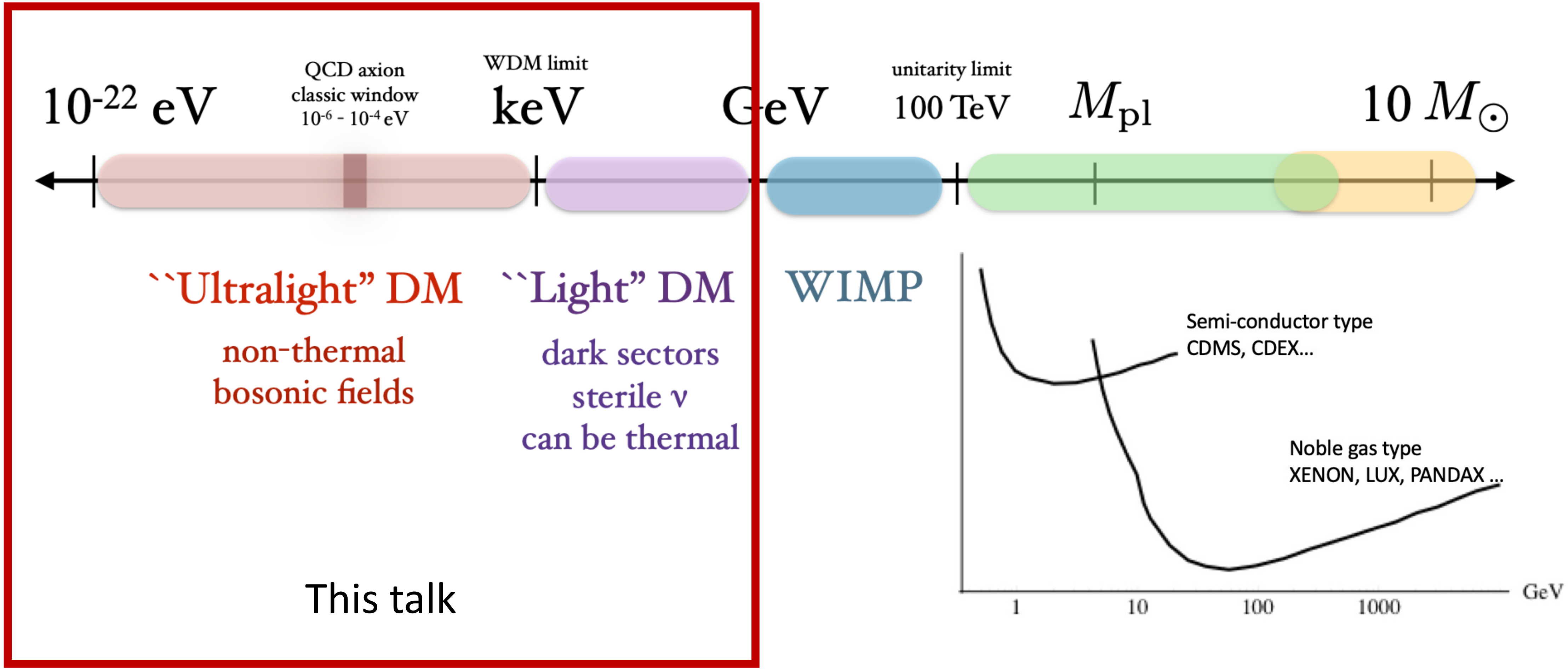
Recent developments in searching for light and ultralight dark matters

Haipeng An (Tsinghua University)

Symposium on Frontiers of Underground Physics

Oct. 29 – Nov. 2, 2023 @Chengdu

Outline



QCD axion
classic window
10^{-6} - 10^{-4} eV
WDM limit
10^{-22} eV
keV
GeV
unitarity limit
100 TeV
$M_{\rm pl}$
$10\ M_\odot$
``Ultralight" DM
non-thermal
bosonic fields
``Light" DM
dark sectors
sterile ν
can be thermal
WIMP
Semi-conductor type
CDMS, CDEX...
Noble gas type
XENON, LUX, PANDAX ...
1
10
100
1000
GeV
This talk

Outline

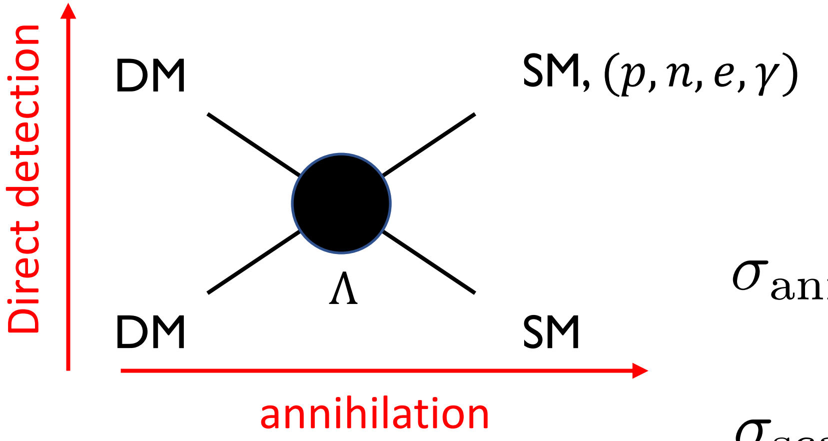
- Direct search for MeV scale dark matters
  - New materials
  - Boosted dark matter
- Ultralight bosonic dark matter
  - Using WIMP detectors to search for ultralight dark matters
  - Resonant cavities
  - Broad band searches
  - Using radio telescopes to search for ultralight dark matters

Thermal freeze-out as a benchmark model

- Freeze-out

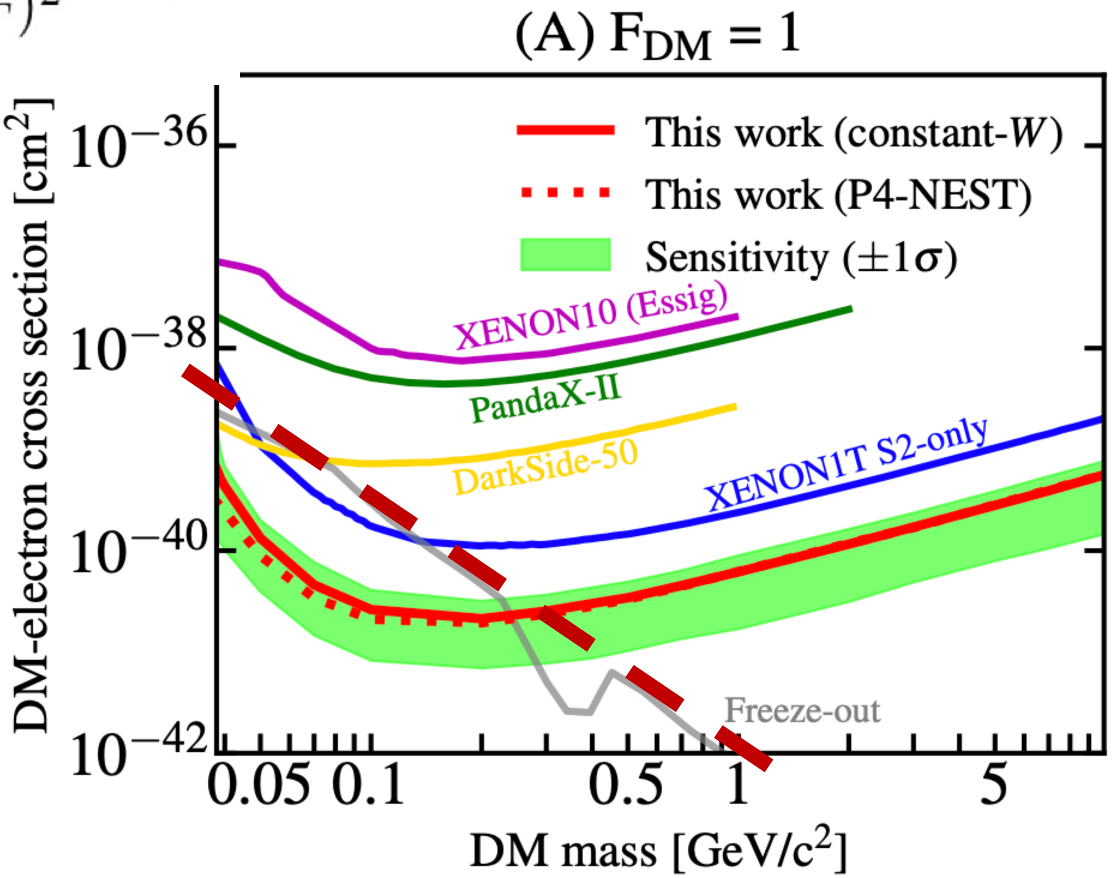
$$E_{\mathrm{recoil}} \sim \frac{m_{\mathrm{DM}} m_T}{(m_{\mathrm{DM}} + m_T)^2} E_{\mathrm{DM}}$$

PandaX-III, PRL 130 (2023) 261001



$$\sigma_{\mathrm{annihilation}} \sim \frac{m_D^2}{\Lambda^4}$$

$$\sigma_{\mathrm{scattering}} \sim \frac{\mu^2}{\Lambda^4}$$



Thermal freeze out

$$\Gamma_A = n_{\mathrm{DM}} < \sigma v > ,$$

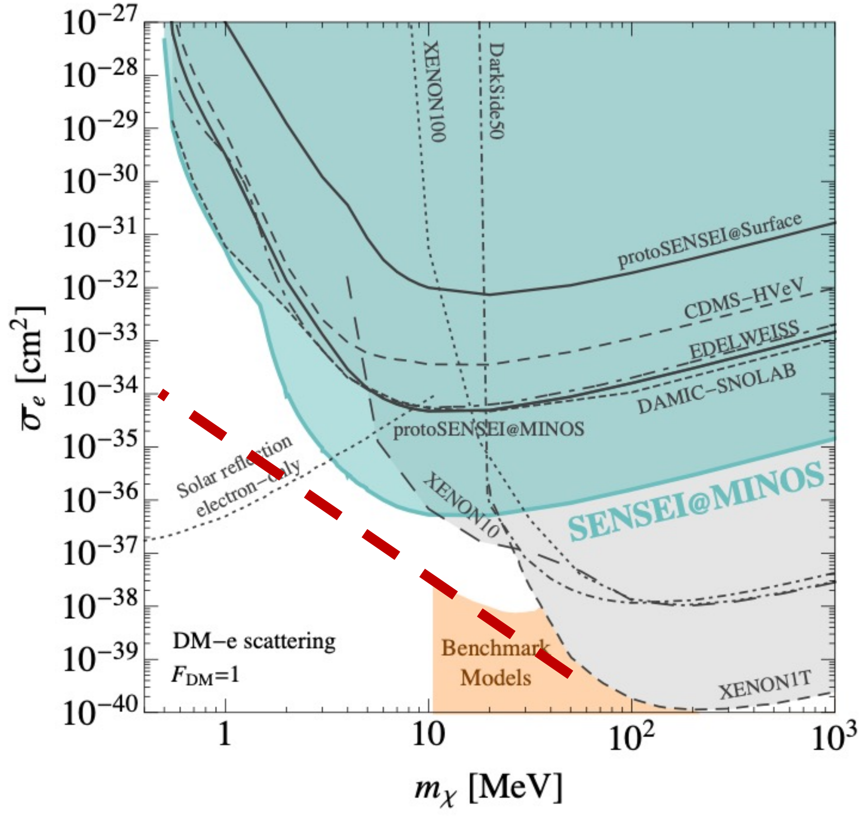
$$\Gamma_A < \mathrm{H}$$

$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$$

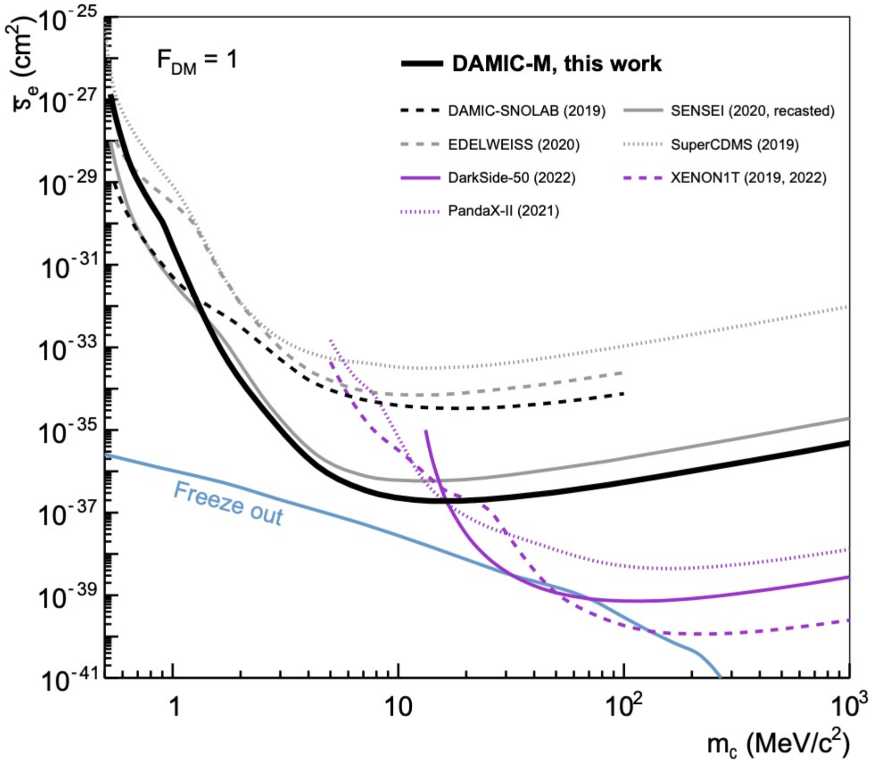
Lighter DM ($m_{DM} < 50$ MeV)

- Materials with lower threshold (Skipper CCD)

SENSEI, PRL 125 (2020) 171802, 48 gram-days



DAMIC-M, PRL 130 (2023) 171003, 85 gram-days



New ideas for light dark matter search

- Superconducting detector O(meV) electron recoil,

  Hochberg et al. PRL 116 (2016) 011301, Hochberg et al. JHEP 08 (2016) 057

- Superfluid helium4 detector O(meV) electron recoil,

  Katelin Schutz and Kathryn Zurek, PRL 117 (2016) 121302,

  Knapen et al. PRD 95 (2017) 056019

- Superfluid helium3 detector sub eV nuclear recoil

  QUEST-DMC, 2310.11304

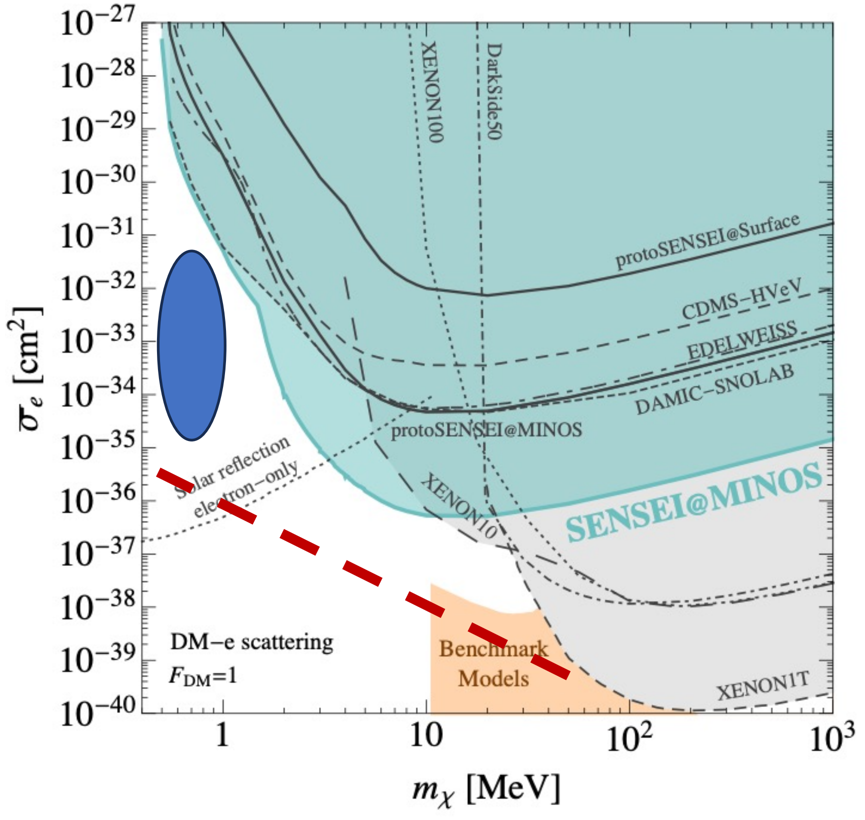
- ALETHEIA: Using liquid helium TPC to search for low mass dark matter (nuclear recoil) , 2209.02320
- All the works to use the Migdal effect to search for small nuclear recoils.

