Search for QCD Axions in CAPP

2024 Fall KSHEP Meeting
November 29, 2024 UNIST

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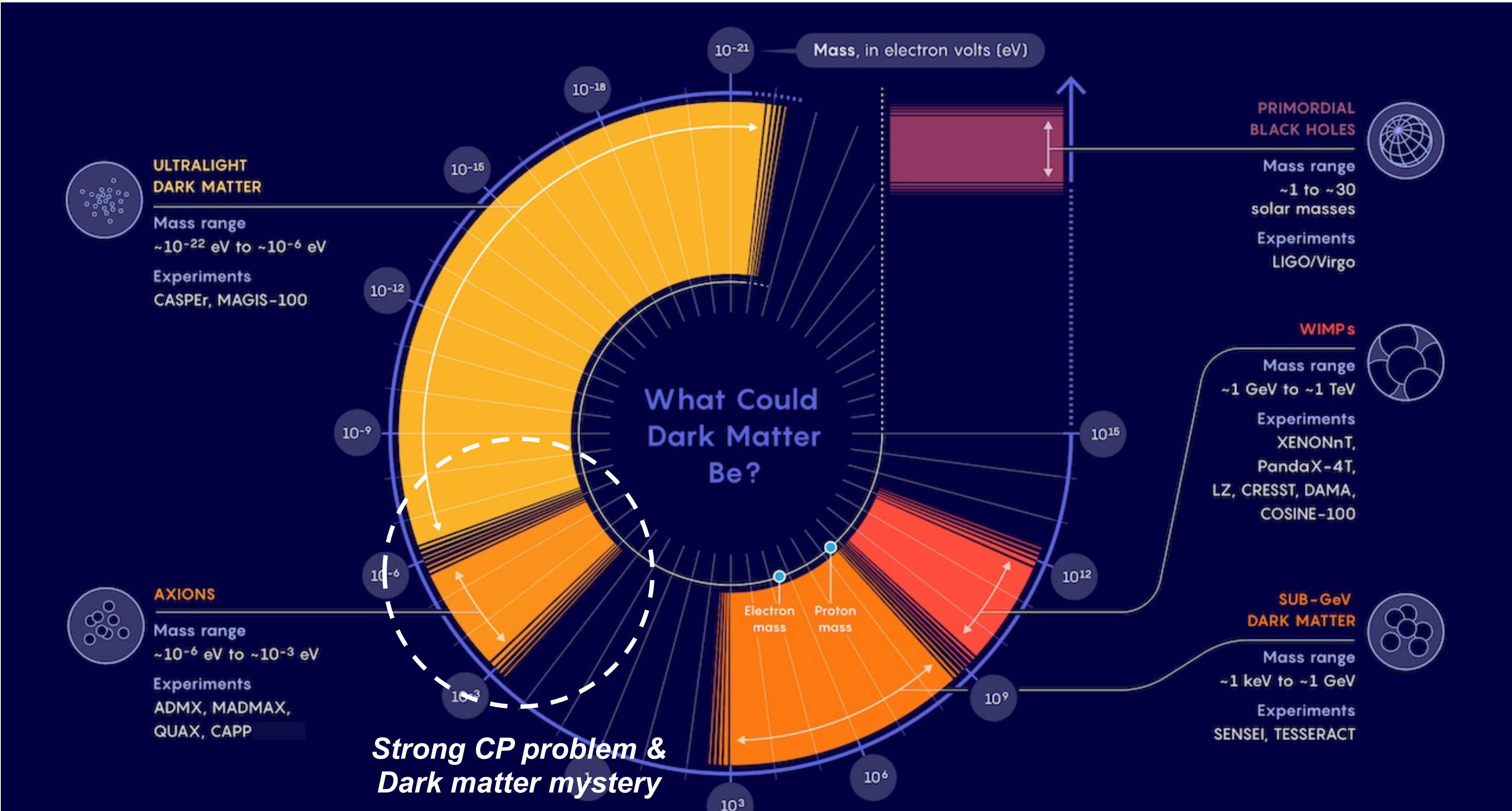
Dark matter business expanding

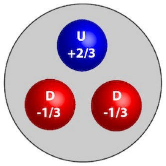


Samuel Velasco/Quanta Magazine

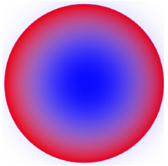
Axion dark matter

- *Strong CP problem*
  - *PQ mechanism (1977)*
    - *U(1) global symmetry and scalar field*
    - *SSB => axion field (1978)*
  - *QCD axion:* $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$ *(cf. ALP)*
  - *Invisible axion (1979):* $m_a \approx 10^{-6} eV \frac{10^{12}\ GeV}{f_a}$

Absence of nEDM

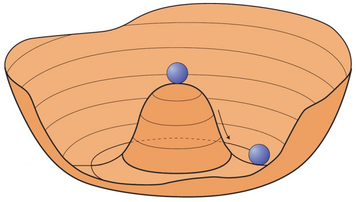


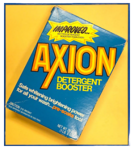
vs.



$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \Rightarrow \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$

***S**pontaneous **S**ymmetry **B**reaking*

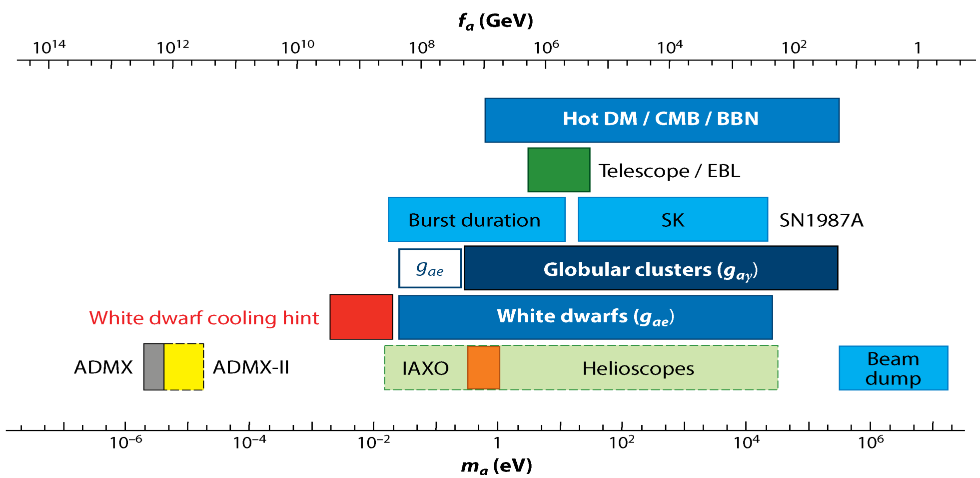




Goldstone boson

$a(x) = \theta \times f_a$ *at minimum*

- *Cosmological implication*
  - *Accounting for dark matter (1983)*



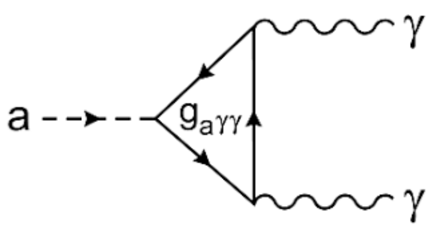
Annu. Rev. Nucl. Part. Sci. 65 485 (2016)

Axion models and detection

- *Axion coupling to SM*

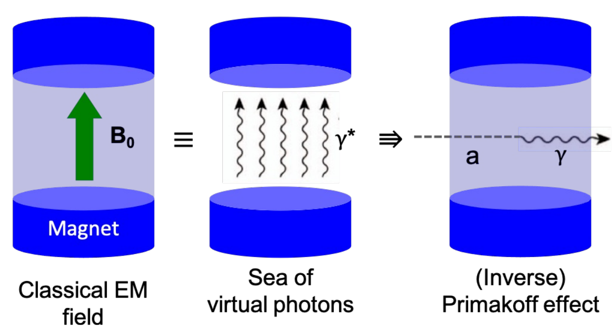
	Photons	*Fermions*	*nEDMs*
Hamiltonian	$g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$	$g_{aff}\nabla a\cdot\hat{\boldsymbol{S}}$	$g_{EDM} a\hat{\boldsymbol{S}}\cdot\boldsymbol{E}$
Observable	*Photon*	*Spin precession*	*Oscillating EDM*
Detection	*Power spectrum, photon counter, …*	*Magnetometer, NMR, …*	*NMR, polarimeter, …*

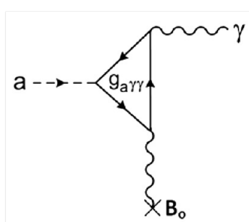
- *Axion models*



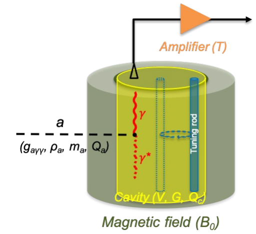
PQWW	*DFSZ*	*KSVZ*
SM ferminons		*BSM fermions*
2 Higgs	*2Higgs+singlet*	*Higgs+singlet*
Standard ($f_a \sim v_{EW}$)	***Invisible ($f_a \gg v_{EW}$)***	
Ruled out	*Benchmark*	

- *Detection principle*
  - *Sikivie effect (1983)*
    - *Macroscopic Primakoff*



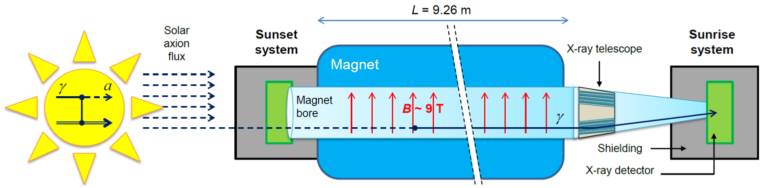


Search strategies



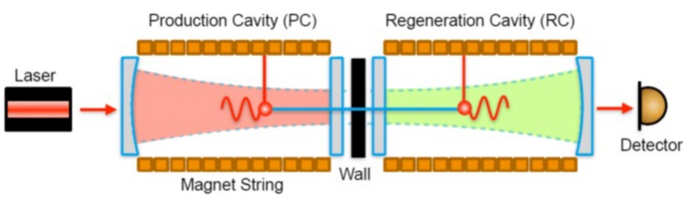
- *Haloscope*
  - *Dark matter halo in our galaxy*
  - $$P_{a\gamma\gamma} \approx 9\times10^{-23}\,W \left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right) \left(\frac{f_a}{1.1\ GHz}\right) \left(\frac{B_0}{10.5\ T}\right)^2 \left(\frac{V}{37\ L}\right) \left(\frac{C}{0.6}\right) \left(\frac{Q_c}{10^5}\right)$$

    ~100 photons/sec



- *Helioscope*
  - *Solar axion*
  - $$\mathcal{P}_{a\to\gamma} \approx 2.6\times10^{-17} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\right)^2 \left(\frac{B_0}{10\ T}\right)^2 \left(\frac{L}{10\ m}\right)^2 \mathcal{F}, \quad \mathcal{F} = \frac{2(1-\cos qL)}{(qL)^2}$$

    ~10 photons/day

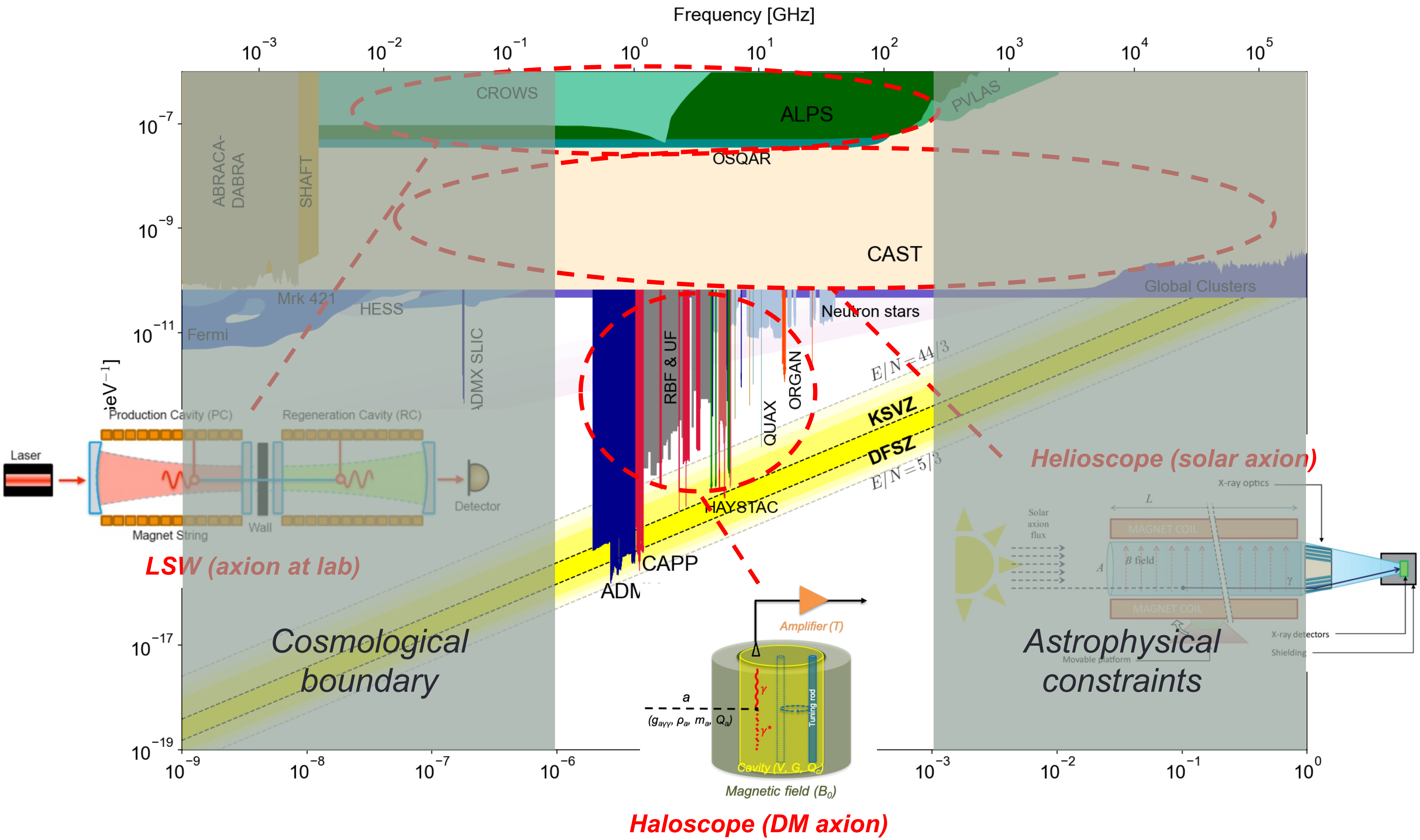


- *Light shinning through a wall*
  - *Axion production at lab*
  - $$\dot{N}_\gamma \approx 4\times10^{-5} Hz \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\right)^4 \left(\frac{P_{laser}}{40\ W}\right) \left(\frac{BL}{560\ Tm}\right) \left(\frac{\beta_{PC}}{5000}\right) \left(\frac{\beta_{RC}}{40000}\right)$$

