Quantum Connections Session 5:

Axions in Stockholm – Reloaded

26 – 30 November 2018
AlbaNova University Center / Nordita
Stockholm, Sweden

A comprehensive approach to axions

Yannis K. Semertzidis, IBS/CAPP & KAIST

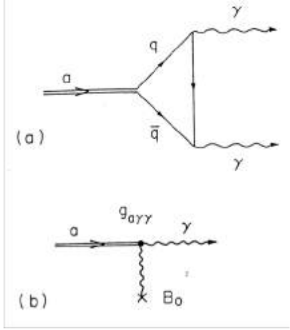
- The technology is here to make decisive axion experiments
- Superconducting devices make the difference!
- HTS is built for axions!
- CAPP is currently taking data with conventional SC, getting ready for our HTS/LTS magnets

IBS/CAPP-Physics approach

Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)

- Cosmic Frontier (Dark Matter axions): Improve in all possible fronts: B-field, Volume, Resonator Quality factor, Physical and Electronic noise.
- Storage ring proton EDM (most sensitive hadronic EDM experiment). Improve theta_QCD sensitivity by three to four orders of magnitude!
- Together with long-range monopole-dipole (axion mediated) forces probe axion Physics!

Axion Couplings



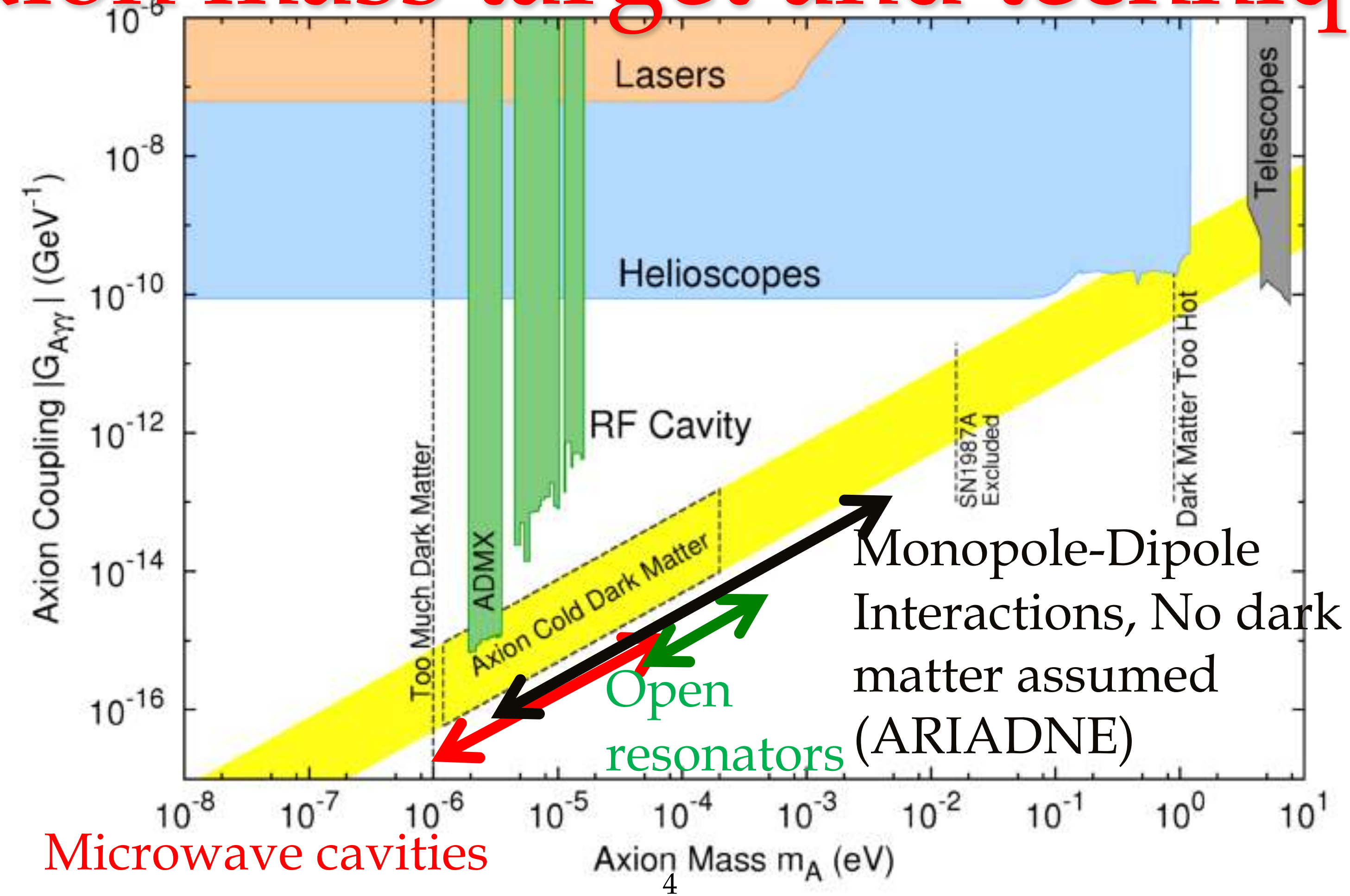
- Gauge fields:
    - Electromagnetic fields $L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$
    -
    - Gluon Fields (Oscillating EDM,…)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

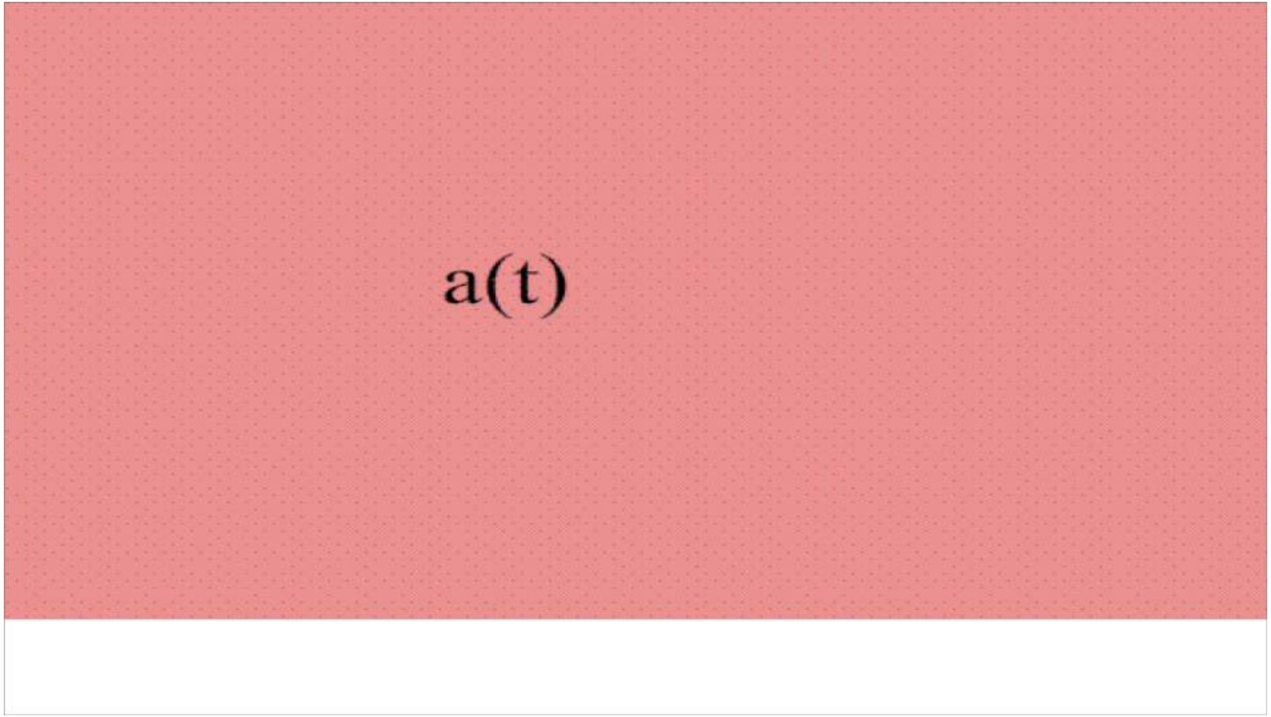
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Axion mass target and technique



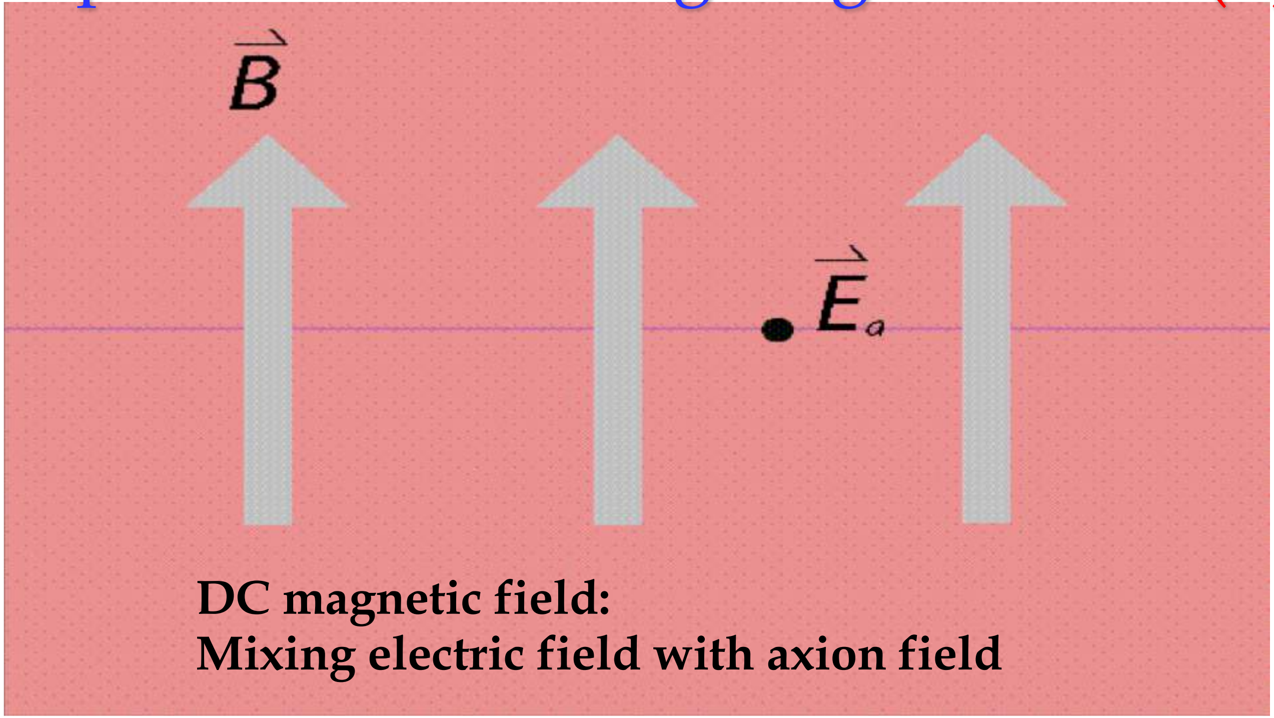
Measure nothing but frequency!

Axion dark matter: Imprint on the vacuum since soon after the Big-Bang!



Animation by Kristian Themann

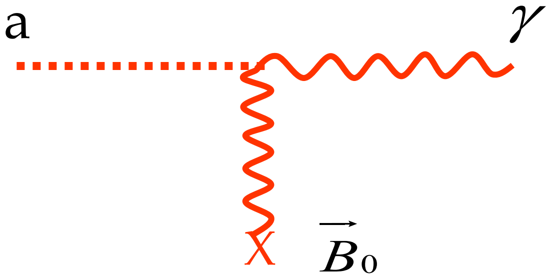
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



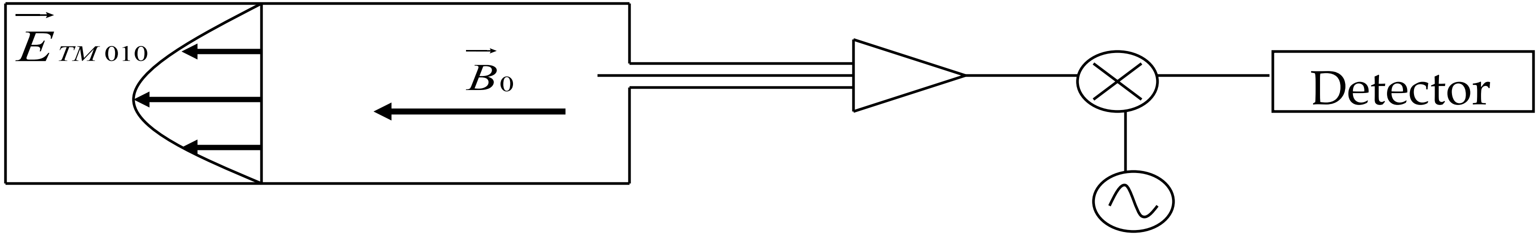
Animation by Kristian Themann

J. Hong, J.E. Kim, S. Nam, YkS
hep-ph: 1403.1576

P. Sikivie's method: Axions convert into microwave photons in the presence of a DC magnetic field (Primakov effect)



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



Need to tune the cavity over a vast frequency range

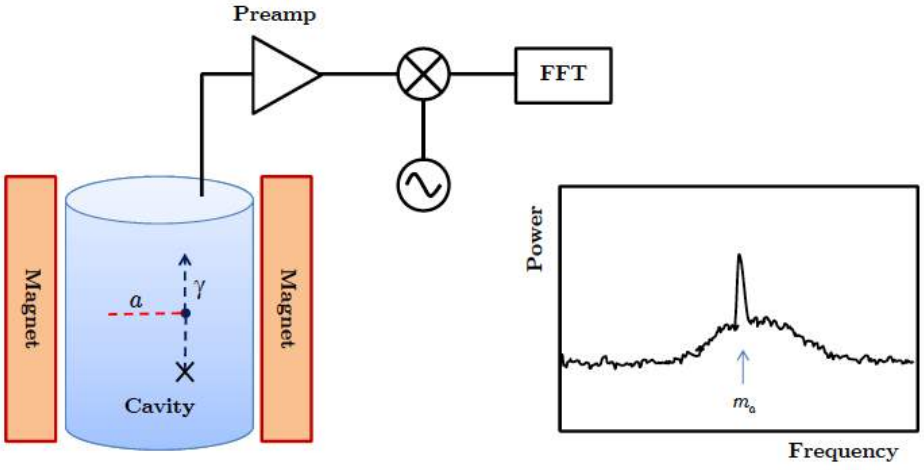


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

$$a \rightarrow \gamma$$

The conversion power on resonance

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V\, B_0^{\,2}\, \rho_a\, C\, m_a^{\,-1}\, Q_L$$

$$= \ 2\cdot 10^{-22}\ \text{Watt} \left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2\left(\frac{C}{0.4}\right)$$

$$\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{5\cdot 10^{-25}\ \text{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\ \text{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

The axion to photon conversion power is very small.

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

Scanning rate:

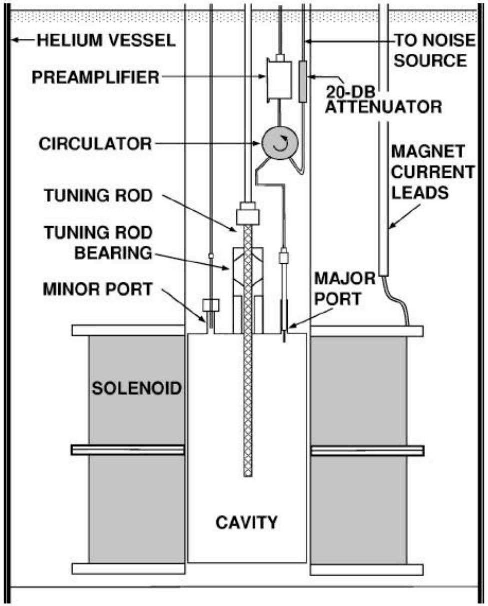
$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^4\left(\frac{5\ \mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \mathrm{K}}{T}\right)^2$$

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

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

The first-generation axion-dark-matter experiment
Rochester Brookhaven Fermilab, at BNL – 1980's

W. Wuensch *et al.*, Phys. Rev. D40 (1989) 3153



First PhD Thesis
Joe Rogers
(1957-2004)

RBF axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Support from BNL
- Questions often asked: existence of DM and axions!

Axion dark detection mechanism

- Sikivie invented a method to detect the "invisible" axions utilizing the inverse Primakoff effect

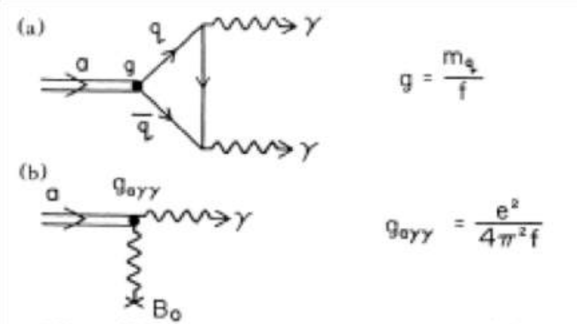


FIG. 1. (a) The coupling of axions to two photons. (b) The Primakoff effect.

$$R_{a\rightarrow\gamma}=(\epsilon_0 c^2/\hbar^2)g_{a\gamma\gamma}^2\omega^{-1}QB_0^2G_j^2.$$

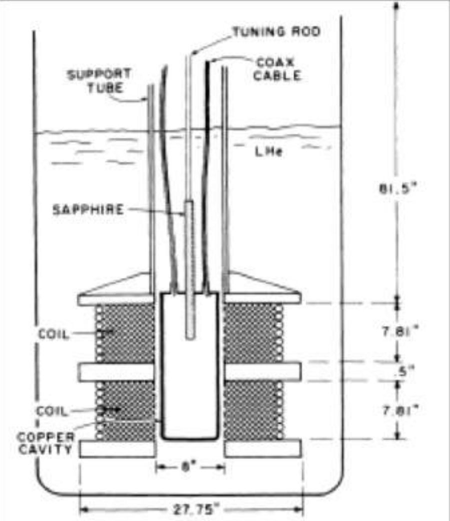
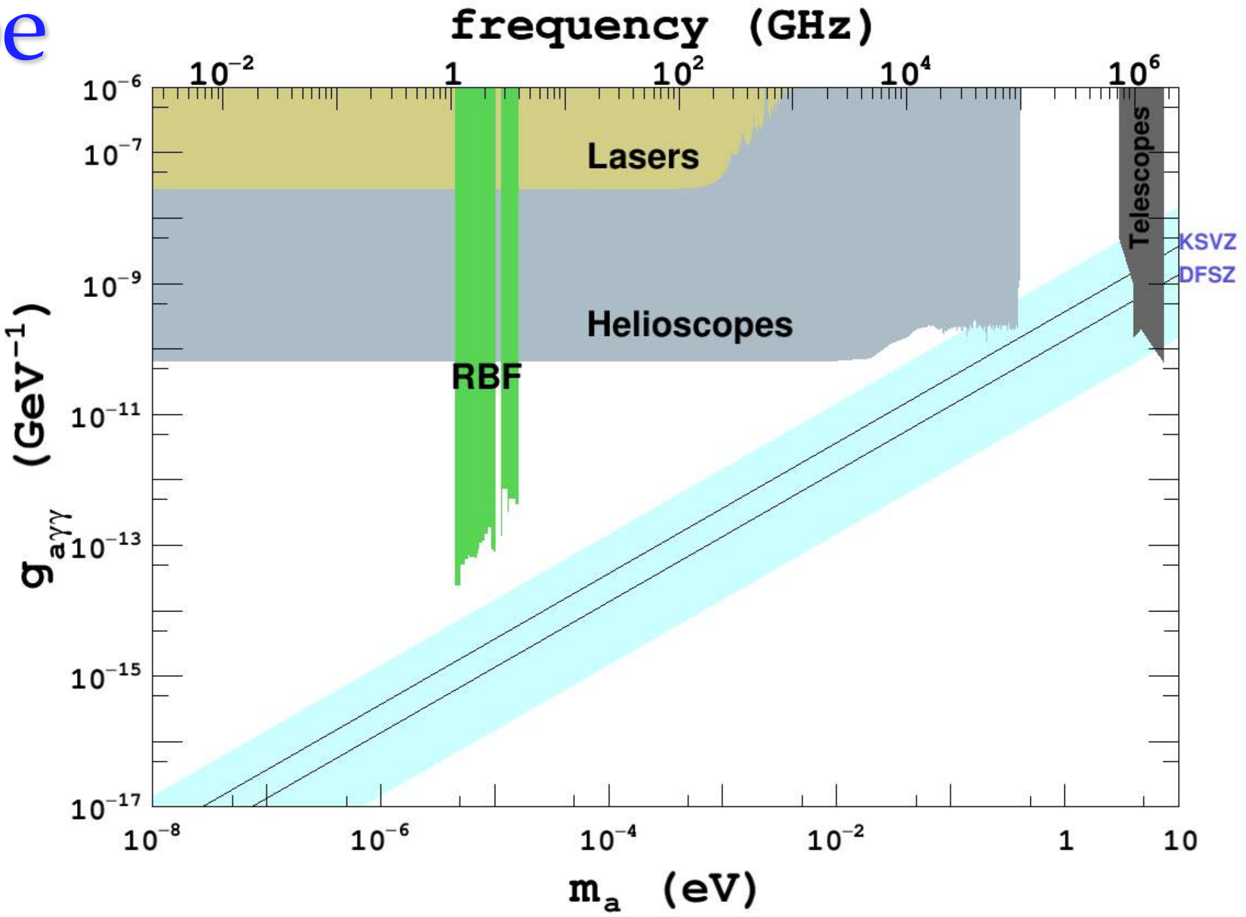


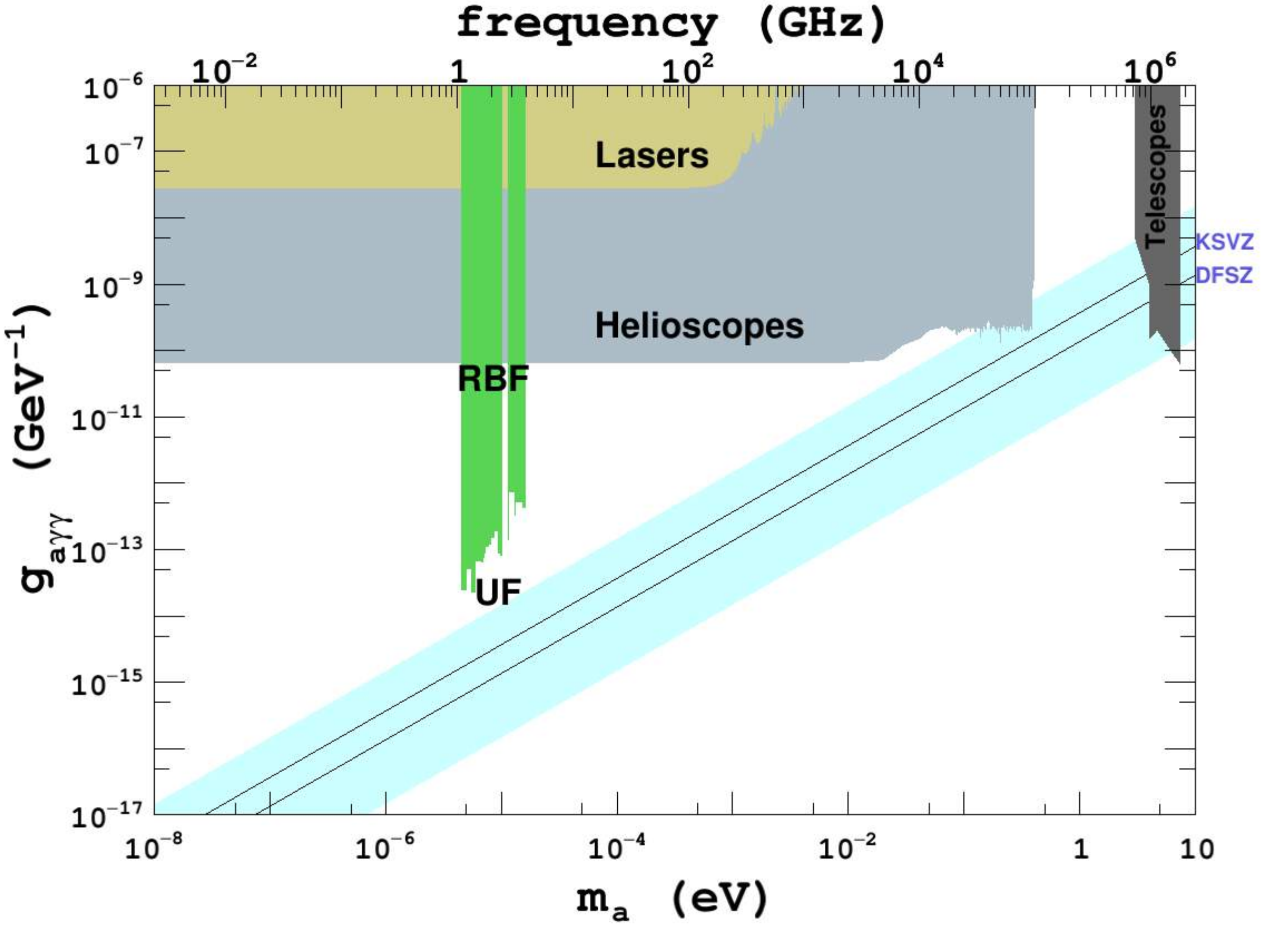
FIG. 2. Schematic diagram of the apparatus.

