Searches for Axion Dark Matter in Korea

KPS-DPF 2022

Dec. 17. 2022 SKKU

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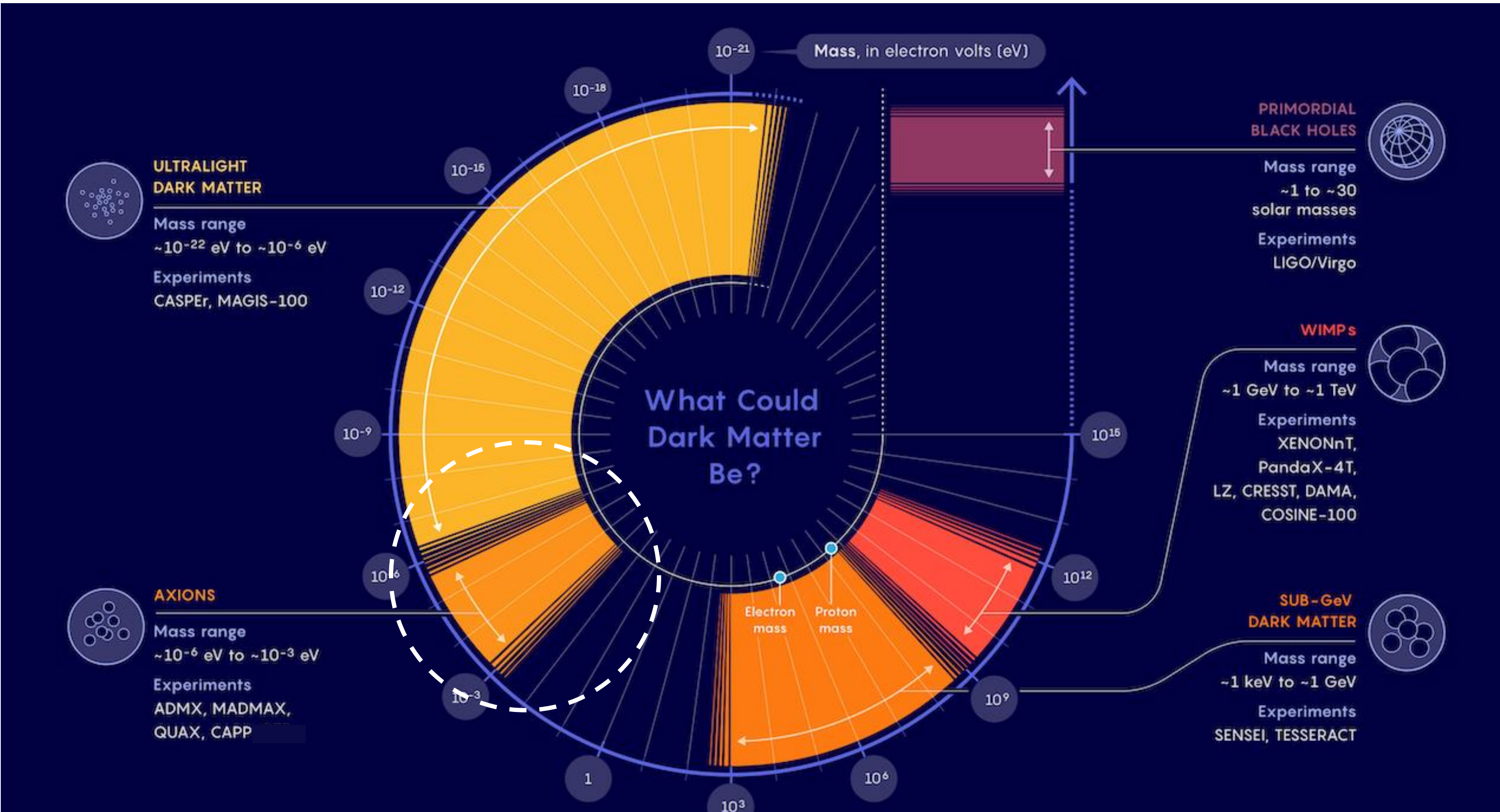
Institute for Basic Science (IBS)

Dark matter business expanding



Samuel Velasco/Quanta Magazine

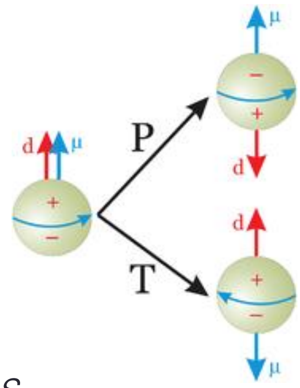
Strong CP problem and axion

- *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*

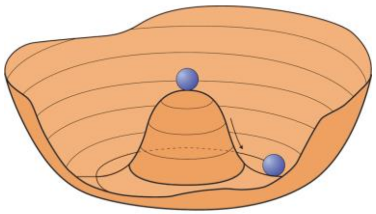


- *PQ mechanism (1977)*
  - U(1) symmetry w/ scalar field a(x)

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

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

Spontaneous symmetry breaking



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

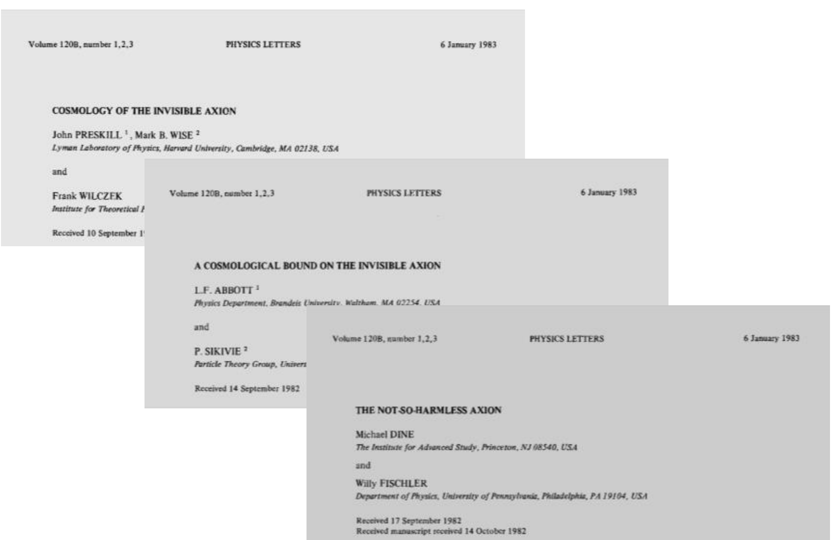
- *Axion (1978)*
  - (pseudo-scalar) Nambu-Goldstone boson
  - QCD axion
    - Mass related to QCD scale: $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$
    - cf. axion-like particle (ALP)

