IBS-PNU BSM workshop
Busan
December 5, 2019

CAPP: status and future

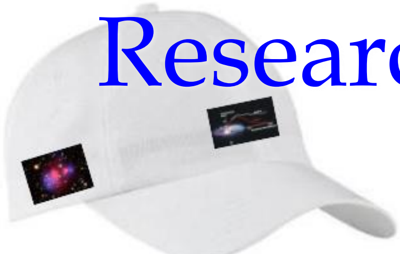
Yannis K. Semertzidis,
IBS/CAPP & KAIST

Next five years: Answer whether axions (1-10 GHz) are a significant part of the local dark matter halo density

In <10 years: Probe axions (1-20 GHz) down to 10%
Precision Physics in storage rings

We have accomplished all our R&D challenges

Center for Axion and Precision Physics Research: IBS/CAPP at KAIST, Korea



First foreign-born IBS-Center Director…

Se-Jung Oh (right), the president of the Institute for Basic Science (IBS) in Korea, and Yannis Semertzidis, after signing the first contract between IBS and a foreign-born IBS institute director. On 15 October, Semertzidis became the director of the Center for Axion and Precision Physics Research, which will be located at the Korea Advanced Institute of Science and Technology in Daejeon. The plan is to launch a competitive Axion Dark Matter Experiment in Korea, participate in state-of-the-art axion experiments around the world, play a leading role in the proposed proton electric-dipole-moment (EDM) experiment and take a significant role in storage-ring precision physics involving EDM and muon g-2 experiments. (Image credit: Ahram Kim IBS.)

CERN Courier, Dec. 2013

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

IBS/CAPP

- Was established October 15, 2013

- To put together the best possible axion dark matter exps and reach the theoretically interesting sensitivities for the widest possible frequency range

- Was very careful not to limit it to a project, but actually to establish a *world-class* center

Principles

- Develop infra-structure

- Develop in-house expertise

- Collaborate with the best around the world on amplifiers (long lead-time) and others as needed

- Collaborate on storage ring/Accel. physics with external labs

Infra-structure

- Seven LVPs: Five axion dark matter exps in parallel possible
- State of the art RF-lab with high-end RF-equipment

- Several dilution refrigerators for R&D and prototype experiments, 1RF-shielding room
- Magnetic shielding room, polarimeter development clean room, etc.

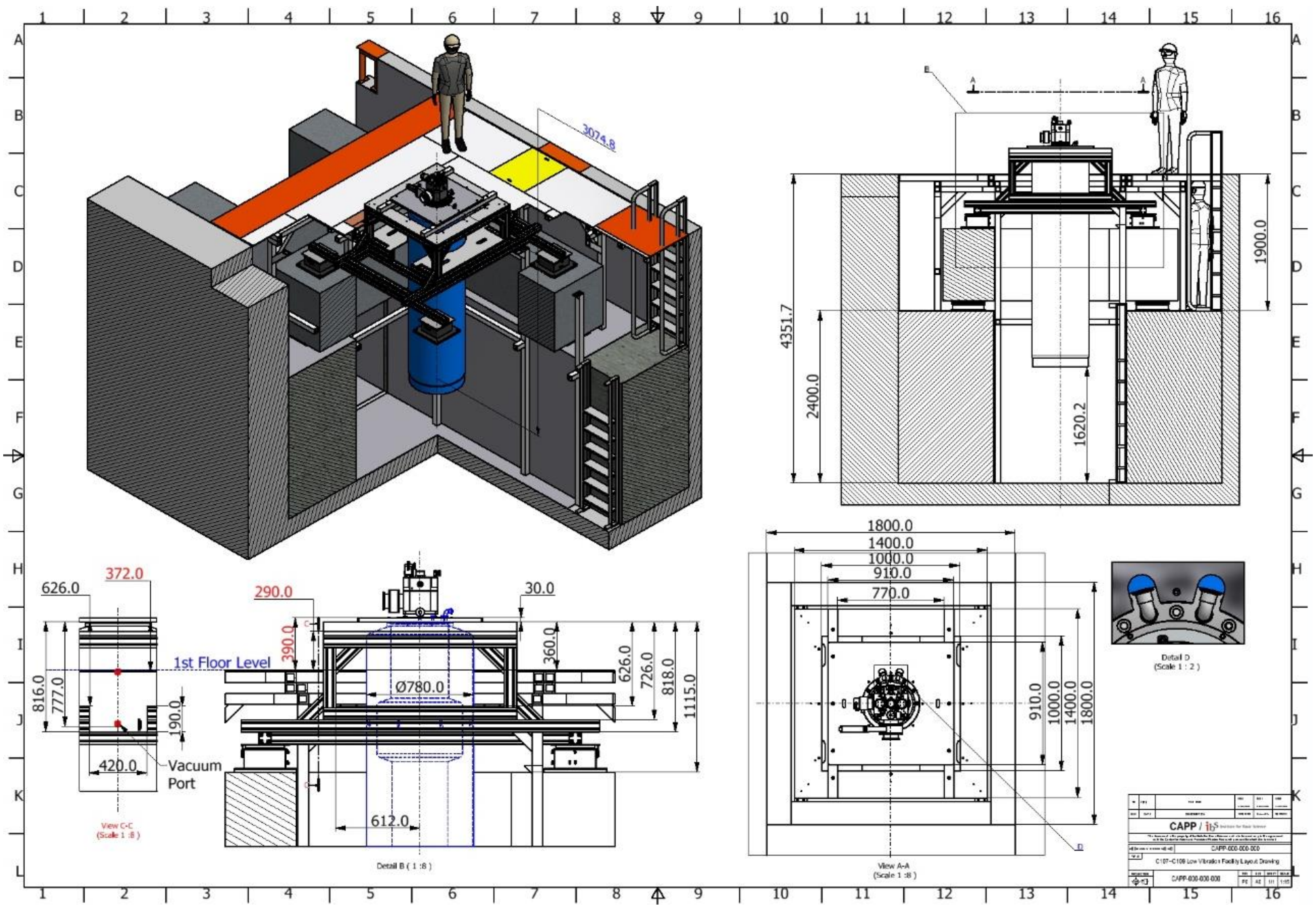
CAPP started from scratch in 2013.
Lab space at KAIST, 2014

Another room at KAIST.

We had to buy even screwdrivers.

7 Low Vibration Pads (LVP) will be hosting axion related experiments. 5 of them are dedicated to axion dark matter experiments.

- Low vibration pad installation



CAPP's lab space at KAIST, 2017

Center for Axion and Precision Physics (IBS/CAPP)

Director: Yannis K. Semertzidis IBS & 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

Members :

- 1 Director
- 1 Group Leader
- ~20 Research Fellows
- 3 Engineers
- 5 Administrators
- ~20 Graduate Students

Refurbished a state of the art lab in an existing bldg.

State of the art infra-structure: 7 low vibration pads for parallel experiments; 6 cryo or dilution refrigerators; high B-field magnets: 25T, 18T, 12T

Organization

- My account people are organized in five teams
  - CAPP-PACE, Team-leader: Woohyun Chang
  - CAPP-12TB, Team-leader: ByeongRok Ko
  - CAPP-QNA, Team-leader: Andrei Matlashov
  - CAPP-MC, Team-leader: SungWoo Youn
  - CAPP-HPPA, Team-leader: MyeongJae Lee

Science Advisory Committee of CAPP

- ✓ Prof. Sergio Bertolucci, Chairman, Former CERN Research Director, Former Director of Frascati
- ✓ Prof. Dima Budker, Berkeley, and Mainz, CASPEr
- ✓ Prof. Axel Lindner, DESY, ALPS
- ✓ Prof. Guido Mueller, Univ. of Florida, LIGO & ALPS
- ✓ Prof. Naohito Saito, Director of J-PARC
- ✓ Prof. Javier Redondo, Max Planck Munich, MADMAX
- ✓ Prof. Pierre Sikivie, University of Florida

High competency, high integrity scientists

IBS/CAPP structure

- ✓ Our Team-leaders work independently, while collaborating and sharing all information in regular weekly meetings.

- ✓ We fully collaborate and support our "Young Scientist" (YS)

- Originally we fully supported the GL (arrived at CAPP June 16, 2016) with people and equipment, including the Kelvinox expensive refrigerator and several other high-end equipment. Expensive and time consuming to acquire.

- GL works independently from us and he moved to the RISP lab where there's a helium liquefier for his 18T project.

IBS/CAPP

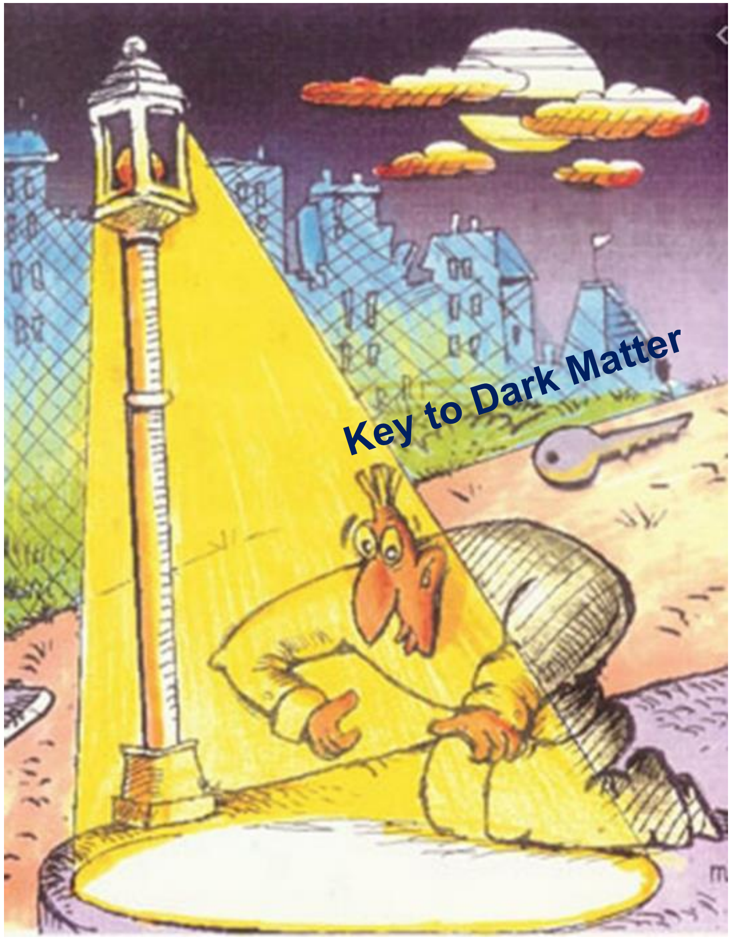
- ✓ Three world-class axion dark matter experiments to reach hadronic axion dark matter sensitivity
- ✓ Cryogenics, microwave expertise, quantum noise limited microwave amplifiers,…
- ✓ Significant player for next five years, working on the next 5-10 years…

- ✓ GNOME (axion dark matter stars over earth), ARIADNE
- ✓ Precision Physics in storage rings: muon g-2 and launch the best hadronic (proton and deuteron) EDM experiment in the world.

Achieving our technical challenges.

Where to look?

- Under (a brighter) lamp-post with microwave resonators
  - LTS, Nb_3Sn magnet: 1-8 GHz
  - HTS magnet: for 8-20GHz



- Open resonators
  - 20-50 GHz (no funding)
- Monopole-dipole interactions (ARIADNE)
  - 100-1000GHz International Collaboration

Weighing the vacuum at CAPP (plan)

- High field magnets with wet cryo systems:
  - Nb_3Sn LTS-12T/320mm from Oxford Instruments
  - HTS-25T/100mm from BNL, on hold…

- High-efficiency/high-frequency axion sensitivity (pizza cavity, etc.). Low cavity temperatures (<50mK) and low-loss RF-lines

- Quantum-noise limited amplifiers: SQUIDs and JPAs; Single photon for >10GHz

- High-quality factor resonators ($>10^6$)

Current status

- Prototype systems: three experiments in DAQ mode
- Getting ready for the Nb_3Sn, LTS-12T/320mm magnet from Oxford Instr., delivery end of January 2020.
- High-efficiency/high-frequency axion sensitivity (pizza cavity, etc.). Low cavity temperatures (<50mK) and low-loss RF-lines
- Quantum-noise limited JPAs for 2.3 GHz; developing JPAs for the whole range 1 – 10GHz
- High-quality factor resonator at 6.9GHz, more…

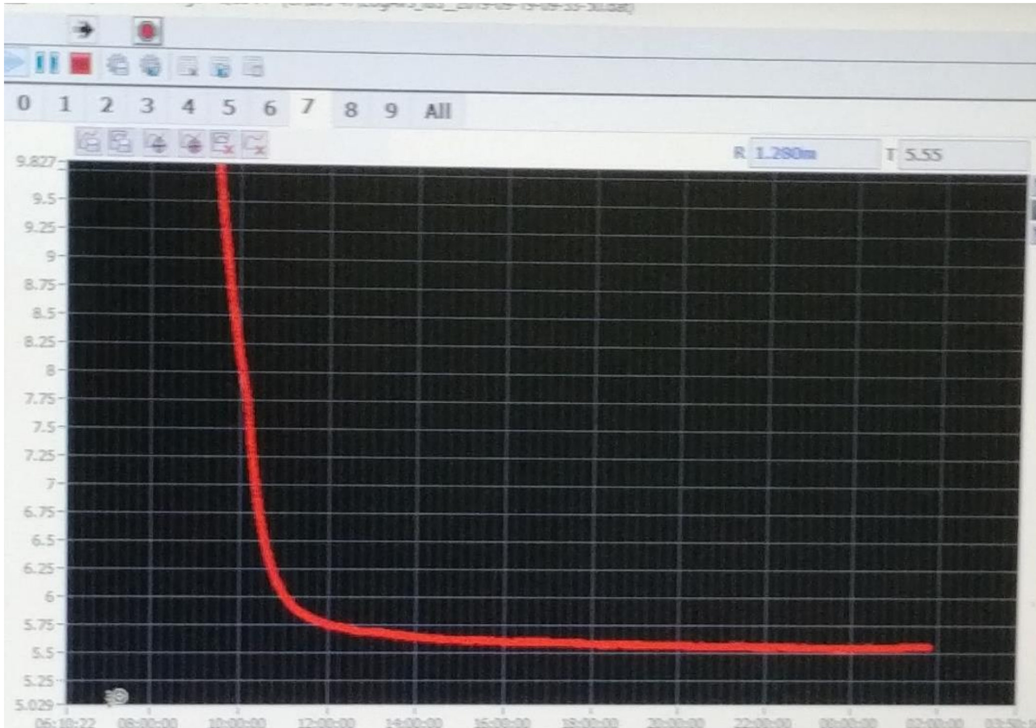
LTS magnet from Oxford Instrs.

Status of LTS-12T/320mm magnet

- Nb_3Sn + NbTi, LTS-12T/320mm from Oxford Instr., delivery end of January 2020.

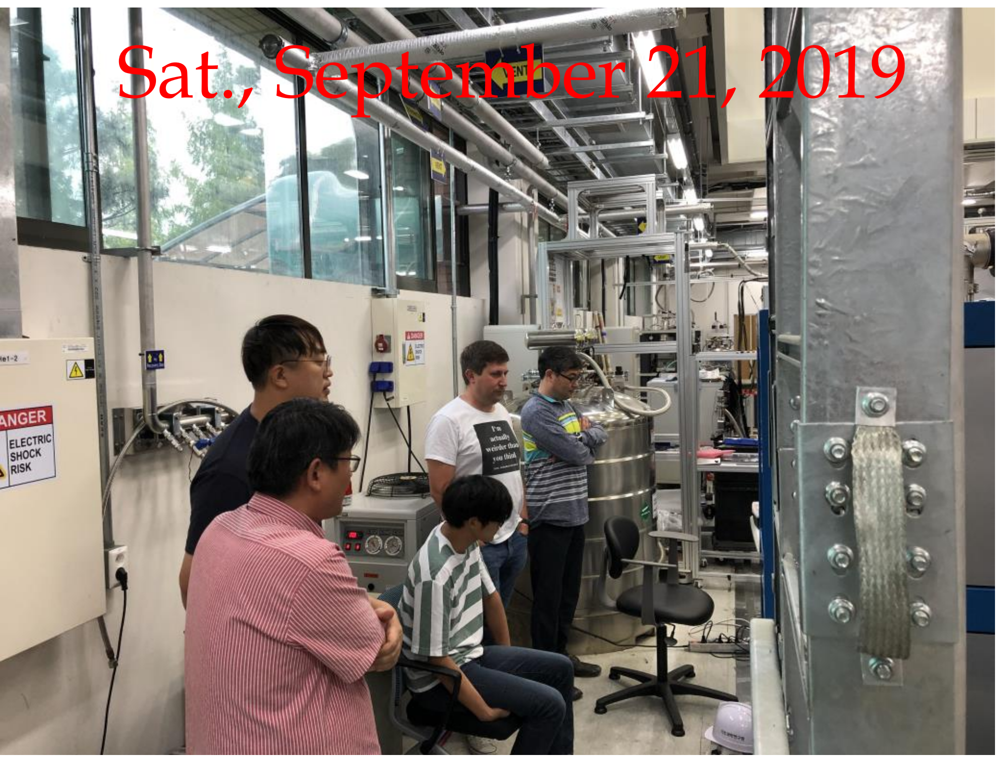
- The moment this system becomes operational we can reach DFSZ level sensitivity in the 1-8 GHz, with present technology.

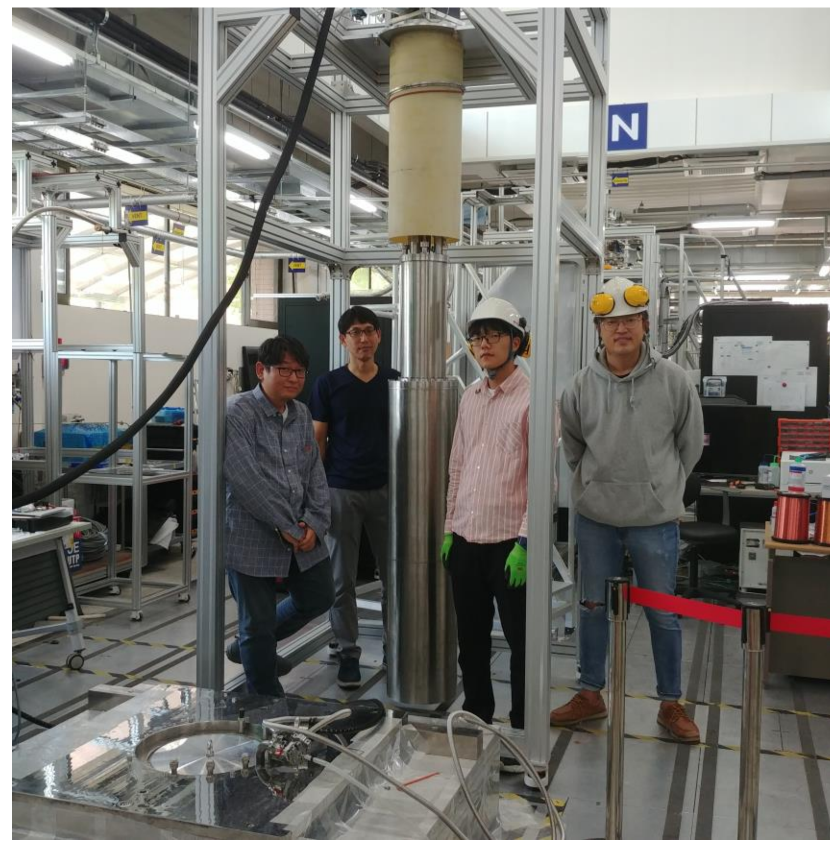
- Wet system,
  Leiden dilution system:
  1.3mW at 120mK,
  achieved 5.6mK.



Status

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





If you don't know the axion mass need to tune

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \text{GHz}}{\text{year}}\left(g_{a\gamma\gamma}10^{15}\,\text{GeV}\right)^4 \left(\frac{5\ \text{GHz}}{f}\right)^2 \left(\frac{4}{SNR}\right)^2 \left(\frac{0.25\ \text{K}}{T}\right)^2 \left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

$$T = T_{\text{N}} + T_{\text{ph}}$$

<B> = 11T

V = 30 l

<T_{ph}> = 50 mK

<T_N> ~ 50mK

c ~ 0.5

Q_0 ~ 150K

SNR = 5

df/dt ~ 10GHz/y

We need full funding now in order to deliver!

Scanning rate (theoretically possible):

$\langle B \rangle = 11T$

$V = 30\ l$

$\langle T_{ph} \rangle = 50$ mK

$\langle T_N \rangle \sim 50$mK

$c \sim 0.5$

$Q_0 \sim 150$K (normal copper)

SNR $= 5$

$df/dt \sim 10$GHz/y at DFSZ

In practice it will take a long time. Fully funding the effort now makes sense!

HTS magnet from BNL

BNL 25T/10cm, HTS magnet review

October 22, 2018

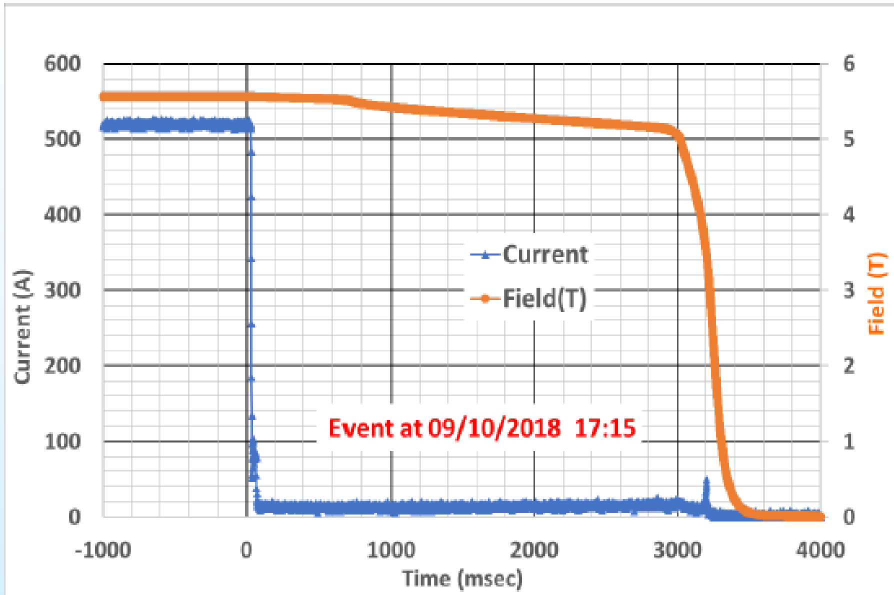
- Magnet construction plan with single layer is sound
- Magnet design with No Insulation is predicted to be safe from quenches and structural integrity
- >50% margins in critical current and stresses
- 16 out of 28 pancakes constructed and tested.

