Experimental searches for axions and axion-like particles

SungWoo YOUN

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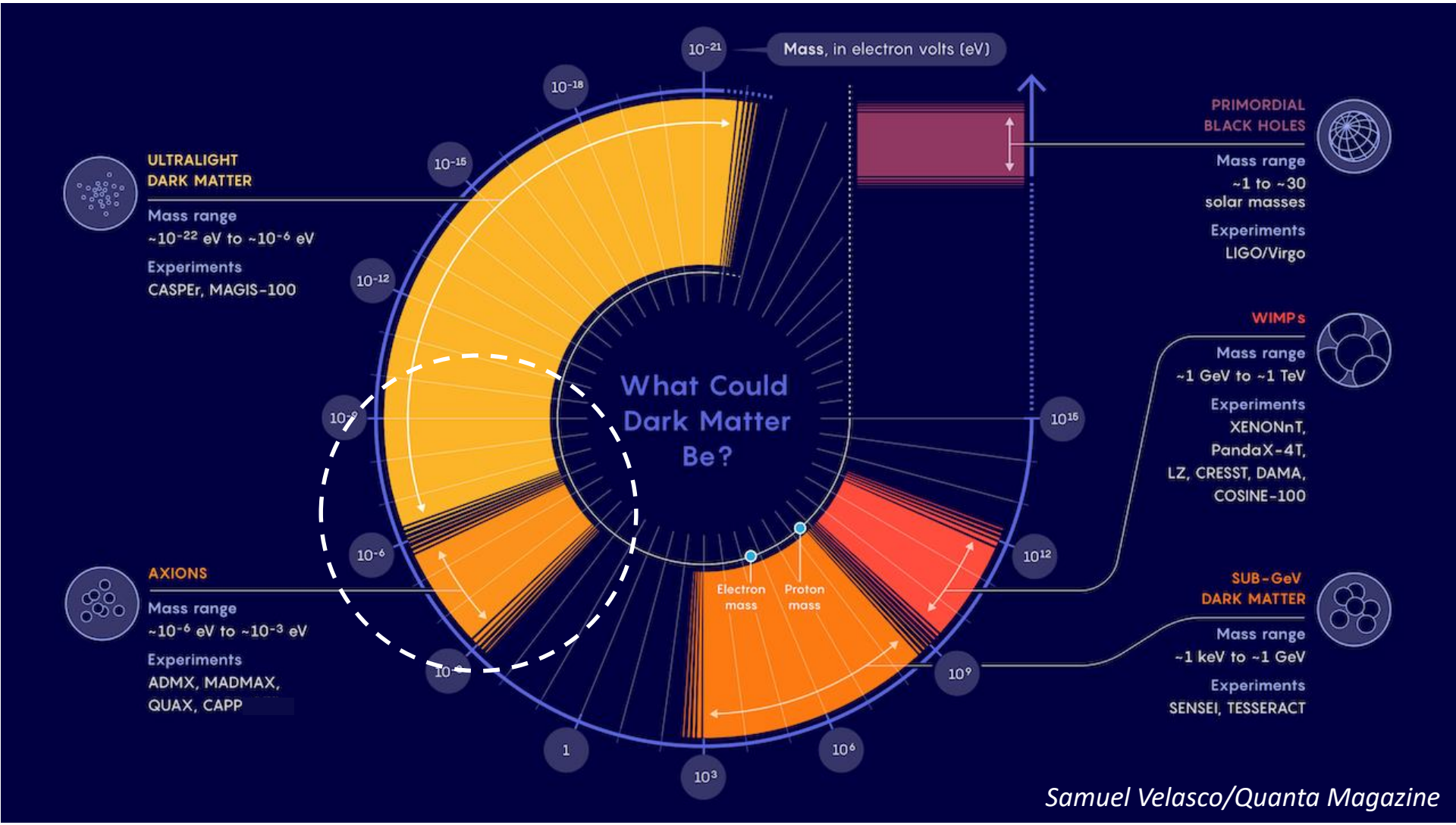
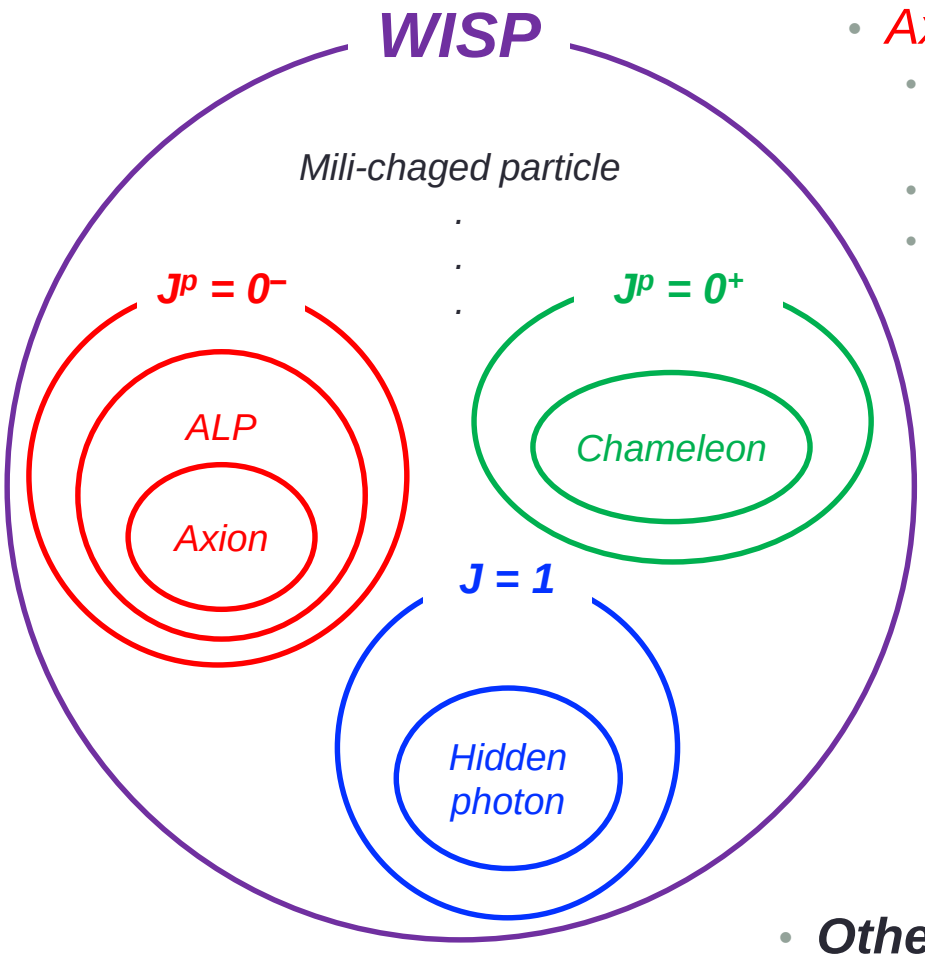
Institute for Basic Science (IBS)

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 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, …*

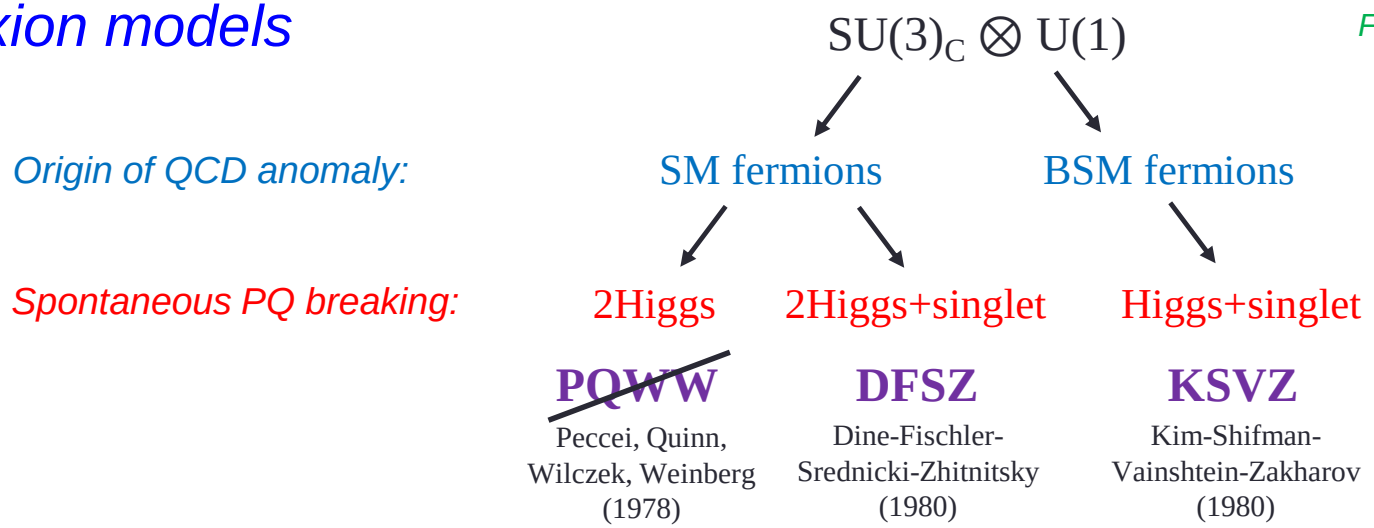
Couplings and models

- *Axion coupling to SM*

	Photons	Fermions	nEDMs
Lagrangian	$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	$g_{aff} (\partial_\mu a) \bar{f} \gamma^\mu \gamma_5 f$	$-\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$
Observable (measurable)	Photon	Spin precession	Oscillating EDM
Detection	Power spectrum, photon counter, …	Magnetometer, NMR, …	NMR, polarimeter, …

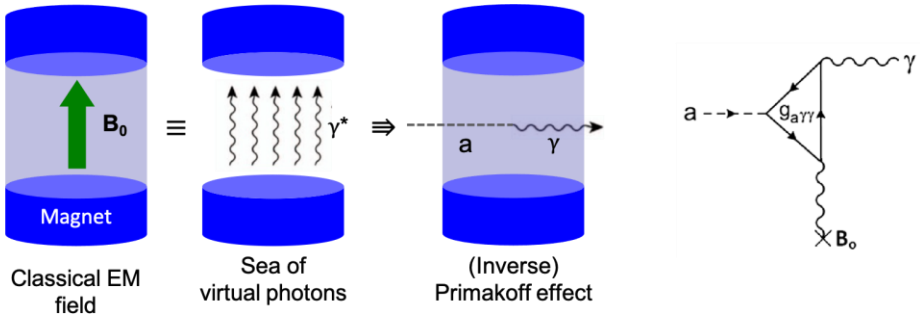
- *Axion models*

From R. Ziegler

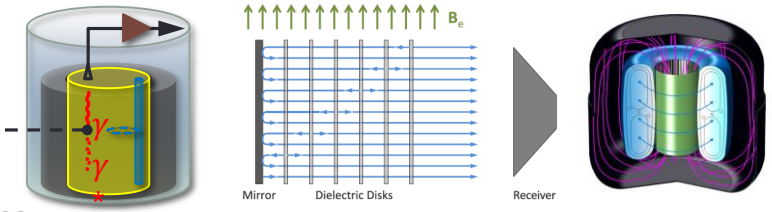


Search strategies

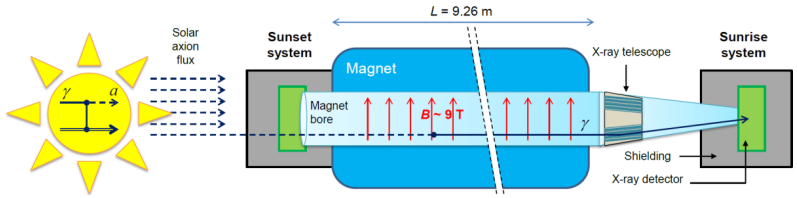
- *Detection principle*
  - *Sikivie effect (1983)*



