Searches for Axion Dark Matter at IBS-CAPP

CAPP
Center for Axion and Precision Physics Research

The Dark Side of the Universe 2022

Dec. 05. 2022 USNW

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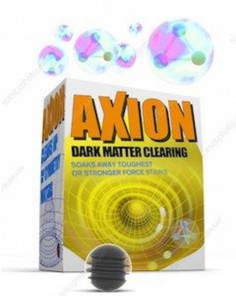
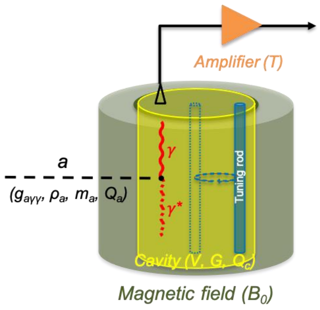
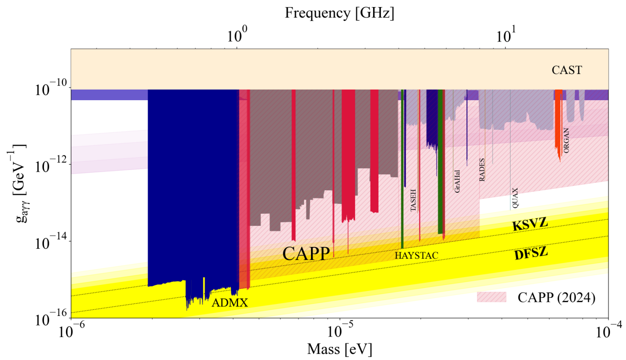
Outline

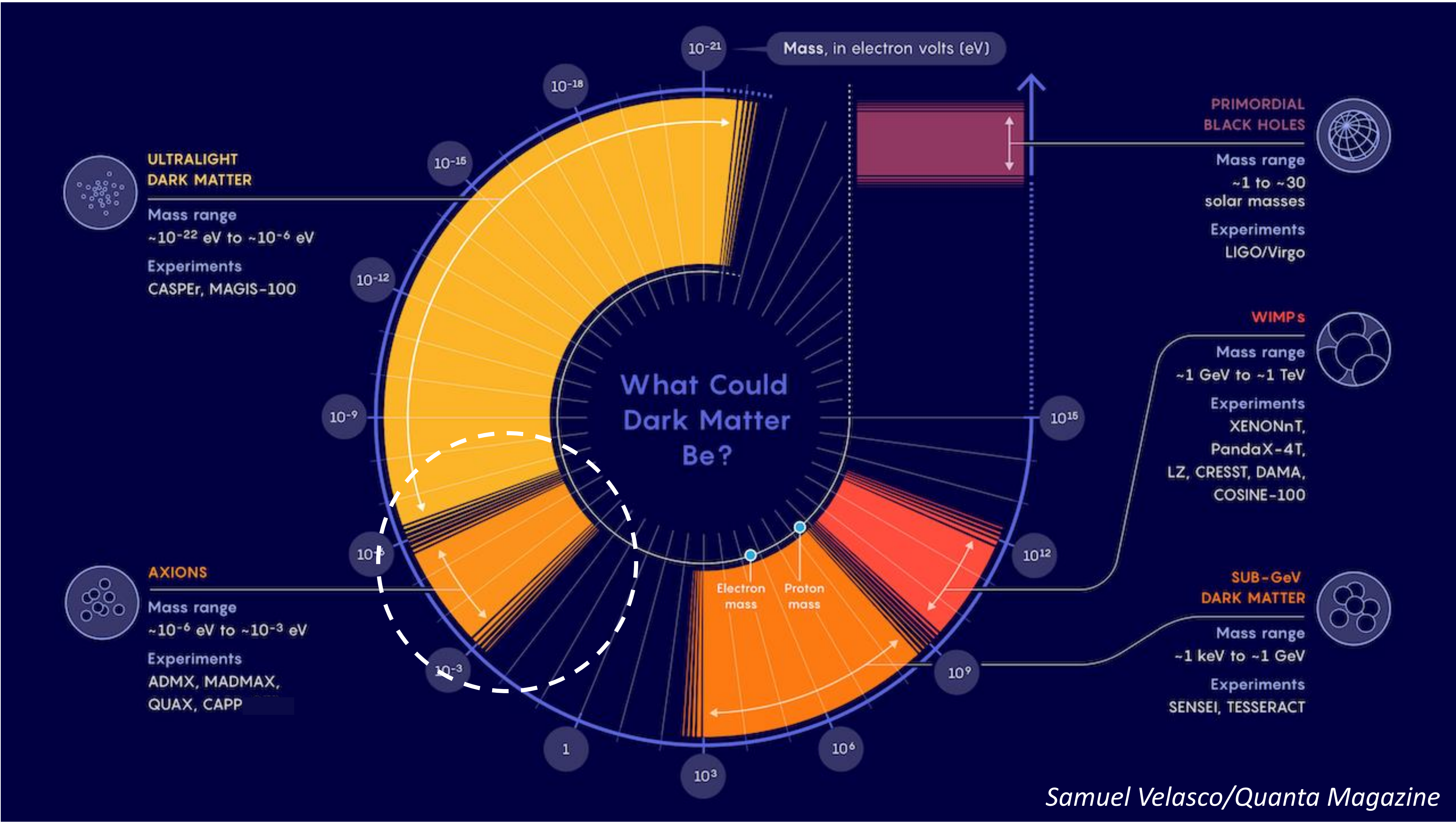
- *Axion dark matter*
  - *Theoretical background*
  - *Experimental search strategies*
- *Axion research at IBS-CAPP*
  - *Ongoing experiments*
  - *Search highlights*
  - *R&D efforts*
  - *Prospects*
- *Summary*







Dark matter business expanding



Samuel Velasco/Quanta Magazine

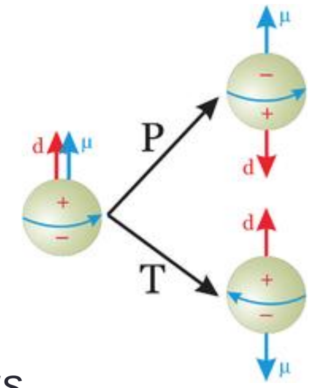
Strong CP problem and axion

- *Strong CP problem*

CPV

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{32\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \Leftrightarrow d_n < 10^{-26}\, cm \cdot e\ (\theta < 10^{-10})$$

Theory: CPV in QCD vs. *Experiment: no nEDM*

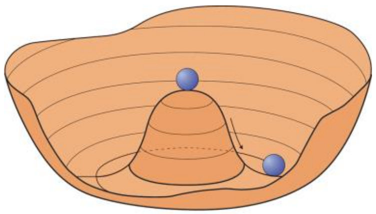


- *PQ mechanism (1977)*
  - *U(1) symmetry w/ scalar field a(x)*

$$\mathcal{L}_{QCD} \supset \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{32\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - *SSB at energy scale f_a*
  - *Dynamic solution to strong CP problem*

Spontaneous symmetry breaking



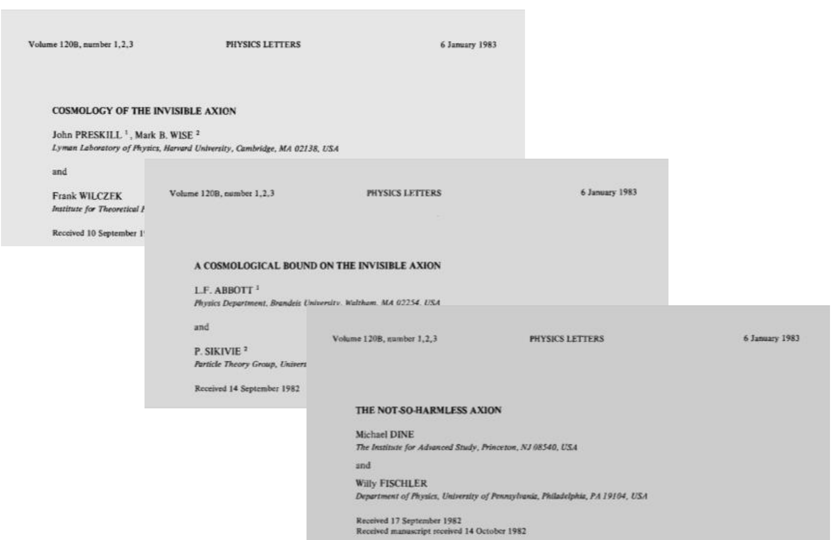
$a(x) = \theta \times f_a$

- *Axion (1978)*
  - *(pseudo-scalar) Nambu-Goldstone boson*
  - *QCD axion*
    - *Mass related to QCD scale:* $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$
    - *cf. axion-like particle (ALP)*

