Direct Detection Experiments
(Review)

Axions in Stockholm 2025

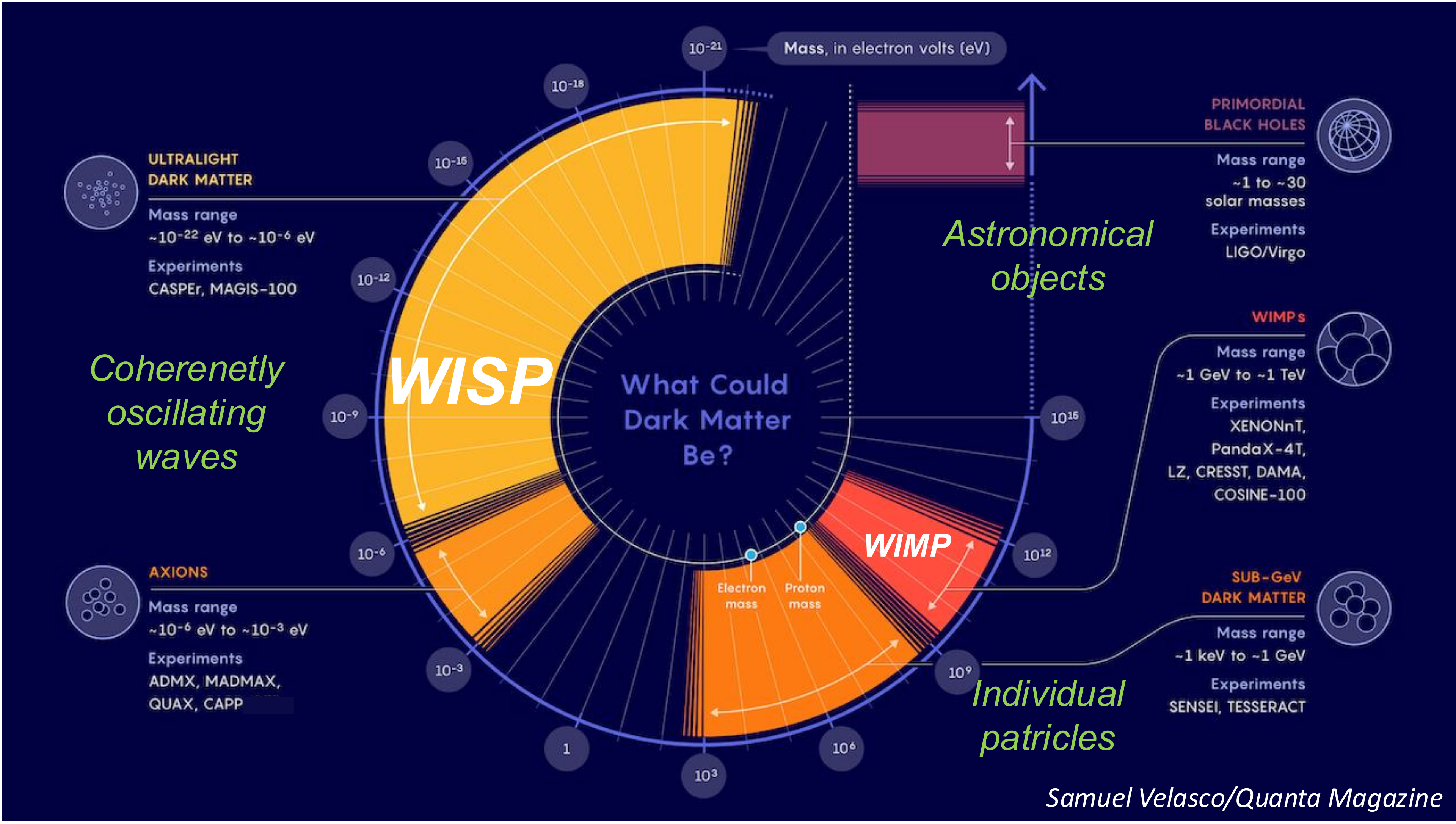
2025. 07. 07 Nordita, Stockholm University

SungWoo YOUN

Dark Matter Axion Group (DMAG)

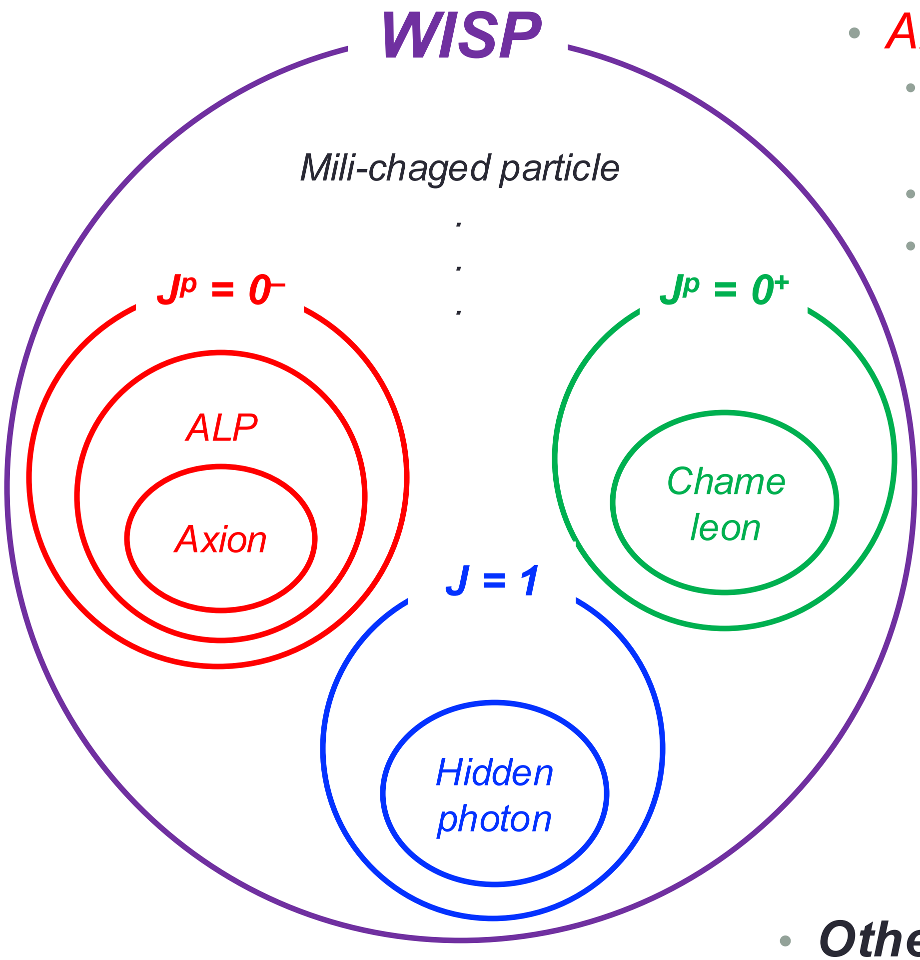
Institute for Basic Science (IBS)

Dark matter business expanding



Samuel Velasco/Quanta Magazine

WISP zoo



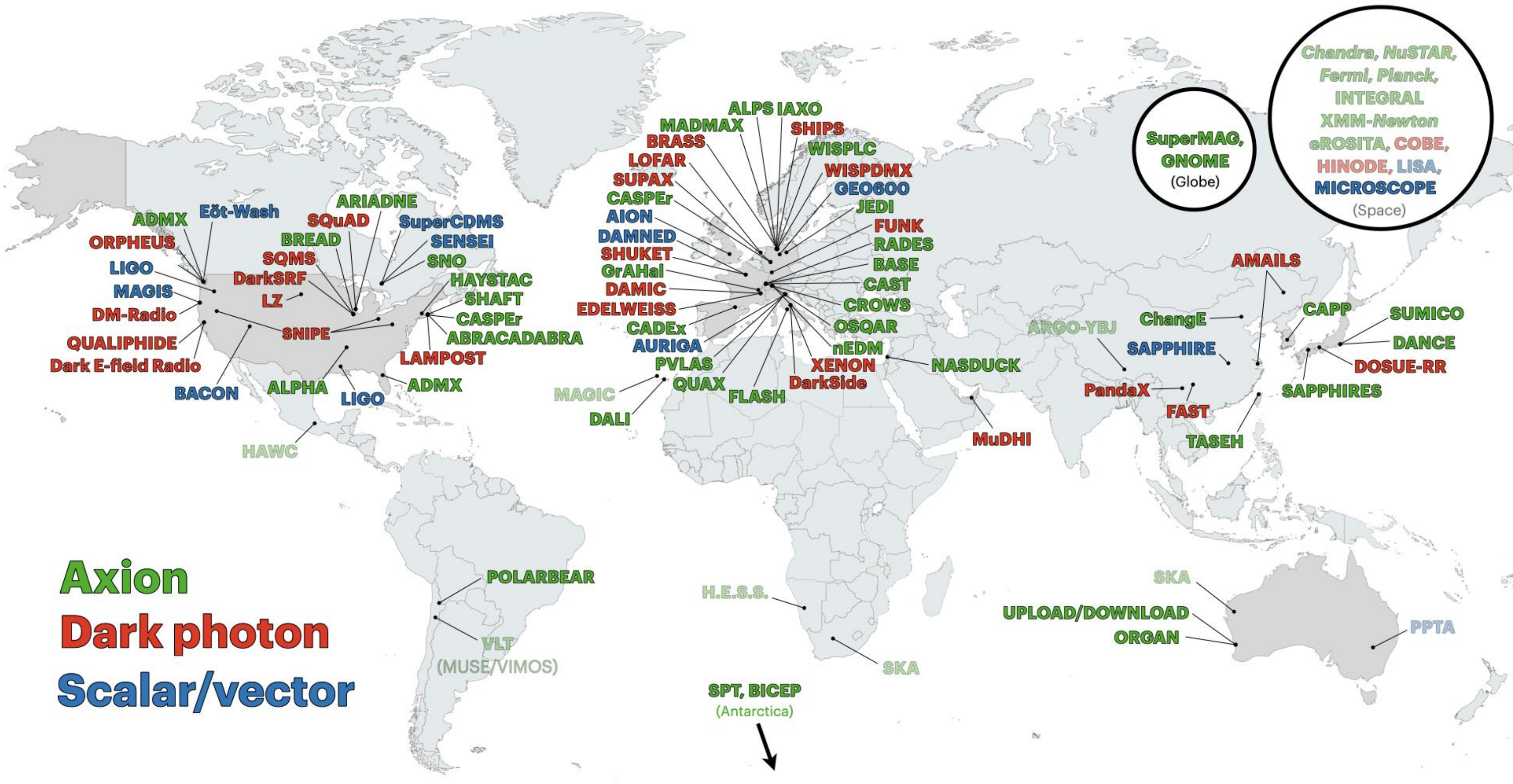
- **Pseudo-scalar**
  - Axion
    - PQ solution to strong CP problem (1977)

      $m_a f_a \sim \Lambda_{QCD}$
    - Invisible axion (1979)
    - Dark matter candidate (1983)
  - Axion-Like Particle (ALP)
    - Generic axion w/o solving the 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, …

Experiment map

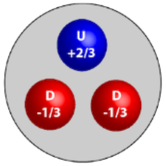
C. O'Hare (2020)



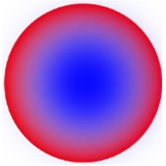
Axion dark matter

- *Solution to 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)*

Absence of nEDM

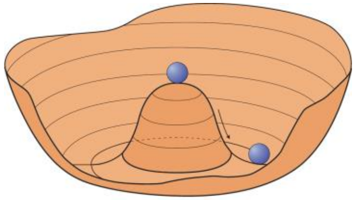


vs.

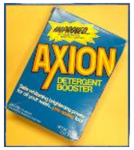


$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \quad \Longrightarrow \quad \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$

Spontaneous Symmetry Breaking



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



Goldstone boson

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

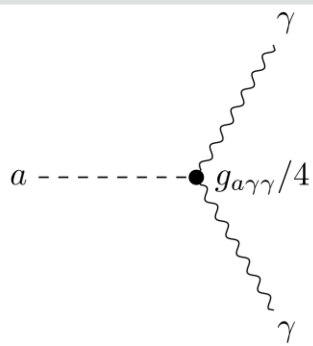
- *Axion models*

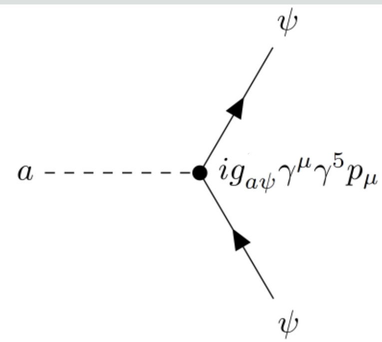
Model	***PQWW***	***DFSZ***	***KSVZ***
QCD anomaly	*SM ferminons*		*BSM fermions*
Spont. breaking	*2 Higgs*	*2Higgs+singlet*	*Higgs+singlet*
f_a *scale*	*Standard* ($f_a \sim v_{EW}$)	*Invisible* ($f_a \gg v_{EW}$)	
Remark	*Ruled out*	*Benchmark*	

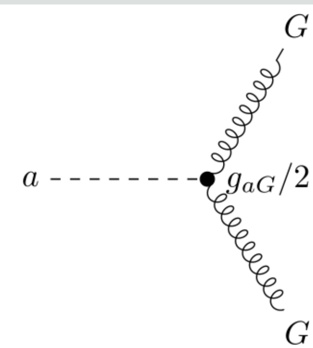
Interaction and detection

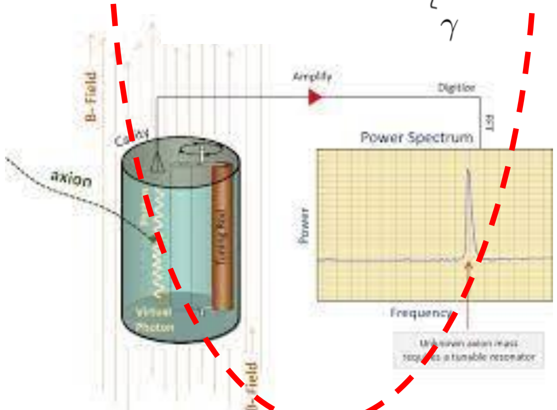
- *Axion coupling*

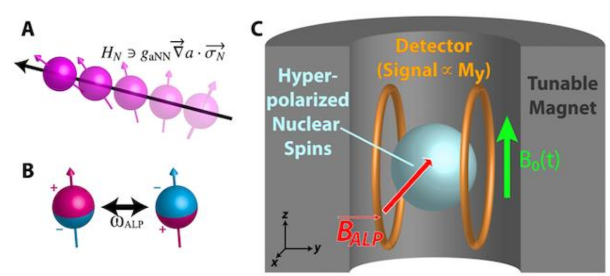
	Photons	***Fermions***	***nEDMs***
Hamiltonian	$g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$	$g_{aff} \boldsymbol{\nabla} a \cdot \hat{\mathbf{s}}$	$g_{EDM} a \hat{\mathbf{s}} \cdot \boldsymbol{E}$
Observable	*Photon*	*Spin precession*	*Oscillating EDM*
Detection method	*Power spectrum, photon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









