4 May 2016
KimFest, Joint CTPU/IBS-SNU Meeting, Seoul

Strong CP Problem: Axion dark matter & Storage ring proton EDM experiments

Yannis Semertzidis, CAPP/IBS and KAIST

Strong CP-Problem

Axion physics: Dark matter in our universe

- Strong magnetic fields: up to 40T, DC, 10cm diameter inner bore, 40cm long
- High sensitivity receivers
- Storage ring proton EDM: 10^4 TeV New Physics reach
- Storage ring EDMs: Great physics opportunity for Korea to host the experiment.

CAPP-Physics

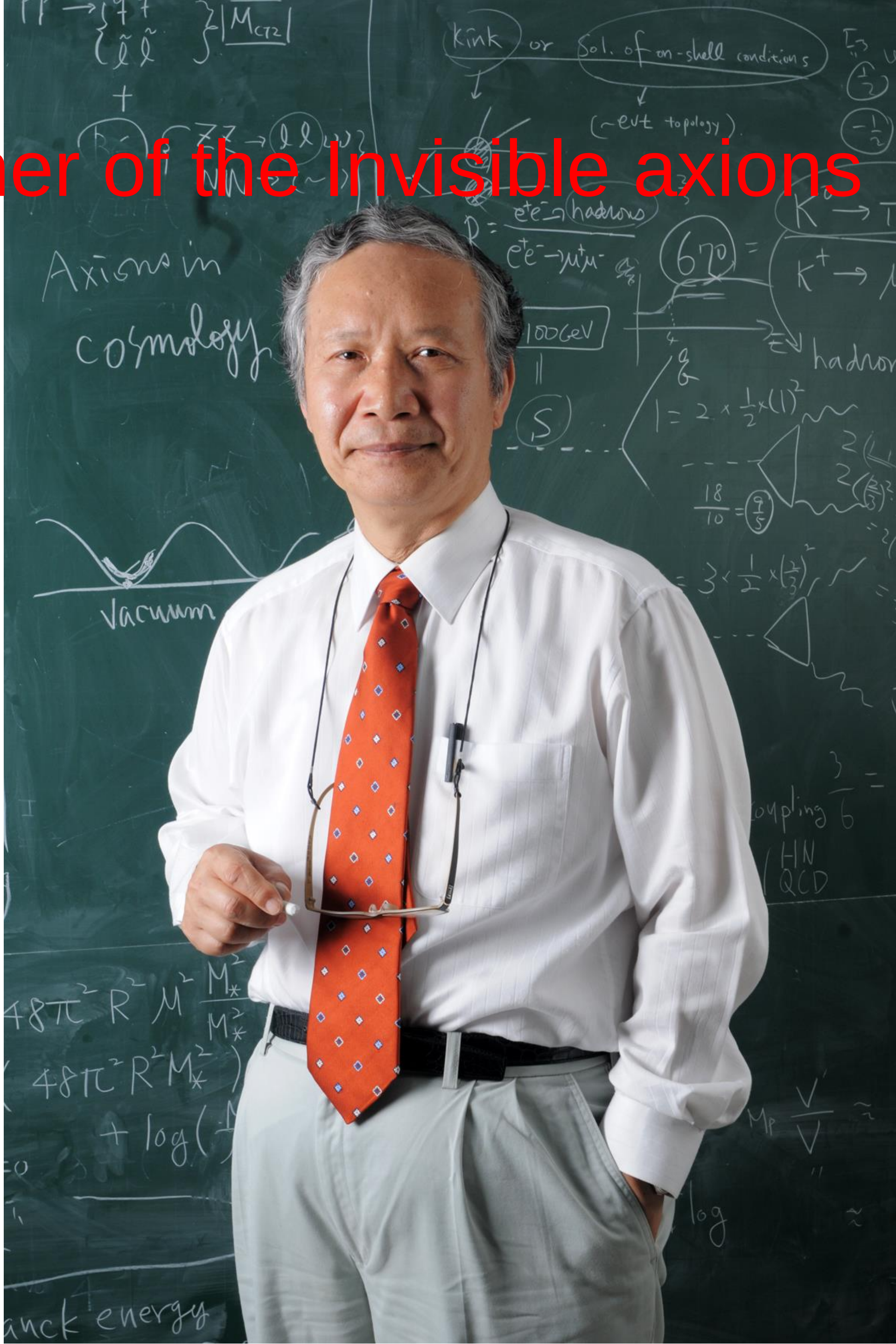
- Establish Experimental Particle Physics group.

Involved in important physics questions:

- Strong CP problem
- Cosmic Frontier (Dark Matter axions)
- Storage ring proton EDM (most sensitive hadronic EDM experiment, flavor conserving CP-violation, BAU)
- Muon g-2; muon to electron conversion (flavor physics)

Happy 70th Birthday

Father of the Invisible axions



Professor Jihn E. Kim!

Thank you for your tireless efforts to establish CAPP/IBS to make axions Visible!

Overall Plan

- Main effort: Comprehensive Axion Dark Matter experiment. Improve on all parameters based on mature technology. Develop as needed.

- Improve Hadronic EDM sensitivity by 3-4 orders of magnitude (proton EDM to $<10^{-29}$e.cm)

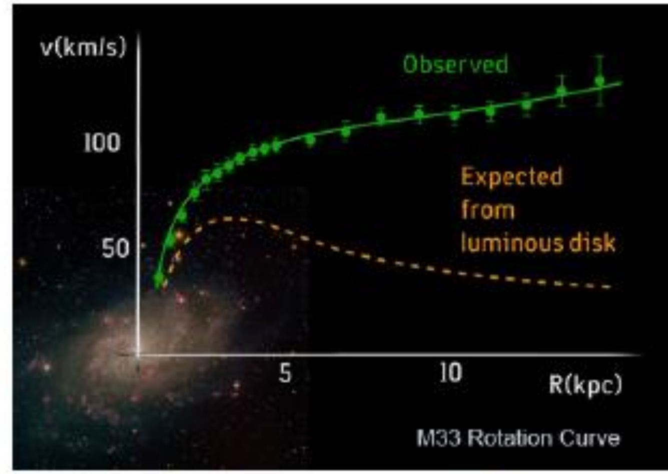
- Search for axion mediated forces (monopole-dipole interactions)

Dark Matter

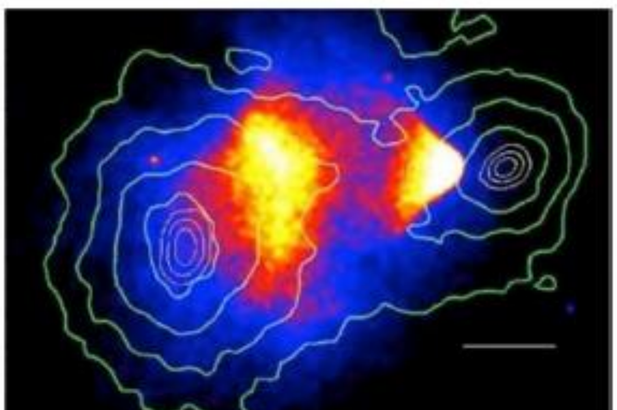
Eric Charles, Fermi-LAT collaboration

Evidence for / Salient Features of Dark Matter

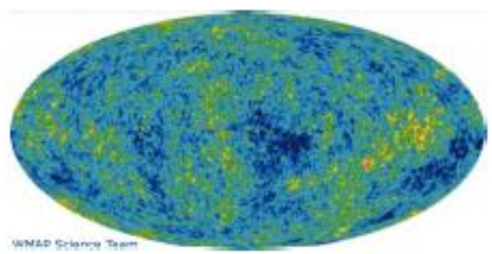
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

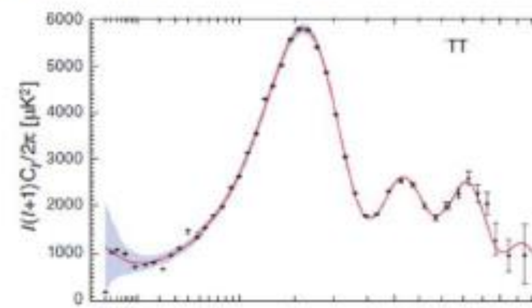


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



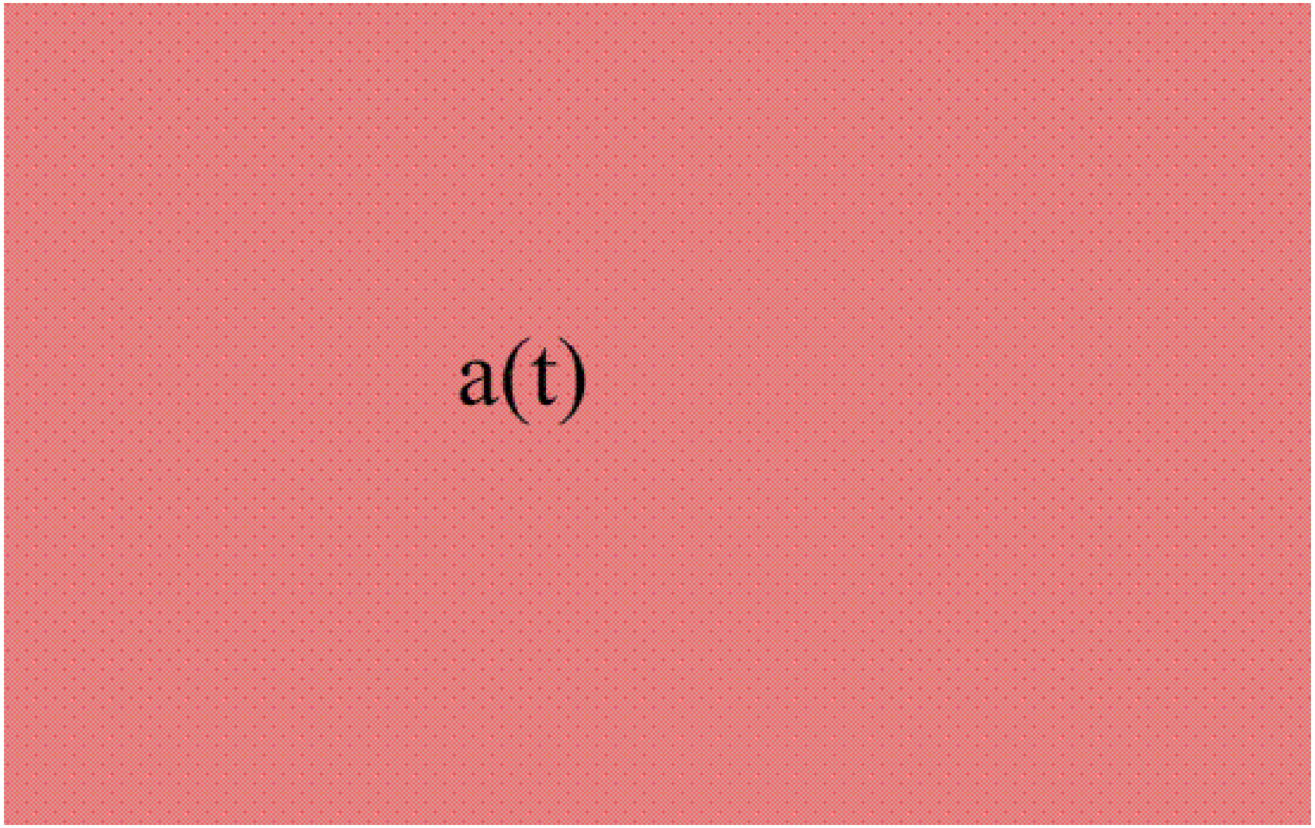


Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Axion Dark matter

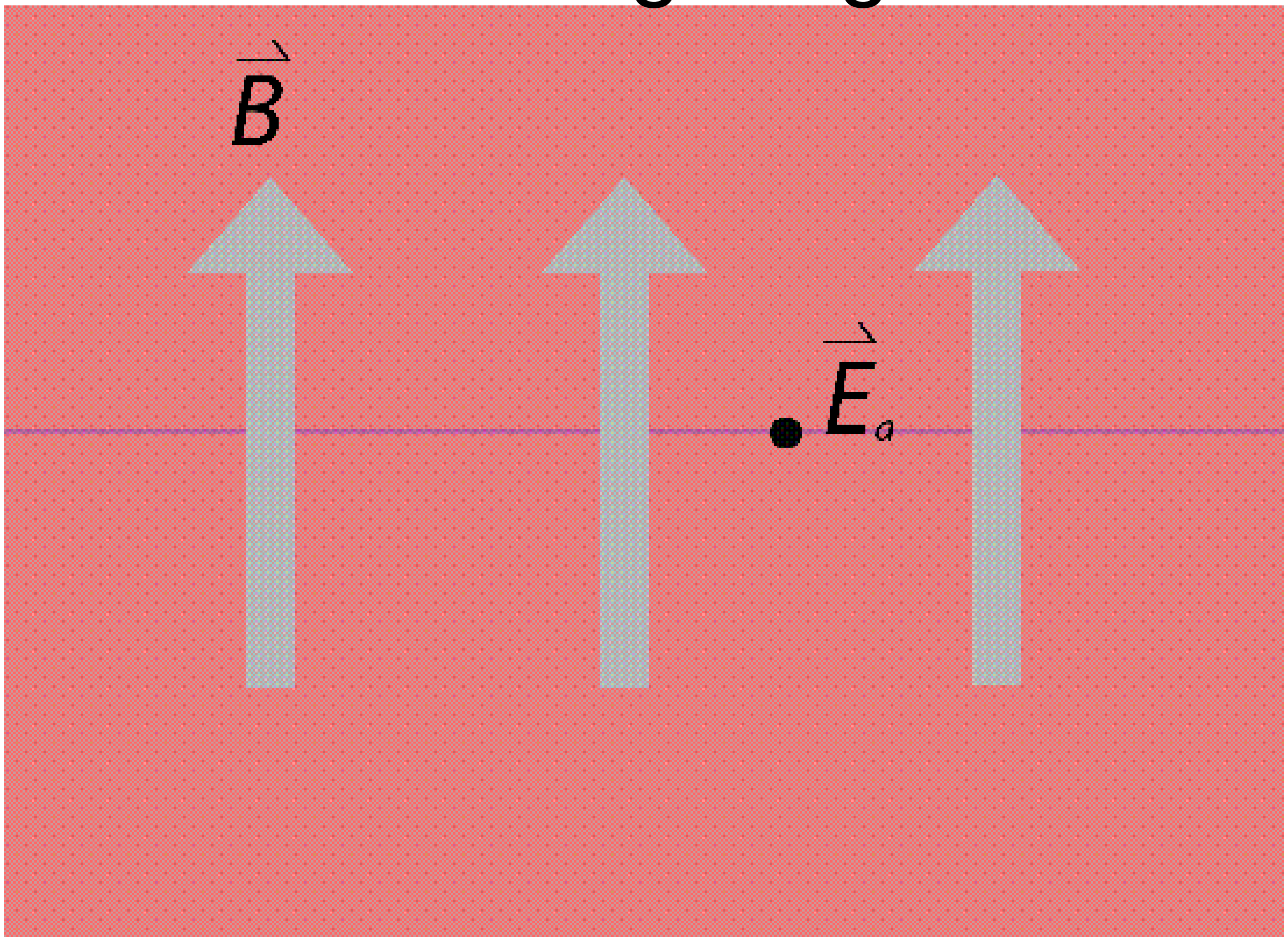
- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Kinetic energy ~$10^{-6} m_a$, very narrow line in spectrum.

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



Animation by Kristian Themann

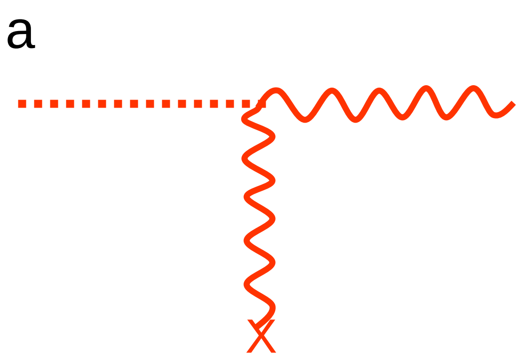
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



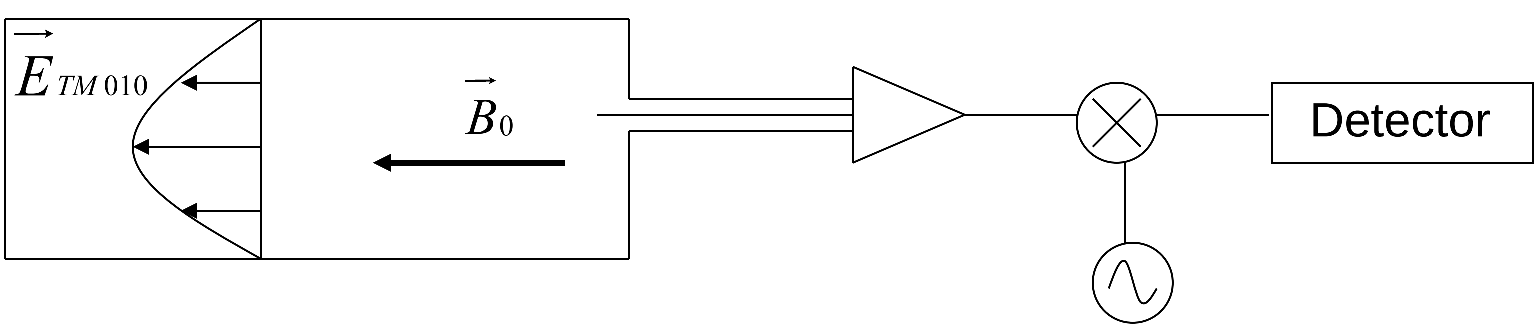
Animation by Kristian Themann

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)



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



$a \to \gamma$

The conversion power on resonance

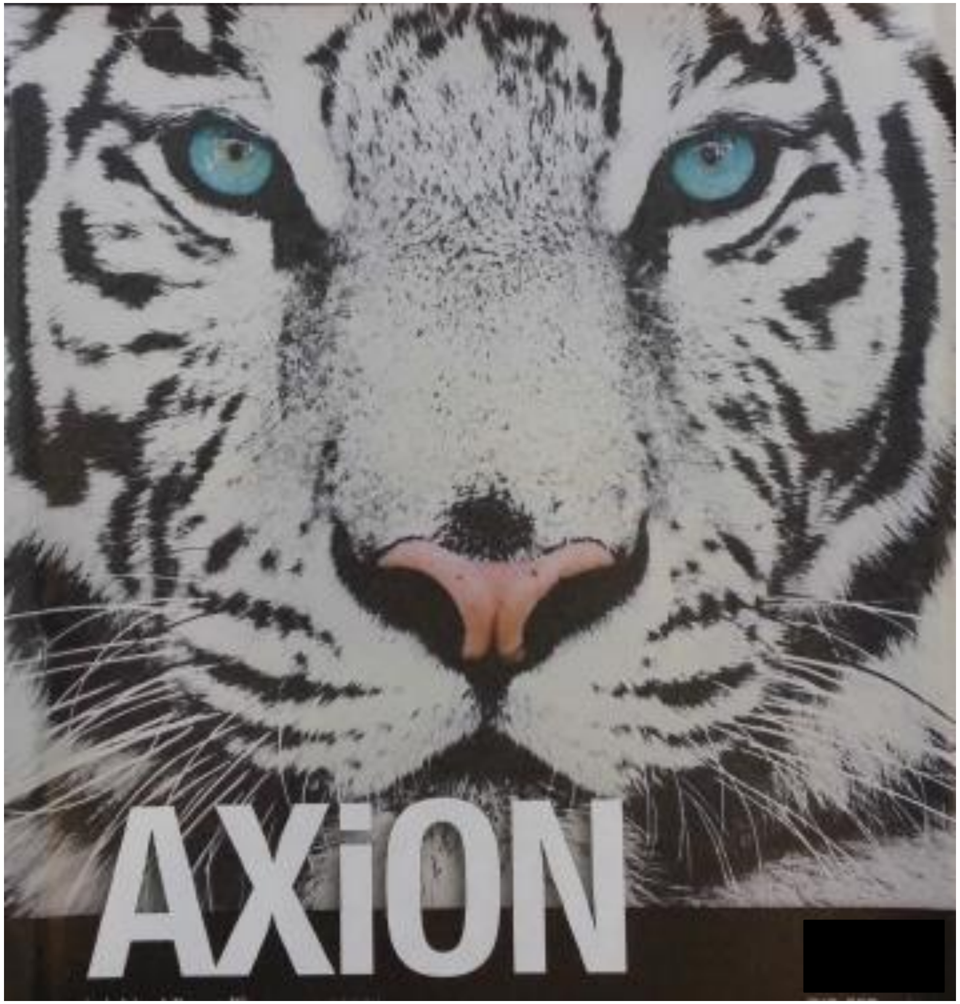
$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

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

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

The axion to photon conversion power is very small. Need to do more.

The CAPP Plan



- High T_c magnets
- Large Volume
- High quality factors
- Lowest temperature

CAPP/IBS axion target plan

Scanning rate:

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

- 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→40T

  High volume magnets/cavities, V: 5*l*→50*l*

  High quality factor of cavity, Q: $10^5 \rightarrow 10^6$

  Low noise amplifiers, T_N: 2K→0.25K

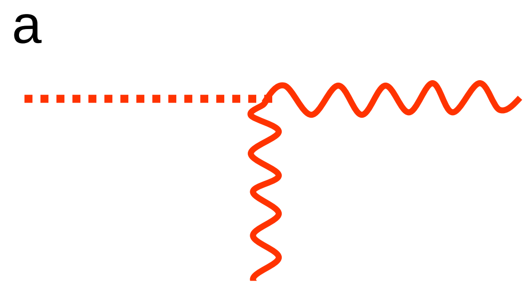
  Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6

Improvement in coupling constant: 70

Axions, the CAPP goals

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



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

- Axion dark matter in the mass range ~1μeV to 100μeV. Plan to either detect or exclude axions down to 10% of dark matter.

CAPP/IBS Plan

1. Establish an axion dark matter exp. based on existing technology. Upgrade equipment as soon as they become available.

2. Procure 25T, inner bore 10 diam., next: 35-40T.

3. Pursuit toroidal geometry: 100cm large diam., 20cm small diam., 80L, 12T.

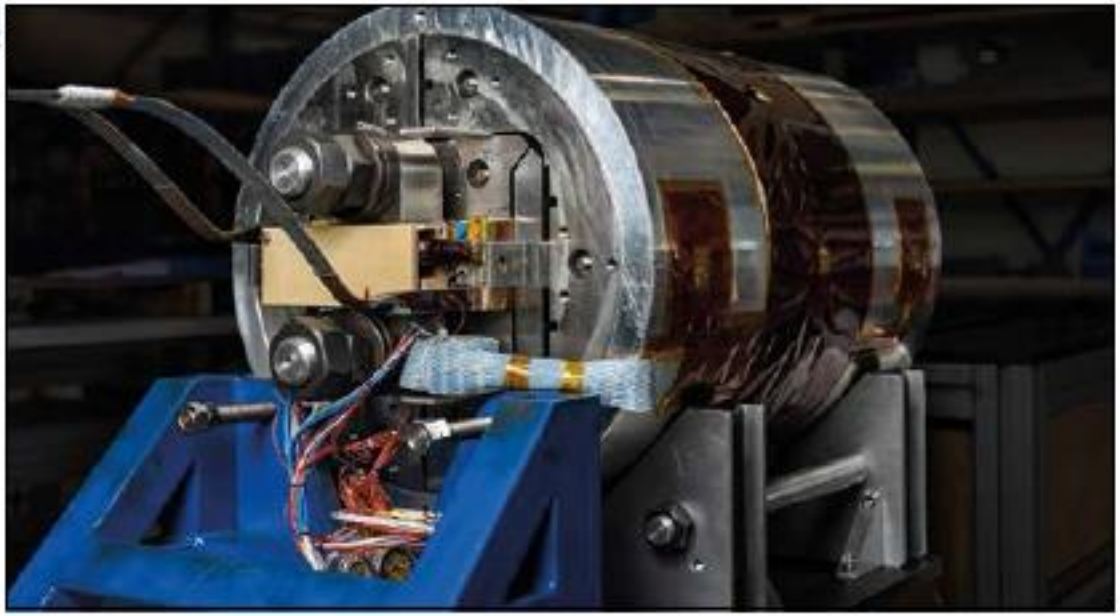
A Revolution in High Field Magnets

Traditional magnets: LHC magnets made with NbTi conductors

9T max Field.

