

# Axion Search where are we?

Die for righteousness  
and live for truth.

의에 죽고 참에 살자

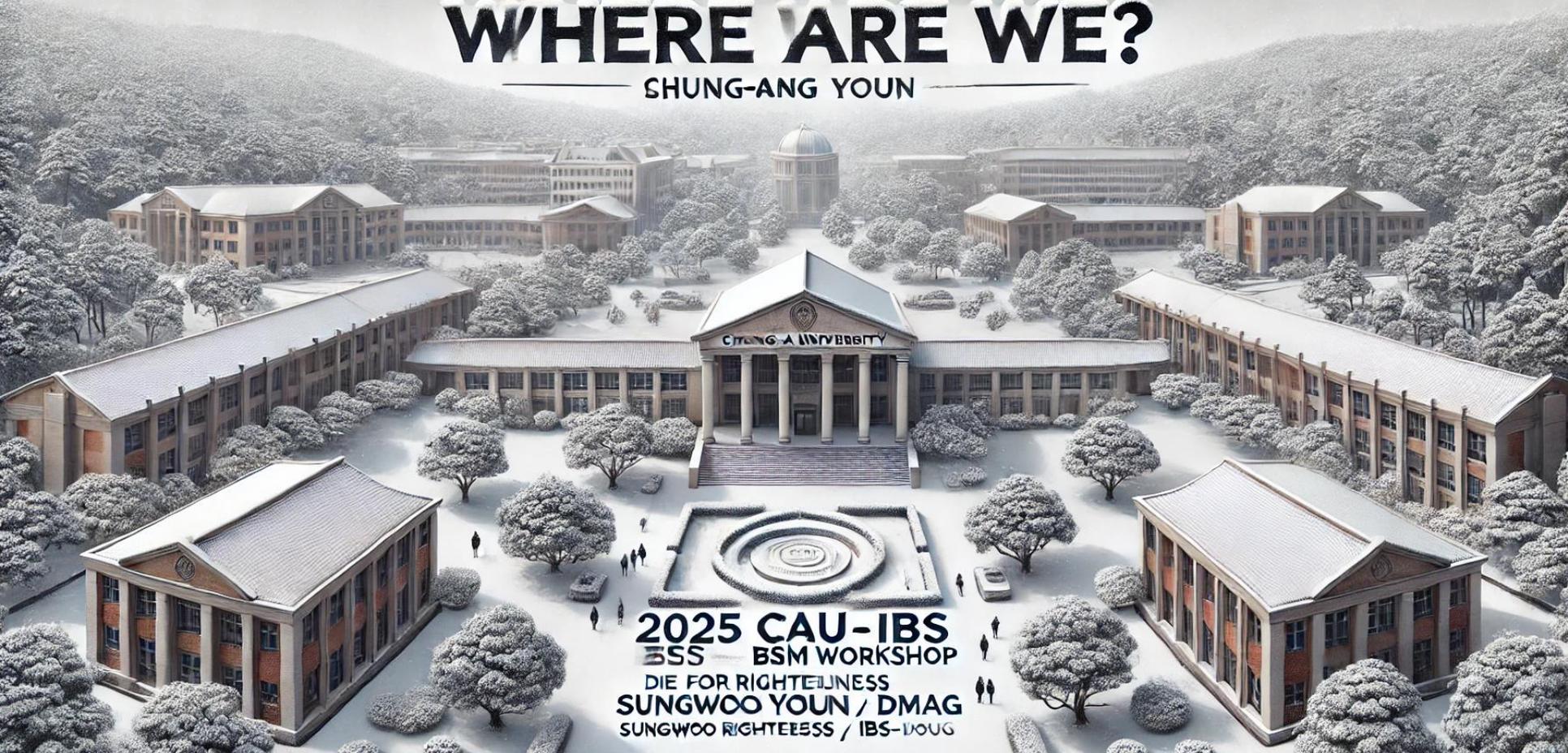
**2025 CAU-IBS BSM Workshop**  
**Feb. 18 2025 Chung-Ang University**

**SungWoo YOUN**  
**Dark Matter Axion Group (DMAG)**  
**Institute for Basic Science (IBS)**

CHUNG-ANG  
UNIVERSITY

# AXION SEARCH WHERE ARE WE?

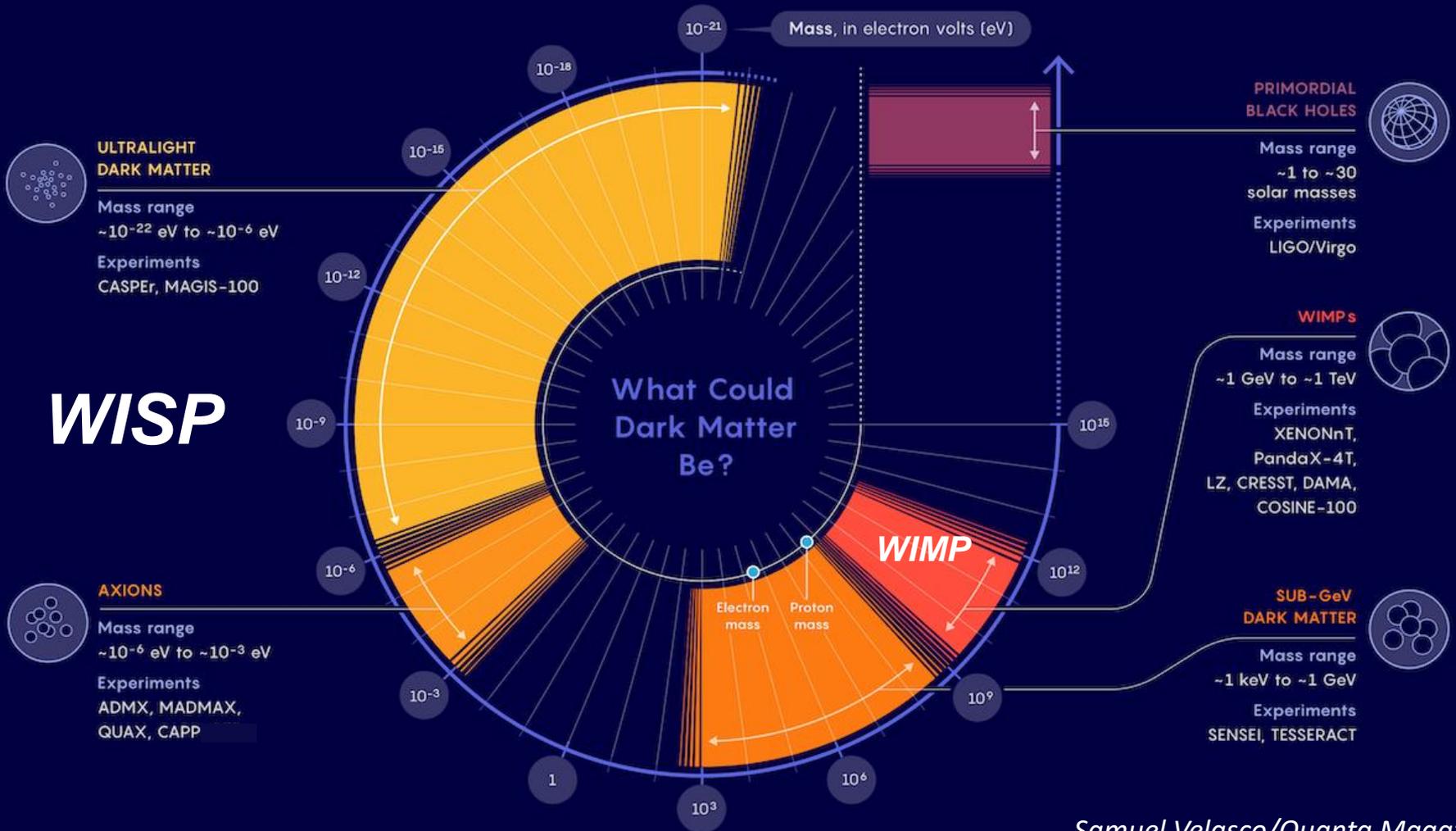
SHUNG-ANG YOUN



**2025 CAU-IBS**  
**BSM BSM WORKSHOP**  
DIE FOR RIGHTEOUSNESS  
**SUNGWOO YOUN / DMAG**  
SUNGWOO RIGHTEOUS / IBS-DOUG



# Where is dark matter?



**WISP**



# 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  
 $m_a f_a \not\sim \Lambda_{QCD}$

- **Scalar**

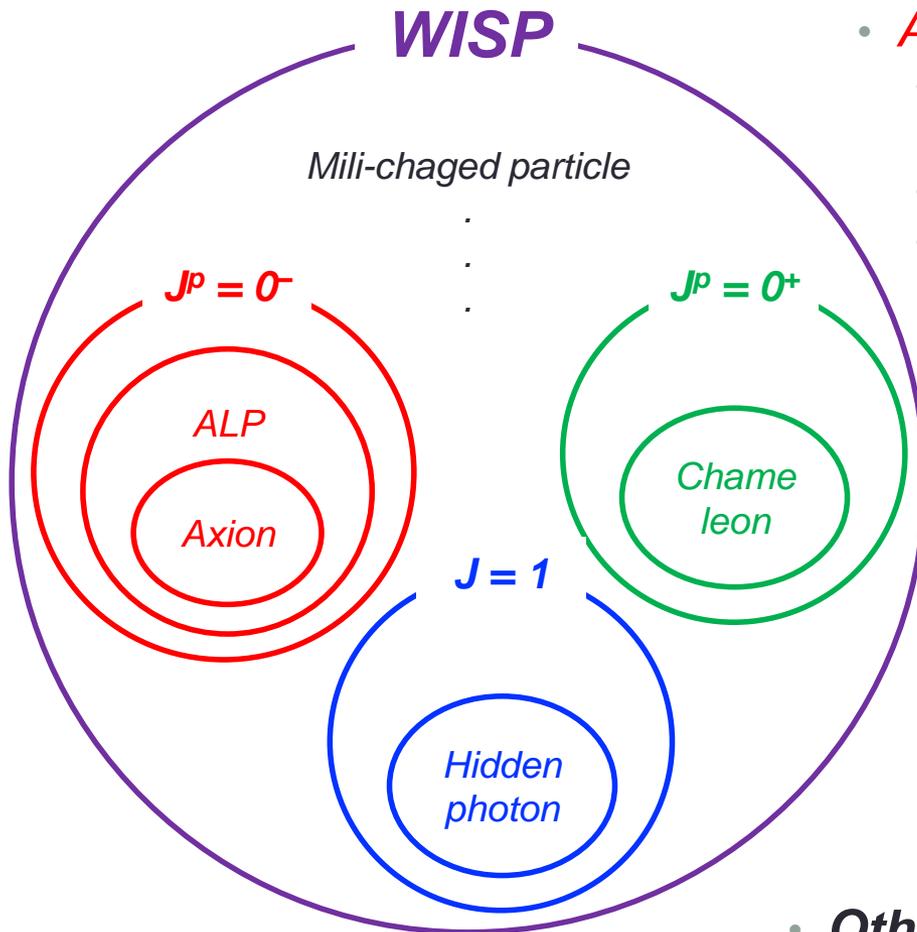
- Chameleon (2003)
- Dark energy candidate

- **Vector**

- Hidden photon
- Gauge field in hidden sector

- **Others**

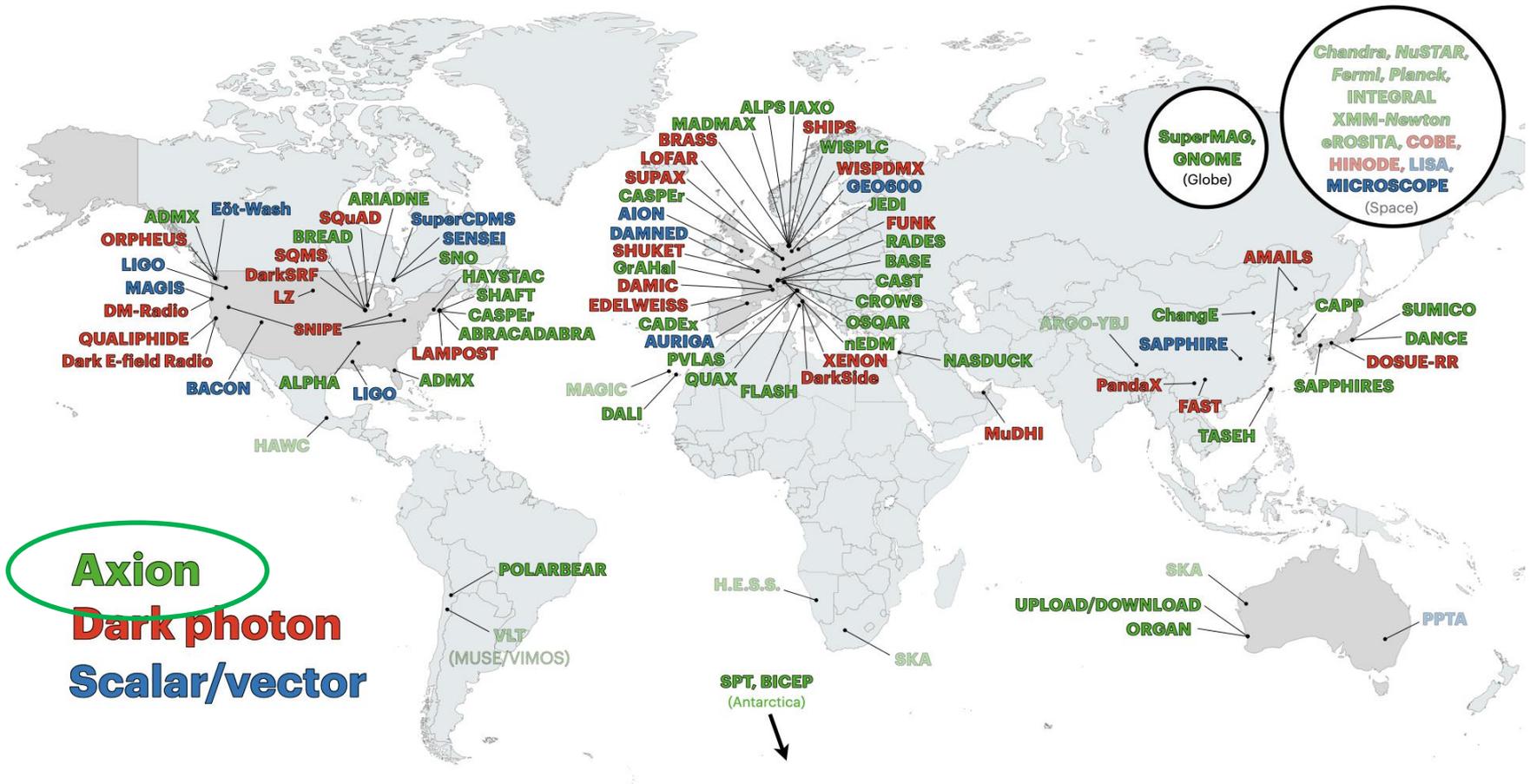
- Mili-charged particle, ...





