Axions and WISPs

17th Patras Workshop on Axions, WIMPs, and WISPs

09/08/2022 JGU Mainz, Germany

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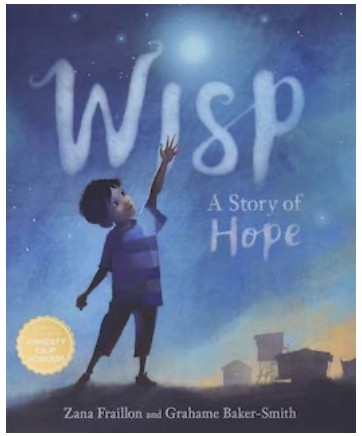
Outline

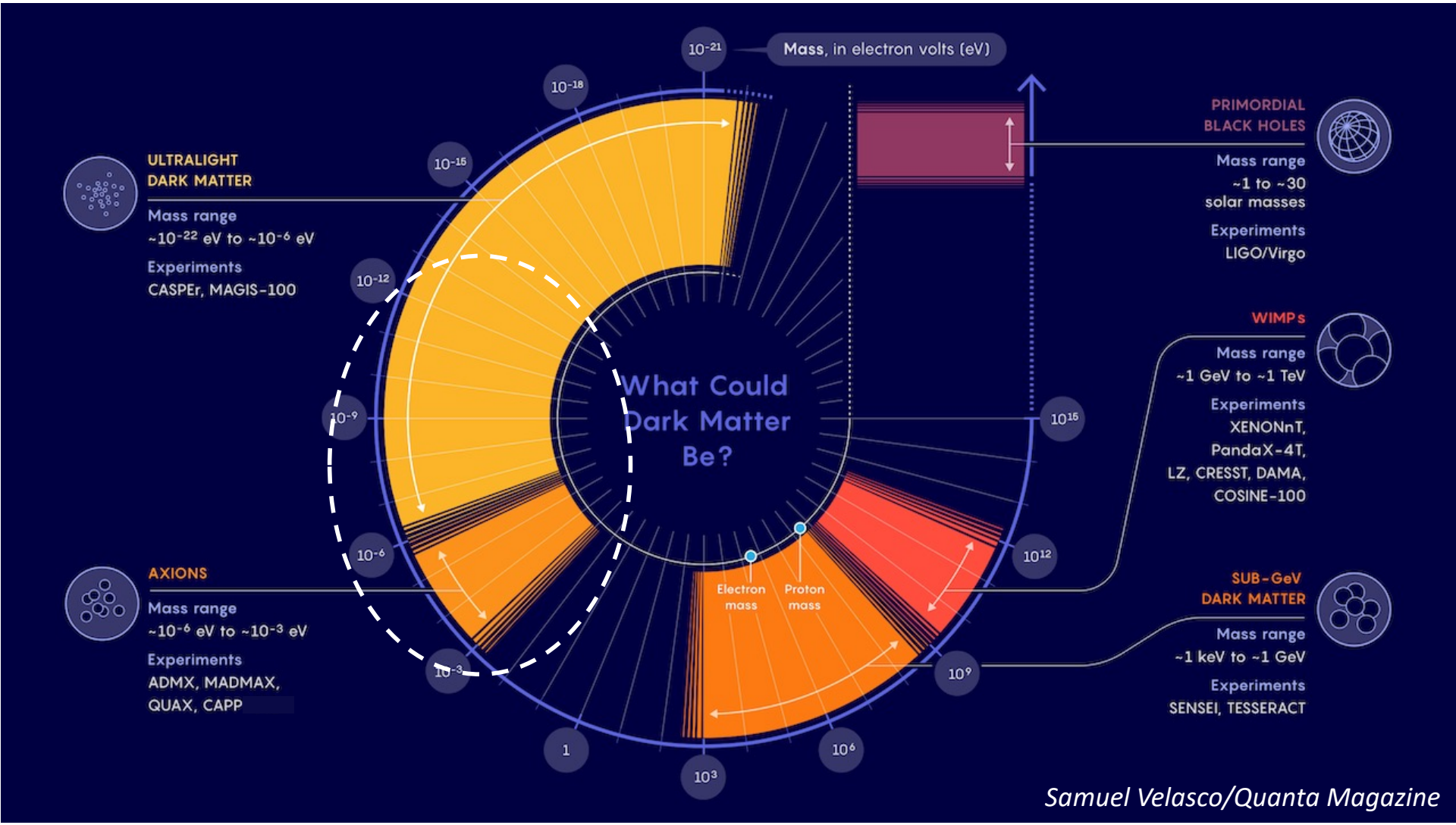
- *Background*
  - *Dark matter and WISP*
  - *Search strategies*
- *Axion (ALP) searches*
  - *Photon coupling*
    - *Haloscope / Helioscope / LSW*
  - *Fermion coupling*
  - *nEDM coupling*
- *Other WISP searches*
  - *Hidden photon*
  - *Chameleon*
- *Prospects and summary*



Disclaimer

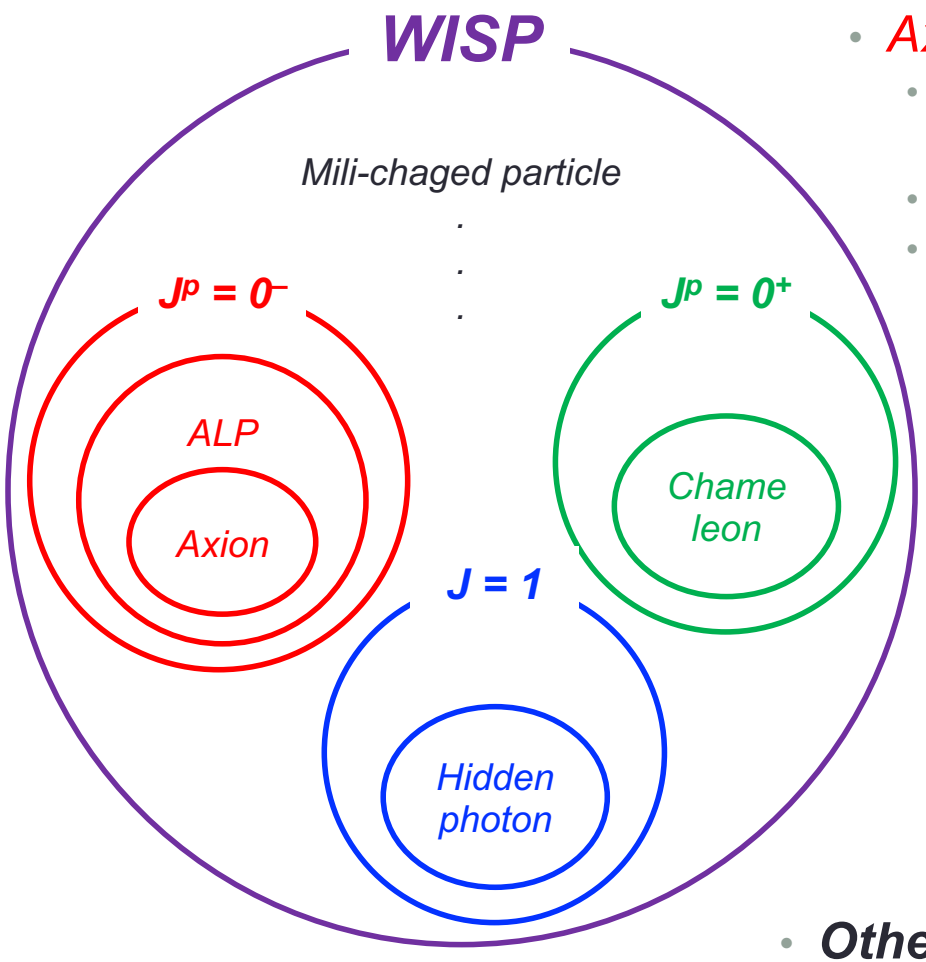
- *My apologies for not covering*
  - *indirect searches*
  - *all individual efforts*
  - *most recent updates*

Dark matter business expanding



Samuel Velasco/Quanta Magazine

WISP zoo



- **Pseudo-scalar**
  - Axion
    - PQ solution to strong CP problem (1977)
      $m_a f_a \sim \Lambda_{QCD}$
    - Invisible axion (1979)
    - Dark matter candidate (1983)
  - Axion-Like Particle (ALP)
    - Generic axion w/o solving the strong CP problem
      $m_a f_a \nsim \Lambda_{QCD}$
  - **Scalar**
    - Chameleon (2003)
    - Dark energy candidate
  - **Vector**
    - Hidden photon
    - Gauge field in hidden sector
- **Others**
  - Mili-charged particle, …

Couplings and models

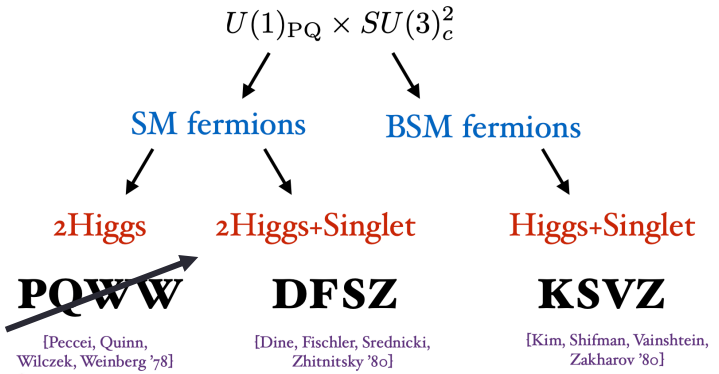
- *Axion coupling to SM*

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

- *Axion models*

Specify origin of QCD anomaly (fermion sector)
and spontaneous PQ breaking (scalar sector)

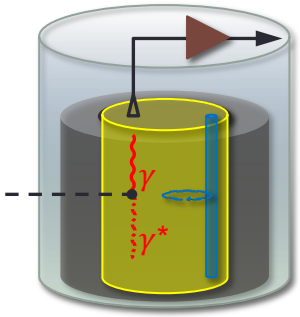
From R. Ziegler

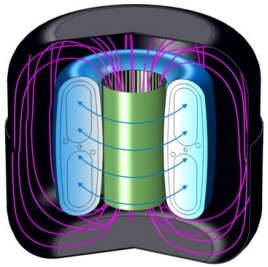


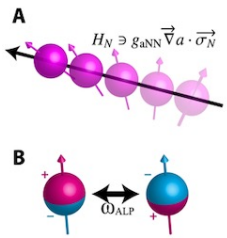
$\langle \text{Singlet} \rangle \gg v$:
"invisible" axion models

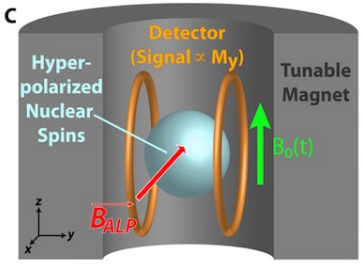
Experimental searches

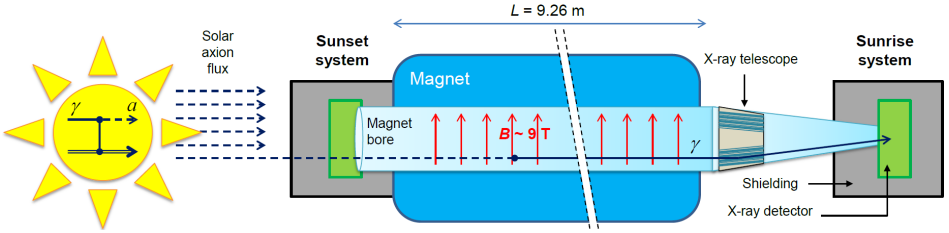
Source \ Coupling	Photons	Fermions	nEDMs
Dark matter	*ADMX, CAPP, MADMAX, DM Radio, …*	*QUAX-ae, GNOME, CASPEr-wind, …*	*CASPEr-electric, srEDM, …*
Solar	*CAST, IAXO*		
Laboratory	*ALPS (II)*	*ARIADNE*	

