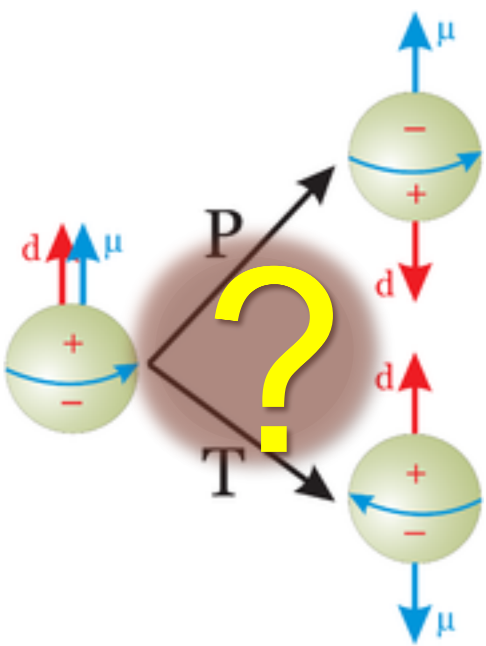
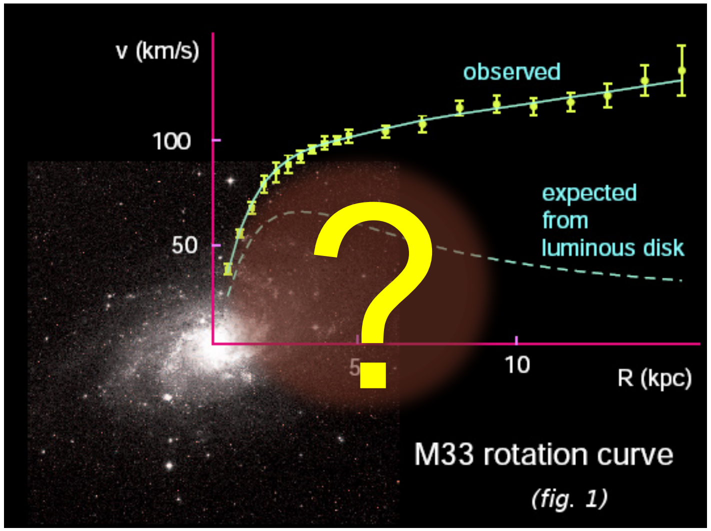
Institute for Basic Science

Axion Research at CAPP/IBS

SungWoo YOUN
CAPP/IBS

CosPA 2015, Daejeon, Korea
Oct. 12~16, 2015





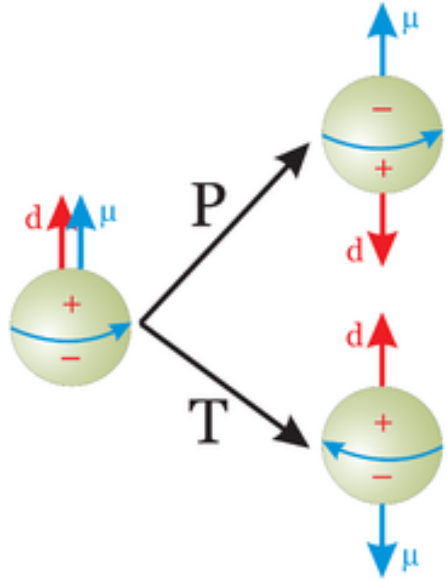
CAPP/IBS

- *Center for Axion and Precision Physics Research*
  - *Funded by the Institute for Basic Science*
  - *Located at KAIST campus in Daejeon, Korea*
  - *Led by Prof. Semertzidis Yannis*

- *Experimental efforts to address the Strong-CP problem*
  - *State of the art dark matter axion experiment*
  - *Storage ring proton EDM*
- *Leading roles in international collaborations in intensity frontier*
  - *Muon g−2*
  - *COMET (μ→e conversion)*
- *Plenary talk by Prof. Semertzidis tomorrow for more details*

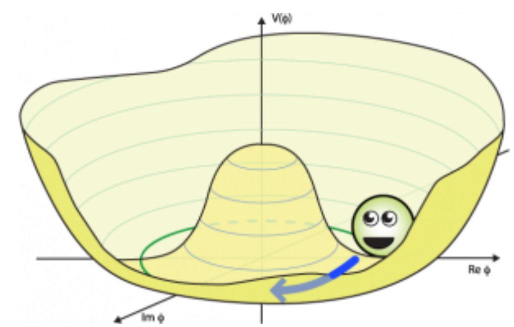
Strong-CP Problem

- *CP symmetry breaking (CPV)*
  - *Matter-antimatter imbalance in our universe*
- *CPV in electroweak interaction*
  - *Observations are consistent with predictions*
  - *CPV phase in CKM matrix*
- *CPV in strong interaction*
  - *Theory: natural CPV term due to non-zero QCD vacuum*
    - *Sizable neutron dipole moment (d_n)*
    - *At least one of the quarks are massless*
  - *Experiment: QCD respects CP symmetry*
    - $d_{n,exp} \leq 10^{-26}$ *e*cm =>* $\Theta_{QCD} \leq 10^{-10}$
    - *None of the quarks are massless*
  - *This is known as strong-CP problem*
  - *One of the most important but unsolved problems in physics*



Axion

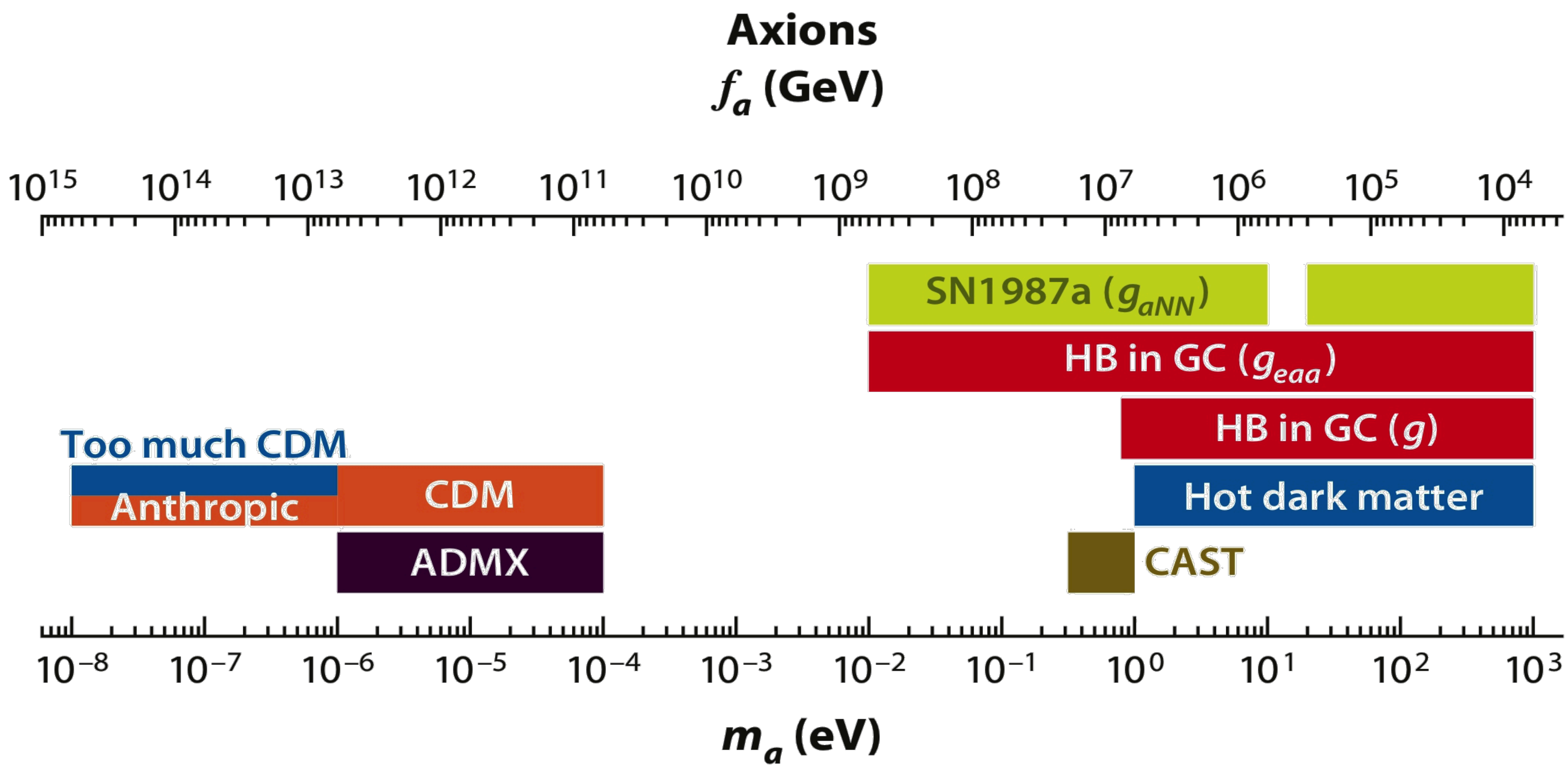
- *Peccei-Quinn theory (1977)*
  - *An elegant idea to solve the strong CP problem*
  - *A new global symmetry, $U(1)_{PQ}$, with a scalar field permeating all space*
  - *Spontaneous (explicit) PQ symmetry breaking involving a new Goldstone boson: axion*
  - *Similar to Higgs mechanism*
    - *Spontaneous EWSB involving the Higgs boson*
    - *Discovery in 2012 has enhanced the interest in the axion and the possibility of its existence*



