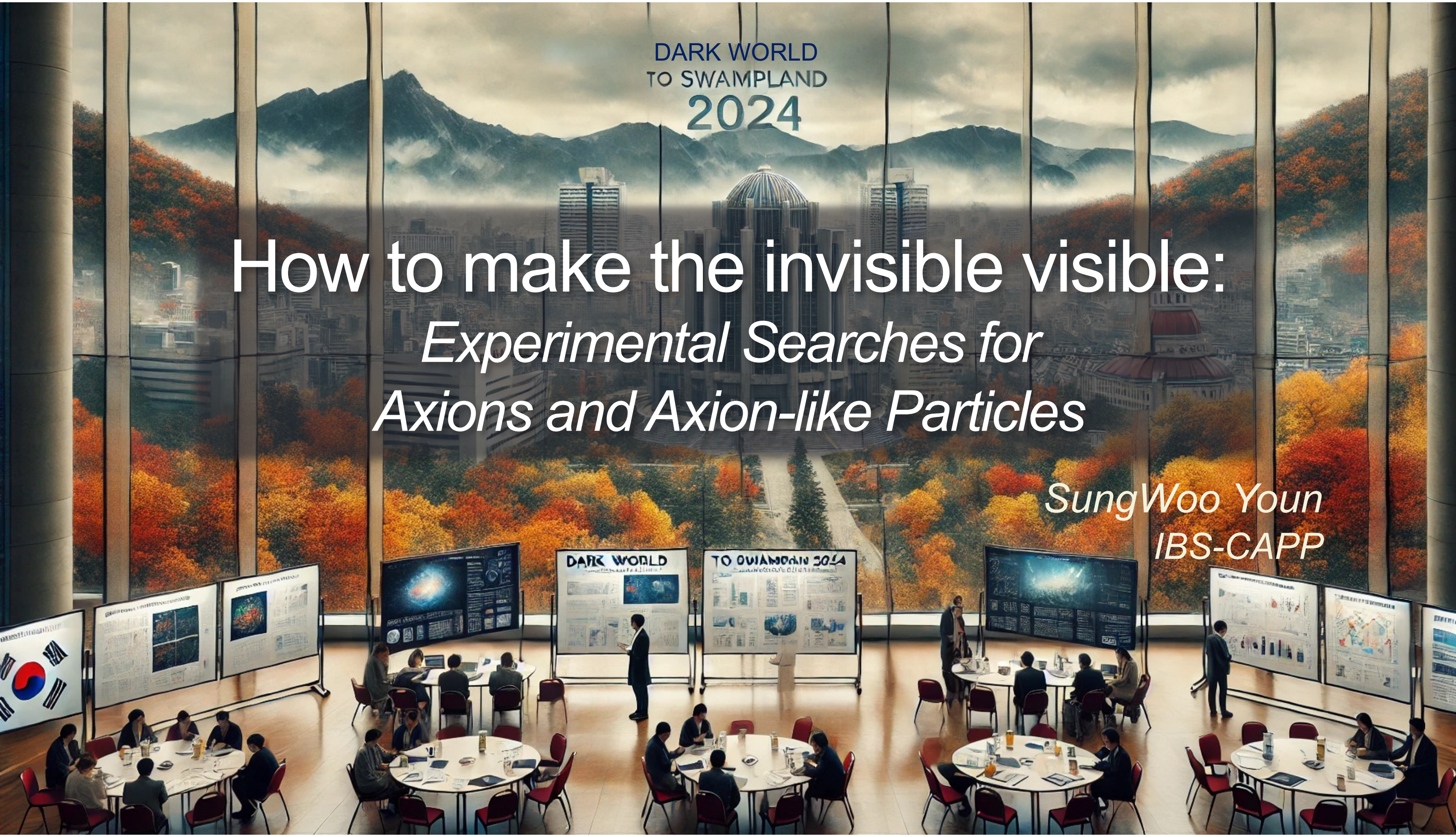


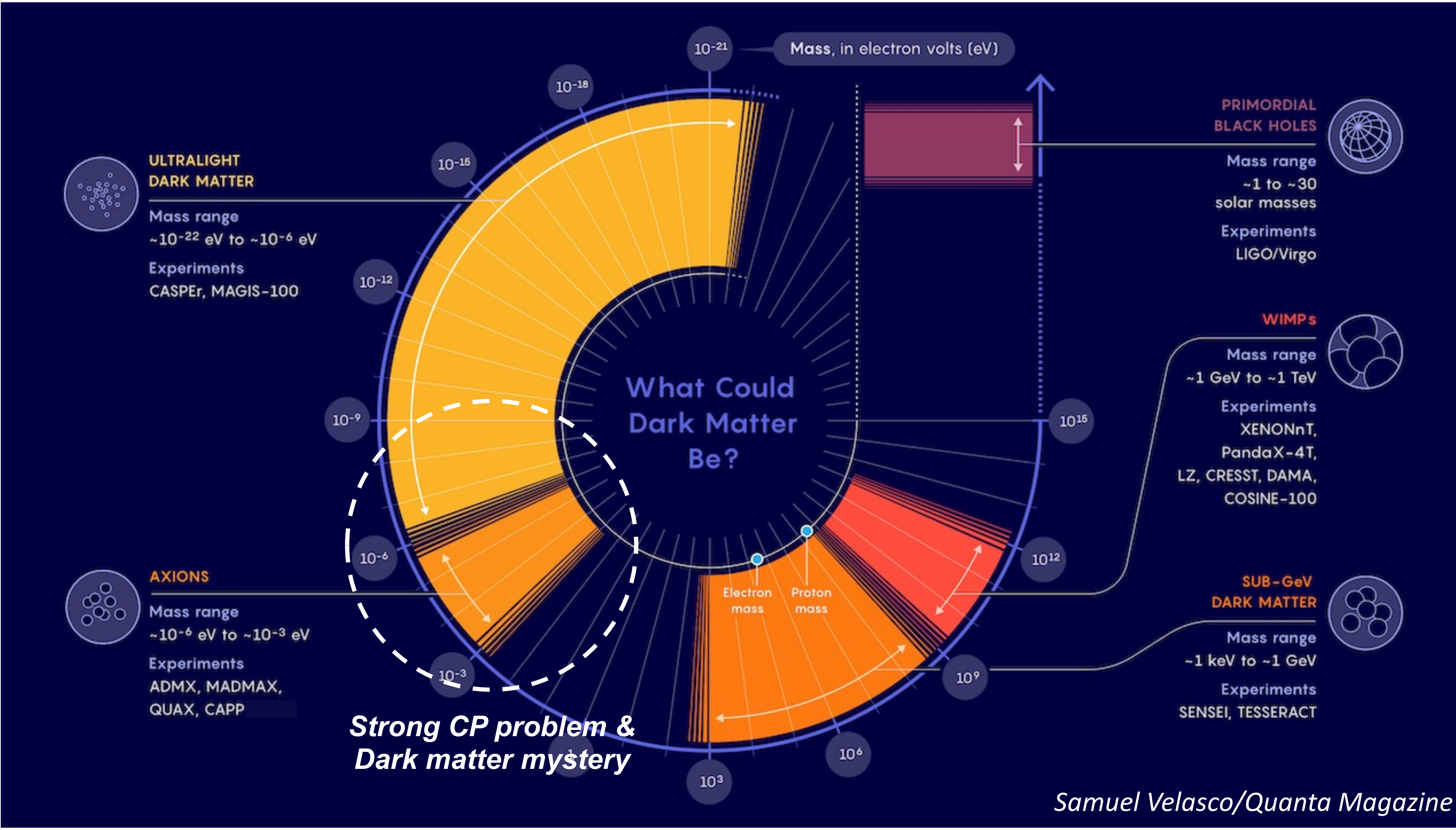
How to make the invisible visible:

Experimental Searches for Axions and Axion-like Particles

SungWoo Youn
IBS-CAPP

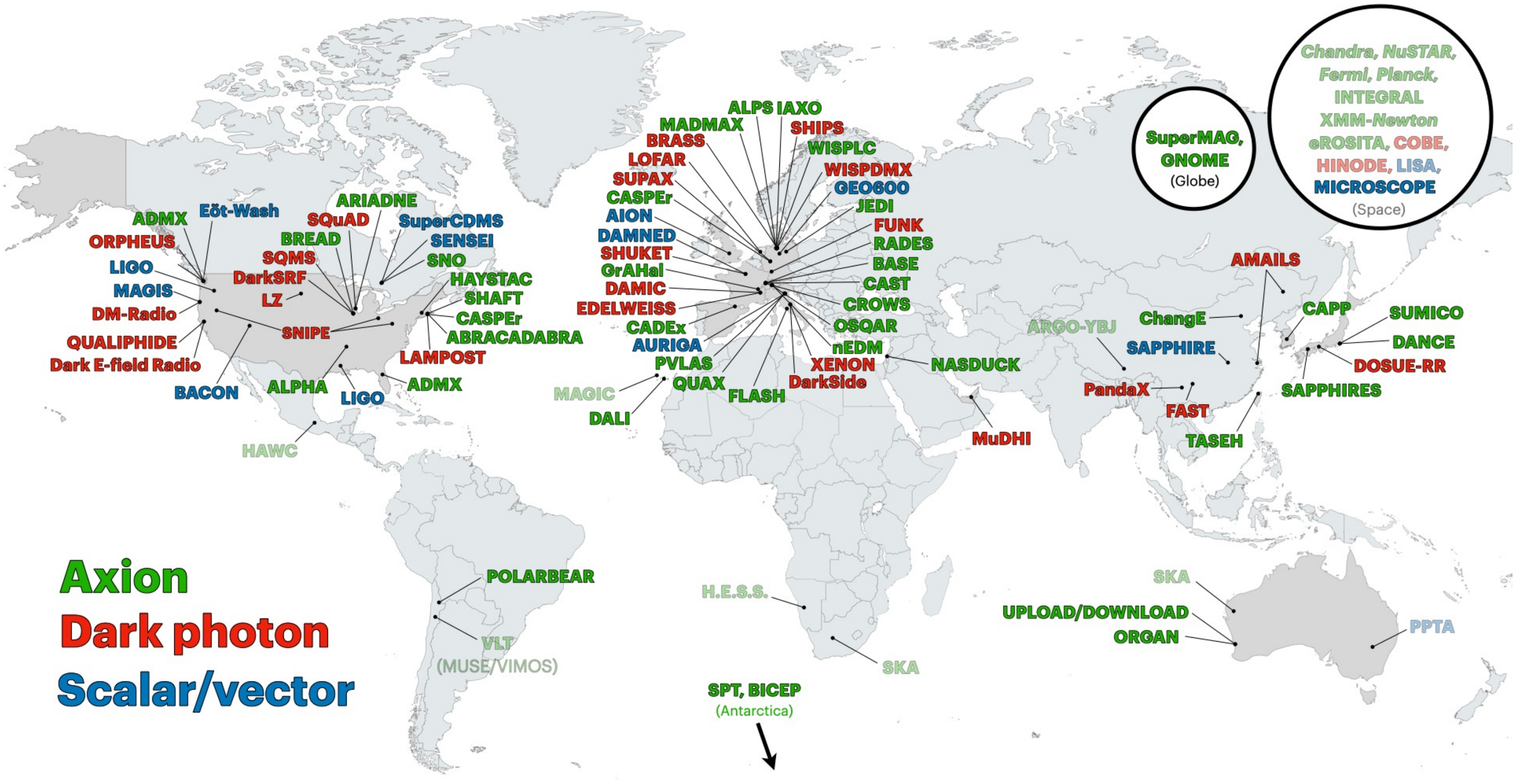
Dark World to Swampland 2024: 9th IBS-IFT Workshop
2024.11.05 Institute for Basic Science, Daejeon

Dark matter business expanding



Experiment map

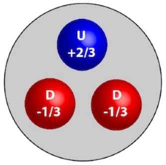
C. O'Hare (2020)



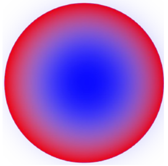
Axion dark matter

- *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

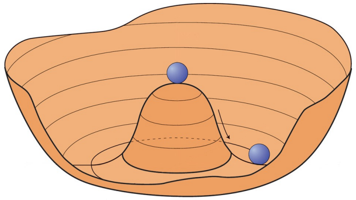


vs.

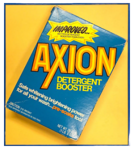


$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \implies \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$

Spontaneous Symmetry Breaking

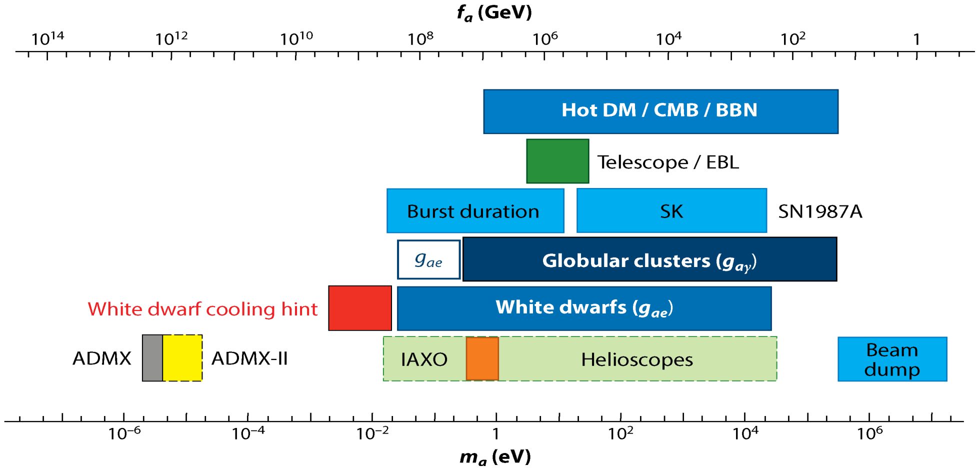


$a(x) = \theta \times f_a$ *at minimum*



Goldstone boson

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



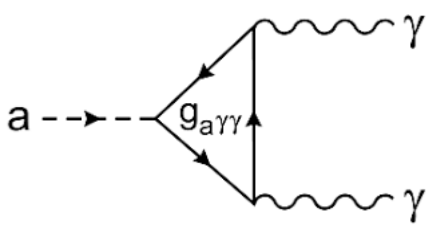
Annu. Rev. Nucl. Part. Sci. 65 485 (2016)

Axion models and detection

- *Axion coupling to SM*

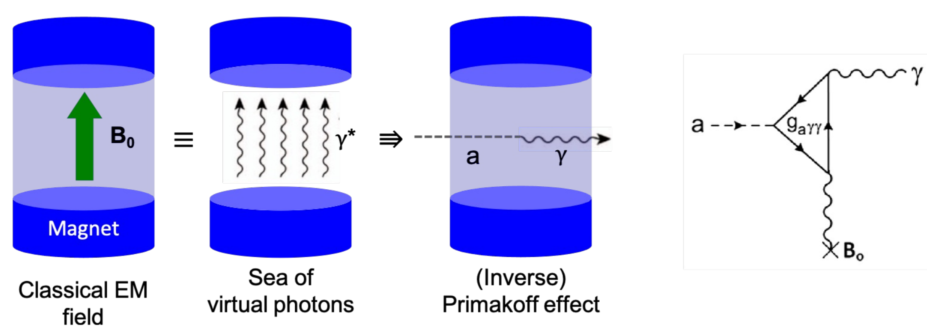
	Photons	Fermions	nEDMs
Hamiltonian	$g_{a\gamma\gamma} a\mathbf{E}\cdot\mathbf{B}$	$g_{aff}\nabla a\cdot\hat{\mathbf{S}}$	$g_{EDM} a\hat{\mathbf{S}}\cdot\mathbf{E}$
Observable	*Photon*	*Spin precession*	*Oscillating EDM*
Detection	*Power spectrum, photon counter, …*	*Magnetometer, NMR, …*	*NMR, polarimeter,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

- *Axion models*

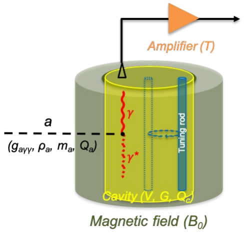


PQWW	DFSZ	KSVZ
SM ferminons		*BSM fermions*
2 Higgs	*2Higgs+singlet*	*Higgs+singlet*
Standard ($f_a \sim v_{EW}$)	***Invisible ($f_a \gg v_{EW}$)***	
Ruled out	*Benchmark*	

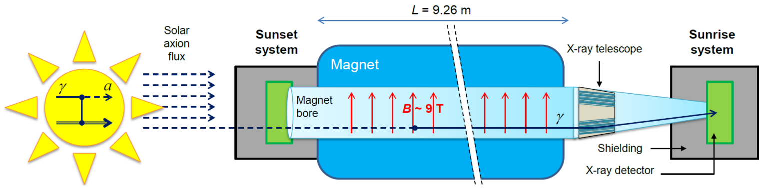
- *Detection principle*
  - *Sikivie effect (1983)*
    - *Macroscopic Primakoff*



