A photon signal from stimulated decays of axion dark matter in the Milky Way

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QCD axions and ALPs - motivation

- QCD axions solve the strong CP problem

$$\mathscr{L}_{\mathrm{QCD}} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a \theta$$

(ALPs: let m_a and f_a be independent parameters)

theory: θ = arbitrary

experiment: $|\theta| \lesssim 10^{-10}$

C. Abel et al. 2001.11966

- possible candidates for dark matter L. F. Abbott & P. Sikivie (1983) …

- explain astrophysical anomalies:
  - Stellar cooling
  - TeV gamma-ray transparency
  - Hard X-ray from neutron stars

G. G. Raffelt et al. 1110.6397
M. Giannotti et al. 1512.08108
K. Kohri & H. Kodama 1704.05189
G. Galanti et al. 2210.05659
Malte Buschmann et al. 1910.04164
…

- string theory, $(g-2)_\mu$ problem, R-parity breaking … etc.

E. Witten (1984), D. Chung et al. 0009292, B. Bellazzini et al. 1702.02152

Axion searches

haloscopes & helioscopes

CAST
IAXO
ADMX
ALPS
MADMAX
…

Image: CAST collaboration

beam dump experiments & coliders

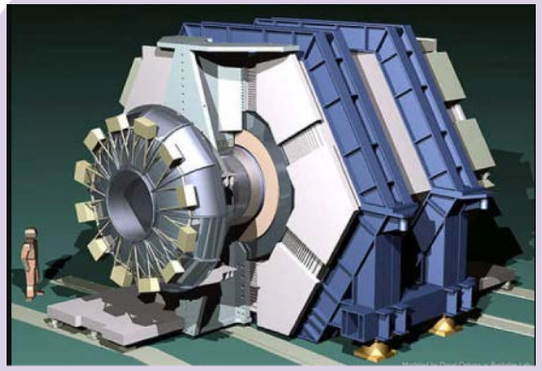


Image: BaBar collaboration

BaBar
E137
E141
CHARM
LEP
…

GRB
Sun
Globular Cluster
NS, WD, SN
Polarizations
…

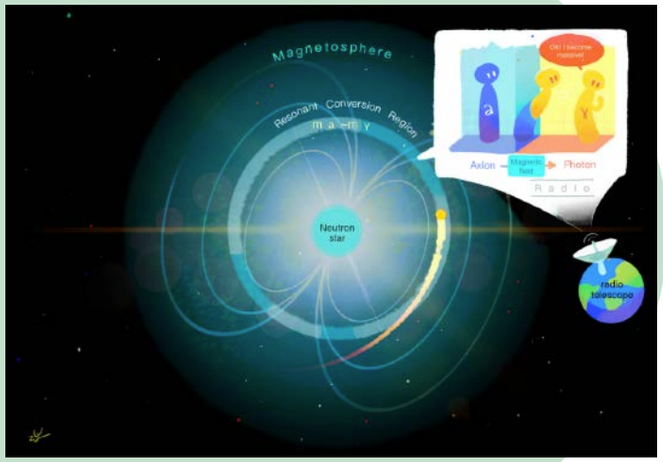


Image: J.H. Buckley et al. 2004.06486

astrophysics

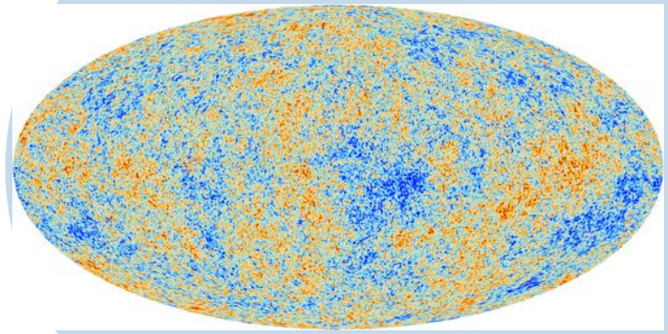


Image: Planck collaboration

CMB spectra
birefringence
D & He abundance
X-ray background
…

cosmology

Settings

- axion-like particle dark matter in the Galaxy
- $m_a \simeq 0.1 - 100\ \mu\text{eV}$
- coupled only to a photon: $\mathscr{L}_{\text{int.}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

Stimulated decay of axion

$$\mathscr{L}_{\text{int.}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Change of a distribution function due to $a(\mathbf{p_a}) \to \gamma(\mathbf{p}_1) + \gamma(\mathbf{p}_2)$ and the inverse

