

DISCOVERING AXION-LIKE PARTICLES USING CMB AS A BACKLIGHT

Harsh Mehta

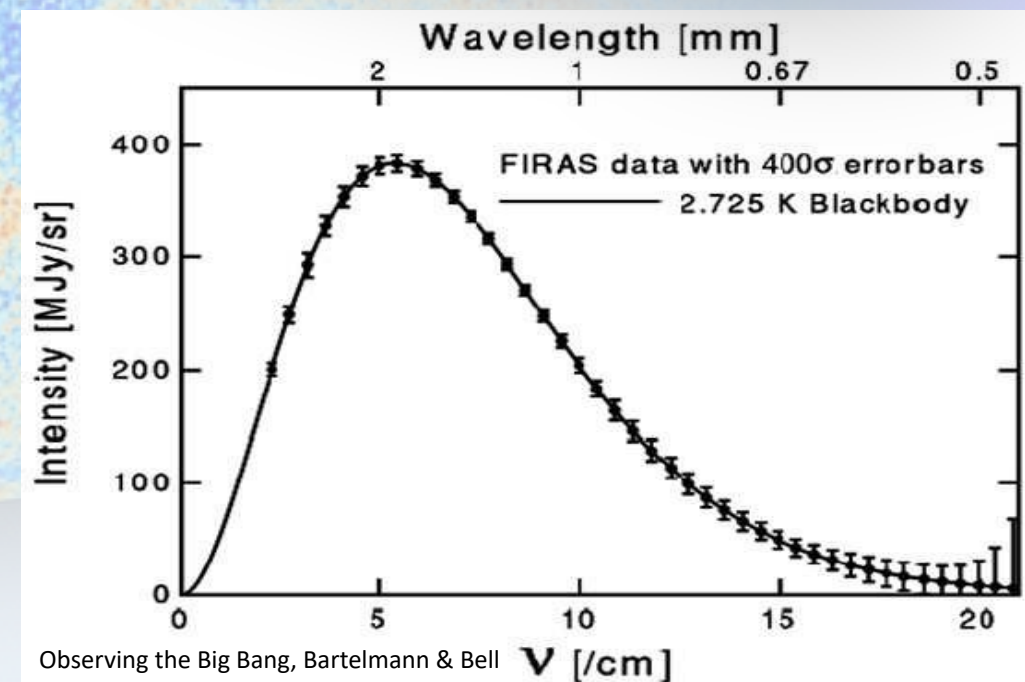
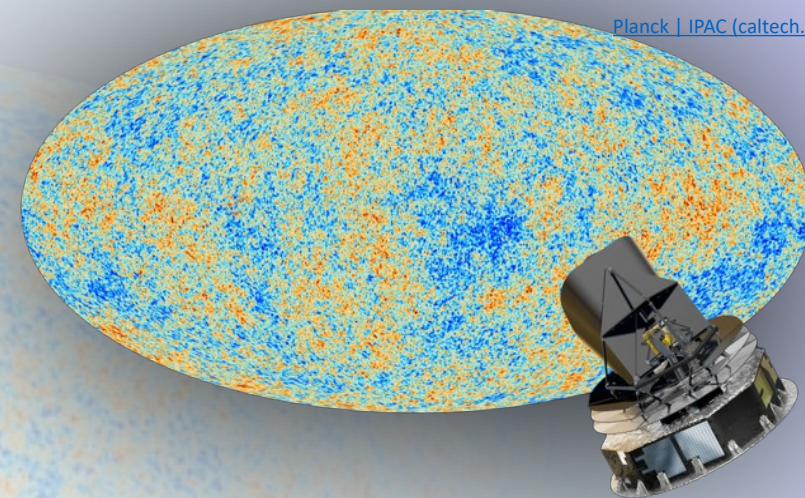
**Department of Astronomy & Astrophysics,
Tata Institute of Fundamental Research, Mumbai, India**

**Challenges at the CMB Frontier
Chino Cultural Complex, Chino, Japan
3rd July, 2026**



Probing Axions using spatial anisotropic spectral distortion

- *Axions or ALPs are cold dark matter candidates.*
- *They have a weak interaction with photons.*
- *The CMB is almost an ideal blackbody with $T_{\text{cmb}} = 2.7255 \text{ K}$ and its power spectrum is well known.*
- *Deviations resulting from weak photon coupling can be probed to detect ALPs.*



CMB photon-ALP resonant conversion

➤ *How it happens?*

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

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

➤ *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:

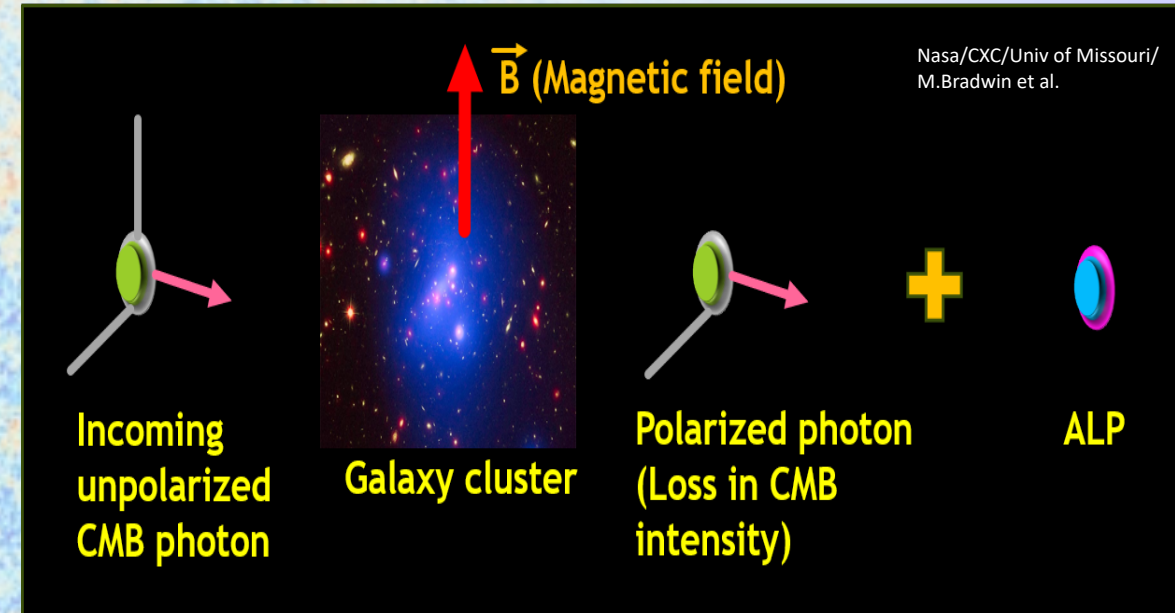
$$P(\gamma \rightarrow a) \approx \pi\gamma,$$

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

➤ *Observable effect:*

❑ *Polarization of CMB photons*

❑ *Change in CMB intensity: $\Delta I(\nu) = P(\gamma \rightarrow a) I_{cmb}(\nu)$*



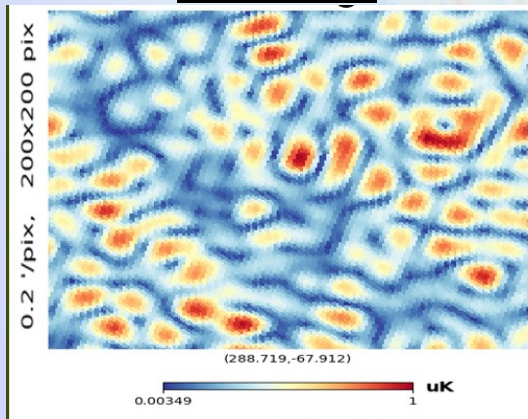


ALP resonant conversion in
galaxy clusters

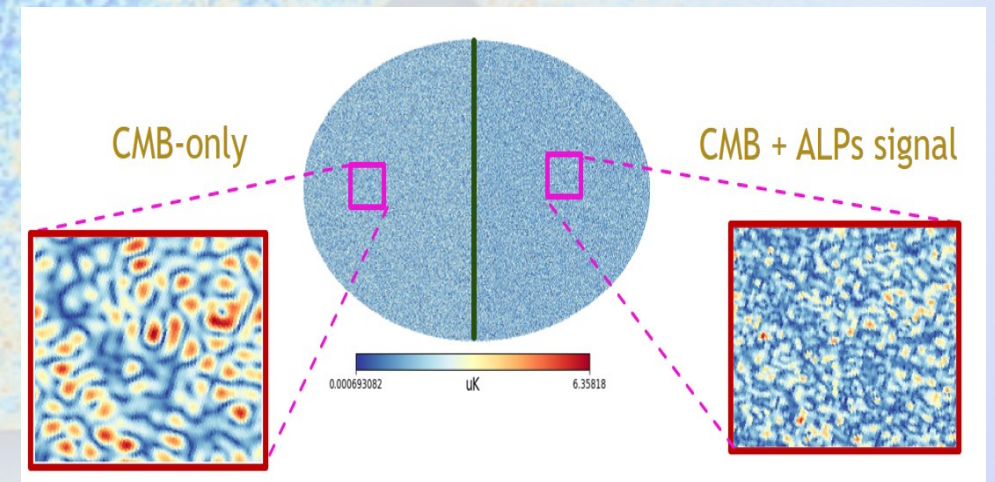
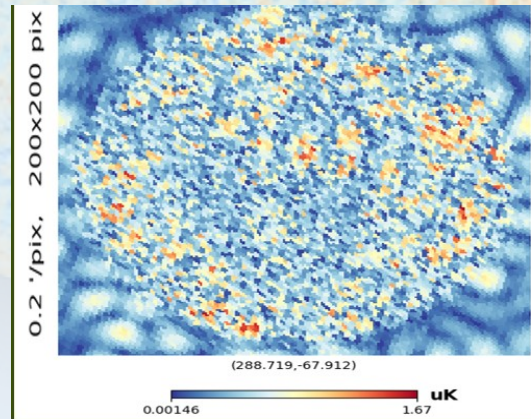
Resolved clusters
Visible at multiple EM
frequencies

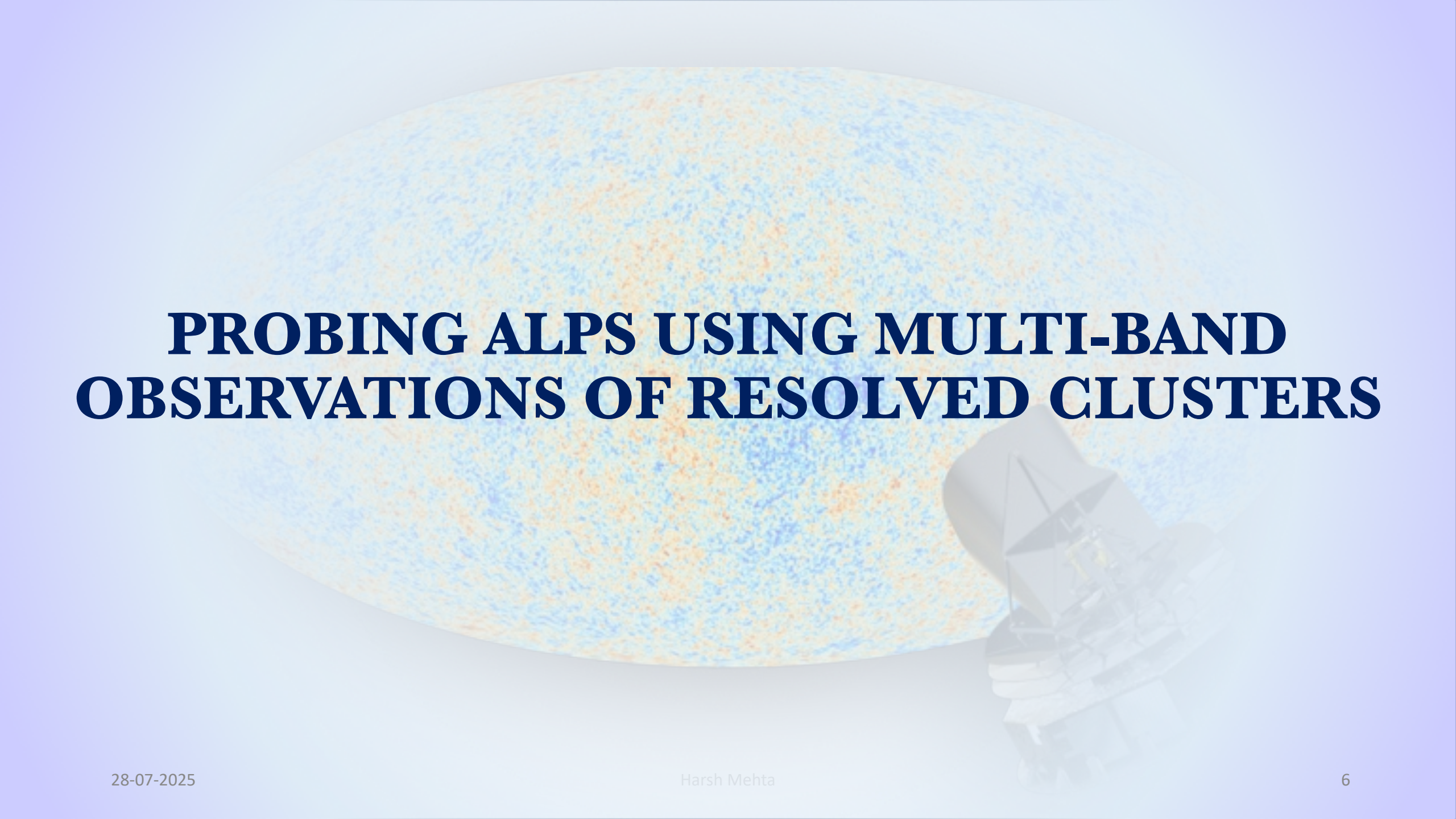
Unresolved clusters
Not visible at multiple
EM frequencies

