Axion Dark Matter Search at IBS/CAPP

Darkness on the table

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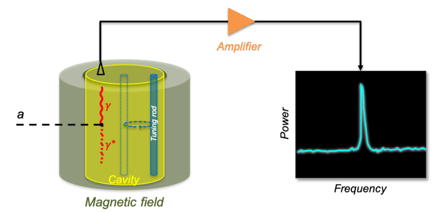
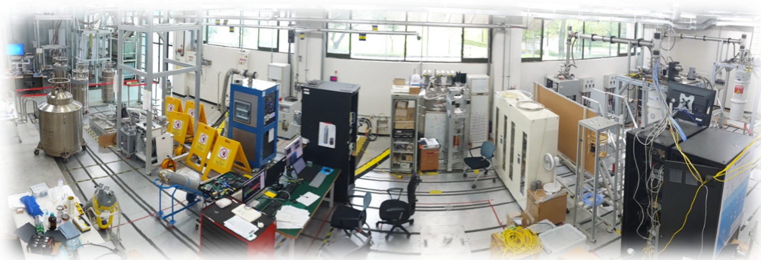
Outline

- *Introduction*
  - *Axion dark matter*
  - *Detection principle*

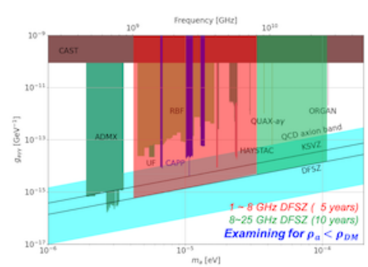


- *Axion haloscope*

- *Axion research at IBS-CAPP*
  - *R&D efforts*
  - *Axion search experiments*



- *Projection & Summary*



Introduction

Axion dark matter

Detection principle

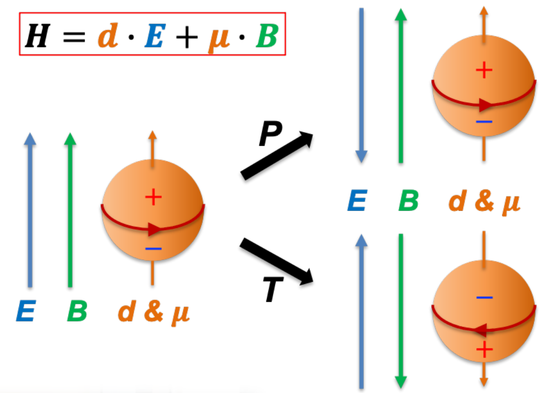
Axion

- *Strong CP problem*

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{32\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

$\Uparrow$ *CPV in strong interaction* $\Downarrow$

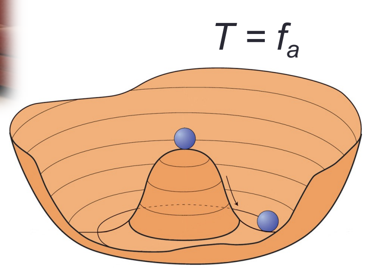
$$d_n < 10^{-26}\, e\cdot cm \ \ (\theta < 10^{-10})$$



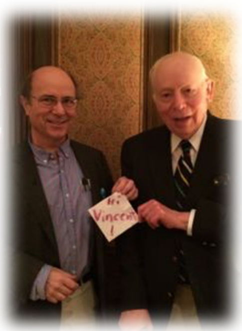
- *PQ mechanism (1977)*
  - New global U(1) symmetry w/ scalar field a

$$\mathcal{L}_{QCD} \supset \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{32\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - Spontaneous breaking: minimum at $a = \theta \cdot f_a$
  - Dynamic solution to strong CP problem

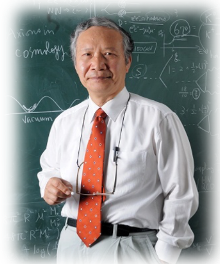


- *Axion (1978)*
  - (pseudoscalar) Nambu-Goldstone boson
  - QCD axion
    - Mass related to QCD scale: $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$
    - cf. axion-like particle (ALP)
  - PQWW axions (EW scale) excluded



Invisible axion and dark matter

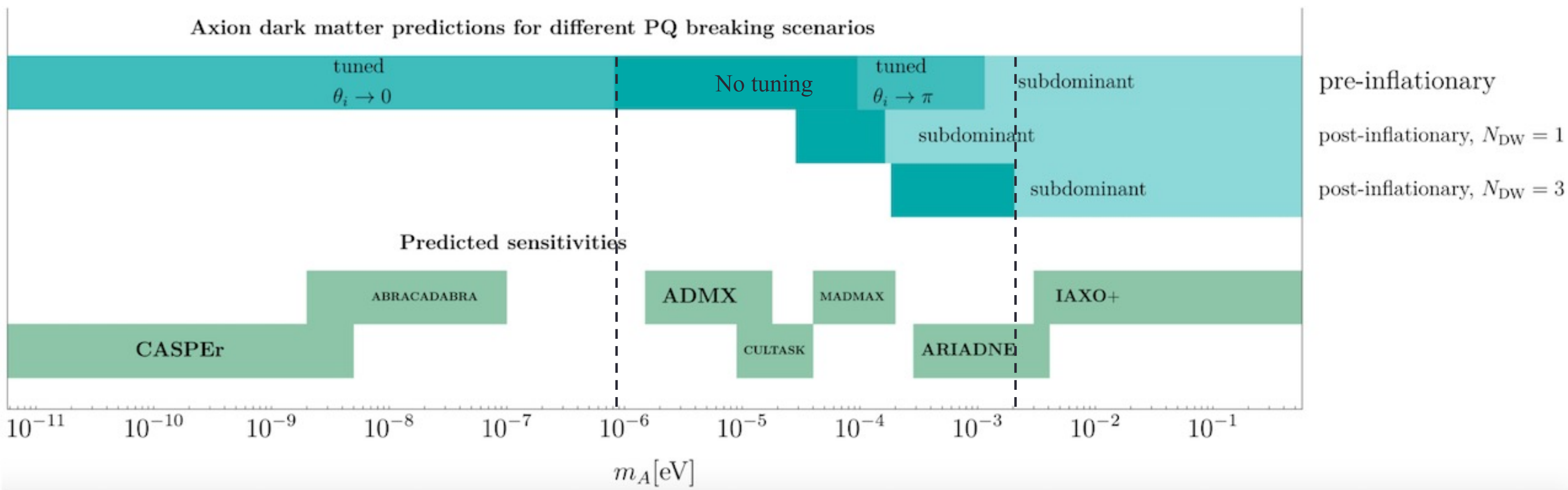
- *Invisible axion (1979)*
  - *Very light axion in early universe at a large energy scale*



$$m_a \approx 6\ \mu eV \frac{10^{12}\ GeV}{f_a}$$

  - *Spanned axion mass range by many orders of magnitude*

- *Cosmic axion (1983)*
  - *May account for dark matter*
  - *Cosmological constraint:*
    $f_a < 10^{12}\ GeV$
  - *Astrophysical observation:*
    SN1987A
  - *Different PQ breaking scenarios predict different mass ranges*



Axion couplings

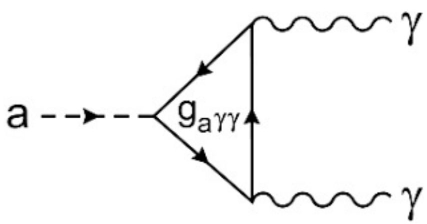
- *Axion interactions with SM fields*

	Photons	Fermions	nEDMs
Coupling	$g_{a\gamma\gamma} a\mathcal{F}\tilde{\mathcal{F}}$	$ig_{aff} a\bar{\psi}\gamma^5\psi$	$ig_d a\bar{\psi}_n\sigma\gamma^5\psi_n\mathcal{F}$
Detection	Resonators in magnetic fields	Magnetometers	NMR
Example	ADMX, CAPP, MADMAX, …	GNOME, QUAX, ARIADNE, …	CASPEr, srEDM, …

- *Most commonly rely on EM interaction*
  - Axion dynamics

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a\mathcal{F}\tilde{\mathcal{F}} = -g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$$

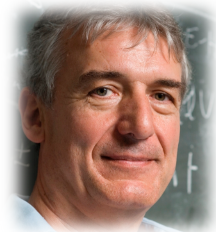
$$g_{a\gamma\gamma}^{QCD} \simeq \frac{\alpha}{2\pi}\frac{1}{f_a}\left(\frac{E}{N} - 1.92\right) \quad \text{cf. } g_{a\gamma\gamma}^{ALP} \simeq \frac{\alpha}{2\pi}\frac{1}{f_a}$$



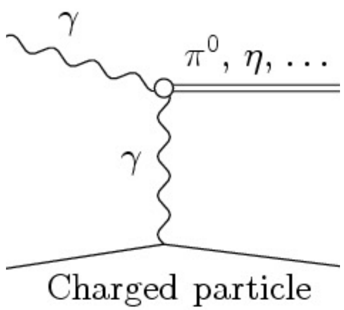
- *Benchmark models*
  - KSVZ: $\frac{E}{N} = 0, 2$ (Heavy quarks) vs. DFSZ: $\frac{E}{N} = \frac{8}{3}$ (Higgs doublet)