Axion properties			
Interaction	*Gravity, EM*	*Mass*	*μeV to eV*
C	*0*	ρ_{local}	*0.45 GeV/cm³*
J^P	0^-	$\beta \sim 10^{-3} \rightarrow Q_a \sim 10^6$	

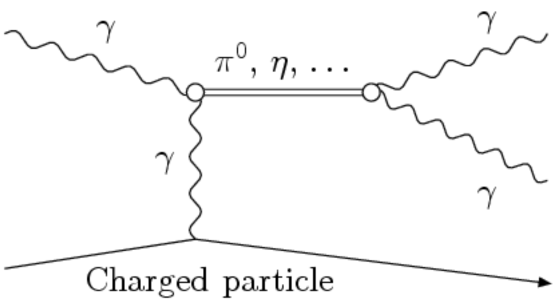
Axion and Dark Matter

- *Attractive dark matter candidate*
  - *If its mass lies between 1 μeV and 100 μeV, the axion can fit the halo model*
  - *Referred to as axion dark matter*

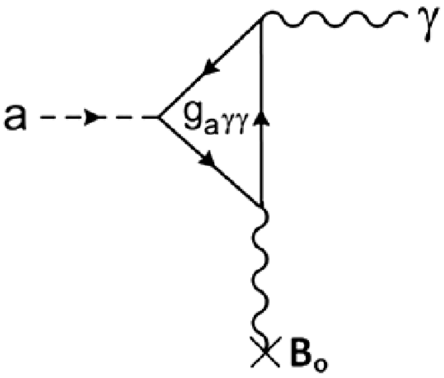


Detection Strategy

- *Primakoff Effect*
  - *Pseudoscalar production by a photon scattering with an EM field*
  - $\gamma\gamma \rightarrow \pi^0, \eta, \ldots$



- *P. Sikivie's method (1983)*
  - *Reverse Primakoff effect*
  - *Conversion of axions into microwave photons*
    - $a \rightarrow \gamma\gamma$ (cf. $\pi^0 \rightarrow \gamma\gamma$)
  - *Detectable in a EM rasontor in the presence of a strong magnetic field*
    - *Principle of haloscope*
    - *Most promising technique for the faintest axion-photon coupling*

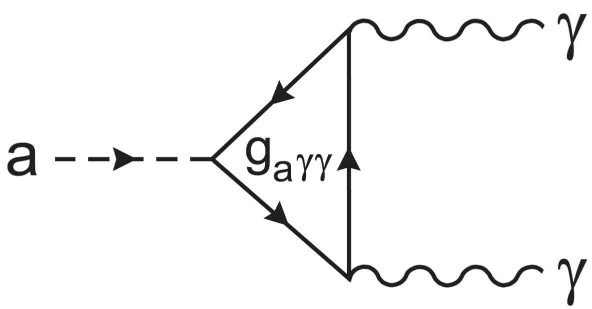


Axion Coupling to Photons

- *Lagrangian*

$$L_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4}\varphi_a F_{\mu\nu}\tilde{F}^{\mu\nu} = -g_{a\gamma\gamma}\varphi_a \mathbf{E}\cdot\mathbf{B}, \quad g_{a\gamma\gamma} \equiv \frac{\alpha}{\pi}\frac{g_\gamma}{f_{PQ}}$$

- *$g_{a\gamma\gamma}$: coupling constant*
- *φ_a: axion field*
- *F: EM field-strength tensor*



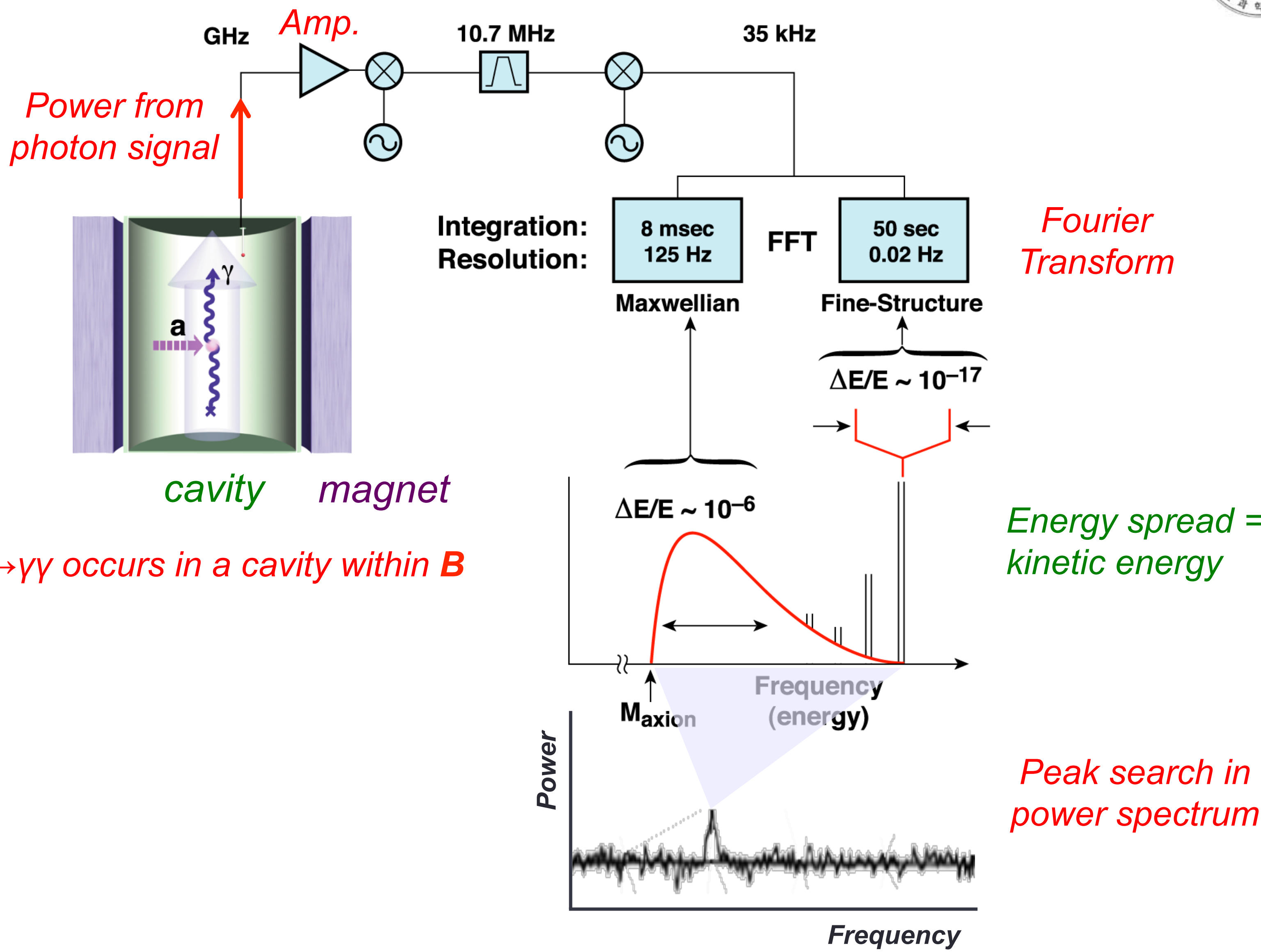
- *α: fine structure constant*
- *g_γ: model-dependent coefficient*
  - *0.97 for KSVZ (hadronic)*
  - *−0.36 for DFSZ (minimum)*

