Search for Axion Dark Matter at IBS-CAPP

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Center for Axion and Precision Physics Research (CAPP), Institute for Basic Science (IBS)

CAPP
Center for Axion and Precision Physics Research

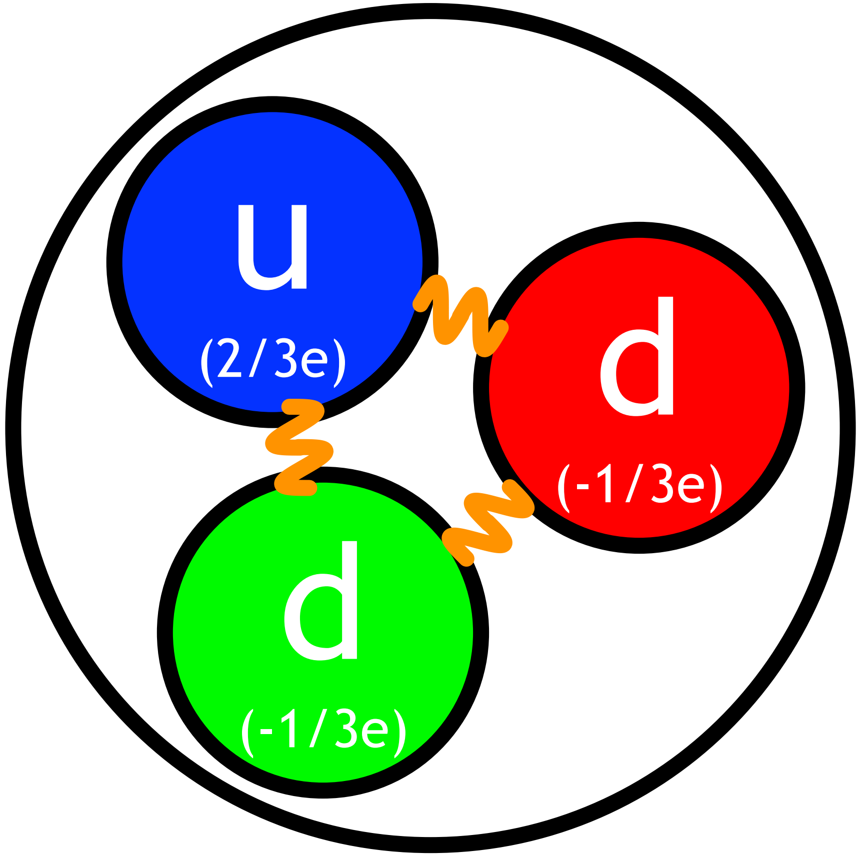
KAIST

June 12, 2023

Axion

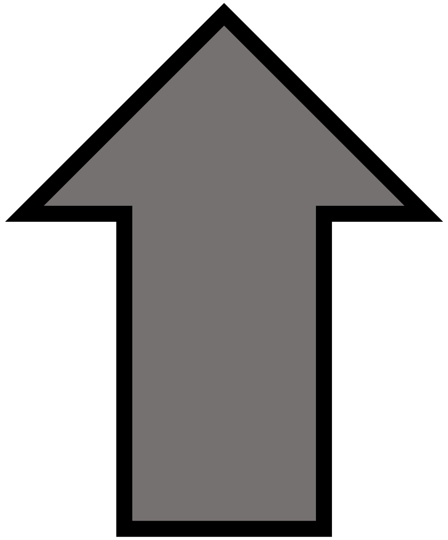
Strong CP Problem and Dark Matter

Neutron



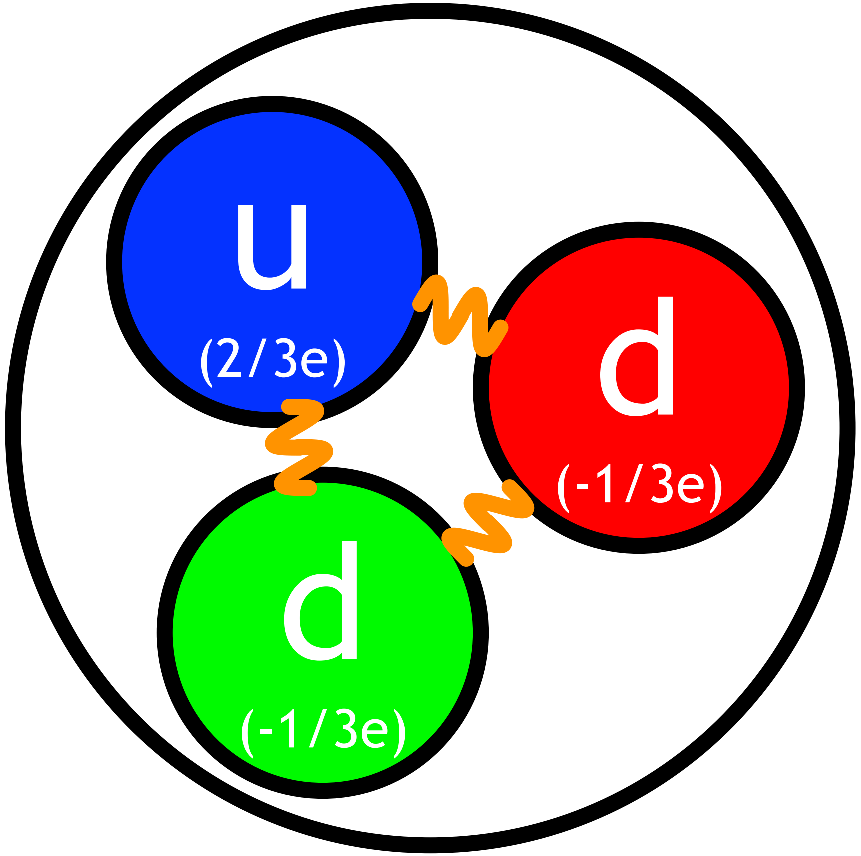
Net charge = 0

Neutron



Spin 1/2

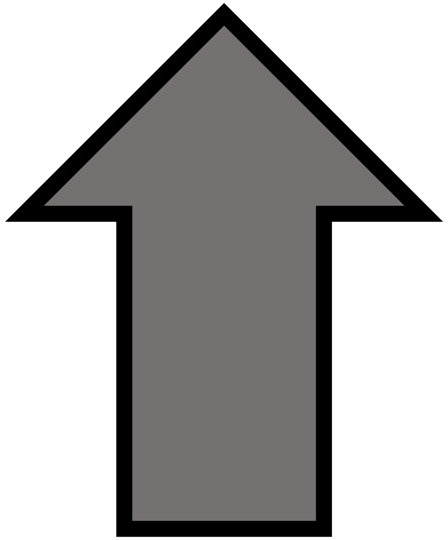
$(\vec{\mu} \parallel \vec{S})$



Non-zero $\vec{\mu}$

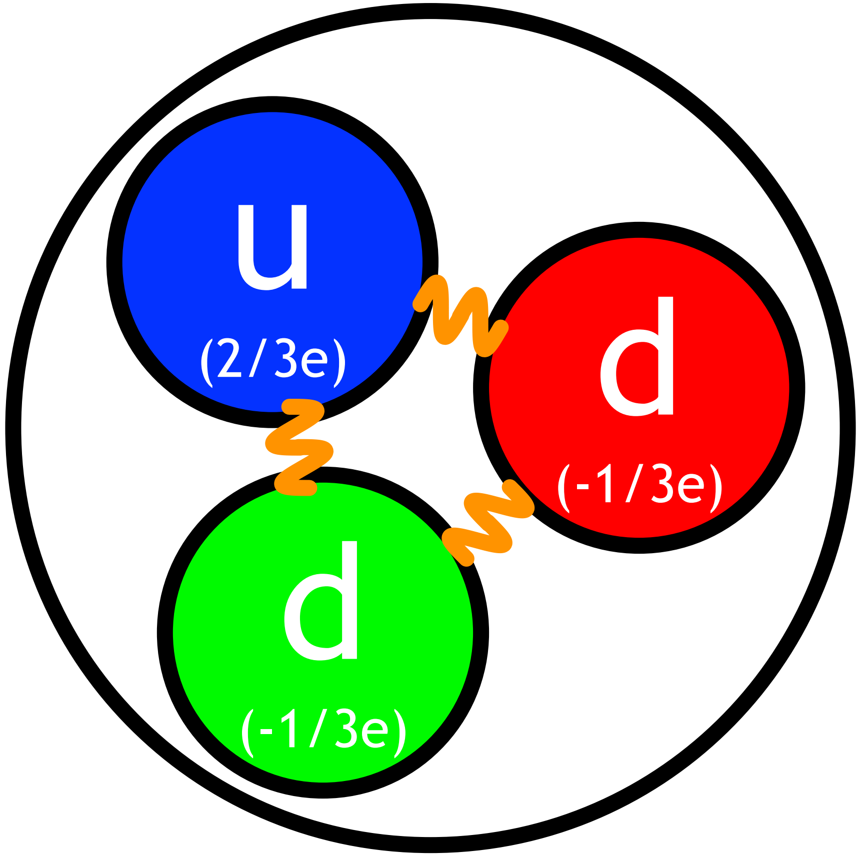
Net charge = 0

Neutron



Spin 1/2

($\vec{\mu} \parallel \vec{S}$)



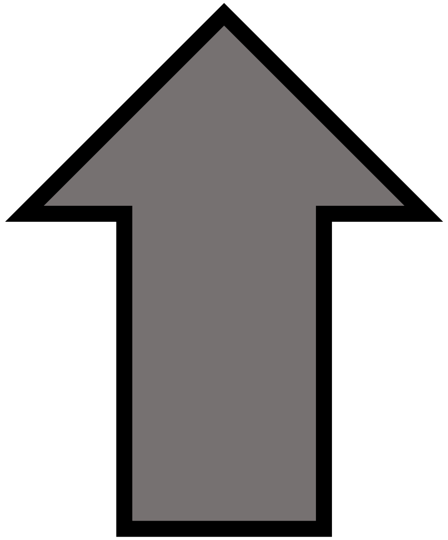
$\vec{\mu}, \vec{d} \parallel \vec{S}$

Does it have $\vec{d}$?

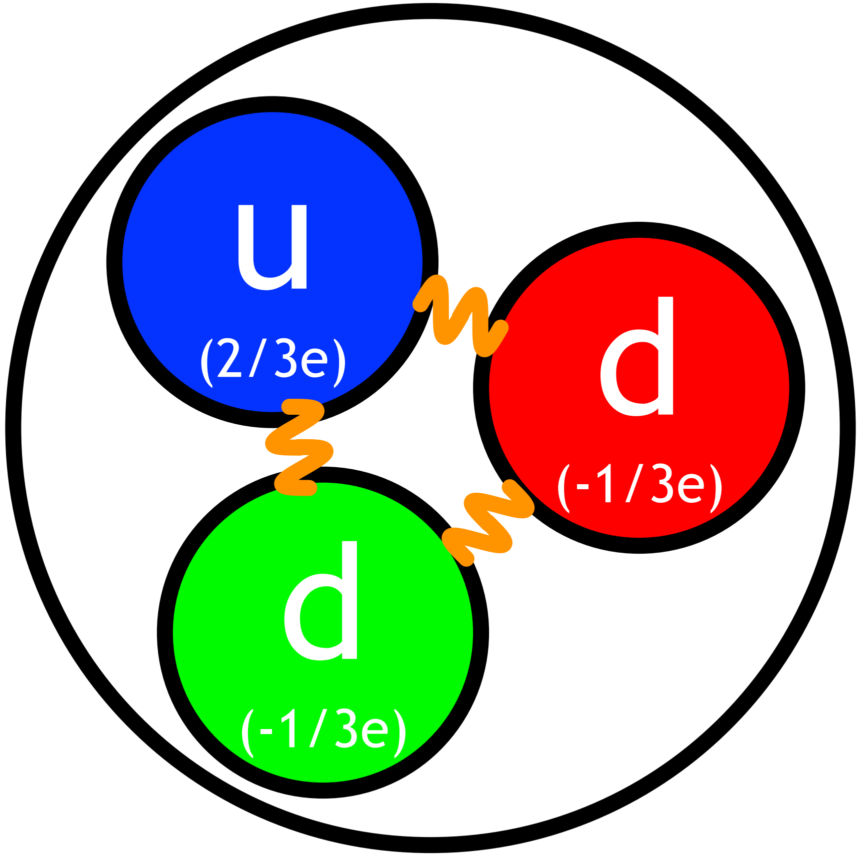
Non-zero $\vec{\mu}$

Net charge = 0

Neutron Electric Dipole Moment



Spin 1/2



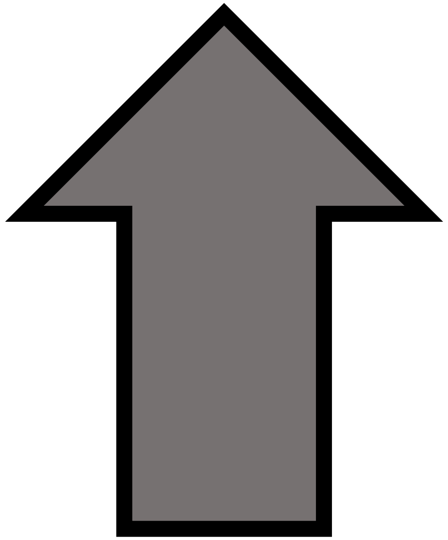
$\vec{\mu}, \vec{d} \parallel \vec{S}$

QCD predicts $\vec{d}$

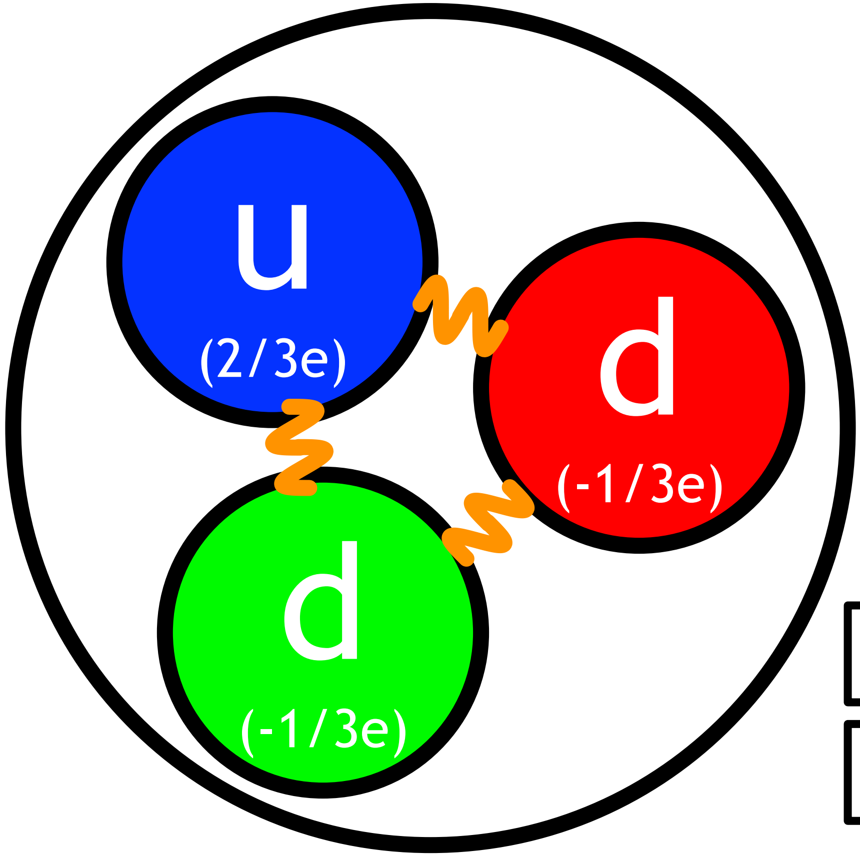
$$\mathcal{L}_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$|\vec{d}| \sim 3\times10^{-16} \bar{\theta}\ e \cdot \mathrm{cm}$$

Neutron Electric Dipole Moment



Spin 1/2



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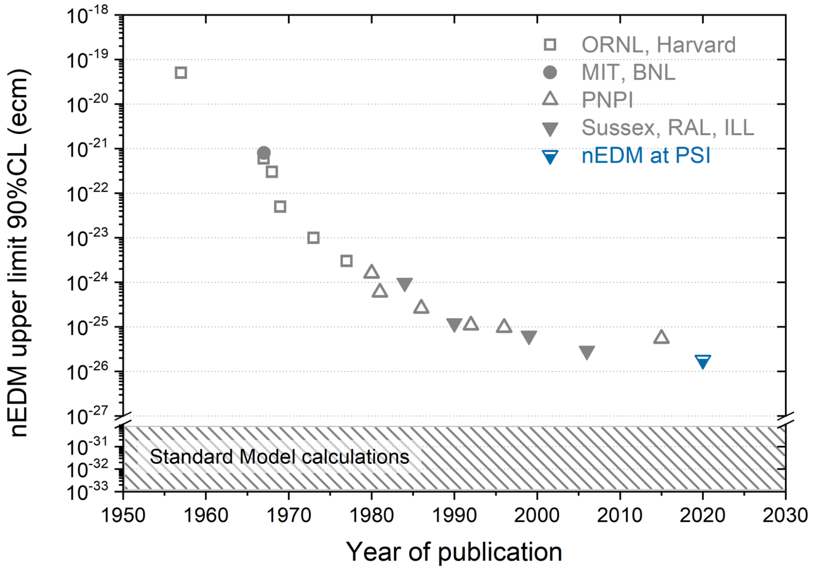
$$\bar{\theta} = \boxed{\theta_0} + \boxed{\arg\det M_q}$$

