Recent developments on wave dark matter

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27th LHC Mini-Workshop

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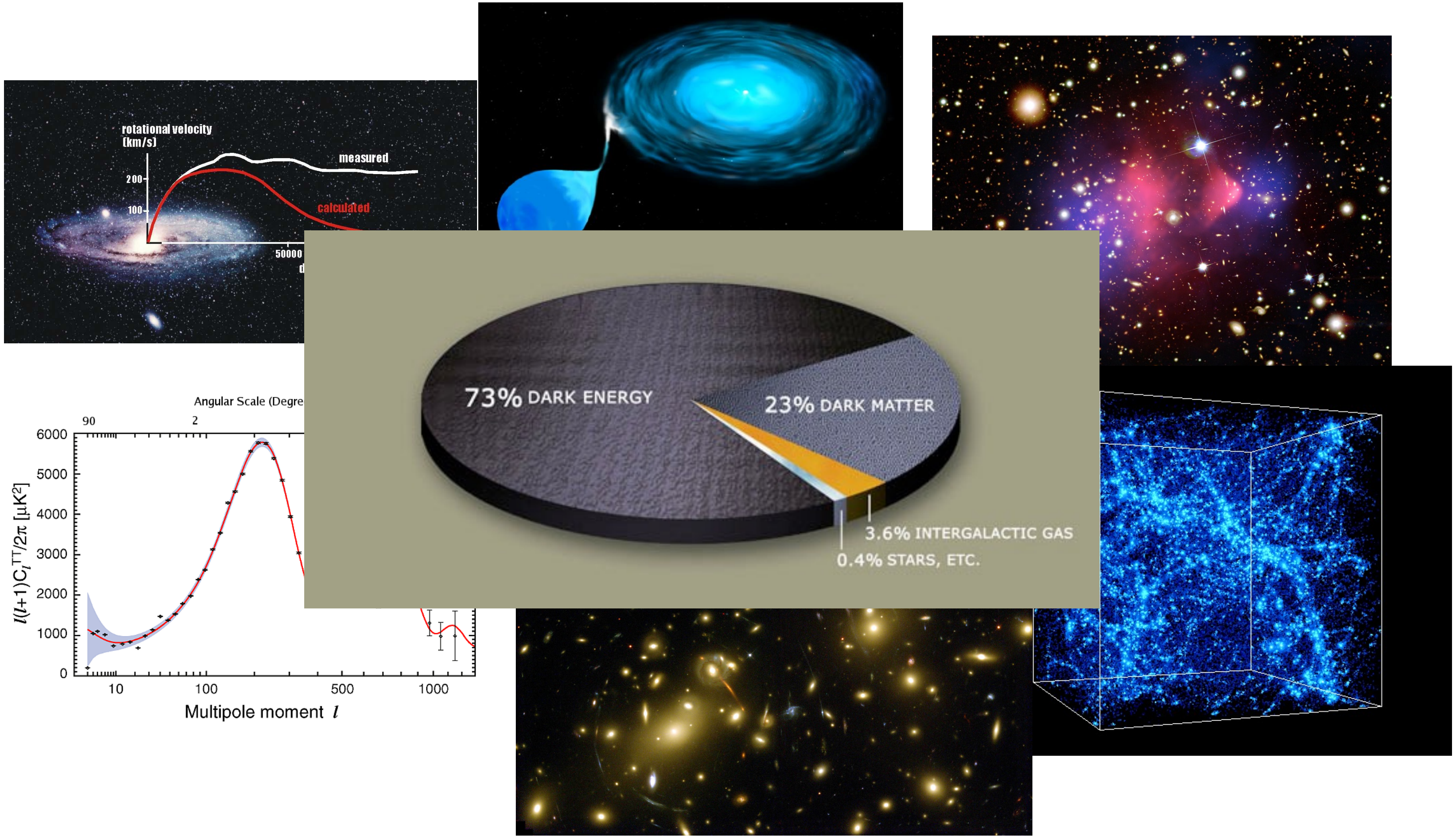
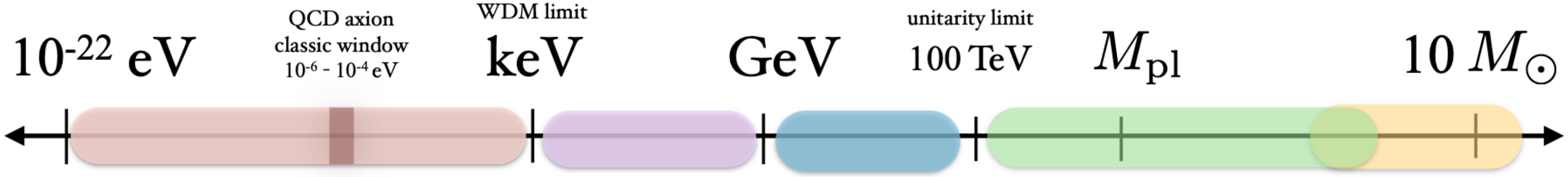
Evidence for dark matter



Theories of dark matter



``Ultralight" DM

non-thermal
bosonic fields

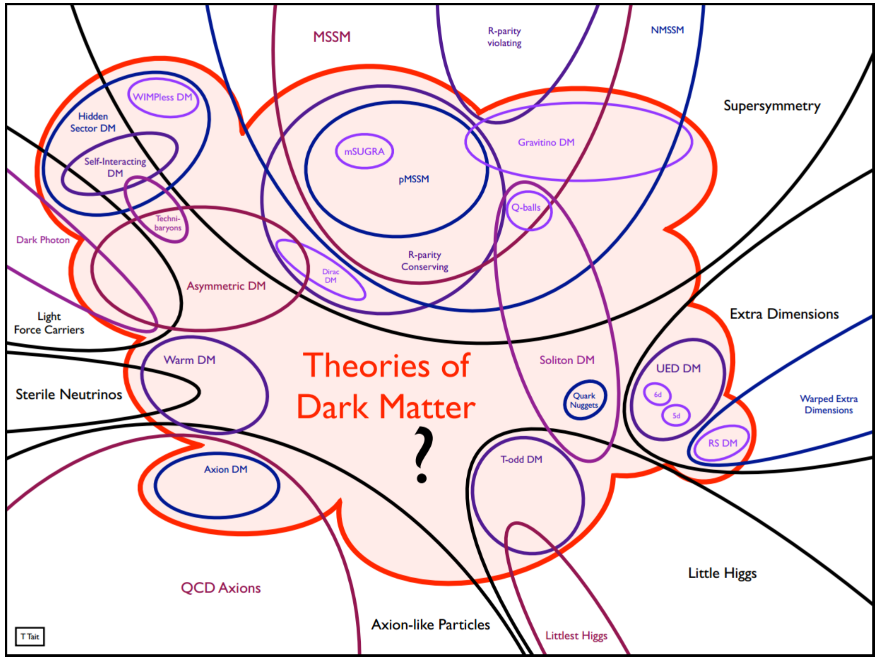
``Light" DM

dark sectors
sterile ν
can be thermal

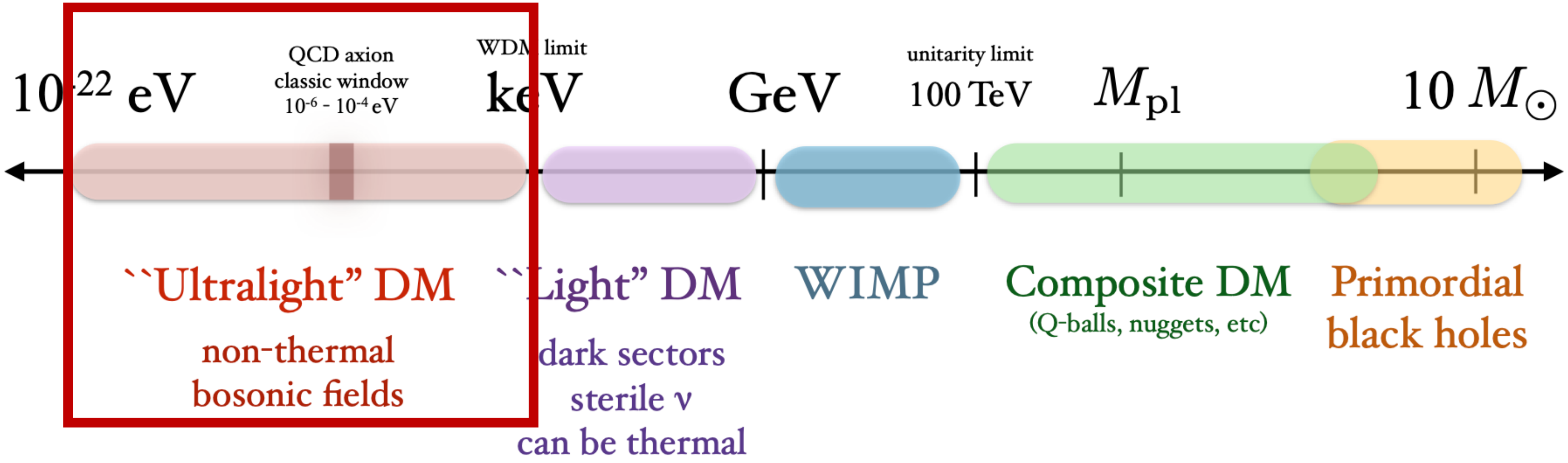
WIMP

Composite DM
(Q-balls, nuggets, etc)

Primordial
black holes



Ultralight dark matters

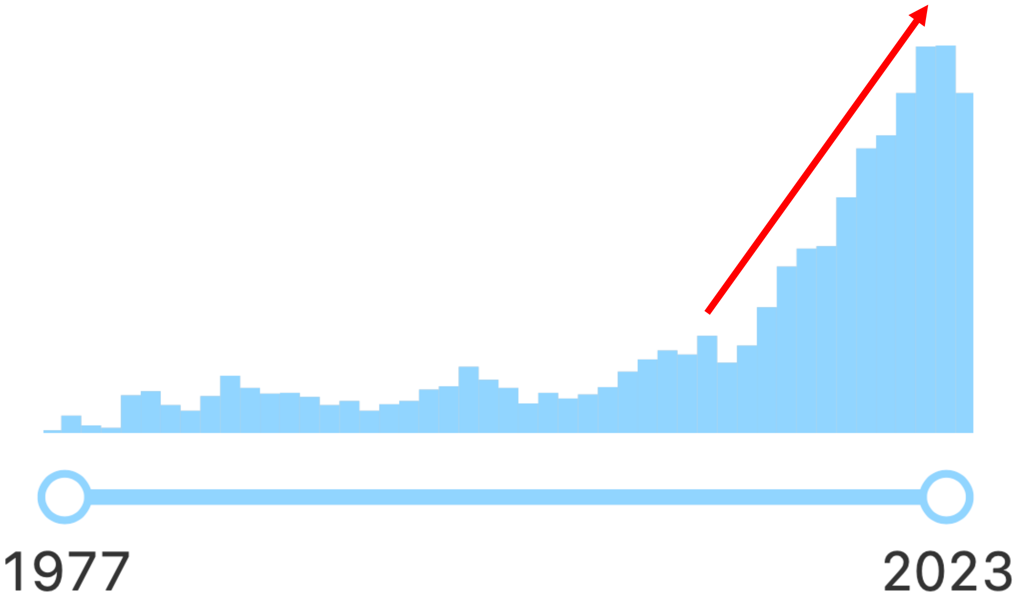


- Axion and axion-like particles

$$aF_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \partial_\mu a\bar{N}\gamma^\mu\gamma_5 N \qquad \partial_\mu a\bar{e}\gamma^\mu\gamma_5 e$$

- Dark photons

$$-\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \qquad A'_\mu(J^\mu_B - J^\mu_L) \qquad A'_\mu(J^\mu_\mu - J^\mu_\tau)$$



Outline

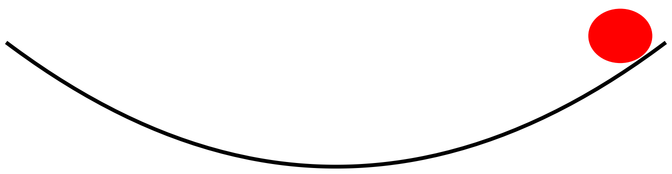
- Basics of axion DM and dark photon DM
- Searches for axion DM
- Searches for dark photon DM
- Theoretical developments
  - QCD axions
  - Dark photon production
- Summary

Axion and dark photon DM

- Dark matter with mass smaller than about 200 eV must not be fermions.
- Axion, a pseudo-scalar particle
- Dark photon, a vector particle mixing with photon
- Produced in the early universe (e.g. misalignment)

Wave DM vs particle DM

- Particle DM:
  - $\rho \approx n_{DM} m_{DM}$
  - $p \approx 0$
- Wave DM:
  - $\rho \approx A^2 m_{DM}^2$
  - $p \approx A^2 m_{DM}^2 \cos 2m_{DM}t$
- We can observe the difference when the observation time scale is smaller than m_{DM}^{-1}.



Searches for axions

- It is a pseudo-scalar field.
- It can interact with all the fields in the standard model.

