Axion Dark Matter Search at CAPP/IBS

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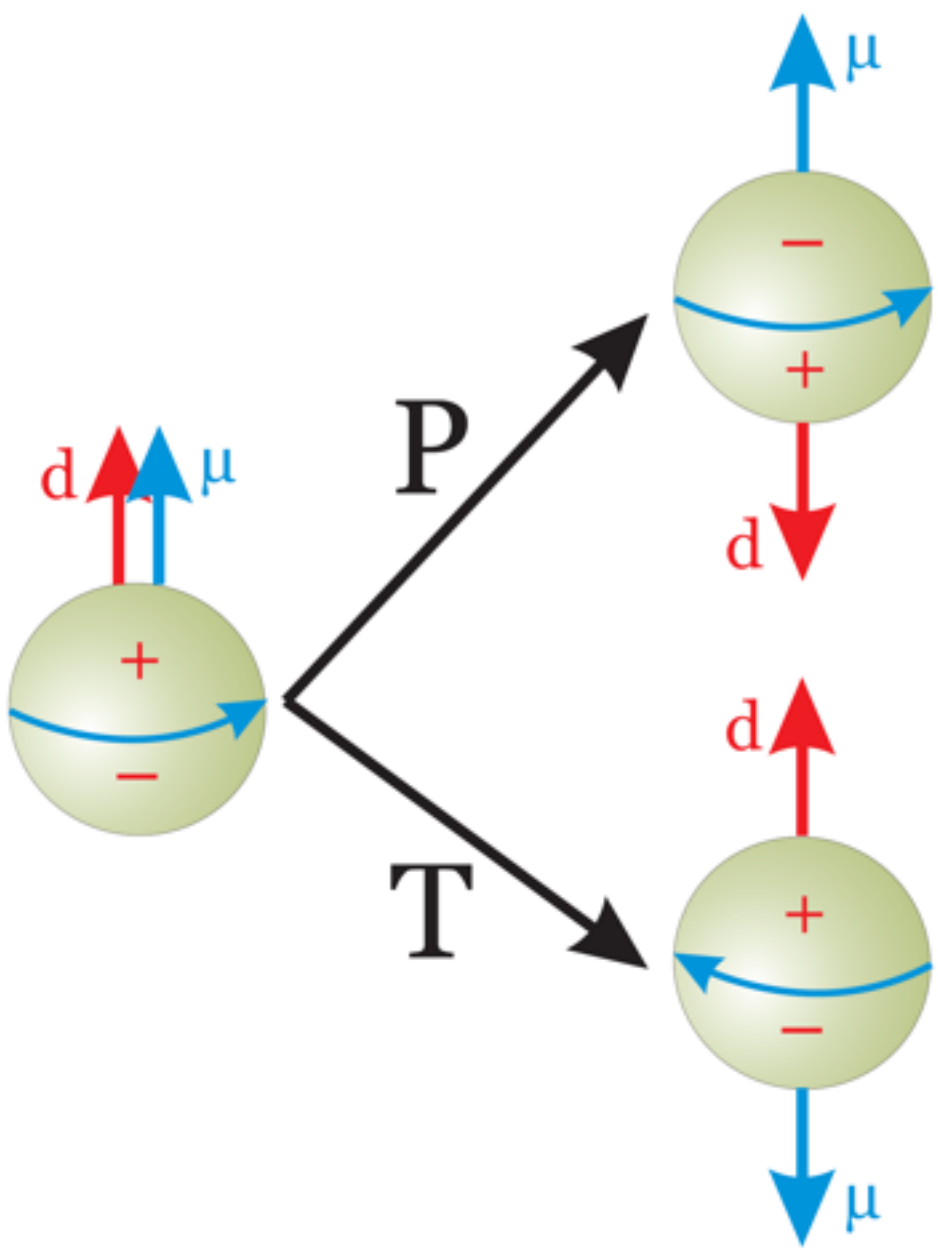
KAIST/IBS

23 November 2016

3rd IBS-MultiDark-IPPP Workshop
Lumley Castle, Durham



- Neutron has magnetic moment
  $\mu_m = -1.04 \times 10^{-3} \mu_B$

- Neutron may have
  an electric dipole moment (nEDM)
  if so: it breaks CP
  T-violation = CP-violation

- The theory of Strong Interaction
  (QCD) which describes
  the quark-gluon in the neutron
  is explicitly CP-violating.

Neutron Electric Dipole Moment (nEDM)

- QCD Lagrangian (a CP violating term)

$$L_{\Theta} = \boxed{(\theta_{QCD} + \arg\det M_q)} \frac{\alpha_s}{8\pi} F_{\mu\nu a} \tilde{F}^{\mu\nu}_{a} = \Theta \frac{\alpha_s}{8\pi} F \tilde{F}$$

Phase from QCD Vacuum

Phase of Quark mass matrix (θ_q)

Gluon field strength

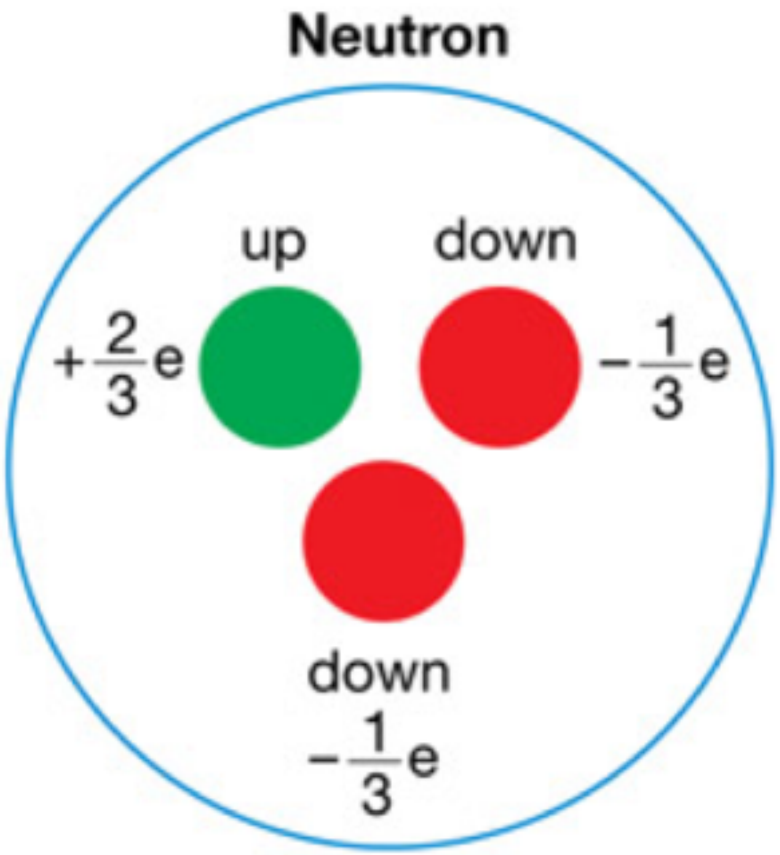
- Non-zero Θ ➜ non-zero neutron electric dipole moment

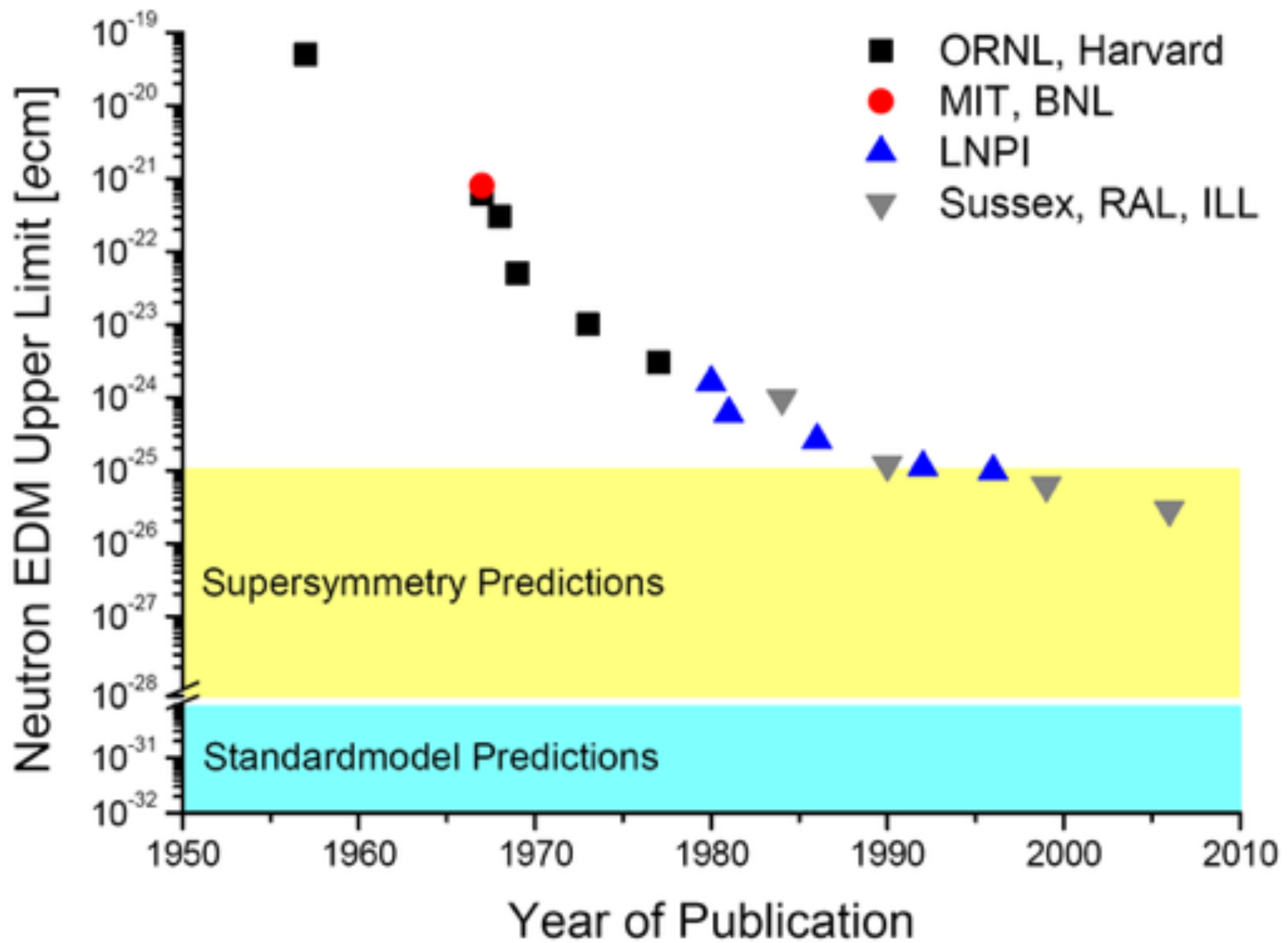
$$|d_n| \simeq |\Theta| 10^{-16}\ e \cdot cm \quad (-\pi < \Theta < \pi)$$

➜ Go and measure the nEDM!

Neutron Electric Dipole Moment (nEDM)

$|d_n| \simeq |\Theta| 10^{-16}$ e · cm





Current bound:

→ $|d_n| < 2.9 \times 10^{-26}$ e · cm

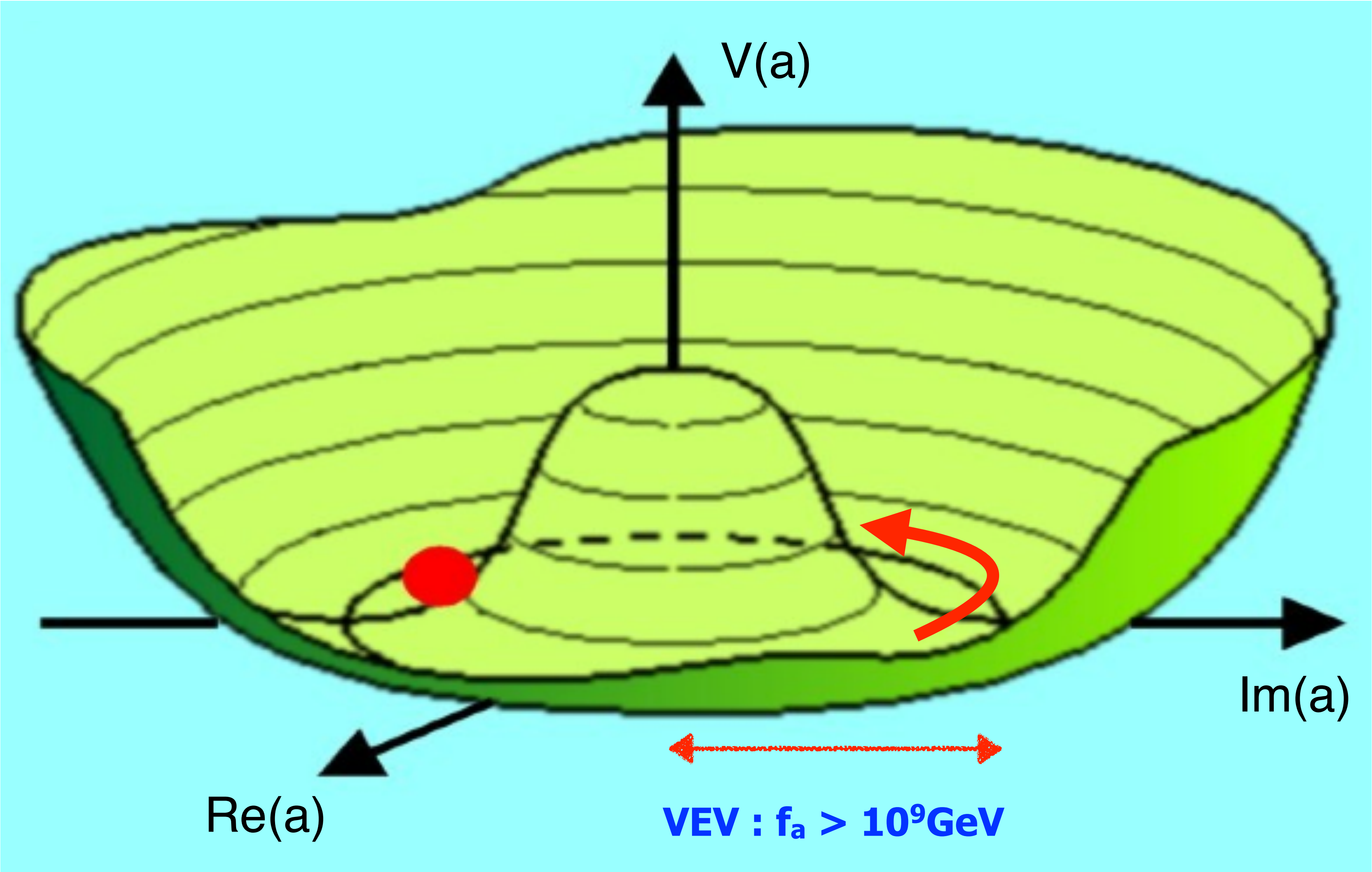
$\Theta <\sim 10^{-9}$

Why the Θ is so small? → Strong CP Problem!

Peccei-Quinn Solution

- Introduce an additional global chiral-symmetry $U(1)_{PQ}$: Peccei-Quinn (1977)

- The associated Nambu-Goldstone boson
  ➜ the new field (a) renders Θ a dynamic parameters Θ➜ a/f_a : $\frac{1}{32\pi^2}\left(\frac{a}{f_a}\right) F_{\mu\nu a}\tilde{F}^{\mu\nu}_a$

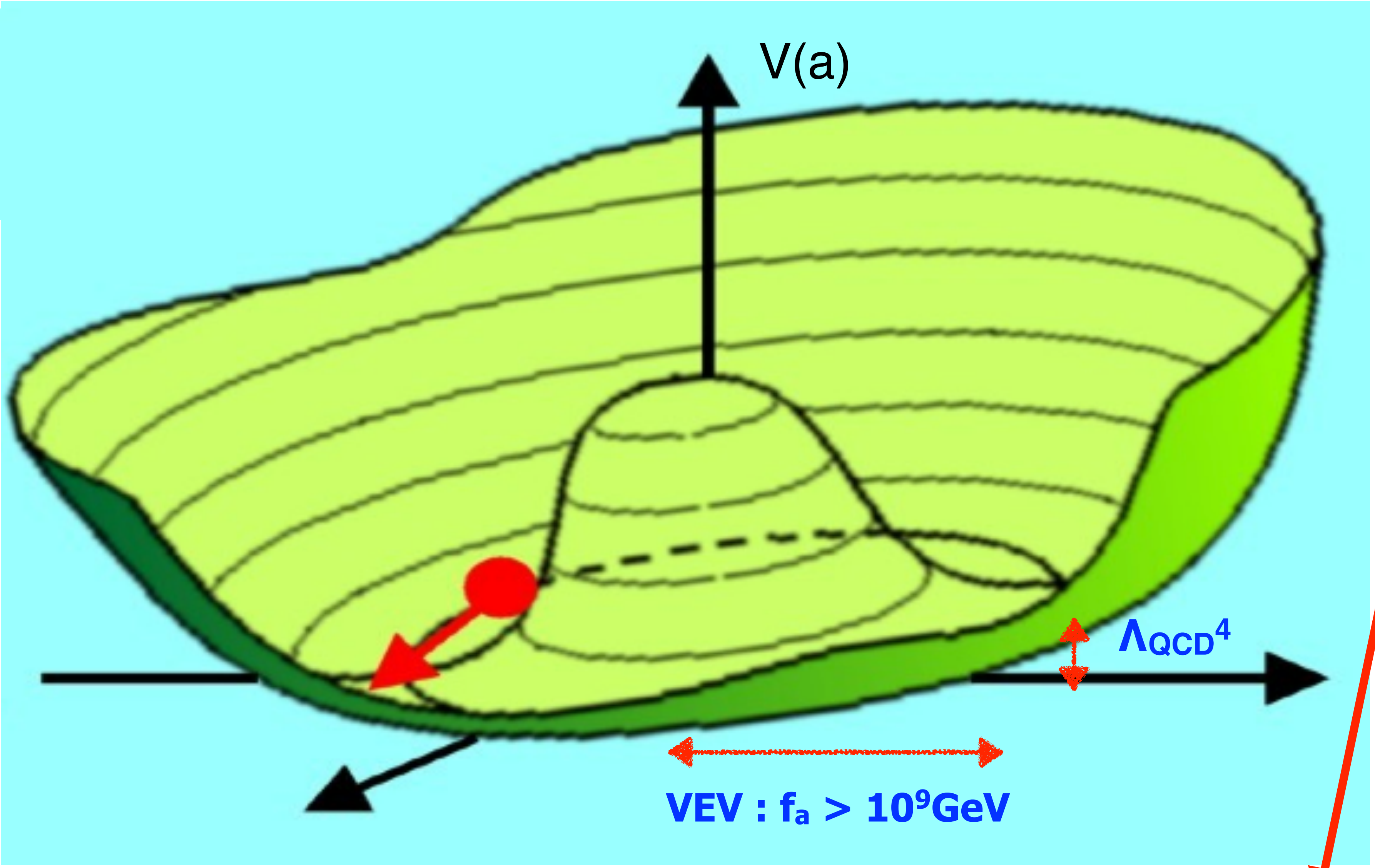


It's quite similar to the Higgs mechanism

$$V(a) = -f_a^2 a^2 + \frac{\lambda}{4!}a^4 + \left(\frac{g^2}{32\pi^2}\arg(a) - \frac{\alpha_s}{8\pi}(\theta_{\rm QCD} + \theta_q)\right)\left\langle F\tilde{F}\right\rangle$$

Peccei-Quinn Solution

- After quark-gluon phase transition, QCD instanton effect tilt the potential : Λ_{QCD}^4 = (~400 MeV)^4
- **Weinberg** and **Wilczek** showed that the PQ-symmetry breaking implies the existence of new pseudo-scalar particle with non-zero mass — the "axion".



