?*
  - *CAPP-PACE / CAPP-8TB / CAPP-MC / CAPP-18T*
- *What do we expect at CAPP?*
  - *Projected sensitivities*

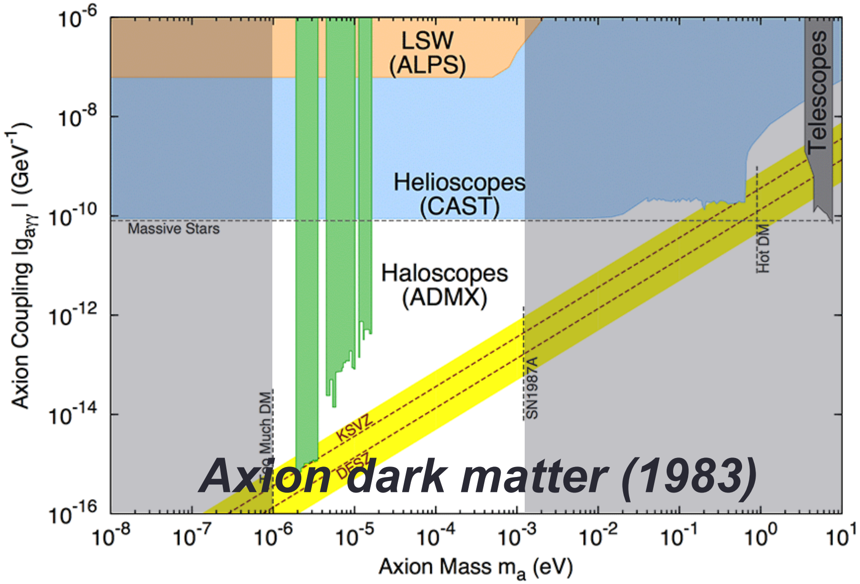
Axion Dark Matter


PQ mechanism (1977)


Invisible axions (1979)

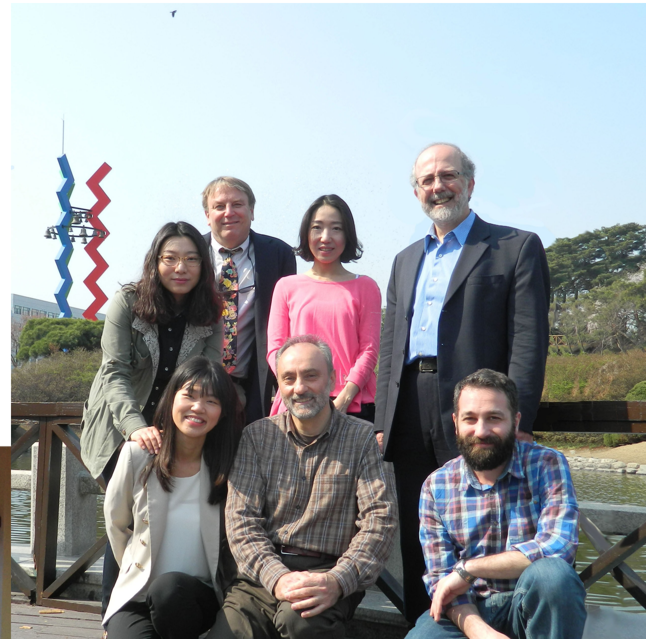

Haloscope (1983)


Axion (1978)

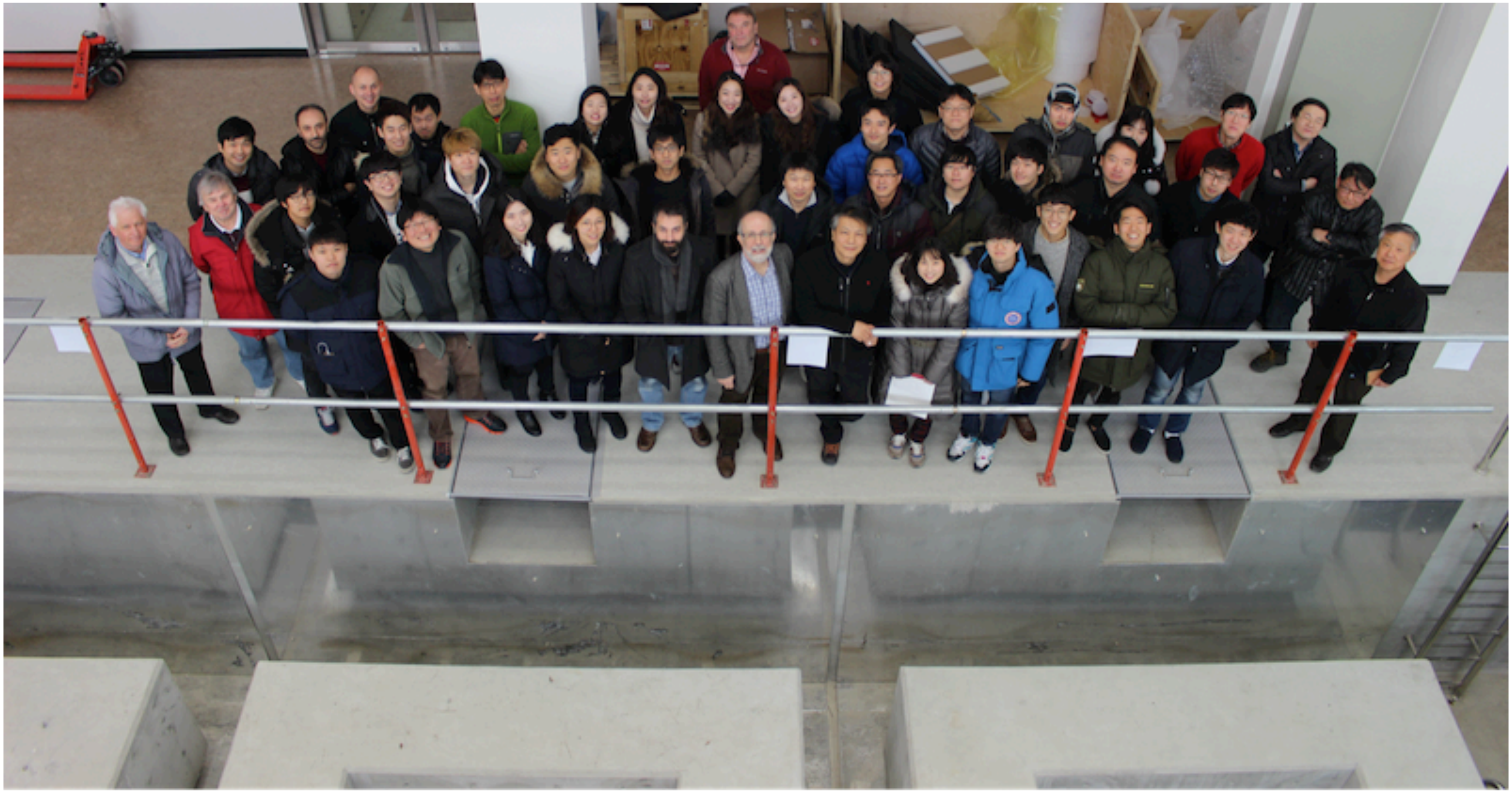


Axion dark matter (1983)

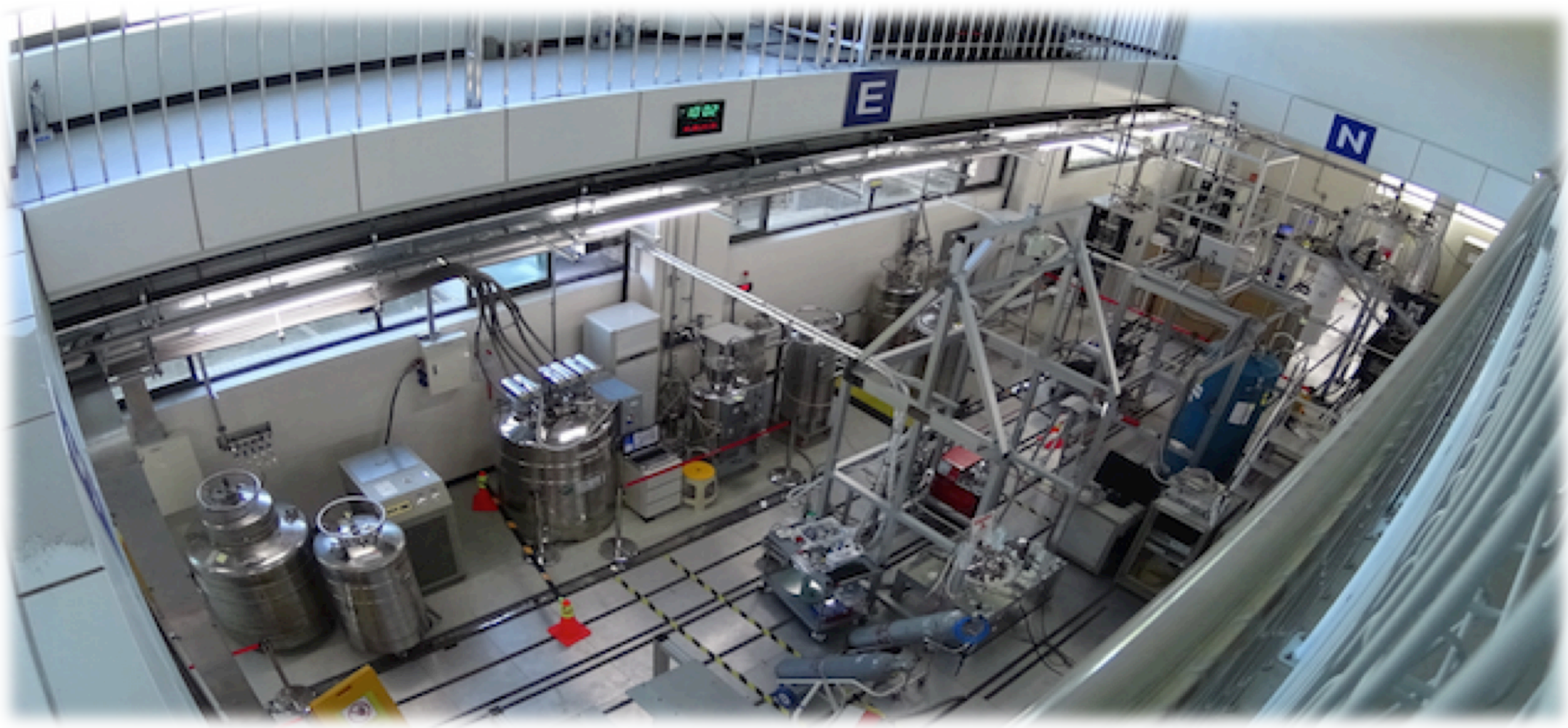
CAPP in Oct. 2017



CAPP in Jan. 2017



CAPP in Jun. 2018



Major Equipment

Refrigerators

Manufacture	Model	T_B [mK]	C.P. [μW@mK]	Install-ation
BlueFors (BF3)	LD400	10	18 @ 20 580 @ 100	2016
BlueFors (BF4)	LD400	10	18 @ 20 580 @ 100	2016
Janis	**HE-3-SSV**	**300**	**25 @ 300**	**2016**
BlueFors (BF5)	**LD400**	**10**	**18 @ 20 580 @ 100**	**2017**
BlueFors (BF6)	**LD400**	**10**	**18 @ 20 580 @ 100**	**2017**
Oxford	**Kelvinox**	**30**	**400 @ 120**	**2017**
Leiden	DRS1000	100	1000 @100	2018