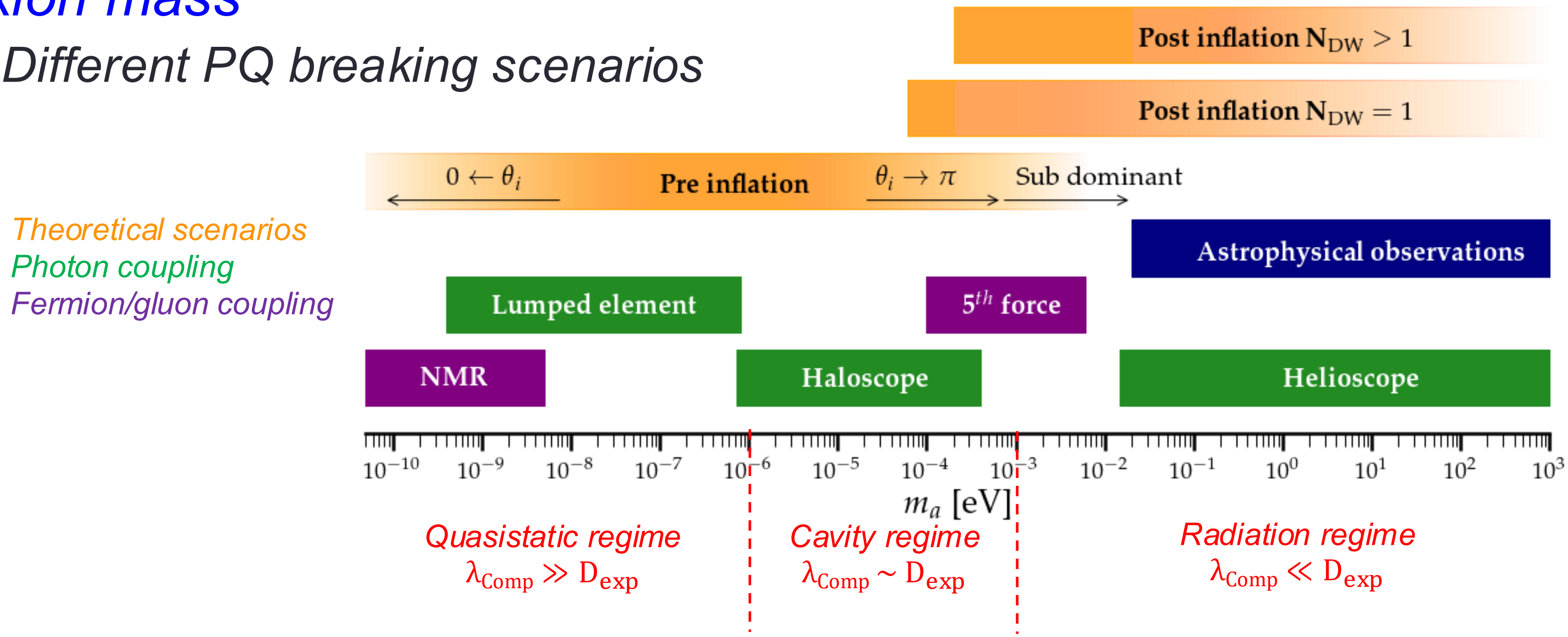


Axionscopes

- *Axion source*

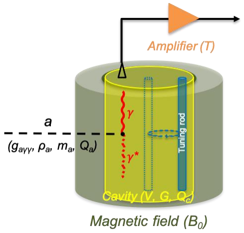
Source	Photons	Fermions	nEDMs
Dark matter	ADMX, CAPP, QUAX, MADMAX, DM Radio, ..	QUAX-ae, GNOME, CASPEr-gradient, …	CASPEr-electric, srEDM, …
Solar	CAST, IAXO		
Laboratory	ALPS (II)	ARIADNE	

- *Axion mass*
  - Different PQ breaking scenarios



Search strategies

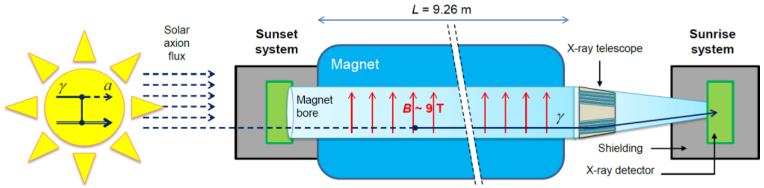
- *Haloscope*
  - *Dark matter halo in our galaxy*



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

~100 photons/sec

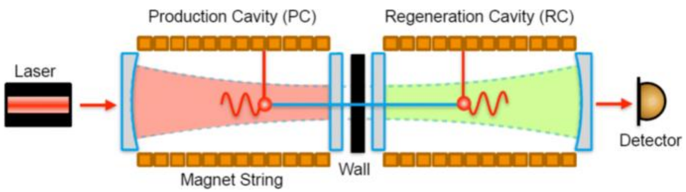
- *Helioscope*
  - *Solar axion*



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

~10 photons/day

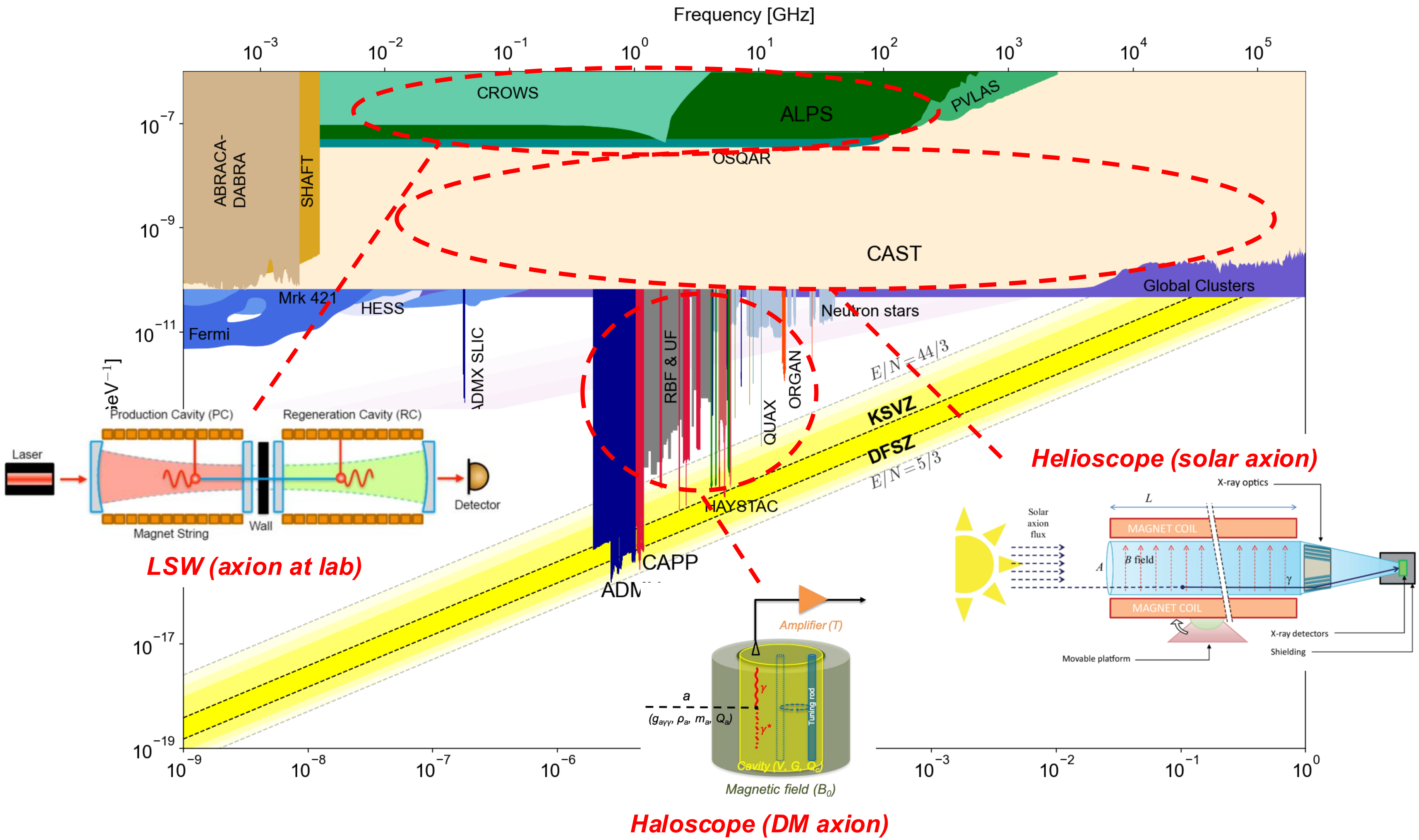
- *Light shinning through a wall*
  - *Axion production at lab*



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

Current status

1 GHz = 4.2 ueV

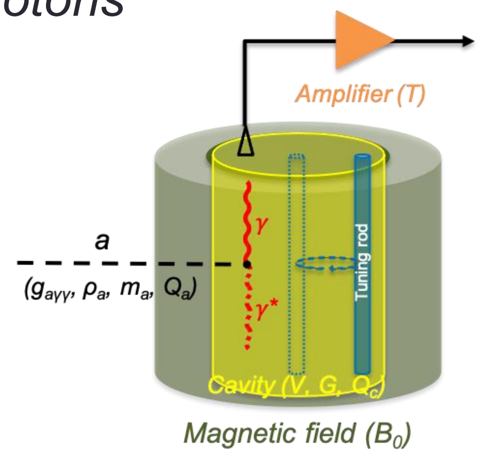


Haloscopes

Cavity haloscope

1 GHz = 4.2 μeV

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



- *Axion-photon conversion power ($a \rightarrow \gamma\gamma$)*

$$P_{a\gamma\gamma} \approx 9 \times 10^{-23}\, W \left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\frac{GeV}{cc}}\right)\left(\frac{f_a}{1.1\, GHz}\right)$$

(~100 photons/sec)

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

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

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{1}{4}\frac{P_{a\gamma\gamma}}{k_B(T_{sys}/0.2\, K)}\sqrt{\frac{\Delta t}{Q_a/10^6}}$$

System noise (in temperature)

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

ex) $0.2\, K \sim 3 \times 10^{-22}\, W$

(~4000 photons/sec)

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

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

Cavity haloscope – in a nutshell

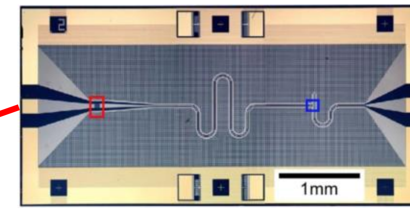
- *Most sensitive for microwave photons*

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

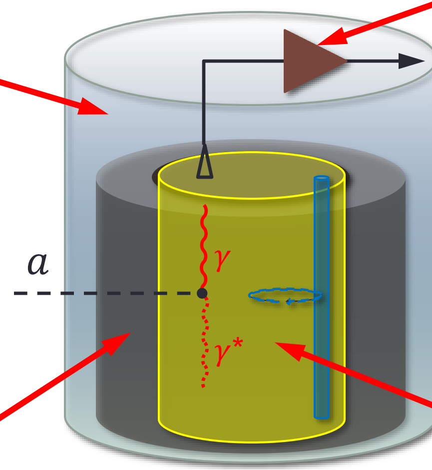
Cryogenics T

Lowering thermal noise

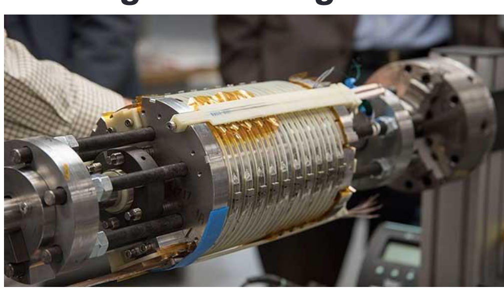
Quantum noise limited amplifier T



Signal amplification w/ minimal noise added



High field Magnet B



Boosting a→γγ conversion rate

Tunable High-Q resonator V, Q, C, Δf

Resonant frequency tuning

Interdisciplinary research !

Form factor

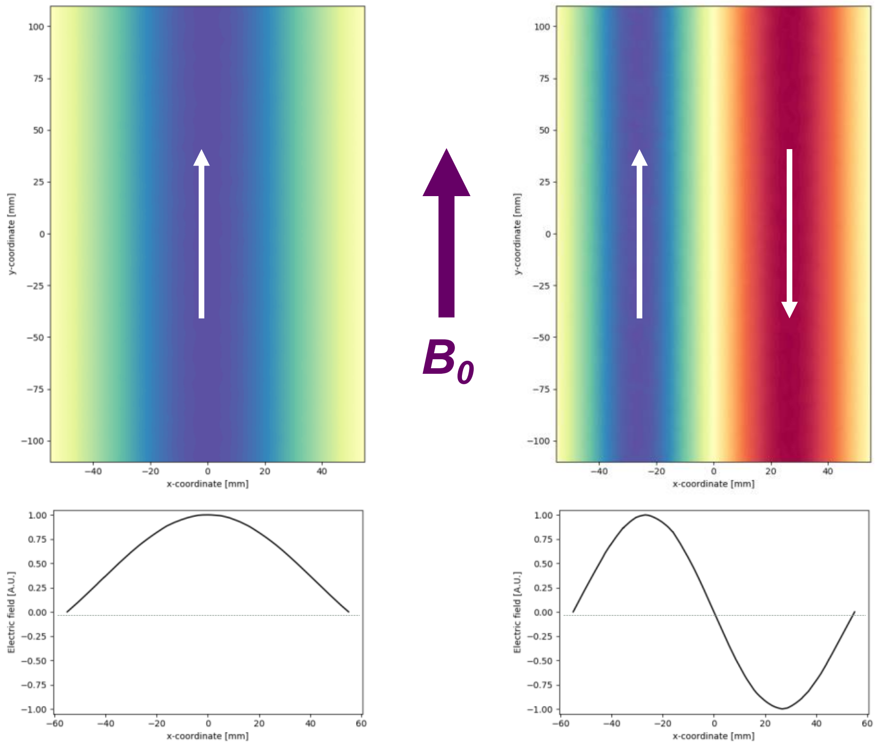
- *Geometry and mode dependent*
  - *Cavity mode and external field*

$$C_{mnp} = \frac{\left| \int \vec{E}_c \cdot \vec{B}_0 \, dV \right|^2}{\int \varepsilon \left| \vec{E}_c \right|^2 dV \int \left| \vec{B}_0 \right|^2 dV}$$

TM_{010} *TM_{110}*

E_c field

E_c profile



$C_{010} = 0.69$ *$C_{110} = 0$*

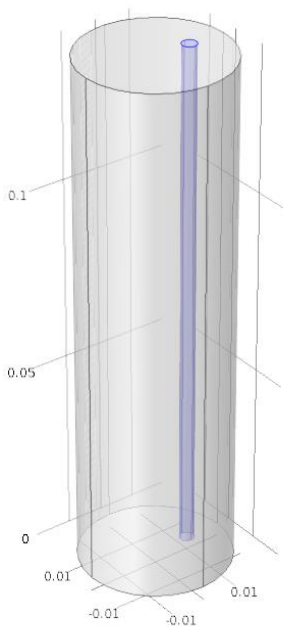
For cylindrical cavities

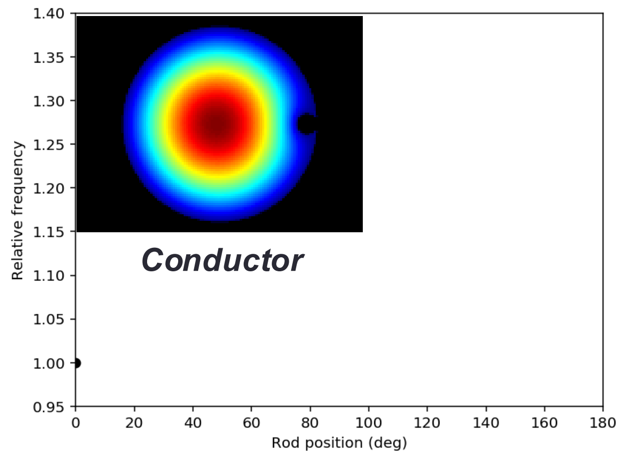
- *z-direction for TM modes*
- *φ-direction for TE modes*