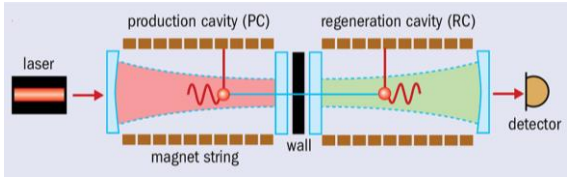
- *Detection methods*
  - *Haloscope*
    - *Dark matter halo*
    - *ADMX, CAPP, MADMAX, DM radio, …*



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



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

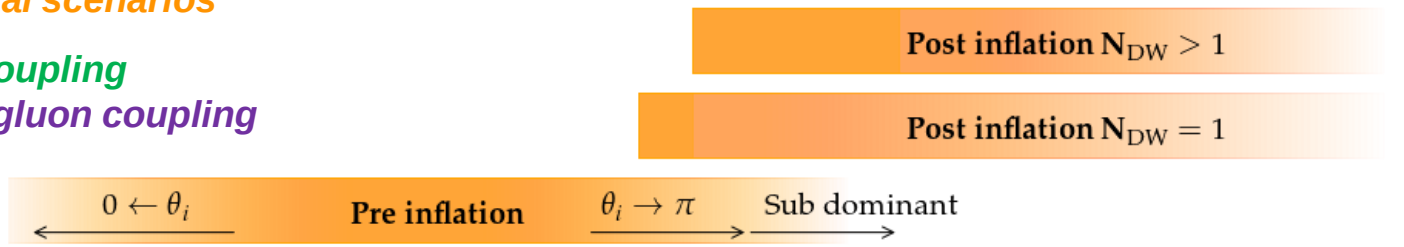


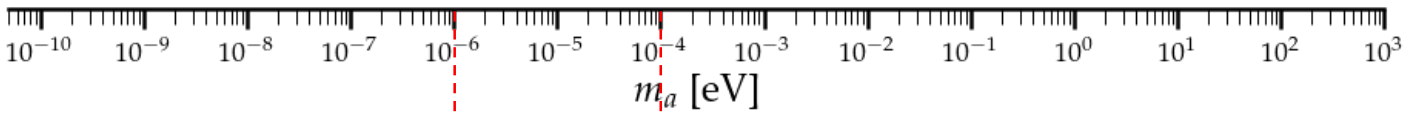
Where are dark matter axions?

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

Theoretical scenarios

Photon coupling
Fermion/gluon coupling





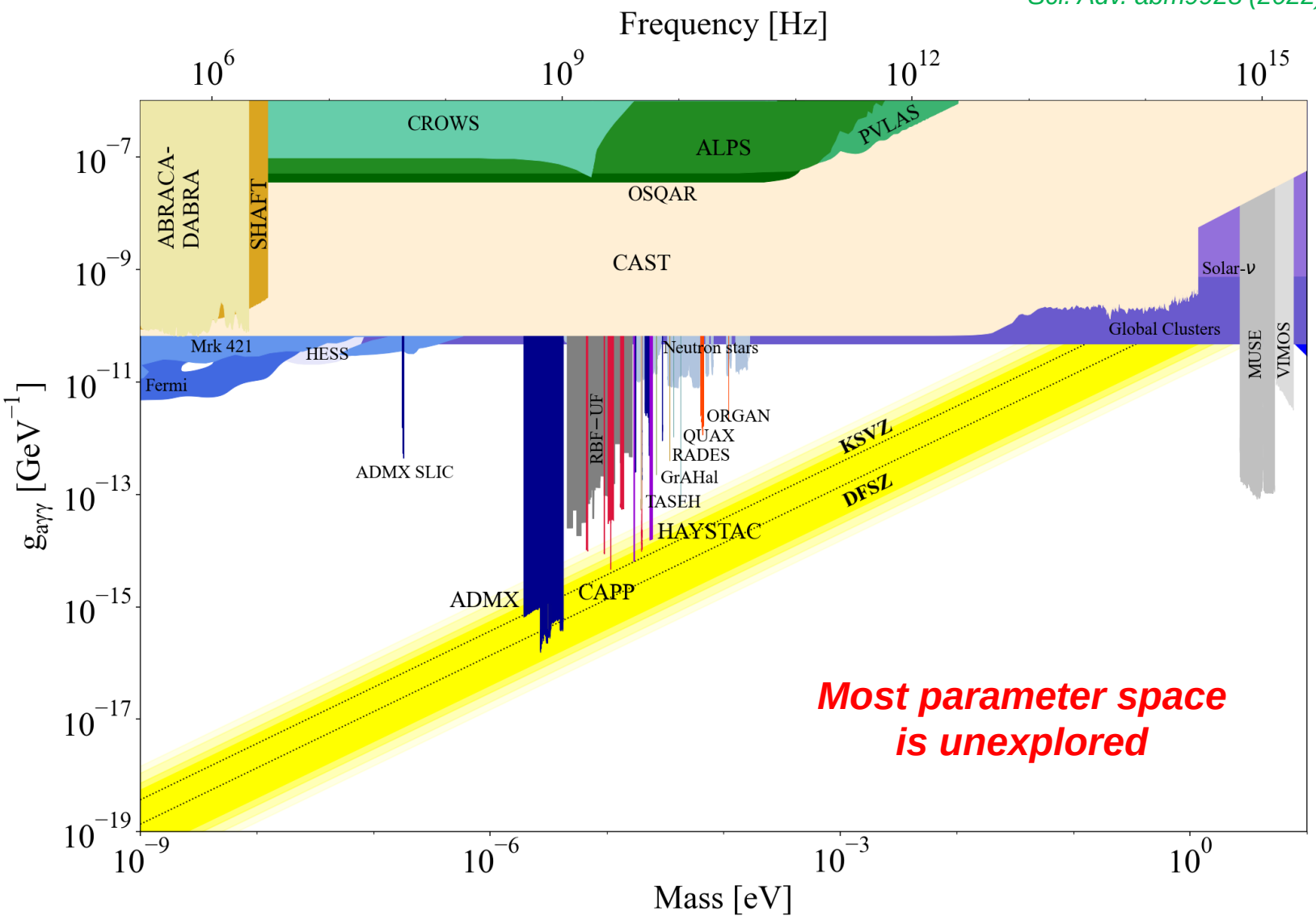
Quasistatic regime
$\lambda_{Comp} \gg D_{exp}$

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

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

Axion searches – present

Sci. Adv. abm9928 (2022)

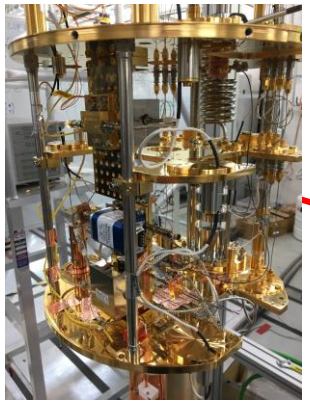


Cavity haloscope – in a nutshell

- *Most sensitive for microwave photons*

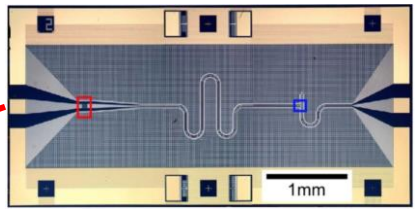
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics T



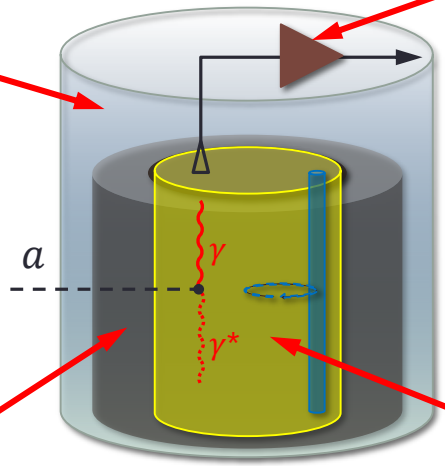
Lowering thermal noise

Quantum noise limited amplifier T

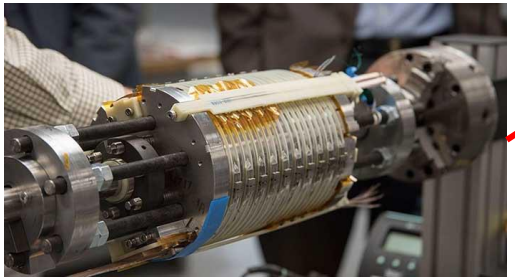


Signal amplification w/ minimal noise added

P ~ 10⁻²³ W



High field Magnet B



Boosting a→γγ conversion rate

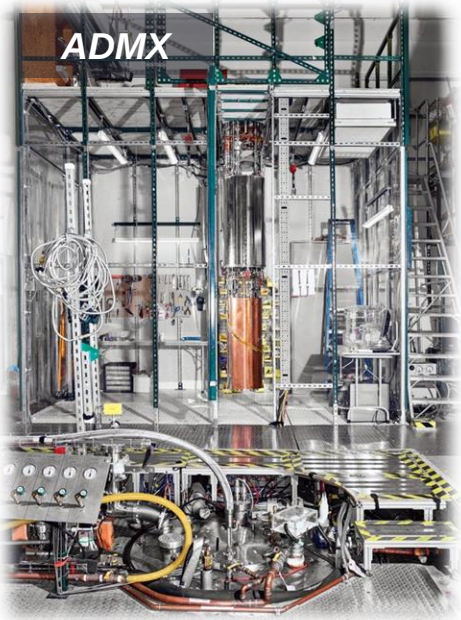
Tunable High-Q resonator
V, Q, C, Δf

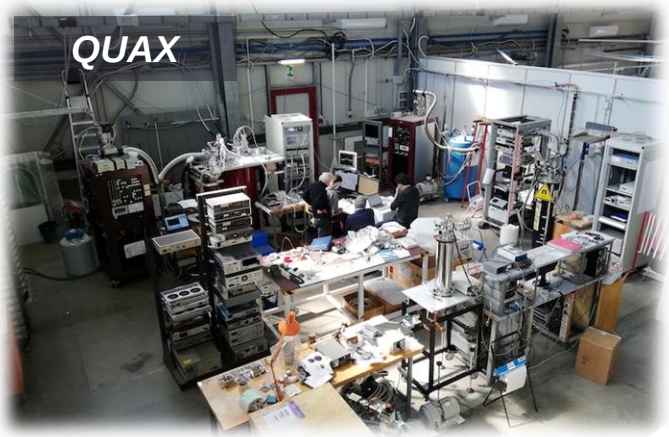
Resonant frequency tuning

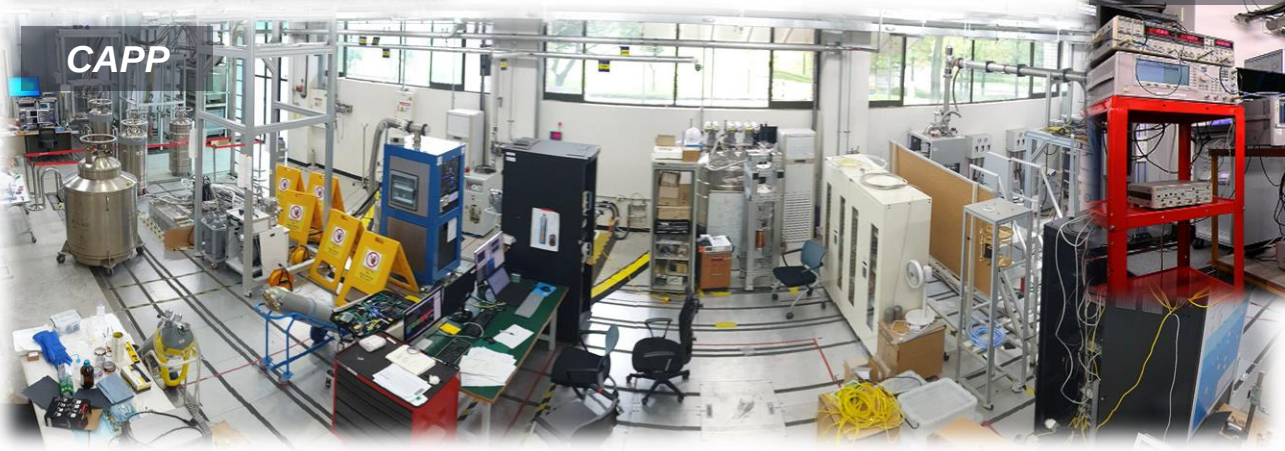
Small-scale experiments!