Invisible axion and dark matter

- *Invisible axion (1979)*
  - *Very light axion*
  - *SSB at a very large f_a (i.e. produced in early universe)*
  - $m_a \approx 6\ \mu eV \frac{10^{12}\ GeV}{f_a}$

- *Cosmological implication (1983)*
  - *May account for dark matter*
  - *10^{-6} eV < m_a < 10^{-2} eV*
    - *Cosmological constraints*
    - *Astrophysical observations*



Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

COSMOLOGY OF THE INVISIBLE AXION

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Received 10 September 1

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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Received 14 September 1982

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

THE NOT-SO-HARMLESS AXION

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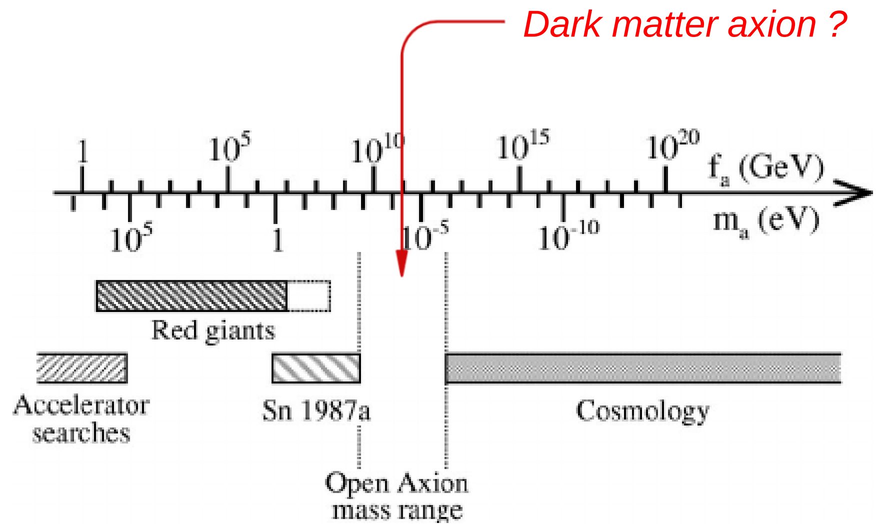
Received 17 September 1982
Received manuscript received 14 October 1982



Couplings and models

- *Axion coupling to SM*

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

- *Axion models*

From R. Ziegler

$U(1)_{PQ} \times SU(3)_c^2$

Origin of QCD anomaly: SM fermions | BSM fermions

Spontaneous PQ breaking: 2Higgs | 2Higgs+singlet | Higgs+singlet

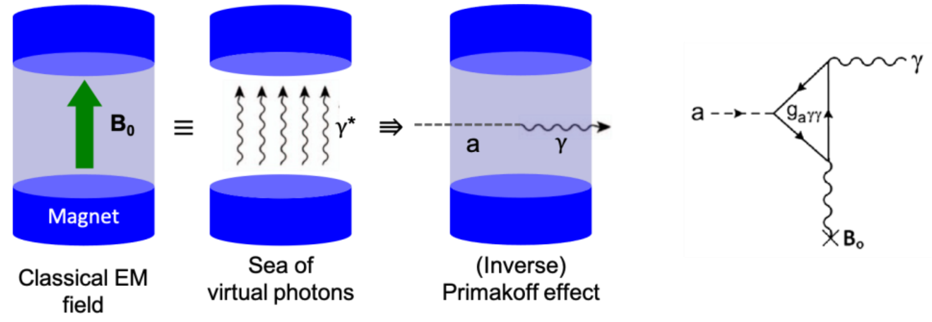
~~**PQWW**~~
Peccei, Quinn, Wilczek, Weinberg (1978)

DFSZ
Dine-Fischler-Srednicki-Zhitnitsky (1980)

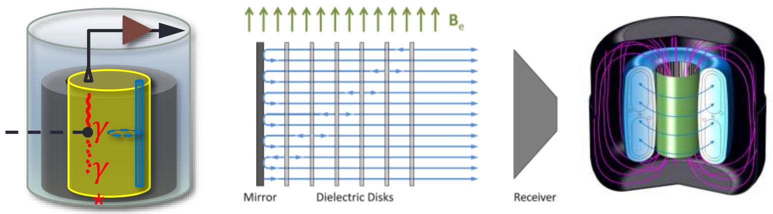
KSVZ
Kim-Shifman-Vainshtein-Zakharov (1980)

Search strategies

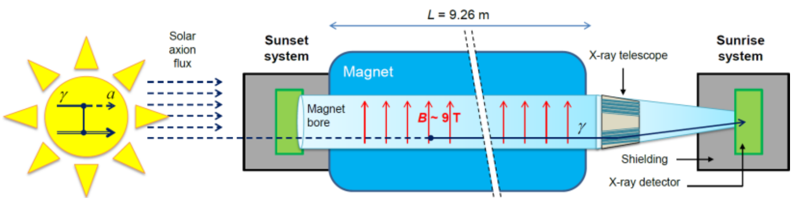
- *Detection principle*
  - *Sikivie effect (1983)*



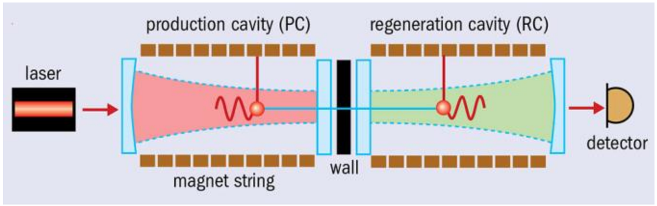
- *Detection methods*
  - *Haloscope*
    - *Dark matter halo*
    - *ADMX, CAPP, MADMAX, DM radio, …*



