Dark Matter Axion Search at KAIST/IBS

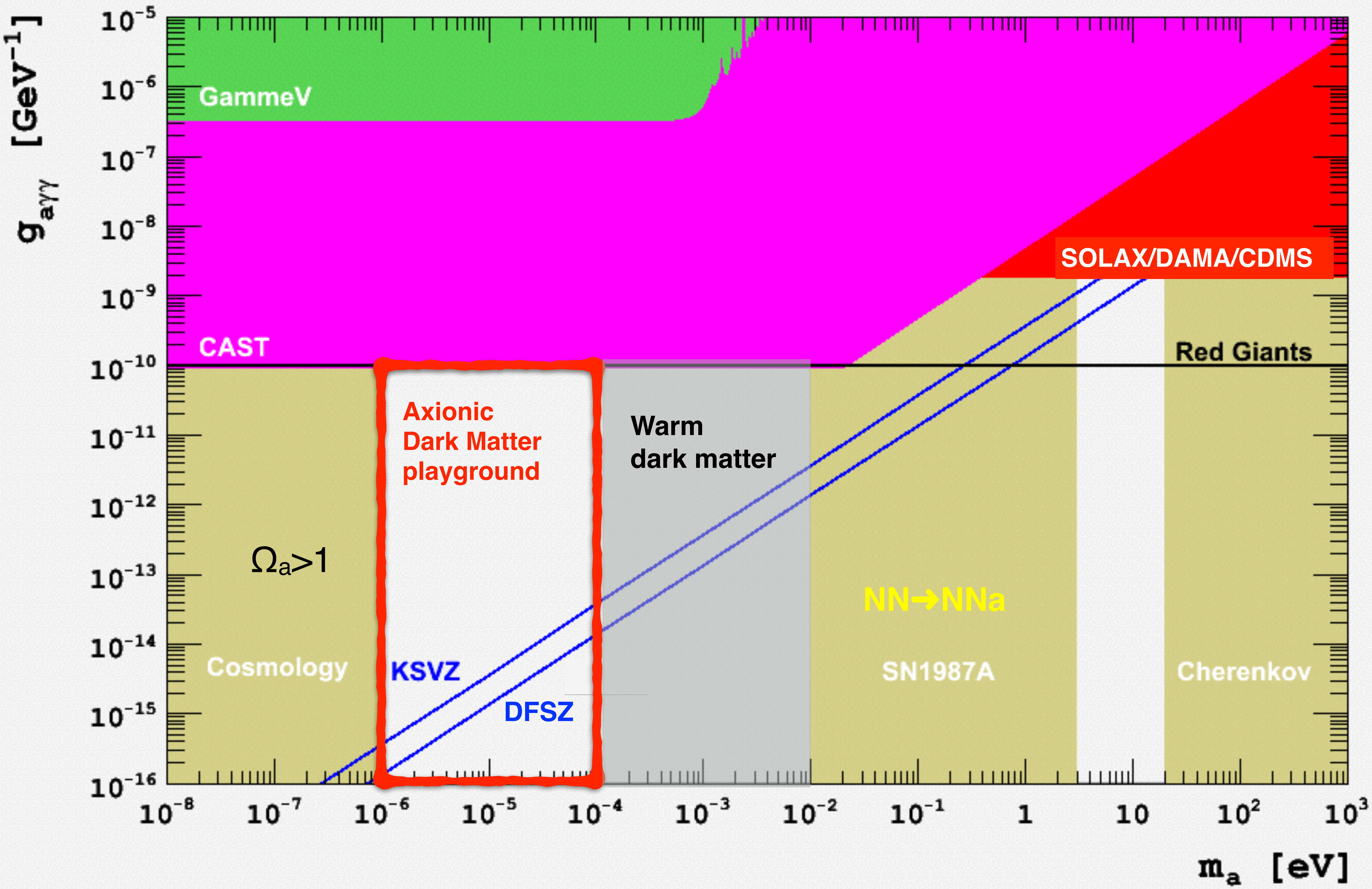
Jonghee Yoo

KAIST/IBS

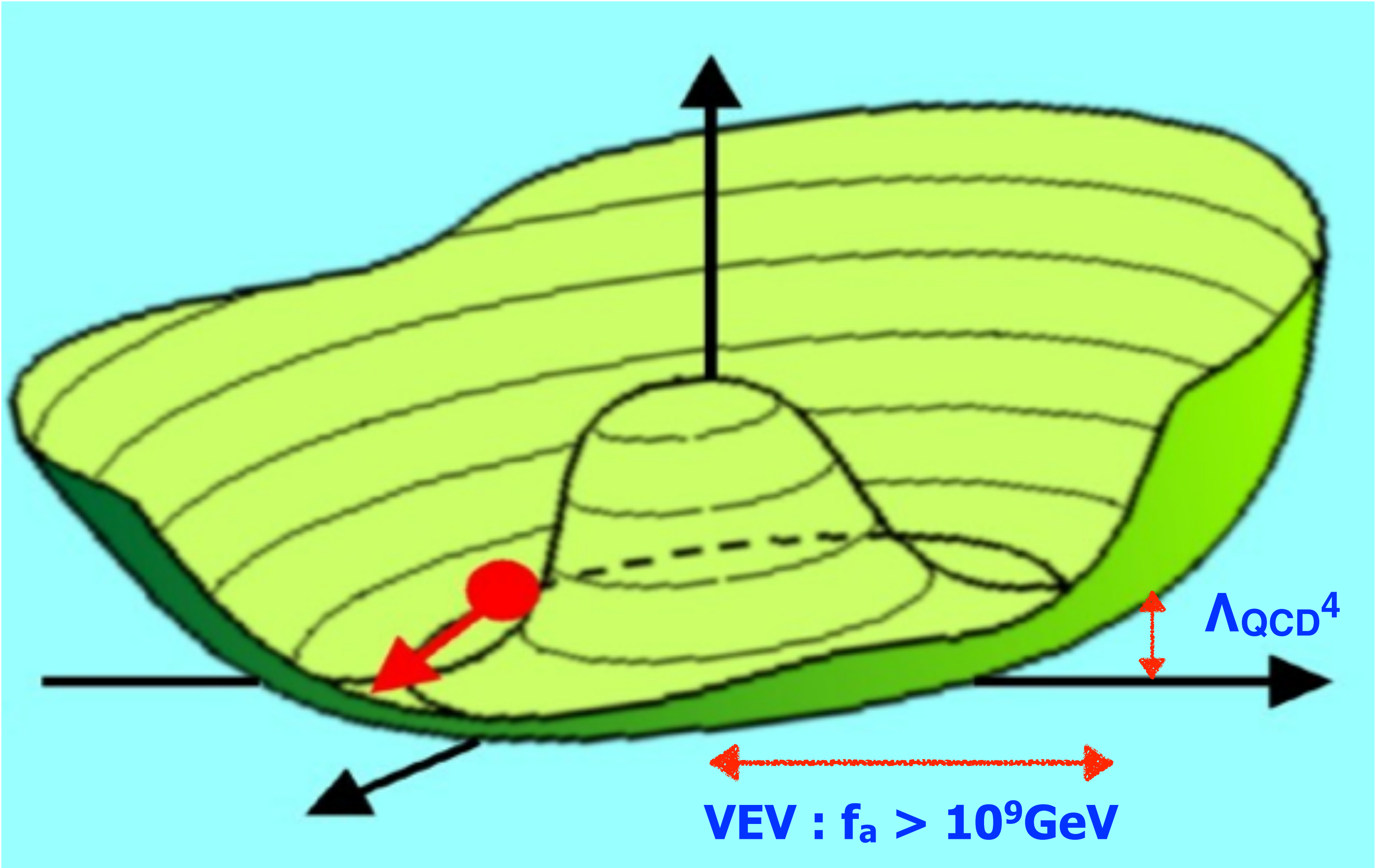
22 February 2018

UCLA Dark Matter 2018

Axion Search

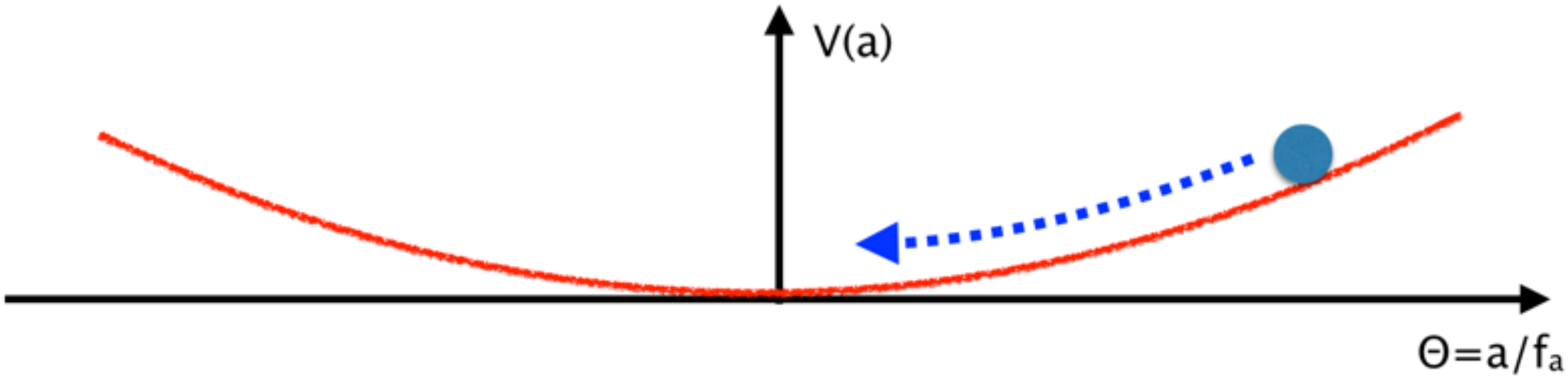


Invented to solve the strong-CP problem in QCD



- Non-thermal mechanism of producing axion dark matter 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 !



Axion Dark Matter Search in A Nutshell

Assume: $m_a \simeq \mu eV$

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

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

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

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

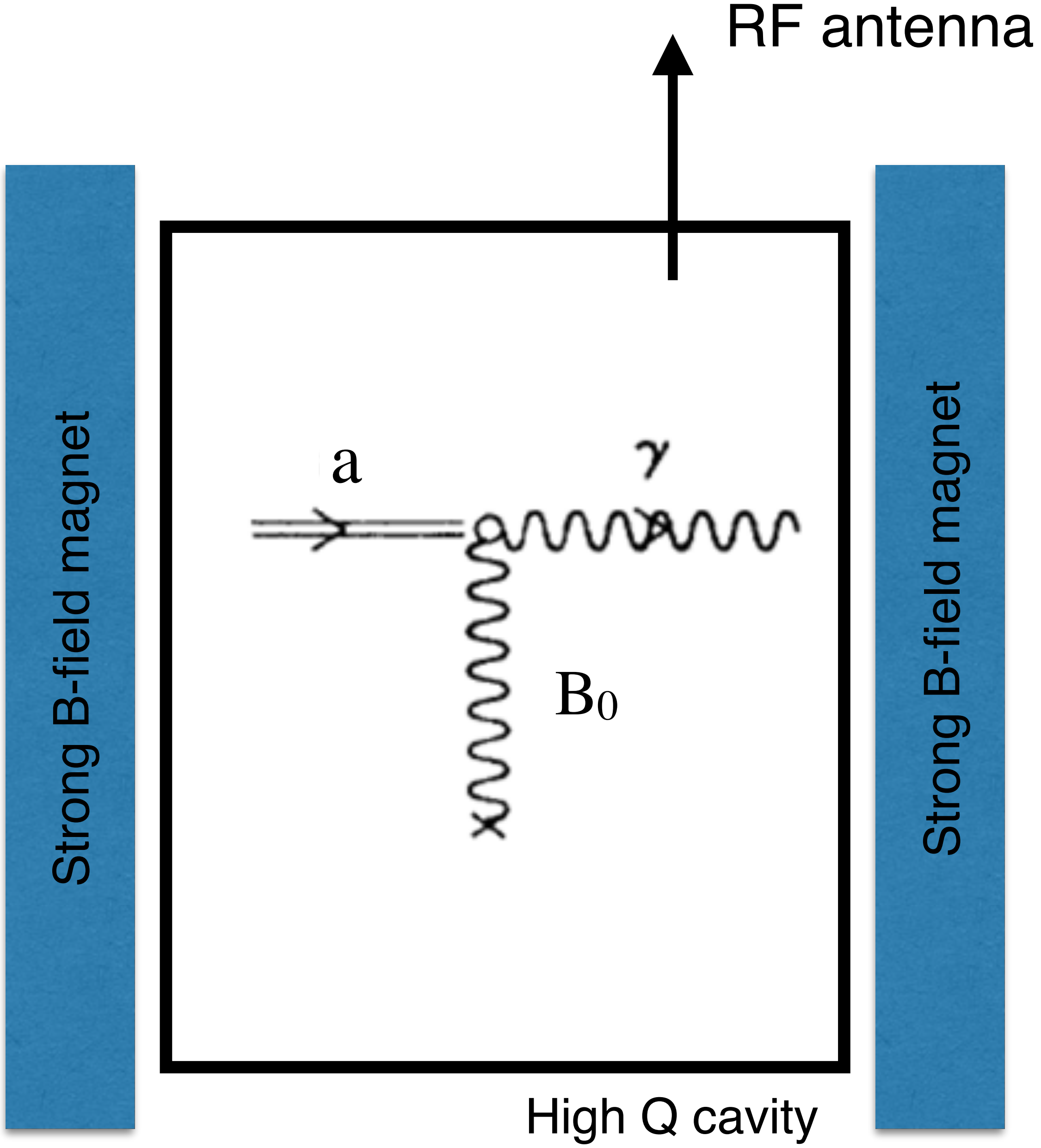
$$\mathcal{L} \equiv -\frac{1}{4} g a F \tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \tilde{F}$$

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

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

Oscillating source current ➔ RF photons

RF photon frequency = axion mass



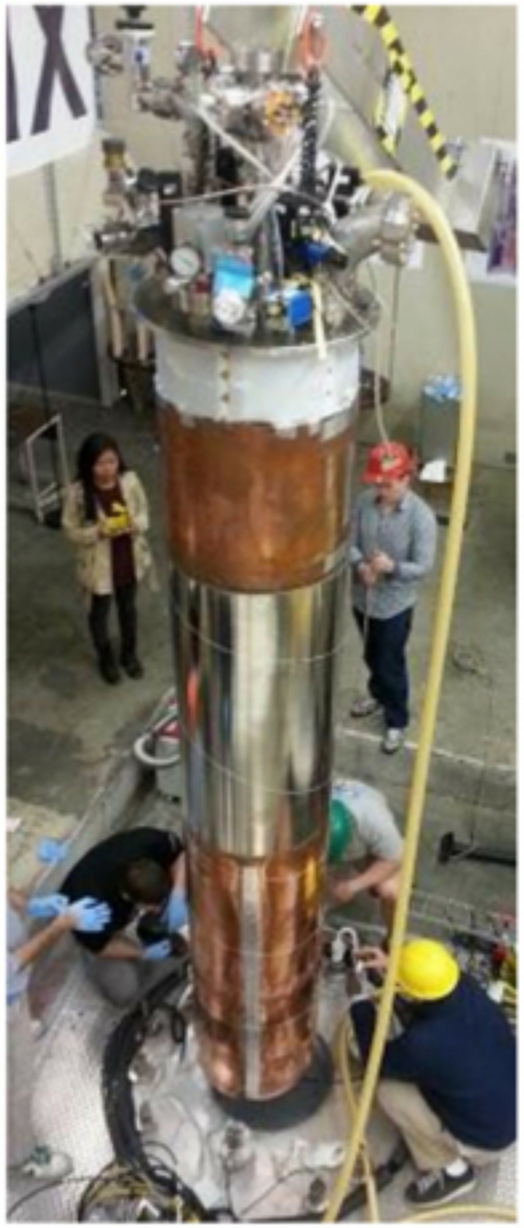
$$P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{cav}, Q_a)$$

~ 10^{-21}W at m_a=μeV

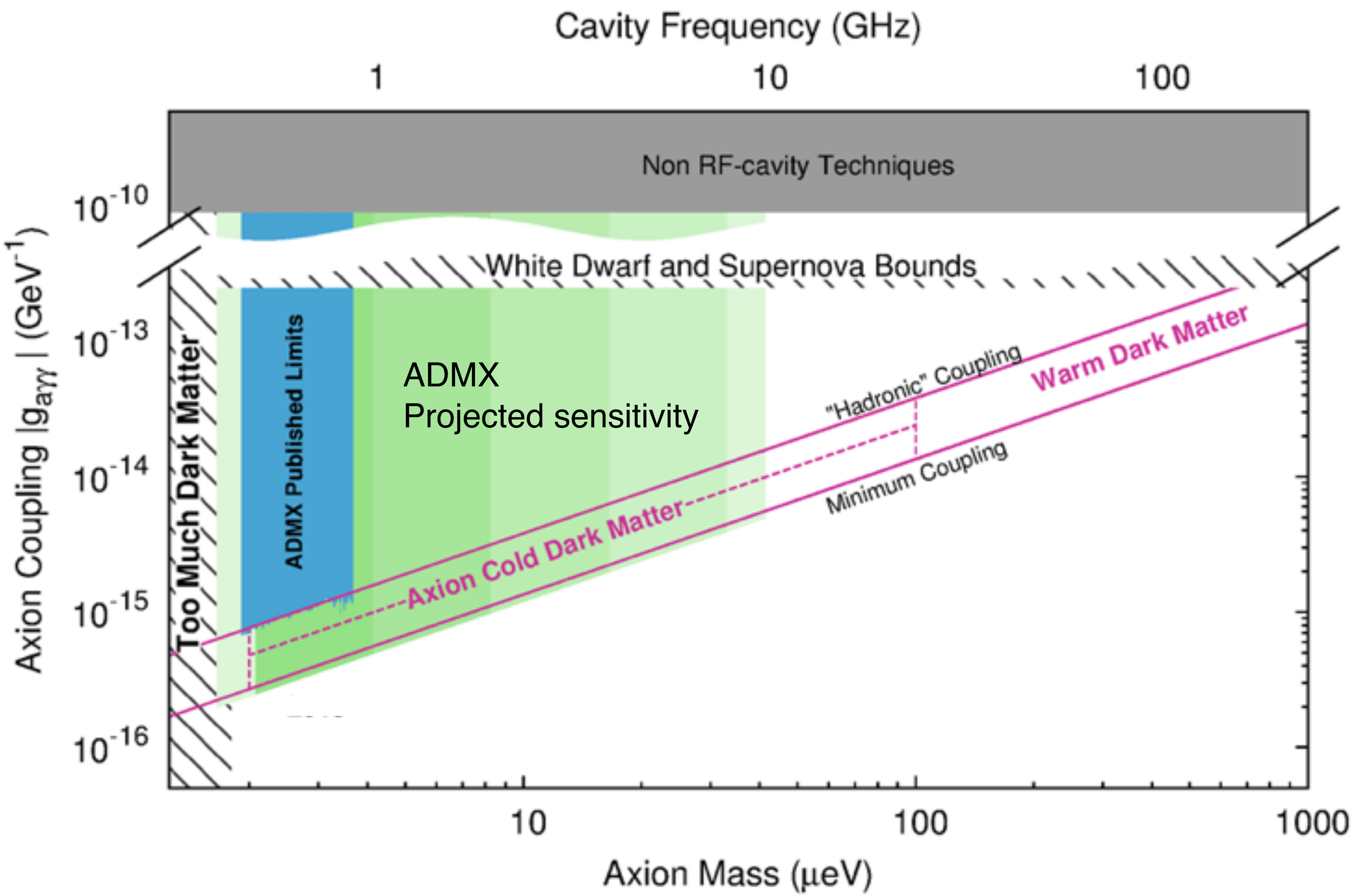
(assuming B=8T, V=0.2 m^3 magnet and cavity Q =10^5)

Axion Dark Matter eXperiment (ADMX)

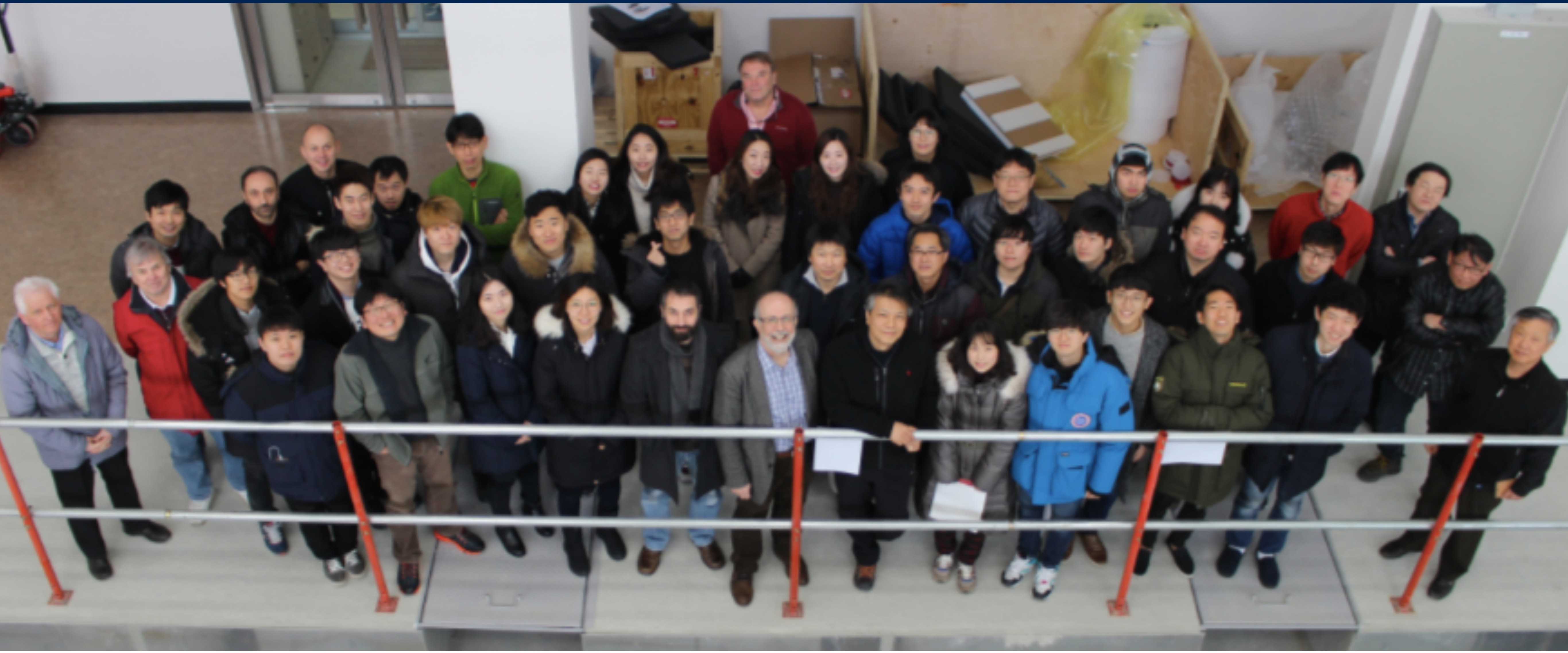
- **ADMX collaboration**
- **Currently the world most sensitive dark matter axion search experiment**
- The experiment is running since 1995 (more than 20-years of efforts)
- Relatively **low magnetic field (8 Tesla)** but large volume (140 liter, Q~60,000)
- Probing low mass (a few μeV) axions



Insert extraction from magnet



Center for Axion and Precision Physics Research (CAPP)



CAPP/IBS at KAIST University launched in October 2013

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

Host Institution
- KAIST University (Korea)
- IBS (Institute for Basic Science)
  ~$10M/year funding for CAPP

Human Resource
- 25 researchers
- 20 graduate students
- 7 staffs (admins/techs)
- Visiting scholars