…

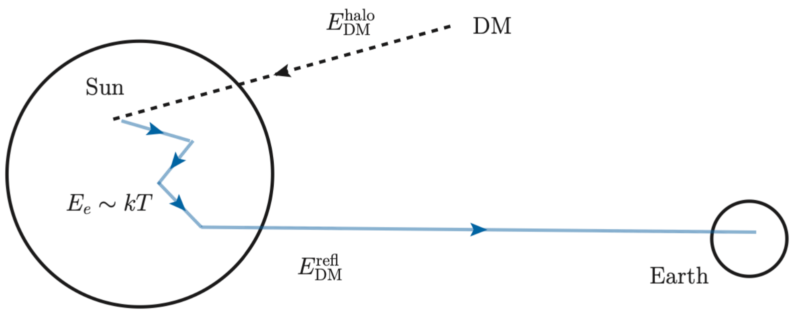
Re-examine the Skipper CCD

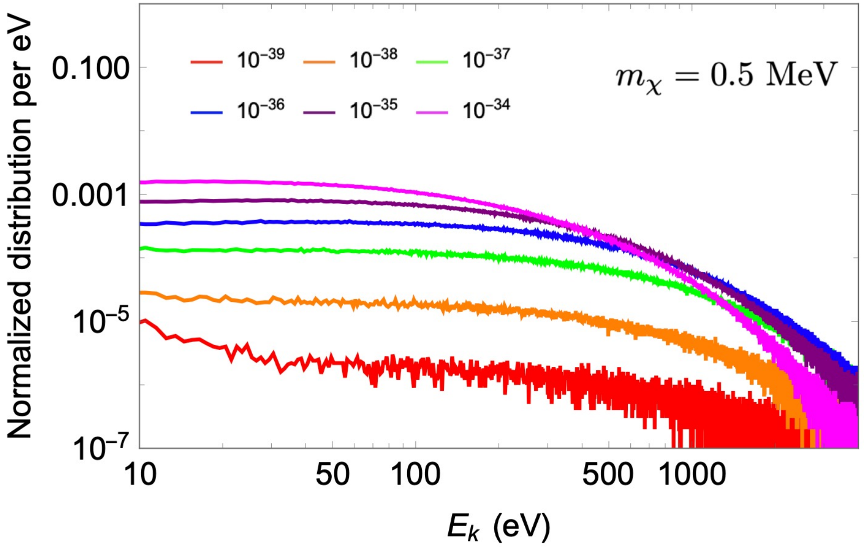
- The region $m_D < 1\ \mathrm{MeV}$ is still hard to search.

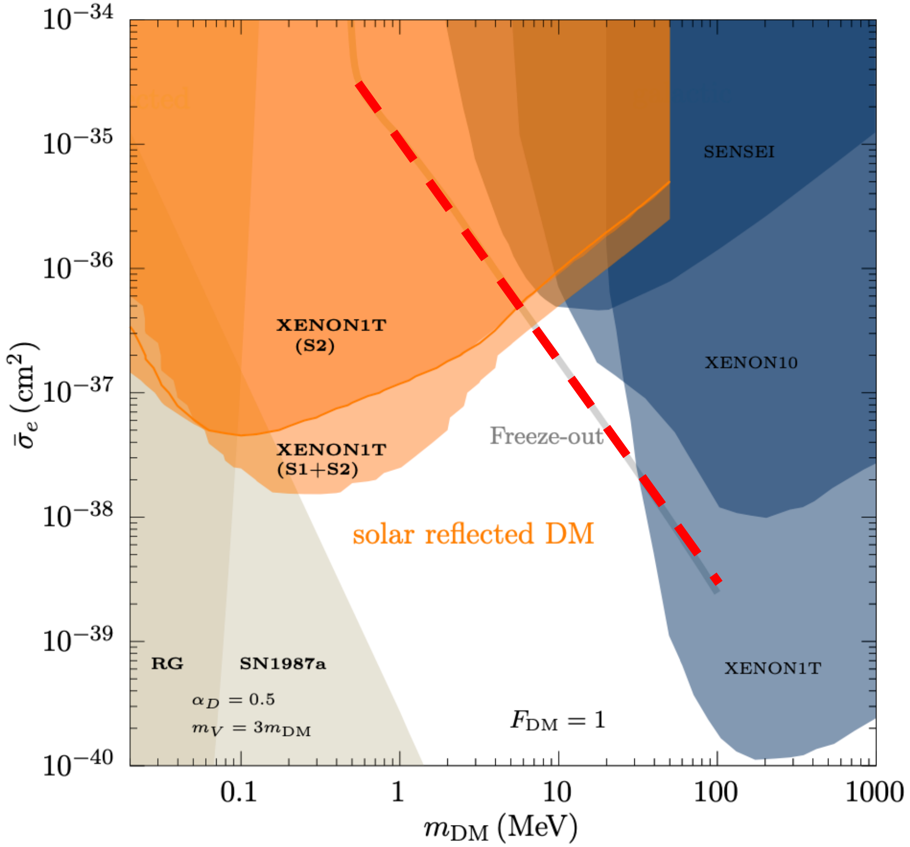
Kinetic energy is too small.
Need a boost.



Solar reflection of dark matter

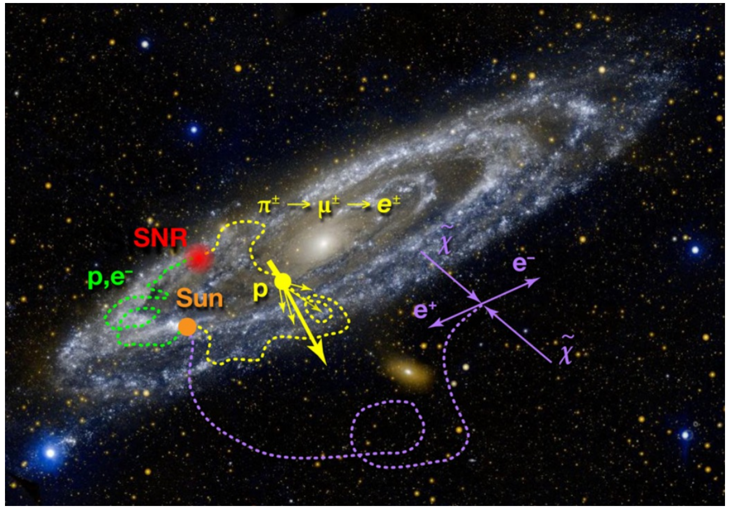


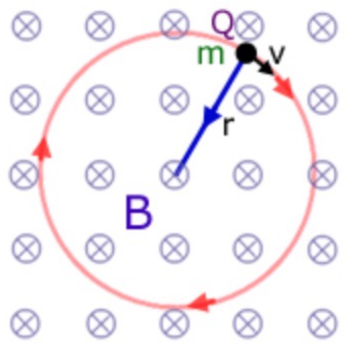


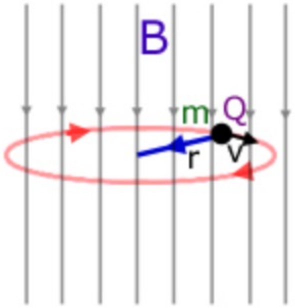


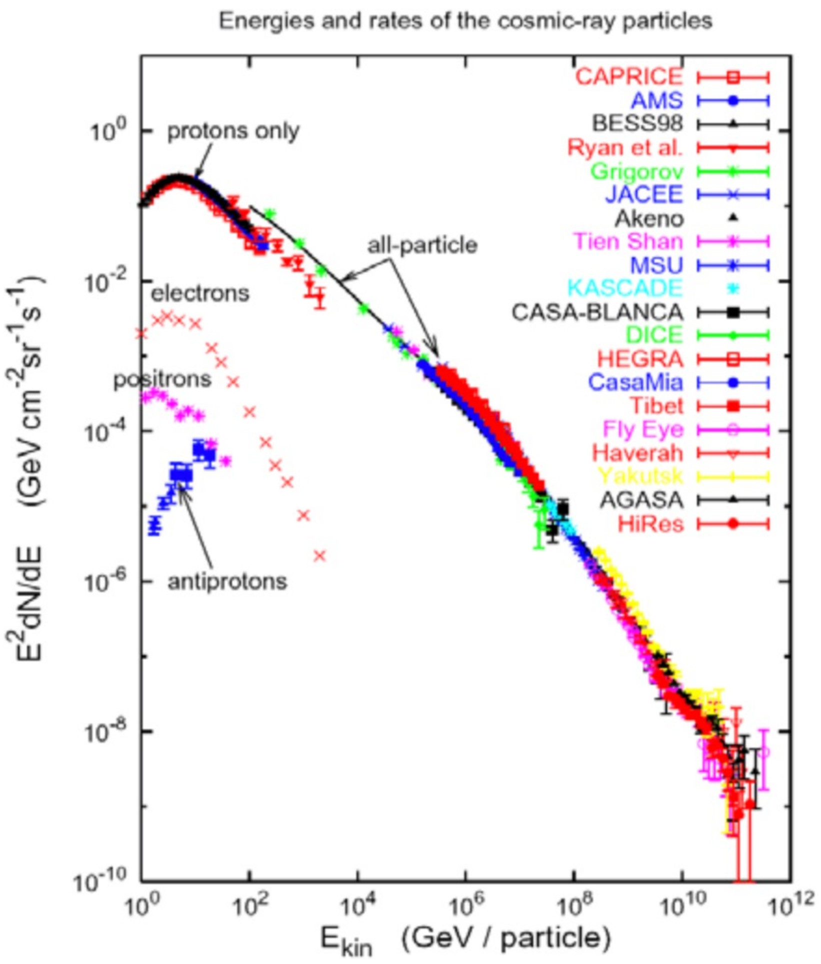
HA, Pospelov, Pradler, Ritz, PRL 120 (2018) 141801
HA, Nie, Pospelov, Pradler, Ritz, PRD 104 (2021) 103026

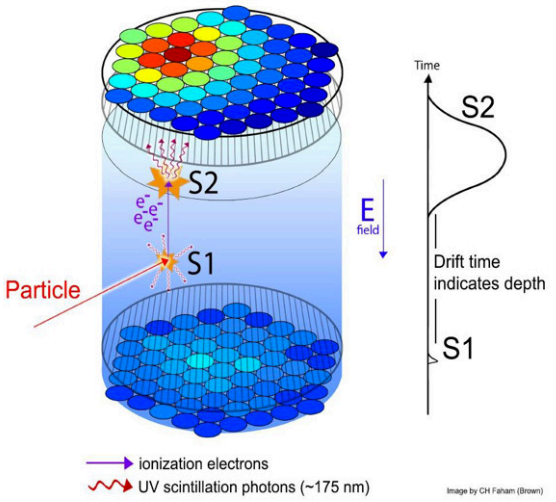
Cosmic ray boosted dark matter







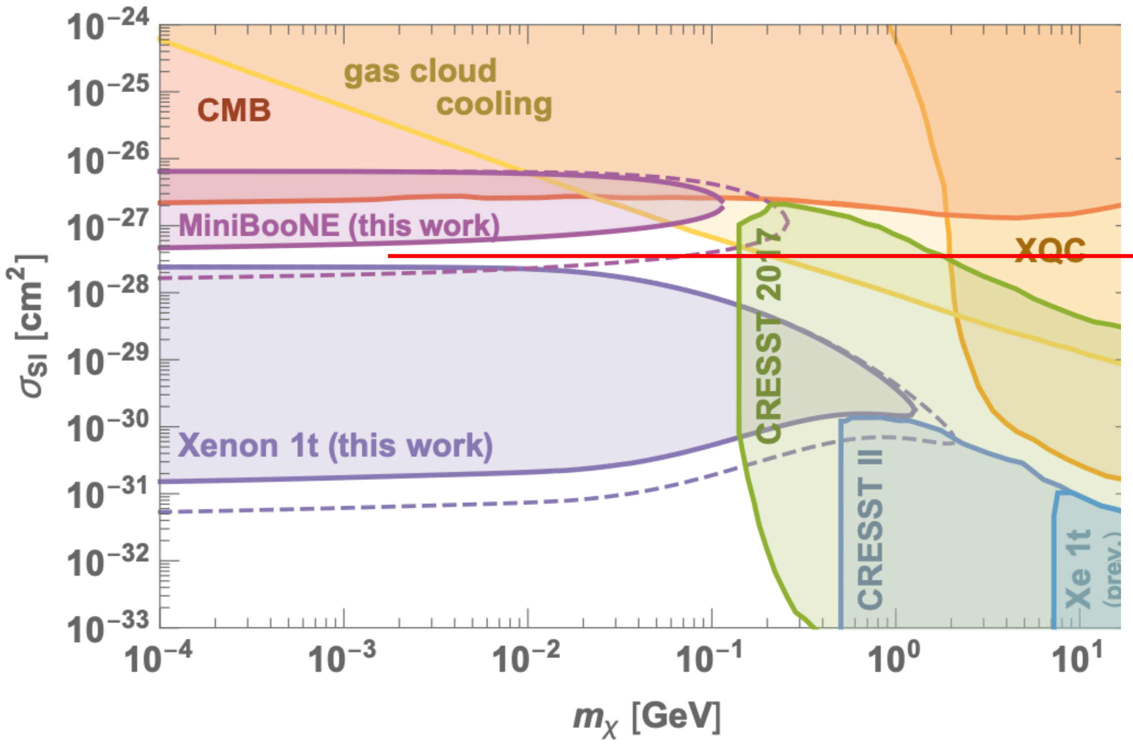




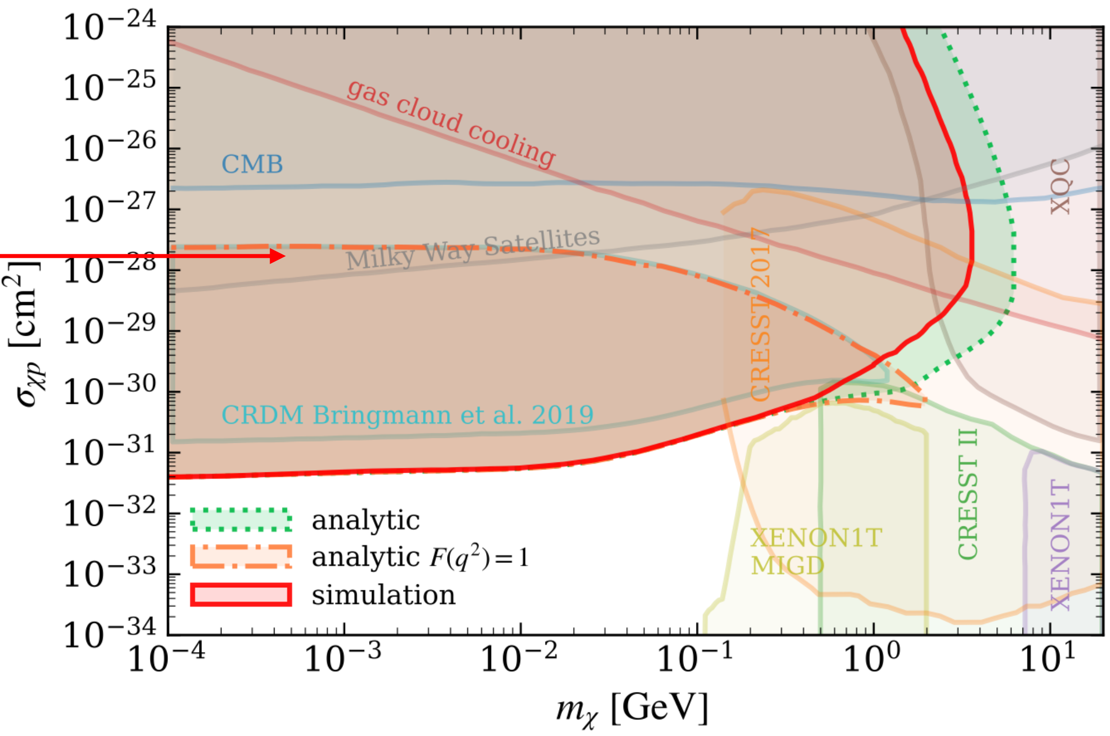
Nuclear recoil

Cosmic ray boosted dark matter

Rock attenuation effect is more carefully considered.