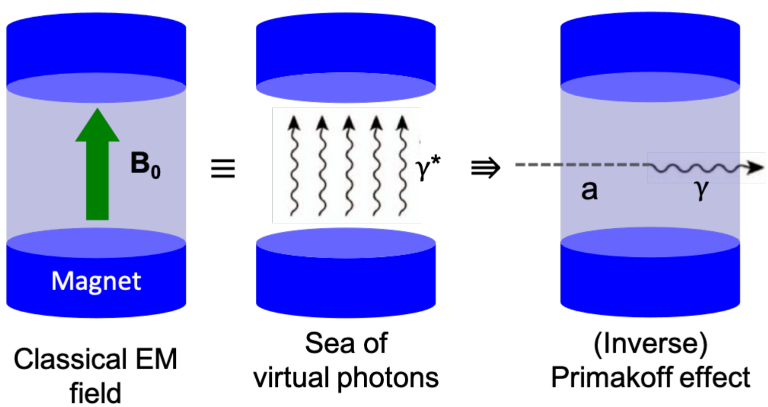
Detection principle

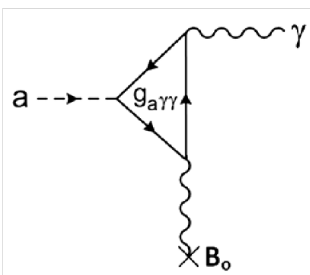
- *EM interaction (axion coupling with photons)*
- *Presence of axion field modifies Maxwell's equations*
  - $\boldsymbol{\nabla} \cdot \boldsymbol{E} = \rho - g_{a\gamma\gamma} \boldsymbol{\nabla} a \cdot \boldsymbol{B}$
  - $\boldsymbol{\nabla} \times \boldsymbol{B} - \dot{\boldsymbol{E}} = j + g_{a\gamma\gamma}(\dot{a}\boldsymbol{B} + \boldsymbol{\nabla} a \times \boldsymbol{E})$
  - *For invisible axions,* $\boldsymbol{\nabla} a \approx 0$, $\dot{a}\boldsymbol{B}$ *is in more effect*
- *(Inverse) Primakoff effect (1983)*



(pseudo)scalar production via γ-γ interactions



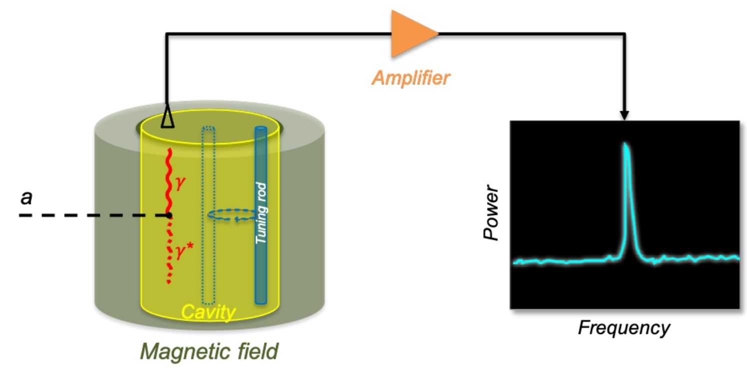




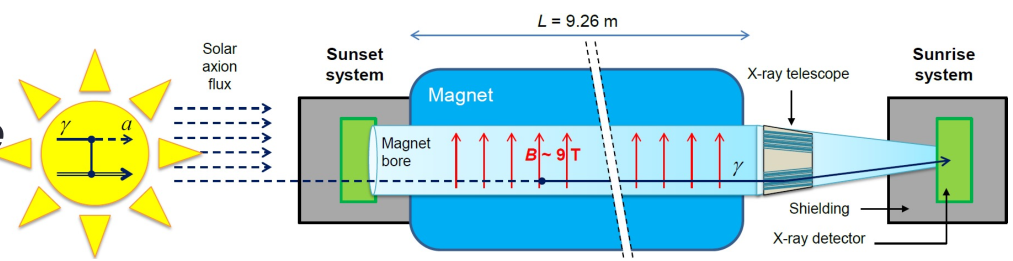
Axions "borrow" virtual photons from a magnetic field to turn into real photons

Search strategies

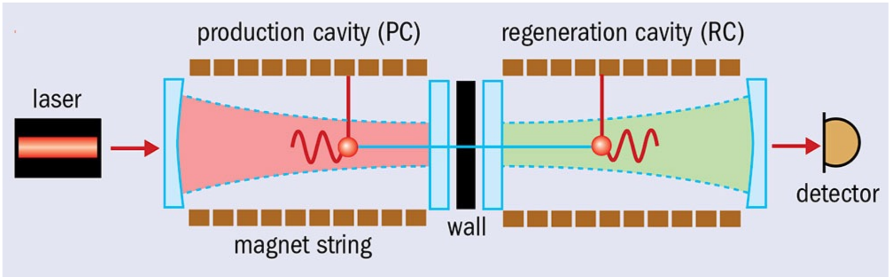
- *Haloscope*
  - *DM axions in our galactic halo*
  - *Microwave resonators*
  - *ADMX, HAYSTAC, CAPP,…*



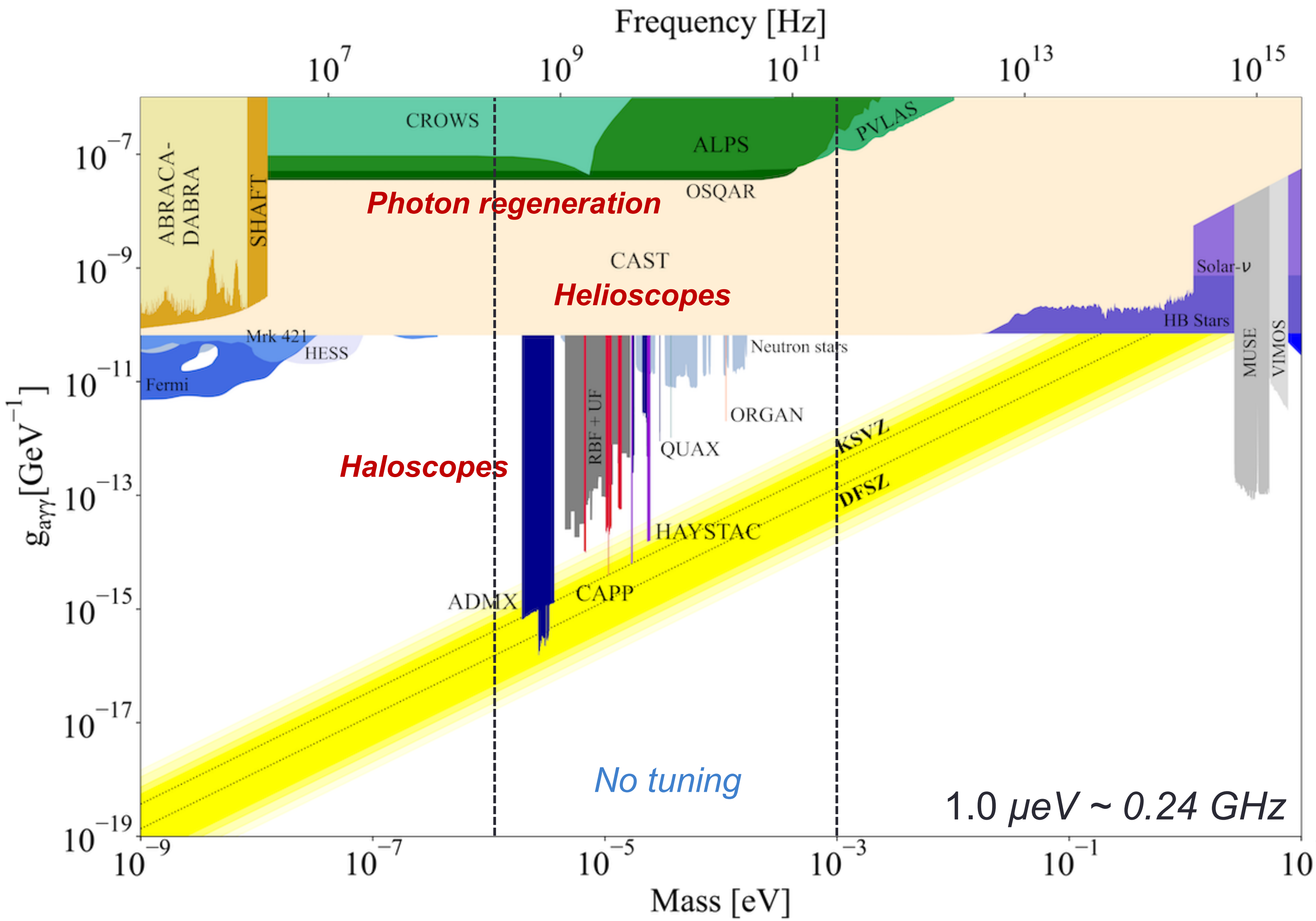
- *Helioscope*
  - *Solar axions*
  - *Emitted from the solar core*
  - *CAST, IAXO,…*



- *Photon regeneration*
  - *Light Shining through Wall*
  - *Axion production/detection in the laboratory*
  - *OSCAR, ALPS (II), …*



Axion searches – present



Axion haloscope

Detector of halo axions

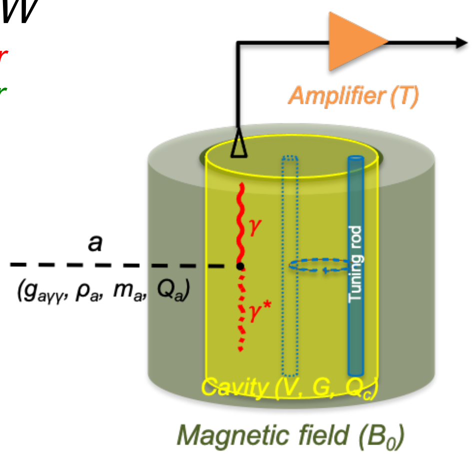
- *Most sensitive approach in μeV regime*
  - *Microwave photons resonantly converted from axions*