CMB only



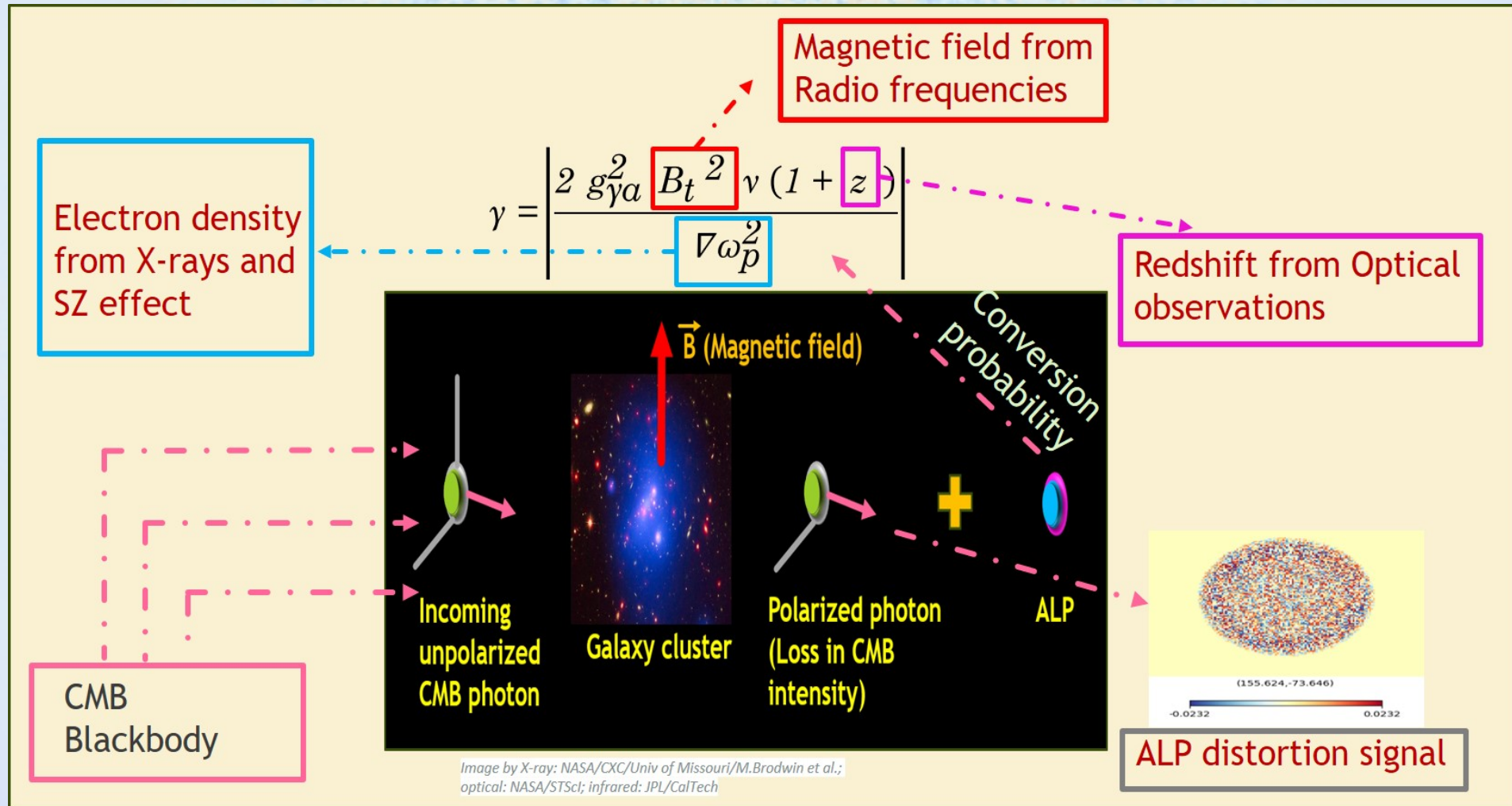
CMB + ALP

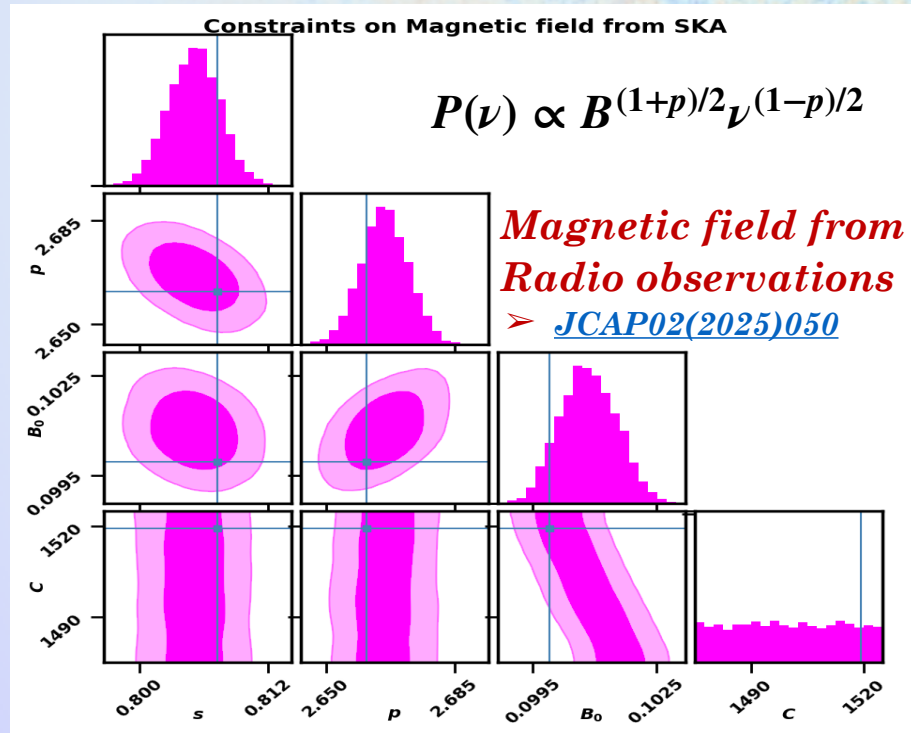
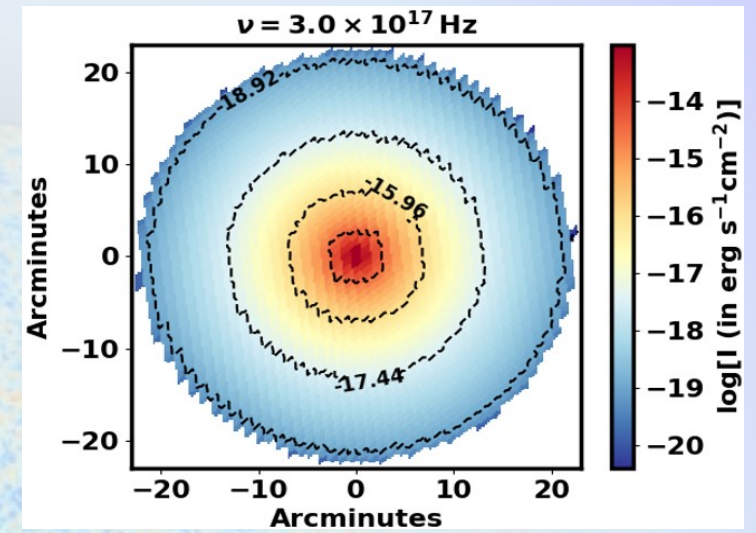
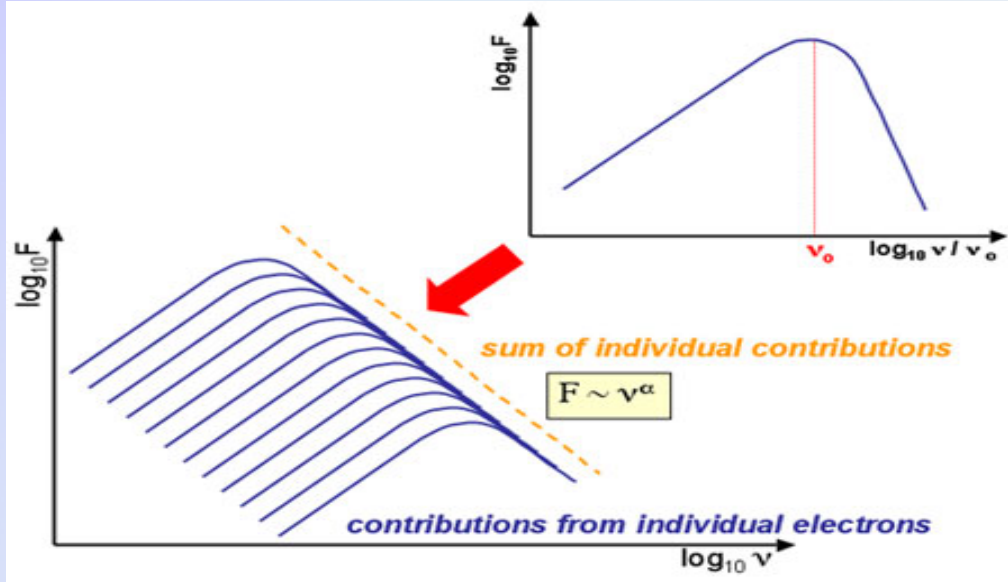




PROBING ALPS USING MULTI-BAND OBSERVATIONS OF RESOLVED CLUSTERS

WHY MULTI-BAND OBSERVATIONS?

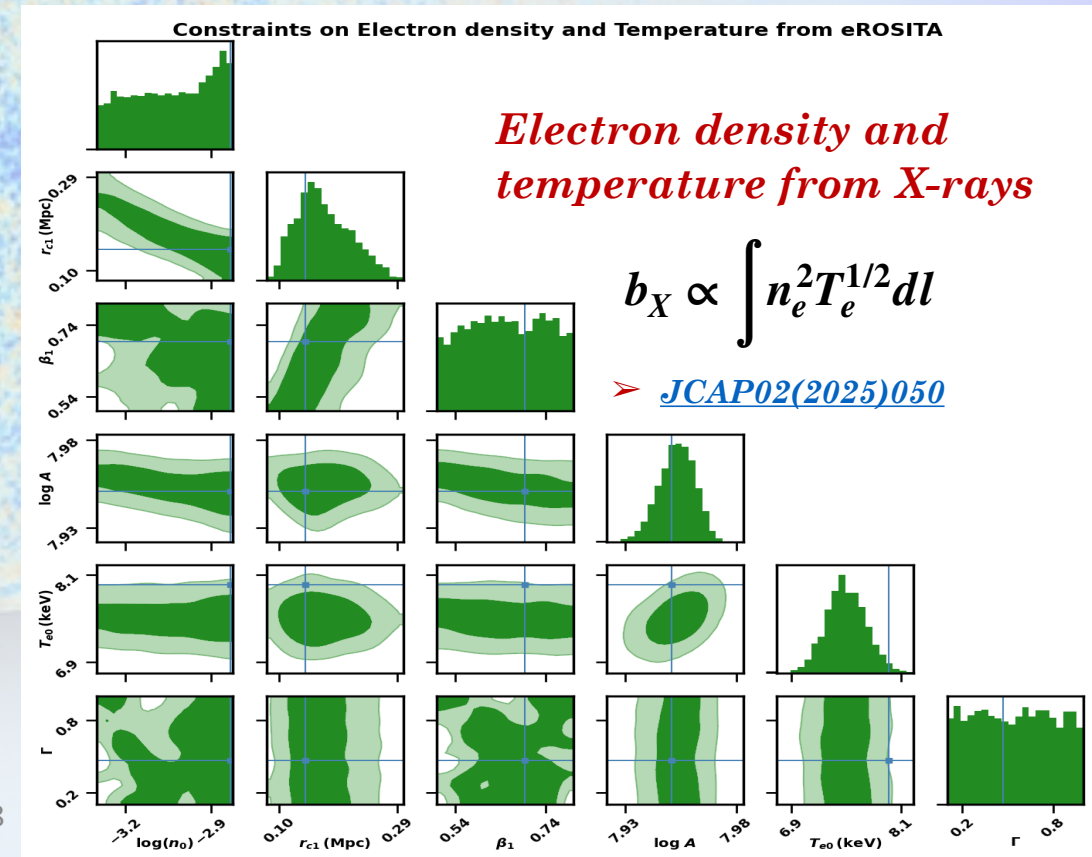


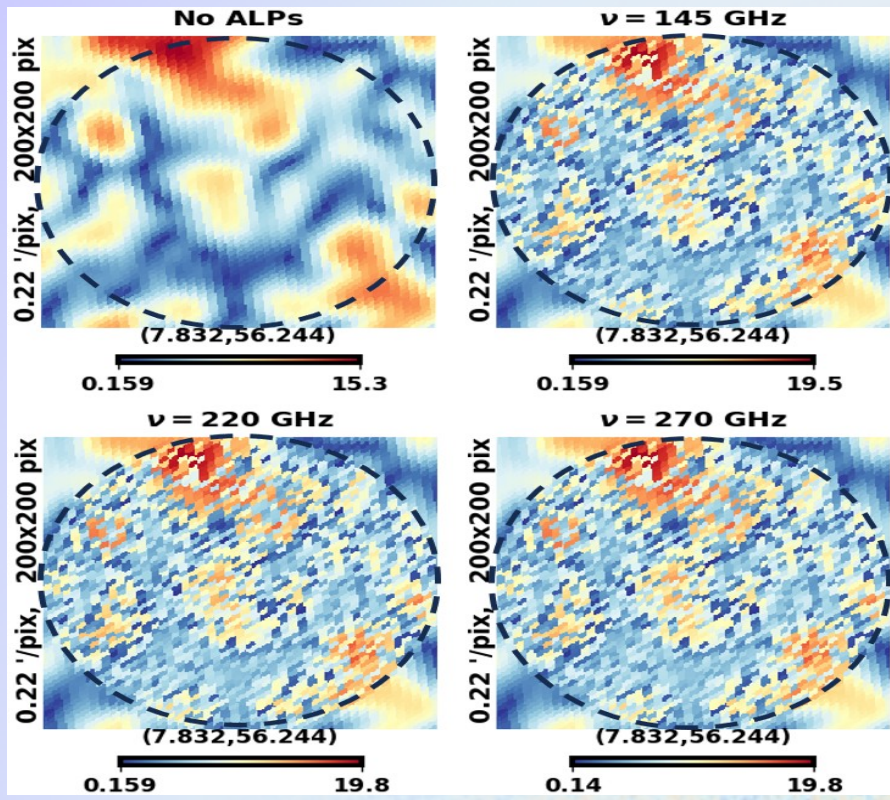


28-07-2025

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➤ [JCAP02\(2025\)050](#)

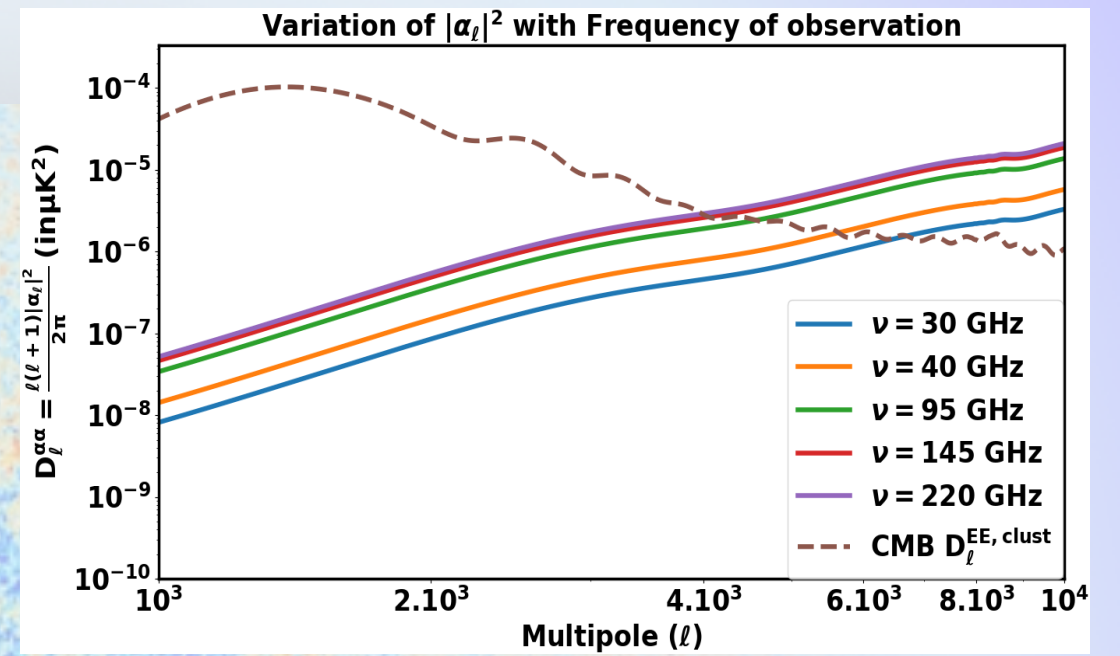
➤ The signal is decomposed to spherical harmonics:

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

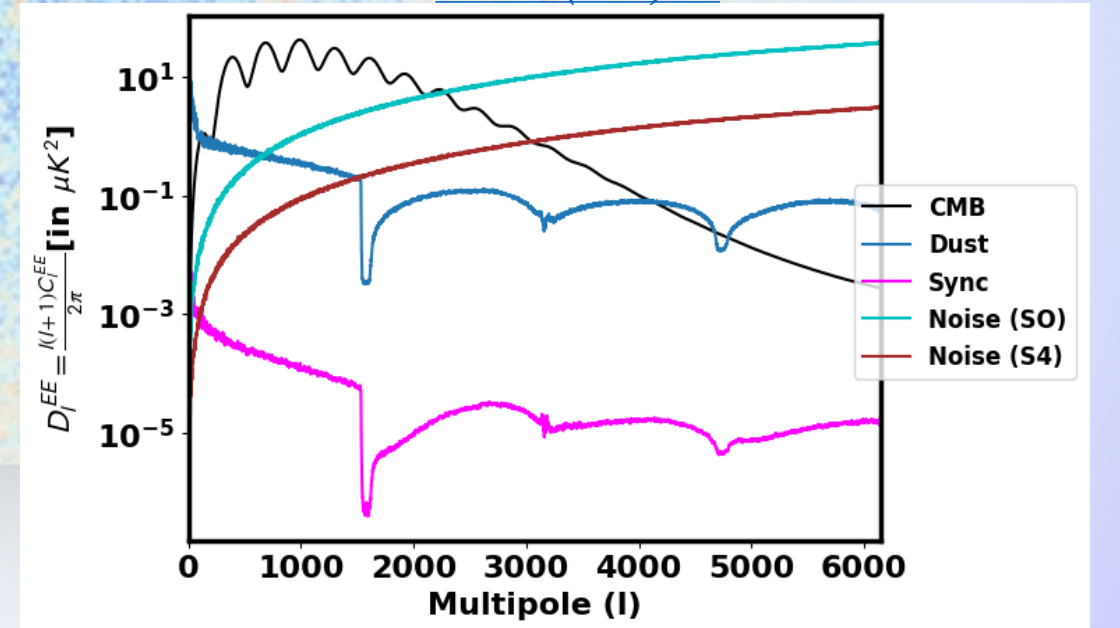
➤ The power spectrum is given as:

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

Harmonic transform

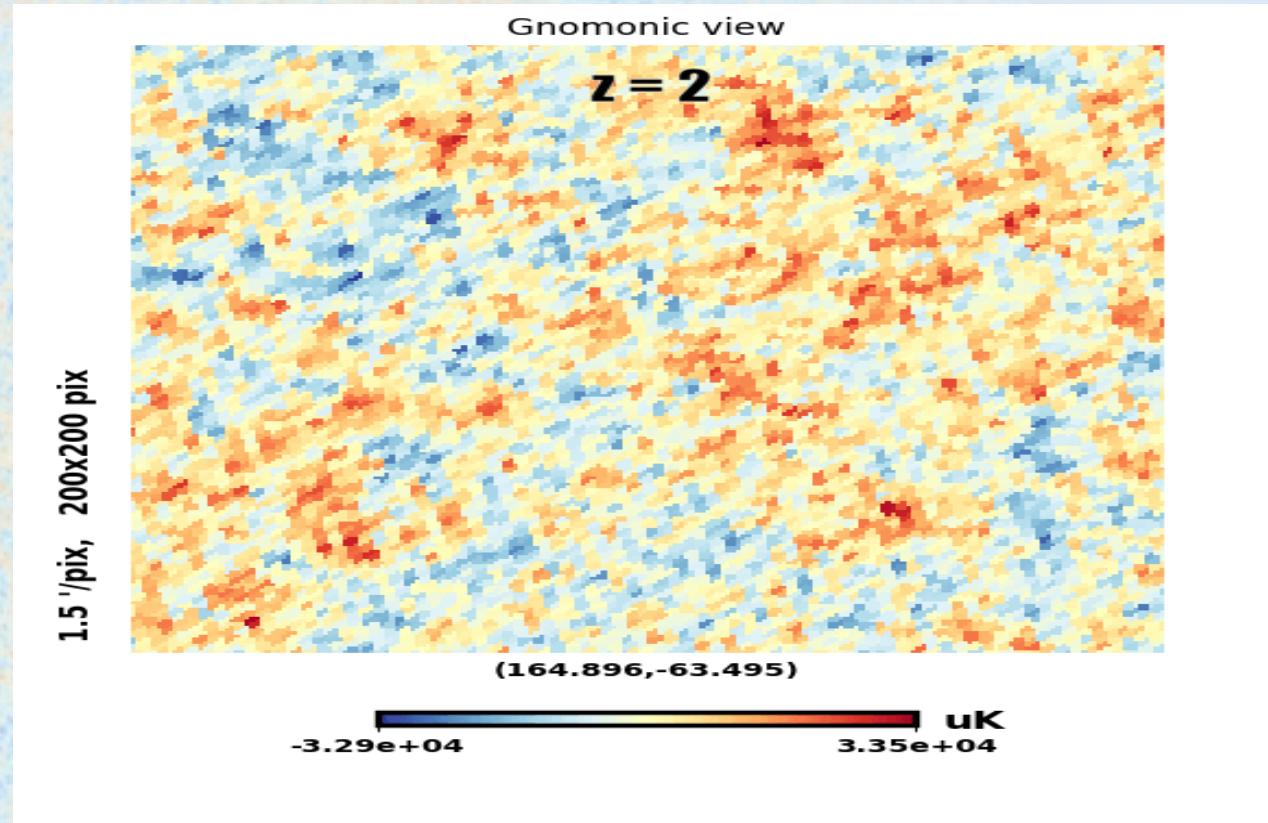


➤ [JCAP07\(2024\)084](#)



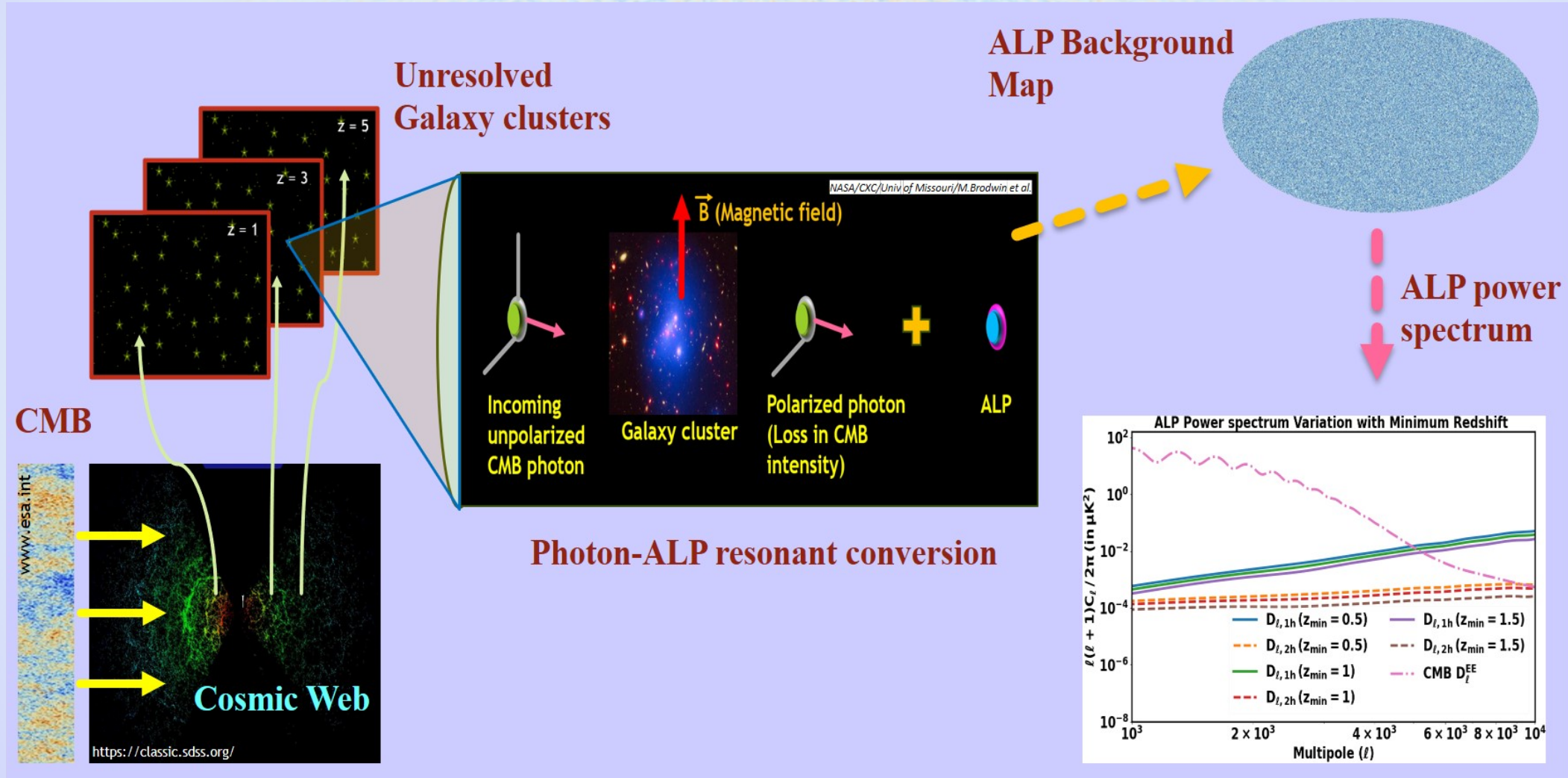
PROBING ALPS USING UNRESOLVED CLUSTERS

BACKGROUND SIGNAL FROM UNRESOLVED CLUSTERS

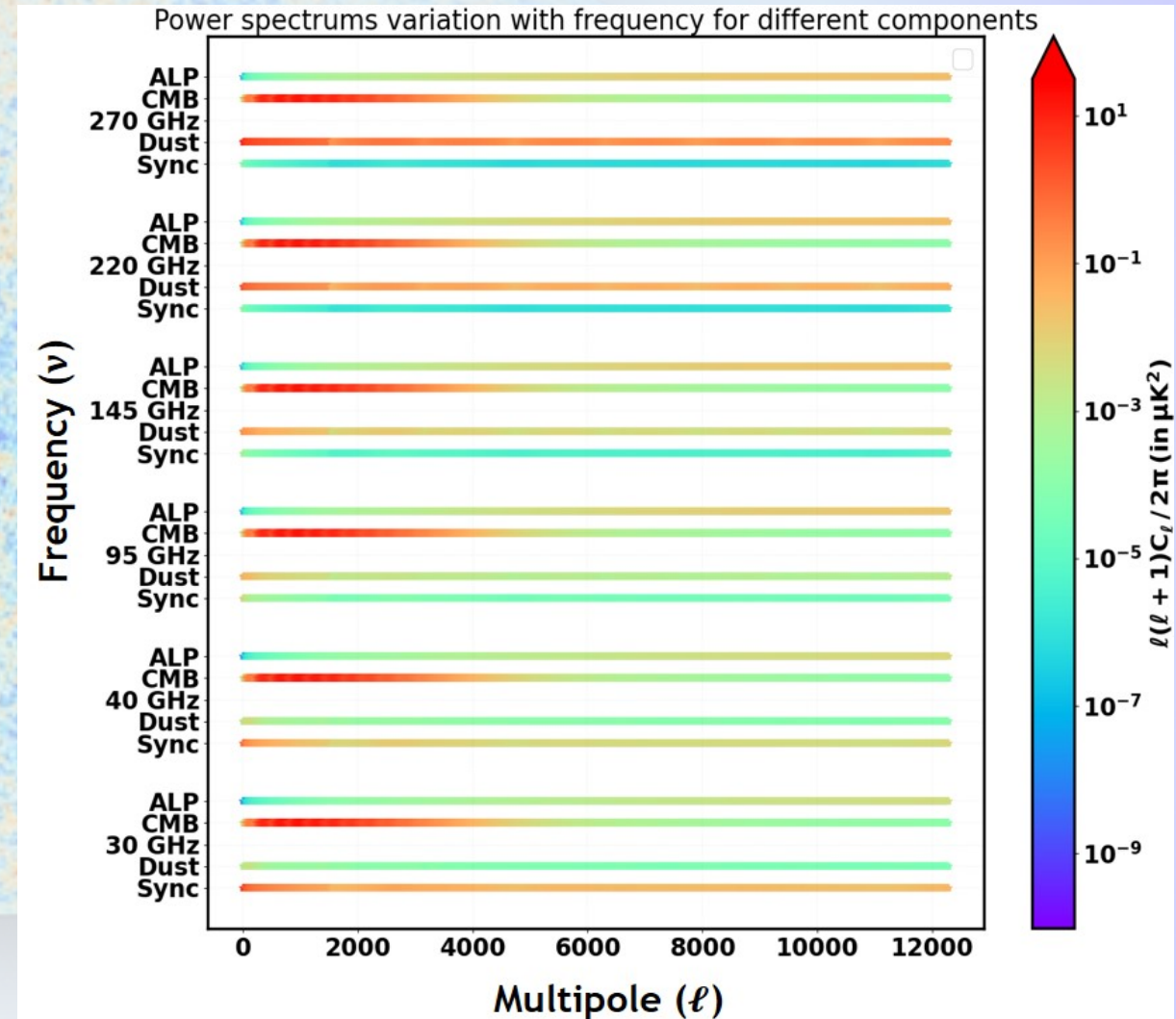
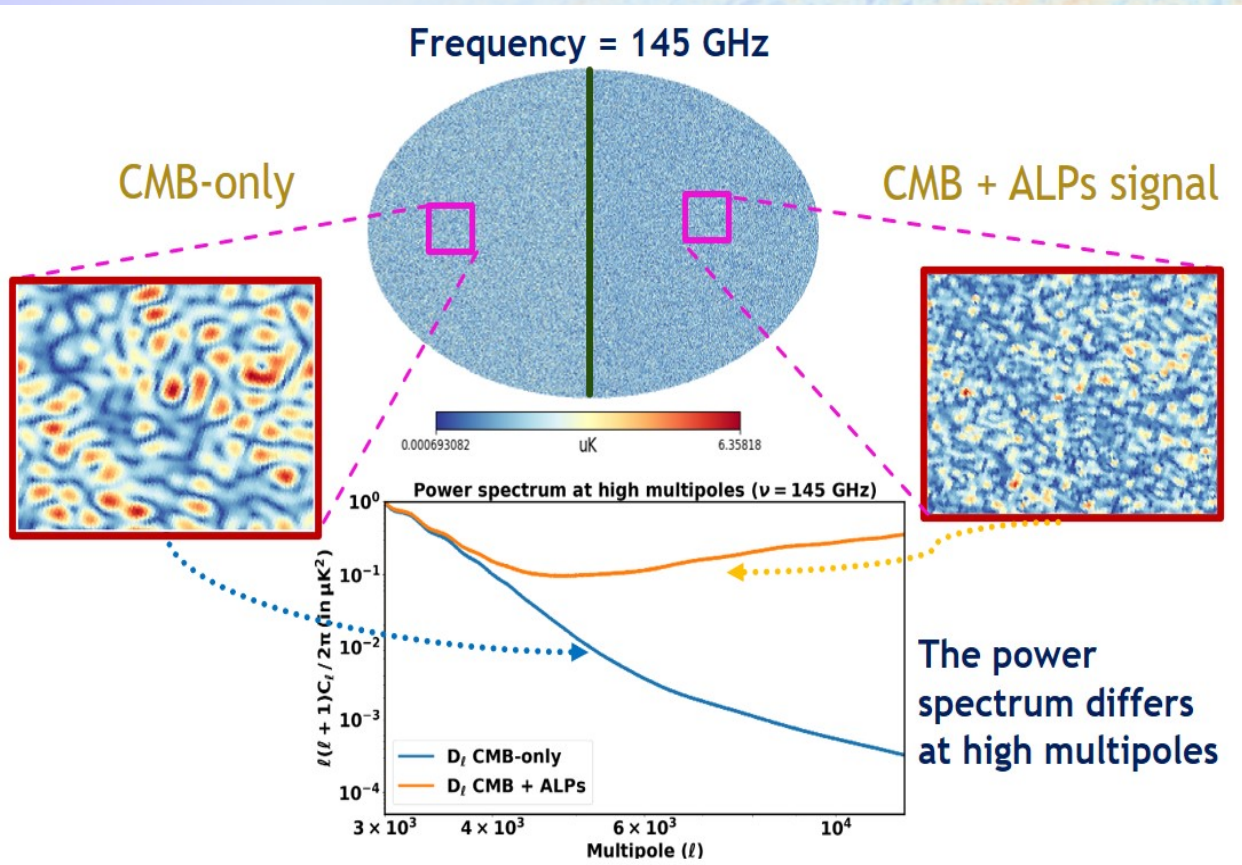


