Physics activities at CAPP

Yannis Semertzidis, CAPP/IBS and KAIST, Korea

Strong CP-Problem

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

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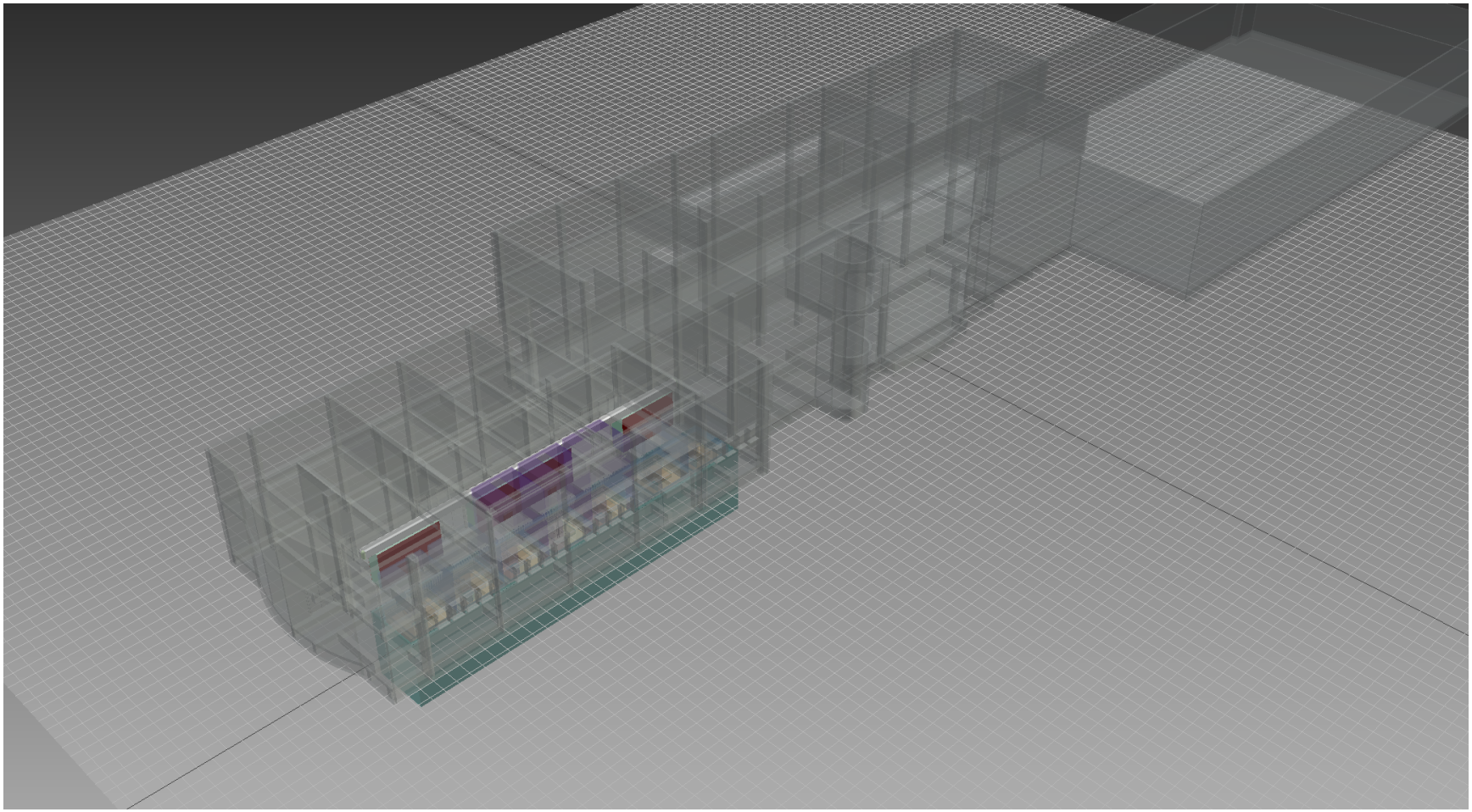
Center for Cognition and Sociality	Center for Synaptic Brain Dysfunctions	Center for Geometry and Physics
Center for Nanomaterials and Chemical Reactions	Academy of Immunology and Microbiology	Center for Nanoparticle Research
Center for Self-assembly and Complexity	Center for RNA Research	Center for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

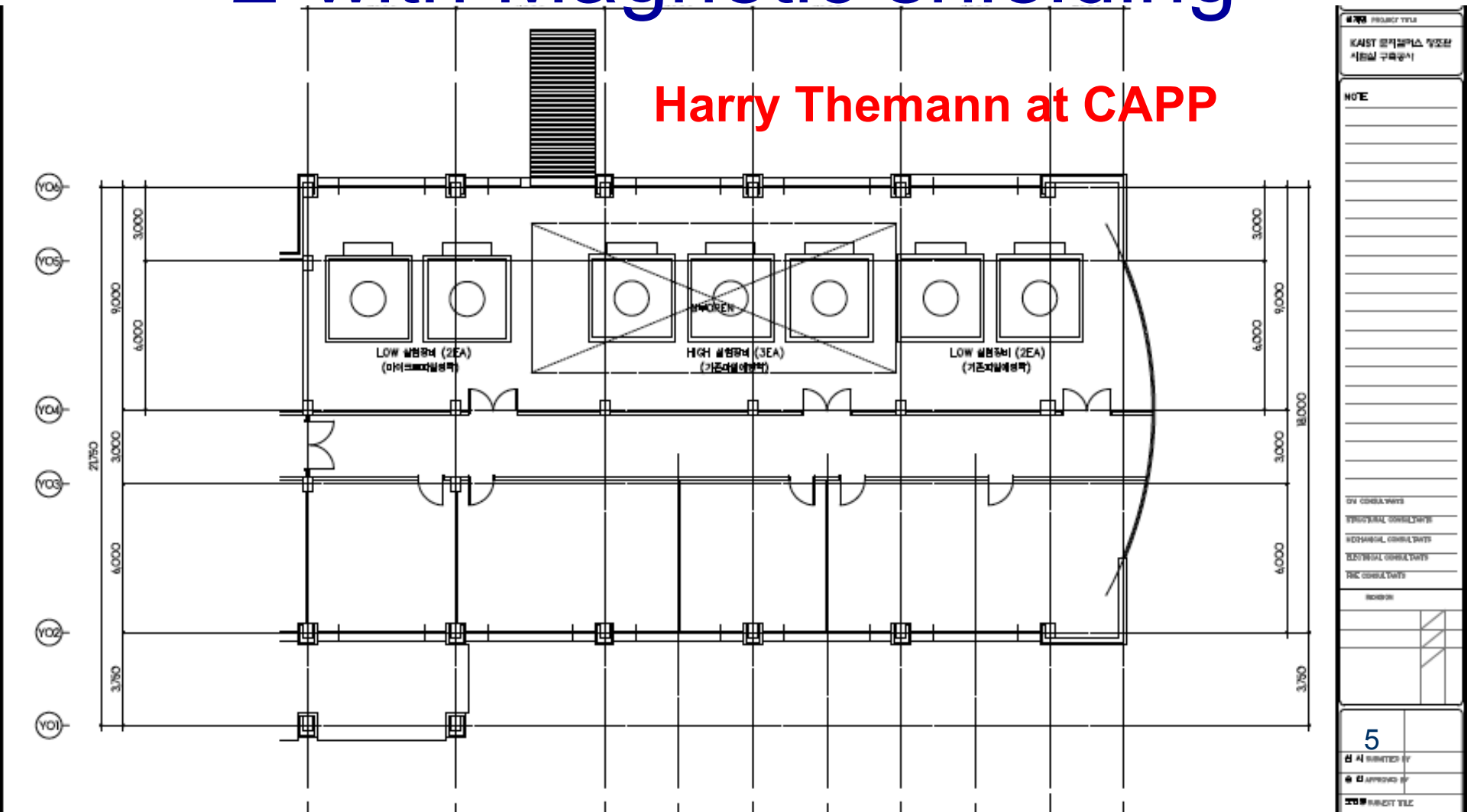
Center for Axion and Precision Physics Research: CAPP/IBS at KAIST, Korea

- Four groups, goal: 50-60 people within 3 years
- 15 research fellows, ~20 graduate students
- 10 junior/senior staff members, Visitor program
- Engineers, Technicians
- Future: IBS building at KAIST

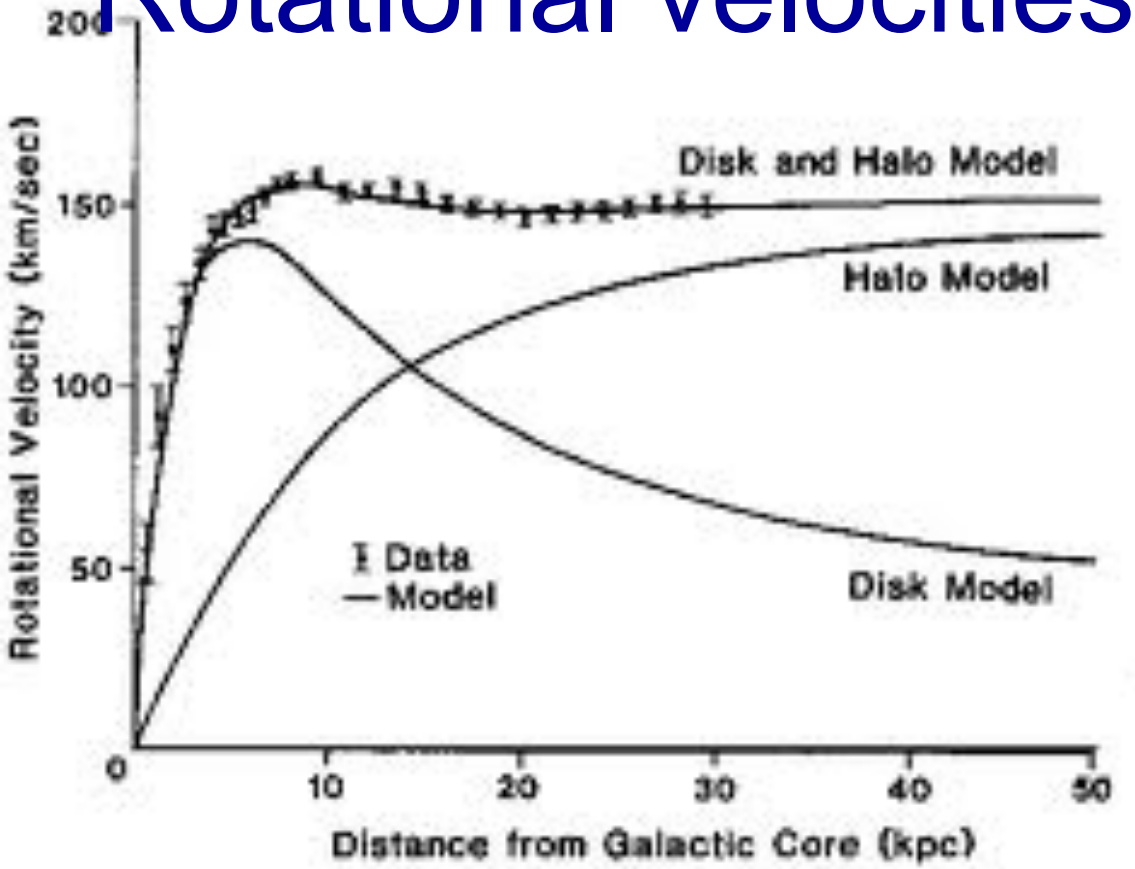
Temp.: Munji campus existing Bldg. (KAIST)

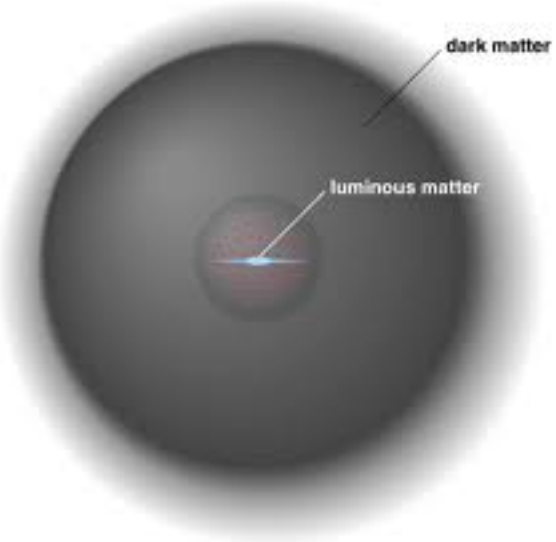


Plans to rectify the Bldg.: 3-storey bldg., w/ 7 pits, vibr. Isol., 2-with Magnetic shielding



Rotational velocities in galaxies





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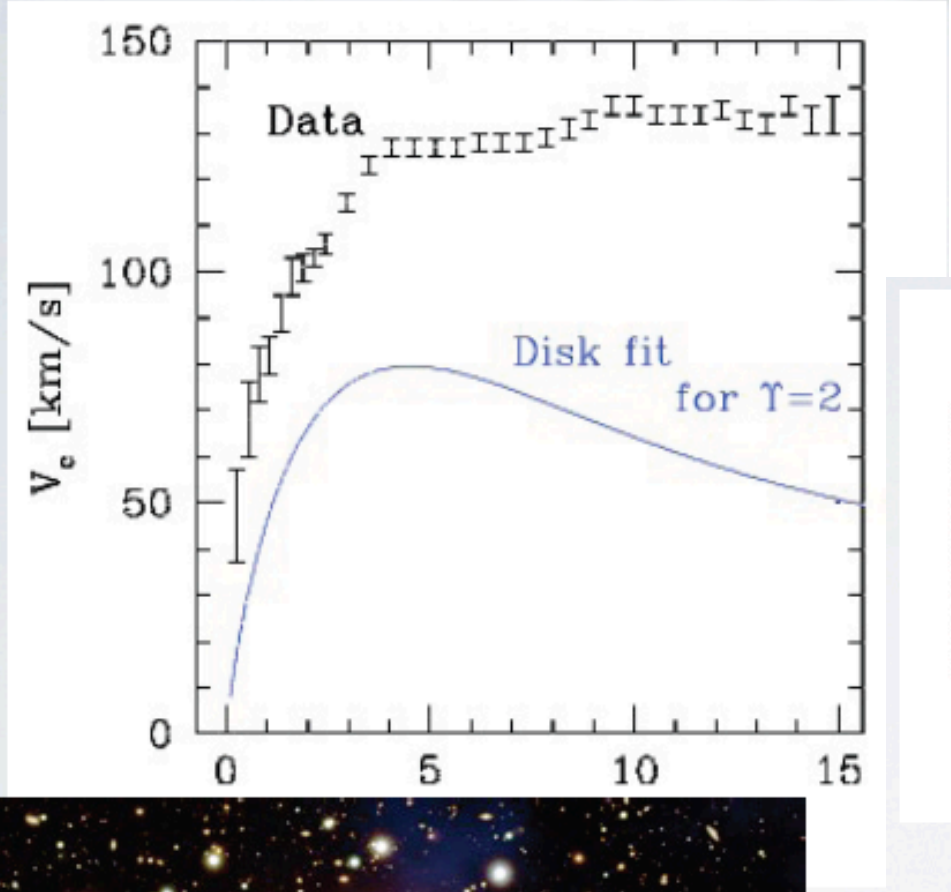
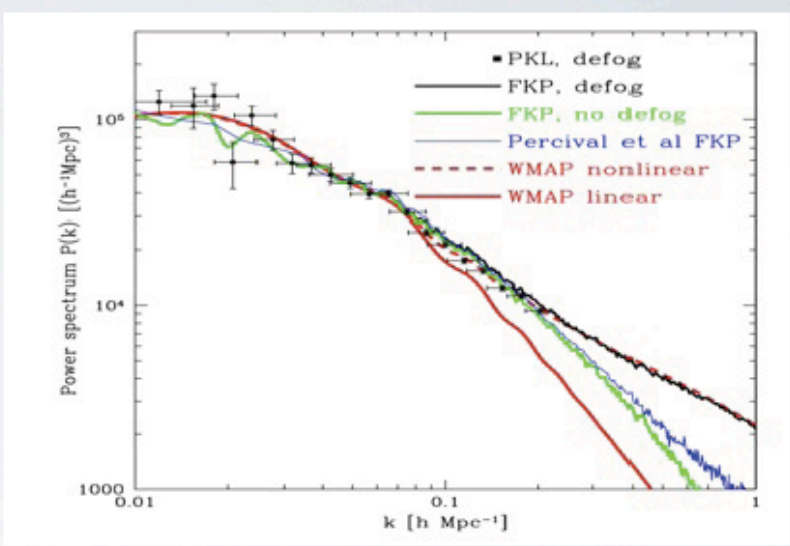
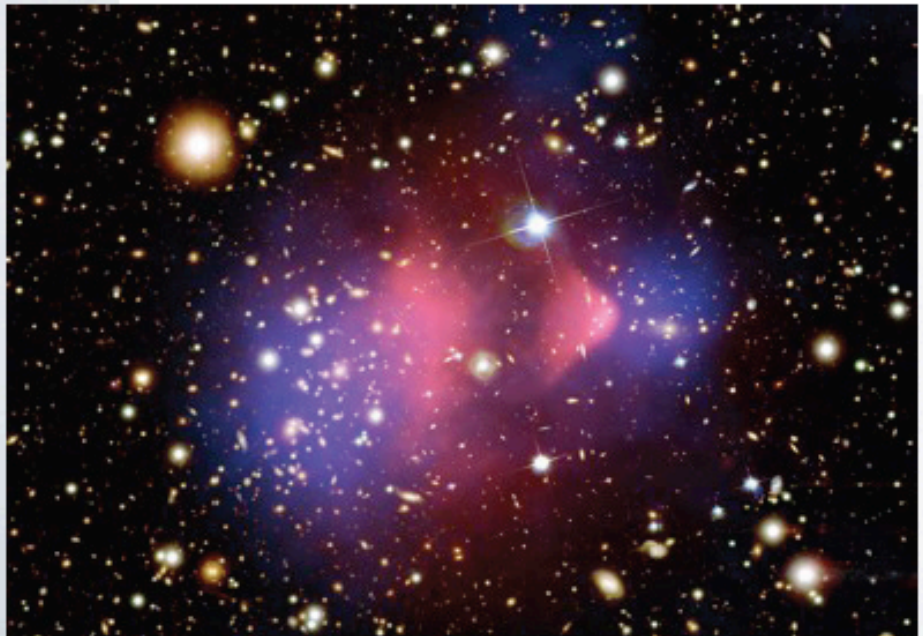
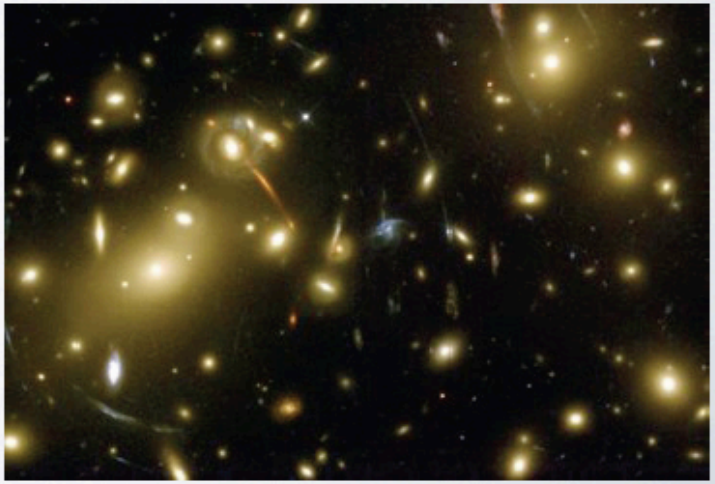
More evidence