- *Conversion signal power (a→γγ)*

- theoretical parameters
- experimental parameters

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a) \sim 10^{-21} W$$

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)*

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

Integration time (t_{int}), *Axion bandwidth (~10^{-6} f)* (Δf_a), *System noise temperature* (T_{syst})

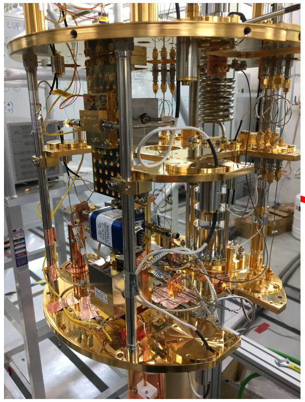
- *Scanning rate (F.O.M.):* $\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2 \left(\frac{P(f)}{k_B T_{syst}}\right)^2 \cdot \frac{Q_a}{Q_L} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$

Haloscope in a nutshell

- *Enhancing the scan rate*

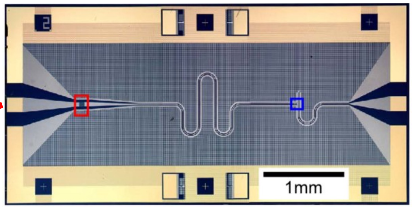
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics T

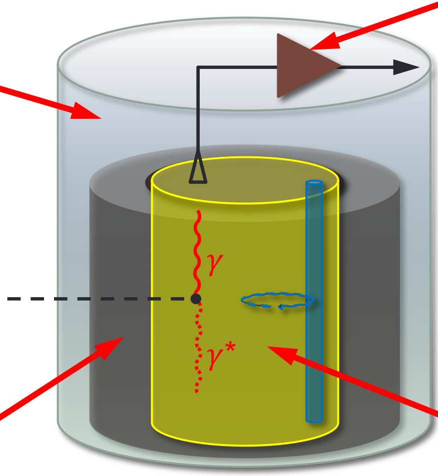


Lowering thermal noise

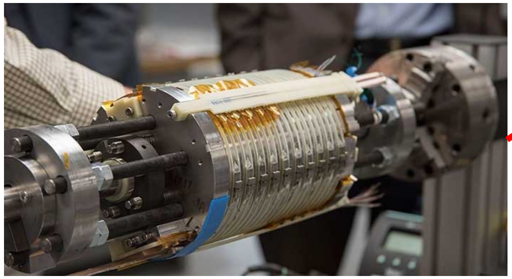
Quantum noise limited amplifier T



Signal amplification w/ minimal noise added



High field HTS Magnet B



Boosting a→γγ conversion rate

Tunable High-Q resonator V, Q, C, Δf

Resonant frequency tuning

University lab-sacle experiments!

Axion research at IBS-CAPP

R&D efforts

Axion search experiments

IBS-CAPP

CAPP-9T MC ***CAPP-12TB*** ***CAPP-PACE*** ***CAPP-8TB***

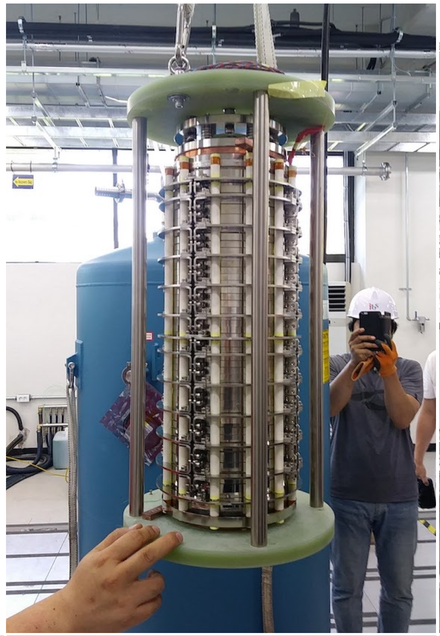
Equipment at CAPP

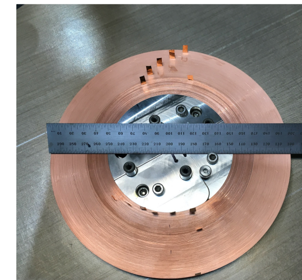
Conducting parallel experiments targeting at different mass ranges!

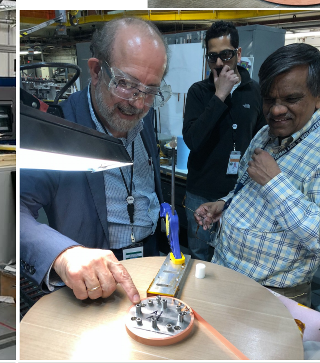
Refrigerators: Manufacture	Model	T_B [mK]	Magnets: Manufacture	B_{max} [T]	Bore [mm]	Experiments: Name
BlueFors (BF3)	LD400	10				
BlueFors (BF4)	LD400	10				
Janis	HE-3-SSV	300	Cryo Magnetics	9	125	CAPP-9T MC
BlueFors (BF5)	LD400	10	AMI	8	125	CAPP-8T (PACE)
BlueFors (BF6)	LD400	10	AMI	8	165	CAPP-8TB
Oxford	Kelvinox	30	SuNAM	18	70	CAPP-18T
Leiden	DRS1000	5	Oxford	12	320	CAPP-12TB
			IBS/BNL	25	100	CAPP-25T

High-field magnets

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





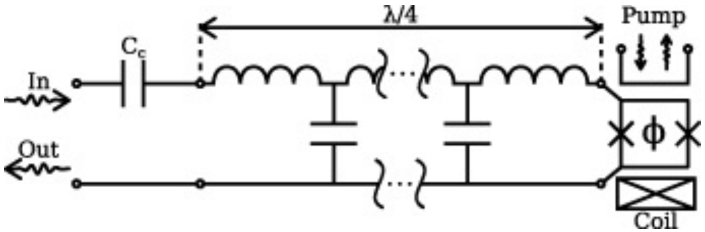


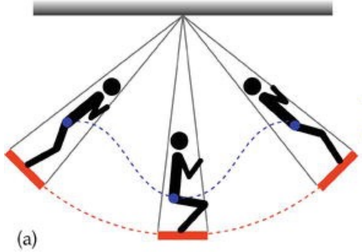
Magnet	CAPP-18T	CAPP-12TB	CAPP-25T
Manufacturer	SuNAM	Oxford	IBS-BNL
B_{max} @ 4 K	18 T	12 T	25 T
Bore (clear)	70 mm	320 mm	100 mm
SC material	GdBCO	Nb_3Sn	YBCO
Delivery	2017	2020	?
Frequency	> 4 GHz	> 1 GHz	> 3 GHz
Sensitivity	KSVZ	DFSZ	DFSZ

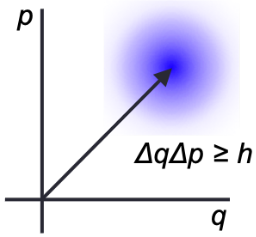
Low noise amplifiers

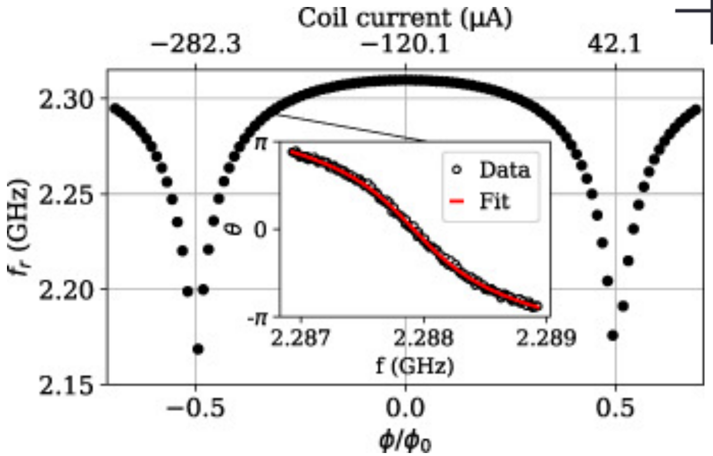
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

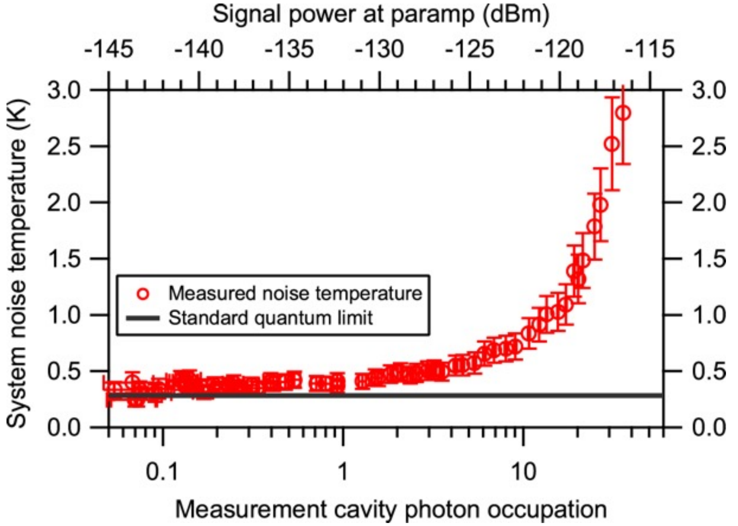
- *Josephson Parametric Amplifier (JPA)*
  - *LC circuit with nonlinear SQUID*
  - *Parametric gain from a pump tone*
    - *Analogous to a swing ride*
  - *Resonant frequency tuning*
    - *DC magnetic flux (SC coil) through the SQ loop*
  - *Quantum noise limited*
    - *$T_{SQL} \approx 50$ mK × f [GHz]*



