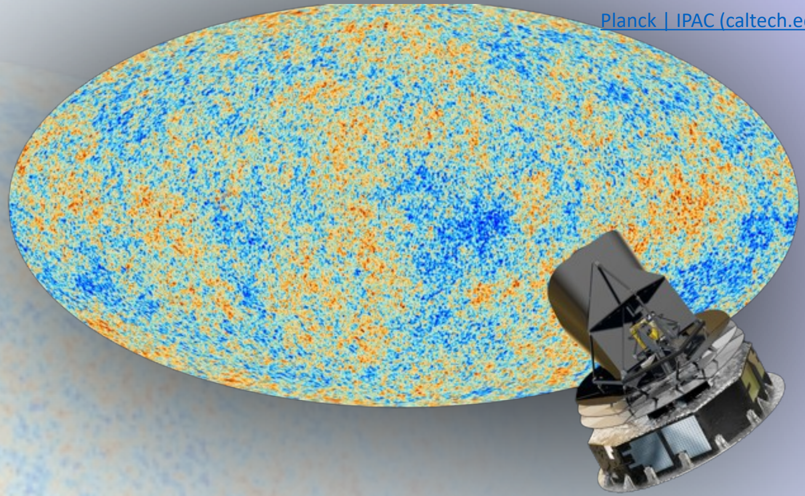
DISCOVERING AXION-LIKE PARTICLES USING CMB AS A BACKLIGHT

Harsh Mehta
Department of Astronomy & Astrophysics,
Tata Institute of Fundamental Research, Mumbai, India

22nd Lomonosov Conference on Elementary Particle Physics
Moscow State University, Moscow
26th August, 2025

Probing Axions using spatial anisotropic spectral distortion

[Planck | IPAC (caltech.edu)]

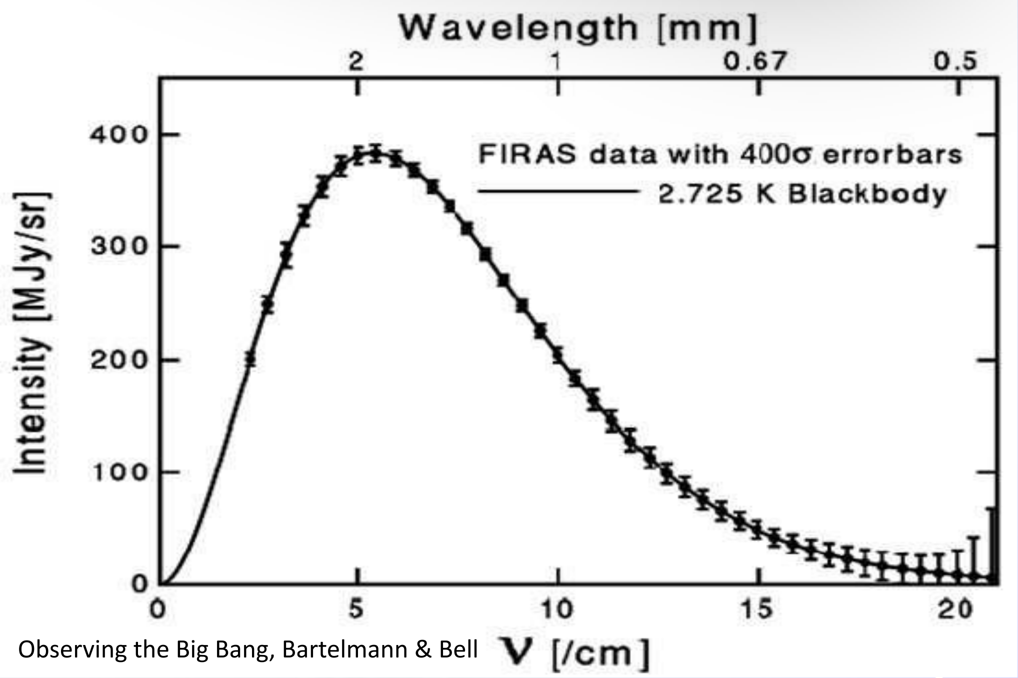


- ➢ ***Axions or ALPs are cold dark matter candidates.***

- ➢ ***They have a weak interaction with photons.***

- ➢ ***The CMB is almost an ideal blackbody with T_{cmb} = 2.7255 K and its power spectrum is well known.***

- ➢ ***Deviations resulting from weak photon coupling can be probed to detect ALPs.***



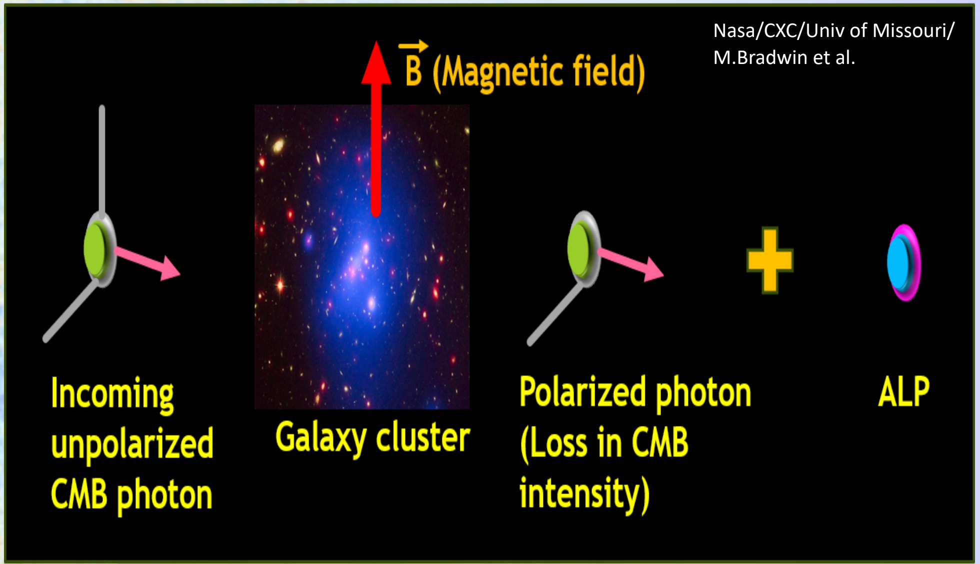
Observing the Big Bang, Bartelmann & Bell

CMB photon-ALP resonant conversion

➢ ***How it happens?***

ALP-photon interaction Lagrangian (where $g_{a\gamma}$ is the ALP coupling constant):

$$\mathcal{L}_{int} = -\frac{g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}}{4} = g_{a\gamma} E \,.\, B_{ext} a$$



➢ ***Where it happens?***

Resonant condition:

$$m_a = m_\gamma = \hbar\omega_p/c^2 = \frac{\hbar}{c^2}\sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

➢ ***How strong is it?***

The probability of conversion at a location in a galaxy cluster:

$$P(\gamma \to a) \approx \pi\gamma,$$

$$\gamma = \left| 2 g_{a\gamma}^2 B_t^2 \omega (1+z) / \nabla \omega_p^2 \right|$$

➢ ***Observable effect:***

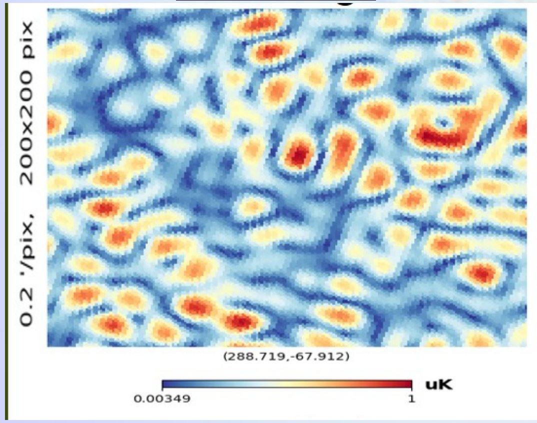
- ***Polarization of CMB photons***
- ***Change in CMB intensity:*** $\Delta I(\nu) = P(\gamma \to a) I_{cmb}(\nu)$

ALP resonant conversion in galaxy clusters

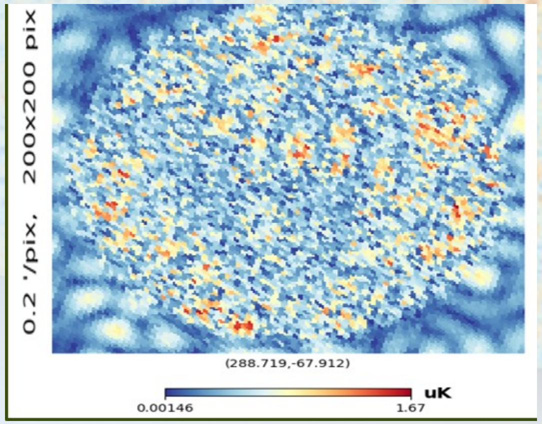
Resolved clusters
Visible at multiple EM frequencies

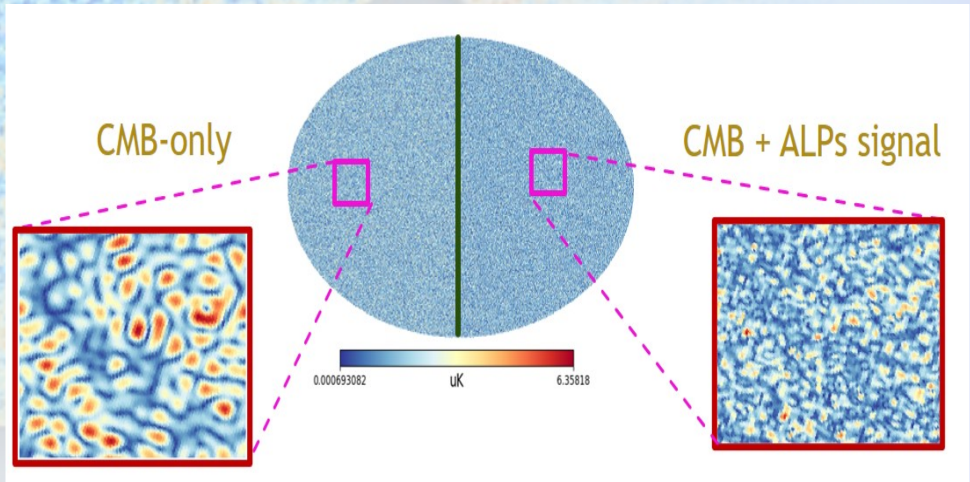
Unresolved clusters
Not visible at multiple EM frequencies

CMB only



CMB + ALP

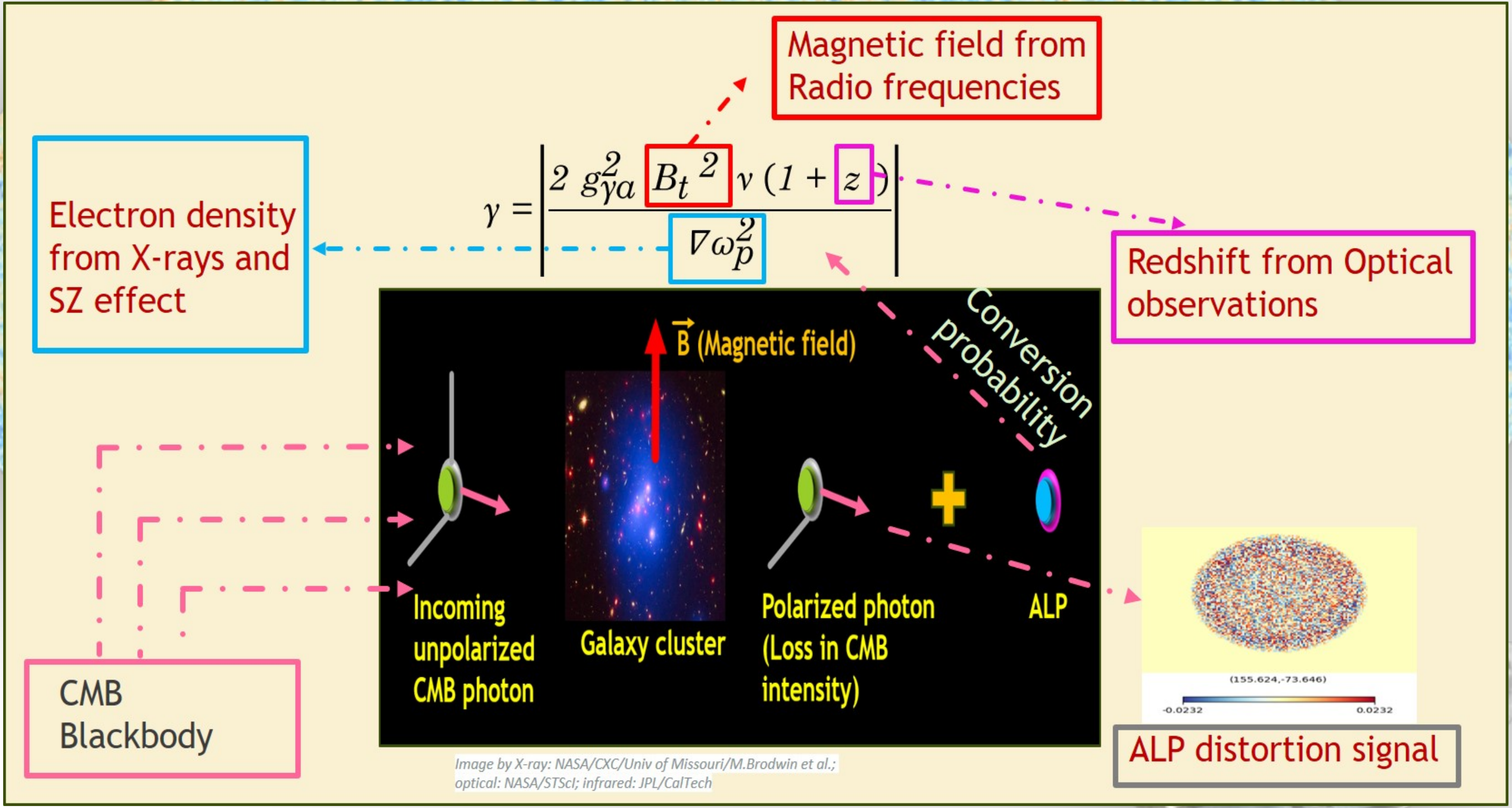




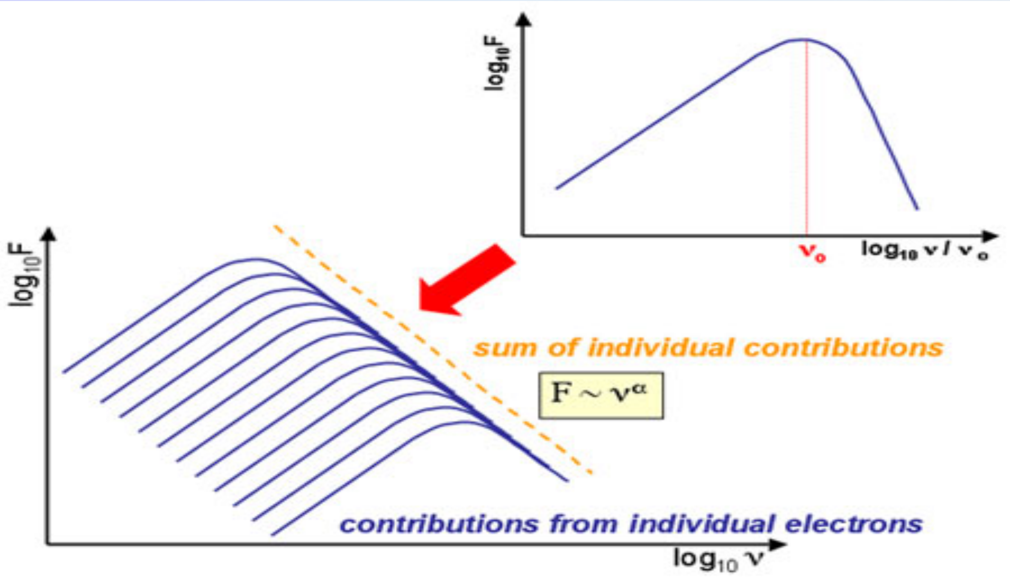
PROBING ALPS USING MULTI-BAND OBSERVATIONS OF RESOLVED CLUSTERS

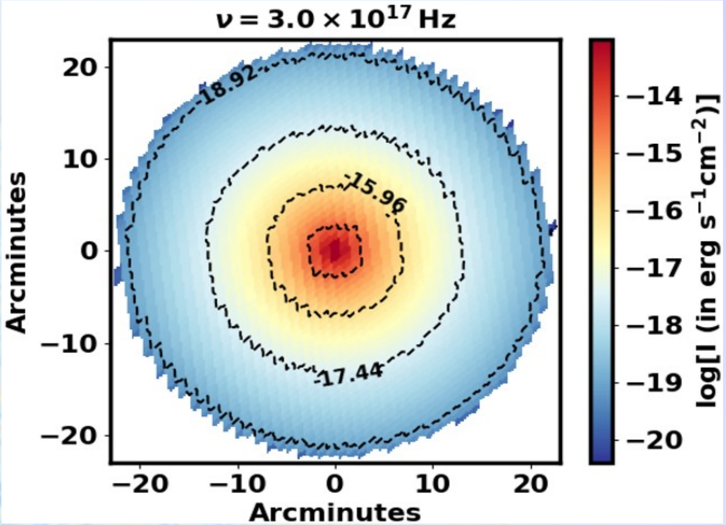
Planck | IPAC (caltech.edu)

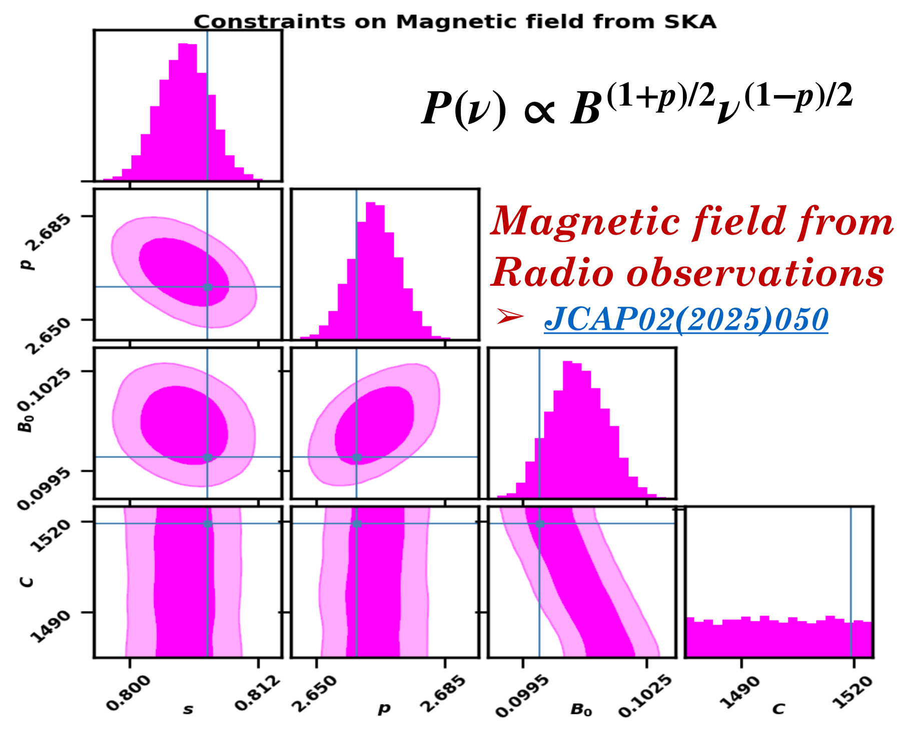
WHY MULTI-BAND OBSERVATIONS?