Next magnets are made with Nb_3Sn conductors

CERN



16T max B-field.

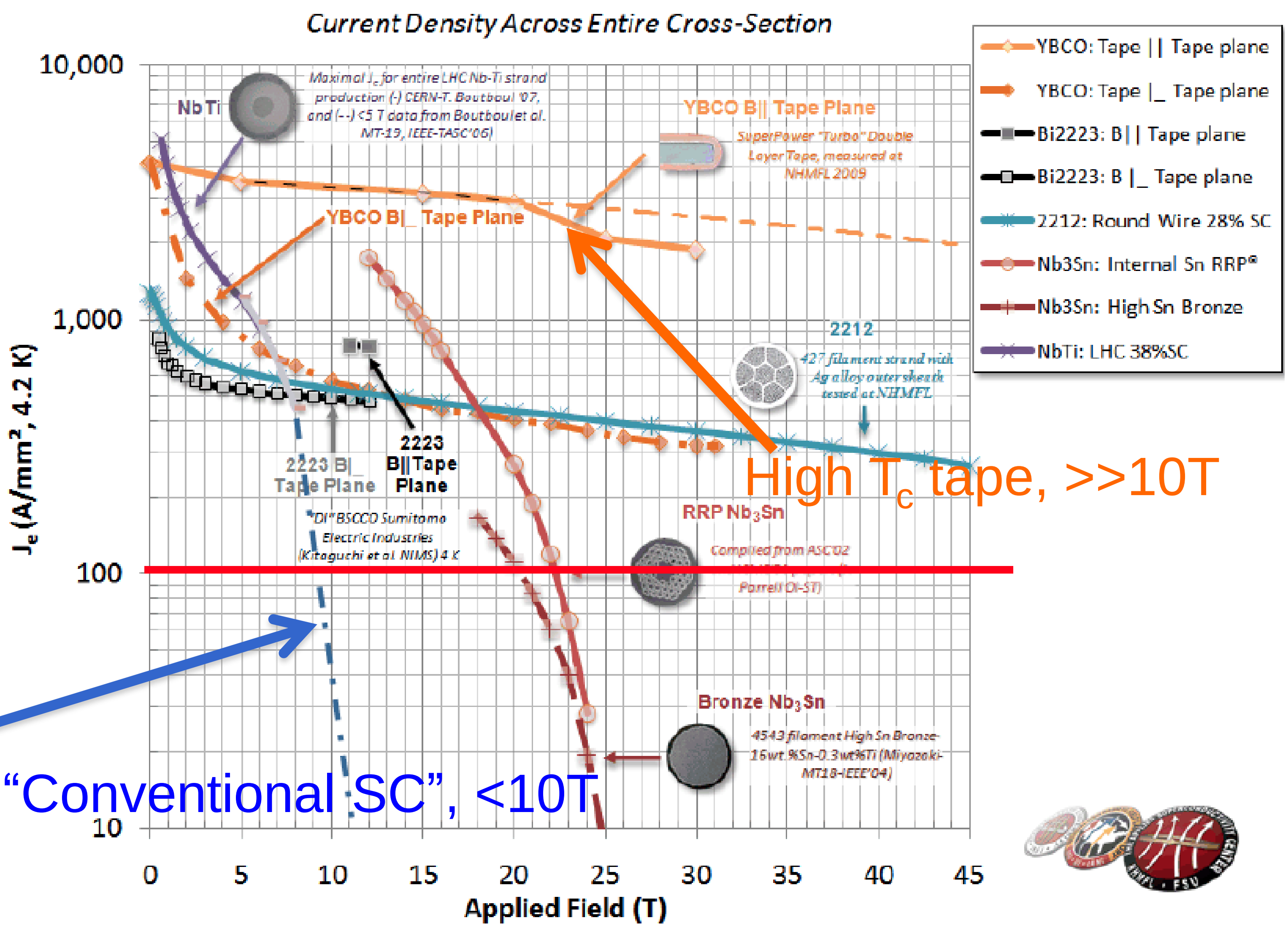
This model magnet recently achieved a field of 16.2 T at CERN, twice the nominal field of the LHC dipoles, offering promise for a long-term accelerator-based future for the laboratory.

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

Future Solenoids:

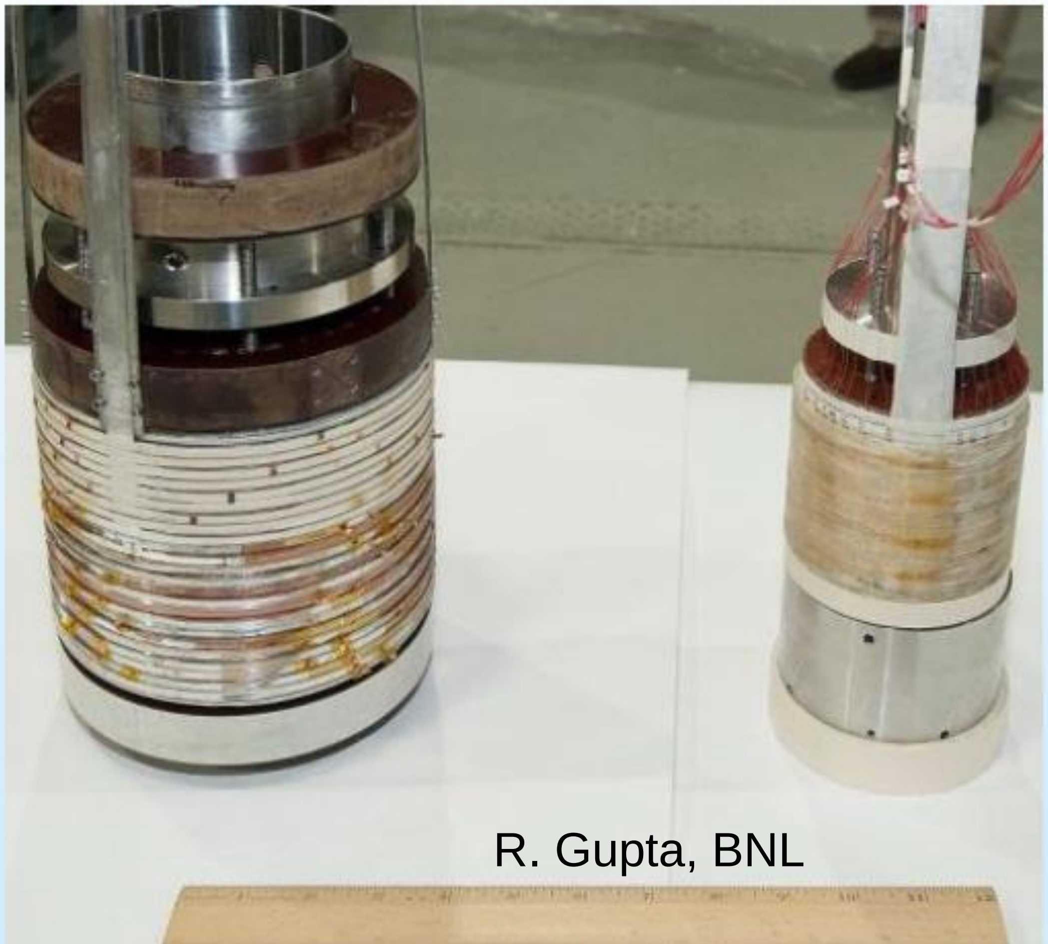
High- Temperature Superconductors



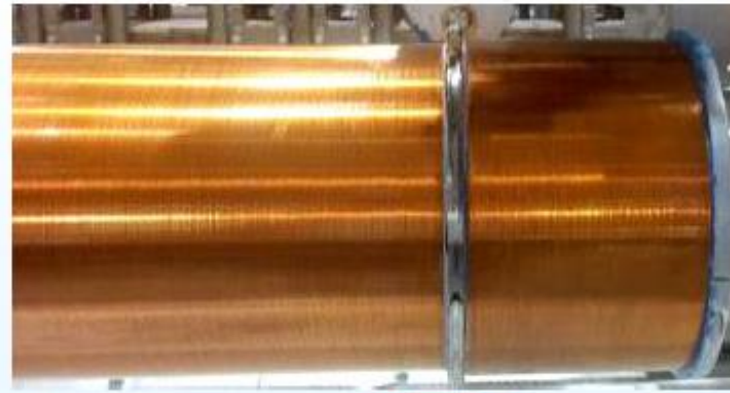
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

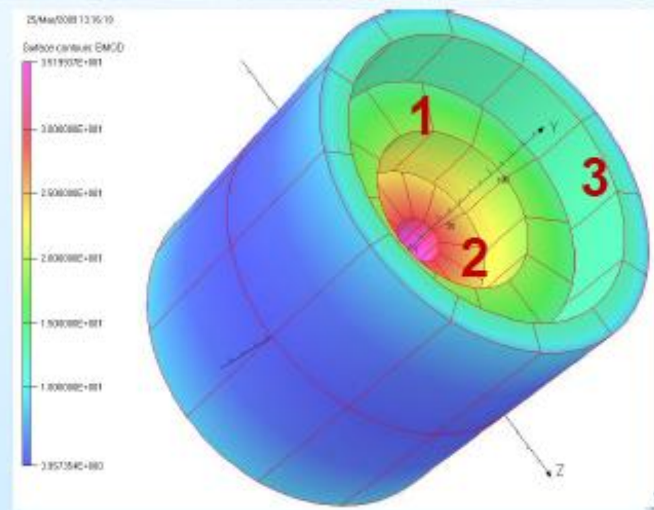
Status of High Field MAP Solenoids

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



R. Gupta, BNL





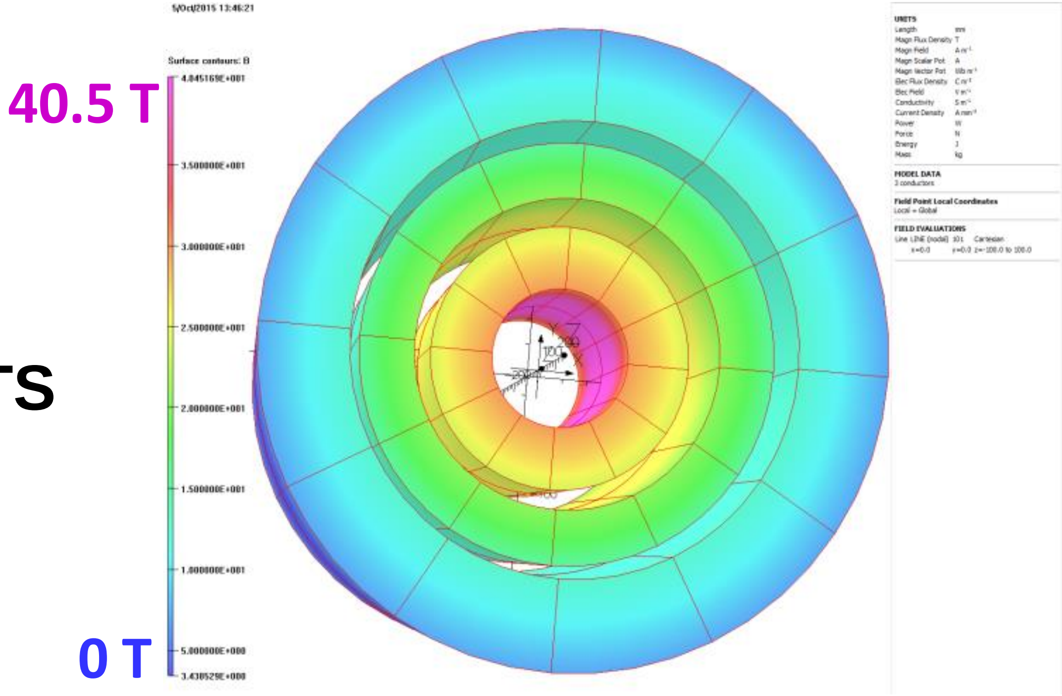
~30 T with NbTi outer
(40 T with Nb_3Sn or more HTS)

Design Considerations

Large aperture, high field
- **35 – 40 T , 100 mm**

HTS must be used
- **But HTS is expensive**

HTS/LTS hybrid design
- **~25 T HTS and 10-15 T LTS**



This magnet pose huge challenges
- **Large stresses**
- **Quench protection**
- **New conductor**

Magnet Development

BNL, Summer 2015

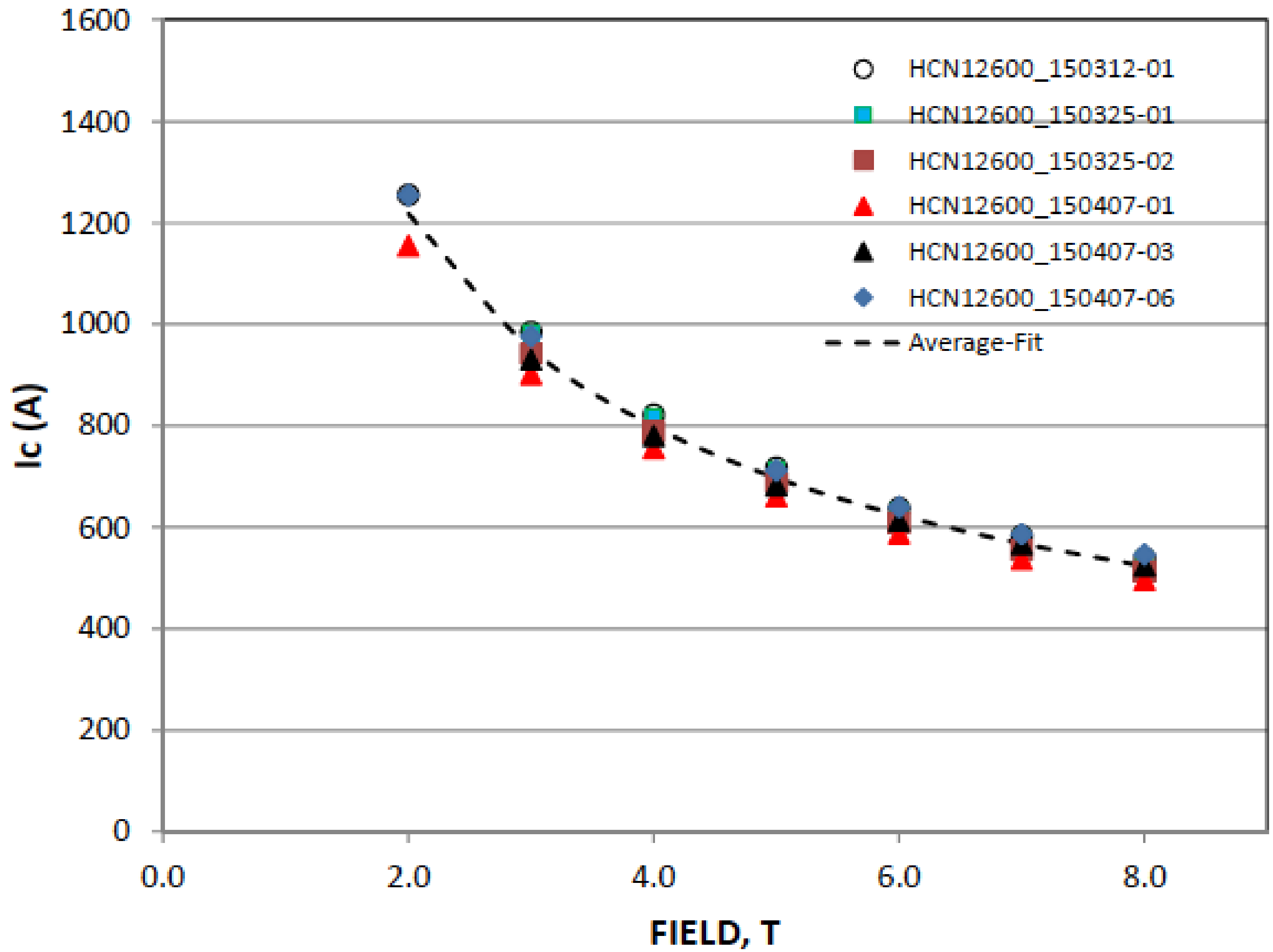


Figure 5 The critical current at 4.2 K versus applied field for the 6 samples. This shows that the variation between the samples is quite small.

Axions, High Quality Q-Factor Cavity in the presence of Large B-fields

CAPP: High quality factor cavities

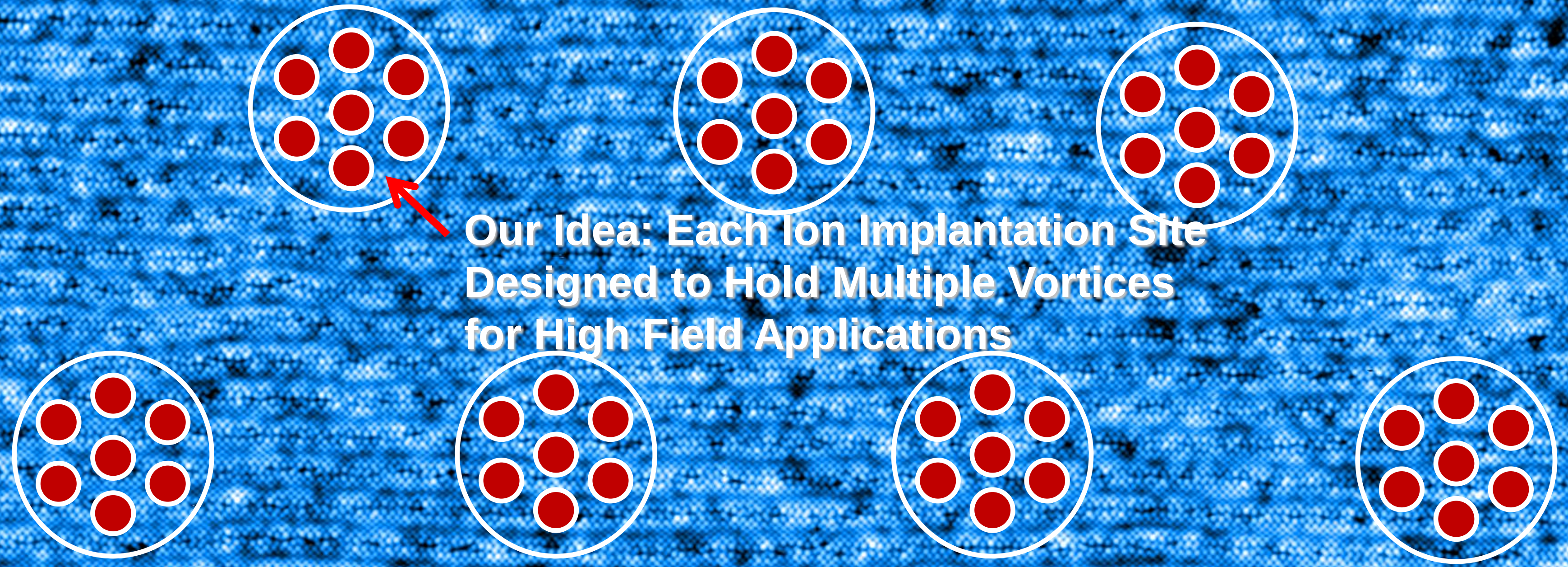
- We have started an R&D program to achieve large Q in the presence of large B-fields.
- Presently: $Q \sim 10^5$ for copper cavities. axion Q_a: $\sim 1.5 \times 10^6$
- CAPP goal: Q: $\sim 10^7$, potential gain factor: 15.

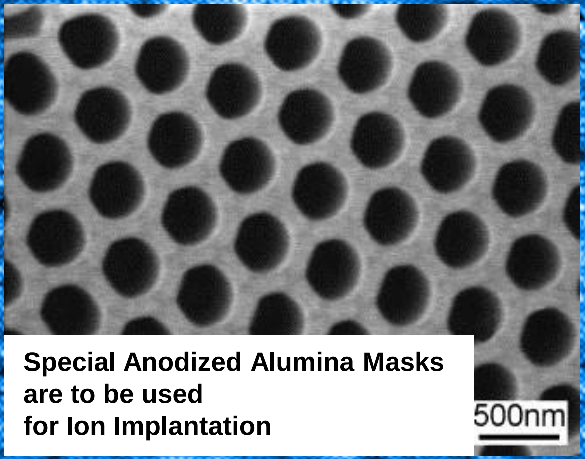
$$Q = \omega \frac{\text{Stored energy}}{\text{Power loss}} \sim \left(\frac{V}{S\delta} \right) = \frac{\pi R^2 L}{2\pi R^2 + 2\pi R L} \frac{1}{\delta} = \frac{L}{R+L} \frac{R}{2\delta}$$

CAPP/IBS: Proposal of Cryogenic STM Research Group

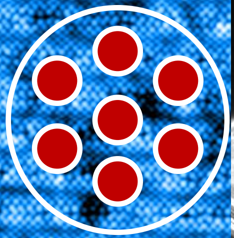
(Prof. Jhinhwan Lee/KAIST and CAPP)

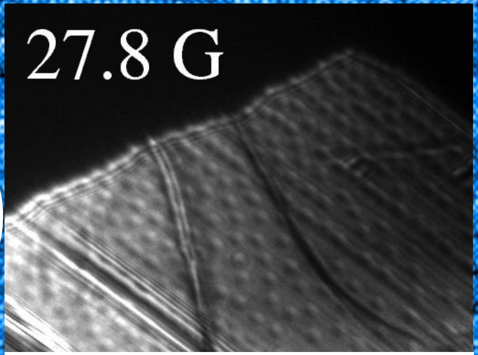
Enhancement of the High Tc Superconductors by Novel Vortex Engineering





Special Anodized Alumina Masks are to be used for Ion Implantation

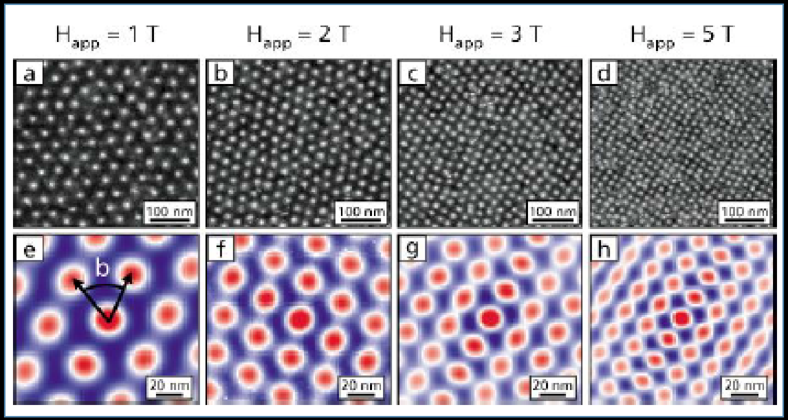


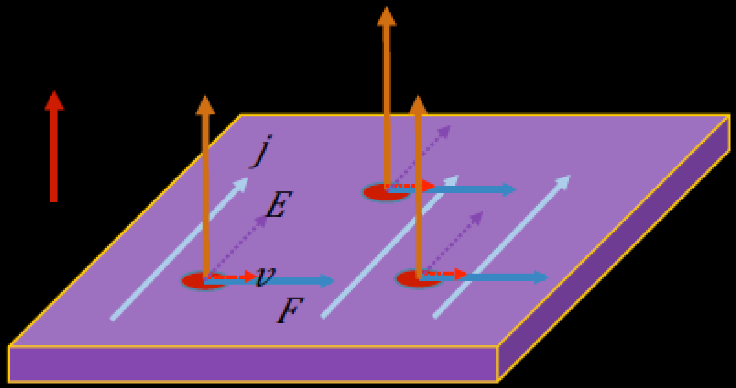


Lorentz Microscopy Visualization of Distributed Vortices on BSCCO

BSCCO
(c) KAIST
Cryogenic SPM Laboratory

Issue: Vortex motion in magnetic field





When Type I superconductor is placed in high magnetic field, superconductivity is broken.

