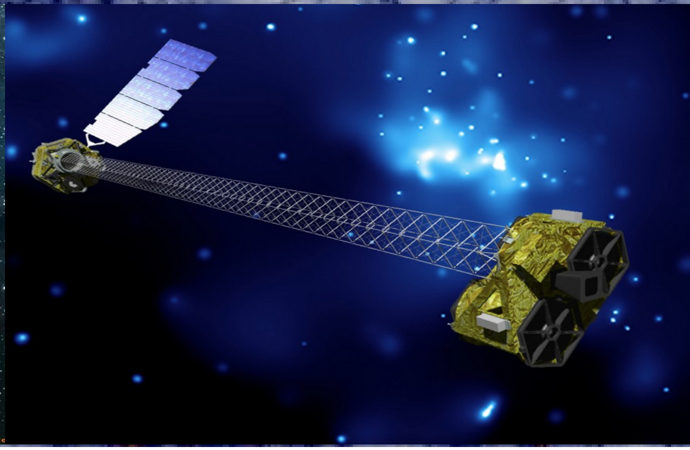
Radio (and X-ray) Signals From Axions



UNIVERSITAS STUDII TAURINENSIS 1404

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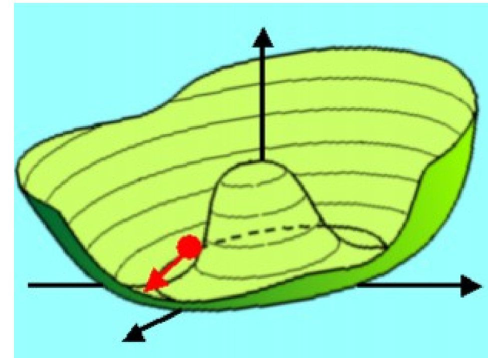
ALPs (axion-like particles)

(pseudo-)scalar particles

mainly pseudo-Nambu-Goldstone bosons

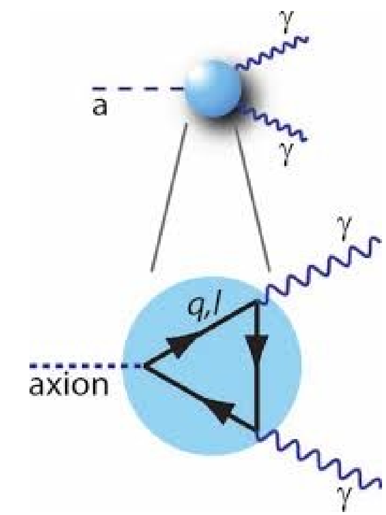
(QCD axion, "stringy" axions, ...)



photon coupling:

ALP-photon coupling described by the low-energy

effective Lagrangian: $\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} \, a \, F_{\mu\nu} \tilde{F}_{\mu\nu}$



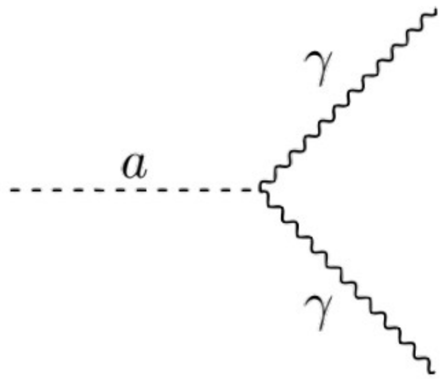
→ decay/conversion into photon(s)

→ "monochromatic" emission for non-relativistic ALPs

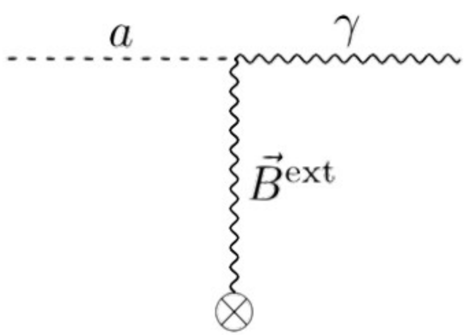
ALP phenomenology (photons)

The ALP-photon coupling → phenomenology related to

decay



conversion

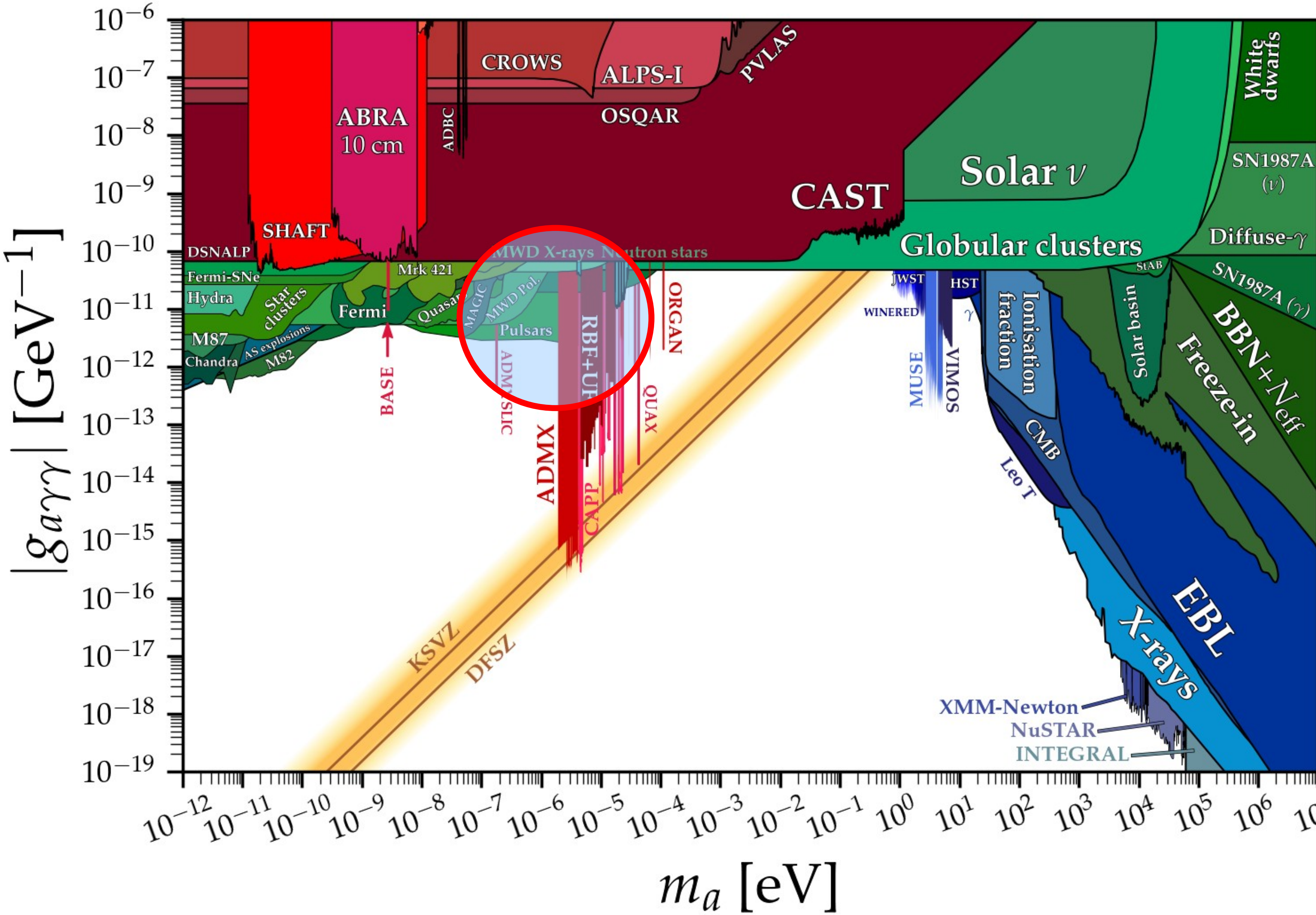


needs **large magnetic field**

- created in lab (haloscopes, helioscopes, light-shining-through-walls)
- astro objects (e.g. neutron stars, Sun)

Or **inverse processes** (γ-ray tansparency, stellar cooling, ...)