# Experiment map

C. O'Hare (2020)





# Axion dark matter

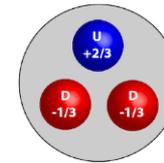
- **Solution to Strong CP problem**
  - PQ mechanism (1977)
    - $U(1)$  global symmetry and scalar field
    - SSB  $\Rightarrow$  axion field (1978)
  - QCD axion:  $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$  (cf. ALP)

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

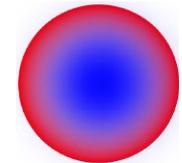
## Axion models

Model	PQWW	DFSZ	KSVZ
QCD anomaly	SM fermions		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	

Absence of  $nEDM$

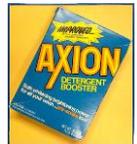
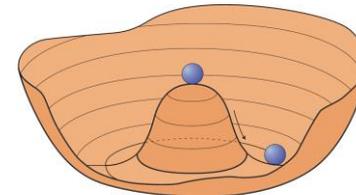


vs.



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

Spontaneous Symmetry Breaking



Goldstone boson

$$a(x) = \theta \times f_a \text{ at minimum}$$

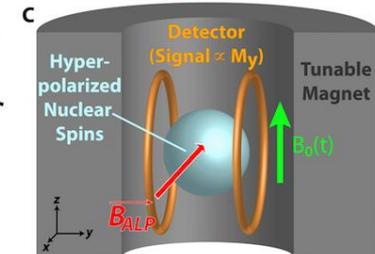
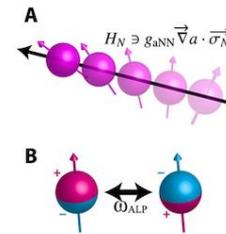
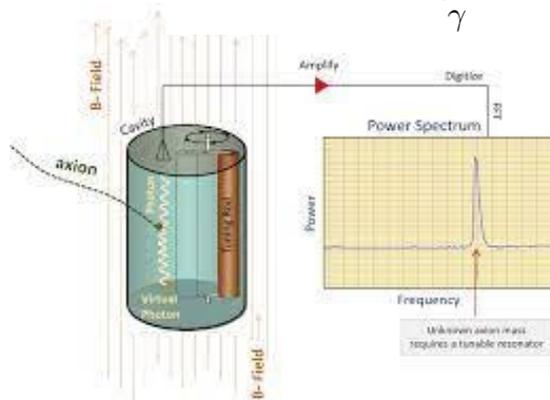
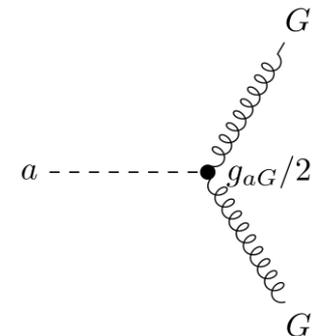
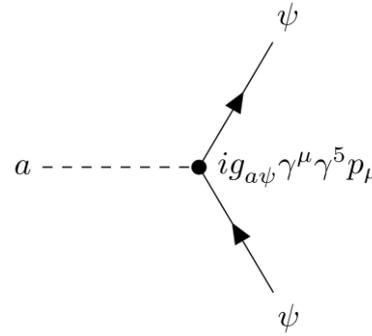
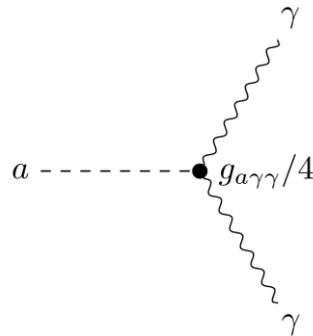




# Interactions and detection

- Axion coupling*

	Photons	Fermions	<i>n</i> EDMs
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 method	Power spectrum, photon counter, ...	Magnetometer, NMR, ...	NMR, polarimeter, ...





# Axionscopes

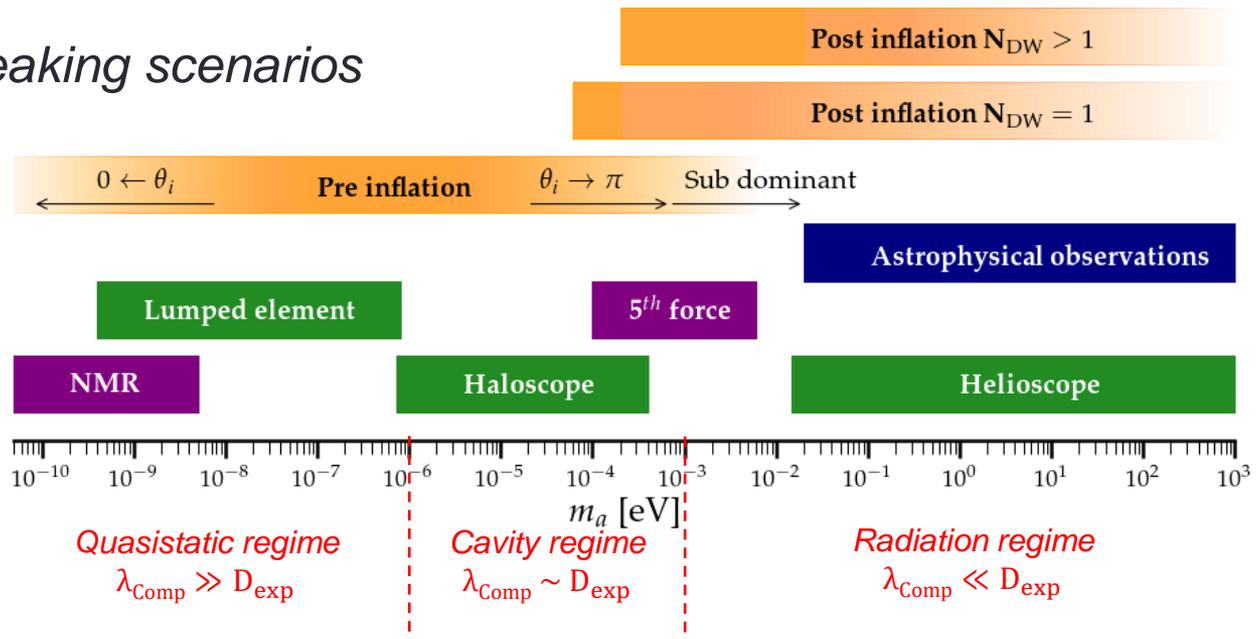
- Axion source**

Source	Photons	Fermions	<i>n</i> EDMs
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

*Theoretical scenarios*  
*Photon coupling*  
*Fermion/gluon coupling*





# ***Axion-photon coupling***



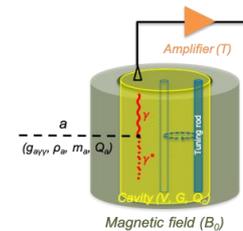
# Most popular choice

## • Haloscope

- Dark matter *halo* in our galaxy

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

~100 photons/sec

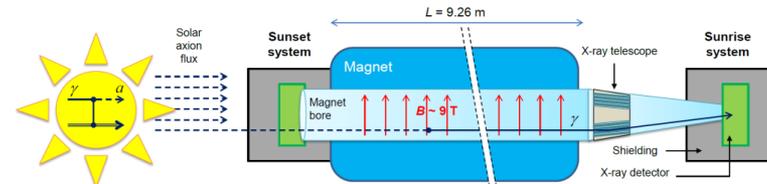


## • Helioscope

- *Solar* axion

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

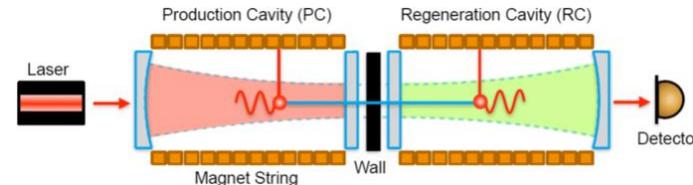
~10 photons/day



## • Light shining through a wall

- Axion production at *lab*

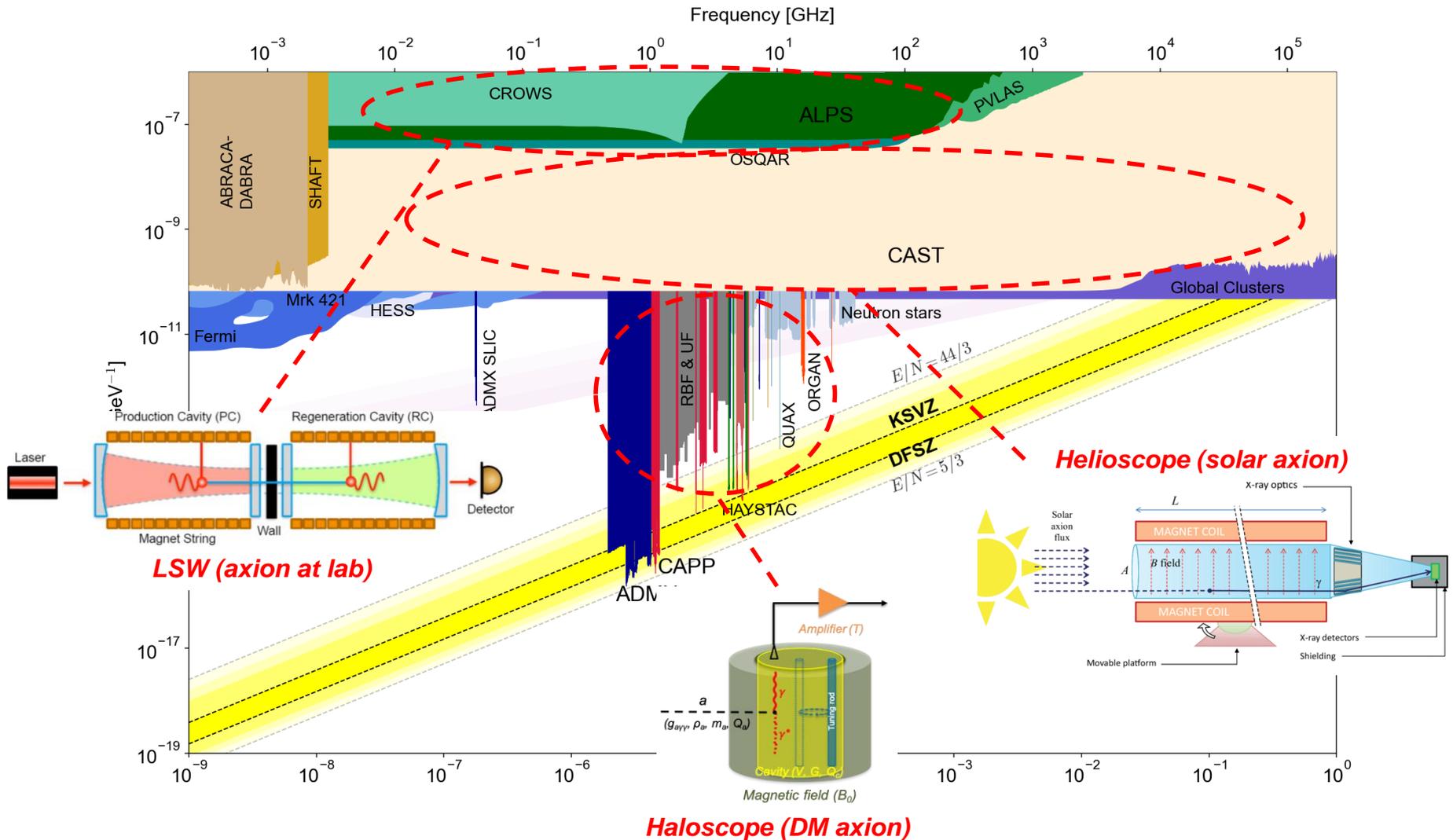
$$\dot{N}_\gamma \approx 4 \times 10^{-5} \text{ Hz} \left(\frac{g_{a\gamma\gamma}}{10^{-10} \text{ GeV}^{-1}}\right)^4 \left(\frac{P_{\text{laser}}}{40 \text{ W}}\right) \left(\frac{BL}{560 \text{ Tm}}\right) \left(\frac{\beta_{PC}}{5000}\right) \left(\frac{\beta_{RC}}{40000}\right) \sim 1 \text{ photons/day}$$





