Axions, and the Strong CP-problem

Yannis Semertzidis, CAPP/IBS and KAIST

Strong CP-Problem

- Axion dark matter search:
  - State of the art axion dark matter experiment in Korea. State of the art axion search.
  - Collaborate with ADMX, CAST…
- Proton Electric Dipole Moment Experiment
  - Storage ring Proton EDM (probe NP ~10^3 TeV)
  - Muon g-2, mu2e, etc.

South Korea: New Institute with emphasis in basic science, $0.5B/year

ibs Institute for Basic Science

IBS looks forward to shaping the future in Basic Science with you. Visit our website for detailed recruitment information and register yourself with the IBS Talent Pool DB for a future career with IBS.

http://www.ibs.re.kr/en http://www.ibs.re.kr/talents

Research Centers in IBS

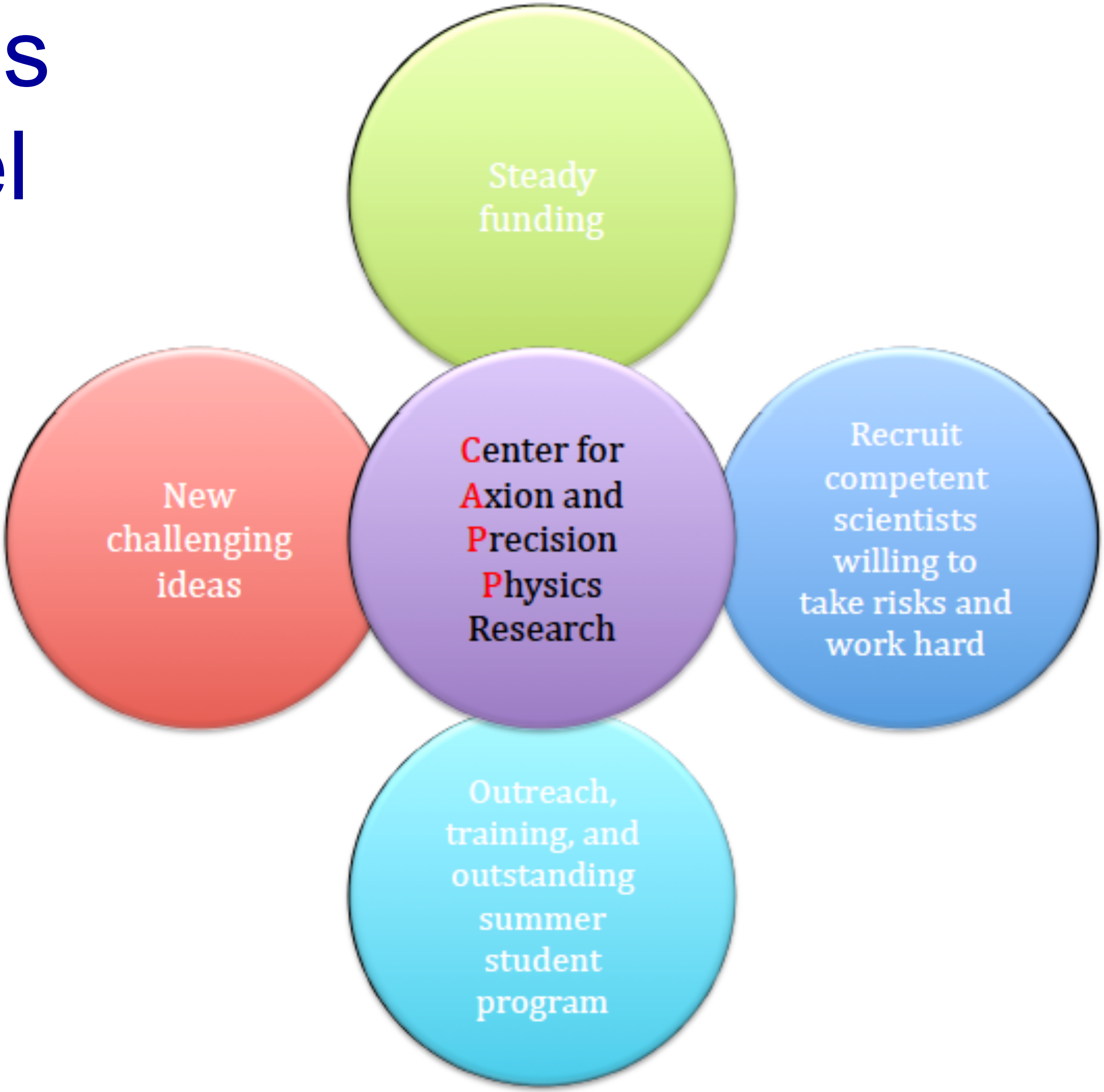
http://www.ibs.re.kr/eng.do

Young Scientist program: 5y program

Senior Scientist program: 3y program

Center for Cognition and Sociality	Center for Synaptic Brain Dysfunctions	Center for Geometry and Physics
Center for Nanomaterials and Chemical Reactions	Academy of Immunology and Microbiology	Center for Nanoparticle Research
Center for Self-assembly and Complexity	Center for RNA Research	Center for Correlated Electron Systems
Center for Catalytic Hydrocarbon Functionalizations	Center for Integrated Nanostructure Physics	Center for Relativistic Laser Science
Center for Plant Aging Research	Center for Artificial Low Dimensional Electronic Systems	Center for Neuroscience Imaging Research
Center for Underground Physics	Center for Axion and Precision Physics Research	Center for Theoretical Physics of the Universe
Center for Multidimensional Carbon Materials	Center for Soft and Living Matter	Center for Genome Engineering

CAPP's Model


Steady funding
New challenging ideas
Center for Axion and Precision Physics Research
Recruit competent scientists willing to take risks and work hard
Outreach, training, and outstanding summer student program

CAPP / IBS

Axion Dark Matter (DM) | **Baryon Asymmetry**

- Challenging 2 major issues in contemporary physics
- High risk, high physics potential
- World-class experimental elementary particle physics center
  - Involved in important physics questions
    - Strong CP problem, cosmic frontier (DM axions)
    - Flavor-conserving CP-violation (most sensitive **proton EDM** experiment)
    - Flavor physics (muon g–2, muon to electron conversion)
  - Physics driven by individual scientists
  - High visibility

... and the most sensitive **axion DM search experiment**

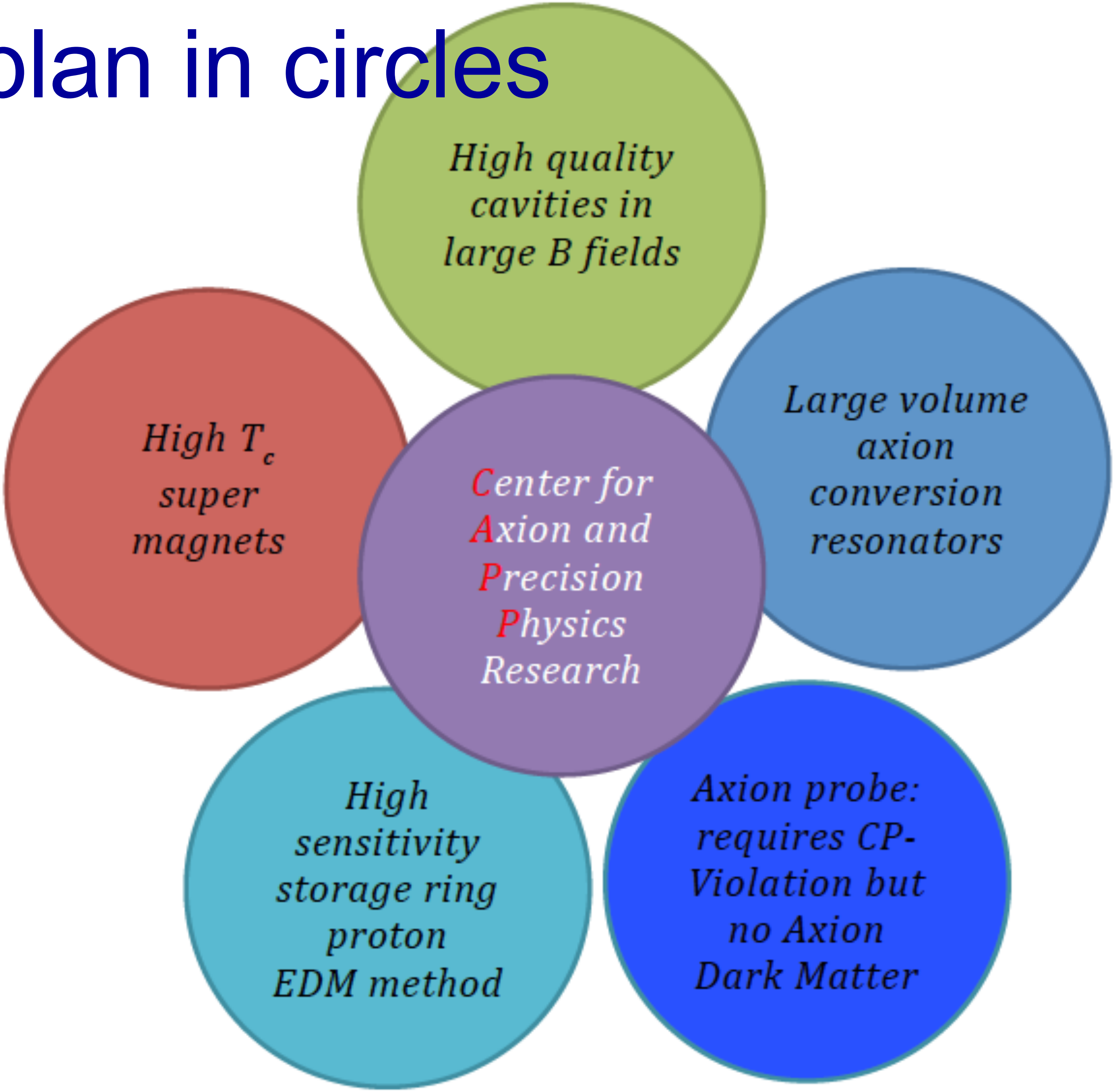
Center for Axion and Precision Physics (CAPP)

http://capp.ibs.re.kr/html/capp_en/

CAPP / IBS, October 2014


CAPP / IBS, May 2015

CAPP plan in circles



CAPP/IBS axion plan

- Build strong collaborations
  - CULTASK (CAPP Ultra-Low-Temp. Axion Search in Korea)
  - ADMX-CAPP/IBS
  - CAST-CAPP/IBS
- Major sensitivity improvements
  - High field, high volume, high quality factor cavities
  - Toroidal geometry, large volume
  - Toroidal geometry, large B-field
- ARIADNE, GNOME

CAPP/IBS axion improvement plan

- Major improvement elements:
  - High field solenoid magnets: B
  - High volume magnets/cavities: V
  - High quality factor of cavity: Q
  - Low noise amplifiers: T_N
  - Low physical temperature: T_{ph}

CAPP research plan

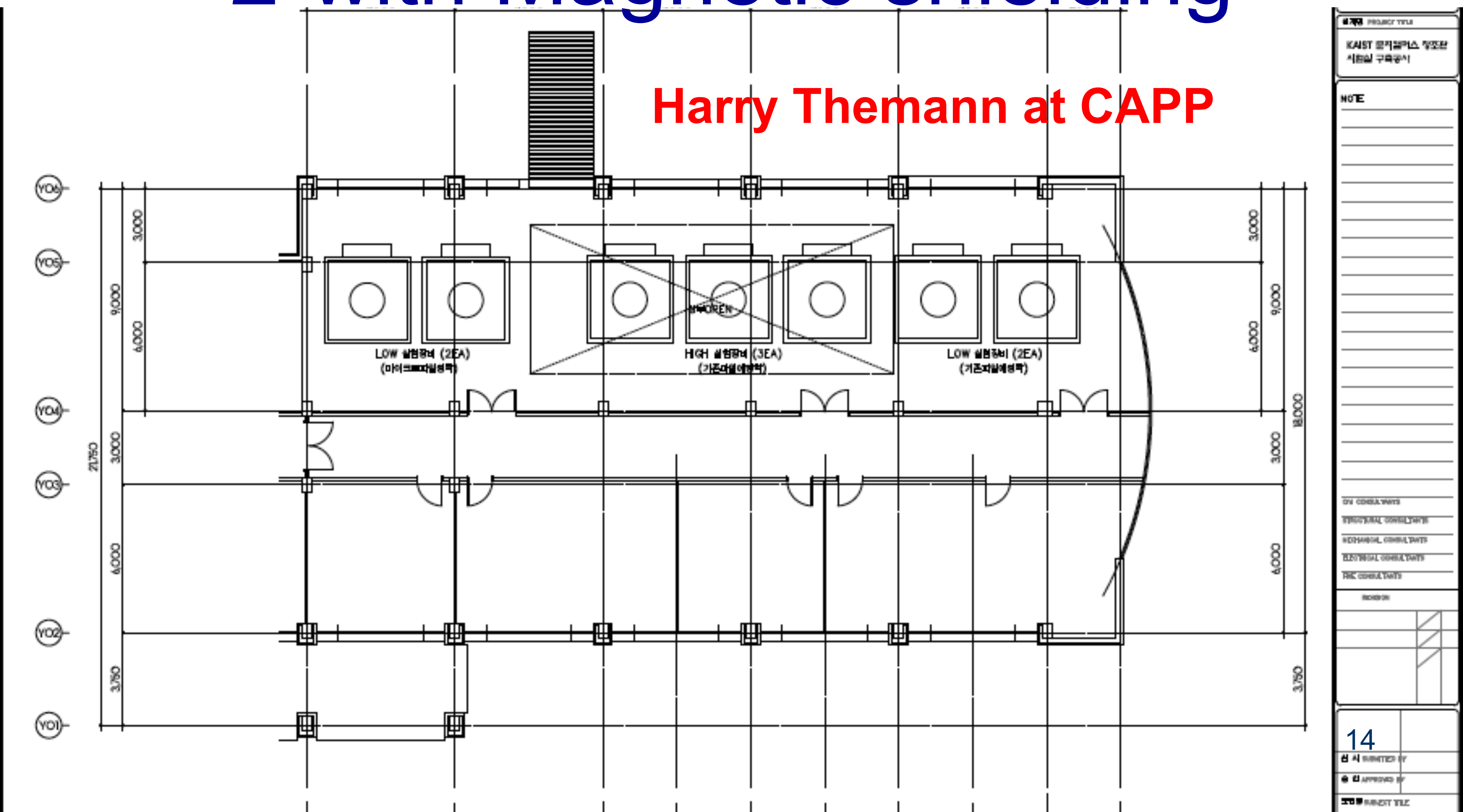
	2015	2016	2017	2018	2019	2020	2021
pEDM	R & D		Ring design		Installation		
g - 2	Preparation		Run		Data analysis		
COMET	Construction I	Run	Construction phase I!			Run phase II	
ARIADNE	R & D			Run	Data analysis		
GNOME	Preparation			Run phase !!	Data analysis & Phase II preparation		
CAST				CAST-CAPP/IBS			
Coldest ADM experiment at KAIST	Preparation		CULTASK		Run		

Plans: Munji campus Bldg. (KAIST)
Refurbish an existing building

Creation Hall

Creation Hall

Plans for lab-building 3-storey bldg., w/ 7 pits, vibr. Isol., 2-with Magnetic shielding



Harry Themann at CAPP

Axions, Dark Matter

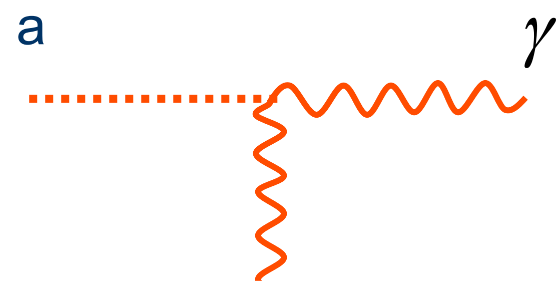
Axion Dark matter

- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Narrow line, kinetic energy ~$10^{-6} m_a$

Axions, the CAPP plan

$$m_a \approx 6\mu\text{eV} \cdot \left(\frac{10^{12}\,\text{GeV}}{f_a}\right);$$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = 0.97\ (\text{KSVZ})\ \text{or}\ \text{-}0.36\ (\text{DFSZ})$$



- Axion dark matter in the mass range ~1μeV to 100μeV. Plan to either detect or exclude axions down to 10% of dark matter.
- Axion long-range interactions (no dark matter requirement), up to ~10 meV axion mass.