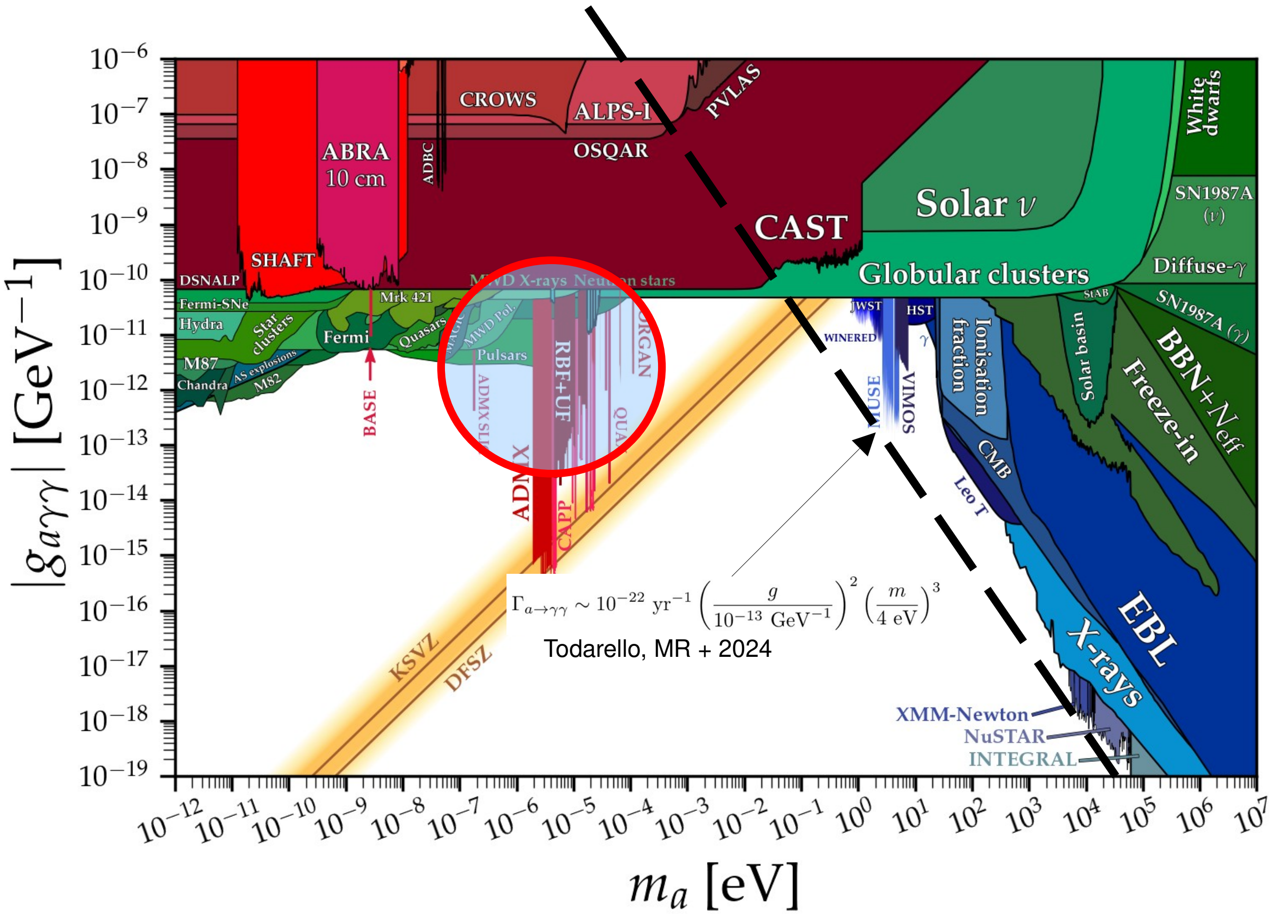
μeV ALPs → radio



https://cajohare.github.io/AxionLimits/

ALP decay

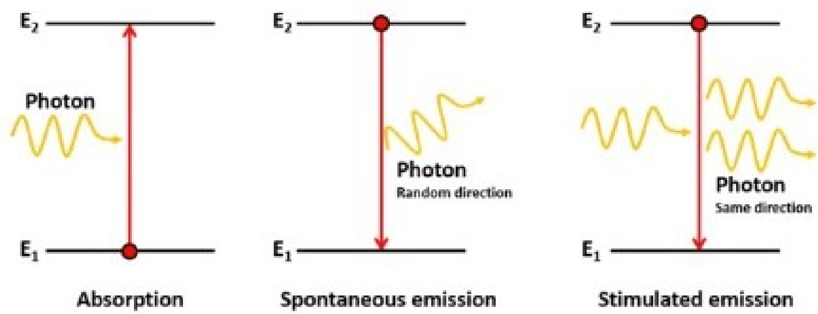
Spontaneous decay rate: $\Gamma_a \equiv g_{a\gamma\gamma}^2 m_a^3/(64\pi)$



Indirect detection via spontaneous decay is hopeless at radio frequencies!