$$g_\gamma = \left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

- *f_{PQ}: PQ symmetry breaking scale (10^{10}~10^{12} GeV)*

$$m_a = \frac{f_\pi m_\pi}{f_{PQ}}\frac{\sqrt{z}}{1+z} \simeq 6\,\mu eV\,\frac{10^{12}GeV}{f_{PQ}}, \quad z = \frac{m_u}{m_d}$$

Axion Detection



*a→γγ occurs in a cavity within **B***

Conversion Power

- *Conversion power*

- Theoretical parameters
- experimental parameters

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

Coupling constant
Axion number density
Magnetic field
Effective volume
Cavity Q factor
Axion Q factor

$$P_a = 5.2\times 10^{-22} W \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{\rho_a}{0.45 GeV/cc}\right)\left(\frac{f_a}{6GHz}\right)\left(\frac{B}{8T}\right)^2\left(\frac{V}{1L}\right)\left(\frac{C_{010}}{0.6}\right)\left(\frac{Q_L}{10^6}\right)$$

Conversion Power and Sensitivity

- Theoretical parameters
- experimental parameters

- **Conversion power**

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

Coupling constant ($g_{a\gamma\gamma}$); Axion number density (ρ_a/m_a); Magnetic field (B); Effective volume (VC_{mnp}); Cavity Q factor (Q_L); Axion Q factor (Q_a)

- **Signal-to-noise ratio (SNR)**

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

Integration time (t_{int}); Axion bandwidth (Δf_a) ($\sim 10^{-6} f$); System noise temperature (T_{syst})

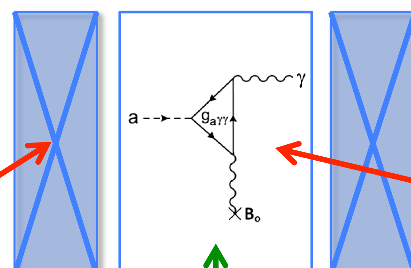
- **Scan rate**

$$\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2 \left(\frac{P(f)}{k_B T_{syst}}\right)^2 \cdot \frac{Q_a}{Q_L} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

$$\frac{df_d}{dt} = \frac{140MHz}{year} \left(\frac{g_\gamma}{0.97}\right)^4 \left(\frac{\rho_a}{0.45GeV/cc}\right)^2 \left(\frac{B}{8T}\right)^4 \left(\frac{V}{1L}\right)^2 \left(\frac{C_{010}}{0.6}\right)^2 \frac{Q_L}{Q_a} \left(\frac{4}{SNR}\right)^2 \left(\frac{4.5K}{T_{sys}}\right)^2 \left(\frac{f}{6GHz}\right)^2$$

Experimental Setup

- *Axion conversion power:* $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

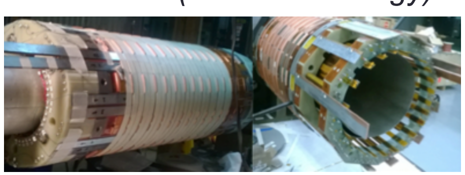


Primakoff Effect

High field SC magnet

25T and then 35T or 40T

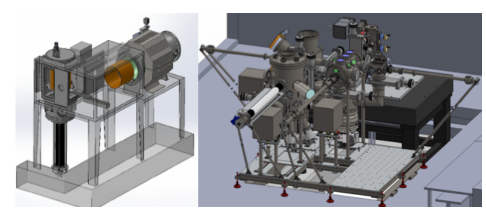
From BNL (HTS Technology)



High Q tunable cavity

Superconducting Coating

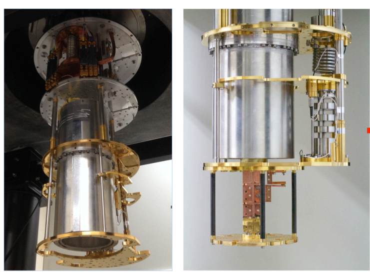
From Prof. Jhinhwan Lee of KAIST



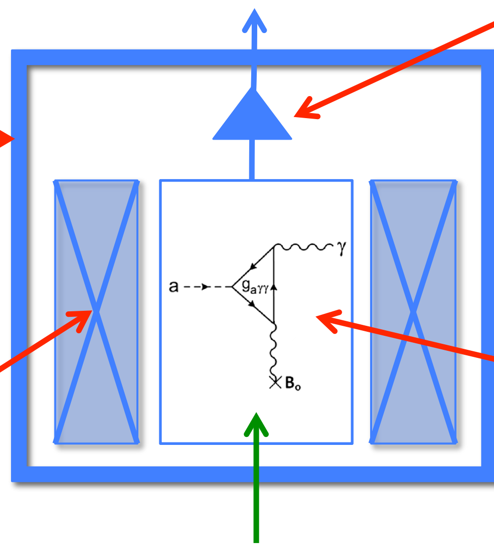
Experimental Setup

- *Axion conversion power:* $$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$
- *Signal-to-Noise Ratio:* $$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$$

Cryogenics
<100mK
Prof. Hyoungsoon Choi from KAIST

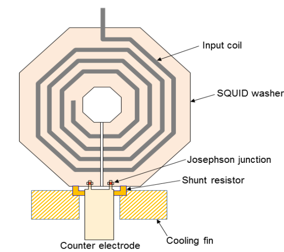


To RF Receiver



Primakoff Effect

SQUID amplifier
Outsourced Research from KRISS



High field SC magnet
25T and then 35T or 40T
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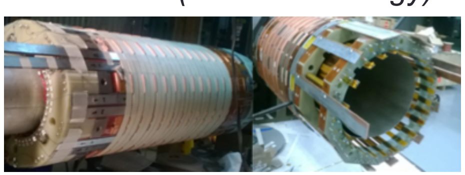