Peccei-Quinn showed that this term becomes explicitly zero!

CPV term vanishes, hence solving Strong CP problem !

$$V(a) = -f_a^2 a^2 + \frac{\lambda}{4!} a^4 + \left(\frac{g^2}{32\pi^2} \arg(a) - \frac{\alpha_s}{8\pi} (\theta_{QCD} + \theta_q) \right) \langle F\tilde{F} \rangle$$

Axion Models

- Initially the temperature f_a was assumed to be of Electroweak scale,
  hence the CP breaking at the scale ➜ predicts relatively high mass axions
  ➜ **This classical axion model was subsequently ruled out by experiments.**

J.E. **K**im realized that f_a can be very big.
"I found a solution that solves both the strong CP problem
and the dark matter problem." (1979)

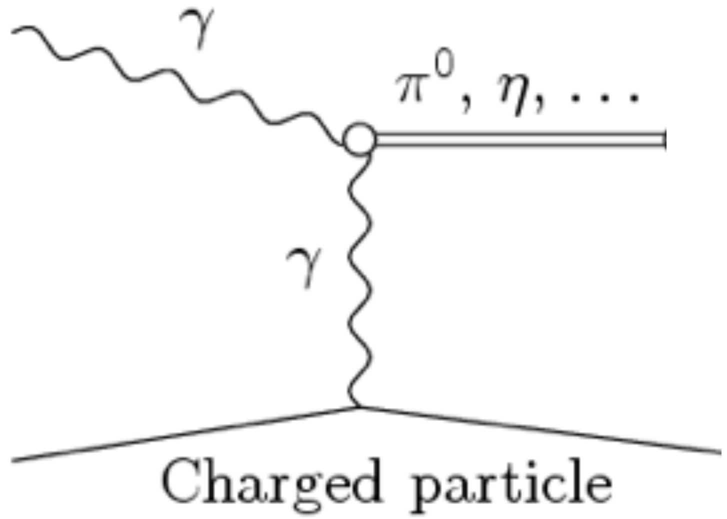
Then, **S**hifman, **V**ainshtein & **Z**akharov (1980)
KSVZ axion model: new heavy quark carries $U(1)_{PQ}$ charge

Also, **D**ine, **F**ischler, **S**rednicki (1981) and **Z**hitniski (1980)
DFSZ axion model: Two Higgs doublets, quarks and leptons carry $U(1)_{PQ}$ charge

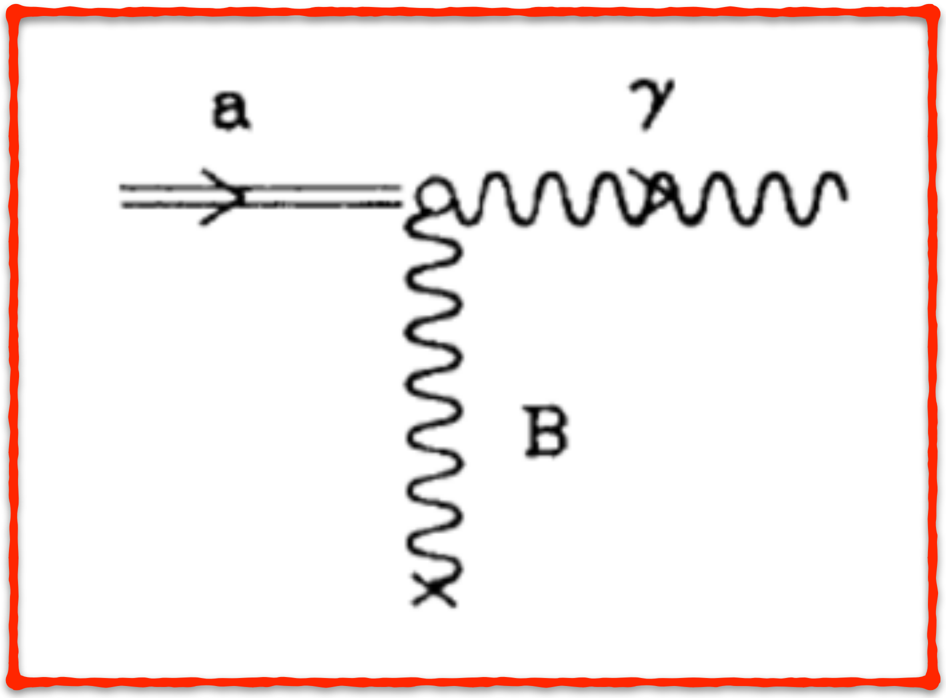
These are called invisible axion models

How to Detect the Axions?

- There are many ways of detecting axions.
  However, the most popular method is to use **inverse Primakoff effect.**



Primakoff effect



EM-field strength tensor

$$L \subset F \cdot \tilde{F} + igaF \cdot \tilde{F} + \frac{1}{2} m_a^2 a^2 + \frac{\lambda}{4!} a^4 + \ldots\ldots$$

(let a ➜ ϕ)

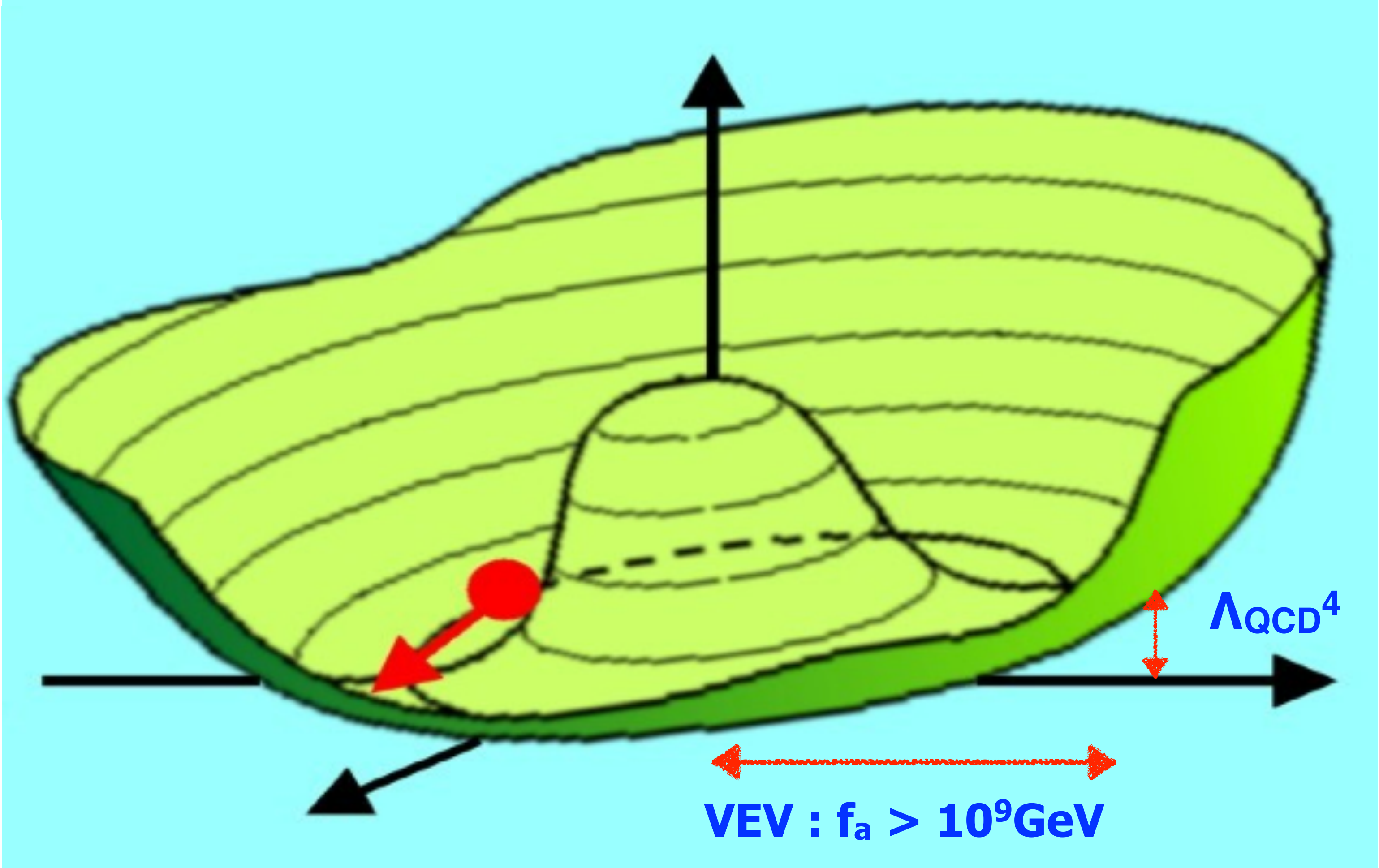
$$\mathcal{L}_{\text{pseudoscalar}} = -\frac{g}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = g\phi(\vec{E}\cdot\vec{B})$$

axion

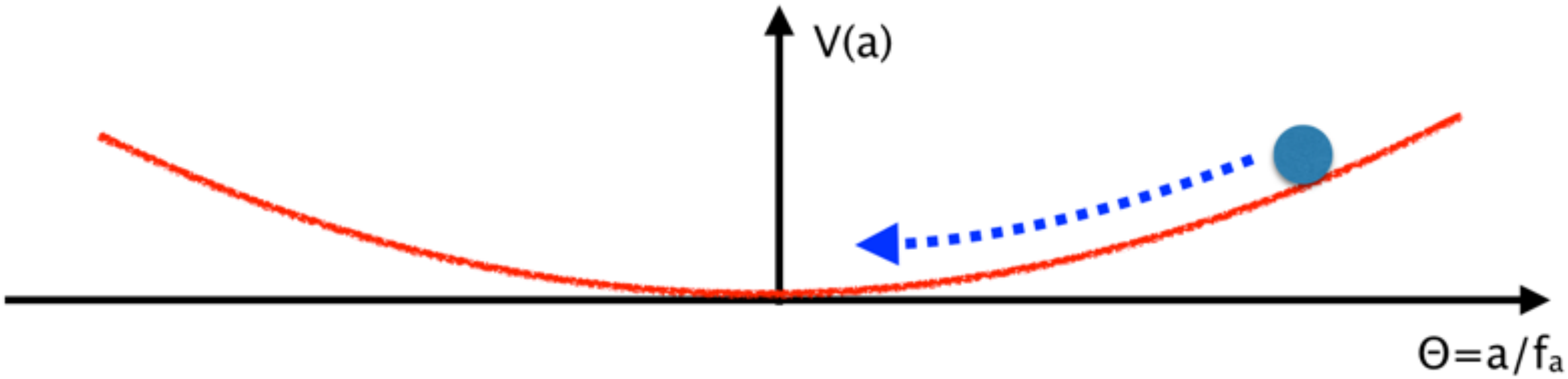
$$\mathcal{L}_{\text{scalar}} = -\frac{g}{4}\phi F_{\mu\nu}F^{\mu\nu} = g\phi(\vec{E}\cdot\vec{E} - \vec{B}\cdot\vec{B})$$

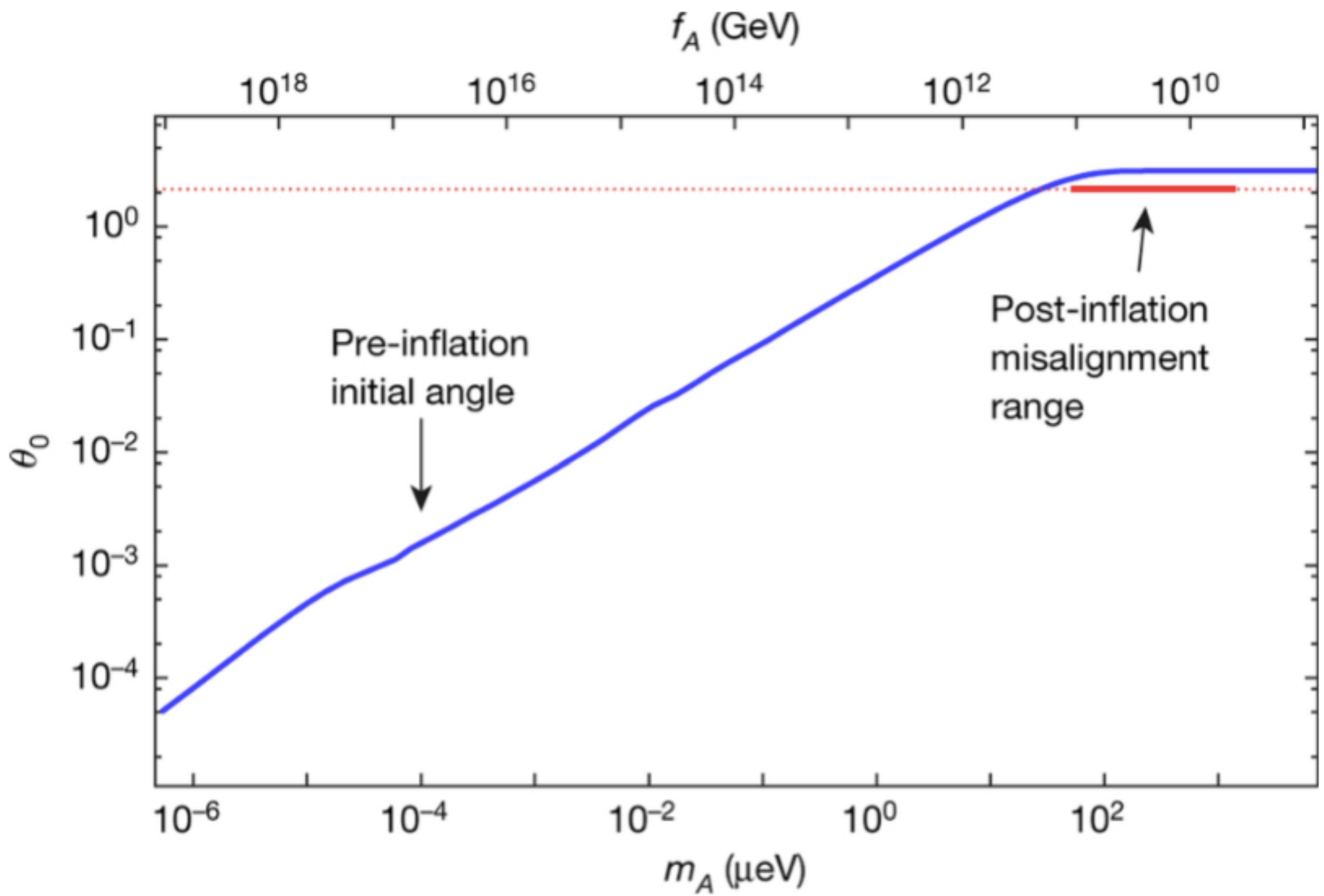
axion like particle

Axion as a Dark Matter



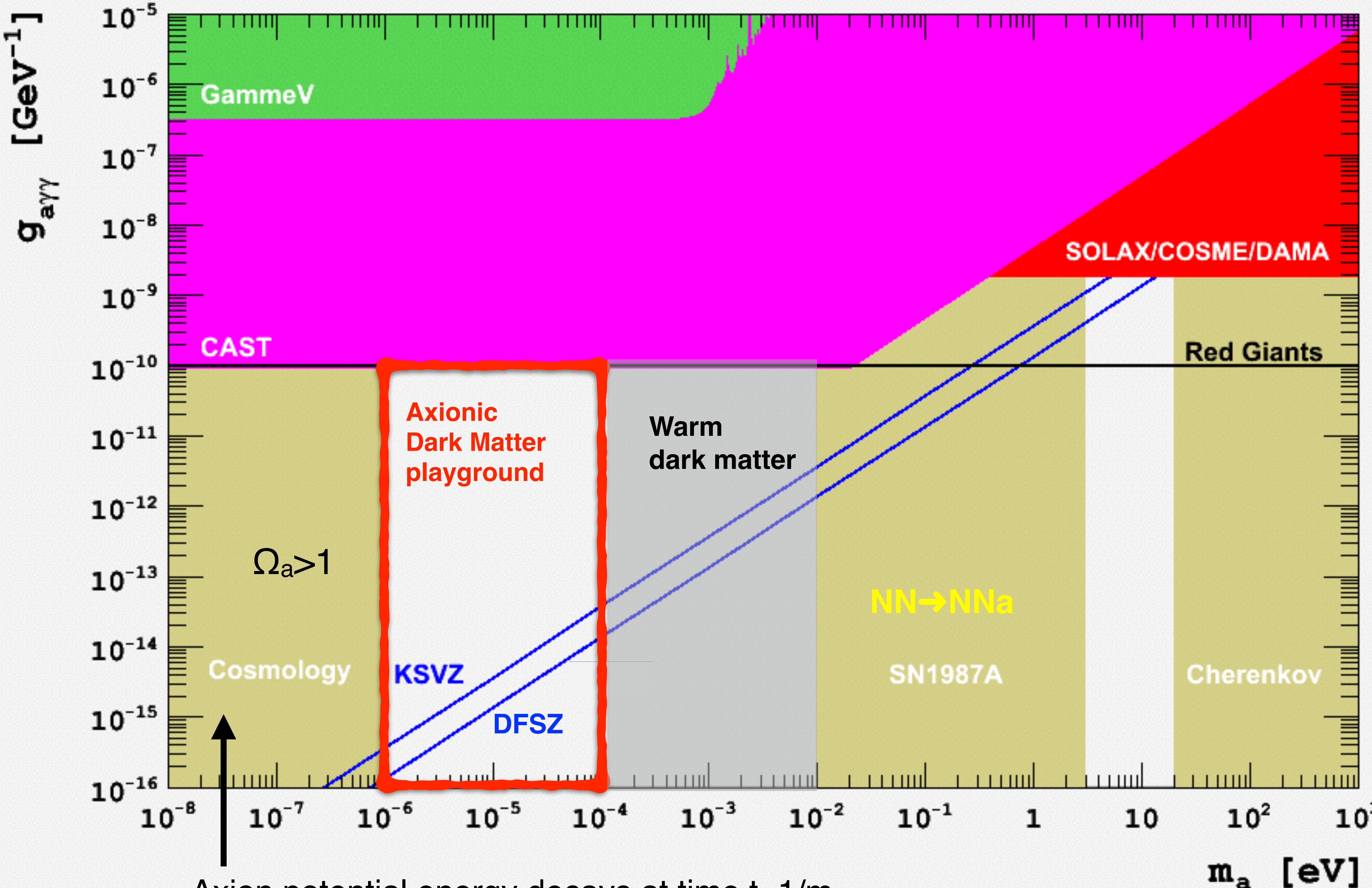
- Nonthermal production of axions in the early Universe
- The initial axial angle Θ determines the potential energy to be released.
- The potential energy density (order of Λ_{QCD}^4) is converted into **cold dark matter**
- Axion dark matter mass is determined by the harmonic oscillator frequency
  $m_a \simeq \Lambda_{QCD}^2/f_a < 10^{-3}$ eV !