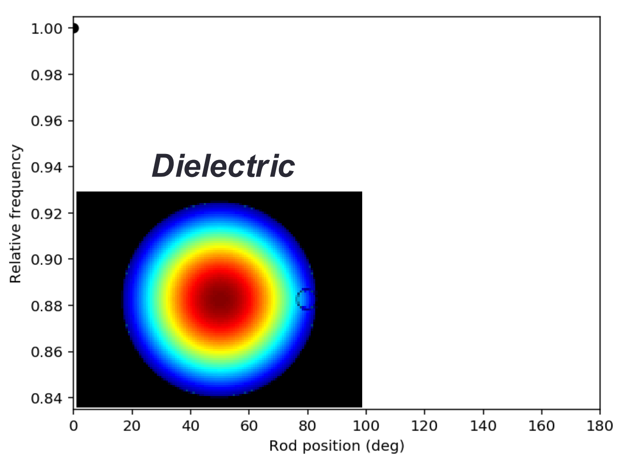
TM_{010} mode

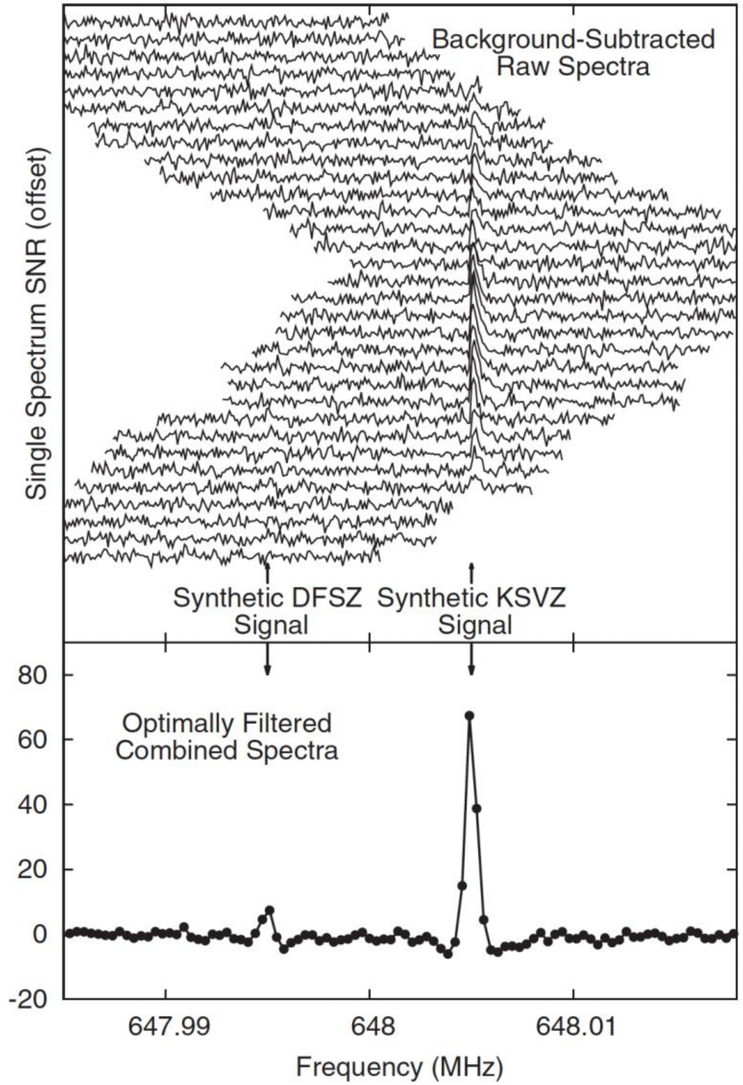
- *Maximum form factor*
- *Typical cavity mode for axion haloscopes*

TM_{010} tuning and signal

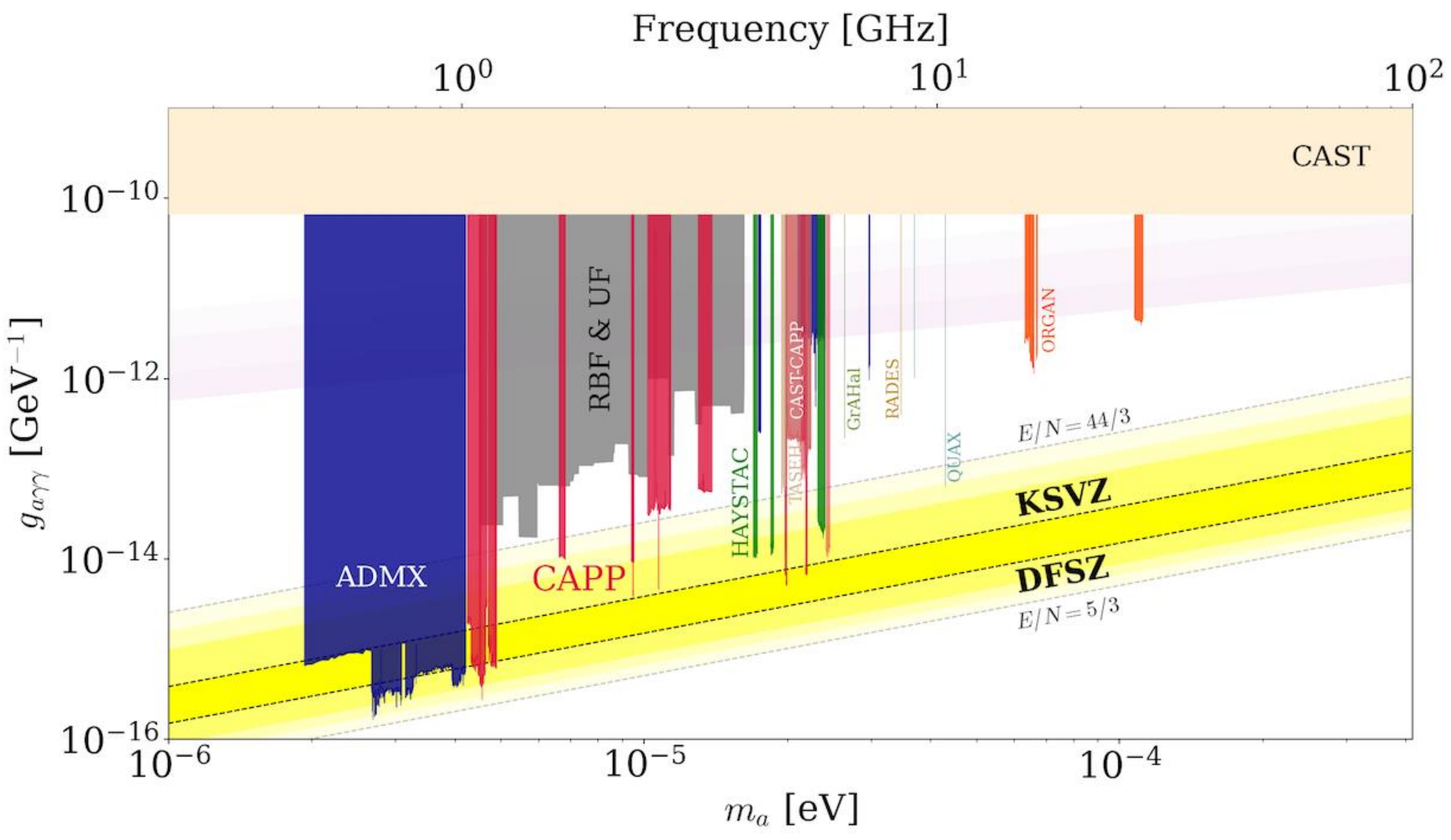








Haloscope searches

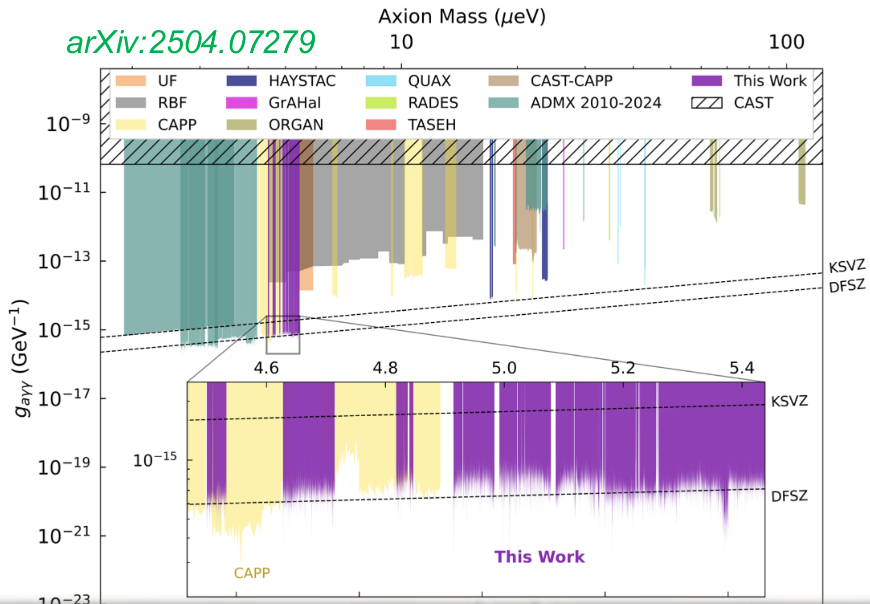


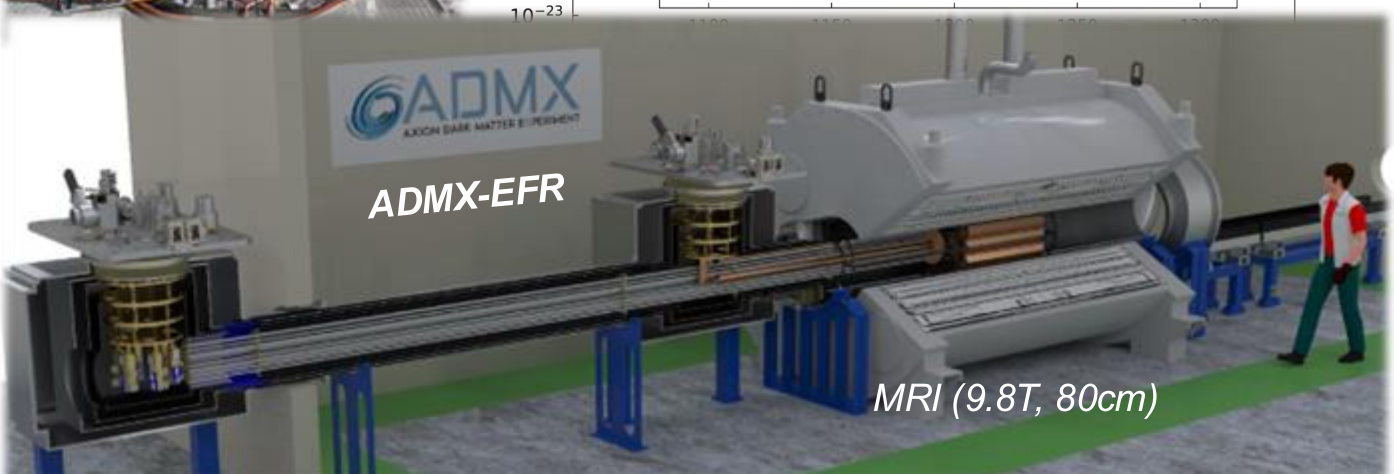
Cavity haloscopes

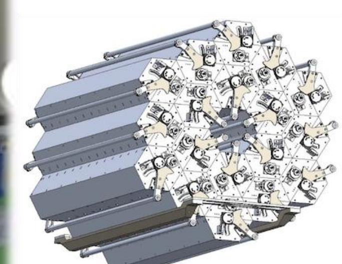
Cavity regime
$\lambda_{\mathrm{Comp}} \sim D_{\mathrm{exp}}$

ADMX

arXiv:2504.07279





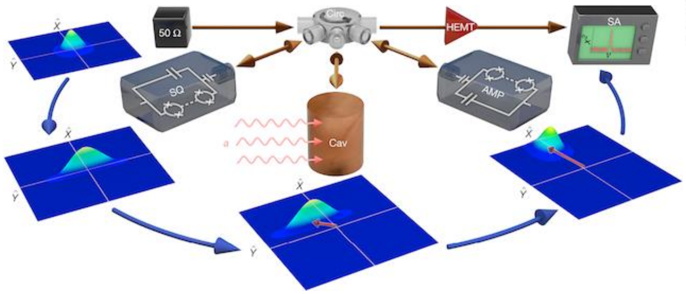


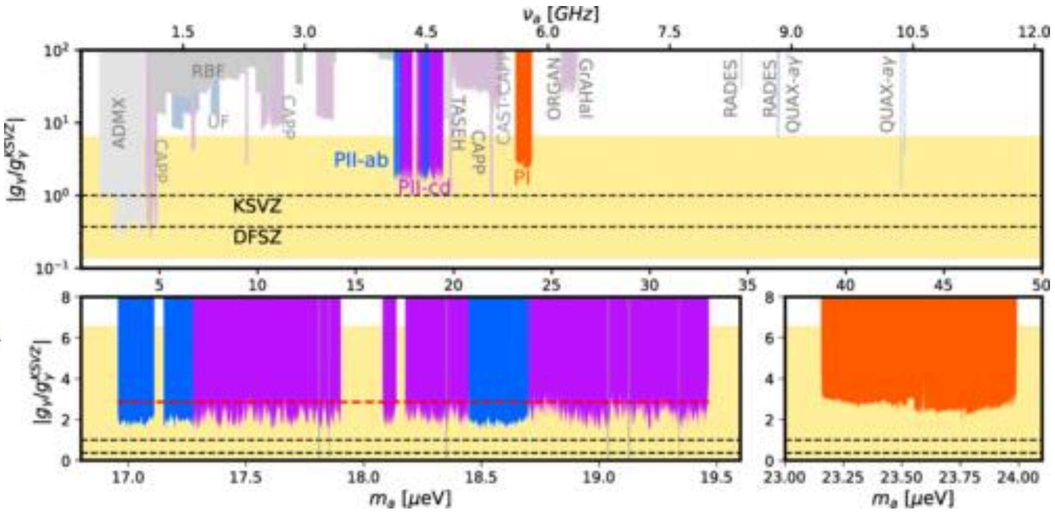
EFR

HAYSTAC

PRD **107** 072007 (2023)
PRL **134** 151006 (2025)

Nature **590** 238 (2021)



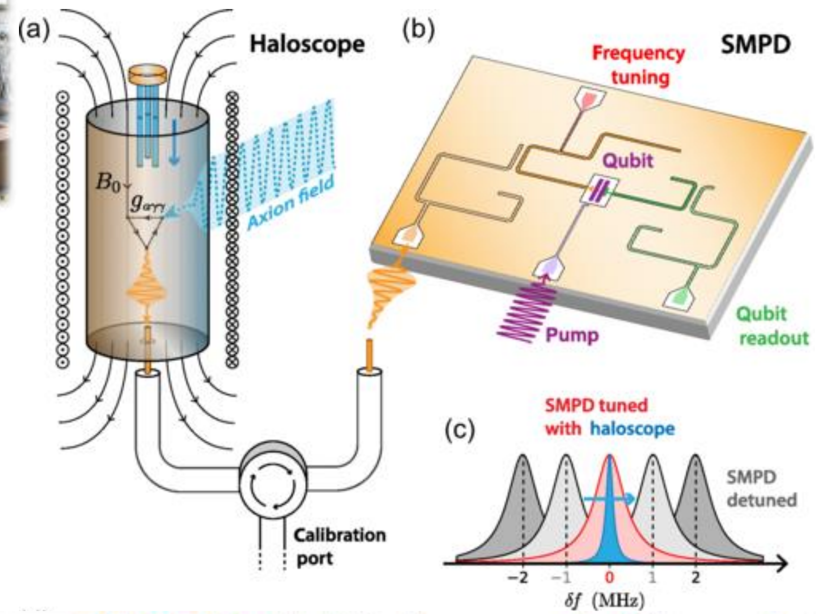


Quantum squeezing ($T_N < T_{SQL}$)

QUAX

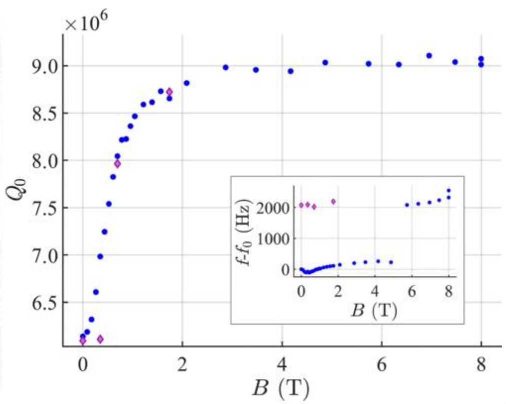
Singl Microwave Photon Detector

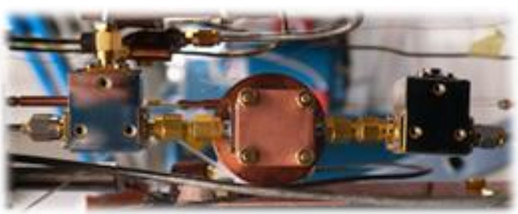
PRX **15** 021031 (2025)