Instanton → θ_0

Higgs mechanism → $\arg\det M_q$

$$|\vec{d}| \sim 3\times 10^{-16} \bar{\theta}\ e \cdot \mathrm{cm}$$

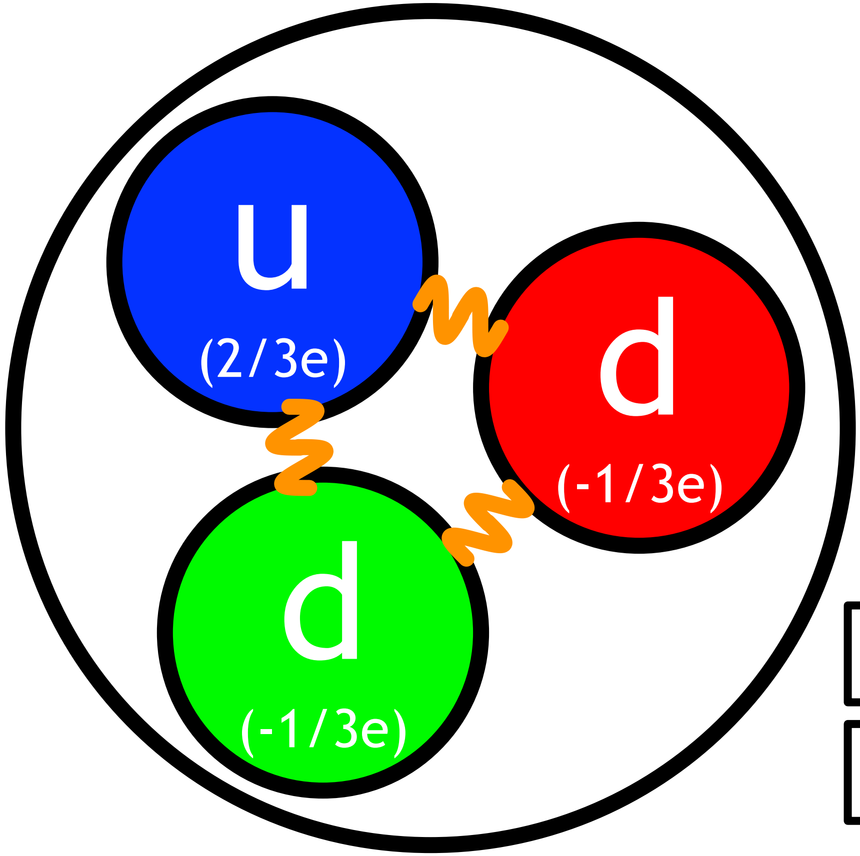
Strong CP Problem



The history of nEDM limits [PSI]

$$\left|\vec{d}\right| < 2\times10^{-26}\ e\cdot\mathrm{cm}$$

$$\bar{\theta} < 10^{-10}$$



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Peccei-Quinn Mechanism

CP-violating Lagrangian

$$\mathcal{L}_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

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Instanton

Higgs mechanism

[R. D. Peccei, H. R. Quinn]

Peccei-Quinn Mechanism

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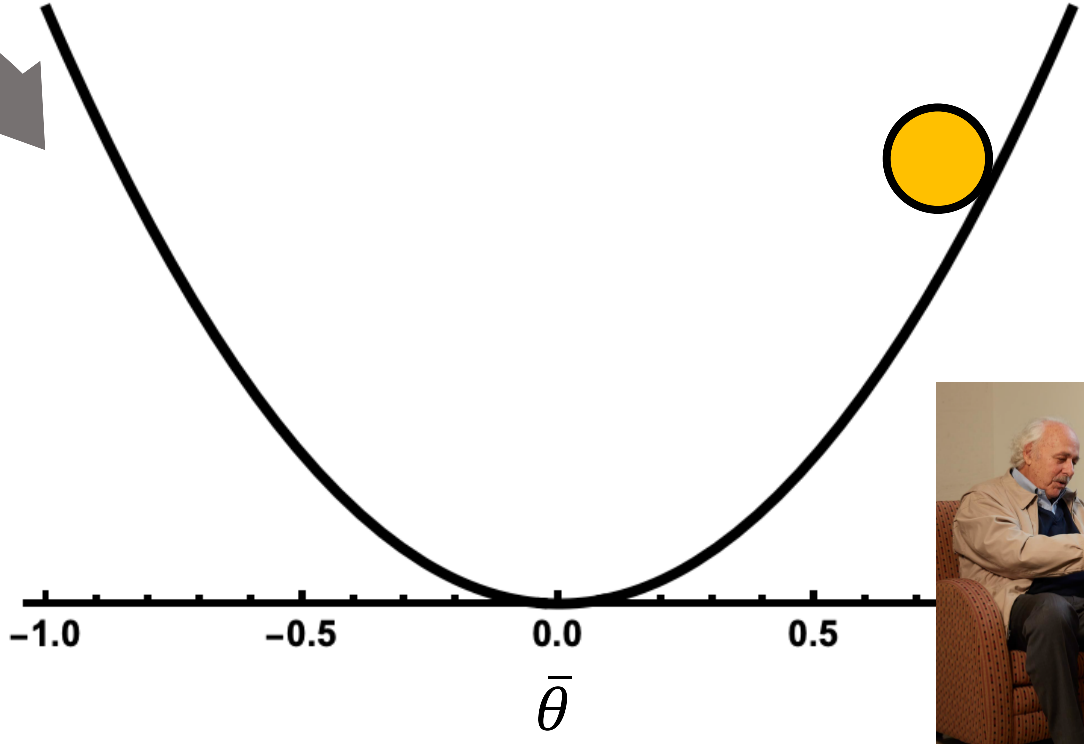
Mininum energy at $\bar{\theta} = 0$



[R. D. Peccei, H. R. Quinn]

Peccei-Quinn Mechanism

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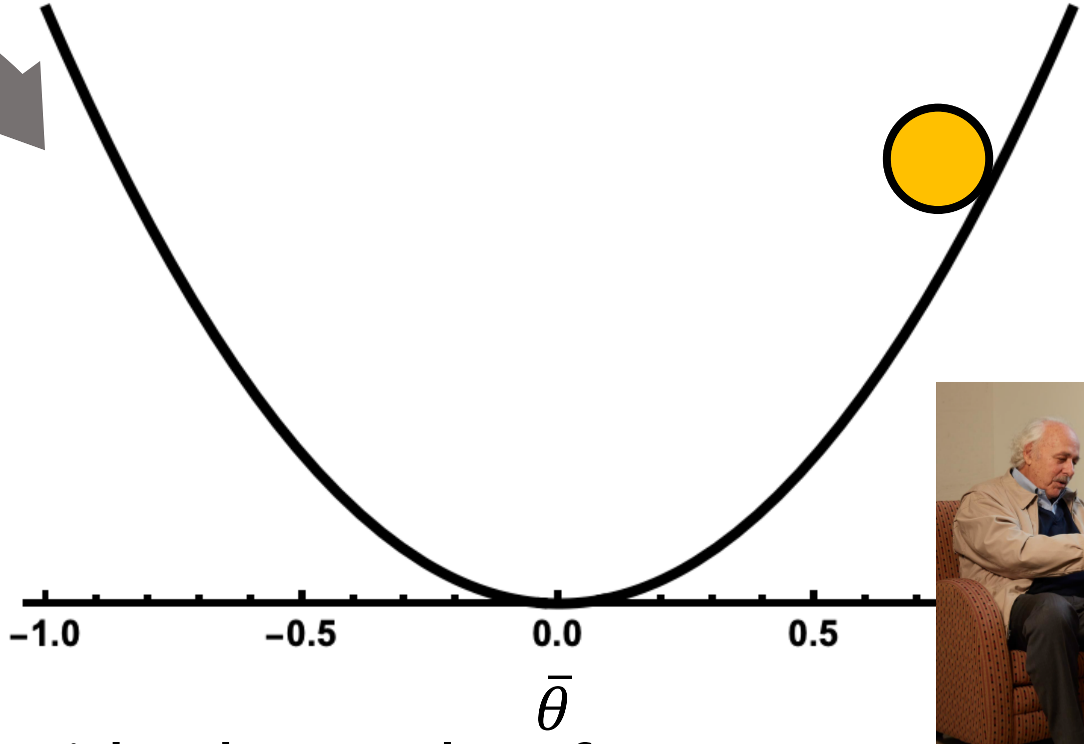

[R. D. Peccei, H. R. Quinn]

Introduce a new field inside the angle of M_q

$\bar{\theta}$: Constant ⇒ Dynamic field

Peccei-Quinn Mechanism

CP-violating Lagrangian

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Instanton

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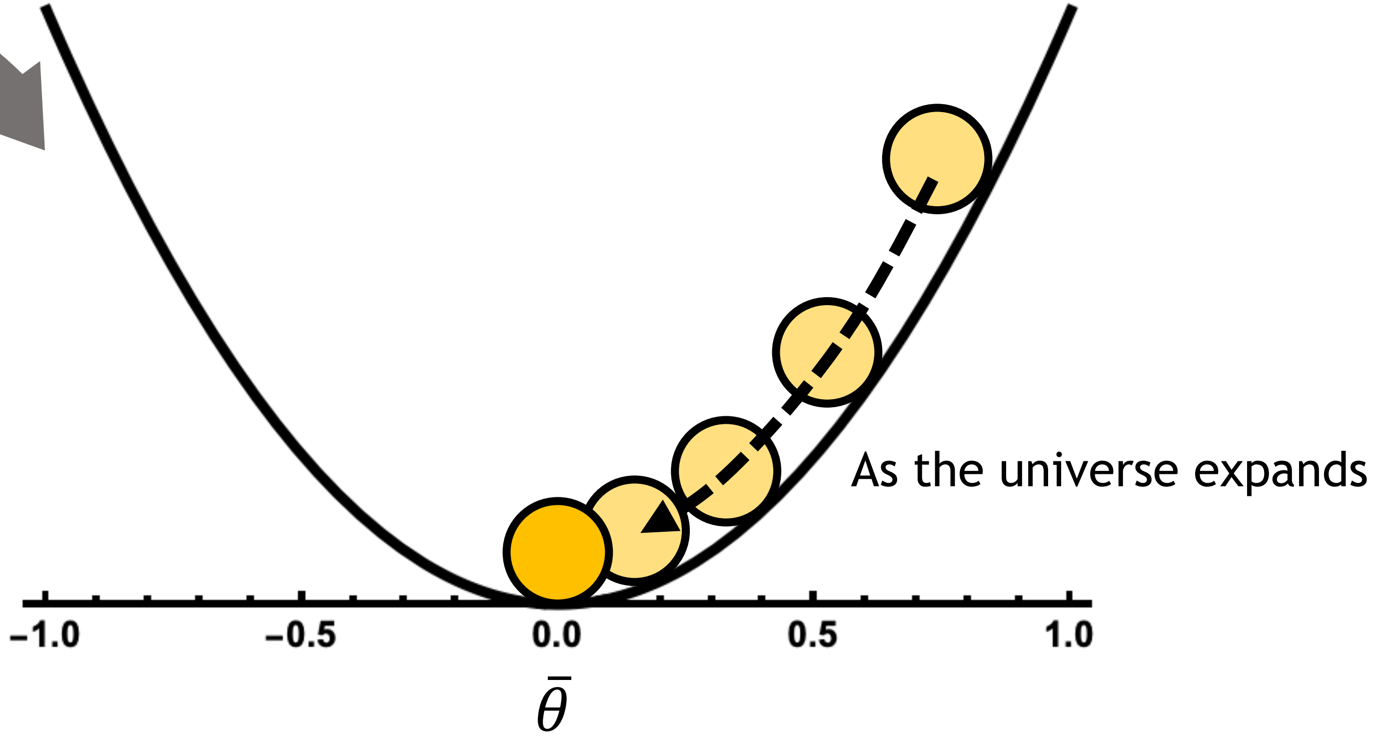

Introduce a new field inside the angle of M_q

$\bar{\theta}$: Constant ⇒ Dynamic field

Axion

CP-violating Lagrangian

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Instanton

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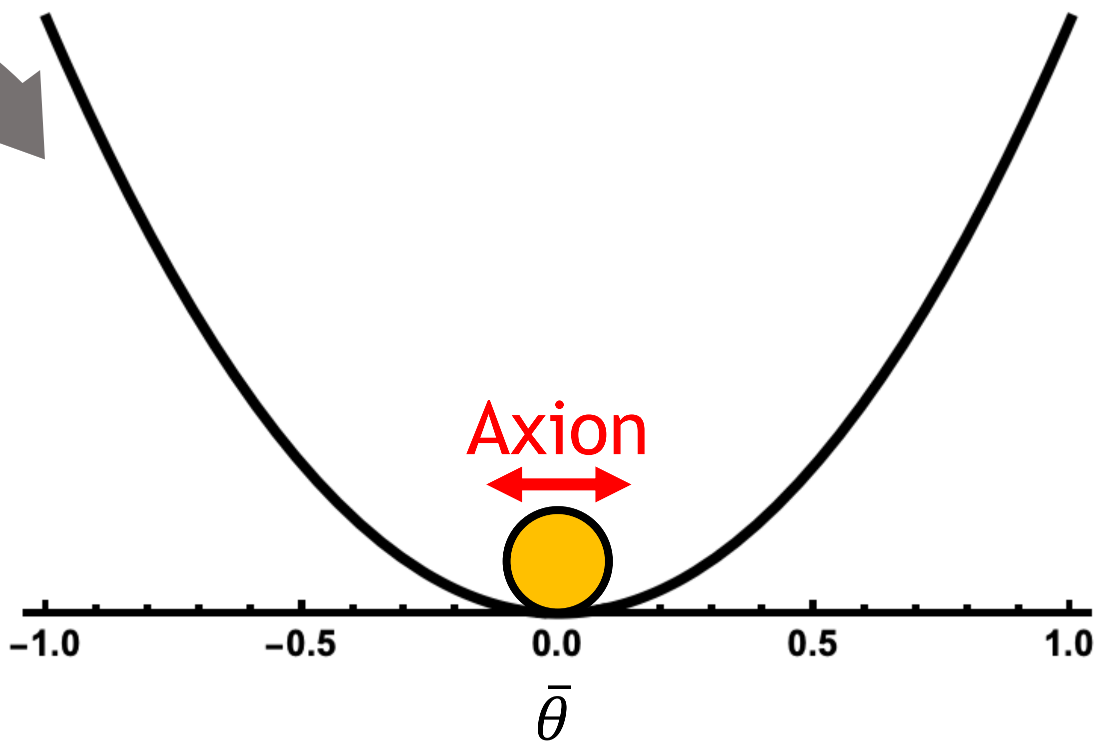
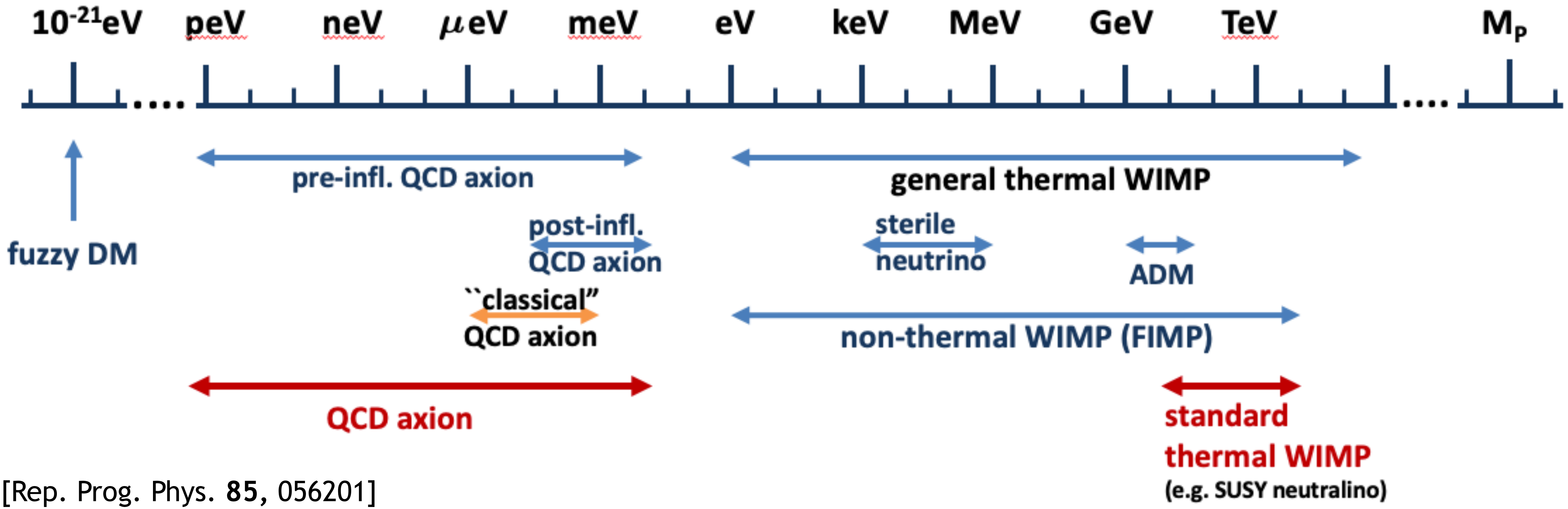


Introduce a new field inside the angle of M_q

$\bar{\theta}$: Constant ⇒ Dynamic field

Dark Matter Candidates

- Invisible Axion $(m_a < 10\ meV)$
- Weakly Interacting Massive Particle (WIMP)
- …

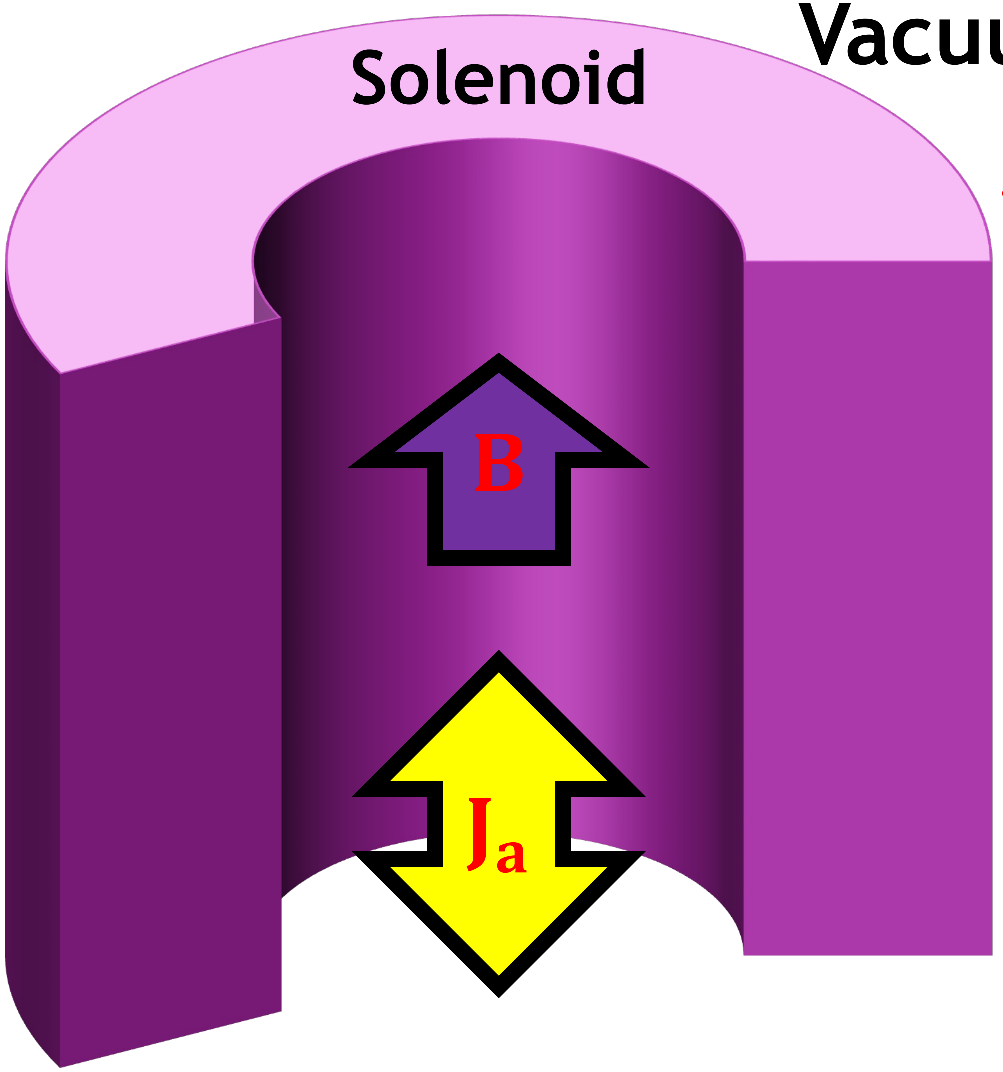


[Rep. Prog. Phys. **85**, 056201]