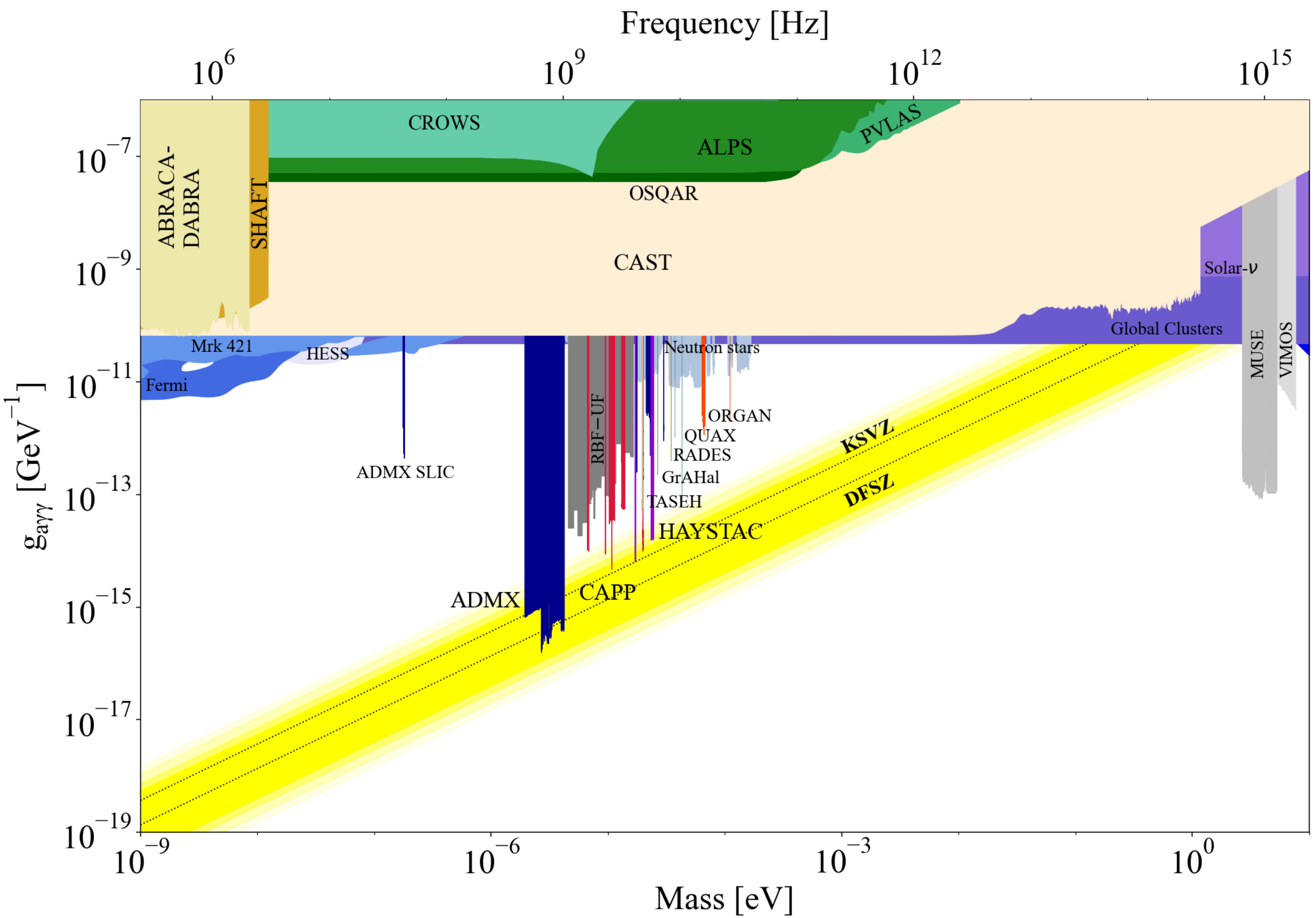
  - *Helioscope*
    - *Solar axions*
    - *CAST, IAXO*



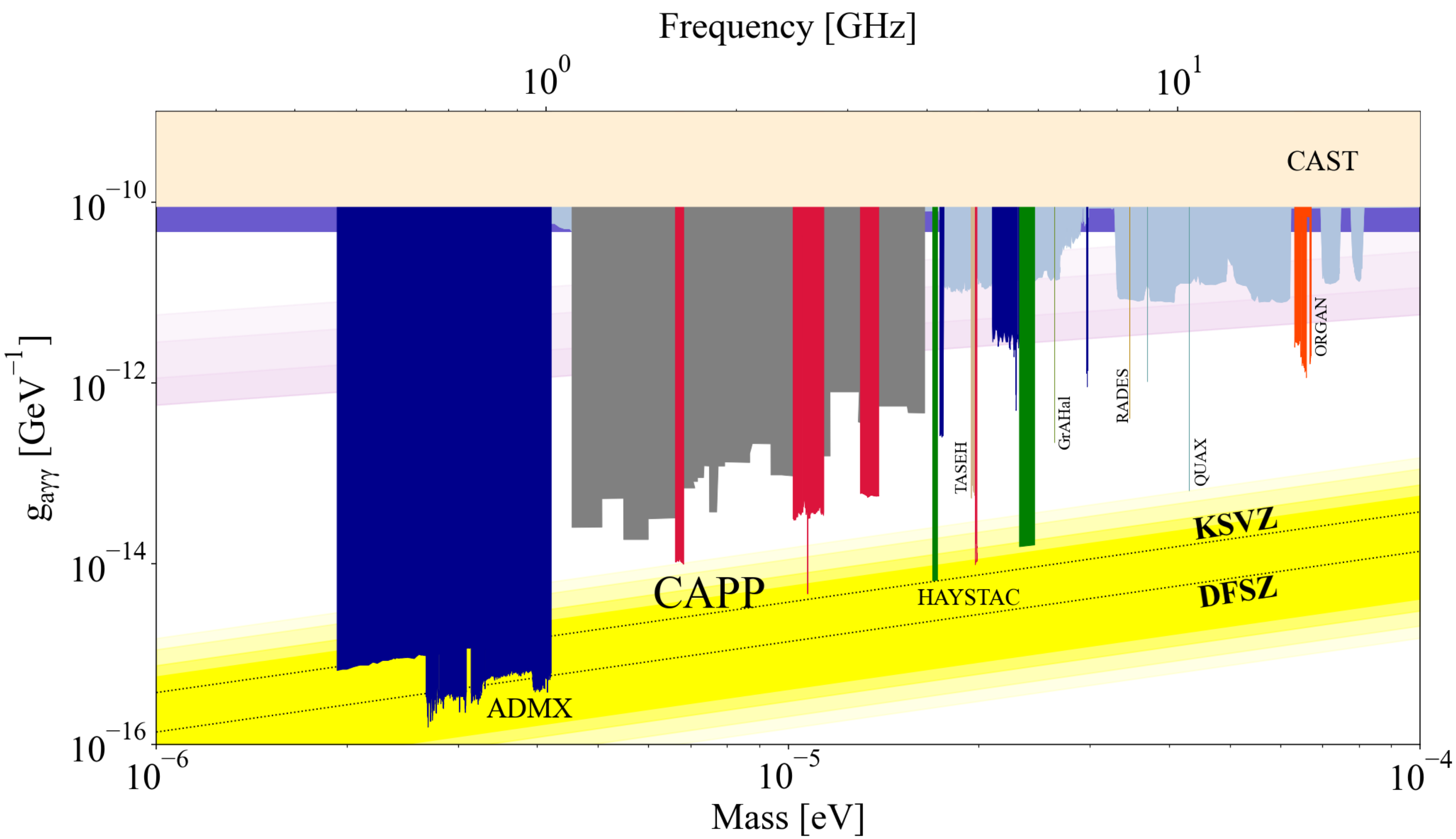
  - *Light shining through walls*
    - *Lab production*
    - *OSQAR, ALPS (II)*



Axion searches



Haloscope searches



Cavity haloscope – in a nutshell

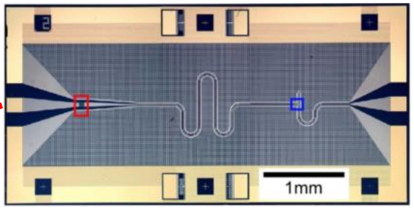
- *Most sensitive for ueV axions*

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

Cryogenics T

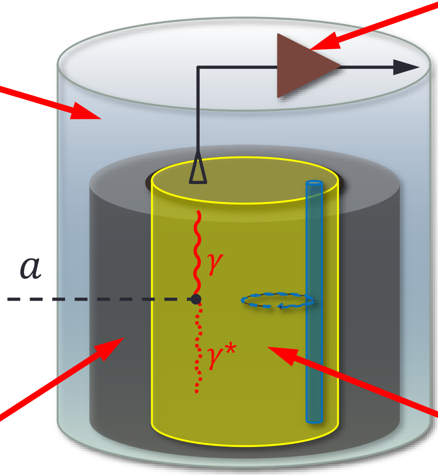
Lowering thermal noise

Quantum noise limited amplifier T

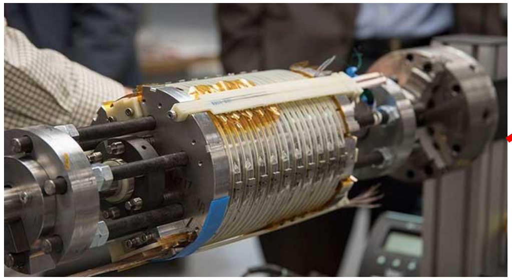


Signal amplification w/ minimal noise added

P ~ 10^{-23} W



High field Magnet B



Boosting a→γγ conversion rate

Tunable High-Q resonator V, Q, C, Δf

Resonant frequency tuning

Small-scale experiments!

