



Searches for Axion Dark Matter with IBS-CAPP



CAPP
Center for
Axion and Precision
Physics Research



*XVIII International Conference
on Topics in Astroparticle and Underground Physics*

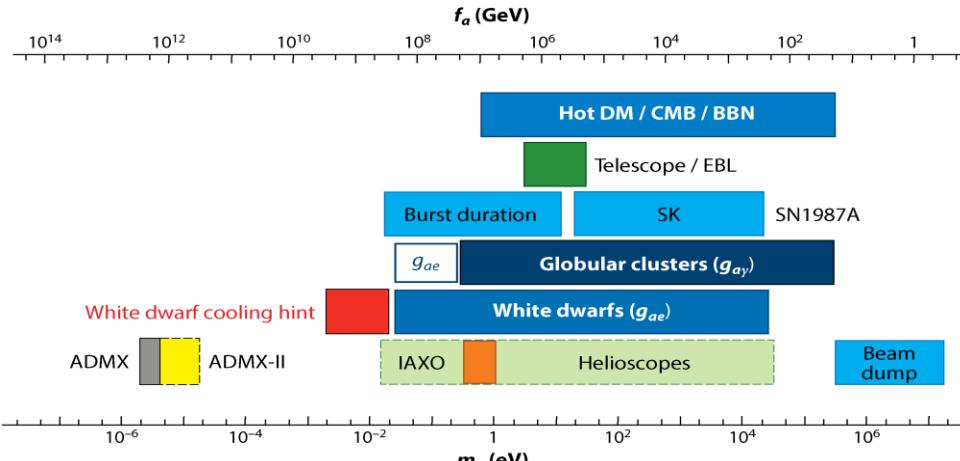
Aug. 28. 2023 University of Vienna

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Institute for Basic Science (IBS)



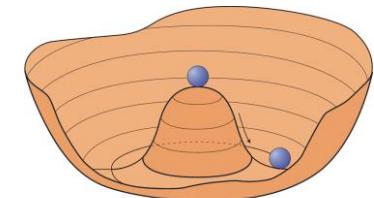
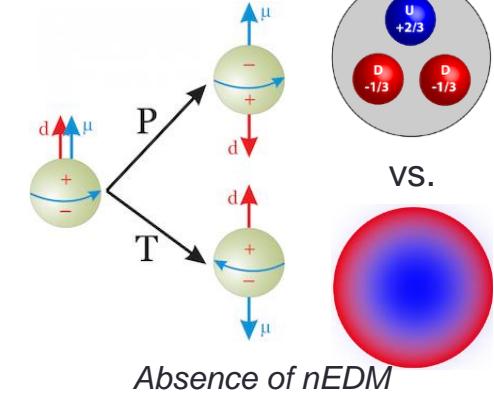
Axion dark matter

- *Solution to the Strong CP problem*
 - PQ mechanism (1977)
 - SSB of $U(1)$ symmetry \Rightarrow Goldstone boson (1978)
 - QCD axion: $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$
 - Cf. axion-like particle (ALP)
 - Invisible axion (1979): $m_a \approx 10^{-6} \text{ eV} \frac{10^{12} \text{ GeV}}{f_a}$
- *Cosmological implication*
 - Account for dark matter (1983)

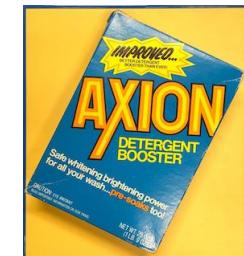


Annu. Rev. Nucl. Part. Sci. 65 485 (2016)

Details by A. Ringwald (Wed.)



Spontaneous PQ symmetry breaking



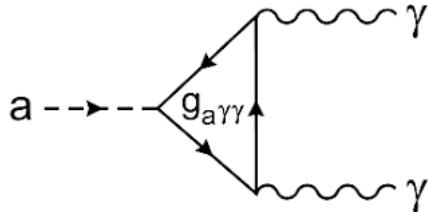
Goldstone boson

Axion models and detection

- Axion coupling to SM*

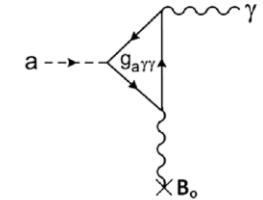
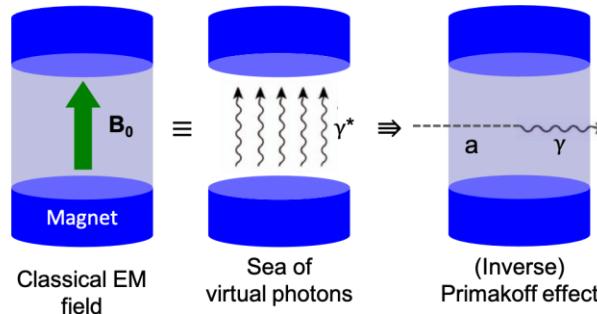
	Photons	Fermions	$nEDMs$
Hamiltonian	$g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$	$g_{aff} \nabla a \cdot \hat{\mathbf{S}}$	$g_{EDM} a \hat{\mathbf{S}} \cdot \mathbf{E}$
Observable	Photon	Spin precession	Oscillating EDM
Detection	Power spectrum, photon counter, ...	Magnetometer, NMR, ...	NMR, polarimeter,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