Axion Haloscope

Search for Axion Dark Matter

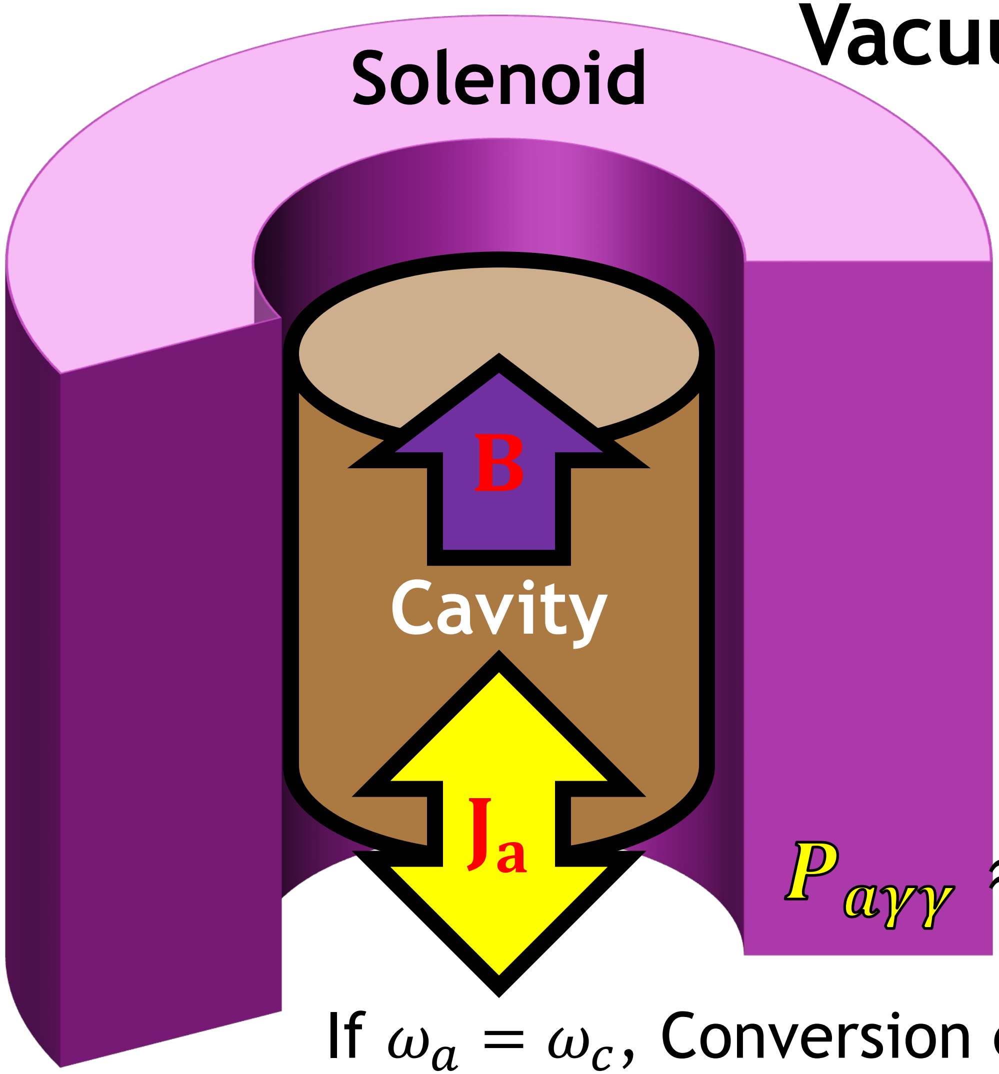
Cavity Haloscope



Vacuum current density

$$g_{a\gamma\gamma}(\nabla a\times\mathbf{E} + \partial_t a\mathbf{B})$$

Cavity Haloscope



If $\omega_a = \omega_c$, Conversion enhanced

Vacuum current density

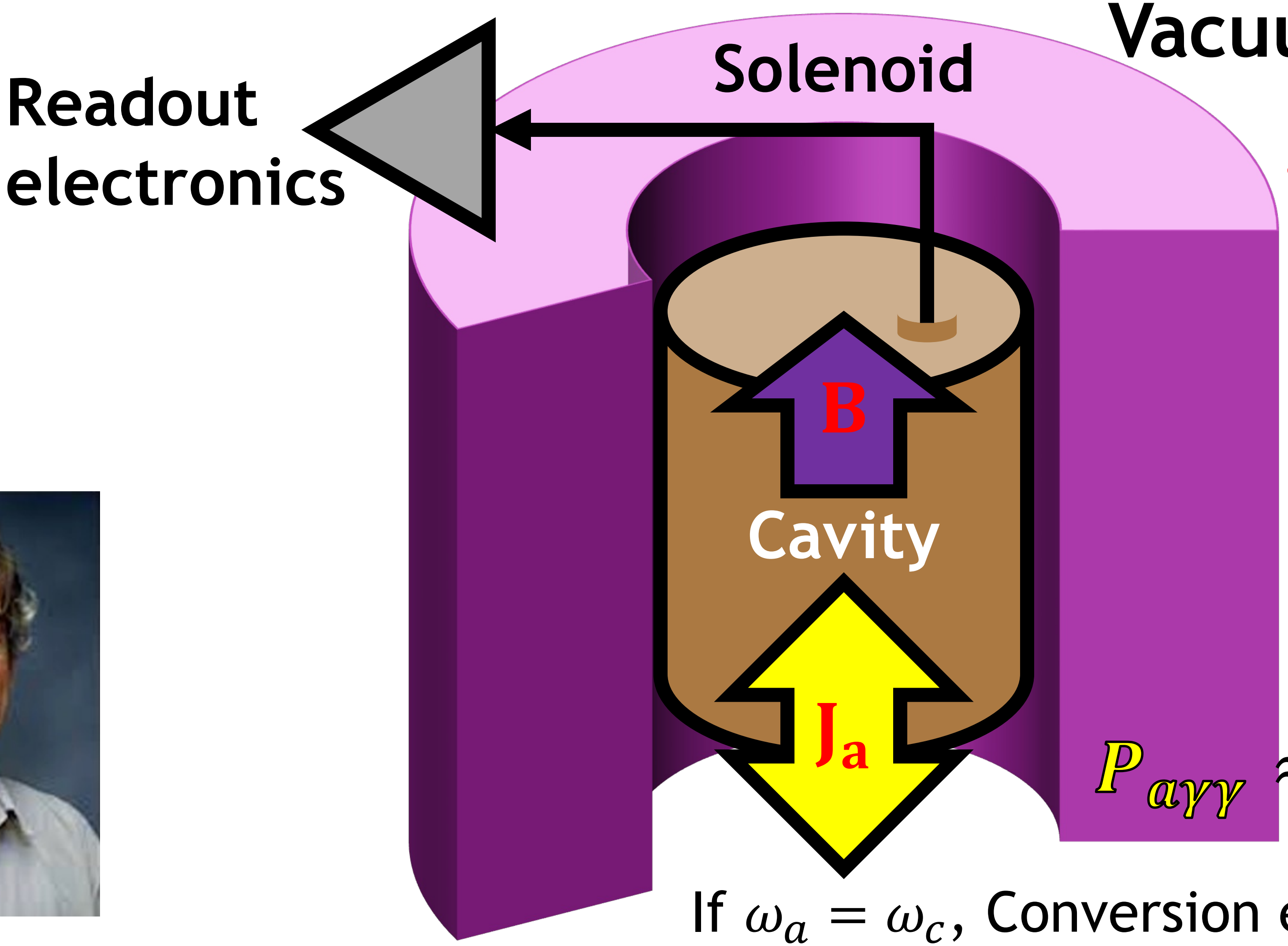
$g_{a\gamma\gamma}(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B})$

Cavity Haloscope

$$P_{a\gamma\gamma} \approx \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \langle B^2 \rangle V_c Q_c C$$

[P. Sikivie]

Cavity Haloscope



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$$P_{a\gamma\gamma} \approx \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \langle B^2 \rangle V_c Q_c C$$

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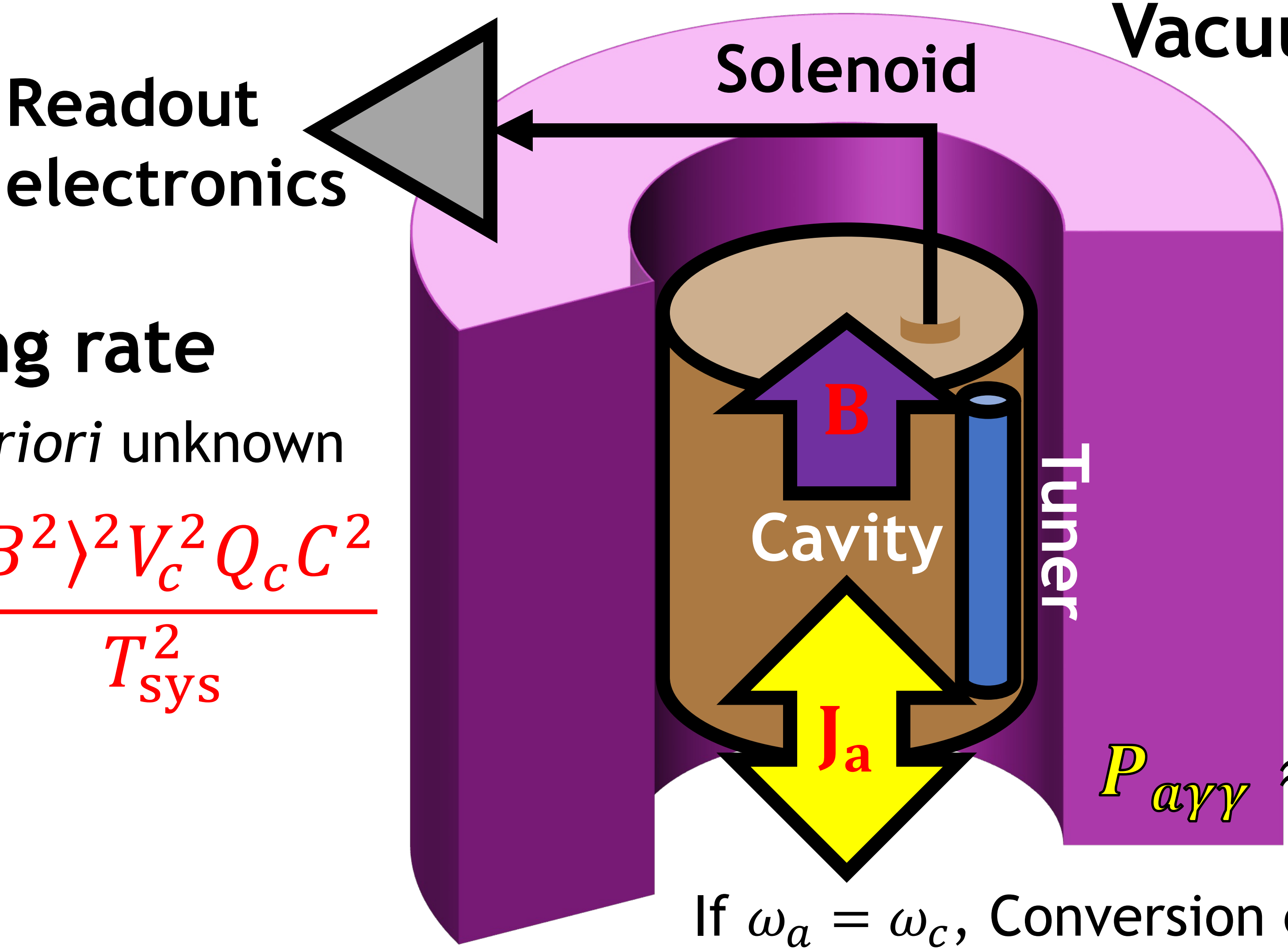
[P. Sikivie]

Cavity Haloscope



Vacuum current density

$g_{a\gamma\gamma}(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B})$

Scanning rate

m_a is *a priori* unknown

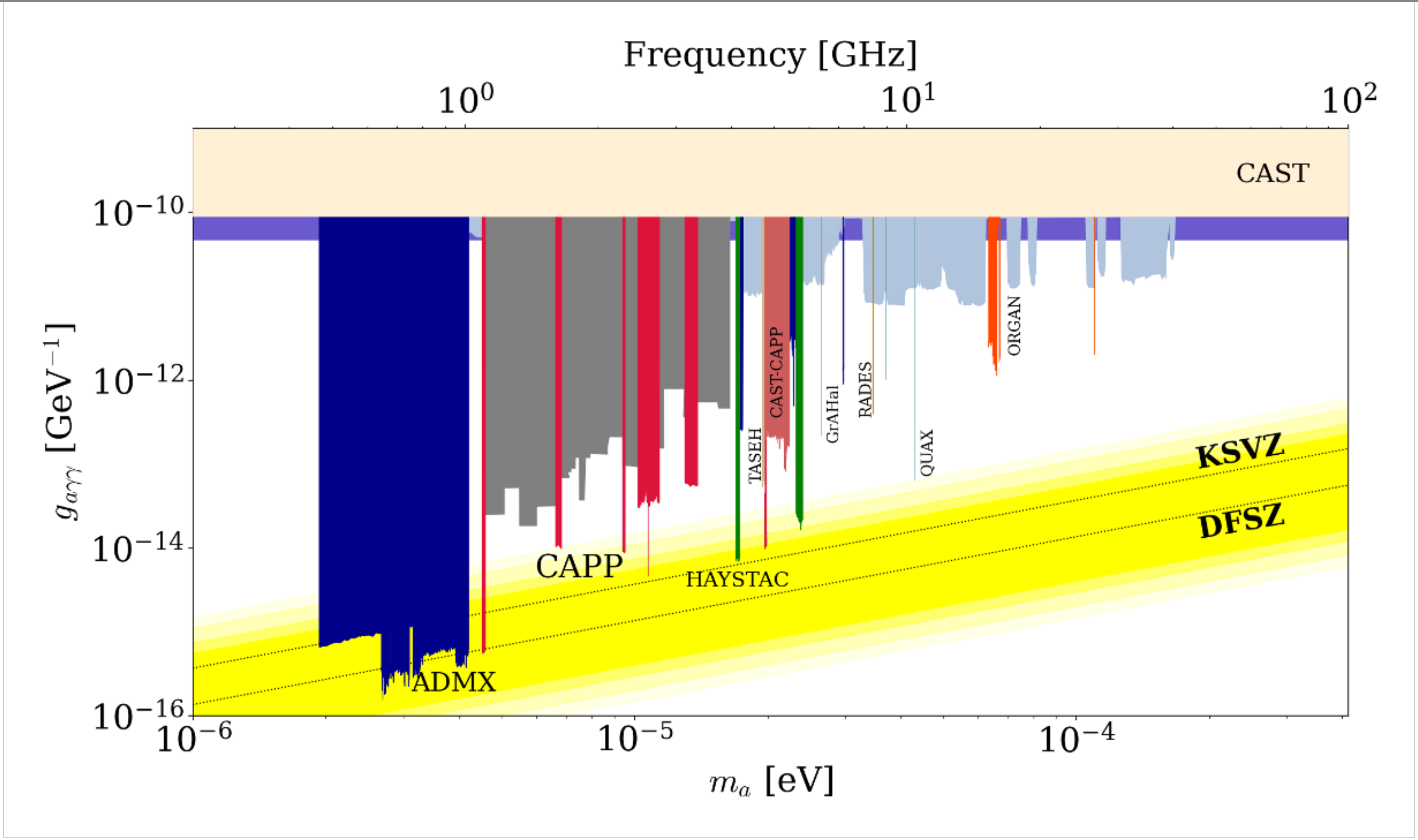
$$\frac{df}{dt} \propto \frac{\langle B^2\rangle^2 V_c^2 Q_c C^2}{T_{\text{sys}}^2}$$

Cavity Haloscope

$$P_{a\gamma\gamma} \approx \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \langle B^2\rangle V_c Q_c C$$