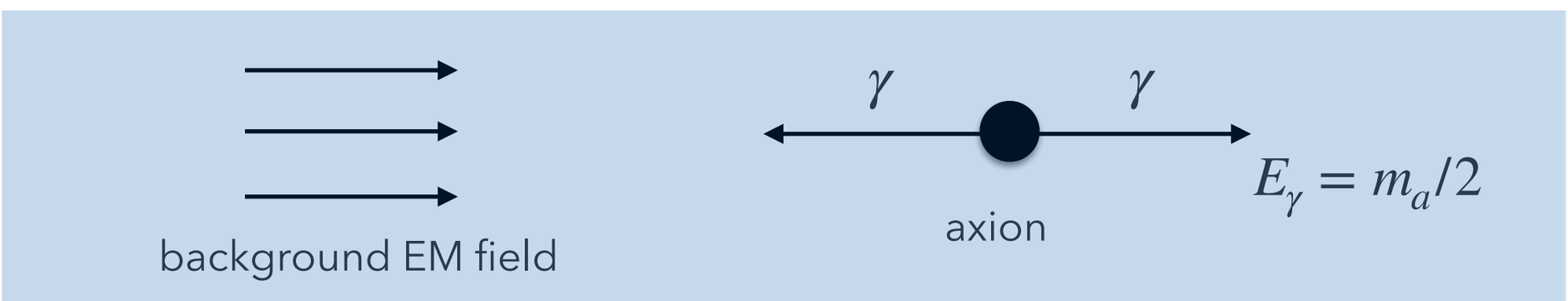
Bose enhancement

$$\frac{\mathrm{d}}{\mathrm{d}t} f_1 = \frac{1}{2E_1} \int \frac{\mathrm{d}^3 p_a}{(2\pi)^3 2E_a} \int \frac{\mathrm{d}^3 p_2}{(2\pi)^3 2E_2} \left|\mathscr{M}\right|^2 \Big(f_a (1 + f_1)(1 + f_2) - f_1 f_2 (1 + f_a) \Big) (2\pi)^4 \delta^4 (p_a - p_1 - p_2)$$

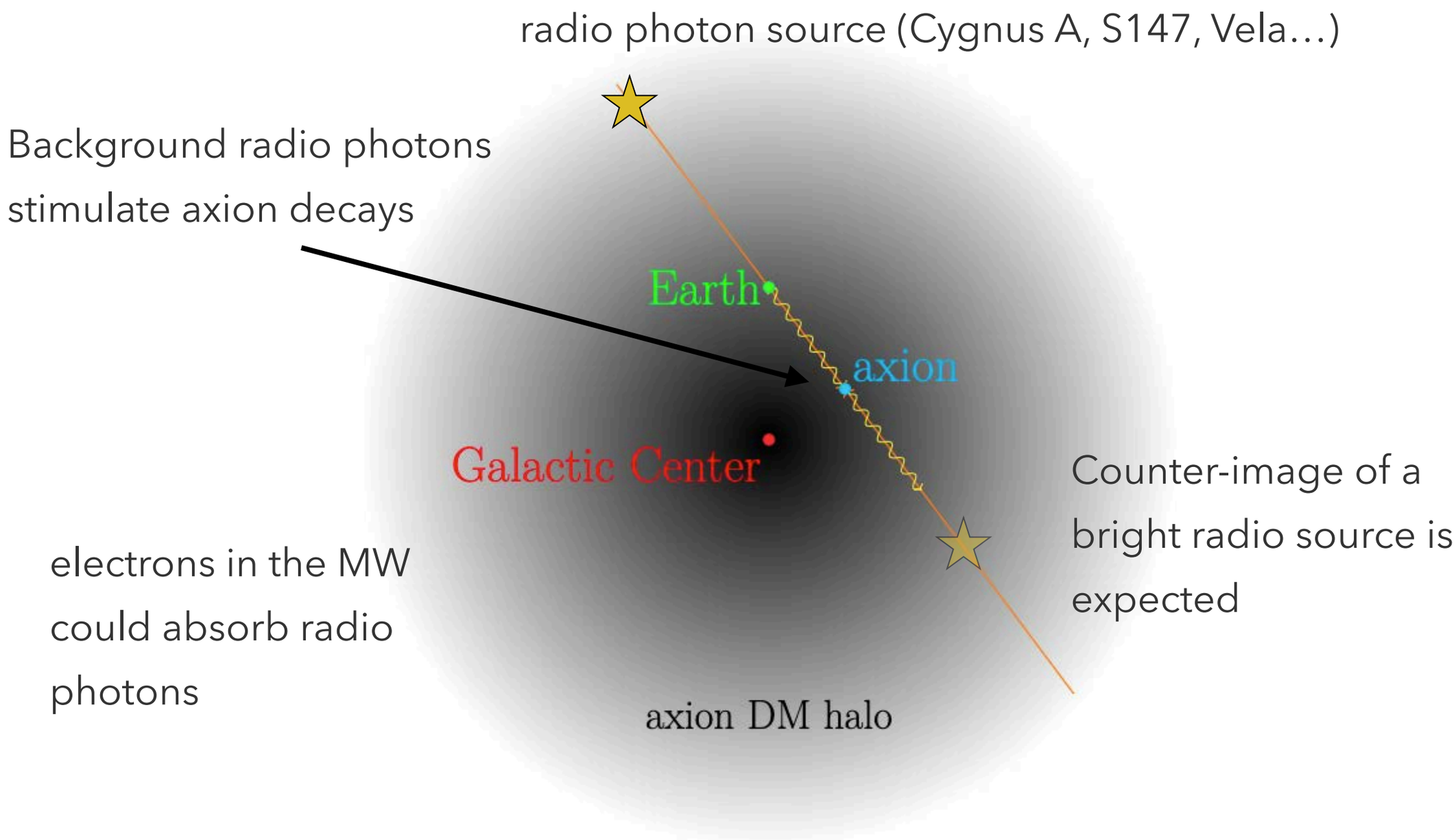
$$= \frac{1}{2E_1} \int \frac{\mathrm{d}^3 p_a}{(2\pi)^3 2E_a} \int \frac{\mathrm{d}^3 p_2}{(2\pi)^3 2E_2} \left|\mathscr{M}\right|^2 \Big(f_a (1 + f_1 + f_2) - f_1 f_2 \Big) (2\pi)^4 \delta^4 (p_a - p_1 - p_2)$$