    ~1 photon/day

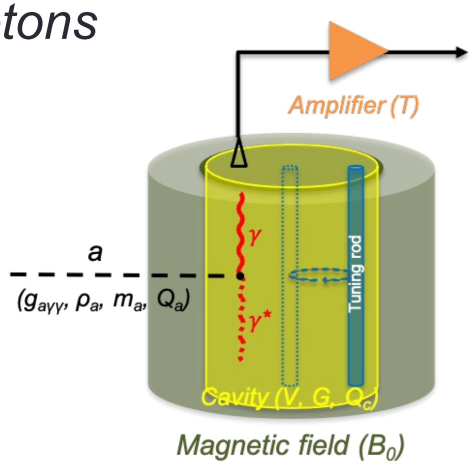
Axion searches

1 GHz = 4.2 ueV



Cavity haloscope

- *Most sensitive for DM axion search in μeV region*
  - *Resonant conversion of axions into microwave photons*



- *Axion-photon conversion power (a→γγ)*

$$P_{a\gamma\gamma} \approx 9\times10^{-23}\,W \left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right)\left(\frac{f_a}{1.1\,GHz}\right) \times \left(\frac{B_0}{10.5\,T}\right)^2 \left(\frac{V}{37\,L}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_c}{10^5}\right)$$

(~100 photons/sec)

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

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{1}{4}\frac{P_{a\gamma\gamma}}{k_B(T_{sys}/0.2\,K)}\sqrt{\frac{\Delta t}{Q_a/10^6}}$$

System noise (in temperature)

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

ex) $0.2\,K \sim 3\times10^{-22}\,W$

(~4000 photons/sec)

- *Unknown mass = > scanning rate (F.O.M.)*

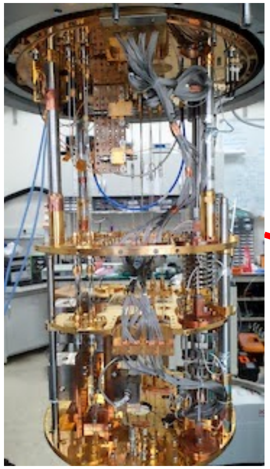
$$\frac{df}{dt} \approx 2\frac{GHz}{year}\left(\frac{5}{SNR}\right)^2\left(\frac{0.2\,K}{T_{sys}}\right)^2\left(\frac{P_{a\gamma\gamma}}{1x10^{-22}\,W}\right)^2\left(\frac{10^5}{Q_c}\right) \sim B_0^4V^2C^2Q_cT_{sys}^{-2}$$

Cavity haloscope – in a nutshell

- *Enhancing the scan rate by improving experimental parameters*

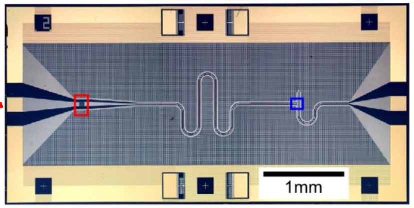
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics T



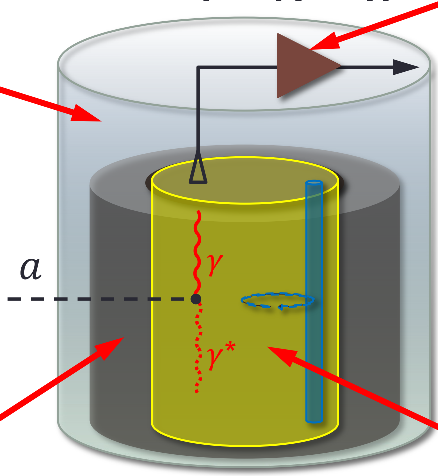
Lowering thermal noise

Quantum noise limited amplifier T

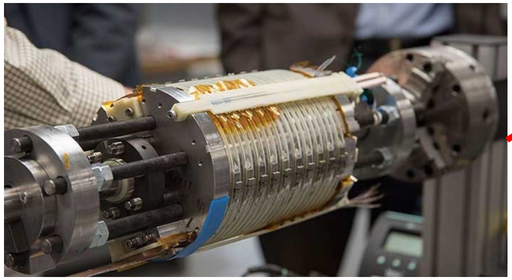


Signal amplification w/ minimal noise added

P ~ 10^{-23} W

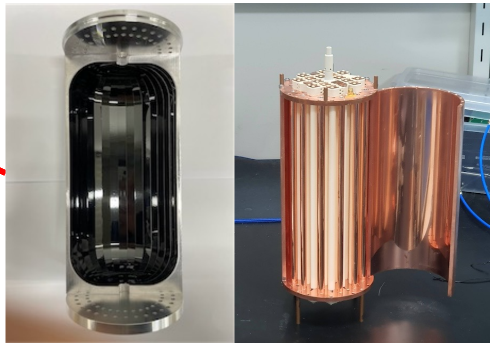


High field Magnet B



Boosting a→γγ conversion

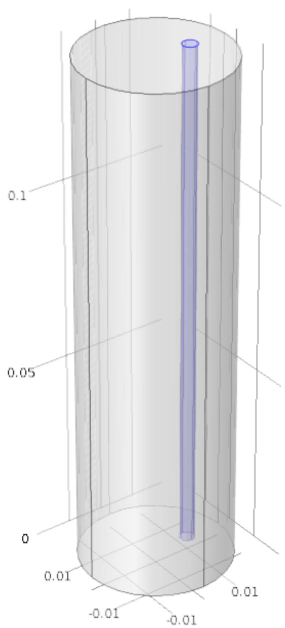
Tunable High-Q resonator
V, Q, C, Δf

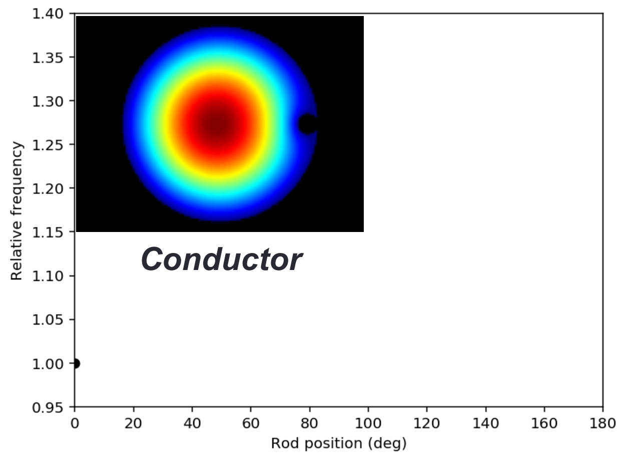


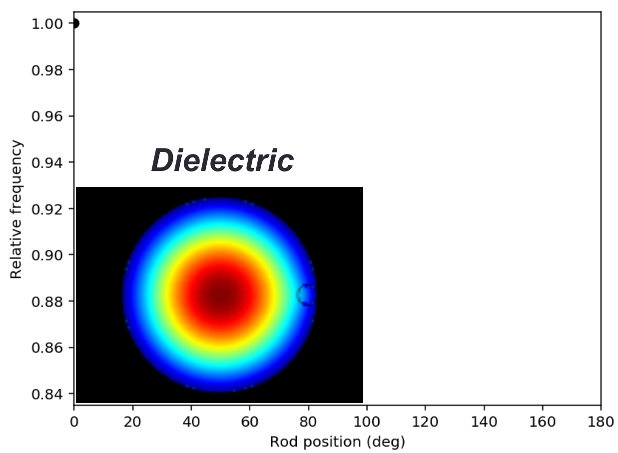
Resonant frequency tuning

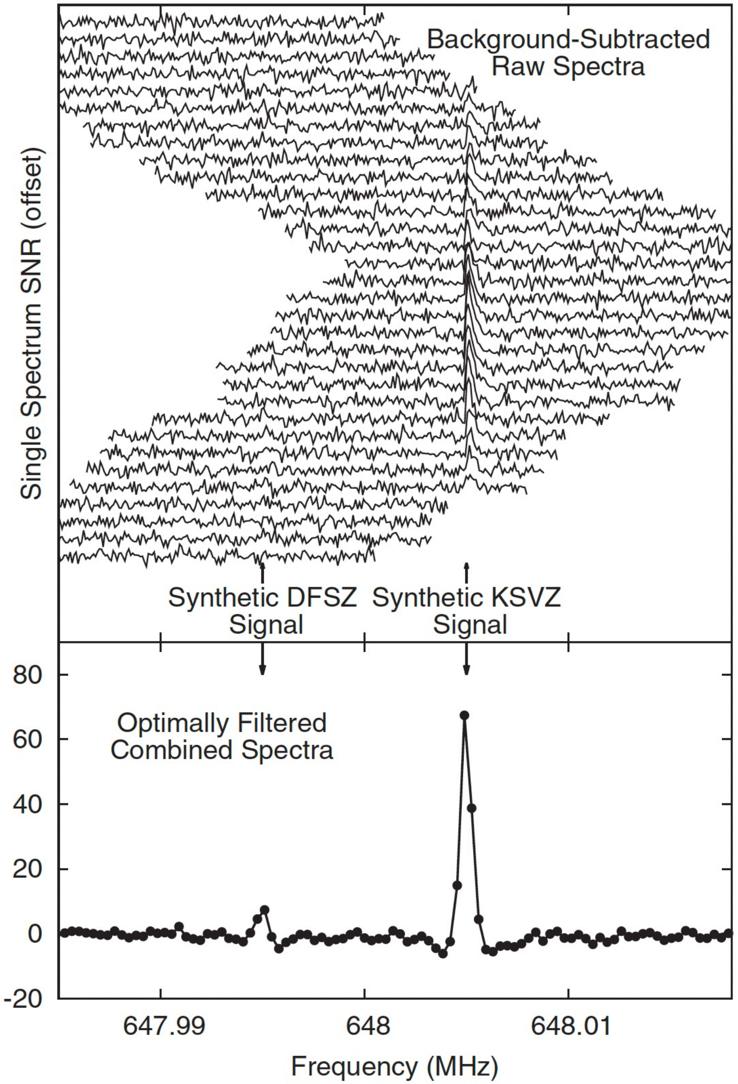
All are advanced and well mature!

Cavity tuning and signal

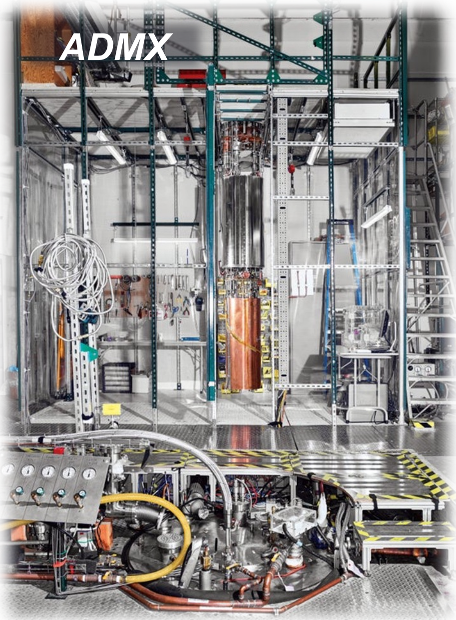


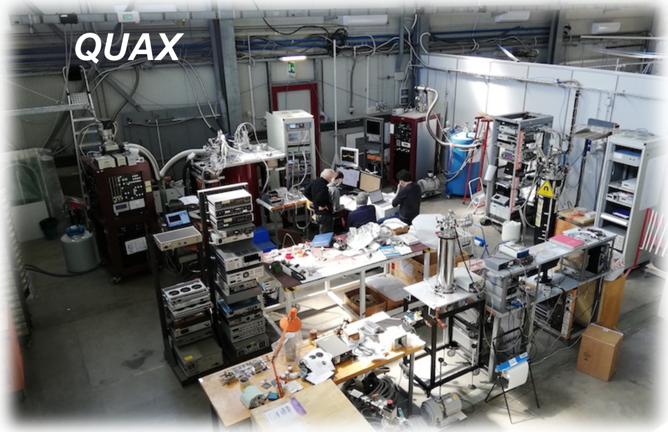




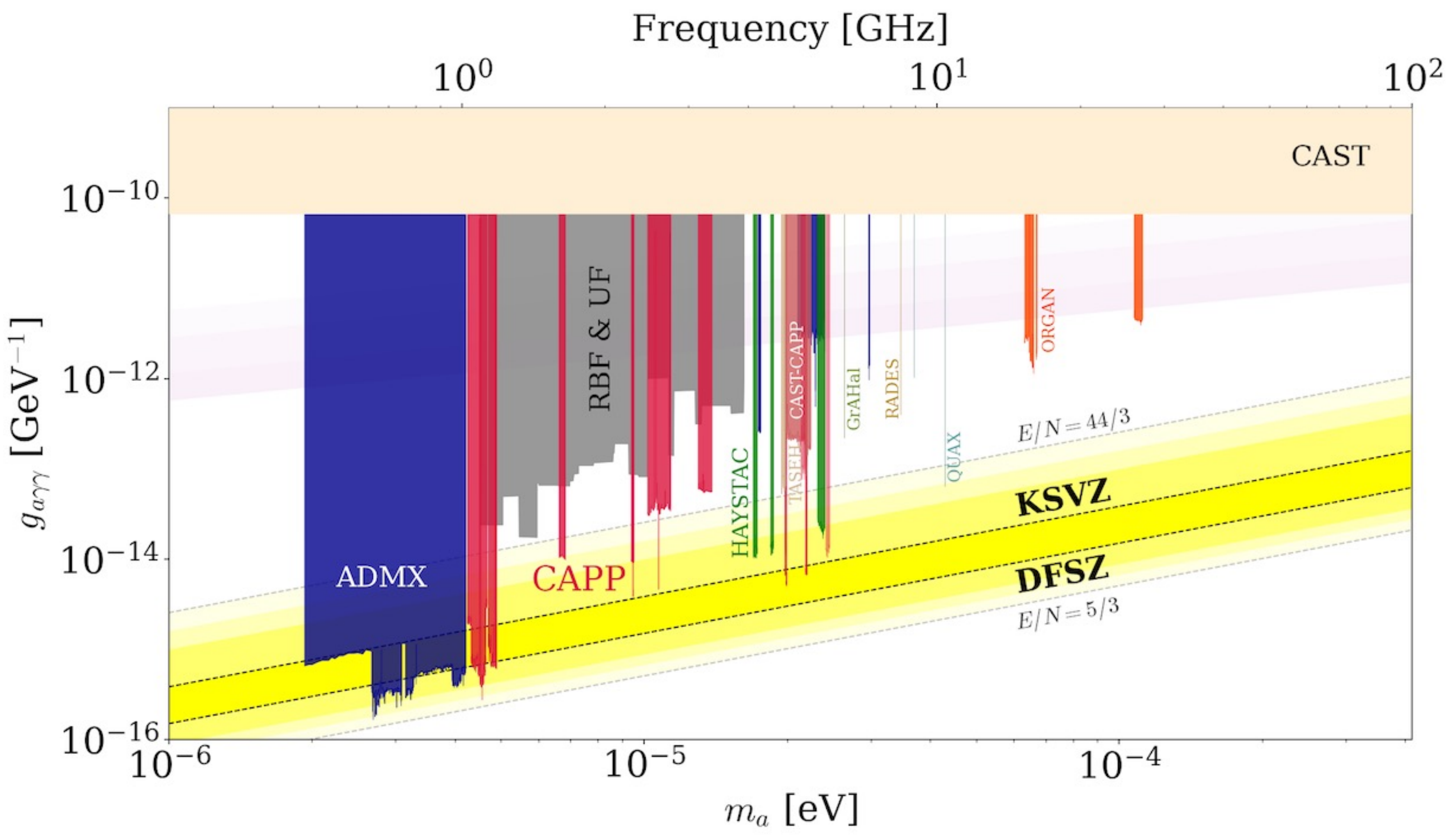


Cavity haloscopes





Haloscope searches



IBS-CAPP (2013~2024)