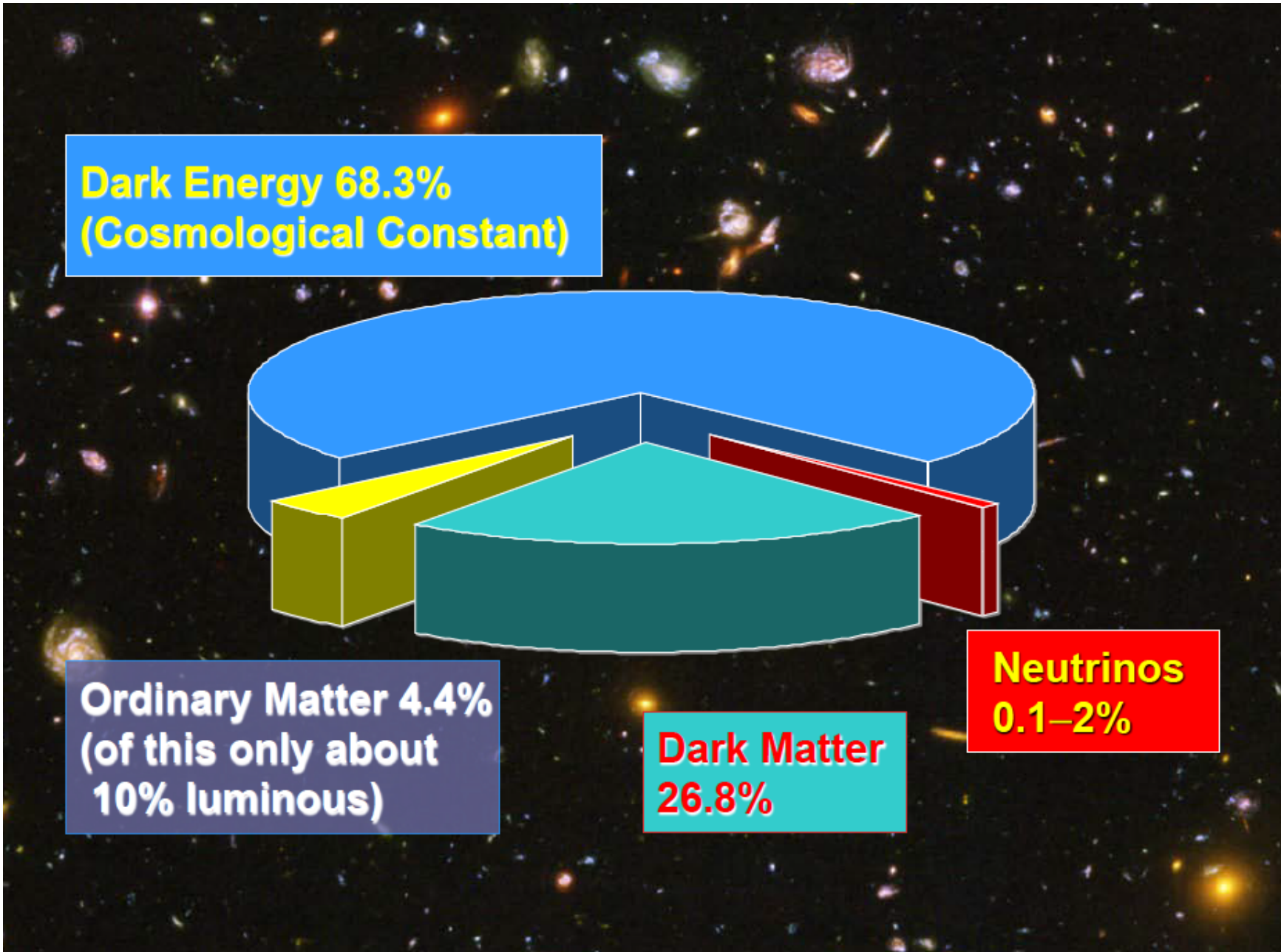






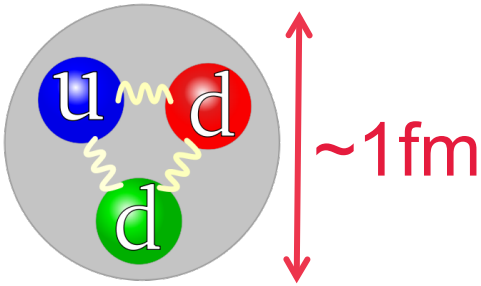


Cosmological inventory



Strong CP-problem and neutron EDM

$$L_{\not{CP}} = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$



Order of magnitude estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

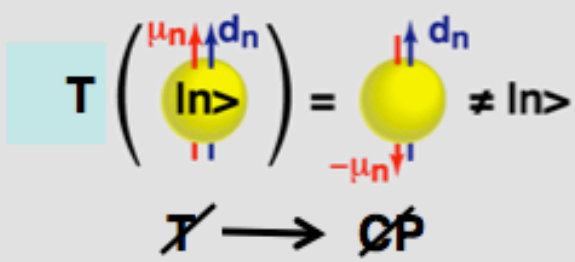
$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm} \rightarrow \bar{\theta} \leq 2\times10^{-10}$$

Why is theta so small? → PQ symmetry

The θ_{QCD} problem

The Strong-CP Problem

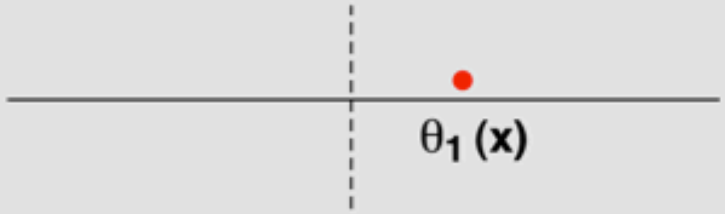
- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



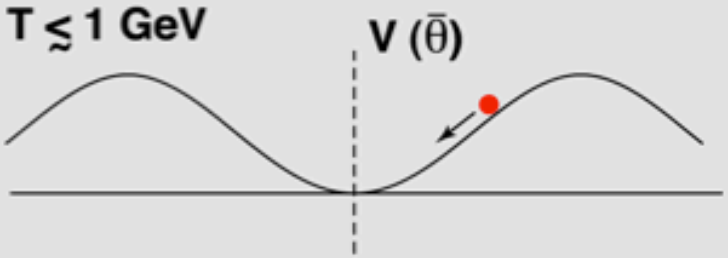
- Why?

Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- $T = f_a$ spontaneous symmetry breaking

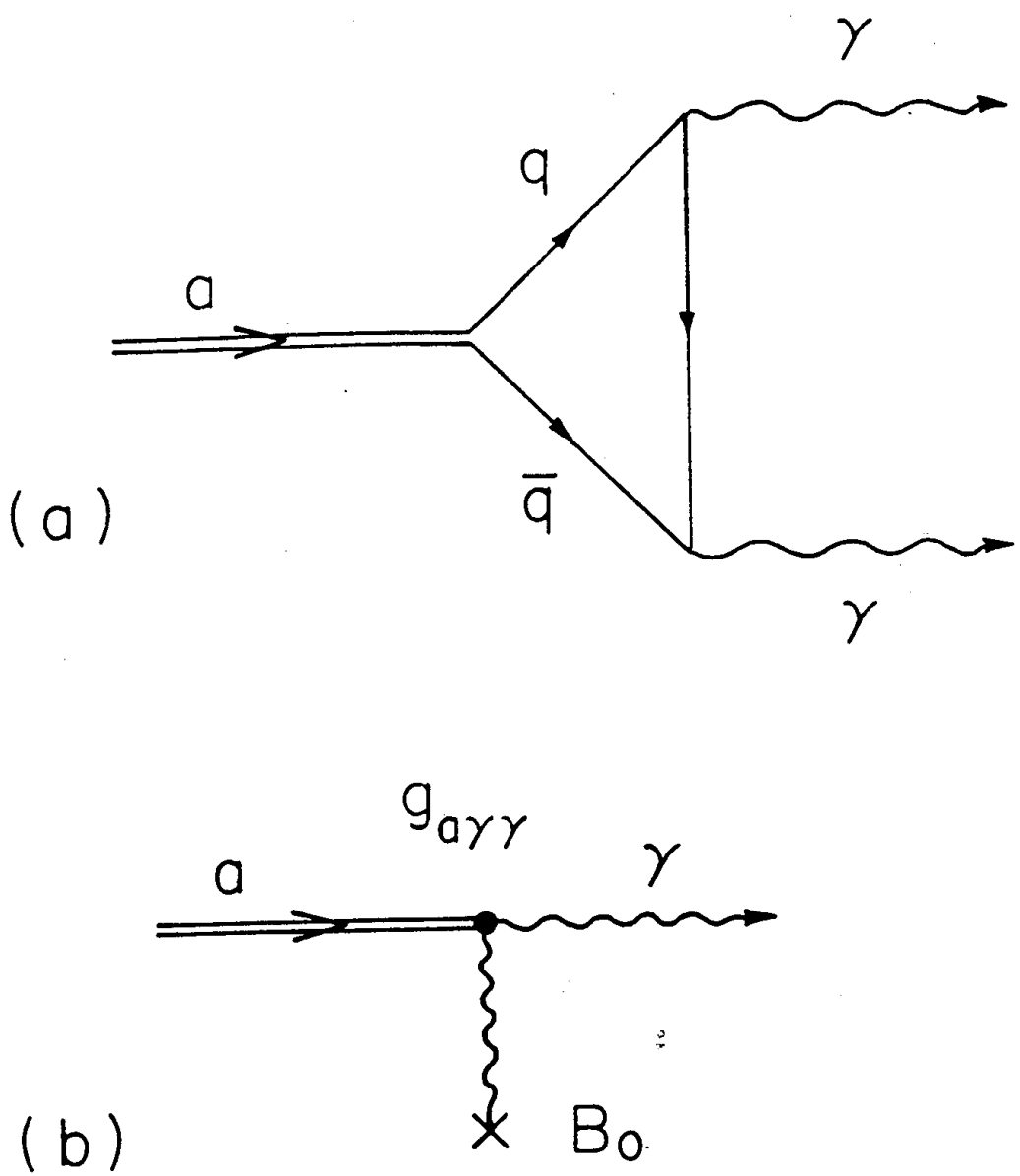


- $T \lesssim 1$ GeV



  - $\bar{\theta}$ dynamically → 0
  - Remnant oscillation = Axion

Peccei-Quinn: 2013 J.J. Sakurai Prize



Axions decay to two photons with very long lifetime. In a strong Electric or Magnetic field they can convert to one photon.

Energy loss from stars

Stars have a finite amount of nuclear fuel

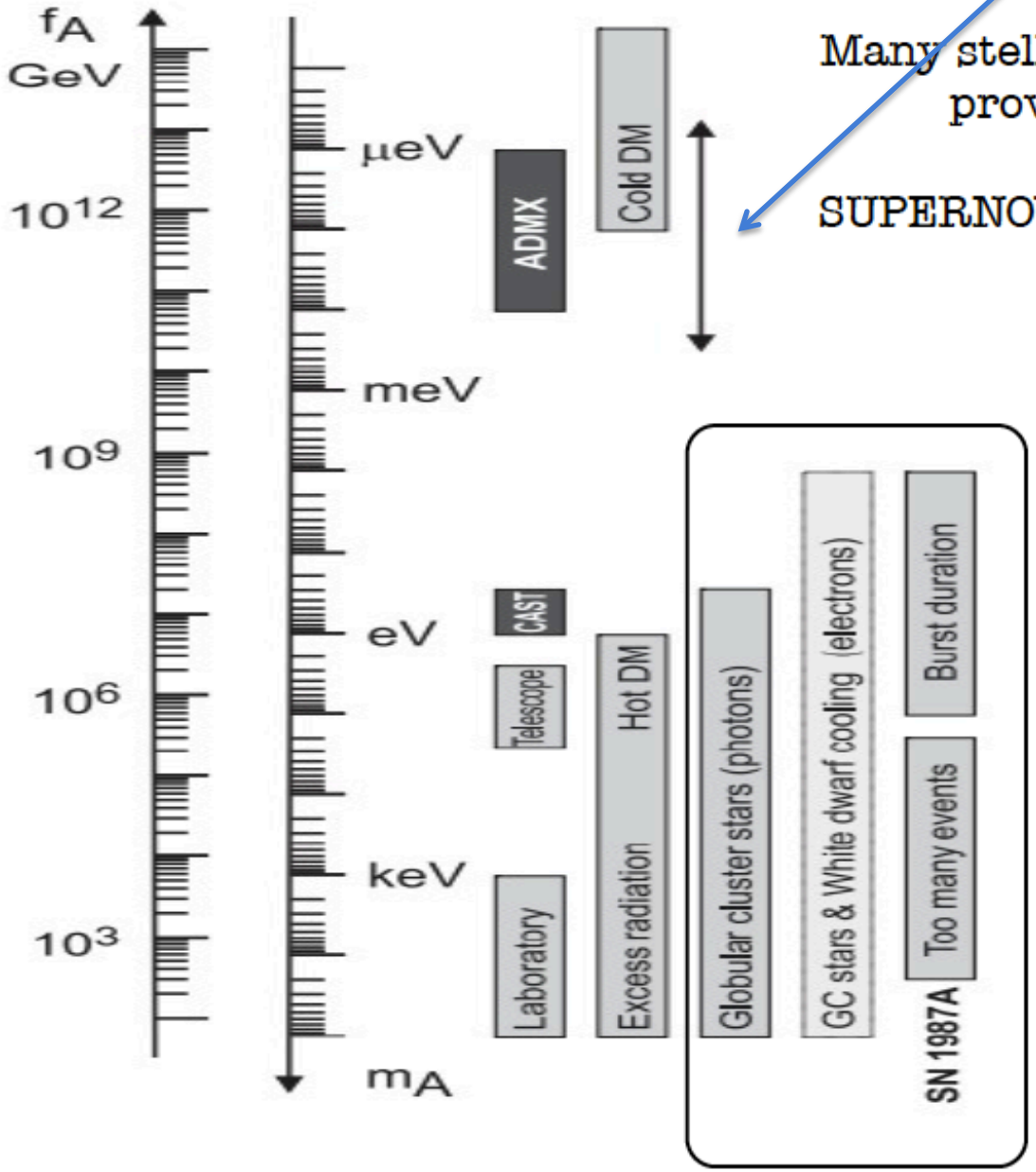
The speed at which it is burned (and thus, the stellar evolution) is limited by the effectiveness of the energy drain from the interior

Main energy losses are:
- Photons from the surface
- Neutrinos from the core

AXIONS?