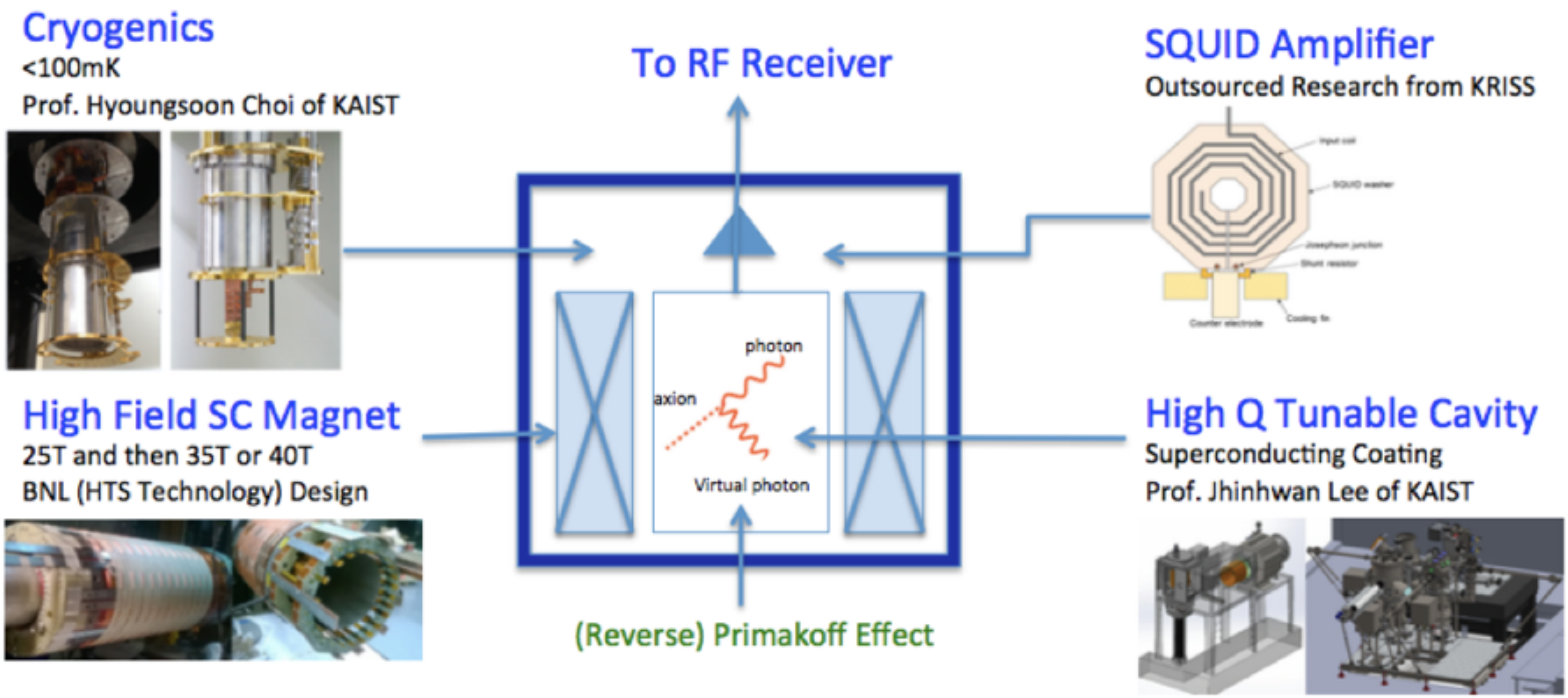
CAPP's Dark Matter Axion Search Strategy

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

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

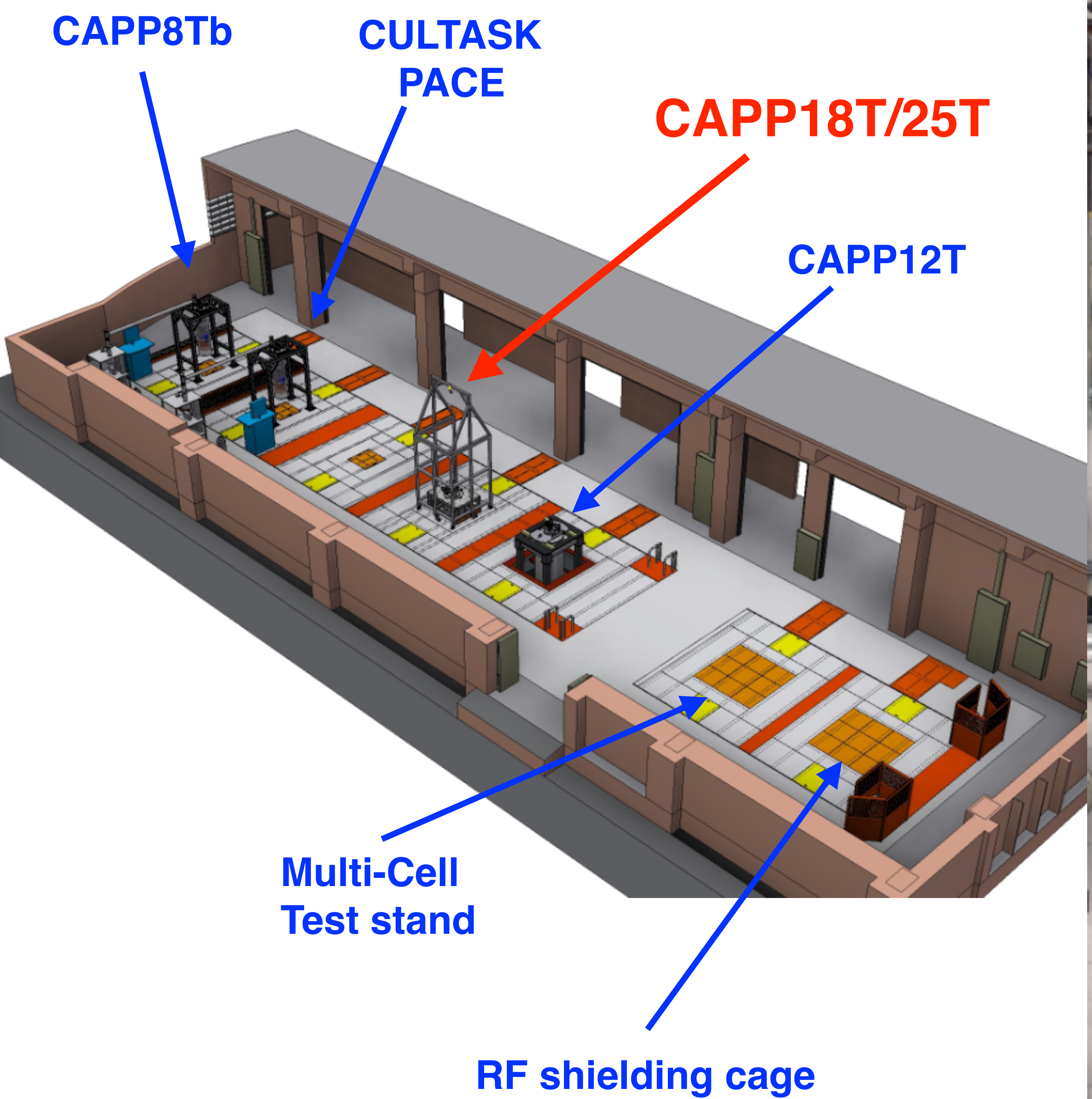
Lower the thermal noise temperature (cryogenics & low noise amplifier)

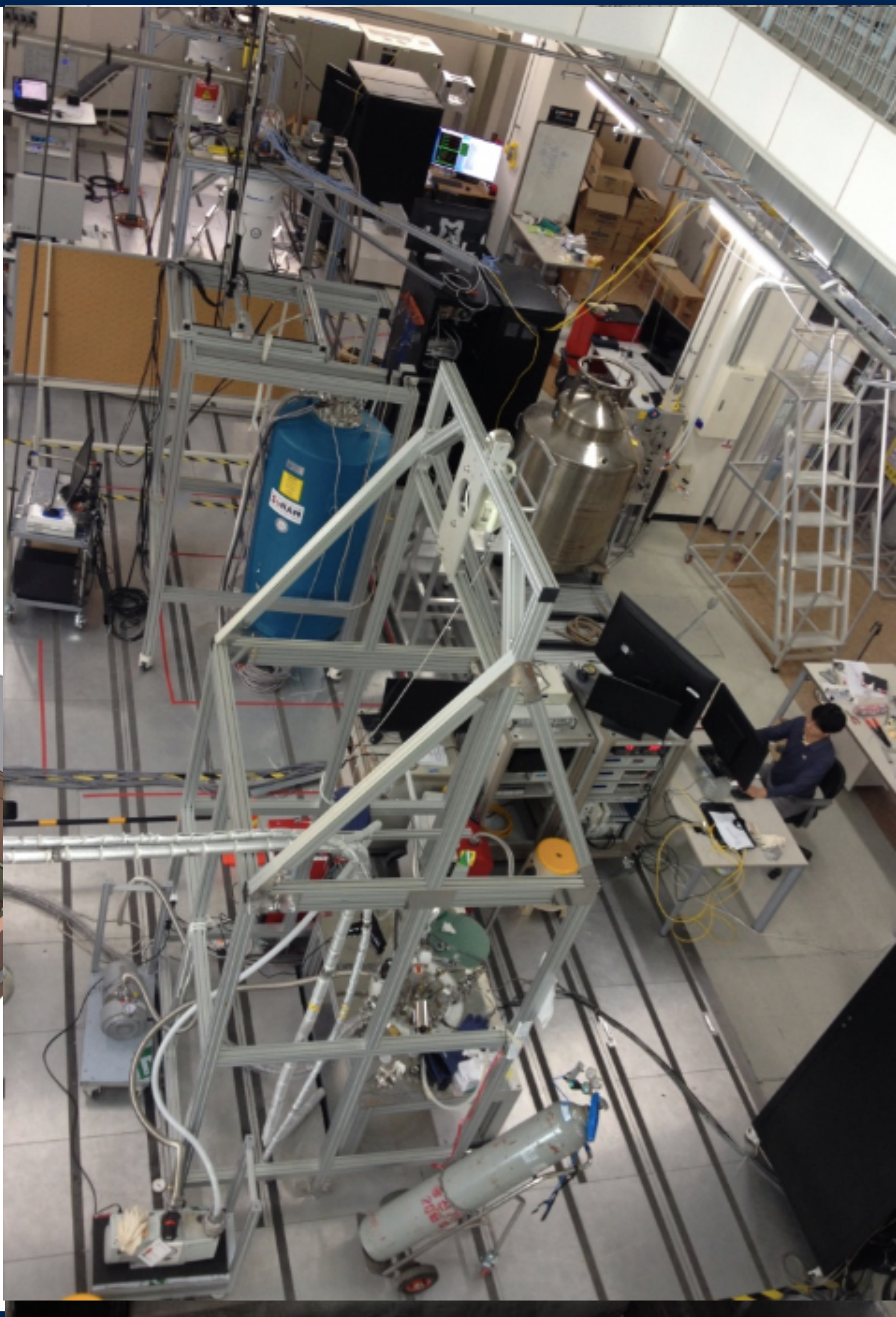
High Q cavity ($Q \sim 10^6$)



Experiment Hall

More than five axion search experiments can be hosted simultaneously





2G HTS Magnet Technology (SuNAM, 2016)

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

quench-safe technique demonstrated

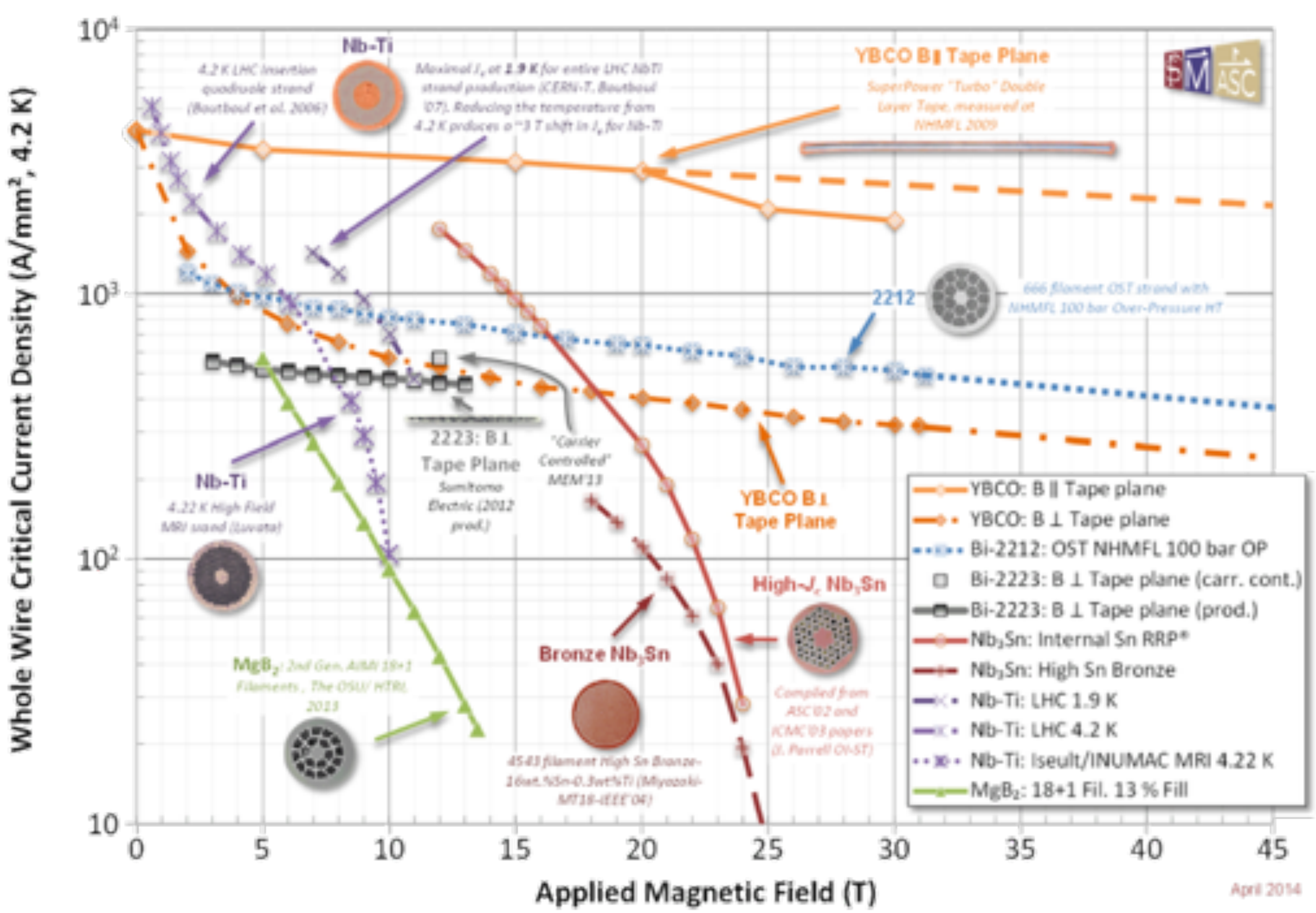
Letter

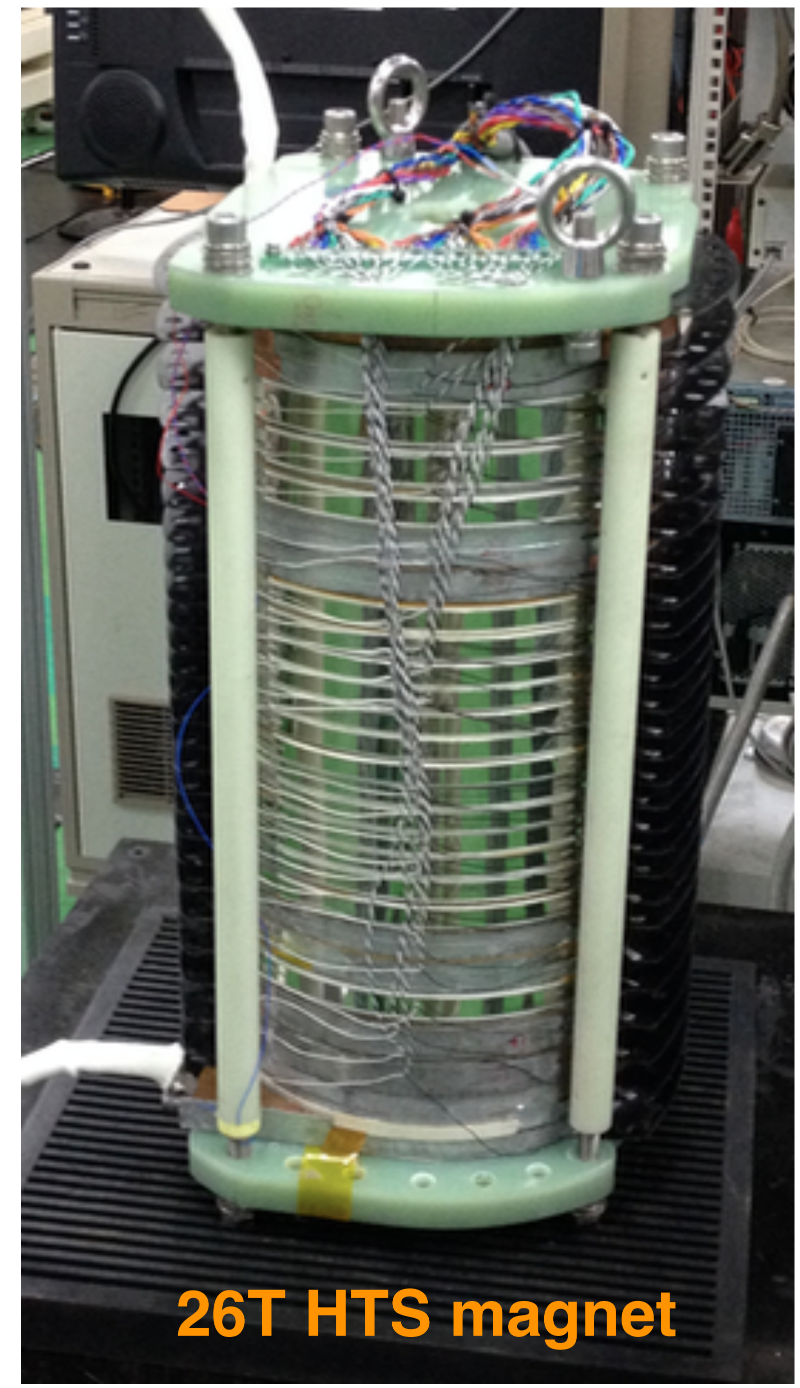
A world record of 26.4T B-field (ϕ35mm bore)
2G HTS magnet by a Korean Company (SuNAM Co. Ltd)

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

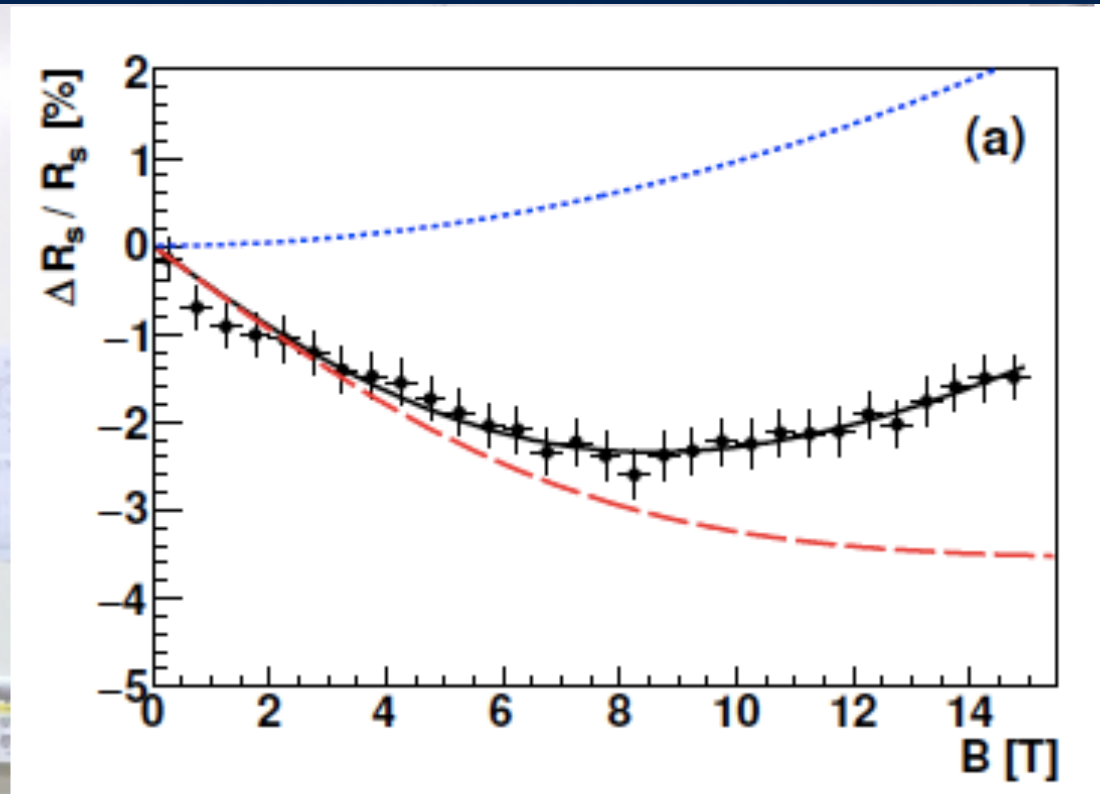
Sangwon Yoon[1], Jaemin Kim[1], Hunju Lee[1], Seungyong Hahn[2,3,4] and Seung-Hyun Moon[1]

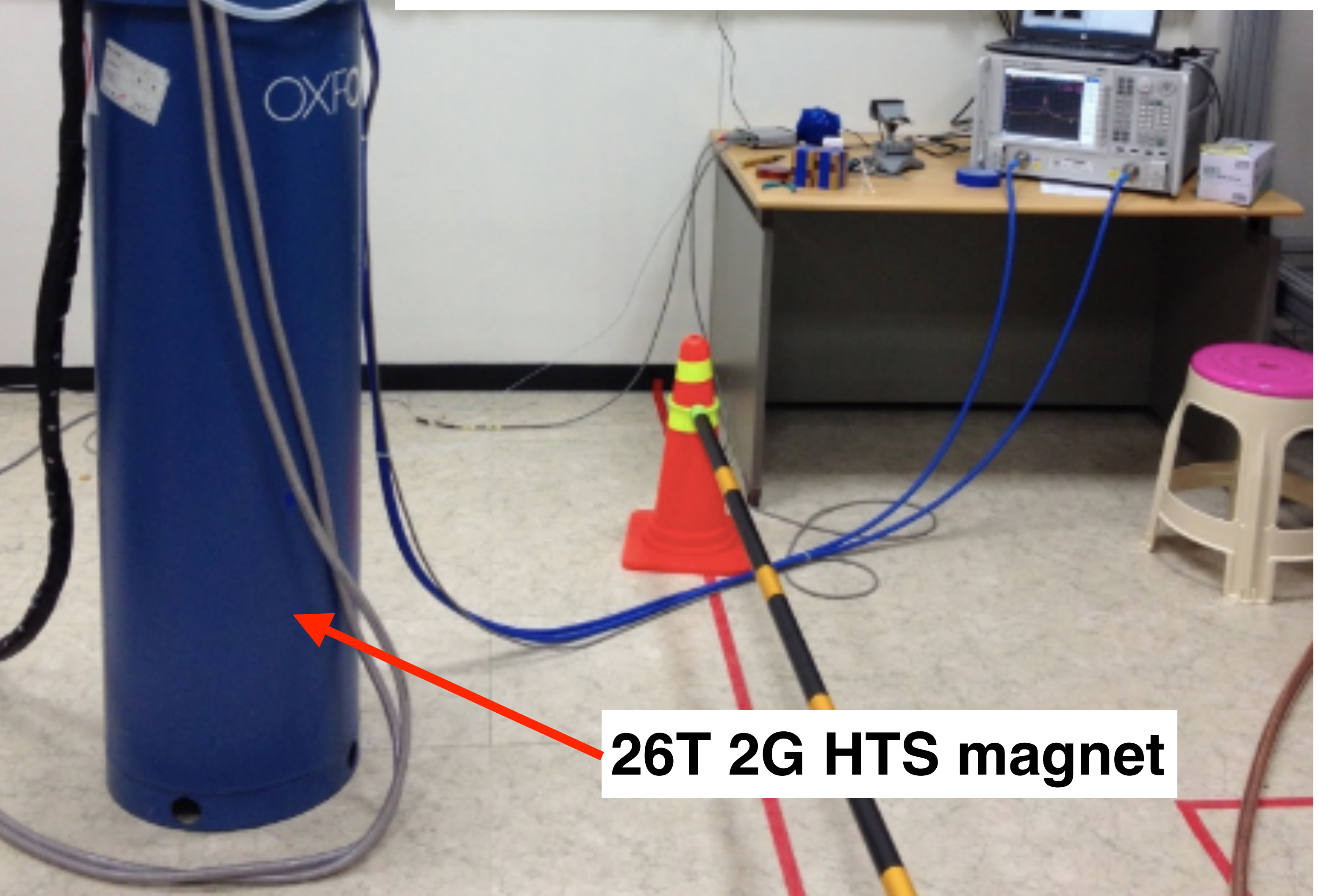
[1] SuNAM Co., Ltd. 103 Seongeun-ri, Wongok-myeon, Anseong-si, Gyeonggi-do, 456-812, Korea
[2] Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, 170 Albany Street, Cambridge, MA 02139, US