If $\omega_a = \omega_c$, Conversion enhanced

Exclusion Limits



Axion Haloscope at IBS-CAPP

Center for Axion and Precision Physics Research

IBS-CAPP

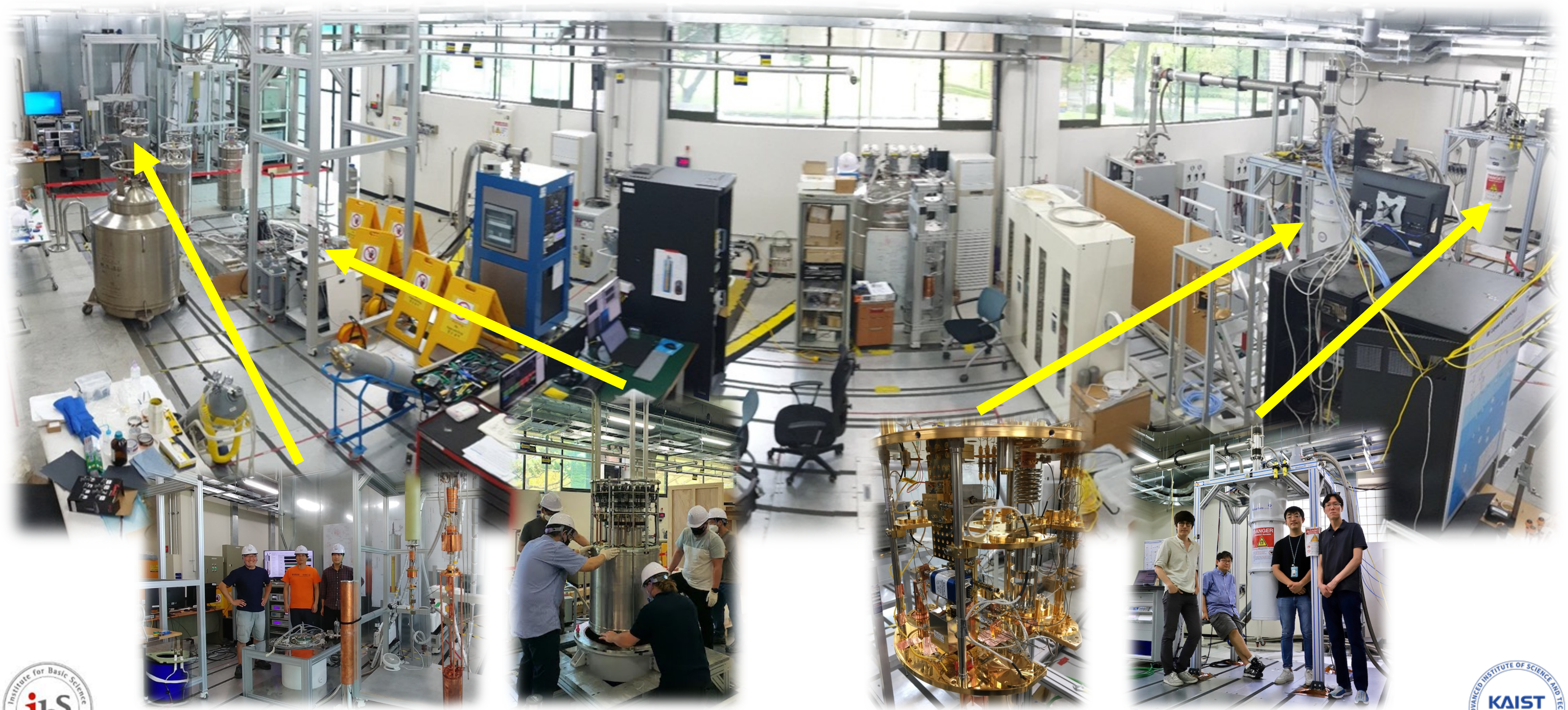
CAPP
Center for
Axion and Precision
Physics Research

Center for Axion and Precision Physics Research

CAPP of Institute for Baisc Science (IBS) at KAIST in Korea since October 2013

Project: Axion dark matter, Storage ring proton EDM, Axion mediated long range force

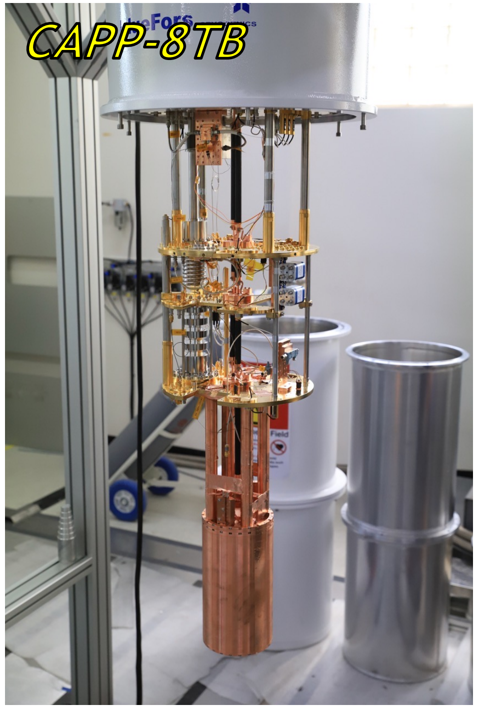
IBS-CAPP



CAPP-8TB

1. CAPP-8TB

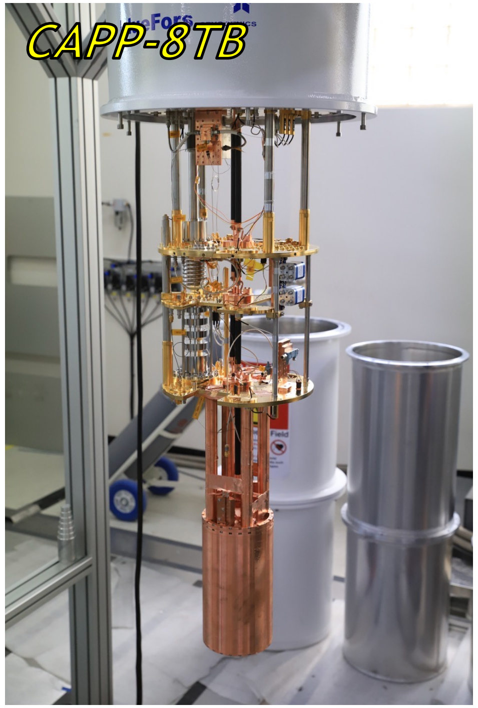
- 8T/ 165mm
- T_{phy} ~ 50 mK
- HEMT ~ 1 K
- 1.6 GHz (50 MHz, 4 KSVZ)



CAPP-8TB, CAPP-9T MC

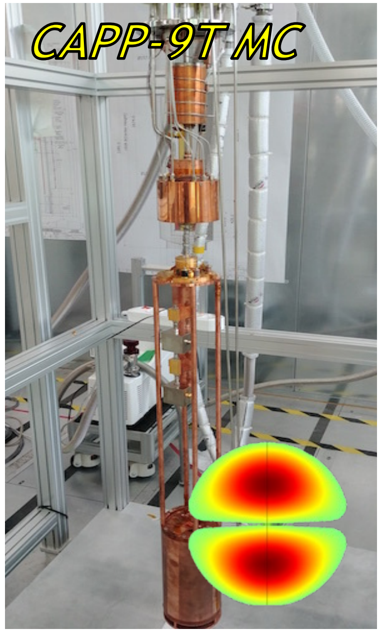
1. CAPP-8TB

- *8T/ 165mm*
- *T_{phy} ~ 50 mK*
- *HEMT ~ 1 K*
- *1.6 GHz*



2. CAPP-9T MC
(Multiple-cell)

- *9T/ 127mm*
- *T_{phy} ~ 2 K*
- *HEMT ~ 1.5 K*
- *> 3 GHz (200 MHz, 10 KSVZ)*



CAPP-8TB, CAPP-9T MC, CAPP-PACE

1. CAPP-8TB

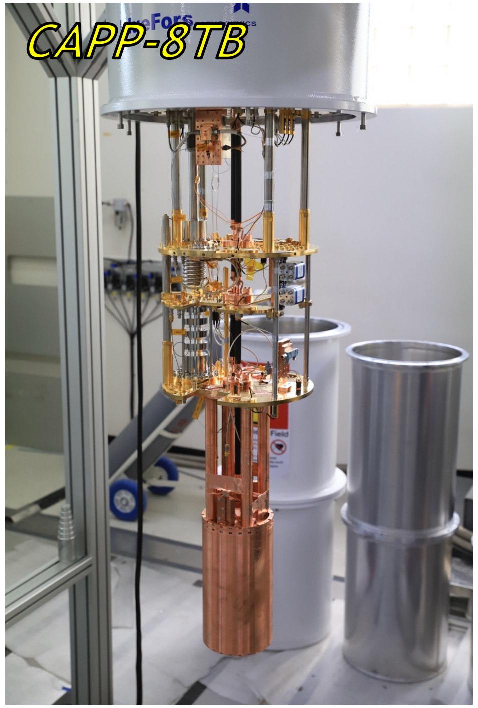
- 8T / 165mm
- T_{phy} ~ 50 mK
- HEMT ~ 1 K
- 1.6 GHz

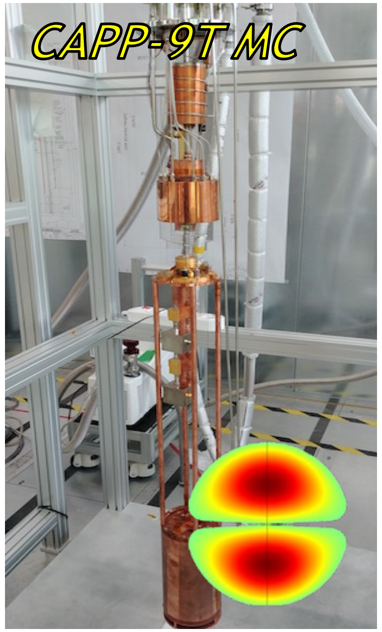
2. CAPP-9T MC (Multiple-cell)

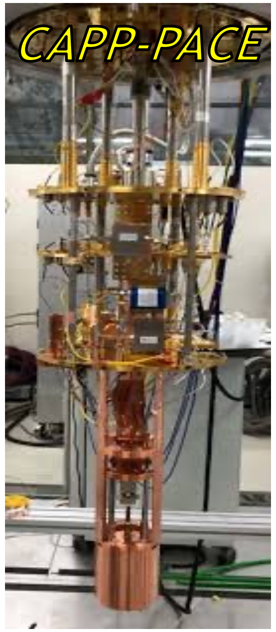
- 9T / 127mm
- T_{phy} ~ 2 K
- HEMT ~ 1.5 K
- > 3 GHz

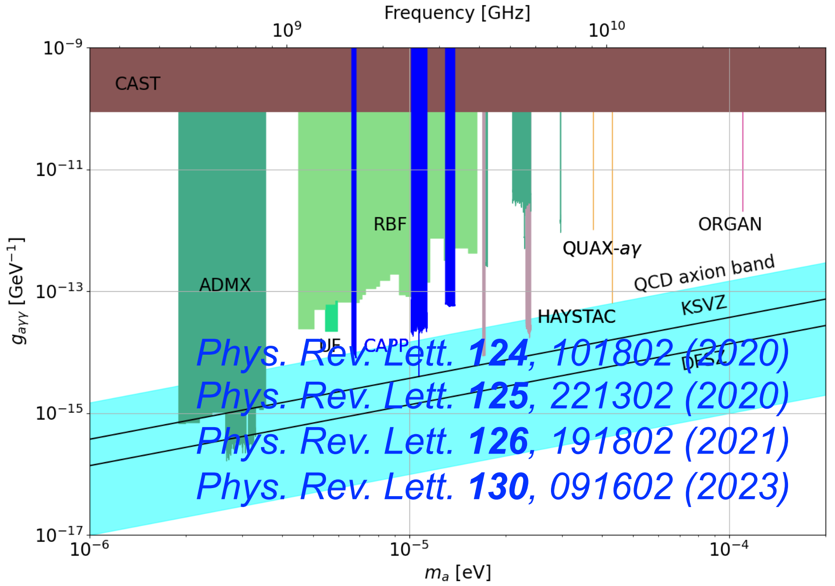
3. CAPP-PACE (Pilot Axion-Cavity Experiment)

- 8T / 127mm
- T_{phy} ~ 40 mK
- HEMT ~ 1 K, QNL AMP: 0.2 K
- 2.5 GHz (300 MHz, 10 & 3 KSVZ)



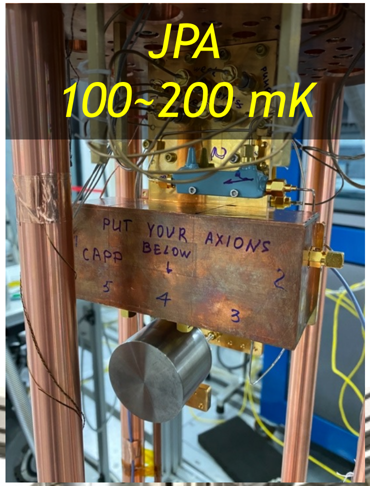


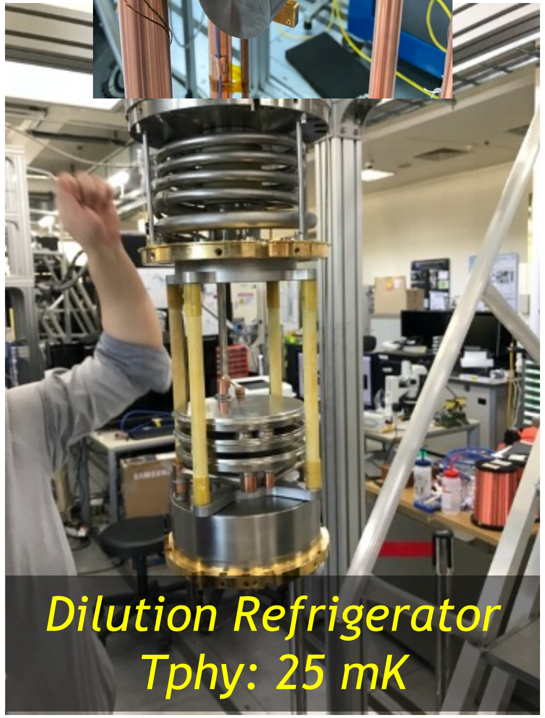




Phys. Rev. Lett. **124**, 101802 (2020)
Phys. Rev. Lett. **125**, 221302 (2020)
Phys. Rev. Lett. **126**, 191802 (2021)
Phys. Rev. Lett. **130**, 091602 (2023)

CAPP-12TB, our Flagship experiment





$$\frac{df}{dt} \propto \frac{\langle B^2\rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

CAPP-12TB, our Flagship experiment

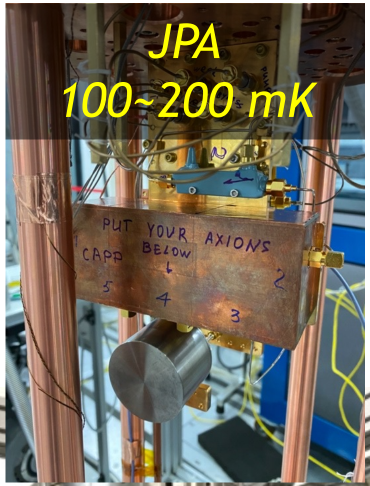
Axion to Photon conversion at 1.15 GHz

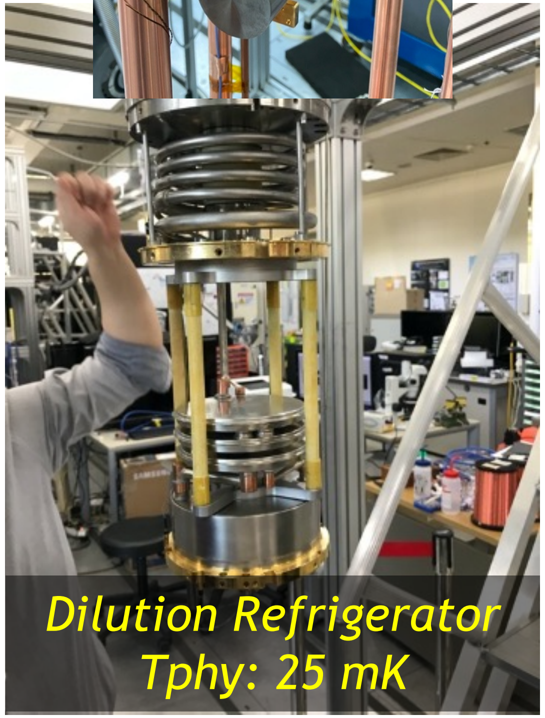
- KSVZ: 6.2×10^{-22} W or 10^3 photons/s
- DFSZ: 0.9×10^{-22} W or 10^2 photons/s

With T_{sys} of 200 mK ($Q_c = 10^5$, eff.=0.8)

- KSVZ: 50 GHz/year
- DFSZ: 1 GHz/year

$$\frac{df}{dt} \propto \frac{\langle B^2\rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$





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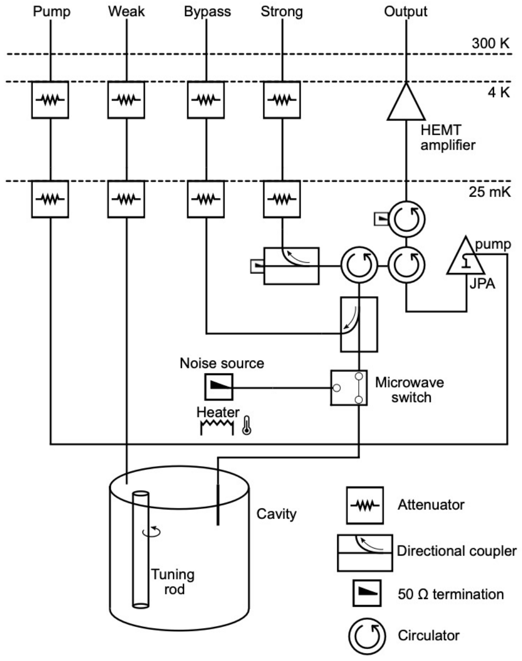
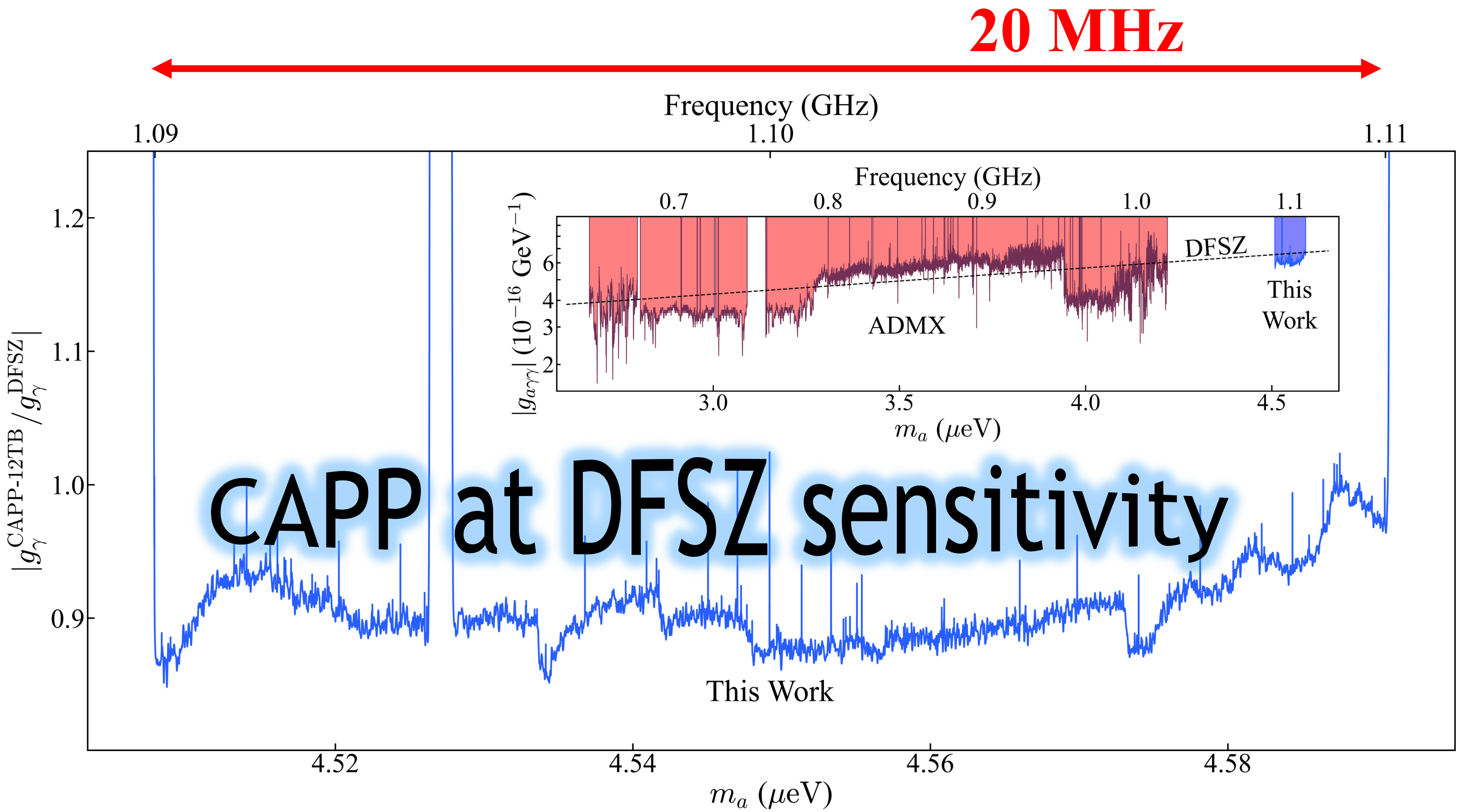


FIG. 2: CAPP-12TB receiver diagram.