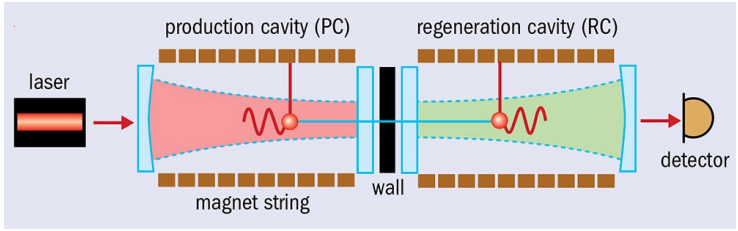






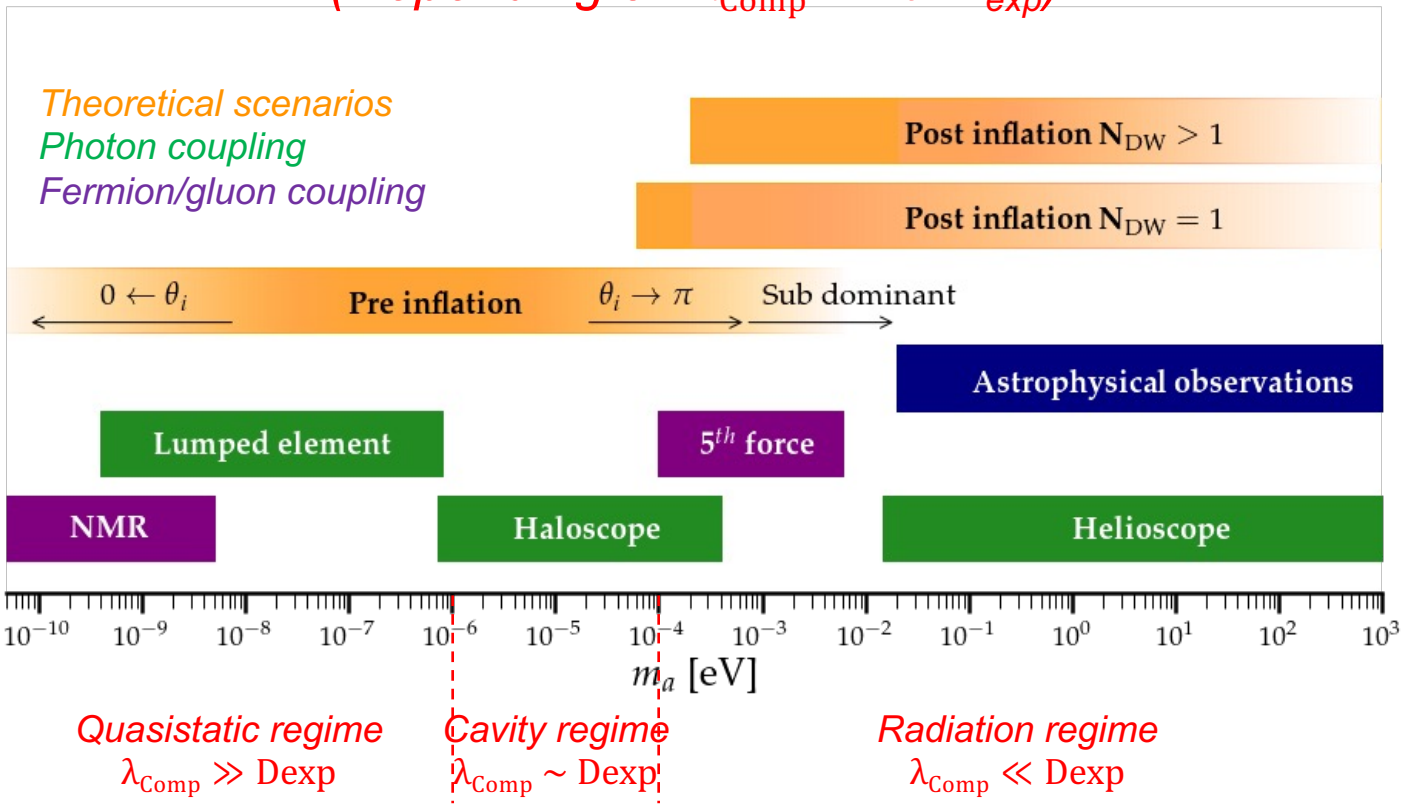




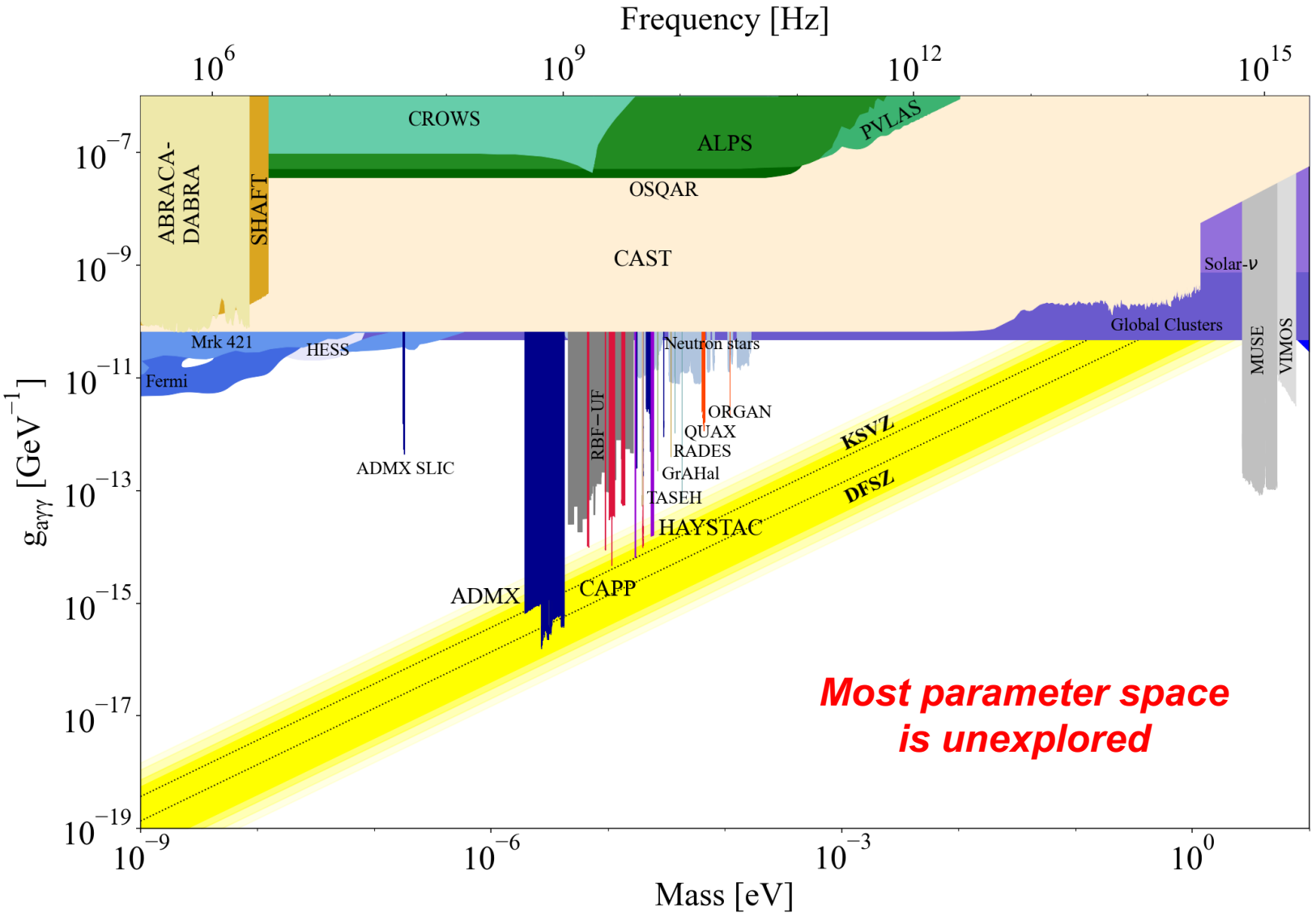


Where are dark matter axions?

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



Axion searches – present



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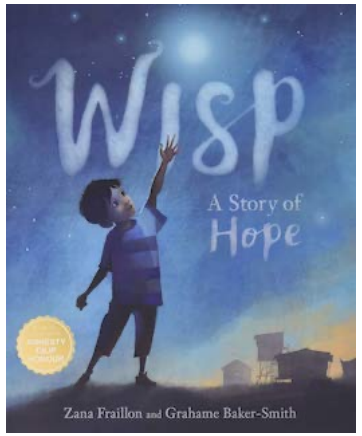

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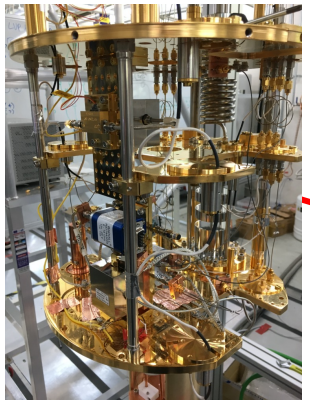
Cavity haloscope – in a nutshell

- *Most sensitive for microwave photons*

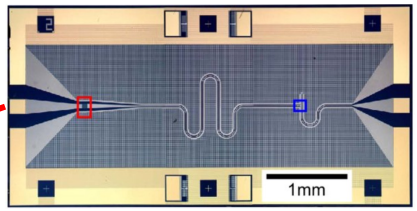
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics T

