Polarized spectral distortion of CMB from low mass ALPs

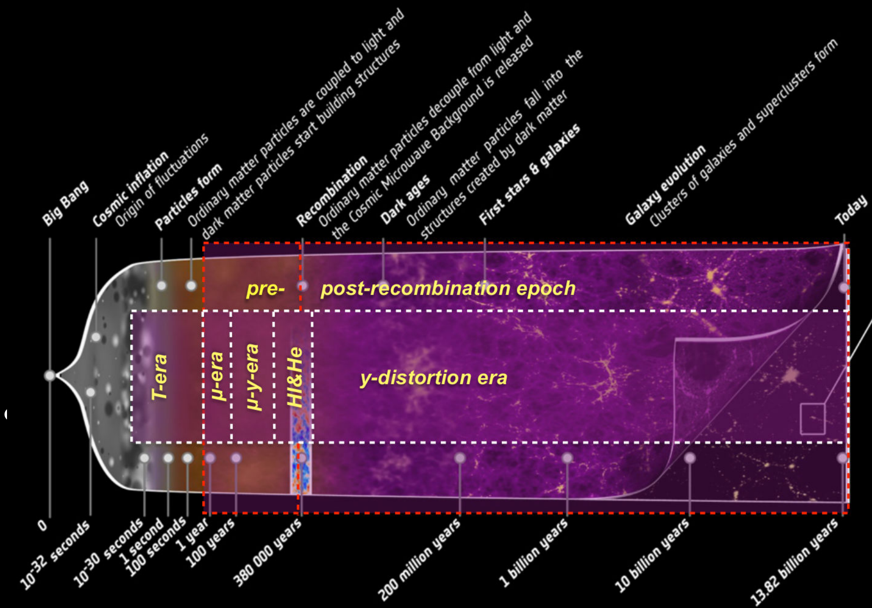
Mukherjee, Khatri, Wandelt

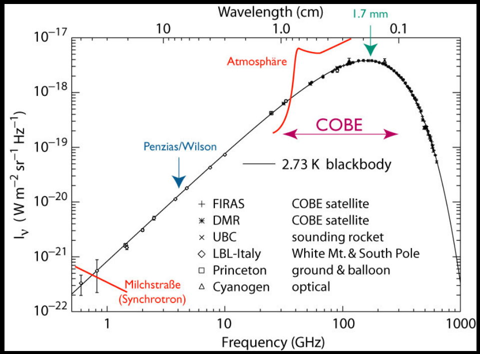
arXiv:1801.09701

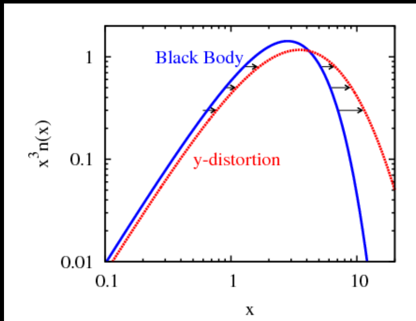
Suvodip Mukherjee

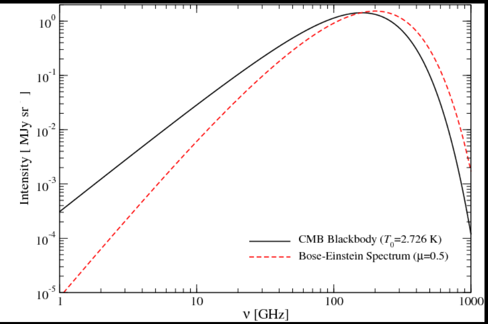
Center for Computational Astrophysics

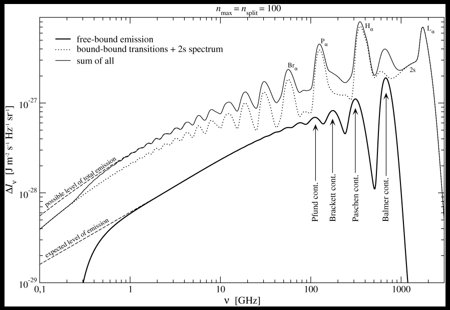
Non-Blackbody (Spectral Distortions) with (or without) spatial fluctuations



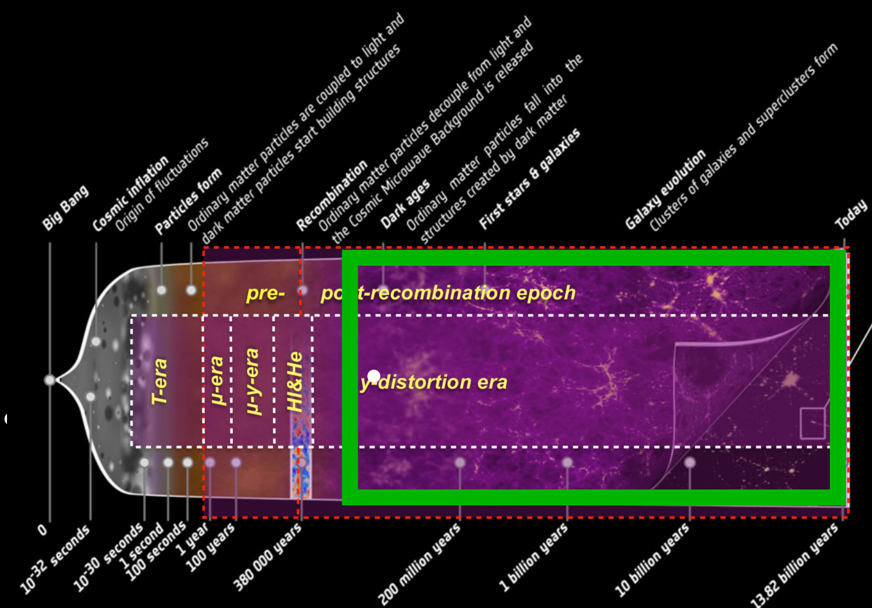


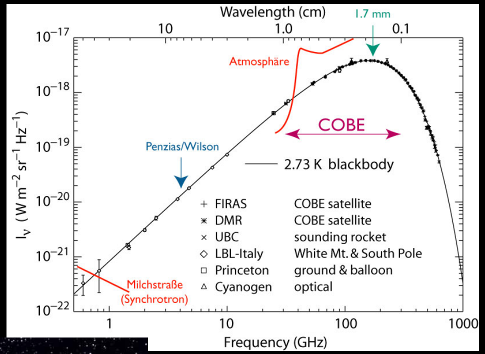


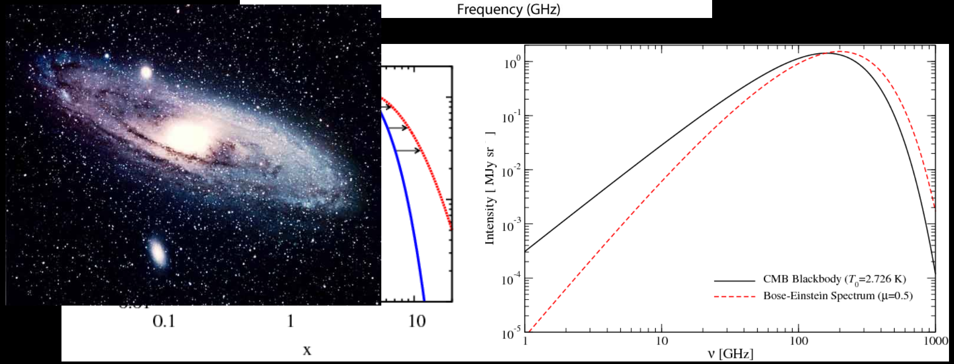




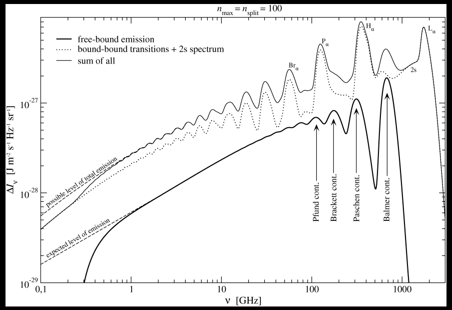
Non-Blackbody (Spectral Distortions) with (or without) spatial fluctuations