Cavity haloscopes

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

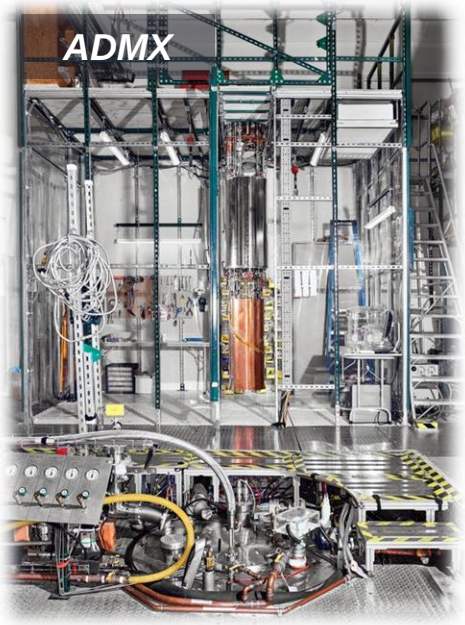


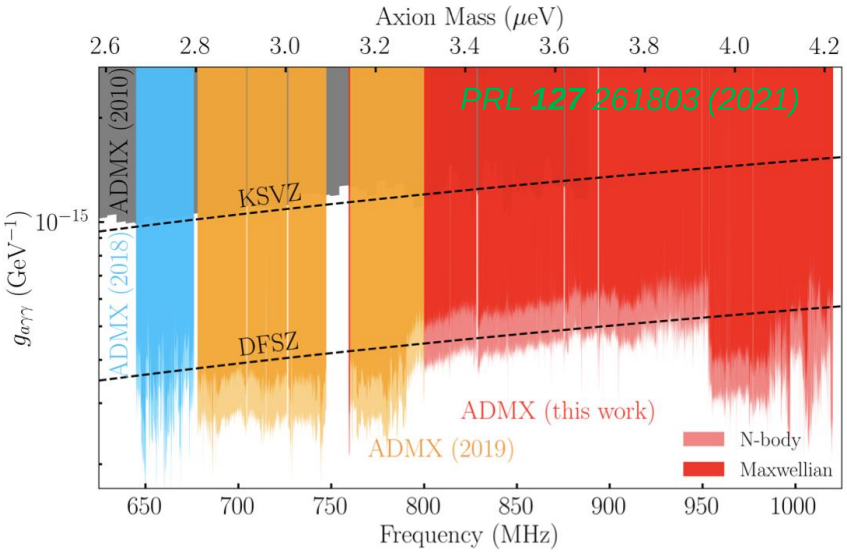




Search highlights

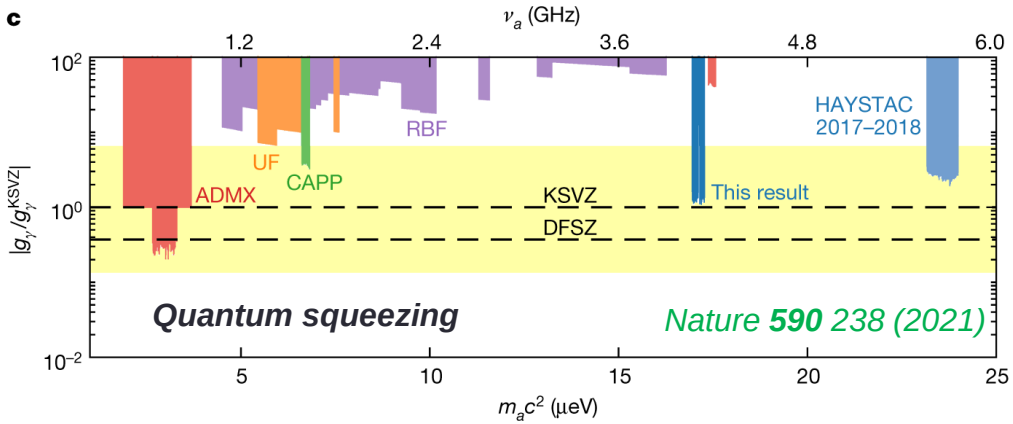
Cavity regime
$\lambda_{Comp} \sim D_{exp}$





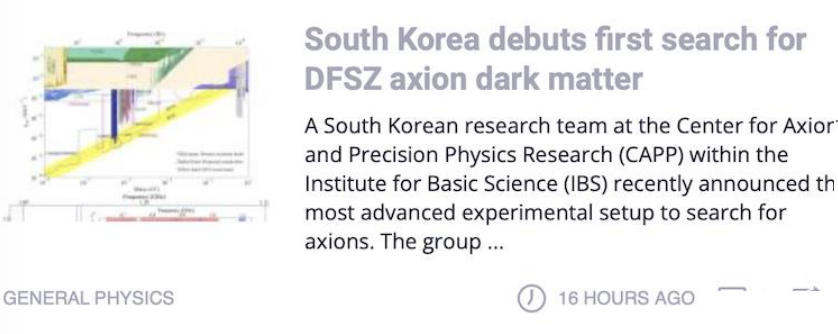
Search highlights

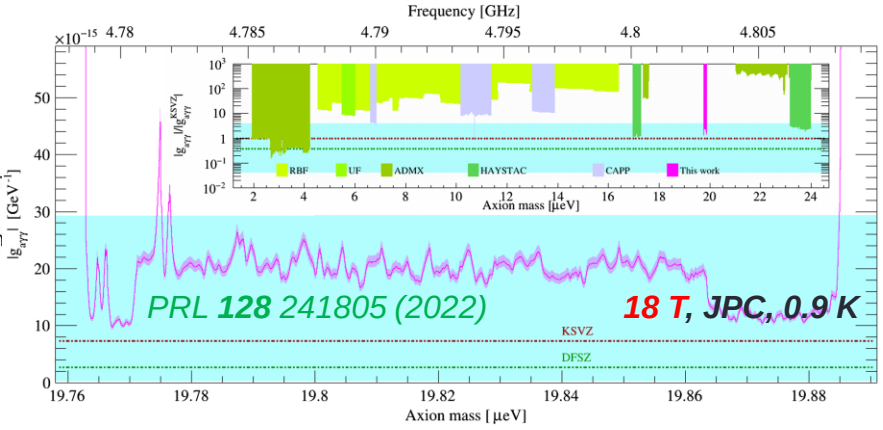
Cavity regime
$\lambda_{\mathrm{Comp}} \sim \mathrm{D}_{\mathrm{exp}}$

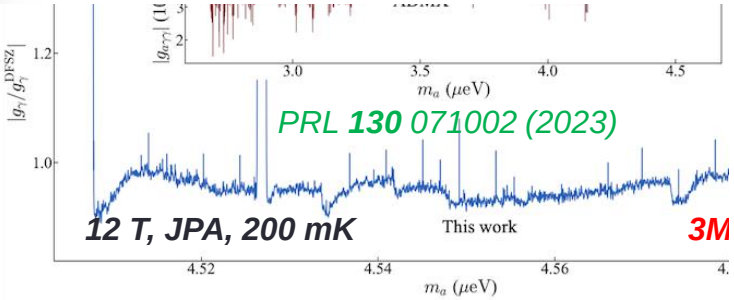


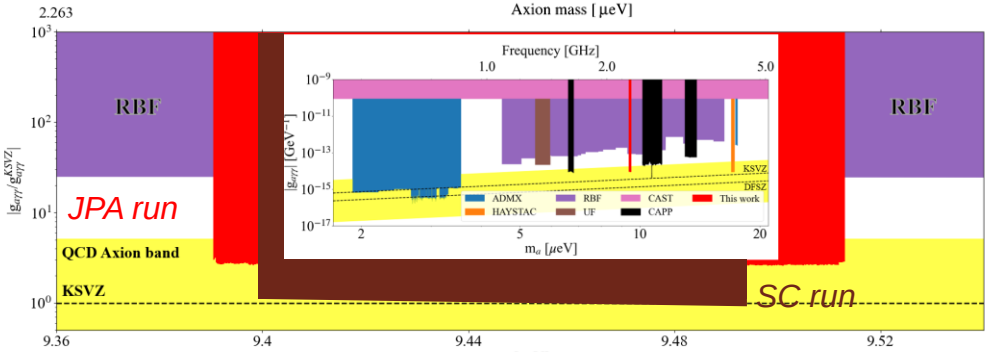
Search highlights

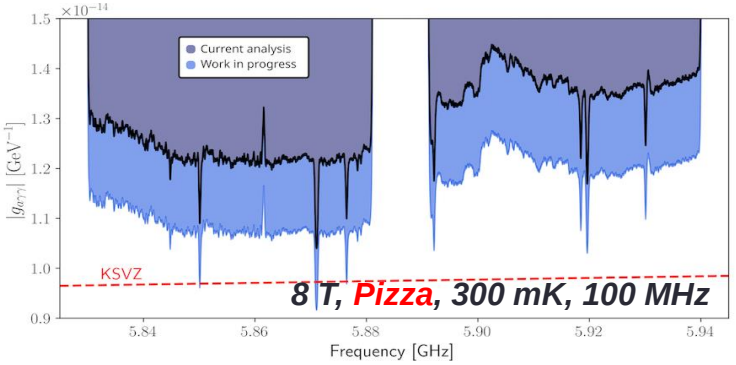
Cavity regime
$\lambda_{Comp} \sim D_{exp}$