stimulated decay of axion axion production from two photons

In the rest frame of axion



Stimulated decay of axion in the Milky Way



Photon signal

free free absorption
(a free electron gains energy
during a collision with an ion by
absorbing a photon)

$$S(\nu) = \frac{m_a^3 g_{a\gamma}^2}{64\pi} \frac{1}{4\pi\Delta\nu} \int \mathrm{d}x \int \mathrm{d}\Omega \; \rho_a(x,\Omega) e^{-\tau(\nu,x,\Omega)} \left(f_\gamma(x, \vec{p}, \Omega, t) + f_\gamma(x, -\vec{p}, \Omega, t) \right)$$

background photons

- CMB
- Extragalactic background

$$T_{\text{exgal}}(\nu) \simeq 1.19 \left(\frac{\text{GHz}}{\nu} \right)^{2.62} \text{K}$$

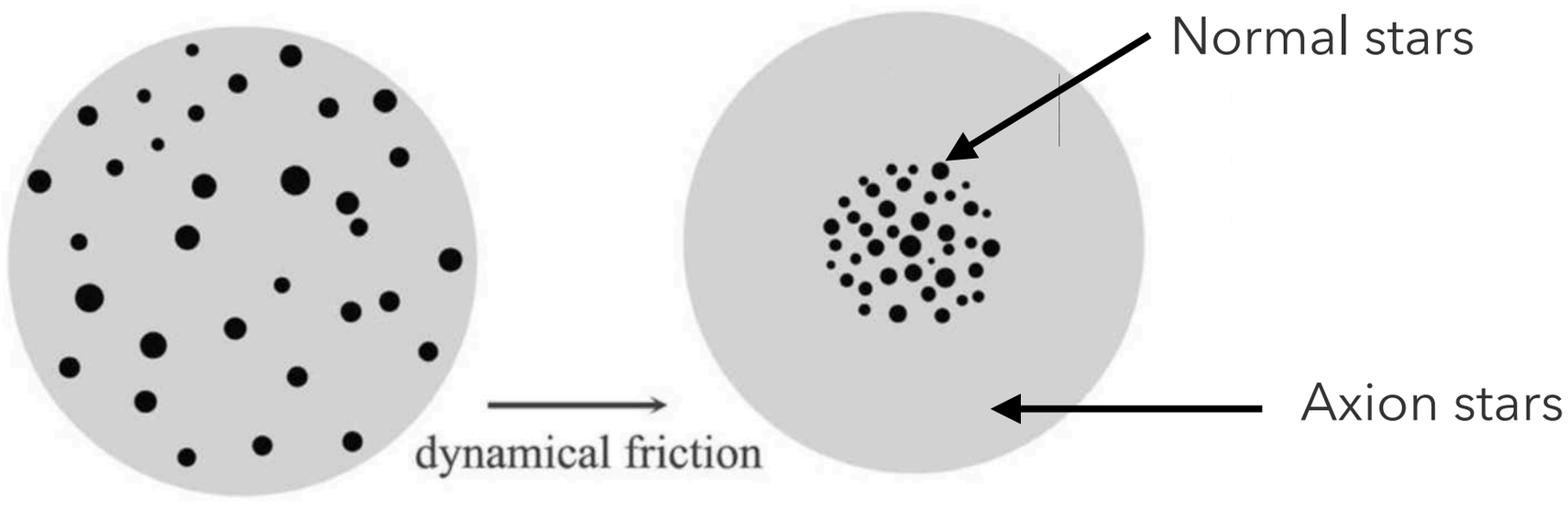
- photons from galactic source (408MHz Haslam map)

Axion stars

$\rho_a(r)$? → NFW profile (cuspy) and Burkert profile (cored)

