20-21 December 2017
Axion physics and dark matter cosmology Workshop
Osaka, Japan

A comprehensive approach to the strong CP-problem

Yannis Semertzidis, IBS/CAPP and KAIST

- IBS/CAPP
- Status of our axion dark matter experiments
- Axion physics, storage ring EDM and future plans

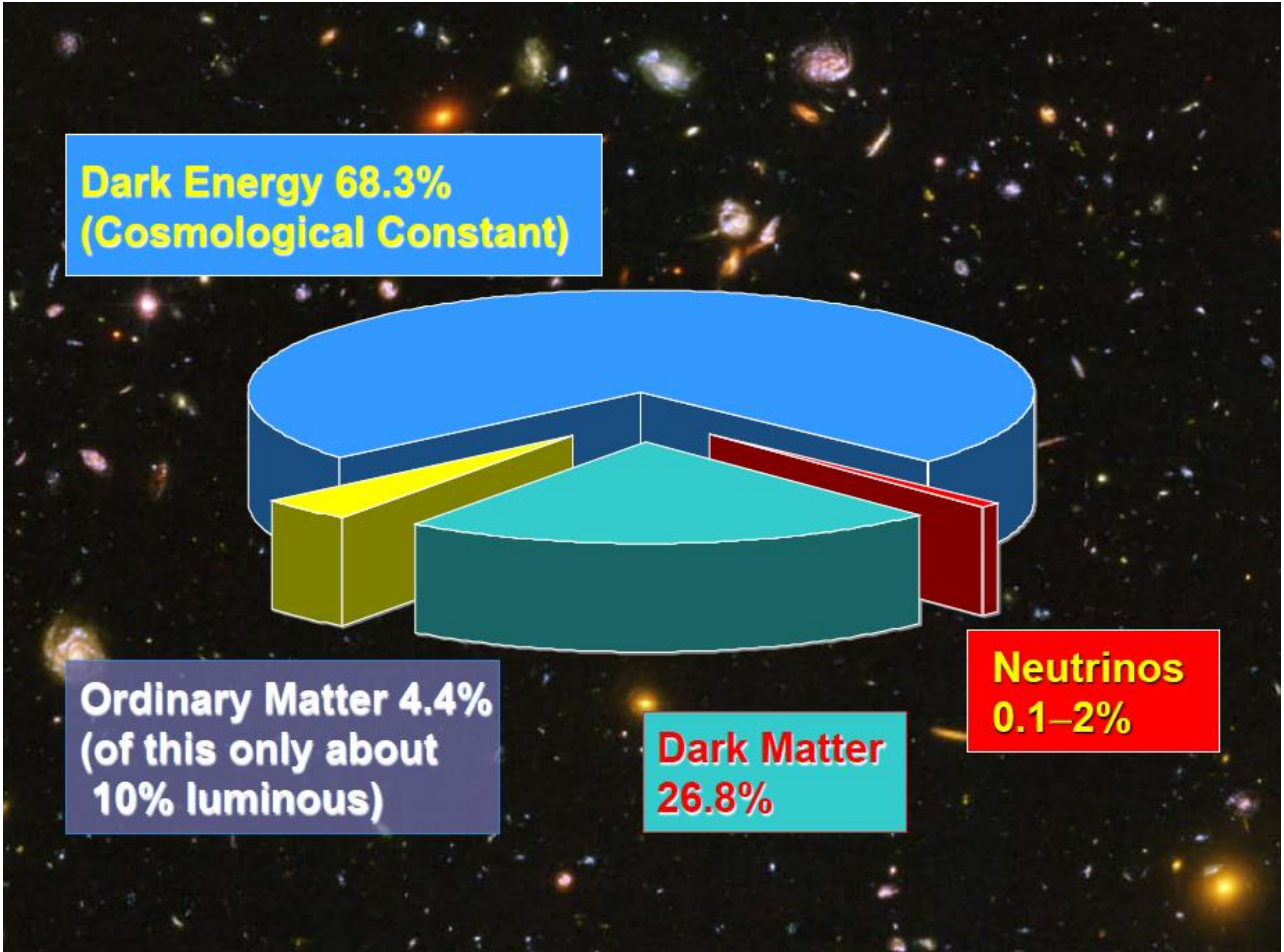
IBS/CAPP

- Was established October 15, 2013

- To put together the best possible axion dark matter exps and reach all the way down to the theoretical predictions

Center for Axion and Precision Physics KAIST, Daejeon, Korea

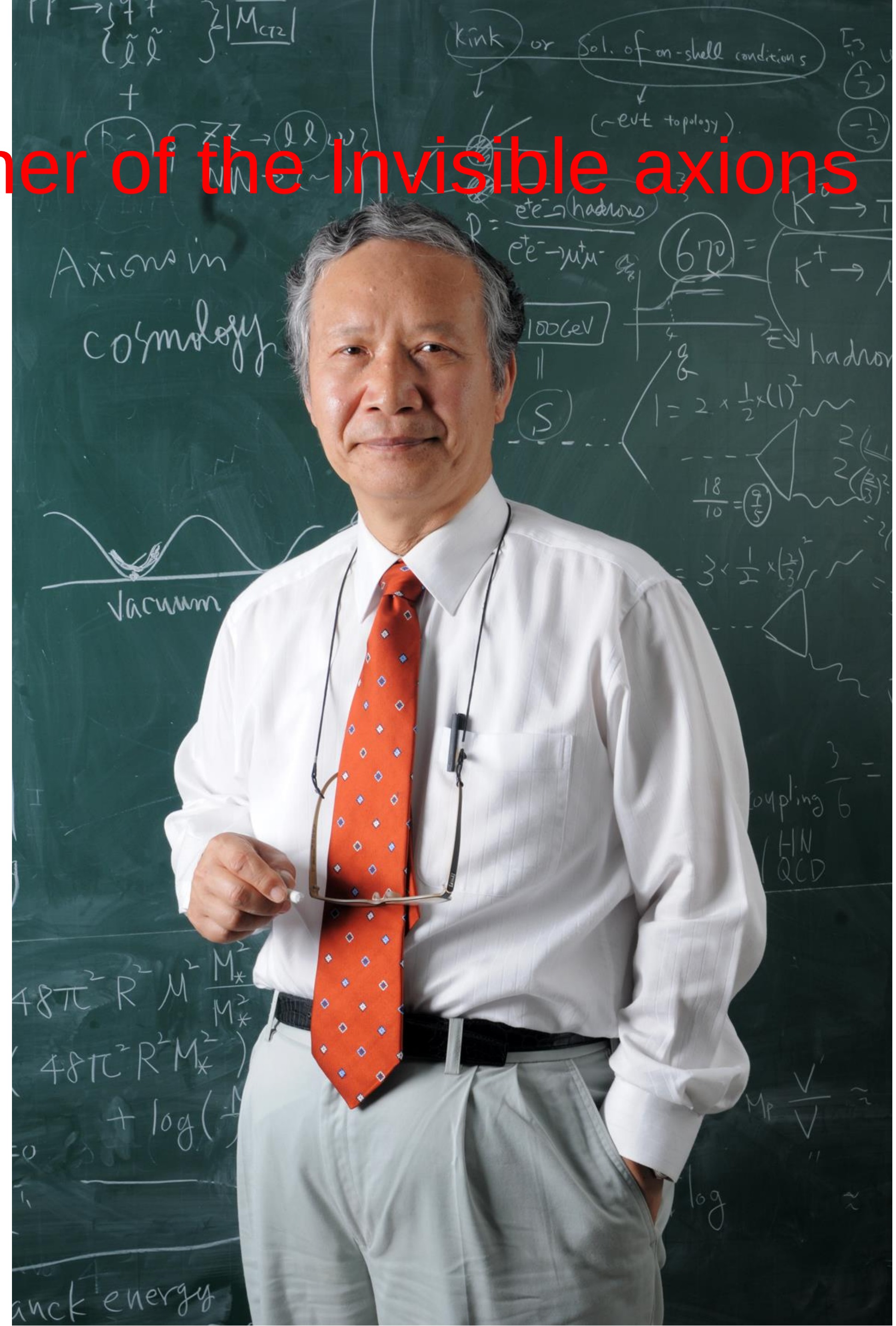
Cosmological inventory



Professor Jihn E. Kim!

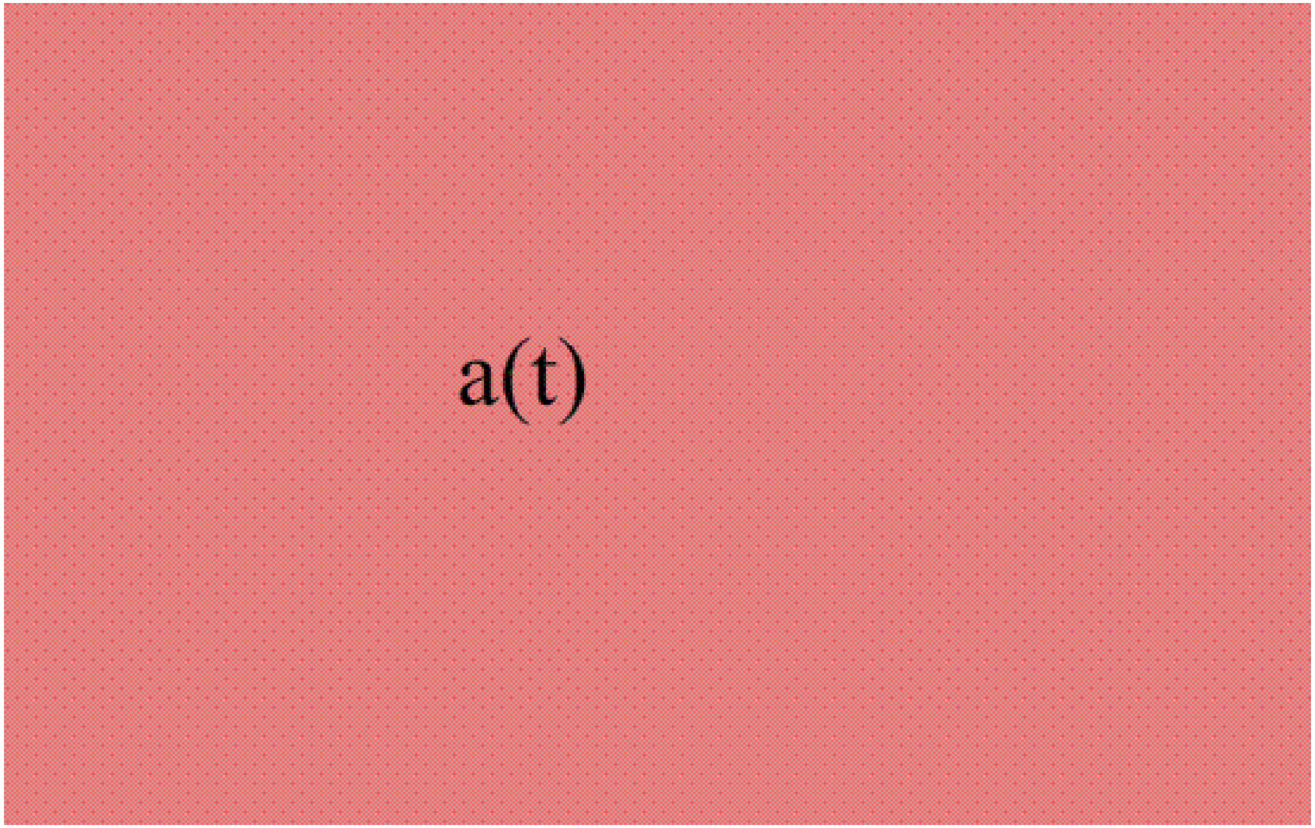
Father of the Invisible axions

Also, worked tirelessly to establish IBS/CAPP to make axions Visible!