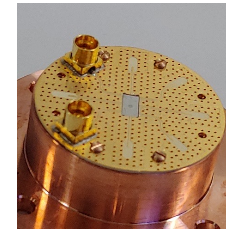






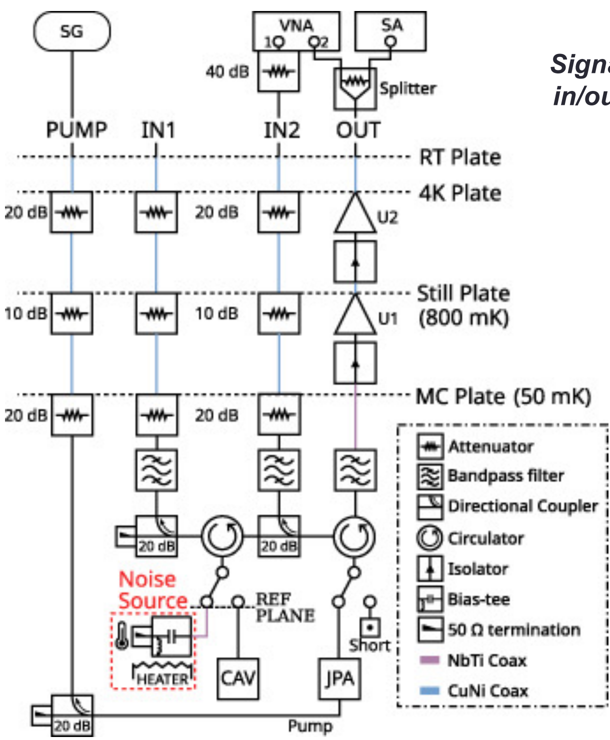


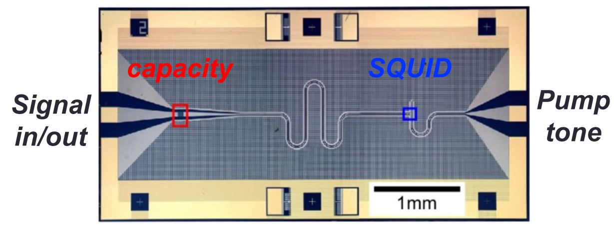
JPAs

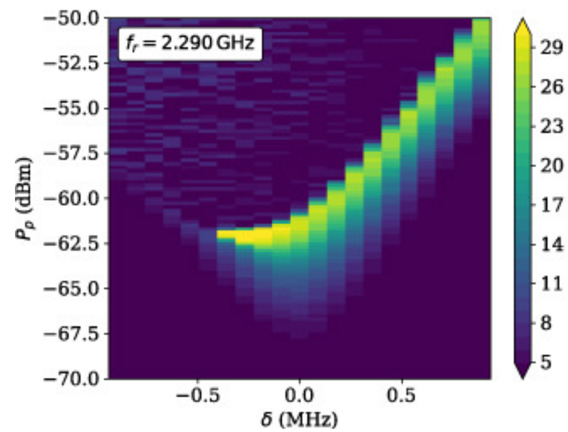


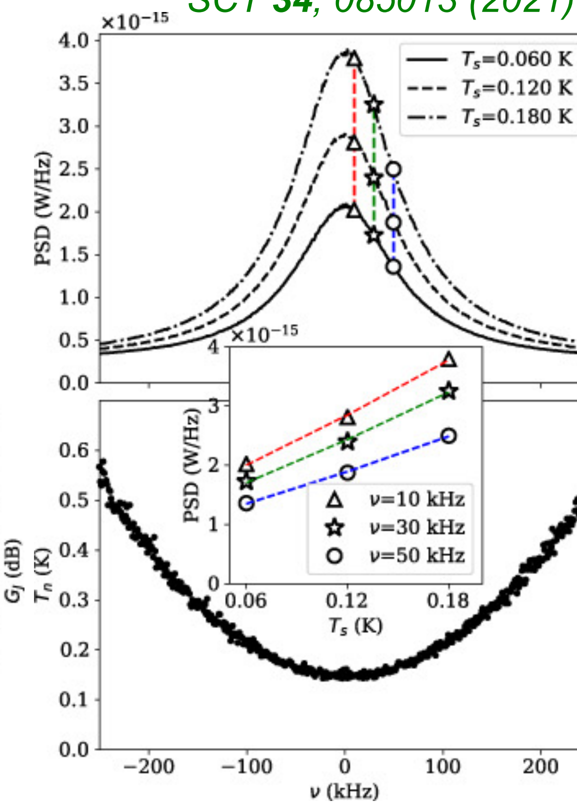
- *Collaboration with U of Tokyo (RIKEN)*
  - *A series of chips covering a wide range (1~6 GHz)*
  - *Characterization at CAPP*
  - *Reasonable gains and nearly QLN*

*SCT **34**, 085013 (2021)*



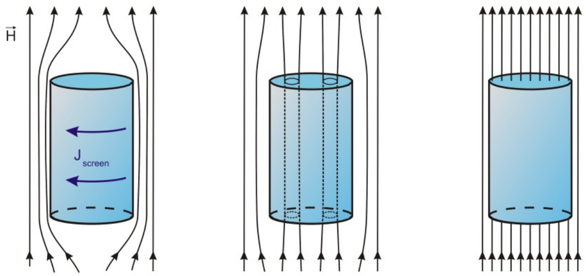




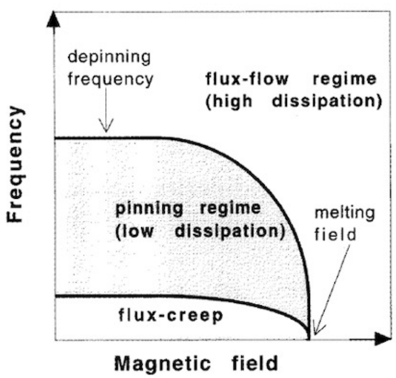


Superconducting Cavities $\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$

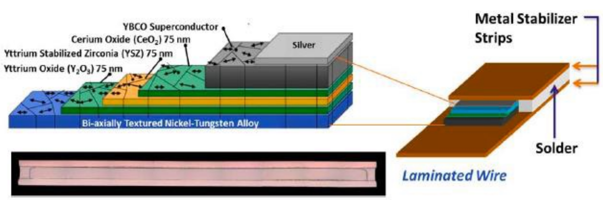
- *Issues*



1. strong field vs. Meissner effect



2. low RF loss vs. vortex vibration

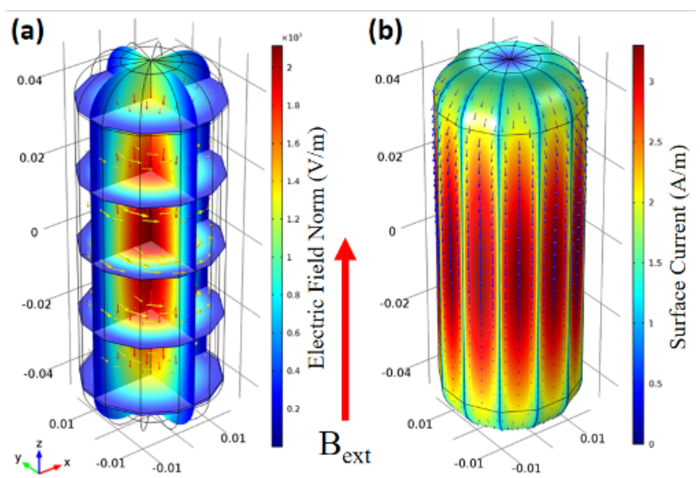


3. biaxially-textured tape

- *Solutions*

1&2. Type II HTS w/ high H_c and high f_{dep}

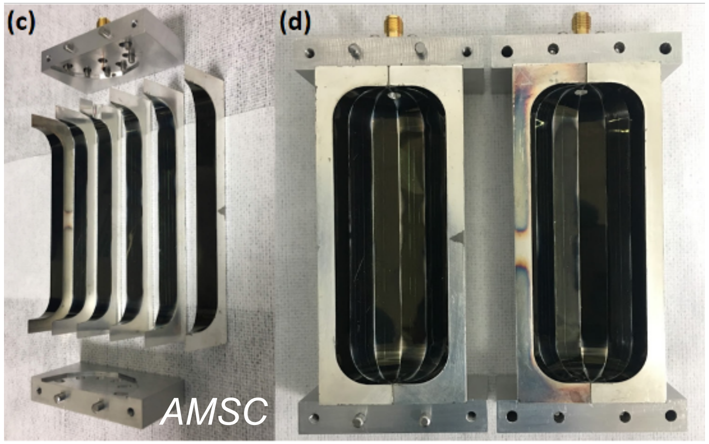
Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)
Nb_3Sn	A15 cubic	Negligible	18	27 T (4 K)
MgB_2	*P6/mmm* hexagonal	2–2.7	39	15 T (4 K)
YBCO	Orthorhombic layered perovskite	7	92	>100 T (4 K)
Bi-2223	Tetragonal layered perovskite	~50–100	108	>100 T (4 K)