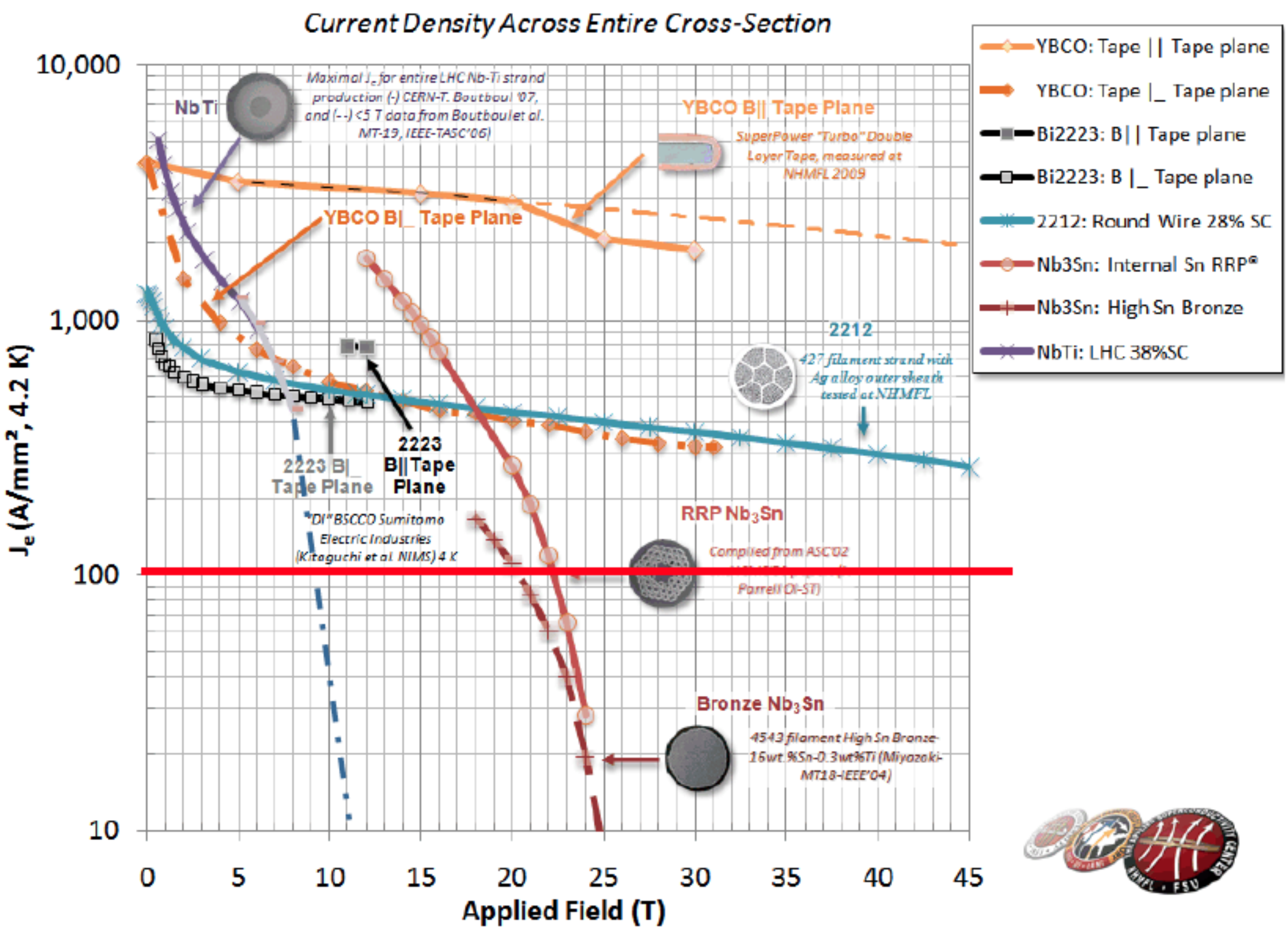
Axions with High Field Solenoid Magnets

(CAPP) Axion dark matter plan

- We have started an R&D program with BNL for new magnets: goal 25T; then 35T. Currently all axion experiments are using <10T.

- Based on high T_c cables (including SuNAM, a Korean high T_c cable company). ~5 year program.

Future Solenoids:
High- Temperature Superconductors

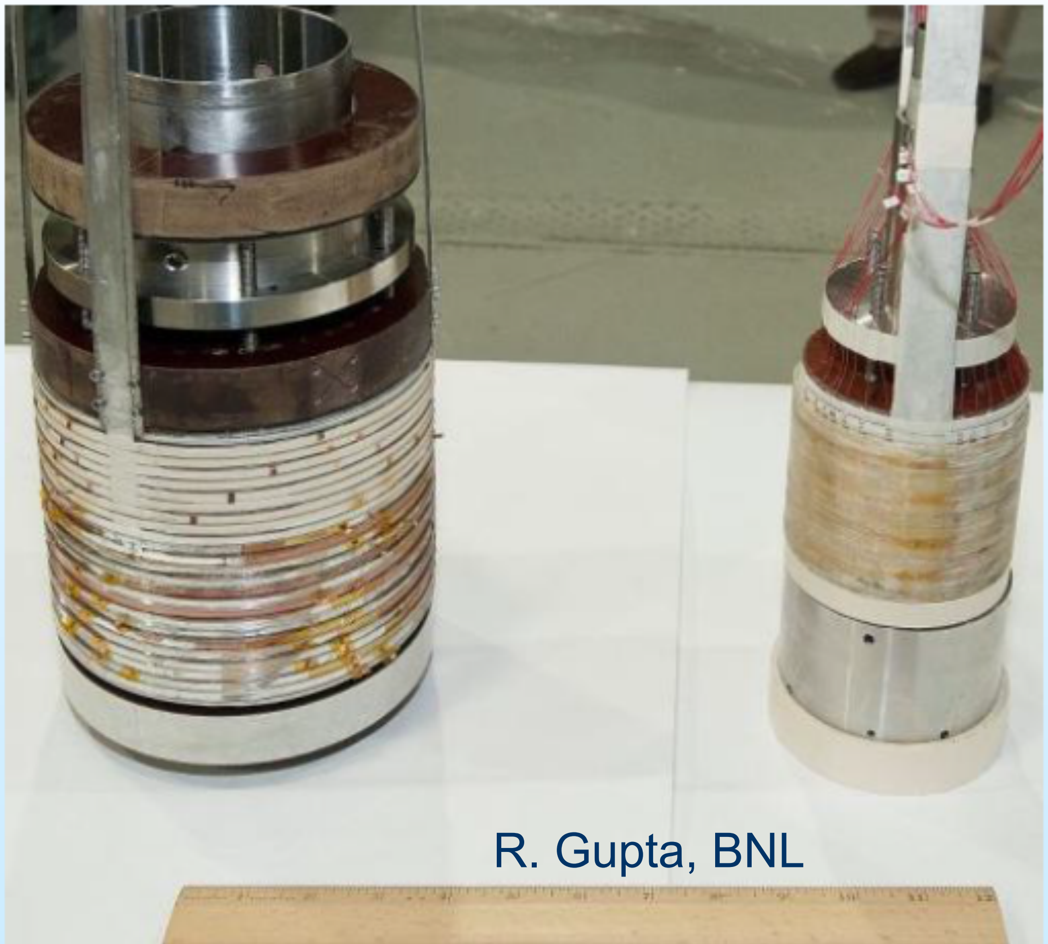


Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

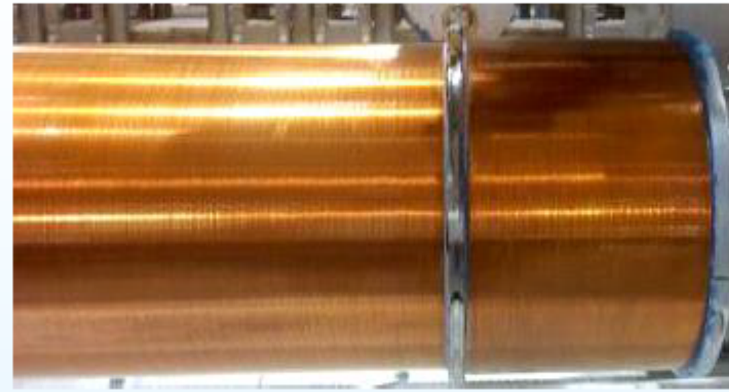
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

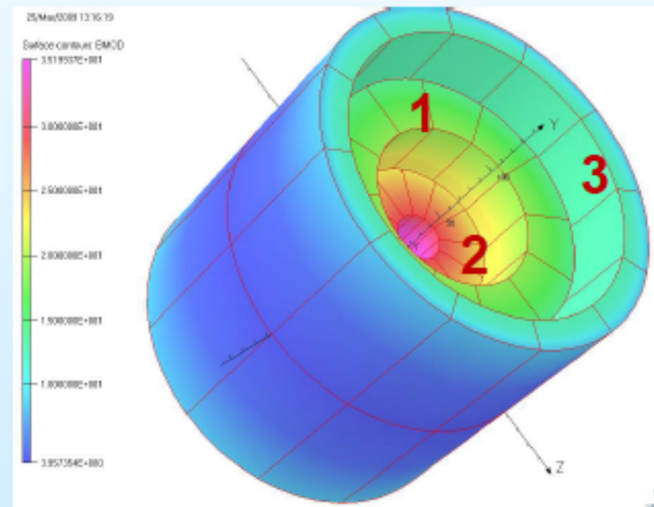
Status of High Field MAP Solenoids

Two HTS coils together made with SuperPower HTS is expected to create 20-25 T, if successful



R. Gupta, BNL

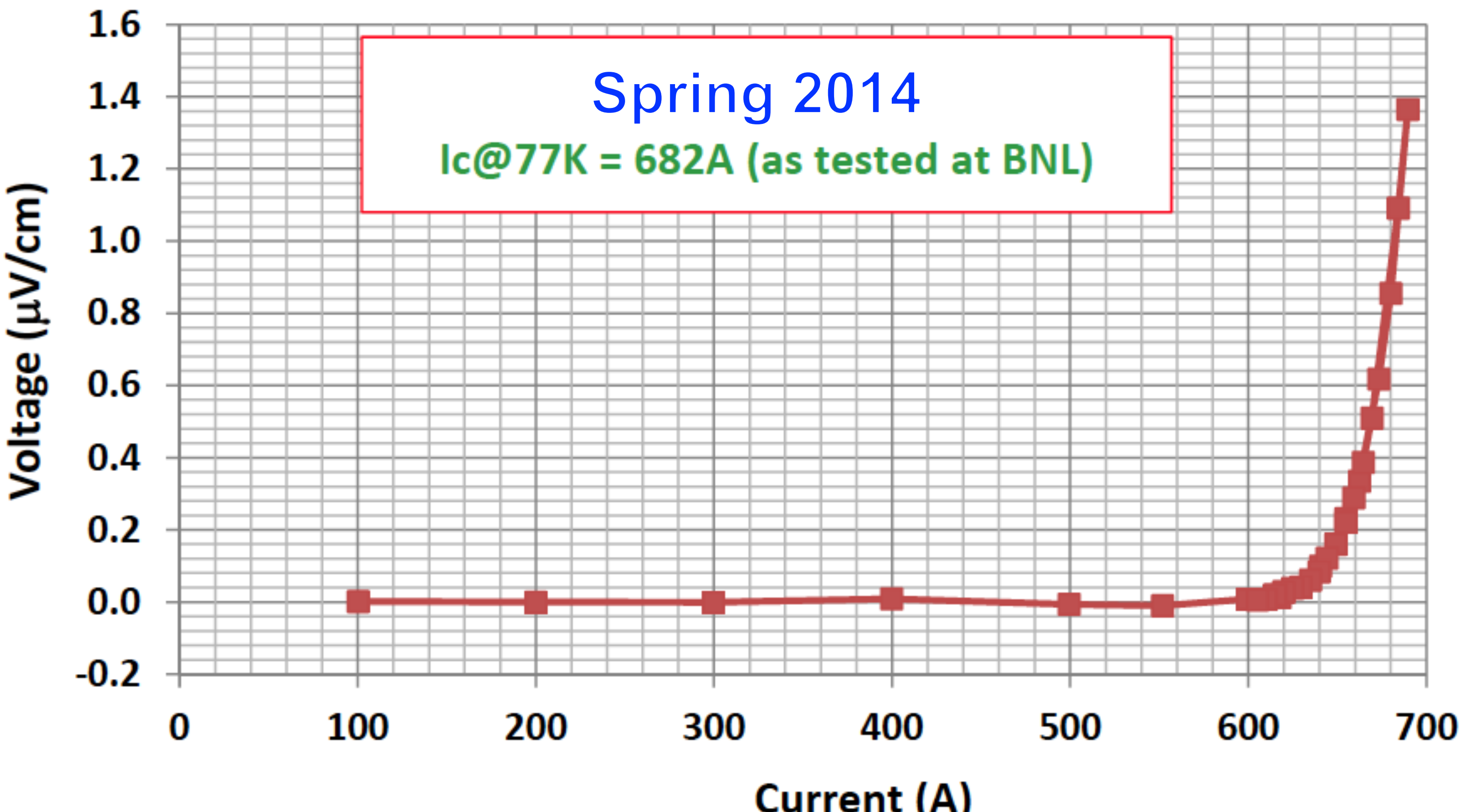




~30 T with NbTi outer
(40 T with Nb_3Sn or more HTS)

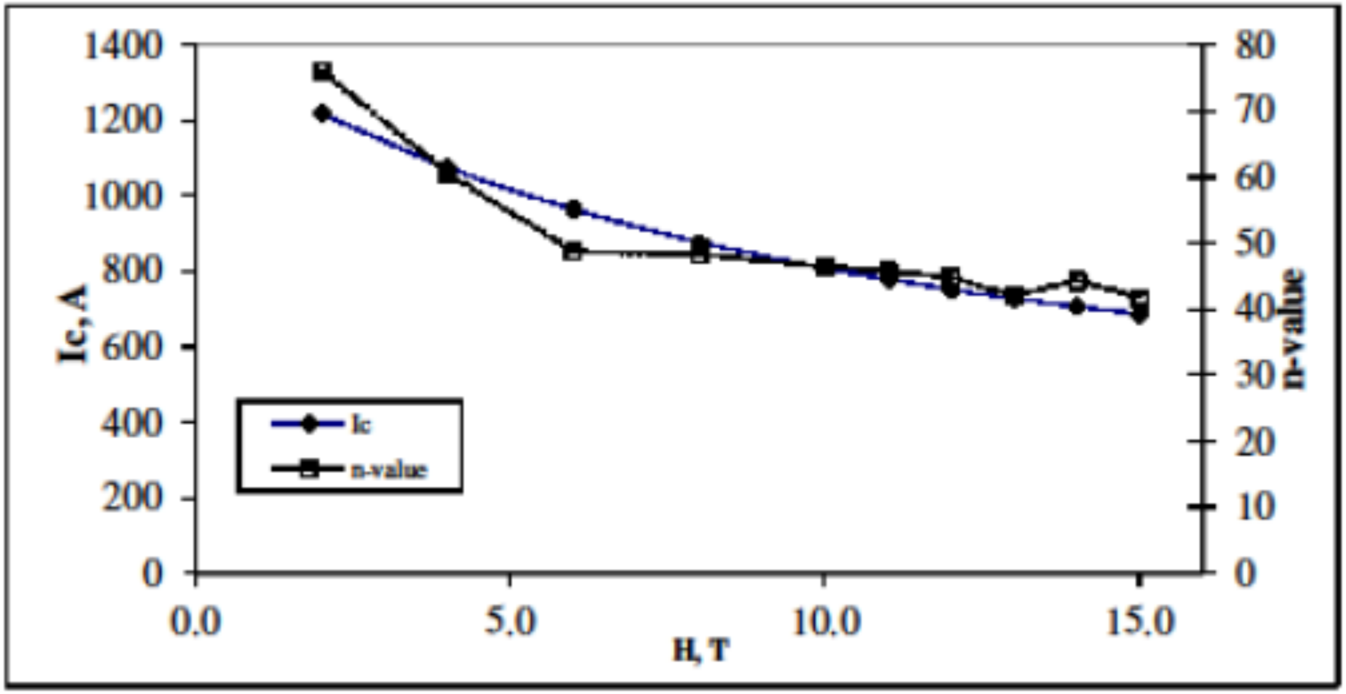
Magnet Development
SuNAM cable

Already signed an agreement for a prototype magnet development between CAPP/IBS and BNL. Duration 1 year.
Goal: Determine the cable for the final design.