Galaxy clusters can be modelled as halos of mass range $10^{13} - 7 \cdot 10^{15} M_{\odot}$

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

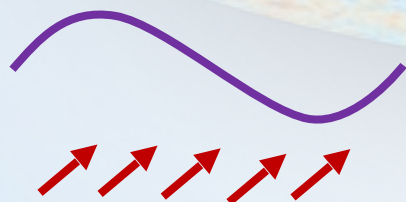
The magnetic field variation scale

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

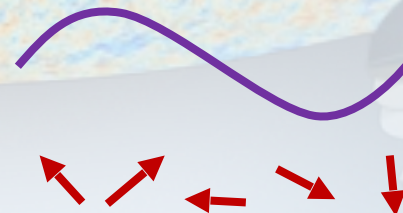
$$\Delta_e = -\omega_p^2/2\omega \quad \Delta_a = -m_a^2/2\omega \quad \Delta_{a\gamma} = g_{a\gamma}B_t/2 \quad \Delta_{osc}^2 = (\Delta_e - \Delta_a)^2 + 4\Delta_{a\gamma}^2$$

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

➤ *Low Coherence length causes depolarization:*



Polarization of the ALP signal retained

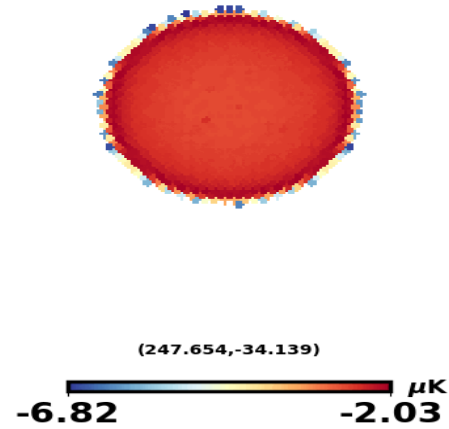


Depolarization of the ALP signal

Varying magnetic field domain size

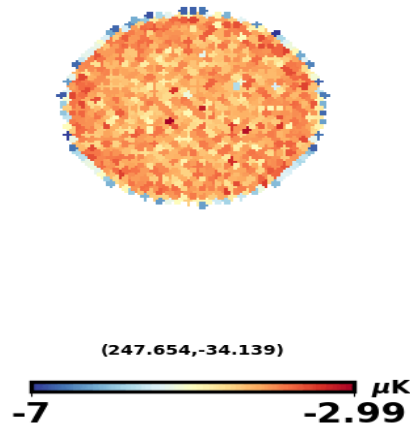
ALP ΔT with $\sigma_e = 0.1 n_e$, $d_B = 100$ pc

0.7 ' / pix, 200x200 pix



ALP ΔP with $\sigma_e = 0.1 n_e$, $d_B = 100$ pc

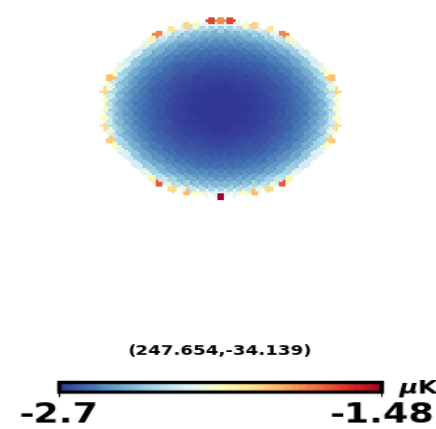
0.7 ' / pix, 200x200 pix



Varying magnetic field inhomogeneity

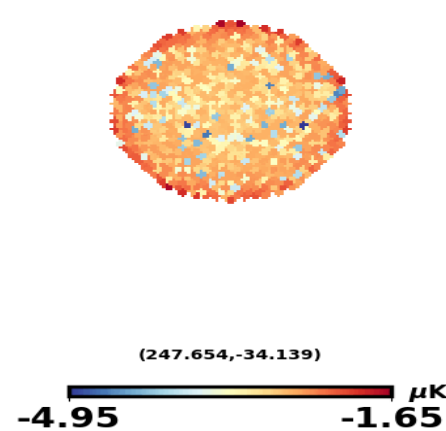
ALP ΔT with $\sigma_e = 0$, $\sigma_B = 0$

0.7 ' / pix, 200x200 pix



ALP ΔP with $\sigma_e = 0$, $\sigma_B = 0$

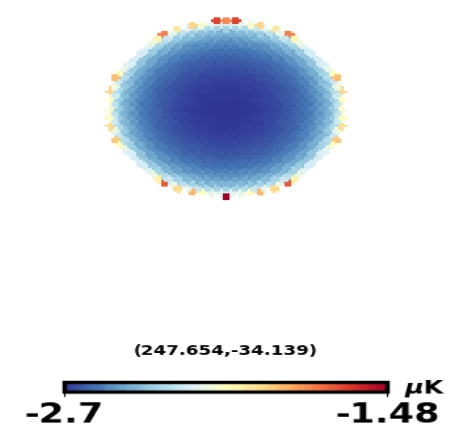
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Varying electron density inhomogeneity

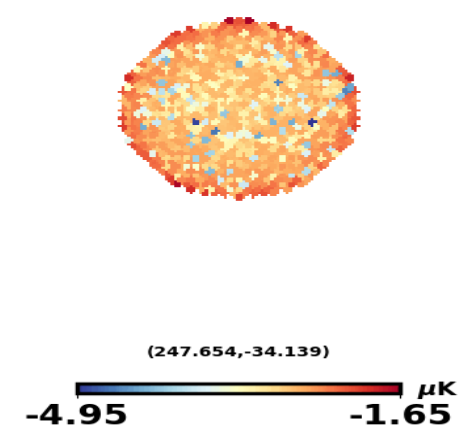
ALP ΔT with $\sigma_e = 0$, $\sigma_B = 0$

0.7 ' / pix, 200x200 pix



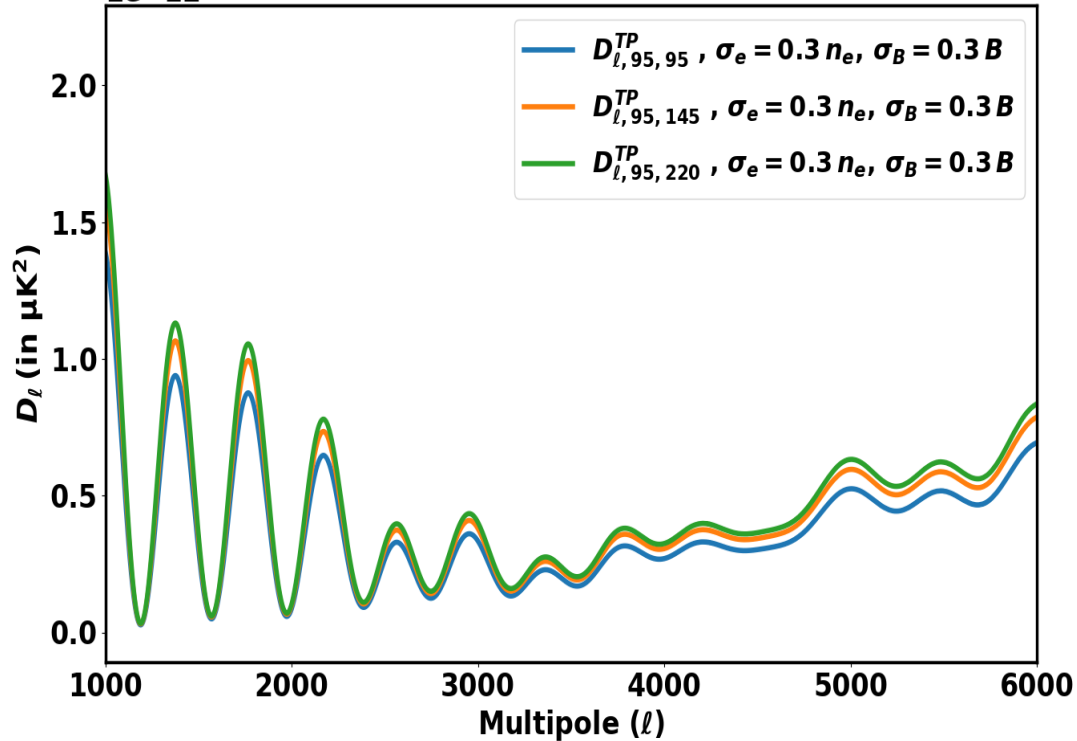
ALP ΔP with $\sigma_e = 0$, $\sigma_B = 0$

0.7 ' / pix, 200x200 pix



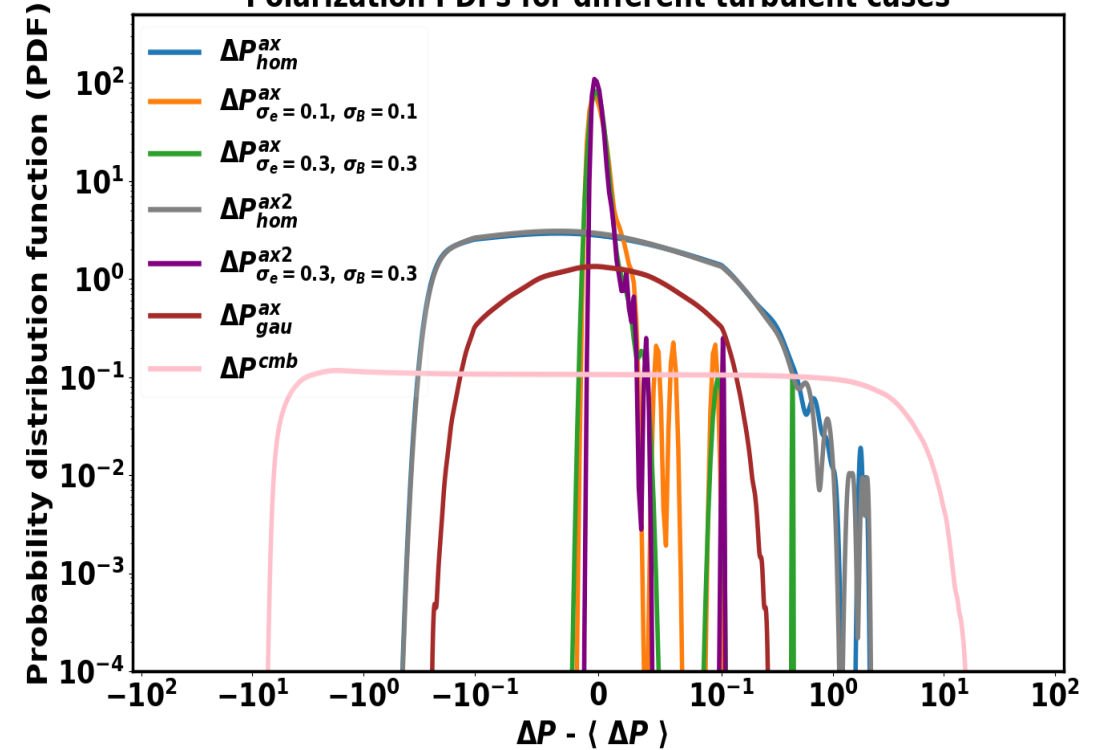
OBSERVABLES TO PROBE THE ALP SIGNAL

ALP $D_{\ell, \nu, \nu'}^{TP}$ spectrum variation with inhomogeneity in $|B|$ and n_e (ν in GHz)
1e-12



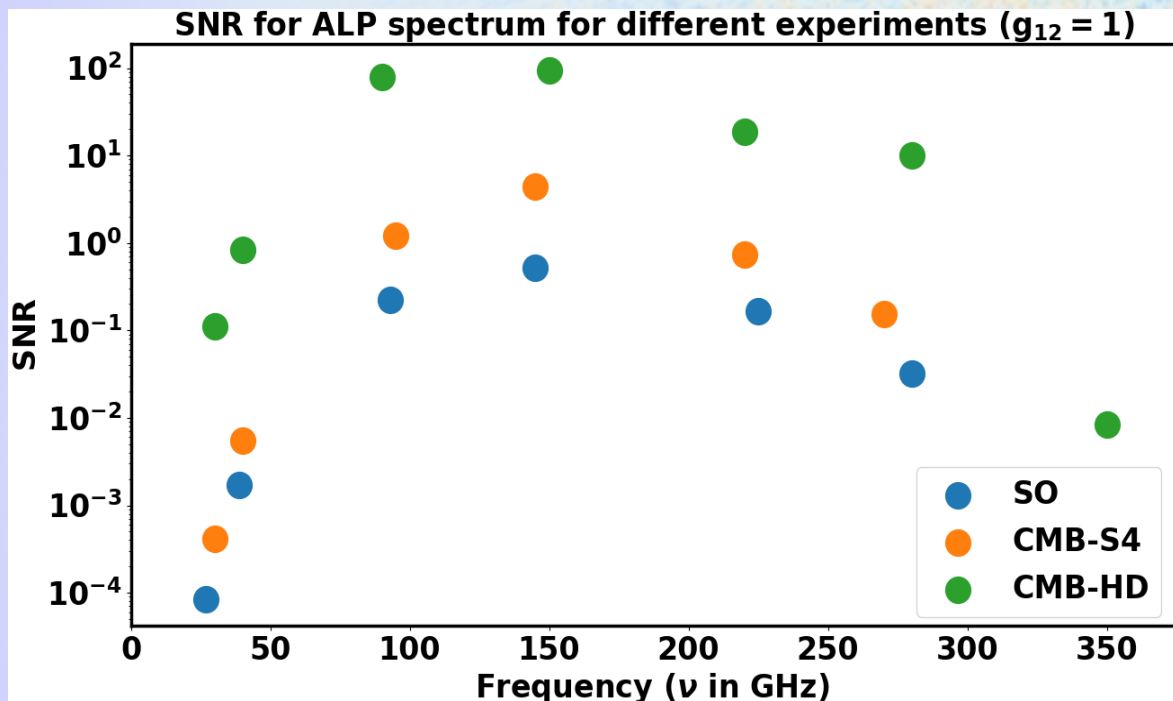
Cross Temperature-Polarization (TP) power spectrum ➤ [JCAP05\(2025\)051](#)