$g\,a\,\mathbf{E}\cdot\mathbf{B}$

- Primakov effect
- Axion mixing with photon
- Birefringence

$g\,\mathbf{E}\cdot\mathbf{d}_{\mathrm{e}}$

Oscillating electric dipole moment

$\mathbf{d}_{\mathrm{e}} \sim a \times \mathrm{spin}$

$g\,\partial_\mu a\,\bar{e}\gamma^\mu\gamma_5 e$

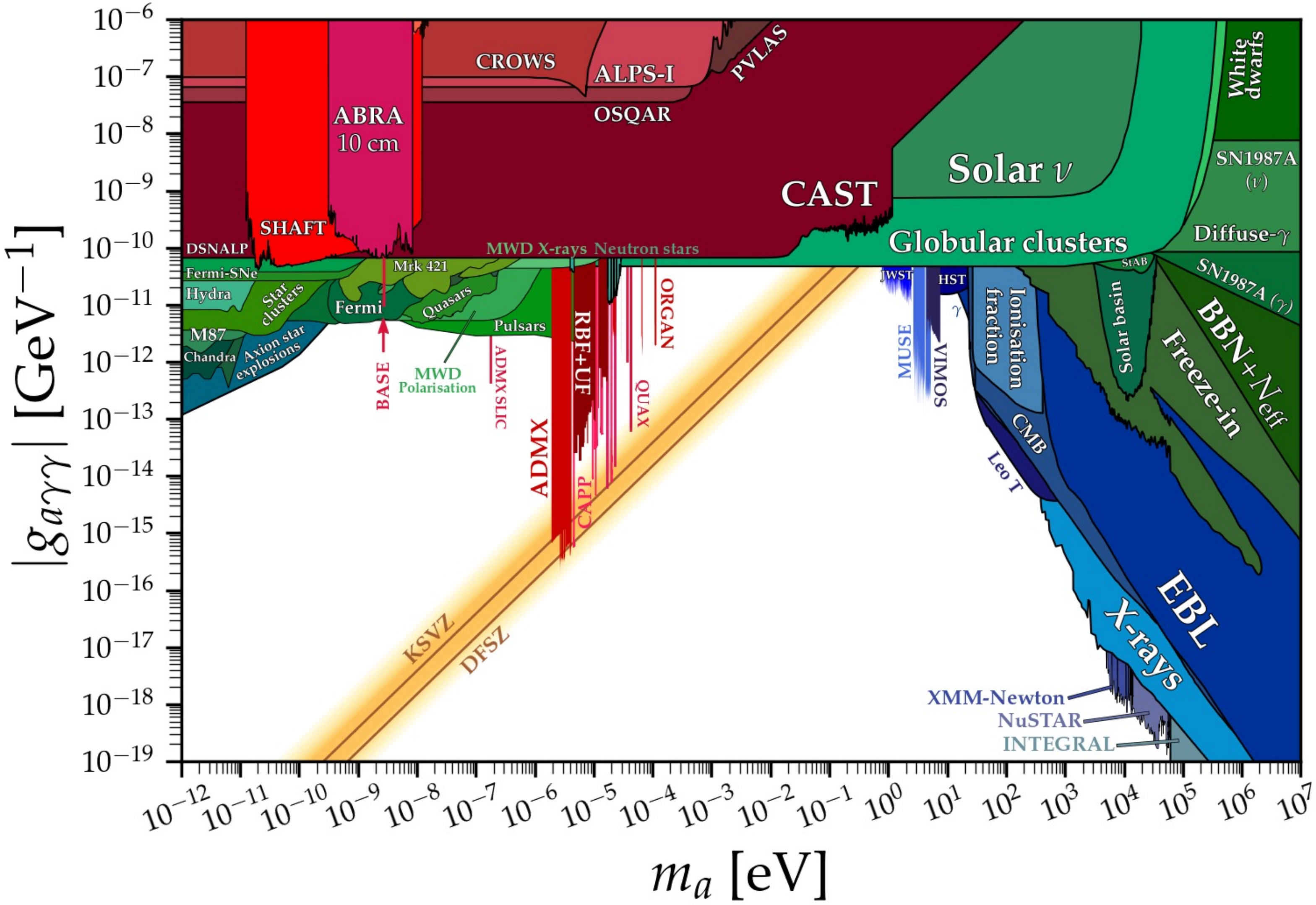
- Compton scattering
- Axion-electron effect

$g\,\partial_\mu a\,\bar{N}\gamma^\mu\gamma_5 N$

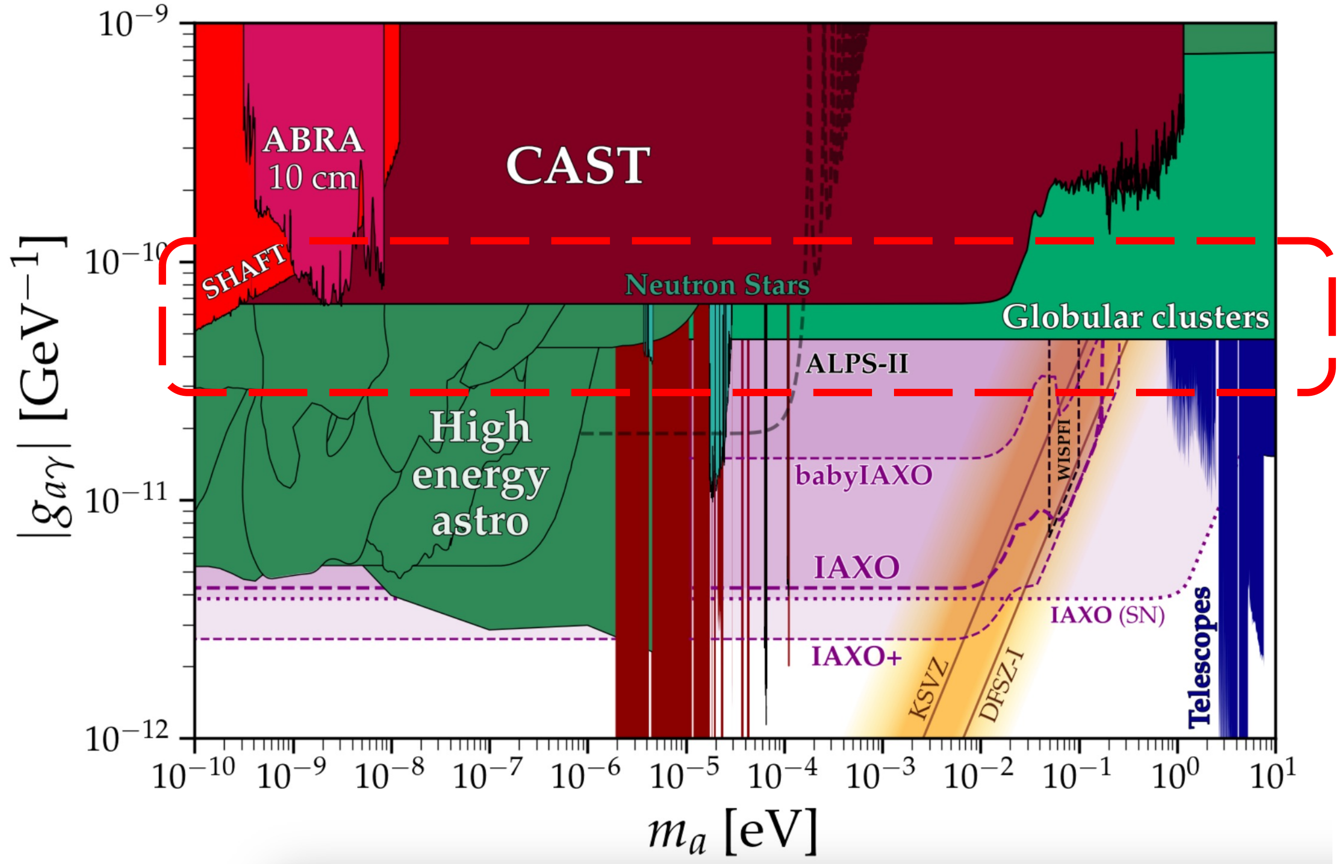
Axion bremstrahlung

…

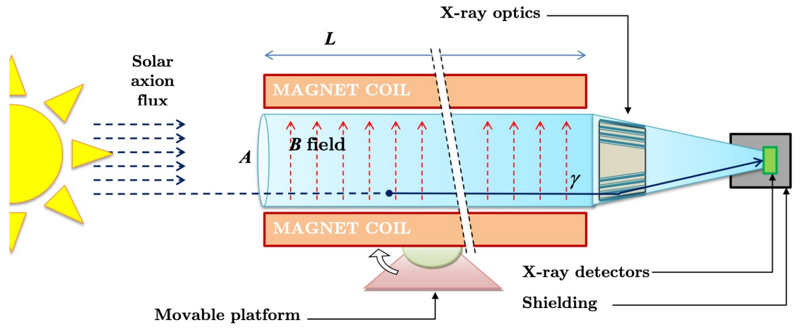
Axion interaction with photons



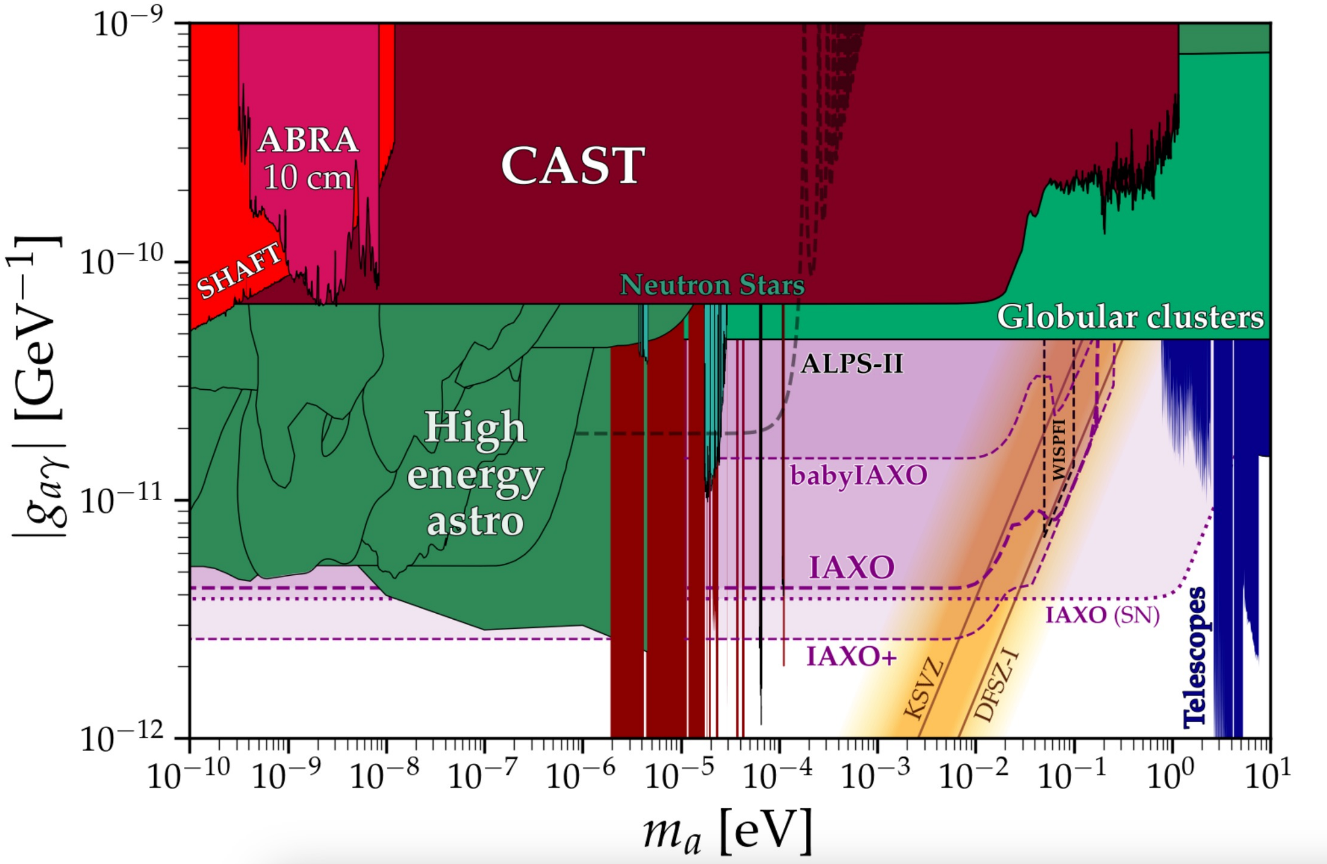
Axion interaction with photons



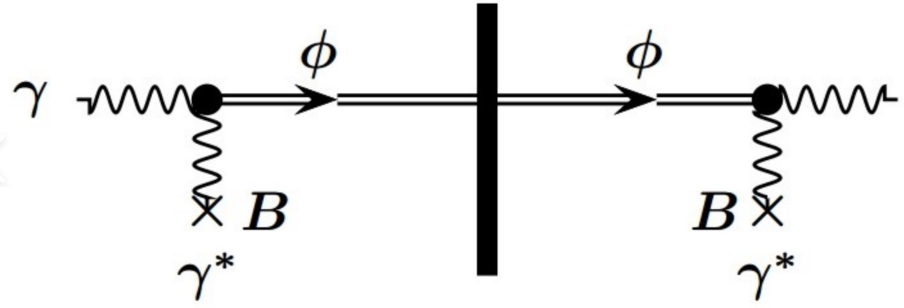
- Star cooling, astrophysics
- Helioscope