Magnet Development

BNL, Summer 2014 – Spring 2015



Axions, High Volume

Under development by CAPP

- Multiple cavities in-phase (tried by ADMX in 90's)
  - Using cryo-piezo actuators for large volume, large B-field
  - Dr. Youn Sung Woo has received an IBS Young-Scientist award with CAPP to develop this system
  - Program duration five years.

Axions, High Quality Q-Factor Cavity

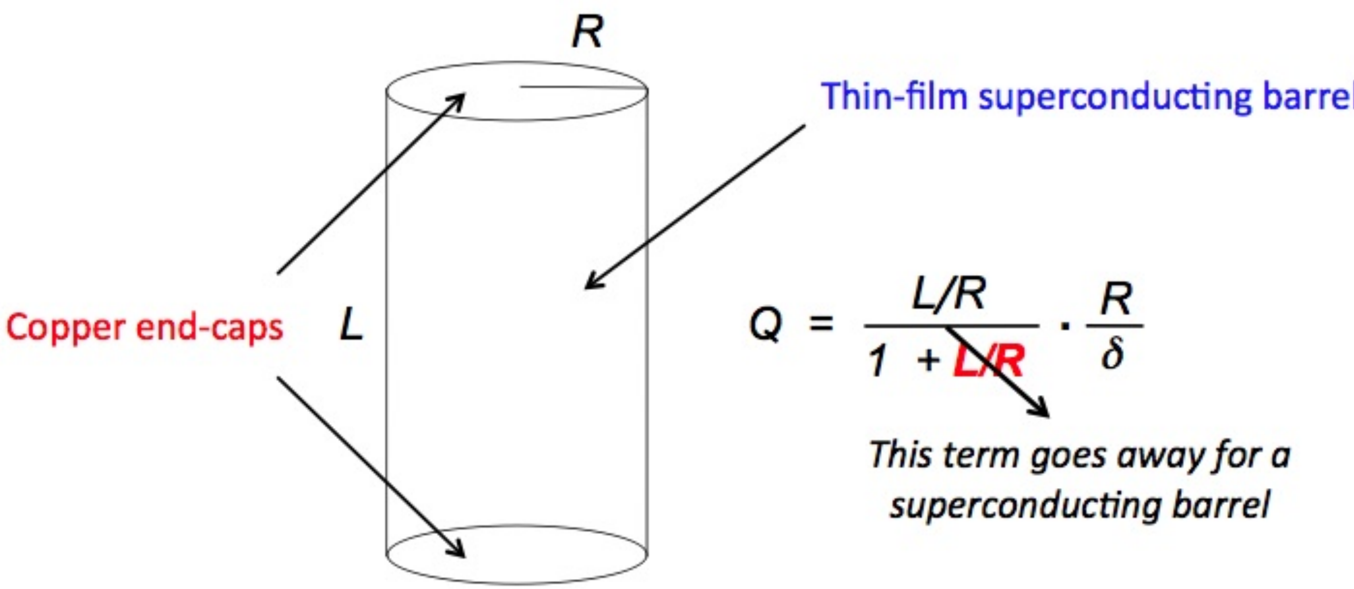
CAPP: High quality factor cavities

- We have started an R&D program to achieve large Q in the presence of large B-fields.
- Presently: $Q \sim 10^5$ for copper cavities. axion Q_a: $\sim 1.5 \times 10^6$
- CAPP goal: Q: $\sim 10^7$, potential gain factor: 15.

$$Q = \omega \frac{\text{Stored energy}}{\text{Power loss}} \sim \left(\frac{V}{S\delta}\right) = \frac{\pi R^2 L}{2\pi R^2 + 2\pi R L}\frac{1}{\delta} = \frac{L}{R+L}\frac{R}{2\delta}$$

Under development by ADMX

The concept of a hybrid superconducting cavity:



$$Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

This term goes away for a superconducting barrel

$$Q_{hybrid} = (1 + L/R) \cdot Q_{cu}$$

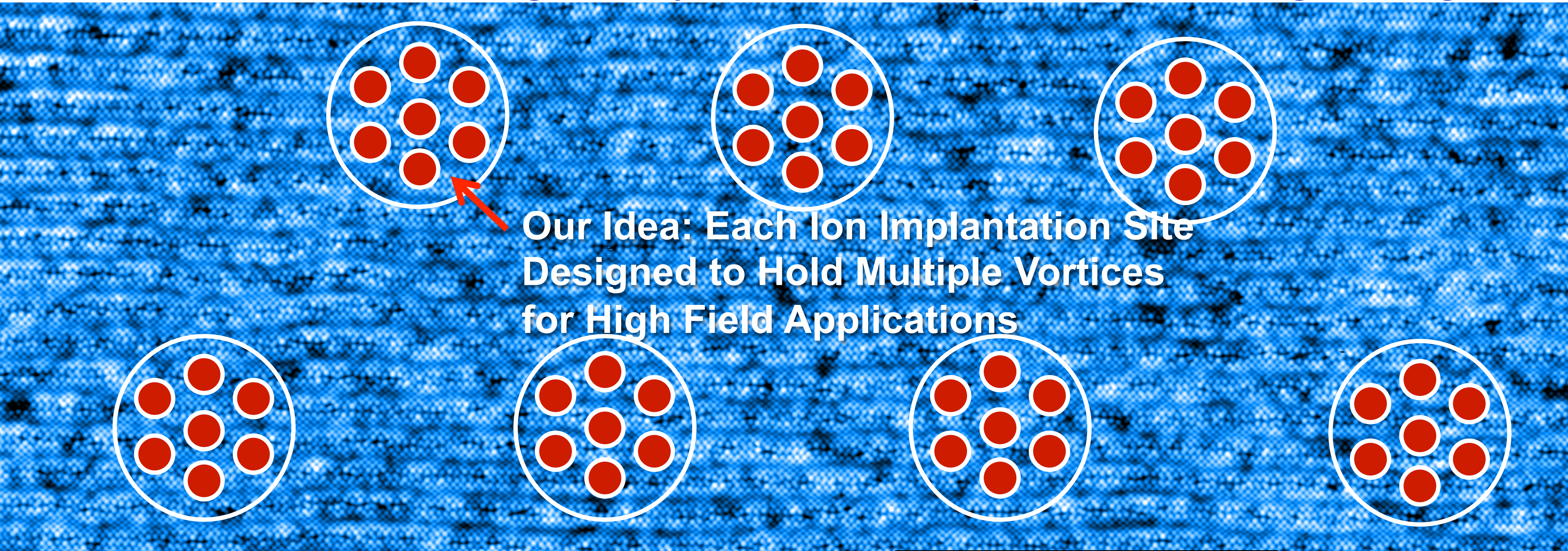
For typical ADMX cavity, L/R = 5, enhancement factor = 6

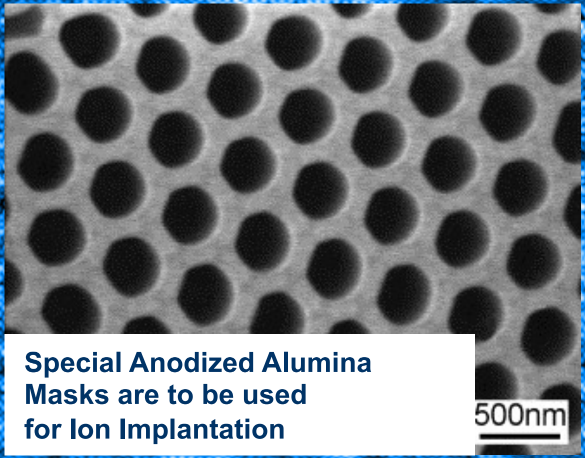
Under development by CAPP

- High quality factor with SC walls including top/bottom plates
  - Acquiring the equipment to develop SC cavities
  - Program length two to three years from now

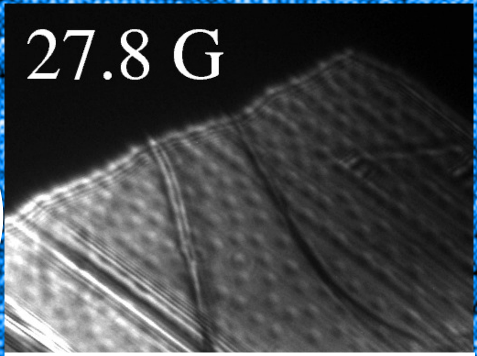
- Toroidal shape cavity
  - Large volume
  - B-field tangential to cavity walls (<1 mrad)
  - 10-year program

CAPP: Proposal of Cryogenic STM Research Group
(Prof. Jhinhwan Lee/KAIST and CAPP)
Enhancement of the High Tc Superconductors by Novel Vortex Engineering





Special Anodized Alumina Masks are to be used for Ion Implantation



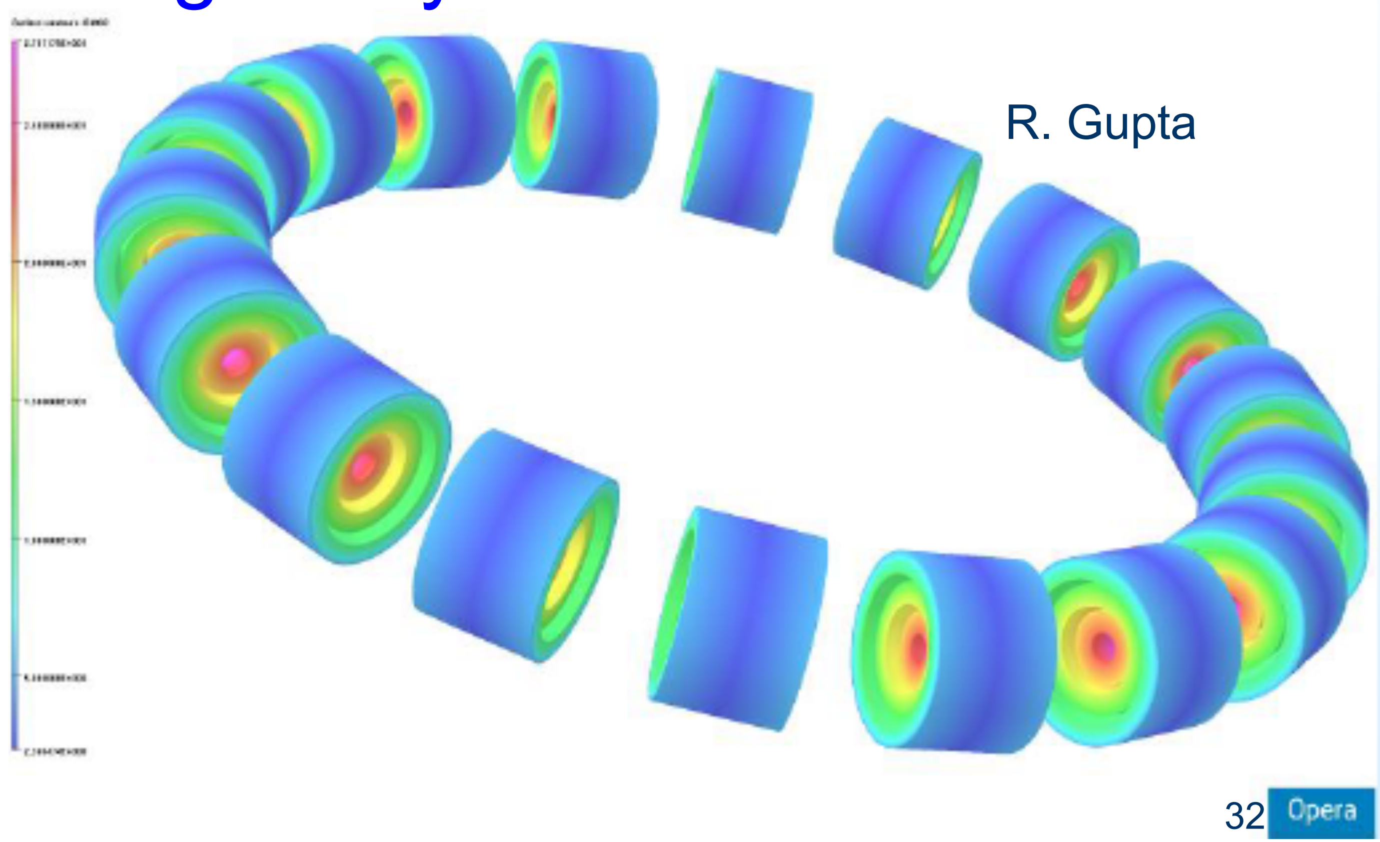
Lorentz Microscopy Visualization of Distributed Vortices on BSCCO

BSCCO
(c) KAIST
Cryogenic SPM Laboratory

Axions with Toroids:
High Volume,
High Quality Factor Cavity

Toroidal magnet

- Effective use of B^2V
- Large volume
- Super-conducting cavity walls



Toroidal magnet

- Major radius R_0: 2m
- Minor radius r_0: 0.5m
- Volume: 9900L
- Central B-field: 5T
- Cavity loaded Q: 10^7

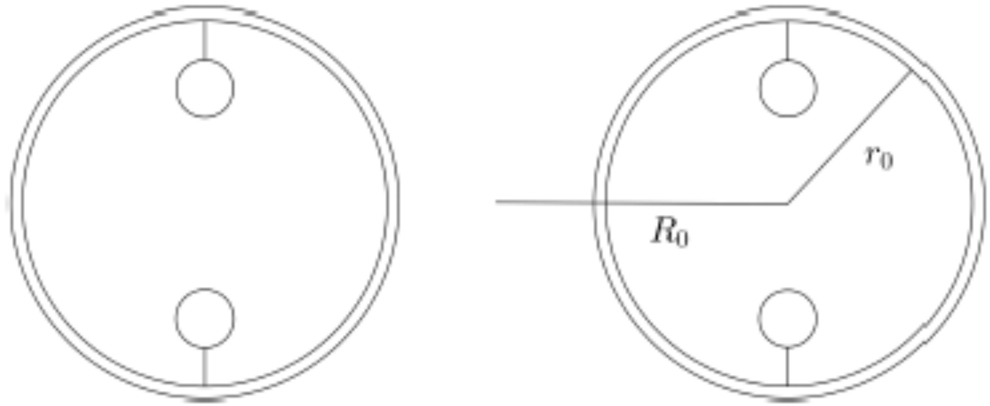
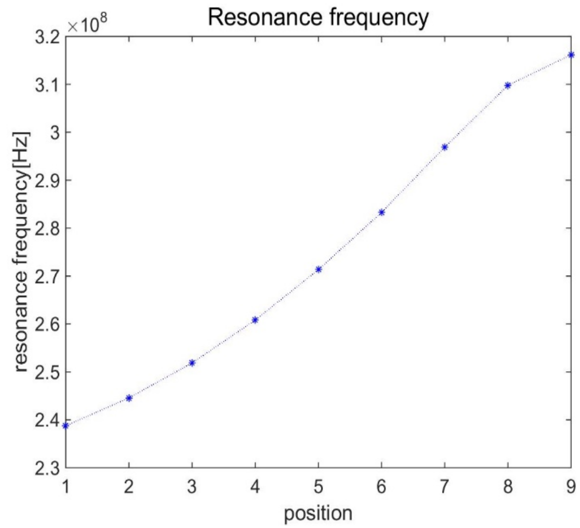
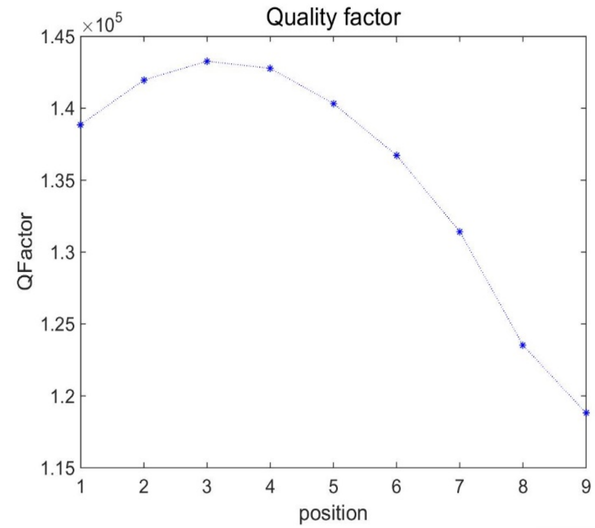