Magnets

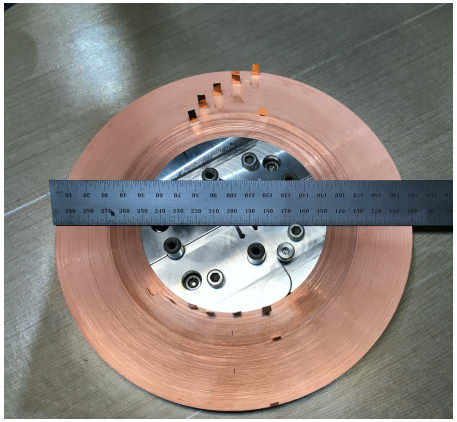
Manufacture	B_{max} [T]	Bore [mm]	Delivery
Cryo Magnetics	**9**	**125**	**2016**
AMI	**8**	**125**	**2017**
AMI	**8**	**165**	**2017**
SuNAM	**18**	**70**	**2017**
Oxford	12	320	2020
IBS/BNL	25	100	2020

High Field Magnet – IBS/BNL

Magnet parameters	
B_{max} (z=0) @ 4 K	25 T
Uniformity	90% (± 100 mm)
Bore (clear)	100 mm
Type	No Insulation
# of D.P.	14
Current Density	500 A/mm^2
Current	450 A
Stored energy	1.3 MJ
Inductance	13.1 Henry
Stress (Azimut.)	< 684 MPa

Coil parameters	
Manufacturer	Superpower
Material	HTS (ReBCO)
Width	12 mm
Thickness	75 μm
# of turns / S.P.	633
Conductor / S.P.	303 m
Total conductor	8.5 km

- *Several SPs were wounded and tested*
- *First DP was made and ready for test at 4 K*



High Field Magnet

Some ADMX Options

M. Bird

Approach	Field, Bore	Advantages	Disadvantages
LTS Outsert	15 T, 25 cm	Allows new magnet system at modest cost and low risk.	CAPP has already ordered this magnet.
LTS Outsert + Insulated REBCO	24 T, 16 cm	Insulated REBCO has had the most systematic development to date. Including extensive quench analysis and testing.	No magnet using insulated REBCO is yet operational. (32 T should be soon.)
All NI-REBCO	30 T, 16 cm	Very high current density allows ultra-high field from a compact magnet. All NI-REBCO has been put into service in 24 T magnet by Hahn at CAPP.	20 x the highest stored energy to-date. Testing of intermediate-scale coils required to verify quench protection system.
LTS Outsert + NI-REBCO	30 T, 16 cm	Stored energy of HTS section is lower than with all-NI approach.	Protection of nested NI-coils is more complicated than of a single NI-coil.
Bi2212, 2223 + LTS	24 T, 16 cm	Bi2223 is a more mature conductor than REBCO. A 24 T coil is operating in Sendai.	Current densities are similar to those of Ins-REBCO.

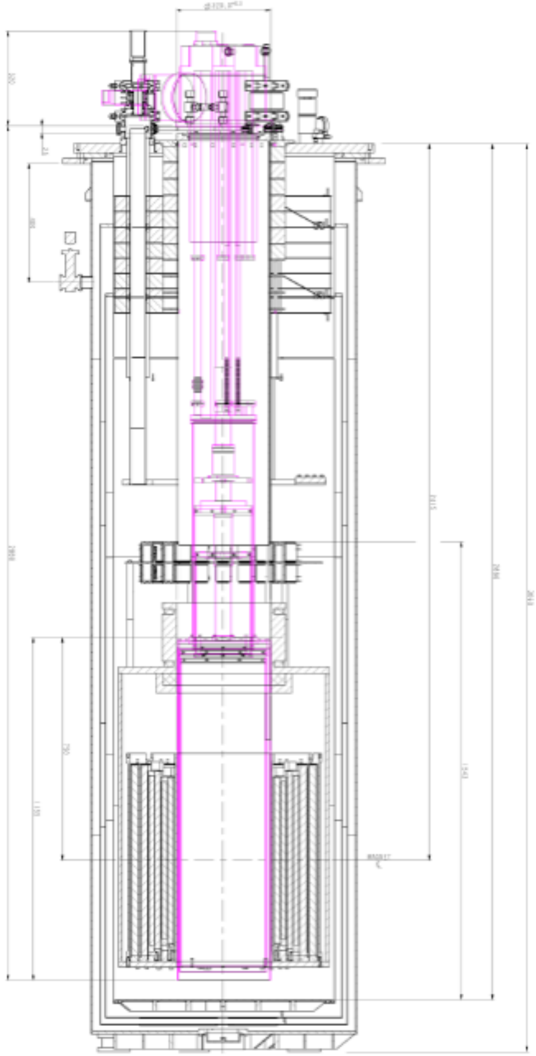
Technology is Evolving Very Quickly.
Things we believed 12 months ago were obsolete 6 months ago.
Things we believed 6 months ago are obsolete today.
All options still require R&D.

Date

26

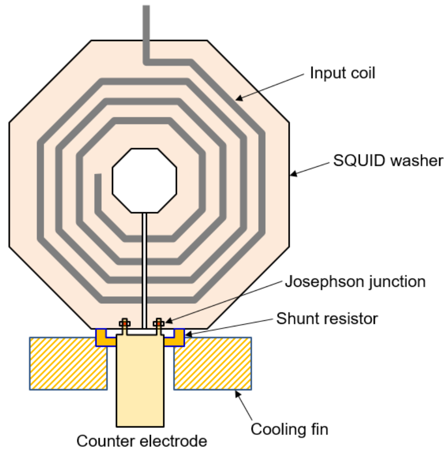
High Field Magnet – Oxford

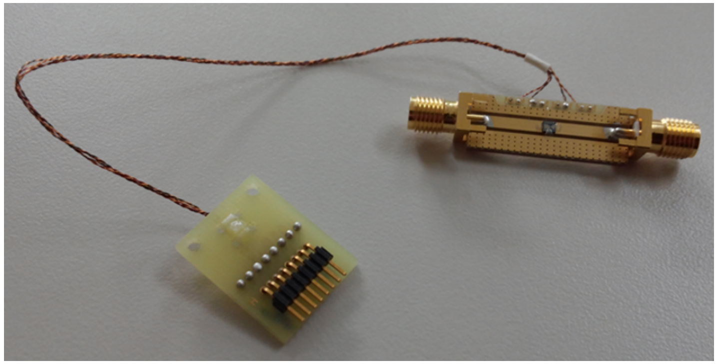
- *15T / 250 mm => 12 T / 320 mm*
  - *Better B^2V at the same cost*
  - *This option is still available for ADMX*
- *12 T / 320 mm LTS magnet*
  - *Order to Oxford*
  - *Conductor: Nb_3Sn*
  - *Delivery in 2020*
- *Will allow us for DFSZ physics between 0.7~ 3.0 GHz within 5 years*



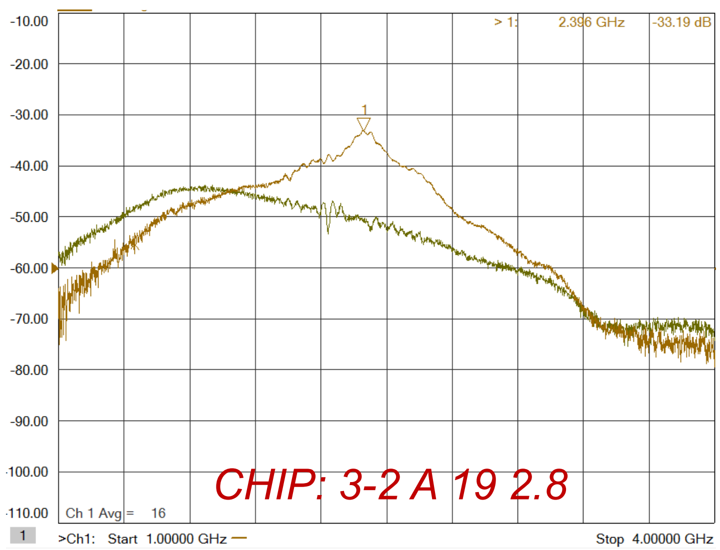
MSA - KRISS

KRISS design: Octagonal washer





F_0 = 2.2–2.5 GHz, ΔF = 100–150 MHz
Gain = 11–19 dB

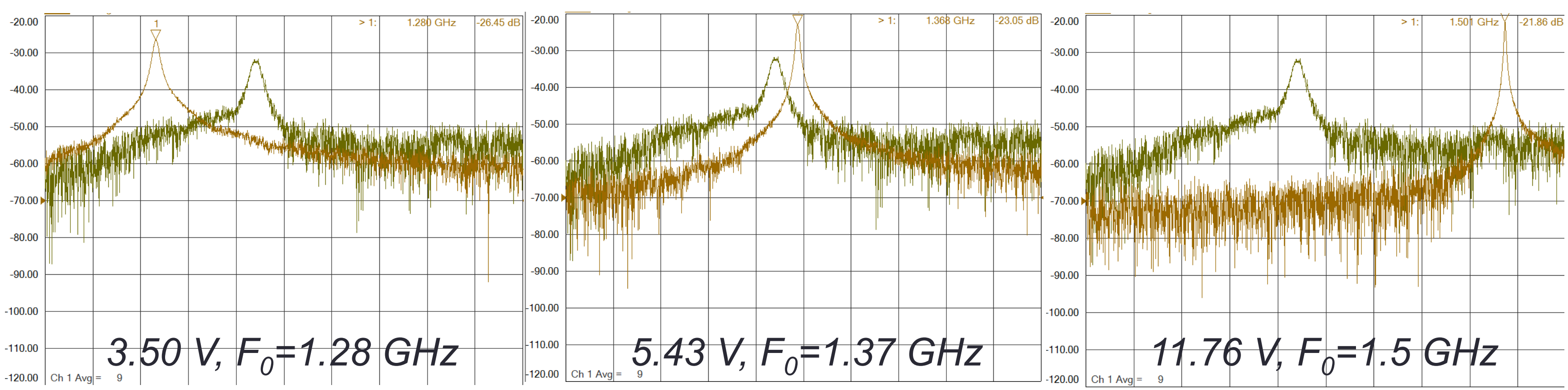


CHIP	Frequency (GHz)	Gain (dB)
3-2 A 19 2.8	2.40	18.7
3-1 B 15 2.7	2.40	15.7
3-2 A 19 1.9	2.40	15.1
3-2 A 19 2.7	2.40	14.3
3-2 A 19 1.8	2.45	13.6
2-12 A 20 2.8	2.30	12.5
3-2 B 15 2.7	2.20	12.2
2-12 A 19 2.8	2.50	11.0

