Probing axion dark matter with radio waves

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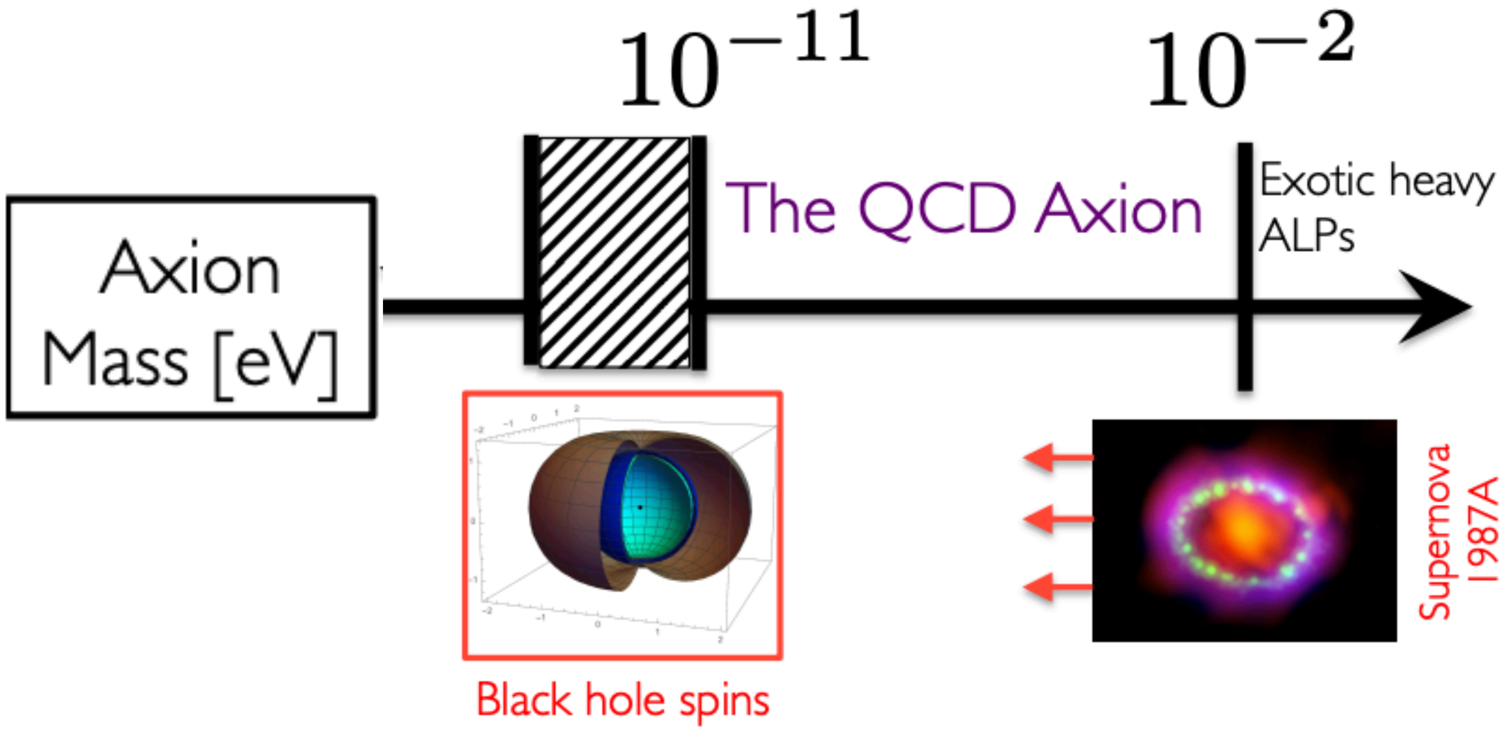
Axion dark matter

QCD axion:

Introduced to solve the strong CP problem

Produced as a NG boson when $U(1)_A$ symmetry was broken and acquires mass at the QCD phase transition