Stellar Evolution

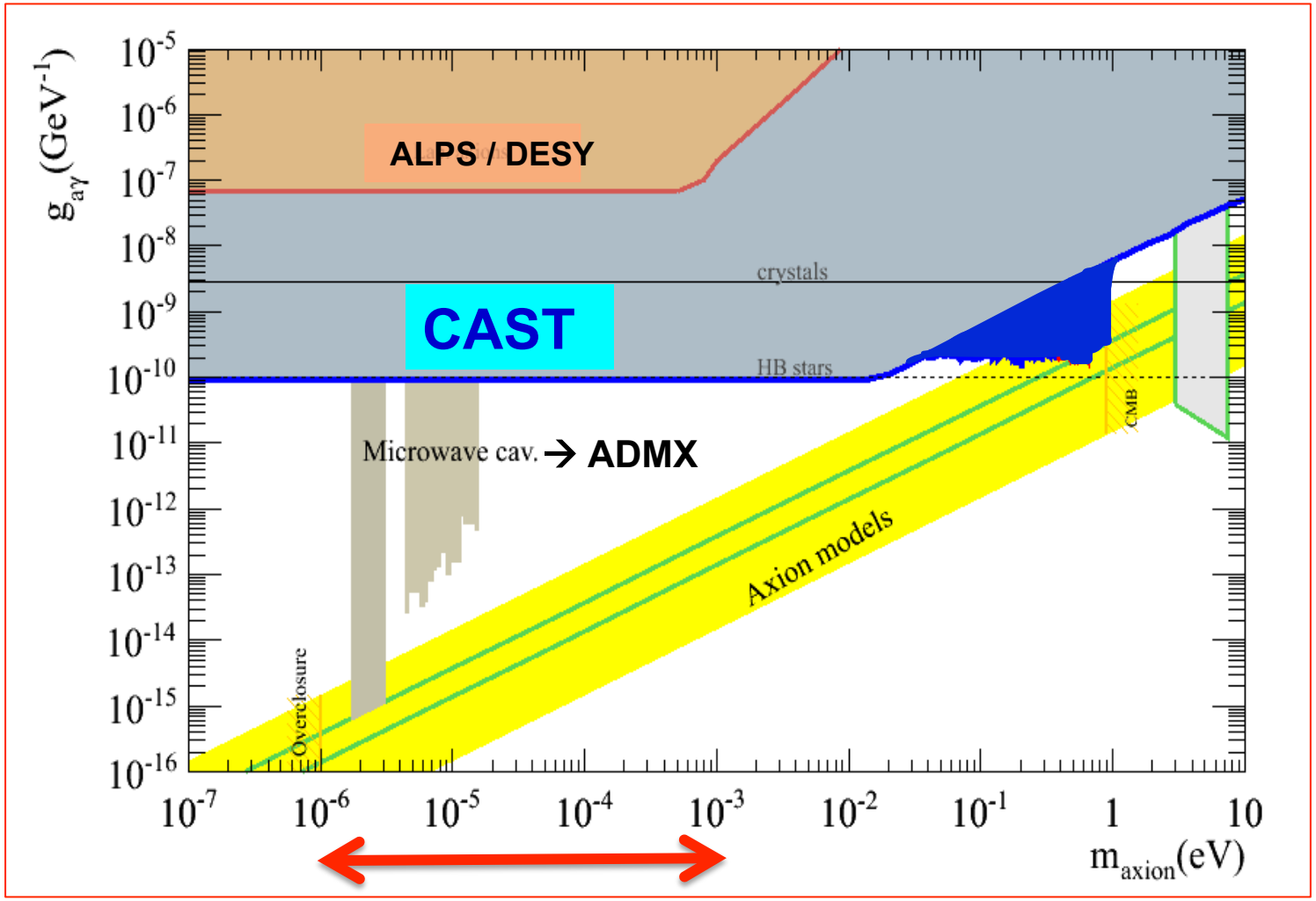
Prof. Jihn Kim: "Invisible" Axions, 1989



Many stellar systems studied in Lit. provide strong BOUNDS

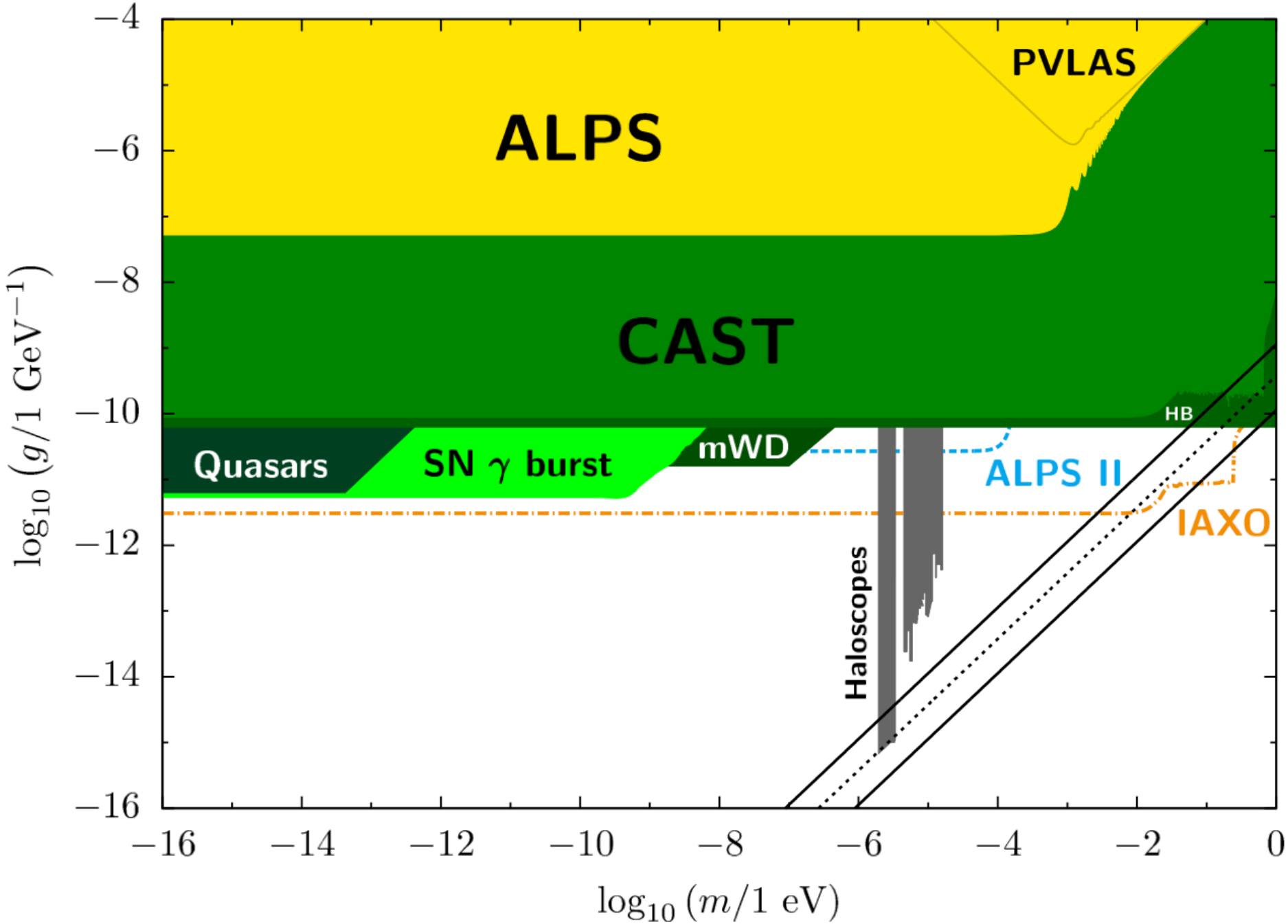
SUPERNOVAE, SUN, RED GIANTS ...

Axions

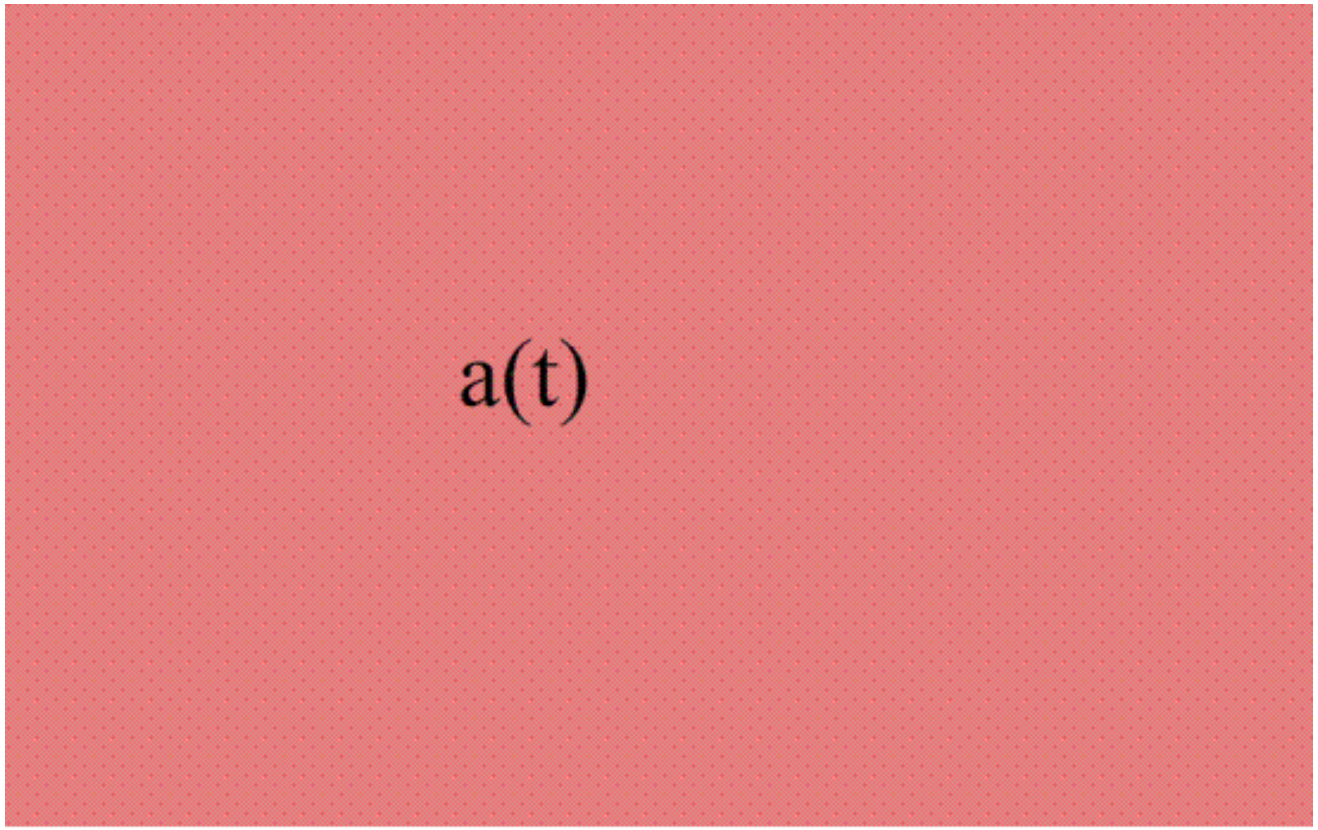


Excellent dark matter candidates

Axion mass range: 1μeV – 1meV

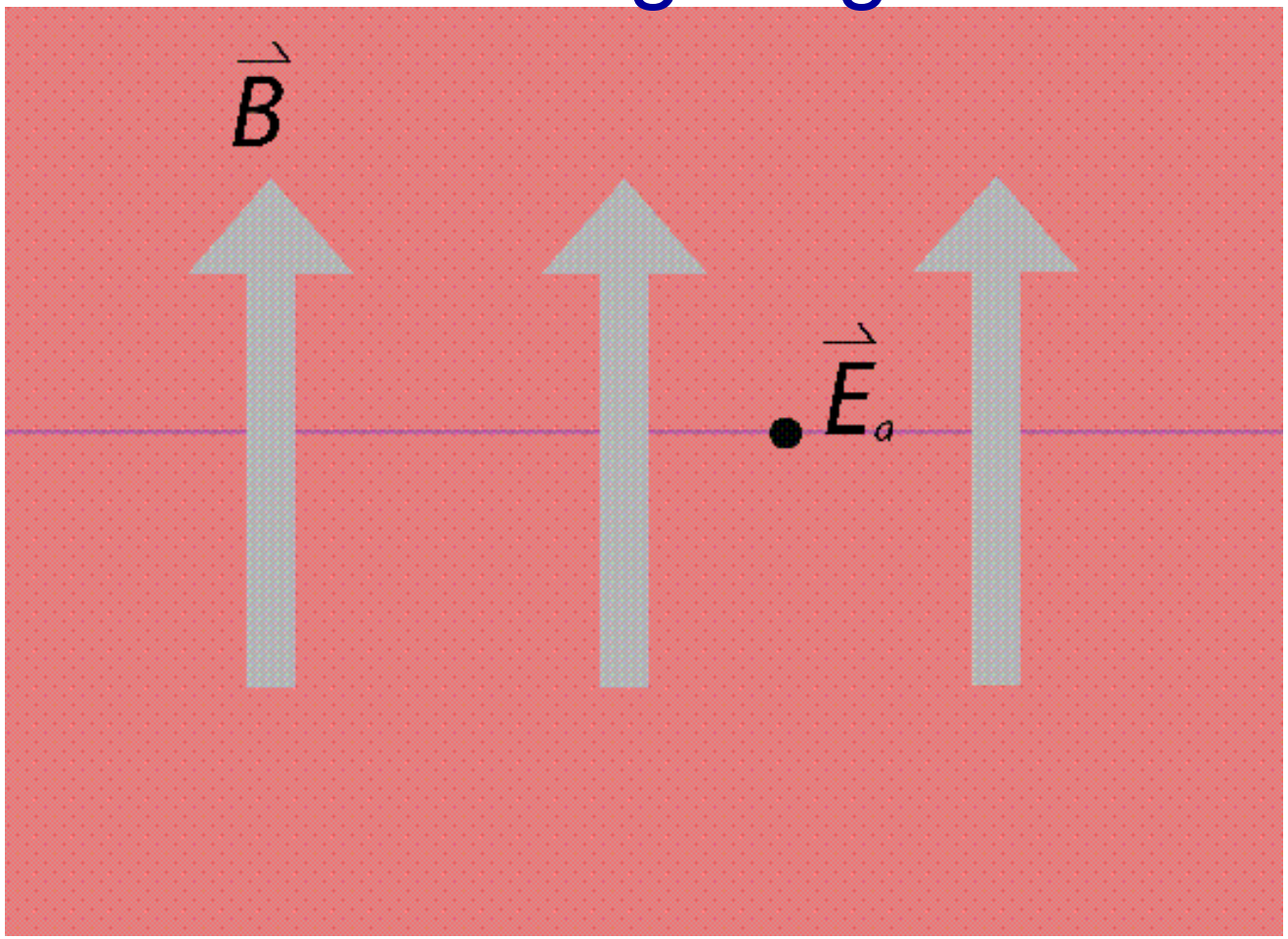

PVLAS
ALPS
CAST
HB
Quasars
SN γ burst
mWD
ALPS II
IAXO
Haloscopes
−4
−6
−8
−10
−12
−14
−16
−16
−14
−12
−10
−8
−6
−4
−2
0
$\log_{10}(g/1\ \mathrm{GeV}^{-1})$
$\log_{10}(m/1\ \mathrm{eV})$

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



Animation by Kristian Themann

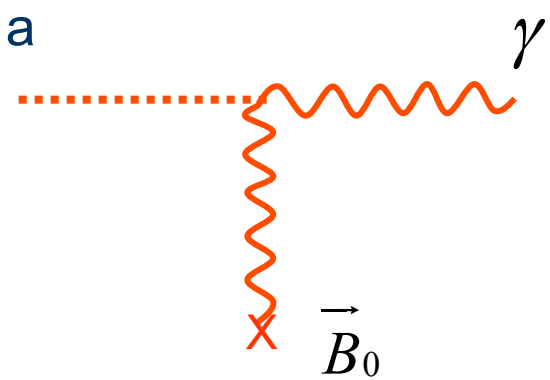
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



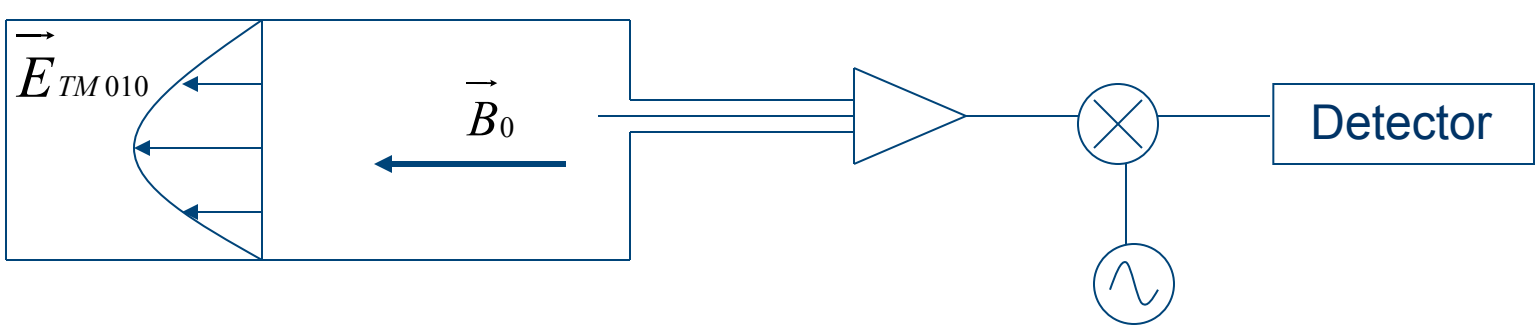
Animation by Kristian Themann

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)



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



$$a \rightarrow \gamma$$

The conversion power on resonance

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

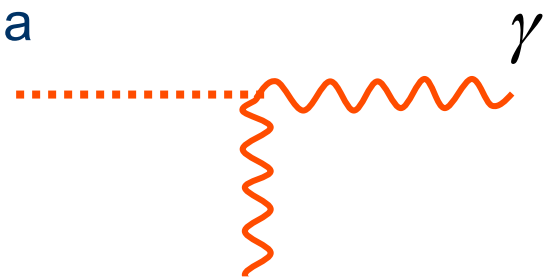
$$= 2 \cdot 10^{-22}\ \text{Watt} \left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2 \left(\frac{C}{0.4}\right)$$

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

The axion to photon conversion power is very small, a great challenge to experimentalists.

Axions, the CAPP plan

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



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

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

What's there to improve over ADMX?

