Radio Signals of non-WIMP Dark Matter

Marco Regis

Ministero dell'Università e della Ricerca

PRIN

Progetti di Ricerca di Rilevante Interesse Nazionale

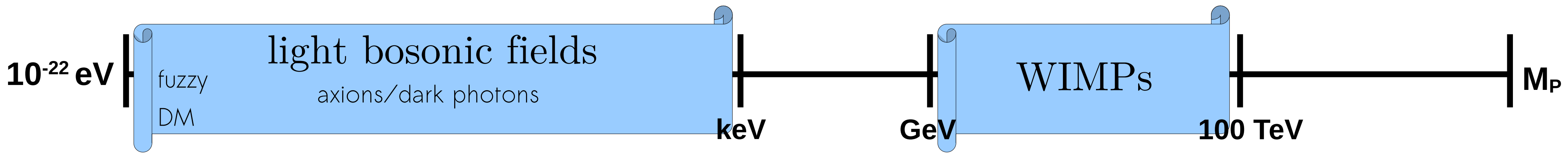
Università di Torino

INFN Istituto Nazionale di Fisica Nucleare

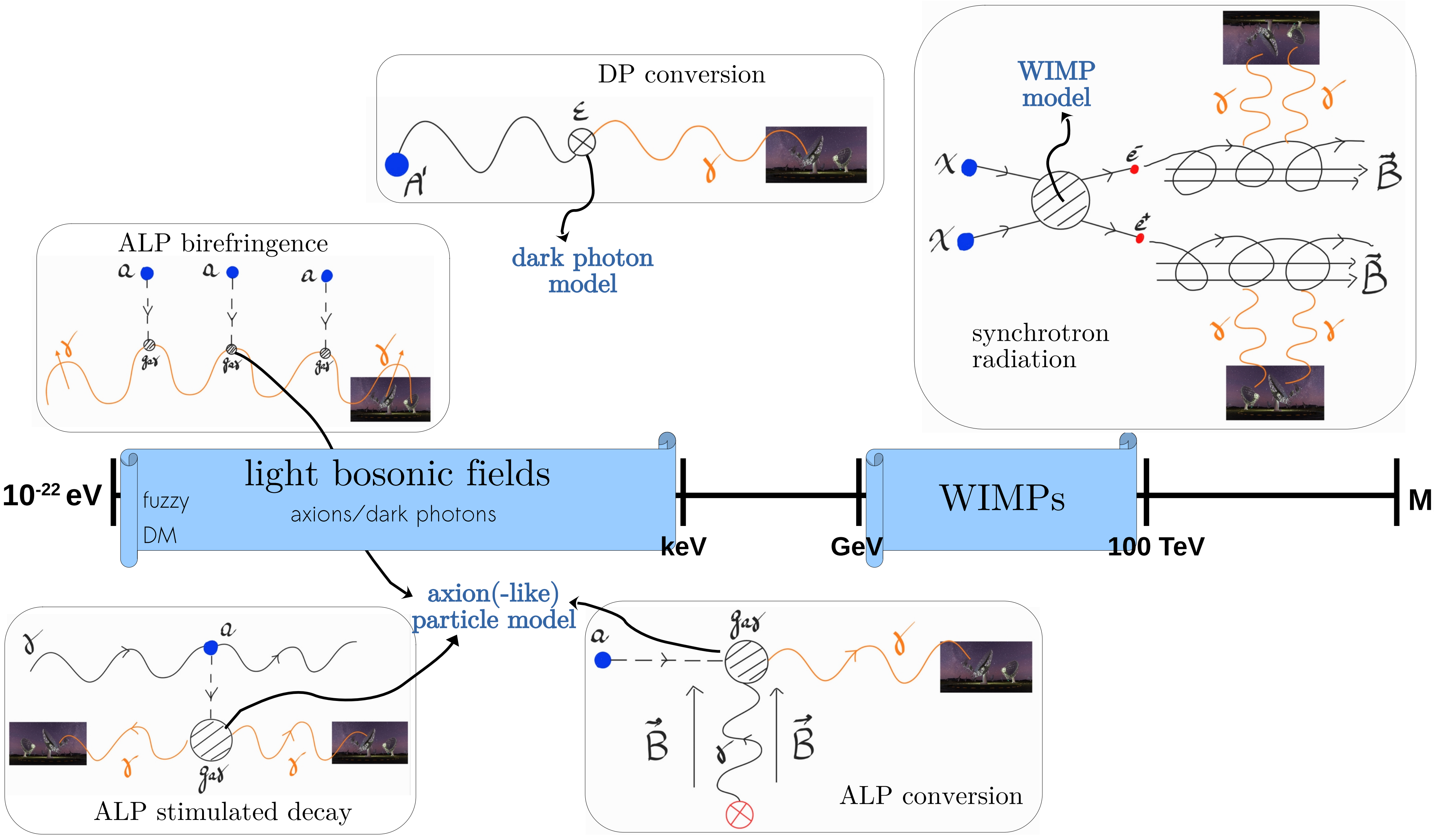
Which Particle Dark Matter?

Two well-motivated classes of DM candidates:

- light bosonic field (**ALPs** and **dark photons**)
- weakly interacting massive particles (**WIMPs**)

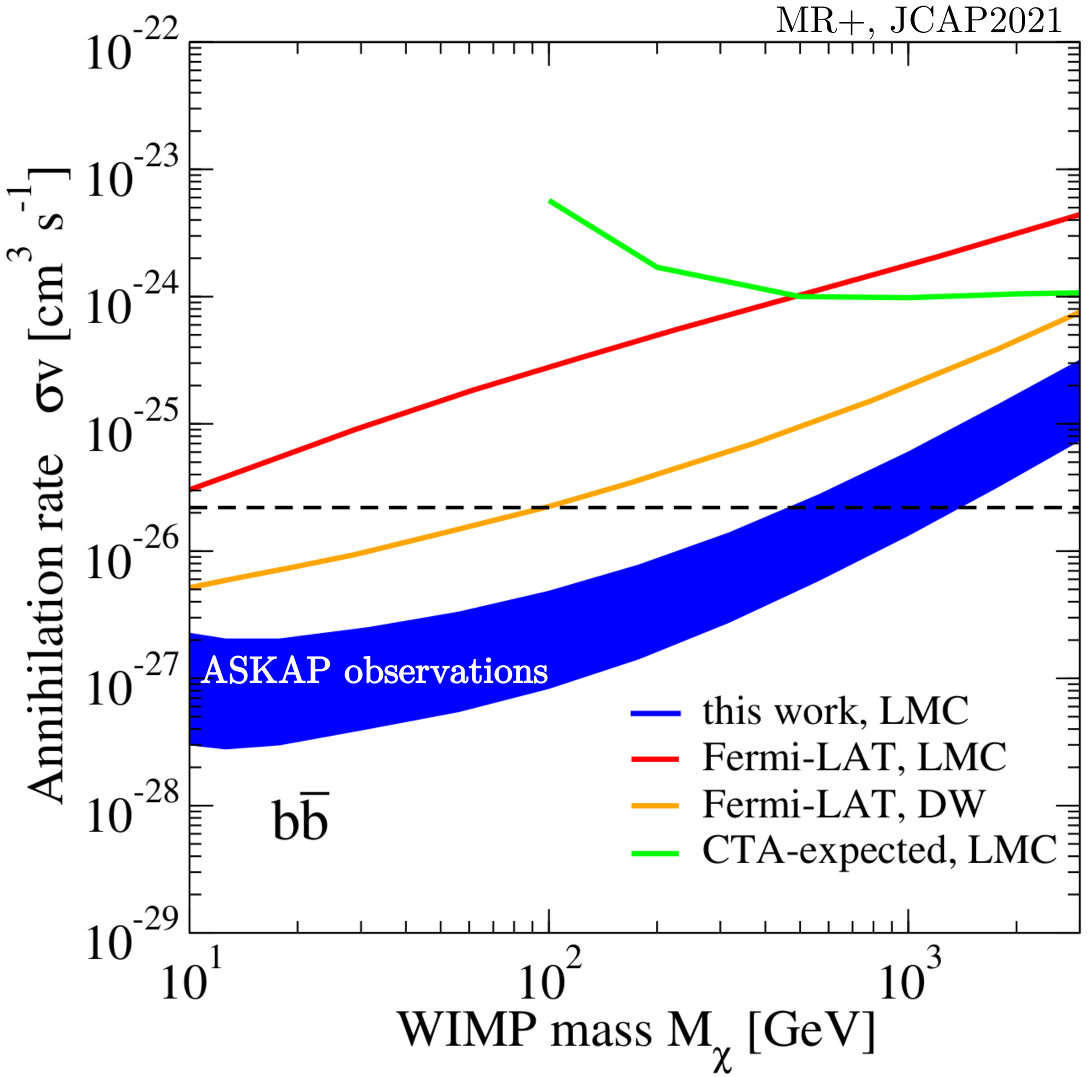


Which Particle Dark Matter?



Comparison with other indirect searches

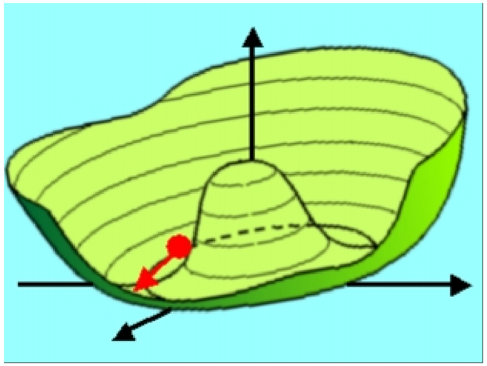
Very competitive bounds if compared to other WIMP indirect searches!