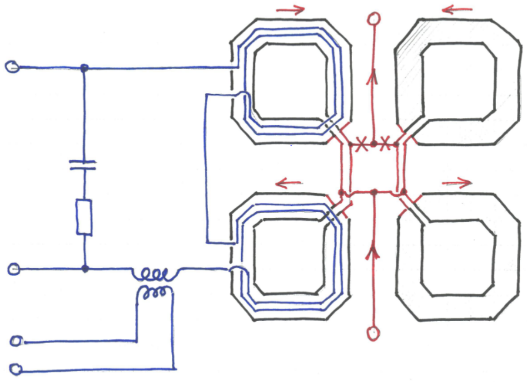
MSA – UC Berkeley

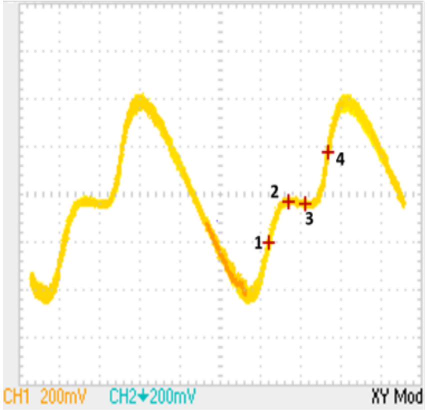
$V_{varactor}$ (V)	F_0 (GHz)	Gain (dB)	ΔF/ΔV (MHz/V)
2.56	1.221	19.3	
3.50	1.280	24.0	56.4
5.43	1.368	24.7	41.0
7.51	1.430	24.4	26.9
9.65	1.472	23.2	17.5
11.76	1.501	23.1	12.8

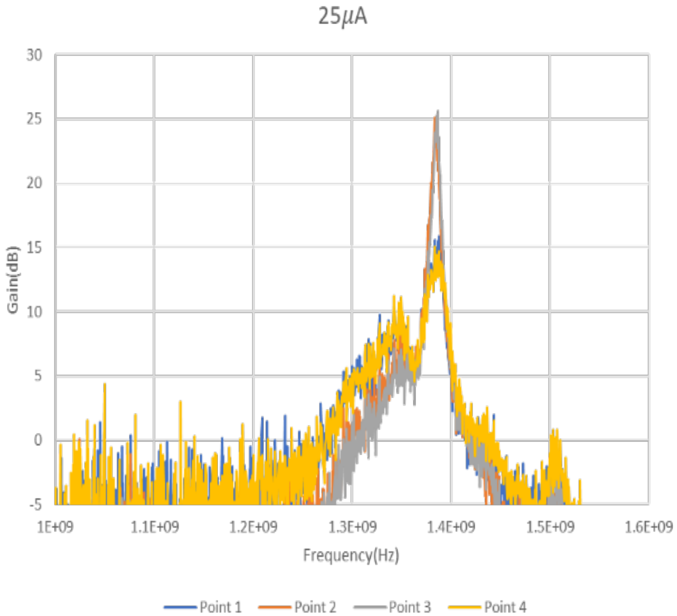
F_0 adjustable in the range 1.2 – 1.5 GHz
ΔF = 2.5 – 5.8 MHz, Gain = 24 dB

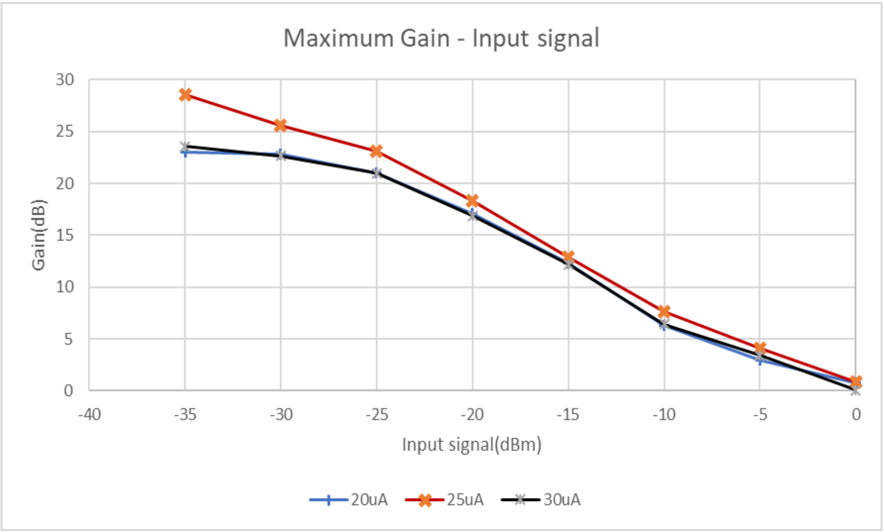


MSA – IPHT (I)

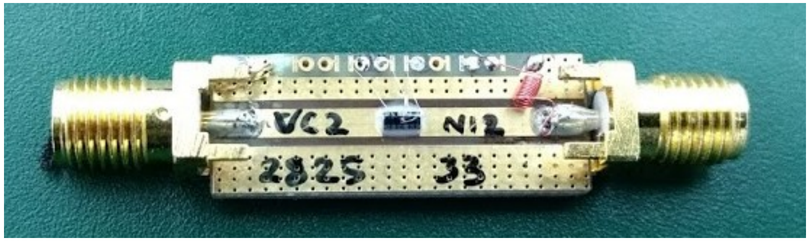




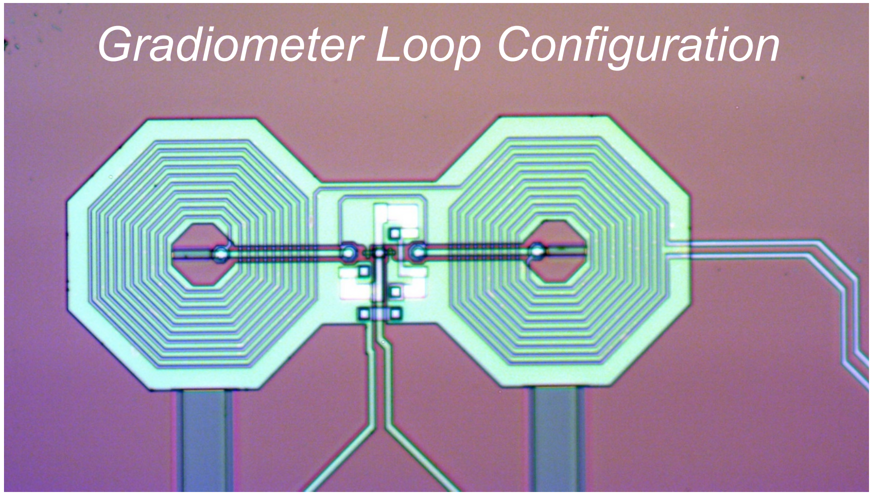




Gain = 25 dB, f_0 = 1.38 GHz
Δf_{20dB} = 8.3 MHz
Δf_{15dB} = 14 MHz

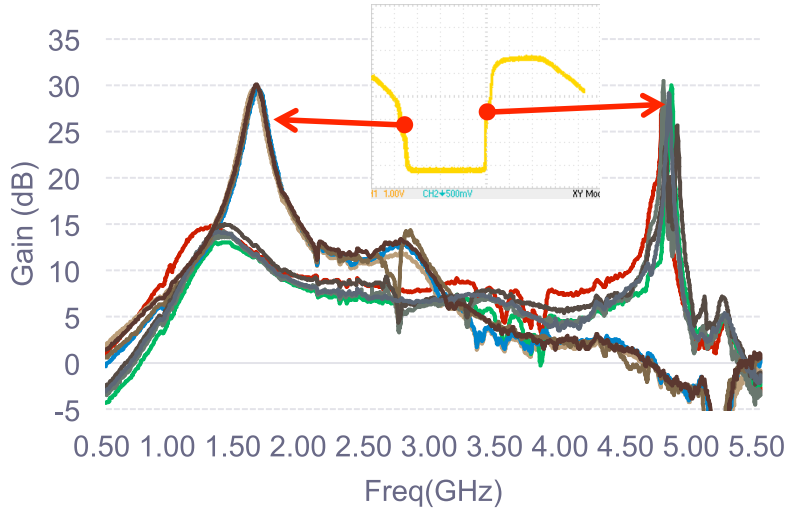


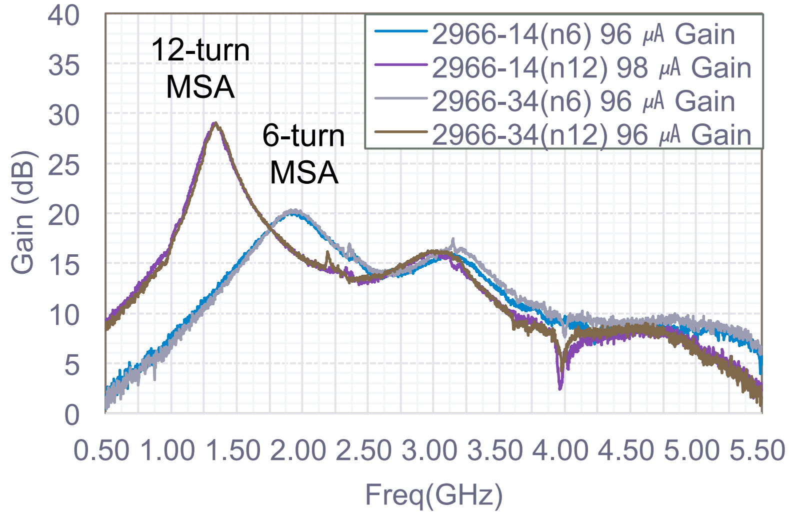
MSA – IPHT (II)



SQUID leads

Input coil leads

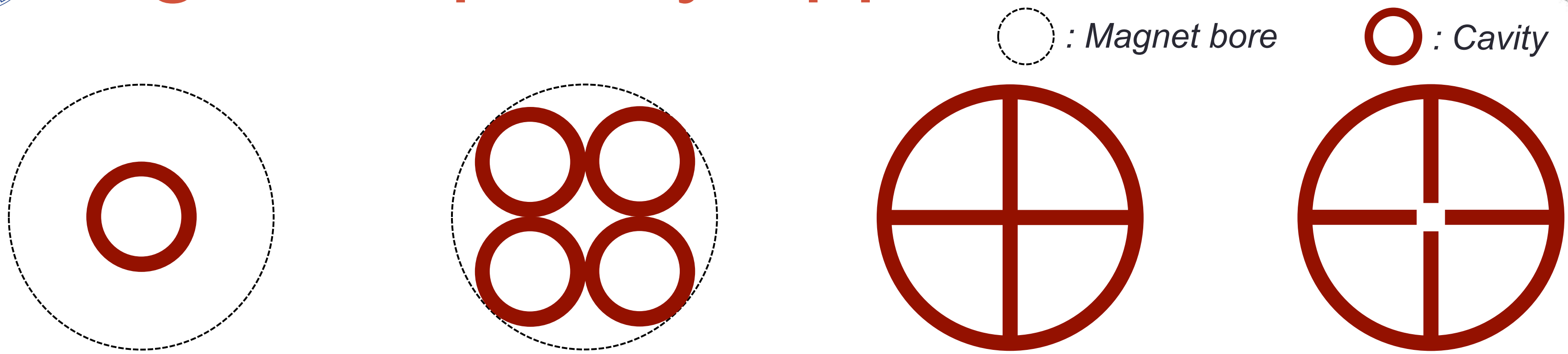




The gradiometer loop design is considerably less sensitive to ambient magnetic fields that lead to significantly relaxed requirements to shielding.