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

- B^2, energy density
- Q, resonator quality factor
- B-field/resonator volume V
- Ampl. noise/physical temperature, S/N

B-field possibilities

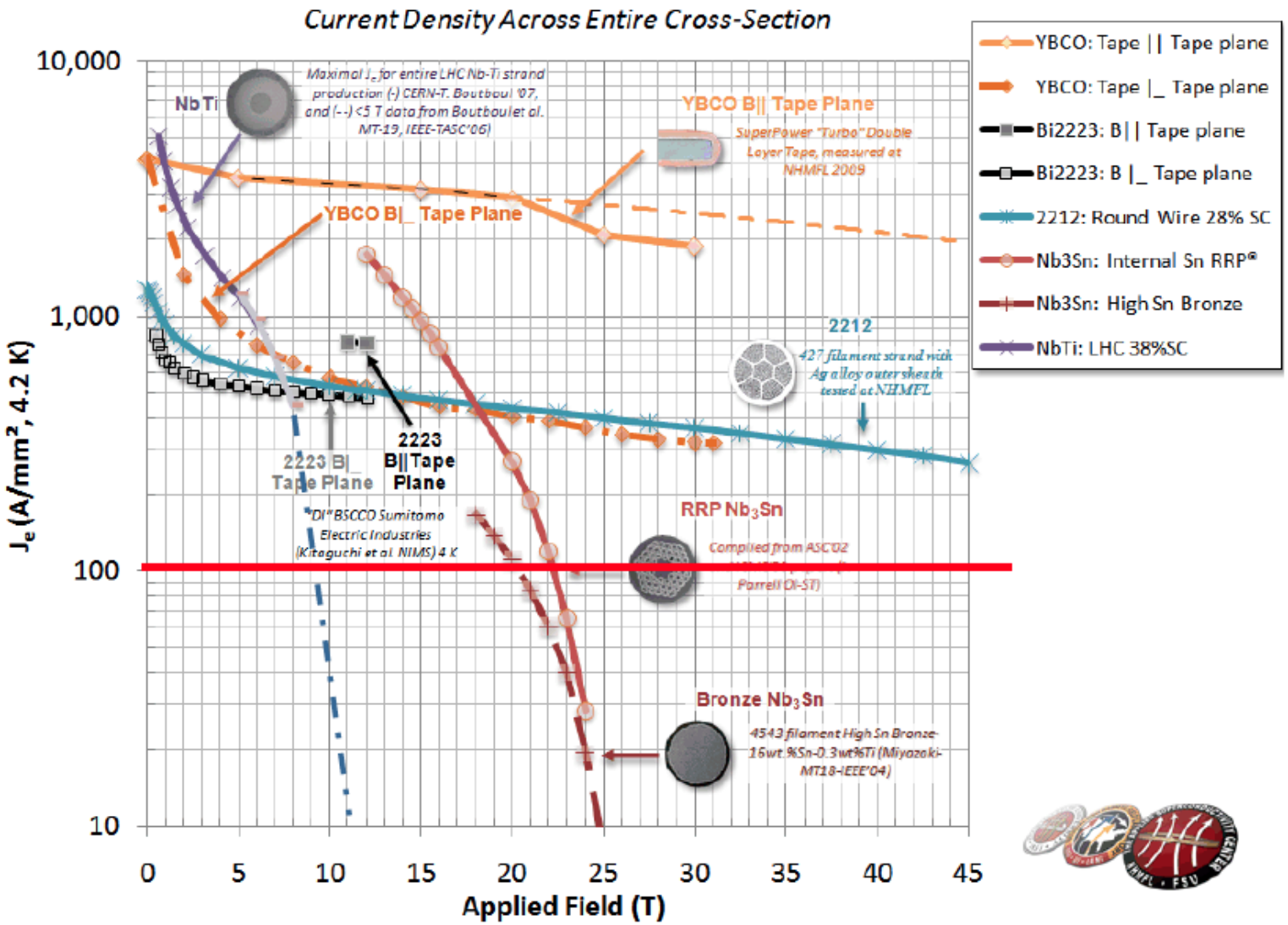
- Magnetic field B:
  - Develop 25T magnet.
  - 35T magnet based on high T_c.

(CAPP) Axion dark matter plan

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

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

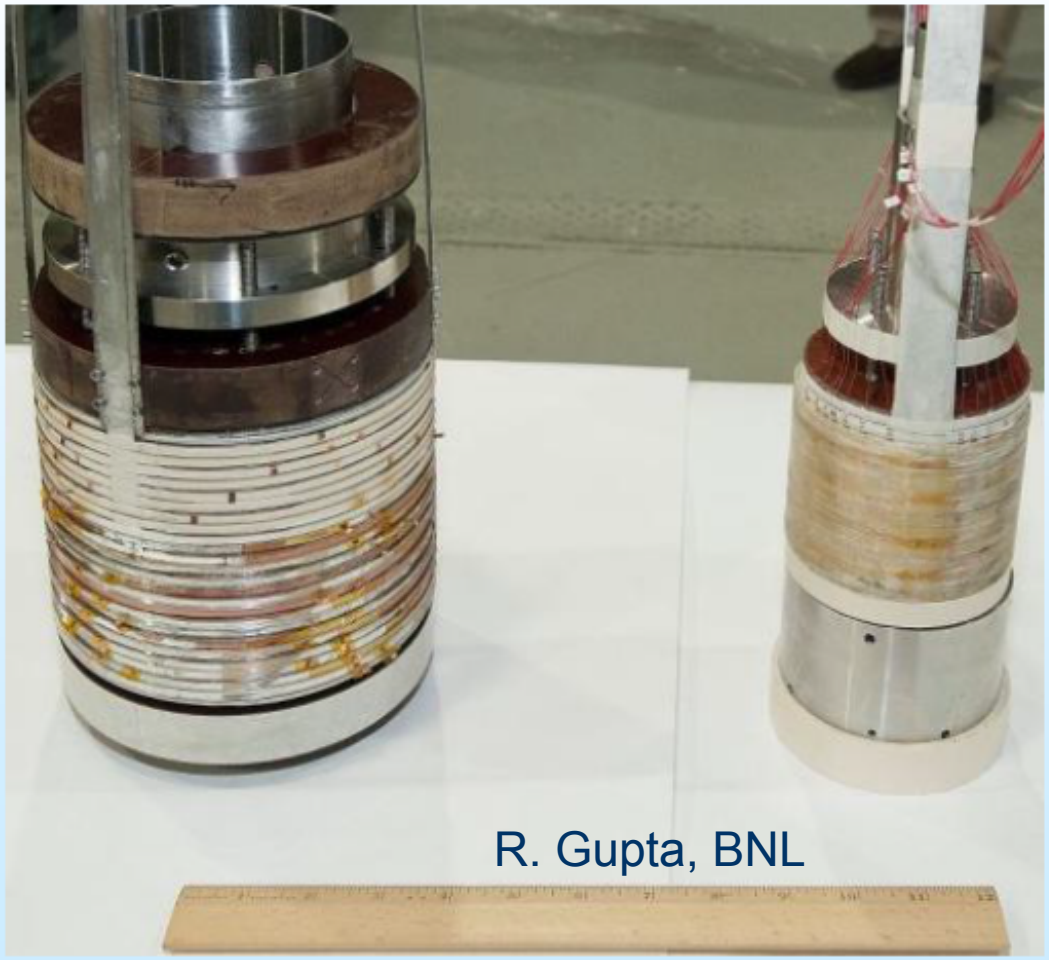
Future Solenoids:
High- Temperature Superconductors



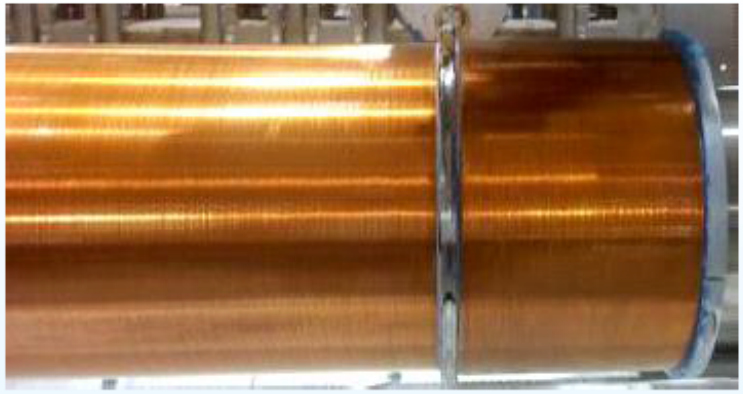
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

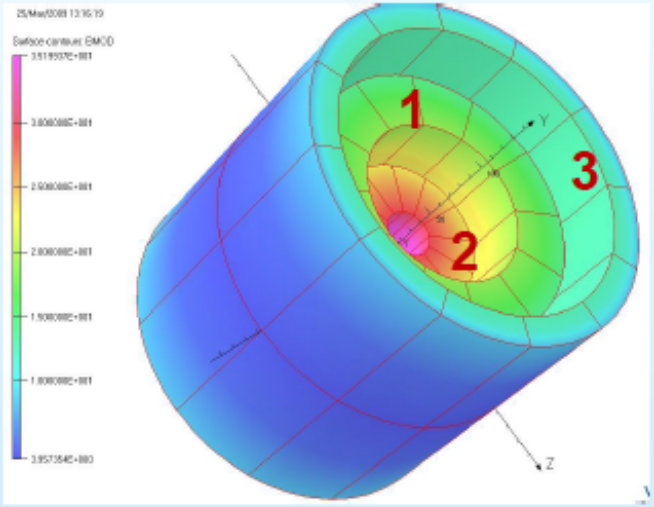
Status of High Field MAP Solenoids

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



R. Gupta, BNL



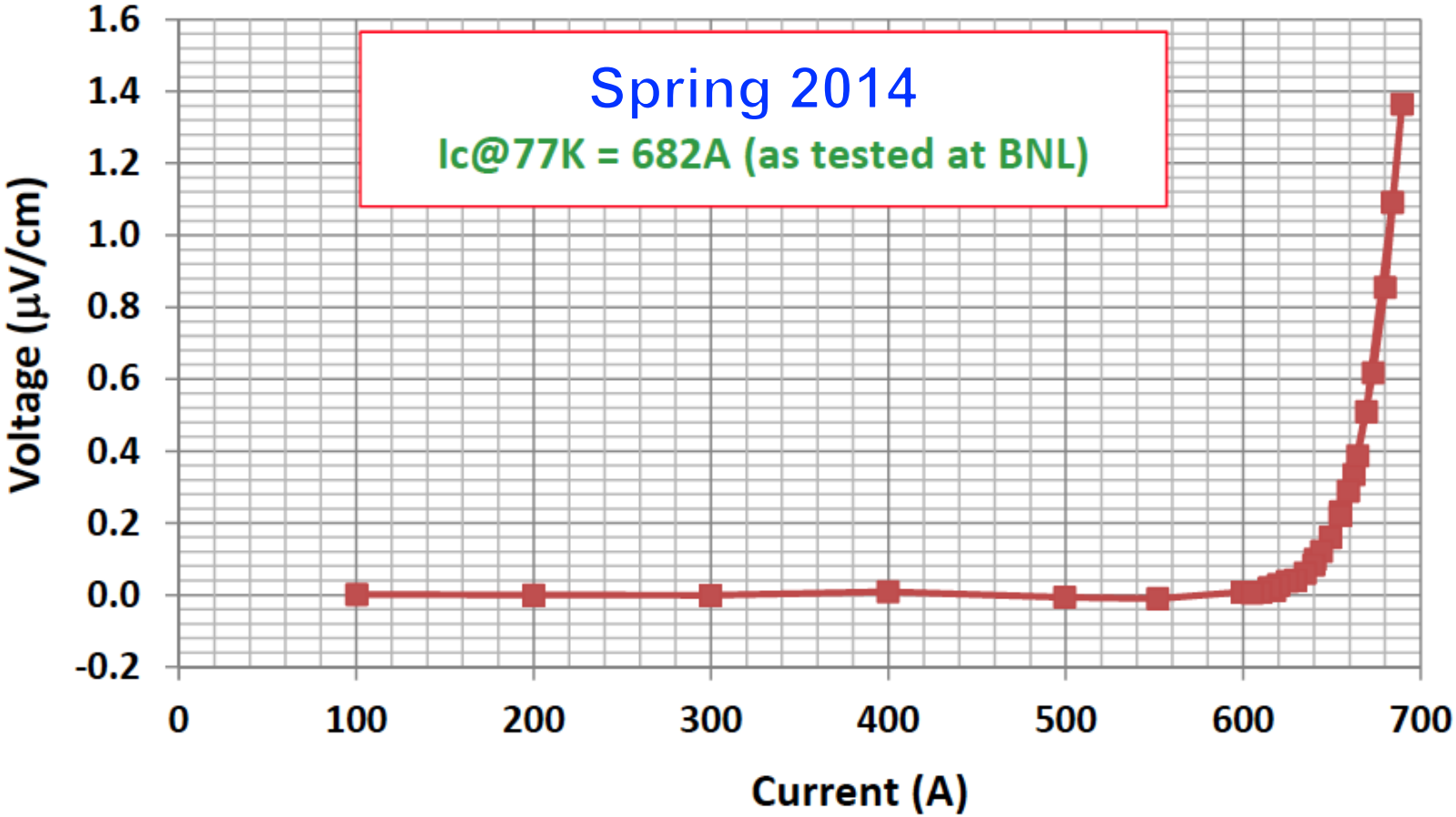


~30 T with NbTi outer

(40 T with Nb_3Sn or more HTS)

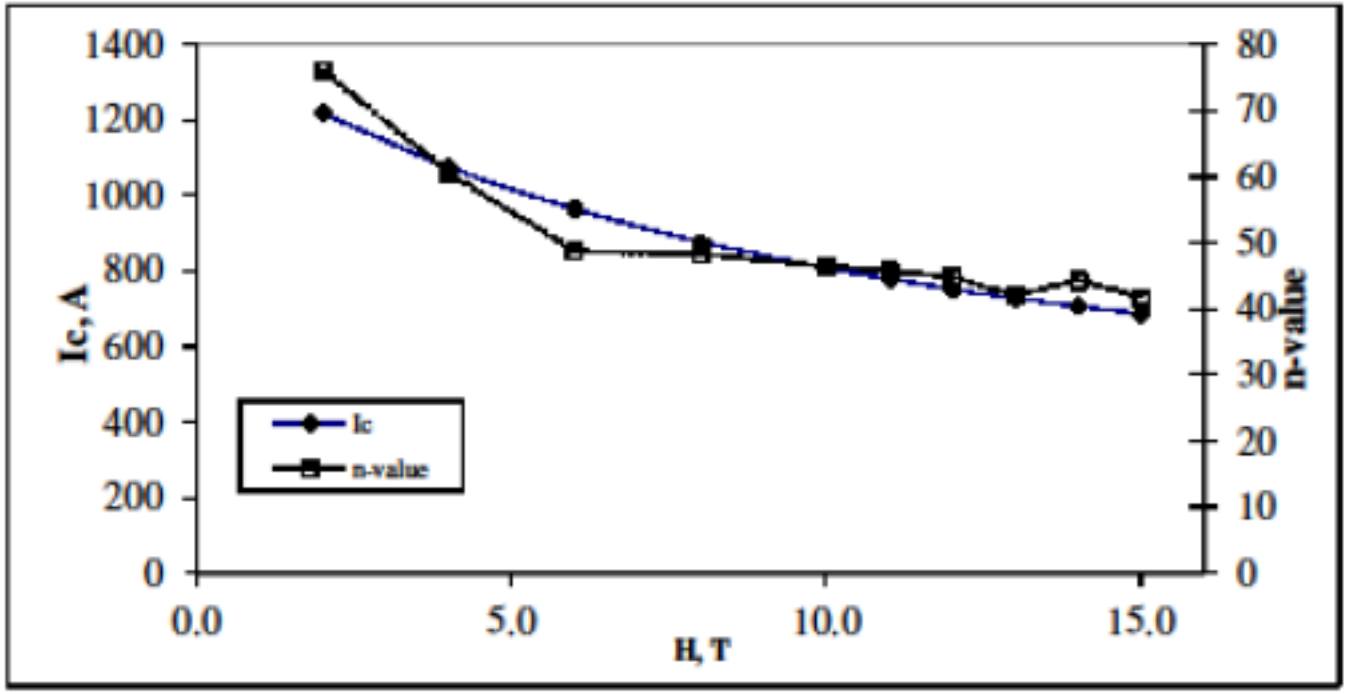
Magnet Development
SuNAM cable

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



Magnet Development

BNL, Summer 2014



Under development by CAPP

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

CAPP: High quality factor cavities

- We have started an R&D program to achieve large Q in the presence of large B-fields.

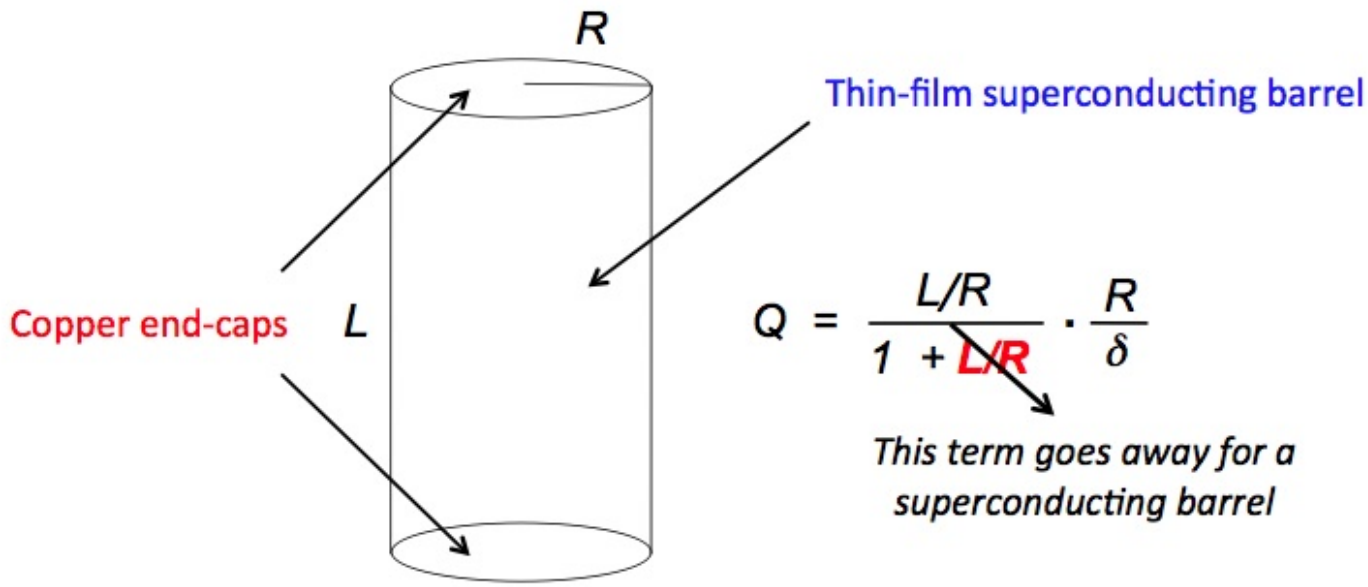
- Presently: Q~10^5 for copper cavities. axion Q_a: ~1.5×10^6

- CAPP goal: Q: ~10^7, potential gain factor: 15.