S. Borsanyl et al. Nature 539, 69–71 (2016)

Axion Search



Axion potential energy decays at time $t \sim 1/m_a$.
If this is too late (too small m_a) in cosmological time
the dark matter can be overproduced relative to the photons

How to Detect Axion Dark Matter?

Assume: $m_a \simeq \mu eV$

$$\rho_{DM} = 3 \times 10^8 \, eV/cc = 2.4 \times 10^{-6} eV^4$$

$$\beta = 10^{-3} \text{ or } < v_a >= 10^{-3} c$$

$$L_{coh} = \frac{1}{p} \simeq 10^9 eV^{-1} \simeq 200\,m$$

$$t_{coh} = \frac{1}{E} \simeq 10^{12} eV^{-1} \simeq msec$$

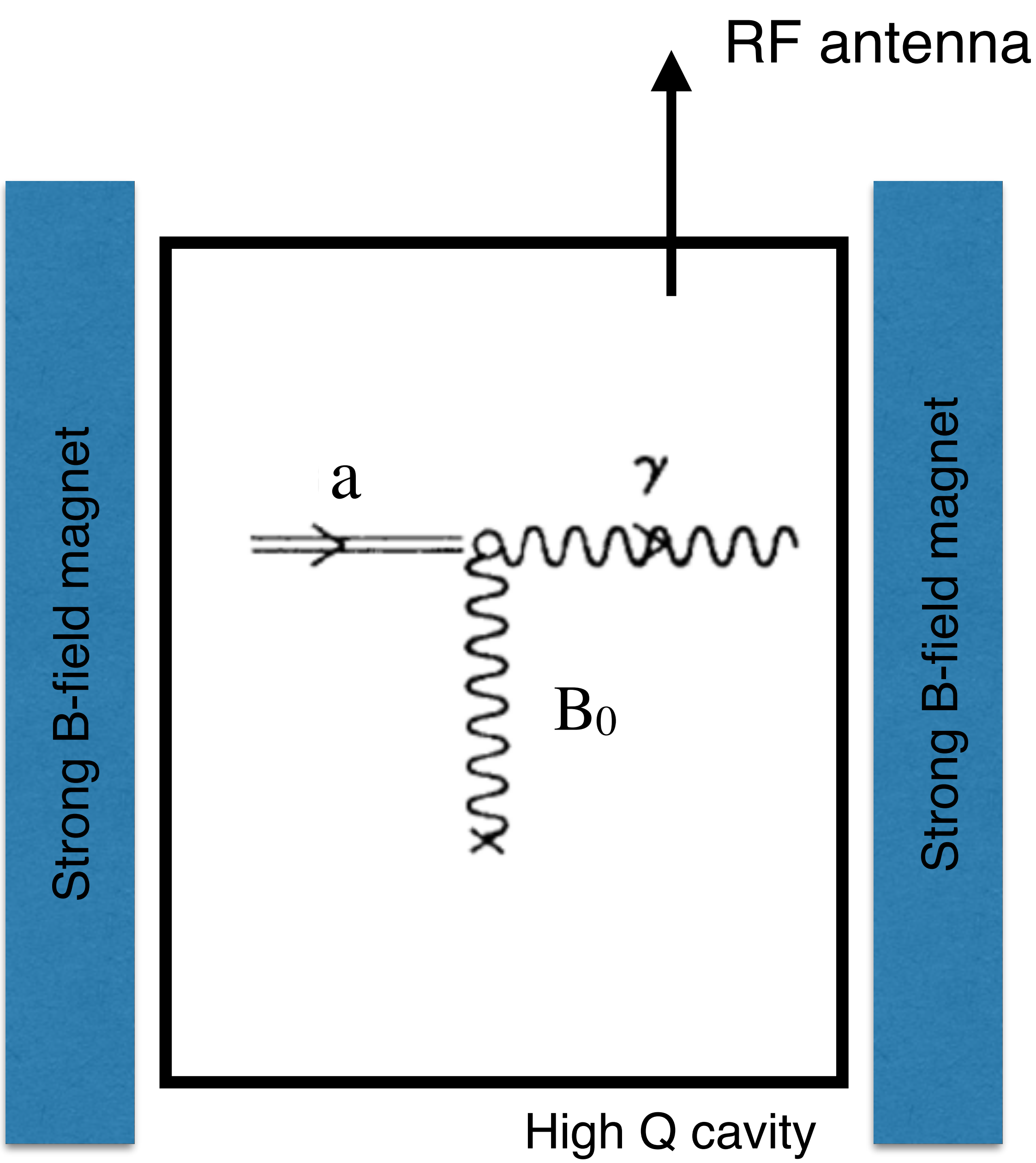
$$\mathcal{L} \equiv -\frac{1}{4} g a F \tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \tilde{F}$$

$$= g a \vec{E} \cdot \vec{B}$$

$$\frac{\partial (\mathbf{E}^2/2)}{\partial t} - \mathbf{E} \cdot (\nabla \times \mathbf{B}) = g_{a\gamma} \dot{a} (\mathbf{E} \cdot \mathbf{B})$$

Oscillating source current ➜ RF photons

RF photon frequency = axion mass



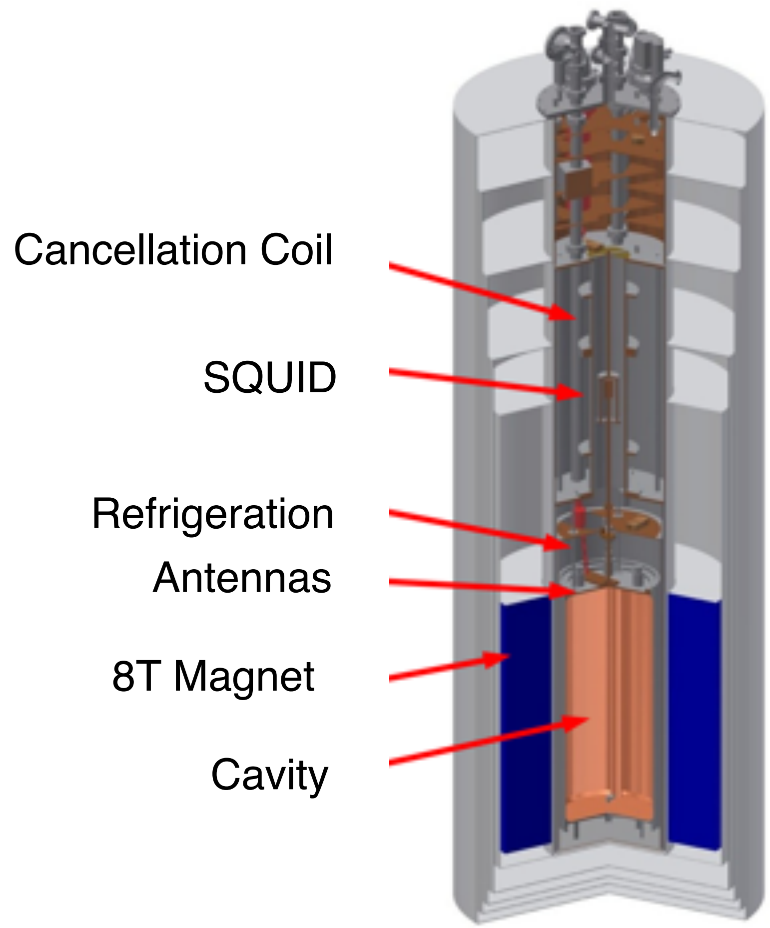
$$P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{cav}, Q_a)$$

~ 10^{-21}W at m_a=μeV

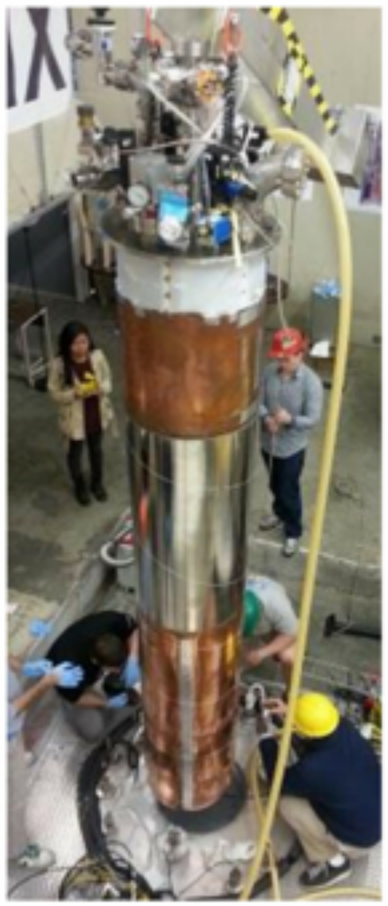
(assuming B=8T, V=0.2 m^3 magnet and cavity Q =10^5)

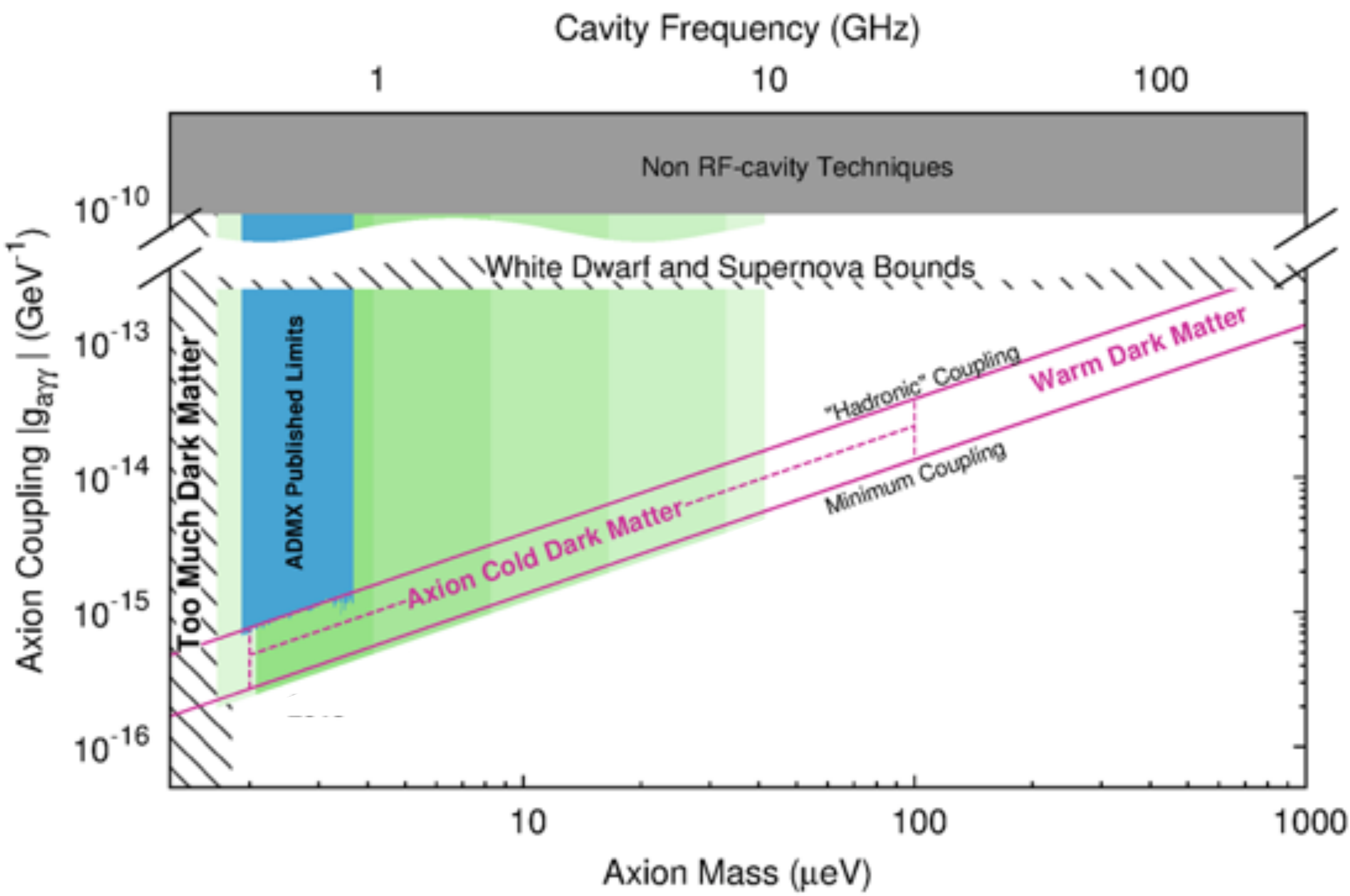
Axion Dark Matter eXperiment (ADMX)

- ADMX collaboration (hosted at the University of Washington)
- “Currently” the world most sensitive dark matter axion search experiment
- The experiment started in 1995 — more than 20 years of efforts
- Relatively low magnetic field (8Tesla) but large volume (140 liter, Q~80,000)
- Probing low mass (~μeV) axions
- The collaboration is upgrading the system to improve the scanning speed of the axion mass