IBS-CAPP (since 2013)

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

Equipment at CAPP

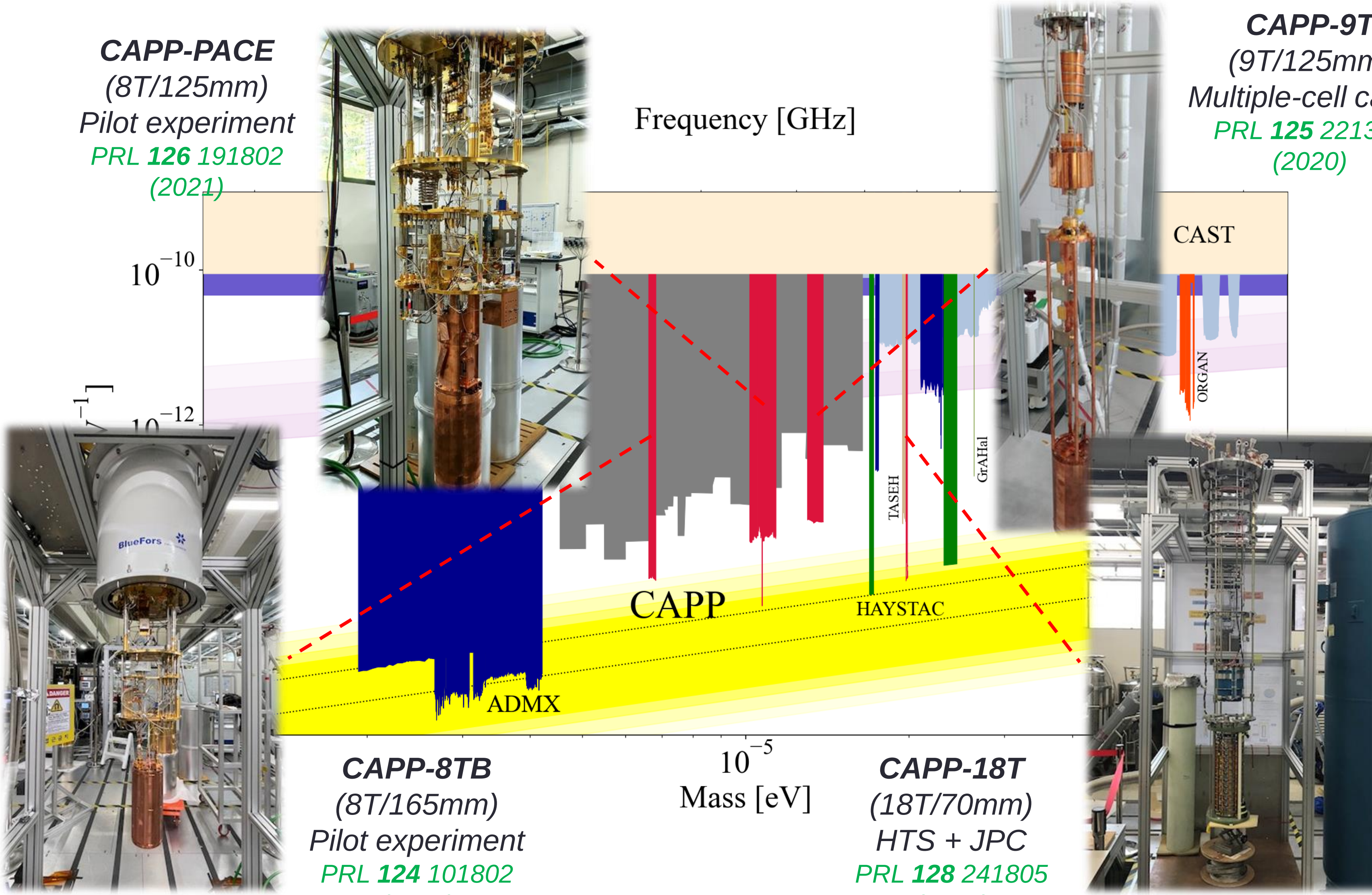
Refrigerators			Magnets			Experiments
Manufacture	**Model**	**T_B [mK]**	**Manufacture**	**B_{max} [T]**	**Bore [mm]**	**Name**
BlueFors (BF3)	***LD400***	***10***	***AMI***	***12***	***96***	***CAPP-12T***
BlueFors (BF4)	*LD400*	*10*				
Janis	***HE-3-SSV***	***300***	***Cryo Magnetics***	***9***	***125***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

Search highlight – published

CAPP-PACE
_(8T/125mm)_
Pilot experiment
PRL **126** 191802
_(2021)_

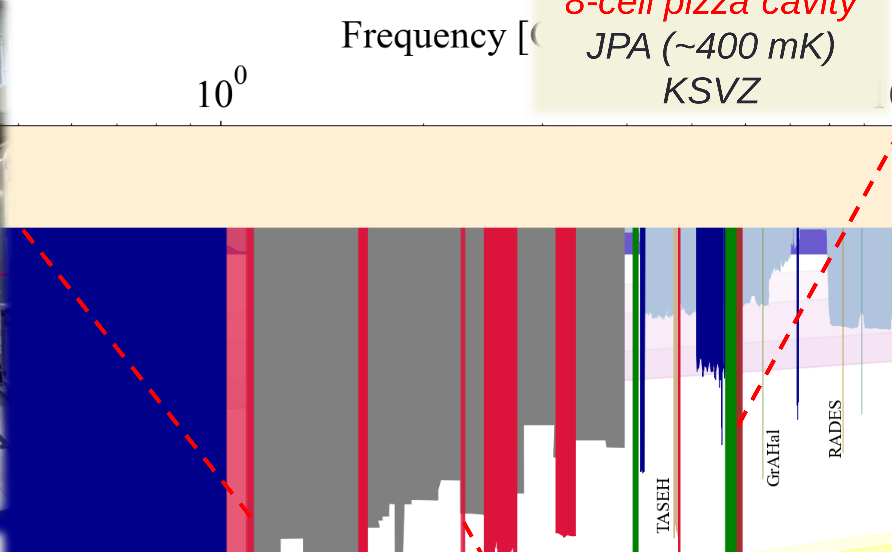
CAPP-9T
_(9T/125mm)_
Multiple-cell cavity
PRL **125** 221302
_(2020)_



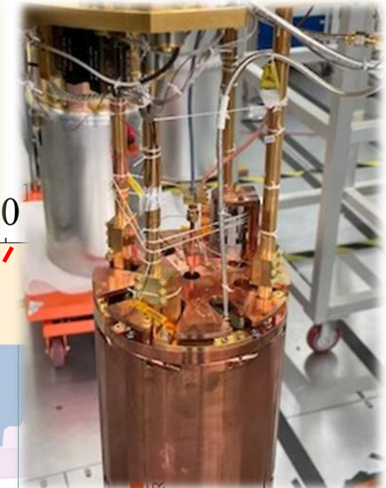
CAPP-8TB
_(8T/165mm)_
Pilot experiment
PRL **124** 101802
_(2020)_