Invisible axion and dark matter

- *Invisible axion (1979)*
  - $f_a \gg v_{EW}$
  - *SSB in early universe*
  - *Very light axion*

    ex) $m_a \approx neV \frac{10^{15}\,GeV}{f_a}$

- *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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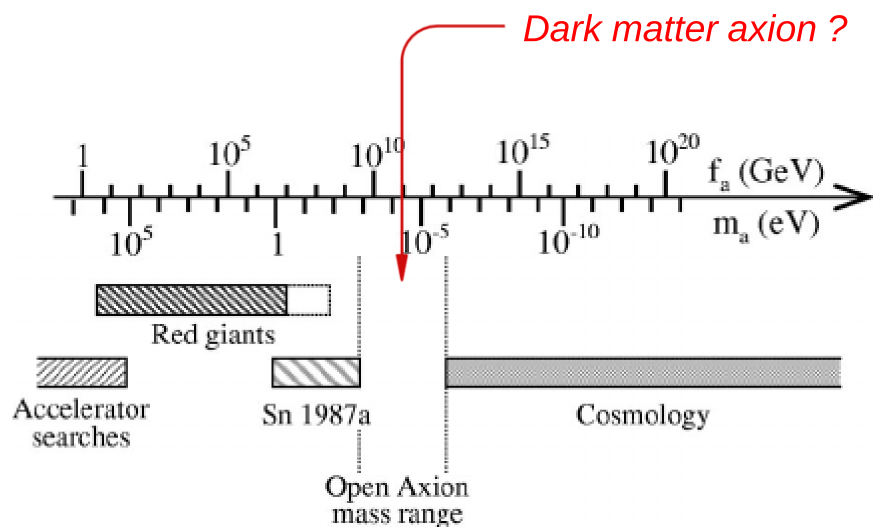
Received 17 September 1982
Received manuscript received 14 October 1982



Couplings and models

- *Axion coupling to SM*

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

- *Axion models*

From R. Ziegler

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

SM fermions BSM fermions

Origin of QCD anomaly:

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

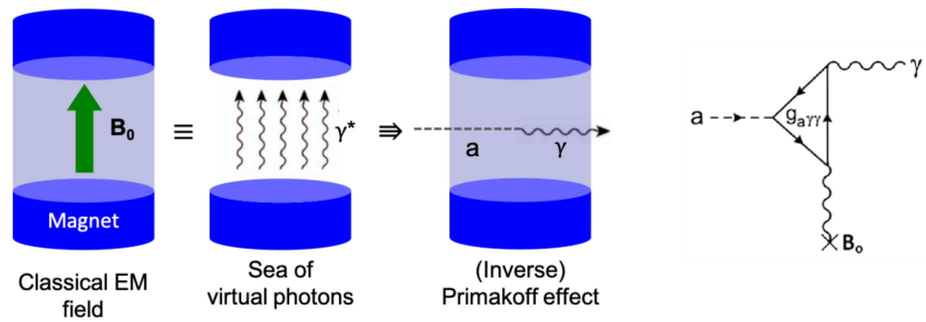
~~PQWW~~ — Peccei, Quinn, Wilczek, Weinberg (1978)

DFSZ — Dine-Fischler-Srednicki-Zhitnitsky (1980)

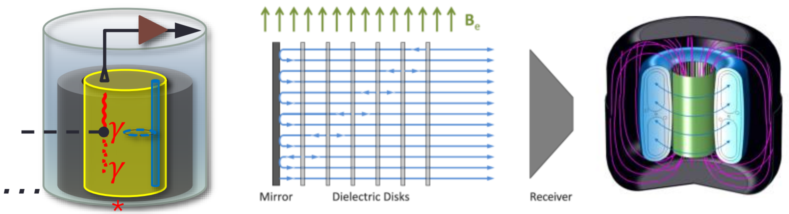
KSVZ — Kim-Shifman-Vainshtein-Zakharov (1980)

Search strategies

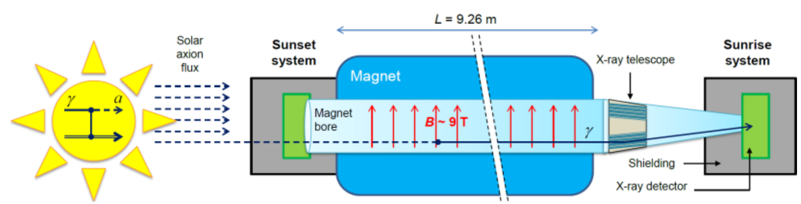
- *Detection principle*
  - *Sikivie effect (1983)*
    - *Macroscopic primakoff*



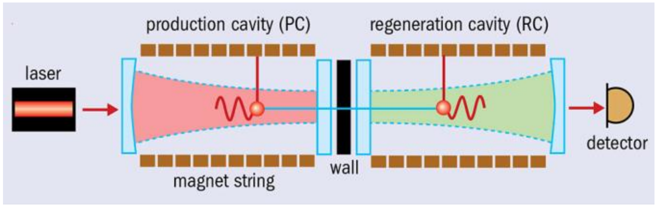
- *Detection methods*
  - *Haloscope*
    - *Dark matter halo*
    - *ADMX, CAPP, MADMAX, DM radio, …*



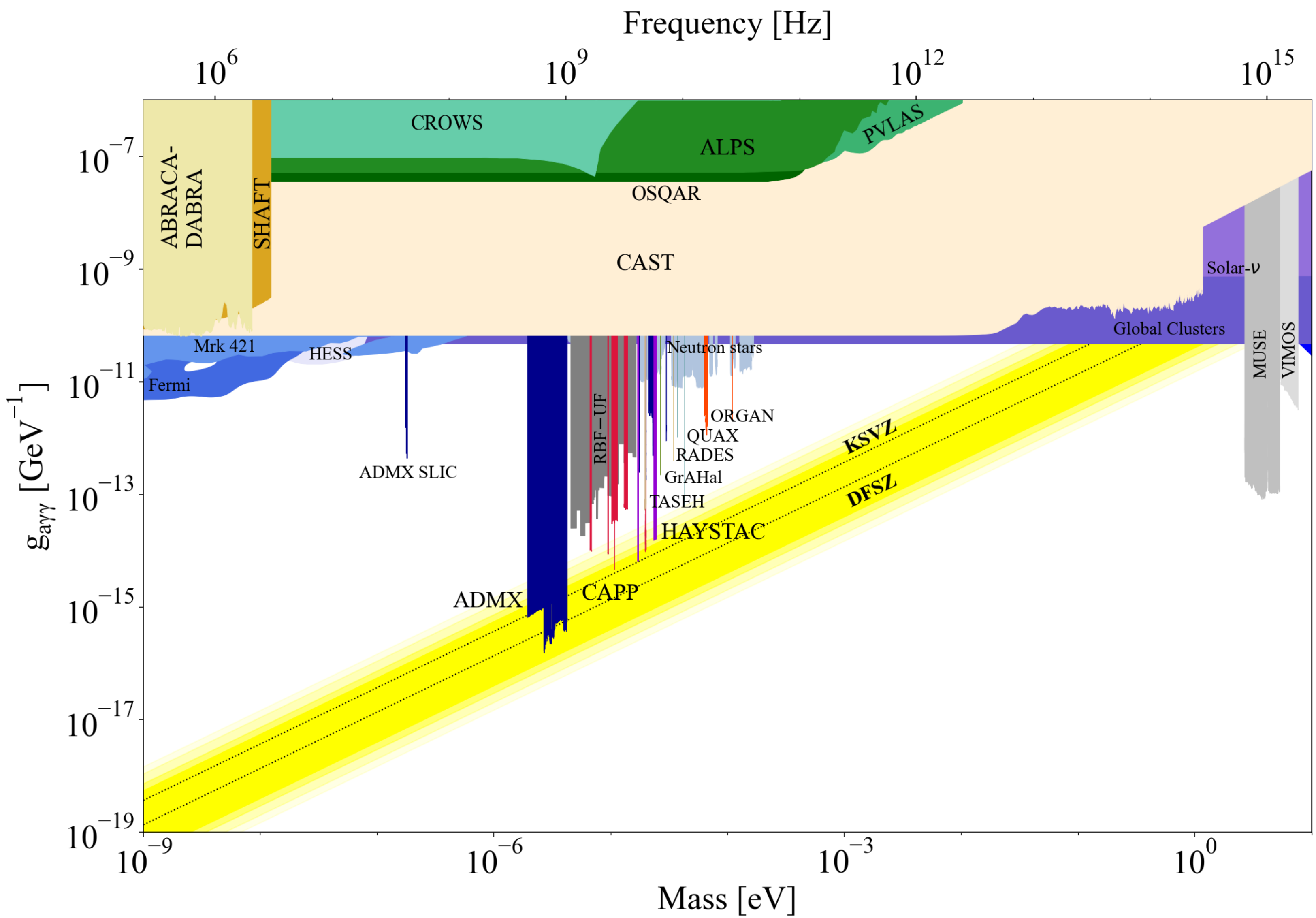
  - *Helioscope*
    - *Solar axions*
    - *CAST, IAXO*