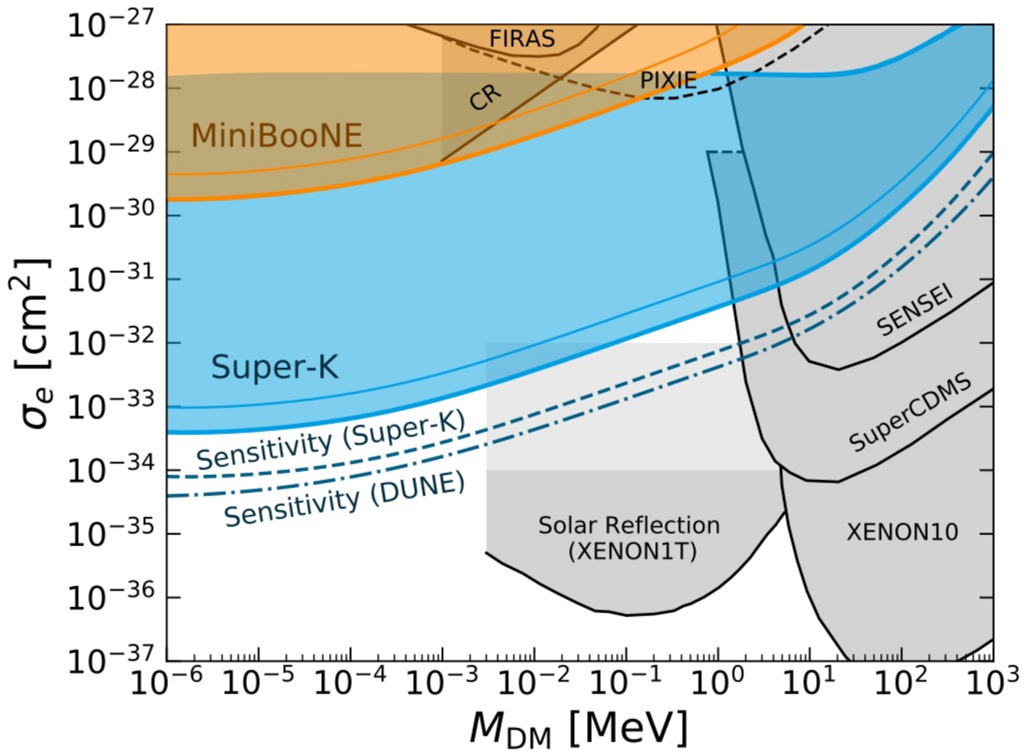


Bringmann, Pospelov, PRL 122 (2019) 171801



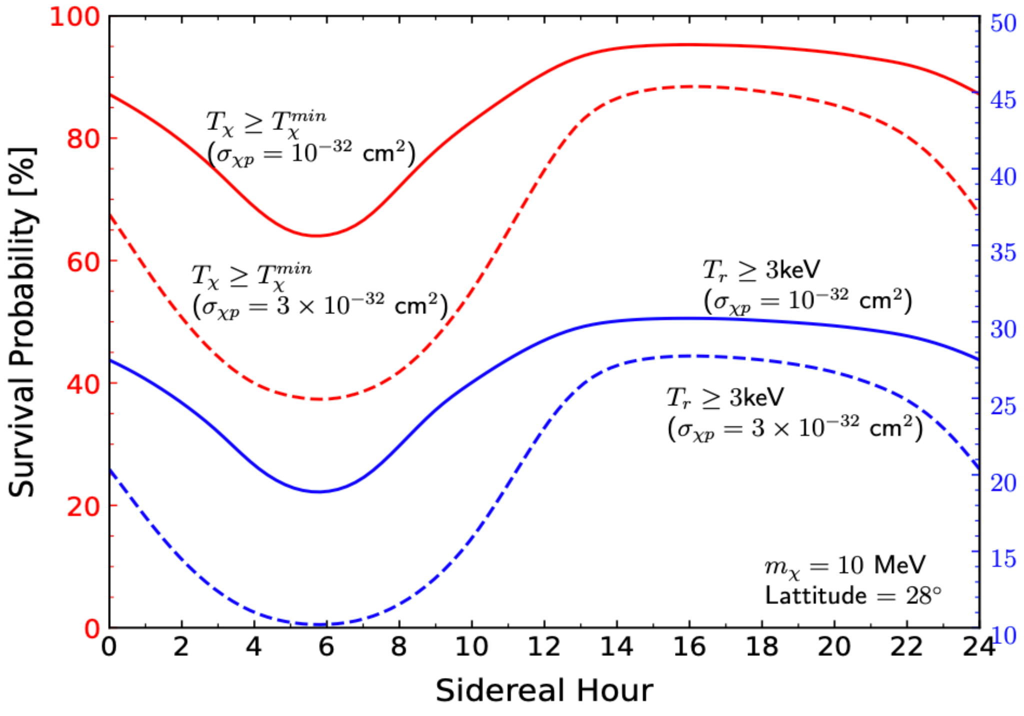
Xia, Xu, Zhou, JCAP 02 (2022) 028

Cosmic ray boosted adrk matter



Ema, Sala, Sato, PRL 122 (2019) 181802

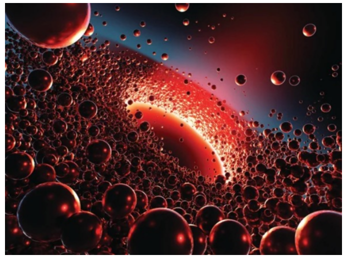
Daily modulation

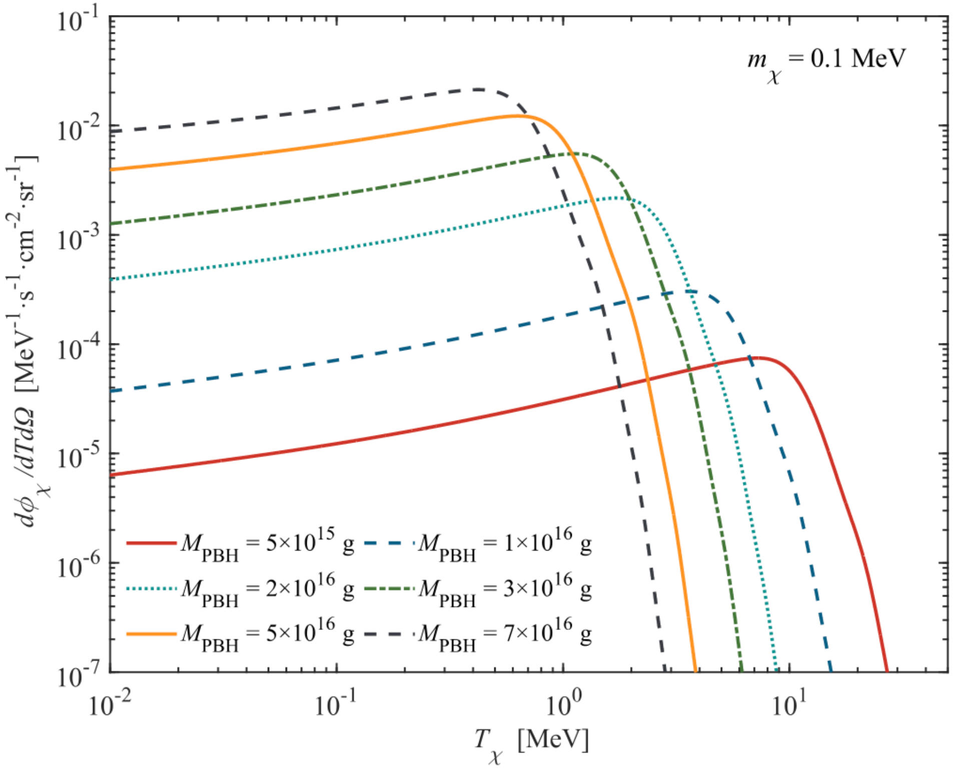


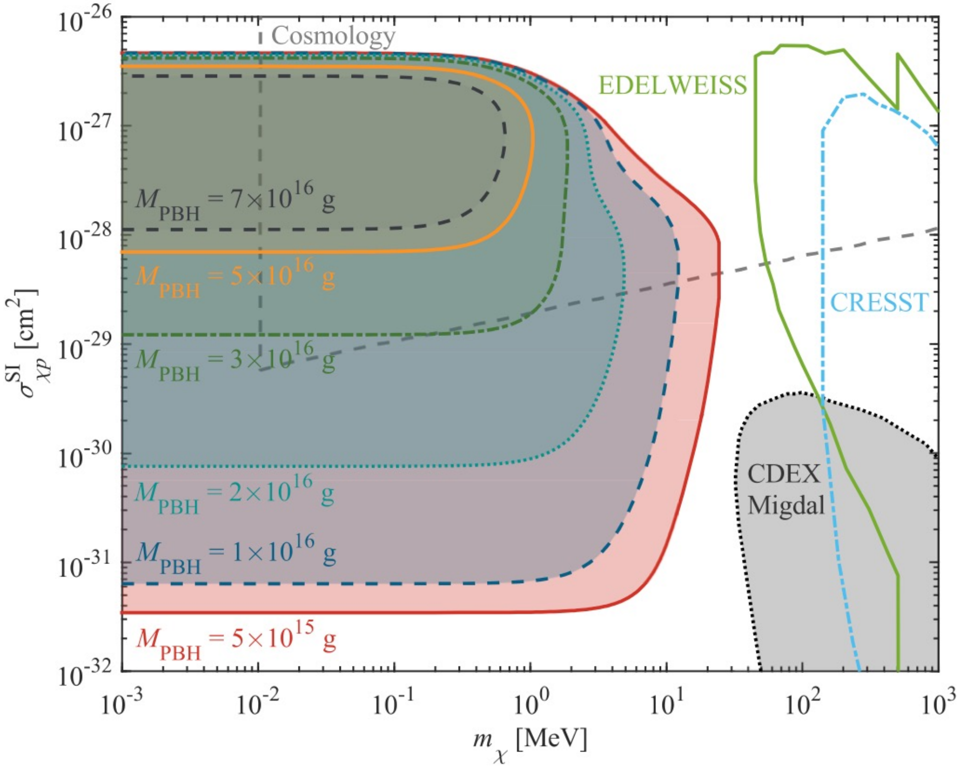
S.Ge, J.Liu, Q.Yuan, N.Zhou, PRL 126 (2021) 091804

Light dark matter from black hole evaporation

Calabrese et al, 2107.13001, 2203.17093



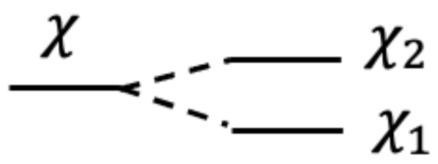




CDEX, PRD 108 (2023) 052006

Self-boosting dark matter

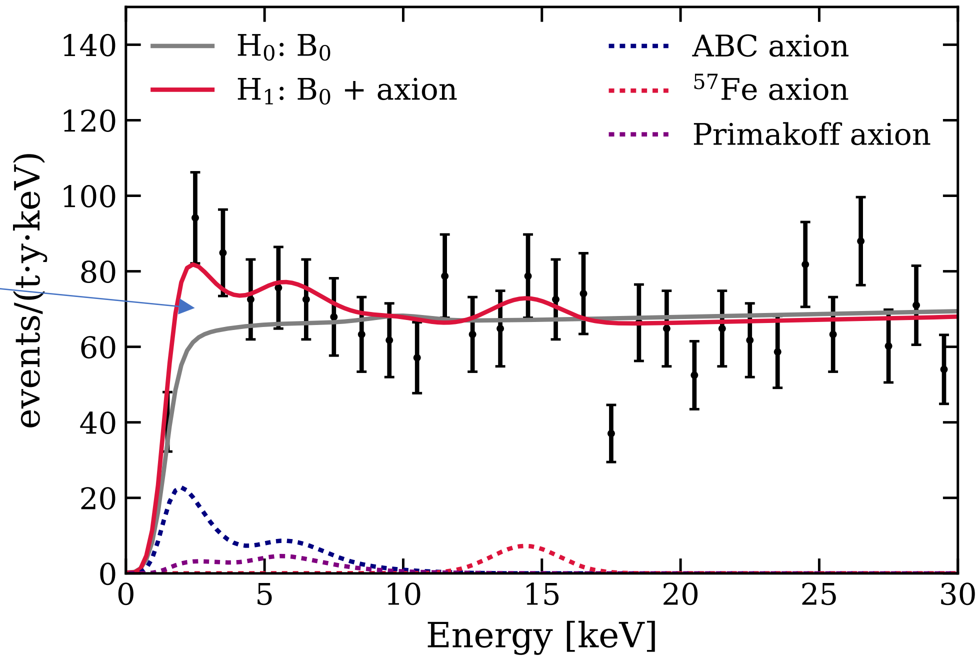
- Down-scattering dark matter



A few keV gap, protected by symmetry

Freeze-out:
K. Harigaya, Y. Nakai, M.Suzuki, 2006.11938
J.Bramante, N. Song, 2006.14089
M.Baryakhtar, A.Berlin, H.Liu, N.Weiner, 2006.13918
Freeze-in:
HA, D.Yang, 2006.15672