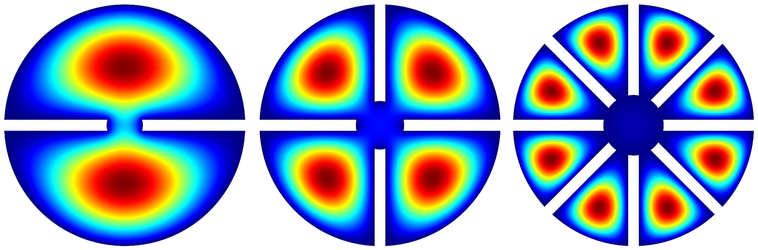
Such MSAs also have significantly higher immunity to RF interferences and electronics ground-loop problems.

High Frequency Approach

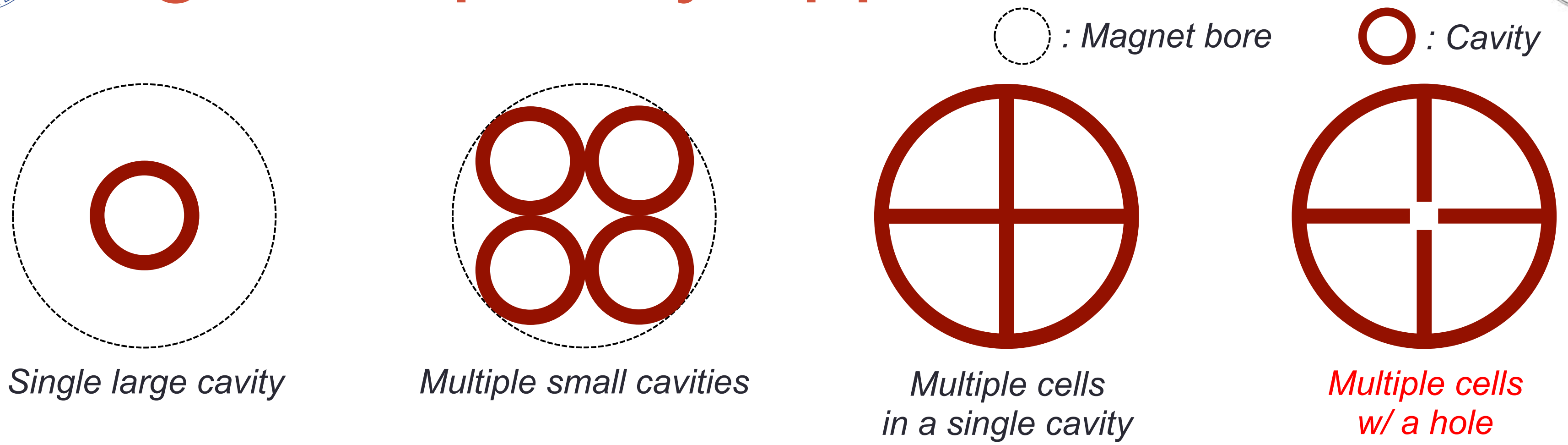


Single large cavity *Multiple small cavities* *Multiple cells in a single cavity* *Multiple cells w/ a hole*

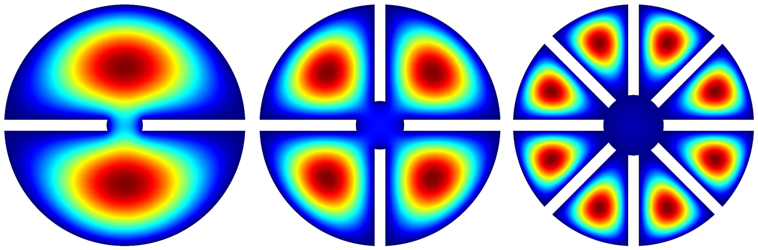
- *Larger volume*
  - *Higher sensitivity*
  - *2 times better than multiple-cavity*
- *Single antenna*
  - *Easier experimental setup*
  - *cf) N antennae for N-cavity systems*
- *Easier phase-matching mechanism*
  - *Less dead time*
  - *< 2 s for double-cell cavities*



High Frequency Approach

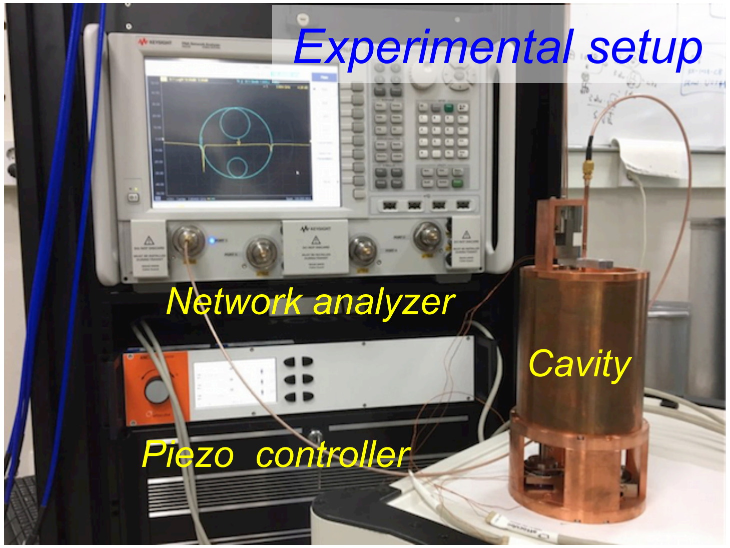


- *Larger volume*
  - *Higher sensitivity*
  - *2 times better than multiple-cavity*
- *Single antenna*
  - *Easier experimental setup*
  - *cf) N antennae for N-cavity systems*
- *Easier phase-matching mechanism*
  - *Less dead time*
  - *< 2 s for double-cell cavities*

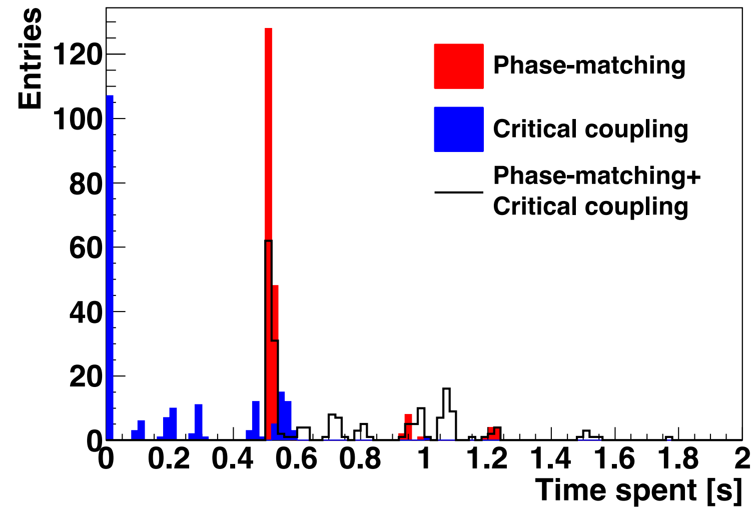


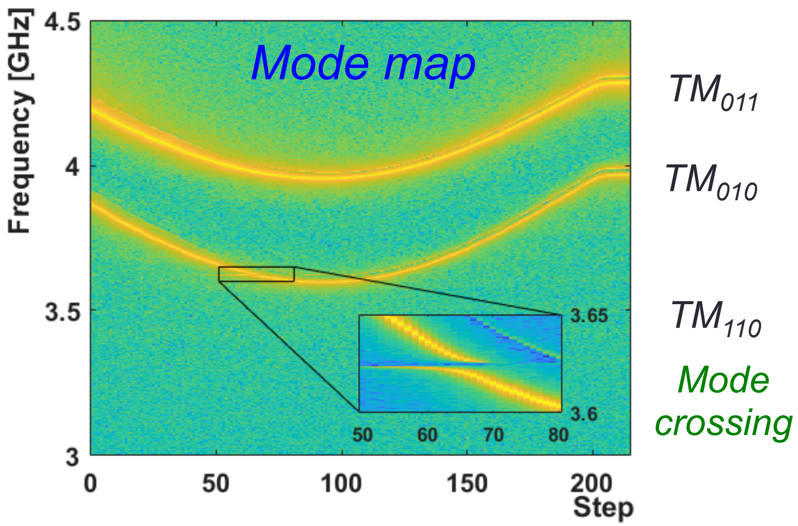
Pizza cavity

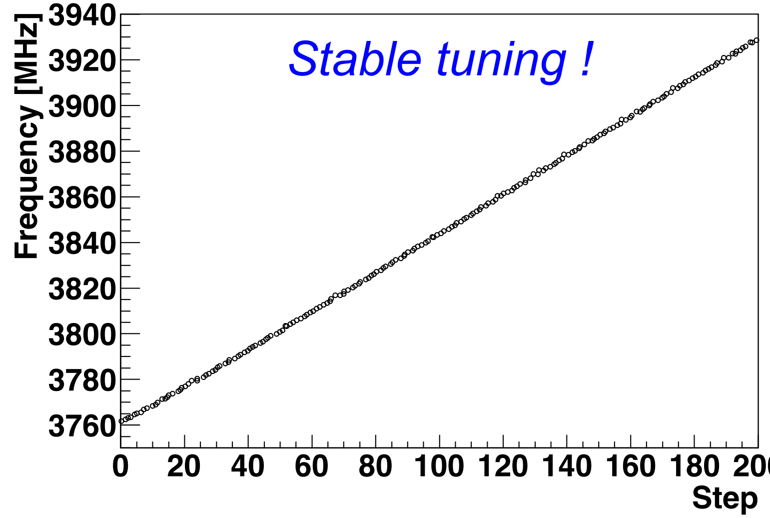
High Frequency Approach



Time for tuning: < 2 sec !