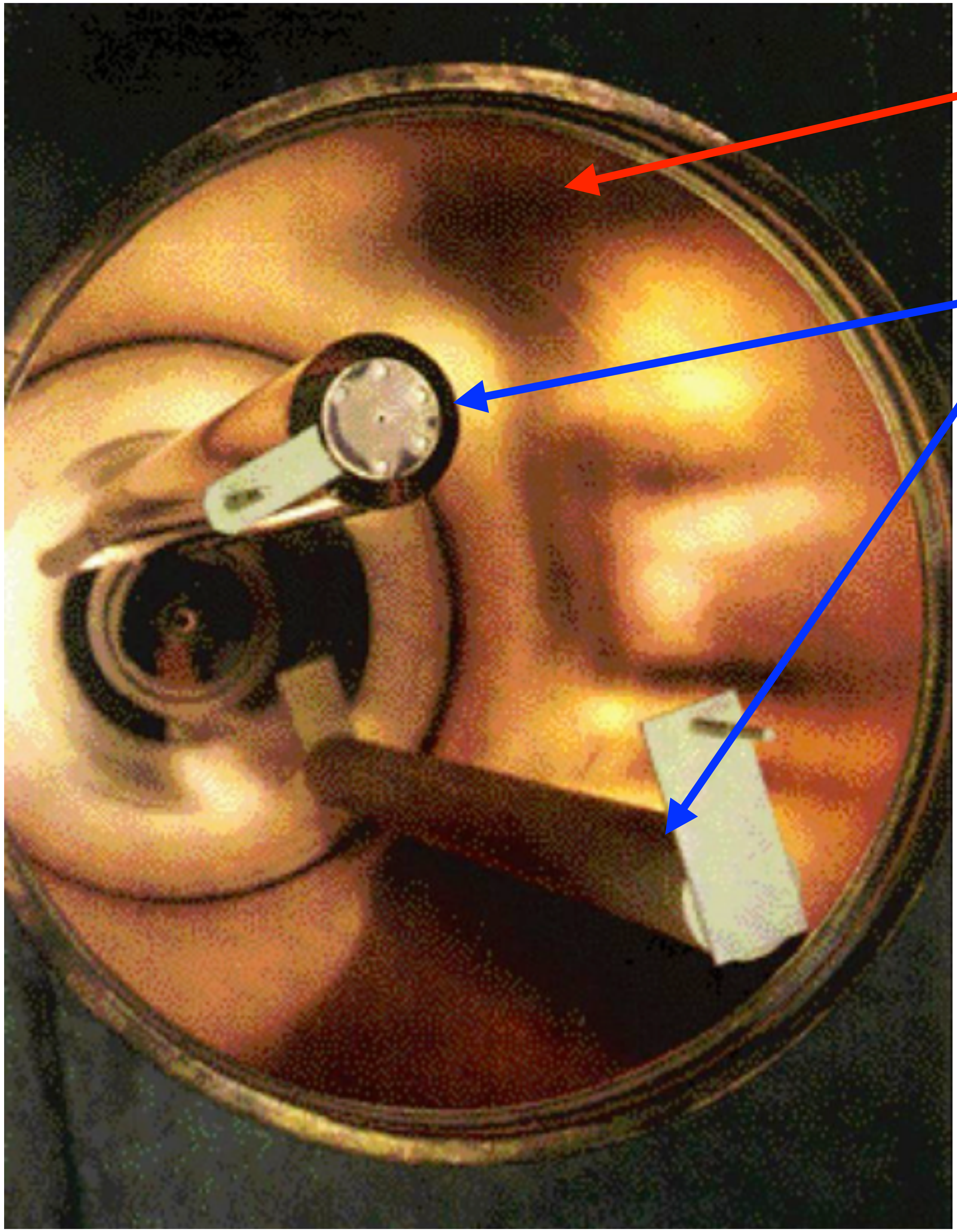


Insert + Magnet Schematic


Insert extraction from magnet

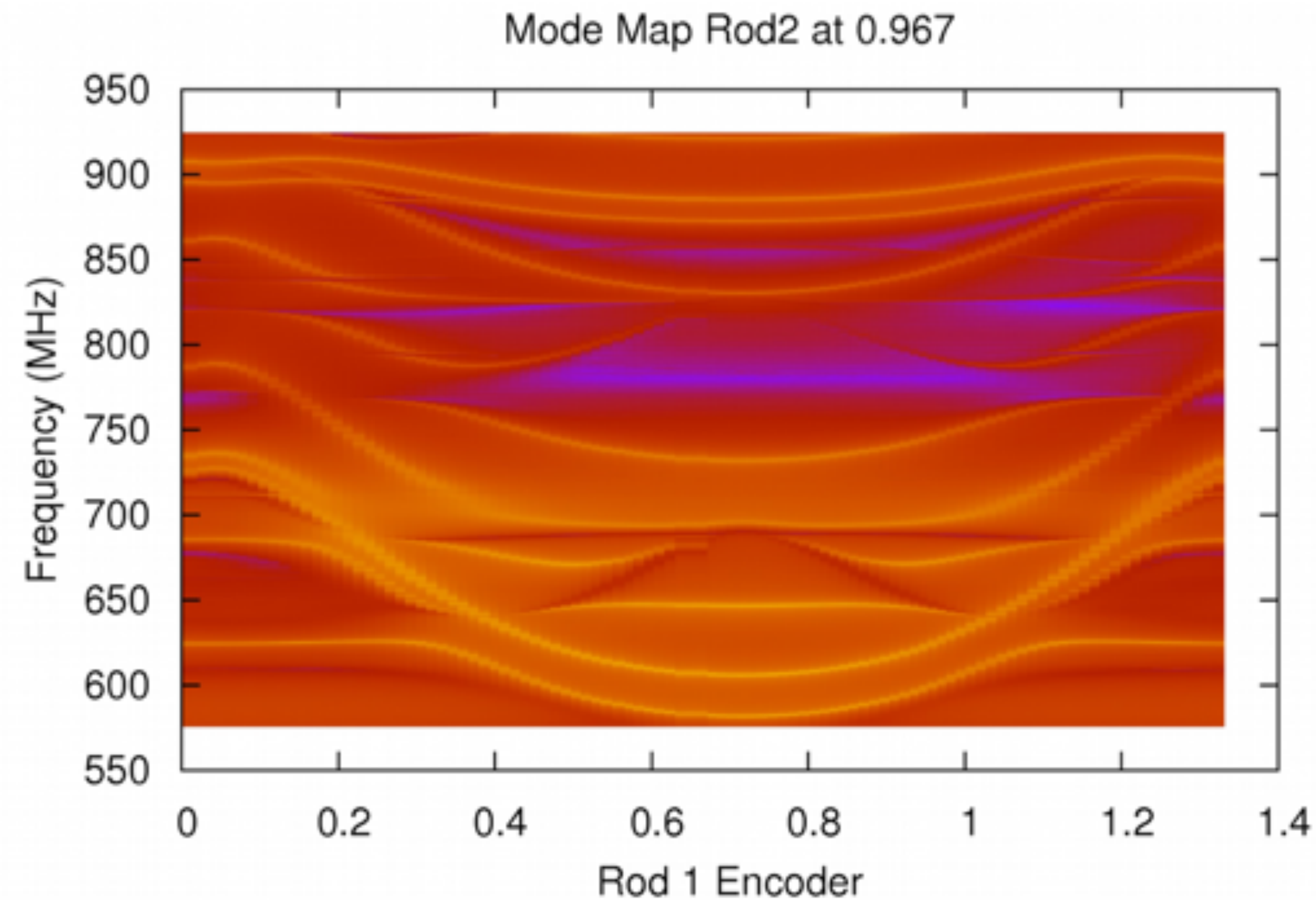


RF Receiver: High-Q Cavity

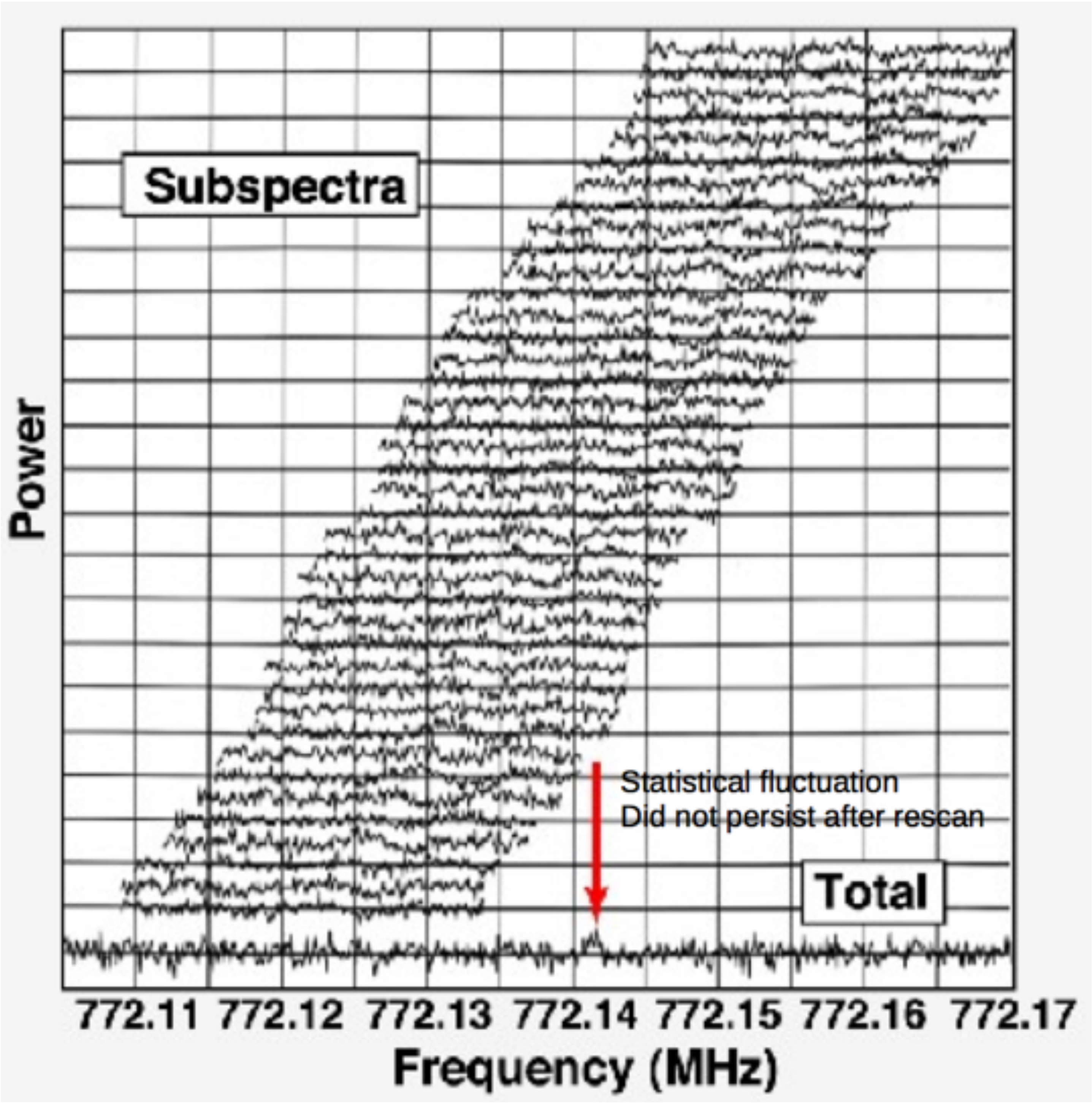


High-Q copper cavity (Q~200,000)

the cavity resonance frequency
is tuned by changing
the two movable rods



ADMX: Power Spectra Scan



Power spectra are measured at each position of rod

If $P_{signal} < P_{noise}$

➜ Average over many measurements to detect the small signal

Integration time for radiometer

$$t_{\mathrm{tune}} = \left(\frac{P_{\mathrm{noise}}}{P_{\mathrm{signal}}}\right)^2 \times \frac{1}{\Delta f}$$

Assume a signal bandwidth of 1kHz, and probe frequency range of 800MHz (3.3μeV) to 900MHz (3.7μeV). 5-minutes per each frequency ➜ takes **1-year**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통영
제주도
울릉도
독도
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(West Sea)
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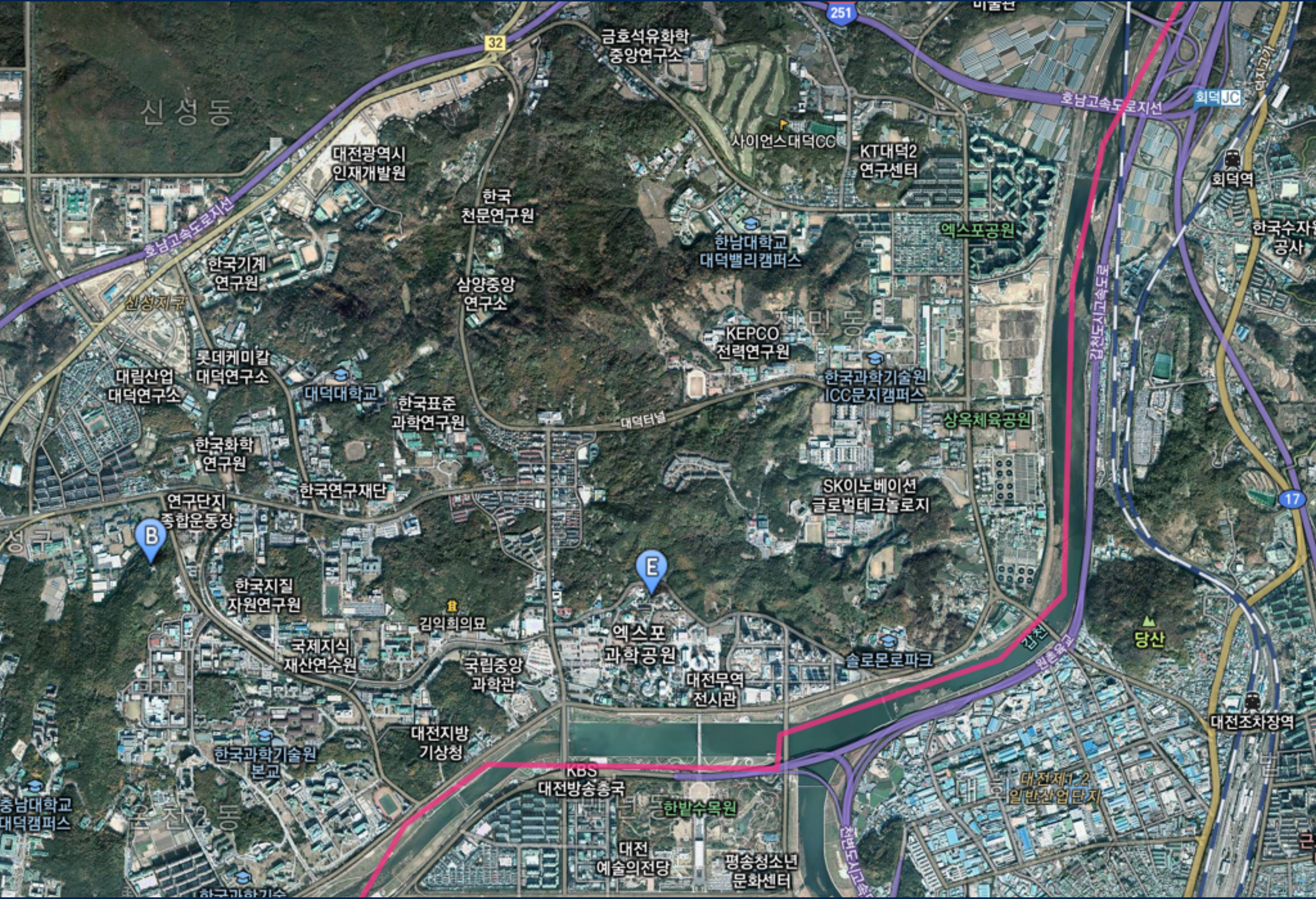
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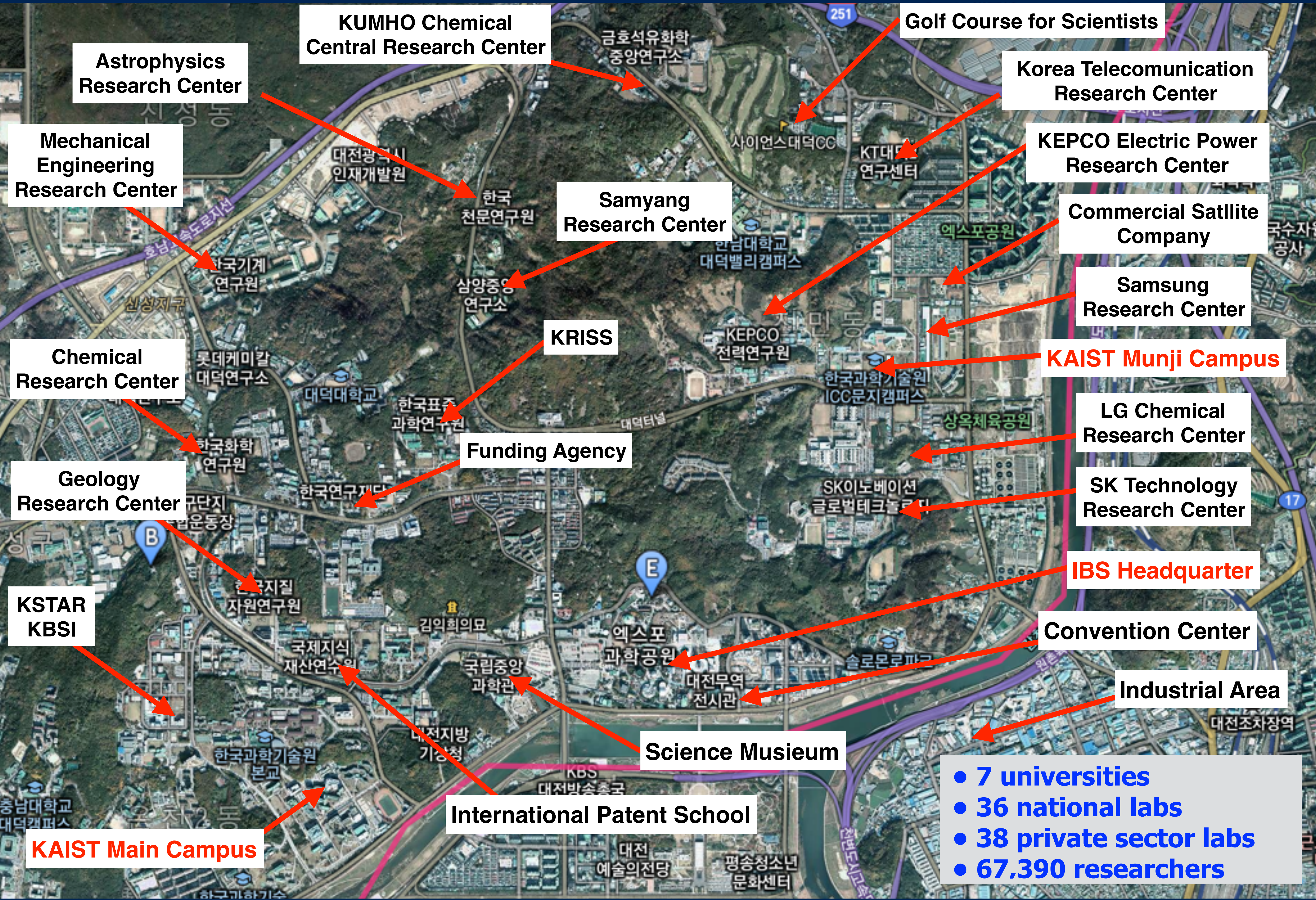
Daejeon



- 7 universities
- 36 national labs
- 38 private sector labs
- 67,390 researchers

Institute for Basic Science (IBS)

IBS Headquarter (Daejoen by 2018)

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

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

Expected HR
- 20 research fellows
- 20 graduate students
- 10 staffs
- Engineers/technicians
- Visiting scholars

CAPP/IBS at KAIST launched in October 2013

CAPP's Dark Matter Axion Search Strategy

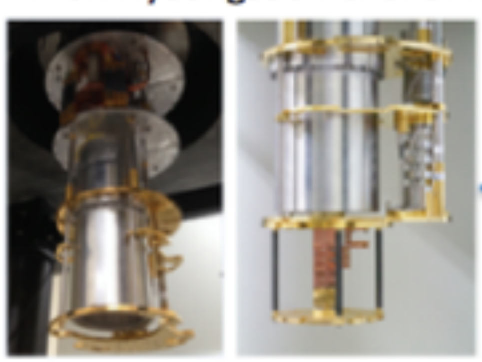
Strong manetic field (18T → 25T → 35T)

$$\frac{df}{dt} = \frac{70\,\mathrm{MHz}}{\mathrm{year}}\left(\frac{4}{[s/n]}\right)^2\left(\frac{\mathrm{V}}{10\ l}\right)^2\left(\frac{\mathrm{B}_0}{10\ \mathrm{T}}\right)^4 \times C^4\left(\frac{g_a}{0.36}\right)^4\left(\frac{\rho_a}{0.3\,\mathrm{GeV/cc}}\right)\left(\frac{1\,\mathrm{K}}{\mathrm{T}_n}\right)^2\left(\frac{f}{\mathrm{GHz}}\right)^2\left(\frac{\mathrm{Q}}{\mathrm{Q}_a}\right)$$

Lower the termal noise temperature (cryogenics & low noise amplifier)

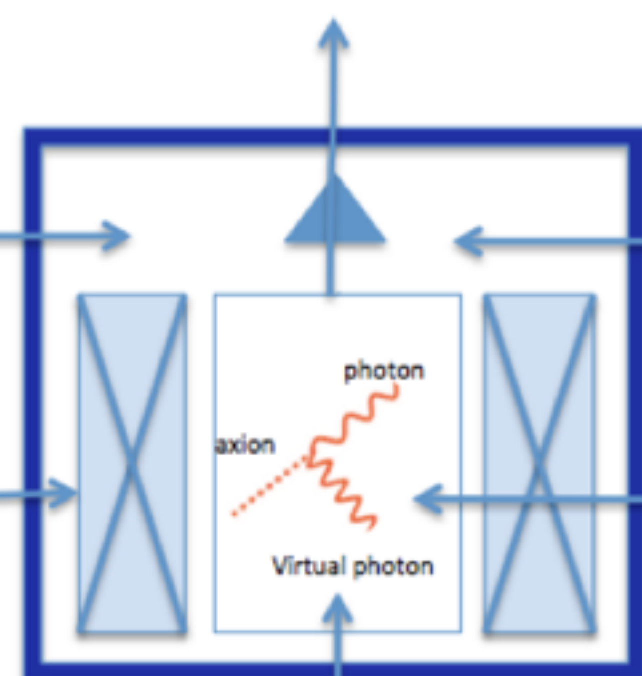
Superconducting cavity (Q~10⁷)

Cryogenics
<100mK
Prof. Hyoungsoon Choi of KAIST



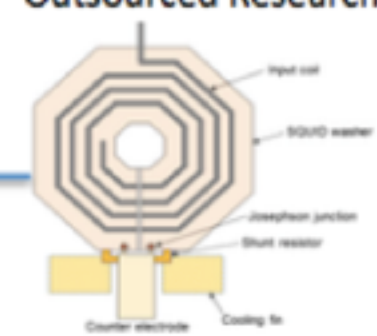
High Field SC Magnet
25T and then 35T or 40T
BNL (HTS Technology) Design