- Axion models*



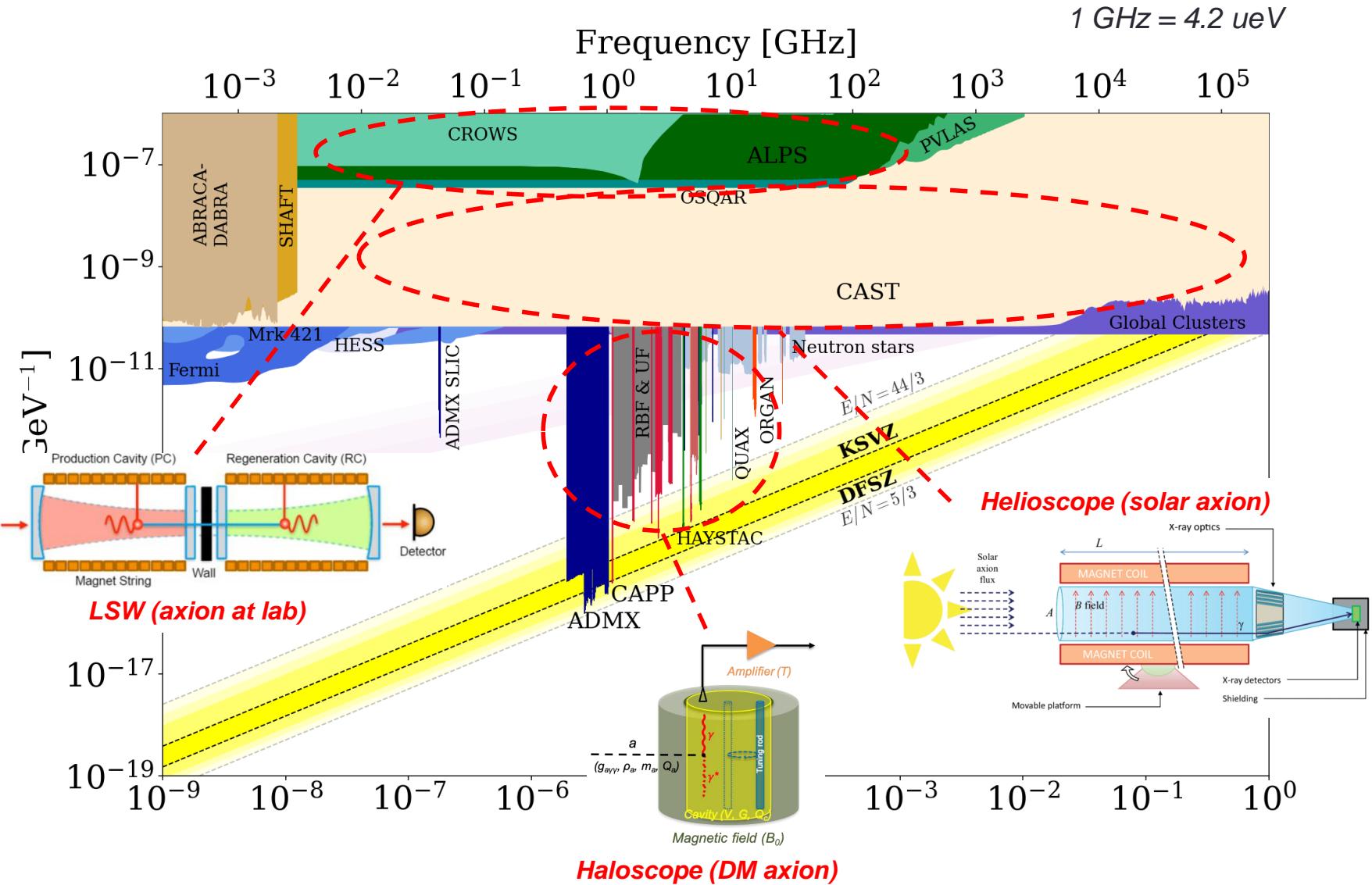
- Detection principle*

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



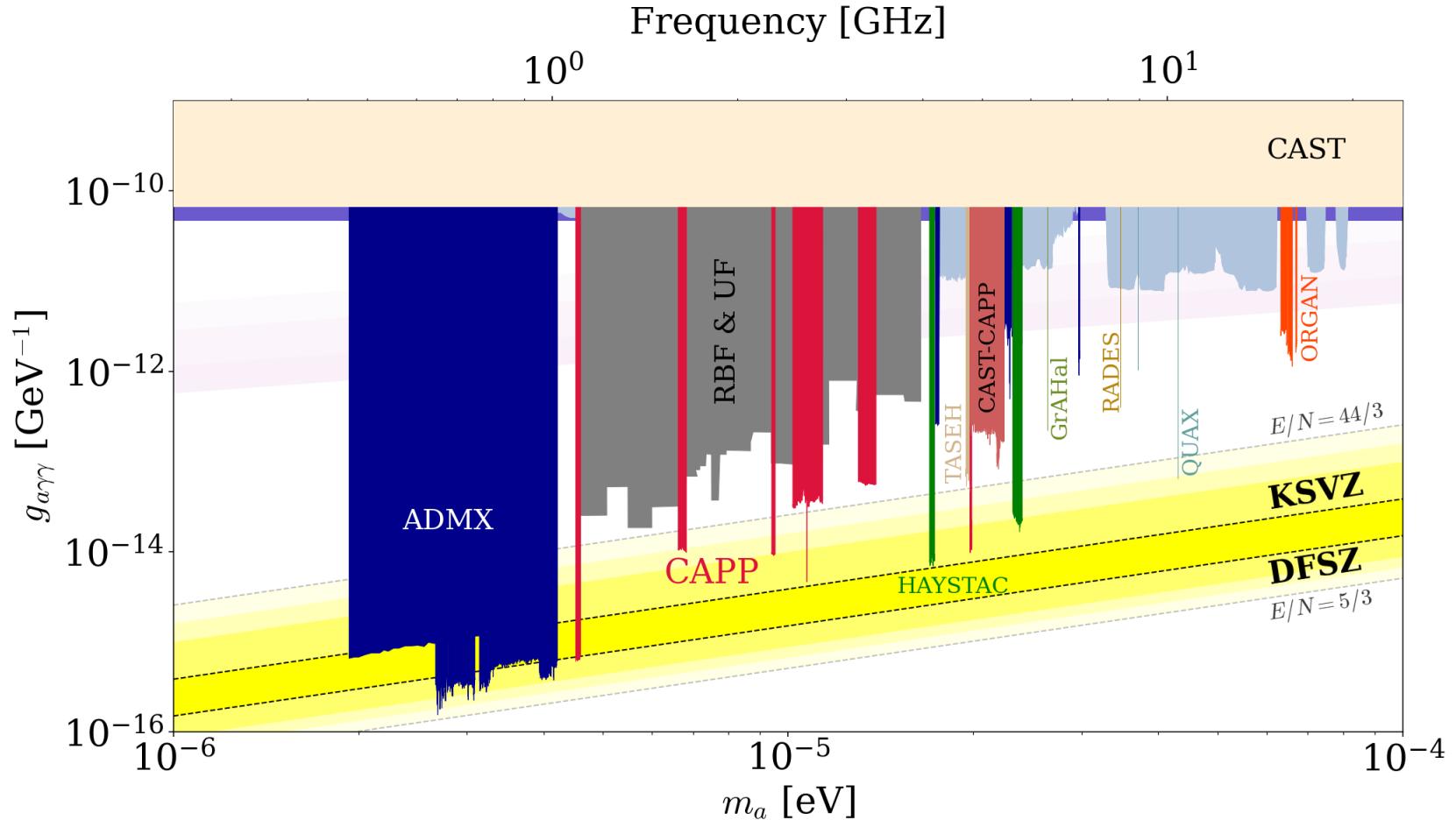


Axion searches





Haloscope searches

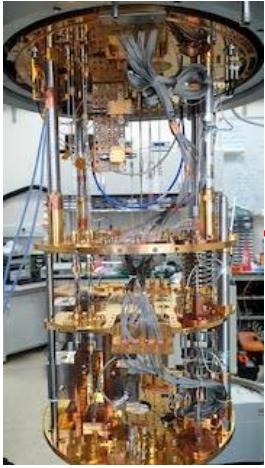




Cavity haloscope – in a nutshell

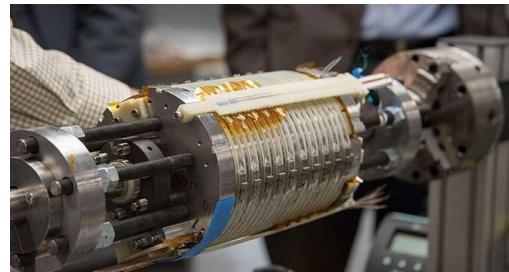
- Most sensitive in the ueV region

Cryogenics T



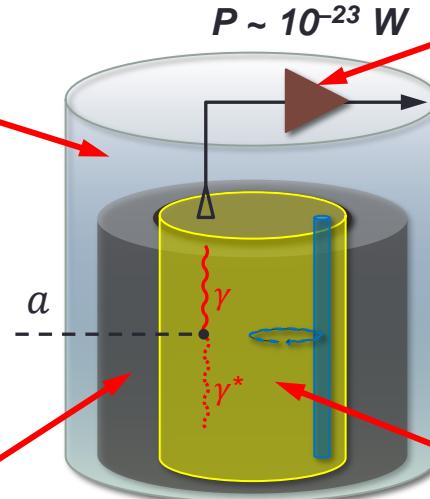
Lowering thermal noise

High field Magnet B



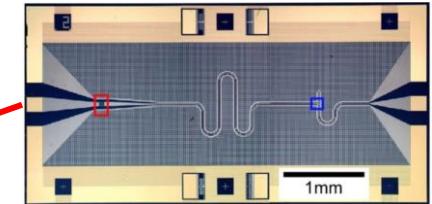
Boosting $a \rightarrow \gamma\gamma$ conversion rate

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



Small-scale experiments!