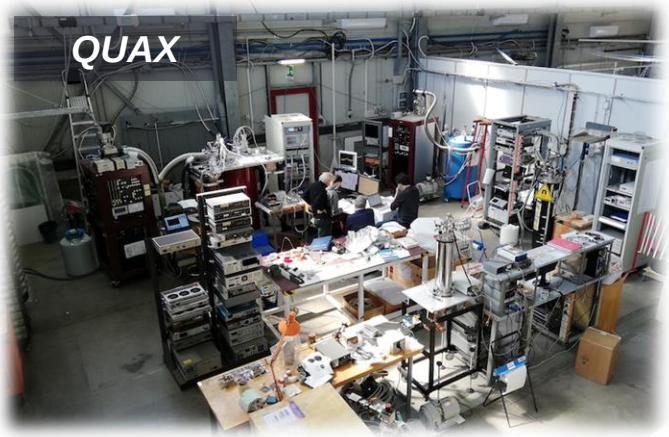


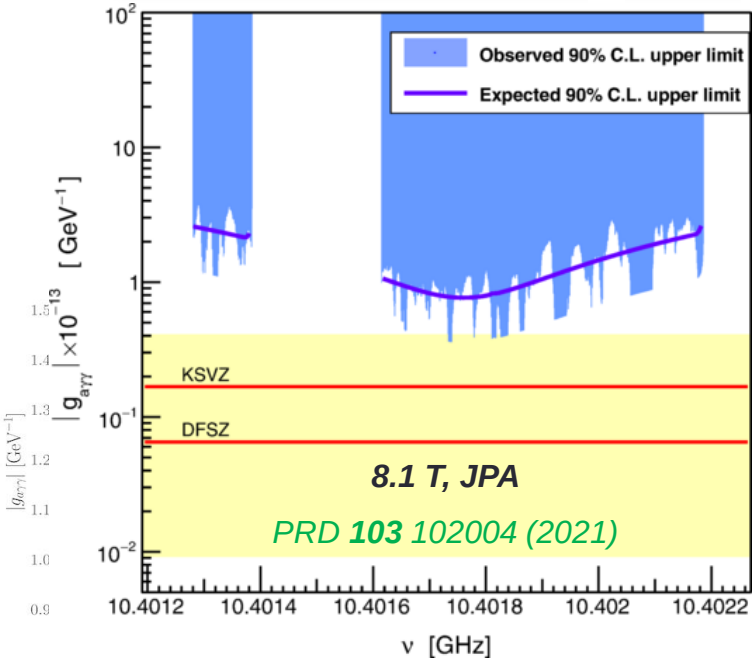




Search highlights

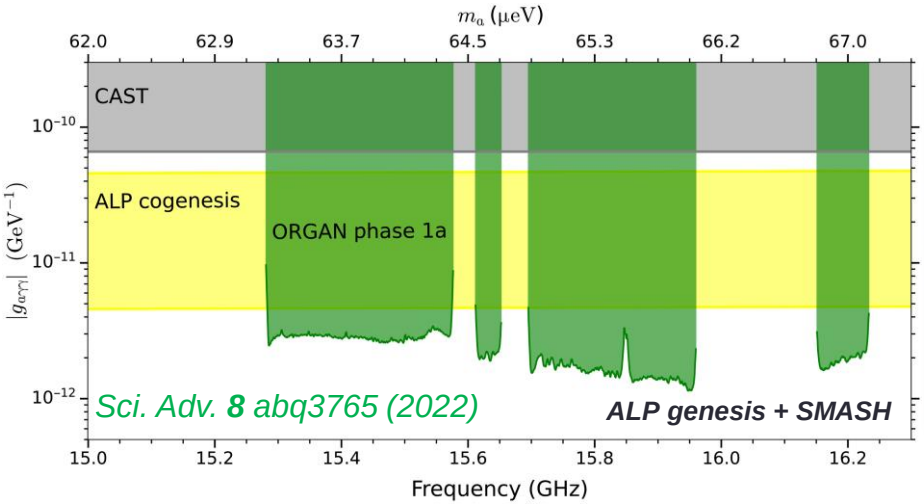
Cavity regime
$\lambda_{Comp} \sim D_{exp}$





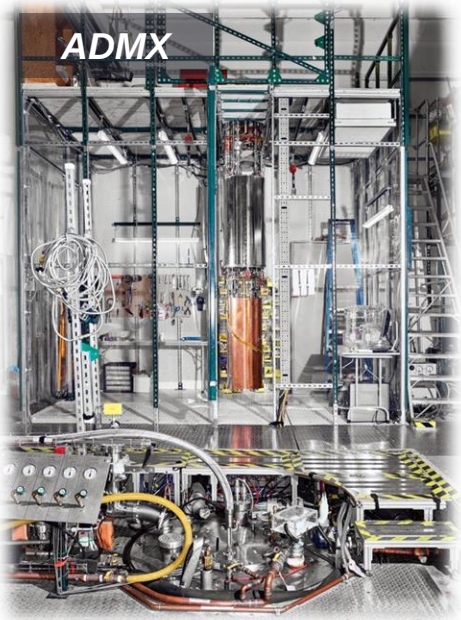
Search highlights

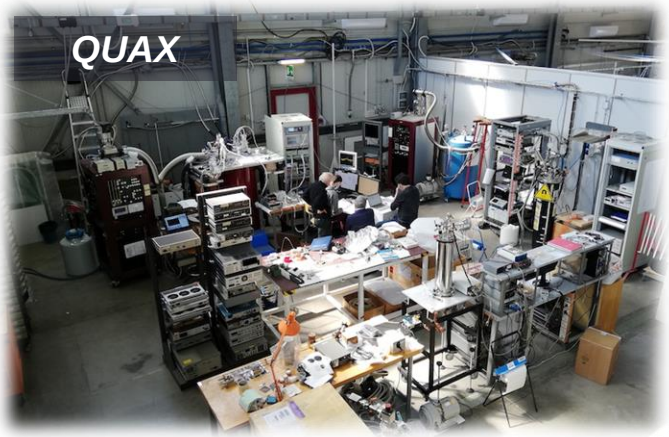
Cavity regime
$\lambda_{Comp} \sim D_{exp}$

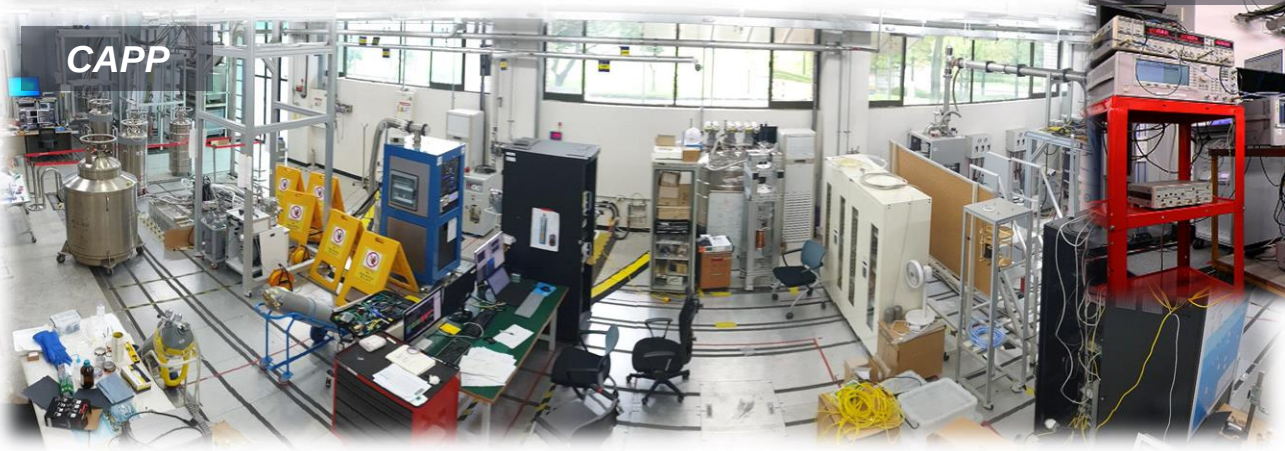


Cavity haloscopes

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





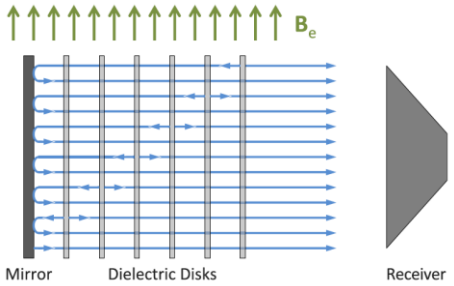


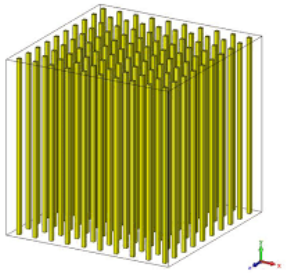
$f_a \lesssim 10\ \mathrm{GHz}$ ...

High frequency haloscopes

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

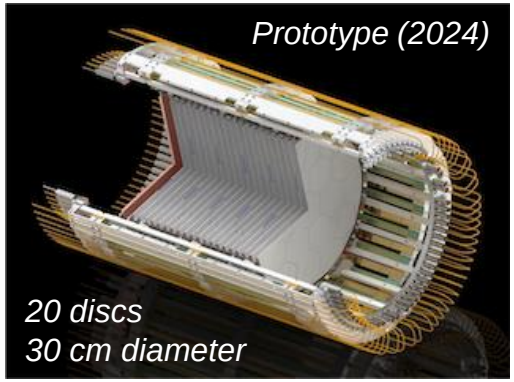
- *Periodic array*
  - *Search frequency independent of detector size*
  - *Suitable for post-inflation scenario (10–100 GHz)*

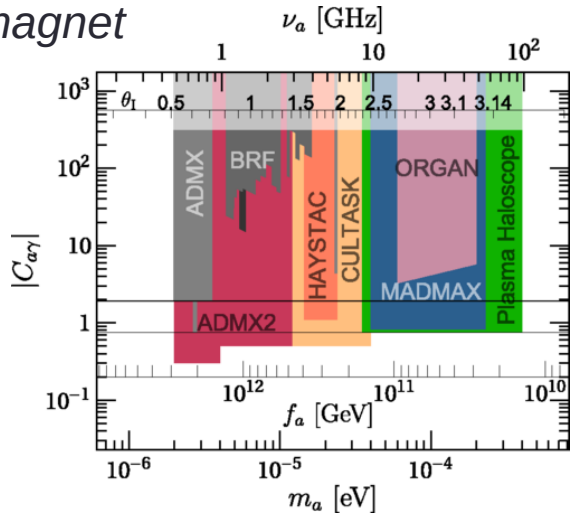


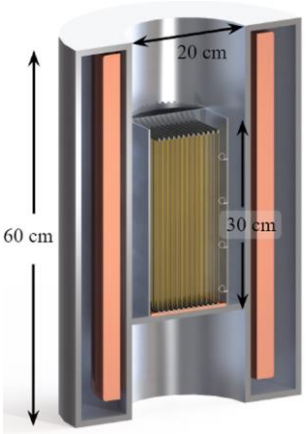


- *MADMAX*
  - *Power boost w/ dielectric disks*
  - *Full scale experiment*
    - *2m-10T dipole / 80 1m² discs ($\epsilon \sim 25$)*
  - *Proof-of-concept and 3D effect*
  - *Prototype using Morpurgo magnet*

- *ALPHA*
  - *Resonance w/ plasma frequency (metamaterial)*
  - *Demonstration of frequency tuning*
  - *Physics data in 2026*







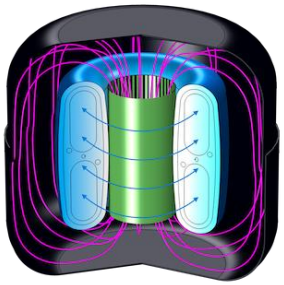
Lumped element haloscopes

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

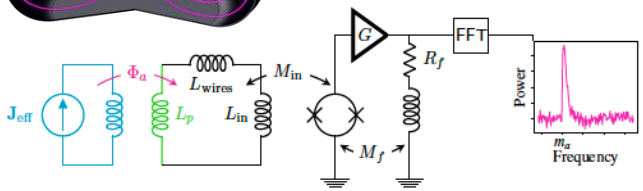
- *Broadband low mass search (< 1 ueV)*
  - *Sensitive to pre-inflation axions*

ABRACADABRA-10cm

*PRL **12** 081801 (2021)*

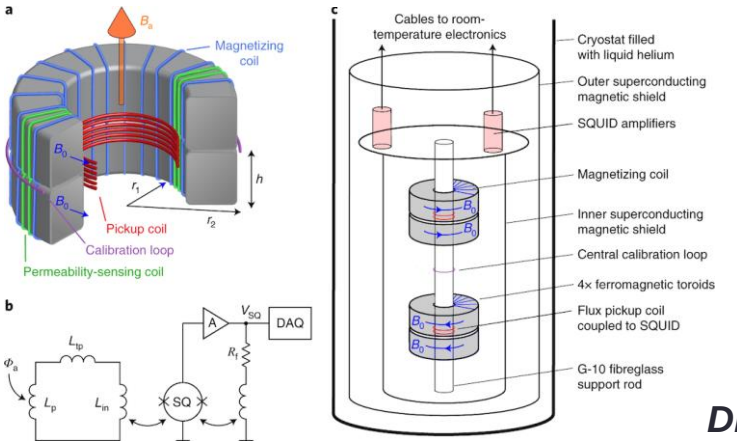


$$J_e = g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\,\boldsymbol{B_0}$$