Polarization PDFs for different turbulent cases

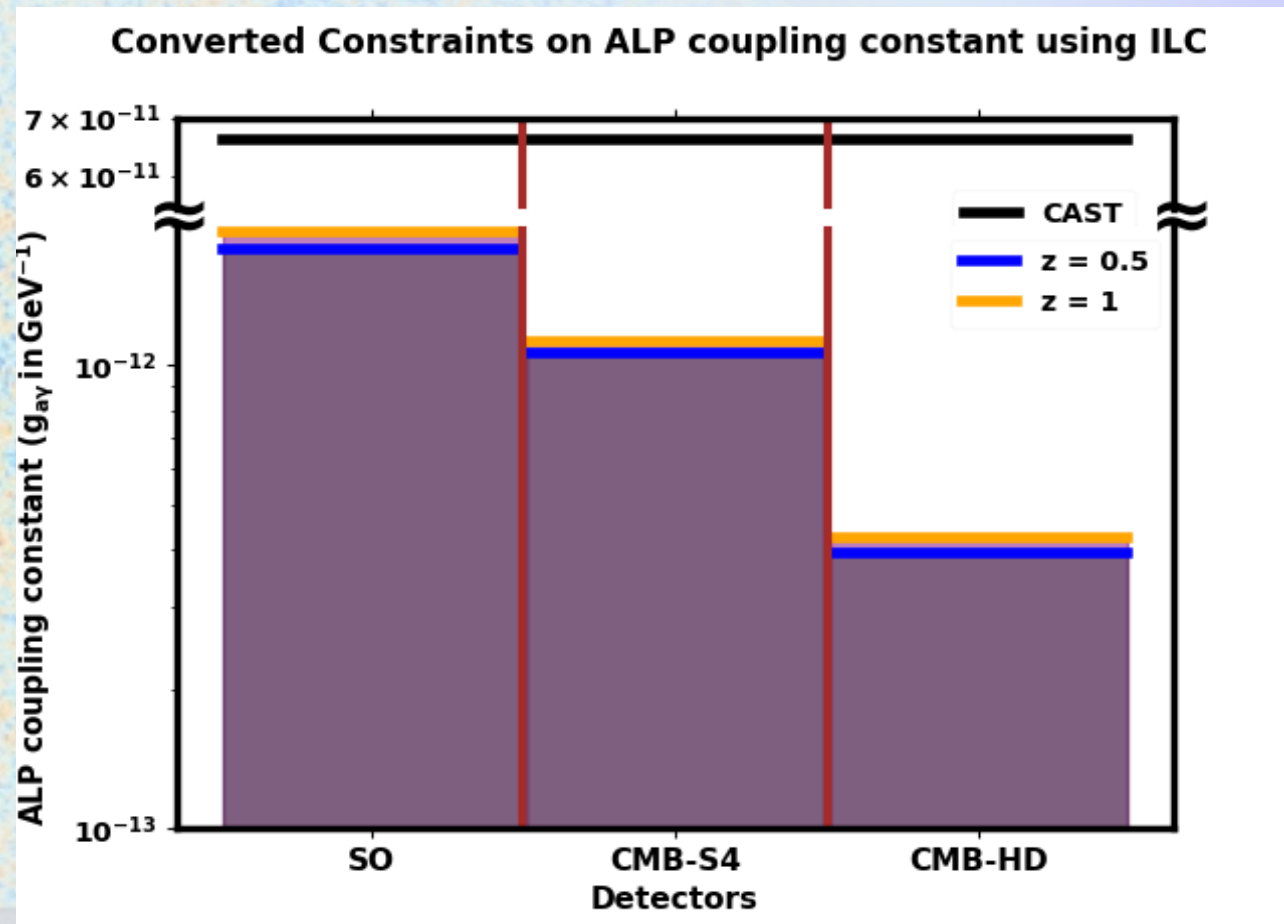


Turbulence dependent non-Gaussian signal ➤ [JCAP05\(2025\)051](#)

HOW WELL CAN THE ALP SIGNAL BE MEASURED?

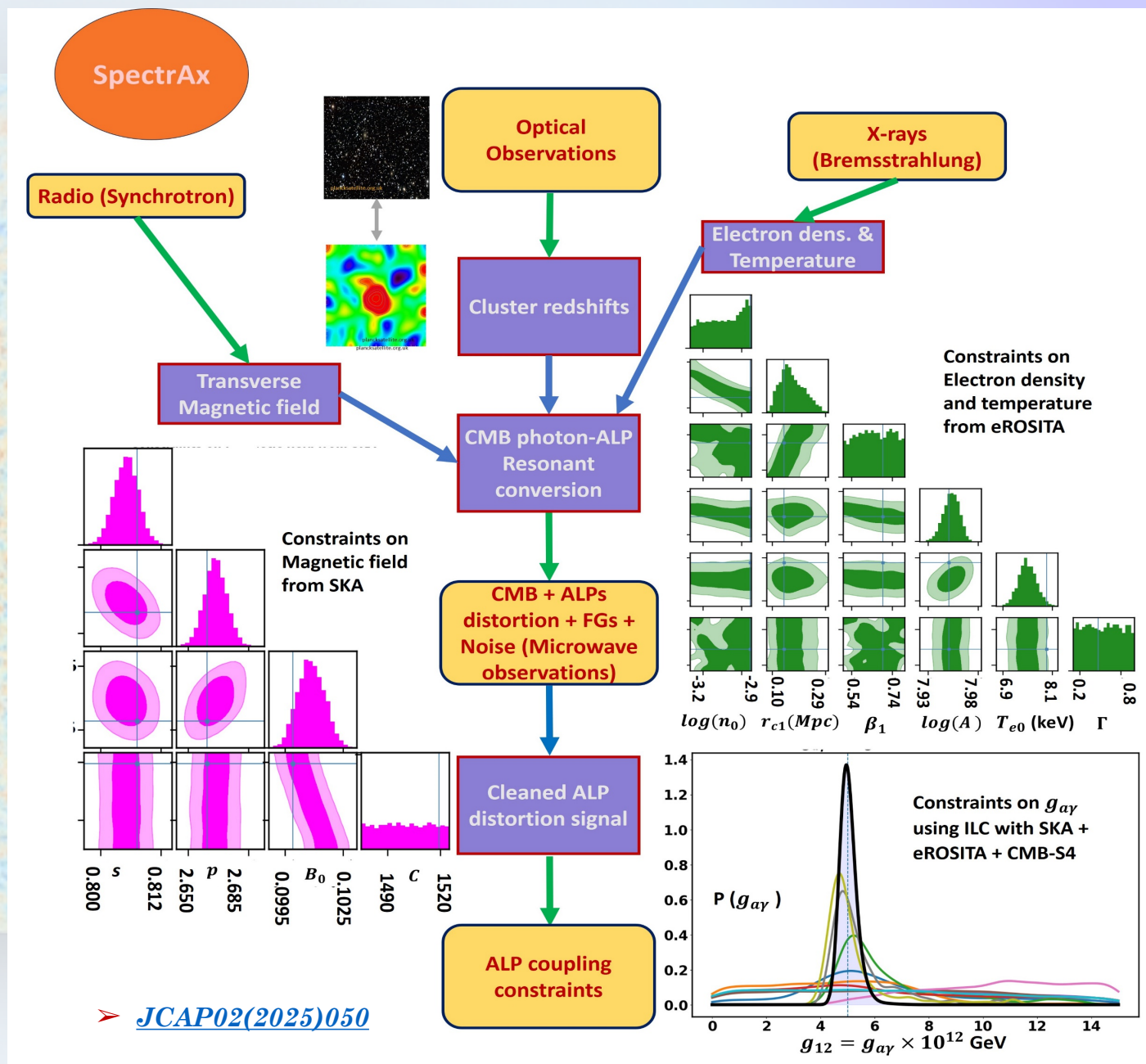
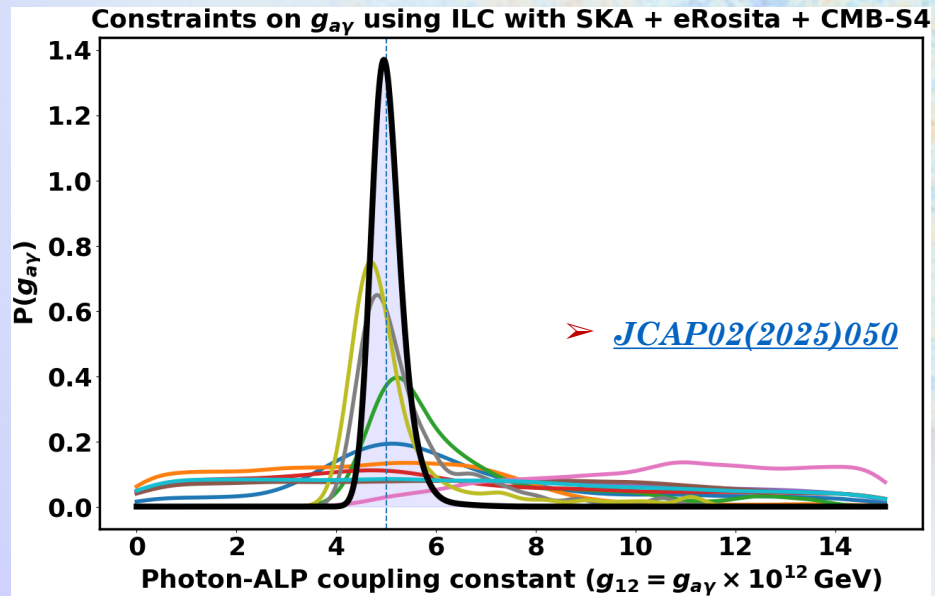
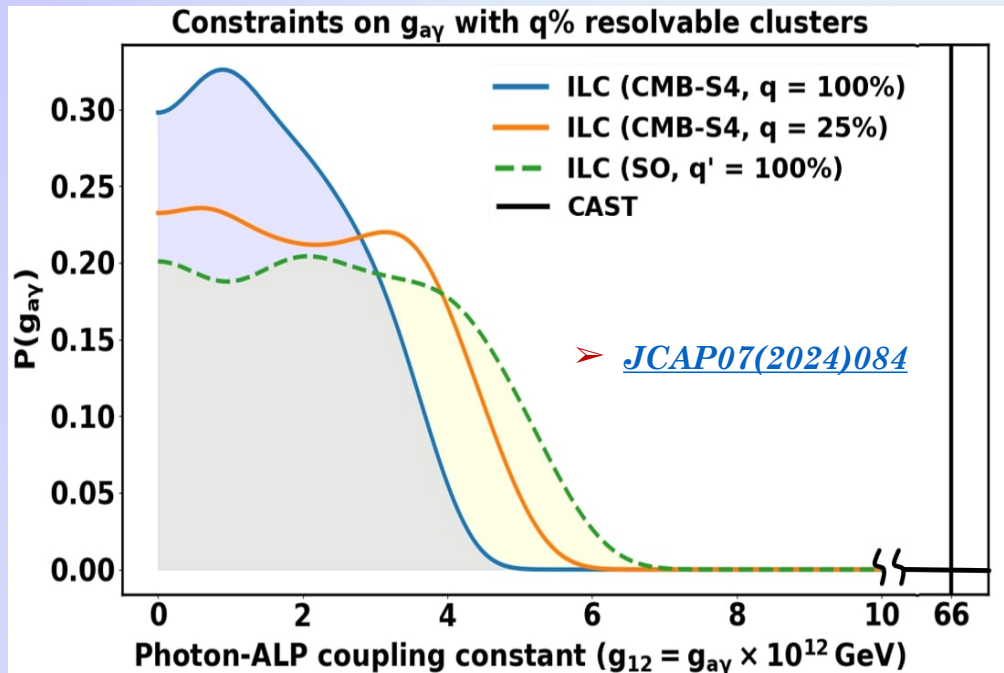


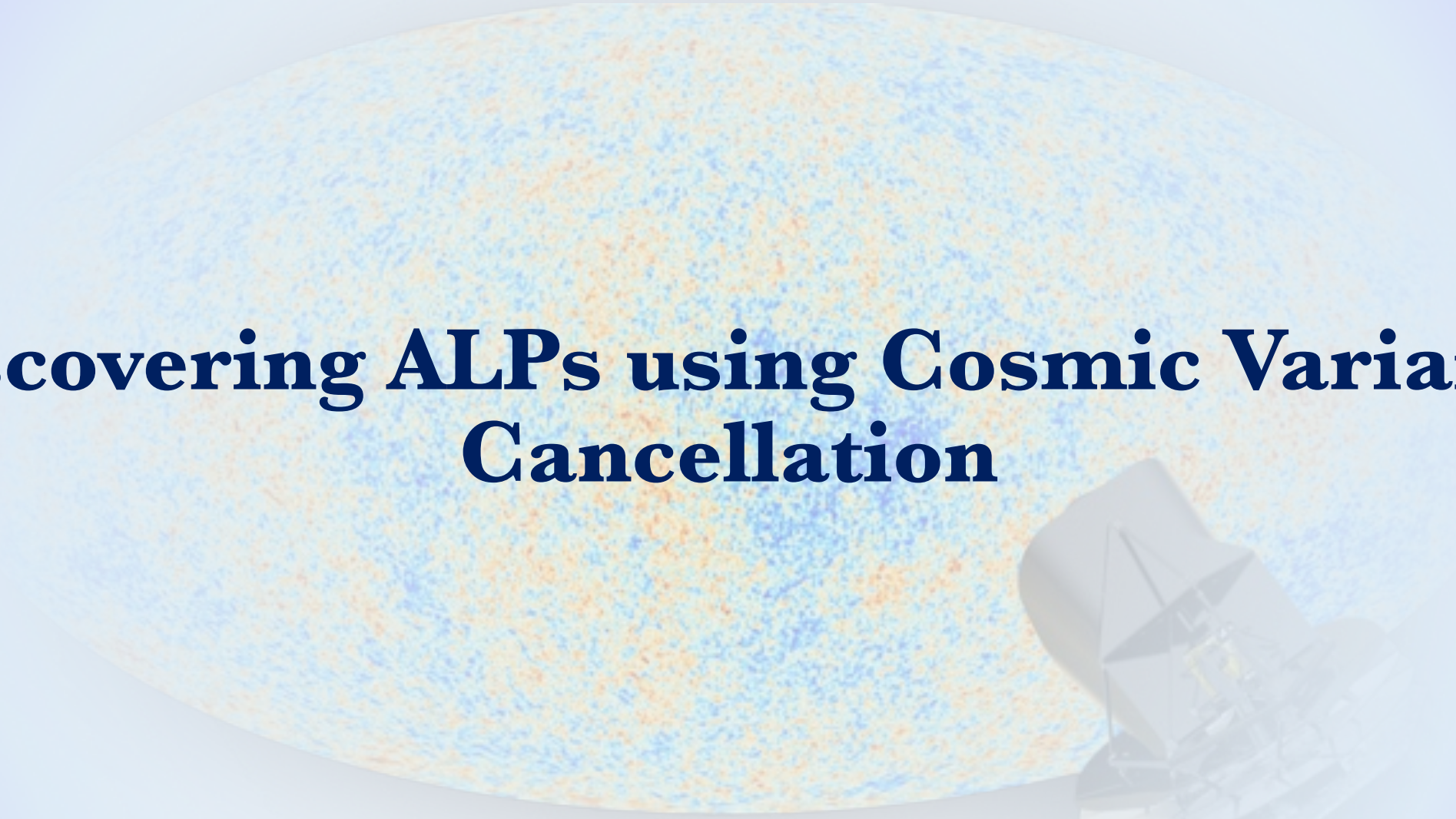
➤ [JCAP07\(2024\)084](#)