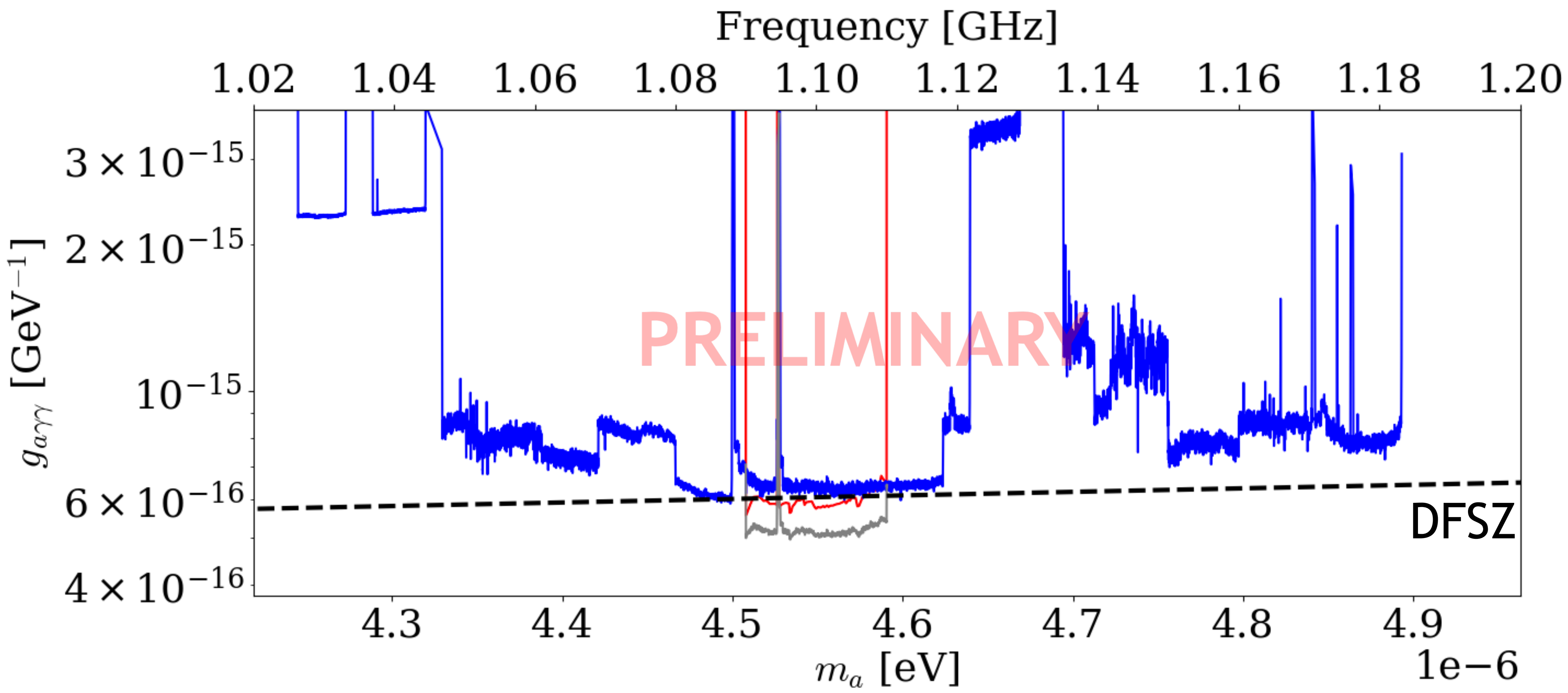


[A. K. Yi et al.], Phys. Rev. Lett. **130**, 071002 (2023)

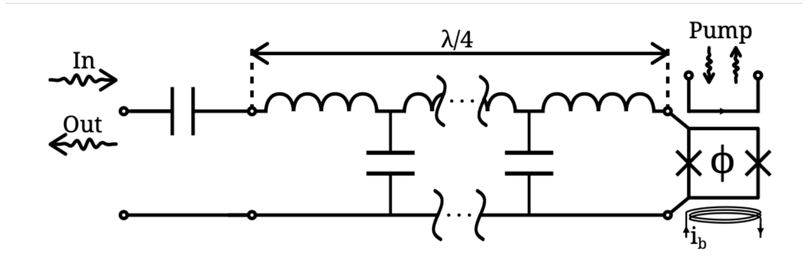
CAPP-12TB, our Flagship experiment

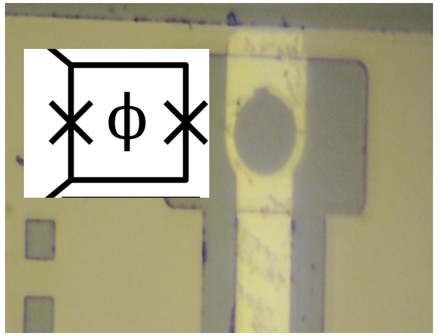
CAPP-12TB, our Flagship experiment

Preliminary results extending search frequencies, (3 MHz/day)

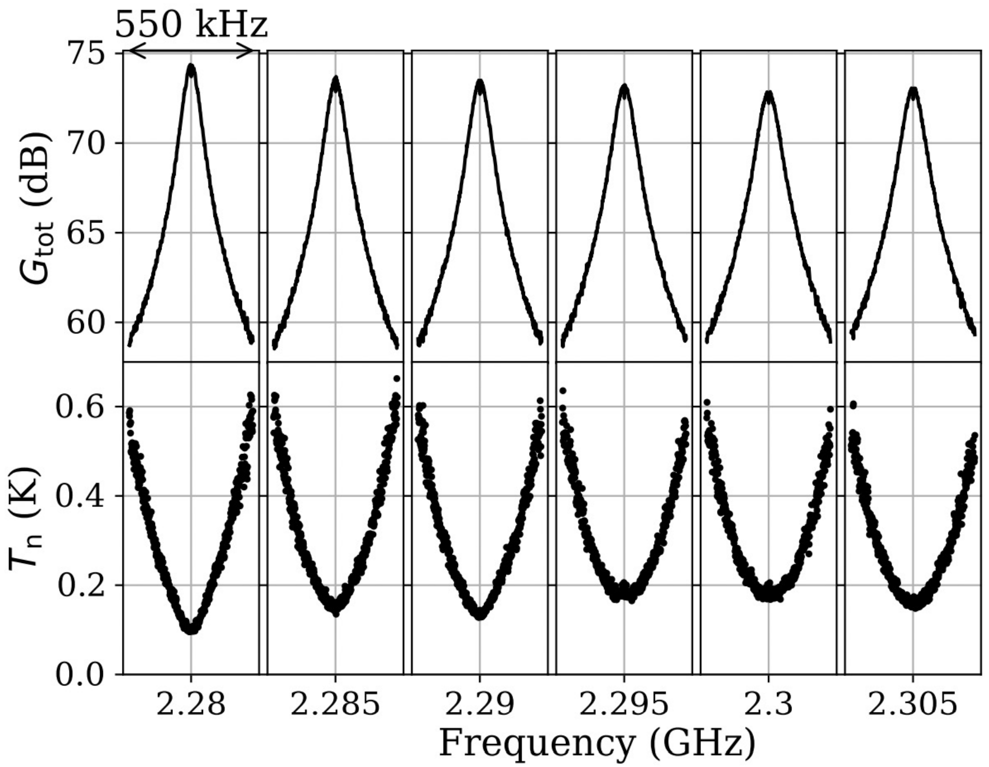


Quantum Noise-Limited Amplifier





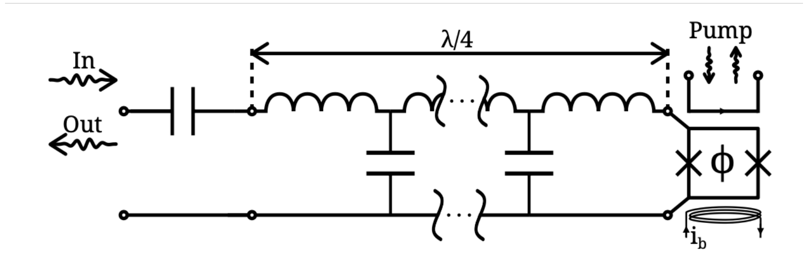
Flux-driven Josephson Parametric Amplifier

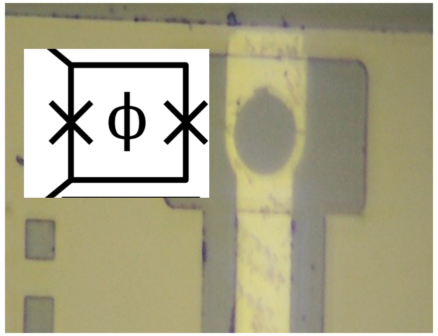


[2021 Supercond. Sci. Technol. 34 085013]

$$T_{sys} = T_{phy} + T_n$$

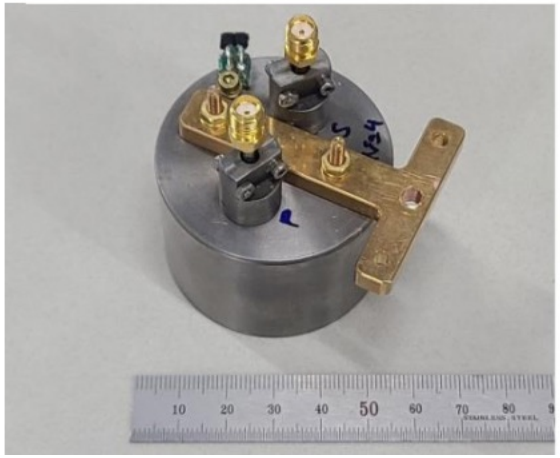
Quantum Noise-Limited Amplifier





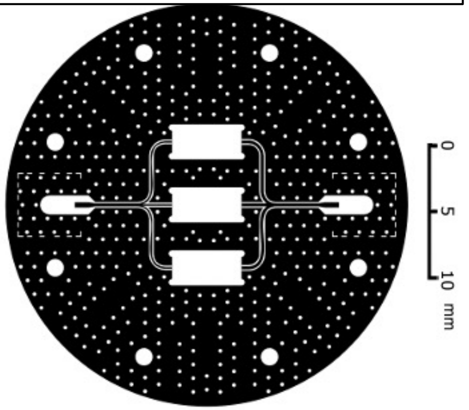
Flux-driven Josephson Parametric Amplifier

3-layer shield (Al-μ metal-NbTi)

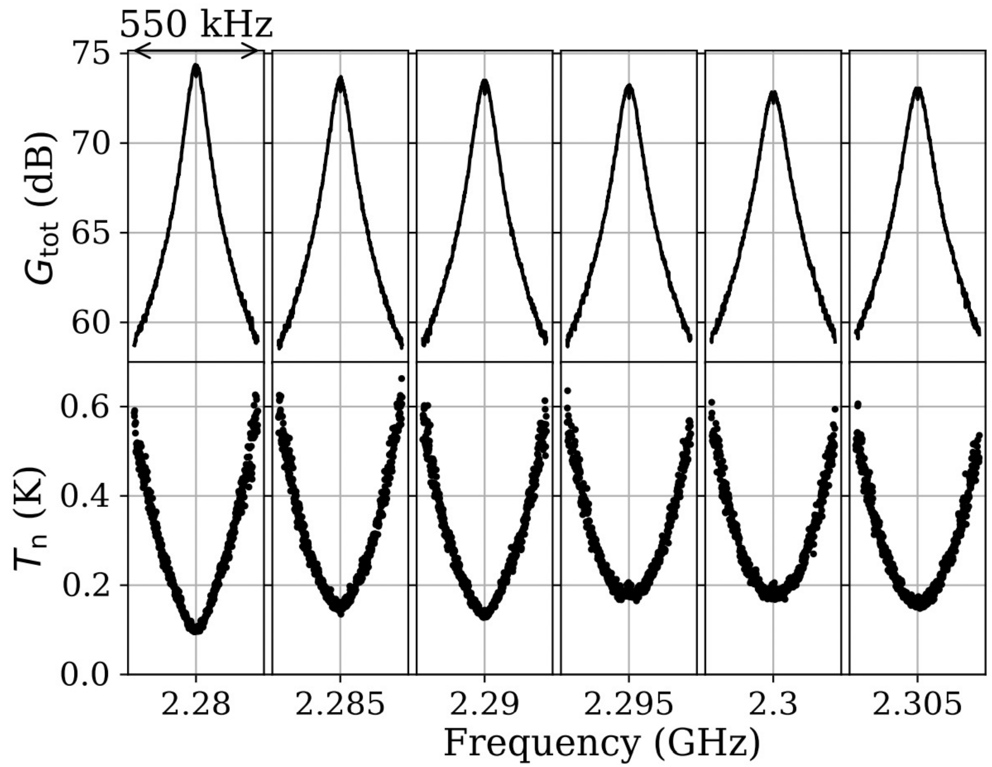


[JPS Conf. Proc. 38, 011201 (2023)]

Parallely connected



[arXiv:2304.04378]

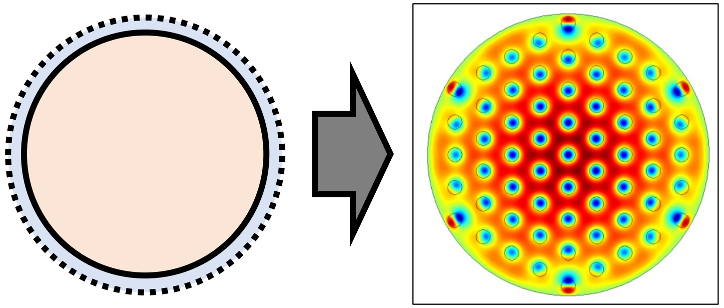


[2021 Supercond. Sci. Technol. 34 085013]

$$T_{\mathrm{sys}} = T_{\mathrm{phy}} + T_n$$

Tunable Photonic Crystal

Photonic crystal

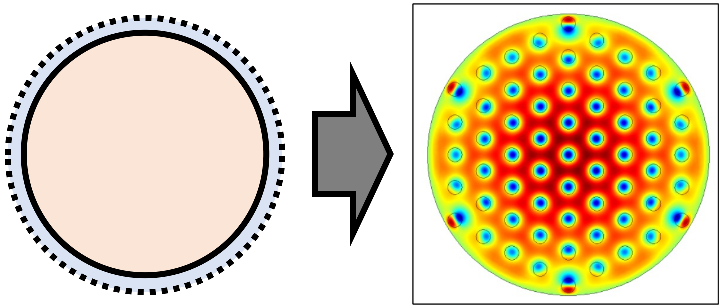


High quality factor
Mediocre form factor

Tuning method?

Tunable Photonic Crystal

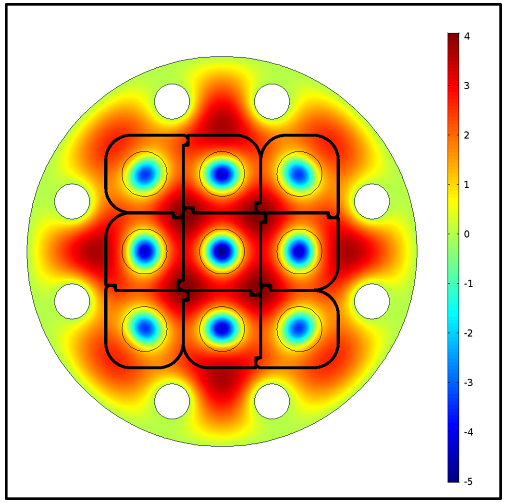
Photonic crystal

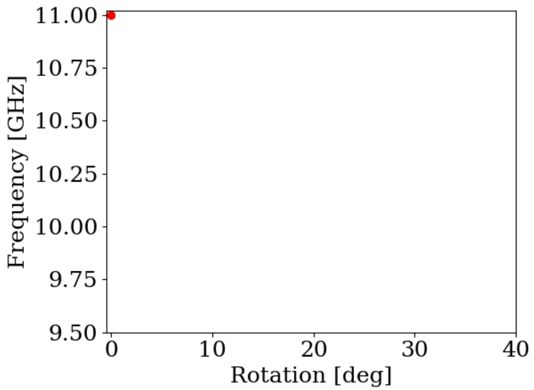


High quality factor
Mediocre form factor

Tuning method?

