Axion Haloscope Searches

Light Dark World 2024
August 12, 2024 KAIST

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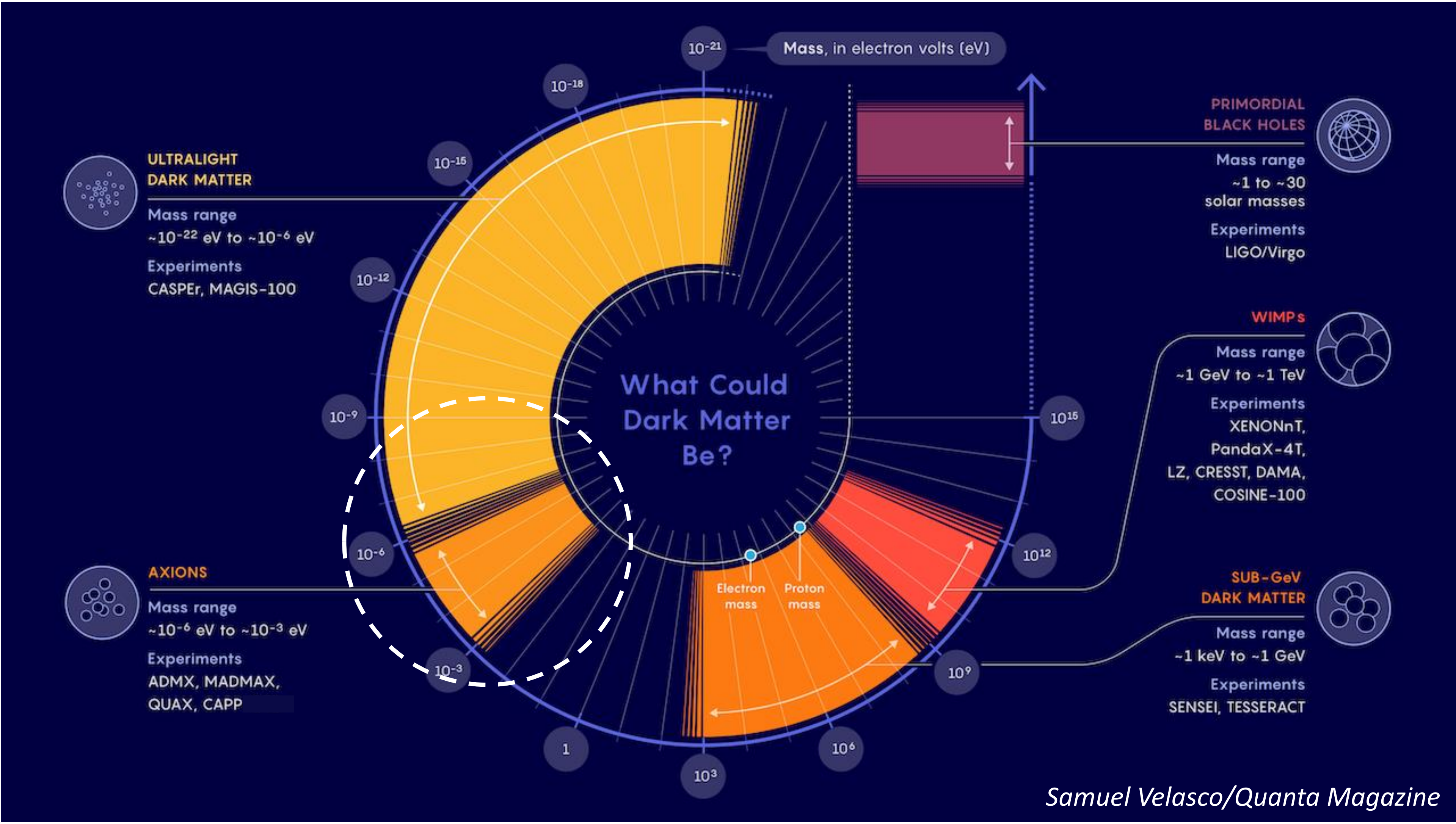
Institute for Basic Science (IBS)

Dark matter business expanding

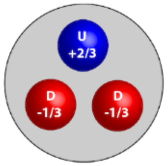


Samuel Velasco/Quanta Magazine

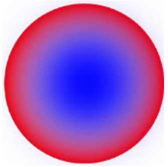
Axion dark matter

- *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

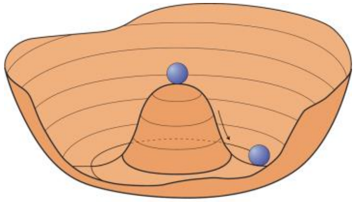


vs.

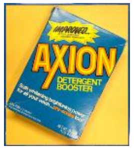


$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \Rightarrow \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$

Spontaneous Symmetry Breaking

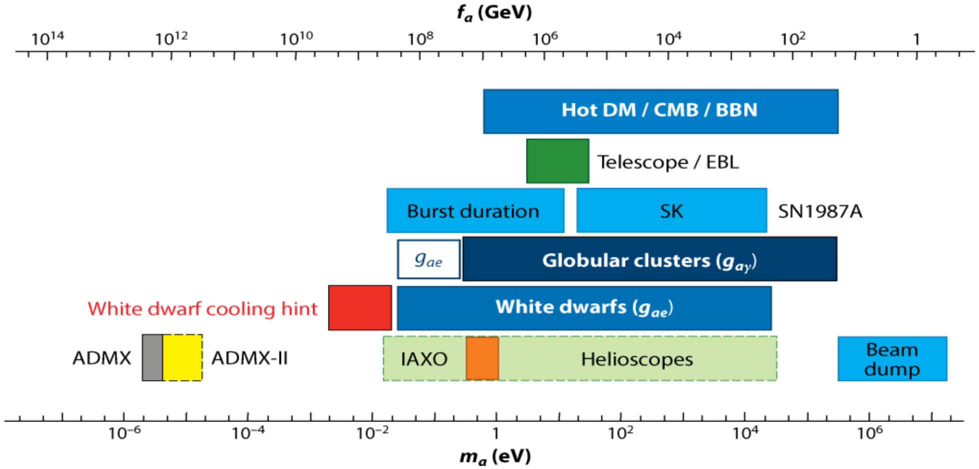


$a(x) = \theta \times f_a$ *at minimum*



Goldstone boson

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



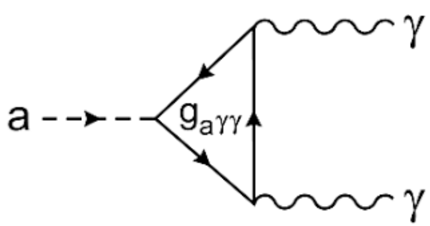
Annu. Rev. Nucl. Part. Sci. 65 485 (2016)

Axion models and detection

- *Axion coupling to SM*

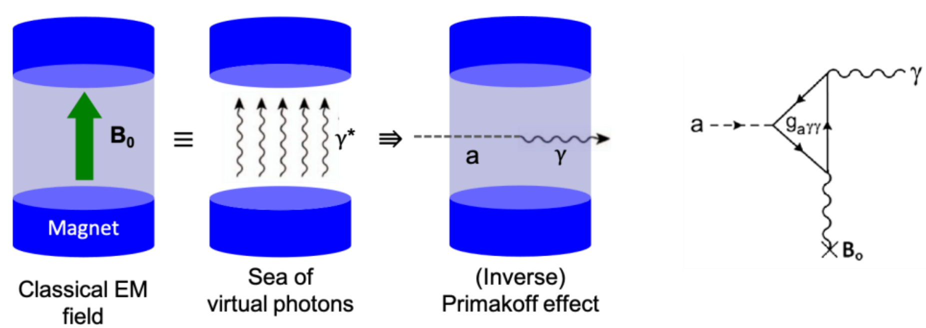
	Photons	Fermions	nEDMs
Hamiltonian	$g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$	$g_{aff}\nabla a\cdot\hat{\boldsymbol{S}}$	$g_{EDM} a\hat{\boldsymbol{S}}\cdot\boldsymbol{E}$
Observable	*Photon*	*Spin precession*	*Oscillating EDM*
Detection	*Power spectrum, photon counter, …*	*Magnetometer,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

- *Axion models*



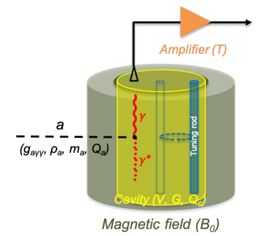
PQWW	DFSZ	KSVZ
SM ferminons		*BSM fermions*
2 Higgs	*2Higgs+singlet*	*Higgs+singlet*
Standard ($f_a \sim v_{EW}$)	***Invisible ($f_a \gg v_{EW}$)***	
Ruled out	*Benchmark*	

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



Search strategies

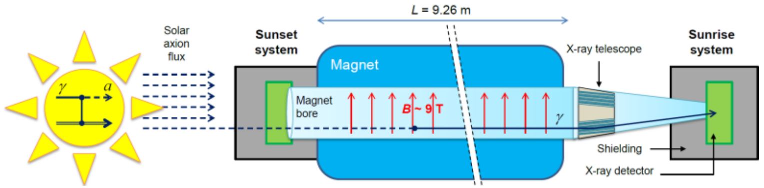
- *Haloscope*
  - *Dark matter halo in our galaxy*