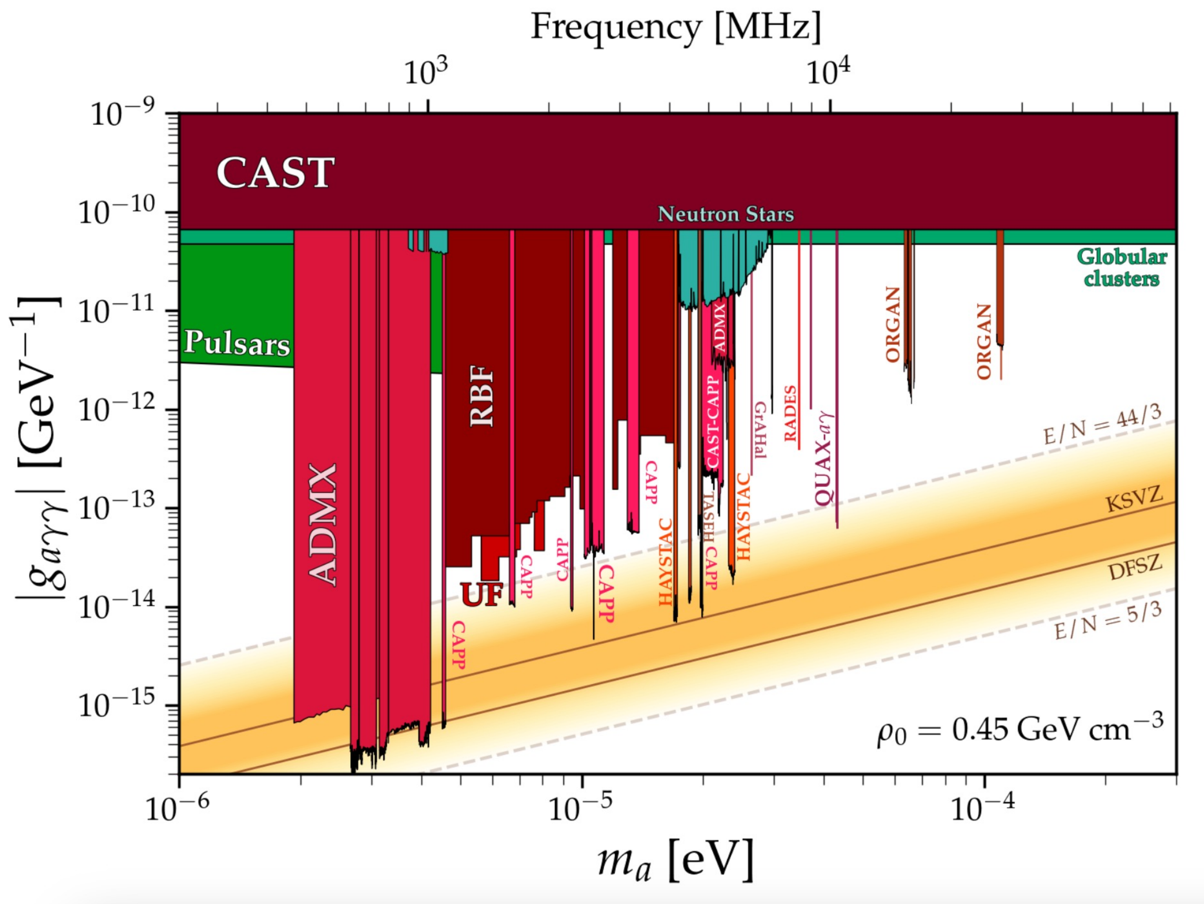
Axion interaction with photons



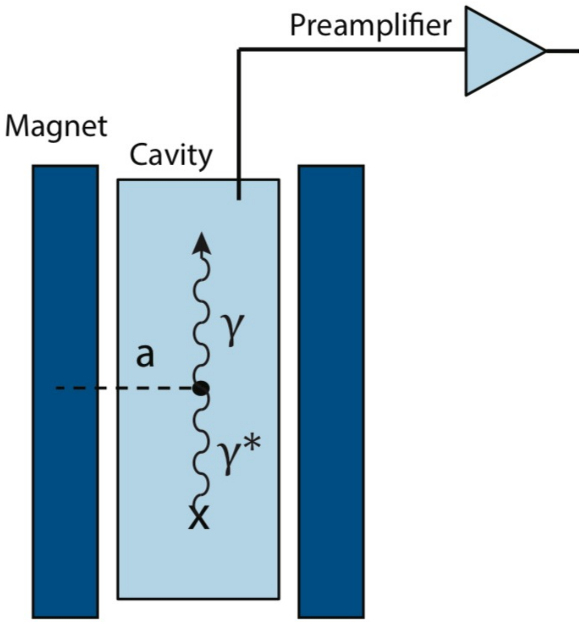
- Light shining through the wall



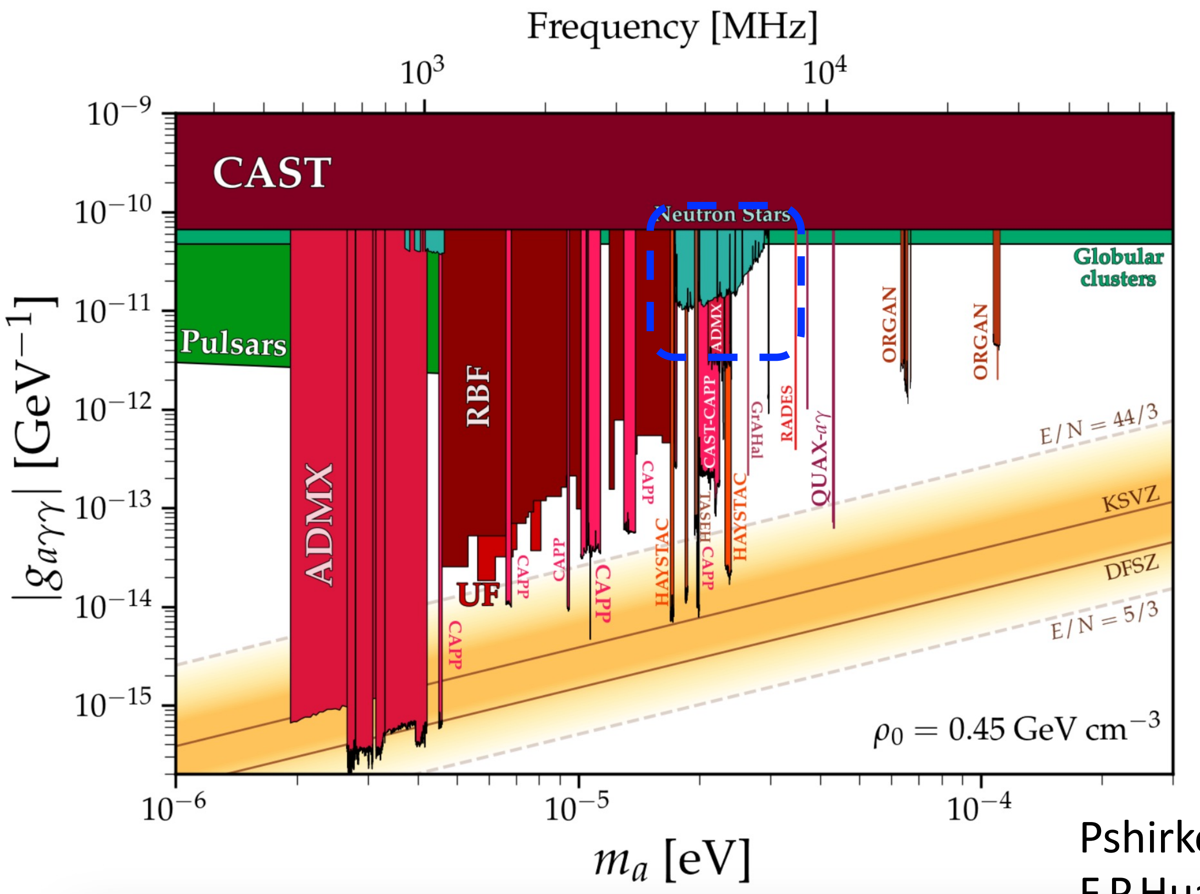
Axion interaction with photons



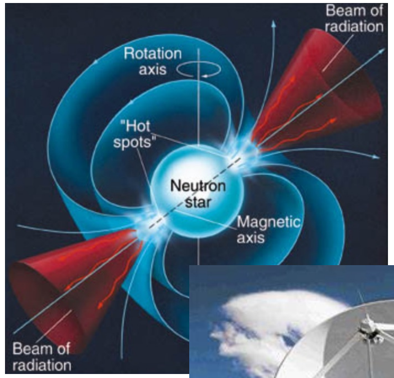
- Resonant chamber
  10^{-5} eV $\rightarrow$ 12 cm



Axion interaction with photons



- Neutron stars

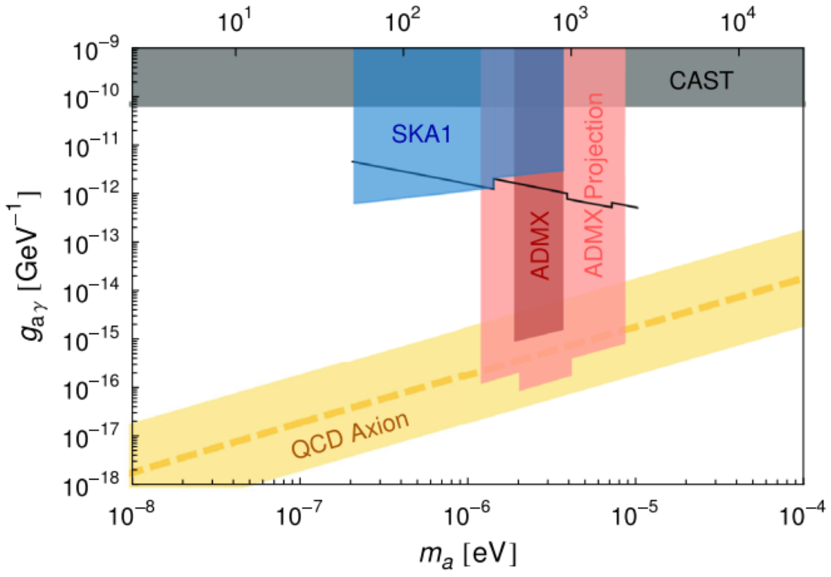


Pshirkov, Popov, 0711.1264
F.P.Huang et al. PRD 97 (2018) 123001
Hook, Kahn, Safdi, Sun, PRL 121 (2018) 241102

What about white dwarves?

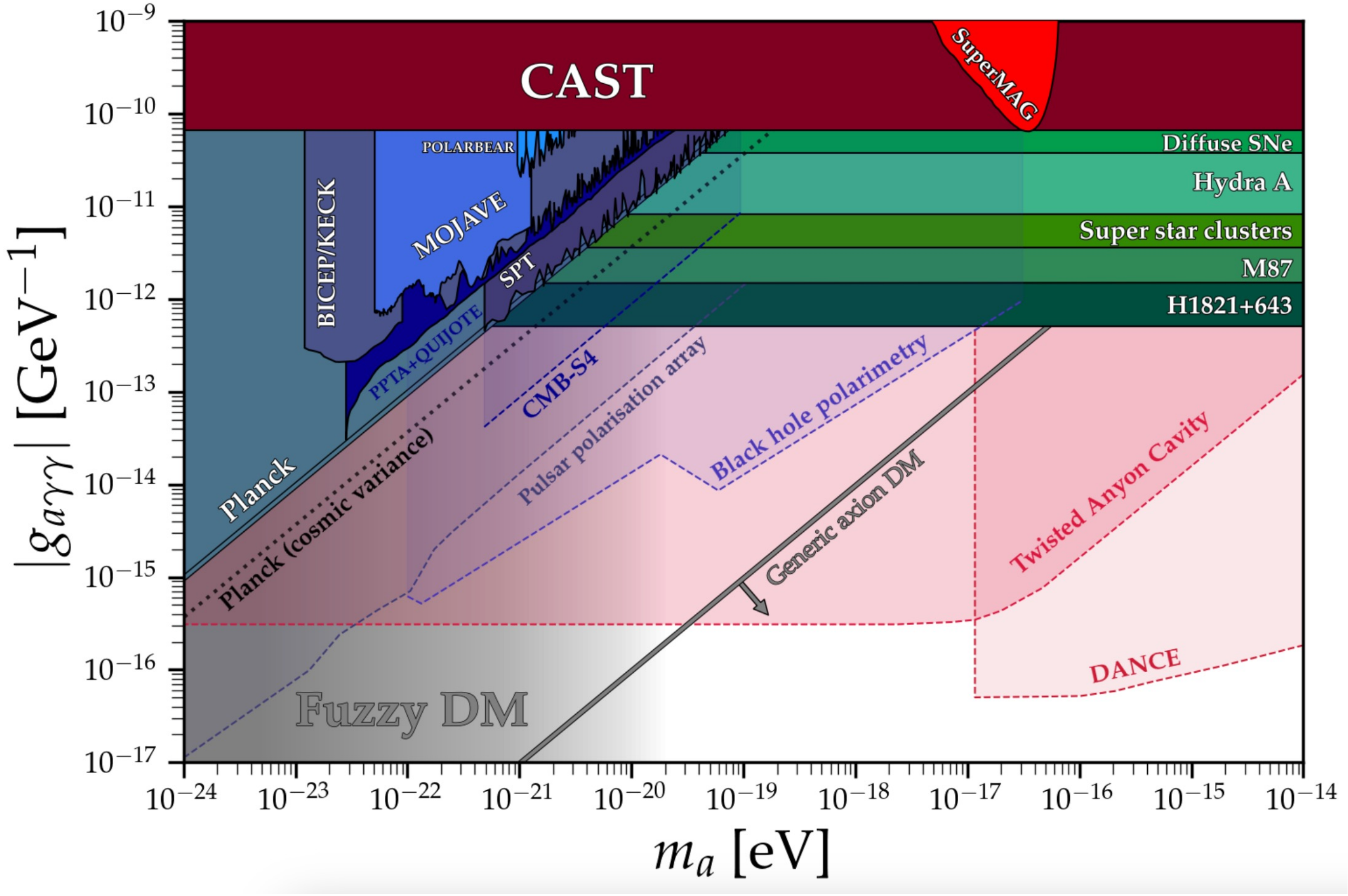
	Neutron Star	White Dwarf
Magnetic field	$\sim 10^{10} - 10^{14}$ Gauss	~10^7 Gauss
Radius	10 km	10^4 km

- $S_{sig} \sim R^3 B_0^2$
- The signal from white dwarves can be as strong as from neutron stars.