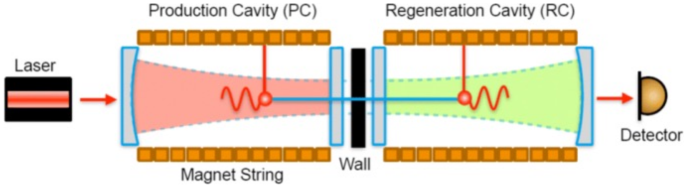
Search strategies



- *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



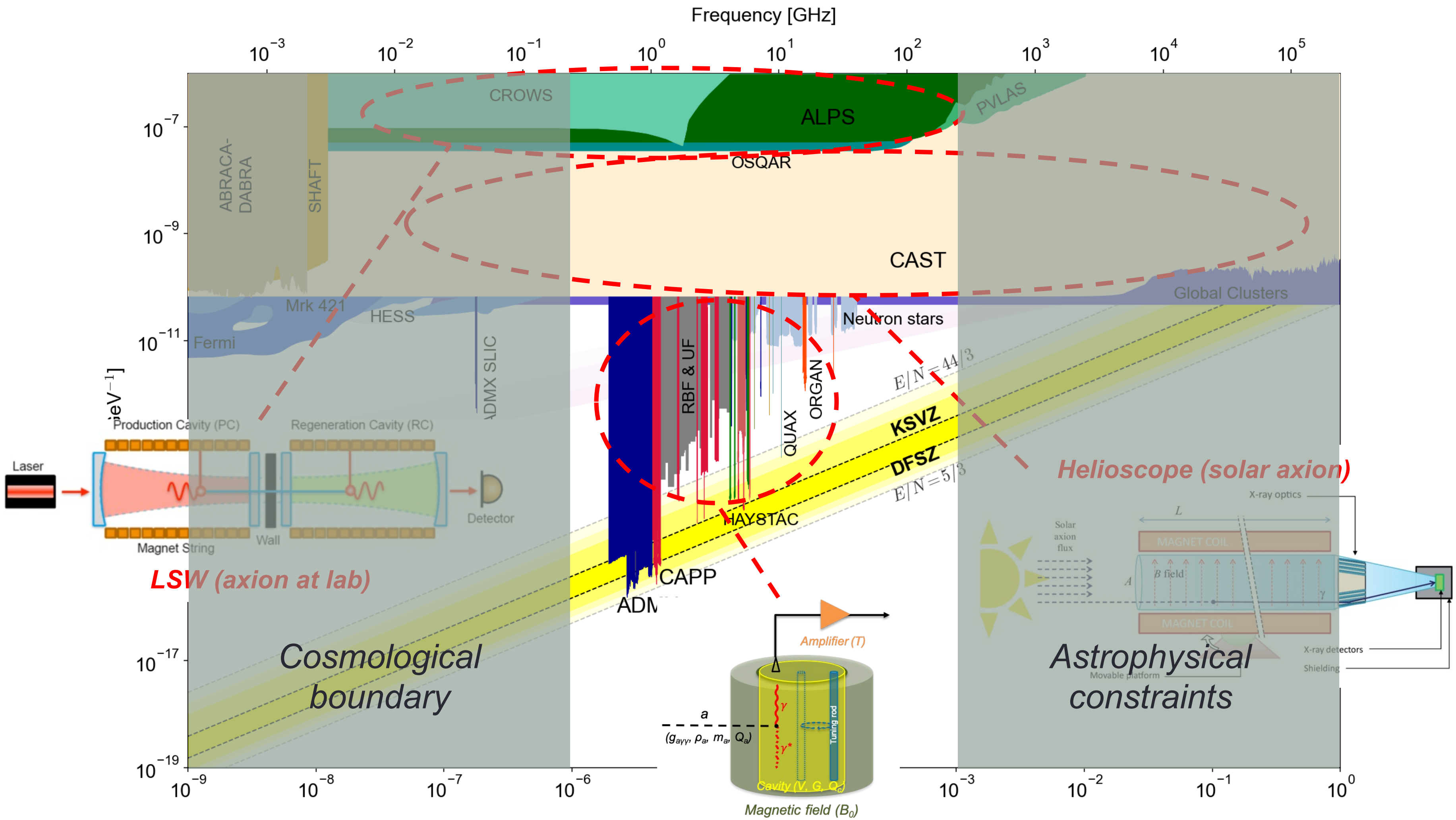
- *Helioscope*
  - *Solar axion*
  - $$\mathcal{P}_{a\to\gamma} \approx 2.6\times10^{-17} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\, GeV^{-1}}\right)^2 \left(\frac{B_0}{10\, T}\right)^2 \left(\frac{L}{10\, m}\right)^2 \mathcal{F}, \quad \mathcal{F} = \frac{2(1-\cos qL)}{(qL)^2}$$
    ~10 photons/day



- *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 photons/day

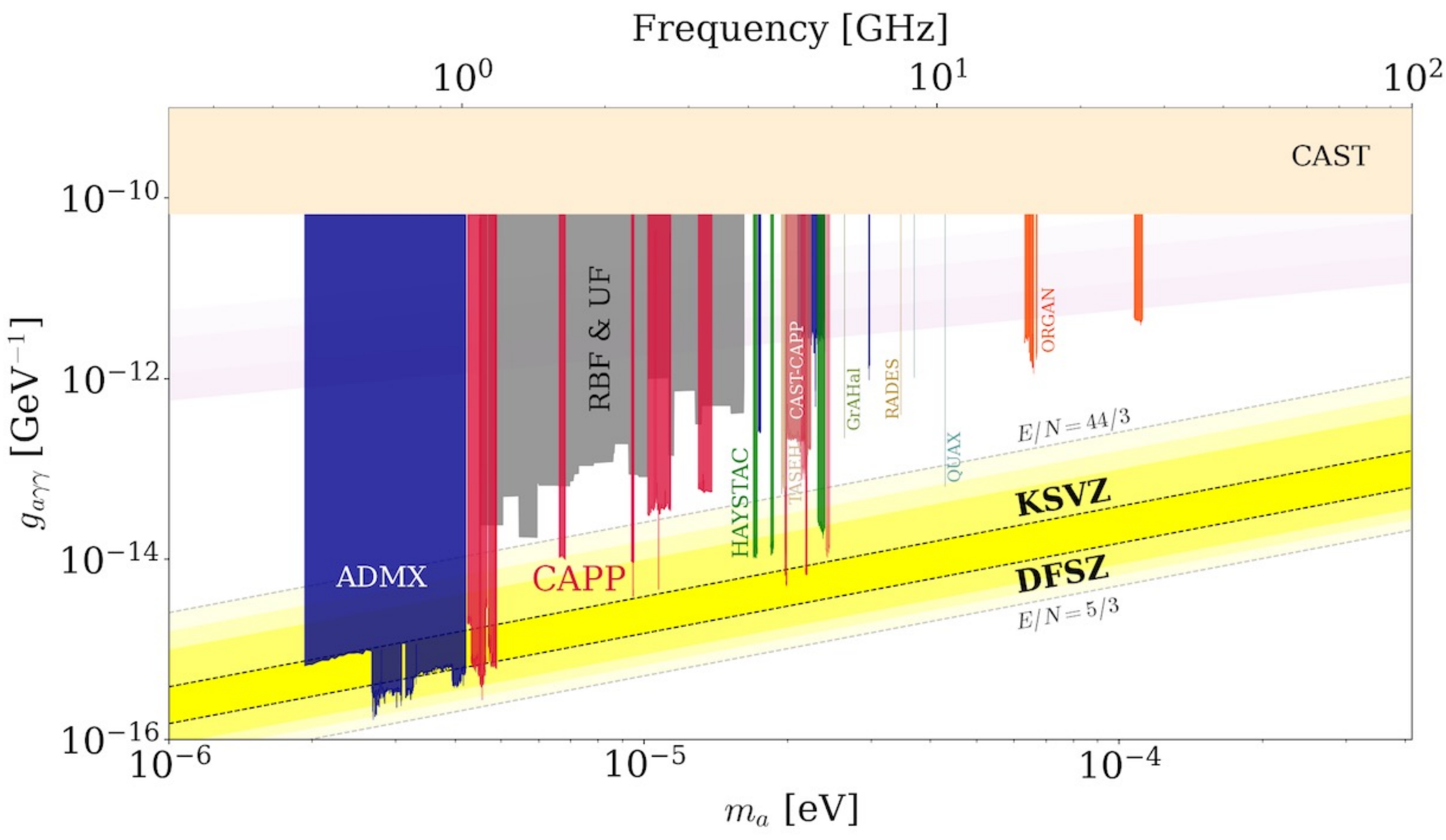
Axion searches

1 GHz = 4.2 ueV

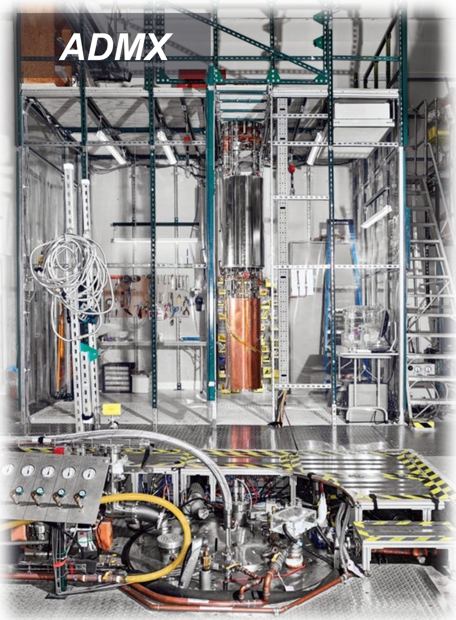


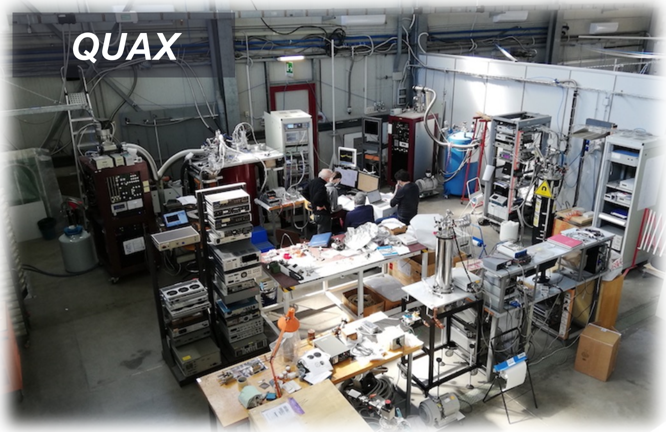
Haloscope Searches

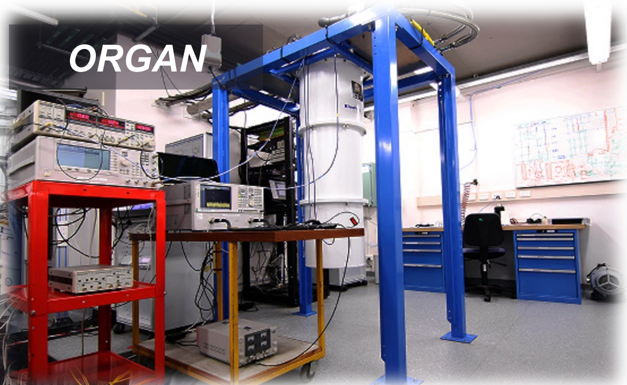
Haloscope searches

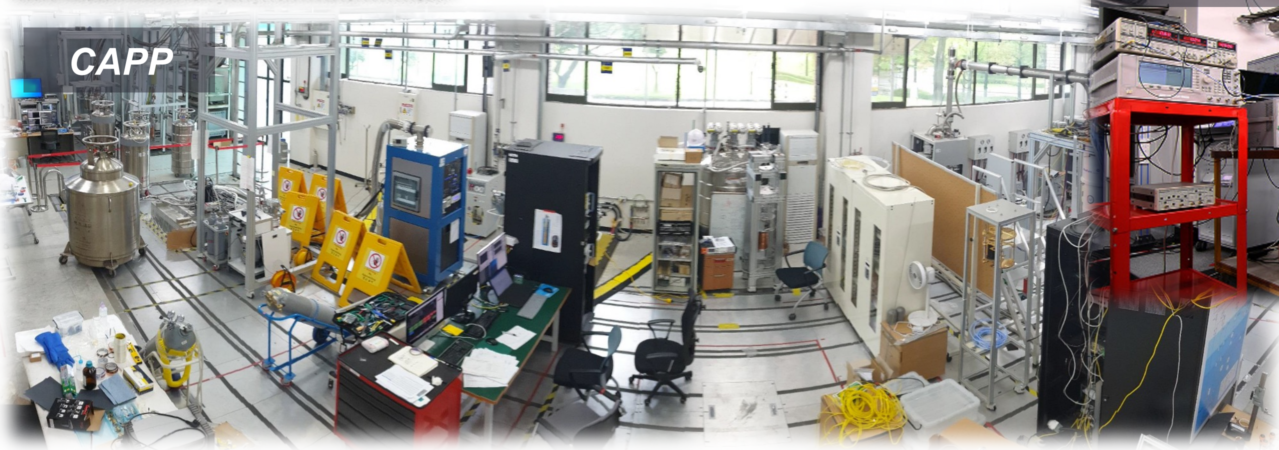


Cavity haloscopes

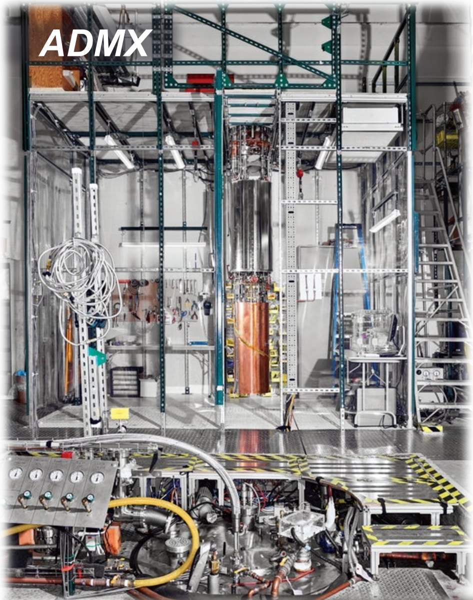


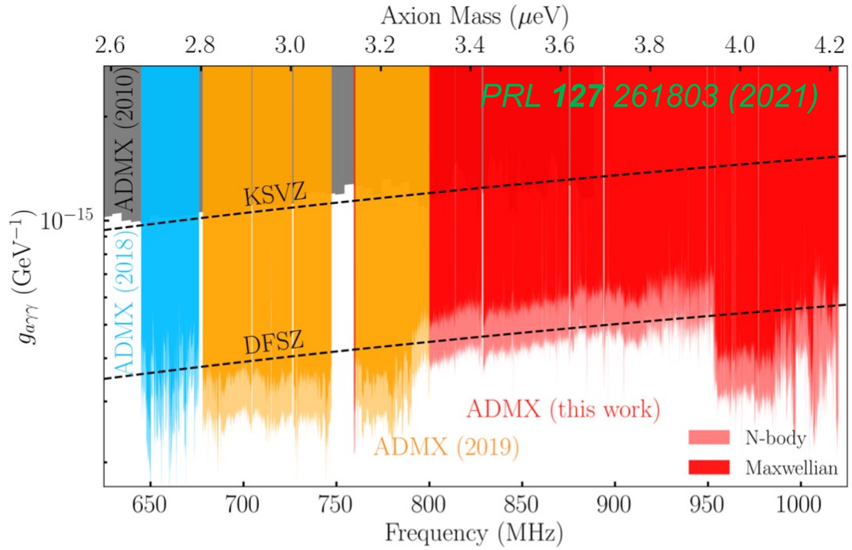


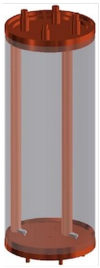




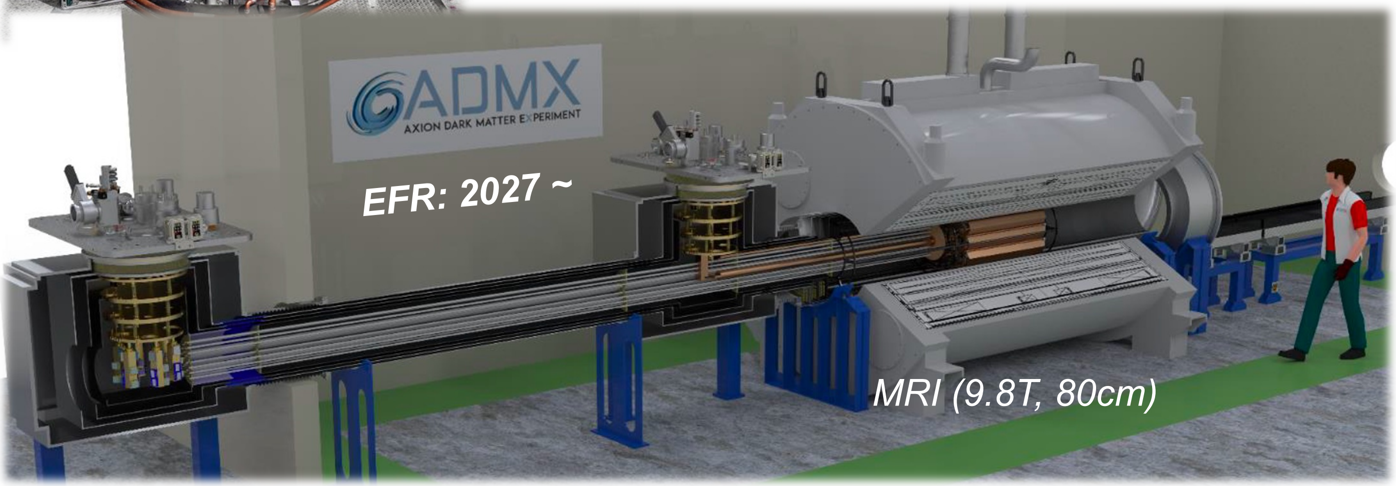
ADMX

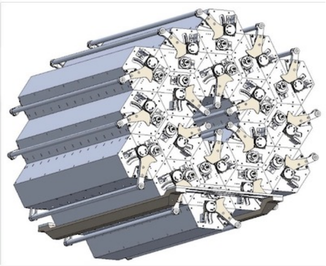





Run 1A-C

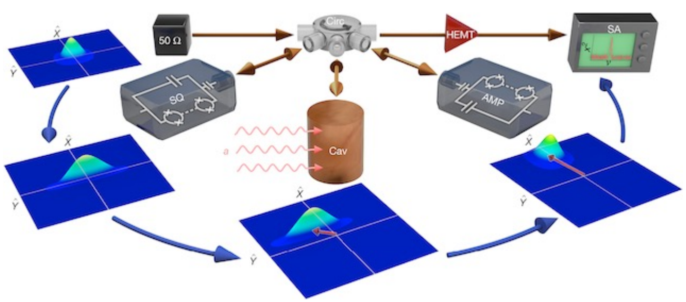

Run 2




EFR

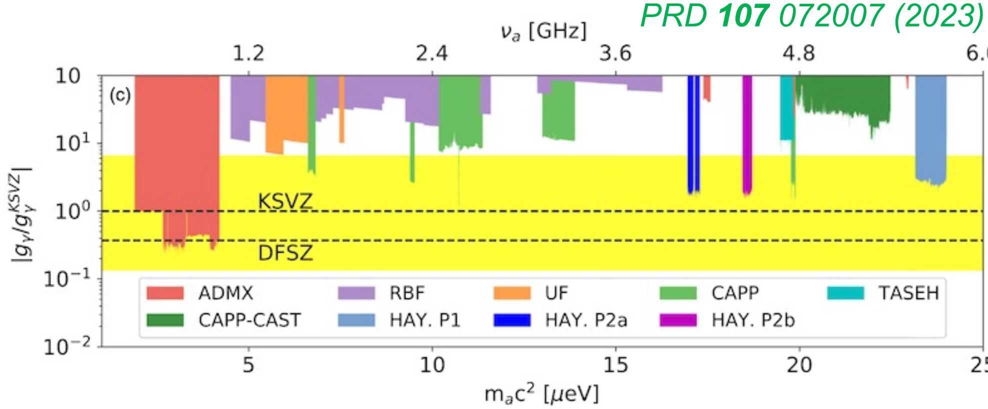
HAYSTAC

Nature ***590*** *238 (2021)*



Quantum squeezing ($T_N < T_{SQL}$)