ALP stimulated decay

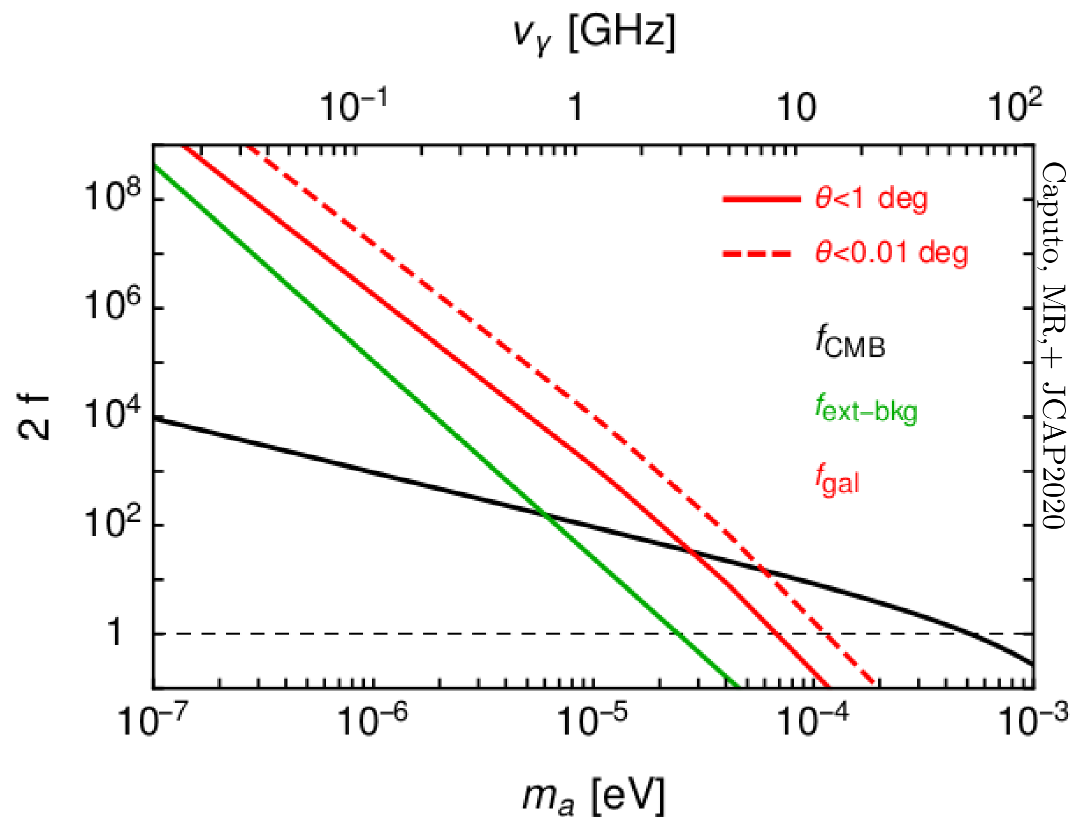
Stimulated decay



Enhancement factor

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

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

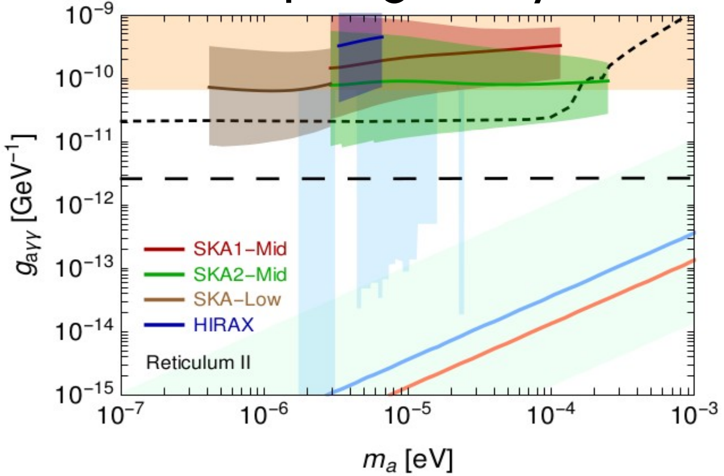


ALP stimulated decay - sensitivity

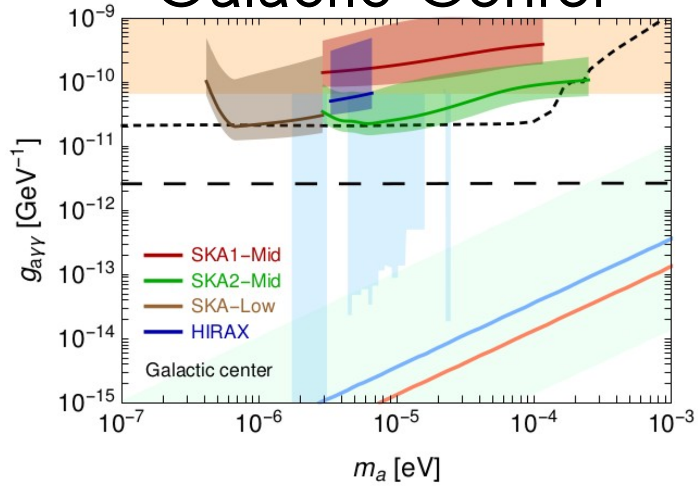
Stimulated emission within the source

Caputo, MR, Taoso, Witte JCAP2019

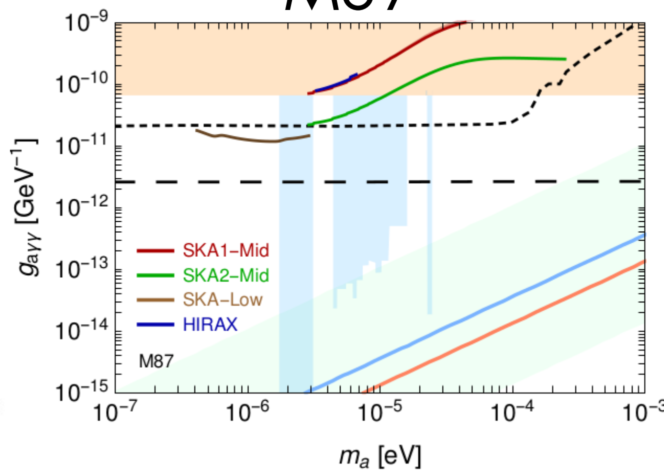
dSph galaxy

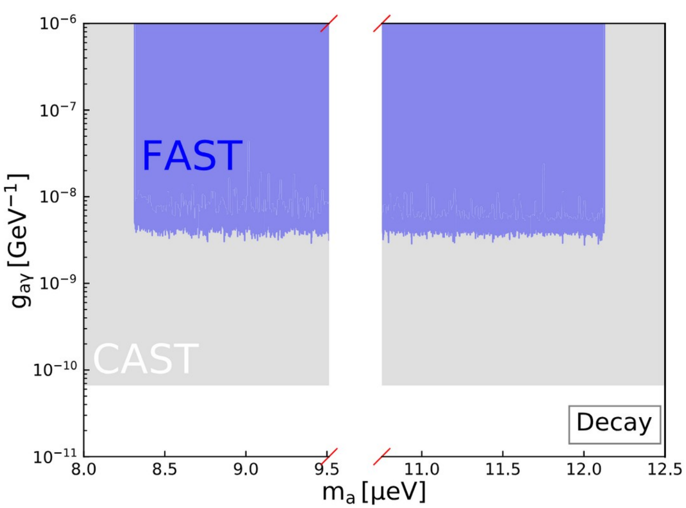


Galactic Center



M87





first attempt with
real data:
2-hour observation
of Coma Berenices

(Guo+ PLB2024)

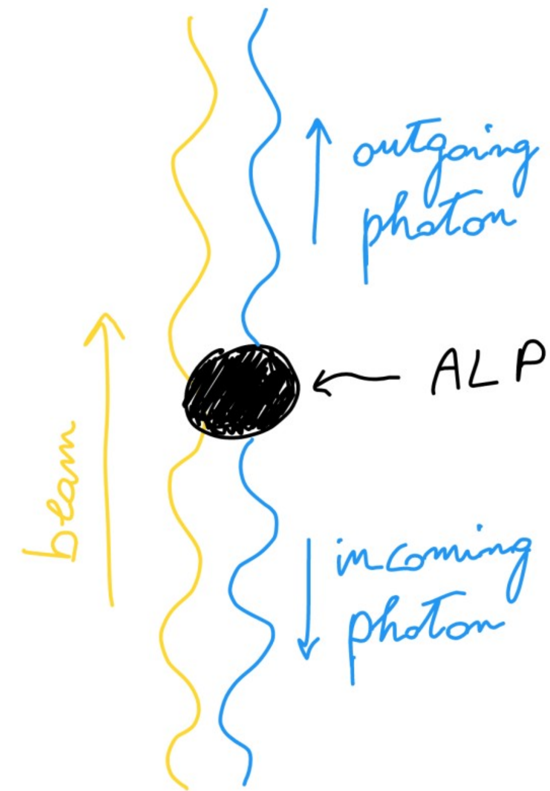
See also
Caputo+ PRD2018
Battye+ PRD2020
Ayad&Beck JCAP2022

ALP stimulated decay - echo

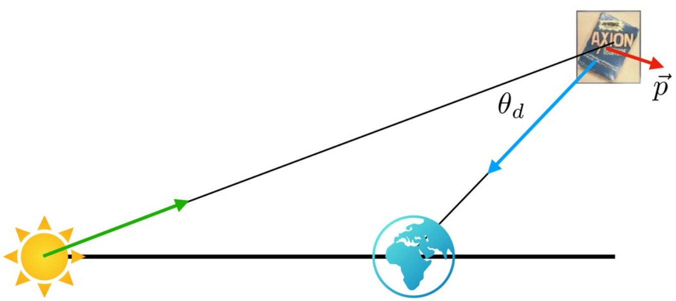
The ALP stimulated decay can be used to

listen for the echo of a powerful radio beam

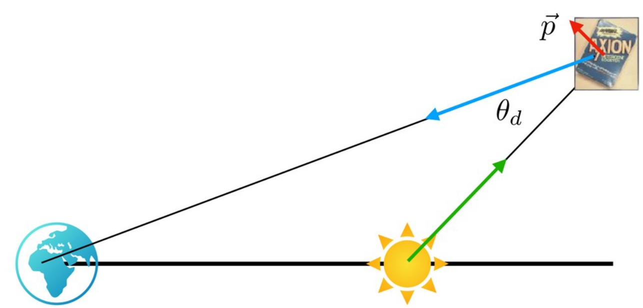
(i.e. faint radio line traveling in the ~opposite direction)



Back-light echo



Front-light echo

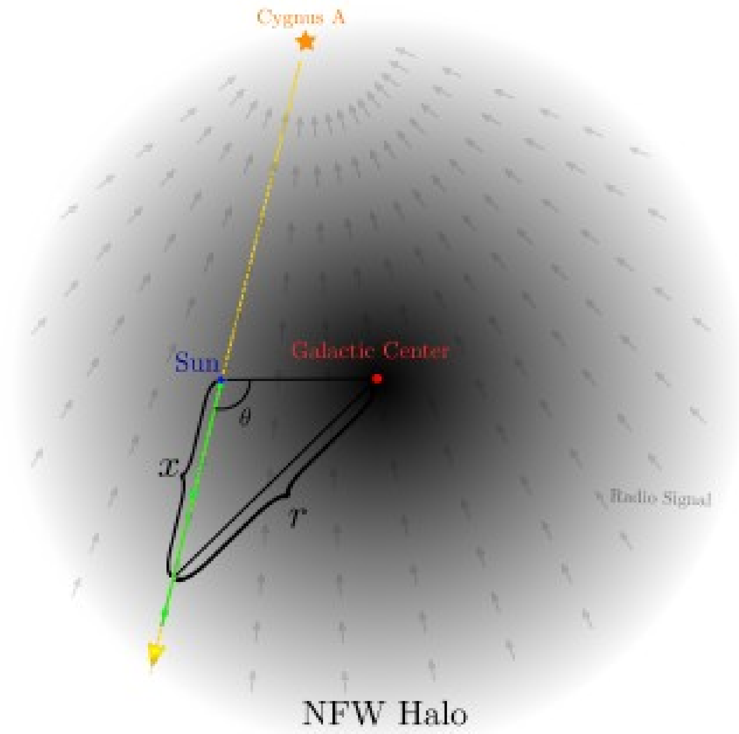


Collinear emission

ALP stimulated decay - echo

NATURAL ASTROPHYSICAL BEAM

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



ARTIFICIAL BEAM

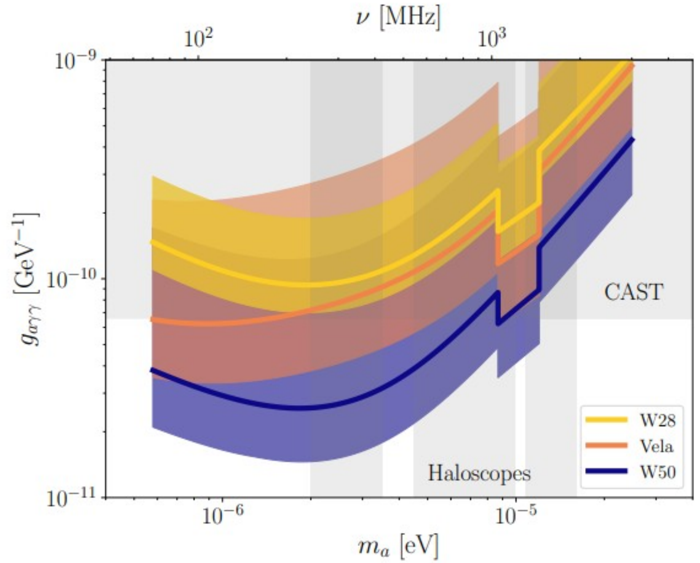
(Arza&Sikivie PRL2019,
Arza&Todarello PRD2022)

ALP echo - sensitivity

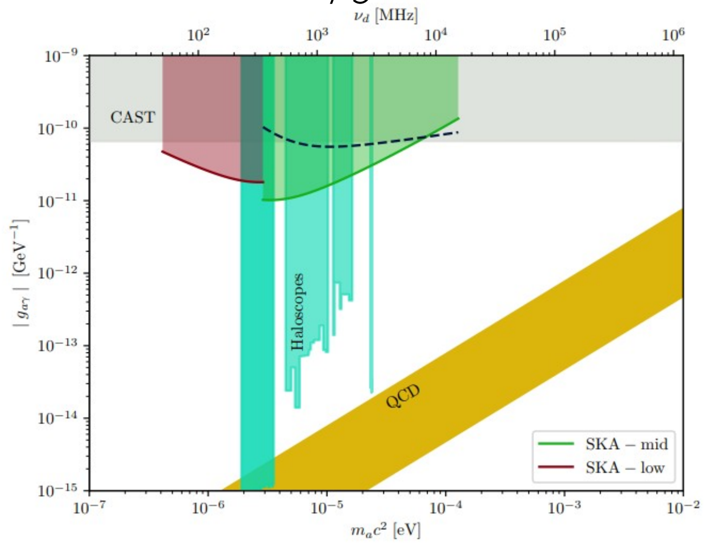
Stimulated emission from a beam going through the Milky Way halo