Quantum noise limited amplifier T



Signal amplification w/
minimal noise added

**Tunable High-Q resonator
 $V, Q, C, \Delta f$**



Resonant frequency tuning



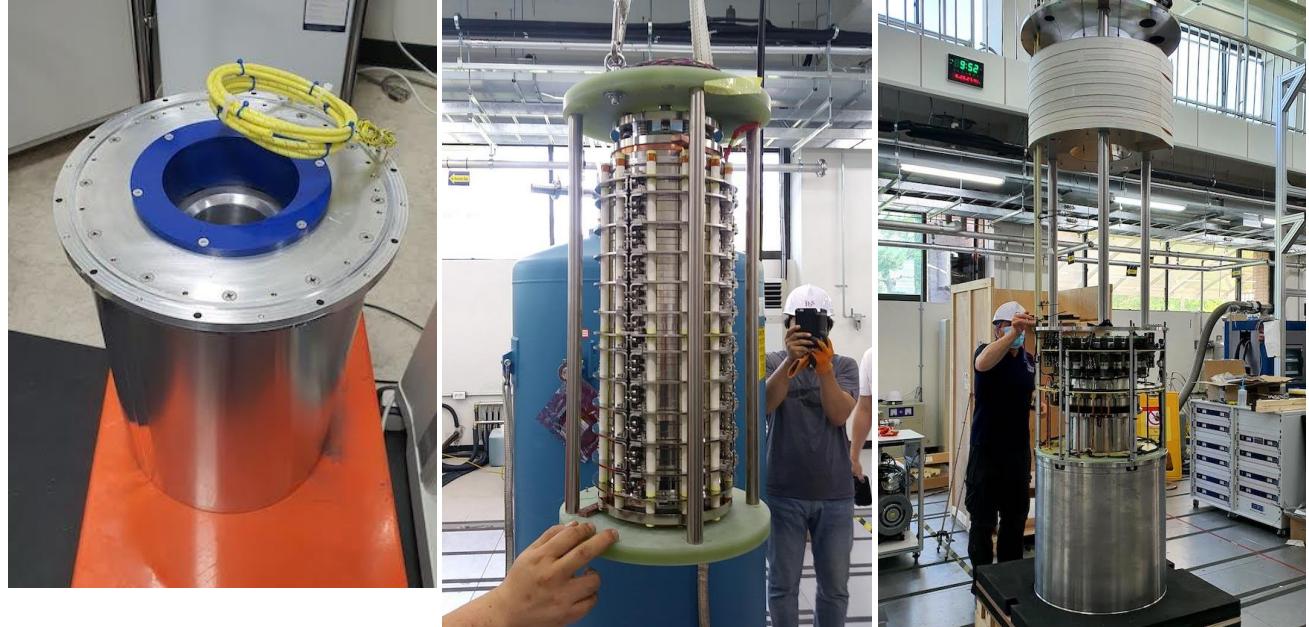
IBS-CAPP (since 2013)

**CAPP-9T****CAPP-12TB****CAPP-18****CAPP-PACE****CAPP-8TB**



High-field SC magnets

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

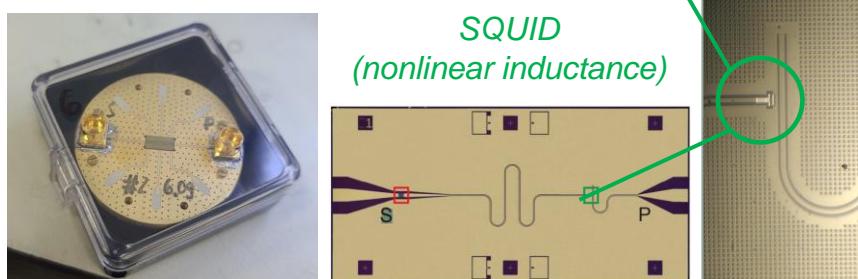
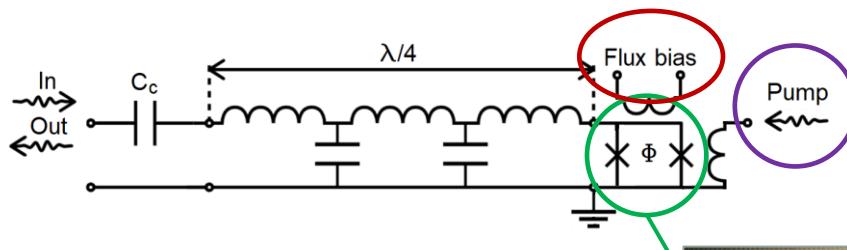
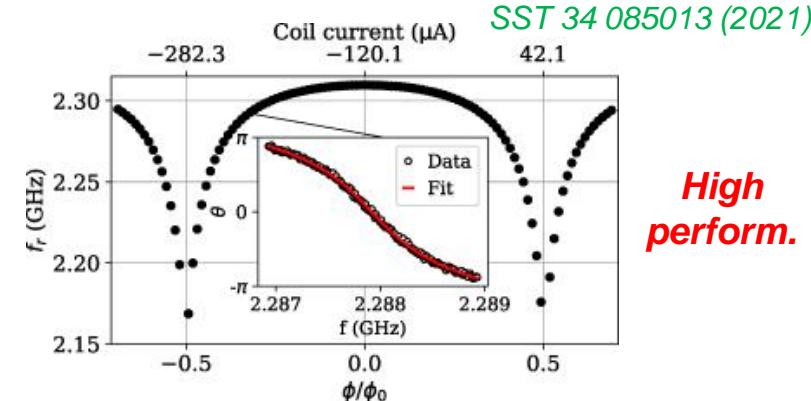


Magnet	CAPP-8T(B), 12T	CAPP-18T	CAPP-12TB
Manufacturer	AMI, Cryomagentics	SuNAM	Oxford
B_{max} @ 4 K	8-12 T	18 T	12 T
Bore (clear)	96-165 mm	70 mm	320 mm
SC material	NbTi, Nb ₃ Sn	GdBCO (HTS)	Nb ₃ Sn
Delivery	2017-2021	2017	2020
Frequency	> 2 GHz	> 4 GHz	> 1 GHz
Sensitivity	KSVZ	KSVZ	DFSZ



QNL amplification

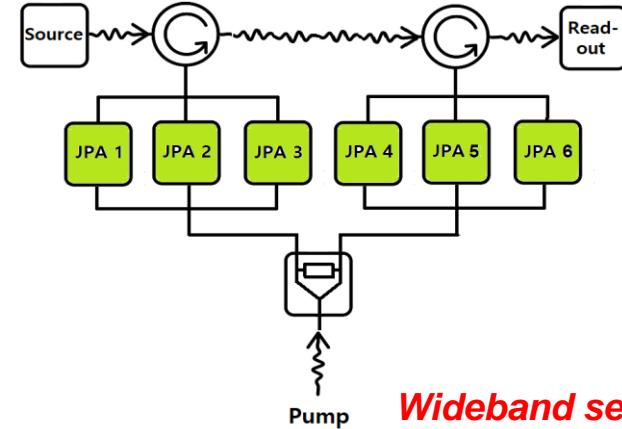
- Flux-driven Josephson parametric amplifiers (JPAs)