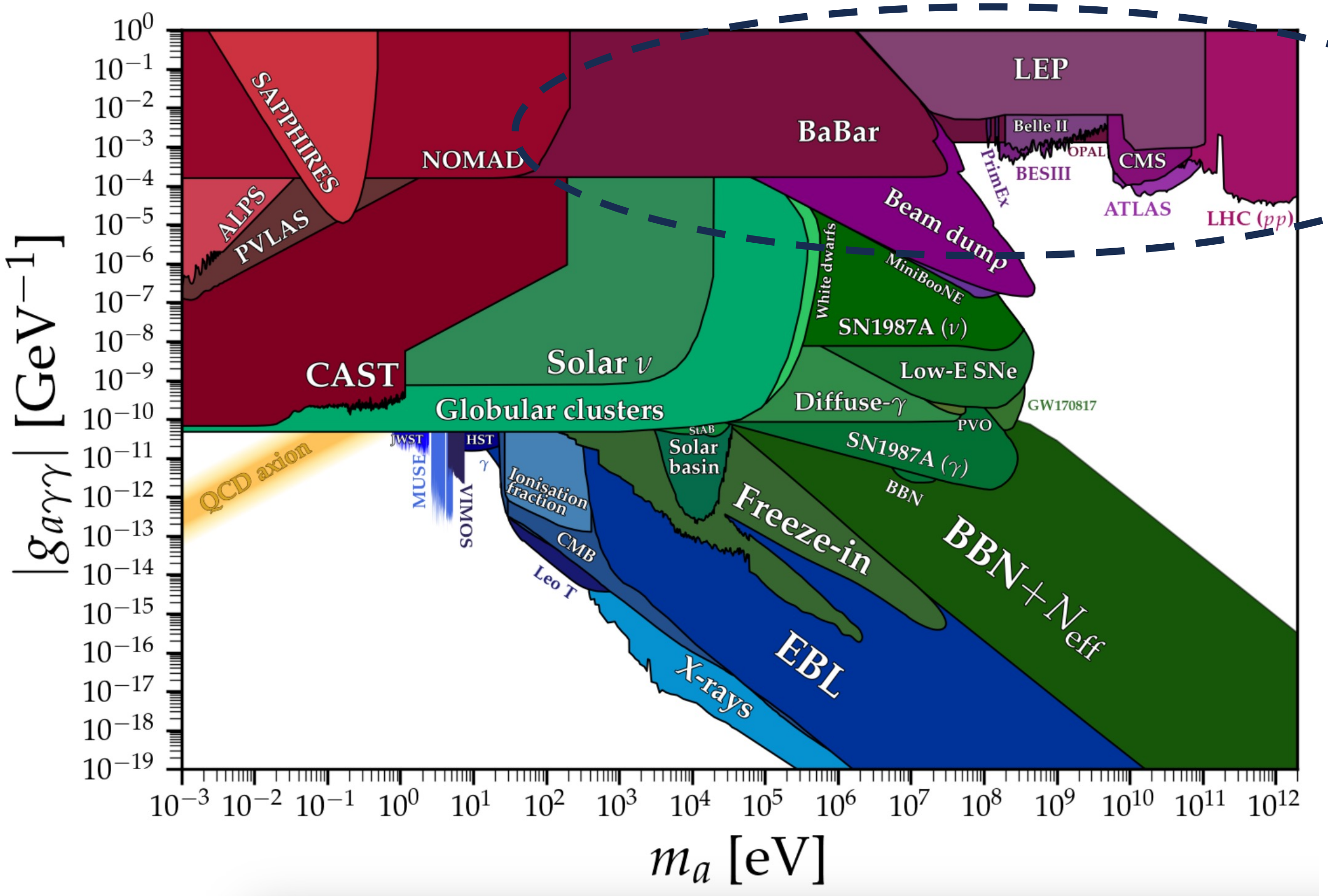
Wang, Bi, Yao, Yin, 2101.02585

Axion interaction with photons



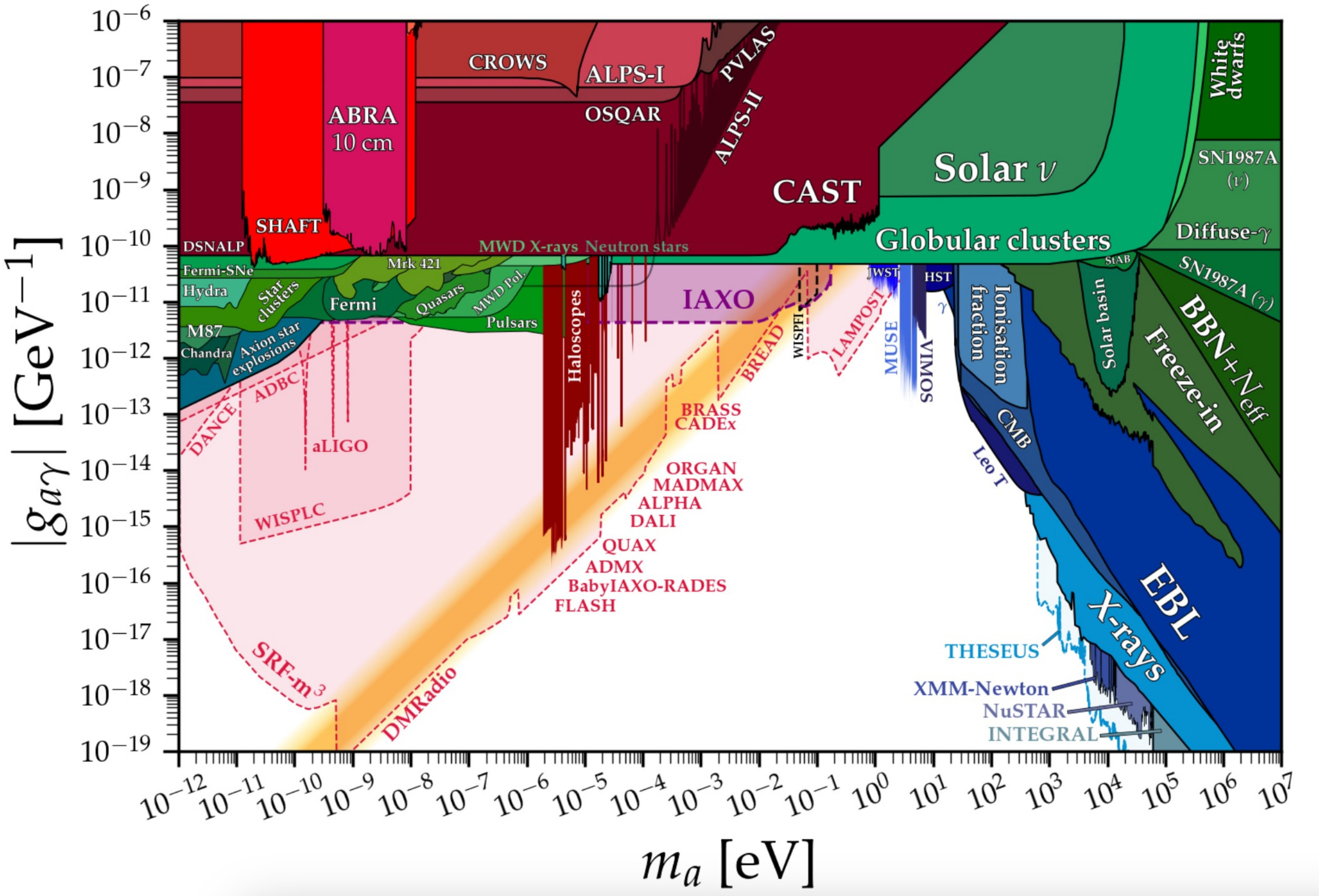
- Photon-axion conversion in magnetic field

Axion interaction with photons

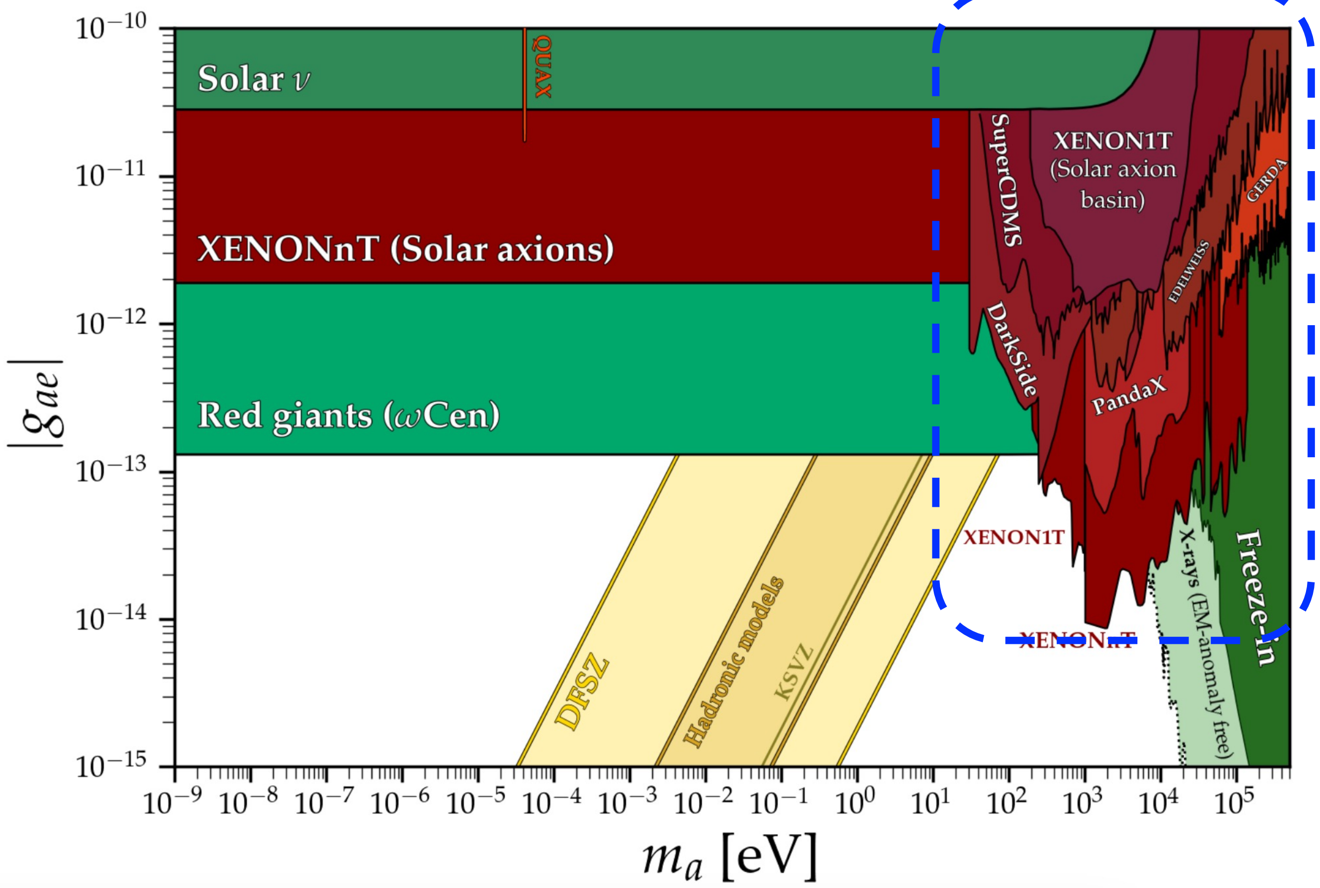


- Collider bound

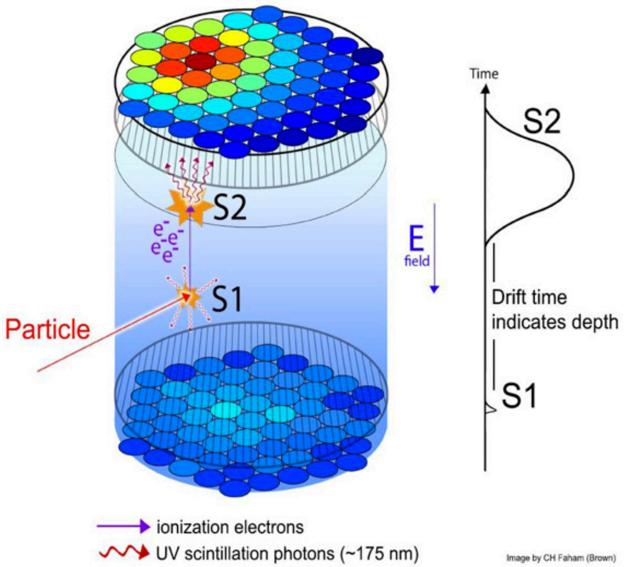
Axion interaction with photons



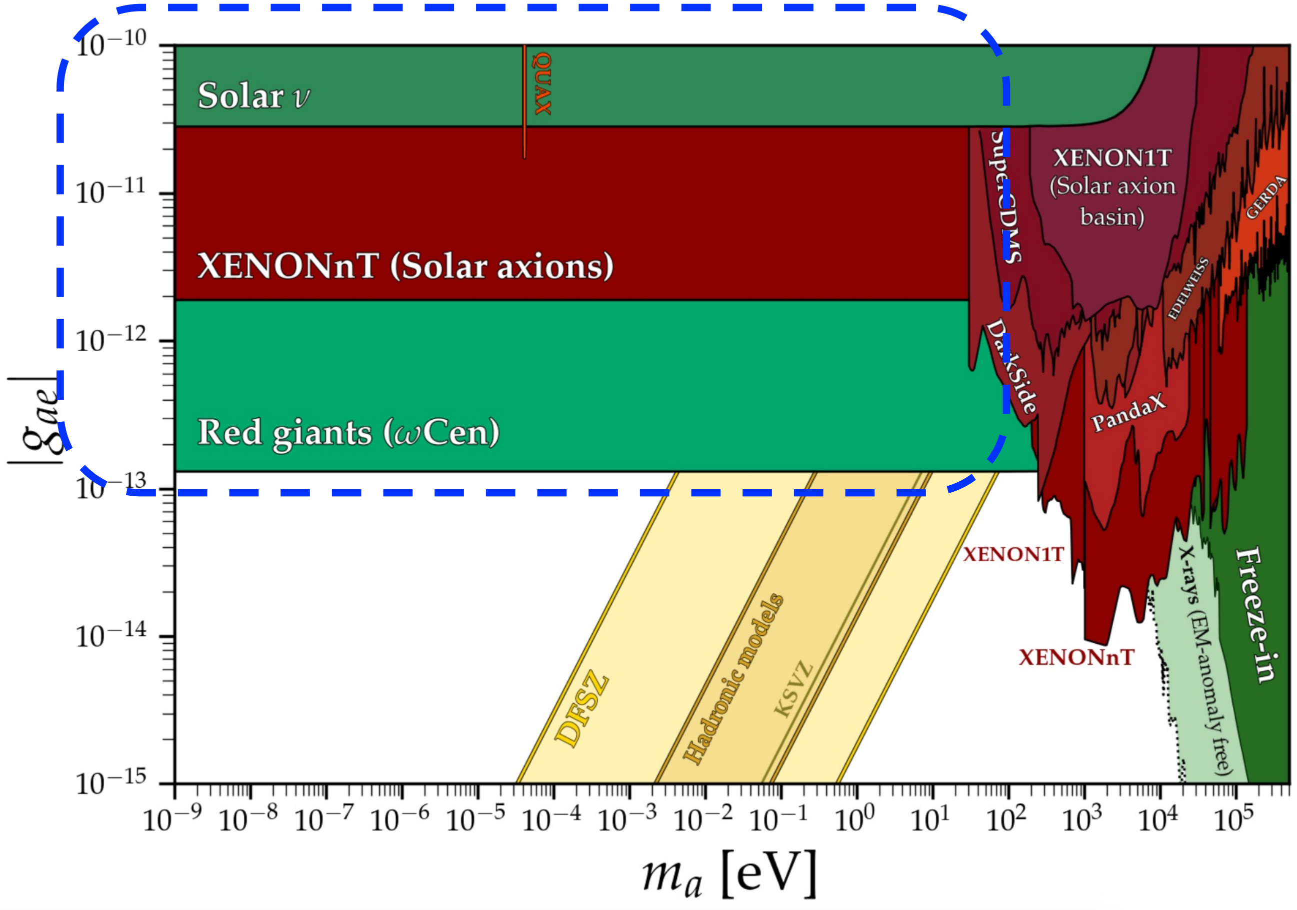
Axion interaction with electrons



- Direct absorption in dark matter direct detection experiments.