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

Under development by ADMX

The concept of a hybrid superconducting cavity:



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

This term goes away for a superconducting barrel

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

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

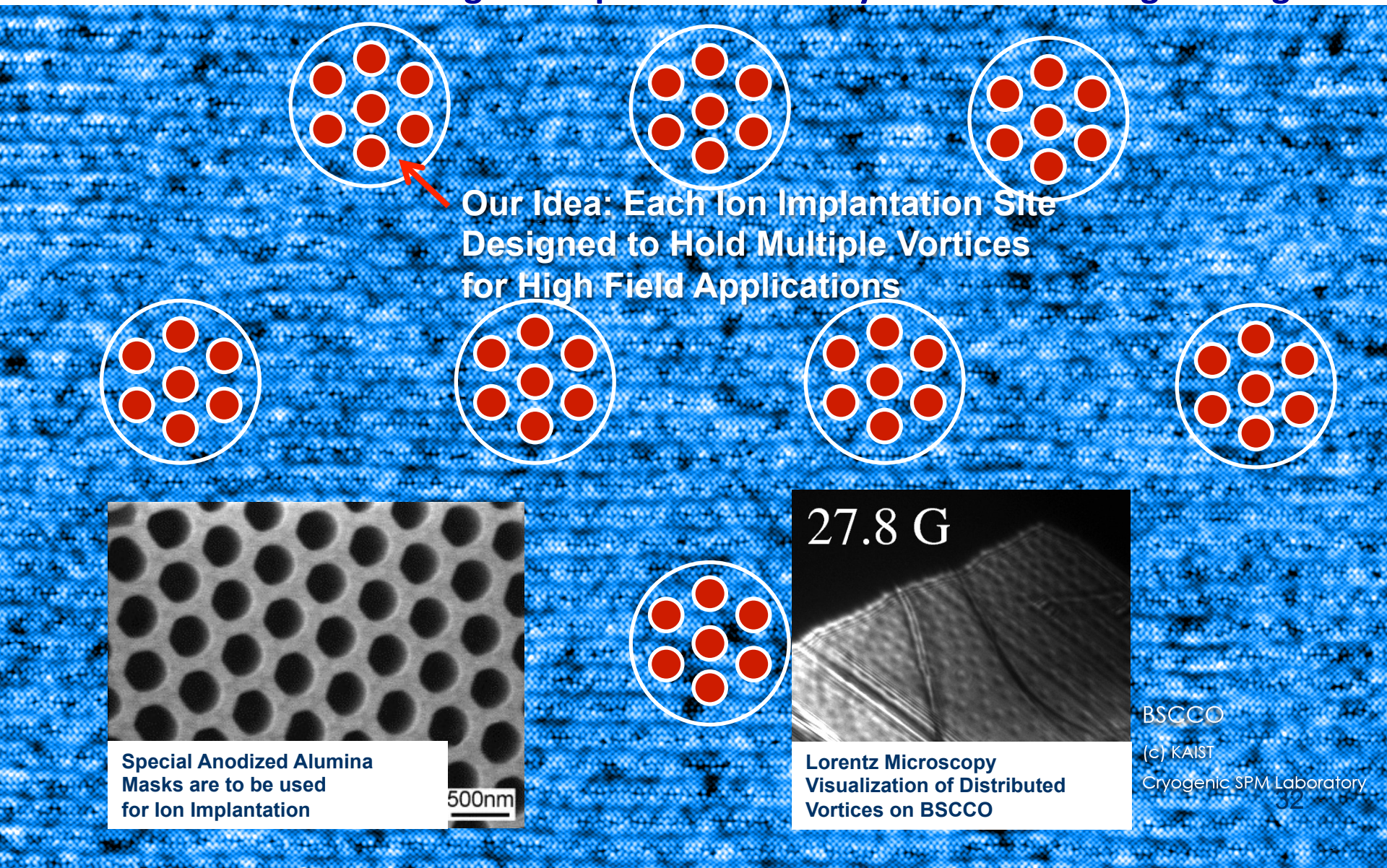
Under development by CAPP

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

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

CAPP: Proposal of Cryogenic STM Research Group (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

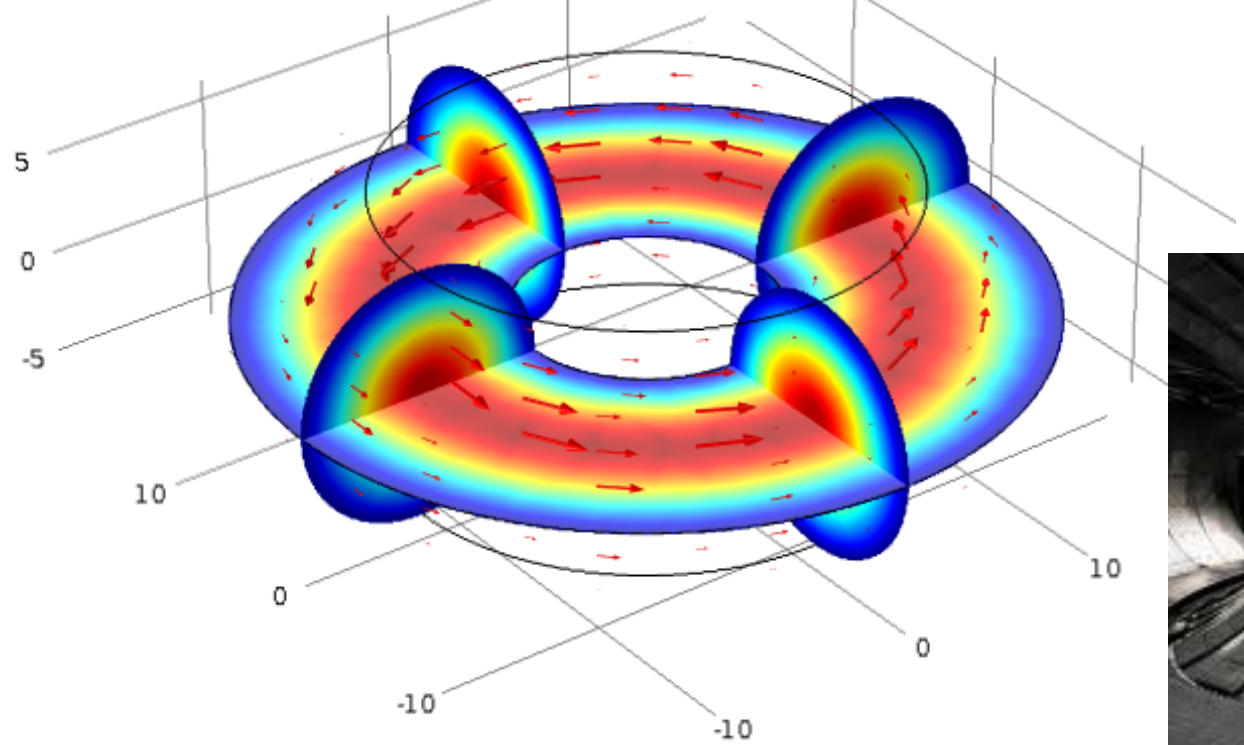
Lorentz Microscopy Visualization of Distributed Vortices on BSCCO

(c) KAIST
Cryogenic SPM Laboratory

CAPP: Toroidal shape cavities

Large volume for low frequencies (e.g., Tokamaks). Critical issue is temperature. Very expensive. Opportunity for large collaborations.

Electric field simulation of a TM010 mode in a toroidal cavity,
Lino Miceli, et al.



KSTAR Tokamac in Korea

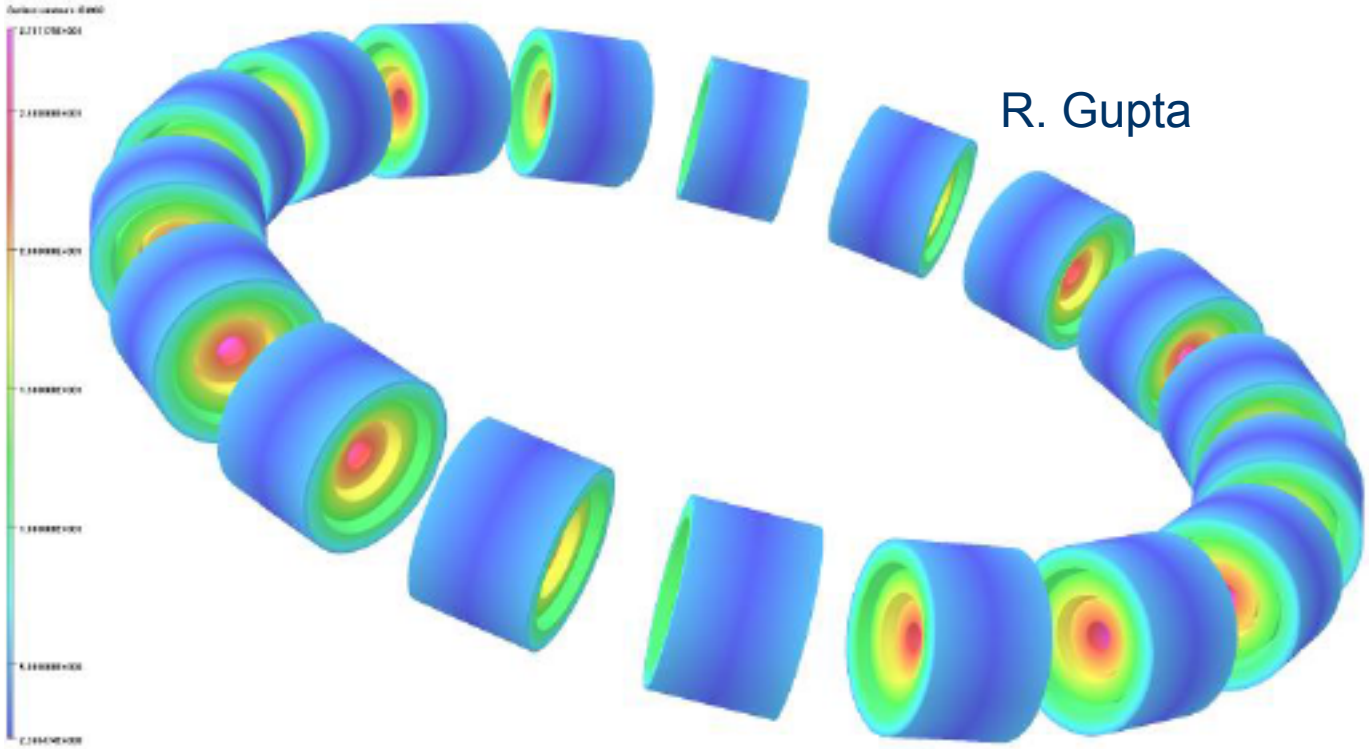
KSTAR specs

- Major radius: 1.8m
- Minor radius: 0.5m
- B-field: 3.5T
- Field alignment: 0.1mrad

- Ideal!
- Too busy with ~100 proposals/year

Toroidal magnet

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



Woohyun Chung at CAPP

Toroidal magnet

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

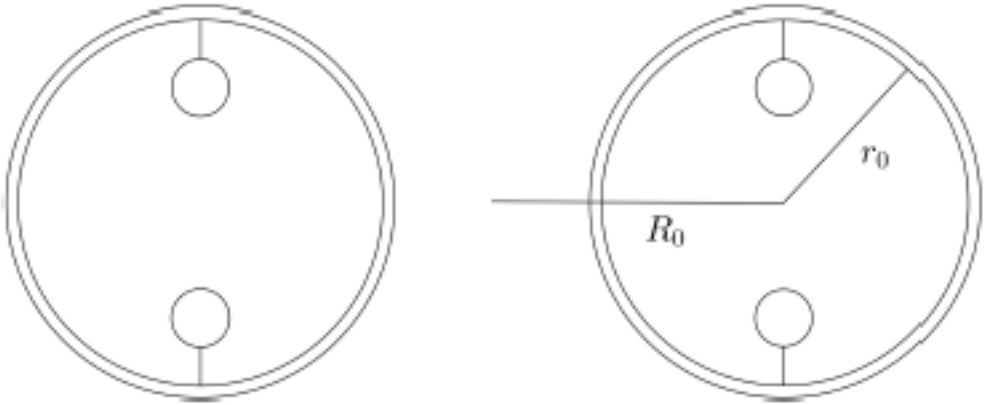
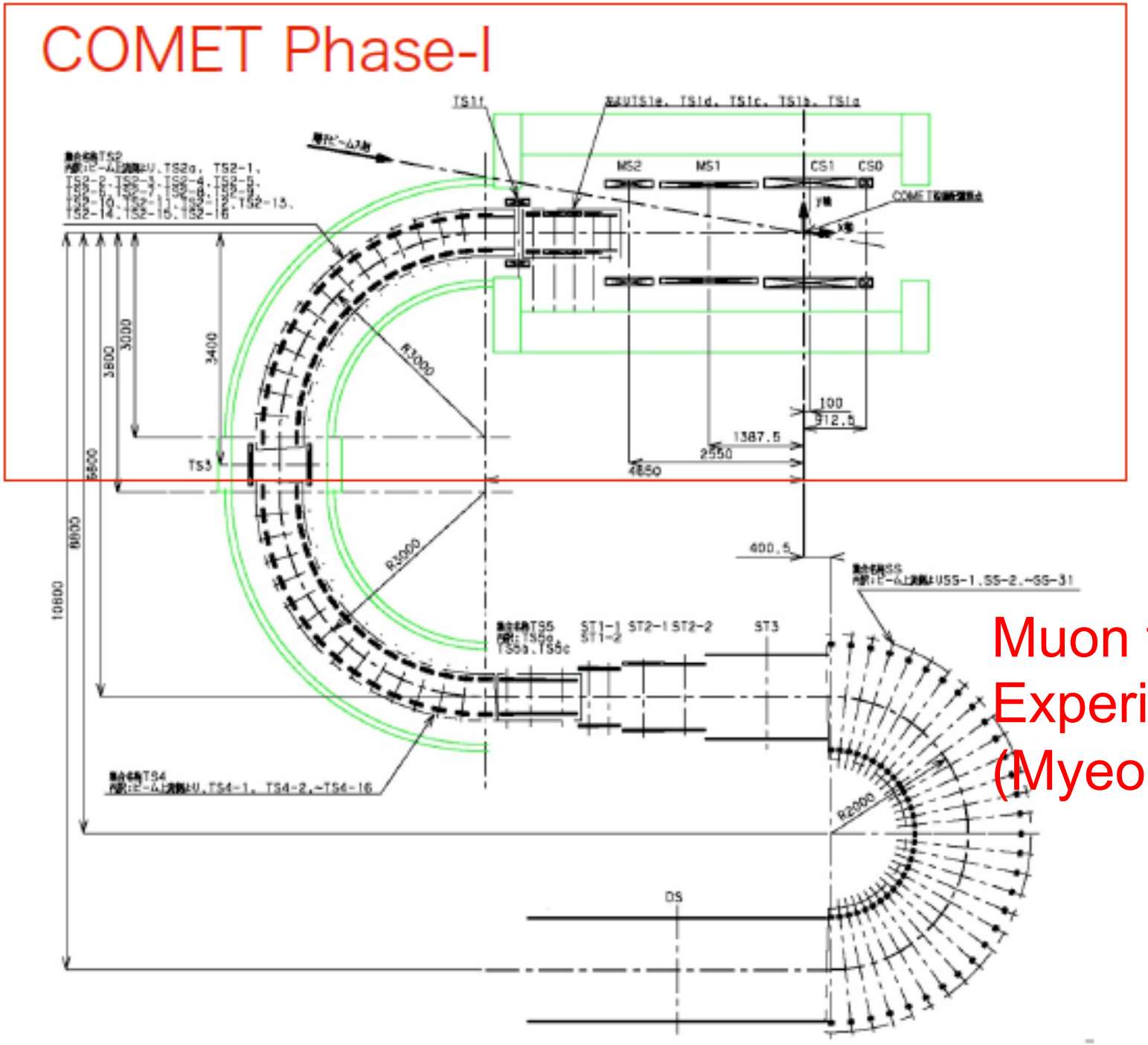


FIG. 1. A cross-section of the toroidal cavity of major radius R_0 and minor radius r_0. Conducting and dielectric tuning rings are supported at several points in the cavity.