Phys. Lett. B ***777*** *412 (2018)*

See J. Jeong's presentation

CAPP Experiments

Refrigerators			Magnets			Experiment
Manufacture	Model	T_B [mK]	Manufacture	B_{max} [T]	Bore [mm]	Name
BlueFors (BF3)	LD400	10				
BlueFors (BF4)	LD400	10				
Janis	**HE-3-SSV**	**300**	**Cryo Magnetics**	**9**	**125**	**CAPP-9T MC**
BlueFors (BF5)	**LD400**	**10**	**AMI**	**8**	**125**	**CAPP-8T (PACE)**
BlueFors (BF6)	**LD400**	**10**	**AMI**	**8**	**165**	**CAPP-8TB**
Oxford	**Kelvinox**	**30**	**SuNAM**	**18**	**70**	**CAPP-18T**
Leiden	DRS1000	100	Oxford	12	320	CAPP-12TB
Oxford	Kelvinox	30	IBS/BNL	25	100	CAPP-25T

CAPP Experiments

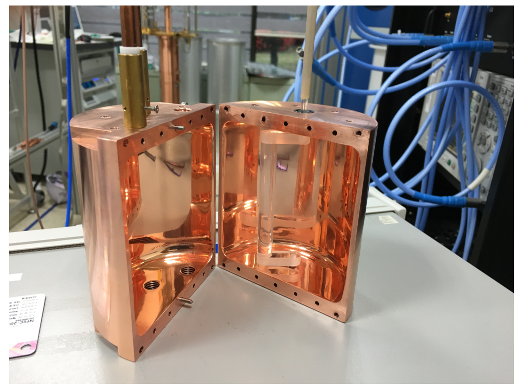
Refrigerators			Magnets			Experiment
Manufacture	**Model**	**T_B [mK]**	**Manufacture**	**B_{max} [T]**	**Bore [mm]**	**Name**
BlueFors (BF3)	*LD400*	*10*				
BlueFors (BF4)	*LD400*	*10*				
Janis	***HE-3-SSV***	***300***	***Cryo Magnetics***	***9***	***125***	***CAPP-9T MC***
BlueFors (BF5)	***LD400***	***10***	***AMI***	***8***	***125***	***CAPP-8T (PACE)***
BlueFors (BF6)	***LD400***	***10***	***AMI***	***8***	***165***	***CAPP-8TB***
Oxford	***Kelvinox***	***30***	***SuNAM***	***18***	***70***	***CAPP-18T***
Leiden	*DRS1000*	*100*	*Oxford*	*12*	*320*	*CAPP-12TB*
Oxford	*Kelvinox*	*30*	*IBS/BNL*	*25*	*100*	*CAPP-25T*

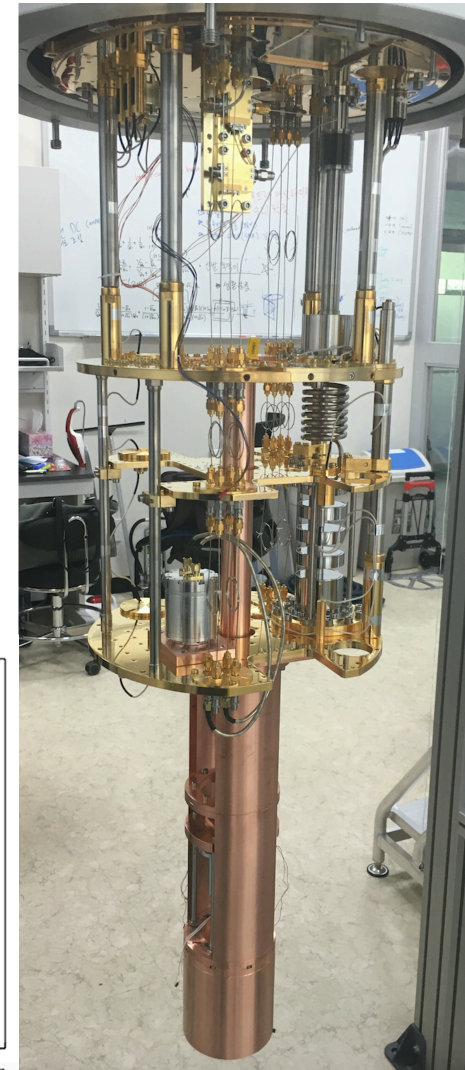
Operating parallel experiments targeting at different mass ranges!

CAPP-PACE

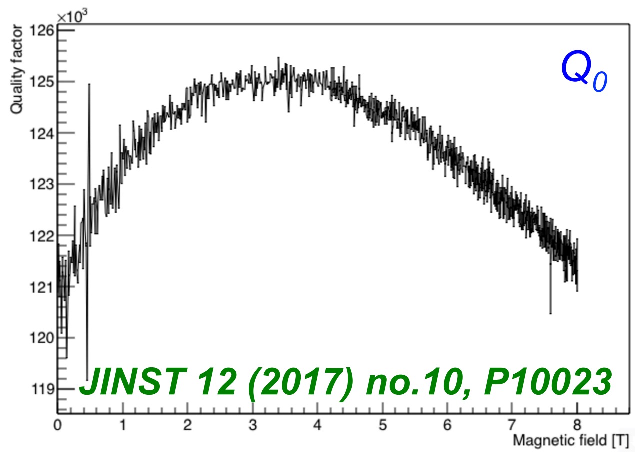
- *Pilot Axion Cavity Experiment*
  - *Preparation for CAPP-25T*
  - *DAQ mode since Jan. 2018*
  - *First data by CAPP*

Split cavity

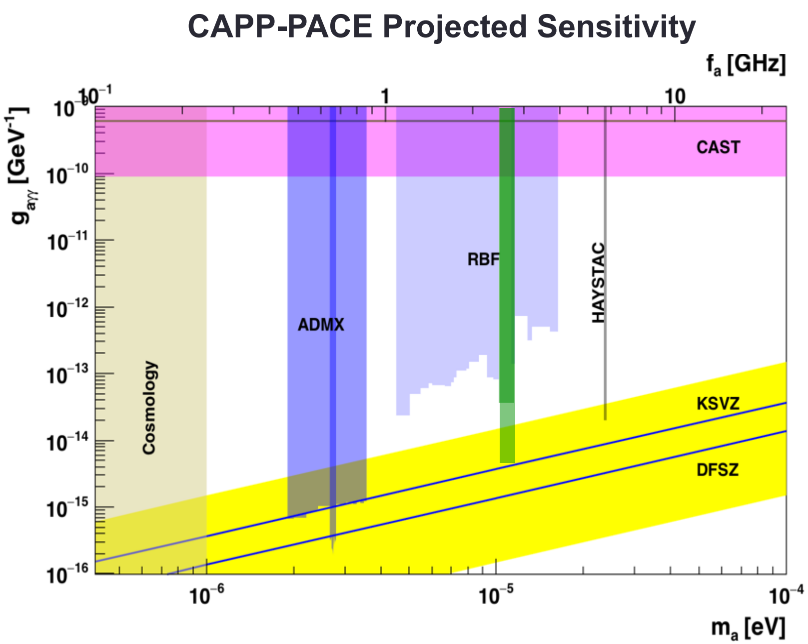




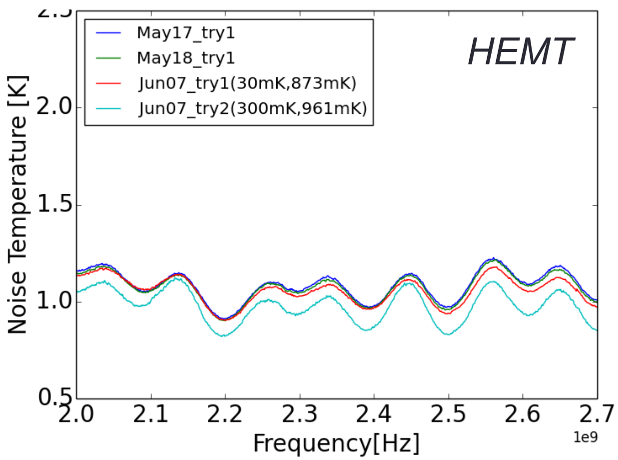
Parameter	Value
Δf	2.45 – 2.76 GHz
B_{max}	8 T
T_{phy}	< 50 mK
T_{amp}	1 - 1.5 K
V_{cav}	1.12 litter
Q_0	120,000
C_{010}	0.55



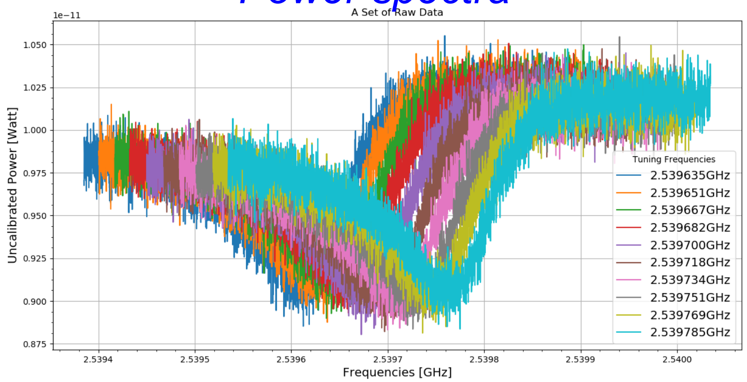
CAPP-PACE



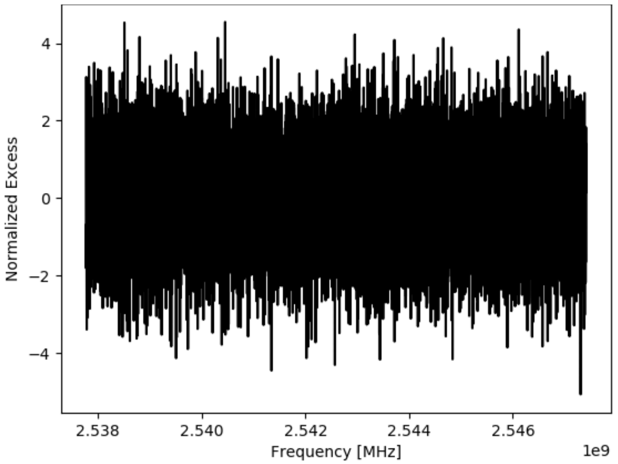
Noise measurement



Power spectra



Grand spectrum

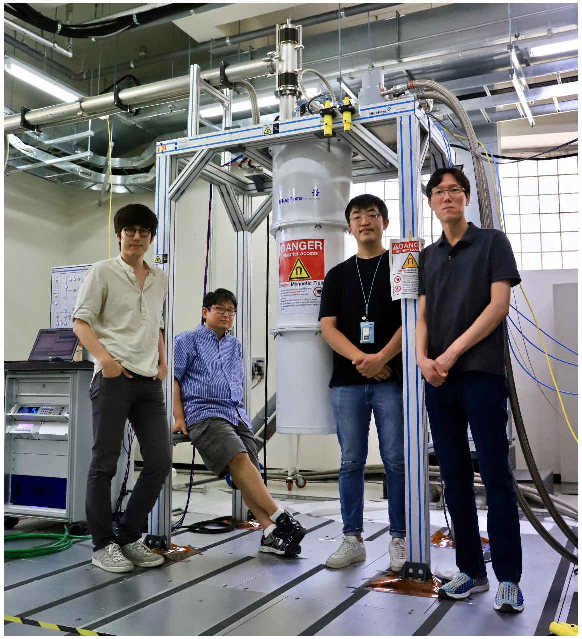


See D. Lee's presentation

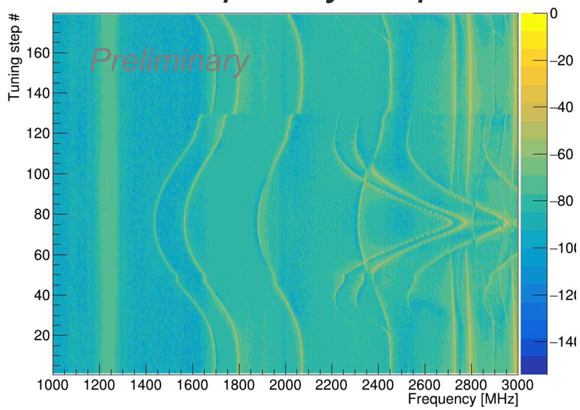
CAPP-8TB

- *Utilizing a 8 T big bore magnet*

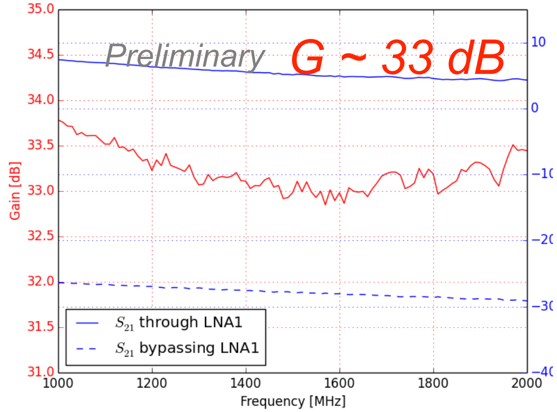
B_{max} (B_{avg})	8 T (7.3 T)
Magnet bore	165 mm
V_{cav}	3.5 L
Q_0	> 100,000
T_{phy}	~40 mK
Target search region	1.6~1.7 GHz (6.6 ~7.0 μeV)