Dielectric cavity

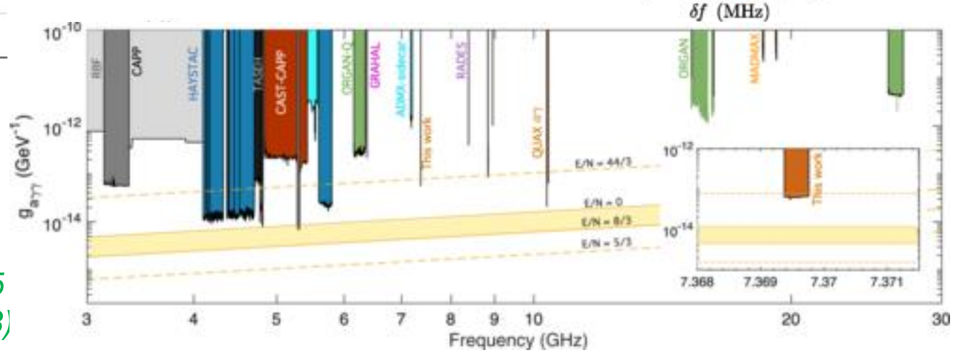
PRApplied **17** 054013 (2022)





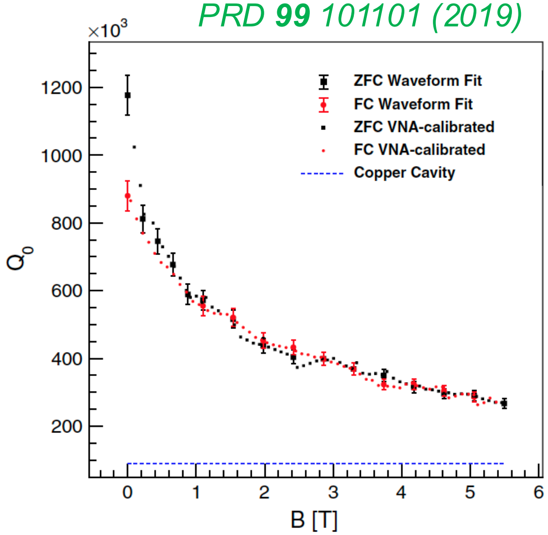
TWPA

PRD **108** 062005 (2023)

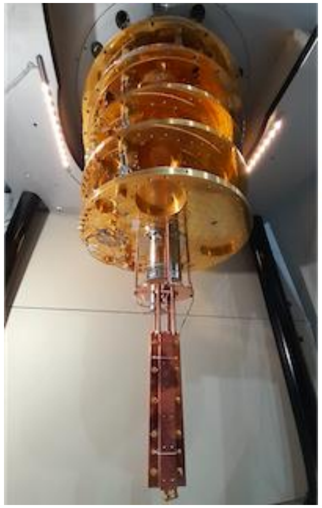


QUAX

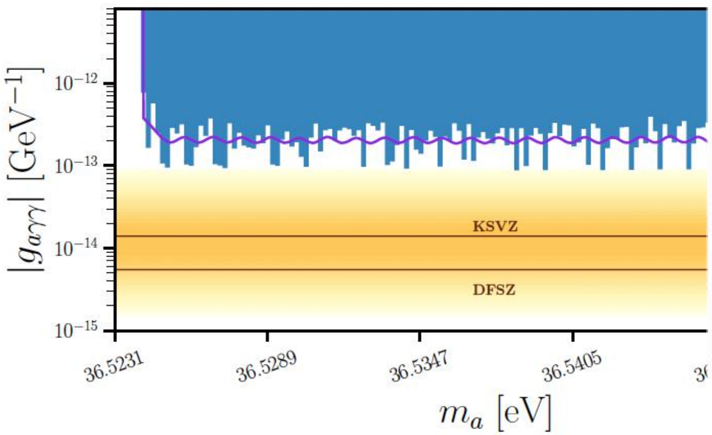
PRD **99** 101101 (2019)

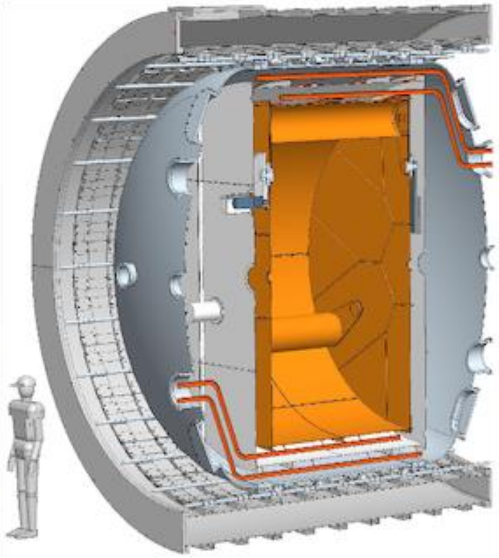


SC (NbTi) cavity



PRD **110** 022008 (2025)





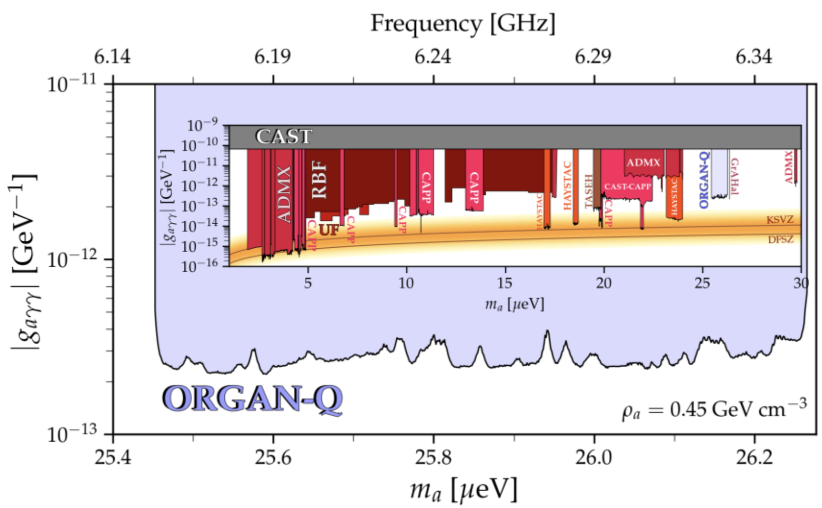
FINUDA

B = 1.1 T
R = 1.4 m

FLASH

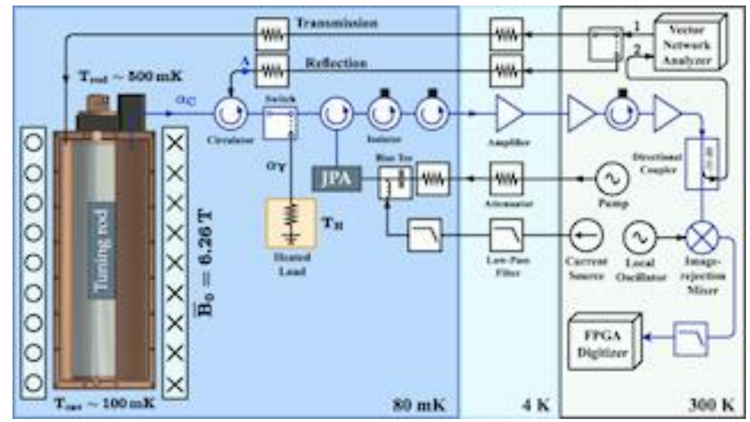
ORGAN

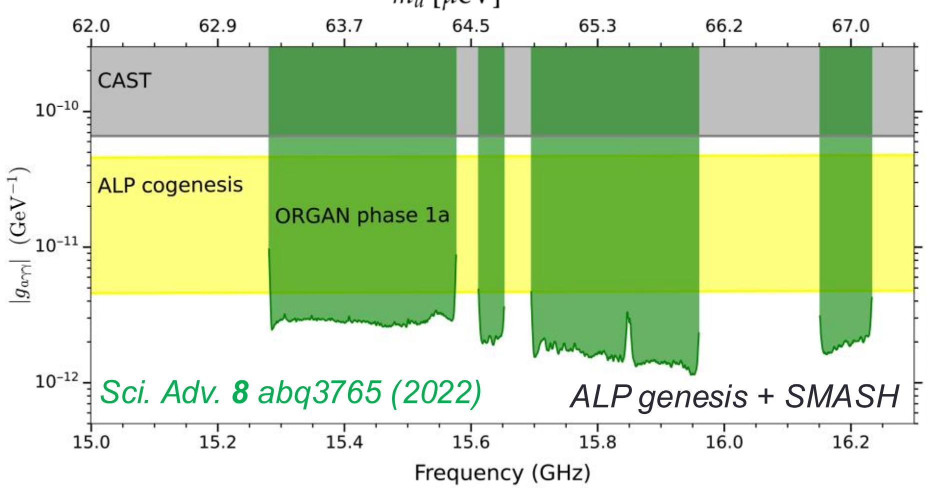
•



JPA run

PRD **111** 095007 (2024)

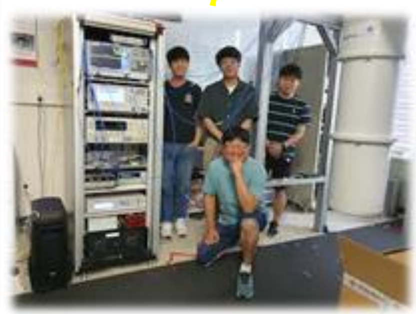




IBS-CAPP

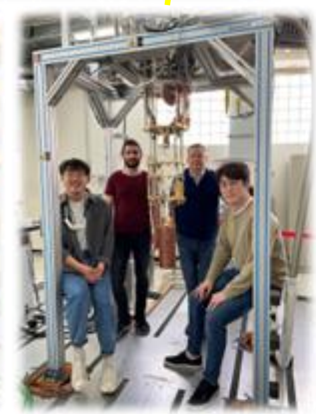
CAPP-9T

CAPP-12TB



CAPP-12T

CAPP-8T

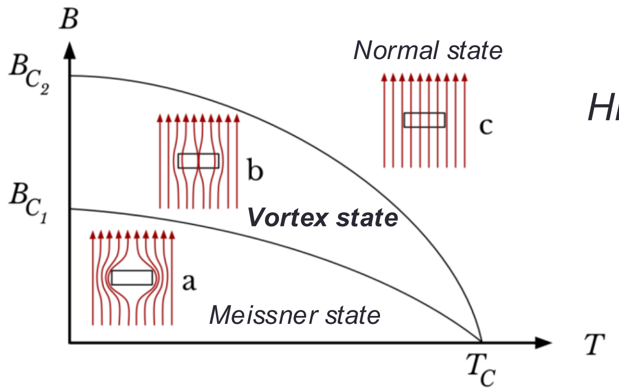


CAPP-8TB

High-Q cavities

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

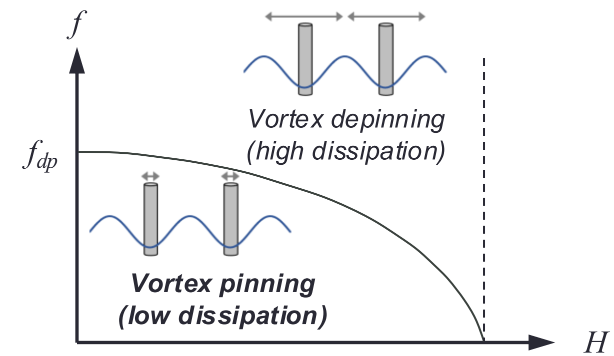
- *Under strong magnetic fields*



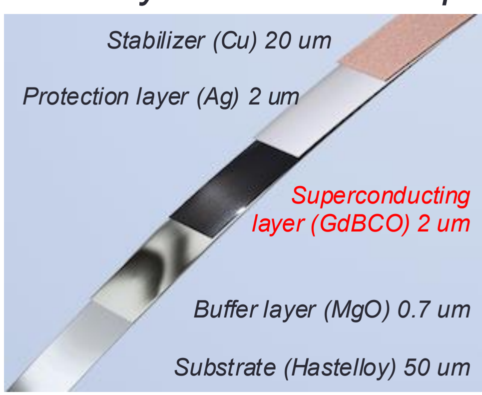
High critical field B_{C2}
&
High depinning frequency f_{dp}

↓↓

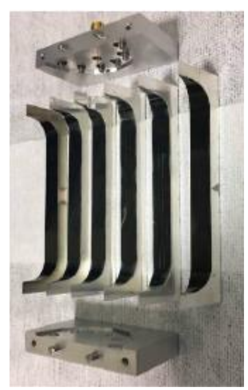
***ReBCO**-based*
High-Temperature Superconductor (HTS)



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

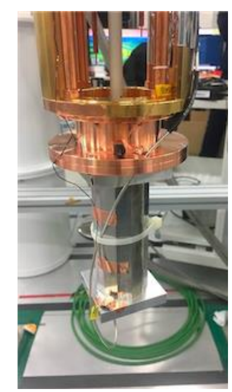


GdBCO HTS tape



Tapes on 2D pieces

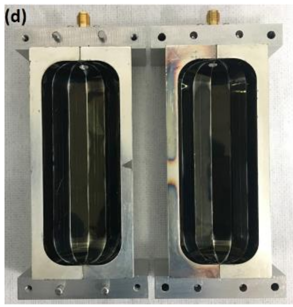
Assembly

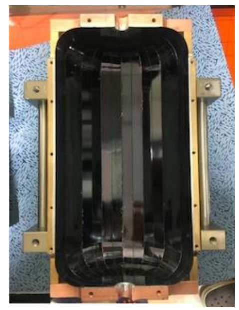


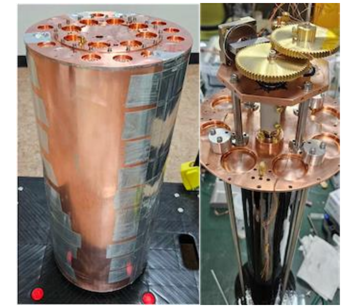
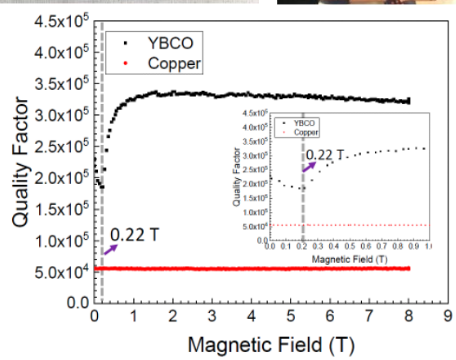
3D SC cavity

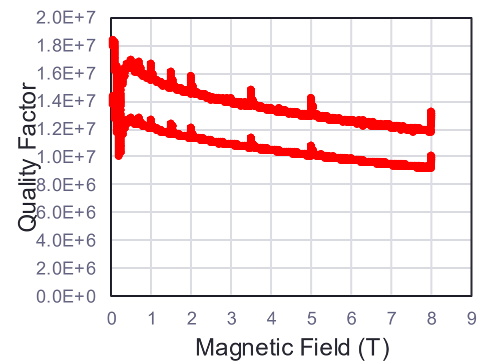
HTS cavities

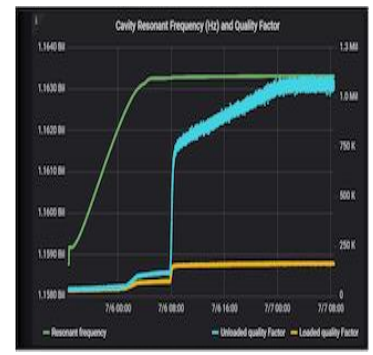
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$







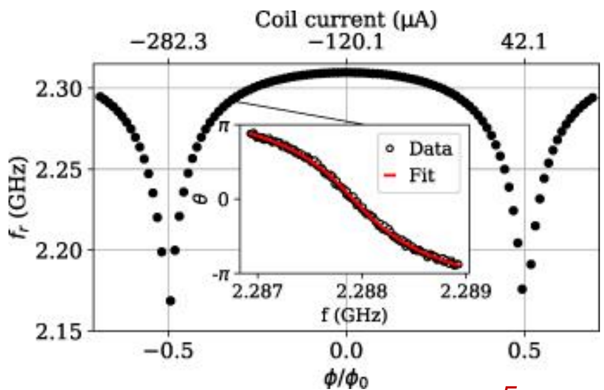


	1st Gen.	2nd Gen.	3rd Gen.		4th Gen.
Material	***Y**BCO*	***Gd**BCO*	***Eu**BCO + APC*		***Eu**BCO + APC*
Manufacturer	*AMSC*	*Theva*	*Fujikura*		*Fujikura*
Volume [L]	*0.3*	*1.5*	*1.5*	*0.2*	*37*
Freq. [GHz]	*6.9*	*2.3*	*2.2*	*5.4*	*1.2*
Q @ 8 T	***0.33 M***	***0.5 M***	***3.5 M***	***13 M***	***1.1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