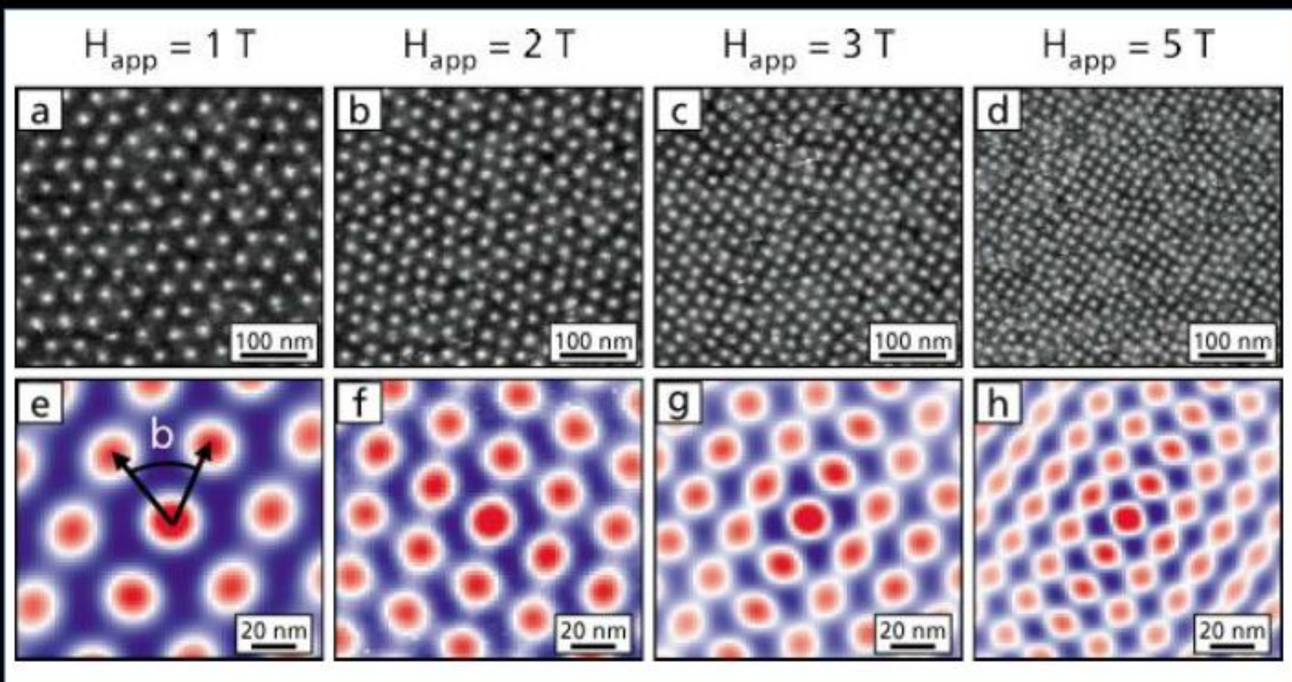
When Type II superconductor is placed in high magnetic field, the magnetic field is split into very small quantities and penetrates the superconductor in the form of vortices. The rest of the area maintains superconductivity.

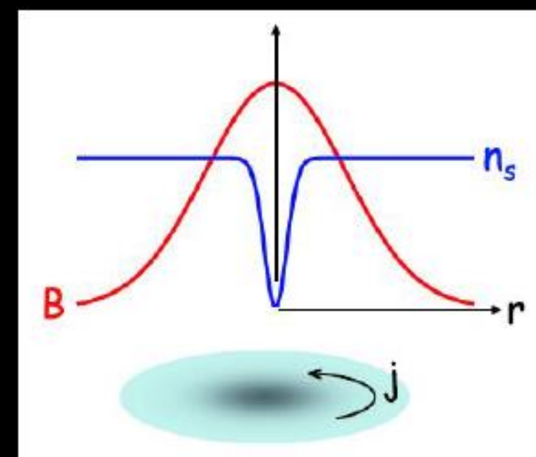
In the presence of surface current the vortices experience Lorentz force. If a vortex moves by the force it will dissipate heat.

→ Build nanoscale structures so that the individual vortices are trapped!

Seeing is everything!

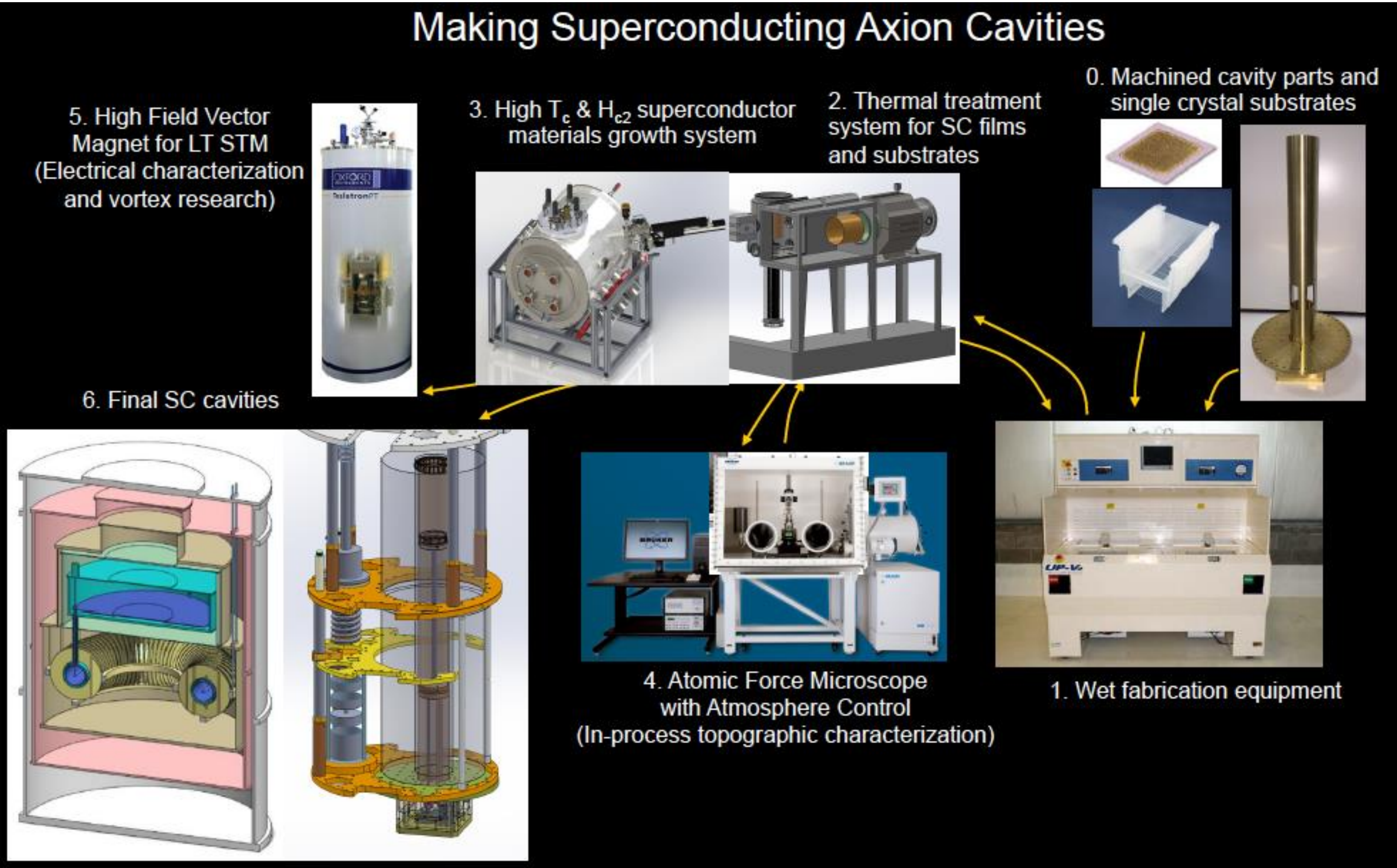
Scanning Tunneling Microscopy is a perfect tool for Axion superconducting cavity research





Using tunneling current, we can visualize the distribution of vortices penetrating a superconductor.

Cryogenic STM Research Group
(Prof. Jhinhwan Lee/KAIST and CAPP/IBS)



Axions with SQUIDS: Quantum-Noise Limited Amplifiers

CAPP: SQUID amplifiers

Five year contract with KRISS:

Korea Research Institute of Standards and Science

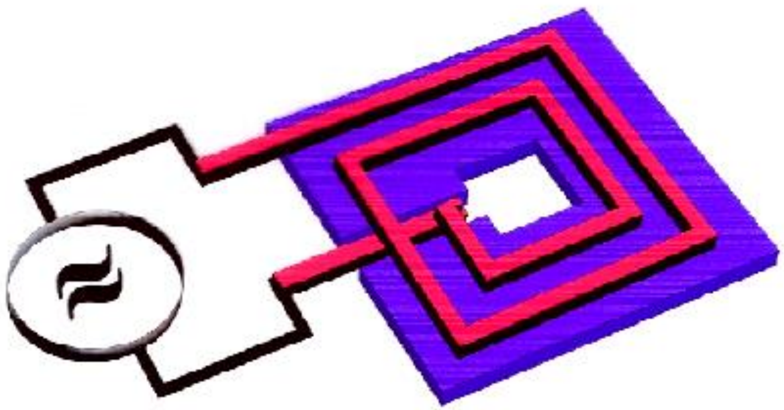
(Yong-Ho Lee's group)

We have started a development program with KRISS to provide us with (near) quantum noise limited SQUID amplifiers in the 1-10 GHz range. Evaluate method for higher frequency.

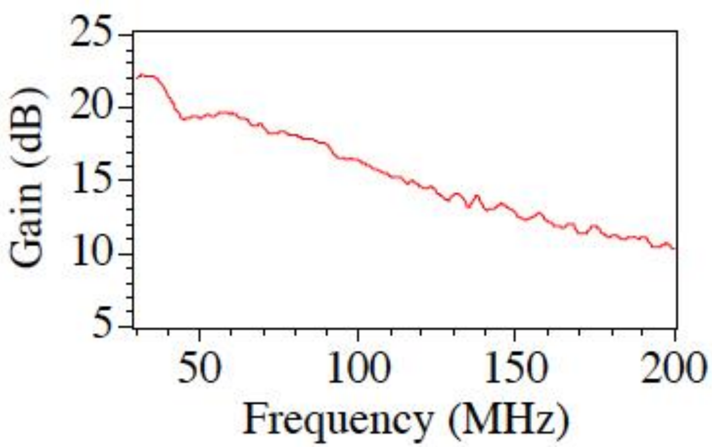
SQUID amplifiers

MSA: Principle

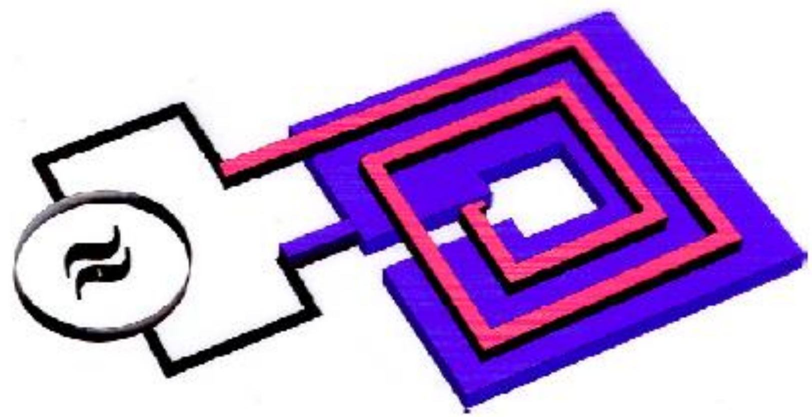
Conventional SQUID Amplifier



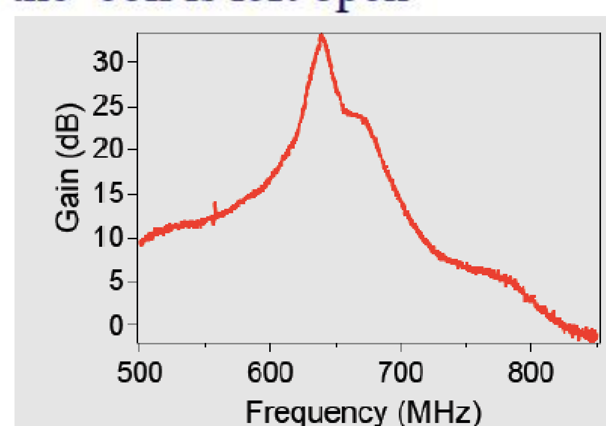
- Source connected to both ends of coil



Microstrip SQUID Amplifier

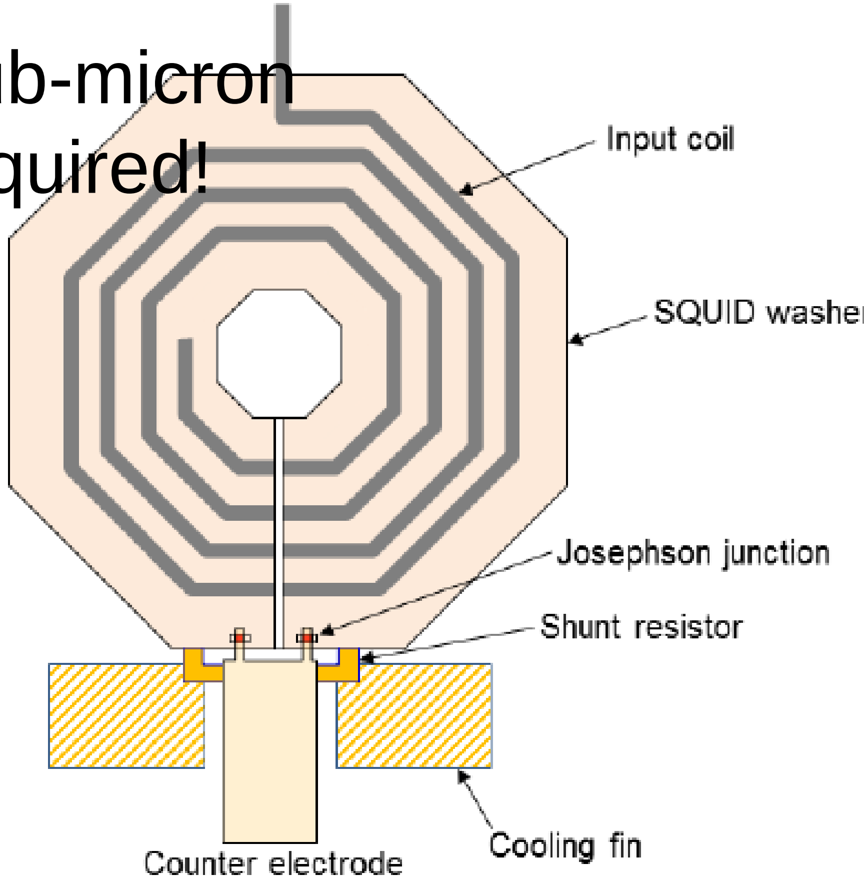


- Source connected to one end of the coil and SQUID washer; the other end of the coil is left open



SQUID amplifiers from KRISS

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



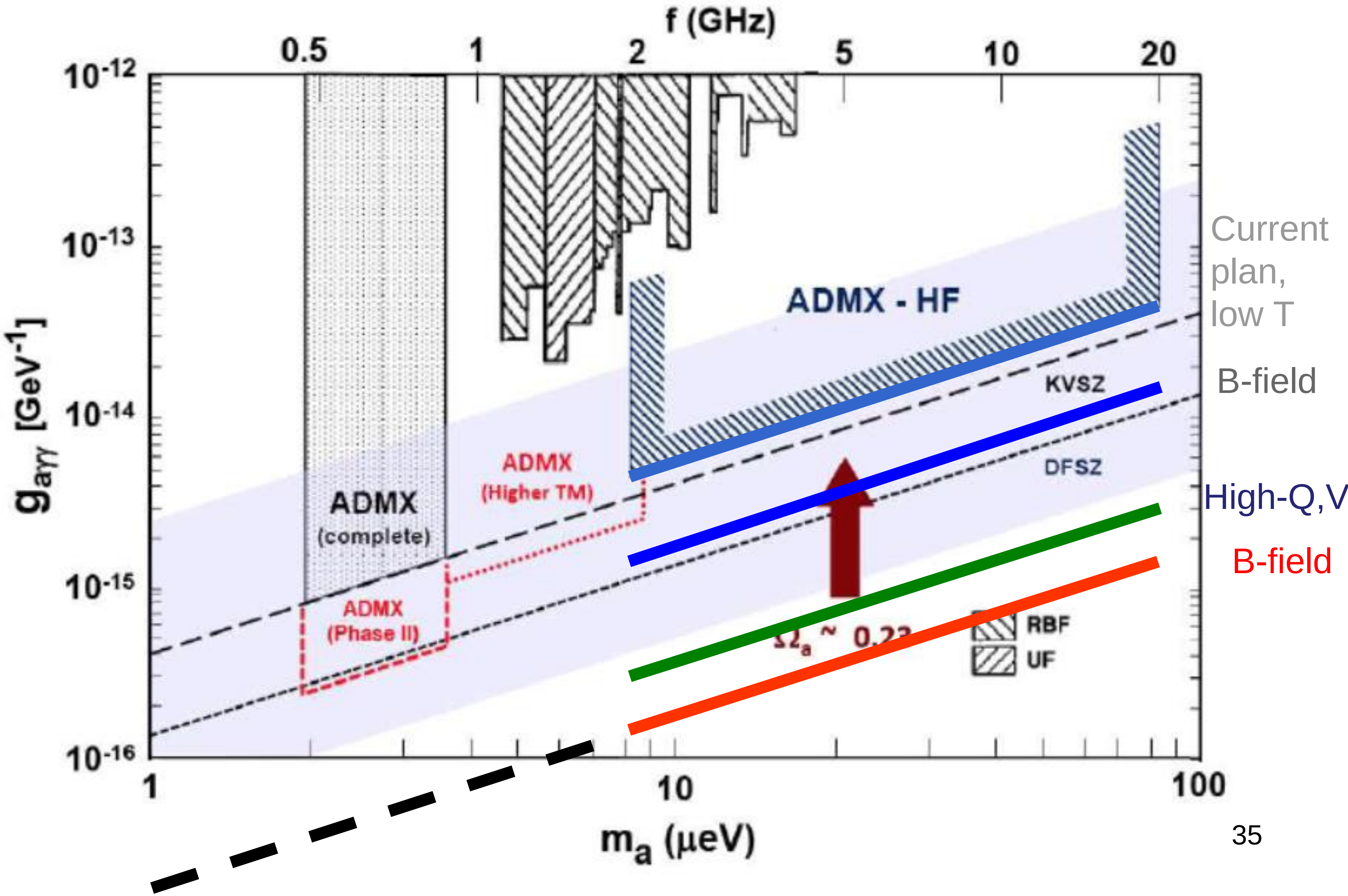
Physical temperature: aiming for 30mK. Quantum noise limit: 50mK at 1GHz, proportional to frequency…

Teamleader: Dr. Woohyun Chung

CAPP Ultra Low Temp Axion Search in Korea

- ✓ "ENGINEERING RUN", building Infrastructure for upcoming experiments, using 9T magnet
- ✓ Ultra-cold axion dark experiment (<100 mK)
  - ✓ Designing cavities with frequency tuning systems (Dr. H. Themann)
    - ✓ Different inner surface coating techniques (ultra pure Cu and Al >6N)
    - ✓ Tuning rod and antenna with piezoelectric actuators
  - ✓ Start with ~5 GHz (4.5 cm id) freq. range
  - ✓ Cryogenic RF (circulators, HEMT and couplers…)
  - ✓ Complete RT Electronics/DAQ almost ready

ADMX goals and CAPP plan

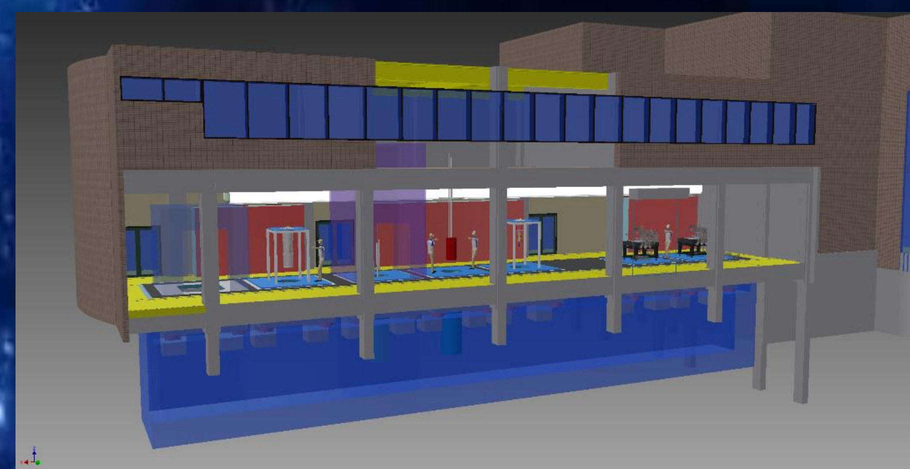


Axion exp. development plan

	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

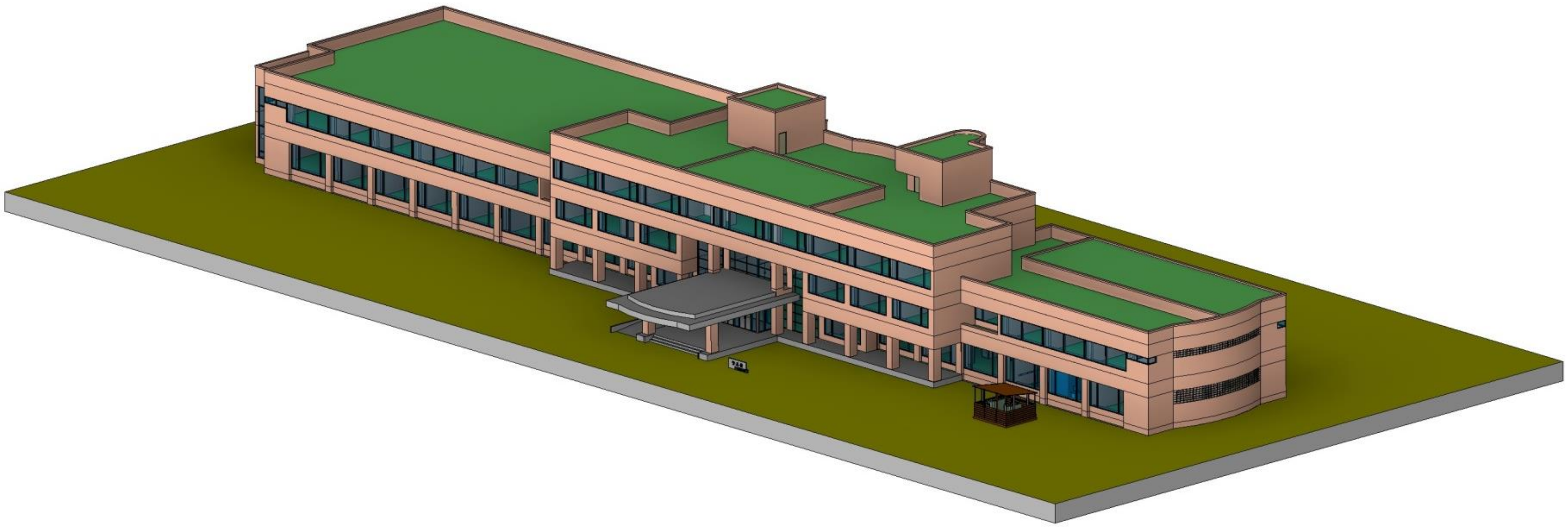
Where are we?