PRD ***107*** *072007 (2023)*



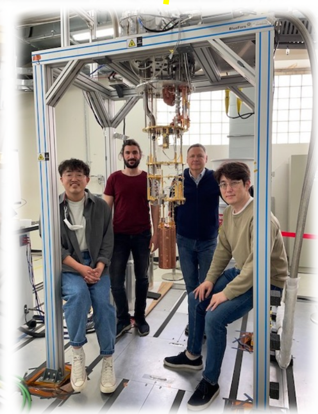
IBS-CAPP

CAPP-9T

CAPP-12TB

CAPP-12T

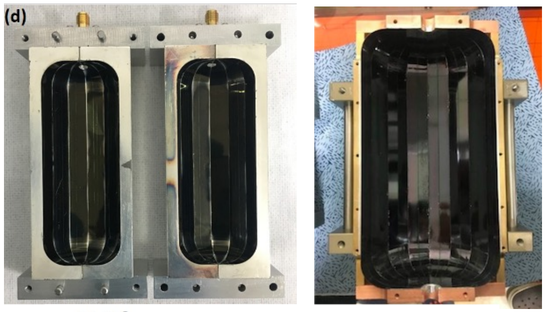
CAPP-8T

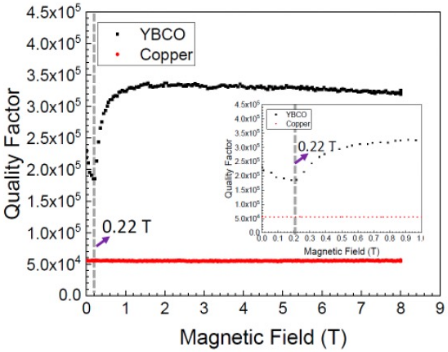


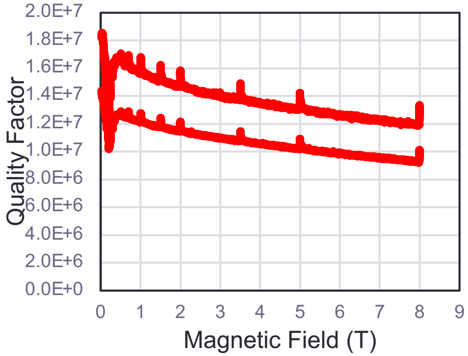
CAPP-8TB

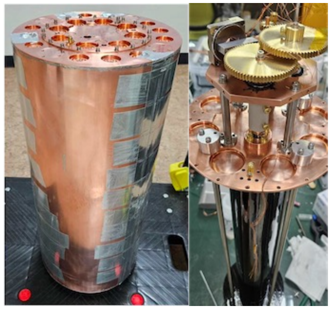
HTS cavities

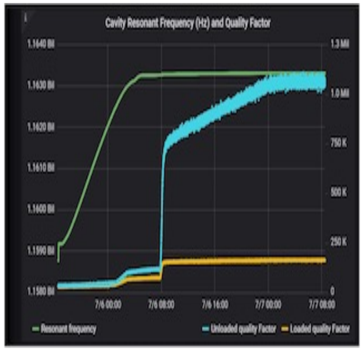
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$









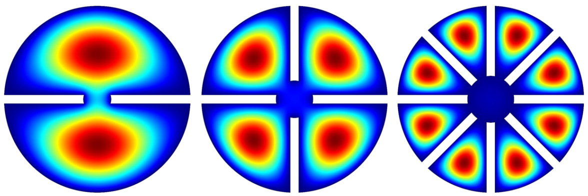


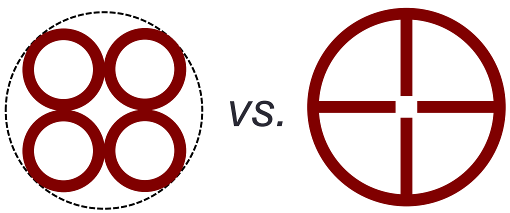
	1^{st} Gen.	2^{nd} Gen.	3^{rd} Gen.		4^{th} Gen.
Material	***Y**BCO*	***Gd**BCO*	***Eu**BCO + APC*		***Eu**BCO + APC*
Manufacturer	*AMSC*	*Theva*	*Fujikura*		*Fujikura*
Volume [L]	*0.3*	*1.5*	*1.5*	*0.2*	*37*
Freq. [GHz]	*6.9*	*2.3*	*2.2*	*5.4*	*1.2*
Q @ 8 T	***0.33 M***	***0.5 M***	***3.5 M***	***13 M***	***1.1 M***
Application	*Demostration*	*Axion search*	*AQN search*	*Axion search*	*Axion search*

High-frequency approaches

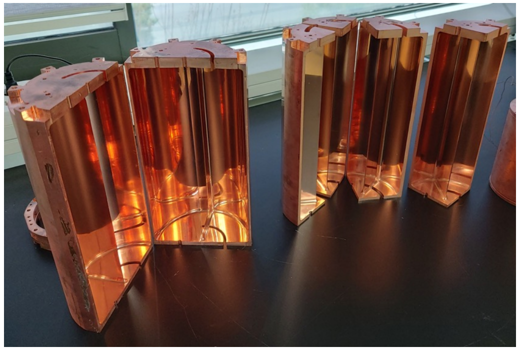
Multiple-cell (pizza)

*PLB **777** 412 (2018)*





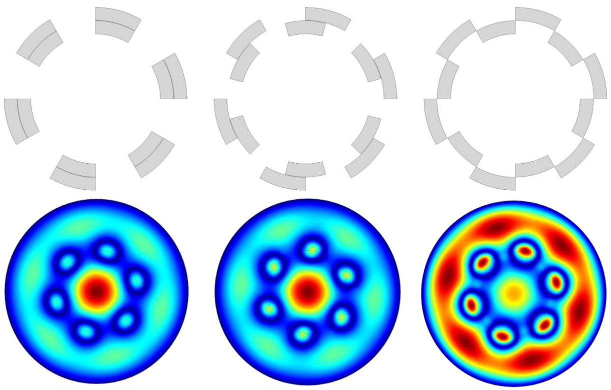
- *Larger volume*
- *Simpler receiver chain*
- *~4 x f_{TM010}*

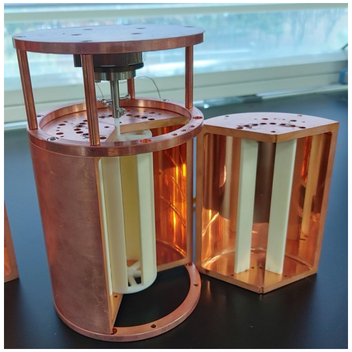


Higher-mode (wheel)

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

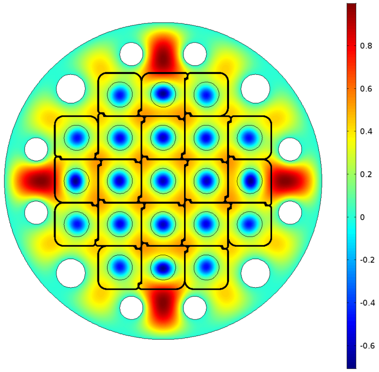
*JPG **47** 035203 (2020)*





Photonic crystal

*PRD **107** 015012 (2022)*

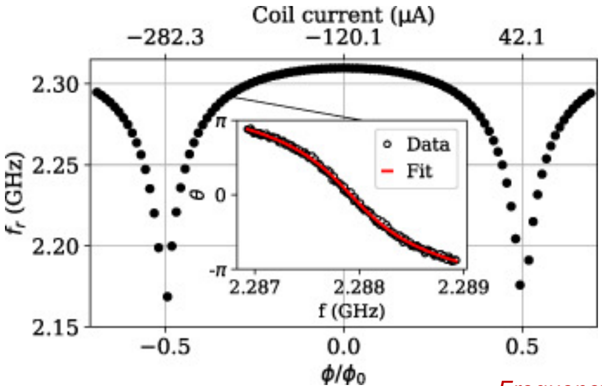


- *f ∝ spacing*
- *~10 x f_{TM010}*
- *Kirigami tuning*

QNL amplification

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

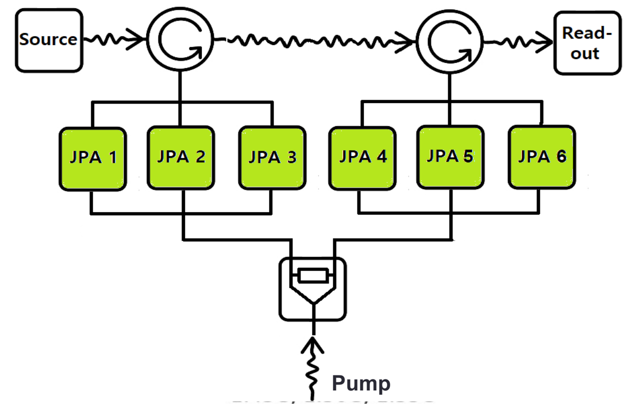
- *Flux-driven Josephson parametric amplifiers (JPAs)*

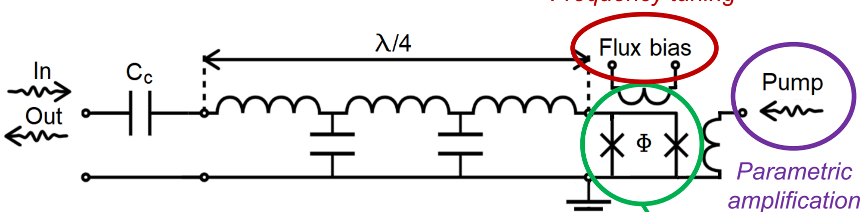


*SST **34** 085013 (2021)*

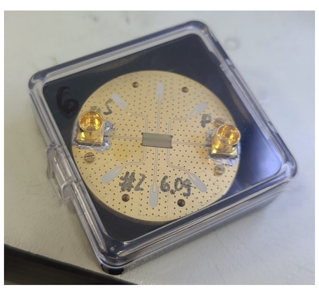
Best performance!

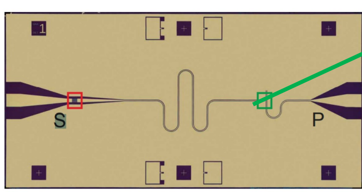
Parallel-Serial configuration

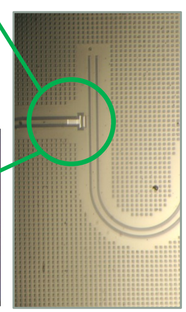




SQUID (nonlinear inductance)







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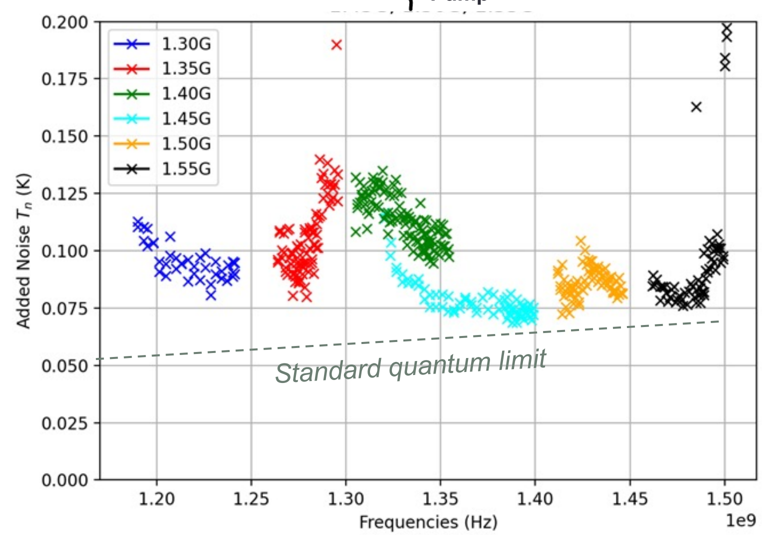
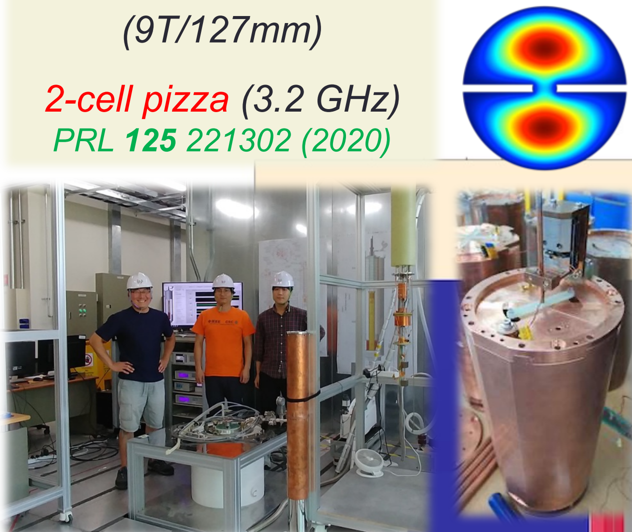
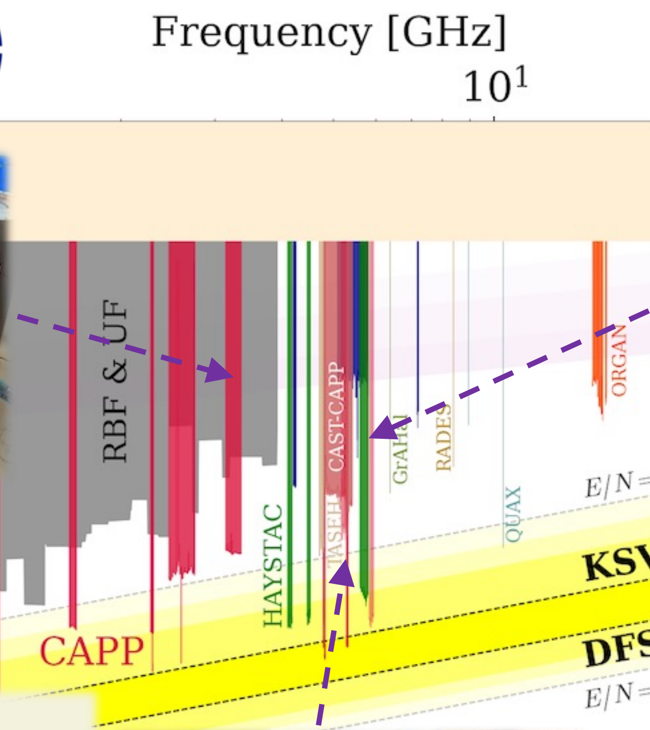
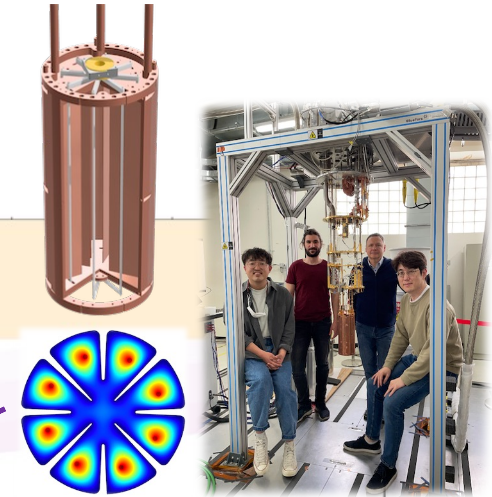


Search highlight (I)

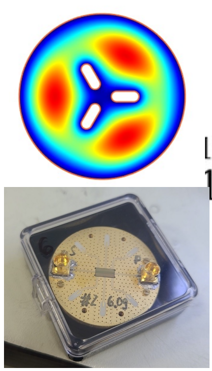
CAPP-9T
(9T/127mm)
2-cell pizza *(3.2 GHz)*
*PRL **125** 221302 (2020)*