- a clump of axions supported by quantum pressure
- solutions of Klein-Gordon equation + Poisson equation + assumptions + simplifications
- $R_a \sim (270\ \mathrm{km})\left(\frac{10\mu\mathrm{eV}}{m_a}\right)^2\left(\frac{10^{-12}M_\odot}{M_a}\right)$ **P. H. Chavanis & L. Delfini 1103.2054**

could be modified by a formation of axion stars and their gravitational interactions with normal stars



→ $\rho_a(r)$ is modified by 10% at most

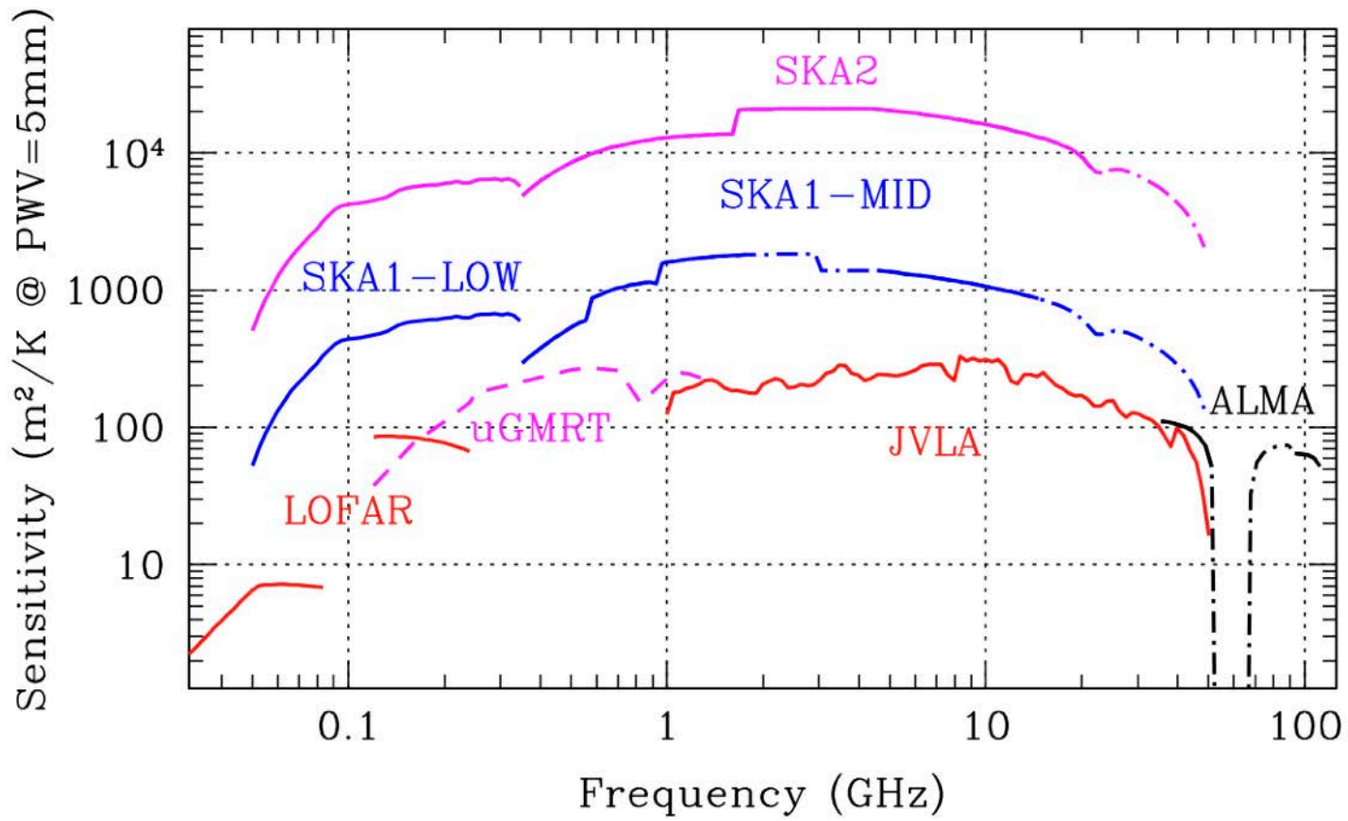
Telescopes

SKA Observatory

Image: SKAO

	SKA-low	SKA-mid
Frequency [MHz]	50-350	350-1540
$N_{\rm tele}$	512	197
D [m]	35	13.5, 15
$\theta_{\rm res}$ [deg]	12-1.7	4-1
$T_{\rm r}$ [K]	40	20