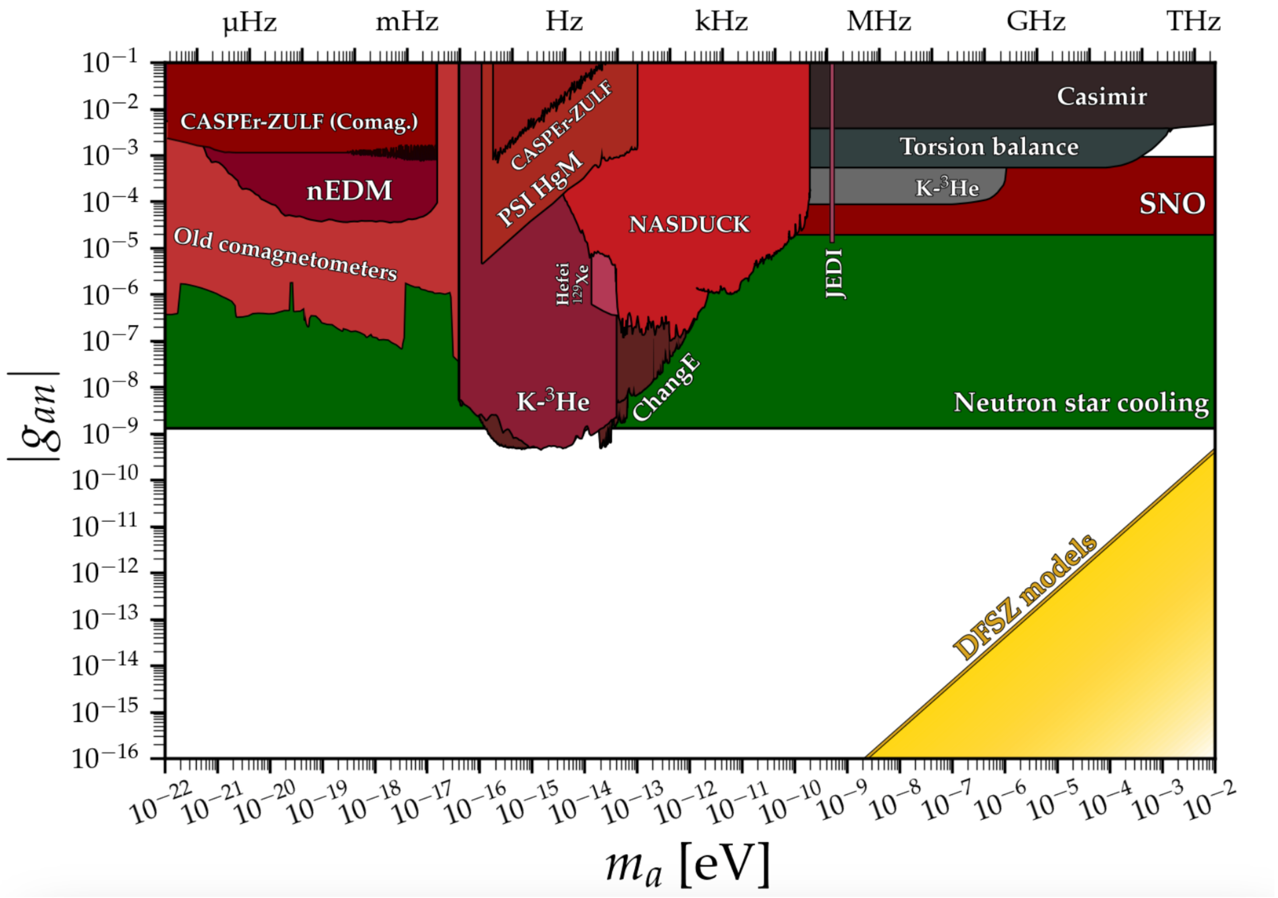


Axion interaction with electrons



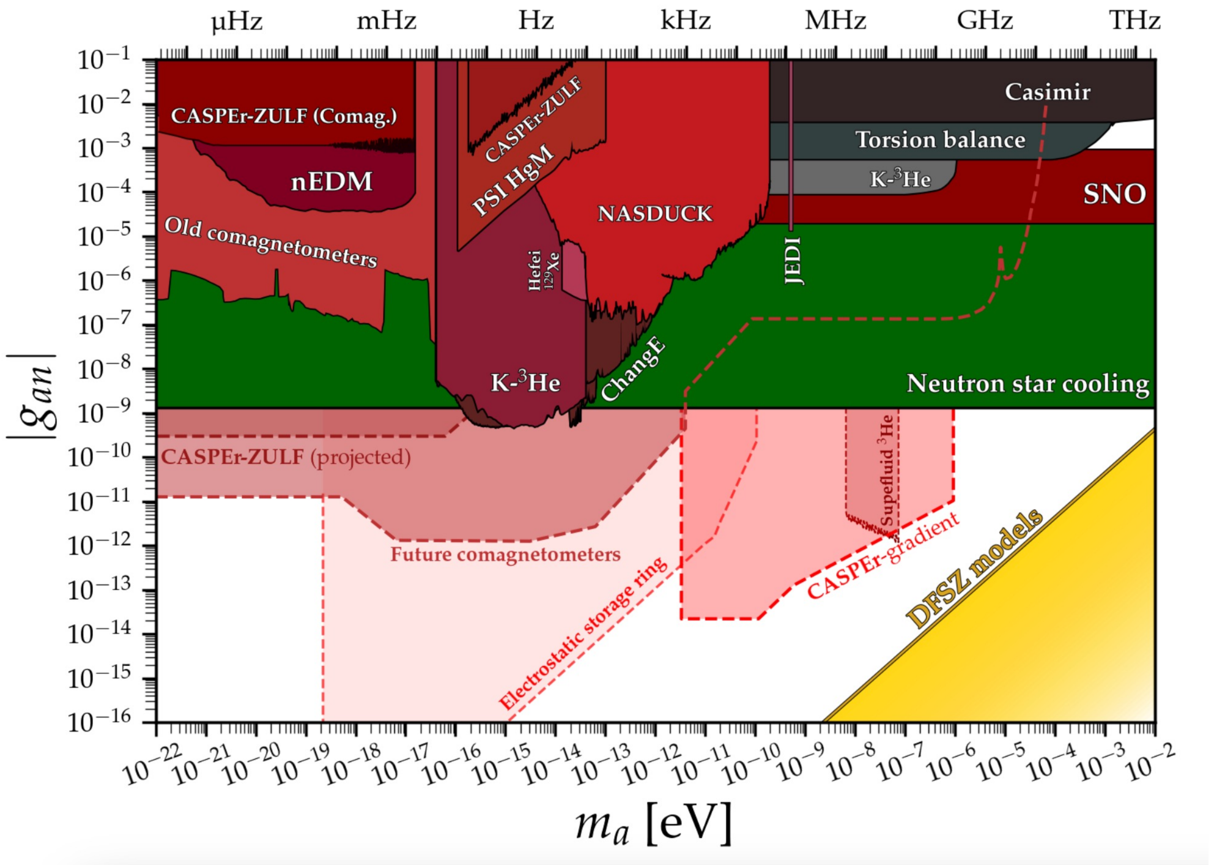
- Star cooling

Axion interaction with neutron

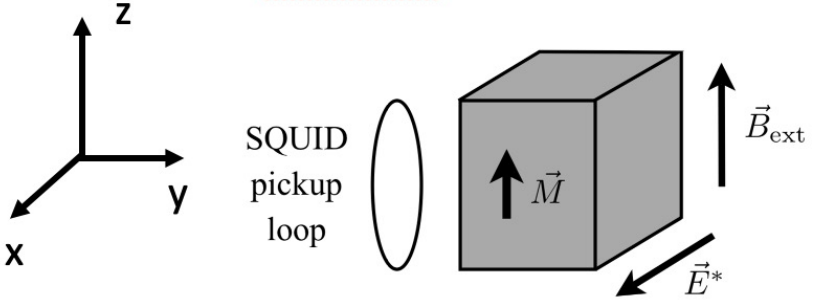


- Neutron star cooling

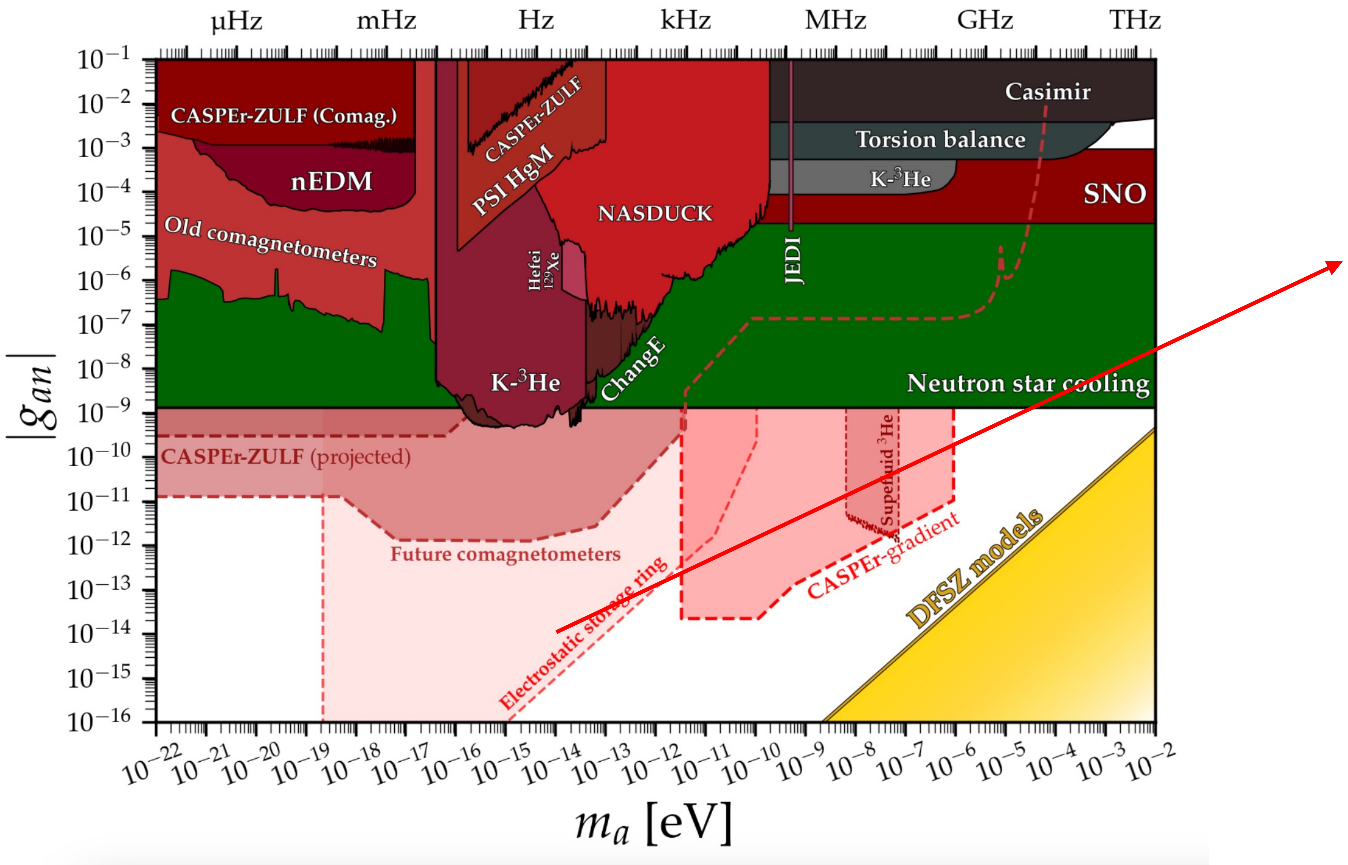
Axion interaction with neutron



CASPEr

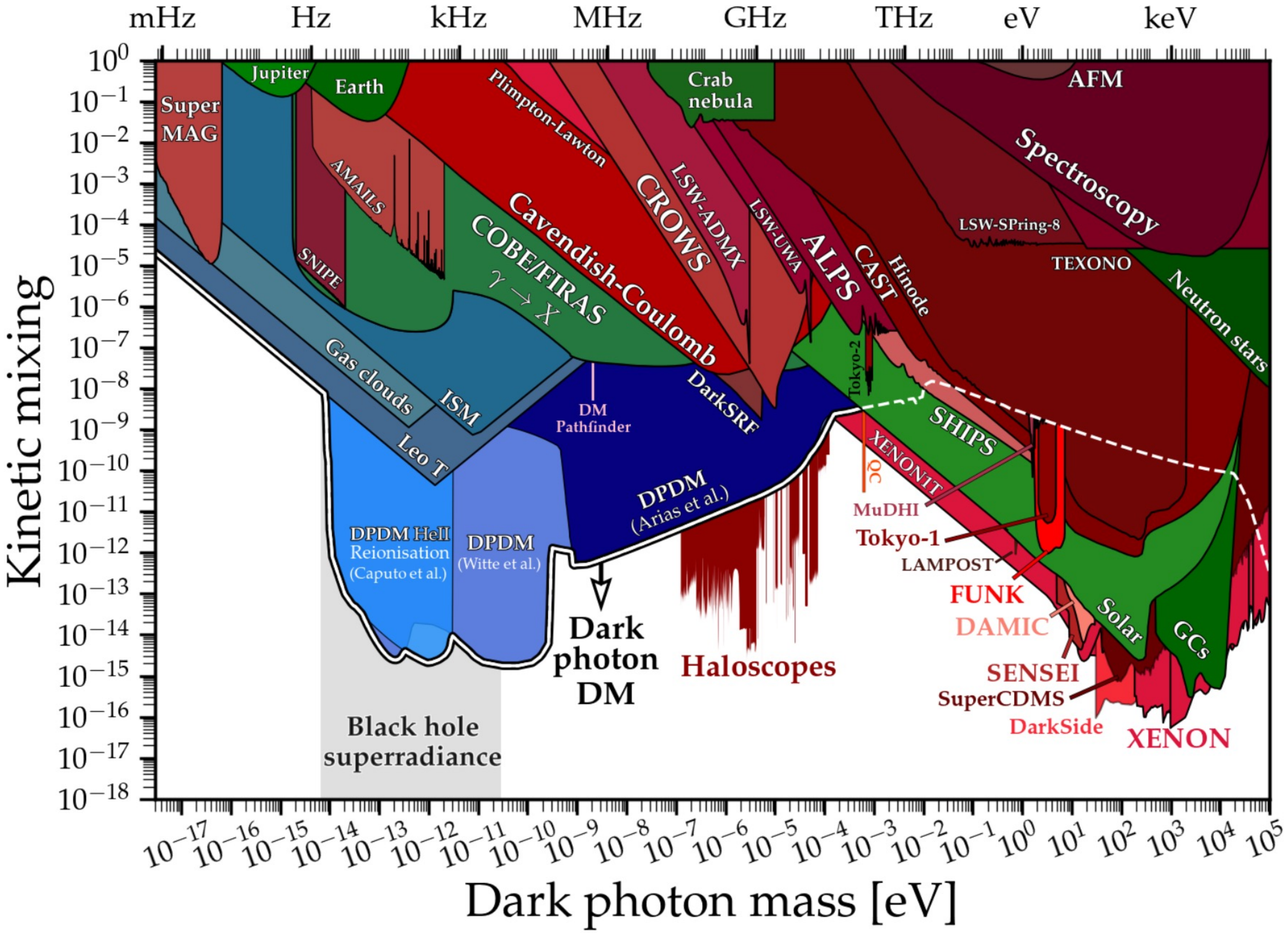


Axion interaction with neutron

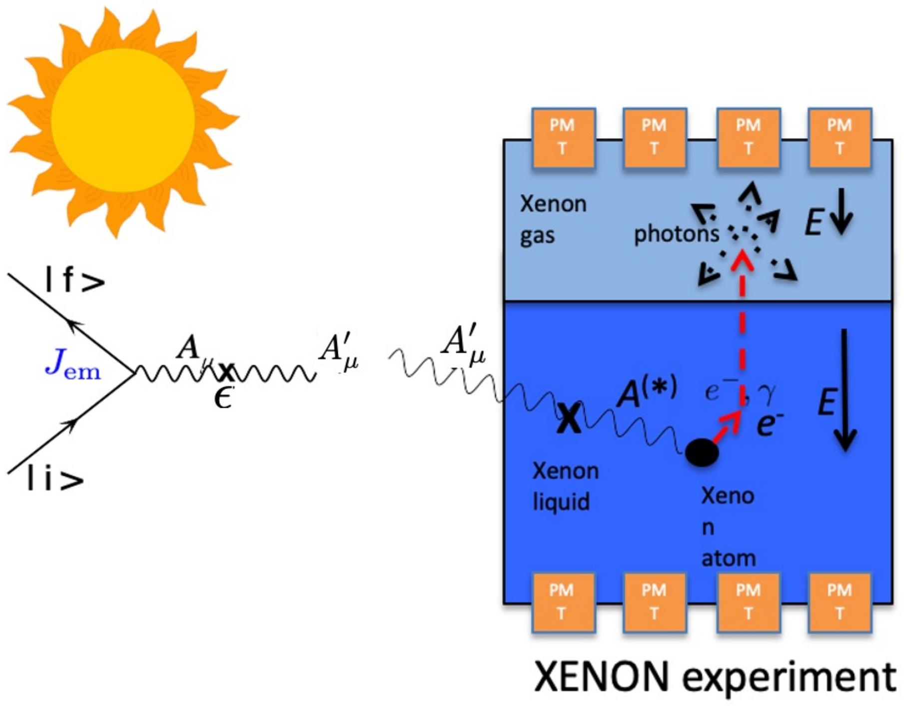


- Can measure 10^{-21} T magnetic field.