To RF Receiver

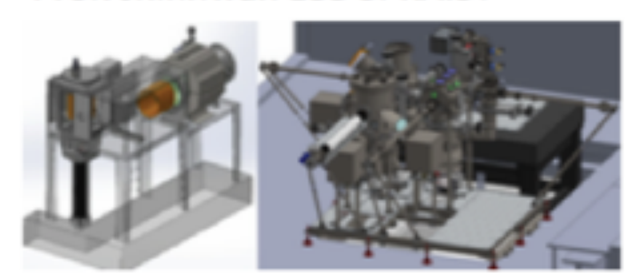


(Reverse) Primakoff Effect

SQUID Amplifier
Outsourced Research from KRISS



High Q Tunable Cavity
Superconducting Coating
Prof. Jhinhwan Lee of KAIST



Reduce Termal Noise

Improve scan speed

$$\frac{dm_a}{dt} \propto \left(\frac{B_0^2 V}{T_N}\right)^2$$

$T_N = T_{amplifier} + T_{physics}$

$$kT_N = h\nu\left(\frac{1}{e^{h\nu/kT}-1} + \frac{1}{2}\right) + kT_A$$

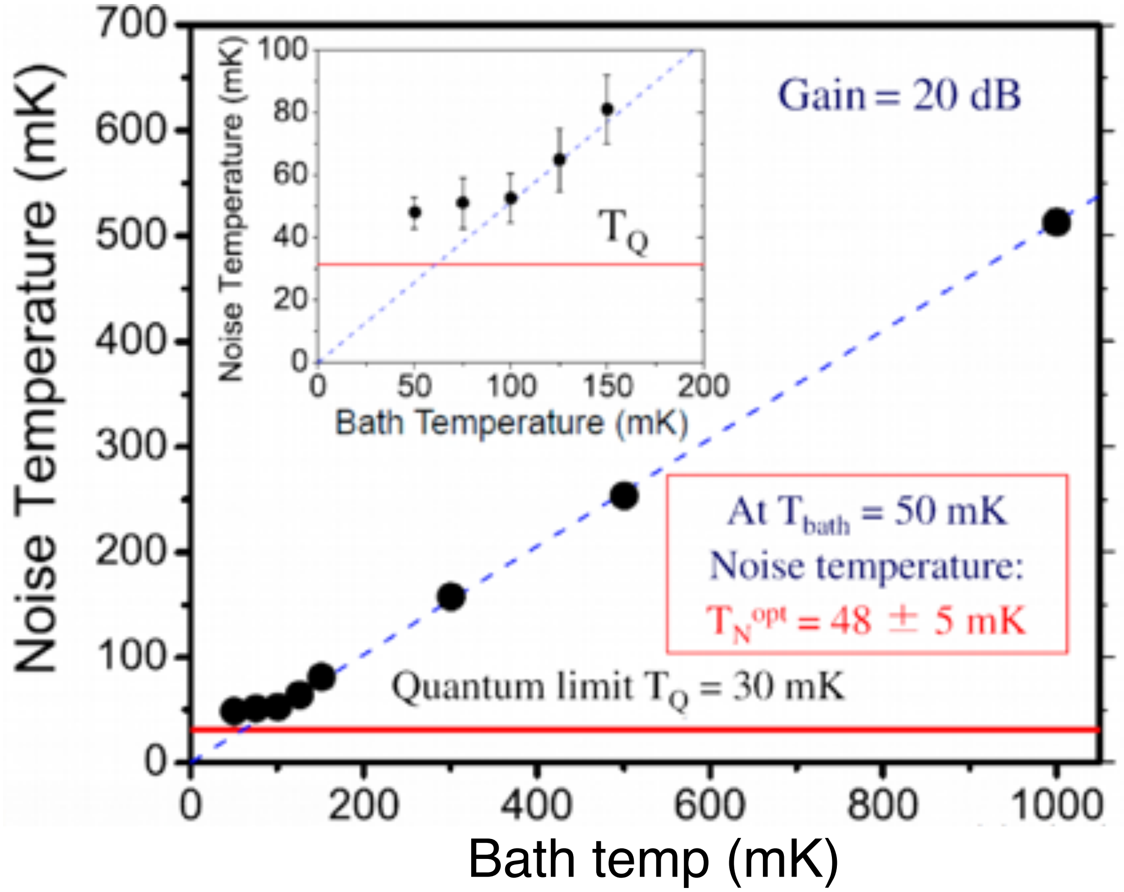
Run colder to reduce thermal noise!

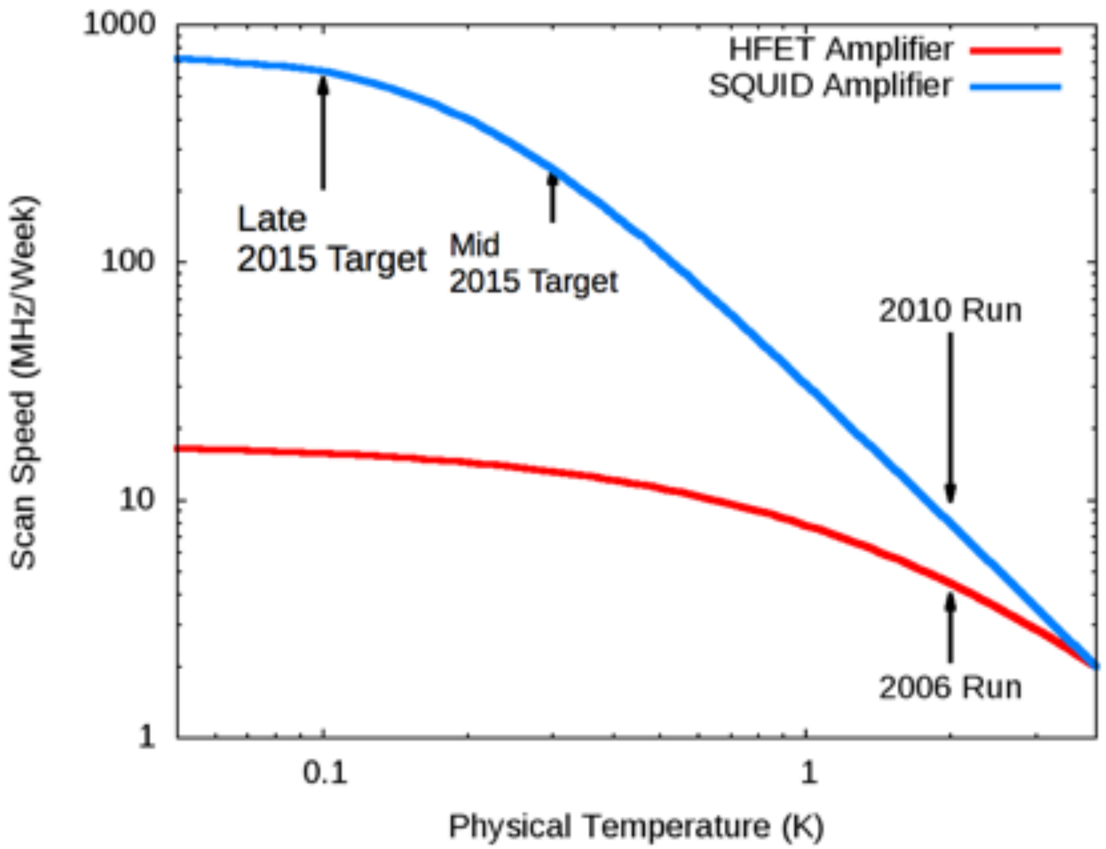
➜ Use dilution refrigerator (~50mK)
➜ Quantum limited amplifiers
- **Microstrip SQUID Amplifier (<1GHz)**
- **Josephson Parametric Amplifier (>1GHz)**

The scan-speed can be improved by factor >100

Collaboration with KRISS SQUID group

J. Clarke





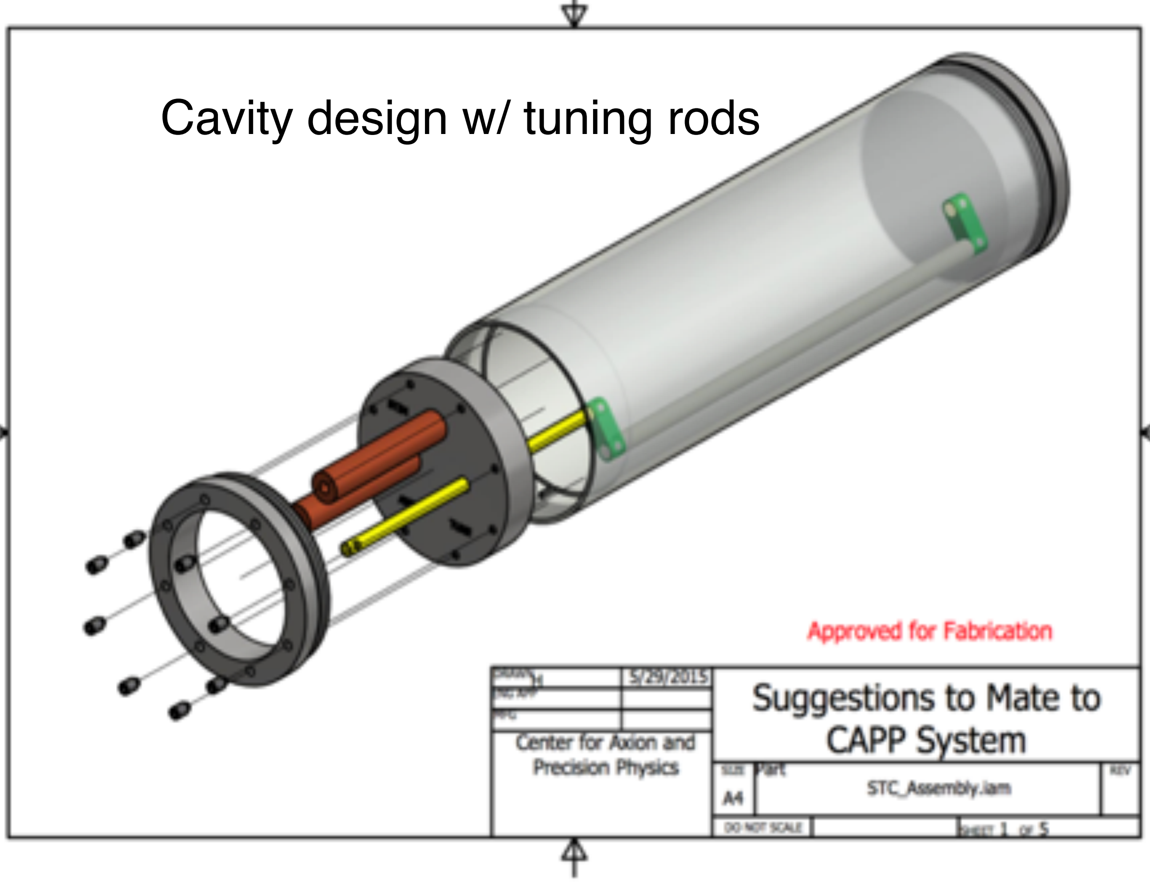
Cavity R&D

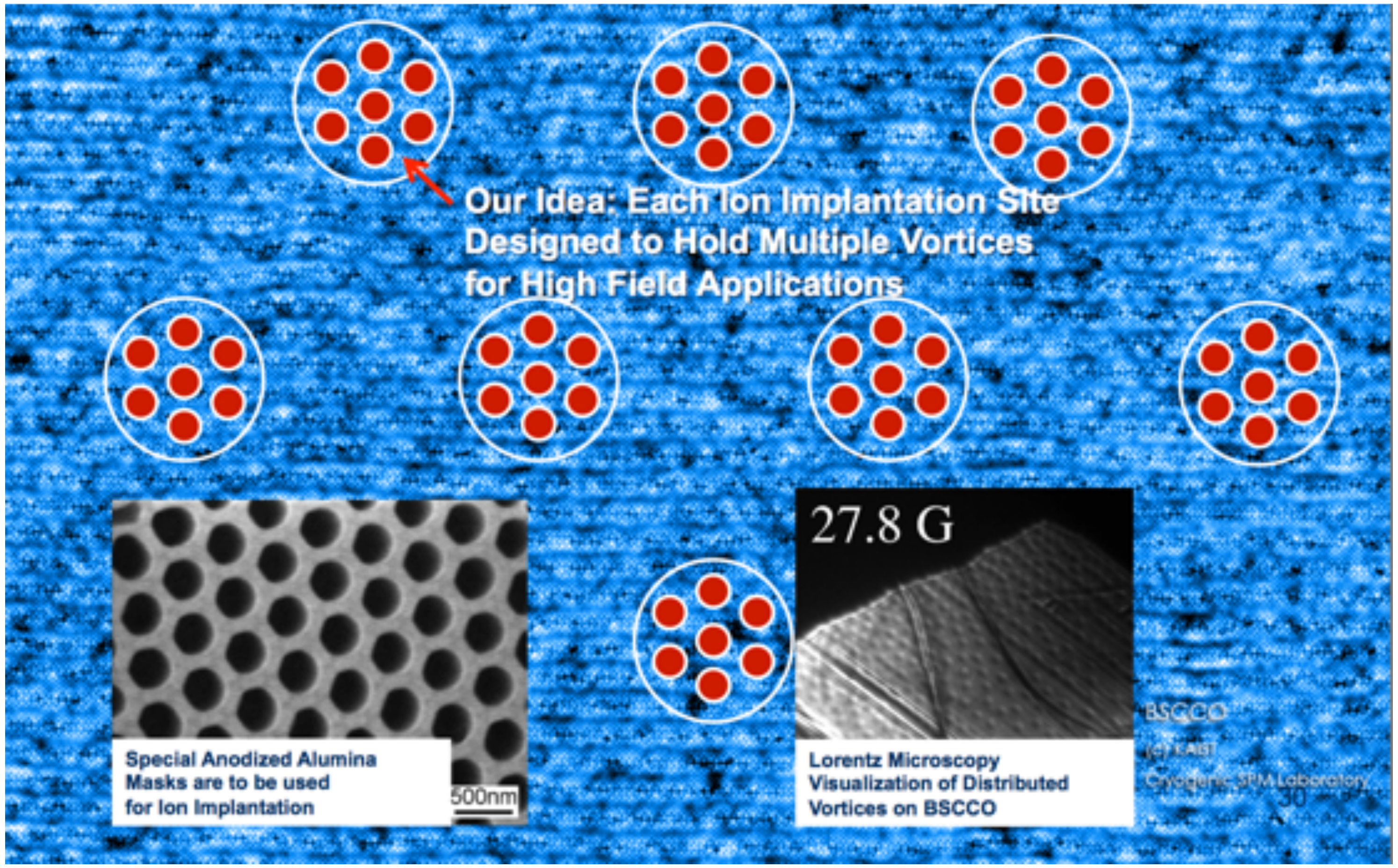
Developing High Q-Factor Cavity

- Sputtering pure Cu and Al (Munich)
- Pure Cu and Al sheet roll in side stainless steel (Seoul)
- Tuning system and frequency mode simulation
- R&D program for Superconducting cavity

Cavity test in dilution refrigerator

- Design to achieve cavity temperature of <100mK
- Integrate Piezo Actuator(s)
- Monitoring, Control and Measurement
- Magnetoresistance study



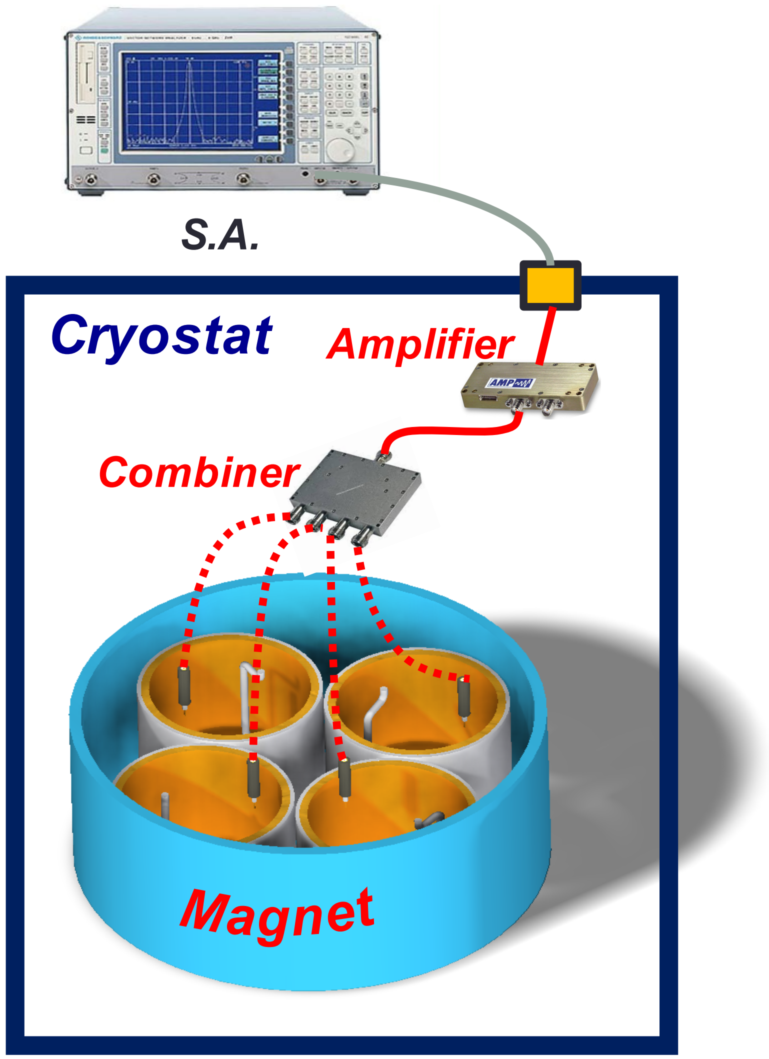


SC doped cavity using novel vortex engineering ($Q \sim 10^7$): Prof. Jihnwhan Lee at KAIST is making a huge progress

Multiple cavity R&D: probe higer frequencies with a large bore magnet

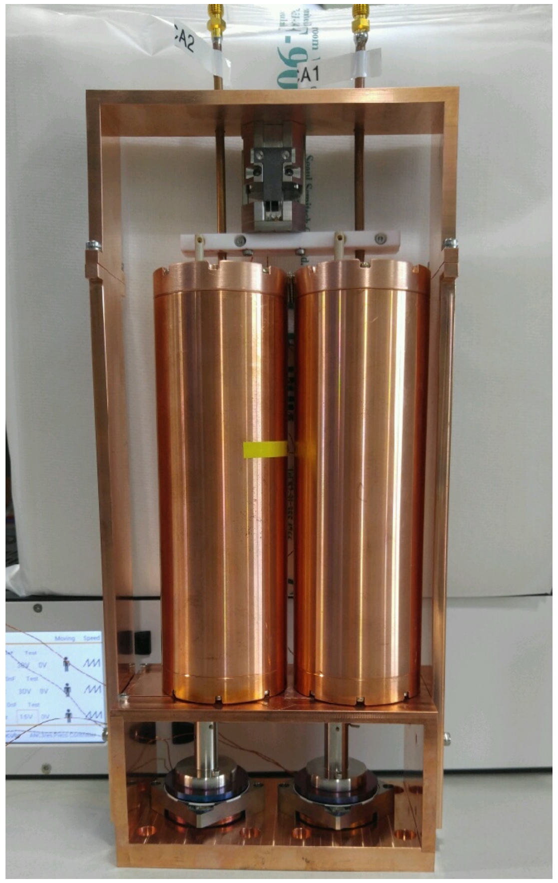
Toroid style cavity R&D: No endcap, huge gain in volume and achive high Q-value