Nasa.gov



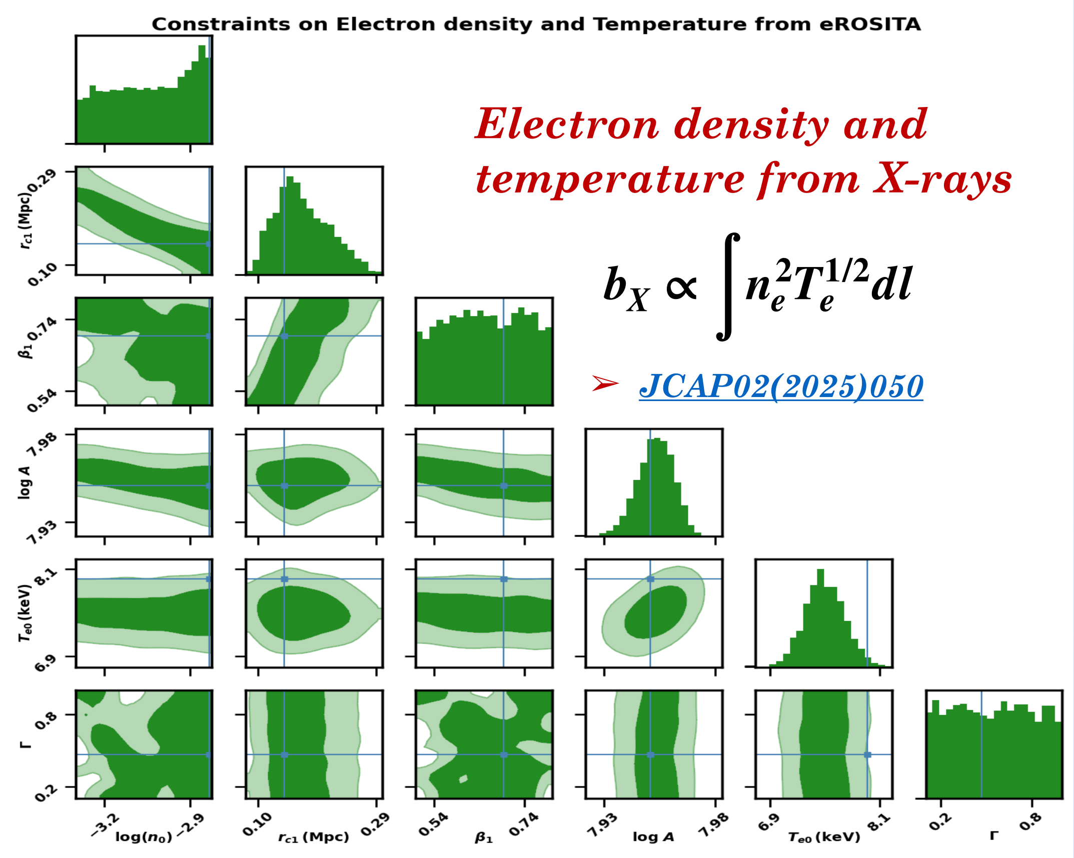




$$P(\nu) \propto B^{(1+p)/2}\nu^{(1-p)/2}$$

Magnetic field from Radio observations

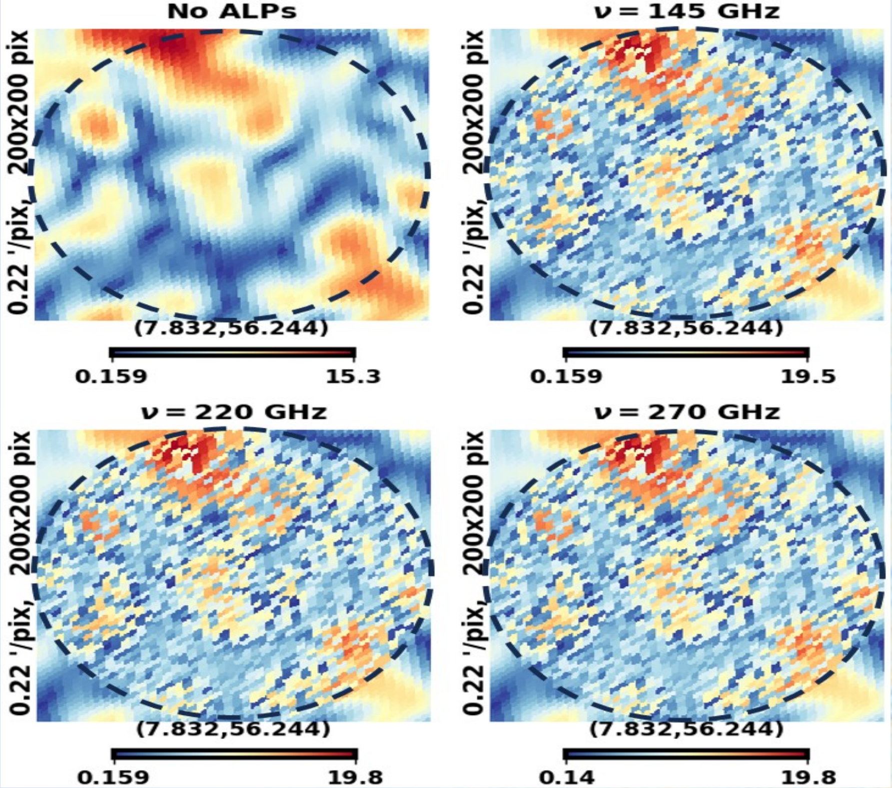
- [JCAP02(2025)050]



Electron density and temperature from X-rays

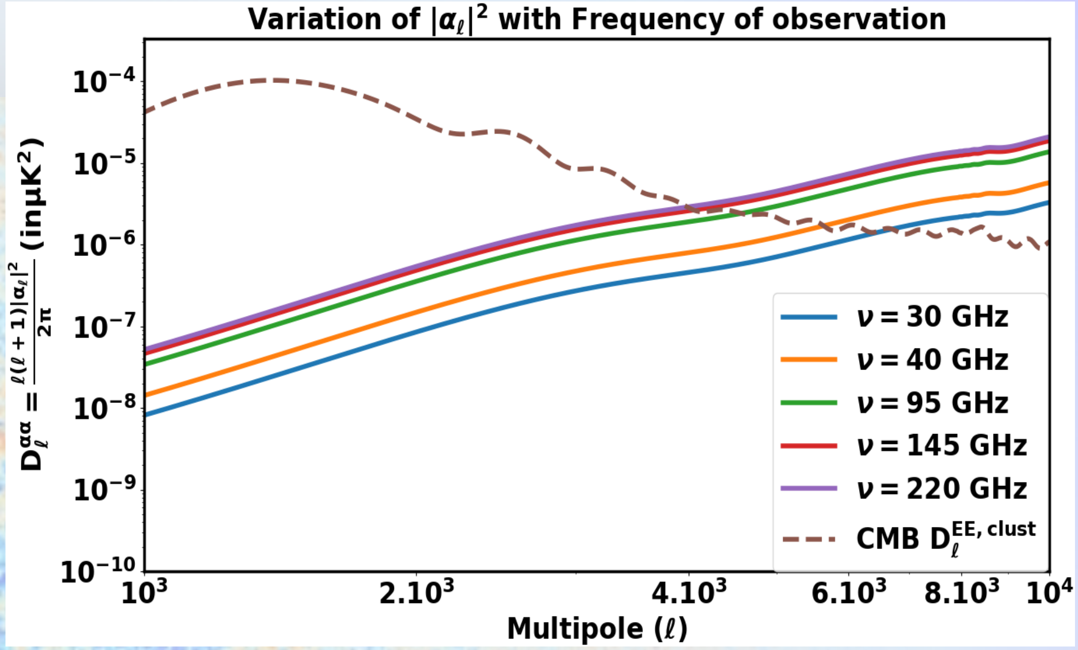
$$b_X \propto \int n_e^2 T_e^{1/2} dl$$

- [JCAP02(2025)050]

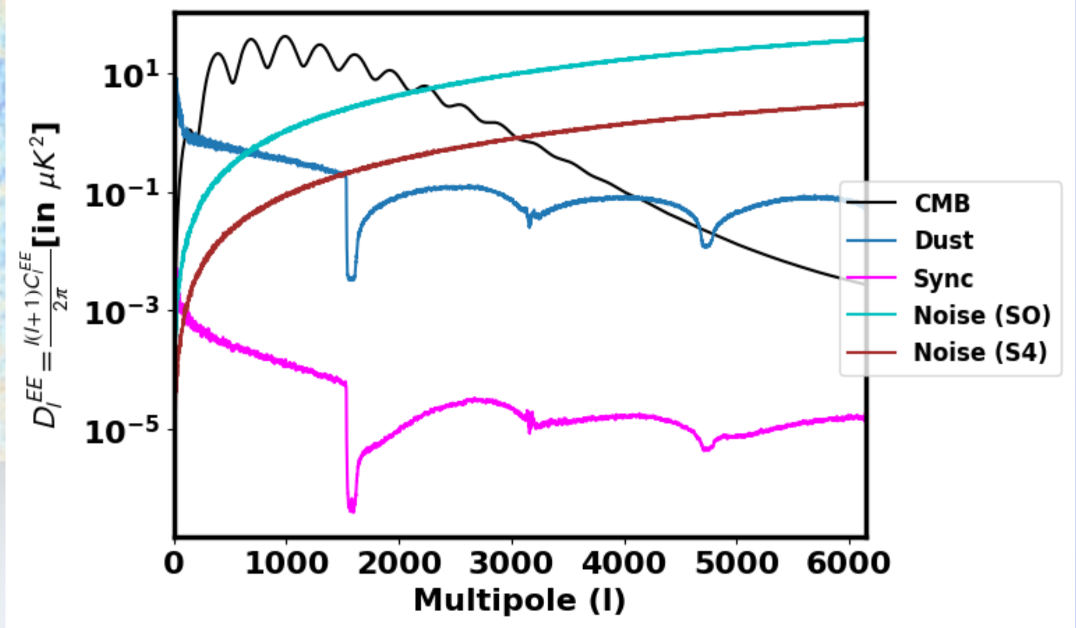


➢ *JCAP02(2025)050*

Harmonic transform



➢ *JCAP07(2024)084*



➢ ***The signal is decomposed to spherical harmonics:***

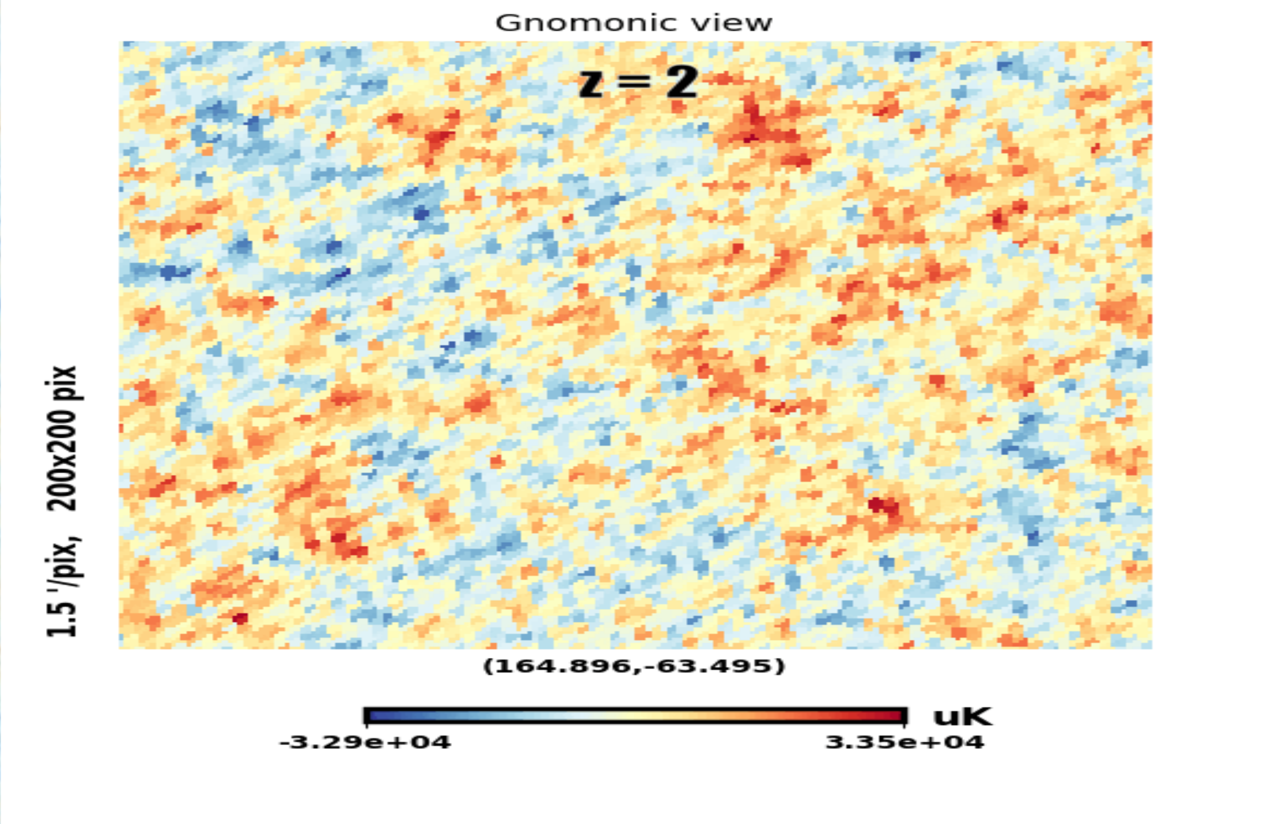
$$I^{ax} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