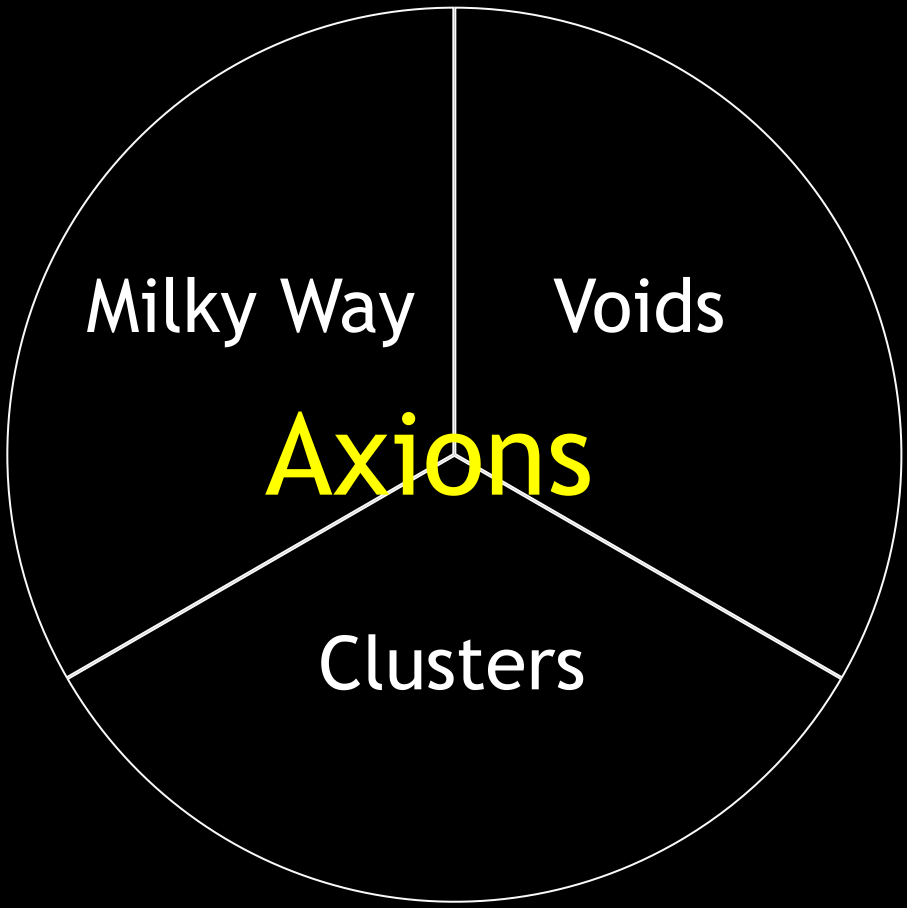




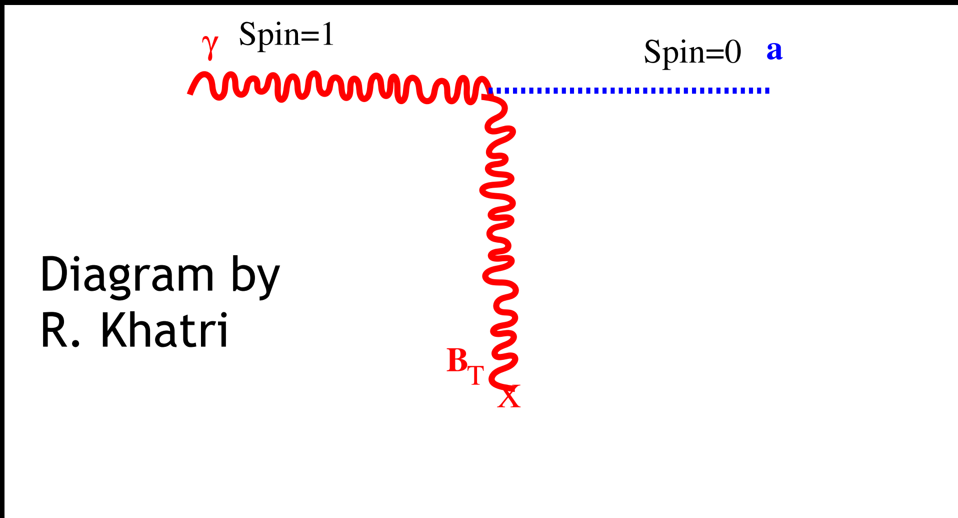


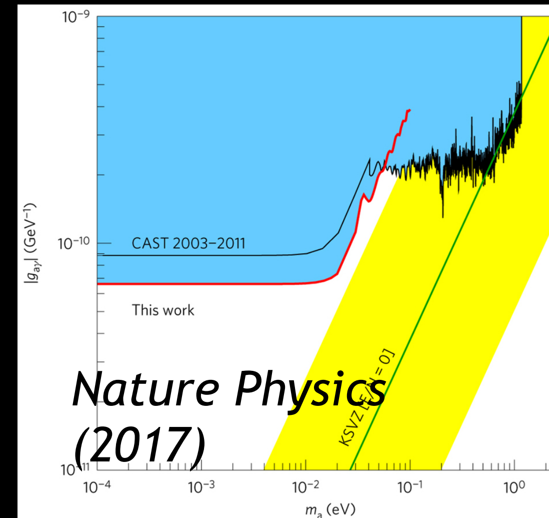
Another spectral distortion from Axions

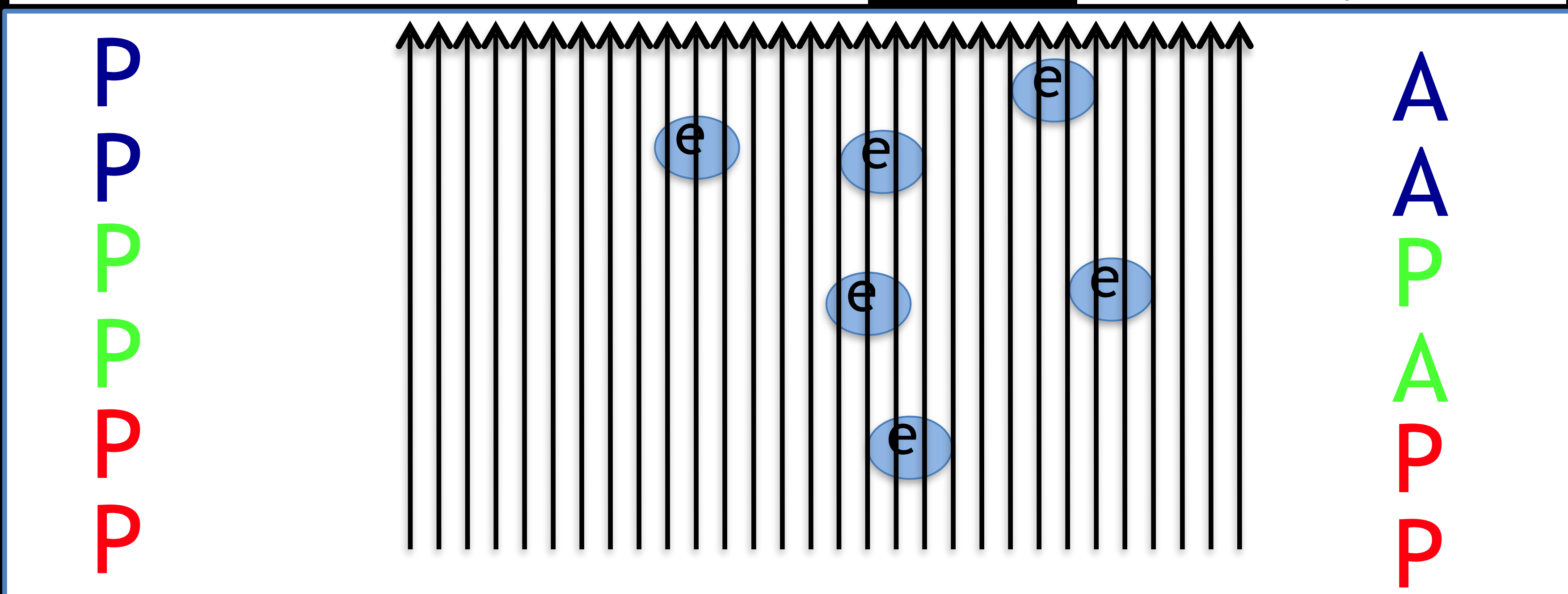



Milky Way
Voids
Axions
Clusters

Aspects of Spectral Distortions from Axions







Aspects of Spectral Distortions from Axions

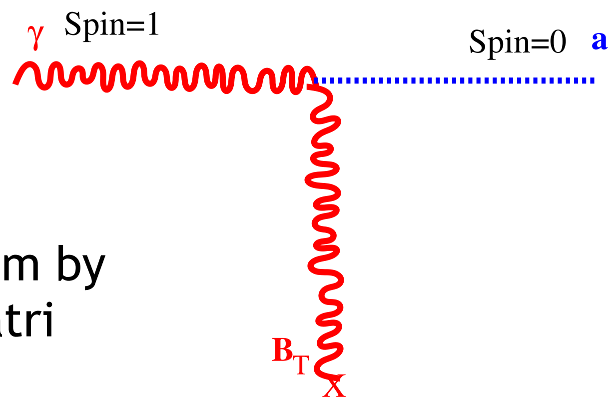
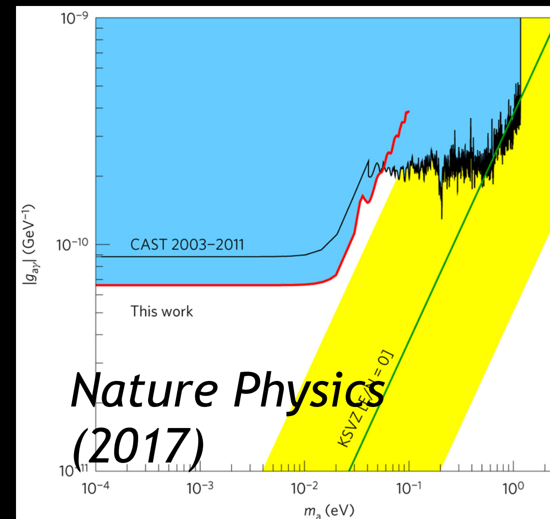
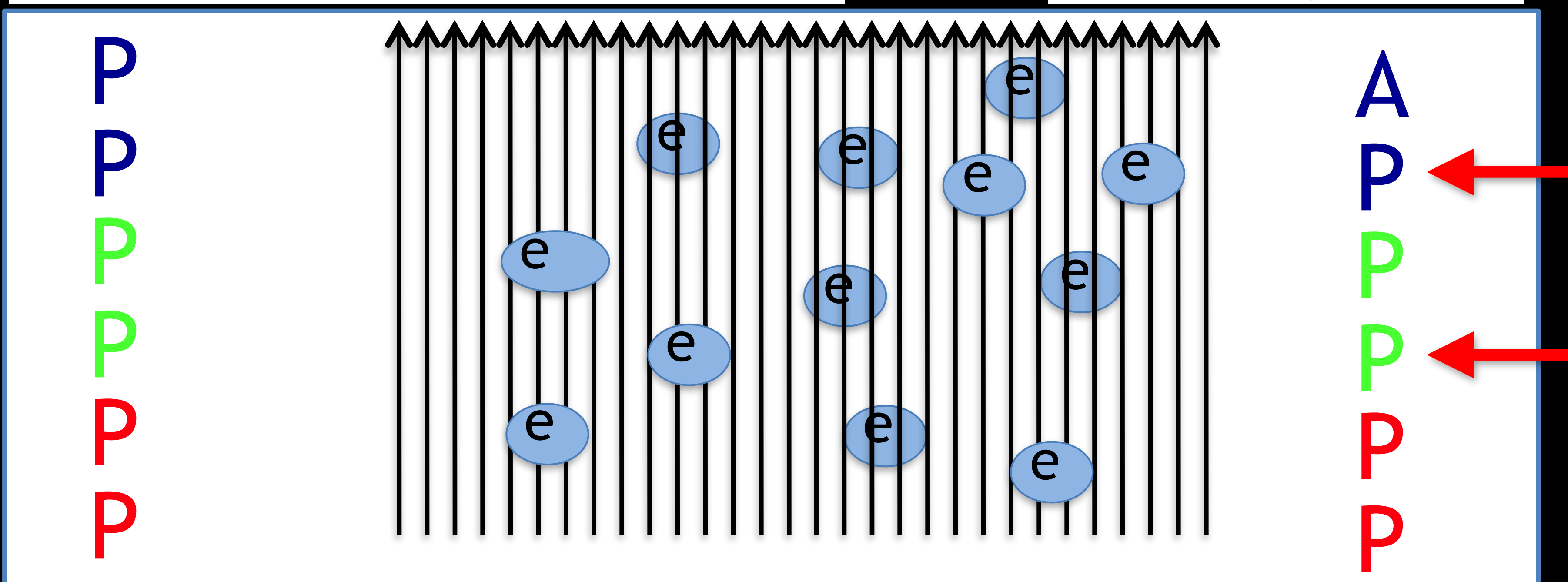
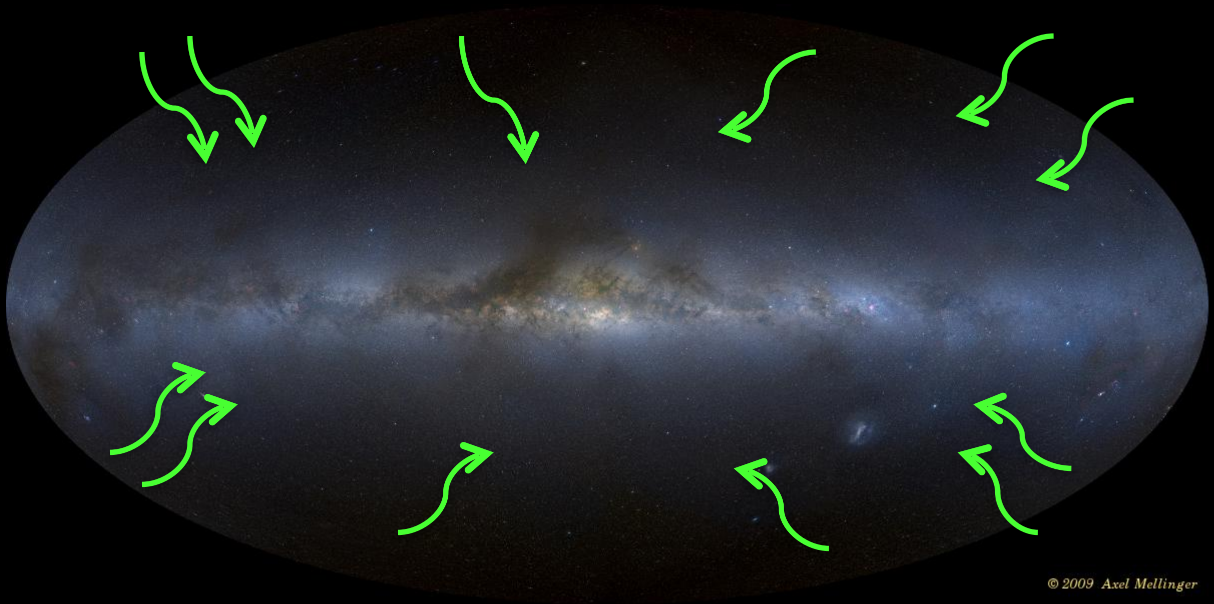