Axion Dark Matter Research at Munji Campus – IBS CAPP KAIST



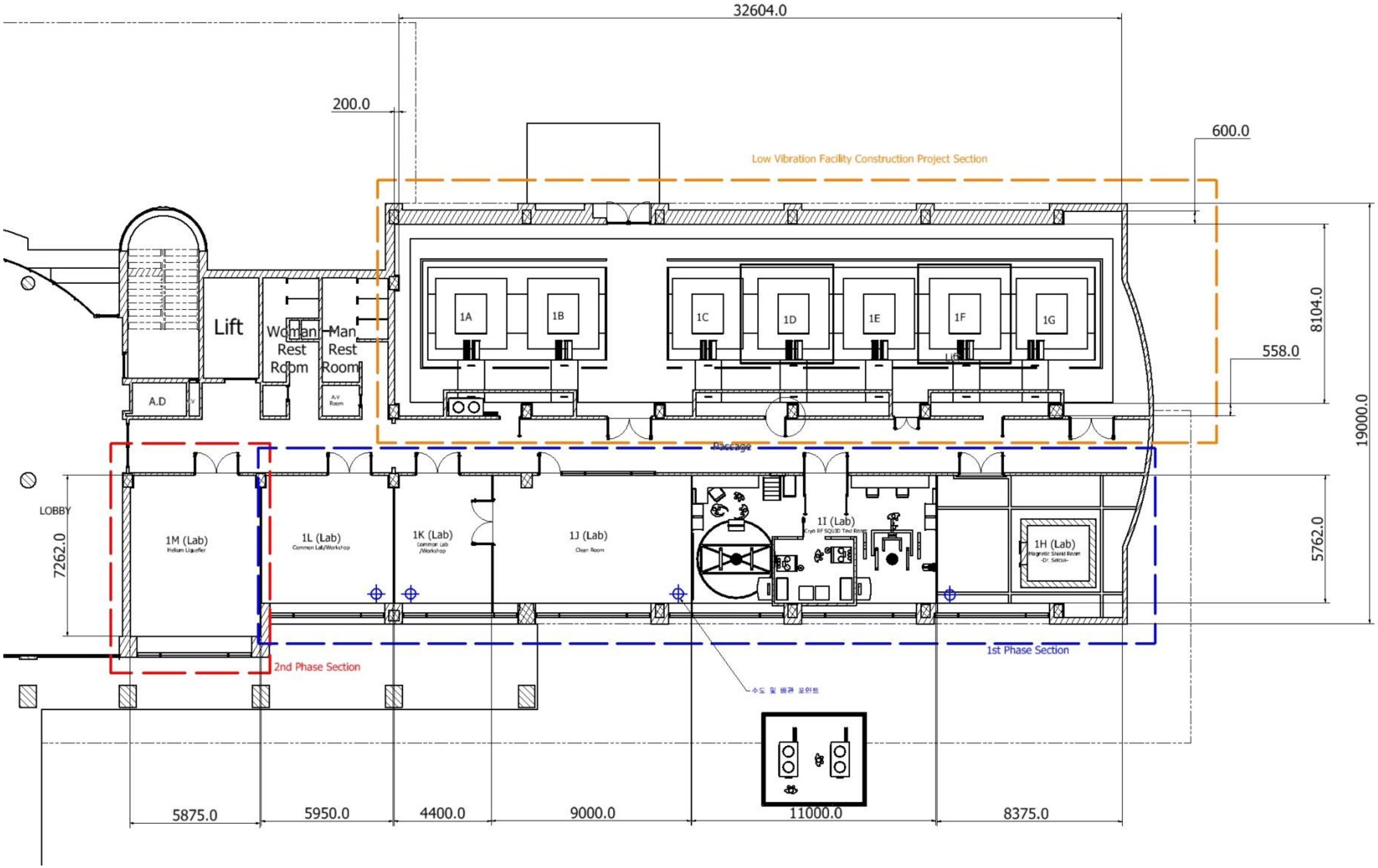
-Creation Hall-

CAPP Research Bldg. at KAIST Munji Campus

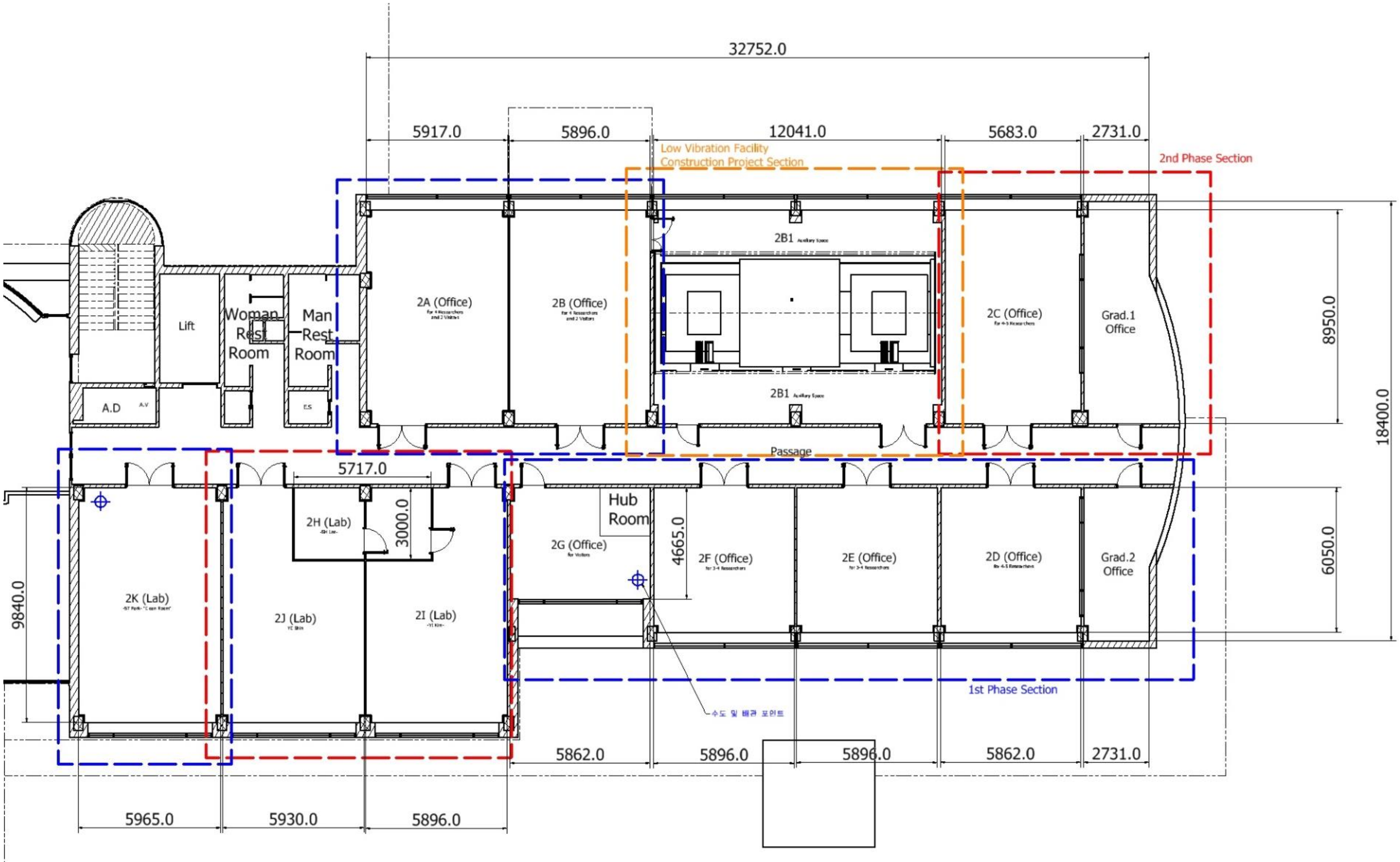


-1st Floor Drawing-

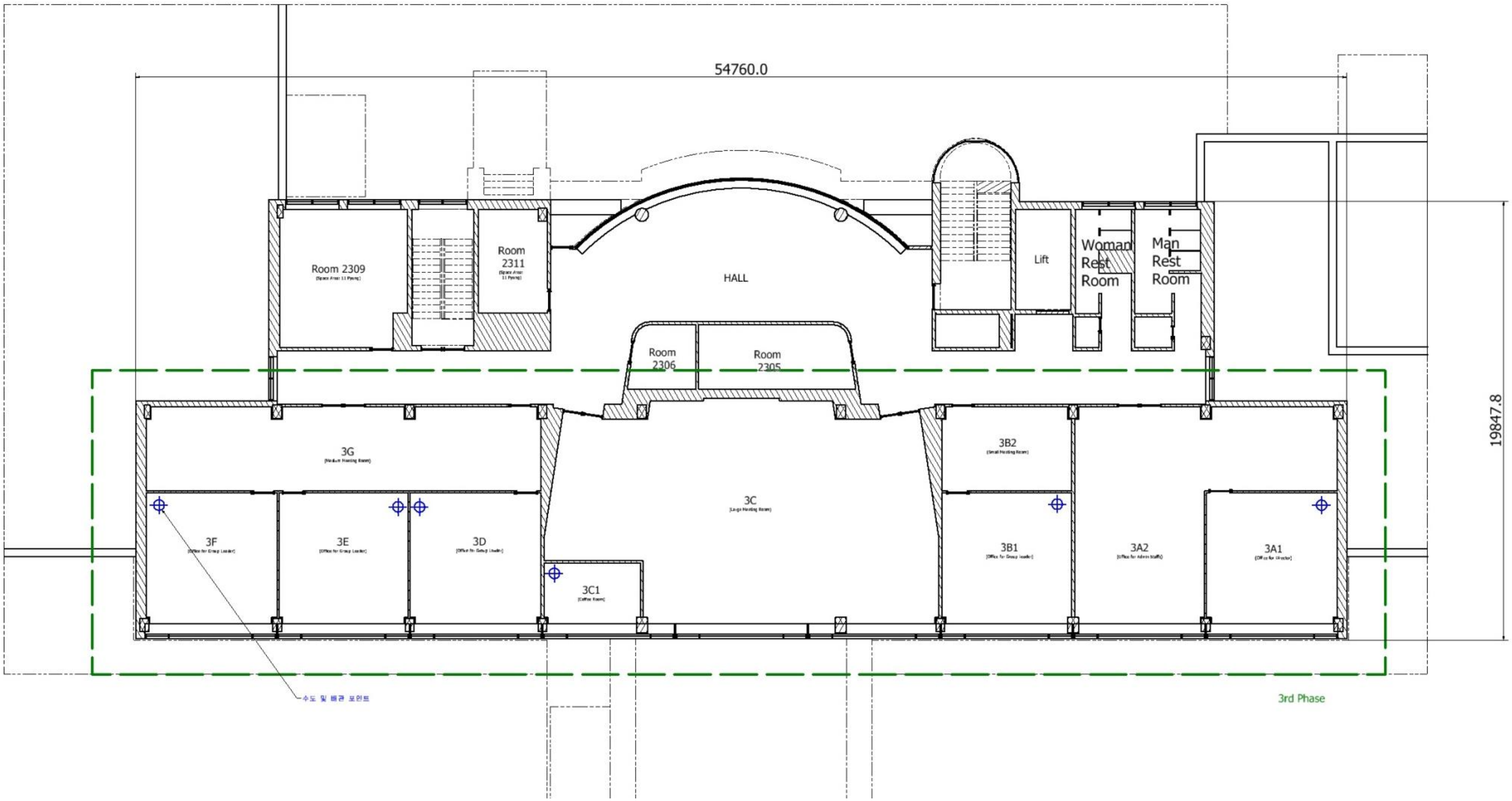
Seven, low vibration pits, two with magnetic shielding