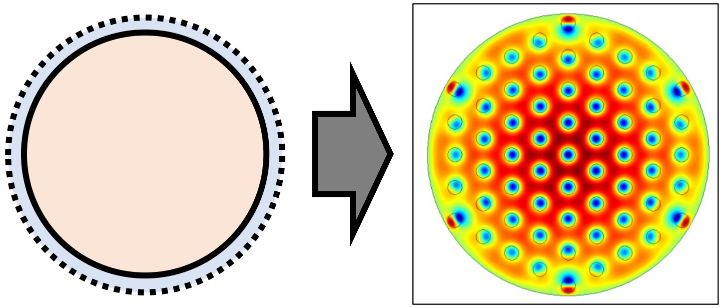
Auxetic structure





Tunable Photonic Crystal

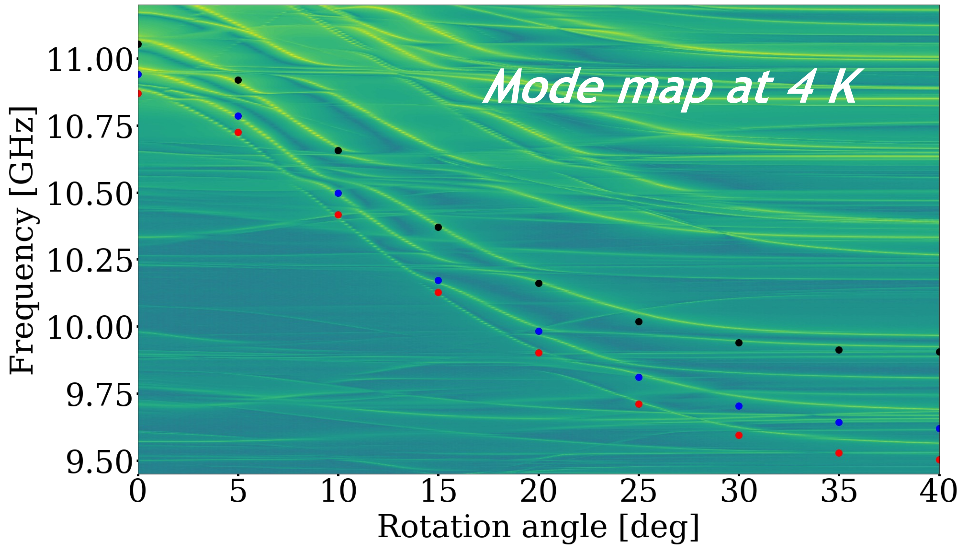
Photonic crystal



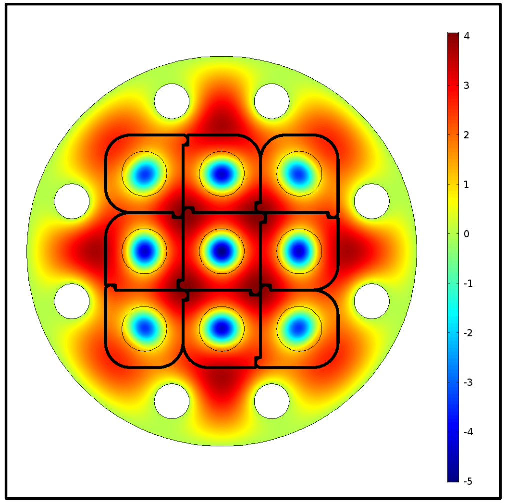
High quality factor
Mediocre form factor

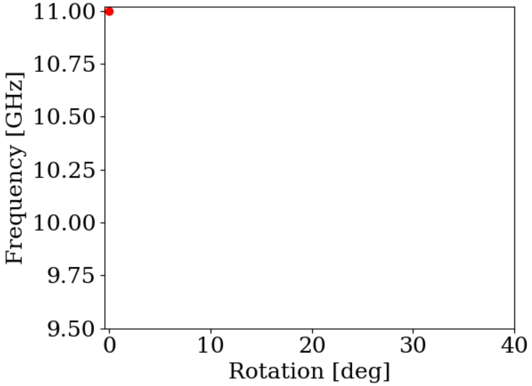
Tuning method?

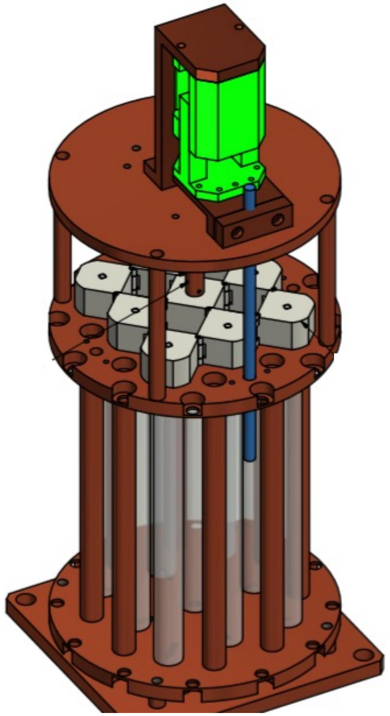
[Phys. Rev. D ***107****, 015012]*

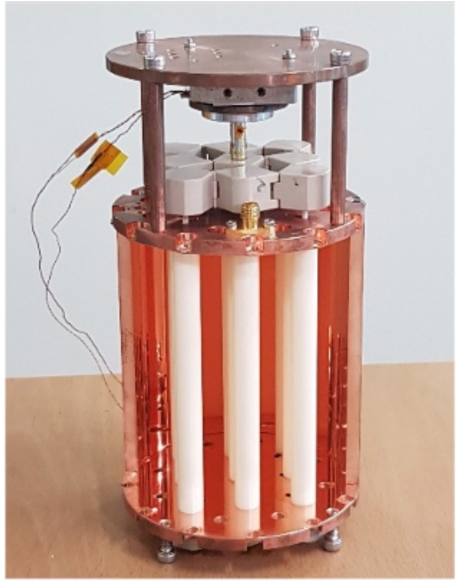


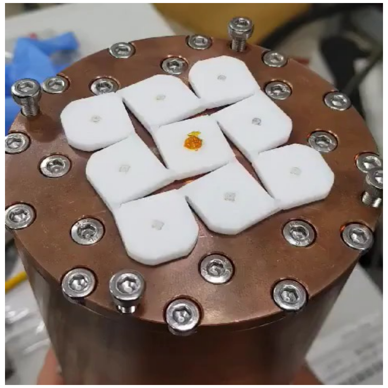
Auxetic structure



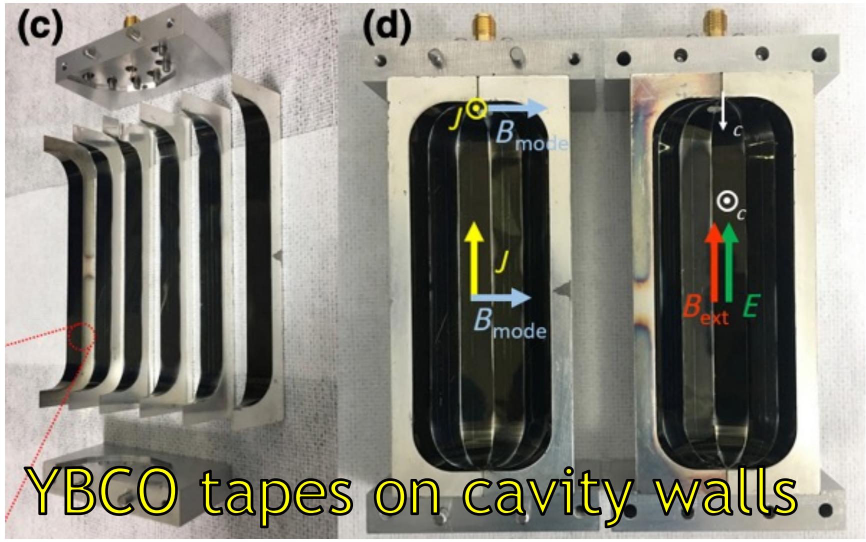








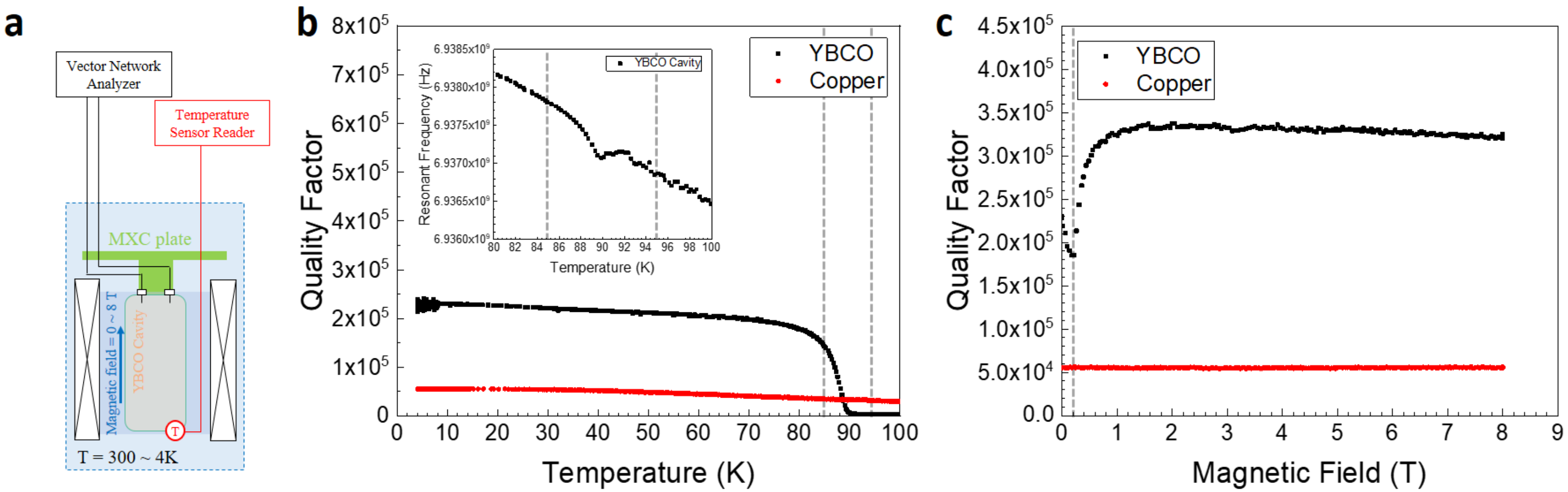
Superconducting cavity *[Next presentation]*



Superconducting cavities under large B-field for first time with HTS tapes.

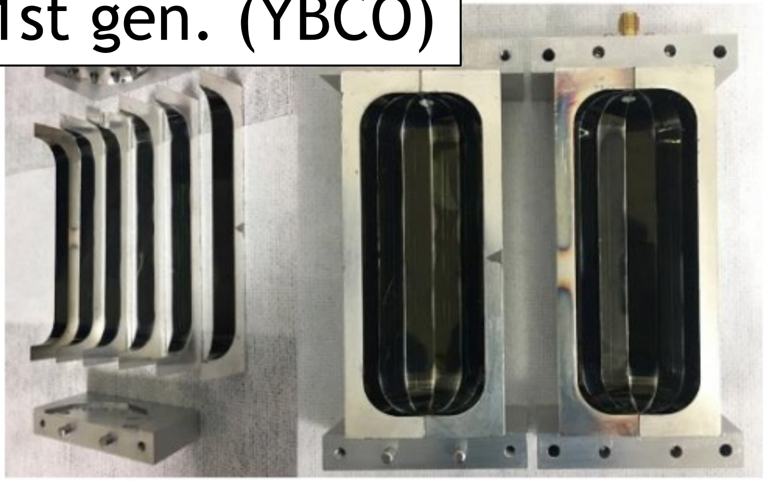
[D. Ahn et al.] Phys. Rev. Applied **17**, L061005 (2022)

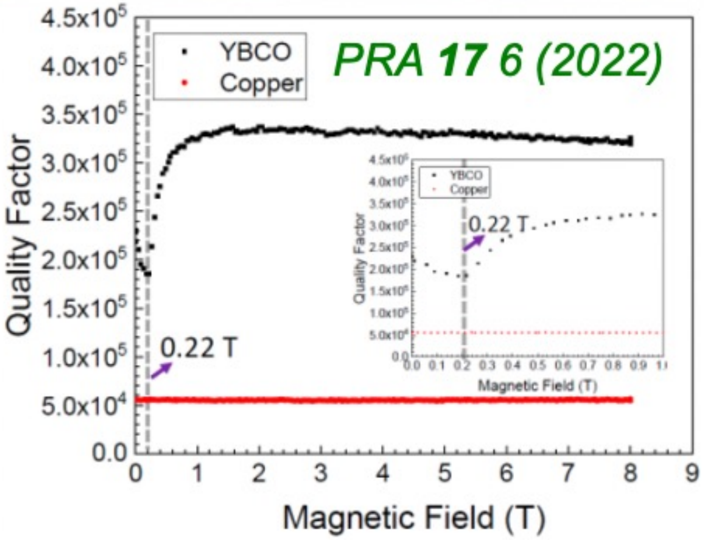
$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$



Superconducting cavity *[Next presentation]*

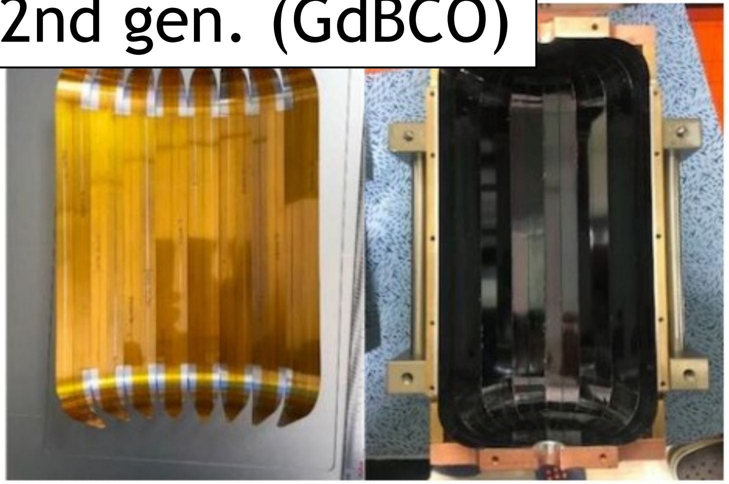
1st gen. (YBCO)

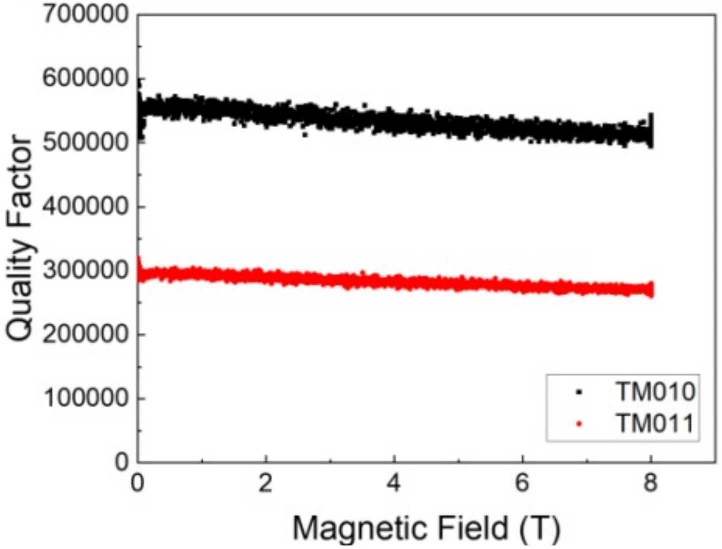




330,000

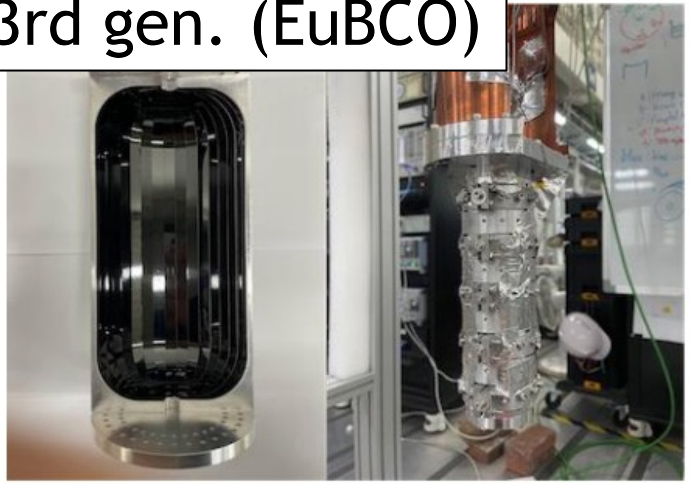
2nd gen. (GdBCO)