➢ ***The power spectrum is given as:***

$$C_\ell^{ax} = \langle a_{\ell m}^* a_{\ell m} \rangle$$

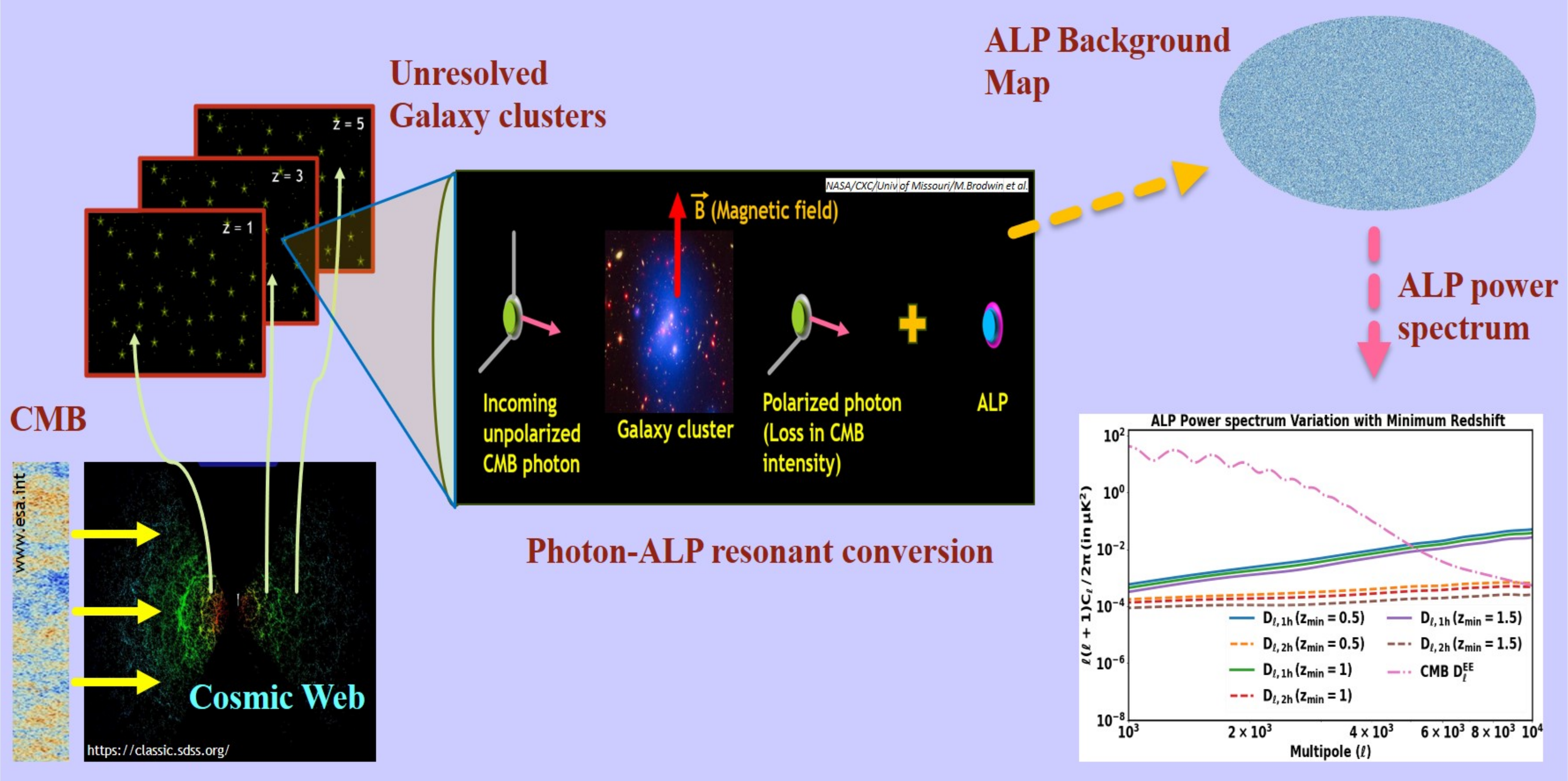
PROBING ALPS USING UNRESOLVED CLUSTERS

BACKGROUND SIGNAL FROM UNRESOLVED CLUSTERS

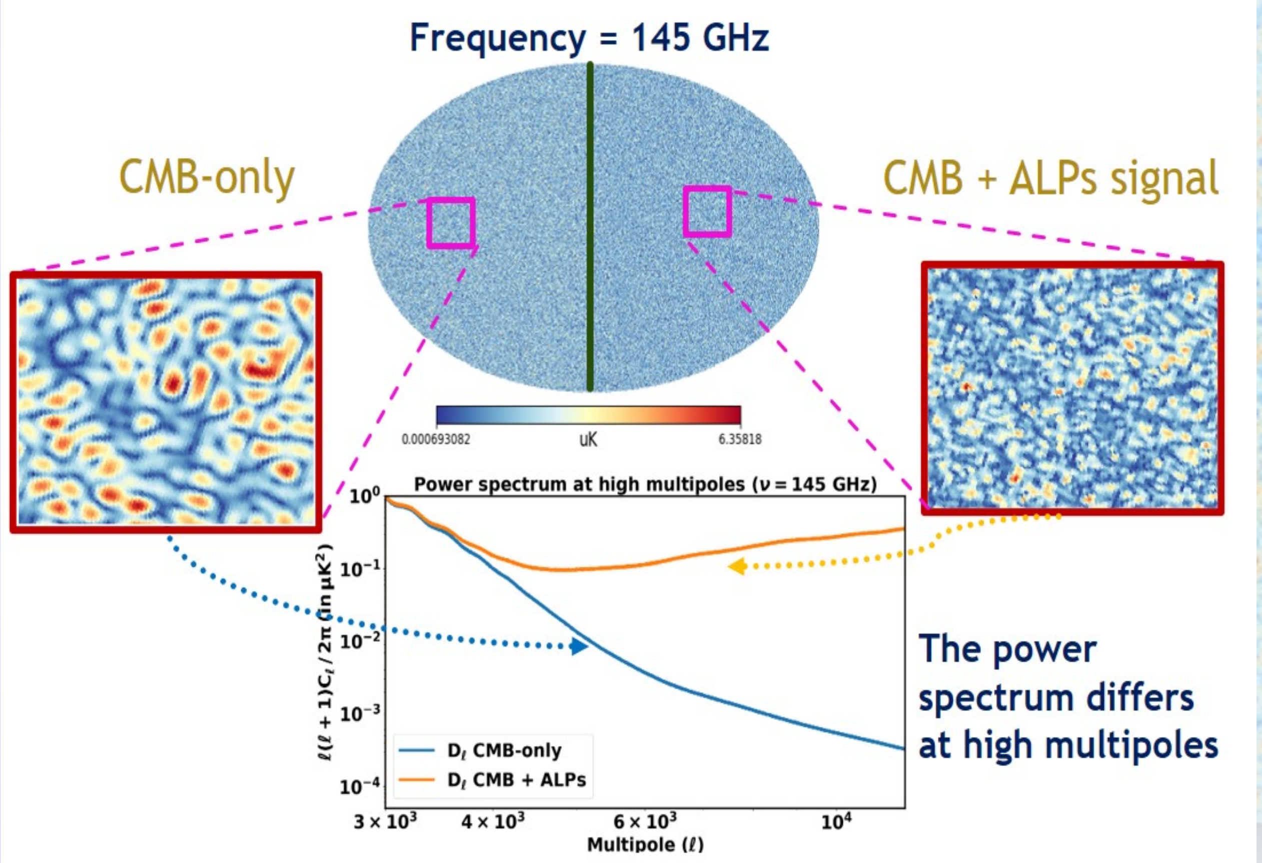


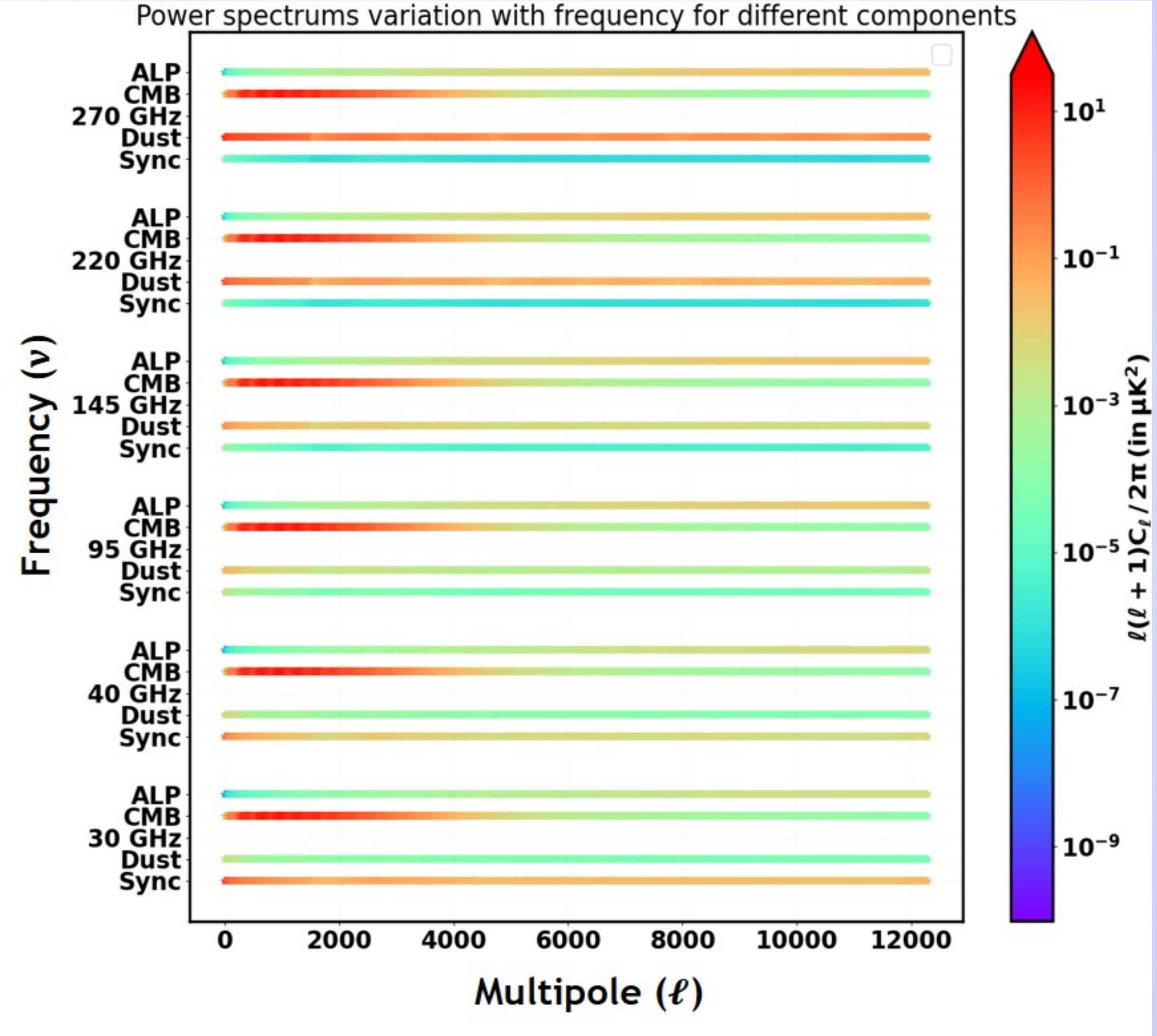
Galaxy clusters can be modelled as halos of mass range $10^{13} - 7 \, . \, 10^{15} \, M_{\odot}$

THE ALP DIFFUSED BACKGROUND



SPECTRAL & SPATIAL VARIATION OF THE ALP SIGNAL





TURBULENT EFFECTS ON THE ALP SIGNAL

Length scales involved

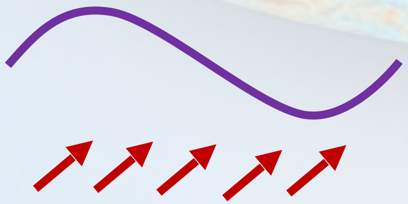
- ***The ALP signal depends on:***
  - *The photon-ALP oscillation scale*
  - *The electron density variation scale*
  - *The magnetic field variation scale*

- ***The probability of conversion at a location in a galaxy cluster:***

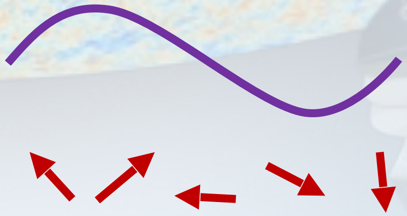
$$\Delta_e = -\,\omega_p^2/2\omega \qquad \Delta_a = -\,m_a^2/2\omega \qquad \Delta_{a\gamma} = g_{a\gamma}B_t/2 \qquad \Delta_{osc}^2 = (\Delta_e - \Delta_a)^2 + 4\Delta_{a\gamma}^2$$

$$\gamma_{ad} = \frac{\Delta_{osc}^2}{|\nabla \Delta_e|} = \left| \frac{2g_{a\gamma}^2 B_t^2 \omega (1+z)}{\nabla \omega_p^2} \right|$$