CAPP-18T
_(18T/70mm)_
HTS + JPC
PRL **128** 241805
_(2022)_

Search highlight – to be published



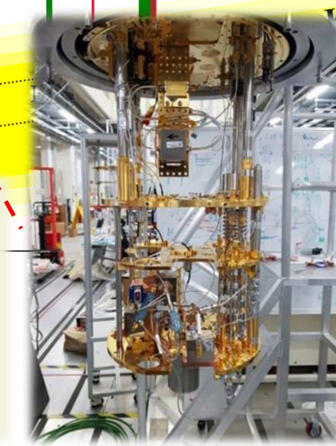
CAPP-8TB
(8T/165mm)
8-cell pizza cavity
JPA (~400 mK)
KSVZ

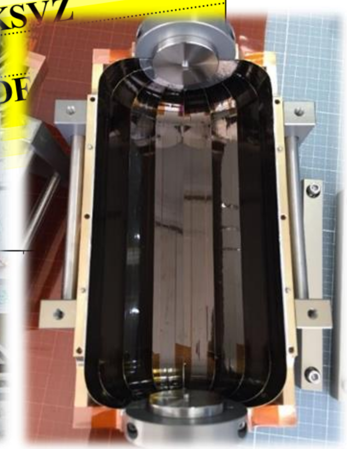


CAPP-12TB
(12T/320mm)
Flagship experiment
T_{cav} < 30 mK

~3 MHz/day @ DFSZ
DFSZ club!
arXiv:2210.10961

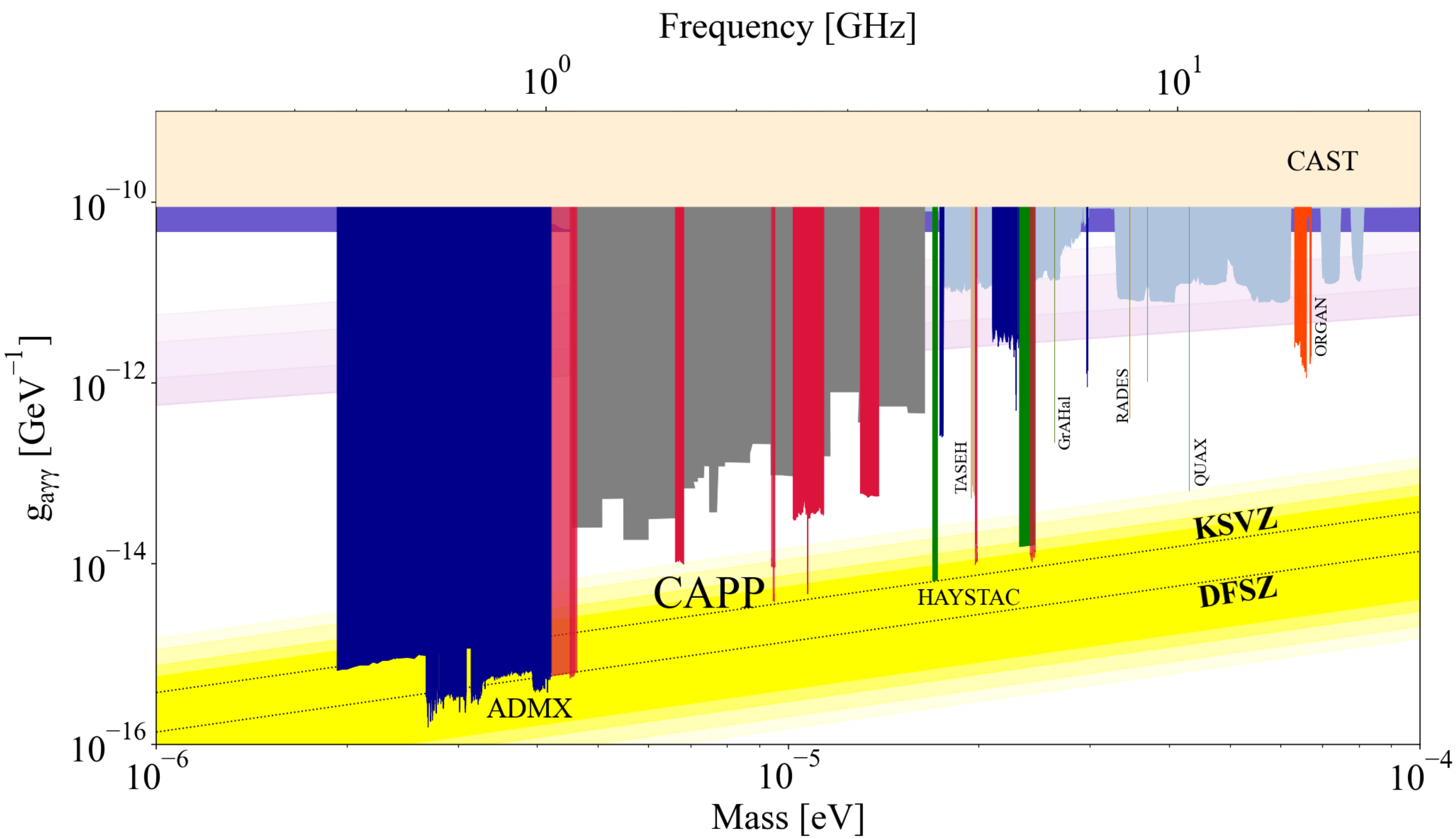
CAPP-PACE
(12T/320mm)
JPA w/ QLN (~200 mK)
HTS SC cavity (Q ~ 0.5 M)
KSVZ
arXiv:2207.13597





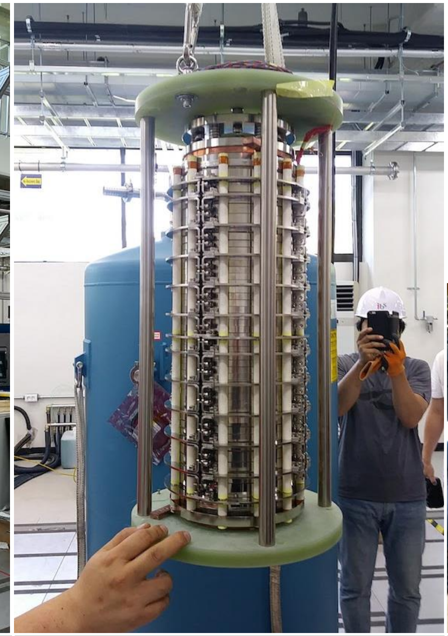
R&D efforts needed

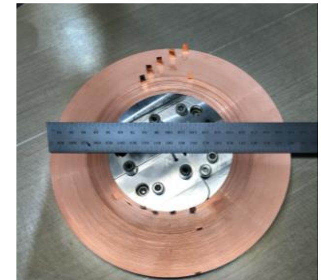
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$



High-field magnets

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



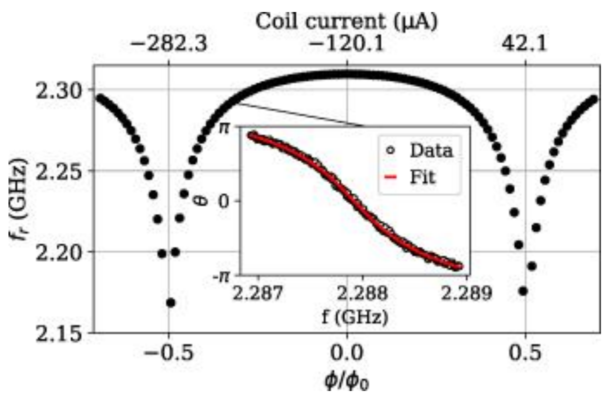


Magnet	*CAPP-12TB*	*CAPP-18T*	*CAPP-25T*
Manufacturer	*Oxford*	*SuNAM*	*IBS-BNL*
B_{max} @ 4 K	***12 T***	***18 T***	*25 T*
Bore (clear)	***320 mm***	*70 mm*	*100 mm*
SC material	Nb_3Sn	***GdBCO***	*YBCO*
Delivery	*2020*	*2017*	*?*
Frequency	*> 1 GHz*	*> 4 GHz*	*> 3 GHz*
Sensitivity	***DFSZ***	***KSVZ***	*DFSZ*