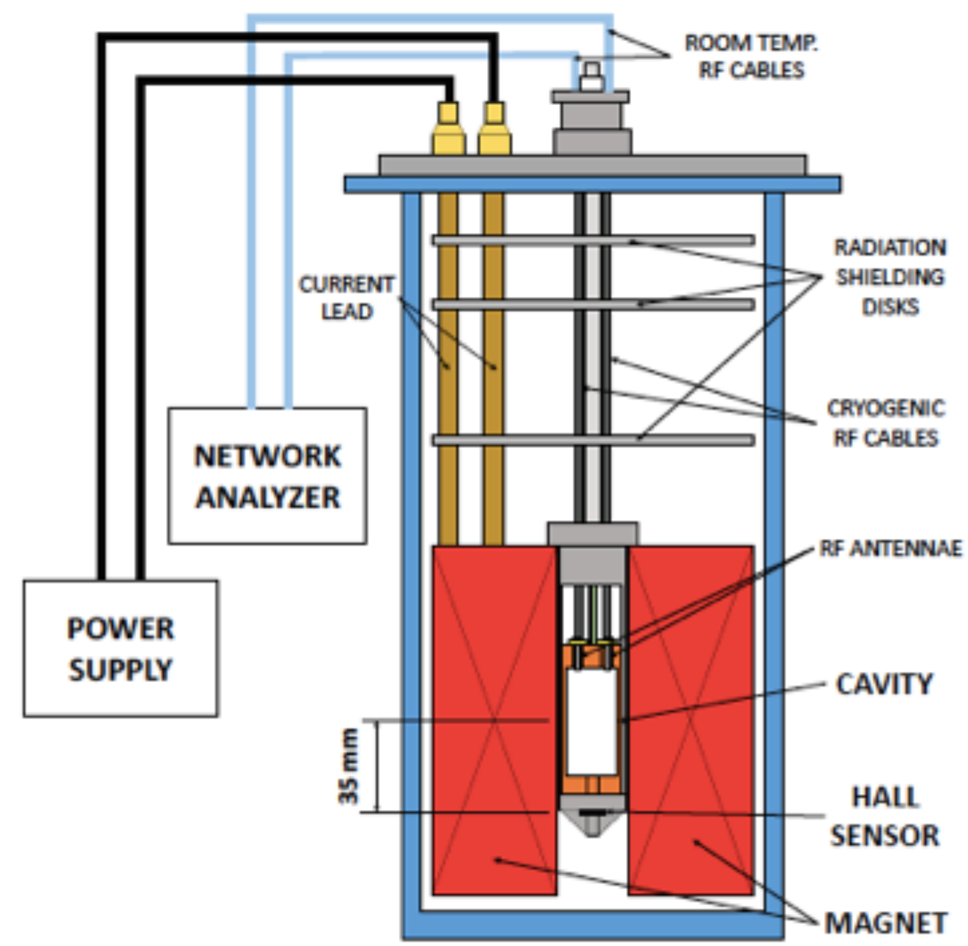
Magnetoresistance Test With High Frequency Cavity





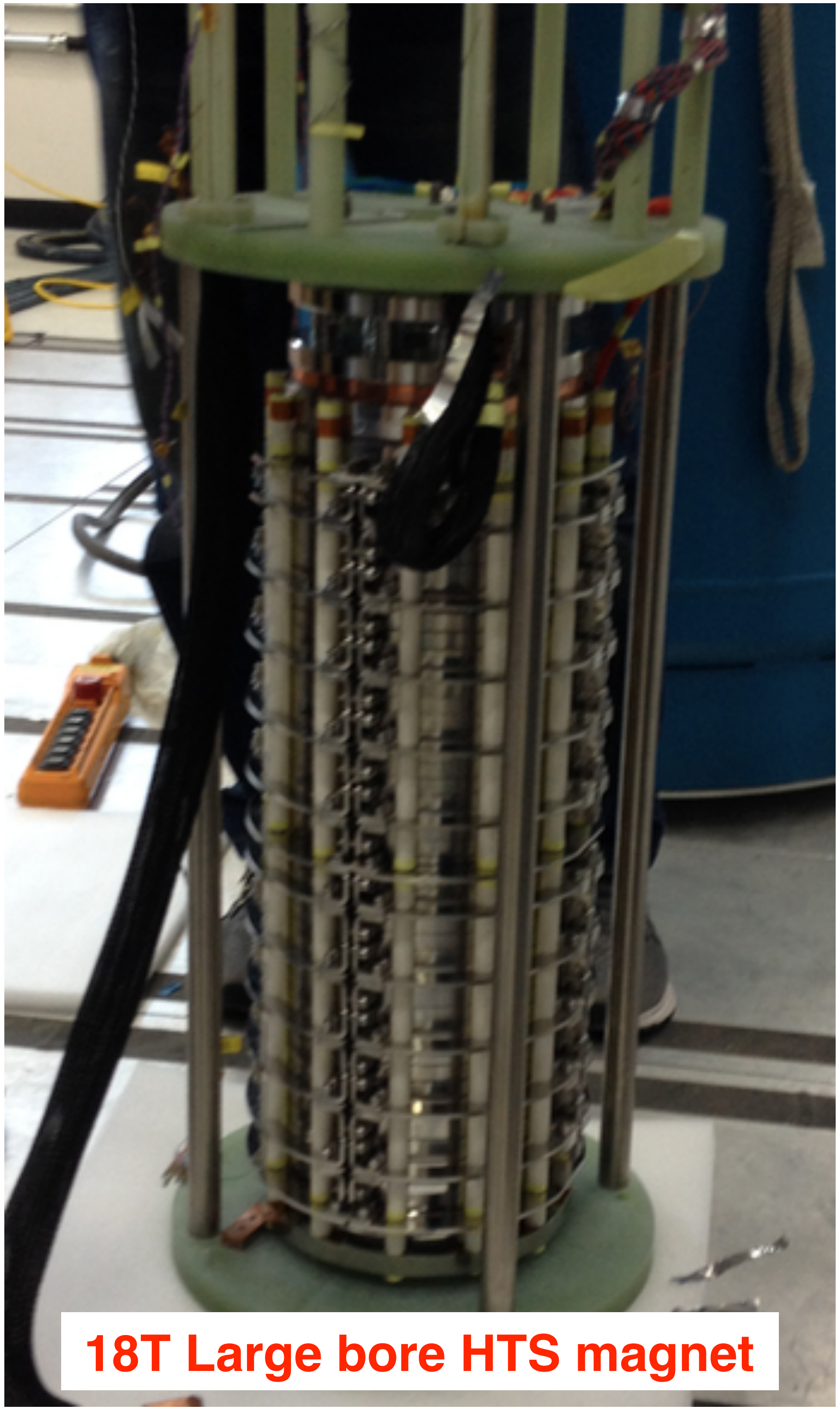
T	frequency	Q_0
300K	12.82 GHz	12160±79
4.2K	12.90 GHz	33686±84

$$\frac{\Delta R_s}{R_s} = -\frac{\Delta Q}{Q}$$



arXiv:1705.04754
published in JINST 12 P10023 (2017)

18T HTS Magnet (Delivered in August 2017)



18T Large bore HTS magnet

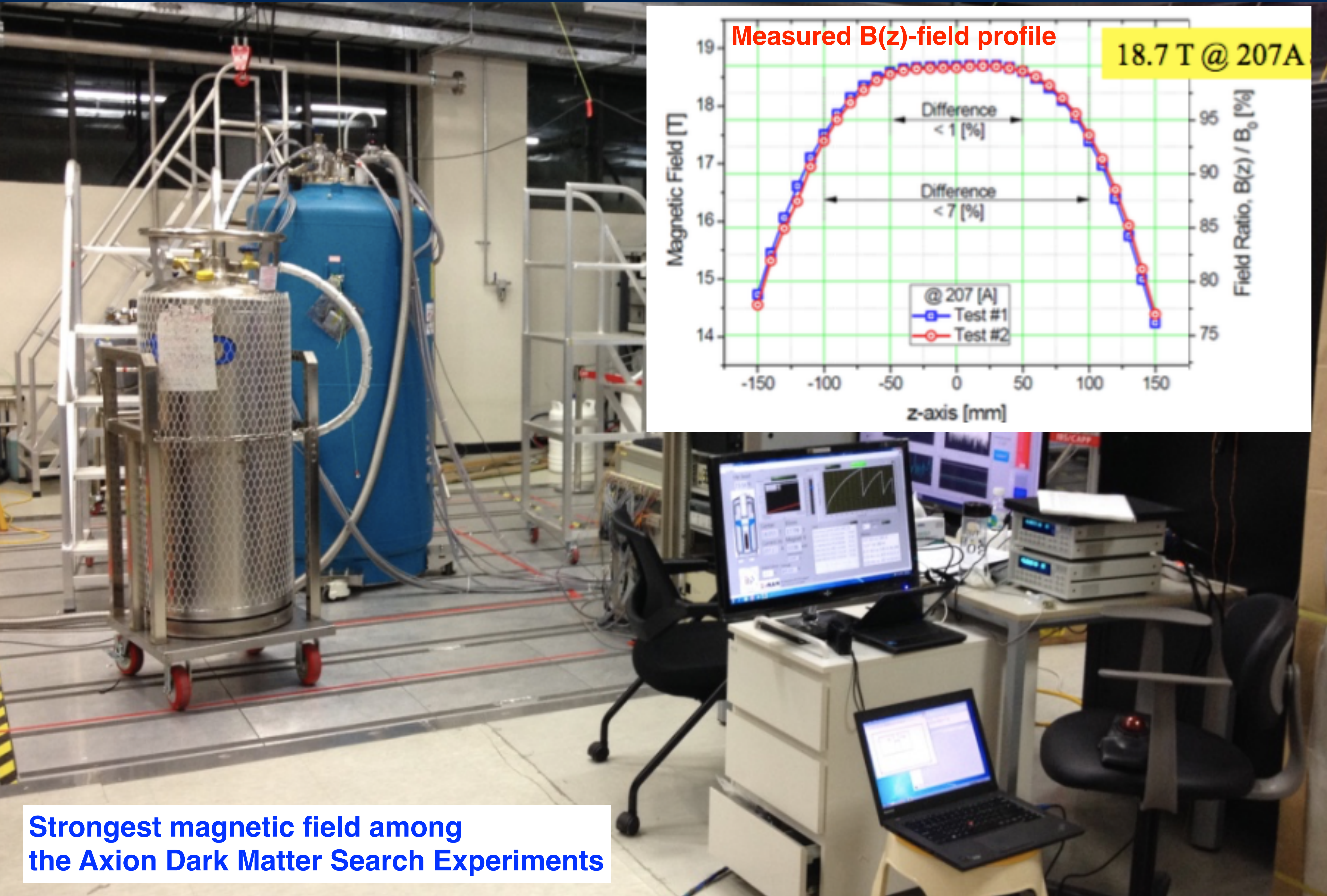
A strong B-field and large bore HTS magnet can be commercially produced by SuNAM Co. Ltd.

2G HTS Superconducting Magnet
Magnetic field : 18 Tesla
Dimension: 70 mm ID / 168mm OD
200 mm uniform field (>90%)
552 mm length
Quench free design (No-Insulation winding)
Compact and easy to operate

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

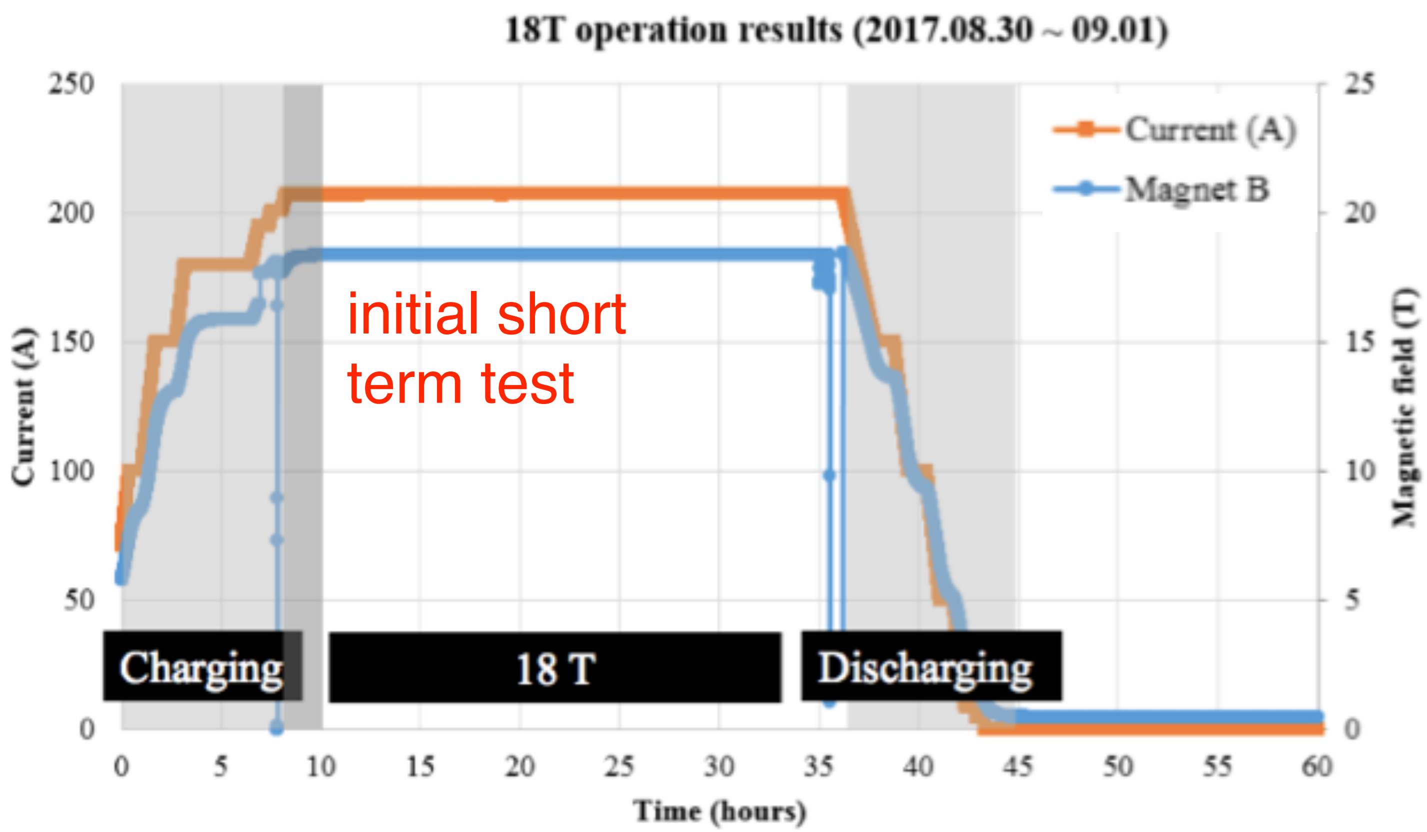
→ Then apply multiple cell method to probe higher mass range search

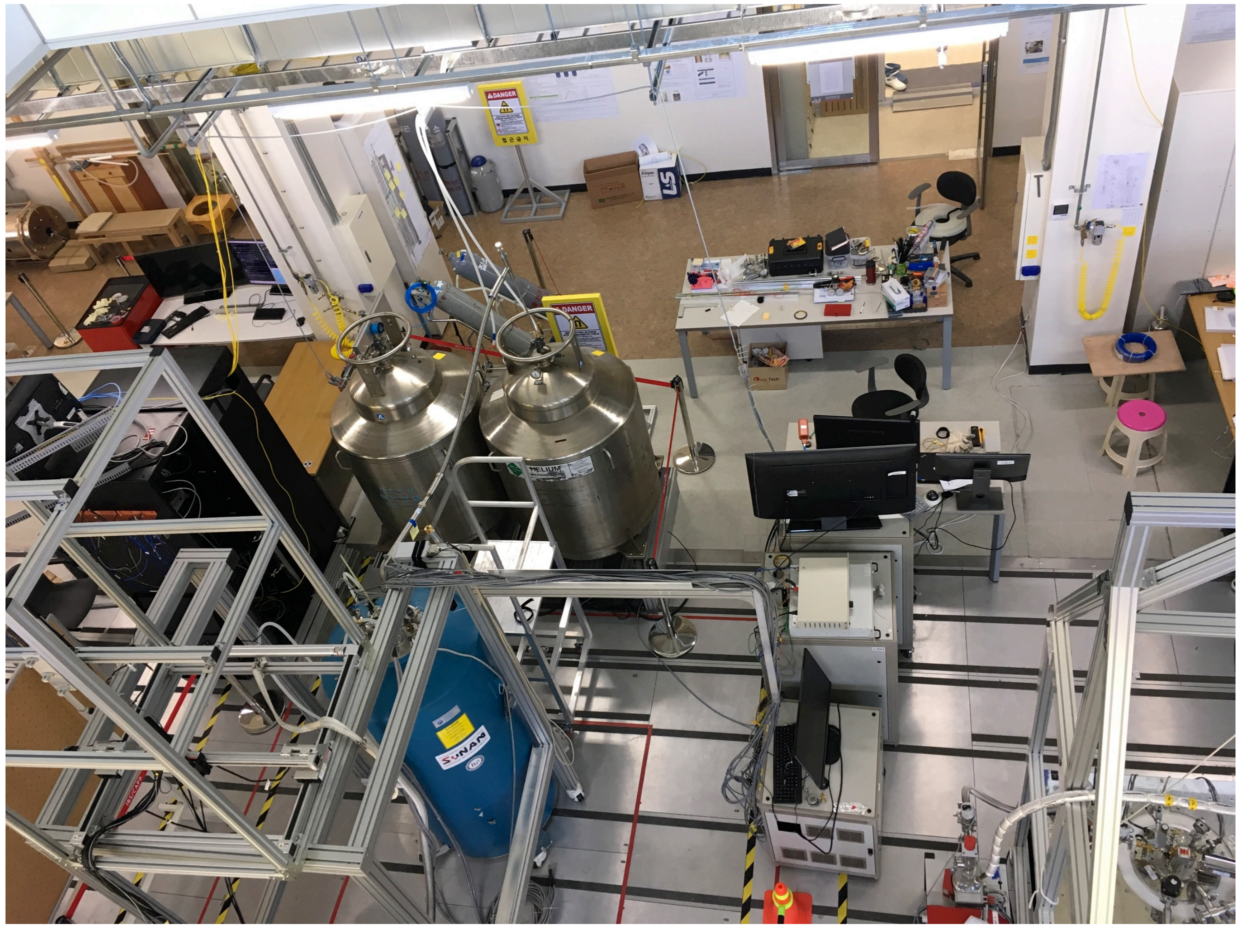
18T HTS Magnet Performance

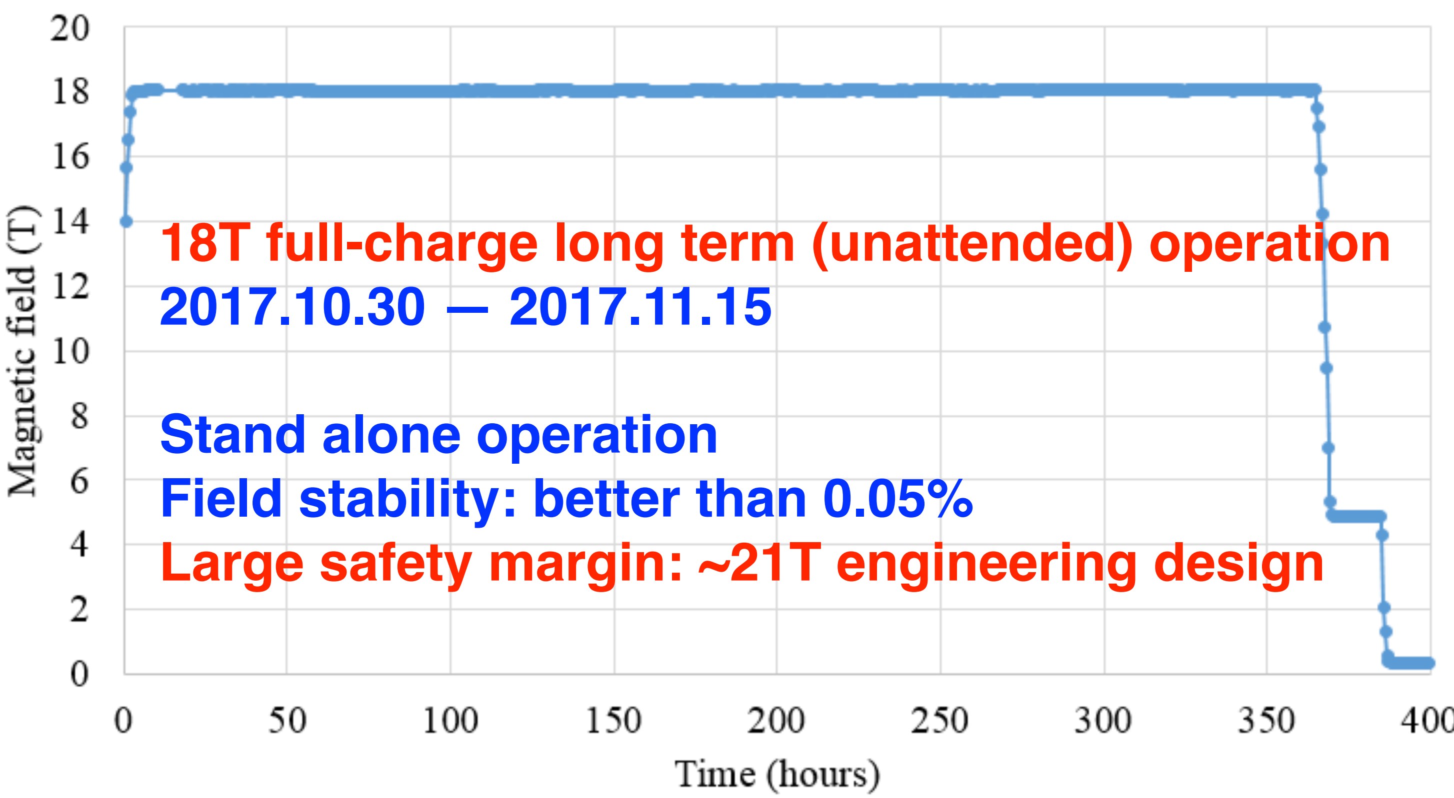


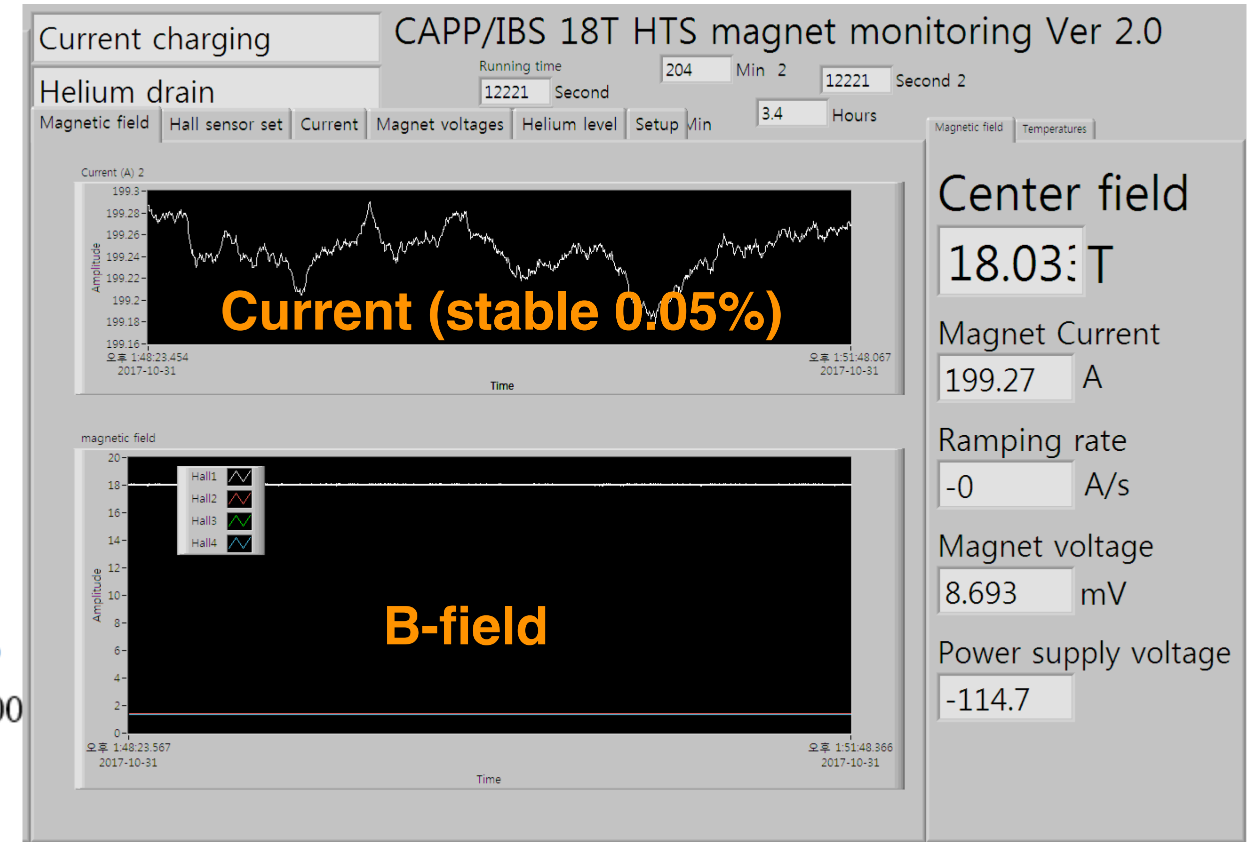
Strongest magnetic field among
the Axion Dark Matter Search Experiments