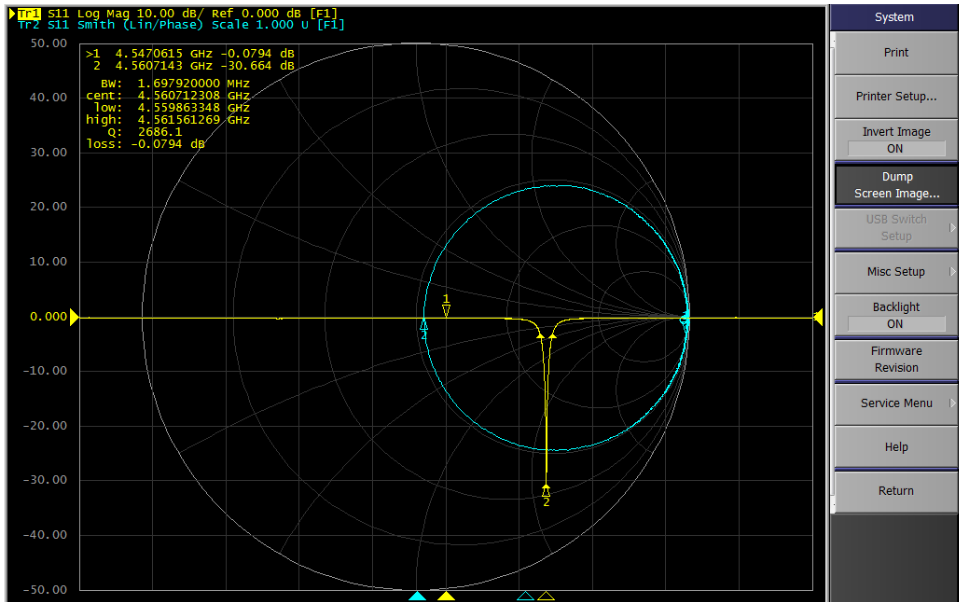
Multiple Cavity System R&D

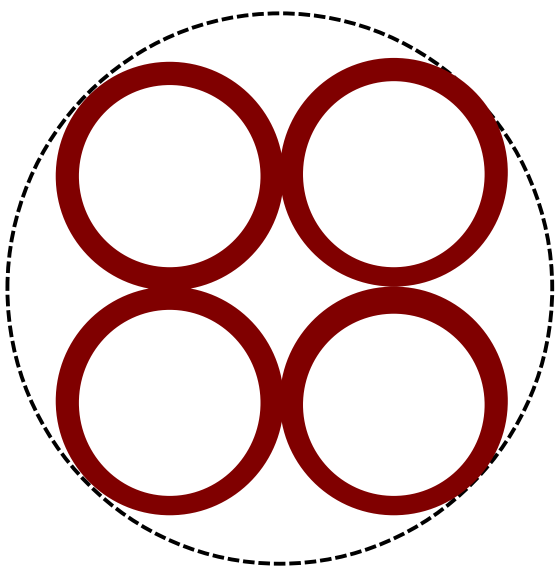


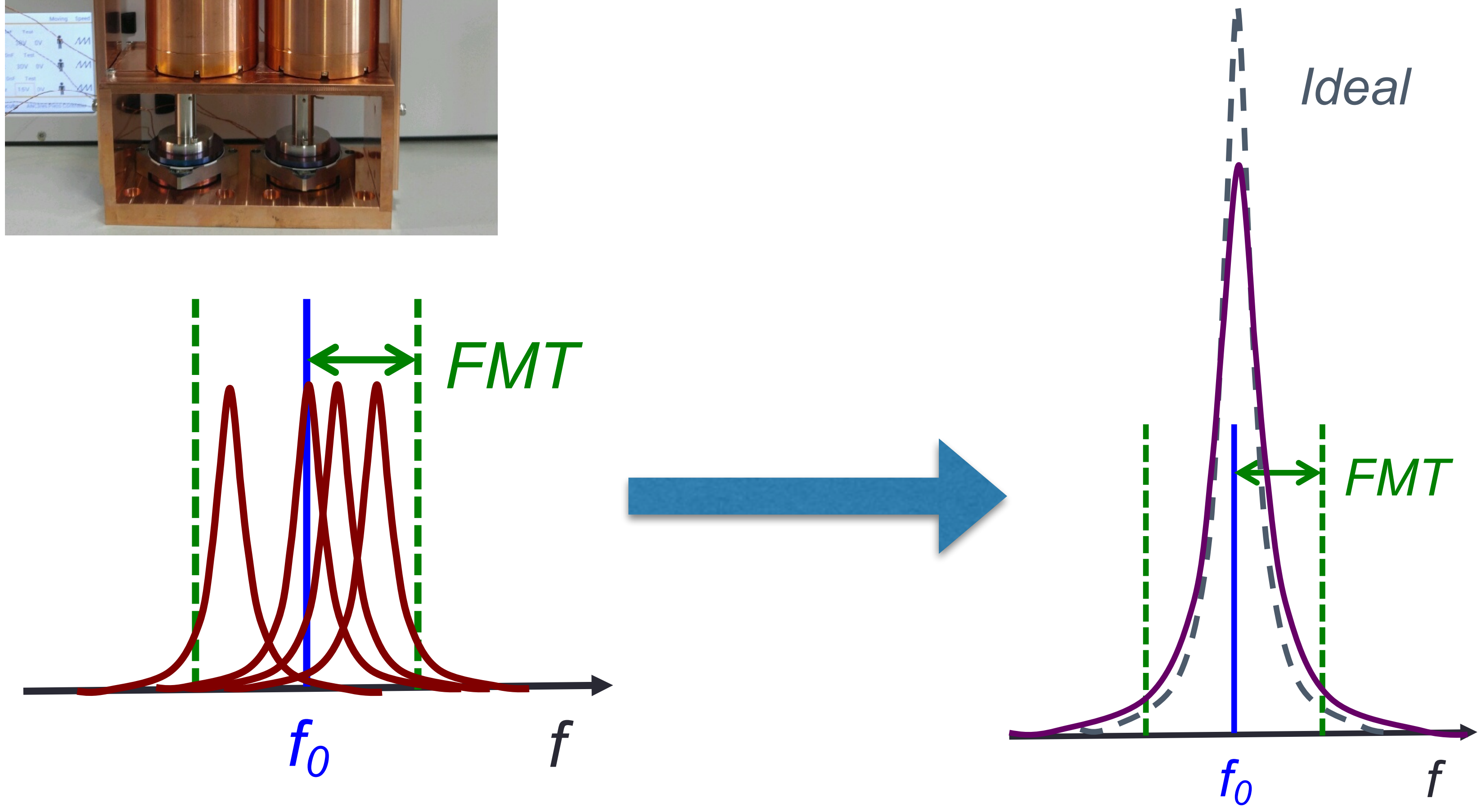
Multiple-cavity detector

- Increase experimental sensitivity at HF regions
- Requres siganl combination in phase (phase matching)

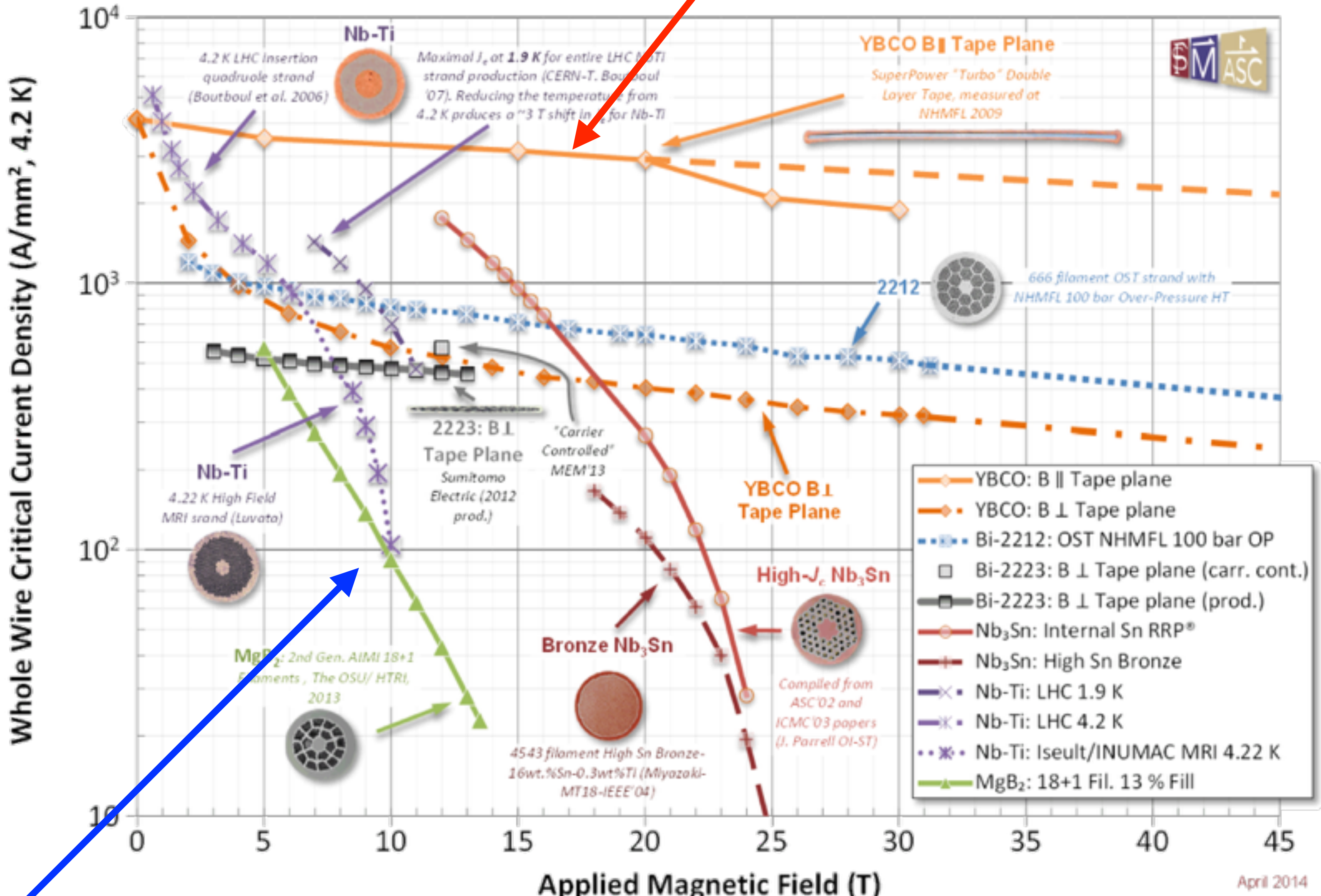








Future technology HTS tech.



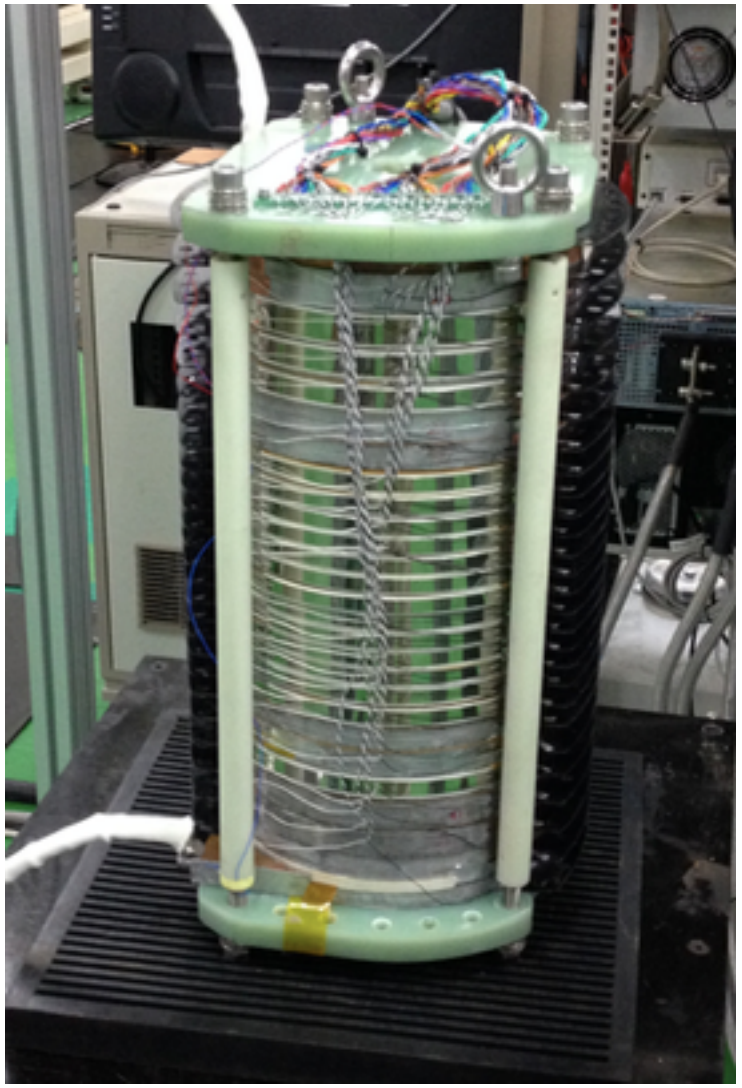
Conventional LTS tech.

A world record of 26.4T B-field (25mm bore)
2G HTS magnet by a Korean Company (SuNAM Co. Ltd)

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **29** (2016) 04LT04 (6pp) doi:10.1088/0953-2048/29/4/04LT04

Letter

26T 35mm all-$GdBa_2Cu_3O_{7-x}$ multi-width no-insulation superconducting magnet



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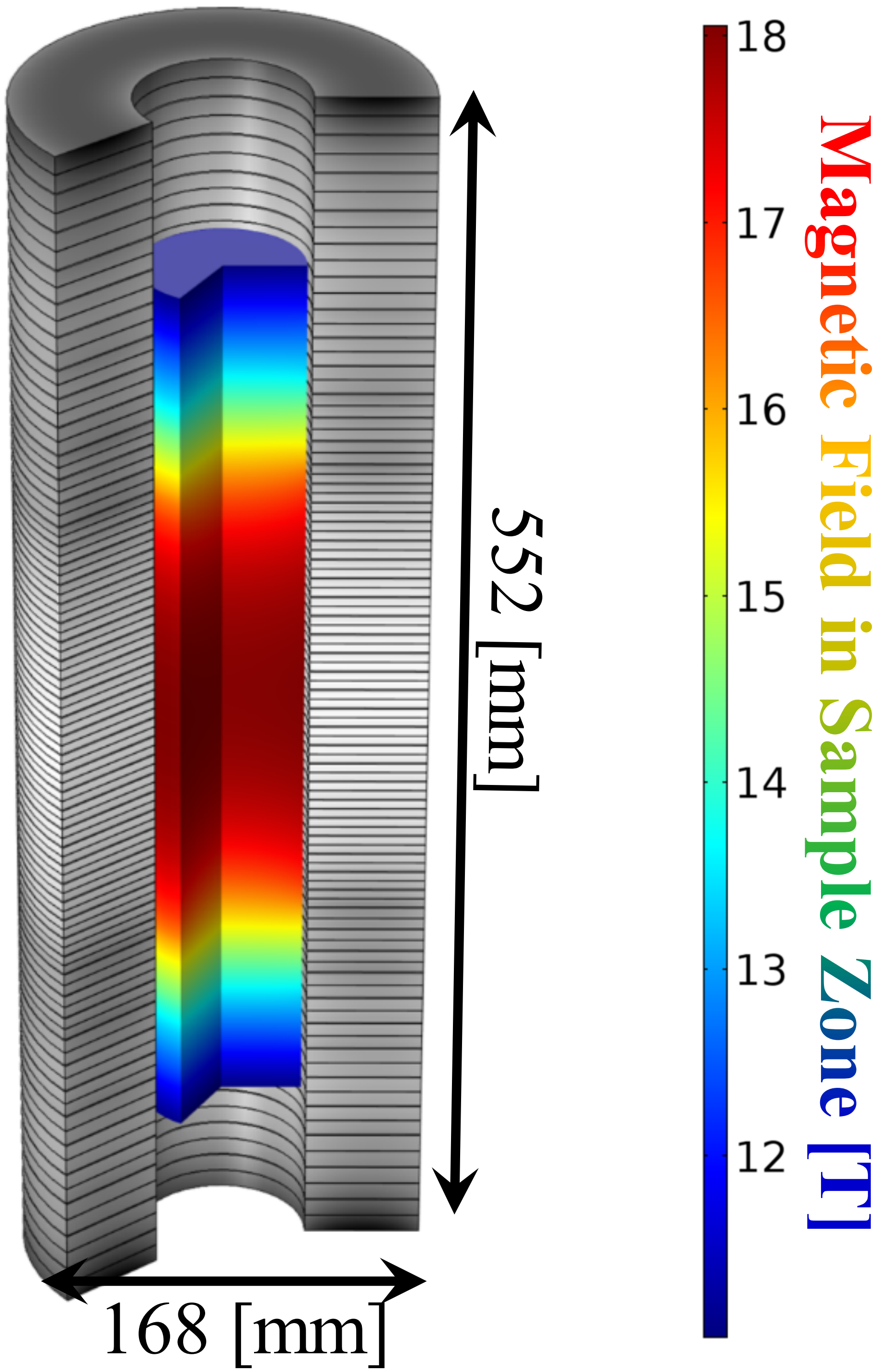
Received 28 July 2015, revised 22 December 2015
Accepted for publication 24 December 2015
Published 10 March 2016

CrossMark

Abstract

A 26 T 35 mm winding diameter all-$GdBa_2Cu_3O_{7-x}$ (GdBCO) magnet was designed by the MIT Francis Bitter Magnet Laboratory, and constructed and tested by the SuNAM Co., Ltd. With the multi-width (MW) no-insulation (NI) high temperature superconductor (HTS) winding technique incorporated, the magnet is highly compact; its overall diameter and height are 172 and 327 mm, respectively. It consists of a stack of 26 NI double pancake coils wound with MW GdBCO tapes in five different widths ranged 4.1–8.1 mm. In a bath of liquid nitrogen at 77 K, the magnet had a charging time constant of 16 min due to the intrinsic NI characteristics. In liquid helium at 4.2 K, the magnet generated a 26.4 T field at the center, a record high in magnetic fields from all-HTS magnets. The results demonstrate a strong potential of MW-NI GdBCO magnets for direct current high-field applications.