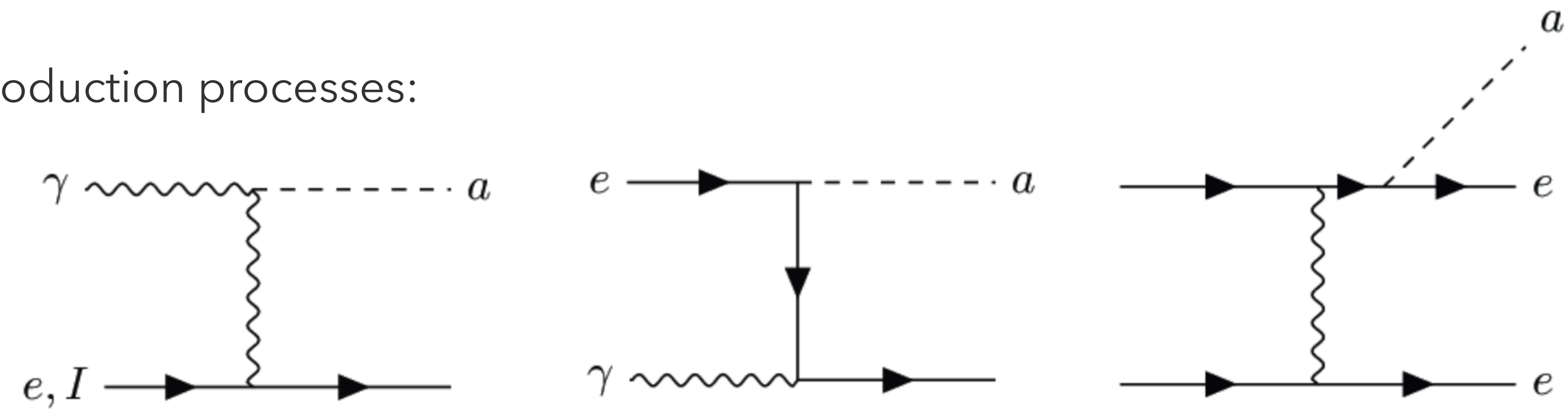


QCD axion: 10^{-11} eV $\lesssim m_a \lesssim 10^{-2}$ eV

QCD axion dark matter: $m_a = \mu$eV $\sim m$eV

Axions in astrophysics

Production processes:



Primakoff process, Compton scattering, bremsstrahlung, etc.

Examples of axion search:

- photons from decays of axions produced in stars
- directly detect axions produced in the sun
- photons from axion-photon conversion in magnetic fields
- photons from stimulated decay of axions

E. Müller et al. 2304.01060
CAST collaboration 1705.02290
M. Diamond et al. 2303.11395

C. Dessert et al. 2008.03305
A. Caputo et al. 2201.09890
A. Caputo et al. 1811.08436
…

Stimulated decay of axion

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

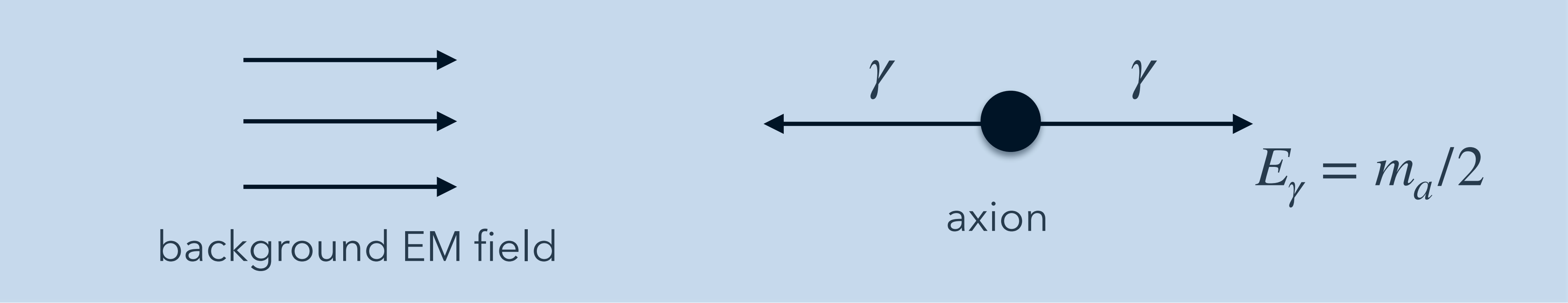
Change of a distribution function due to $a\left(\mathbf{p_a}\right) \to \gamma\left(\mathbf{p}_1\right) + \gamma\left(\mathbf{p}_2\right)$ and the inverse