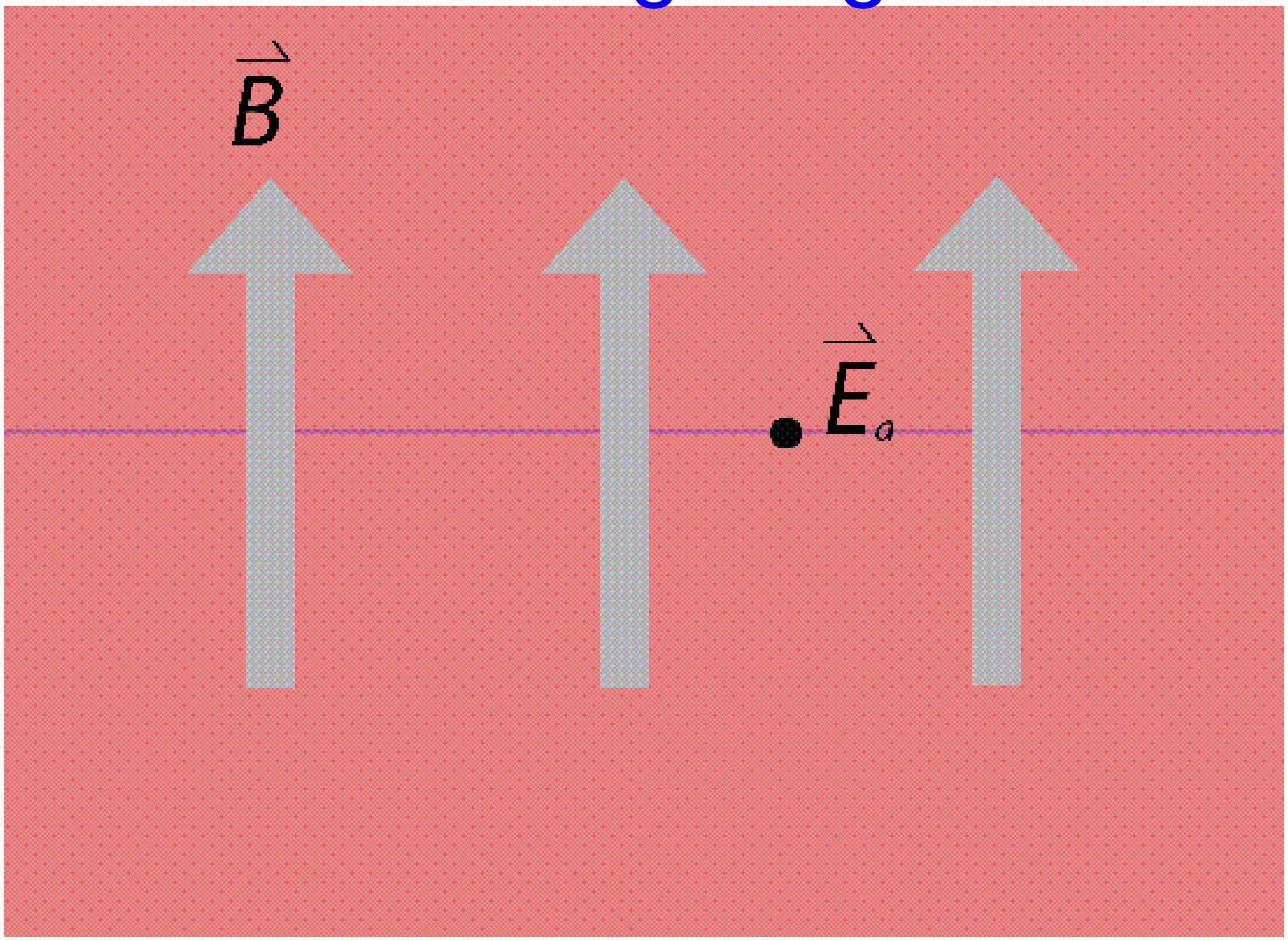
Jihn E. Kim and ASK2011

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



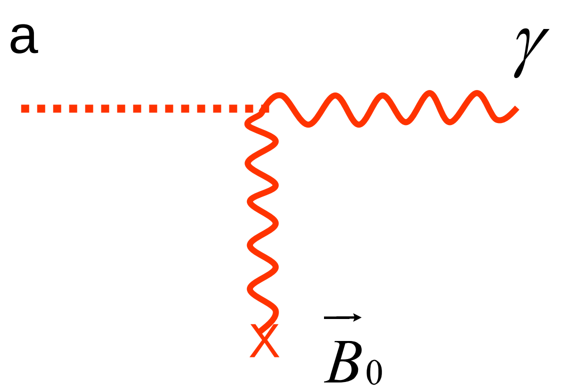
Animation by Kristian Themann

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

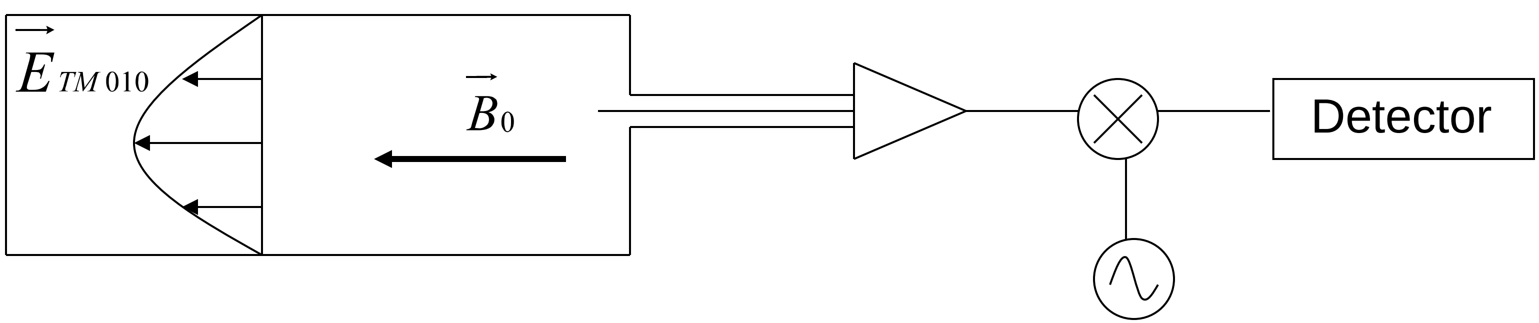


Animation by Kristian Themann

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



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



$$a \rightarrow \gamma$$

The conversion power on resonance

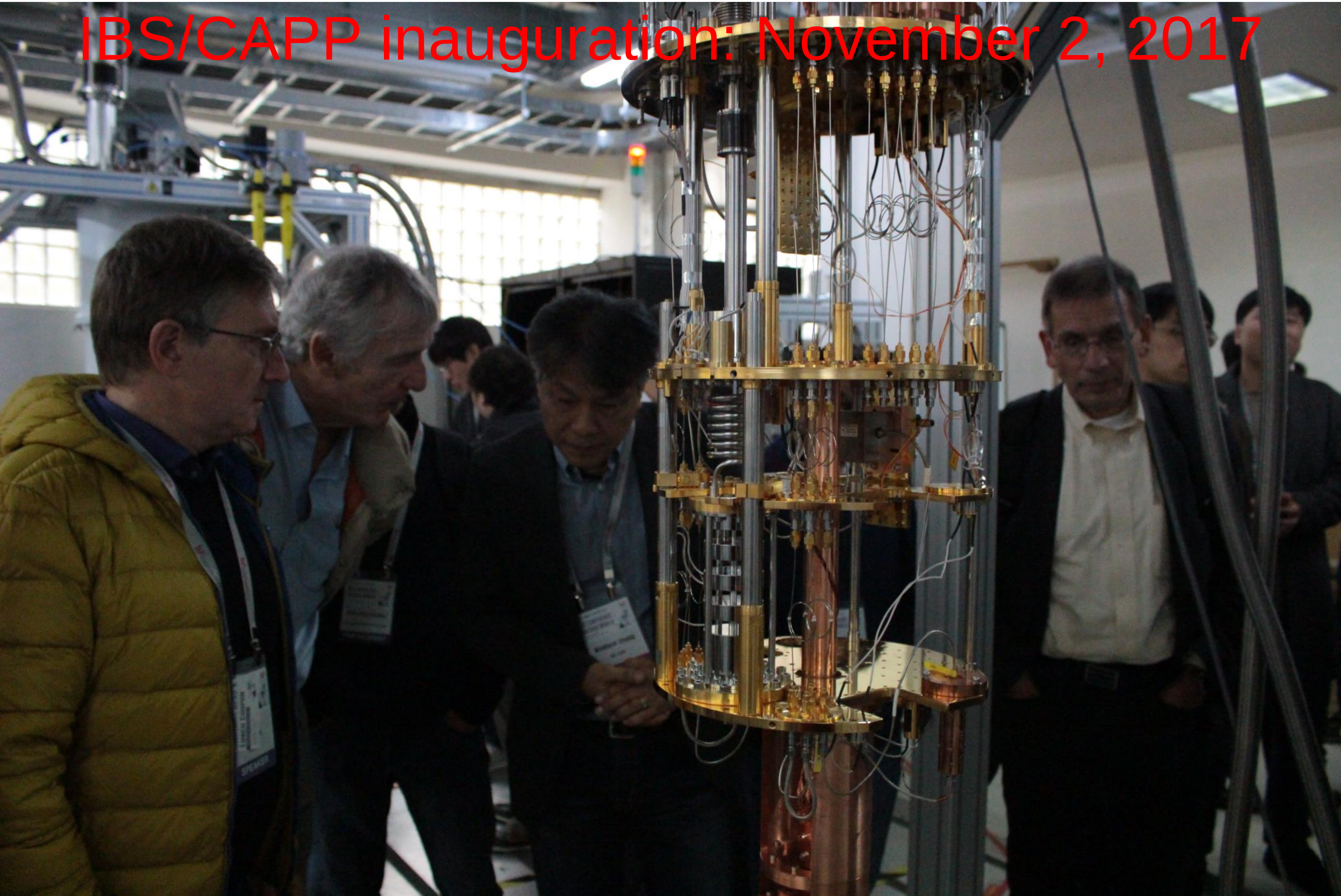
$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V\, B_0^{\,2}\, \rho_a\, C\, m_a^{-1}\, Q_L$$

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

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

IBS/CAPP inauguration: November 2, 2017

IBS/CAPP inauguration: November 2, 2017



Center for Axion and Precision Physics Research (CAPP)

IBS/CAPP at KAIST launched in October 2013

Physics
- Axion Search
- Proton EDM
- Muon g-2 / mu2e

Funding
- Funded by IBS (Korea)
- ~$10 M/year for 10-years of startup

Human Resource
- 20 research fellows
- 20 graduate students
- 10 staffs
- Engineers/technicians
- Visiting scholars

Center for Axion and Precision Physics (IBS/CAPP)

Director: Yannis K. Semertzidis IBS & KAIST

- CAPP of Institute for Basic Science (IBS) at KAIST in Korea since October 2013.
- Projects : Axion dark matter, Storage ring proton EDM, Axion mediated long range forces

Members :

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

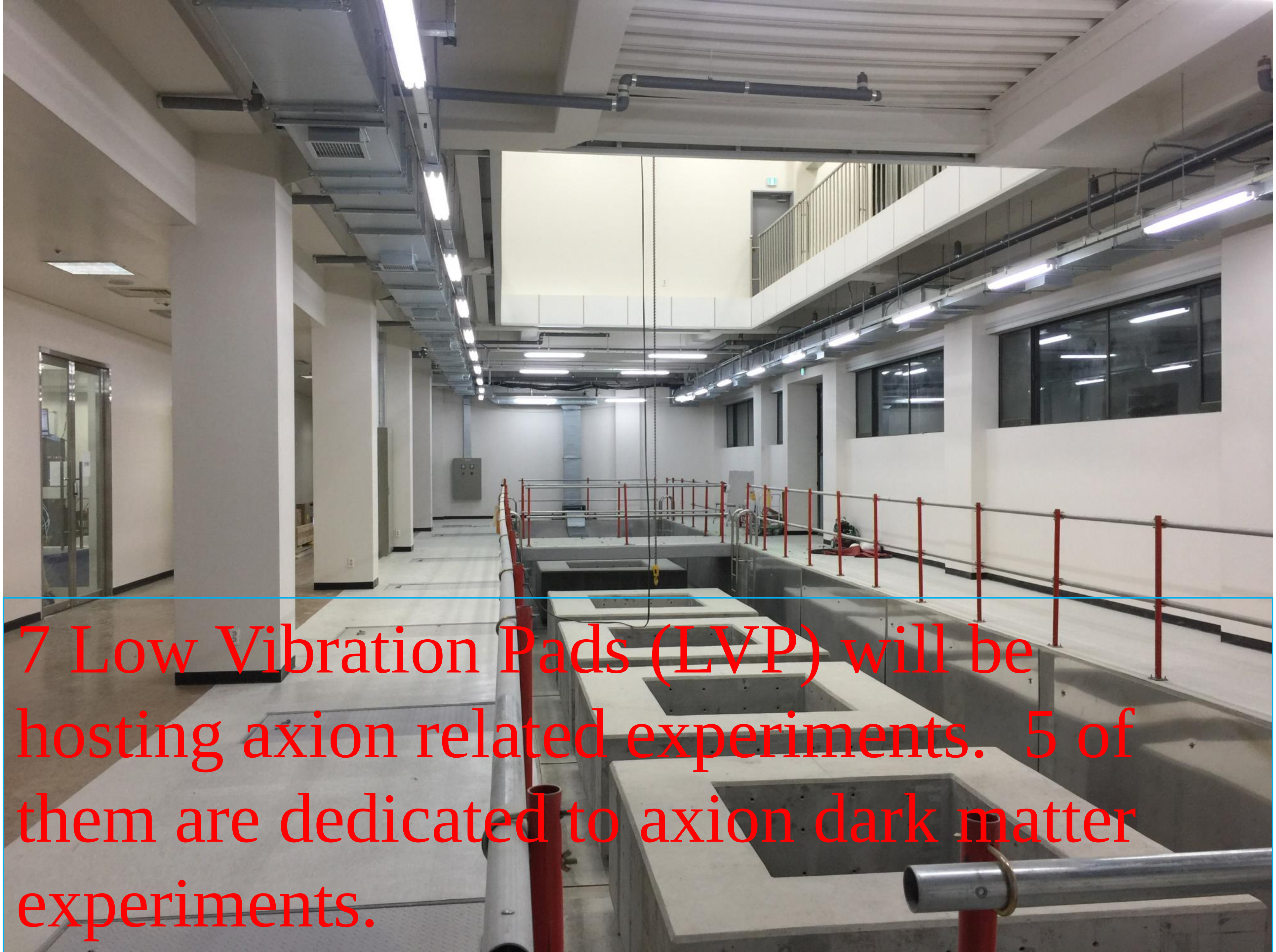
Refurbished a state of the art lab in an existing bldg.

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

IBS/CAPP-Physics approach

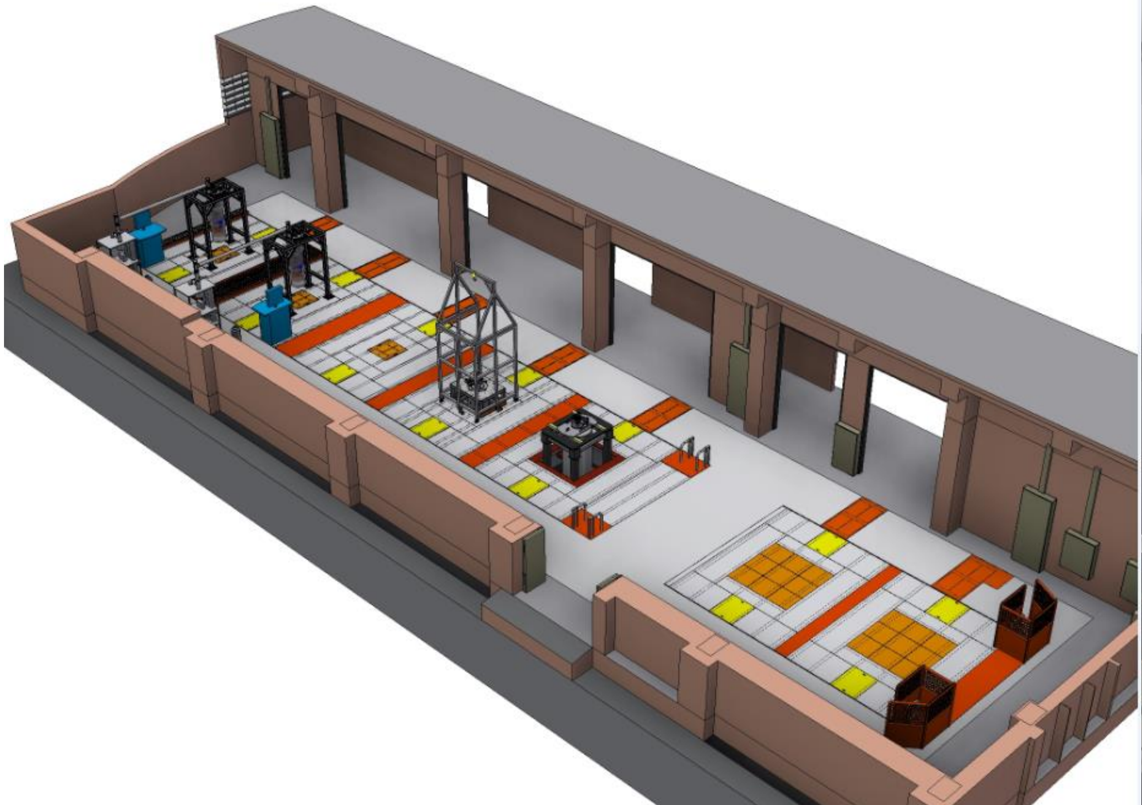
Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)

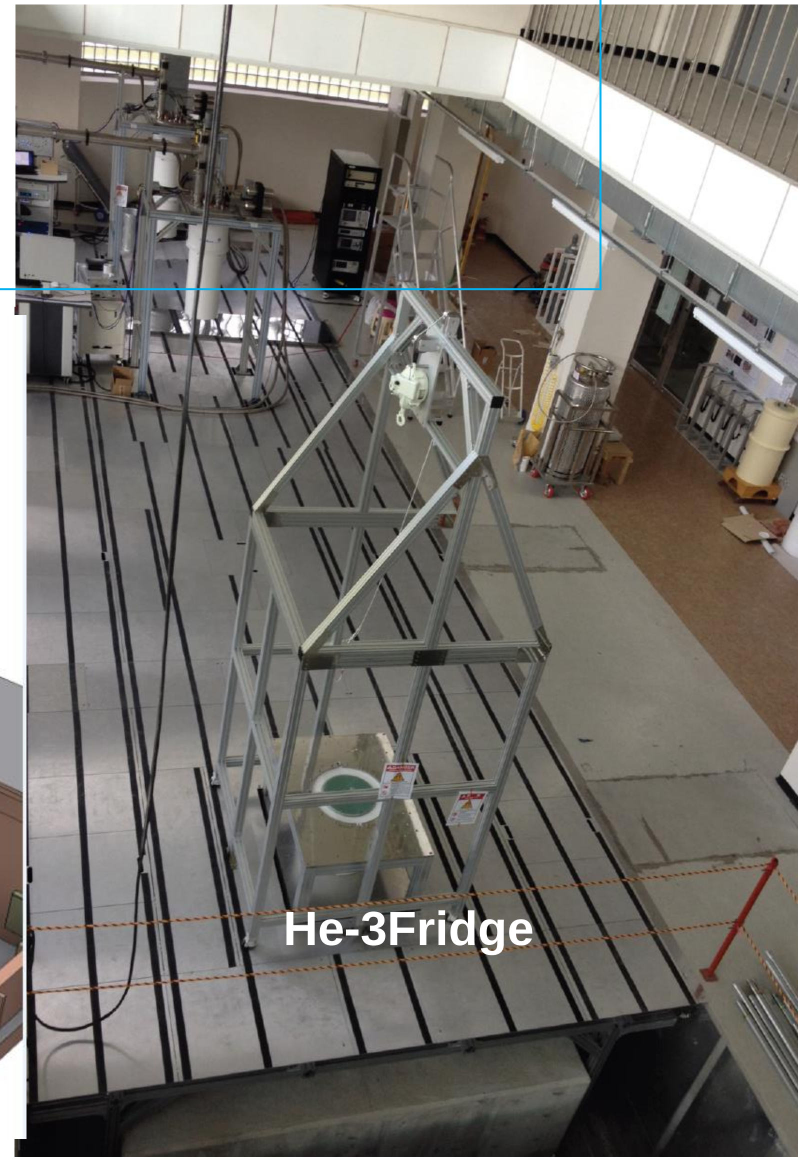
- Cosmic Frontier (Dark Matter axions): Improve in all possible fronts: B-field, Volume, Resonator Quality factor, Physical and Electronic noise. Check dark matter down to 10% of axion content.
- Storage ring proton EDM (most sensitive hadronic EDM experiment). Improve theta_QCD sensitivity by three to four orders of magnitude!
- Together with long-range monopole-dipole (axion mediated) forces probe axion Physics!



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

LVP facility at IBS/CAPP
Up to seven haloscope axion exps in parallel





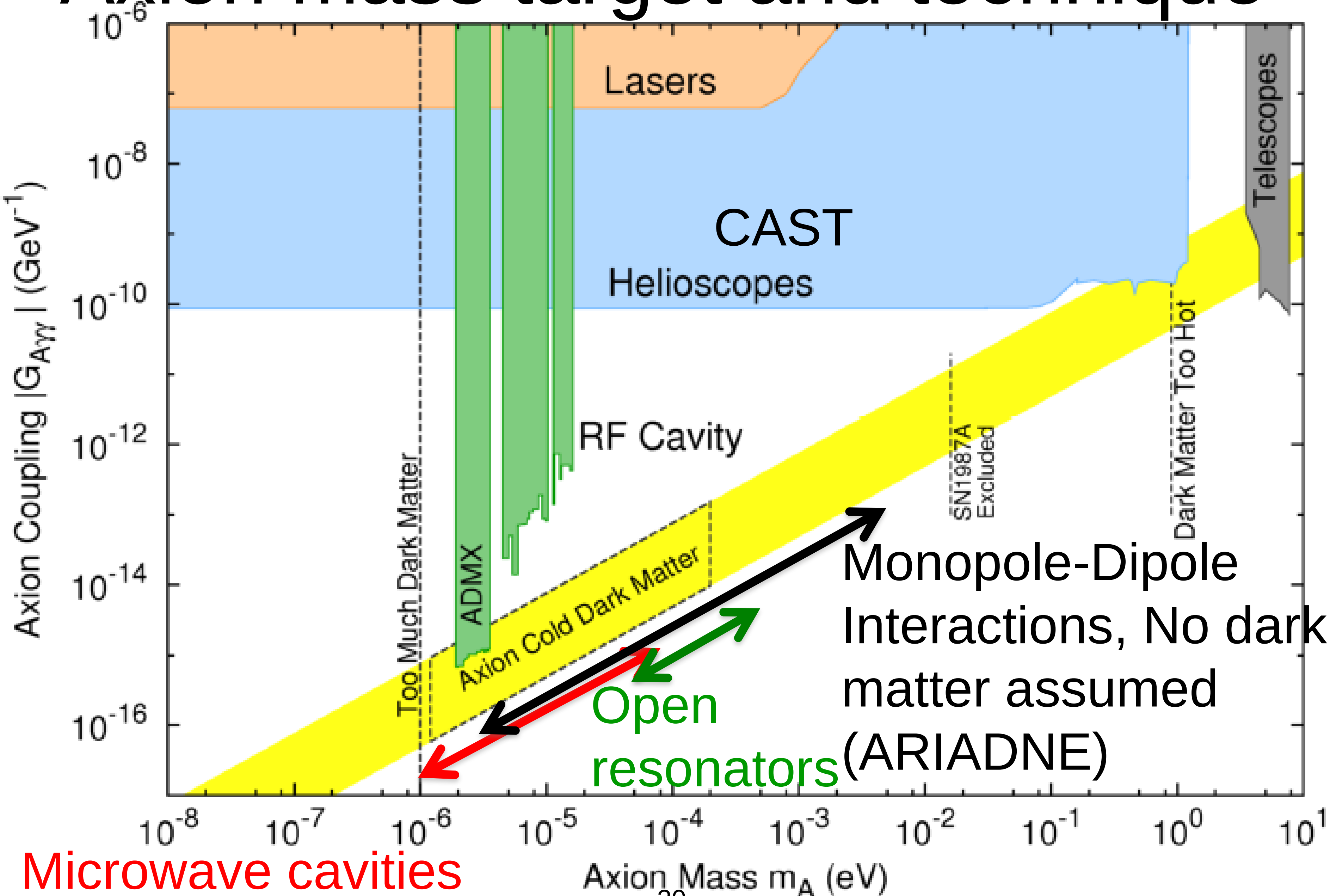
CAPP’s lab space at KAIST, 2017

IBS/CAPP

- ✓ Three world-class axion dark matter experiments to reach hadronic axion dark matter sensitivity
- ✓ Cryogenics, microwave expertise, quantum limited noise microwave amplifiers,…
- ✓ Develop open resonator exps.
- ✓ Significant player for next ten years…

