Axion Gegenschein

Dark Countersources of Bright Radio Objects

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» Photons from axion decay

Interaction term involving axions and photons

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

Axion decay $a \rightarrow \gamma\gamma$ leads to two photons each of frequency ν s.t.
$h\nu_d = m_a c^2/2$
with an estimated decay lifetime

$$\tau_{a\gamma} = \frac{64\pi\hbar}{m_a^3 c^6 g_{a\gamma}^2} = 1.7 \times 10^{43} \left(\frac{5.7 \times 10^{-6} \mathrm{eV}}{m_a c^2} \right)^3 \times \left(\frac{C_{a\gamma} 1.16 \times 10^{-15} \mathrm{GeV}^{-1}}{g_{a\gamma}} \right)^2 \mathrm{yr} \tag{2}$$

» Stimulated decay

Evolution of axion number density

$$\dot{n}_a = \simeq -n_a \Gamma_a (1 + 2N_\gamma) \quad (3)$$

with decay rate $\Gamma_a = \tau_a^{-1}$
Photon occupation number in the ambient radiation related to its energy density

$$N_\gamma = \frac{\pi^2 \rho_\gamma}{E_\gamma^3} \quad (4)$$

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Stimulated decay of axions: decay rate enhanced by quantum occupation number of photons of frequency $\sim m_a c^2/2\hbar$

$\downarrow$

One of the two final state photons in a momentum state opposite to that of incoming radiation

$\downarrow$

Creation of a "countersource" made of axions

Analogous to zodiacal light, the decay photons traveling backwards $\looparrowright$ axion gegenschein

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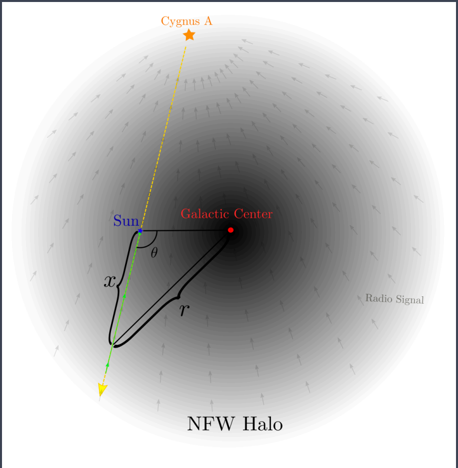
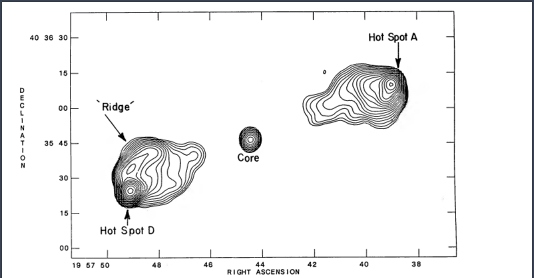
Backscattering of astrophysical radio pulses in the MW Halo along line of sight → dark countersources for every radio-bright object



Axion gegenschein in the Milky Way's dark matter halo

» Source selection

Cygnus A ($\ell = 76.20°, b = 5.75°$)
Brightest extragalactic radio source: Type II Seyfert galaxy hosting AGN



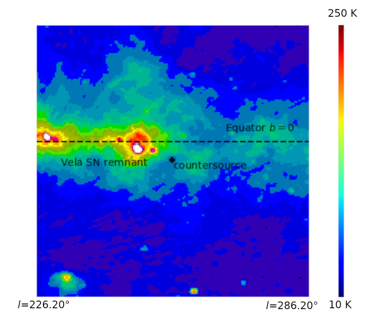
Spectral flux:

$$\log S_{A\nu_d}(\nu_d) = a + b\log\nu_d + c\log^2\nu_d \tag{5}$$

$\theta = 103.74°$, angular separation between Cygnus A & Sun wrt GC

» Countersource of Cygnus A

Location: 180° apart ($\ell = 256.20°, b = -5.75°$)



Countersource in radio sky (60°×60° cutout of 408-MHz sky)