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

    ~100 photons/sec

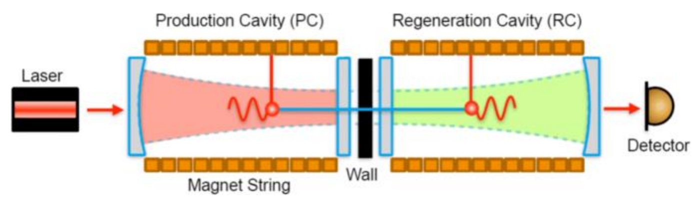
- *Helioscope*
  - *Solar axion*



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

    ~10 photons/day

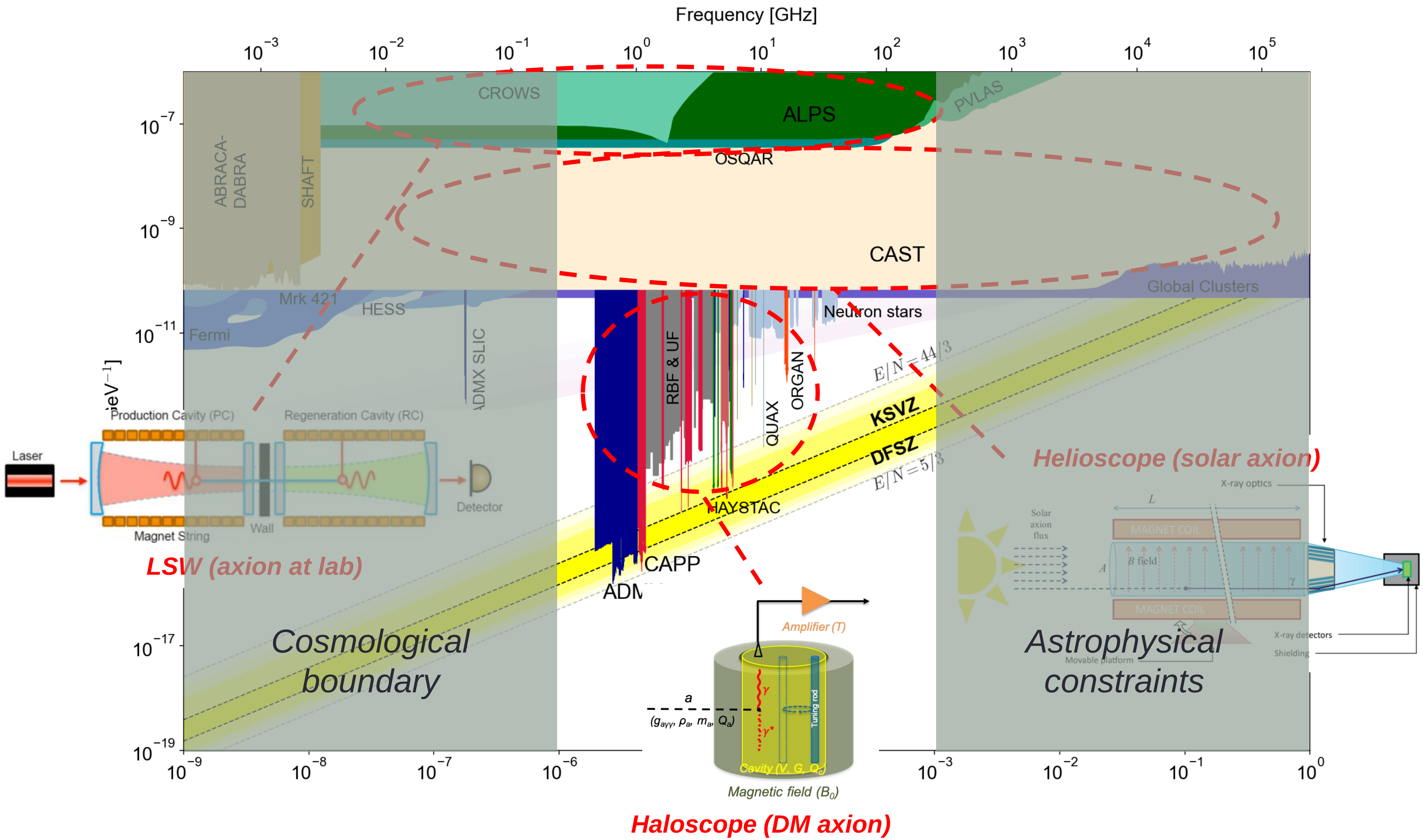
- *Light shinning through a wall*
  - *Axion production at lab*



  - $\dot{N}_\gamma \approx 4 \times 10^{-5} Hz\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}}\right)^4\left(\frac{P_{laser}}{40\ W}\right)\left(\frac{BL}{560\ Tm}\right)\left(\frac{\beta_{PC}}{5000}\right)\left(\frac{\beta_{RC}}{40000}\right)$ ***~1 photons/day***

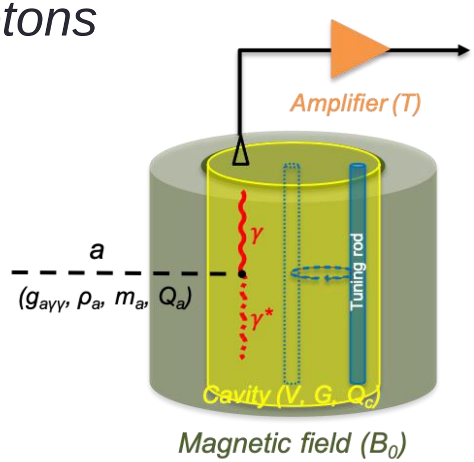
Axion searches

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)*

$$P_{a\gamma\gamma} \approx 9\times10^{-23}\,W \left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right)\left(\frac{f_a}{1.1\ GHz}\right)$$

(~120 photons/sec)

$$\times\left(\frac{B_0}{10.5\ T}\right)^2\left(\frac{V}{37\ L}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_c}{10^5}\right)$$

- *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)

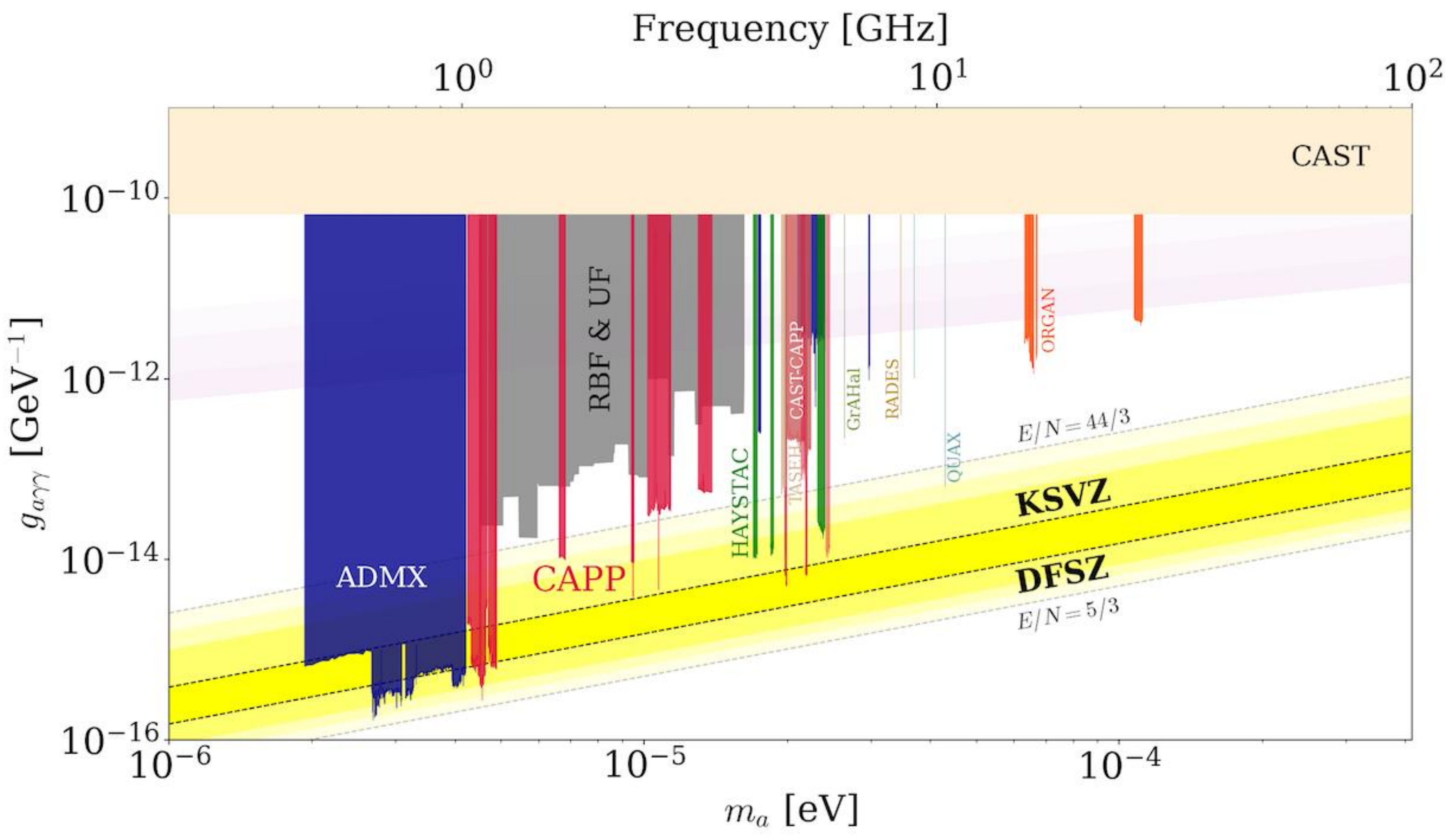
$$T_{sys} = T_{thr} + T_{add}$$

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

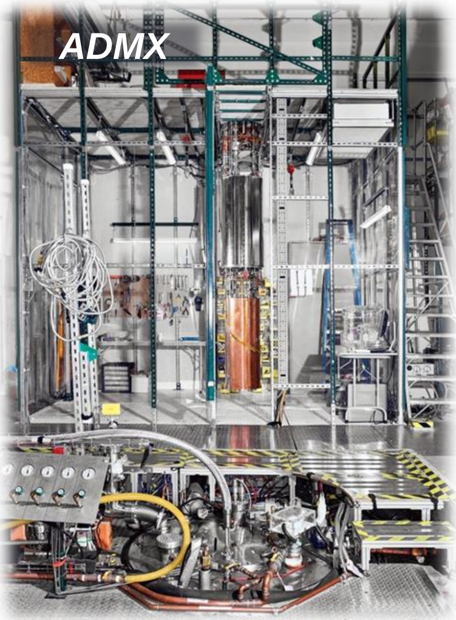
- *Unknown mass = > scanning rate (F.O.M.)*

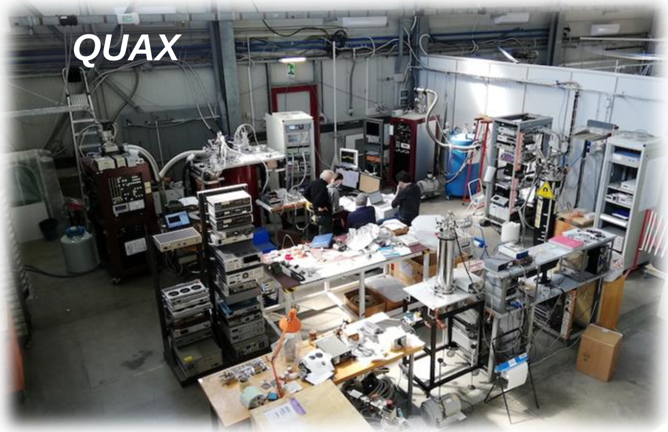
$$\frac{df}{dt} \approx 2\frac{GHz}{year}\left(\frac{5}{SNR}\right)^2\left(\frac{0.2\ K}{T_{sys}}\right)^2\left(\frac{P_{a\gamma\gamma}}{1\text{x}10^{-22}\ W}\right)^2\left(\frac{10^5}{Q_c}\right) \sim B_0^4V^2C^2Q_cT_{sys}^{-2}$$