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

Axion mass target and technique



Axion Detection Scheme

P. Sikivie's Axion Haloscope method:

Axion Conversion Power (~10^{-24}W): $$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

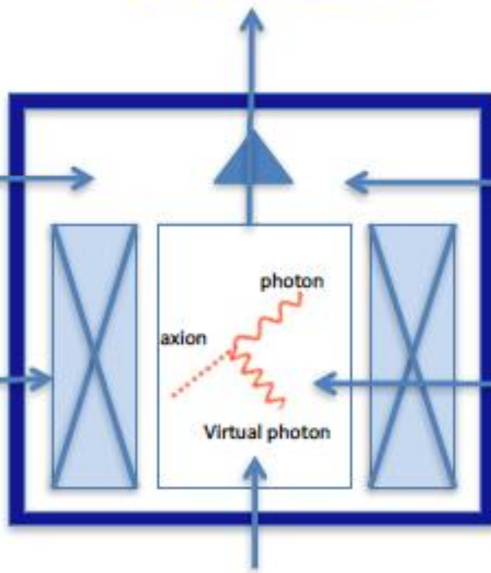
Signal to Noise Ratio: $$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$$

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

Cryogenics

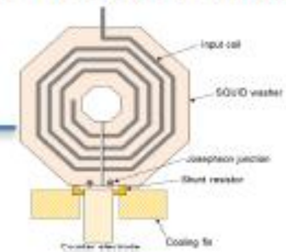
<50mK

To RF Receiver



Quantum Limited Amplifier

SQUID or JPA (commercial?)



High Field SC Magnet

25T and then 35T

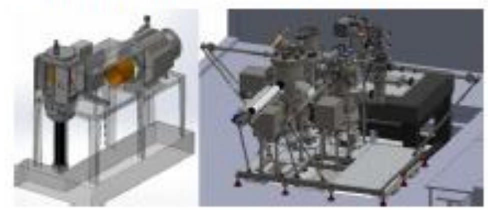
BNL (HTS Technology) Design

(Reverse) Primakoff Effect

High Q Tunable Cavity

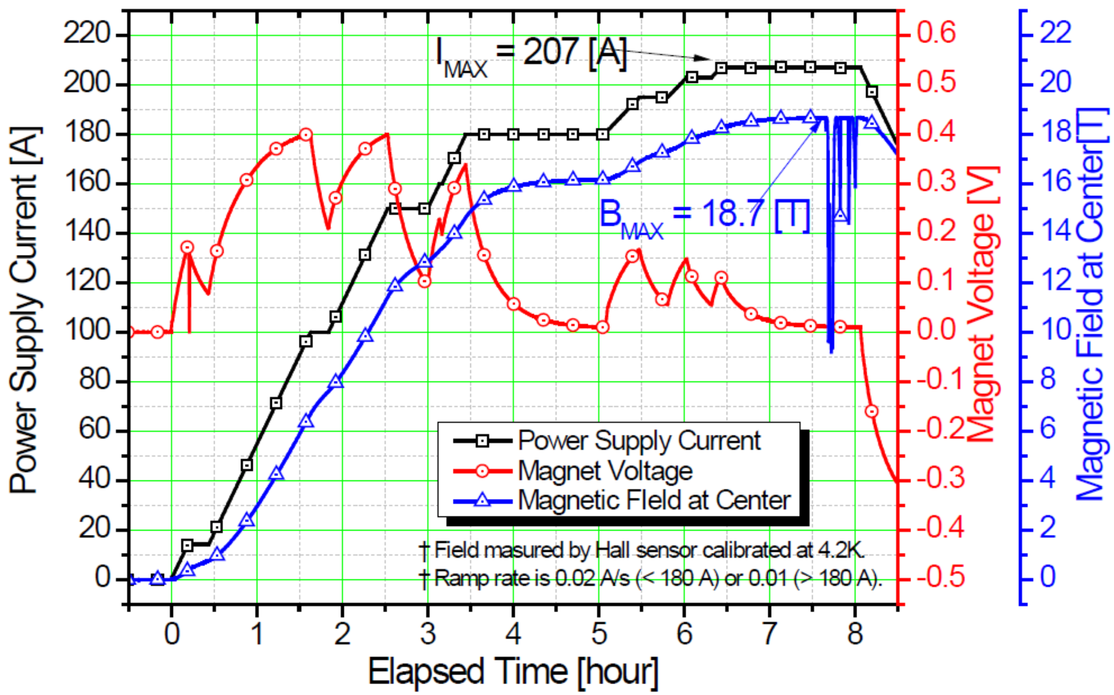
Superconducting Coating

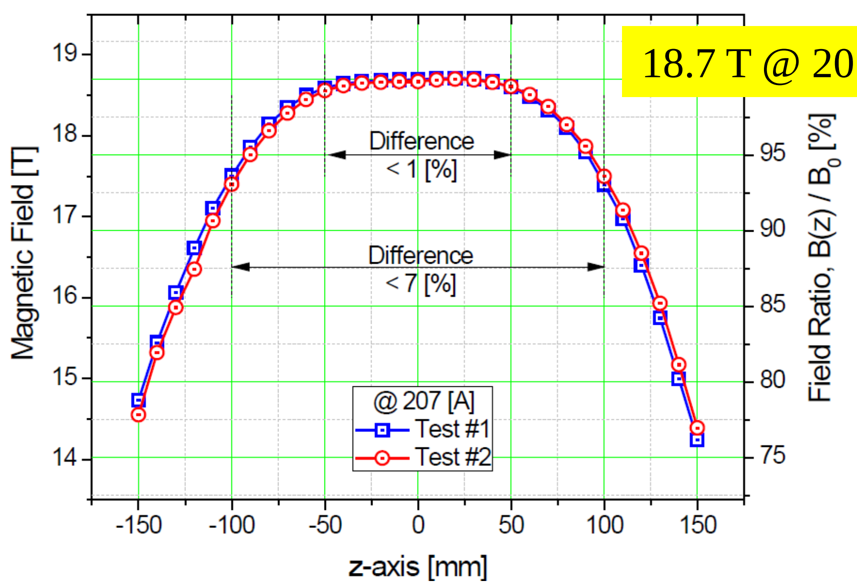
Prof. Jhinhwan Lee of KAIST



Woohyun Chung's slide

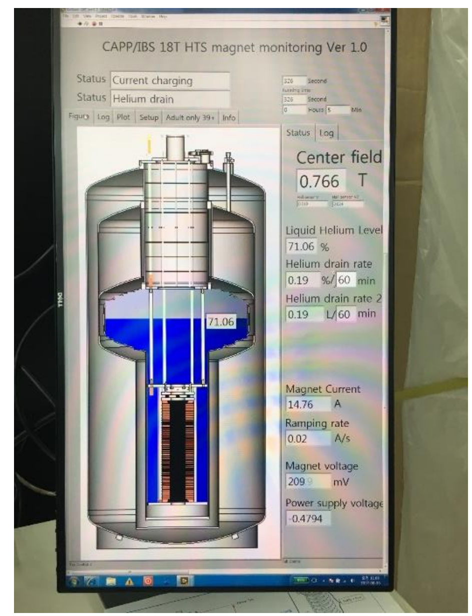
Magnet charging (207A, 18T)





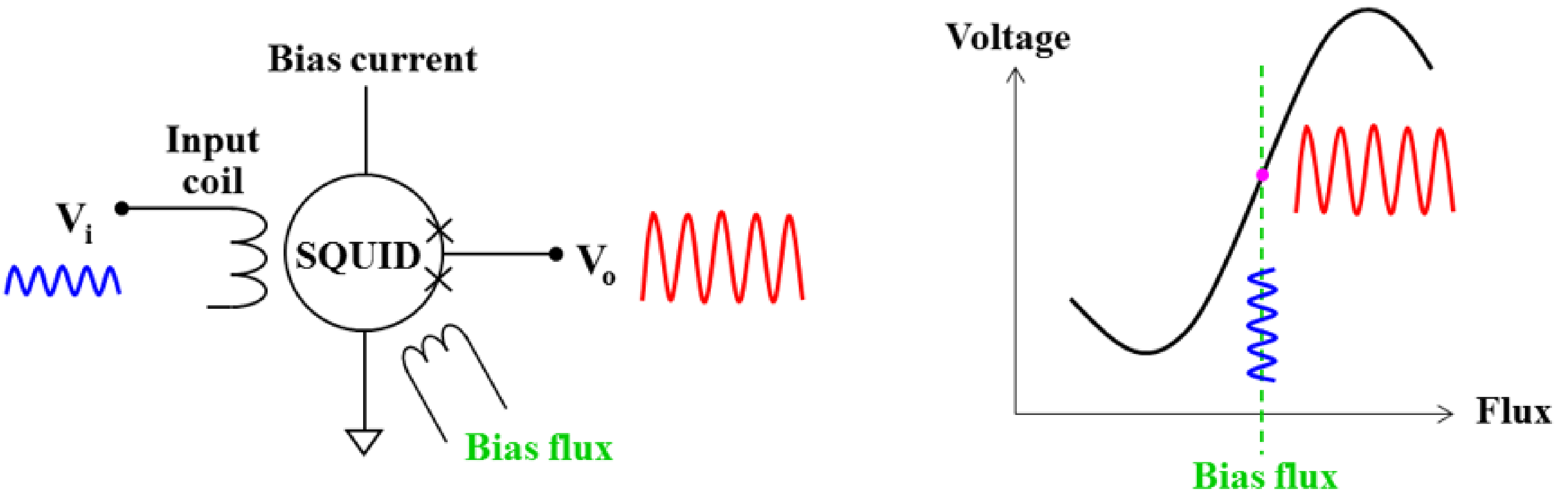
18.7 T @ 207A after 8 hours

Power output



Monitoring program

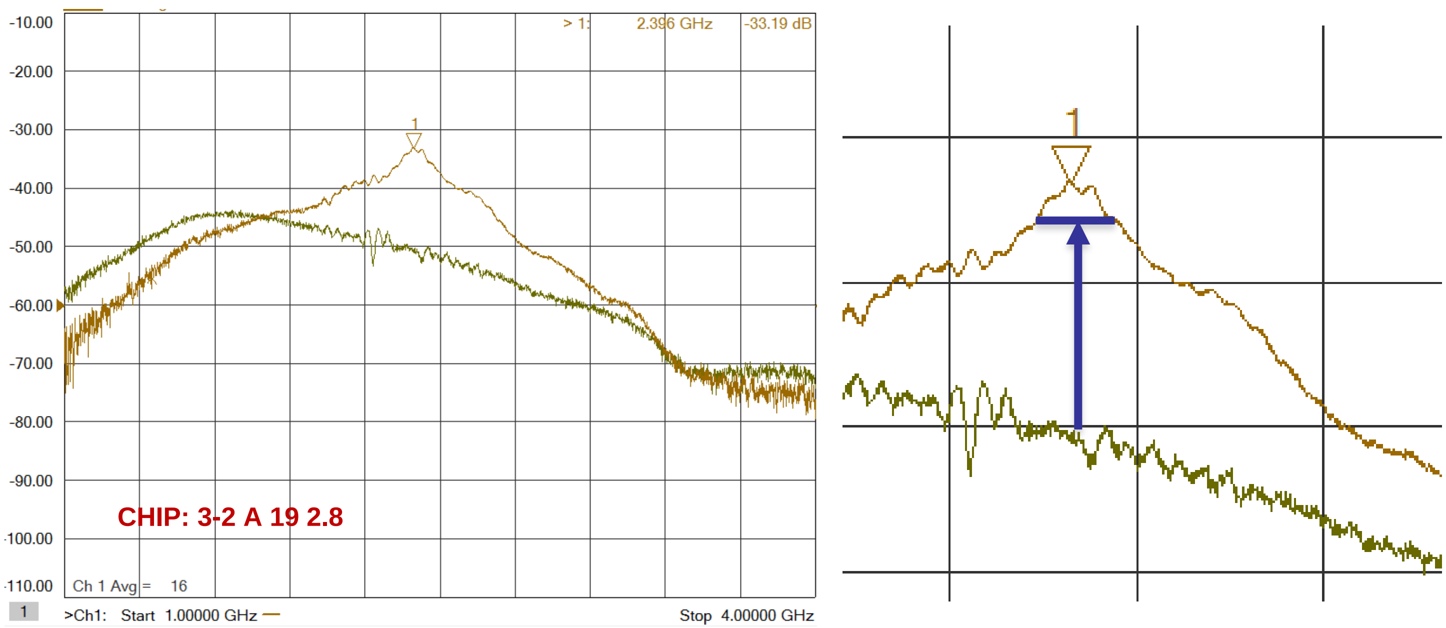
Microstrip SQUID Amplifiers (MSA) for 1.0 – 3.0 GHz band



(a) (b)

Andrei Matlashov’s slide

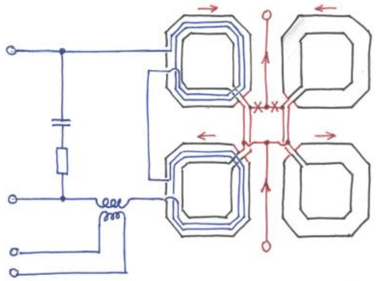
MSA from KRISS, Korea

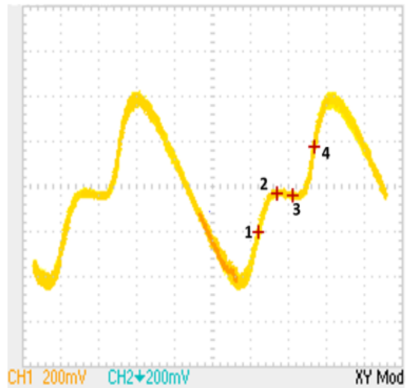


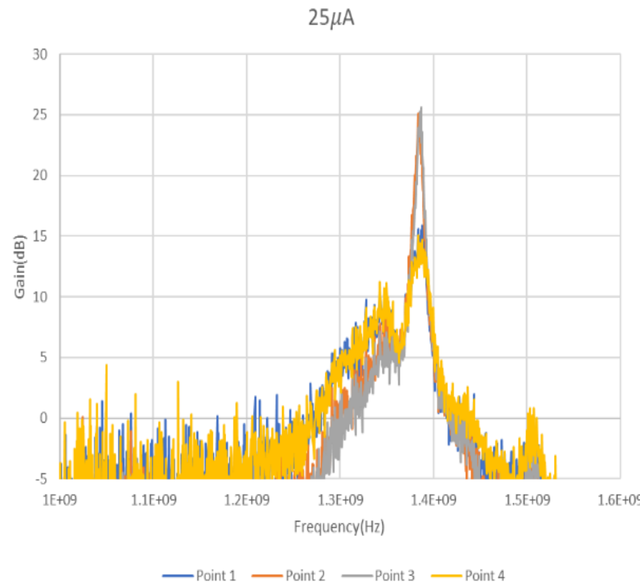
F_0 = 2396 MHz, ΔF = 100 MHz, Gain = 15 dB