Magnet (18T/7cm HTS Magnet)



A strong B-field and large bore HTS magnet is commercially available by the Korean company

2G HTS Superconducting Magnet

Magnetic field : 18 Tesla

Dimension: 70 mm ID / 168mm OD

20 mm uniform field (>90%)

552 mm length

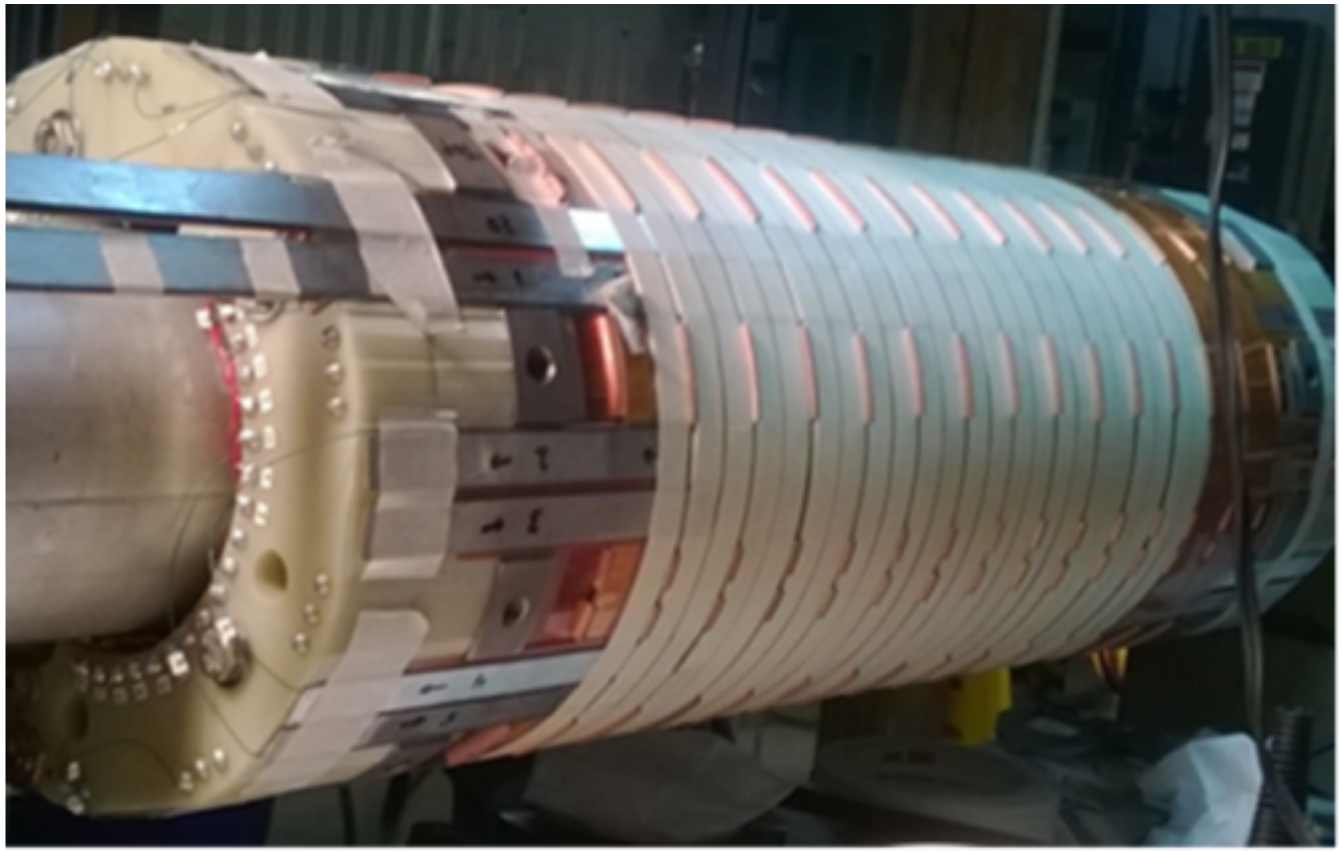
Quench free design (no-insulation)

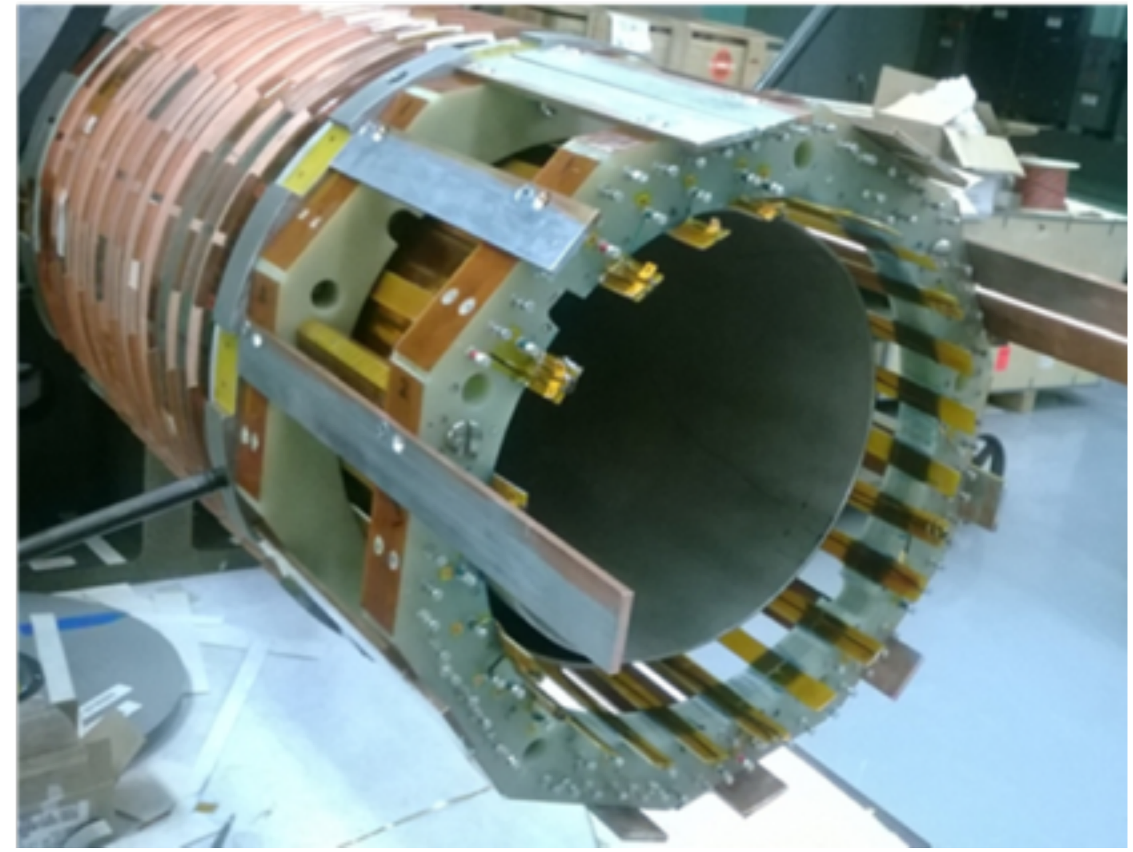
Compact and easy to operate

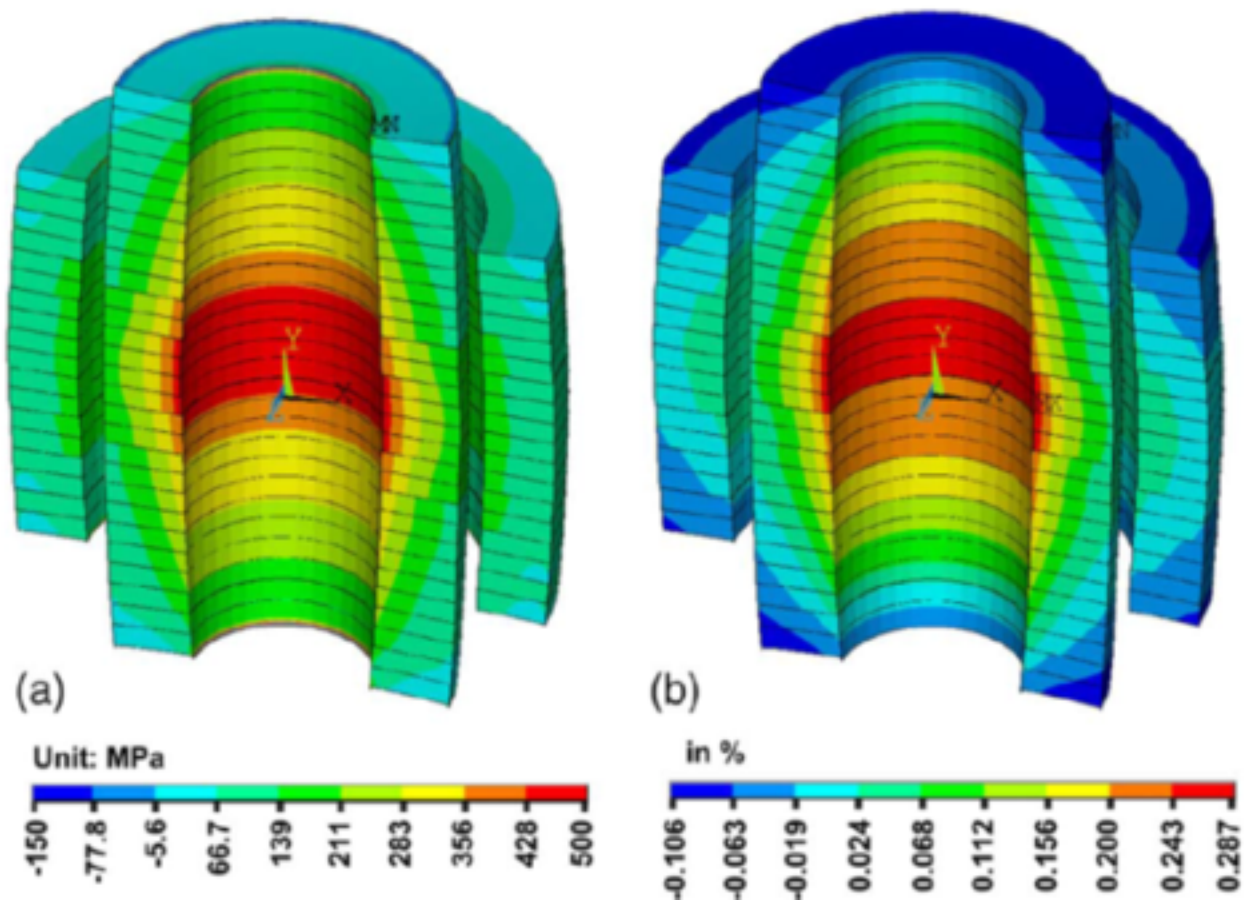
Target DM axion mass range to probe: 14 μeV to 20 μeV range

The experiment will begin by summer 2017

25T HTS Magnet Development at BNL

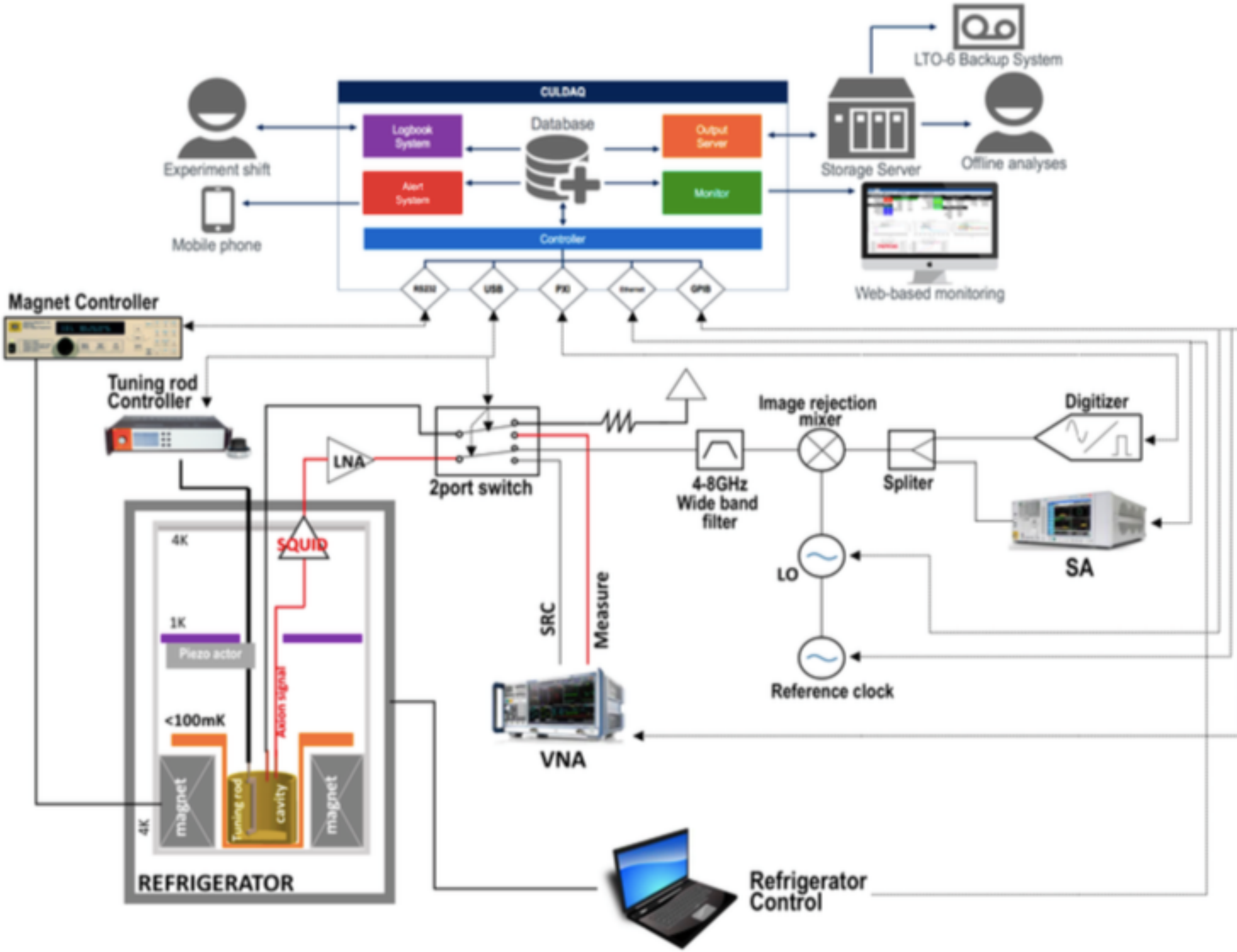




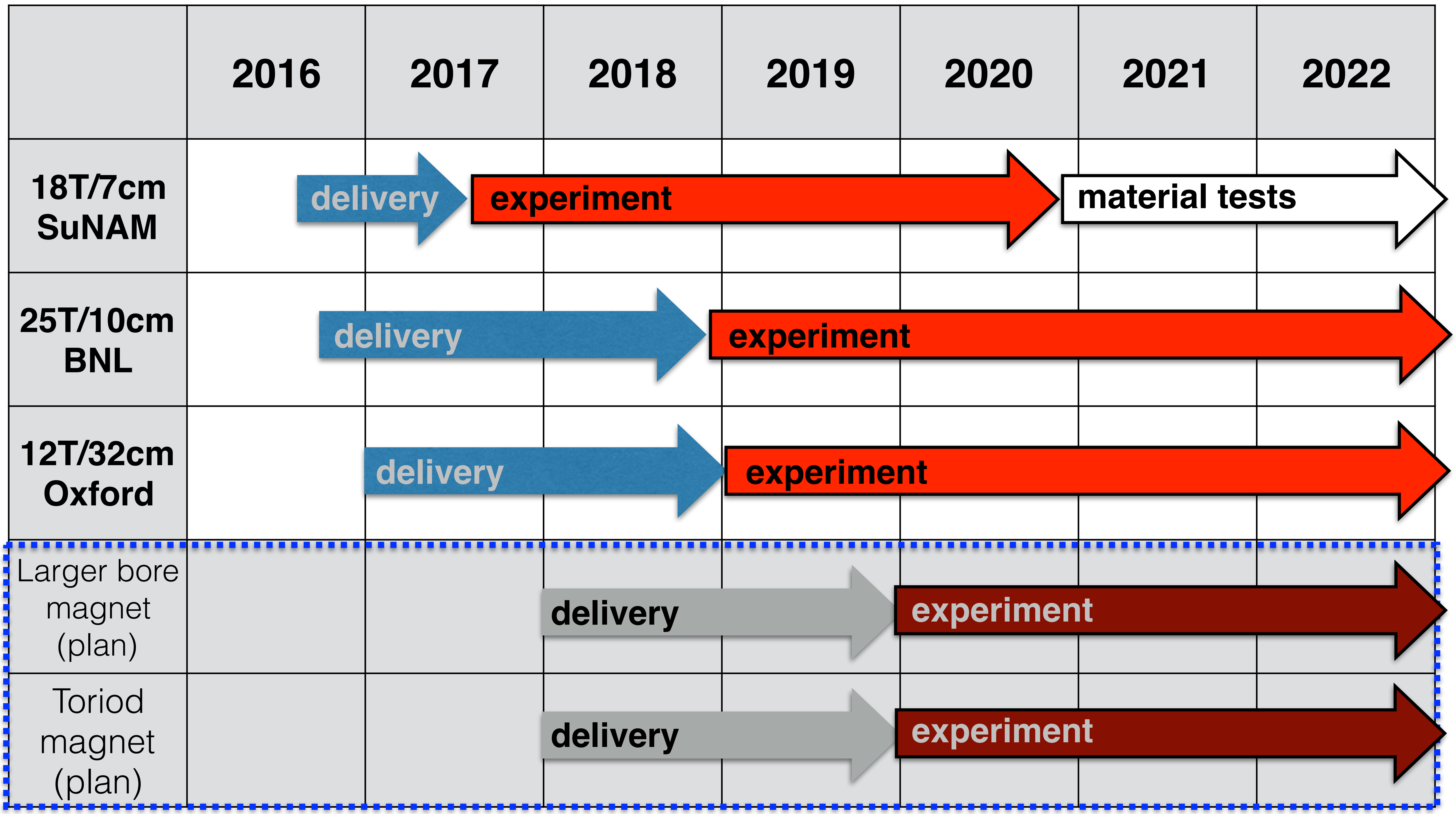


- 25T/10cm large bore magnet
- Probe axion mass above 10μeV
- IBS contract with BNL (progress)
- Production schedule by 2018
- Experiment will start in 2019