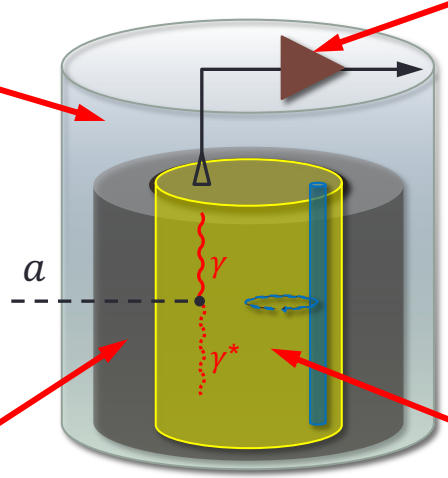


Lowering thermal noise

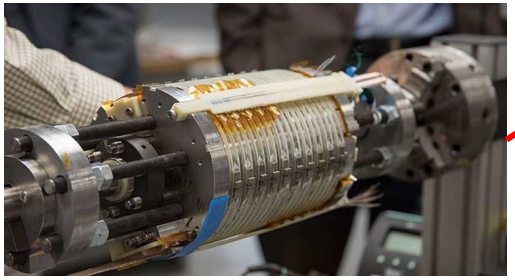
Quantum noise limited amplifier T



Signal amplification w/ minimal noise added



High field Magnet B



Boosting a→γγ conversion rate

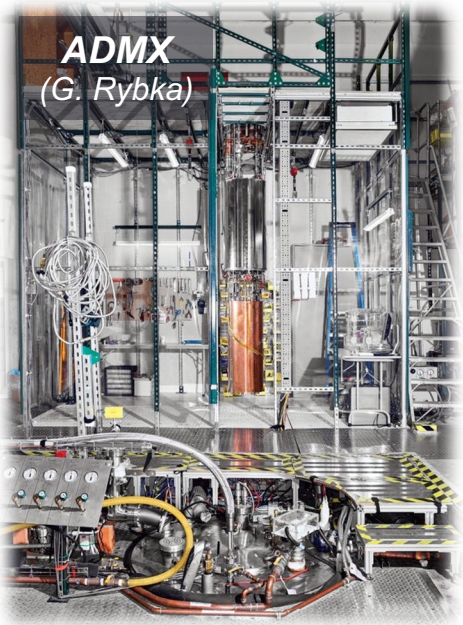
Tunable High-Q resonator
V, Q, C, Δf

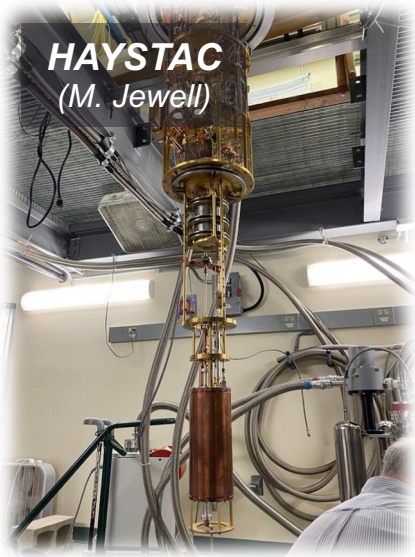
Resonant frequency tuning

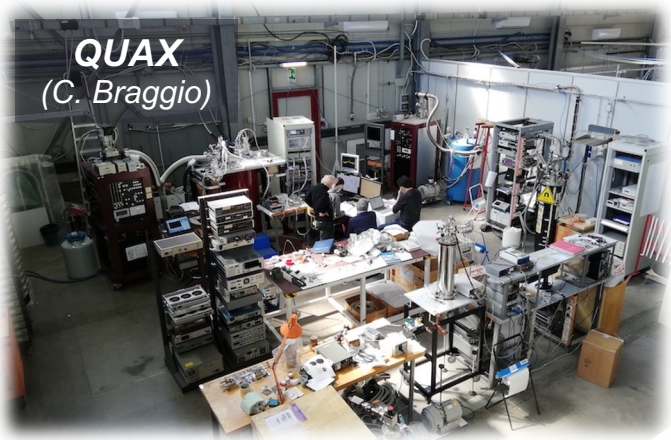
Tabletop experiments!

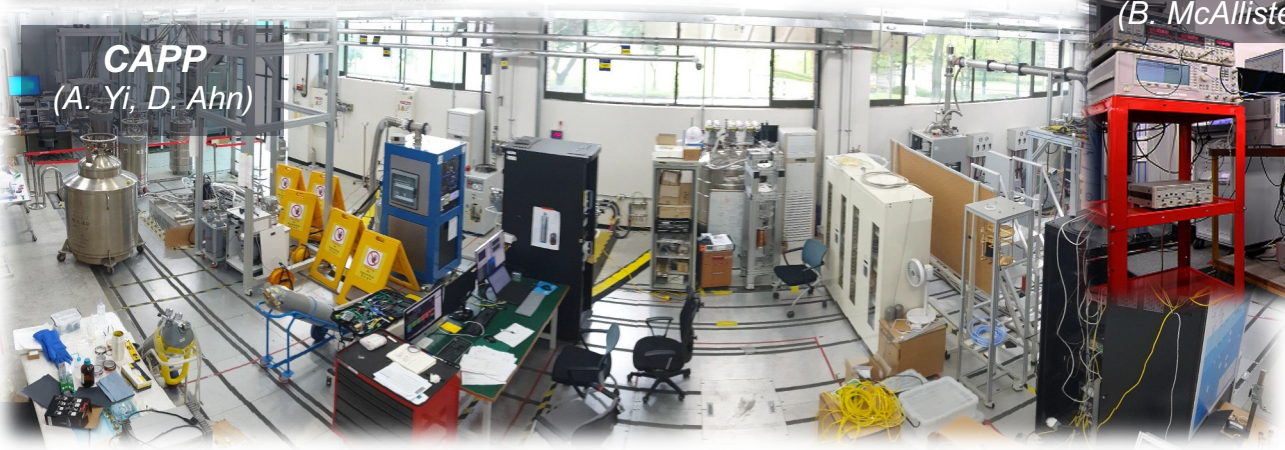
Cavity haloscopes

Cavity regime
$\lambda_{\mathrm{Comp}} \sim$ Dexp

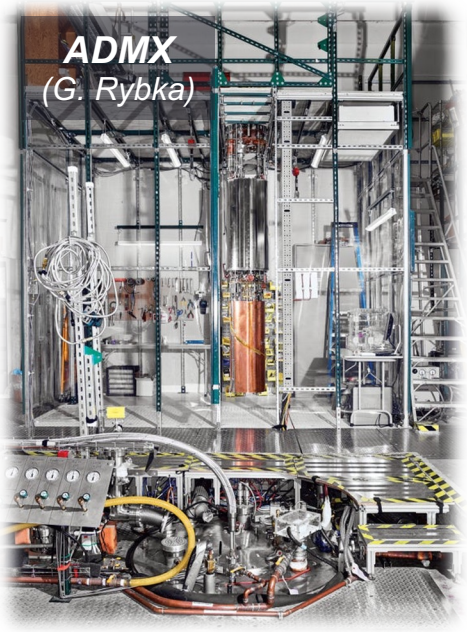


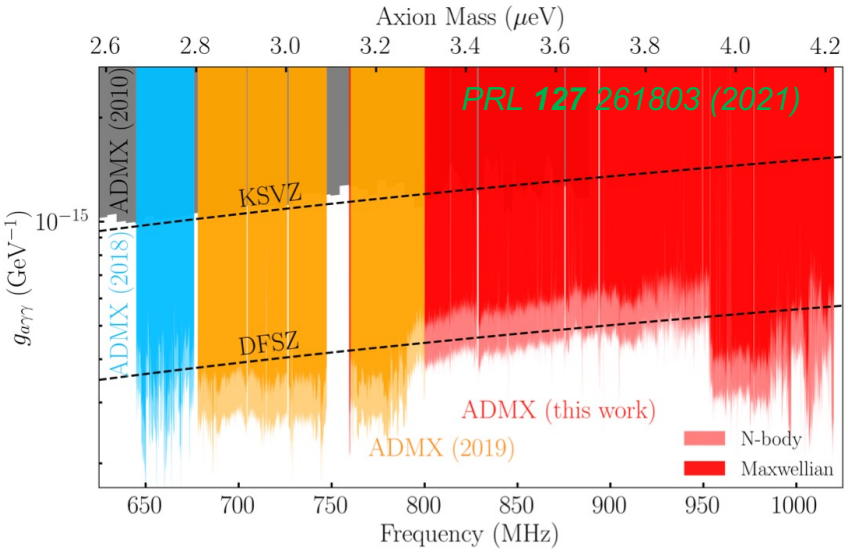






Search highlights





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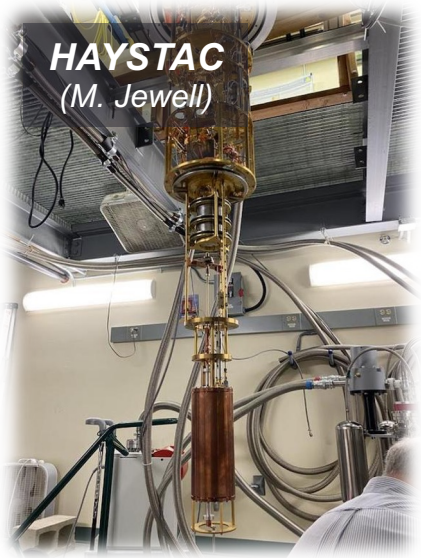

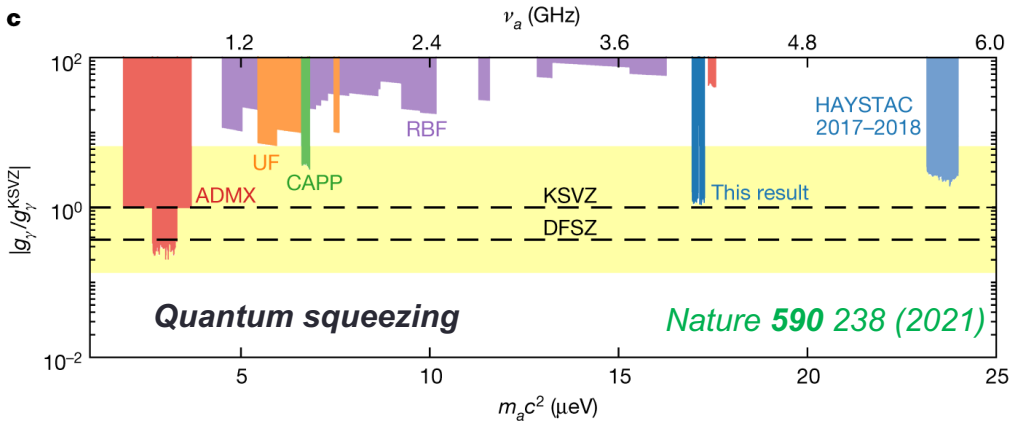

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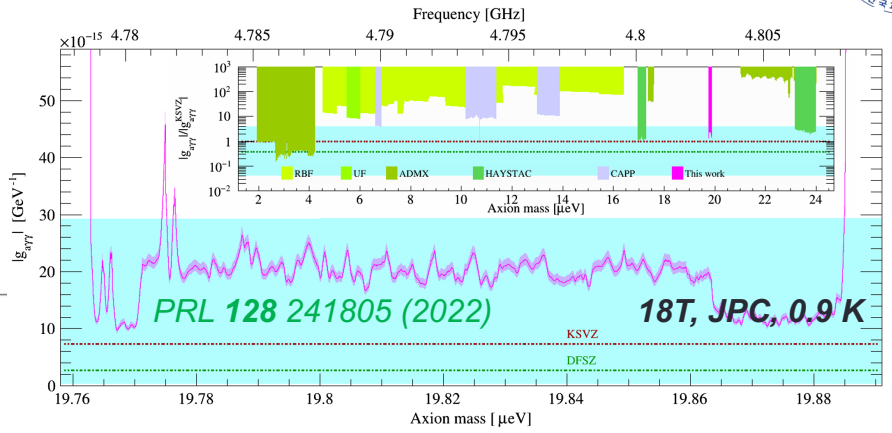