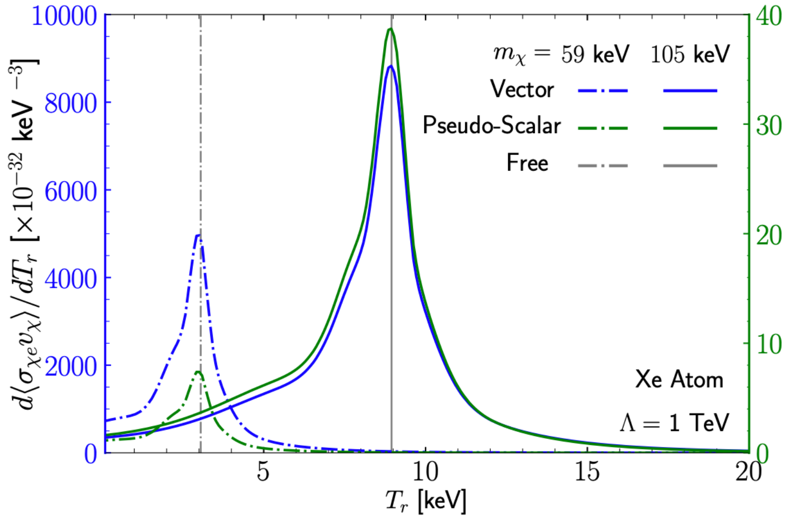
XENON1T, PRD 102 (2020) 072004

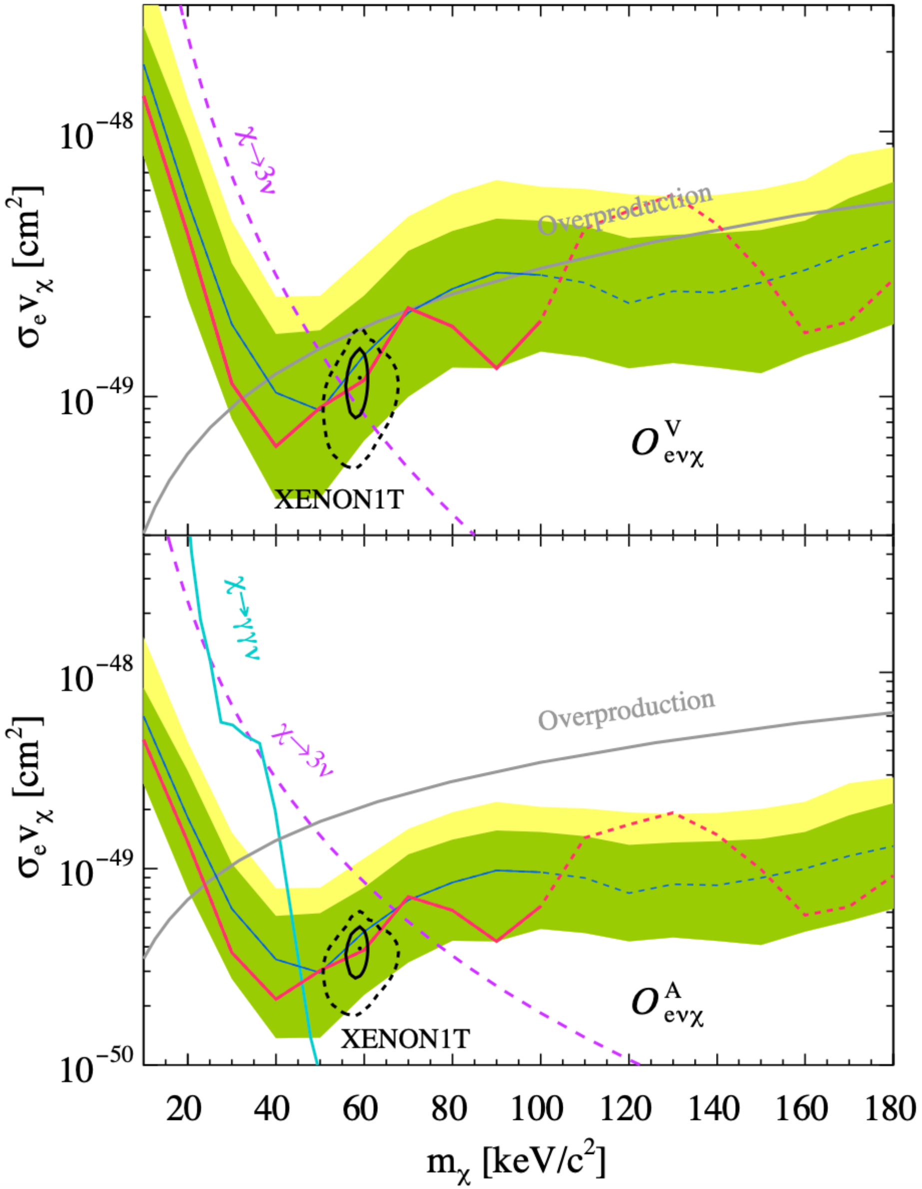


Fermionic DM Absorptior

Ge et al., 2201.11497
PandaX, PRL 129, 161804 (2022)

$$\mathcal{O}^S_{e\nu\chi} \equiv (\bar{e}e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^P_{e\nu\chi} \equiv (\bar{e}i\gamma_5 e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^V_{e\nu\chi} \equiv (\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L),$$
$$\mathcal{O}^A_{e\nu\chi} \equiv (\bar{e}\gamma_\mu\gamma_5 e)(\bar{\nu}_L\gamma^\mu\chi_L),$$
$$\mathcal{O}^T_{e\nu\chi} \equiv (\bar{e}\sigma_{\mu\nu} e)(\bar{\nu}_L\sigma^{\mu\nu}\chi_R),$$

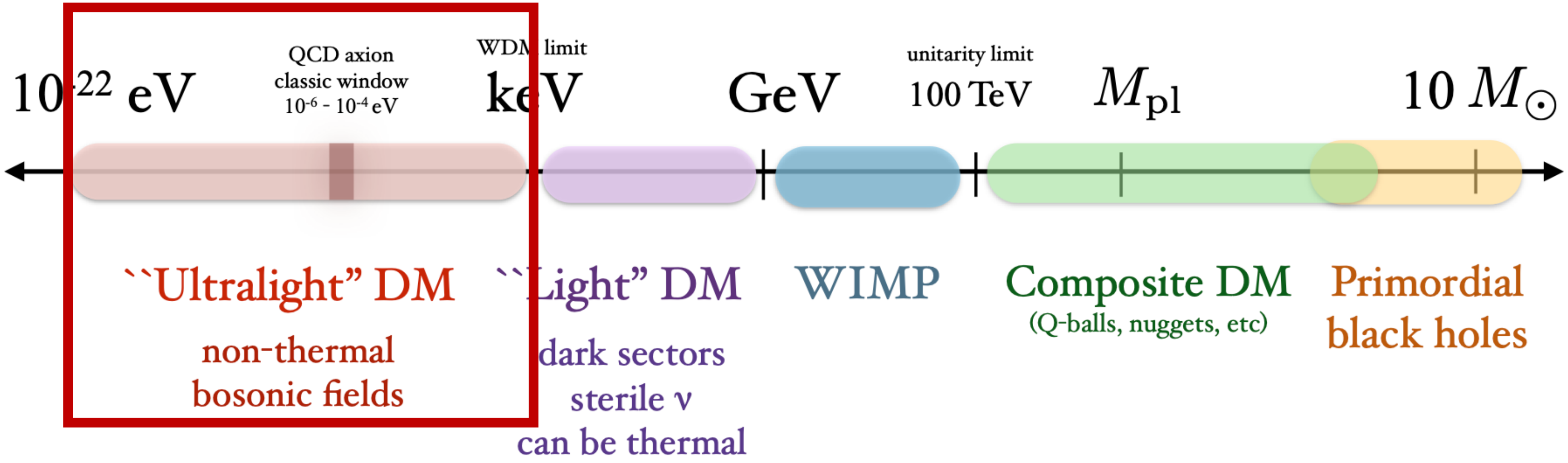




Other proposals and constraints

- Dark matter boosted by supernovae neutrinos Lin et al. 2206.06864
- Atmospheric resonant production Darme et al. 2205.09773
- Blazor boosted DM (by protons from SMBH accretion) Granelli et al. 2111.13644, 2202.07598
- Electron recoils from terrestrial upscattering of inelastic DM Emken et al., 2112.08957
- Terrestrial Probes of Electromagnetically Interacting Dark Radiation Kuo et al., 2102.08409
- Millicharged cosmic rays and Low Recoil Detectors Harnik et al., 2010.11190
- …

Ultralight dark matters

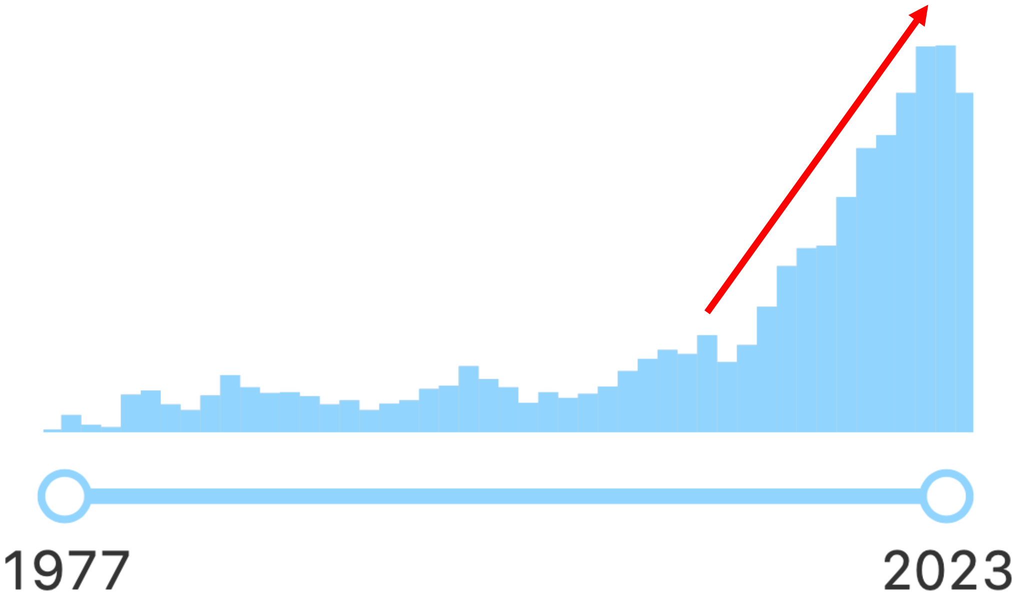


- Axion and axion-like particles

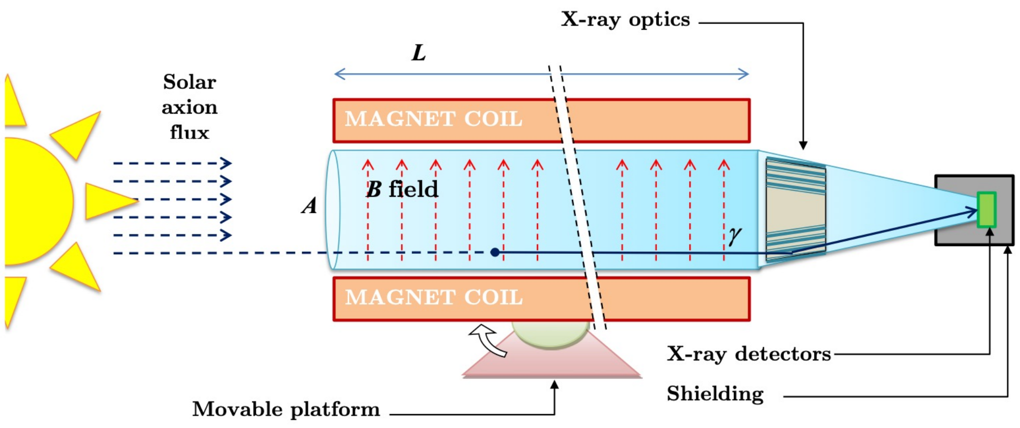
$$a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \partial_\mu a \bar{N}\gamma^\mu\gamma_5 N \qquad \partial_\mu a \bar{e}\gamma^\mu\gamma_5 e$$