One needs **continuum observations** with **high sensitivity** and good characterization of the **magnetic properties** of the target

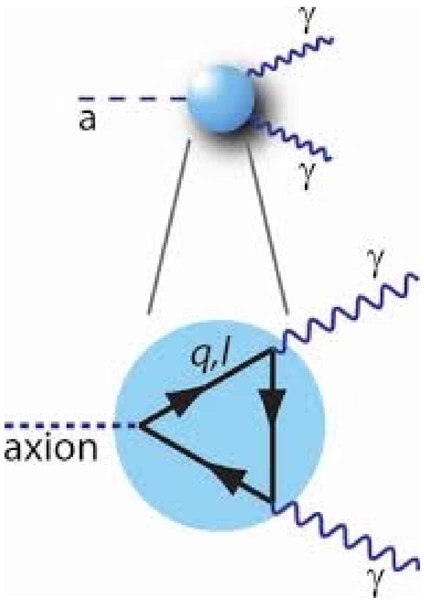
ALPs (axion-like particles)

(pseudo-)scalar particles
mainly pseudo-Nambu-Goldstone bosons
(QCD axion, “stringy” axions, ...)



photon coupling:

ALP-photon coupling described by the low-energy effective Lagrangian: $\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}_{\mu\nu}$



→ axion electrodynamics!

Axion electrodynamics

Lagrangian:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_{[a]}^{(2)} a^{(2)} - \frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} - \mu_{[0]}\mathcal{J}^\mu \mathcal{A}_\mu + \frac{1}{4} g_{[a\gamma]} a \mathcal{F}_{\mu\nu}\widetilde{\mathcal{F}}^{\mu\nu}$$

Euler-Lagrange equations:

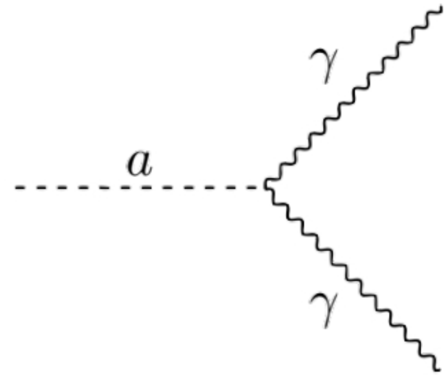
$$\frac{\partial \mathcal{L}}{\partial \mathcal{A}_\rho} - \partial_\lambda \left(\frac{\partial \mathcal{L}}{\partial(\partial_\lambda \mathcal{A}_\rho)} \right) = 0$$

Maxwell equations:

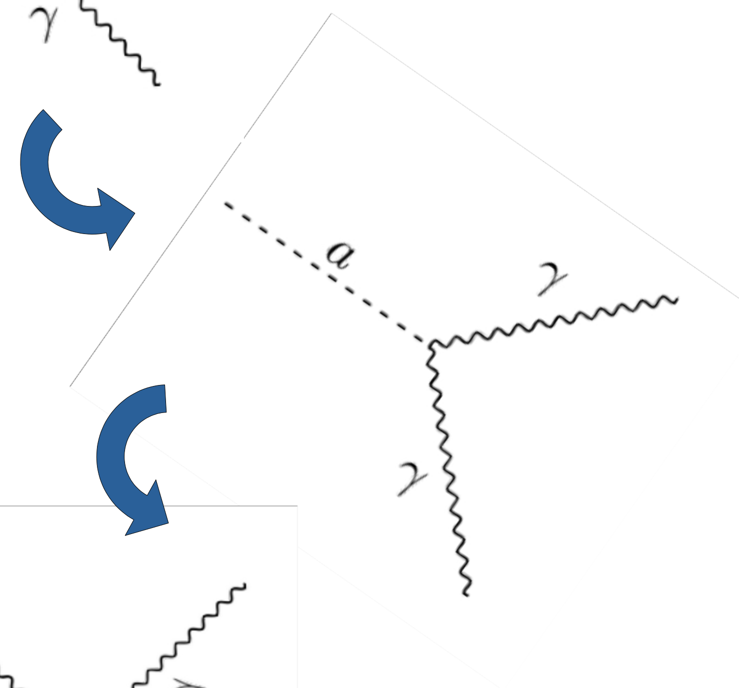
$$\begin{cases} \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \\ \nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \epsilon_0 \partial_t \mathbf{E} \end{cases} \longrightarrow \begin{cases} \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} - \boxed{c g_{[a\gamma]} \nabla a \cdot \mathbf{B}} \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \\ \nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \epsilon_0 \partial_t \mathbf{E} + \boxed{\frac{g_{[a\gamma]}}{c}(\mathbf{B}\partial_t a + \nabla a \times \mathbf{E})} \end{cases}$$

Phenomenology

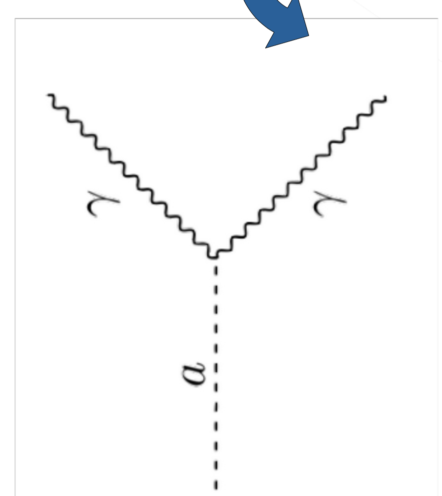
- axion (stimulated) decay in two photons



- axion conversion into a photon

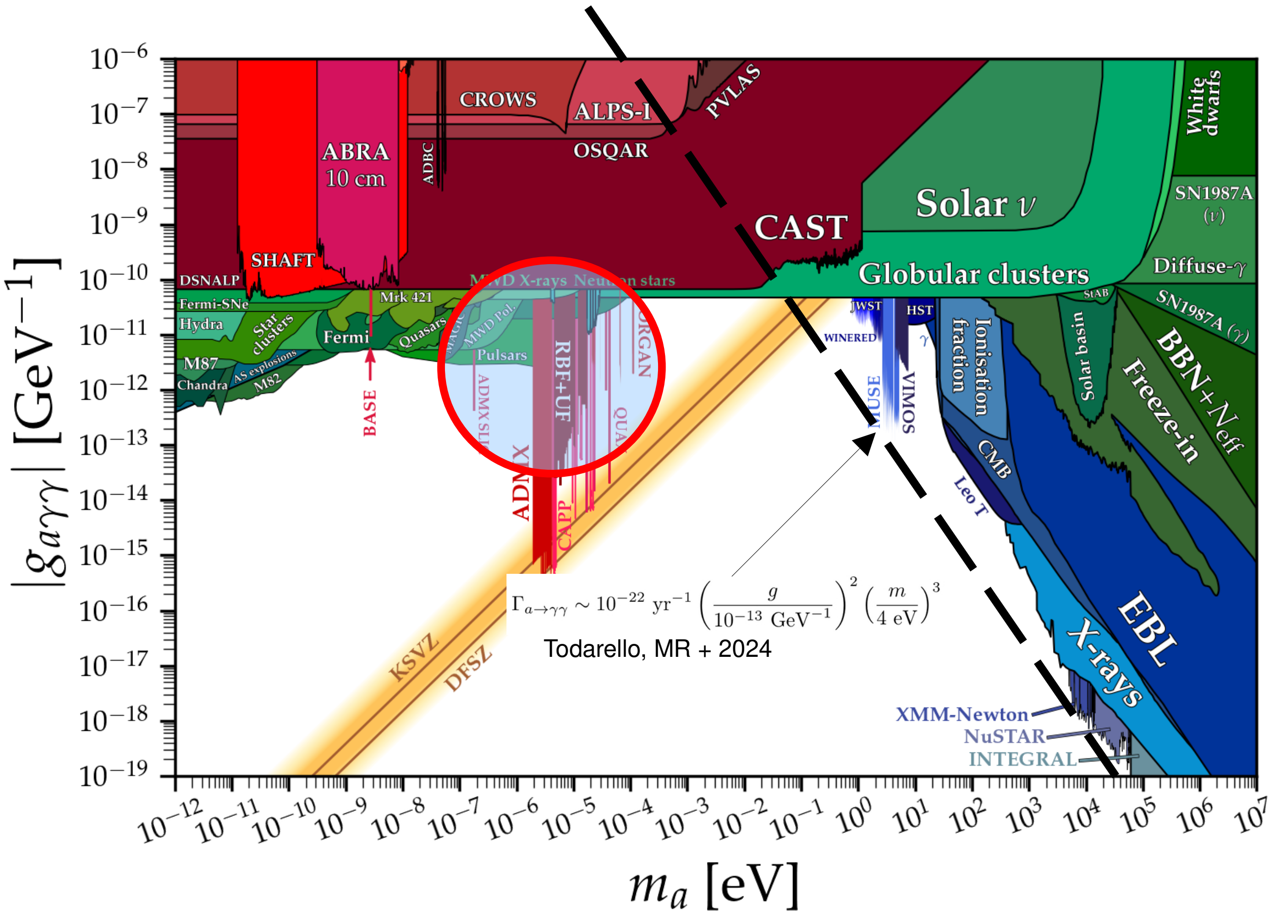


- rotation of the polarization angle of photons



ALP decay

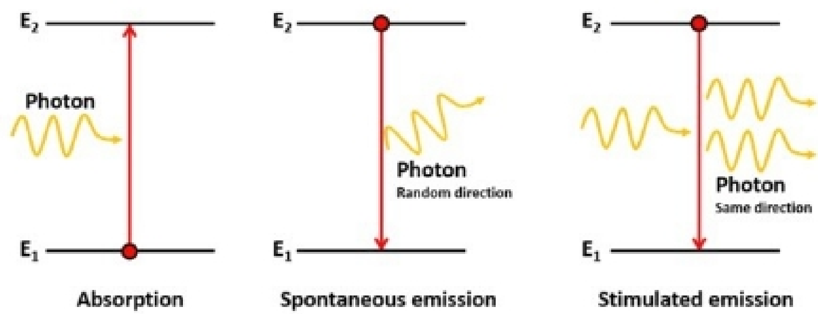
Spontaneous decay rate: $\Gamma_a \equiv g_{a\gamma\gamma}^2 m_a^3/(64\pi)$



Indirect detection via spontaneous decay is hopeless at radio frequencies!