18T HTS Magnet Performance





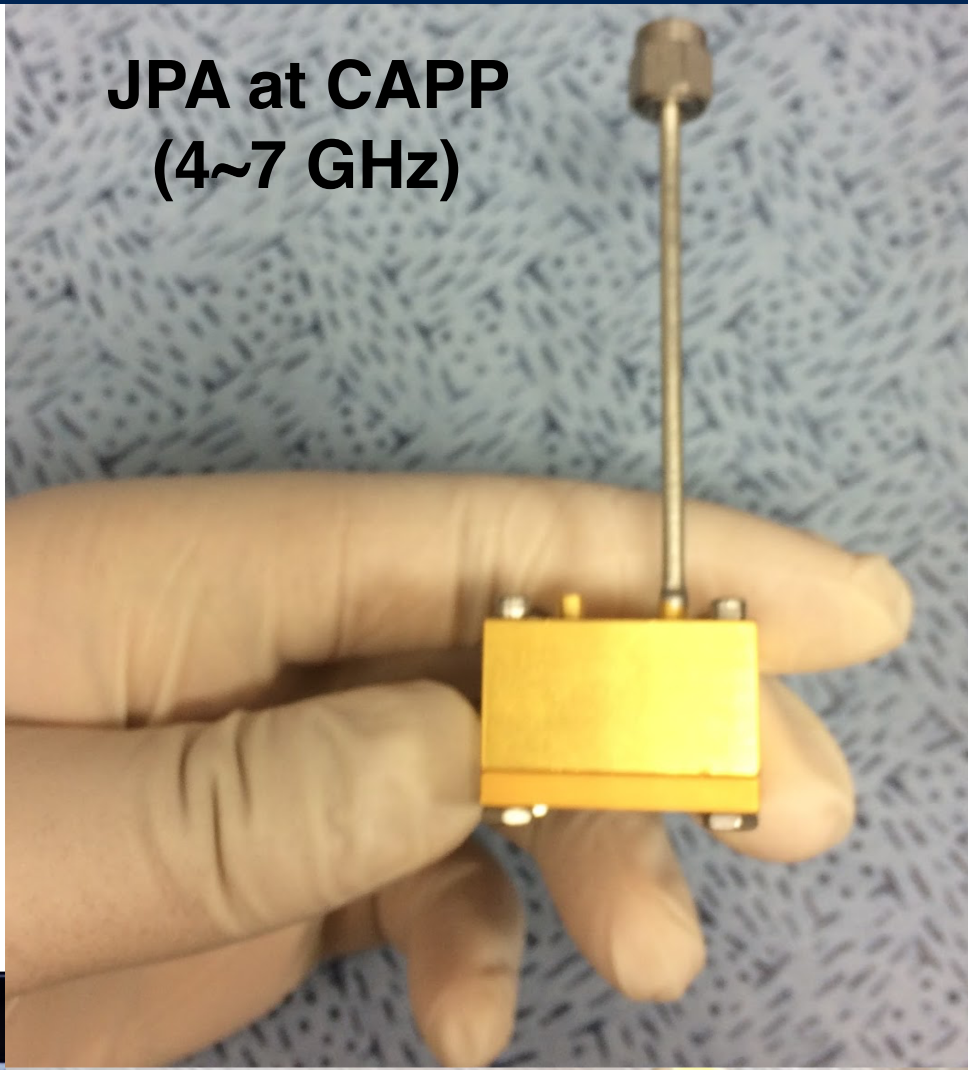


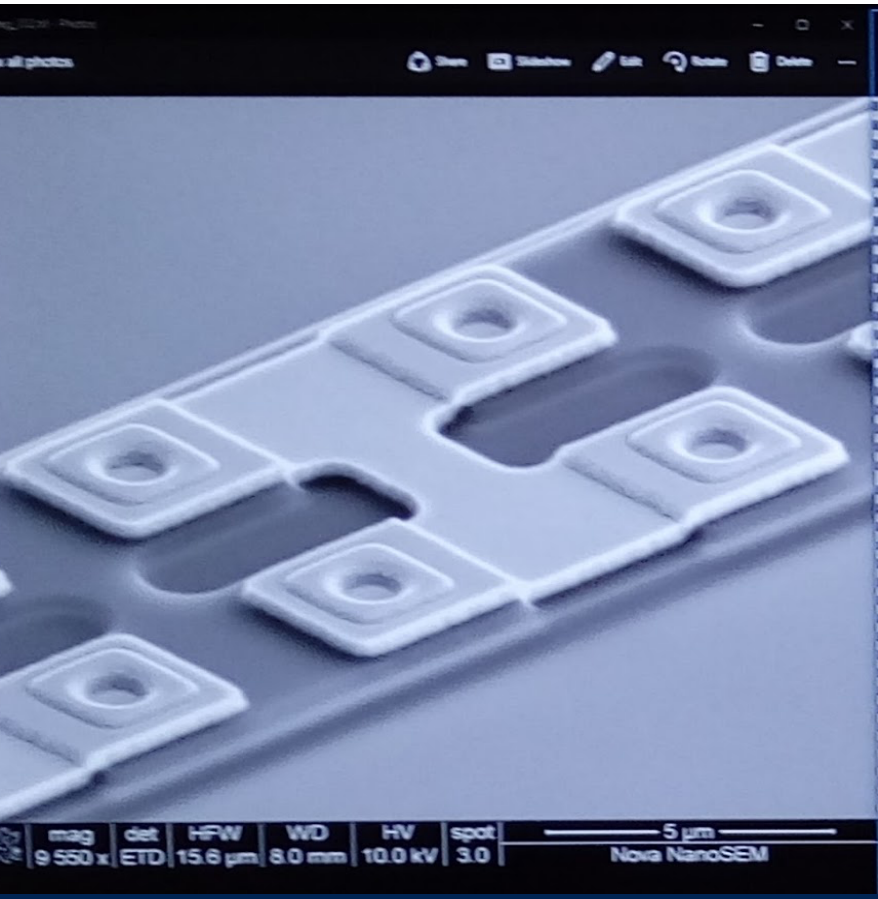


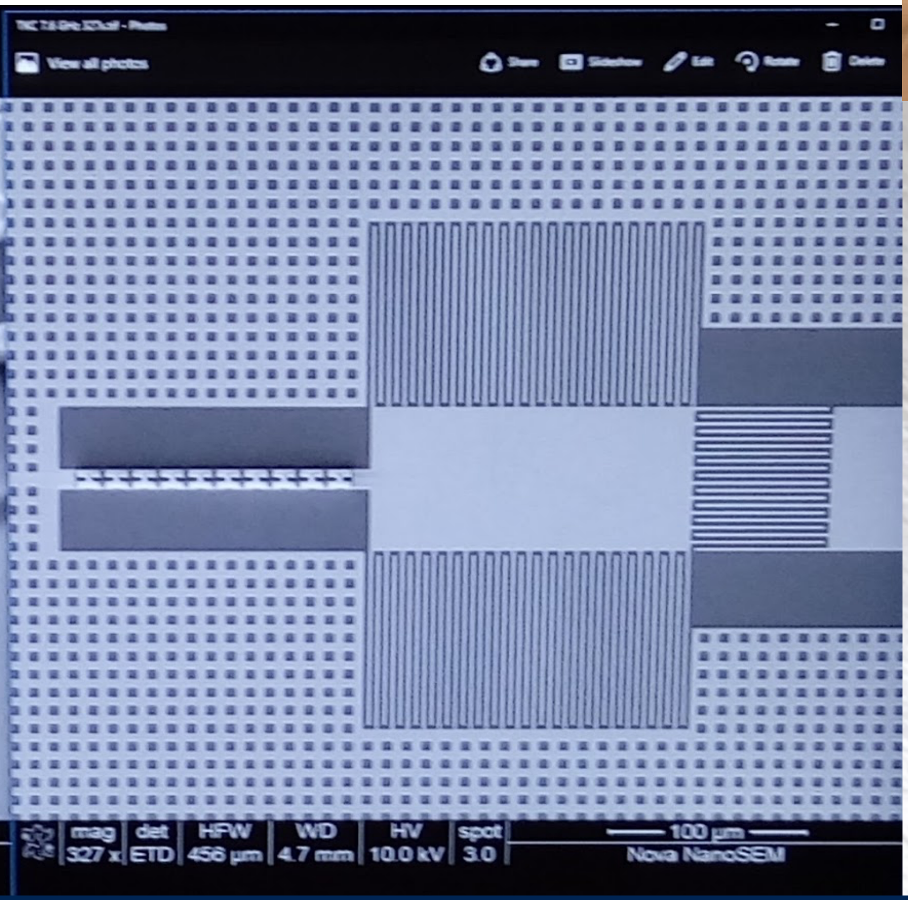
Josephson Parametric Amplifier (JPA)

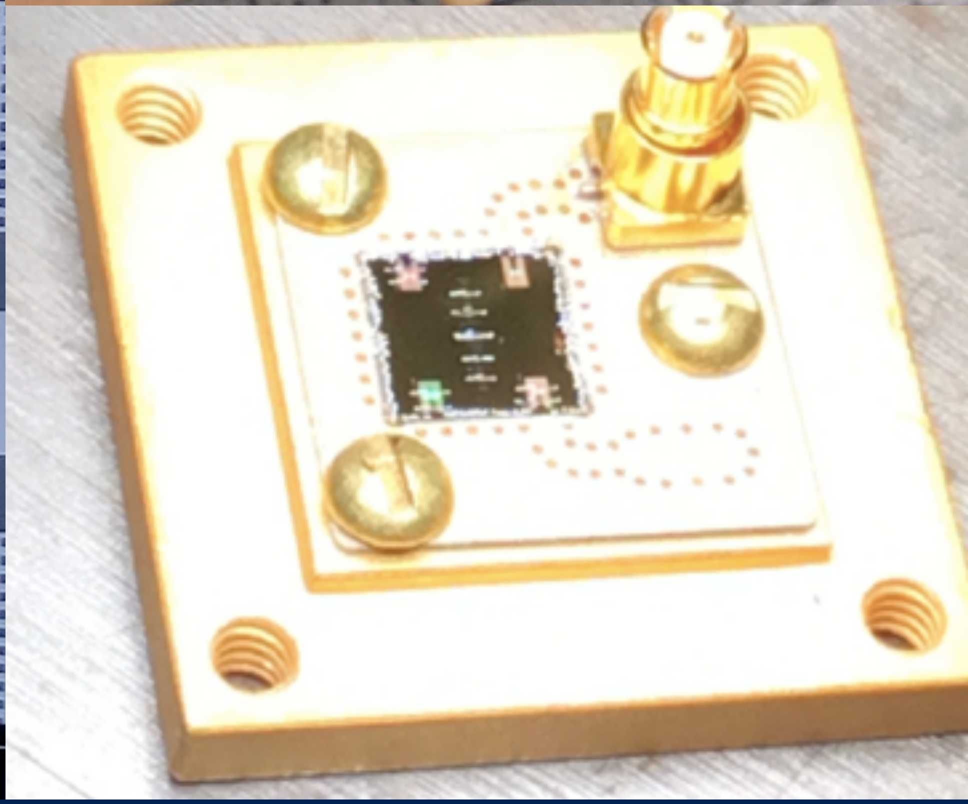
CAPP18T experiment plan to employ JPA in oder to amplify the weak axion signal power

- JPA from K. Lehnert (JILA)
- Operation temperature (300mK)
- JPA consists of an array of many tiny SQUIDs (400-1500)
  JPA has about 1000 times smaller pickup loop area compared to that of single large scale SQUID amplifier
  - ➔ Not sensitive to trapped magnetic fluxes
  - ➔ Not sensitive to Radio-Frequency-Interference
  - ➔ Not sensitive to ambient DC and AC magnetic noise
- We plan to acquire JPC from QCI (Yale) as well