Characteristics:

* Size comparable to source size with spatial features preserved
* Smoothing owing to dark matter velocity dispersion $\perp$ l.o.s.
* Distant sources advantageous owing to longer round-trip time

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Intensity due to stimulated decay (I_g)

$\approx$ wave intensity from spontaneous decay (I_{sp}) $\times$ photon occupation number in incoming wave (N_γ)

Spectral intensity being $I_\nu(\nu) = (\nu/c)^2 h\nu N_\gamma$, spontaneous intensity owing to axion number density $\rho_a(x)/m_a$ over time dt is

$$dI_{sp} = \rho_a / (m_a \tau_a)\, h\nu_d (cdt/4\pi) \tag{6}$$

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Thus, the gegenschein intensity is

$$I_g = \int_0^\infty dx \frac{\rho_a(x)}{m_a \tau_a} \frac{c^2}{4\pi\nu_d^2} I_{s\nu}(\nu_d, x) \tag{7}$$

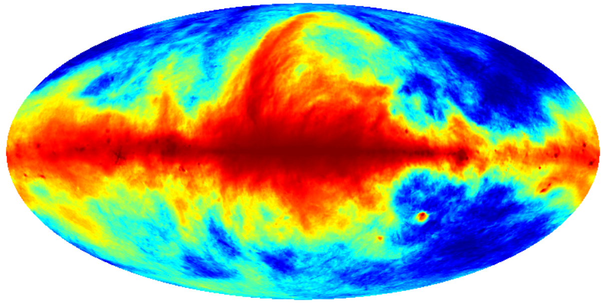
Replacing decay lifetime τ_a

$$I_g = \frac{\hbar c^4}{16} g_{a\gamma}^2 \int_0^\infty dx I_{s\nu}(\nu_d, x)\, \rho_a(x) \tag{8}$$

Note: the incoming radio intensity (from the astrophysical source) $I_{s\nu}$ is conserved along the line of sight

» Radio sensitivity

Galactic and extragalactic background in synchrotron radio emission



408-MHz Haslam all-sky map

» Radio sensitivity

Considering the contribution of atmospheric radio noise and CMB (blackbody)

$$T_{\mathrm{s}} = T_{\mathrm{a}} + T_{\mathrm{CMB}} + T_{\mathrm{bg}} + T_{\mathrm{r}} \tag{9}$$

Synchrotron background estimated as power law $T_{\mathrm{bg}}(\nu) \propto \nu^{\beta}$ with $\beta = -2.55$.
Thus

$$T_{\mathrm{bg}} = 60 \left(\frac{300\mathrm{MHz}}{\nu} \right)^{2.55} \mathrm{K} \tag{10}$$

T_{bg}=27 K at the sky coordinate of the countersource at 408 MHz.

» Radio sensitivity

SKA-low (50-350 MHz)
Dipole array with number of elements $\sim$ 131,000
Collection area (A_{coll}) $\sim$ 419,000 m^2
$T_r = 40K$
SKA-mid: (350 MHz-15.3 GHz)
$N_{tele} \sim 5600$
Diameter D=15 m for each dish
$T_r = 20K$
Efficiency of SKA: $\eta = 0.8$

» Radio sensitivity

Radio power of background

$$P_{\text{noise}} = 2k_B T_s \sqrt{\frac{\Delta\nu}{t_{\text{obs}}}} \quad (11)$$

Radio power of gegenschein signal

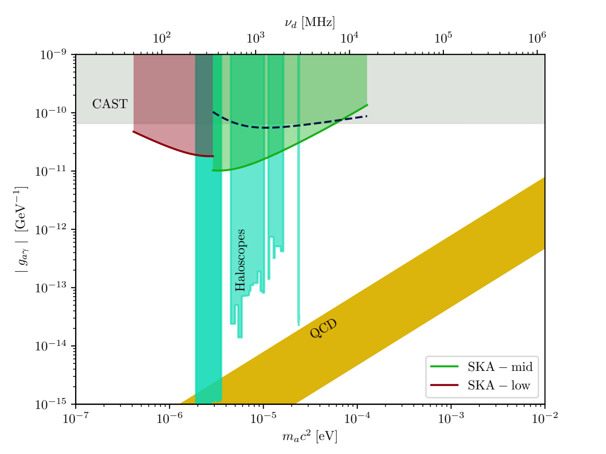
$$P_{\text{signal}} = \eta A S \quad (12)$$