Sensitivity

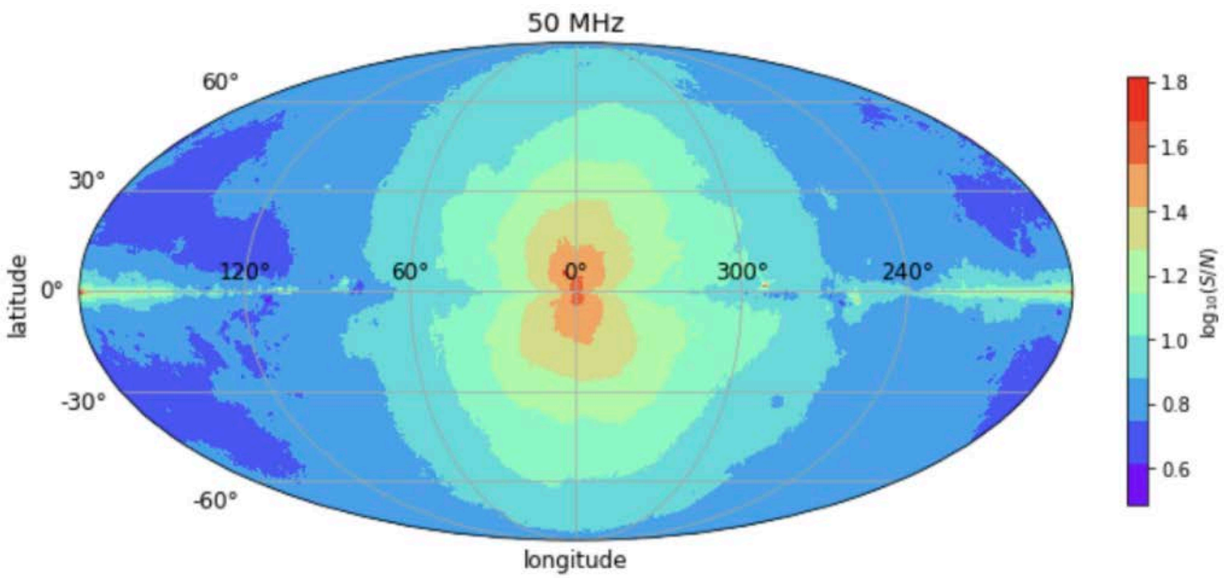


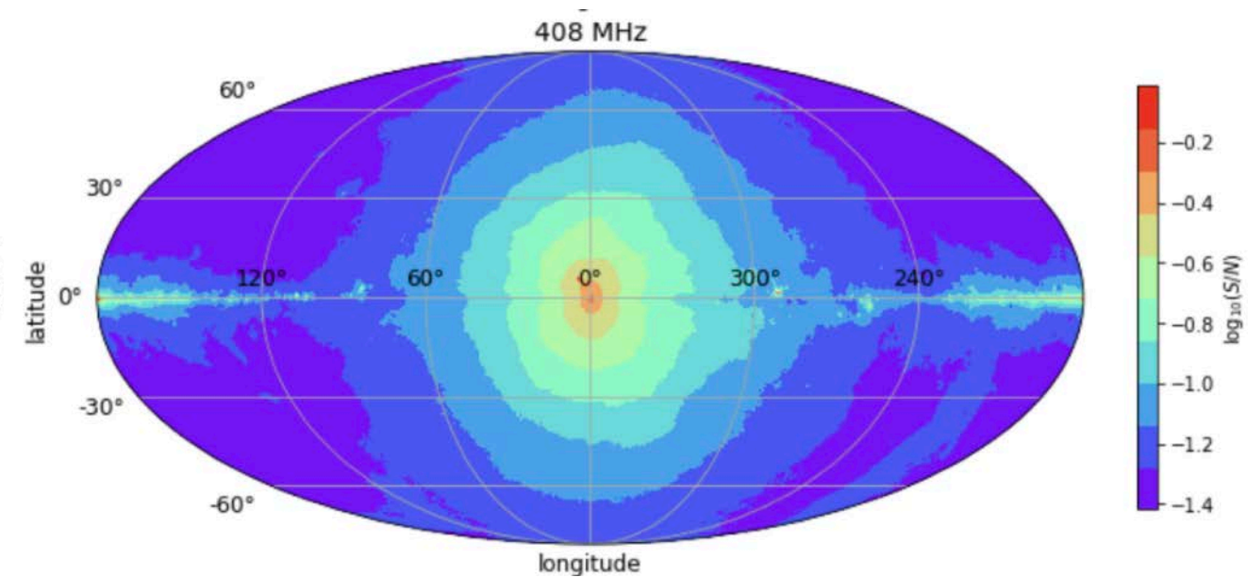
R. Braun et al. 1912.12699

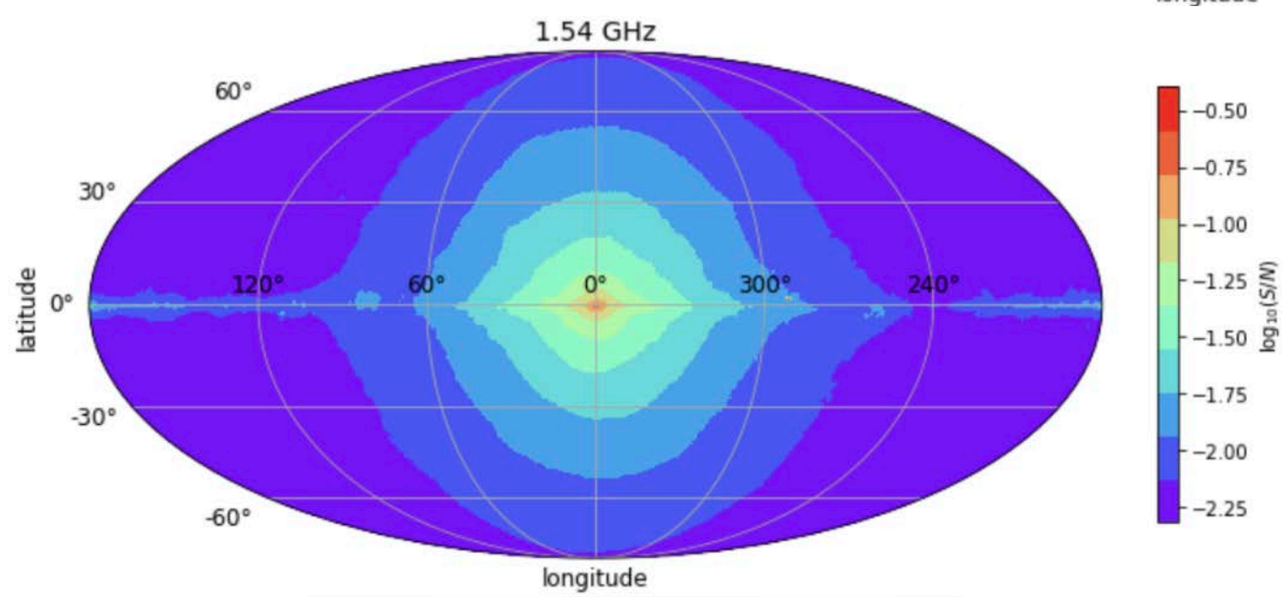
Signal-to-noise ratio of a single antenna

$$\frac{S}{N} = \frac{m_a^3 g_{a\gamma}^2}{512\pi^2}\frac{\eta A f_\Delta}{k_B