Figure 2.67: Manufacturing process (10 HTS coils).

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)

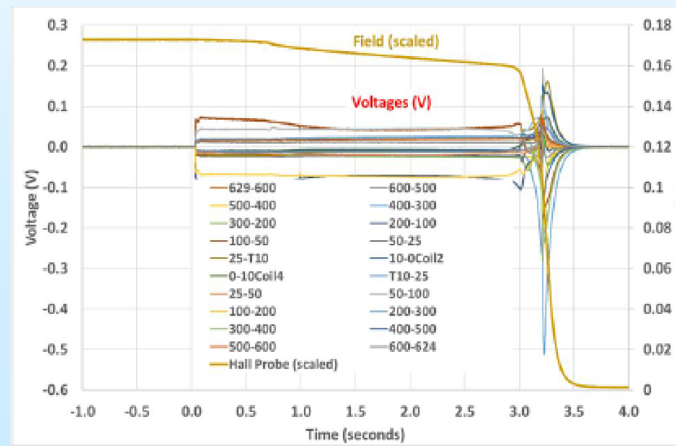


- No significant energy is extracted during shut-offs or quenches in the no-insulation coils
- Energy is dumped/distributed inside the whole coil with contact resistance between the turns
- Whether coil recovers or runs away depends on how far away it is from critical surface
- Crucial test of inter-connect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

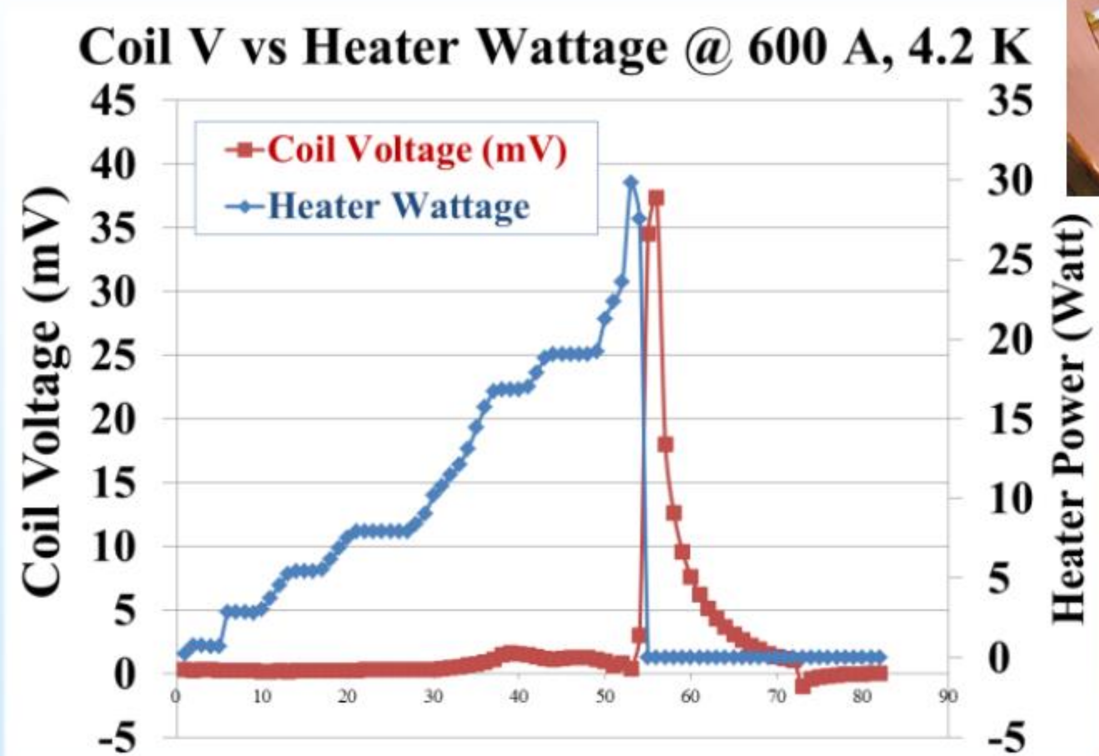
This coil recovered (no runaway) up to 400 A

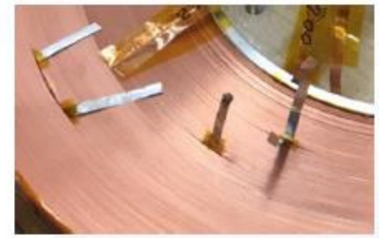


Punishing tests

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

Axion dark matter HTS magnet specs

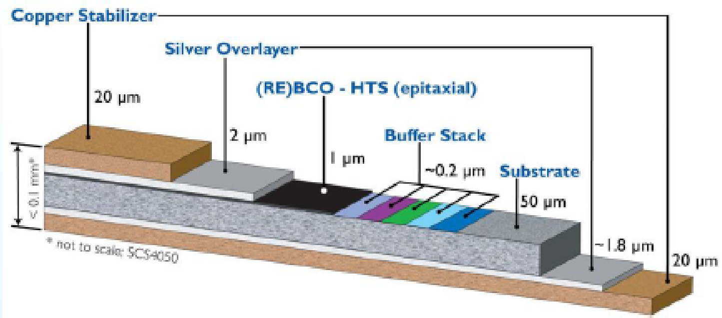
- No Insulation quenches the magnet fast!
- Quenches safely. (Further tests with 3DP, 7DP, 14DP)
- What's next? Material strength…

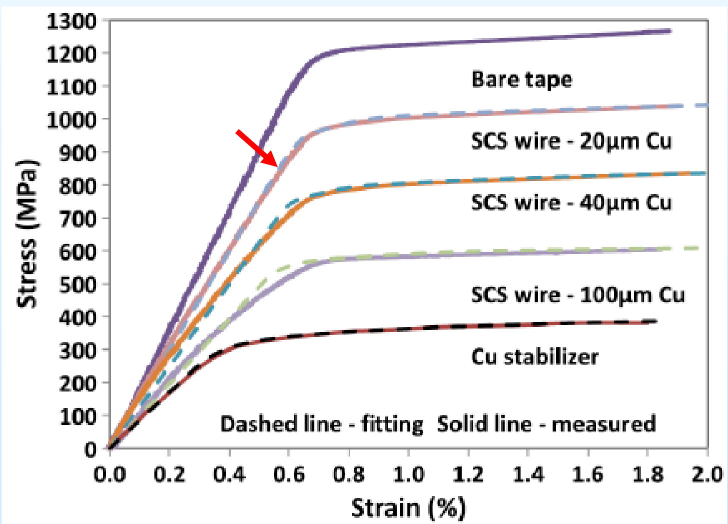
>50% margins

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 will come up with a plan to finish the project.

- We need support from the community to do this.

Axion Dark Matter Search at IBS/CAPP

- *Center for Axion and Precision Physics Research (CAPP)*
  - *Established in Oct. 2013*
- *Completion of infrastructure*
  - *7 low vibration pads for parallel experiments*
  - *Several refrigerators and SC magnets*
- *Constructing experiments*
  - *Accomplished all technical challenges*
  - *Described in numerous publications in literature*
  - *Three experiments in DAQ mode in 2019*

Refrigerator			Magnet			Experiment
Manufacturer	**Model**	**T_B [mK]**	**Manufacturer**	**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 Instr.	Kelvinox	30	BNL Magnet Div.	25	100	CAPP-25T

Operating several experiments targeting different axion mass ranges in parallel.

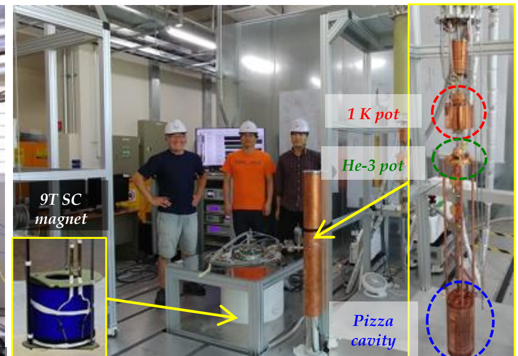
* The Kelvinox refrigerator will be reused for CAPP-25T

IBS/CAPP Prospects

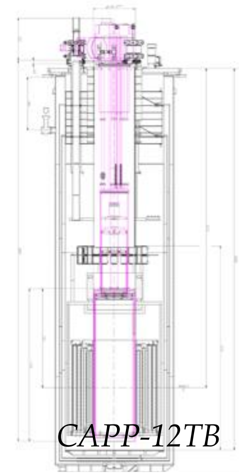
- *All the ingredients together, we will reach the DFSZ sensitivity even for 10% axion content in the local dark matter halo.*

CAPP-PACE

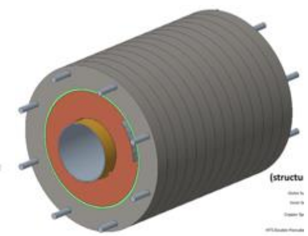
CAPP-8TB



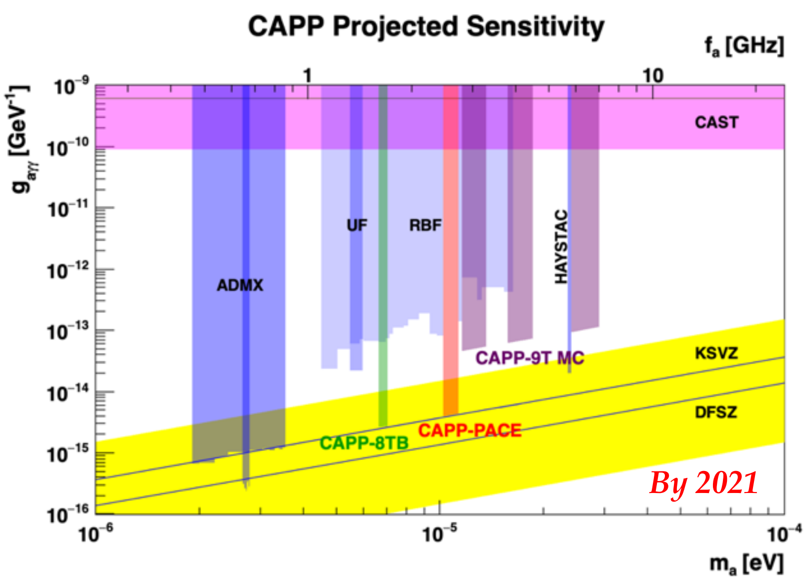
CAPP-9T MC

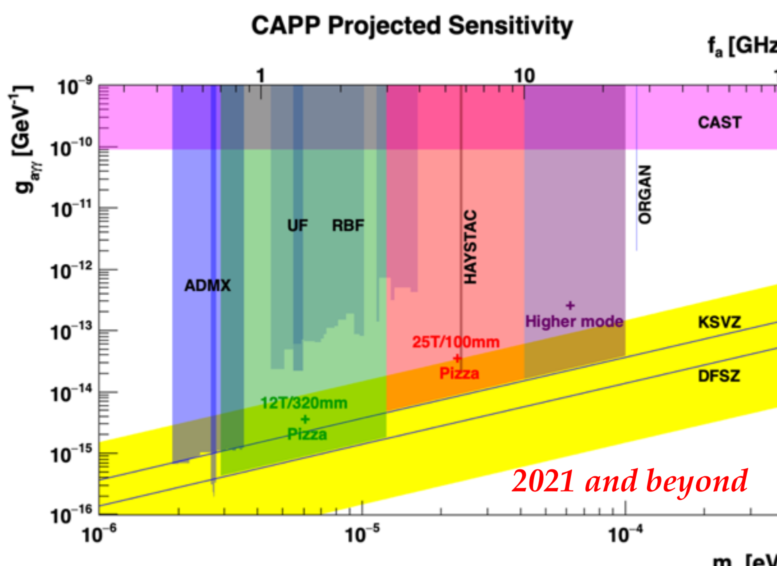


CAPP-12TB



CAPP-25T

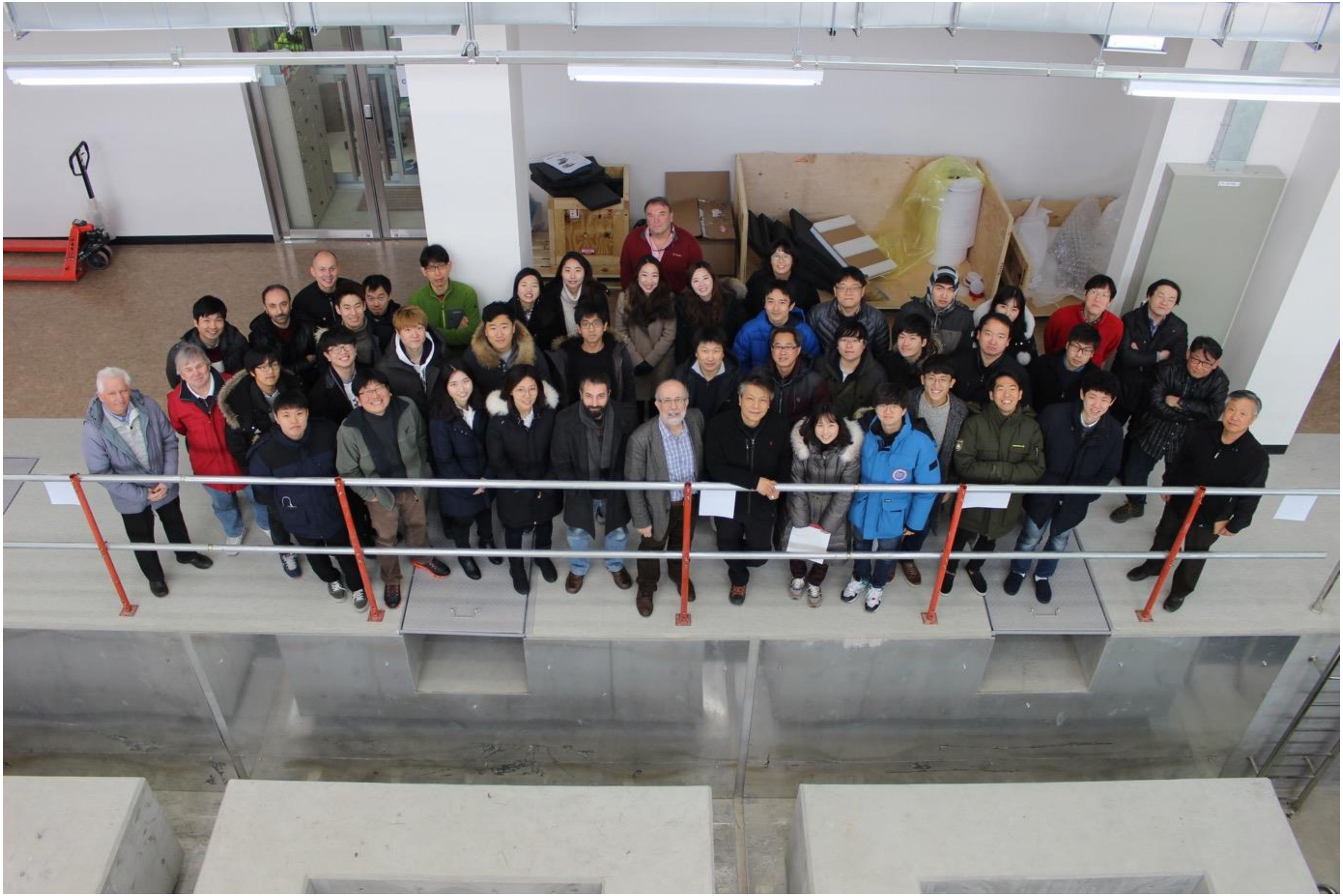




- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

CULTASK:
CAPP's Ultra-Low Temperature Axion Search in Korea

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



CAPP Experimental Hall (LVP)

Woohyun Chung's slide

CAPP's base plan

- Delivery of 12T/320mm LTS (Nb_3Sn) magnet early 2020; 25T/100mm (HTS, funding limited, 2021?).

- In the meantime, we are getting ready for it:
  - Quantum noise limited JPAs, SQUID-amplifiers
  - Superconducting cavities in large B-fields
  - Cryo-expertise, reach lowest physical temperature (down to <50mK)
  - Demonstrate efficient high-frequency, high-volume resonators
  - Efficient DAQ
  - Prepare systems for large magnets

Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-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.

Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019

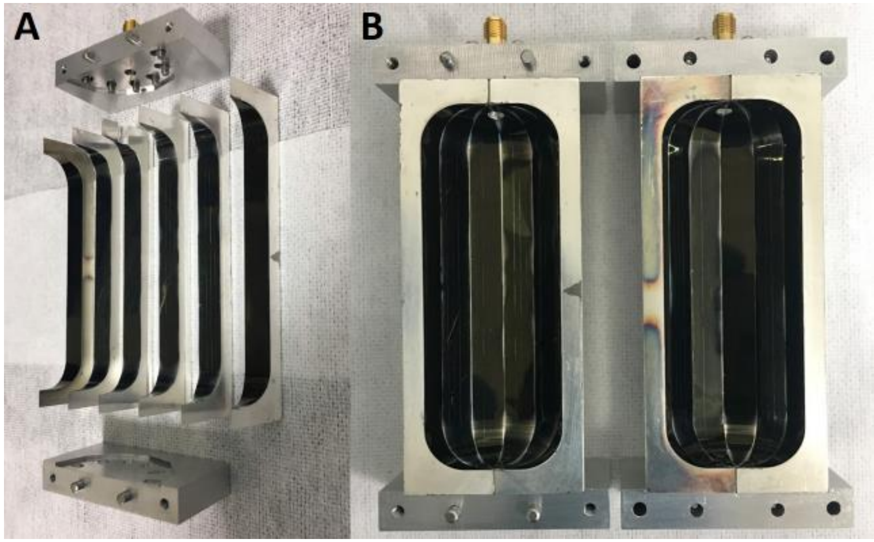
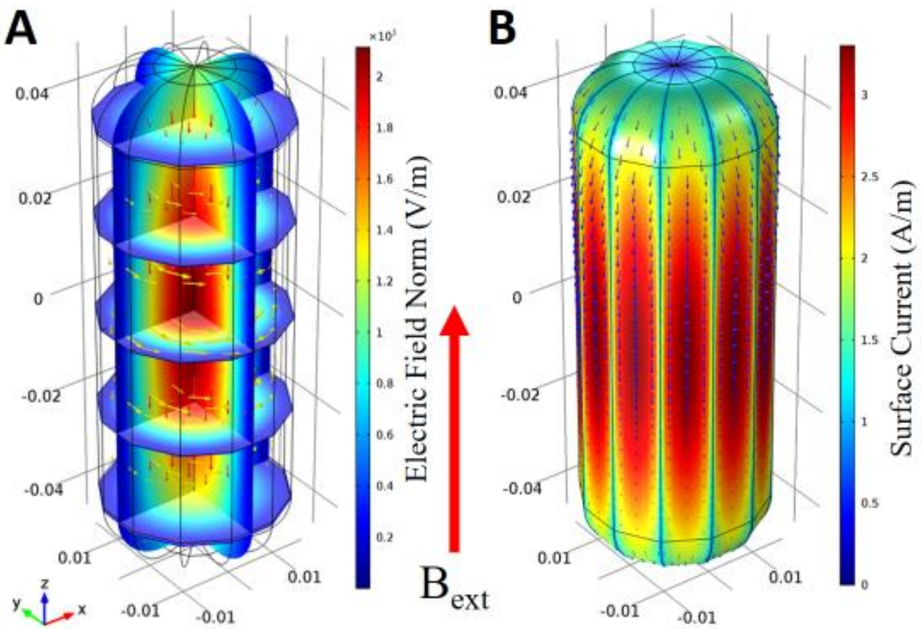


FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

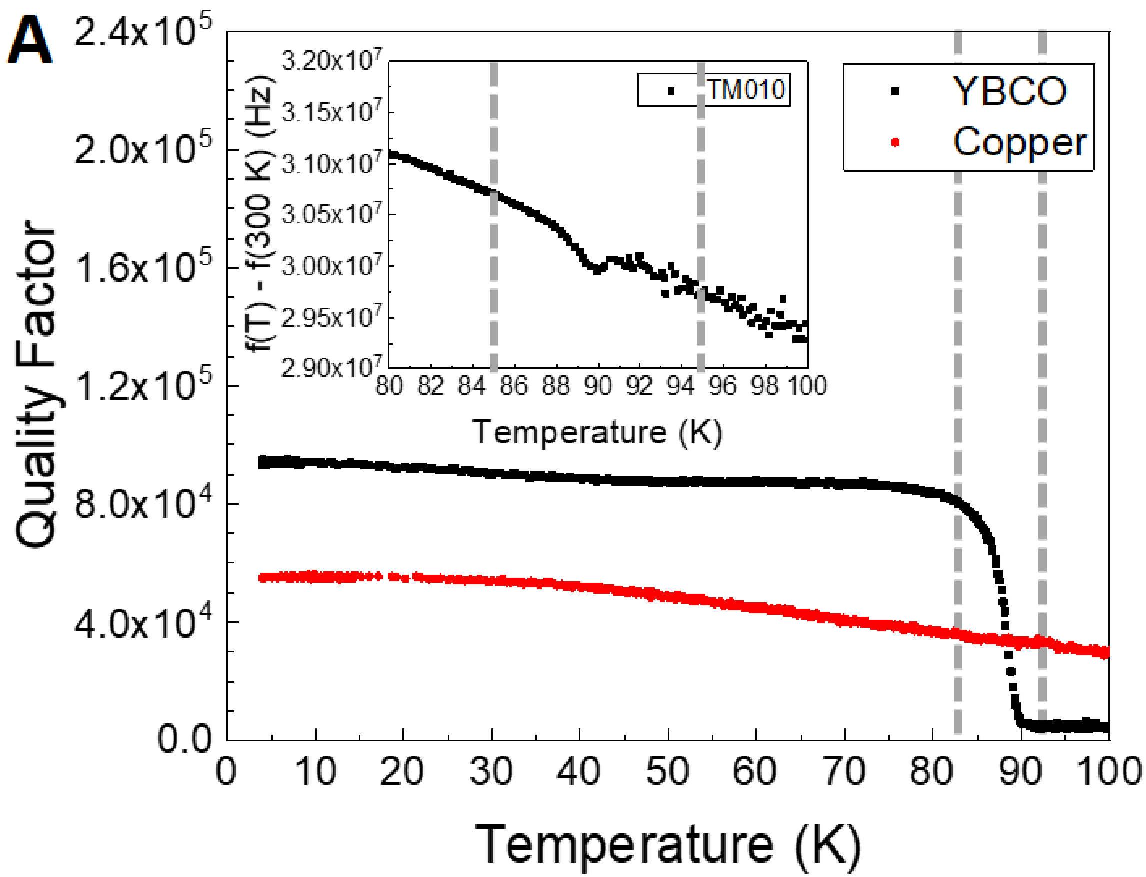
TM_{010} mode



YBCO tapes placed on cavity slices!