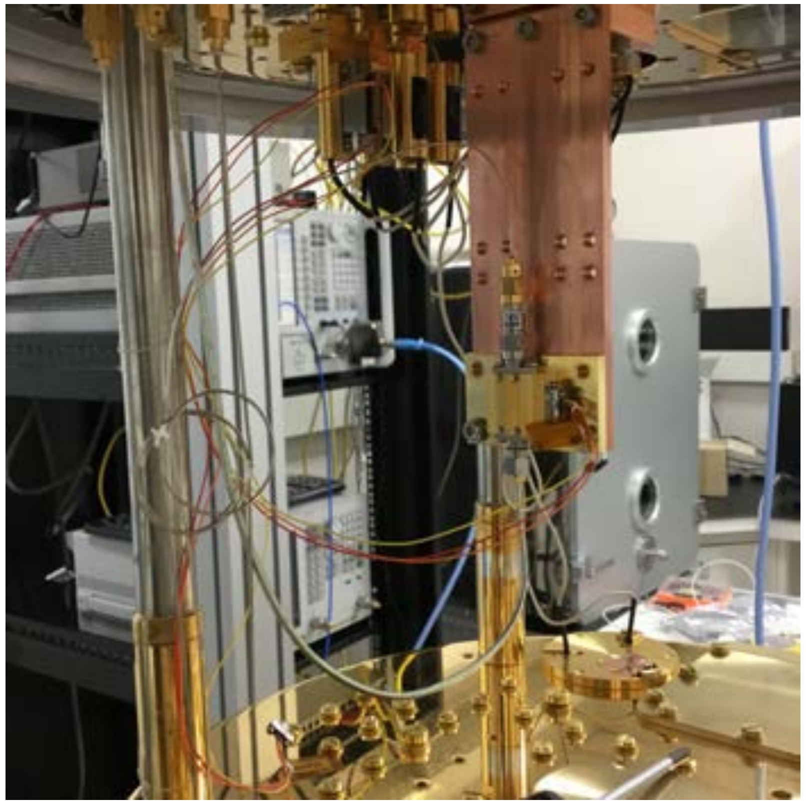


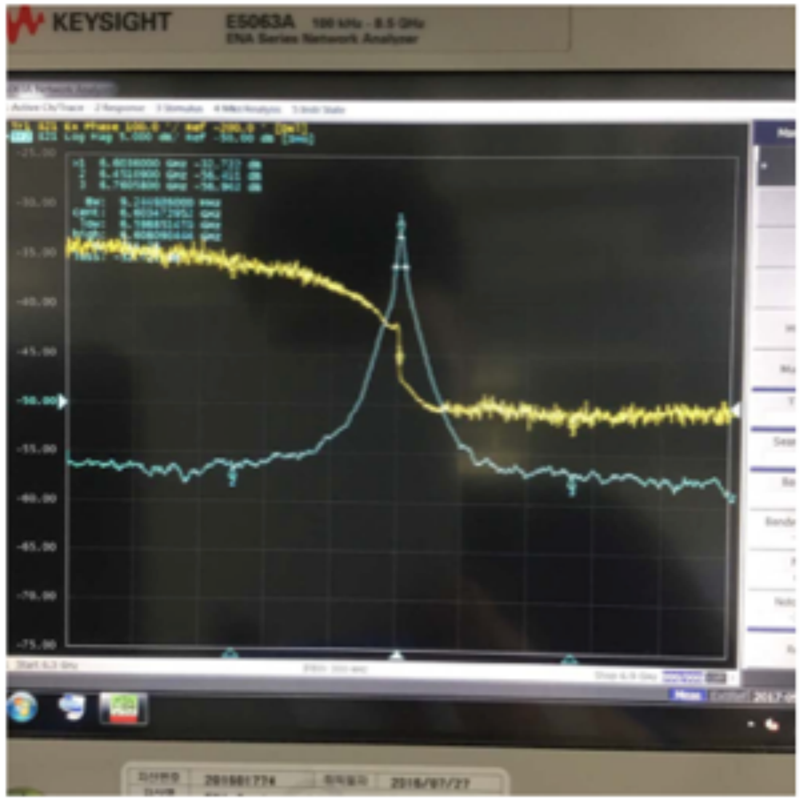


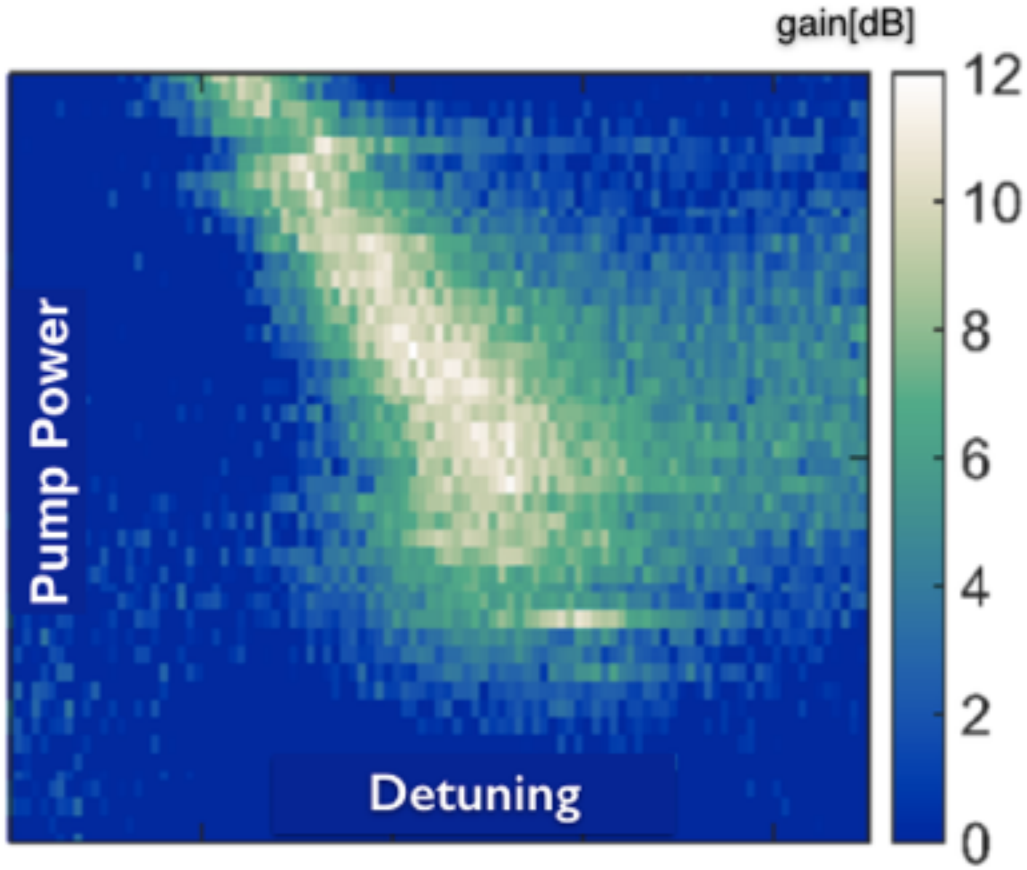


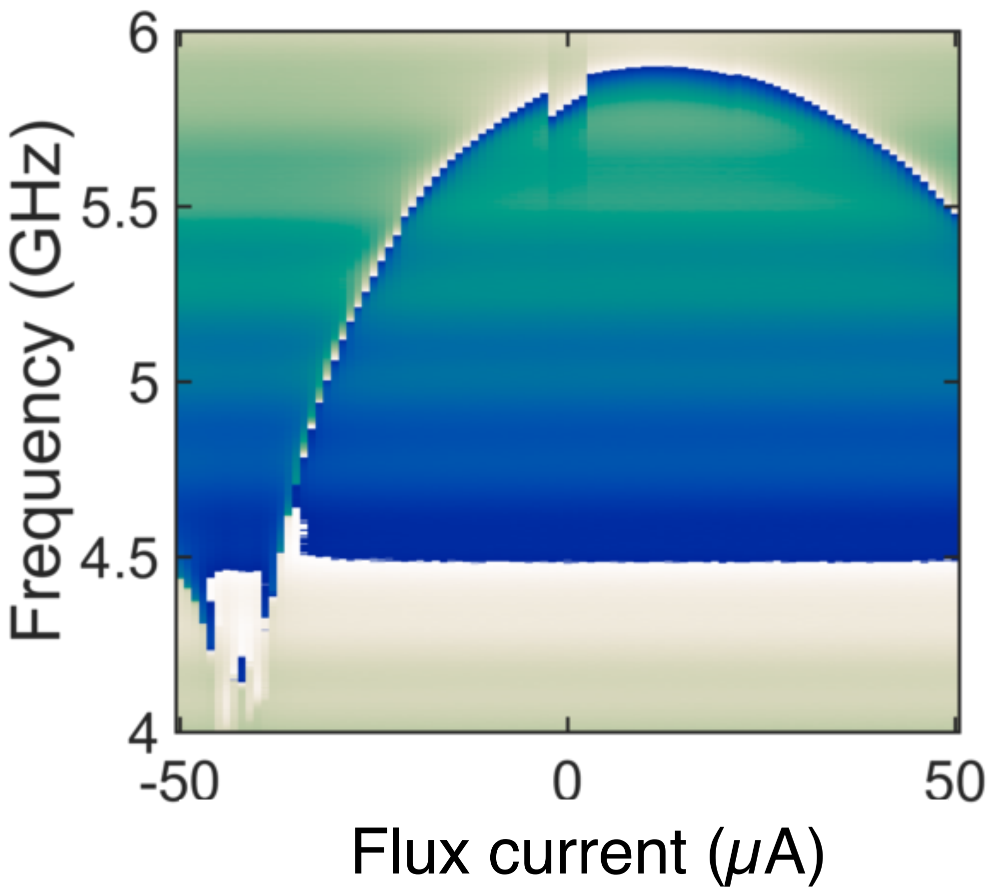


JPA Test







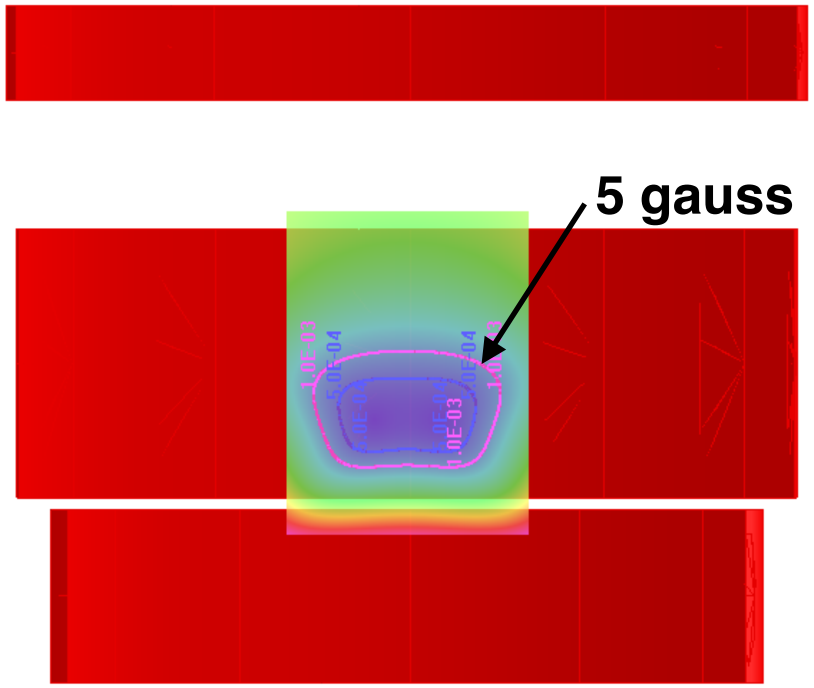


Confirmed our JPA is working OK

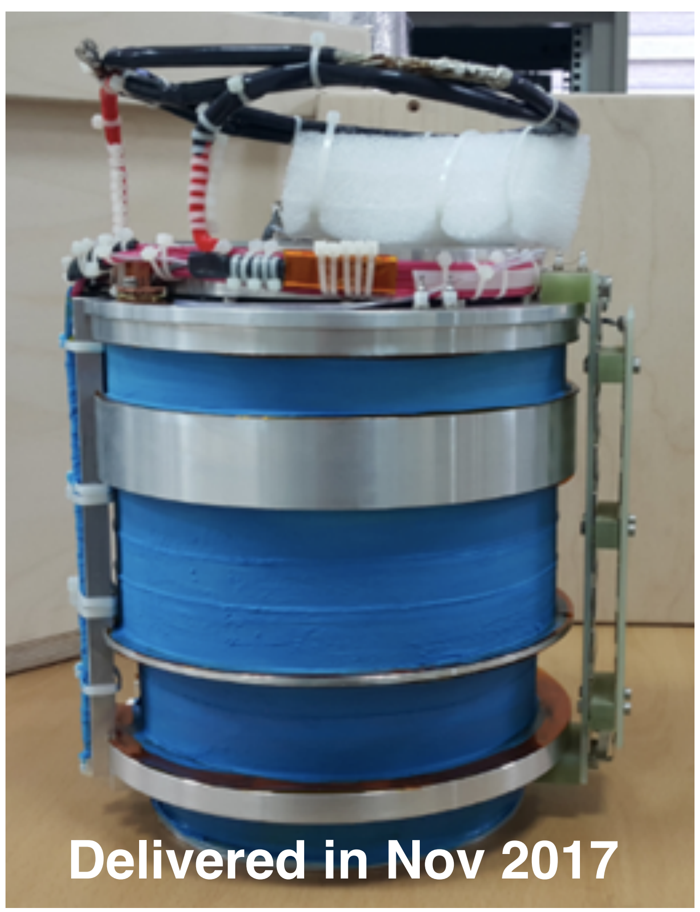
Currently working on:

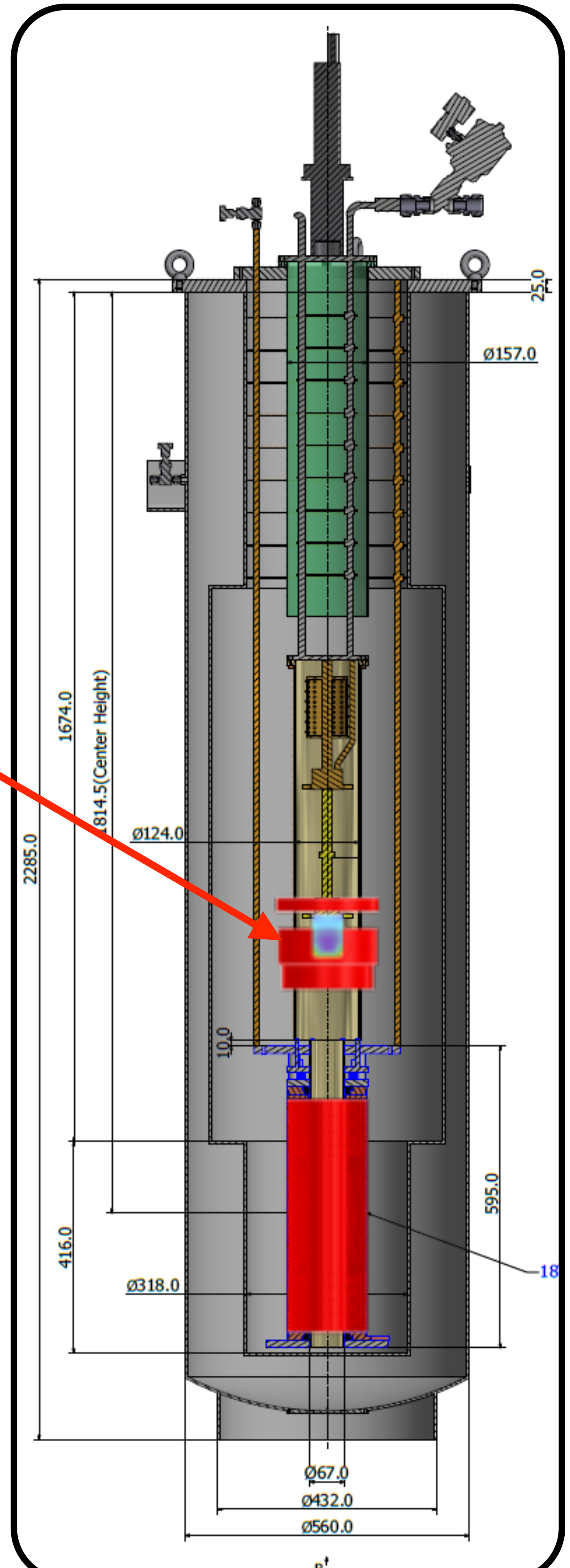
- **Improving JPA gain (up to ~20dB)**
  - **rewiring thermal contacts**
  - **proper grounding scheme**
  - **B-field active/passive shielding**
  - **accurate control of pumping freq.**
- **Check noise figure**
- **Automatic frequency tuning feedback**

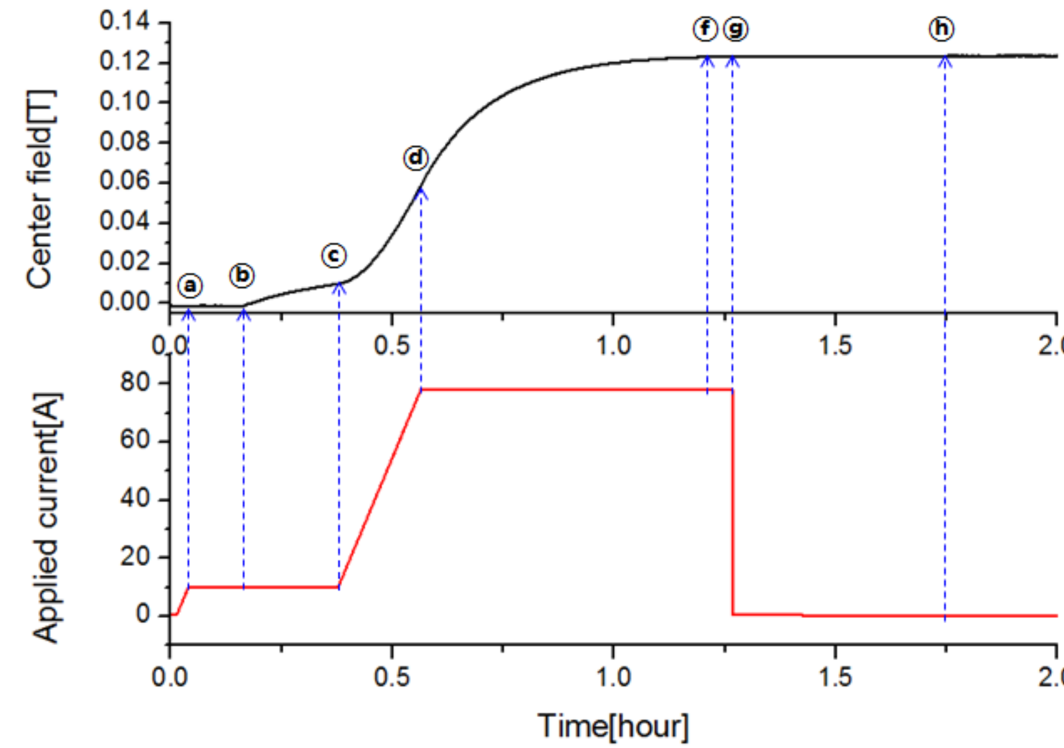
Cancellation Magnet Development



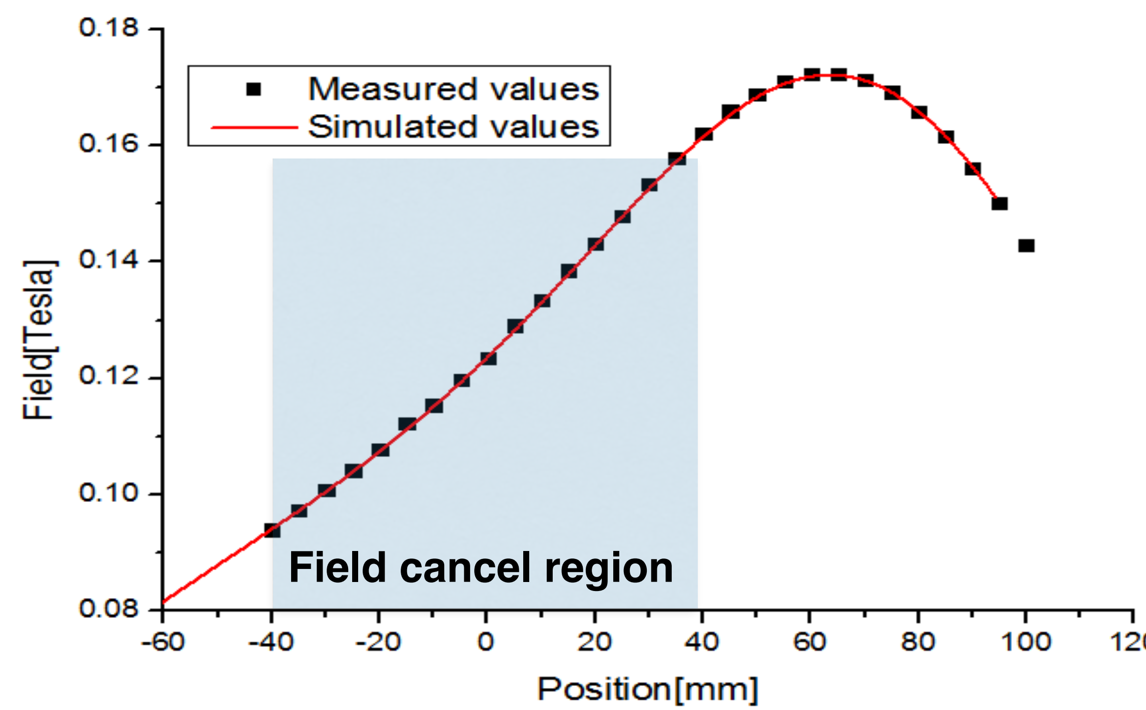
Cancellation Coil



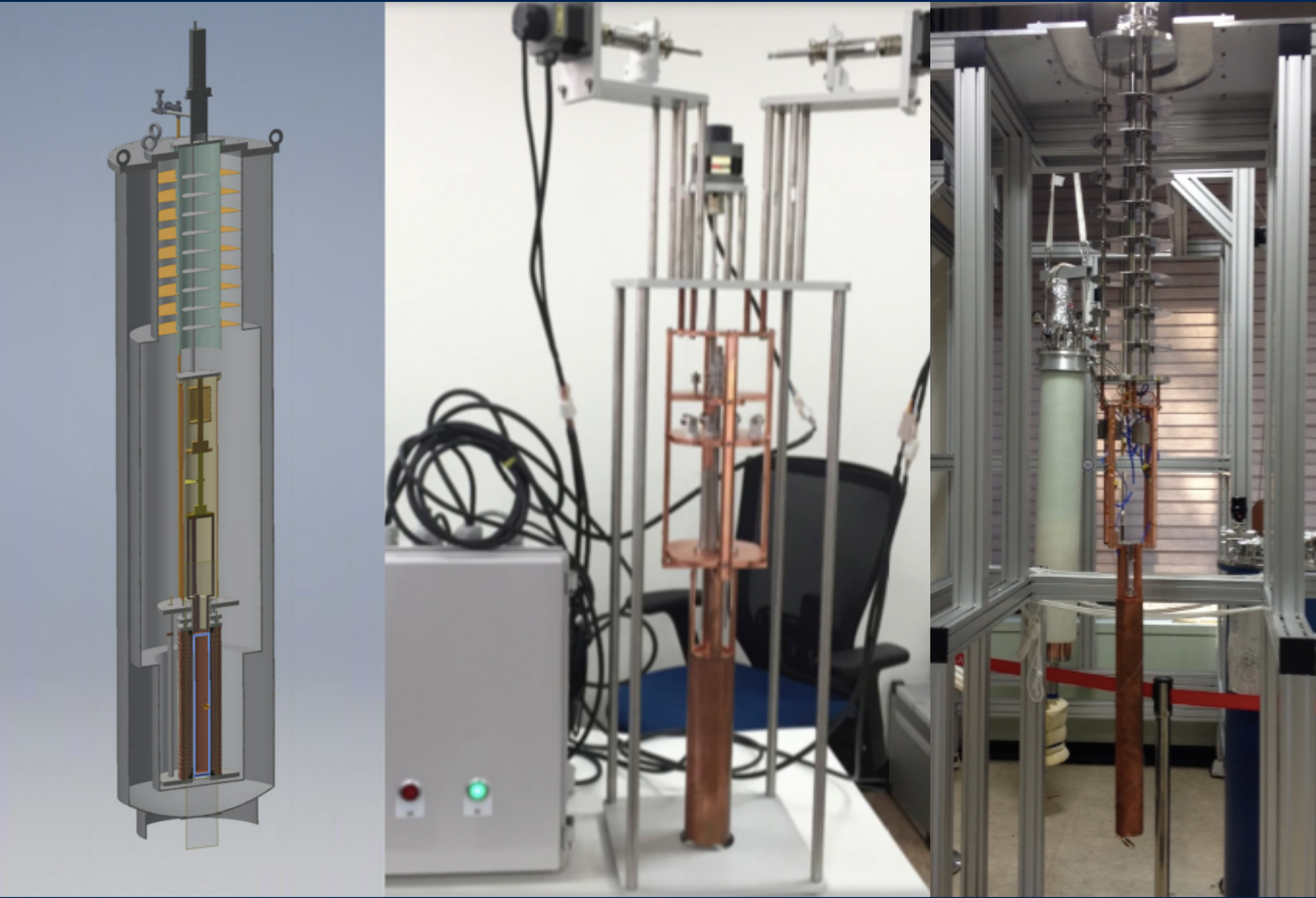


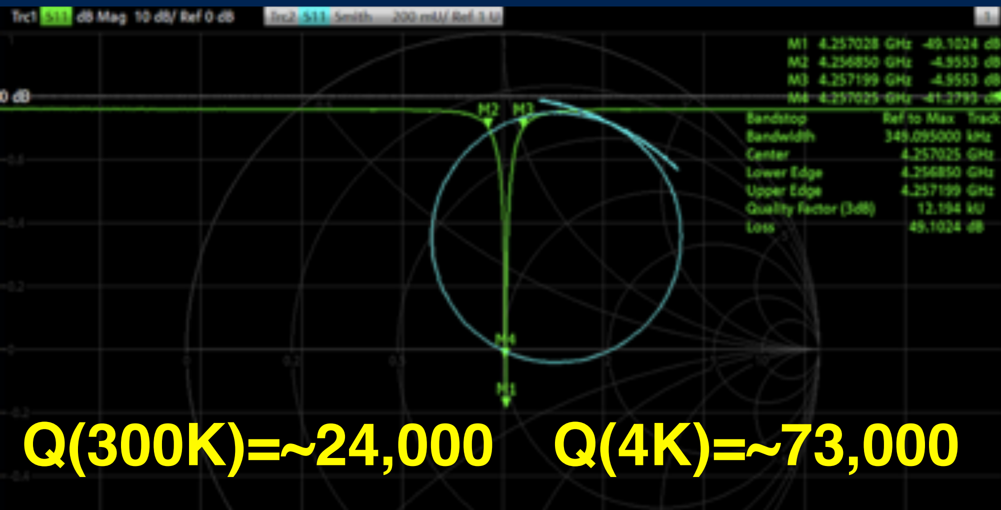


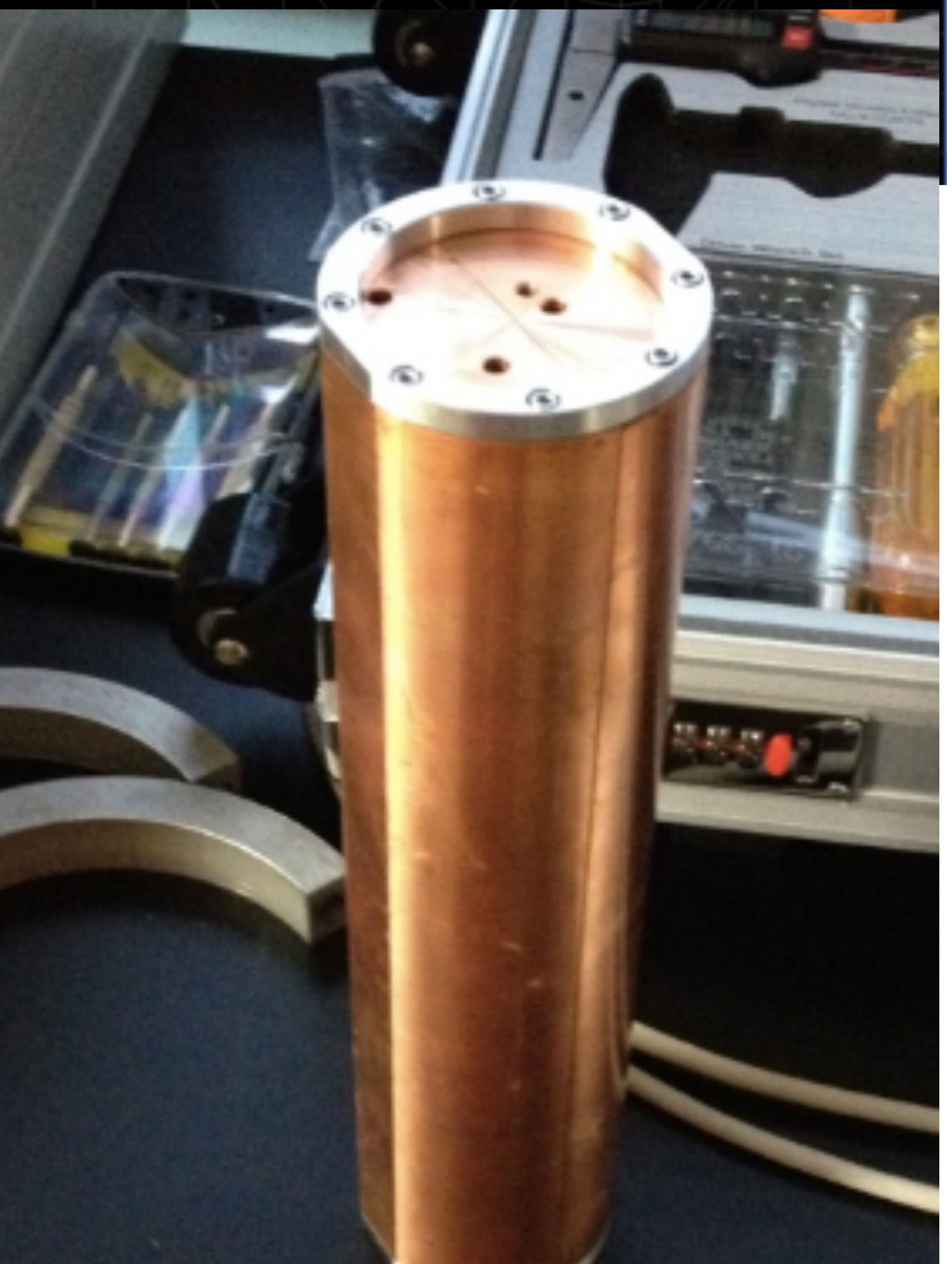
- Cancel out ~kG of stray field to a few G
- Field stability ~25ppm/hr
- Field profile test & quench test passed



Cryogenics and Frequency Tuning System



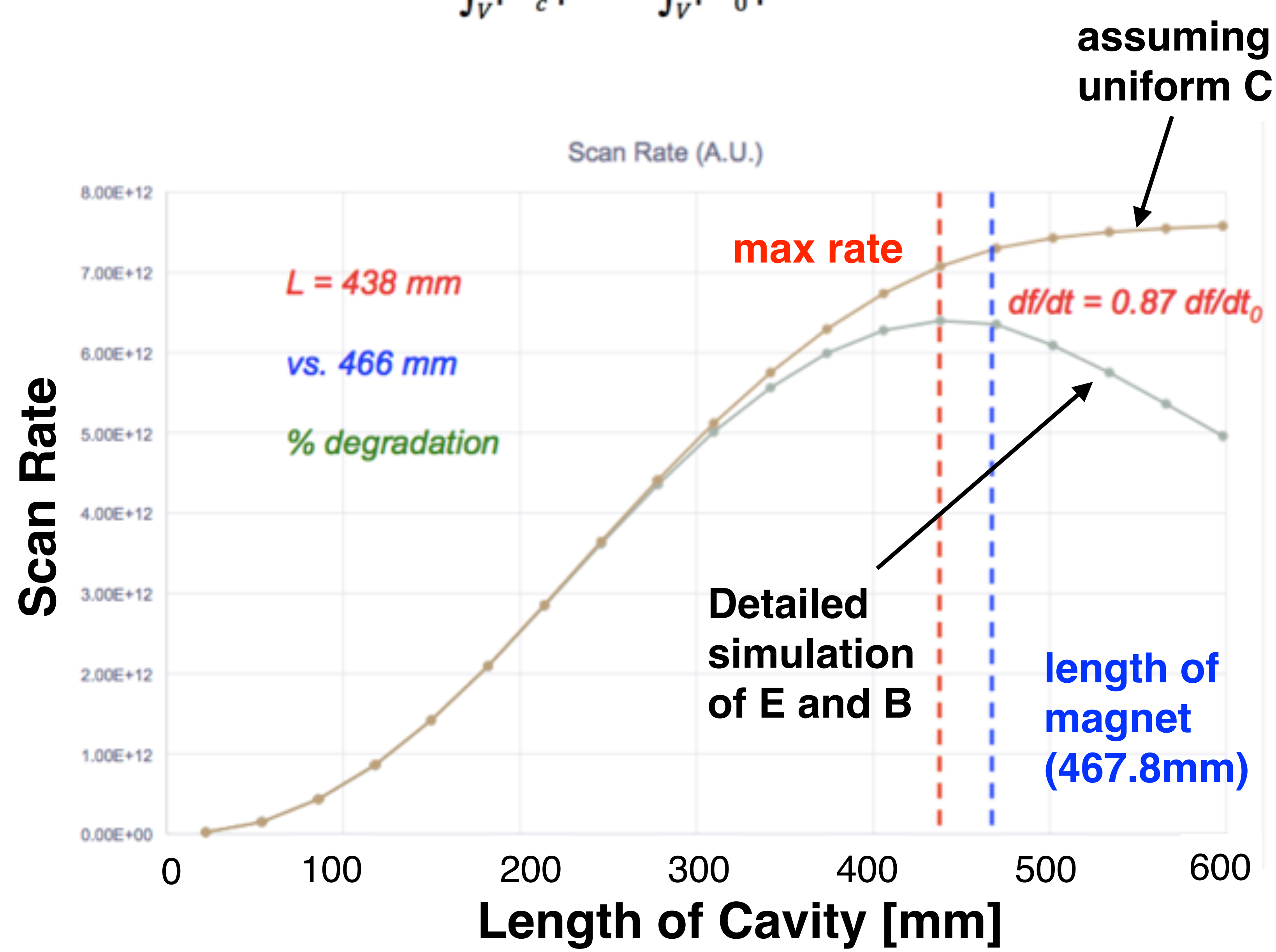




- **Scanning Rate vs. Length of Cavity**

$$\frac{df}{dt} = \left(\frac{1}{snr}\right)^2 \left(\frac{P_{signal}}{k_B T_{syst}}\right)^2 \frac{Q_a}{Q_L} = g_{a\gamma\gamma}^4 \left(\frac{\rho_a}{m_a}\right)^2 \left(\frac{B^2 VC}{k_B T_{syst}}\right)^2 Q_0 Q_a \frac{\beta^2}{(1+\beta)^3}$$

$$C = \frac{\left|\int_V \vec{E}_c \cdot \vec{B}_0 \, dV\right|^2}{\int_V |\vec{E}_c|^2 \, dV \cdot \int_V |\vec{B}_0|^2 \, dV}$$