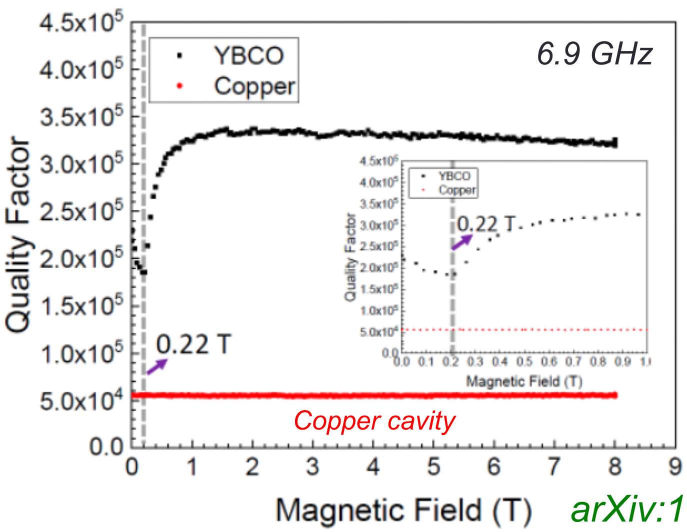


3. polygon-shaped cavity

Superconducting cavities

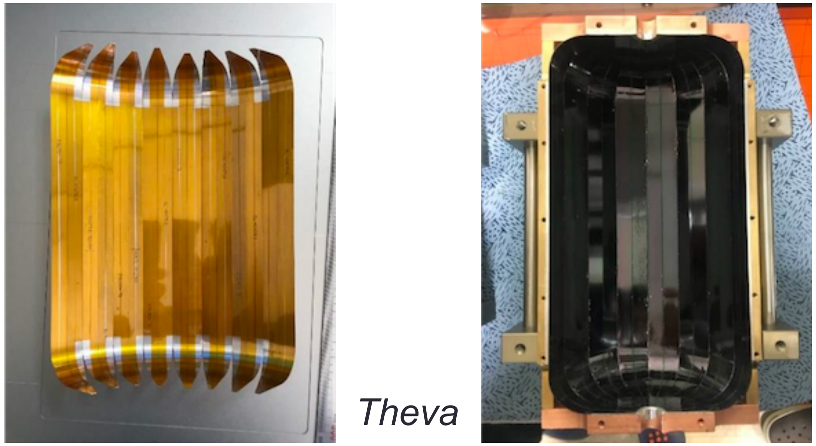
- *Melon cavity – 12 pieces*

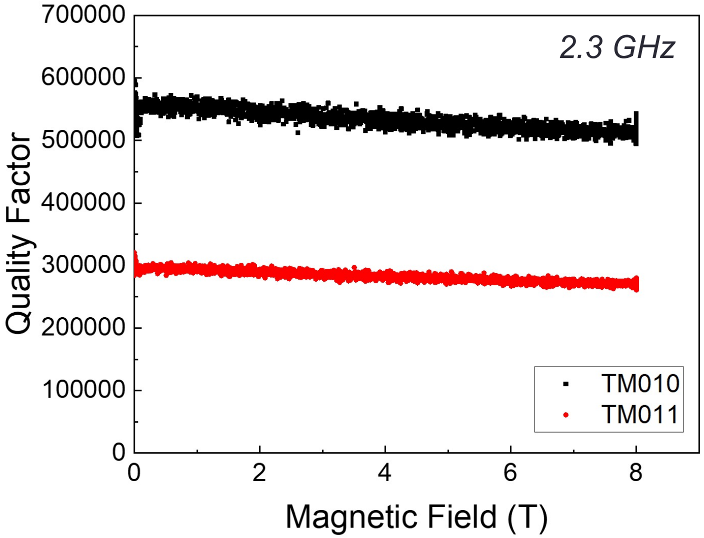




arXiv:1904.05111

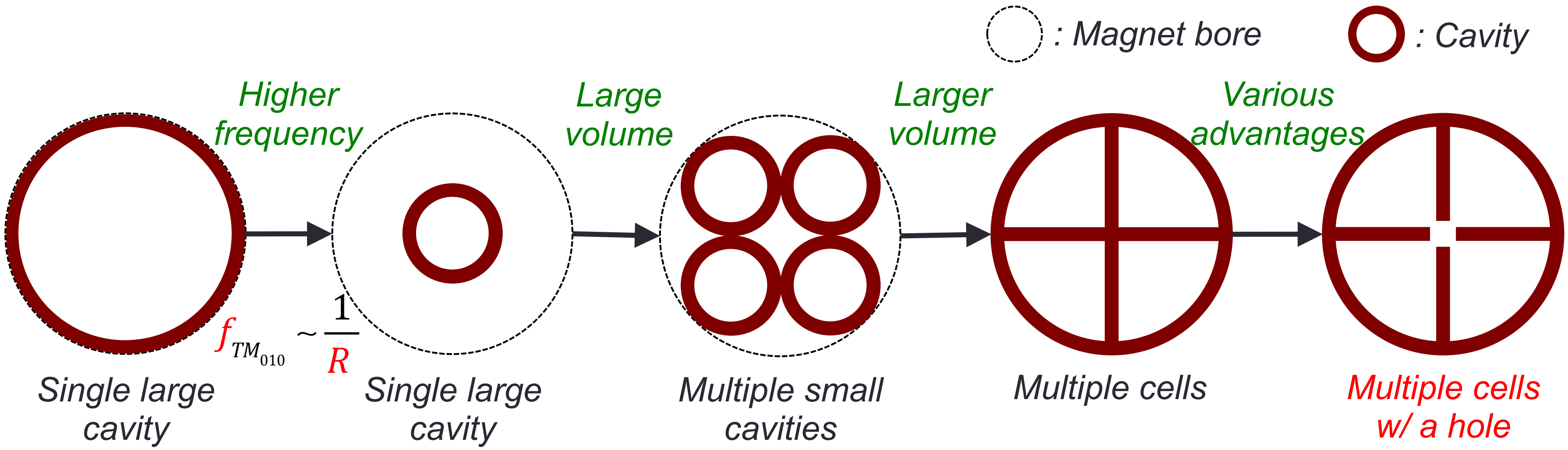
- *Barbeque cavity – 32 pieces*



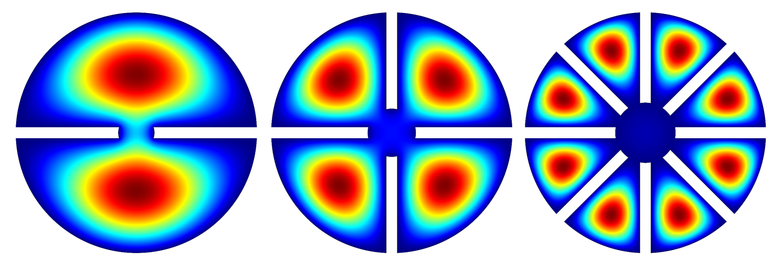


High freq. approach

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



- *Larger volume*
  - *Higher sensitivity*
    - *2 times better than multiple-cavity*
- *Single antenna*
  - *Easier experimental setup*
    - *cf) N receivers for N-cavity systems*
- *Easier phase-matching mechanism*
- *Experimental demonstration*
  - *Superior to multiple-cavity detectors*

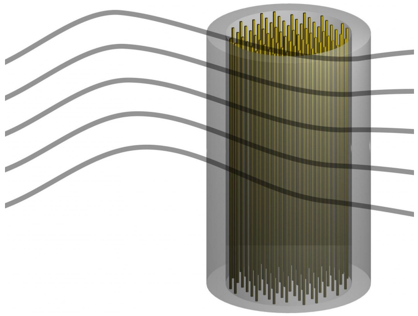


*PLB **77**, 412 (2018)*

High freq. approach

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

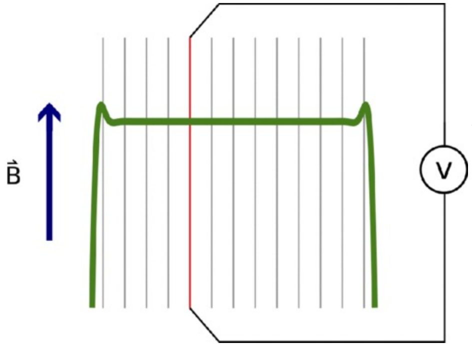
- *Plasma haloscope*
  - *Array of thin metal wires*



$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 log(\frac{s}{d})}$$

  - *Resonance w/ electron plasma ($\omega_a = \omega_p$)*
  - *ω_p depends on d & s*
    - *d: wire diameter / s: inter space*
  - *Independent of cavity size*

=> Large detection volume

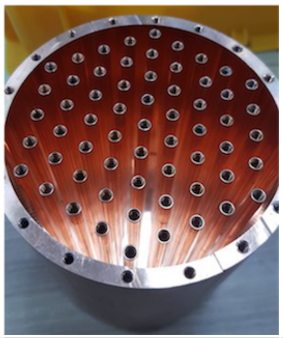


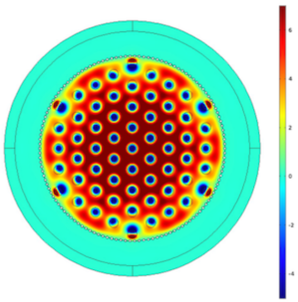
Periodic structure

↓

Meta-material (bulk plasmon)

- *Development at CAPP*





Metal wires	*Metal posts*	*Dielectric posts*
C ~ 0.9	*C ~ 0.8*	*C ~ 0.2*
Q < 10^3	*10^3 < Q < 10^4*	*Q > 10^5*
Dens. > 3 /cm²	*Dens. ~ 1 /cm²*	*Dens. ~ 1 /cm²*
TM_{010}-like	*TM_{010}-like*	*TM_{020}-like*
Freq. tuning is challenging		*Freq. tuning is less challeng.*