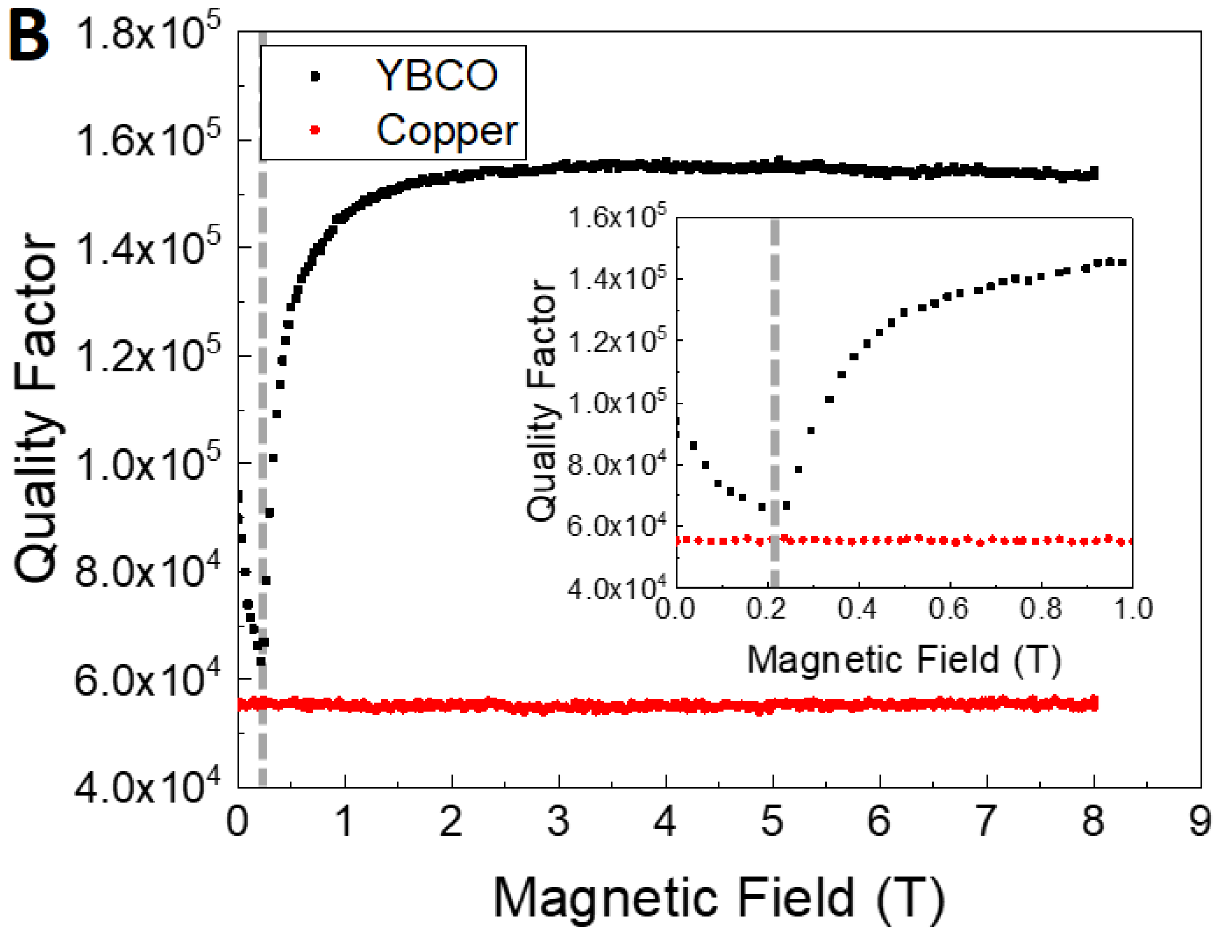
Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019



Superconducting cavity in large B-field!

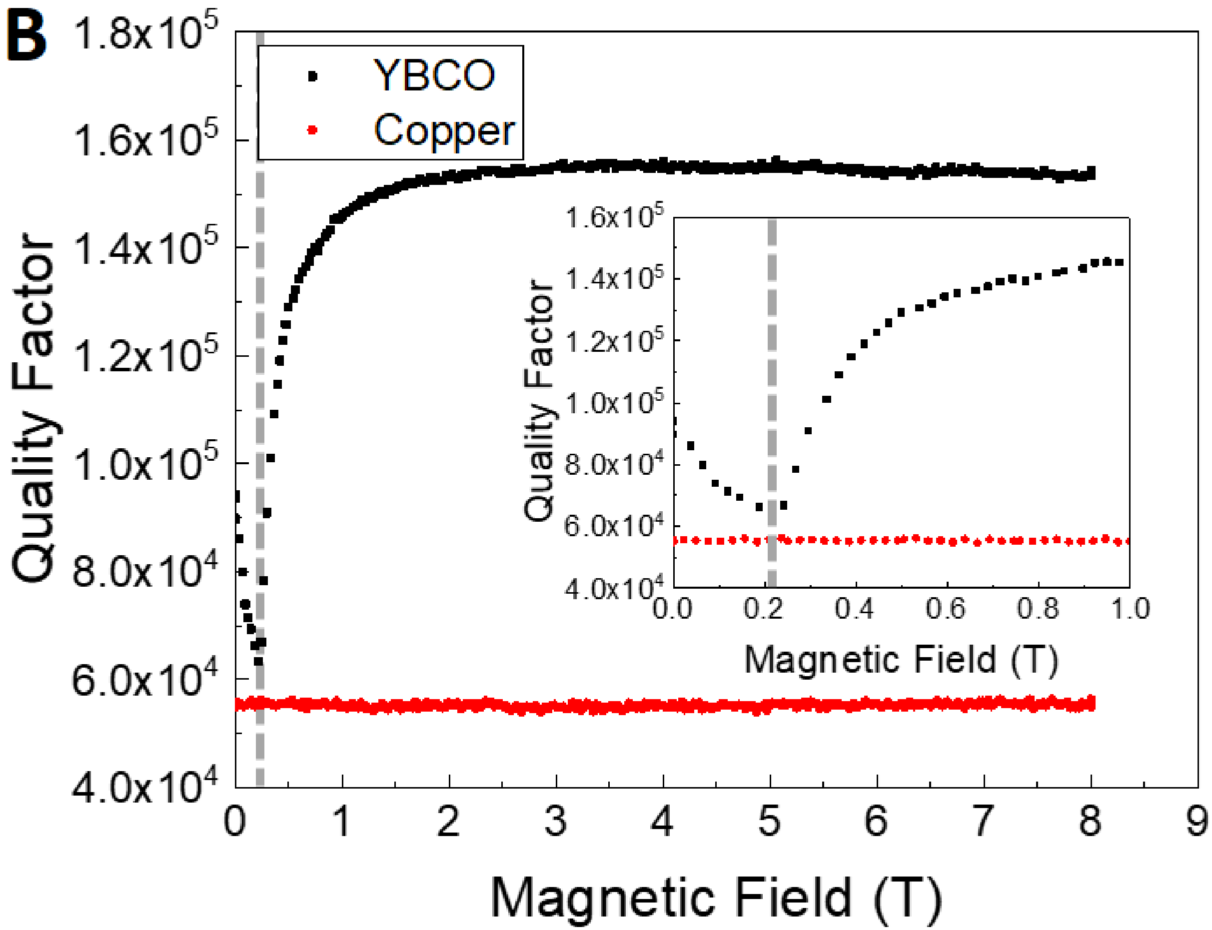
arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019



Our first YBCO cavity results. The second cavity showed much improved results!

Superconducting cavity in large B-field!

arXiv:1904.05111v1 [physics.ins-det] 10 Apr 2019



The SC cavities will allow us to probe DFSZ axions even if they are only 10% of the local dark halo density

Quantum Noise Limited Amplifiers

RF-amplifiers and CAPP

- KRISS/S. Korea, delivered first functional MSA at >1GHz, 2016
- Private companies sprung up producing MSAs, JPAs
- Quantum computing is fueling the development. Single photon detection (SPD) is possible on the bench! SPD over 10 GHz are winners.
- Next year, fall 2020, we are going to host a joint meeting between the qubit/quantum electronics community and the axion community. Our funding cuts affect our ability to be credible players internationally.

Quantum-noise limited RF-amplifiers

- Frequency of interest: 1-10 GHz
- Currently working at: 1-2 GHz, 2-3 GHz, 3-7 GHz
- Longer term: 7-10 GHz, 10-15 GHz, and finally up to 20 GHz
- Single photon R&D? No funding for it.

Quantum noise-limited RF amplifiers

Development of SQUID Amplifiers for Axion Search Experiments

Sergey Uchaikin, Andrei Matlashov, Doyu Lee,
Woohyun Chung, Seon Jeong Oh, Yannis Semertzidis
Center for Axion and Precision Physics Research
IBS, DaejeonSouth Korea
uchaikin@ibs.re.kr

Vyacheslav Zakosarenko
Supracon AG
Jena
Germany

Çağlar Kutlu
Dept. of Physics, KAIST
Daejeon, South Korea

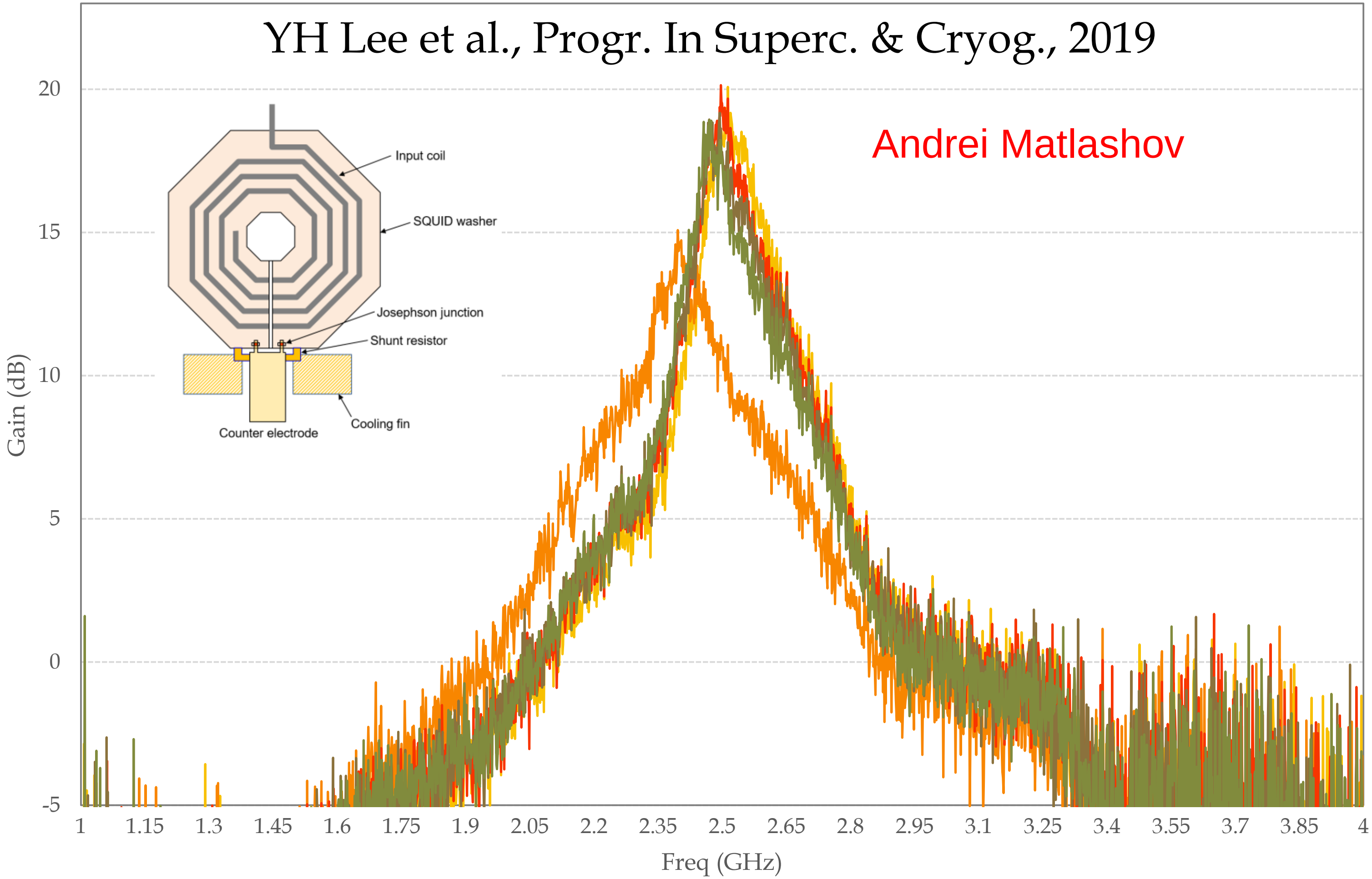
Arjan van Loo, Yoshiro Urade, Shingo Kono
RIKEN
Saitama, Japan

Matthias Schmelz, Ronny Stolz
IPHT
Jena, Germany

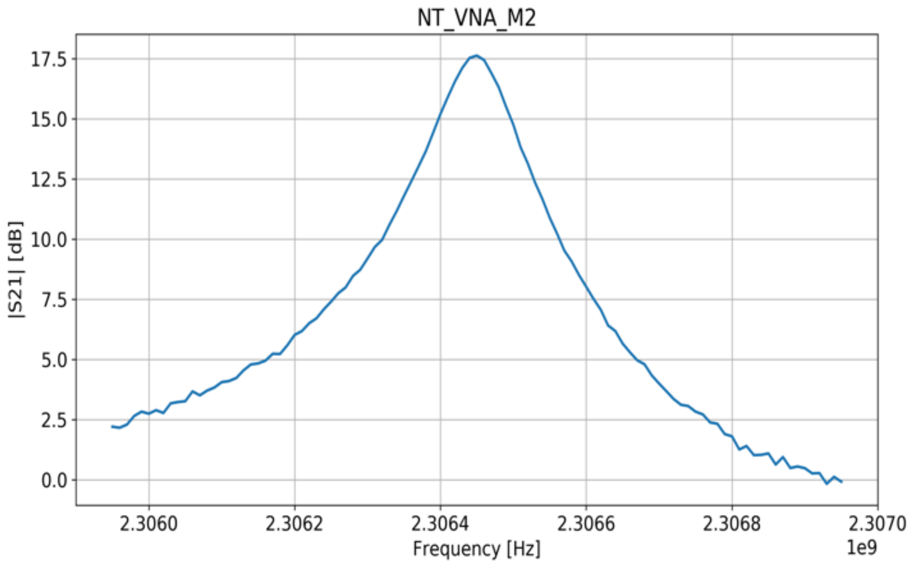
Yasunobu Nakamura
University of Tokyo
Japan

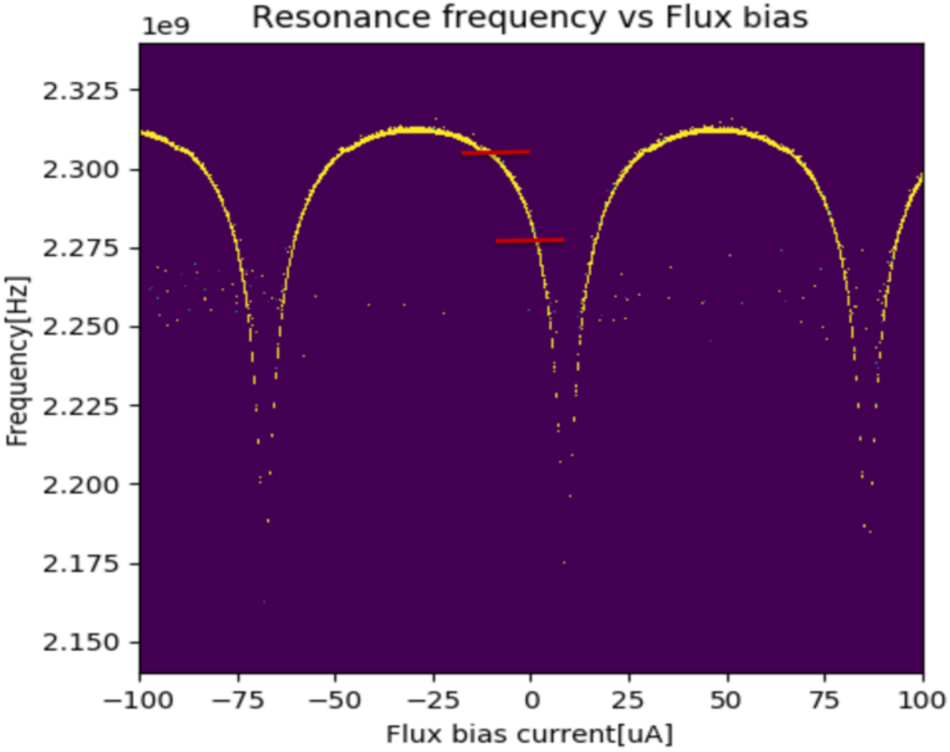
International collaboration for applications in axion research

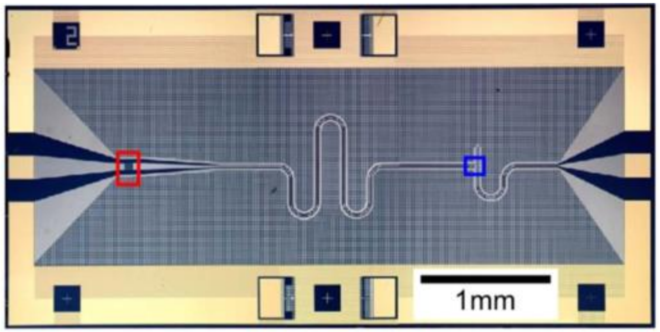
MSAs from Yong-Ho Lee, KRISS: World's first at 2.2-2.5GHz, 2016



Josephson Parametric Amplifier at 2.3 GHz
JPAs were provided by RIKEN/Univ. of Tokyo







Reasonable gain and tunability to about 30 MHz

JPA results at 2.3 GHz

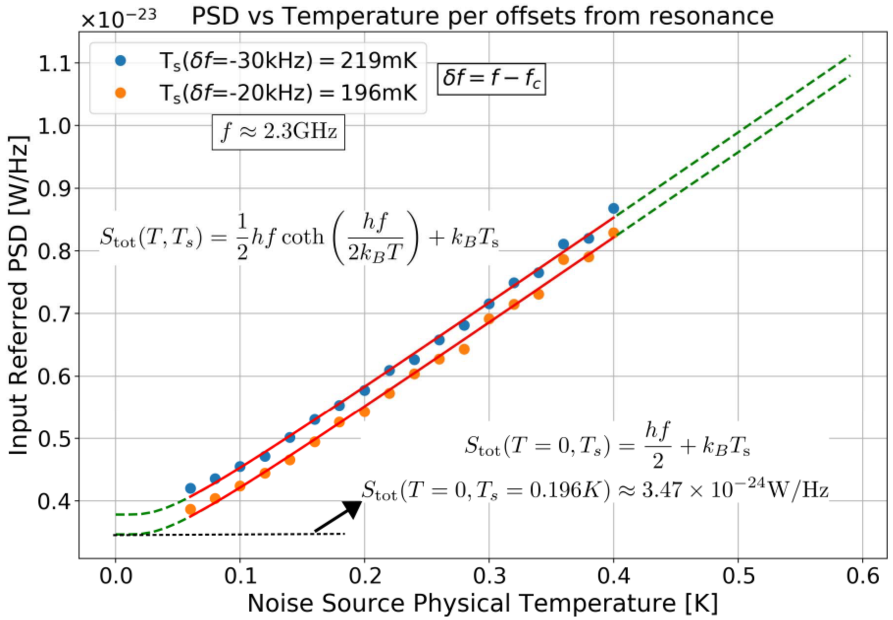


Fig. 5. PSD dependence on the temperature of 50Ω noise source for a 2.3 GHz JPA. The green line corresponds to the resistance noise PSD including quantum fluctuation corrections.