-2nd Floor Drawing-



-3rd Floor Drawing-



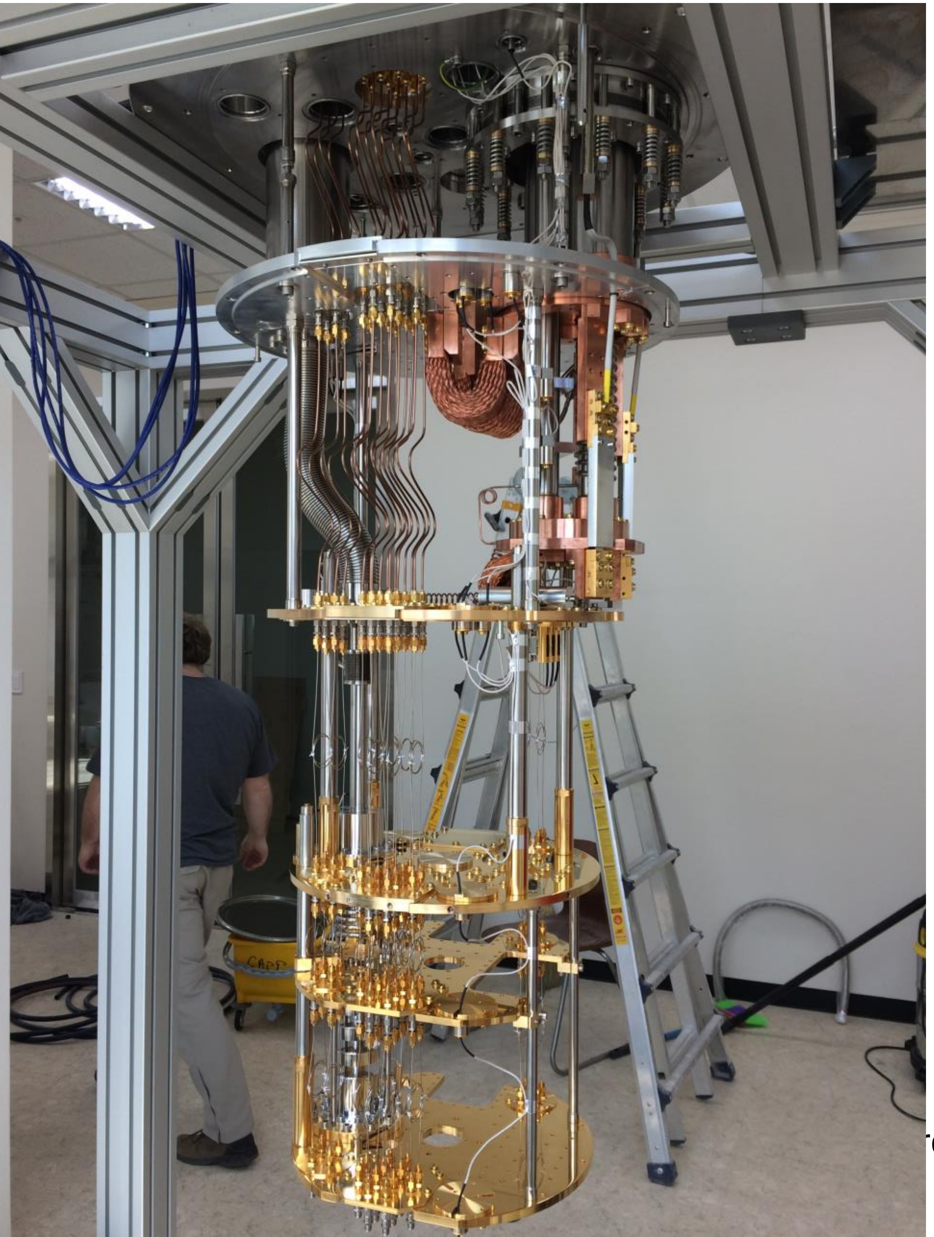
- 1st Phase Creation Hall Site Picture-

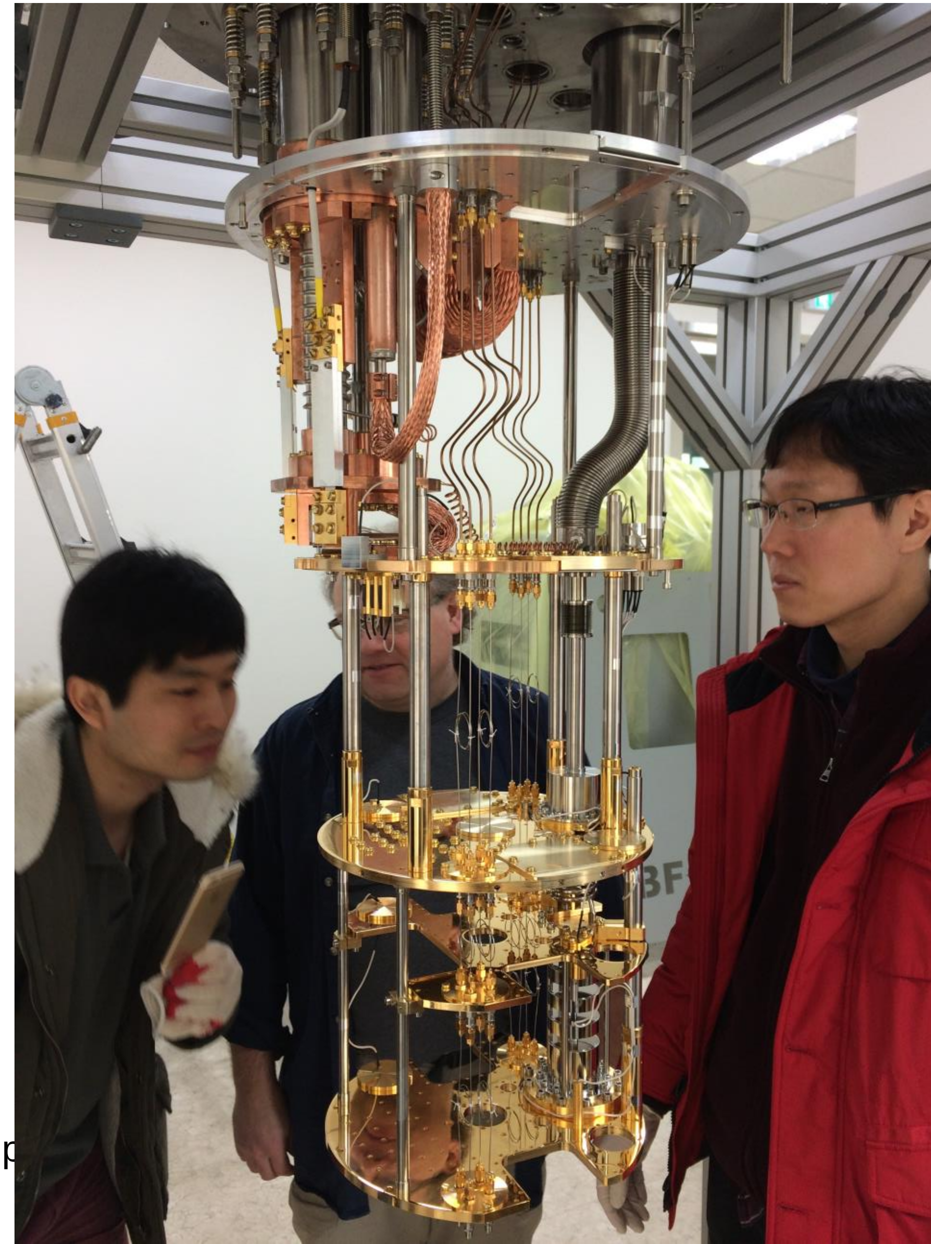
- Low Vibration Site Picture-

- Low Vibration Site Picture-

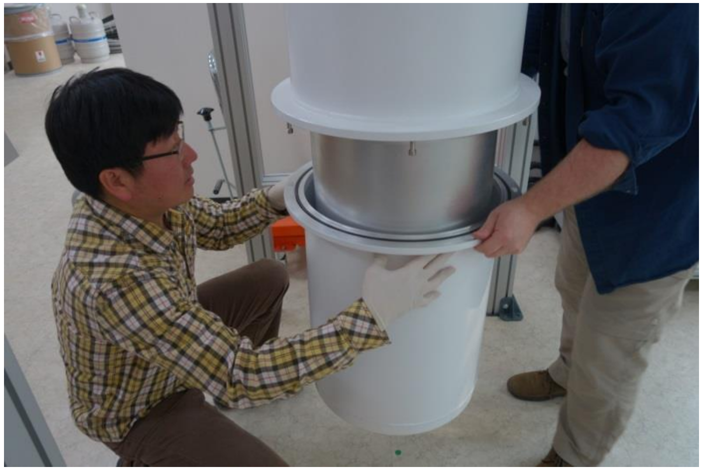
- 1st Phase Creation Hall Site Picture-

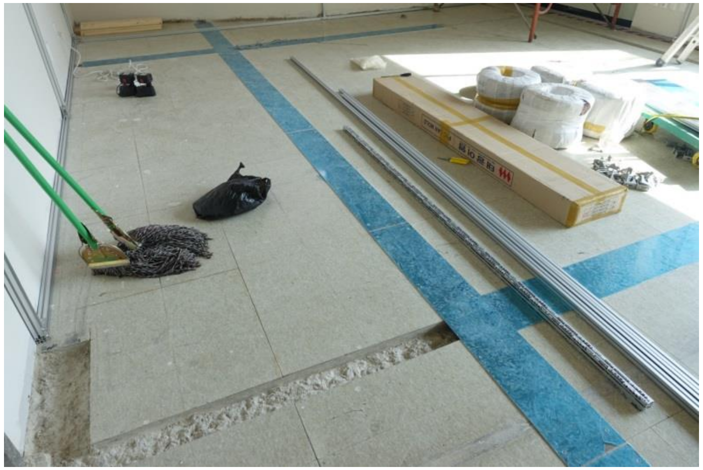
DR Installation & Tests



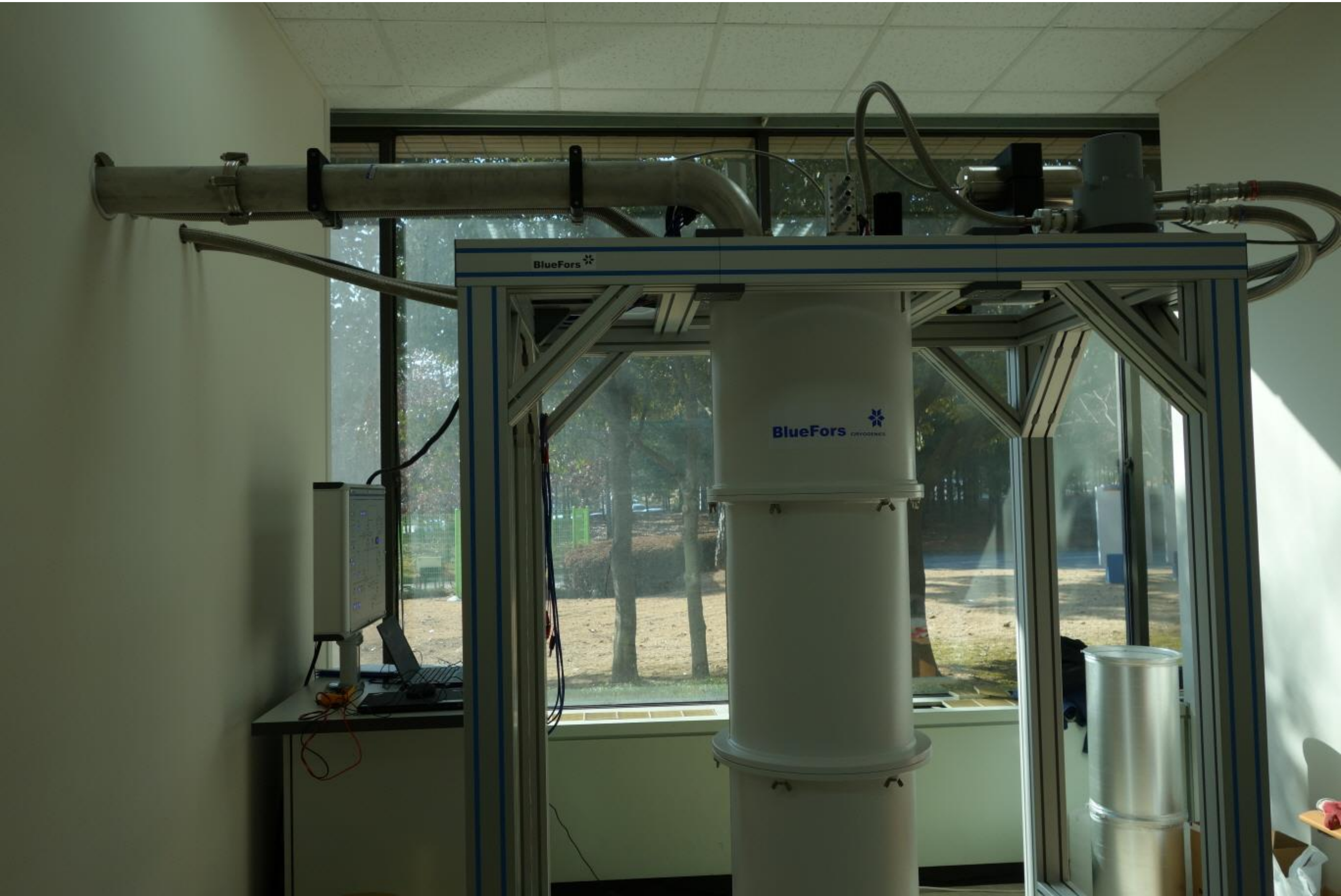


- 1st Phase Creation Hall Site Picture-





DR Installation & Tests



DR Installation & Tests

DR Installation & Tests

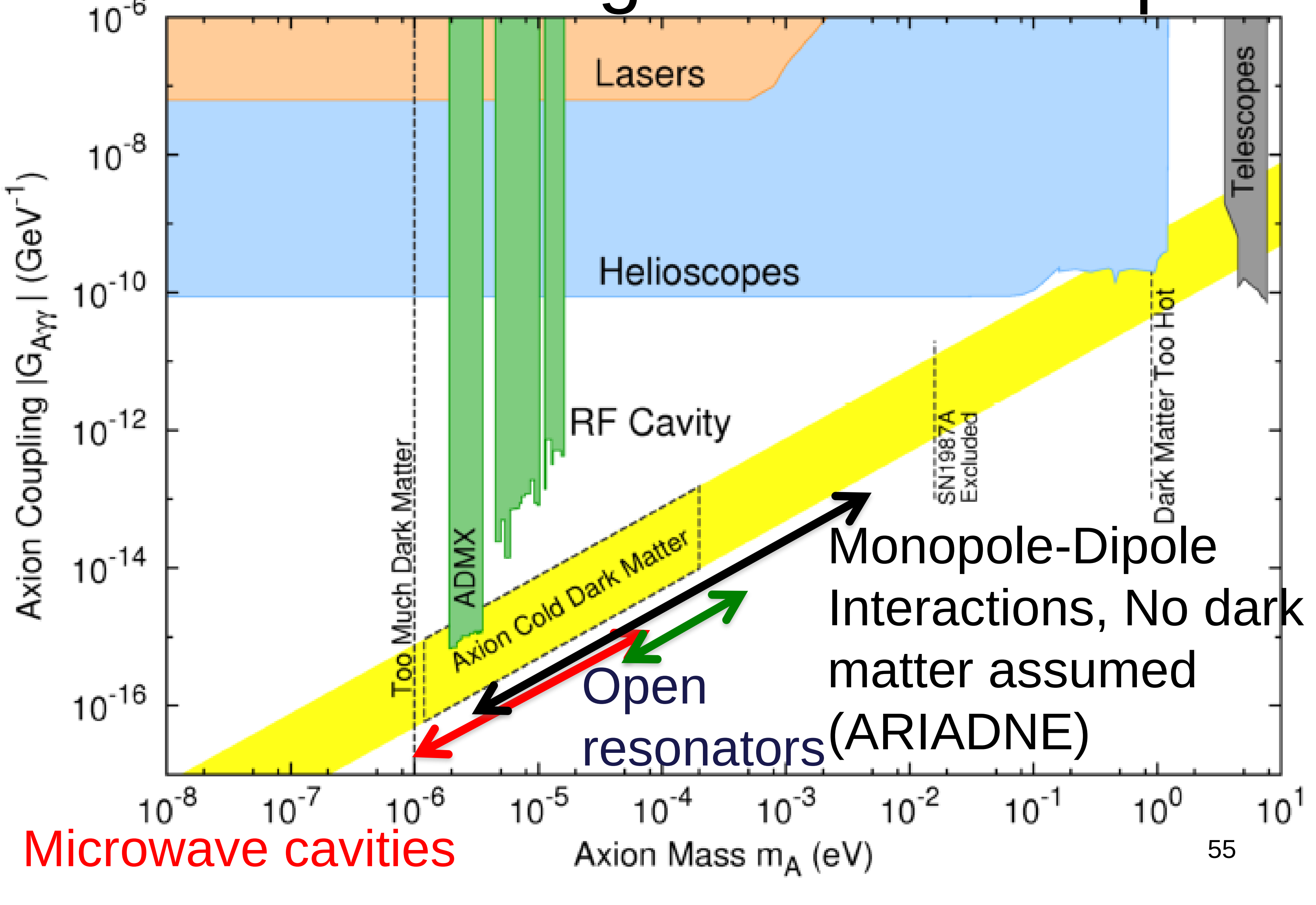
- In the morning, BF#4 at ~4 K, BF#3 at ~10 K
- Start dilution on BF#4 and reached 7.1 mK
- SC Magnet turned on → reached 8T in 4 hours
- Start dilution on BF#3 and reached around 9 mK
- Ramping down SC Magnet
- Test results (cooling powers) were all satisfactory!!!

DR Installation & Tests

DR Installation & Tests

Chillers

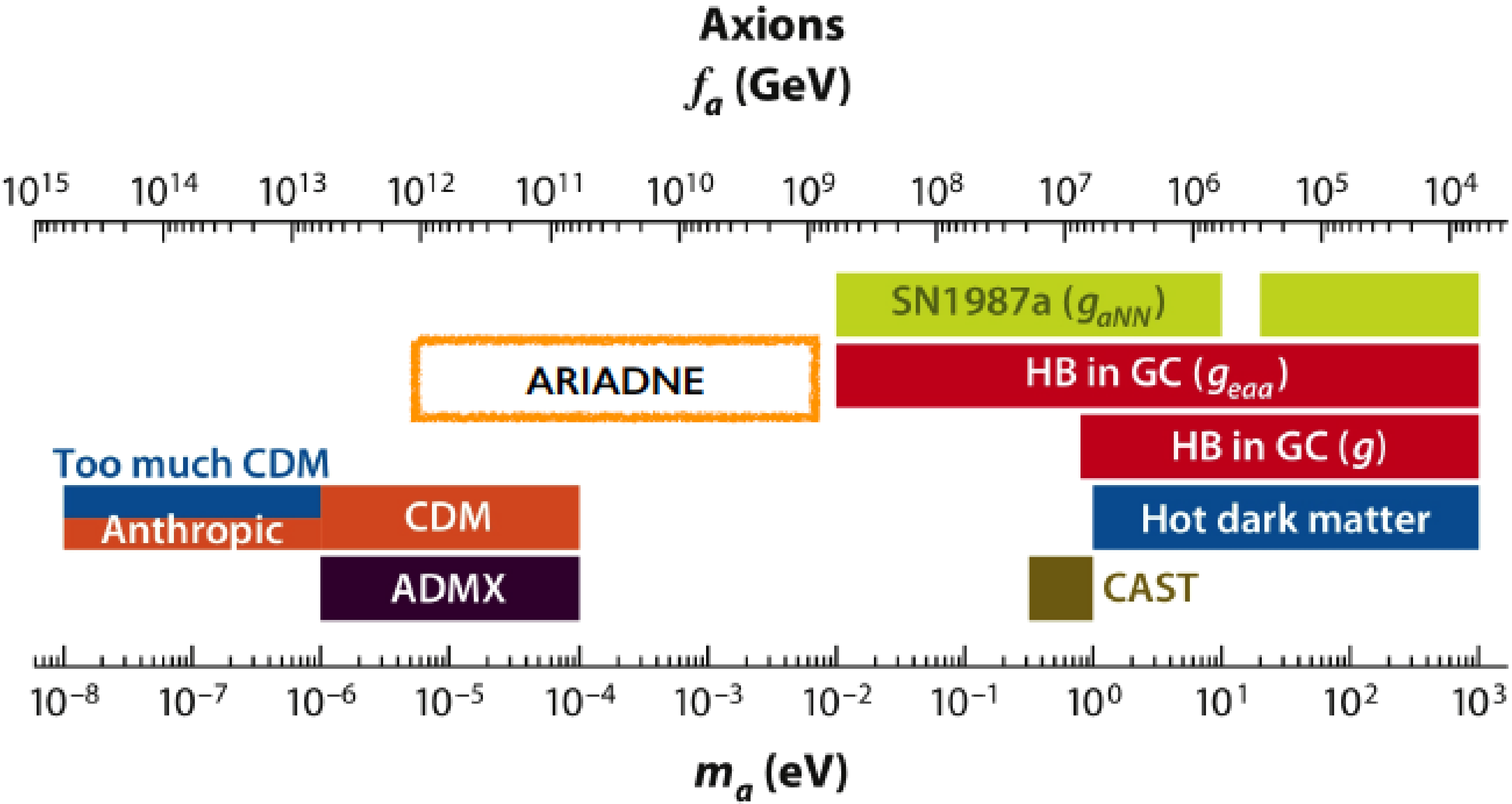
Axion mass target and technique



Axions with ARIADNE:

Axion Resonant InterAction DetectioN Experiment

ARIADNE’s axion mass range reach



In the plot, the areas marked ADMX and CAST include the future search ranges.

PROPOSED CONCEPT

Axion Resonant InterAction Detection Experiment

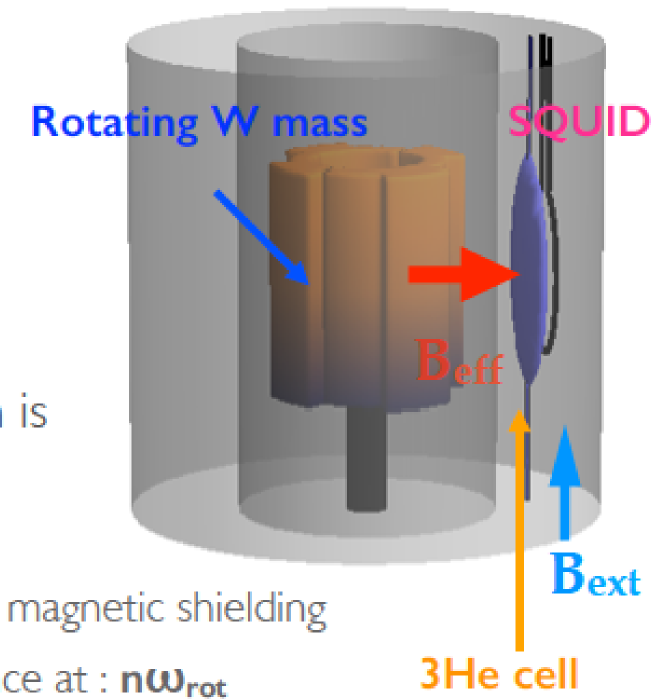
The effective potential between monopole and dipole is

$$U_{sp}(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{\lambda_a r} + \frac{1}{r^2}\right)e^{-\frac{r}{\lambda_a}}(\hat{\sigma}\cdot\hat{r}) = -\vec{\nabla}V_{a_s}(r)\cdot\hat{\sigma}_f$$

where $V_{a_s}(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{e^{-\frac{r}{\lambda_a}}}{r}\right)$ is axion potential

The effective magnetic field induced from this interaction is

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



- The effective magnetic field is not screened by superconducting magnetic shielding
- Non-magnetic rotating mass oscillates the interaction in resonance at : $n\omega_{rot}$
- A dense ensemble of polarized ^{3}He gas with precession at : ω_{3He}
- The NMR sample (^{3}He) develops a magnetization perpendicular to its polarization

$$M(t) \simeq \frac{1}{2}n_s p \mu_N \gamma_N B_{eff} t\cos(\omega t)$$

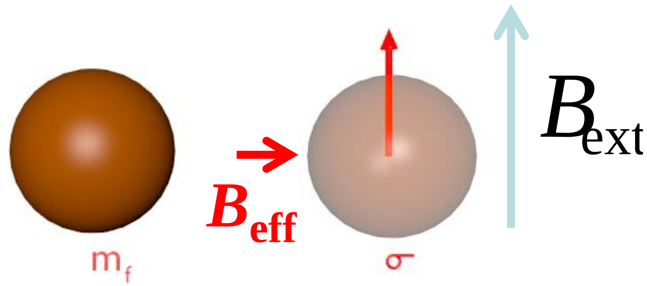
Teamleader: Yun-chang Shin

[1] A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014).

Resonant enhancement method

Spin ½ ^{3}He Nucleus

A. Geraci



Oscillate the mass a
Larmor frequency

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

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

Bloch Equations

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

$$|\uparrow\rangle$$

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

$$|\downarrow\rangle$$

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

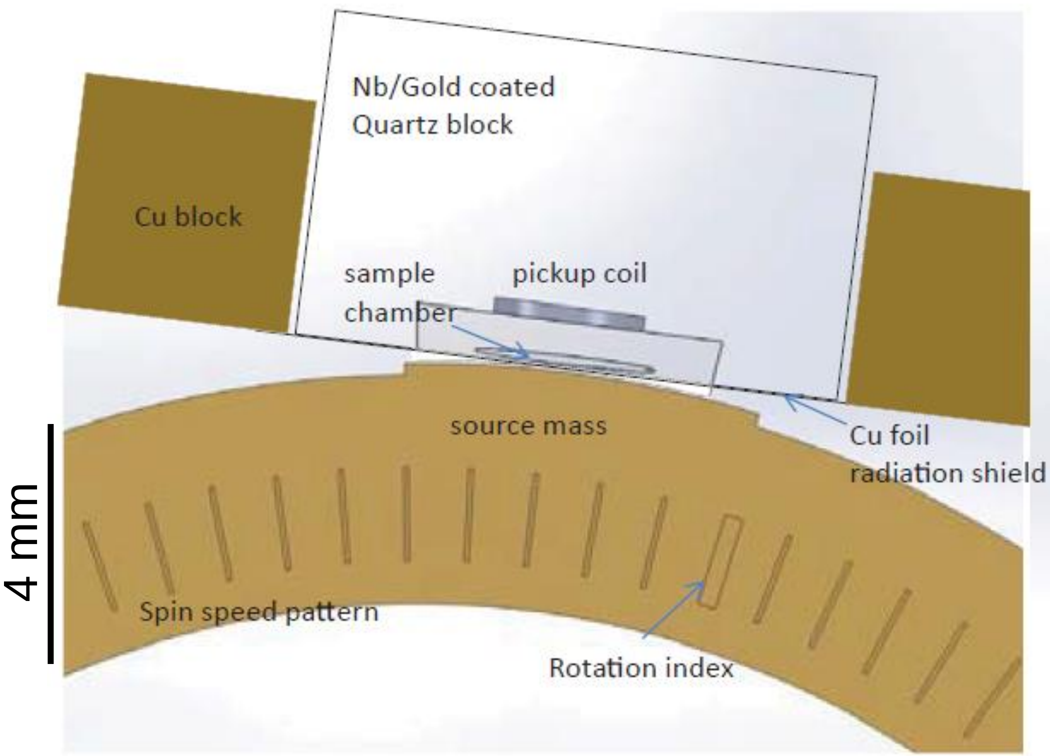
Amplitude is resonantly enhanced by Q factor ~ ωT_2.

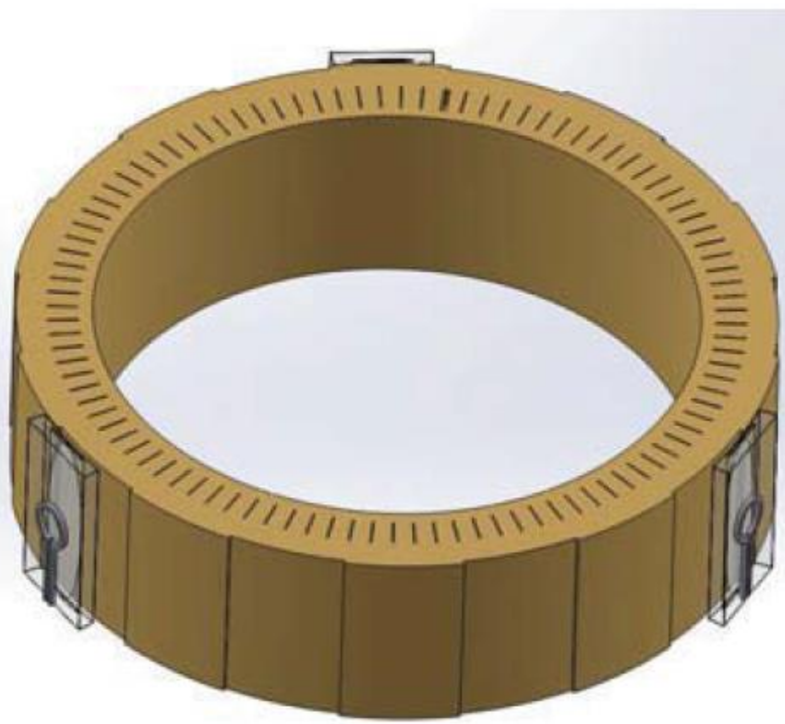
Can be detected with a SQUID

Experimental parameters

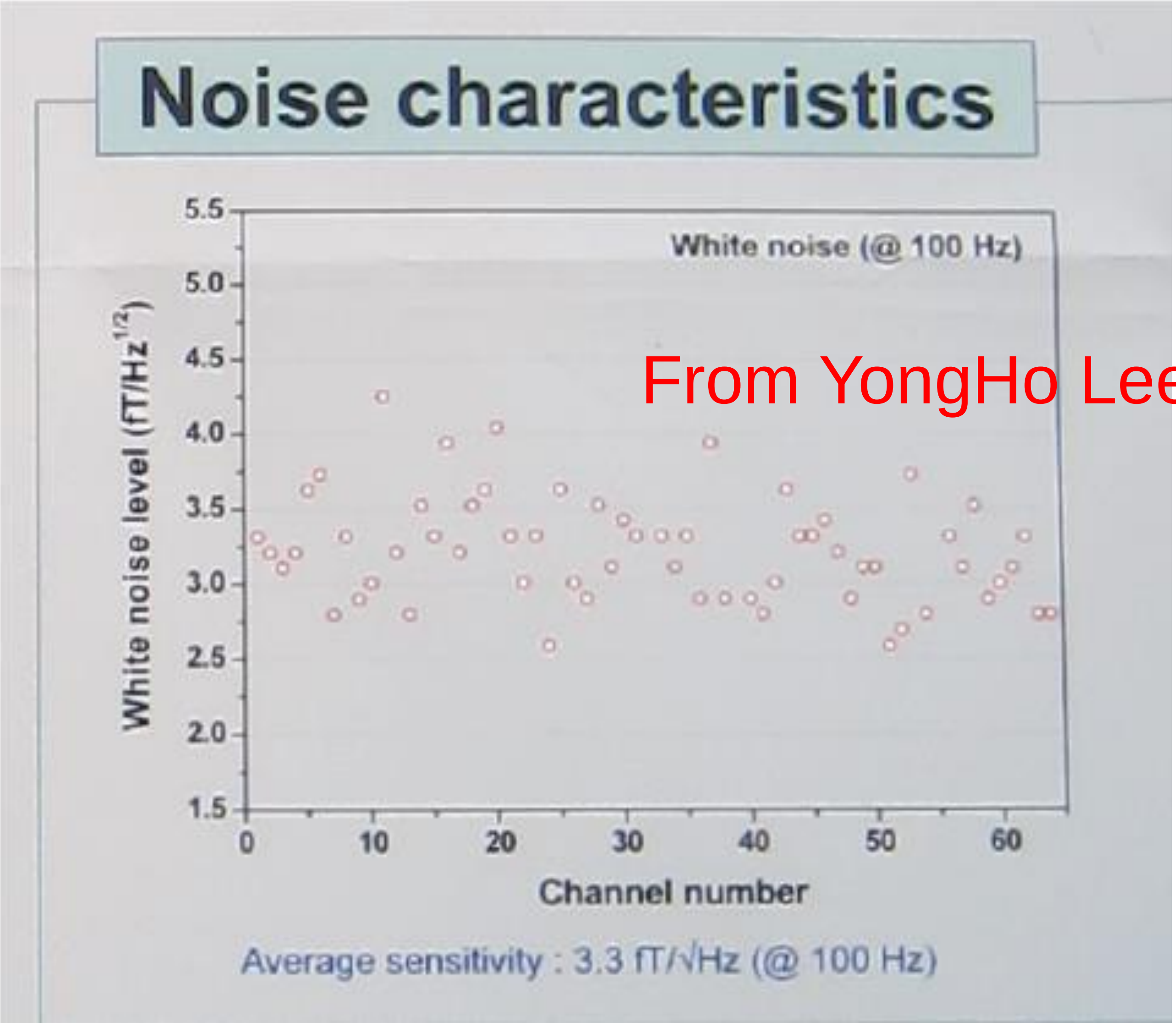
11 segments
100 Hz nuclear spin precession frequency
2×10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