Diagram by
R. Khatri





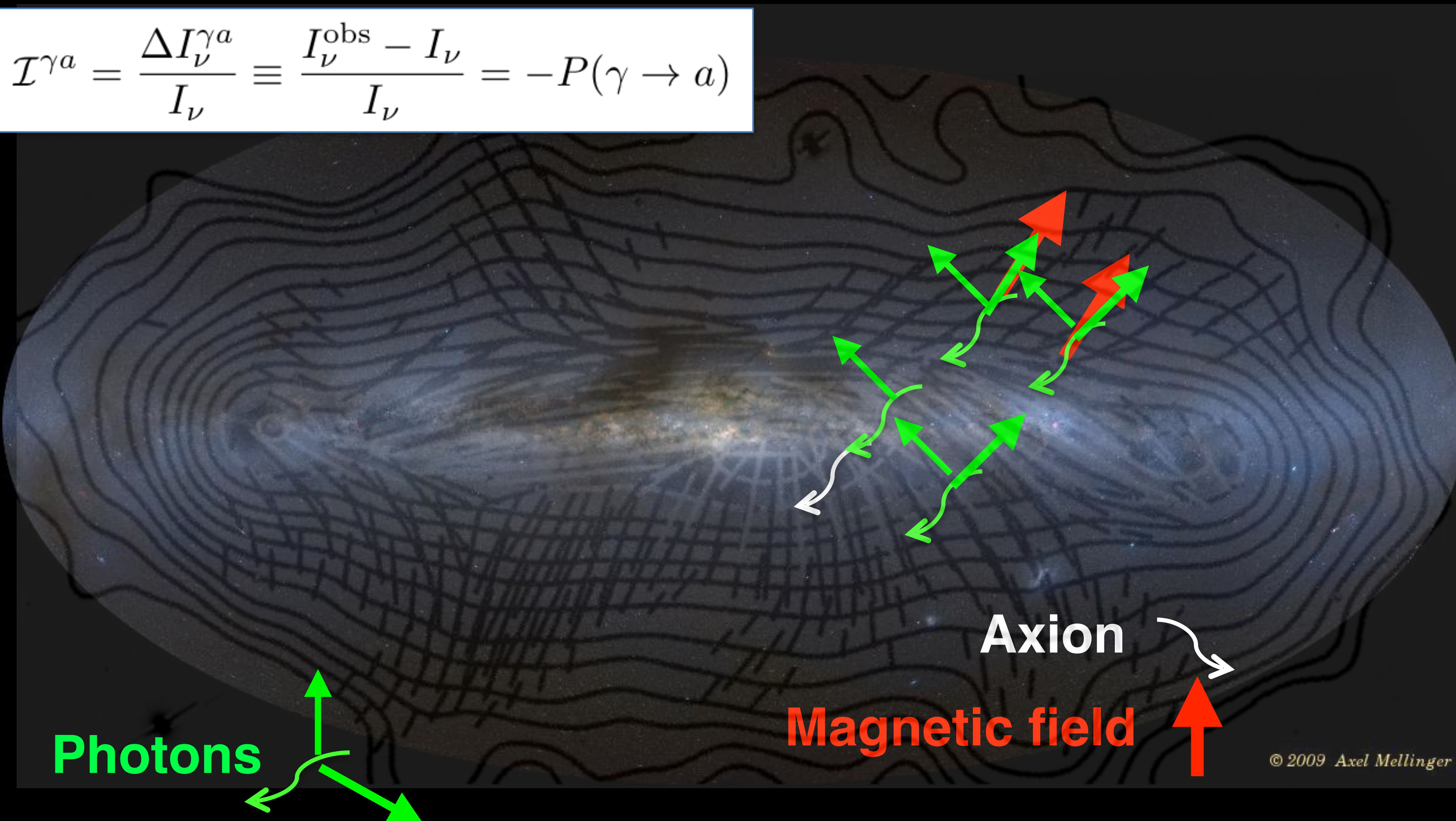
Milky Way scenario



Photons

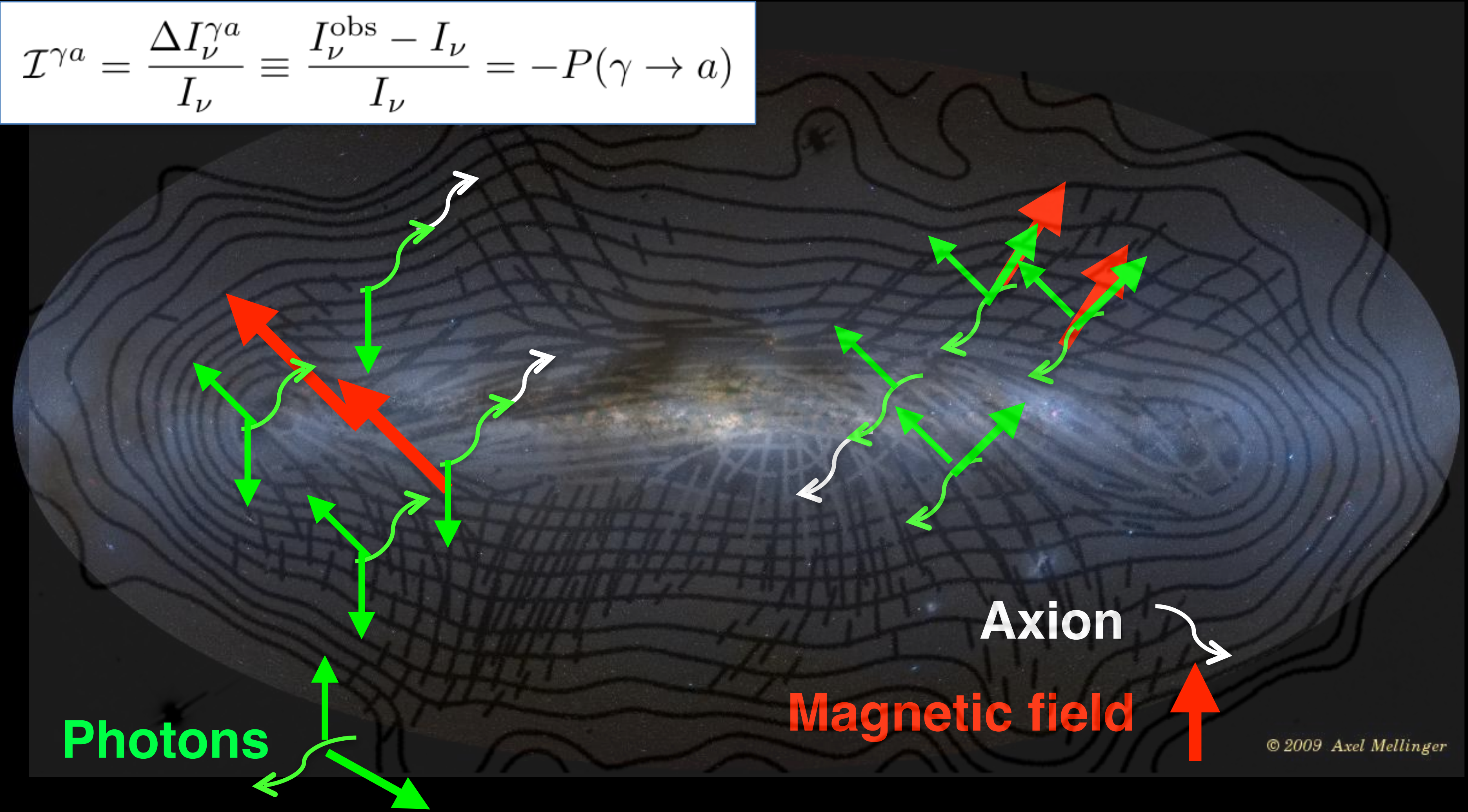
Photon to axion in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



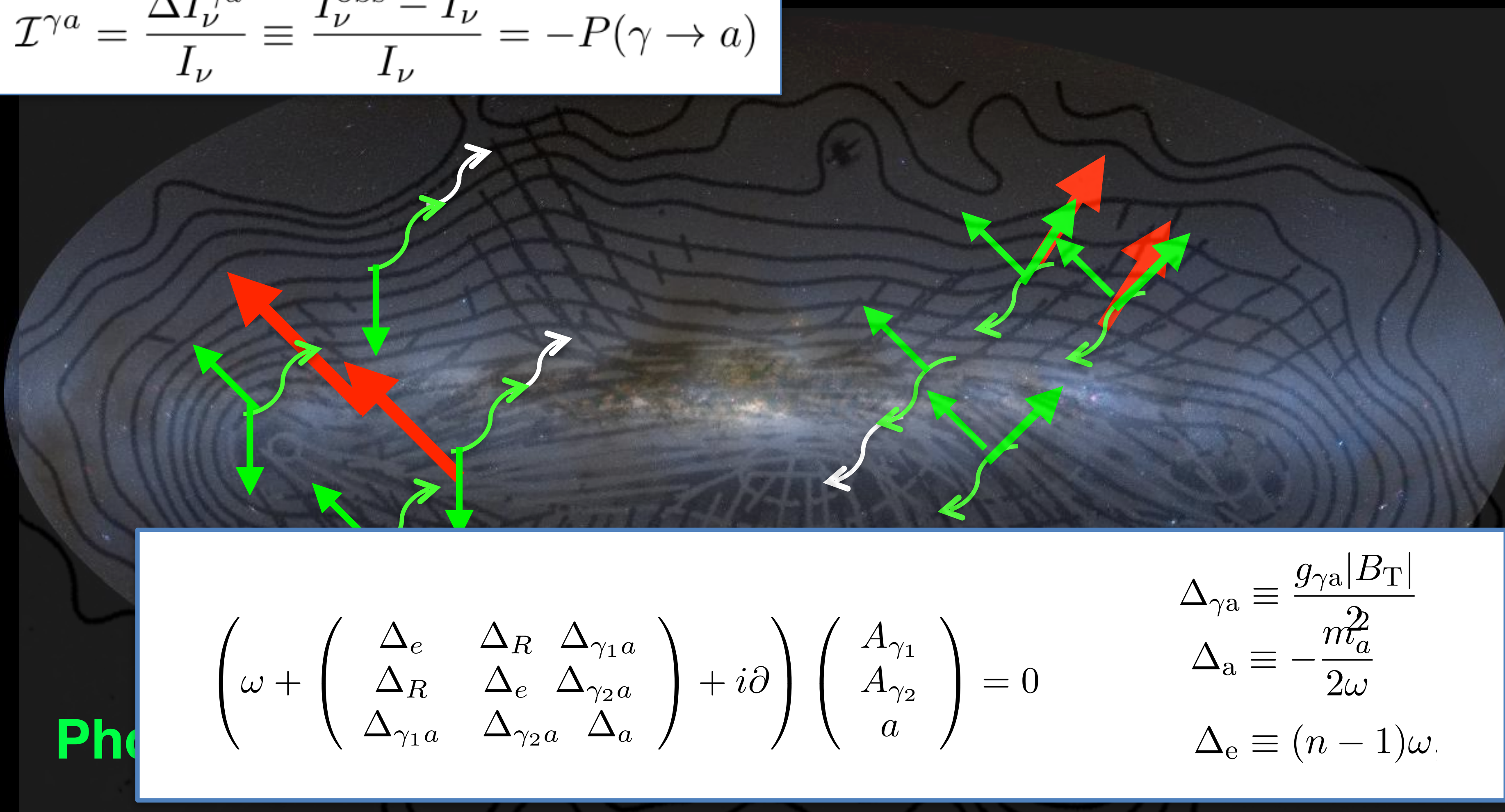
Photon to axion in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



Photon to axion in Milky Way

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$



$$\left(\omega + \begin{pmatrix} \Delta_e & \Delta_R & \Delta_{\gamma_1 a} \\ \Delta_R & \Delta_e & \Delta_{\gamma_2 a} \\ \Delta_{\gamma_1 a} & \Delta_{\gamma_2 a} & \Delta_a \end{pmatrix} + i\partial\right)\begin{pmatrix} A_{\gamma_1} \\ A_{\gamma_2} \\ a \end{pmatrix} = 0$$

$$\Delta_{\gamma \rm a} \equiv \frac{g_{\gamma \rm a}|B_{\rm T}|}{2}$$

$$\Delta_{\rm a} \equiv -\frac{m_a^2}{2\omega}$$

$$\Delta_{\rm e} \equiv (n-1)\omega$$

Two kinds of conversion

Resonance conversion

Happen at places where axion mass equals photon mass in the plasma

Non-Resonance conversion

Happens throughout the line of sight

MAGNETIC FIELD and
ELECTRON DENSITY
for milky way

Magnetic Field of MW

$$B^{\rm tor}(r,z) = e^{-|z|/z_0} L(z, h_{disk}, w_{disk}) \times \begin{cases} B_n(1 - L(r, r_n, w_h)) & z > 0, \\ B_s(1 - L(r, r_s, w_h)) & z < 0, \end{cases}$$

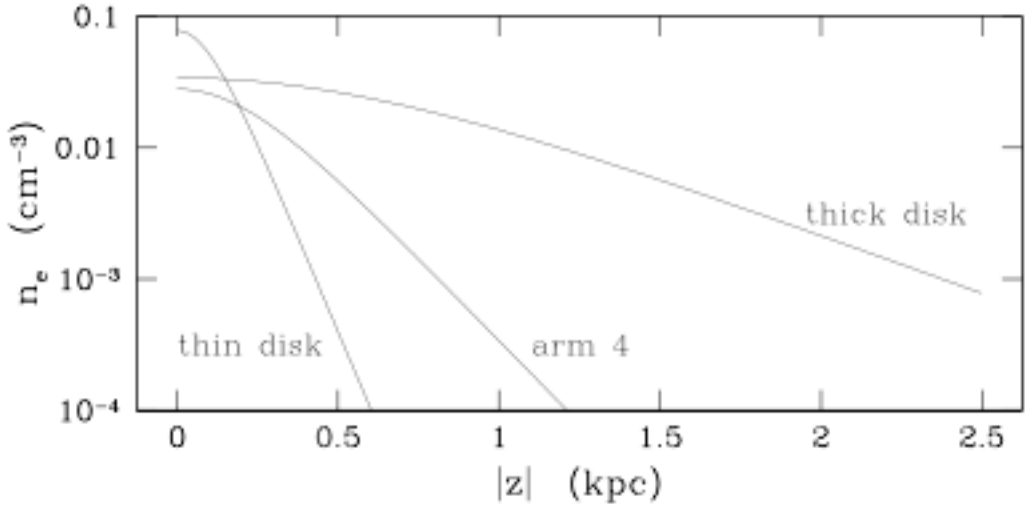
$$B^{\rm pol}(r,z) = B_X e^{-r_p/r_X} \times \begin{cases} \left(\frac{r_p}{r}\right), \text{with } r_p = r - |z|/\tan(\Theta^0_X) & r > r_X, \\ \left(\frac{r_p}{r}\right)^2, \text{with } r_p = \frac{r r^C_X}{r^c_X + |z|/\tan(\Theta^0_X)} & r < r_X \;\& \\ \Theta_X(r,z) = \tan^{-1}\left(\frac{|z|}{r - r_p}\right). \end{cases}$$

$$L(l,h,w) = \left(1 + e^{-2(|l|-h)/w}\right)^{-1}$$

Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\ \mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\ \mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\ \mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1°$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length

