Axion Searches in the Next Ten Years

16th Patras Workshop on Axions, WIMPs, and WISPs

2021.06.14~18, Trieste (Online)

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Outline

- *Introduction*
  - *Axion and search strategies*
- *Axion searches*
  - *Haloscope searches*
  - *Low mass axion searches*
  - *Helioscope searches*
  - *LSW searches*
- *Additional CPV*
  - *ARIADNE and pEDM*
- *Projection & Summary*

Disclaimer

- *Based on arXiv:2104.14831*
  - *Focus only on direct searches*
- *My apologies for not covering*
  - *Indirect searches*
  - *All individual efforts*
  - *Updated information*

Introduction

Axion (dark matter)

Search strategies

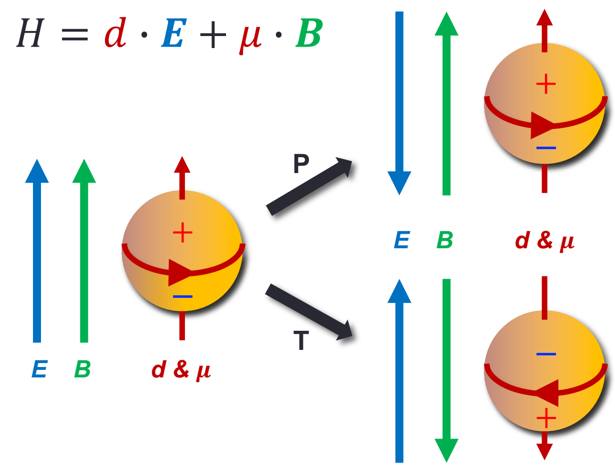
Axion

- *Strong CP problem*

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{32\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

$$\Updownarrow$$

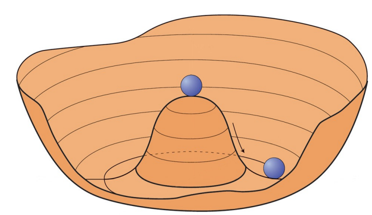
$$d_n < 10^{-26}\, e \cdot cm \;\; (\theta < 10^{-10})$$



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

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

  - *Spontaneous breaking: minimum at $a = \theta \cdot f_a$*
  - *Dynamic solution to strong CP problem*



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

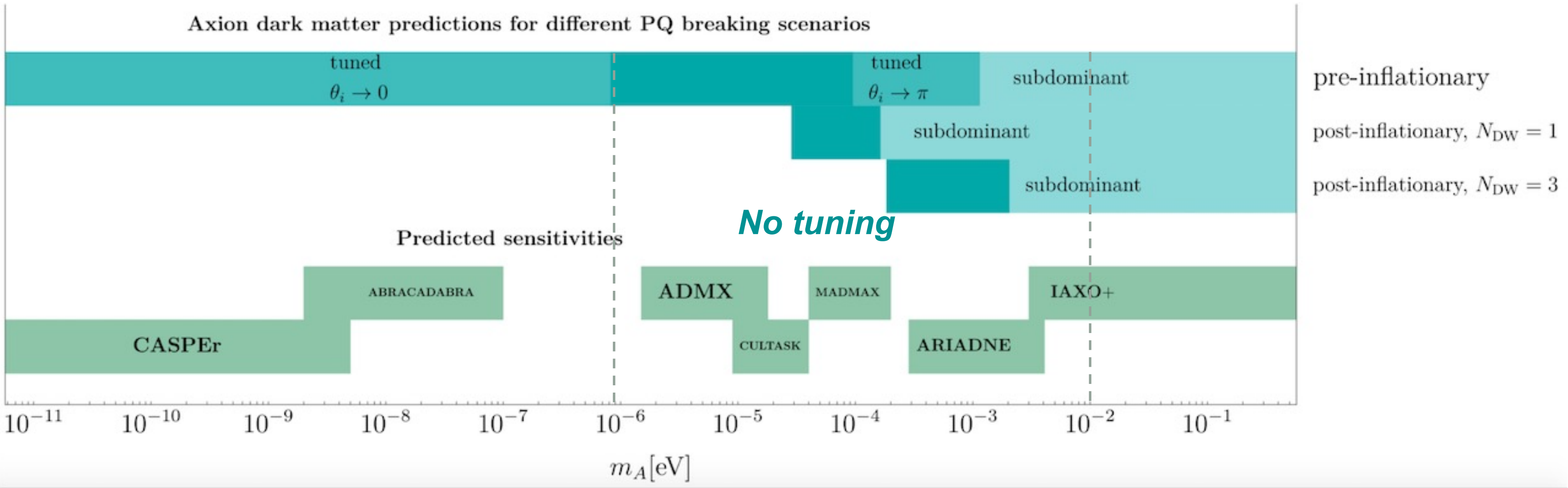
Invisible axion and dark matter

- *Invisible axion (1979)*
  - *Very light axion in early universe at a large energy scale*

$$m_a \approx 6\ \mu eV \frac{10^{12}\ GeV}{f_a}$$

  - *Spanned axion mass range by many orders of magnitude*

- *Cosmic axion (1983)*
  - *May account for dark matter*
  - *Cosmological constraint:* $f_a < 10^{12}\ GeV$
  - *Astrophysical observation:* *SN1987A*
  - *Different PQ breaking scenarios predict different mass ranges*

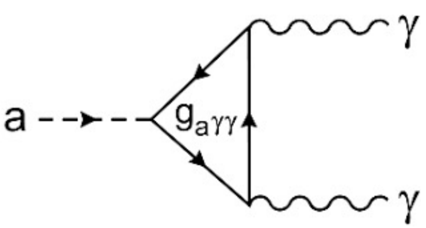


Axion couplings

- *Axion interactions with SM fields*

	Photons	Fermions	nEDMs
Source	$g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$	$g_{aff} \nabla a \cdot \hat{\boldsymbol{S}}$	$g_{EDM} a \hat{\boldsymbol{S}} \cdot \boldsymbol{E}$
Detection	Resonators in magnetic fields	Magnetometers	NMR
Example	ADMX, CAPP, MADMAX, …	GNOME, QUAX, ARIADNE, …	CASPEr, srEDM, …

- *Most commonly rely on EM interaction*
  - Axion dynamics



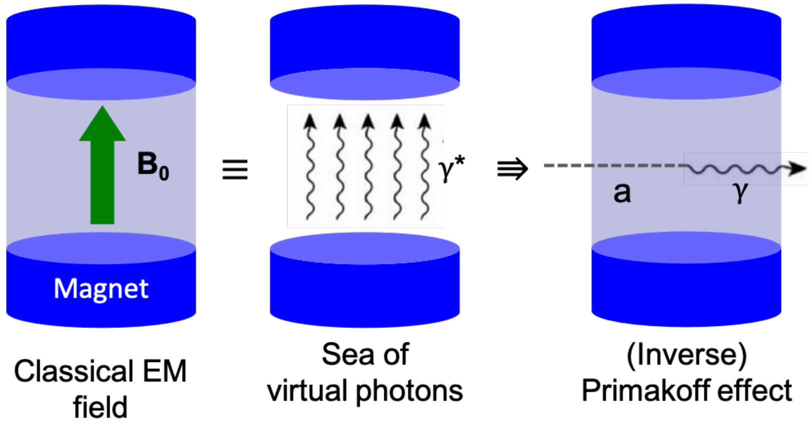
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \mathcal{F}\tilde{\mathcal{F}} = -g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

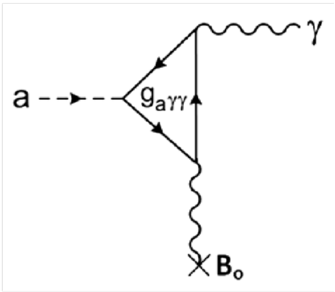
$$g_{a\gamma\gamma}^{QCD} \simeq \frac{\alpha}{2\pi} \frac{1}{f_a} \left(\frac{E}{N} - 1.92 \right) \qquad \text{cf. } g_{a\gamma\gamma}^{ALP} \simeq \frac{\alpha}{2\pi} \frac{1}{f_a}$$

  - Benchmark models
    - KSVZ: E/N = 0, 2 (Heavy quarks)
    - DFSZ: E/N = 8/3 (Higgs doublet)

Detection principle

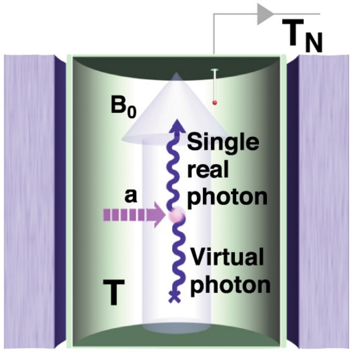
- *EM interaction mediating axion-photon coupling*
- *Presence of axion field modifies Maxwell's equations*
  - $\boldsymbol{\nabla} \cdot \boldsymbol{E} = \rho - g_{a\gamma\gamma} \boldsymbol{\nabla} a \cdot \boldsymbol{B}$
  - $\boldsymbol{\nabla} \times \boldsymbol{B} - \dot{\boldsymbol{E}} = j + g_{a\gamma\gamma} (\dot{a} \boldsymbol{B} + \boldsymbol{\nabla} a \times \boldsymbol{E})$
  - *For invisible axions,* $\boldsymbol{\nabla} a \approx 0$, $\dot{a}\boldsymbol{B}$ *is in more effect*
- *Axion-to-photon conversion (1983)*
  - *Axions "borrow" virtual photons from a magnetic field to turn into real photons*



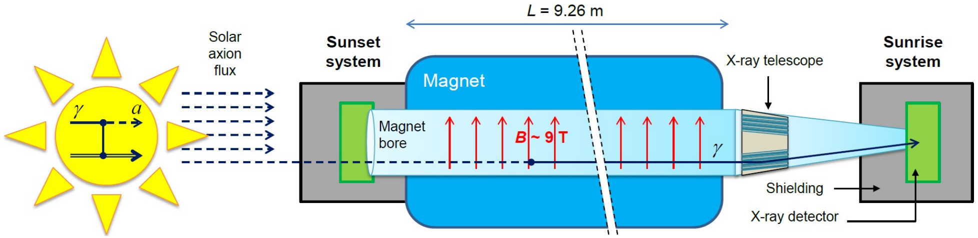


Search strategies

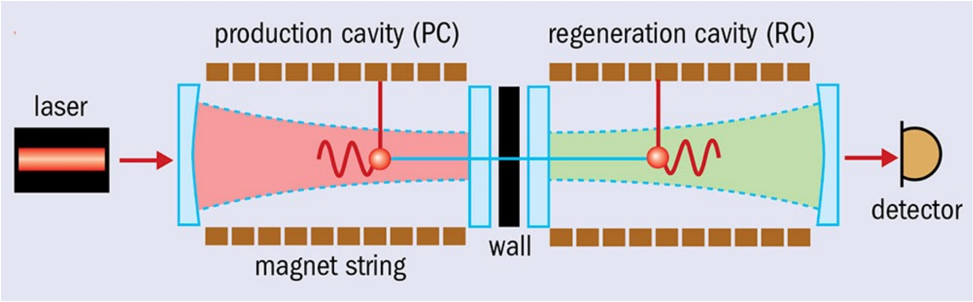
- *Haloscope*
  - *DM axions in our galactic halo*
  - *Microwave resonators*
  - *ADMX, HAYSTAC, CAPP,…*



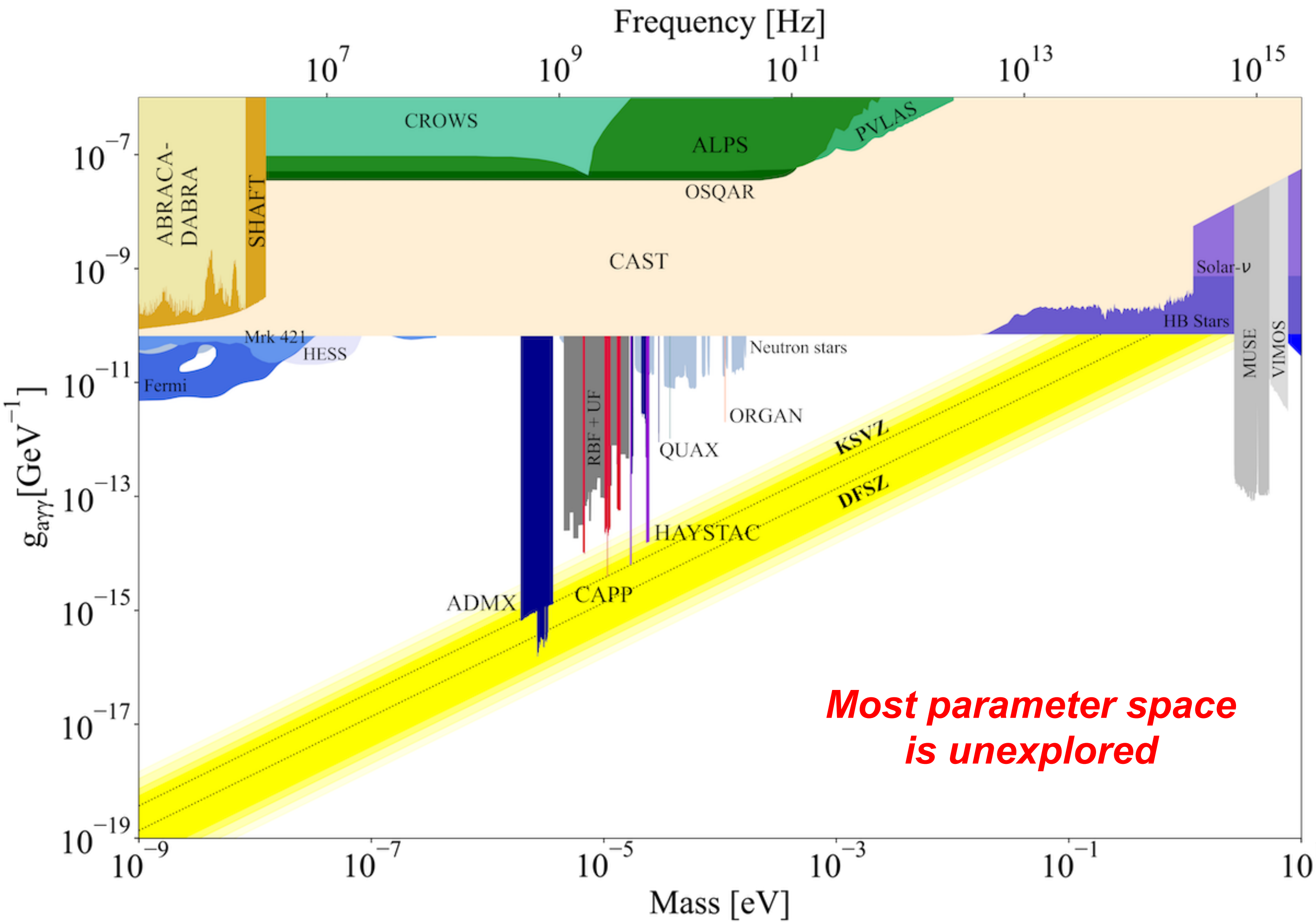
- *Helioscope*
  - *Solar axions*
  - *Emitted by the solar core*
  - *CAST, IAXO,…*