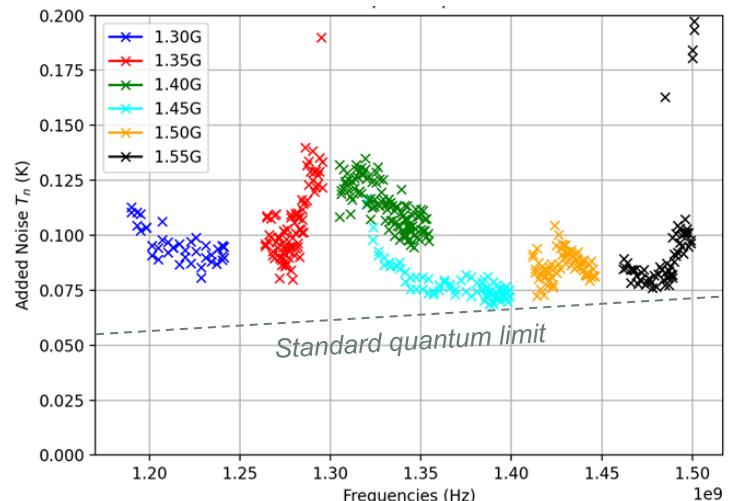
U. of Tokyo & RIKEN

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

Parallel-Serial configuration



Wideband search

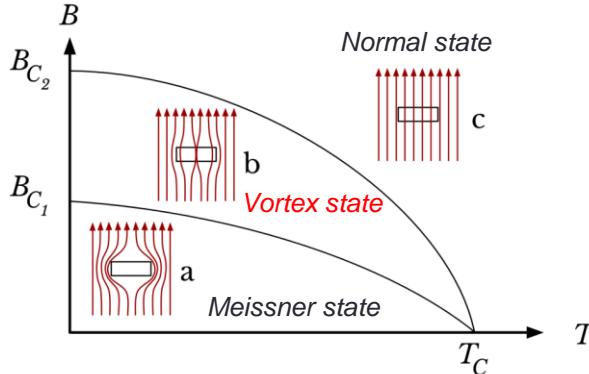




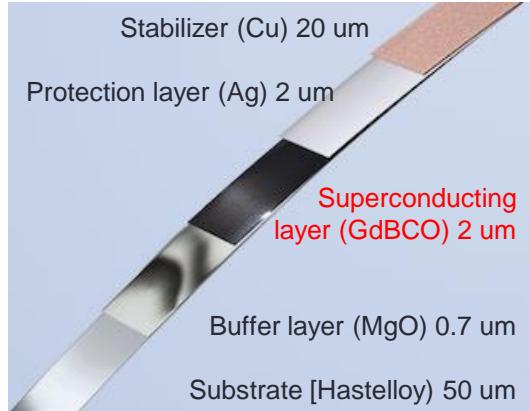
Superconducting cavities

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

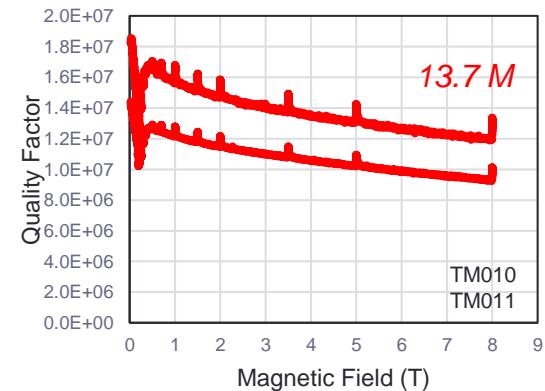
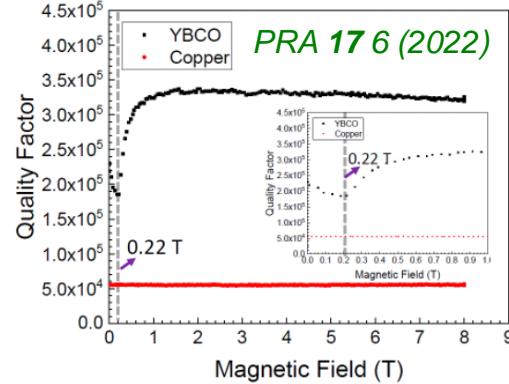
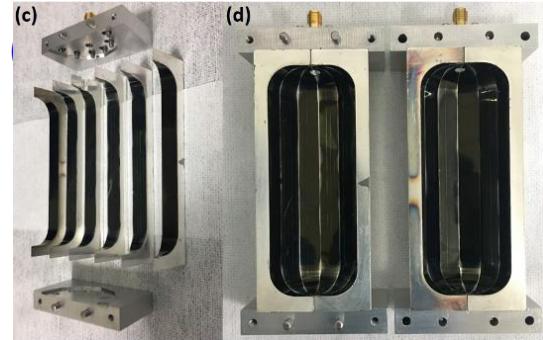
High-Temp. Superconductor



ReBCO HTS tapes (2D)



+ 3D body = SC cavity



Generation	1 st	2 nd	3 rd
Material	YBCO	GdBCO	EuBCO+APC
Substrate	<i>NiW</i>	<i>Hastelloy</i>	<i>Hastelloy</i>
V [L]	0.3	1.5	1.5
f [GHz]	6.9	2.3	2.2
Q	0.33 M	0.5 M	4.5 M
			13 M

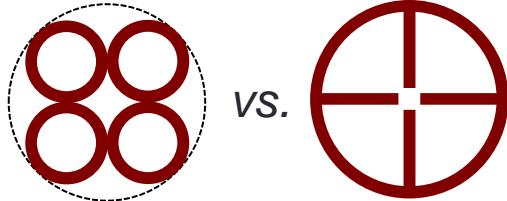
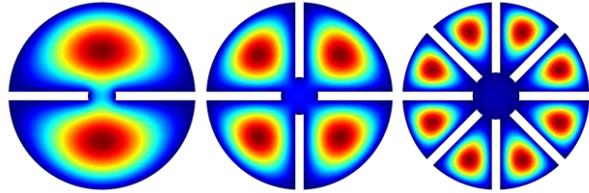


High-frequency approach

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

Multiple-cell (pizza)

PLB 777 412 (2018)



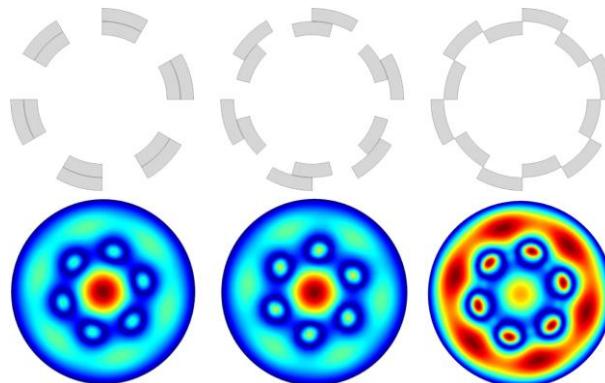
- Larger volume
- Simpler receiver chain
- $\sim 4 \times f_{TM010}$



Higher-mode (wheel)