Jansson & Farrar
Astrophys.J. 757 (2012) 14

Electron Density Model of MW



J.M.Cordes & T.J.W.Lazio

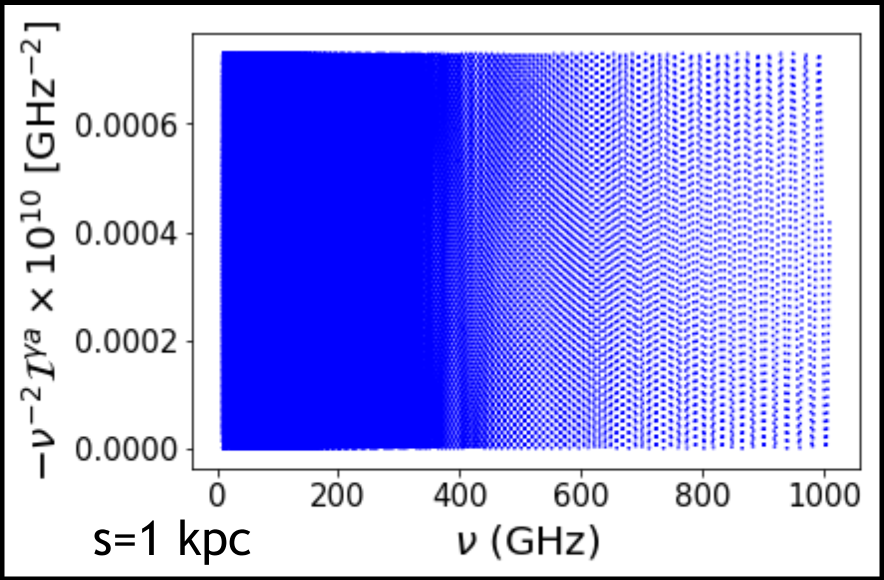
arXiv: astro-ph/0207156

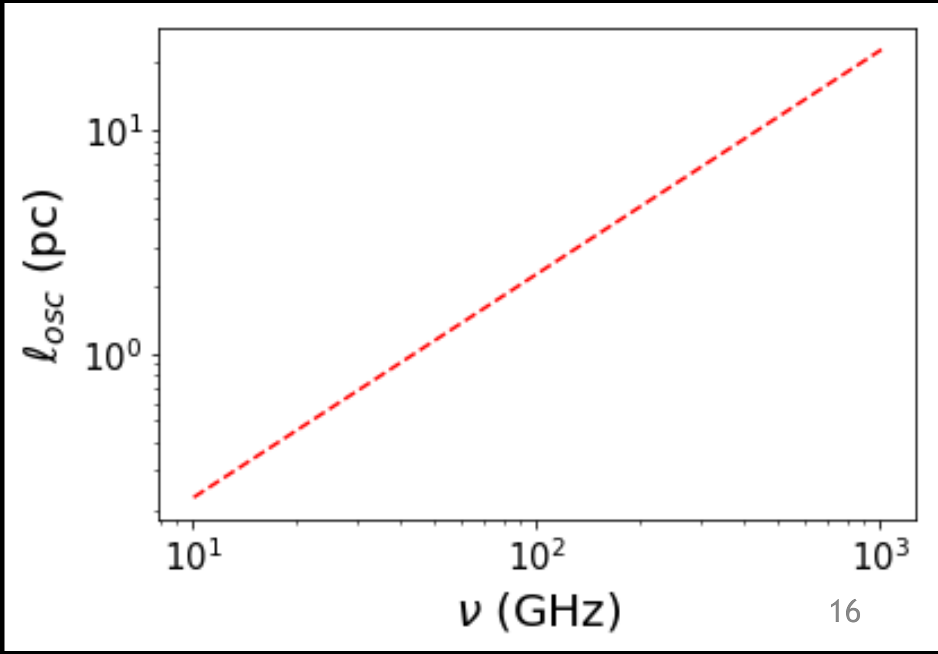
Gaensler et al. arXiv: 0808.2550[astro-ph]

$$n_e(r,l) = n_1\left[\frac{\cos(\pi r/2A_1)}{\cos(\pi R_\odot/2A_1)}\right]\mathrm{sech}^2(|l|/H)U(r-A_1),$$

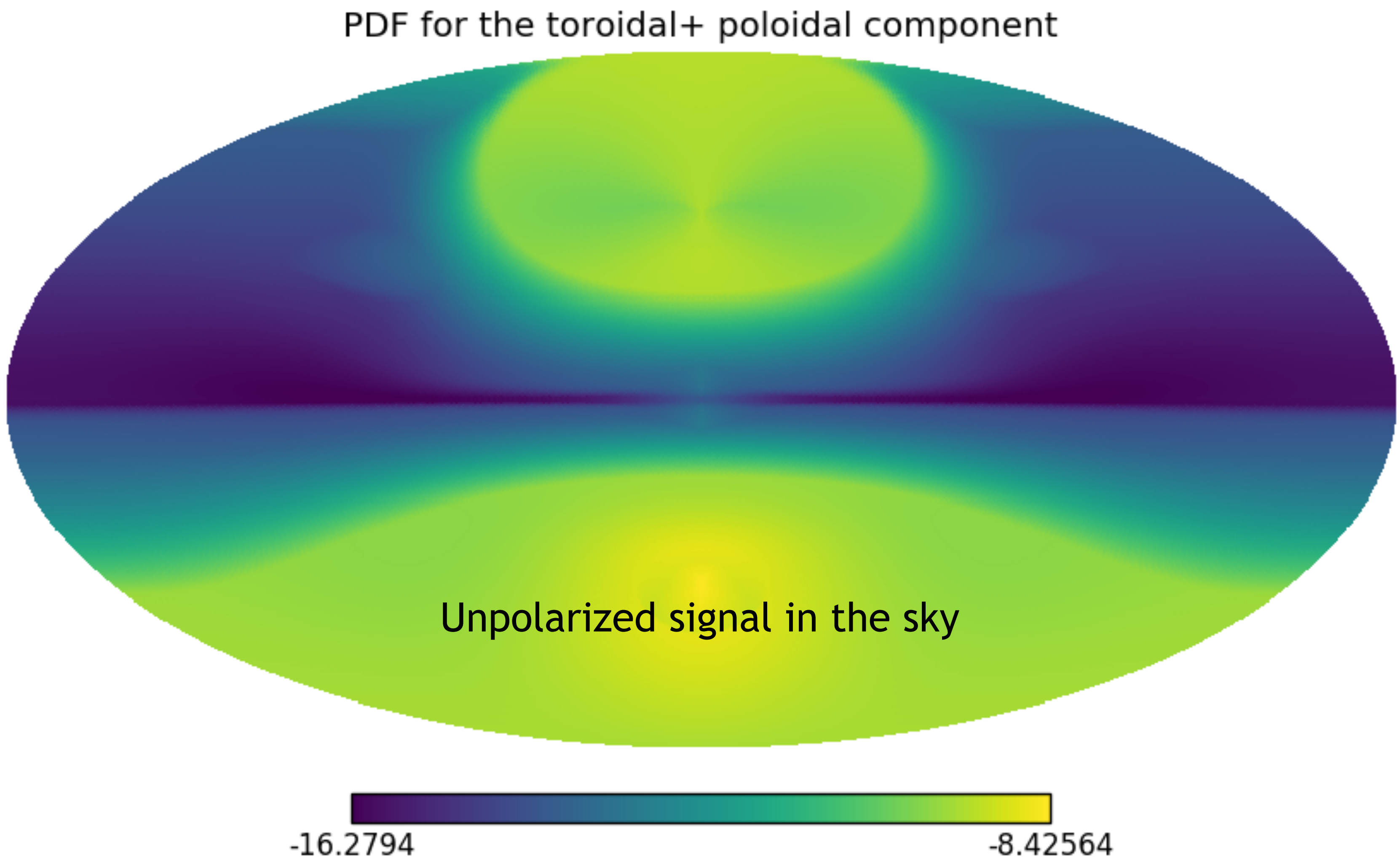
Low density regions have higher probability of conversion.
So high altitudes are preferred!

$$\mathcal{I}^{\gamma a} = \frac{\Delta I_\nu^{\gamma a}}{I_\nu} \equiv \frac{I_\nu^{\rm obs} - I_\nu}{I_\nu} = -P(\gamma \to a)$$





Non-Resonant conversion for homogeneous limit: Only an upper Bound



Non-Resonant conversion

Magnetic field and electron density are not homogeneous

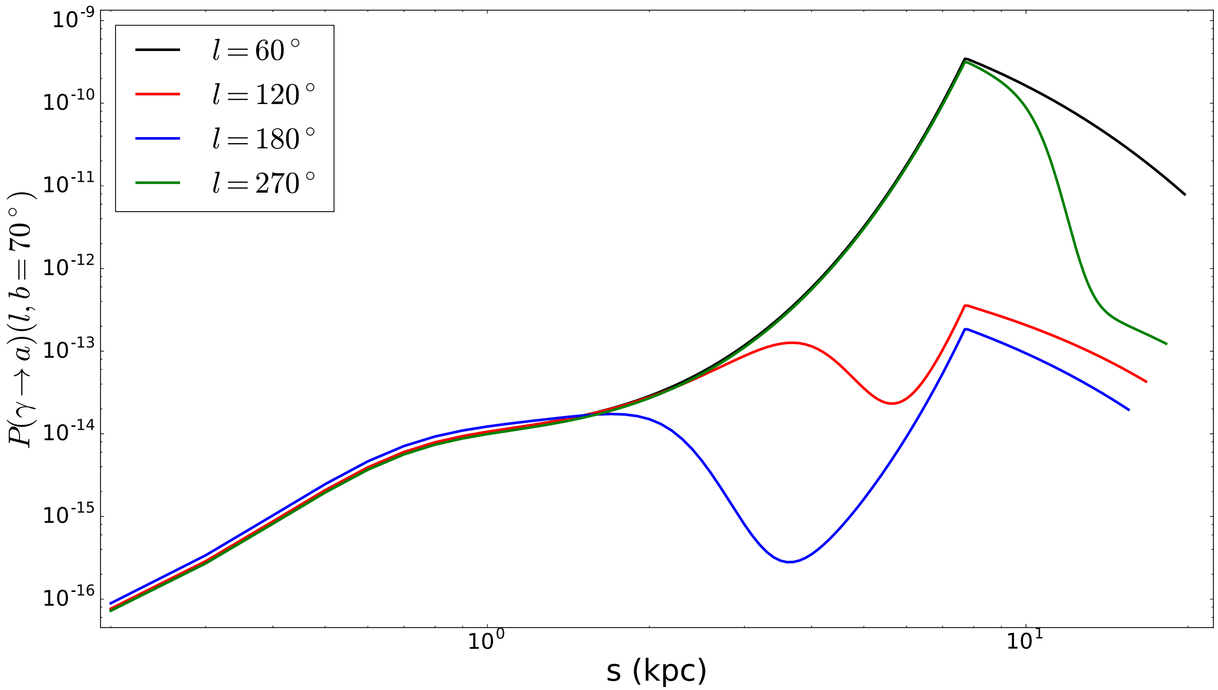
$$\left(\omega + \begin{pmatrix} \Delta_e & \Delta_R & \Delta_{\gamma_1 a} \\ \Delta_R & \Delta_e & \Delta_{\gamma_2 a} \\ \Delta_{\gamma_1 a} & \Delta_{\gamma_2 a} & \Delta_a \end{pmatrix} + i\partial\right) \begin{pmatrix} A_{\gamma_1} \\ A_{\gamma_2} \\ a \end{pmatrix} = 0$$