CAPP-9T CAPP-12TB CAPP-12T CAPP-8T CAPP-8TB

Equipment

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

Refrigerators			Magnets			Experiments
Manufacture	Model	T_B [mK]	Manufacture	B_{max} [T]	Bore [mm]	Name
BlueFors (BF3)	LD400	10	AMI	12	96	CAPP-12T
BlueFors (BF4)	LD400	10				
Janis	HE-3-SSV	300	Cryo Magnetics	9	125	CAPP-9T
BlueFors (BF5)	LD400	10	AMI	8	125	CAPP-8T
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

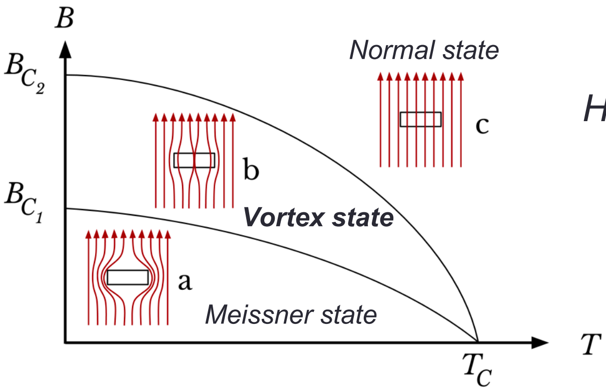
*Conducting **parallel** experiments targeting **different mass** regions!*

R&D in CAPP

High-quality factor

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

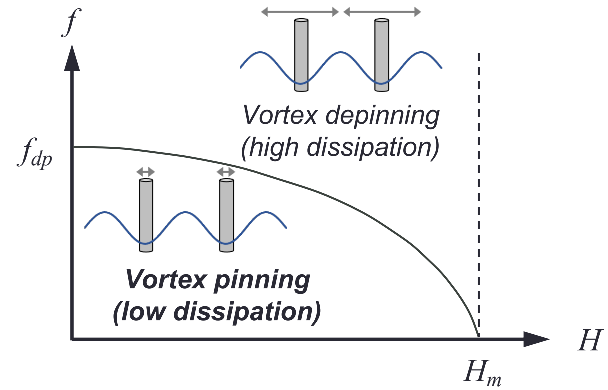
- *Minimal energy loss under a high magnetic field*



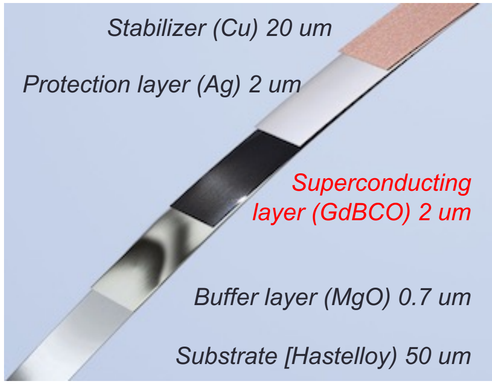
High critical field B_{C2}
&
High depinning frequency f_{dp}

↓↓

***ReBCO**-based*
High-Temperature Superconductor (HTS)



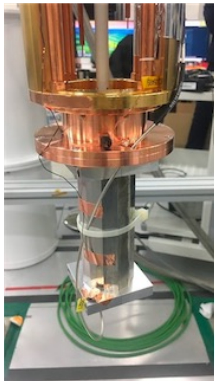
- *ReBCO HTS*
  - *Biaxially-textured 2D tapes (commercially available)*



GdBCO HTS tape

Tapes on 2D pieces

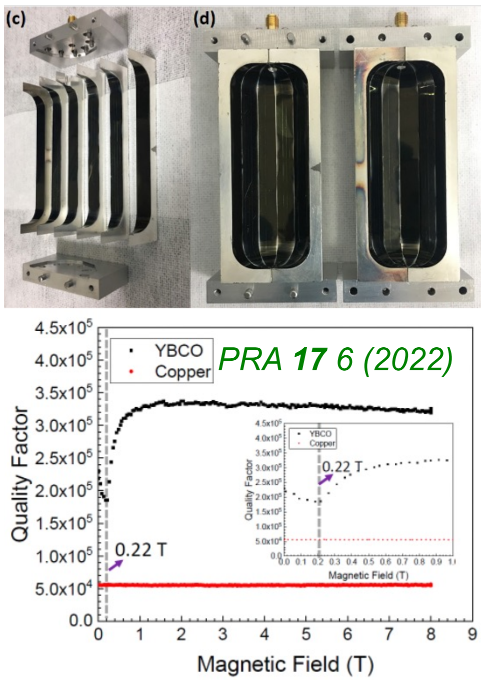
Assembly

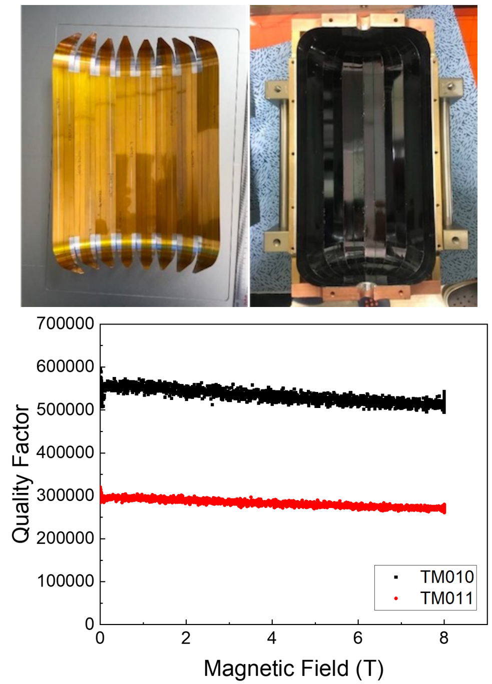


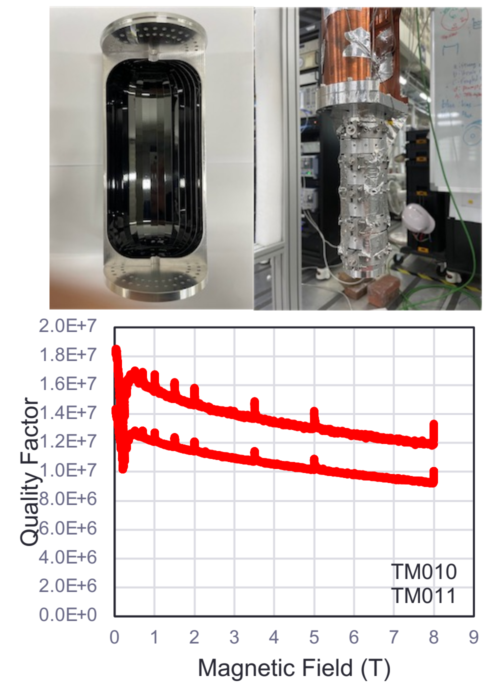
3D SC cavity

HTS cavities

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







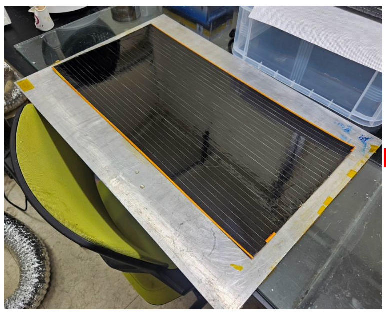
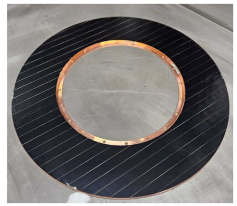
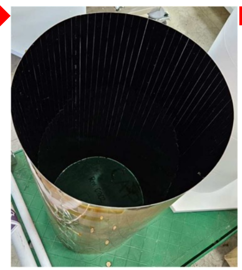
	1st generation	2nd generation	3rd generation	
Material	**Y**BCO	**Gd**BCO	**Eu**BCO + APC	
Manufacturer	AMSC	Theva	Fujikura	
Volume [L]	0.3	1.5	1.5	0.2
Freq. [GHz]	6.9	2.3	2.2	5.4
Q-factor @ 8 T	**0.3 M**	**0.5 M**	**3.5 M**	**13 M**
Application	Demonstration	Axion search	AQN search	Axion search

cf. $Q_a \sim 10^6$

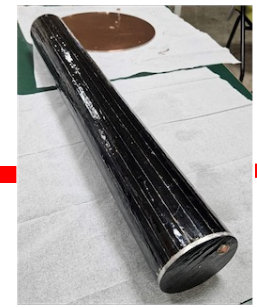
HTS cavities

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

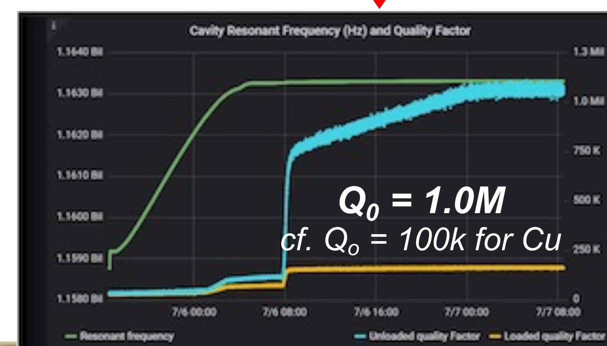
- *Uniquely developed and mature production technique*

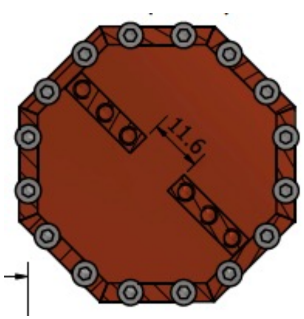

37-L HTS cavity

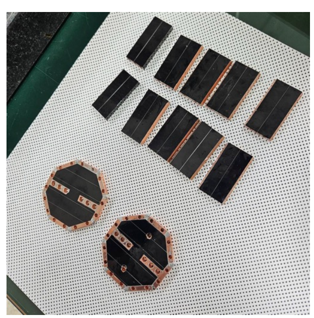


HTS rod



- *Integration with HF cavity designs*



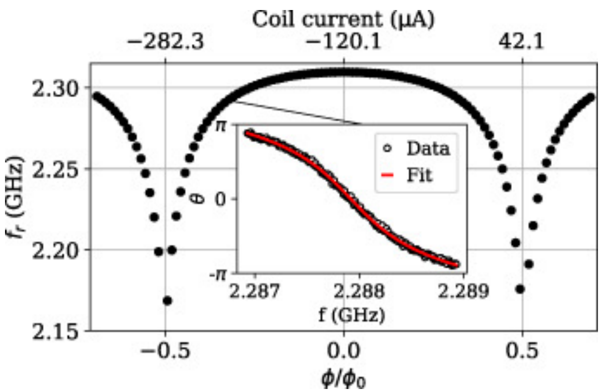



$Q_{HTS} \sim 10 \times Q_{Cu}$

Quantum amplification

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

- *Flux-driven Josephson parametric amplifiers (JPAs)*



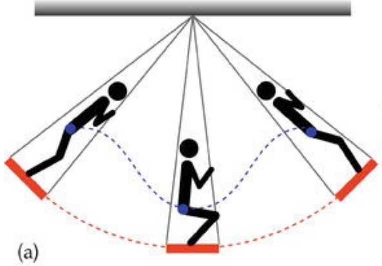
Frequency tuning

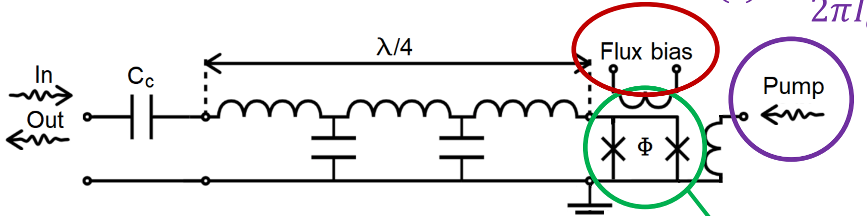
$$I_C = IC_c \cos\left(\frac{\pi\Phi}{\Phi_0}\right)$$

Parametric amplification

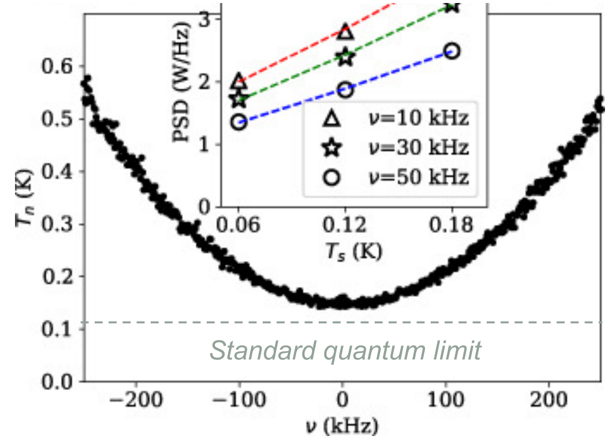
$$L(I) = \frac{\Phi_0}{2\pi I_c}\left[1 + \frac{1}{2}\frac{I^2}{I_c^2}\right]$$