Signal Power and Scan Rate

- **Conversion power = 2.6 × 10^{-23} W**

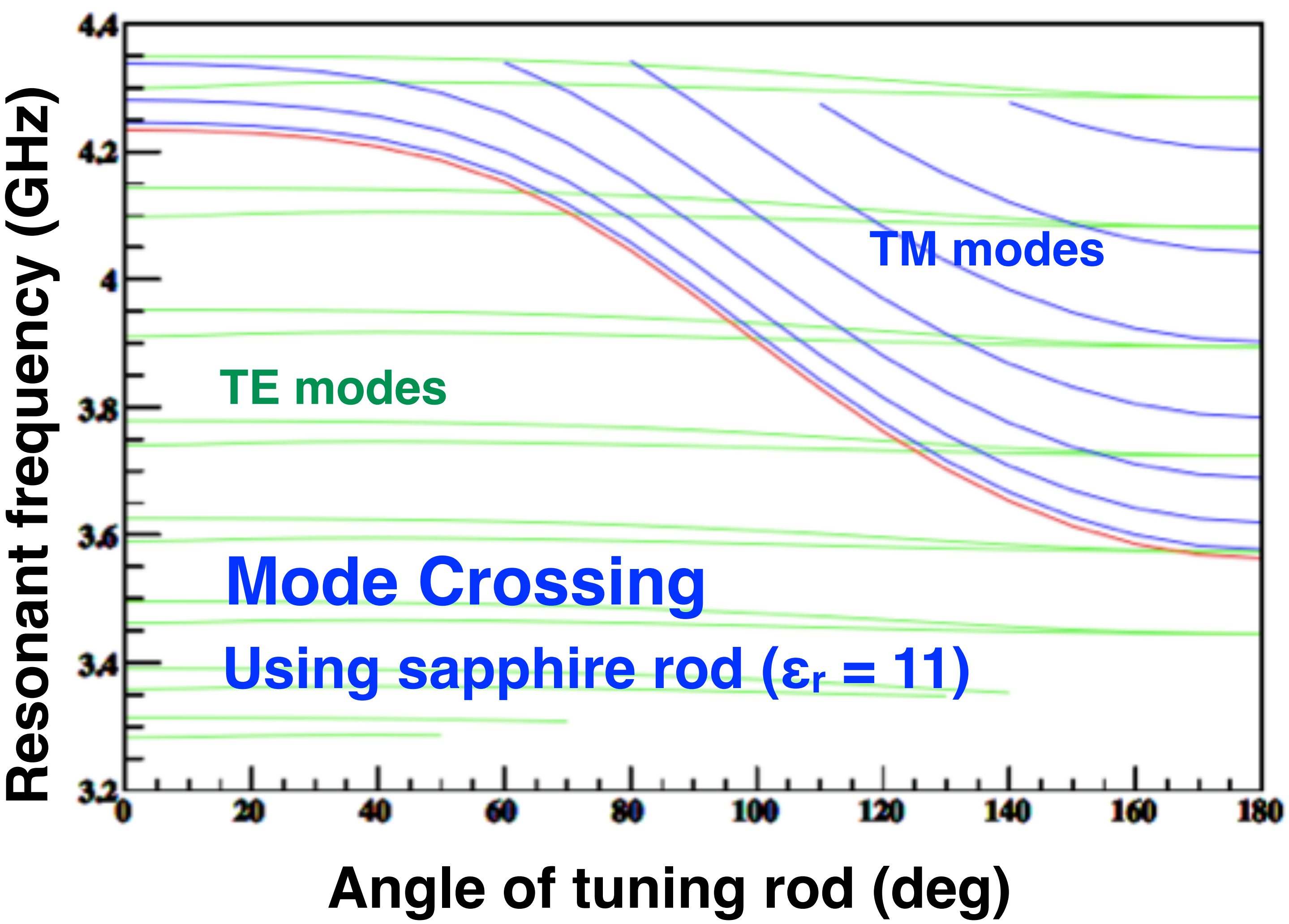
$$P_{a\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C Q_L, \quad Q_L = \frac{1}{1+\beta} Q_0$$

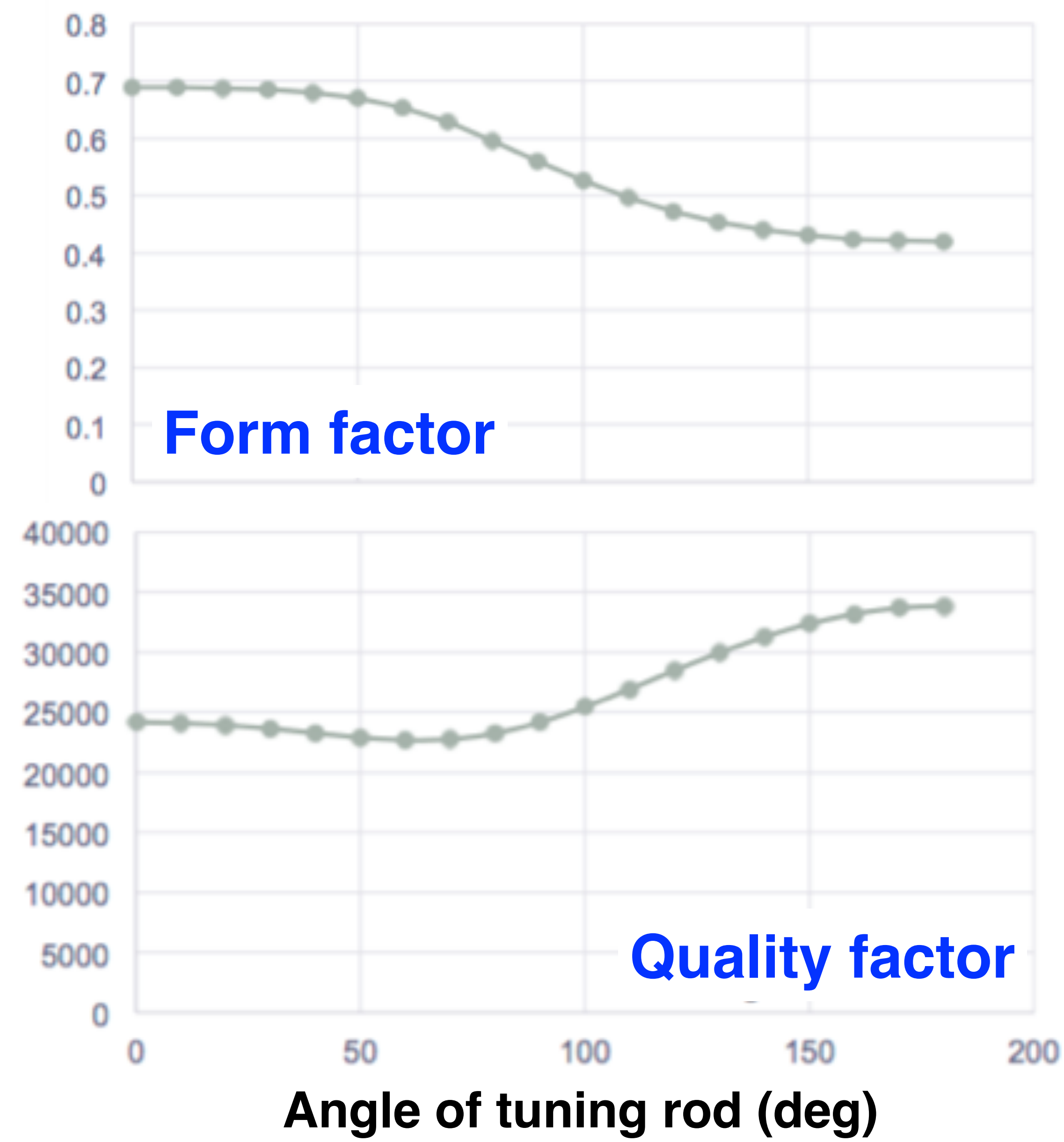
Scan frequency ranges:

using dielectric rod: 3.6~4.6 GHz
using copper rod: 4.6~6.0 GHz
- SQUID for lower freq probe
- JPA/JPC for higher freq probe

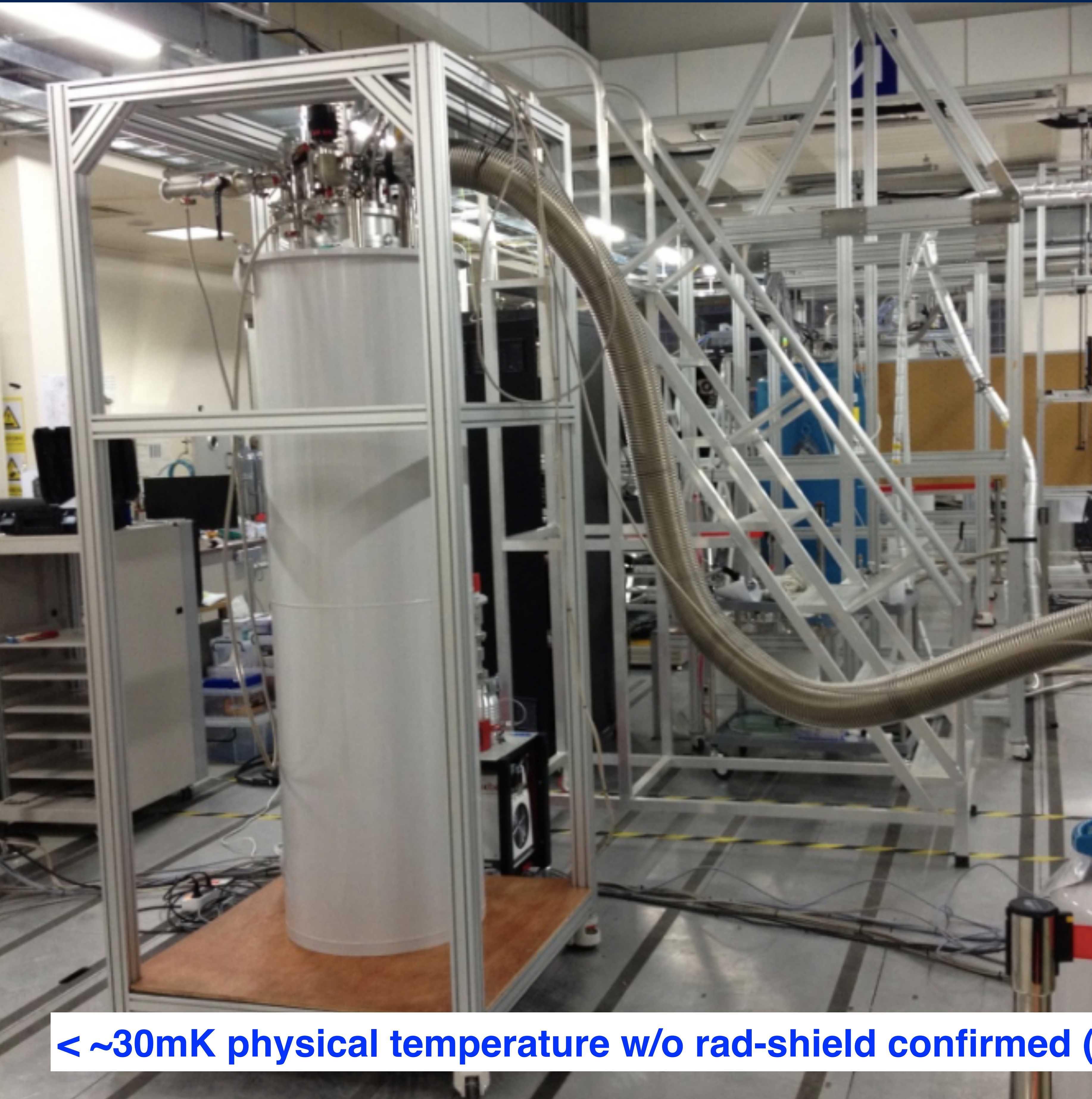
- **Scan rate = ~150 MHz/year (KSVZ) with 0.4K T_{ph}**

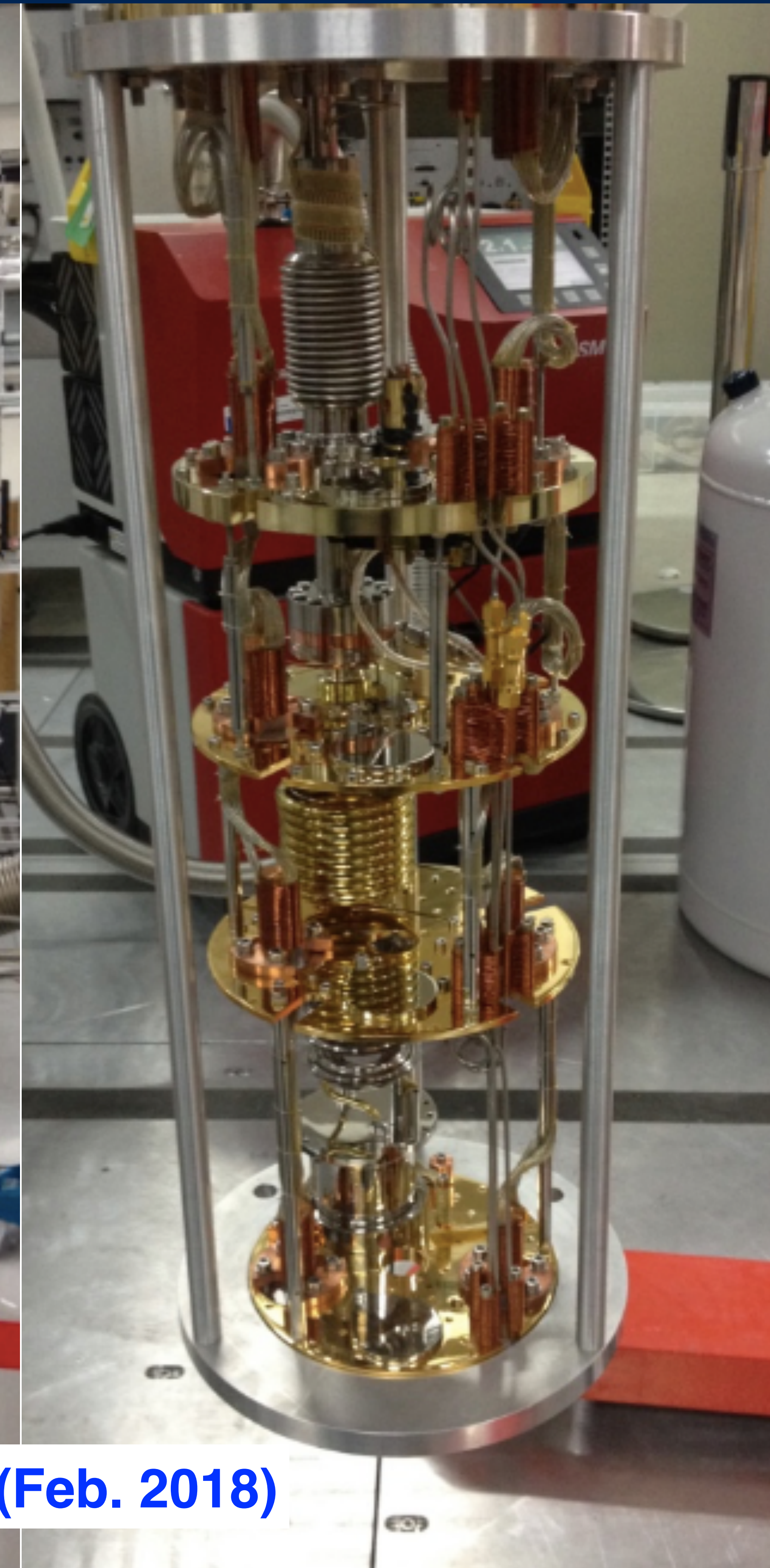
$$\frac{df}{dt} = \left(\frac{1}{snr}\right)^2 \left(\frac{P_{signal}}{k_B T_{syst}}\right)^2 \frac{Q_a}{Q_L} = g_{a\gamma\gamma}^4 \left(\frac{\rho_a}{m_a}\right)^2 \left(\frac{B^2 V C}{k_B T_{syst}}\right)^2 Q_0 Q_a \frac{\beta^2}{(1+\beta)^3}$$





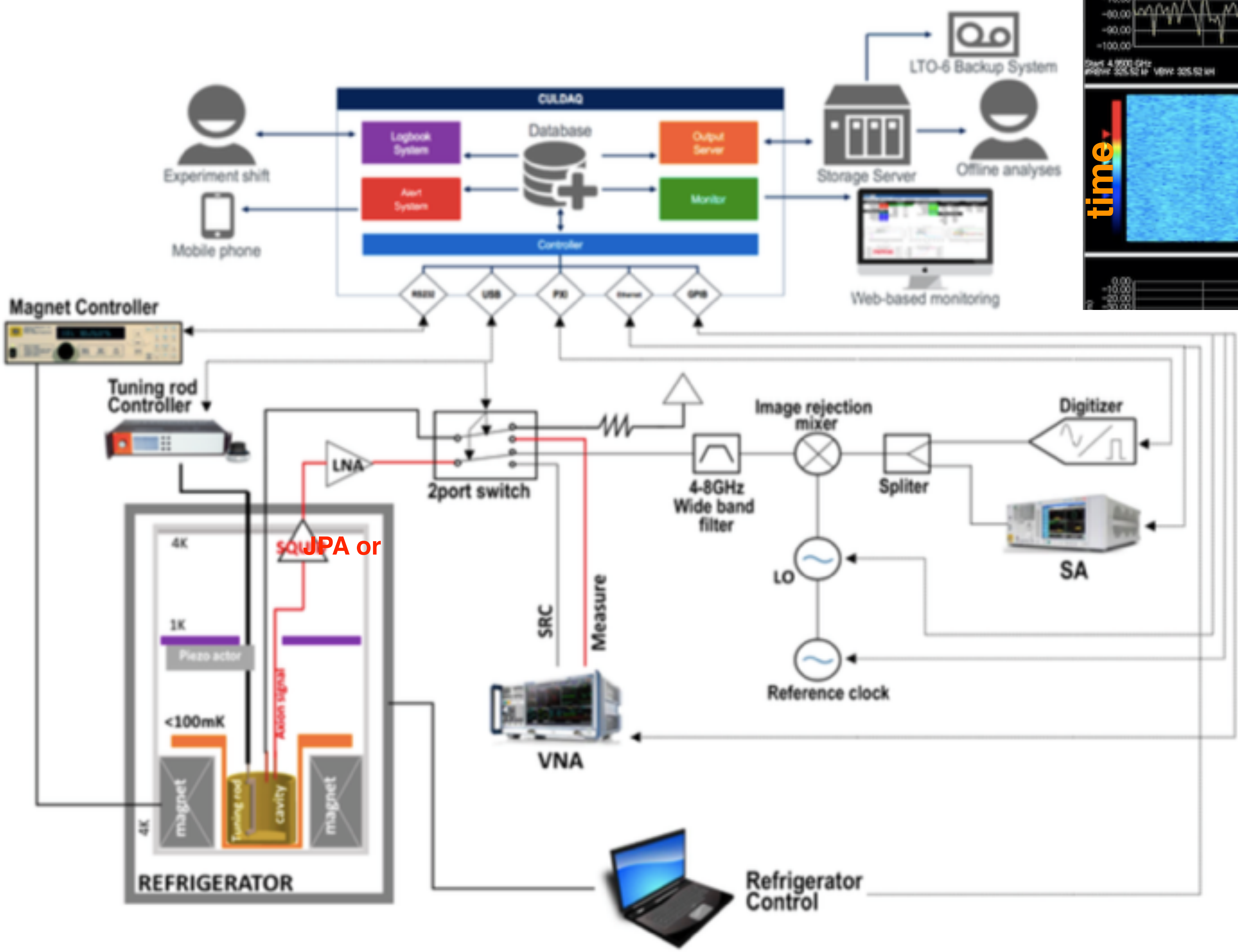
Kelvinox 400 (Oxford)

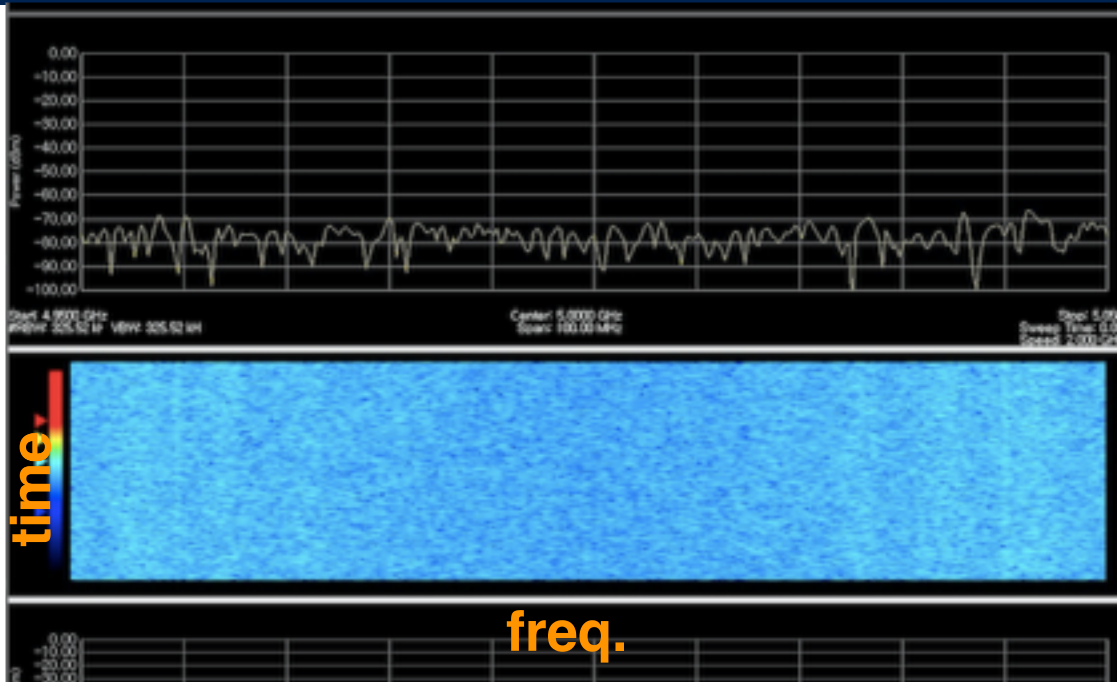




< ~30mK physical temperature w/o rad-shield confirmed (Feb. 2018)