Stimulated decay

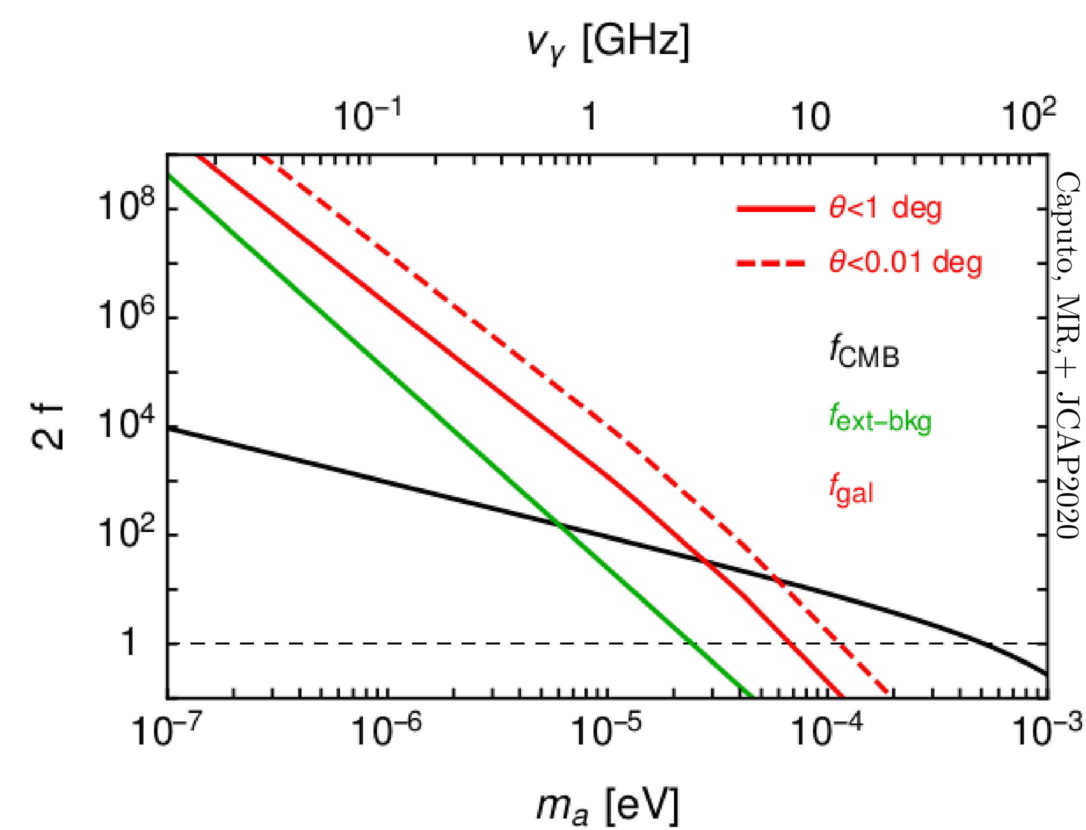
Stimulated decay



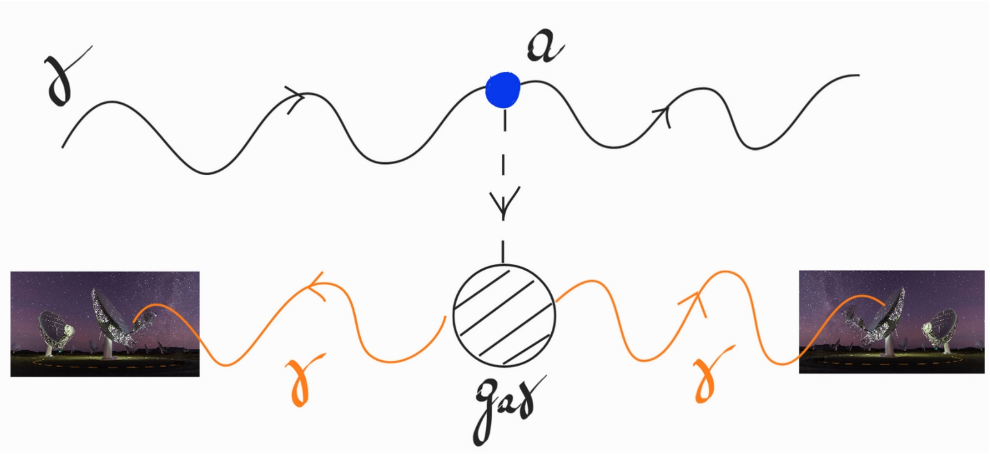
Enhancement factor

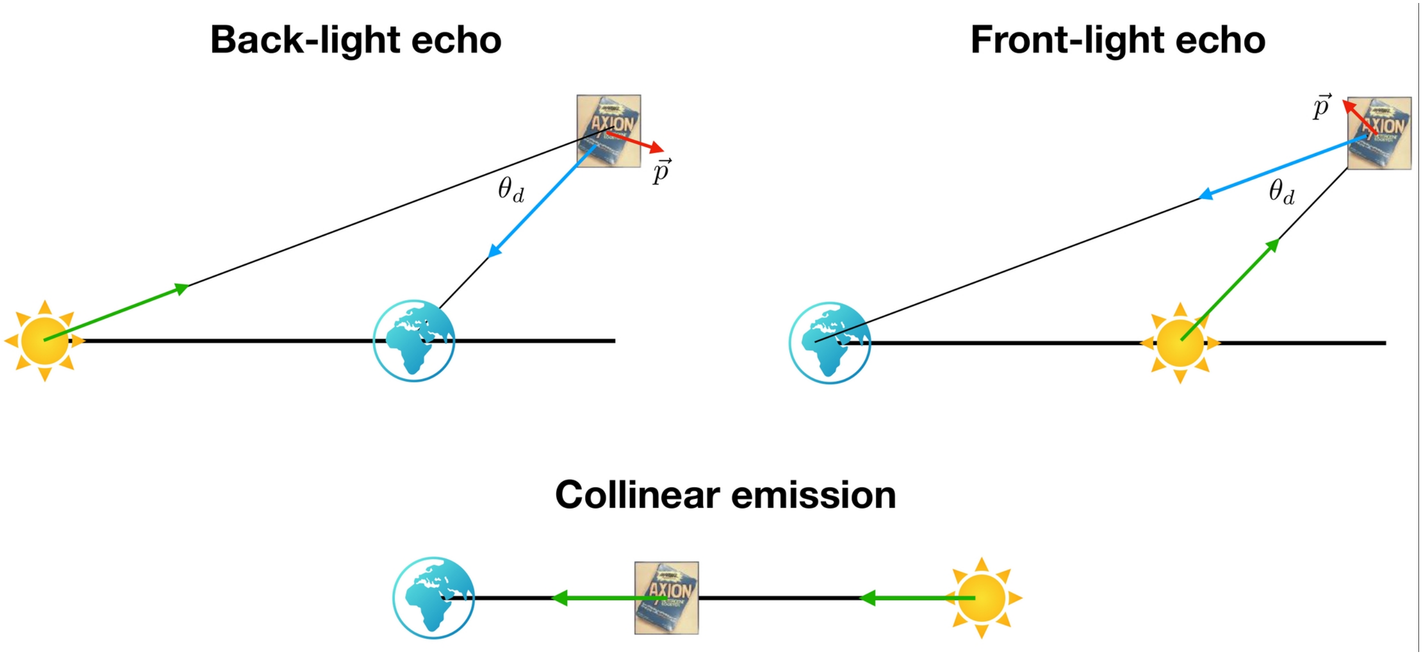
$$2\,f = \frac{\text{stimulated emission}}{\text{spontaneous emission}}$$