T}\sqrt{\frac{t_{\rm obs}}{\Delta\nu}}\int {\rm d}x \int {\rm d}\Omega\ \rho_a(x,\Omega) e^{-\tau(\nu,x.\Omega)}\left(f_\gamma(x,\vec{p},\Omega,t) + f_\gamma(x,-\vec{p},\Omega,t)\right)$$

All-sky maps







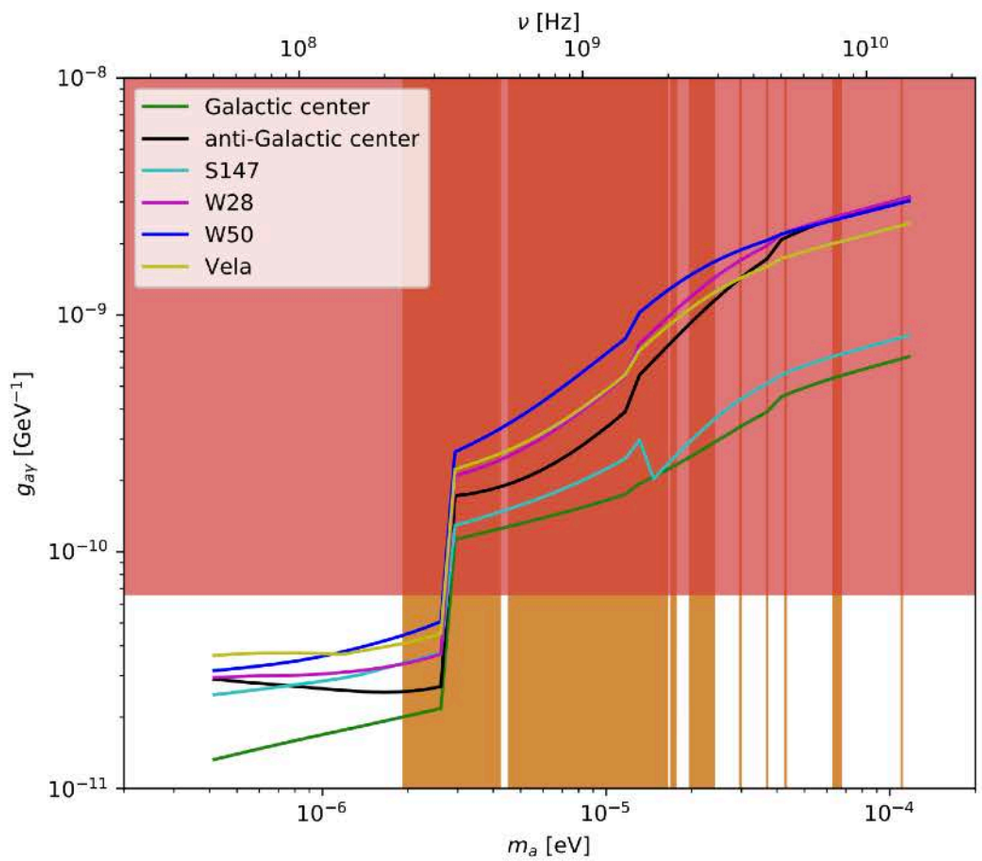
The large signal-to-noise ratio is obtained in