QNL amplification

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

- *Flux-driven Josephson parametric amplifiers*

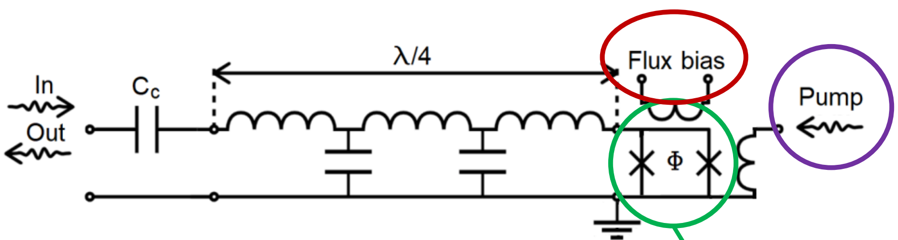


Frequency tuning

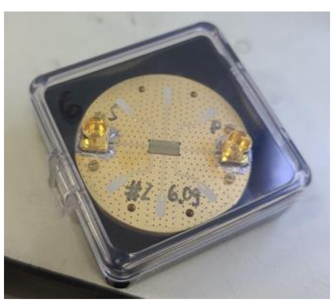
$$I_C = IC_c \cos\left(\frac{\pi\Phi}{\Phi_0}\right)$$

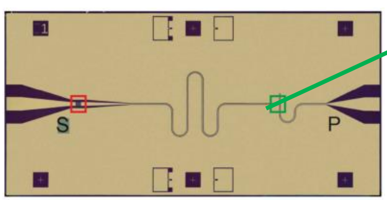
Parametric amplification

$$L(I) = L_0\left[1 + \frac{1}{2}\frac{I^2}{I_c^2}\right], L_o = \frac{\Phi_0}{2\pi I_c}$$

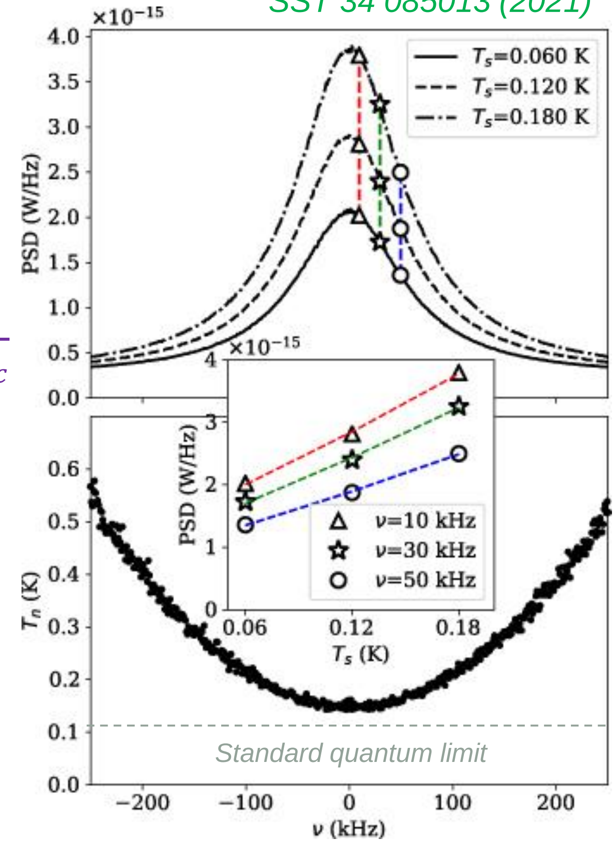


SQUID (nonlinear inductance)





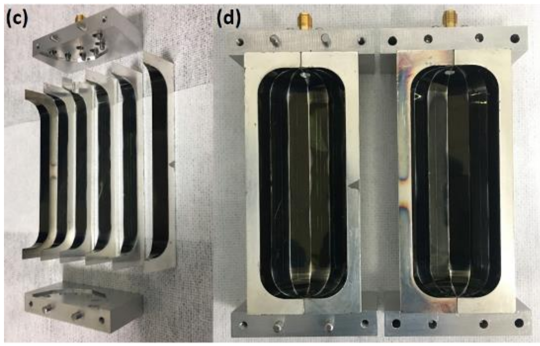
SST 34 085013 (2021)

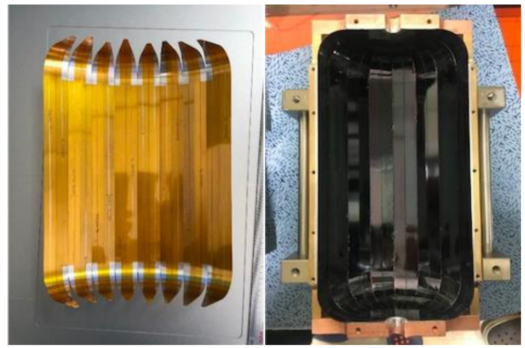


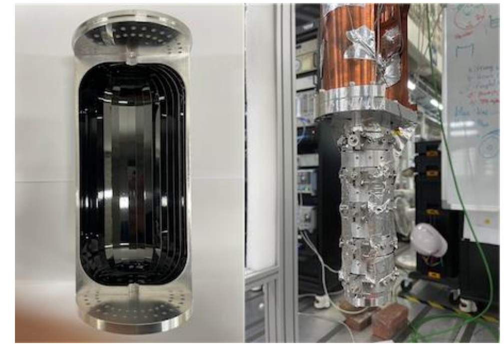
- *>25 JPAs covering 1 to 6 GHz (U. of Tokyo & RIKEN)*

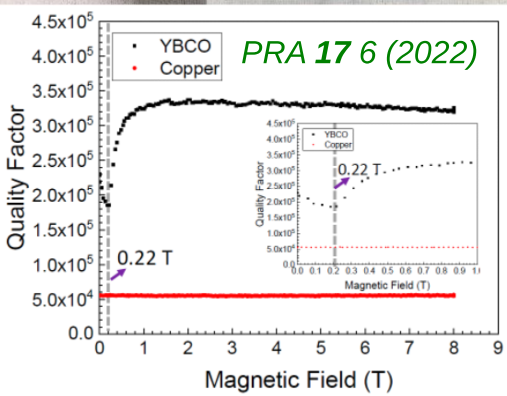
Superconducting cavities

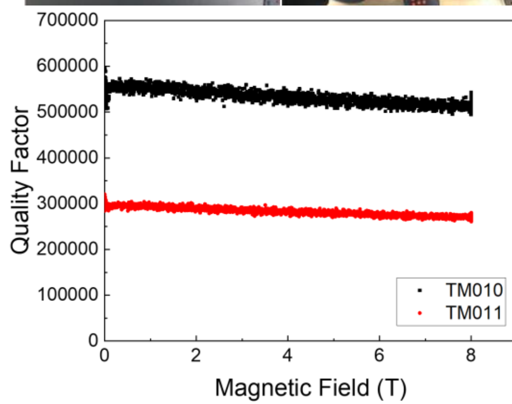
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

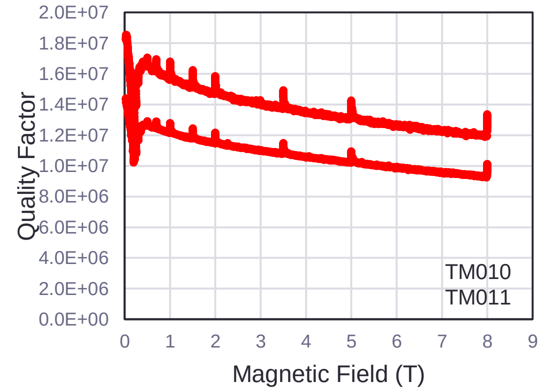












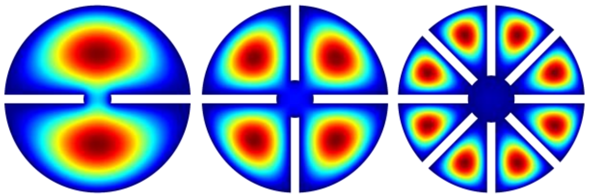
	1st generation	*2nd generation*	*3rd generation*	
Material	*YBCO*	*GdBCO*	*EuBCO+APC*	
Substrate	*NiW*	*Hastelloy*	*Hastelloy*	
Volume [L]	*0.3*	*1.5*	*1.5*	*0.2*
Frequency [GHz]	*6.9*	*2.3*	*2.2*	*5.4*
Q-factor	***0.33 M***	***0.5 M***	***4.5 M***	***13 M***