# Current status

1 GHz = 4.2 ueV





# ***Axion-photon coupling (Haloscopes)***



# Cavity haloscope – in a nutshell

- *Most sensitive for microwave photons*

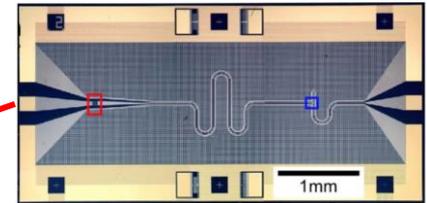
**Cryogenics  $T$**



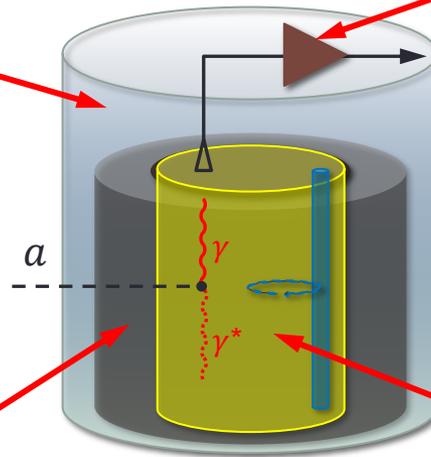
Lowering thermal noise

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

**Quantum noise limited amplifier  $T$**



Signal amplification w/ minimal noise added

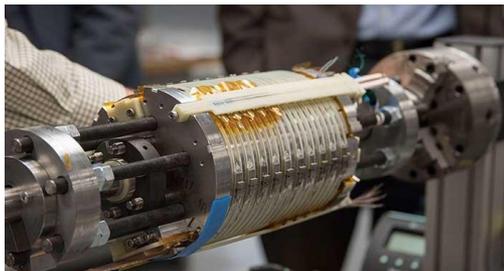


**Tunable High-Q resonator  $V, Q, C, \Delta f$**



Resonant frequency tuning

**High field Magnet  $B$**

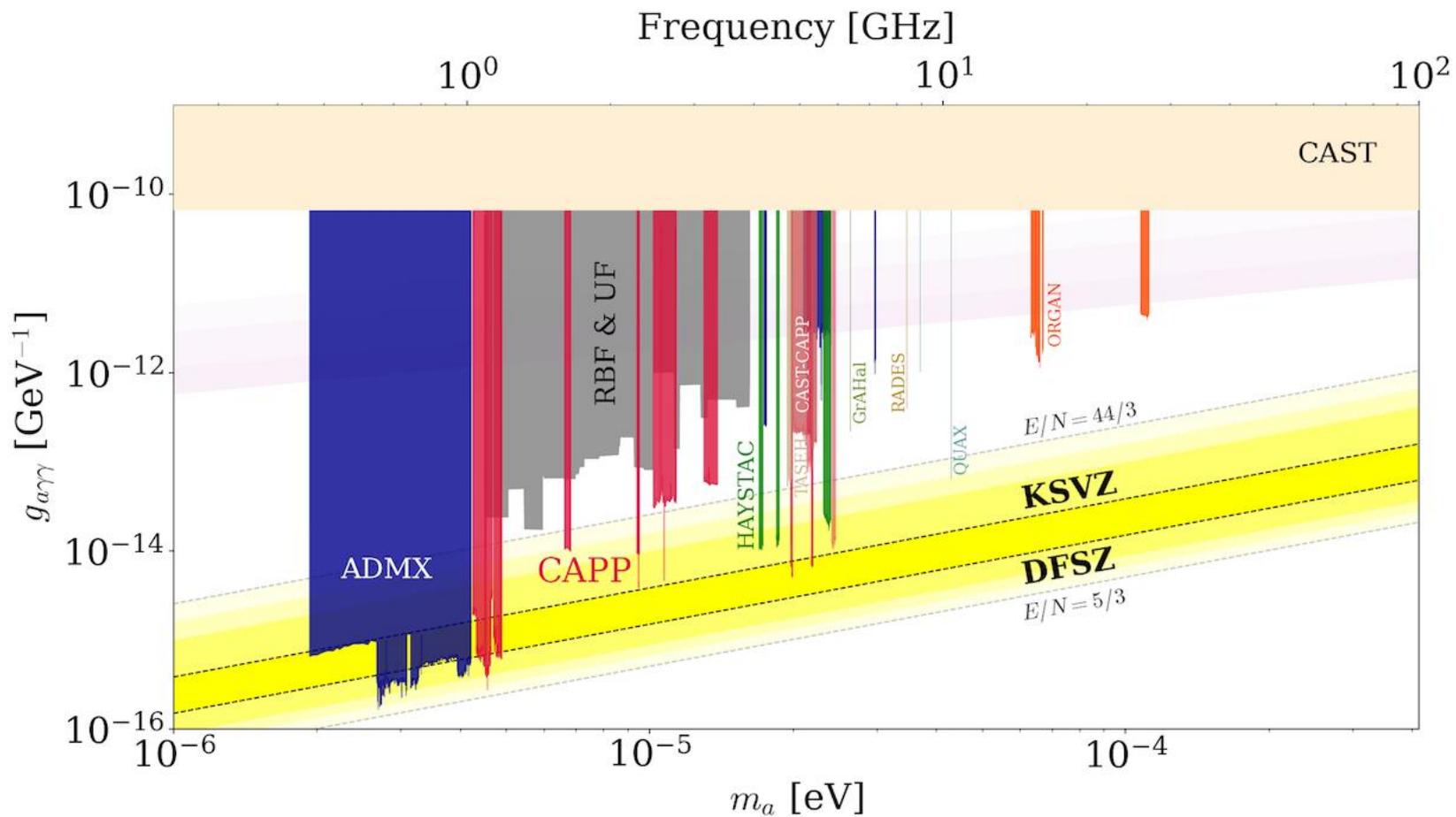


Boosting  $a \rightarrow \gamma\gamma$  conversion rate

**Small-scale experiments!**



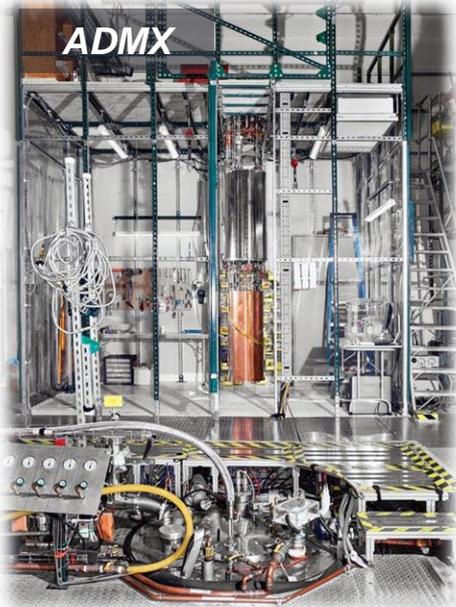
# Haloscope searches





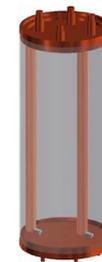
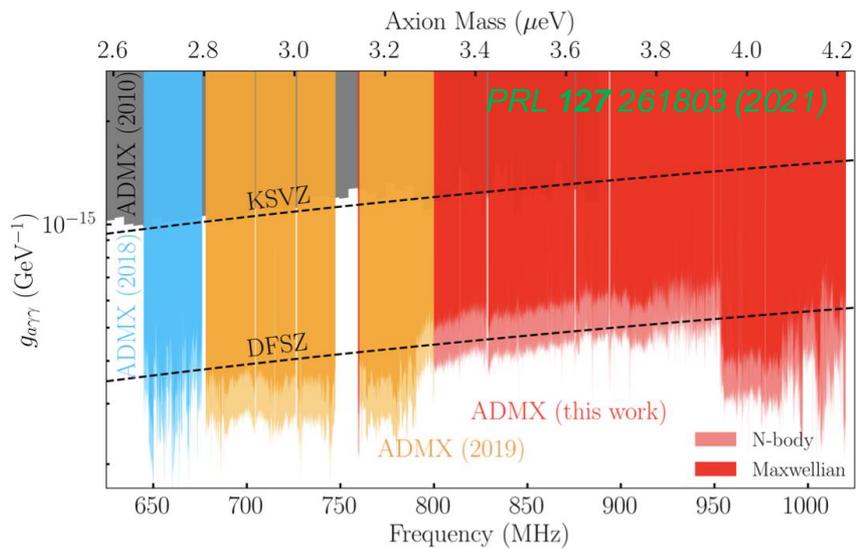
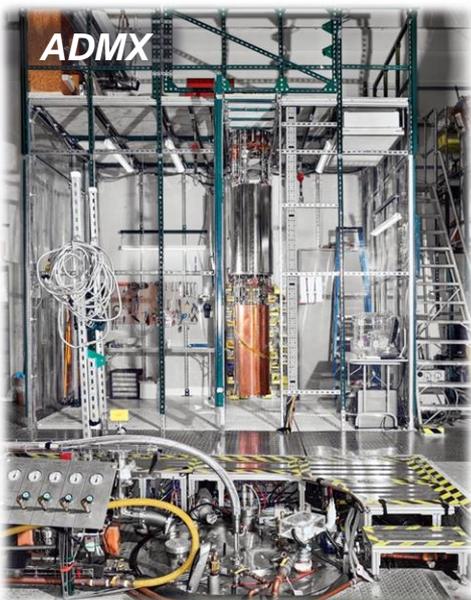
# Cavity haloscopes

*Cavity regime*  
 $\lambda_{\text{Comp}} \sim D_{\text{exp}}$





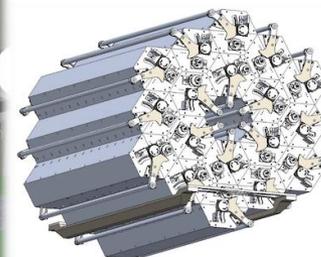
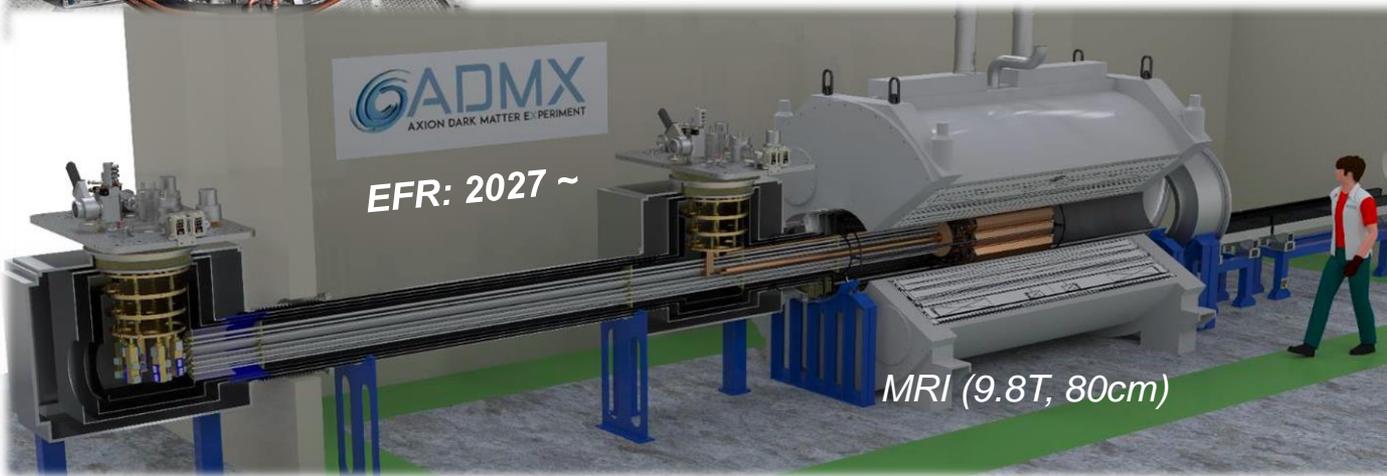
# ADMX