Bose enhancement

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

stimulated decay of axion axion production from two photons

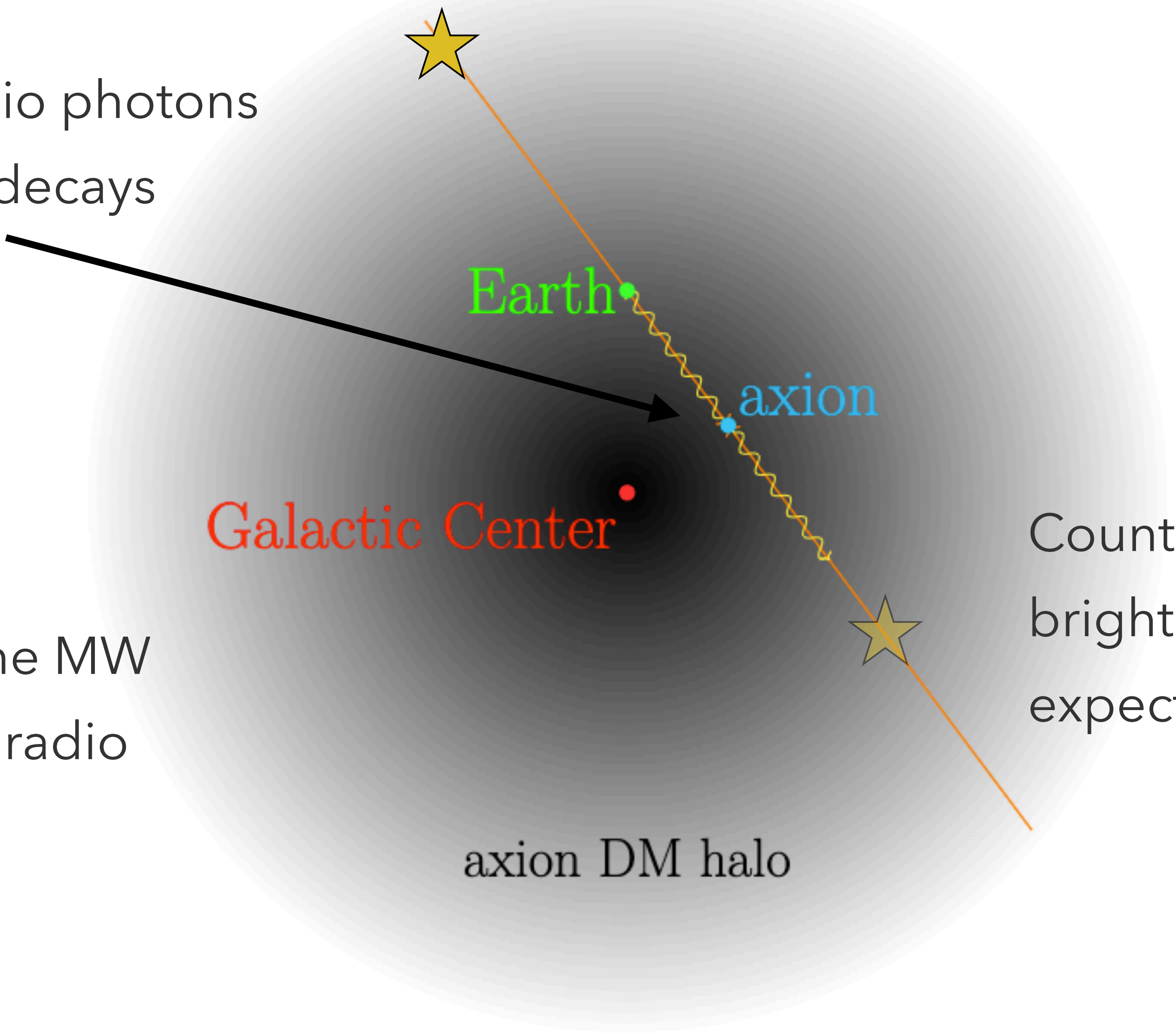
In the rest frame of axion



Stimulated decay of axion in the Milky Way

radio photon (SNR, Galactic emission, Ex-Gal emis., CMB)

Background radio photons stimulate axion decays



Counter-image of a bright radio source is expected

electrons in the MW could absorb radio photons

Figure: O. Ghosh et al. 2008.02729

Photon signal

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

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

background photons

- CMB
- Extragalactic background

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

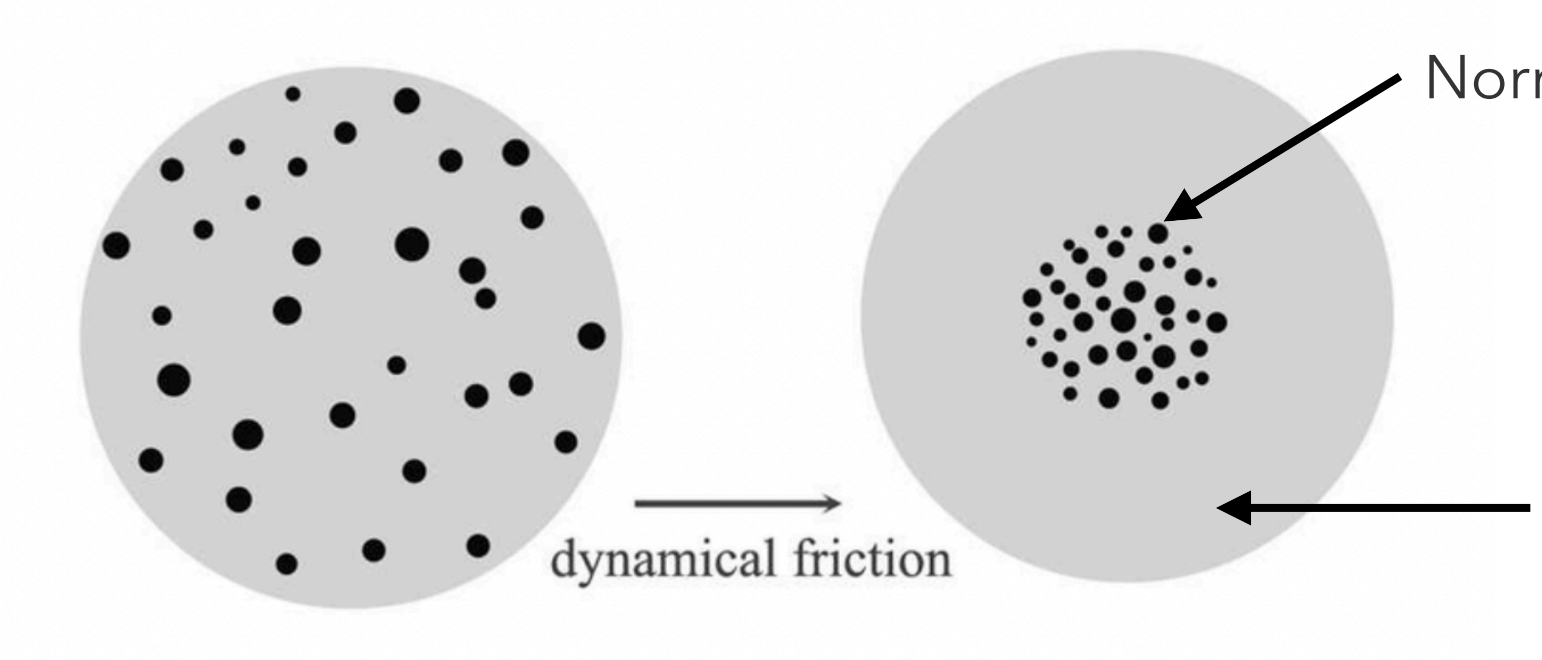
- photons from galactic source (408MHz Haslam map)