COMET Phase-I

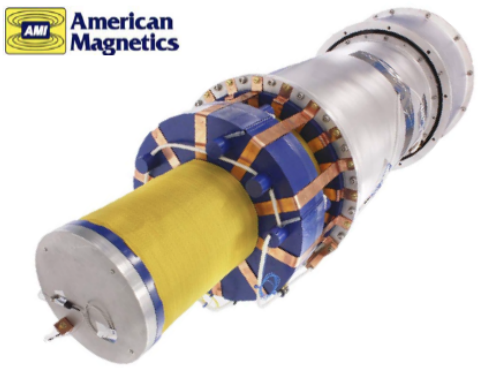


Muon to electron Experiments (MyeonJae. Lee)

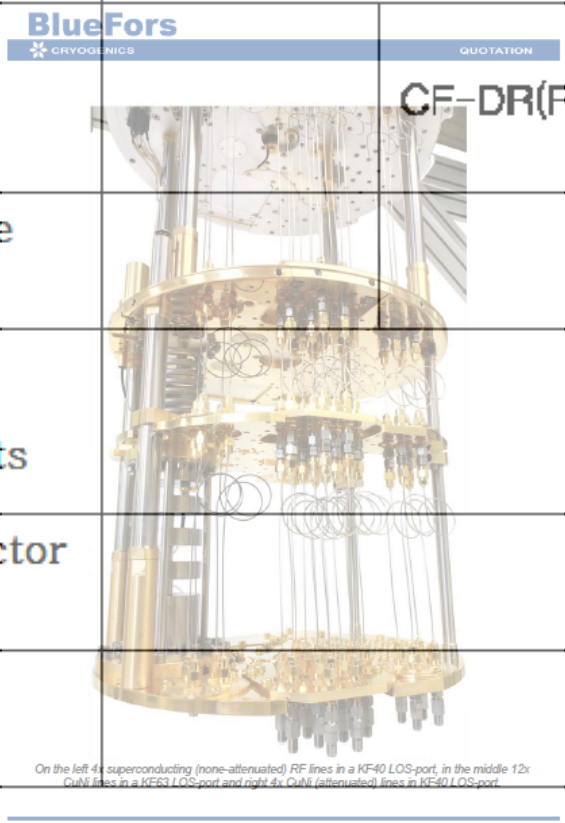
Cryo Development plan

(Yonuk Chong, KRISS)

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



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



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

Axion exp. development plan

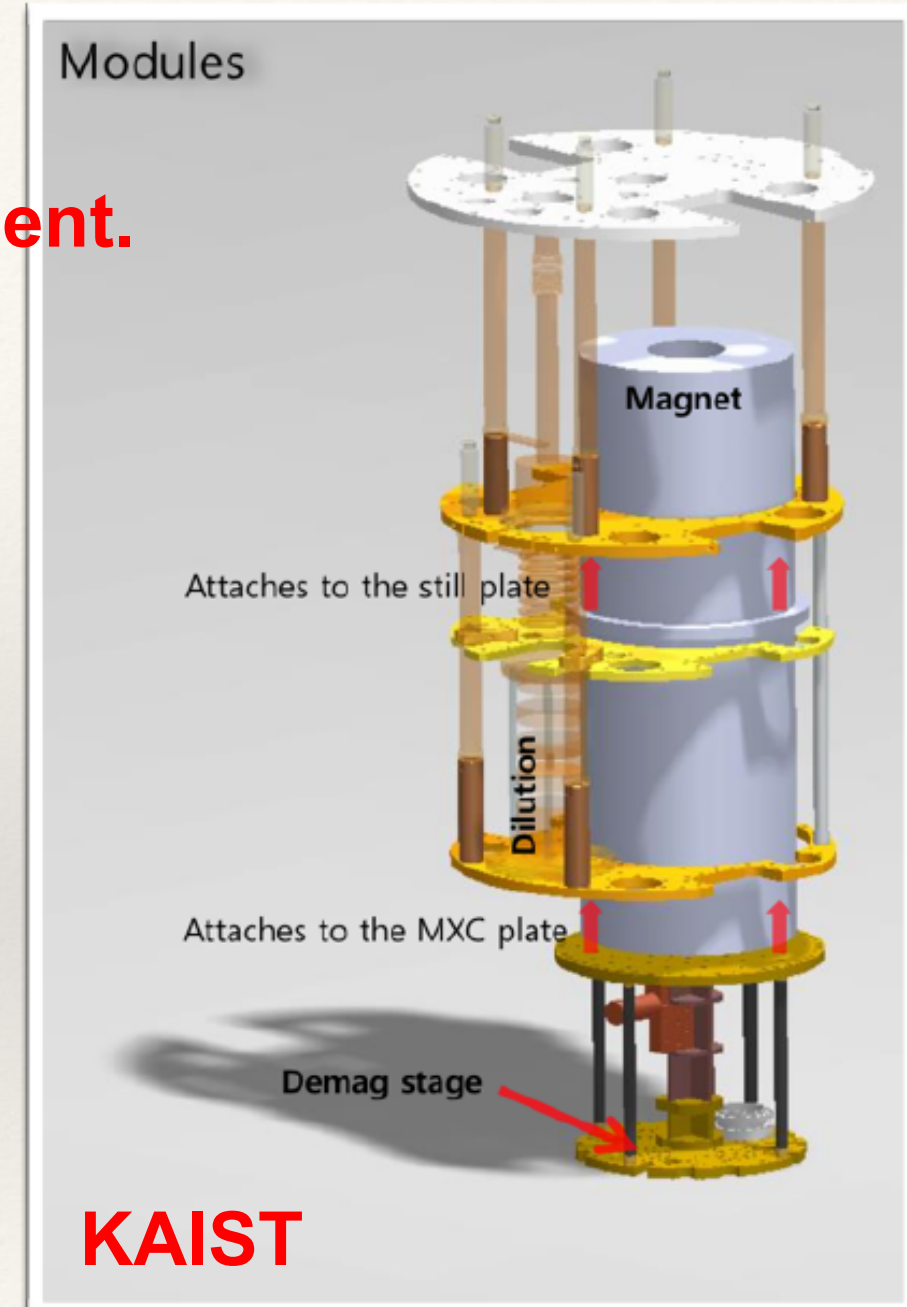
	2014	2015	2016	2017	2018
Magnet	Prototype, testing of cable characteristics.		25T, 3cm inner bore design	Work on 35T, 3cm inner bore construction	Magnet delivery; design of 25T, 10cm bore
Lab space	Temporary building. Design of new build.		Constr. of new building		Delivery of new building
Axion dark 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

Within 2015 we plan to install the <u>coldest</u> Axion dark matter experiment. Shooting for <50mK

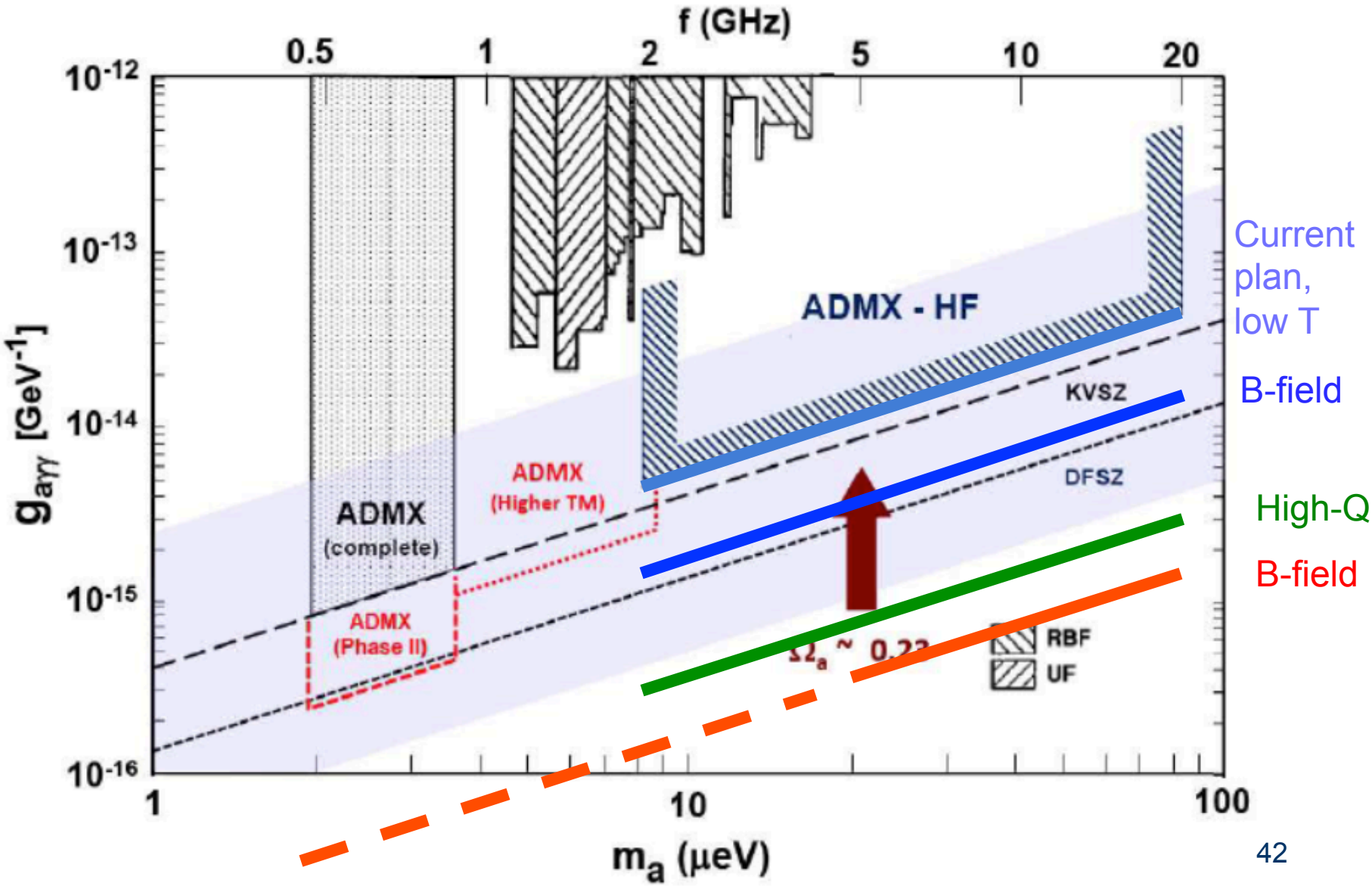
Design Features

- **Compact design:** magnet does not hang below the dilution refrigerator.
- **Fully modular design:** individual modules for high field applications (e.g. nuclear stage, microwave cavity) can be designed to be put on the mixing chamber plate.

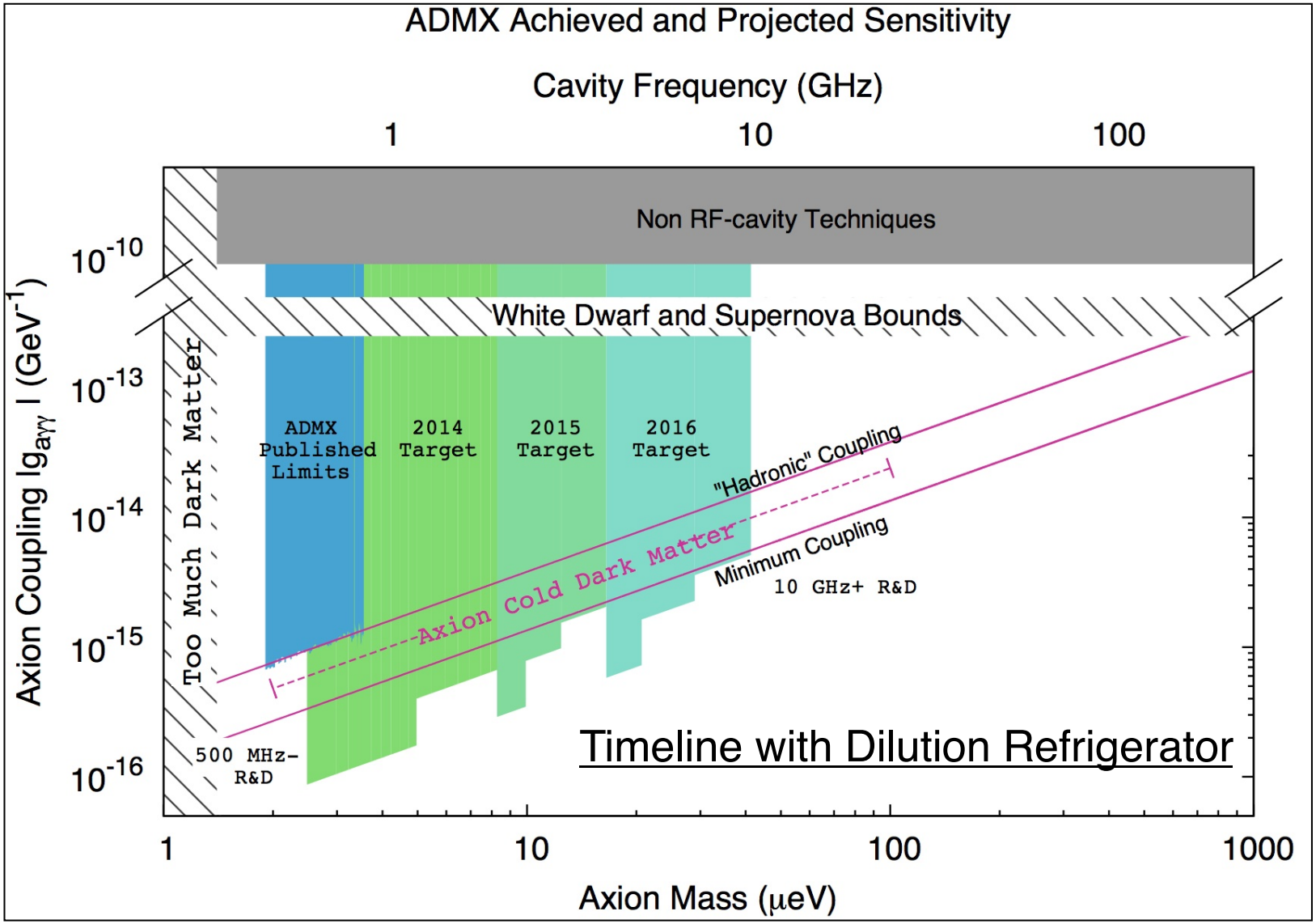
Hyoungsoon Choi/KAIST and CAPP



ADMX goals and CAPP plan



ADMX "Gen 2": Science



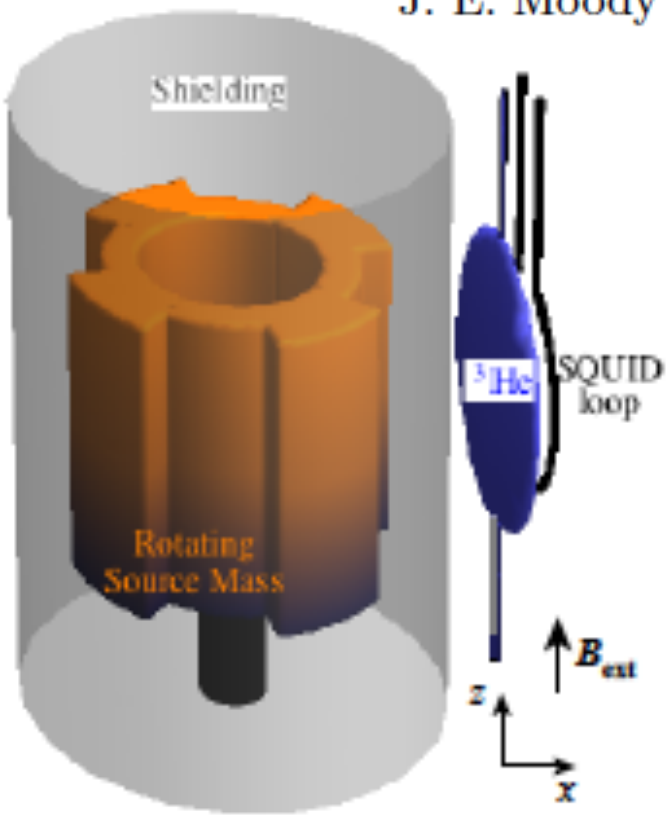
Axion mediated long range forces

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

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

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

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



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

Yun-chang Shin at CAPP

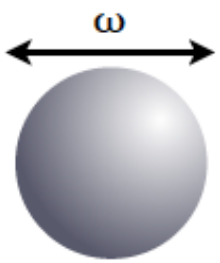
Axion field gradient creates effective B-field

Axion mediated long range forces

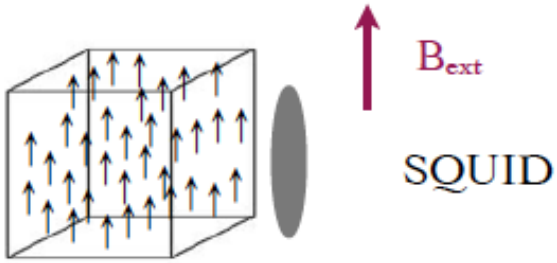
Detection Strategy

Just like a magnetic field

AA and Geraci (2014)