- *Photon regeneration*
  - *Light Shining through Wall*
  - *Axion production at the lab*
  - *ALPS,…*



Axion searches – present



Most parameter space is unexplored

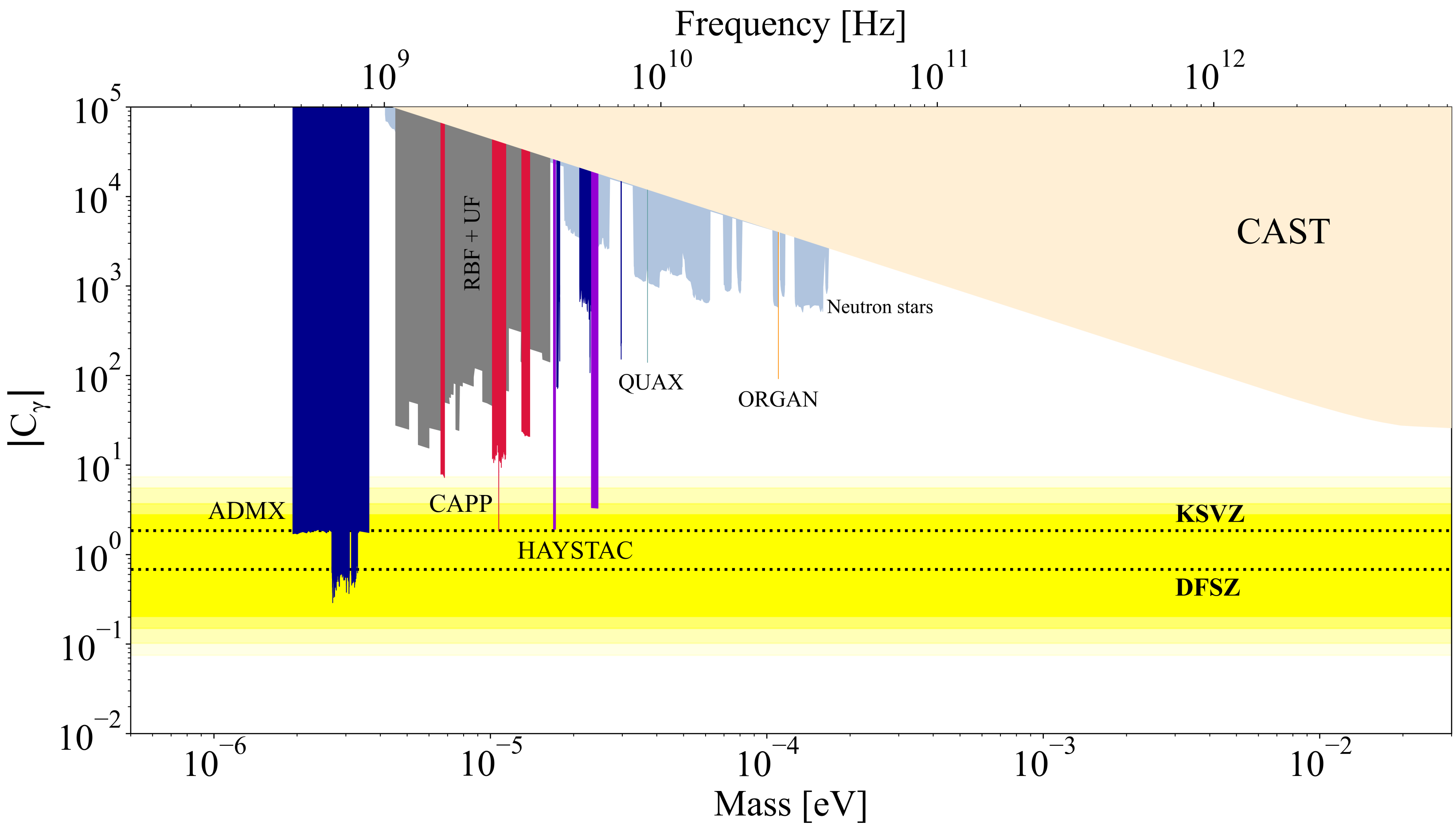
Haloscope Searches

Cavity haloscopes

Dielectric haloscopes

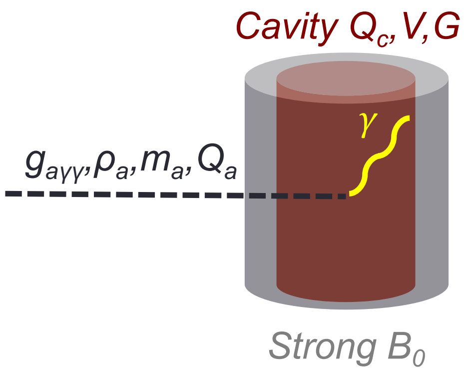
Other haloscopes

Haloscope searches – present



Cavity haloscopes

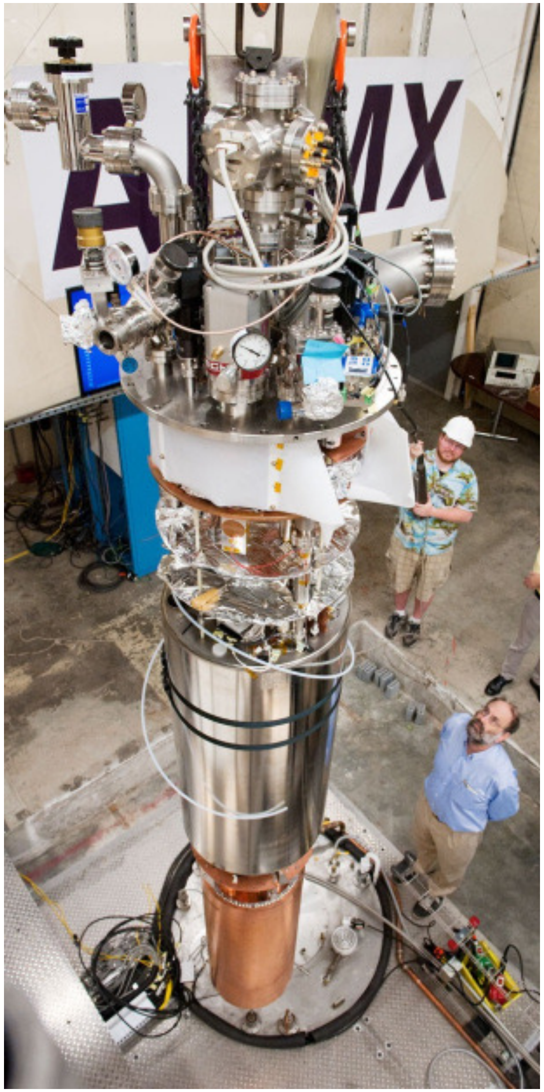
- *Most sensitive approach*
  - *Microwave photon signals from axions in our galactic halo*
  - *Resonant effect w/ a strong magnetic field*
- *Axion-photon conversion power*
  - $P_{a\gamma\gamma} = 1.0\times10^{-23}\, W \left(\frac{C_\gamma}{0.75}\right)^2 \left(\frac{\rho_a}{0.45\,\frac{GeV}{cm^3}}\right) \left(\frac{\nu_a}{1\,GHz}\right) \left(\frac{B_0}{10\,T}\right)^2 \left(\frac{V}{30\,L}\right) \left(\frac{G}{0.5}\right) \left(\frac{Q_c}{10^5}\right)$
- *Unknown mass = > scan rate (FOM)*
  - $\frac{d\nu}{dt} = 1.0\,\frac{GHz}{year} \left(\frac{5}{snr}\right)^2 \left(\frac{0.15\,K}{T_{sys}}\right)^2 \left(P_{a\gamma\gamma}\right)^2 \left(\frac{10^5}{Q_c}\right)$



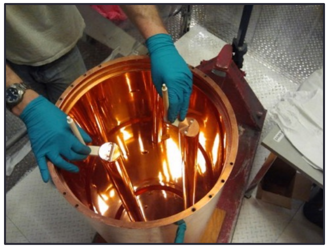
- *History*
  - *Rochester-Brookhaven-Fermilab & UF*
  - *ADMX, HAYSTAC*
  - *CAPP, ORGAN, QUAX, …*

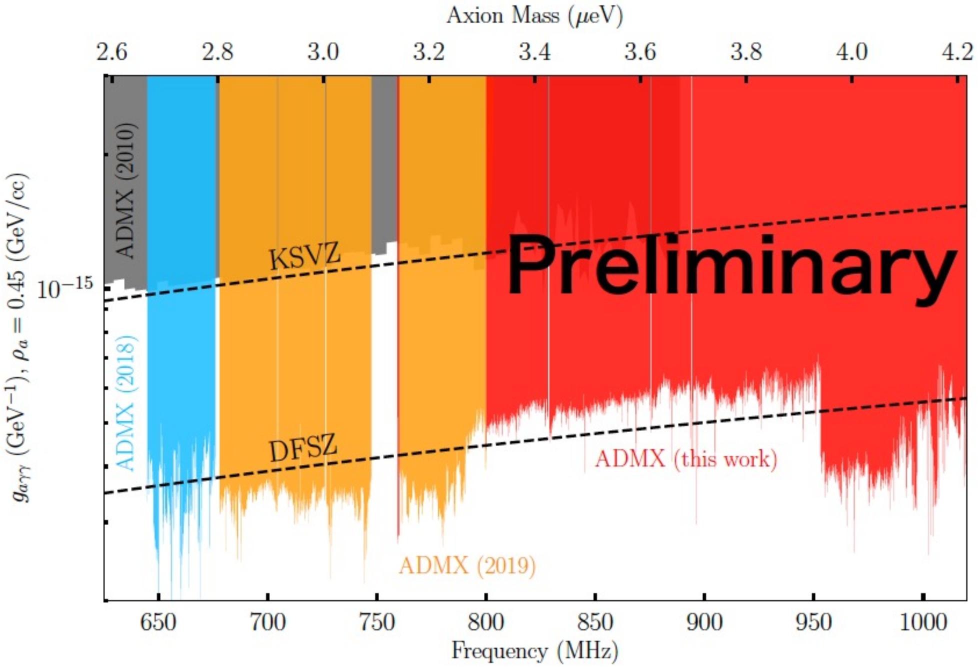
ADMX

T. Nitta (Mon), A. Hipp (Wed), B. Jois (Thu)



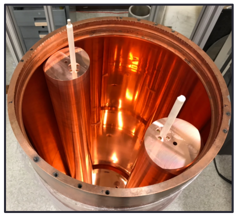
- *Axion Dark Matter eXperiment (UW)*
  - *7.6T SC solenoid*
  - *150 liter copper plated cavity*
  - *T_{phy} ~ 100 mK*
  - *QNLA (MSA/JPA) ~ 200 mK*
  - *DFSZ sensitivity for up to 1 GHz*



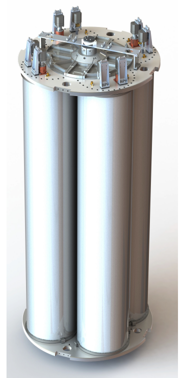


ADMX

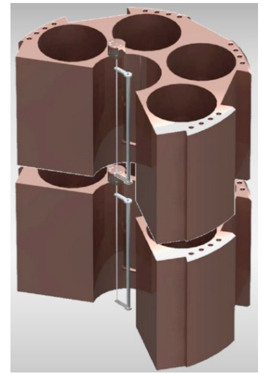
A. Hipp (Wed) and B. Jois (Thu)