Axion stars

$\rho_a(r)$: NFW profile ($\rho \propto r^{-1}$ at the center) and Burkert profile ($\rho = const.$ at the center)

- 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



Normal stars

Axion stars

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

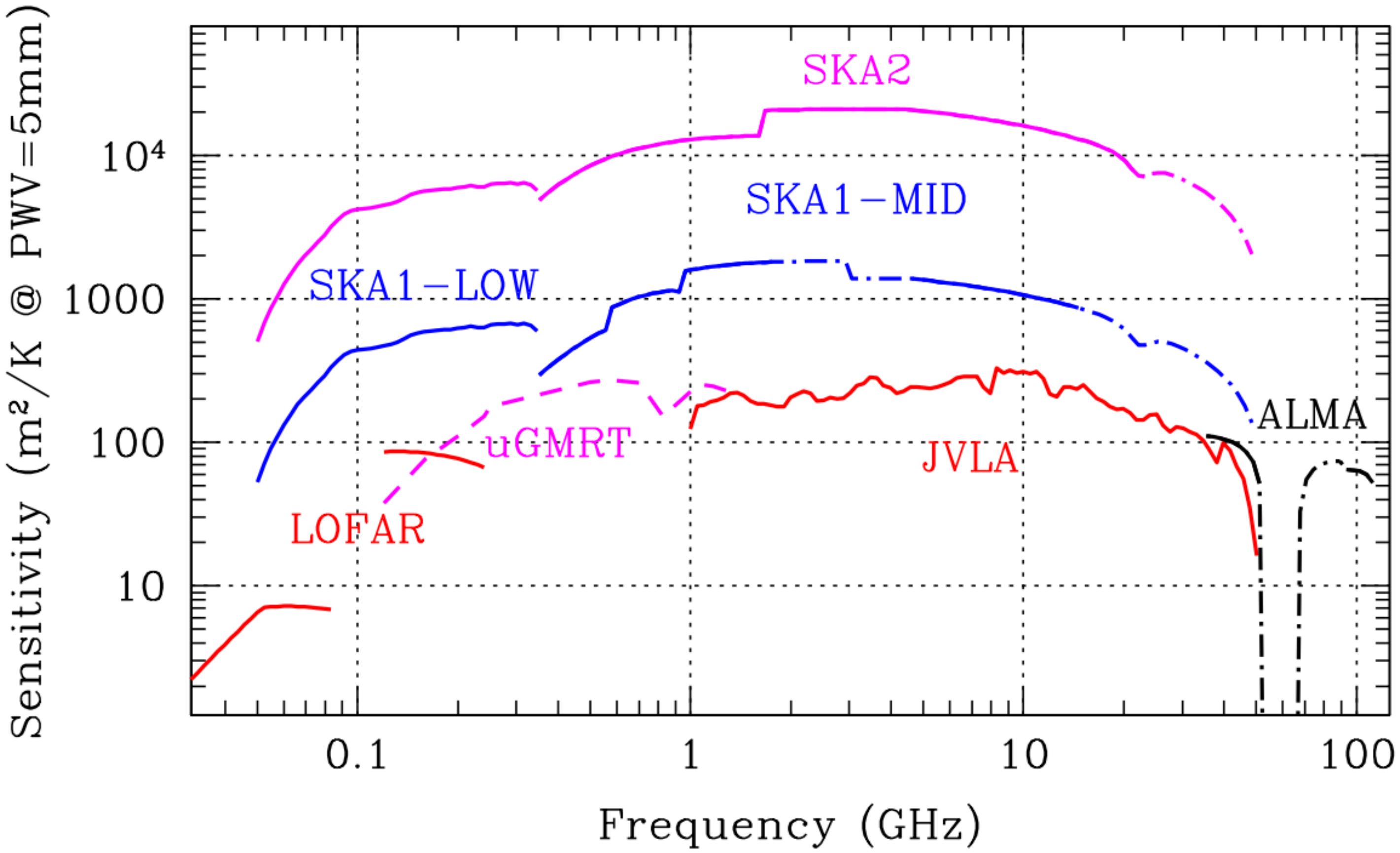
Telescopes

SKA Observatory

Image: SKAO

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

Sensitivity

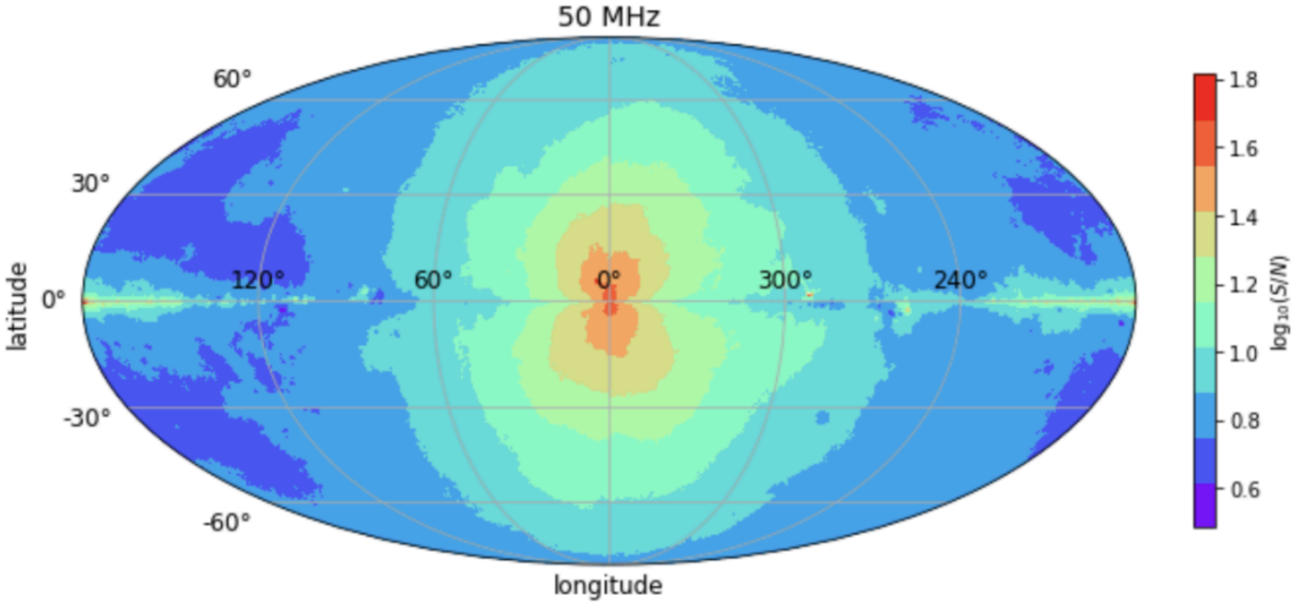


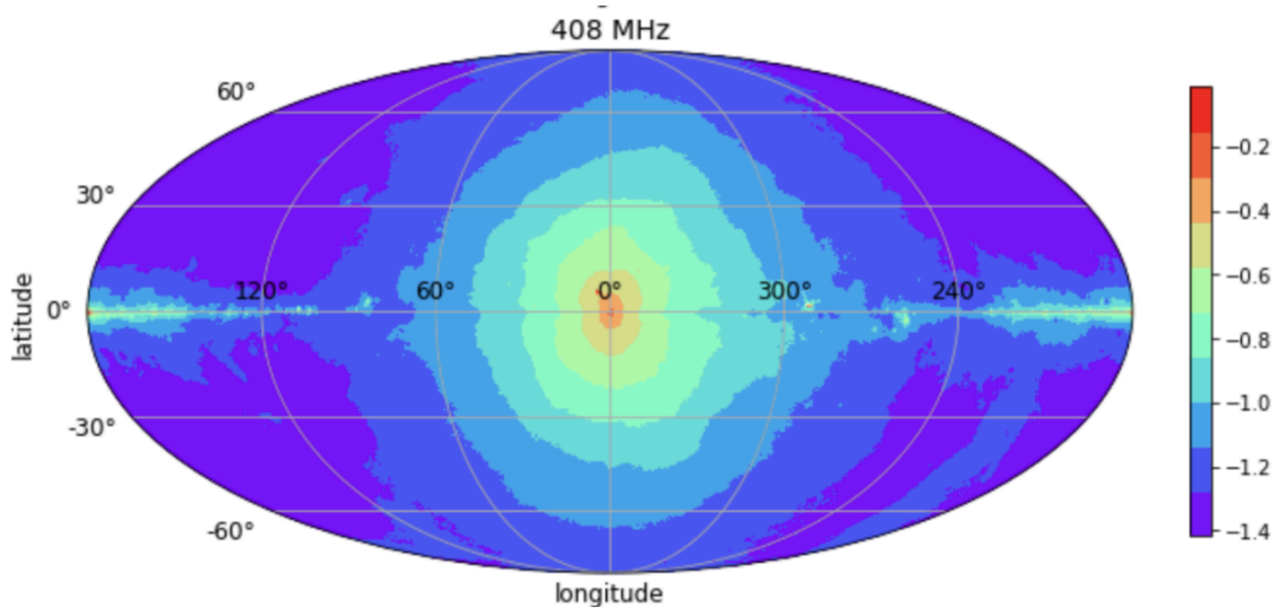
R. Braun et al. 1912.12699