- ***Low Coherence length causes depolarization:***

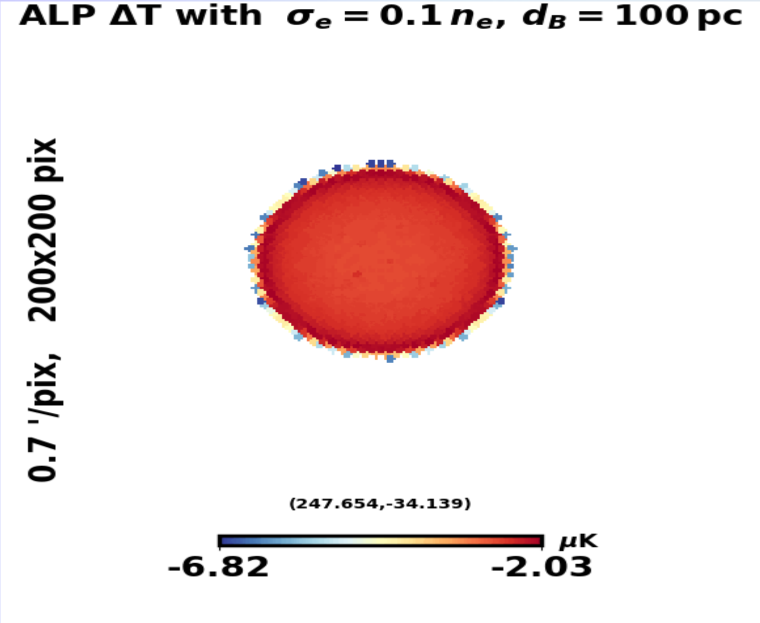


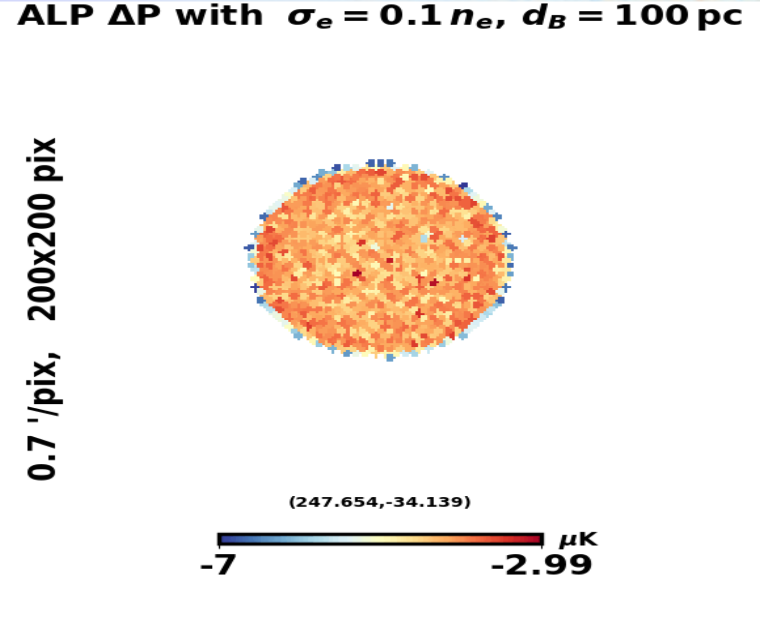
Polarization of the ALP signal retained



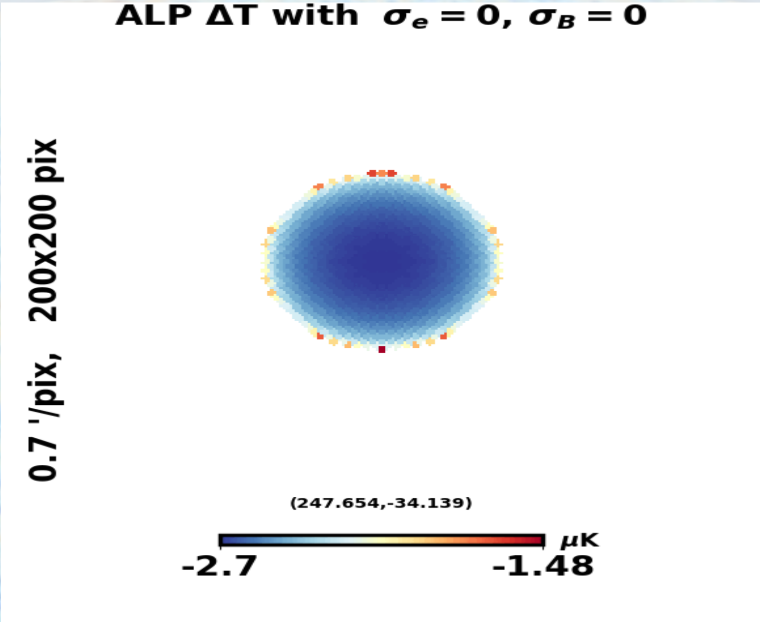
Depolarization of the ALP signal

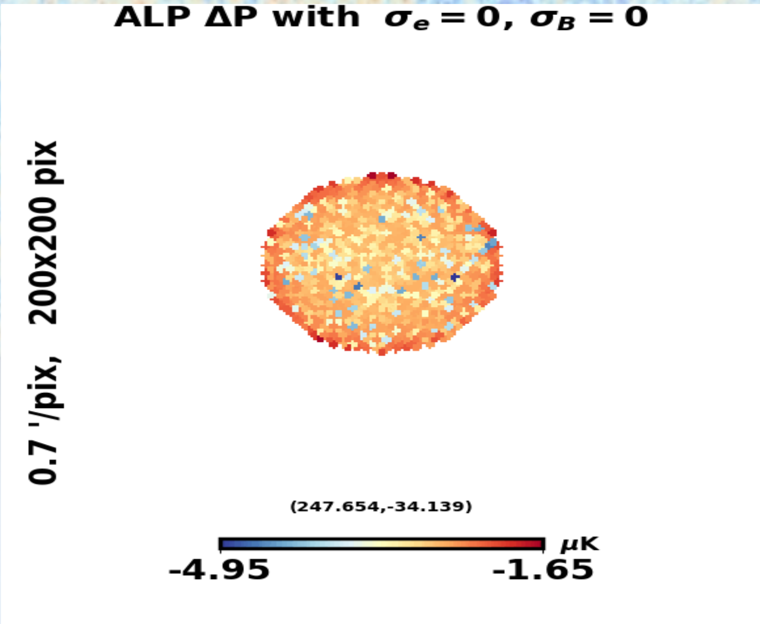
Varying magnetic field domain size



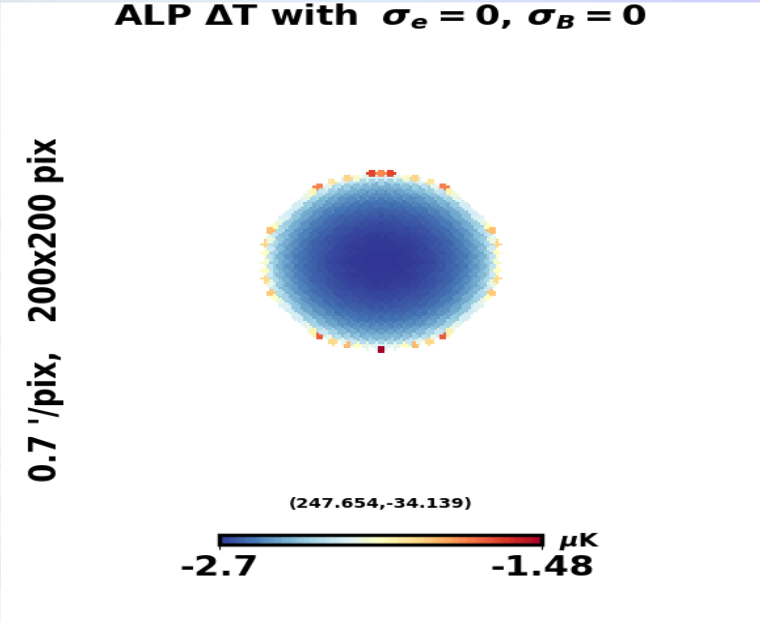


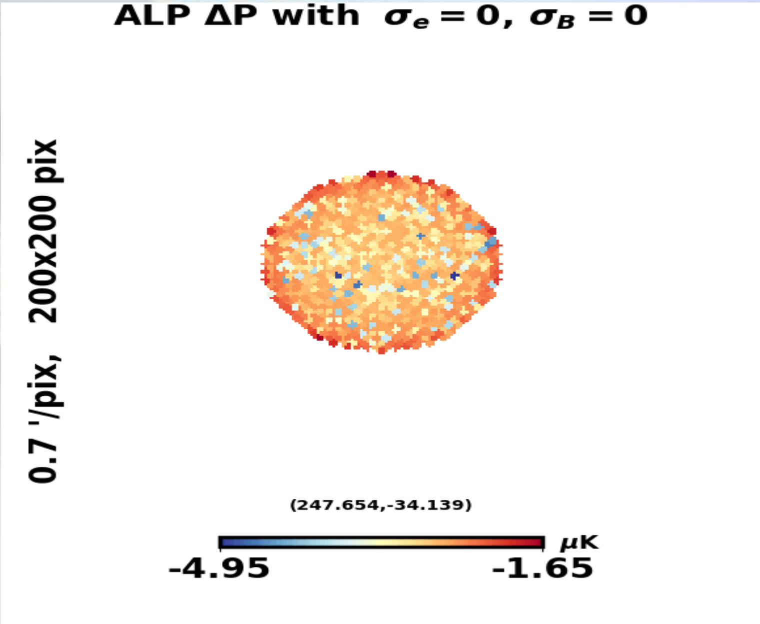
Varying magnetic field inhomogeneity



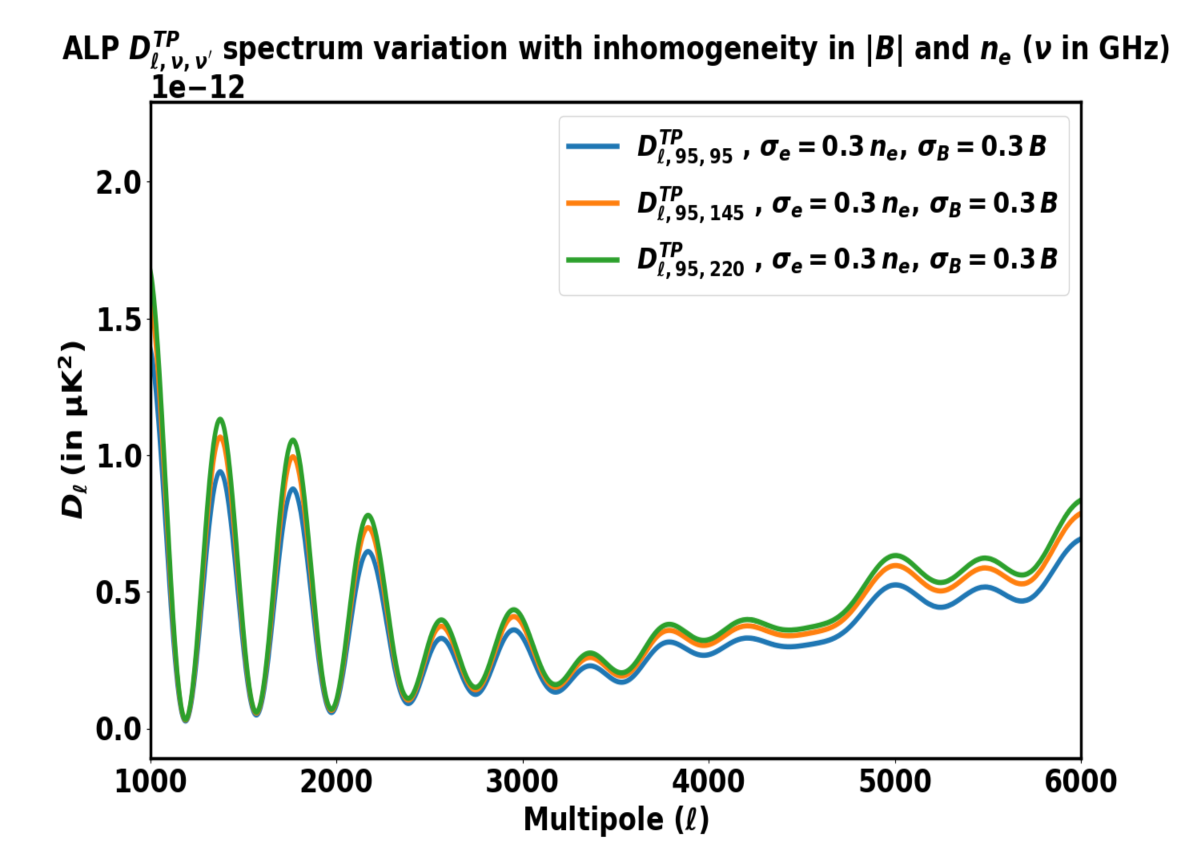


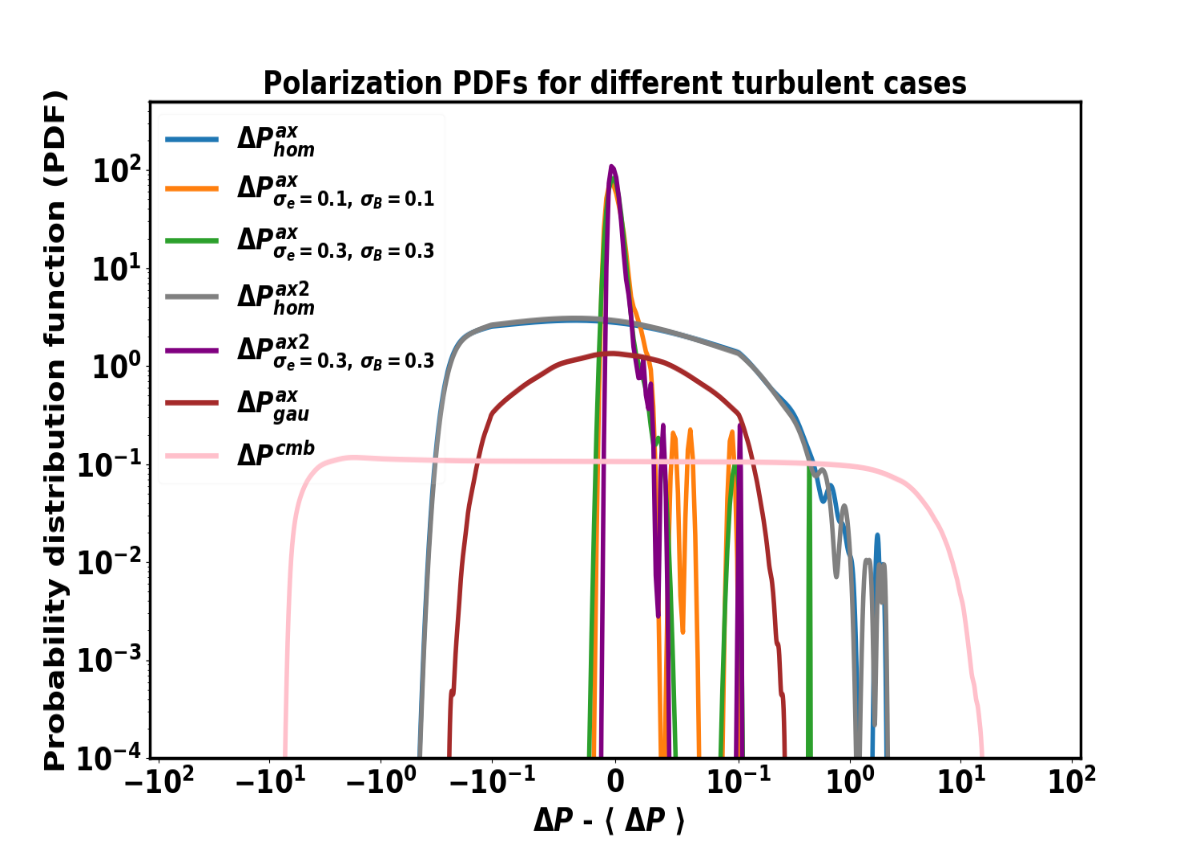
Varying electron density inhomogeneity





OBSERVABLES TO PROBE THE ALP SIGNAL

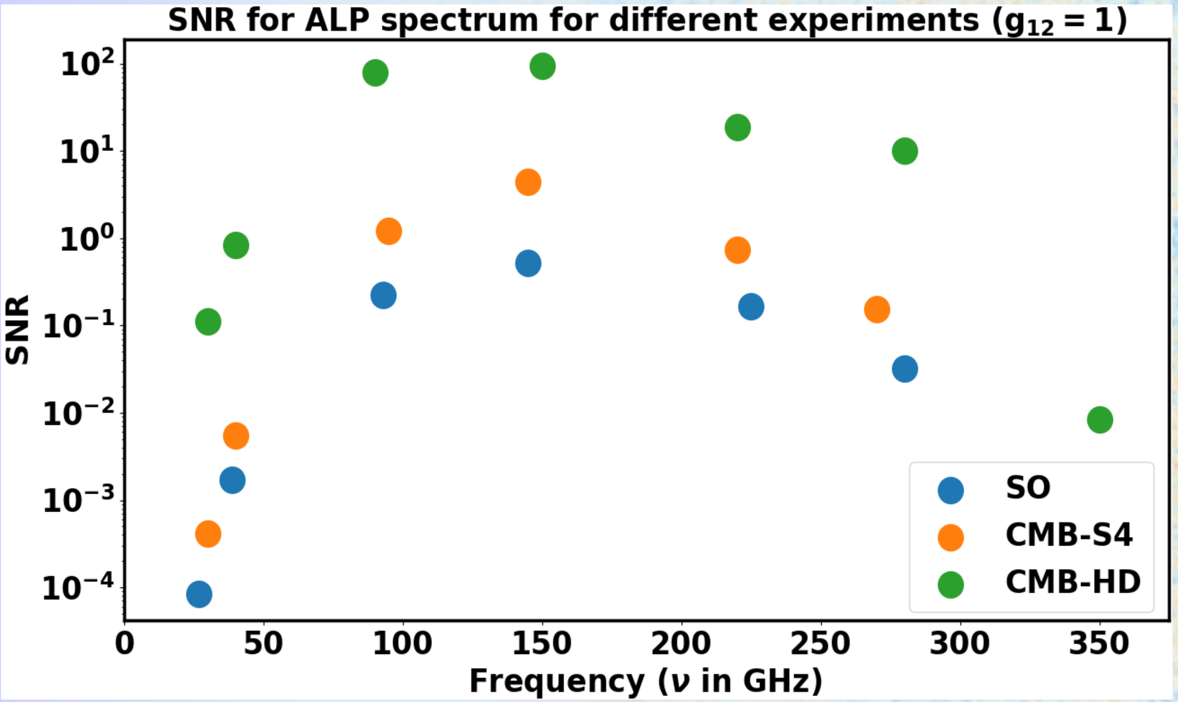




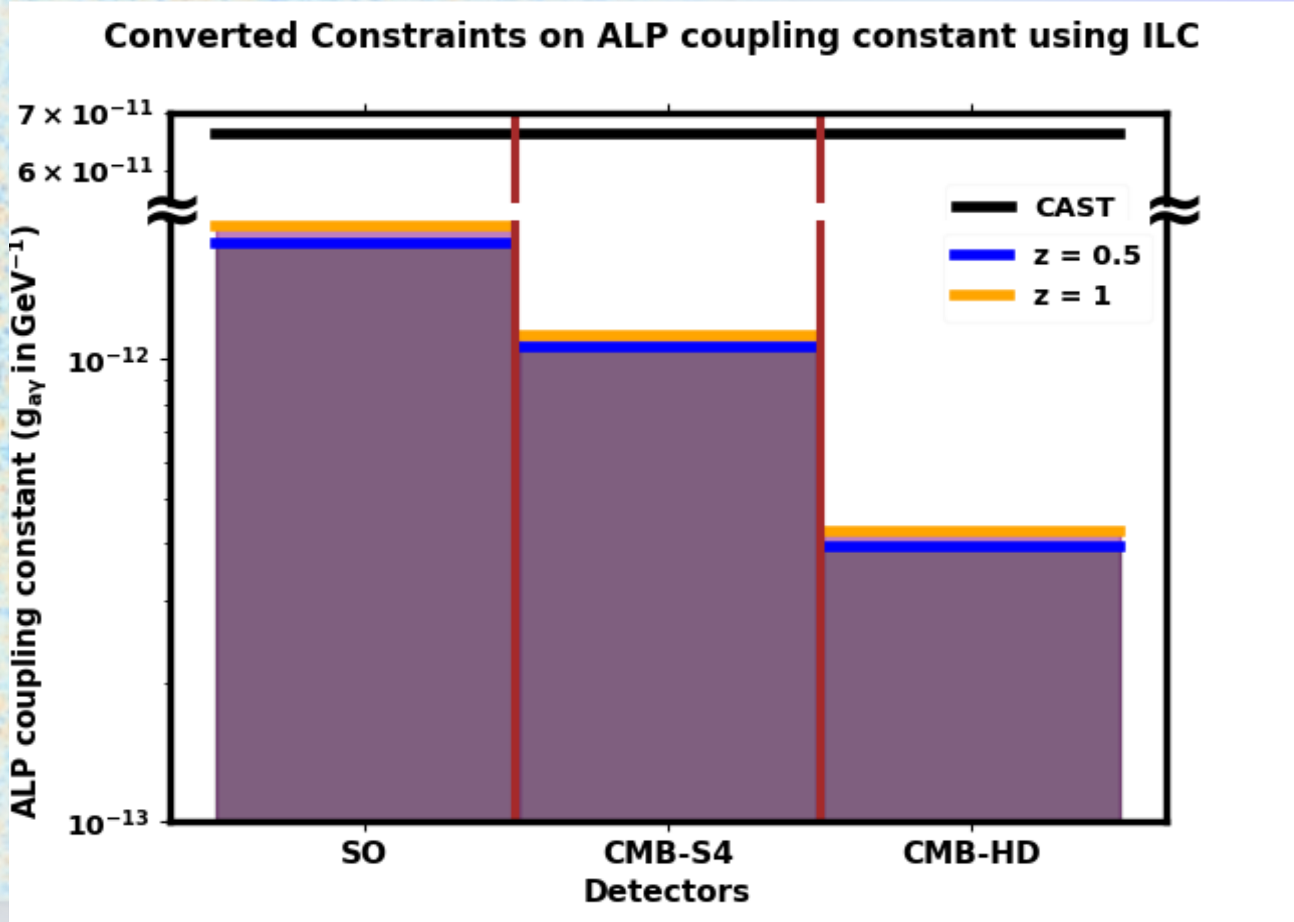
Cross Temperature-Polarization (TP) power spectrum
➢ *JCAP05(2025)051*

Turbulence dependent non-Gaussian signal
➢ *JCAP05(2025)051*

HOW WELL CAN THE ALP SIGNAL BE MEASURED?

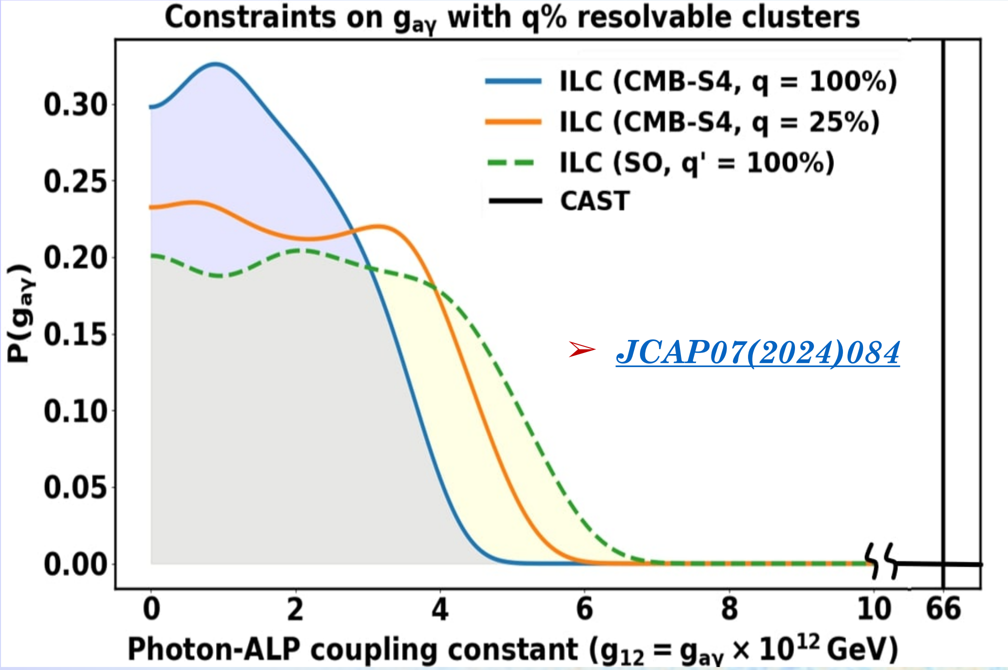


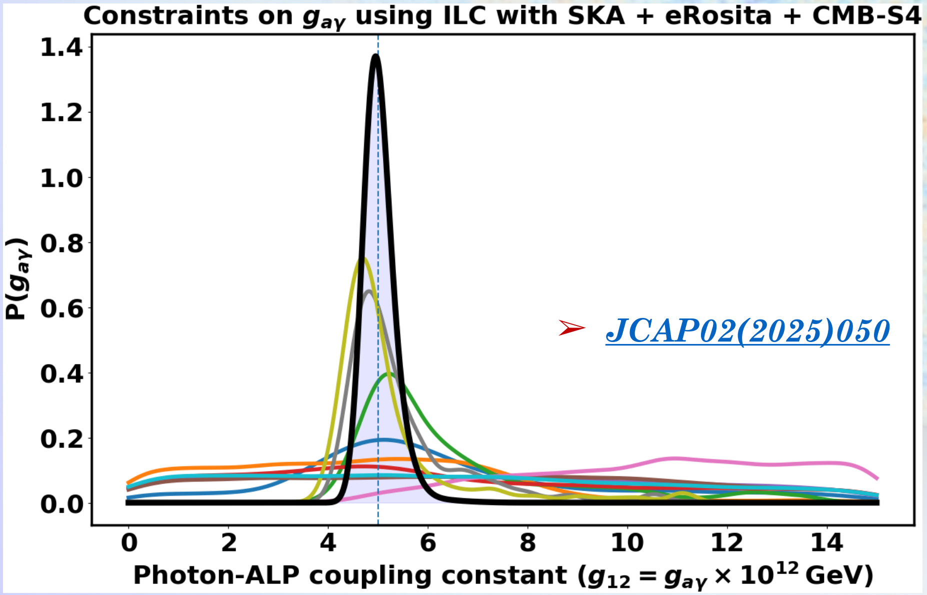
➢ *JCAP07(2024)084*

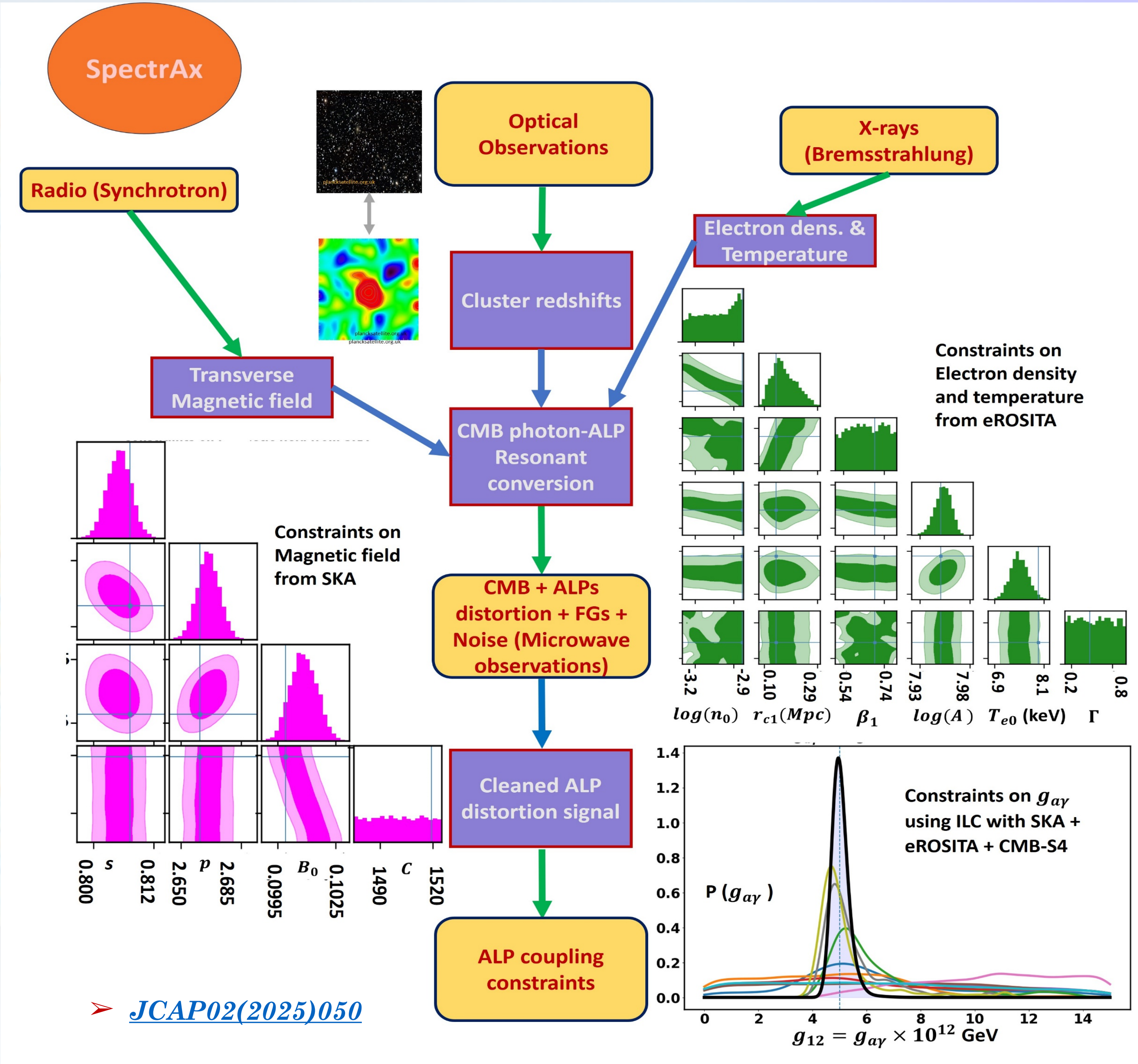


➢ *JCAP07(2024)084*

ALP mass range:
10^{-15} - 10^{-11} eV


Constraints on $g_{a\gamma}$ with q% resolvable clusters
ILC (CMB-S4, q = 100%)
ILC (CMB-S4, q = 25%)
ILC (SO, q' = 100%)
CAST
$P(g_{a\gamma})$
Photon-ALP coupling constant ($g_{12} = g_{a\gamma} \times 10^{12}$ GeV)
➢ JCAP07(2024)084