CAPP18T DAQ System





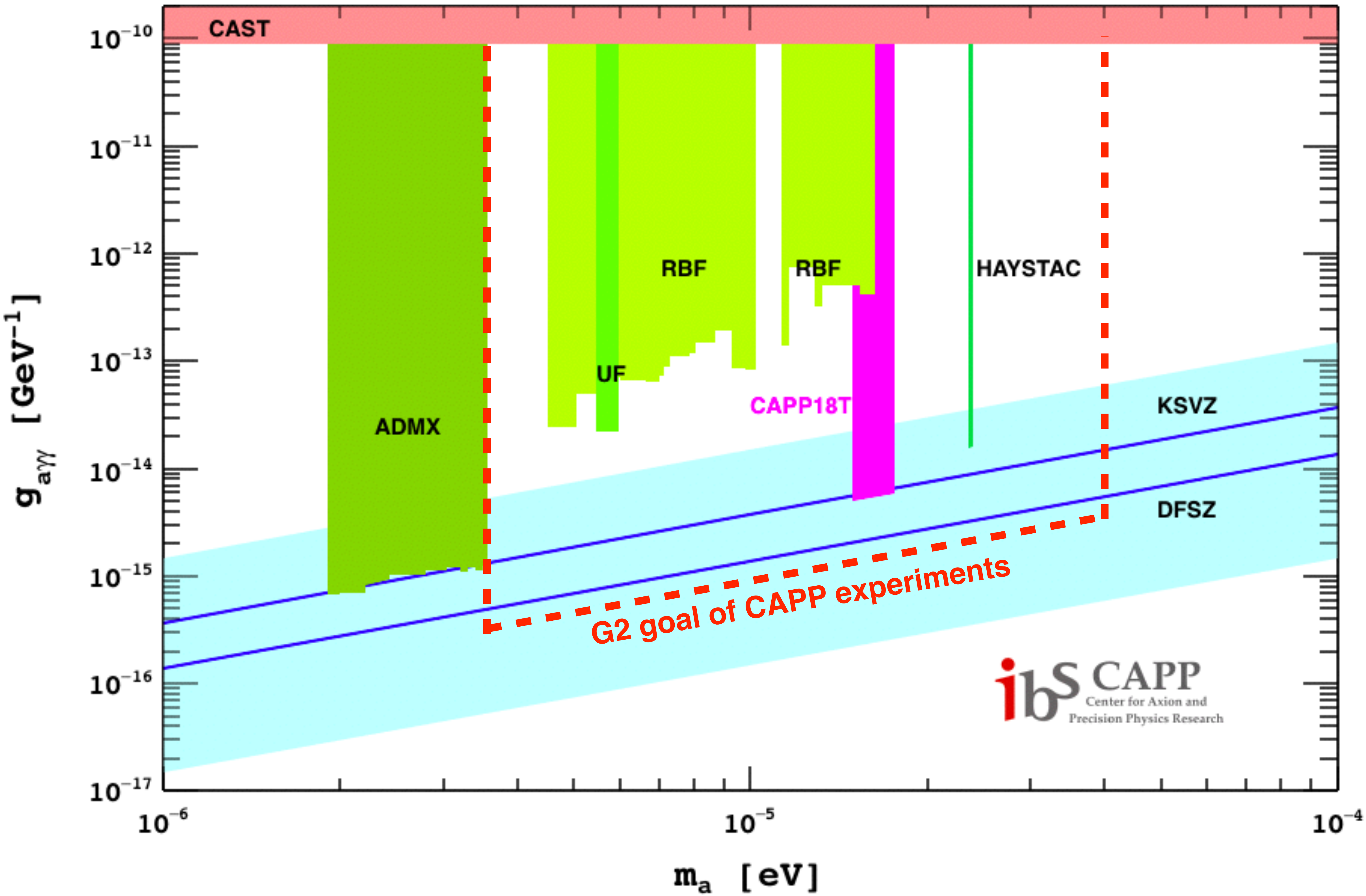
- We are trying to achieve dead-time free DAQ (both in time-domain and freq-domain)

CAPP Dark Matter Axion Search Schedule

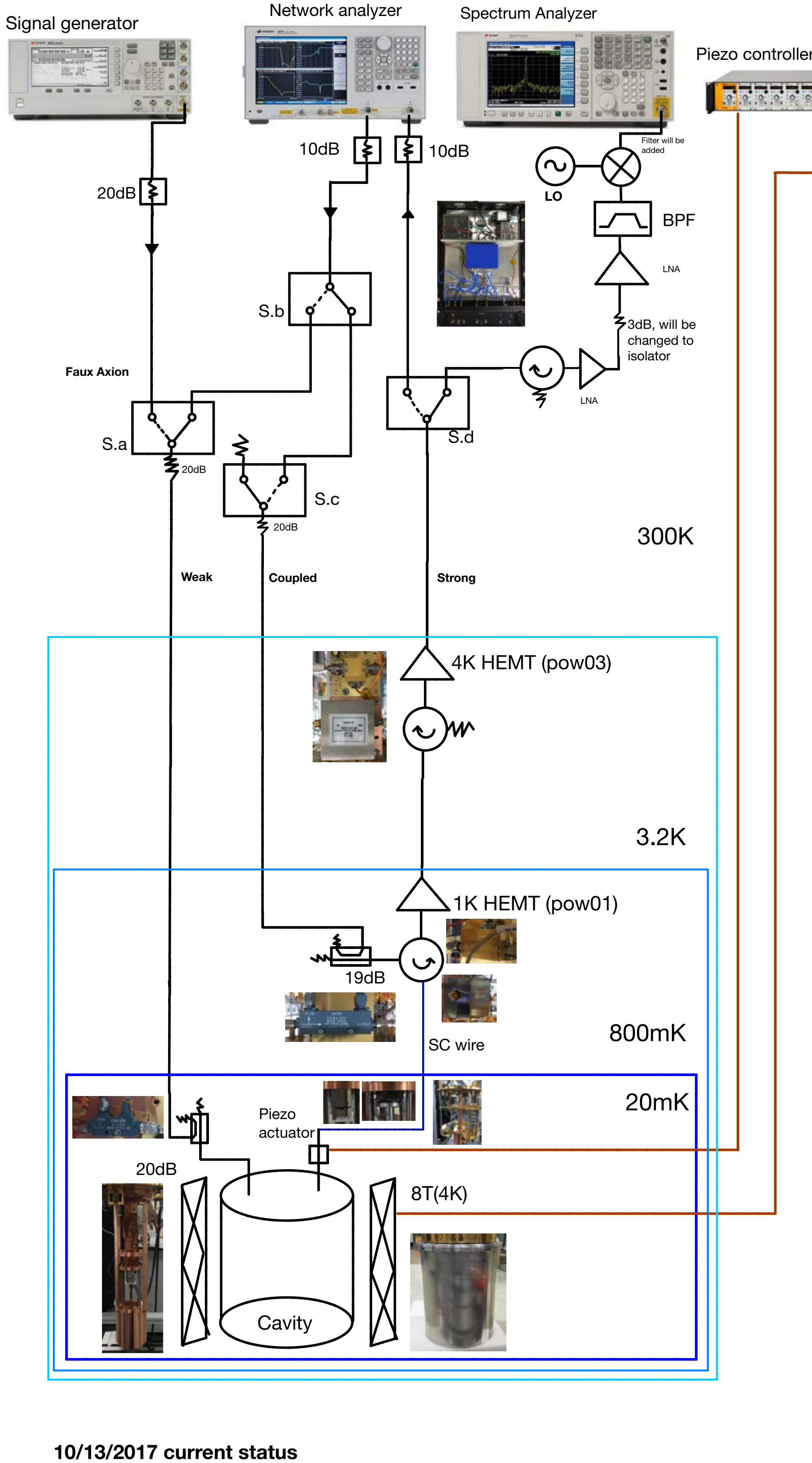
	2017	2018	2019	2020	2021	2022
8T/16cm CAPP8Tb (BlueFos)	setup		experiment		multiple cavity	
18T/7cm CAPP18T (SuNAM)	setup		experiment		multiple cavity	
25T/10cm CAPP25T (BNL)			setup		experiment	
12T/32cm CAPP12T (Oxford)			setup		experiment	

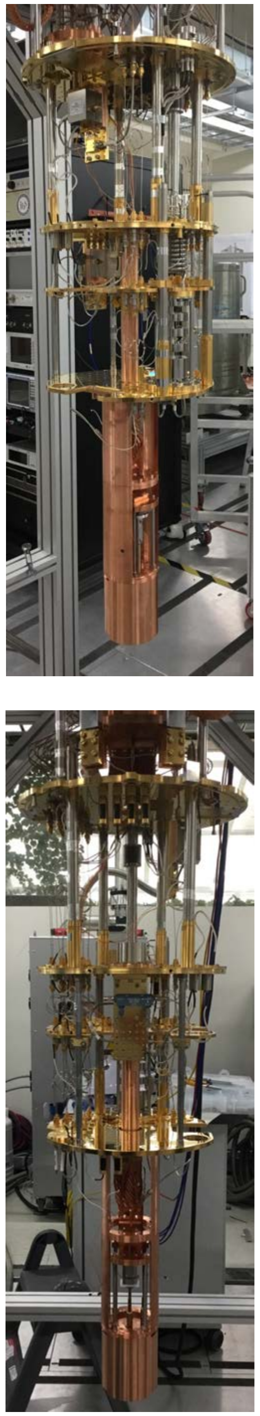
There are R&D efforts for higher mass dark matter axion search (>40μeV)

Axion Dark Matter Search at CAPP

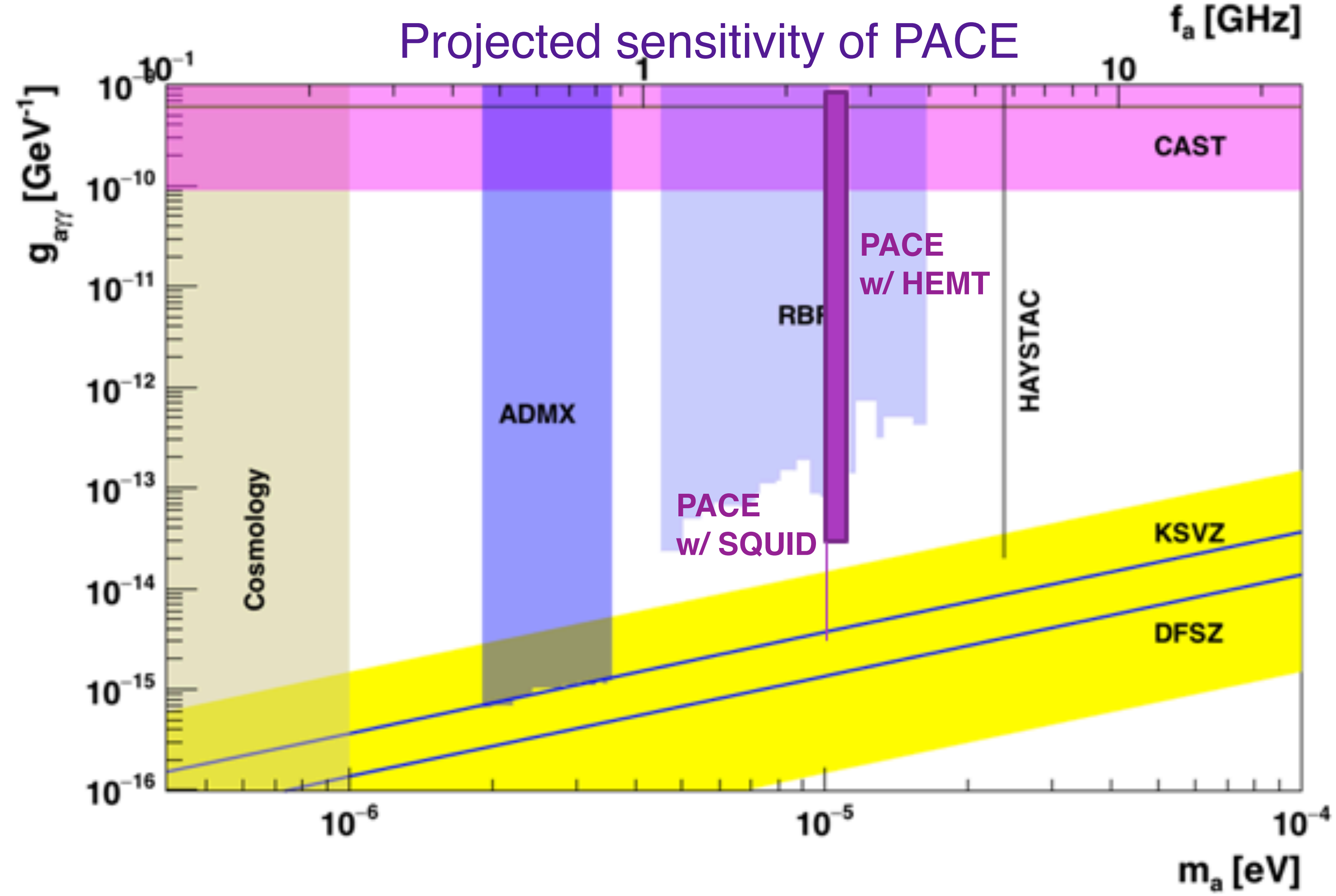


CULTASK-PACE (Pilot Axion Cavity Experiment)

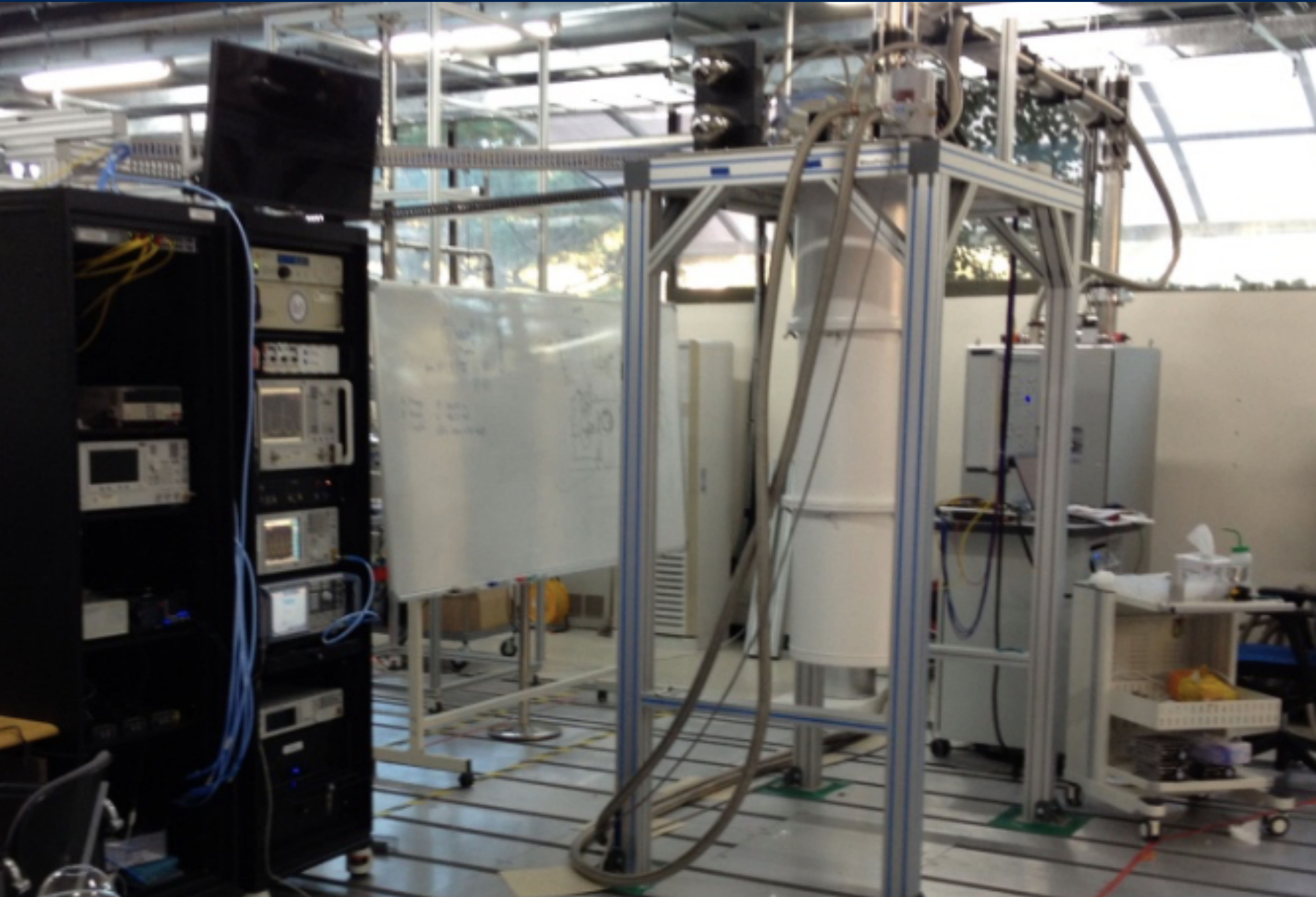




Magnetic Field: 7.94 T
Cavity Volume: 0.59 liter
Physical Temp. Of Cavity: 40 mK
Amplifier T(noise): ~2 K (w/ HEMT amplifier)
~500 mK (w/ SQUID later)
Sensitivity: ~ 10 x KSVZ
Scan (RBF-missing) axion mass range:
2.462 – 2.734 GHz (~ 4 months w/ HEMT)
< 0.5 months w/ SQUID)

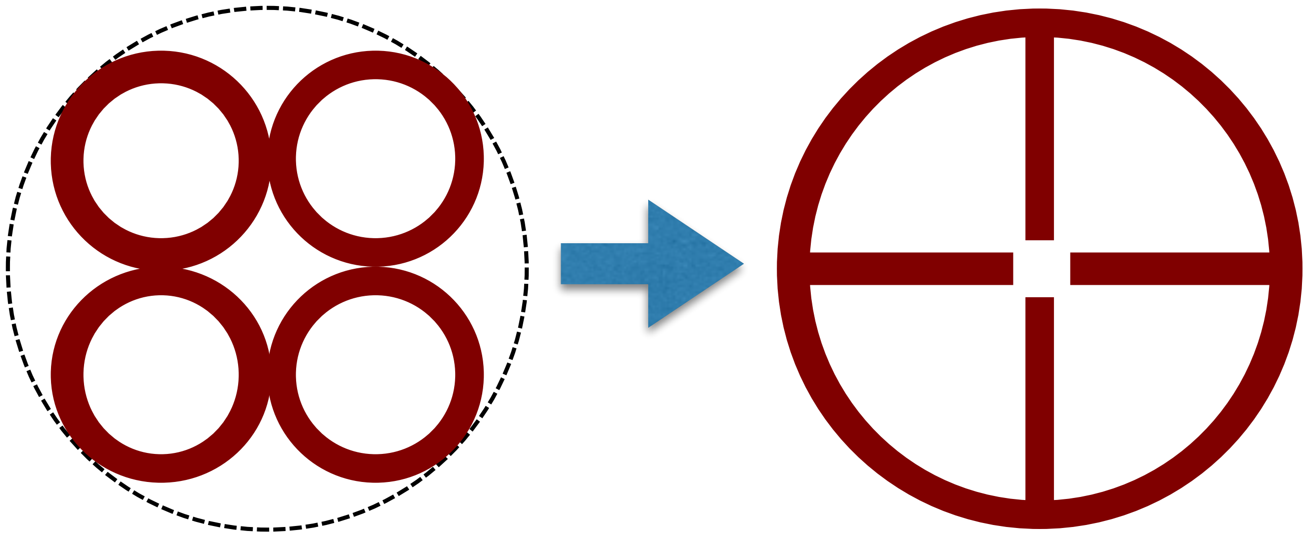


CULTASK-PACE (8T/10cmD) Setup



CAPP8Tb (8T/16cmD) Setup

Multi-Cell Cavity R&D



Probe higher frequency modes using the same size magnet without loosing fiducial volume space
PLB 777 412-419 (arXiv:1710.06969)

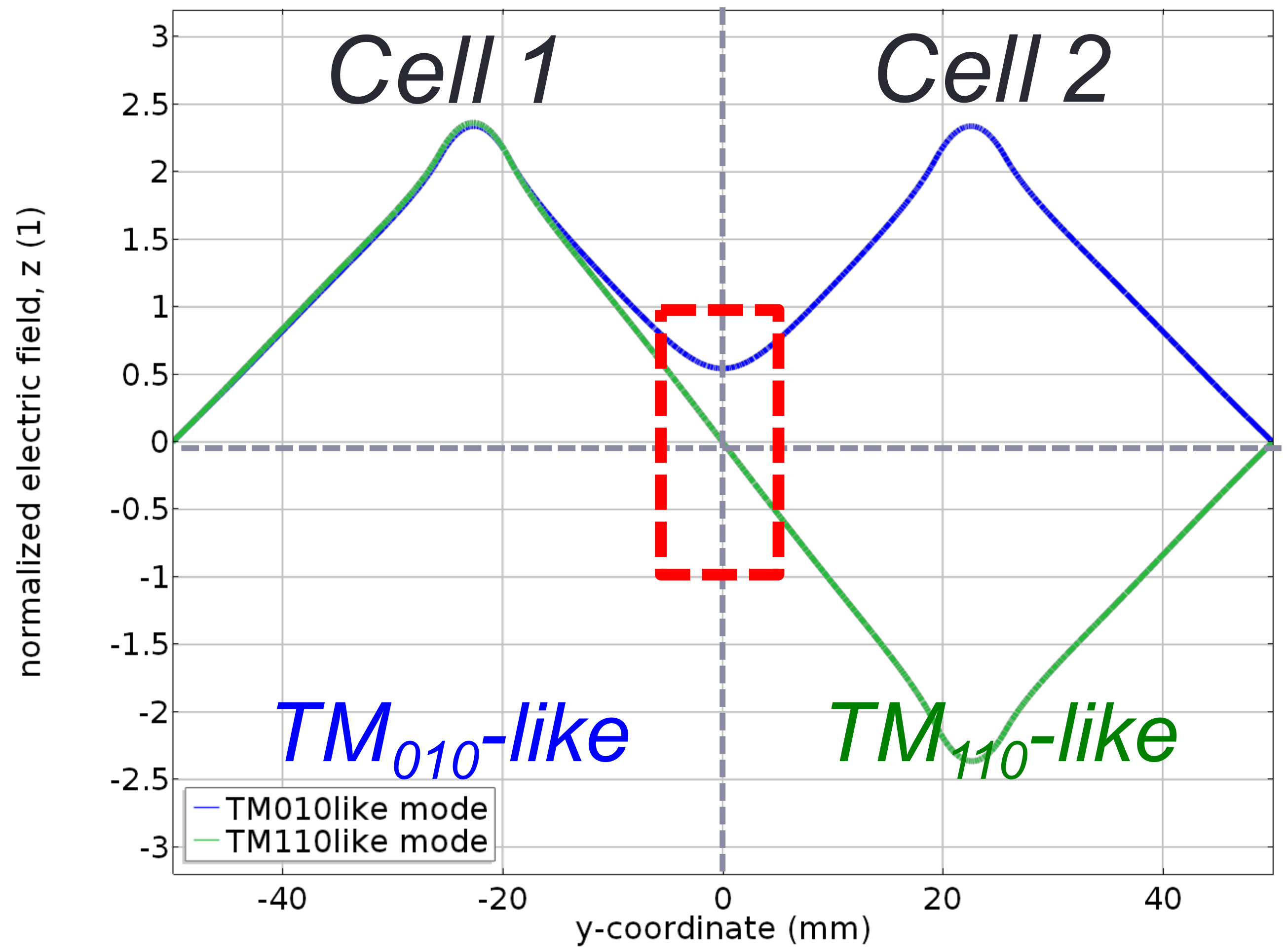
$$[df/dt]_{\text{4-cells}} \simeq 2 \times [df/dt]_{\text{4-cavity}}$$