Galactic SN remnants

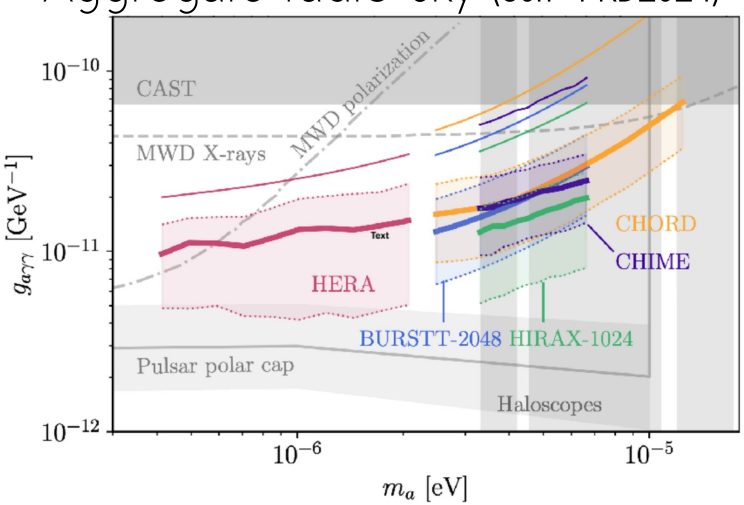
(Sun+ PRD2022, Buen-Abad+ PRD2022)

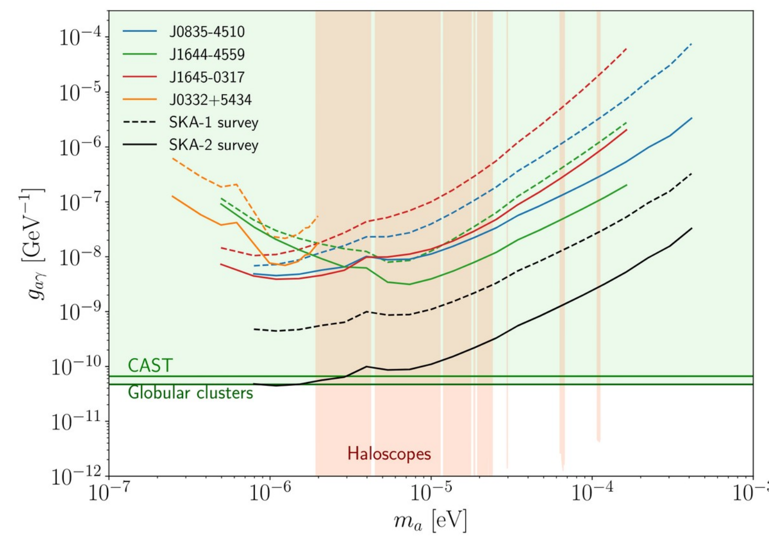


Cygnus A (Ghosh+, 2020)



Aggregate radio sky (Sun+ PRD2024)





Pulsars

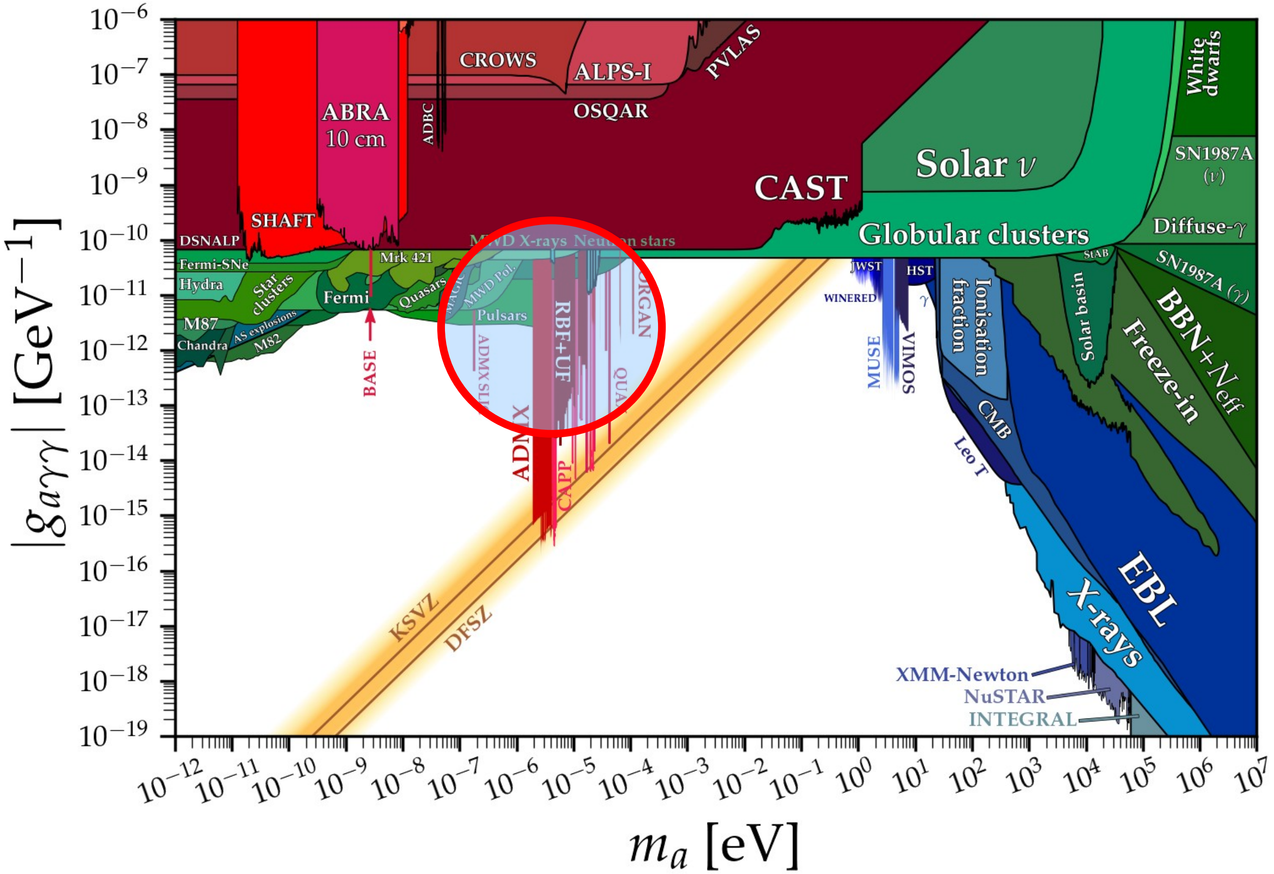
(Todarello, MR, Calore JCAP2024)

with also for a detailed derivation of the effect

ALP conversion

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

$$\omega_q(r) = 1.17\mu eV\sqrt{n_e(r)/(10^9 cm^{-3})}$$



Great progresses in the theoretical description and also some observations! Focused on neutron stars:

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

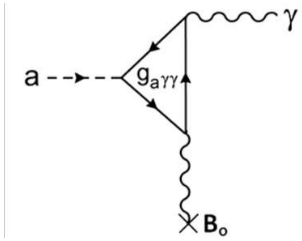
For axion in pulsar polar caps

→ see Sam Witte's talk

(Prabhu PRD2021, Noordhuis PRL2023, ..)

ALP conversion in neutron stars

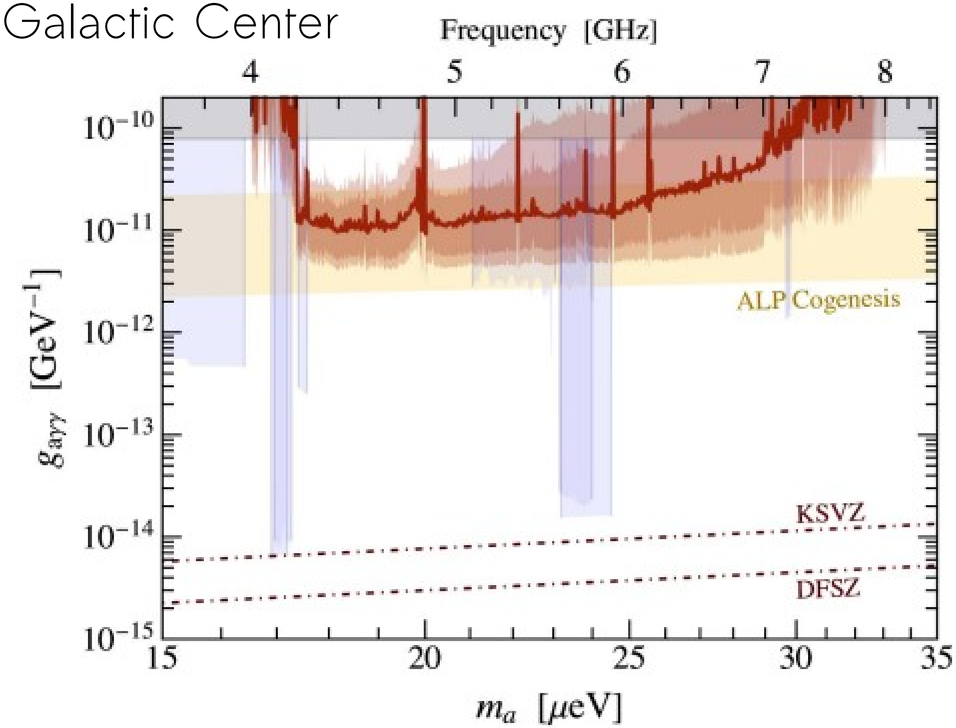
ALPs may convert to radio waves in the strong magnetic fields around **neutron stars**