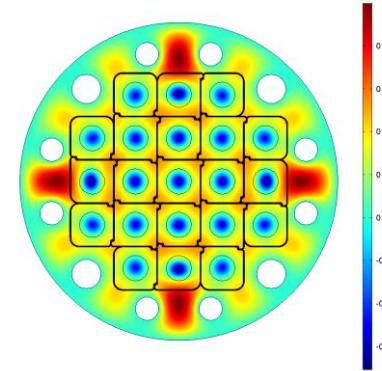
Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM_{010}	1	1	1	0.69
TM_{030}	3.6	1.9	1	0.05

JPG 47 035203 (2020)



Photonic crystal

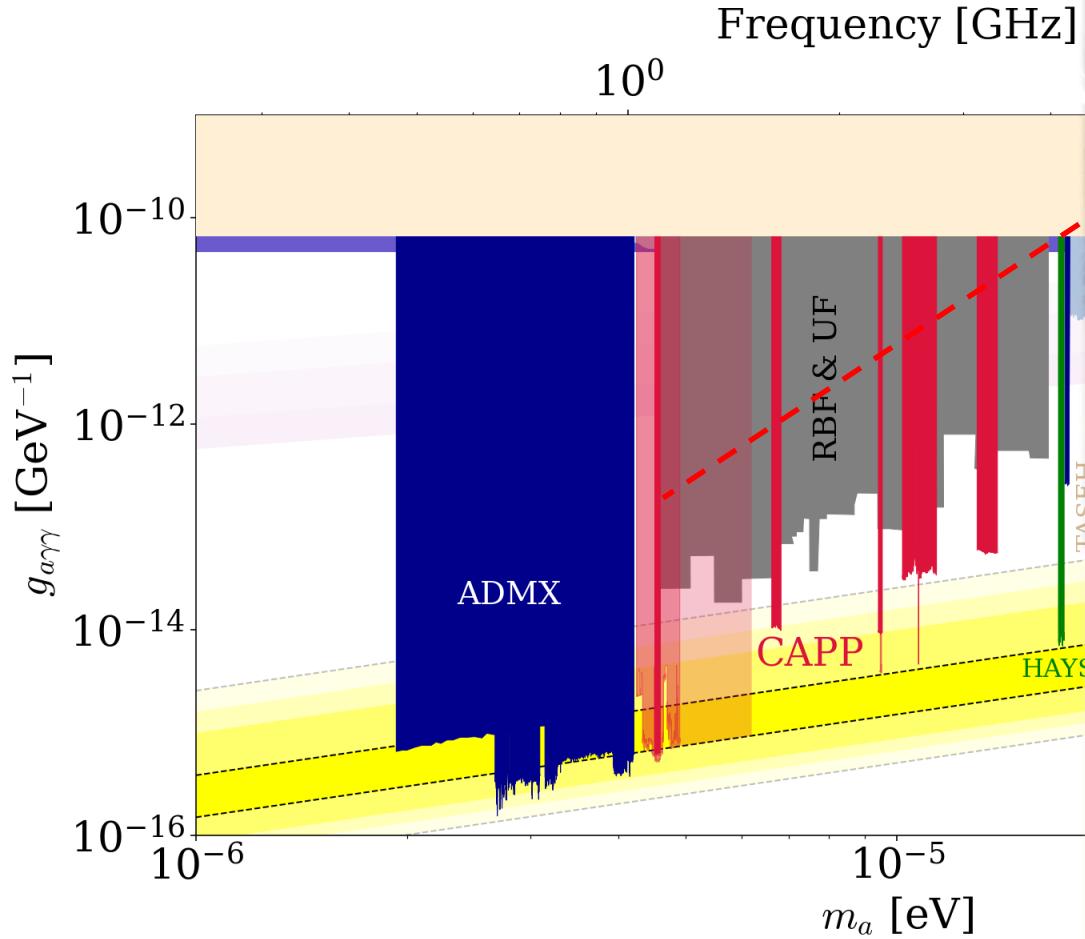
PRD 107 015012 (2022)



- $f \propto \text{spacing}$
- $\sim 10 \times f_{TM010}$
- Boosting effect



Search highlight

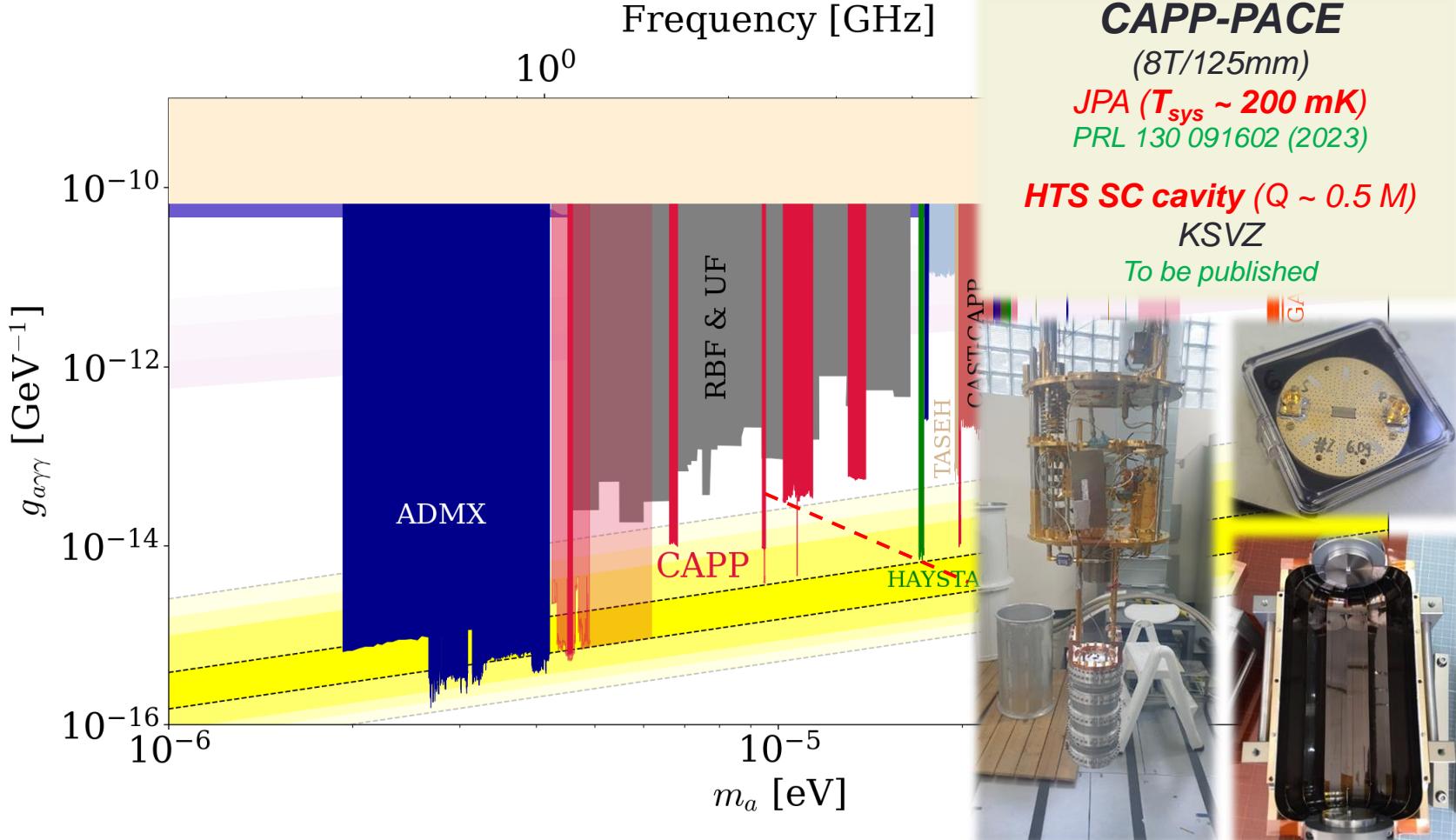


KSVL
CAPP-12TB
 $(12T/320mm)$
 $T_{\text{sys}} < 250 \text{ mK}$
 $df/dt \sim 1.5 \text{ MHz/day} @ \text{DFSZ}$
DFSZ club!
PRL 130 071002 (2023)