➤ [JCAP07\(2024\)084](#)

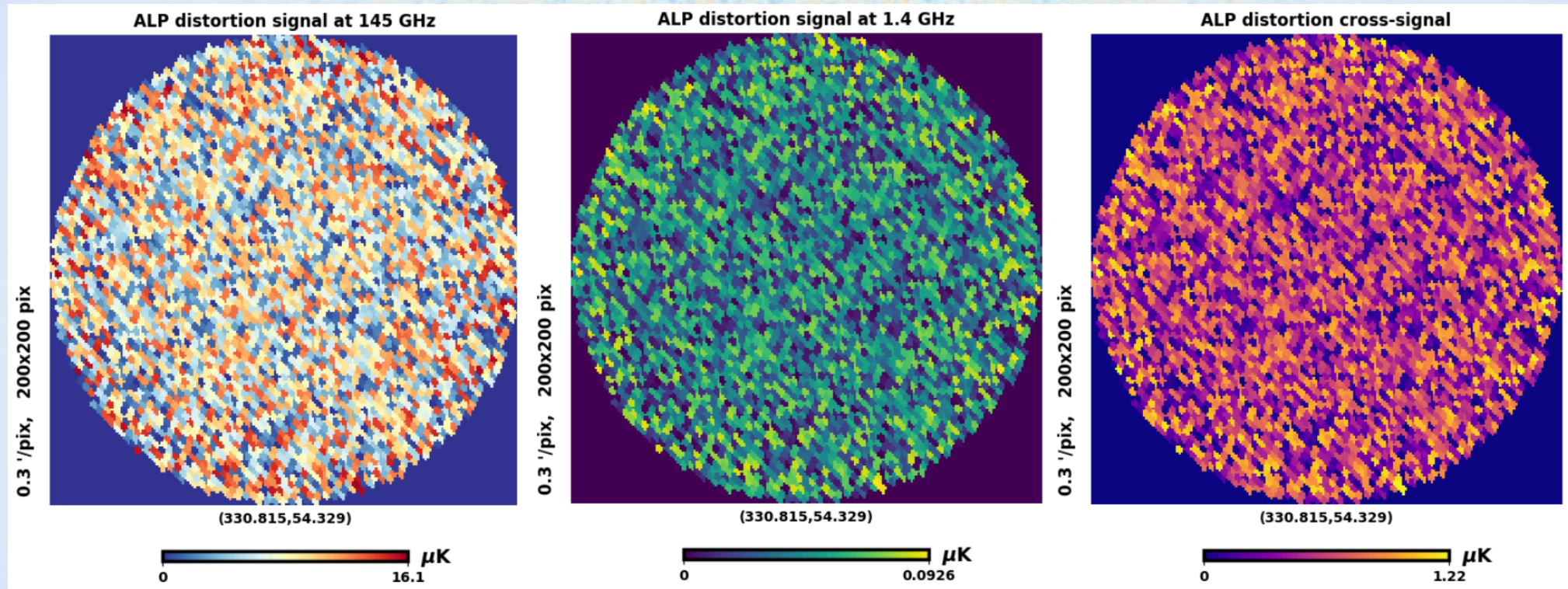
ALP mass range:
 $10^{-15} - 10^{-11} \text{ eV}$





Discovering ALPs using Cosmic Variance Cancellation

Spectral behaviour of the ALP signal



Cosmic Variance Cancellation

➤ *The power spectra for a and b fields:*

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

➤ *The ratio parameter:*

$$\xi = \sqrt{\frac{C_{\ell}^{bb}}{C_{\ell}^{aa}}},$$

➤ *Using auto power spectra:*

$$(\sigma_{\xi}^2)_{\text{auto}} = \frac{\xi^2}{2\ell + 1}.$$

➤ *Will be able to probe new physics from CMB:*

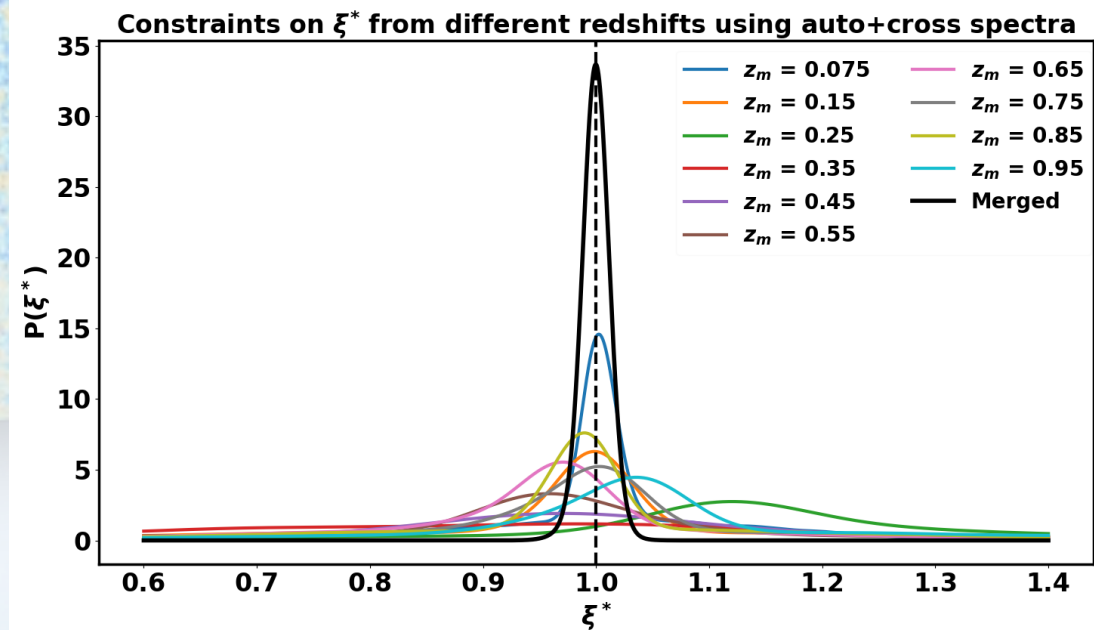
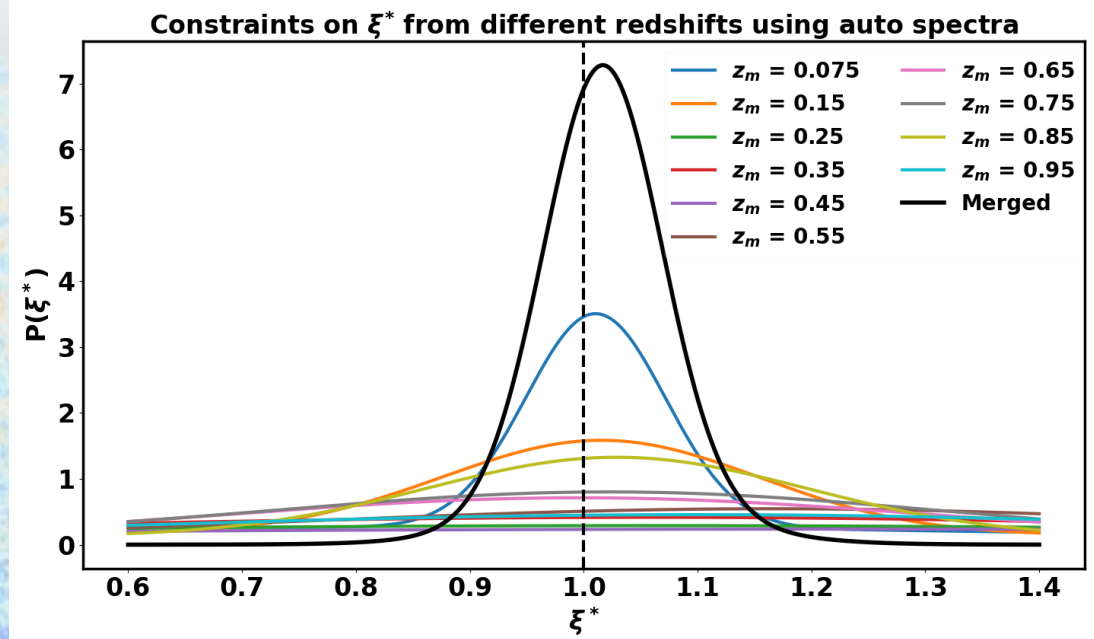
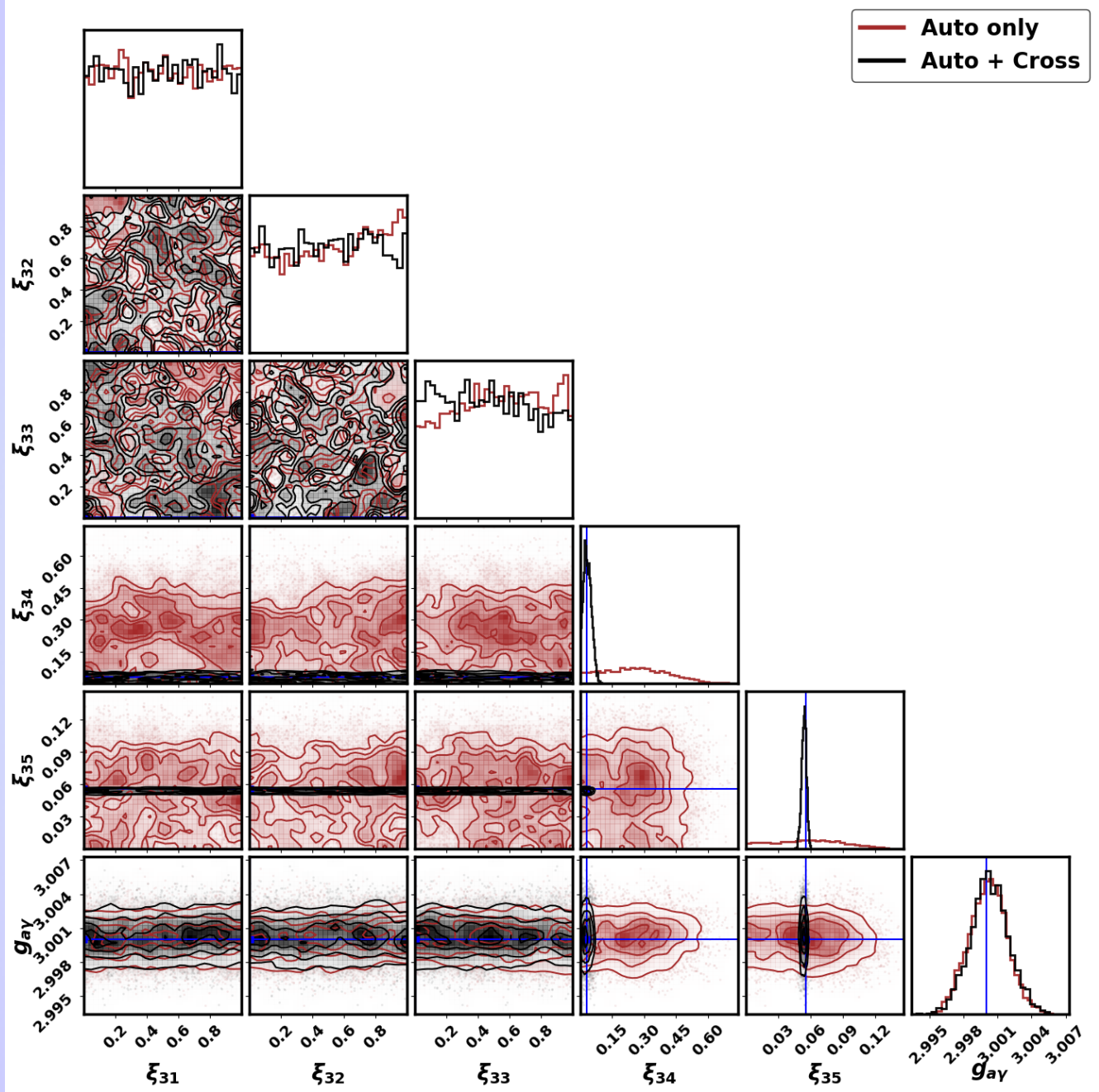
$$(\sigma_{\xi}^2)_{\text{CVC}} = \frac{1}{2\ell + 1} \left(\frac{N_{\ell}^{bb}}{C_{\ell}^{aa}} + \xi^2 \frac{N_{\ell}^{aa}}{C_{\ell}^{aa}} \right)$$

For $N_{\ell}^{aa} \ll C_{\ell}^{aa}$,

$$(\sigma_{\xi}^2)_{\text{CVC}} \rightarrow \frac{1}{2\ell + 1} \frac{N_{\ell}^{bb}}{C_{\ell}^{aa}}$$