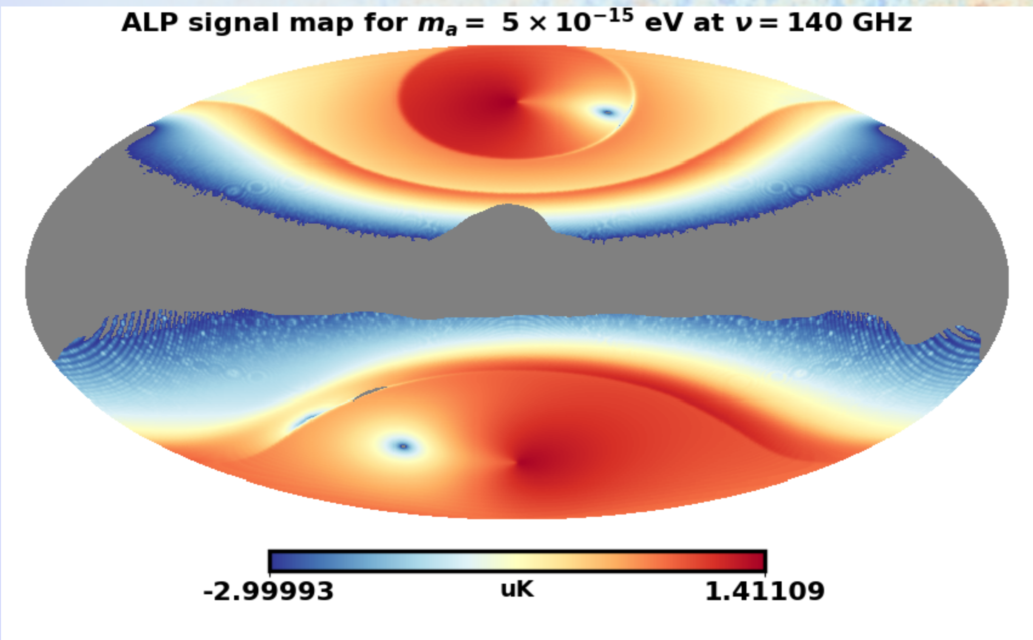

Constraints on $g_{a\gamma}$ using ILC with SKA + eRosita + CMB-S4
$P(g_{a\gamma})$
Photon-ALP coupling constant ($g_{12} = g_{a\gamma} \times 10^{12}$ GeV)
➢ JCAP02(2025)050


SpectrAx
Radio (Synchrotron)
Optical Observations
X-rays (Bremsstrahlung)
Electron dens. & Temperature
Cluster redshifts
Transverse Magnetic field
CMB photon-ALP Resonant conversion
CMB + ALPs distortion + FGs + Noise (Microwave observations)
Cleaned ALP distortion signal
ALP coupling constraints
Constraints on Magnetic field from SKA
Constraints on Electron density and temperature from eROSITA
Constraints on $g_{a\gamma}$ using ILC with SKA + eROSITA + CMB-S4
$P(g_{a\gamma})$
$g_{12} = g_{a\gamma} \times 10^{12}$ GeV
➢ JCAP02(2025)050

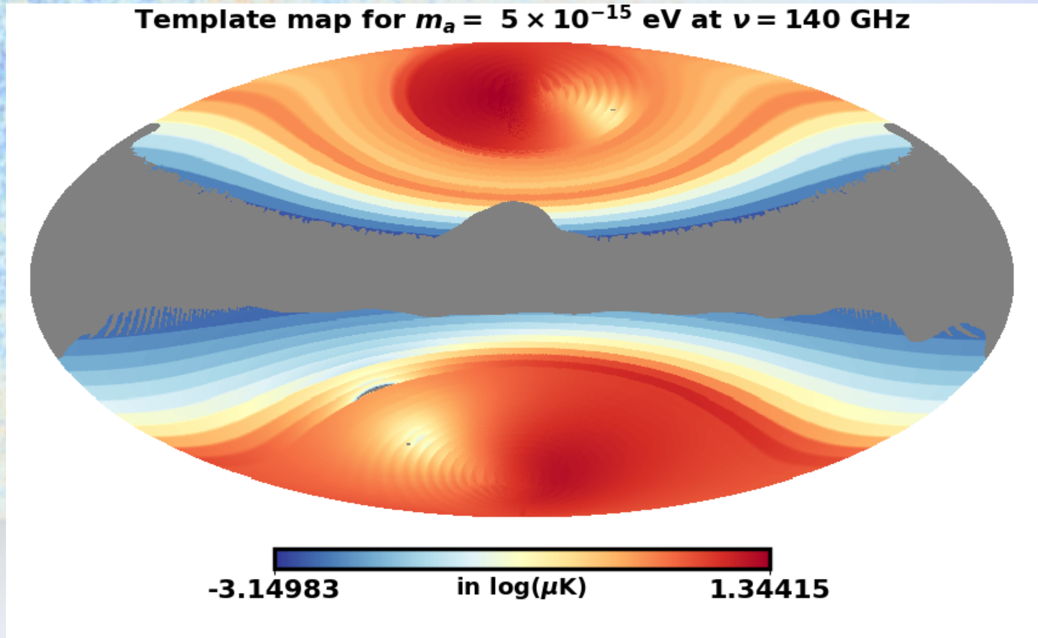
ALP CONVERSION IN THE MILKY WAY

GALACTIC ALP SIGNAL MODELLING

- ➢*Turbulent profiles, difficult to model*
- ➢*Highly non-Gaussian signal contaminated by foregrounds*
- ➢*Computationally expensive 3D simulations*
- ➢***Solution:*** *Spatial sky-template-based search for ALPs (fast & captures signal non-Gaussianity)*

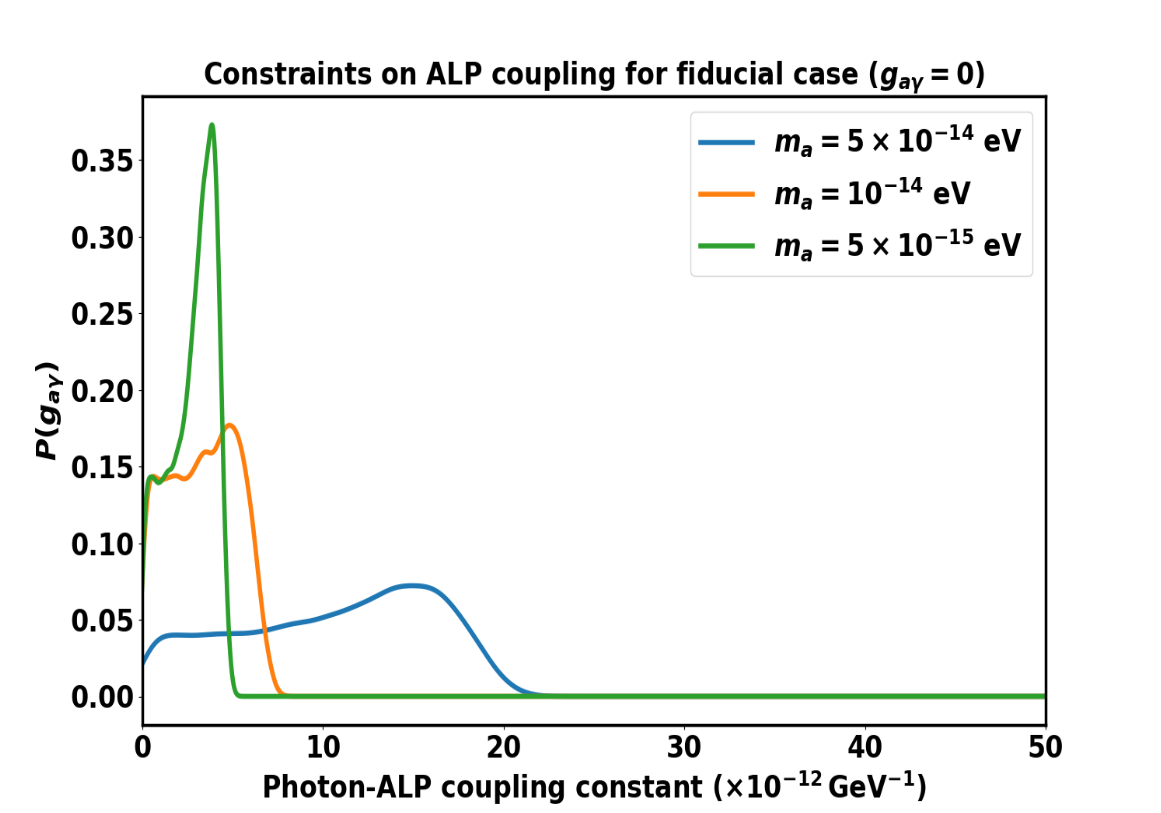


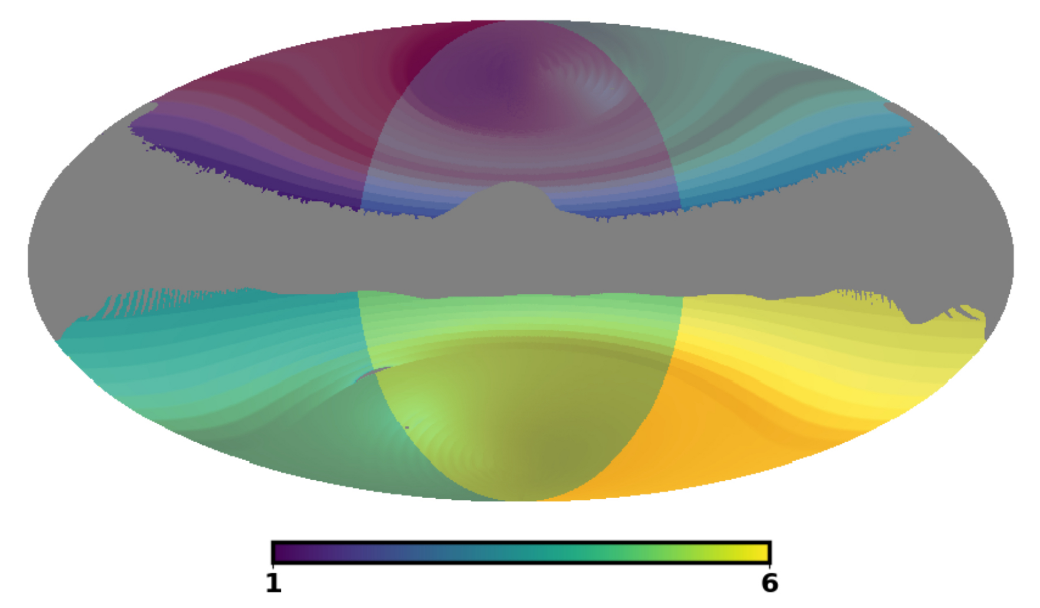
Galactic ALP distortion signal

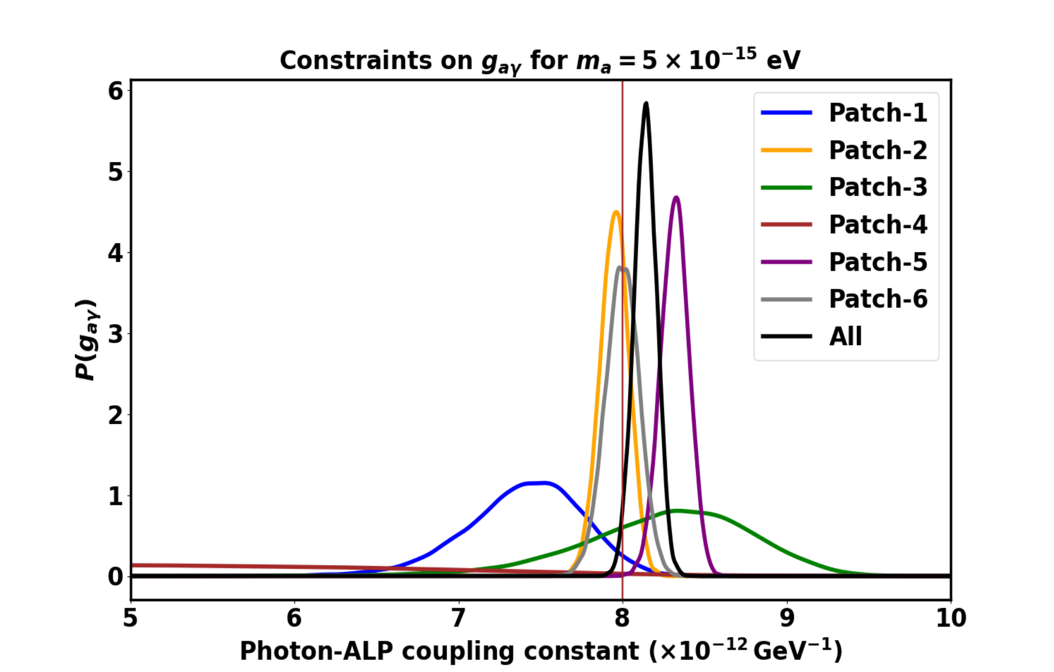


Best-fit template

ROBUSTNESS OF THE SKY-TEMPLATE TECHNIQUE







Constraints using Best-fit template

➢ *https://arxiv.org/abs/2505.11592*

Patch-dependent inference

➢ *https://arxiv.org/abs/2505.11592*

SUMMARY & FUTURE OUTLOOK

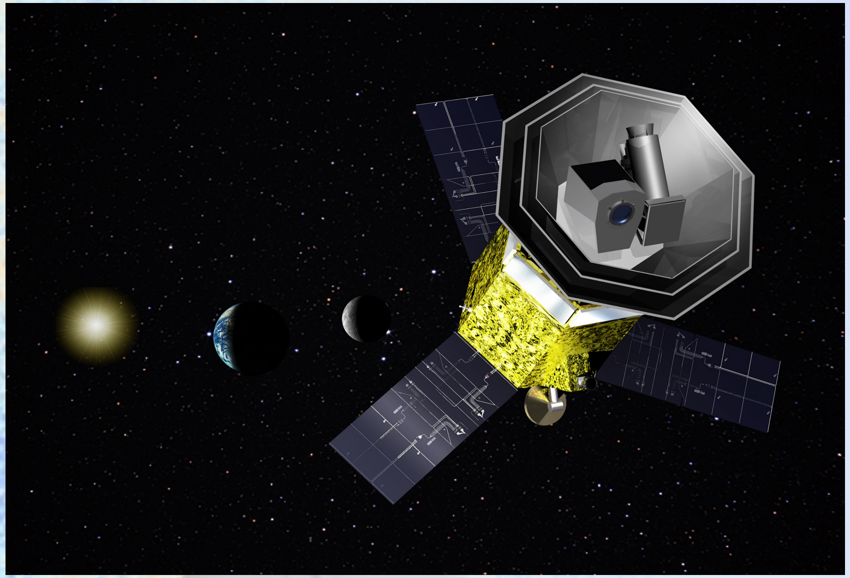
- ➢ *ALPs can be detected using SO and CMB-S4, which will observe a large number of clusters.*

- ➢ *ALP signal from the Milky way using LiteBIRD.*

- ➢ *Simulation grid can be used for other astrophysical systems (neutron stars, CGM, etc.)*

- ➢ *Applying our pipelines on data from Atacama Cosmology Telescope (ACT), South Pole Telescope (SPT), Simons Observatory (SO), CMB-S4, etc.*

- ➢ *SpectrAx can be used to study other cluster phenomena like Sunyaev-Zeldovich (SZ), synchrotron emission, etc.*



RELEVANT PUBLICATIONS

- *A power spectrum approach to the search for Axion-like Particles from resolved galaxy clusters using CMB as a backlight, (Mehta and Mukherjee)* JCAP09(2024)037

- *A Diffused Background from Axion-like Particles in the Microwave Sky, (Mehta and Mukherjee)* JCAP07(2024)084

- *SpectrAx: spectral search of axion-like particles using multi-band observations of galaxy clusters from SKA, SO, CMB-S4 and eROSITA, (Mehta and Mukherjee)* JCAP02(2025)050

- *Turbulence Induced Non-Gaussian Spectral Distortion in the Microwave Sky from Photon-Axion Conversion in Galaxy Clusters, (Mehta and Mukherjee)* JCAP05(2025)051

- *The Prospect from the Upcoming CMB Experiment LiteBIRD to Discover Axion-like Particles Using Milky Way , (Mehta and Mukherjee)* https://arxiv.org/abs/2505.11592 *(Accepted in JCAP)*

ACKNOWLEDGEMENT

Thanks to Suvodip Mukherjee

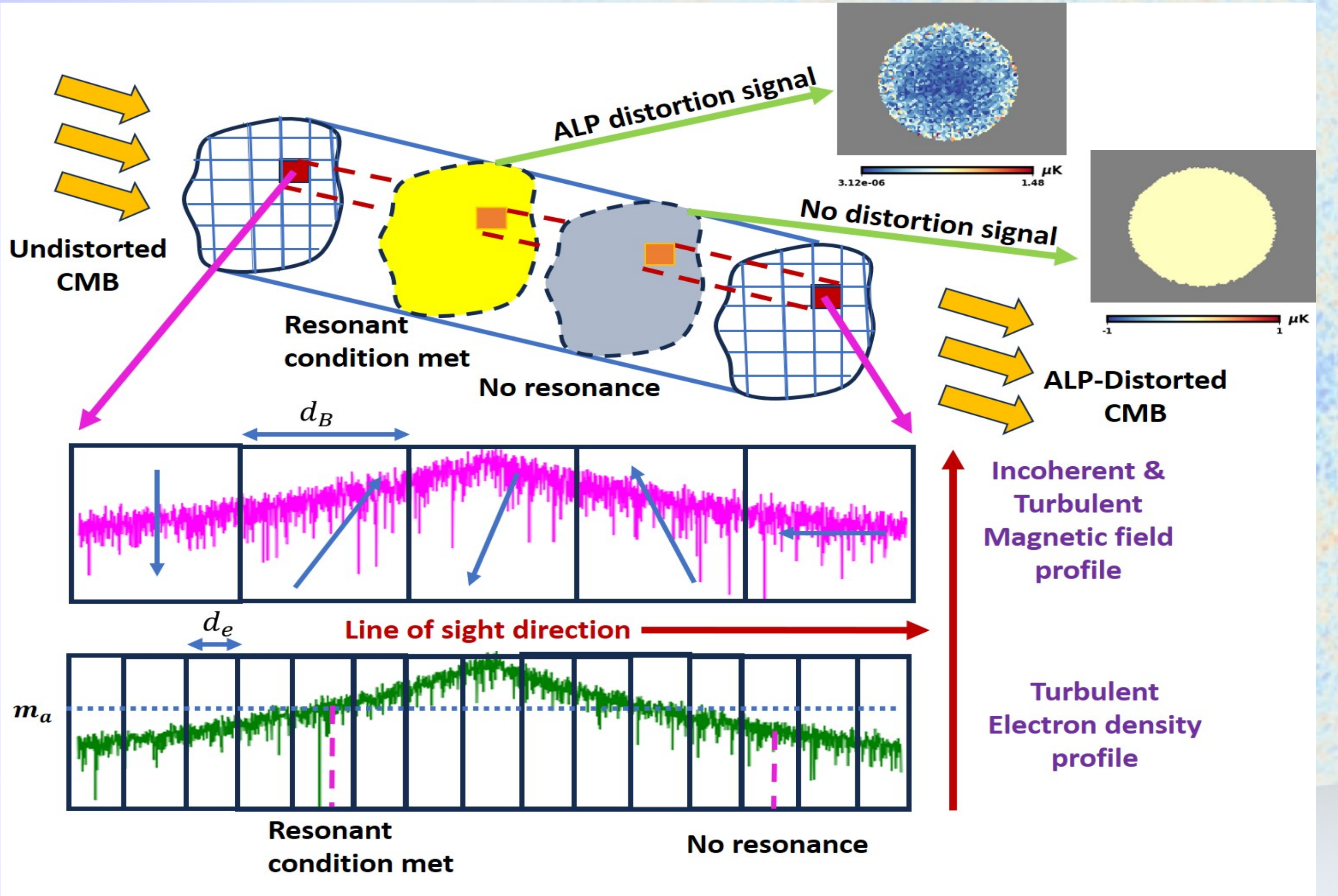
Thanks to <Data|Theory> Universe Lab at TIFR