High Q tunable cavity
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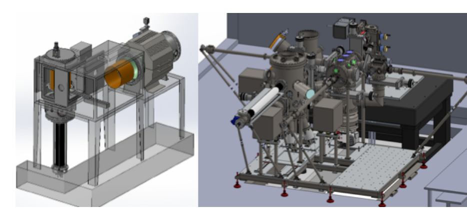


CAPP/IBS Axion Research

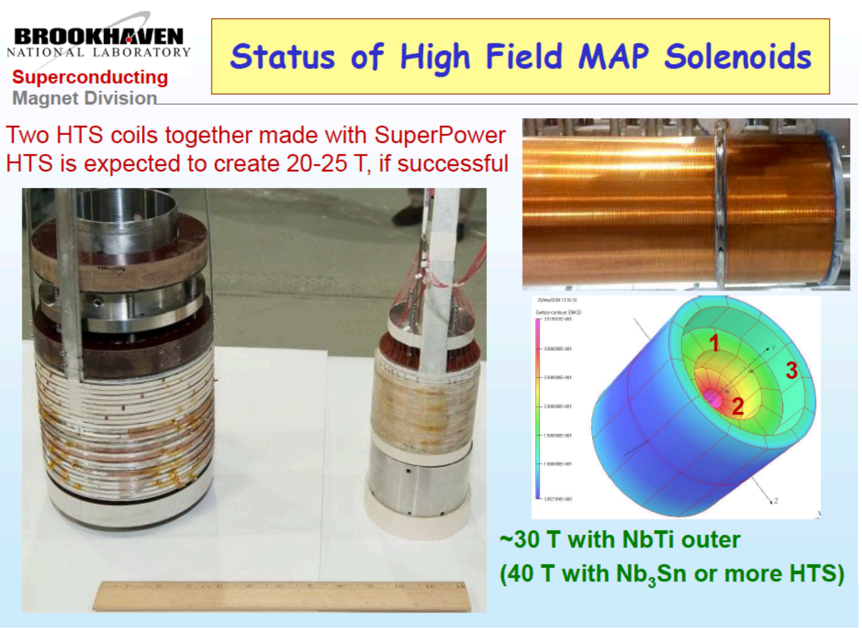
- *Focuses on improvements in experimental parameters*

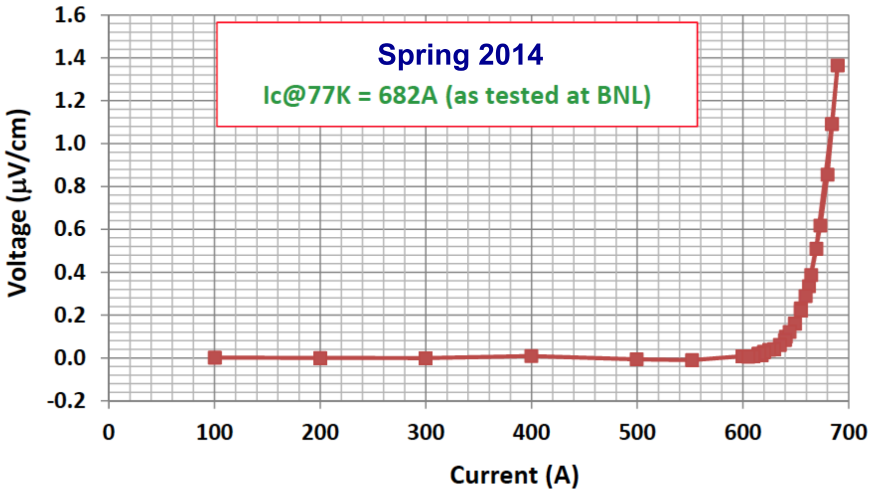
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

- *Magnetic Field*
  - *Critical (4th power), but technically challenging and expensive*
- *Cavity volume*
  - *Limited by the magnet bore size*
  - *Higher frequencies require smaller cavities*
- *Quality factor*
  - *Several ideas in community – pure metal, superconductor, …*
- *System temperature*
  - *Dilution refrigerator technique*
  - *SQUID amplifier*

High Magnetic Field: B

- *Launched a R&D program*
  - *BNL's Superconducting Magnet R&D Group (Dr. R. Gupta)*
  - *Determining the cable for the final design within a year*
- *Two stage program*
  - *25 T with 10 cm bore (HTS)*
  - *35(40) T with10 cm bore – hybrid design HTS(inner)/LTS(outer)*
  - *cf. current axion experiments use < 10 T*



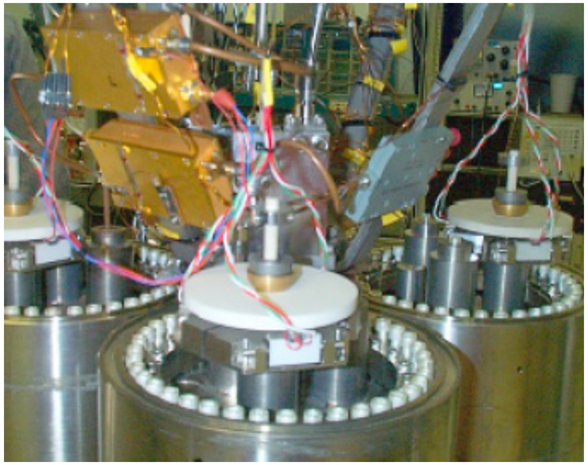


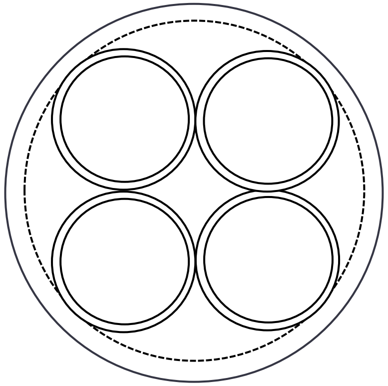
Large Cavity Volume: V

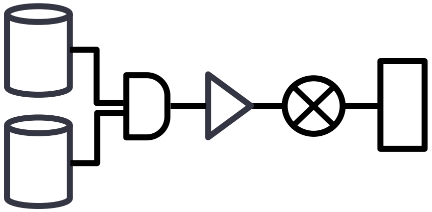
- *Multiple cavities in-phase*
  - *First experimental trial by ADMX (2000) using a 4 cavity system*
- *Improves sensitivity by up to N w.r.t. a single cavity system*

$$SNR: \frac{N \cdot P_S}{\sqrt{N \cdot P_C + P_A}} \quad v.s. \quad \frac{P_S}{P_C + P_A}$$

  - *N: cavity multiplicity*
- *Key issue is phase-locking*
  - *Challenging*
  - *Phase matching in both frequency and time domains*
- *I have received the 5-year IBS Young-Scientist award with CAPP to develop this system*





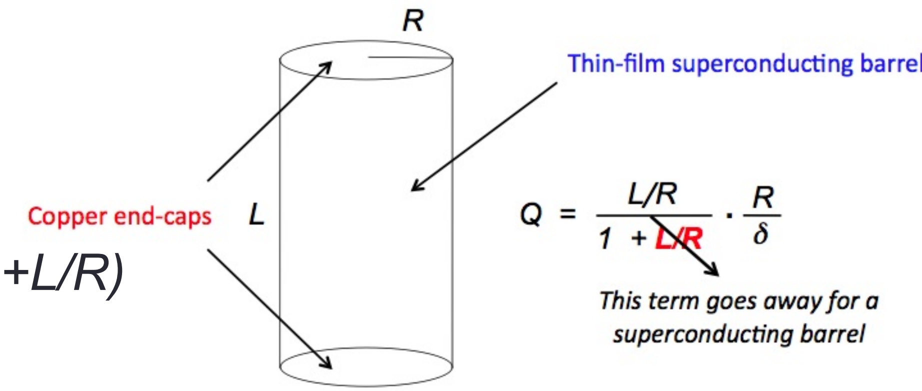


High Quality Factor: Q

- *Typical Cu cavity*
  - *Q_{max} ~ 10^5 with annealing*
    - *cf. Q_a ~ 10^6*
- *Superconducting cavity*
  - *Hybrid design improves Q by (1+L/R)*