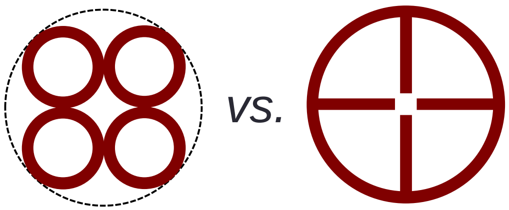
High freq. approach

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

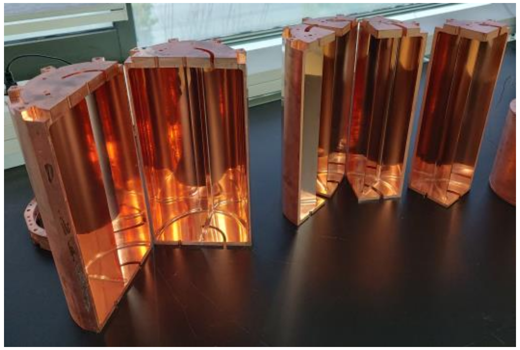
Multiple-cell (pizza)

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





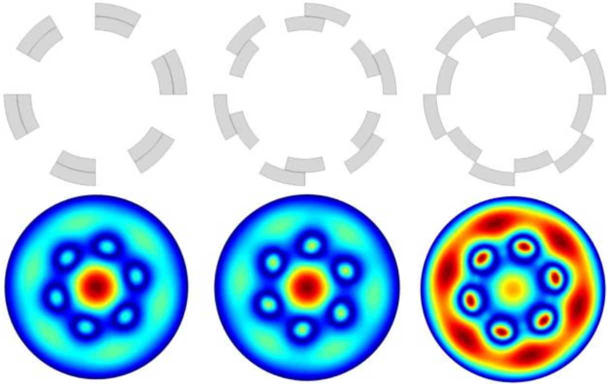
- *Larger volume*
- *Simpler receiver chain*
- *~4 x f_{TM010}*



Higher-mode (wheel)

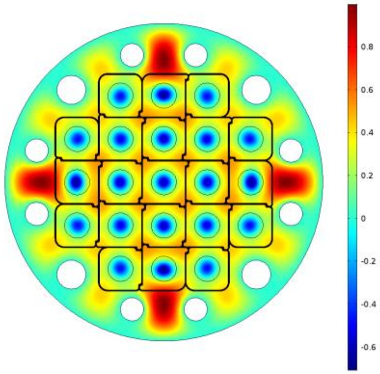
Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM_{010}	1	1	1	0.69
TM_{030}	3.6	1.9	1	0.05

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



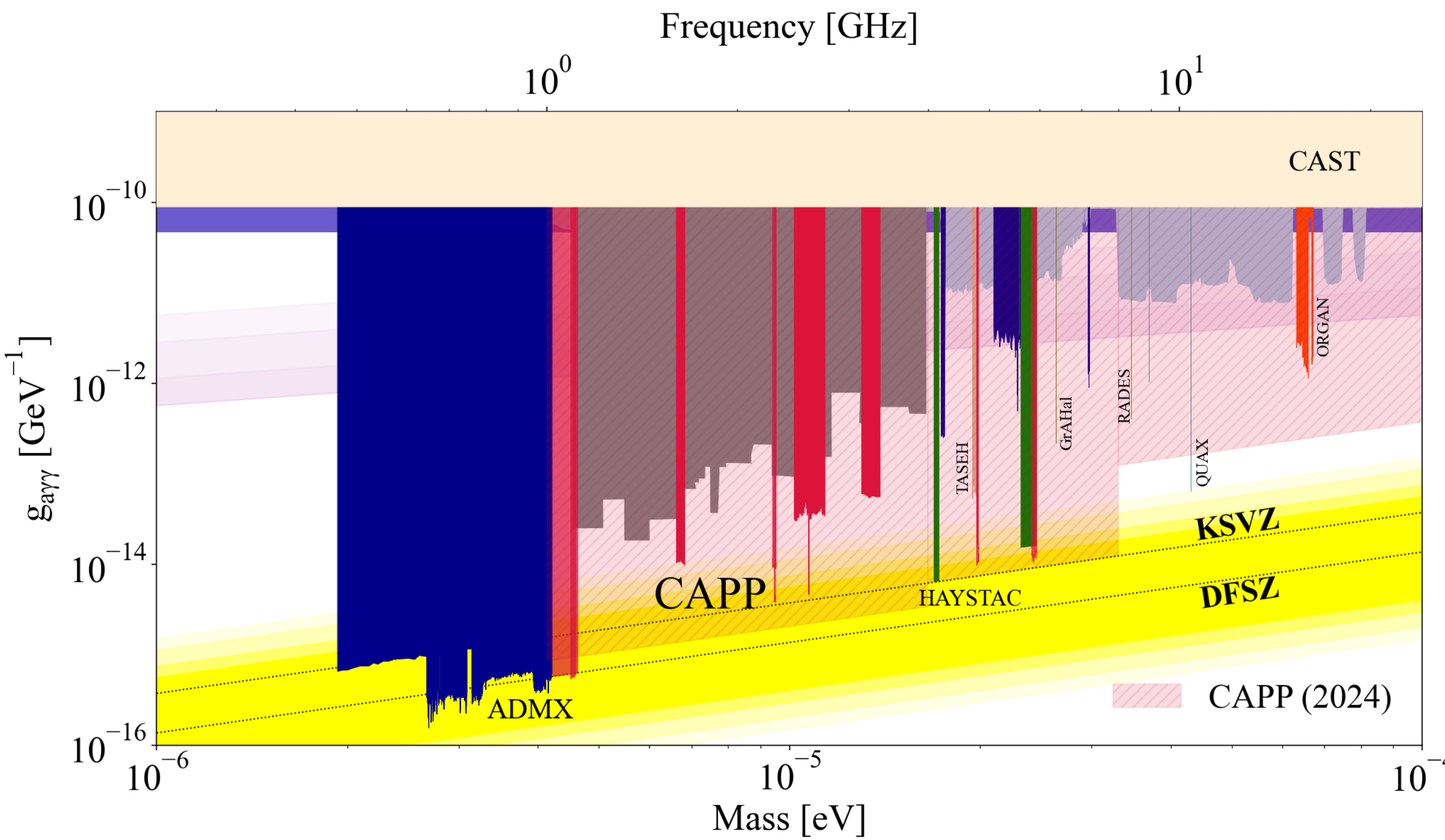
Photonic crystal

arXiv:2205.08885 (2022)



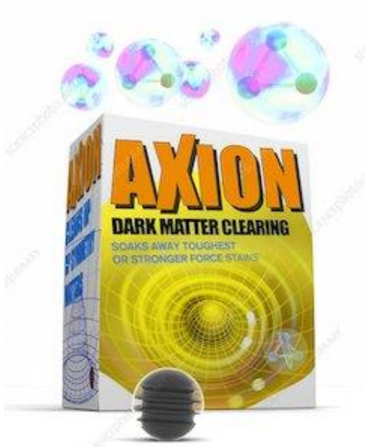
- *f ∝ spacing*
- *~10 x f_{TM010}*
- *Boosting effect*

