Axion gegenschein

Radio counter-sources from axion decay

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Axion gegenschein

Axions: spontaneous and stimulated emission

Interaction term for axions and photons

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

with axion mass

$$m_a = 6 \times 10^{-6} \mathrm{eV} \left(\frac{10^{12} \mathrm{GeV}}{f_a} \right) \quad (2)$$

Axion decay $a \to \gamma\gamma$

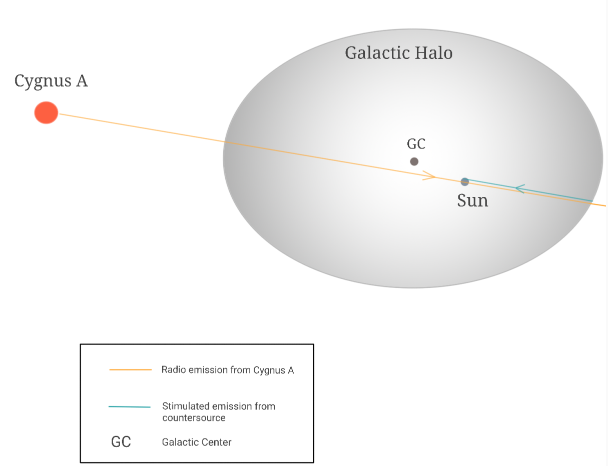
$$\tau_a = \frac{64\pi}{m_a^3 g_{a\gamma\gamma}^2} \quad (3)$$

Contribution of CMB, galactic, and extragalactic background

$$f_\gamma (\ell, \Omega, m_a) \simeq f_{\gamma,\mathrm{CMB}} (m_a) + f_{\gamma,\mathrm{gal}} (\ell, \Omega, m_a) + f_{\gamma,\mathrm{ext-bkg}} (m_a) \quad (4)$$

Axion gegenschein

Stimulated emission → Backscattering of astrophysical radio pulses in the MW Halo

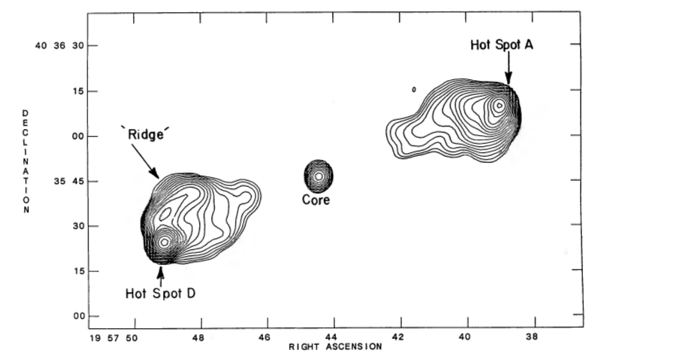


Axion gegenschein in the Milky Way's dark matter halo

Source selection

Flux density of Cygnus A

$$S_{CygA} = S_0 \left(\frac{\nu}{\nu_0} \right)^{-0.58} \qquad (5)$$



Radio contours of Cygnus A

Countersource features

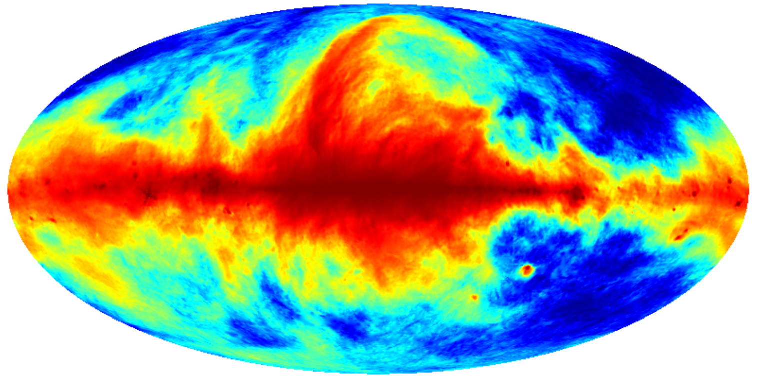
Projection of dark matter undergoing stimulated emission along line of site $\longrightarrow$ Counterimage/countersource
Characteristics:

- Size comparable to source size
- Aberration owing to velocity dispersion $\perp$ l.o.s.