$$f \sim \nu^{-3} \sim m_a^{-3}$$



ALP stimulated decay



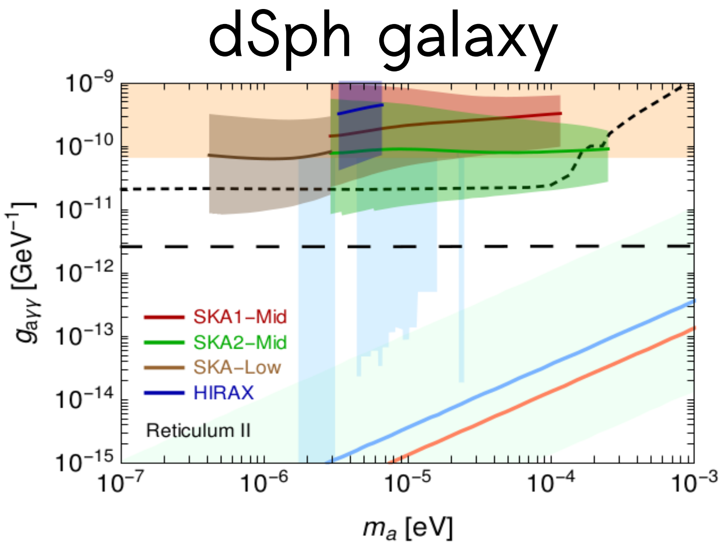


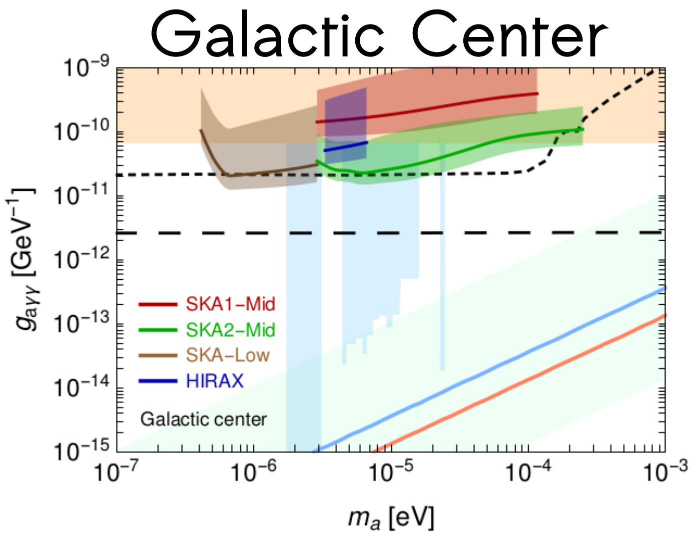
Todarello, MR, Calore JCAP2024

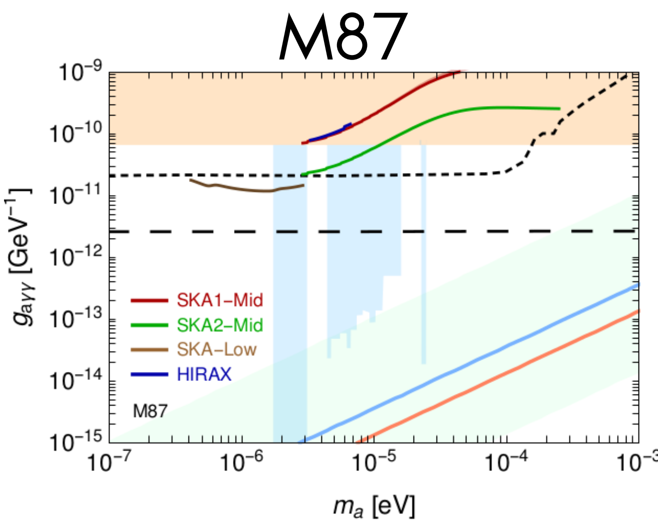
ALP stimulated decay - sensitivity

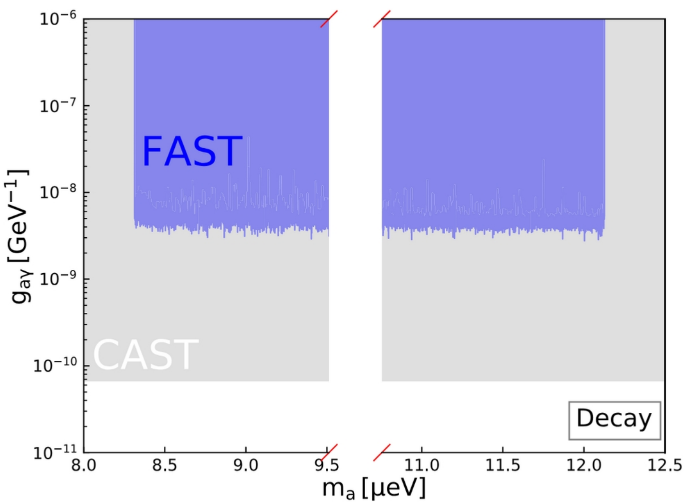
Stimulated emission within the source

Caputo, MR, Taoso, Witte JCAP2019









first attempt with

real data:

2-hour observation

of Coma Berenices

(Guo+ PLB2024)

See also

Caputo+ PRD2018
Battye+ PRD2020
Ayad&Beck JCAP2022

ALP stimulated decay - echo

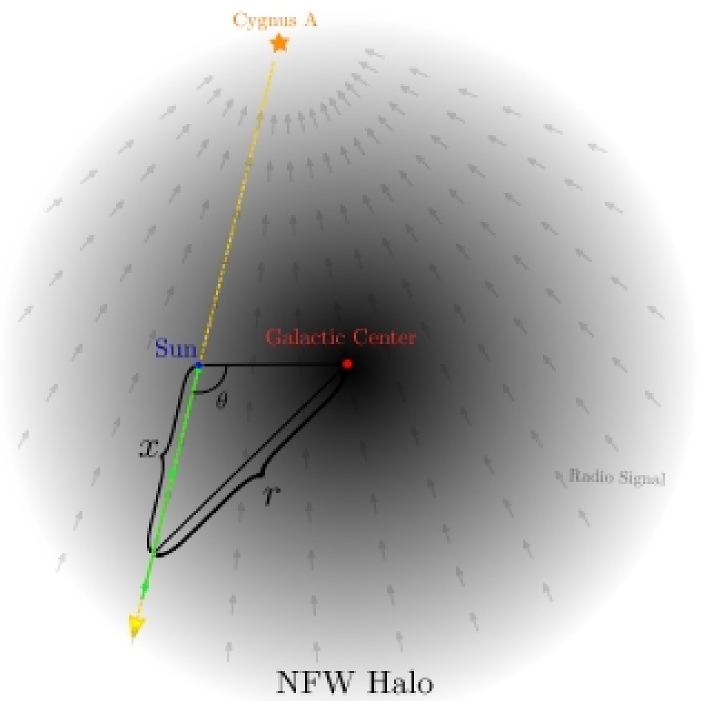
The ALP stimulated decay can be used to

listen for the echo of a powerful radio beam

(i.e. faint radio line traveling in the ~opposite direction)

NATURAL ASTROPHYSICAL BEAM

(Ghosh+ 2020, Sun+ PRD2022, PRD2024, Buen-Abad+ PRD2022, Todarello, MR, Calore JCAP2024, Dev+ JCAP2024)



ARTIFICIAL BEAM

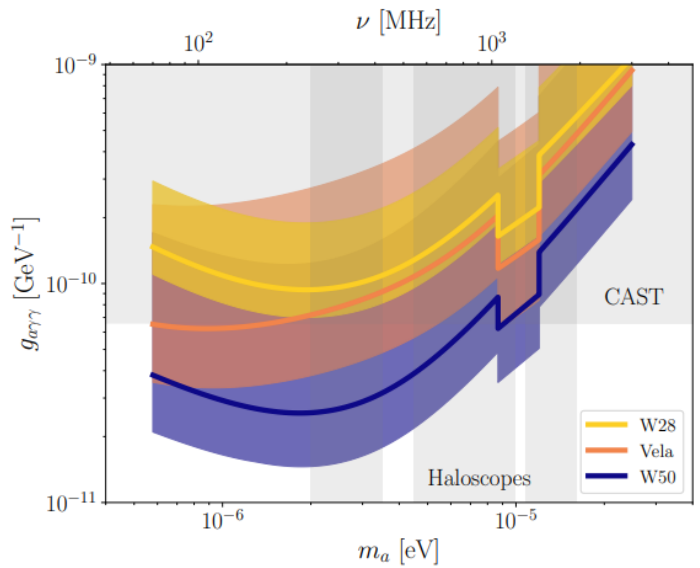
(Arza&Sikivie PRL2019, Arza&Todarello PRD2022)

ALP echo - sensitivity

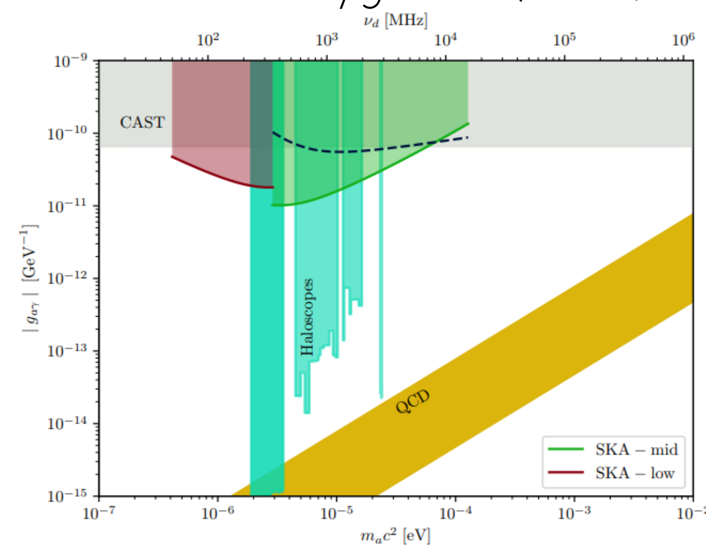
Back-light echo due to axion DM in the Milky Way halo

Galactic SN remnants

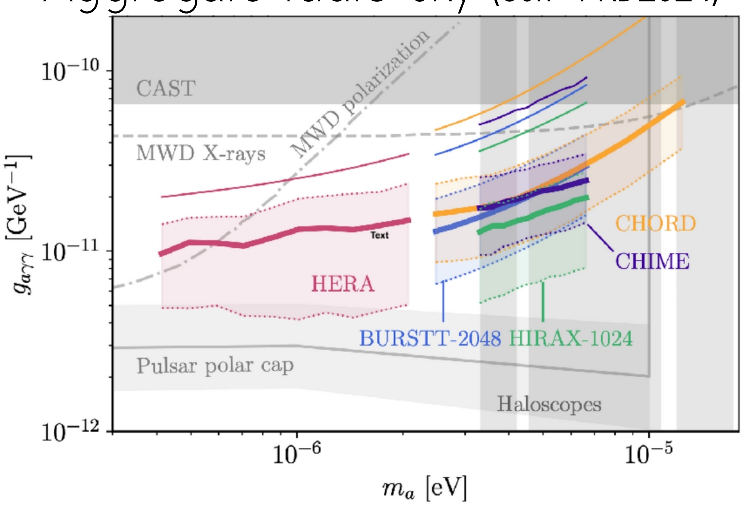
(Sun+ PRD2022, Buen-Abad+ PRD2022)

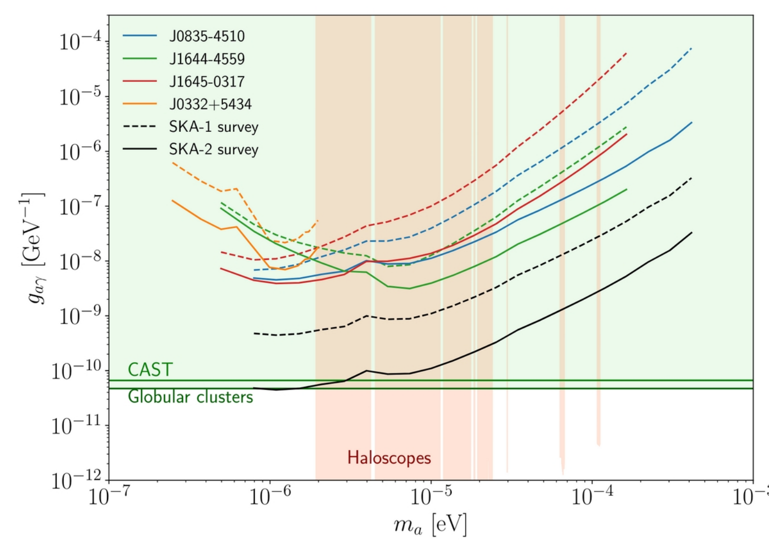


Cygnus A (Ghosh+, 2020)



Aggregate radio sky (Sun+ PRD2024)