Non-Resonant conversion

Magnetic field and electron density are not homogeneous

$$\left(\omega + \begin{pmatrix} \Delta_e & \Delta_R & \Delta_{\gamma_1 a} \\ \Delta_R & \Delta_e & \Delta_{\gamma_2 a} \\ \Delta_{\gamma_1 a} & \Delta_{\gamma_2 a} & \Delta_a \end{pmatrix} + i\partial\right) \begin{pmatrix} A_{\gamma_1} \\ A_{\gamma_2} \\ a \end{pmatrix} = 0$$

Weak Signal in the galaxy due to the inhomogeneous part



inhomogeneous limit

$$\bar{P}(\gamma \to a)(r) = \frac{1}{3}\left(1 - e^{(-3P(\gamma\to a)r/2d_0)}\right) \qquad r >> d_0$$

$$\begin{aligned}\gamma_{\rm ad} &= \left|\frac{\pi}{\ell_{\rm osc}\nabla\theta}\right| \\ &= \left|\frac{\Delta_{\rm osc}}{\sin(2\theta)\cos(2\theta)\nabla(\ln\Delta_{\gamma \rm a}) + \sin(2\theta)\Delta_{\rm e}/\Delta_{\rm osc}\nabla(\ln\Delta_{\rm e})}\right|\end{aligned}$$

Adiabaticity parameter

$$\gamma_{\rm ad} \approx 2\left(\frac{n_{\rm e}}{10^{-5}\ {\rm cm}^{-3}}\right)^2\left(\frac{10^{-10}\ {\rm GeV}^{-1}}{g_{\gamma \rm a}}\right)\left(\frac{1\ \mu{\rm G}}{B_T}\right)\left(\frac{10^4\ {\rm pc}^{-1}}{k_B}\right)$$

$$\begin{aligned}\bar{P}(\gamma \to a) &\approx \frac{P(\gamma\to {\rm a})R}{2s} \\ &\approx \frac{\Delta_{\gamma \rm a}^2 Rs}{2} = 10^{-9}\left(\frac{g_{\gamma \rm a}}{10^{-10}\ {\rm GeV}^{-1}}\right)^2\left(\frac{B_T}{1\ \mu{\rm G}}\right)^2\left(\frac{R}{1000{\rm pc}}\right)\left(\frac{s}{10^{-4}\ {\rm pc}}\right)\end{aligned}$$

Very Weak Signal

inhomogeneous limit

$$\bar{P}(\gamma \to a)(r) = \frac{1}{3}\left(1 - e^{(-3P(\gamma\to a)r/2d_0)}\right) \qquad r >> d_0$$

$$\begin{aligned}\gamma_{\rm ad} &= \left|\frac{\pi}{\ell_{\rm osc}\nabla\theta}\right| \\ &= \left|\frac{\Delta_{\rm osc}}{\sin(2\theta)\cos(2\theta)\nabla(\ln\Delta_{\gamma\rm a}) + \sin(2\theta)\Delta_{\rm e}/\Delta_{\rm osc}\nabla(\ln\Delta_{\rm e})}\right|\end{aligned}$$

Adiabaticity parameter

$$\gamma_{\rm ad} \approx 2\left(\frac{n_{\rm e}}{10^{-5}\ {\rm cm}^{-3}}\right)^2 \left(\frac{10^{-10}\ {\rm GeV}^{-1}}{g_{\gamma\rm a}}\right)\left(\frac{1\ \mu{\rm G}}{B_T}\right)\left(\frac{10^4\ {\rm pc}^{-1}}{k_B}\right)$$

$$\begin{aligned}\bar{P}(\gamma \to a) &\approx \frac{P(\gamma \to {\rm a})R}{2s} \\ &\approx \frac{\Delta_{\gamma\rm a}^2 Rs}{2} = 10^{-9}\left(\frac{g_{\gamma\rm a}}{10^{-10}\ {\rm GeV}^{-1}}\right)^2\left(\frac{B_T}{1\ \mu{\rm G}}\right)^2\left(\frac{R}{1000{\rm pc}}\right)\left(\frac{s}{10^{-4}\ {\rm pc}}\right)\end{aligned}$$

Very Weak Signal

Non-resonant effects are weak in galaxy!!

Resonant Conversion

$$\Delta_{\mathrm{e}} = \Delta_{\mathrm{a}}$$

$$\begin{aligned}\gamma_{\mathrm{ad}} &= \left|\frac{\pi}{\ell_{\mathrm{osc}}\nabla\theta}\right| \\ &= \left|\frac{\Delta_{\mathrm{osc}}}{\sin(2\theta)\cos(2\theta)\nabla(\ln\Delta_{\gamma\mathrm{a}}) + \sin(2\theta)\Delta_{\mathrm{e}}/\Delta_{\mathrm{osc}}\nabla(\ln\Delta_{\mathrm{e}})}\right|\end{aligned}$$

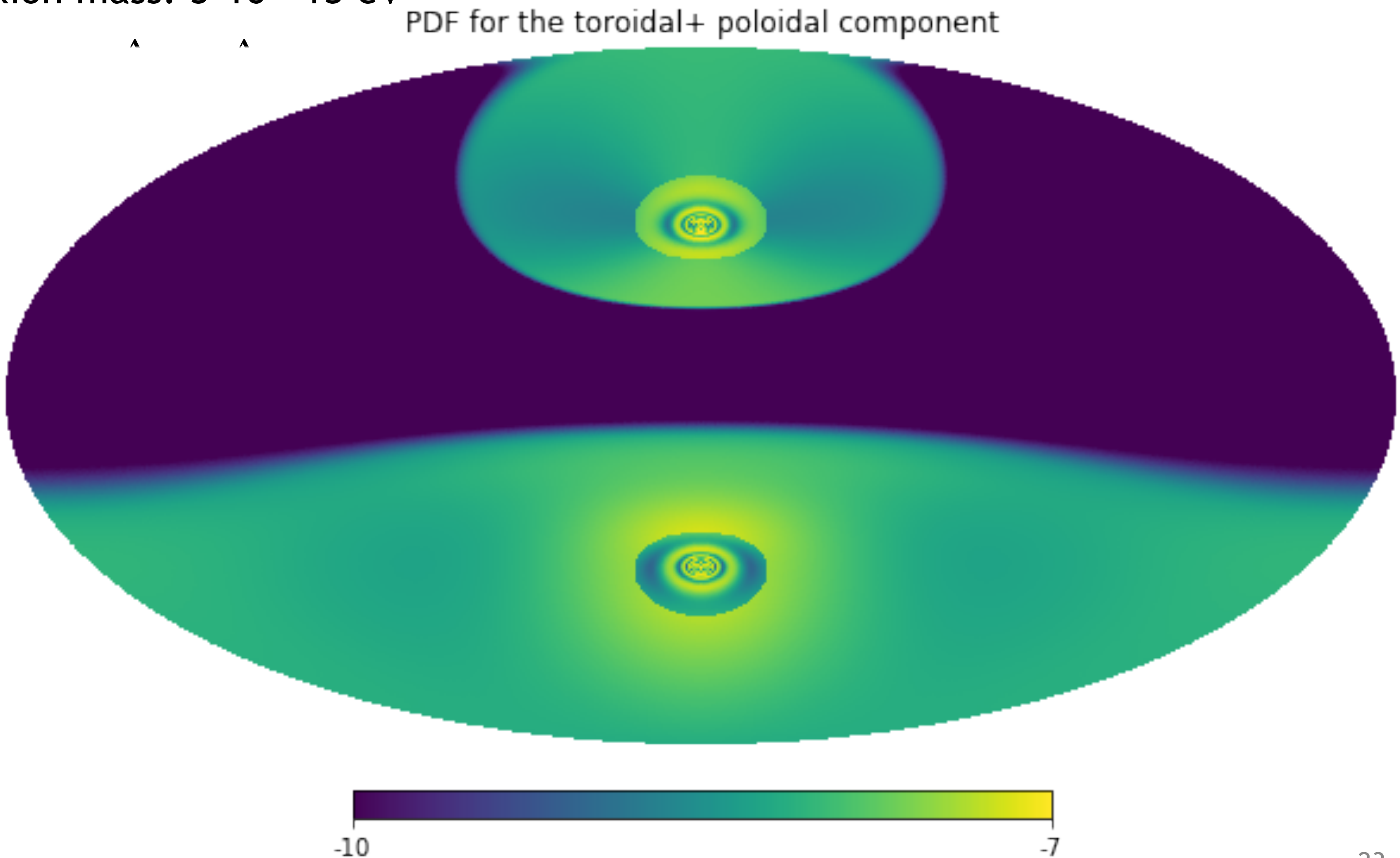
$$\gamma_{\mathrm{ad}}(\mathrm{resonance}) = \frac{4\Delta_{\gamma\mathrm{a}}^2}{|\nabla\Delta_{\mathrm{e}}|}.$$

$$P(\gamma \to a) = 1 - p \approx \frac{\pi\gamma_{\mathrm{ad}}}{2} \approx \frac{2\pi\Delta_{\gamma\mathrm{a}}^2}{|\nabla\Delta_{\mathrm{e}}|} \lesssim 10^{-4}$$

$$\Delta_{\gamma\mathrm{a}} \lesssim \left(\frac{10^{-4}\,|\nabla\Delta_{\mathrm{e}}|}{2\pi}\right)^{1/2},$$