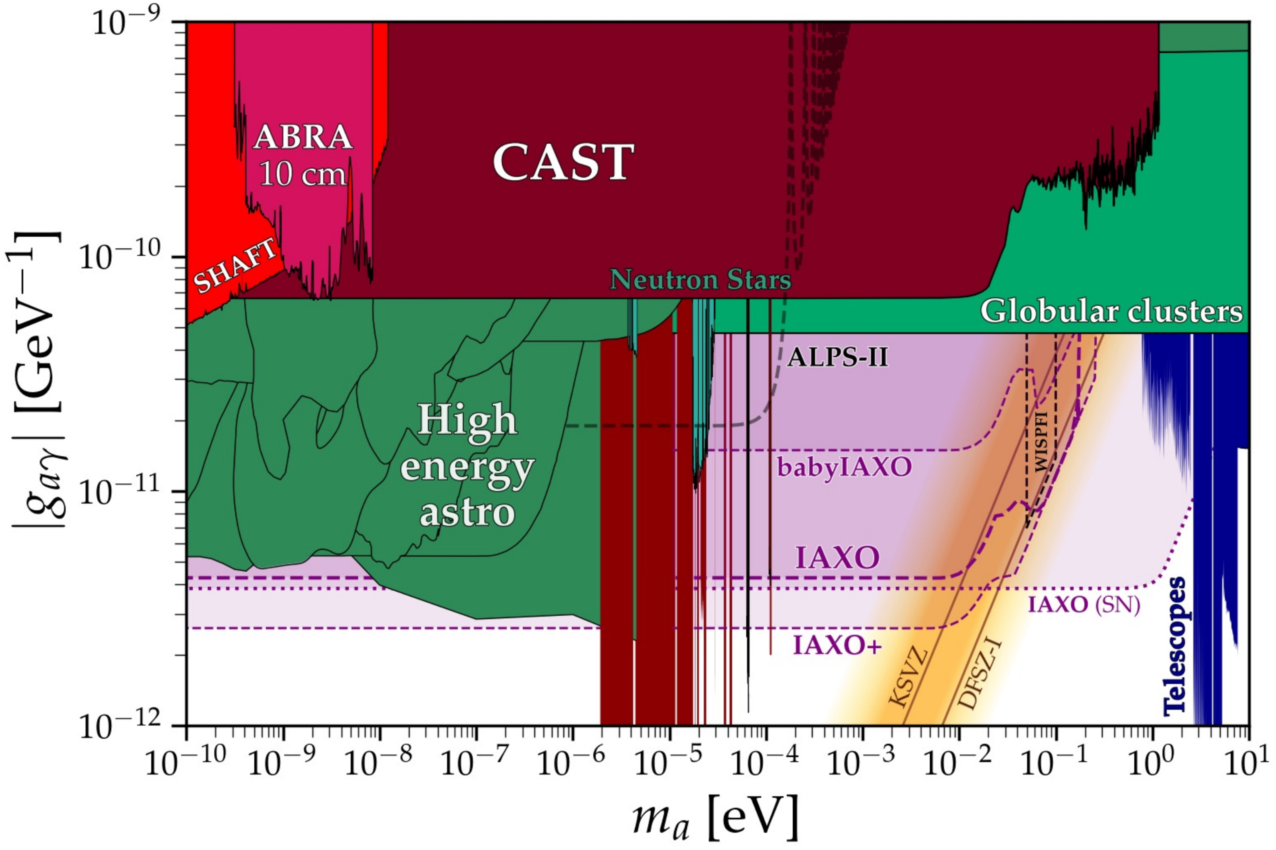
- Dark photons

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

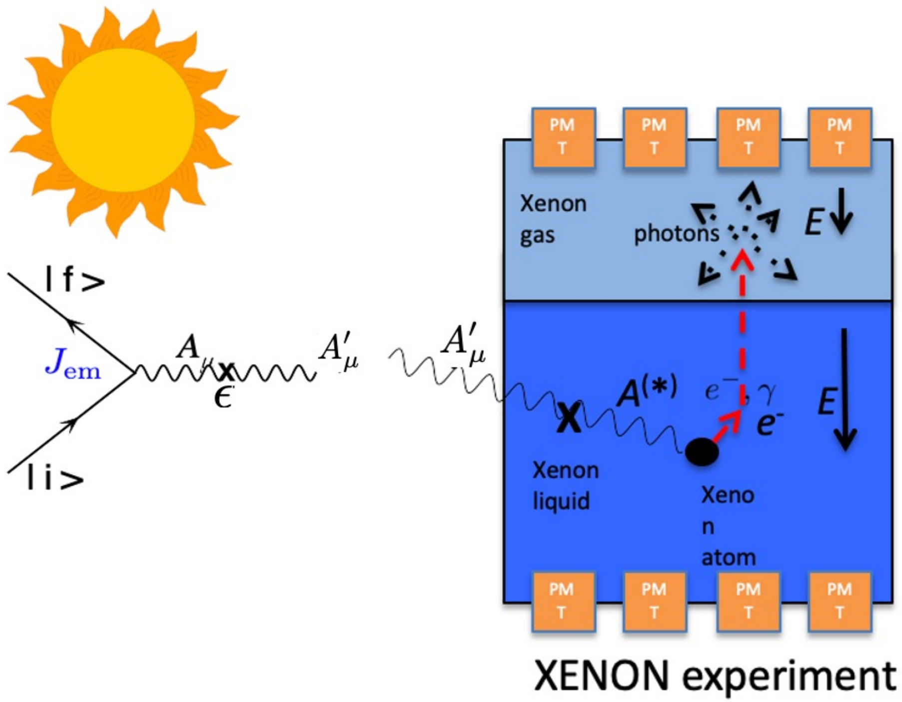


Helioscopes for axions

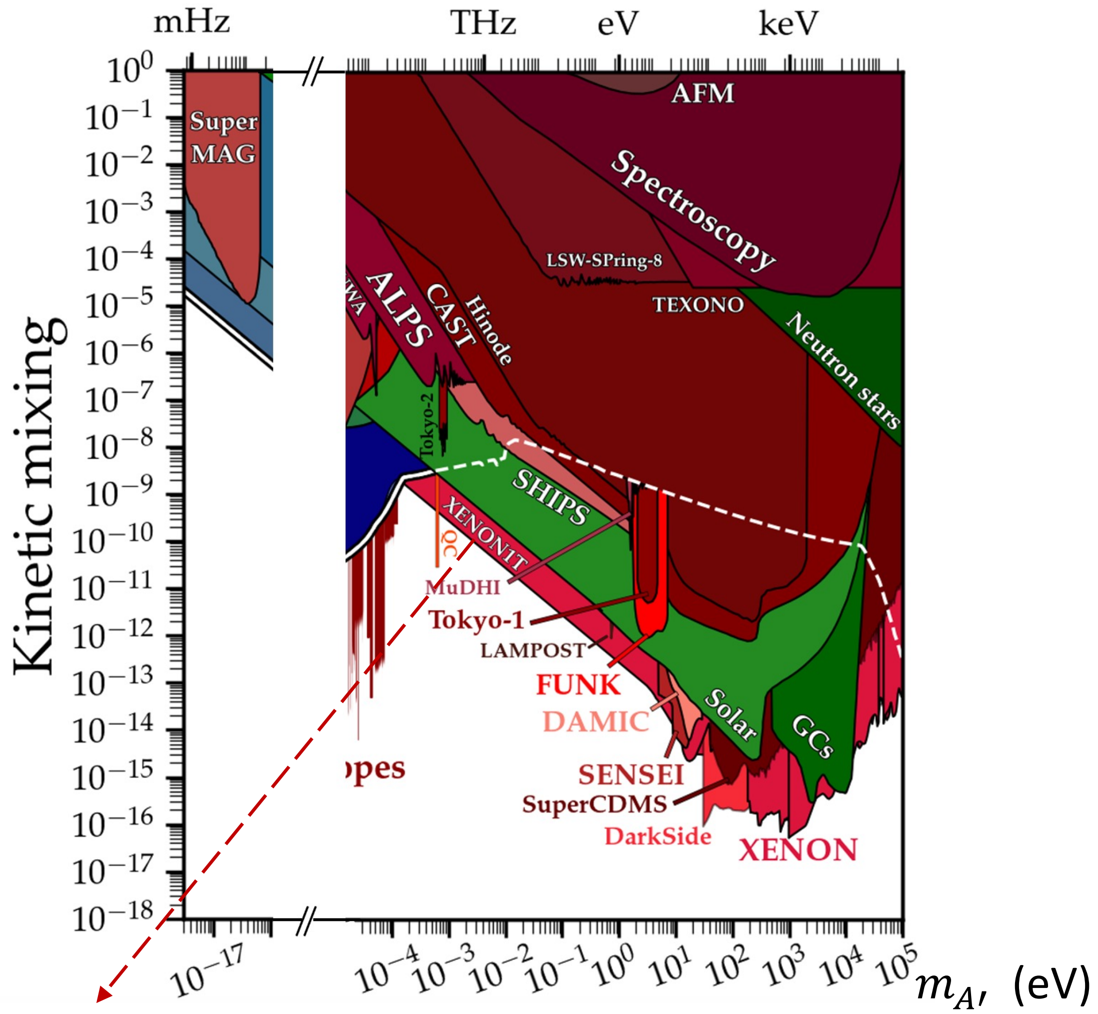




Helioscopes for dark photon

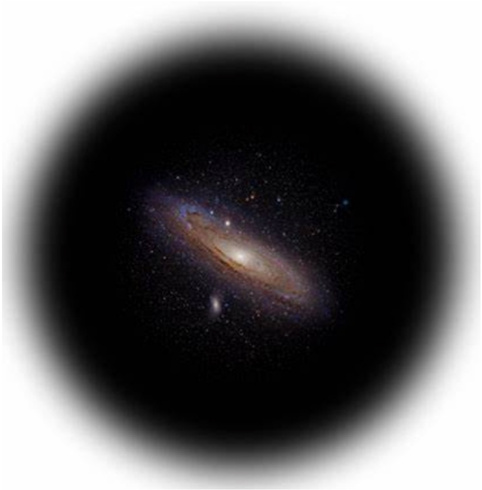


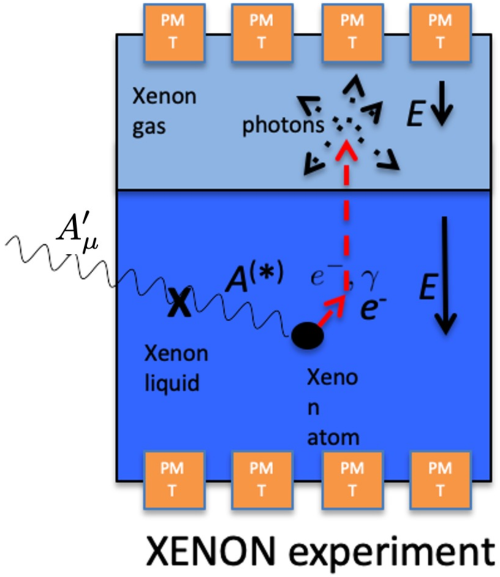
HA, Pospelov, Pradler, PLB 725 (2013) 190,
& PRL 111 (2013) 041302

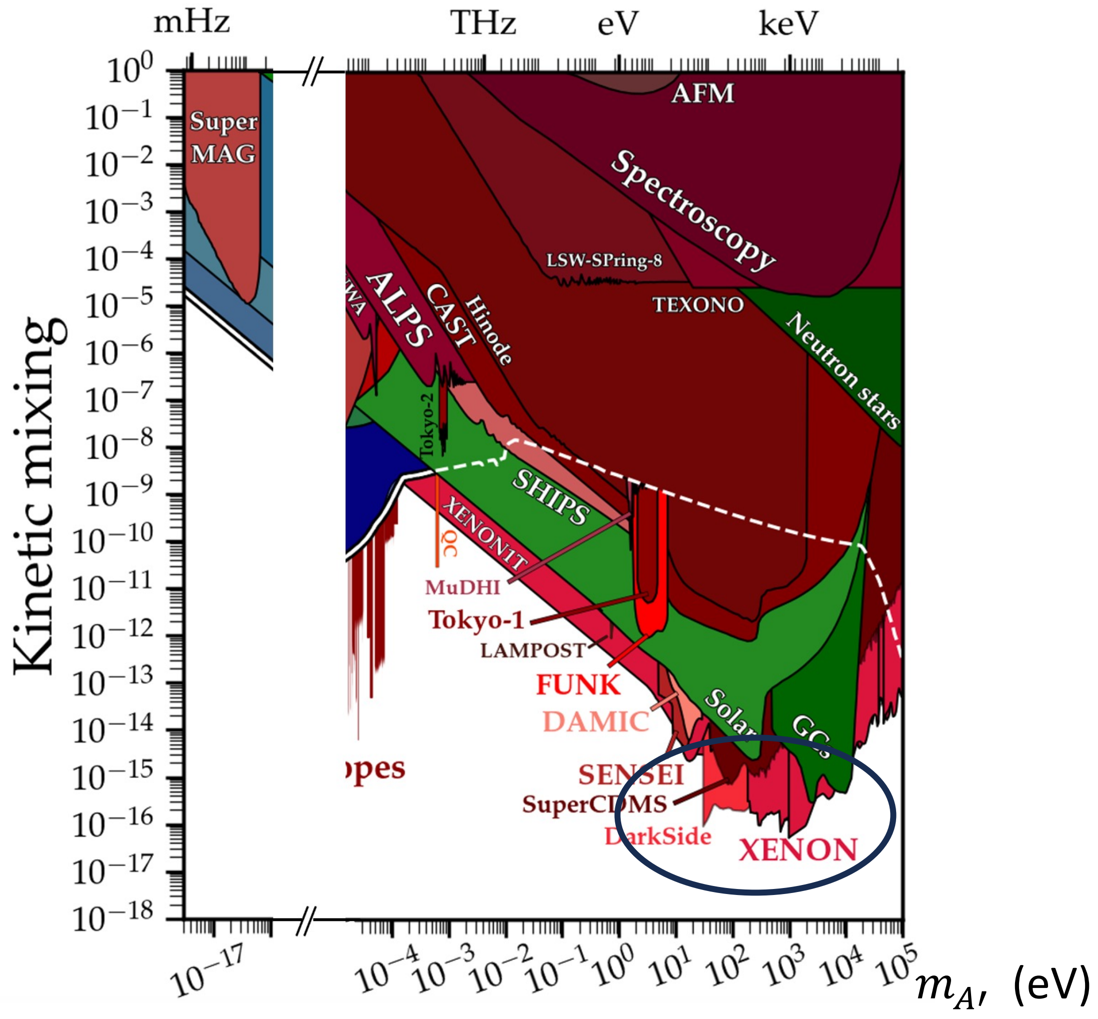


HA, Pospelov, Pradler, Ritz, PRD 102 (2020) 115022
XENON1T, PRD 106 (2021) 022001

Searching for ultralight dark matter directly with WIMP detectors



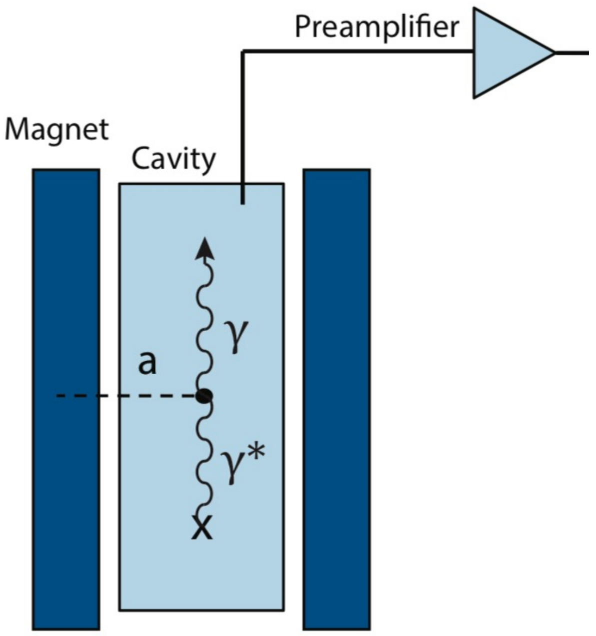




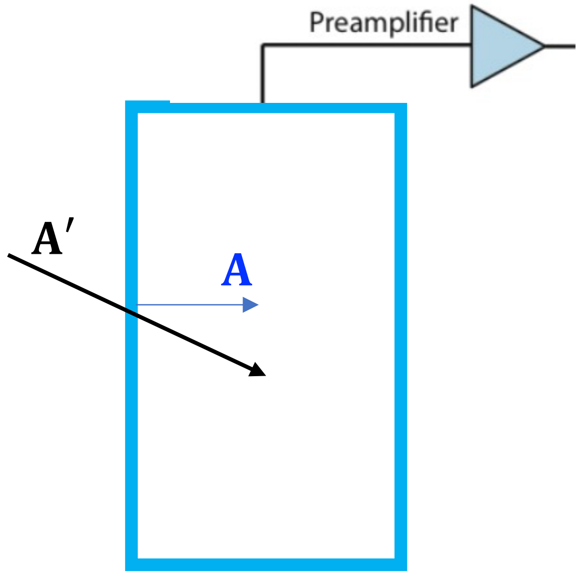
HA, Pospelov, Pradler, Ritz, PLB 747 (2015) 190-195

Resonant cavities

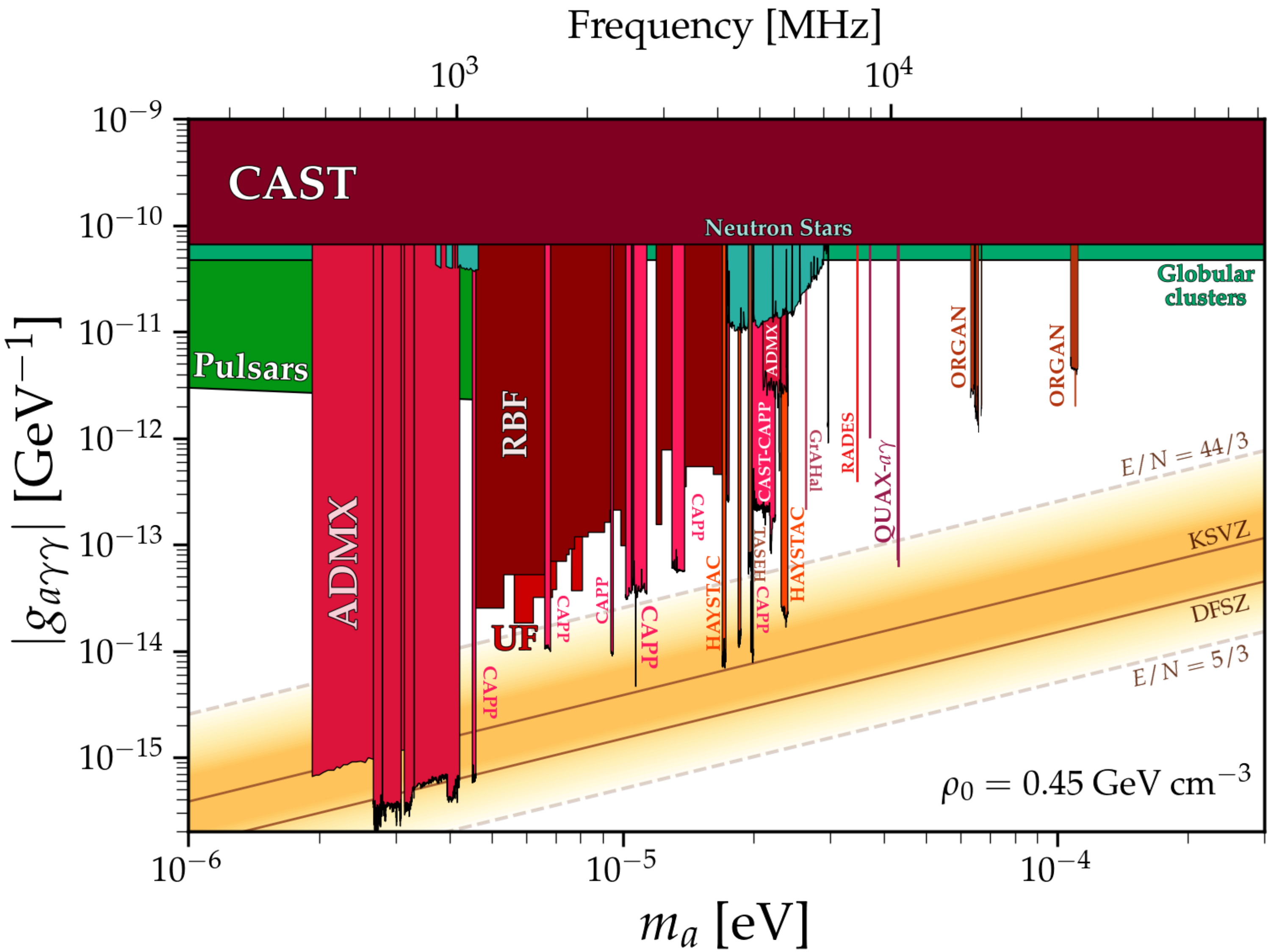
- Axion: $a, \mathbf{E}$ mixing, $aF_{\mu\nu}\tilde{F}^{\mu\nu} \to a\mathbf{E}\cdot\mathbf{B} \to a\mathbf{E}\cdot\mathbf{B_0}$
- Dark photon: $\mathbf{A}$, $\mathbf{A}'$ mixing, $\epsilon F_{\mu\nu}F'^{\mu\nu} \to e(A_\mu - \epsilon A'_\mu)J^\mu_{\rm em}$