First haloscope limits: Rochester, Brookhaven, Fermilab



First haloscope limits:
Rochester,
Brookhaven,
Fermilab.

Then
University of
Florida

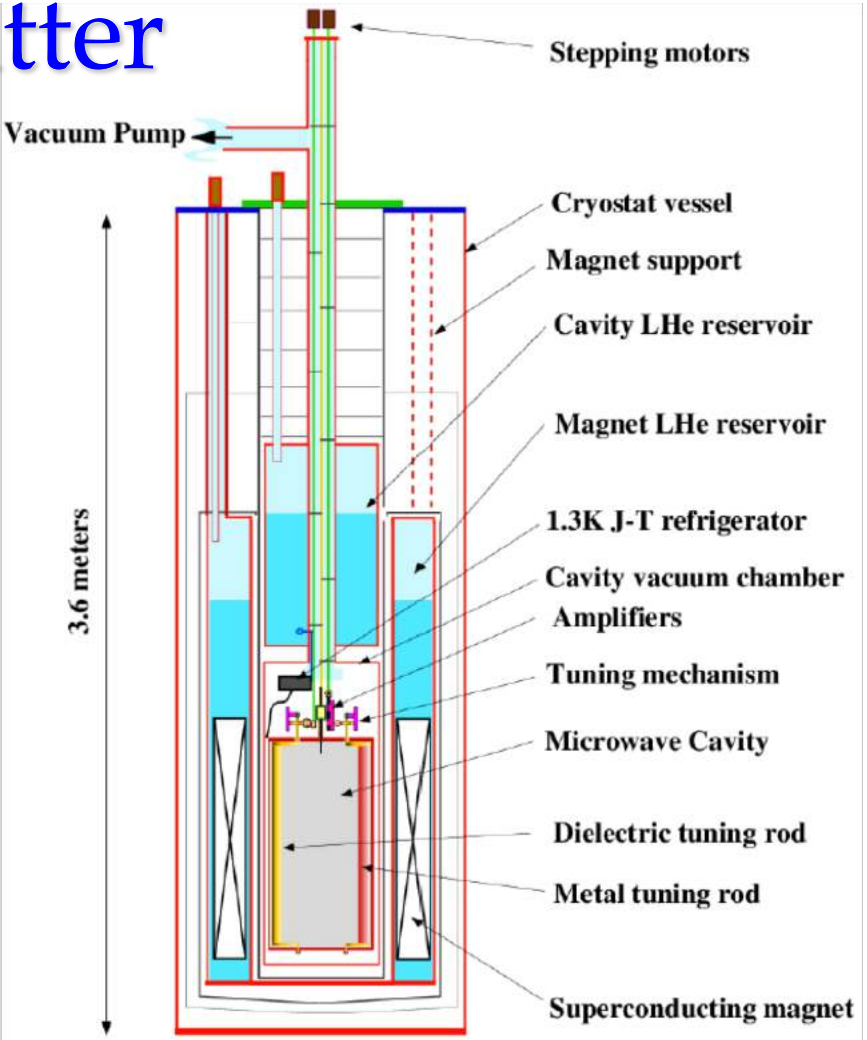


The first axion dark matter revolution

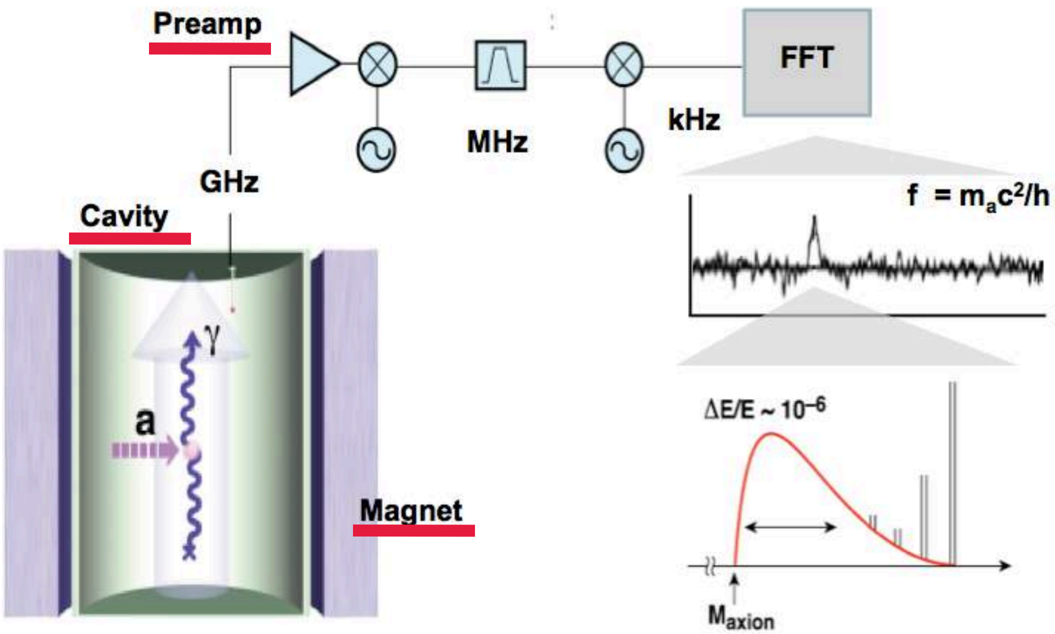
- Dilution refrigerators became ”push-button” operations (<0.1K)
- Quantum-noise limited amplifiers became possible (John Clark, SQUID-amplifiers, f<1GHz, T<1K)

Axion Dark Matter eXperiment

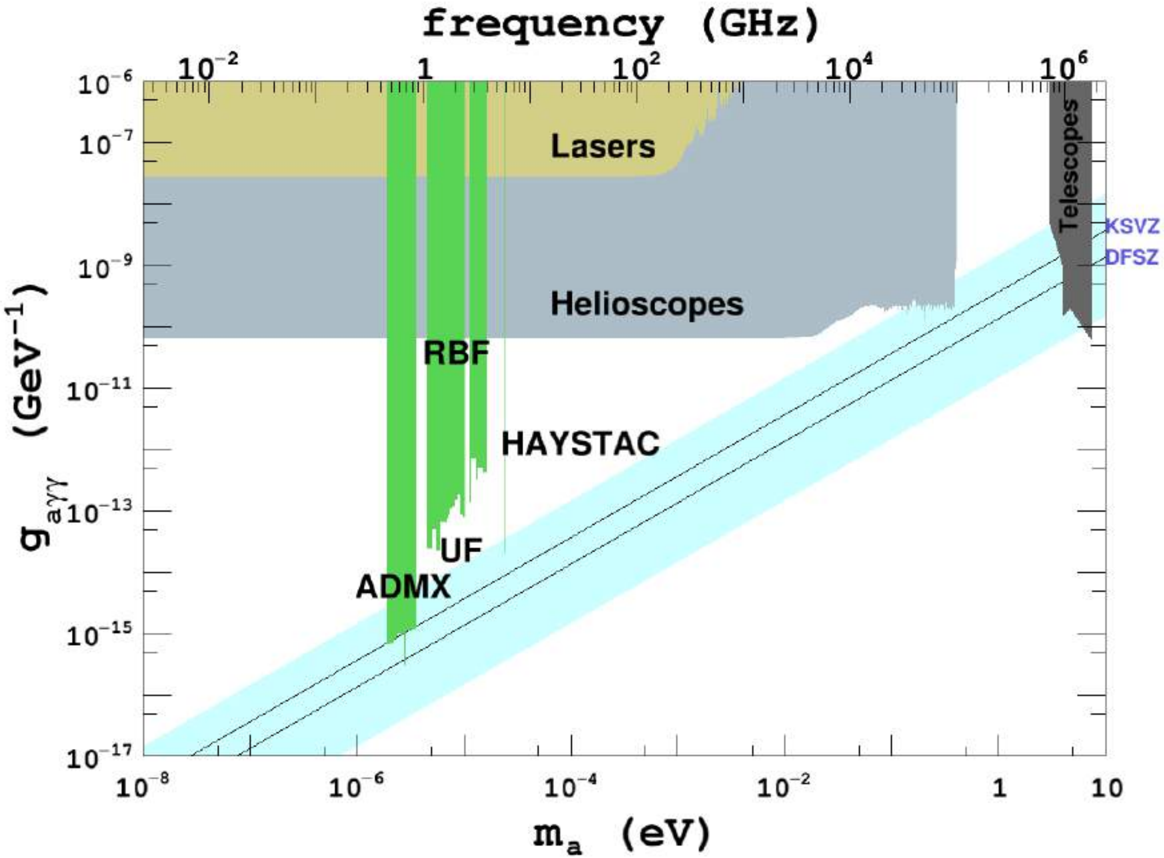
- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity (140*l*)
- Low noise amplifiers
  - From 12K to 1K
  - Currently SQUID and JPA (<1K)



The full ADMX receiver



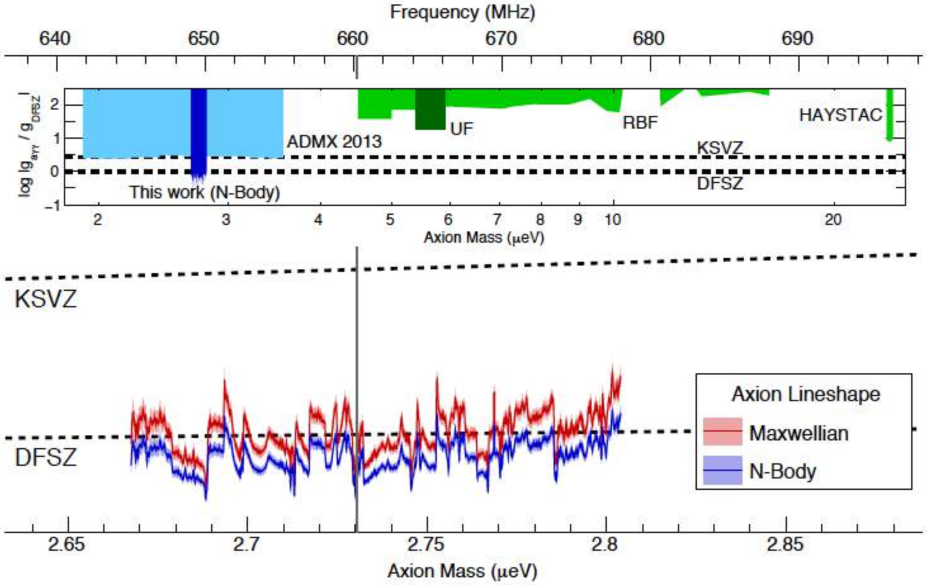
$$P_{sig} \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23} W \qquad s/n = \frac{P_{sig}}{kT_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$



frequency (GHz)
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{-6}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
Lasers
Helioscopes
Telescopes
KSVZ
DFSZ
RBF
HAYSTAC
UF
ADMX
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10
m_a (eV)

ADMX results

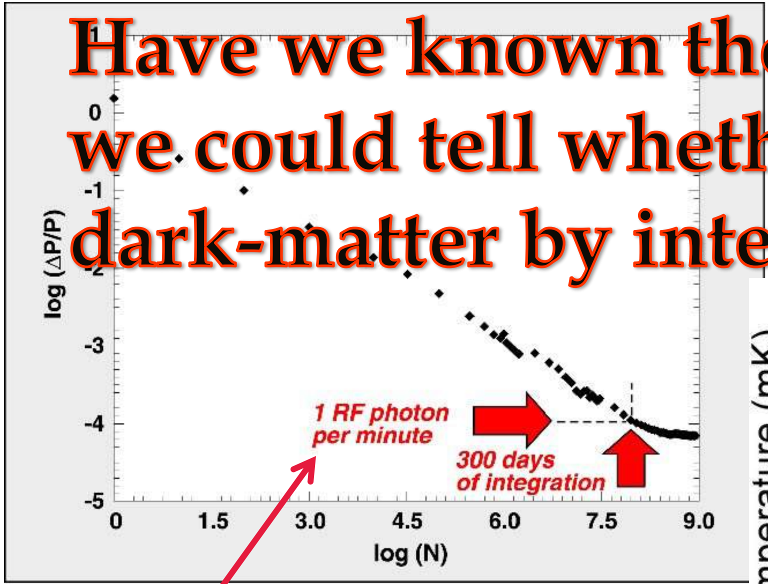
ADMX Exclusion Limits 2017



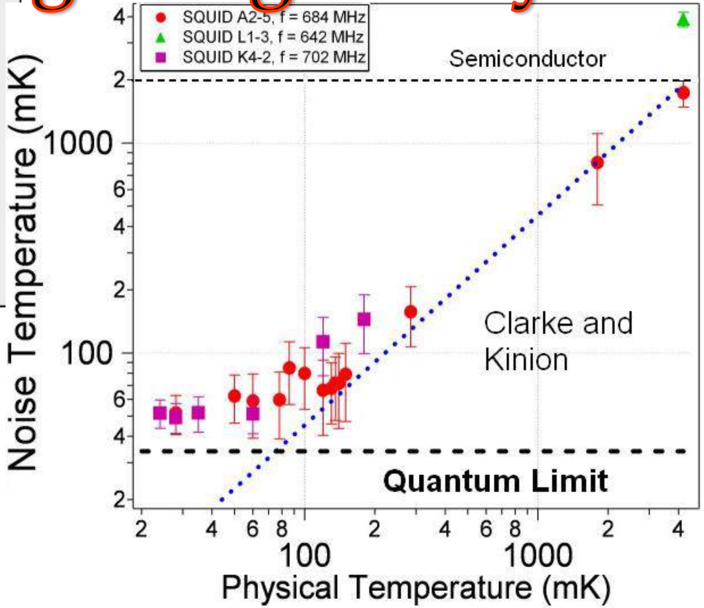
N. Du *et al.* (ADMX Collaboration), "Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment," Phys. Rev. Lett. 120, 151301 (2018).

SQUID Amplifier Noise (ADMX)

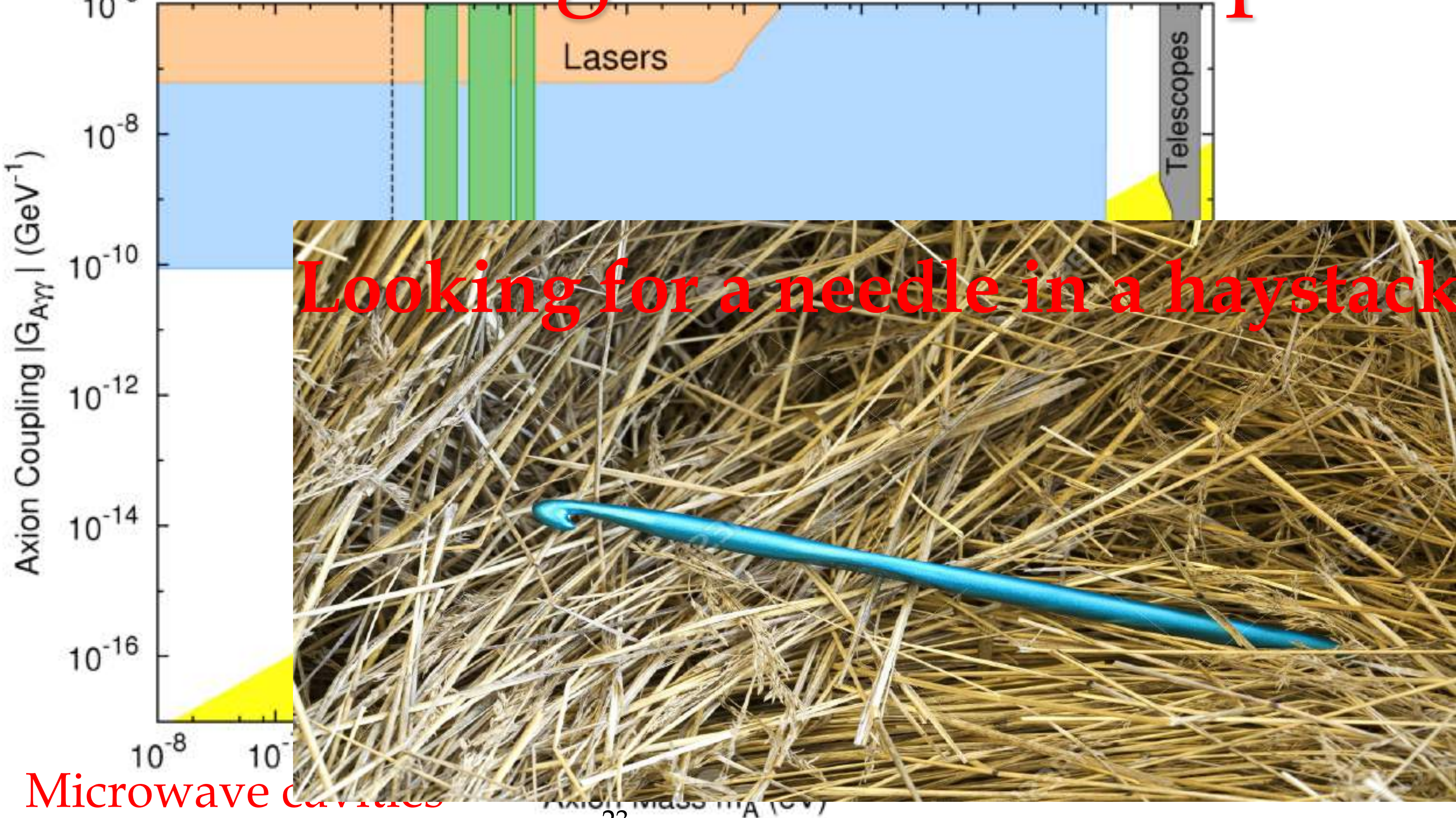
Have we known the axion mass we could tell whether it's the dark-matter by integrating ~1 day!



10^{-26} W



Axion mass target and technique



Microwave cavities

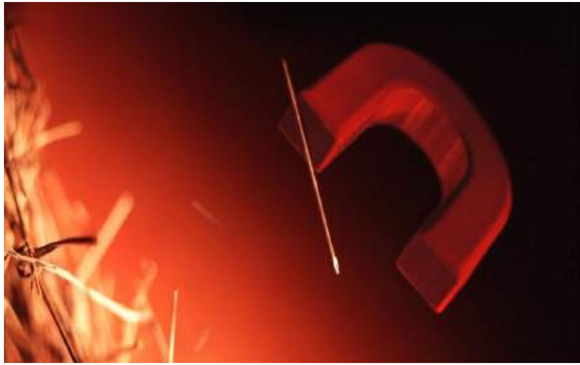
Axion dark matter search

- The axion mass is un ber in a phone book. The wa

- Once it's discovered, o dial in… and talk to it. In the mean-time…speed-up dialing…!