Searches at CAPP – projection

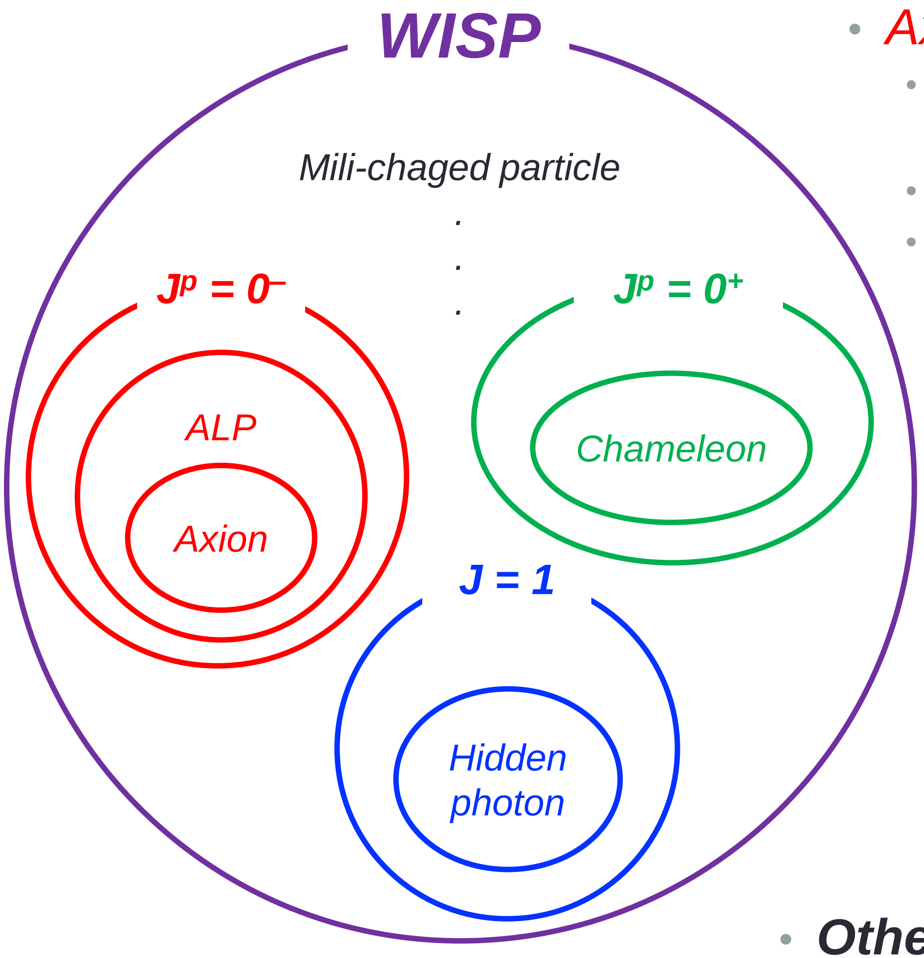


Summary

- *Axions could address fundamental questions*
  - *Strong CP problem and dark matter mystery*
- *Haloscope is the most sensitive method*
  - *Probing theoretical models*
- *IBS-CAPP is a leading group in axion hunting*
  - *Tremendous effort to build the world's best infrastructure*
  - *Several haloscopes are ongoing*
  - *DFSZ and KSVZ*
  - *Magnet / JPA / SC cavity / high frequency*
- *Next a couple of years must be exciting*
  - *Covering a wide range 4–100 ueV (1–25 GHz)*
  - *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, …*

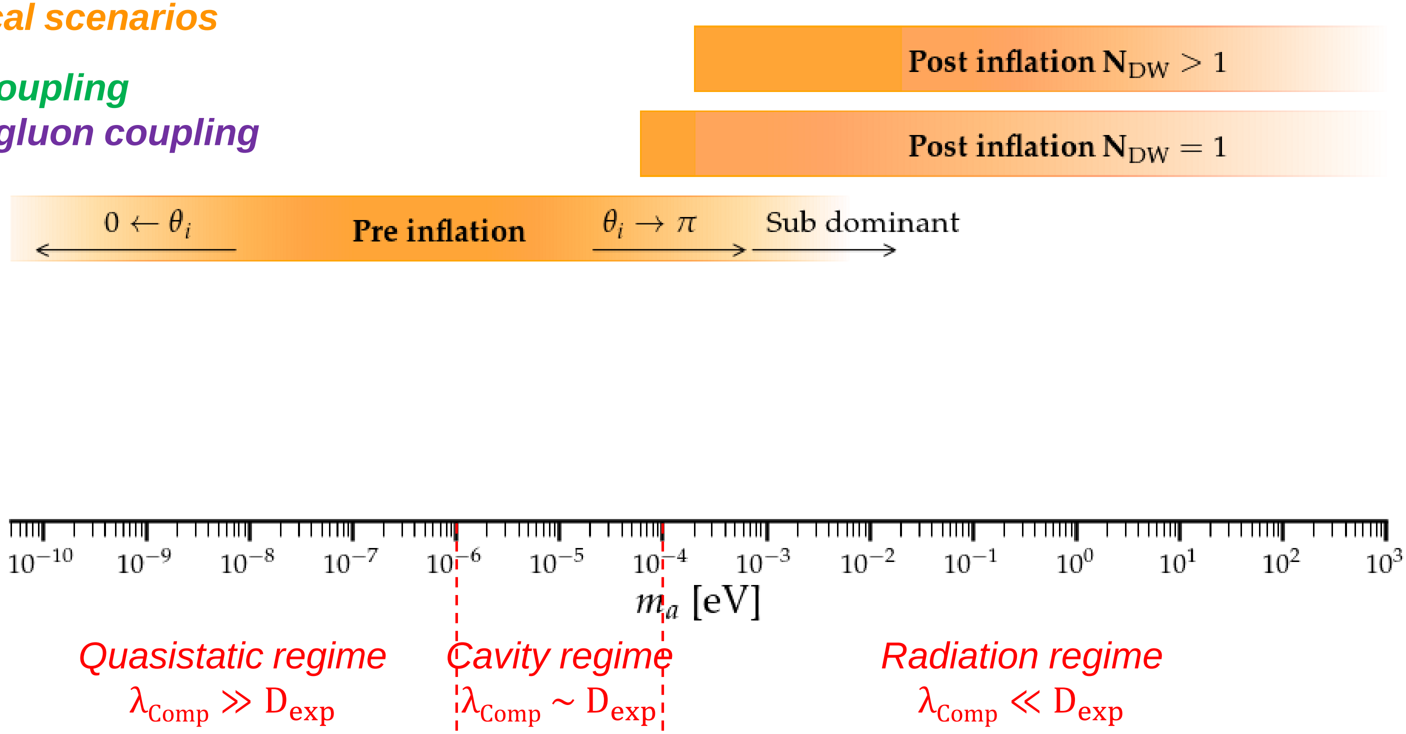
Where are dark matter axions?

- *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



Detector of halo axions

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

- *Conversion signal power (a→γγ)*

- theoretical parameters
- experimental parameters

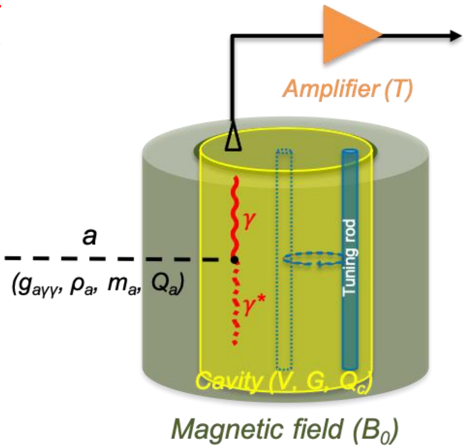
$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a) \sim 10^{-21} W$$

Coupling constant · *Axion number density* · *Magnetic field* · *Effective volume* · *Cavity Q factor* · *Axion Q factor*

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

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{\text{int}}}{\Delta f_a}}$$

System noise temperature · *Integration time* · *Axion bandwidth ($\sim 10^{-6} f$)*



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

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