*Extended scan ($\Delta f \sim 120 \text{ MHz}$)
to be published
Ready for up to 1.5 GHz*

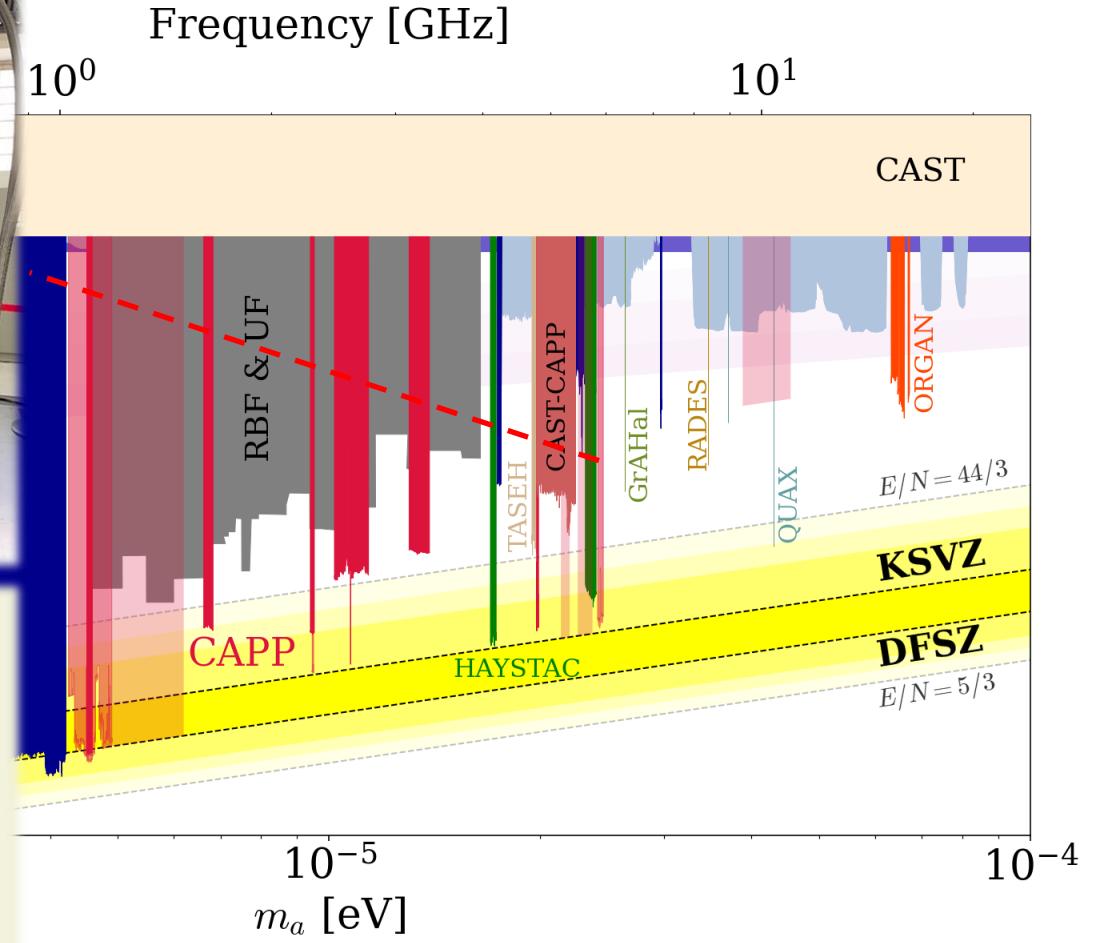
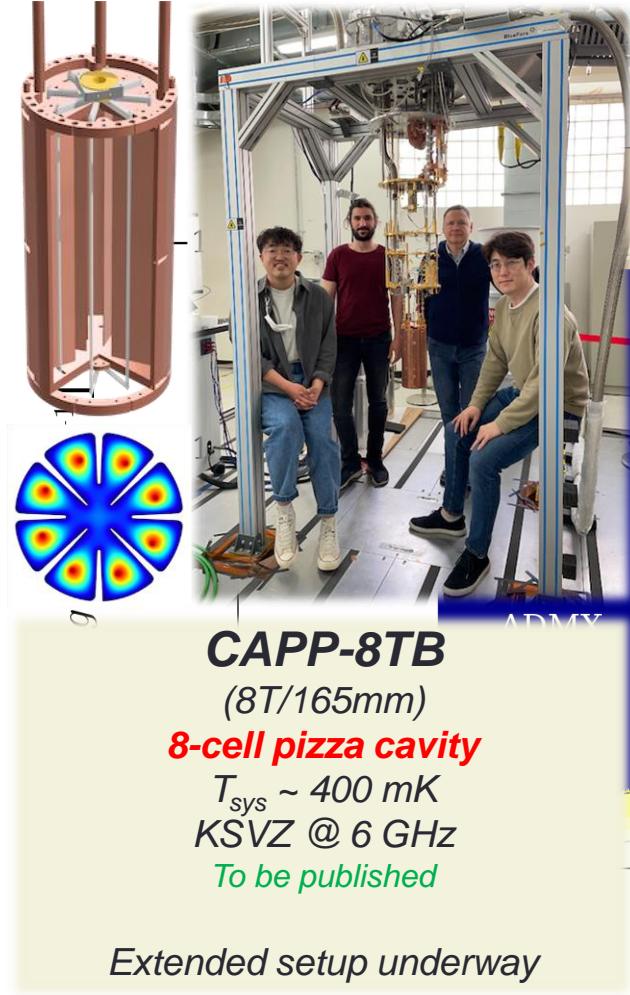