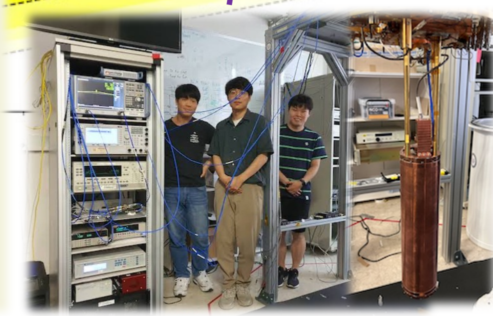




CAPP-8TB
(8T/165mm)
8-cell + JPA
(5.9 GHz, 400 mK)
Near KSVZ sensitivity
Paper in preparation



CAPP-12T
(12T/96m)
3-cell + JPA
(5.3 GHz, 400 mK)
KSVZ sensitivity
NM algorithm
*PRL **133** 051802 (2024)*



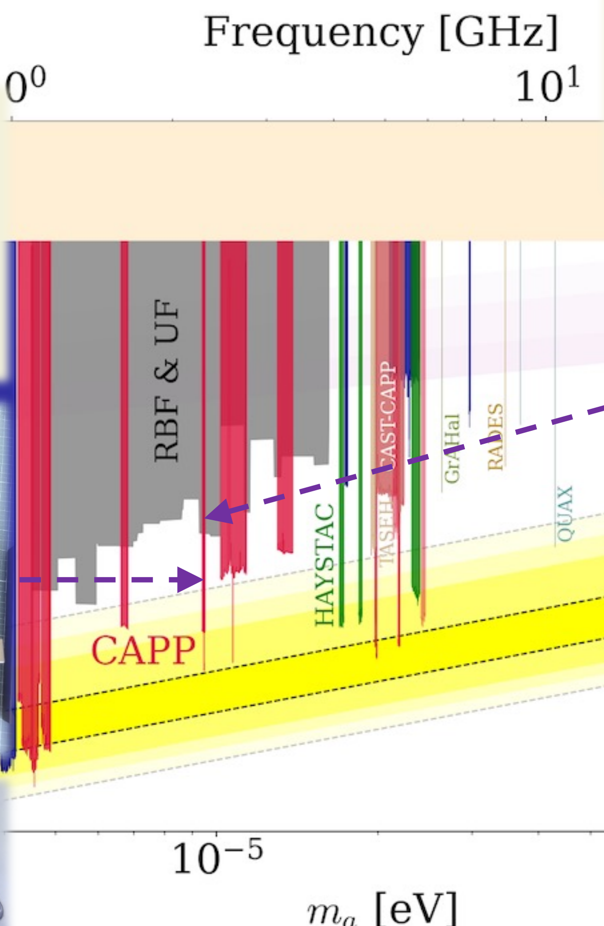
Search highlight (II)

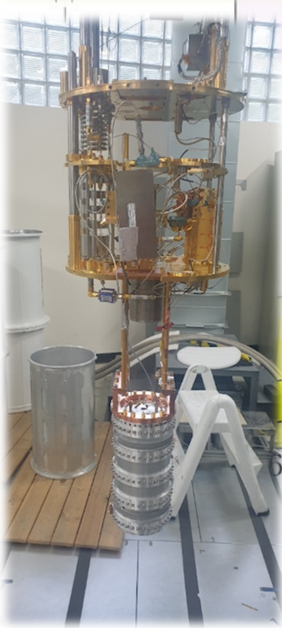
CAPP-8T
(8T/125mm)

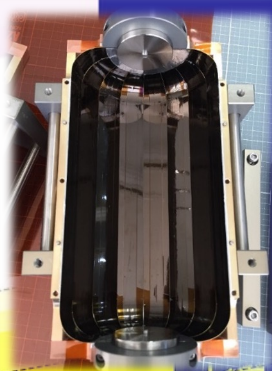
HTS SC cavity + JPA
(2.3 GHz, Q ~ 0.5 M)
KSVZ sensitivity
Paper in preparation

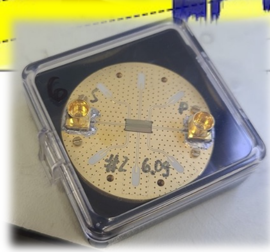
CAPP-8T
(8T/125mm)

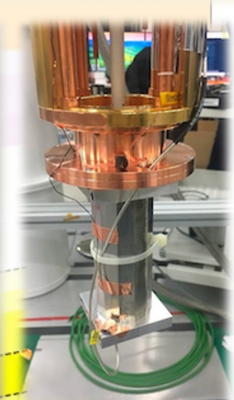
HTS SC cavity + JPA
(2.3 GHz, Q ~ 3.5 M)
AQN search
Paper in preparation

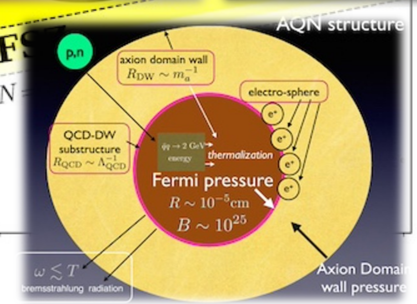












Search highlight (III)

CAPP-9T
(9T/127mm)

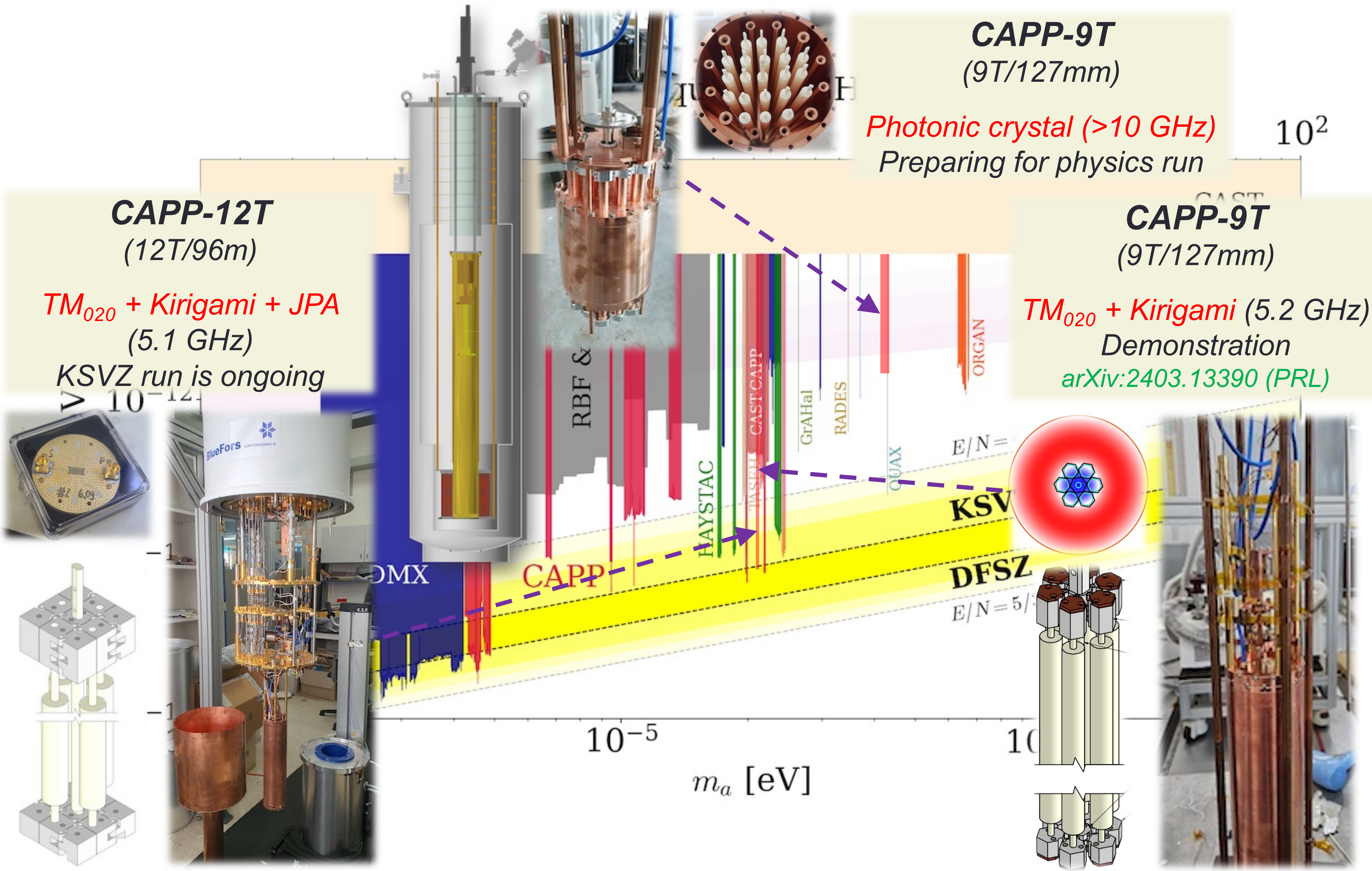
Photonic crystal (>10 GHz)
Preparing for physics run

CAPP-12T
(12T/96m)

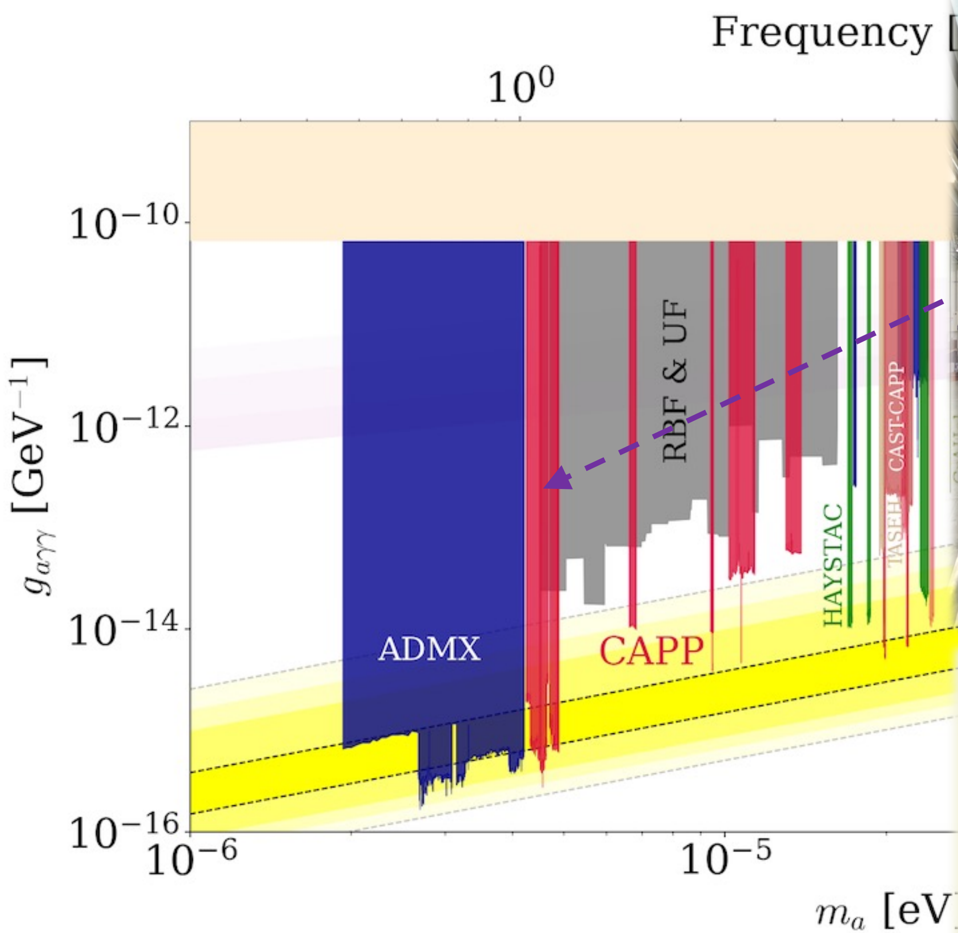
TM_{020} + Kirigami + JPA
(5.1 GHz)
KSVZ run is ongoing

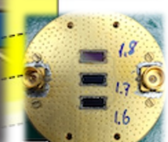
CAPP-9T
(9T/127mm)

TM_{020} + Kirigami (5.2 GHz)
Demonstration
arXiv:2403.13390 (PRL)



Search highlight (IV)





CAPP-12TB

(12T/320mm)

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

df/dt ~ 2 MHz/day @ DFSZ

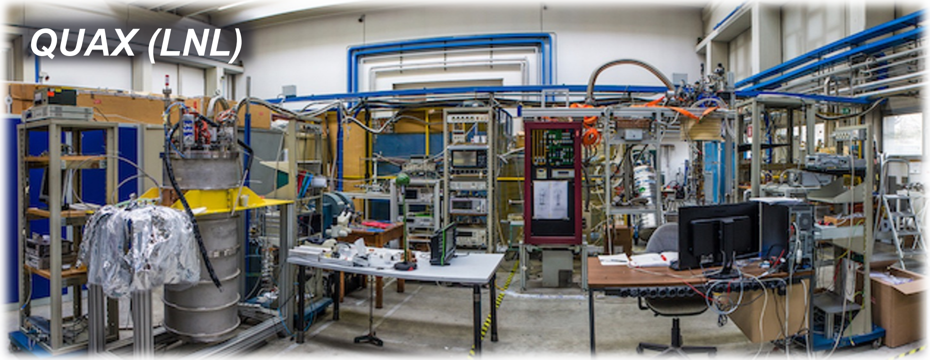
*PRL **130** 071002 (2023)*

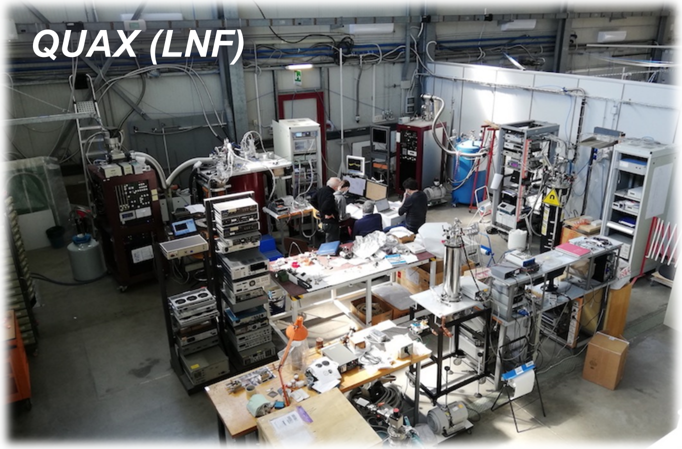
Extended scan (Δf ~120 MHz)