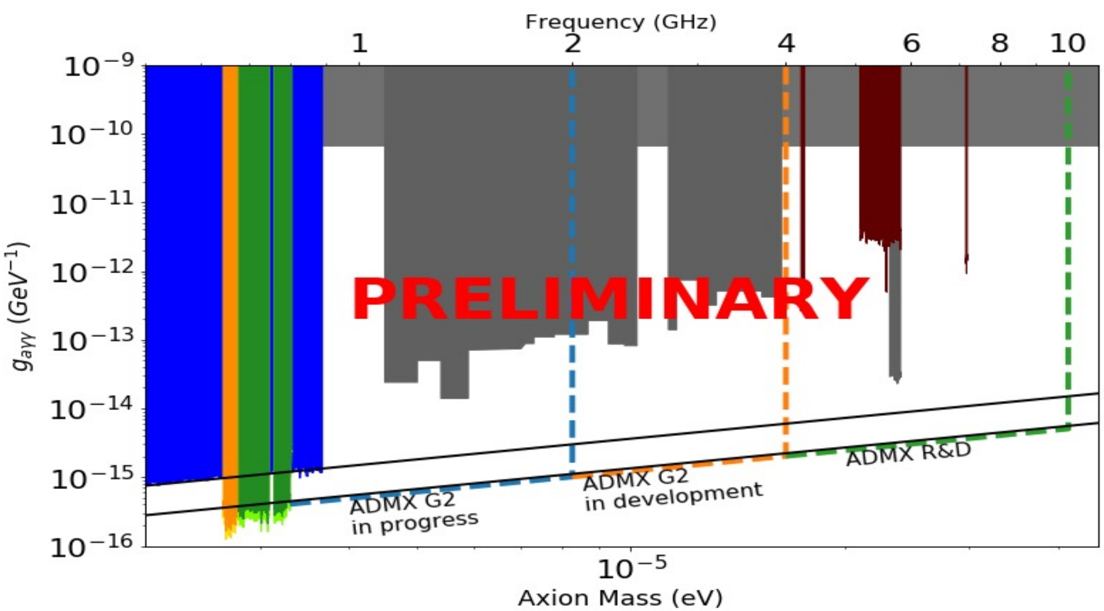
Single cavity w/ large rods



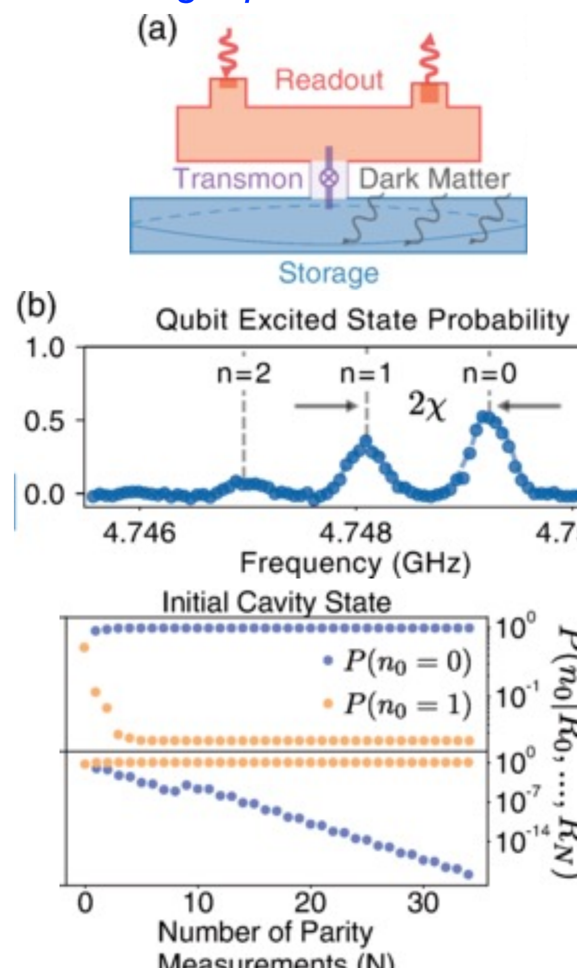
4-cavity array



14-cavity array



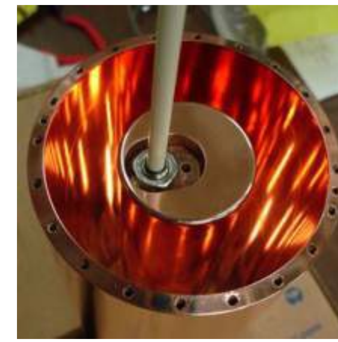
Single photon detector

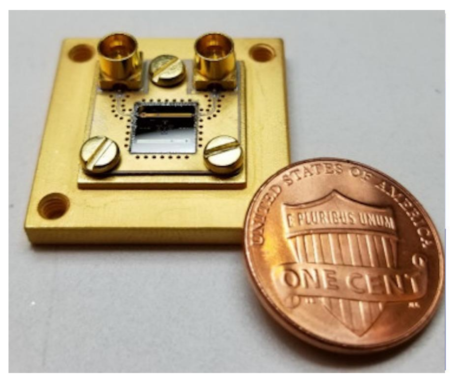


- *Repeated NDM*
- *Noise reduction: −15.6 dB*

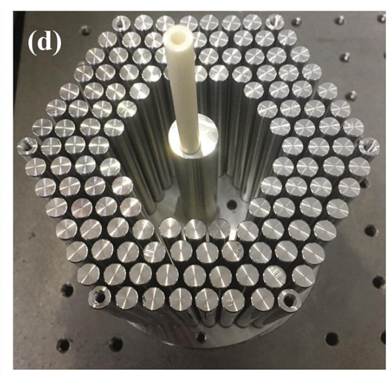
HAYSTAC

- *Haloscope At Yale Sensitive To Axion CDM*
  - *9T SC solenoid*
  - *127 mK + JPA (~500 mK)*
  - *Sensitive to ~5 GHz axions*
  - *First result in 2017*

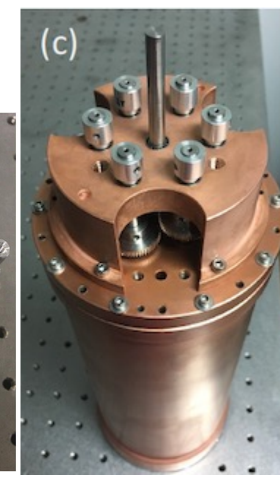




Josephson Parametric amplifiers



Photonic band gap structure



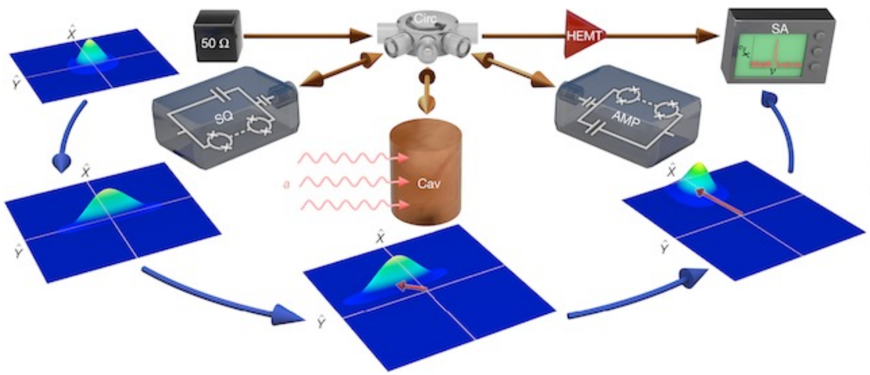
Multi-rod tunable cavity

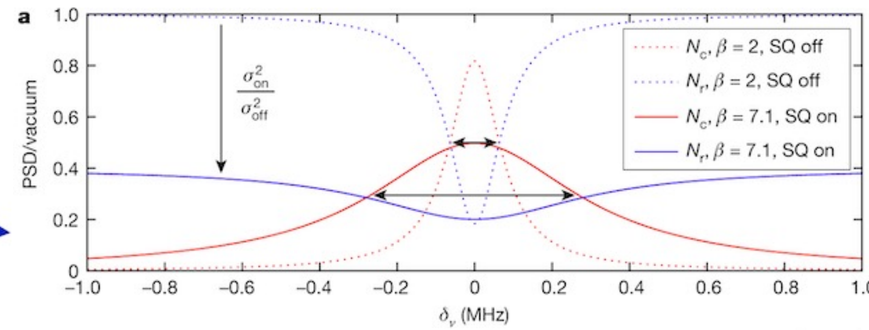
HAYSTAC

- *Quantum enhanced search*
  - *Squeezed-state receiver (SSR)*

*Nature **590**, 238*

Wider bandwidth => Doubling scan rate



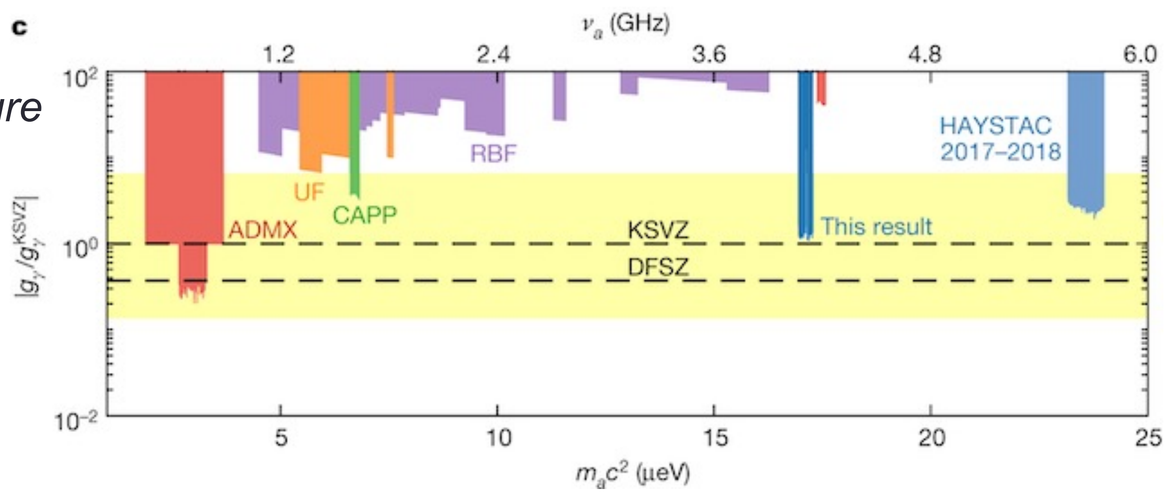


Two JPA system

SQJPA: squeezing a quadrature

Axion: displacing the state

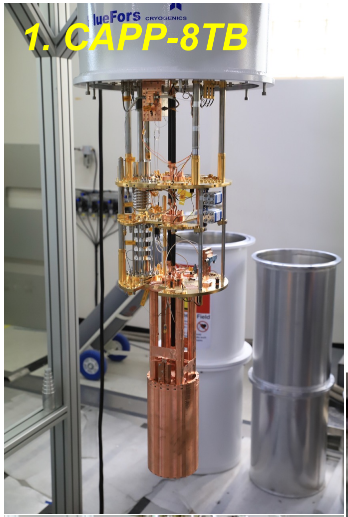
AMP JPA: unsqueezing + amplifying the displacement

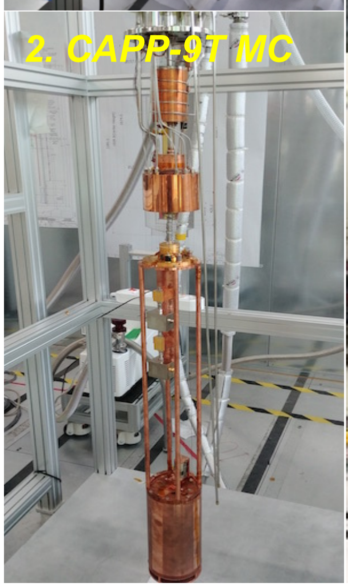


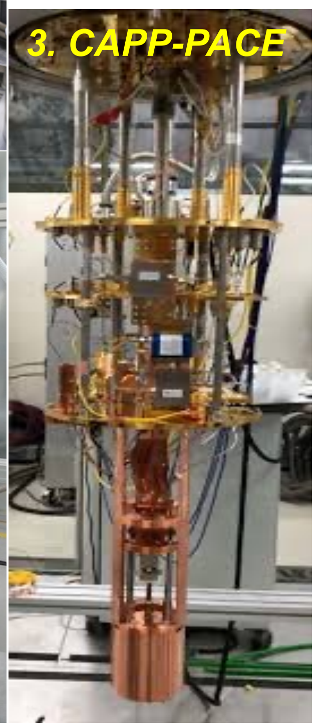
IBS-CAPP

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

IBS-CAPP



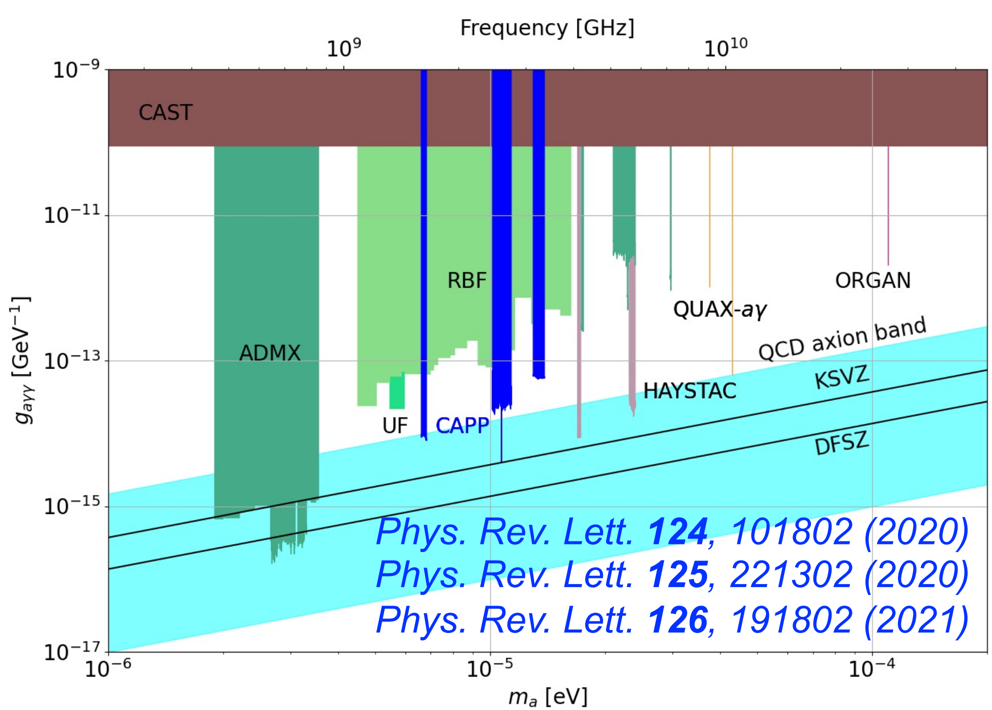




1. CAPP-8TB
- 8T/165mm
- T_{phy} ~ 50 mK
- HEMT ~ 1 K
- 1.6 GHz
- First result

2. CAPP-9T MC
- 9T/127mm
- T_{phy} ~ 2 K
- HEMT ~ 1.5 K
- > 3 GHz
- Pizza cavity

3. CAPP-PACE
- 8T/127mm
- T_{phy} ~ 40 mK
- HEMT ~ 1 K
- 2.5 GHz
- ~300 MHz



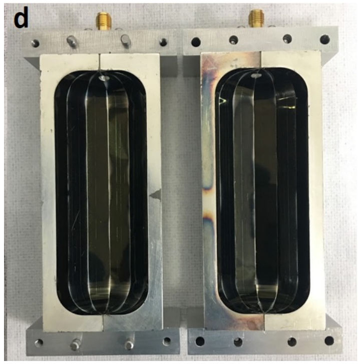
IBS-CAPP

CAPP-12TB

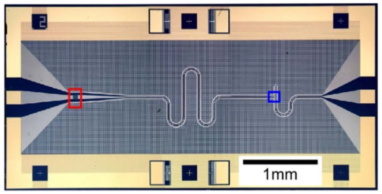
DFSZ sensitive

A. Yi (Thu)

D. Ahn (Tue)



SC cavity (Q > 1M)