CAPP Dark Matter Axion Search Experiment



KAIST Dark Matter Axion Search Schedule



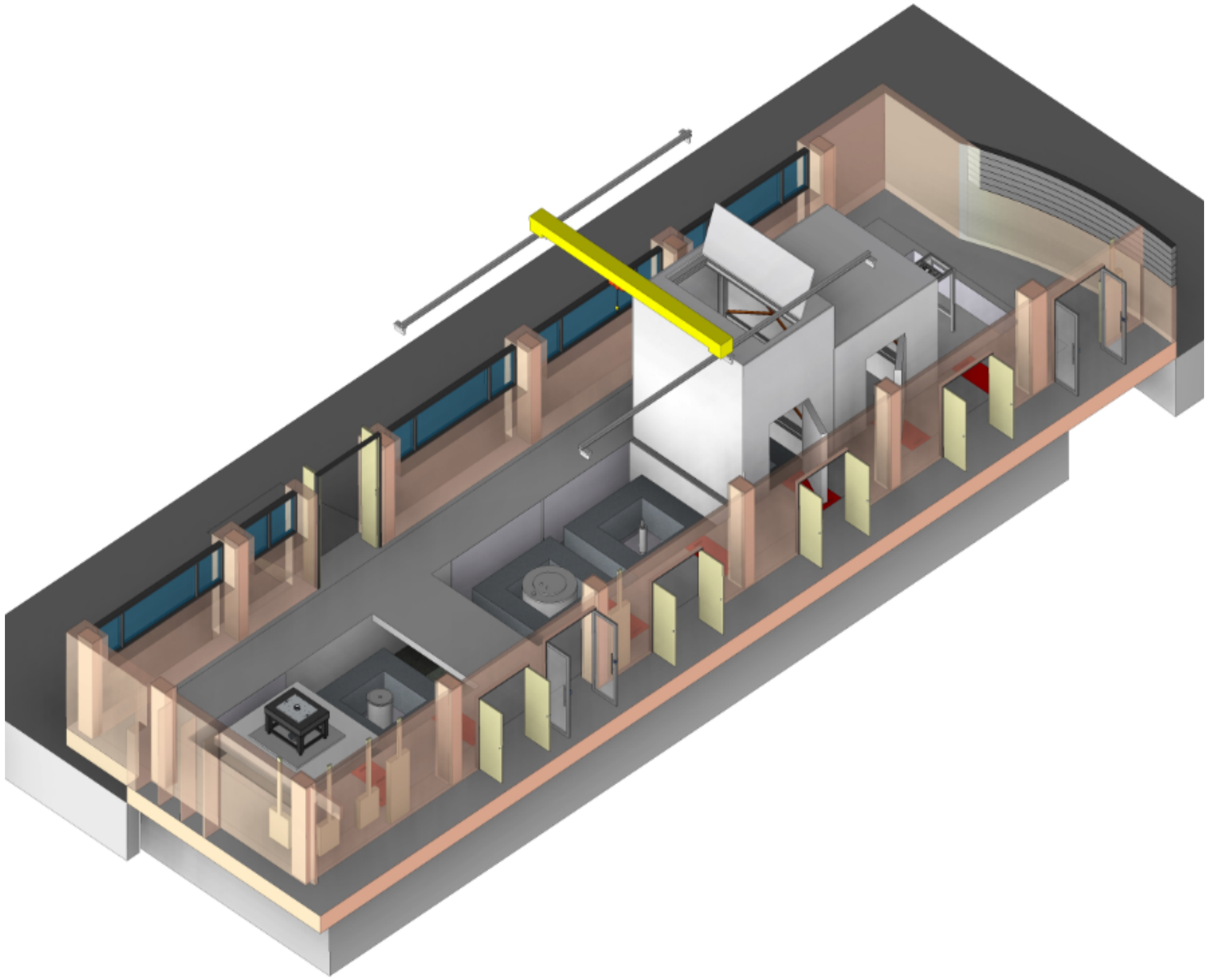
There are research and development efforts for higher mass dark matter axion search experiments above 40 μeV

Experiment Hall

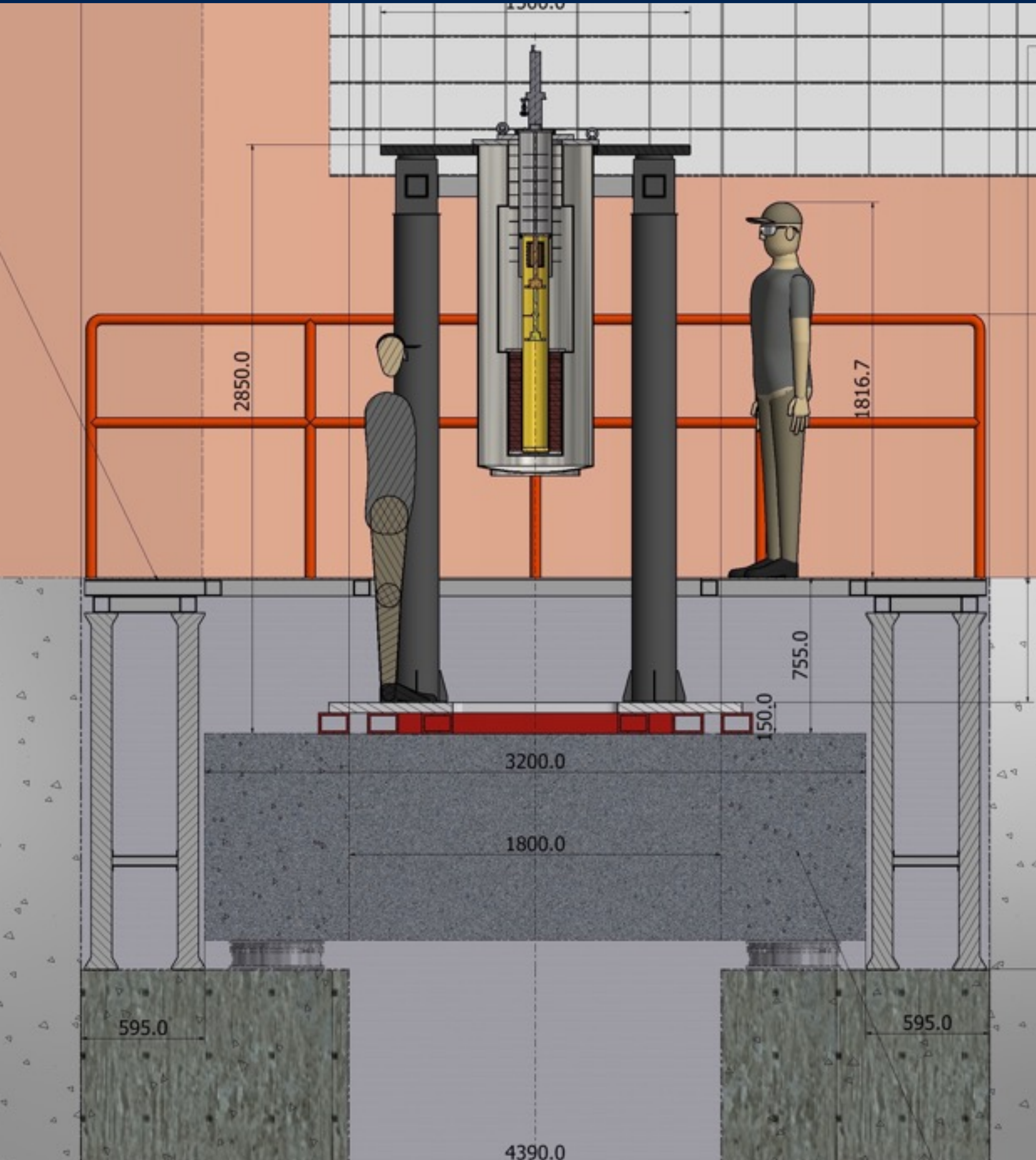
Low vibration facility is ready

The building will be ready in 2016

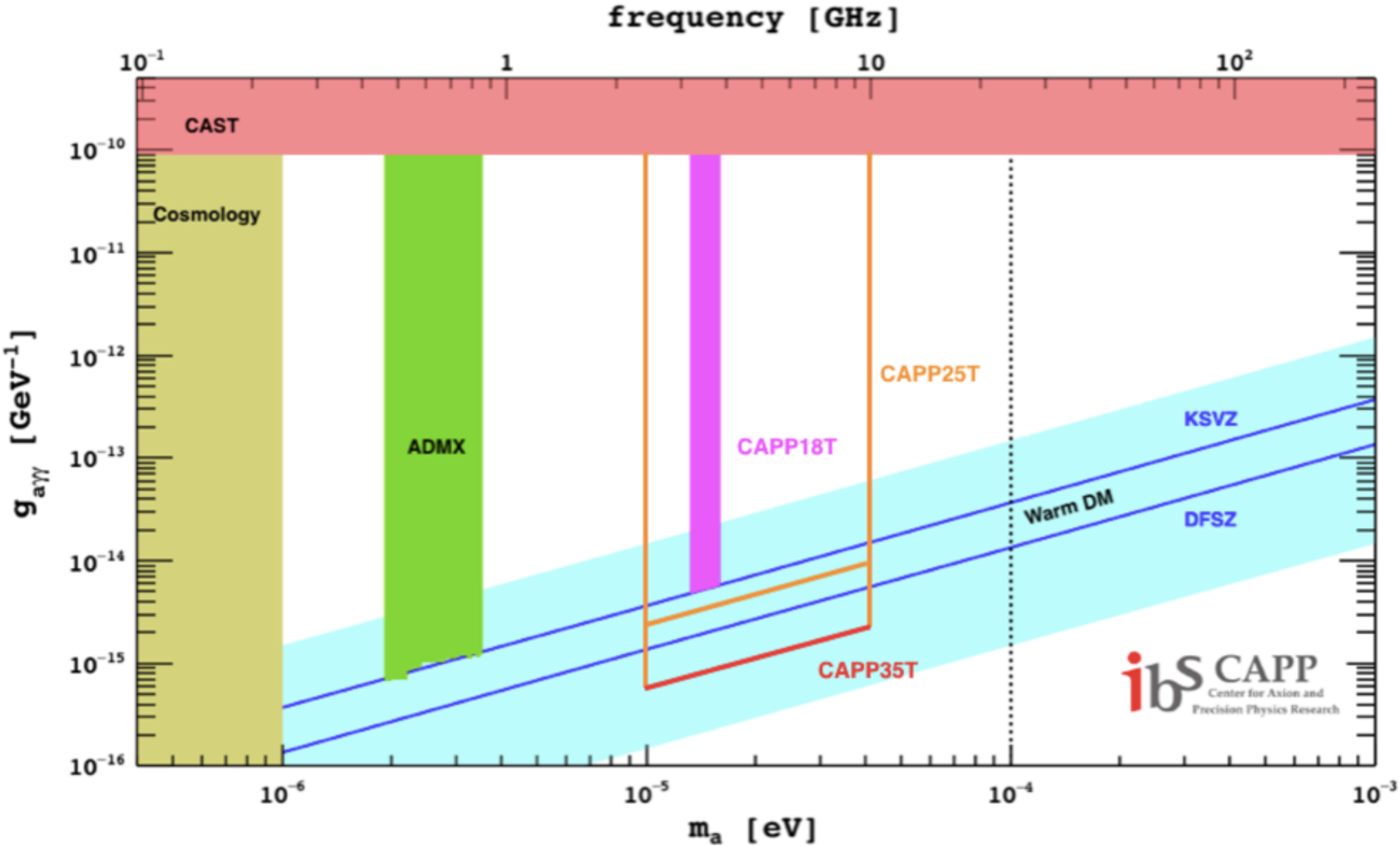
More than five large scale axion search experiments can be hosted and operated



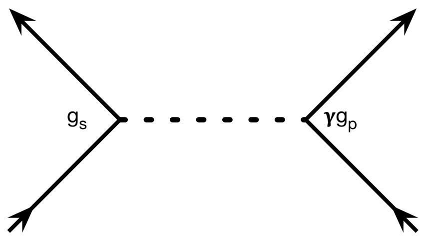
Dilution Refrigerator



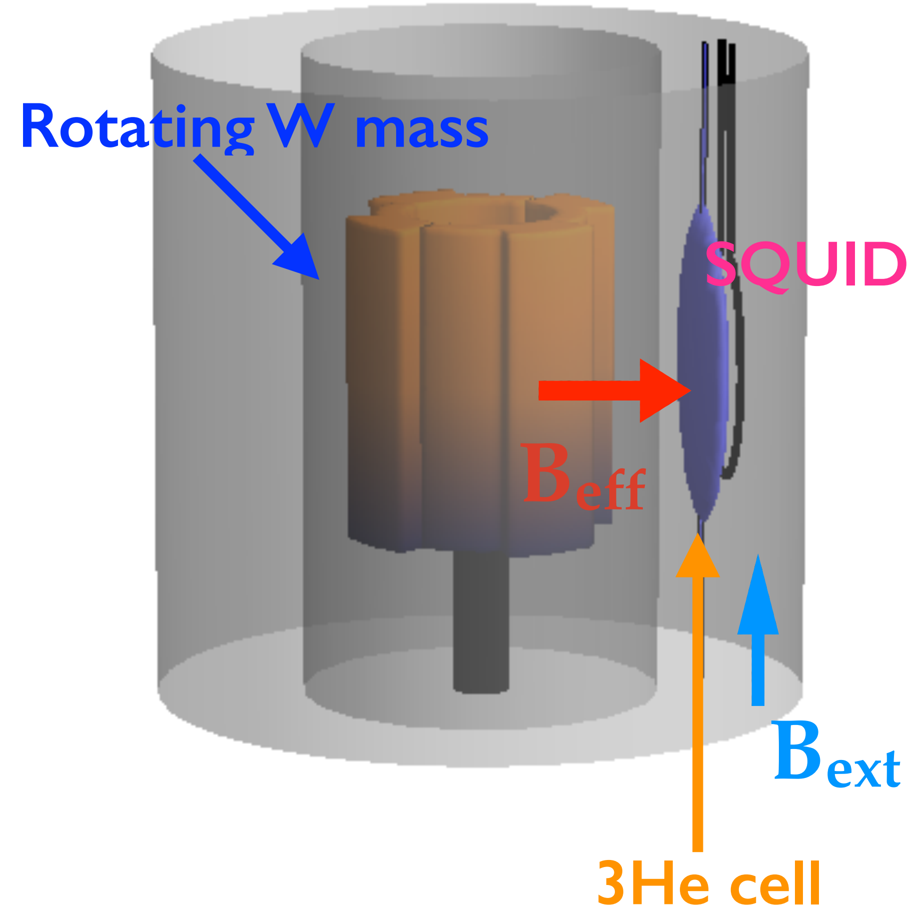
CAPP Axion Dark Matter Search



Long range effective potential by a boson exchange



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



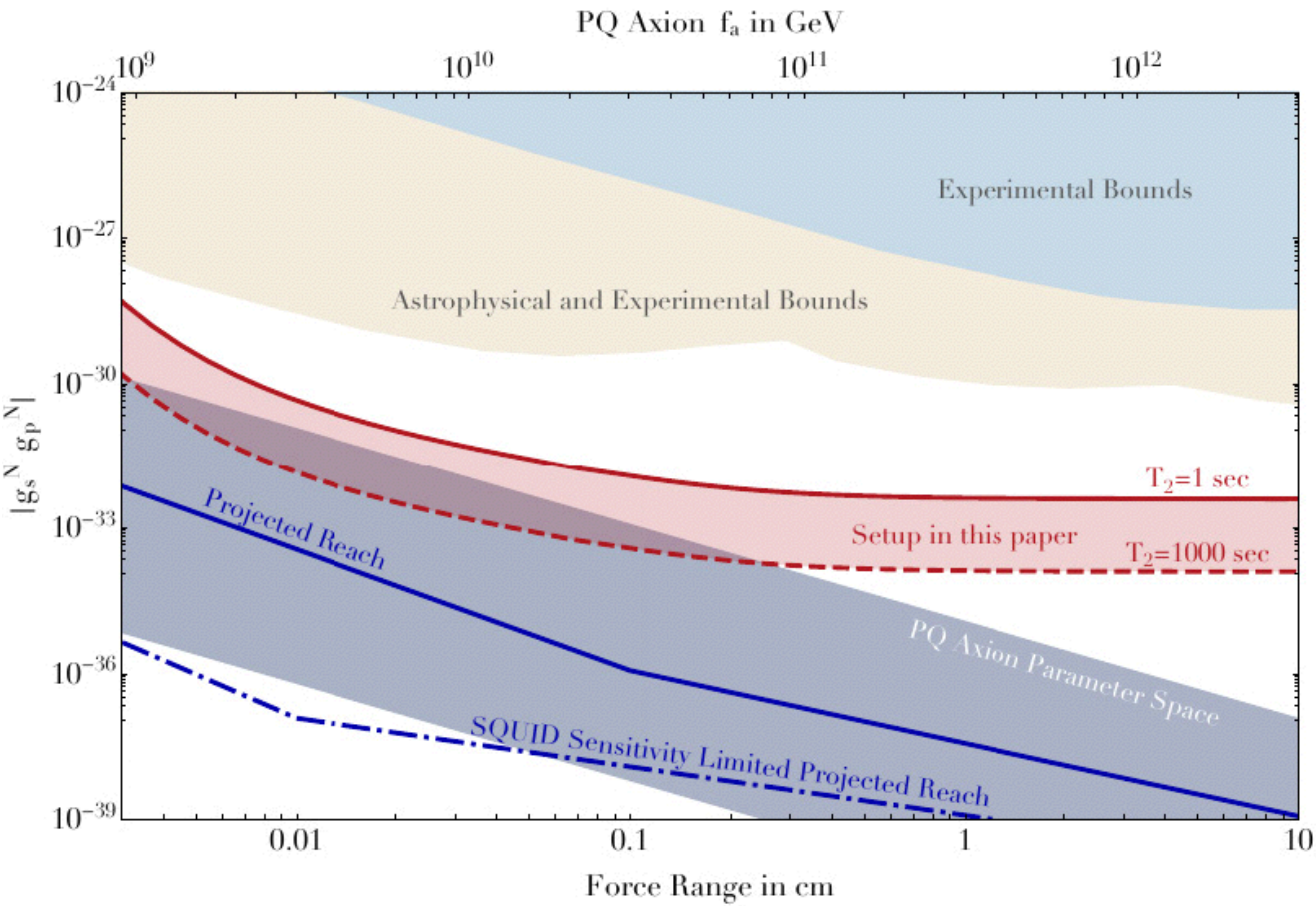
Induced magnetic field

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

- Non-magnetic rotating mass oscillates the interaction in resonance at : $n\omega_{rot}$
- A dense ensemble of polarized ^3He gas with precession at : $n\omega_{3He}$
- NMR sample (^3He) develops a magnetization perpendicular to its polarization

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

Axion Mediated Long Range Force



Summary

- Axions, if discovered, the half-century long Strong CP problem in the Standard Model will be finally put to rest

- Axions could also be the main component of the dark matter

- Exciting Axion Search Program at CAPP/KAIST-IBS

- Discovery may happen anytime soon!