$\omega_p = 2\omega_s$

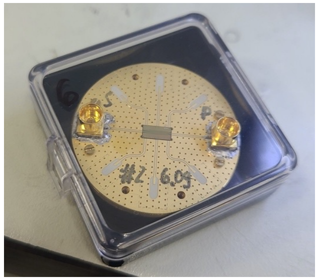


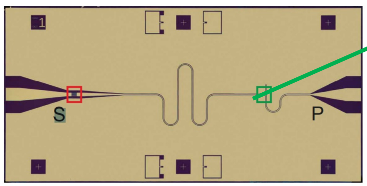


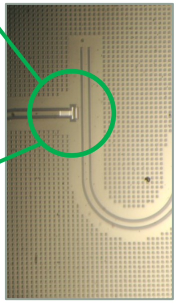
*SST **34** 085013 (2021)*



SQUID
(nonlinear inductance)







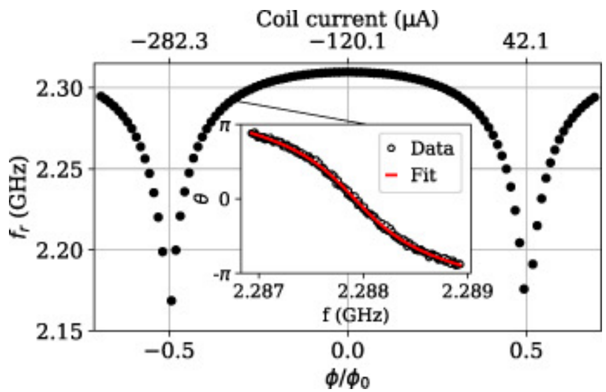
U. of Tokyo & RIKEN

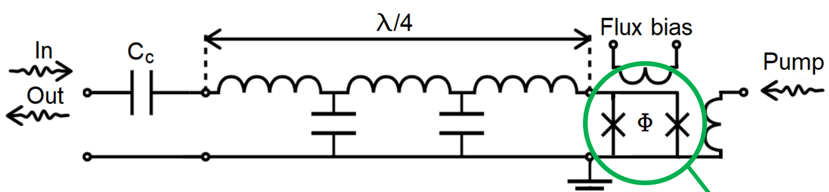
Best performance
in axion search application

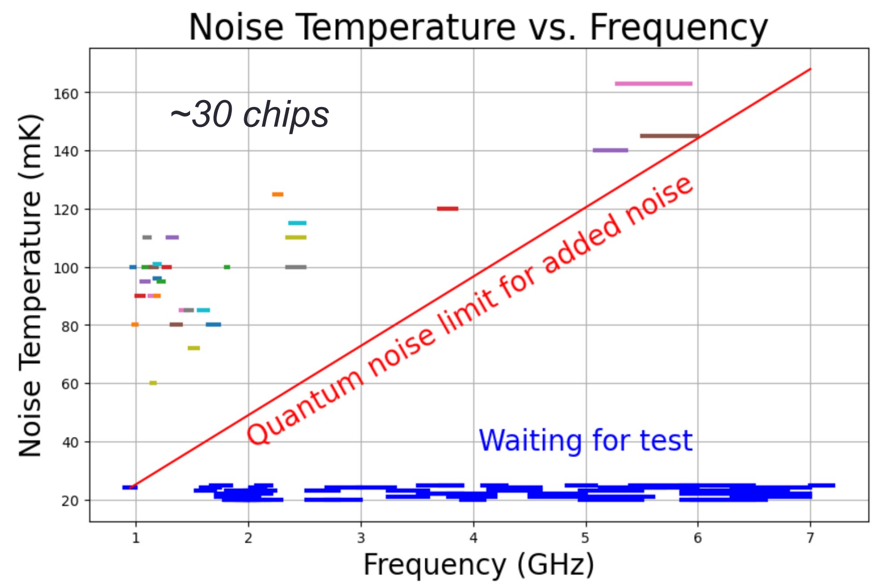
Quantum amplification

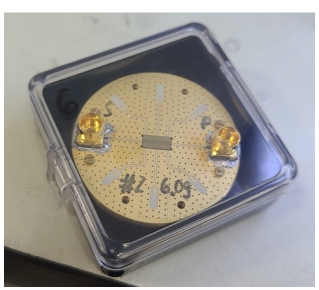
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

- *Flux-driven Josephson parametric amplifiers (JPAs)*









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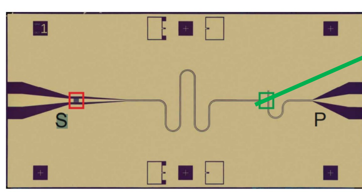
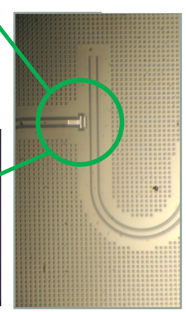
(nonlinear inductance)





But, … narrow bandwidth!

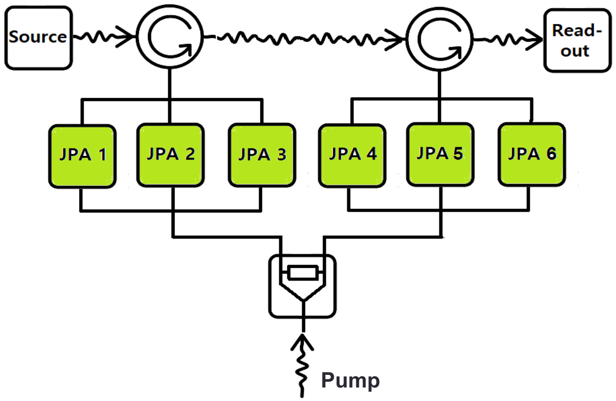
U. of Tokyo & RIKEN

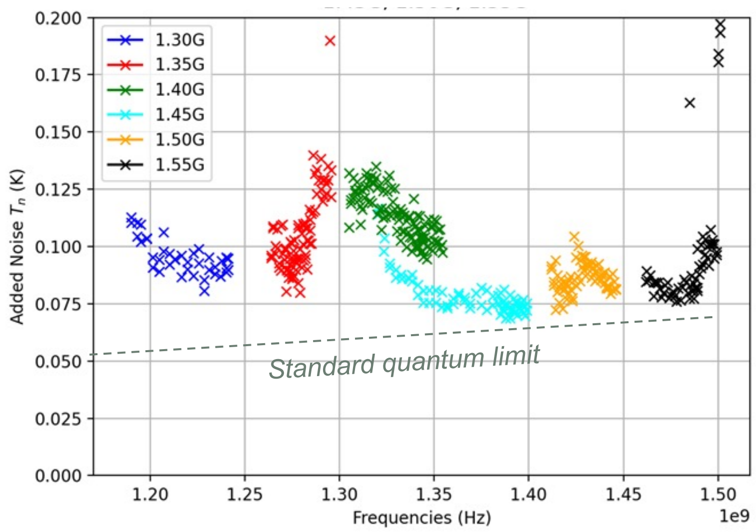
Quantum amplification

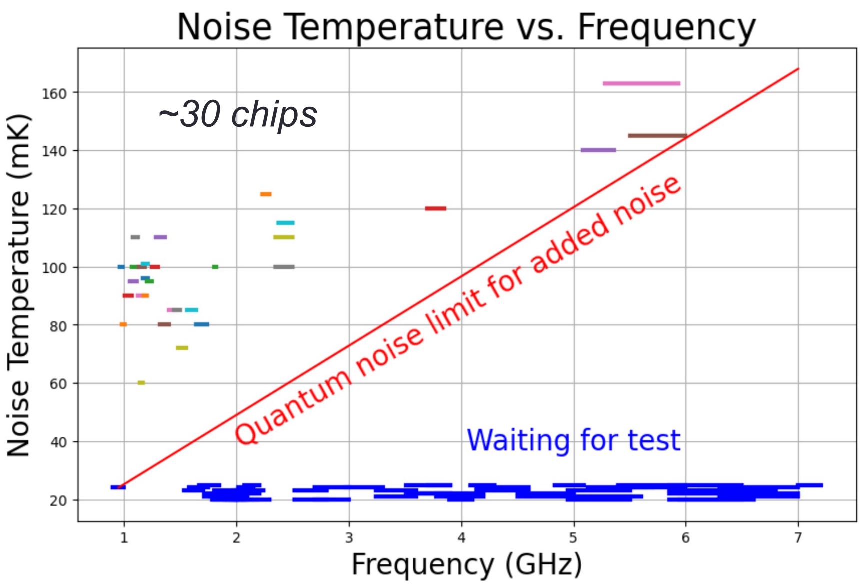
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

- *Flux-driven Josephson parametric amplifiers (JPAs)*

Parallel-Serial configuration



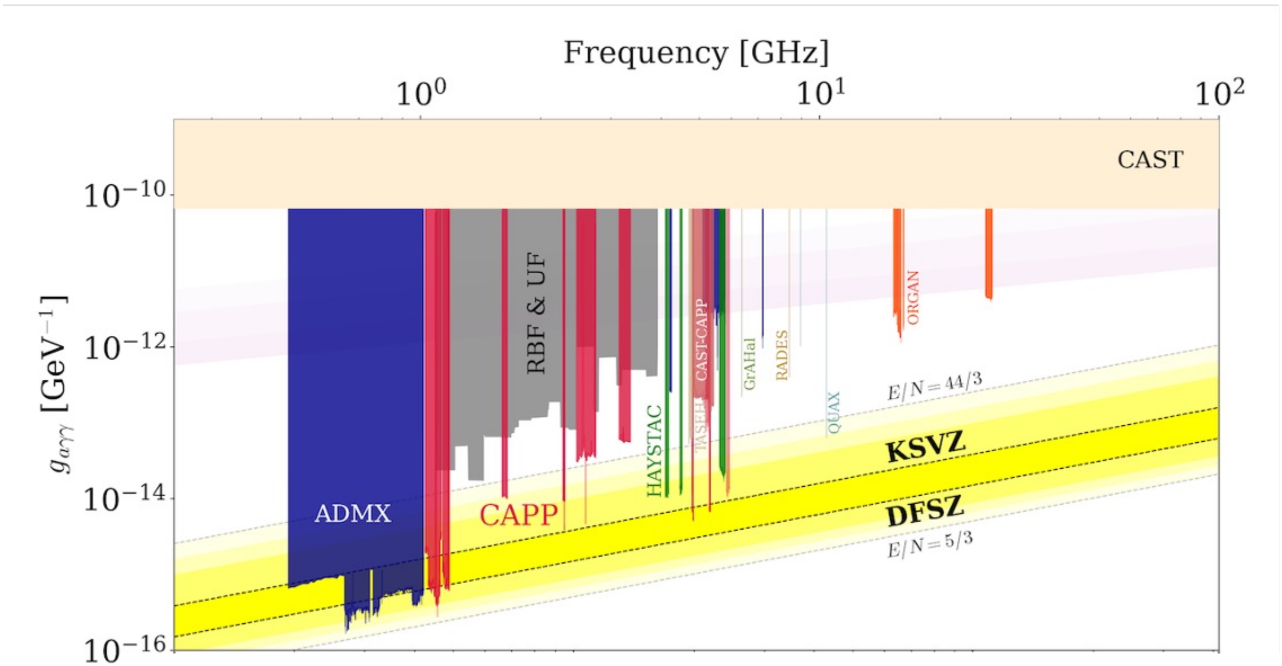


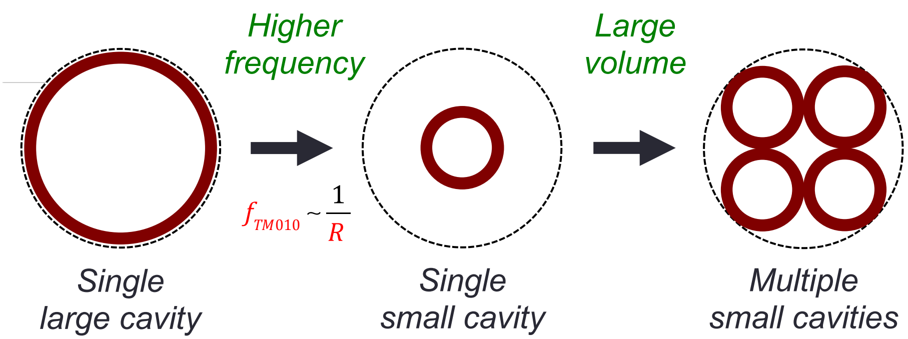


But, … narrow bandwidth!

U. of Tokyo & RIKEN

Searches vs. predictions



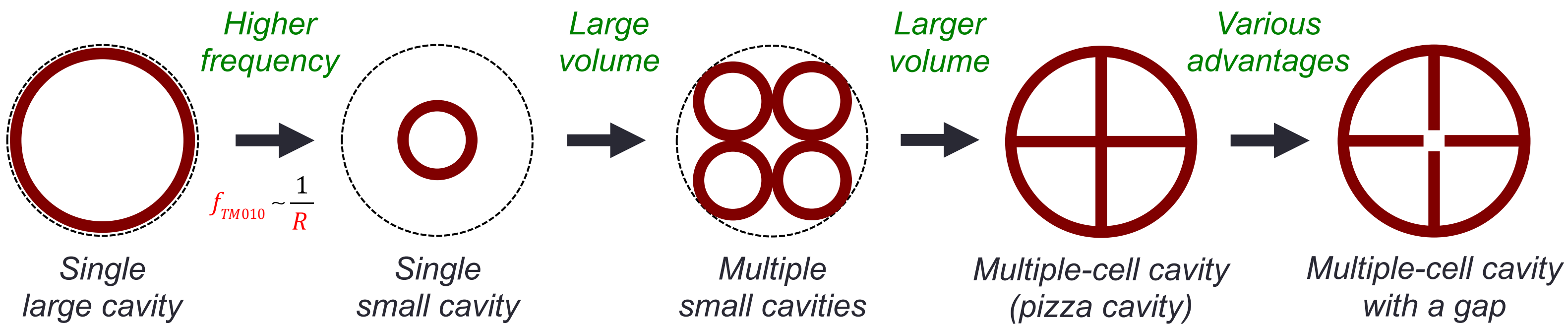


Strategy pursued by ADMX

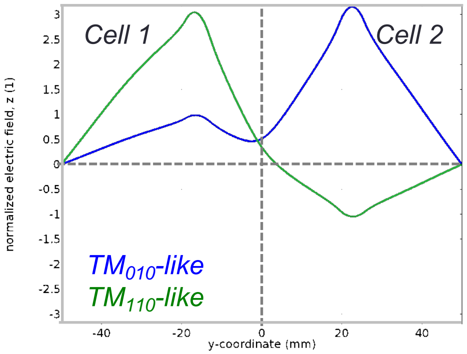
CAPP confirmed the methodology
Astropart. Phys. ***97****, 33 (2018)*

HF (I): multi-cell

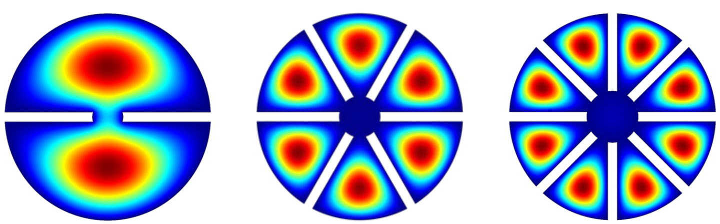
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$