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

The concept of a hybrid superconducting cavity:



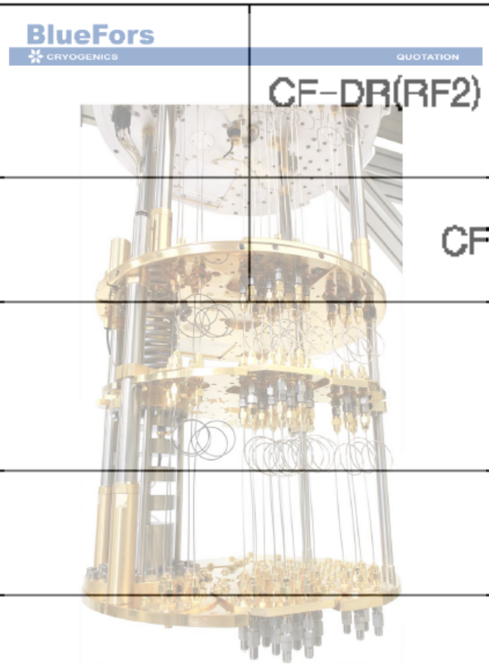
$$Q_{hybrid} = (1 + L/R) \cdot Q_{cu}$$

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

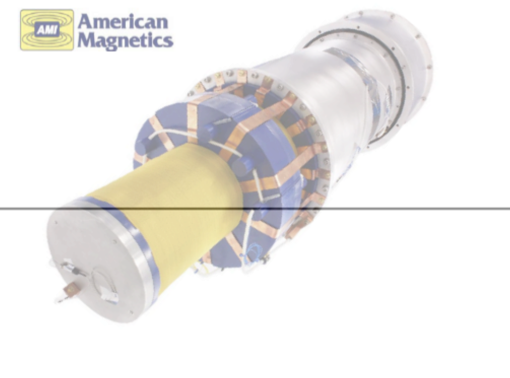
- *R&D program with Prof. J. Lee (KAIST/IBS) for SC cavity*
  - *SC walls including top/bottom plates*
  - *CAPP goal: up to Q ~10^7 in high B-field*

Low System Temperature: T – Cryostats

	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			



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.

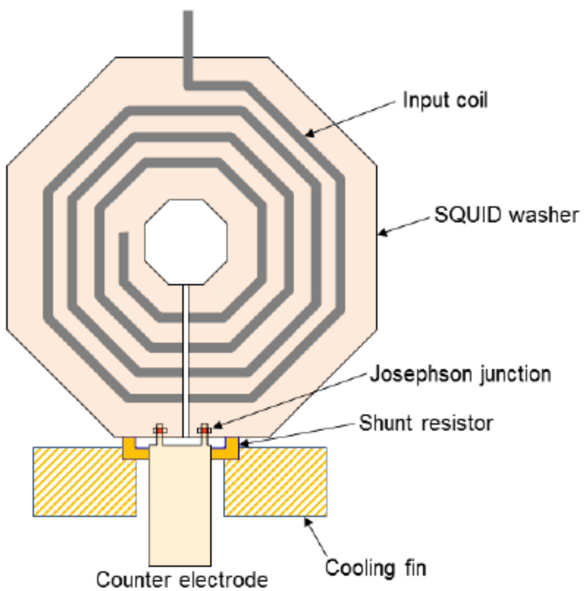


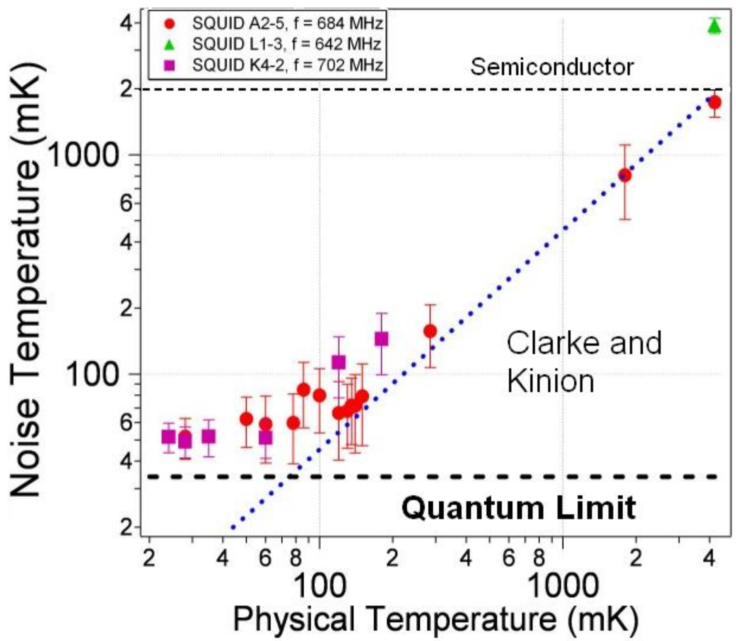
Example of a 7T-100mm cryogen free AMI magnet integrated with a BF-LD system (Protective aluminum magnet cover shield not shown in picture).

Yonuk Chong, KRISS

Low System Temperature: T – SQUID

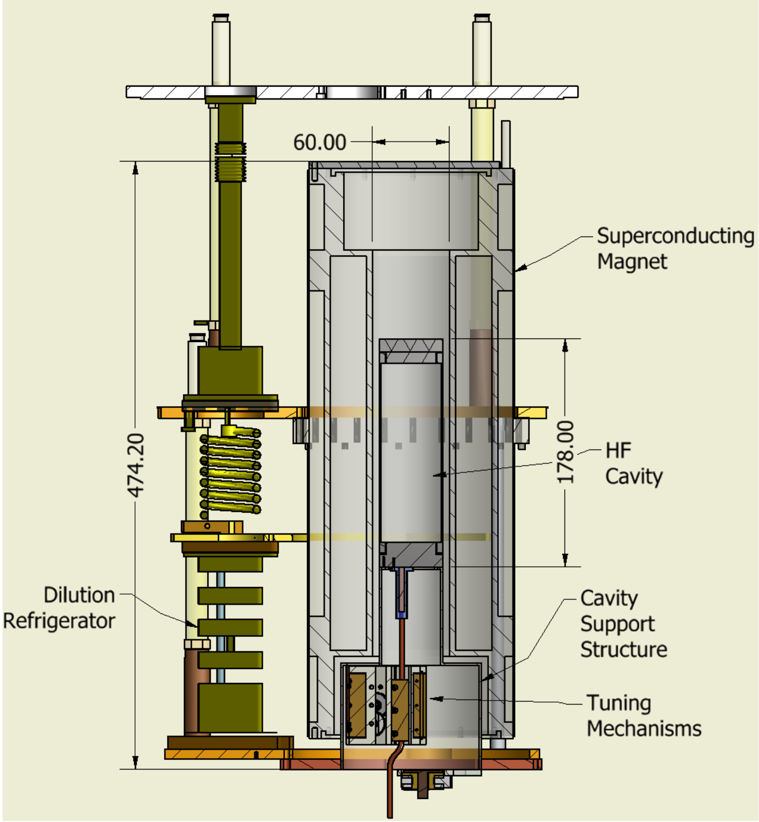
- *Started a development program with KRISS (5 year)*
  - *Korea Research Institute of Standards and Science*
  - *Providing us with (near) quantum noise limited SQUID amplifiers in the 1-20 GHz range*
    - $T_{quantum} \approx 50$ mK * f (GHz))
  - *Evaluating methods for higher frequencies*