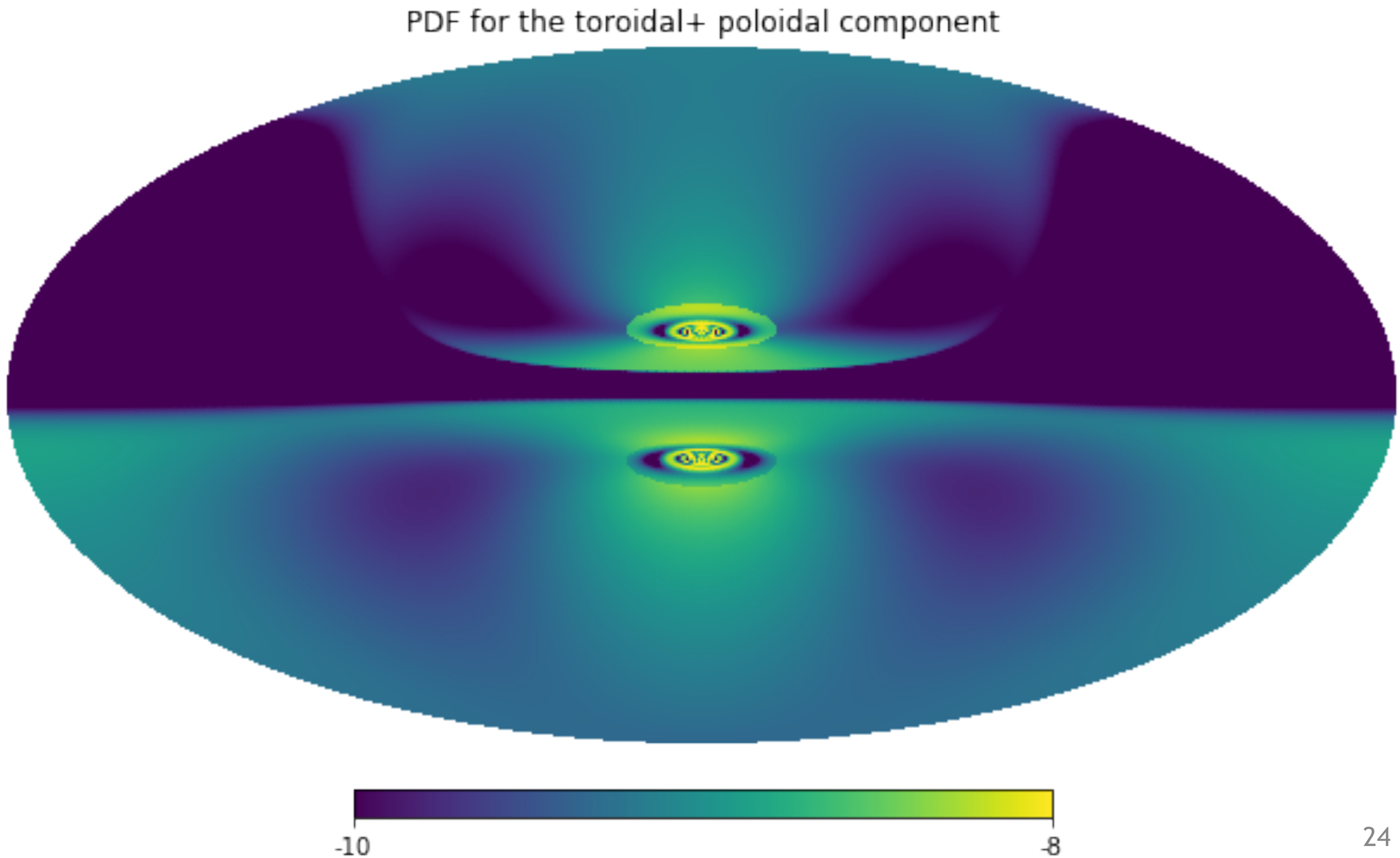
Resonant Conversion

axion mass: 5*10^-13 eV



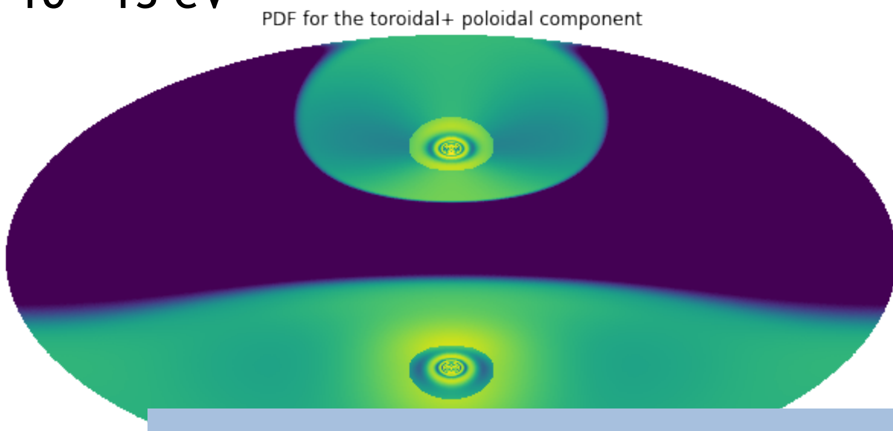
Resonant Conversion

axion mass: 5*10^-12 eV



Resonant Conversion

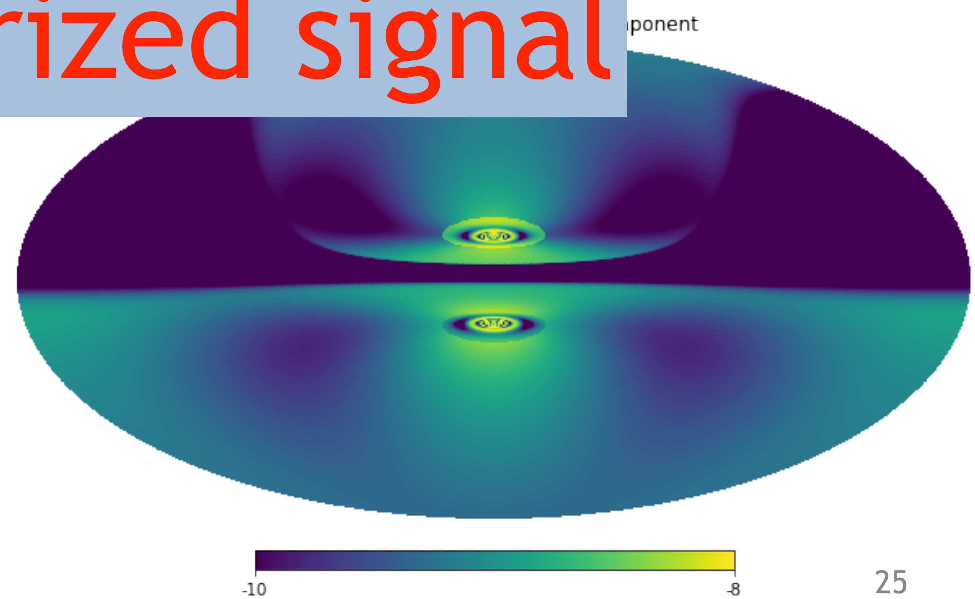
5*10^-13 eV



$\overline{\nabla(\ln \Delta_e)}\Big|$

5*10^-12 eV

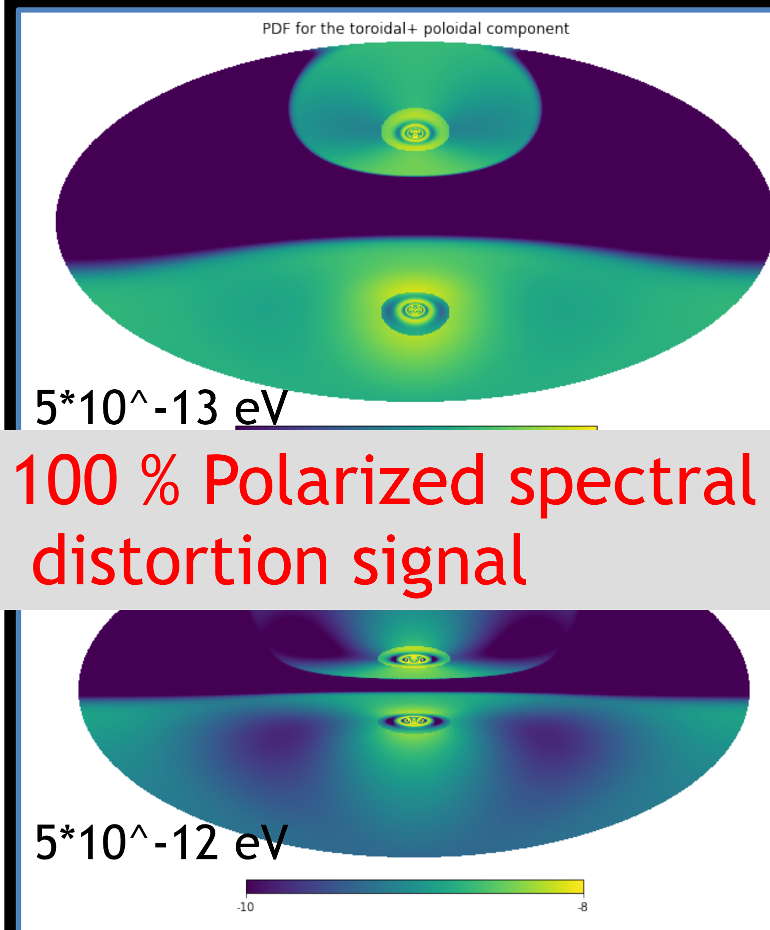
100 % Polarized signal



Do not need an absolute calibrator

Two kinds of conversion: Solving in the MW scenario

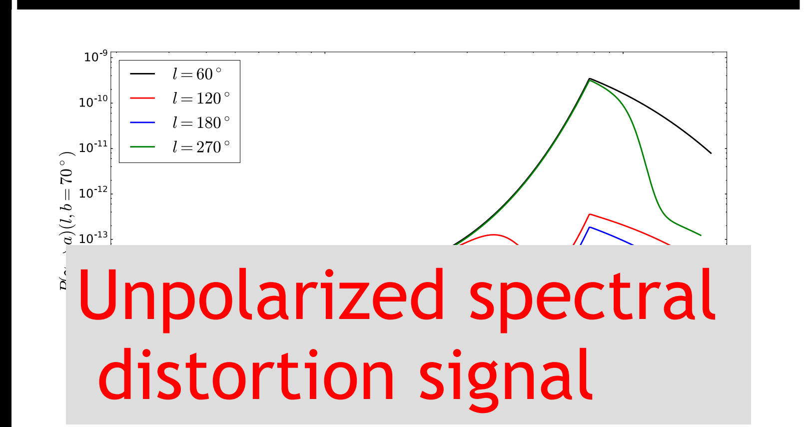
Resonance conversion



100 % Polarized spectral distortion signal

Non-Resonance conversion

Happens throughout the line of sight



Unpolarized spectral distortion signal

Non-Resonant conversion from voids

This is only an estimate.

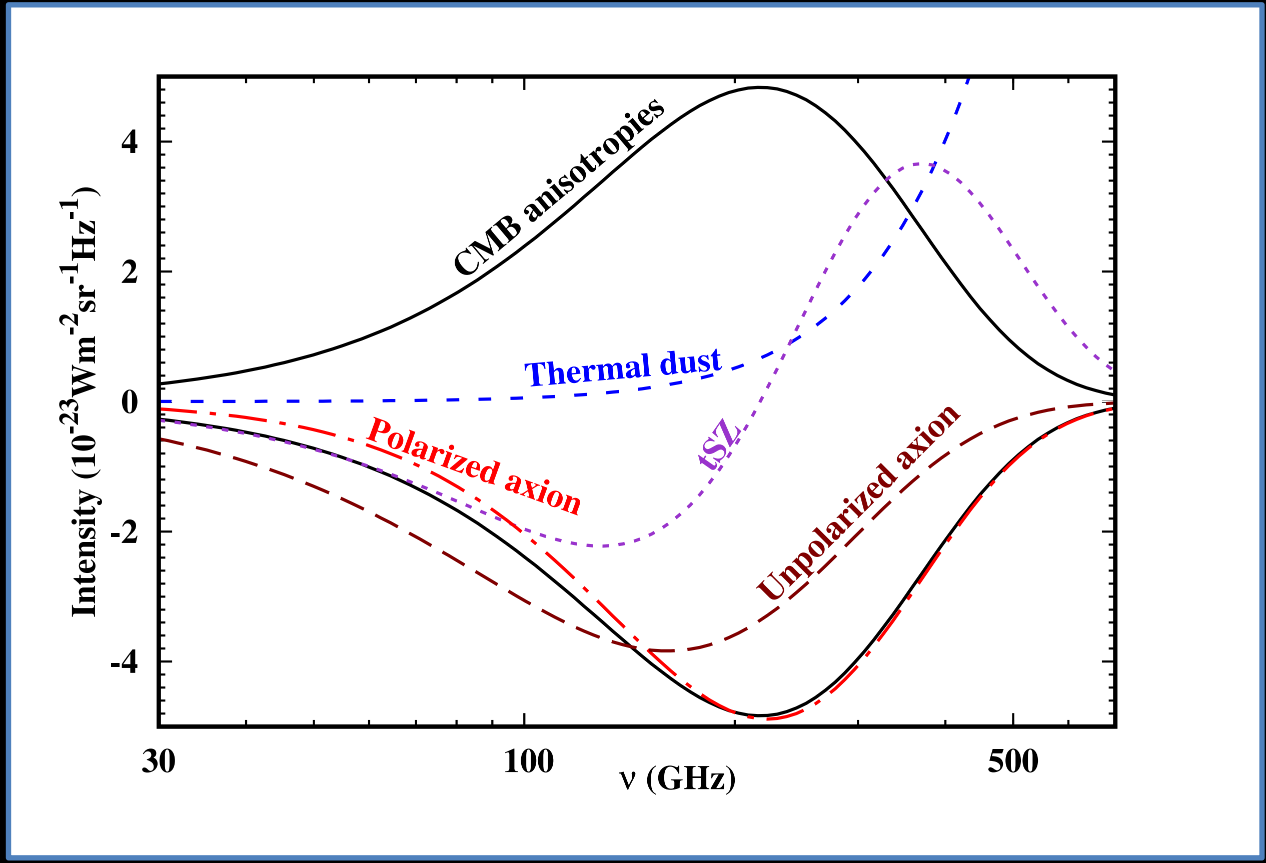
From magnetic field simulation in voids

$$\gamma_{\mathrm{ad}} \approx \left| \frac{\Delta_{\mathrm{osc}}}{\sin(2\theta)\,(k_B + k_e)} \right|$$
$$\approx 2 \left(\frac{n_{\mathrm{e}}}{10^{-9}\ \mathrm{cm}^{-3}} \right)^2 \left(\frac{10^{-10}\ \mathrm{GeV}^{-1}}{g_{\gamma \mathrm{a}}} \right) \left(\frac{1\ \mathrm{nG}}{B_T} \right) \left(\frac{0.1\ \mathrm{pc}^{-1}}{k_B} \right)$$

$$\bar{P}(\gamma \to a) \approx \frac{P(\gamma \to \mathrm{a}) R_{\mathrm{V}}}{2s}$$
$$\approx \frac{\Delta_{\gamma \mathrm{a}}^2 R_{\mathrm{V}} s}{2} = 10^{-4} \left(\frac{g_{\gamma \mathrm{a}}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 \left(\frac{B_T}{1\ \mathrm{nG}} \right)^2 \left(\frac{R_{\mathrm{V}}}{1\ \mathrm{Gpc}} \right) \left(\frac{s}{10\ \mathrm{pc}} \right)$$