Haloscope searches

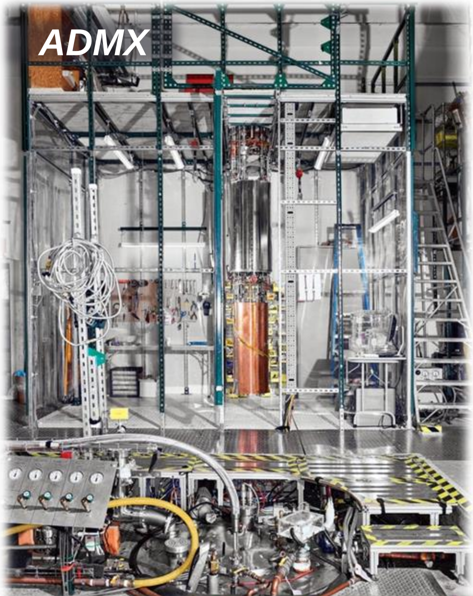


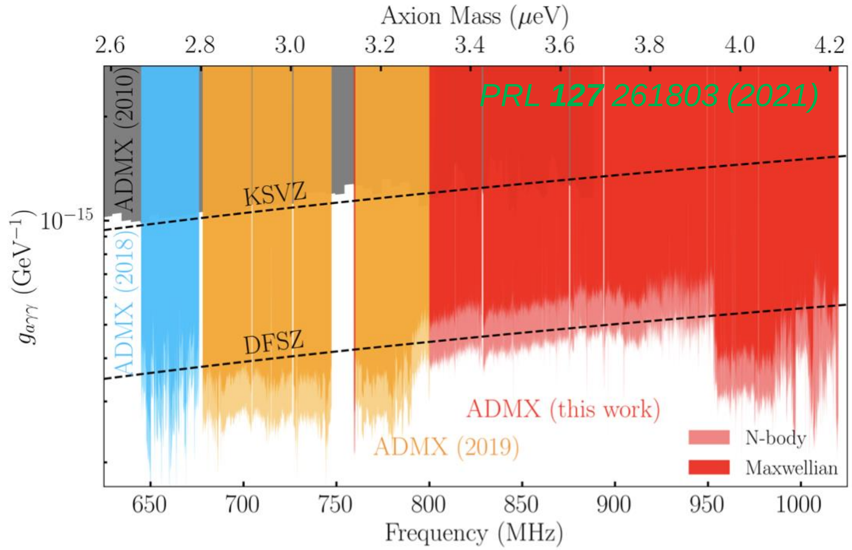
Cavity haloscopes

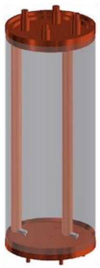




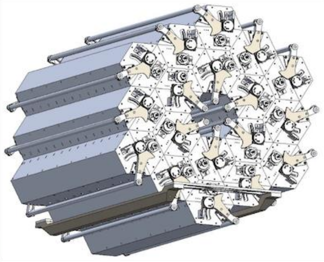
ADMX






Run 1A-C


Run 2


EFR

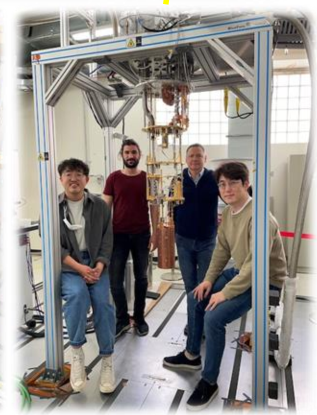
IBS-CAPP

CAPP-9T

CAPP-12TB

CAPP-12T

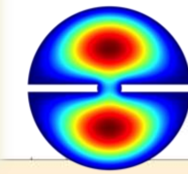
CAPP-8T

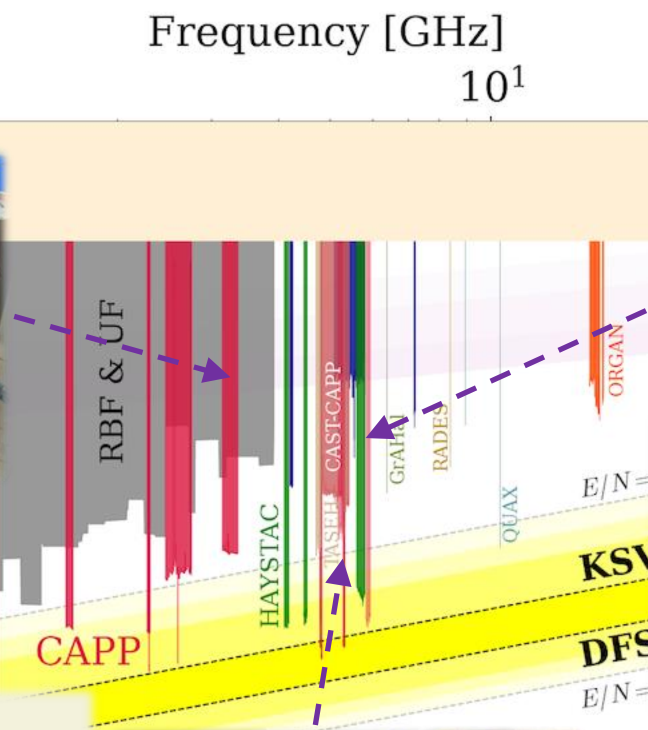


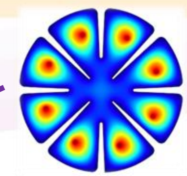
CAPP-8TB

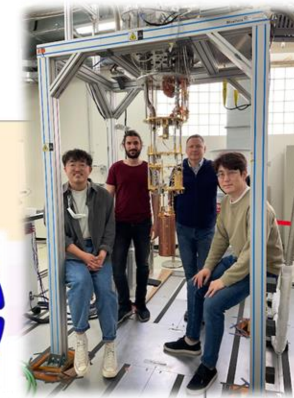
CAPP (I)

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

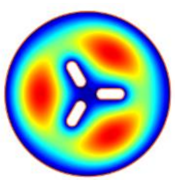




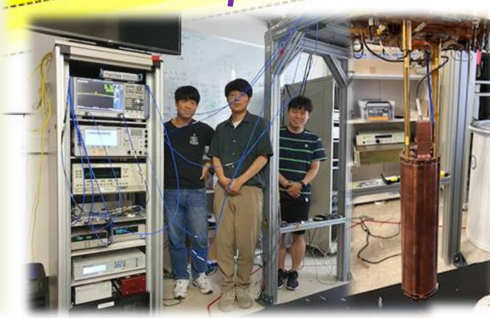




CAPP-8TB
(8T/165mm)
8-cell + JPA
(5.9 GHz, 400 mK)
Near KSVZ sensitivity
Paper in preparation



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



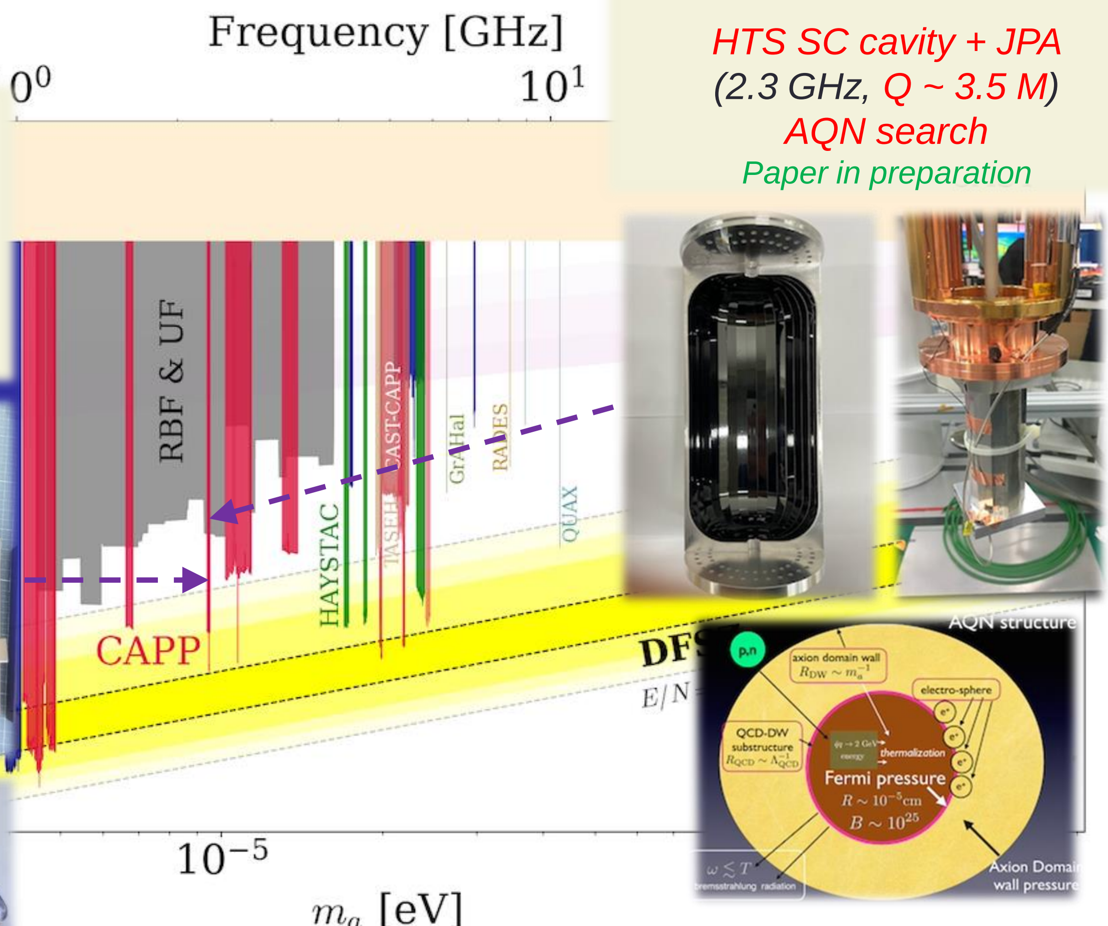
CAPP (II)

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

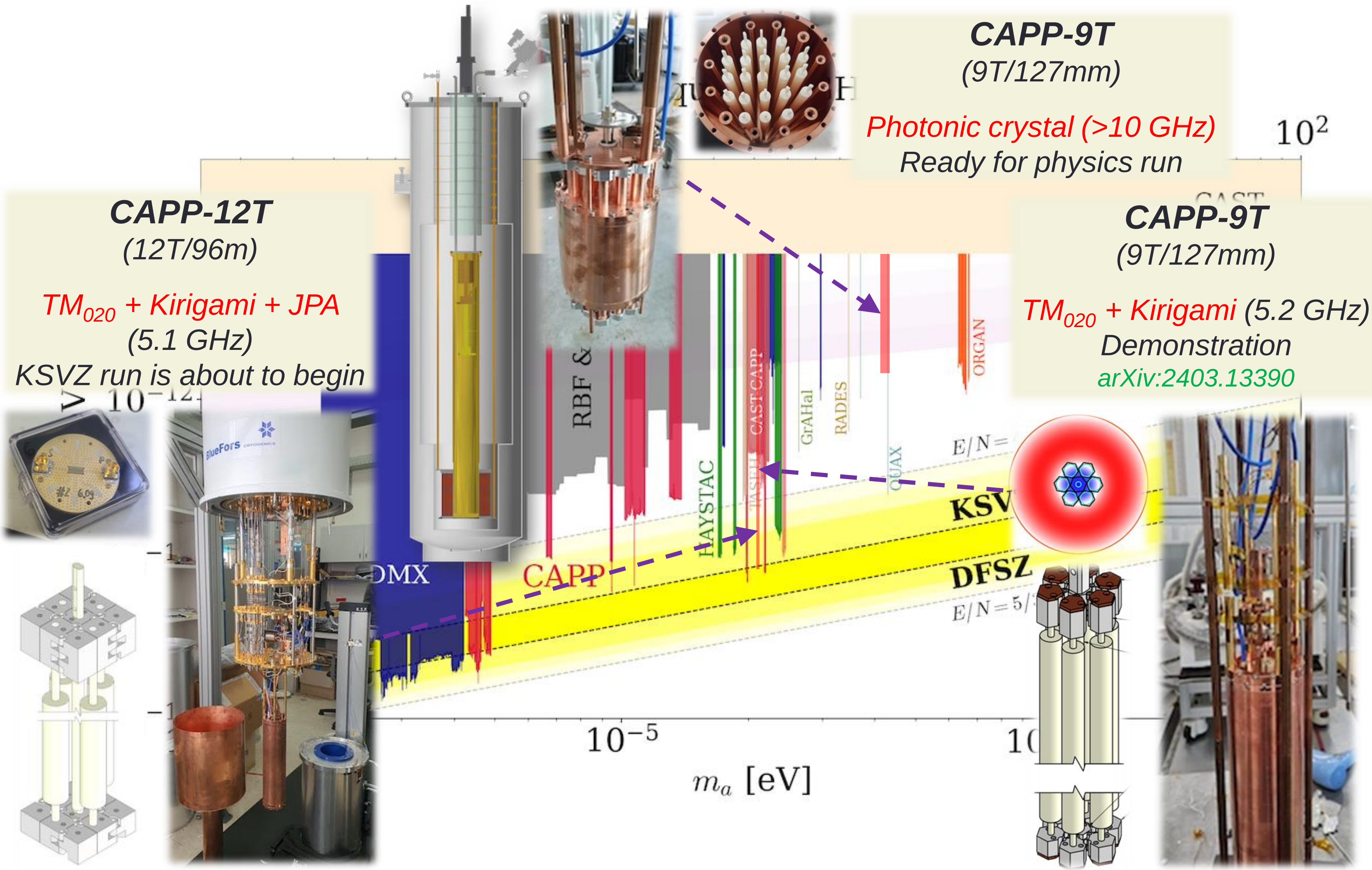


CAPP (III)