A. Geraci



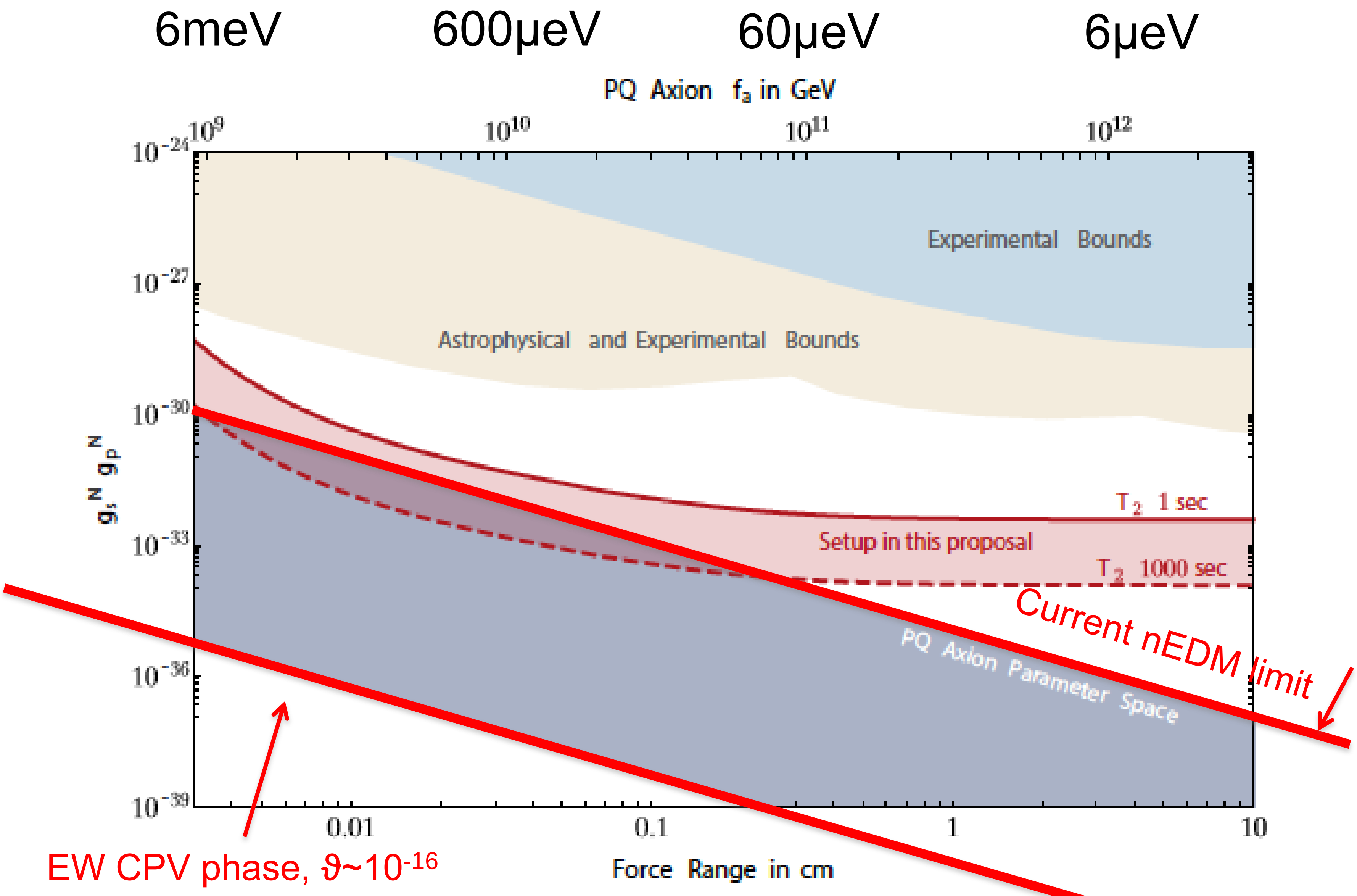


Total noise of (65) commercially available SQUID gradiometers at KRISS

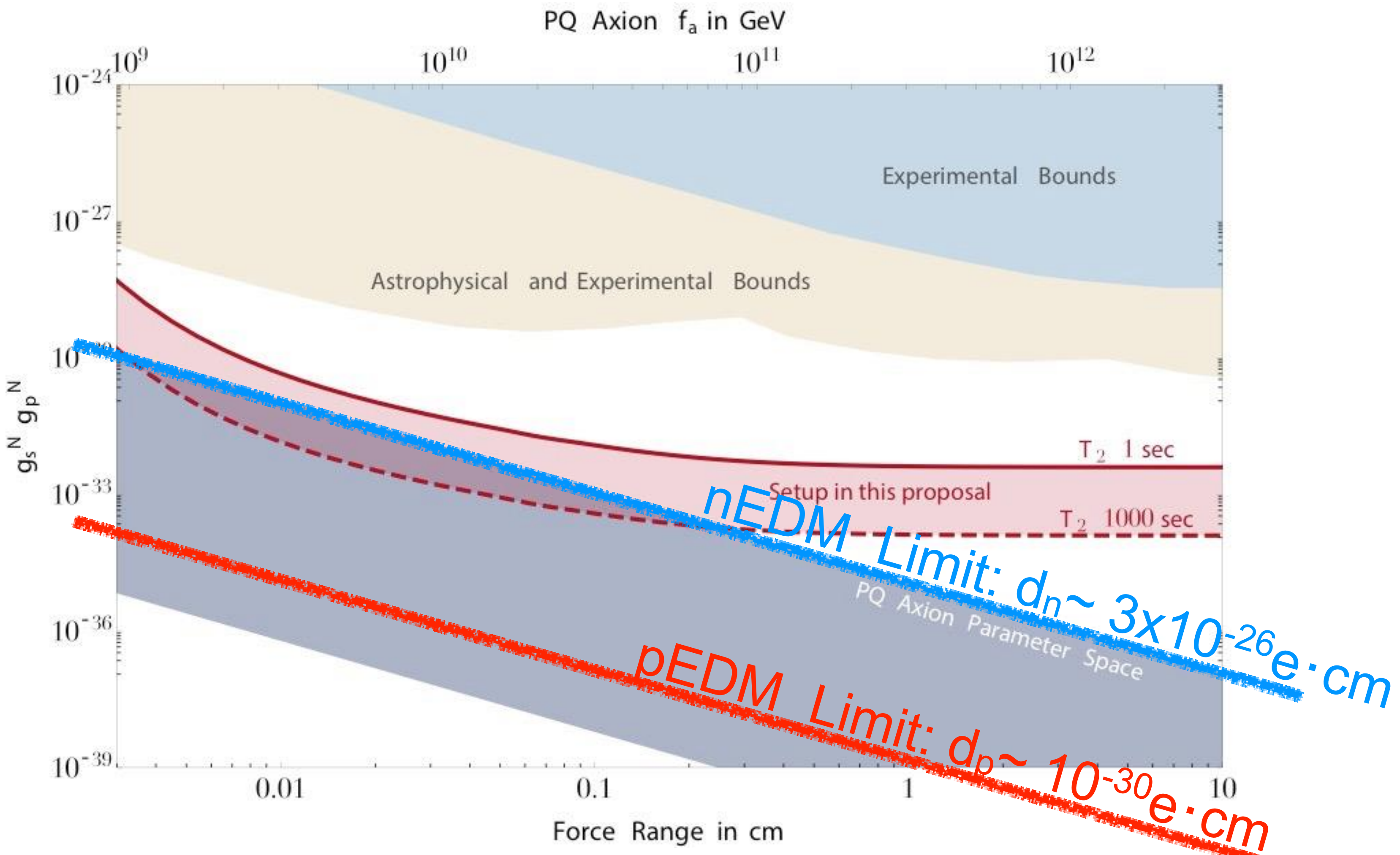


From YongHo Lee's group

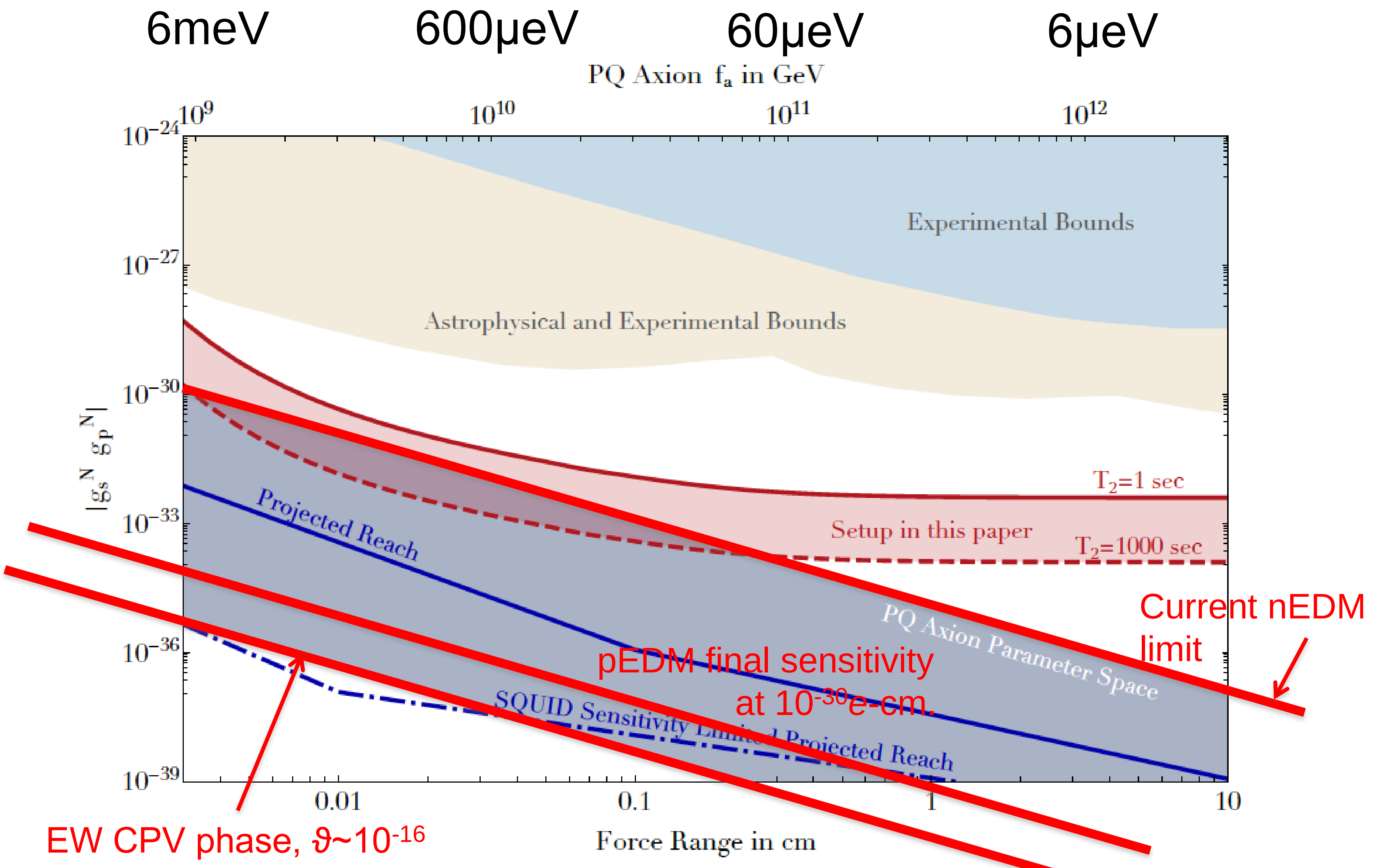
Axion mediated long range forces



Expected reach



Axion mediated long range forces

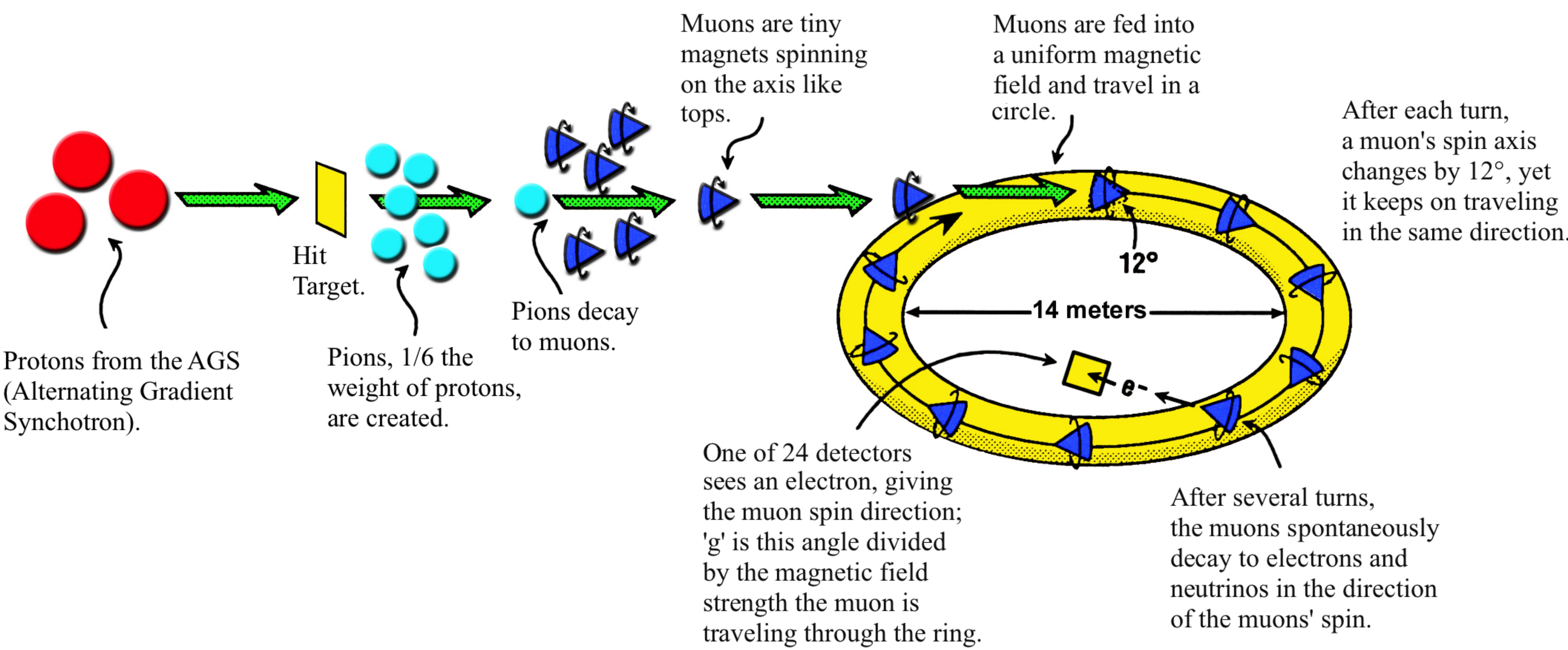


Storage Ring Proton EDM Experiment

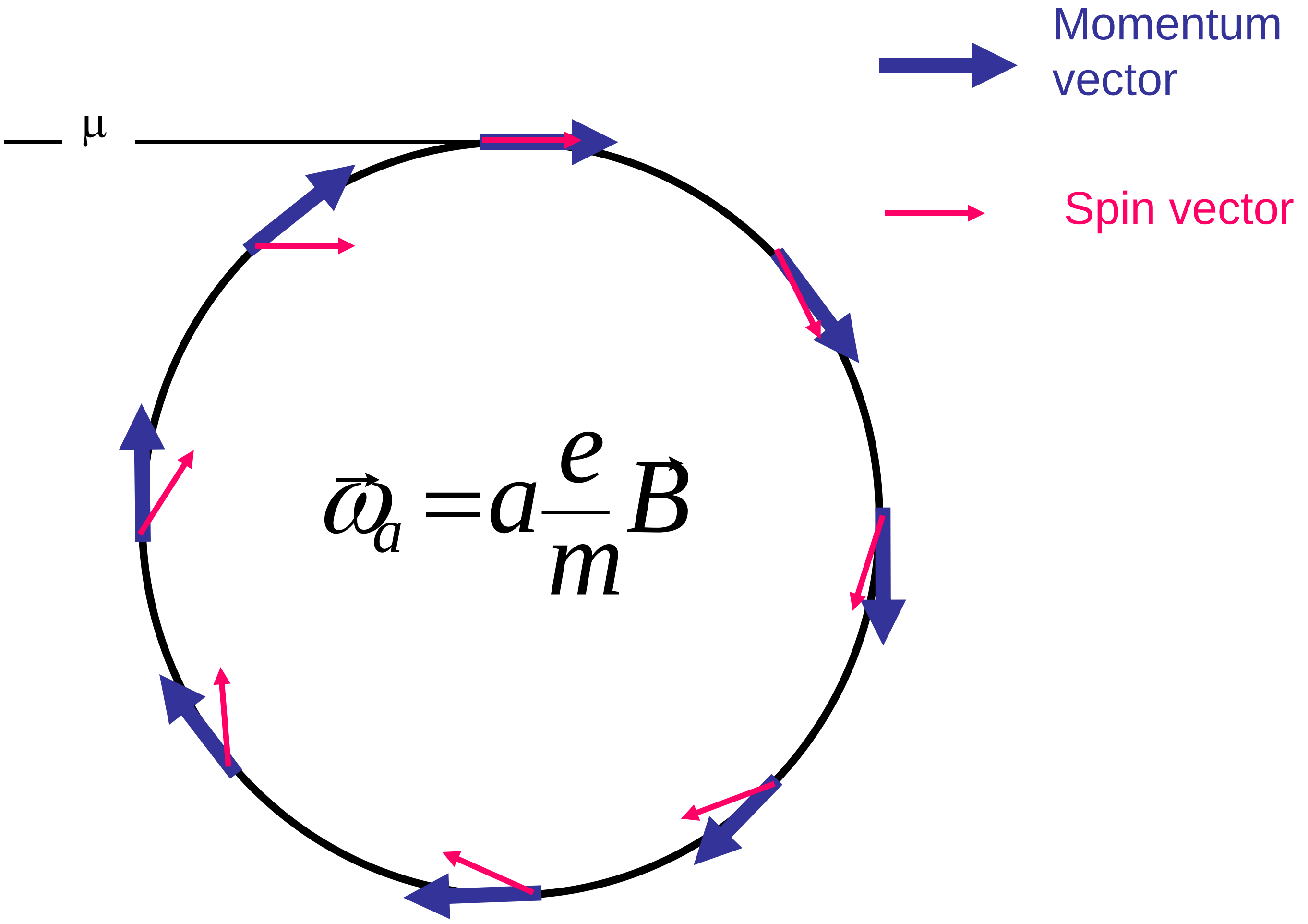
Muon g-2 experiment: Best challenge to the Standard Model

- E821 at BNL: 1997-2004
- E969 at FNAL: first data in 2017

LIFE OF A MUON:
THE g-2 EXPERIMENT



Spin Precession in g-2 Ring (Top View)



$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

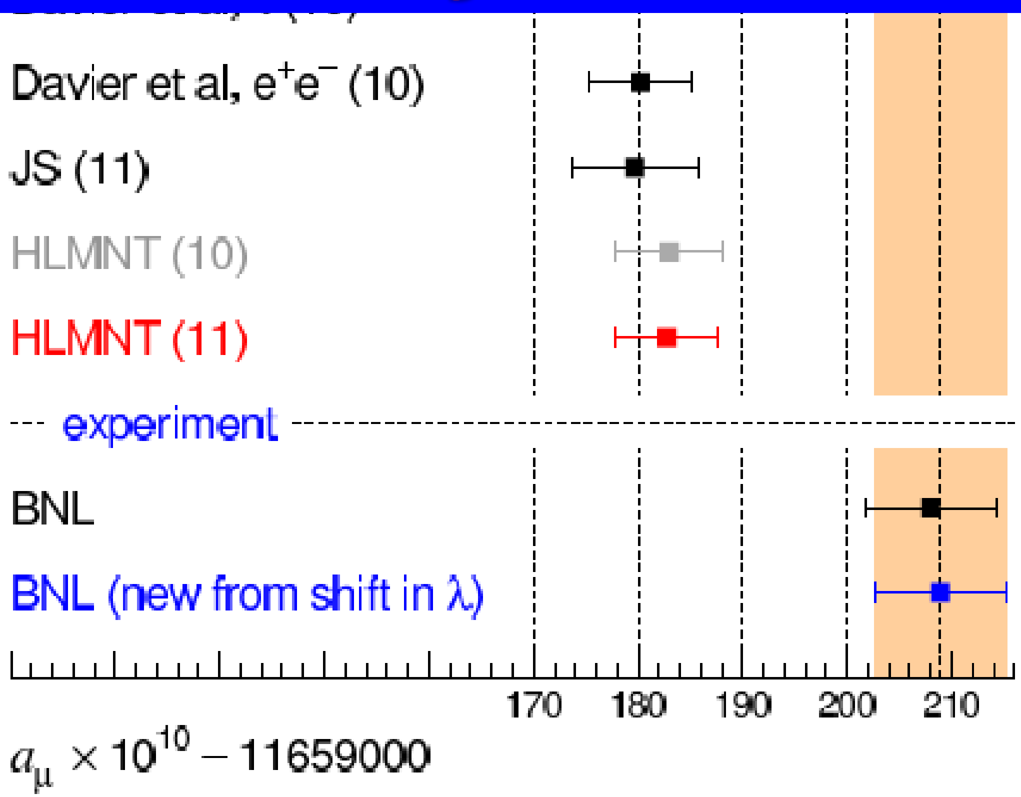
The electric focusing does not influence the g-2 precession rate

- **The Muon Storage Ring: $B \approx 1.45T$, $P_\mu \approx 3$ GeV/c**

- Previous muon g-2 Experiment at Brookhaven National Laboratory

Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?



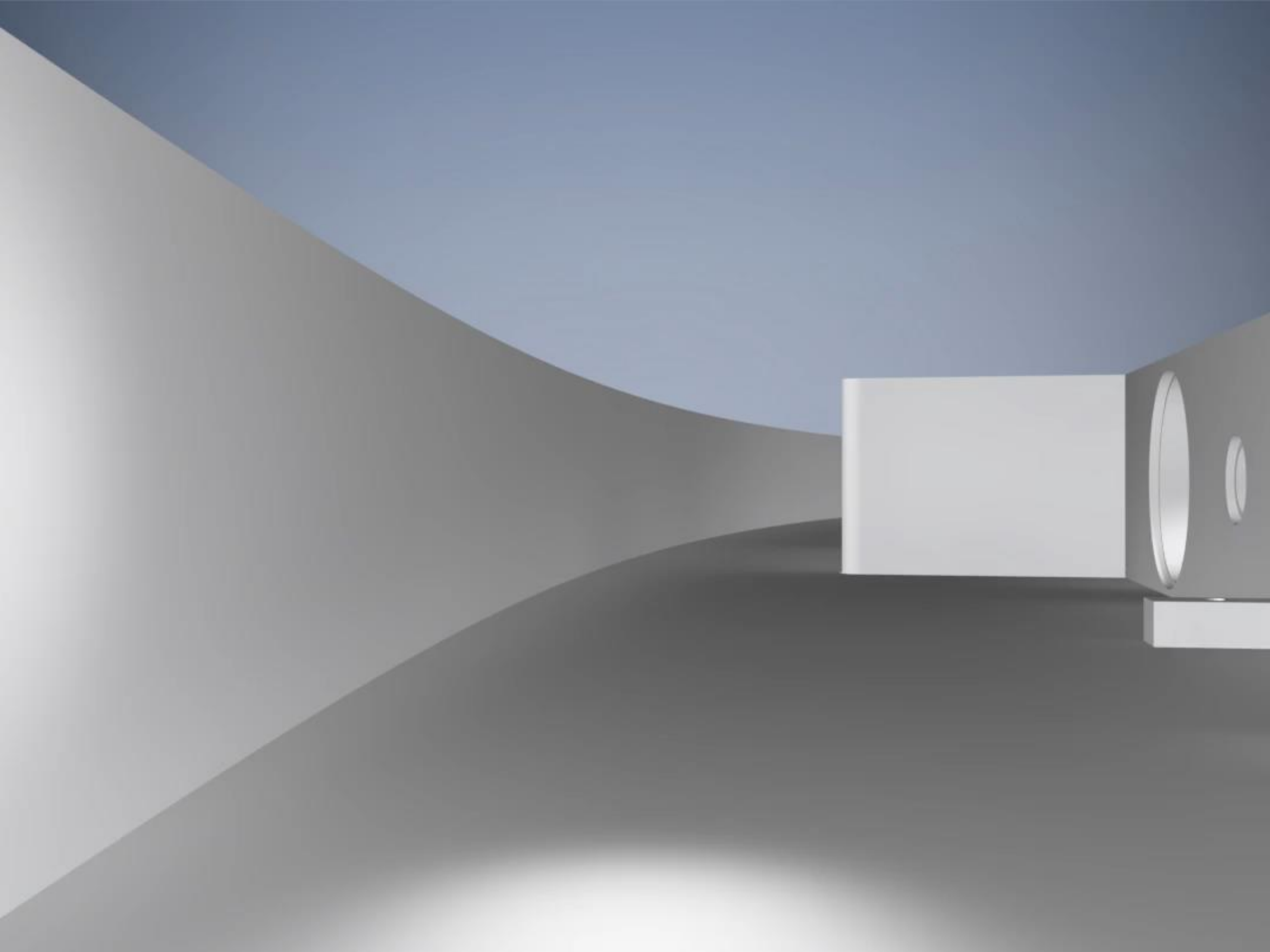
Yannis Semertzidis

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

The ring has been reassembled and fully powered to 1.45T! First data: 2017

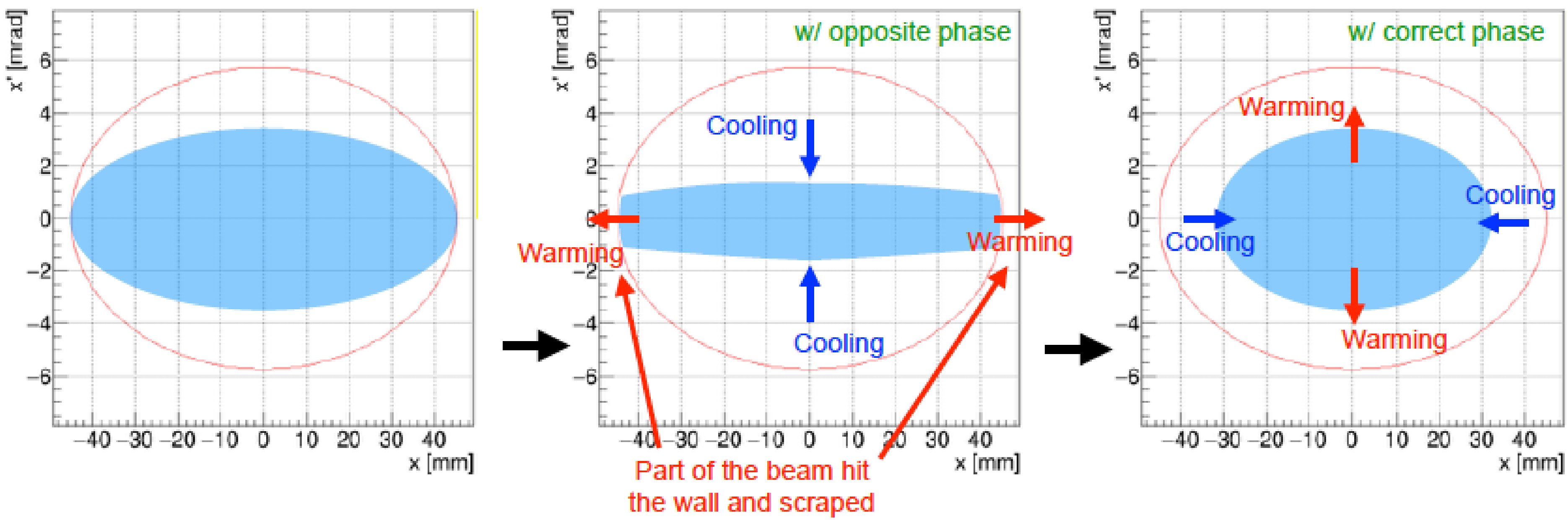
Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

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



Yet another idea with RF matching

- RF matching can be another solution for the scraping
- Stretching the beam with opposite phase, and bring it back with correct phase



Storage Ring Proton EDM Breakthrough:

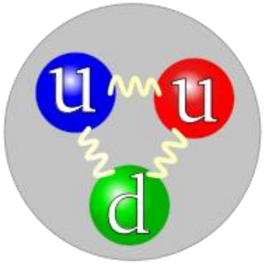
Statistics!

Instead of using the secondary, low intensity beams, use the original proton beam!