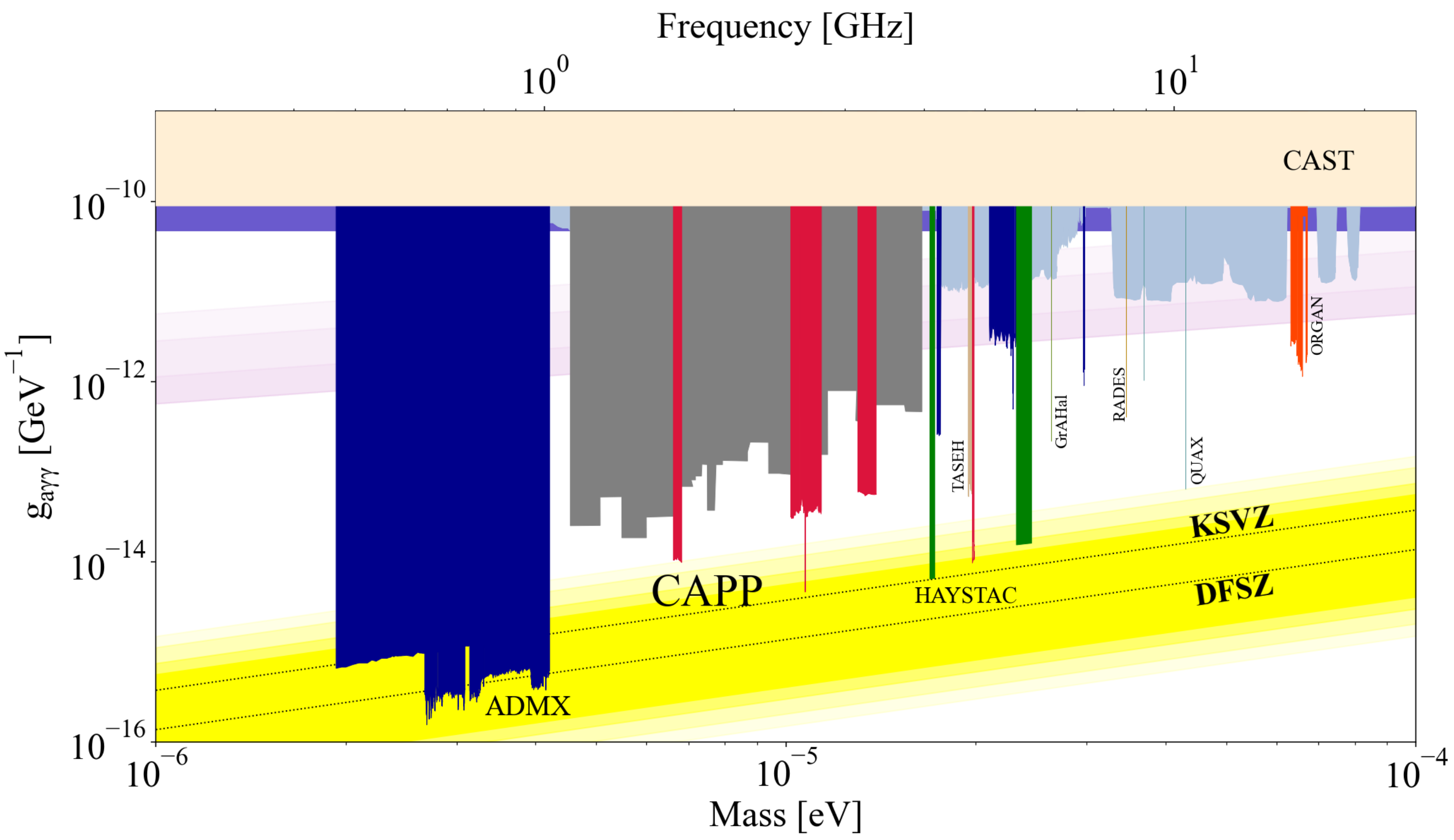
  - *Light shining through walls*
    - *Lab production*
    - *OSQAR, ALPS (II)*



Axion searches



Haloscope searches



Cavity haloscope – in a nutshell

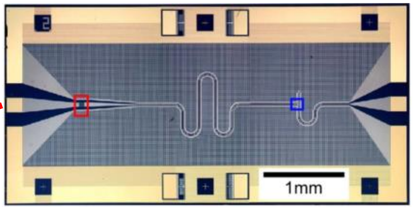
- *Most sensitive for ueV axions*

Cryogenics T

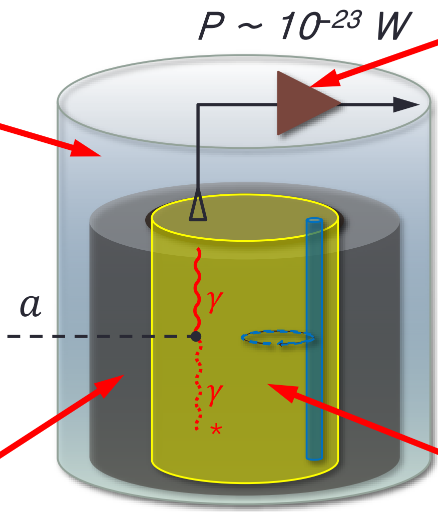
Lowering thermal noise

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

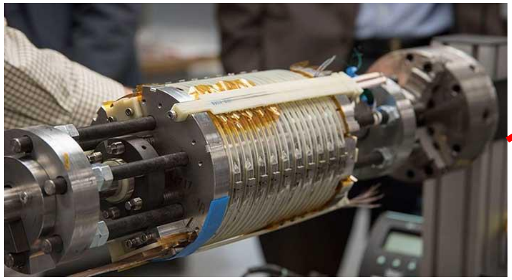
Quantum noise limited amplifier T



Signal amplification w/ minimal noise added



High field Magnet B



Boosting a→γγ conversion rate

Small–scale experiments!

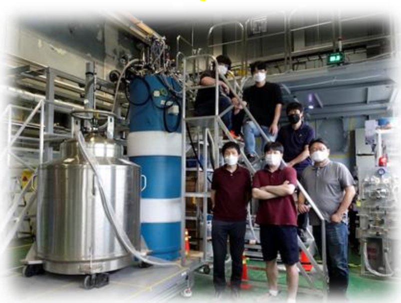
Tunable High-Q resonator V, Q, C, Δf

Resonant frequency tuning

IBS-CAPP (since 2013)

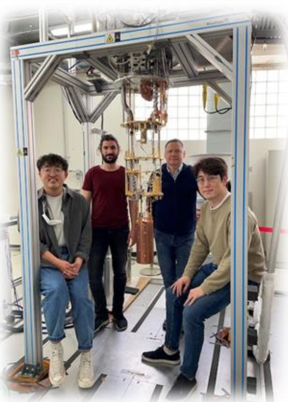
CAPP-9T

CAPP-12TB



CAPP-18

CAPP-PACE



CAPP-8TB

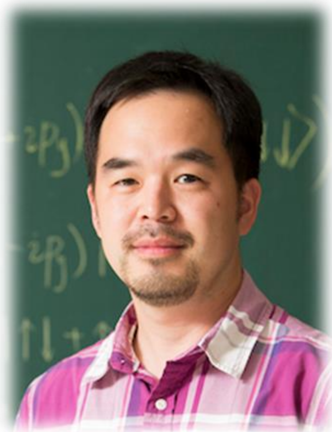
Collaborators in Korea

KRISS => SKKU

KRISS

Korea U.