Overall CAPP Plan

- Main effort: Comprehensive Axion Dark Matter experiments.
- Use different type of resonators depending on the resonant frequency.
- Use new powerful magnets,…
- Operate experiments in parallel



CAPP/IBS axion target plan

Scanning rate:

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

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

- 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}

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

CAPP/IBS axion target plan

- Major improvement elements:
  - High field solenoid magnets, B: 9T→25T→35T
  - High volume magnets/cavities, V: 5*l*→50*l*
  - High quality factor of cavity, Q: 10^5→10^6
  - Low noise amplifiers, T_N: 2K→0.25K
  - Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6

Improvement in coupling constant: 70

Major activities

1. Develop lab infra-structure

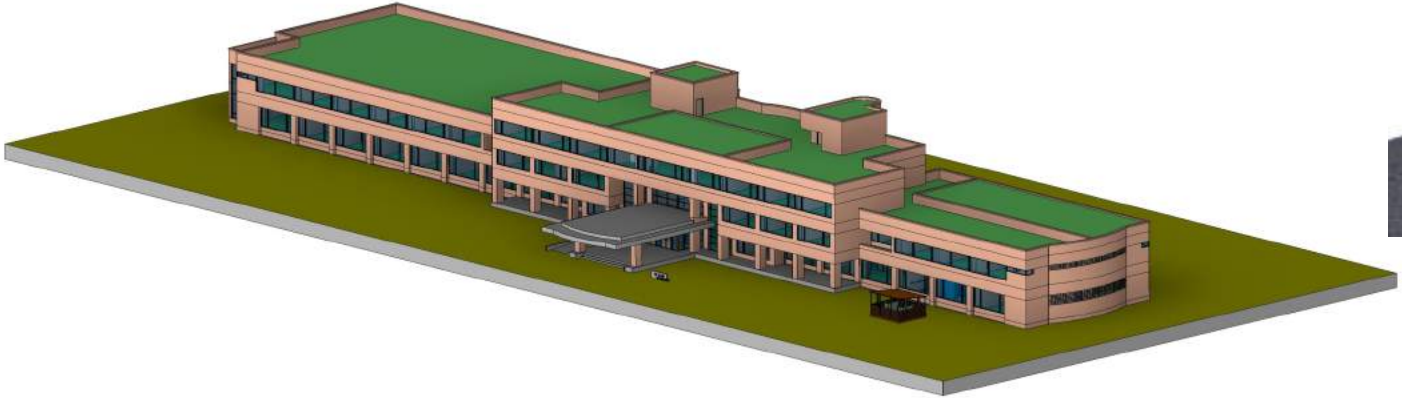
2. Run several axion dark matter experiments (4 – 5 LVP) in Korea, including CAST-CAPP/IBS project at CERN

3. Develop ARIADNE, and GNOME

4. Proton EDM systems development for an exp. @ CERN

-Creation Hall-

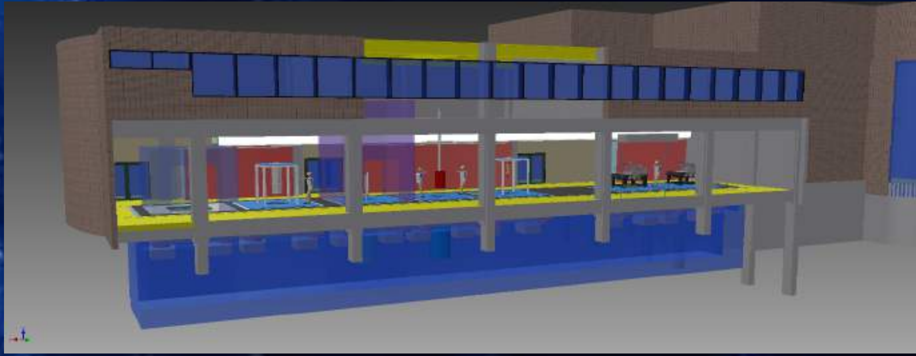
CAPP Research Bldg. at KAIST Munji Campus



Renovation supervision:
DongMin Kim, Engineer

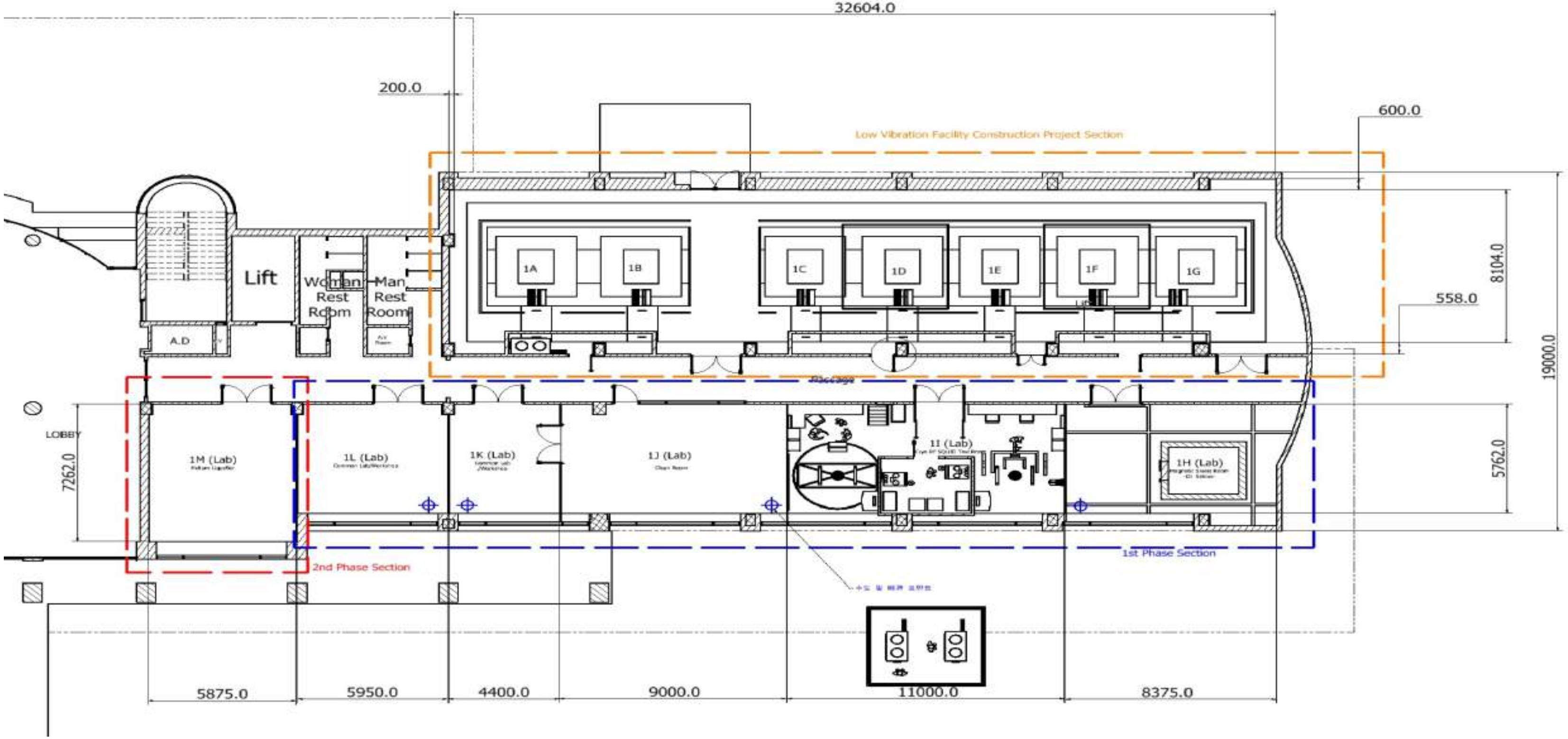
Concluding renovation: end of February 2017.

Axion Dark Matter Research at Munji Campus – IBS CAPP KAIST



-1st Floor Drawing-

Seven, low vibration pits, two with magnetic shielding



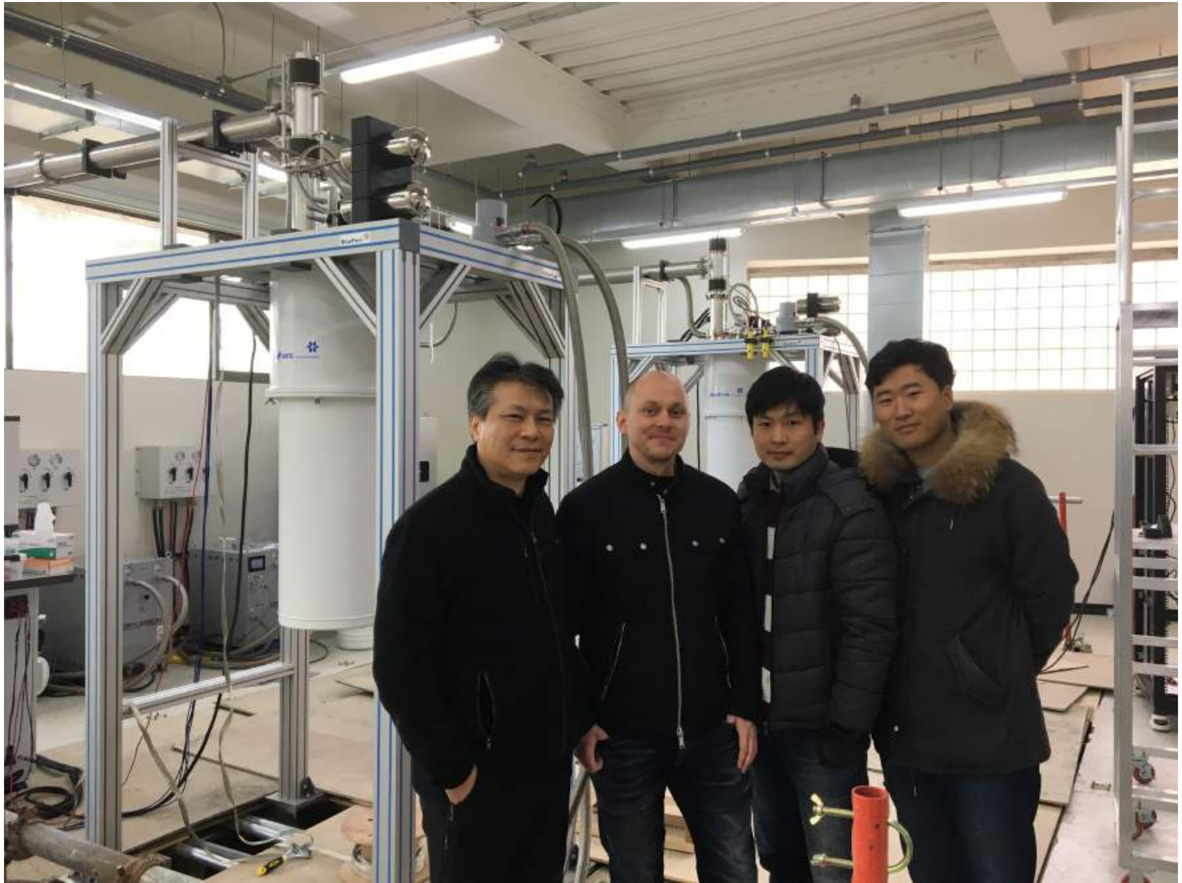
- Low Vibration Site Picture-

- Low Vibration Site Picture-

- Low Vibration Site Picture-

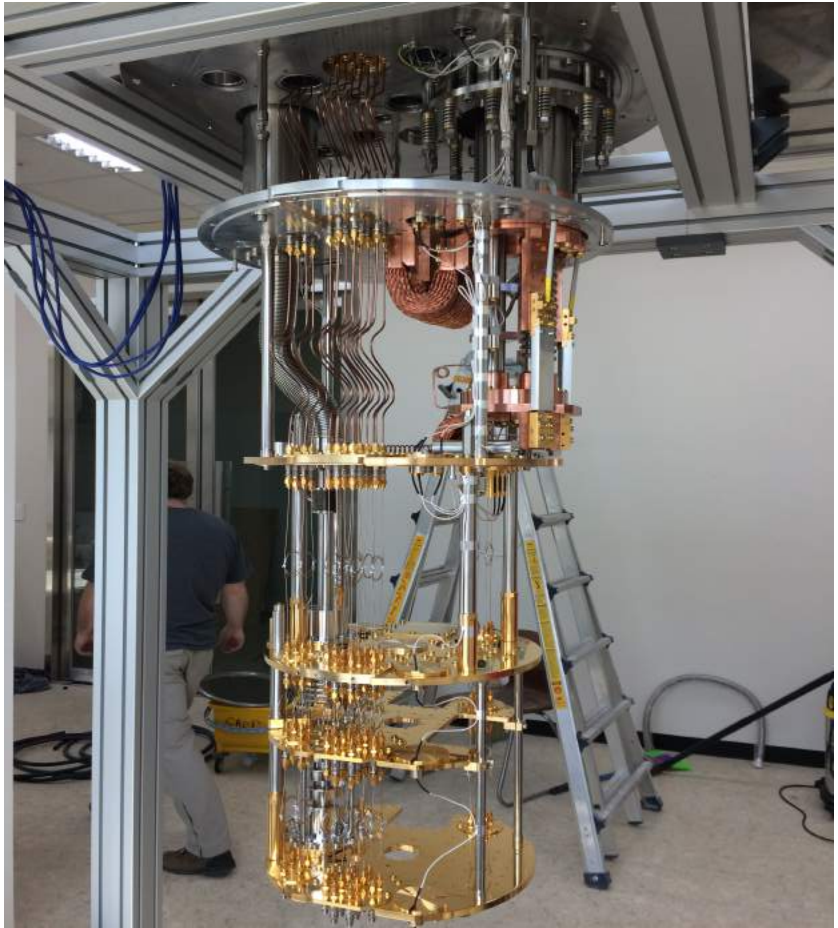
7 Low Vibration Pads (LVP) will be hosting axion related experiments. 5 of them are dedicated to axion dark matter experiments.

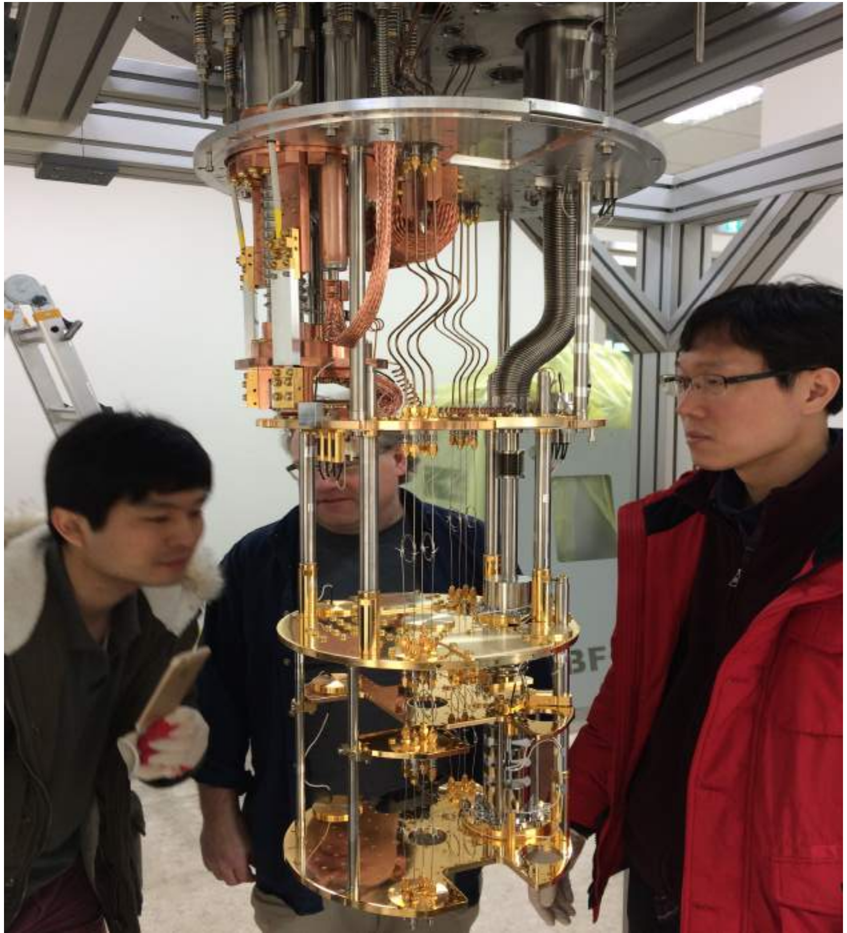
Two Dil. Refr. installed



Two Dil. Refr. installed

DR Installation & Tests





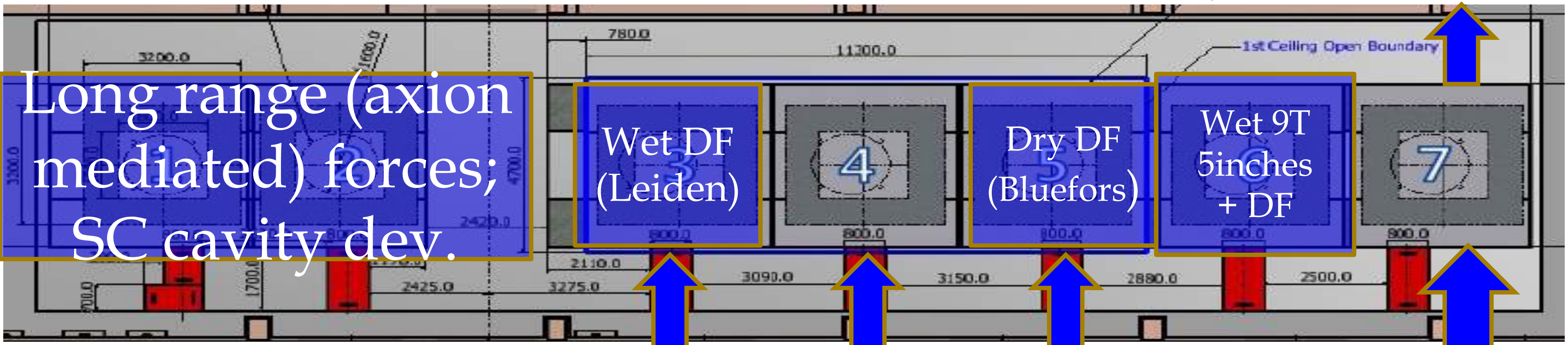
DR Installation & Tests

- In the morning, BF#4 at ~4 K, BF#3 at ~10 K
- Start dilution on BF#4 and reached 7.1 mK
- SC Magnet turned on → reached 8T in 4 hours
- Start dilution on BF#3 and reached around 9 mK
- Ramping down SC Magnet
- Test results (cooling powers) were all satisfactory!!!

Slide: Woohyun Chung

Low Vibration Pad Assignment

take out Dry 8T/155 mm + DF



wide bore magnet

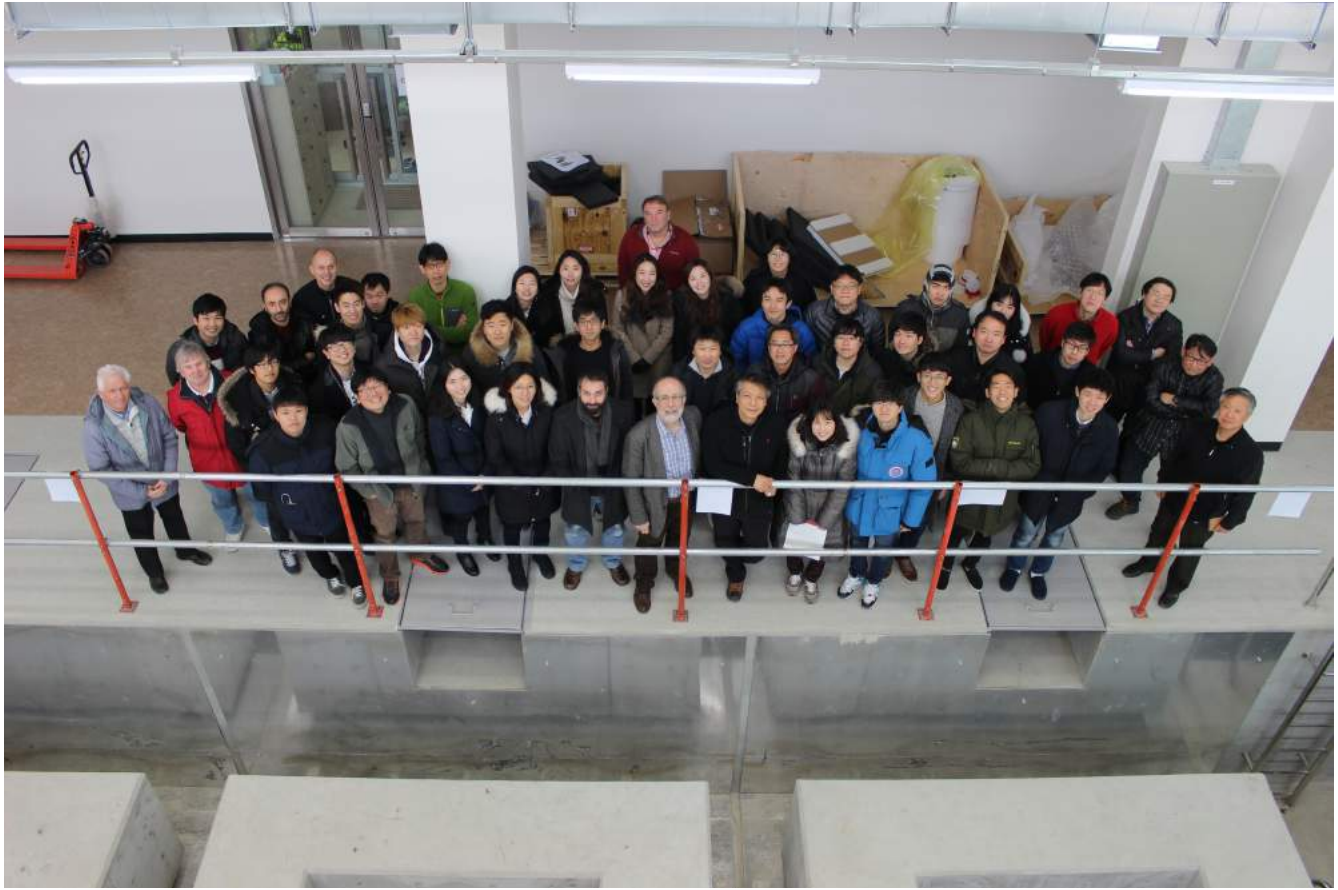
12T magnet
+ new DF.
Add 25T magnet

18T Magnet

small toroidal magnet (1m diameter) + new DF

Slide: ByeongRok Ko

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



The experimental hall

Several high power dilution refrigerators have been procured, installed and are running at mK temps.