Background and sensitivity

Background and sensitivity

Galactic and extragalactic background in synchrotron radio emission



408-MHz Haslam all-sky map

Background and sensitivity

Radio power from the countersource:

$$P_{\text{radio}} = \frac{1}{16} g_{a\gamma\gamma}^2 \rho \left(\frac{dP_0}{d\nu} \right) \bigg|_{\nu=\frac{m_a}{4\pi}} t \tag{6}$$

Spectral power of the astrophysical source (Cygnus A):

$$\frac{dP_0}{d\nu} = S_{total} A_{eff} \tag{7}$$

where

$$A_{eff} = \eta A_{coll} \tag{8}$$

Background and sensitivity

S_{total}: Total flux density evaluated at $\nu = m_a/4\pi$

SKA-low

Dipole array with number of elements $\sim$ 131,000

Collection area (A_{coll}) $\sim$ 419,000 m^2

SKA-mid

$N_{tele} \sim 5600$

Diameter D=15 m for each dish

Efficiency of SKA: $\eta = 0.8$

Background and sensitivity

Detectable radio power

$$P_{\text{radio}} = \left[\frac{dP_{\text{min}}}{d\nu} \Delta\nu \right] \Bigg|_{\nu = \frac{m_a}{4\pi}} \tag{9}$$

Minimum detectable spectral power

$$\frac{dP_{\text{min}}}{d\nu} = \frac{2T_{sys}}{\sqrt{t_{obs}\Delta B}} \tag{10}$$

$$\Delta B = \Delta\nu = \nu\sigma_{disp} \tag{11}$$

Background and sensitivity

System noise temperature

$$T_{sys} = T_{sky} + T_{rcvr} \tag{12}$$

Atmospheric noise temperature

$$T_{sky} = 60 \left(\frac{\lambda}{1\mathrm{m}}\right)^{2.55} = 60 \left(\frac{300\mathrm{MHz}}{\nu}\right)^{2.55} \tag{13}$$

and
$T_{rcvr} = 20K$ (SKA-mid)
$T_{rcvr} = 40K$ (SKA-low)

Background and sensitivity

$$\left[\frac{dP_{\text{min}}}{d\nu}\Delta v\right]\bigg|_{v=\frac{ma}{4\pi}} = \frac{1}{16} g_{a\gamma\gamma}^2 S_{\text{CygA}}\bigg|_{v=\frac{m_a}{4\pi}} A_{eff}\int_0^\infty \rho(r)dx \tag{14}$$

Dark matter density in the MW Halo follows the NFW profile

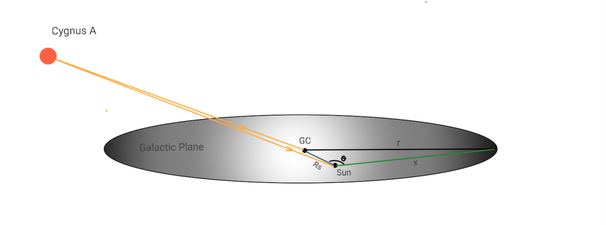
$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)\left(1 + r/r_s\right)^2} \tag{15}$$

Background and sensitivity

Integration is performed numerically using

$$r^2 = x^2 + R_s^2 - 2xR_s \cos\theta \tag{16}$$

$R_s = 8$ kpc, distance of Sun from the Galactic Center
r: radial distance



A geometric construction to illustrate the integration variable

θ: Angular separation between Cygnus A and the Sun w.r.t. the Galactic Center

Radio observation

Single-dish observation

Angular resolution

$$\theta_{FWHM} \simeq 1.22\frac{\lambda}{D} \simeq 0.7^\circ \left(\frac{1\mathrm{GHz}}{v}\right)\left(\frac{15\mathrm{m}}{D}\right) \tag{17}$$

Noise temperature of the instrument

$$T_{\text{ant}} = \frac{A_{\text{eff}} \langle S \rangle}{2k_b} \tag{18}$$

For each telescope

$$\left(\frac{S}{N}\right)_{sd,\,\text{single}} = \frac{T_{\text{ant}}^{\mathrm{pb}}}{T_{\text{min}}} \tag{19}$$