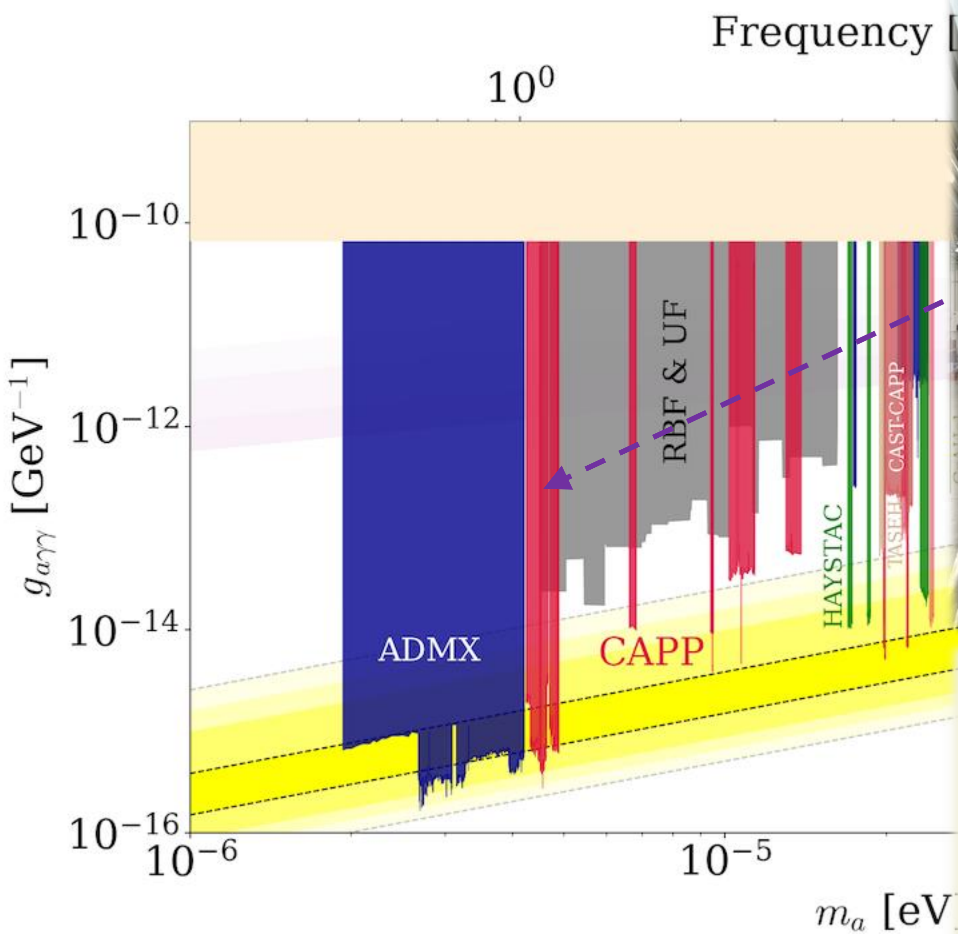
CAPP-9T
_(9T/127mm)_
Photonic crystal (>10 GHz)
Ready for physics run

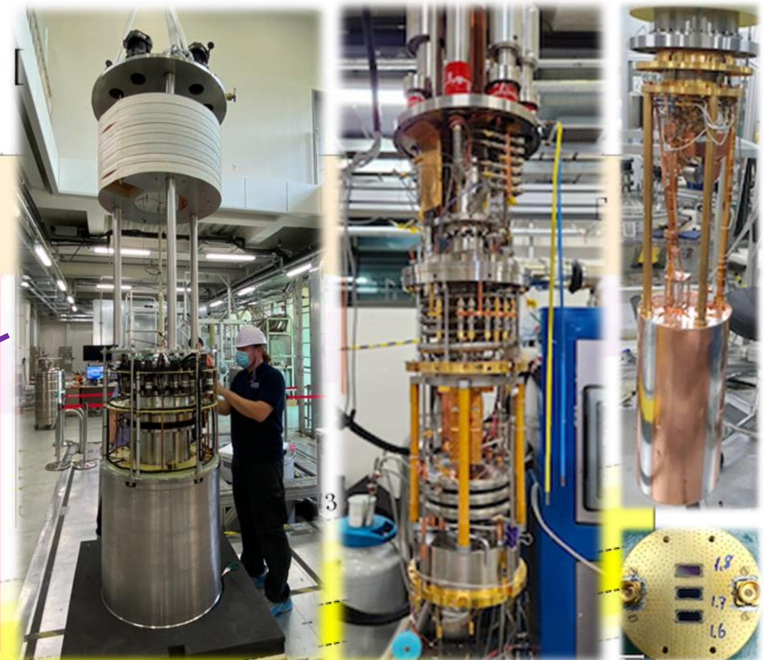
CAPP-12T
_(12T/96m)_
_TM_{020} + Kirigami + JPA_
(5.1 GHz)
KSVZ run is about to begin

CAPP-9T
_(9T/127mm)_
_TM_{020} + Kirigami (5.2 GHz)_
Demonstration
arXiv:2403.13390



CAPP (IV)





CAPP-12TB

(12T/320mm)

$f > 1$ GHz, $V = 37$ L, $T_{sys} < 250$ mK

df/dt ~ 2 MHz/day @ DFSZ

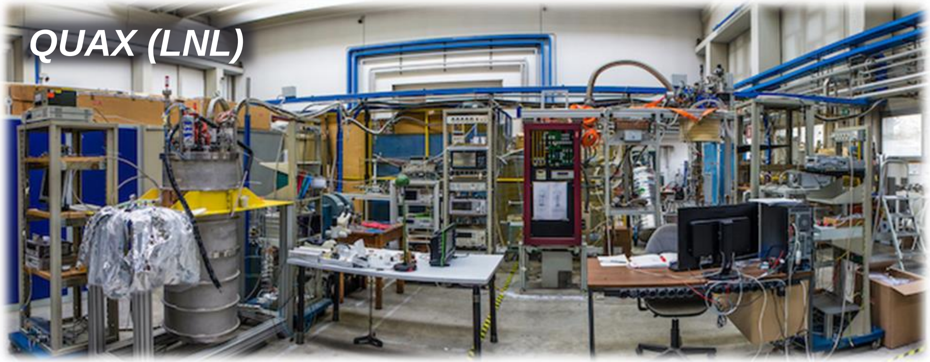
*PRL **130** 071002 (2023)*

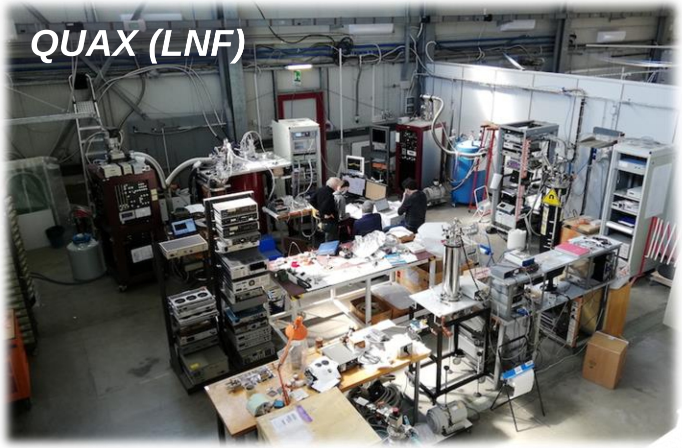
Extended scan (Δf~120 MHz)

arXiv:2402.12892 (PRX)