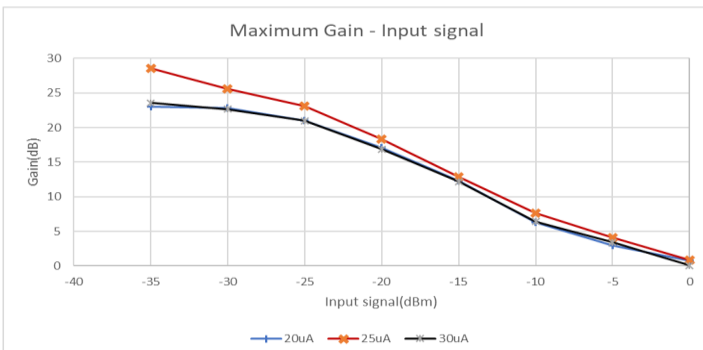
Andrei Matlashov’s slide

Resonant MSAs from IPHT, Jena, Germany









F_0 = 1382 MHz, ΔF_{20dB} = 8.3 MHz, ΔF_{15dB} = 14 MHz

Andrei Matlashov's slide

CAPP8TB

•search range $\in$ [1.6, 1.7] GHz $\Leftrightarrow$ [6.6, 7.0] μeV

•conventional AMI magnet

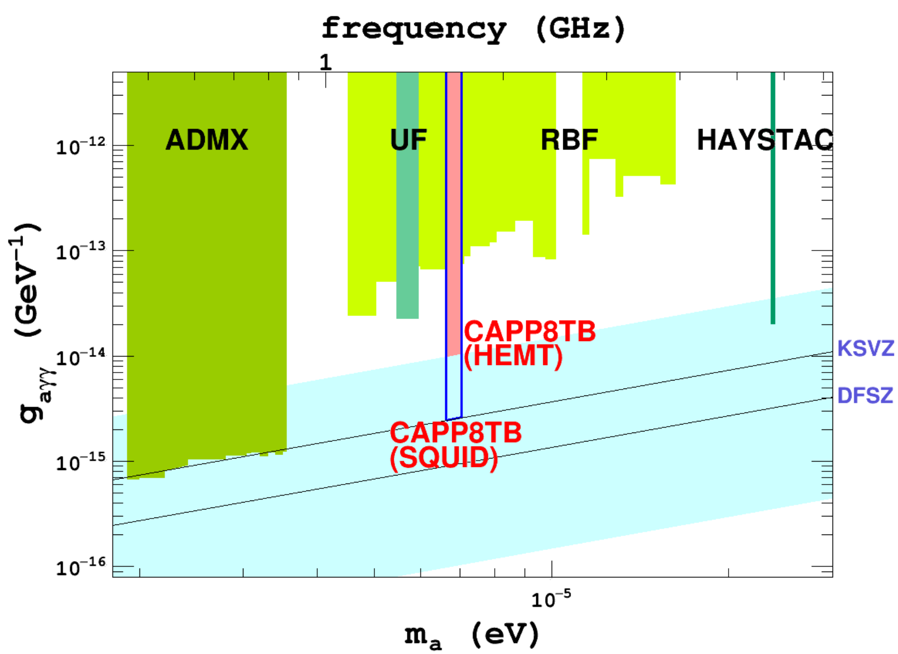
–cold bore = 165 mm → V_{cavity}~3.5 L

–B_{center} = 8 T

•BlueFors DL-400

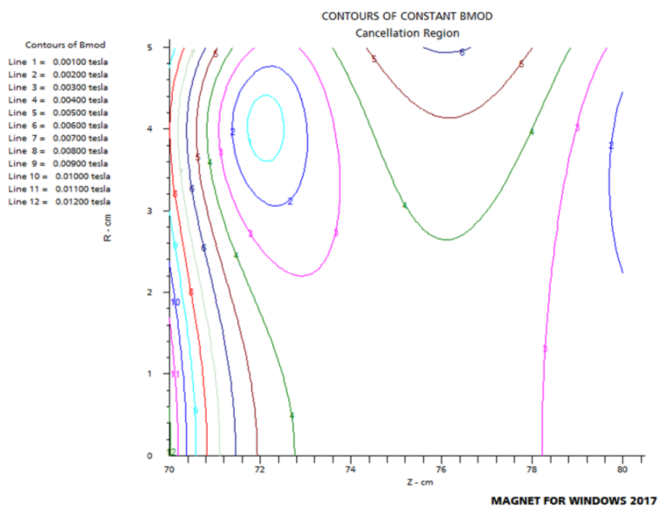
– ~ 0.45 mW cooling power @ 100 mK

	2017	2018	2019
HEMT based	→	→	
SQUID based		→	→

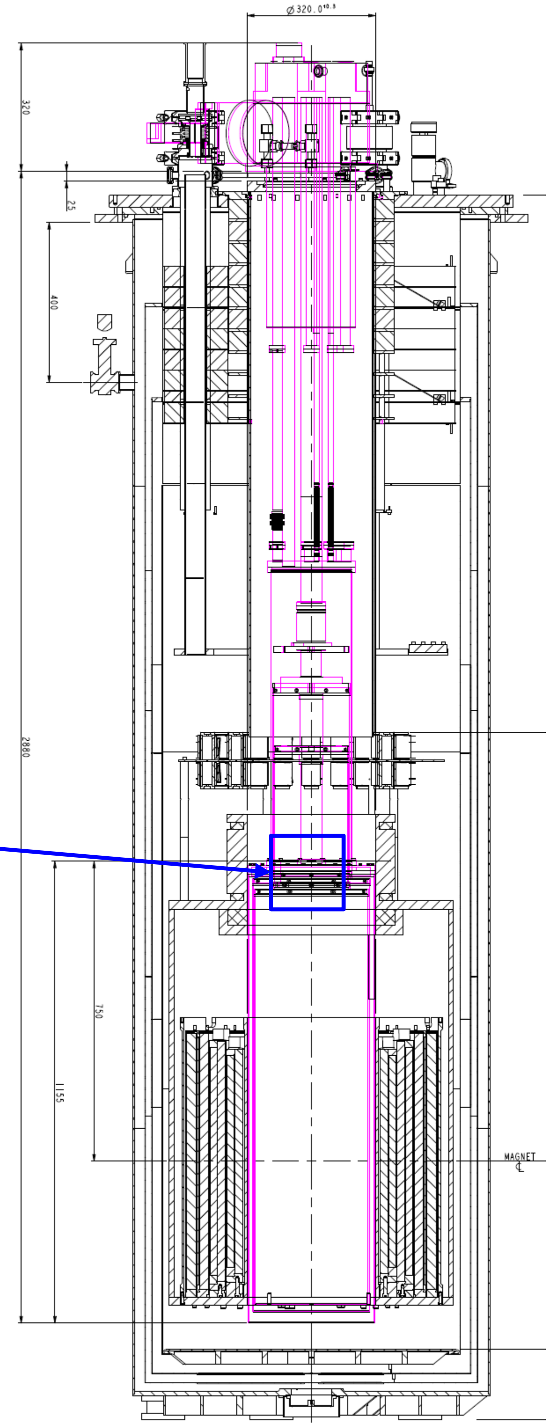


Axion haloscopes with the Oxford-Leiden system

- Oxford magnet
  - cold bore = 320 mm → V_{cavity}~30 L
  - B_{center} =12 T @ 4.2 K
  - cancellation region (<100 G) of 100 mm × 100 mm around the mixing plate of the Leiden dilution fridge

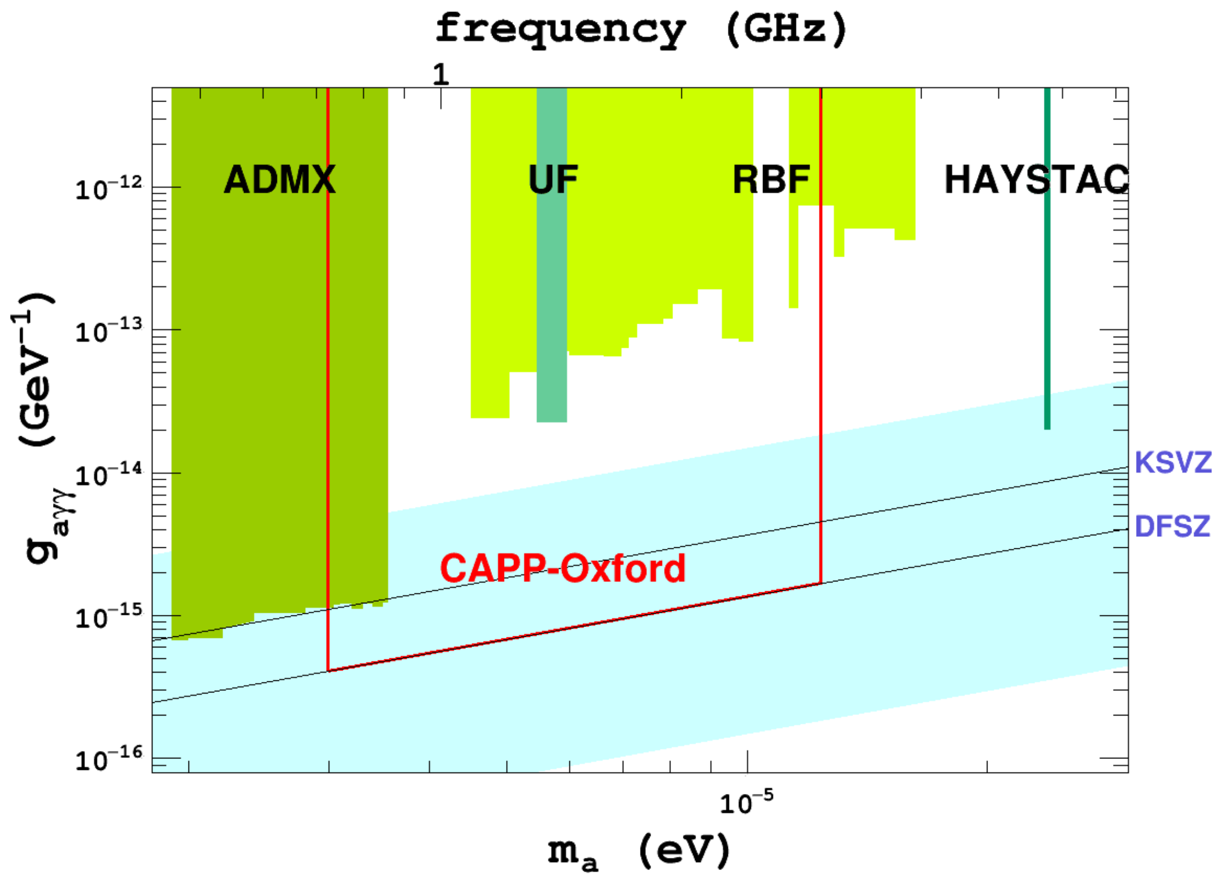


- Leiden dilution fridge (magenta region)
  - 1 mW cooling power @ 100 mK
  - can load up to 200 kg



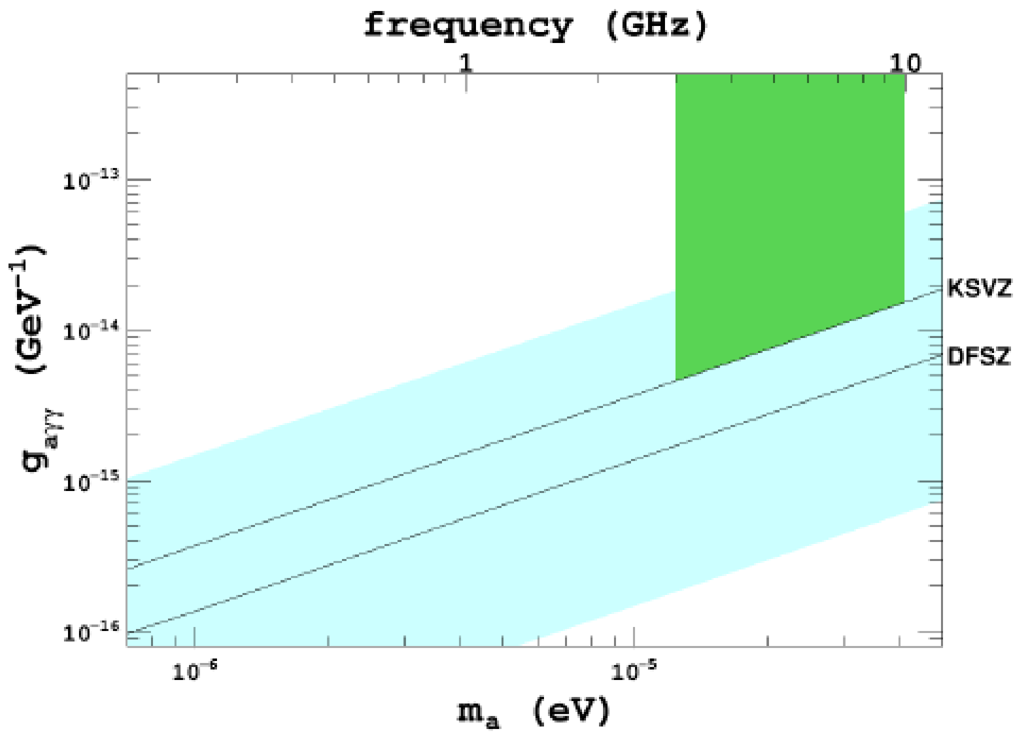
Axion haloscopes with the Oxford-Leiden system

	2016	2017	2018	2019	2020	2021	2022	2023	2024
Leiden DF									
Oxford magnet									



25T High Tc magnet from BNL

- quantum noise limited amplifier based experiments, 70 mK for 1 GHz
- single-cavity experiments only

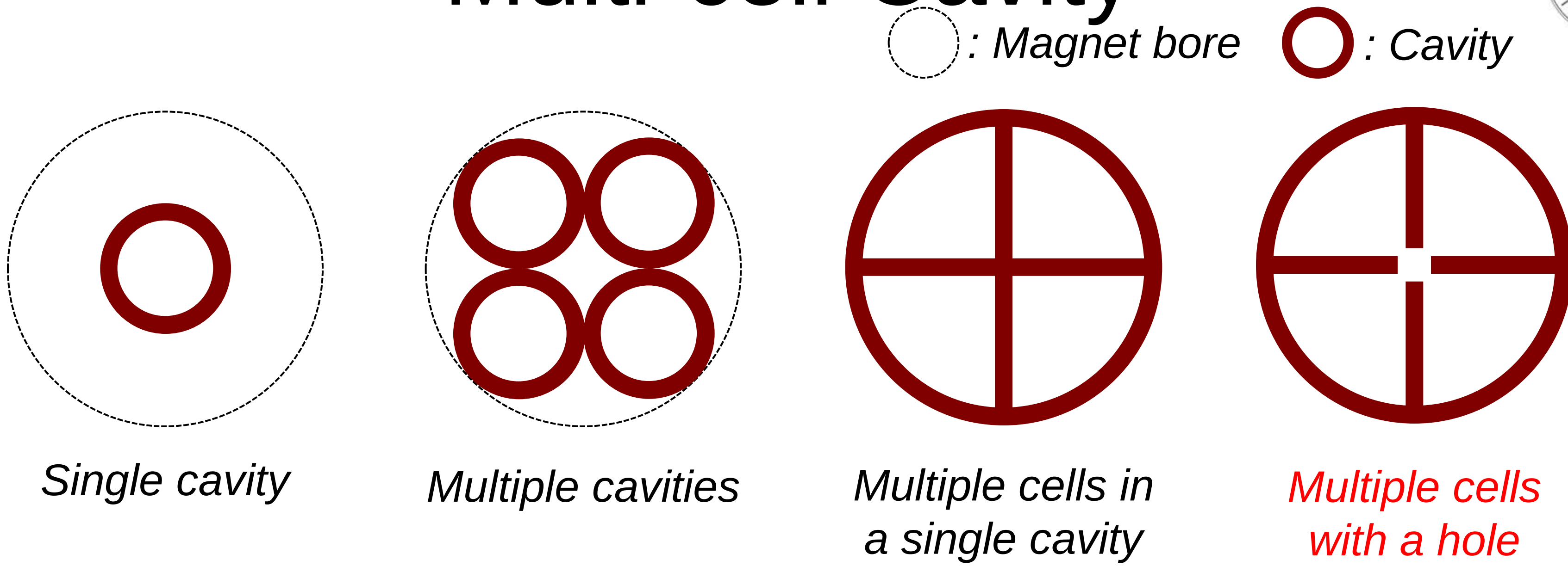


ByeongRok Ko

- can touch the KSVZ line from 3 to 10 GHz

Slide by SungWoo Youn

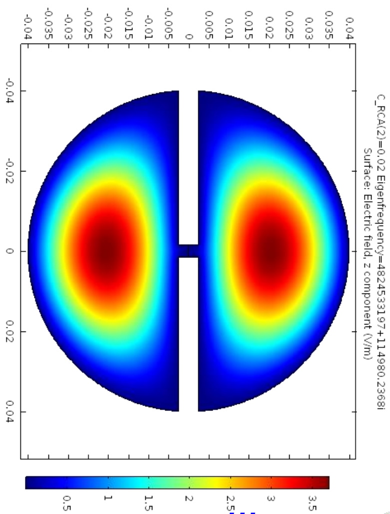
Multi-cell Cavity



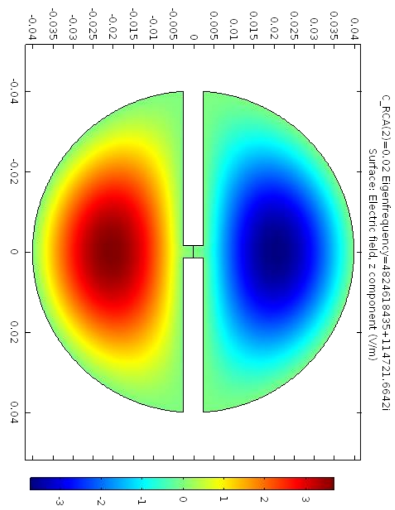
- *Superior to conventional multiple-cavity*
  - *Larger detection volume*
    - $V_{4\text{-cell}} \approx 1.7 \times V_{4\text{-cavity}}$ => $df/dt_{4\text{-cell}} \approx 2.0 \times df/dt_{4\text{-cavity}}$
  - *Simpler receiver chain*
    - *Single antenna => No power combiner*
  - *Easier phase-matching mechanism*