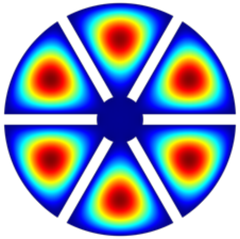


JPA

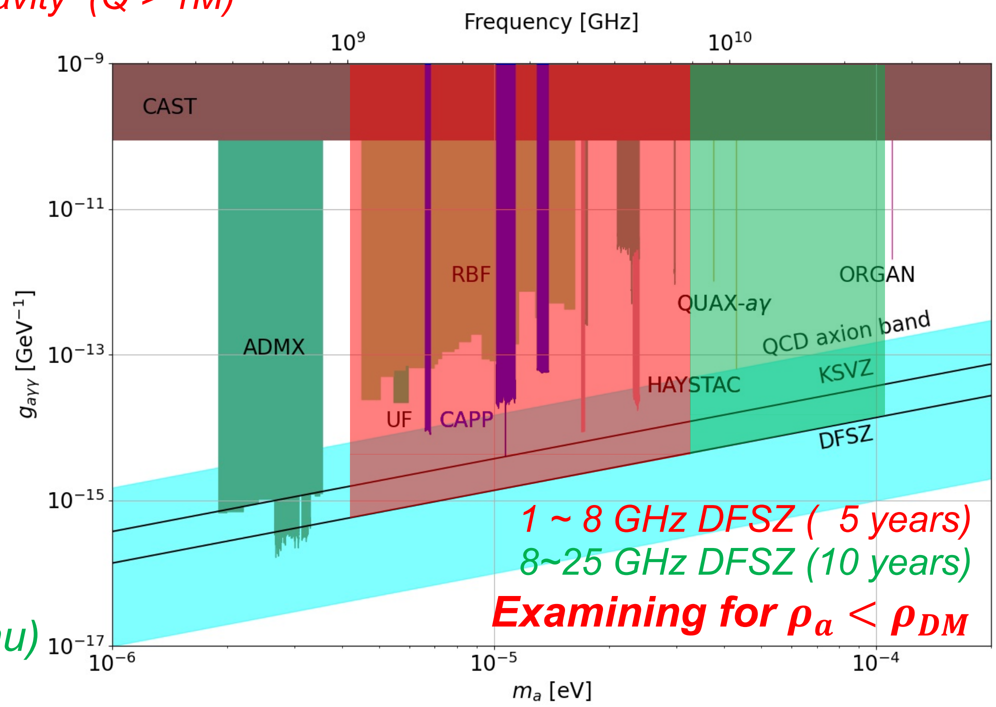
f = 1 ~ 6 GHz

(T_n = 2~4 QLN)

J. Jeong (Thu)



High frequency



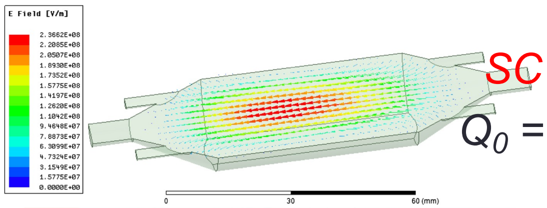
1 ~ 8 GHz DFSZ (5 years)

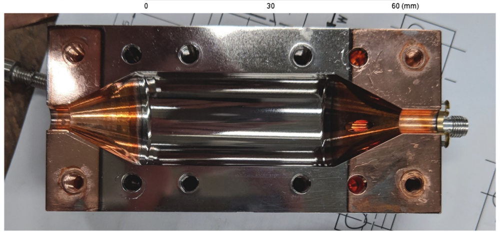
8~25 GHz DFSZ (10 years)

Examining for $\rho_a < \rho_{DM}$

Other cavity haloscopes

- *QUAX-aγ* — *A. Rettaroli (Wed)*, *L. Kuzmin (Thu)*





SC (NbTi) cavity

$Q_0 = 2 \times 10^5$ @2T

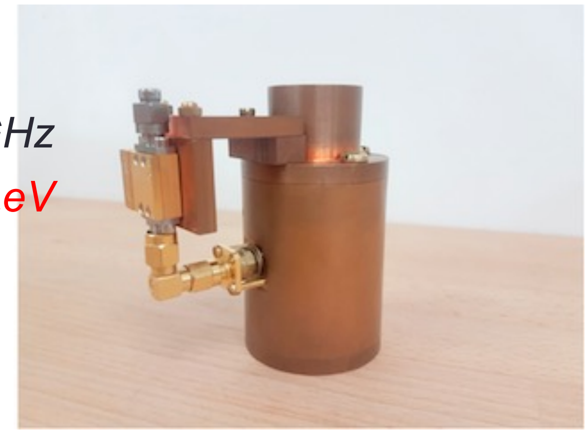
$f_a = 9$ GHz

- *ORGAN* — *B. Mcallister (Thu)*

$B = 14$ T

$f_a = 26.5$ GHz

$m_a = 110\ \mu eV$



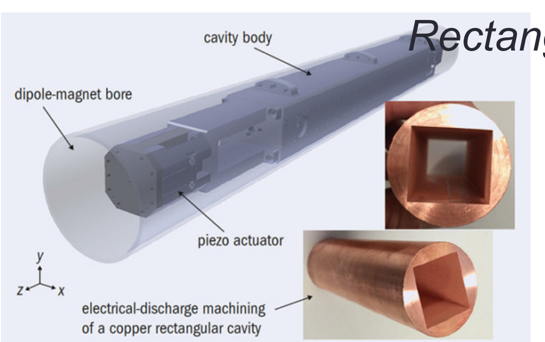
- *CAST-CAPP* — *M. Maroudas (Wed)*

CAST dipole magnet (9T)

Phase-matching

Rectangular cavities

$m_a \sim 20\ \mu eV$



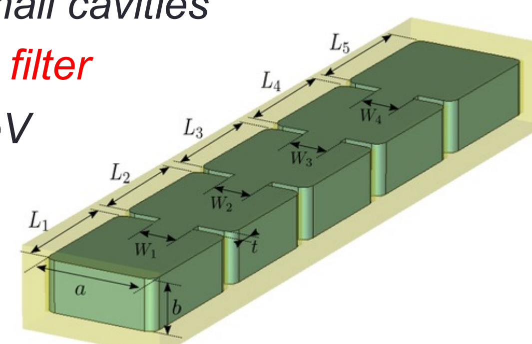
- *RADES* — *S. Cuendis (Fri)*

CAST dipole magnet (9T)

Array of small cavities

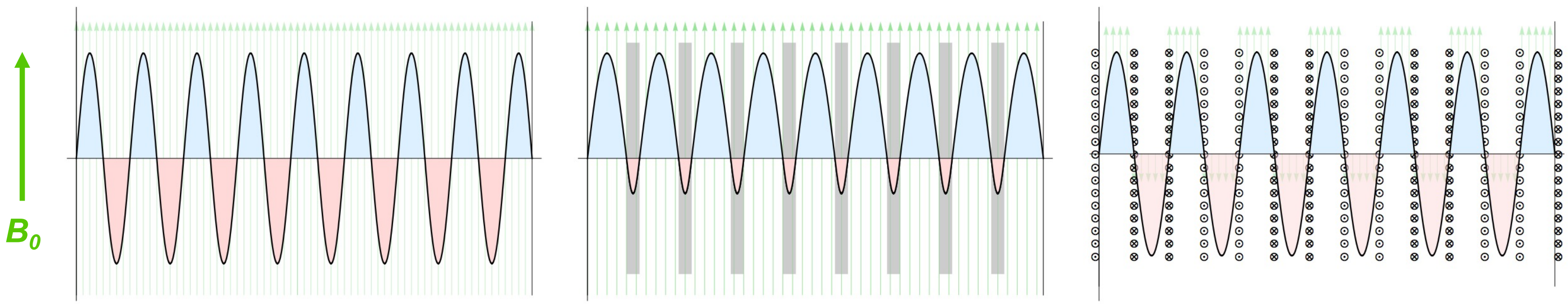
Microwave filter

$m_a \sim 34\ \mu eV$



Dielectric haloscopes

- *Periodic planes for short wavelength*
  - *Non-vanishing form factors*

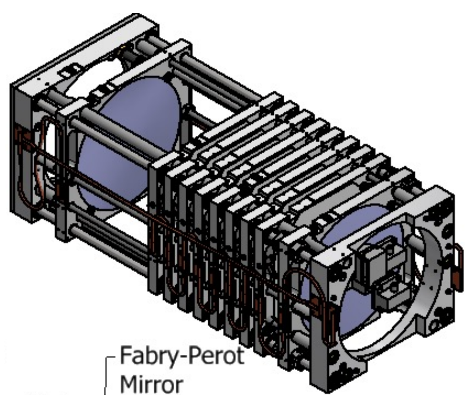


Form factor vanishes w/ a static B field

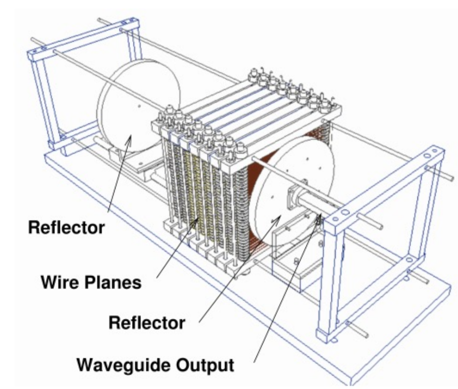
Suppressing negative E field (dielectric planes)

Producing alternating B field (wire planes)

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



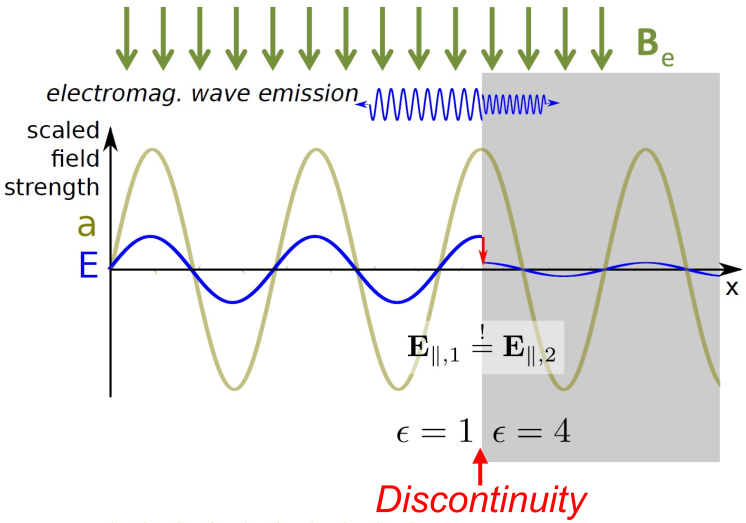
Electric Tiger



ORPHEUS
*PRD **91**, 011701 (2015)*

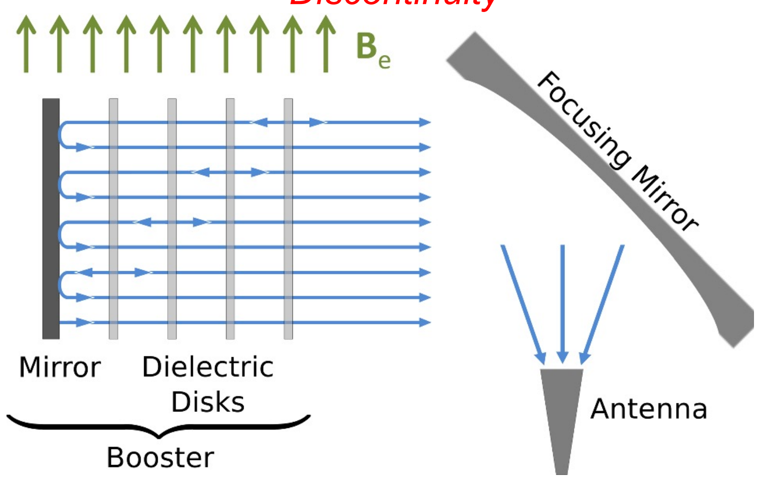
MADMAX

- *MAgnetized Disk-and-Mirror Axion eXperiment*

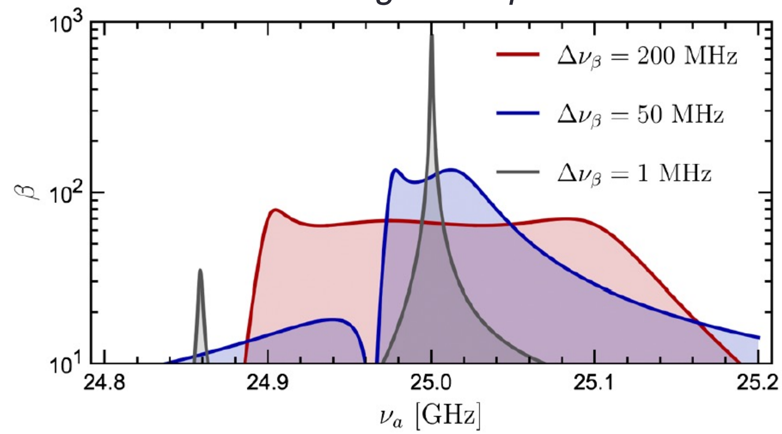


$$P_{a\gamma\gamma} = 1.6\times10^{-22}\,W \left(\frac{\beta^2}{5\times10^4}\right)\left(\frac{A}{1\,m^2}\right)\left(\frac{B_e}{10\,T}\right)^2\left(\frac{C_{a\gamma}}{1}\right)^2\left(\frac{\rho_a}{0.45\,GeV cm^{-3}}\right)$$

- *Frequency: distance b/w disks*
- *40–400 μeV (10–100 GHz)*
- *Suitable for high mass searches*