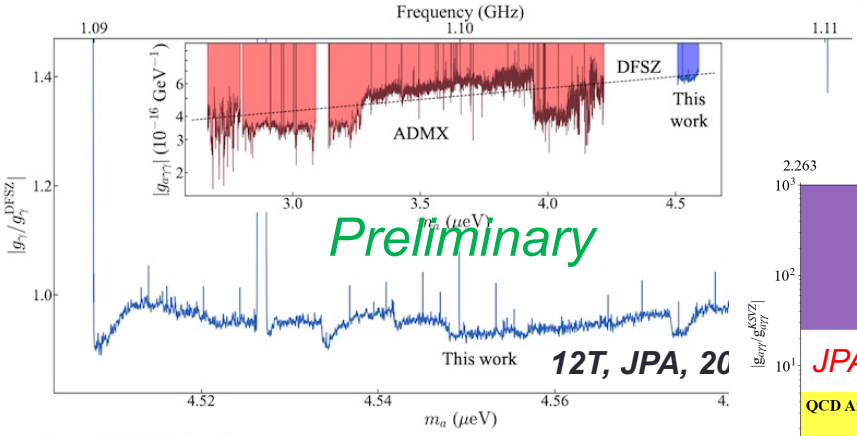

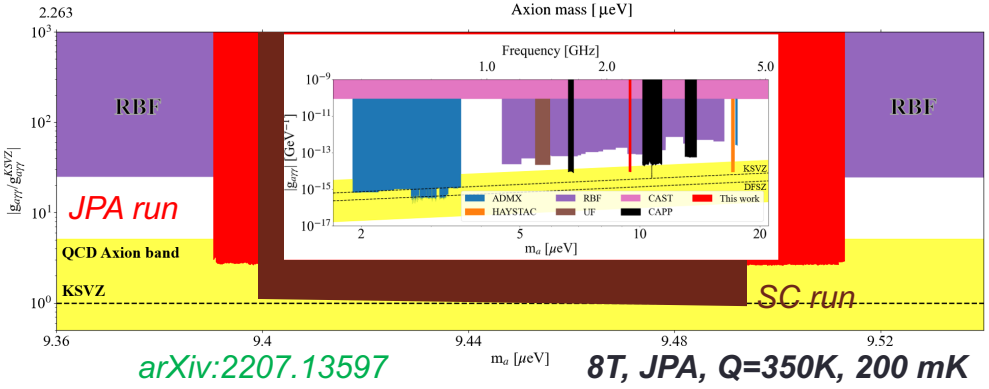

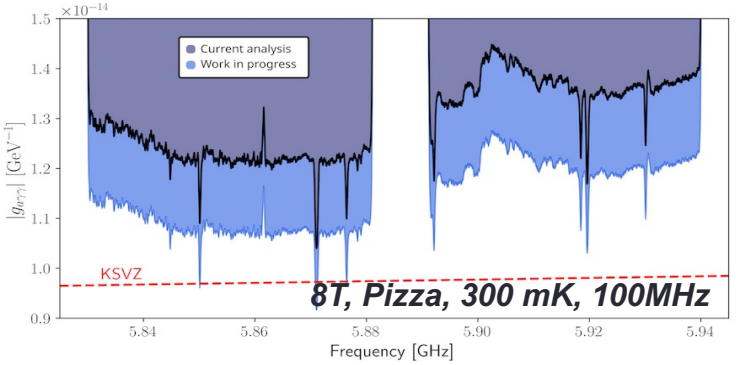

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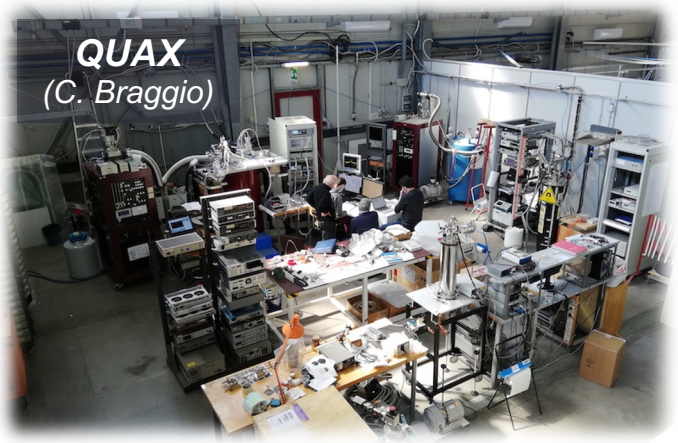
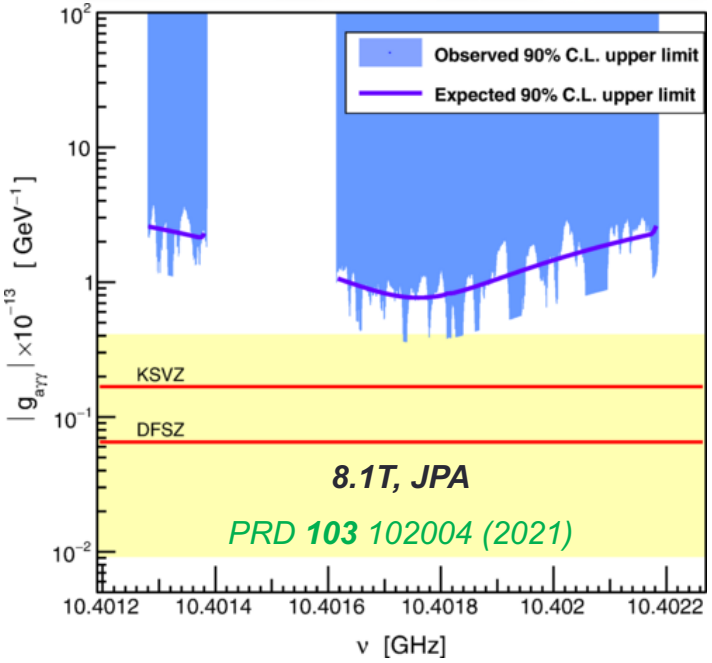
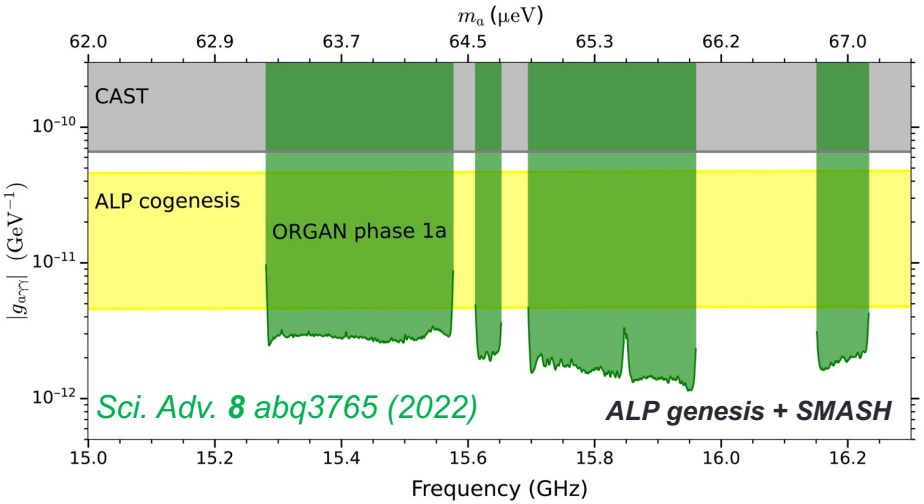


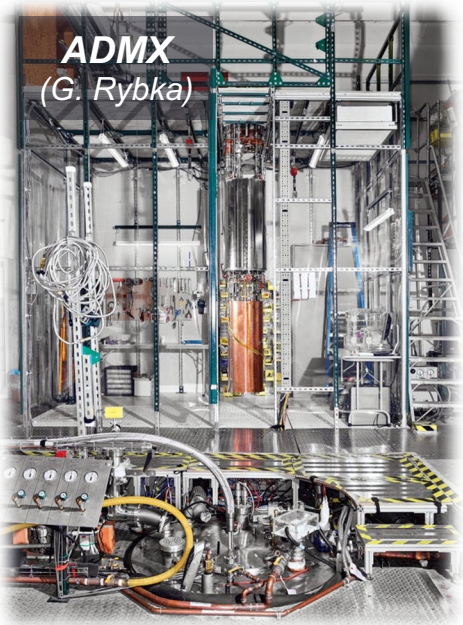


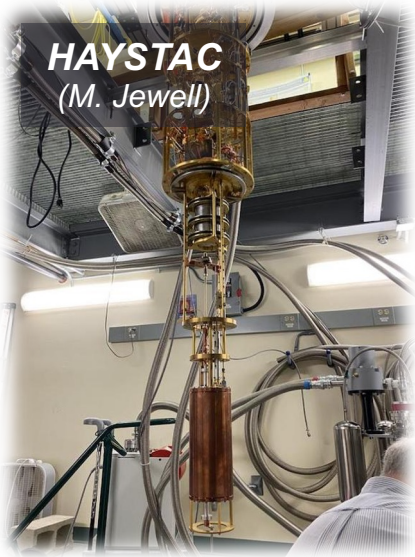
Search highlights

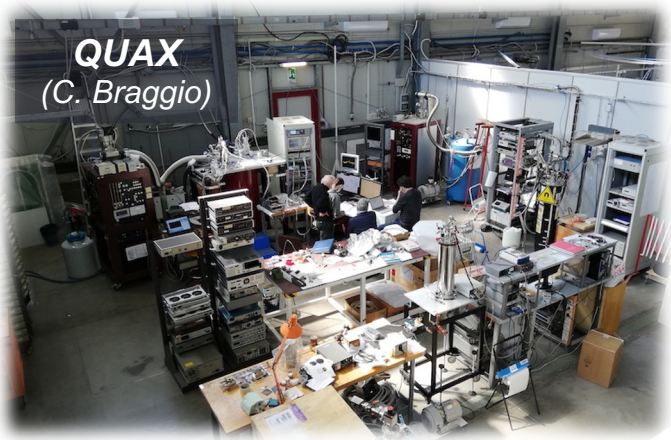


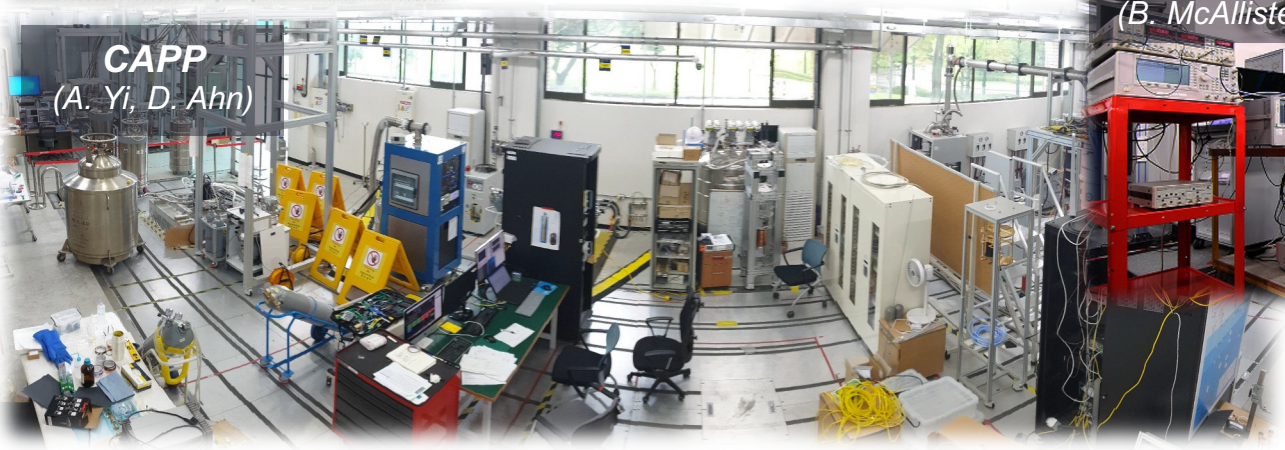
Cavity haloscope

Cavity regime
$\lambda_{\mathrm{Comp}} \sim$ Dexp





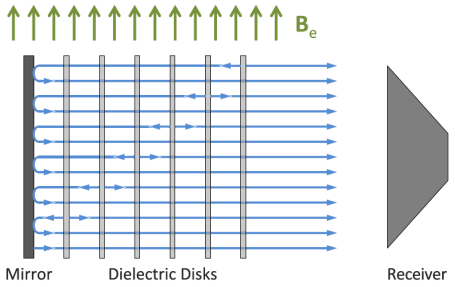


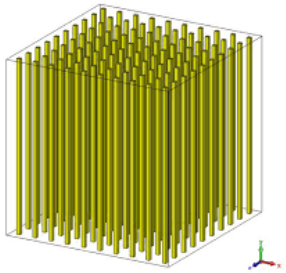


High frequency haloscope

Radiation regime
$\lambda_{Comp} \ll Dexp$

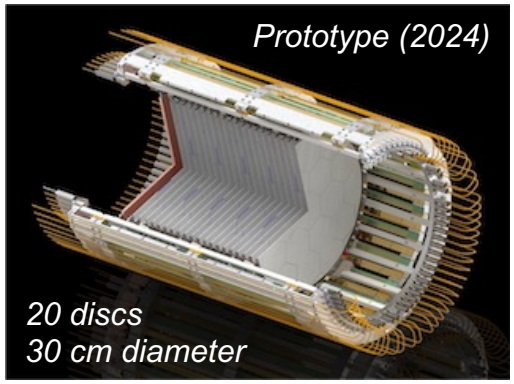
- *Periodic array*
  - *Search frequency independent of detector size*
  - *Suitable for post-inflation scenario (10–100 GHz)*