QNL amplification

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

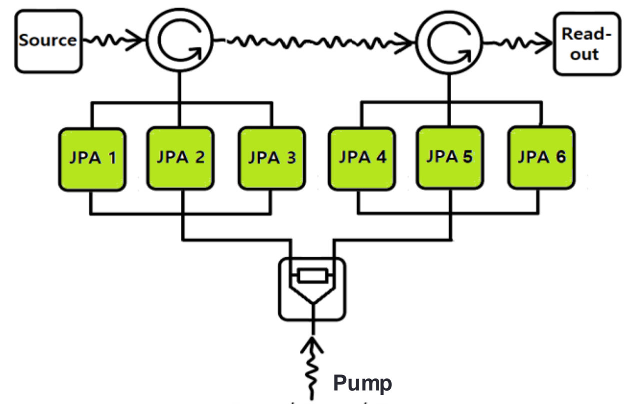
- *Flux-driven Josephson parametric amplifiers (JPAs)*

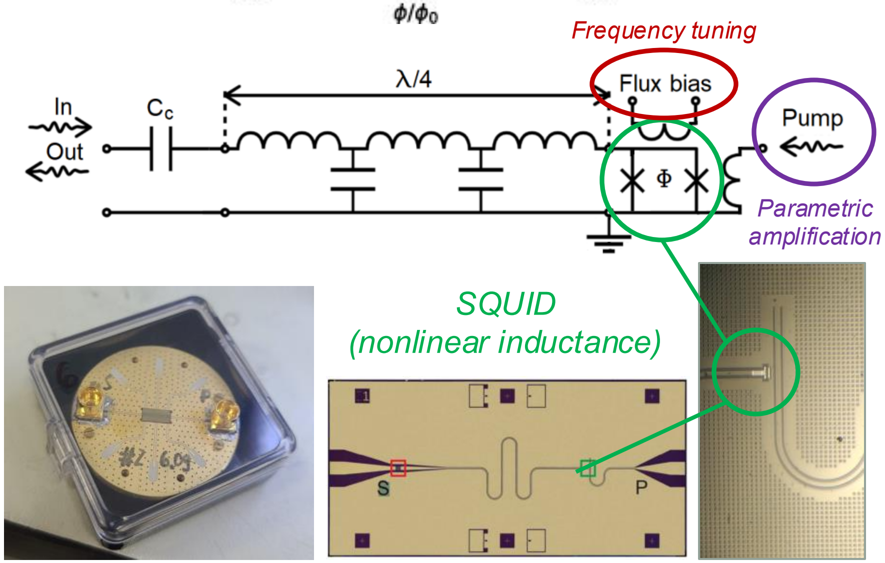


*SST **34** 085013 (2021)*

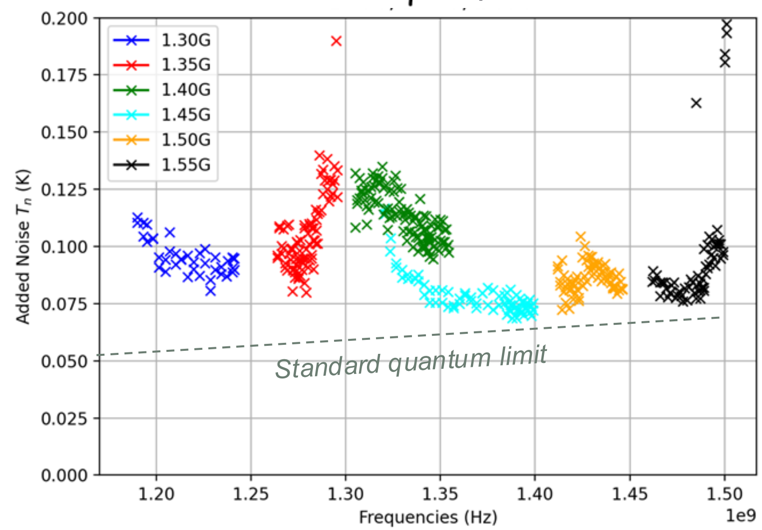
Best performance!

Parallel-Serial configuration





U. of Tokyo & RIKEN

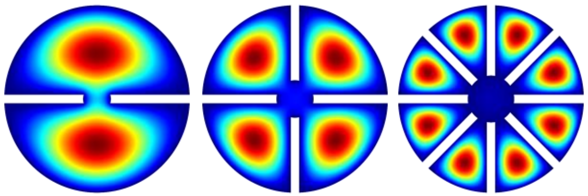


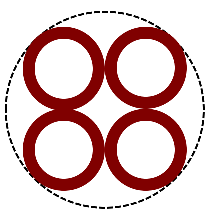
HF approach

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

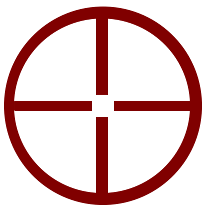
Multiple-cell (pizza)

PLB **777** 412 (2018)

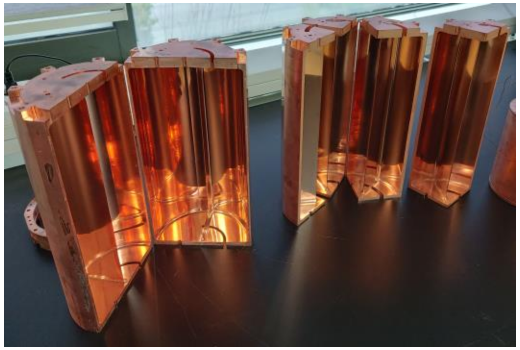




vs.



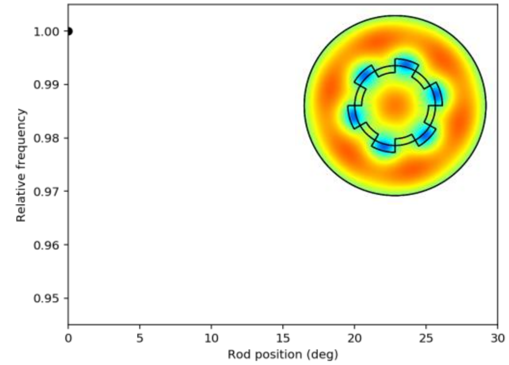
- *Larger volume*
- *Simpler receiver chain*
- *~4 x f_{TM010}*



Higher-mode (wheel)

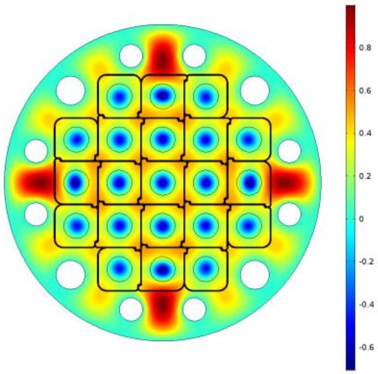
Mode	f_{rel}	Q_{rel}	V_{rel}	C_{abs}
TM_{010}	1	1	1	0.69
TM_{020}	2.3	1.5	1	0.13
TM_{030}	3.6	1.9	1	0.05

JPG **47** 035203 (2020)



Photonic crystal

PRD **107** 015012 (2022)

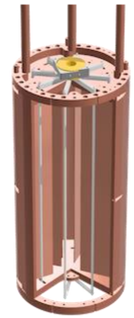
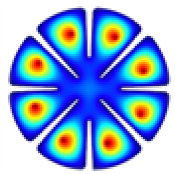
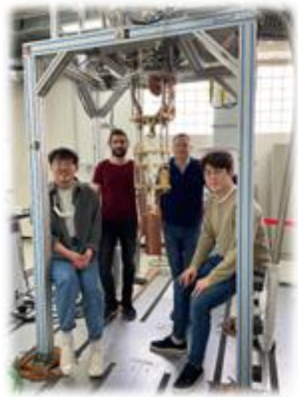


- *f ∝ spacing*
- *~10 x f_{TM010}*
- *Kirigami tuning*

IBS-CAPP

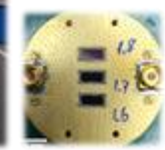
CAPP-8T
(8T/125mm)
HTS SC cavity + JPA
(2.3 GHz, Q ~ 3.5 M)
AQN search
Paper in preparation



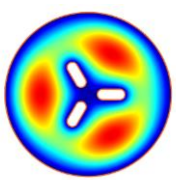




CAPP-8TB
(8T/165mm)
8-cell + JPA
(5.9 GHz, 400 mK)
Near KSVZ sensitivity
arXiv:2507.04344

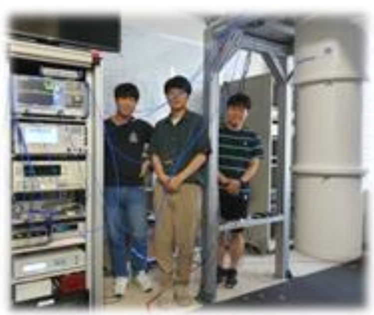


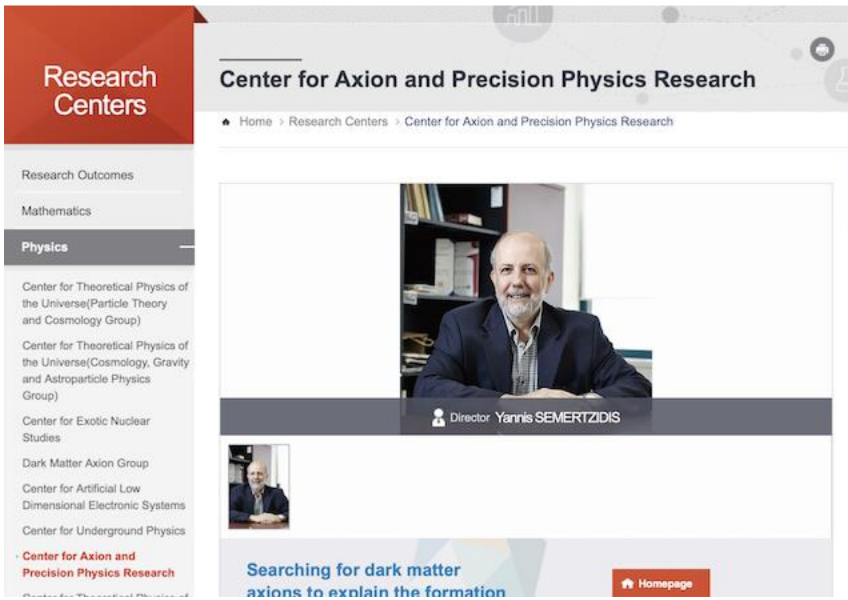
CAPP-12TB
(12T/320mm)
f > 1 GHz, V = 37 L, T_{sys} < 250 mK
df/dt ~ 2 MHz/day @ DFSZ
*PRL **130** 071002 (2023)*
Extended scan (Δf ~120 MHz)
*PRX **14** 031023 (2024)*
Ready for 300-MHz run w/ SC cavity



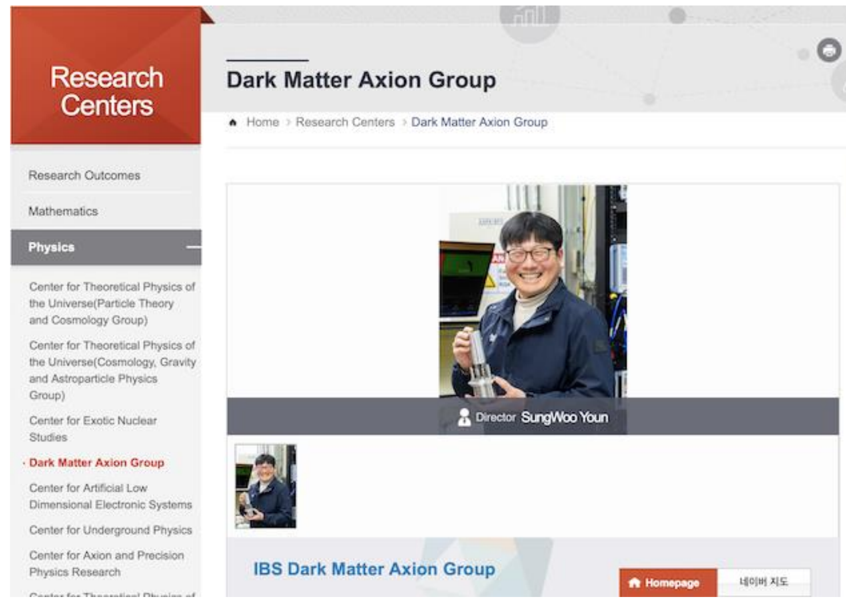

CAPP-12T
(12T/96m)
3-cell + JPA
(5.3 GHz, 400 mK)
KSVZ sensitivity
NM algorithm
*PRL **133** 211803 (2024)*