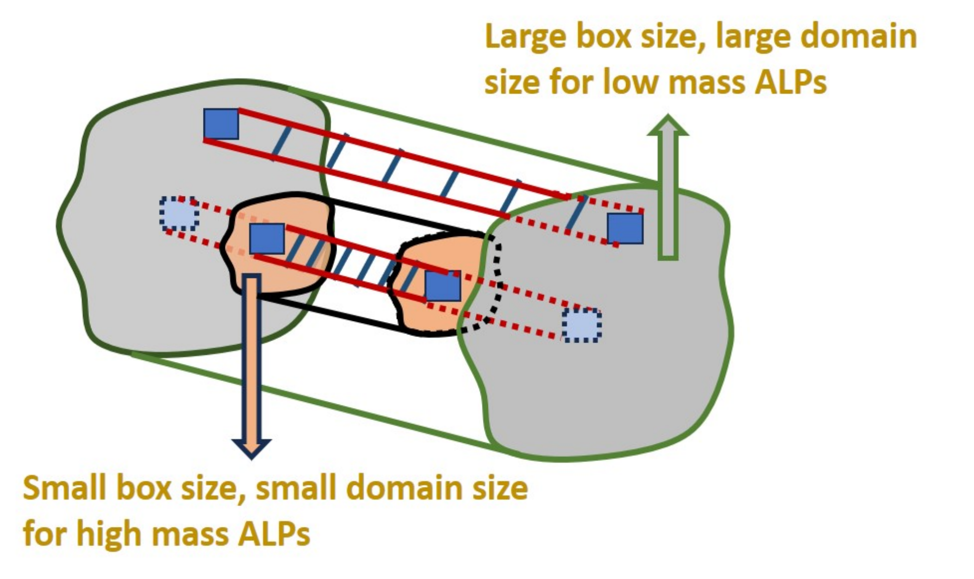
Thanks to the Lomonosov Conference Team

THANK YOU!

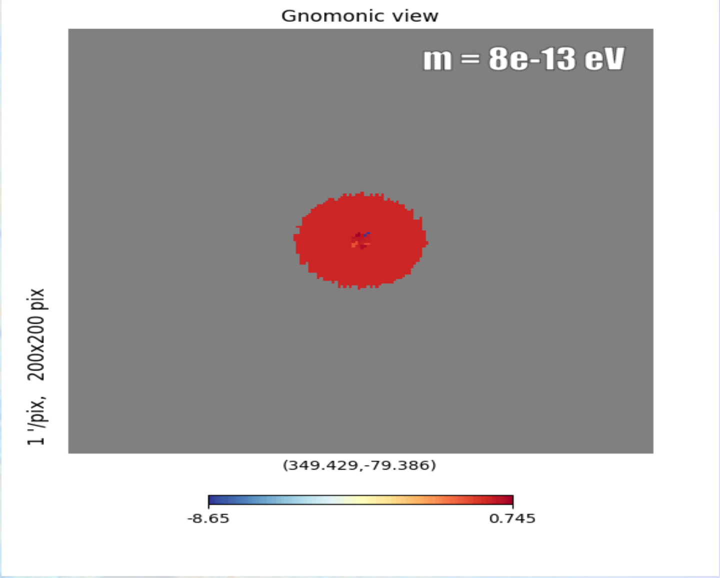
BACKUP SLIDES

Cluster Realization Grid





How will the ALP signal look like?



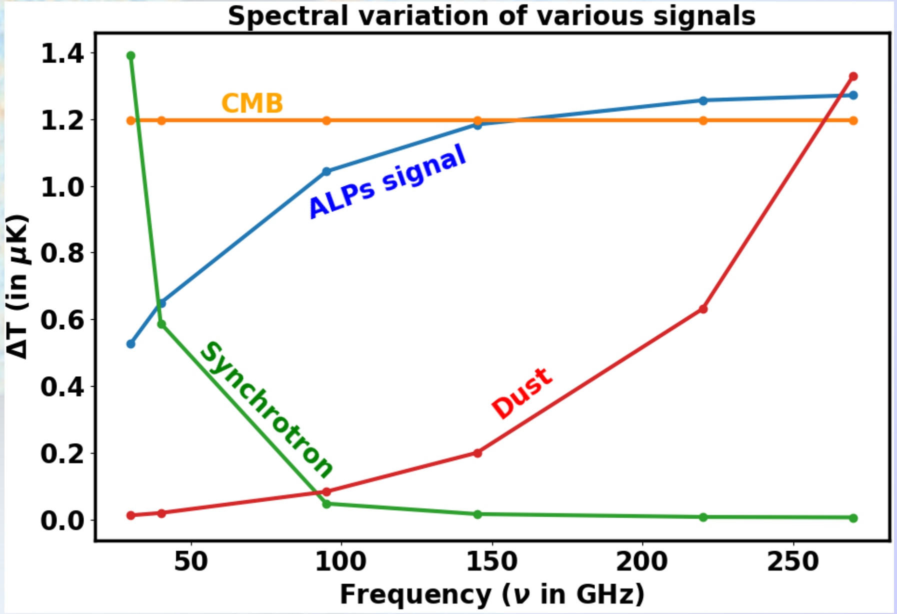
- ***The ALPs of a particular mass form in a spherical shell within the spherically symmetric cluster***

- ***Observed as a disk along the cluster line of sight***

- ***Disk size generally increases for low ALP masses (m_a)***

- ***Probable mass range:*** 10^{-15} - 10^{-11} ***eV***

- ***Detecting the ALP signal:***
  - ***Challenges: Galactic foregrounds and noise***
  - ***Approaches: Power spectrum-based or Pixel-based***



HALO MODELLING OF THE ALP BACKGROUND SIGNAL

- *ALP Power spectrum can be separated into one and two halo terms*
- *One halo: Correlations between locations within the same cluster*

$$C^{ax}_{\ell,1h} = \int_{z_{min}}^{z_{max}} dz \frac{dV_c}{dz} \int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} \left|\alpha_\ell(M,z)\right|^2,$$

- *Two halo: Correlations between locations in different clusters*

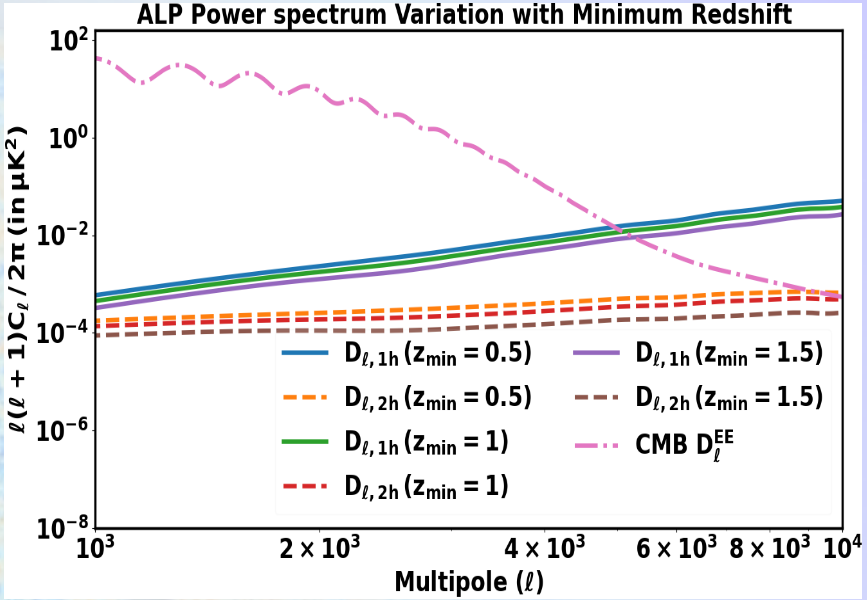
$$C^{ax}_{\ell,2h} = \int_{z_{min}}^{z_{max}} dz \frac{dV_c}{dz} P_m\left(k = \frac{\ell + 1/2}{r(z)}, z\right) \times \left[\int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} b(M,z)\alpha_\ell(M,z)\right]^2,$$

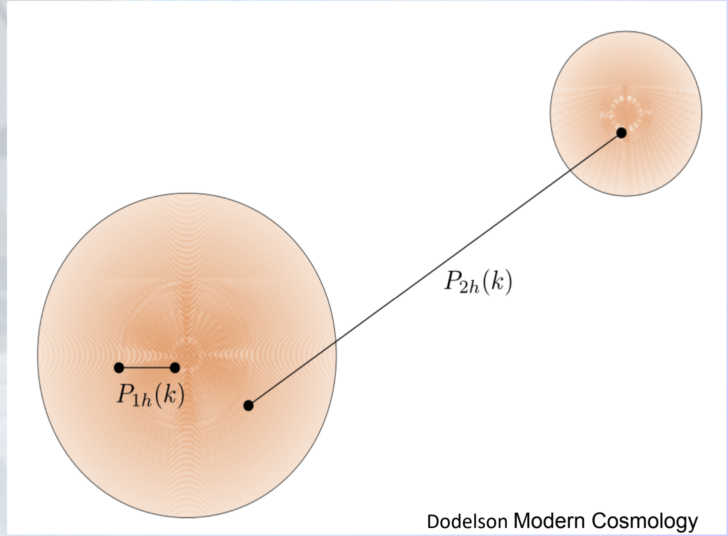
(Relatively Weak)

where halo correlation has been used:

$$P_h(k, M_1, M_2, z) = b(M_1, z) b(M_2, z) P_m(k,z),$$

b(M,z) is the bias factor, $P_m(k,z)$ ***is the matter power spectrum,*** V_c ***is the comoving volume,*** $\left|\alpha_\ell(M,z)\right|^2$ ***is the ALP power spectrum from a cluster.***





CONTAMINANTS

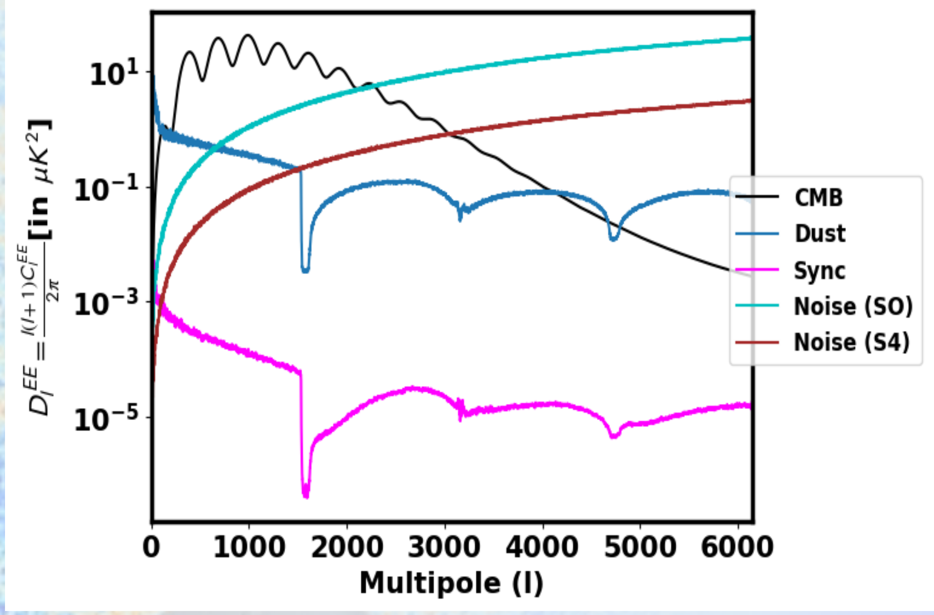
- *The galactic plane is a major source of foreground contaminations.*

- *Masking is required along the galactic plane and over the bright patches*

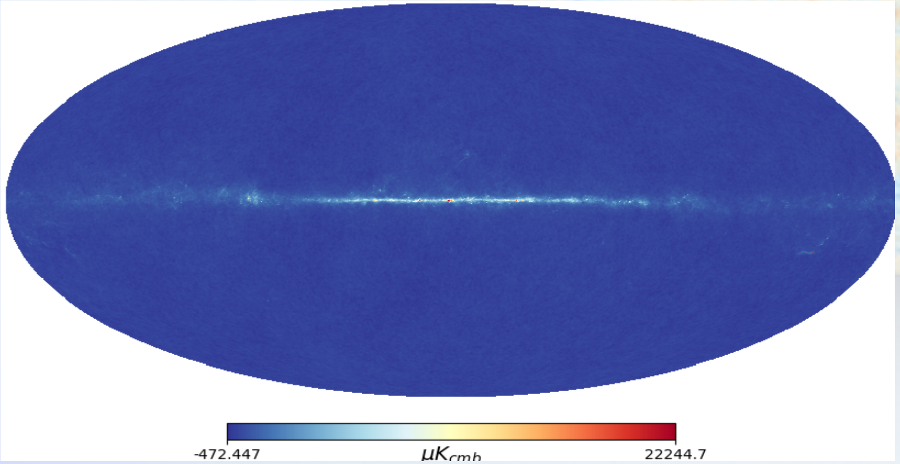
- *Internal Linear Combination method (ILC) weights:*

$$w_{a\gamma}=C_s^{-1}f_{a\gamma}\left(f_{a\gamma}^T C_s^{-1} f_{a\gamma}\right)^{-1}$$

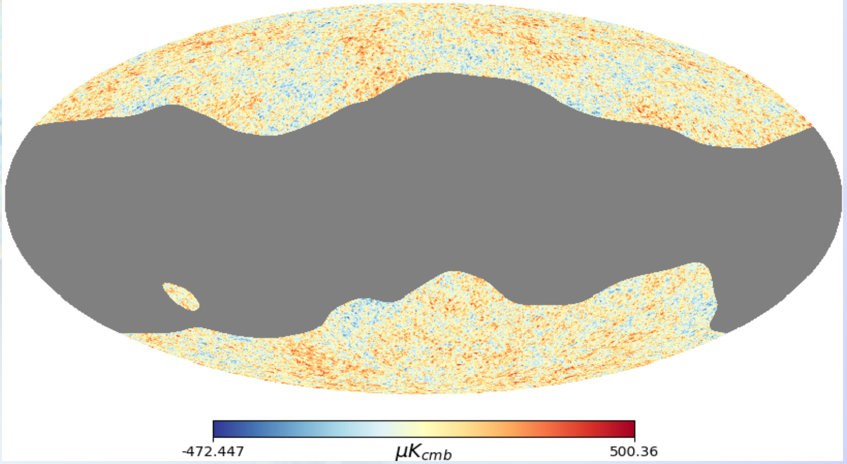
- *Observations also affected by:*
  - *Instrument beam*
  - *Instrument noise*