- *Multiple-cavity*
  - *Inefficient volume usage (< 50%)*
  - *Multiple readout / signal combination / frequency-matching*
- *Multiple-cell design*
  - *More effective volume use (>90%)*
  - *Single readout / tuning structure => simple design*
  - *Field configuration => In-situ cavity characterization*



Cavity center



~4 x f_{TM010}

Pizza with a saver

PLB **777** 412 (2018)
NIMA **1053** 168327 (2023)

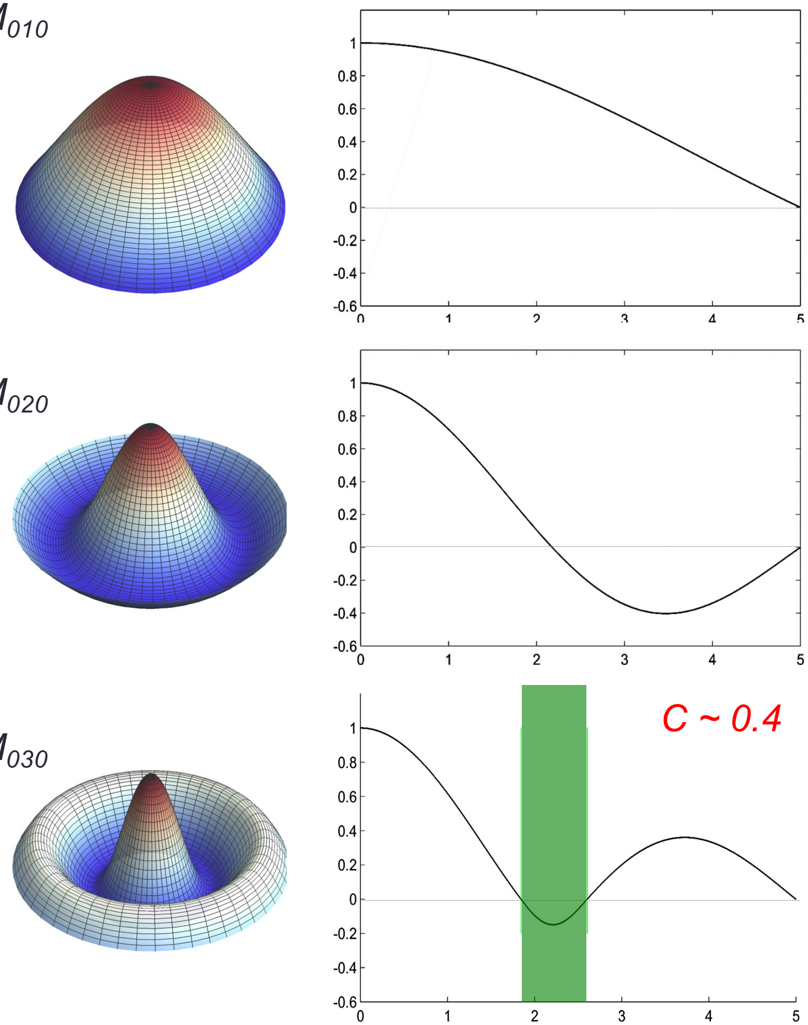
HF (II): higher modes

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

TM$_{010}$

TM$_{020}$

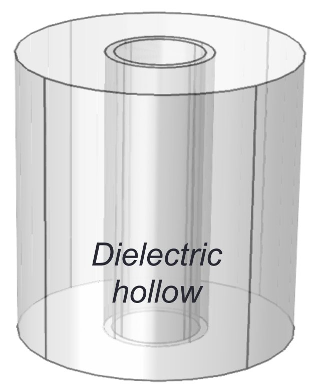
TM$_{030}$



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

Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM$_{010}$	1	1	1	0.69
TM$_{020}$	2.3	1.5	1	0.13
TM$_{030}$	3.6	1.9	1	0.05

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

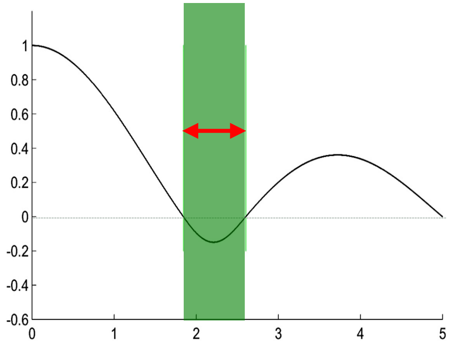


How to tune the frequency?

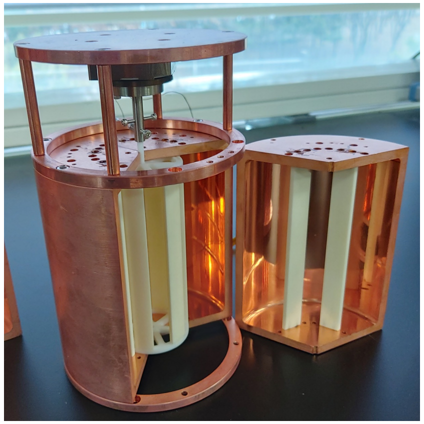
HF (II): higher modes

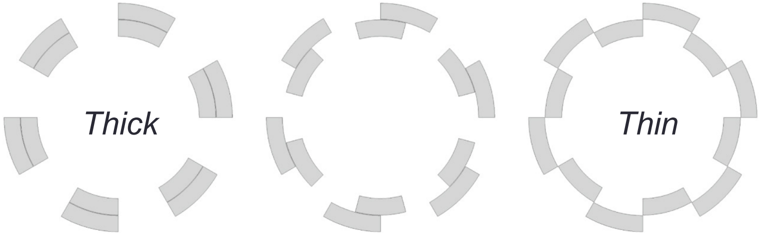
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

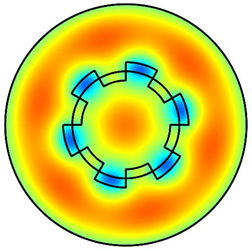
- *Frequency tuning for higher-order modes*

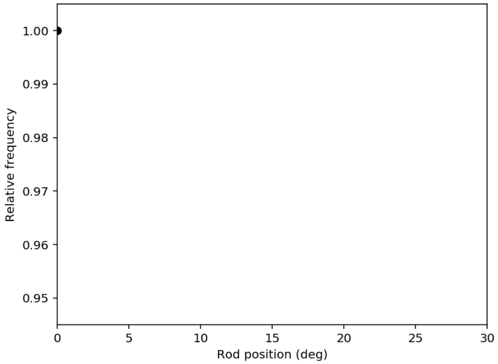


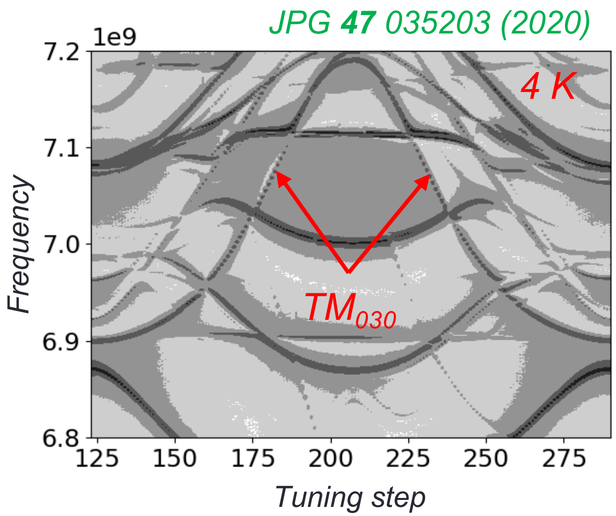
Thickness	Frequency [GHz]
λ/5	8.99
λ/4	8.20
λ/3	7.22
λ/2	7.05
λ/1.5	6.86





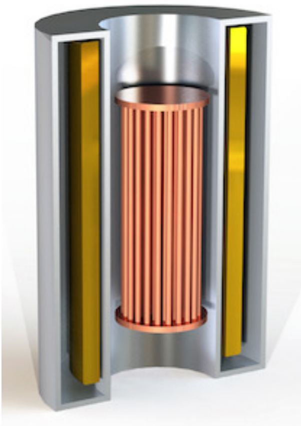




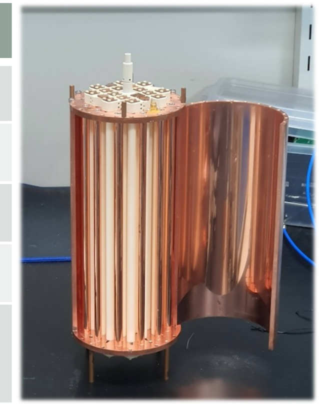


HF (III): photonic crystal

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



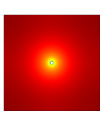
Metal		Dielectric
TM_{010}-like	Resonant mode	Monopole
~ 0.9	Form factor C	~ 0.2
< 10^3	Quality factor Q	> 10^5
> 3/cm^2	# density	~ 1/cm^2
Challenging	Construction / frequency tuning	Doable



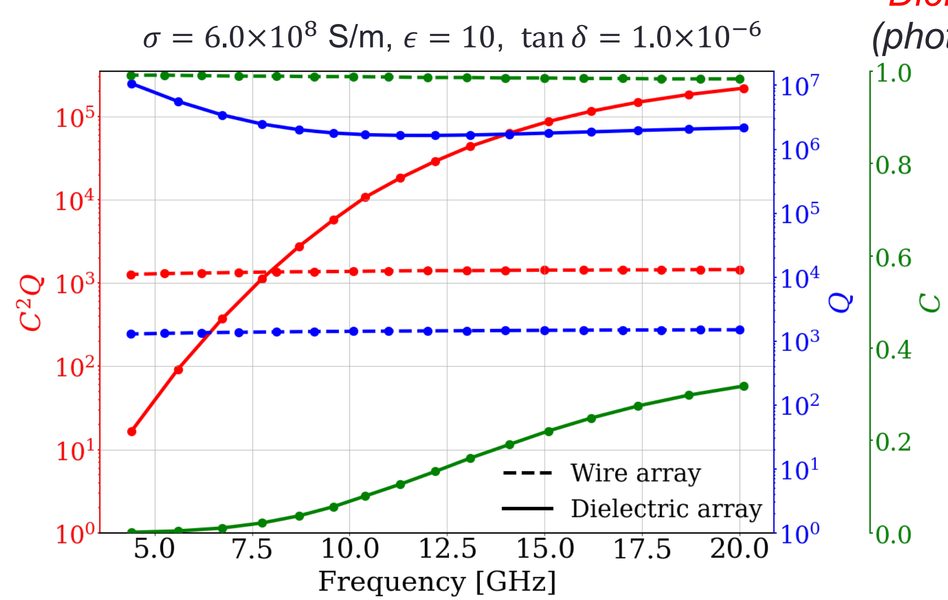
Wire array
(plasma)

PRL ***123*** *141082 (2019)*

ALPHA
consortium

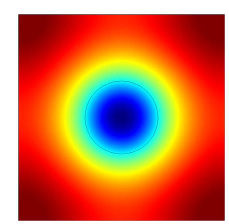


Unit cell



Dielectric array
(photonic crystal)

>10 x f_{TM010}



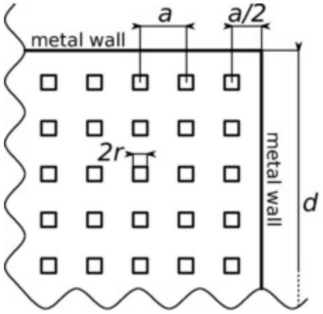
Unit cell

HF (III): photonic crystal

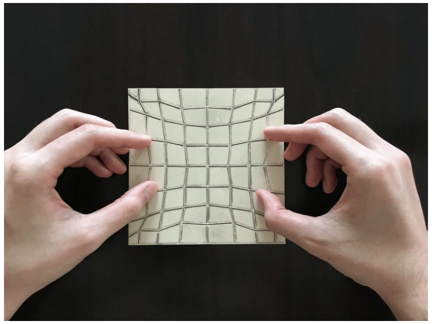
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

- *Frequency tuning*
  2D (isotropic) expansion/contraction

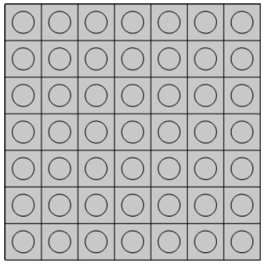
$$\omega_p^{\ 2} = \frac{2\pi}{a^2 \log(\frac{a}{2r})}$$



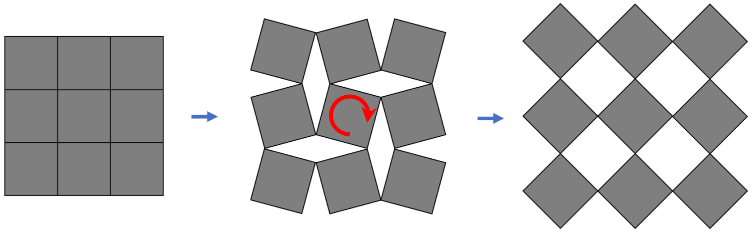
- *Kirigami tessellations w/ auxetic behavior*