Slide by SungWoo Youn

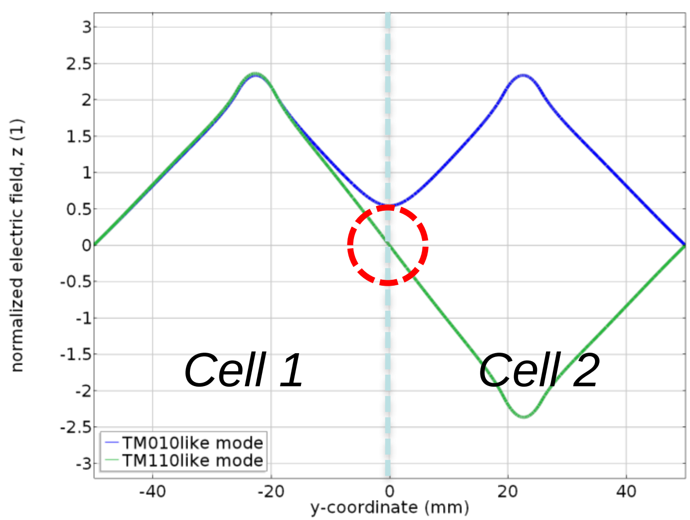
Multi(Double)-cell Cavity



TM_{010}-like



TM_{110}-like

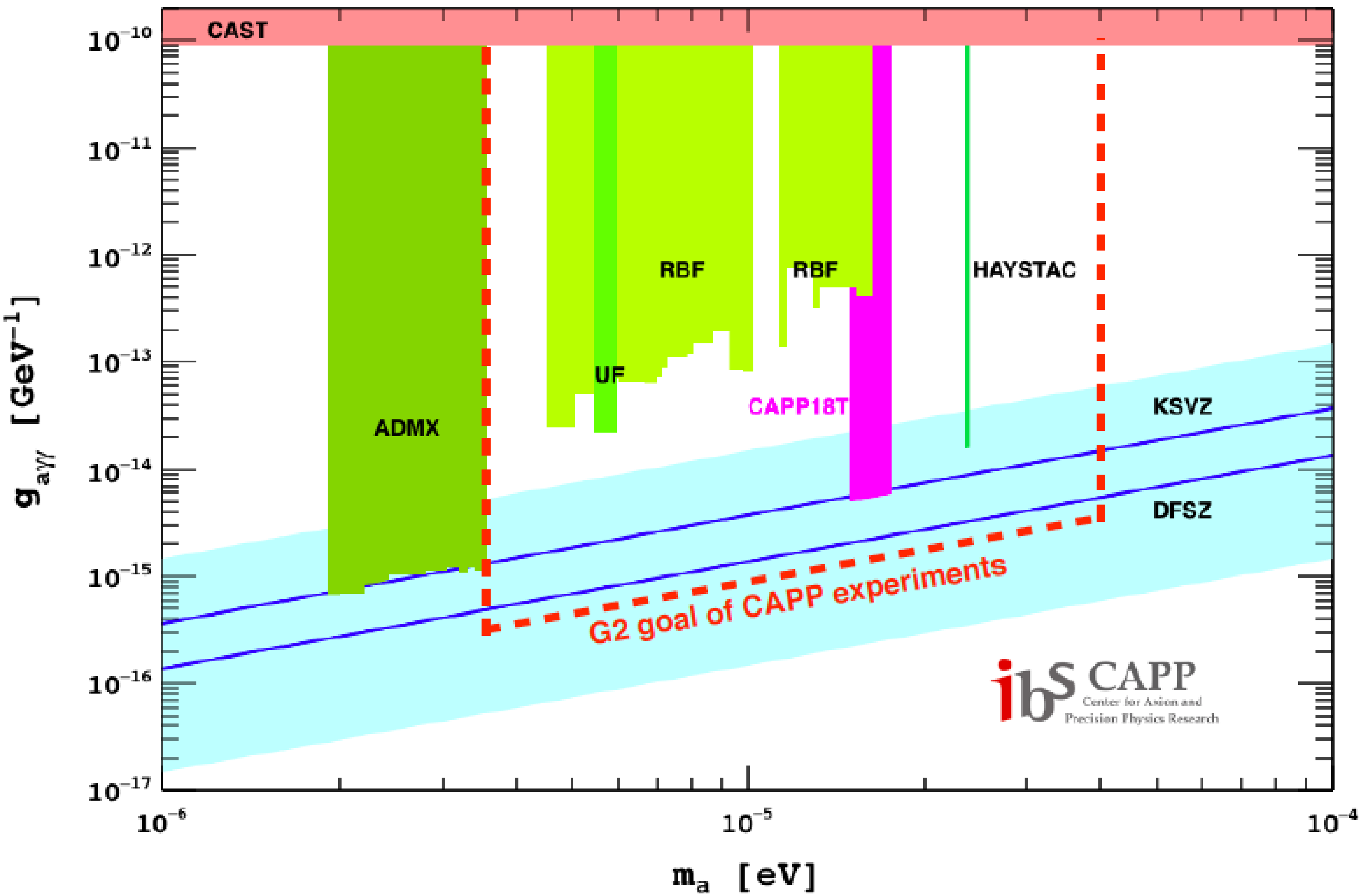


- *Opening breaks the frequency degeneracy*
  - *Lowest mode => TM_{010}-like*
- *C=0 for higher mode(s)*
  - *Does not interfere with sensitivity*

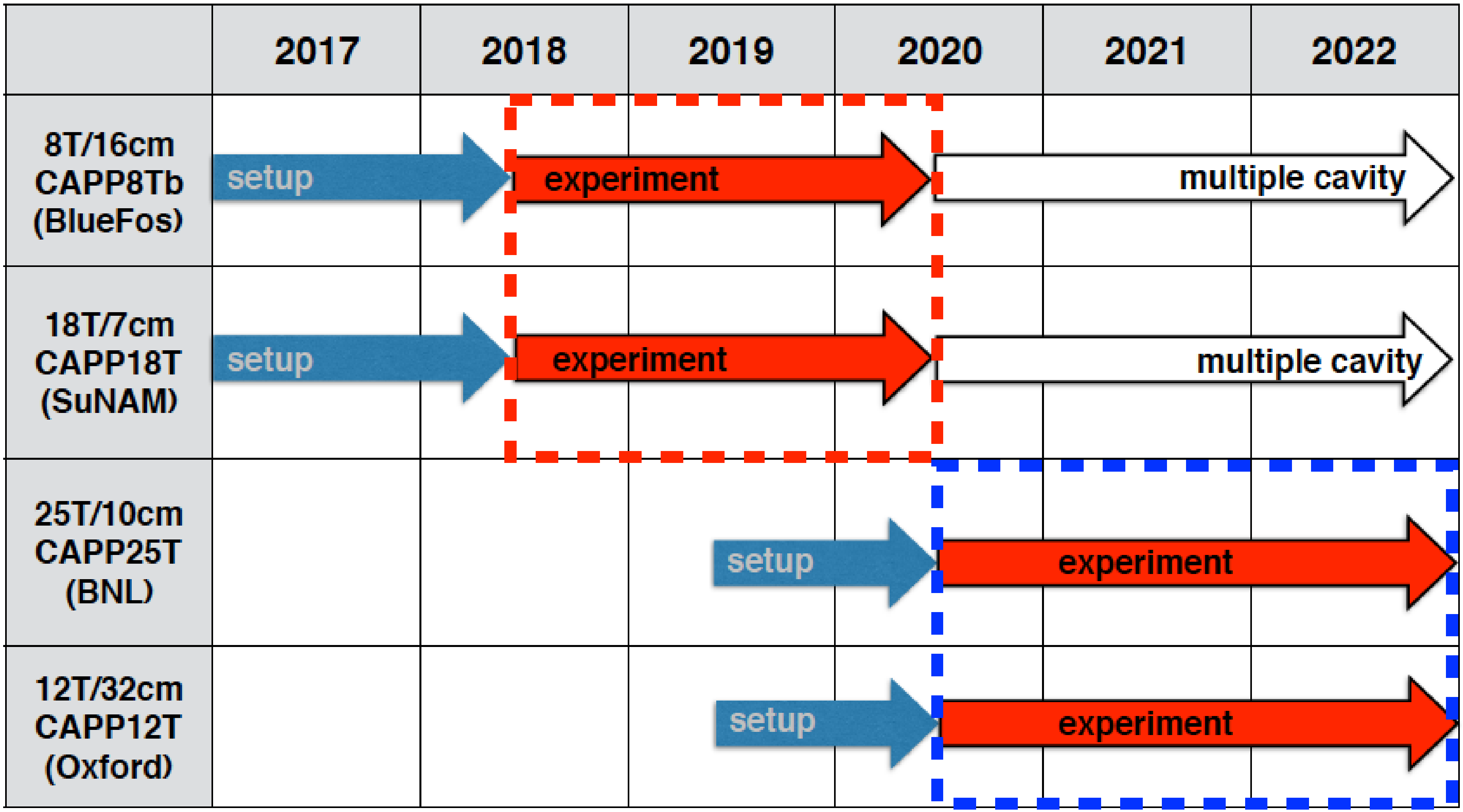
- *Symmetric field distribution*
  - *Condition of phase-matching*
- *E=0 at center for higher mode(s)*
  - *Vanishing of higher mode peaks in S parameter => phase-matching*

- *Promising design for higher frequency regions*

Axion Dark Matter Search at KAIST



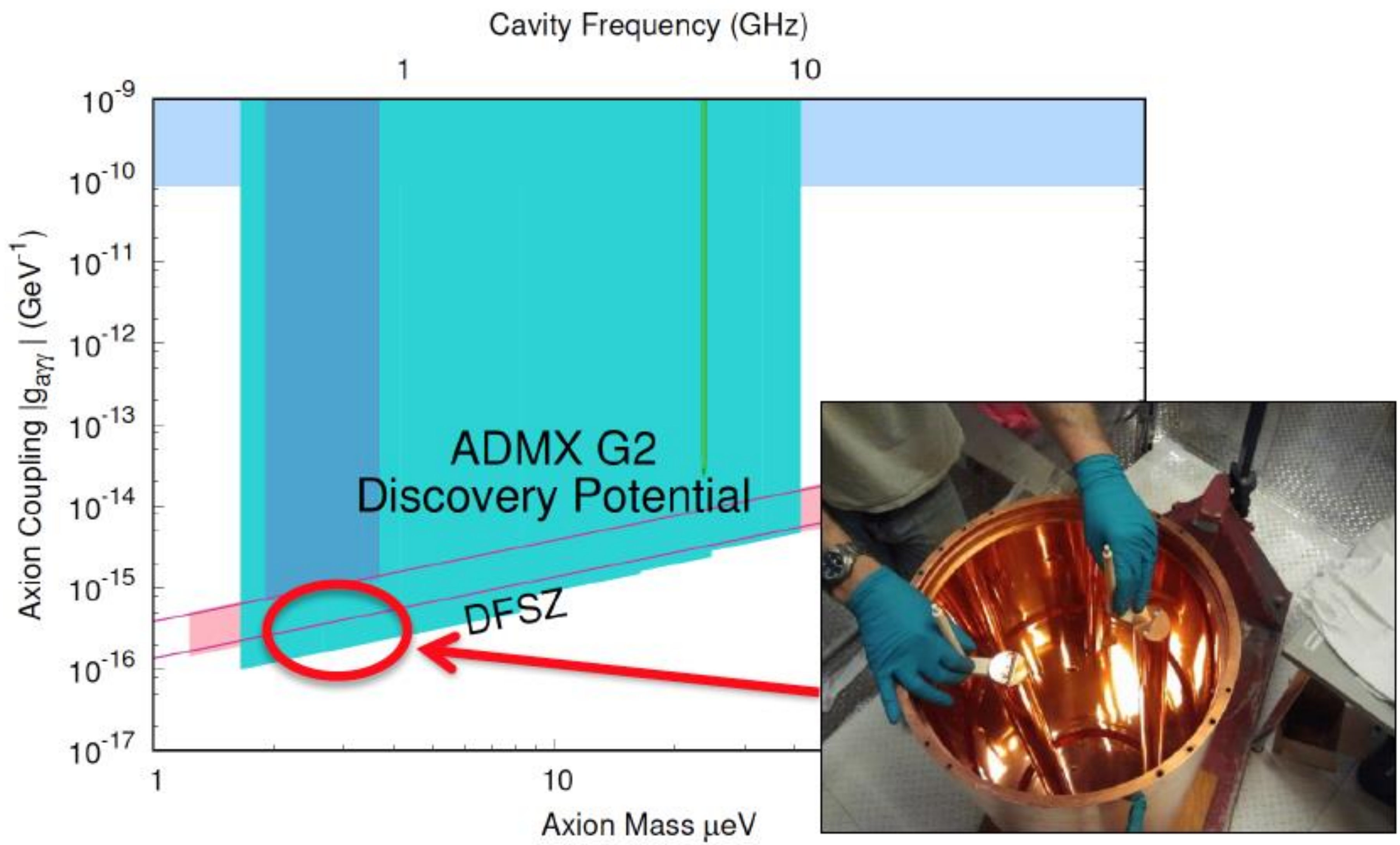
CAPP Dark Matter Axion Search Schedule



There are R&D efforts for higher mass dark matter axion search (>40μeV)

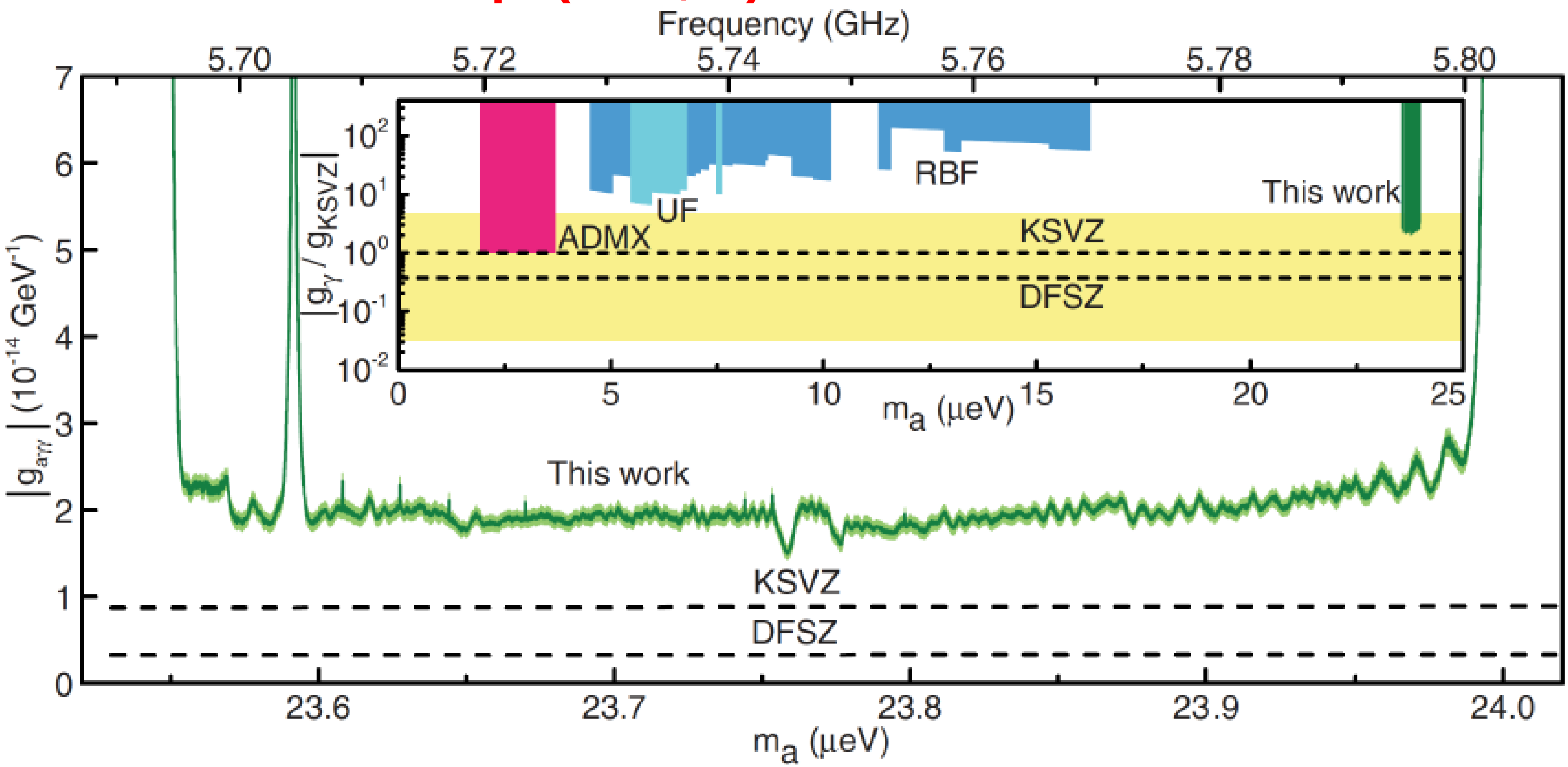
“Others”

ADMX Main Cavity: Initial run 0.65-1 GHz



First results at 24 μeV: no axion yet

HAYSTAC exp. (Yale,…)



Results: B.M. Brubaker *et al.*, Phys. Rev. Lett. 118 (2017) 061302.
Design details: S. Al Kenany *et al.*, Nucl. Instrum. Methods A 854 (2017) 11-24.