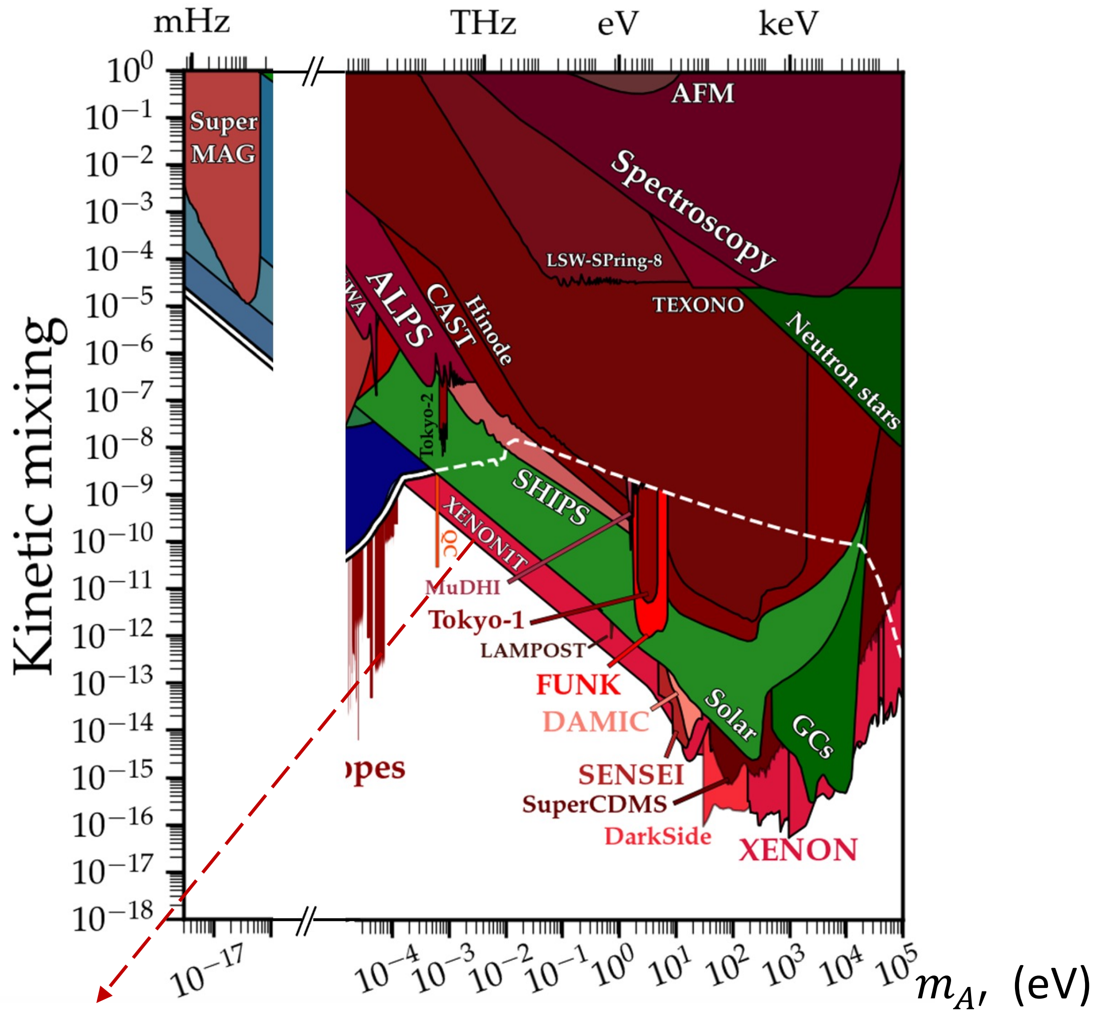
Searches for dark photon DM



Helioscopes for dark photon

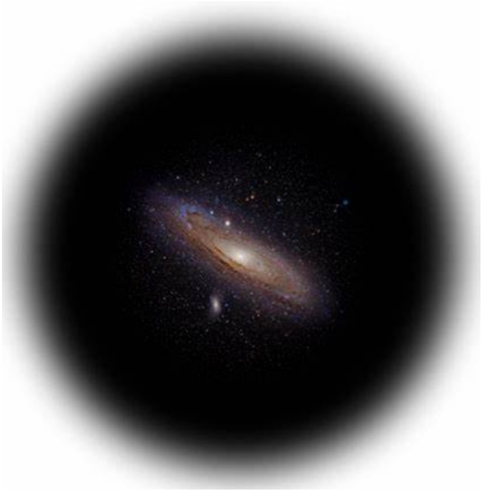


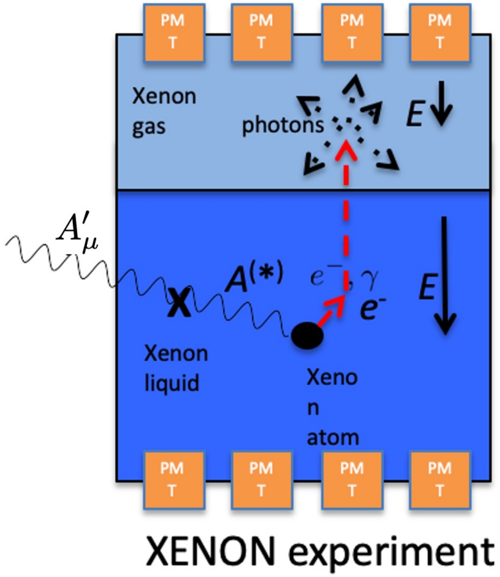
HA, Pospelov, Pradler, PLB 725 (2013) 190, & PRL 111 (2013) 041302



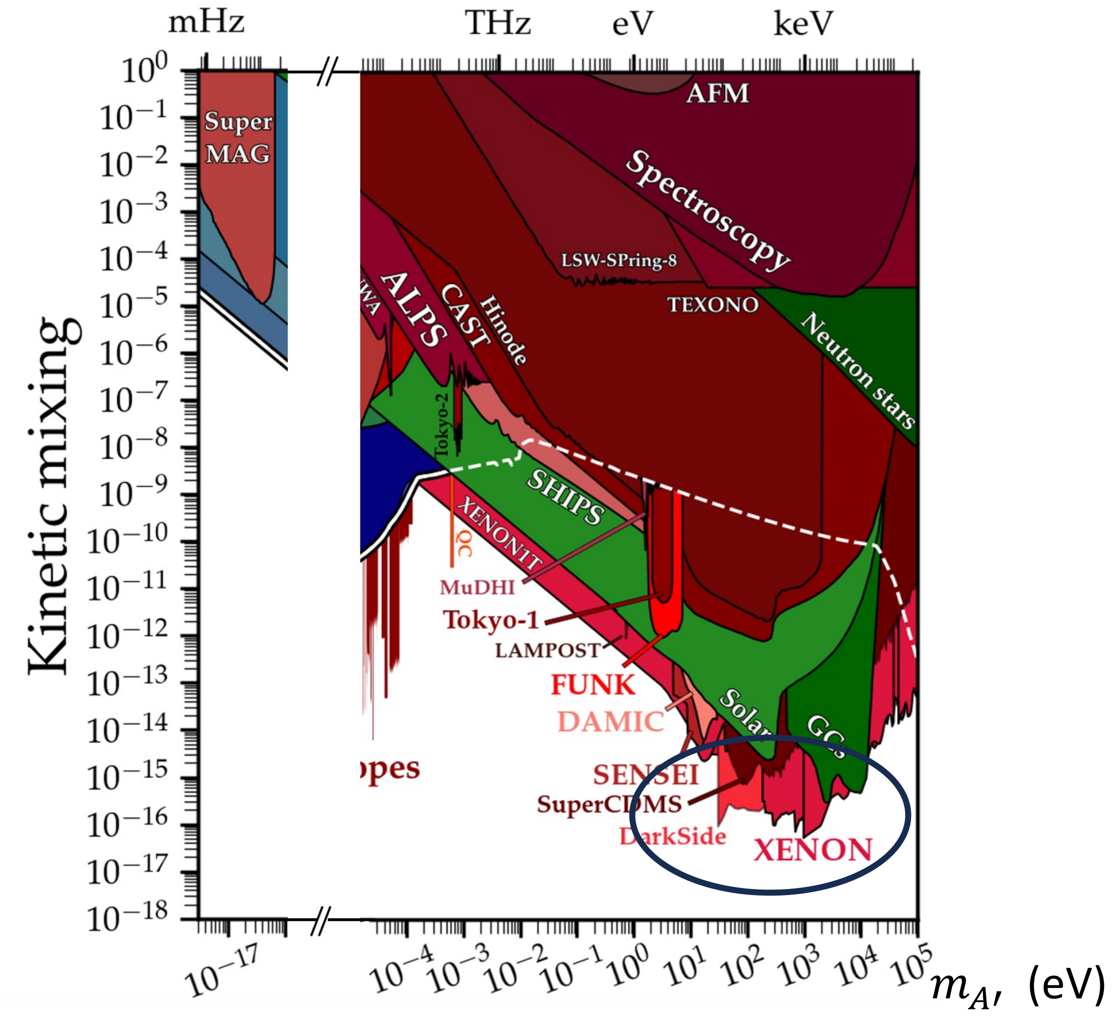
HA, Pospelov, Pradler, Ritz, PRD 102 (2020) 115022
XENON1T, PRD 106 (2021) 022001

Searching for ultralight dark matter directly with WIMP detectors

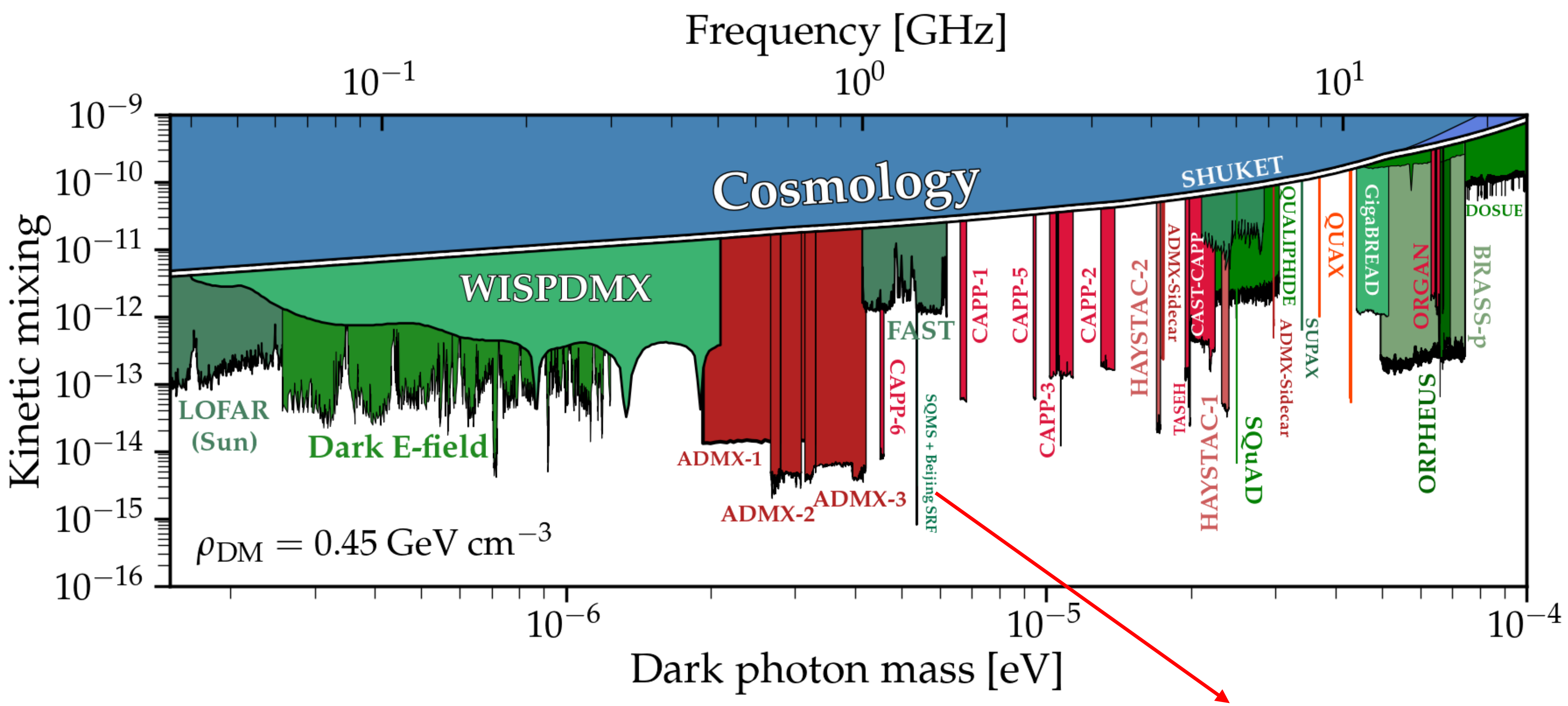


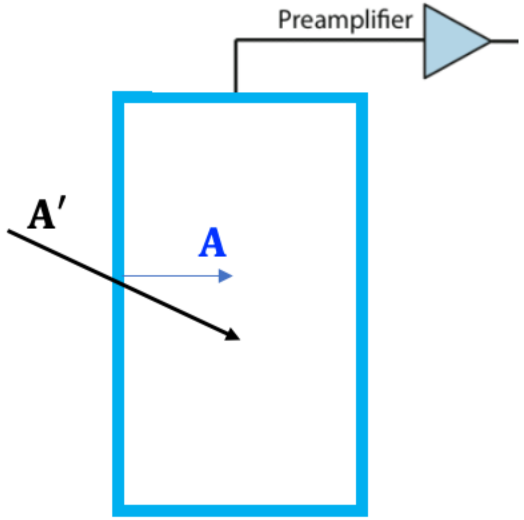


HA, Pospelov, Pradler, Ritz, PLB 747 (2015) 190-195



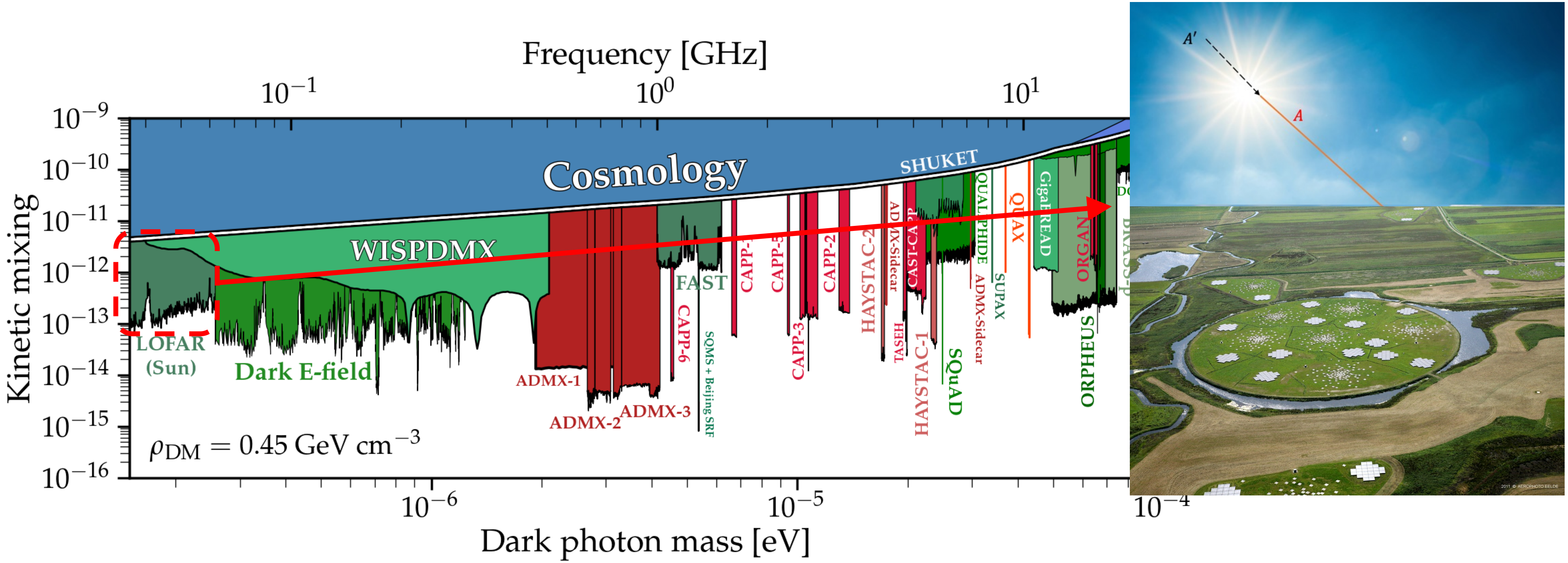
Resonant cavities for dark photon dark matter