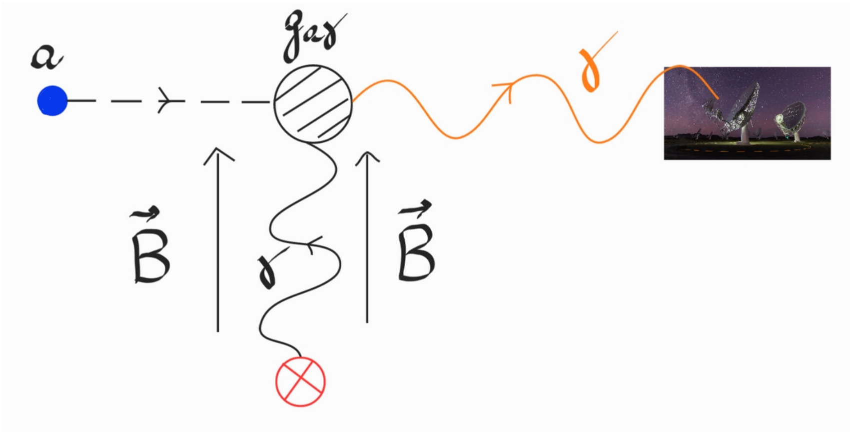


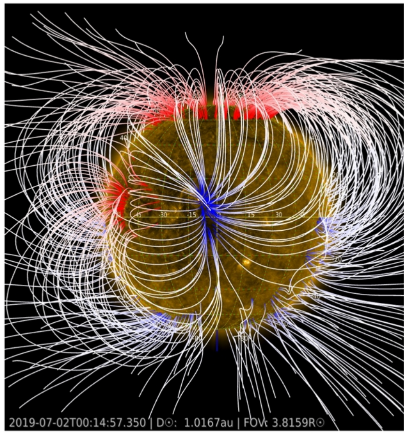


Pulsars

(Todarello, MR, Calore JCAP2024)

ALP conversion





$$P_{a\to\gamma} \simeq \frac{\pi}{2}\frac{g_{a\gamma}^2 B_\perp^2}{v_a \omega'_{q|res}} \qquad \omega'_{q|res} = d\omega_q/dr$$

resonant condition: $m_a = \omega_q(r) = 1.17\,\mu\text{eV}\sqrt{n_e(r)/(10^9\,\text{cm}^{-3})}$

High magnetic field and plasma density

TARGETs:

Neutron stars (magnetars): stronger, more uncertain

Sun: weaker, more solid

ALP conversion in neutron stars

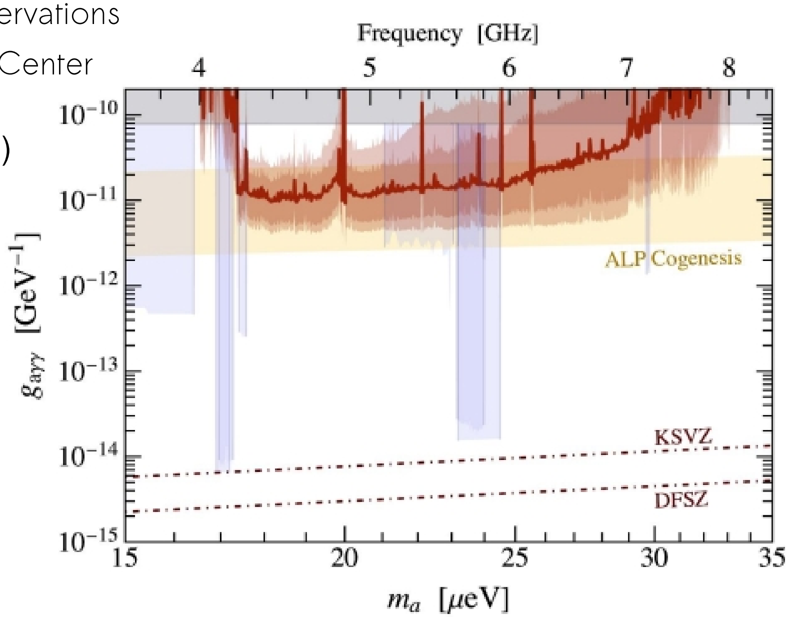
Neutron stars (magnetars): B ~ 10^{14} G

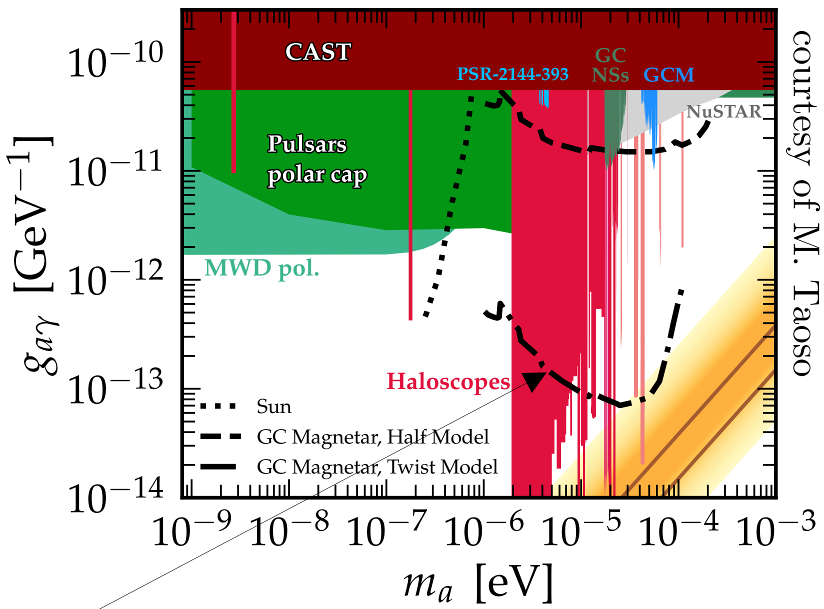
→ promising technique with significant systematics

GBT observations

Galactic Center

(Foster+, PRL2022)





courtesy of M. Taoso

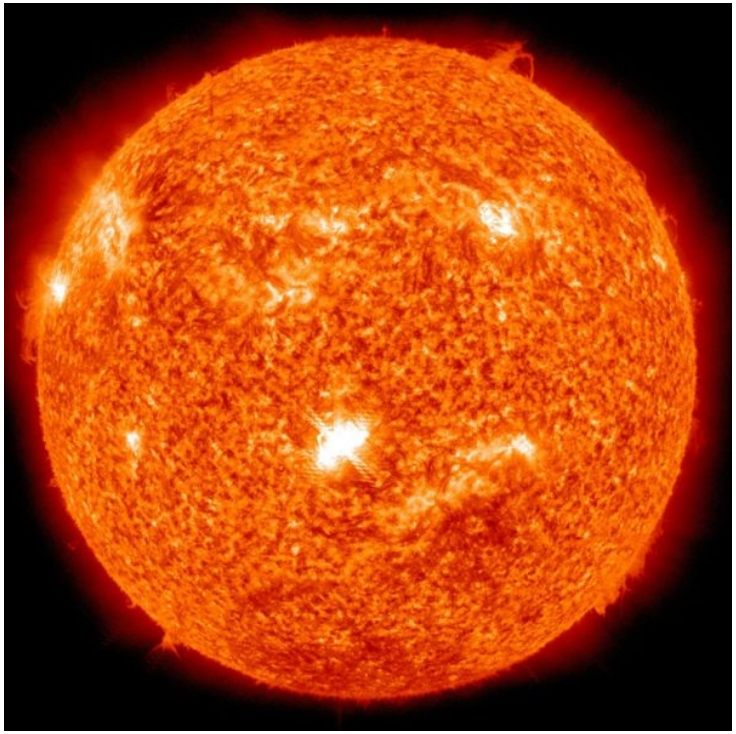
Great progresses in the theoretical description and also some observations!

Hook+ PRL2018, Huang+ PRD2018, Safdi+ PRD2019, Battye+ PRD2020, JHEP 2021, PRD2022, Leroy+ PRD2020, Foster+ PRL2020 and PRL2022, Prabhu+ JCAP2020, Prabhu PRD2021, Millar+ JCAP2021, Witte+ PRD2021, PRD2023, Wang+ PRD2021, Noordhuis PRL2023, McDonald+ JCAP2023, PRD2023, Tjemsland+ PRD2024, Ginés+ PRD2024, Bhura+ JCAP2024, Roy+ 2025, ...

Prduction in NS magnetospheres? (small-scale oscillations in the e.m. fields of pulsar polar caps)

Formation of bound axion clouds? (axion gravitationally captured)

ALP conversion in the Sun



Theoretical expectations comparable to the case of an isolated NS in the Galactic halo

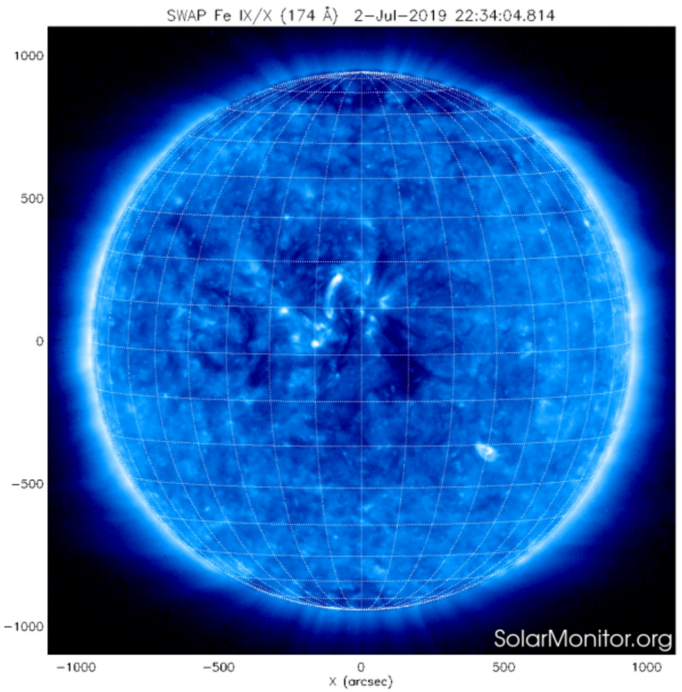
Prediction are not affected by strong systematics