Run 1A-C



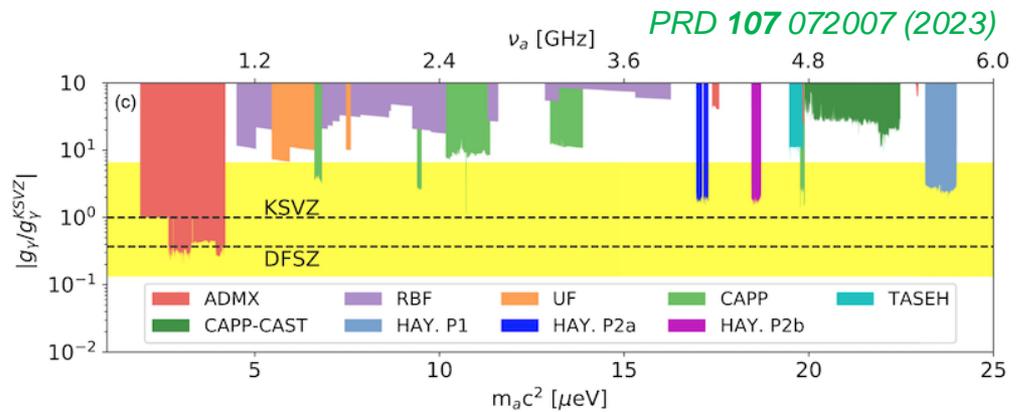
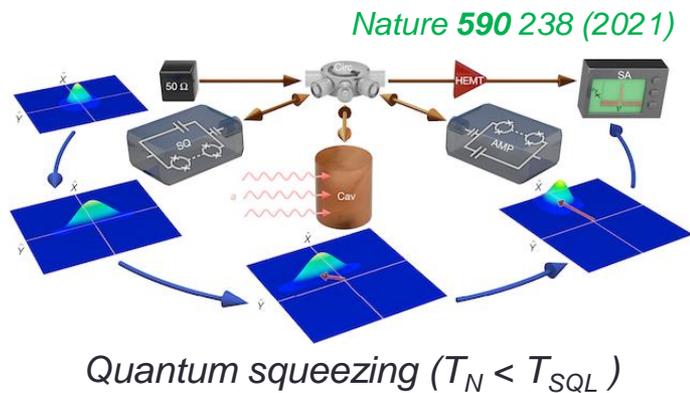
Run 2



EFR



# HAYSTAC





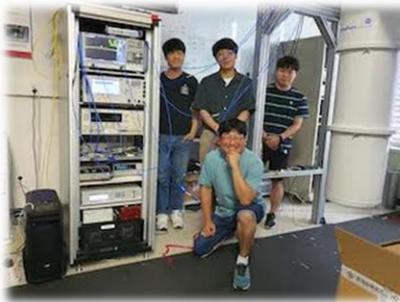
# IBS-CAPP



**CAPP-9T**



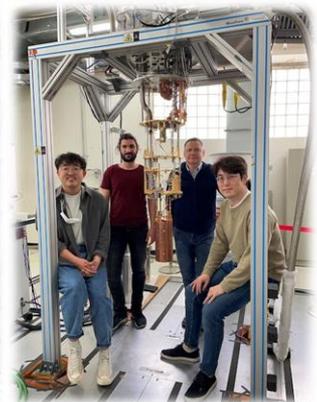
**CAPP-12TB**



**CAPP-12T**



**CAPP-8T**



**CAPP-8TB**



# IBS-CAPP

## CAPP-8T

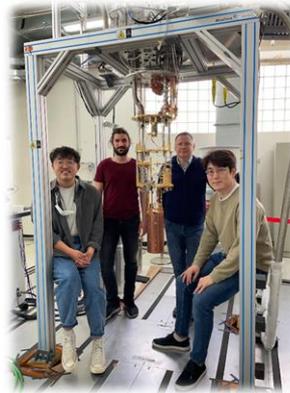
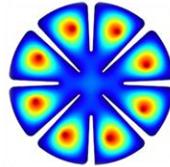
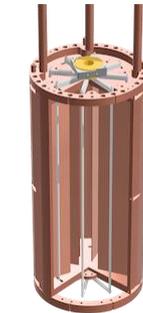
(8T/125mm)

HTS SC cavity + JPA

(2.3 GHz,  $Q \sim 3.5 M$ )

AQN search

Paper in preparation



## CAPP-8TB

(8T/165mm)

8-cell + JPA

(5.9 GHz, 400 mK)

Near KSVZ sensitivity

Paper in preparation



## CAPP-12T

(12T/96m)

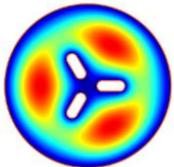
3-cell + JPA

(5.3 GHz, 400 mK)

KSVZ sensitivity

NM algorithm

PRL 133 211803 (2024)



## CAPP-12TB

(12T/320mm)

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

$df/dt \sim 2 \text{ MHz/day}$  @ DFSZ

PRL 130 071002 (2023)

Extended scan ( $\Delta f \sim 120 \text{ MHz}$ )

PRX 14 031023 (2024)

Ready for 300-MHz run w/ SC cavity



# CAPP to DMAG

**Research Centers**

**Center for Axion and Precision Physics Research**

Home > Research Centers > Center for Axion and Precision Physics Research

Research Outcomes

Mathematics

**Physics**

- Center for Theoretical Physics of the Universe(Particle Theory and Cosmology Group)
- Center for Theoretical Physics of the Universe(Cosmology, Gravity and Astroparticle Physics Group)
- Center for Exotic Nuclear Studies
- Dark Matter Axion Group
- Center for Artificial Low Dimensional Electronic Systems
- Center for Underground Physics
- Center for Axion and Precision Physics Research**



Director: Yannis SEMERTZIDIS



Searching for dark matter axions to explain the formation [Homepage](#)

2013.10 ~ 2024.12

**Research Centers**

**Dark Matter Axion Group**

Home > Research Centers > Dark Matter Axion Group

Research Outcomes

Mathematics

**Physics**

- Center for Theoretical Physics of the Universe(Particle Theory and Cosmology Group)
- Center for Theoretical Physics of the Universe(Cosmology, Gravity and Astroparticle Physics Group)
- Center for Exotic Nuclear Studies
- Dark Matter Axion Group**
- Center for Artificial Low Dimensional Electronic Systems
- Center for Underground Physics
- Center for Axion and Precision Physics Research



Director: SungWoo Youn



IBS Dark Matter Axion Group [Homepage](#) [네이버 지도](#)

2025.01 ~

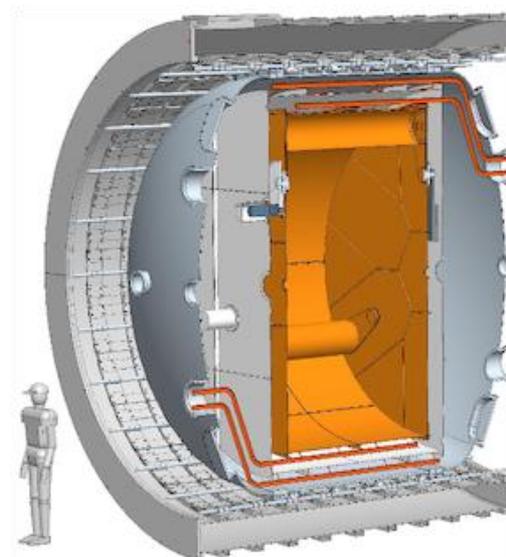
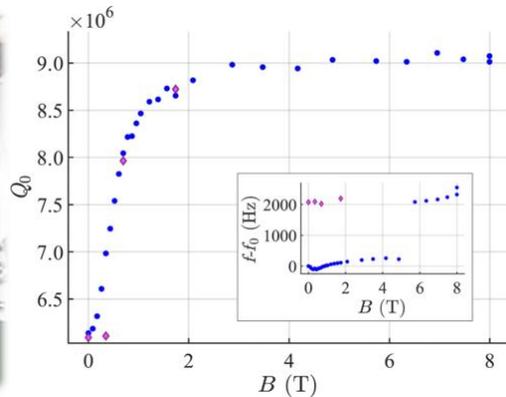


# QUAX



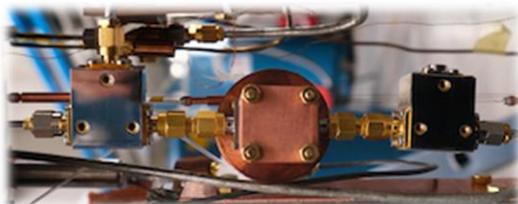
Dielectric cavity

*PRApplied 17 054013 (2022)*



**FINUDA**

$B = 1.1 T$   
 $R = 1.4 m$



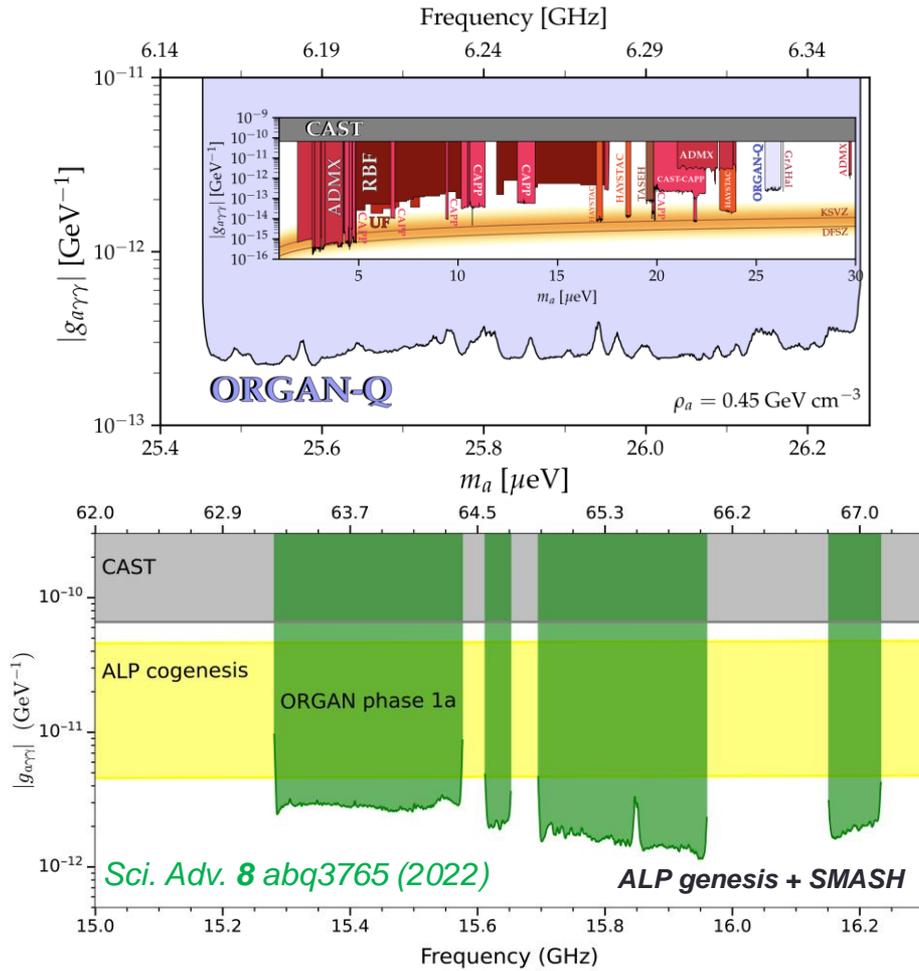
TWPA

*PRD 108 062005 (2023)*

**FLASH**

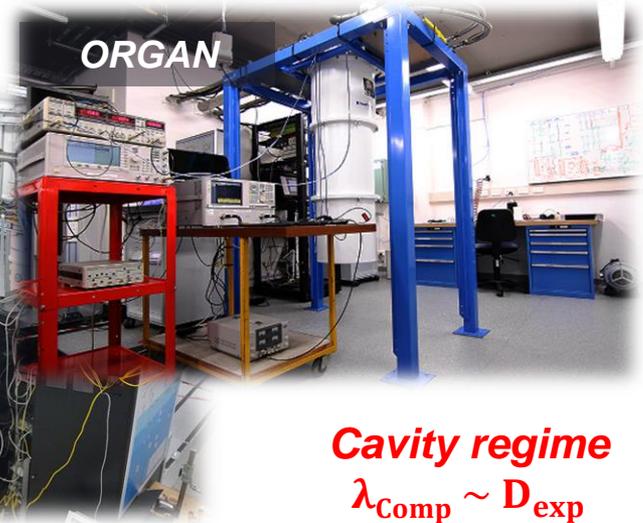
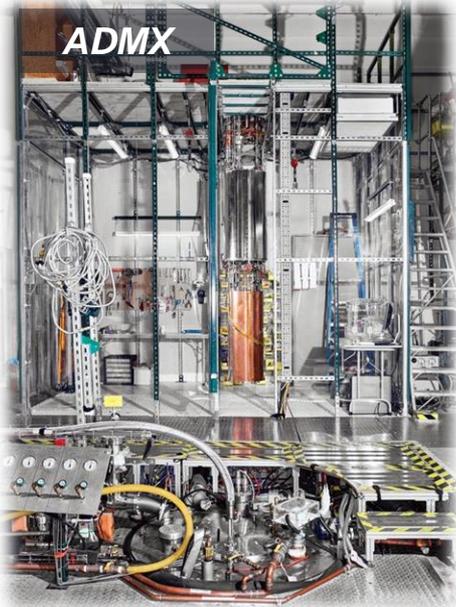