KAIST => IBS



KAIST

KAIST

Equipment at CAPP

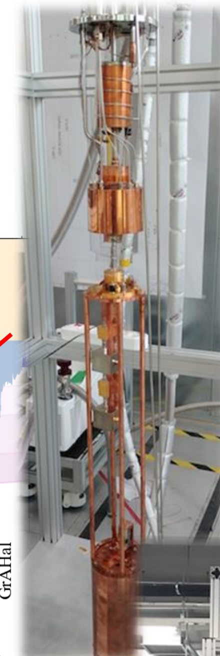
Refrigerators			Magnets			Experiments
Manufacture	Model	T_B [mK]	Manufacture	B_{max} [T]	Bore [mm]	Name
BlueFors (BF3)	***LD400***	***10***	***AMI***	***12***	***96***	***CAPP-12T***
BlueFors (BF4)	*LD400*	*10*				
Janis	***HE-3-SSV***	***300***	***Cryo Magnetics***	***9***	***125***	***CAPP-9T***
BlueFors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

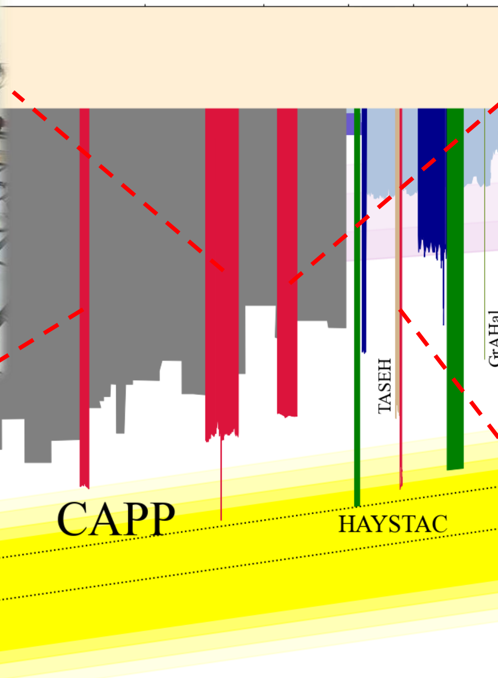
*Conducting **parallel** experiments targeting **different mass** regions!*

Search highlight – published

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

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





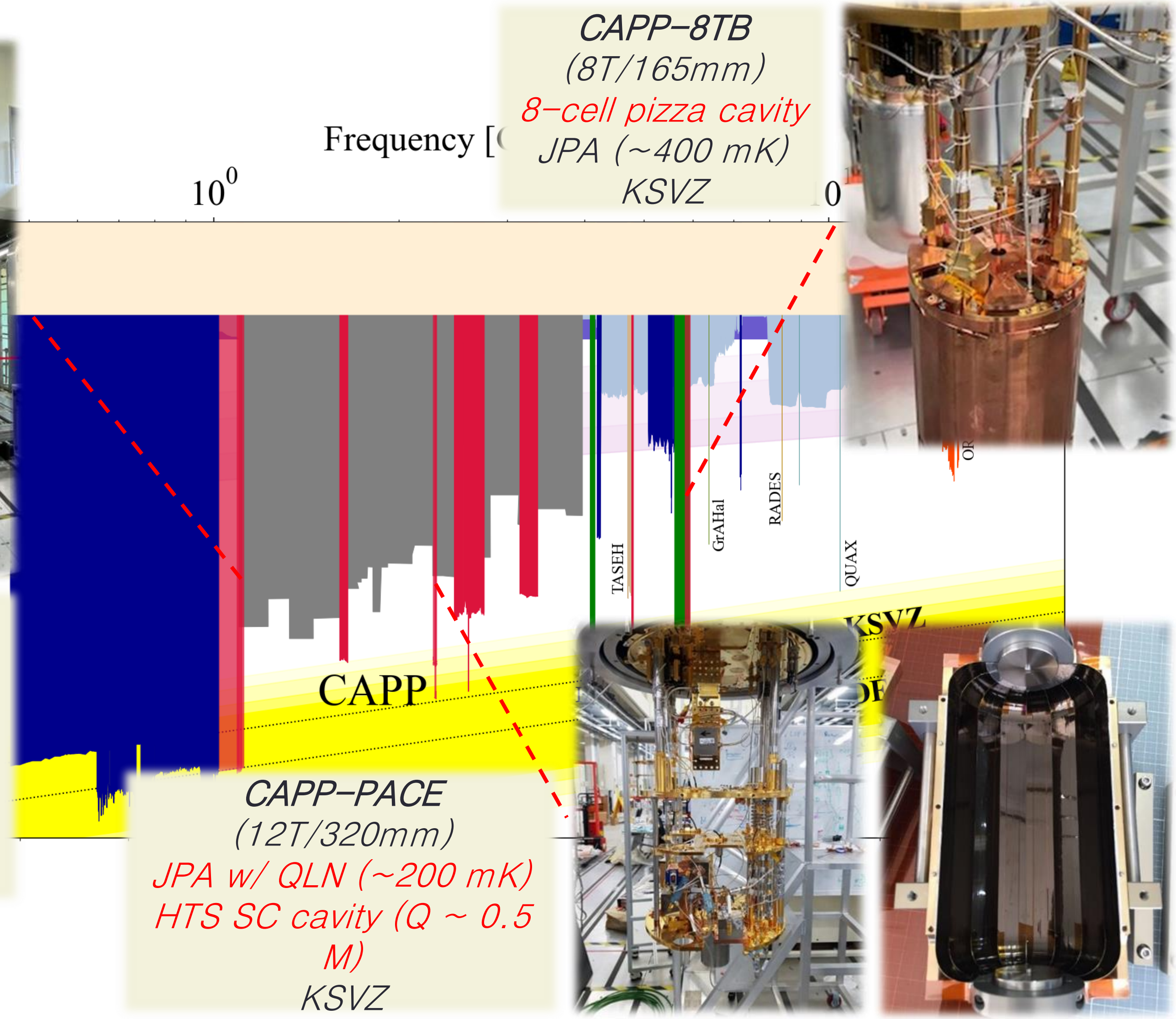
CAPP-8TB
(8T/165mm)
Pilot experiment
PRL ***124*** *101802 (2020)*