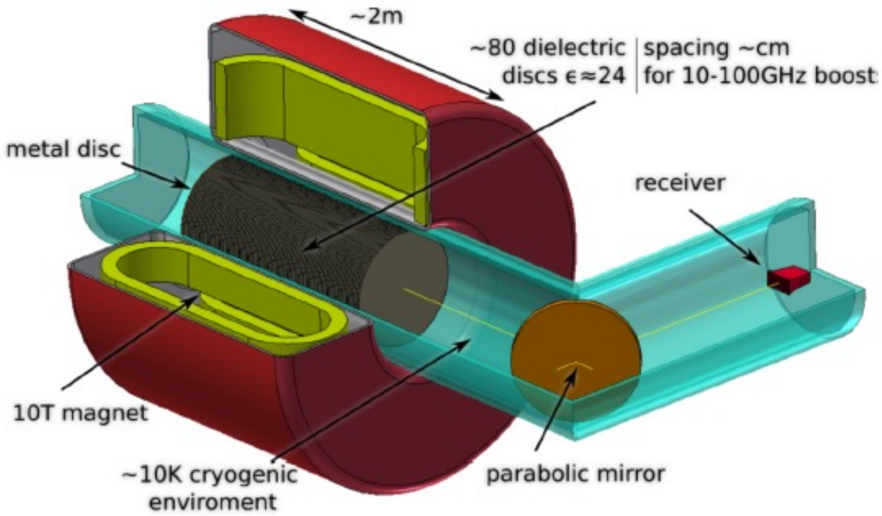


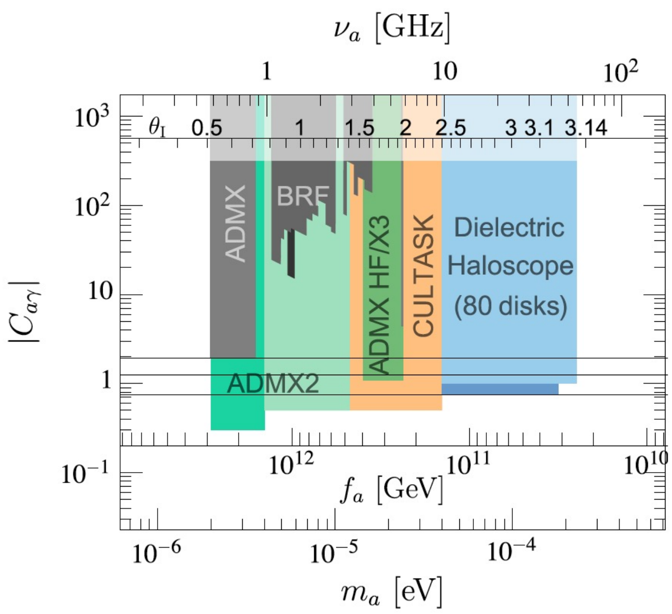
Boosting factor β



MADMAX

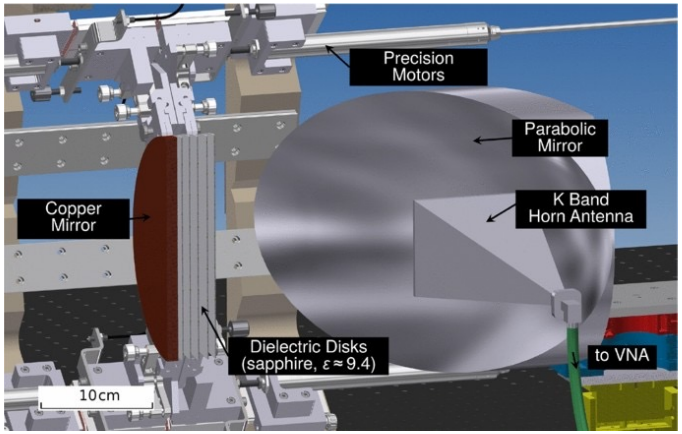
- *Full scale experiment*





- *2m / 10T dipole magnet*
- *80 1m² dielectric disks (ϵ~25)*
- *40–400 μeV (10–100 GHz)*
- *C. Krieger (Fri)*

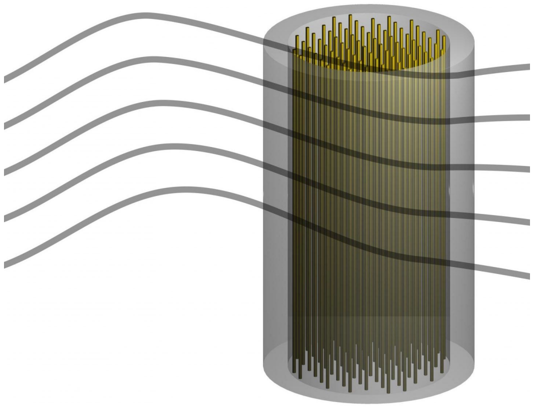
- *Proof of principle booster setup*
- *< 5 sapphire disks*



Plasma haloscope

- *Resonance w/ plasma frequency*

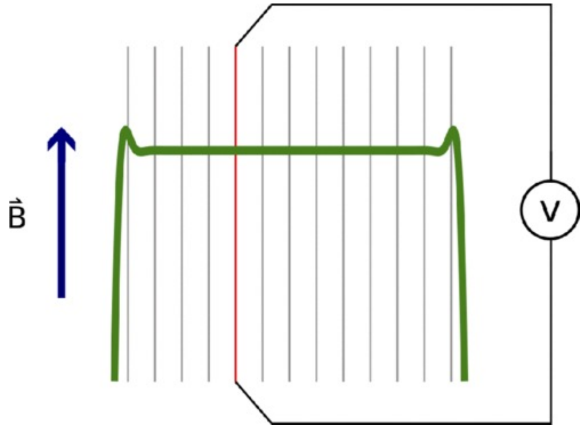
M. Lawson (Fri)



$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 \log(s/d)}$$

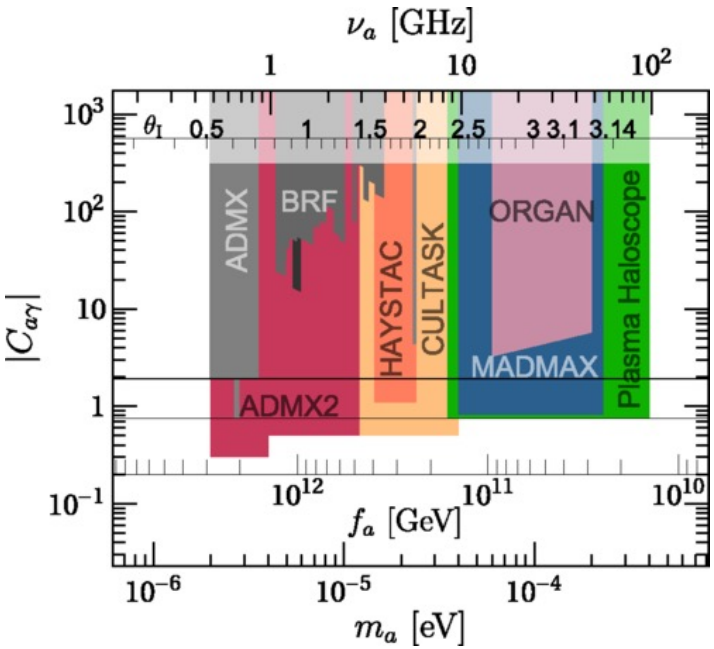
ω_p depends on s & d
- *s: inter space*
- *d: wire radius*

=> *Large conversion volume at high frequencies*



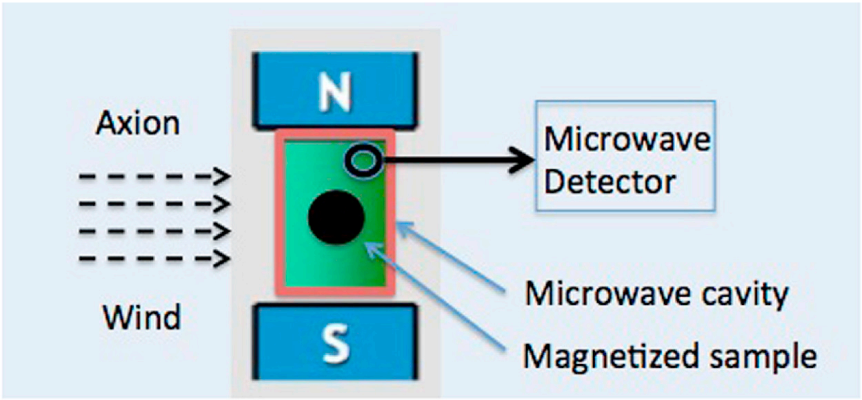
Periodic structure
↓
Meta-material (bulk plasmon)

$$\varepsilon_z = 1 - \frac{\omega_p^2}{\omega^2 - k_z^2 - i\omega\Gamma}$$

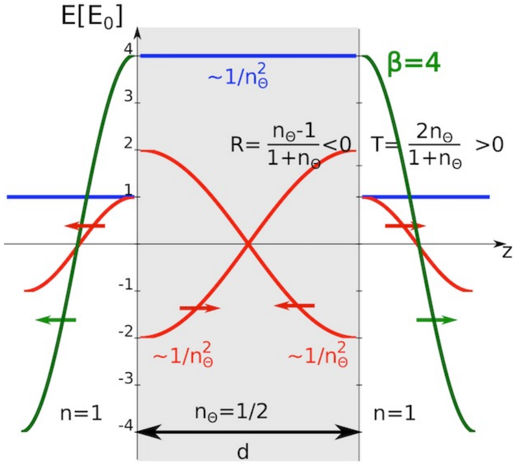


Other haloscopes

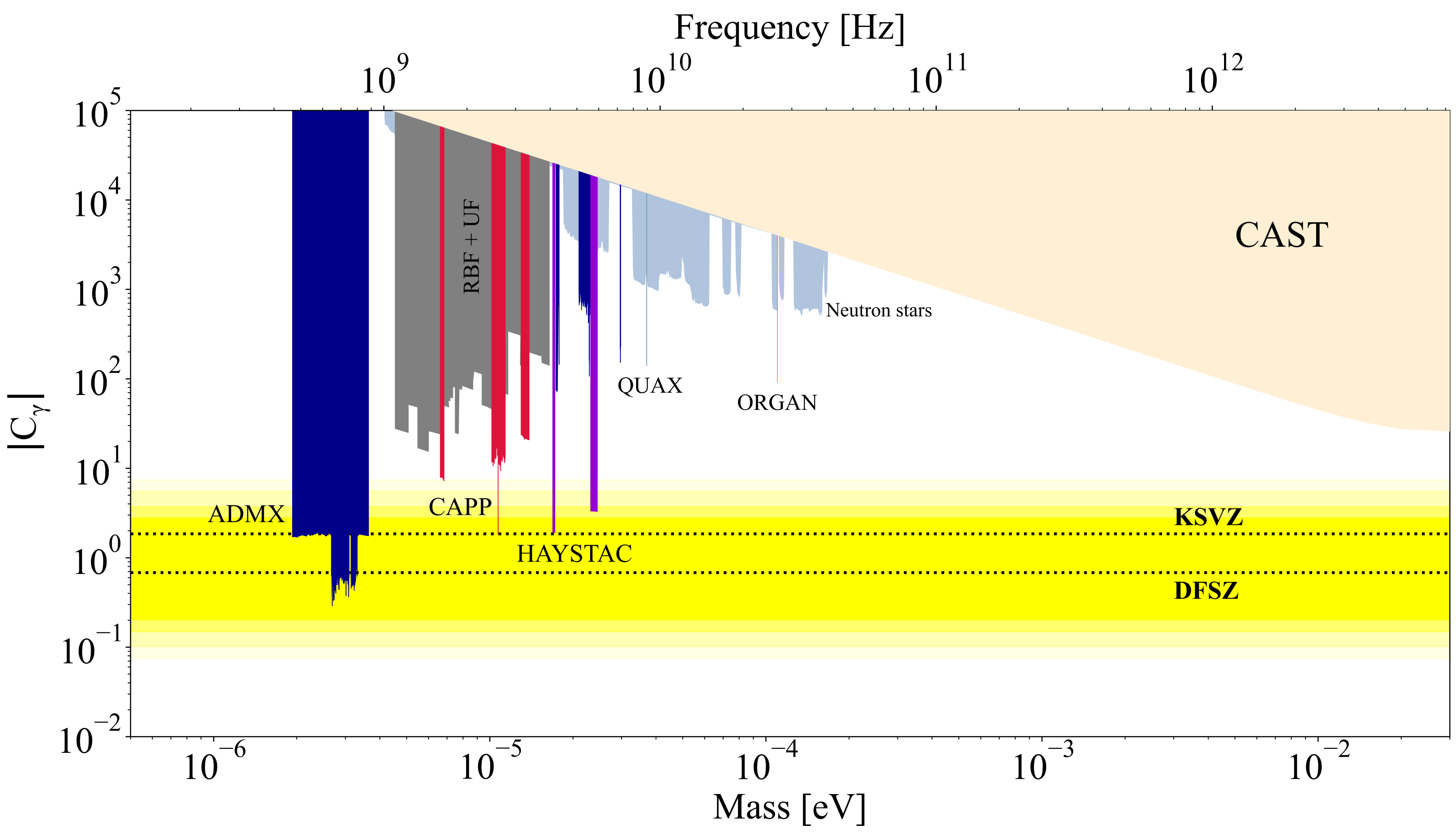
- *QUAX-ae*
  - *Ferromagnetic haloscope*
  - *Axion-electron coupling*
  - *Photon-magnon system*
    - *Series of YIG spheres*
    - *TM_{110} of a cylindrical cavity*
  - *Upgraded with JPA*
  - *Best limit near $m_a \sim 43\ \mu eV$*