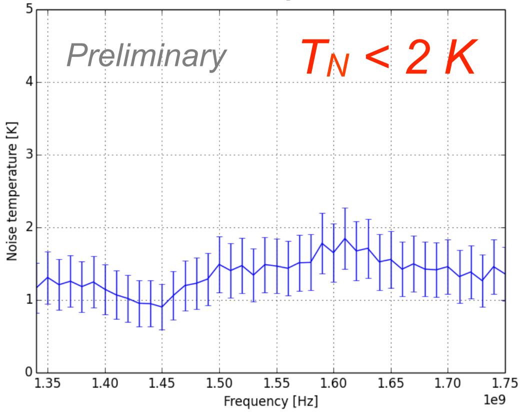
Frequency map



Gain

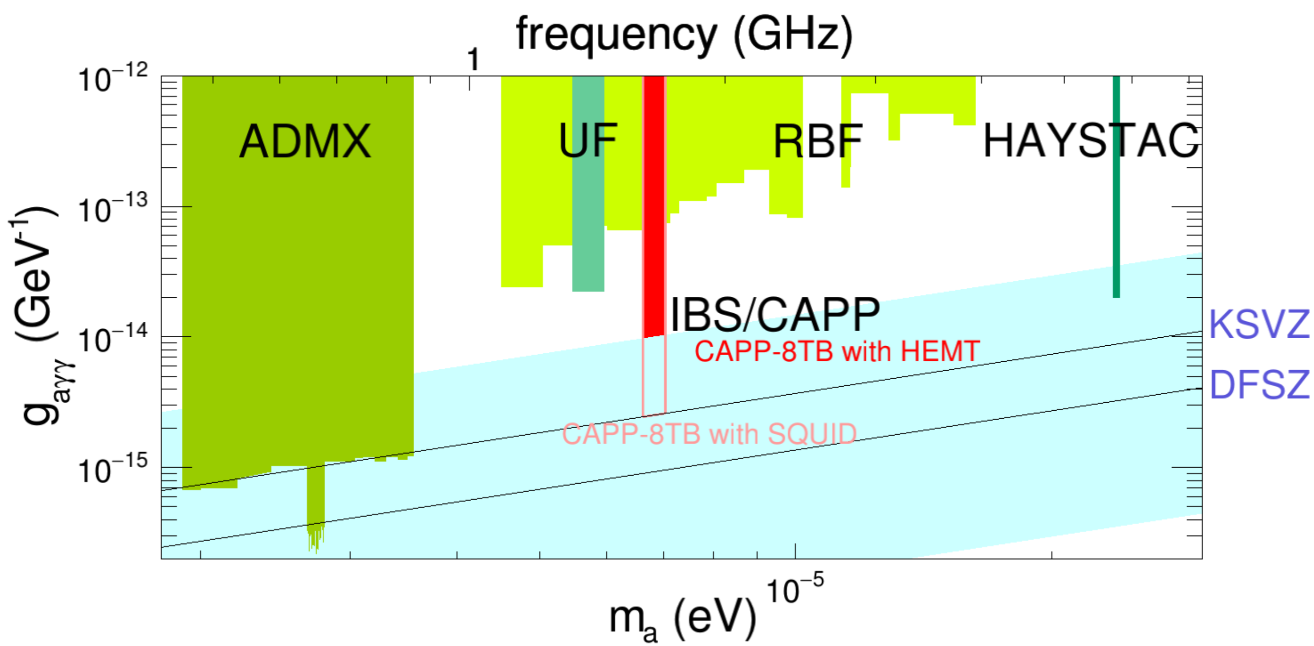


Noise temperature

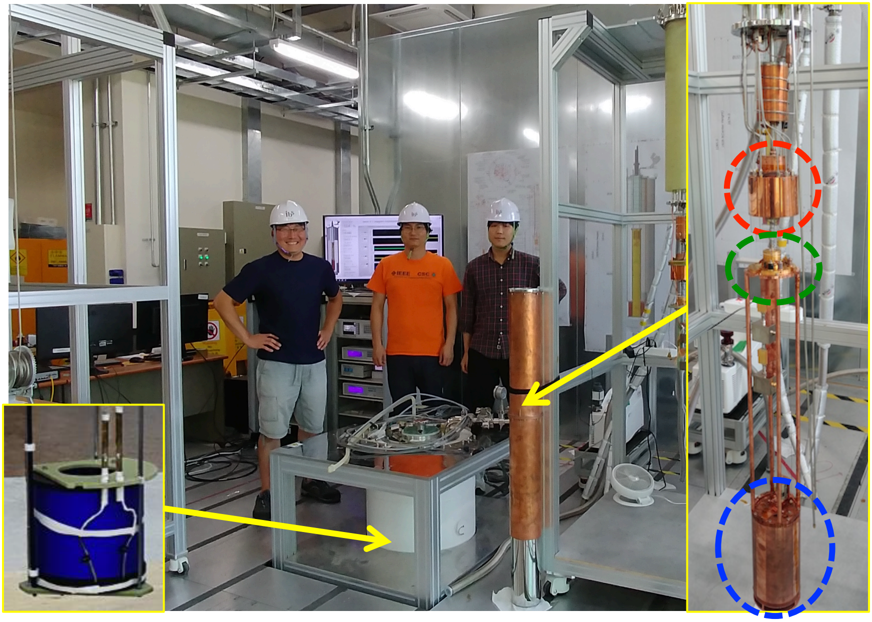


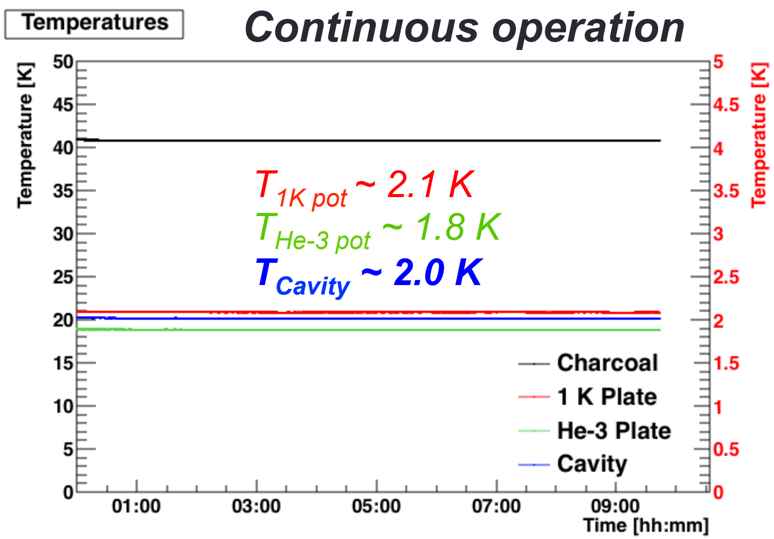
CAPP-8TB

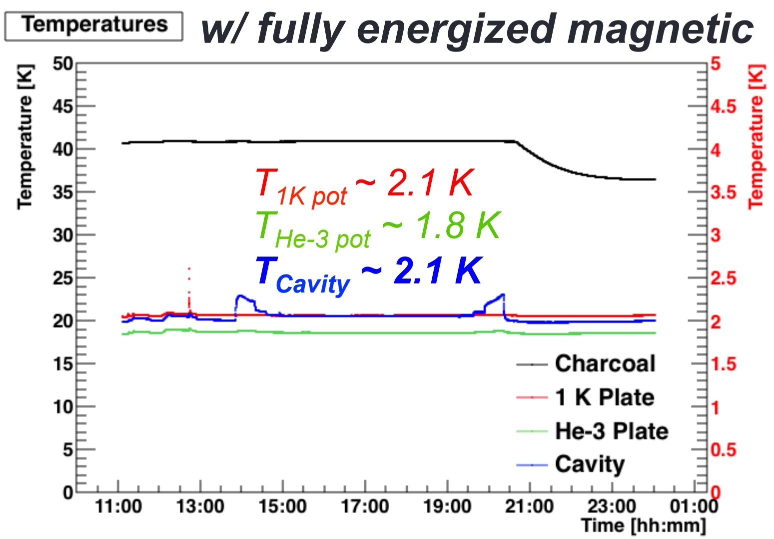
- *Two stage experiment*
  - *1st stagew/ HEMT-based amplifier (~3 months of operation)*
    - *Touching QCD axion band*
  - *2nd stage: w/ SQUID-based amplifier*
    - *Reach to KSVZ sensitivity*