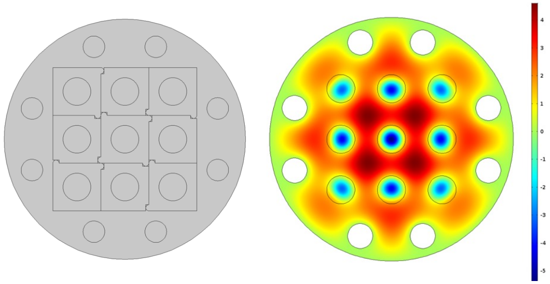


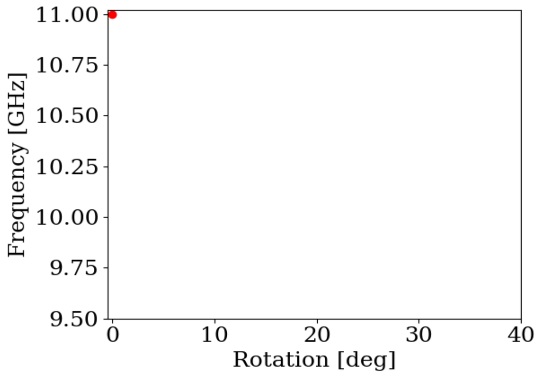
Nature materials ***18****, 999*



Rotating regular squares



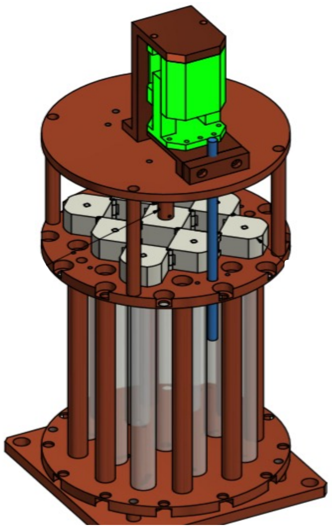


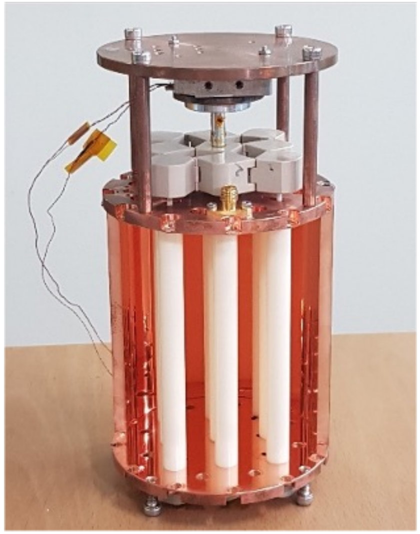


- *Rotation of the center block*
  - *Achievable using a single rotator*

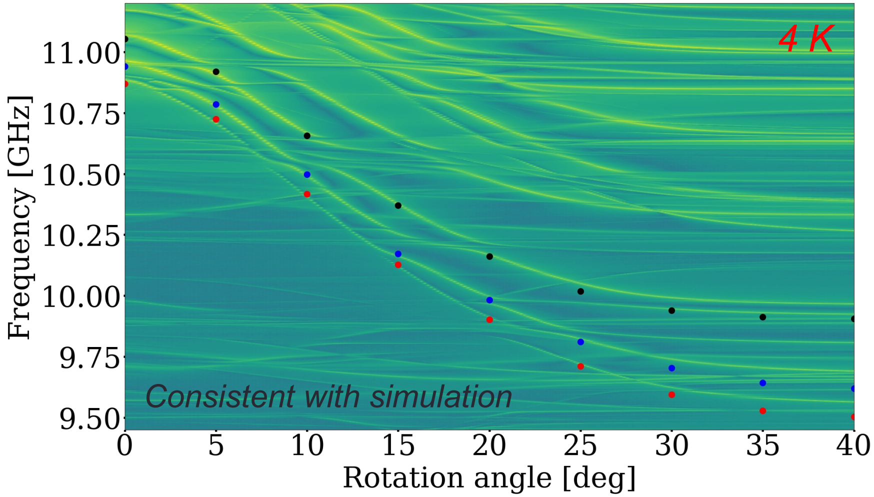
HF (III): Demonstration

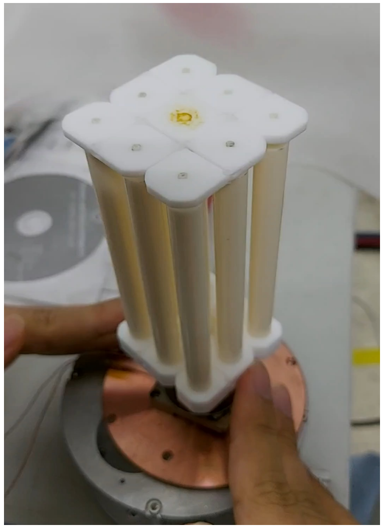
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$



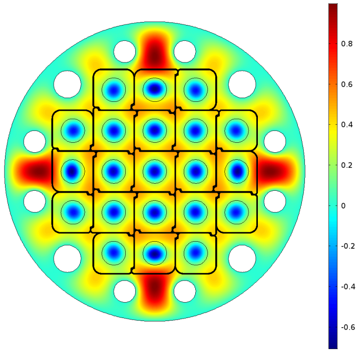


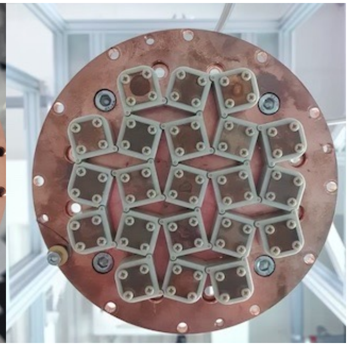
*PRD **107** 015012 (2023)*





- *Extending to a 5x5 array for larger volume*
- *Experimental seutp for > 10 GHz ongoing*

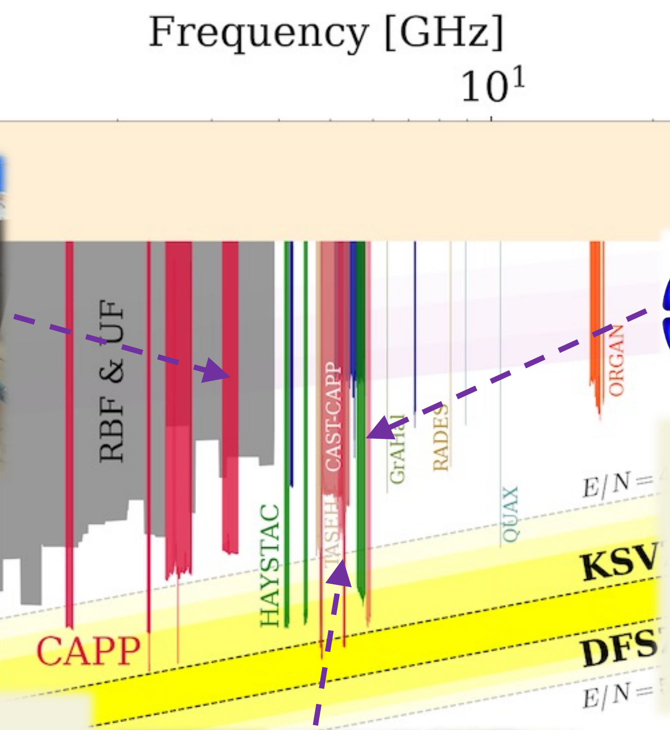


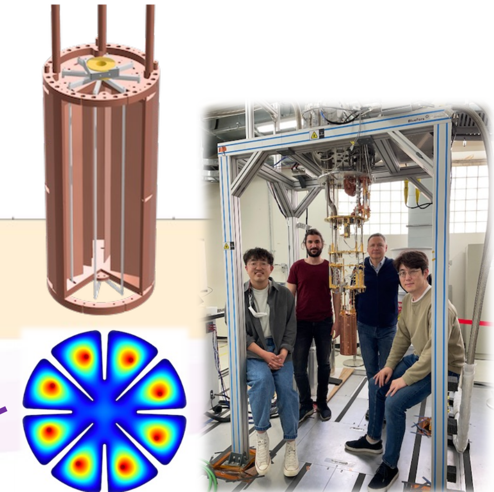


Axion Searches by CAPP

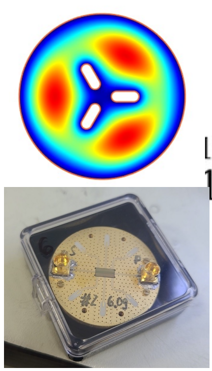
Search highlight (I)

CAPP-9T
(9T/127mm)
2-cell pizza (3.2 GHz)
*PRL **125** 221302 (2020)*

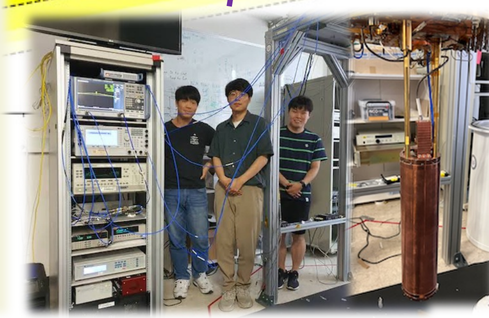




CAPP-8TB
(8T/165mm)
8-cell + JPA
(5.9 GHz, 400 mK)
Near KSVZ sensitivity
Paper in preparation



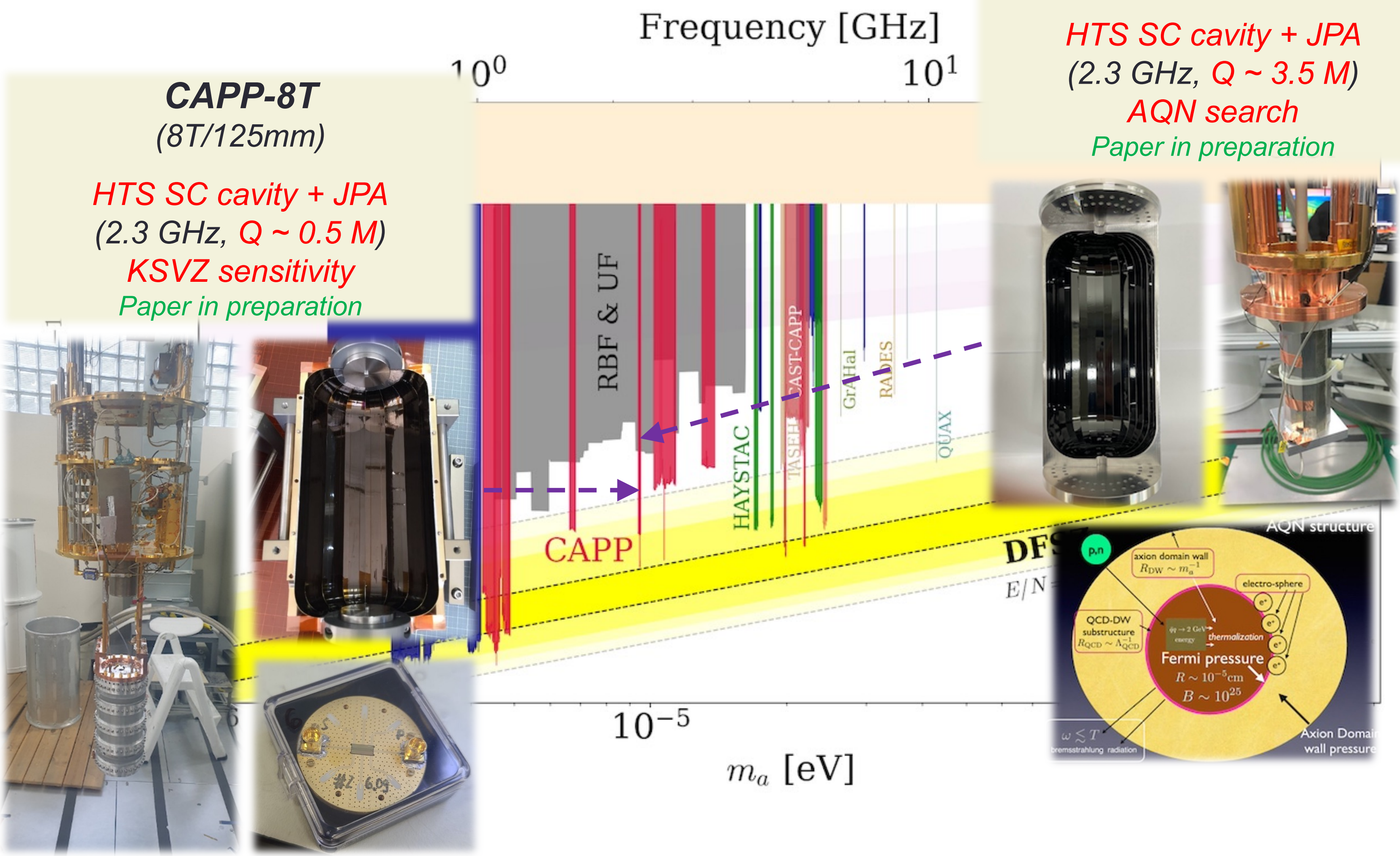
CAPP-12T
(12T/96m)
3-cell + JPA
(5.3 GHz, 400 mK)
KSVZ sensitivity
NM algorithm
arXiv:2312.11003 (PRL)



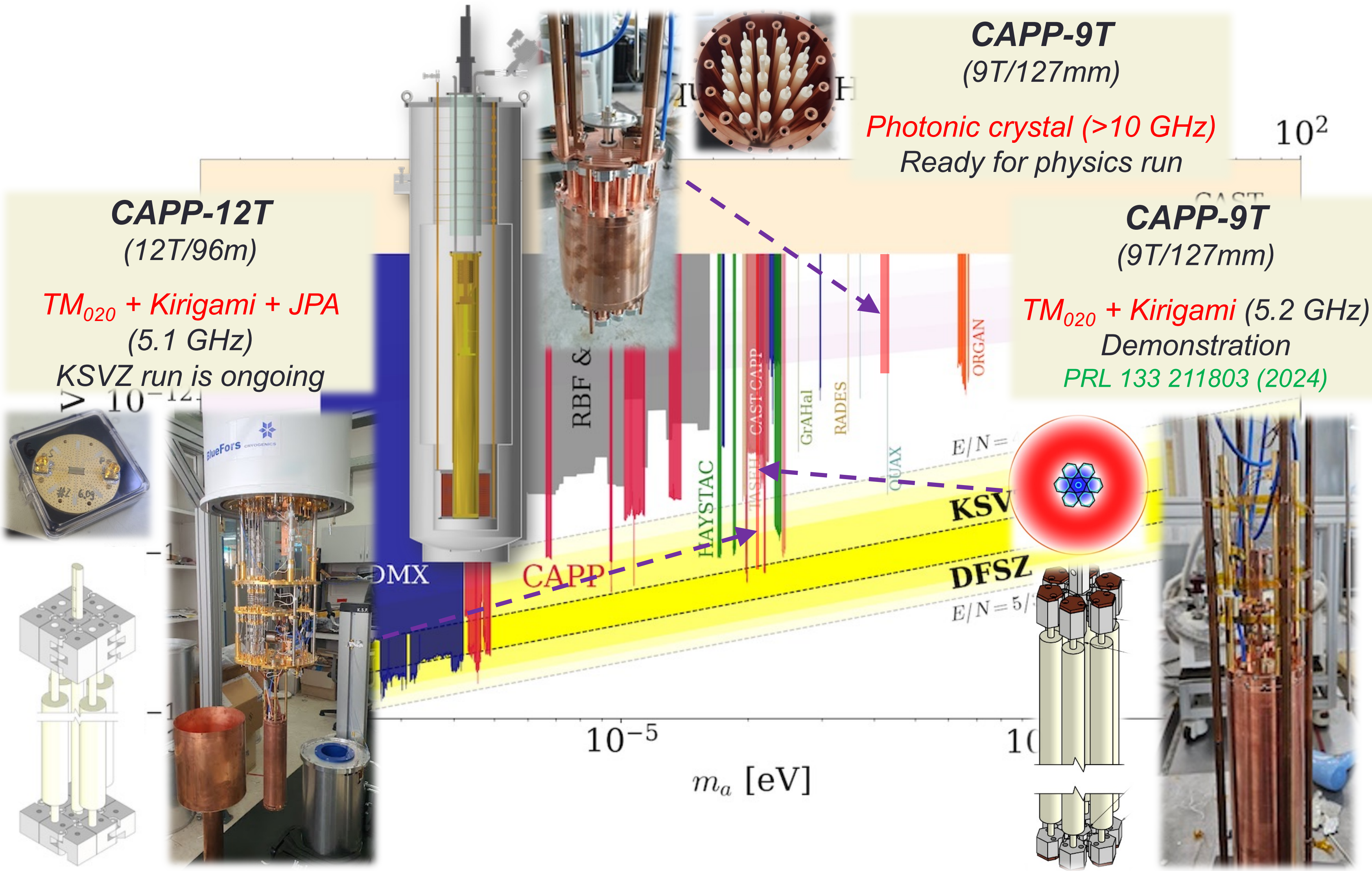
Search highlight (II)