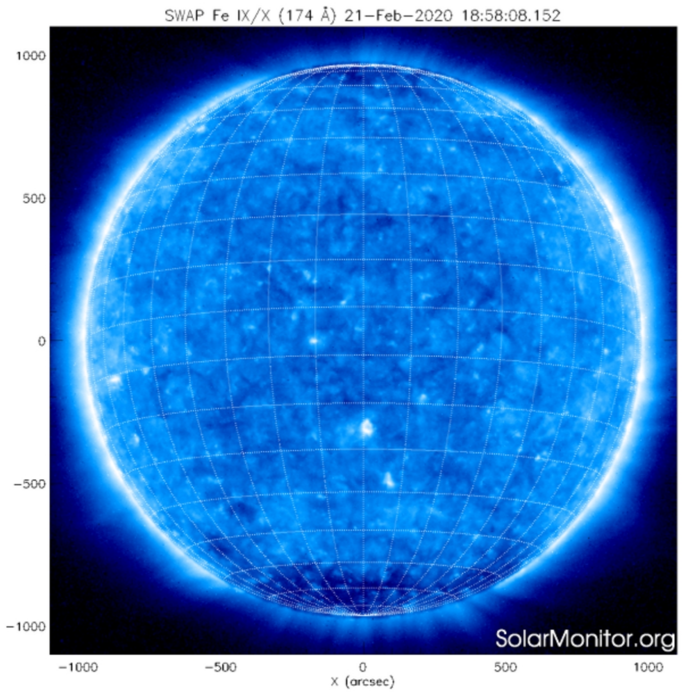
Conversion surface — Magnetic field — Distance

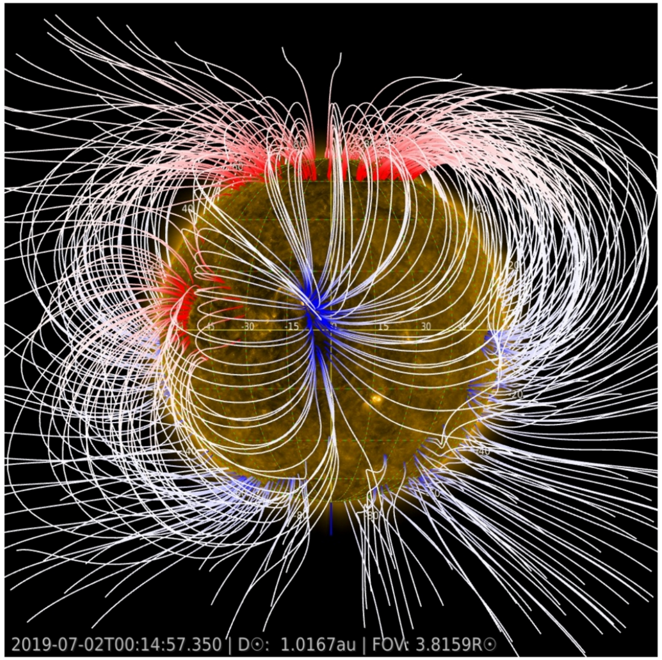
$$S \propto \left(\frac{h_{c,s}\,\ell_s^2}{5\times 10^{12}\,\mathrm{km}^3}\right)\left(\frac{B_s}{5\,\mathrm{G}}\right)^2\left(\frac{1.5\times 10^8\,\mathrm{km}}{d_s}\right)^2 \simeq \left(\frac{r_{c,NS}}{200\,\mathrm{km}}\right)^3\left(\frac{B_{NS}}{10^{12}\,\mathrm{G}}\right)^2\left(\frac{1\,\mathrm{kpc}}{d_{NS}}\right)^2$$