CAPP to DMAG



2013.10 ~ 2024.12



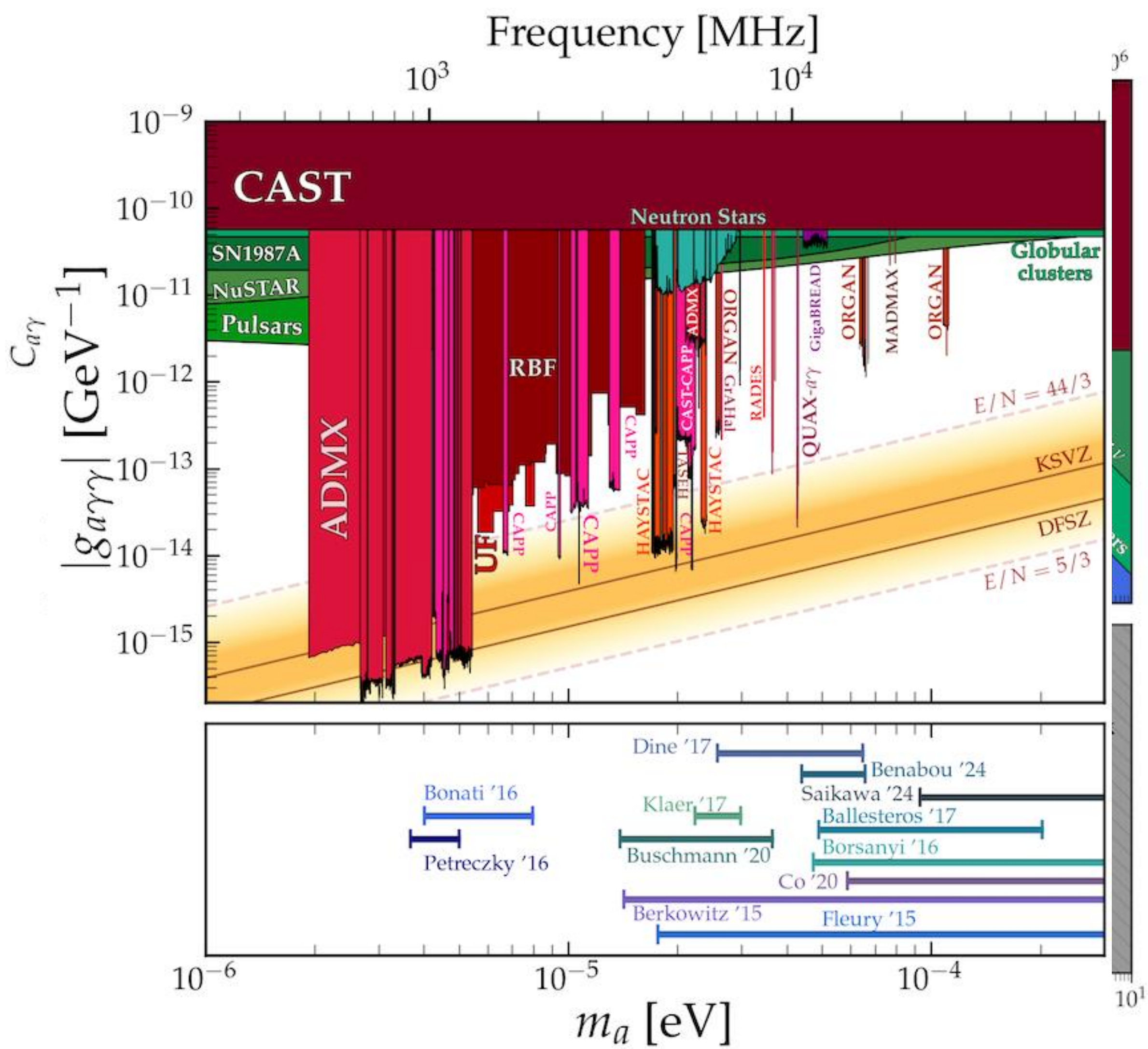
2025.01 ~

Cavity haloscopes

Cavity regime
$\lambda_{\mathrm{Comp}} \sim D_{\mathrm{exp}}$

Cavity regime
$\boldsymbol{\lambda_{\mathrm{Comp}} \sim D_{\mathrm{exp}}}$

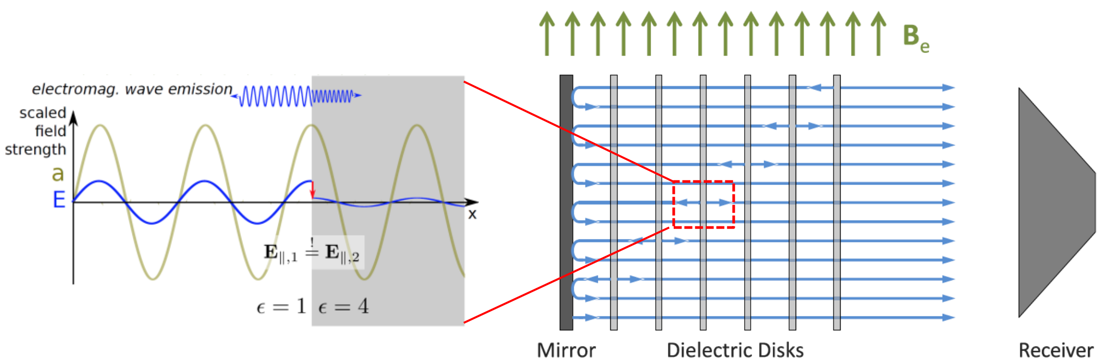
Axion mass predictions



MADMAX

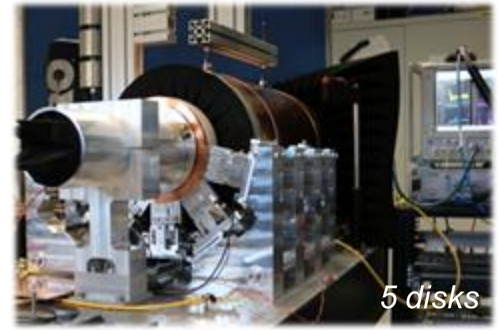
Radiation regime
$\lambda_{\mathrm{Comp}} \ll D_{\mathrm{exp}}$

- *Dielectric power booster* PRL **118** 091801 (2017)

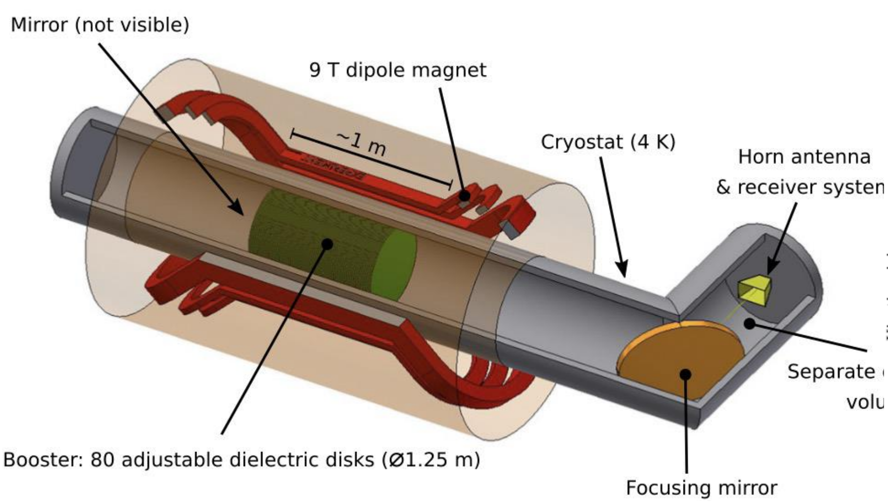


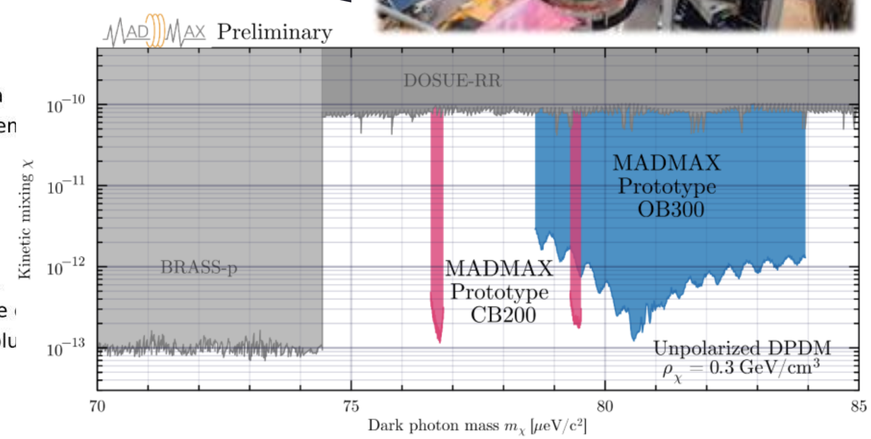
Suitable for 10~100 GHz

Proof-of-concept



Prototype (2024)



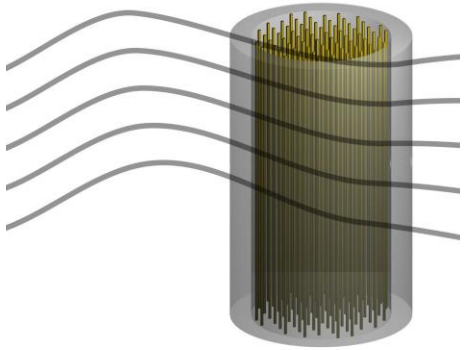


PRL **134** 151004 (2025)

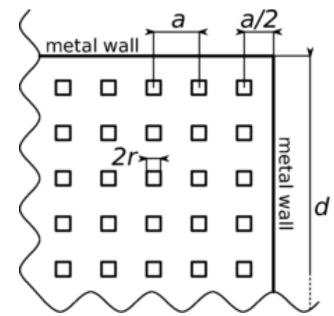
ALPHA

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

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



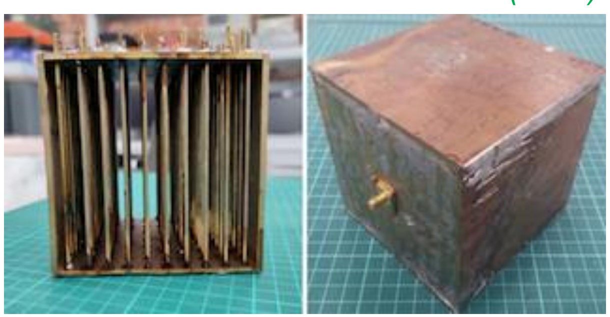
$$\omega_p{}^2 = \frac{2\pi c^2}{a^2 \log(\frac{a}{2r})}$$

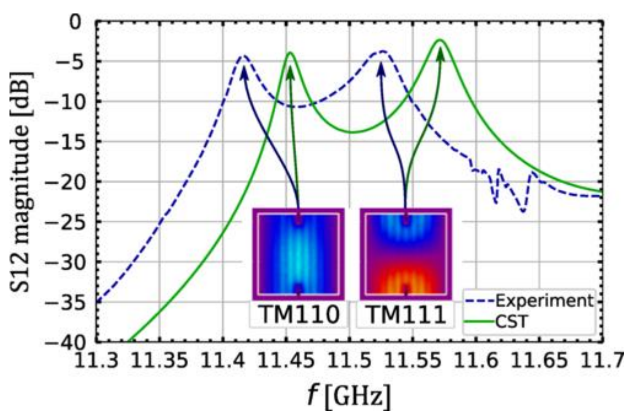


- *ω_p independent of the detector size*
- *Large conversion volume at high frequencies*

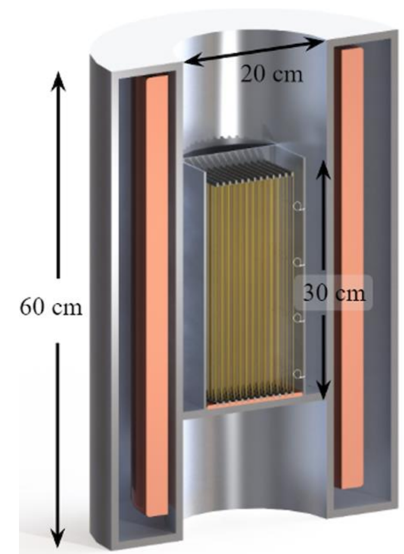
Resonant conversion when $m_a = \omega_p$

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





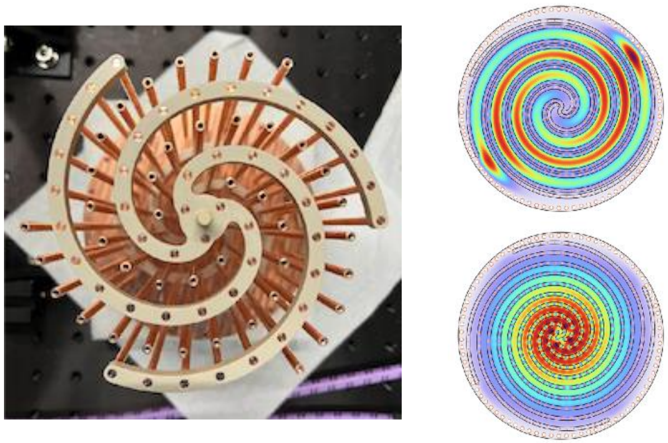
Prototype 10x10 array (11.4 GHz)



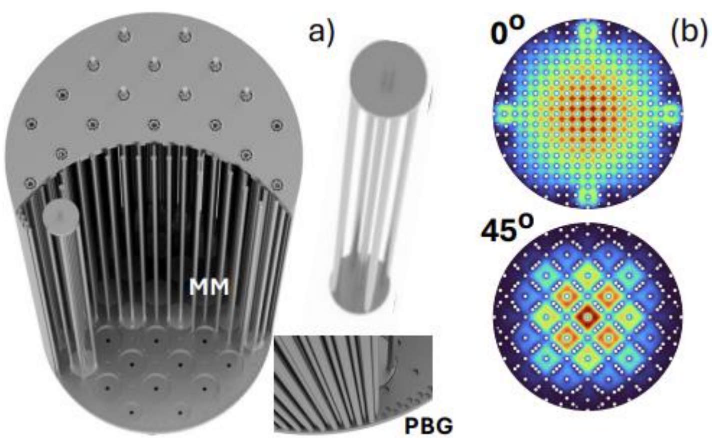
16x16 array

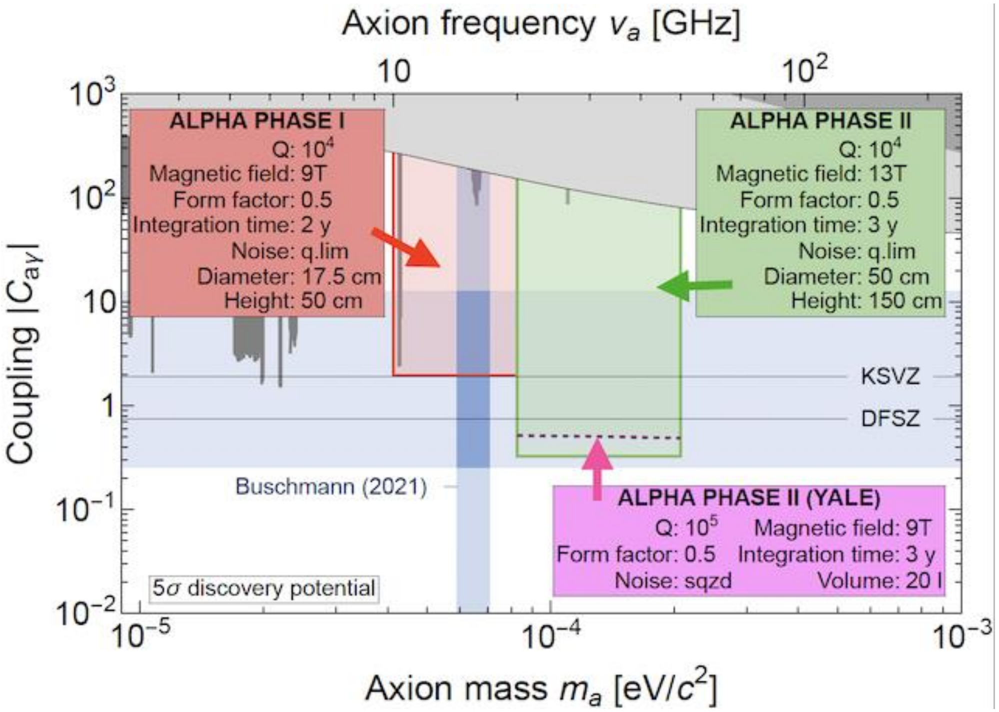
ALPHA

Spiral Tuning (Stockholm)



Quadropode Spinor (Yale)

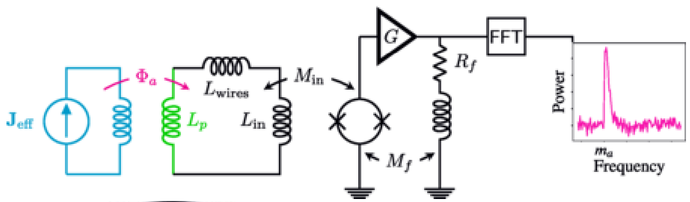




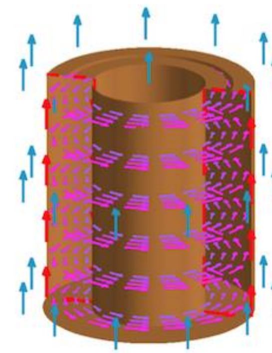
DM Radio

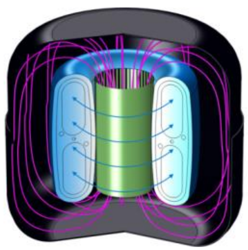
Quasistatic regime
$\lambda_{\text{Comp}} \gg D_{\text{exp}}$

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



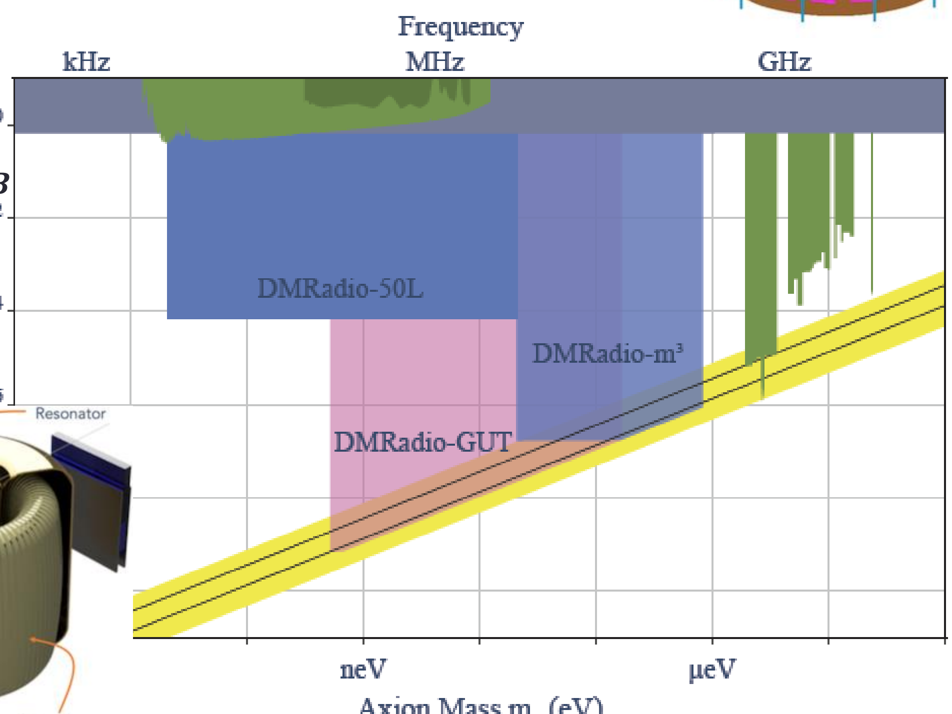
DM Radio-m³
Solenoidal geometry
*PRD **106** 103008 (2022)*