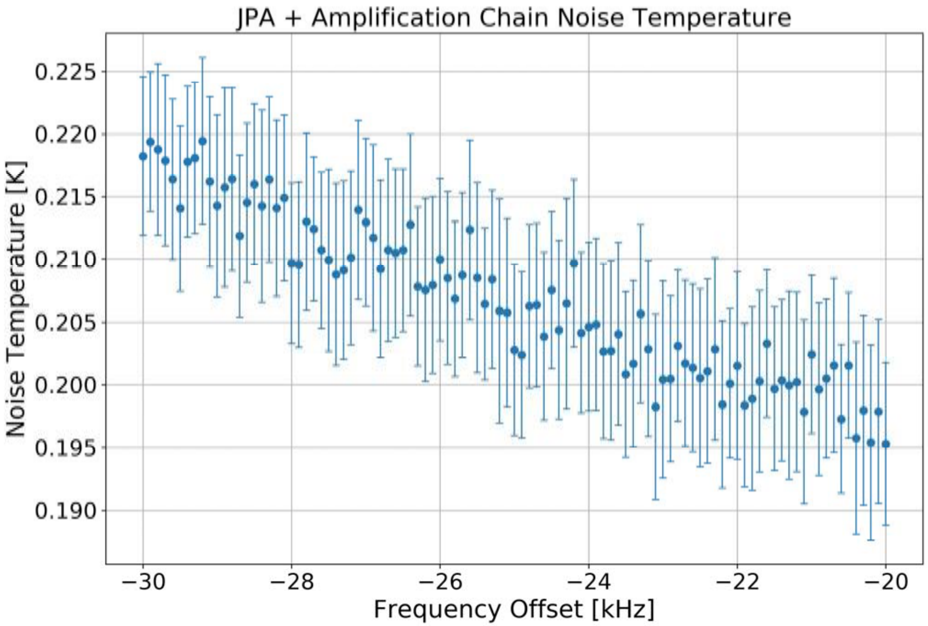
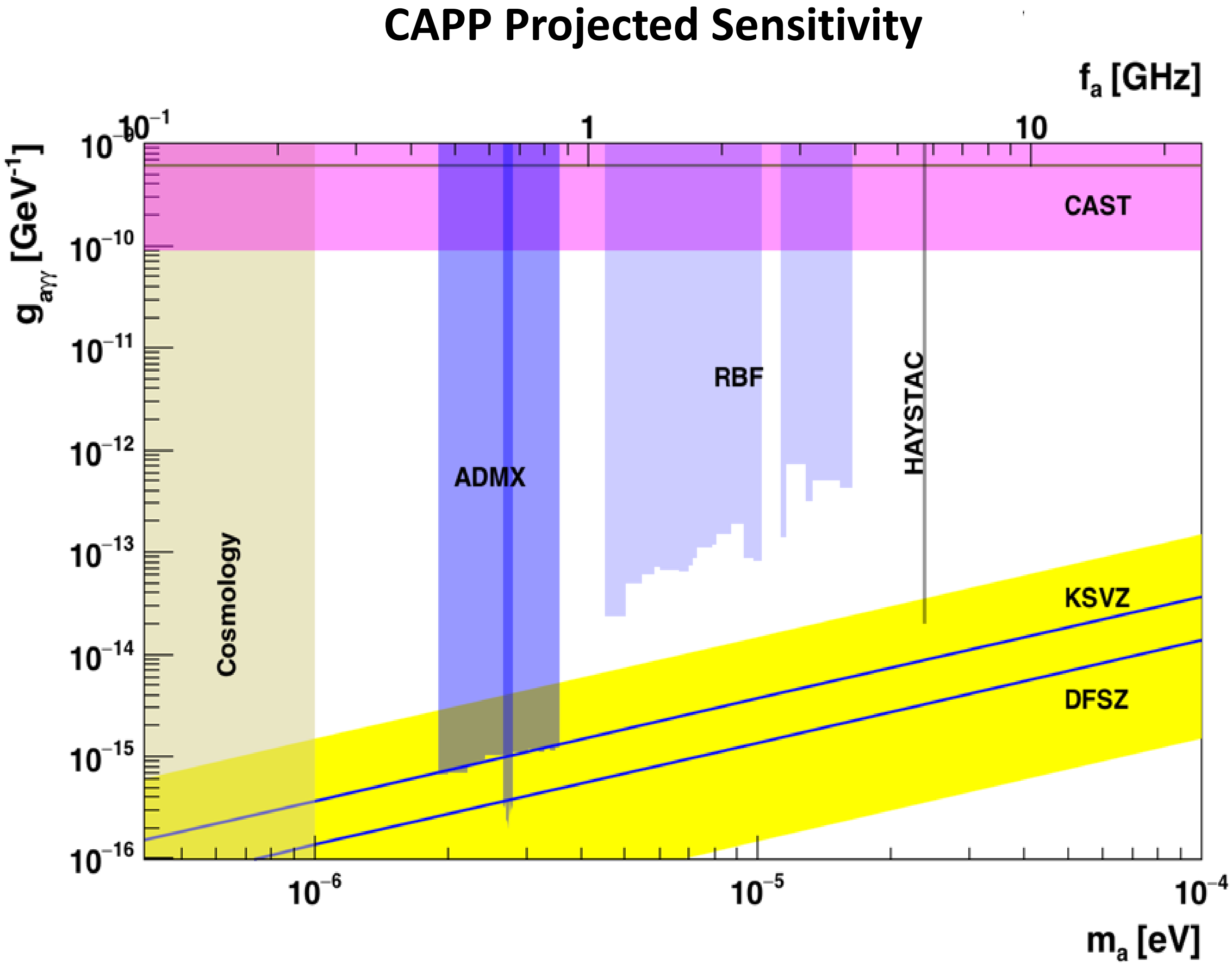


Fig. 6. Frequency dependence of the system noise temperature for 2.3 GHz JPA.

- Quantum noise limit (QNL): 50mK / GHz
- Noise level of this JPA a little over the quantum limit
- Next JPA at 2.3 GHz was measured to be at QNL

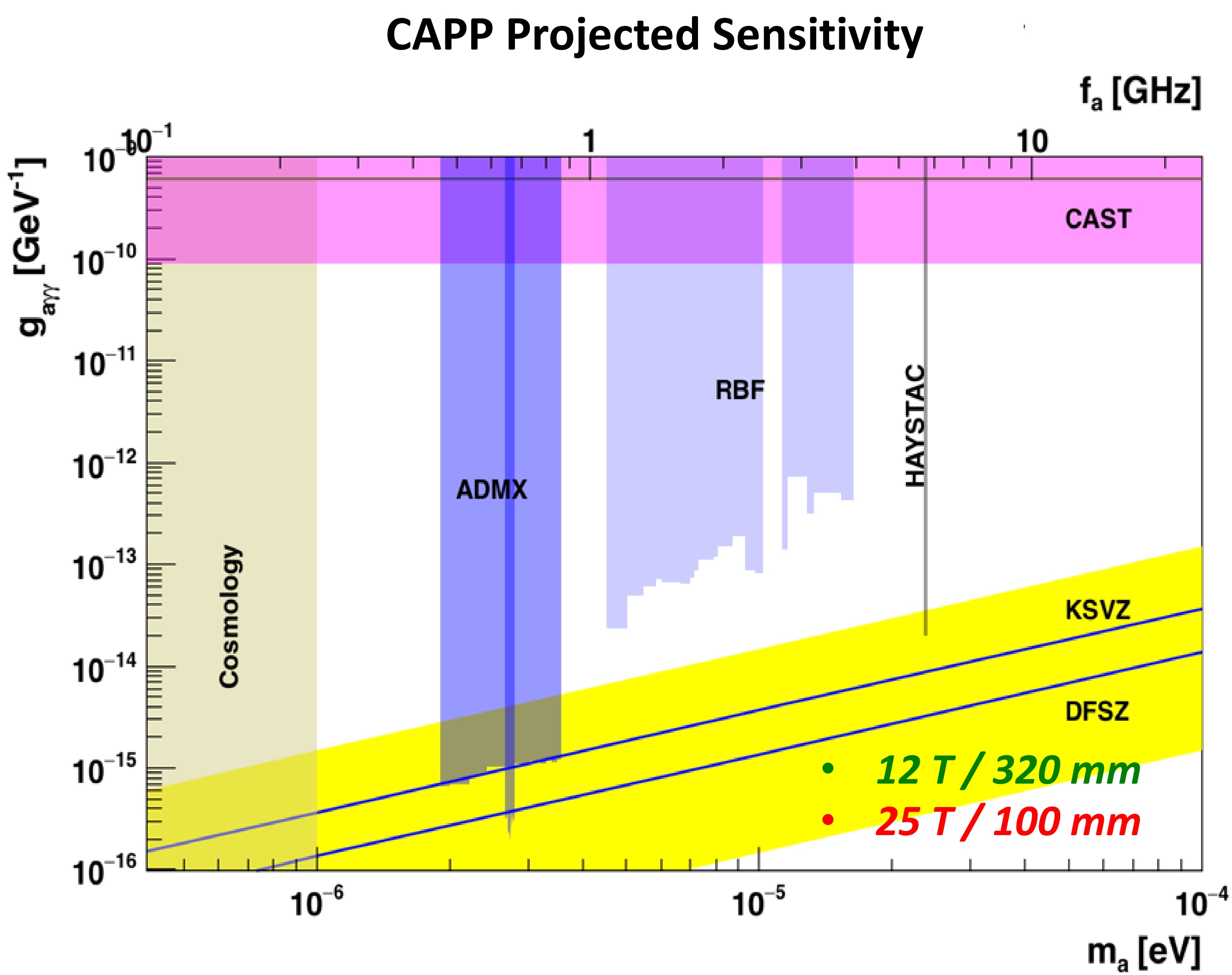
CULTASK:
CAPP's axion dark matter search by 2021

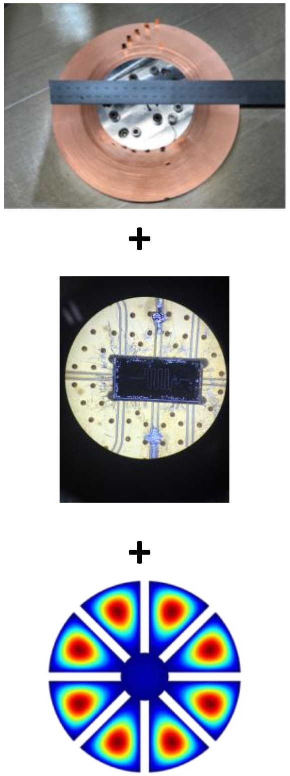


- *CAPP-8TB*
- *CAPP-PACE*
- *CAP-9T MC*

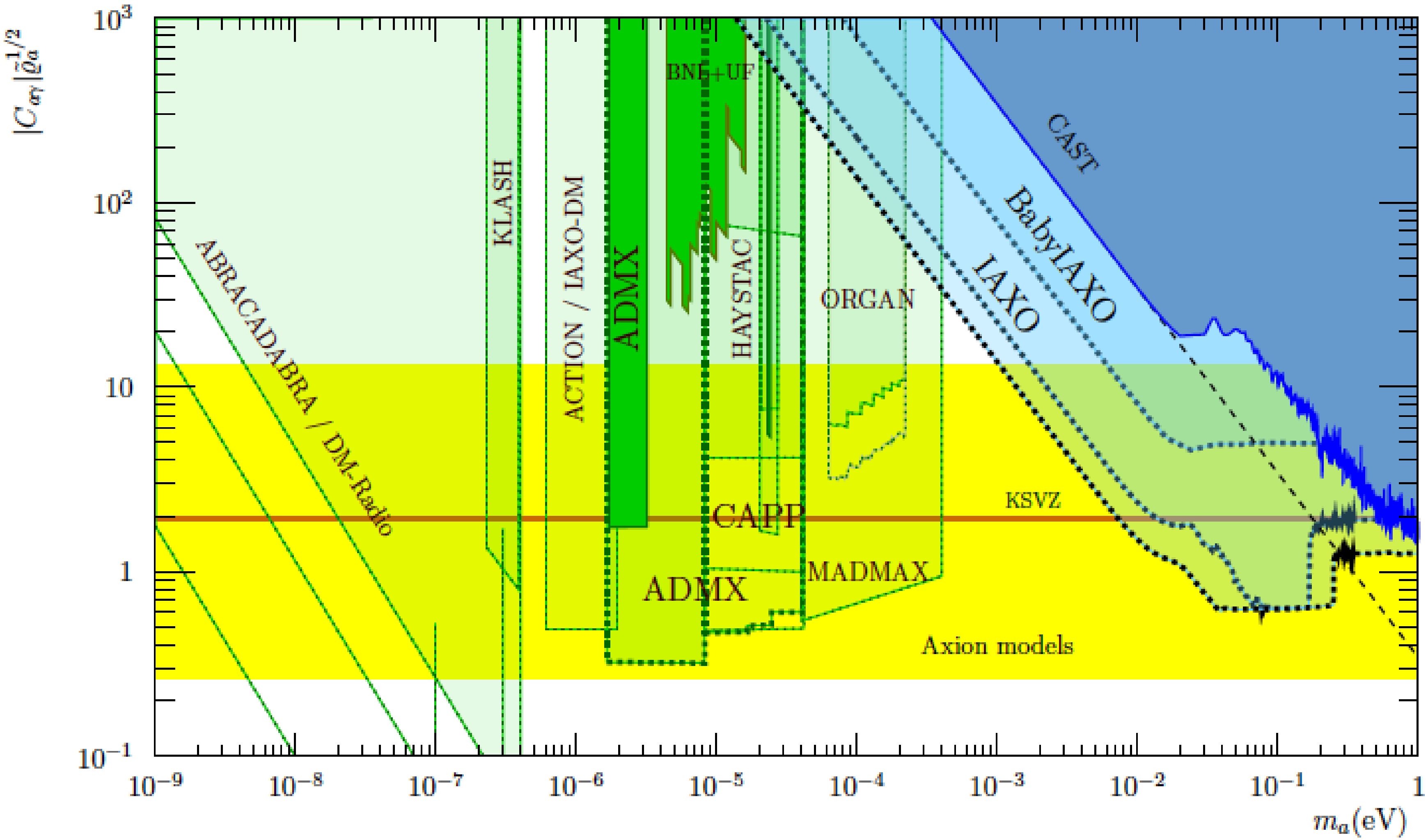
CULTASK: CAPP's axion dark matter search

CULTASK Sensitivity (5 year plan)





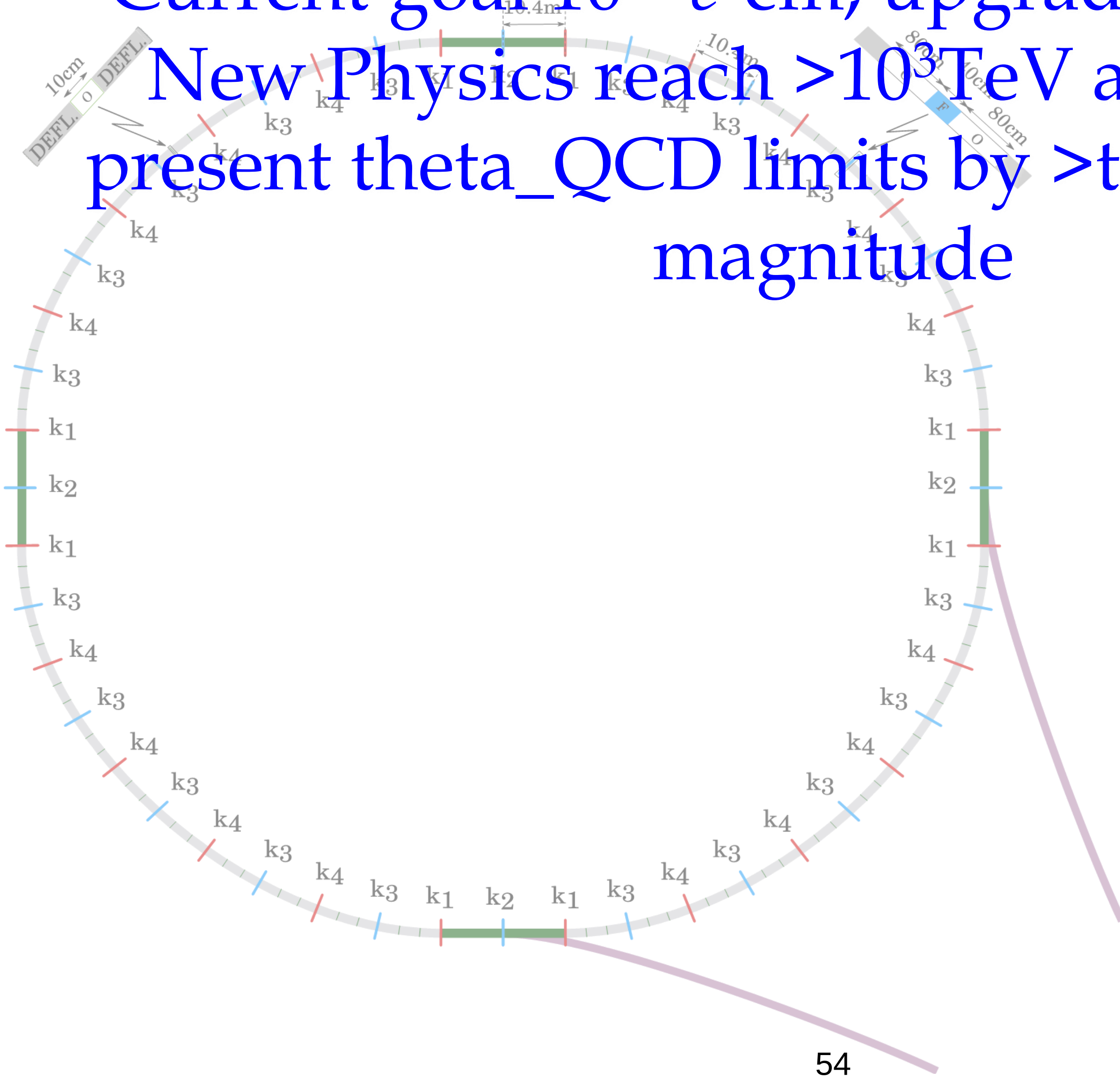
Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

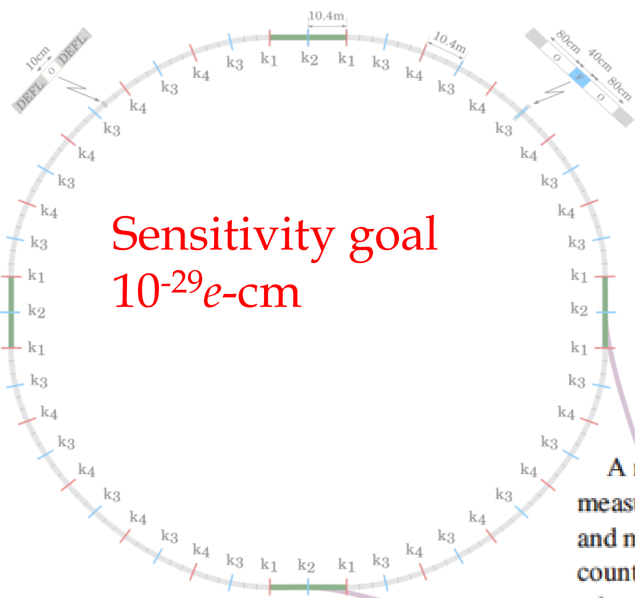
Accelerator-based Precision Physics

The proton EDM electric ring, 500m circ.
Current goal 10^{-29} *e*-cm; upgraded: 10^{-30} *e*-cm.
New Physics reach $>10^{3}$ TeV and improve present theta_QCD limits by >three orders of magnitude



New breakthrough idea from IBS/CAPP: hybrid storage ring

- It eliminates the main syst. error sources: ext. B-fields
- Makes the ring construction simpler



Sensitivity goal
$10^{-29}e$-cm

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 034001 (2019)

Hybrid ring design in the storage-ring proton electric dipole moment experiment

S. Hacıömeroğlu[1] and Y. K. Semertzidis[1,2,*]

[1]*Center for Axion and Precision Physics Research, Institute for Basic Science (IBS/CAPP), Daejeon 34051, Republic of Korea*

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

(Received 25 October 2018; published 5 March 2019)

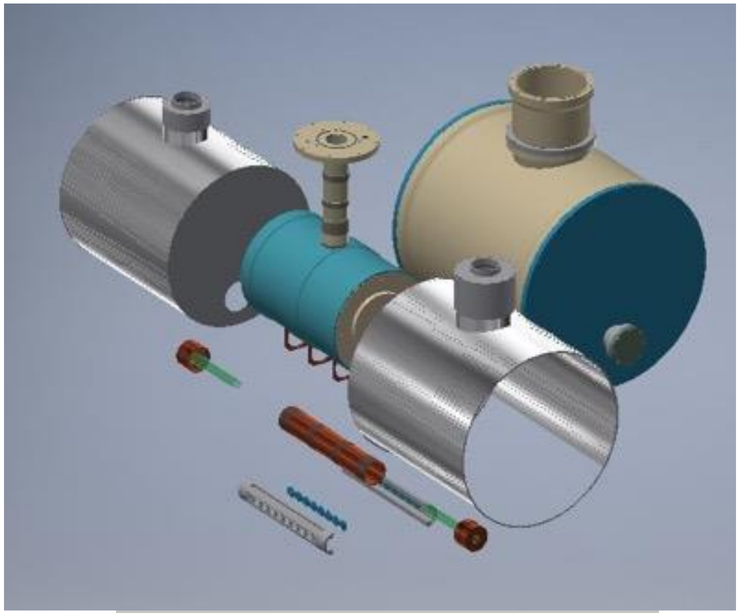
A new, hybrid design is proposed to eliminate the main systematic errors in the frozen spin, storage ring measurement of the proton electric dipole moment. In this design, electric bending plates steer the particles, and magnetic focusing replaces electric. The magnetic focusing should permit simultaneous clockwise and counterclockwise storage to cancel systematic errors related to the out-of-plane dipole electric field. Errors related to the quadrupole electric fields can be eliminated by successive runs of magnetic focusing with different strengths.

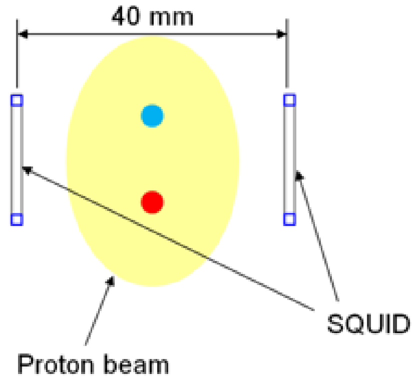
DOI: 10.1103/PhysRevAccelBeams.22.034001

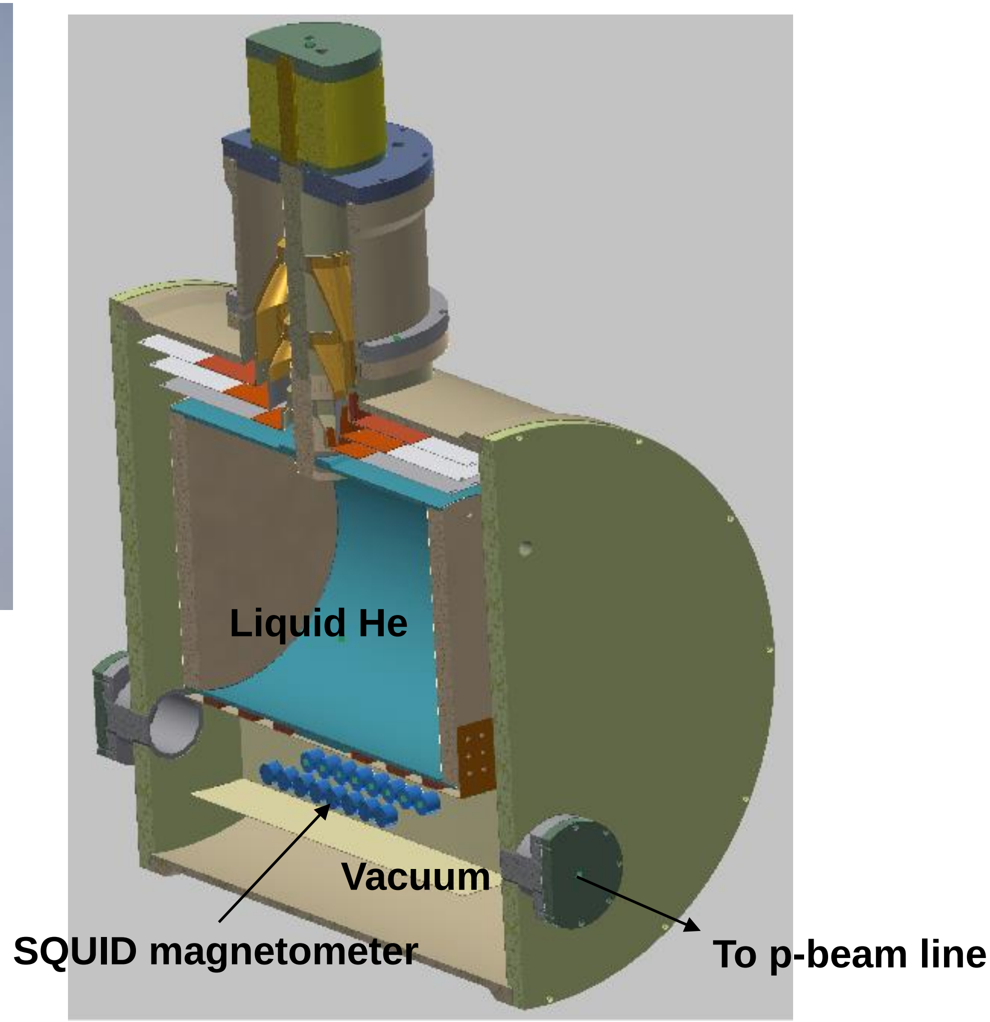
Flattening the ring

- Beam-based alignment using S-BPMs. Resolution of S-BPMs: 10nm/sqrt(Hz)!
- Radially polarized bunches

Beam position monitor: SQUID array

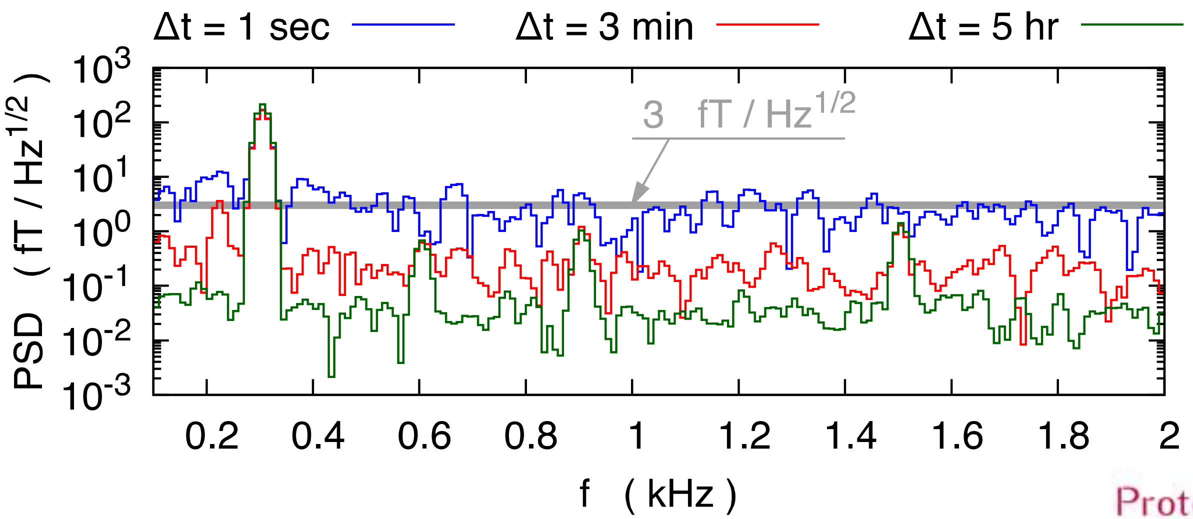






Cylindrical Dewar: original design (KRISS)

SQUID-based BPMs, Korea



Next: Testing the concept at an accelerator in Korea.