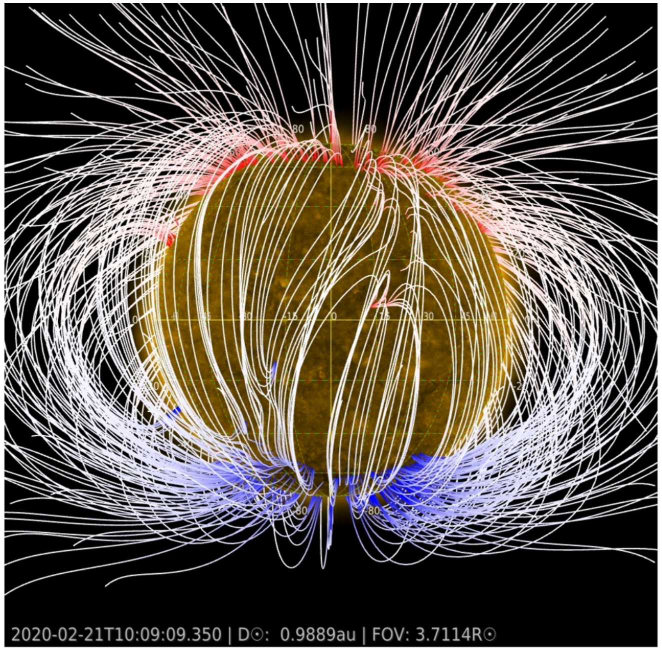
Solar magnetic field

OBSERVATIONS



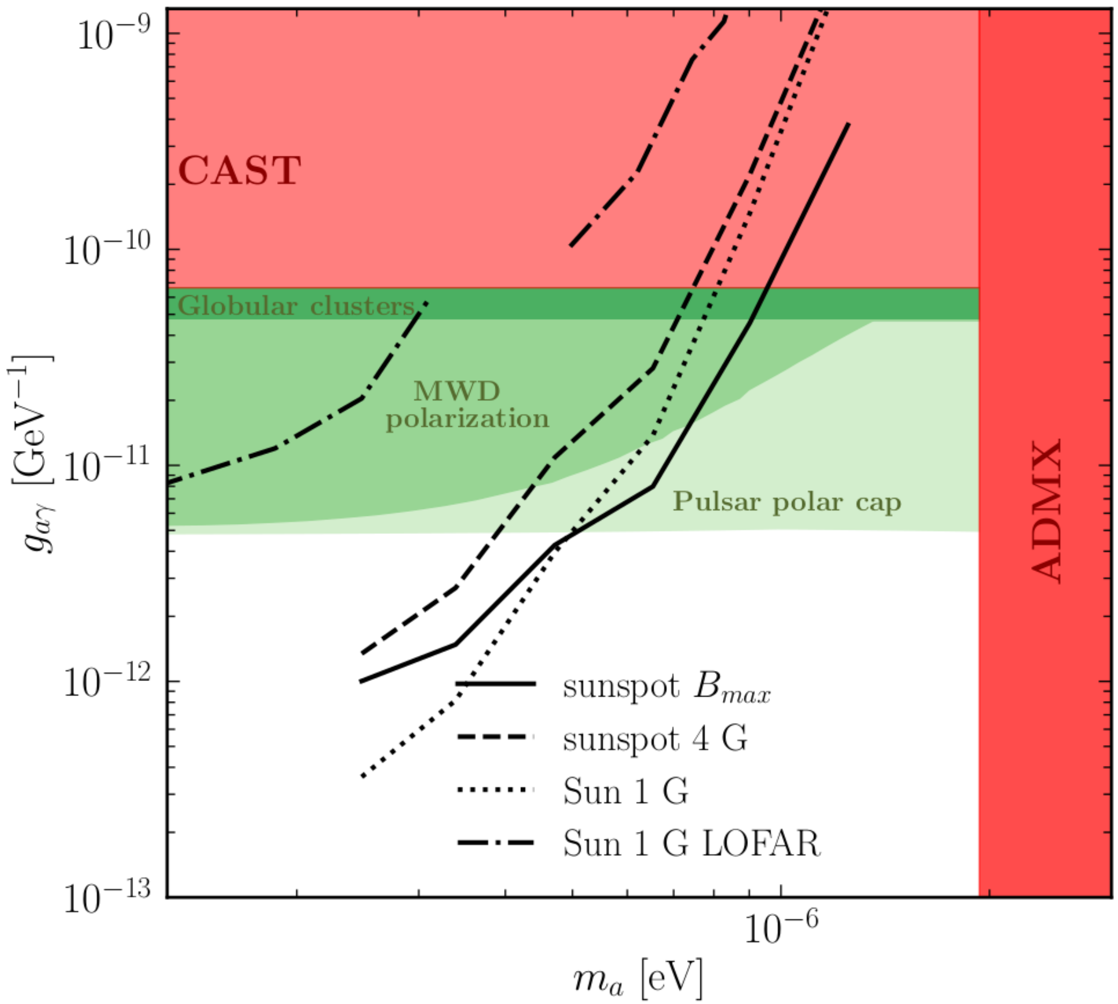






SIMULATIONS

Radio sensitivity to ALP conversion in the Sun

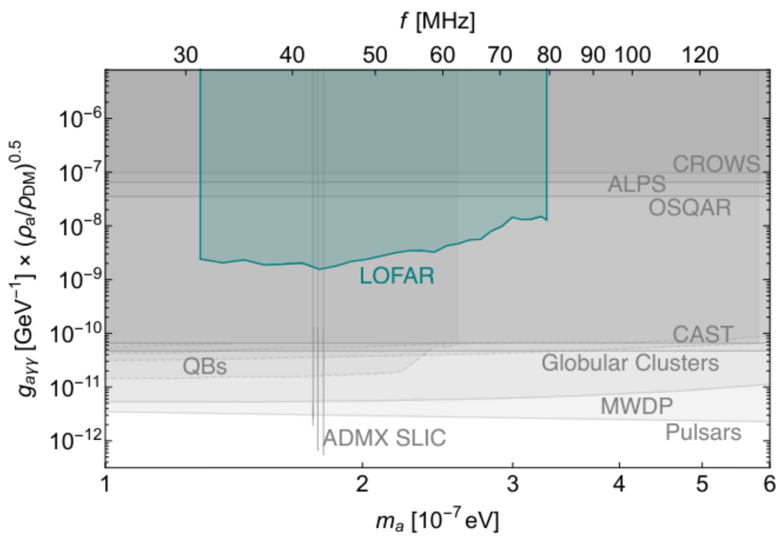


Todarello, MR+, PLB2024

Interesting prospects

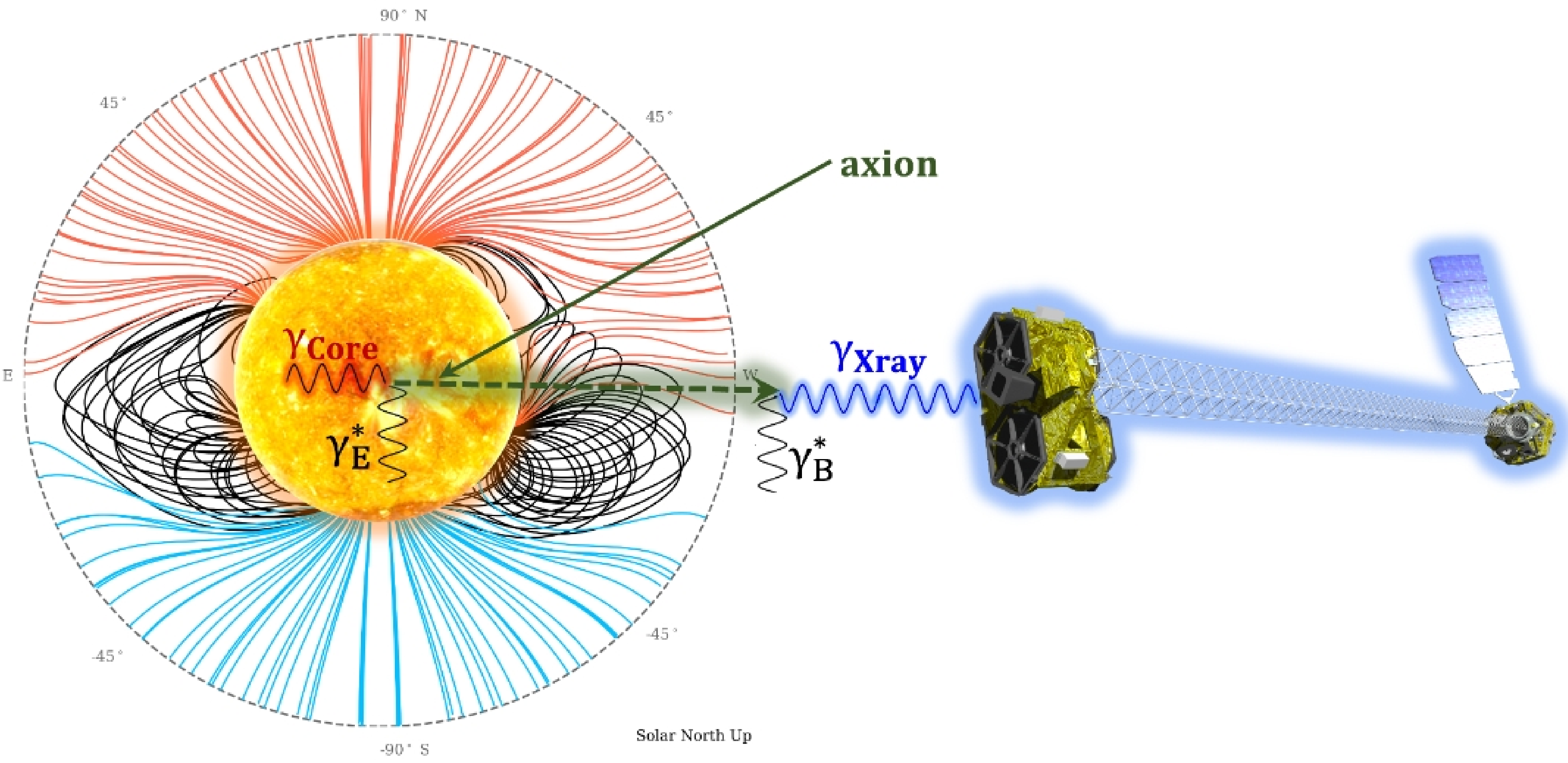
Observations challenging
→ sensitivity to be revisited with data at hand

from 17 minutes of LOFAR data



An+, Nature Comm. 2024

X-rays from ALP conversion in the Sun

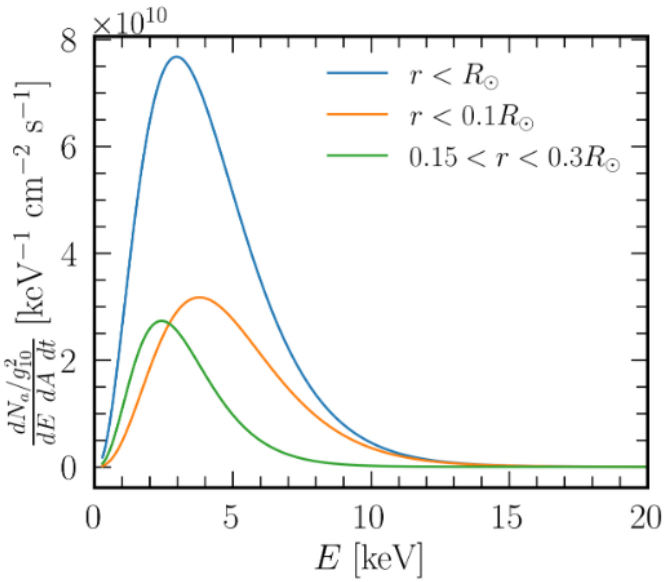


NuSTAR as an axion helioscope

axion production in the Sun

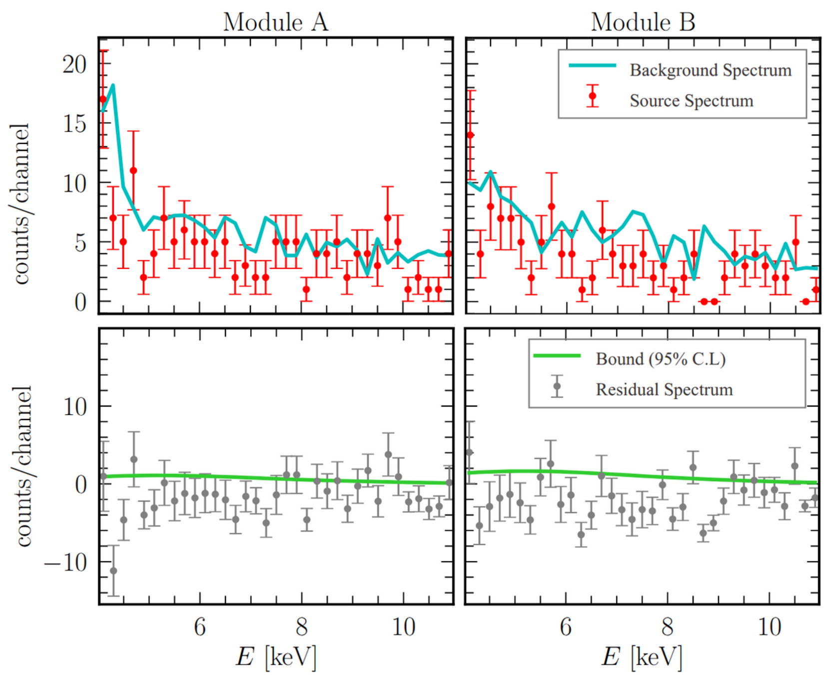
(uncertainty at % level,

e.g., Hoof+ JCAP2021)