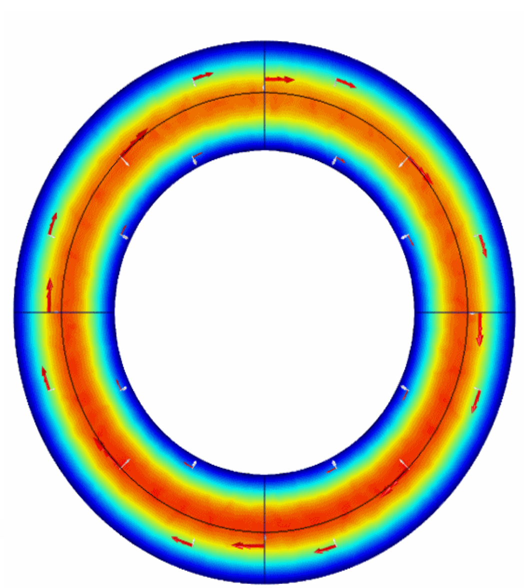
FIG. 1. A cross-section of the toroidal cavity of major radius R_0 and minor radius r_0. Conducting and dielectric tuning rings are supported at several points in the cavity.

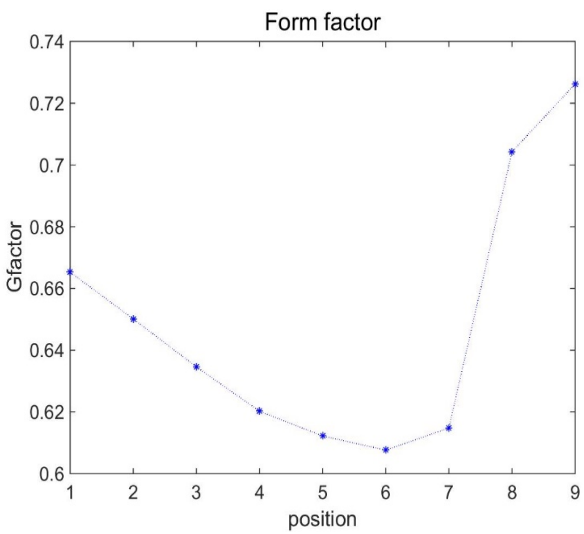
Simulation by Doyu Lee

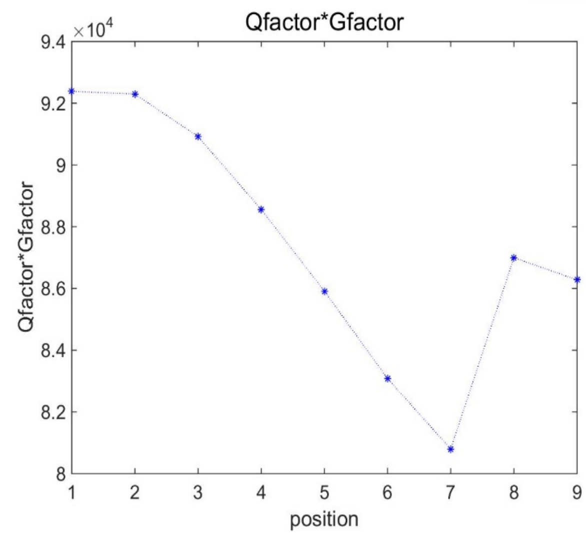
Copper wall + copper ring

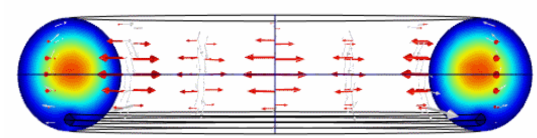




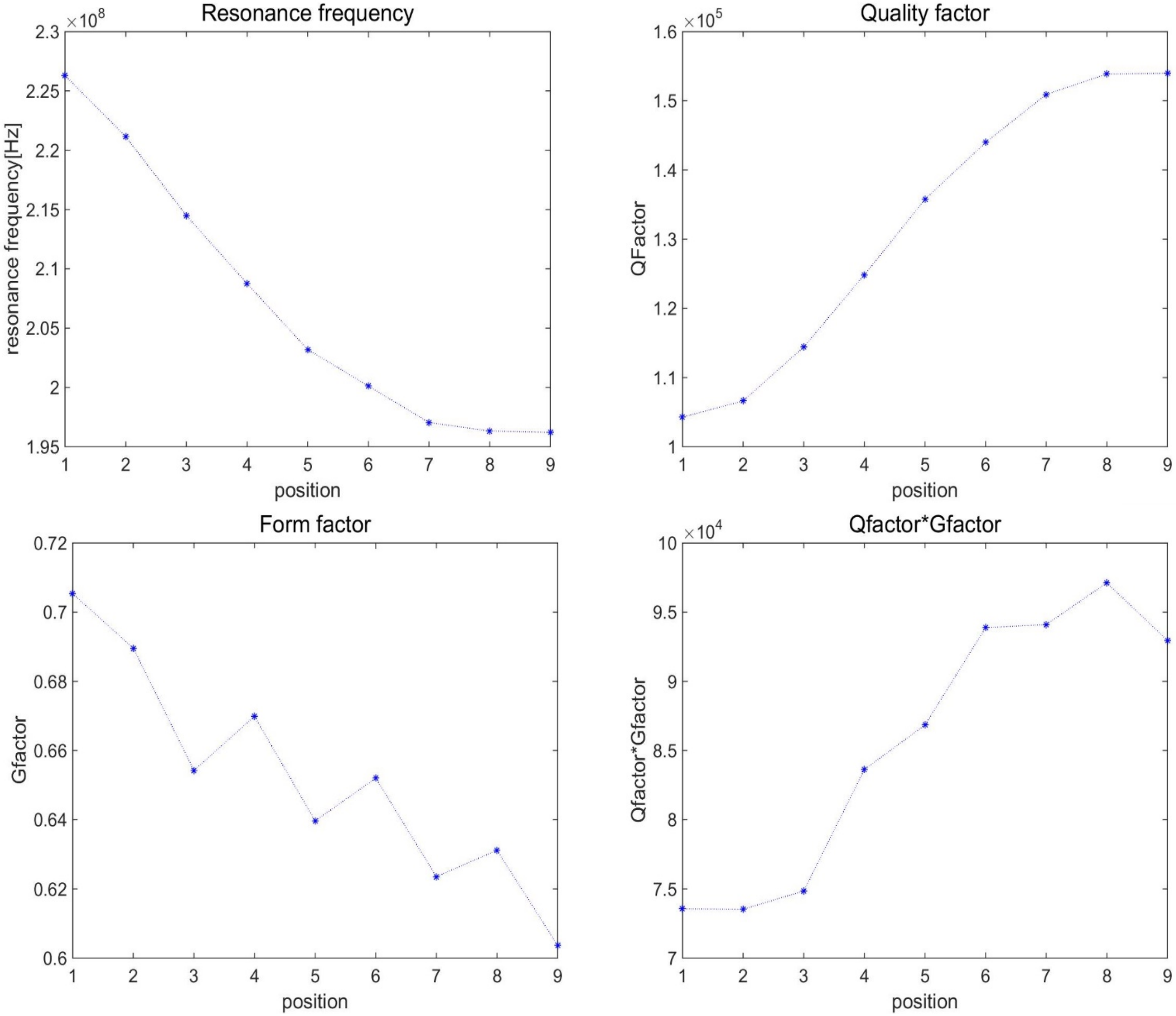


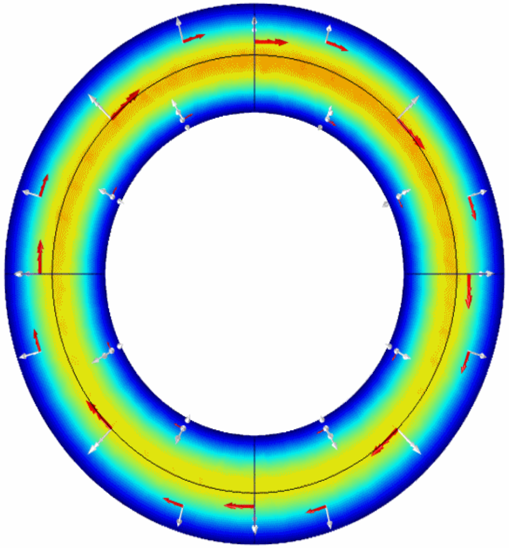


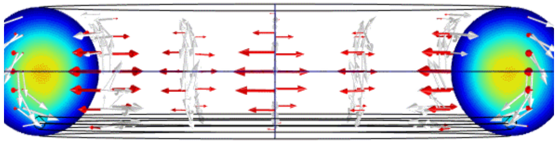




Copper wall + dielectric ring







Axions with SQUIDS: Quantum Limited Noise Amplifiers

CAPP: SQUID amplifiers

Five year contract with KRISS:

Korea Research Institute of Standards and Science

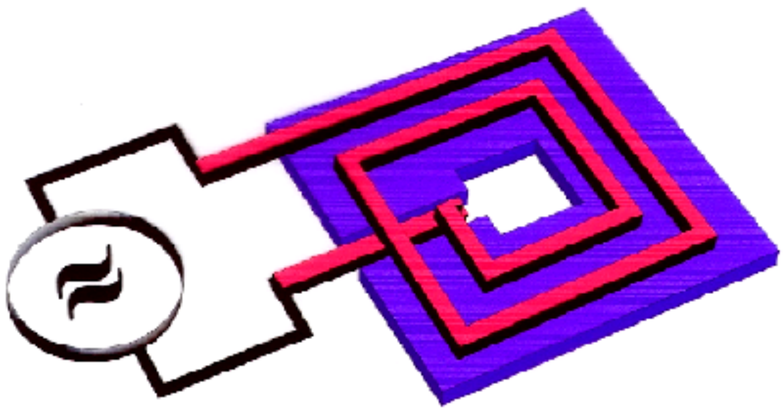
(Yong-Ho Lee's group)

We have started a development program with KRISS to provide us with (near) quantum noise limited SQUID amplifiers in the 1-20 GHz range. Evaluate method for higher frequency.

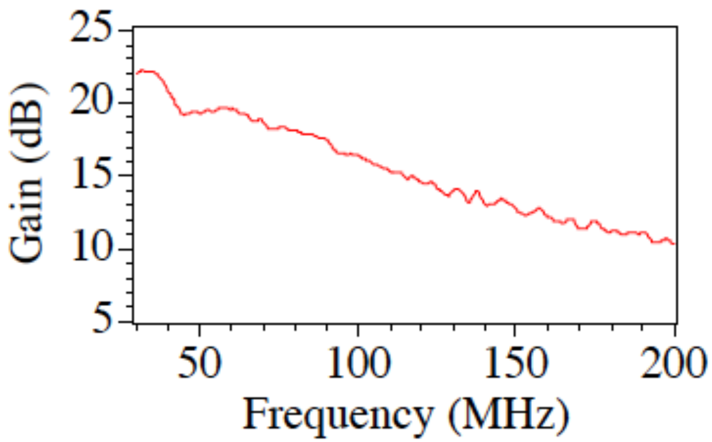
SQUID amplifiers

MSA: Principle

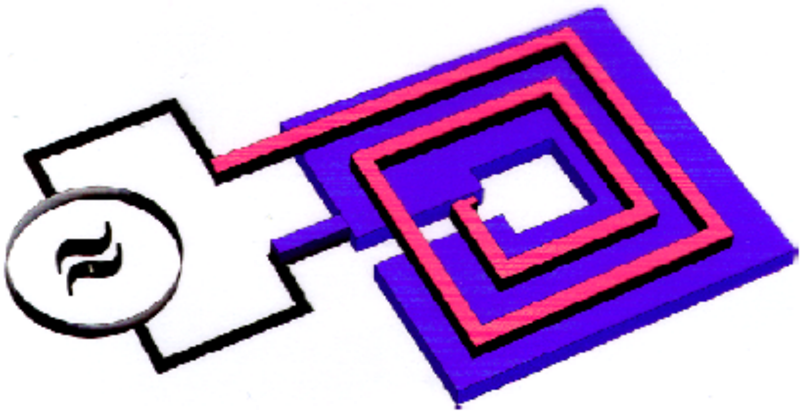
Conventional SQUID Amplifier



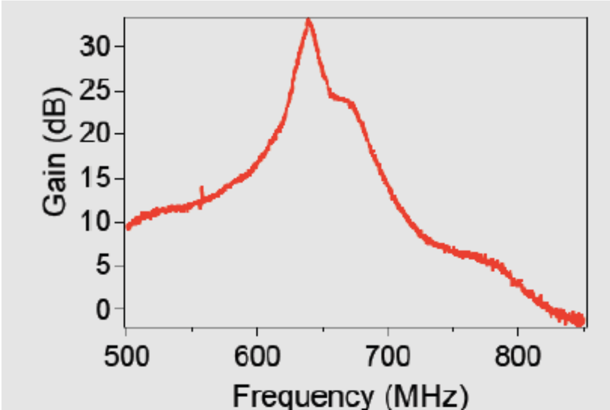
- Source connected to both ends of coil



Microstrip SQUID Amplifier

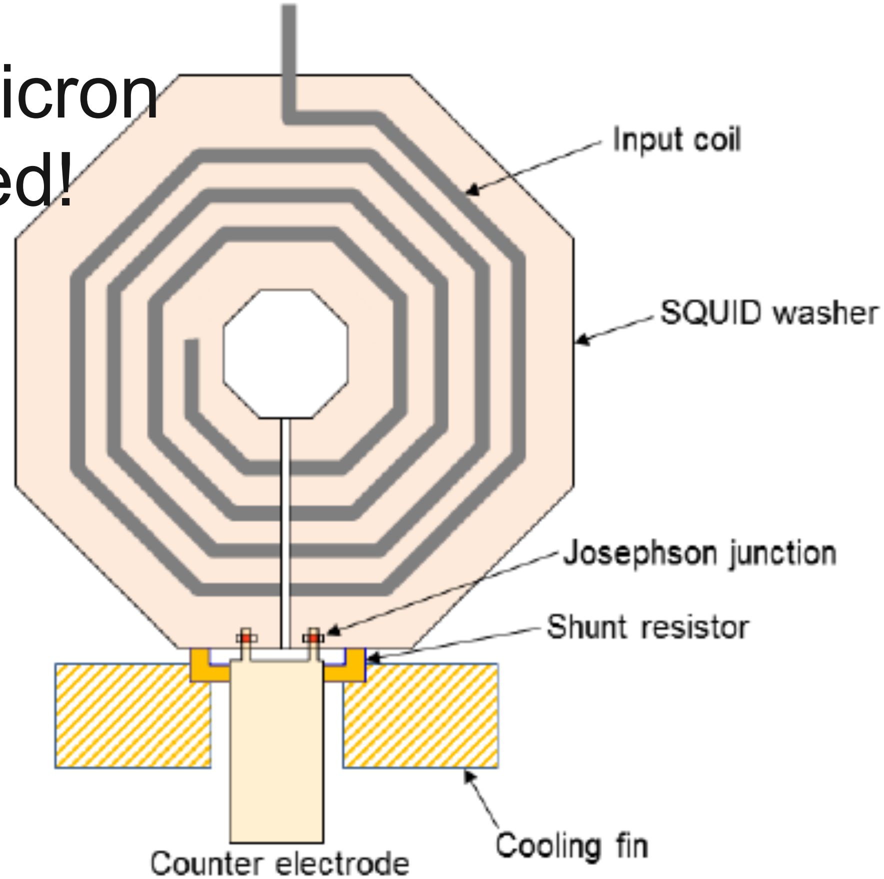


- Source connected to one end of the coil and SQUID washer; the other end of the coil is left open



SQUID amplifiers from KRISS

For f>5GHz, sub-micron resolution is required!