Power spectra at $\nu = 145$ Hz

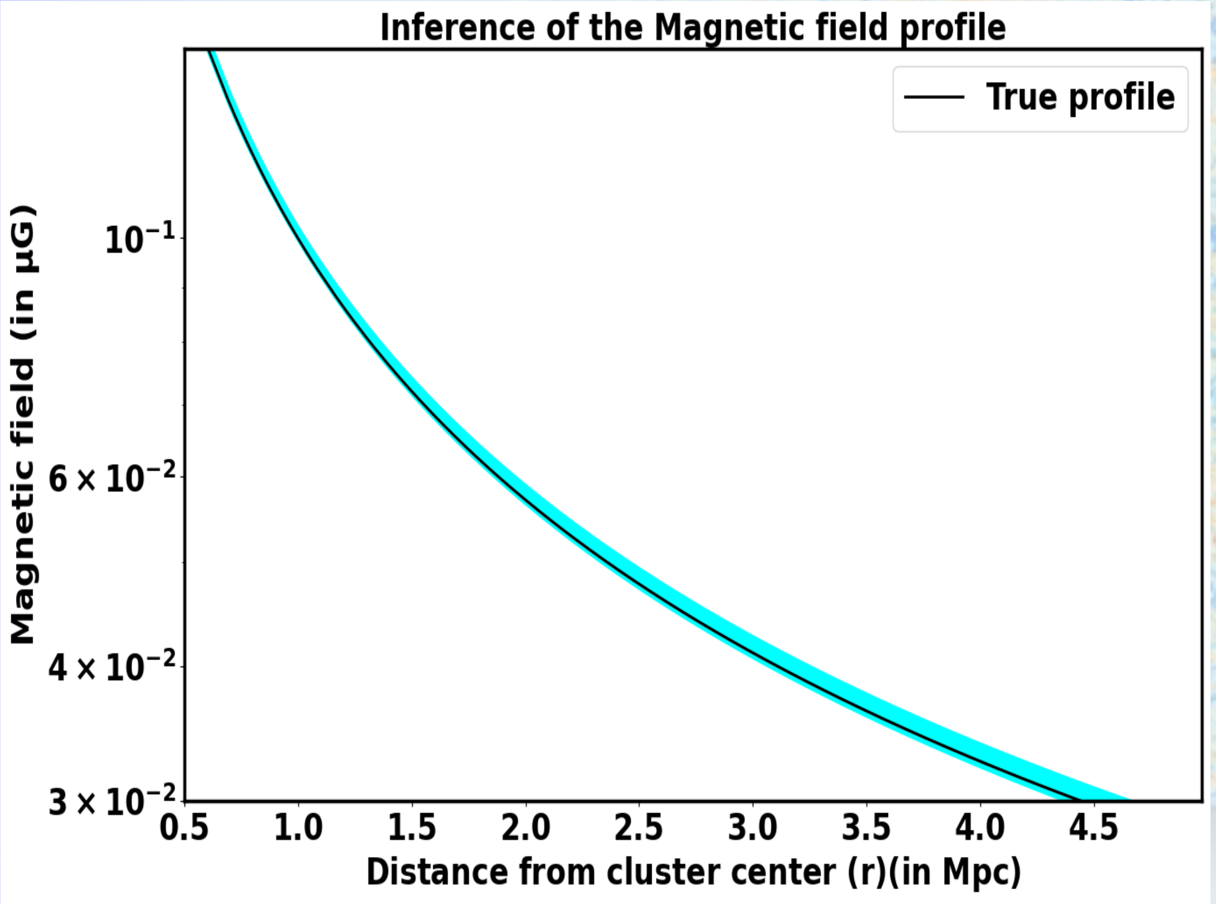


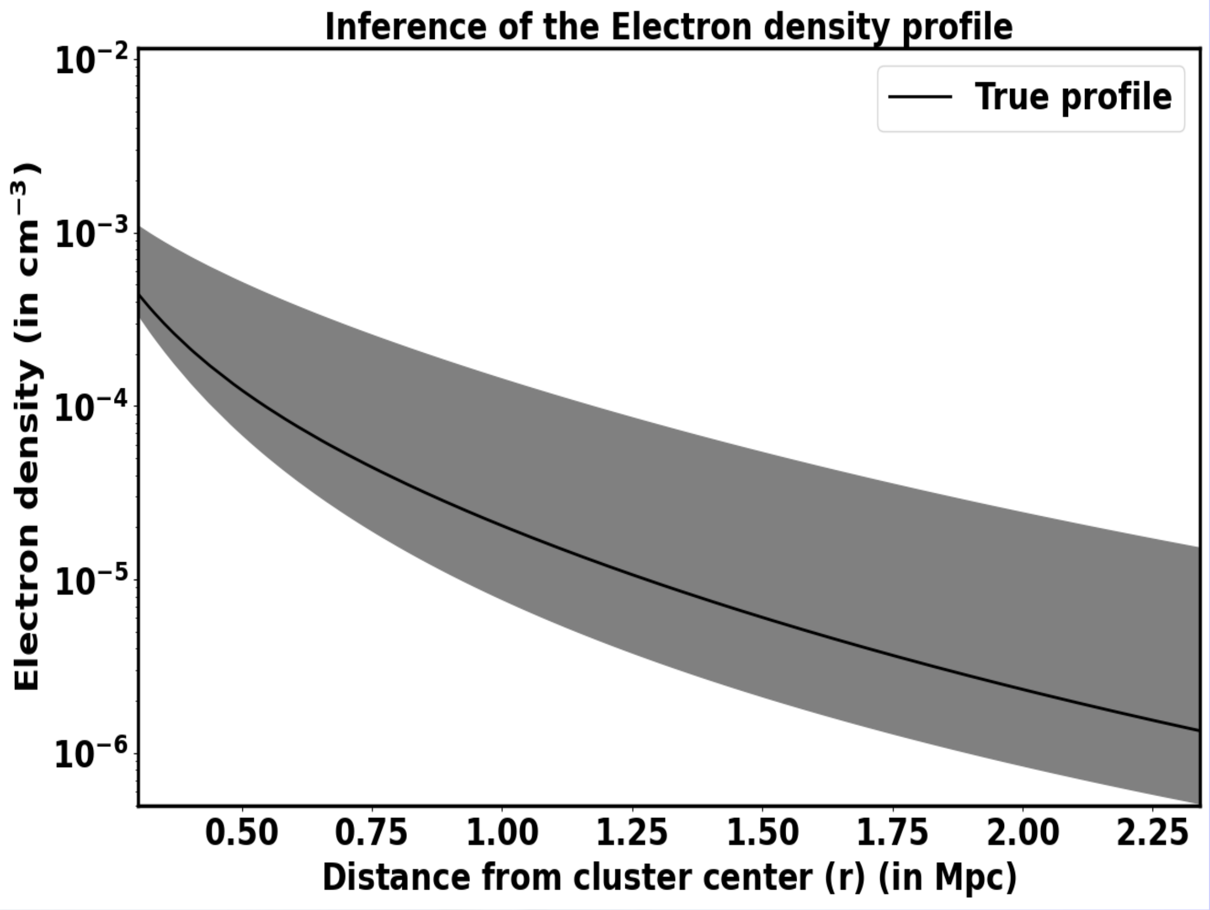
Contaminated map



Masked map

PROFILE INFERENCES





CONVERSION PROBABILITY

- *ALPs interact with photons through the Lagrangian:*

$$\mathscr{L}_{int} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\mathbf{E}\cdot\mathbf{B_t}$$

- *The resonant conversions are defined as:*

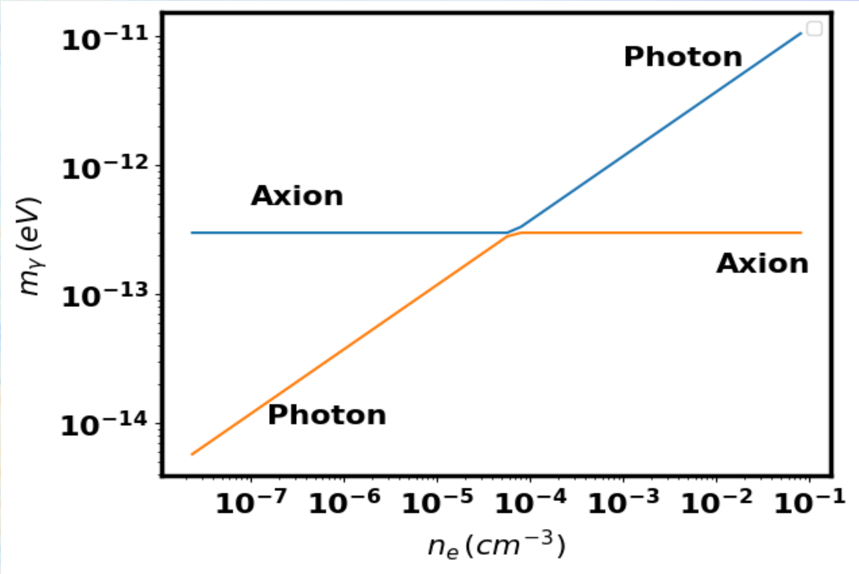
$$m_a = m_\gamma = \frac{\hbar\omega_p}{c^2} \approx \frac{\hbar}{c^2}\sqrt{n_e e^2/m_e\epsilon_0}$$

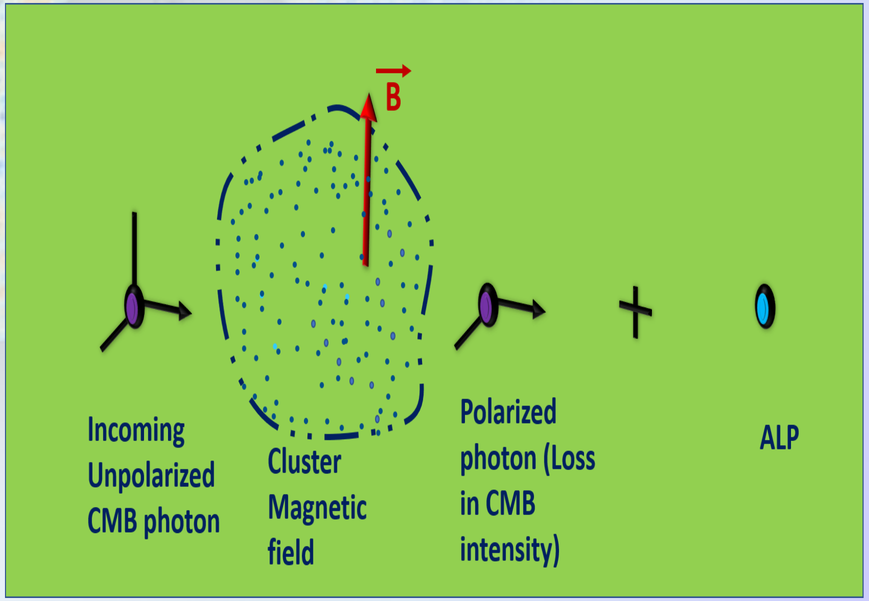
- *The probability of branch shift is given as:* $p = e^{-\pi\gamma/2}$*, where*

$$\gamma = \left| \frac{2 g_{\gamma a}^2 B_t^{\,2} \nu(1+z)}{\nabla\omega_p^2} \right|$$

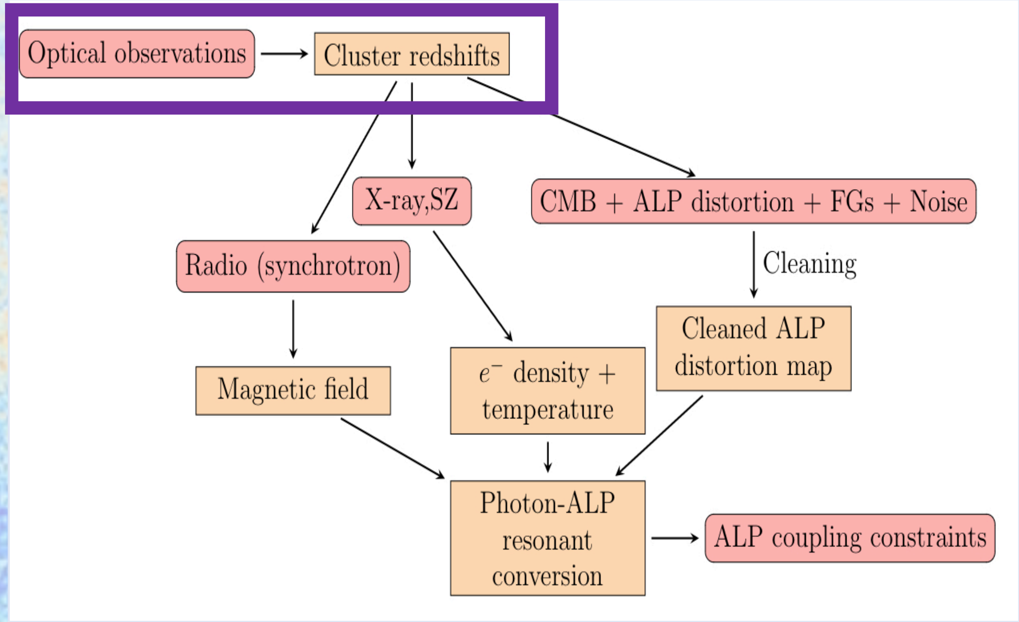
- *Probability of conversion at a resonance :* $1 - p$

- *In a galaxy cluster, conversion probability:* $P(\gamma \to a) = 2\,p\,(1 - p)$





CROSS-MATCHING WITH OPTICAL SURVEYS



- *Galaxy cluster detection methods: Red Sequence method or the BCG method*

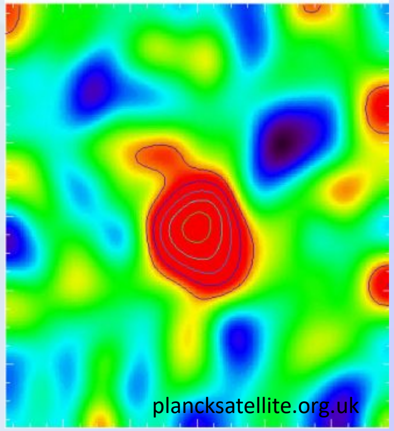
- *Redshift measurements are obtained using spectroscopic or photometric measurements*

- *Photo-z errors considered: Up to 10% in the analysis*

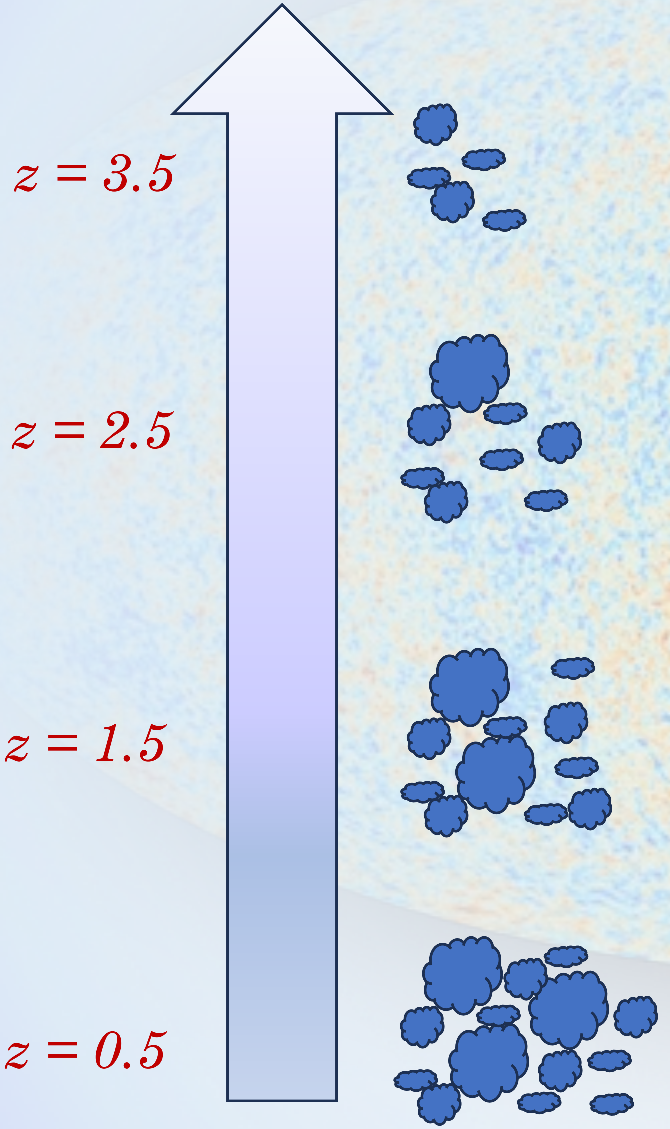
- *The clusters are cross matched with optical surveys to obtain the redshift measurements*

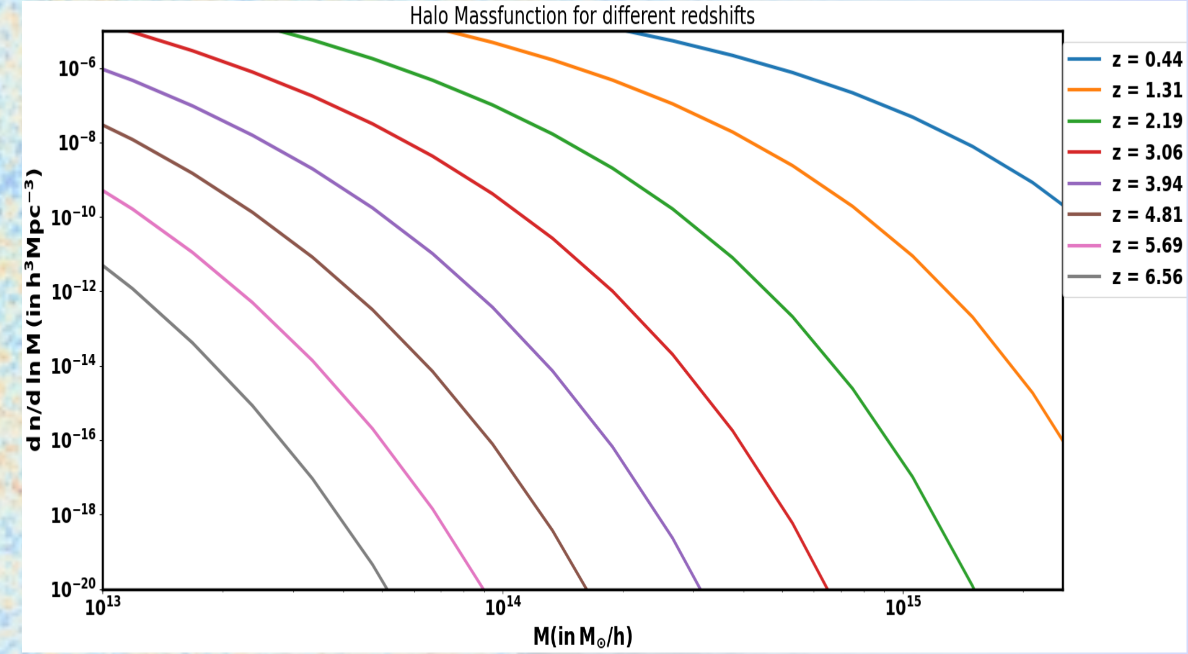
- *The redshift distribution of clusters is used for binning them*

Abell 2319 cross matching



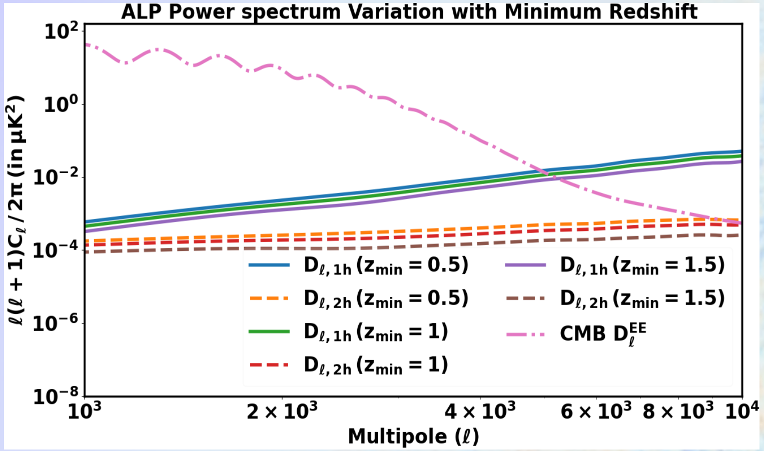
DISTRIBUTION OF HALOS



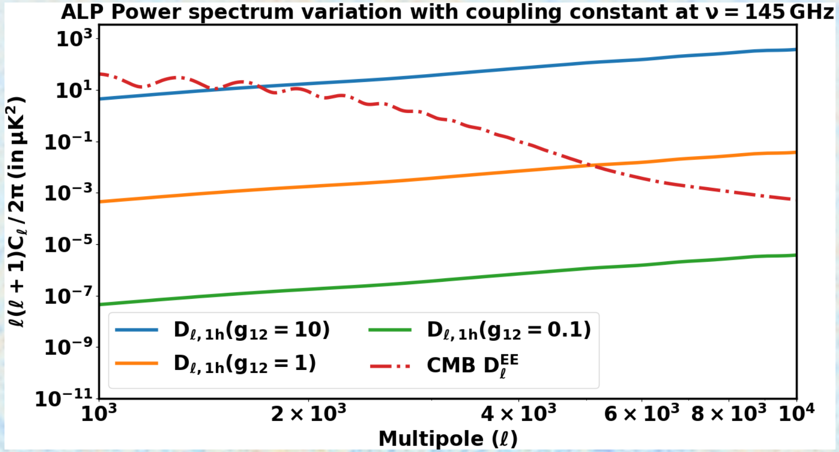


Cosmological Variations

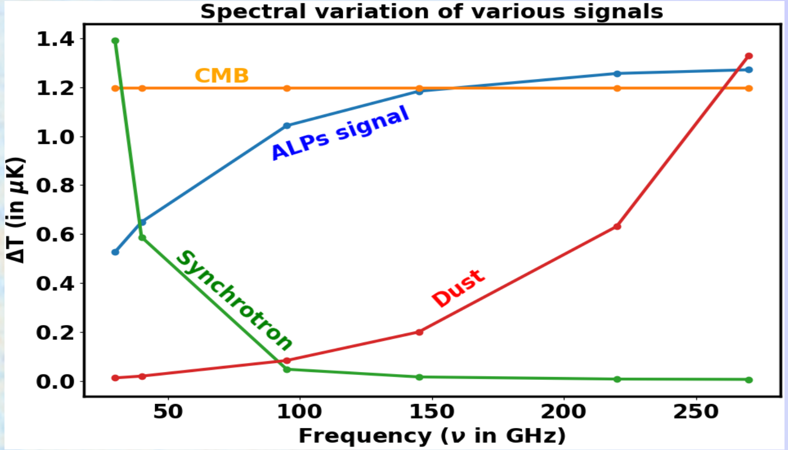
$$P(\gamma\rightarrow a) \propto \gamma = \left| \frac{2\, g_{a\gamma}^{2}\, B_t^{\;2}\, \nu(1+z)}{\nabla\, \omega_p^{2}} \right|$$