For an array of single-dish telescopes

$$\left(\frac{S}{N}\right)_{sd,\,\text{array}} = \sqrt{N_{\text{tele}}\, n_{\text{pol}}} \left(\frac{S}{N}\right)_{\text{single}} = \sqrt{N_{\text{tele}}\, n_{\text{pole}}}\, \frac{T_{\text{ant}}^{pb}}{T_{\text{min}}} \tag{20}$$

Observation in the interferometric mode

Angular resolution of primary beam

$$\theta_{pb} = 12.5' \left(\frac{1\mathrm{GHz}}{\nu}\right)\left(\frac{100\mathrm{m}}{D}\right) \tag{21}$$

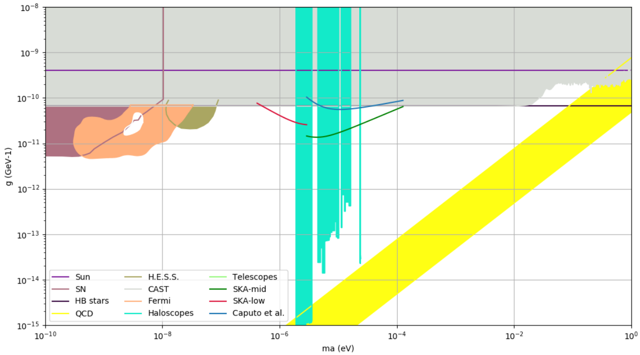
Minimum detectable flux density

$$S_{\mathrm{min}} = SNR \frac{\mathrm{SEFD}}{\sqrt{n_{\mathrm{pol}} \Delta B t_{\mathrm{obs}}}} \tag{22}$$

with

$$\mathrm{SEFD} = \frac{T_{\mathrm{sys}}(\nu)}{G} \tag{23}$$

Phenomenological implications



Axion mass vs. axion photon coupling. Limits shown are for axion gegenschein using SKA-mid (green) and SKA-low (red) sensitivities. Bounds from stimulated emission in dSphs shown in blue [Caputo et al. (2018)]

Conclusions

Key takeaways and further explorations

- Astrophysical radio pulses from galactic and extragalactic sources can induce stimulated emission in the Milky Way's halo.
- Stimulated emission from halo dark matter can lead to a detectable signal at future-generation radio telescopes with conservative SNR ~ 1.
- *Axion gegenschein* provides **100-fold increase in radio sensitivity compared to contemporary frameworks!**
- Detection of fainter countersources feasible with improved radio sensitivity in the future.
- Axion gegenschein opens up a new indirect detection scheme for dark matter. Several other radio-loud sources could provide optimal stimulated emission.
- Further boost in (stimulated) radio emission can occur owing to dwarfs along the line of sight.

The End

Thank you for your attention!

Questions?

In terms of the electric and magnetic fields, $\vec{E}(x)$ and $\vec{B}(x)$:

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}\frac{\alpha}{\pi}\frac{1}{f_a}a(x)\vec{E}(x)\cdot\vec{B}(x), \tag{24}$$

Strong CP problem and Peccei-Quinn symmetry breaking

CP-violating term leading to neutron EDM

$$\mathcal{L}_{\theta,\mathrm{QCD}} = \frac{\theta_{\mathrm{QCD}}}{32\pi^2} \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu} \quad (25)$$

→Axions as pseudo-Goldstone bosons arising from spontaneous breaking of PQ symmetry

→Dynamical non-perturbative solution of the CP problem using dilute instanton gas approximation

$$m_{a,\mathrm{QCD}} \approx 6 \times 10^{-6}\mathrm{eV} \left(\frac{10^{12}\mathrm{GeV}}{f_{a/C}} \right) \quad (26)$$

Several theoretical frameworks including
Peccei-Quinn-Wilczek-Weinberg (PQWW),
Kim-Shifman-Vainshtein-Zakharov (KSVZ), &
Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) formalisms.