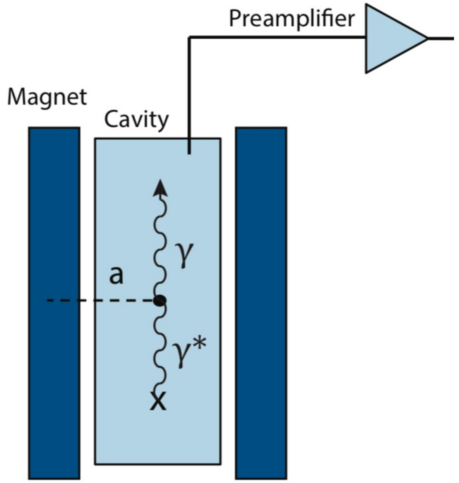


Ultralight dark matter ⟷ Standing EM waves

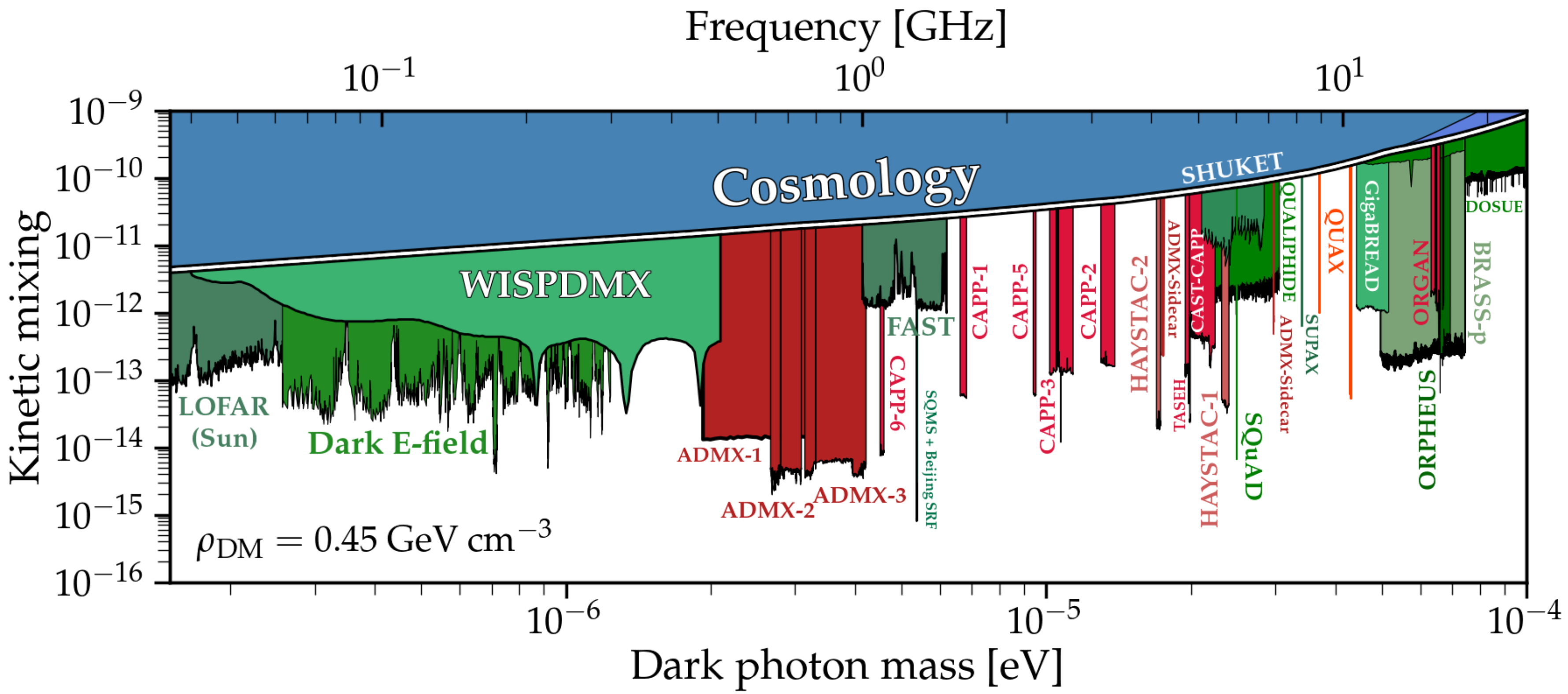


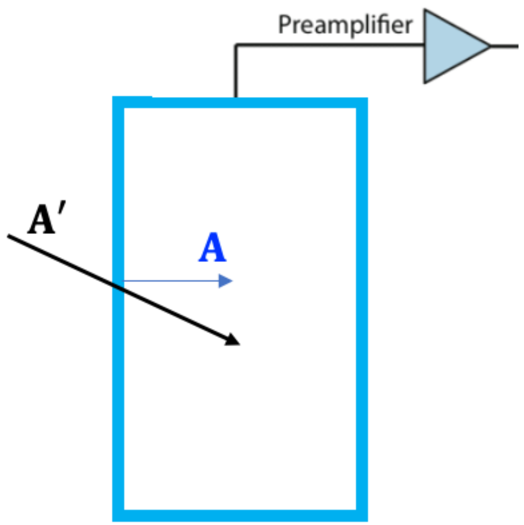
Resonant cavities for axions





Resonant cavities for dark photon dark matter

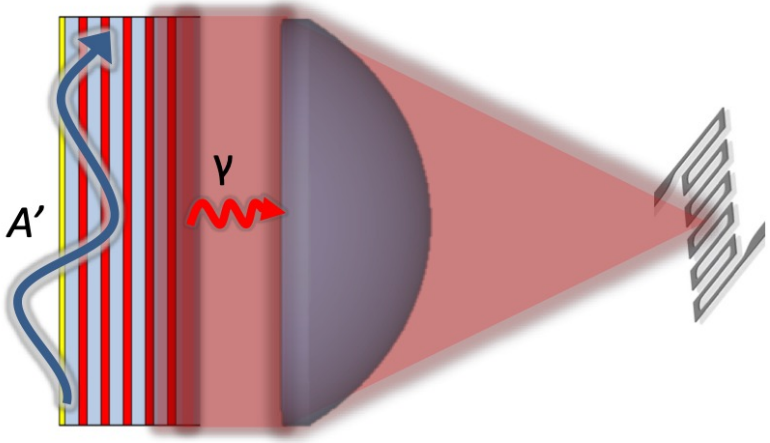




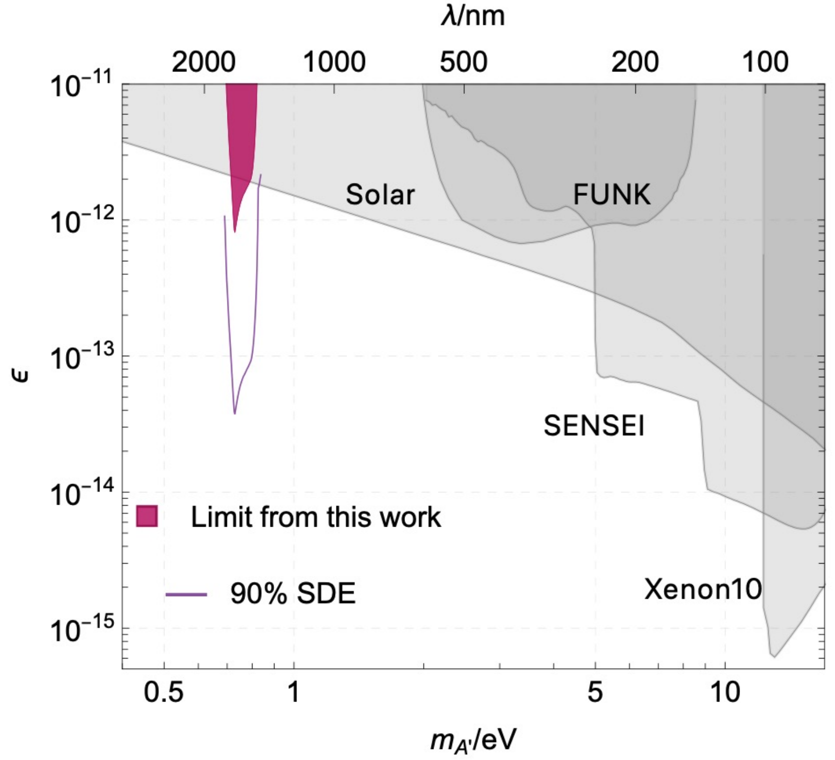
Searching for high frequency axions and dark photons with di-electric layers

- 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.



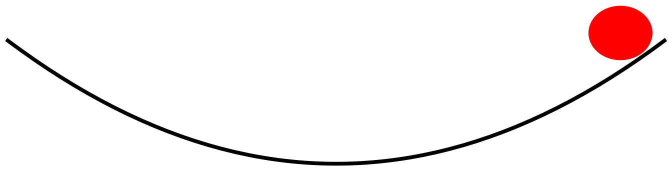
Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006



LAMPOST, PRL 128 (2022) 231802

Broad band searches

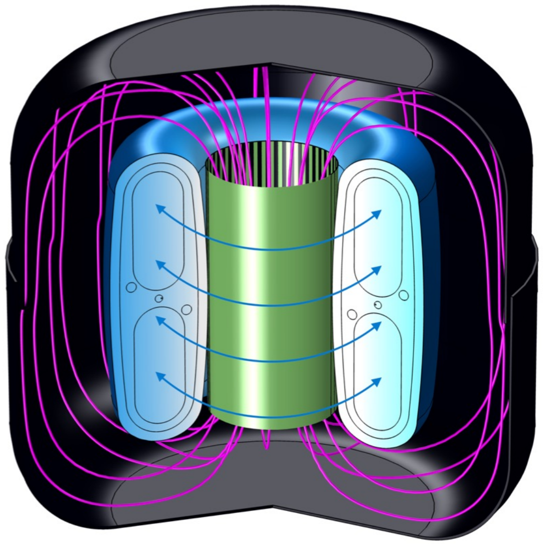
- Axion induced alternative current

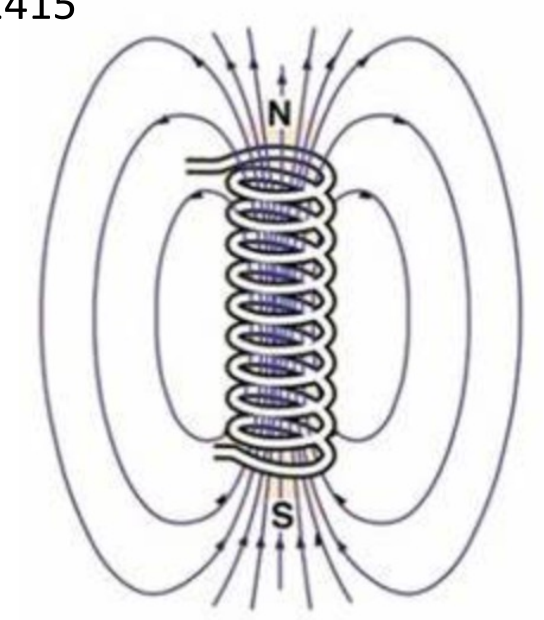


$$g\, a\, \mathbf{E}\cdot\mathbf{B} \longrightarrow \mathbf{J}_{\text{eff}} = g\dot{a}\,\mathbf{B}$$

Sikivie, PRL 51 (1983) 1415

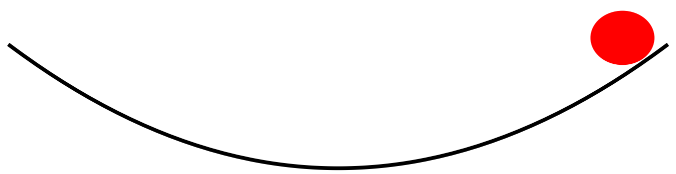
ABRACADABRA





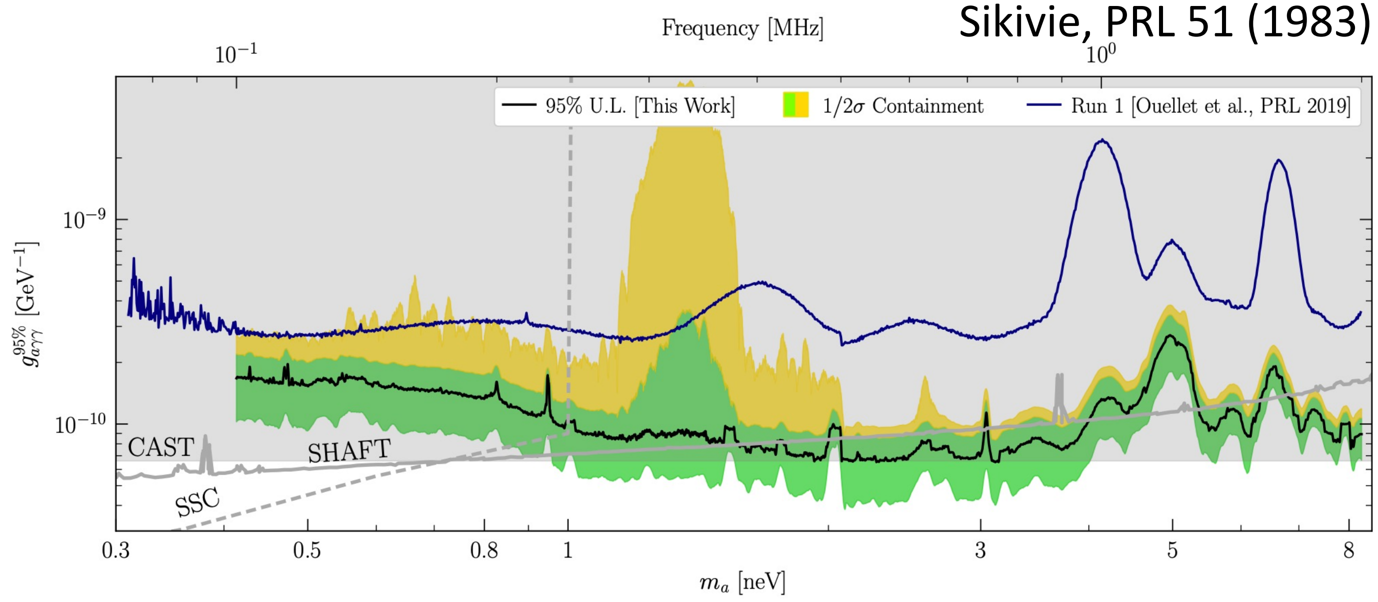
Broad band searches

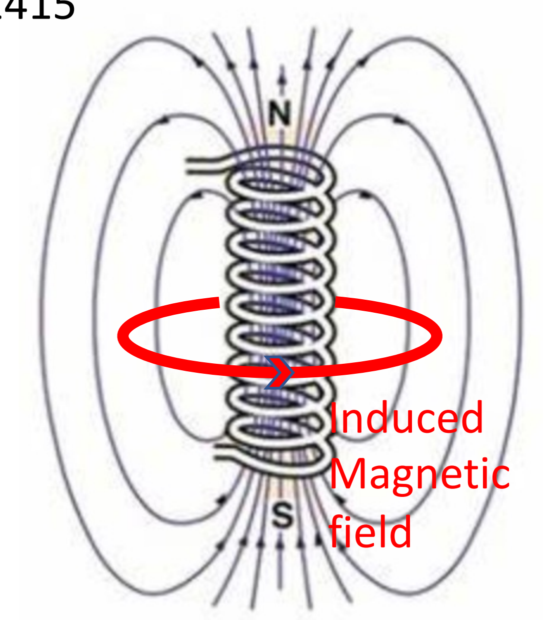
- Axion induced alternative current



$$g\, a\, \mathbf{E} \cdot \mathbf{B} \longrightarrow \mathbf{J}_{\rm eff} = g \dot{a}\, \mathbf{B}$$