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

Search highlight – to be published


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

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

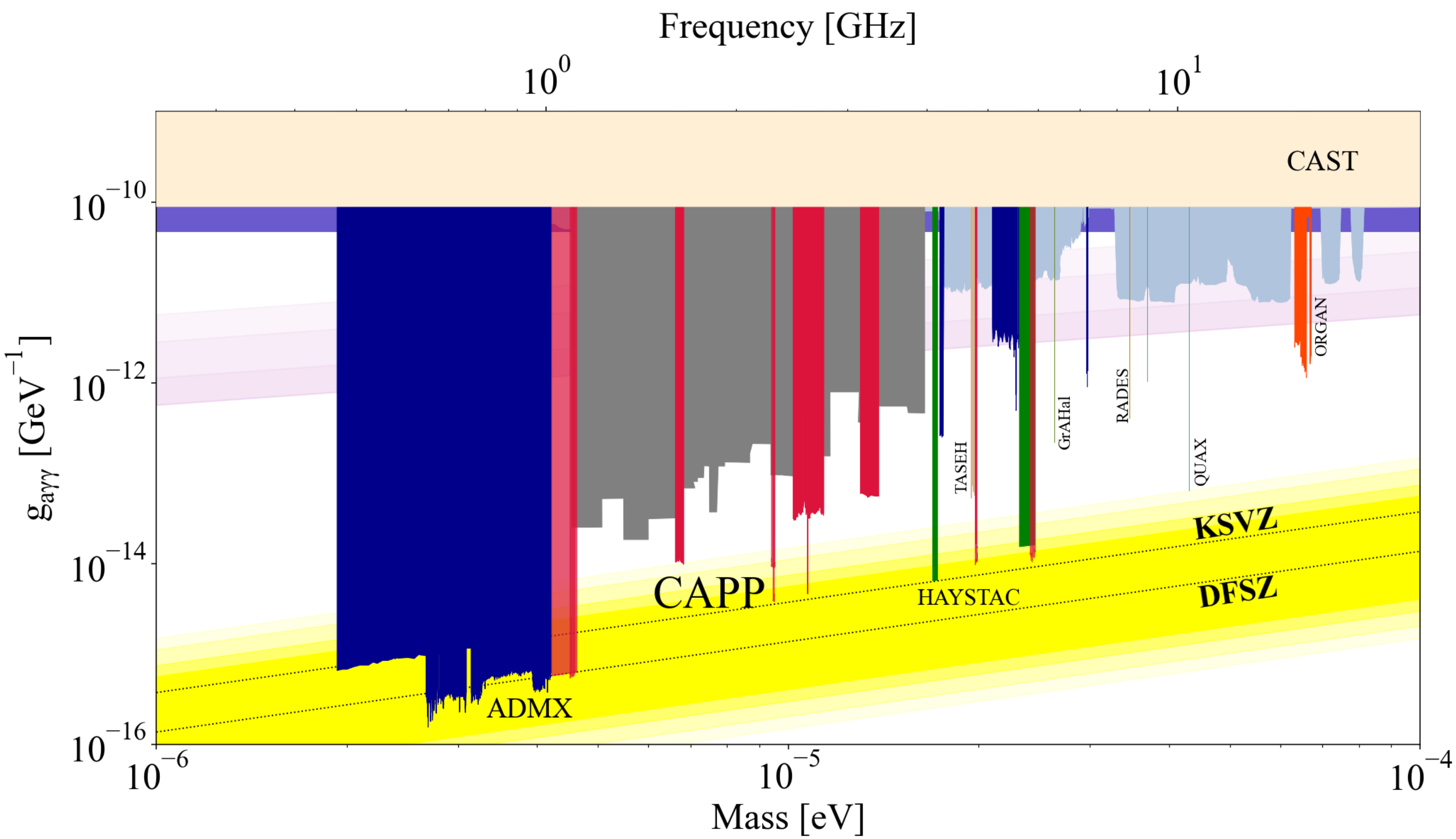


CAPP–8TB
(8T/165mm)
8–cell pizza cavity
JPA (~400 mK)
KSVZ

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

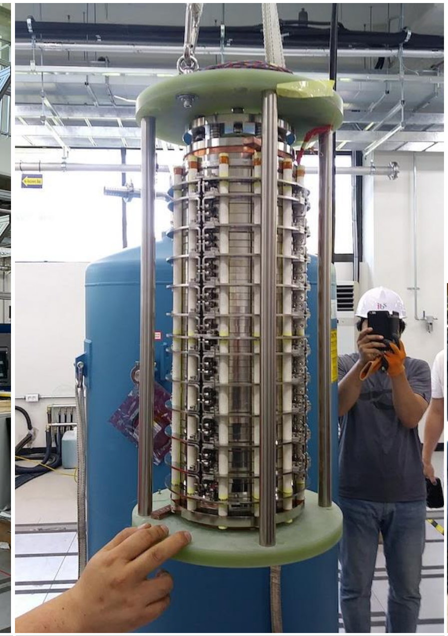
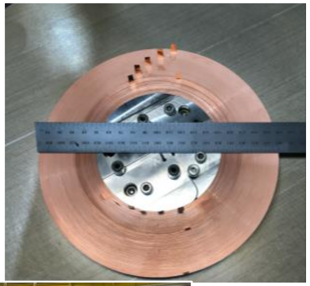
R&D efforts needed

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



High-field magnets

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

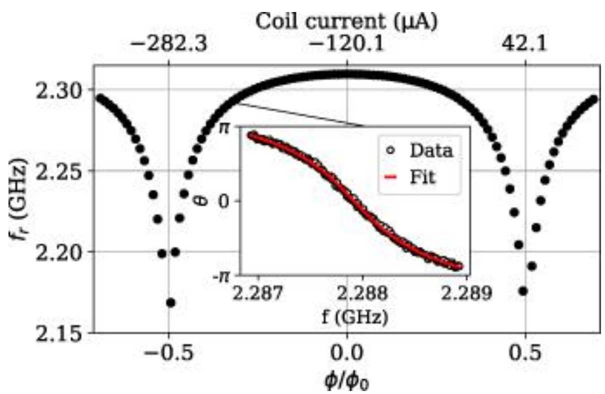





Magnet	CAPP-12TB	CAPP-18T	CAPP-25T
Manufacturer	Oxford	SuNAM	IBS-BNL
B_{max} @ 4 K	**12 T**	**18 T**	25 T
Bore (clear)	**320 mm**	70 mm	100 mm
SC material	Nb_3Sn	**GdBCO**	YBCO
Delivery	2020	2017	?
Frequency	> 1 GHz	> 4 GHz	> 3 GHz
Sensitivity	**DFSZ**	**KSVZ**	DFSZ