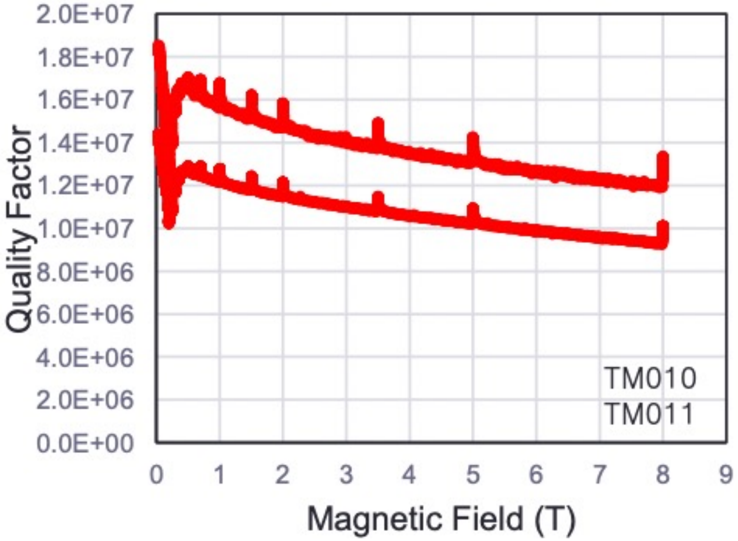




500,000

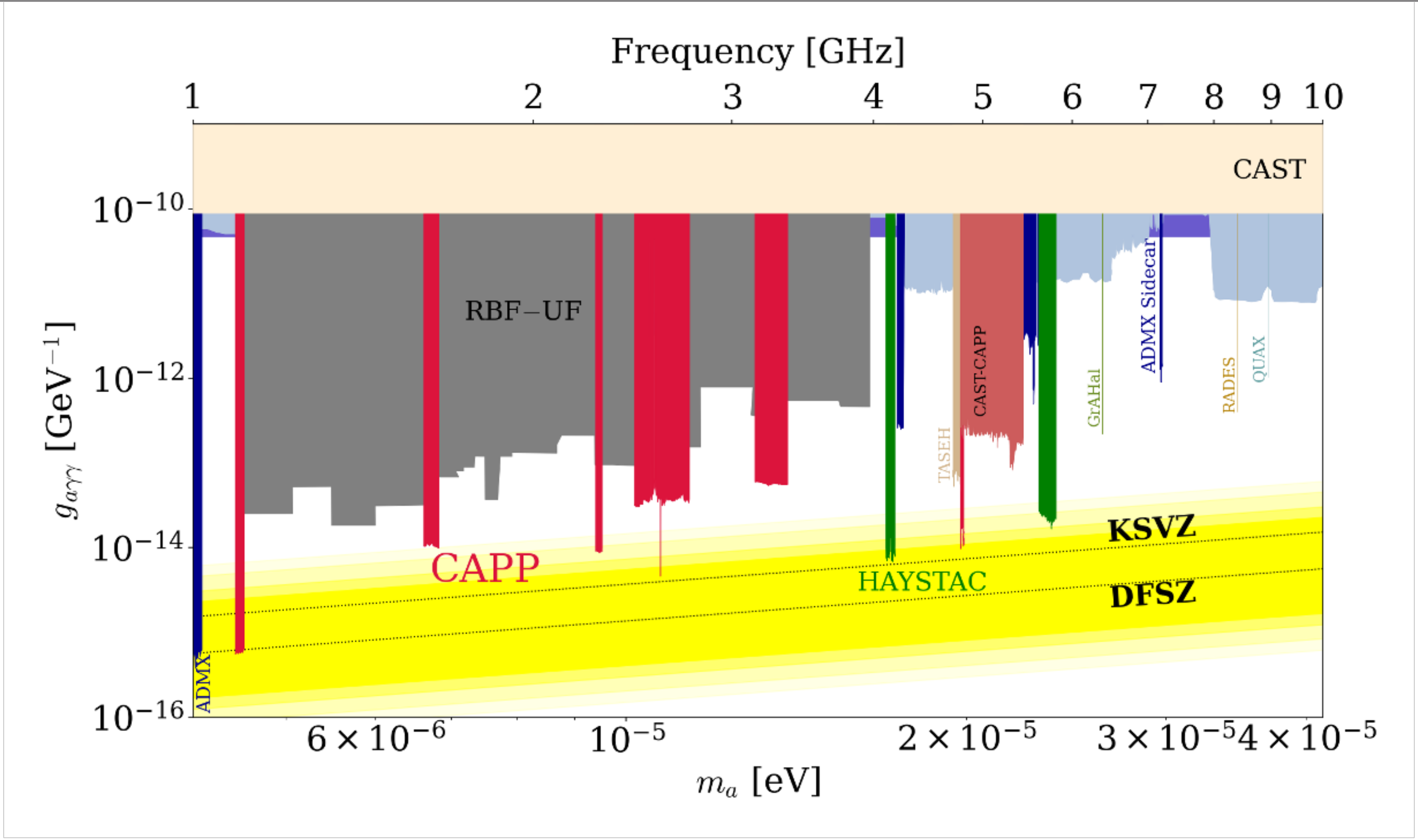
3rd gen. (EuBCO)



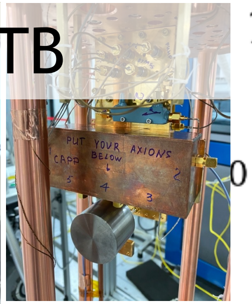


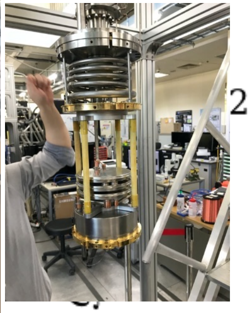
4,500,000 & 13,000,000

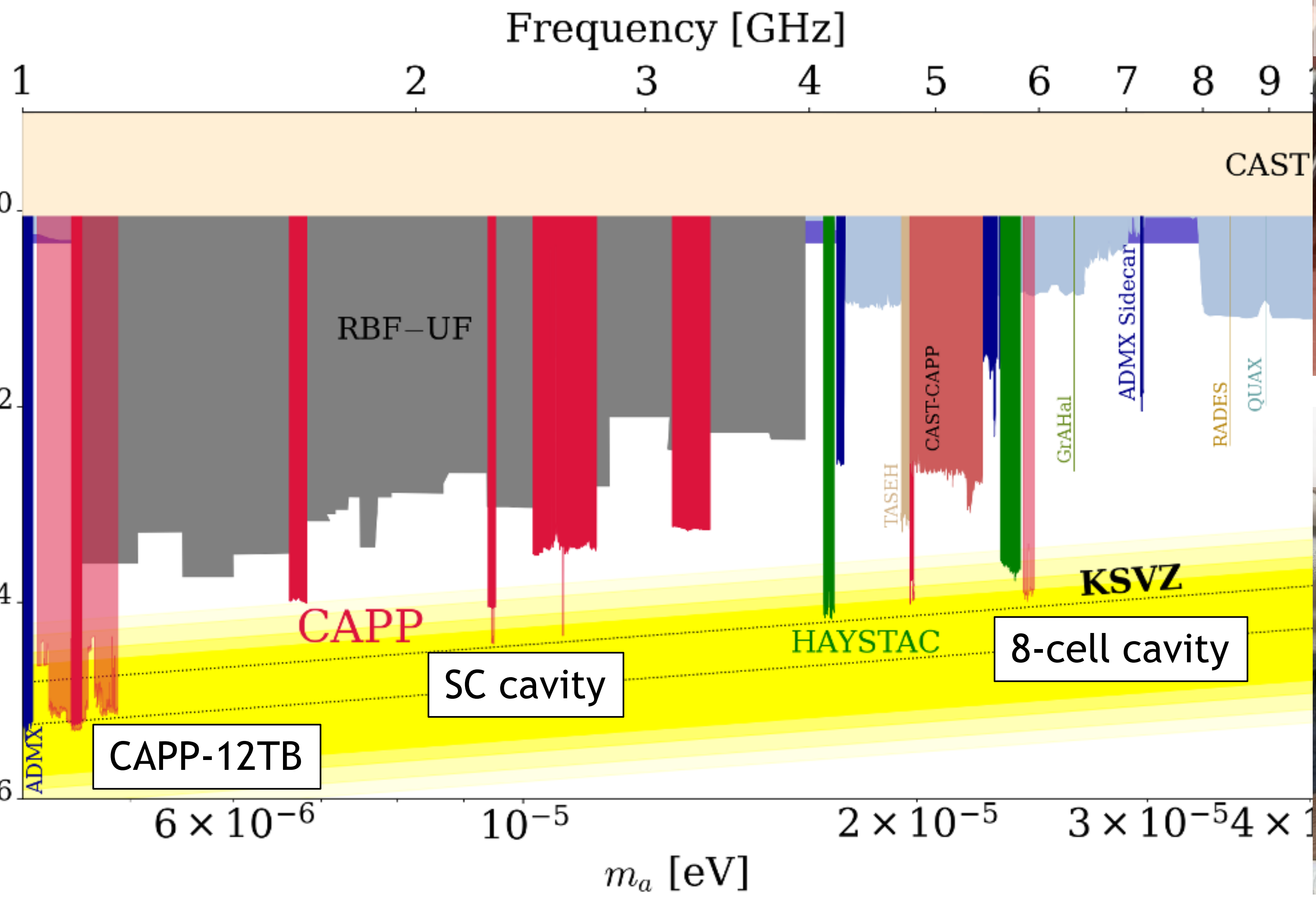
Exclusion Limits



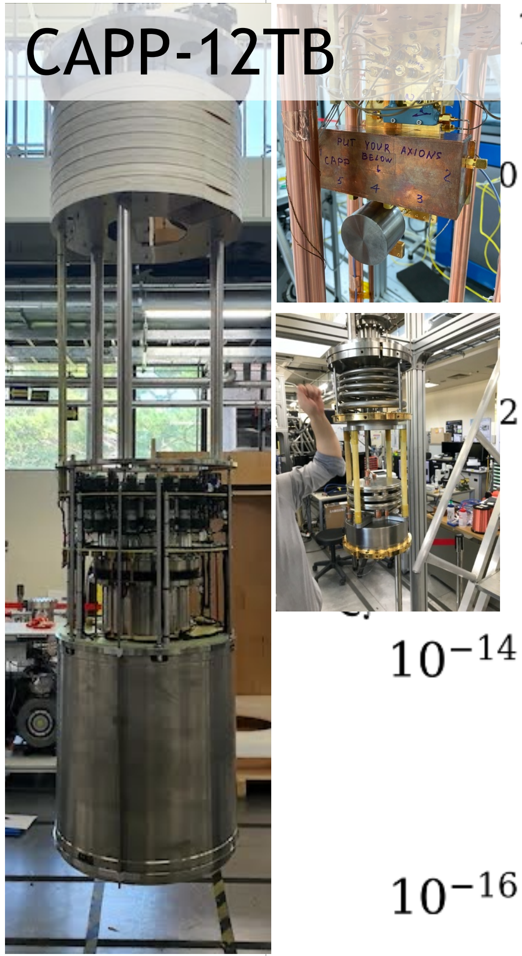
Preliminary Limits

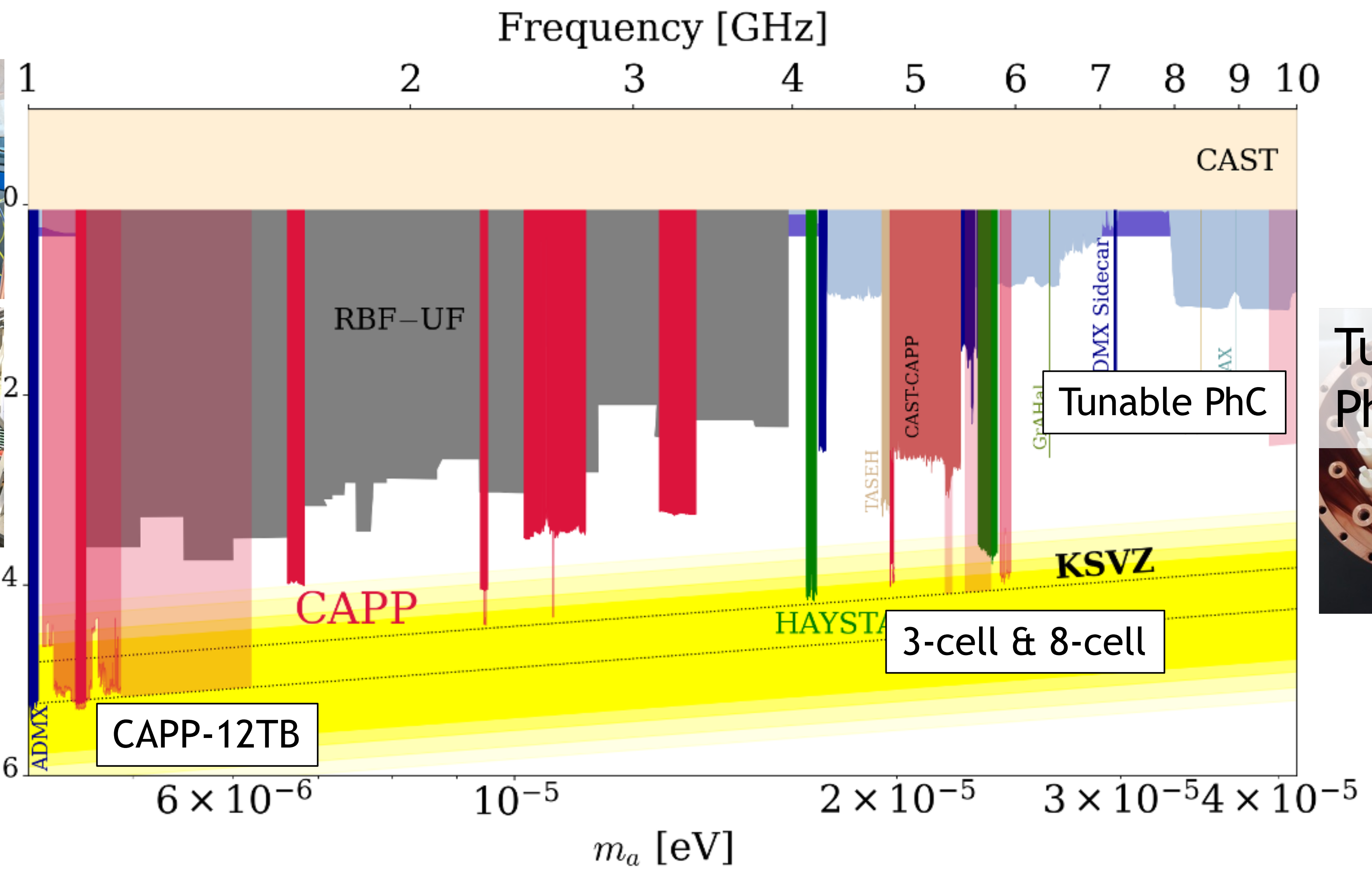






Projection by 2023





Summary (1)

- **Axion** is a hypothetical particle proposed to resolve the strong CP problem.
- The invisible axion is one of the strong candidates for dark matter.

- **Cavity haloscope** is the most sensitive methodology to search for dark matter axions in the microwave region.

Summary (2)

- **CAPP** is one of the world leading groups of CDM axion search.
- **CAPP-12TB reached the DFSZ sensitivity** with large volume, strong magnetic field and low noise temperature.
- At the same time, CAPP is running several haloscopes in parallel.

- CAPP operates several dilution refrigerators and **Josephson parametric amplifiers** for low noise temperature.
- CAPP has developed a **multiple-cell cavity** and **tunable photonic crystal** design for high-frequency searches.
- CAPP has developed **superconducting cavities**, which can further improve the scanning rate.

Backup

Spontaneous Symmetry Breaking

CP-violating Lagrangian

$$\mathcal{L}_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \boxed{\theta_0} + \boxed{\arg\det M_q}$$

Instanton

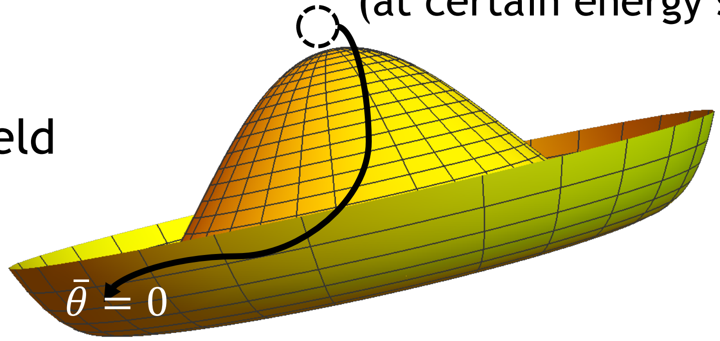
Higgs mechanism

Higgs-like mechanism

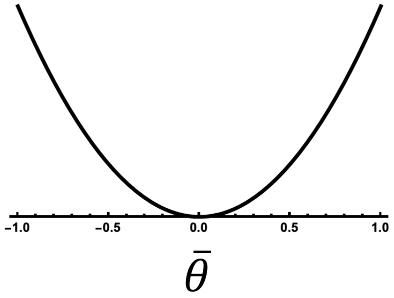
Introduce a global chiral $U(1)$ symmetry for spontaneous symmetry breaking (SSB)

(at certain energy scale, f_a)

SSB of scalar field



Tilted Mexican hat potential



Introduce a new field inside the angle of M_q

$\bar{\theta}$: Constant ⇒ Dynamic field

Invisible Axion

CP-violating Lagrangian

$$\mathcal{L}_\theta = \frac{g^2 \bar{\theta}}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \boxed{\theta_0} + \boxed{\arg \det M_q}$$

Instanton → θ_0

Higgs mechanism → $\arg \det M_q$

KSVZ model

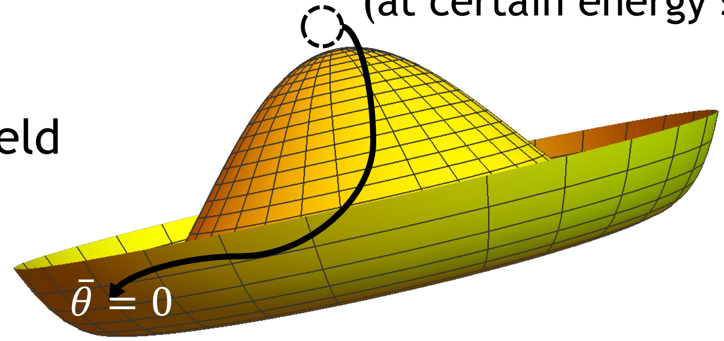
- Heavy Quark + PQ scalar Field

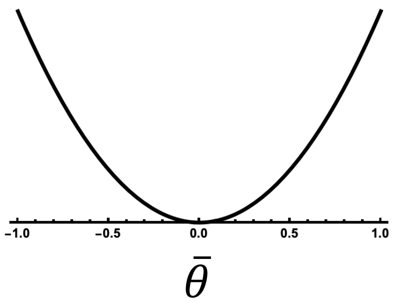
DFSZ model

- 2 Higgs + PQ scalar Field

(at certain energy scale, f_a)

SSB of scalar field





Tilted Mexican hat potential

Introduce a new field inside the angle of M_q

$\bar{\theta}$: Constant ⇒ Dynamic field

Axion-Photon Interaction

Axion-Gluon coupling

$$\mathcal{L}_\theta = \frac{g^2 a/f_a}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Axion-Photon Interaction