Preparation for 300 MHz run w/ SC cavity

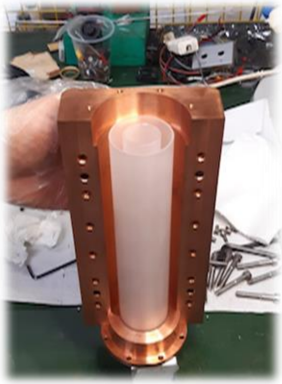
QUAX

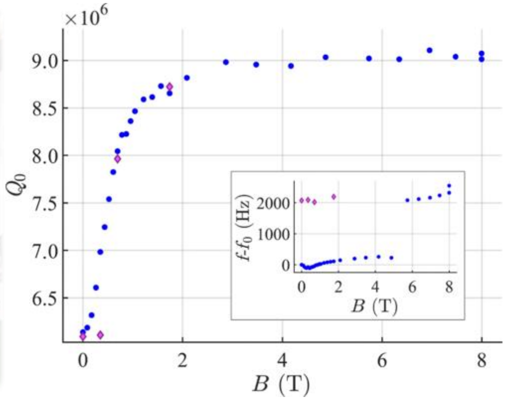


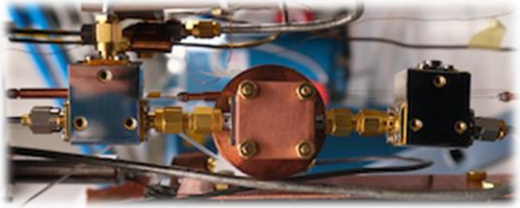


Dielectric cavity

*PRApplied **17** 054013 (2022)*

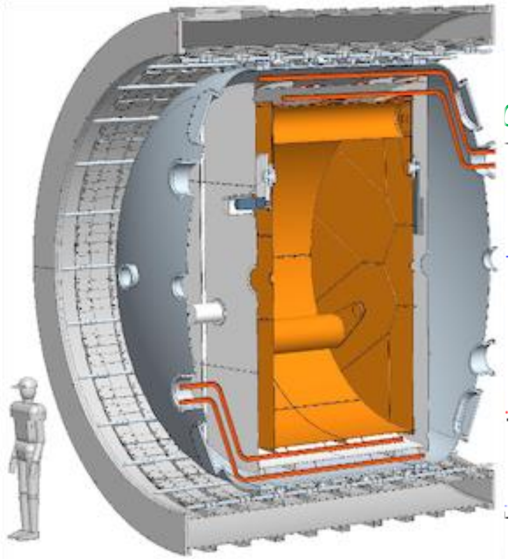






TWPA

*PRD **108** 062005 (2023)*

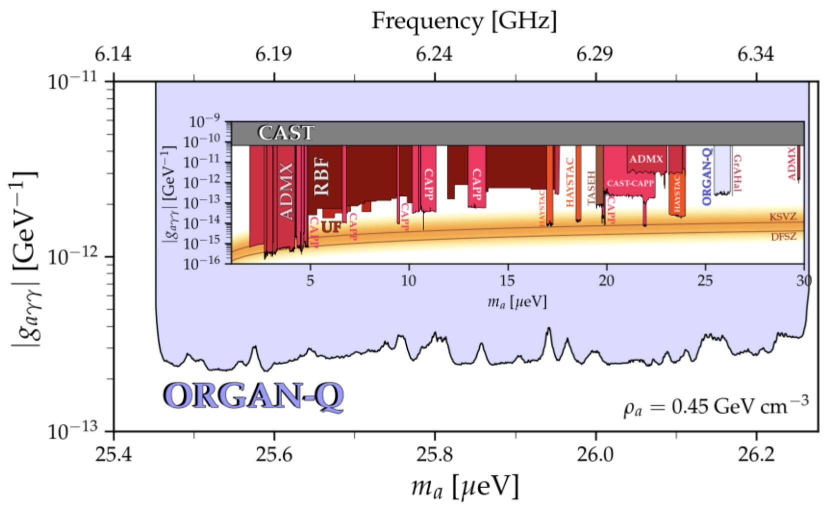


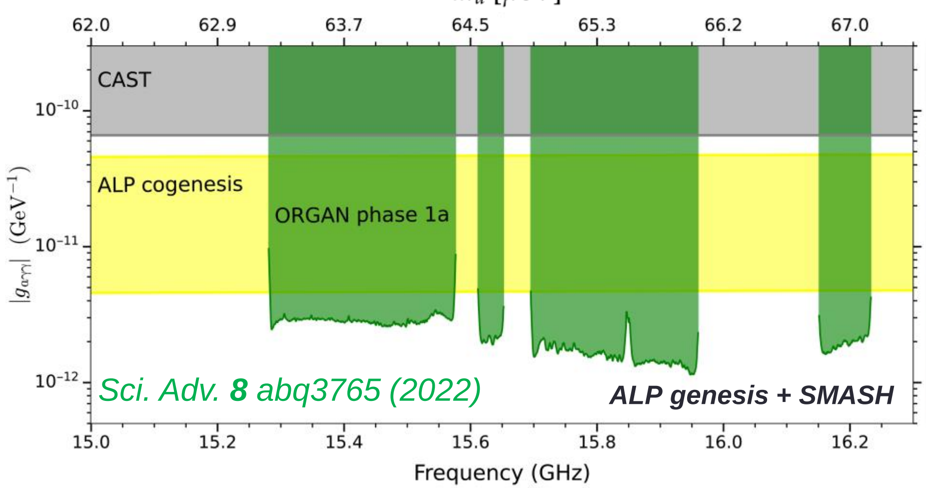
FINUDA

B = 1.1 T
R = 1.4 m

FLASH

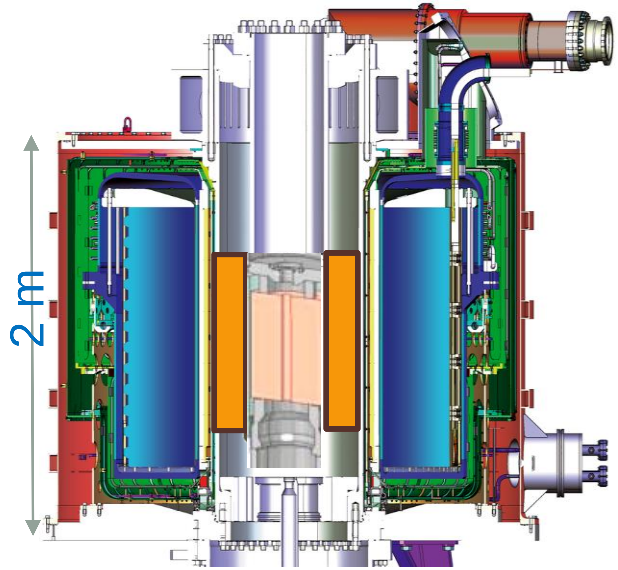
ORGAN


Frequency [GHz]
6.14
6.19
6.24
6.29
6.34
10^{-11}
10^{-12}
10^{-13}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
CAST
ADMX
RBF
UF
CAPP
HAYSTAC
TASEH
CAST-CAPP
ORGAN-Q
GrAHal
KSVZ
DFSZ
m_a [μeV]
ORGAN-Q
$\rho_a = 0.45$ GeV cm^{-3}
25.4
25.6
25.8
26.0
26.2
m_a [μeV]


62.0
62.9
63.7
64.5
65.3
66.2
67.0
CAST
ALP cogenesis
ORGAN phase 1a
$|g_{a\gamma\gamma}|$ (GeV^{-1})
10^{-10}
10^{-11}
10^{-12}
Sci. Adv. **8** abq3765 (2022)
ALP genesis + SMASH
15.0
15.2
15.4
15.6
15.8
16.0
16.2
Frequency (GHz)

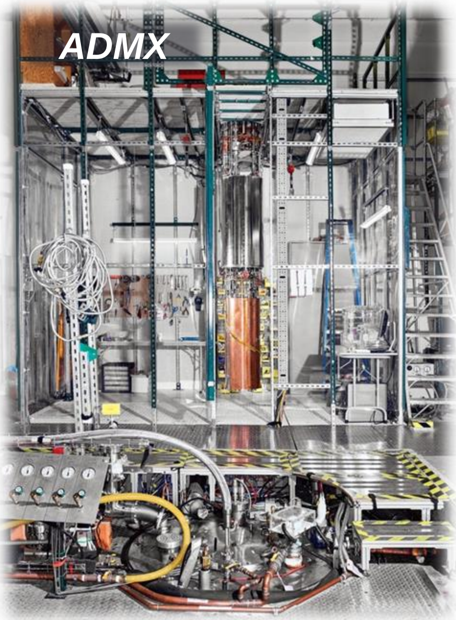

ORGAN

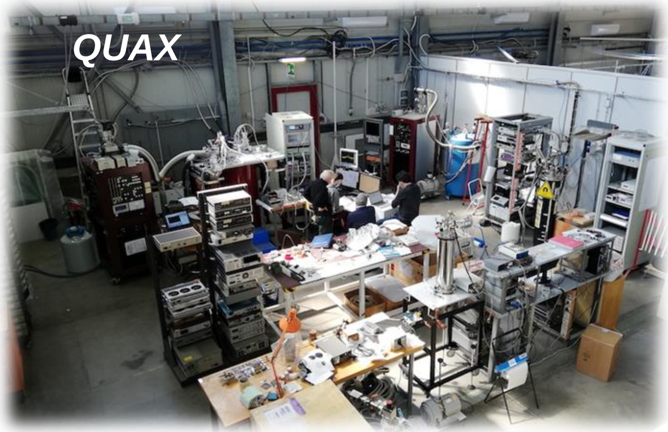
GrAHal



Field [T]	Φ [mm]	B^2V [T^2m^3]	f [GHz]
9	800	40	0.34
17.5	375	6.6	0.79
27	170	3.5	2.67
40	50	0.6	6.76
43	34	0.5	11.5