QNL amplification

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

- *Flux-driven Josephson parametric amplifiers*

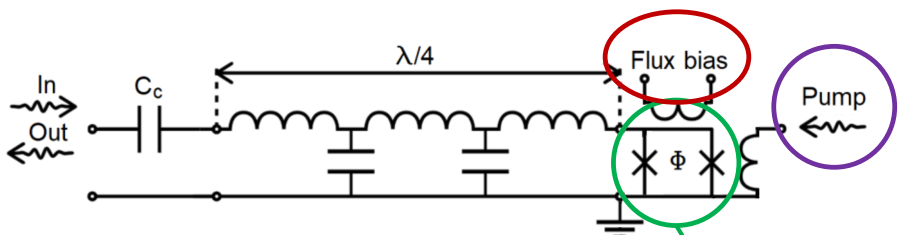


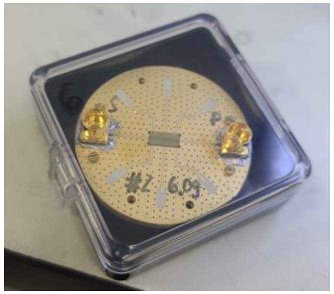
Frequency tuning

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

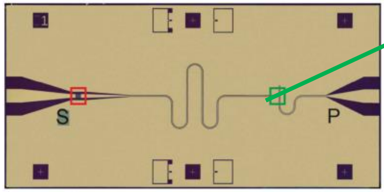
Parametric amplification

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

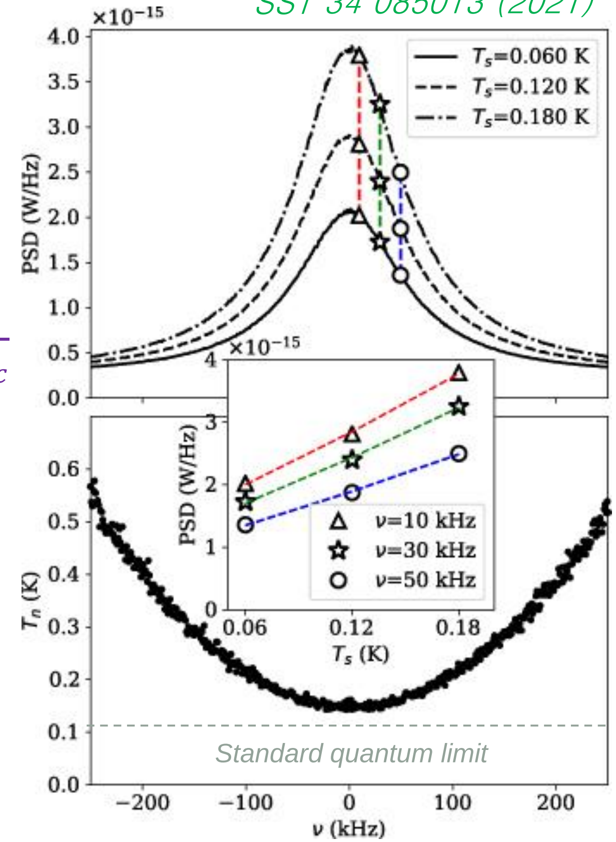




SQUID (nonlinear inductance)



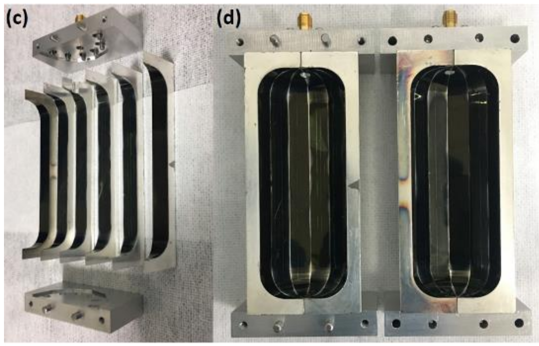
SST 34 085013 (2021)

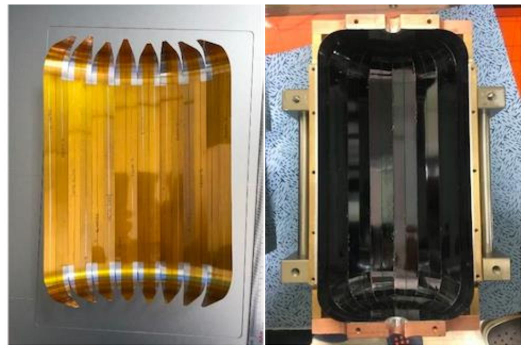


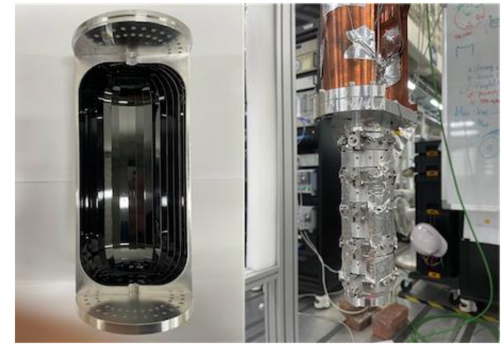
- *>25 JPAs covering 1 to 6 GHz (U. of Tokyo & RIKEN)*

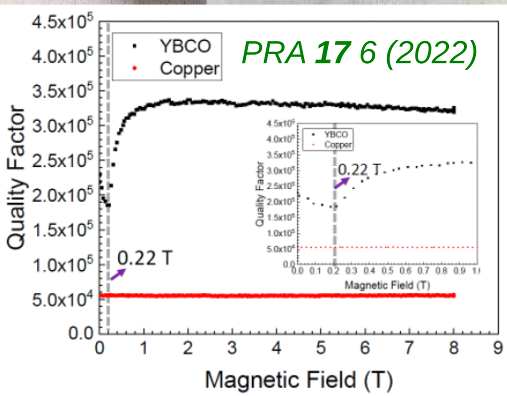
Superconducting cavities

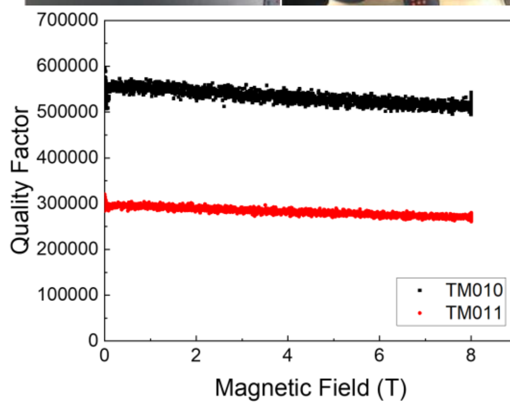
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

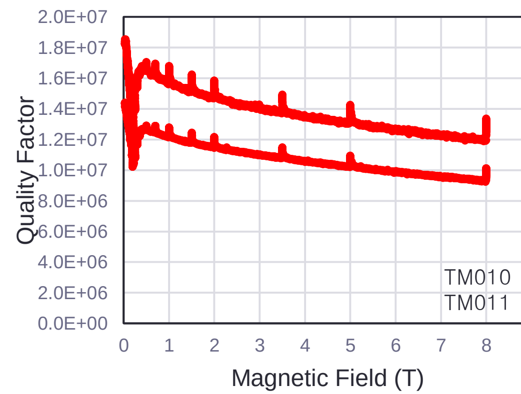












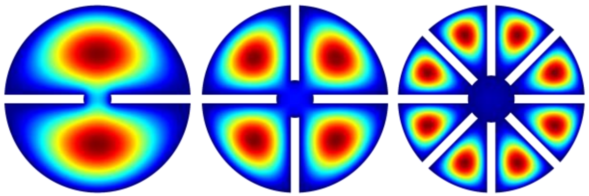
	1st generation	*2nd generation*	*3rd generation*	
Material	*YBCO*	*GdBCO*	*EuBCO+APC*	
Substrate	*NiW*	*Hastelloy*	*Hastelloy*	
Volume [L]	*0.3*	*1.5*	*1.5*	*0.2*
Frequency [GHz]	*6.9*	*2.3*	*2.2*	*5.4*
Q-factor	*0.33 M*	*0.5 M*	*4.5 M*	*13 M*

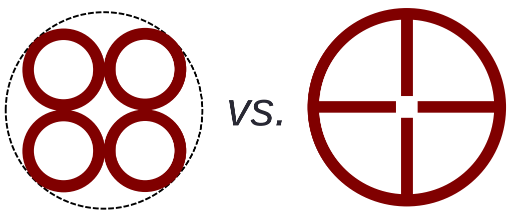
High freq. approach

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

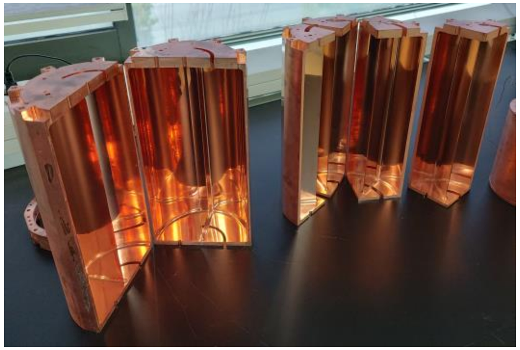
Multiple-cell (pizza)