# ORGAN





# Cavity haloscope



**Cavity regime**  
 $\lambda_{\text{Comp}} \sim D_{\text{exp}}$

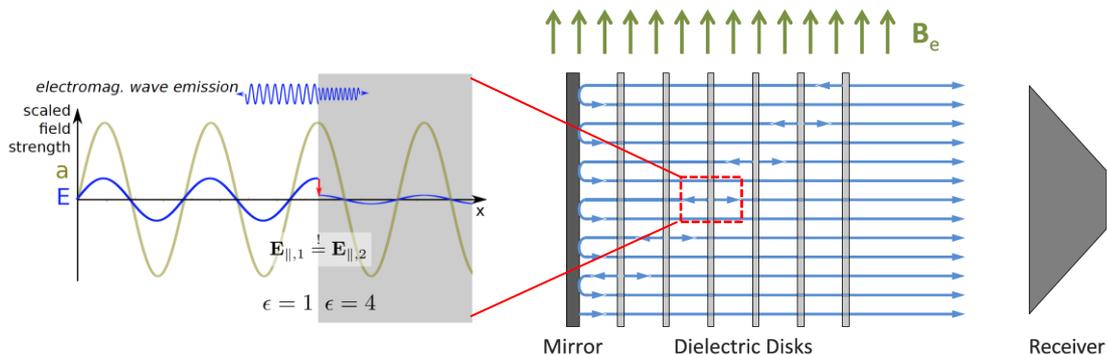


# MADMAX

*Radiation regime*  
 $\lambda_{\text{Comp}} \ll D_{\text{exp}}$

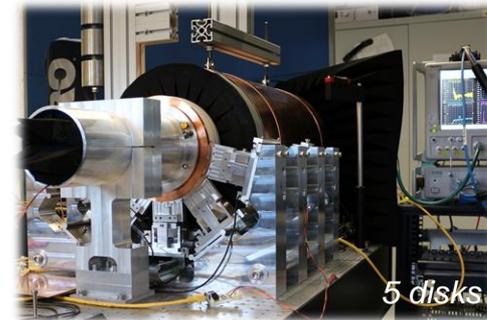
- Dielectric power booster

PRL 118 091801



Suitable for 10~100 GHz

Proof-of-concept



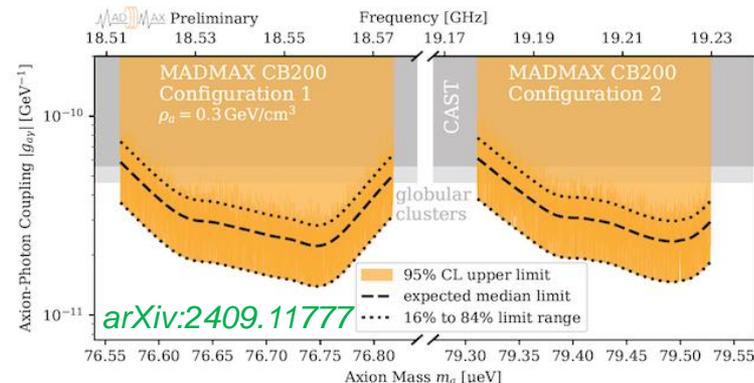
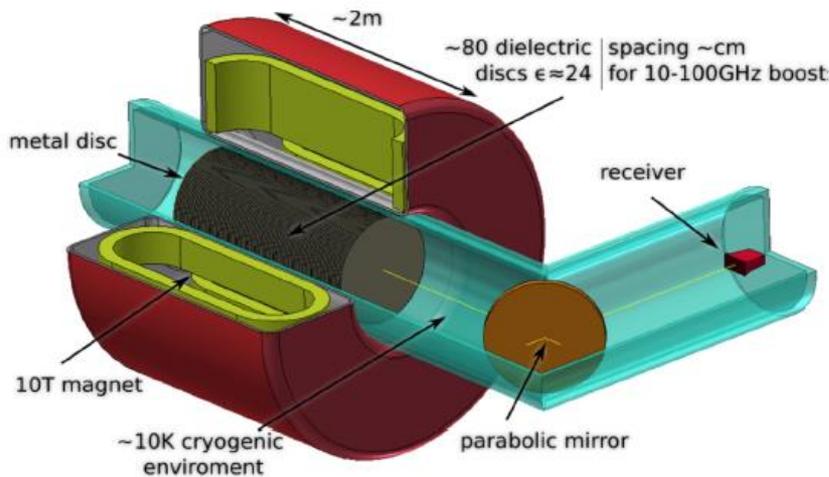
5 disks

Prototype (2024)



Morpurgo (1.6T)  
3 disks

## Full scale experiment





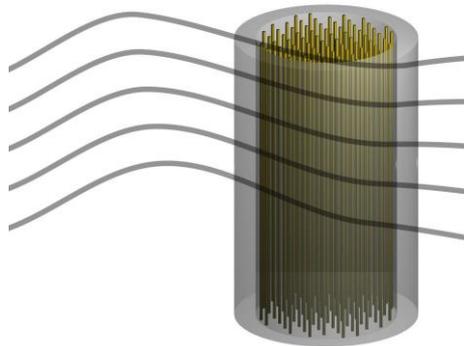
# ALPHA

*Radiation regime*  
 $\lambda_{\text{Comp}} \ll D_{\text{exp}}$

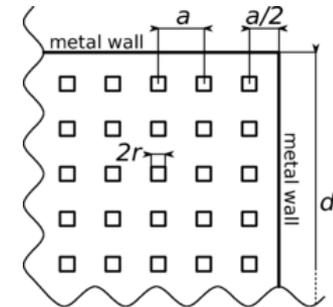
- Plasma haloscope**

PRL 123 141802 (2019)

- Wire metamaterial => bulk plasmon



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



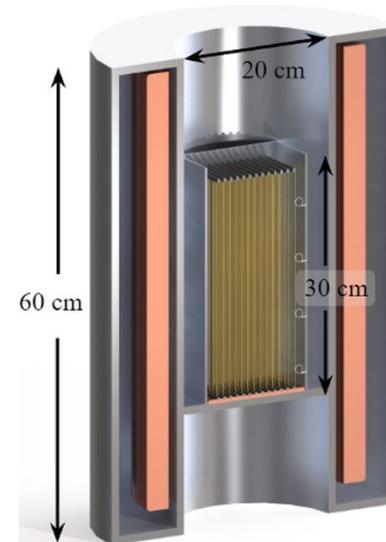
- $\omega_p$  independent of the detector size
- Large conversion volume at high frequencies

*Resonant conversion when  $m_a = \omega_p$*

PRD 107 055013 (2023)



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



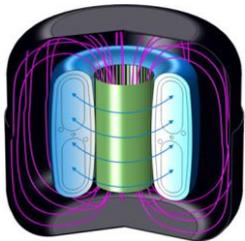
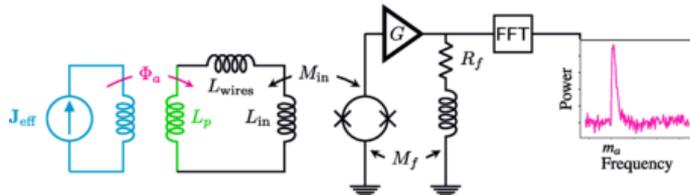
**Physics data  
in 2026**



# DM Radio

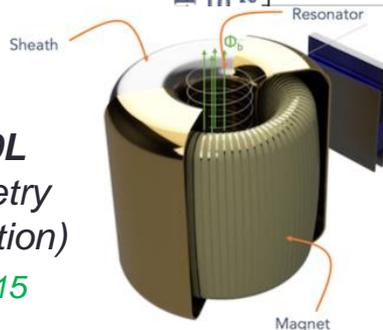
*Quasistatic regime*  
 $\lambda_{\text{Comp}} \gg D_{\text{exp}}$

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



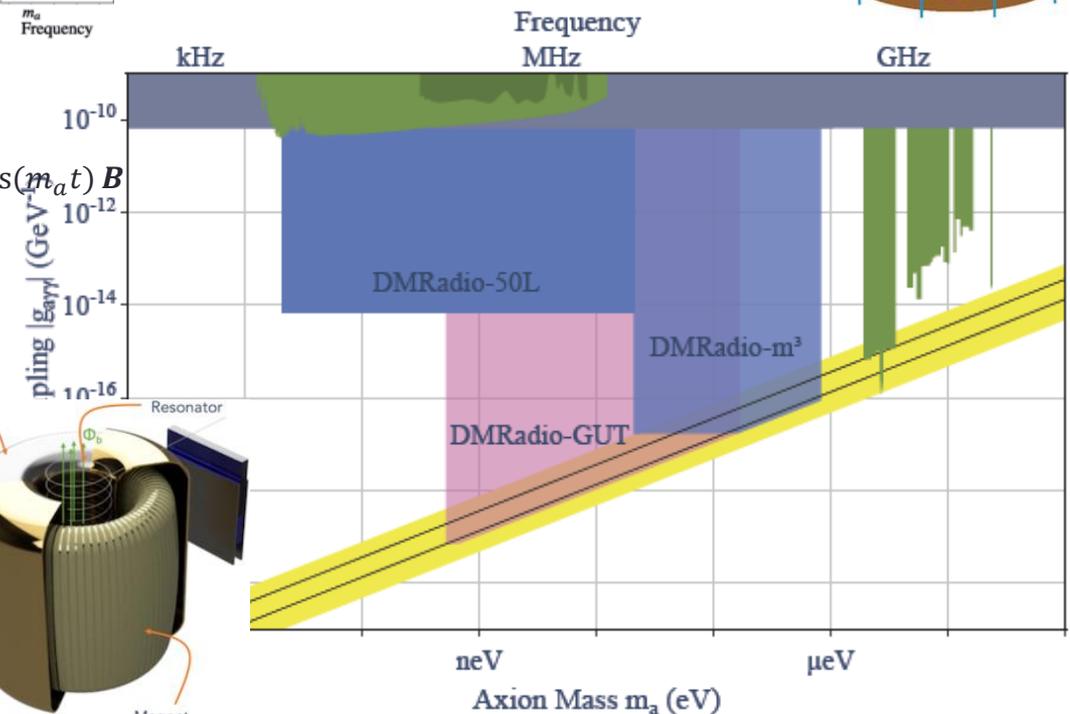
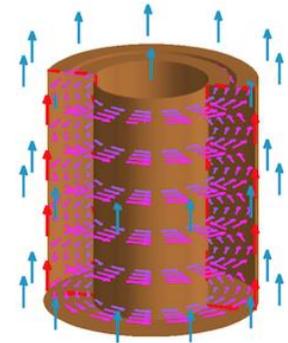
**ABRACADABRA-10cm**  
*PRL 127 081801 (2021)*

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



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

**DM Radio- $m^3$**   
*Solenoidal geometry*  
*PRD 106 103008 (2022)*





# Other haloscopes

## Recent

- **CAST-CAPP**: phase-matched cavities,  $\sim 20$   $\mu\text{eV}$  Nat. Comm. **13**, 6180 (2022)
- **RADES**: microwave fiber,  $\sim 34$   $\mu\text{eV}$  JHEP **2021** 75 (2021)
- **Grenoble Axion Haloscope** arXiv:2110.14406
  - 14T/52mm magnet,  $\sim 26$   $\mu\text{eV}$
- **Taiwan Axion Search Experiment with Haloscope** PRL **129** 111802 (2022)
  - 4.7 GHz,  $11 \times g_{\text{arr}}^{\text{KSVZ}}$
- **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  $\mu\text{eV}$