Issue: Our severe budget reduction doesn't allow it.

Prototype

- The new design is to be delivered by summer
- Will be $2fT\sqrt{Hz}$
- We will make wire tests in Korea
- Would be good to test here at COSY

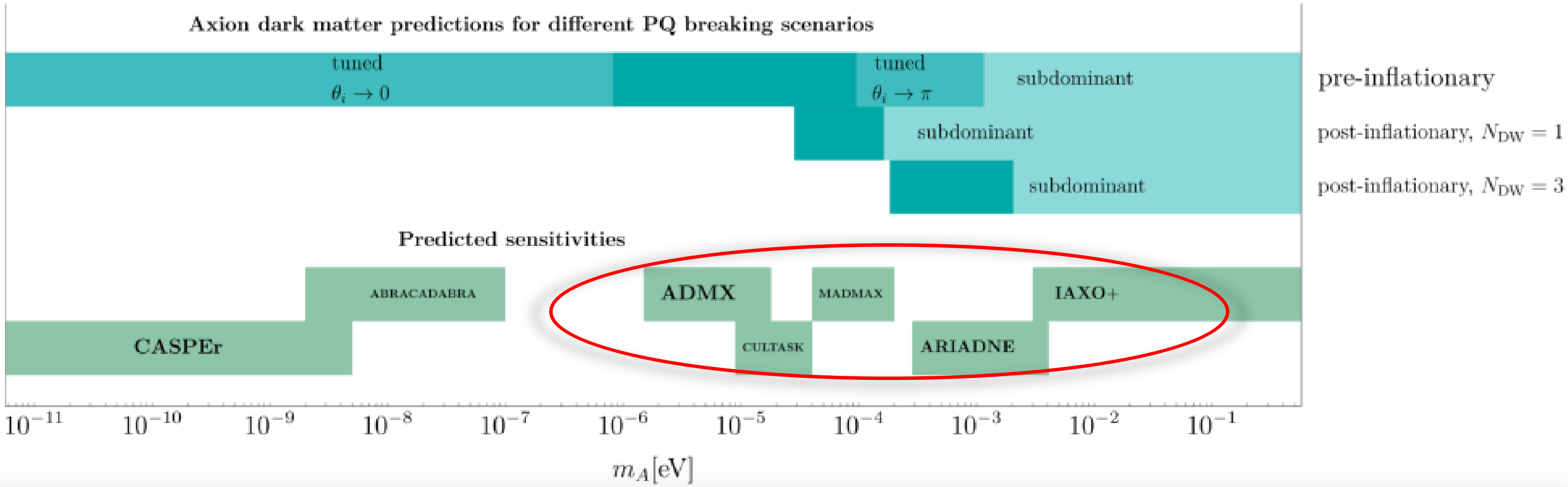
Selcuk Haciomeroglu, IBS-CAPP

Where to look?

Axion Dark Matter

Summary

- Dark-matter axion mass spans a huge range:



- Particularly well-motivated range: No Tuning

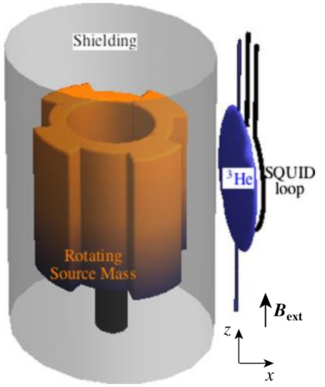
ARIADNE needs an extra CP violating source to see an effect. Can we use it to probe large mass axions?

ARIADNE:

Axion Resonant InterAction DetectioN Experiment

YES! When used with proton EDM!

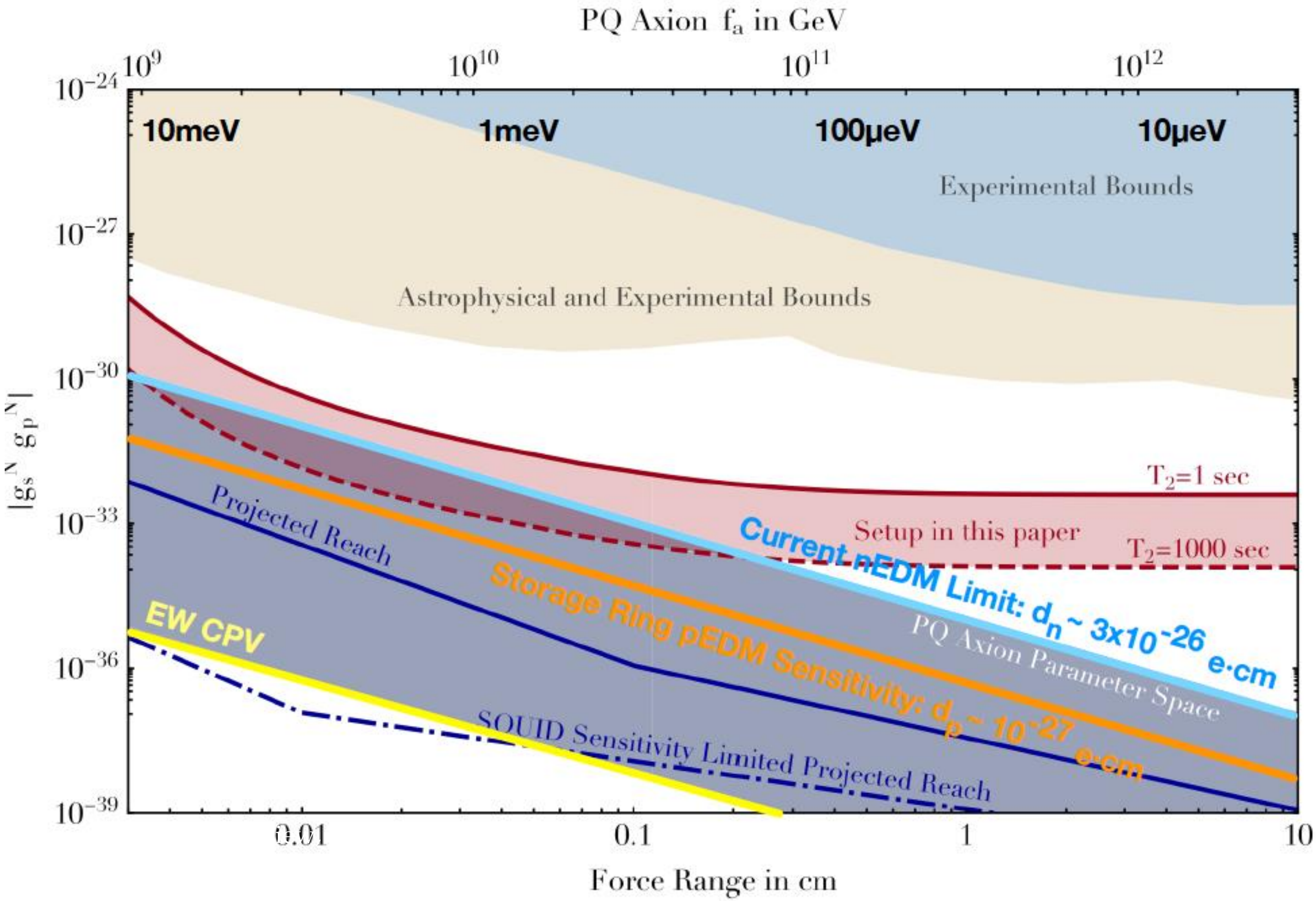
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$



ARIADNE

- If ARIADNE finds a signal, then we are done. We will know the axion mass → axion dark matter experiment.
- If ARIADNE doesn't observe a signal, then it could be due to the absence of extra CP-violating source.
- Proton EDM experiment can clarify the situation. The large axion mass can be probed effectively.

Probing high-mass axions with ARIADNE and pEDM

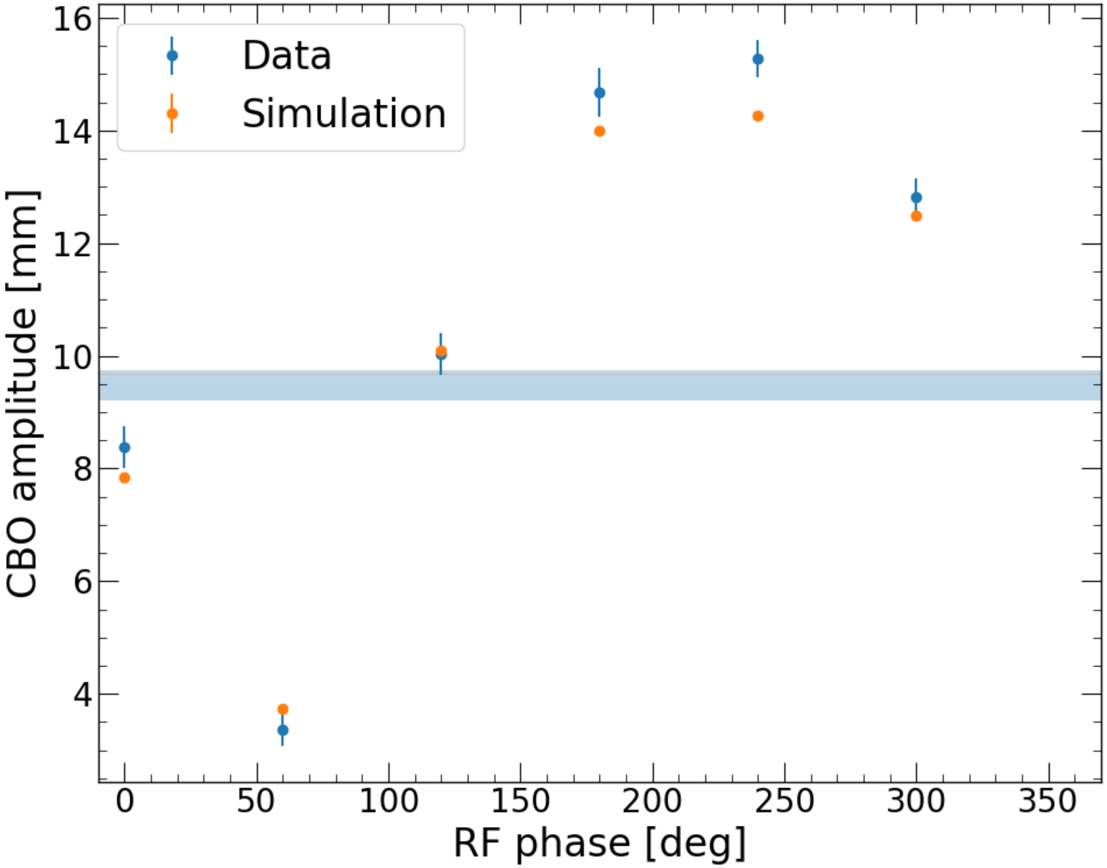


Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

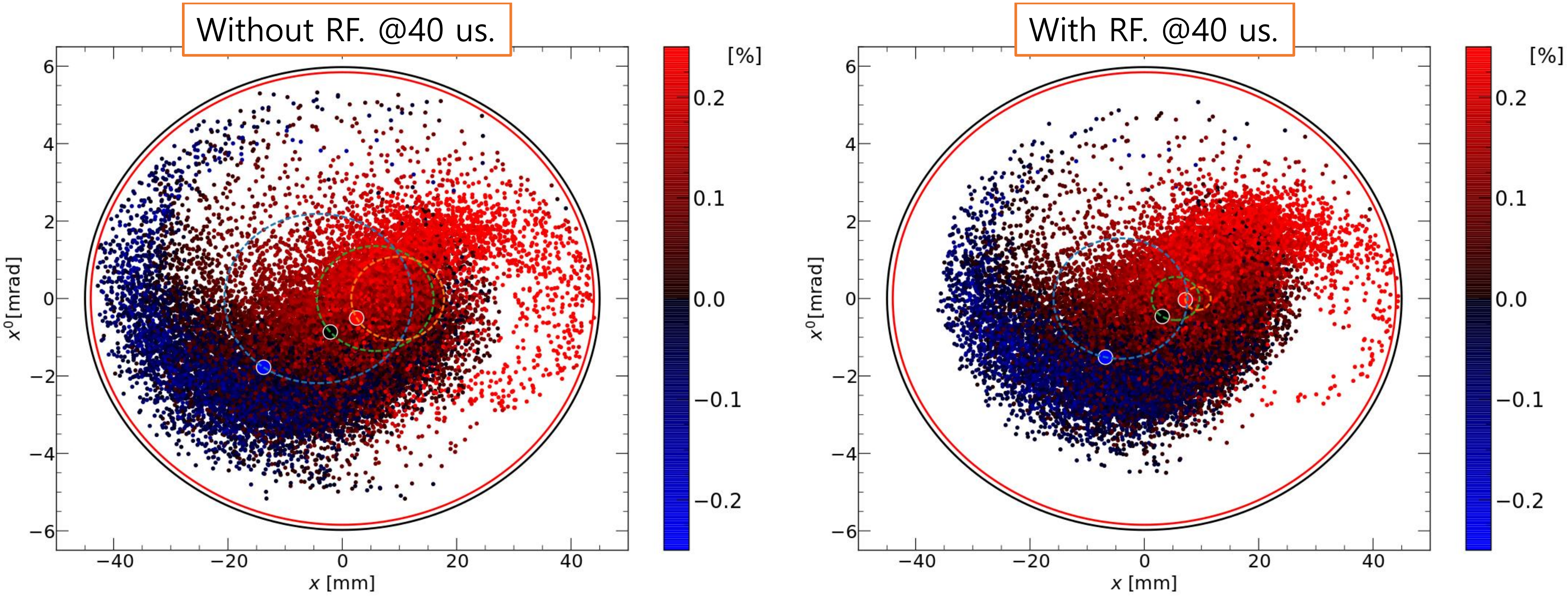
CBO Data vs. Simulation

- Compared with the simulation



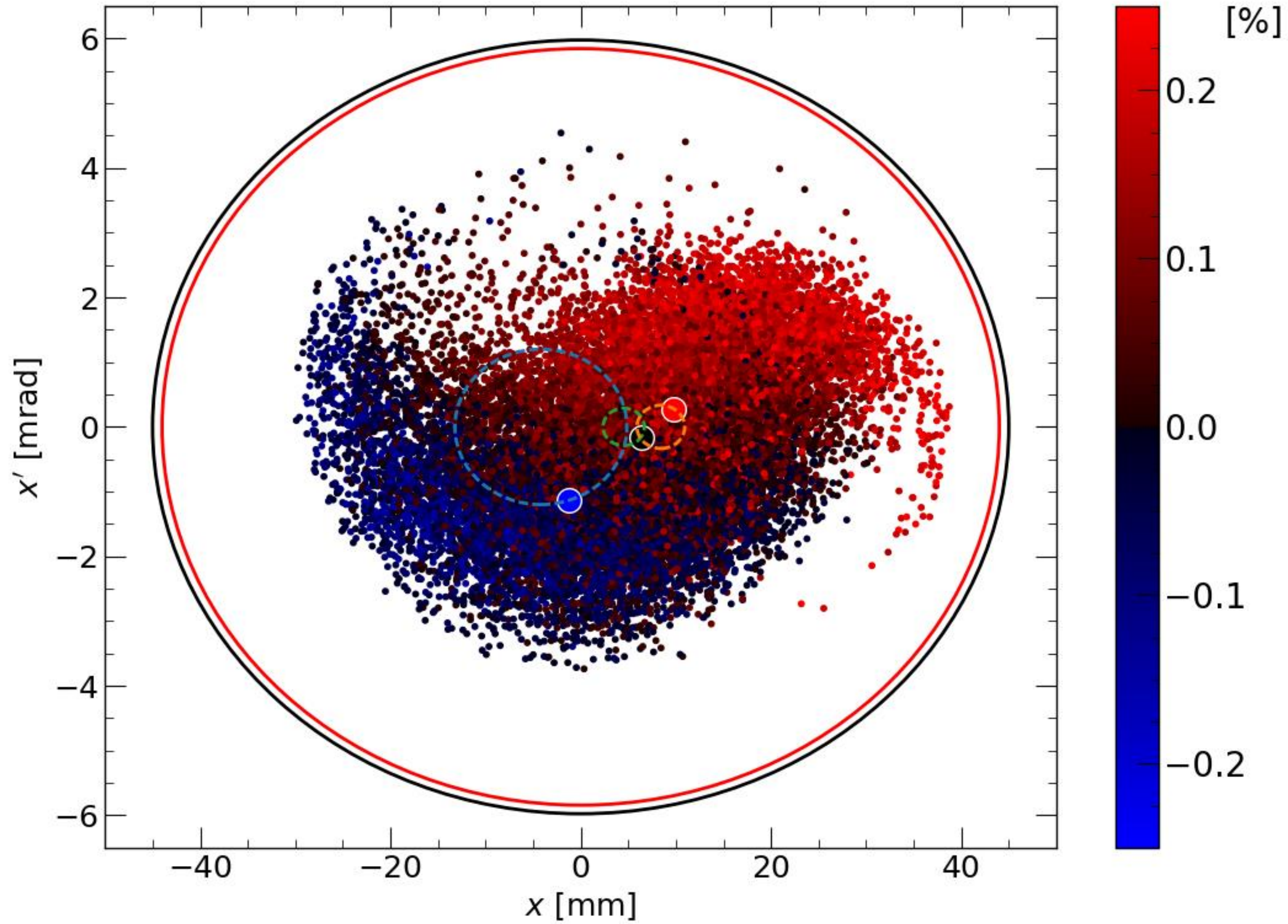
RF-CBO reduction and RF-scraping

CBO reduction with RF doesn't reduce muon losses by default.
When RF-scraping is also applied (next…)



RF-CBO reduction and RF-scraping

>5mm gap from aperture! Great promise for significantly less muon losses



RF-CBO reduction and RF-scraping

IBS/CAPP has the leadership of the RF project at FNAL. Our students and researchers cannot take full credit due to extremely limited budget for travel. In 2020 we plan to follow it from Korea…

Reduction of the coherent betatron oscillations in a muon g-2 storage ring experiment using RF fields

On Kim,[1,2] Meghna Bhattacharya,[3] SeungPyo Chang,[1,2] Jihoon Choi,[1] Jason D. Crnkovic,[4] Sudeshna Ganguly,[5] Selcuk Haciömeroğlu,[1,*] Manolis Kargiantoulakis,[6] Young-Im Kim,[7] Soohyung Lee,[1] William M. Morse,[4] Hogan Nguyen,[6] Yuri F. Orlov,[8] B. Lee Roberts,[9] Yannis K. Semertzidis,[1,2] Vladimir Tishchenko,[4] Nam H. Tran,[9] and Esra Barlas Yucel[5]

Highlights

- Averaging about 15-20 publications/year since established
- The innovation level is amazing!
- The collaboration level between the scientists is exemplary
- We have the “critical mass” to do what we need to, and we deliver.

Highlights

- ✓ Coldest axion cavities (<50 mK); Woohyun Chung, S. Lee, et al.
- ✓ LVPs for several axion dark matter exps in parallel; Woohyun Chung, DongMin Kim, et al.
- ✓ High efficiency, high freq., high volume (Pizza plus wheel tuner); SungWoo Youn, Junu Jeong, OhJoon Kwon, Jinsu Kim
- ✓ Quantum noise limited amplifiers; Andrei Matlashov, Sergey Uchaikin, Doyu Lee, SeonJeong Oh, et al.

Highlights

- ✓ High field, high volume magnets (LTS and HTS); ByeongRok Ko, Jingeun Kim, et al.
- ✓ Superconducting cavity (YBCO) with large B-field; Danho Ahn, Ohjoon Kwon, DojunYoum, Woohyun Chung, et al.
- ✓ CAPP-GNOME is reporting, ARIADNE, SQUID gradiometer and SC shielding. NSF approved; Dongok Kim, Younggeun Kim, Yun Chang Shin
- ✓ Digitizing, low dead-time DAQ; MyeongJae Lee, Beomki Yeo
- ✓ Axion-EDM feasibility study at COSY; SeongTae Park, SeungPyo Chung, et al.