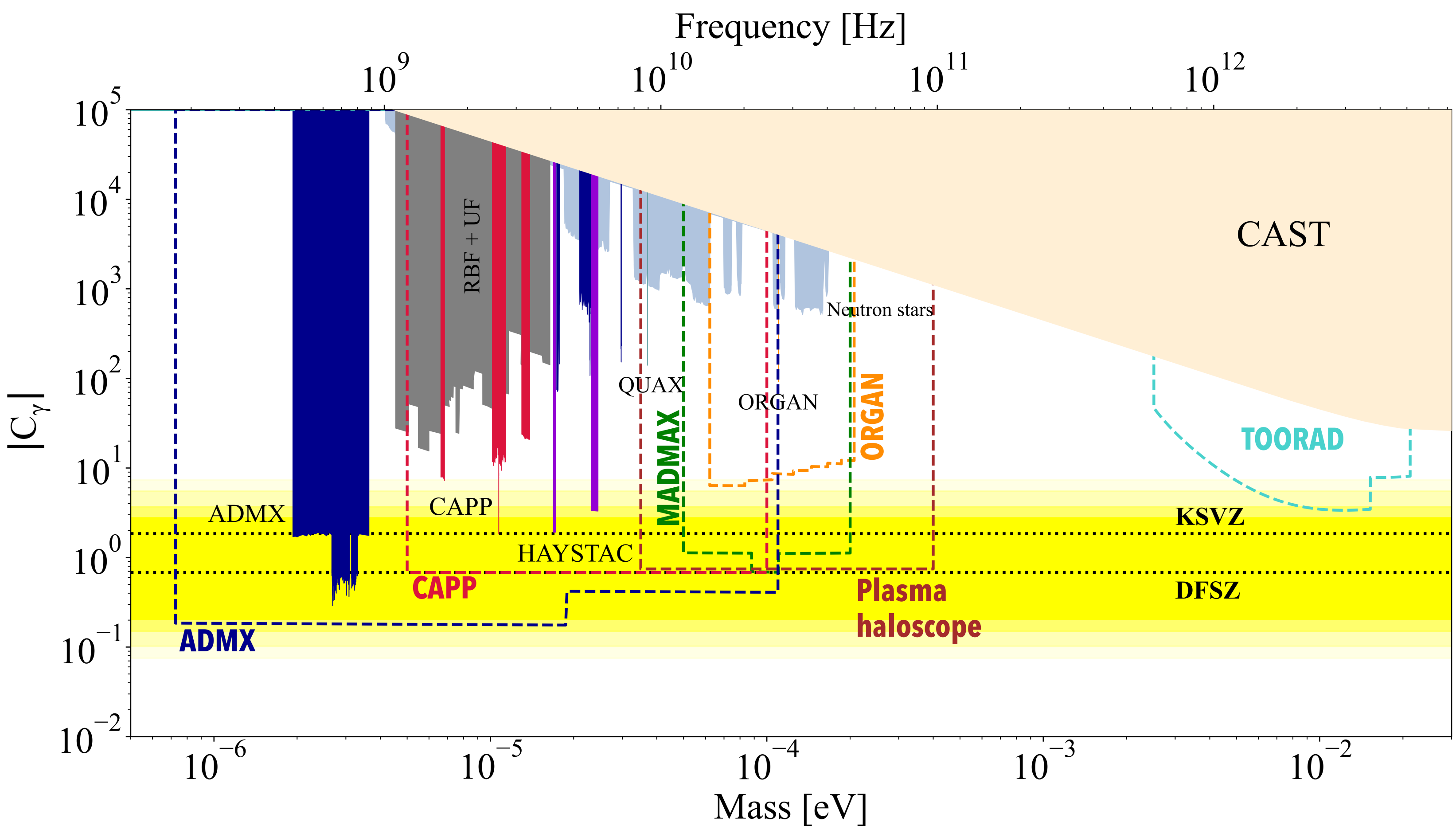
- *TOORAD* *D. Marsh (Fri)*
  - *Axion quasiparticles (AQs) in topological insulators (TI)*
    - *Hybridizes with E field*
  - *Resonance leading to n < 1*
    - *Enhancing E field inside TI*
  - *Internal reflection*
    - *Boosting E field signal*
  - *Proposal for $m_a \sim meV$ ($f_a \sim THz$)*



Haloscope searches – present



Haloscope searches – future



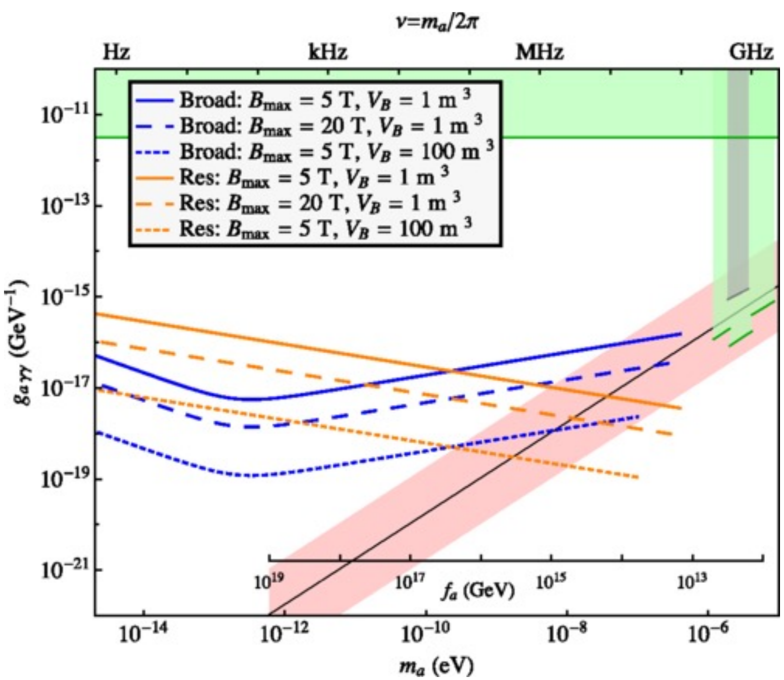
Low mass axion searches

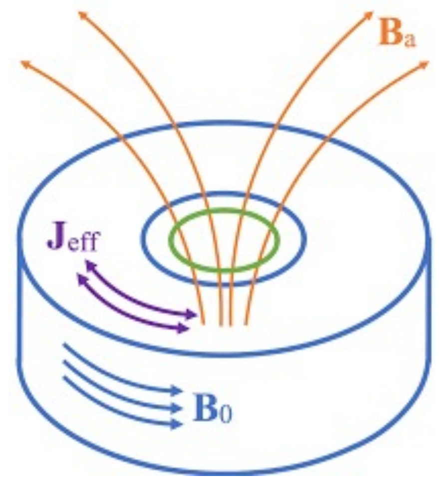
Lumped element searches

NMR-based searches

Lumped element searches

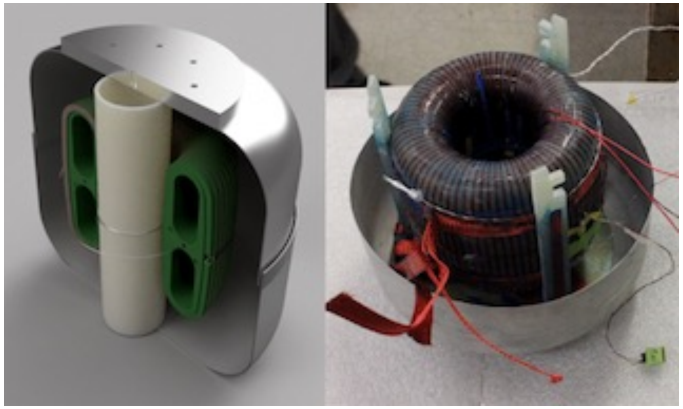
- *ABRACADABRA*
  - *Toroidal magnetic background*
    => time-varying effective current
    => oscillating magnetic field B_a
  - *Sensitive to low mass axions*





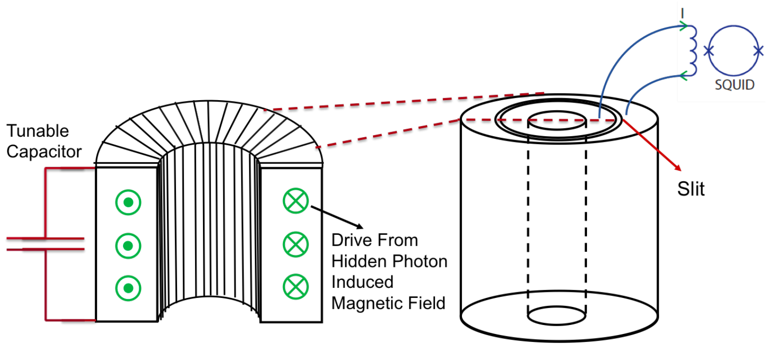
$$J_{eff} = g_{a\gamma}\sqrt{2\rho_a}\cos(m_a t)\,\mathbf{B_0}$$

ABRACADABRA-10cm

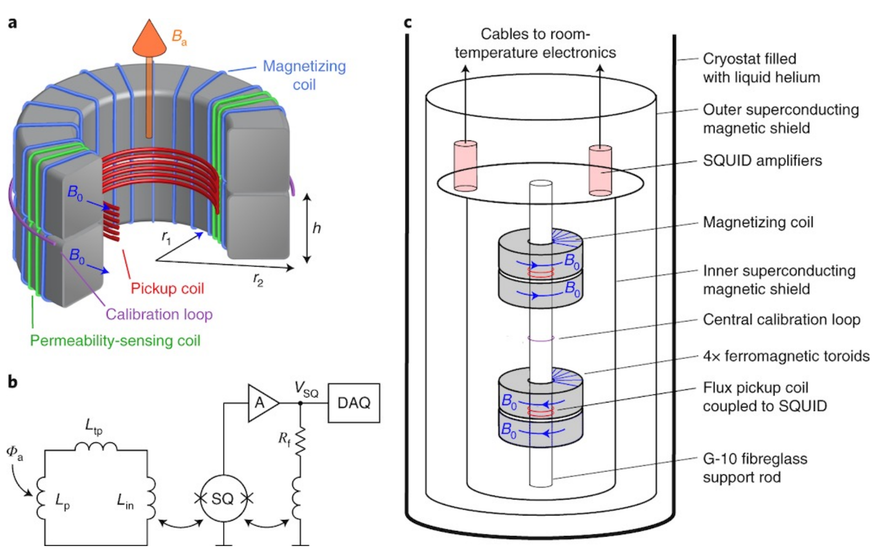


Lumped element searches

- *DM Radio* — *R. Henning (Mon)*
  - *Solenoidal version*
    - *Dual search program*
  - *Joint w/ ABRACADABRA*
  - *Optimized SC LC circuit*
    - *10 peV to μeV*
  - *Series of experiments*
    - *DMRadio-50L, -m^3, -GUT*
  - *Pathfinder for pre-inflation QCD axions*



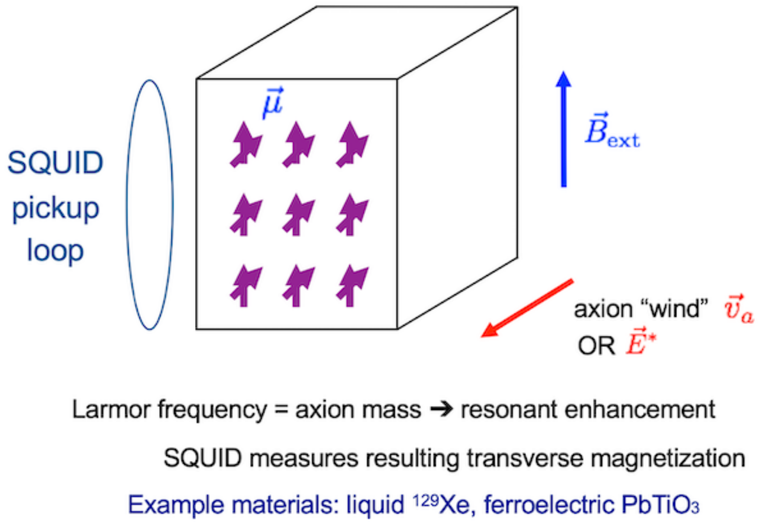
- *SHAFT* — *A. Sushkov (Thu)*
  - *Ferromagnetic toroidal magnets (B_0 = 1.5 T)*
  - *Two pairs for stacked toroids*
    - *Separate pickup coil*
    - *B fields in opposite direction*
    - *Reduction of correlated systematic noise (150 $aT/\sqrt{Hz}$)*
  - *Low mass 10^{-11} to 10^{-8} eV*

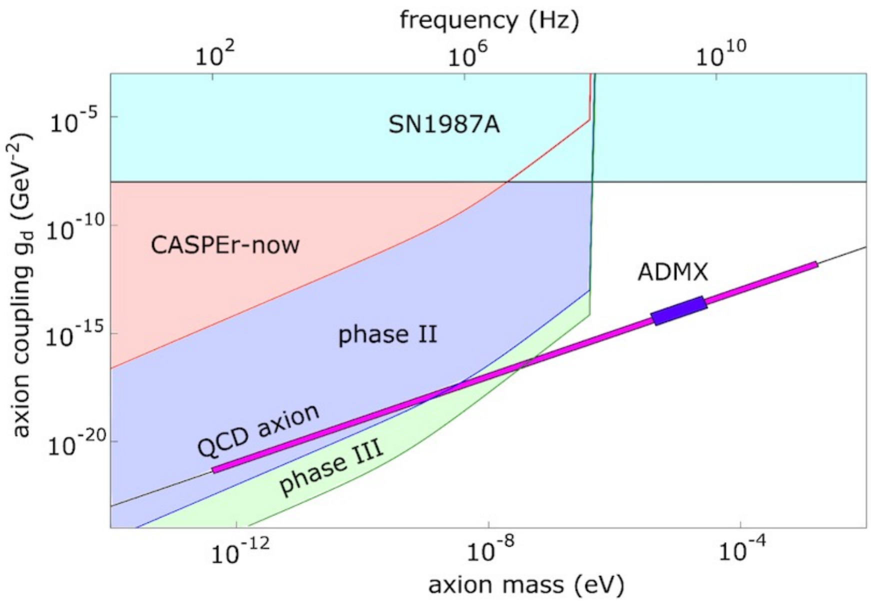


NMR-based search

- *CASPEr (Cosmic Axion Spin Precession Experiment)*
  - *Axion dark matter field => oscillating nuclear EDM*
    - $d_{EDM}(t) = g_{EDM}\sqrt{2\rho_a}\cos(m_a t)/m_a$
  - *Nuclear magnetic resonance effect*
    - *Larmor frequency (depending on B_{ext}) = oscillating frequency*
  - *Pick up by SQUID magnetometer*
  - *Highly sensitive to m_a < 10 neV*