PLB **777** 412 (2018)





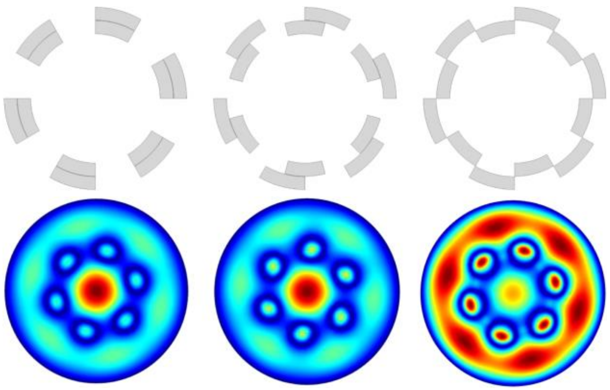
- Larger volume
- Simpler receiver chain
- ~4 x f_{TM010}



Higher-mode (wheel)

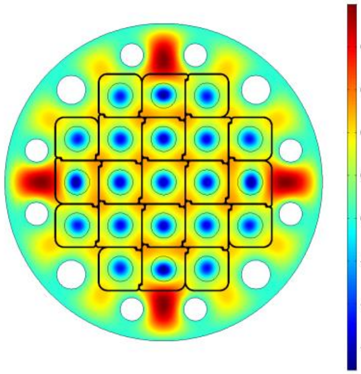
Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM_{010}	1	1	1	0.69
TM_{030}	3.6	1.9	1	0.05

JPG **47** 035203 (2020)



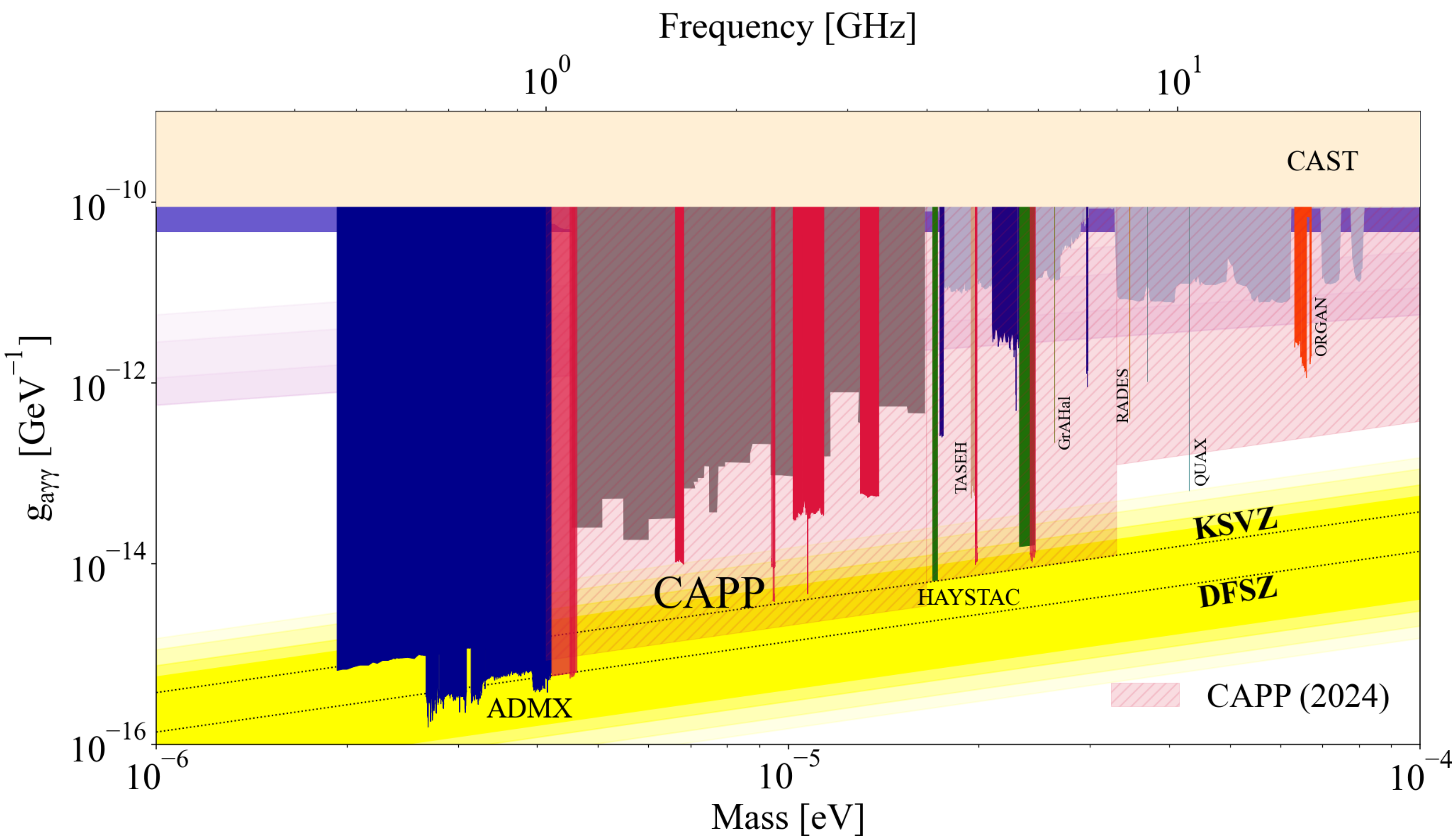
Photonic crystal

arXiv:2205.08885



- $f \propto$ spacing
- ~10 x f_{TM010}
- Boosting effect

Searches at CAPP – projection

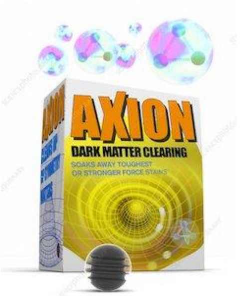


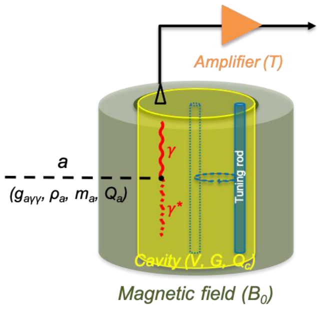
Summary

- *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*
  - *Both 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*

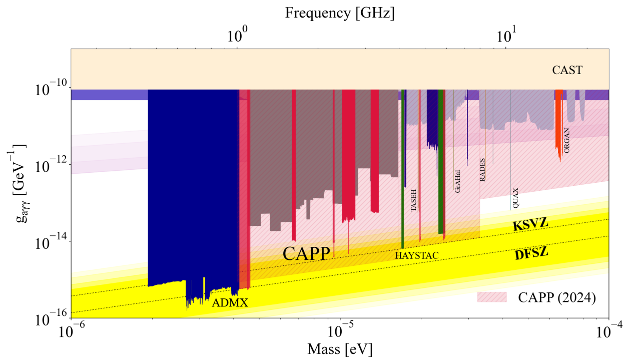
Outline

- *Axion dark matter*
  - *Theoretical background*
  - *Experimental search strategies*