Physical temperature: aiming for 30mK. Quantum noise limit: 50mK at 1GHz, proportional to frequency…

CULTASK

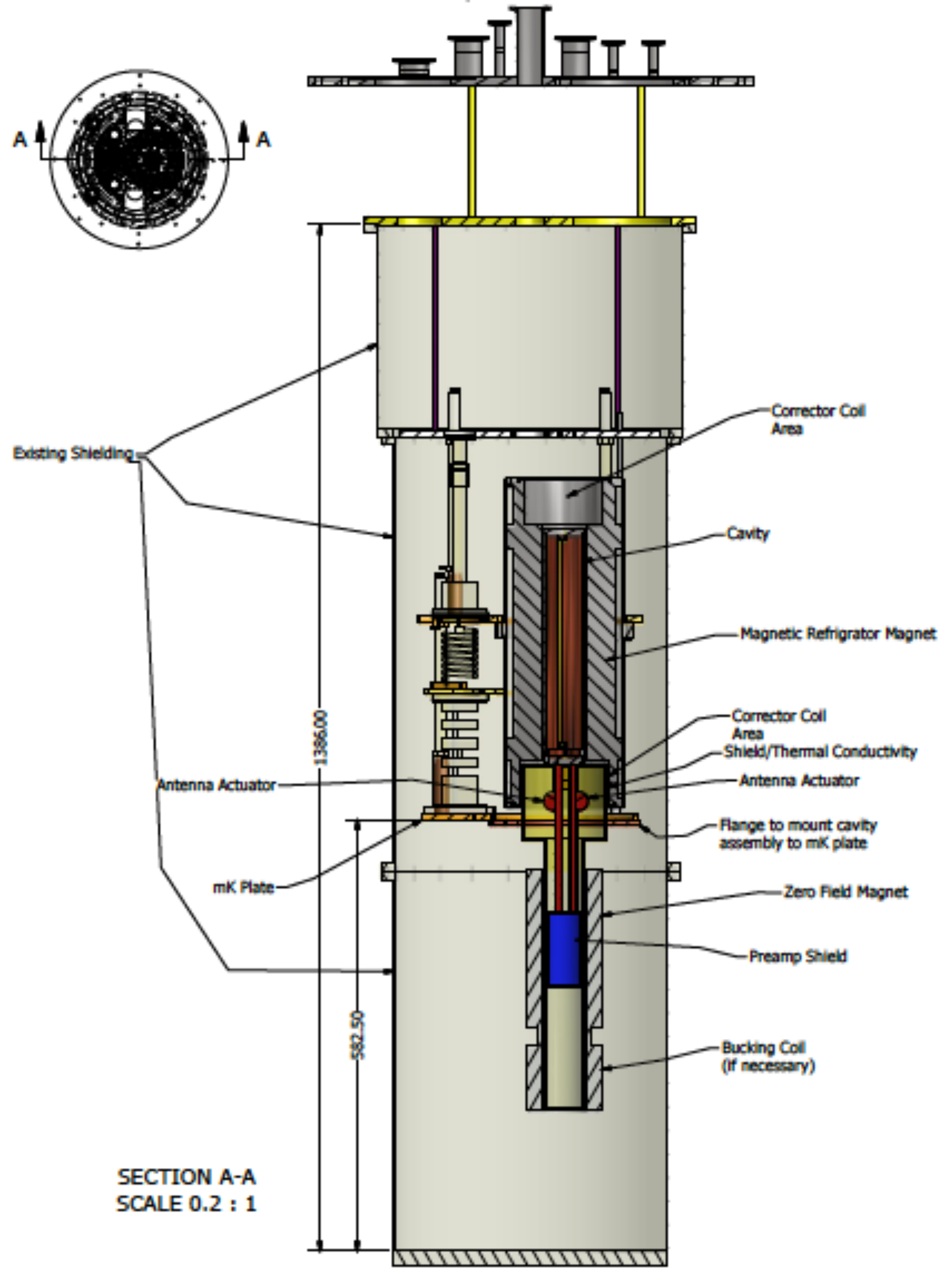
CAPP Ultra Low Temperature Axion Search in KOREA

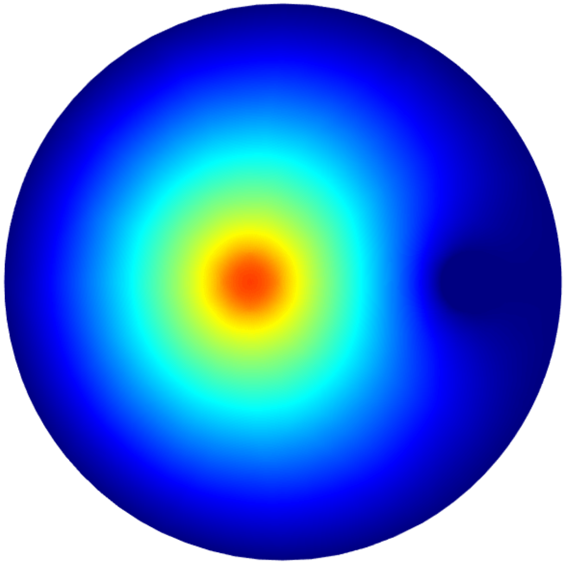
Woohyun Chung

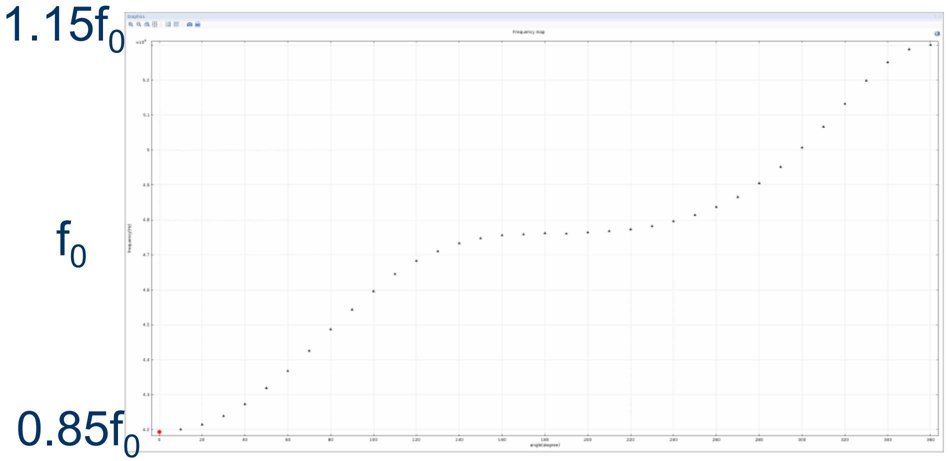
CULTASK:

The coldest (<50mK) axion dark matter experiment.

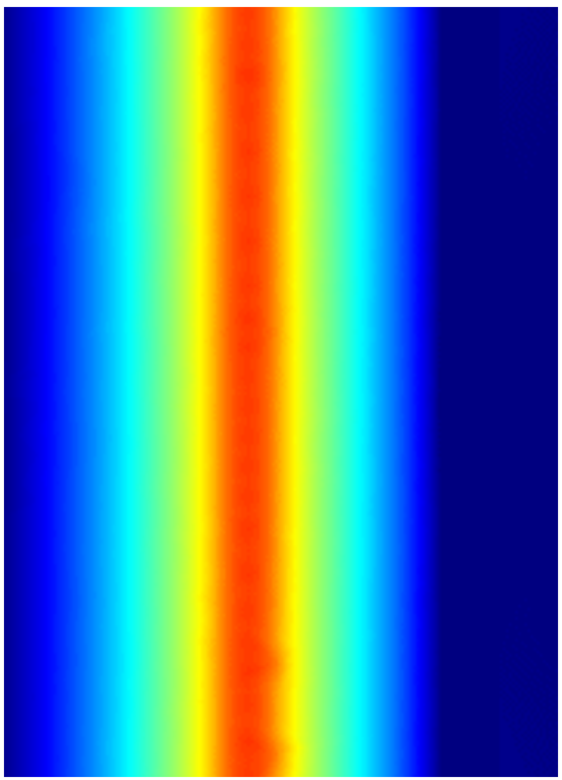
Freq.: ~6 GHz

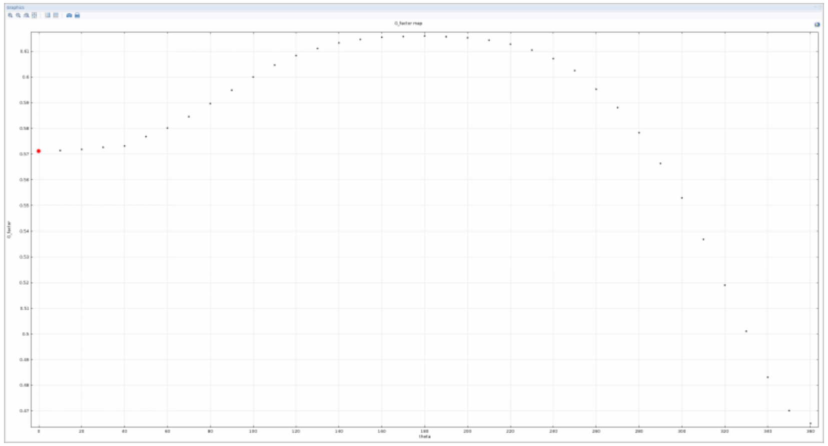


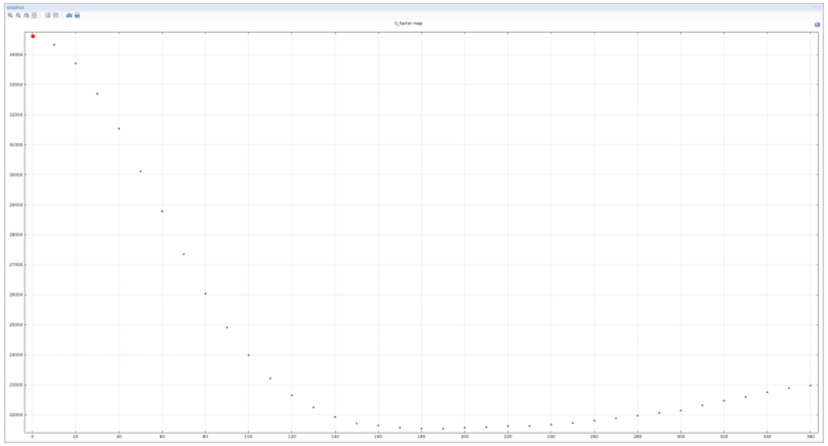




$1.15f_0$
f_0
$0.85f_0$

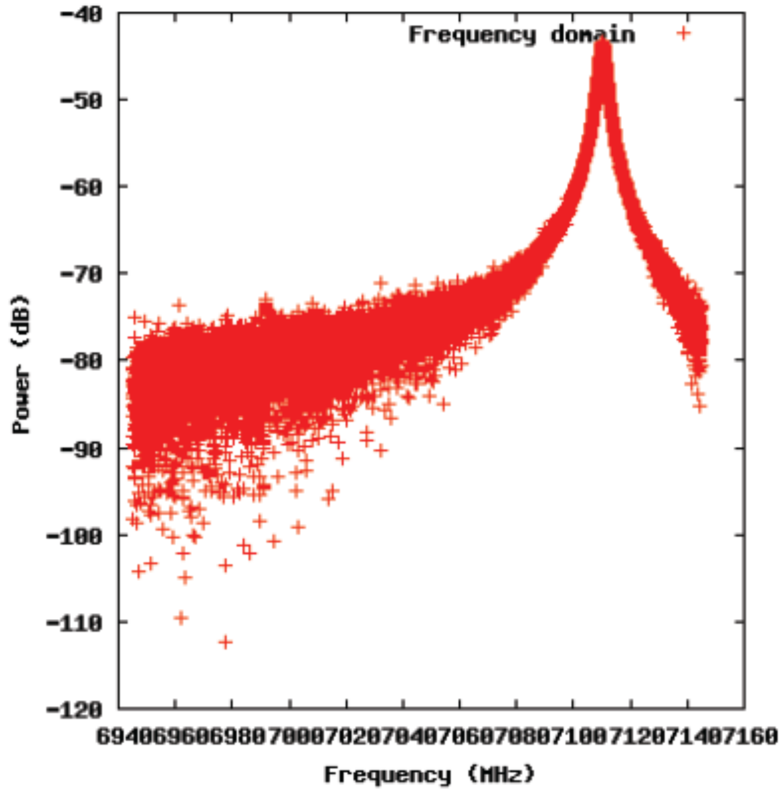


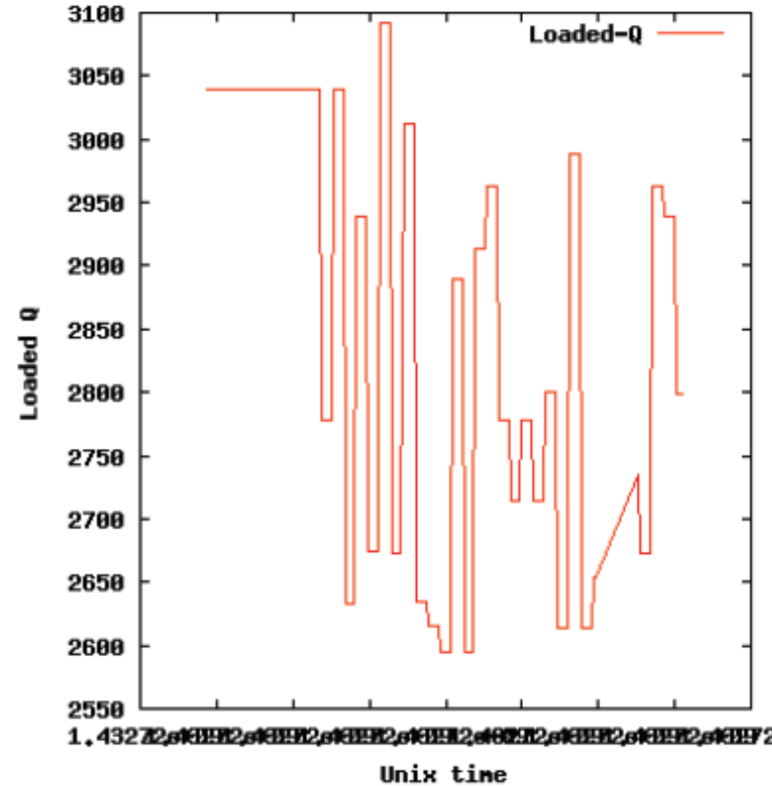




CAPP: CULTASK at KAIST

Loaded Q = 2799.339 at resonance frequency = 7110.320 MHz





Experimental Global

Experiment Name CULTASK 2015 Summer Enginee Experiment No. 1

Axions, CAST-CAPP/IBS

CAST: CERN Axion Solar Telescope

PHYSICAL REVIEW D 85, 035018 (2012)