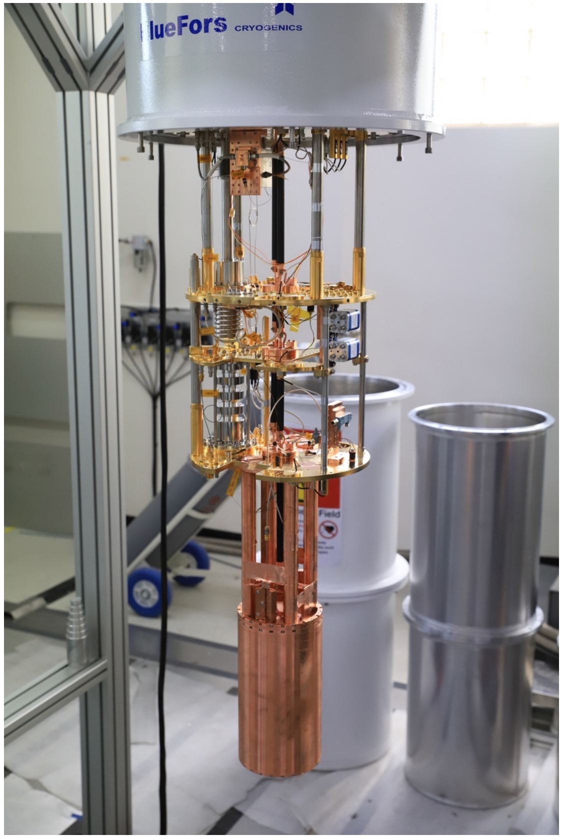
- *Dielectric post array design is suitable for f > 10 GHz*
- *Further development is ongoing*

Axion research at IBS-CAPP

R&D efforts

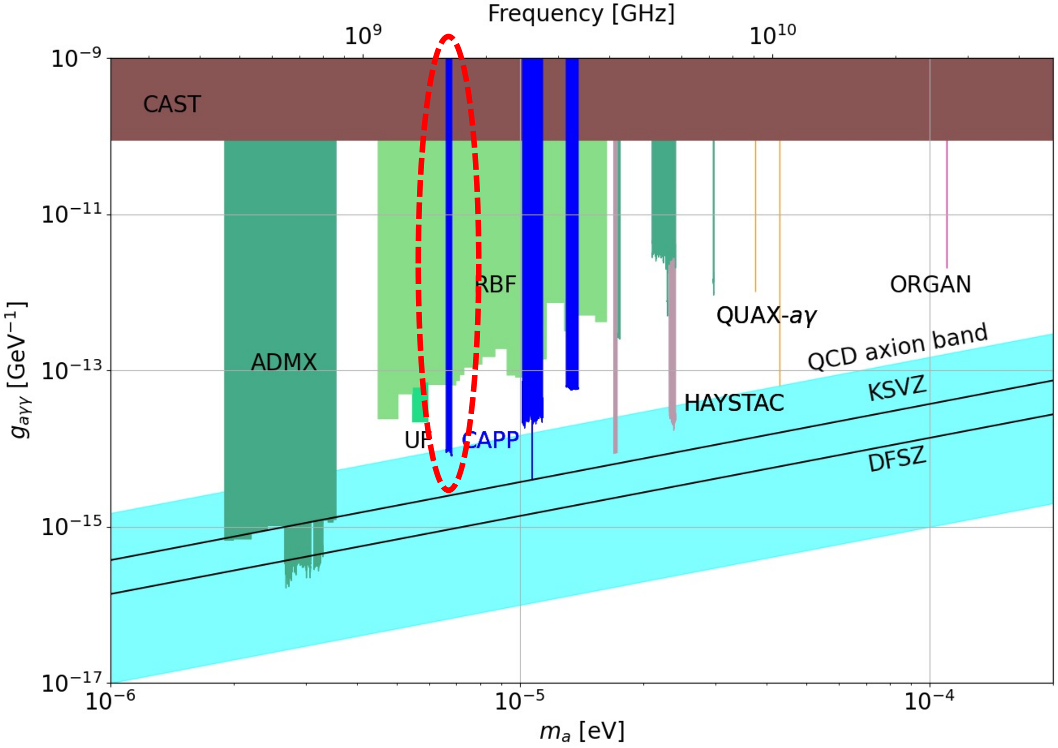
Axion search experiments

CAPP-8TB



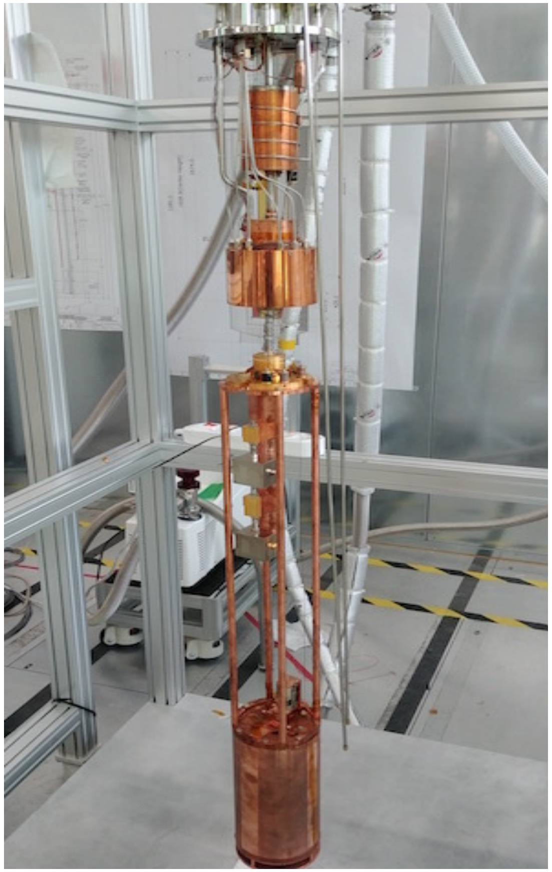
- *8T/165mm SC magnet*
- *BlueFors Dilution (T_{phy} ~ 50 mK)*
- *HEMT amplifiers*

*PRL **124**, 101802 (2020)*



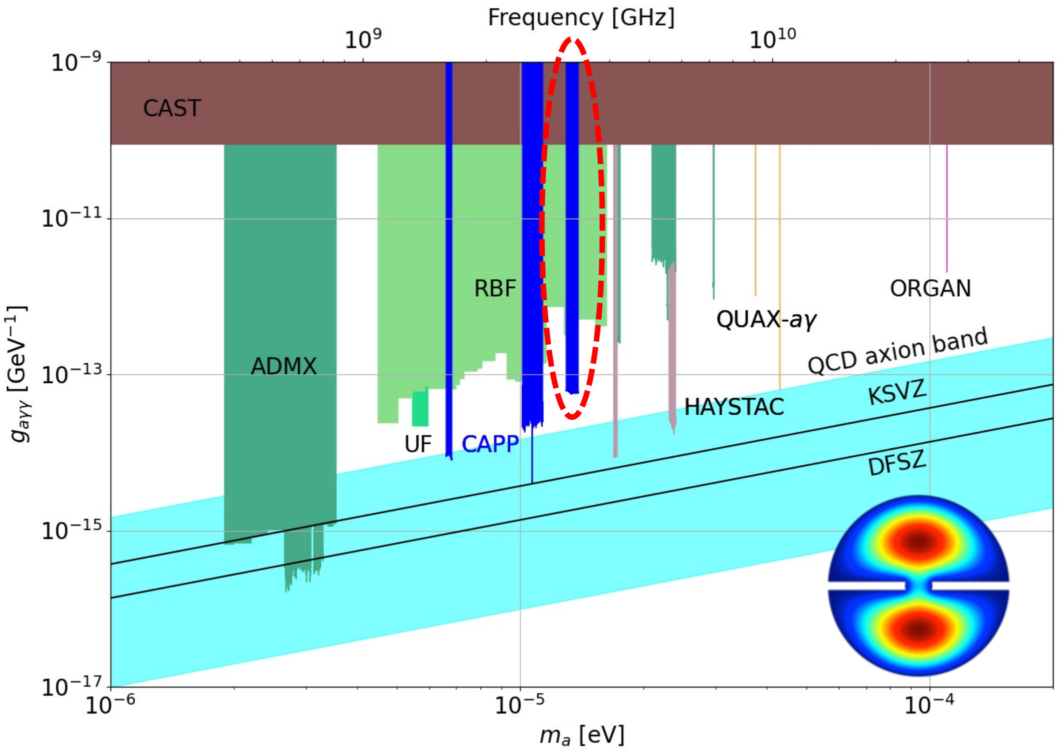
- *First result from IBS-CAPP*
- *m_a ~ 6.6 μeV (Δm_a ~ 0.2 μeV)*
- *Sensitivity: g_{arr} ~ 4 KSVZ @ 90% C.L.*
- *Upgrade for 6 GHz search*

CAPP-9T (MC)



- *9T/127mm SC magnet*
- *JANIS cryogenic syst.*
  (T_{phy} ~ 2 K)
- *HEMT amplifiers*