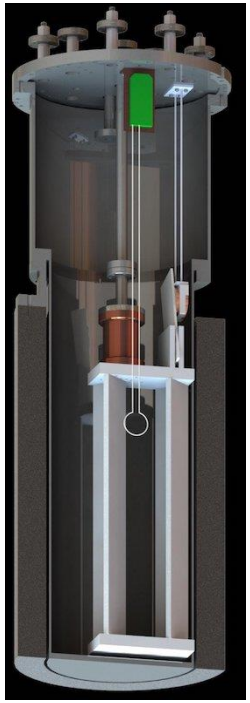


SHAFT

*Nature Phys. **17** 79 (2021)*

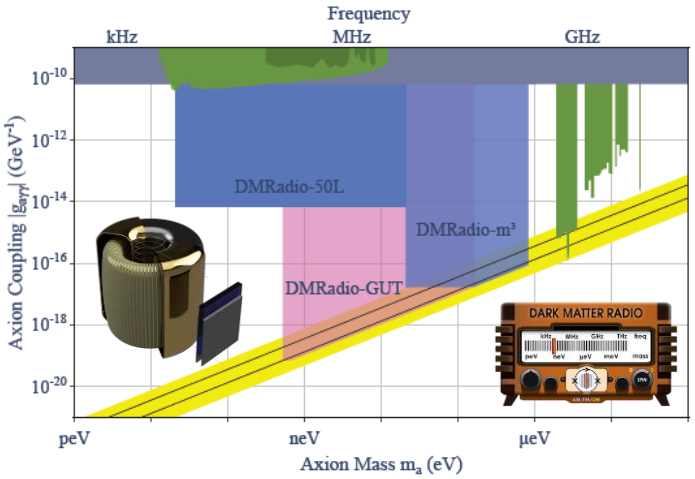


ADMX SLIC



*PRL **124** 241101 (2020)*

DM Radio

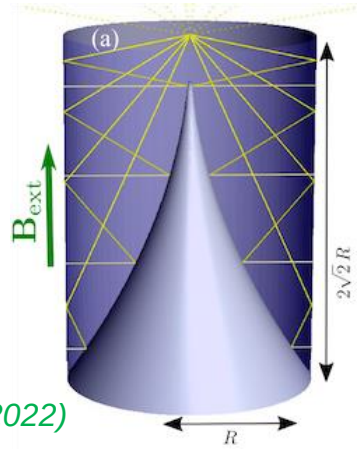


Other searches

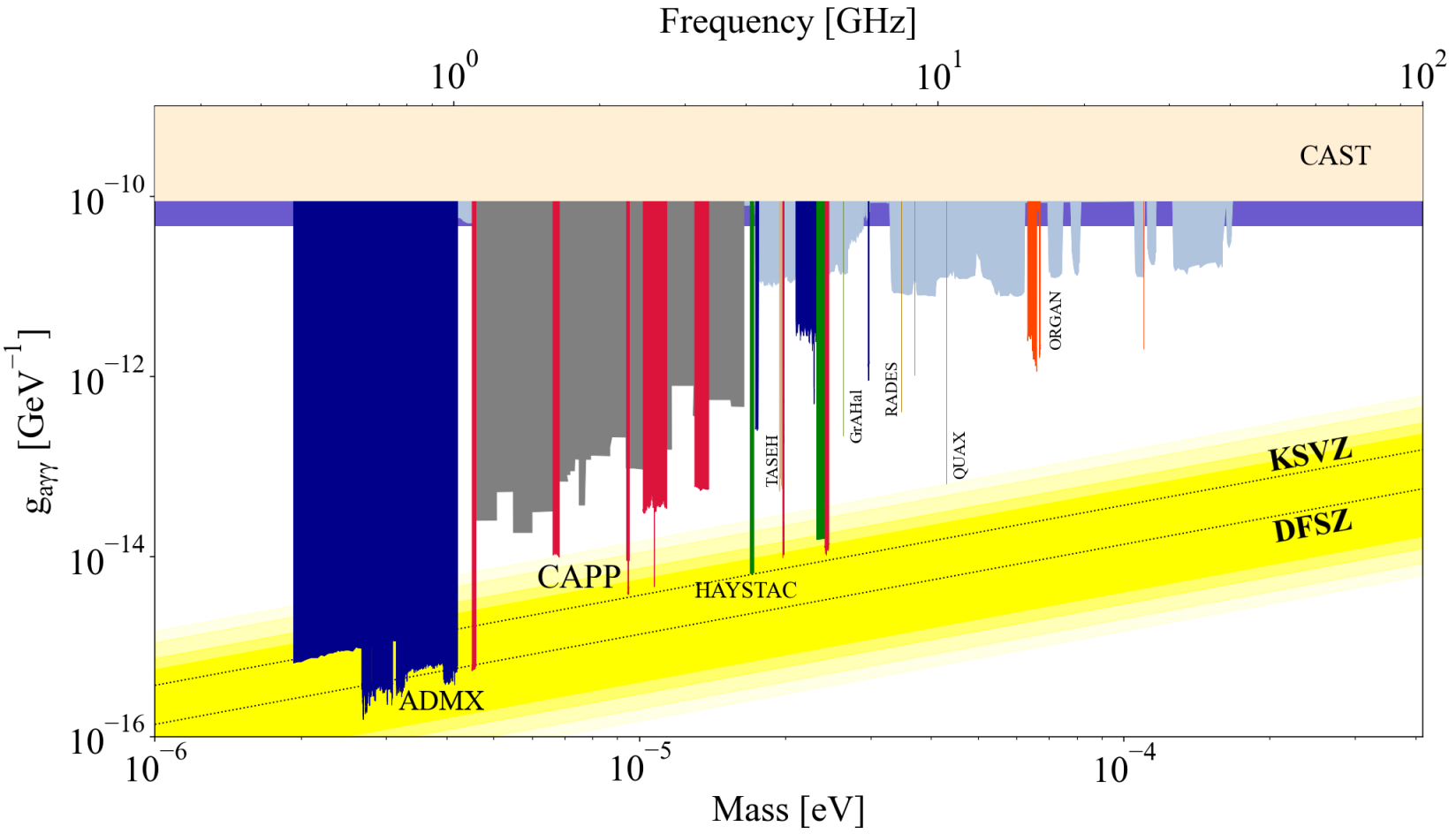
- *CAST dipole (9T)*
  - *CAST-CAPP* *Nat. Commun. **13** 6180 (2022)*
    - *Phase-matched cavities, ~20 ueV*
  - *Relic Axion Dark matter Exploratory Setup*
    - *Microwave fiber, ~34 ueV* *JHEP **2021** 75 (2021)*

- *Newly joined*
  - *Grenoble Axion Haloscope*
    - *14T/52mm magnet, ~26 ueV* *ArXiv:2110.14406*
  - *Taiwan Axion Search Experiment with Haloscope*
    - *4.7 GHz, 11 x g_{arr}^{KSVZ}* *RSI **93** 084501 (2022)*

- *Proposed*
  - *Broadband Reflector Experiment for Axion Detection*
    - *Parabolic reflector, THz region* *PRL 128 131801 (2022)*
  - *Canfranc Axion Detection Experiment*
    - *90 GHz (W-band), Kinetic Induction Detectors* *JCAP 11 044 (2022)*



Haloscope searches – present

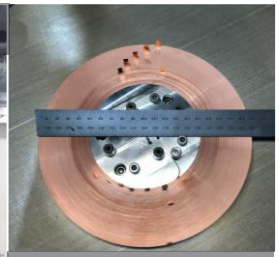


Magnet


ADMX (8T/600mm)

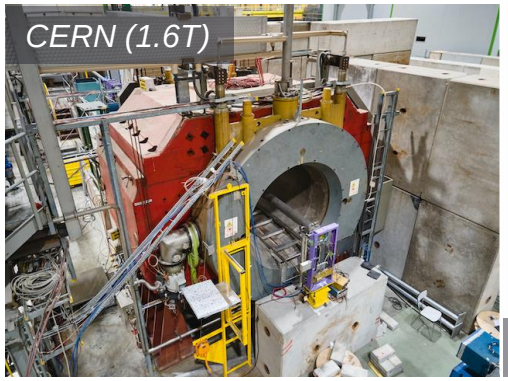

CAPP (12T/320mm)

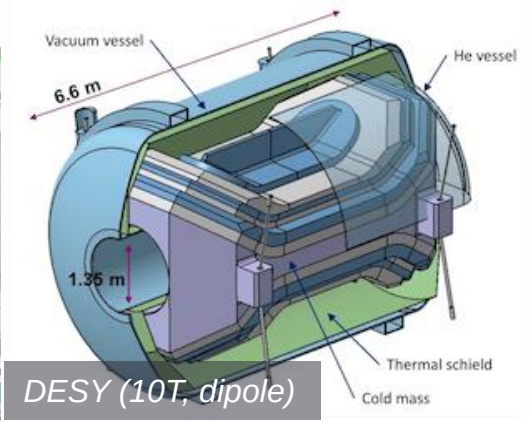

CAPP (18T/70mm)


YBCO pancakes

Grenoble (43T/34mm)

UIC (9.4T/800mm)

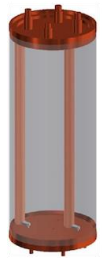

CERN (1.6T)



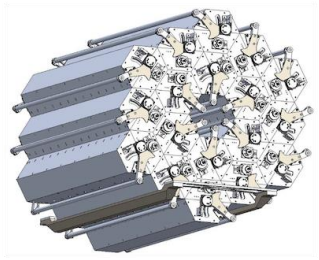
DESY (10T, dipole)

Cavity

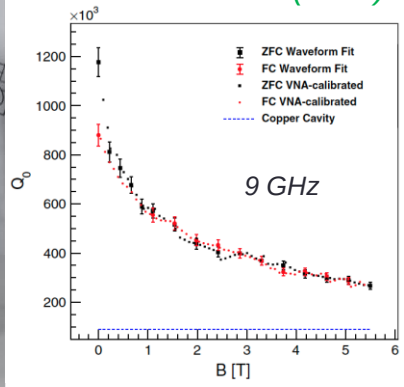
arXiv: 2203.14923


Run 1A-C

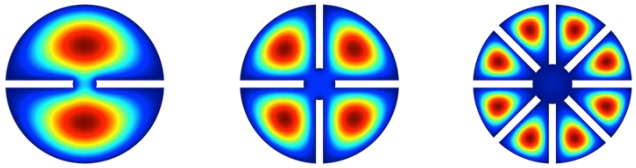

Run 2


EFR

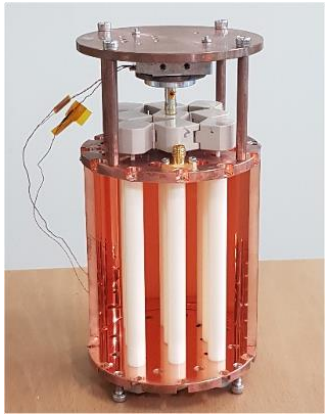
*PRD **99** 101101 (2019)*



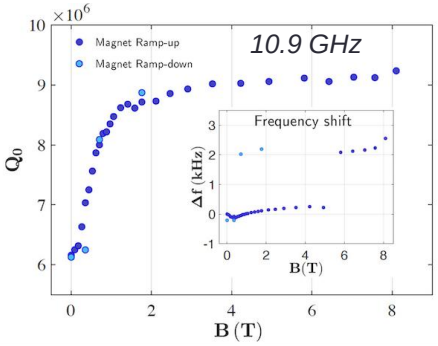
*PRL **125** 221302 (2020)*

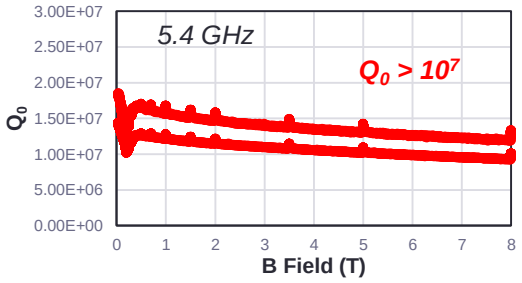


arXiv: 2205.08885



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



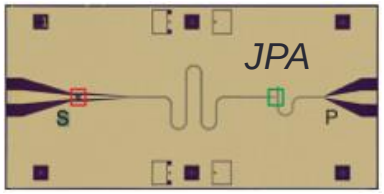


Microwave photon detection

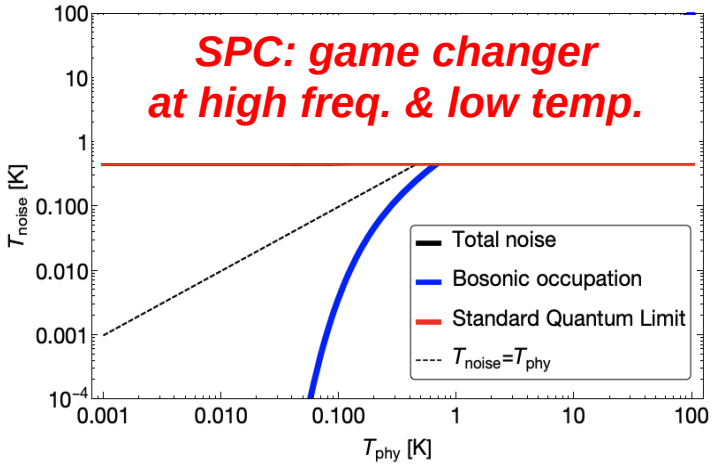
Power detection vs. photon counting

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

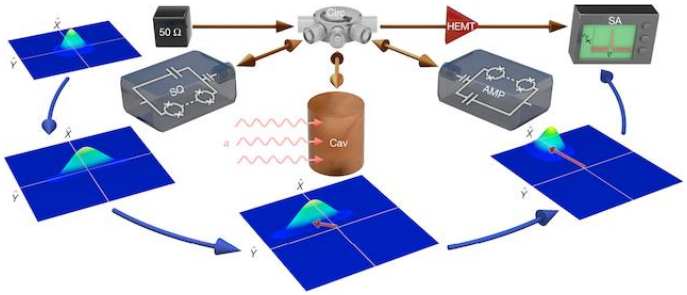
Transistor-based
(T_N ~ K)