D. Budker and D. Aybas (Thu)



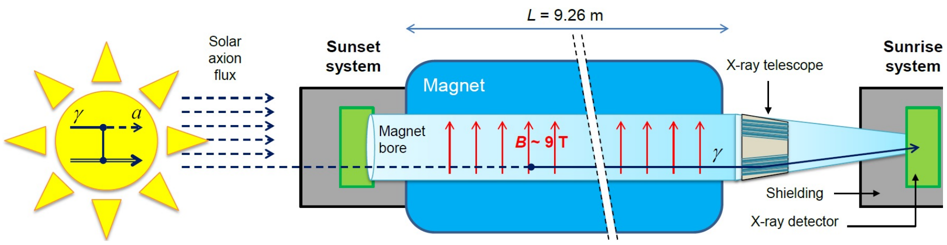


Helioscope searches

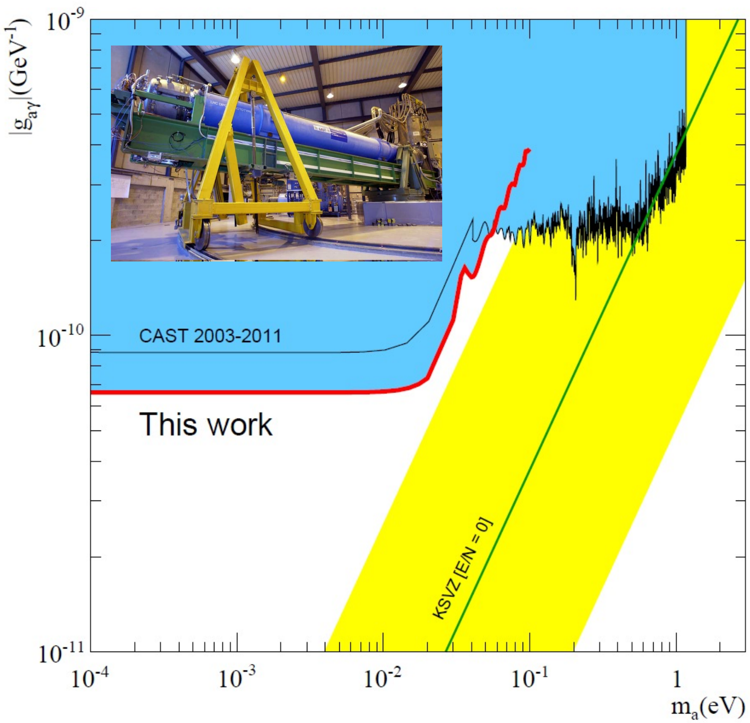
CAST, IAXO

Helioscope searches

- *Stars are the strongest sources to produce axions*
  - *Primakoff scattering of charged particles in the stellar plasma*
- *Solar axion to X-ray conversion telescope*



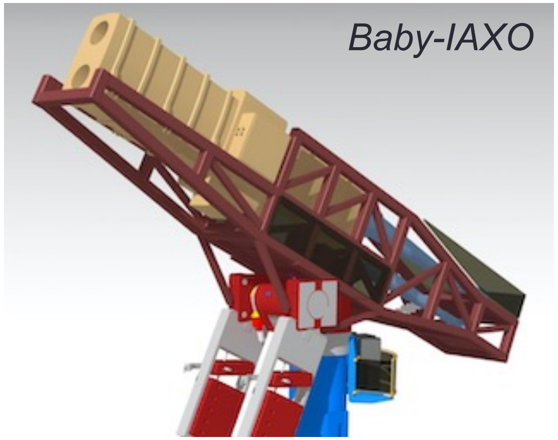
$$P_{a\gamma\gamma} \sim \left(\frac{g_{a\gamma\gamma} B_0}{q}\right) \sin\left(\frac{qL}{2}\right), q \equiv \frac{m_a^2}{2E_a}$$

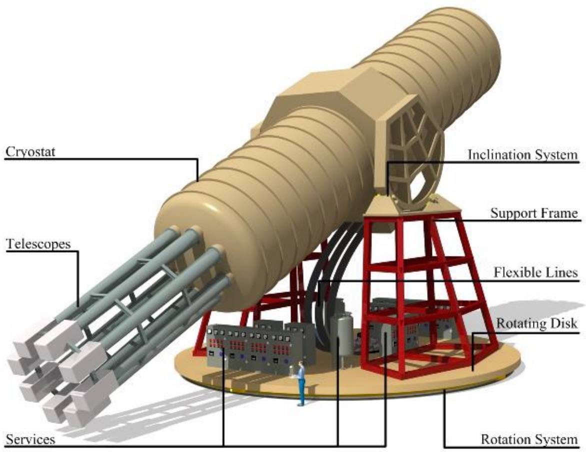


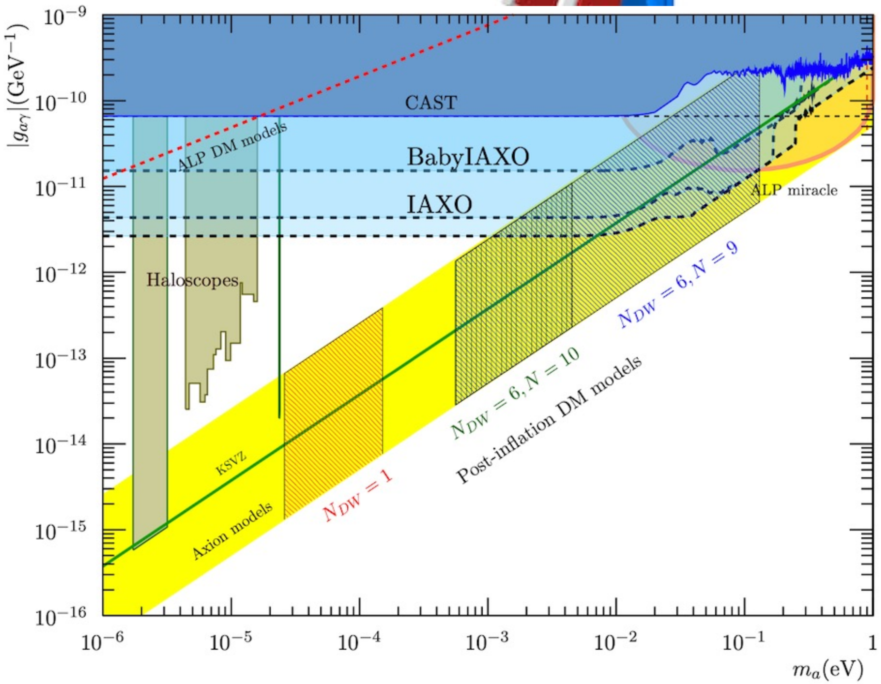
- *History*
  - *BNL, JAPAN*
  - *CAST completed in 2015*
  - *IAXO in plan*

IAXO

- *International AXion Observatory*
  - *Large toroidal helioscope*
    - *8 magnets w/ L=20 m*
    - *5.4 T / 600 mm bore*
  - *Baby-IAXO approved in 2020 (DESY)*
    - *First step towards full IAXO*
    - *4 T / 10 m long => 10 x CAST*
    - *E. Choliz (Thu)*





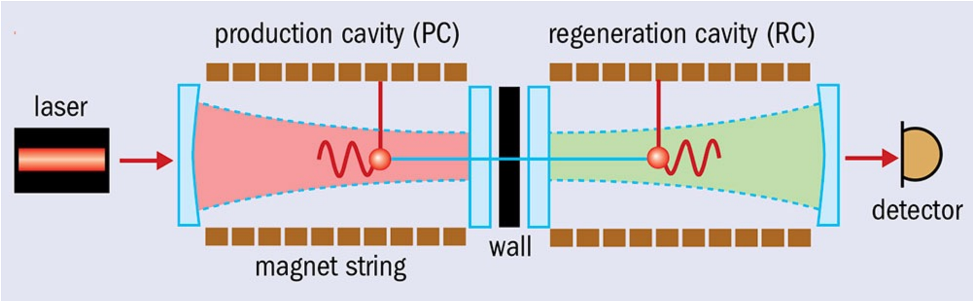


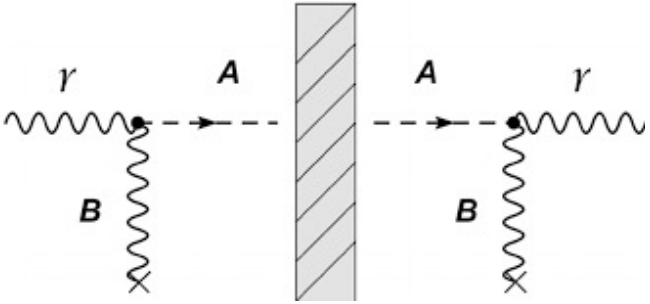
LSW searches

ALPS, ALPS II

LSW searches

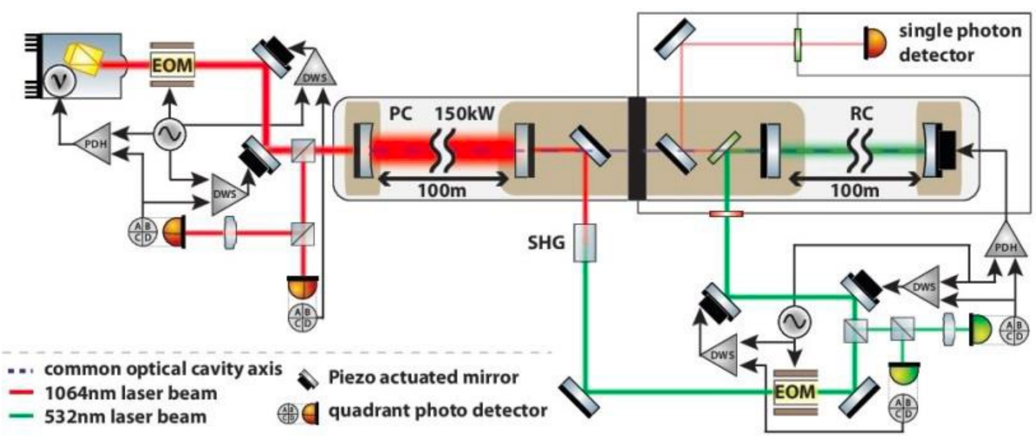
- *Light Shining through Wall*
  - *ALPs can be sought in lab by photon regeneration*
  - *Combination of a highly intense laser beam and strong magnetic fields*
- *Characteristics*
  - *Uncertainty reduction on production mechanism*
  - *No cosmological assumption (no dark matter, no solar axion models)*
  - *Two vertices => fourth power of coupling*
- *History*
  - *BFRT (Brookhaven-Fermilab-Rochester-Trieste)*
  - *OSQAR (LHC dipole at CERN) – most stringent limit*
  - *ALPS (HERA dipole at DESY)*