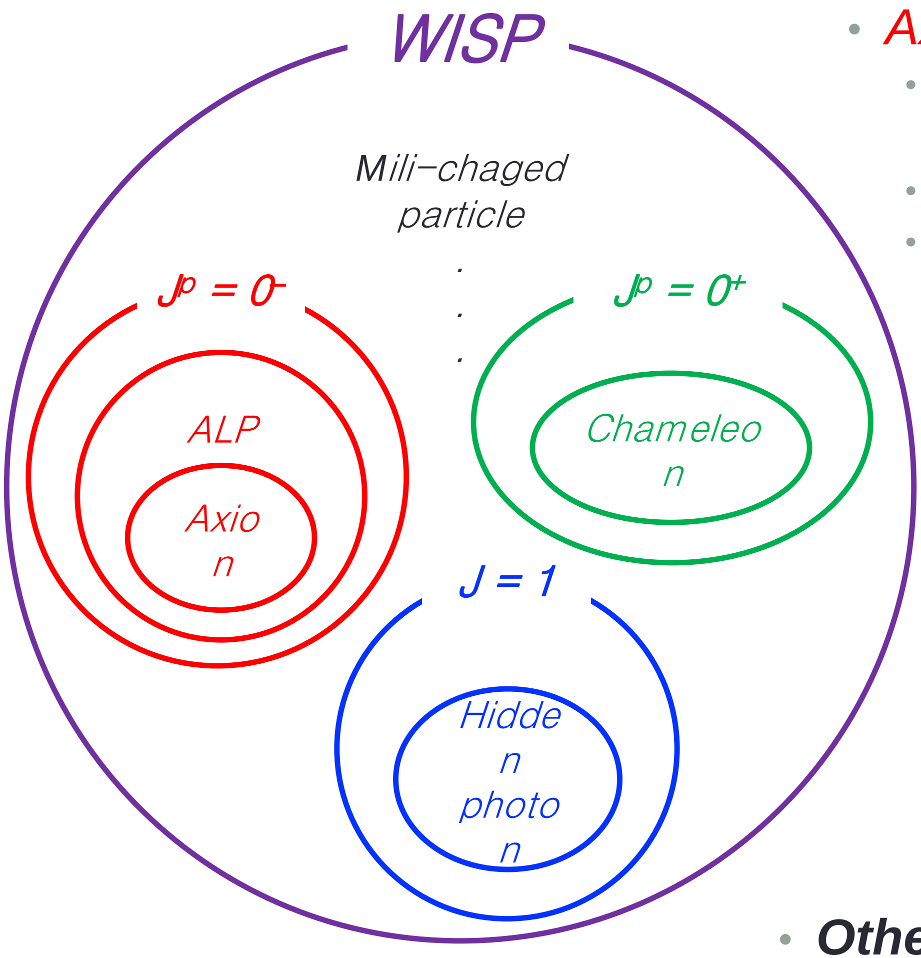


- *Axion research at IBS-CAPP*
  - *Ongoing experiments*
  - *Search highlights*
  - *R&D efforts*
  - *Prospects*



- *Summary*

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

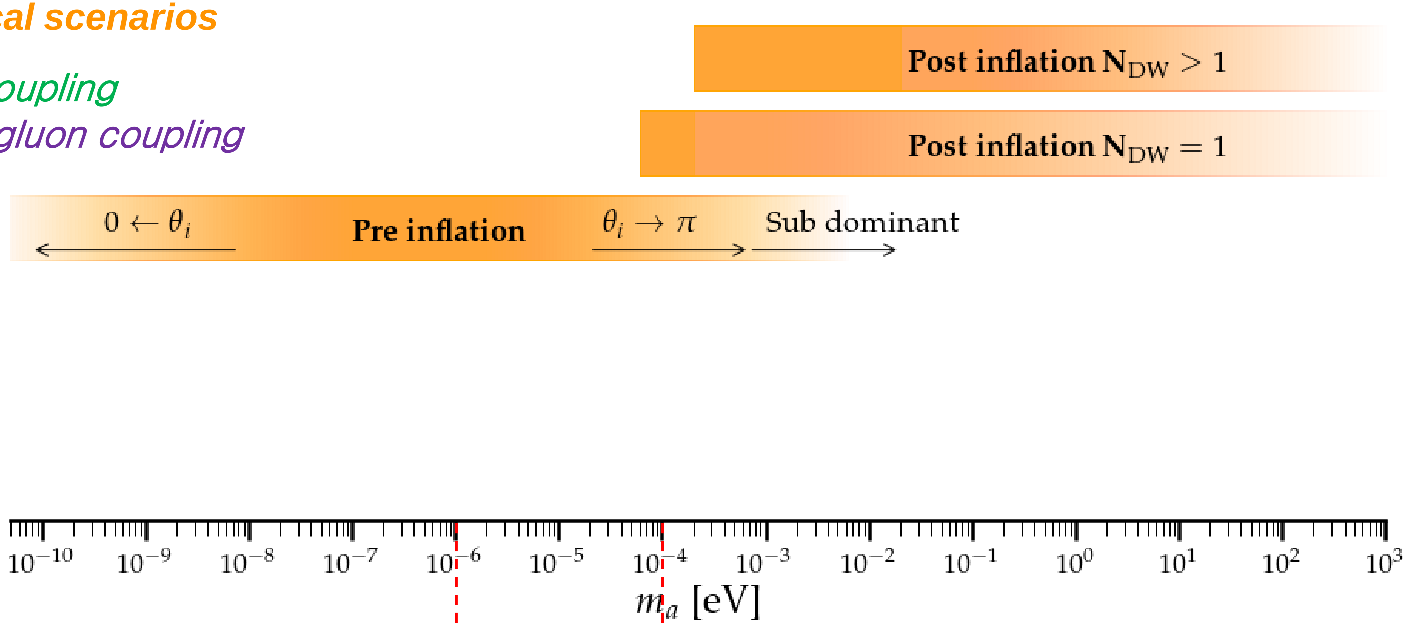
  => Different search strategies

  Depending on λ_{Comp} w.r.t. $\mathrm{D}_{\mathrm{exp}}$

Theoretical scenarios

Photon coupling

Fermion/gluon coupling



Quasistatic regime $\lambda_{\mathrm{Comp}} \gg \mathrm{D}_{\mathrm{exp}}$

Cavity regime $\lambda_{\mathrm{Comp}} \sim \mathrm{D}_{\mathrm{exp}}$

Radiation regime $\lambda_{\mathrm{Comp}} \ll \mathrm{D}_{\mathrm{exp}}$

Detector of halo axions

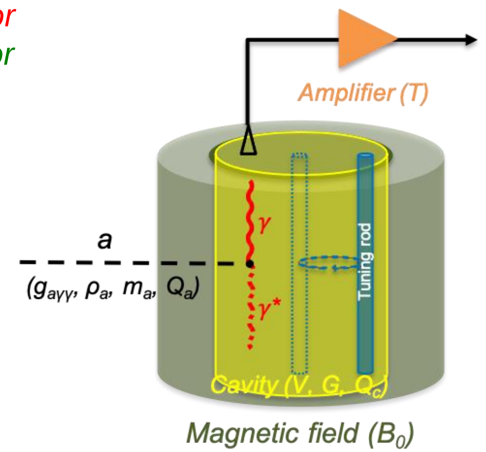
- *Most sensitive approach in μeV regime*
  - *Microwave photons resonantly converted from axions*

- *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)*

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

System noise temperature; *Integration time*; *Axion bandwidth (~10^{-6} f)*

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

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