(a) *Variation with redshift*

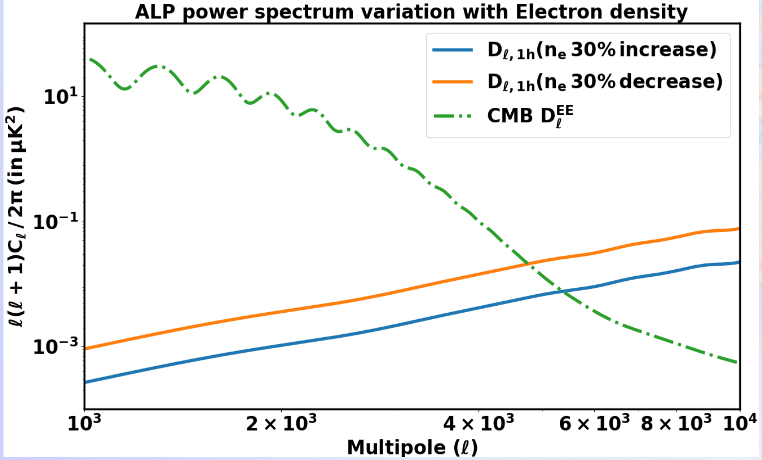


(b) *Variation with Coupling constant*

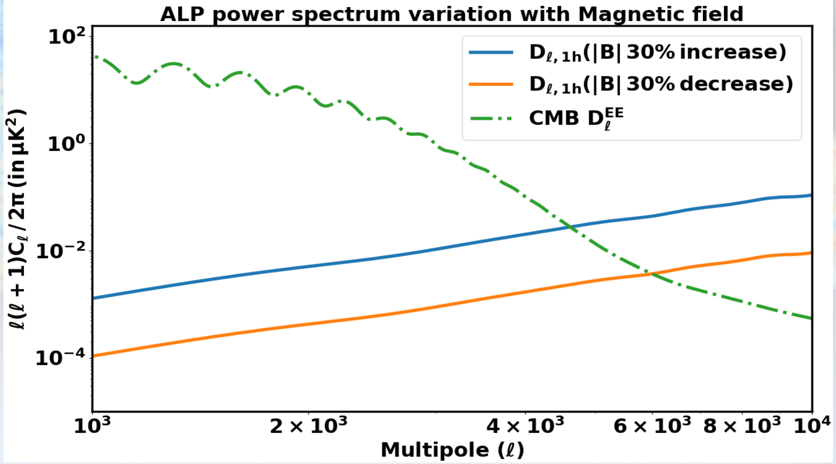


(c) *Variation with frequency*

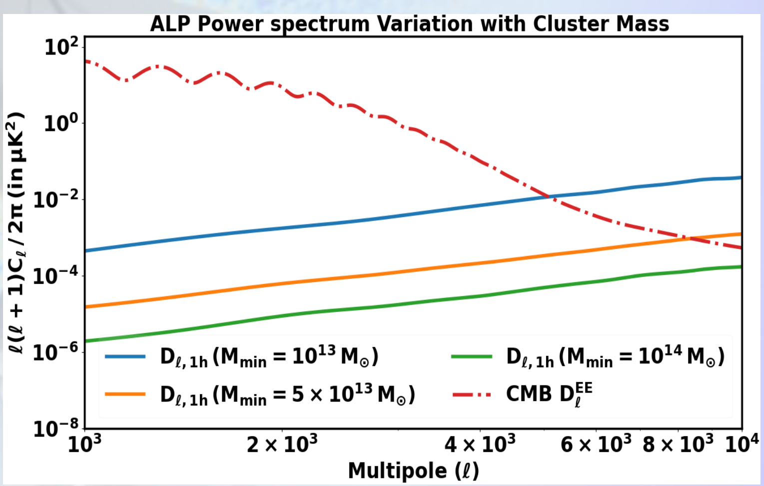
Astrophysical Variations



(a) *Variation with Electron density strength*



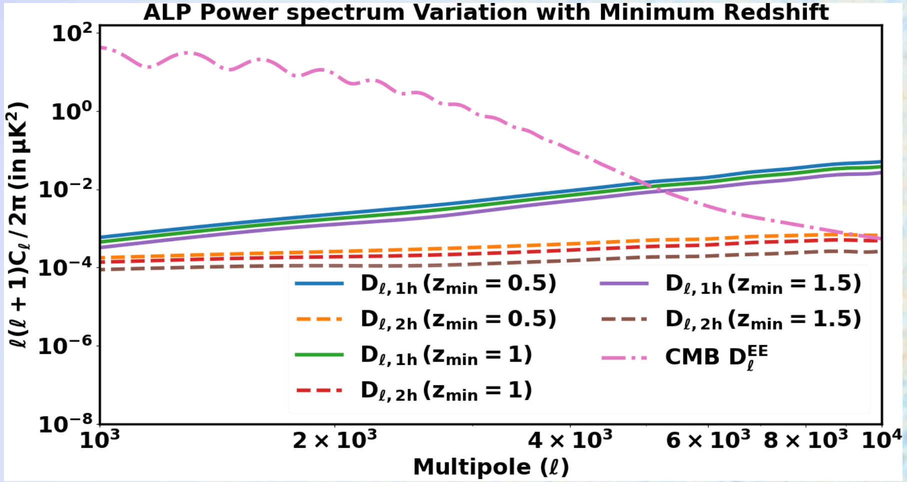
(b) *Variation with Magnetic field steepening*



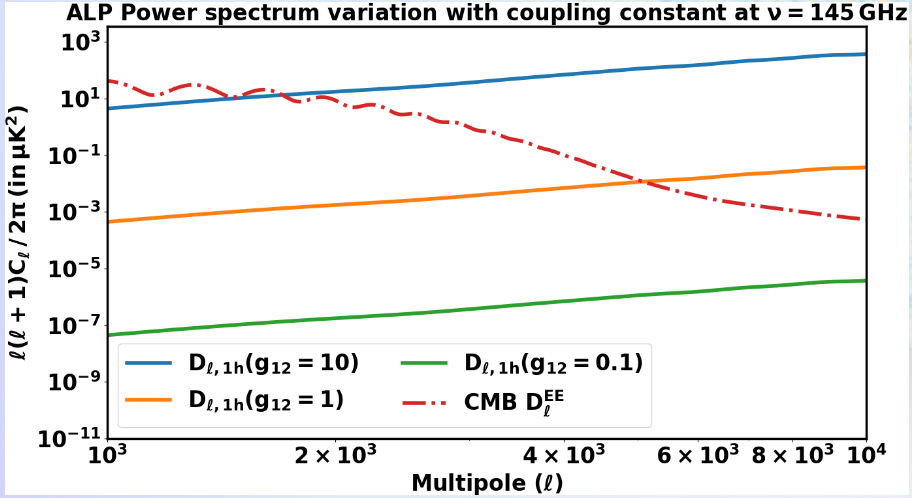
(c) *Variation with Cluster Mass*

$$P(\gamma \rightarrow a) \propto \gamma = \left| \frac{2\, g_{a\gamma}^2\, B_t{}^2\, \nu(1+z)}{\nabla\, \omega_p^2} \right|$$

Cosmological

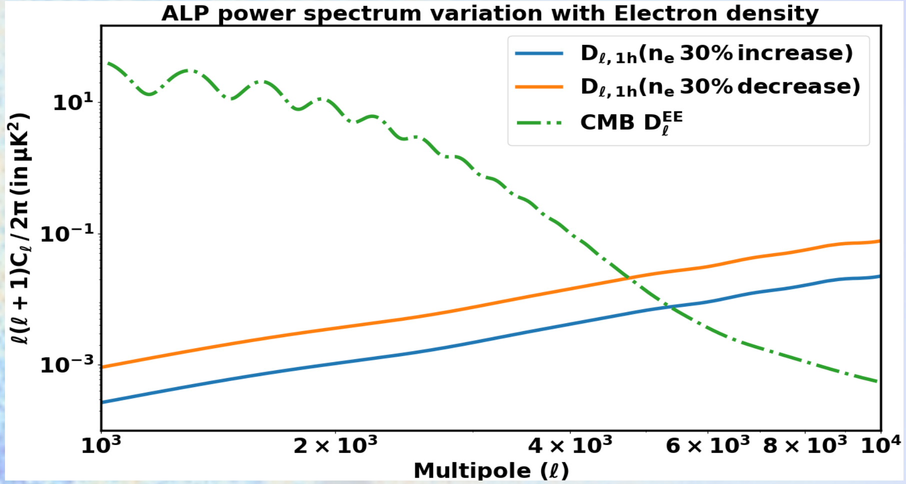


(a) *Variation with redshift*

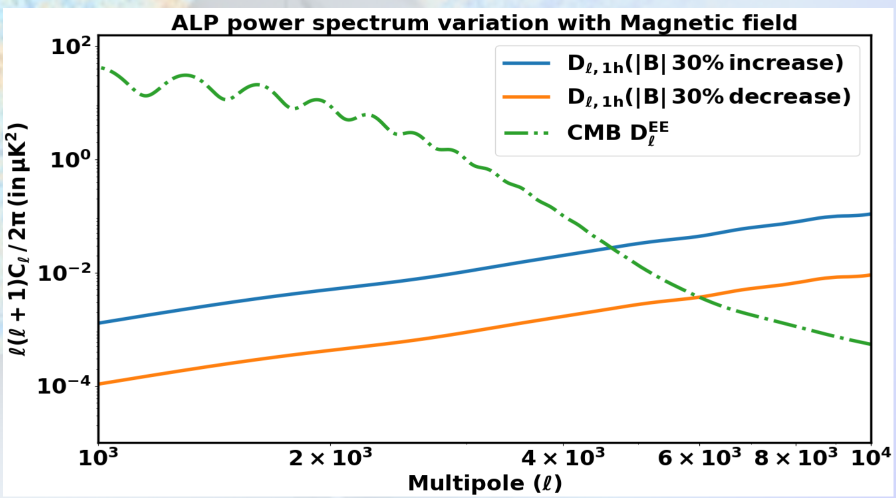


(b) *Variation with Coupling constant*

Astrophysical



(a) *Variation with Electron density strength*



(b) *Variation with Magnetic field steepening*

Simulation setup

➢*Axes being considered:*

$$\hat{z} \rightarrow cos\theta_z$$
$$\hat{x} \rightarrow sin\theta_z cos\theta_x$$
$$\hat{y} \rightarrow sin\theta_z sin\theta_x$$

➢*Local gradient in electron density:*

$$\nabla n_e(x + d_e) = \frac{n_e(x + d_e) - n_e(x)}{d_e}$$

➢*Profiles & Turbulence considered:*

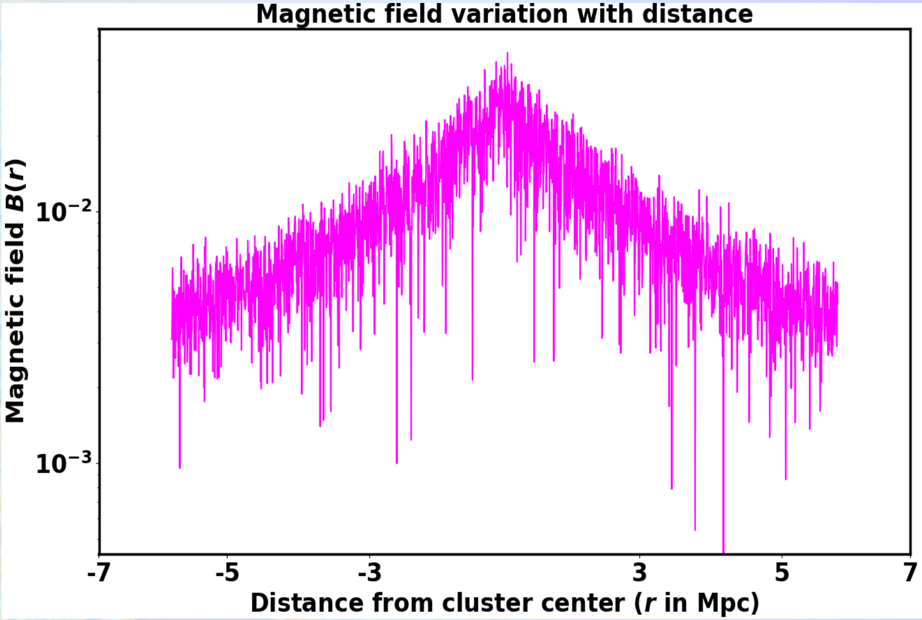
Electron density:

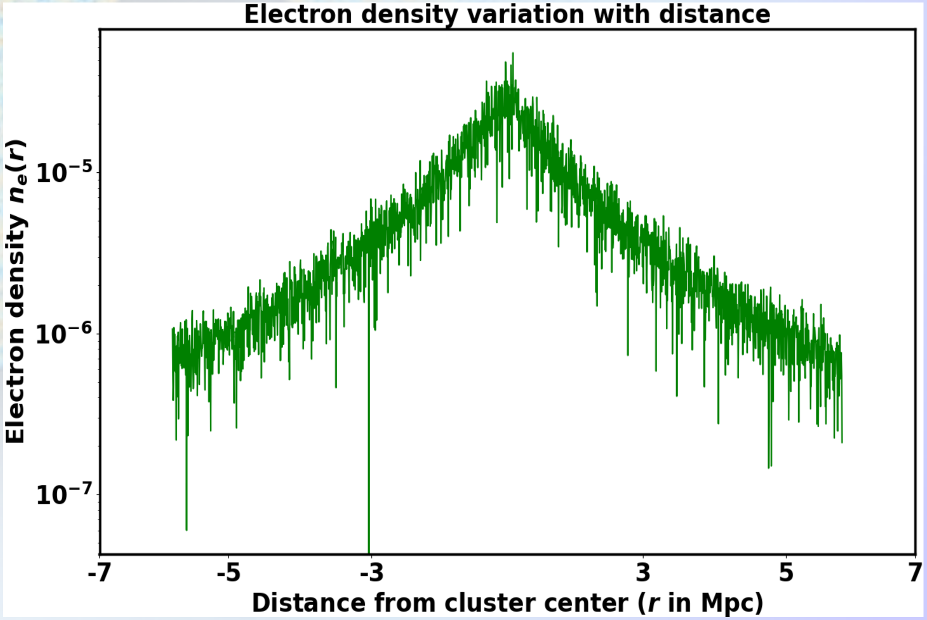
$$n_{es}^2 = Z\left[n_0^2 \frac{(r/r_{c1})^{-\alpha}}{(1 + r^2/r_{c1}^2)^{3\beta-\alpha/2}} \frac{1}{(1 + r^\gamma/r_s^\gamma)^{\epsilon/\gamma}} + \frac{n_{02}^2}{(1 + r^2/r_{c2}^2)^{3\beta_2}}\right]$$

$$n_e(x, y, z) = n_{es}(r) + \mathcal{G}\left[n_{es}(r), \sigma_e\right]$$

Magnetic field:

$$B_s(r) = B_0 r^{-s}$$





ALP DISTORTION IN TEMPERATURE & POLARIZATION

➢ ***ALP signal in temperature:***

$$\Delta I_T(\gamma \to a) = \frac{\pi}{2}\sum_{i=1}^{N} \gamma_{\mathrm{ad},i}\, I_0$$

➢ ***ALP signal in polarization:***

$$\Delta I_Q(\gamma \to a) = \frac{\pi}{2}\sum_{i=1}^{N} \gamma_{\mathrm{ad},i}\left(cos2\theta_x\right)_i I_0, \qquad \Delta I_U(\gamma \to a) = \frac{\pi}{2}\sum_{i=1}^{N} \gamma_{\mathrm{ad},i}\left(sin2\theta_x\right)_i I_0,$$

$$\Delta I_P(\gamma \to a) = \sqrt{\Delta I_Q^2 + \Delta I_U^2}$$

➢ ***The signal is decomposed to spherical harmonics:***

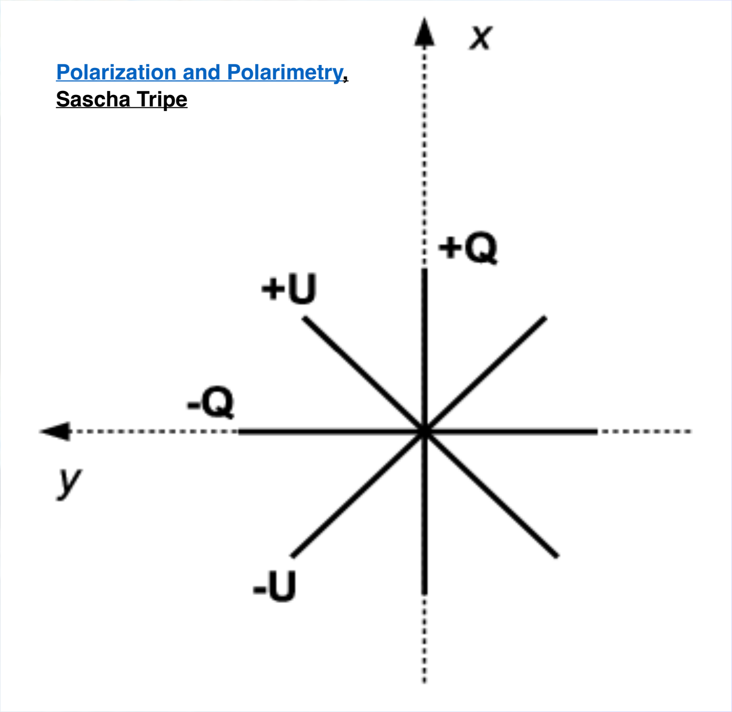
$$I^{ax} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

➢ ***The multipoles can be approximated as:***

$$\ell = \frac{180^o}{\theta\ (in\ degrees)}$$

➢ ***The power spectrum is given as:***

$$C_\ell^{ax} = \left\langle a_{\ell m}^{ax\,*} a_{\ell m}^{ax} \right\rangle$$



Summary statistics of the CMB: Power spectrum

- ***The signal is decomposed to spherical harmonics:***

$$I^{ax} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

- ***The multipoles can be approximated as:***

$$\ell = \frac{180^o}{\theta \text{ (in degrees)}}$$

- ***The signal is affected by beam:*** $\tilde{a}^{ax}_{\ell m} = B_\ell \, a^{ax}_{\ell m}$

Here $B_\ell = exp\left[-\ell(\ell+1)\theta^2_{beam}/2\right]$

- ***The power spectrum is given as:***

$$C^{ax}_\ell = \langle a^{ax\,*}_{\ell m} a^{ax}_{\ell m} \rangle$$

- ***The ALP power spectrum is estimated as:*** $\hat{C}^{ax}_\ell = \frac{B_\ell^{-2}}{2\ell+1} \sum_{m=-\ell}^{\ell} \tilde{a}^{ax\,*}_{lm} \tilde{a}^{ax}_{lm}$