- the direction of the GC and the anti-GC
- the opposite direction to bright radio sources

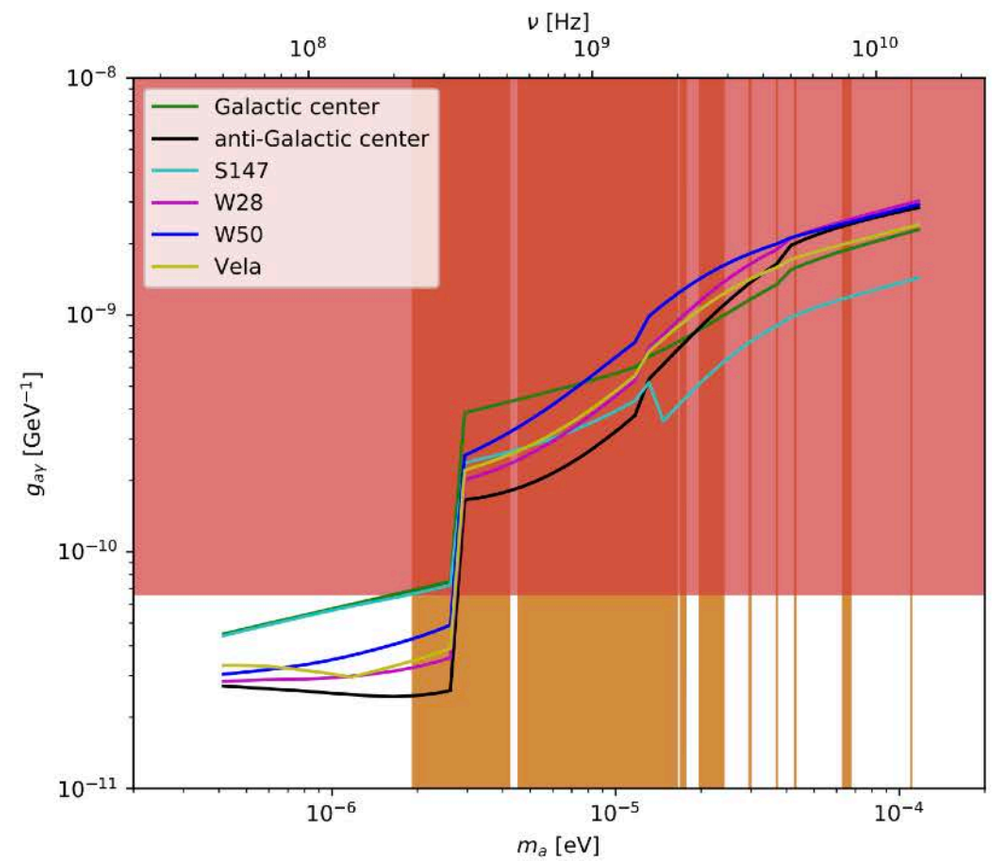
Detectability

Detectability of photons from a stimulated decay of axions from several directions (Galactic center, anti-Galactic center, S147, W28, W50, Vela) by 100 hrs of observation