GBT observations

Galactic Center

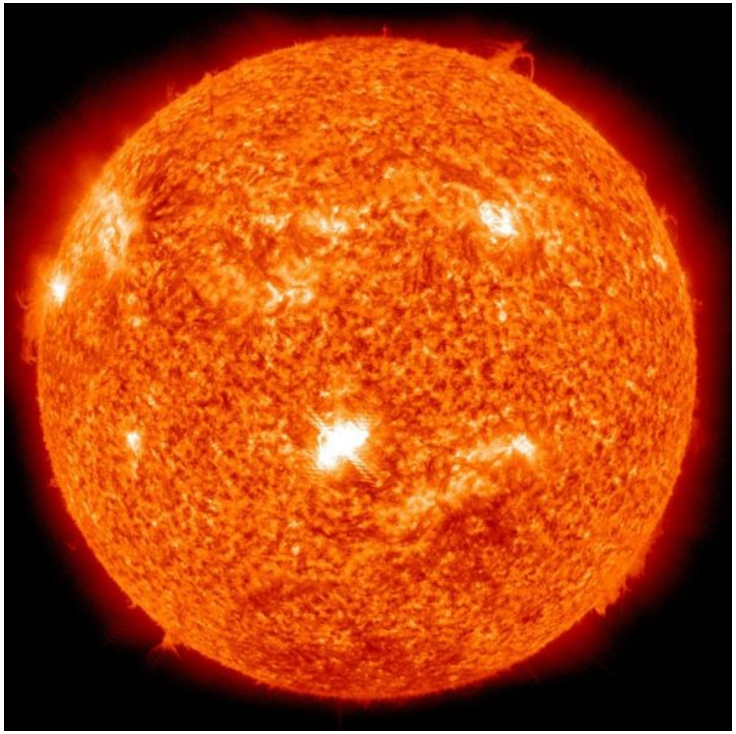
Foster+, PRL2022



Very promising technique but significant systematics

$$\frac{d\mathcal{P}}{d\Omega} \simeq 5.7\times 10^{9}\ \mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^{2}\left(\frac{r_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^{5/2}\left(\frac{m_{\mathrm{a}}}{\mathrm{GHz}}\right)^{4/3} \times\left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{5/6}\left(\frac{P}{\mathrm{sec}}\right)^{7/6}\left(\frac{\rho_{\mathrm{DM}}^{\infty}}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{M_{\mathrm{NS}}}{\mathrm{M}_{\odot}}\right)^{1/2} \times\left(\frac{200\,\mathrm{km\,s^{-1}}}{v_0}\right)\frac{3(\hat{\mathbf{m}}\cdot\hat{\mathbf{r}})^2+1}{\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}}-\cos\theta_{\mathrm{m}}\right|^{7/6}},$$

ALP conversion in the Sun



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

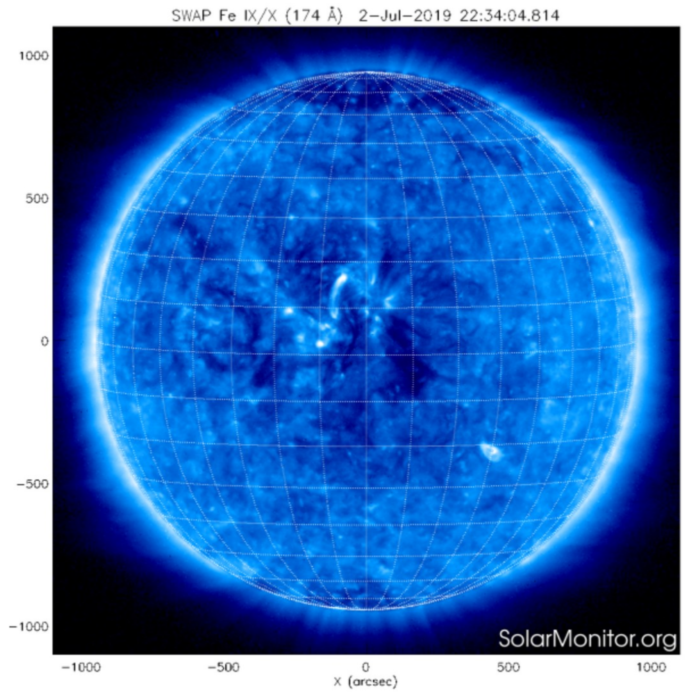
Prediction are not affected by strong systematics

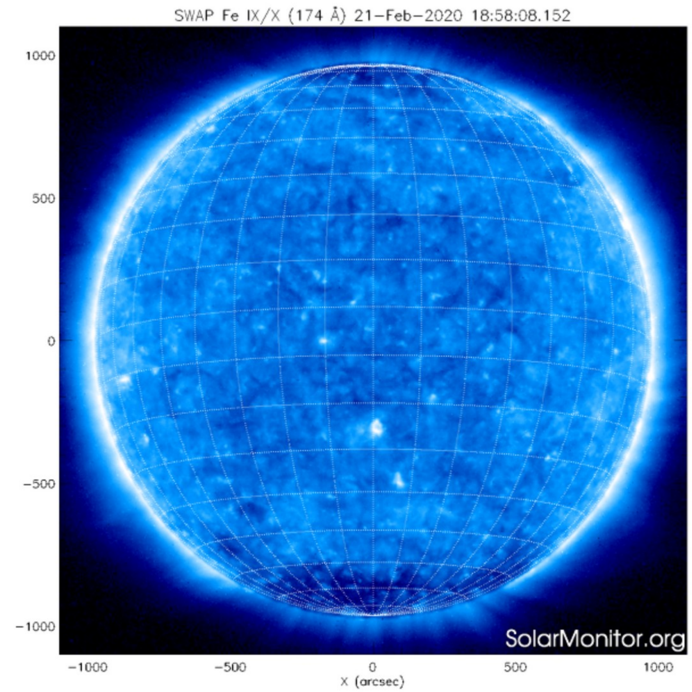
Conversion surface | Magnetic field | Distance

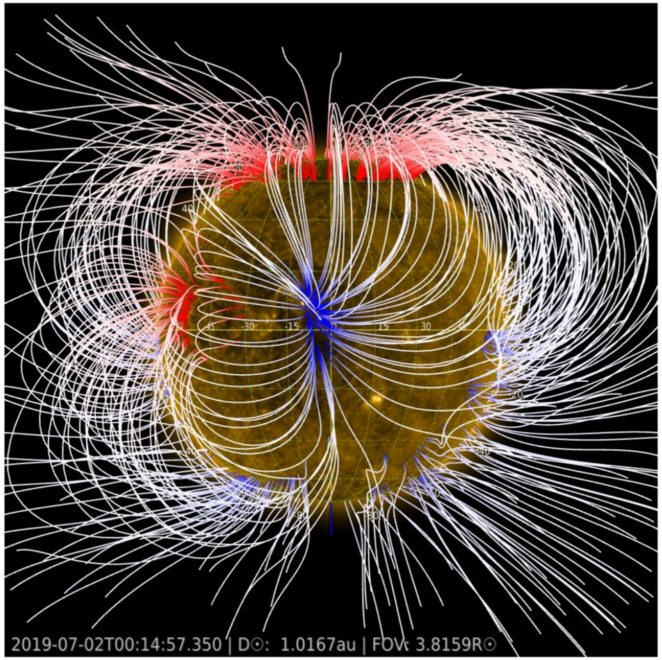
$$S \propto \left(\frac{h_{c,s}\,\ell_s^2}{5\times 10^{12}\,\mathrm{km}^3} \right) \left(\frac{B_s}{5\,\mathrm{G}} \right)^2 \left(\frac{1.5\times 10^8\,\mathrm{km}}{d_s} \right)^2 \quad \simeq \left(\frac{r_{c,NS}}{200\,\mathrm{km}} \right)^3 \left(\frac{B_{NS}}{10^{12}\,\mathrm{G}} \right)^2 \left(\frac{1\,\mathrm{kpc}}{d_{NS}}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