Sikivie, PRL 51 (1983) 1415





ABRACADABRA, Phys. Rev. Lett. 127, 081801 (2021)

Searching for ultralight DM with radio telescopes

- For axion or dark photon:

$$\omega^2 - k^2 = m^2$$

- For photon in plasma:

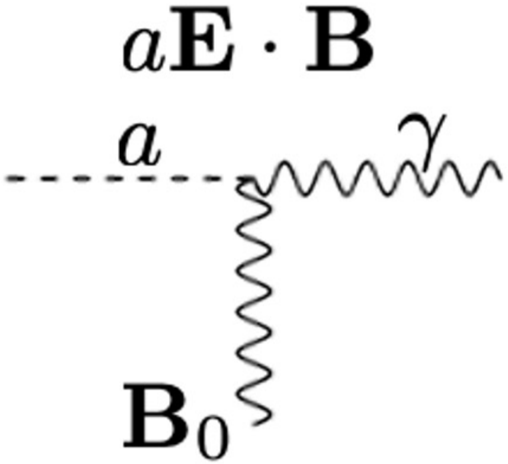
$$\omega^2 - k^2 = \omega_p^2$$

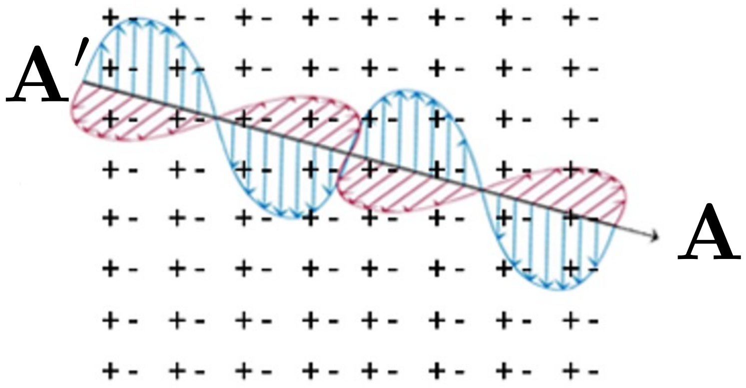
- For axions:

  plasma + magnetic field

- For dark photon:

  plasma

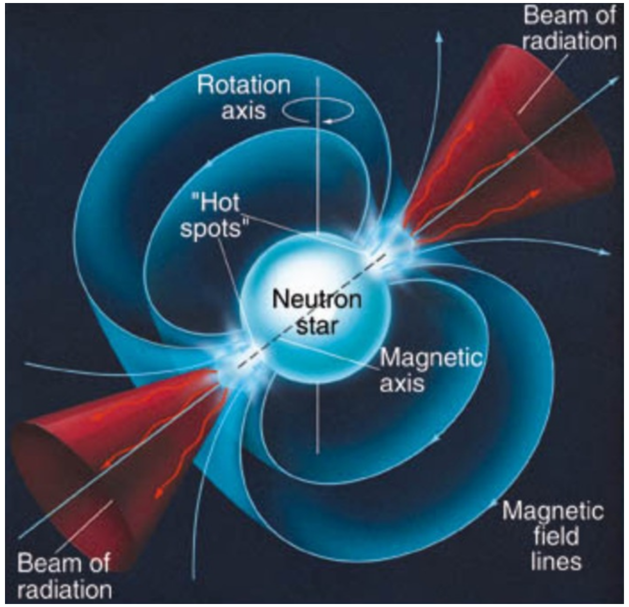




Ultralight axions dark matter

- Strong magnetic field to make the mixing larger.
- Electrons trapped by the magnetic field provide a plasma mass for photons.

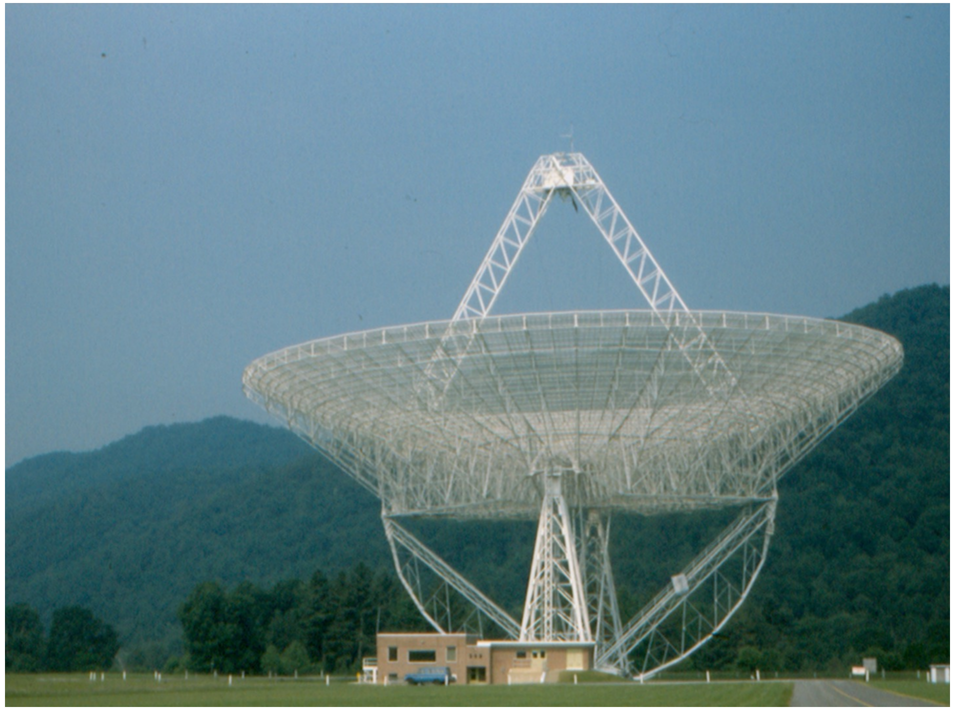
$10^{10} \sim 10^{14}$ Gauss

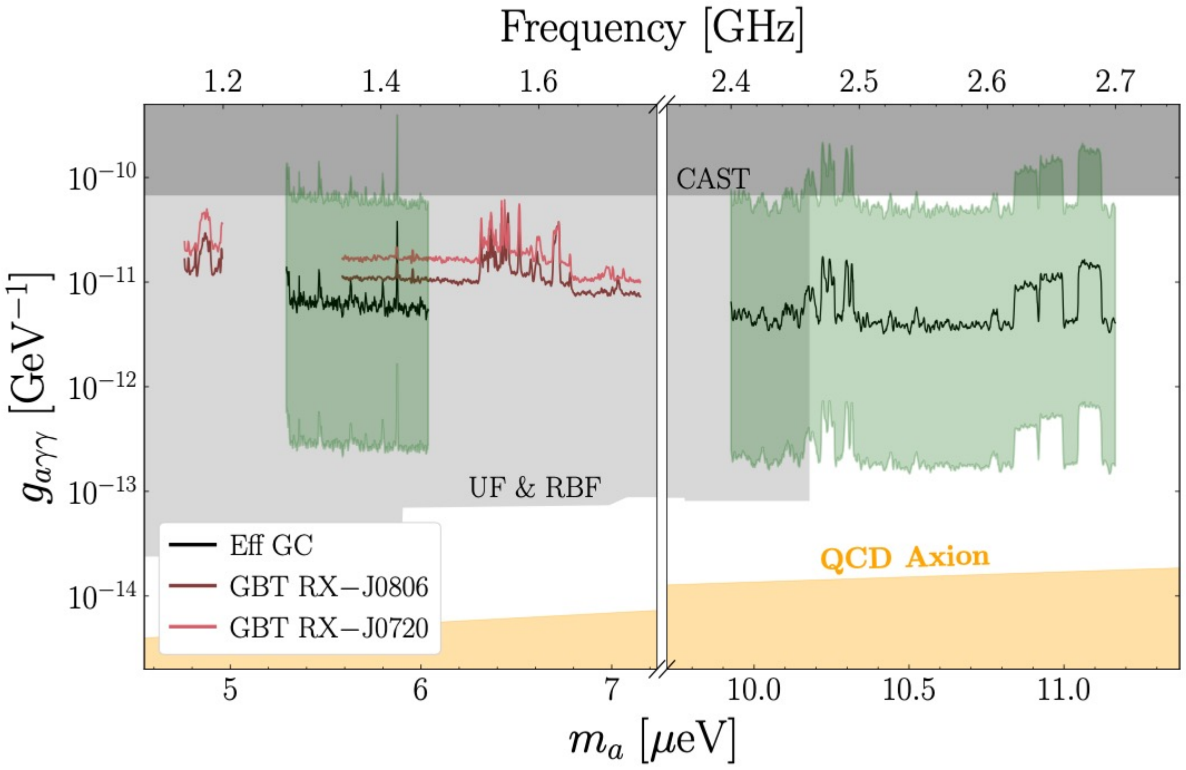


Pshirkov, Popov, 0711.1264
F.P.Huang et al. PRD 97 (2018) 123001
Hook, Kahn, Safdi, Sun, PRL 121 (2018) 241102

Result from Green Bank Telescope

100 meter diameter



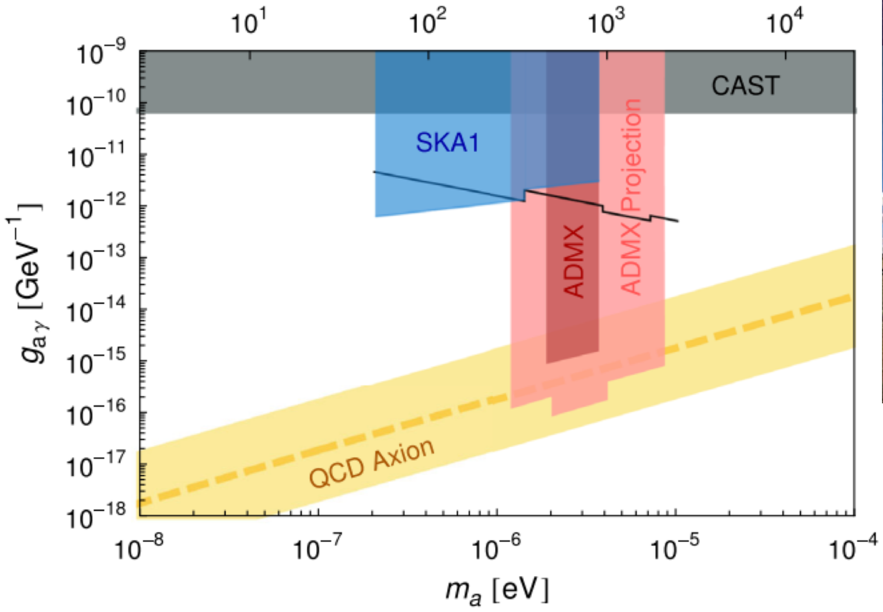


Foster et al., Phys.Rev.Lett. 125 (2020) 171301

What about white dwarves?

	Neutron Star	White Dwarf
Magnetic field	$\sim 10^{10} - 10^{14}$ Gauss	$\sim 10^{7}$ 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.