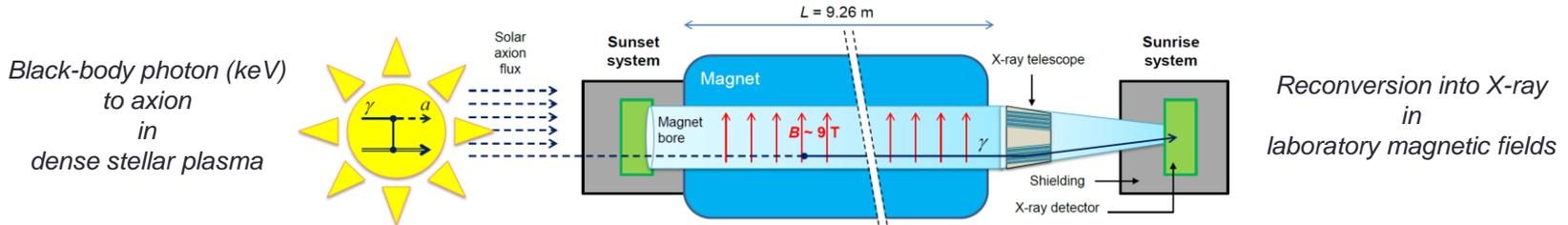


# ***Axion-photon coupling (Helioscope, LSW)***



# Helioscope

## Solar axion telescope



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

### History

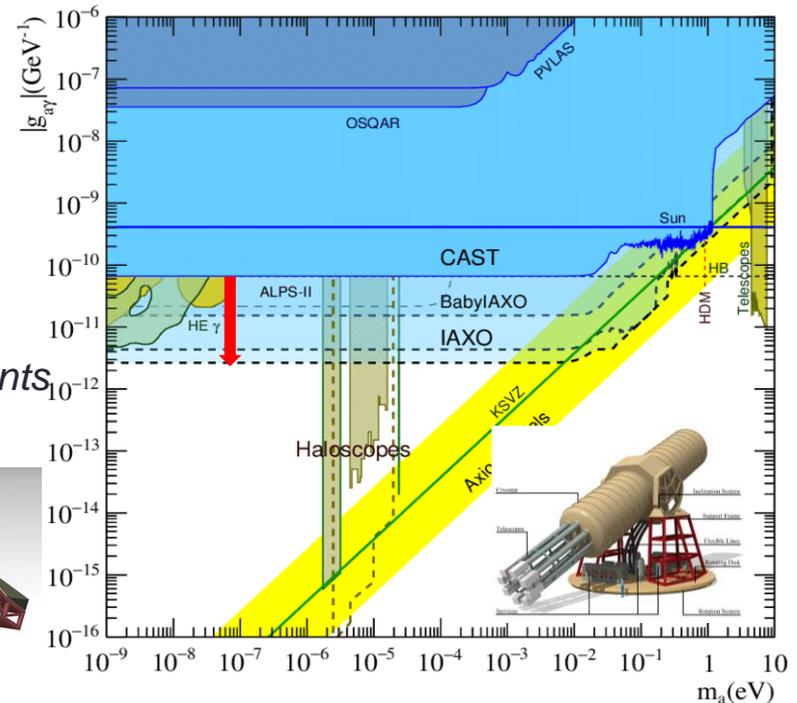
- BNL => SUMICO => CAST => IAXO

## International AXion Observatory

- 8 dipoles (5.4 T, 20 m, 600 mm)
- Goal:  $g_{a\gamma} \sim 10^{-12} \text{ GeV}^{-1}$
- Diverse physics over wide range
  - QCD axions / ALP miracle / astrophysical hints

## Baby-IAXO (DESY)

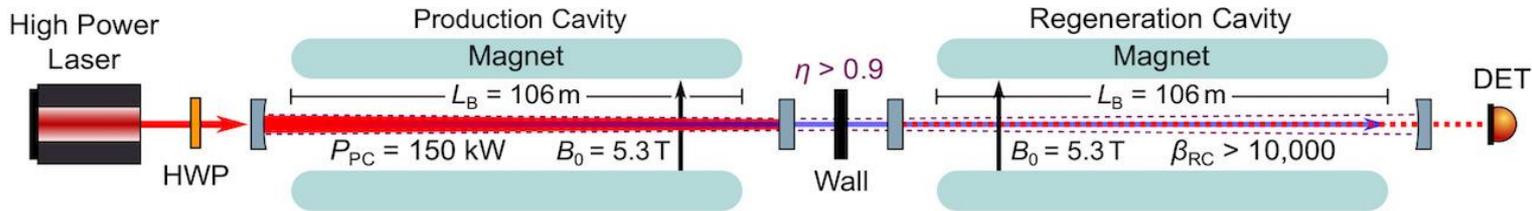
- First step towards full IAXO
- 4 T / 10 m => 10 x MFOM<sub>CAST</sub>





# Light shining through a wall

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



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

~1 photons/day

### Model independent search

- No need of cosmo./astrophys. source

### History

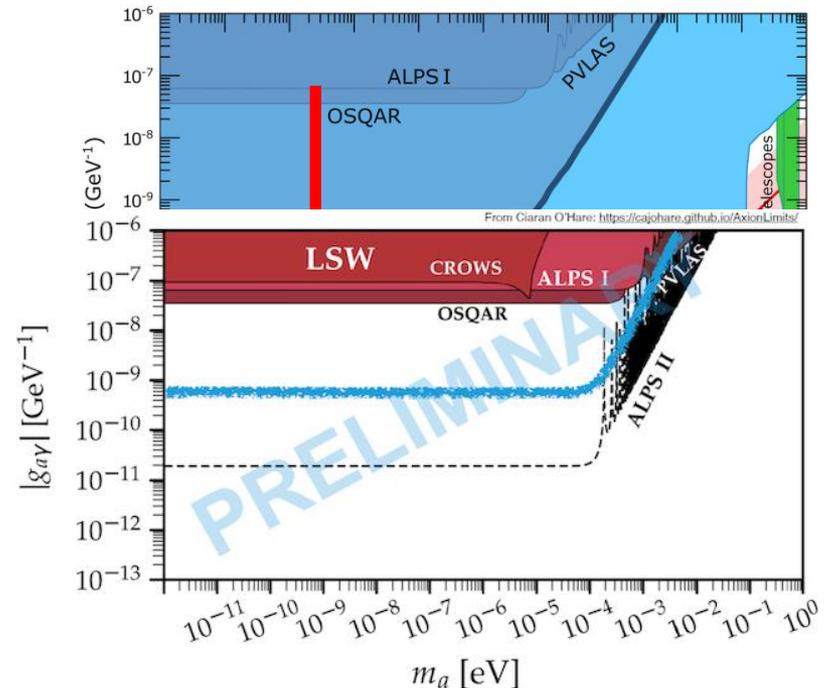
- BFRT => OSQAR => ALPS => ALPS II

## Any Light Particle Search II

- 2 x 12 Hera dipoles (8.8 m & 5.3 T)
- HPL / dual  $\mathcal{F}$  FP / TES
- Goal:  $g_{a\gamma\gamma} \sim 10^{-11} \text{ GeV}^{-1}$  below 0.1 eV

## First science run in May 2023

- $10^5 \text{ s data} \Rightarrow g_{a\gamma} \sim 6 \times 10^{-10} \text{ GeV}^{-1}$





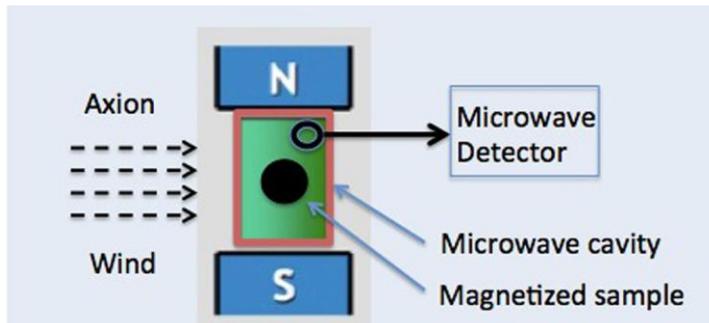
# ***Axion-fermion coupling***



# Electron spin

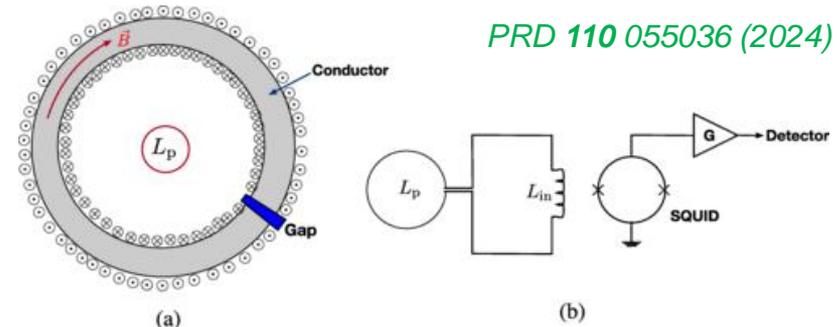
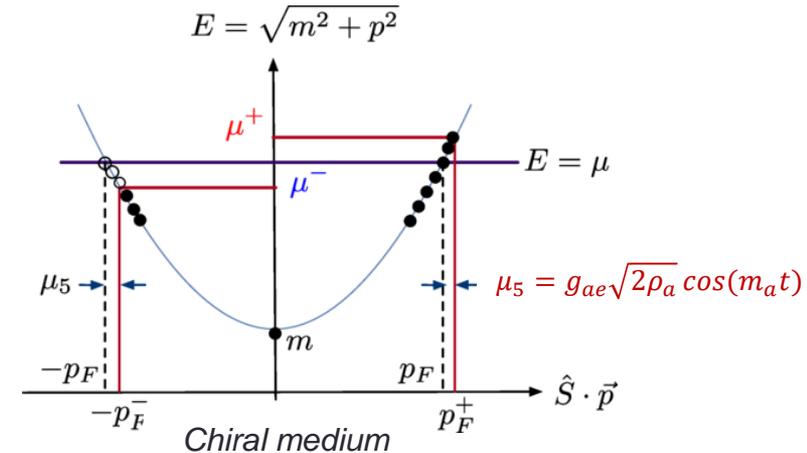
- **QUAX-ae**
  - Ferromagnetic haloscope
  - **Axion-magnon** interaction
    - Series of YIG spheres
    - $B_{ext} \Rightarrow$  magnon at  $\omega_L$
    - Axion  $\Rightarrow$  magnon excitation
    - Relaxation  $\Rightarrow$  RF photon
    - Cavity resonance ( $TM_{110}$ )
  - $\omega_a = \omega_L = \omega_c$
  - Best limit near  $m_a \sim 43 \mu\text{eV}$

PRL 124 171801 (2020)



- **LACME**

- **Axion Chiral Magnetic Effect**
- Axion  $\Rightarrow$  axial chemical potential  $\Rightarrow$  helicity imbalance  $\Rightarrow$  AC current



PRD 110 055036 (2024)



# Nuclear spin

## GNOME

- Topological defects
  - *Axion domain walls, axion stars*

$$H_a = \frac{\hbar}{c} \hat{s} \cdot \nabla a(\vec{r})$$

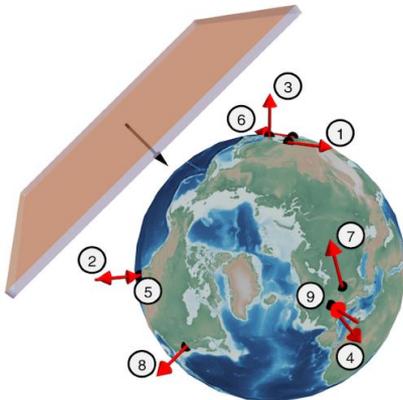
- Optical magnetometers
  - Axion-atomic spin
  - Alkali atoms (Rb, K)
- Global network
  - > dozen stations
  - Correlated signals with GPS time

## ARIADNE

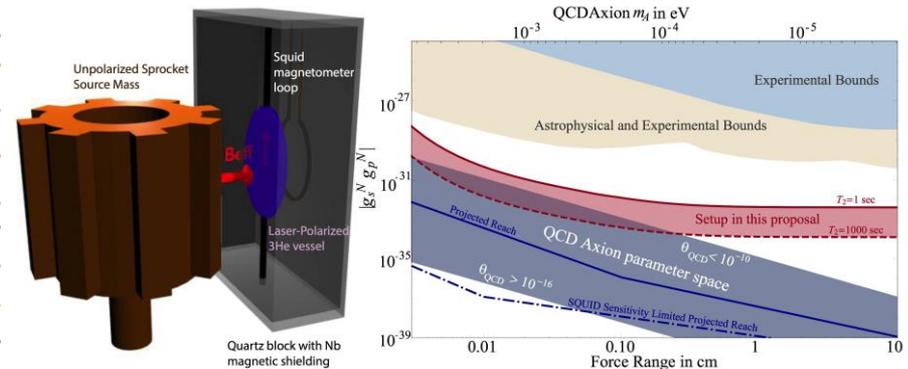
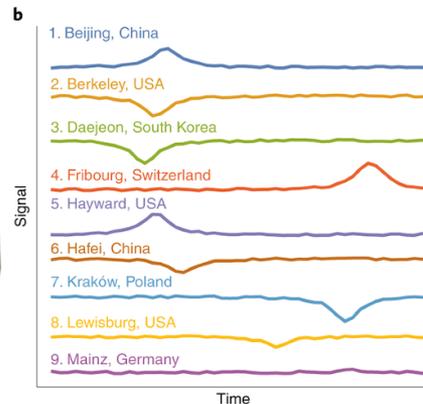
- Fifth-force experiment
  - *Axion-mediated* spin-dependent
 
$$U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8\pi m_f} \left( \frac{1}{\lambda_a r} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma} \cdot \hat{r})$$

$$\equiv \mu \cdot B_{eff}$$
  - Rotating source mass ( $g_s$ ) and polarized  $^3\text{He}$  spins ( $g_p$ )
  - NMR technique
- Potential probe for 0.1~10 meV
  - Complementary method

a



Nature Phys. 17 1396 (2021)