CAPP Experimental Hall (LVP)

CAPP experimental hall, top view

CULTASK Refrigerators and Magnets

Refrigerators

Vendor	Model	T_B (mK)	Cooling power	Installation
BlueFors (BF3)	LD400	10	18µW@20mK 580µW@100mK	2016
BlueFors (BF4)	LD400	10	18µW@20 580µW@100	2016
Janis	HE3	300	25µW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18µW@20mK 580µW@100K	**2017**
BlueFors (BF6)	LD400	10	18µW@20mK 580µW@100K	2017
Leiden	DRS1000	100	1mW @100mK	2018
Oxford	Kelvinox	<30	400 @120mK	2017

Magnets

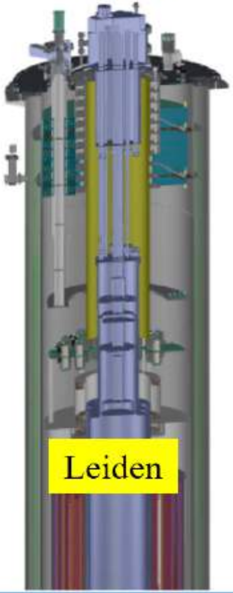
B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	**10**	HTS	BNL/CAPP	2020
12T	**32**	Nb_3Sn	Oxford	2020

18 T HTS magnet

25 T
HTS magnet

Oxford
- kelvinox

Oxford
- Leiden

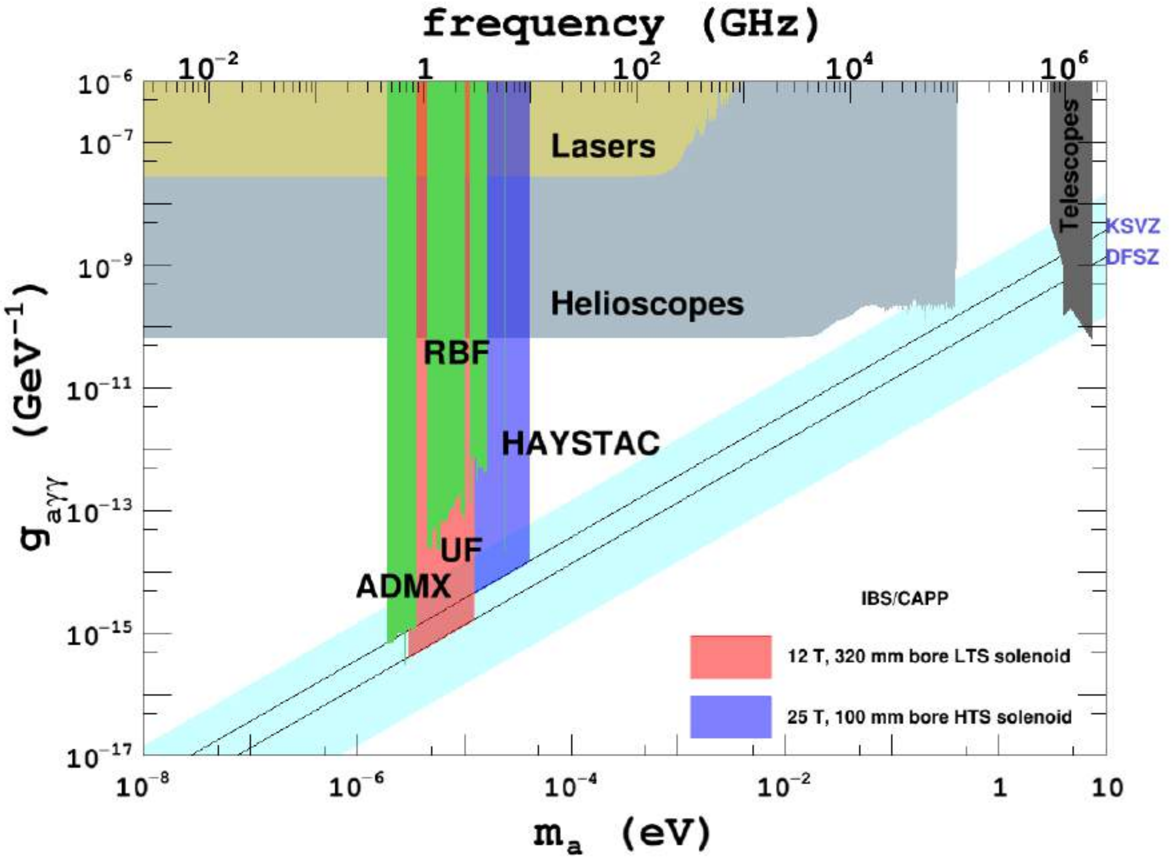


9 T
LTS, Janis

18 T	25 T	9 T	12 T	9 T
70 mm	100 mm	50 mm	320 mm	120 mm
4 K	4 K	30 mK	30 mK	300 mK
Working	2019	Testing	2018	Working

Liquid helium type superconducting magnet system at CAPP

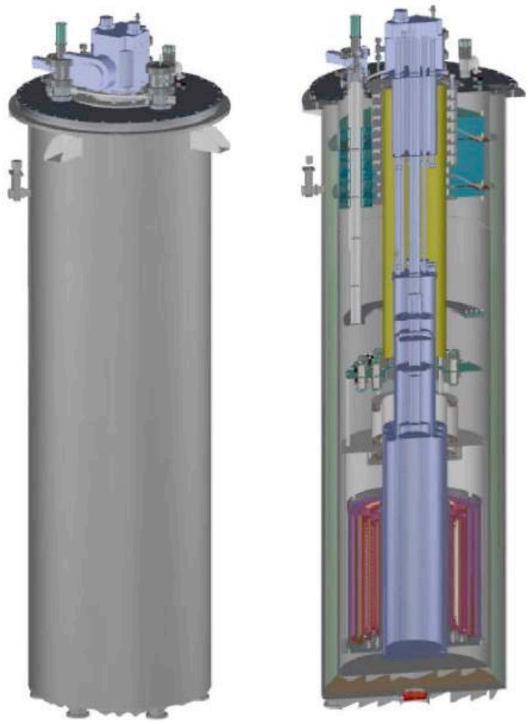
Potential shown based on single cavities (existing technology only)
1st phase: 0.7-10 GHz, 2nd phase: 10-20 GHz

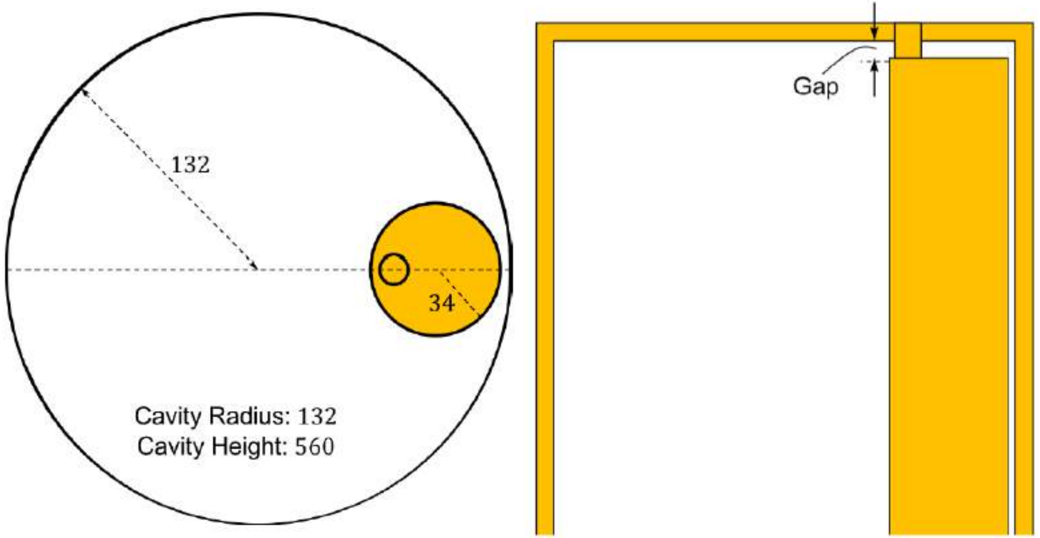


CAPP's base plan

- Delivery of 25T/10cm and 12T/32cm magnets in 2019/2020.

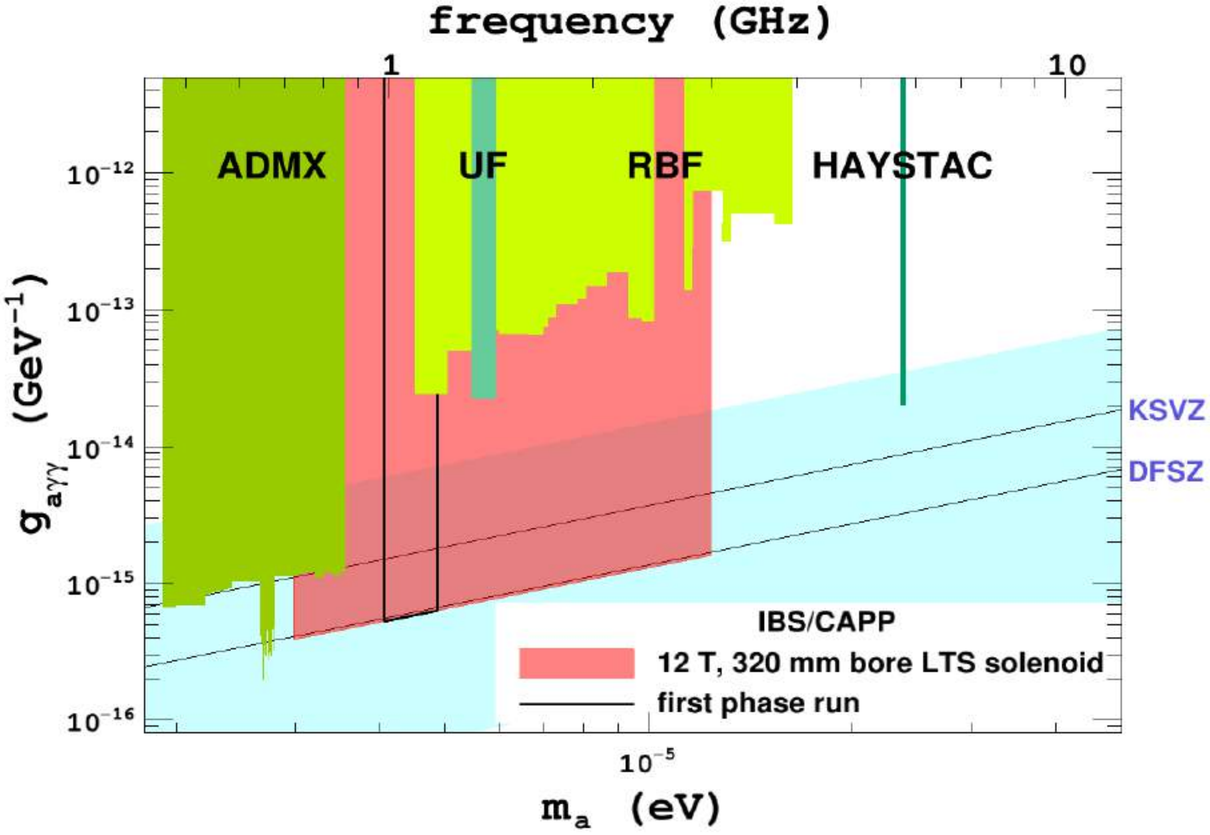
- In the meantime, we are getting ready for it:
  - Quantum noise limited SQUID, JPA-amplifiers
  - Cryo-expertise, reach lowest physical temperature (down to <50mK)
  - Demonstrate efficient high-frequency, high-volume operation
  - Efficient DAQ
  - Prepare systems for large magnets



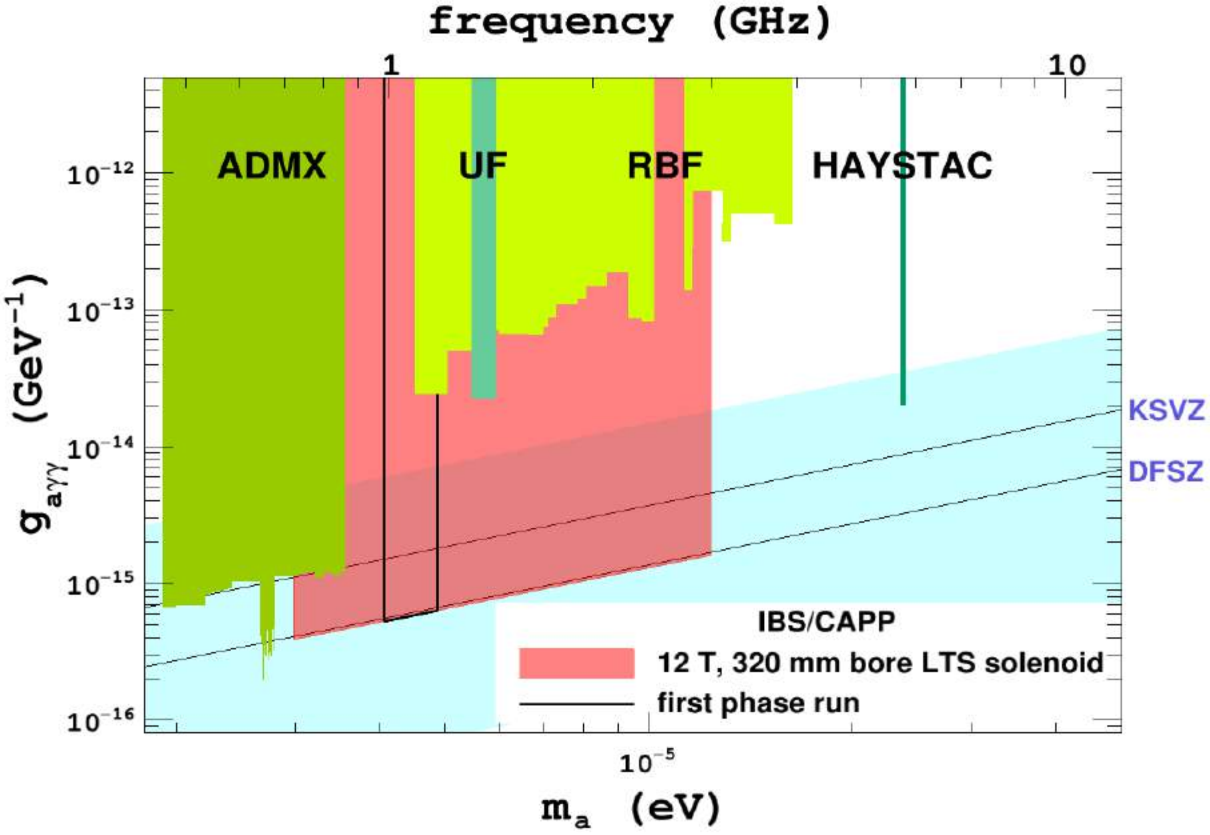


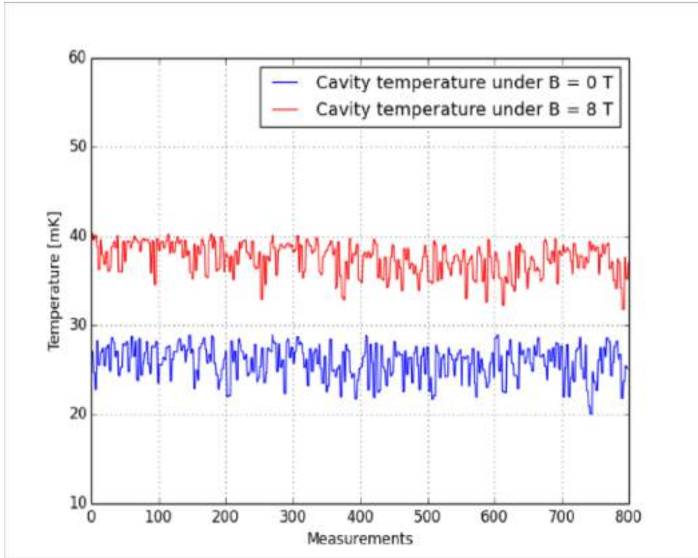
Left: The cryostat, and dilution refrigerator for the LTS, 12T/32cm Nb_3Sn magnet from Oxford. Right: Microwave cavity dimensions in mm.

Potential shown based on single cavities (existing technology only)
1st phase: 0.7-10 GHz, 2nd phase: 10-20 GHz



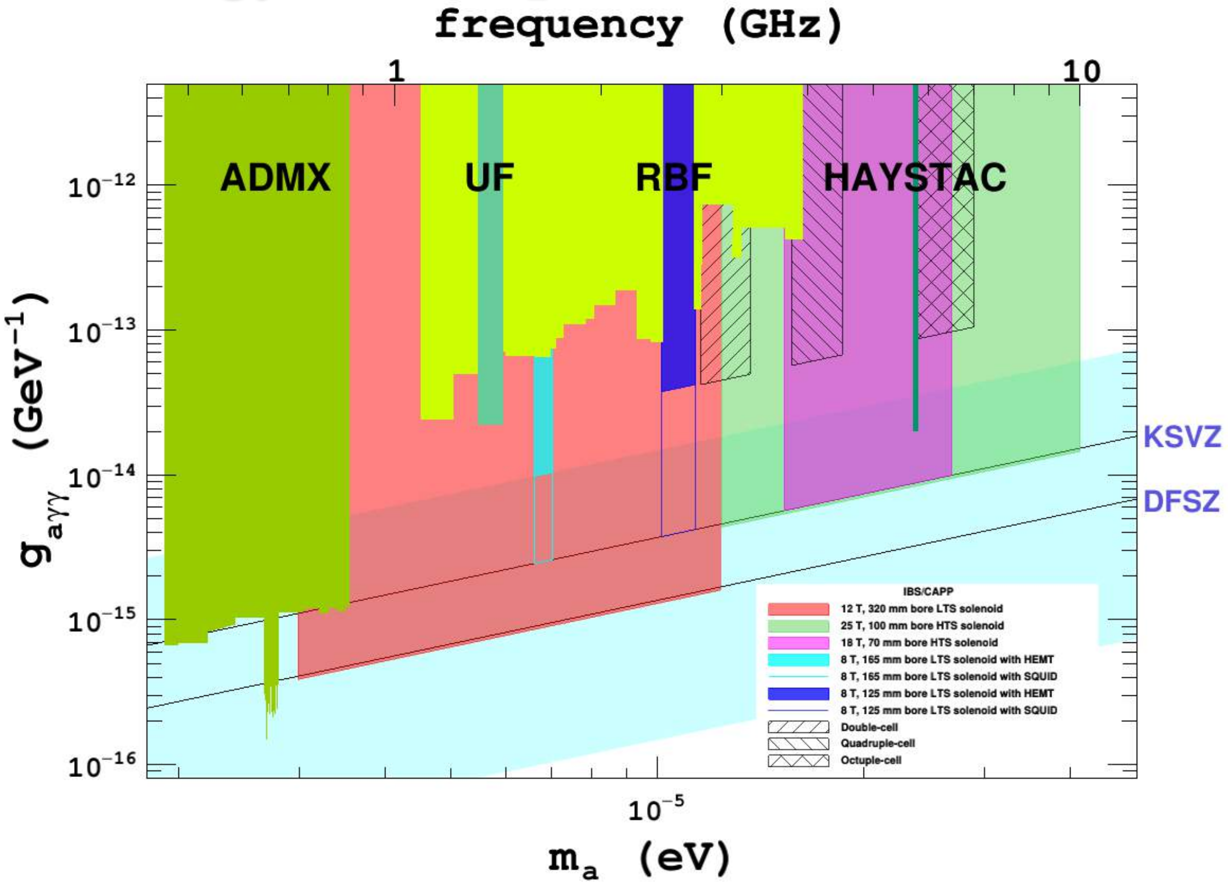
Potential shown based on single cavities (existing technology only)
1st phase: 0.7-10 GHz, 2nd phase: 10-20 GHz



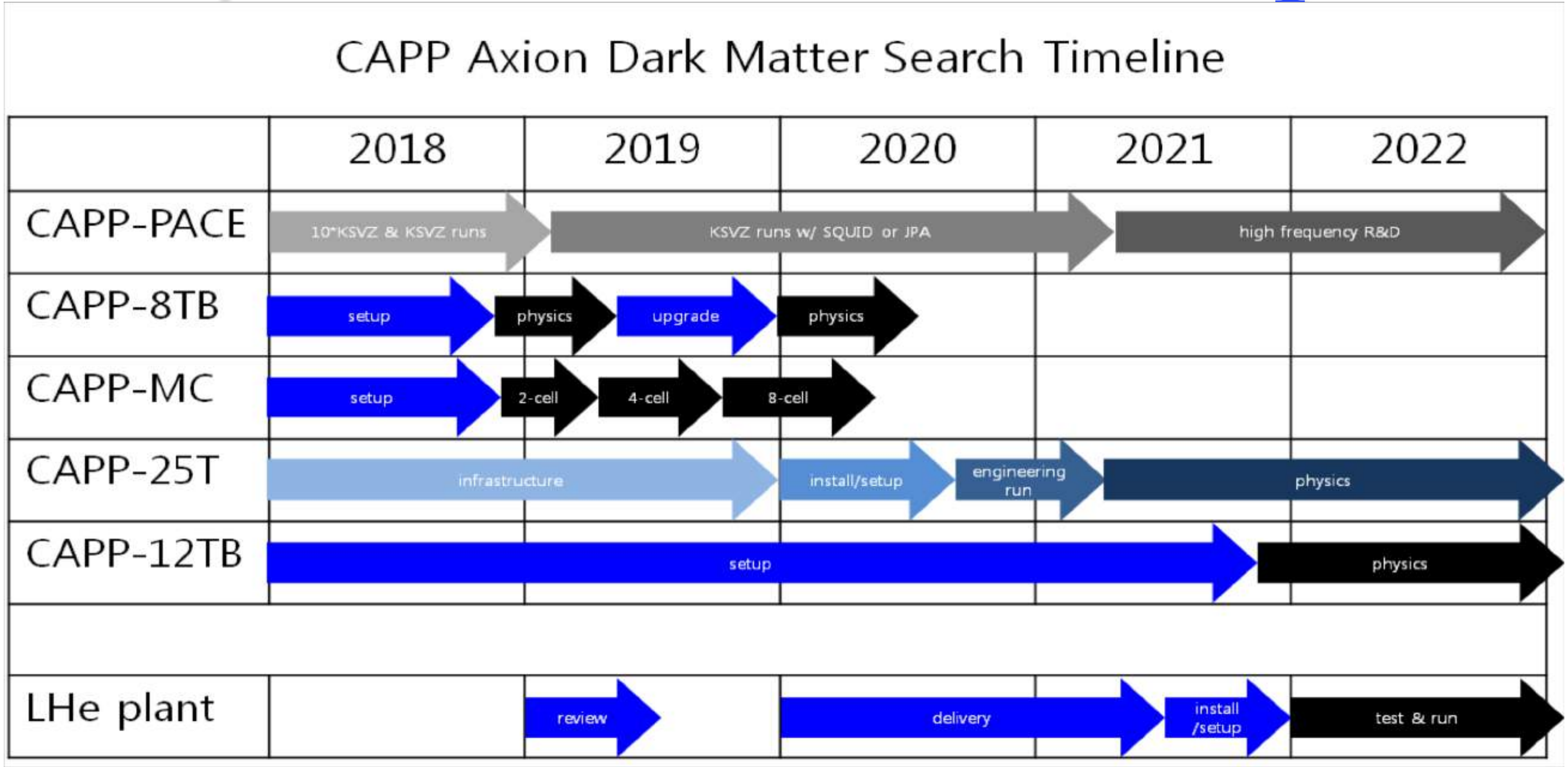


Measurements of cavity temperature with (red) and without (blue) an external magnetic field.

Potential shown based on single cavities: <10 GHz
Technology developed at CAPP for 10-20 GHz



IBS/CAPP Timeline, 1st phase



CAPP's plan

- Establish a facility to take immediate advantage of currently available technology
  - LTS (NbTi, and Nb_3Sn) magnets, and
  - HTS
- Low temperature, high quality resonators (near SC?)
- Quantum-noise limited RF-detectors (SQUIDs, JPAs)
- Single photon RF-detectors (>10GHz). (First appl. of qubits?)