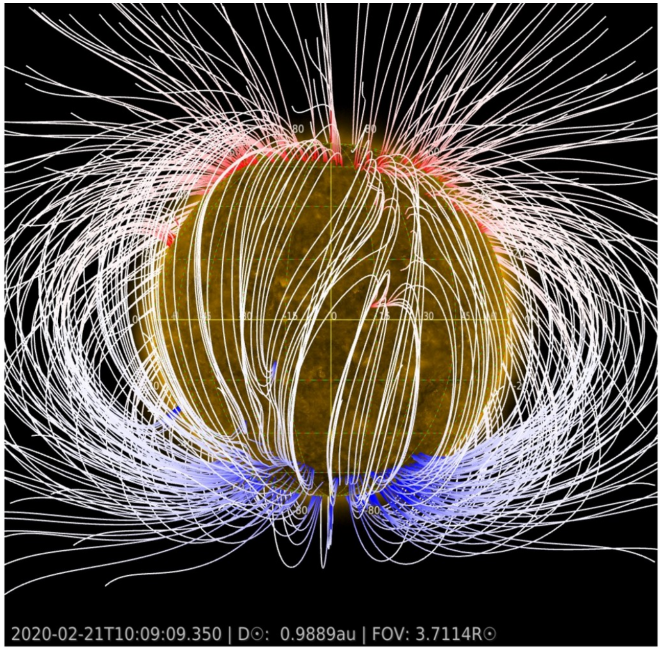
Solar magnetic field

OBSERVATIONS



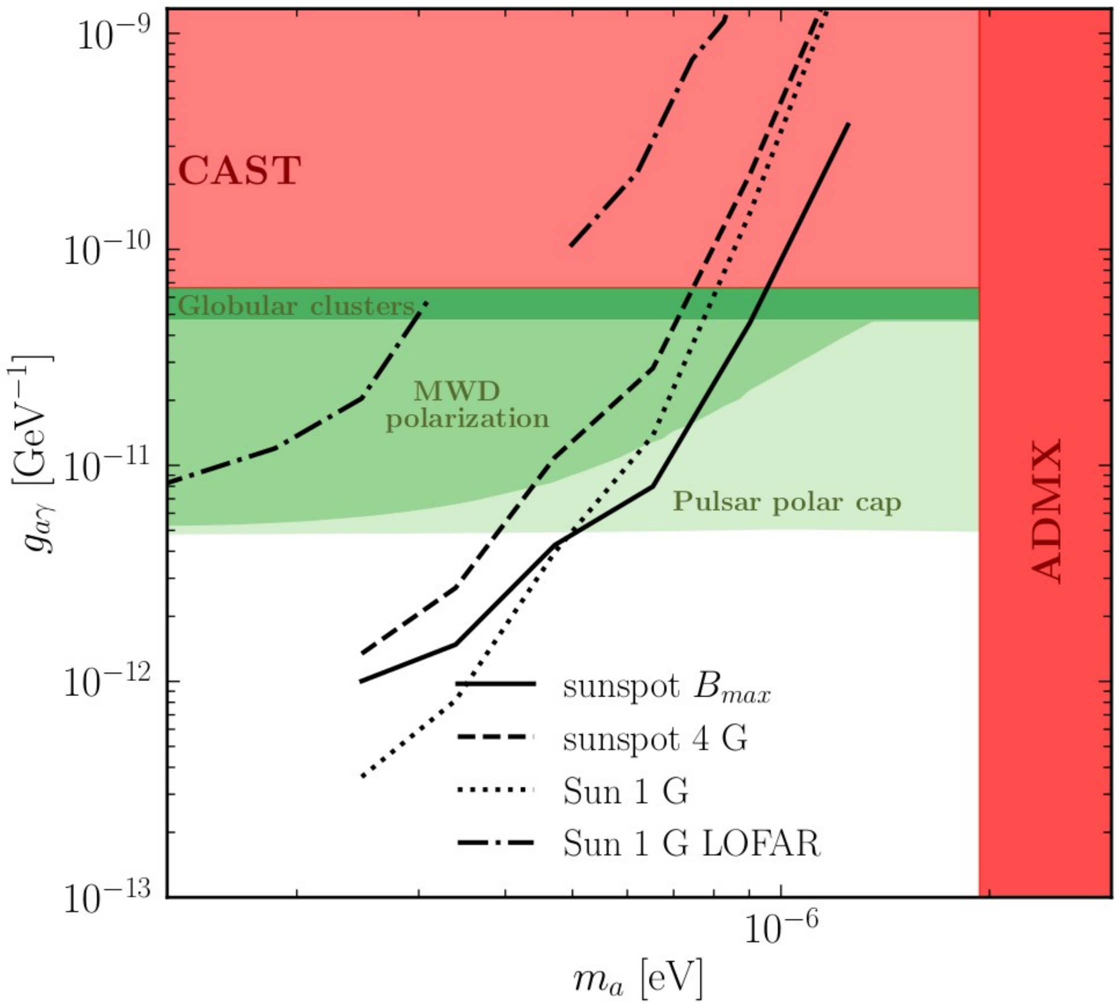






SIMULATIONS

Radio sensitivity to ALP conversion in the Sun



Todarello, MR+, PLB2024

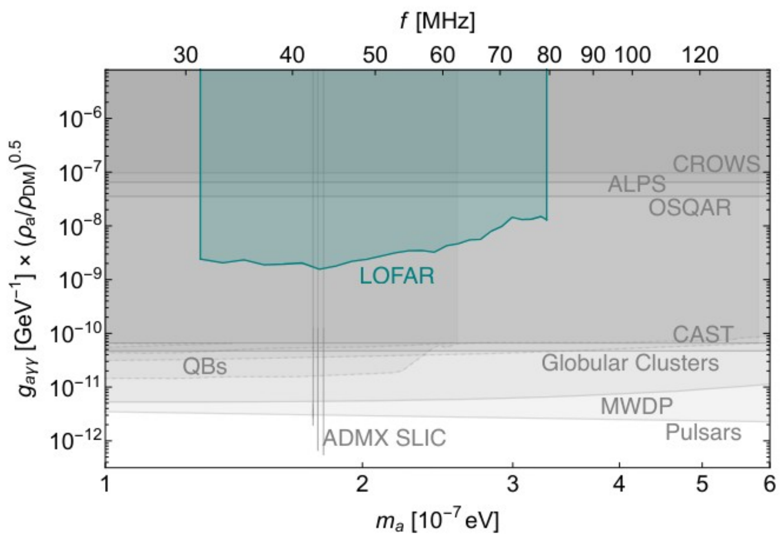
Interesting prospects

Observations challenging

→ sensitivity to be revisited

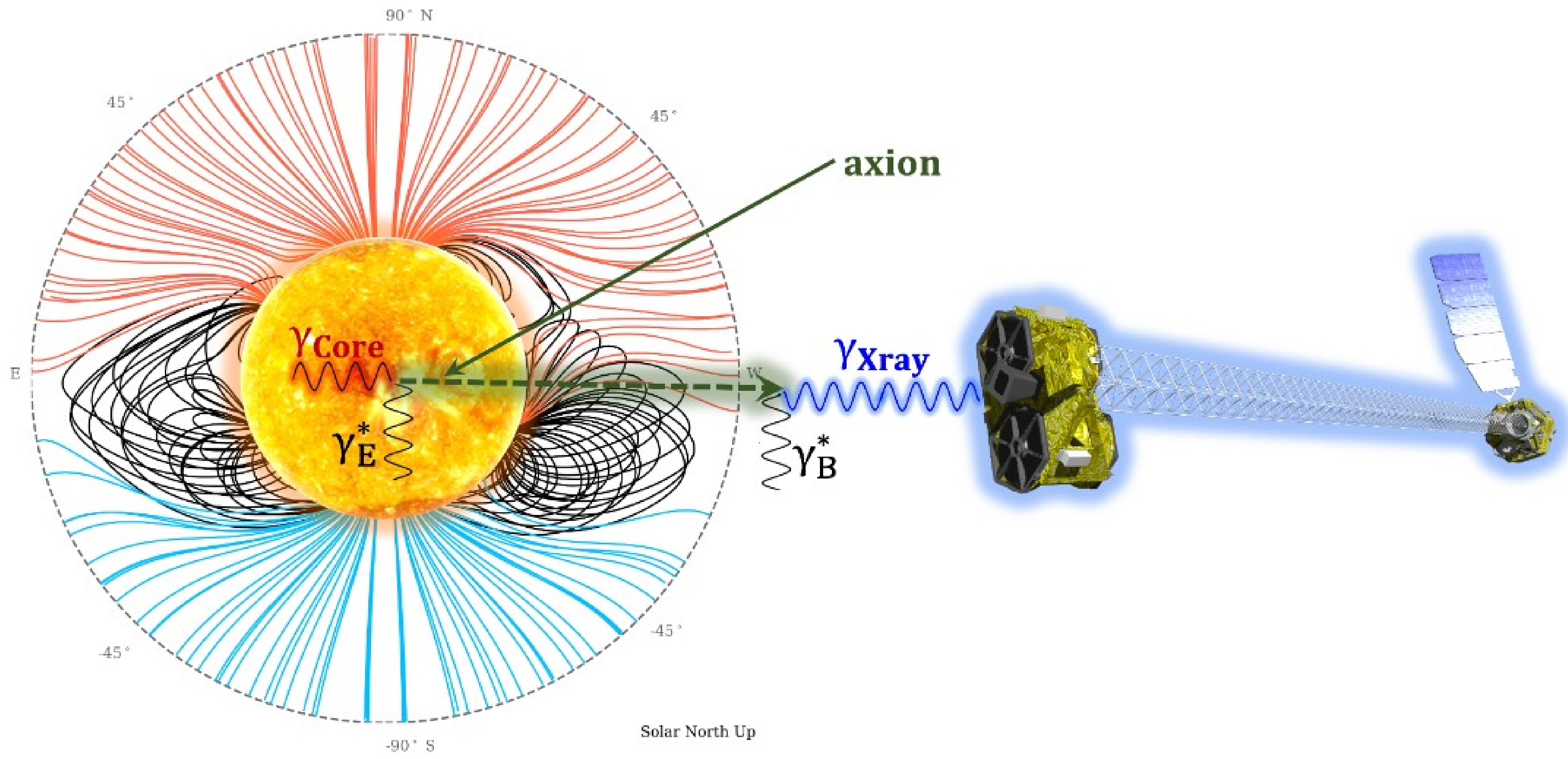
with data at hand

from 17 minutes of LOFAR data



An+, Nature Comm. 2024

X-rays from ALP conversion in the Sun

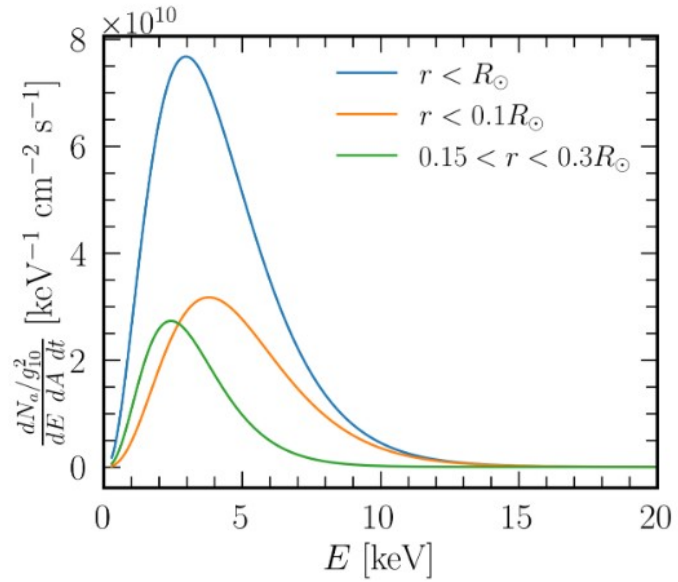