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

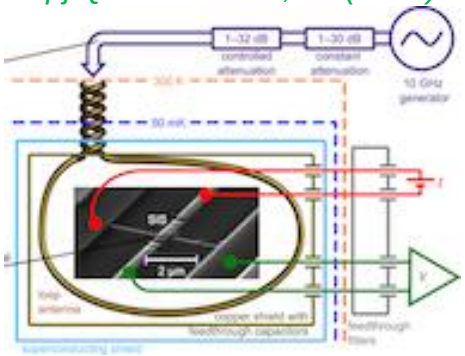


*Nature **590** 238 (2021)*

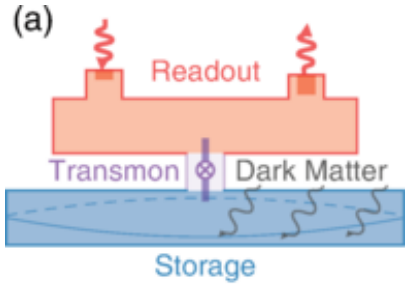


Quantum squeezing ($T_N < T_{SQL}$)

*npj Quantum Inf **8**, 61 (2022)*



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

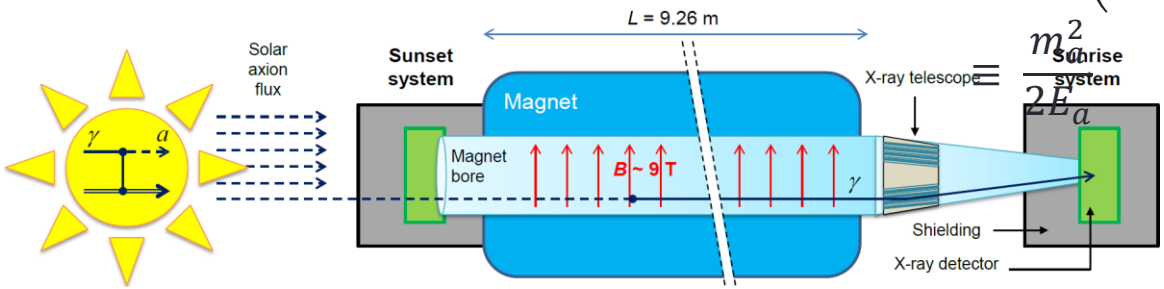


Not subject to SQL
($T_N << T_{SQL}$)

Helioscope

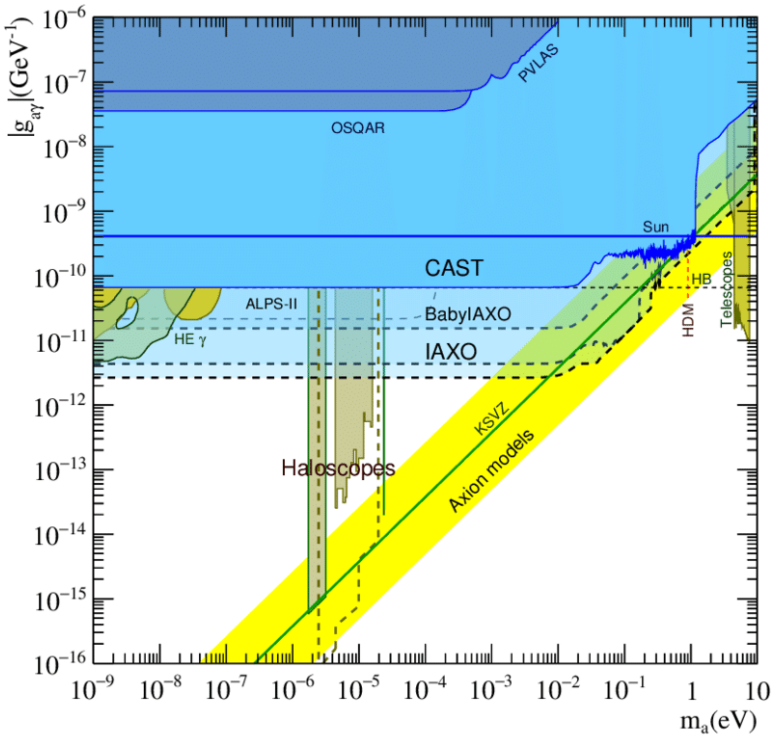
- *Solar axion telescope*

$$P_{a\gamma\gamma} \sim \left(\frac{g_{a\gamma\gamma} B_0}{q}\right) \sin\left(\frac{qL}{2}\right), q \equiv \frac{m_a^2}{2E_a}$$



Axion to X-ray in lab. magnetic fields

Black-body photon (keV) to axion in dense stellar plasma

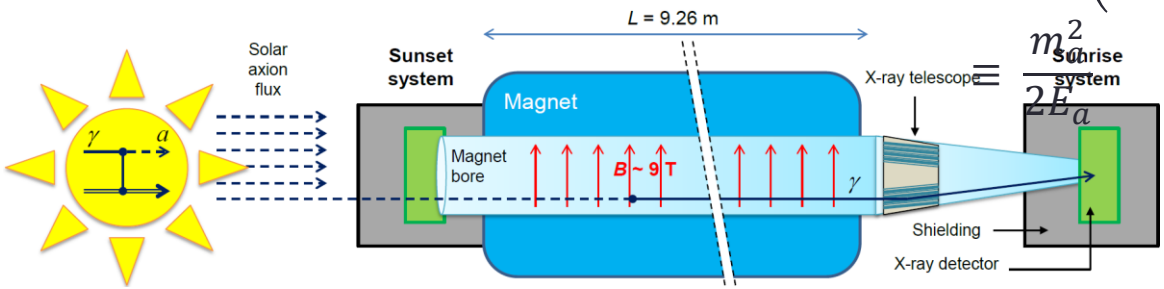


- *History*
  - *BNL => SUMICO => CAST => IAXO*

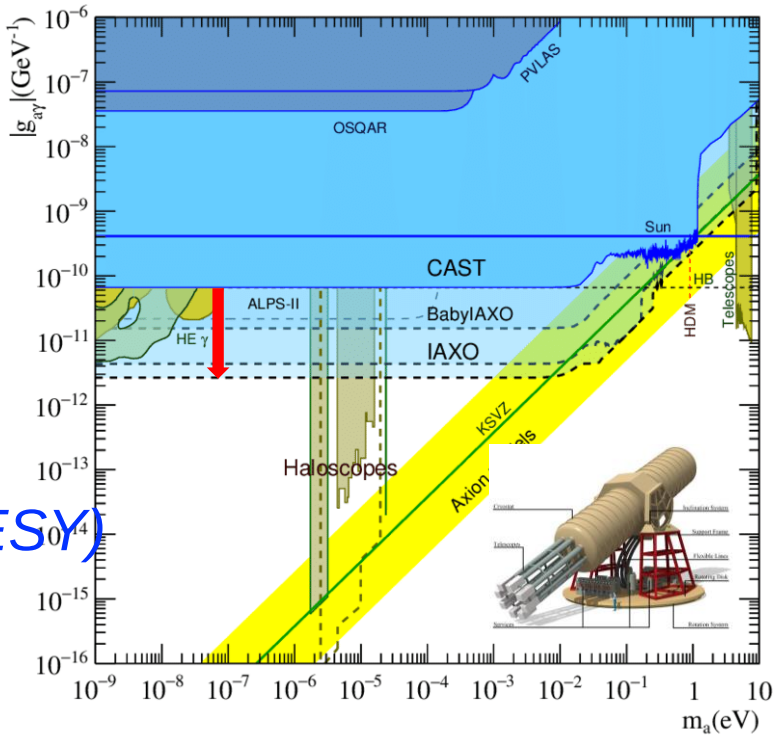
Helioscope

- *Solar axion telescope*

$$P_{a\gamma\gamma} \sim \left(\frac{g_{a\gamma\gamma} B_0}{q}\right) \sin\left(\frac{qL}{2}\right), q \equiv \frac{m_a^2}{2E_a}$$

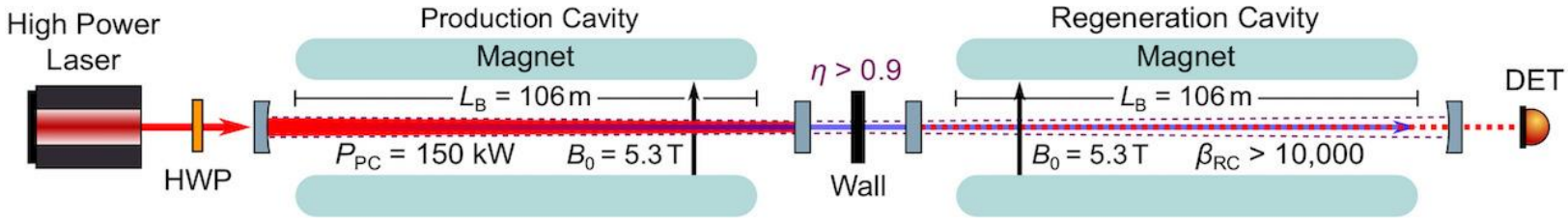


- *International AXion Observatory*
  - *8 dipoles (5.4 T, 20 m, 600 mm)*
  - *Goal:* $g_{a\gamma} \sim 10^{-12}\ GeV^{-1}$
  - *Diverse physics over wide range*
    - *QCD axions*
    - *ALP miracle (DM & inflation)*
    - *Astrophysical hints*
- *Baby-IAXO under construction (DESY)*
  - *First step towards full IAXO*
  - *4 T / 10 m => 10 x* $MFOM_{CAST}$