High quality resonators (YBCO tape)

- Work in progress

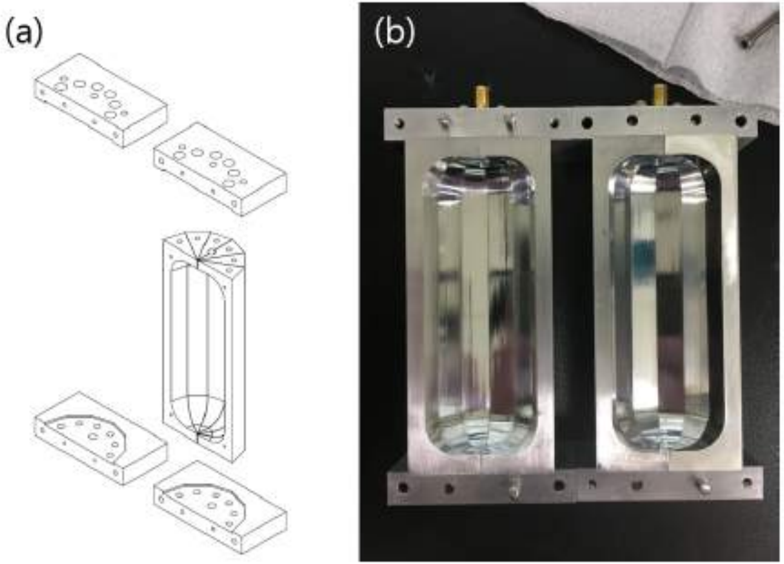


Figure 3: (a) The schematic of the polygon cavity, (b) The picture of the polygon cavity.

	Aluminum	YBCO(1)	$YBCO(4)_1$	$YBCO(4)_2$	$YBCO(4)_3$
Q_0 (4.2 K)	21,300	22,700	28,300	28,400	32,300
R_s ratio (4.2 K)	1	0.260	0.258	0.250	-0.021
Q_0 (0.5 K)	3,000,000	870,000	-	175,400	361,200
R_s ratio (0.5 K)	0.007	0.210	-	0.350	0.162

IBS/CAPP magnet projects

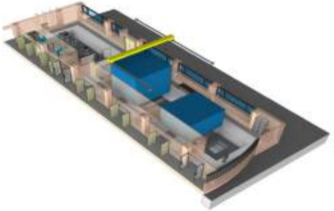
- NI-HTS, 18T, 70mm diam. Delivered Summer 2017 from SuNAM. No Insulation (NI) works!
- NI-HTS, 25T, 100mm diam. (BNL) delivery in 2019/2020.
- Insulated LTS (Nb_3Sn), 12T, 320mm diam. to be delivered in 2019/2020 by Oxford.

CAPP's Axion Research

Axion Research at CAPP

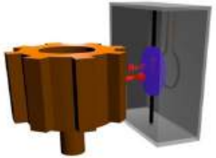
- CULTASK
  25T/10cm HTS from BNL
- CAST-CAPP
- ARIADNE
- 12T/32cm
  LTS, Oxford

Lead: Woohyun Chung
25T/10cm, from BNL
Complete RF chain (w/ DAQ) at LVP



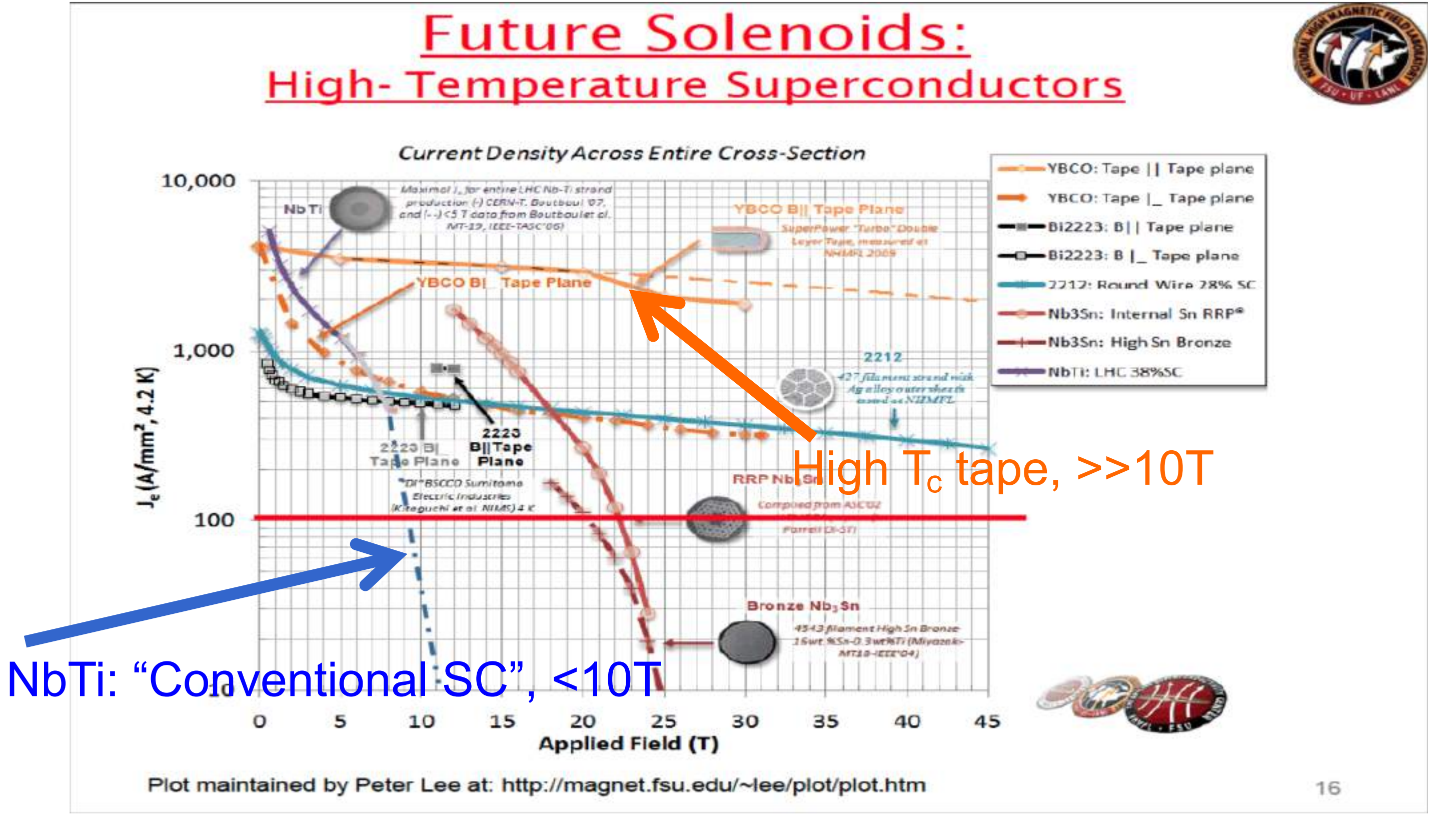
Lead/CAPP: Lino Miceli

Lead: Yunchang Shin
NMR based
R&D in progress



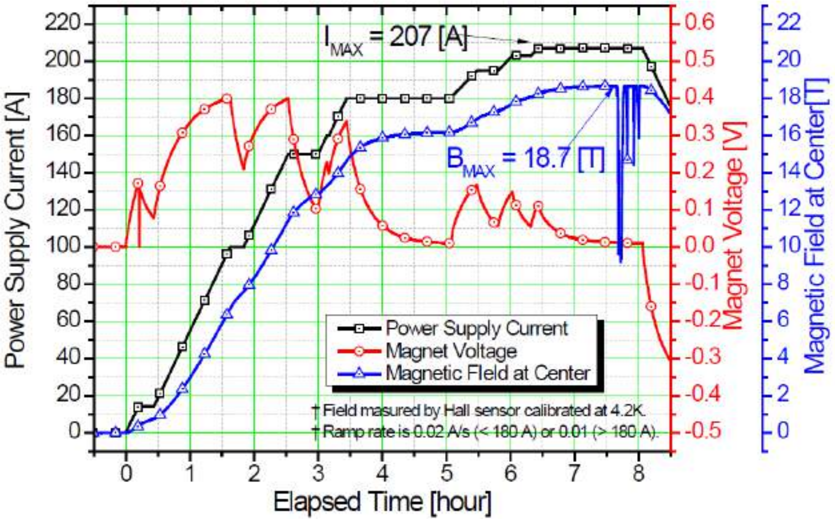
Lead: Beongrok Ko

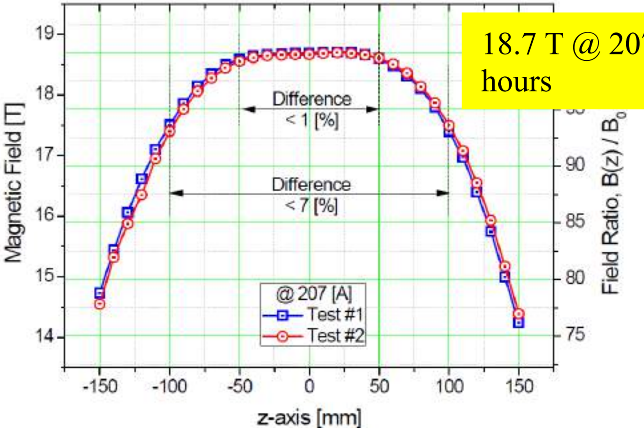
High Field magnet 18T/7cm aperture from SuNAM: Group Leader JongHee Yoo


Future Solenoids:
High- Temperature Superconductors
Current Density Across Entire Cross-Section
YBCO: Tape || Tape plane
YBCO: Tape |_ Tape plane
Bi2223: B|| Tape plane
Bi2223: B |_ Tape plane
2212: Round Wire 28% SC
Nb3Sn: Internal Sn RRP®
Nb3Sn: High Sn Bronze
NbTi: LHC 38%SC
YBCO B|| Tape Plane
YBCO B|_ Tape Plane
NbTi
2223 B||Tape Plane
2223 B|_ Tape Plane
2212
RRP Nb3Sn
Bronze Nb3Sn
J_e (A/mm², 4.2 K)
Applied Field (T)
High T_c tape, >>10T
NbTi: "Conventional SC", <10T
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm
16

Magnet charging (207A, 18T)

Group leader: JongHee Yoo



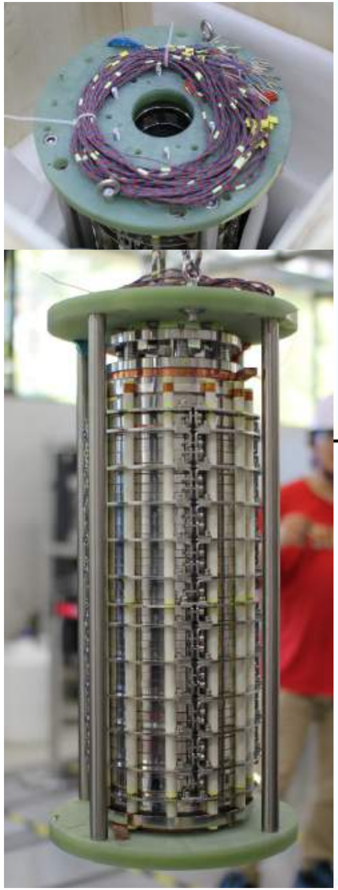


18.7 T @ 207A after 8 hours

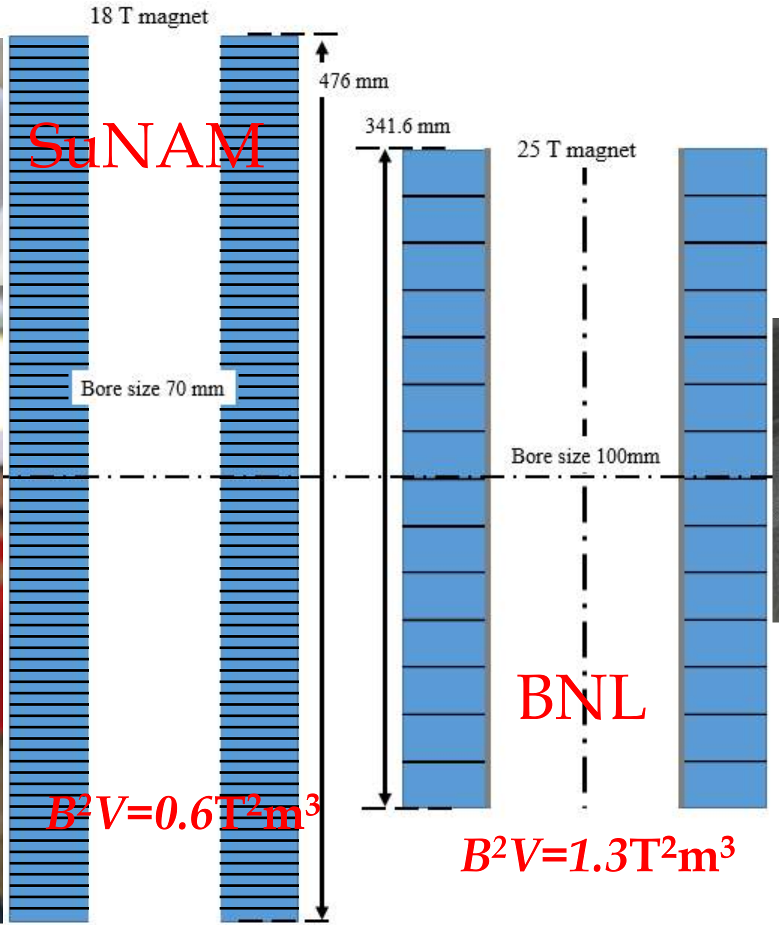
Power output

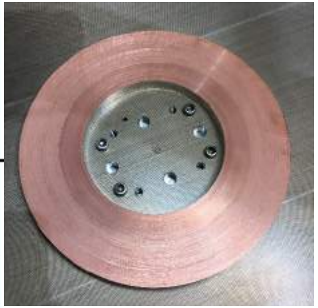
Monitoring program

18 T no insulation magnet



44 double pancake coils





1st coil
for 25 T magnet
1/28

IBS: Prototype high T_c magnet development with Brookhaven National Laboratory (Dr. R. Gupta, Magnet Division)

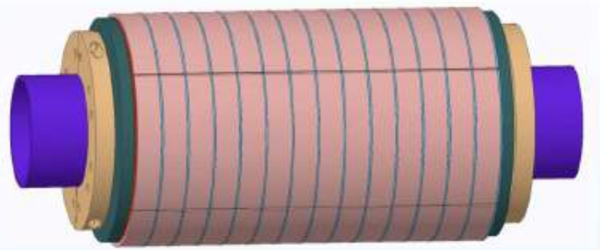
Building: 25 T, 10 cm diameter High Tc magnet!

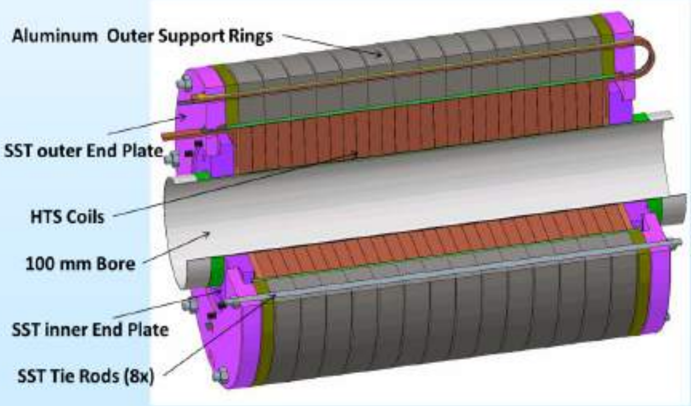
R. Gupta, BNL

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

IBS HTS Solenoid Design Summary

- Design Field: 25 T
- Operating Temperature: ~4 K
- Cold Bore: 100 mm
- Coil i.d.: ~105 mm
- Coil o.d.: ~200 mm
- Single Layer
- Conductor: 12 mm wide ReBCO (50 μm Hastelloy, 20 μm Cu)
- Conductor per Pancake: ~300 m
- Number of Pancakes: 28
- Current: ~450 A
- Current Density: ~500 A/mm²
- Stored Energy: ~1.3 MJ
- Inductance: ~13 Henry
- Maximum Hoop Stress: ~480 MPa
- Maximum Axial Stress: ~180 MPa
- Outer Support Ring: High Strength Aluminum

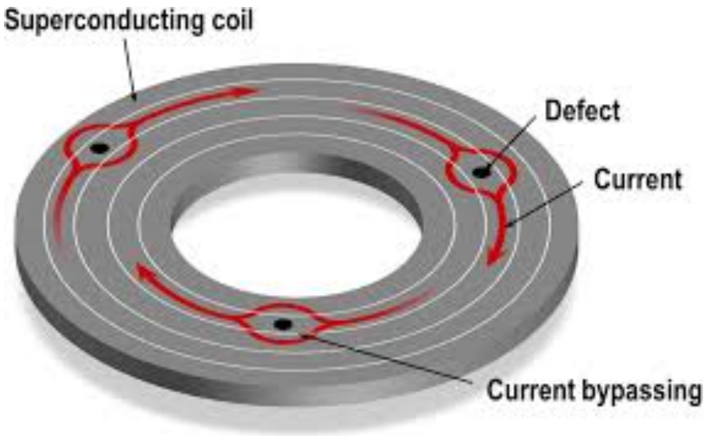




Is HTS safe?

- 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.

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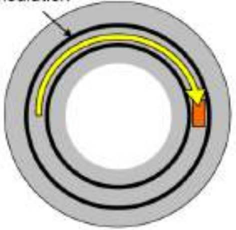
Superconducting Magnet Division

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

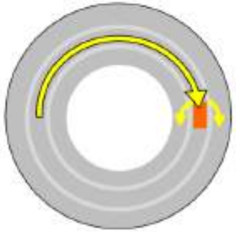
No-Insulation HTS Winding Technique

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

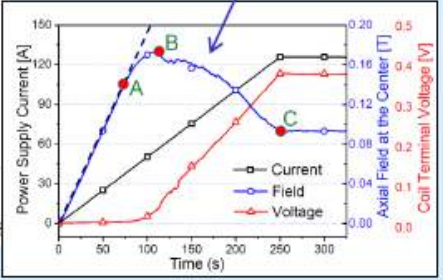
Seungyong Hahn

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

WAMHTS-3
Lyon, France

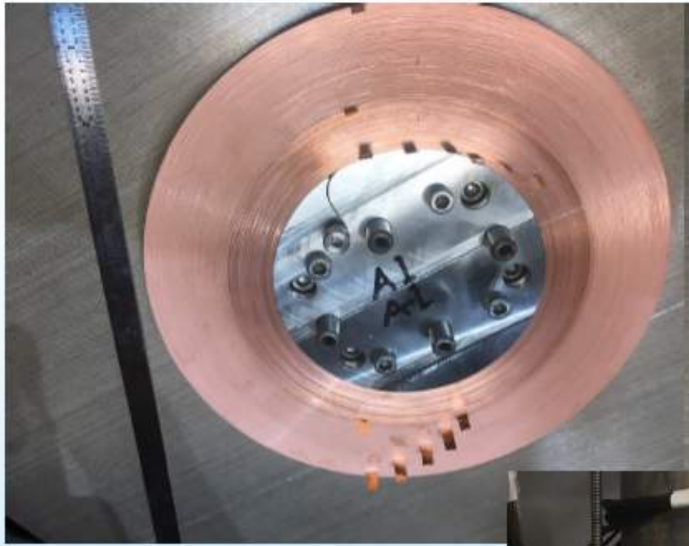
September 11, 2015

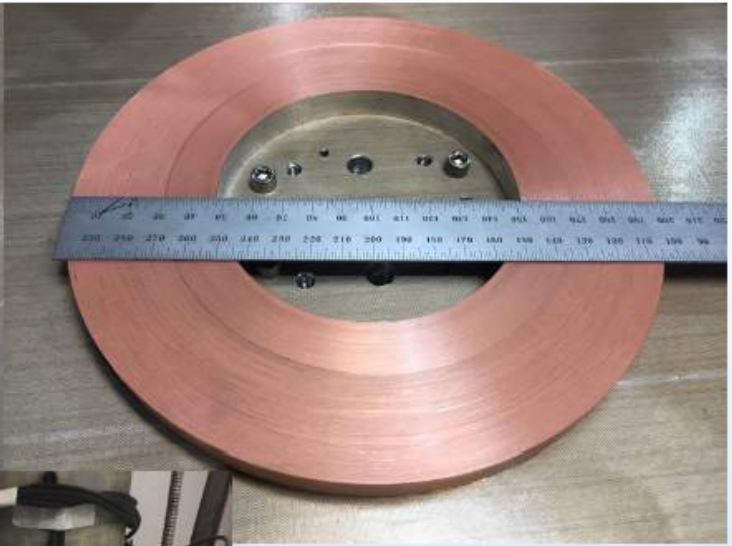
A decrease in field implies that more and more turns are getting shorted



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)

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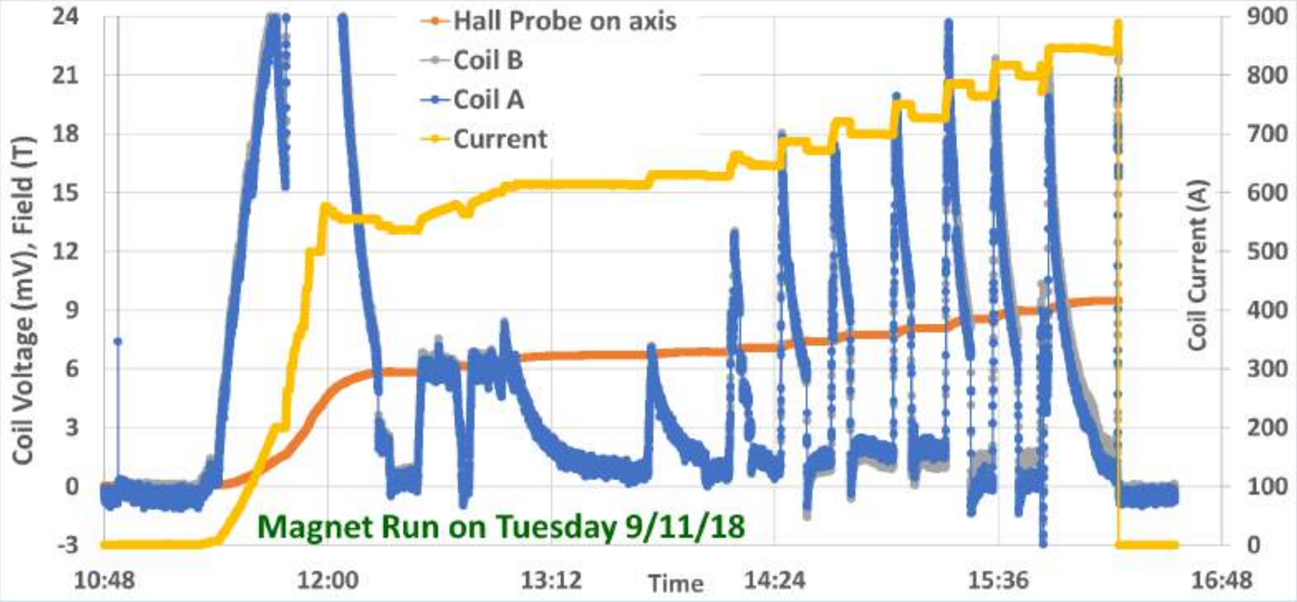
Superconducting Magnet Division