*PRX **14** 031023 (2024)*

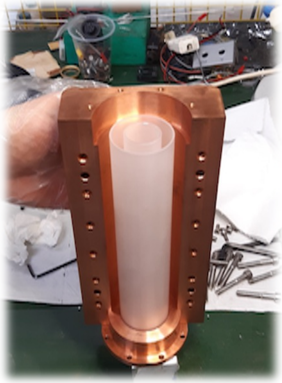
Ready for 300-MHz run w/ SC cavity

QUAX

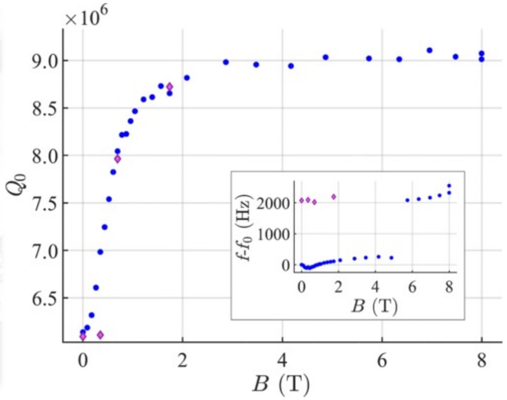


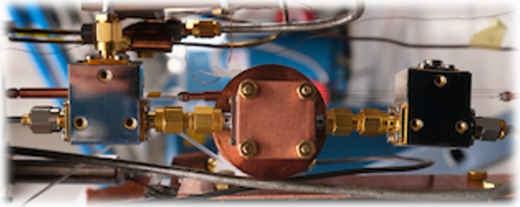


Dielectric cavity



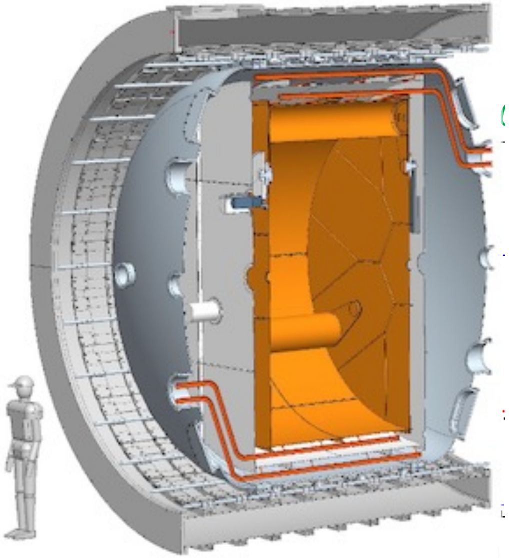
*PRApplied **17** 054013 (2022)*





TWPA

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

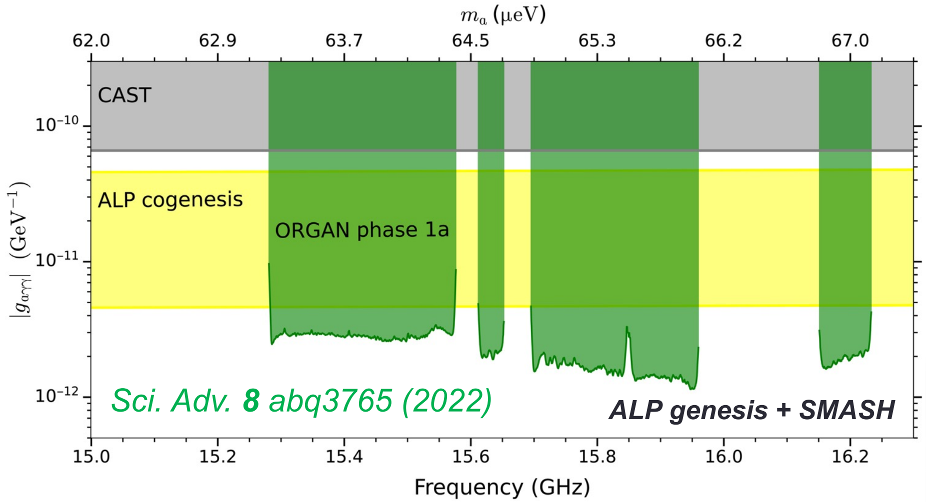


FINUDA

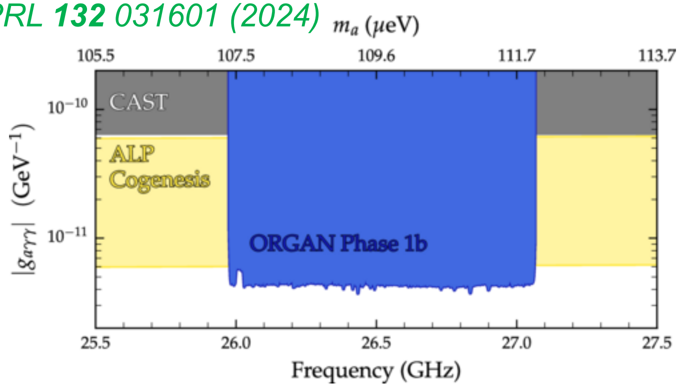
B = 1.1 T
R = 1.4 m

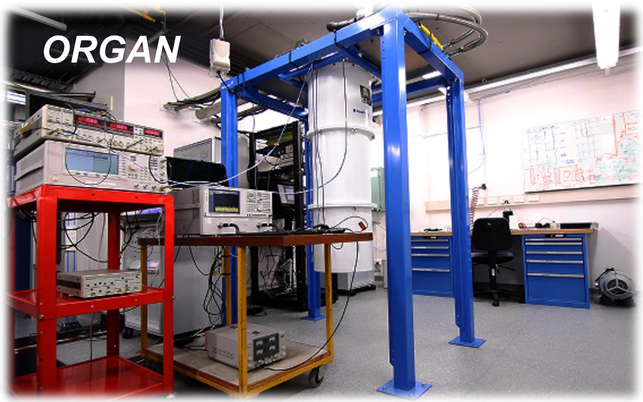
FLASH

ORGAN

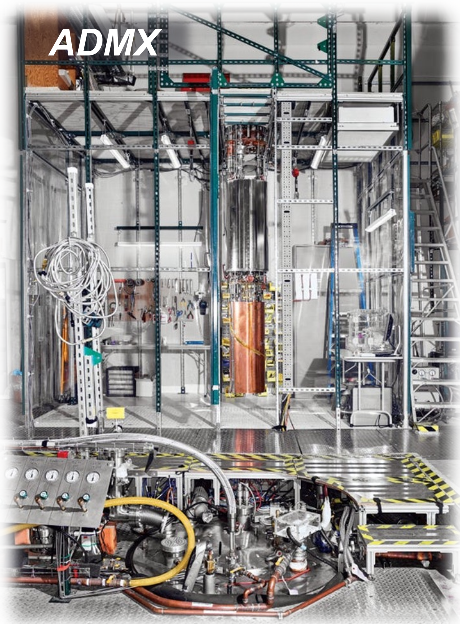


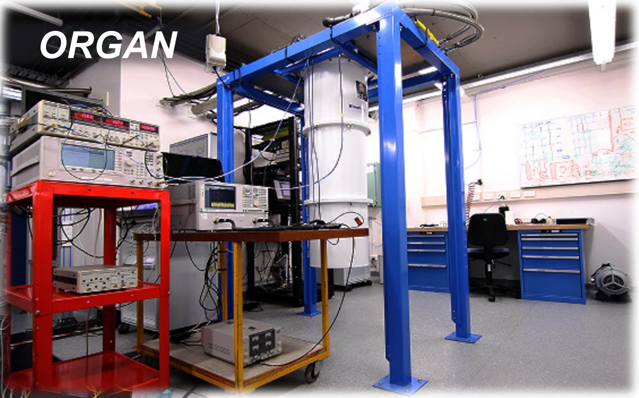
PRL **132** 031601 (2024)

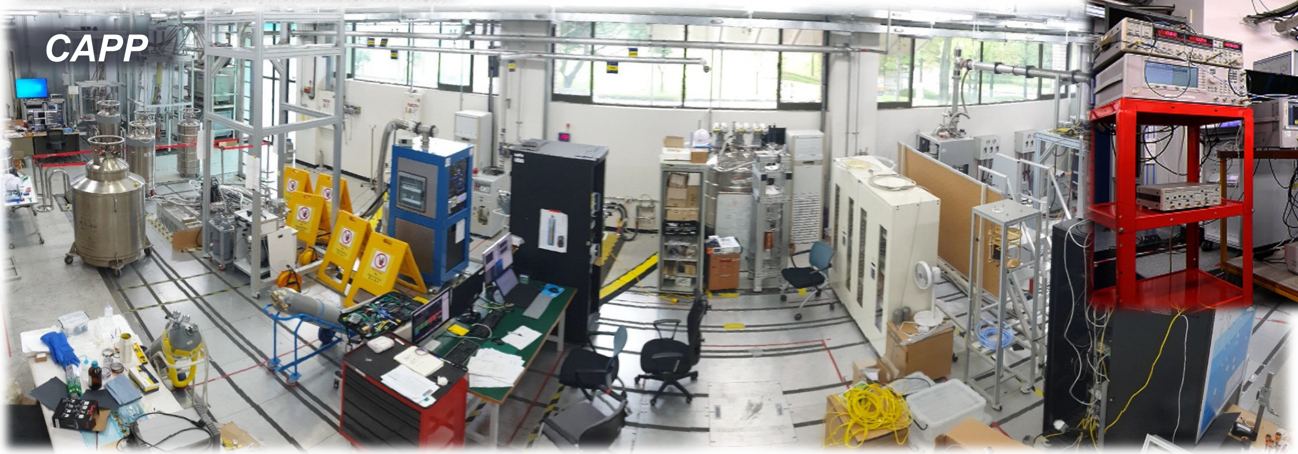




Cavity haloscopes

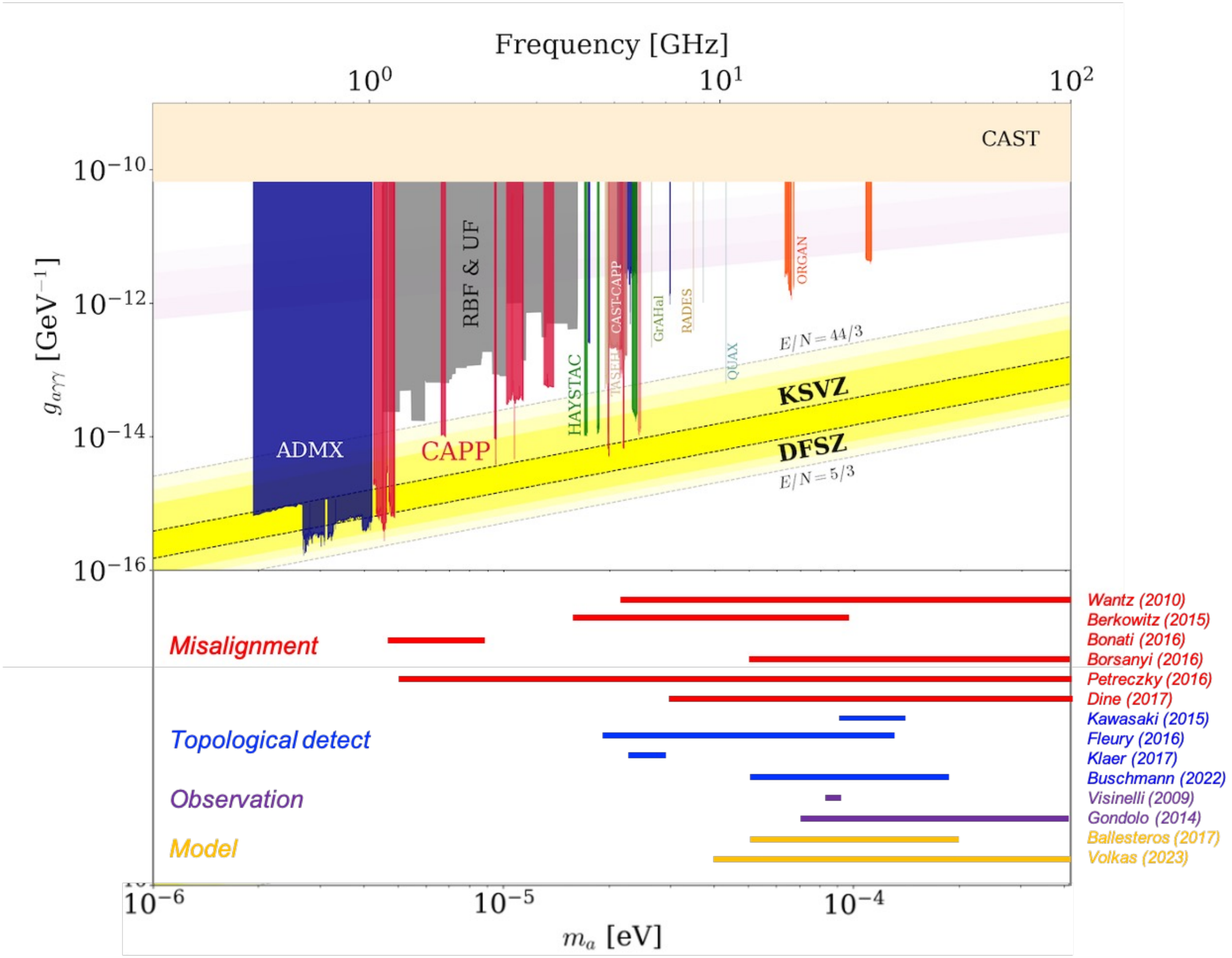






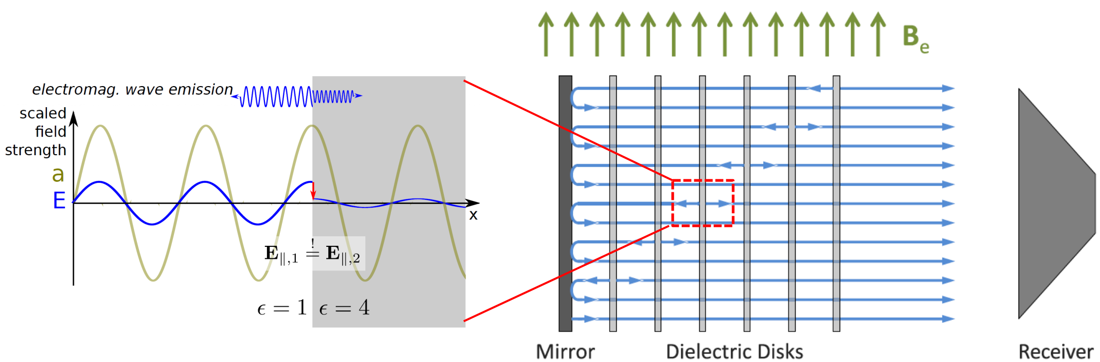
$$f_a \lesssim 10\ GHz$$

Searches vs. predictions



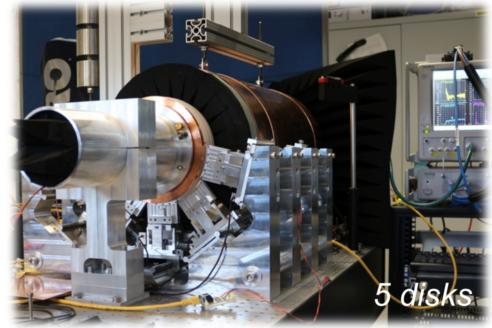
MADMAX

- *Dielectric power booster* PRL 118 091801

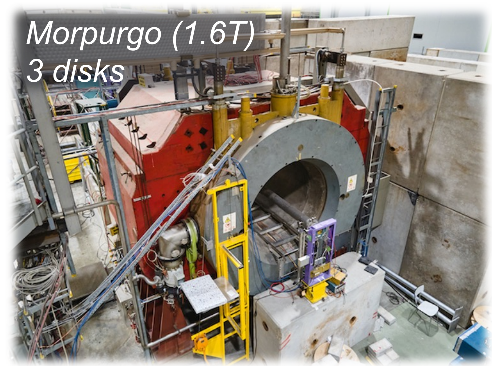


Suitable for high-freq. search

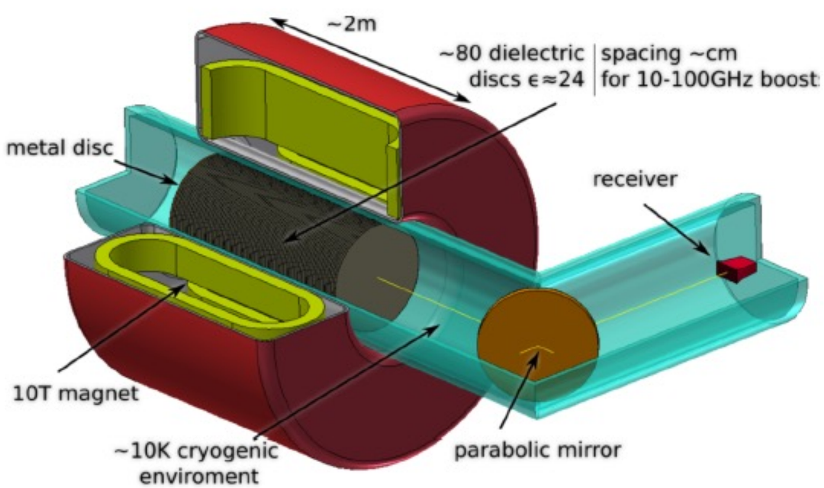
Proof-of-concept

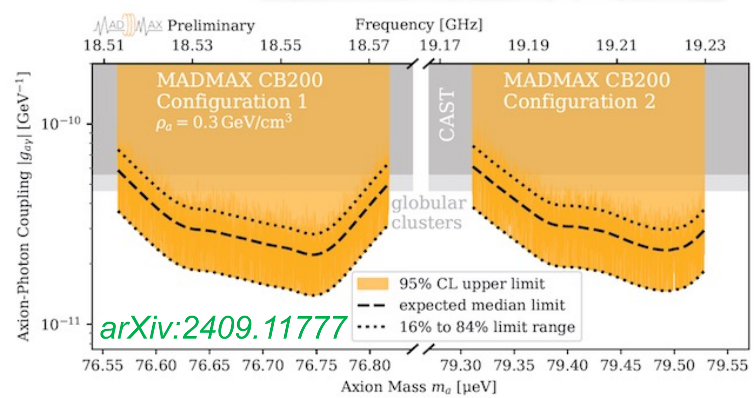


Prototype (2024)



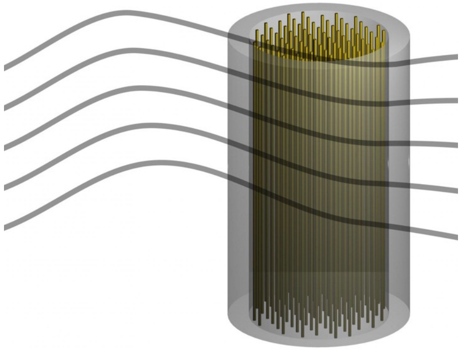
Full scale experiment



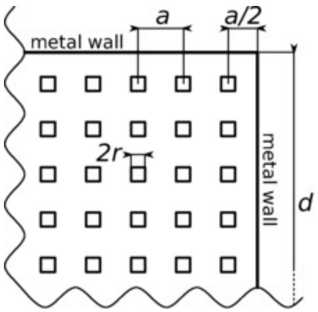


ALPHA

- *Plasma haloscope* PRL **123** 141802 (2019)
  - *Wire metamaterial => bulk plasmon*



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

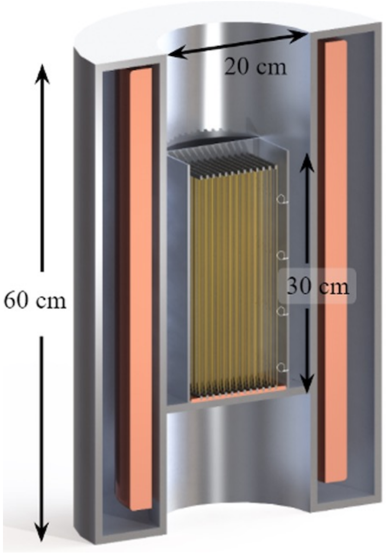


- ω_p *independent of the detector size*
- *Large conversion volume at high frequencies*

Resonant conversion when $m_a = \omega_p$

PRD **107** 055013 (2023)

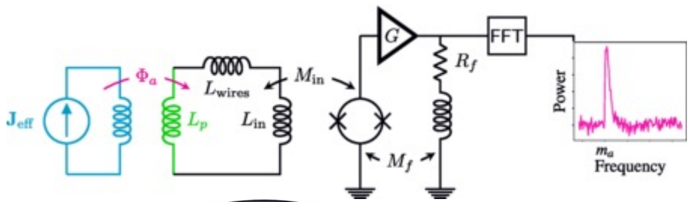
Prototypes (10x10 & 16x16) array (11.4 GHz)



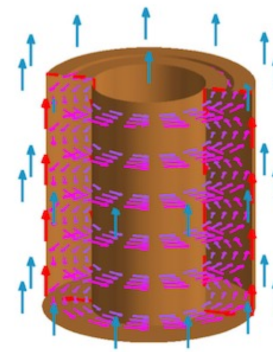
Physics data in 2026

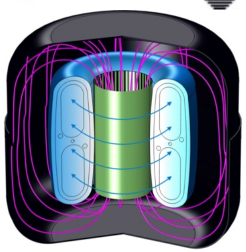
DM Radio

- *Lumped element haloscope*
  - *Broadband low mass (<1 ueV) search*
  - *Sensitive to pre-inflationary scenario*