For $N_{\ell}^{aa} \ll C_{\ell}^{aa}$ and $N_{\ell}^{bb} \ll C_{\ell}^{aa}$,

$$(\sigma_{\xi}^2)_{\text{CVC}} \rightarrow 0$$

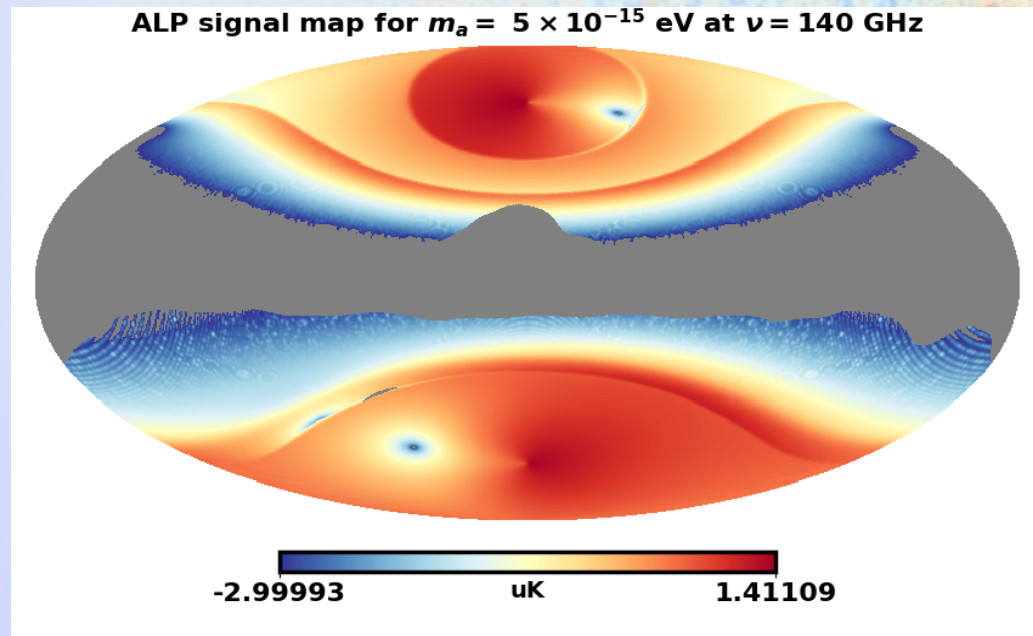




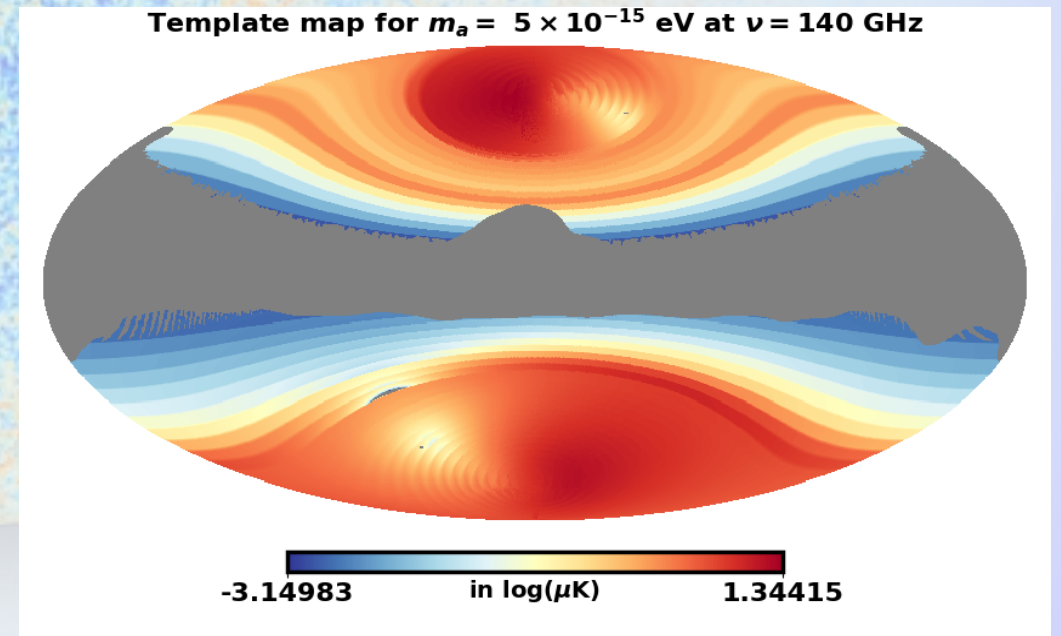
ALP CONVERSION IN THE MILKY WAY

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)*

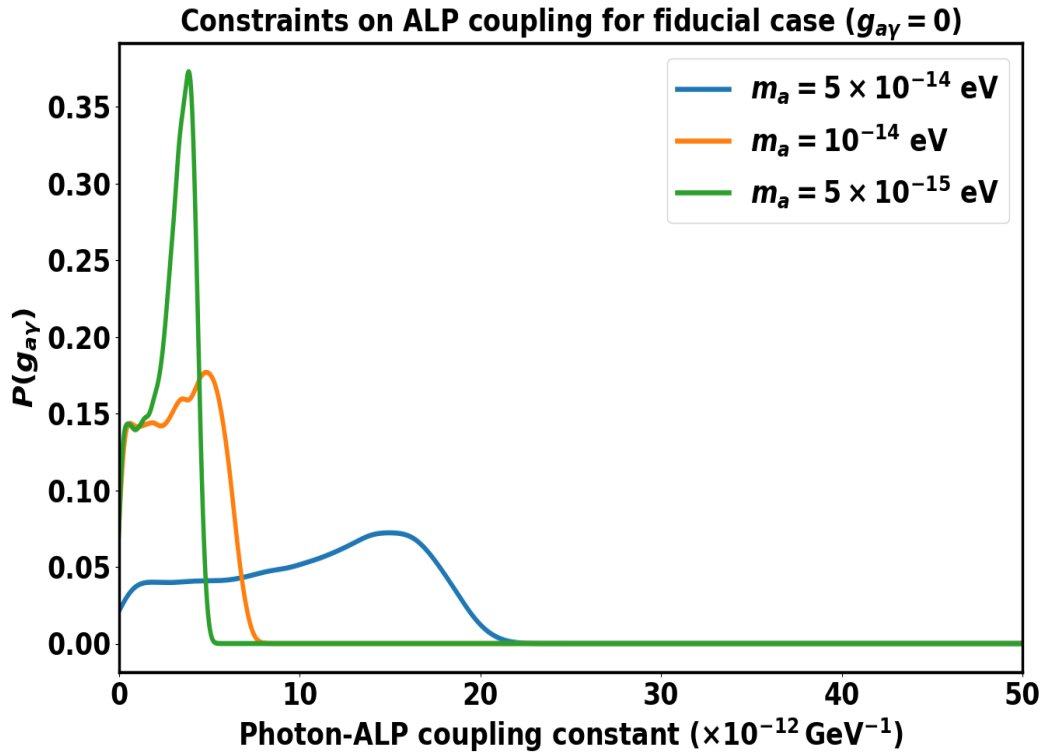


Galactic ALP distortion signal



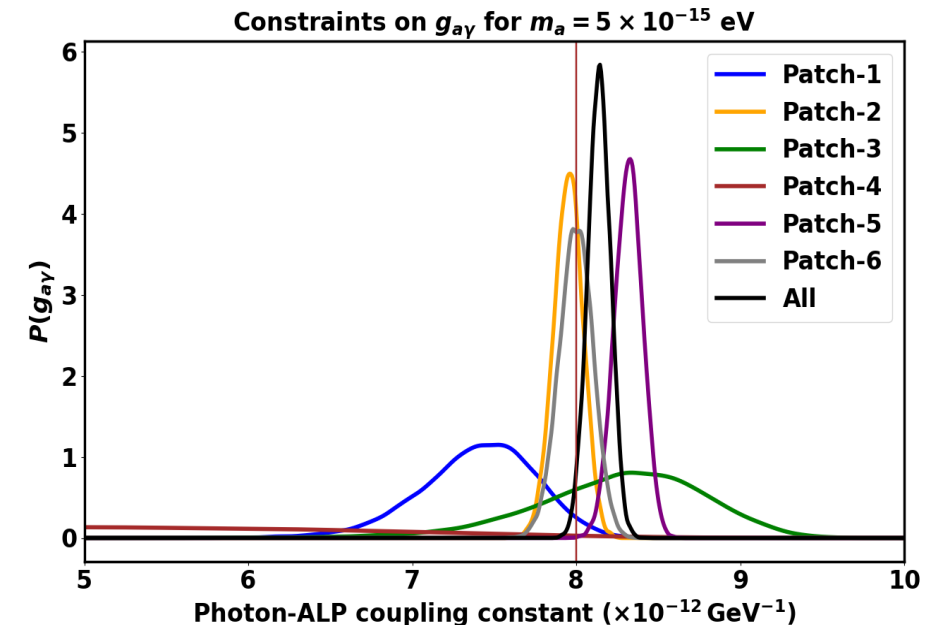
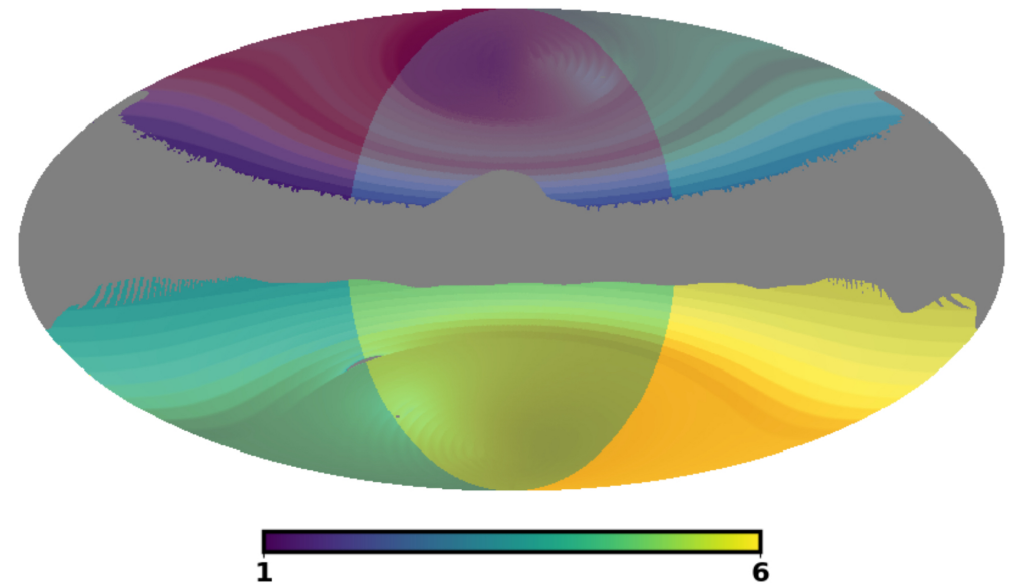
Best-fit template

ROBUSTNESS OF THE SKY-TEMPLATE TECHNIQUE



Constraints using Best-fit template

➤ <https://arxiv.org/abs/2505.11592>

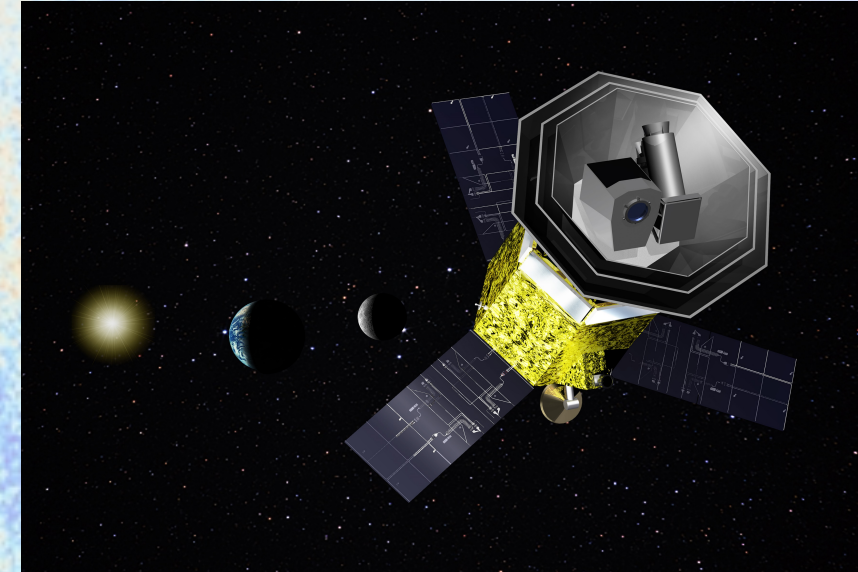


Patch-dependent inference

➤ <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.*



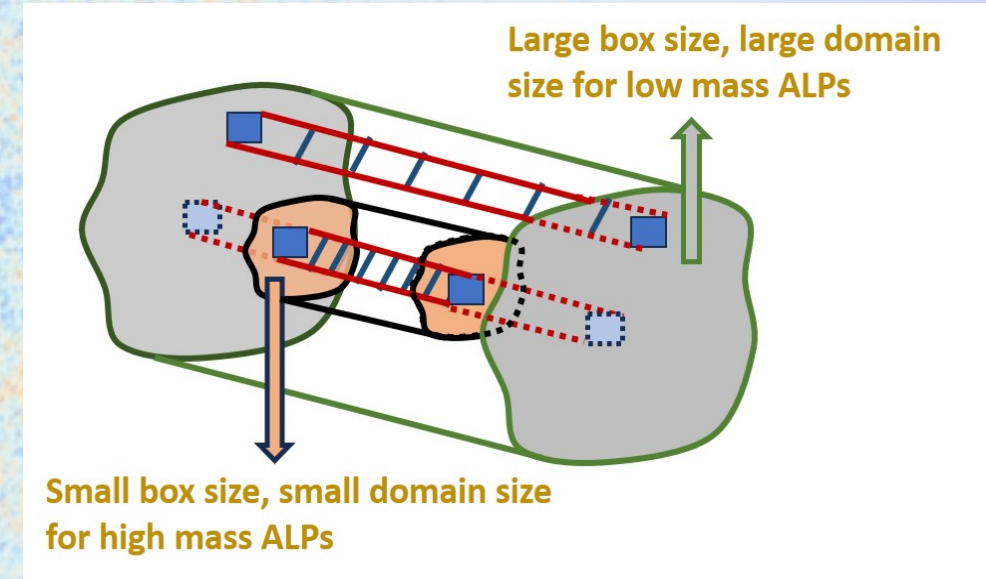
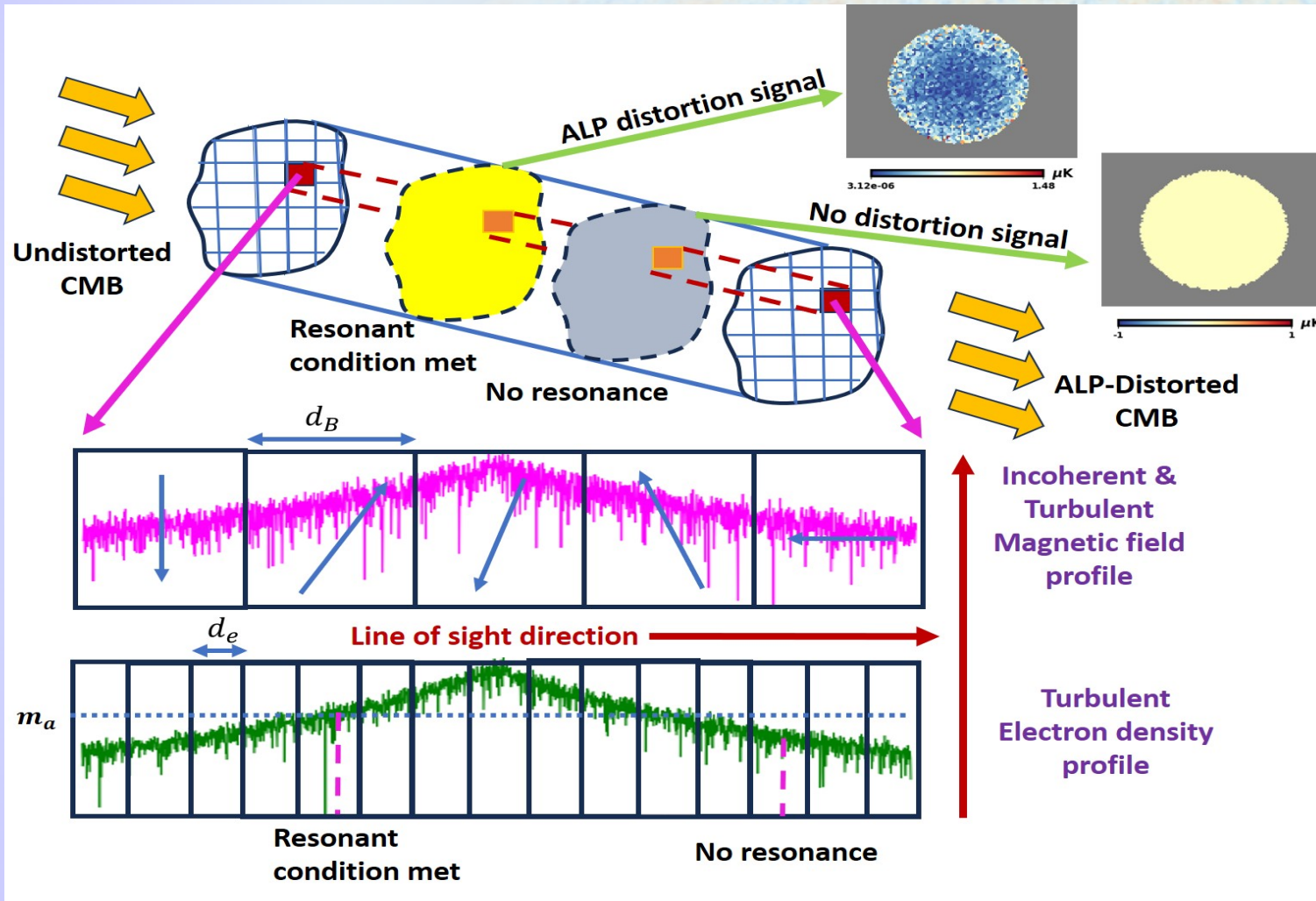
RELEVANT PUBLICATIONS

- *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) [JCAP08\(2025\)081](#)*
- *Detecting Axion-like particles using Cosmic Variance Cancellation with CMB and Radio surveys, (Mehta, Dixit, Mukherjee and Silk) <https://arxiv.org/abs/2505.11592> (Submitted in JCAP)*

THANK YOU!