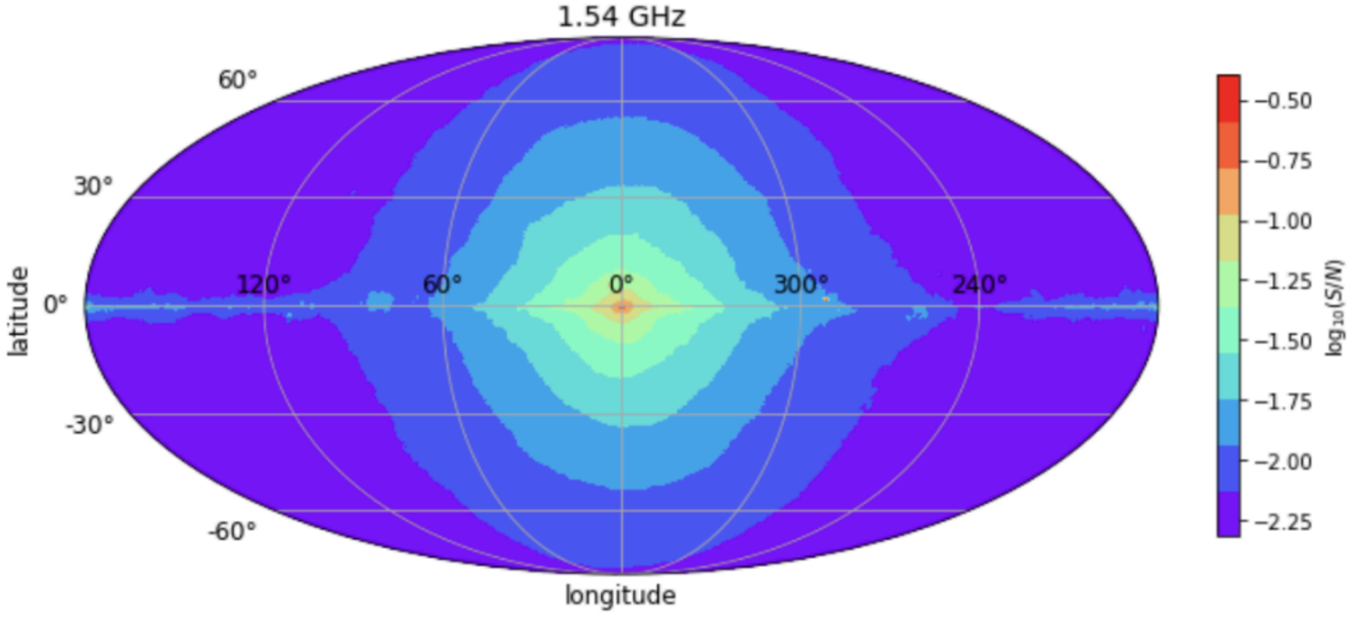
Signal-to-noise ratio of a single antenna

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

All-sky maps







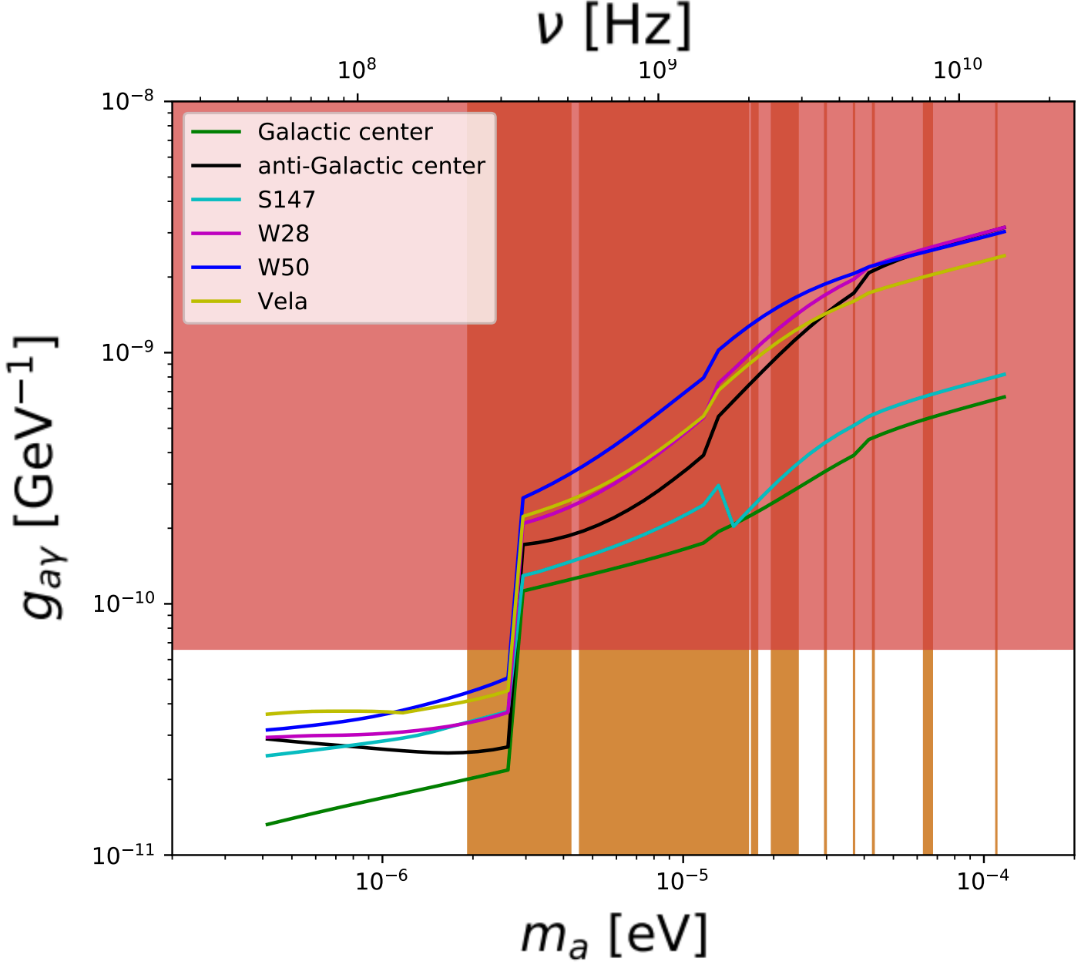
The large signal-to-noise ratio is obtained in