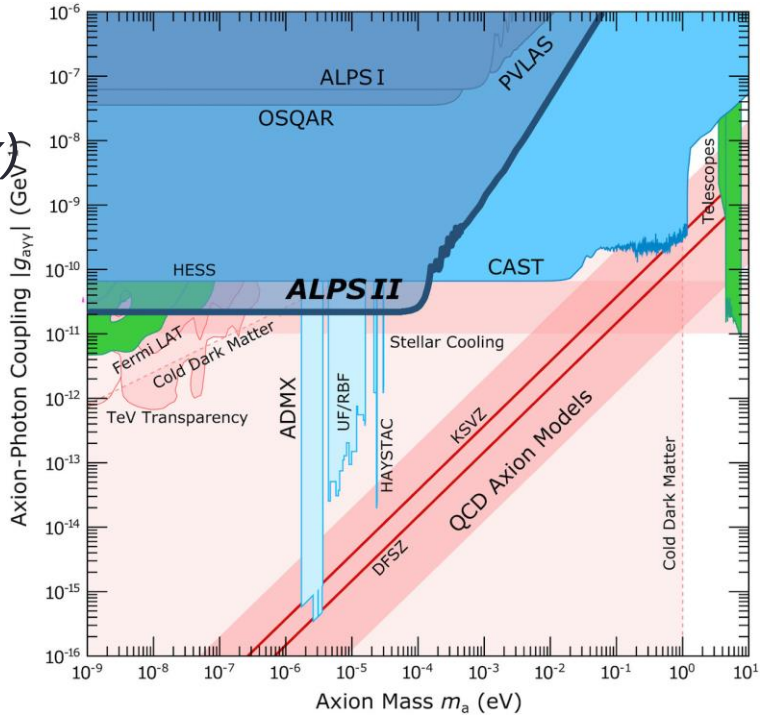


Light shining through a wall

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

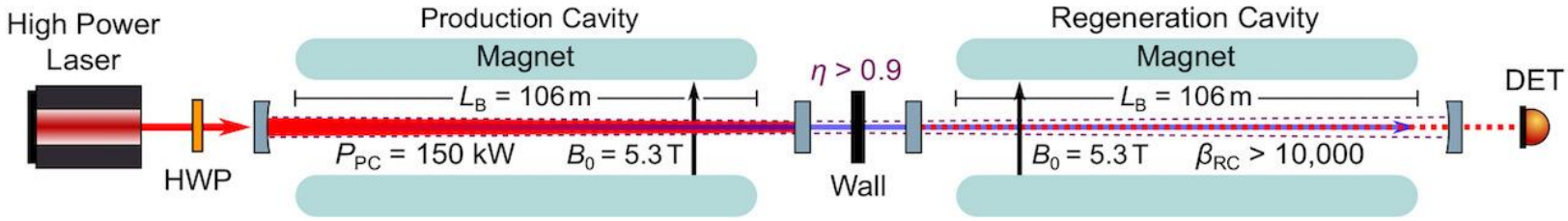


- *Model independent search*
  - *No need of cosmo./astrophys. source*
  - *cf. halo(helio)scope needs density (flux)*
- *History*
  - *BFRT => OSQAR => ALPS => ALPS II*

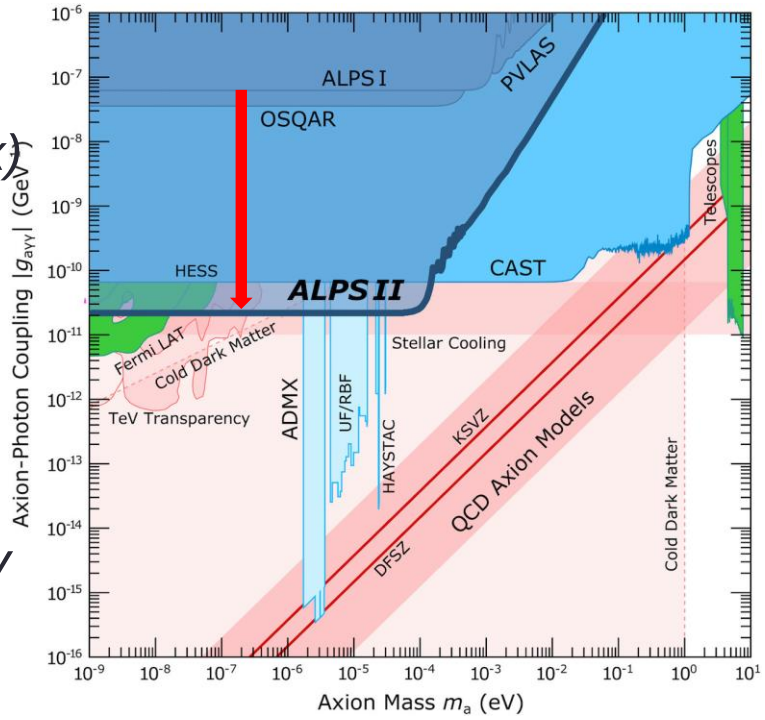


Light shining through a wall

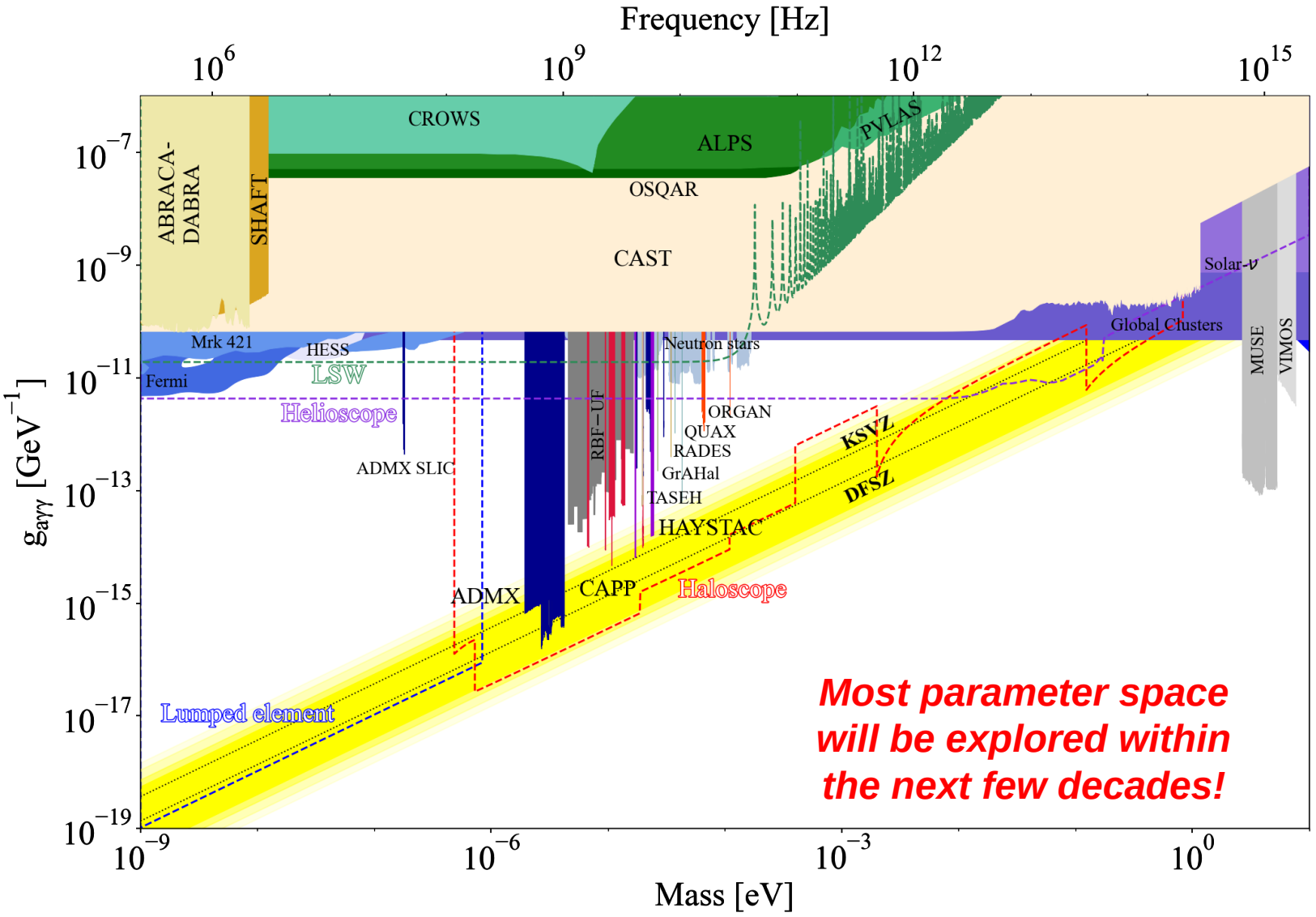
- *Axion-production/photon-regeneration at the lab*



- *Model independent search*
  - *No need of cosmo./astrophys. source*
  - *cf. halo(helio)scope needs density (flux)*
- *Any Light Particle Search II*
  - *2 x 12 Hera dipoles (8.8 m & 5.3 T)*
  - *Dual high-finesse optical cavities*
  - *Alignment sensing: PDH/DWS*
  - *Photon detector: HET/TES*
  - *Goal: $g_{a\gamma\gamma} \sim 10^{-11}\ GeV^{-1}$ below 0.1 eV*
    - *Improvement by 3 orders of magnitude*



Axion searches – future



Summary

- *Axions could address fundamental questions*
  - *Strong CP problem and dark matter mystery*
- *Theoretically well motivated but experimentally challenging*
  - *Weak coupling and unknown mass*
- *Tremendous search efforts*
  - *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*
  - *Covering a substantial portion of the parameter space*
  - *Uncovering the nature of dark matter*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Detector of halo axions

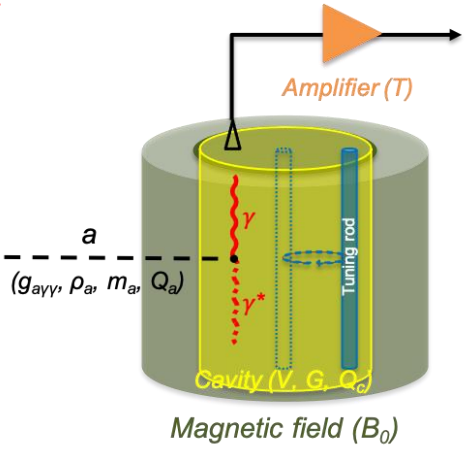
- *Most sensitive approach in μeV regime*
  - *Microwave photons resonantly converted from axions*

- *Conversion signal power (a→γγ)*

- theoretical parameters
- experimental parameters

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

- $g_{a\gamma\gamma}$: Coupling constant
- ρ_a: Axion number density
- B: Magnetic field
- C_{mnp}: Effective volume
- Q_L: Cavity Q factor
- Q_a: Axion Q factor



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

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

- t_{int}: Integration time
- Δf_a: Axion bandwidth (~10^{-6} f)
- T_{syst}: System noise temperature

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

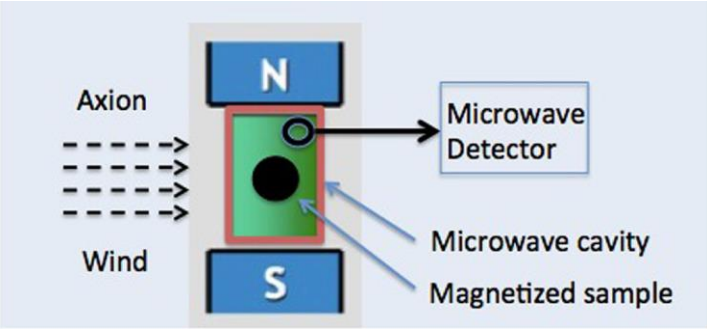
$$\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2 \left(\frac{P(f)}{k_B T_{syst}}\right)^2 \cdot \frac{Q_a}{Q_L} \propto B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Fermion coupling

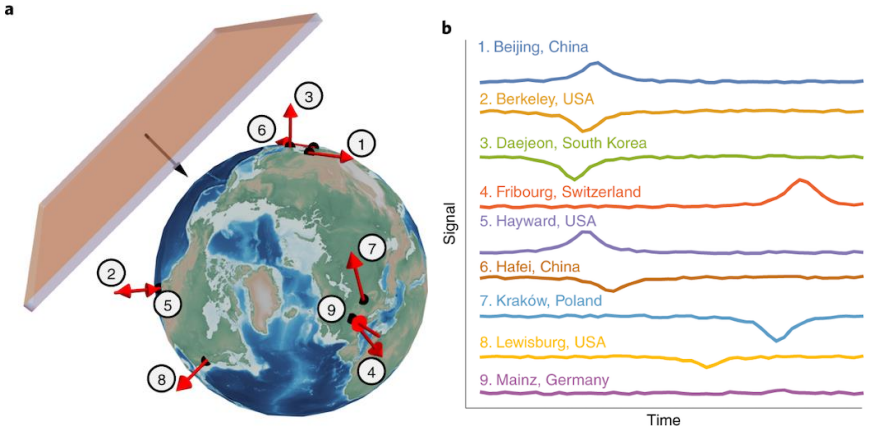
- *QUAX-ae*
  - *Ferromagnetic haloscope*
    - *Axion-electron spin*
  - *Photon-magnon system*
    - *Series of YIG spheres*
    - *TM_{110} of a cylindrical cavity*
  - *Upgraded with JPA*
  - *Best limit near $m_a \sim 43\ \mu eV$*