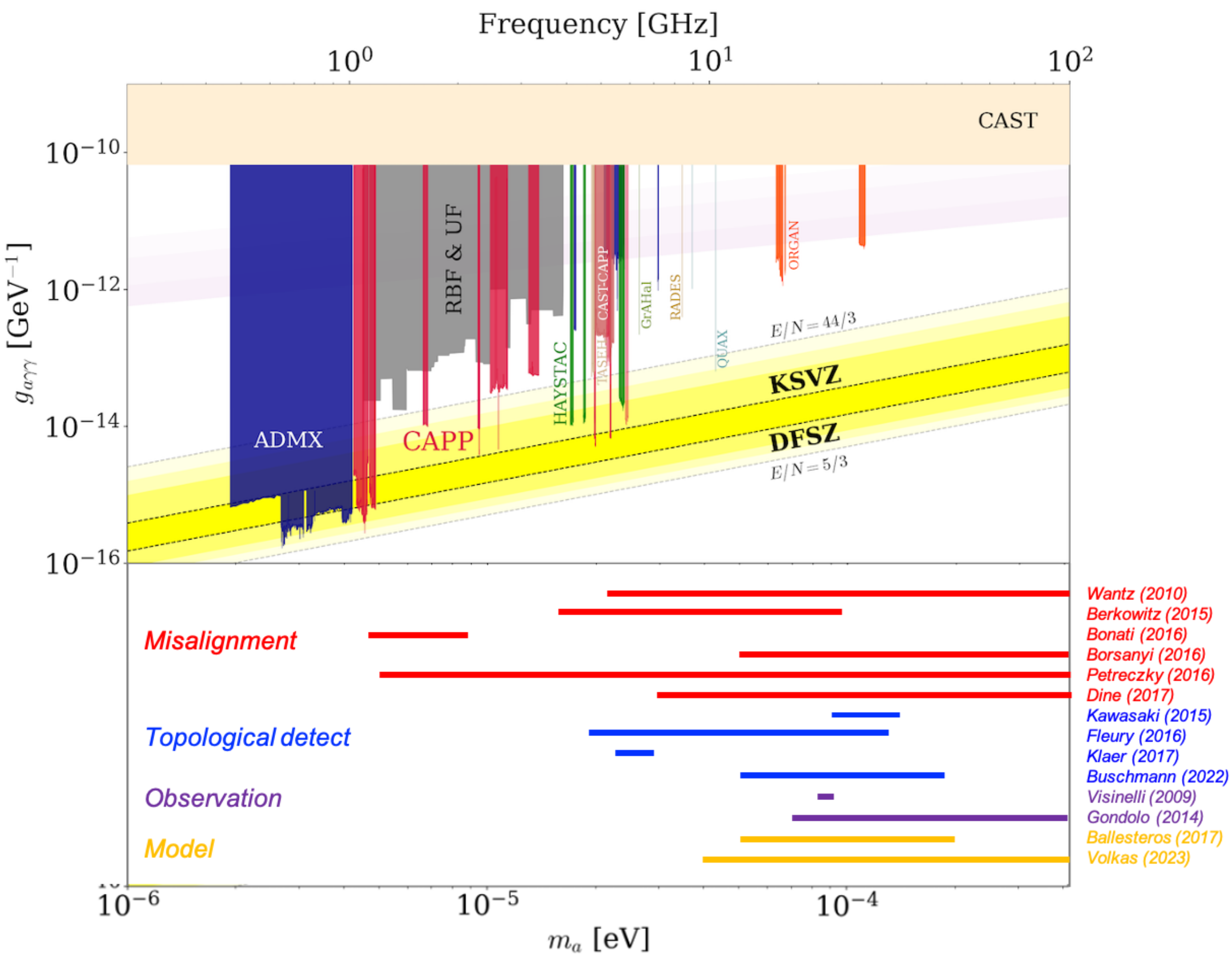
Cavity haloscopes





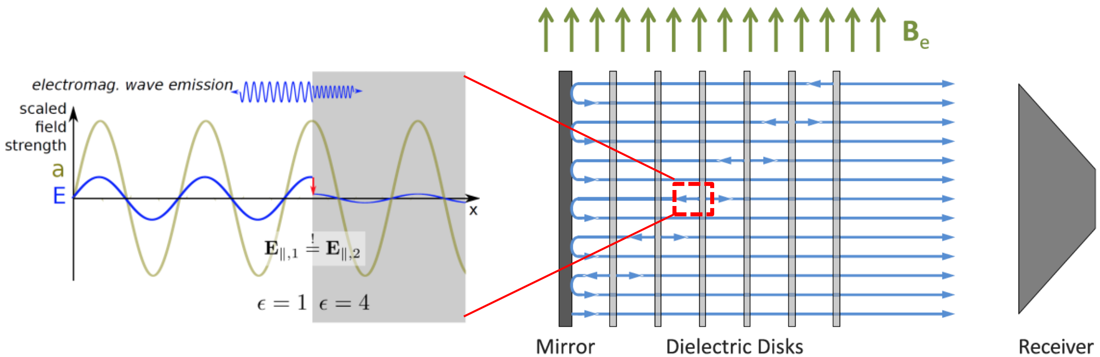
$$1 \lesssim f_a \lesssim 10\ GHz$$

Searches vs. predictions



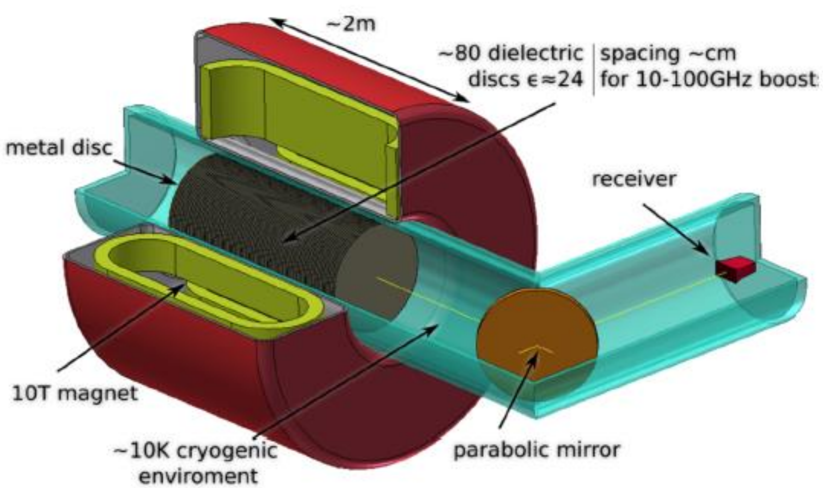
MADMAX

- *Dielectric power booster*

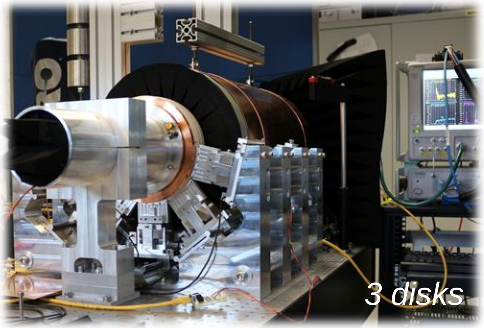


Suitable for high-freq. search

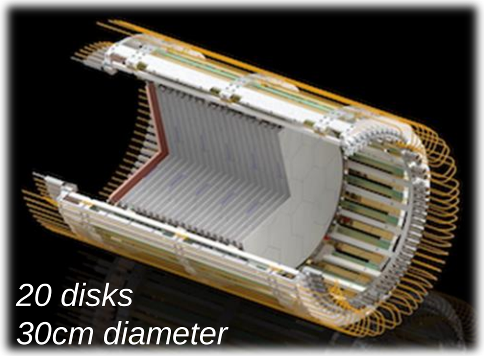
Full scale experiment



Proof-of-concept

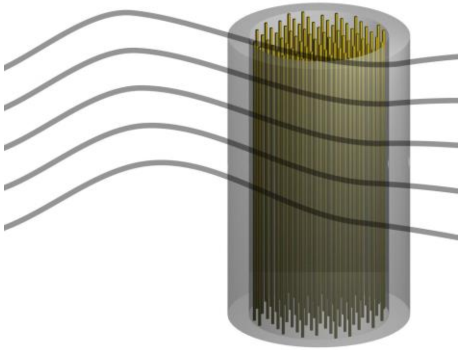


Prototype (2024)



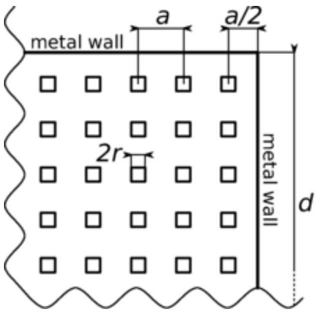
ALPHA

- *Plasma haloscope*
  - *Wire array => plasma metamaterial*



Axion-plasmon interaction

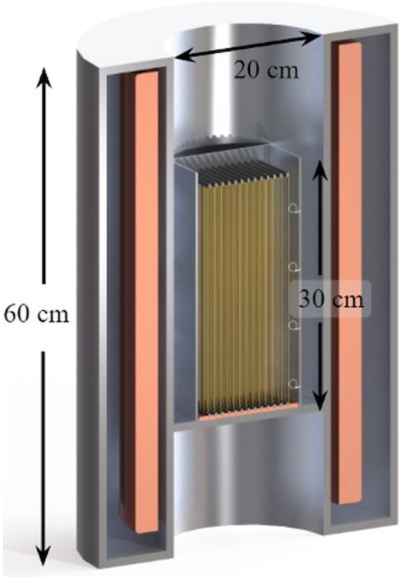
$$\omega_p{}^2 = \frac{2\pi}{a^2 \log(\frac{a}{2r})}$$



- ω_p *independent of the detector size*
- *Large conversion volume at high frequencies*

*PRD **107** 055013 (2023)*

Prototype cavity of 10x10 array

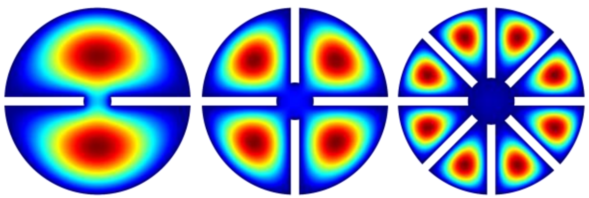


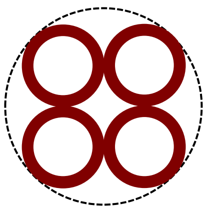
Physics data in 2026

CAPP-HF

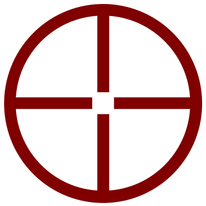
Multiple-cell (pizza)

PLB **777** 412 (2018)

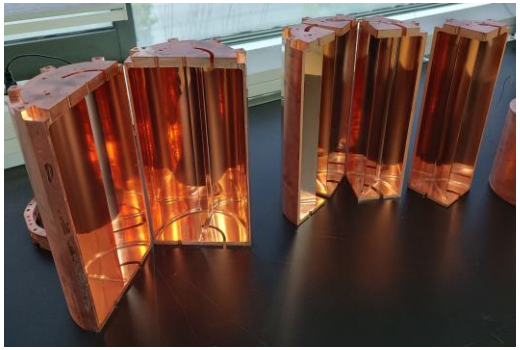




vs.



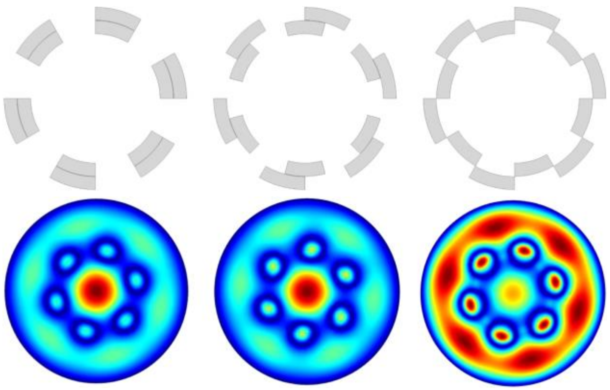
- *Larger volume*
- *Simpler receiver chain*
- *~4 x f_{TM010}*



Higher-mode (wheel)

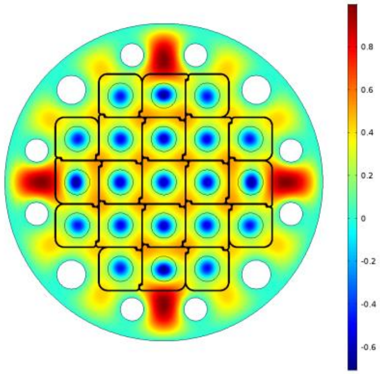
Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM_{010}	1	1	1	0.69
TM_{030}	3.6	1.9	1	0.05

JPG **47** 035203 (2020)



Photonic crystal

PRD **107** 015012 (2022)



- *f ∝ spacing*
- *~10 x f_{TM010}*
- *Boosting effect*

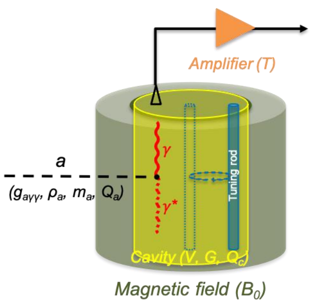
Other haloscopes

- *CAST-CAPP*
  - *Phase-matched cavities, ~20 ueV* — *Nat. Comm. **13** 6180 (2022)*
- *RADES*
  - *HTS cavity, 11.7 T, ~36.5 ueV* — *arXiv:2403.07790*
- *Taiwan Axion Search Experiment with Haloscope*
  - *4.7 GHz, 11 x g_{arr}^{KSVZ}* — *PRL **129** 111802 (2022)*
- *Broadband Reflector Experiment for Axion Detection*
  - *Parabolic reflector, THz region* — *PRL **132** 131004 (2024)*
- *SUPerconducting AXion search*
  - *SC cavity, 14T, 8.4 GHz* — *PoS EPS-HEP2023 (2024) 140*
- *Canfranc Axion Detection Experiment*
  - *90 GHz (W-band), Kinetic Induction Detectors* — *JCAP **11** 044 (2022)*

Summary

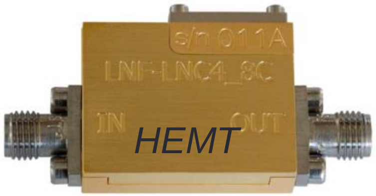
- *Axion could address two fundamental questions*
  - *Strong CP problem & dark matter mystery*

- *Enormous experimental effort to explore the parameter space*
  - *Different technologies targeting at different mass ranges*
- *Haloscope is among the most sensitive search methods*
  - *Resonant effects to enhance detection sensitivity*
  - *New results, new groups and new ideas*

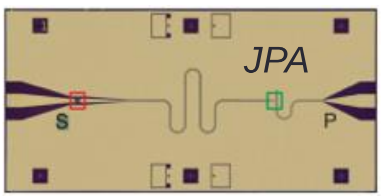


- *Progress is gradual yet unwavering*
  - *Endurance within the scientific community is essential.*
  - *Next few decades are promising to unveil the nature of dark matter*

Microwave signal detection



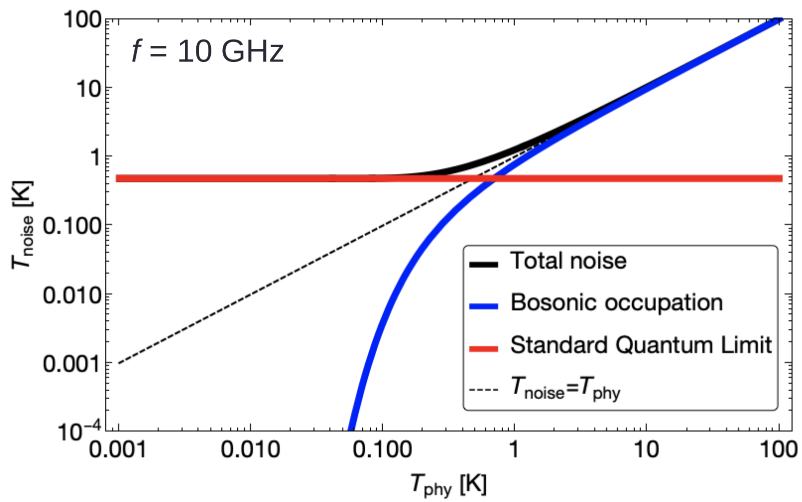
Transistor-based
(T_N ~ K)



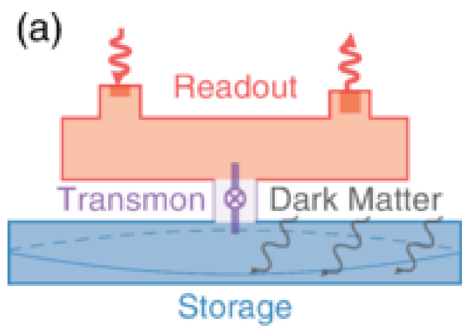
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection vs. photon counting