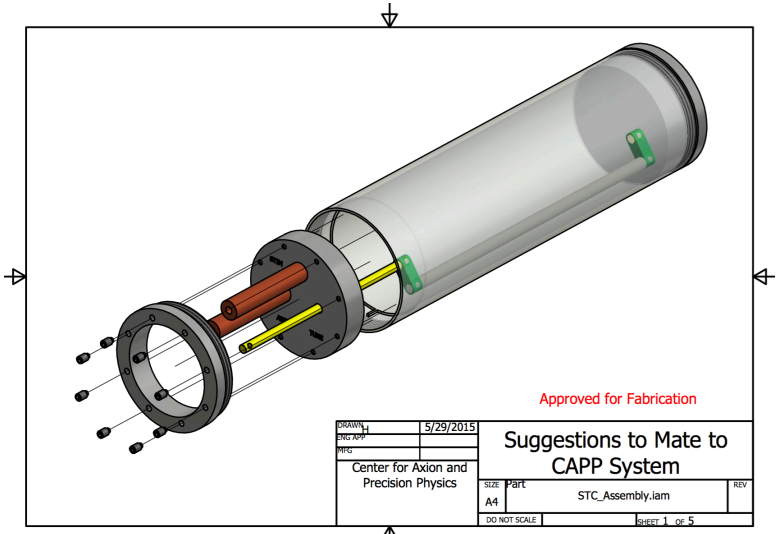
CULTASK

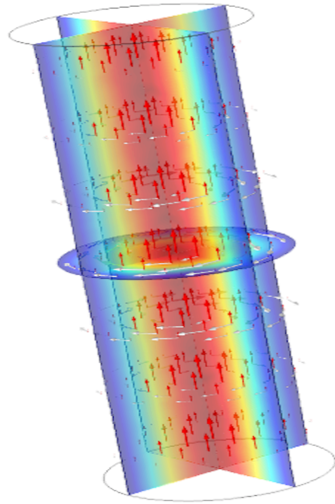
- *CAPP Ultra Low Temp Axion Search in Korea*
  - *Corporate body of axion research efforts at CAPP*
  - *Coldest axion experiment (<100 mK)*

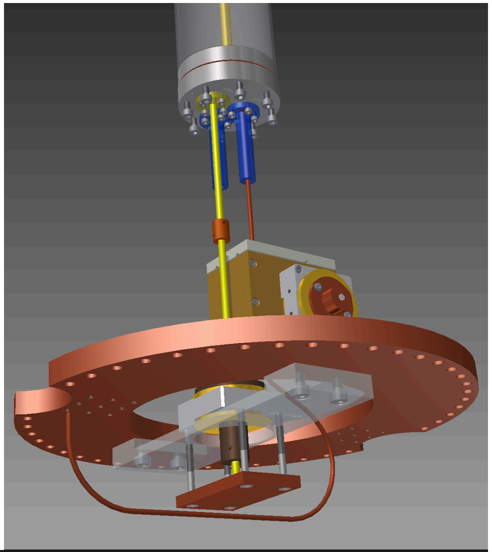


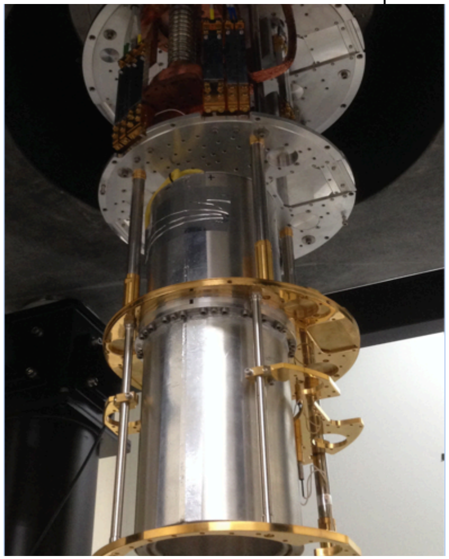
- *Currently in engineering run*
  - *Building infrastructure*
- *Status*
  - *Designing cavities with tuning mechanism*
  - *Completed RT electronics test*
  - *Cryogenic RF circuits test ongoing*
  - *DAQ system ready*
  - *Start with ~ 5GHz (ID: 4.5 cm)*

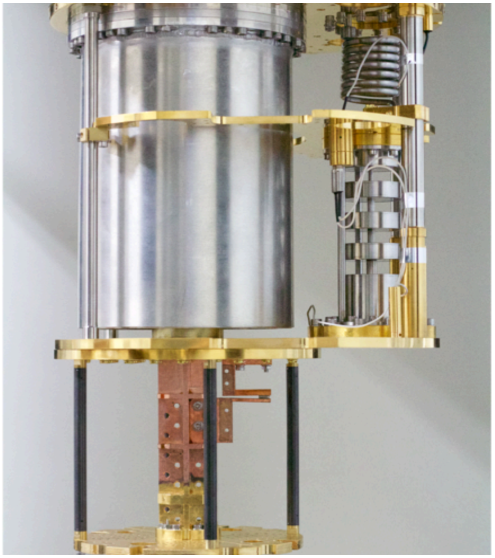
CULTASK

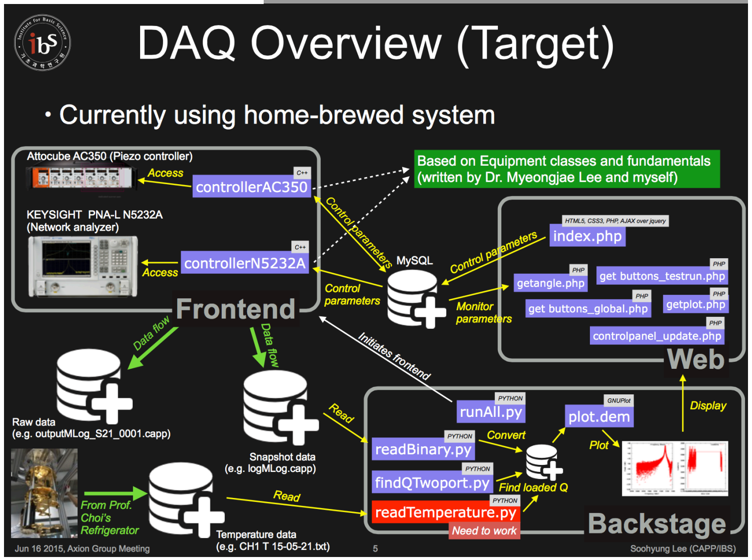

Approved for Fabrication
DRAWN
5/29/2015
ENG APP
MFG
Center for Axion and Precision Physics
Suggestions to Mate to CAPP System
SIZE
A4
Part
STC_Assembly.iam
REV
DO NOT SCALE
SHEET 1 OF 5










DAQ Overview (Target)
• Currently using home-brewed system
Attocube AC350 (Piezo controller)
Access
controllerAC350
KEYSIGHT PNA-L N5232A
(Network analyzer)
Access
controllerN5232A
Based on Equipment classes and fundamentals
(written by Dr. Myeongjae Lee and myself)
Control parameters
MySQL
Control parameters
Control parameters
Monitor parameters
index.php
getangle.php
get buttons_testrun.php
get buttons_global.php
getplot.php
controlpanel_update.php
Web
Frontend
Data flow
Data flow
Initiates frontend
Raw data
(e.g. outputMLog_S21_0001.capp)
Snapshot data
(e.g. logMLog.capp)
Read
runAll.py
plot.dem
Display
readBinary.py
Convert
Plot
findQTwoport.py
Find loaded Q
readTemperature.py
Need to work
Backstage
From Prof. Choi's Refrigerator
Read
Temperature data
(e.g. CH1 T 15-05-21.txt)
Jun 16 2015, Axion Group Meeting
5
Soohyung Lee (CAPP/IBS)