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

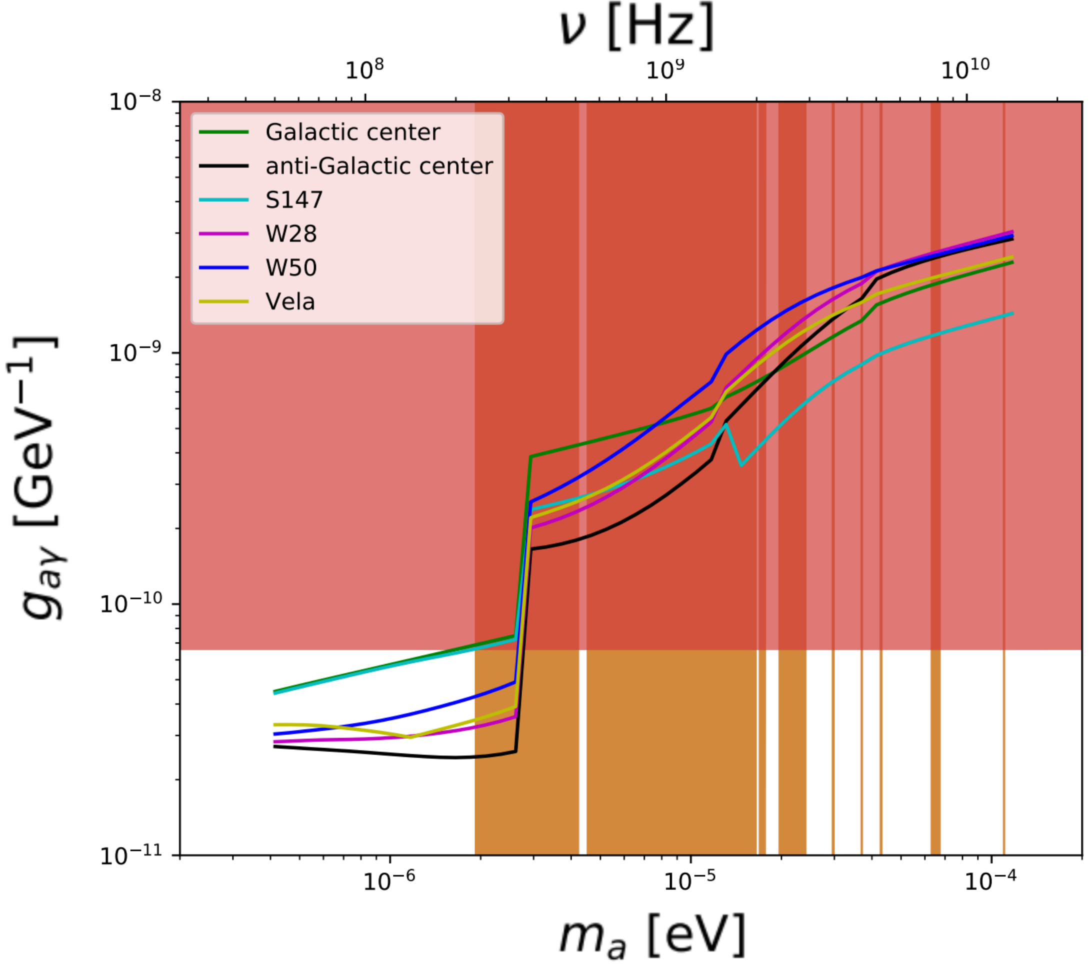
Detectability

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

NFW profile



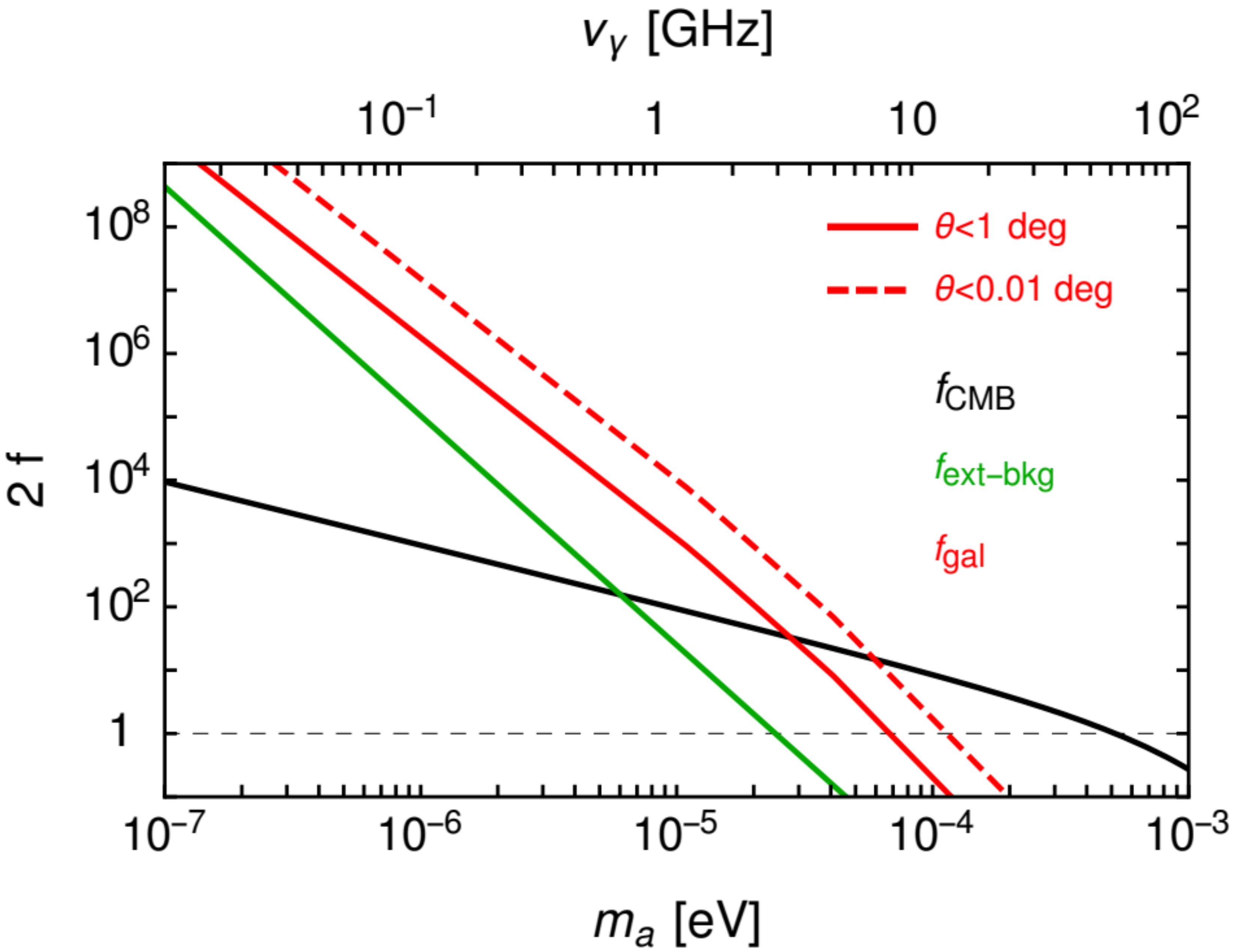
Burkert profile



$g_{a\gamma} \gtrsim 2 \times 10^{-11}$ 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:

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

$r_s \simeq 20$ 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:

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

$r_{sb} = 12.67$ 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

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:

Assume 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 take an average over scales larger than m_a

Gross-Pitaevskii-Poisson equations are obtained

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

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

Supernova remnant

Evolution of supernova:

- ejecta-dominated phase ($t \lesssim 100$ yrs)

  flux is assumed to be $S_\nu =$ const.

- Sedov-Taylor phase (100 yrs $\lesssim t \lesssim \mathcal{O}(10^4)$ yrs)

  $S_\nu \propto t^{2(\gamma+1)/5}$ or $t^{4\gamma/5}$ where $\gamma = 2\alpha + 1$

	S147	W28	Vela	W50
age [yr]	40000	34500	12000	29000
α	0.3(1.2)	0.42	0.74	0.7
γ	1.6(3.4)	1.84	2.48	2.4
S_ν [Jy]	59	310	610	85
galactic coordinates (l, b)	(180.0, -1.7)	(6.4, -0.1)	(263.9, -3.3)	(39.7, -2.0)
distance [pc]	1200	1900	287	50000
size [arcmin]	65	48	255	60