Prospects for searching axionlike particle dark matter with dipole, toroidal, and wiggler magnets

Oliver K. Baker,[1] Michael Betz,[2] Fritz Caspers,[2] Joerg Jaeckel,[3] Axel Lindner,[4] Andreas Ringwald,[4] Yannis Semertzidis,[5] Pierre Sikivie,[6] and Konstantin Zioutas[7]

Lino Miceli's/CAPP: at the CAST-CAPP Axion DM proposal

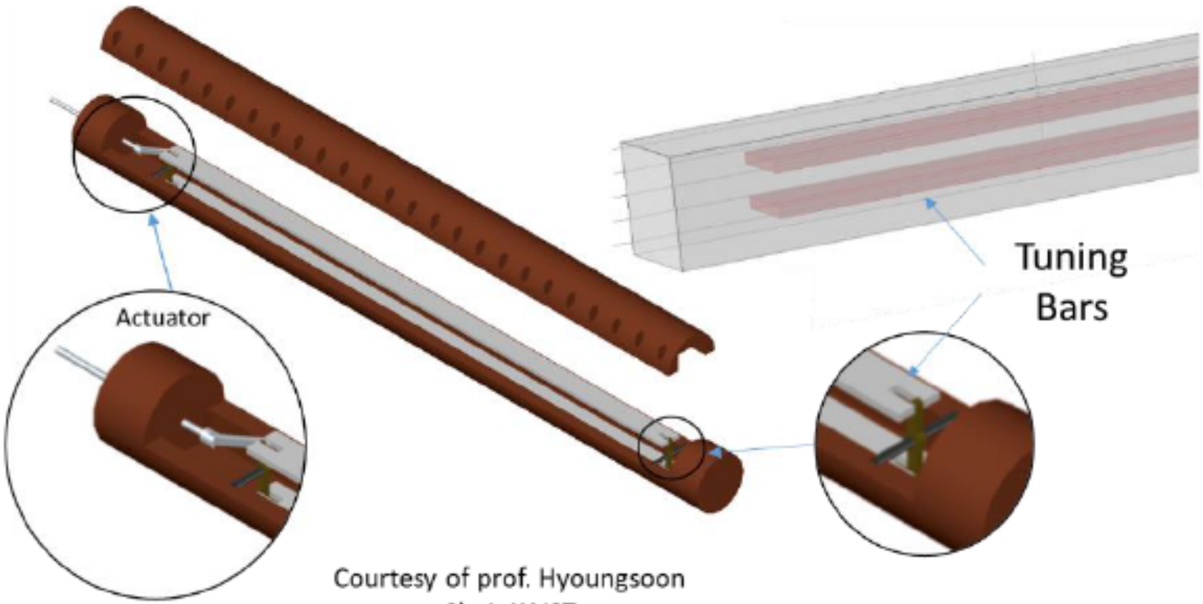


Figure 3: Conceptual engineering design of a possible tuning solution for a 2.5cm x 2.4cm X 50cm prototype cavity with dielectric tuning bars. The cavity is tuned by one single piezo actuator placed externally, while the bars are kept parallel to each other. This image does not necessarily represent the way in which the cavity will be assembled.

Lino Miceli's/CAPP: at the CAST-CAPP Axion DM proposal

"TE_{011}", f = 5.83 GHz, bar penetration distance 1 mm. Dielectric permittivity = 9.

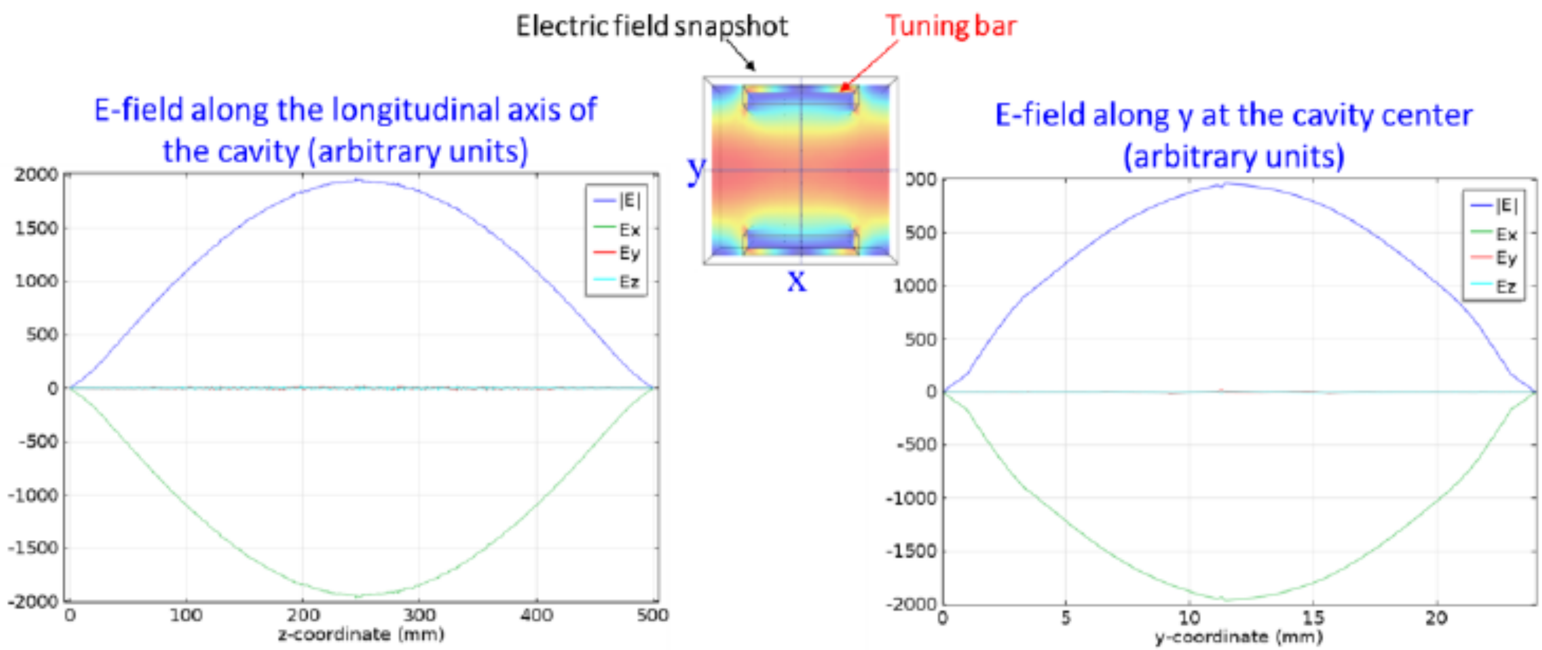


Figure 6: The electric field inside the resonator when the dielectric tuning bars are at a distance of 1 mm from the cavity walls. Notice how the electric field distribution is altered by the presence of the tuning bars. The field is more intense in the red, compared to the yellow, areas of the XY map (inset).

Lino Miceli's/CAPP: at the CAST-CAPP/IBS Axion DM proposal

Mode localization issues

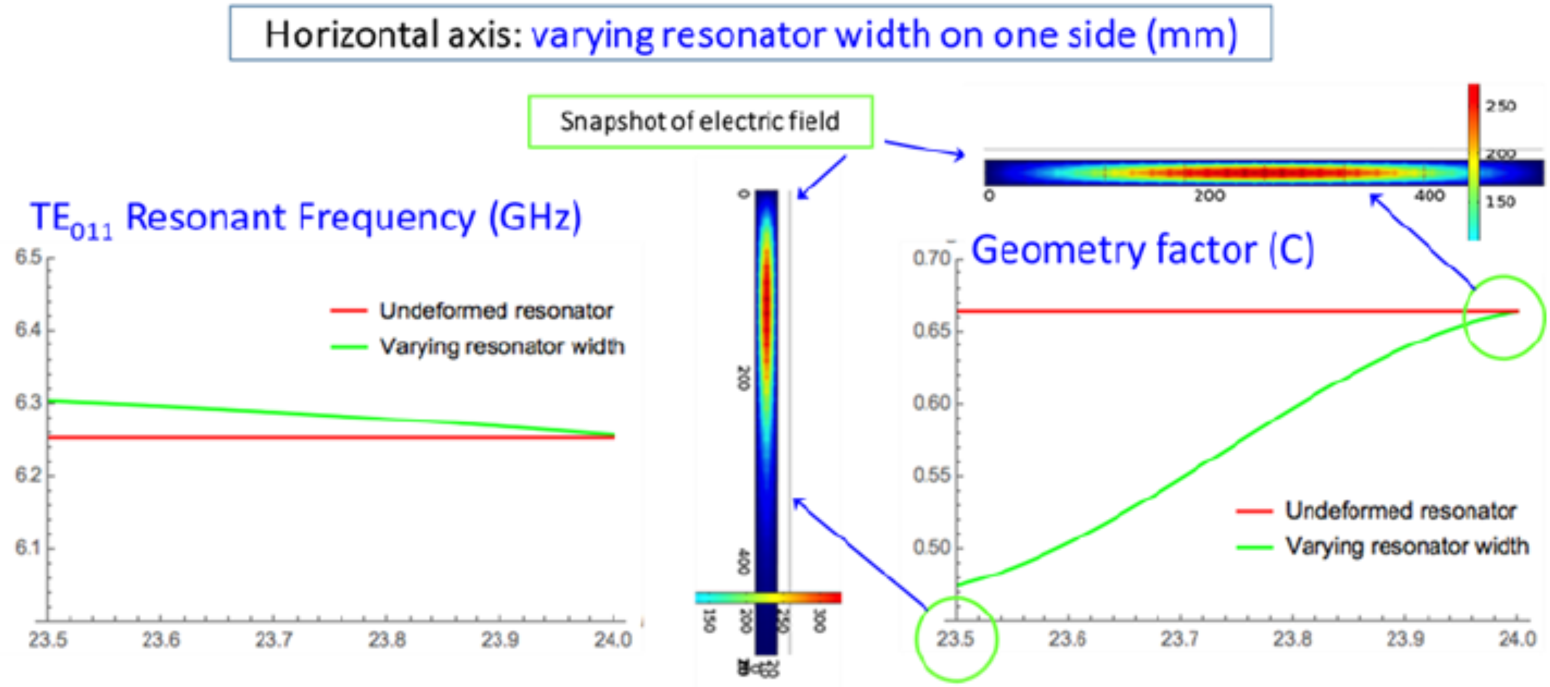
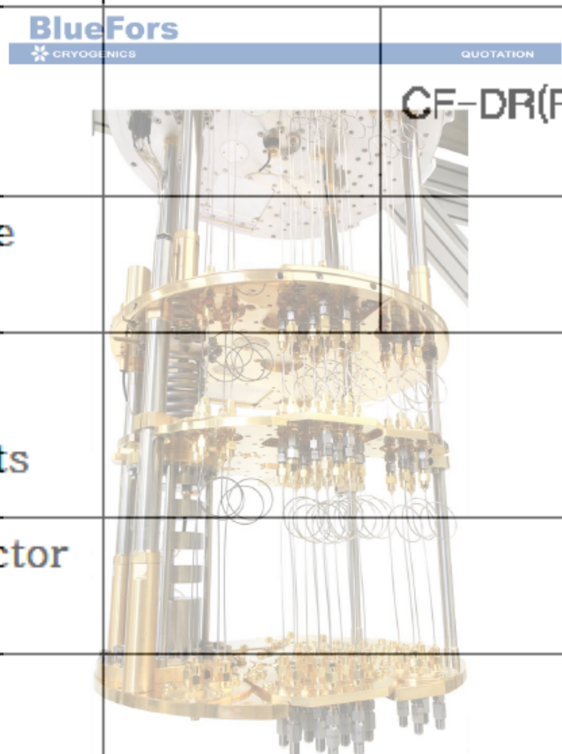


Figure 7: Mechanical tolerances and mode localization in a 2.5cm x 2.4cm x 50cm cavity.

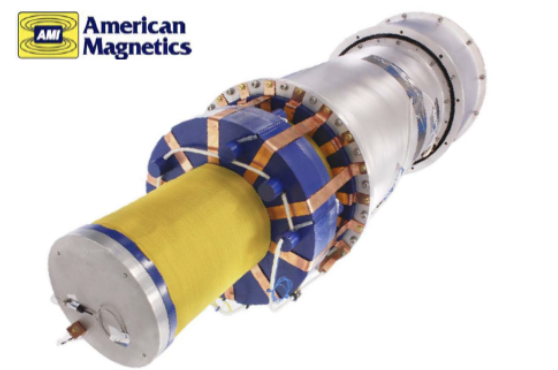
Axions: Timeline and Goals

Cryo Development plan
(Yonuk Chong, KRISS)

	2014	2015	2016	2017	2018	……
Essential Equipments	CF-DR(RF1) CF-DR(magnet) Wet-He3(large bore)					
Quantum Amplifier Research		CF-DR(RF2)				
Small-sclae Integration		CF-DR(testbed)				
Low-noise Experiments			Wet-DR1(precision) Wet-DR2(precision)			
AxionDetector main				Main DR (Axion Detector)		
Helium Liquefier			Helium Liquefier			



On the left 4x superconducting (none-attenuated) RF lines in a KF40 LOS-port, in the middle 12x CuNi lines in a KF63 LOS-port and right 4x CuNi (attenuated) lines in KF40 LOS-port

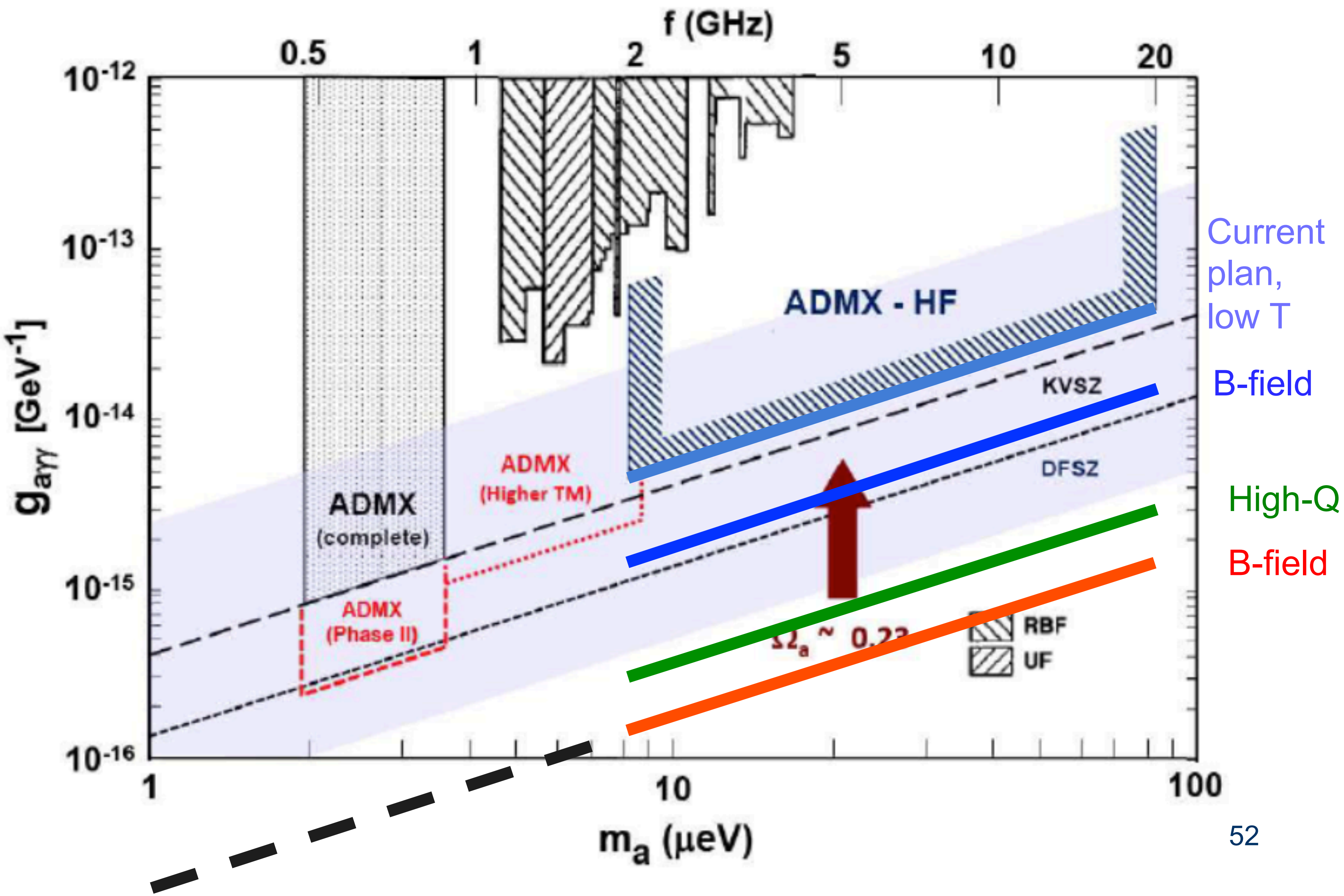


Example of a 7T-100mm cryogen free AMI magnet integrated with a BF-LD system (Protective aluminum magnet cover shield not shown in picture).