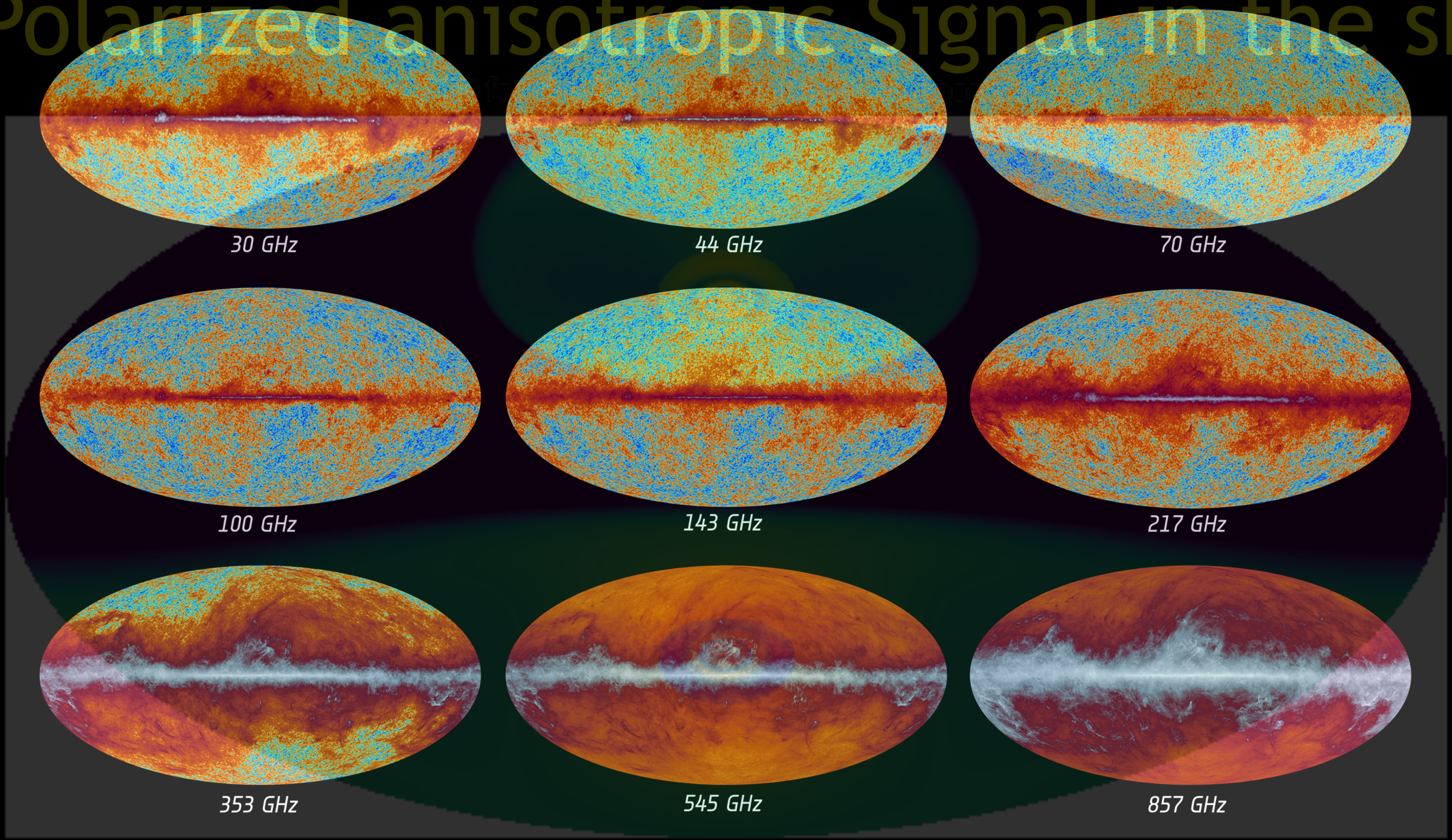
A unpolarized signal from voids are expected

Two new signals of spectral distortions



Mukherjee,
Khatri, Wandelt
(In Preparation)

Polarized anisotropic Signal in the sky



Contaminations

Several sources of contaminations

$$\Delta I_\nu = \Delta T_{\rm CMB} s_\nu^{\rm CMB} + A_{\gamma{\rm a}} s_\nu^{\gamma{\rm a}} + A_{\rm Dust} s_\nu^{\rm Dust} + y s_\nu^{\rm y},$$

$$s_\nu^{\rm CMB} = \frac{2k_{\rm B}\nu^2}{c^2}\frac{x^2 e^x}{(e^x-1)^2}, \qquad x = h\nu/(k_{\rm B}T_{\rm CMB}),\ T_{\rm CMB} = 2.7255\,{\rm K},$$

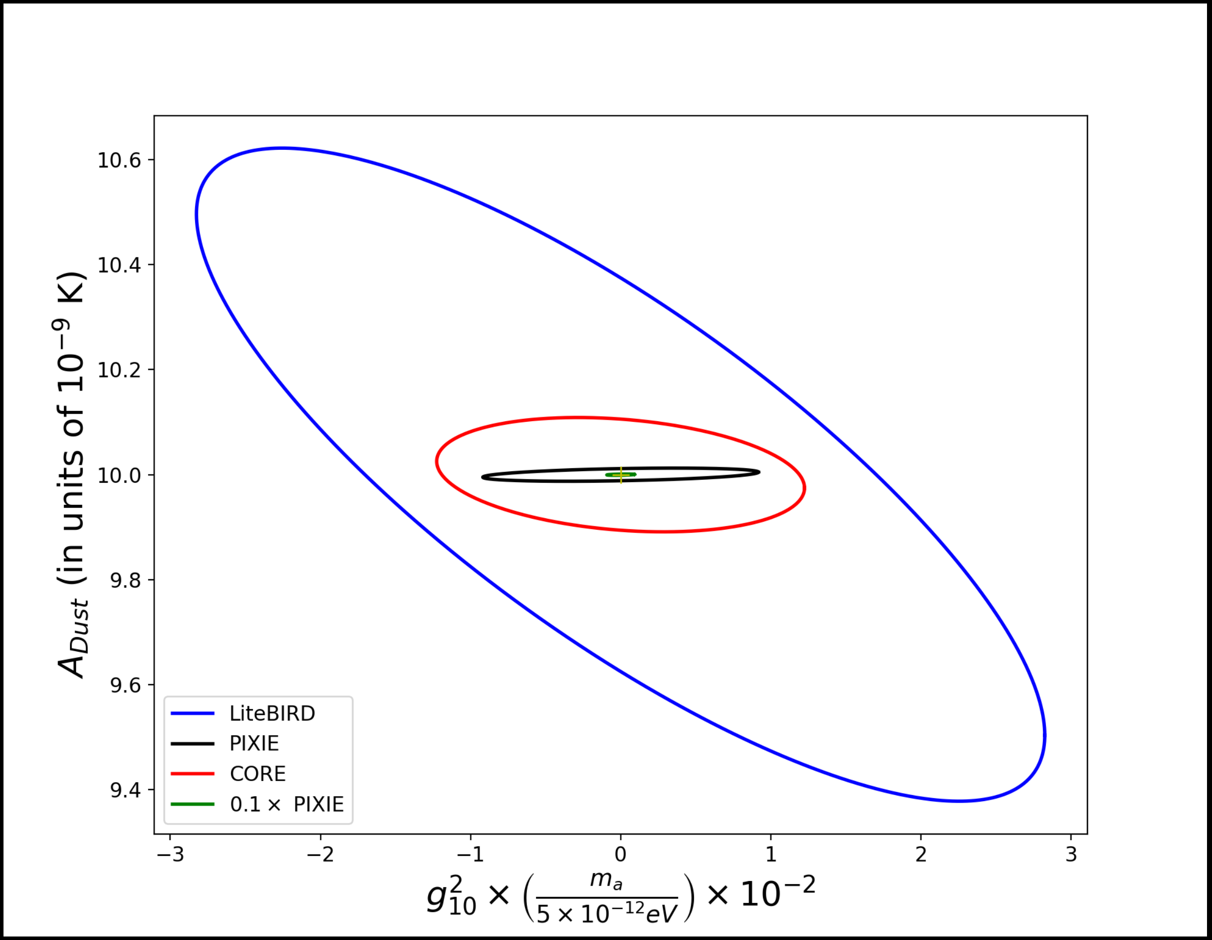
$$s_\nu^{\rm Dust} = \frac{2k_{\rm B}\nu^2}{c^2}\left(\frac{\nu}{\nu_0}\right)^{\beta_d+1}\left(\frac{e^{h\nu_0/(k_{\rm B}T_d)}-1}{e^{h\nu/(k_{\rm B}T_d)}-1}\right), \qquad T_d = 18{\rm K}, \nu_0 = 545{\rm GHz},$$

$$s_\nu^{\rm y} = \frac{2h\nu^3}{c^2}\left(\frac{xe^x}{(e^x-1)^2}\right)\left(\frac{x(e^x+1)}{e^x-1}-4\right),$$

$$s_\nu^{\gamma{\rm a}} = \frac{h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)\frac{\mathcal{I}^{\gamma{\rm a}}(\nu_0, m_{\rm a})}{(e^x-1)},$$

$$F_{ij} = \sum_{\alpha=1}^{n}\frac{\partial \Delta s(\nu_\alpha)}{\partial p_i}\frac{1}{(\Delta s_\nu^n)^2}\frac{\partial \Delta s(\nu_\alpha)}{\partial p_j};$$

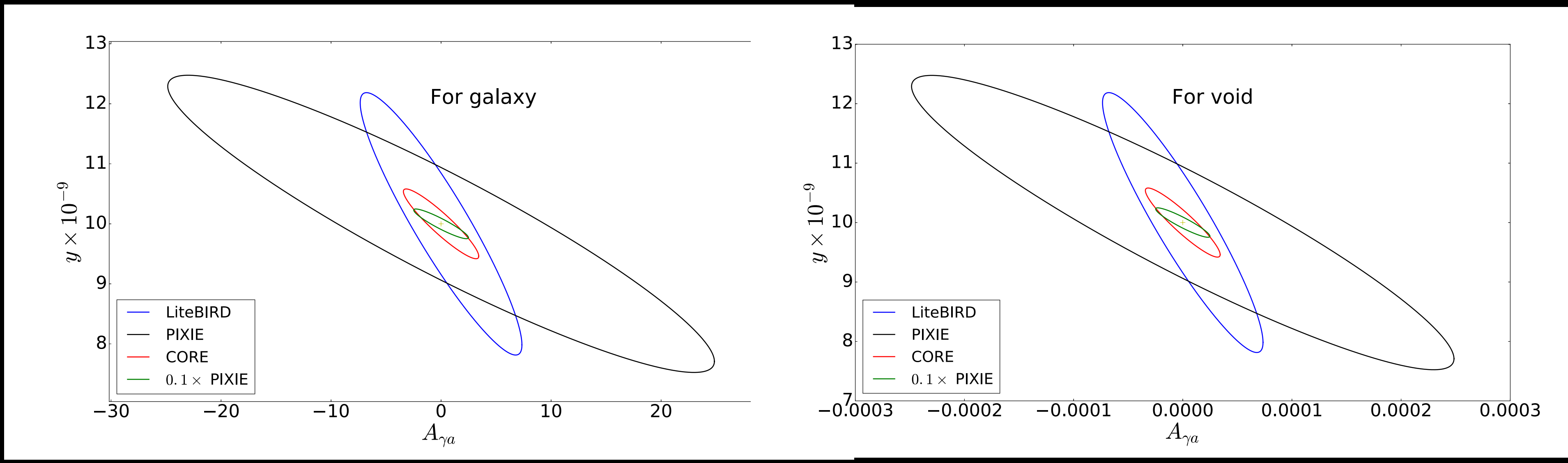
Resonant case



Non-Resonant case

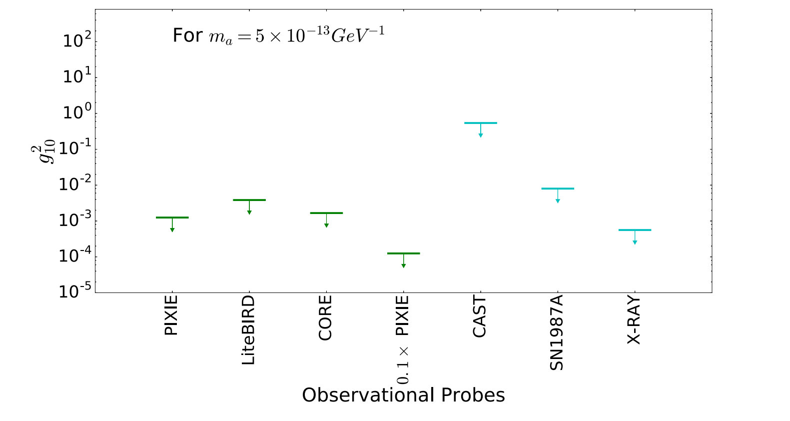
$$A_{\gamma \mathrm{a}} \equiv \left(\frac{g_{\gamma \mathrm{a}} B_T^{\mathrm{rms}}}{10^{-10}\ \mathrm{GeV}^{-1}\ \mathrm{nG}} \right)^2 \qquad : \text{voids},$$

$$A_{\gamma \mathrm{a}} \equiv \left(\frac{g_{\gamma \mathrm{a}} B_T^{\mathrm{rms}}}{10^{-10}\ \mathrm{GeV}^{-1}\ \mu\mathrm{G}} \right)^2 \qquad : \text{Galaxy},$$