CAPP-8T
(8T/125mm)
HTS SC cavity + JPA
(2.3 GHz, Q ~ 0.5 M)
KSVZ sensitivity
Paper in preparation

CAPP-8T
(8T/125mm)
HTS SC cavity + JPA
(2.3 GHz, Q ~ 3.5 M)
AQN search
Paper in preparation



Search highlight (III)



CAPP-9T
(9T/127mm)
Photonic crystal (>10 GHz)
Ready for physics run

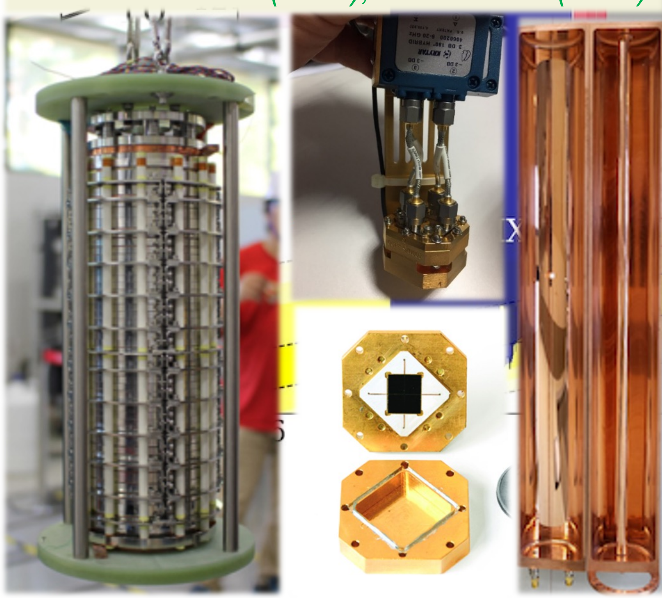
CAPP-12T
(12T/96m)
TM_{020} + Kirigami + JPA
(5.1 GHz)
KSVZ run is ongoing

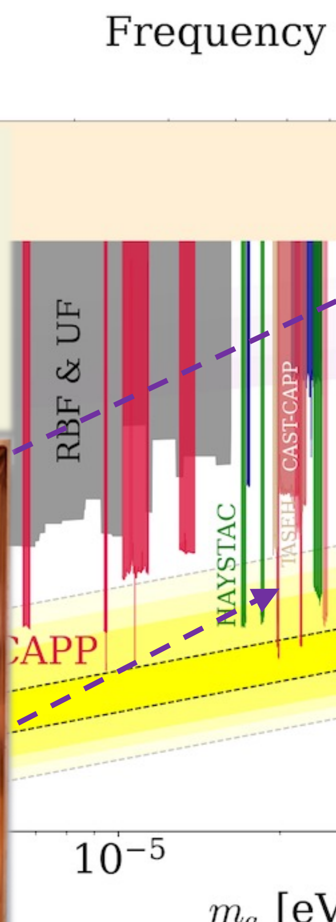
CAPP-9T
(9T/127mm)
TM_{020} + Kirigami (5.2 GHz)
Demonstration
PRL 133 211803 (2024)

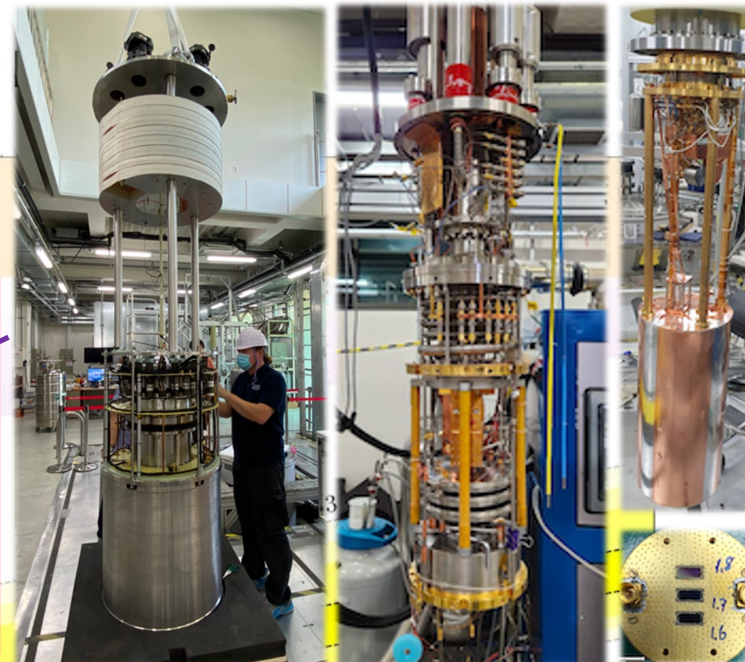
Search highlight (IV)

CAPP-18T
(18T/70mm)

HTS magnet + JPC
(4.8 GHz)
KSVZ sensitivity
*PRL **128** 241805 (2022), **131** 081801 (2023)*





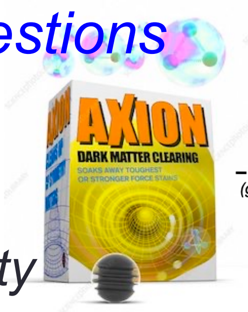


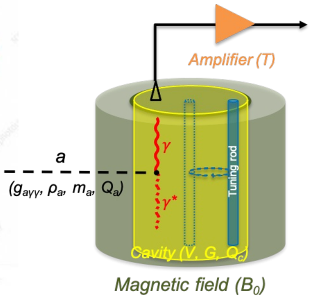
CAPP-12TB
(12T/320mm)
f > 1 GHz, V = 37 L, T_{sys} < 250 mK

df/dt ~ 2 MHz/day @ DFSZ
*PRL **130** 071002 (2023)*
Extended scan (Δf ~120 MHz)
*PRX **14** 031023 (2024)*
Ready for 300-MHz run w/ SC cavity

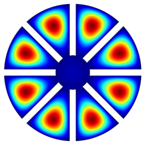
Summary

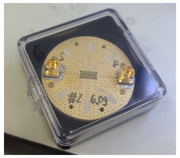
- *QCD axions could address fundamental questions*
  - *Strong CP problem & dark matter mystery*



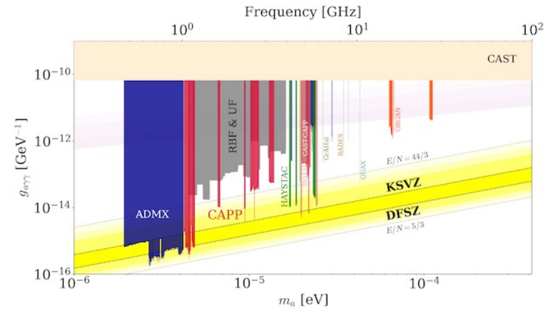


- *Haloscope is the most sensitive method*
  - *IBS-CAPP has established a world-leading facility*
- *Research and development in CAPP*
  - *High-frequency / HTS cavity / quantum devices*
  - *Substantial improvement for exploring the parameter space*





- *Productive scientific results from CAPP*
  - *Experimental searches*
    - *CAPP-9T, -8T, -8TB, -12T, -18T and -12TB*
  - *Groundbreaking R&D products*



- *Continued contributions are needed*
  - *To advance our understanding of nature*

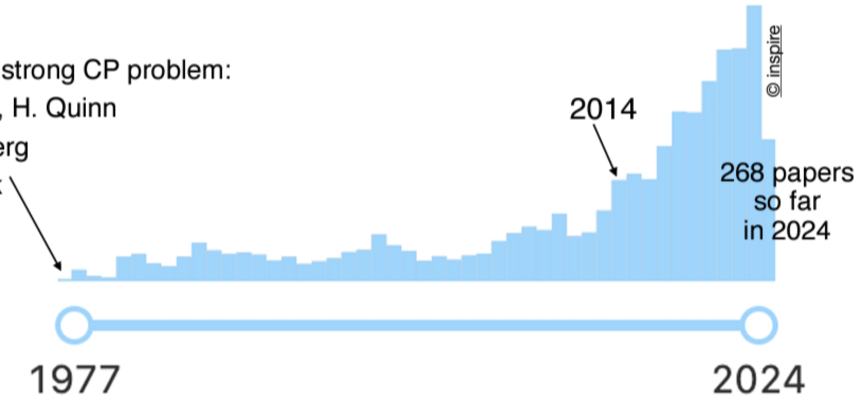
Axion community growing fast

August 4–10 ICISE 2024

Why a conference dedicated to axion searches?

Date of paper
Axions & ALPs

Solve the strong CP problem:
R. Peccei, H. Quinn
S. Weinberg
F. Wilczek



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Karl A. van Bibber	92
Jihn E. Kim	86
Javier Redondo	79
Theopisti Dafni	72
Thomas Papaevangelou	69

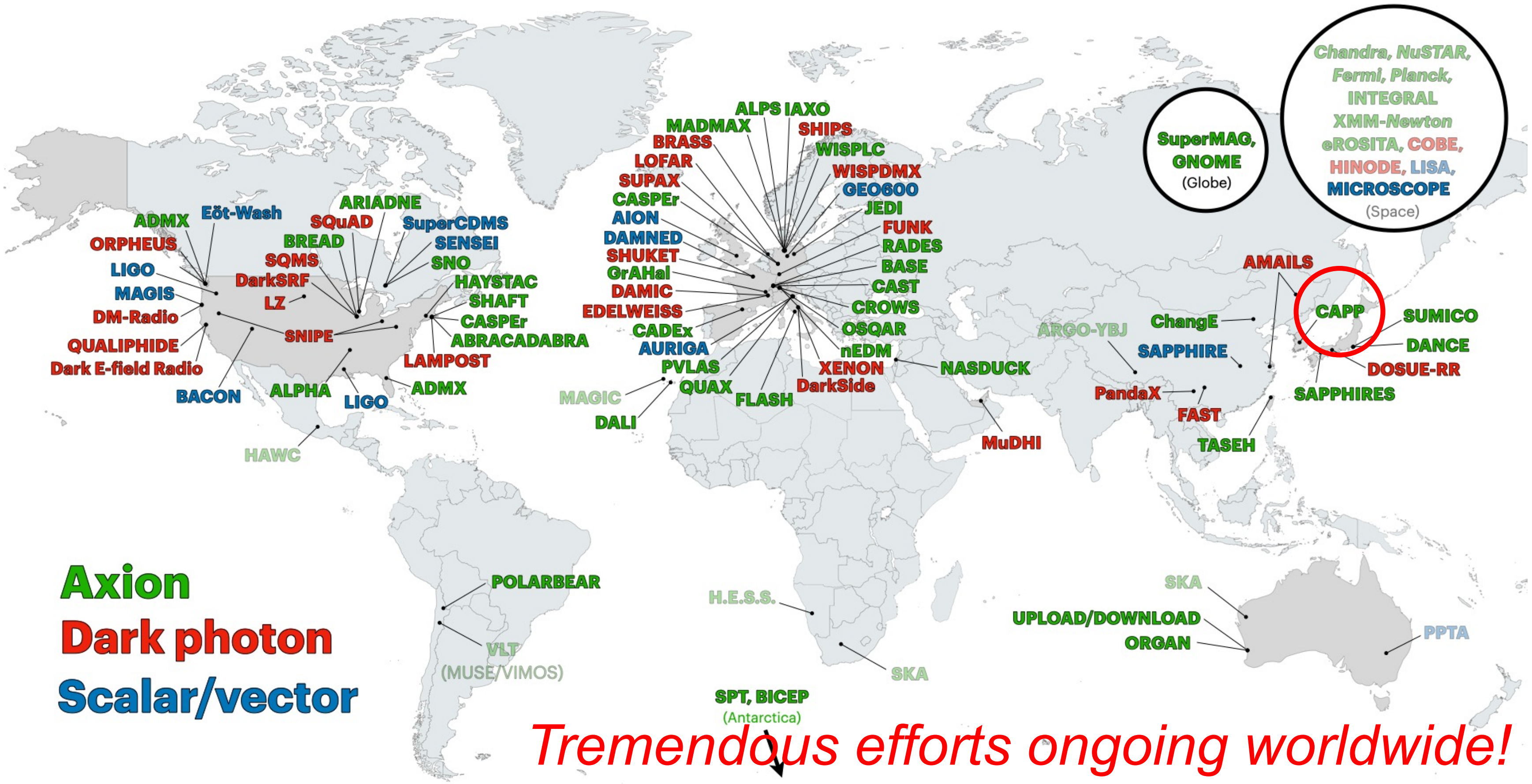
Show 90 more

- Axion is an excellent candidate for the long-sought non baryonic Dark Matter.

➛ **Keynote talk will be given by Yannis Semertzidis**

Experiment map

C. O'Hare (2020)



Tremendous efforts ongoing worldwide!

Next few decades promise to be exciting in this field!