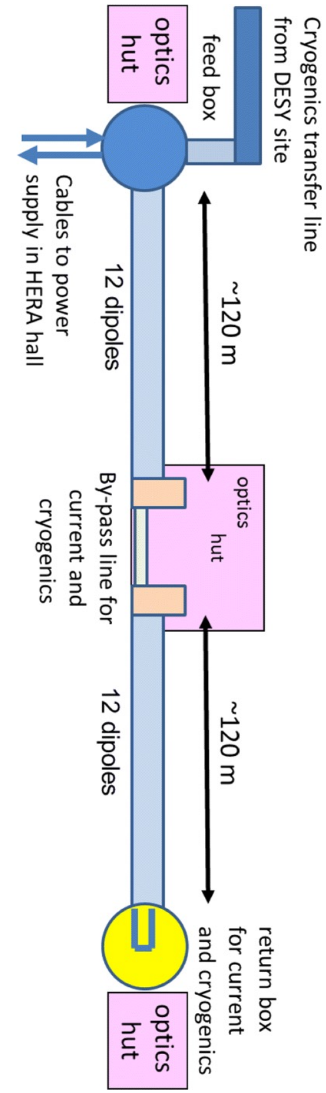




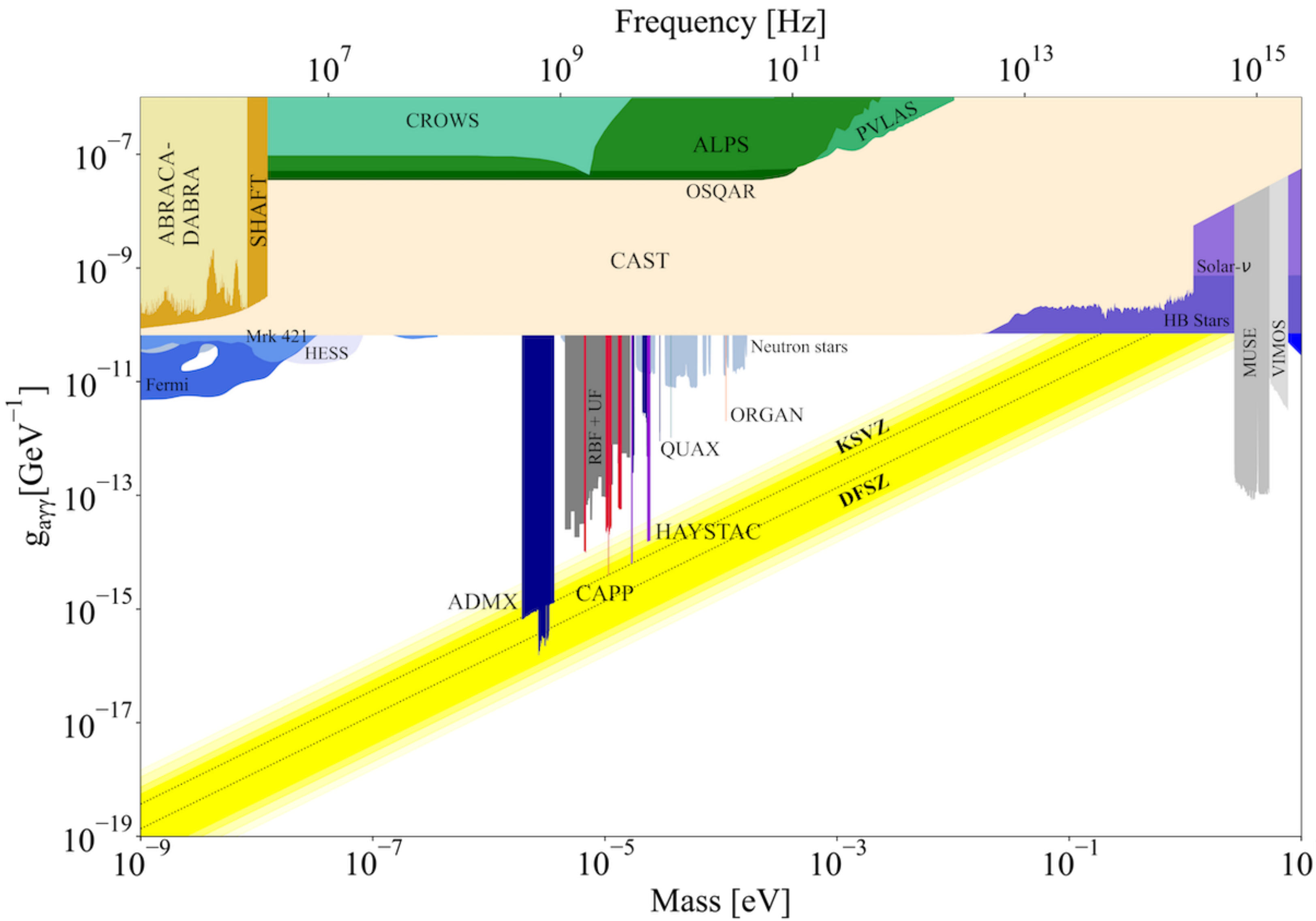
ALPS II

- *Upgrade featured by* L. Wei (Mon)
  - *Dual optical cavities*
    - *Second Fabry-Perot resonator in the axion production side*
  - *Phase-locking between two cavies*
    - *Significant improvement in photon regeneration probability*
  - *Longer and stronger magnetic field*
    - *2 x 12 HERA magnets (10 m & 5.3 T)*
- *Sensitivity improvement by 3 orders of magnitude*
  - $g_{a\gamma\gamma} > 10^{-11}\ GeV^{-1}$ *up to 0.1 eV*

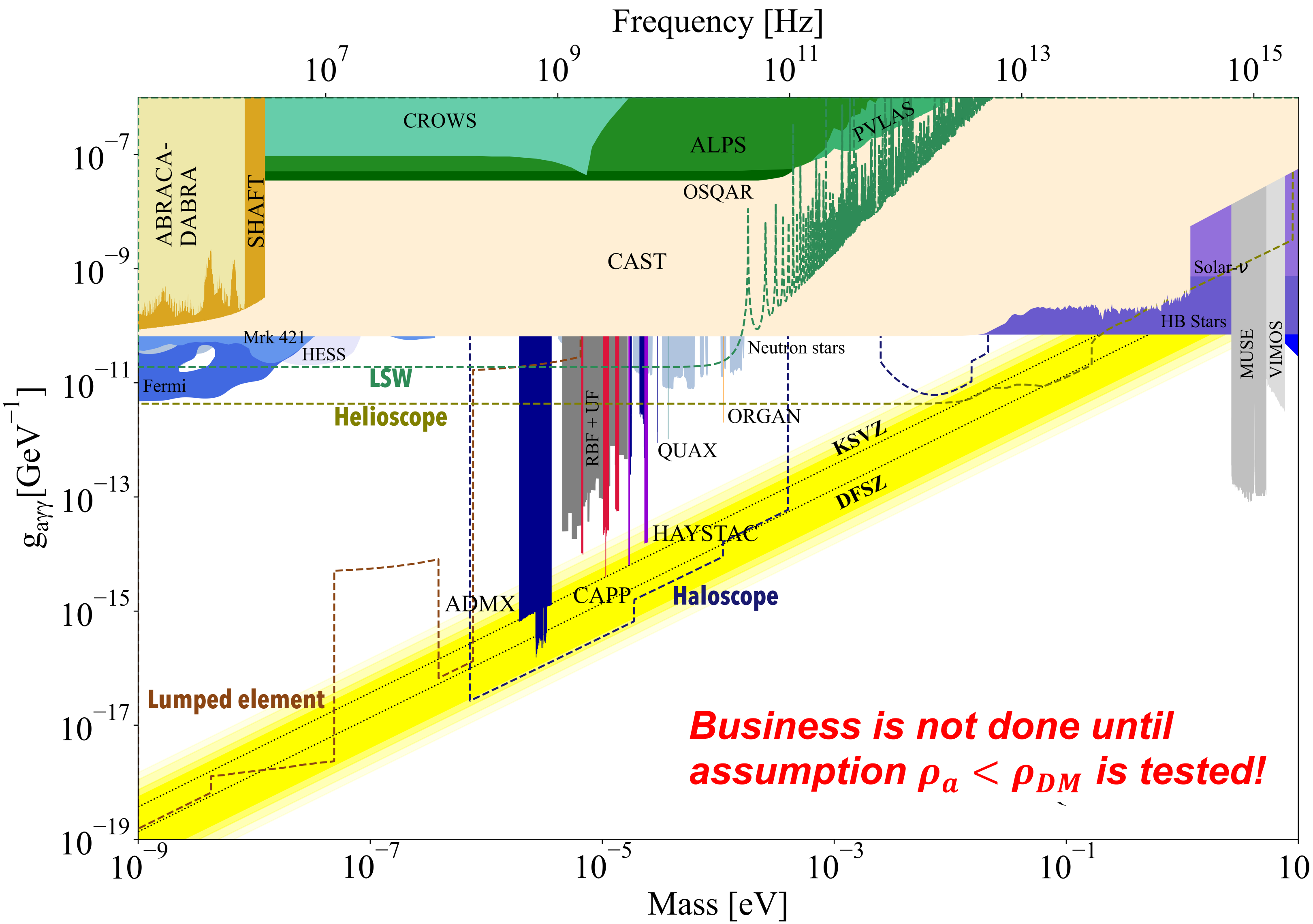




Axion searches – present



Axion searches – future



Business is not done until assumption $\rho_a < \rho_{DM}$ is tested!

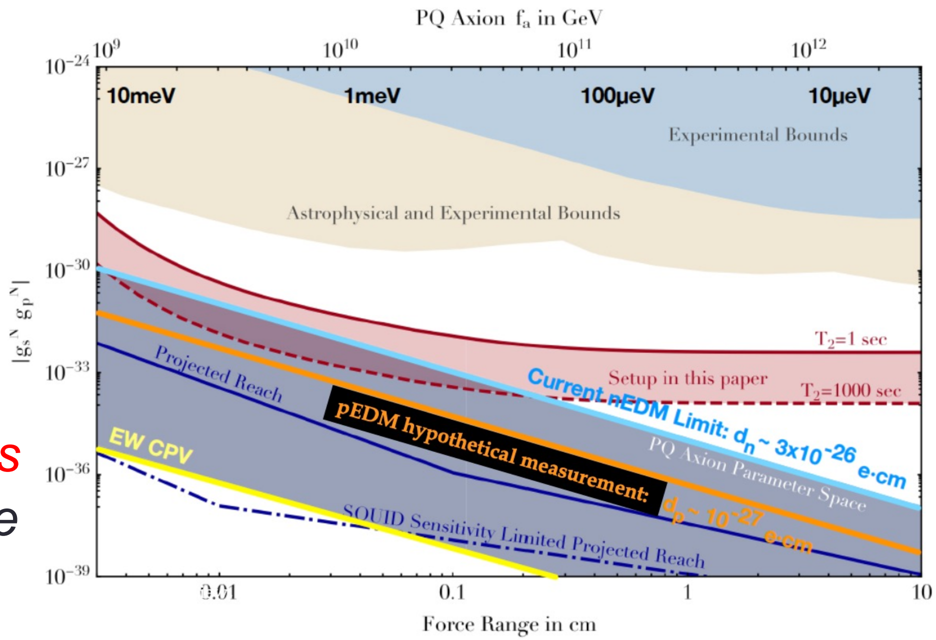
Additional CPV

ARIADNE, srEDM

Additional CPV

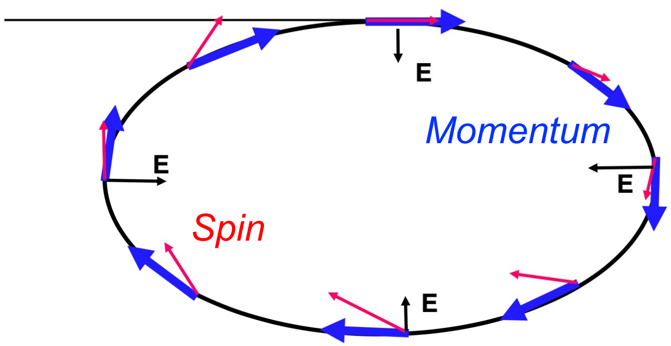
- QCD axion
  - $\theta_{eff} \equiv \theta_{QCD} - \frac{a}{f_a} = 0$
  - n,pEDM = 0
- Additional CPV in nature
  - $\theta_{eff} \neq 0$ (cf. EW CPV)
  - n,pEDM ≠ 0
- Storage ring proton beam
  - Direct probe of EDM
  - Sensitivity improvement
    - pEDM ~$10^{-29}\ e \cdot cm$
- ARIADNE A. Geraci (Tue)
  - $\theta_{eff} \neq 0$ produces axion fields
  - Can mediate monopole-dipole interactions

- Negative results from both independent experiments
  - Decisive exclusion of existence of axions
  - 0.1 meV < m_a < 10 meV

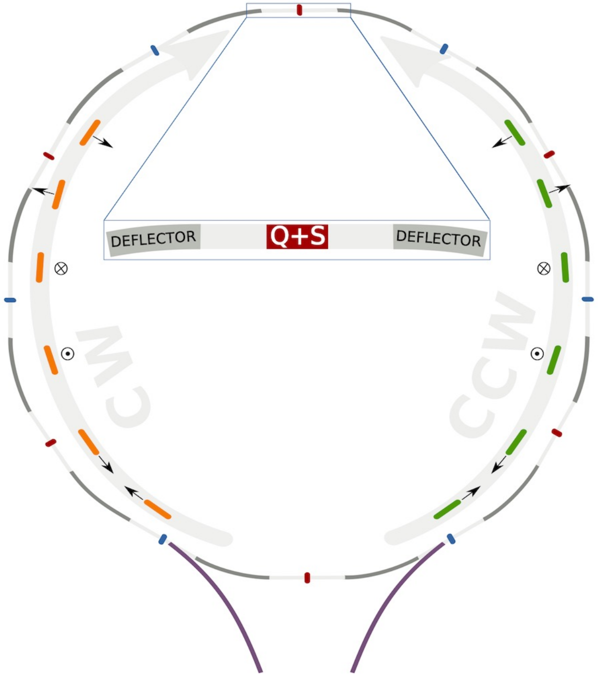


Storage ring proton EDM

- *Independent approach to θ_{QCD}*
  - *High intense polarized proton beam in a ring with E bending fields*
  - *Magic momentum locks the spin along the momentum*
  - *Non-zero EDM precess the spin out of plane*
- *3 orders of magnitude improvement*
  - *nEDM* $\sim 10^{-26}\ e \cdot cm$ *vs. pEDM* $\sim 10^{-29}\ e \cdot cm$



$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

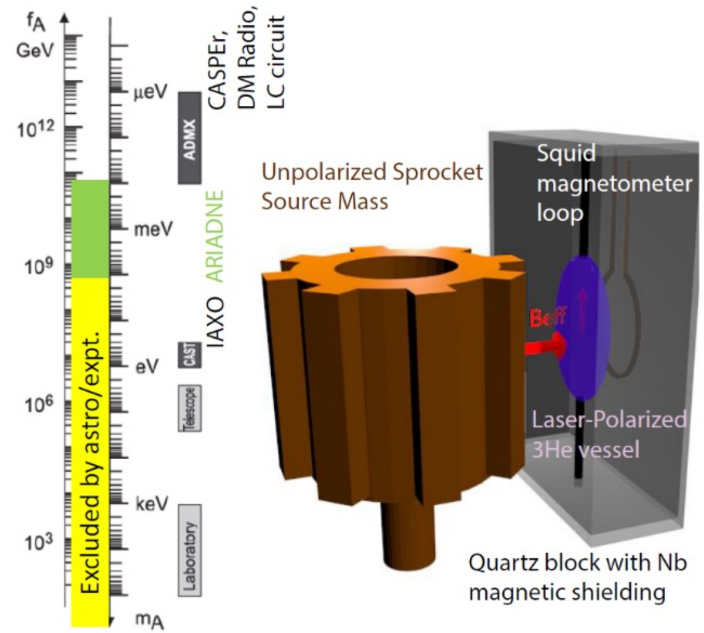


New hybrid-symmetric lattice simplifies the experiment

arXiv:2007.10332

ARIADNE

- *Axion = new force mediator b/w two fermions* *A. Geraci (Tue)*
  - *Monopole-dipole interaction*
    - *b/w unpolarized and polarized fermions*
  - *No cosmological assumption*
  - *Axion production at the lab*



- *Particular significance*
  - *Search for the fifth force*
  - *Covers the missing mass range*
    - *0.1 meV < m_a < 10 meV*
  - *Additional CPV source BSM*
    - *Combination w/ EDM results => decisive exclusion*
  - *Potential reach to experimentally allowed axion parameter space*

Summary

- *Axion is very charming*
  - *Strong CP problem & dark matter mystery*
- *Theoretically well motivated but experimentally very challenging*
  - *Small coupling and unknown mass*
- *Tremendous search efforts*
  - *Different technologies targeting at different mass ranges*
- *Axion community is getting larger*
  - *New results and new ideas (during the workshop)*
- *Next ten years must be critical/exciting*
  - *Covering a substantial portion of the parameter space*
  - *Addressing the fundamental questions*