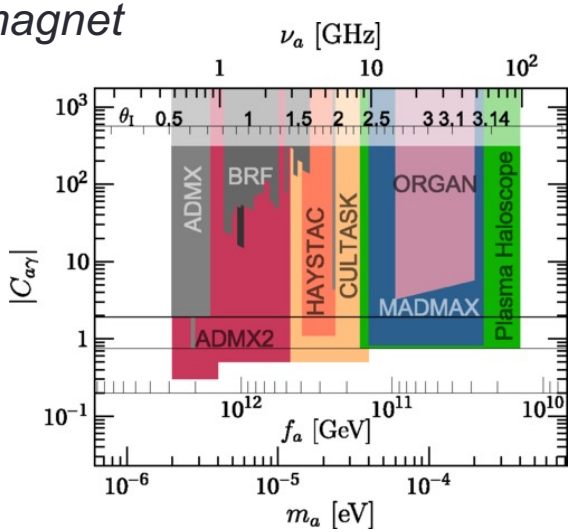


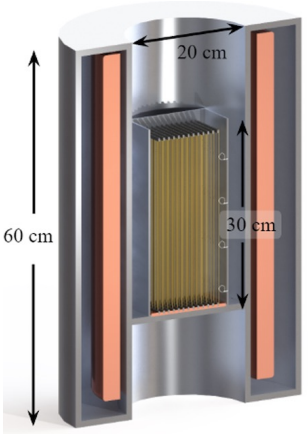
- *MADMAX*
  - *Power boost w/ dielectric disks*
  - *Full scale experiment*
    - *2m-10T dipole / 80 1m² discs ($\epsilon \sim 25$)*
  - *Proof-of-concept and 3D effect*
  - *Prototype using Morpurgo magnet*

A. Gardikiotis (Thu)



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



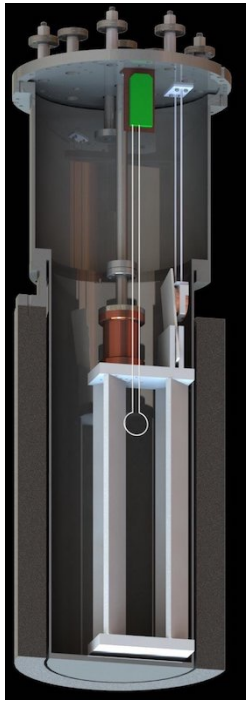


Lumped element haloscope

Quasistatic regime
$\lambda_{Comp} \gg Dexp$

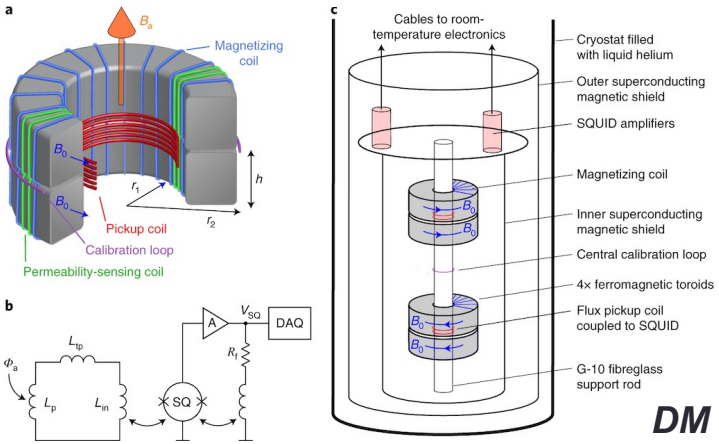
- *Broadband low mass search (< 1 ueV)*
  - *Sensitive to pre-inflation axions*

ADMX SLIC



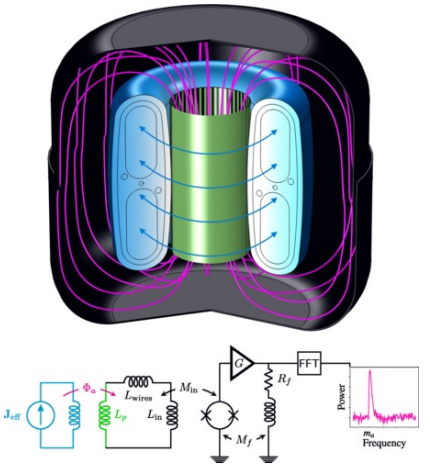
PRL124, 241101 (2020)

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



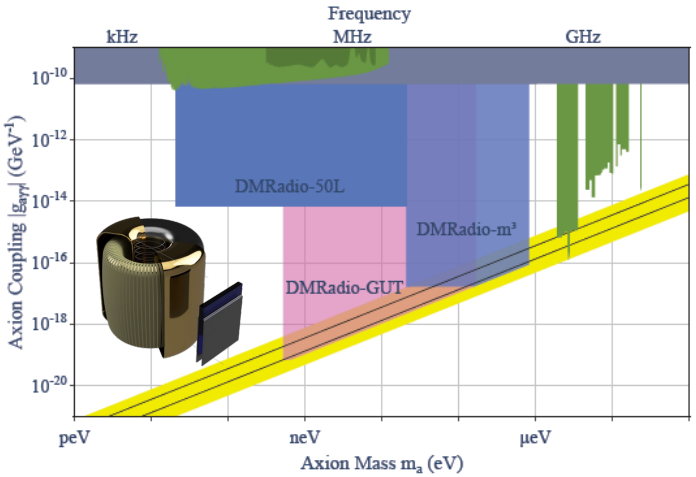
ABRACADABRA-10cm

*PRL **127** 081801 (2021)*



M. Smanovskaia (Thu)

DM Radio

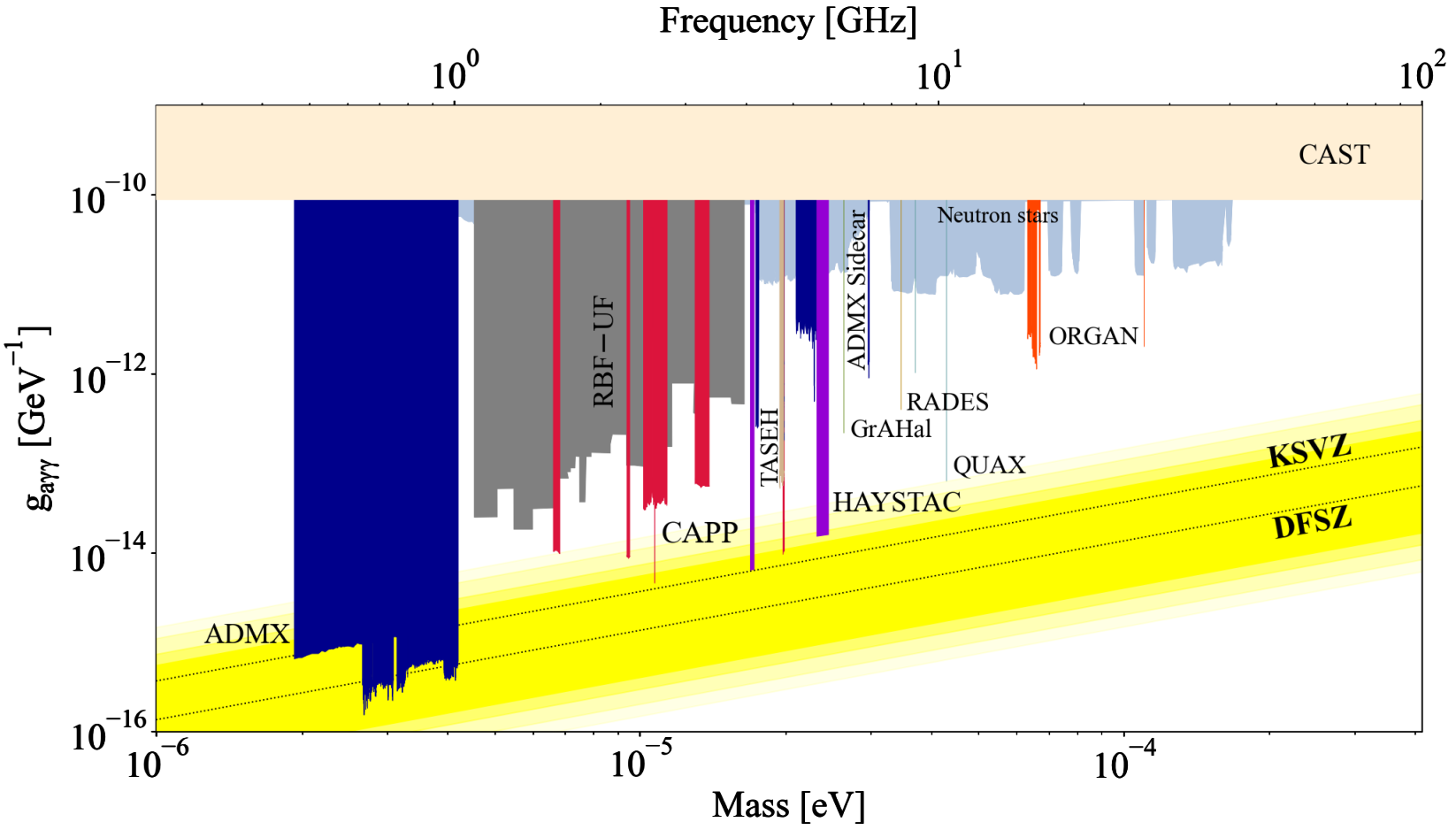


Other experiments

- *Running*
  - *CAST dipole (9T)*
    - *CAST-CAPP: phase-matched cavities, ~20 ueV* — *M. Maroudas (Tue)*
    - *RADES: microwave fiber, ~34 ueV* — *JHEP **2021** 75 (2021)*
- *New*
  - *Grenoble Axion Haloscope* — *ArXiv:2110.14406*
    - *14T/52mm magnet, ~26 ueV*
  - *Taiwan Axion Search Experiment with Haloscope* — *arXiv:2205.05574*
    - *4.7 GHz, 11 x g_{arr}^{KSVZ}*
  - *Superconducting axion search* — *K. Schmieden (Mon)*
    - *SC cavity, 14T, 8.4 GHz (under construction)*
- *Proposed*
  - *Broadband Reflector Experiment for Axion Detection* — *PRL 128 131801 (2022)* *S. Knirck (Wed)*
    - *Parabolic reflector, THz region*
  - *Canfranc Axion Detection Experiment* — *arXiv:2206.02980*
    - *90 GHz (W-band), Kinetic Induction Detectors*

Haloscope searches

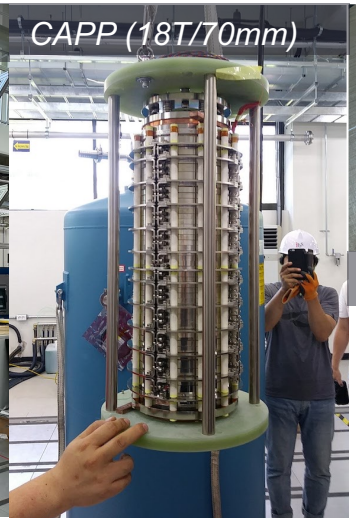
Present (~2022)

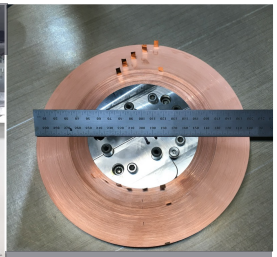


Magnet


ADMX (8T/600mm)

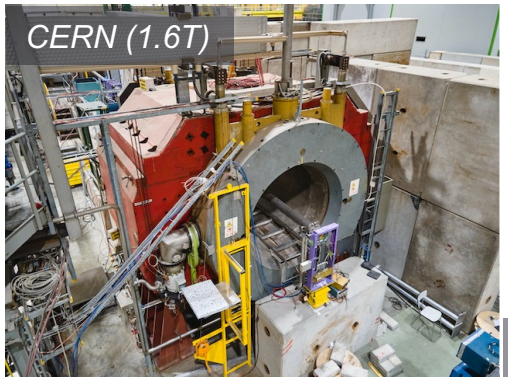

CAPP (12T/320mm)