Axion exp. development plan

	2014	2015	2016	2017	2018
Magnet	Prototype, testing of cable characteristics.		25T, 10cm inner bore design	Work on 35T, 10cm inner bore construction	Magnet delivery of 35T, 10cm bore
Lab space	Temporary building: Lab design and preparation		Occupation		
Axion dark matter	Proc. Equipment Study res. geom.	Development of high Q resonators		Production of high-Q resonators	
Electronics, amplifiers	Establ. Collabor. w/ KRISS	Design for 1-10GHz Obtain JPAs, test. Develop higher freq. ampl.		Ampl. deliveries from KRISS	
Axion cavity Exp.	Design of exp., procure a low field magnet		Experimental setup. First test run.		Swap magnets

ADMX goals and CAPP plan



Axions with ARIADNE: Axion Resonant InterAxion DetectioN Experiment

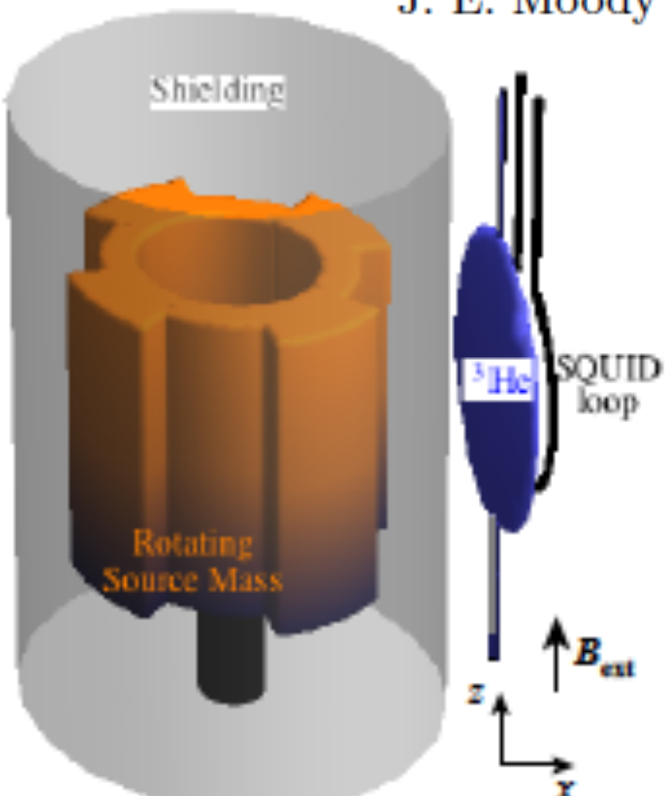
Axion mediated long range forces

$$U_{sp}(r) = -\vec{\nabla} V_{a_s}(r) \cdot \hat{\sigma}_2,$$

Here $V_{a_s}(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f} \frac{e^{-\frac{r}{\lambda_a}}}{r}$ for monopole-dipole interactions.

A. Arvanitaki, A. A. Geraci, arXiv:1403:1290

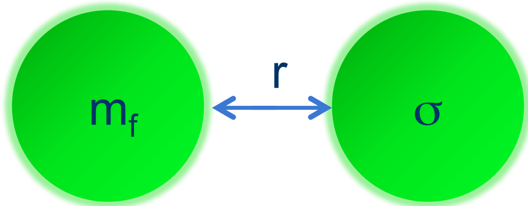
J. E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984).



$$\vec{B}_{\text{eff}} \approx \frac{1}{\hbar \gamma_N} \nabla V_a(r)(1 + \cos(n\omega_{\text{rot}} t)),$$

Yun-chang Shin,
Dong Ok, Ph.D. Student

Spin-dependent forces



A. Geraci

Monopole-Dipole axion exchange

$$U(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r}) \qquad \equiv \mu \cdot B_{\text{eff}}$$

- Different than ordinary B field
- Does not couple to angular momentum
- Unaffected by magnetic shielding

Coupling constants

$$6\times10^{-27}\left(\frac{10^9\,\text{GeV}}{f_a}\right) < g_s < 10^{-21}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

$$g_p = \frac{C_f m_f}{f_a} = C_f 10^{-9}\left(\frac{m_f}{1\,\text{GeV}}\right)\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

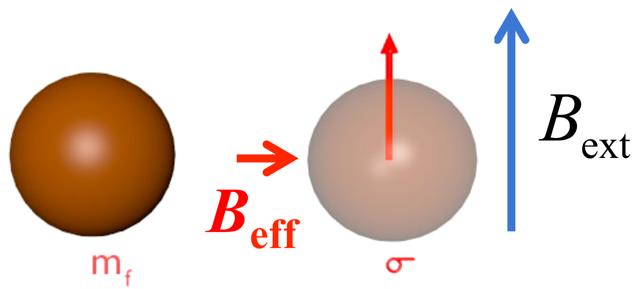
Resonant enhancement method

Spin ½ ³He Nucleus

A. Geraci

Oscillate the mass a
Larmor frequency

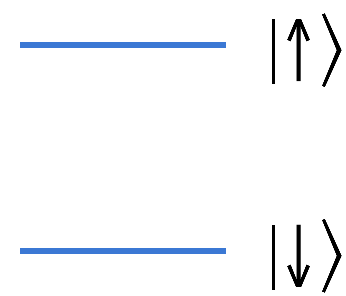
$$B_{\text{eff}} = B_{\perp}\cos(\omega t)$$



$$U = \mu \cdot B_{\text{ext}}$$

Bloch Equations

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$



$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

Time varying Axion B_{eff} drives spin precession
→ produces transverse magnetization

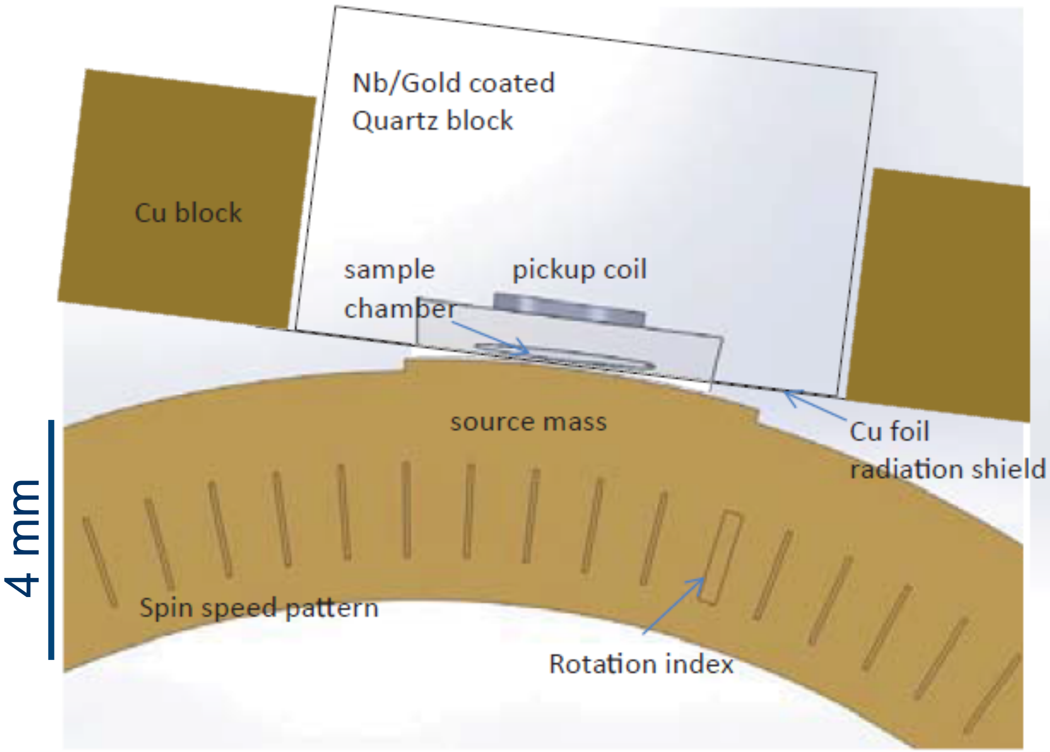
Amplitude is resonantly enhanced by Q factor ~ ωT_2.

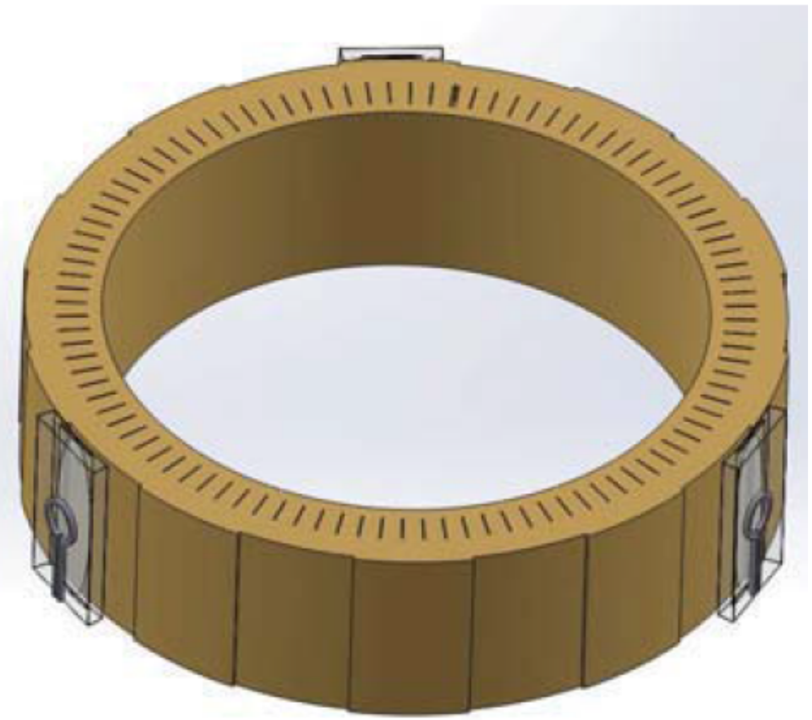
Can be detected with a SQUID

Experimental parameters

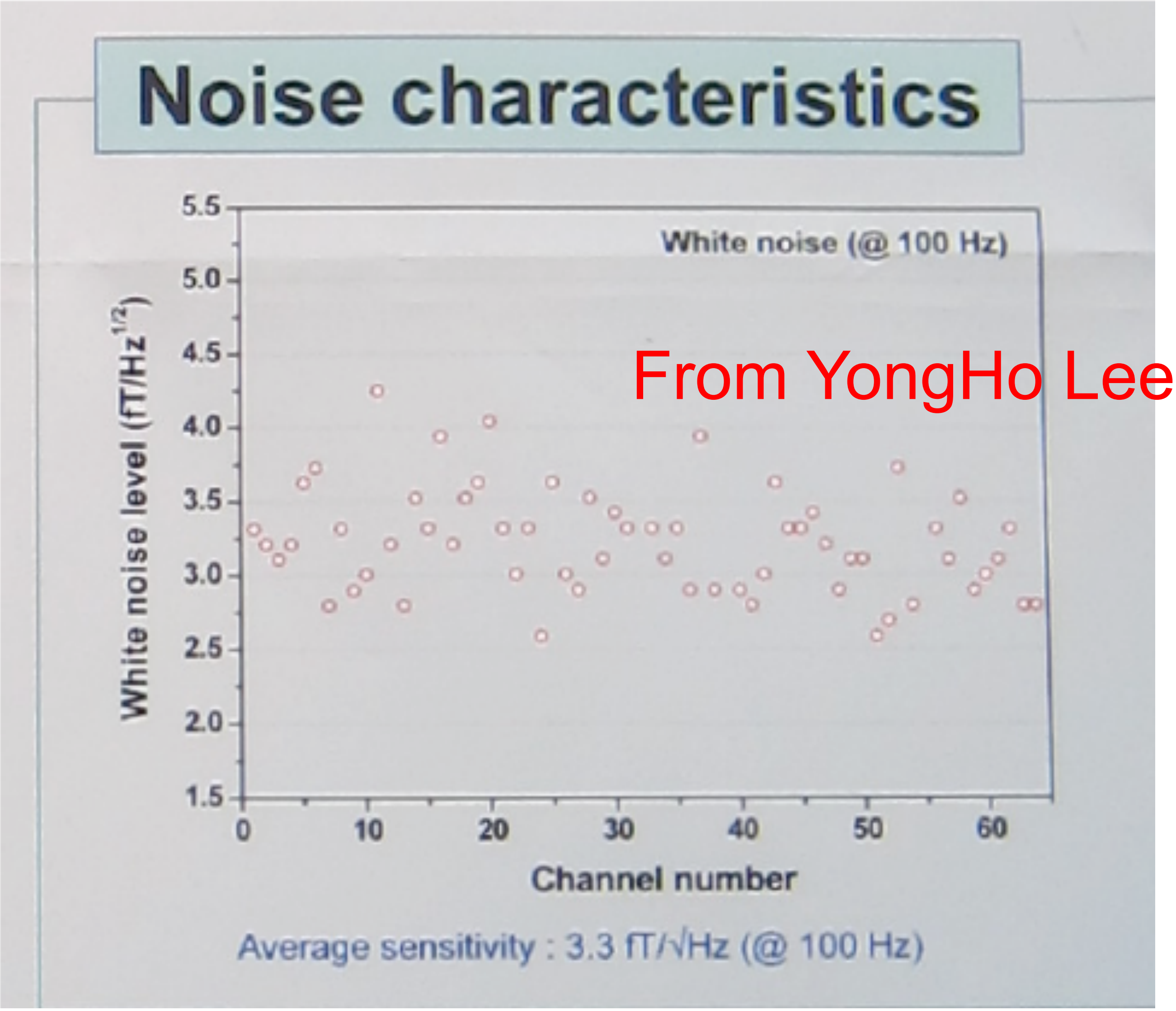
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 μm volume
Separation 200 μm
Tungsten source mass (high nucleon density)