NuSTAR as an axion helioscope

axion production in the Sun

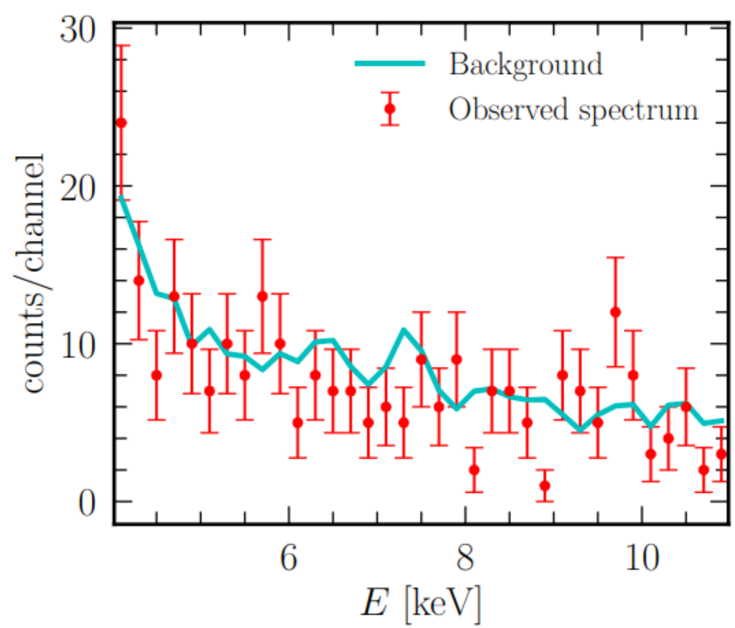
(uncertainty at % level,

e.g., Hoof+ JCAP2021)



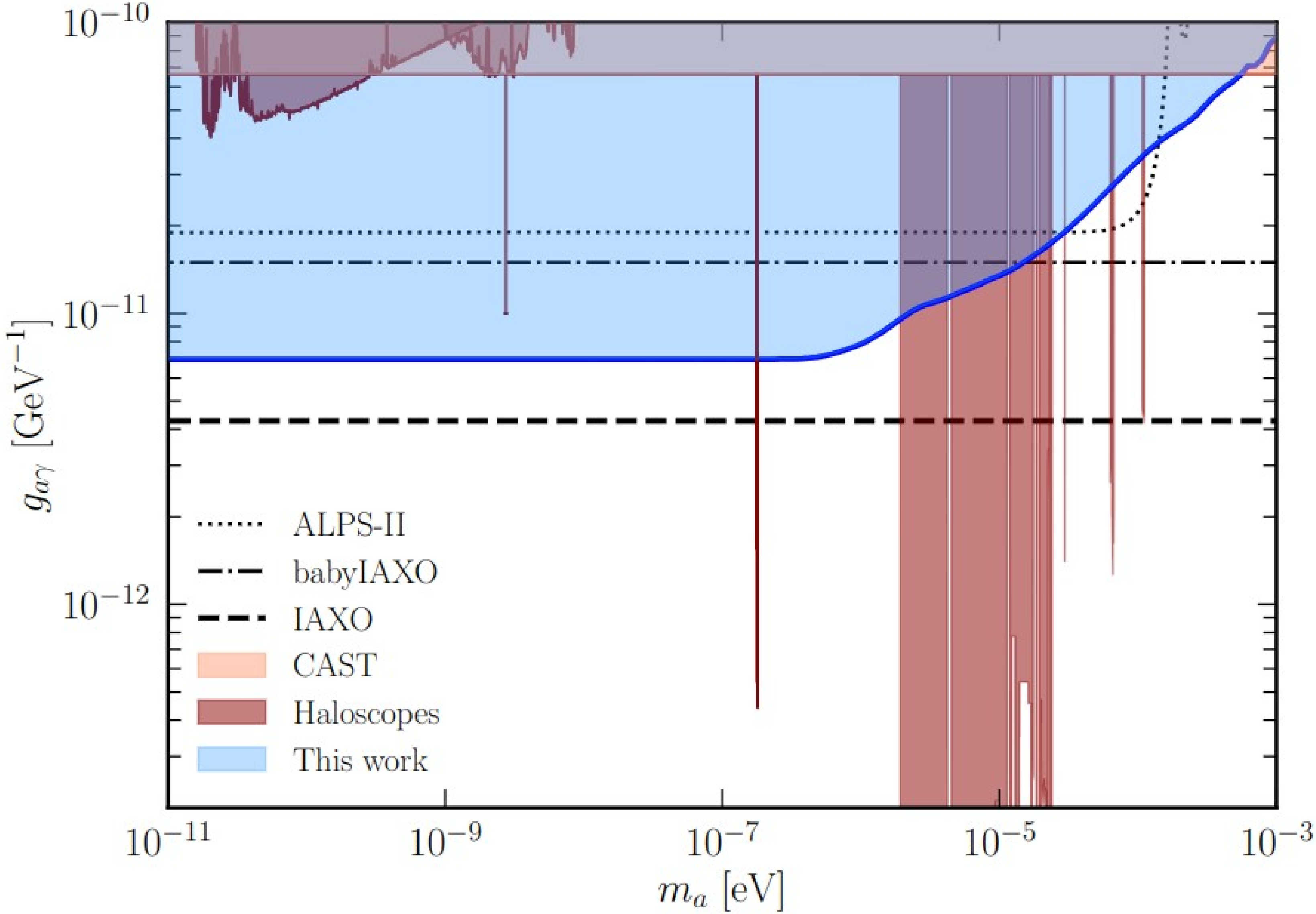
accurate determination of the magnetic field

good X-ray data from NuSTAR!



NuSTAR limit from ALP conversion in the Sun

Ruz, Todarello, MR, +, in preparation

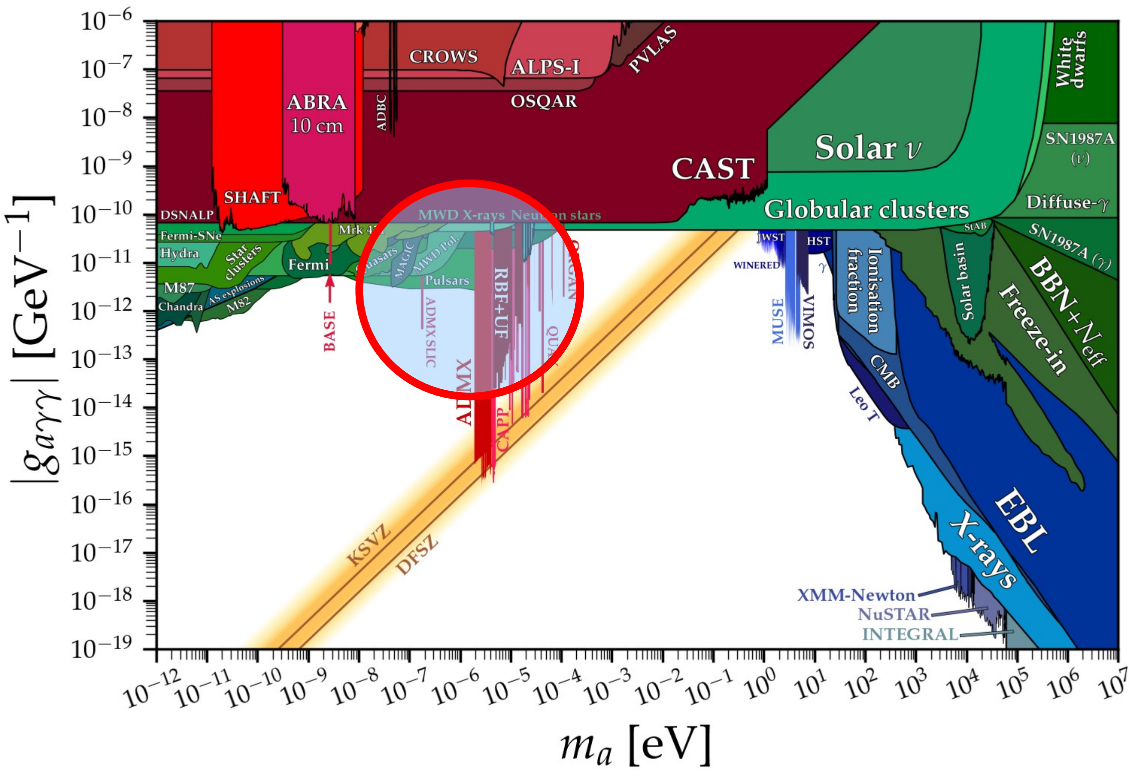


Summarizing

Astrophysical search of μeV axions with radio (and x-ray) observations is currently a quite active field