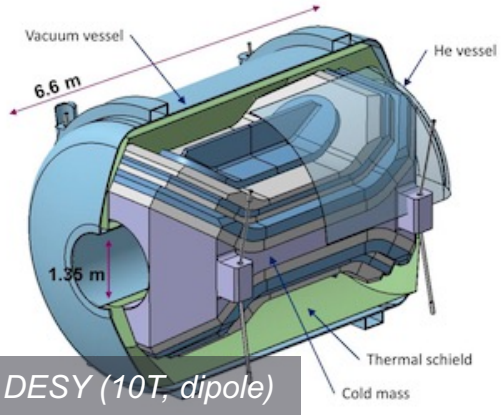

CAPP (18T/70mm)


YBCO pancakes


Grenoble (43T/34mm)
LNCMI

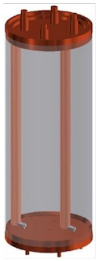

ADMX
AXION DARK MATTER EXPERIMENT
BREAD
UIC (9.4T/800mm)


CERN (1.6T)

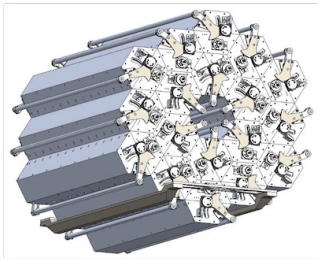

Vacuum vessel
He vessel
6.6 m
1.35 m
Thermal schield
Cold mass
DESY (10T, dipole)

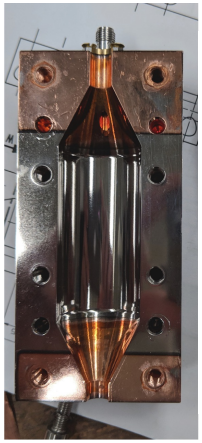
Cavity

arXiv: 2203.14923

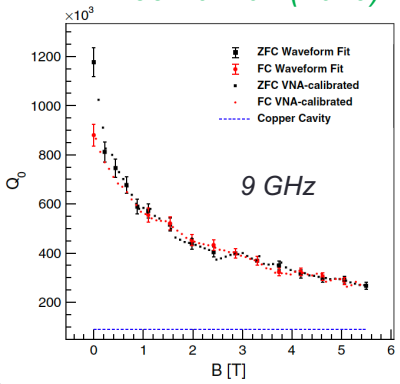

Run 1A-C


Run 2

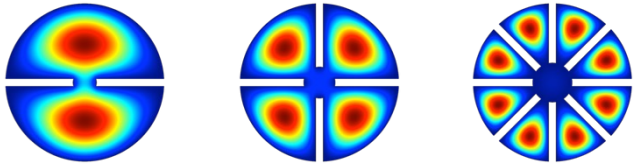

EFR



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

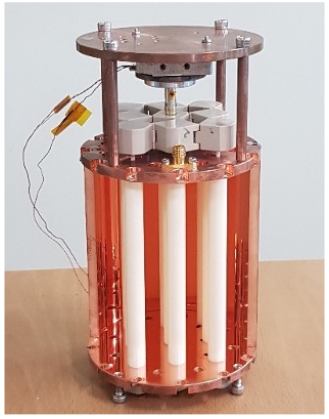


*PRL **125** 221302 (2020)*

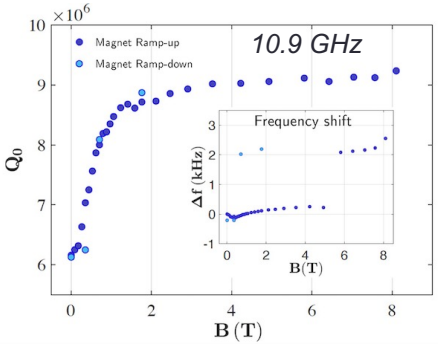


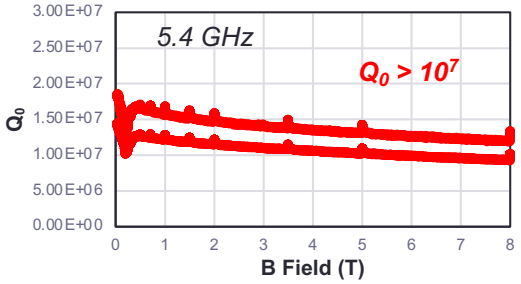
D. Ahn (Tue)

arXiv: 2205.08885

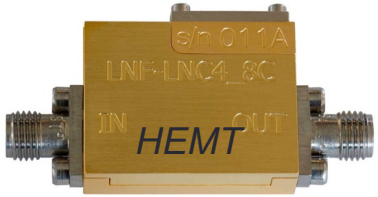


*NIM **985** 164641 (2021)*

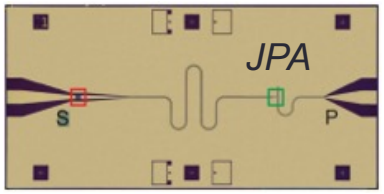




Microwave photon detector



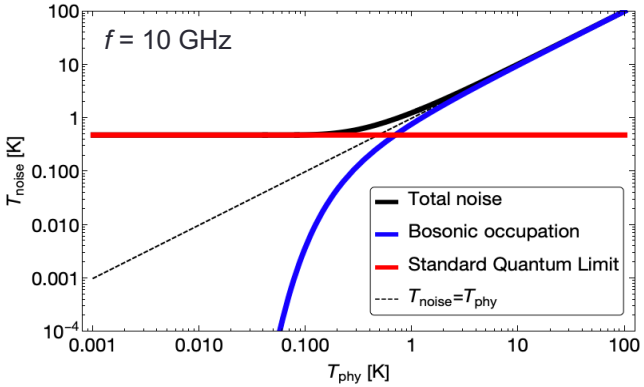
Transistor-based
(T_N ~ K)



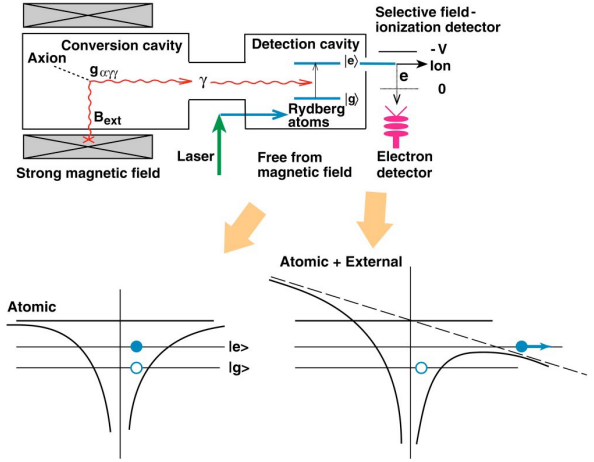
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection vs. photon counting

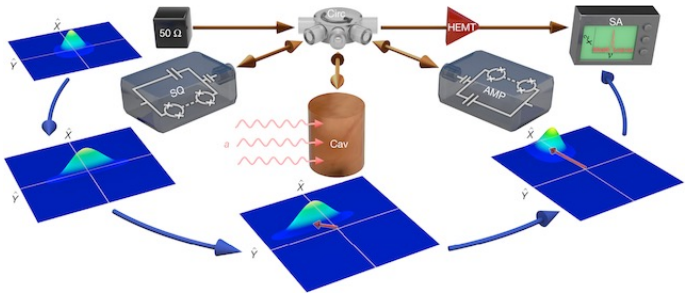
(w/ amplifiers) *(w/ single photon detector)*



Game changer
at high freq. and low temp.

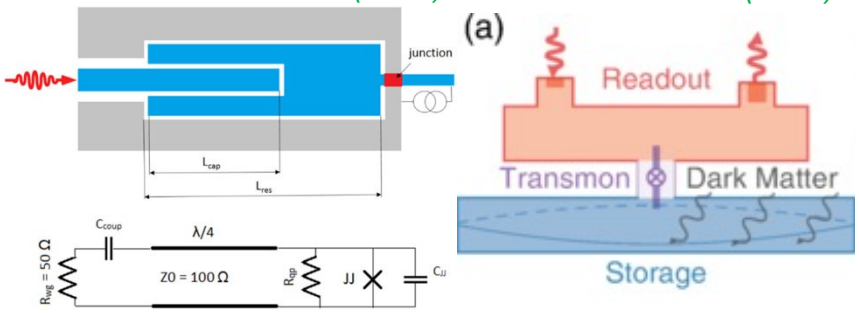


*Nature **590** 238 (2021)*



Quantum squeezing (T_N < T_{SQL})

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

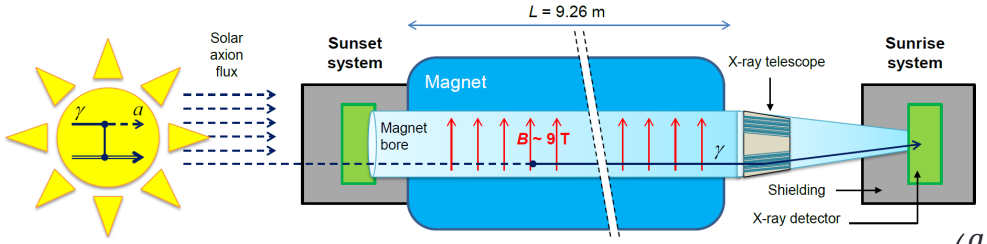


Single photon counting (T_N << T_{SQL})

Helioscope

- *Solar axion telescope*

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



Reconversion into X-ray in laboratory magnetic fields

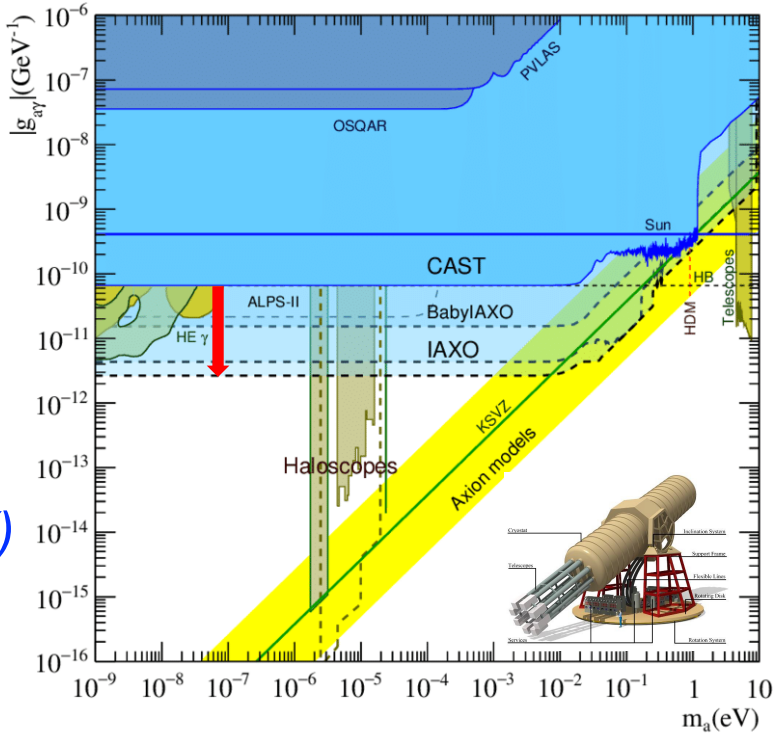
$$P_{a\gamma\gamma} \sim \left(\frac{g_{a\gamma\gamma}B_0}{q}\right)\sin\left(\frac{qL}{2}\right), q \equiv \frac{m_a^2}{2E_a}$$