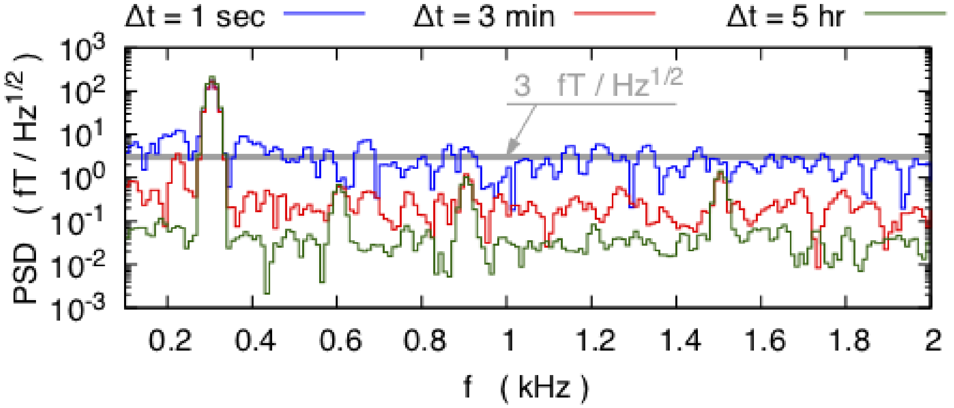
Highlights

Proton EDM for 10^{-29} *e*-cm, 10^3 TeV New mass scale reach

✓ Proton EDM syst. error studies; Selcuk Haciomeroglu, et al.

✓ SQUID-based beam position monitor: <10nm/(Hz)$^{1/2}$

✓ Proton EDM hybrid ring



Muon g-2:

✓ CAPP's magnetometer; SeungPyo Chang, SeongTae Park, et al.

✓ RF-reduction of CBO; On Kim, Selcuk Haciomeroglu, et al.

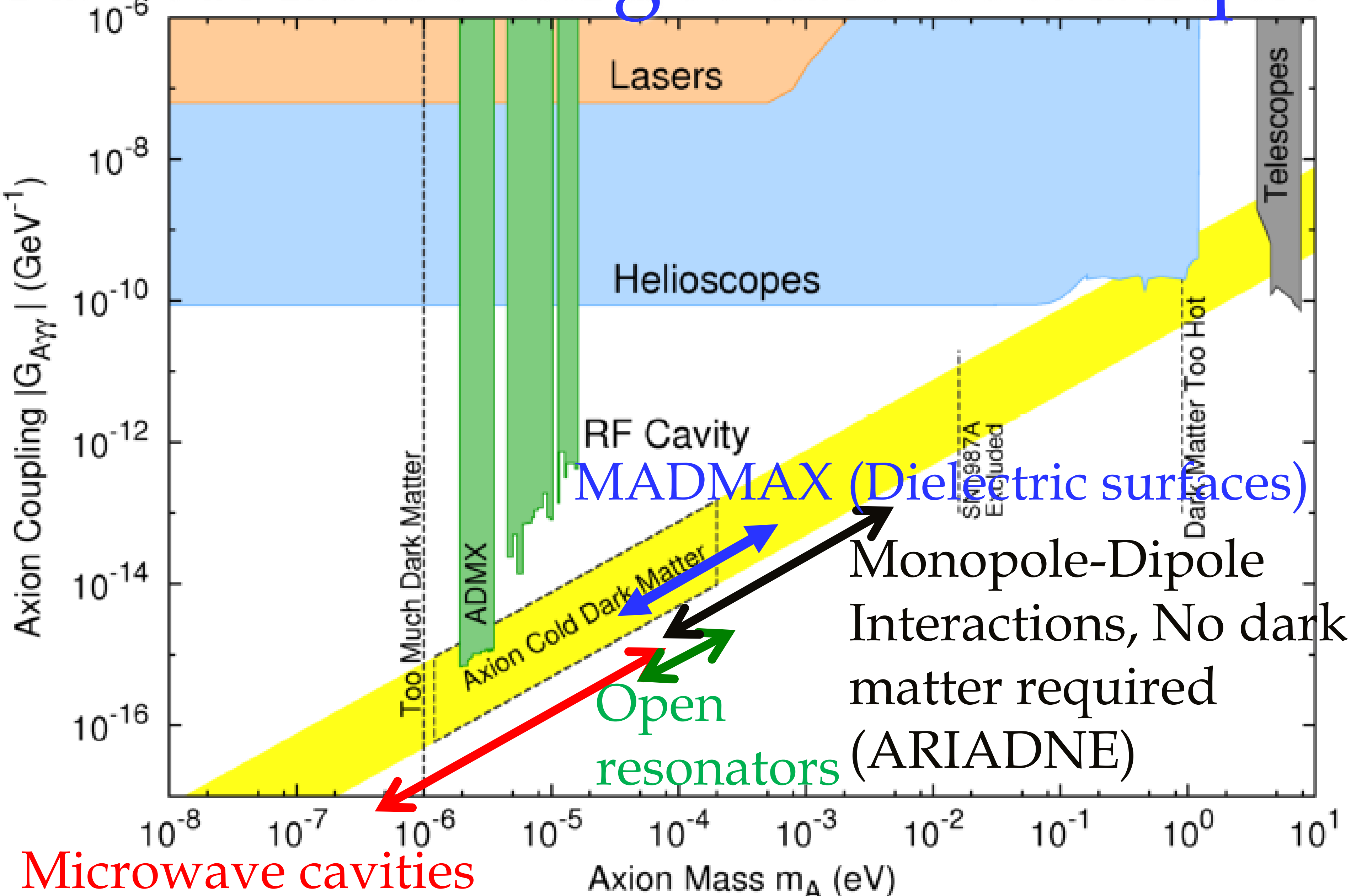
✓ Systematic error reduction/elimination; Zhanibek Omarov, et al.

Summary

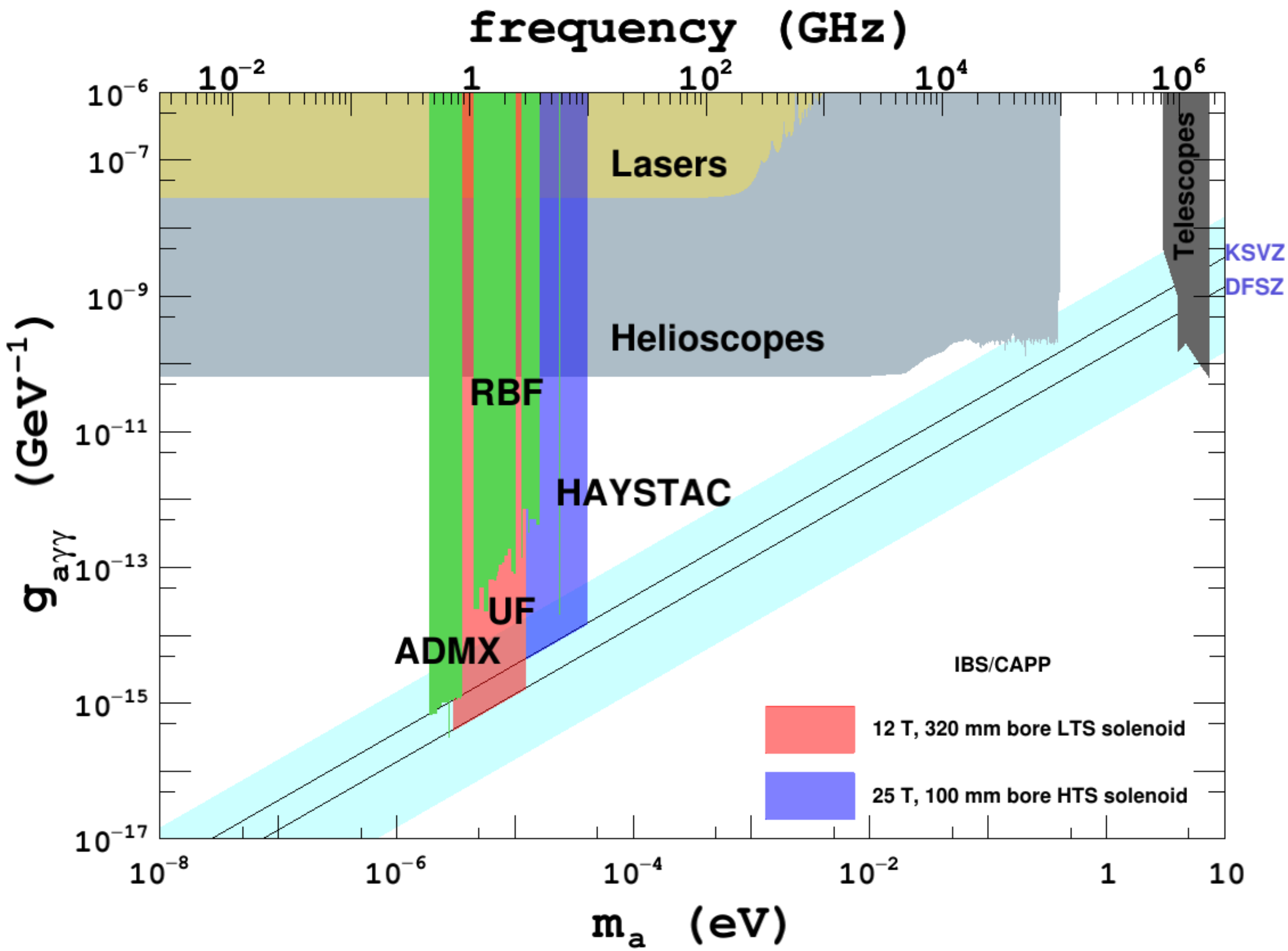
- The Center is competent and ready to run. The main risk factor is the funding level that is < half of the promised and even the contract I signed! Restoring the funding now will enable CAPP to become the best in the world for a long time.
- The role of quantum noise limited RF (for 1-15 GHz) and single photon (for >10 GHz) detectors is critical. Fall 2020, workshop in Daejeon/Korea
- Over the next years we may very well know whether axions are 100% (within five years) or even 10% (within next ten years) of local dark matter… ARIADNE/pEDM can probe the large mass (meV) range.

Extra Slides

Axion mass target and technique



Potential shown based on single cavities
Possible to extend to >10GHz



$$L_{int} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

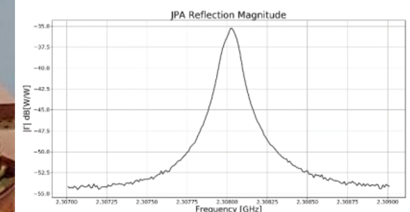
Axion Activities at IBS/CAPP

Enhancing the scanning rate

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

Cryogenics (T)
Lowering thermal noise

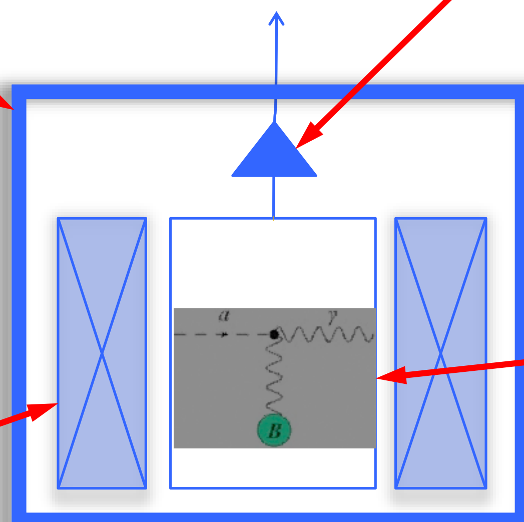
Quantum noise limited amplifier (T)
Amplification w/ noise squeezing
(U. of Tokyo & RIKEN)



JPA gain measurement:
20 dB @ 2.3 GHz

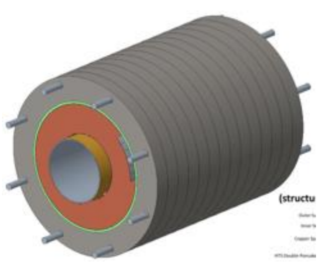
Functional JPA w/ in-house expertise

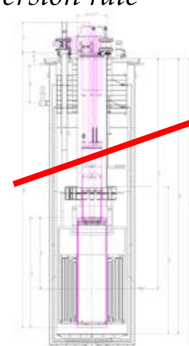
RF readout chain



Axion-photon conversion
(Sikivie's method)

High field HTS Magnet (B)
Boosting a→γγ conversion rate

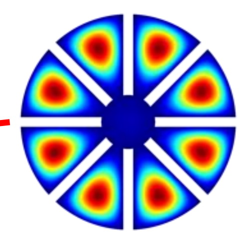


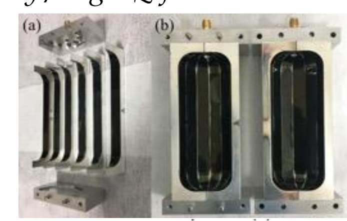


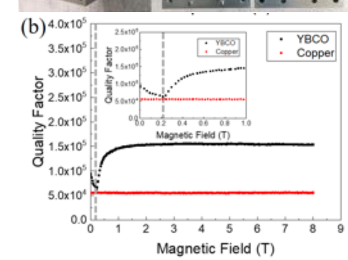
HTS 25T/100mm
w/ BNL
(funding limited)
IEEE T. Appl. Supercon. **29**, 5 (2019)

LTS 12T/320mm (Oxford Instr., 2019/2020)

Microwave resonator (V,C,Q)
High frequency / high Q factor





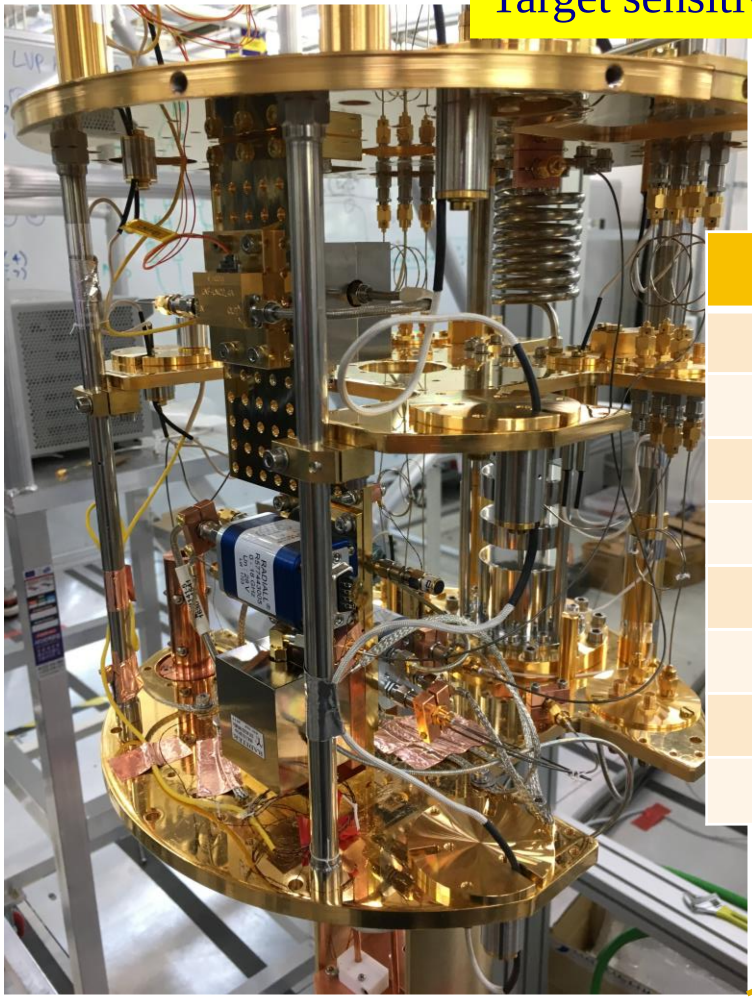


Pizza cavity for high frequency
Phys. Lett. B **777** 412 2018

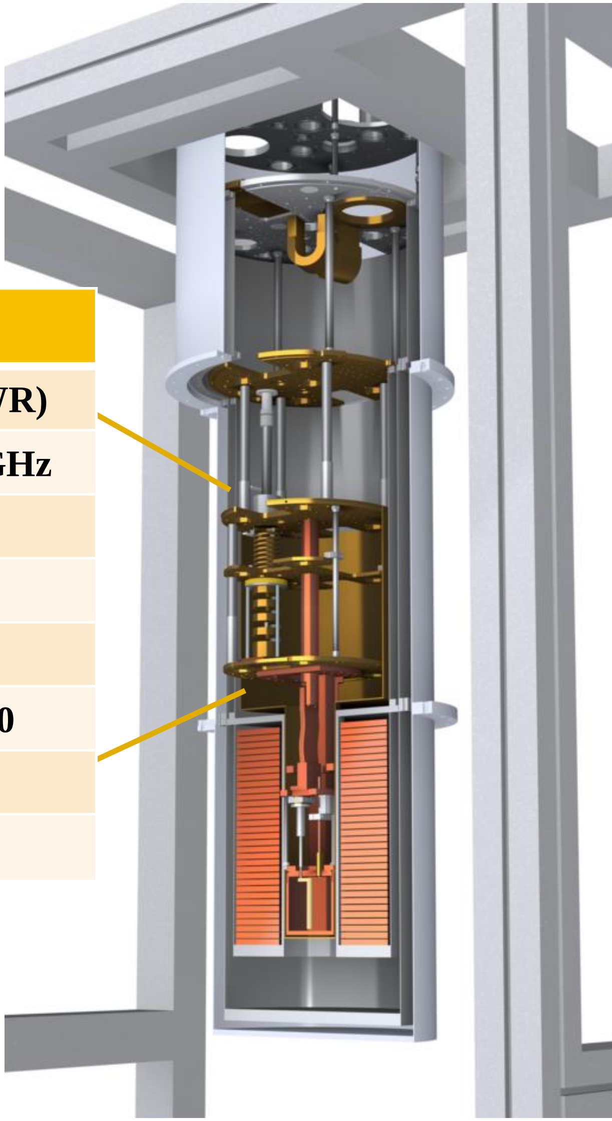
SC (YBCO) cavity under high B field
Arxiv: 1904.05111

CAPP-PACE

Target sensitivity: **10*KSVZ, KSVZ**



parameters	value
T_{cavity}	**<40mK (WR)**
Frequency	**2.45~2.70GHz**
Magnetic field	**8 T**
Bore size	**11.8 cm**
Cavity volume	**1.12 L**
Q unloaded	**~ 100,000**
C (form factor)	**~ 0.6**
T_{system}	**< 1.5 K**



Woohyun Chung's slide

CAPP-PACE results

From Caglar Cutlu

Woohyun Chung's slide

Results

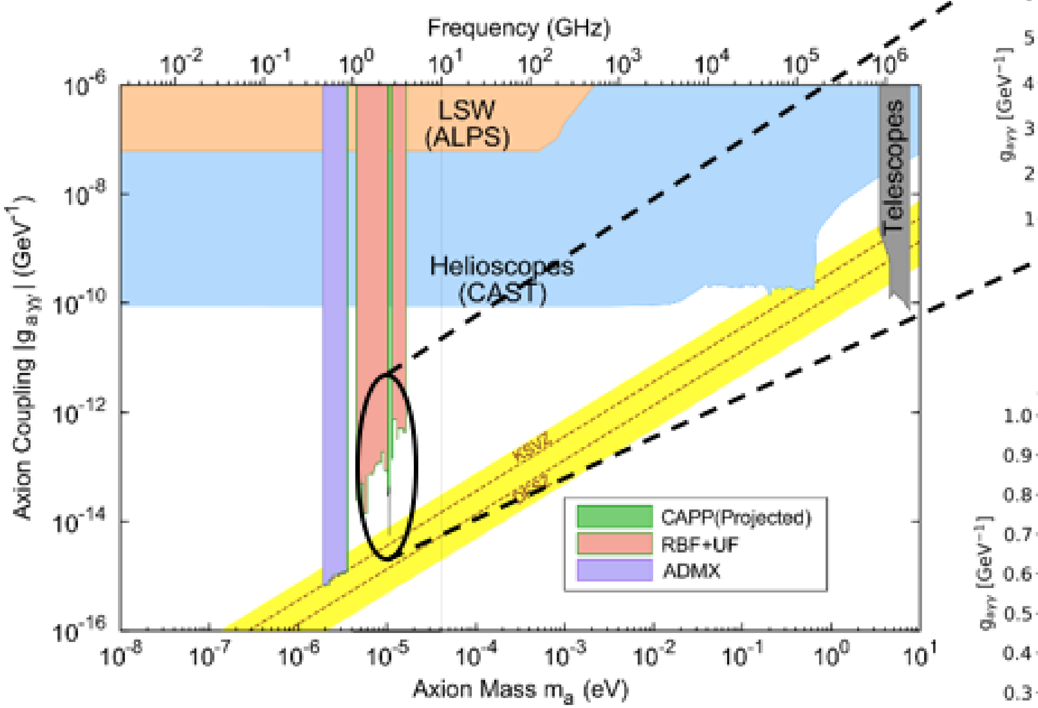


Figure 9: Exclusion plot showing CAPP-PACE results along with other haloscope experiments.