NFW profile



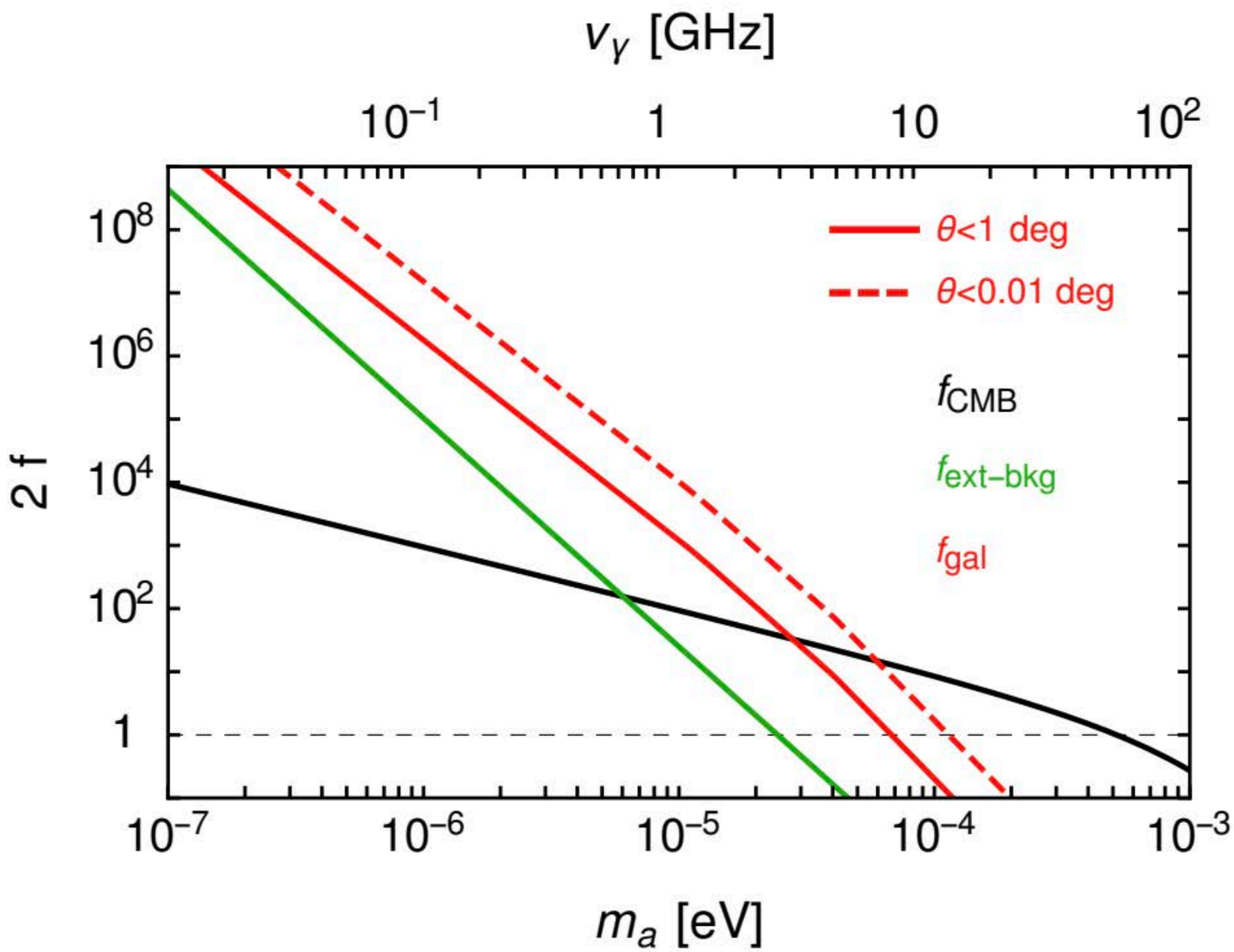
Burkert profile



$g_{a\gamma} \gtrsim 2 \times 10^{-11}$ GeV^{-1} ($m_a \simeq 10^{-6}$ eV) produce the radio photon flux detectable at the SKA Observatory

Backup slides

Occupation numbers of photons



A. Caputo et al. 1811.08436

Distribution of ALP

The NFW profile:

$$\rho_a(r) = \frac{\delta_c \rho_c}{(r/r_s)\,(1 + r/r_s)^2} \qquad \delta_c = \frac{\Delta_{\rm vir}}{3} \frac{r_c^3}{\ln(1 + r_c) - r_c/(1 + r_c)}$$

$r_s \simeq 20$ kpc : the scale radius

$\Delta_{vir} = 200$

$R_{vir} \simeq 221$ kpc : the virial radius

$r_c \equiv R_{vir}/r_s$

The Burkert profile:

$$\rho(r) = \frac{\rho_s}{\left(1 + \frac{r}{r_{sb}}\right)\left(1 + \frac{r}{r_{sb}}\right)^2}$$

$r_{sb} = 12.67$ kpc

Noise

Four contributions to the noise temperature T

- atmospheric radio wave $T \sim 3\ \mathrm{K}$
- CMB $T \sim 2.725\ \mathrm{K}$
- noise of receiver $T \sim 20{,}40\ \mathrm{K}$
- Synchrotron radiation from the Galactic or extragalactic system

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

Axion stars

Physics of a scalar field coupled to gravity is described by the action

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{16\pi G} R \right]$$

Trick to solve a resulting EoM:

Assuming axion is non-relativistic

$$\phi(\boldsymbol{r}, t) \approx \frac{1}{\sqrt{2m_a}} \left(\psi(\boldsymbol{r}, t) e^{-im_a t} + \psi^*(\boldsymbol{r}, t) e^{+im_a t} \right)$$

and taking an average over scales larger than m_a

Gross-Pitaevskii-Poisson equations are obtained

$$i\dot{\psi} = -\frac{1}{2m_a} \nabla^2 \psi + \left[V'_{\text{eff}} \left(\psi^* \psi \right) + m_a \Phi \right] \psi$$

$$\nabla^2 \Phi = 4\pi G m_a \psi^* \psi$$