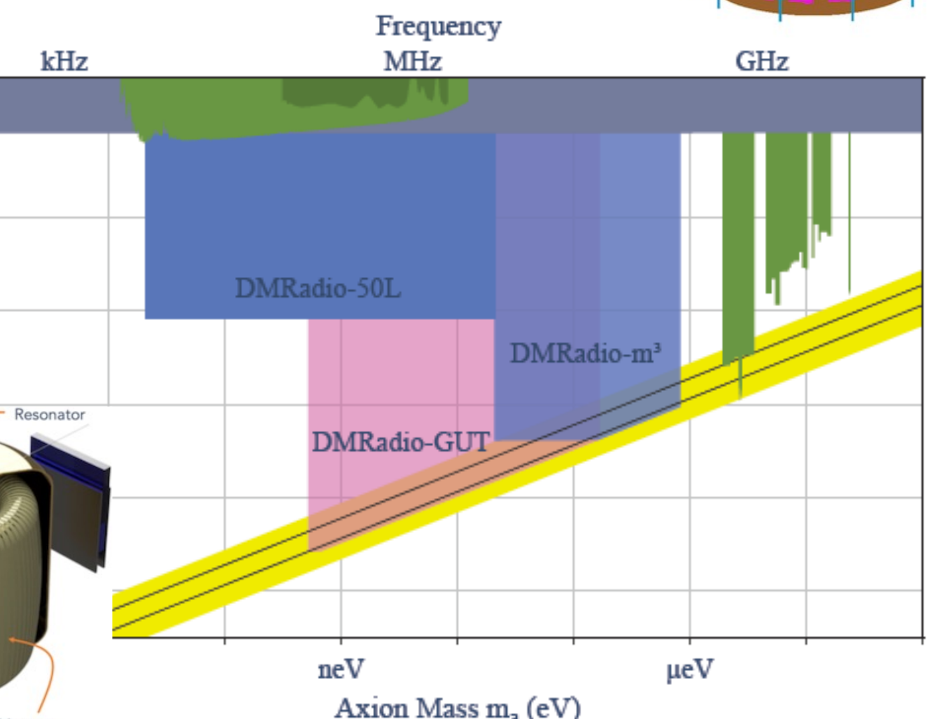


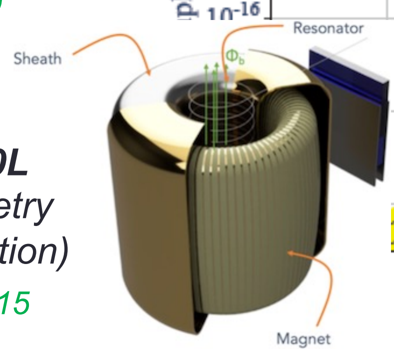
DM Radio-m³
Solenoidal geometry
*PRD **106** 103008 (2022)*





ABRACADABRA-10cm
*PRL **127** 081801 (2021)*





DM Radio-50L
Toroidal geometry
(under construction)
arXiv:2210.07215

Other haloscopes

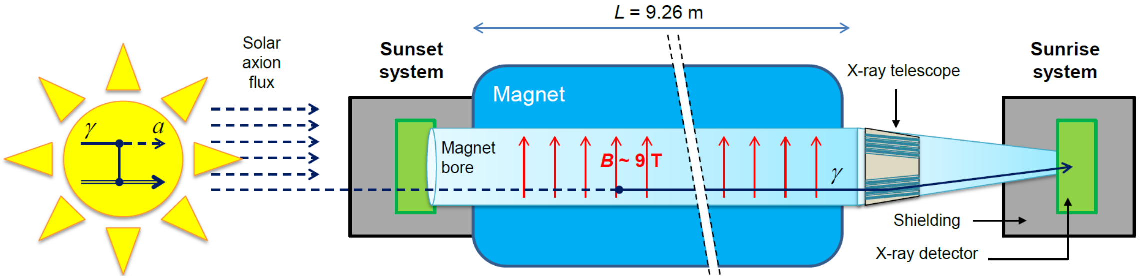
- *Recent*
  - *CAST-CAPP: phase-matched cavities, ~20 ueV* — *Nat. Comm. **13**, 6180 (2022)*
  - *RADES: microwave fiber, ~34 ueV* — *JHEP **2021** 75 (2021)*
  - *Grenoble Axion Haloscope* — *arXiv:2110.14406*
    - *14T/52mm magnet, ~26 ueV*
  - *Taiwan Axion Search Experiment with Haloscope* — *PRL **129** 111802 (2022)*
    - *4.7 GHz, 11 x g_{arr}^{KSVZ}*
  - *Broadband Reflector Experiment for Axion Detection* — *PRL **132** 131004 (2024)*
    - *Parabolic reflector, THz region*

- *Proposed*
  - *Canfranc Axion Detection Experiment* — *JCAP **11** 044 (2022)*
    - *90 GHz (W-band), Kinetic inductance detectors*
  - *Superconducting axion search* — *arXiv:2308.08337*
    - *SC cavity, 14T, 8.4 GHz (under construction)*
  - *GrAHal-CAPP* — *Front. Phys. 12:1358810 (2024)*
    - *9T/800mm magnet, SC cavity, 1~3 ueV*

Helioscope Searches

Helioscope

- *Solar axion telescope*

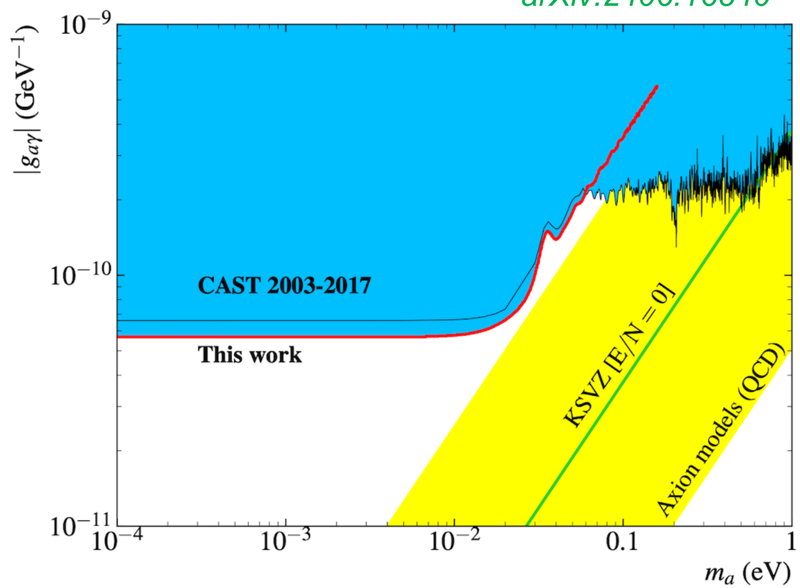


Black-body photons (keV) to axions In dense stellar plasma

Reconversion into photons (X-ray) in laboratory magnetic fields

$$\mathcal{P}_{a\to\gamma} \sim \left(\frac{g_{a\gamma\gamma} B_0 L}{2}\right)^2 \mathrm{sinc}^2\left(\frac{qL}{2}\right), q \equiv \frac{m_a^2}{2E_a}$$

arXiv:2406.16840

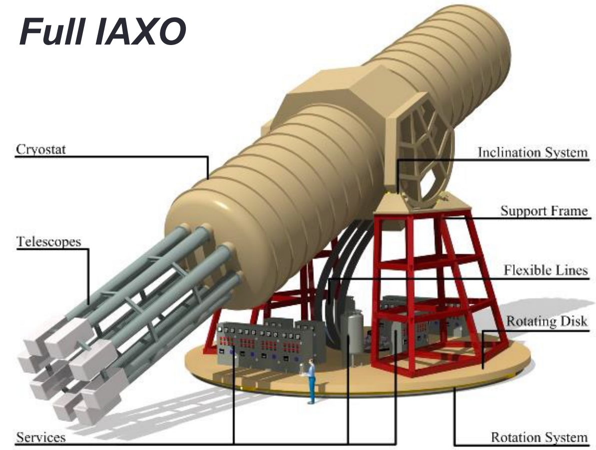


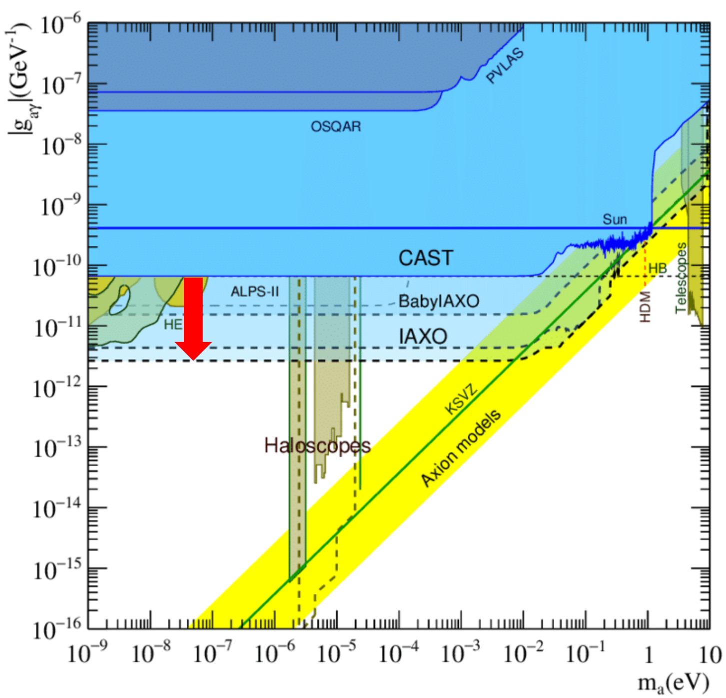
- *History*
  - *BNL, JAPAN*
  - *CAST (decommissioned in 2021)*
  - *IAXO in plan*

IAXO

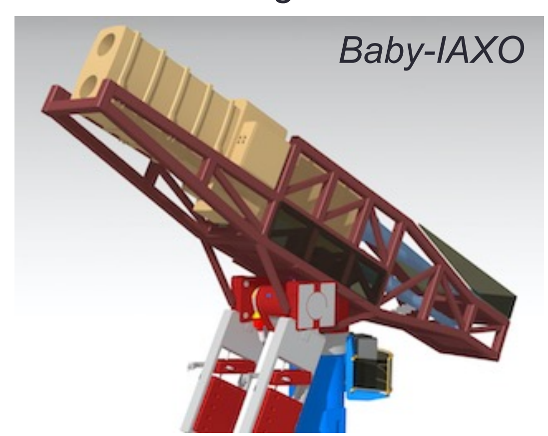
- *International AXion Observatory*
  - *Large toroidal helioscope*
    - *8 dipoles (5.4 T, 20 m x Φ600 mm)*
  - *Diverse physics over wide range*
    - *Axions / ALP miracle / Astrophysical hints*
  - Goal : $g_{a\gamma} \sim 10^{-12}\ GeV^{-1}$

Full IAXO





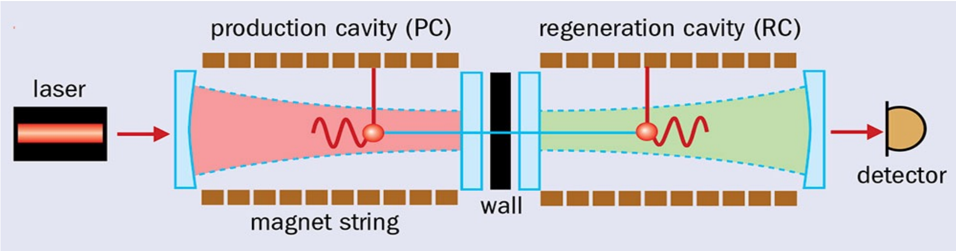
- *Baby-IAXO* *arXiv:2010:12076*
  - *Approved in 2020 (DESY)*
  - *First step towards full IAXO*
    - *4 T / 10 m long => 10 x $MFOM_{CAST}$*

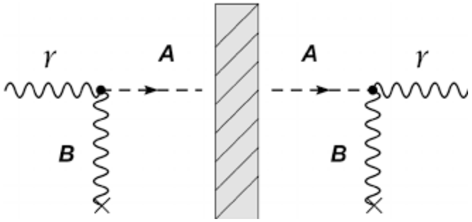


LSW Searches

Light shining through a wall

- *Axion production at laboratory*

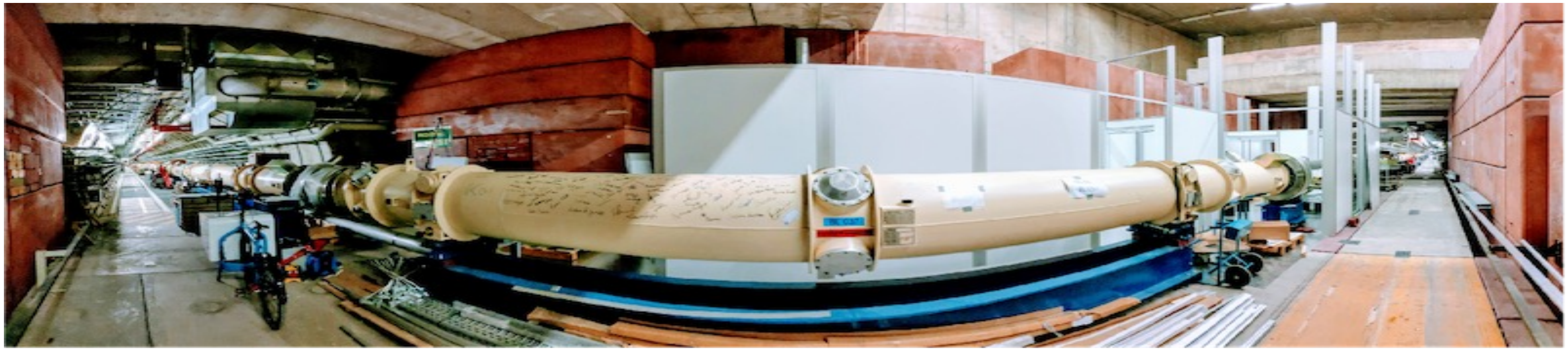




Two vertices => fourth power of coupling

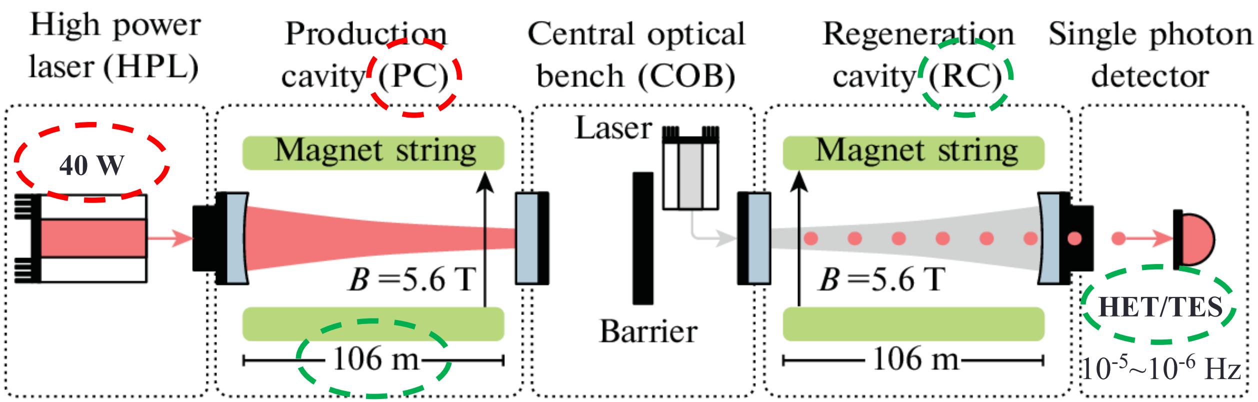
  - *Model independent search*
    - *No need of cosmo./astrophys. source => pure axion-photon coupling*

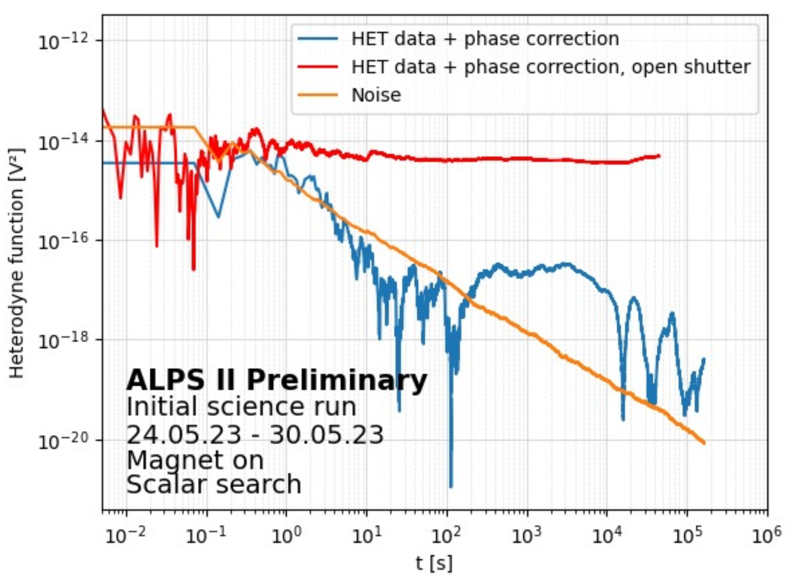
- *History*
  - *BFRT (Brookhaven-Fermilab-Rochester-Trieste)*
  - *OSQAR (LHC dipole at CERN)*
  - *ALPS (HERA dipole at DESY)*