Future of axion research …

CAPP (2013)
Center for Axion and Precision Physics Research

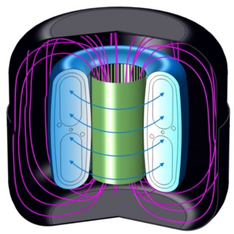
↓↓

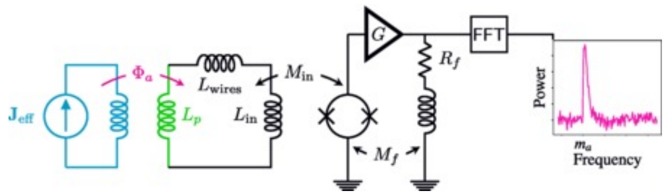
GAP (2025)
Group for Axion Physics

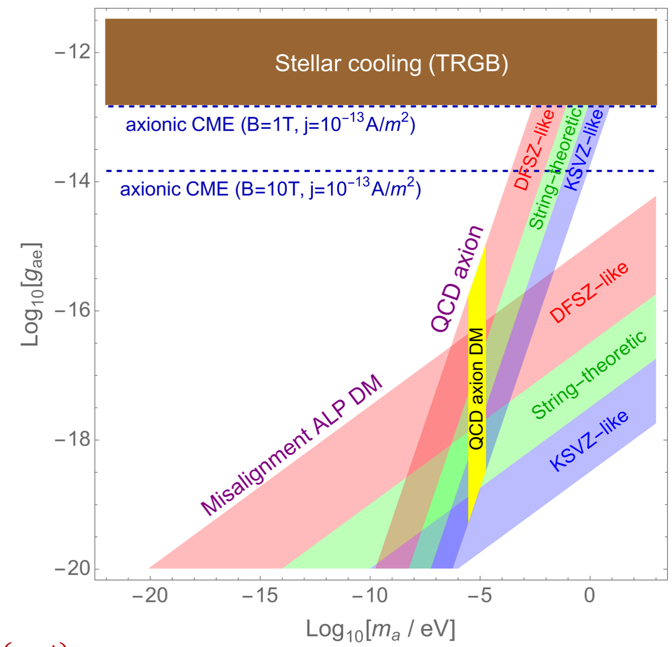
HAS-GAP
Hearing Axion Sounds through GAP

Axionic chiral magnetic effect

- *Low temperature Axion Chiral Magnetic Effect*





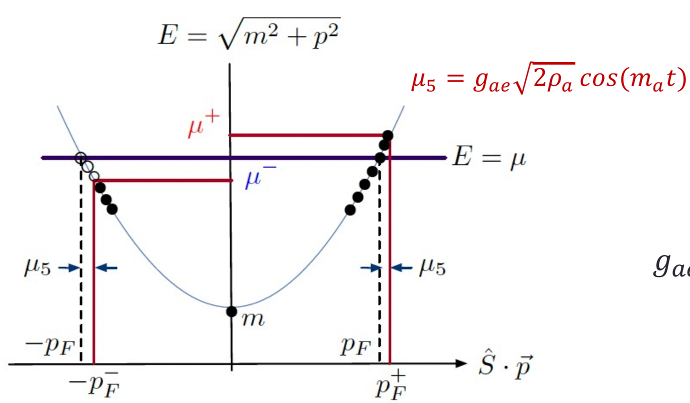


ABRACADABRA		LACME
$-\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	*Coupling*	$g_{ae}\delta_\mu a\psi\gamma^\mu\gamma_5\psi$
Effective current (vacuum)	*Axion*	*Chemical potential (polarized medium)*
$g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\,\boldsymbol{B}$	$\boldsymbol{j}_{(eff)}$	$v_F\frac{e^2}{2\pi}g_{ae}\sqrt{2\rho_a}\cos(m_a t)\,\boldsymbol{B}$

μ_5 adds p to e^- along $\hat{S}$

$\boldsymbol{B}$ polarizes e^-

Helicity imbalance => current flow

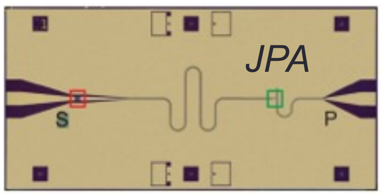


Chiral medium

$$g_{ae} \simeq \begin{cases} \mathcal{O}(1) & \text{DFSZ-like models} \\ \mathcal{O}(10^{-4} \sim 10^{-3}) & \text{KSVZ-like models} \\ \mathcal{O}(10^{-3} \sim 10^{-2}) & \text{string-theoretic axions} \end{cases}$$

Microwave signal detection

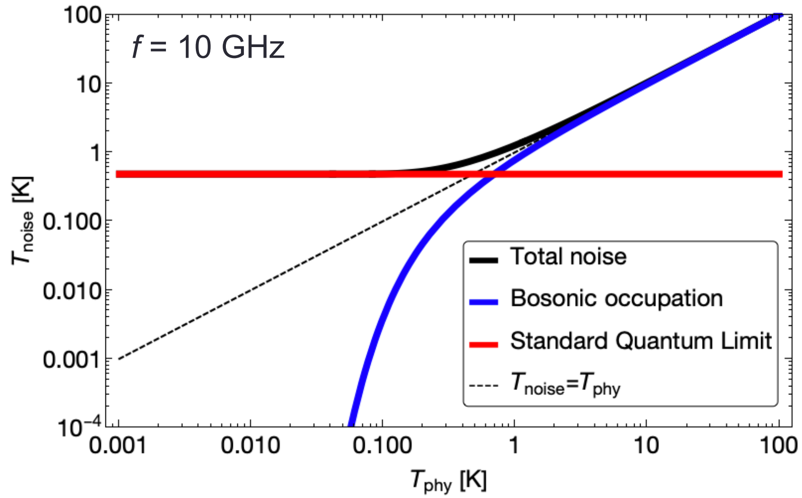
Transistor-based
(T_N ~ K)



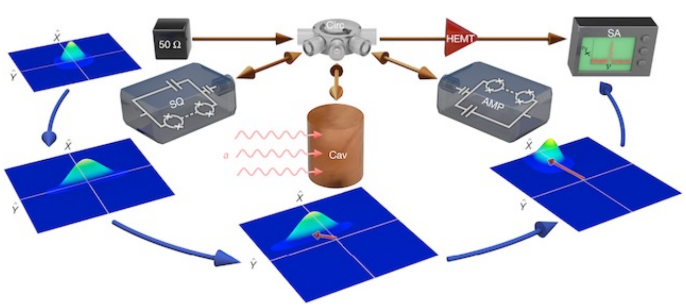
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection vs. photon counting

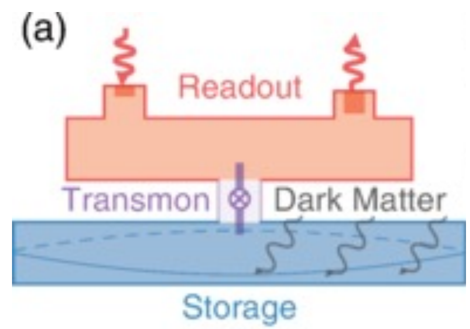
(w/ amplifiers) *(w/ single photon detector)*



Single photon detector (SPD)
↓
Game changer at high frequencies and low temperatures



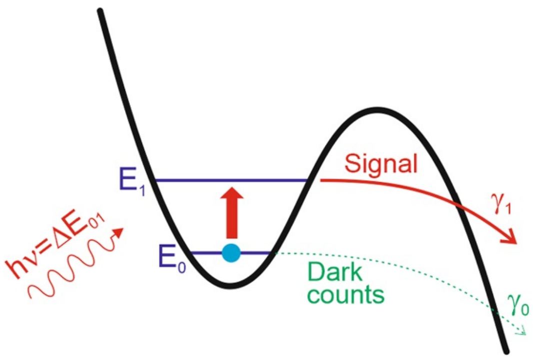
Quantum squeezing (T_N < T_{SQL})



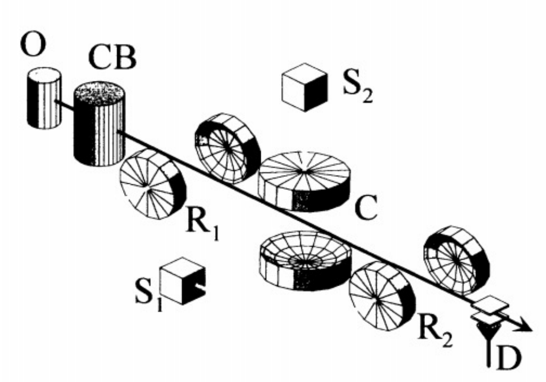
Single photon counting
Not subject to SQL
(T_N << T_{SQL})

SPD schemes

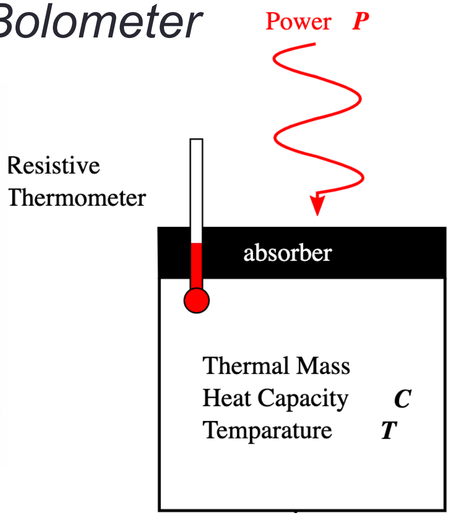
Excitation



Interference



Bolometer

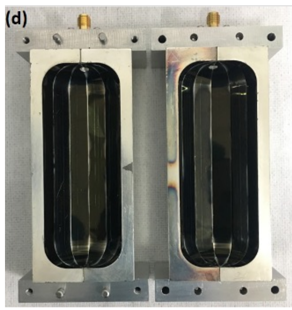


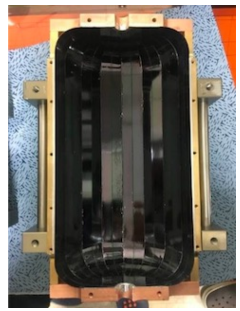
	Excitation	Intereference	Bolometer
Basis	**Qubit**	**JJ-Qubit**	**JJ-TES**
Quantity	Electron	Phase	Heat
Pros	High sensitivity	Non-demolition	Wide bandwith Robust
Cons	Bandwidth vs. Dark cout rate Low tunability	Narrow bandwidth Low tunability	High noise level Dead (relaxation) time

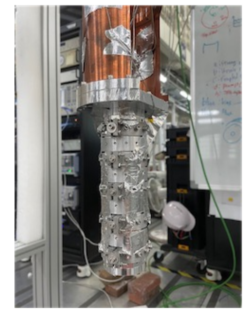
HTS cavities

D. Ahn

- *Uniquely developed and matured fabrication technique*

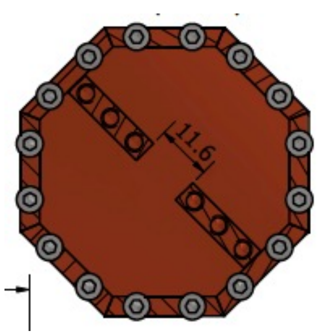


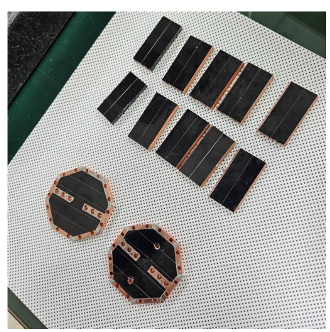





	1st Gen.	2nd Gen.	3rd Gen.		4th Gen.
Material	**Y**BCO	**Gd**BCO	**Eu**BCO + APC		**Eu**BCO + APC
Volume [L]	0.3	1.5	1.5	0.2	37
Freq. [GHz]	6.9	2.3	2.2	5.4	1.2
Q-factor @ 8 T	**0.33 M**	**0.5 M**	**3.5 M**	**13 M**	**1.1 M**

- *Integration with HF cavity designs*



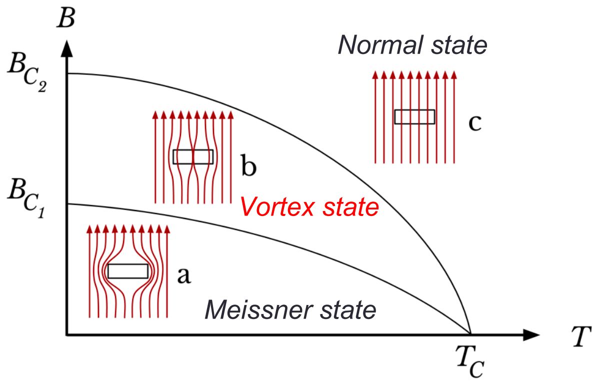



$Q_{HTS} \sim 10 \times Q_{Cu}$

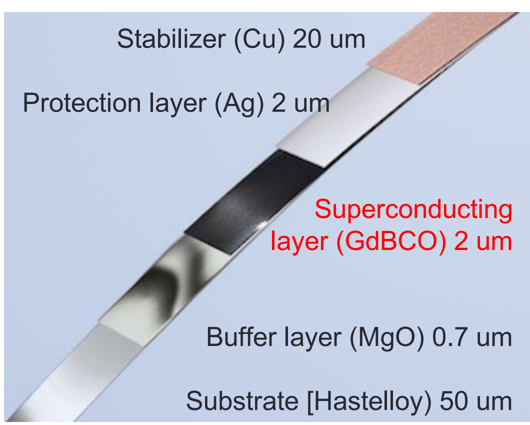
HTS cavities

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

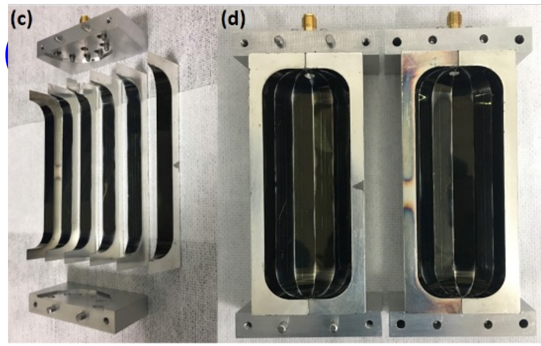
High-Temp. Superconductor

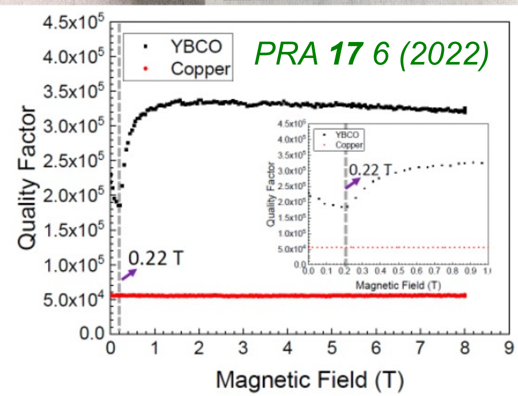


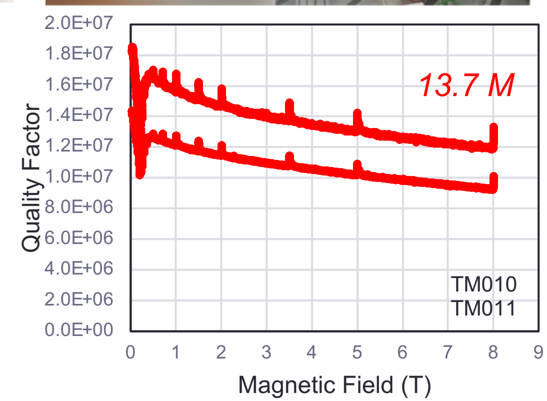
ReBCO HTS tapes (2D)



+ 3D body = SC cavity







Generation	1st	2nd	3rd	
Material	**YBCO**	**GdBCO**	**EuBCO+APC**	
Manufacture	AMSC	Theva	Fujikura	
V [L]	0.3	1.5	1.5	0.2
f [GHz]	6.9	2.3	2.2	5.4
Q	**0.33 M**	**0.5 M**	**3.5 M**	**13 M**