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

- *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*

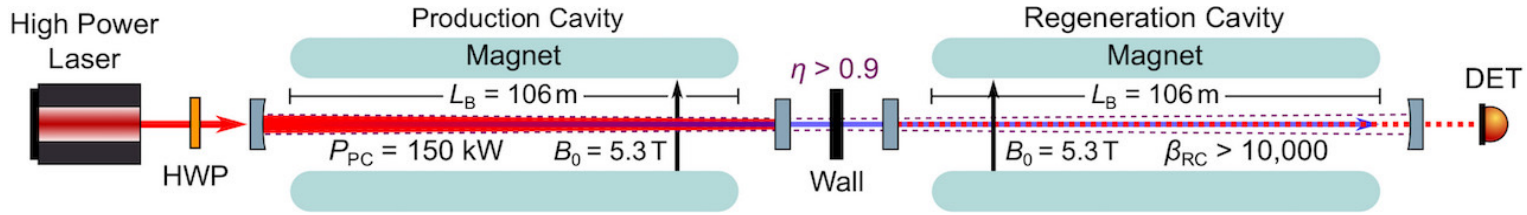
T. Schiffer (Tue)

- *Baby-IAXO under construction (DESY)*
  - *First step towards full IAXO*
  - *4 T / 10 m => 10 x* $MFOM_{CAST}$



Light shining through a wall

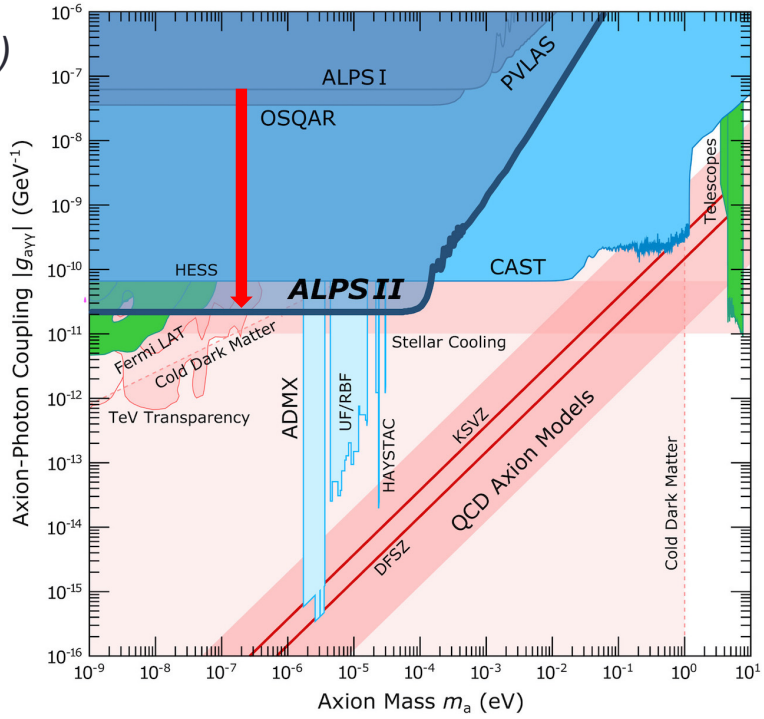
- *Axion-production/photon-regeneration at the lab*



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

G. Othman (Tue)

- *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*
    - *Three orders of magnitude of ALPS*

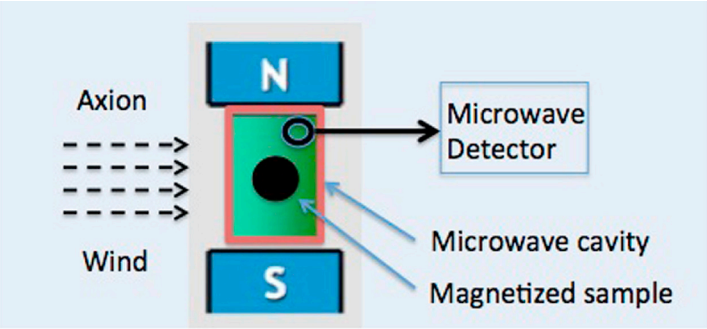


Fermion coupling

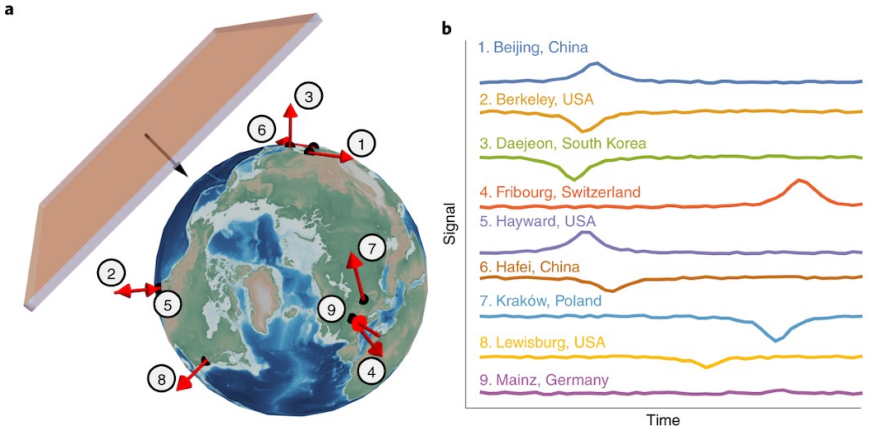
- *QUAX-ae*
  - *Ferromagnetic haloscope*
    - *Axion-electron spin*
  - *Photon-magnon system*
    - *Series of YIG spheres*
    - *TM_{110} of a cylindrical cavity*
  - *Upgraded with JPA*
  - *Best limit near $m_a \sim 43\ \mu eV$*

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

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

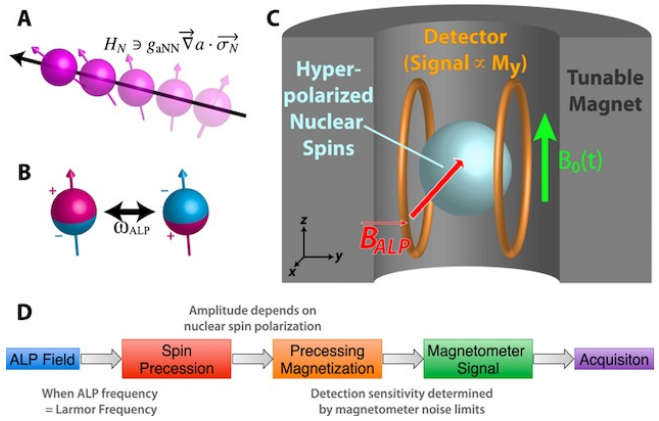


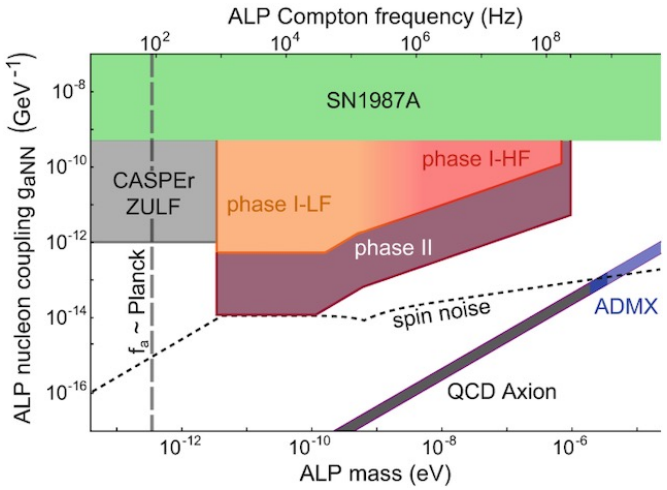
*Nature Phys. **17** 1396 (2021)*

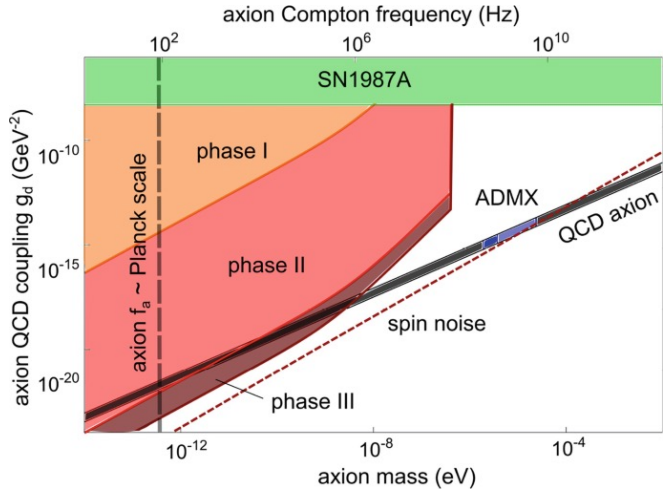


Fermion/EDM coupling

- *Cosmic Axion Spin Precession Experiment* — *H. Bekker, Thu*
  - *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*







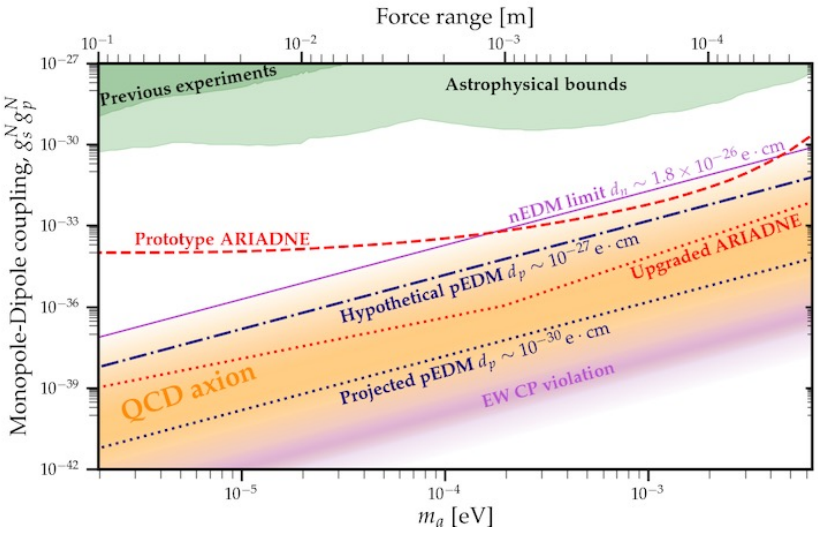
CPV and EDM

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

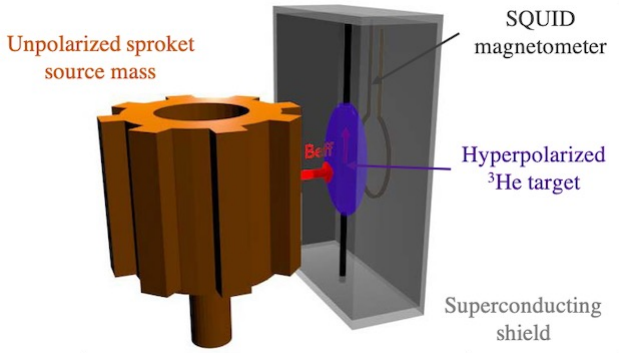
vs.