Axion sensitivity

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

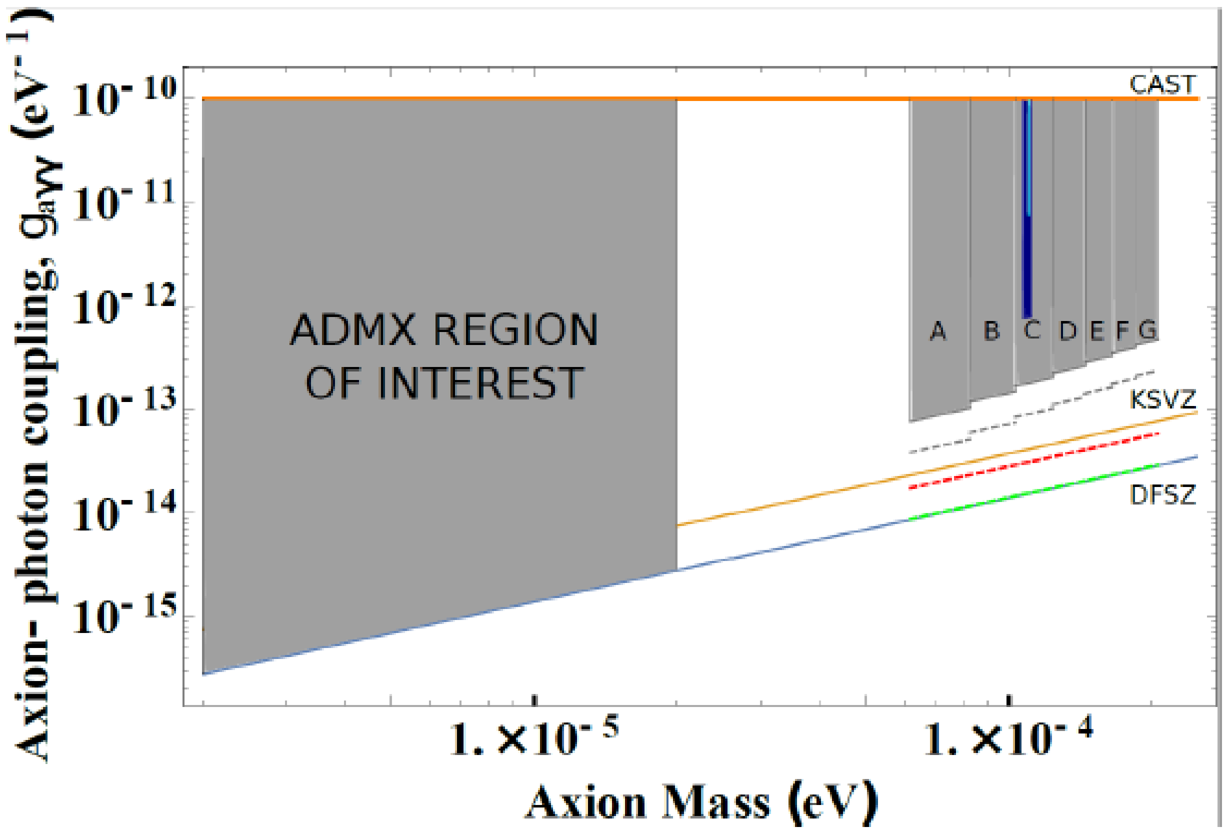
$$\times \left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

Parameter dependence	ADMX plans	IBS/CAPP & KAIST	Gain factor
B^4	7.5 – 9T	25 – 35T	100-250
Q	50-300K	10^7 (10^6)	3-10
T^2	50mK	50-30mK	1
V^2	V_1	1-7 x V_1	1-50

Up to 5-7 parallel experiments at IBS/CAPP.

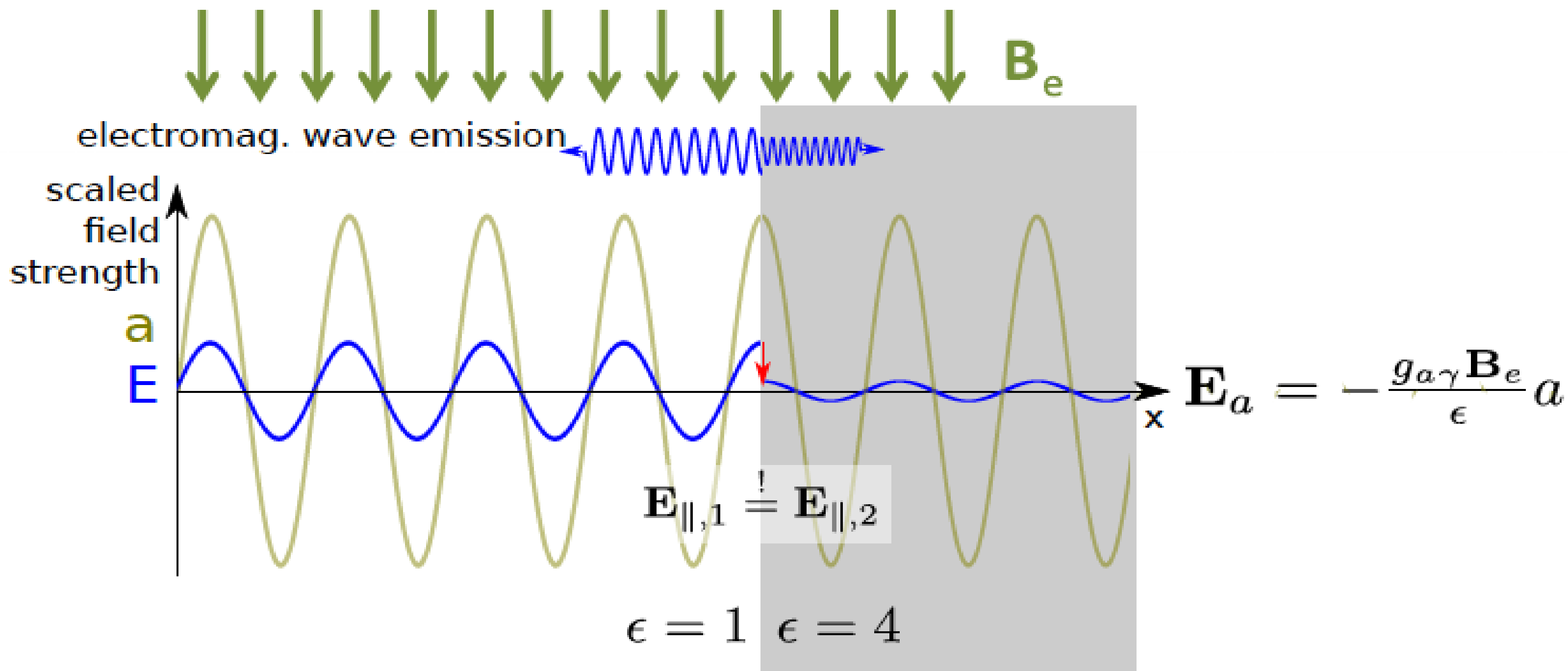
Total gain in scanning rate: 300 – 10^5; gain in g_γ: 4 - 18

Sensitivity Projections



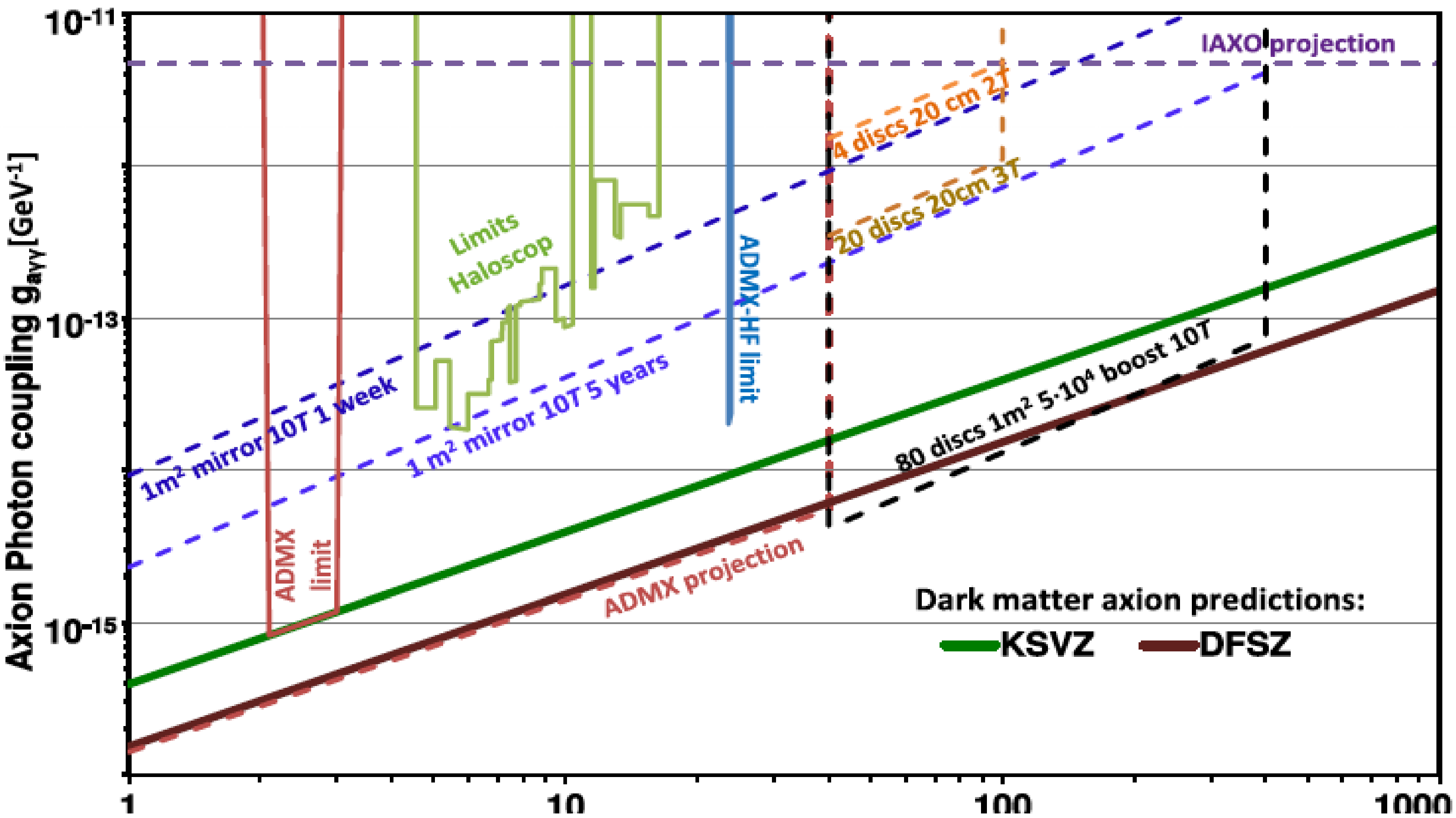
- Narrow aqua bar is pathfinder result
- Wider navy bar is 2018 run, 26-27 GHz
- A→G are the 2018-2025 runs, with 14 T magnet and SQL Amps
- Dashed limits depend on new technology and R&D ie Squeezed vacuum to beat SQL, upgrade magnet again to 28 T

MADMAX principle: axion-photon mixing



$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right) C_{a\gamma}{}^2 \cdot f(\epsilon_1, \epsilon_2)$$

MADMAX projected sensitivity



5-10 years away:

Storage ring proton EDM and ARIADNE

- Proton EDM exp. and ARIADNE together probing axion physics like no other exps!

- It is hard to look for large axion mass (>20GHz) as dark matter with existing techniques. For large axion mass ARIADNE has the best chance of pointing out its mass if a signal is detected. After that we can design a dedicated axion dark matter experiment for that mass…

- For example: a proton EDM signal at $10^{-27}e$-cm and the absence of a signal with related ARIADNE sensitivity can exclude axions from a large parameter space!

Leadership at CAPP:
Yun Chang Shin

Axions with ARIADNE:
Axion Resonant InterAction DetectioN Experiment

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

A. Arvanitaki and A. Geraci
PRL 113, 161801 (2014)

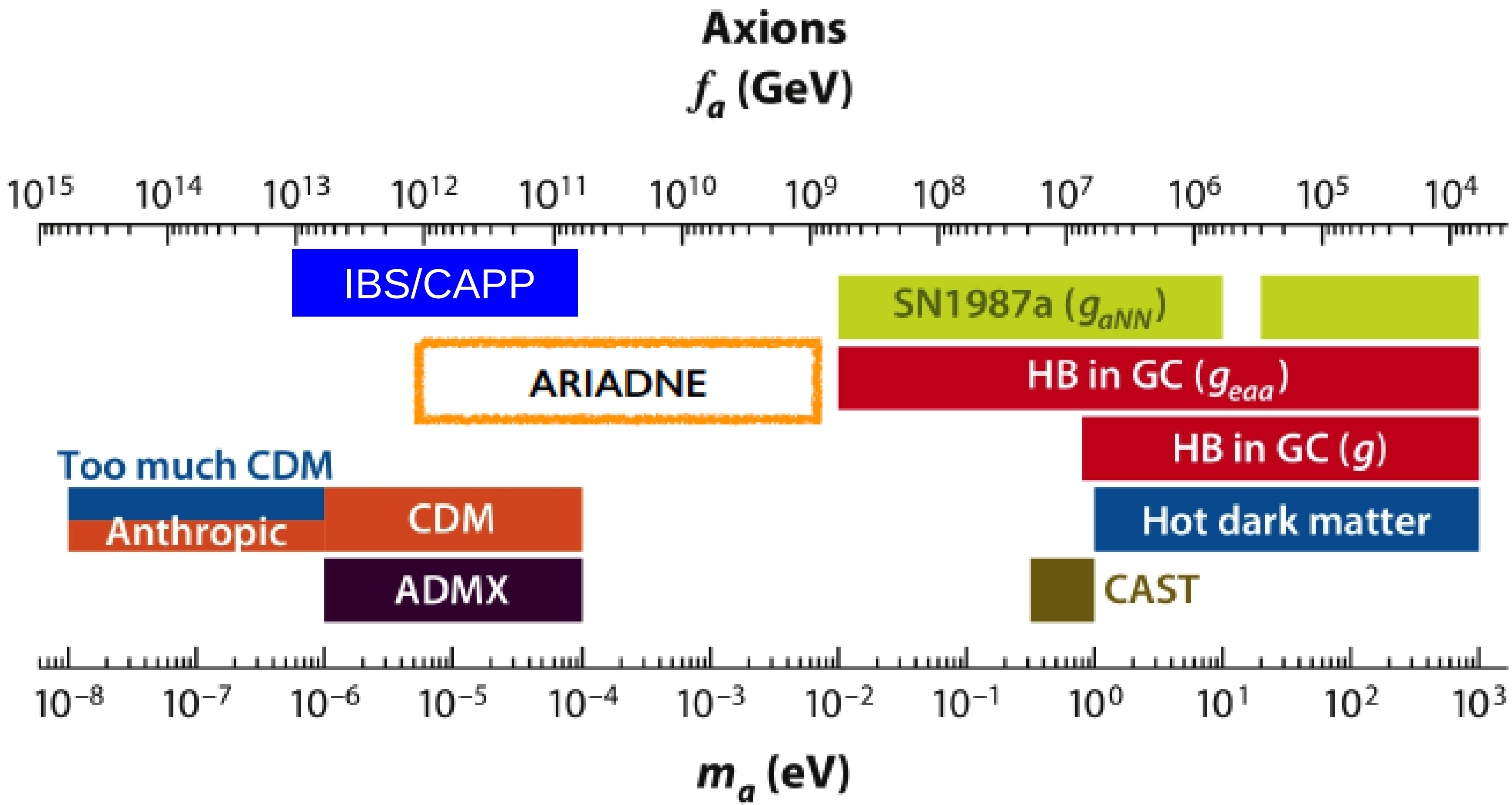
New macroscopic forces?

ARIADNE PI: A. Geraci

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating axion monopole-dipole forces are proposed.

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

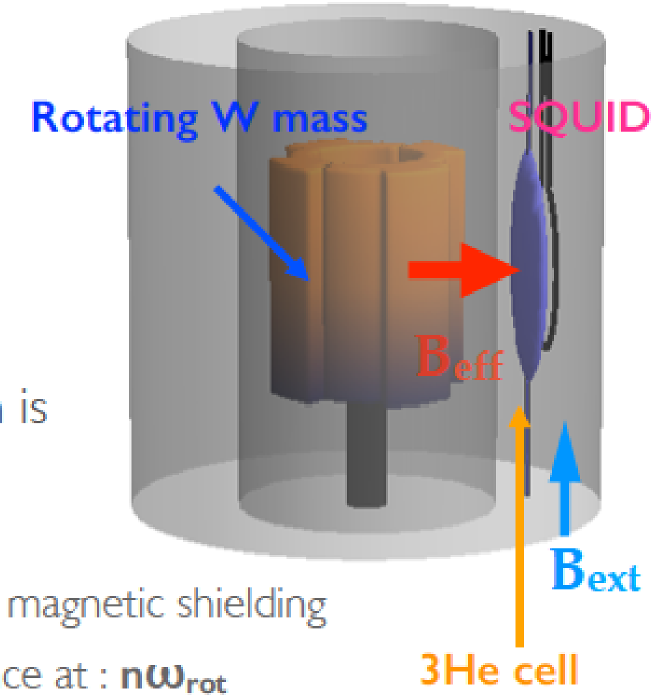
The effective potential between monopole and dipole is