For an $n - \sigma$ detection, $P_{\text{signal}} / P_{\text{noise}} = n$
The spectral flux owing to gegenschein emission of Cygnus A is

$$S_{Ag} = \frac{\hbar c^4}{16} g_{a\gamma}^2 S_{A\nu}(\nu_d) \int_0^\infty dx \rho_a[r(x)] \quad (13)$$

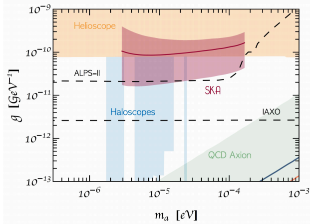
» Radio sensitivity

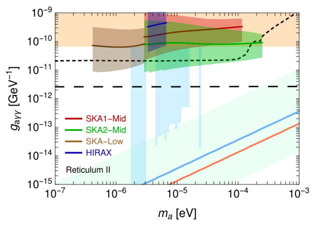
For a conservative S/N = 1 and standard NFW halo model,

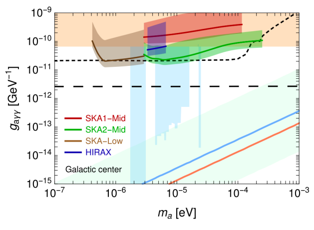


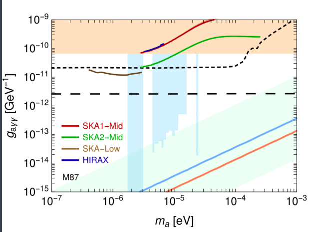
Solid lines: Axion gegenschein in MW, *this work*
Dashed line: Stimulated decay of axions in dSphs

» Other proposed probes









Caputo et al. 1805.08780, 1811.08436

» Other proposed probes

For a top-hat frequency profile of bandwidth, the optimal frequency width to achieve maximum S/N

$$\Delta\nu = 2.17\nu_d \frac{\sigma_d}{c} \tag{14}$$

Spectral flux S_{Ag} is reduced by

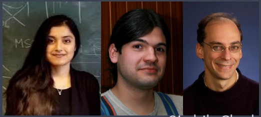
$$f_\triangle = 0.721 \tag{15}$$

A decrease in number of photons photon collected within each frequency bin
Radio sensitivity must be adjusted by a correction factor $\Rightarrow$ goes down by $\sim \frac{1}{0.49}$ in radio power, thus goes up by ~ 0.7 in $g_{a\gamma}$!

» Key takeaways

- Astrophysical radio pulses from galactic and extragalactic sources can induce stimulated emission in the Milky Way's halo, emission line feature with a spread characterized by DM velocity dispersion
- Detectable at future-generation radio telescopes even with a conservative S/N ~ 1
- Axion gegenschein provides **100-fold increase in radio sensitivity compared to proposed frameworks**
- Probing dark matter overdensities at large distances
- Axion gegenschein opens up a new (and relatively clean) indirect search method for dark matter: stimulated emission from radio-bright sources

Axion Gegenschein, *arXiv: 2008.02729*
OG, J. Salvado, J. Miralda-Escudé



» The End

Thank you for your attention!

Questions?