Observation in the interferometric mode

For each synthesized beam in the interferometric mode, angular resolution

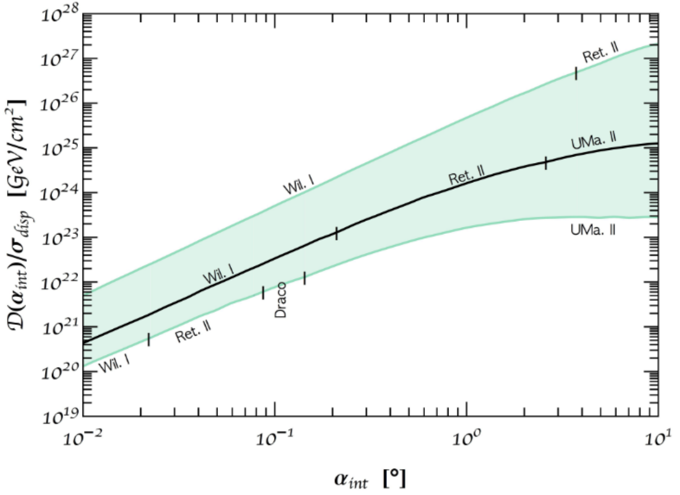
$$\theta_{\mathrm{synth}} \approx 50'' \left(\frac{1\mathrm{GHz}}{f}\right)\left(\frac{1\mathrm{km}}{B_{\mathrm{max}}}\right) \tag{27}$$

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

$$\delta\chi^2 = n_{\mathrm{pol}} t_{\mathrm{obs}} G_{\mathrm{array}}^2 \sum_{i=1}^{N_{\mathrm{synth}}} \frac{F_i^2}{B_i T_i^2} \tag{28}$$

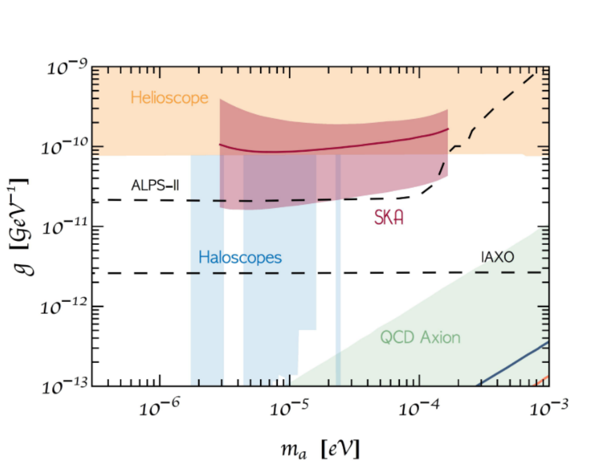
Scaling relation for antenna gain $G_{\mathrm{array}} \sim N_{\mathrm{tele}}\left(N_{\mathrm{tele}} - 1\right) G$

Radio signal from dwarfs



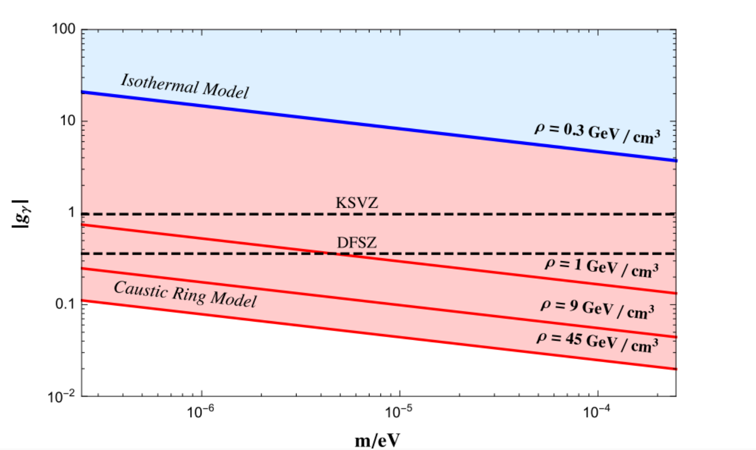
$D(\alpha_{int})/\sigma_{disp}$ as a function of the field of view of the telescope

Radio signal from dwarfs



Sensitivity of SKA in the $g_{a\gamma\gamma} - m_a$ parameter space denoted using median $\pm95\%$ confidence interval in the dSph with largest

Radio signal from echo wave



Sensitivity in $|g_\gamma|$ vs. axion mass m_a for an outgoing power of 10 MW/year [Sikivie et al. (2019)]

References i

- 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`

References ii

- 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
- 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.