A. Geraci



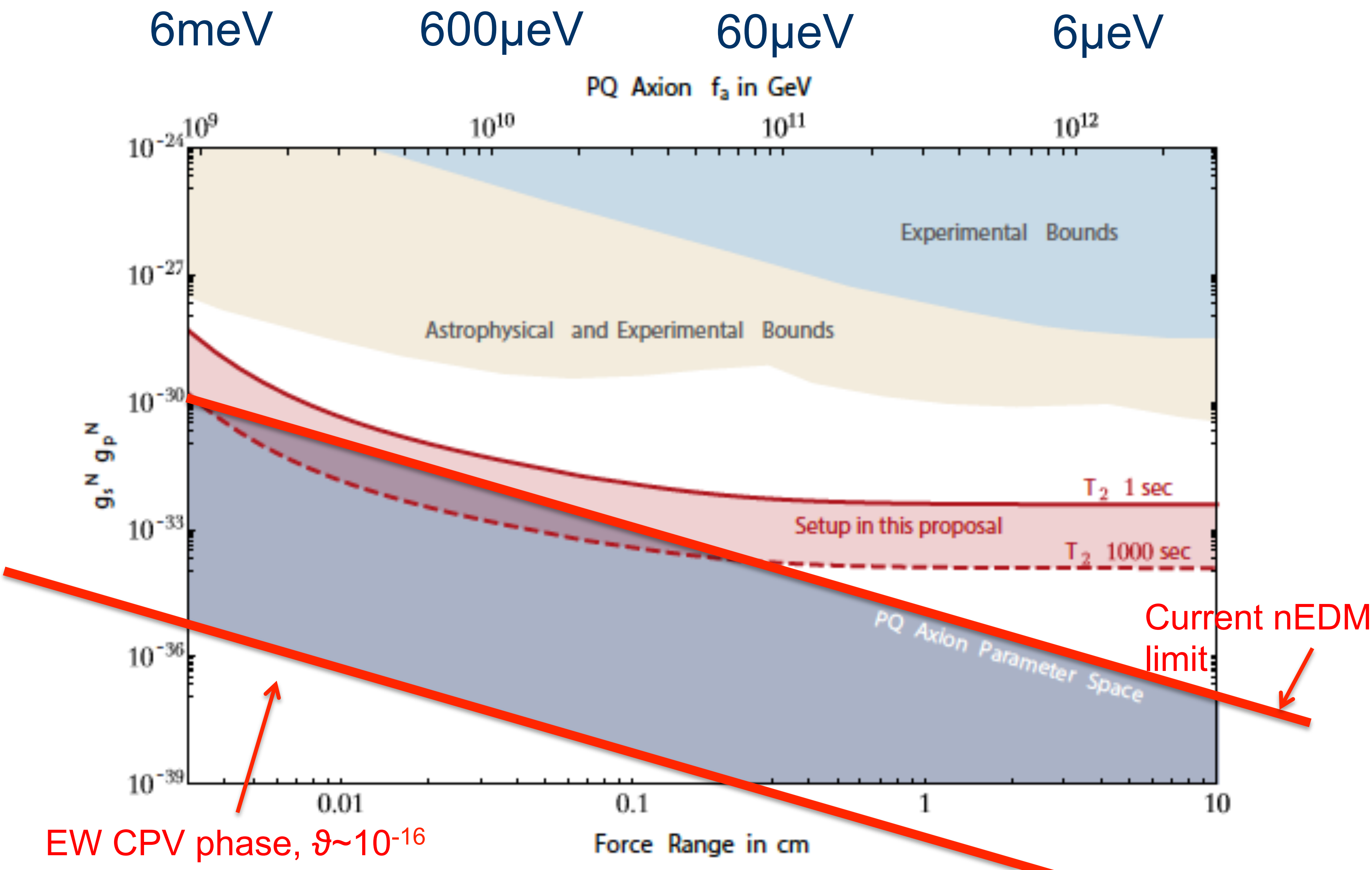


Total noise of (65) commercially available SQUID gradiometers at KRISS

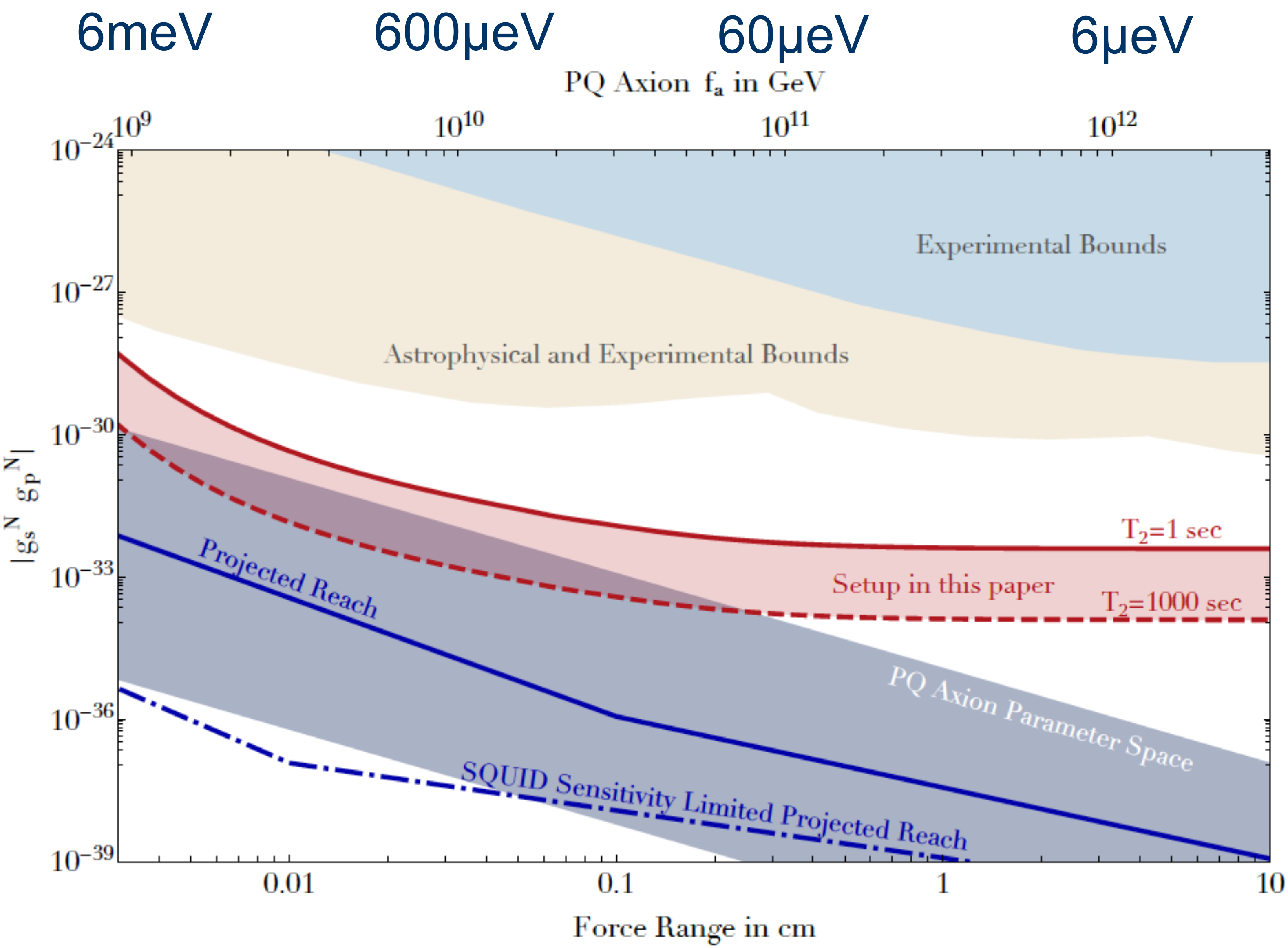


From YongHo Lee's group

Axion mediated long range forces



Axion mediated long range forces

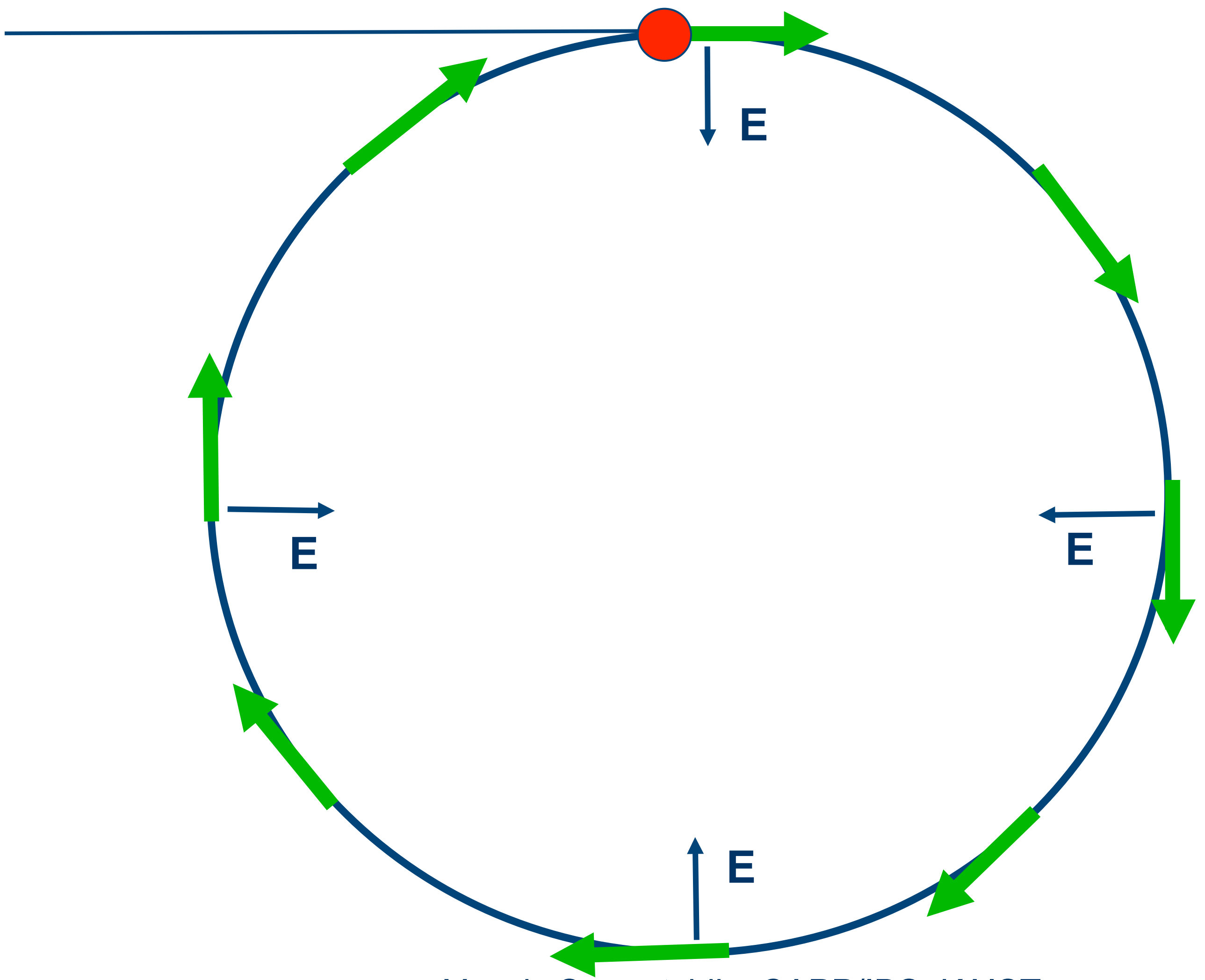


The Storage Ring Proton EDM experiment at 10^{-29} *e*•cm

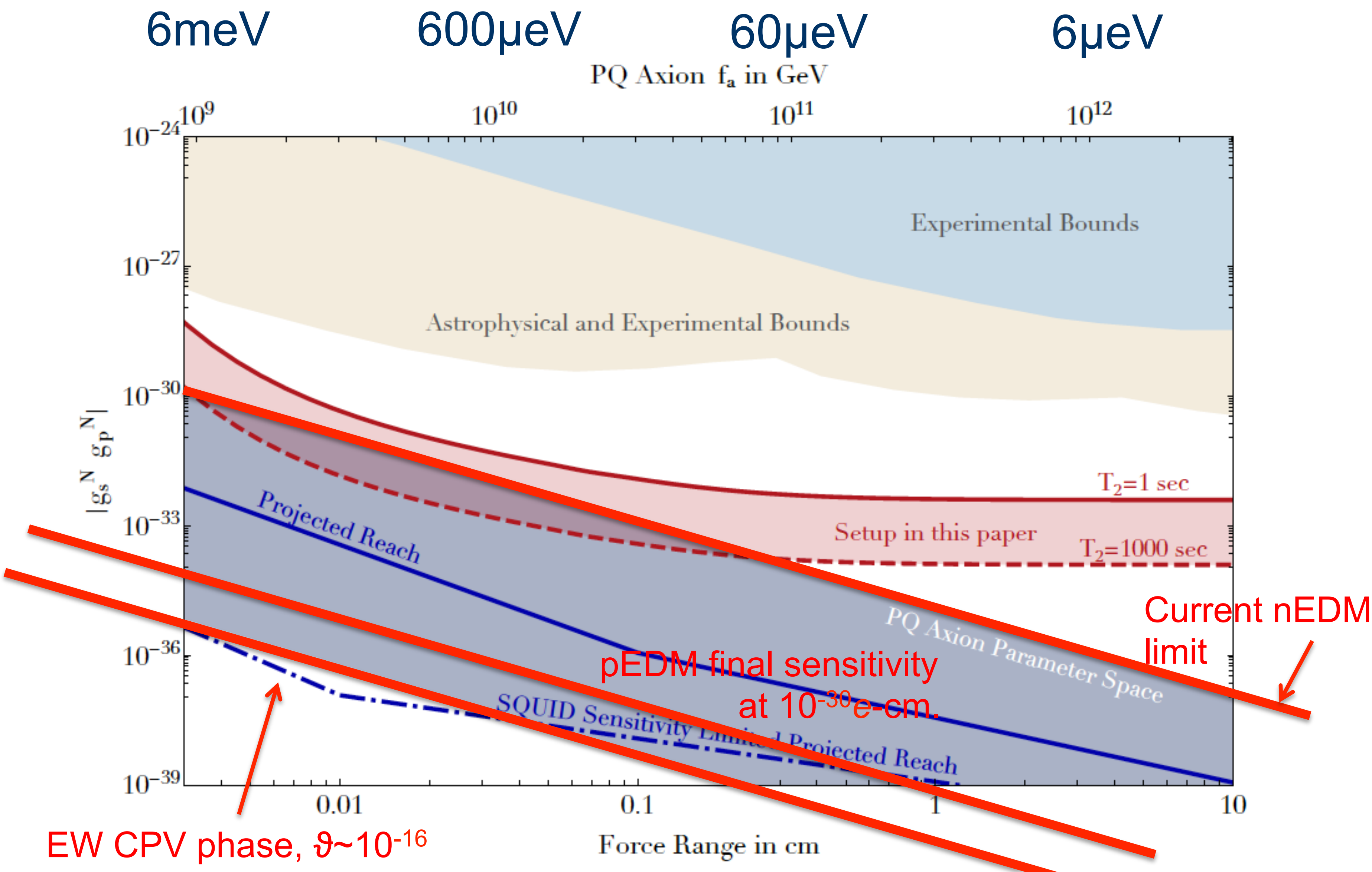
Proton EDM

- We are in systems development phase for 10^{-29} *e*•cm.
- Projected future sensitivity: $<10^{-30}$ *e*•cm
- Improvement on ϑ by more than four orders of magnitude

Storage ring proton EDM method: A revolution in statistics.



Axion mediated long range forces



Summary

- Major R&D effort on axion dark matter:
- Higher B-field: 25 T and then 35 T
- Higher Q-value with B-field present
- Toroidal cavity geometry: Volume ~10, collaboration opportunities

- Detect axions in the 1-100μeV even at 10% DM
- Monopole-dipole forces sensitive to large range of axion masses well into meV. No dark-matter needed.
- Proton EDM at 10^{-29}-10^{-30} $e \cdot$cm, ~4 orders in ϑ.

Extra slides