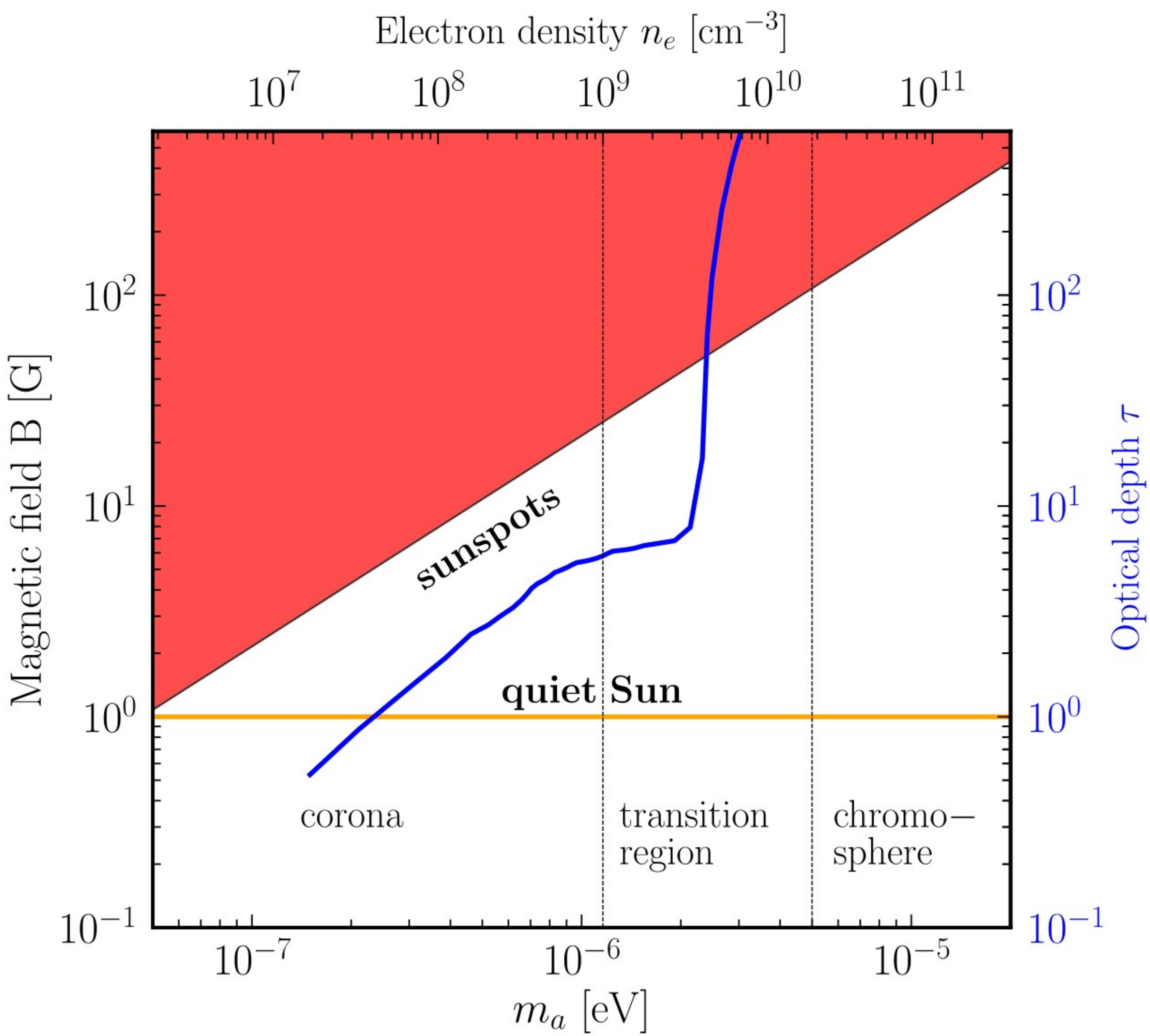
→ several ideas of new techniques popping out

→ observational capability to test a significant portion of the ALP parameter space, now and in the years to come

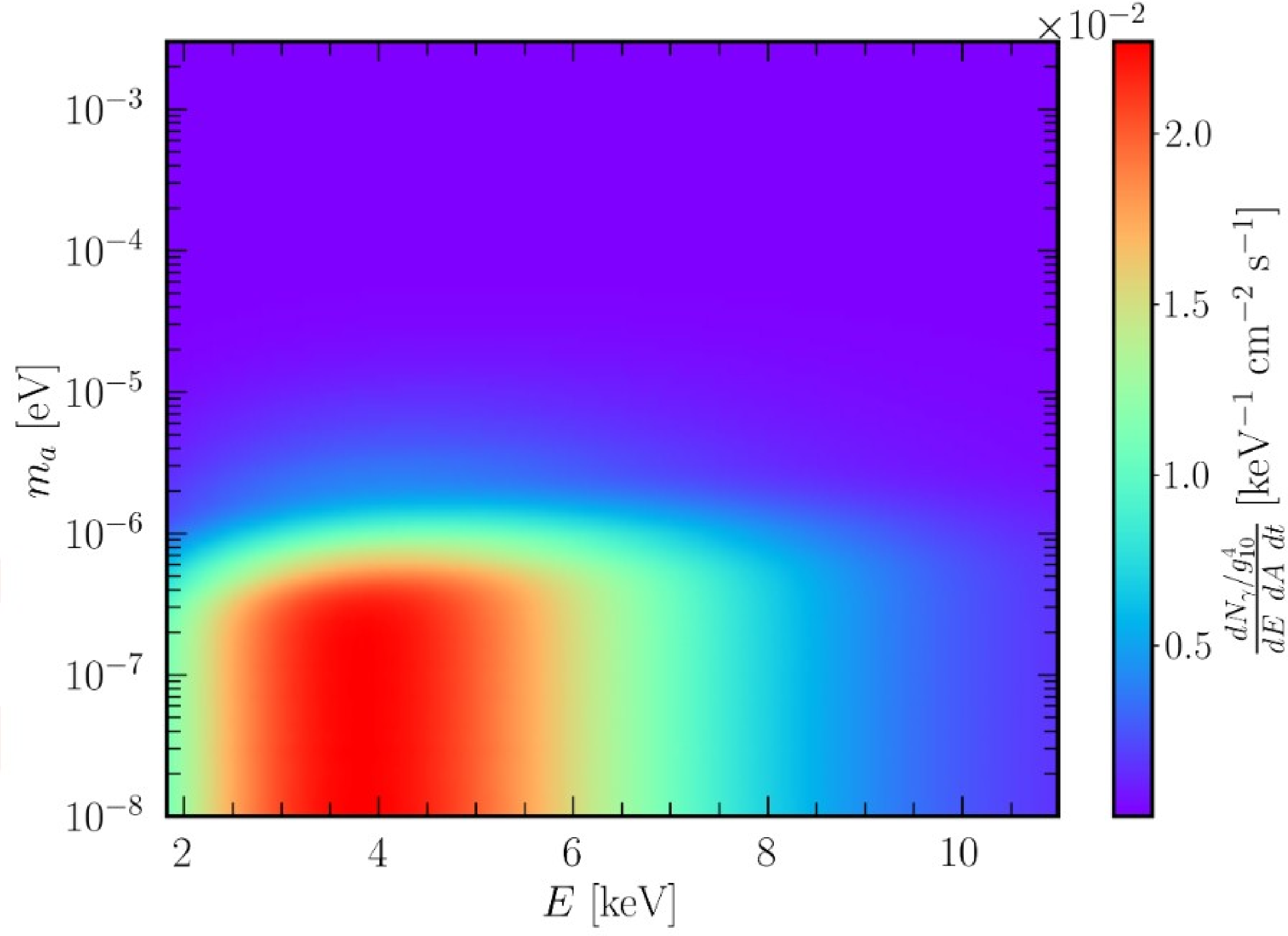


BACKUP SLIDES

ALP radio emission in the Sun



ALP x-ray emission in the Sun



Conversion in the Sun