» Backup slides

Single dish mode
Angular resolution

$$\theta_{FWHM} \simeq 1.22\frac{\lambda}{D} \simeq 0.7^\circ \left(\frac{1\mathrm{GHz}}{\nu}\right)\left(\frac{15\mathrm{m}}{D}\right) \tag{16}$$

Noise temperature of the instrument

$$T_{\mathrm{ant}} = \frac{A_{\mathrm{eff}} \langle S \rangle}{2k_b} \tag{17}$$

For each telescope

$$\left(\frac{S}{N}\right)_{sd,\ \mathrm{single}} = \frac{T_{\mathrm{ant}}^{\mathrm{pb}}}{T_{\mathrm{min}}} \tag{18}$$

For an array of single-dish telescopes

$$\left(\frac{S}{N}\right)_{sd,\ \mathrm{array}} = \sqrt{N_{\mathrm{tele}}\, n_{\mathrm{pol}}} \left(\frac{S}{N}\right)_{\mathrm{single}} = \sqrt{N_{\mathrm{tele}}\, n_{\mathrm{pole}}}\, \frac{T_{\mathrm{ant}}^{pb}}{T_{\mathrm{min}}} \tag{19}$$

» Backup slides

Interferometric mode
Angular resolution of primary beam

$$\theta_{pb} = 12.5' \left(\frac{1\text{GHz}}{\nu}\right)\left(\frac{100\text{m}}{D}\right) \tag{20}$$

Minimum detectable flux density

$$S_{\text{min}} = SNR \frac{\text{SEFD}}{\sqrt{n_{\text{pol}} \Delta B t_{\text{obs}}}} \tag{21}$$

with

$$\text{SEFD} = \frac{T_{\text{sys}}(\nu)}{G} \tag{22}$$

» Backup slides

Observation in the interferometric mode

For each synthesized beam in the interferometric mode, angular resolution

$$\theta_{\mathrm{synth}} \approx 50'' \left(\frac{1\mathrm{GHz}}{f}\right)\left(\frac{1\mathrm{km}}{B_{\mathrm{max}}}\right) \tag{23}$$

SNR is expressed as $\sqrt{\delta\chi^2}$

$$\delta\chi^2 = n_{\mathrm{pol}}\, t_{\mathrm{obs}}\, G^2_{\mathrm{array}} \sum_{i=1}^{N_{\mathrm{synth}}} \frac{F_i^2}{B_i T_i^2} \tag{24}$$

Scaling relation for antenna gain $G_{\mathrm{array}} \sim N_{\mathrm{tele}}\,(N_{\mathrm{tele}} - 1)\, G$

» References

- Borka Jovanovic, V., & Urosevic, D. (2011). Temperature, brightness and spectral index of the Cygnus radio loop. *Mexican magazine of astronomy and astrophysics*, 47 (1), 159–171.
- Carilli, C. L., Perley, R. A., Dreher, J. W., & Leahy, J. P. (1991). Multifrequency radio observations of Cygnus A-Spectral aging in powerful radio galaxies. The Astrophysical Journal, 383, 554–573.
- SKA Science Imaging Performance. `https://www.skatelescope.org/wp-content/uploads/2014/03/SKA-TEL-SCI-SKO-SRQ-001-1-Level-0-Requirements-1.pdf`
- SKA Whitepaper, Retrieved May 26, 2019, from `https://www.skatelescope.org/wp-content/uploads/2014/03/SKA-TEL-SKO-0000308-SKA1-System-Baseline-v2-Descript pdf`

» References (cont.)

- Haslam, C. G. T., Klein, U., Salter, C. J., Stoffel, H., Wilson, W. E., Cleary, M. N., ... & Thomasson, P. (1981). A 408 MHz all-sky continuum survey. I-Observations at southern declinations and for the North Polar region. Astronomy and Astrophysics, 100, 209-219.
- Caputo, A., Garay, C. P., & Witte, S. J. (2018). Looking for axion dark matter in dwarf spheroidal galaxies. Physical Review D, 98(8), 083024.
- Arza, A. (2019). Photon enhancement in a homogeneous axion dark matter background. The European Physical Journal C, 79(3), 250.
- Caputo, A., Regis, M., Taoso, M., & Witte, S. J. (2019). Detecting the stimulated decay of axions at radio frequencies. Journal of Cosmology and Astroparticle Physics, 2019(03), 027.