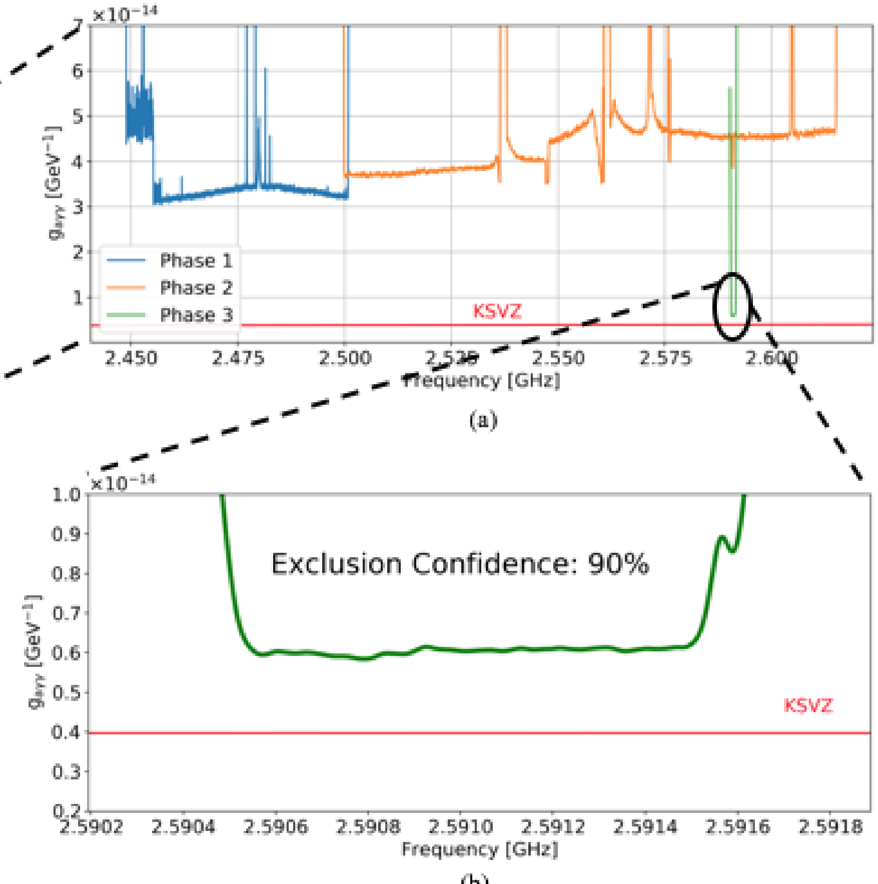
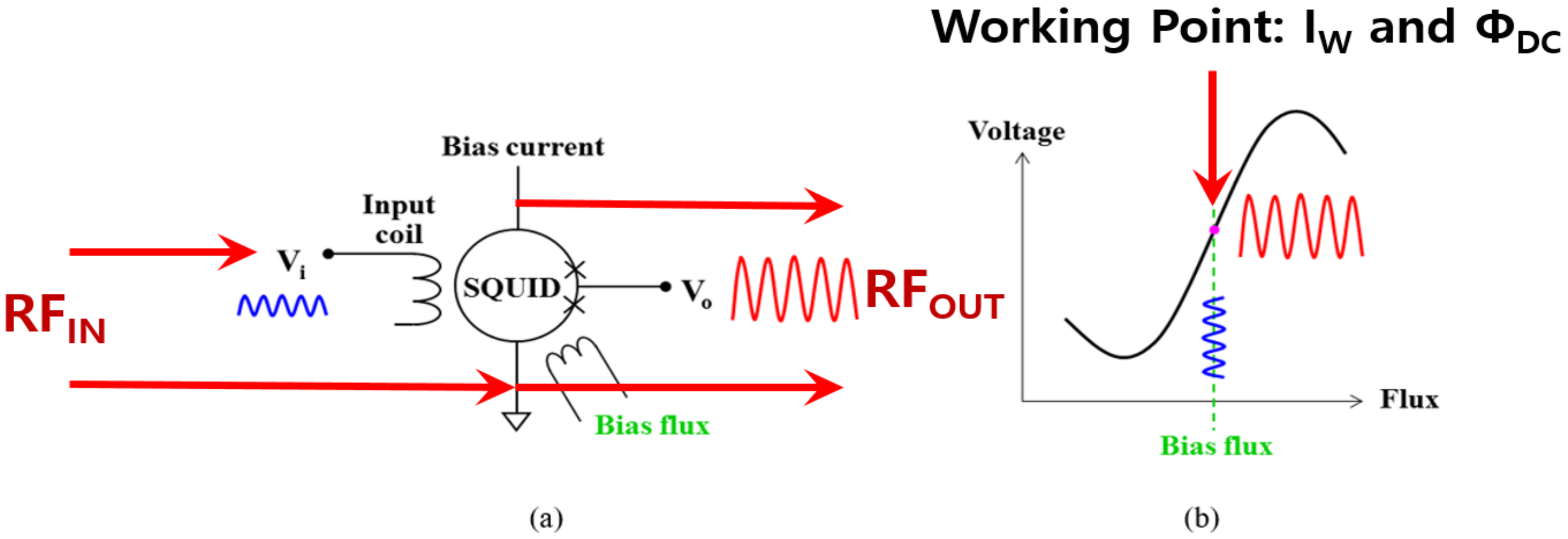


Figure 10: (a) Exclusion region with all the physics run combined done in 2018. (b) A zoomed view of the high sensitivity result.

KSVZ sensitivity with conventional Supercond. magnet and HEMT amplifier

Microstrip SQUID Amplifiers (MSA)

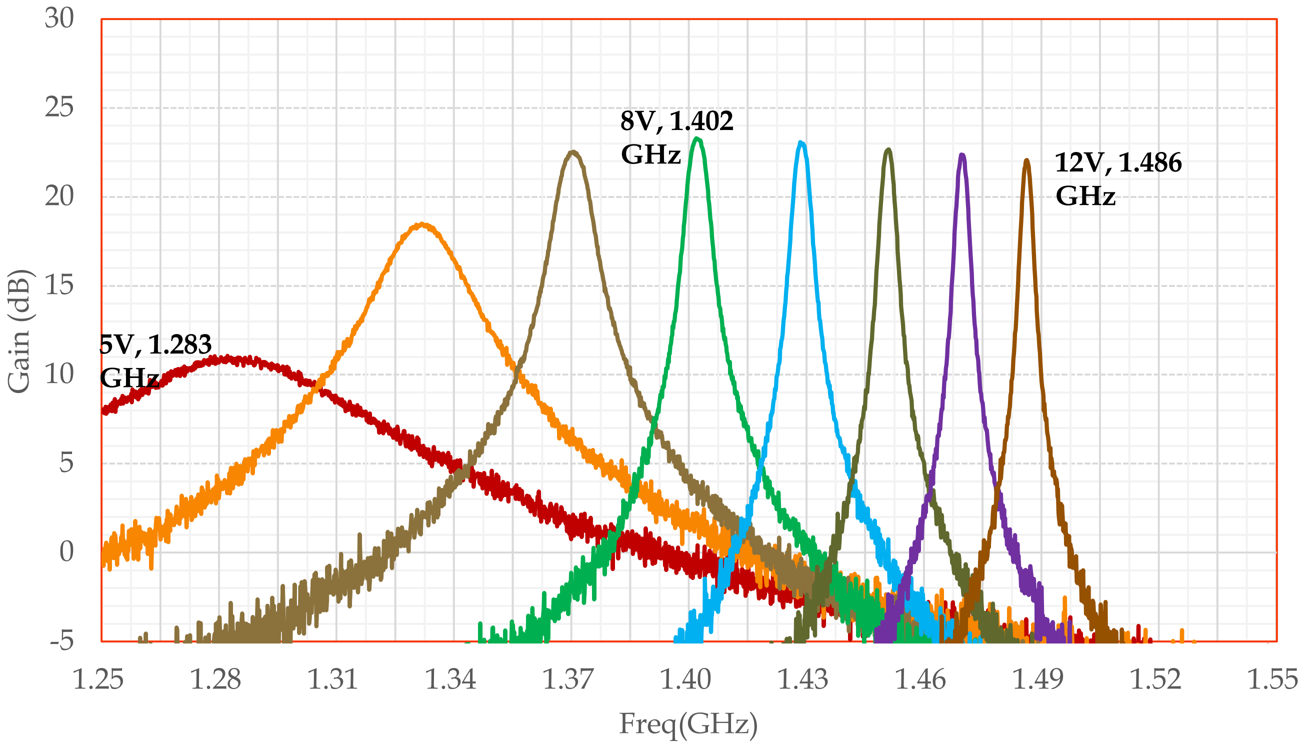


Principe of operation: (a) schematics, (b) $dV/d\Phi$ transfer coefficient

Andrei Matlashov

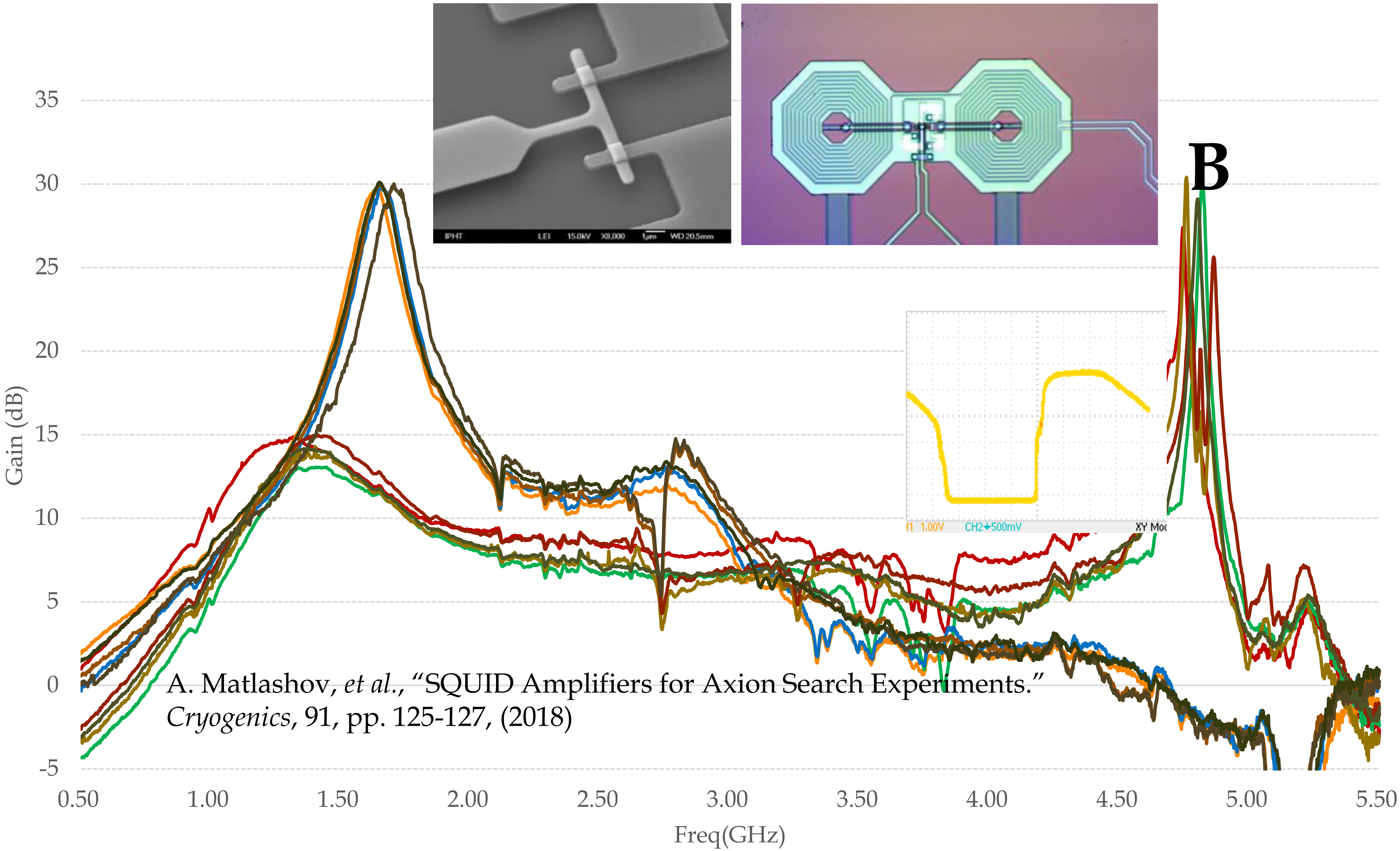
MSA from Berkeley at CAPP

CAPP
Center for Axion and Precision Physics Research



Resonant frequency f_0 vs. varactor voltage (from 5 V to 12 V with 1 V step)

Broadband MSAs:
CAPP collaboration with IPHT, Germany

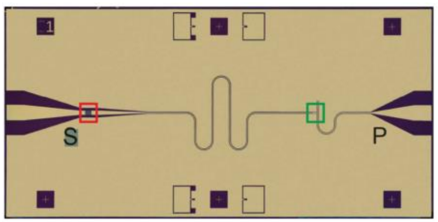


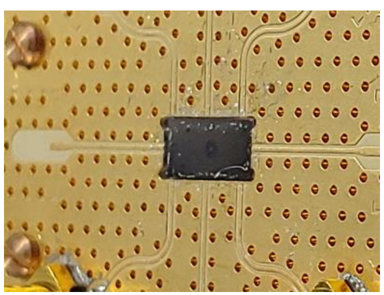
A. Matlashov, *et al.*, “SQUID Amplifiers for Axion Search Experiments.” *Cryogenics*, 91, pp. 125-127, (2018)

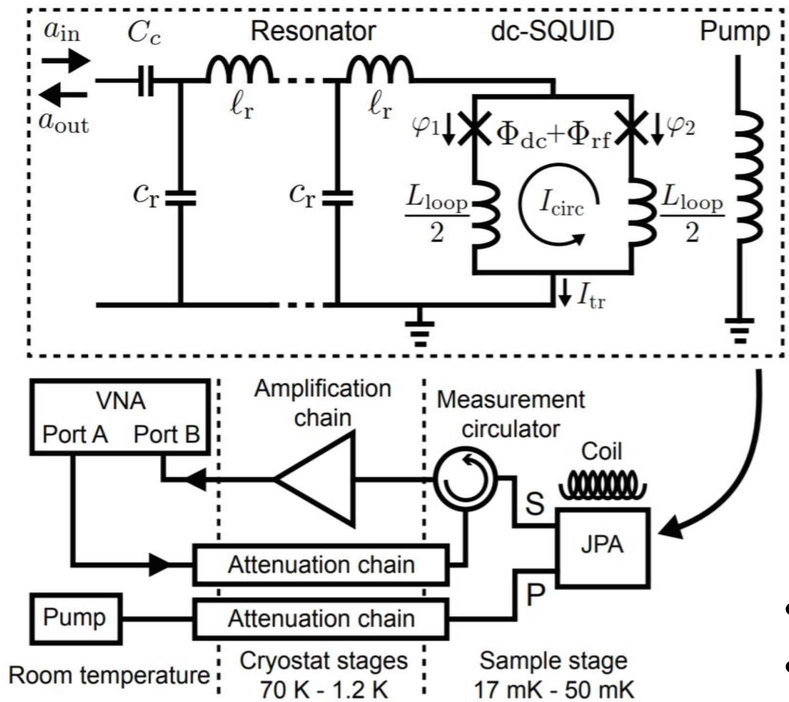
Josephson Parametric Amplifier

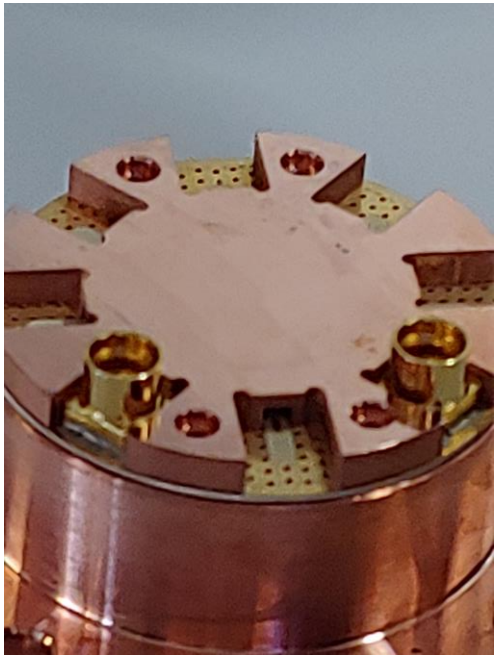
Prof. Nakamura’s lab, Univ. of Tokyo

RIKEN, U. of Tokyo
L. Zhong, Y. Nakamura et al, 2013





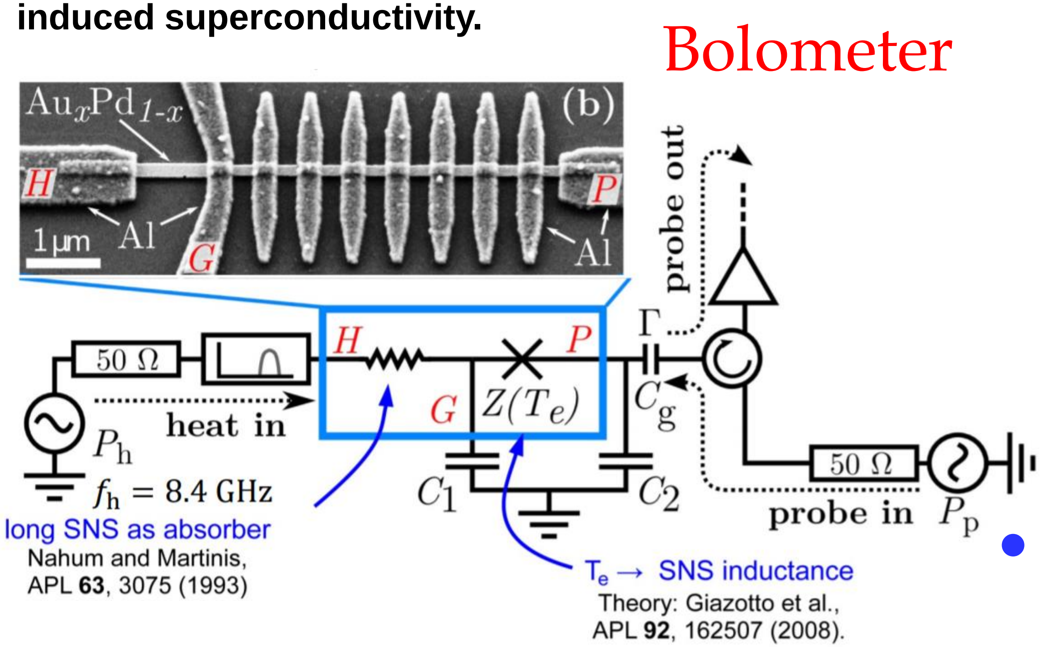




- **Quantum-limited noise**
- **Noise Squeezing**
- **$T_N \leq$ 167 mK @ 5.6 GHz**

Started Collaboration with Aalto University (Finland)
Prof. Mikko Mottonen's lab.

A microwave nanobolometer based on a normal-metal nanowire with proximity-induced superconductivity.



QCD Labs, Aalto University

"Detection of Zeptojoule Microwave Pulses…"
J. Govenius *et al.*, Phys. Rev. Lett. 117, (2016)

- Wideband frequency range
- Bandwidth defined by cavity
- 1.1×10^{-21} J (7.0 meV)

CULTASK: CAPP's axion dark matter search

Refrigerators and Magnets

Refrigerators				
Vendor	Model	Base T (mK)	Cooling power	Install
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016
BlueFors (BF4)	LD400	10	18μW@20mK 580μW@100mK	2016
Janis	HE3	300	25μW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100mK	**2017**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100mK	2017
Oxford	Kelvinox	<30	400μW@120mK	2017
Leiden	DRS1000	100	1.3mW @120mK	2019

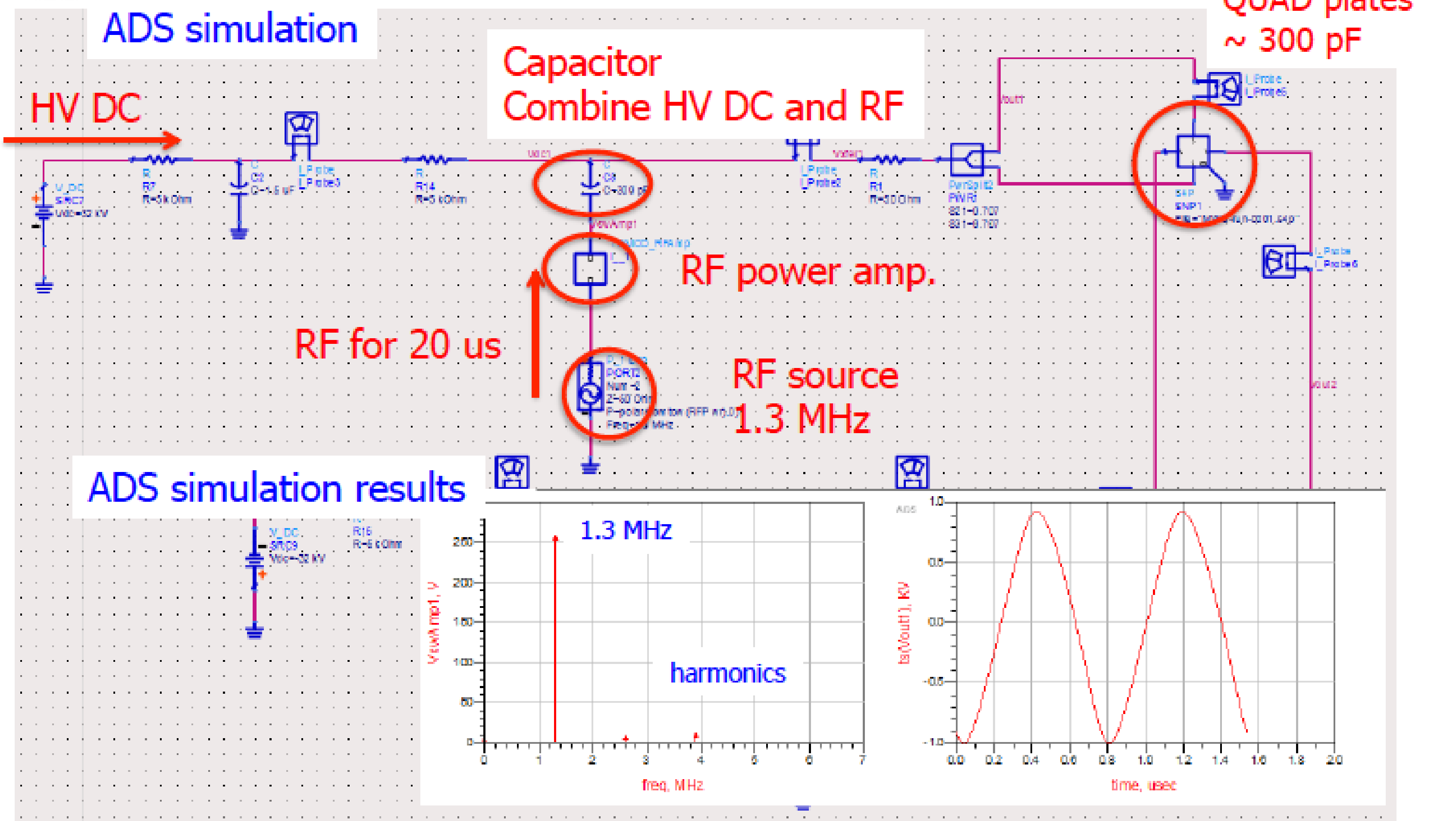
Magnets				
B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	**10**	HTS	BNL/CAPP	2020
12T	**32**	Nb_3Sn	Oxford	2020

EXP
BF3 & BF4 for testing RF, QA and cavities
CAPP-MC
CAPP-PACE
CAPP-8TB
Preparing for CAPP-12TB and CAPP-25T

Leiden has also been delivered, at commissioning stage

Woohyun Chung's slide

Circuit simulation



Slide: Dr. YoungIm Kim

- Low vibration pad installation

a) Resonant frequency by inner pressure of anti-vibration band (Resonance frequency)

Tank Pressure	Resonant Frequency	Remarks
2 bar	<5.1 Hz	In case of Support load 3500kg per unit
3 bar	<4.3 Hz	
3.5 bar	<3.6 Hz	Design pressure
4 bar	<2.9 Hz	

b) Anti-vibration efficiency in the frequency domain (Isolation efficiency)*

Frequency [Hz]	Anti-vibration efficiency	
	dB	Ratio [%]
10	-15 dB	75 (0.25)
20	-25 dB	93 (0.07)
30 ~ 100	-35 dB	97 (0.03)