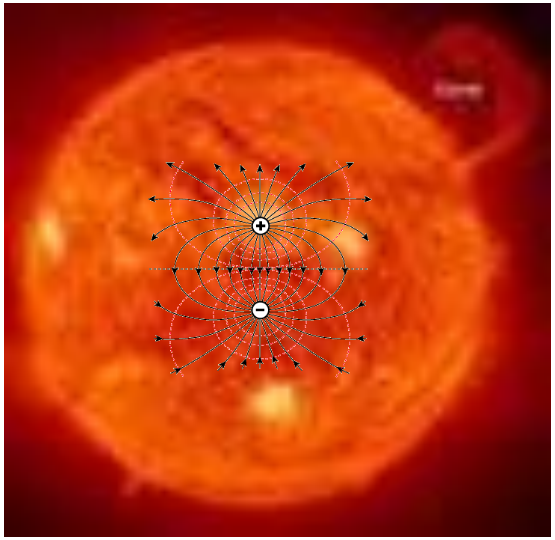
Proton EDM proposal: d=10^{-29}e•cm

- 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

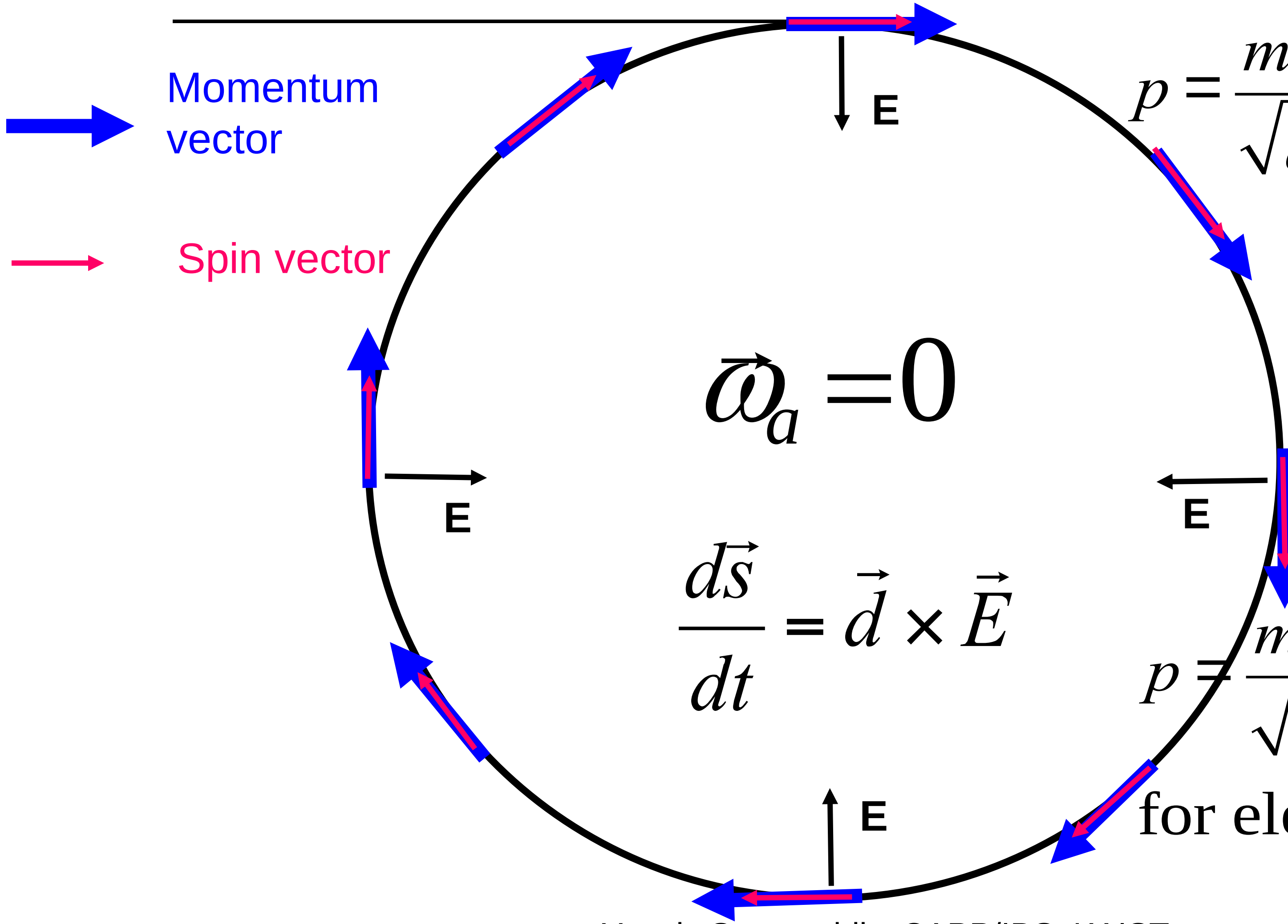


$$\vec{d} = q\vec{r}$$

srEDM Collaboration Meeting at KAIST, KAIST, 21 April, 2016.

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

at the magic momentum



$$p = \frac{mc}{\sqrt{a}} = 0.7\ \mathrm{GeV/c}$$

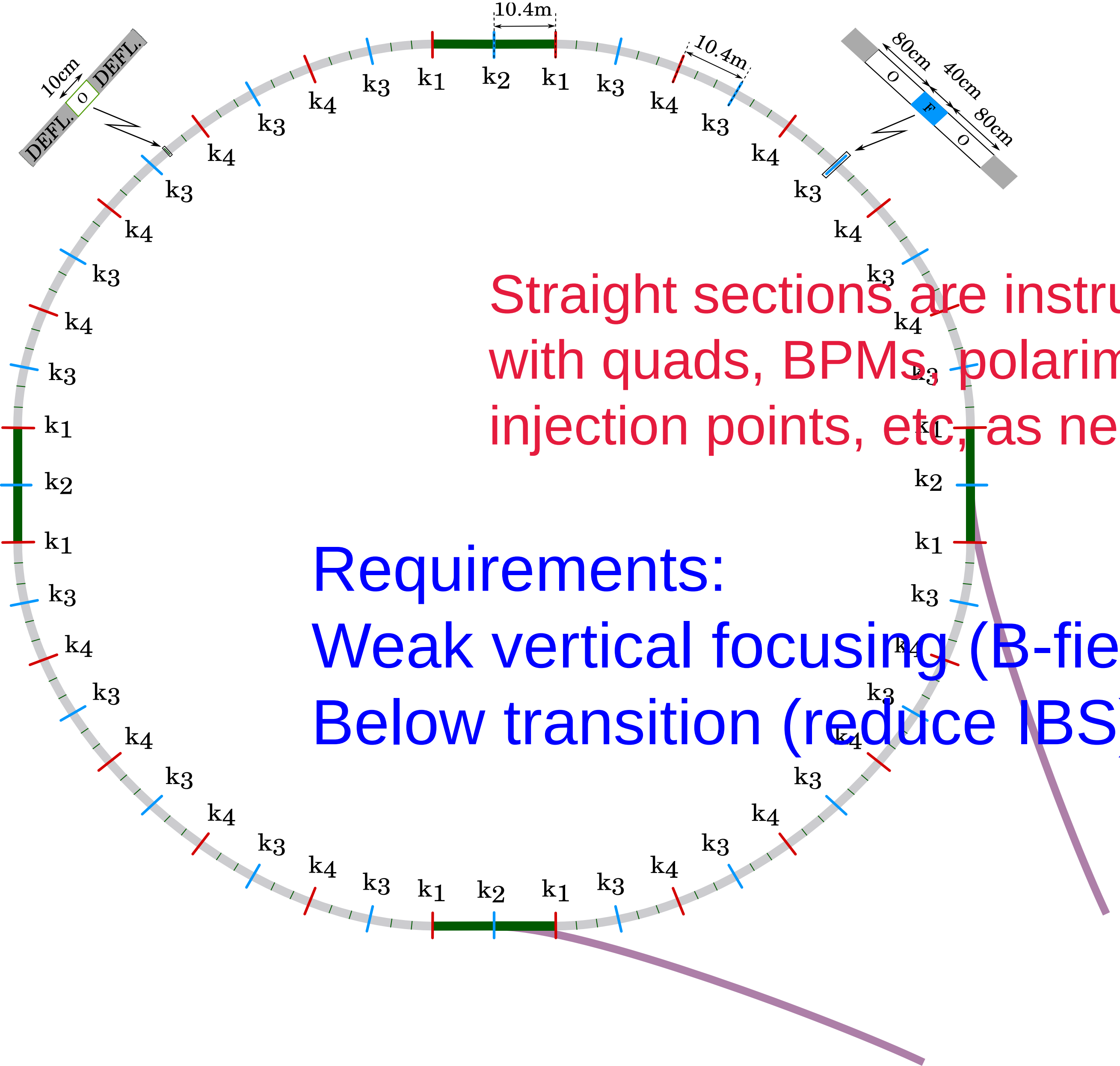
$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

$$p = \frac{mc}{\sqrt{a}} = 15\mathrm{MeV/c}$$

for electrons!

The proton EDM ring (alternate gradient)



Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc, as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)

Proton Statistical Error (230MeV):

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

τ_p : 10^3s Polarization Lifetime (Spin Coherence Time)

A : 0.6 Left/right asymmetry observed by the polarimeter

P : 0.8 Beam polarization

N_c : 10^{11}p/cycle Total number of stored particles per cycle

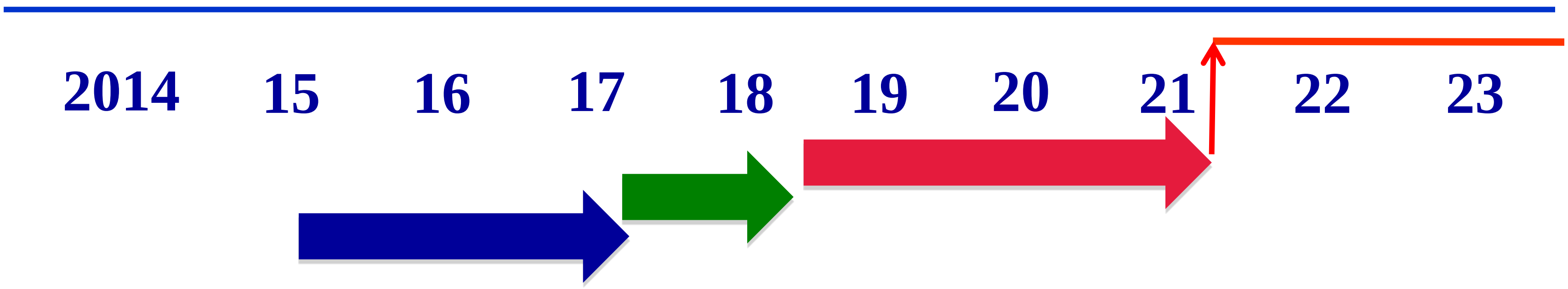
T_{Tot}: 10^7s Total running time per year

f : 1% Useful event rate fraction (efficiency for EDM)

E_R : 7 MV/m Average radial electric field strength

$$\sigma_d = 1.0 \times 10^{-29} \text{ e-cm / year}$$

Technically driven pEDM timeline



- Two years systems development (R&D); CDR; ring design, TDR, installation
- CDR by fall of 2017
- Proposal to a lab: fall 2017

Marciano, CM9/KAIST/Korea, Nov 2014

Generic Physics Reach of $d_p \sim 10^{-29}$e-cm

$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$

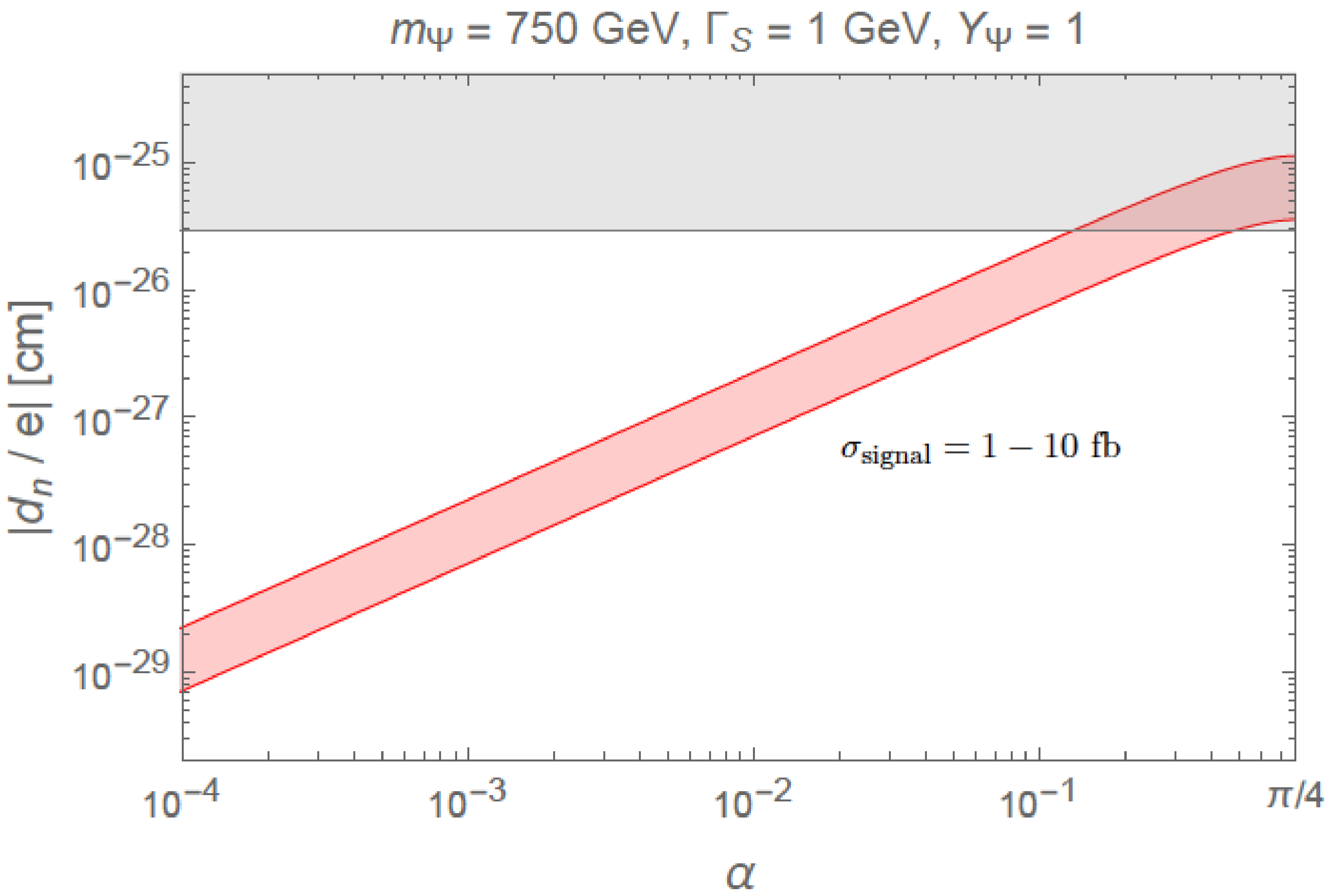
$\mathbf{\sim 10^{-22}(1TeV/\Lambda_{NP})^2 \tan\phi^{NP} e\text{-}cm}$

If ϕ^{NP} is of O(1), Λ_{NP}~<u>3000TeV</u> Probed!

If Λ_{NP}~O(1TeV), $\phi_{NP} \sim 10^{-7}$ Probed!

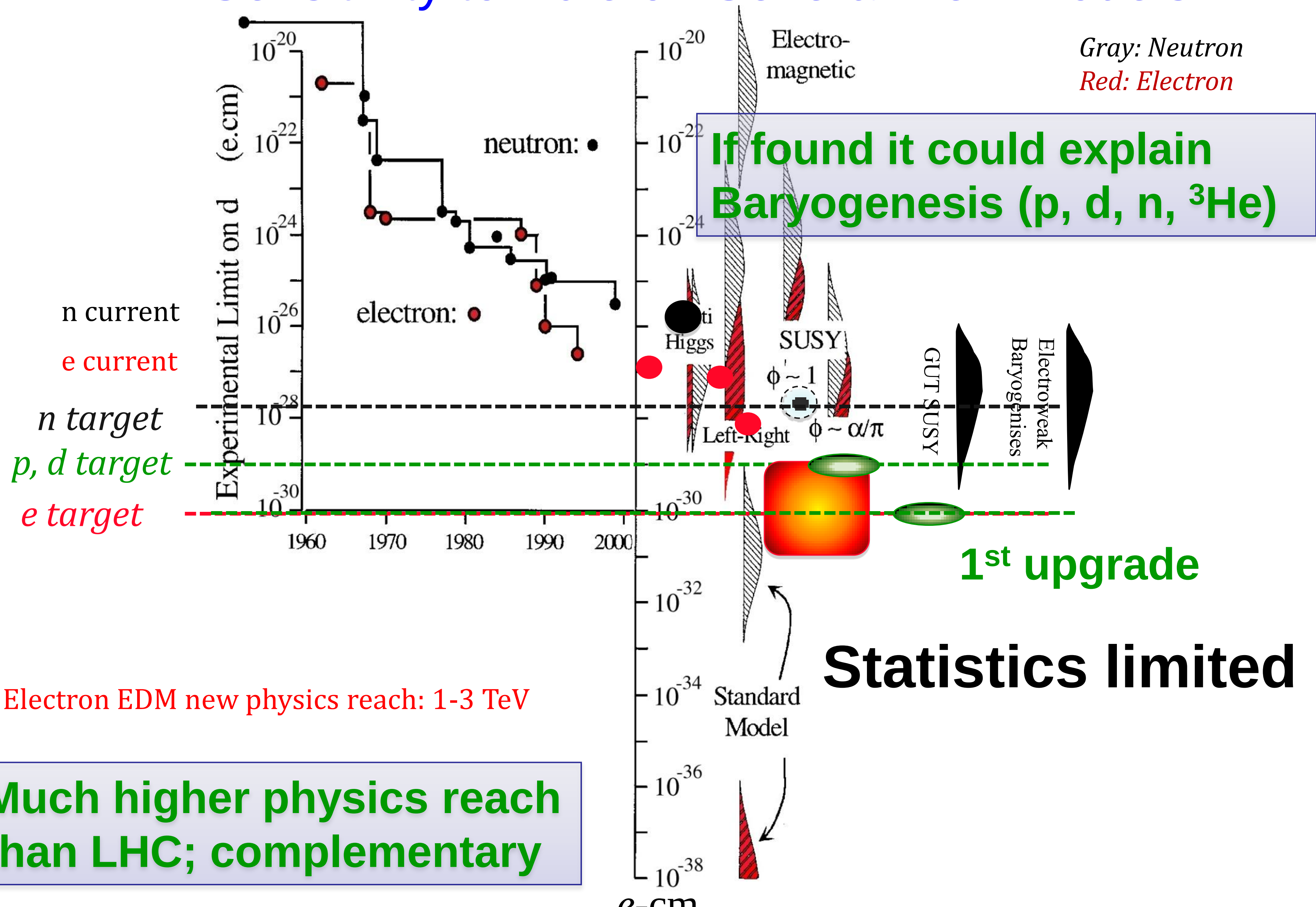
<u>Unique Capabilities!</u>

Expected neutron EDM (similar for proton EDM) from the 750 GeV resonance sector



1605.00206 K. Choi, S. H. Im, H. J. Kim, D. Y. Mo

Sensitivity to Rule on Several New Models



J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Storage ring EDM

- High precision experiments: Proton EDM experiment is a must do.

- Complementary approach to:
  - LHC in Europe
  - ILC in Japan
  - Very large hadron collider (SppC) in China
  - Neutrino Physics in the USA

- Unique opportunity for Korea for high impact, high visibility project in HEP/NP. It can transform Korea’s international position with a potentially major discovery!

Why should we be part of it

- High precision experiments can provide the next breakthrough in HEP/NP.
- Needed as input to indicate New-Physics level before next large accelerator project.
- Great for students, post docs, faculty. Well rounded physics education, opportunities for new ideas.

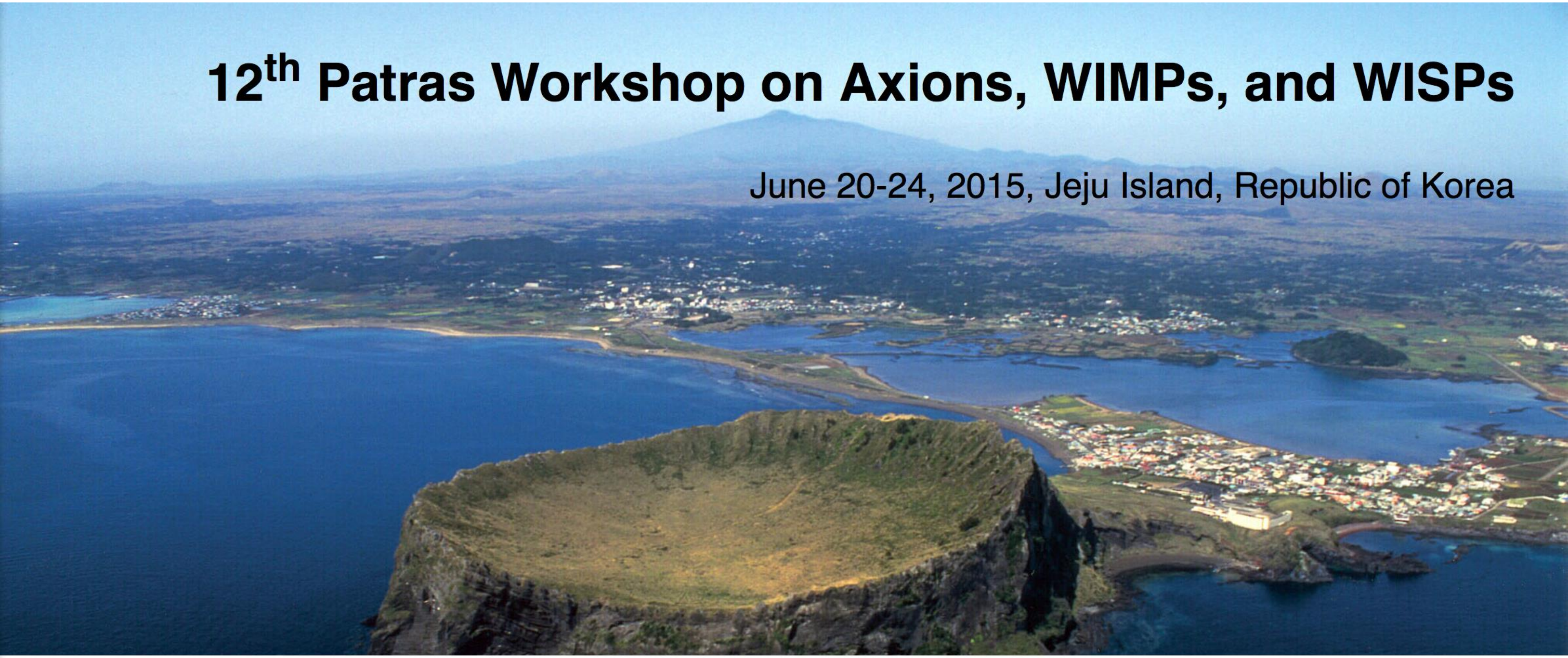
Summary

- Storage ring EDM effort is timely
- Ultimate sensitivity for p < 10^{-29}-10^{-30} e-cm
- SUSY-like physics reach: 10^{3}-10^{4}TeV, it can show the way ahead.
- Korea should seize the MOMENT!

Summary

- Axions are well motivated: neutron/proton EDM exp. limits are too small whereas QCD theory demands them to be large
- Axions in the 1-100μeV mass range are ideal dark matter candidates
- Strong magnetic fields with large volume are critical to their discovery
- Detect axions in the 1-100μeV even at 10% DM

https://axion-wimp2016.desy.de



June 20 - 24, 2016

Republic of Korea, Jeju Island

Extra slides

Korea Undergraduate / Graduate / H.S. Science Program (KUSP)

CAPP/IBS at KAIST, Summer 2016

KUSP

We are happy to answer any of your questions about KUSP 2016. Please contact us!

KUSP team: +82-42-350-8168, +82 -42-350-8166 / kusp@ibs.re.kr

multicultural environment, which will extremely enrich personal experience.