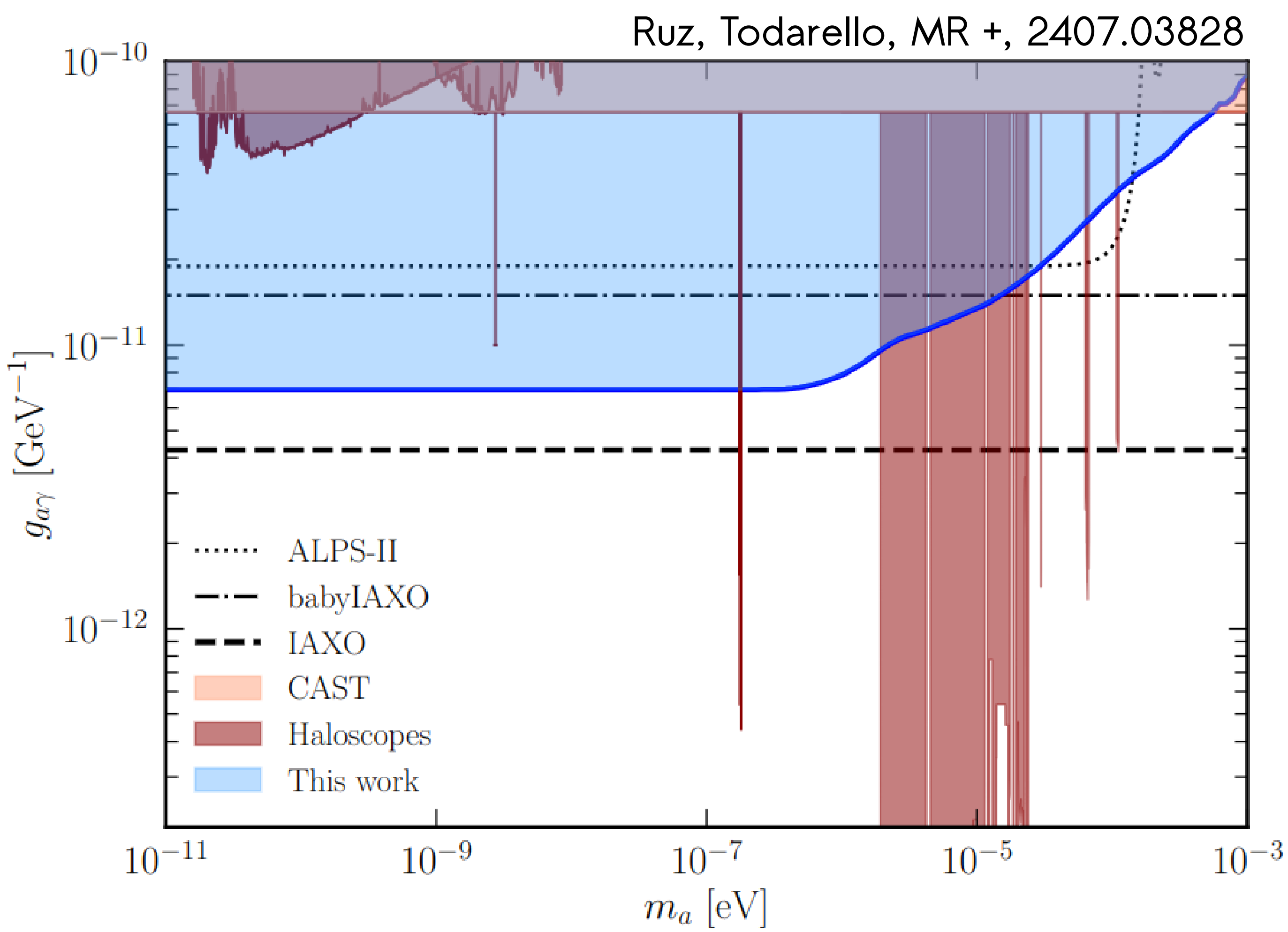


accurate determination of the magnetic field

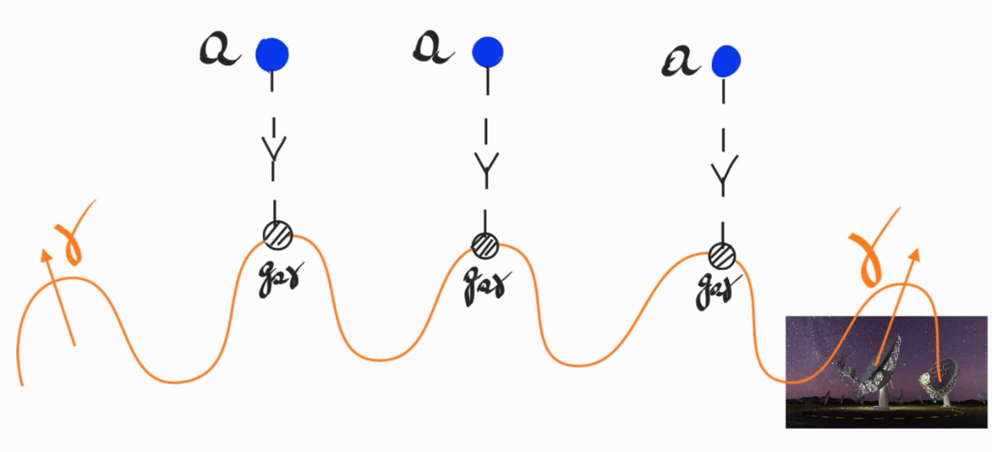
good X-ray data from NuSTAR!



NuSTAR limit from ALP conversion in the Sun



ALP birefringence

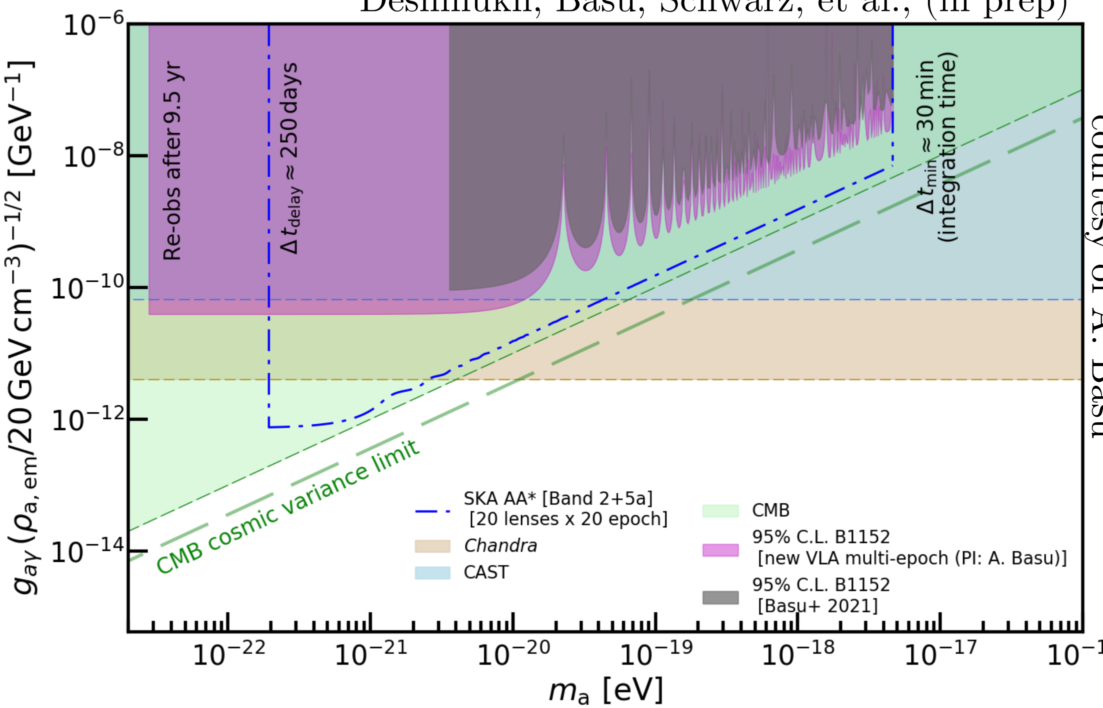


Maybe already detected in CMB data?

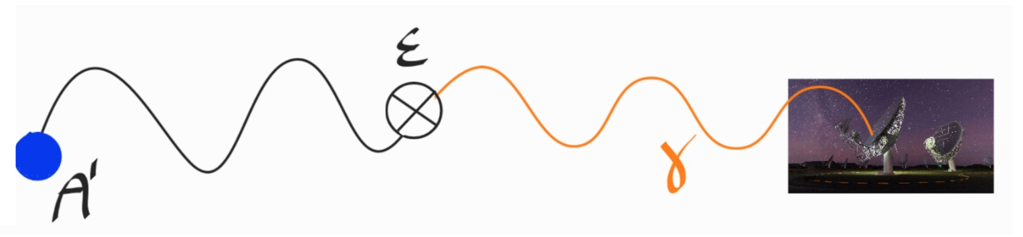
Planck → $\beta = 0.34° + 0.09°$

ACT → $\beta = 0.20° + 0.08°$

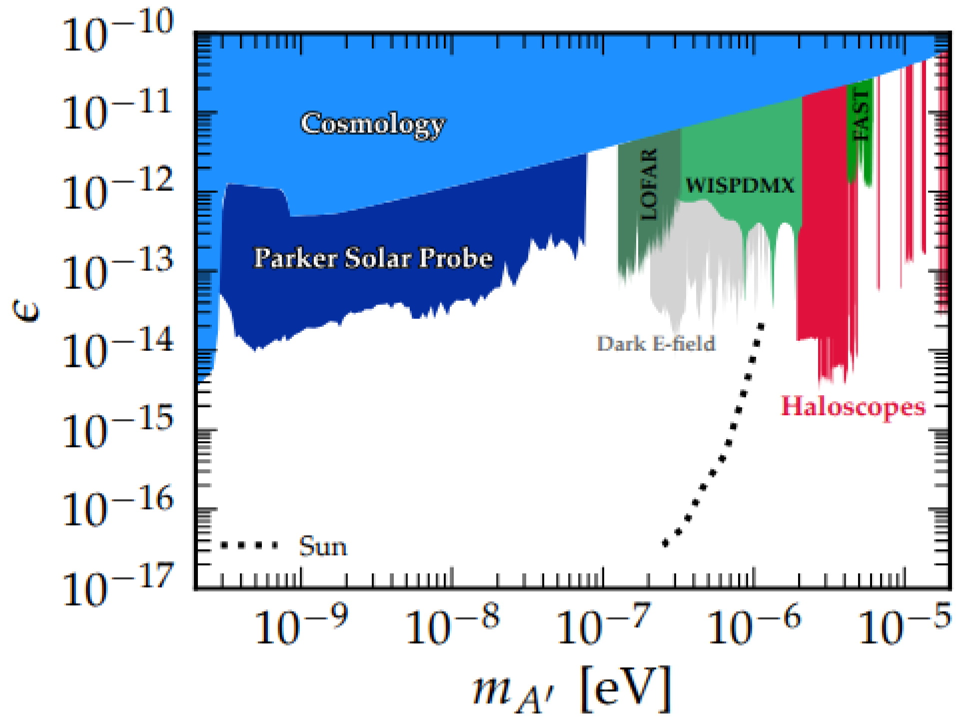
Multiple images of gravitationally lensed polarised objects allow **differential birefringence measurement**



$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu}_{DP}$$ →



Conversion probability similar to the axion case: $g_{a\gamma} B_\perp \to \sqrt{2/3}\, \epsilon\, m_{A'}$



courtesy of M. Taoso

Intensity mapping with the ALP/DP line

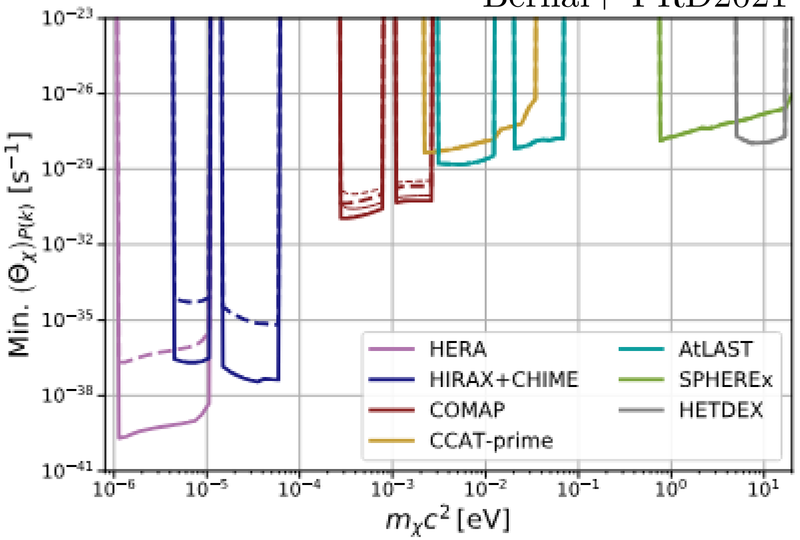
Cosmological radio emission originated from axion-like particles (decay/conversion) or dark-photons (conversion) in DM halos

→ collection of lines at different wavelength and each line corresponds to a given redshift

→ cross correlation of the radio emission line signal with the spatial position of galaxies in redshift surveys

Bernal+ PRD2021

Radio SKAO forecasts in progress...



Radio observations of Particle Dark Matter