Timeline

<table>
<tr><th></th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th></tr>
<tr><td>Lab Space</td><td>Munji Campus Design & Renovation</td><td colspan="4">Occupation</td></tr>
<tr><td>High Field Magnet</td><td>Prototype, testing of SuperC cables</td><td>25T, 10cm bore SuperC Magnet design</td><td>Work on 35T, 10 cm bore SuperC magnet</td><td colspan="2">Magnet Delivery</td></tr>
<tr><td>SC Cavity Development</td><td>Procure Equip. Study res. and geom.</td><td>Development of high Q SC resonator</td><td colspan="3">Production of high Q resonator</td></tr>
<tr><td>SQUID Amplifier</td><td colspan="2">Design and production of prototype SQUID for 1-10 GHz
Acquire JPA and test</td><td colspan="3">SQUID delivery from KRISS
Develop higher freq. amplifier</td></tr>
<tr><td>Axion Cavity Experiment</td><td>Building infrastructure. Engineering Run at KAIST</td><td colspan="2">Experimental Setup at Munji Test Runs</td><td colspan="2">High Field Magnet + SQUID + SC Cavity</td></tr>
<tr><td>Cryogenics</td><td>Setup plan, acquisition</td><td>DR’s(2) + Wet He3 & DR</td><td>DR’s(2)</td><td colspan="2">Main DR and He liquefier</td></tr>
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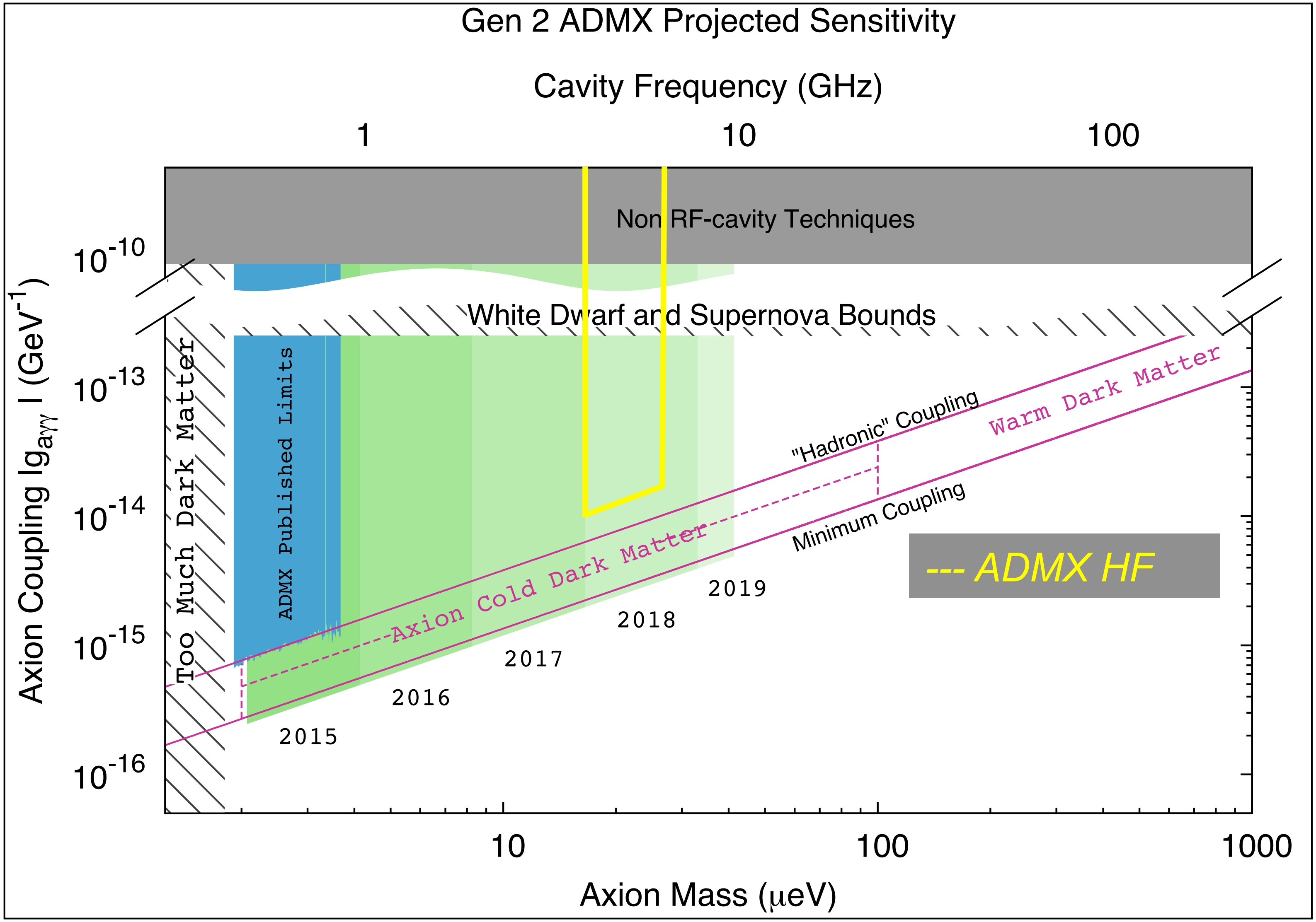
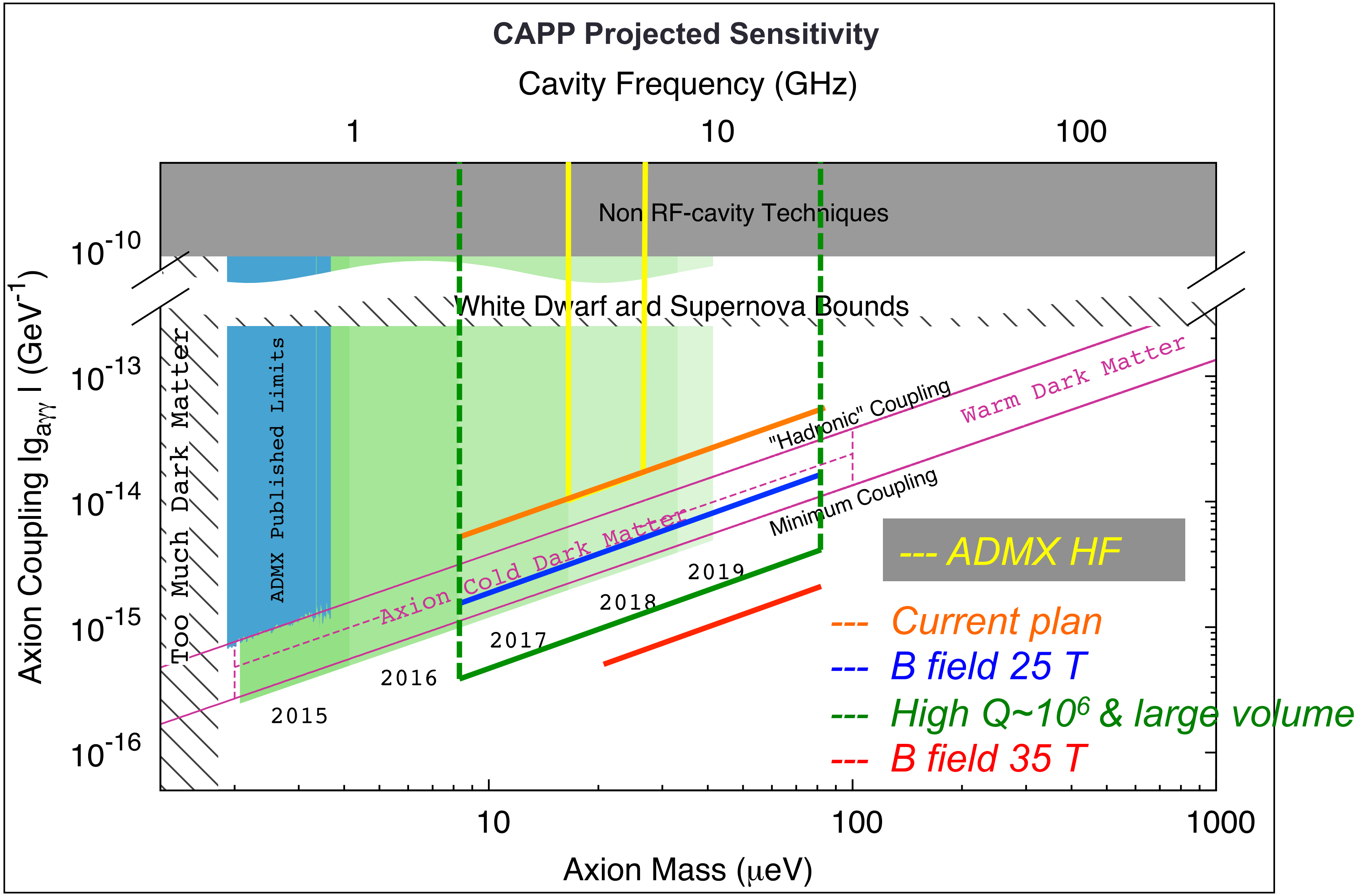
Projected Sensitivity – ADMX Gen 2