Jing Shu's experiment

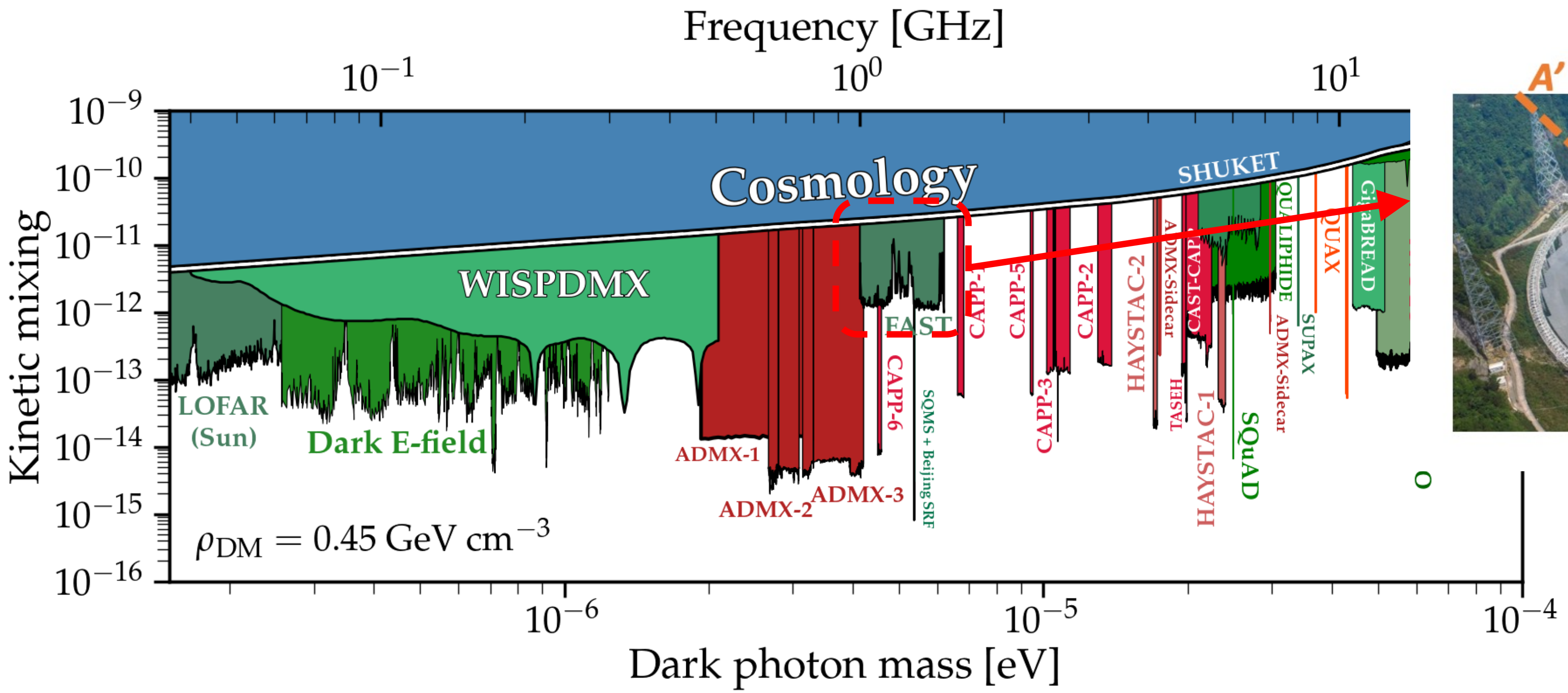
Resonant cavities for dark photon dark matter

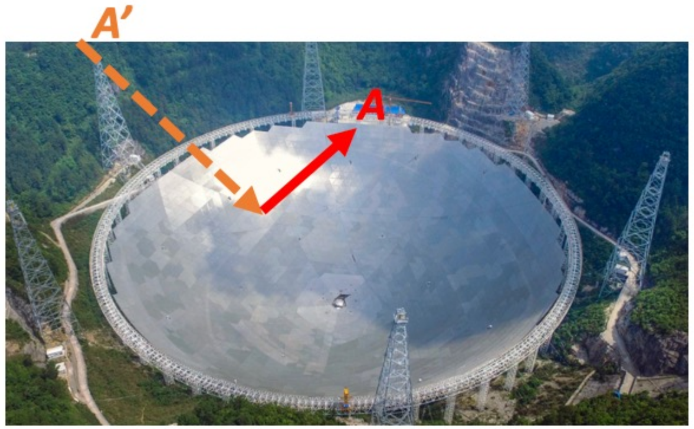


HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

HA, X. Chen, S. Ge, J. Liu, Y. Luo, 2301.03622, accepted by Nature Communications

Resonant cavities for dark photon dark matter



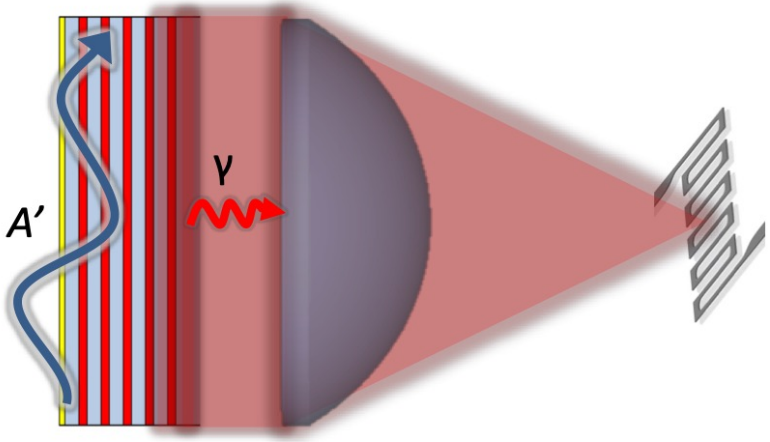


HA, S. Ge, W.-Q. Guo, X. Huang, J. Liu, Z Lu, 2207.05767, PRL 130 (2023) 181001

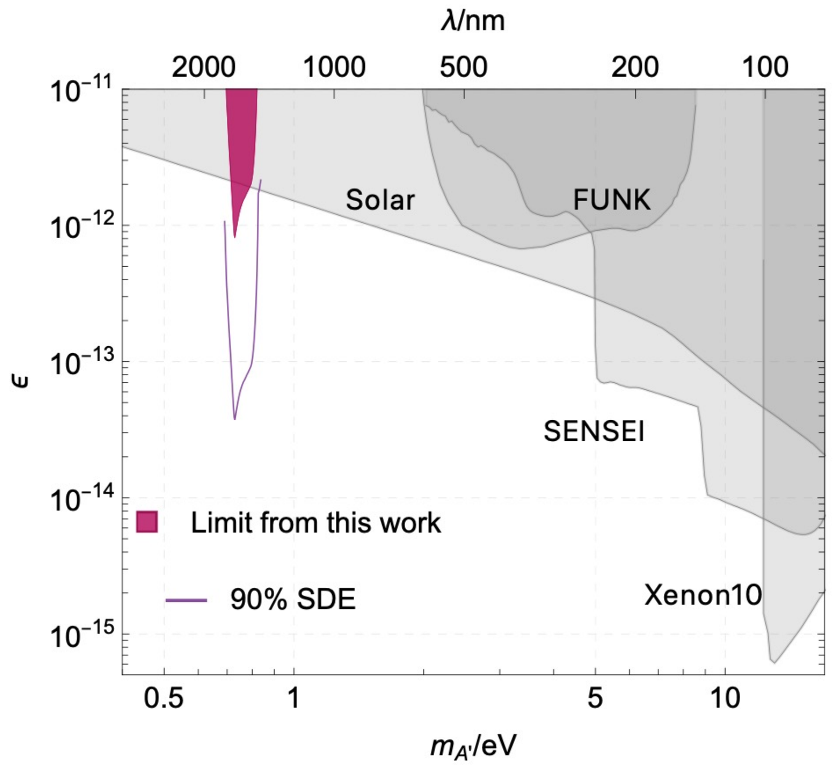
Searching for high frequency axions and dark photons with di-electric layers

- Dark photon dark matter oscillate to on-shell photons

A stack of dielectric layers, with alternating indices of refraction, provide a non-zero momentum for the photon to propagate.



Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006



LAMPOST, PRL 128 (2022) 231802

A little summary

- The searches for axions and dark photons are different.

- Axion and axion-like particles

$$a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \partial_\mu a \bar{N}\gamma^\mu\gamma_5 N \qquad \partial_\mu a \bar{e}\gamma^\mu\gamma_5 e$$

Dimension five operators

- Dark photons

$$-\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \qquad A'_\mu(J^\mu_B - J^\mu_L) \qquad A'_\mu(J^\mu_\mu - J^\mu_\tau)$$

Marginal operators

The QCD axion

- QCD Lagrangian

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q \gamma_5}\right) q - \frac{1}{4} G^{a\,\mu\nu} G^a_{\mu\nu} + \theta \frac{g_s^2}{32\pi^2} G^{a\,\mu\nu} \tilde{G}^a_{\mu\nu}$$

- θ term breaks P and CP, and causes the strong CP problem

- $E(\theta) = -2K e^{-\frac{8\pi^2}{g_s^2}} \cos\theta$ (only the instanton gas contribution included)

- Lift θ to a field to solve the problem, $\theta \to \theta + \frac{a(x)}{f}$

The axion quality problem

- $a(x)$ is a goldstone boson corresponding to a sponstaneously broken symmetry (Peccei-Quinn symmetry). $\Phi = \frac{1}{\sqrt{2}}(f_a + \rho_a)e^{ia/f_a}$.
- The axion potential caused by QCD is too shallow.
- All the global symmetries are broken by quantum gravity, we expect Planck scale suppressed operators to generate potential for axion.

$$-V^n_{\mathrm{PQ-break}} = \frac{\lambda_n |\Phi|^{2m} \left(e^{-i\delta_n}\Phi^n + e^{i\delta_n}\Phi^{\dagger n}\right)}{m_{\mathrm{Pl}}^{d-4}} \supset \frac{\lambda_n f_a^4}{2}\left(\frac{f_a}{\sqrt{2}m_{\mathrm{Pl}}}\right)^{d-4} \cos\left(\frac{na}{f_a} - \delta_n\right)$$

- Requires $d \geq 8, 10, 12$ for $f_a \sim 10^8, 10^{10}, 10^{15}$ GeV.

Solutions to axion quality problem

- Gauge potection

Introduce more gauge symmetries to make PQ symmetry an accidental symmetry. (e.g. SU(6), SU(7) model by Ning Chen.)

- Tune the gravitational coupling

$$-V^n_{\mathrm{PQ-break}} = \frac{\lambda_n |\Phi|^{2m}\left(e^{-i\delta_n}\Phi^n + e^{i\delta_n}\Phi^{\dagger n}\right)}{m_{\mathrm{Pl}}^{d-4}} \supset \frac{\lambda_n f_a^4}{2}\left(\frac{f_a}{\sqrt{2}m_{\mathrm{Pl}}}\right)^{d-4} \cos\left(\frac{na}{f_a} - \delta_n\right)$$

- Heavy axions

Solutions to axion quality problem

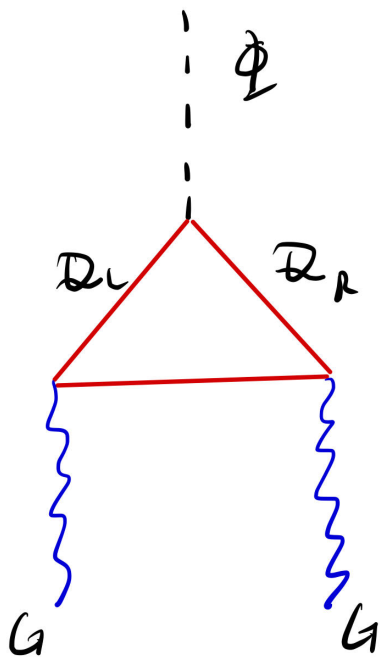
- Mirror sector model (heavy axions)

$$\mathcal{L} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a(x)}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \longrightarrow \frac{\alpha_3}{8\pi}\left(\frac{a}{f_a} + \bar{\theta}\right)\left(G\tilde{G} + G'\tilde{G}'\right)$$

Hook, Kumar, Liu, Sundrum, 1911.12364

- $\Lambda'_{QCD} \gg \Lambda_{QCD}$ to strengthen the axion potential.
- The axion becomes much heavier and cannot be DM.

The axion domain wall problem



- Take the KSVZ example

$$\mathcal{L} = \frac{g_S^2 N_{\rm DW}}{32\pi^2} G\tilde{G}$$

- In QCD $N_{\rm DW}$ equals number of copies of Q.
- Domain wall will cause problems unless $N_{\rm DW} = 1$.

If $N_{\rm DW} > 1$, domain walls will form network, and dominate the universe.