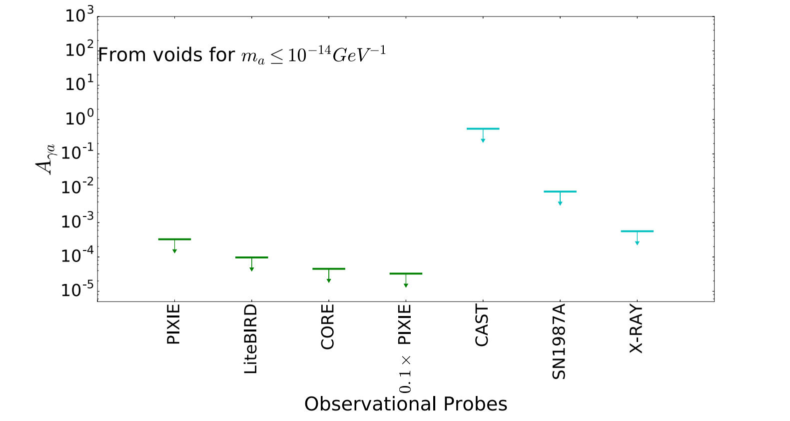


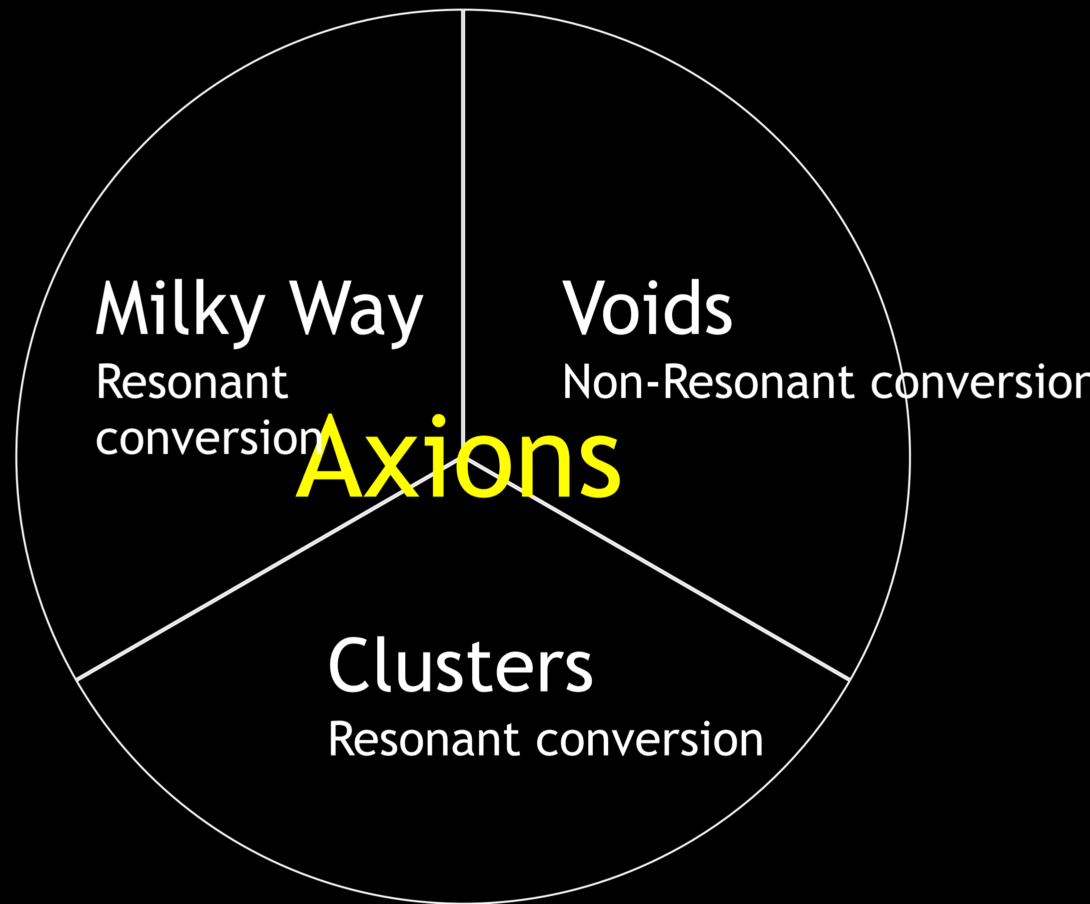
Forecast for future CMB mission for channels above 100 GHz

Resonance conversion

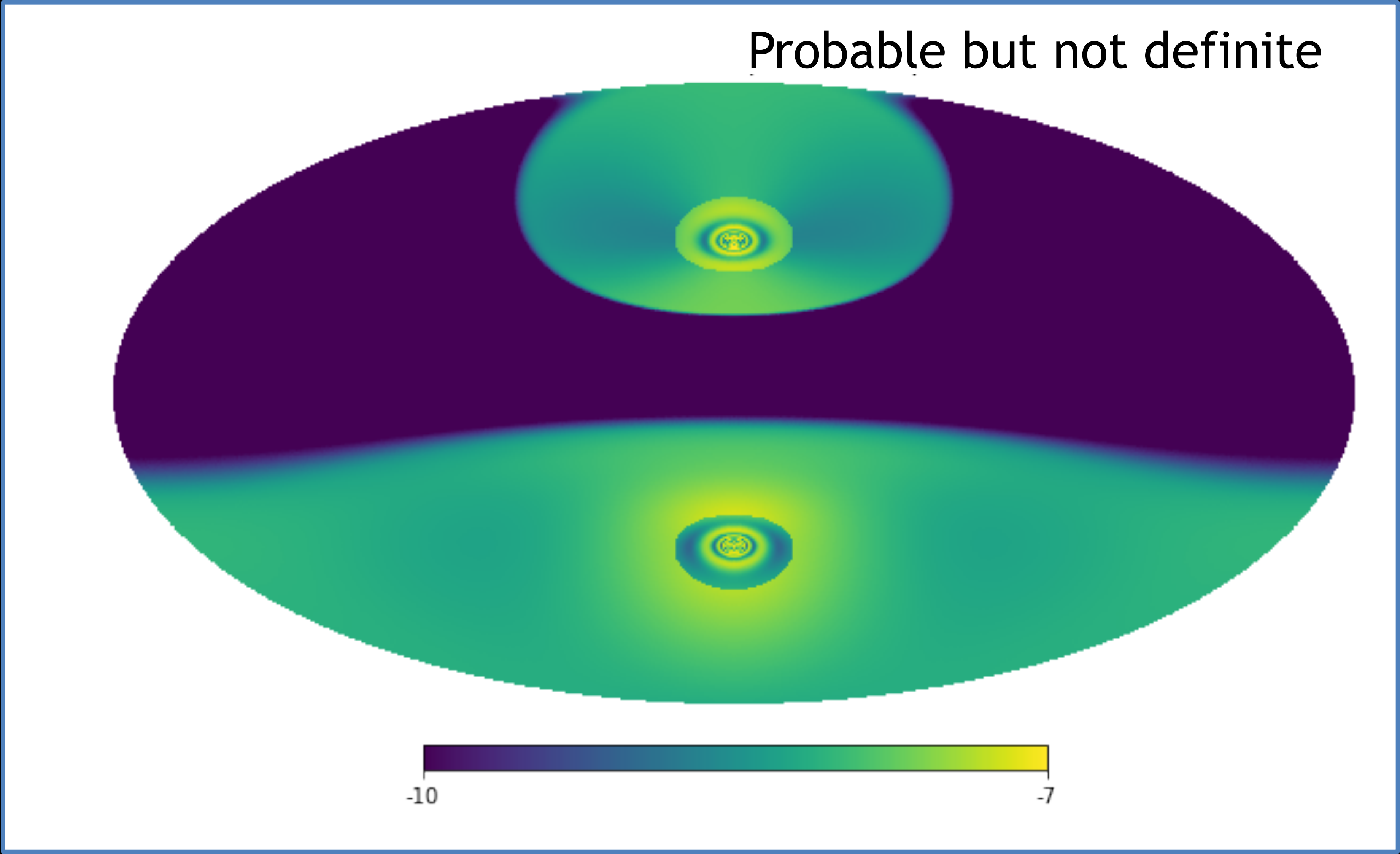


Non-Resonance conversion



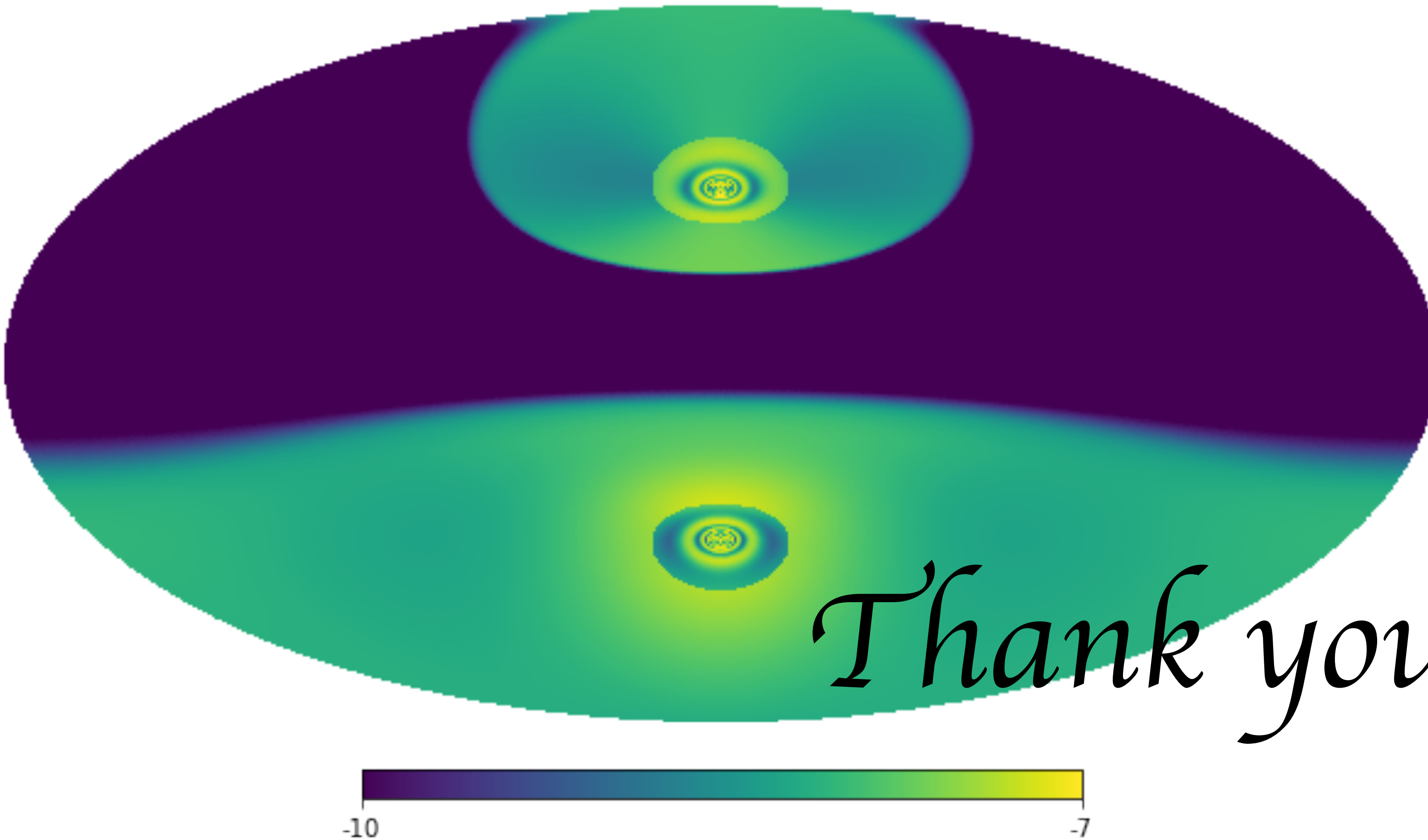

Milky Way
Resonant
conversion
Voids
Non-Resonant conversion
Axions
Clusters
Resonant conversion

Let's look for this



Let’s look for this

Probable but not definite



Thank you