Tuesday Run Summary

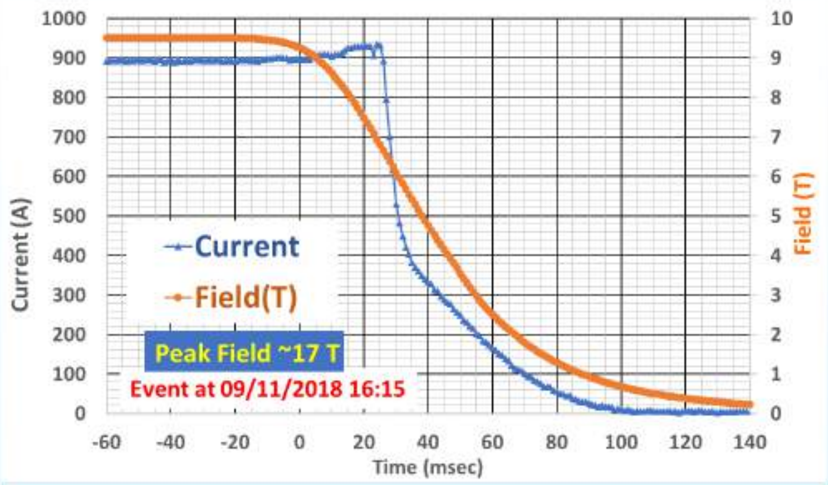


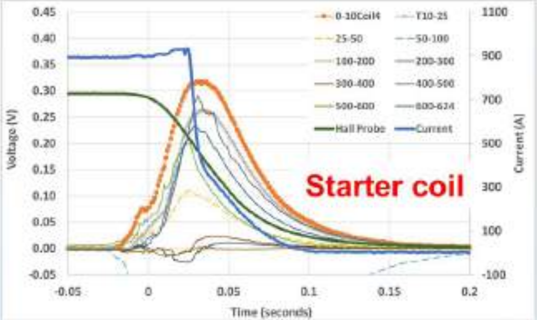
- Continue increasing current in steps to the maximum it could go
- Quenched when going from 850 A to 900 A (design current: ~450 A)
- It reached maximum field in bore ~9 T and in coil ~17 T
- Quench data discussed in more details in the next slide

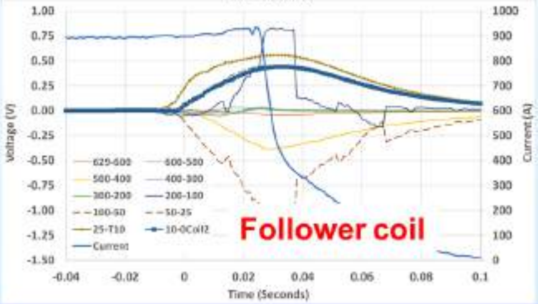
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

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





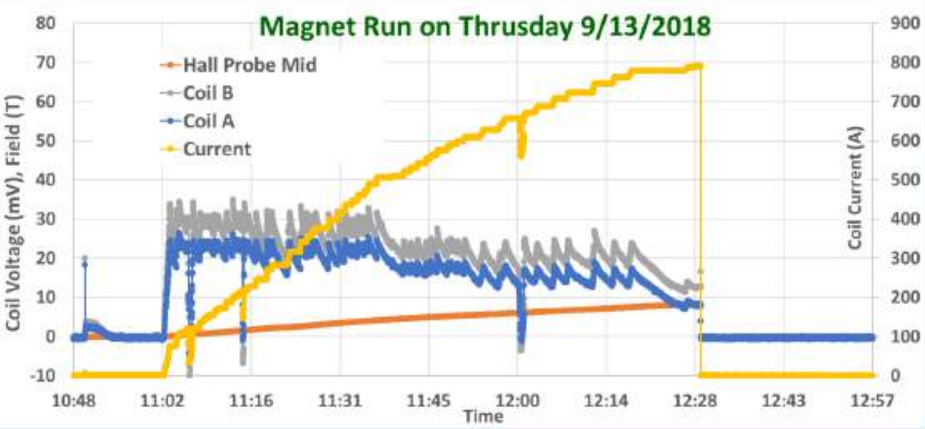


The 1st IBS double pancake coil became normal in < 200 msec (even faster than in many LTS magnets)

- **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**

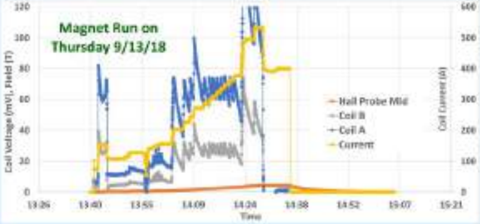
- **More discussion with many test results in the 4 K test presentation**

Thursday Run Summary

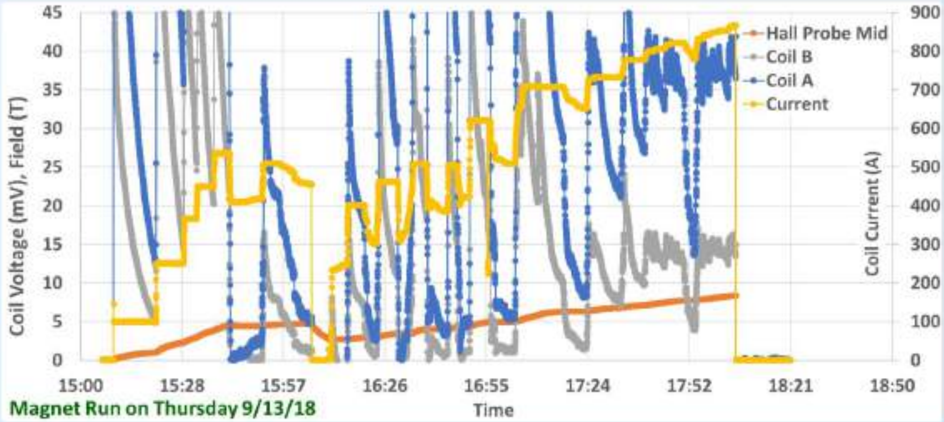


Second quench at ~800 A (design: ~450 A)

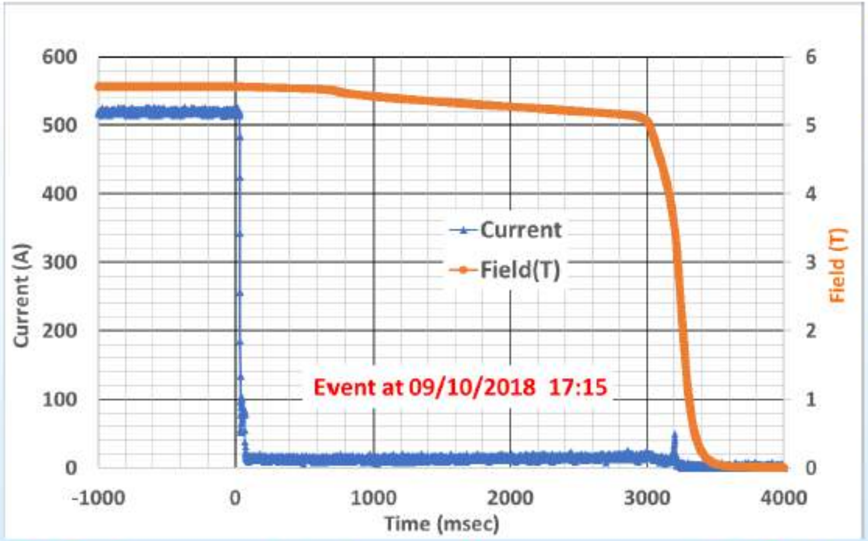
Third quench at ~850 A (design: ~450 A)



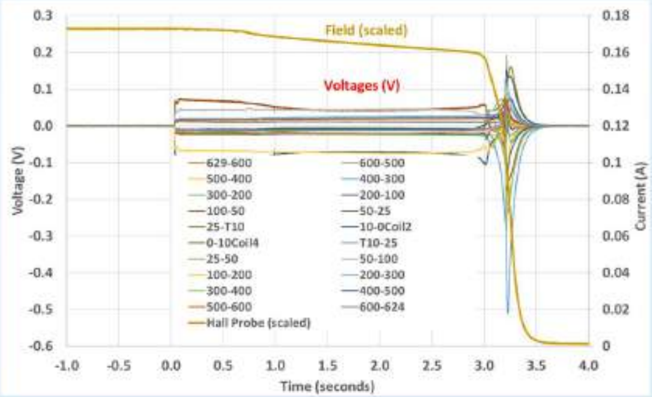
Shut-off near design current



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

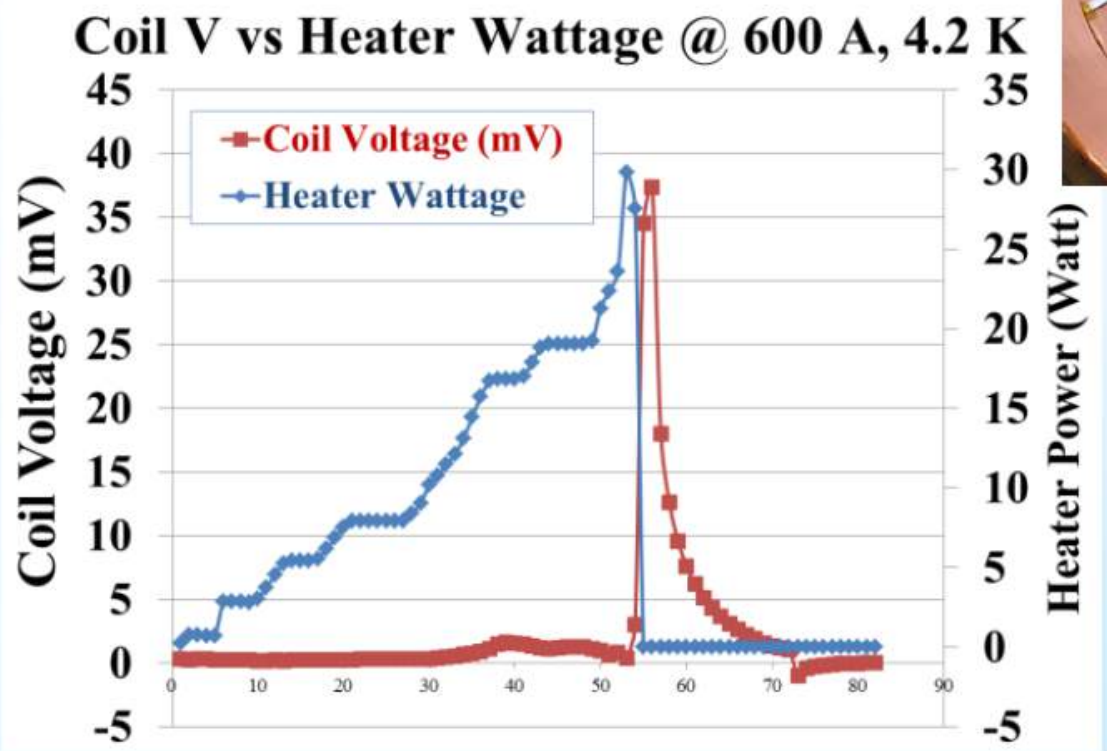


550 A example (operating current 450 A):

- **Slow internal deposition of energy (3 sec)**
- **Fast run-away (<0.5 sec), once triggered**

This coil recovered (no runaway) up to 400 A

Study of Large Local Defects @4.2 K (simulated with heaters up to ~30 W)

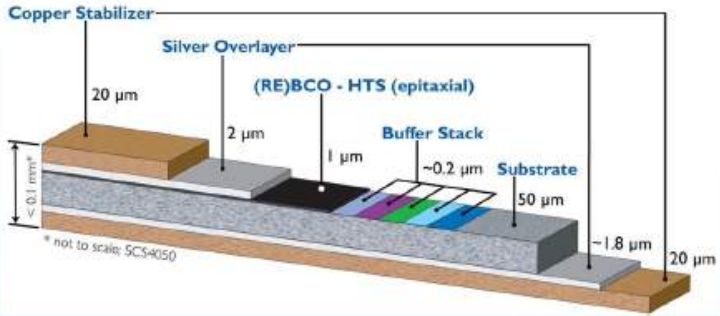


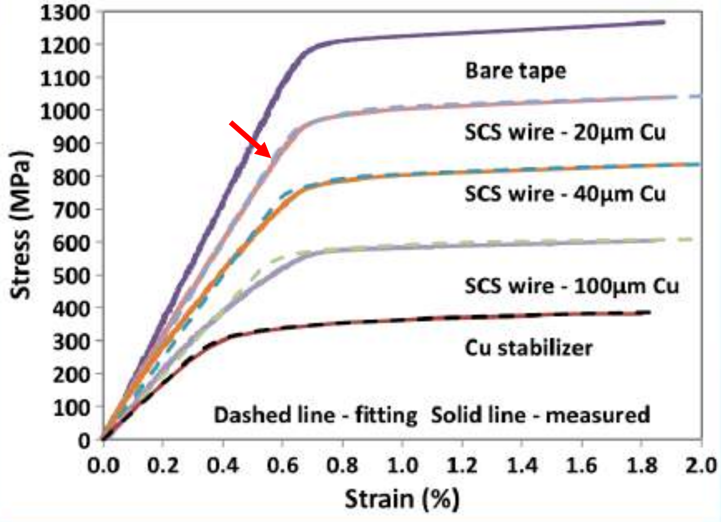
No degradation in the coil performance observed

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…

Choice of Conductor





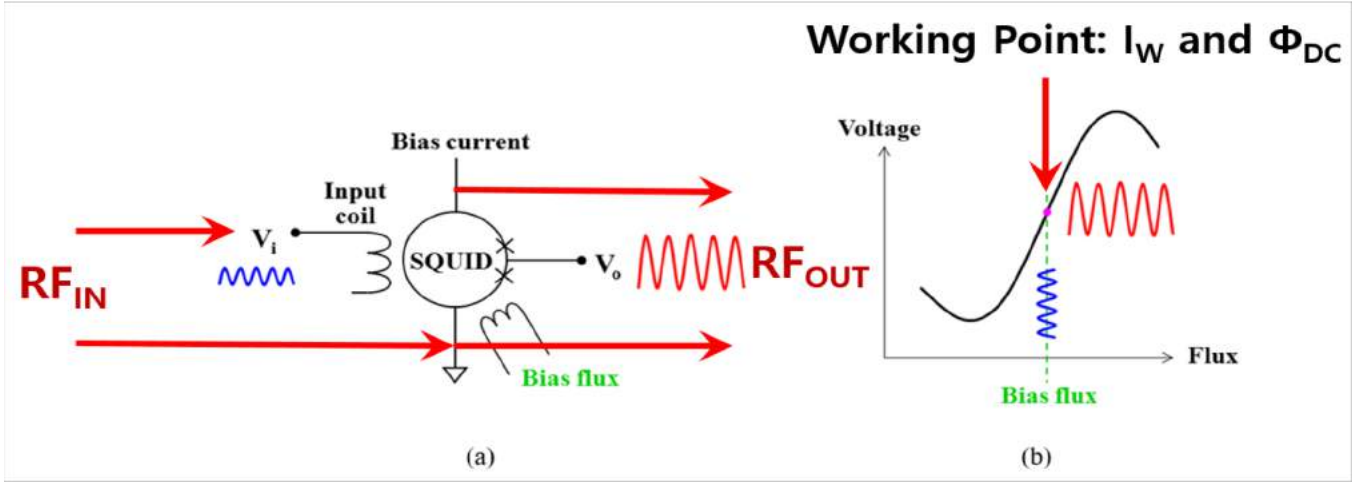
- Removing insulation increases the current densities in coils
- This creates higher stresses within the coil
- Reducing amount of copper allows us to deal with the higher stresses
- Copper reduced from 40/ 65 microns in SMES to 20 microns in IBS solenoid while keeping the Hastelloy same (50 microns)
- This choice offers >50% margin on hoop stresses

BNL 25T/10cm, HTS magnet review

October 22, 2018

- Magnet construction plan with single layer is sound
- Magnet design with NI is predicted to be safe from quenches and structural integrity
- >50% margins in critical current and stresses

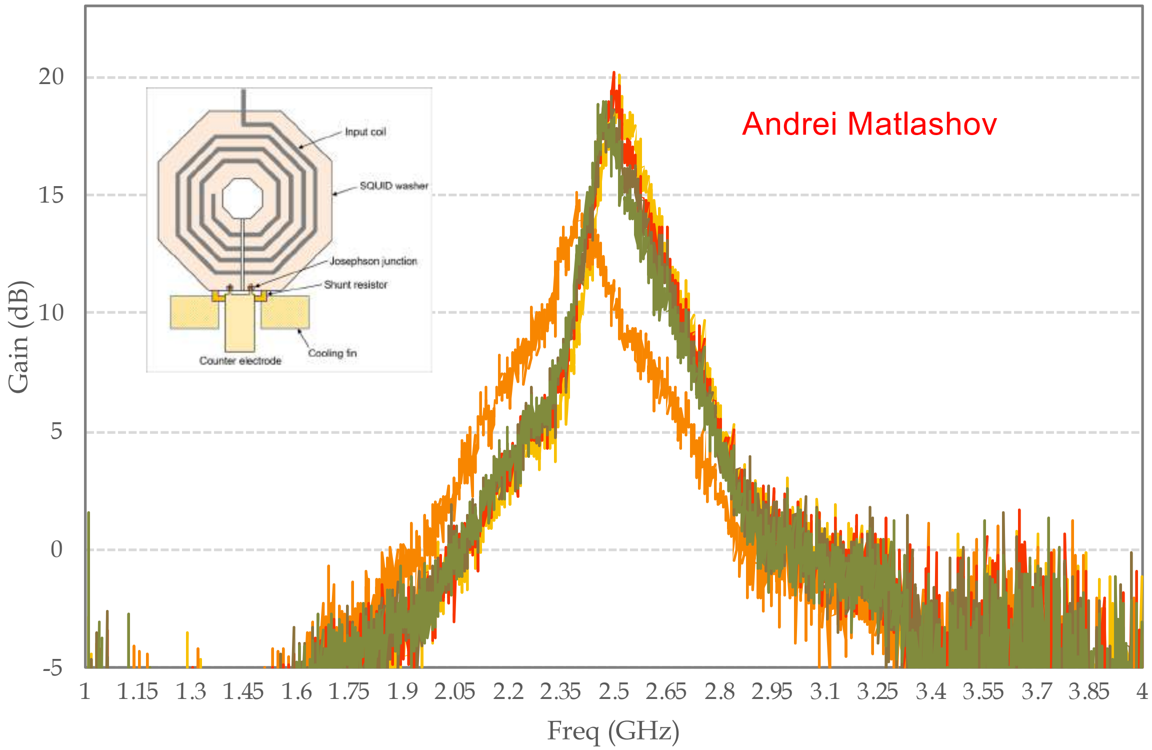
Microstrip SQUID Amplifiers



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

Andrei Matlashov

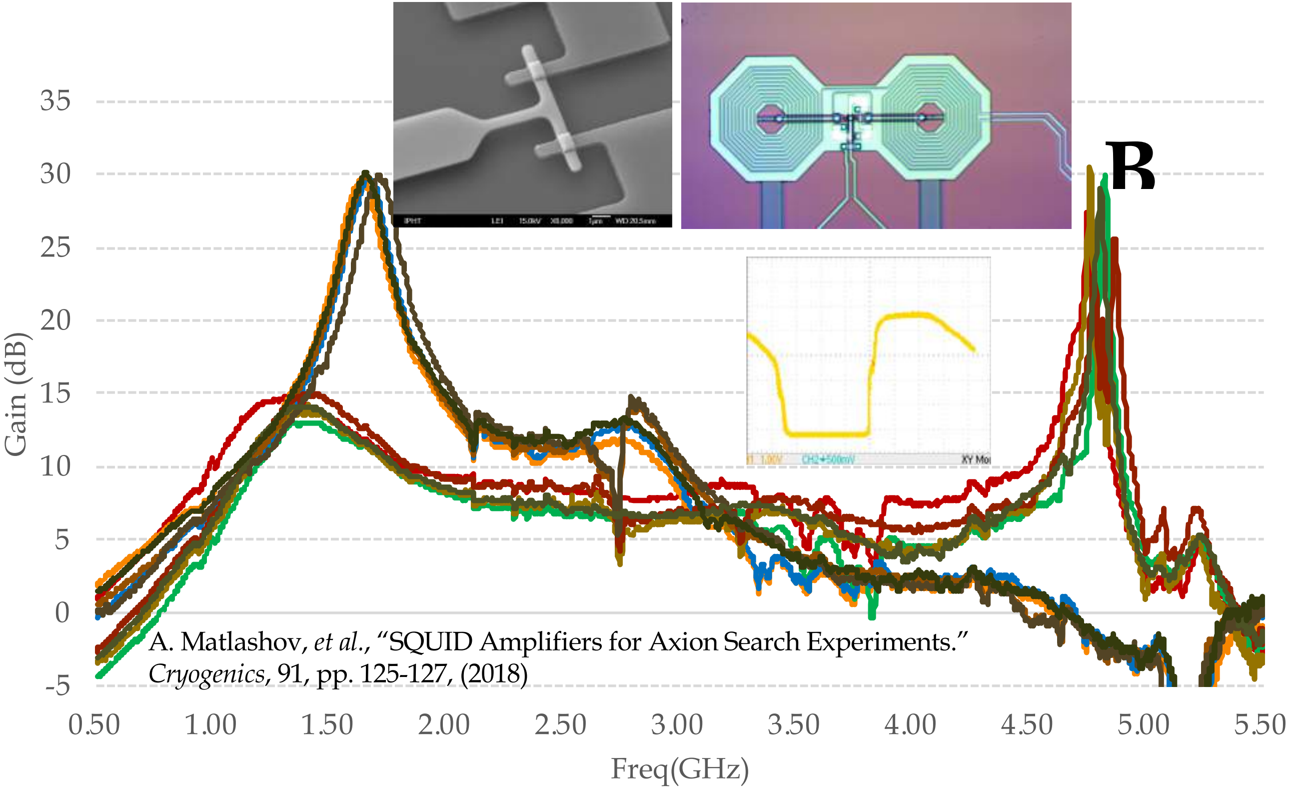
MSAs from Yong-Ho Lee, KRISS: World's first at 2.2-2.5GHz, 2016



RF-amplifiers and CAPP

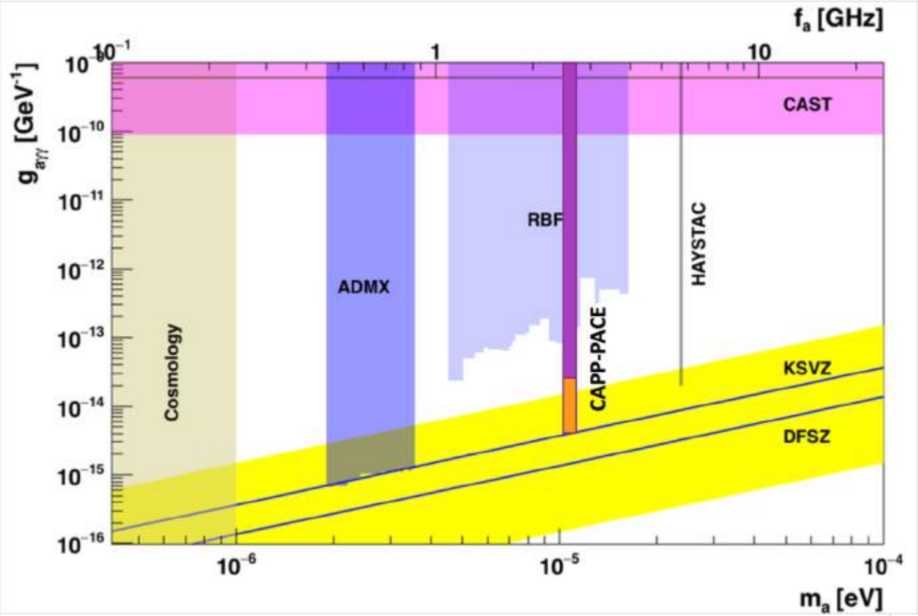
- KRISS delivered first functional MSA at >1GHz, 2016
- Private companies sprung up producing MSAs, JPAs
- Quantum computing is fueling the development. Single photon detection is possible on the bench?
- "She/he who controls this technology is …the great master!" Bolometer type?