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

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

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



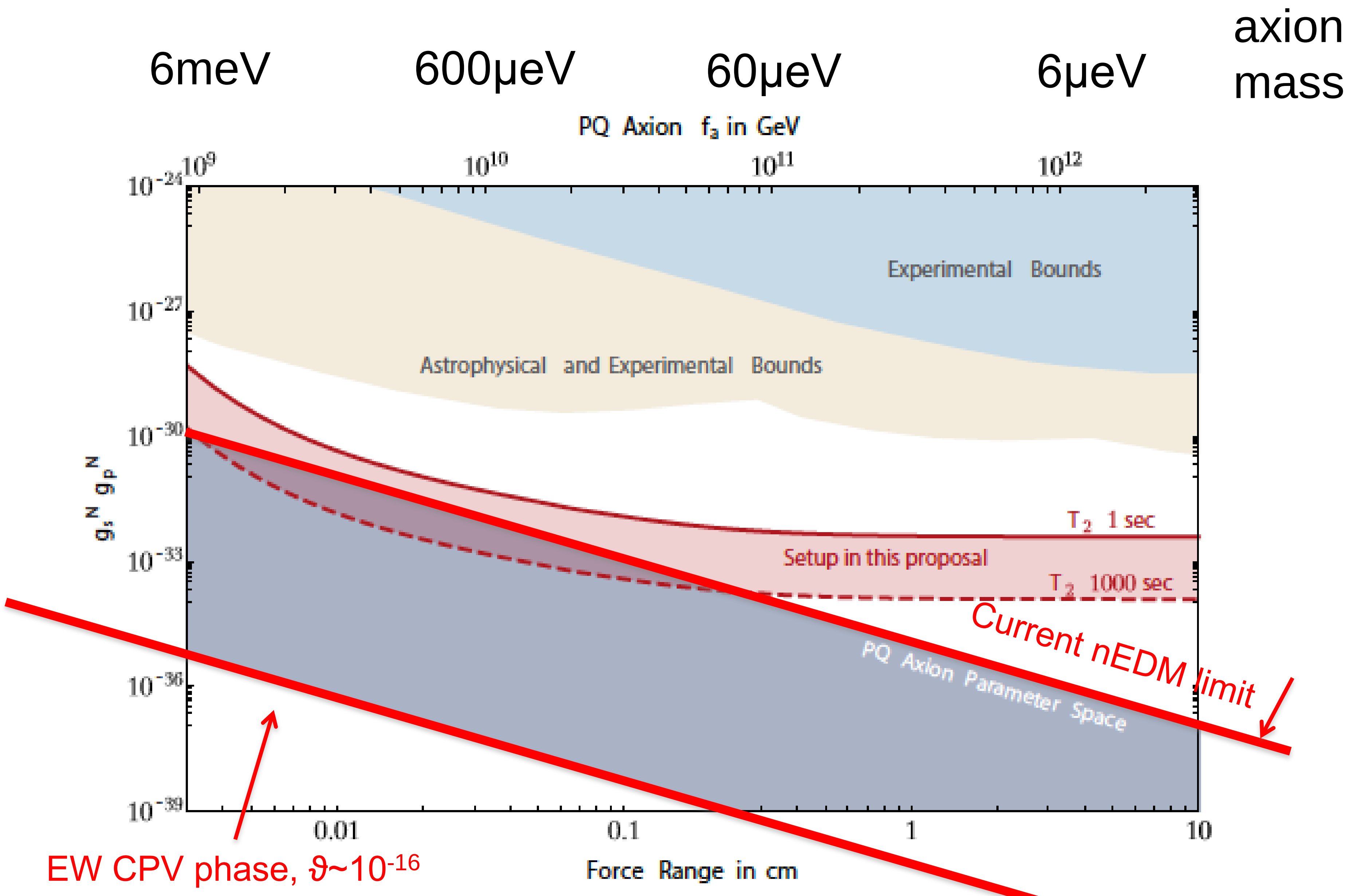
- The effective magnetic field is not screened by superconducting magnetic shielding
- Non-magnetic rotating mass oscillates the interaction in resonance at : **$n\omega_{rot}$**
- A dense ensemble of polarized ^{3}He gas with precession at : ω_{3He}
- The NMR sample (^{3}He) develops a magnetization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

Axion mediated long range forces

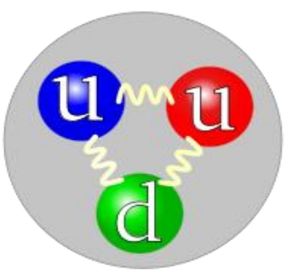


Fundamental particle EDM: study of CP-violation beyond the Standard Model

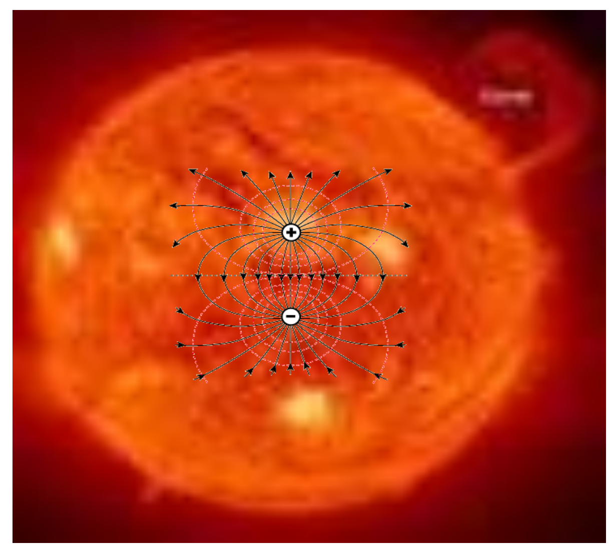
Proton EDM proposal: d=$10^{-29}$$e$•cm

- 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

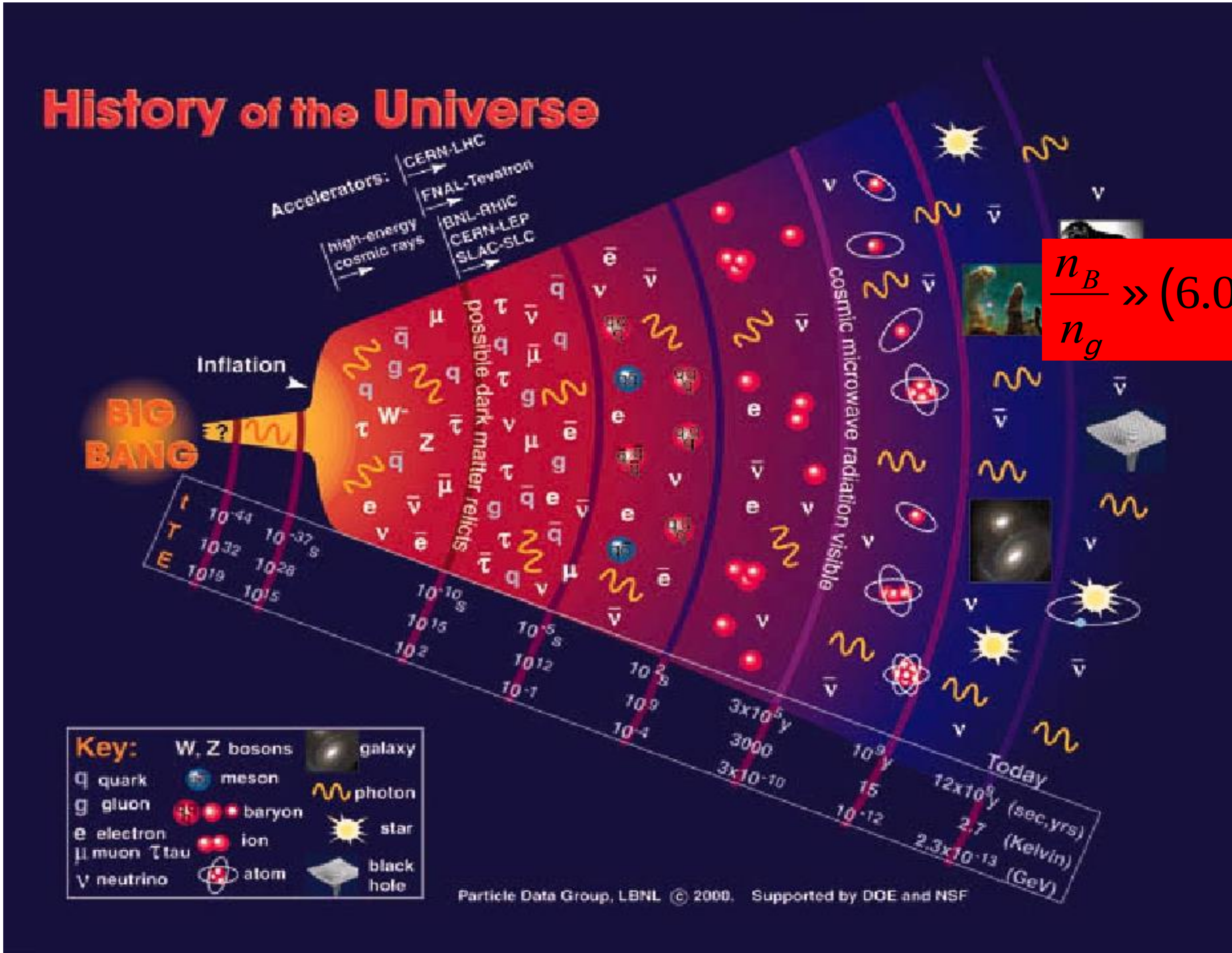


Sun



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

Why is there so much matter after the Big Bang:



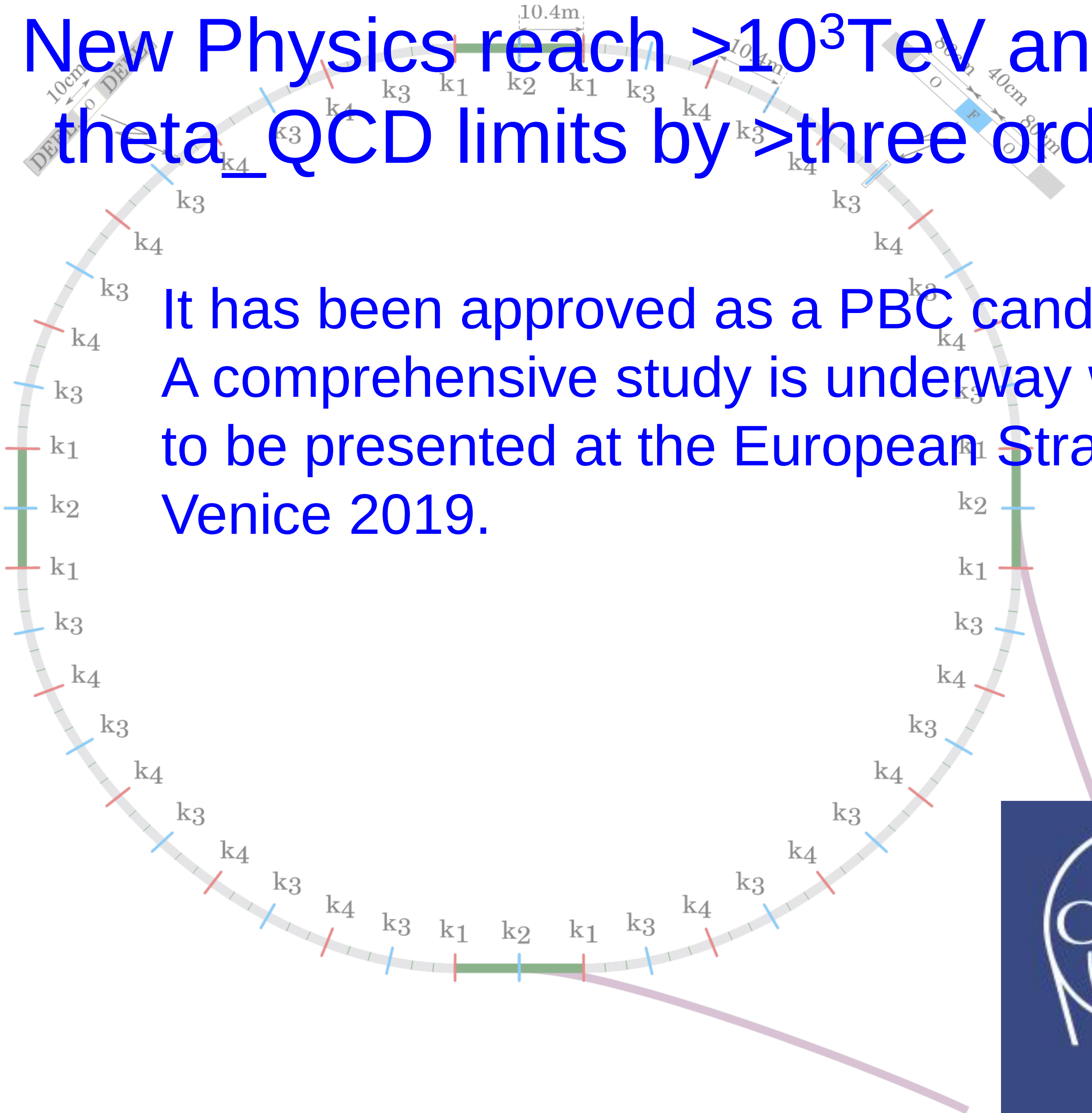
We see:

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

From the SM:

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

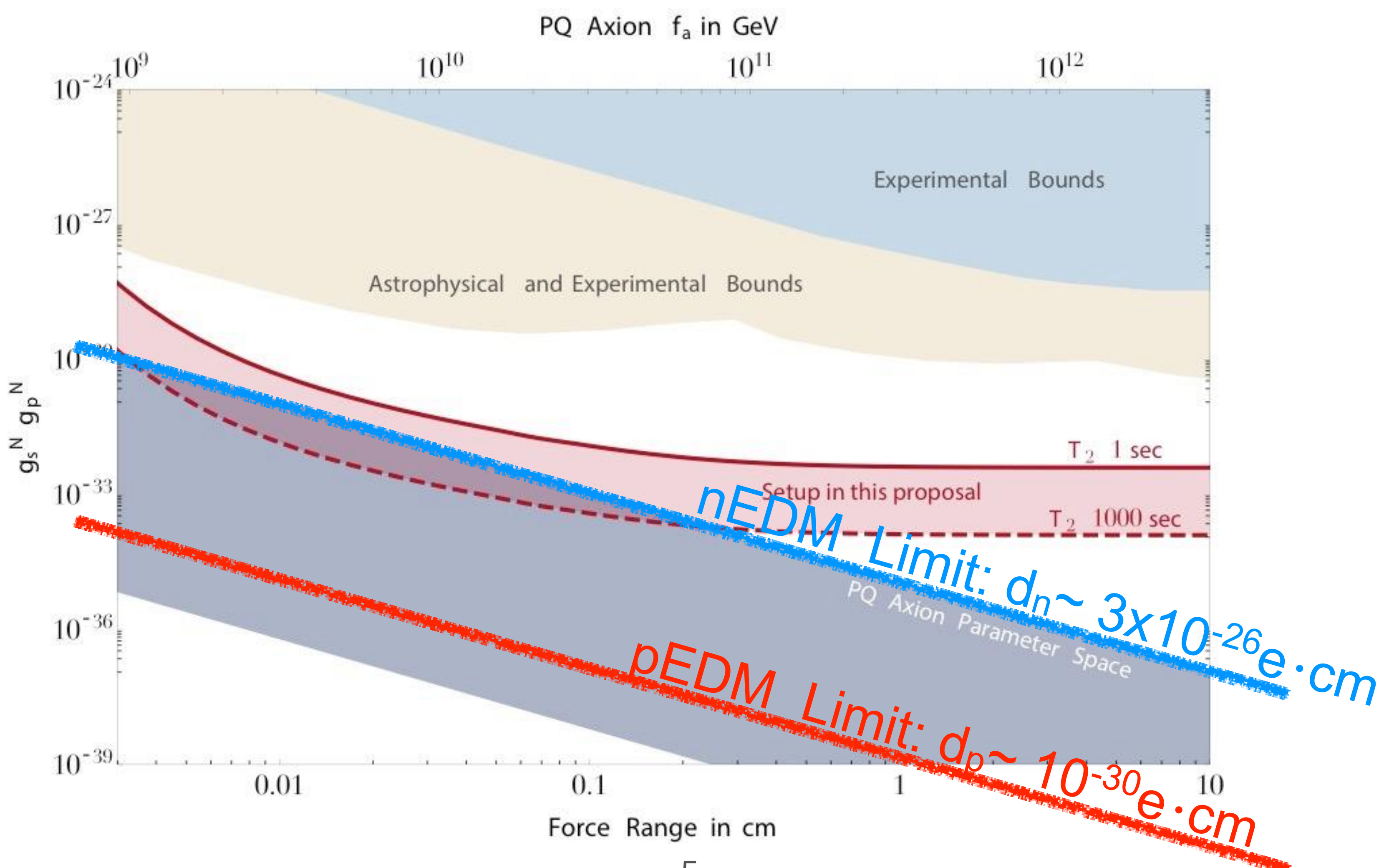
The proton EDM electric ring, 500m circ. Current goal 10^{-29}e-cm; upgraded: 10^{-30}e-cm. New Physics reach >10^{3}TeV and improve present theta_QCD limits by >three orders of magnitude



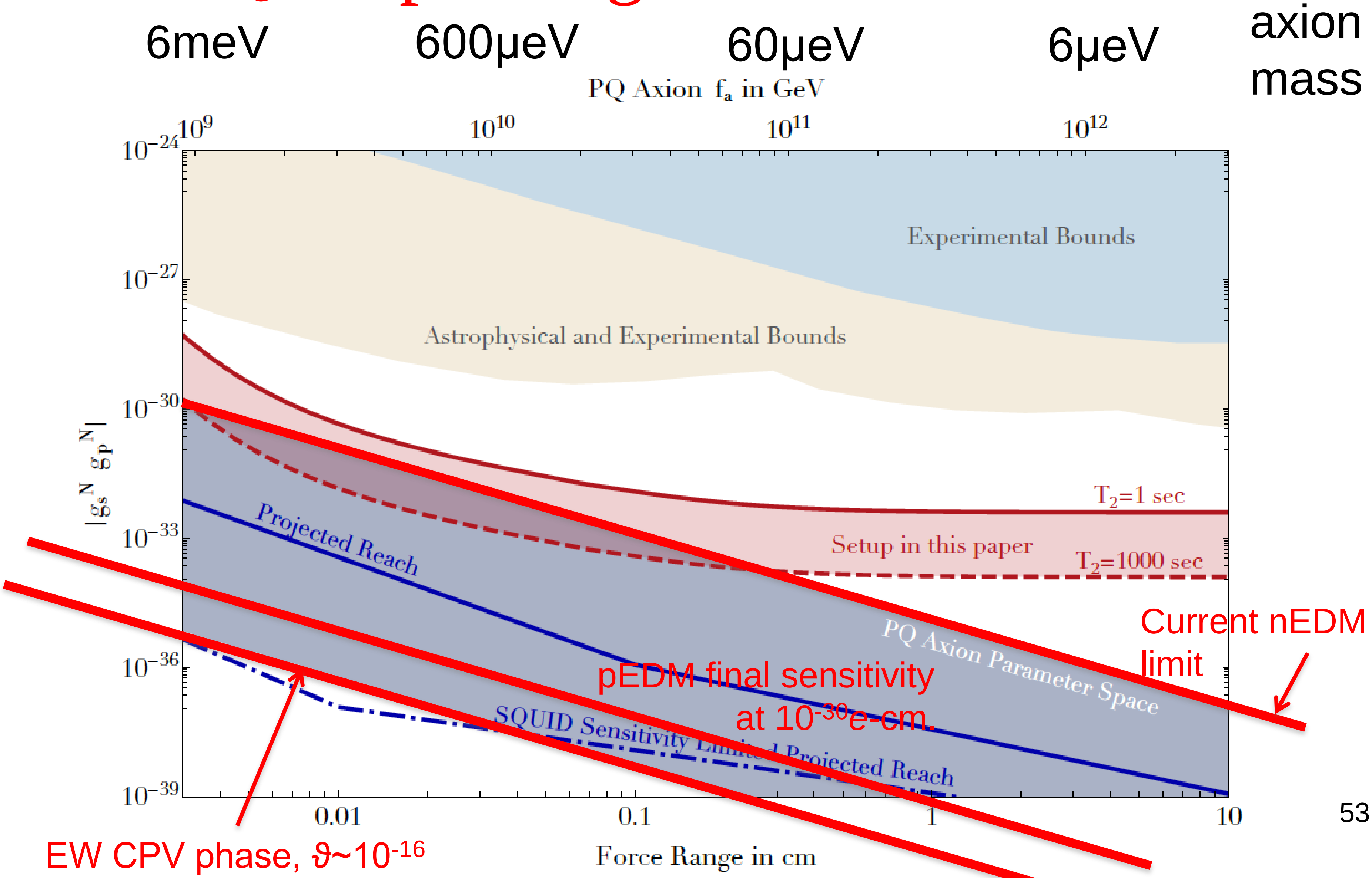
It has been approved as a PBC candidate project at CERN. A comprehensive study is underway with the conclusions to be presented at the European Strategy meeting in Venice 2019.