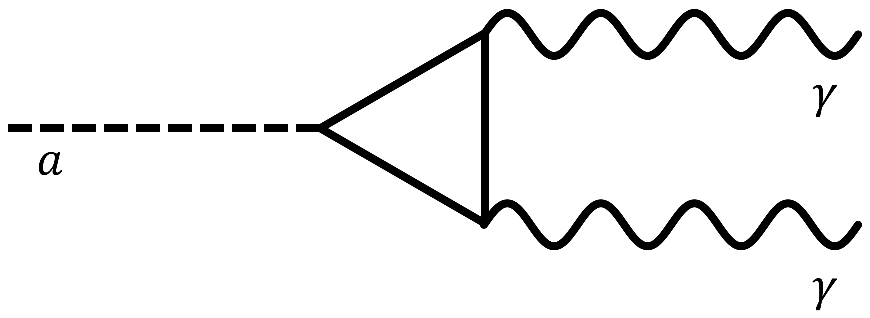
Axion-Gluon coupling

$$\mathcal{L}_\theta = \frac{g^2 a/f_a}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

low energy

Axion-Photon coupling

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a\mathbf{E}\cdot\mathbf{B}$$



Axion-Photon Interaction

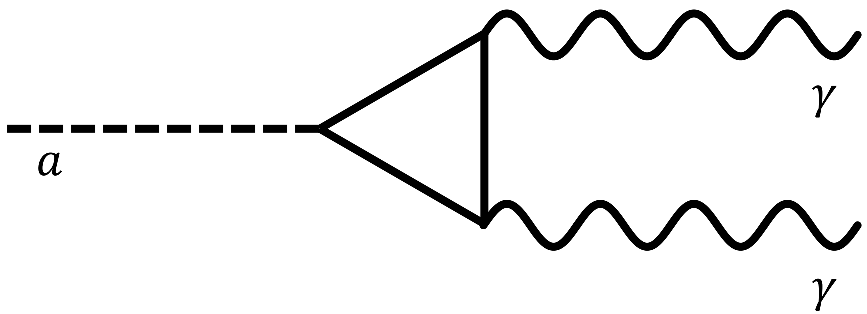
Axion-Gluon coupling

$$\mathcal{L}_\theta = \frac{g^2 a/f_a}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

low energy

Axion-Photon coupling

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a\mathbf{E}\cdot\mathbf{B}$$



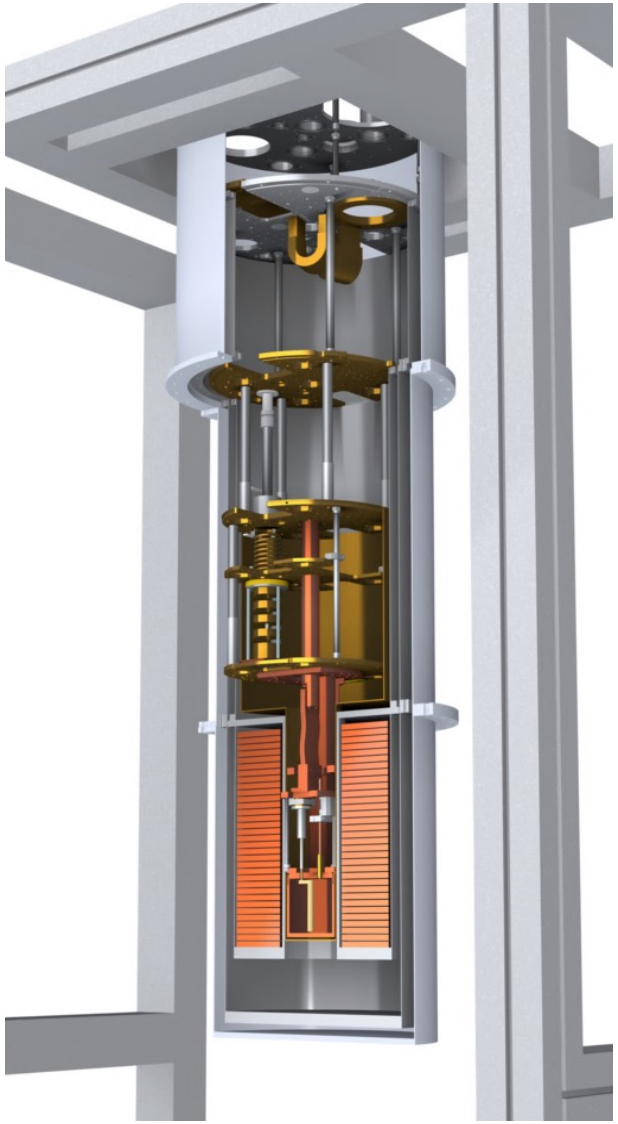
least action principle

Classical Equation of Motion

$$\nabla\cdot\mathbf{E} = \rho_e - g_{a\gamma\gamma}\nabla a\cdot\mathbf{B}$$
$$\nabla\cdot\mathbf{B} = 0$$
$$\nabla\times\mathbf{E} = -\partial_t\mathbf{B}$$
$$\nabla\times\mathbf{B} = \partial_t\mathbf{E} + \mathbf{J}_e + g_{a\gamma\gamma}(\nabla a\times\mathbf{E} + \partial_t a\mathbf{B})$$

CAPP Equipment

Refrigerator		
Manufacturer	*Model*	*T_B [mK]*
BlueFors (BF3)	*LD400*	*10*
BlueFors (BF4)	*LD400*	*10*
Janis	*HE-3-SSV*	*300*
BlueFors (BF5)	*LD400*	*10*
BlueFors (BF6)	*LD400*	*10*
Oxford	*Kelvinox*	*30*
Leiden	*DRS1000*	*10*

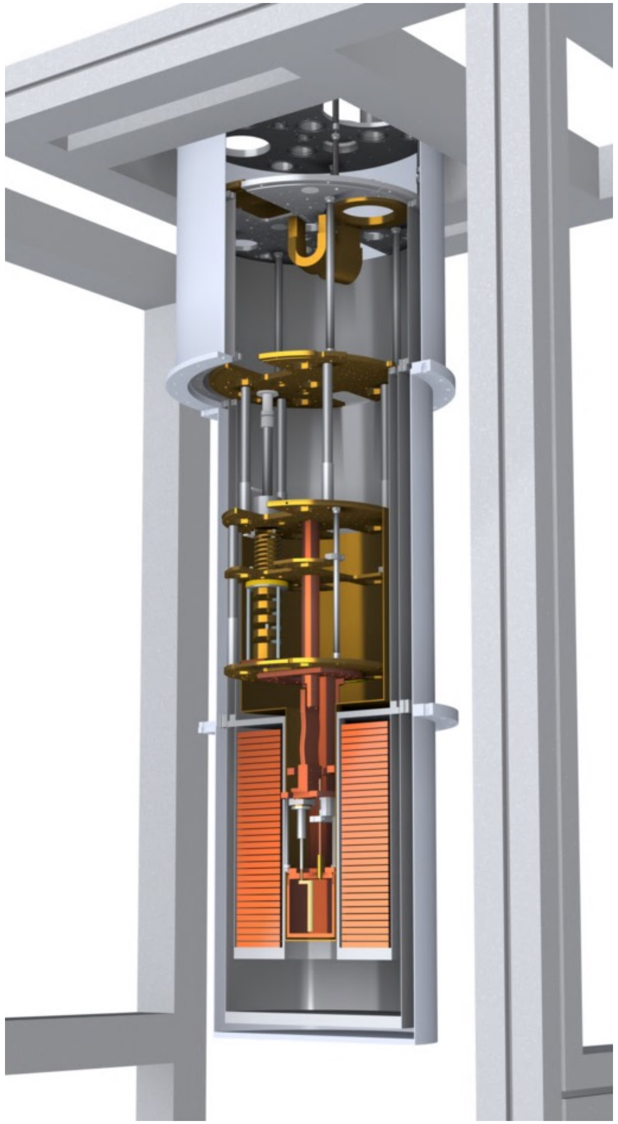


$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{\mathrm{sys}}^2}$$

$$T_{\mathrm{sys}} = T_{\mathrm{phy}} + T_{\mathrm{add}}$$

CAPP Equipment

Refrigerator			*Magnet*		
Manufacturer	*Model*	*T_B [mK]*	*Manufacturer*	*B_{max} [T]*	*Bore [mm]*
BlueFors (BF3)	*LD400*	*10*	*AMI*	*12*	*88*
BlueFors (BF4)	*LD400*	*10*			
Janis	*HE-3-SSV*	*300*	*Cryo Magnetics*	*9*	*125*
BlueFors (BF5)	*LD400*	*10*	*AMI*	*8*	*125*
BlueFors (BF6)	*LD400*	*10*	*AMI*	*8*	*165*
Oxford	*Kelvinox*	*30*	*SuNAM*	*18*	*70*
Leiden	*DRS1000*	*10*	*Oxford*	*12*	*320*



$$\frac{df}{dt} \propto \frac{\langle B^2\rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

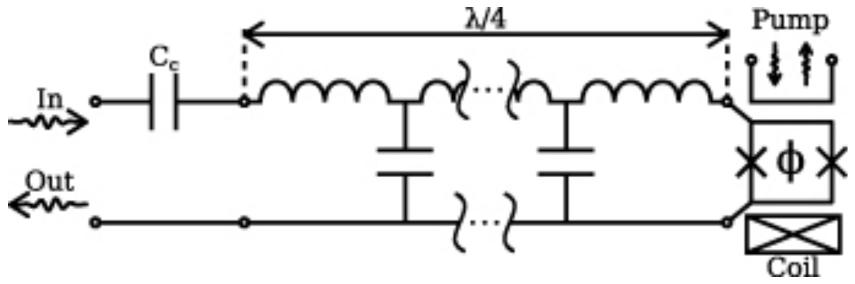
$$T_{sys} = T_{phy} + T_{add}$$

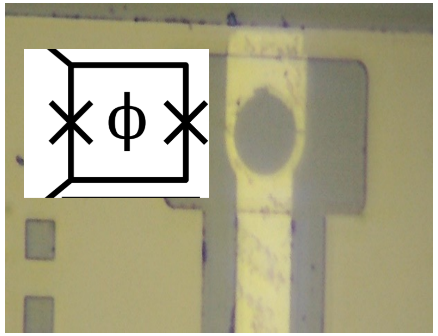
CAPP Experimets

Refrigerator			*Magnet*			*Experiment*
Manufacturer	***Model***	***T_B [mK]***	***Manufacturer***	***B_{max} [T]***	***Bore [mm]***	***Name***
BlueFors (BF3)	*LD400*	*10*	*AMI*	*12*	*88*	*CAPP HF*
BlueFors (BF4)	*LD400*	*10*				
Janis	*HE-3-SSV*	*300*	*Cryo Magnetics*	*9*	*125*	*CAPP-9T MC* [2]
BlueFors (BF5)	*LD400*	*10*	*AMI*	*8*	*125*	*CAPP-PACE* [3],[6]
BlueFors (BF6)	*LD400*	*10*	*AMI*	*8*	*165*	*CAPP-8TB* [1]
Oxford	*Kelvinox*	*30*	*SuNAM*	*18*	*70*	*CAPP-18T* [4]
Leiden	*DRS1000*	*10*	*Oxford*	*12*	*320*	*CAPP-12TB* [5]

[1] S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)
[2] J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020)
[3] O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 (2021)
[4] Y. Lee *et al.*, Phys. Rev. Lett. **128**, 241805 (2022)
[5] A. K. Yi *et al.*, Phys. Rev. Lett. **130**, 071002 (2023)
[6] J. Kim *et al.*, Phys. Rev. Lett. **130**, 091602 (2023)

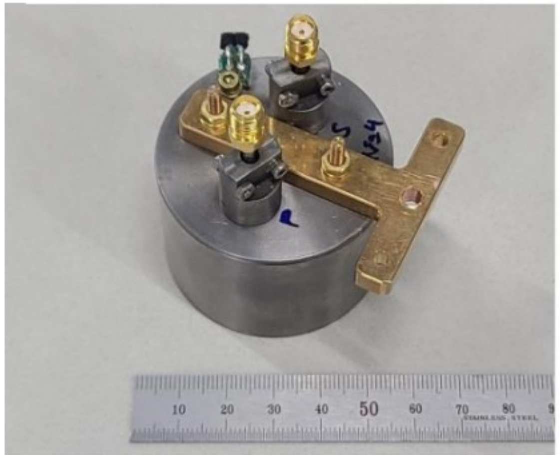
Quantum Noise-Limited Amplifier

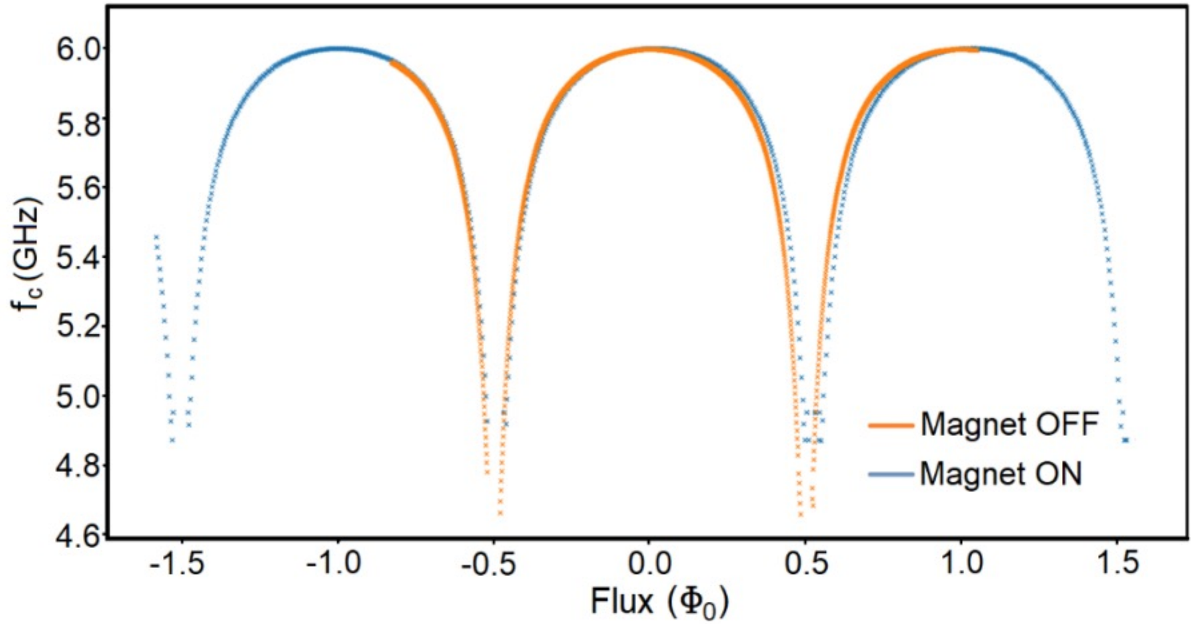




Flux-driven Josephson Parametric Amplifier

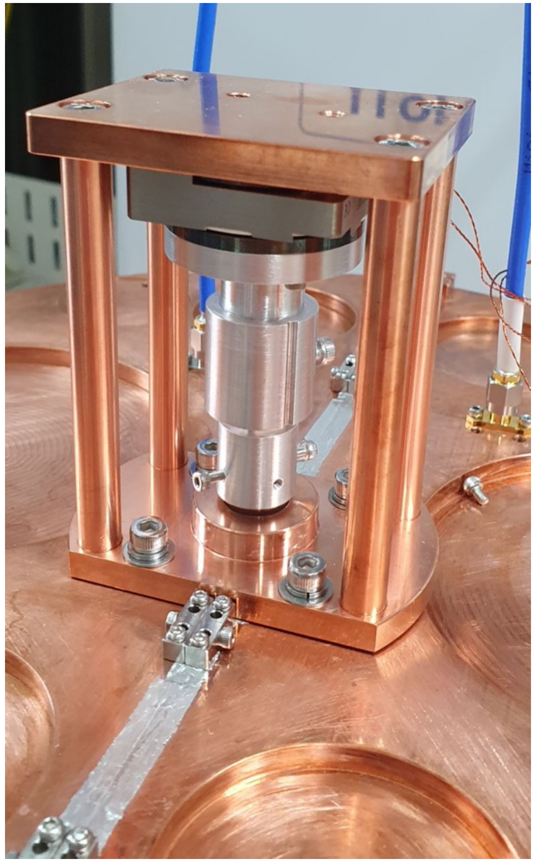
3-layer shield (Al-μ metal-NbTi)

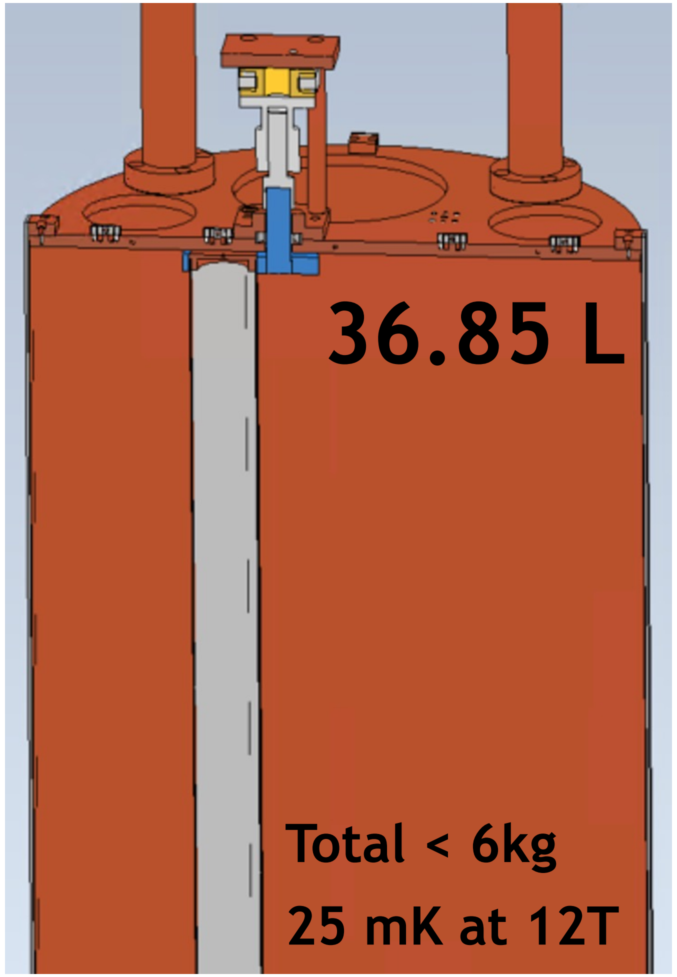




[JPS Conf. Proc. 38, 011201 (2023)]

Ultra light cavity





$$T_{\mathrm{sys}} = T_{\mathrm{phy}} + T_{\mathrm{add}}$$

Multiple-cell cavity