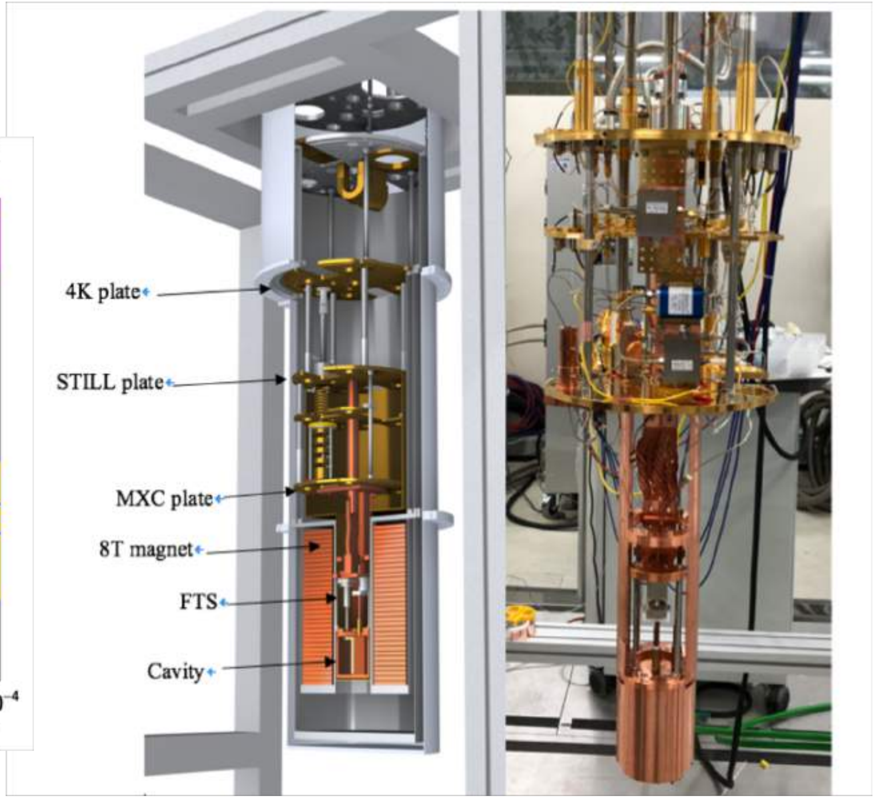
Broadband MSAs:
CAPP collaboration with IPHT, Germany



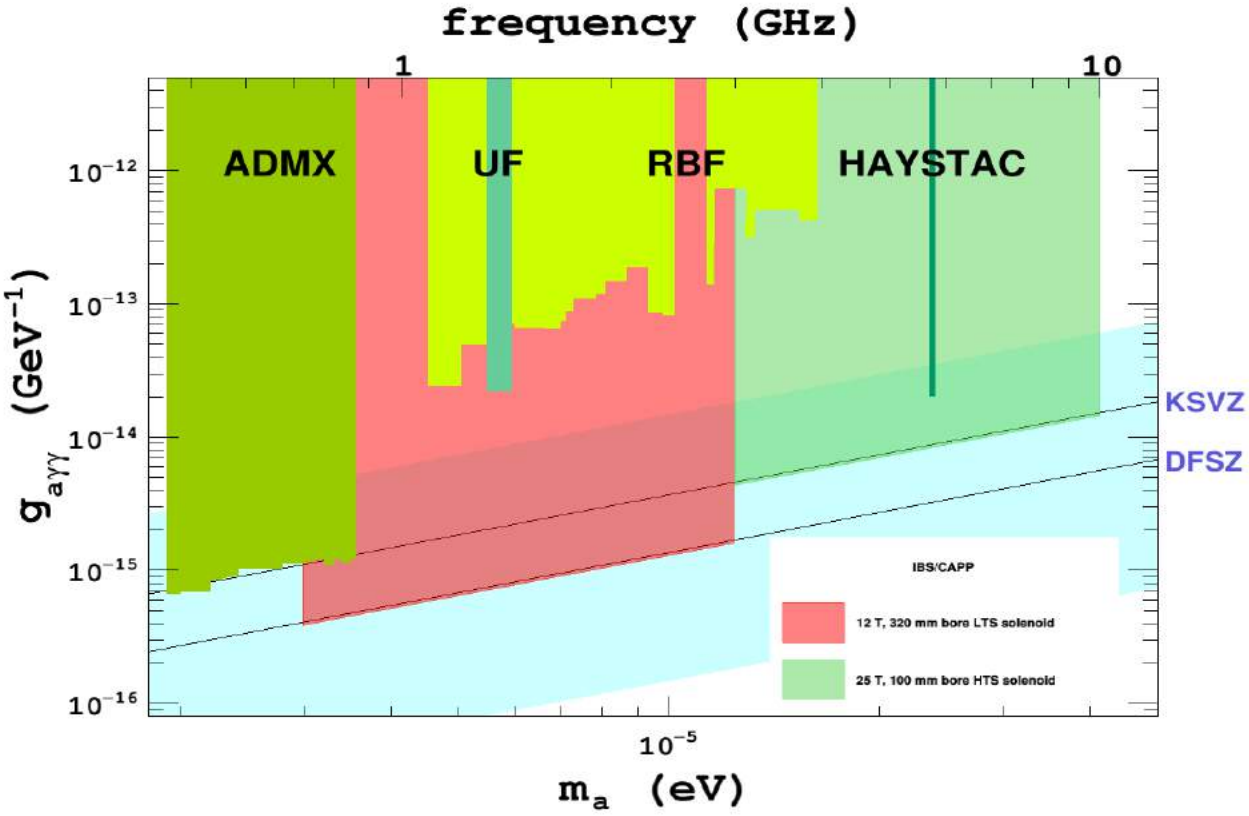
A. Matlashov, *et al.*, “SQUID Amplifiers for Axion Search Experiments.” *Cryogenics*, 91, pp. 125-127, (2018)

Prototype PACE, 8T, with HEMT (1K) amplifier





CAPP 25T/100mm



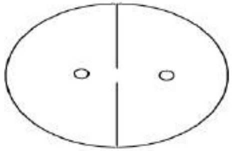
Other highlights

- B^2V for *dipole* magnets is large! CAST-CAPP prototype!
- GNOME is operating (axion domain walls)
- ARIADNE (NSF funded, CAPP responsible for SQUID-gradiometers)
- Storage ring EDM (EDM, a new hybrid design), Axion-EDM with feasibility tests at COSY, SQUID-based EDM, RF-reduction of muon beam CBO (major systematic error source)

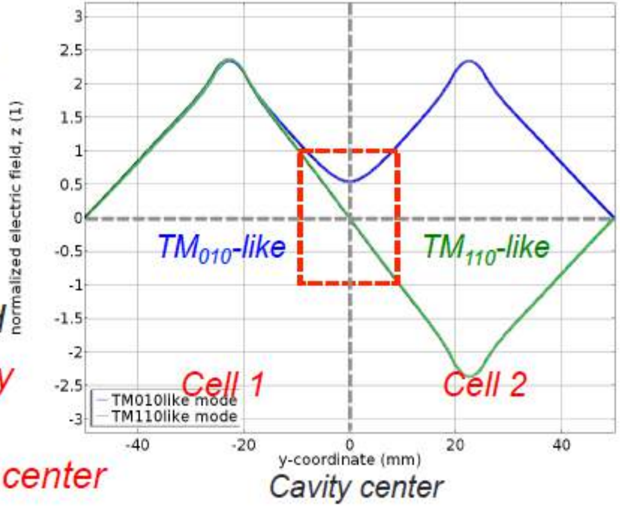
Demonstrating feasibility of Pizza-Cavity, PI: SungWoo Youn

Characteristics – III

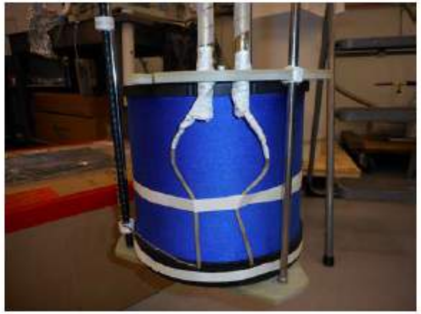
- *Electric field profile*
  - *Field distribution (profile) varies depending on the rod alignment*
  - *Phase-matching produces symmetric field profiles*
    - *TM_{010}-like (lowest) mode: in phase*
    - *Higher modes: out of phase*

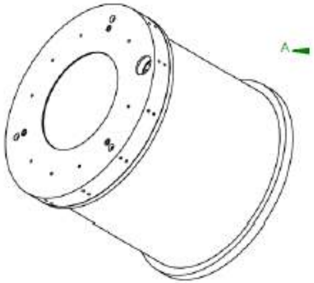


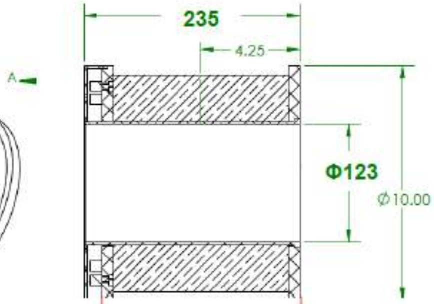
- *Under phase-matching*
  - *Higher modes => zero field*
  - *TM_{010}-like mode => non-zero field*
  - *Only TM_{010}-like mode is electrically coupled*
  - *A single monopole antenna at the center*



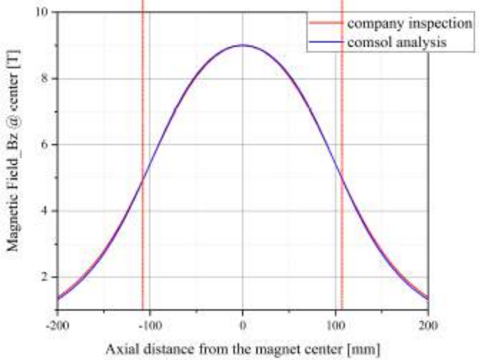
SC Magnet







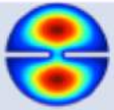
Property	Specification
Manufacturer	Cryomagnetics
Superconductor	NbTi
B_{max}	9 T (4.2 K)
Inner bore	123 mm
Height	235 mm
Operating current	80 A
Operation mode	Persistent

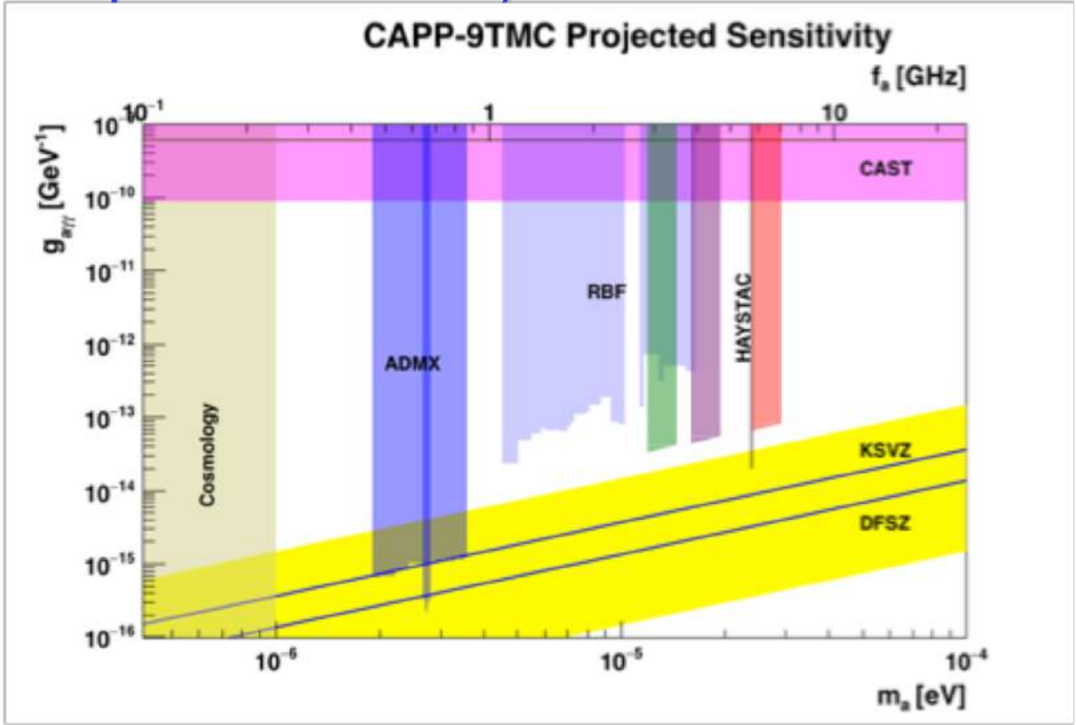


Pizza-cavity, single readout

Pizza-cavity, single readout

Running, to be completed in 2019/2020.

#-cell	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]	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]	5.4	4.8	5.0
Scan time (mon)	1.1	1.8	2.9



CAPP's base plan

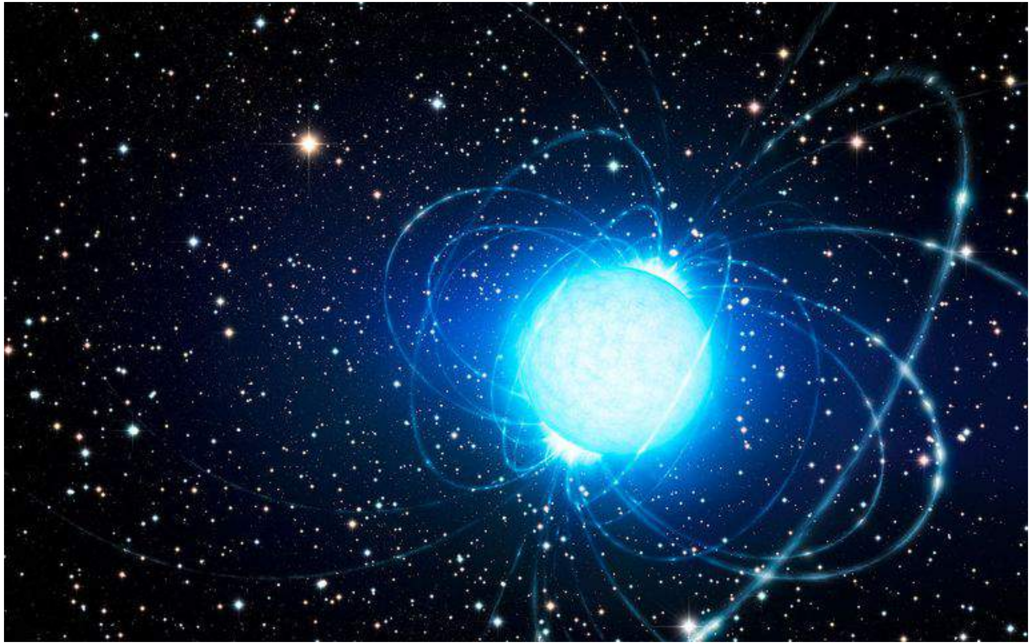
- Microwave cavities 0.7-20 GHz, using 25T/10cm and 12T/32cm magnets
- Then (we wish to) combine the two magnets to obtain >30T
- Phase-lock two or more axion dark matter exps.
- Wide band axion-mass network… Be prepared for a large transient! Check it with conventional experiment

Axions at IBS/CAPP

- Establish lowest cavity temperature (<50mK)
- Develop Microstrip SQUID Amplifiers (MSAs) from KRISS, IPHT, …; JPAs
- R&D on SC cavity w/ B-field
- Single photon detector (>10GHz), based on qubits?
- Open-resonators R&D for higher frequency (Collaboration with UW, KAIST)
- Neutron stars for signals (and transients?), check it with conventional experiment
- srEDM for axion-EDM

Axions: How IBS/CAPP is making a difference

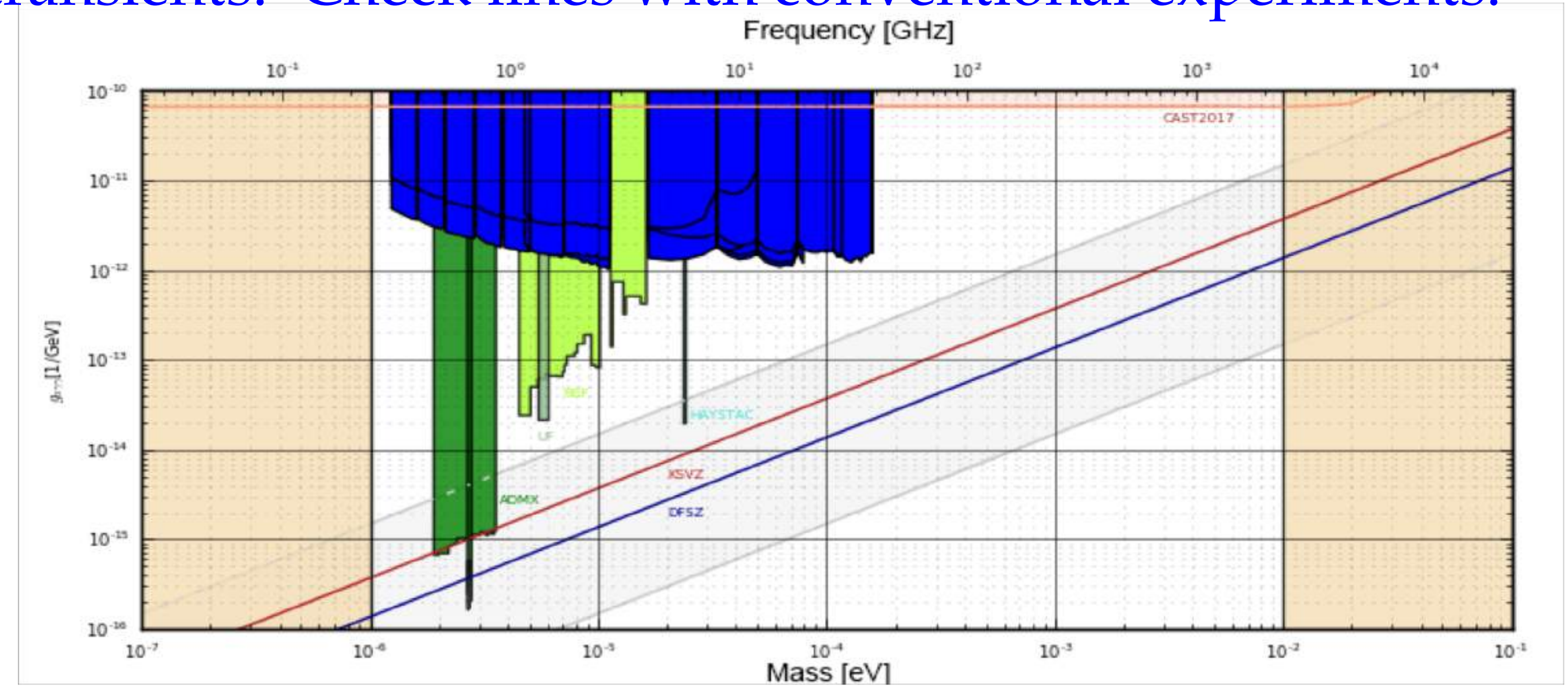
- Proposal to look for axion to photon conversion lines at neutron stars, PI: Jihoon Choi, IBS/CAPP



Neutron stars have the strongest magnetic fields in the universe, up to 10^{10} T.

Axions: How IBS/CAPP is making a difference

- Look for lines in neutron stars. Best systems for axion star transients. Check lines with conventional experiments.



Axion parameter space estimate from current telescope capabilities (GBT, 24 hour observation)

Precision physics: How IBS/CAPP is making a difference

- srEDM for a proton storage-ring EDM experiment at CERN with $10^{-29}e$-cm sensitivity
  - Hybrid ring (low systematics)
  - Prototype development: A thousand-fold improvement in sensing Coherent Betatron Oscillations of beams in storage-rings

- Muon g-2: RF-reduction of CBO, major syst. error source

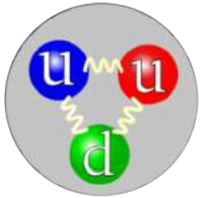
- COMET exp. in Japan

Hadronic EDMs:
That's where it all started!