Though it will be held in Korea, KUSP is an international program and thereby the official language will be English.

http://kusp.ibs.re.kr/

1. Date

July 4 - August 5, 2016 (5 weeks)

2. Target students

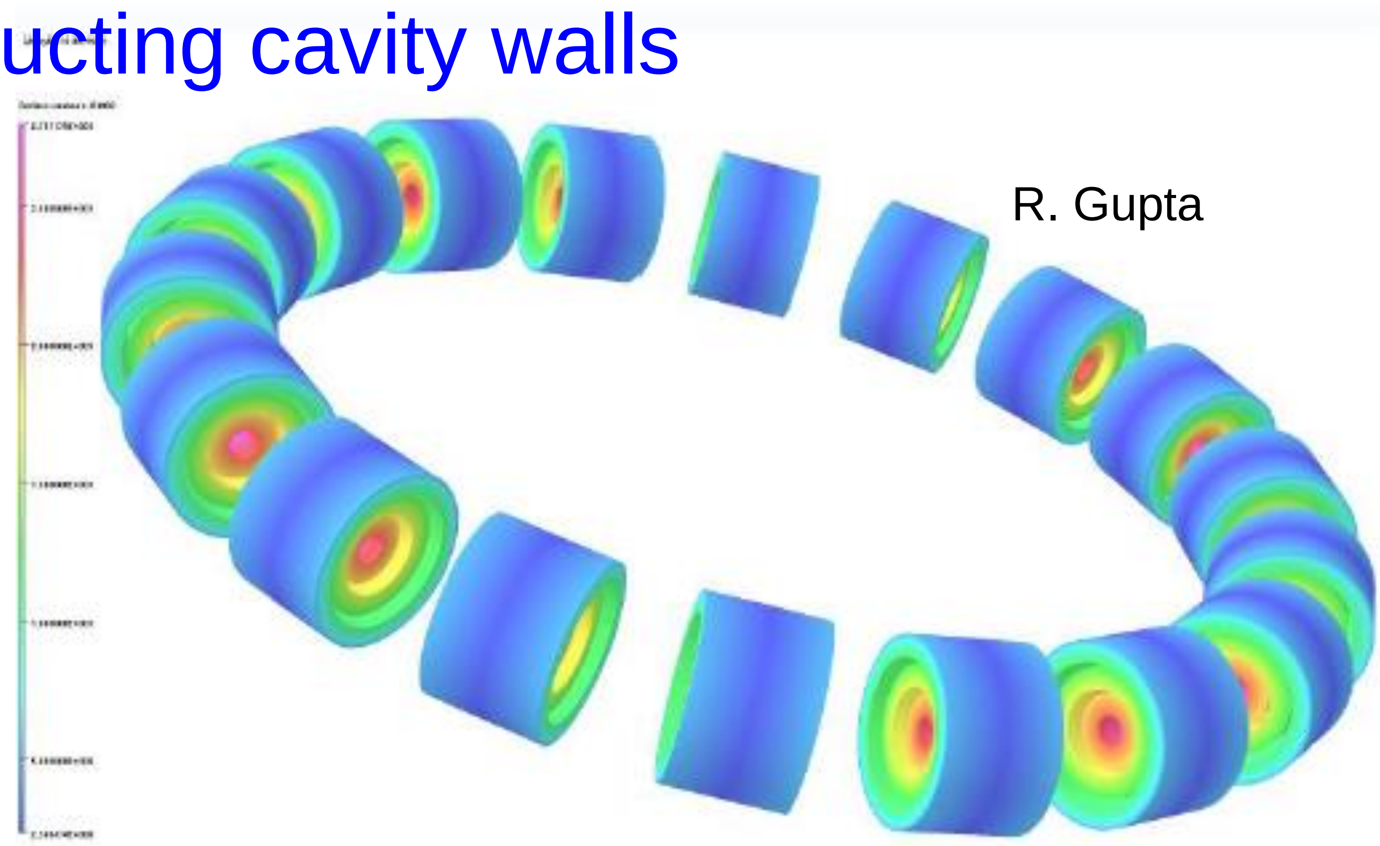
-International and domestic undergraduate and graduate students in physics or related disciplines
(e.g. electric engineering, computer science, mathematics, etc.)
-Highly motivated high school students

3. Eligibility

Axions with Toroids:
High Volume,
High Quality Factor Cavity

Toroidal magnet

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



Opera

Toroidal magnet

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

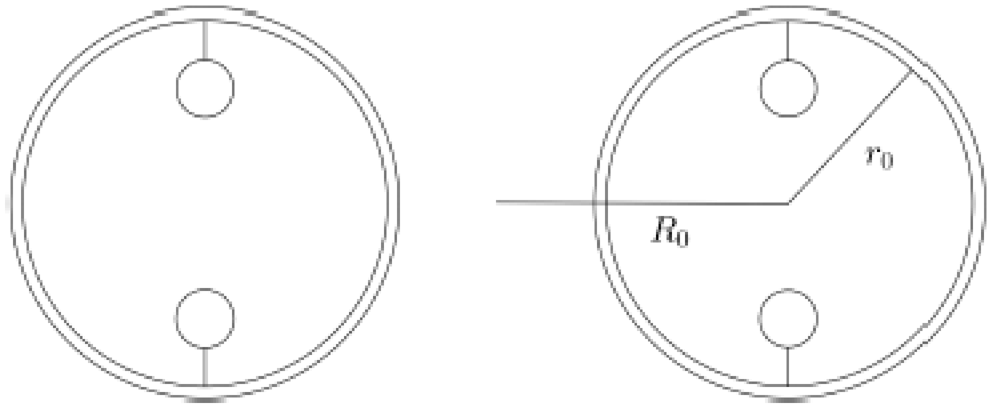
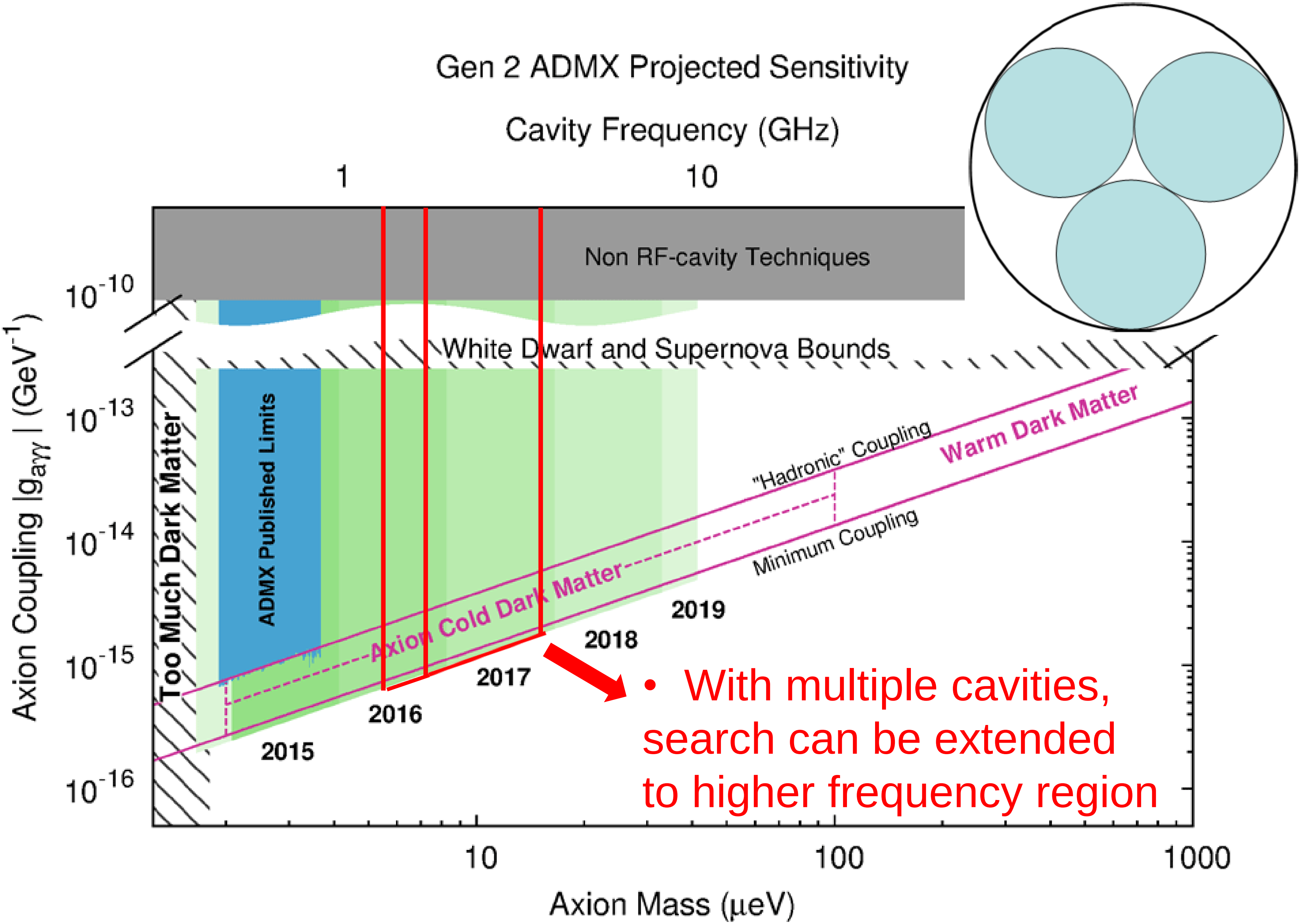
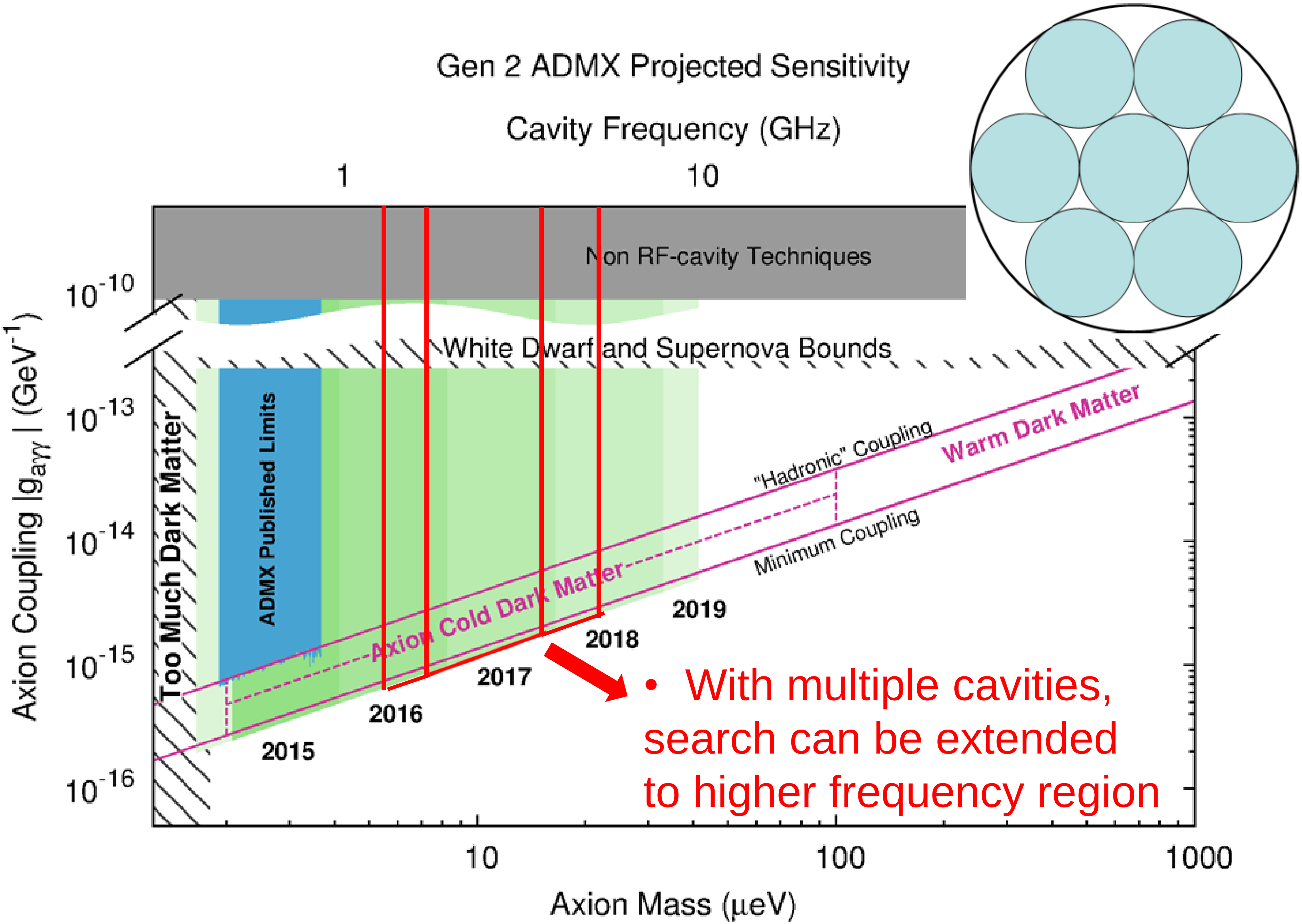


FIG. 1. A cross-section of the toroidal cavity of major radius R_0 and minor radius r_0. Conducting and dielectric tuning rings are supported at several points in the cavity.


Gen 2 ADMX Projected Sensitivity
Cavity Frequency (GHz)
1
10
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX Published Limits
"Hadronic" Coupling
Warm Dark Matter
Axion Cold Dark Matter
Minimum Coupling
2015
2016
2017
2018
2019
10^-10
10^-13
10^-14
10^-15
10^-16
Axion Coupling |gaγγ | (GeV^-1)
10
100
1000
Axion Mass (μeV)
• With multiple cavities, search can be extended to higher frequency region



- With multiple cavities, search can be extended to higher frequency region

Importance and Promise of Electric Dipole Moments

Frank Wilczek

January 22, 2014

Support letter to P5 for the proton EDM

The additional symmetry has another remarkable consequence. It predicts the existence of a new very light, very weakly interacting spin 0 particle, the *axion*. The possible existence of axions raises the stakes around these ideas, because it entails major cosmological consequences. Indeed, if axions exist at all, they must provide much of the astronomical "dark matter", and quite plausibly most of it.

Better bounds on θ, or especially an actual determination of its value, would allow us to sharpen these considerations considerably. Better measurements of fundamental electric dipole moments are the most promising path to such bounds, or measurement.

P5: Particle Physics Project Prioritization Panel setup by DOE and NSF. It took more than a year for the HEP community to come up with the report.

In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!

Breakthrough concept: Freezing the horizontal spin precession due to E-field

$$\vec{\omega}_a = -\frac{q}{m}\left\{a\vec{B} - \left[a - \left(\frac{mc}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\}$$

Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

The "magic" momentum concept was used in the muon g-2 experiments at CERN, BNL, and …next at FNAL.

Fundamental particle EDM: study of CP-violation beyond the Standard Model

Electric Dipole Moments: P and T-violating when $\vec{d}$ // to spin

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s},$$

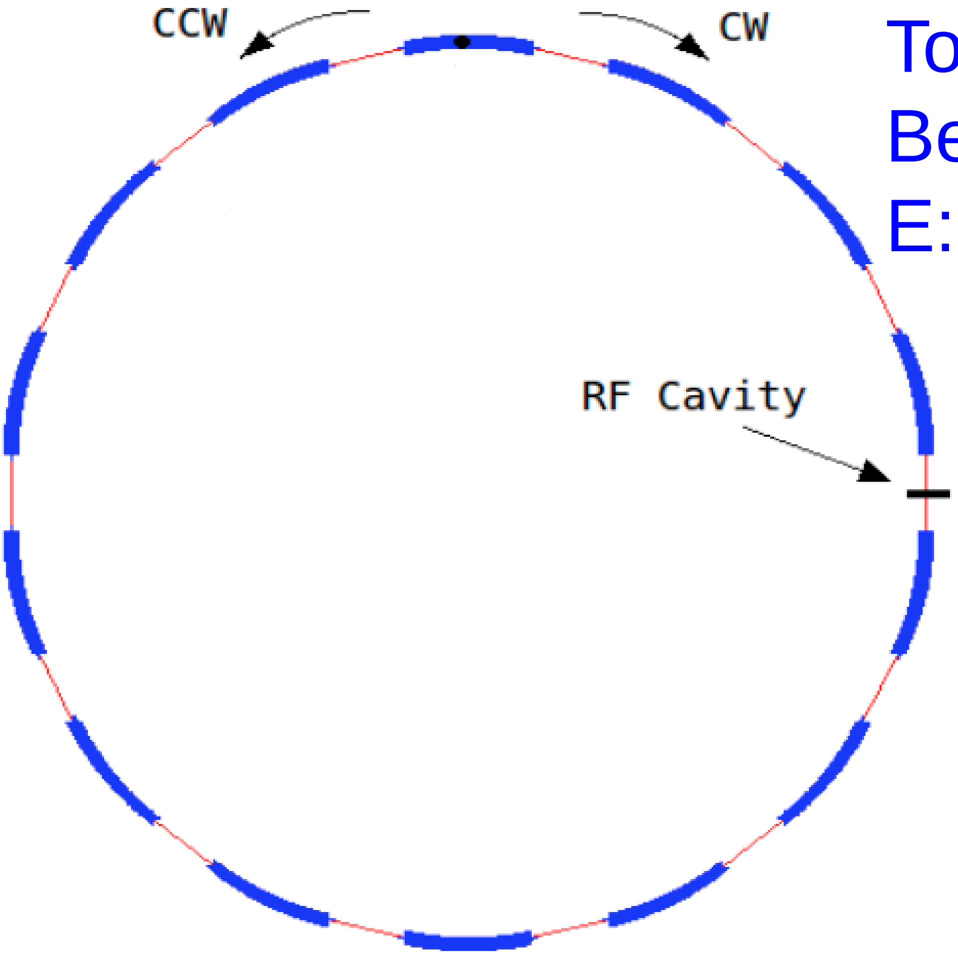
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

T-violation: assuming CPT cons. → CP-violation

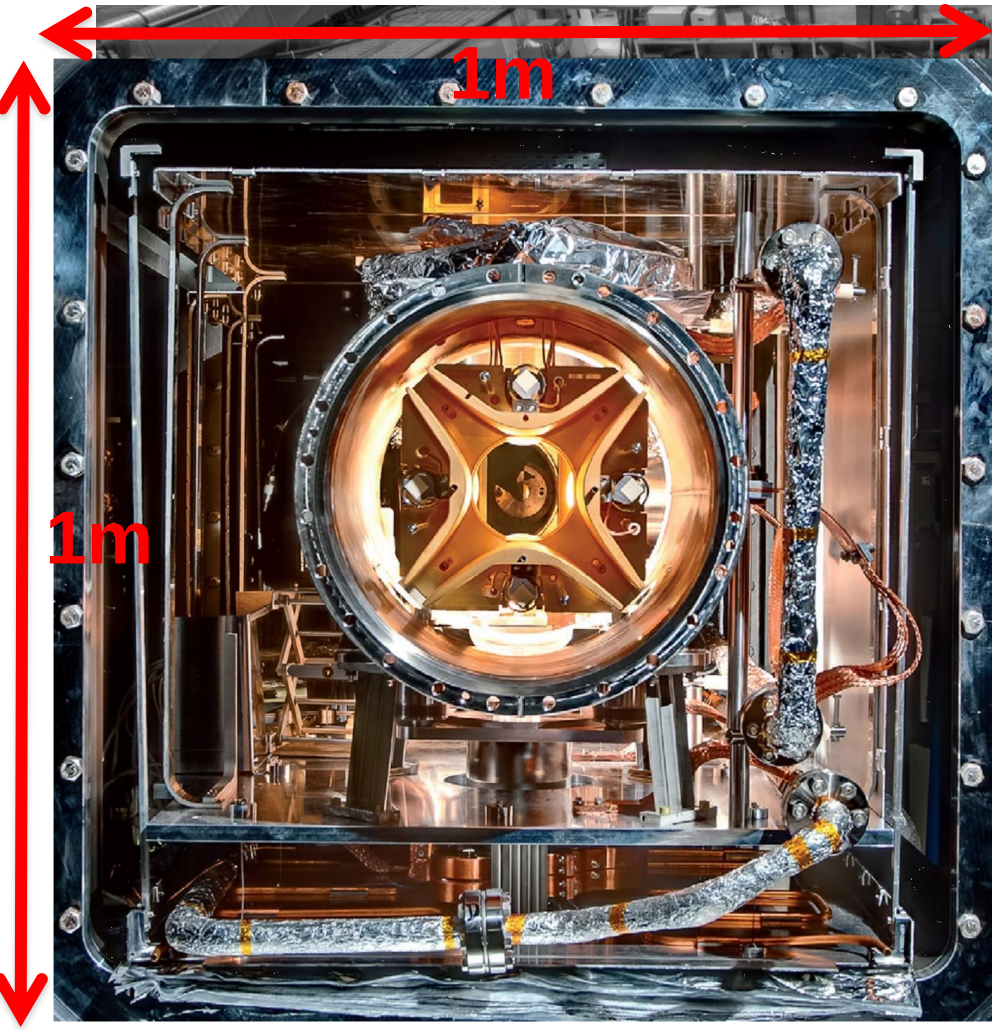
Example: The proton EDM ring

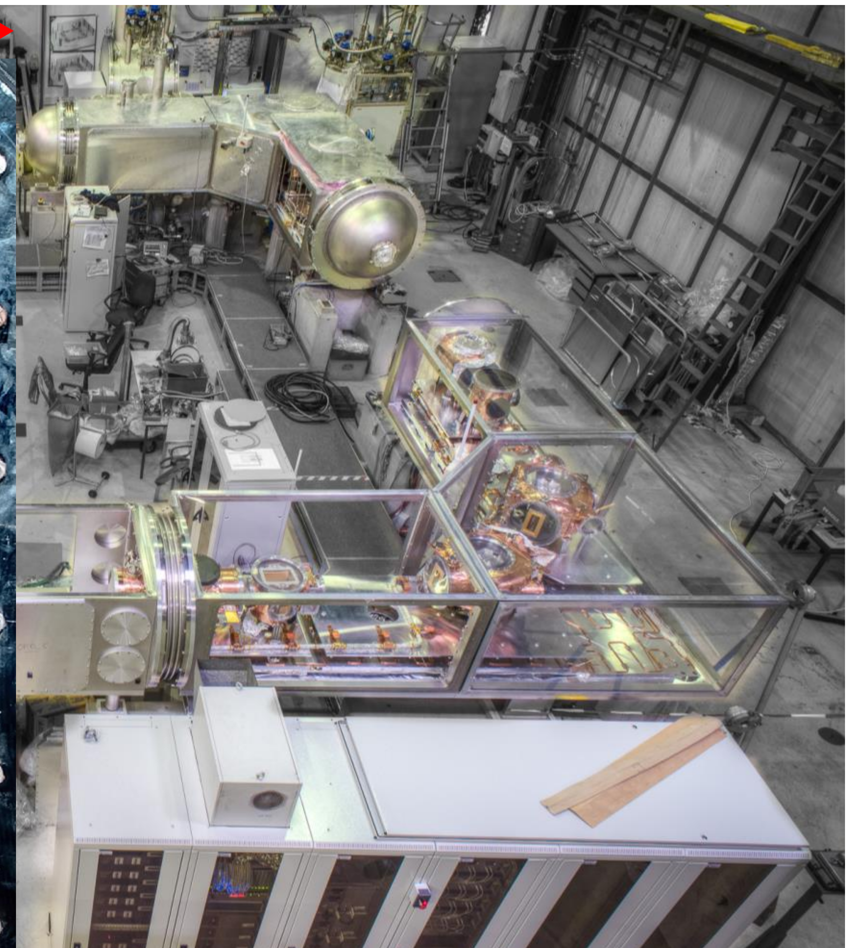


Total circumference: 300 m
Bending radius: 40 m
E: 10 MV/m

Weak vertical focusing
Stronger horizontal focusing

Currently: CSR, Heidelberg, 35 m circ., 10^{-13} Torr





What has been accomplished?

- ✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- ✓ Precision beam/spin dynamics tracking.
- ✓ Stable lattice, IBS lifetime: ~10^4s (Lebedev, FNAL)
- ✓ Spin coherence time 10^3 s; role of sextupoles understood (using stored beams at COSY).
- ✓ Feasibility of required electric field strength >10 MV/m, 3cm plate separation (JLab)
- ✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
- ✓ (Paper already published or in progress.)

Physics strength comparison (Marciano)

System	Current limit [e cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$-10^{-30}	10^{-29}-10^{-30}

Let's indulge on proton sensitivity

- Spin coherence time (10^4 seconds), stochastic cooling-thermal mixing, …
- Higher beam intensity, smaller IBS

- Reliable E-field 15 MV/m with negligible dark current
- >5% efficient polarimeter, run longer

- Potential gain $>10^2$ in statistical sensitivity: $\sim 10^{-30}$-10^{-31} e-cm!