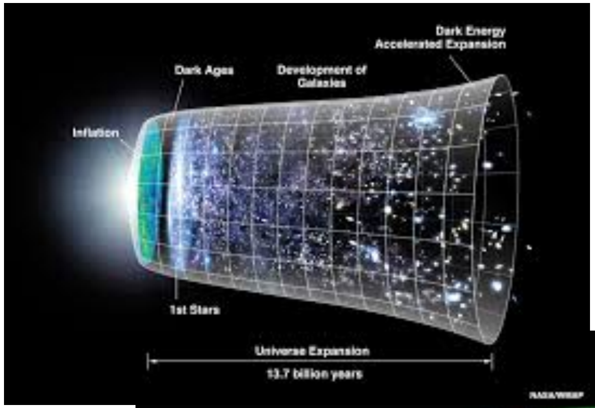
Projected Sensitivity – CAPP



Summary

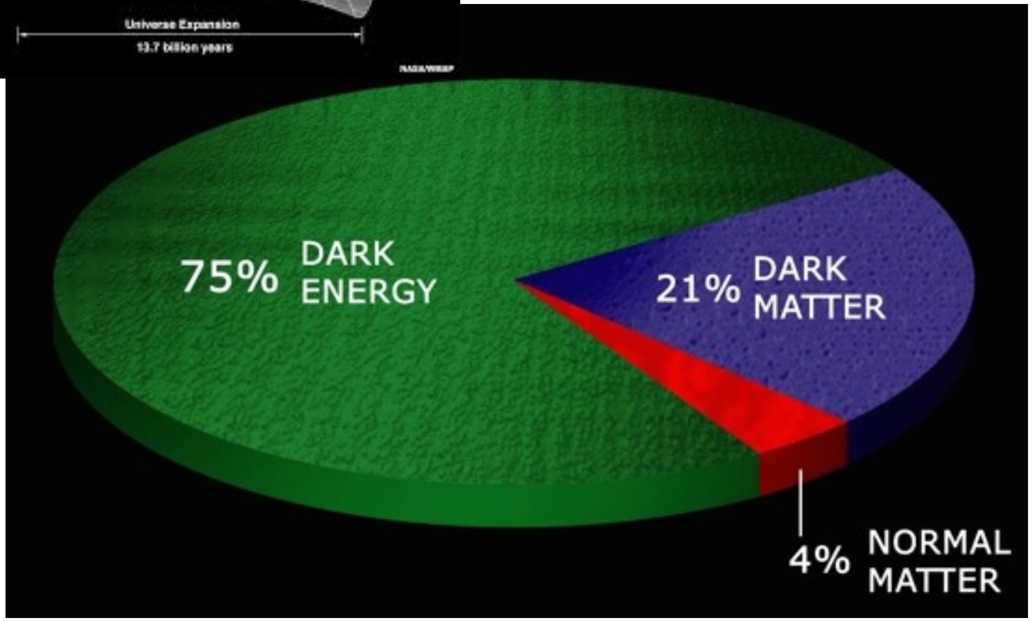
- *Axion is the key particle to solve the strong-CP problem and dark matter issue*
- *Cavity-based approach is promising to detect the challenging axion-photon coupling*
- *CAPP/IBS is an experimental particle physics group dedicated to dark matter axion searches in Korea*
- *Exciting results are expected in a few years*

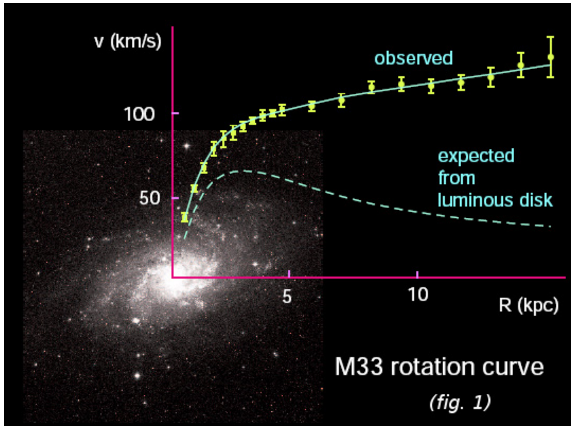
Our Universe



Dark Energy

Expanding universe



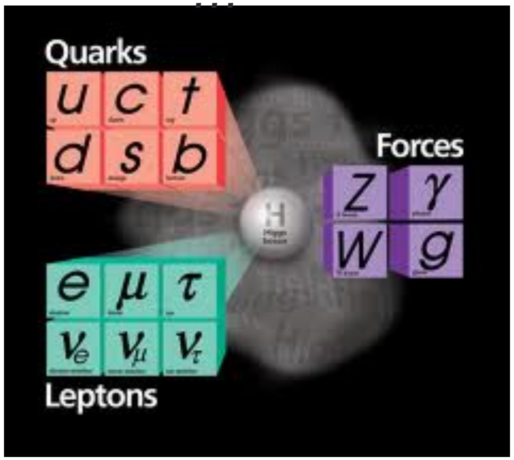


Dark Matter

Rotation velocity of galaxies

Gravitational Lensing

Cosmic Microwave Background



Normal Matter

Standard Model

(EM, weak, strong)

High Quality Factor: Q (II)

- *RRR (Residual Resistance Ratio)*

$$Q \sim \frac{V}{S\delta}, \quad \delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

  - *Comprehensive studies for Cu and Al*
  - *Magnetic field effect*
- *DC vs. AC*
  - *Anomalous behavior of skin depth at high frequencies at low temperatures*
  - *High purity Al is preferable (?)*
  - *Dedicated study is planned*