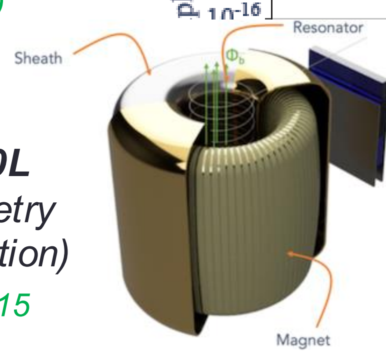




ABRACADABRA-10cm
*PRL **127** 081801 (2021)*

$$j_{eff} = g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\, B$$





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

Other haloscopes

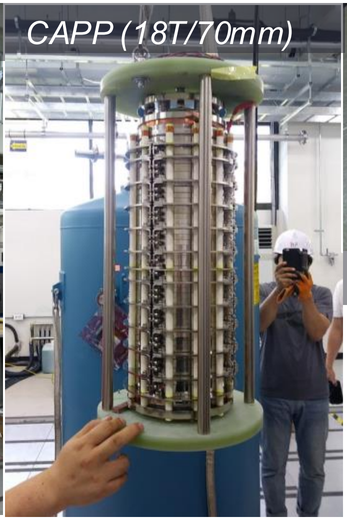
- *Recent*
  - *CAST-CAPP: phase-matched cavities, ~20 ueV* — *Nat. Comm. **13**, 6180 (2022)*
  - *RADES: microwave fiber, ~34 ueV* — *JHEP **2021** 75 (2021)*
  - *Grenoble Axion Haloscope* — *arXiv:2110.14406*
    - *14T/52mm magnet, ~26 ueV*
  - *Taiwan Axion Search Experiment with Haloscope* — *PRL **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:2505.07541*
    - *SC (NbN) cavity, 14T, 8.4 GHz*
  - *GrAHal-CAPP* — *Front. Phys. 12:1358810 (2024)*
    - *9T/800mm magnet, SC cavity, 1~3 ueV*

Magnet


ADMX (8T/600mm)

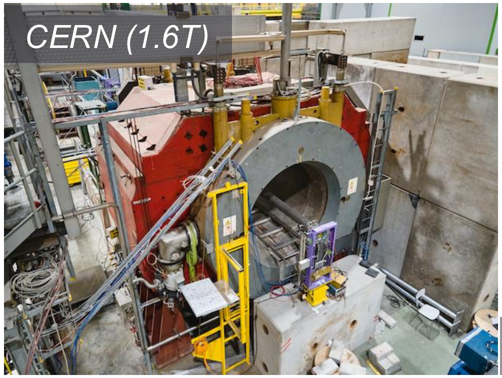

CAPP (12T/320mm)

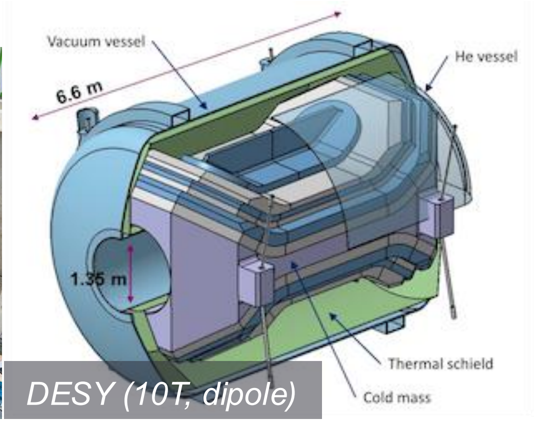

CAPP (18T/70mm)


YBCO pancakes

Grenoble (43T/34mm)

UIC (9.4T/800mm)

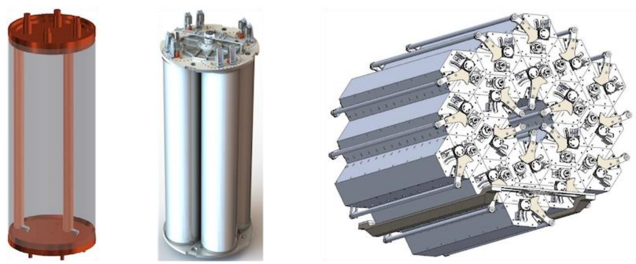

CERN (1.6T)



DESY (10T, dipole)

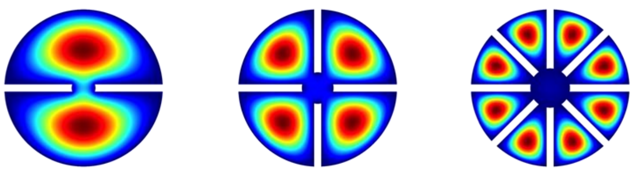
Cavity

arXiv: 2203.14923

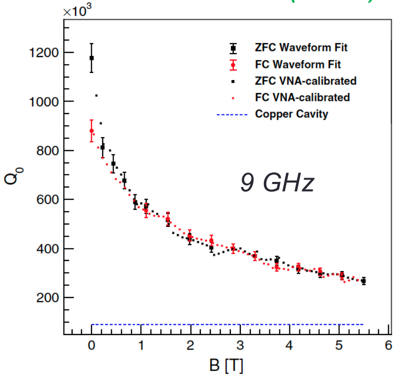


Run 1A-C Run 2 EFR

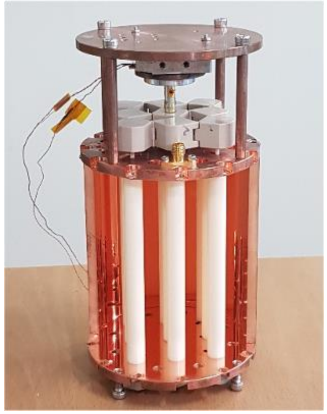
*PRL **125** 221302 (2020)*



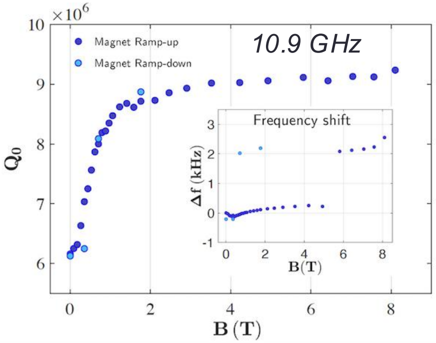
*PRD **99** 101101 (2019)*

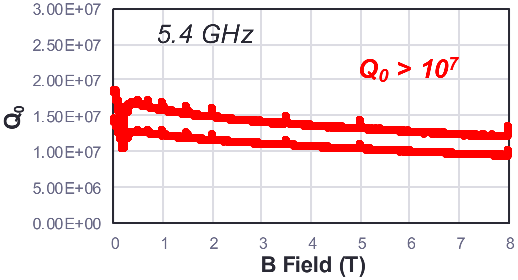


*PRD **107** 015012 (2022)*



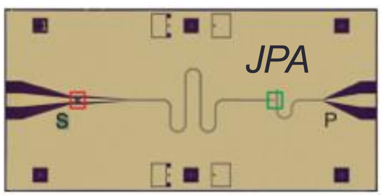
*NIM **985** 164641 (2021)*





Microwave photon detector

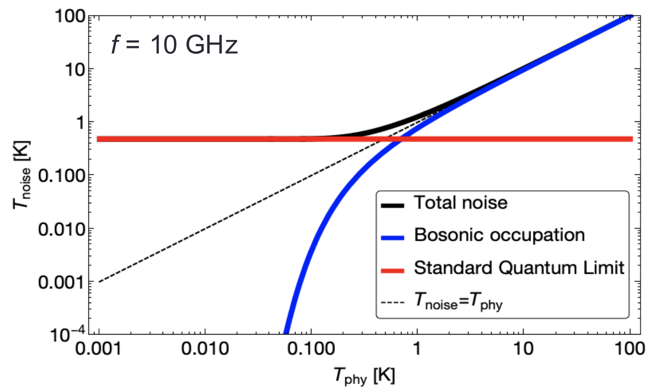
Transistor-based
(T_N ~ K)



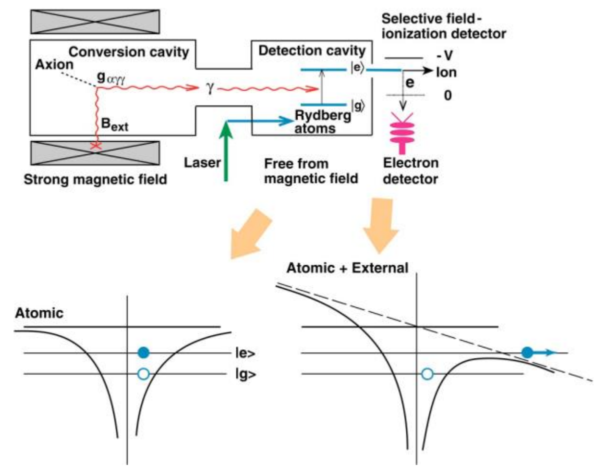
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection vs. photon counting

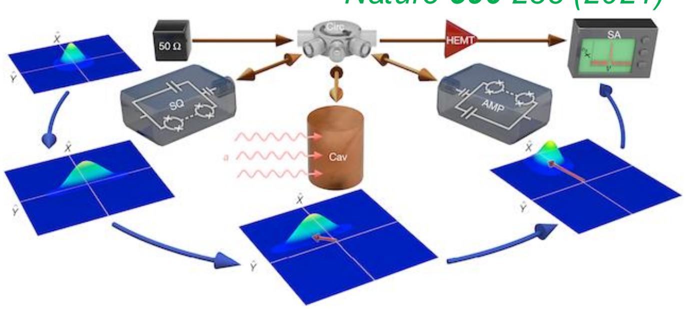
(w/ amplifiers) *(w/ single photon detector)*



Game changer
at high freq. and low temp.

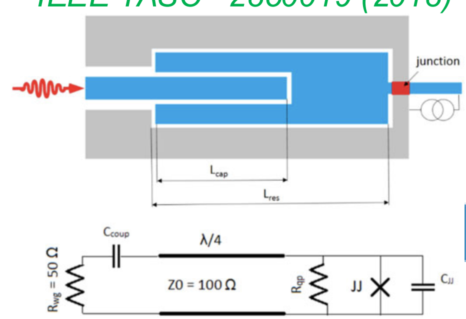


*Nature **590** 238 (2021)*

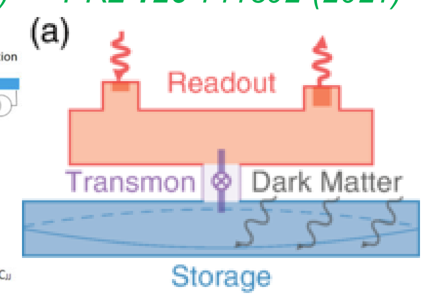


Quantum squeezing ($T_N < T_{SQL}$)

IEEE TASC 2850019 (2018)



*PRL **126** 141302 (2021)*



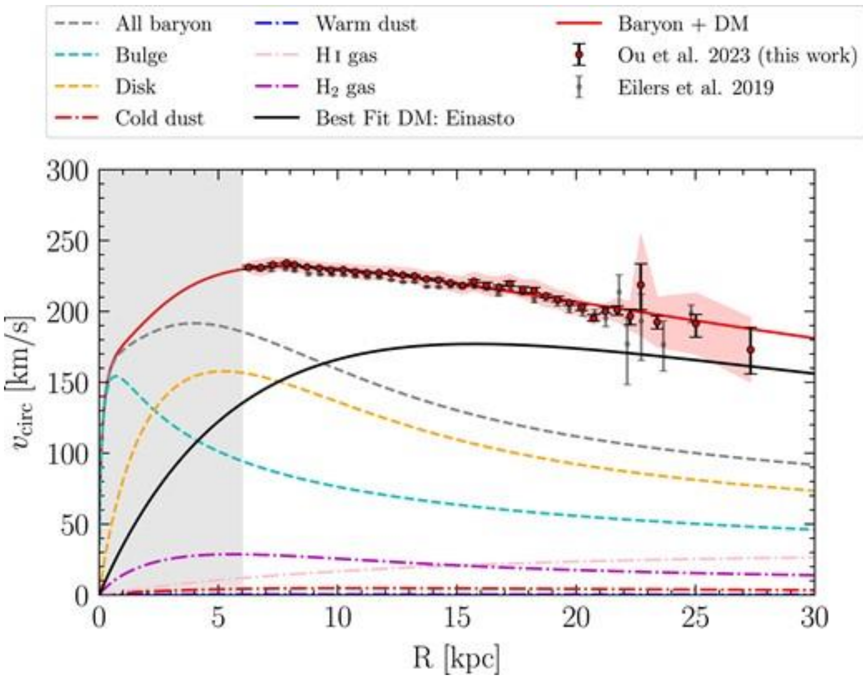
Single photon counting ($T_N << T_{SQL}$)

Local dark matter density

- $\rho_{axion} = 0.45\ GeV/cm^3$ (cf. $\rho_{WIMP} = 0.3\ GeV/cm^3$)

- *Gaia DR3 and APOGEE DR17*
- *Circular velocity curve of MW*

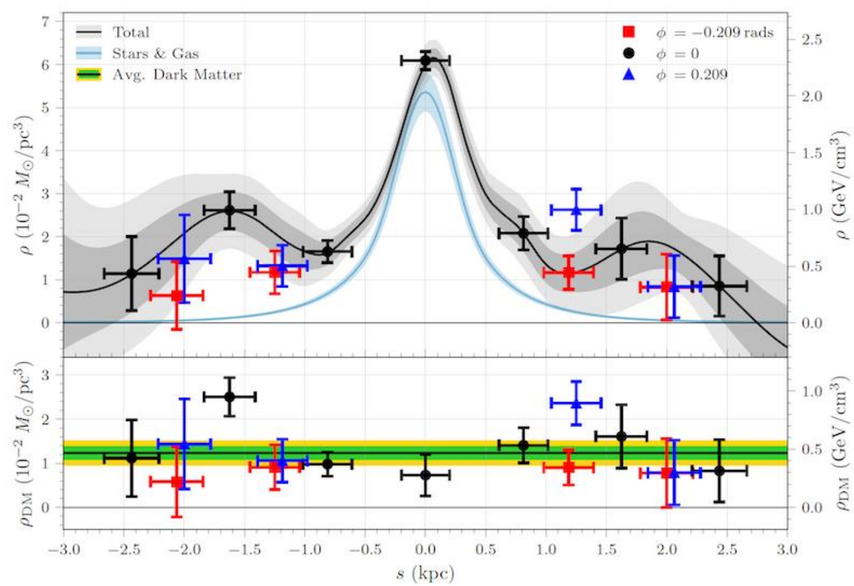
Mon. Not. R. Astron. Soc. ***528*** *693 (2024)*



$\rho_{DM,local} = 0.447 \pm 0.004\ GeV/cm^3$

- *Phase space distribution of 6M stars (Gaia DR3)*
- *Unsupervised machine learning*

JCAP01 021 (2025)



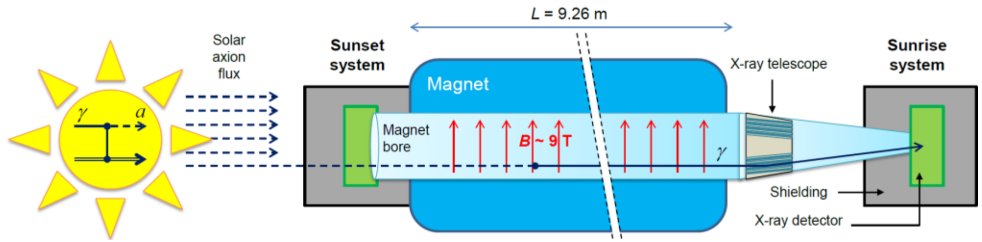
$\rho_{DM,local} = 0.47 \pm 0.05\ GeV/cm^3$