To solve the domain wall problem

- $N_{DW} = 1$
- PQ symmetry breaking before inflation, the observed universe is in one domain.
- Re-examine the SM gauge group.

$SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group has a nontrivial center. $\Gamma = Z_6$

- If we gauge $SU(3)_C \times SU(2)_L \times U(1)_Y / \mathrm{K}$, $K \subset \Gamma$, and non trivial, the global structure will be changed.
- Fractional instantons may help annihilate the domain walls.

Cordova, Hong, Wang, 2309.05636

Dark photon DM production

- Produced through quantum fluctuations during inflation.

  Graham, Mardon, Majendra (2015)

- Produced through parametric resonance.

  Co, Pierce, Zhang, Zhao (2018)

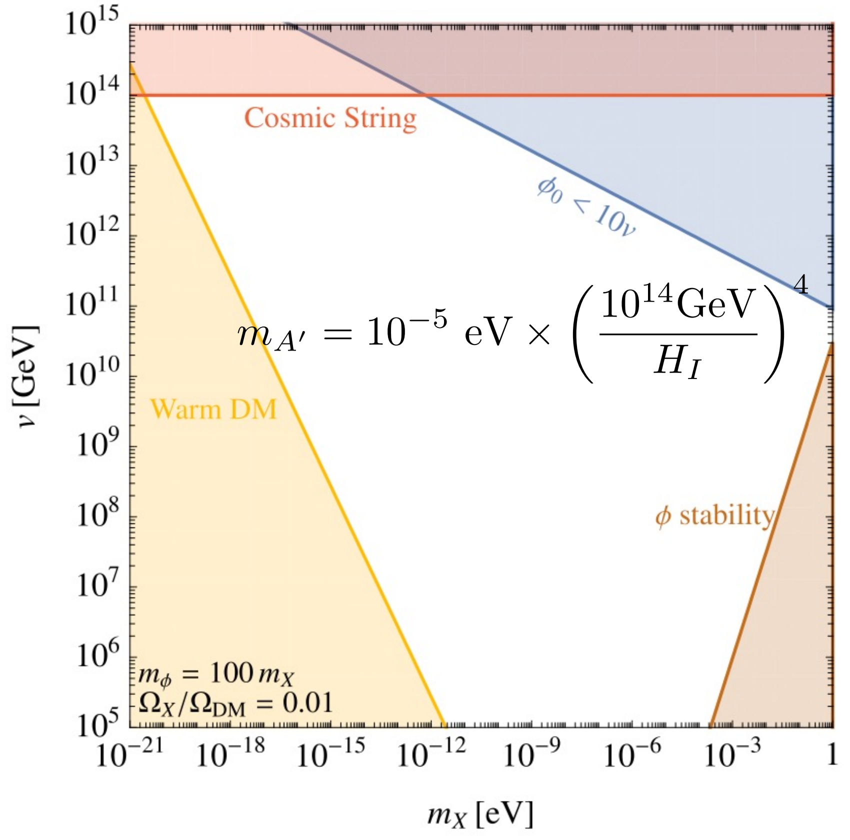
  Dror, Harigaya, Narayan (2018)

  Bastero-Gil, Santiago, Ubaldi, Vega-Morales (2018)

  Agrawal, Kitajima, Reece, Sekiguchi, Takahashi (2018)

- From decay of cosmic rays

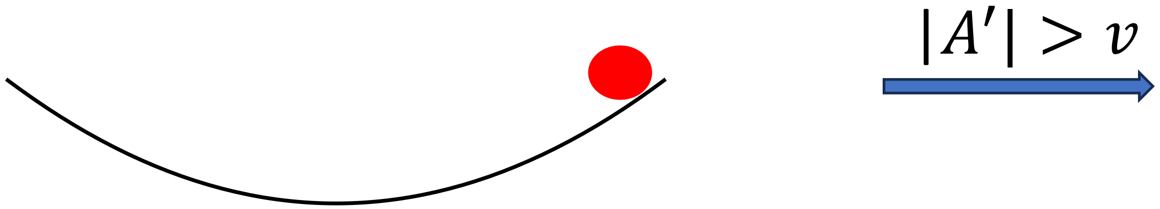
  Long, Wang (2019)

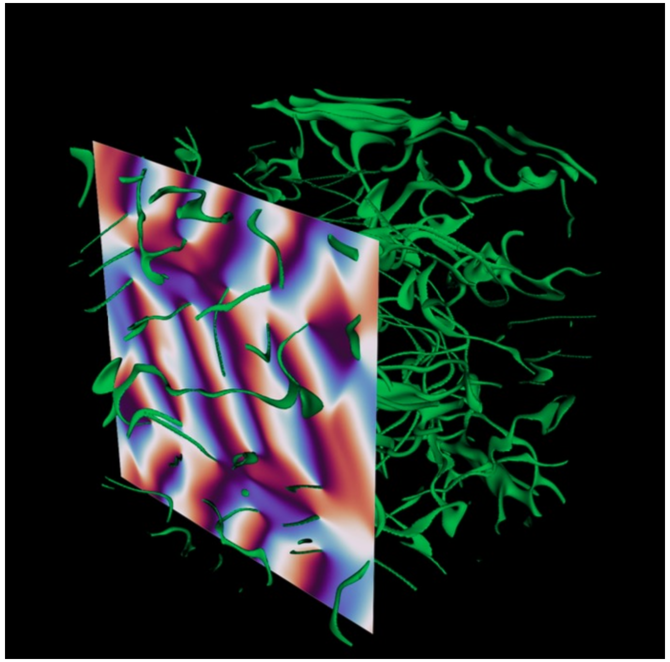


Problems with DPDM production

- Coherent oscillation of dark photon is not the ground state when the amplitude is large and the dark photon is Higgsed.

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + (D^\mu\phi)^* D_\mu\phi - \lambda(|\phi|^2 - v^2)^2$$





- In the early universe $|A'|$ is huge, models with Higgs are not favored.

East and Huang, 2206.12432

Dark photon DM production

Simplest version are not favored.

- Produced through quantum fluctuations during inflation.

  Graham, Mardon, Majendra (2015)

- Produced through parametric resonance.

  Co, Pierce, Zhang, Zhao (2018)

  Dror, Harigaya, Narayan (2018)

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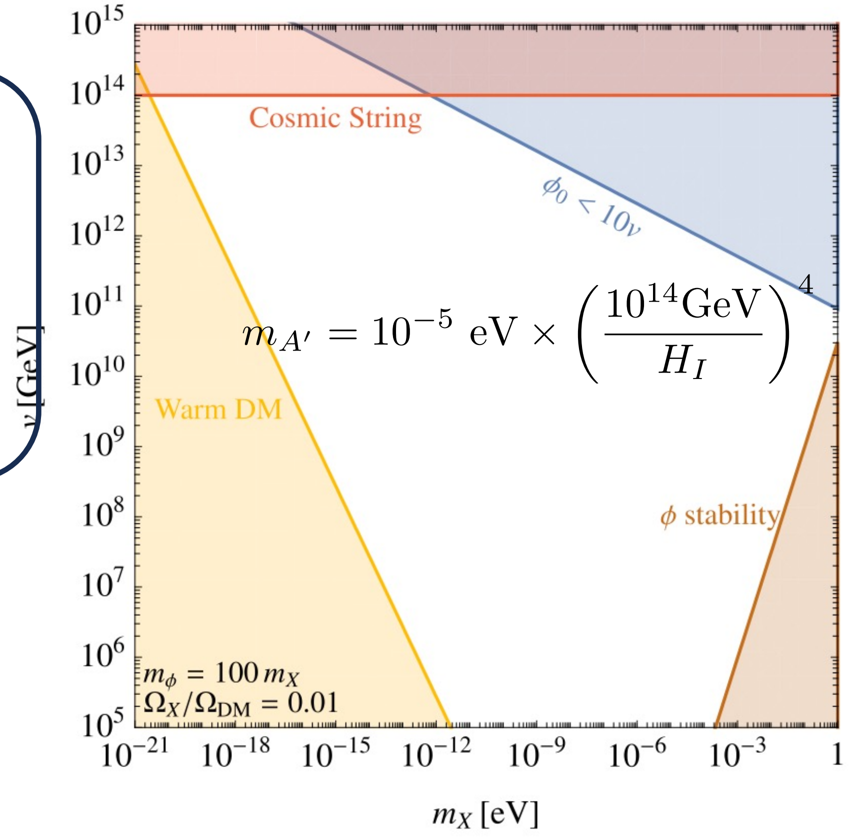


Ways out

- Dark photon is completely Stueckelberg --- No Higgs. Produced during inflation through quantum fluctuations.
- No cosmic strings in the spectrum. Graham, Mardon, Majendra (2015)
- But, there is still constraint from the weak gravity conjecture.

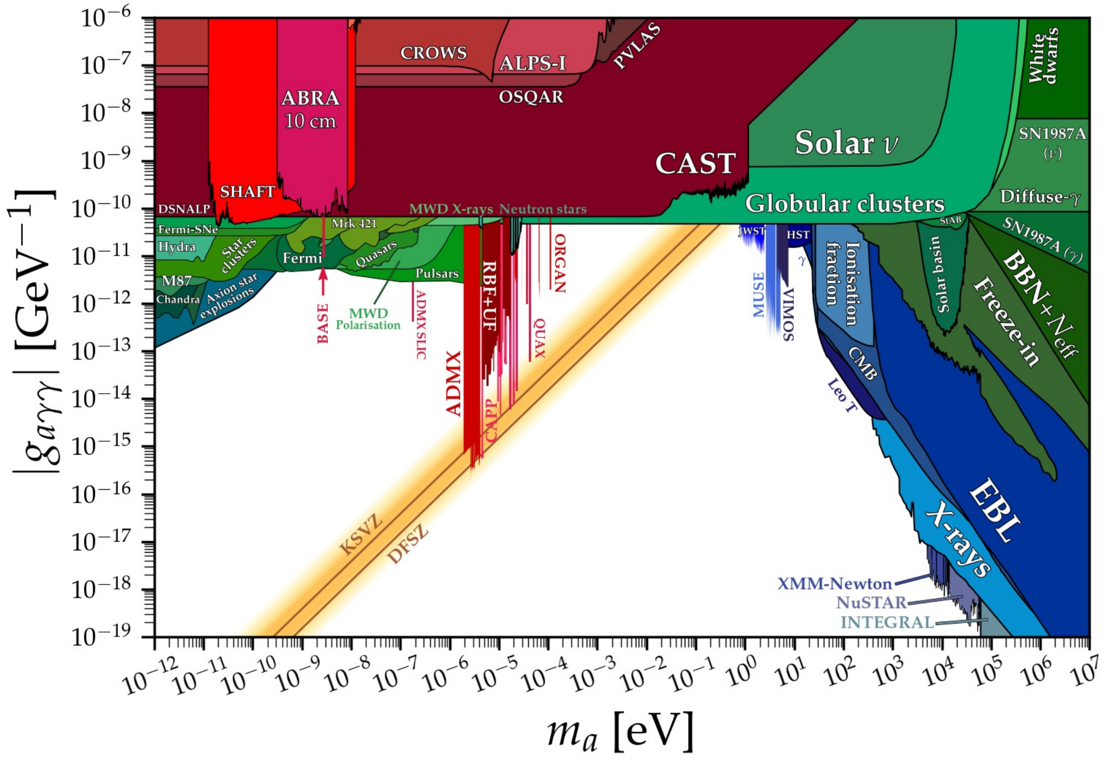
  Reece 1808.09966, Montero et al., 2207.09448

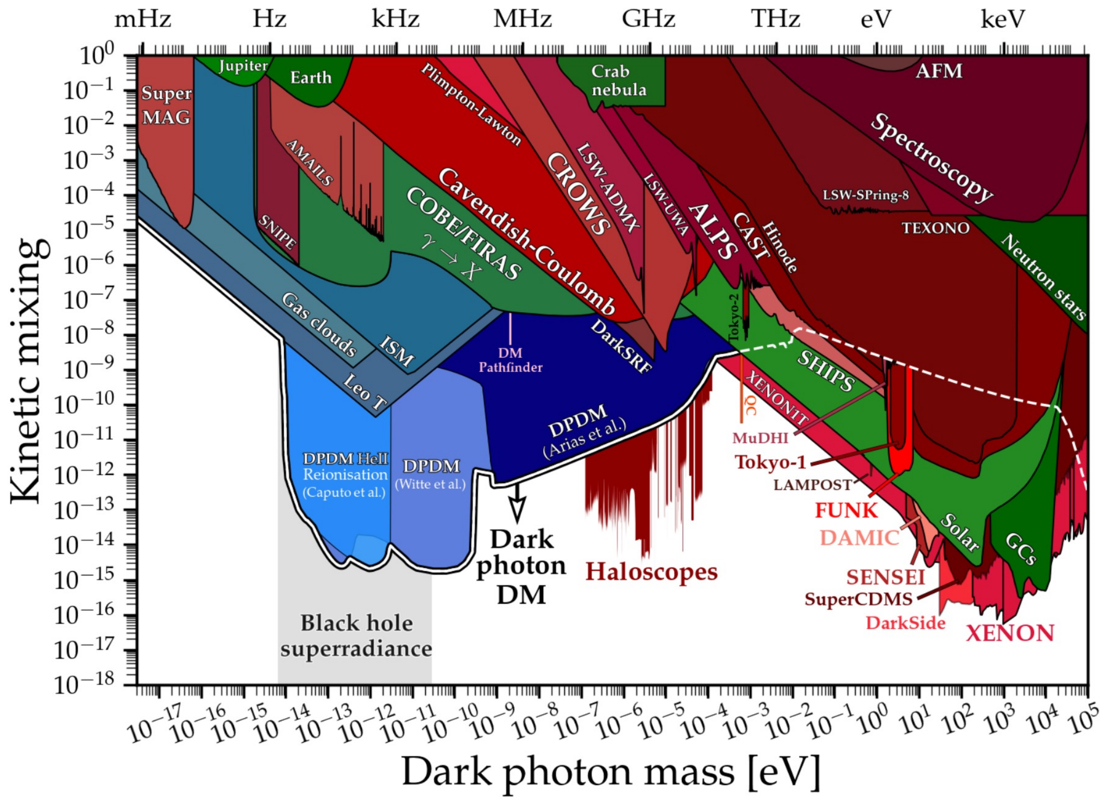
- However, DPDM might be rescued using vector clockwork.

  Craig and Garcia, 1810.05647

Summary

- A lot of searches for wave DMs.





Summary

- Not all the parameter space that can be covered by current and future experiments have good motavitions.
- In this sense, for wave dark matter experiments are more advanced than theories.
- The wave dark matter experimental searches provide a good opportunity for theorists to build models.

Motivations for ultralight dark matter

- Fuzzy dark matter for small-scale anomalies?
  - Core-cusp
  - To-big-to-fail
  - Missing satellite
- Very strong constraints already for $m \sim 10^{-22}$ eV fuzzy dark matter
  - Lensing
  - Lyman-alpha
  - …
- The booming of wave DM is almost completely because theorists are tired of WIMPs.