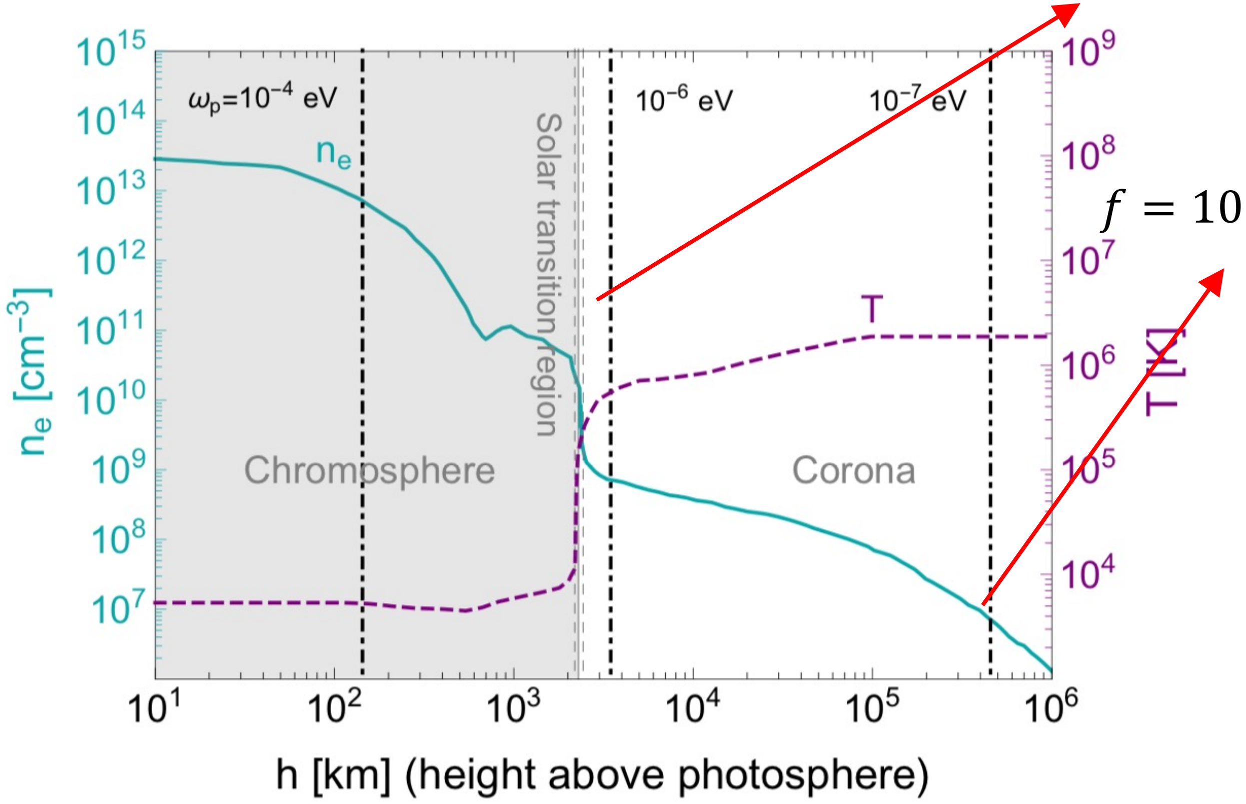


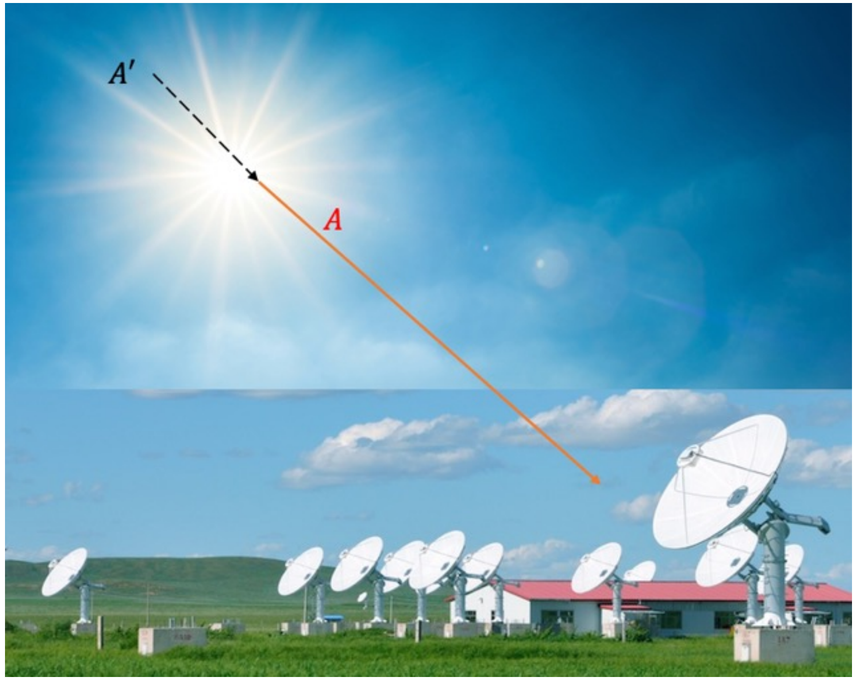
Wang, Bi, Yao, Yin, 2101.02585

Searching for dark photon dark matter resonant conversion in the Sun’s atmosphere

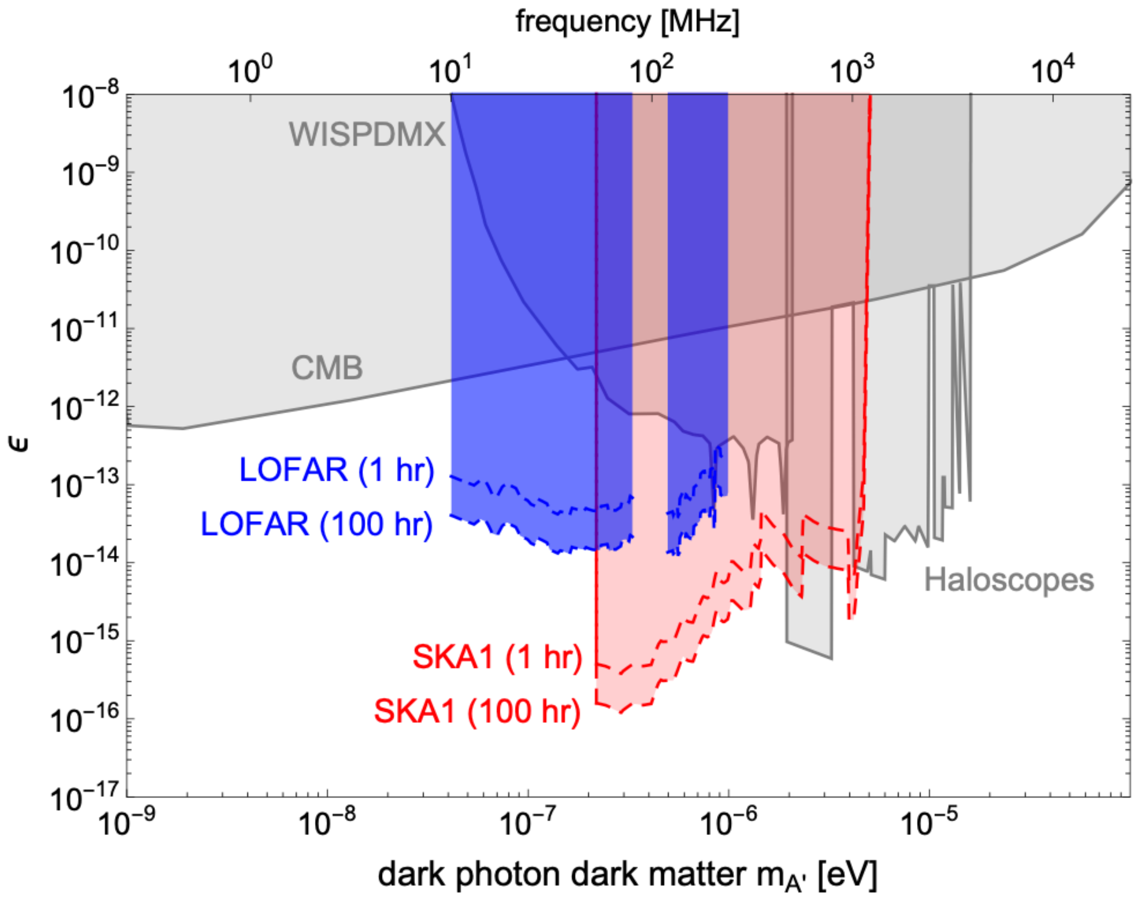
$f = 1$ GHz

$f = 10$ MHz





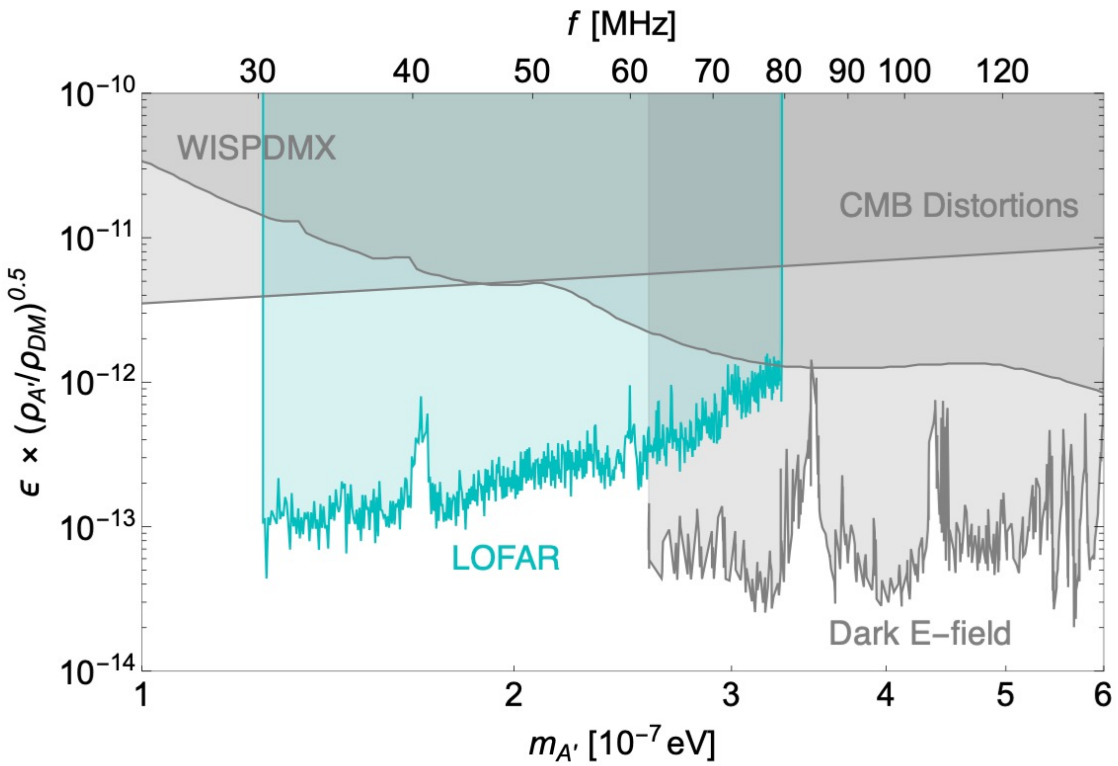
Radiofrequency Dark Photon DM



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

Radiofrequency Dark Photon DM

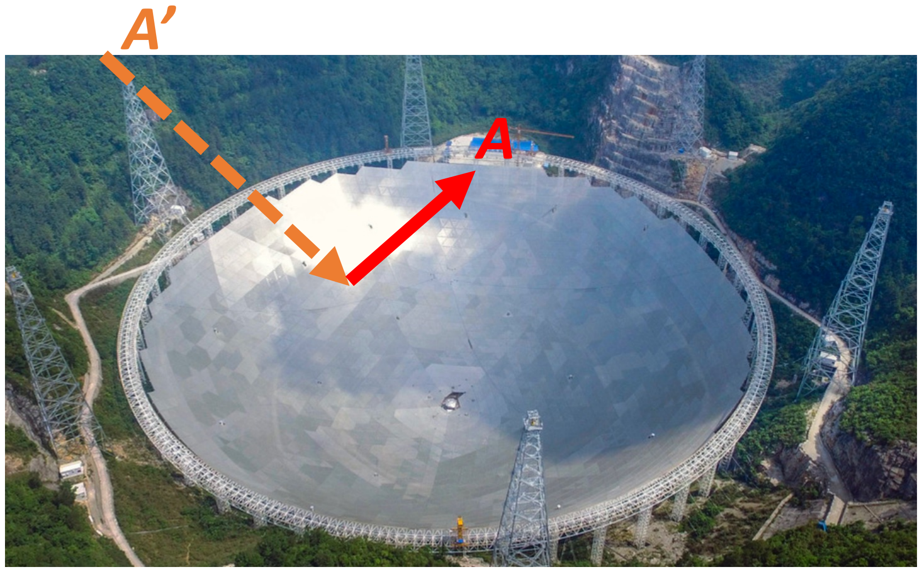
- Searching for dark photon DM in LOFAR data

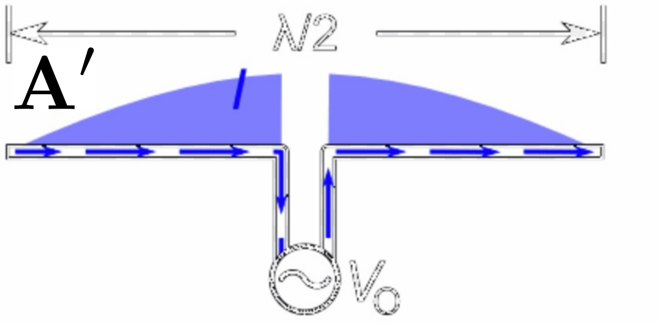


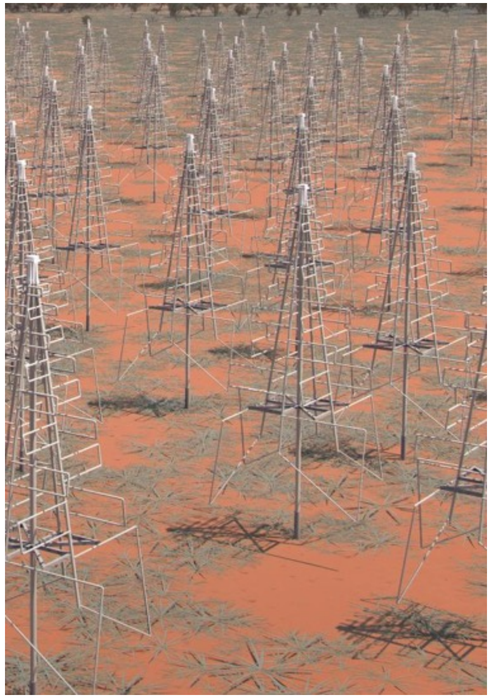
HA, X. Chen, S. Ge, J. Liu, Y. Luo, 2301.03622

Searching for dark photon dark matter directly with radio telescopes

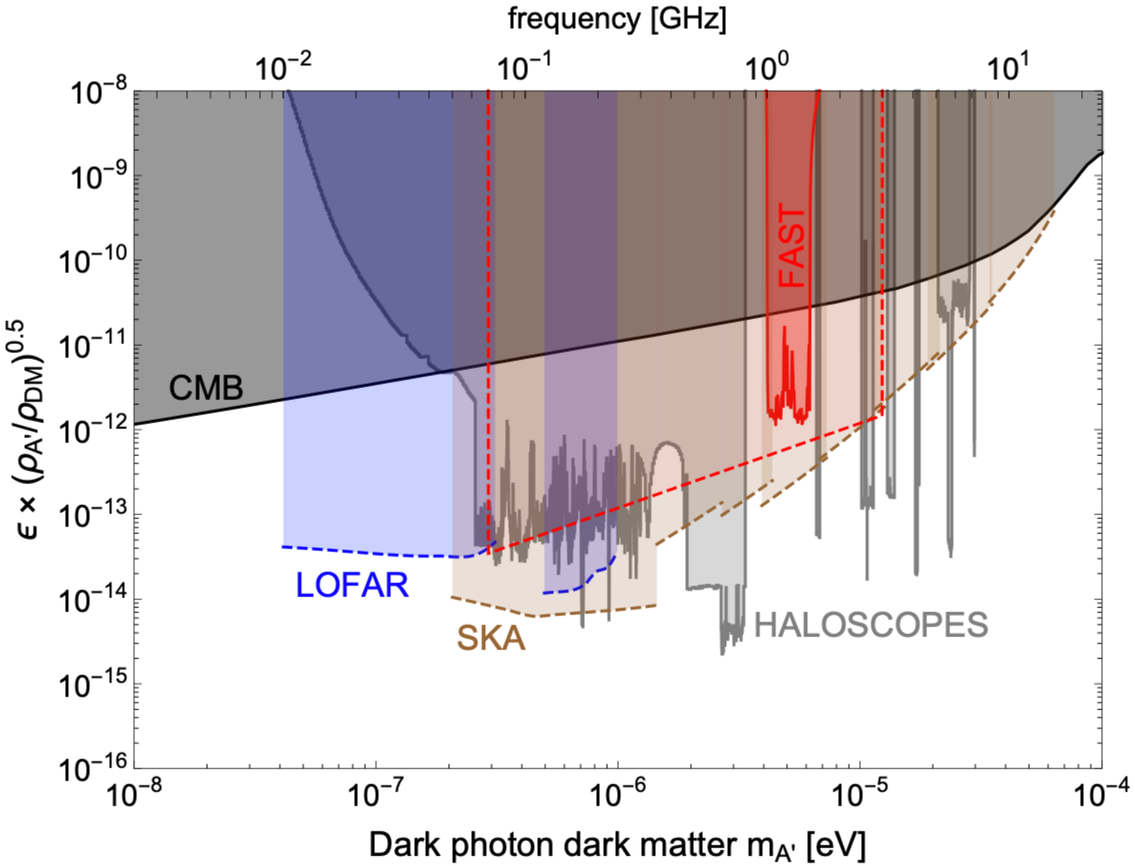
- The metal plate converts A' to A
- The dark photon dark matter has an interaction with the electric current, $\epsilon e A'_{\mu} J^{\mu}$.







Searching for dark photon dark matter directly with radio telescopes



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

Summary

We need more ideas to search for dark matter.