Oscillating Source Mass



NMR

$$\Delta E_{NMR} = \frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

On resonance:

$$\vec{M}(t) = n_{NMR}\, p\vec{\mu}\, \Delta E_{NMR}\, t \sin \omega t$$

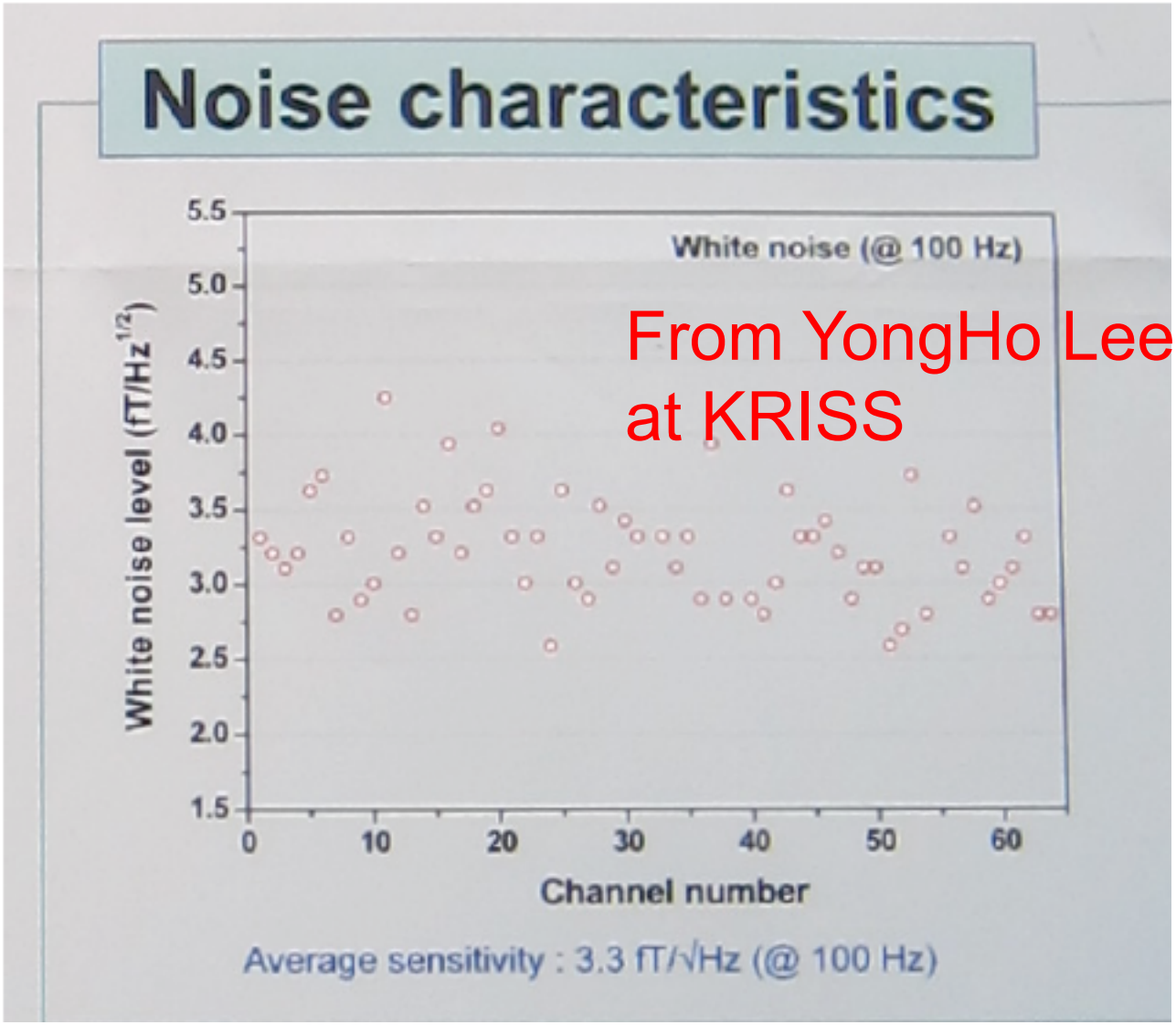
Signal grows till T_2

p: polarized fraction, n_{NMR}: density of spin in the detector, T_2: spin relaxation time

- Unpolarized Source Mass

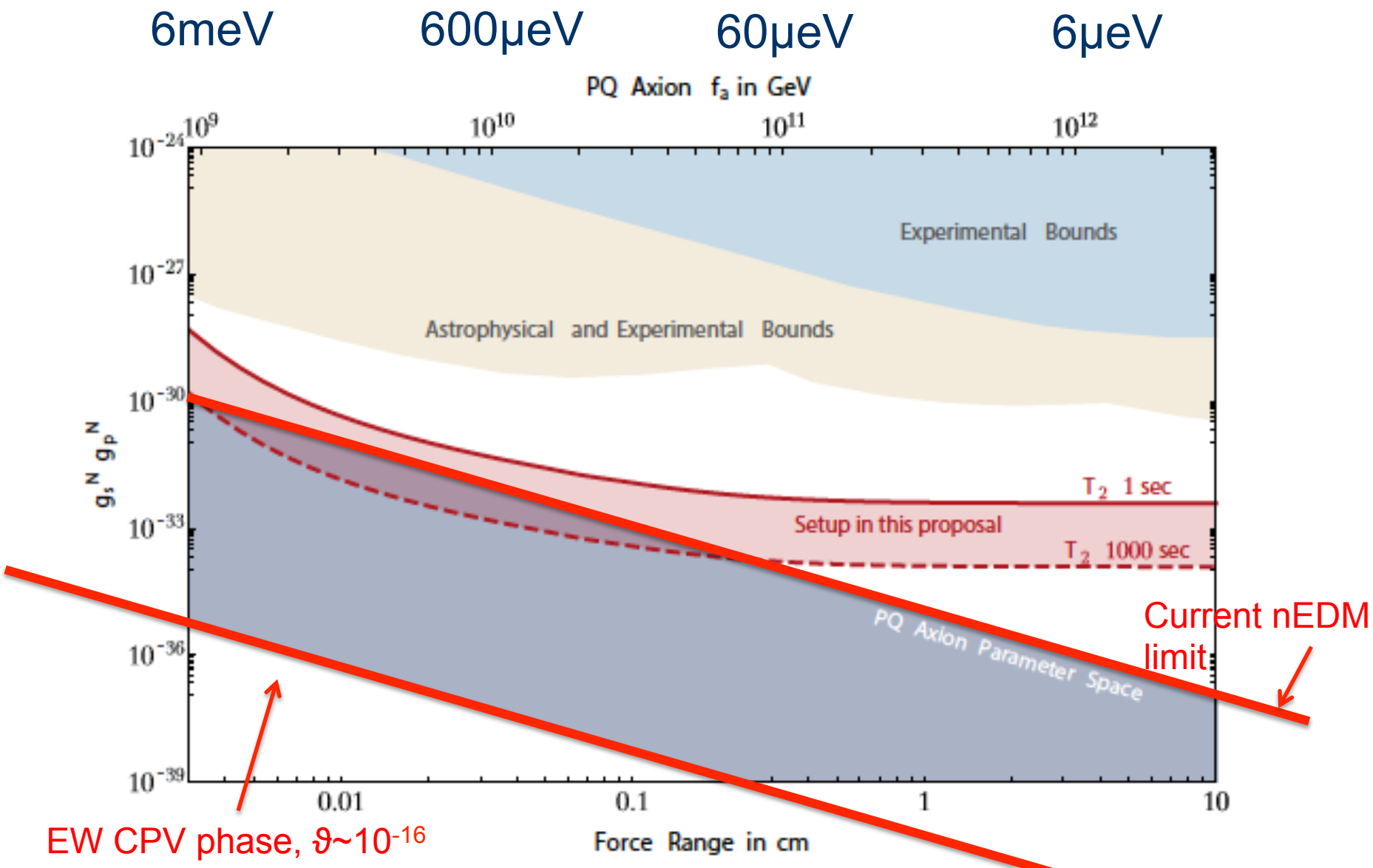
A. Arvanitaki,
Patras Workshop, 2014

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

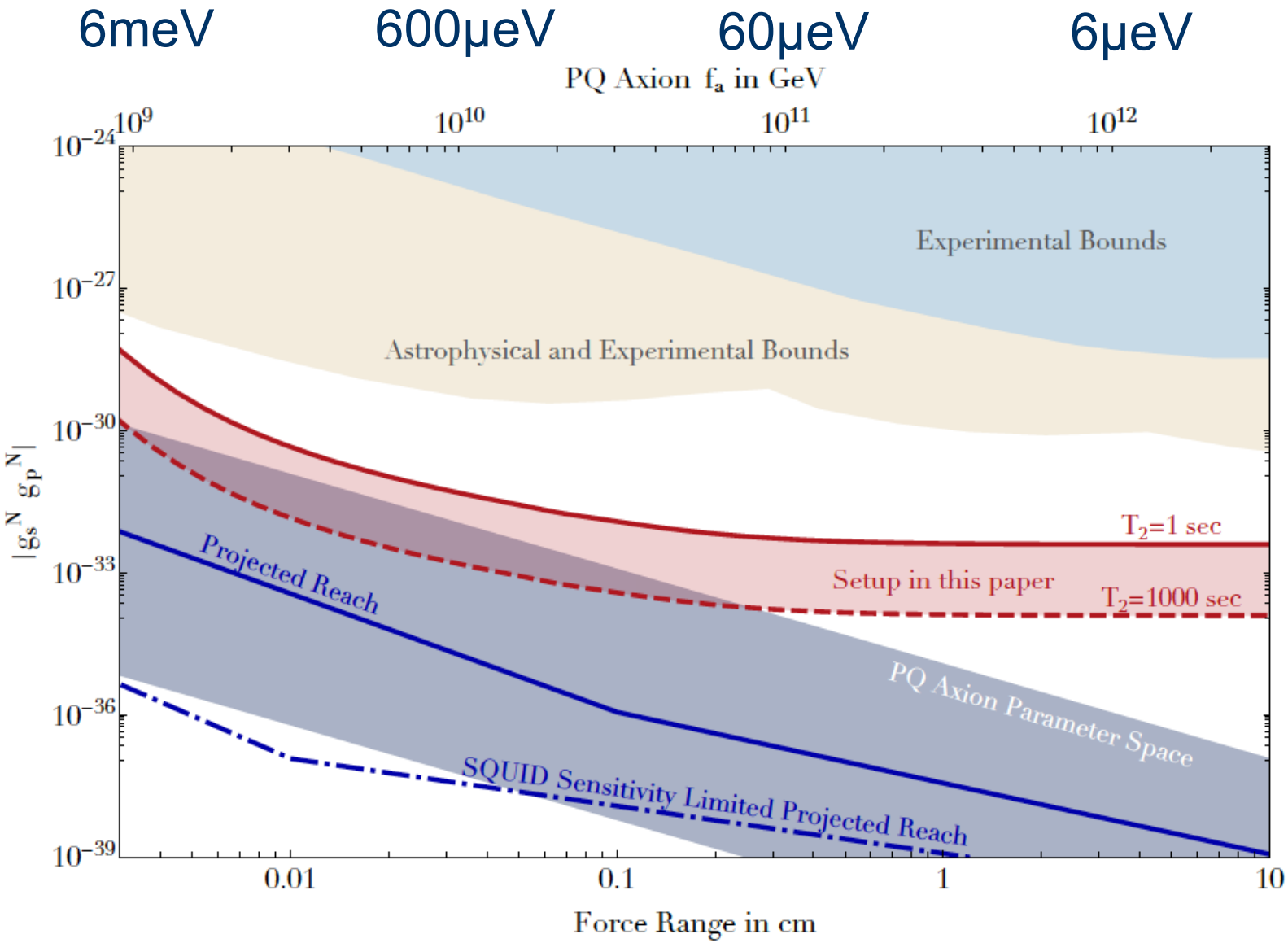


From YongHo Lee's group at KRISS

Axion mediated long range forces



Axion mediated long range forces



Dipole Moments in Storage Rings:

a. Muon g-2/EDM experiments (J-PARC, FNAL)

b. Storage ring EDM experiments (proton, deuteron)

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

Proton EDM

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

Marciano from CM9/Korea, last week

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

$$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$$
$$\sim \mathbf{10^{-22}(1TeV/\Lambda_{NP})^2 \tan\phi^{NP} e\text{-}cm}$$

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

If Λ_{NP}~O(1TeV), ϕ_{NP}~10^{-7} Probed!

<u>Unique Capabilities!</u>

Marciano from CM9/Korea, last week Outlook:

Heavy Leptons…

EDMs may soon be discovered: $d_e, d_n, d_p \ldots d_D$

Or significantly constrain "New Physics"

Eg CP violation in ***H→γγ*** ***(Contemporary topic)***

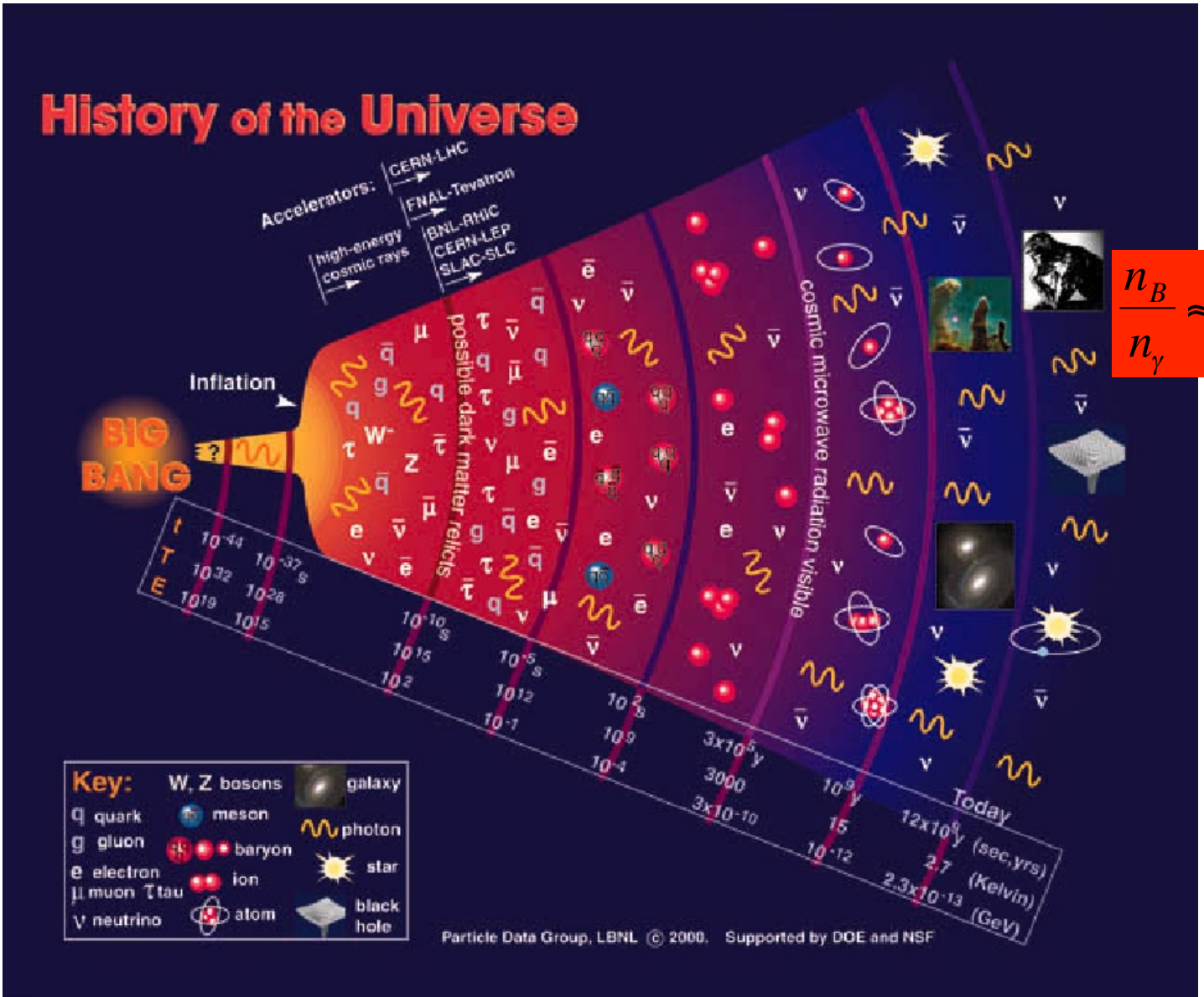
CP violation better explored by 2 loop edms

than all diboson (*γγ, ZZ, WW…*) modes at the LHC!

Atomic, Molecular. Neutron, ***Storage Ring*** (All Complementary)

45

Matter-antimatter asymmetry points to BSM CP-violation



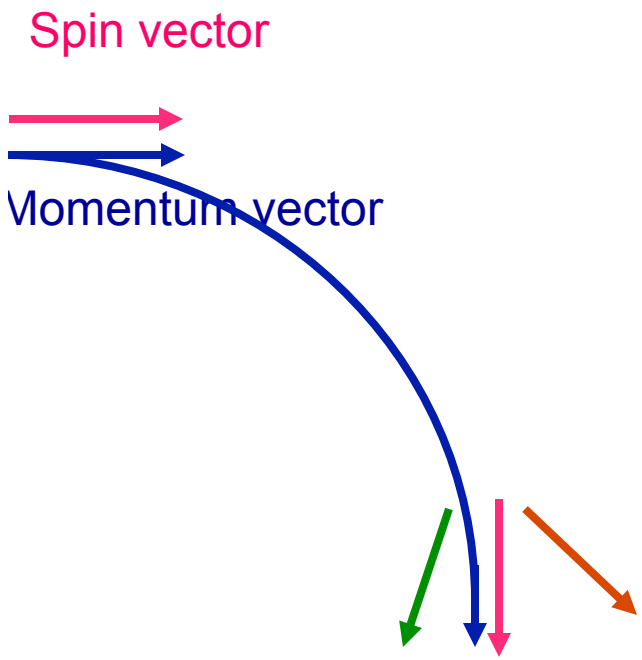
We see:

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

From the SM:

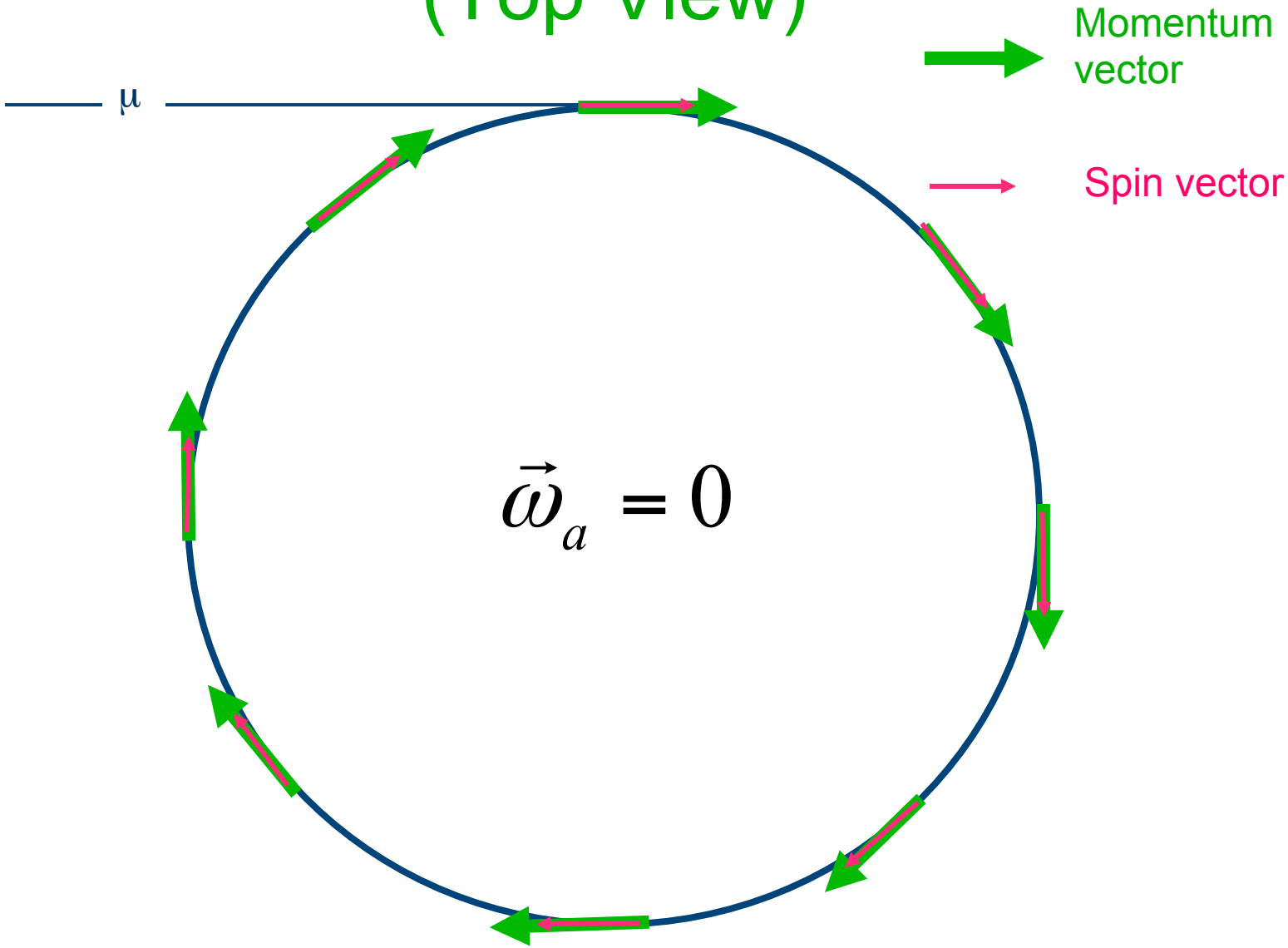
$$\frac{n_B}{n_\gamma} = 10^{-18}$$

Effect of Radial Electric Field

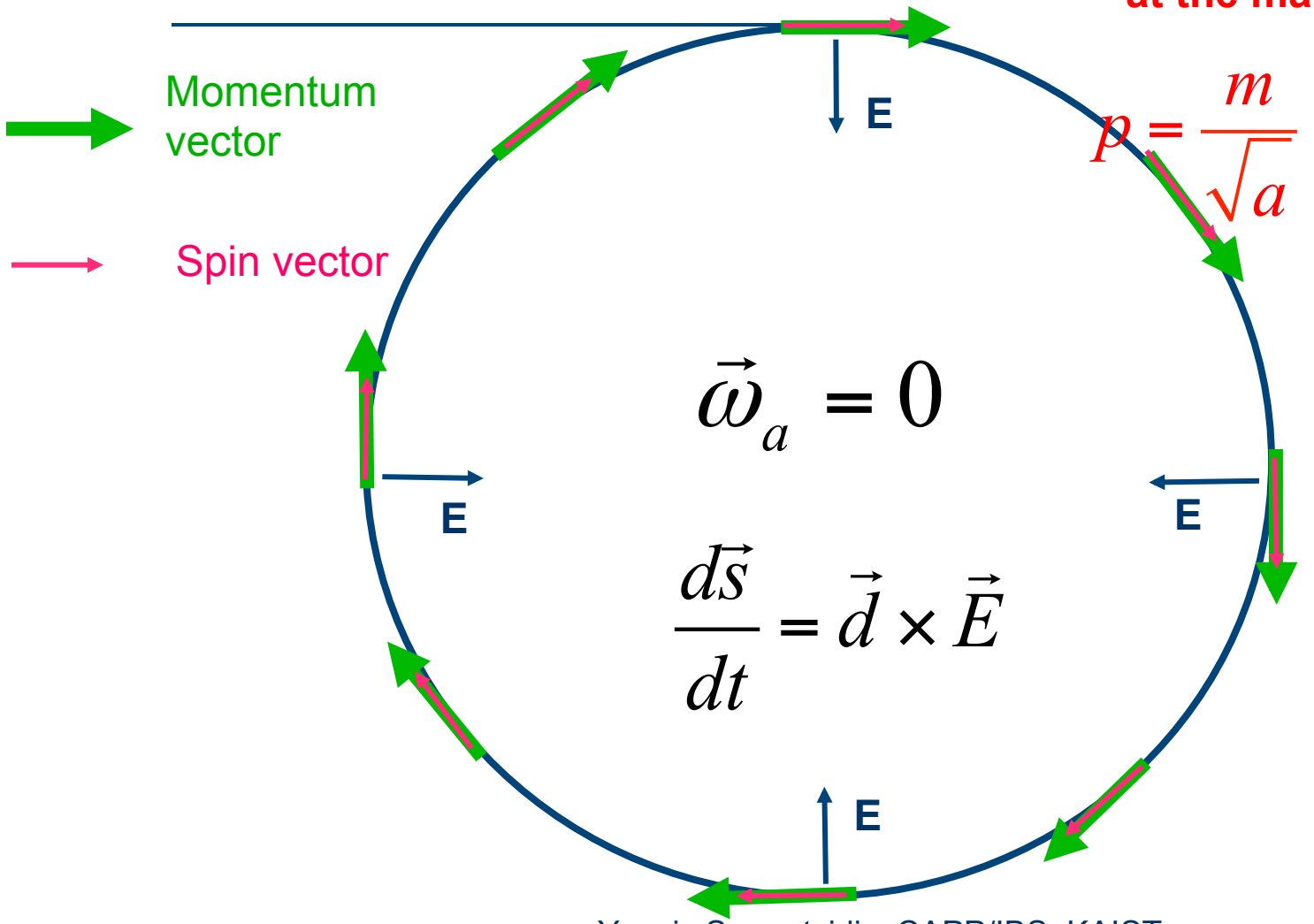


- Low energy particle
- …just right
- High energy particle

Spin Precession in EDM Ring (Top View)



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



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

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

at the magic momentum

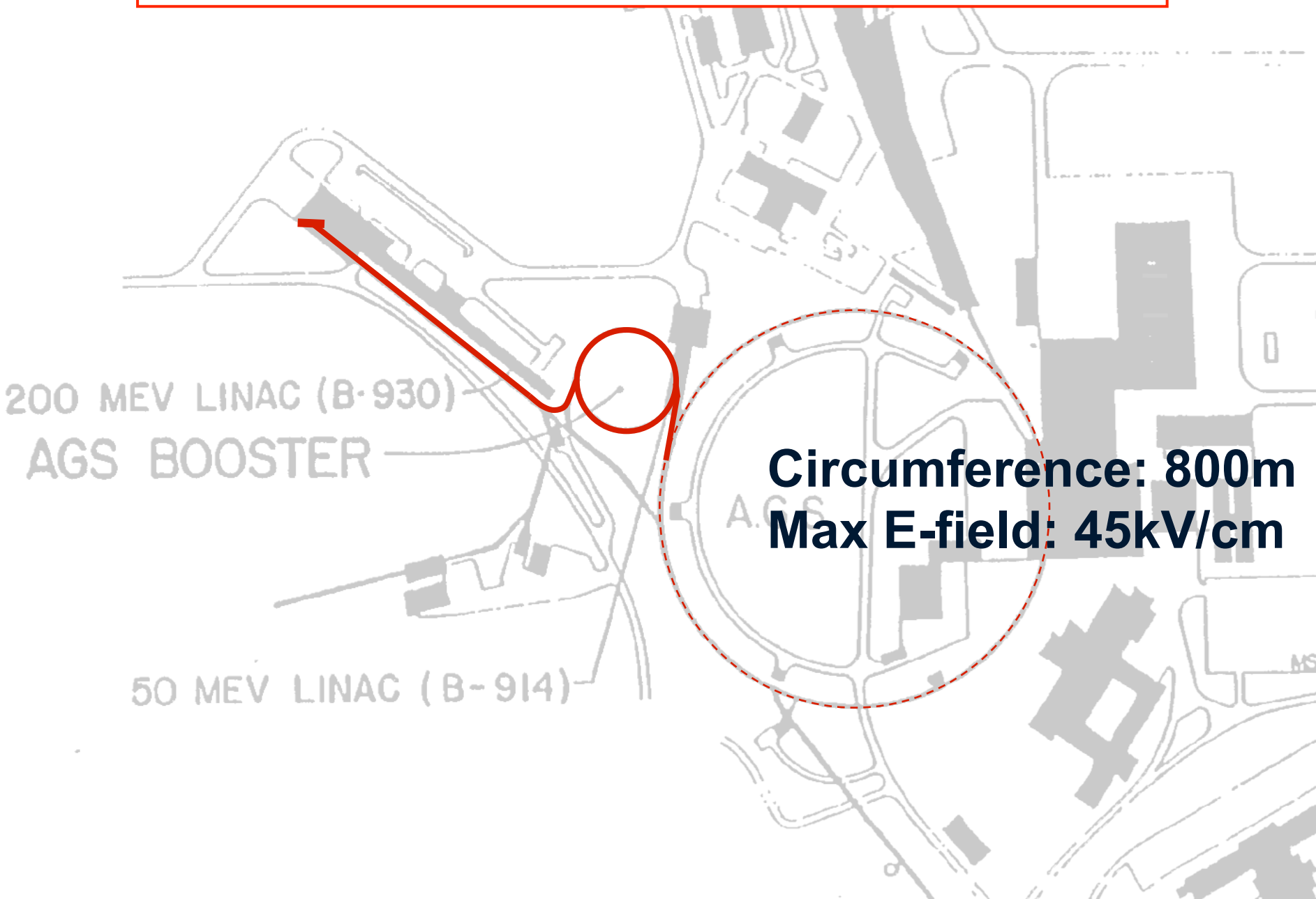
$$p = \frac{m}{\sqrt{a}} = 0.7 \text{ GeV/c}$$

As in muon g-2 experiment at BNL and FNAL

Two different labs could host the storage ring EDM experiments

- AGS/BNL, USA: proton "magic" (simpler) ring
- COSY/IKP, Jülich/Germany: deuteron or a combination ring

The proton EDM in the AGS tunnel at BNL



Circumference: 800m
Max E-field: 45kV/cm

Major characteristics of a successful Electric Dipole Moment Experiment

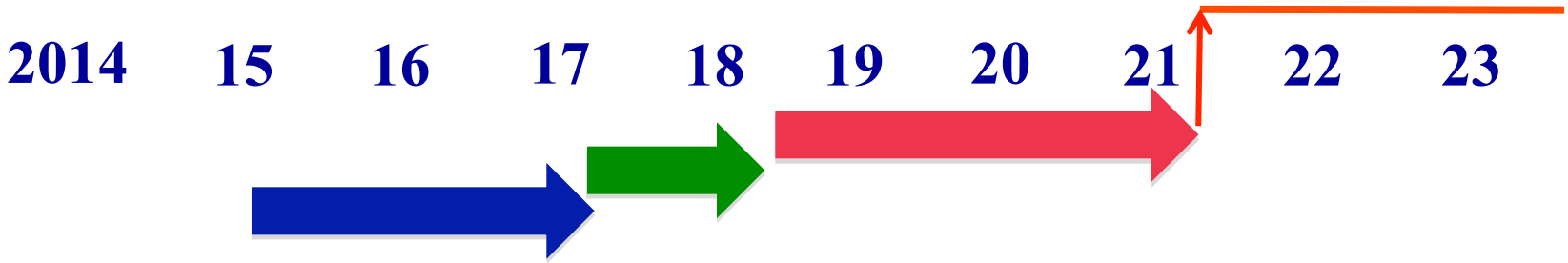
- Statistical power:
  - High intensity beams
  - Long beam lifetime
  - Long Spin Coherence time
- An indirect way to cancel B-field effect
- A way to cancel geometric phase effects
- Control detector systematic errors

The storage ring Proton EDM method has it all!

What has been accomplished?

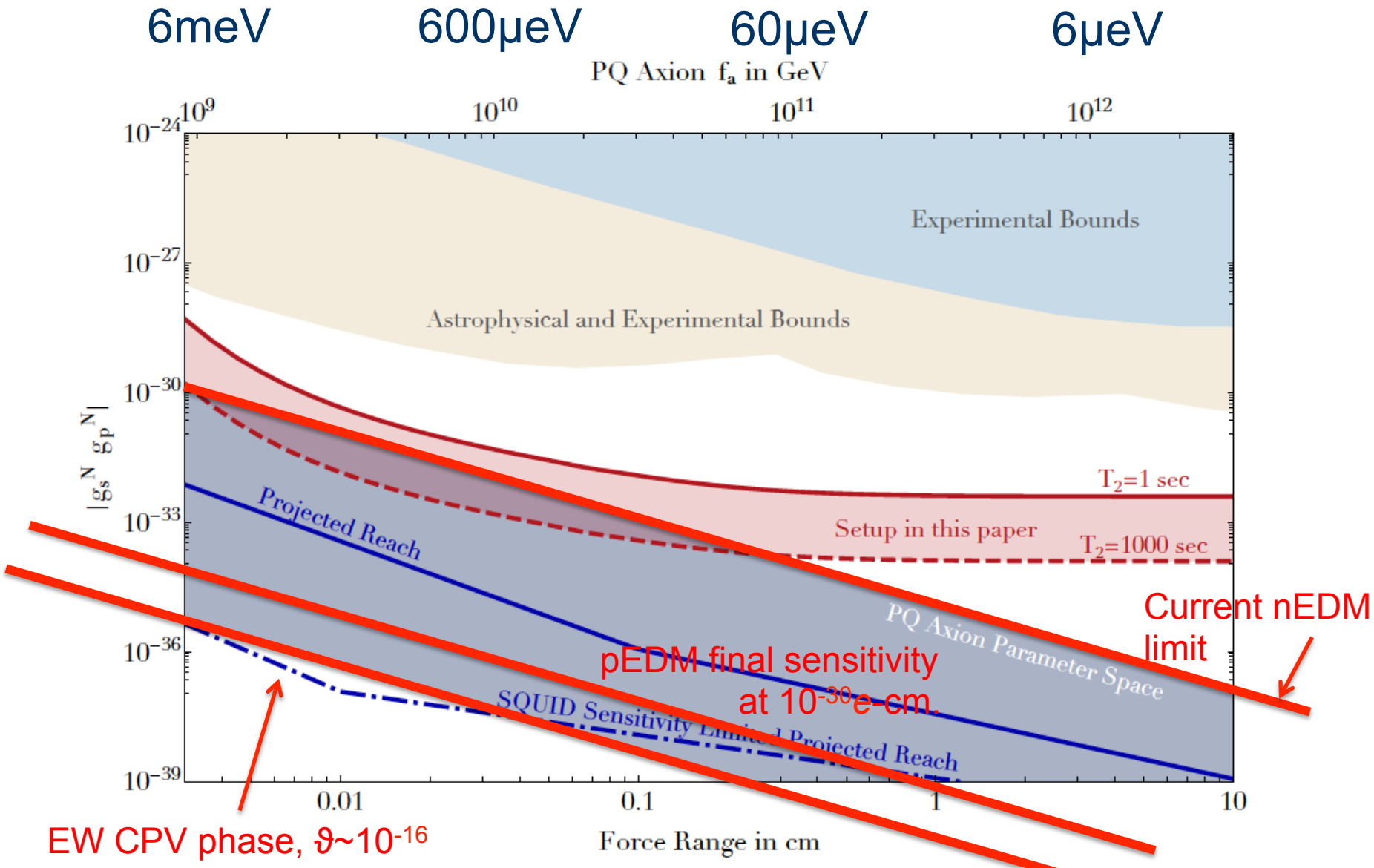
- ✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- ✓ Precision beam/spin dynamics tracking.
- ✓ Stable lattice, IBS lifetime: 10^4 s.
- ✓ Spin coherence time 10^3 s; role of sextupoles understood (using stored beams at COSY).
- ✓ Feasibility of required electric field strength 5 MV/m, 3cm plate separation (JLab, FNAL)
- ✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
- ✓ (Paper already published or in progress.)

Technically driven pEDM timeline



- Two years systems development (R&D); Ring design; Installation.
- Cost (2011, 2012 engineering cost): $70M + tunnel.
- Proposed cost-sharing with AGS tunnel:
  - Owned by DOE-HEP; DOE-NP partner with running costs.
- Foreign contributions: electric field plates, vacuum chambers, SQUID-based magnetometers

Axion mediated long range forces



Center for Axion and Precision Physics (CAPP)

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

The team at CAPP, students

- Hyoungsoon Choi, Yonuk Chong, Woohyun Chung, Martin Gaisser, Selcuk Haciomeroglu, Sookyung Jung, Mi Ran Kim, Yong-Ho Lee, Young-Im Kim, Jhinhwan Lee, MyeongJae Lee, Soohyung Lee, Yujung Lee, Lino Miceli, Seongtae Park, Yannis Semertzidis, Yunchang Shin, Harry Themann, John Vergados, Eunil Won, Hyeran Yoon
- Seungpyo Chang, Dongok Kim, Young Geun Kim, Doyu Lee, Bayu Adi Nugraha Putra, BeomKi Yeo

Summary-1

- Major R&D effort on improving the axion dark matter experiment:
- Higher B-field: 25 T and then 35 T
- Higher Q-value with B-field present (factor of >10 improvement)
- Toroidal cavity geometry: Volume ~10
- Detect axions in the 1-100μeV even at 10% DM by 2018-2020.
- Monopole-dipole forces sensitive to large range of axion masses well into meV. No dark-matter needed.

Summary-2

- The storage ring proton EDM method has been developed. The breakthrough? Statistics!
- Best sensitivity hadronic EDM method.
- pEDM first goal 10^{-29} ecm.

- Complementary to LHC; probes New Physics $>10^3$ TeV.

- Important role in the muon g-2/EDM experiments