CAPP-MC

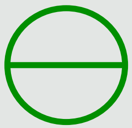


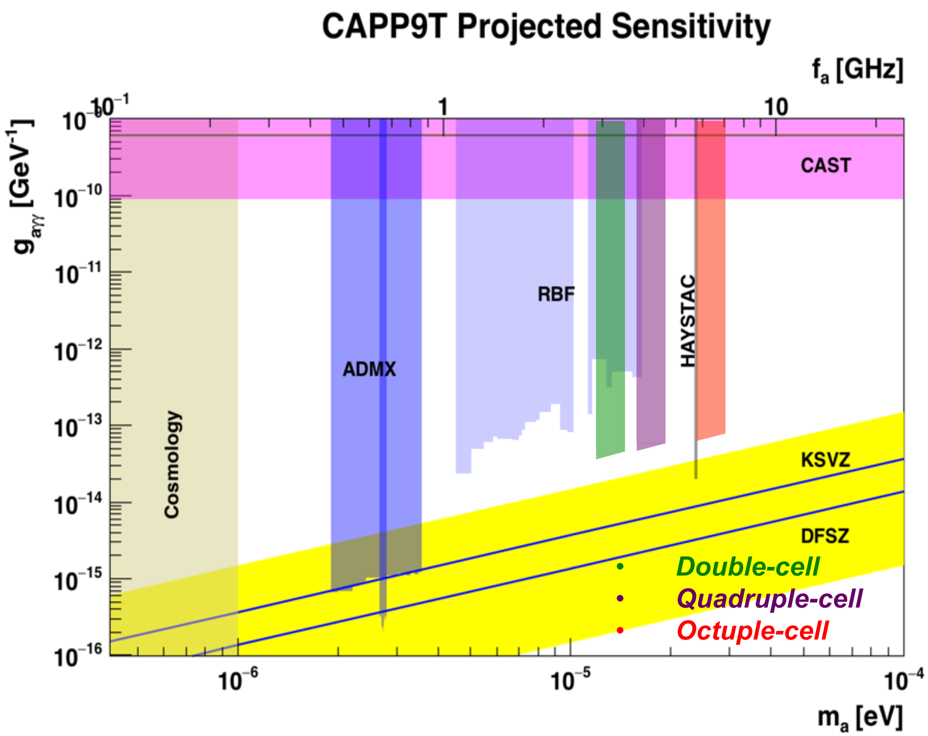




- *Demonstration experiment of multiple-cell cavities*
- *Janis He-3 system with a 9 T / 125 mm SC magnet*
- *Continuous operation at 2.1 K with a HEMT*

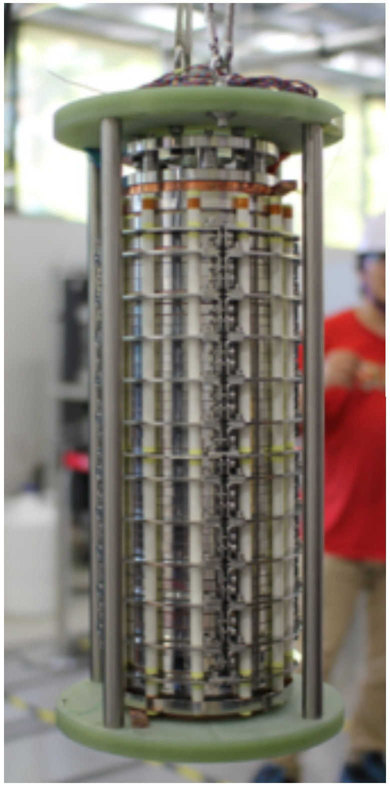
CAPP-MC

	2-cell	4-cell	8-cell
Geometry			
F_{010} [GHz]	[2.8,3.3]	[3.8,4.5]	[5.8,7.0]
Q_0	60,000	51,000	51,000
C_{010}	0.45	0.45	0.40
B_{avg} [T]	7.8		
V [L]	2.0	1.9	1.7
P_{sig} [10^{-21} W] (β=2)	0.51	0.56	0.68
T_{sys} [K]	2.1+2.0	2.1+3.0	2.1+4.0
SNR	5		
DAQ efficiency	0.5		
df/dt [GHz/year] (KSVZ×10)	5.4	4.8	5.0
Scan time (mon)	1.1	1.8	2.9

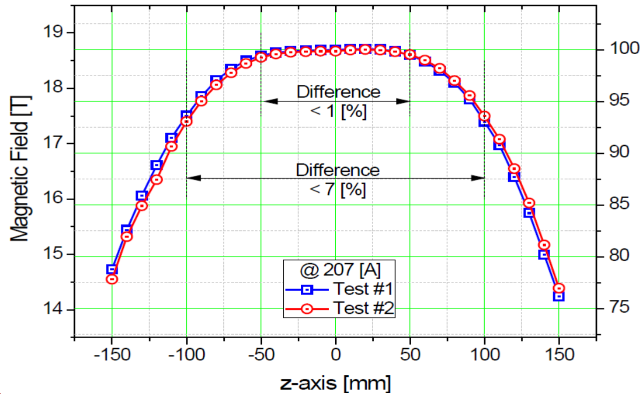


Year	2018				2019				2020
Quarter	1	2	3	4	1	2	3	4	1
Double-cell									
Quadruple-cell									
Octuple-cell									

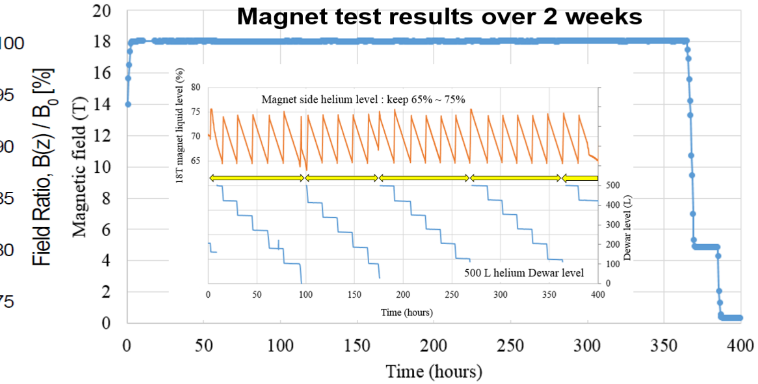
CAPP-18T



- *GdBCo HTS*
- *Multi-width*
- *B_{max} = 18 T*
- *I.D. = 70 mm*
- *No-insulation*

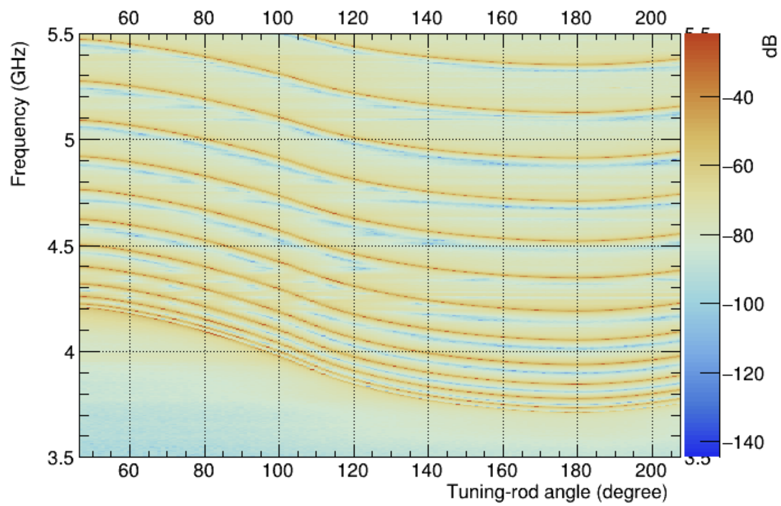


Uniformity: 93% (±100 mm)