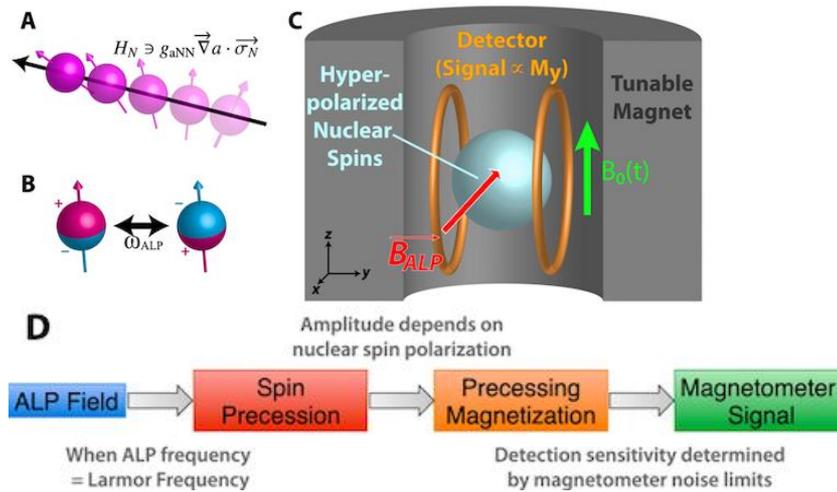




# Nuclear spin/EDM

## Cosmic Axion Spin Precession Experiment

### NMR experiment

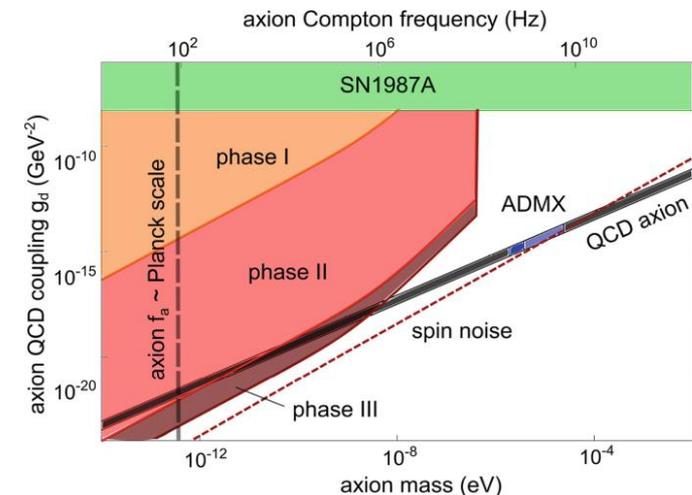
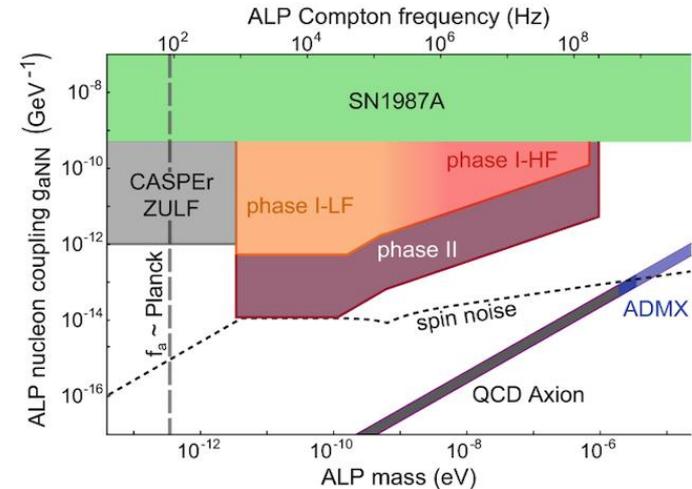


### CASPER-Gradient

- $H_{spin} = g_{aNN} \nabla a \cdot \hat{s} \Rightarrow \tau_{spin} = \mu_N \times B_a$
- Dark matter axion

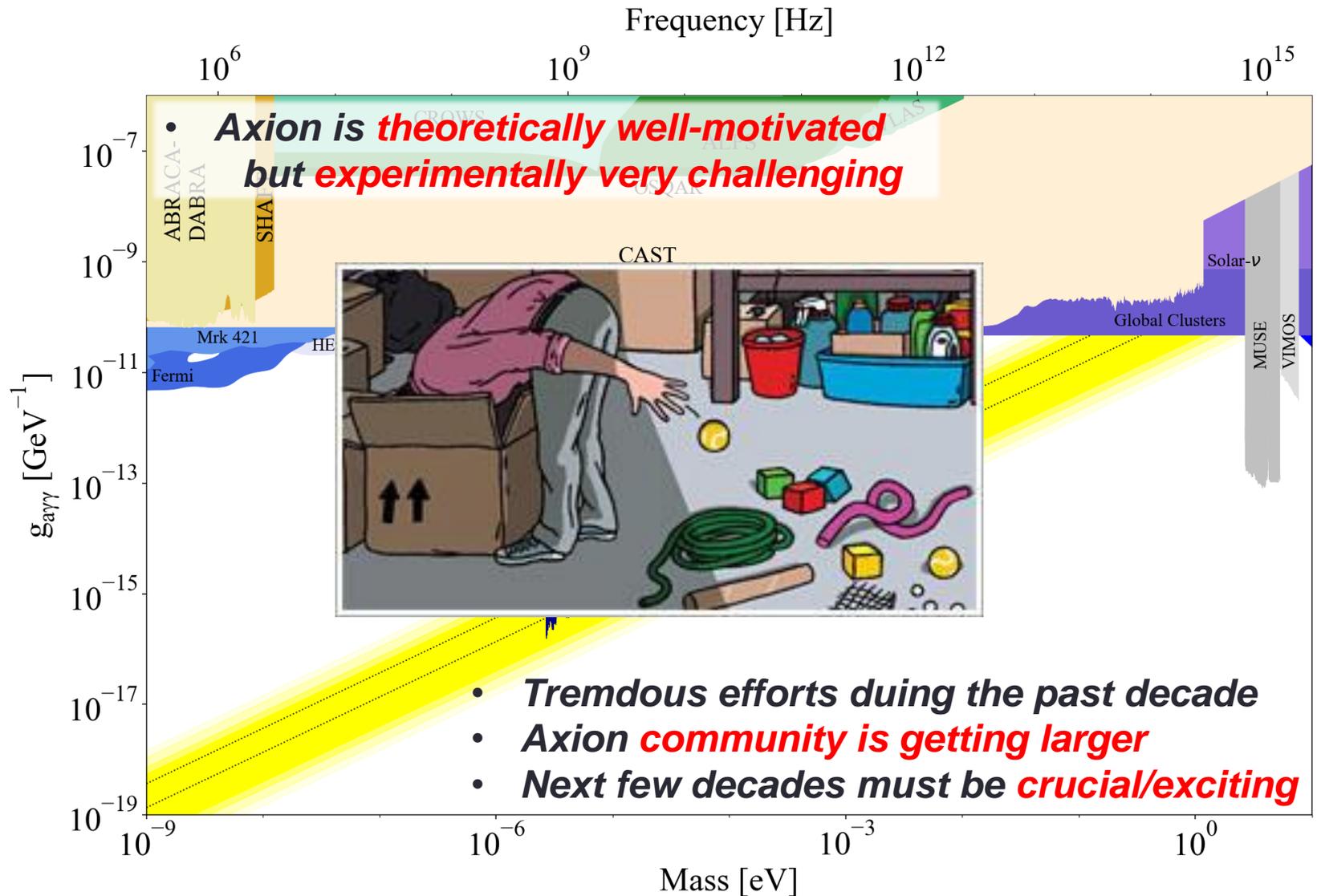
### CASPER-Electric

- $d_N = g_{aGG} a(t) \hat{s} \Rightarrow \tau_{EDM} = d_N \times E$
- QCD axion





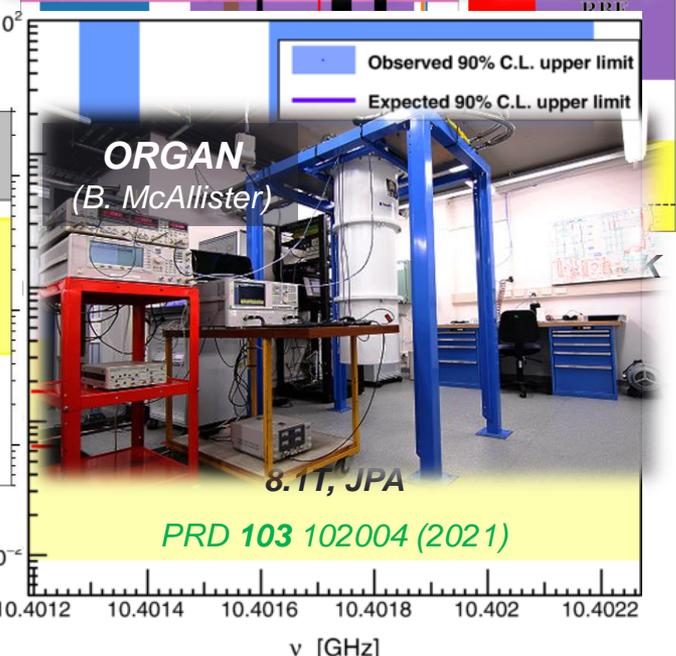
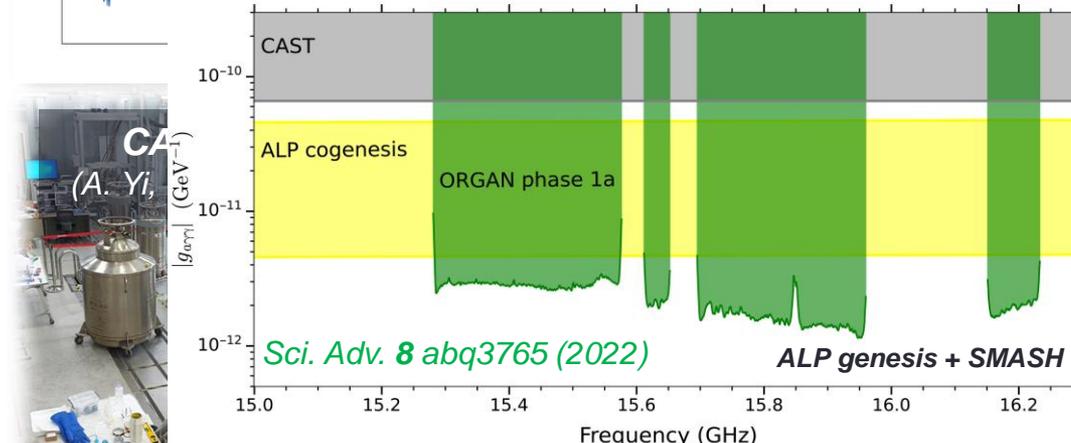
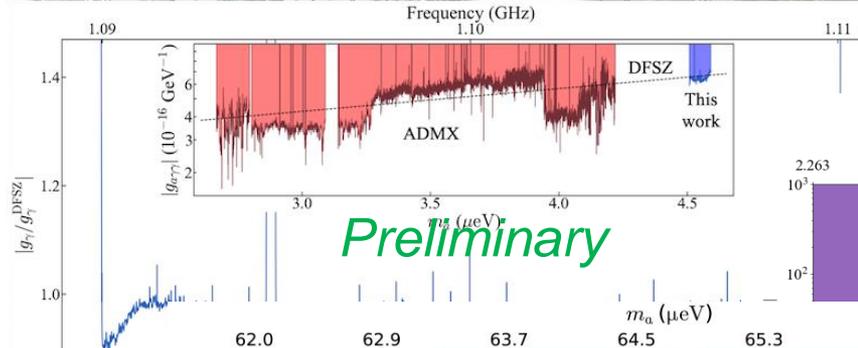
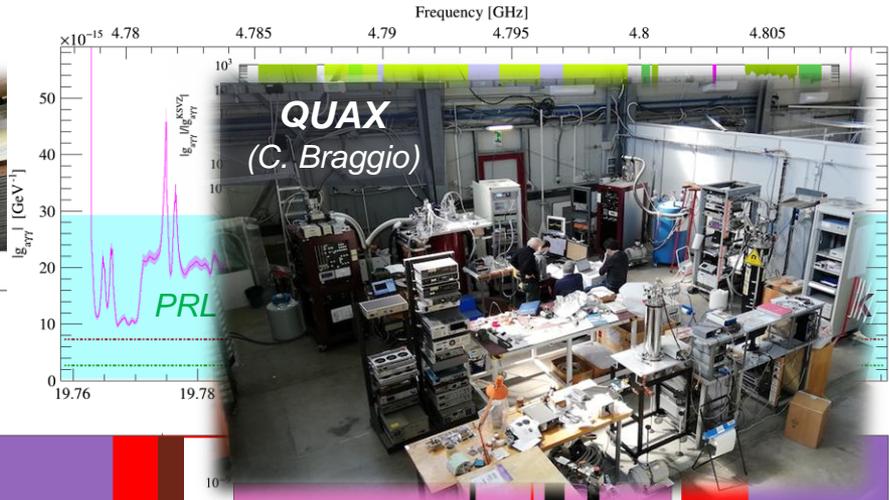
# Summary







# Search highlights





# Magnet



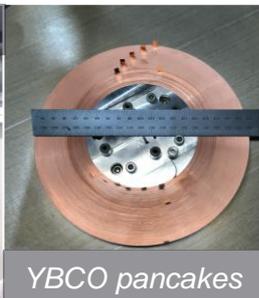
ADMX (8T/600mm)



CAPP (12T/320mm)