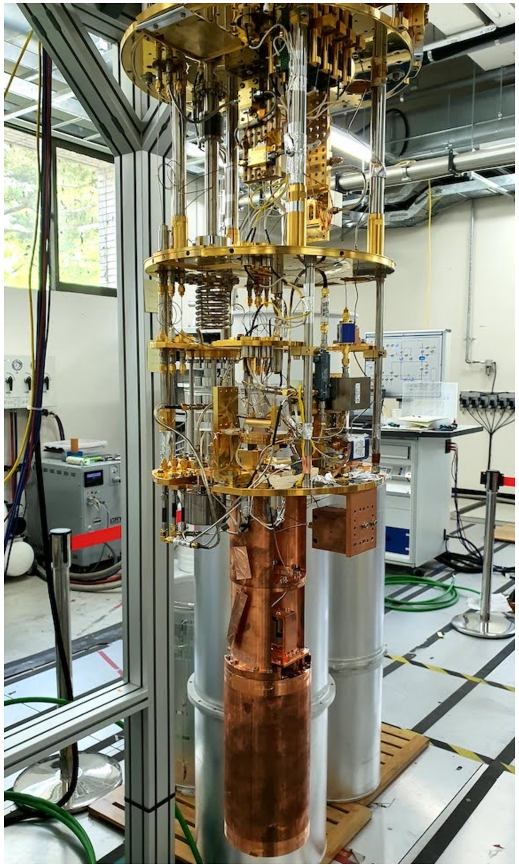
PRL ***125****, 221302 (2021)*

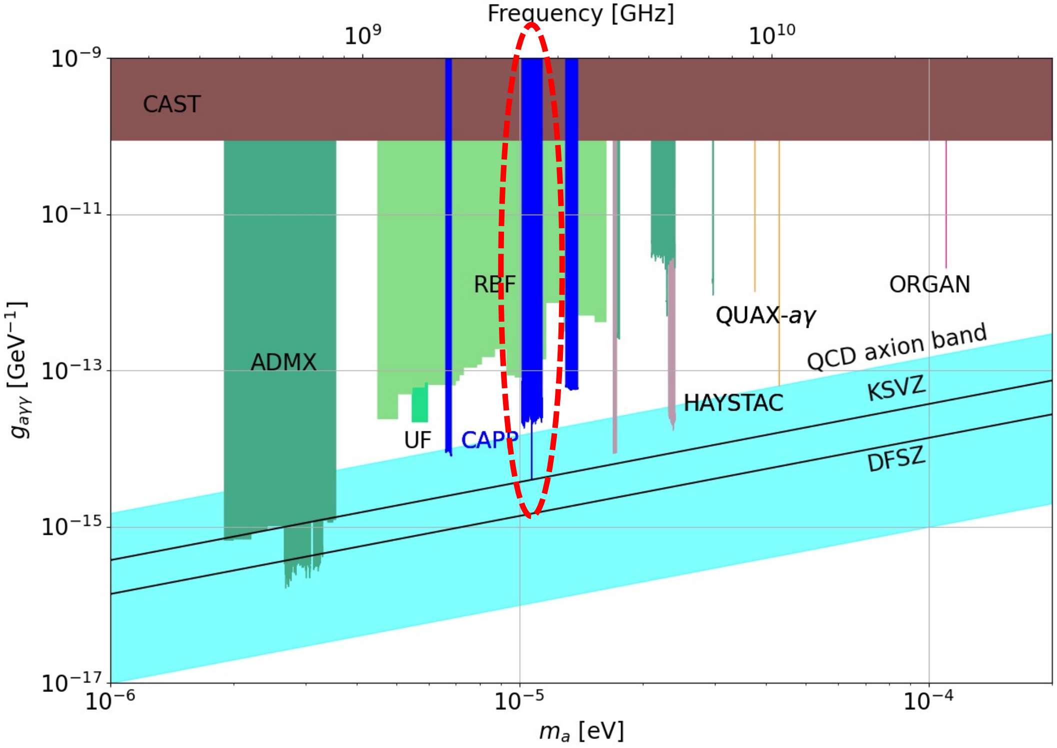


- *Demonstration of multiple-cell cavity design*
- *m_a ~ 13 μeV (Δm_a ~ 1 μeV)*
- *Sensitivity: g_{arr} ~ 10 KSVZ @ 90% C.L.*

CAPP-PACE

*PRL **126**, 191802 (2021)*



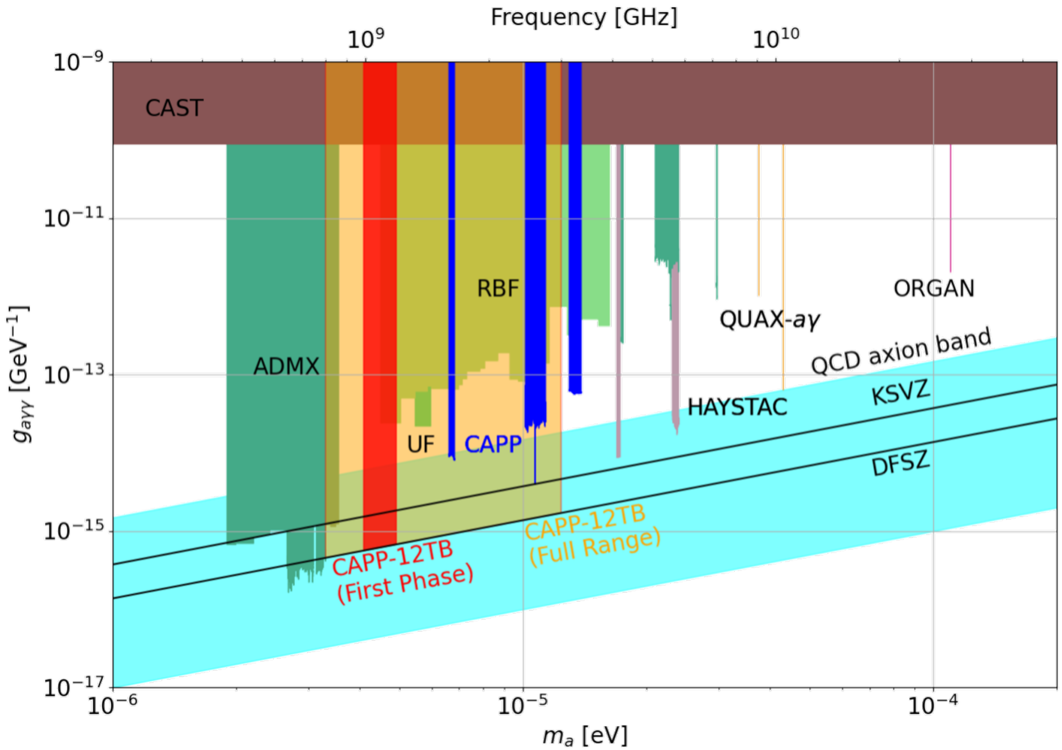


- *8T/127mm SC magnet*
- *BlueFors Dilution (T_{phy} ~ 40 mK)*
- *HEMT amplifiers*

- *First results around 10.7 ueV*
- *Δm_a ~ 1.2 μeV*
- *Sensitivity: g_{arr} ~ 9 KSVZ @ 90% C.L.*
- *Upgrade for SC cavity experiment*

CAPP-12TB

- *12T/320mm SC magnet*
- *Leiden Dilution (T_{phy} ~ 50 mK)*
- *JPA (T_{add} ~ 100 mL)*
- *Cavity > 30 L*



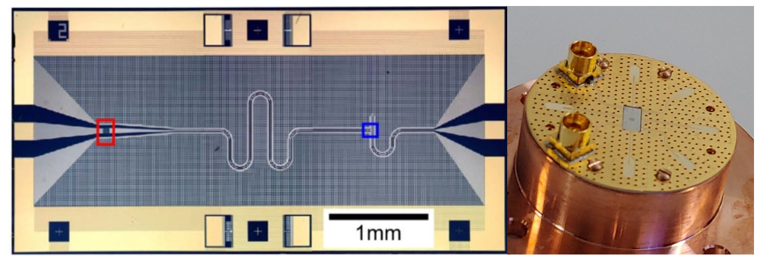
- *Flagship experiment at CAPP*
- *DFSZ sensitivity for f_a > 1 GHz (m_a > 5 μeV)*
- *Δf_a ~ 0.1 GHz => 3 GHz => 8 GHz*
- *First data expected in late 2021*

Projection & summary

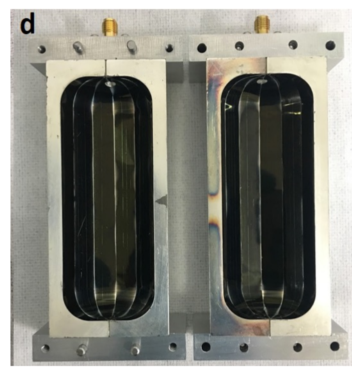
IBS-CAPP

Oxford SC magnet => 12 T
Leiden dilution => T = 5.6 mK
Cavity => V > 30 L

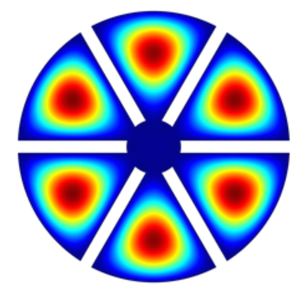
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$



JPA
(f = 1~6 GHz, T_n = 2~4 SQL)