- *GNOME*
  - *Topological defect dark matter*
    - *Axion-nucleon spin*
  - *Global network of optical magnetometers*
    - *Correlated signal*

*PRL **124** 171801 (2020)*

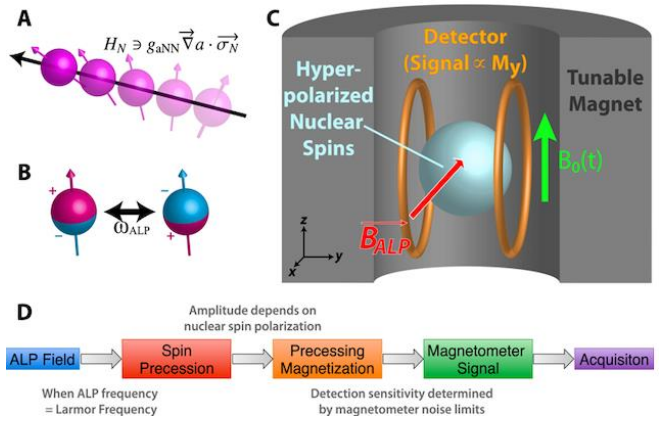


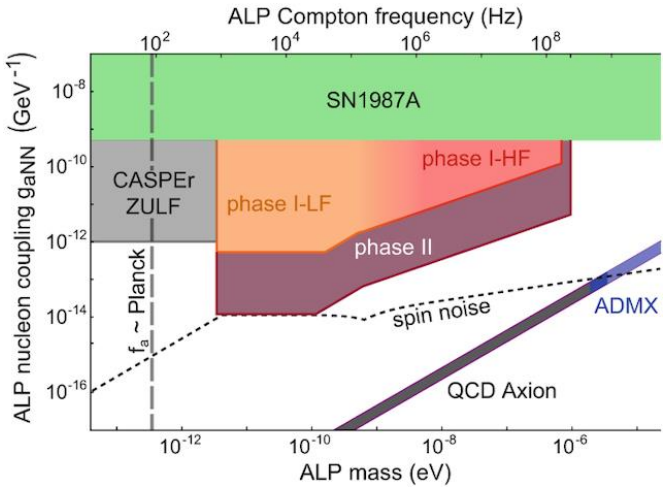
*Nature Phys. **17** 1396 (2021)*

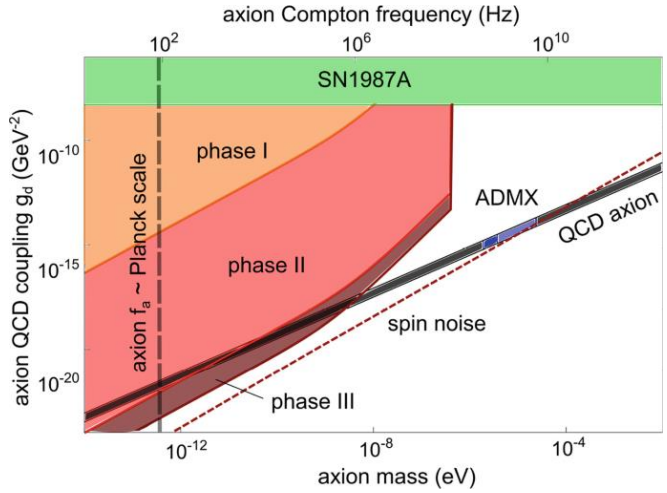


Fermion/EDM coupling

- *Cosmic Axion Spin Precession Experiment*
  - *CASPEr-wind(gradient)*
    - *Axion-nuclear spin (axion wind)*
  - *CASPEr-electric*
    - *Axion-nEDM (electric field)*
    - *Probe for $aG\tilde{G}$ (QCD axion?)*
  - *Nuclear magnetic resonance*
    - $\omega_L(\propto B_0) = m_a$
    - *Highly sensitive to $m_a < 10^{-8}$ eV*







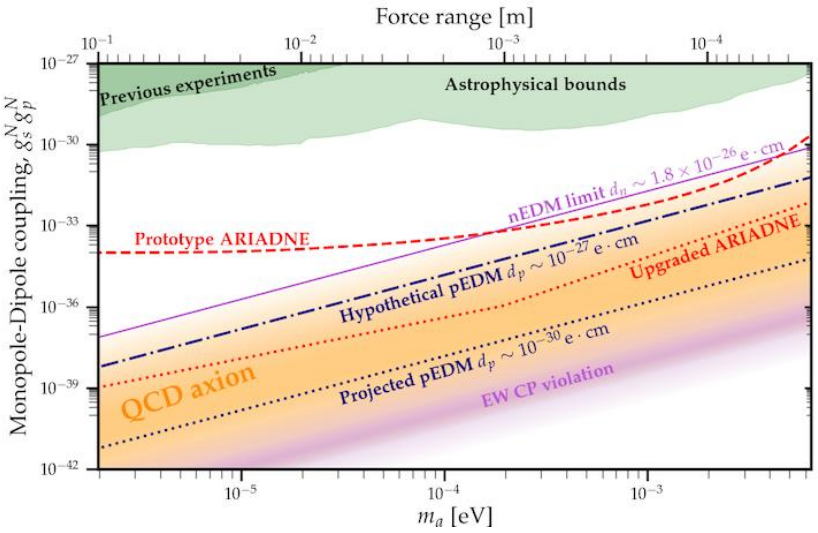
CPV and EDM

- *CPV in QCD*
  - $\theta_{eff} \equiv \theta_{QCD} - \frac{a}{f_a} = 0$
  - *QCD axion => EDM = 0*

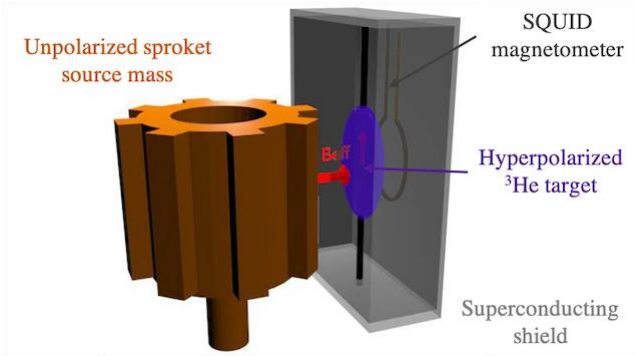
vs.

- *Additional CPV in nature*
  - $\theta_{eff} \equiv \theta_{QCD} - \frac{a}{f_a} + \ ... \neq 0$
  - *EDM ≠ 0 => non-QCD axion field?*

- *Storage ring proton beam*
  - *Direct probe for pEDM*
  - *Sensitivity improvement*
    - *pEDM ~10^{-29} $e \cdot cm$*



- *ARIADNE*
  - *Nucleon-nucleon interactions*
    - *5th force mediator*
  - *No cosmological assumptions*

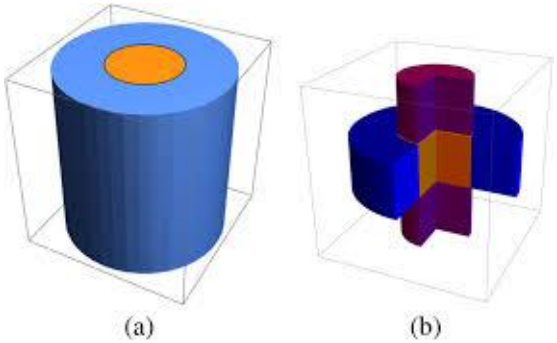


- *Decisive exclusion*
  - *Negative results from the two independent experiments*
  - *0.1 meV < m_a < 10 meV*

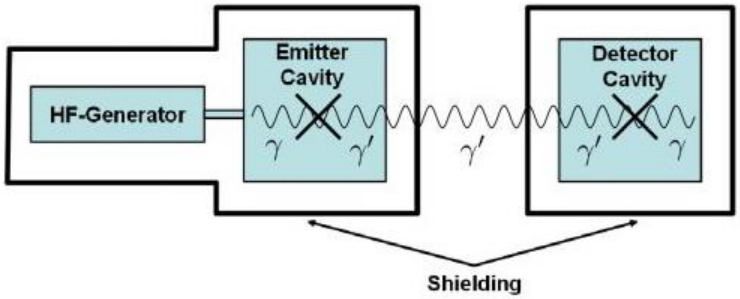
Hidden photon

- *Vector field*
  - *Gauge boson in hidden sector + dark matter*
  - *Kinetic mixing with SM gauge fields*

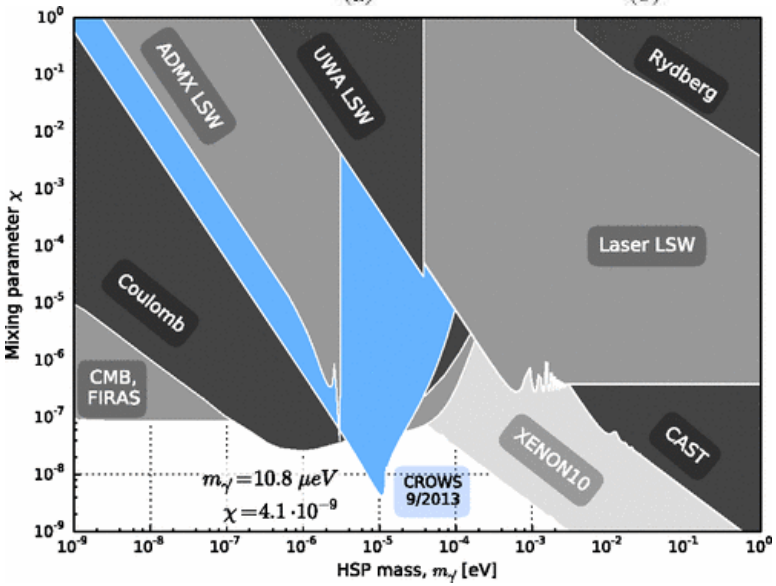
*PRD **103** 055004 (2021)*



- *LSW-type w/ no magnets* *PLB **659** 509 (2008)*



- *Cavity searches*
  - *ADMX* *PRL **105** 171801 (2010)*
  - *UWA* *PRD **82** 052003 (2010)*
  - *CROW* *PRD **88** 075014 (2013)*
  - *SC cavities and …*
  - *New ideas*



Chameleon

- *Scalar field*
  - *Dark energy candidate* PRD 69 044026 (2004)
- *Effective potential dependent on ambient matter / EM field*

$$V_{eff}(\phi,\vec{r}) = \Lambda^4 e^{\frac{\Lambda^n}{\phi^n}} + e^{\frac{\beta_m}{M_{Pl}}\phi}\rho_m(\vec{r}) + e^{\frac{\beta_\gamma}{M_{Pl}}\phi}\rho_\gamma(\vec{r})$$

Matter coupling Photon coupling

- *Searches*
  - *Afterglow effect*
    - *GammeV, CHASE, ADMX, …*
  - *Solar chameleon*
    - *Similar to solar axion search*
    - *CAST ($\phi-\gamma$) and KWISP ($\phi-m$)*
    - $P_{\phi\to\gamma,m} \propto \beta_{\gamma,m}^2 B^2 L^2$

Phys. Dark Univ. 26 100367 (2019)