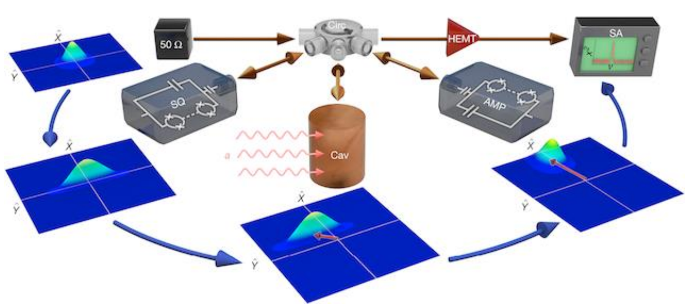
(w/ amplifiers) *(w/ single photon detector)*



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



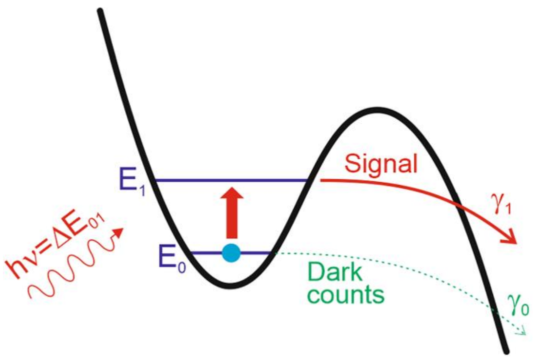
Single photon counting
Not subject to SQL
(T_N << T_{SQL})



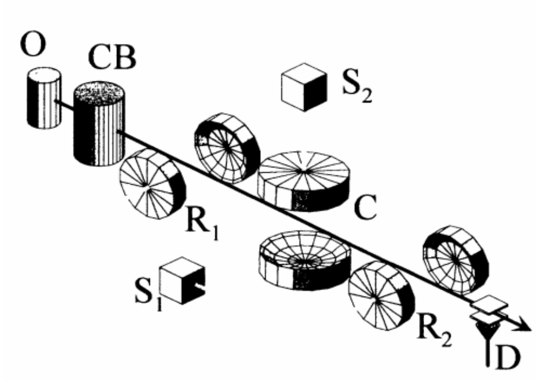
Quantum squeezing (T_N < T_{SQL})

SPD schemes

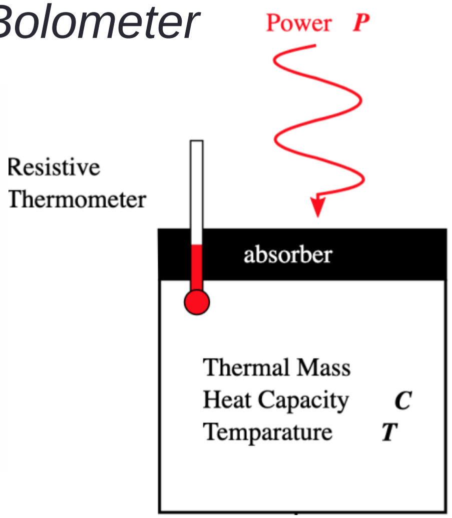
Excitation



Interference



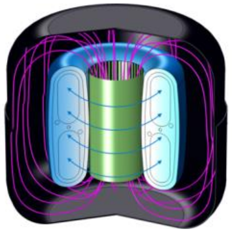
Bolometer

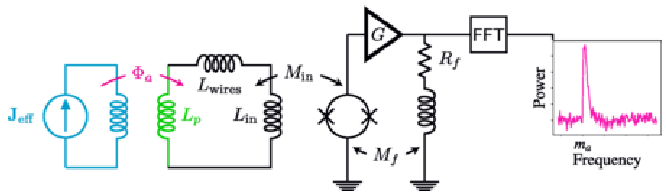


	Excitation	Intereference	Bolometer
Basis	***Qubit***	***JJ-Qubit***	***JJ-TES***
Quantity	*Electron*	*Phase*	*Heat*
Pros	*High sensitivity*	*Non-demolition*	*Wide bandwith* *Robust*
Cons	*Bandwidth vs. Dark cout rate* *Low tunability*	*Narrow bandwidth* *Low tunability*	*High noise level* *Dead (relaxation)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

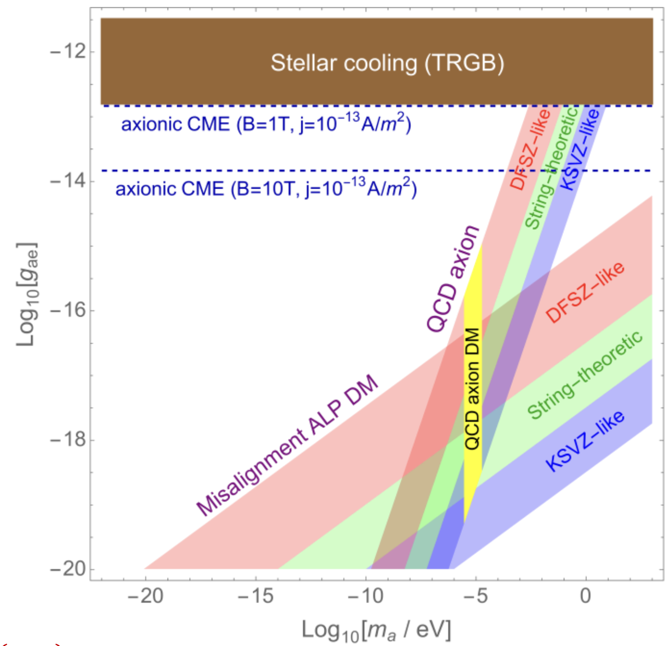
Axionic chiral magnetic effect

- *Low temperature Axion Chiral Magnetic Effect*





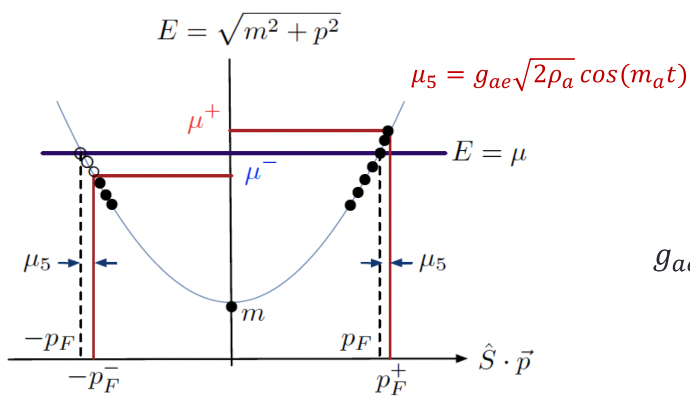
ABRACADABRA		LACME
$-\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	*Coupling*	$g_{ae}\delta_\mu a\psi\gamma^\mu\gamma_5\psi$
Effective current (vacuum)	*Axion*	*Chemical potential (polarized medium)*
$g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\,\boldsymbol{B}$	$\boldsymbol{j}_{(eff)}$	$v_F\frac{e^2}{2\pi}g_{ae}\sqrt{2\rho_a}\cos(m_a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



μ_5 *adds* p *to* e^- *along* $\hat{S}$

$\boldsymbol{B}$ *polarizes* e^-

Helicity imbalance => current flow



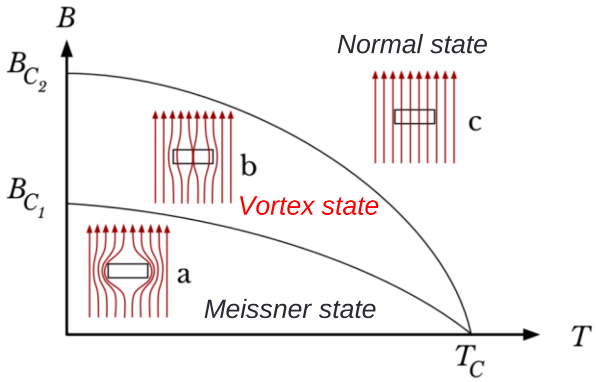
Chiral medium

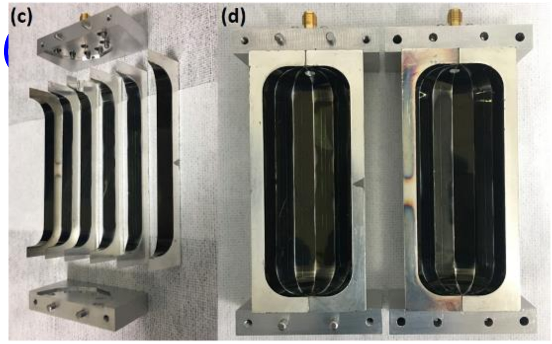
$$g_{ae} \simeq \begin{cases} \mathcal{O}(1) & \text{DFSZ-like models} \\ \mathcal{O}(10^{-4} \sim 10^{-3}) & \text{KSVZ-like models} \\ \mathcal{O}(10^{-3} \sim 10^{-2}) & \text{string-theoretic axions} \end{cases}$$

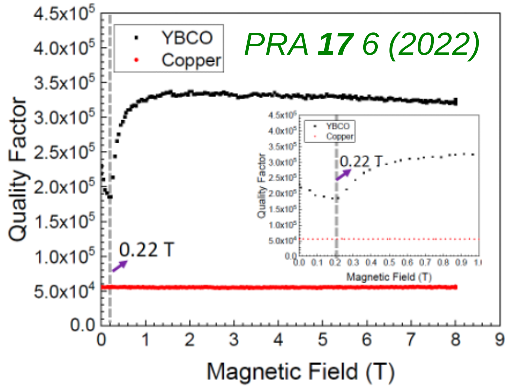
HTS cavities

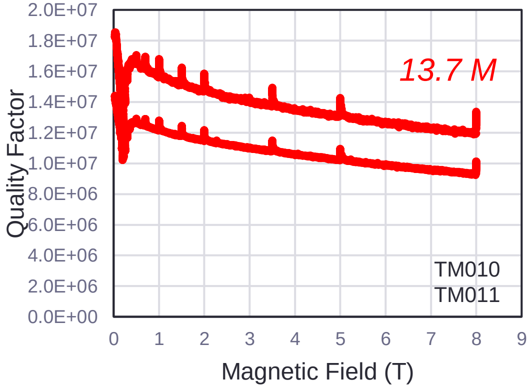
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

High-Temp. Superconductor (

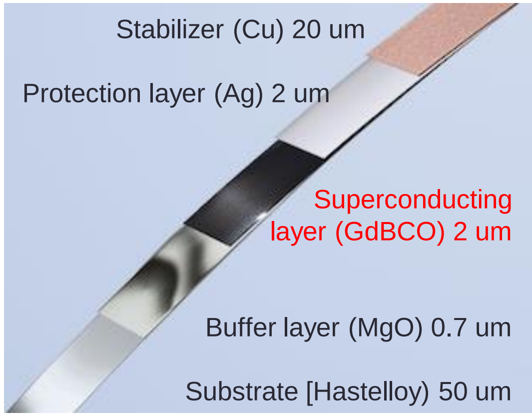








ReBCO HTS tapes (2D)