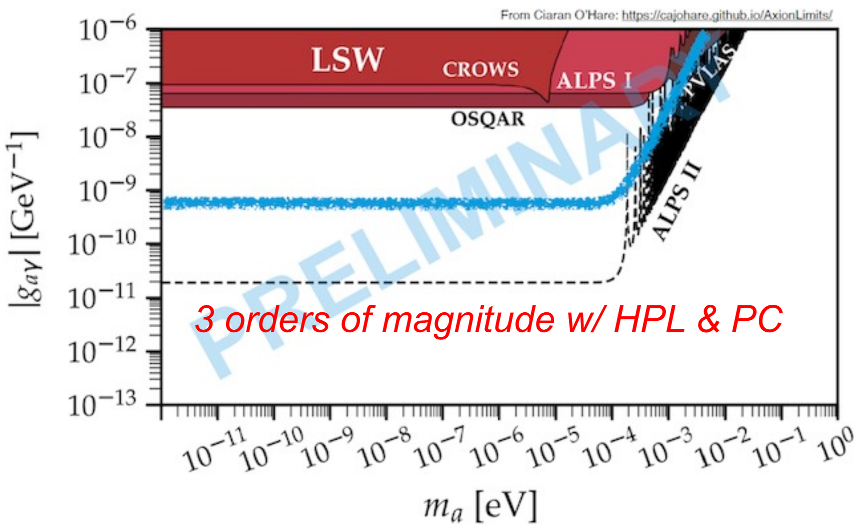
ALPS II

- *Any Light Particle Search II*





First science run (30 x ALPS)

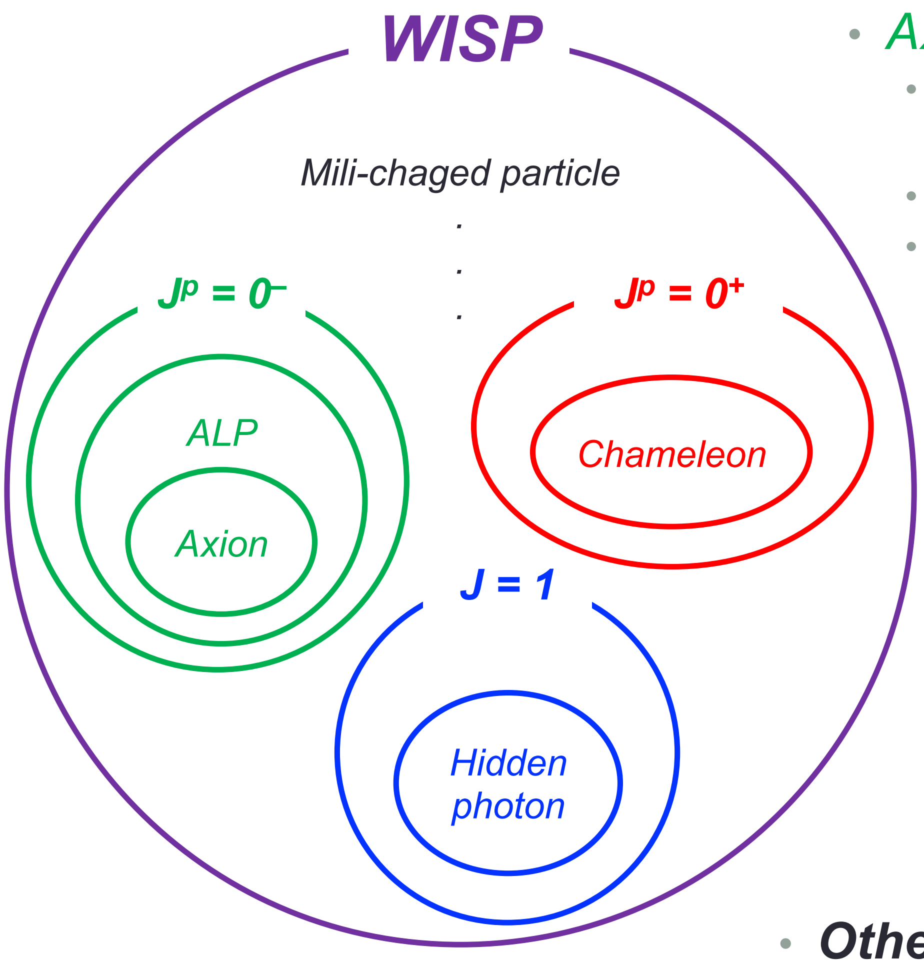


3 orders of magnitude w/ HPL & PC

Summary

- *Axions address two fundamental questions*
  - *Strong CP problem & dark matter mystery*
- *Theoretically well motivated but experimentally challenging*
  - *Weak coupling and unknown mass*
- *Tremendous search efforts*
  - *Different technologies targeting at different mass ranges*
- *Axion community is getting larger*
  - *New results, new groups and new ideas*
- *Next few decades must be critical/exciting*
  - *Covering a substantial portion of the parameter space*
  - *Uncovering the nature of dark matter*

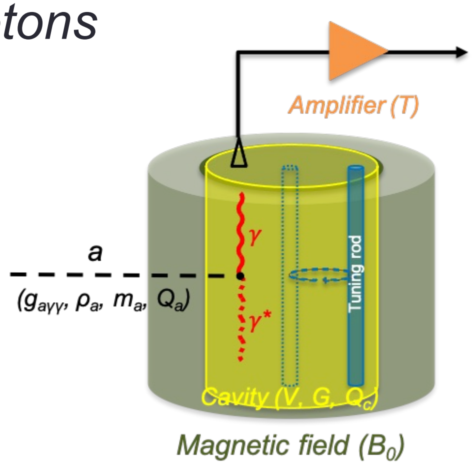
WISP zoo



- **Pseudo-scalar**
  - Axion
    - PQ solution to strong CP problem (1977)
      $m_a f_a \sim \Lambda_{QCD}$
    - Invisible axion (1979)
    - Dark matter candidate (1983)
  - Axion-Like Particle (ALP)
    - Generic axion w/o solving strong CP problem
      $m_a f_a \nsim \Lambda_{QCD}$
- **Scalar**
  - Chameleon (2003)
    - Dark energy candidate
- **Vector**
  - Hidden photon
    - Gauge field in hidden sector
- **Others**
  - Mili-charged particle, …

Cavity haloscope

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



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

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

(~120 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) $0.2\ K \sim 3\times10^{-22}\ W$

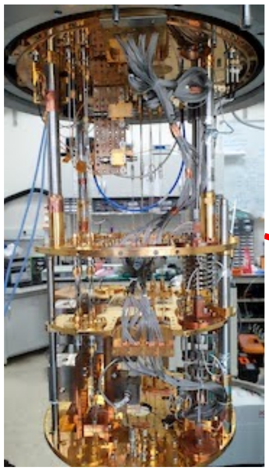
- *Unknown mass = > scanning rate (F.O.M.)*

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

Cavity haloscope – in a nutshell

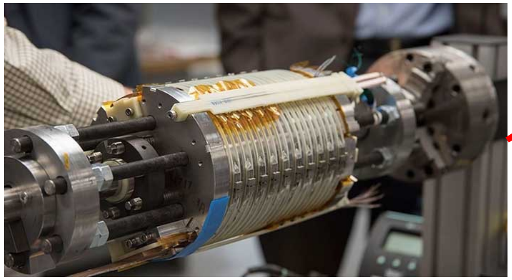
- *High scanning rate by improving experimental parameters*

Cryogenics *T*



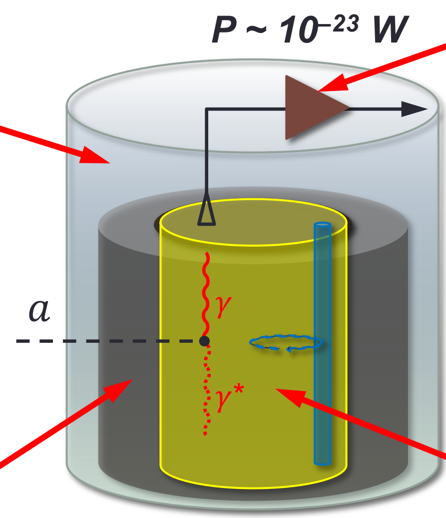
Lowering thermal noise

High field Magnet *B*

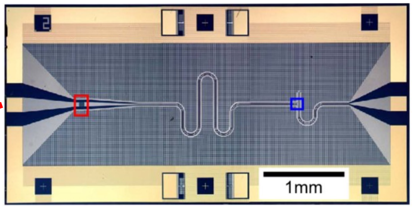


Boosting a→γγ conversion

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

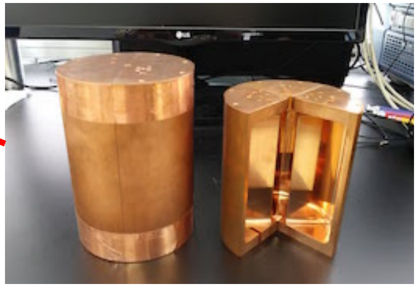


Quantum noise limited amplifier *T*



Signal amplification w/ minimal noise added

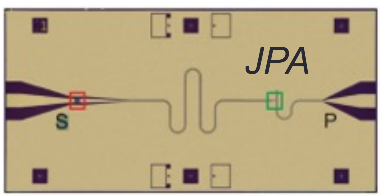
Tunable High-Q resonator *V, Q, C, Δf*



Resonant frequency tuning

Microwave signal detection

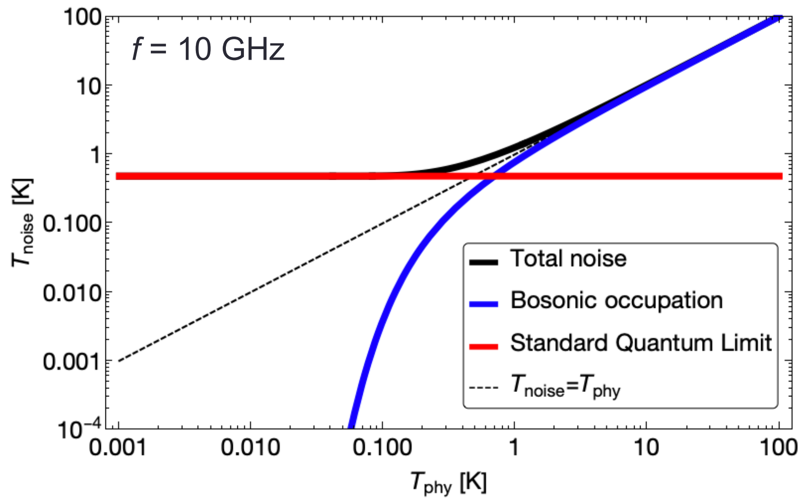
Transistor-based
(T_N ~ K)



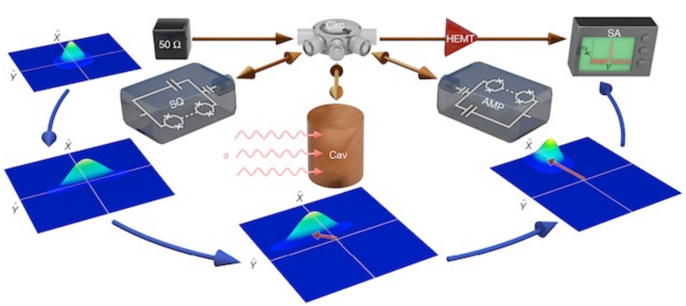
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection* vs. *photon counting

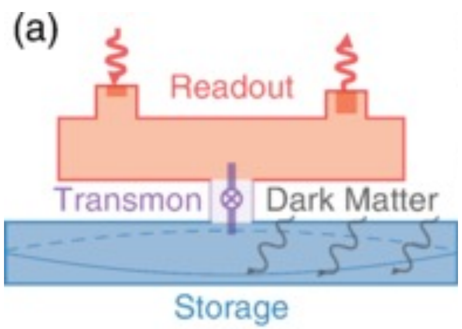
(w/ amplifiers) *(w/ single photon detector)*



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



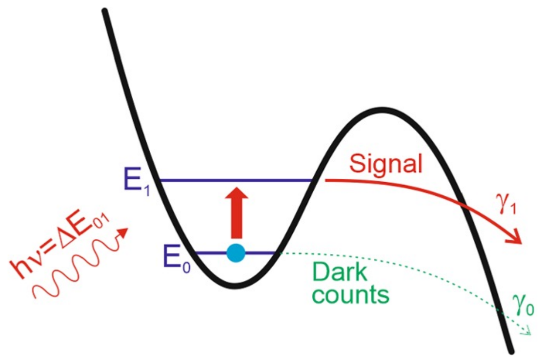
Quantum squeezing ($T_N < T_{SQL}$)



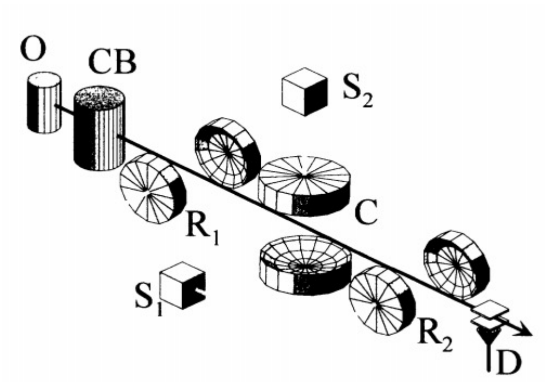
Single photon counting
Not subject to SQL
($T_N << T_{SQL}$)

SPD schemes

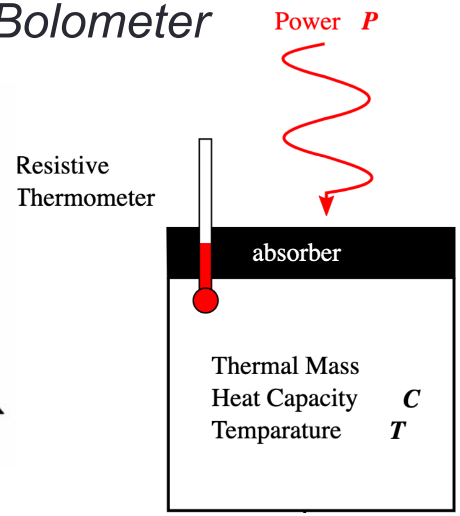
Excitation



Interference



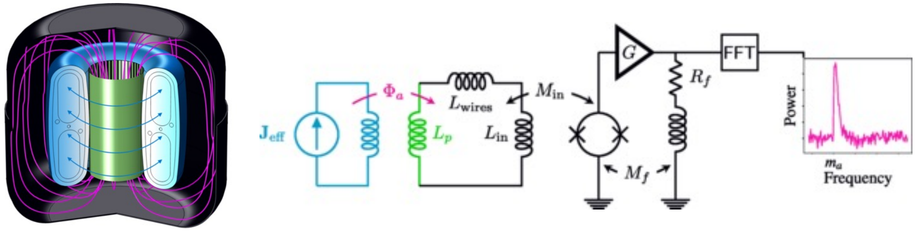
Bolometer

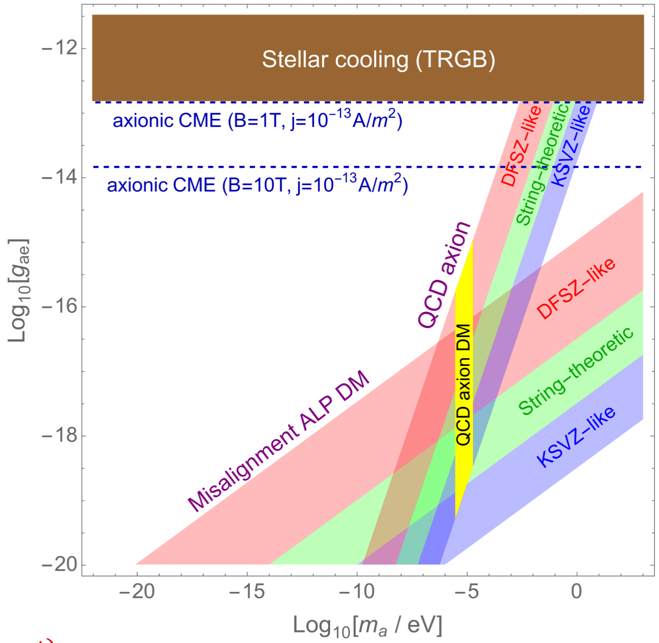


	Excitation	***Intereference***	***Bolometer***
Basis	***Qubit***	***JJ-Qubit***	***JJ-TES***
Quantity	*Electron*	*Phase*	*Heat*
Pros	*High sensitivity*	*Non-demolition*	*Wide bandwith* *Robust*
Cons	*Bandwidth vs. Dark cout rate* *Low tunability*	*Narrow bandwidth* *Low tunability*	*High noise level*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

Axionic chiral magnetic effect

- *Low temperature Axion Chiral Magnetic Effect*



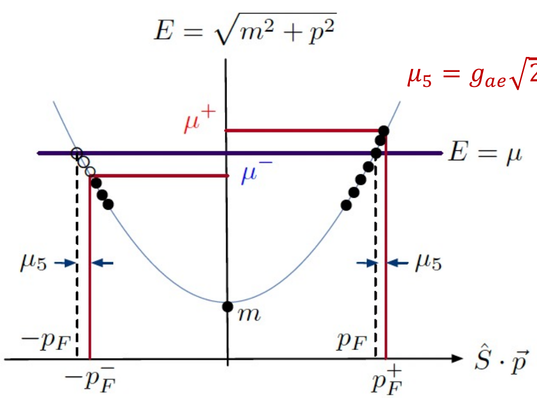


ABRACADABRA		LACME
$-\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$	Coupling	$g_{ae}\delta_\mu a\psi\gamma^\mu\gamma_5\psi$
Effective current (vacuum)	Axion	Chemical potential (polarized medium)
$g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\,\boldsymbol{B}$	$\boldsymbol{j}_{(eff)}$	$v_F\frac{e^2}{2\pi}g_{ae}\sqrt{2\rho_a}\cos(m_a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