Helioscope / LSW

Helioscope

- *Solar axion telescope*

Photon (keV) to axion in dense stellar plasma



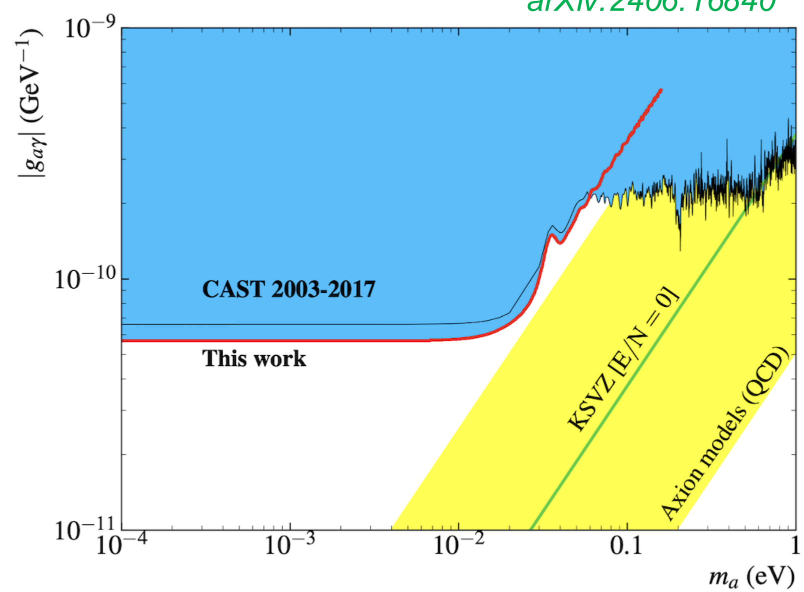
Conversion into X-ray in laboratory B fields

~10 photons/day

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

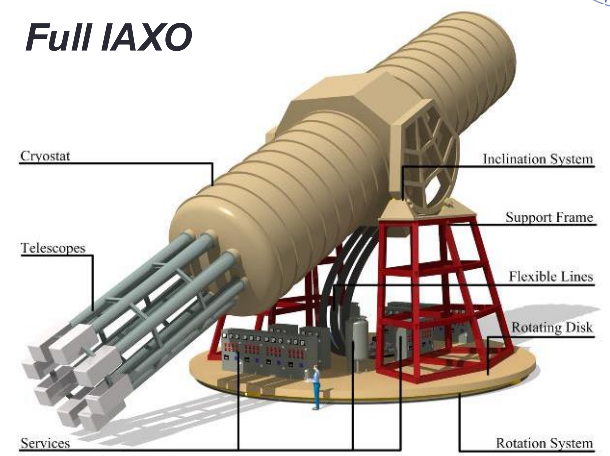
- *History*
  - *BNL => SUMICO => CAST => IAXO*

arXiv:2406.16840

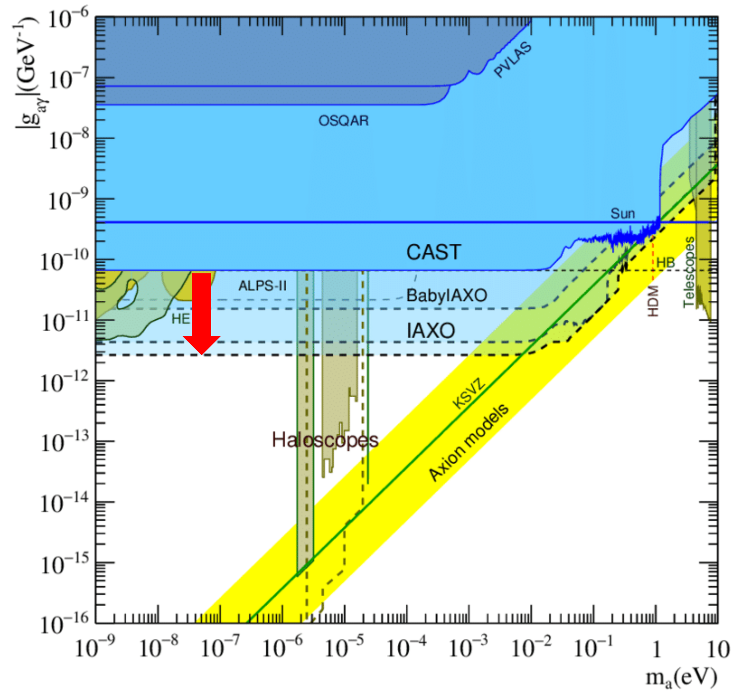


IAXO

- *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 : $g_{a\gamma} \sim 10^{-12}\ GeV^{-1}$

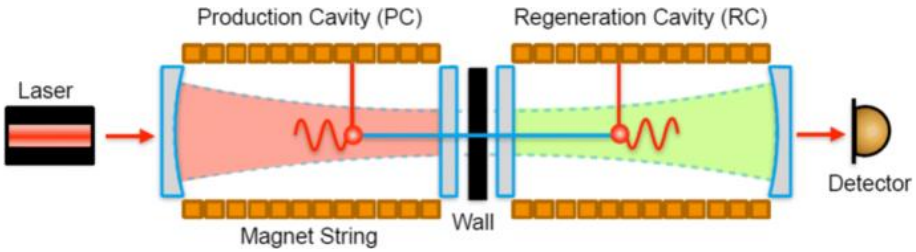


- *Baby-IAXO* *arXiv:2010:12076*
  - *Approved in 2020 (DESY)*
  - *First step towards full IAXO*
    - *4 T / 10 m long => 10 x MFOM$_{CAST}$*



Light shining through a wall

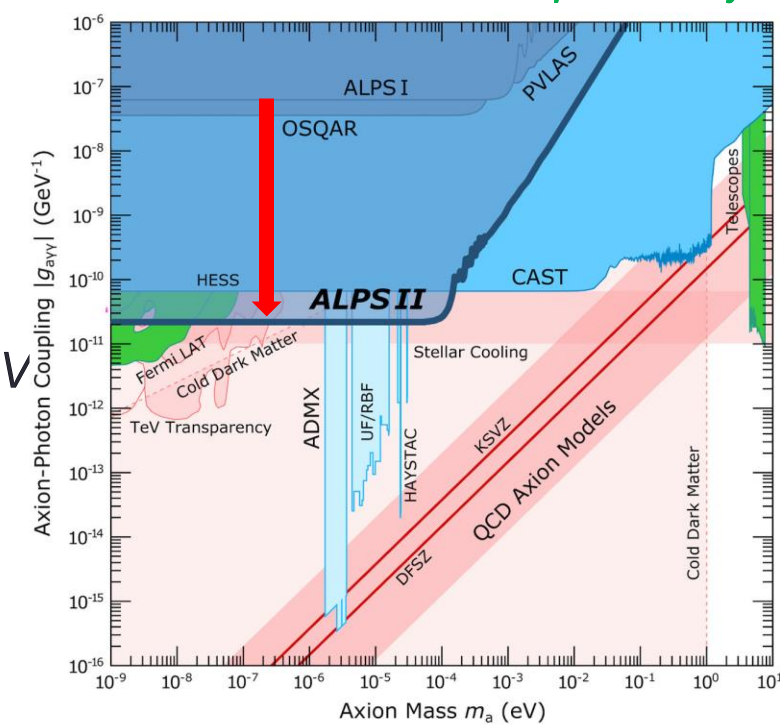
- *Axion-production/photon-regeneration at the lab*



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

~1 photons/day

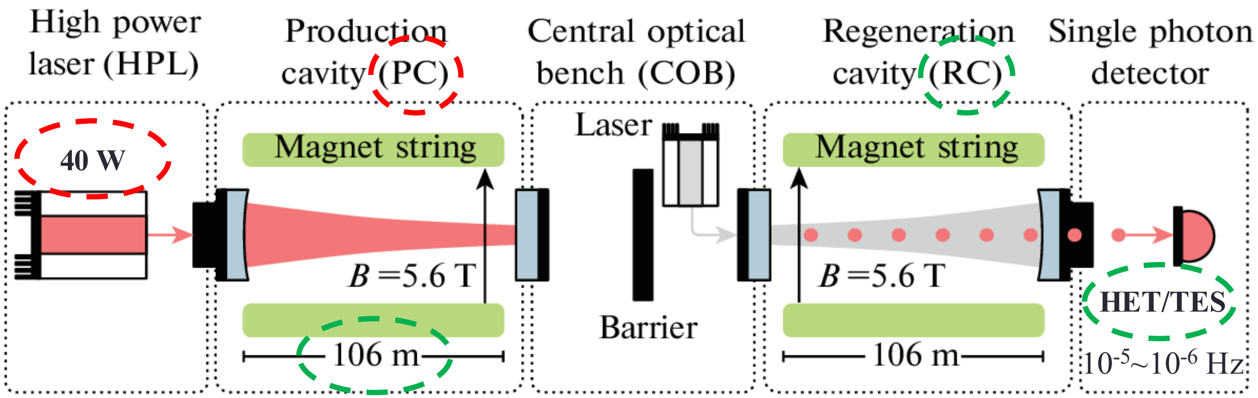
- *Model independent search*
  - *No need of cosmo./astrophys. source*
  - *Pure axion-photon coupling*
- *History*
  - *BFRT => OSQAR => ALPS => ALPS II*
- *Goal: $g_{a\gamma\gamma} \sim 10^{-11}\ GeV^{-1}$ below 0.1 eV*

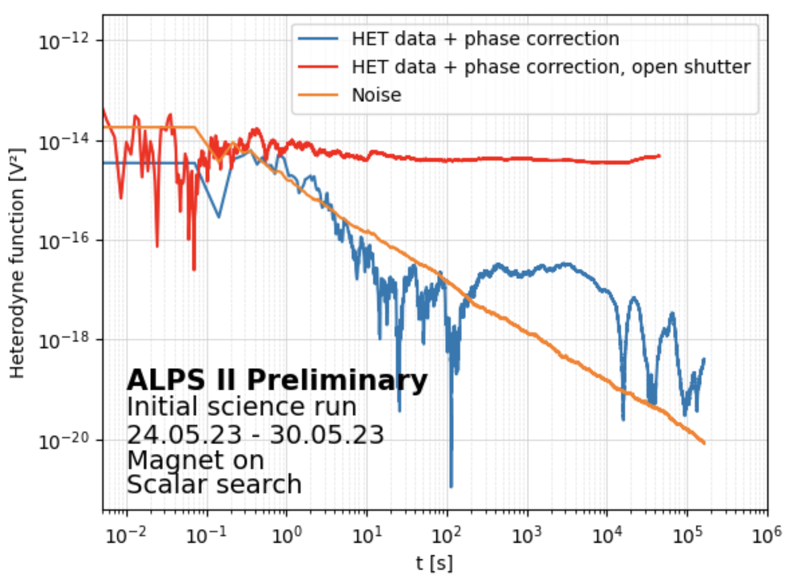



ALPS II, DESY

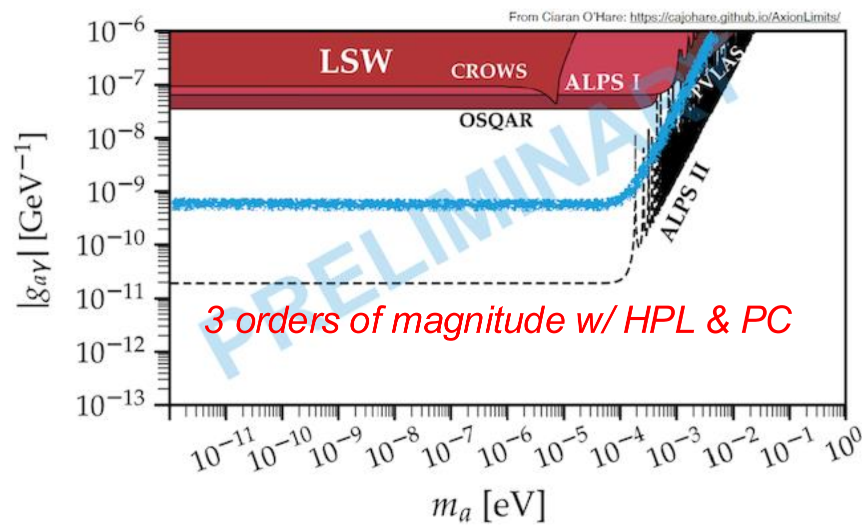
ALPS II

- *Any Light Particle Search II*

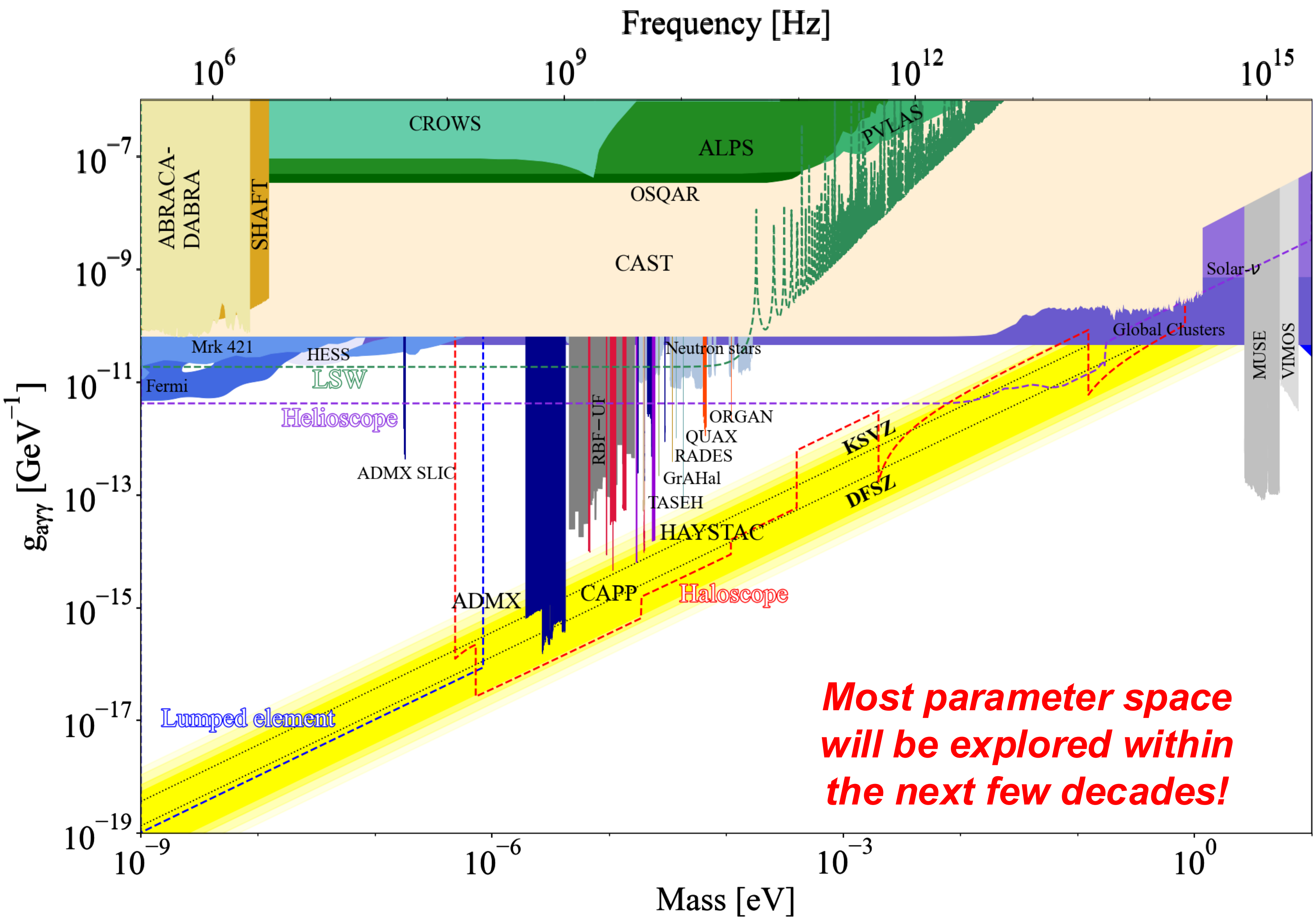




***First science run** (30 x ALPS)*



Axion searches – future



Most parameter space will be explored within the next few decades!

Summary

C. O'Hare (2020)

- ***Axion is*** ***theoretically well-motivated*** ***but*** ***experimentally very challenging***

- ***Tremdous efforts duing the past decades***
- ***Axion*** ***community is getting larger***
- ***Next few decades must be*** ***crucial/exciting***