Search highlight



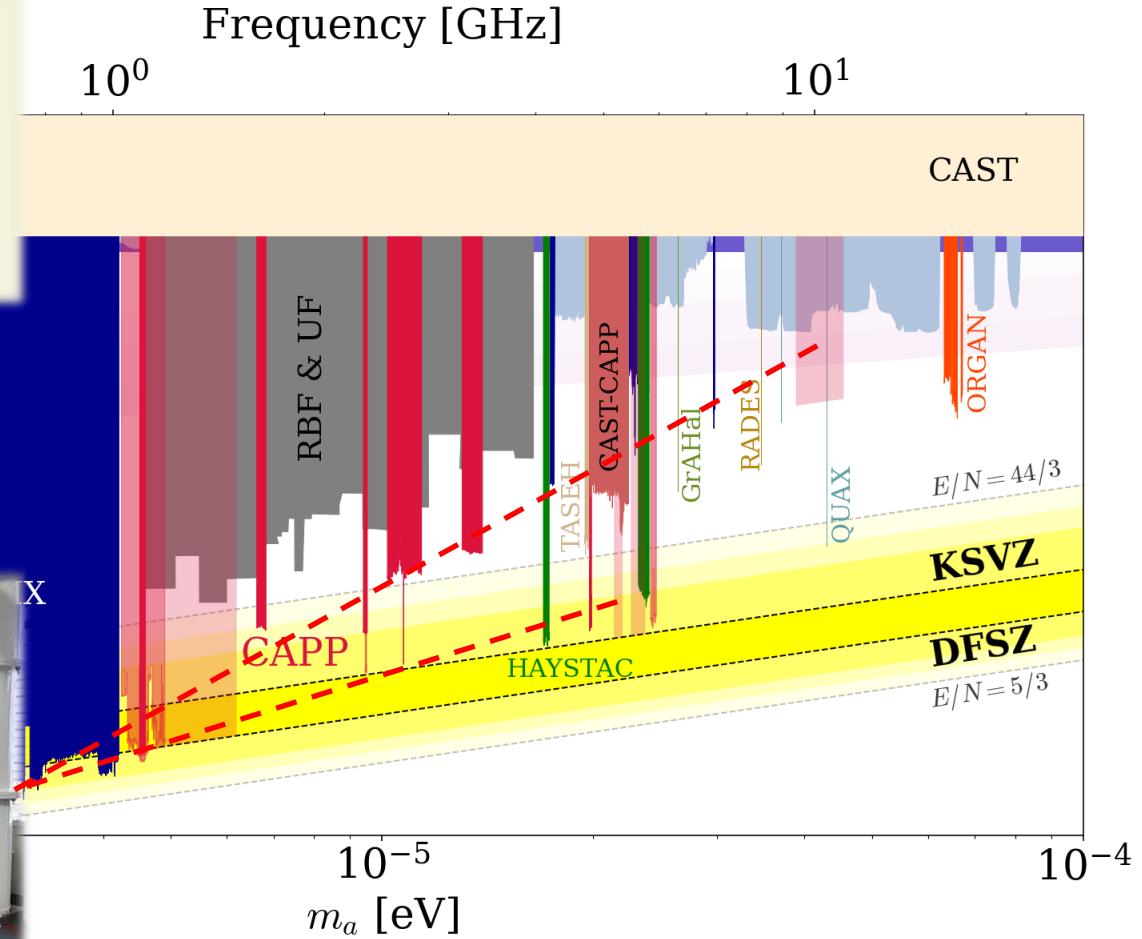
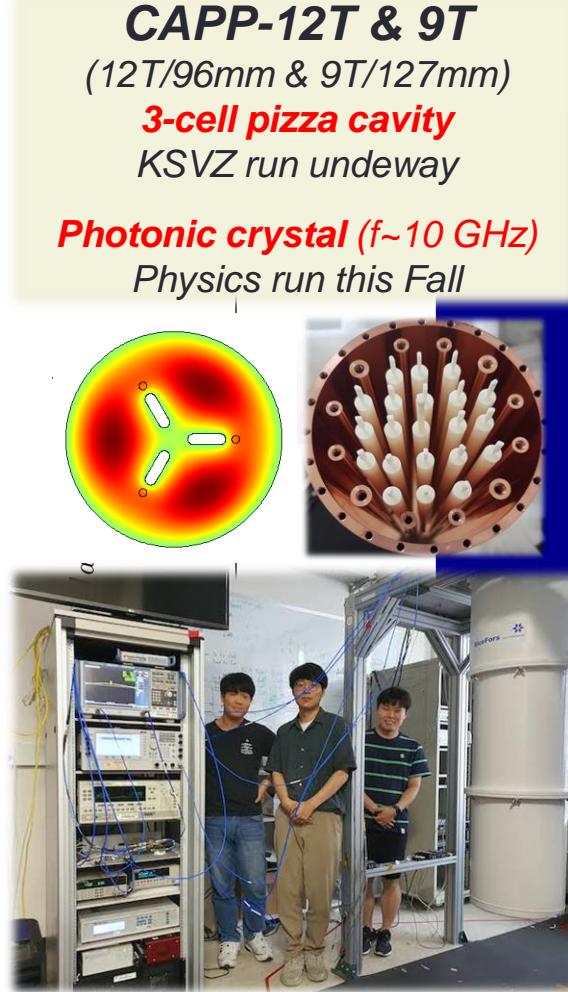


Search highlight





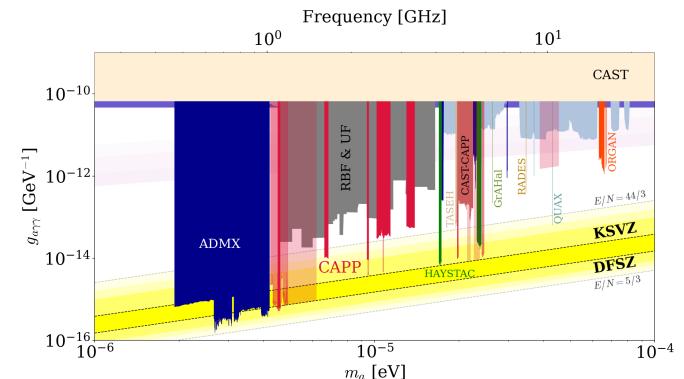
Search highlight





Summary

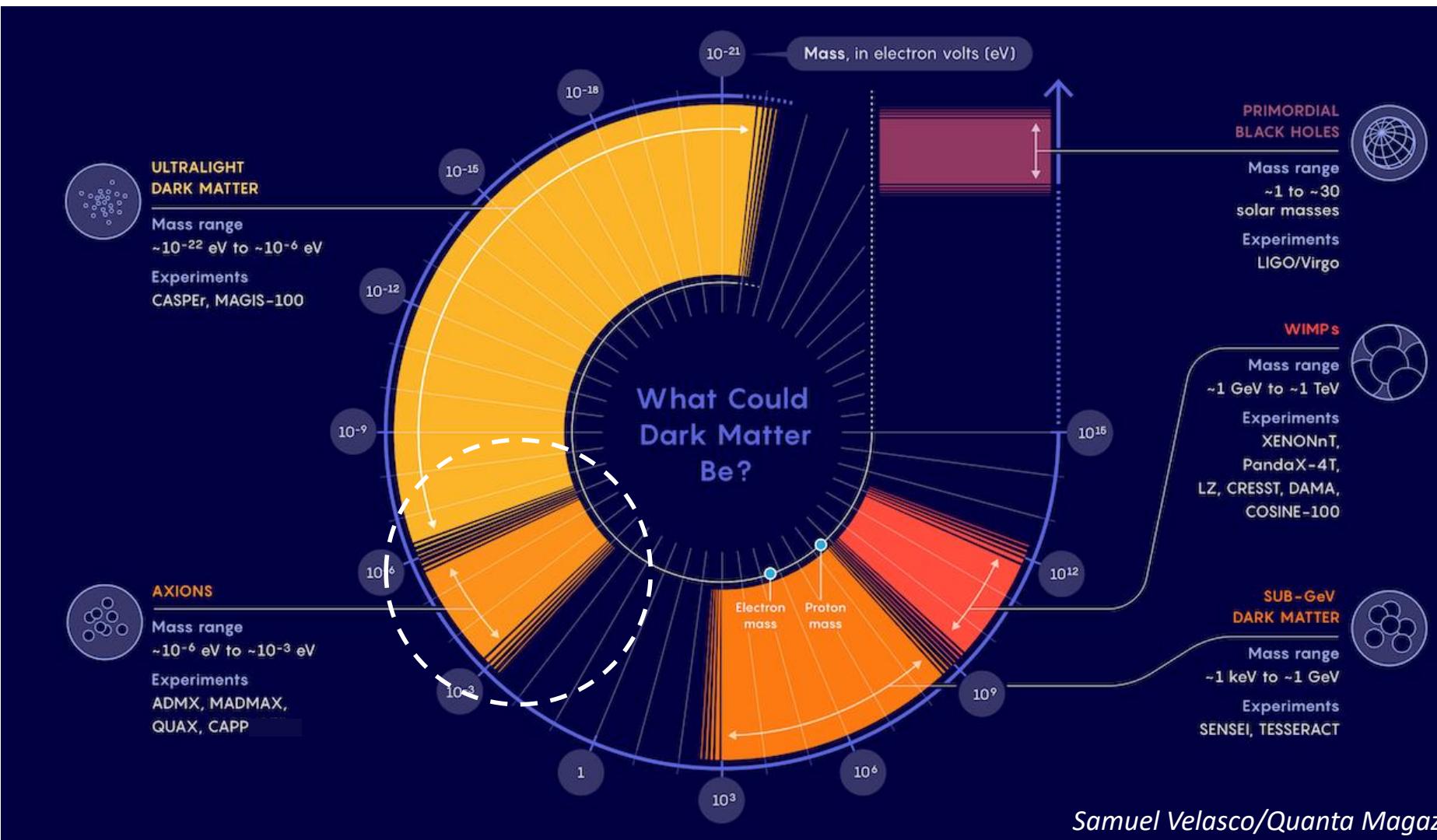
- Axion addresses fundamental questions
 - Strong CP problem and dark matter mystery
- Experimental efforts are growing internationally
- CAPP makes substantial contributions to this business
 - Powerful equipment and high-performance devices
 - Unique development of high-frequency, high-quality cavities
 - Multi-experimental search in different mass regions
- Next decade must be exciting
 - Uncovering the nature of dark matter
- Please stay tuned!