* Damping efficiency when the design pressure is applied to the tank

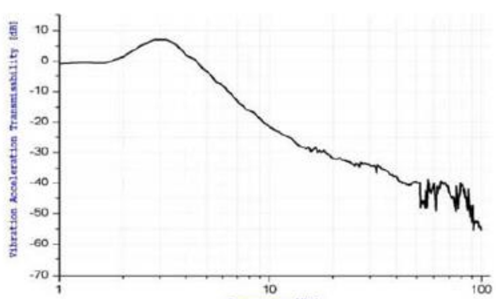
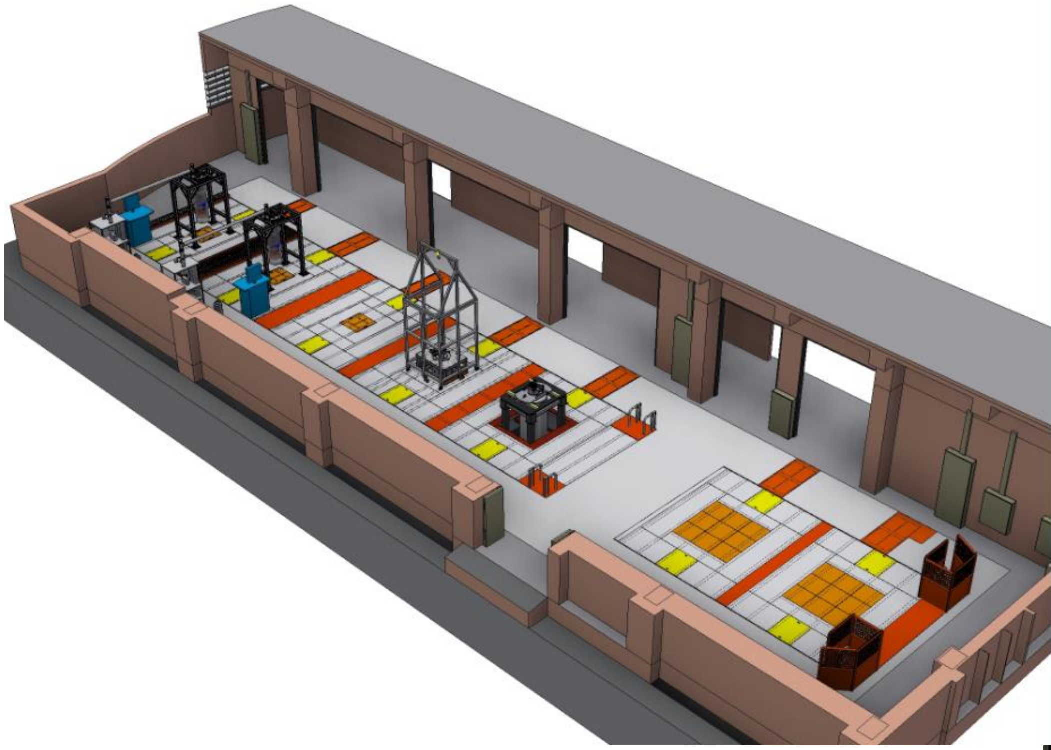
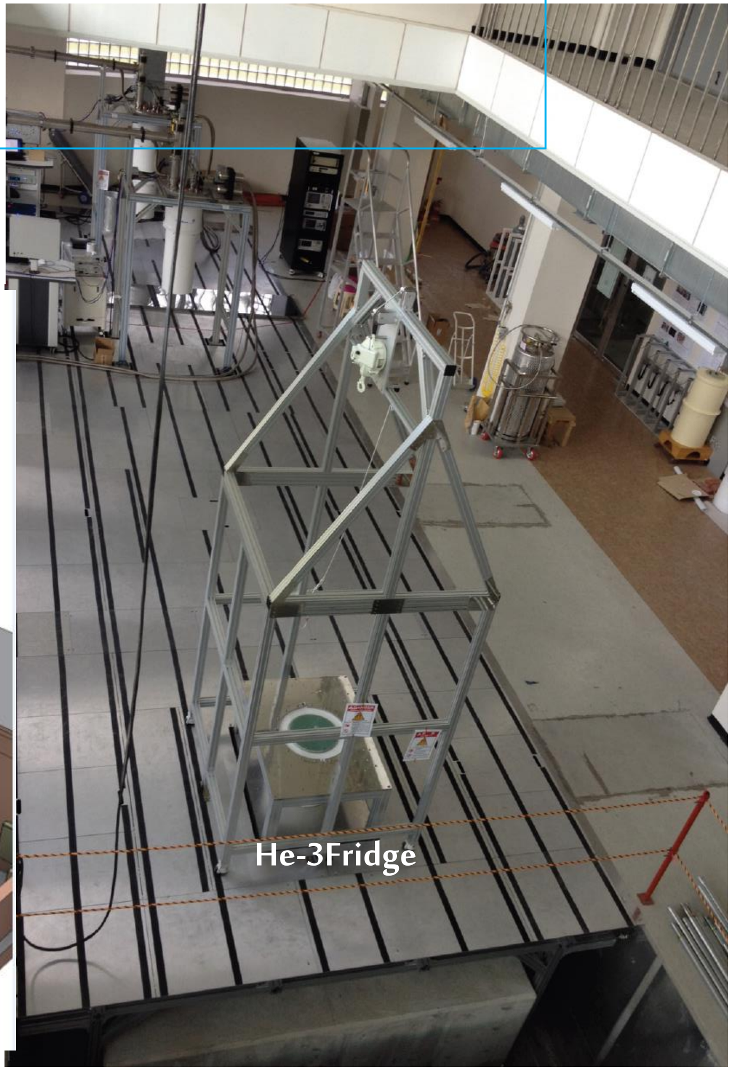


Figure I-7: Vibration transfer characteristic curves and Low vibration block(LVB) & air-type passive vibration isolators of manual anti - vibration dampers

The Sikivie axion haloscope method is applied here!

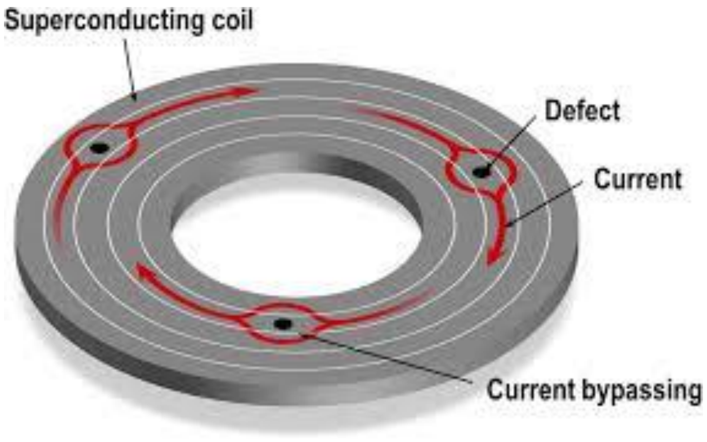




Is HTS safe?

- HTS tape propagates quench slowly
- Too much energy deposited on small part of the coil
- It can damage the coil

HTS No Insulation (NI)



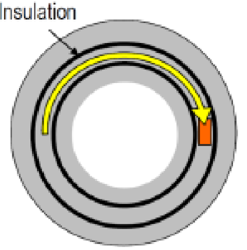
Prof. Seungyong Hahn of SNU recently demonstrated advantages of this technique for REBCO tape magnets, including self-protection.

No Insulation Approach to Magnet Protection (slides courtesy S. Hahn)

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

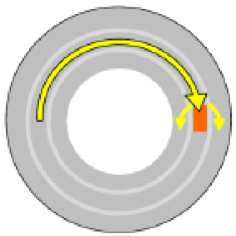
No-Insulation HTS Winding Technique

INS: Difficulty in Protection



- ❑ Slow normal zone propagation in HTS
  - ➔ Slow quench detection
- ❑ Larger enthalpy (stability margin) of HTS
  - ➔ Difficulty in "activate-heater" protection

NI: "Quench Current Bypass"



- ❑ "Automatic bypass" of quench current through turn-to-turn contacts

REF: S. Hahn, D. Park, J. Bascuñán, and Y. Iwasa, "HTS Pancake Coil without Turn-to-Turn Insulation," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1592 – 1595, 2011.

S. Hahn <shahn@fsu.edu> | No-Insulation HTS Magnet WAMHTS-3, Lyon, France (September 11, 2015) | 5/18

No Protection Device: No-Insulation HTS Magnets

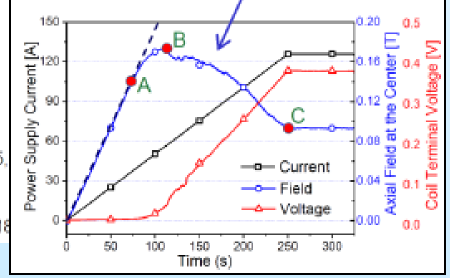
Seungyong Hahn

Applied Superconductivity Center
National High Magnetic Field Laboratory
Department of Mechanical Engineering
Florida State University

WAMHTS-3
Lyon, France

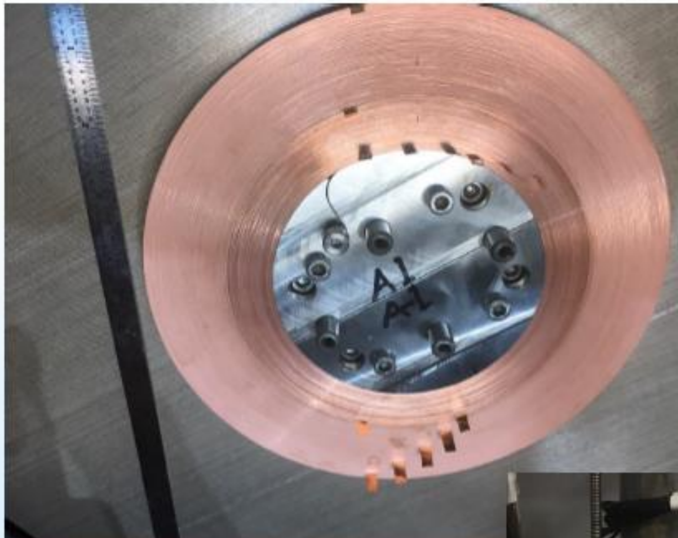
September 11, 2015

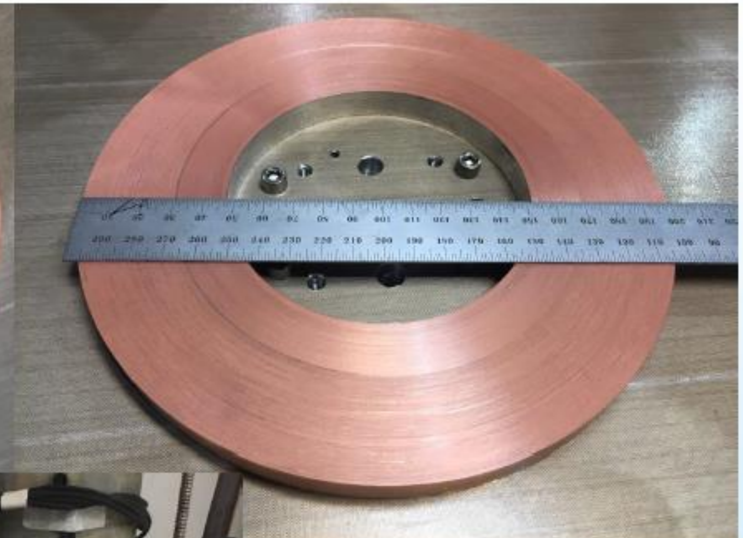
A decrease in field implies that more and more turns are getting shorted



Successfully demonstrated to work in small coils, but not yet in big coils at 4K

IBS Production Coil
(two single pancakes spliced to a double pancake)



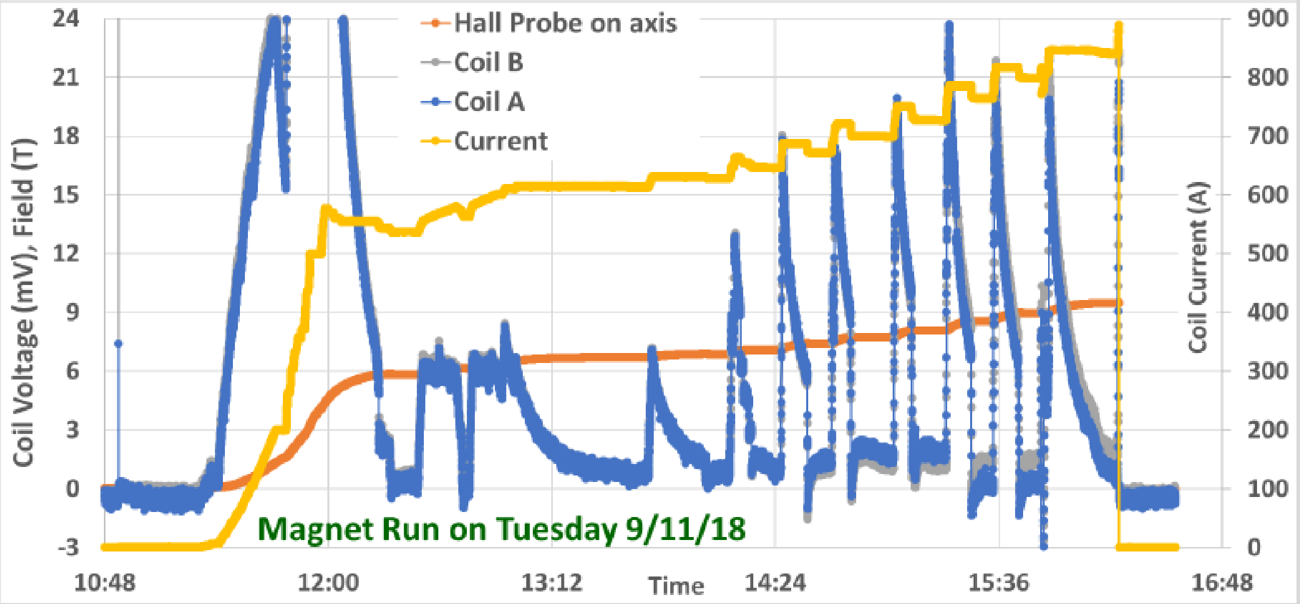


Major parameters:

- i.d. : 105 mm
- o.d. 200 mm
- Turns: ~1250 (DP)

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

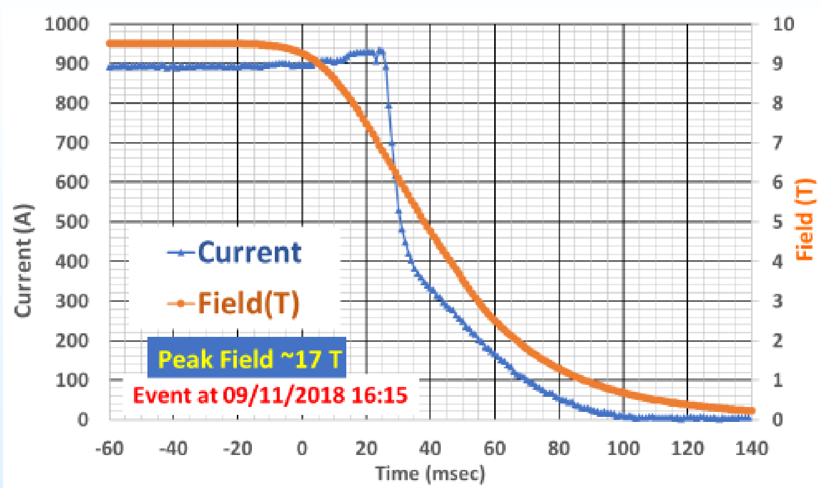
Tuesday Run Summary



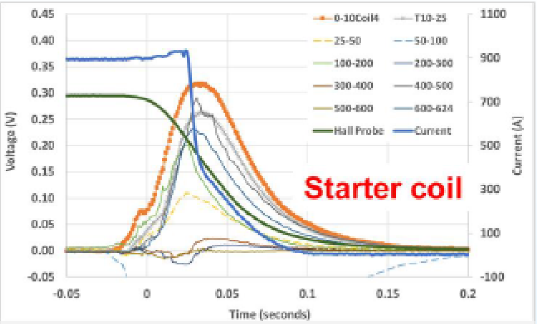
- Continue increasing current in steps to the maximum it could go
- Quenched when going from 850 A to 900 A (design current: ~450 A)
- It reached maximum field in bore ~9 T and in coil ~17 T
- Quench data discussed in more details in the next slide

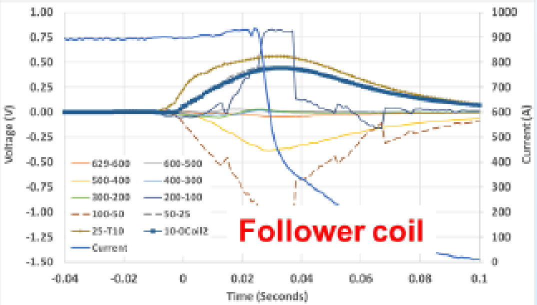
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

A Robust Quench Protection Solution for IBS (fast propagation proven with recent 4K test)



The 1st IBS double pancake coil became normal in < 200 msec (even faster than in many LTS magnets)





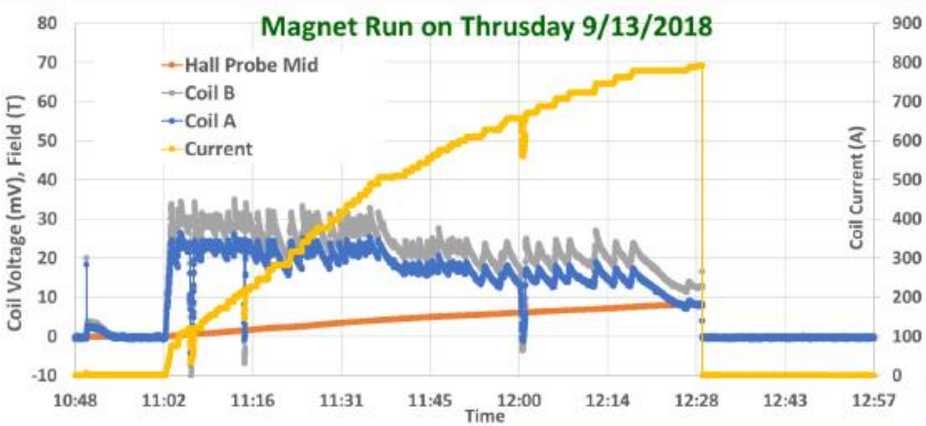
- Within a pancake: fast propagation due to resistive heating through contact resistance between turns when the current flows across (not around) in a "No-insulation" coil
- Pancake to pancake: fast propagation due to inductive coupling of the drop in local field
- The mechanism seems scalable to long solenoids with many pancakes

- **More discussion with many test results in the 4 K test presentation**

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Thursday Run Summary

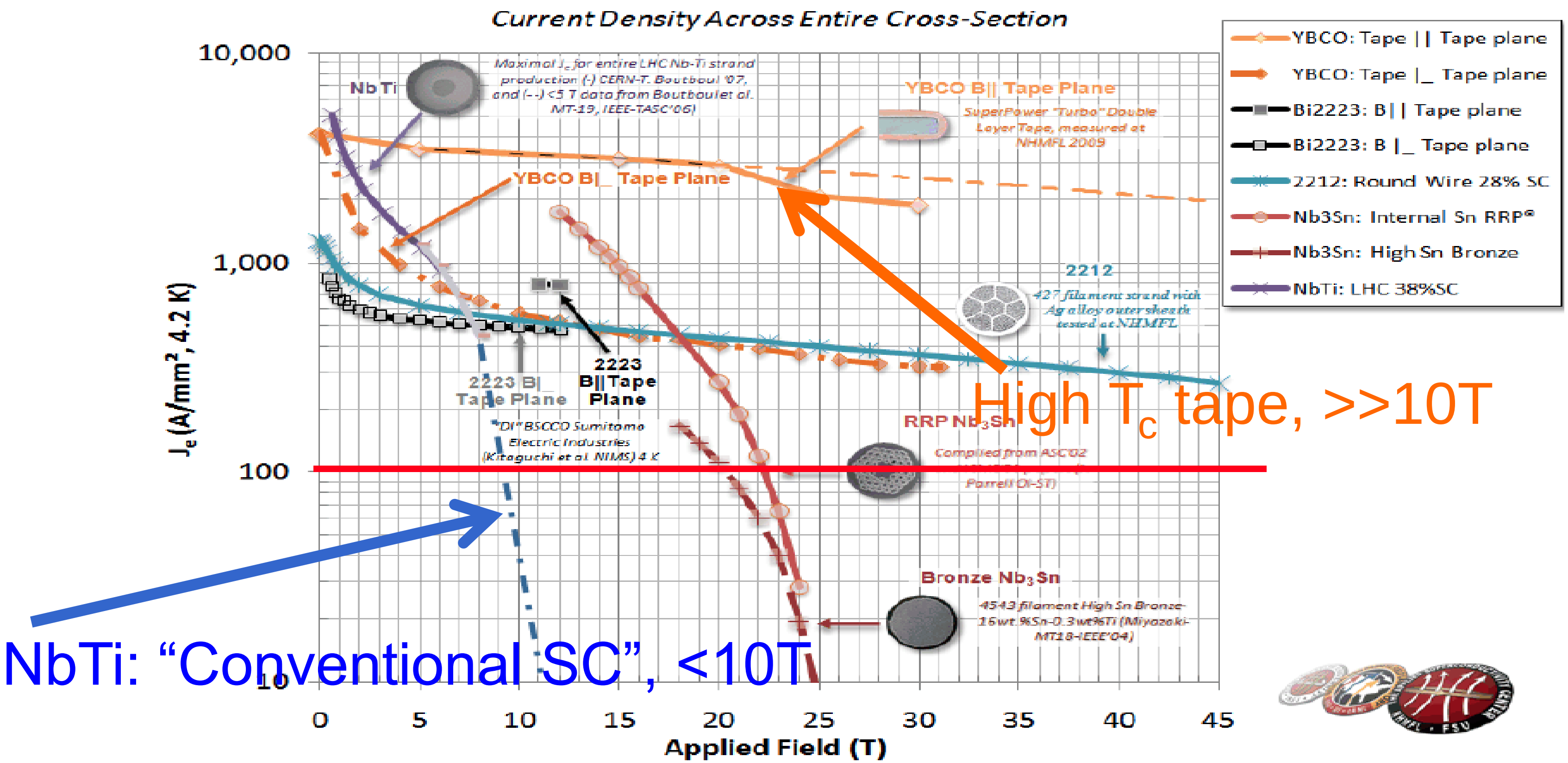


Second quench at ~800 A (design: ~450 A)

Third quench at ~850 A (design: ~450 A)

Shut-off near design current

Future Solenoids:
High- Temperature Superconductors



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