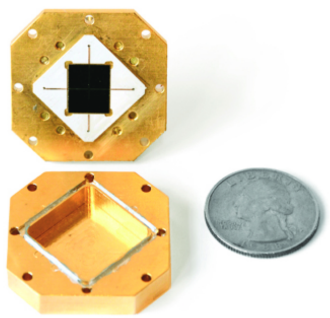


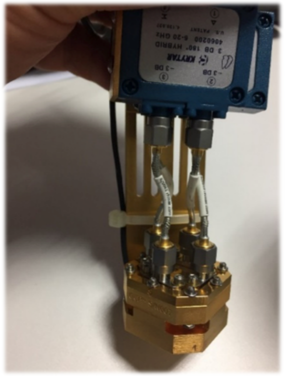
Stability: <0.05% for 2 weeks

Frequency map

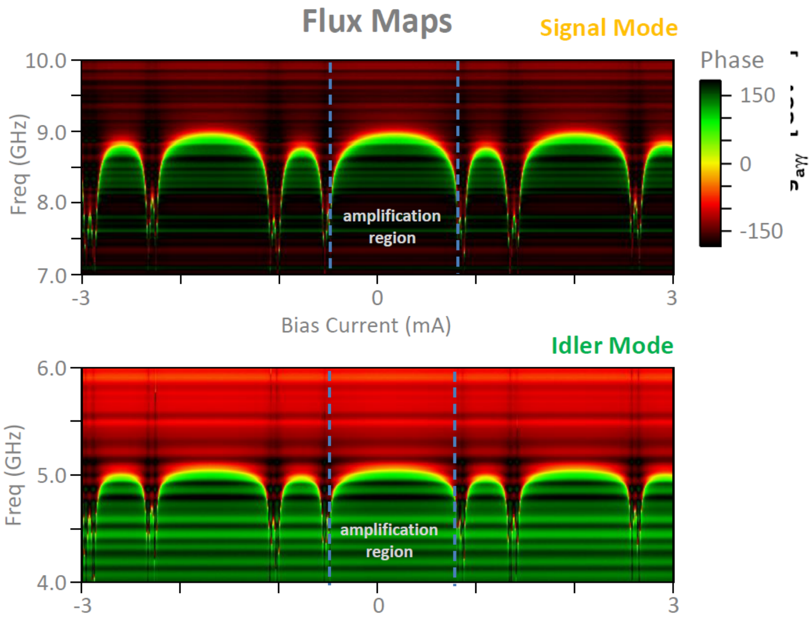


CAPP-18T

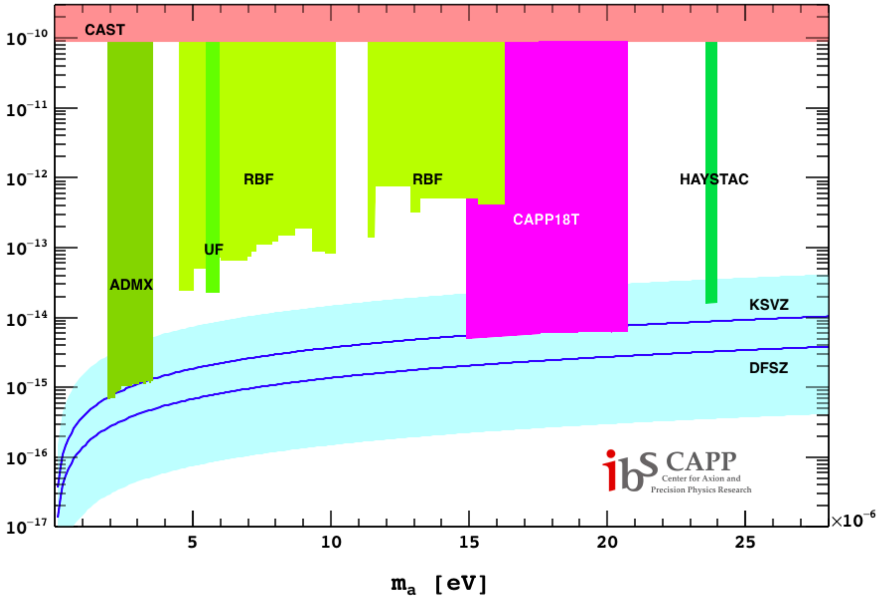




JPC from QCI

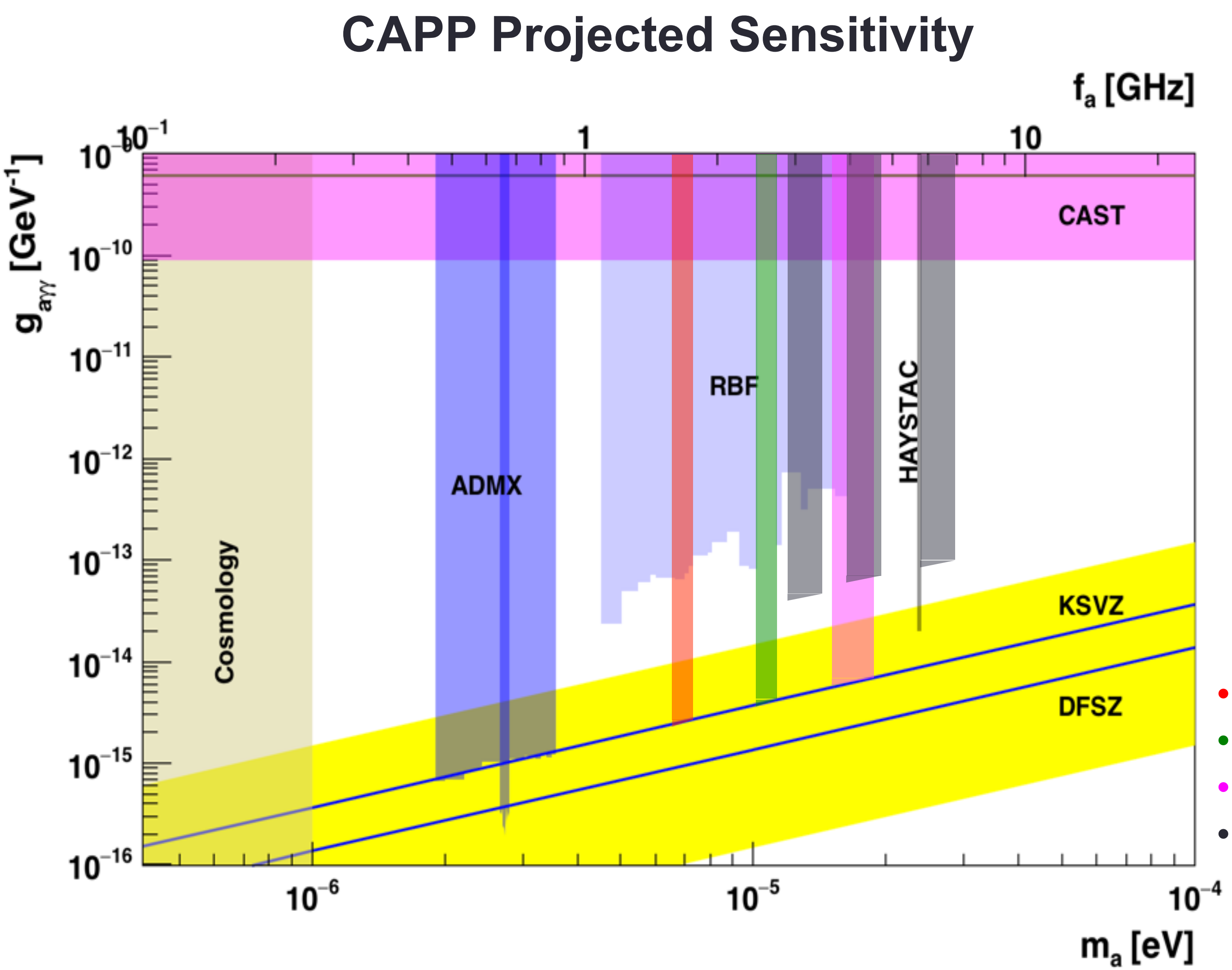


CAPP-18T projected sensitivity



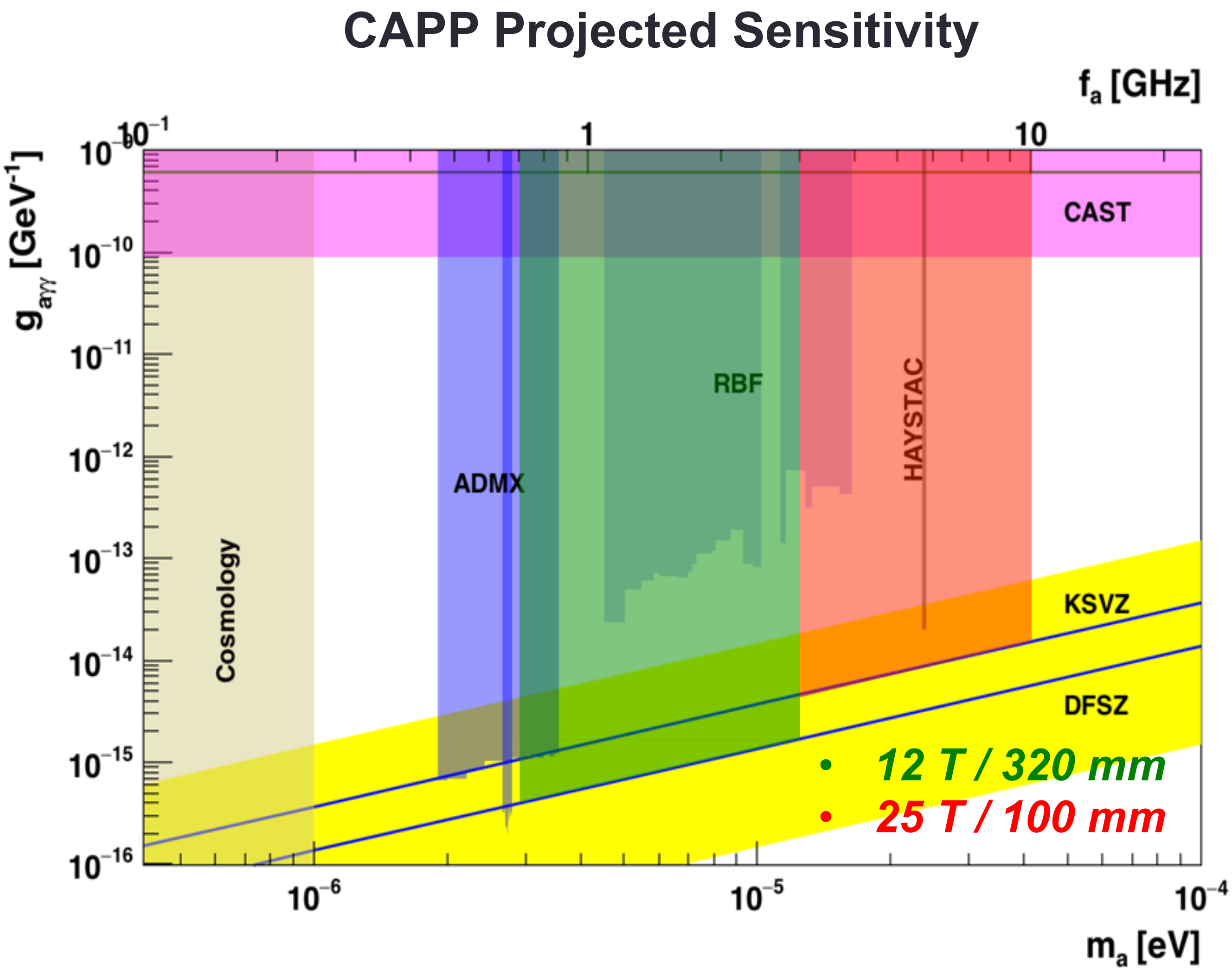
3.6~4.2 GHz at KSVZ

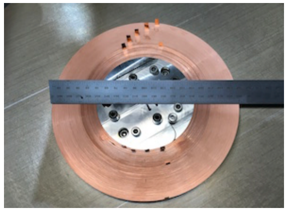
Projected Sensitivity – 2 Year



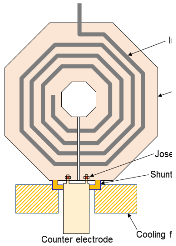
- *CAPP-8TB*
- *CAPP-PACE*
- *CAPP-18T*
- *CAP-9T MC*

Projected Sensitivity – 5 Year

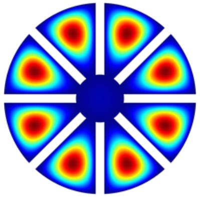




+



+



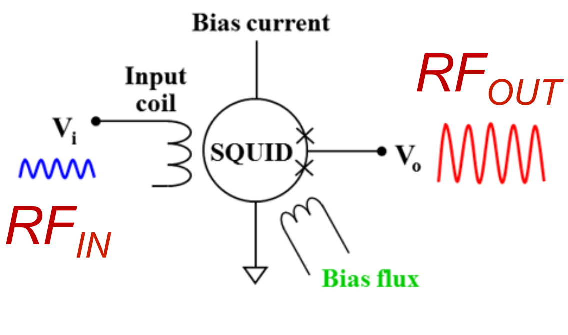
Summary

- *Axion research at IBS/CAPP is getting mature*
- *Major R&D focuses*
  - *High field / large volume magnets*
  - *Development of quantum noise limited amplifers*
  - *Cavity design for higher masses*
- *Multiple experiments are under preparation in parallel*
  - *Targeting at different mass ranges*
- *Probing up to 10 GHz with sensitivity of the QCD axion within next five years*

Backup Slides

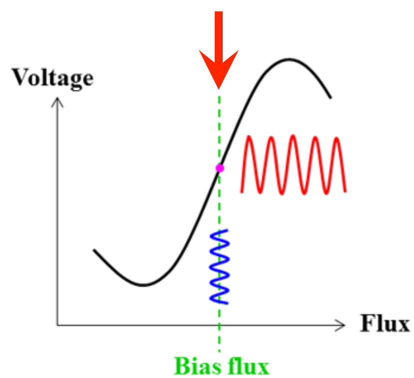
Microstrip SQUID Amplifier

- *Superconducting Quantum Interference Device (SQUID)*
- *RF input signal comes to resonant microstrip input coil*
- *It modulates input flux in SQUID loop and produces RF output voltage on SQUID leads*

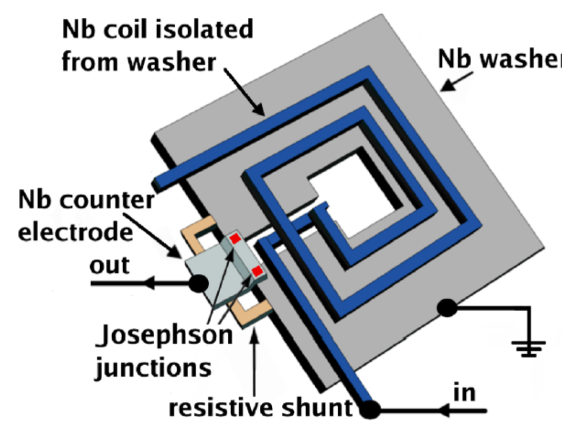


(a)

Working Point: I_W and Φ_{DC}



(b)



Timeline

Experiment											
	201 8	2019		2020		2021		2022		2023	
PACE											
CAPP-8TB											
CAPP-MC											
CAPP-18T											
CAPP-12TB											
CAPP-25T											
CAPP-25T											