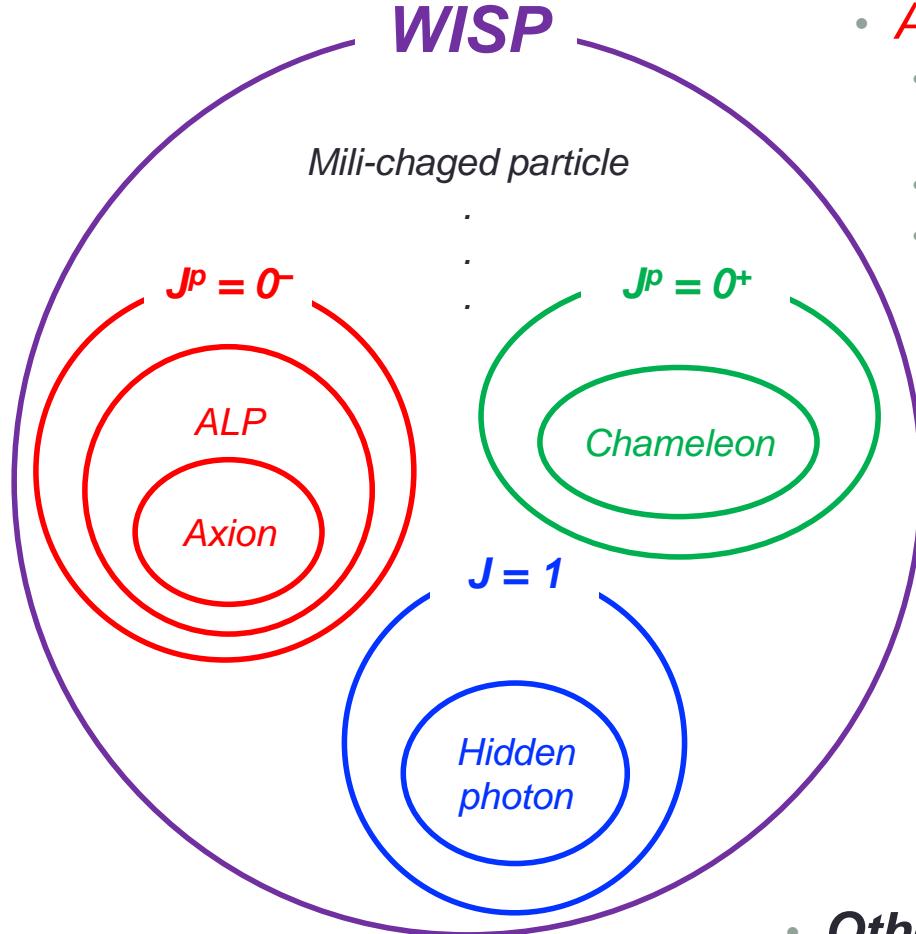




Dark matter business expanding



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
 $m_a f_a \not\sim \Lambda_{QCD}$
- **Scalar**
 - Chameleon (2003)
 - Dark energy candidate
- **Vector**
 - Hidden photon
 - Gauge field in hidden sector
- **Others**
 - Mili-charged particle, ...



Where are dark matter axions?

- *Different PQ breaking scenarios*
=> *Different mass ranges*
=> *Different search strategies*
Depending on λ_{Comp} w.r.t. D_{exp}

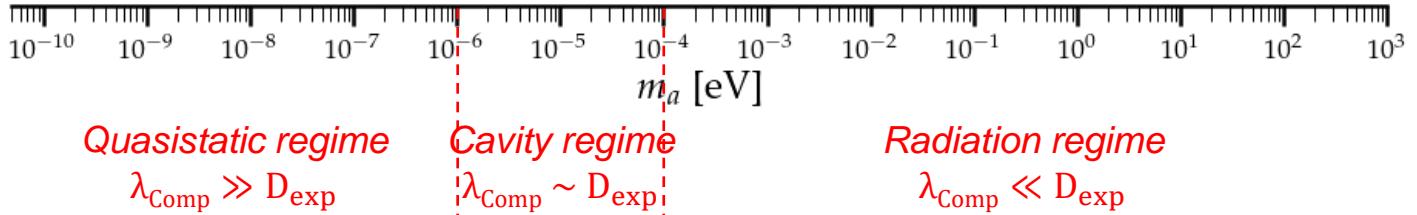
Theoretical scenarios

Photon coupling

Fermion/gluon coupling

Post inflation $N_{\text{DW}} > 1$

Post inflation $N_{\text{DW}} = 1$





Detector of halo axions

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

- *Conversion signal power ($a \rightarrow \gamma\gamma$)*

$$P_{a \rightarrow gg} = g_{agg}^2 \frac{r_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a) \sim 10^{-21} W$$

Annotations for the equation:

- $\boxed{?}$ Coupling constant
- $\boxed{?}$ Axion number density
- $\boxed{?}$ Effective volume
- $\boxed{?}$ Magnetic field
- $\boxed{?}$ Cavity Q factor
- $\boxed{?}$ Axion Q factor

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

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a \rightarrow gg}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{Df_a}}$$

Annotations for the equation:

- $\boxed{?}$ Integration time
- $\boxed{?}$ Axion bandwidth ($\sim 10^{-6} \text{ Hz}$)
- $\boxed{?}$ System noise temperature

- *Scanning rate (F.O.M.):*

$$\frac{df}{dt} = \left(\frac{1}{SNR} \right)^2 \left(\frac{P(f)}{k_B T_{syst}} \right)^2 \cdot \frac{Q_a}{Q_L} \square B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Annotations for the equation:

- $\boxed{?}$