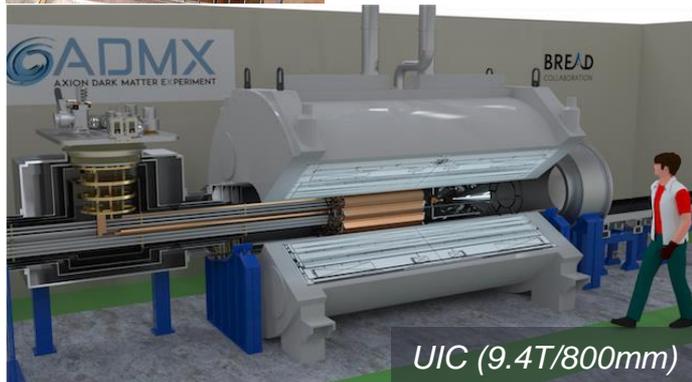
CAPP (18T/70mm)



YBCO pancakes



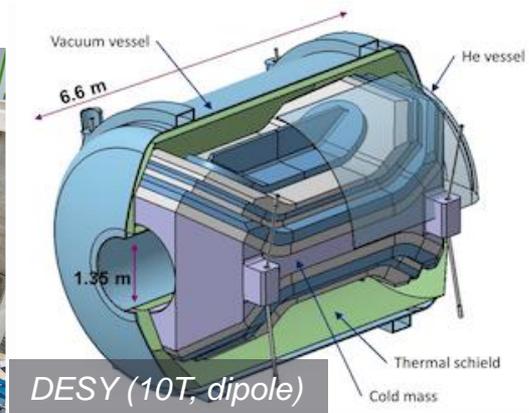
Grenoble (43T/34mm)



UIC (9.4T/800mm)



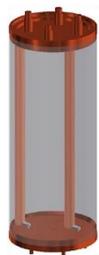
CERN (1.6T)



DESY (10T, dipole)



# Cavity

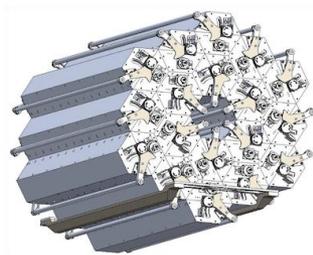


Run 1A-C



Run 2

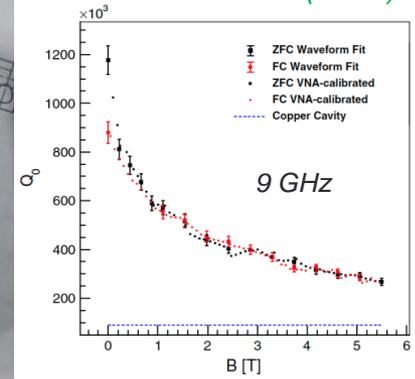
arXiv: 2203.14923



EFR

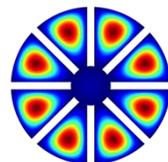
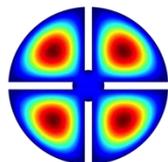
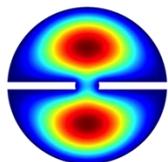


PRD 99 101101 (2019)

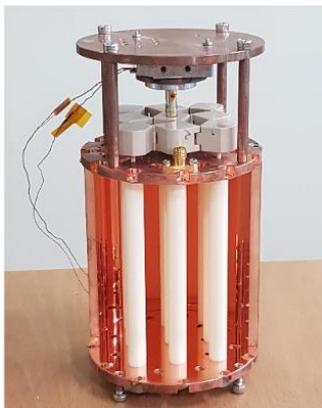


D. Ahn (Tue)

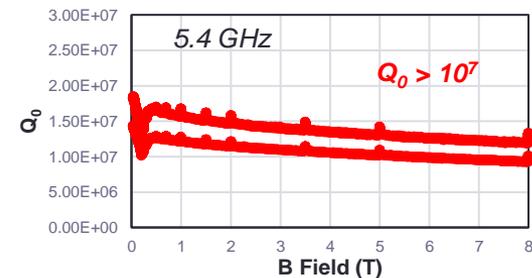
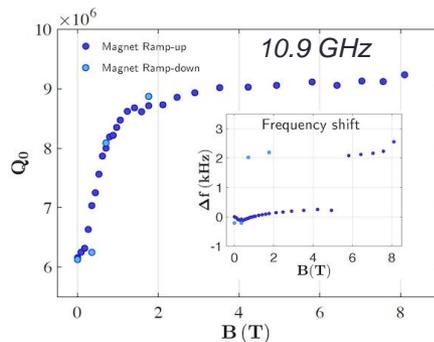
PRL 125 221302 (2020)



arXiv: 2205.08885



NIM 985 164641 (2021)

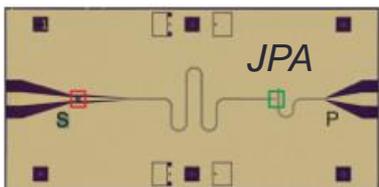




# Microwave photon detector

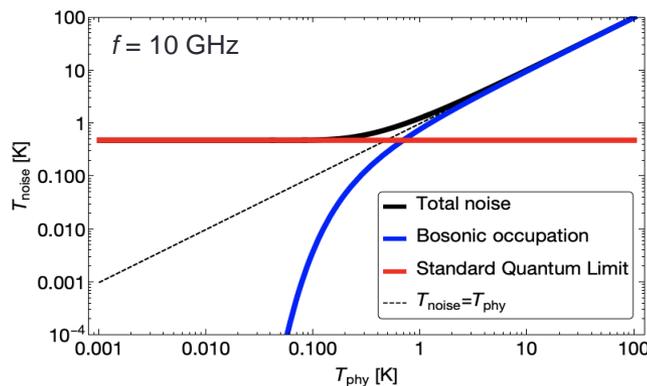


Transistor-based  
( $T_N \sim K$ )

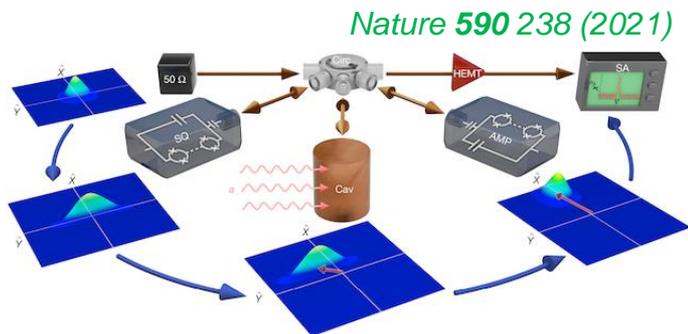
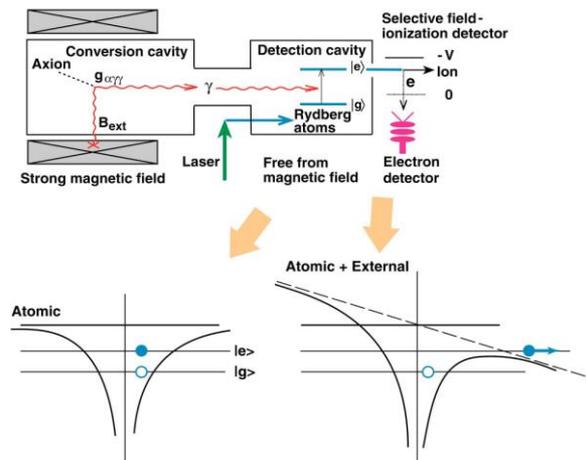


Quantum limited  
( $T_{SQL} \sim 50 \text{ mK} \times f \text{ [GHz]}$ )

## Power detection vs. photon counting (w/ amplifiers) (w/ single photon detector)

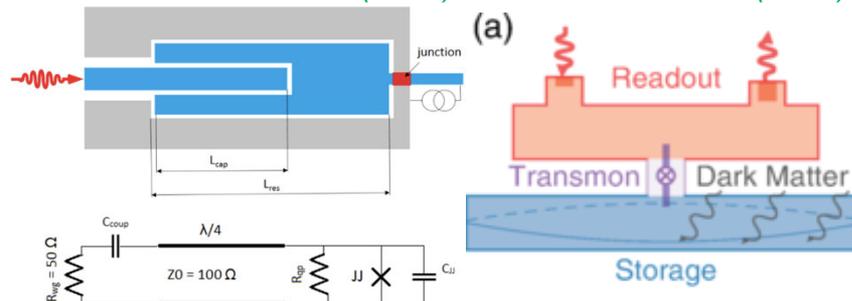


**Game changer  
at high freq. and low temp.**



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

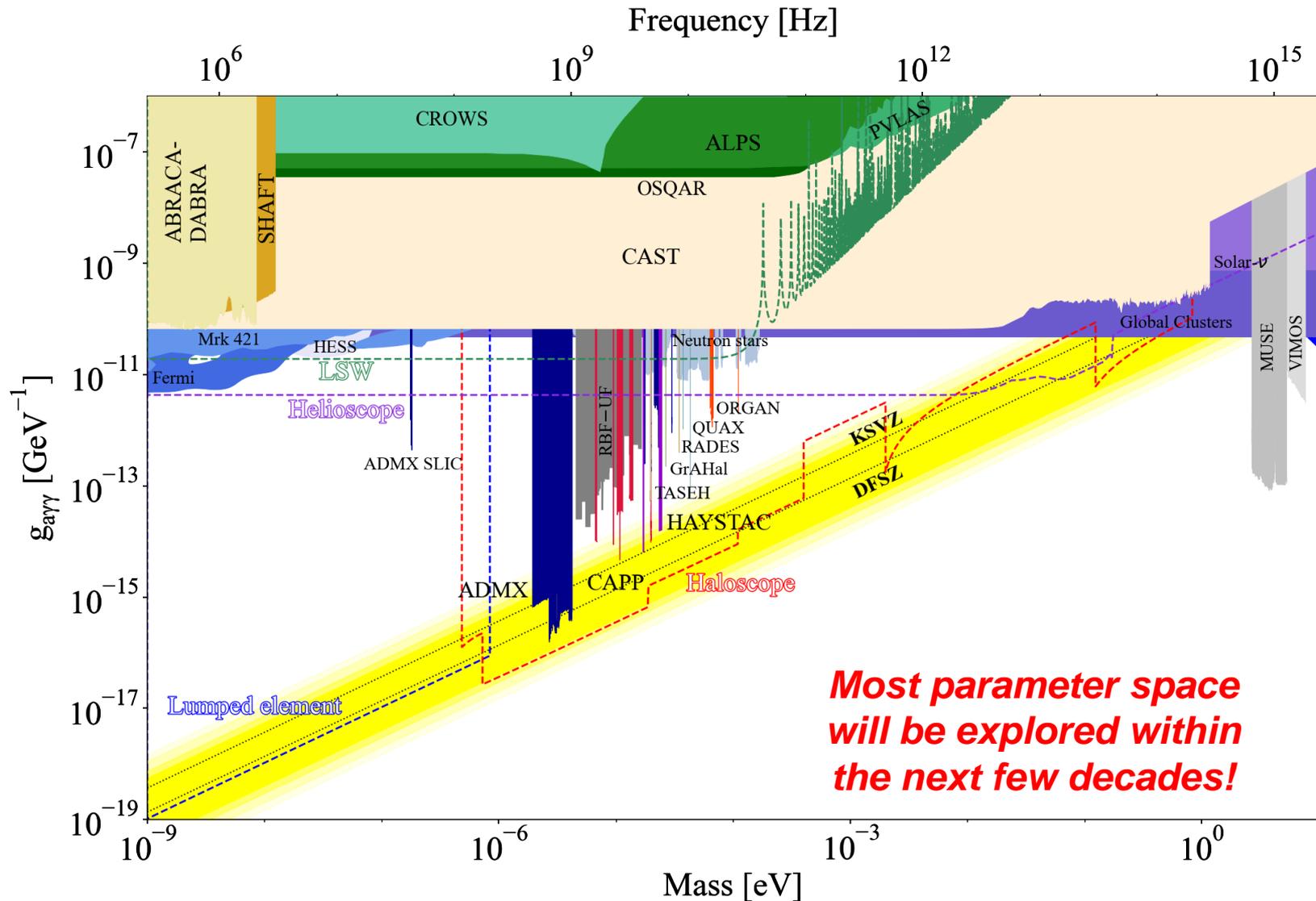
IEEE TASC 2850019 (2018) PRL 126 141302 (2021)



Single photon counting ( $T_N \ll T_{SQL}$ )



# Axion searches – future





# Experiment map

C. O'Hare (2020)

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



- Tremendous efforts during the past decade
- Axion **community is getting larger**
- Next few decades must be **crucial/exciting**



# Summary

- *Axion is a theoretically well motivated particle*
  - *Offering a solution to the strong CP problem*
  - *Addressing the dark matter mystery*
- *But, experimental search is very challenging*
  - *Weak coupling and unknown mass*
- *Tremendous efforts have been made over the past decade*
  - *Different technologies targeting at different mass ranges*
- *Axion community is getting larger*
  - *New results, new groups and new ideas*
- *Next a few decades must be critical/exciting*
  - *Exploring a substantial portion of the parameter space*