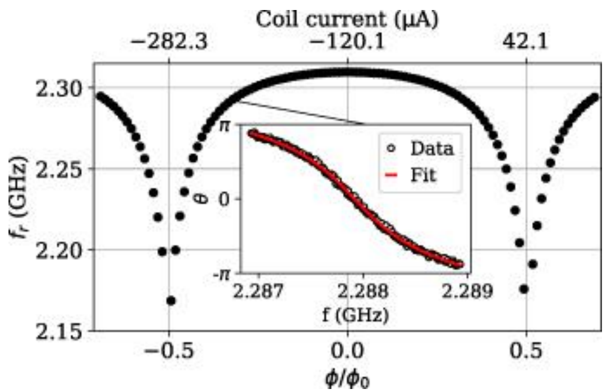
+ 3D body = SC cavity

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***

QNL amplification

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

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

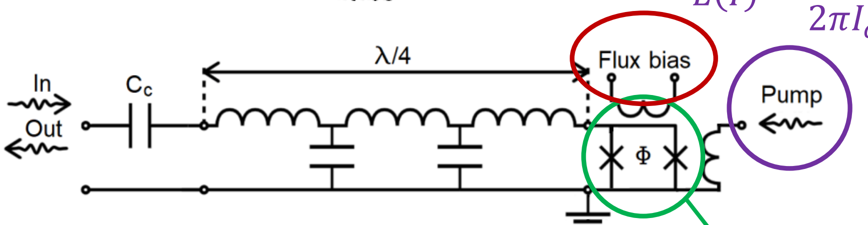


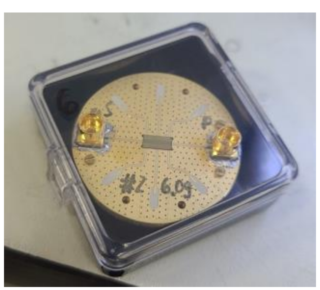
Frequency tuning

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

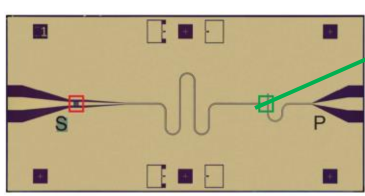
Parametric amplification

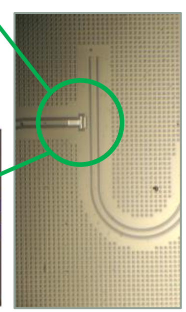
$$L(I) = \frac{\Phi_0}{2\pi I_c}\left[1 + \frac{1}{2}\frac{I^2}{I_c^2}\right]$$





SQUID
(nonlinear inductance)





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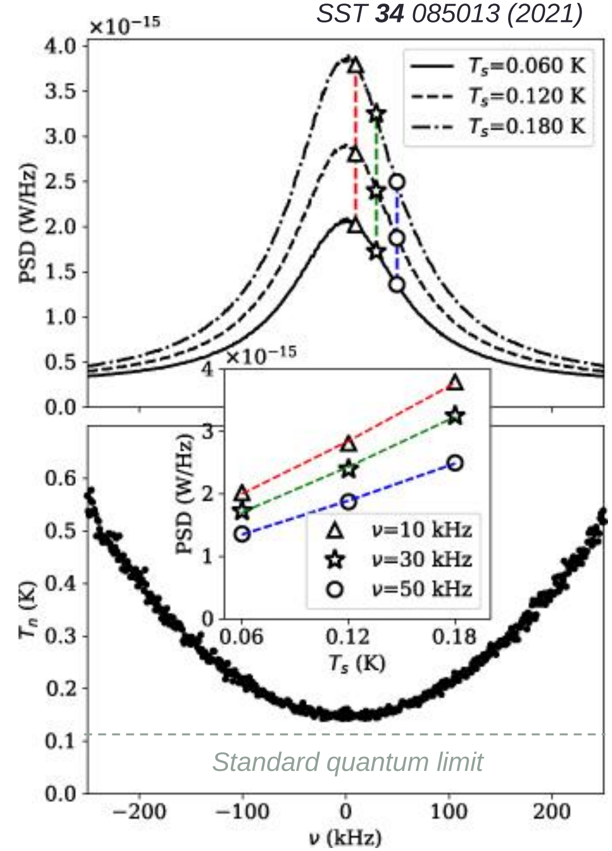
*SST **34** 085013 (2021)*



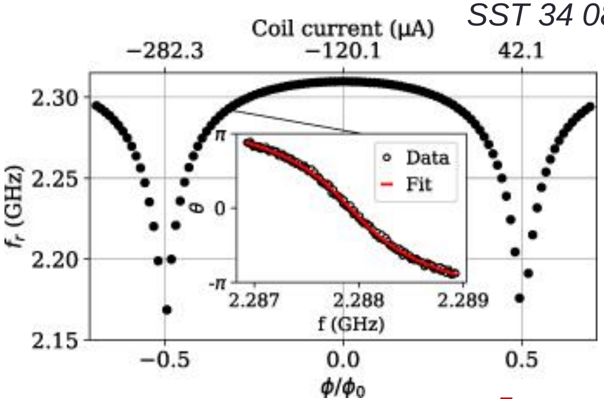
Best performance
in axion search application

QNL amplification

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

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

SST 34 085013 (2021)



Best performance!

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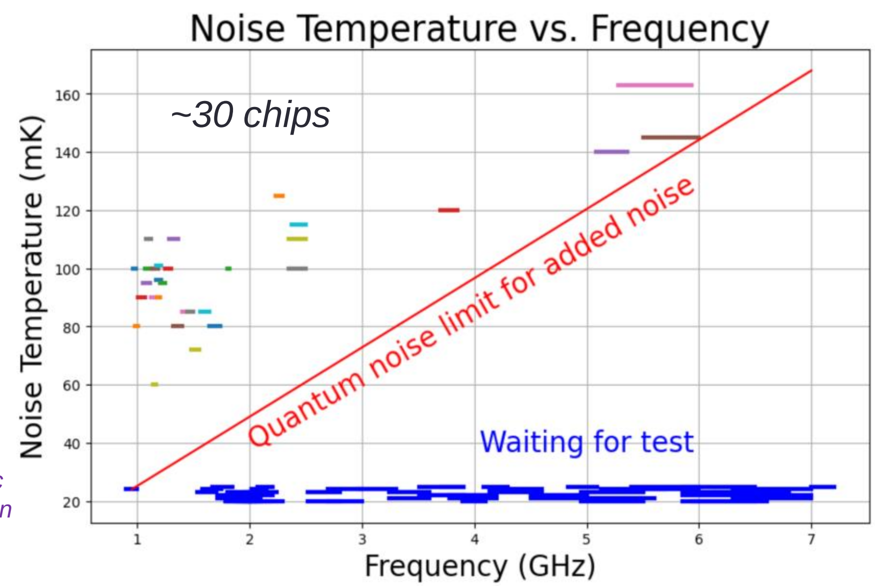
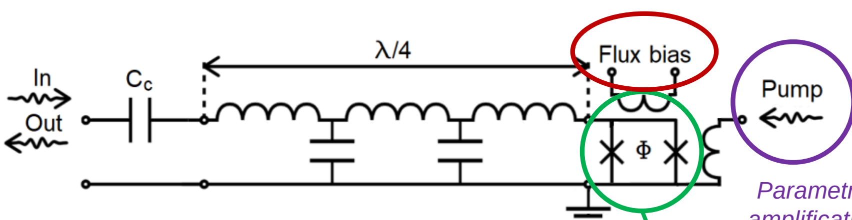
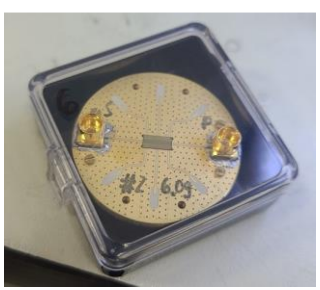


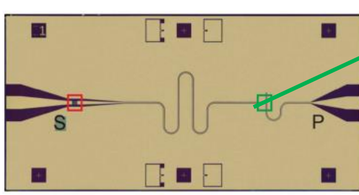
Frequency tuning

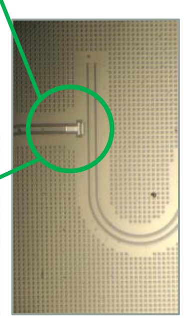


Parametric amplification



SQUID (nonlinear inductance)





But, … limited bandwidth!

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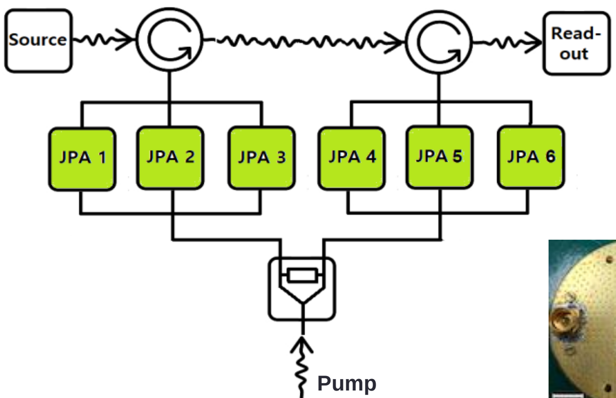
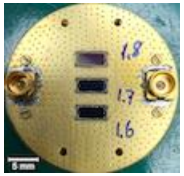
QNL amplification

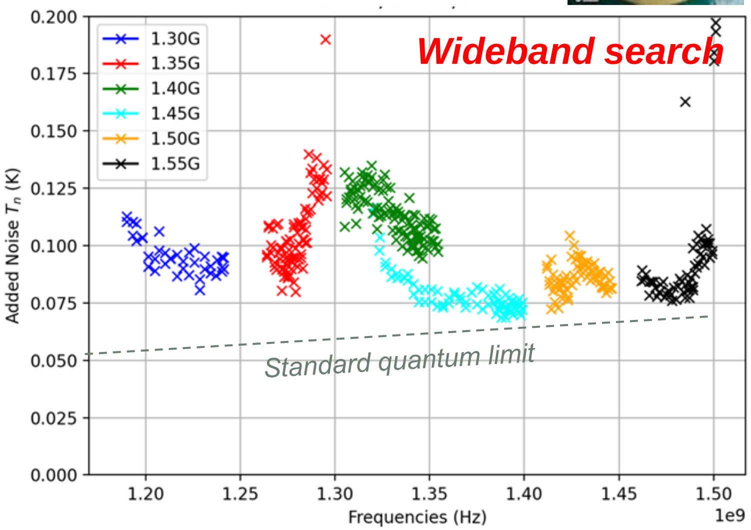
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

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

Parallel-Serial configuration







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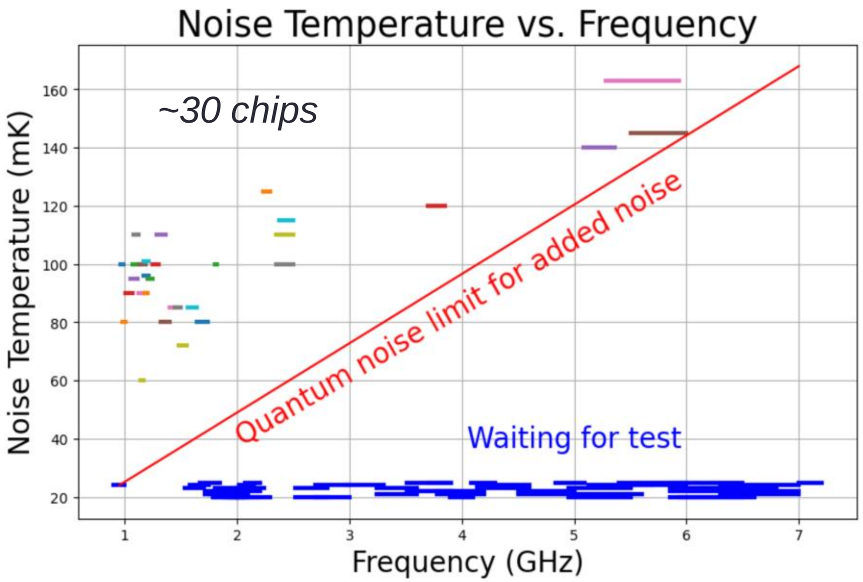

But, … limited bandwidth!

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