- *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* ~$10^{-29}\ e \cdot cm$



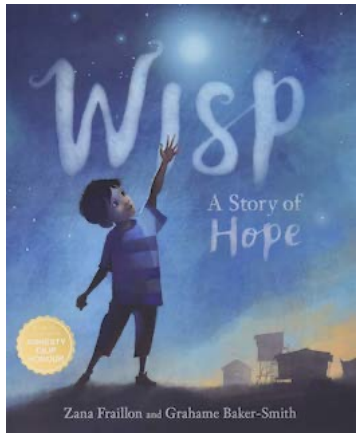
- *ARIADNE* — *A. Geraci (Thu)*
  - *Nucleon-nucleon interactions*
    - *5th force mediator*
  - *No cosmological assumptions*



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

Outline

- *Background*
  - *Dark matter and WISP*
  - *Search strategies*
- *Axion (ALP) searches*
  - *Photon coupling*
    - *Haloscope / Helioscope / LSW*
  - *Fermion coupling*
  - *nEDM coupling*
- *Other WISP searches*
  - *Hidden photon*
  - *Chameleon*
- *Prospects and summary*



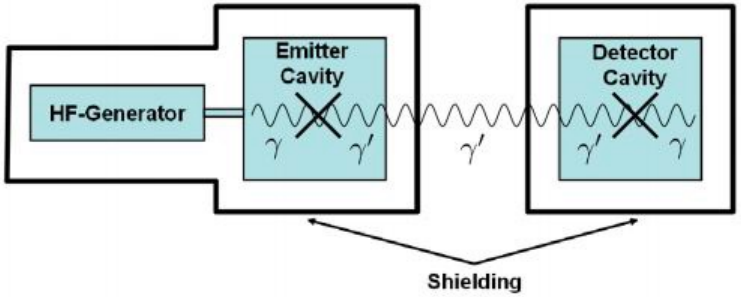
Disclaimer

- *My apologies for not covering*
  - *indirect searches*
  - *all individual efforts*
  - *most recent updates*

Hidden photon

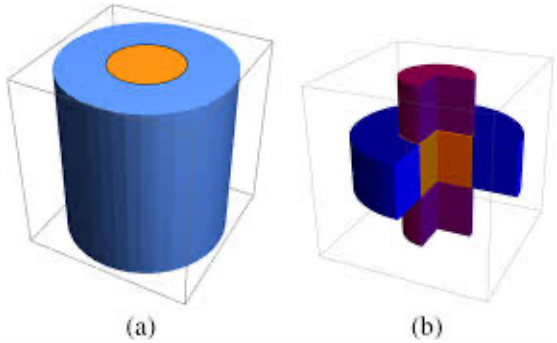
- *Vector field*
  - *Gauge boson in hidden sector + dark matter*
  - *Kinetic mixing with SM gauge fields*

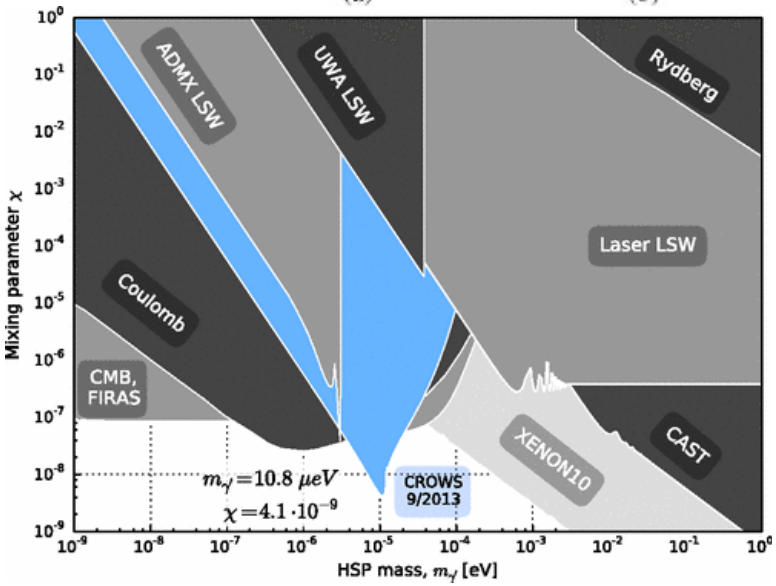
- *LSW-type w/ no magnets* *PLB **659** 509 (2008)*



- *Cavity searches*
  - *ADMX* *PRL **105** 171801 (2010)*
  - *UWA* *PRD **82** 052003 (2010)*
  - *CROW* *PRD **88** 075014 (2013)*
  - *SC cavities and …*
  - *New ideas* *R. Cervantes, O. Tajima (Thu)*

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





Chameleon

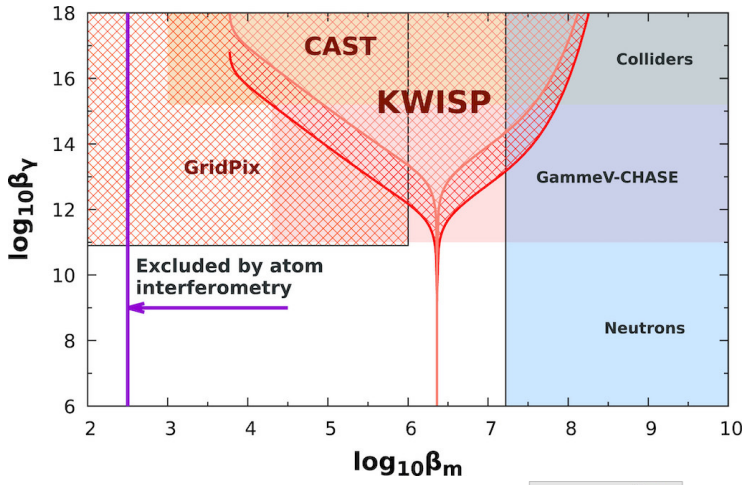
- *Scalar field*
  - *Dark energy candidate* PRD 69 044026 (2004)
- *Effective potential dependent on ambient matter / EM field*

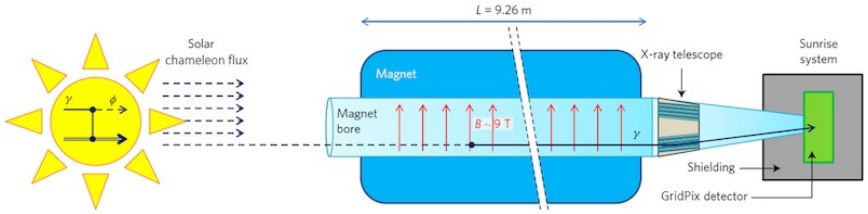
$$V_{eff}(\phi,\vec{r}) = \Lambda^4 e^{\frac{\Lambda^n}{\phi^n}} + e^{\frac{\beta_m}{M_{Pl}}\phi}\rho_m(\vec{r}) + e^{\frac{\beta_\gamma}{M_{Pl}}\phi}\rho_\gamma(\vec{r})$$

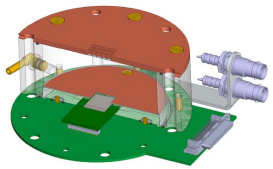
Matter coupling Photon coupling

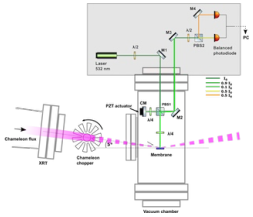
- *Searches*
  - *Afterglow effect*
    - *GammeV, CHASE, ADMX, …*
  - *Solar chameleon*
    - *Similar to solar axion search*
    - *CAST ($\phi-\gamma$) and KWISP ($\phi-m$)*
    - $P_{\phi\to\gamma,m} \propto \beta_{\gamma,m}^2 B^2 L^2$

Phys. Dark Univ. 26 100367 (2019)





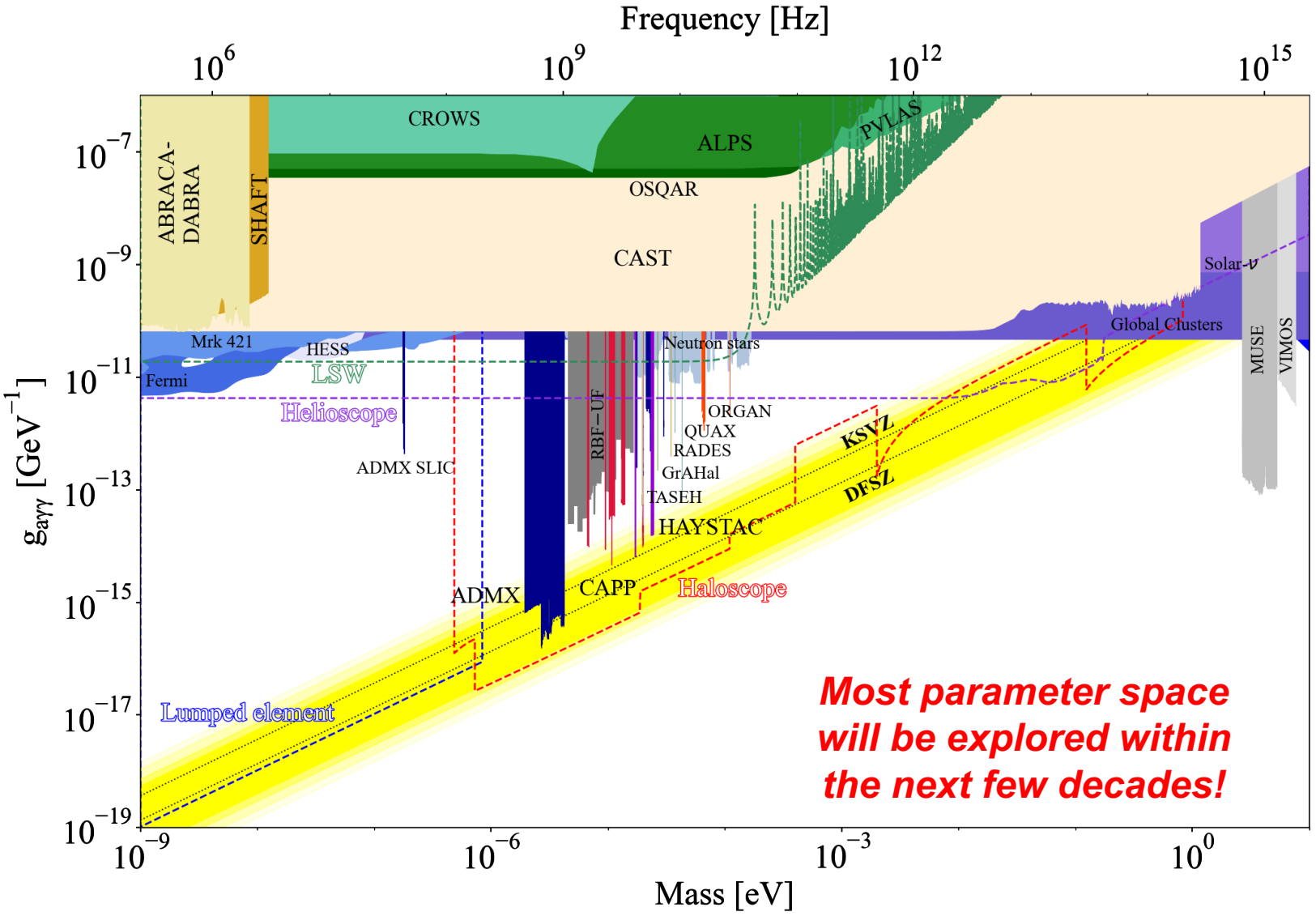




New ideas

- *The piezoaxionic effect (A. Madden, Mon)*
- *WISPFI: Searching for ALPs-photon conversion on fiber interferometer (J. M. B. Berenguer, Tue)*
- *T-RAX: Transvers Resonant Axion eXperiment (C. Lee, Thu)*
- *New axion dark matter search technologies (M. Tobar, Thu)*
- *Searching for wavelike dark matter with SRF cavities (R. Cervantes, Thu)*
- *Radiometric broadband searches for light dark matter with BRASS-p (L. H. Nguyen, Fri)*
- *WISPLC: Search for Dark Matter with LC Circuit (Z. Zhang et al. Mon)*

Axion searches – future



Conclusion

- *Axions and WISPs are leading candidates for dark matter*
  - *QCD axions solves the strong CP problem*
- *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 (during the workshop)*
- *Next a few decades must be critical/exciting*
  - *Covering a substantial portion of the parameter space*
  - *Uncovering the nature of dark matter*