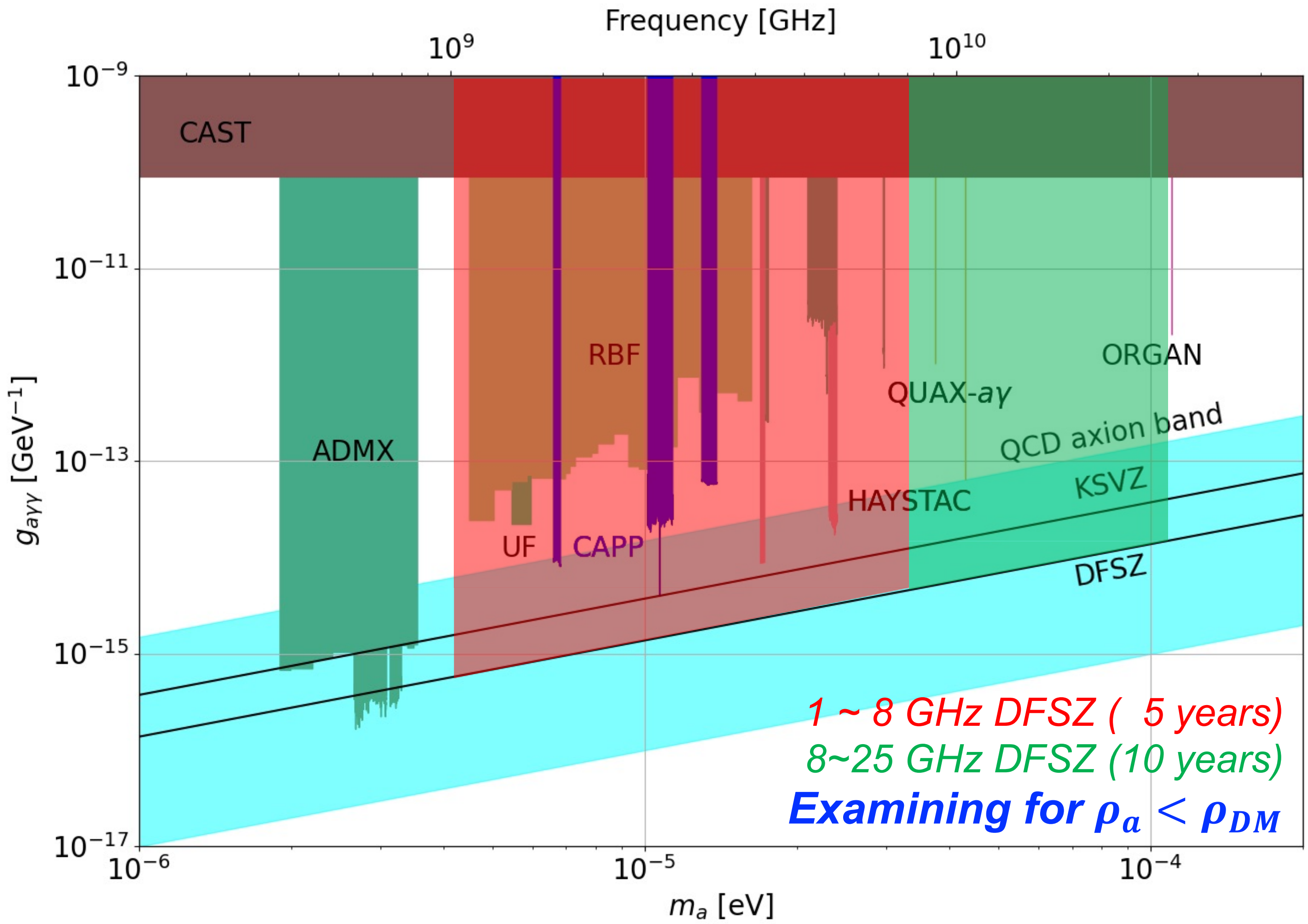


SC cavity
(Q > 1 M)



High frequency

Projected sensitivity



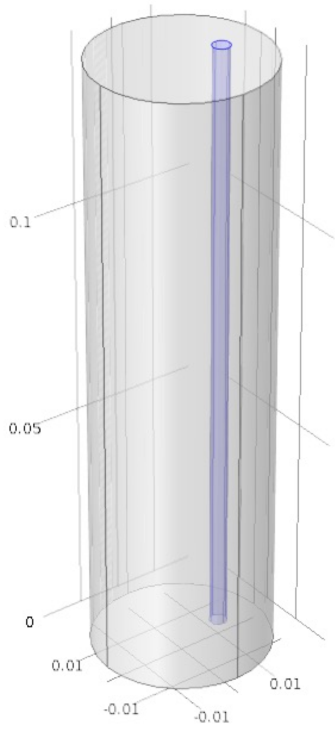
Summary

- *Axion is very charming*
  - *Strong CP problem & dark matter mystery*
- *Haloscope is the most sensitive approach*
  - *University lab-scale experiments*
- *IBS-CAPP is a serious axion hunter*
  - *Magnet / JPA / SC cavity / high frequency*
  - *Parallel experiments are on going*
- *IBS-CAPP will play a leadership role in axion business within a few years*
  - *Probing a large mass range (up to 100 μeV) with sensitivity of the QCD axion in next 10 to 20 years*
  - *Addressing the fundamental questions*

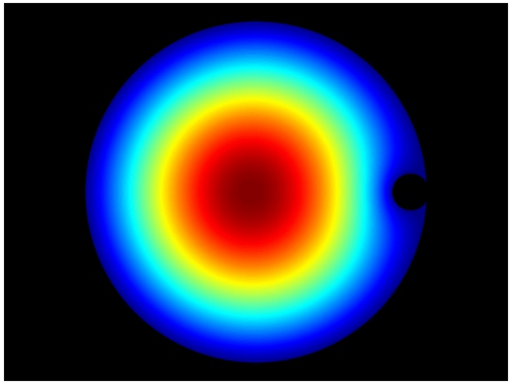
Backup Slides

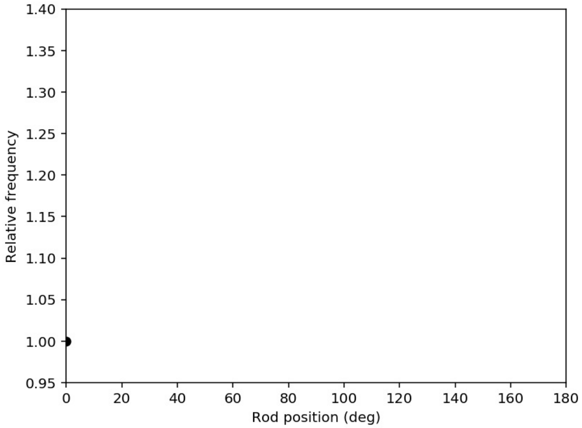
Frequency tuning

Cylindrical cavity
↓
Tuning rod(s)

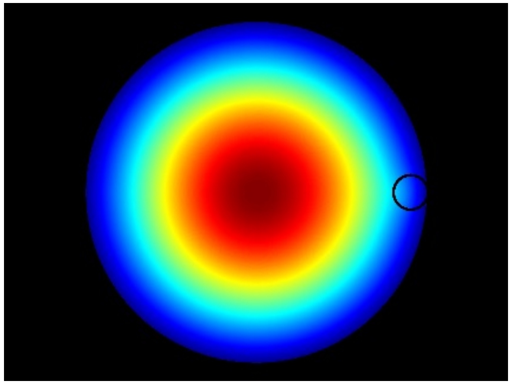


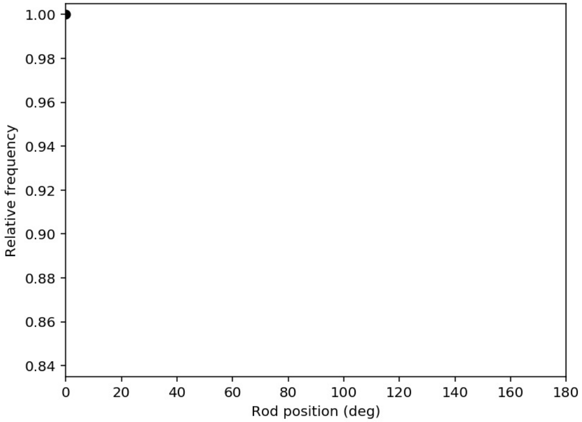
Conductor rod (TM_{010})





Dielectric rod (TM_{010})





Form factor

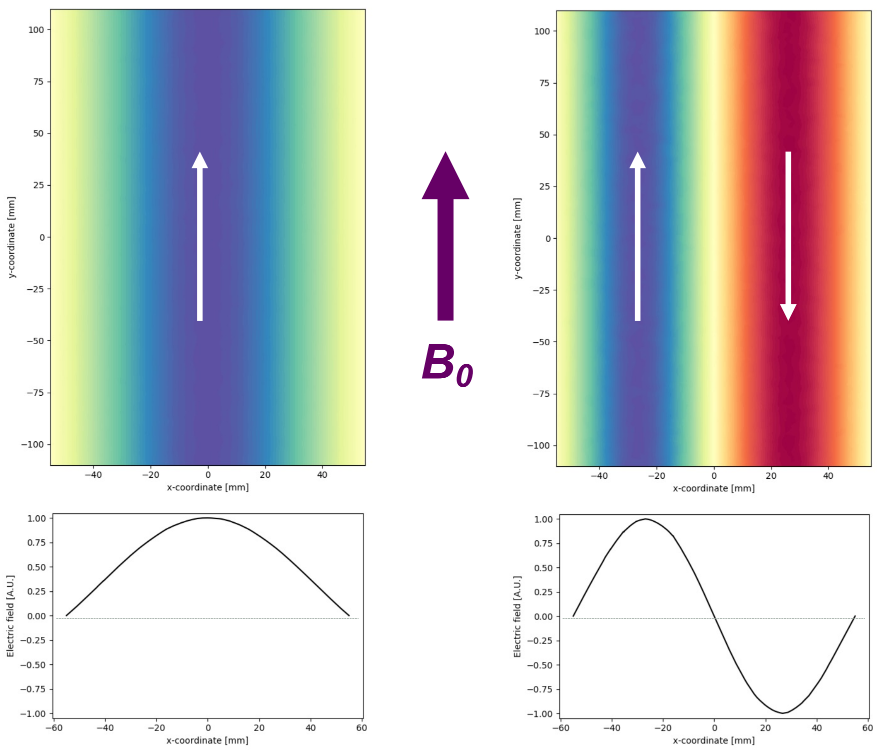
- *Geometry and mode dependent*
  - *Cavity mode and external field*

$$C_{mnp} = \frac{\left| \int \vec{E}_c \cdot \vec{B}_0 \, dV \right|^2}{\int \varepsilon \left| \vec{E}_c \right|^2 dV \int \left| \vec{B}_0 \right|^2 dV}$$

TM_{010} *TM_{110}*

E_c field

E_c profile



C_{010} = 0.69 *C_{110} = 0*

For cylindrical cavities

- *z-direction for TM modes*
- *φ-direction for TE modes*

TM_{010} mode

- *Maximum form factor*
- *Typical cavity mode for axion haloscopes*