μ_5 adds p to e^- along $\hat{S}$

$\boldsymbol{B}$ polarizes e^-

Helicity imbalance => current flow



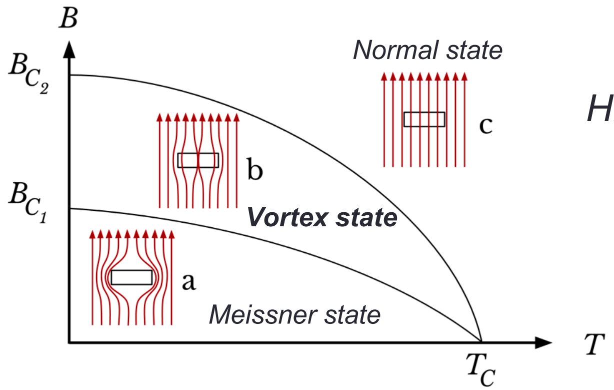
Chiral medium

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

High-quality factor

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

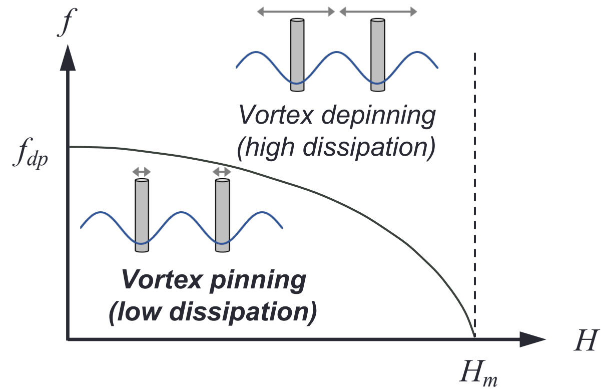
- *Minimal energy loss under a high magnetic field*



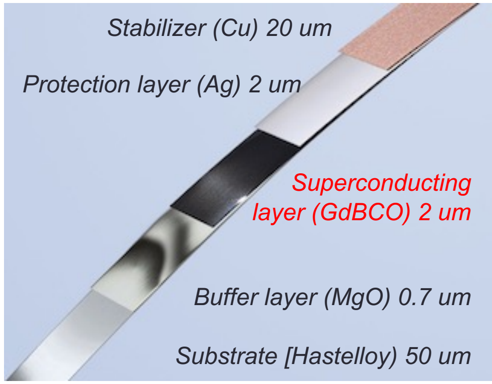
High critical field B_{C2}
&
High depinning frequency f_{dp}

↓↓

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



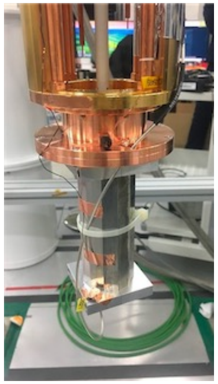
- *ReBCO HTS*
  - *Biaxially-textured 2D tapes (commercially available)*



GdBCO HTS tape

Tapes on 2D pieces

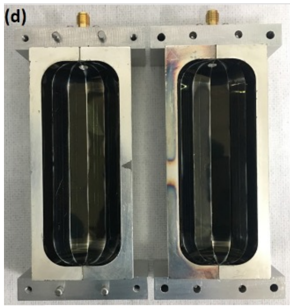
Assembly

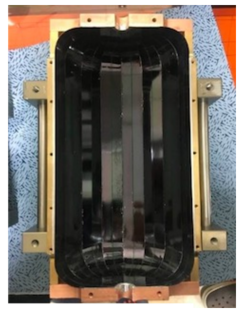
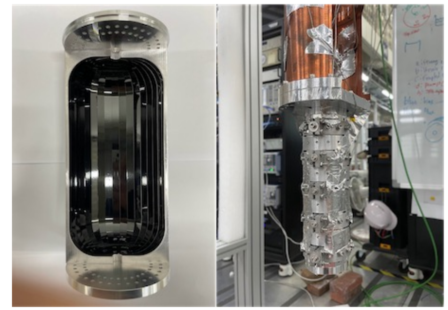
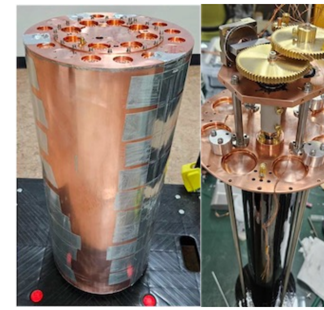
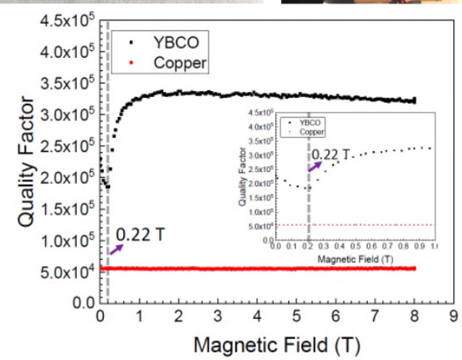


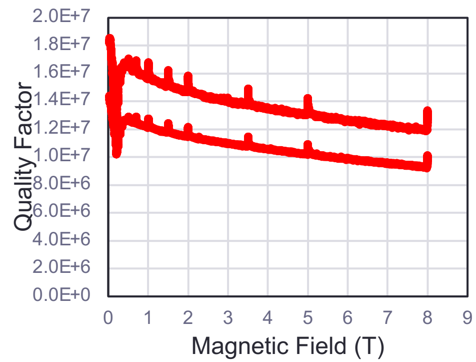
3D SC cavity

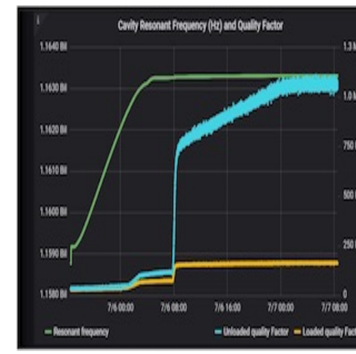
HTS cavities

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





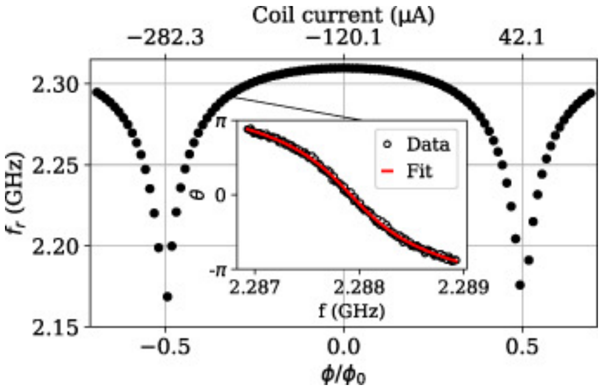


	1st Gen.	*2nd Gen.*	*3rd Gen.*		*4th Gen.*
Material	***Y**BCO*	***Gd**BCO*	***Eu**BCO + APC*		***Eu**BCO + APC*
Manufacturer	*AMSC*	*Theva*	*Fujikura*		*Fujikura*
Volume [L]	*0.3*	*1.5*	*1.5*	*0.2*	*37*
Freq. [GHz]	*6.9*	*2.3*	*2.2*	*5.4*	*1.2*
Q @ 8 T	***0.33 M***	***0.5 M***	***3.5 M***	***13 M***	***1.1 M***
Application	*Demostration*	*Axion search*	*AQN search*	*Axion search*	*Axion search*

Quantum amplification

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

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



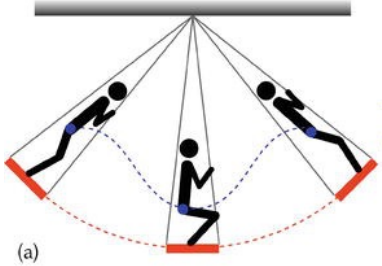
Frequency tuning

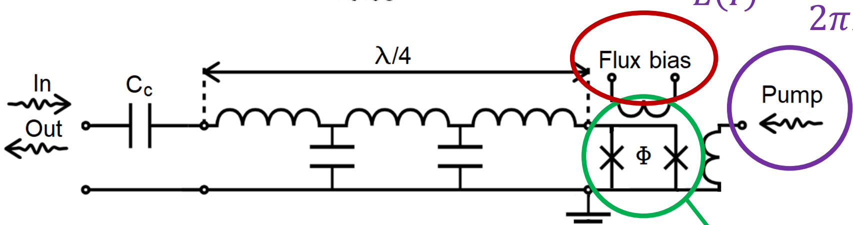
$$I_C = IC_c \cos\left(\frac{\pi\Phi}{\Phi_0}\right)$$

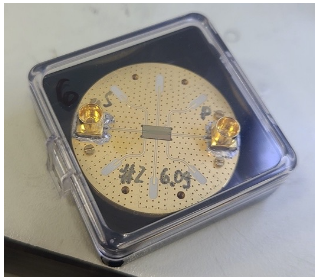
Parametric amplification

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

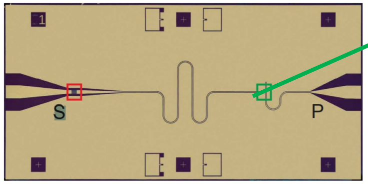
$\omega_p = 2\omega_s$

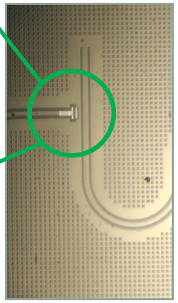






SQUID (nonlinear inductance)





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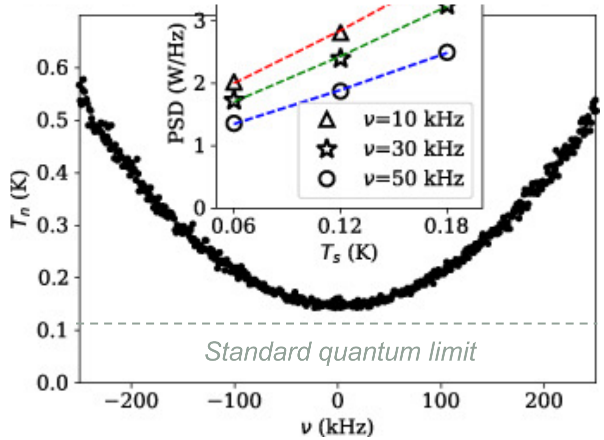
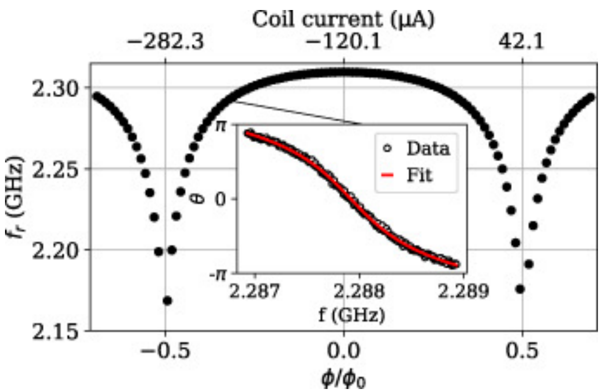


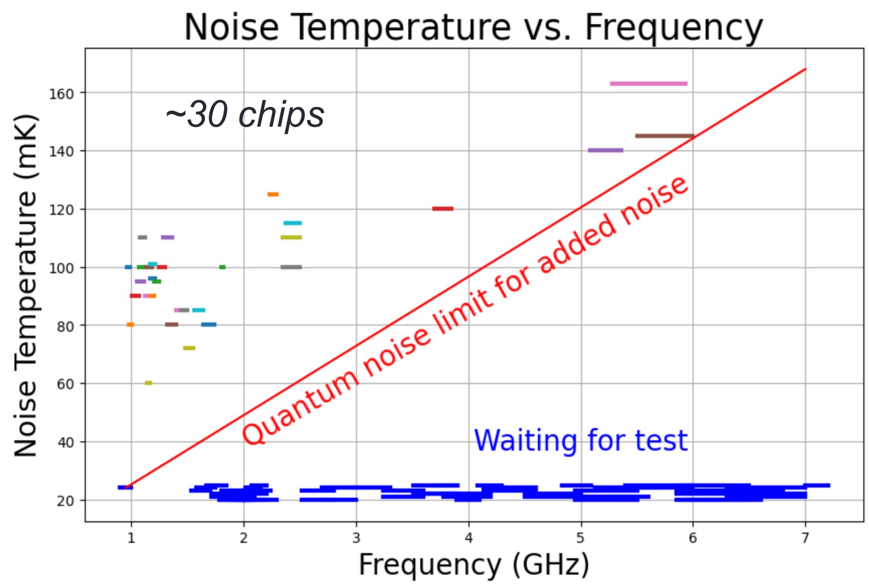
Best performance
in axion search application

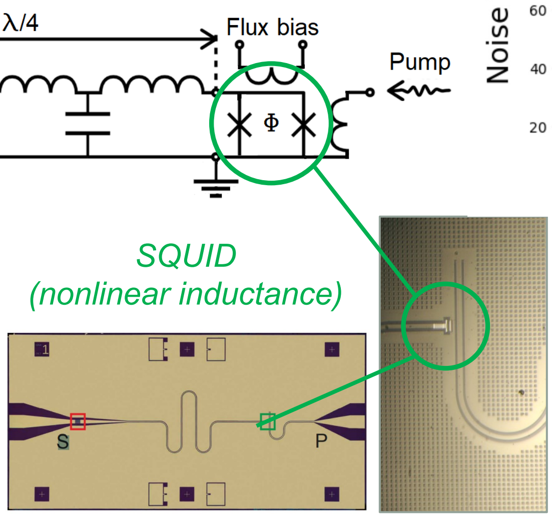
Quantum amplification

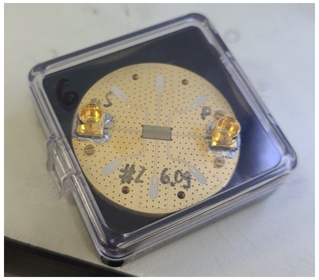
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

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









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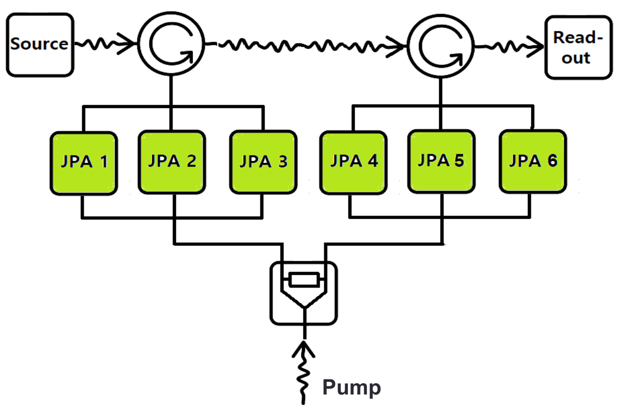
But, … limited bandwidth!

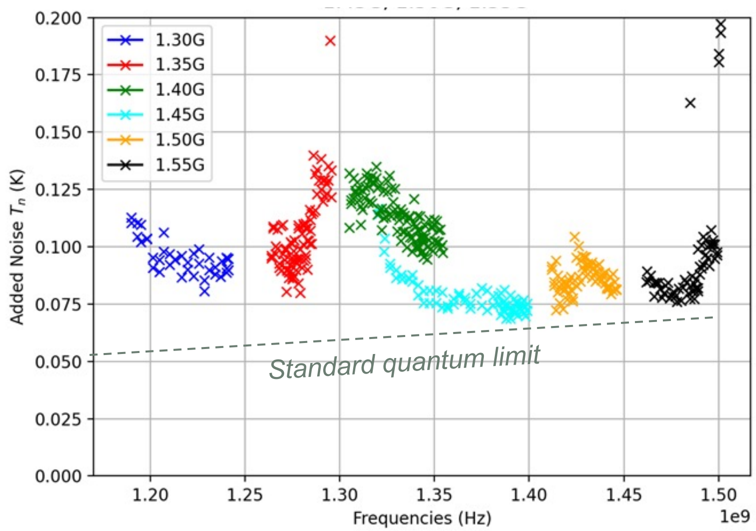
Quantum amplification

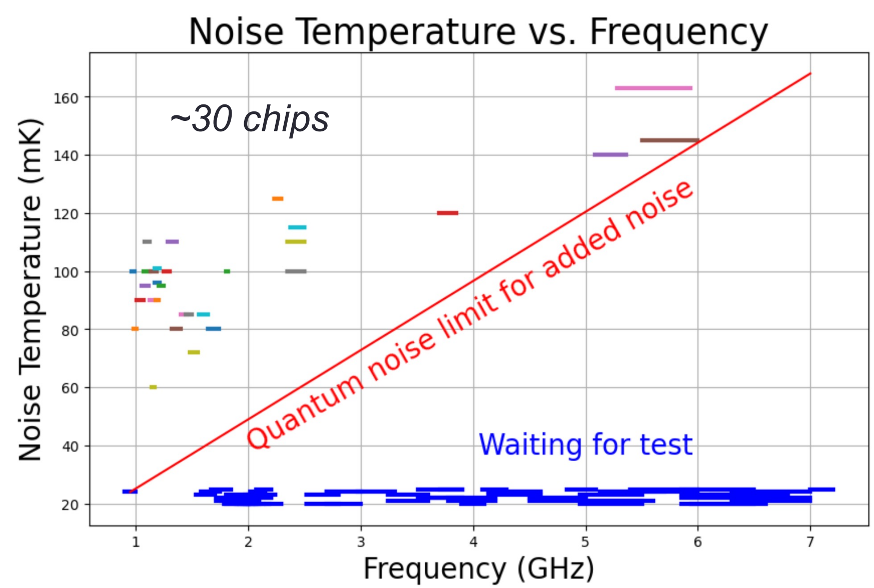
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

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

Parallel-Serial configuration







But, … limited bandwidth!

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