Better than multiple-cavity design

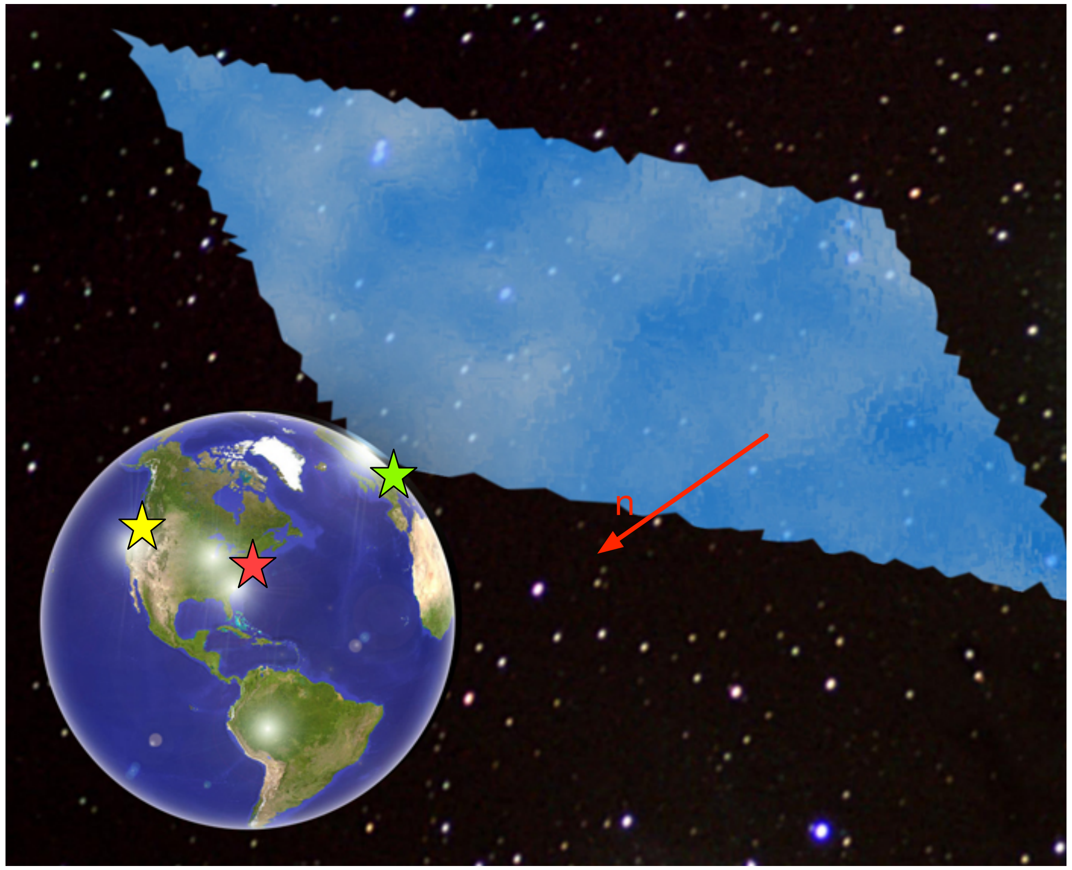
Effective use of a magnet volume
x1.7 in volume (x2.0 faster in scan rate)

Simple receiver chain
A single antenna (No signal combiner)

Easy phase-matching mechanism
E = 0 at the center for higher modes



Global Network of Optical Magnetometers for Exotic physics (GNOME)

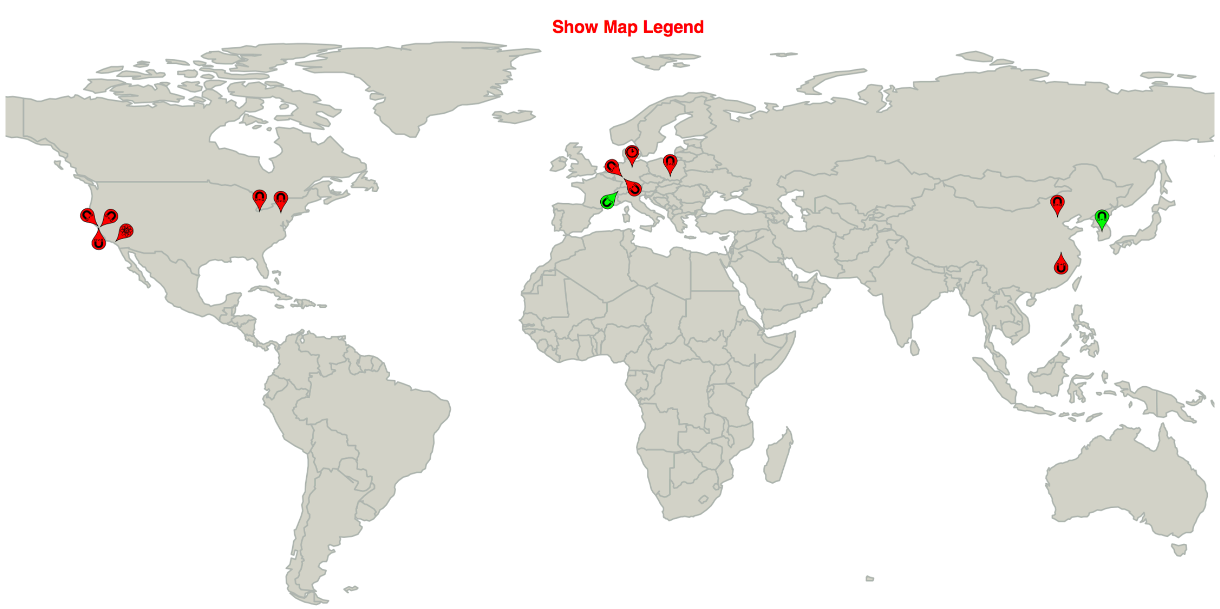


Axionic domain wall may exert toque on atomic spin.

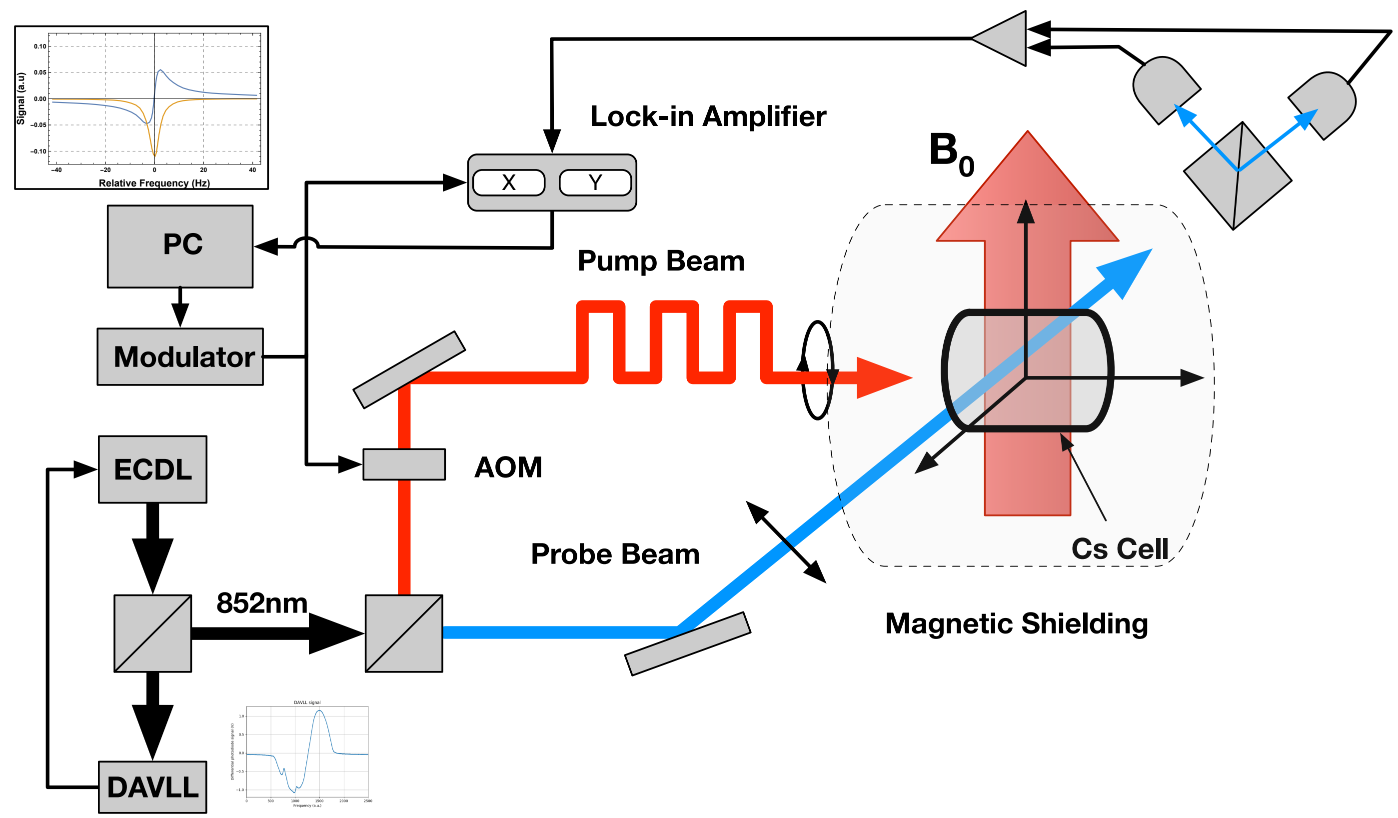
$$H_a = \frac{\hbar c}{f}\mathbf{S}\cdot\nabla a(\mathbf{r})$$

CAPP detector is built and running since Nov 2017

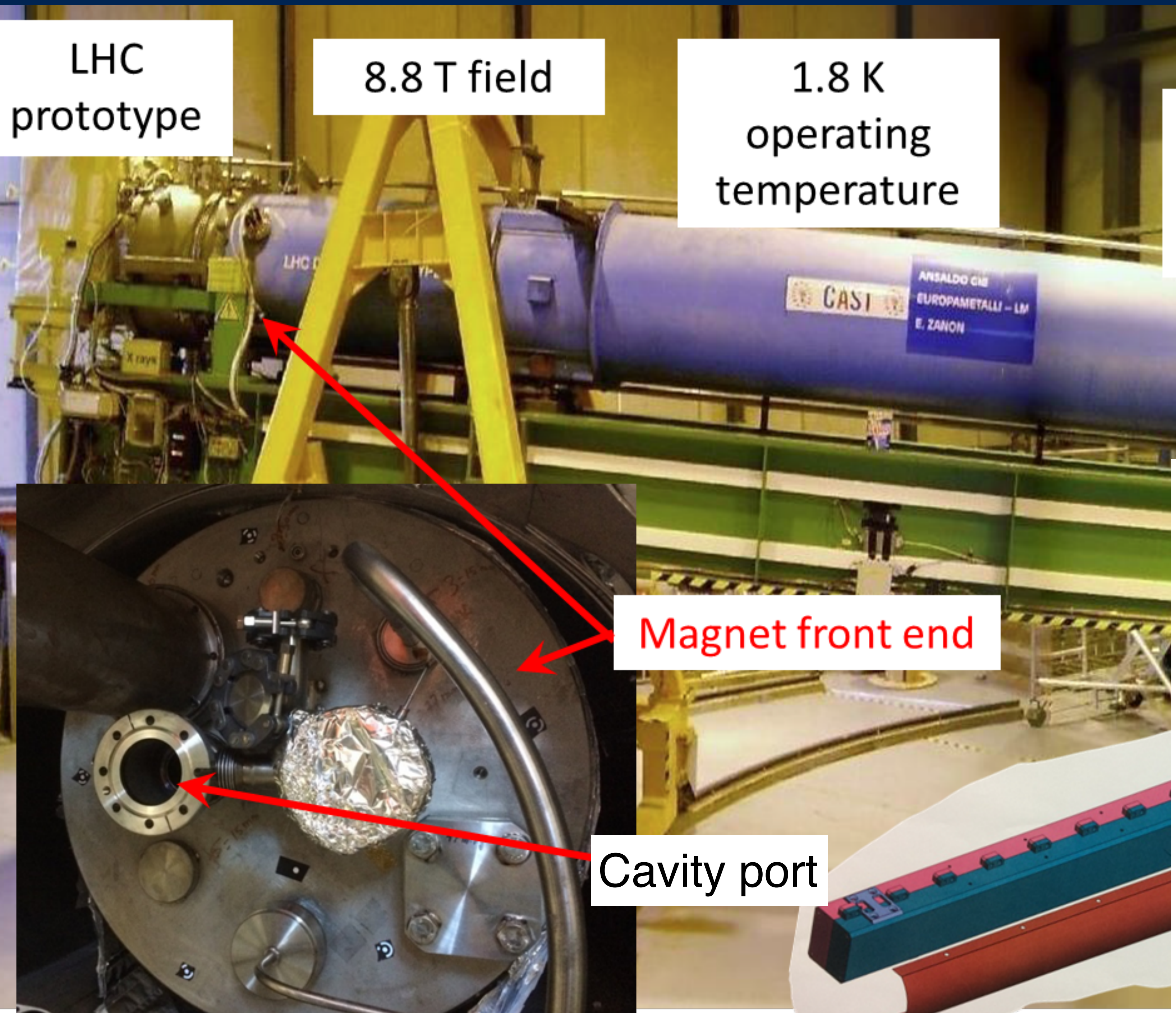
- Cs based supersensitive magnetometer
- Sensitivity ~100 fT/√Hz, BW=50Hz

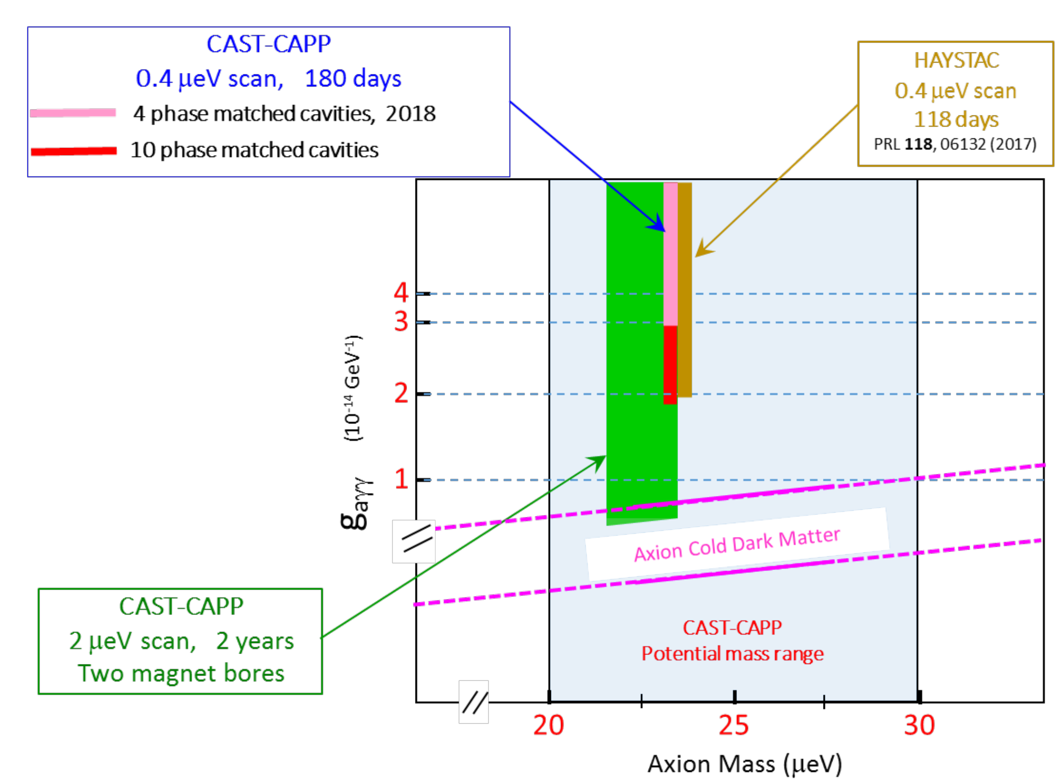


GNOME network around the world



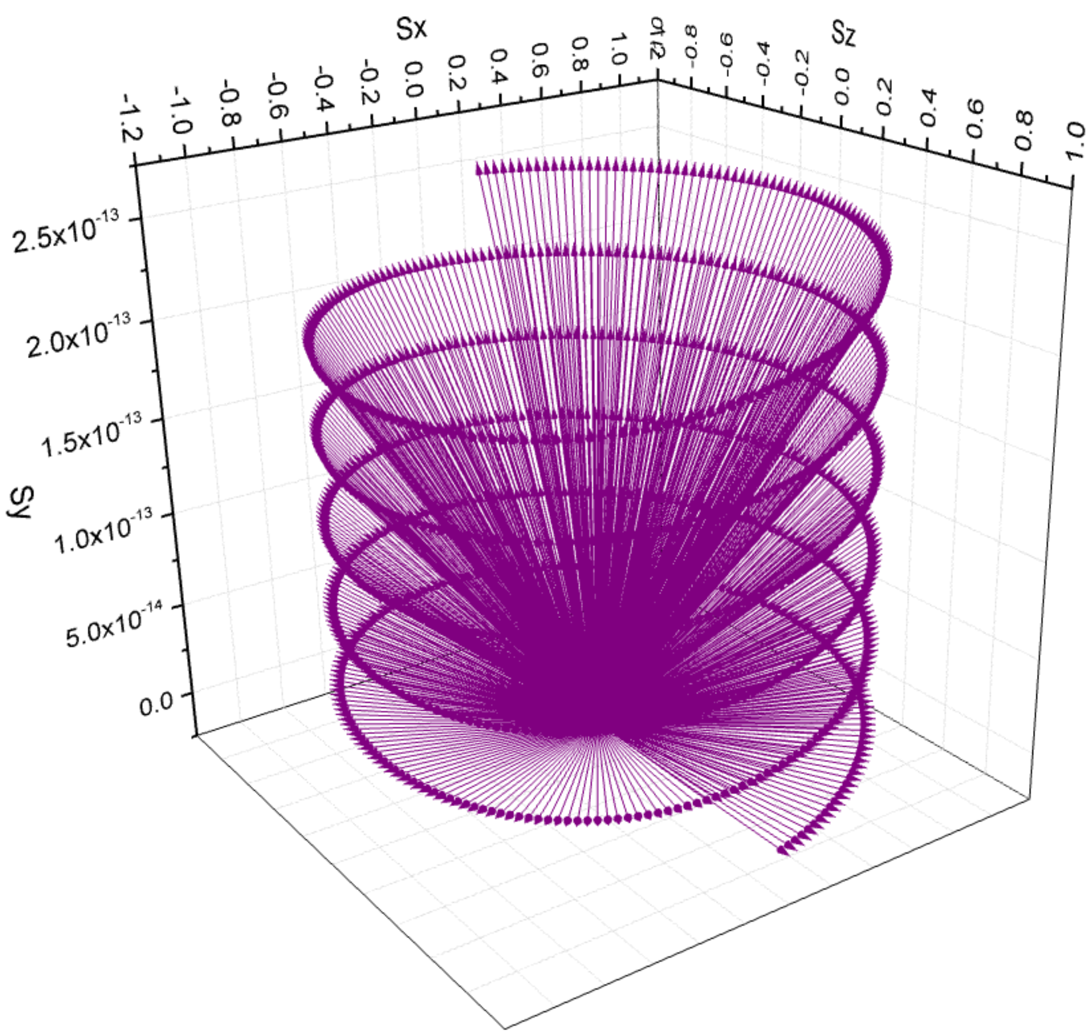
IBS/CERN Axion Search (Using CAST Magnet)



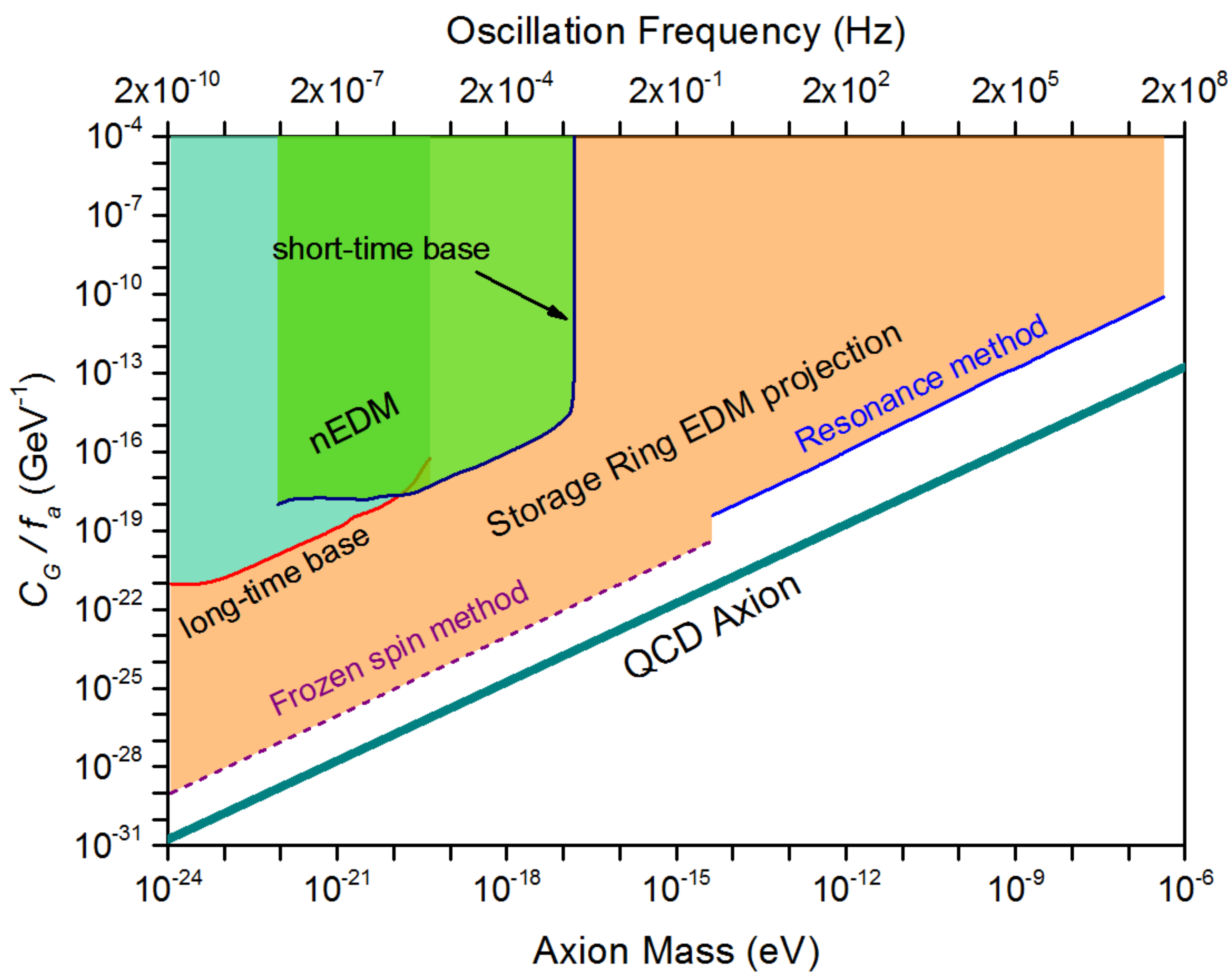


Axion Search in Storage Ring EDM

- Oscillating axion field is coupled with gluons, fermions, nucleon, etc.
- **Oscillating EDM Method (arXiv:1710.05271)**
  Resonance condition between g-2 precession and axion induced oscillating EDM
    mHz<f_{axion}<100 MHz: Use resonance method
    f_{axion}<mHz: Use Frozen spin method
- Benefits: Can utilize large effective electric field (>10 MV/m)



EDM precession accumulate
at the resonant condition



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 Programs at KAIST-IBS/CAPP
- Discovery may happen anytime soon!