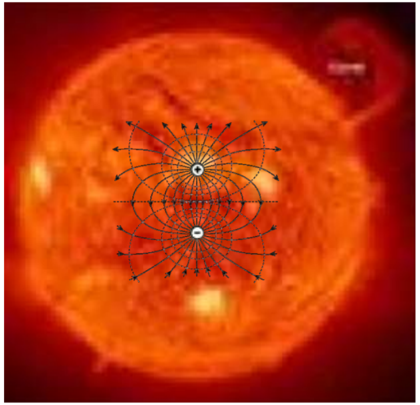
Proton EDM proposal: d=10^{-29}e·cm

- High sensitivity experiment:
- Blowing up the proton to become as large as the sun, the sensitivity to charge separation along N-S would be r < 0.1 μm!

proton

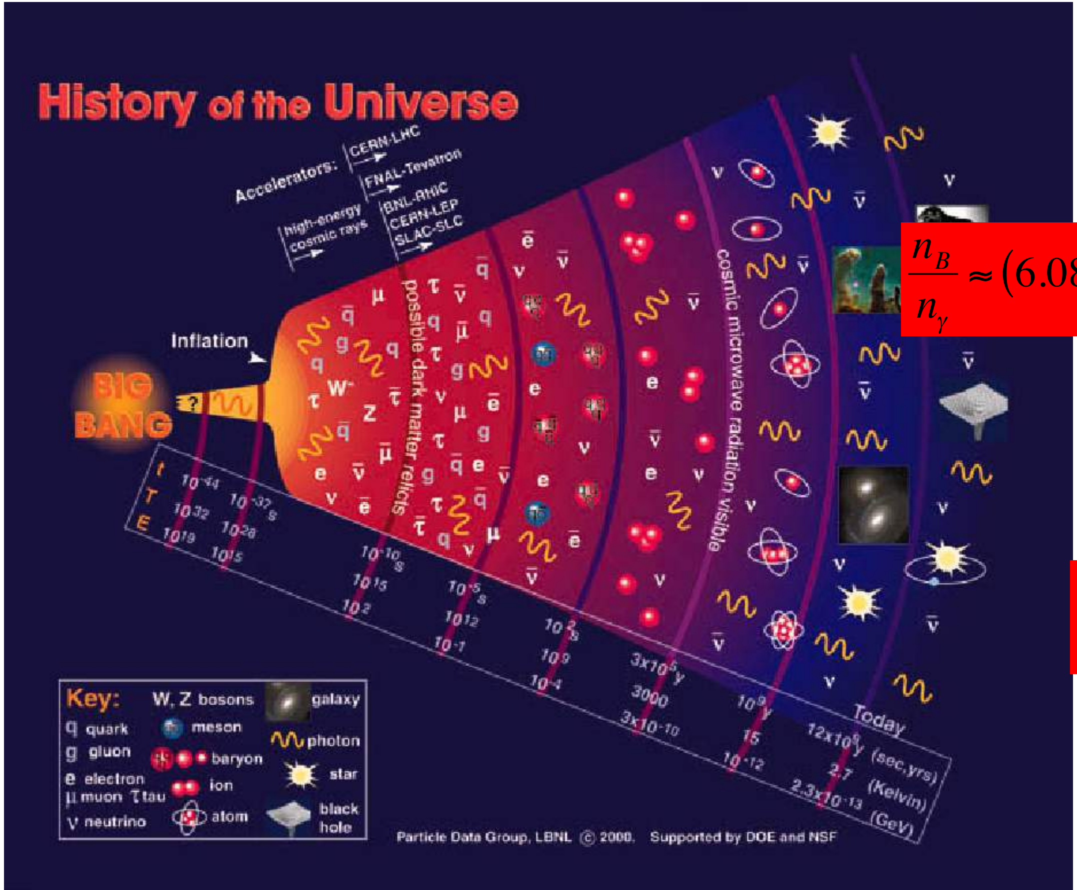


Sun



$$\vec{d} = q\vec{r}$$

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

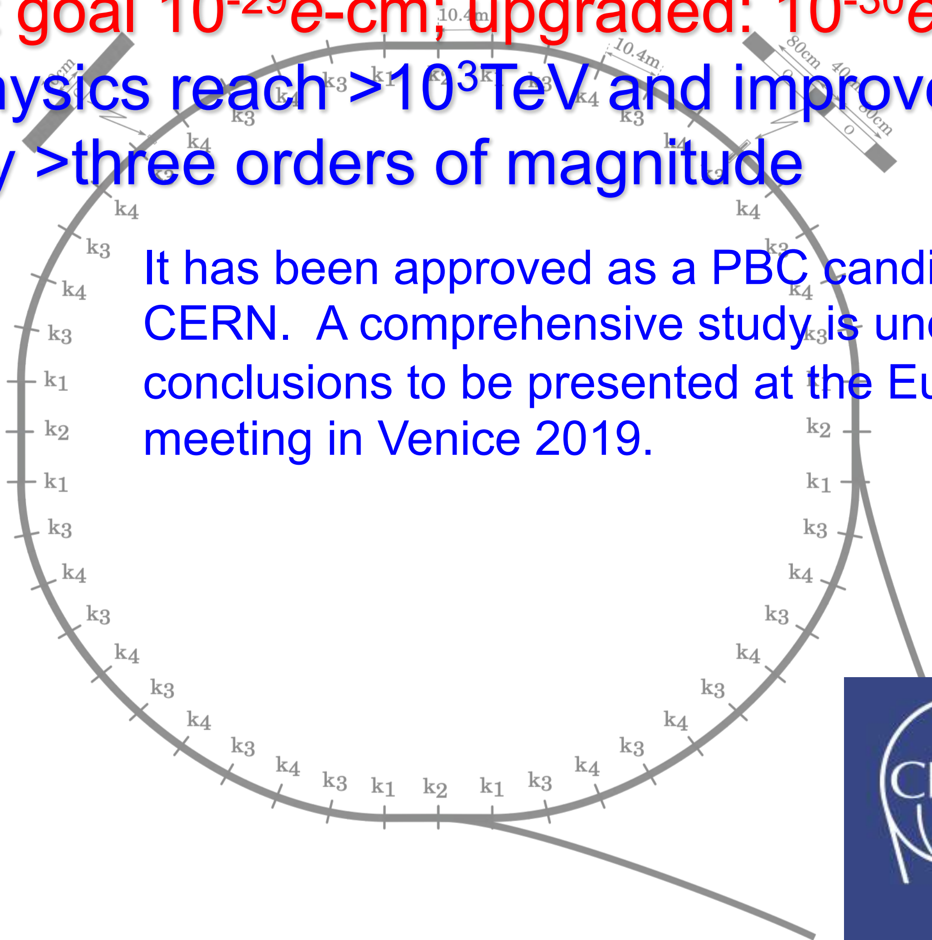
From the SM:

$$\frac{n_B}{n_\gamma} \approx 10^{-18}$$

The proton EDM electric ring

Current goal 10^{-29}e-cm; upgraded: 10^{-30}e-cm.

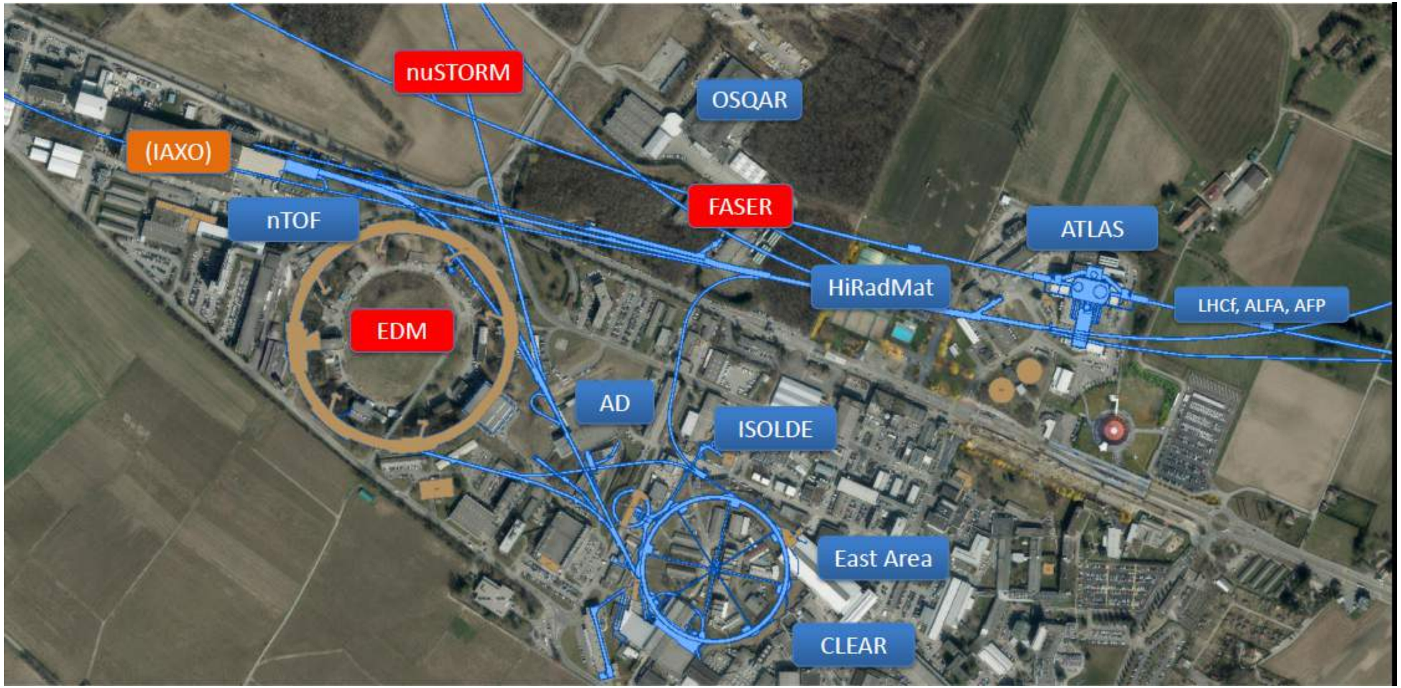
New Physics reach >10^{3}TeV and improve present theta_QCD limits by >three orders of magnitude



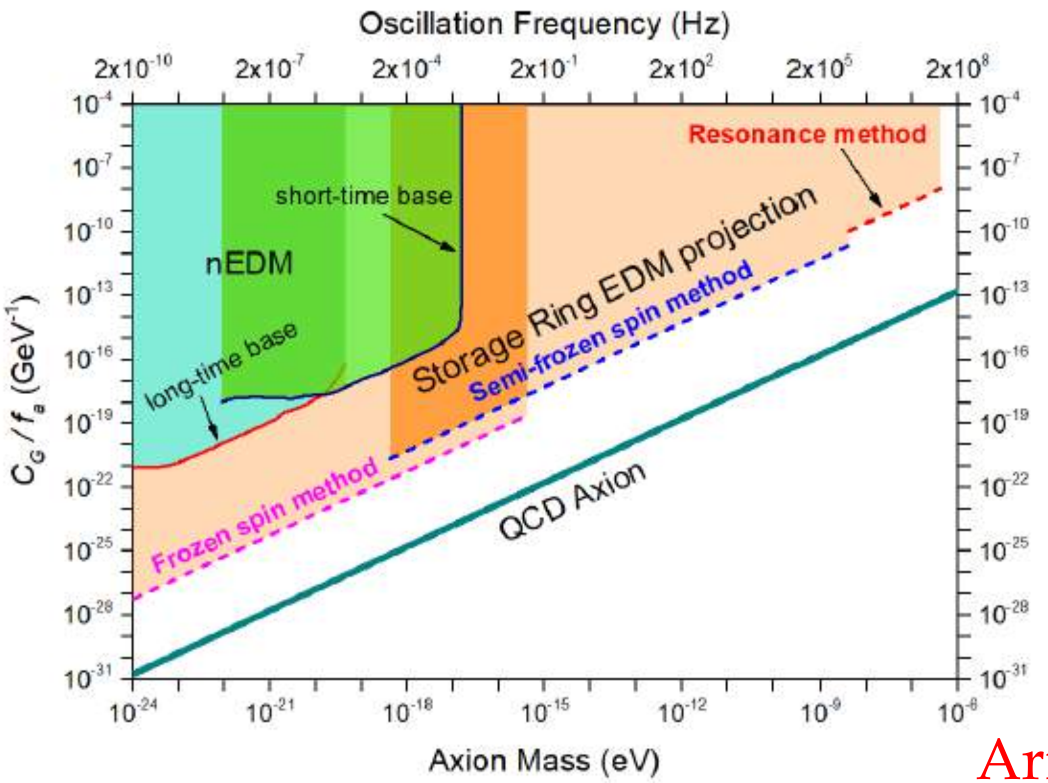
It has been approved as a PBC candidate project at CERN. A comprehensive study is underway with the conclusions to be presented at the European Strategy meeting in Venice 2019.

srEDM Collaboration Meeting at KAIST, 21 April, 2016.

Mike Lamont, CERN



Axion-EDM: Projected, preliminary

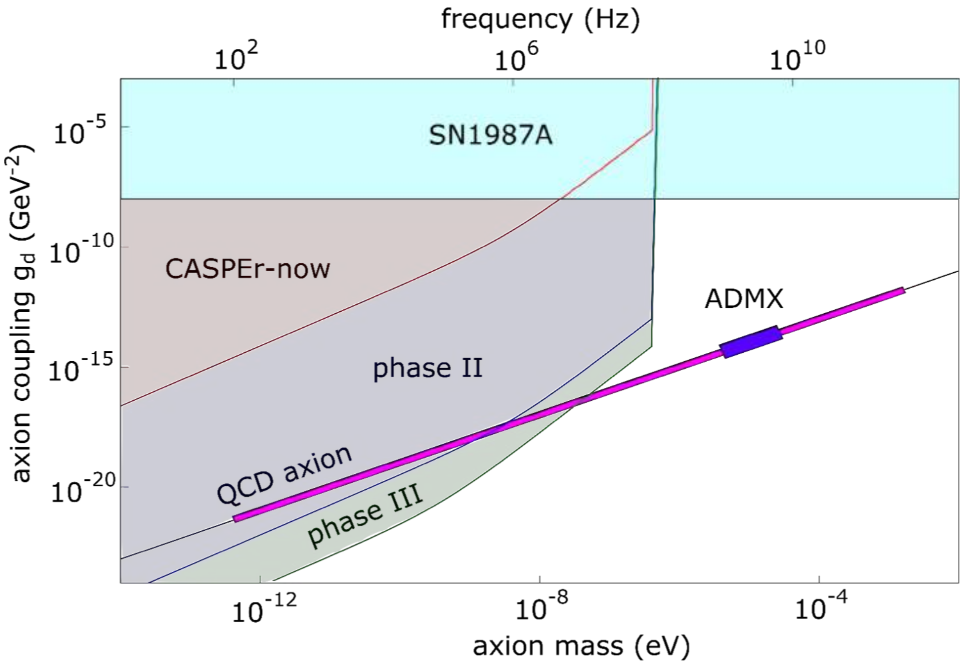


Arxive1710.05271

De Broglie wavelength >1km, the whole ring is within axion-field coherence.
In the Frozen spin method, the measurement is parasitic to the DC-EDM measurement, without the need to know the axion oscillation frequency.

Dima Budker

The experimental reach of CASPEr



CASPEr-now at BU:

- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

phase II:

- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

phase III:

- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

[*Phys. Rev. X* **4**, 021030 (2014)]

Slide by Alex Suskov (adapted)

CPEDM collaboration,
Juelich, March 9, 2018

COSY ring and detection signal

Feasibility study at COSY/Juelich

Scanning for a day: 10^{-24} e-cm

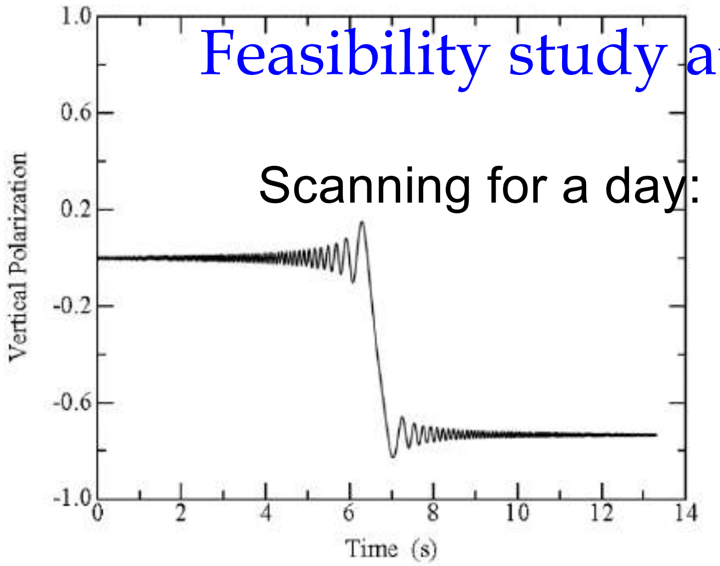


Figure 1: A "no-lattice" [14] calculation of the resonance crossing with a scan rate of 0.5 Hz/s. The strength of the oscillating EDM is 1.6×10^{-21} e·cm. Within the span of less than one second, this causes a jump of −0.75 in the p[Y] component of the beam polarization (assumed to initially be completely polarized in the ring plane).

New idea: hybrid storage ring

- Reduces systematic error risks

arXiv:1806.09319v2 [physics.acc-ph] 26 Jun 2018

A hybrid ring design in the storage-ring proton electric dipole moment experiment

S. Hacıömeroğlu[1], Y.K. Semertzidis[1,2,*1]
[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*
[*1] *Corresponding author, yannis@kaist.ac.kr*

(Dated: 27 June 2018)

A new hybrid design is proposed for the frozen spin, storage-ring electric dipole moment method, which can essentially eliminate the impact of the main systematic errors. We are proposing using electric bending plates to steer the particles, and use alternate magnetic focusing instead of electric focusing. The magnetic focusing should permit simultaneous clock-wise and counter-clock-wise storage to cancel systematic errors related to out of plane dipole electric fields. The quadrupole electric fields can be eliminated by successive storage using alternate magnetic focusing each time with different strength. The beta-functions, related to the beam envelops of the counter-rotating beams, are going to be somewhat varying depending on the sign of the magnetic quadrupole currents. However, even this small effect can be eliminated since alternate runs with flipped currents in the magnetic quadrupoles will allow the counter-rotating beams to trace, on average, the same paths everywhere.

Summary

- Axion-dark-matter efforts are becoming very exciting: Cryogenics, High field magnets (HTS, No Insulation is Axion-ready), High volume-high frequency, detectors, …

- A discovery can be announced at any moment (depending on the frequency value). Axions require the modification of Maxwell's equations in vacuum!

- Within the next five to ten years we may very well know whether axions are 100% of the dark matter…

- IBS/CAPP in South Korea is playing a major role in the axion research and precision physics

Extra Slides

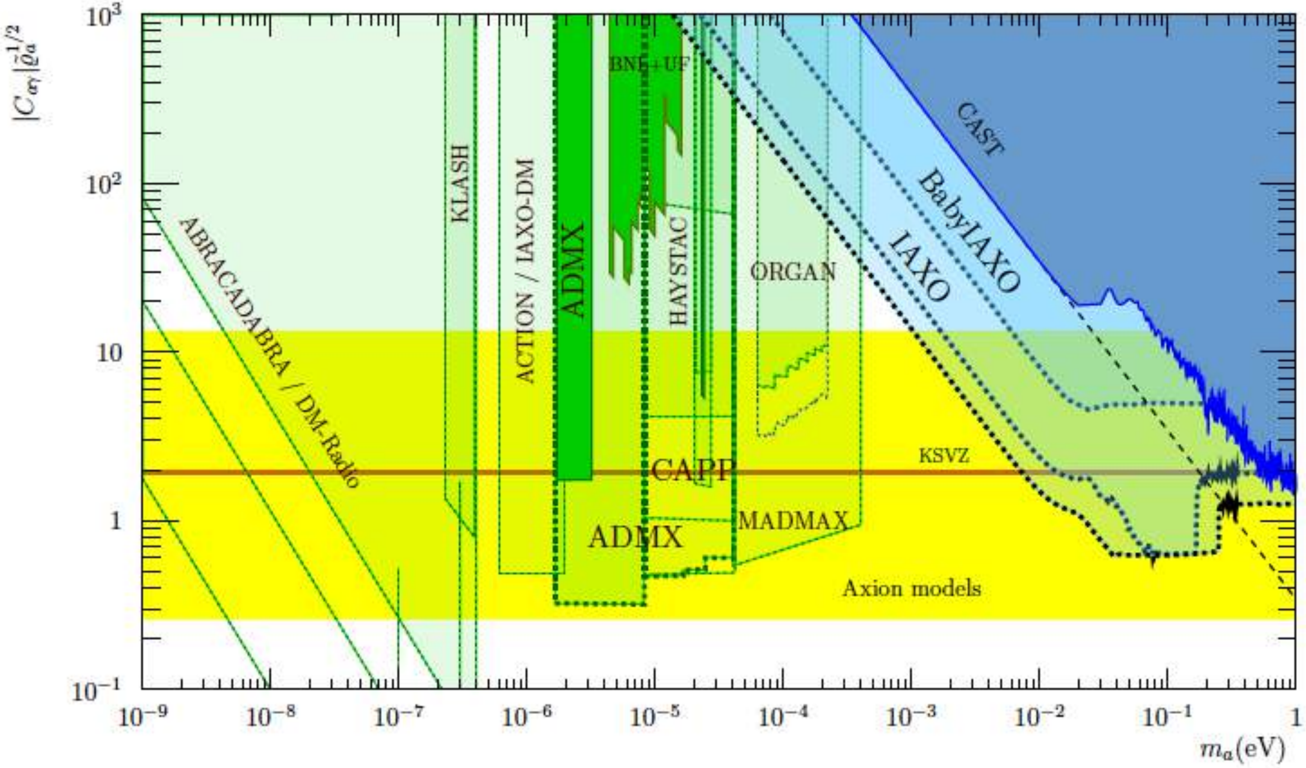
New idea: hybrid storage ring

- Use E-field for particle bending. Alternate magnetic focusing, allows simultaneous CW/CCW storage

- It reduces the radial B-field dependence by several orders of magnitude

- Strong focusing is possible, reduces risk due to E-field effects

Actively planned axion exps.



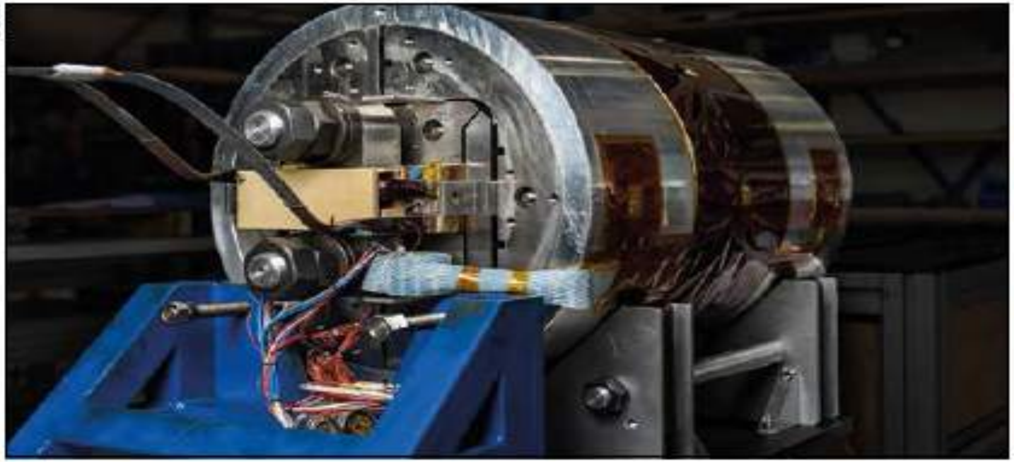
Irastorza, Redondo 1801.08127v2

Traditional SC magnets: LHC magnets made with NbTi conductors

9T max field.

Next magnets are made with Nb_3Sn conductors

CERN



16T max B-field.

This model magnet recently achieved a field of 16.2 T at CERN, twice the nominal field of the LHC dipoles, offering promise for a long-term accelerator-based future for the laboratory.

By Fabiola Gianotti

Over the next five years, key events shaping the future of particle physics will unfold. We will have results from the second run of the LHC, and from other particle and astroparticle physics projects around the world. These will help us to chart the future scientific road map for our field. The international collaboration