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

CPV new physics induces a non-zero theta_QCD, probing the axion mechanism!



SUSY-like physics induces a non-zero theta_QCD probing the axion mechanism!



Search for axion dark matter in storage rings

Axion dark matter search with the storage ring EDM method

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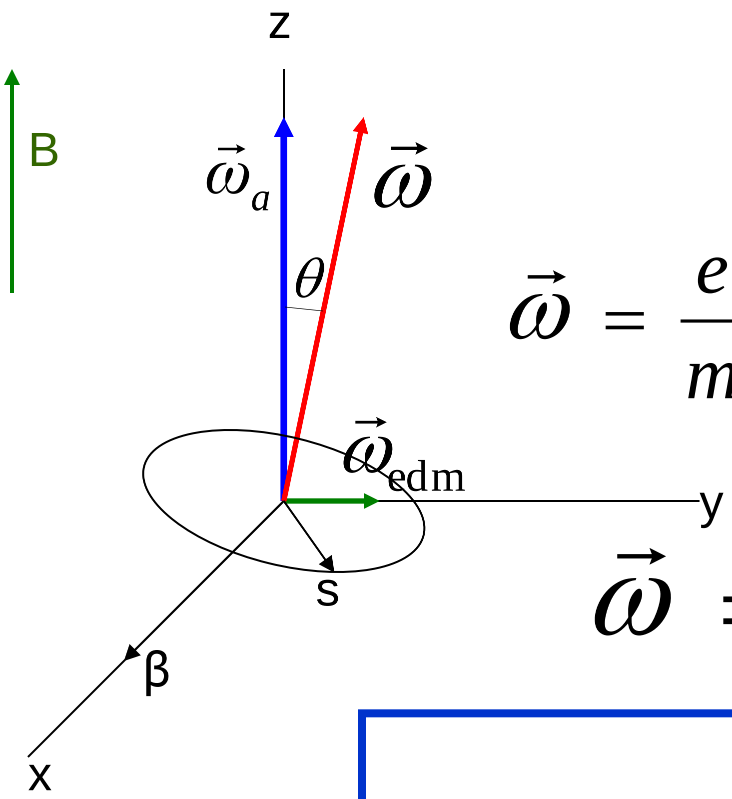
arXiv:1710.05271v1 [hep-ex] 15 Oct 2017

Abstract

We propose using a modified storage ring EDM method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of B and E-fields to produce a resonance between the $g-2$ precession frequency and the background axion field oscillation to greatly enhance the sensitivity to it. An axion frequency range of 100Hz to 100MHz can be scanned with large sensitivity, corresponding to f_a range of 10^{13} GeV $\leq f_a \leq 10^{19}$ GeV the breakdown scale of the global symmetry generating the axion or axion like particles (ALPs).

Indirect Muon EDM limit from the g-2 Experiment



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e}\cdot\mathrm{cm}\ 95\%\ \mathrm{C.L.}$

Axion dark matter search in storage rings

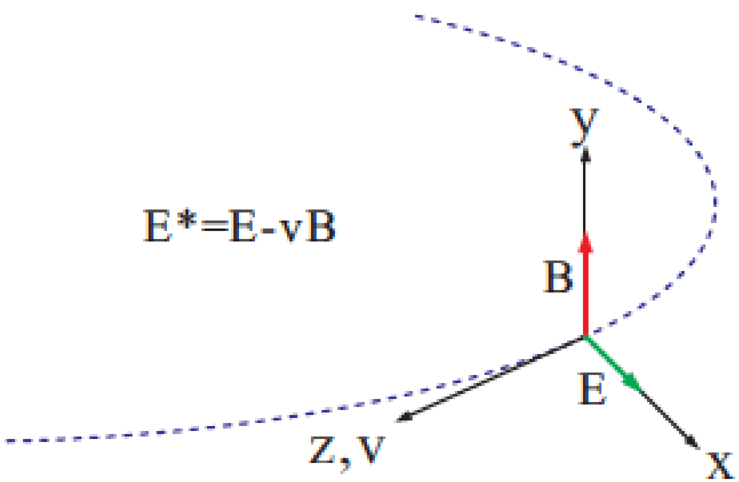
- A modified storage ring EDM method can search for the oscillating theta term.
- Oscillating axion field in resonance with the g-2 frequency.
- Frequency range: 100MHz all the way down to sub-micro-Hz.
- Great physics output, simpler systematic errors

Search for axion dark matter in storage rings

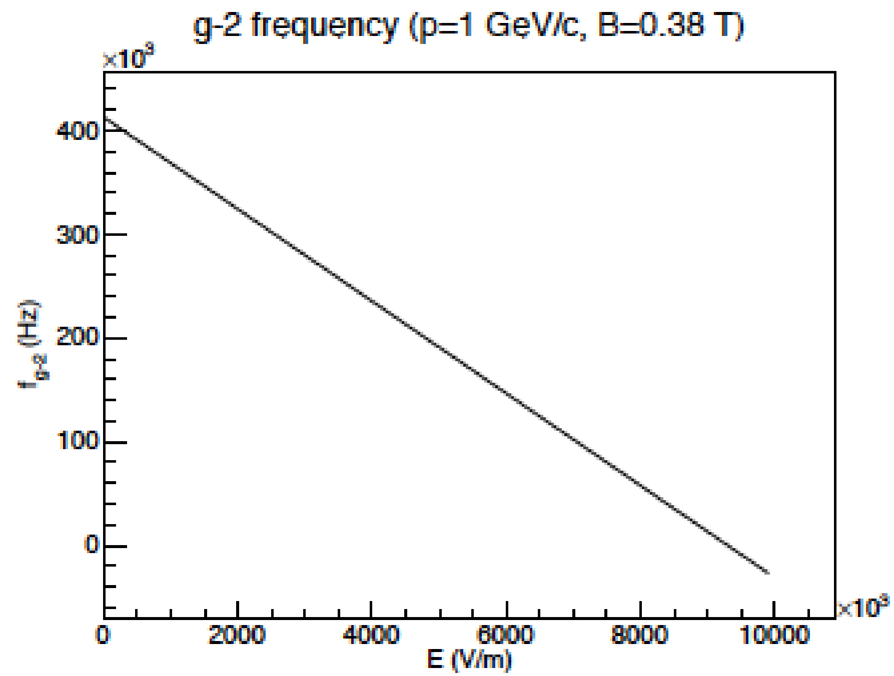
- The axion field (dark matter) induces an oscillating EDM in nucleons P. Graham and S. Rajendran PRD 84, 055013, 2011 and PRD 88, 035023, 2013.

- A combination of the storage ring EDM method plus the g-2 principle we can search for axion dark matter!
- Large effective E-field
- High statistical power
- Large axion frequency coverage
- Can take advantage of large axion coherence time since the stability of the g-2 tune is shown to be at the 10^{-10} per 100s level! (Work at COSY)

Search for axion dark matter in storage rings (1710.05271)



(a) The coordinate of B, E and v



(b) $g-2$ frequency vs E field

Figure 2: E/B combined ring for $g-2$ frequency tunning

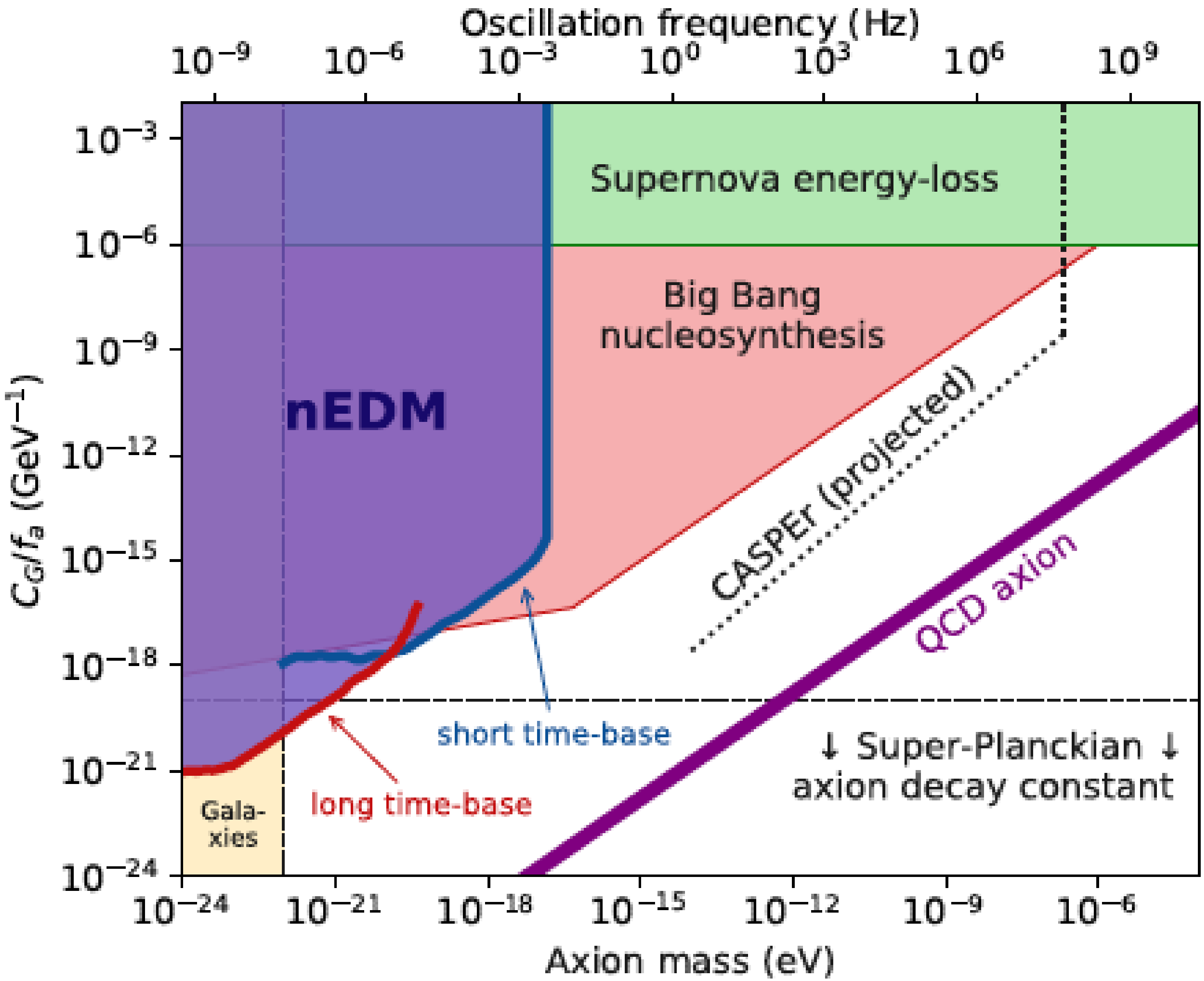
Search for axion dark matter in storage rings (1710.05271)

Table 1: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Deuteron). The analyzing power was assumed to be $A = 0.36$ for both B-ring and E/B combined ring.

B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm)		Ring
					a	b	
0.38	0.9429	10^2	8.82×10^6	4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	E/B ring ($r = 10$ m)
0.38	0.9433	10^3	8.80×10^6	4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
0.38	0.9473	10^4	8.65×10^6	4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
0.38	**0.988**	$\mathbf{10^5}$	$\mathbf{7.05 \times 10^6}$	4.60×10^7	5.5×10^{-30}	$\mathbf{1.8 \times 10^{-31}}$	
0.38	1.035	2×10^5	5.06×10^6	5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
0.38	1.133	4×10^5	3.47×10^5	5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	
0.38	1.239	6×10^5	-5.47×10^6	6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	
0.38	1.355	8×10^5	-1.26×10^7	7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
0.38	1.484	10^6	-2.14×10^7	9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
0.80	2.513	10^6	-9.13×10^6	2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
0.9198	2.7574	10^6	0	2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring ($r = 10$ m)
9.1977	27.574	10^7	0	2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	

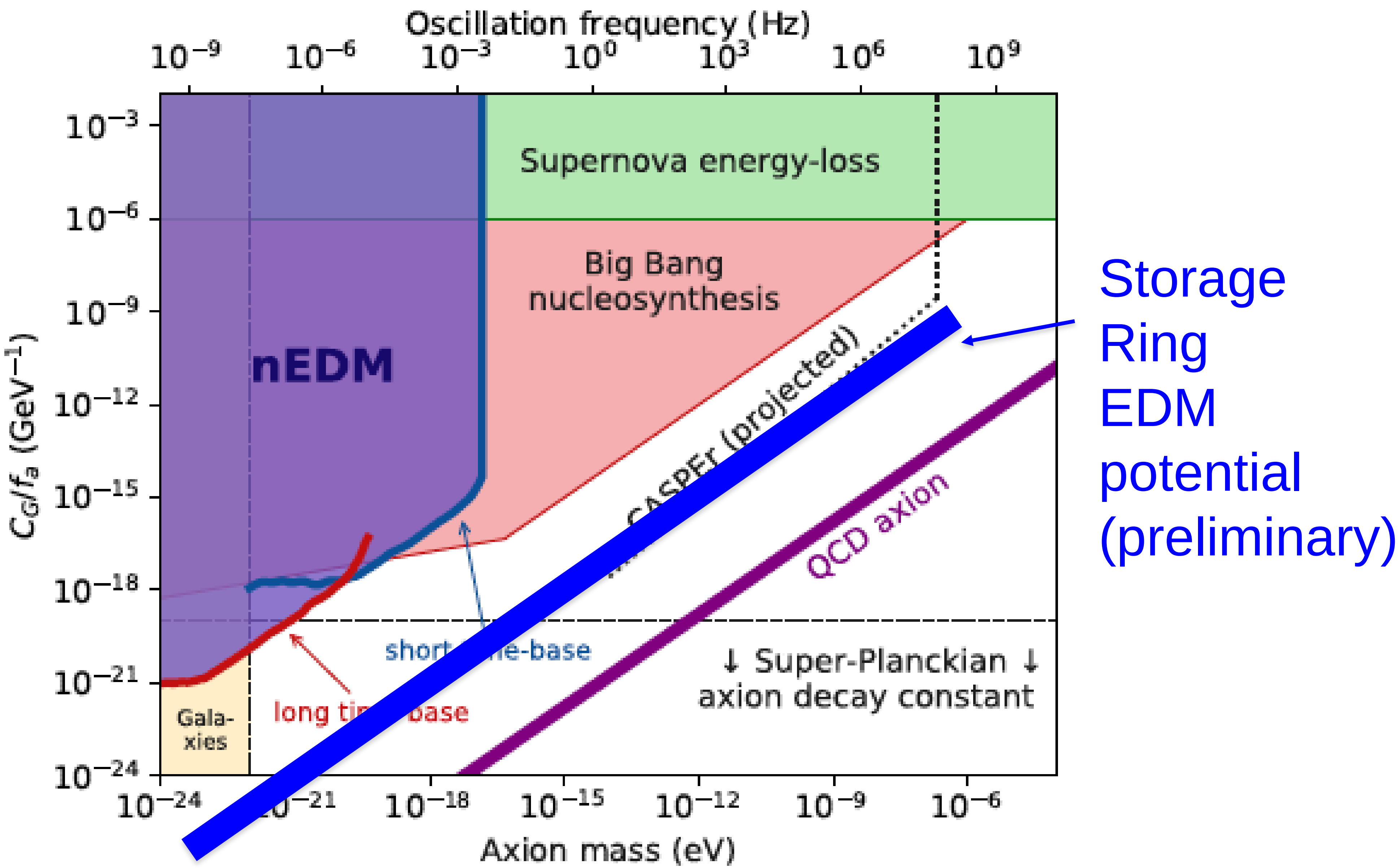
a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.



arXiv:1708.06367v1

PhysRevX.7.041034



arXiv:1708.06367v1

Summary

- Dark matter is a great mystery and challenge
- IBS/CAPP goal is to make a significant progress answering whether or not axions are the dark matter of our universe.
- New powerful magnets/new techniques in the axion dark matter search
- Very soon we will be reaching the theoretical axion parameters in the mass range possible by microwave cavities.
- Next: Open resonators

- Proton EDM exp. and ARIADNE combined probe axion Physics in a way that no other experiments can
- Storage ring EDM in search of low frequency axion dark matter!

Extra Slides