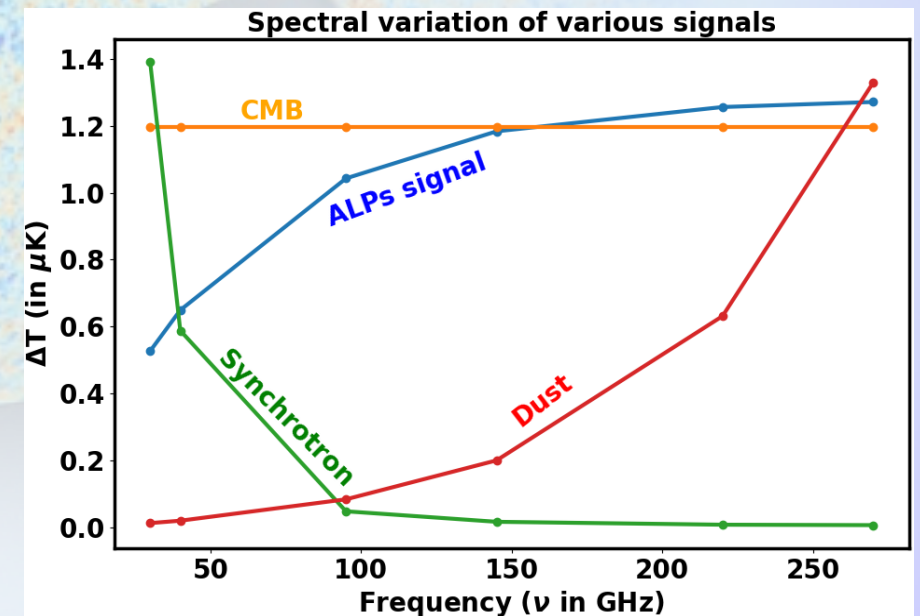
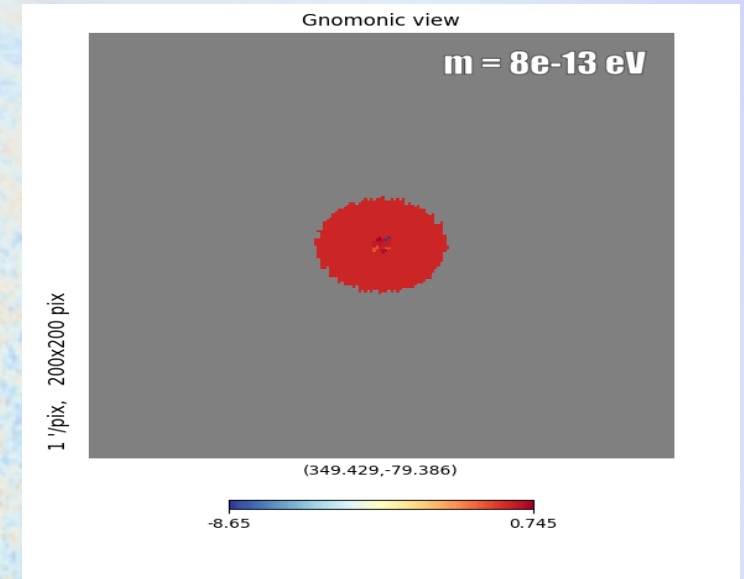
BACKUP SLIDES

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*

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

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

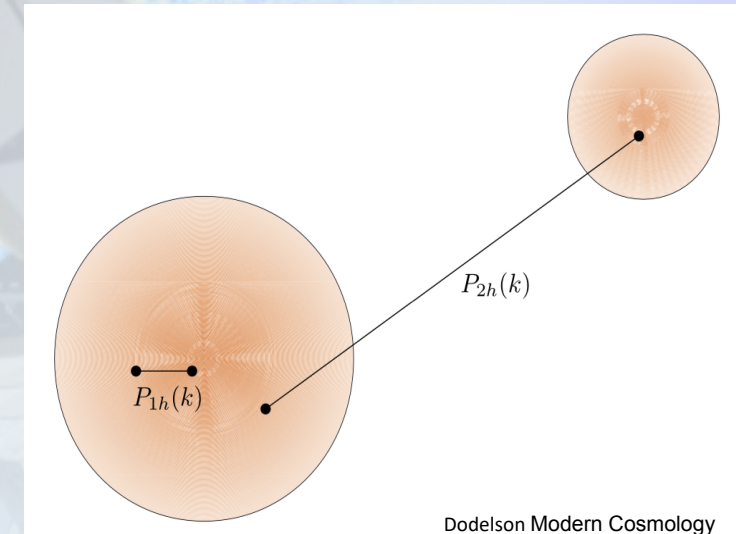
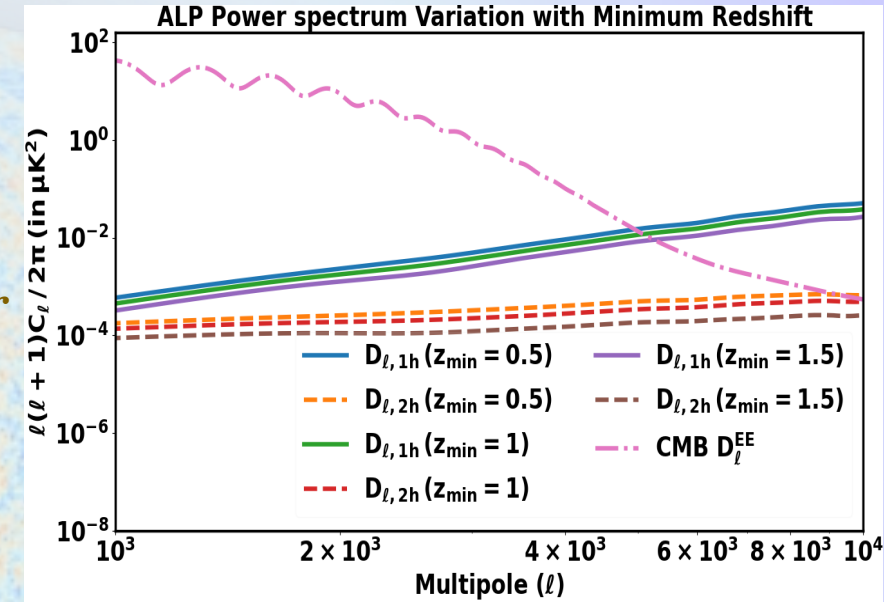
$$C_{\ell,2h}^{ax} = \int_{z_{min}}^{z_{max}} dz \frac{dV_c}{dz} P_m \left(k = \frac{\ell + 1/2}{r(z)}, z \right) \times \left[\int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} b(M,z) \alpha_{\ell}(M,z) \right]^2,$$

(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.



Dodelson Modern Cosmology

CONTAMINANTS

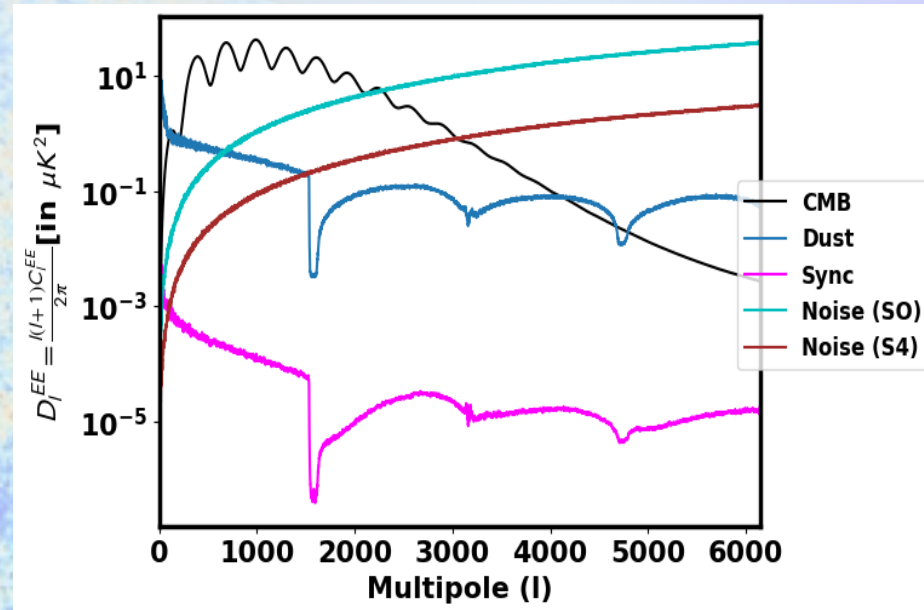
- *The galactic plane is a major source of foreground contaminations.*
- *Masking is required along the galactic plane and over the bright patches*

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

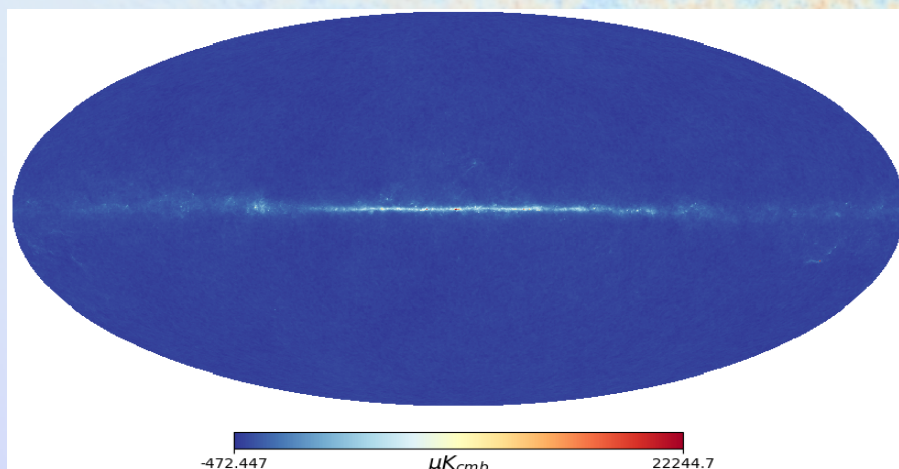
$$w_{a\gamma} = C_s^{-1} f_{a\gamma} \left(f_{a\gamma}^T C_s^{-1} f_{a\gamma} \right)^{-1}$$

- *Observations also affected by:*

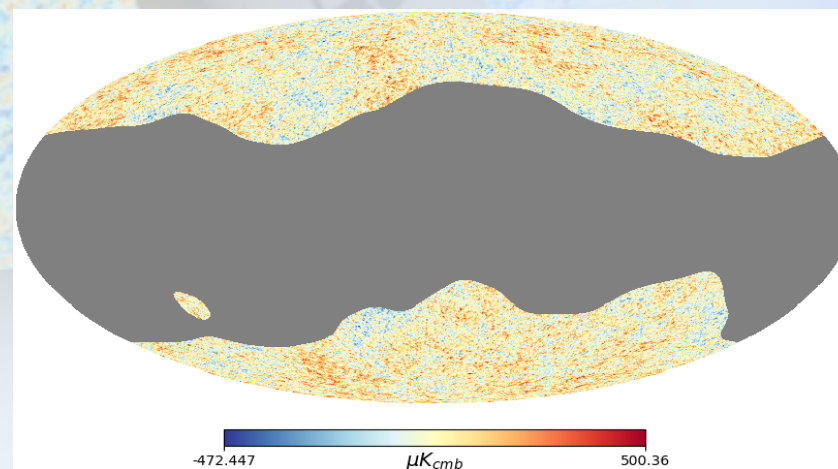
- *Instrument beam*
- *Instrument noise*



Power spectra at $\nu = 145$ Hz

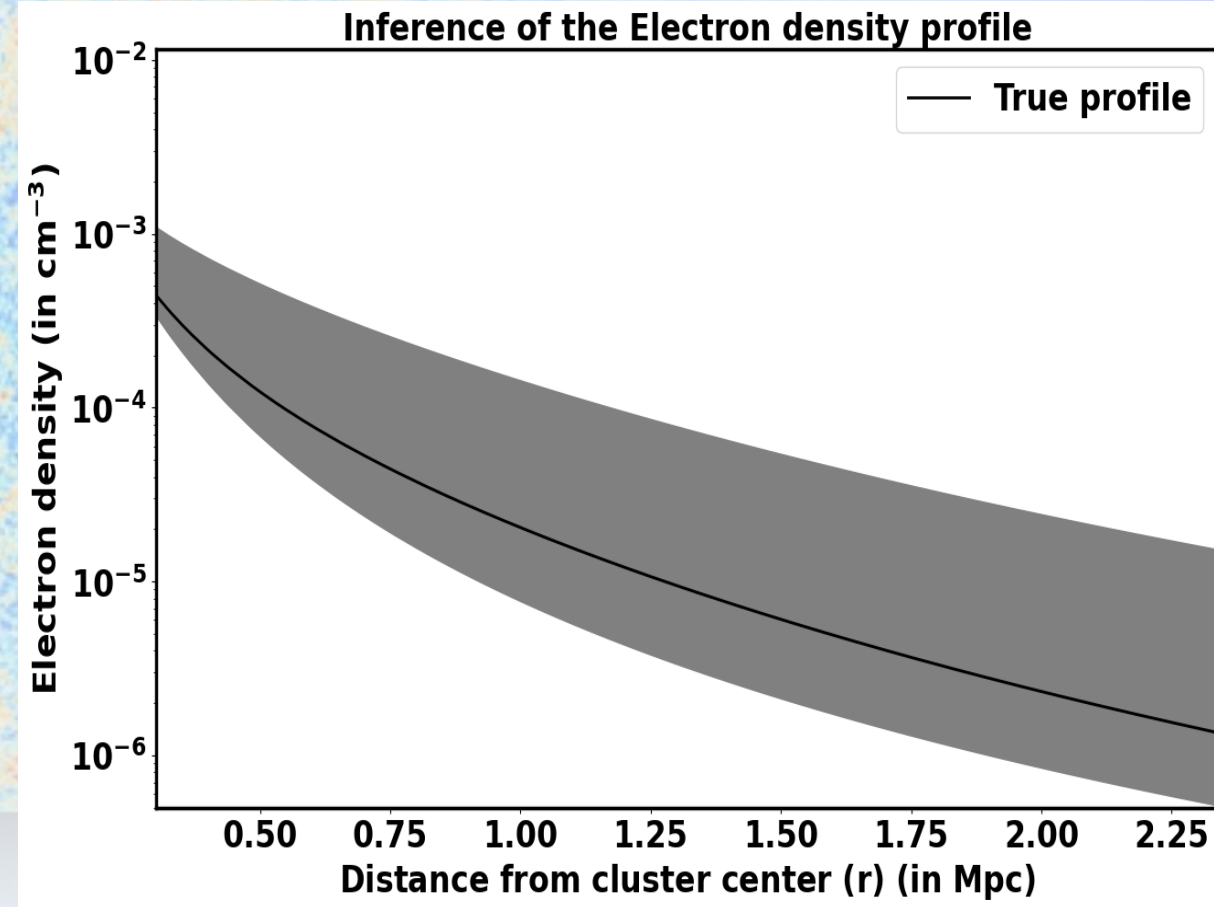
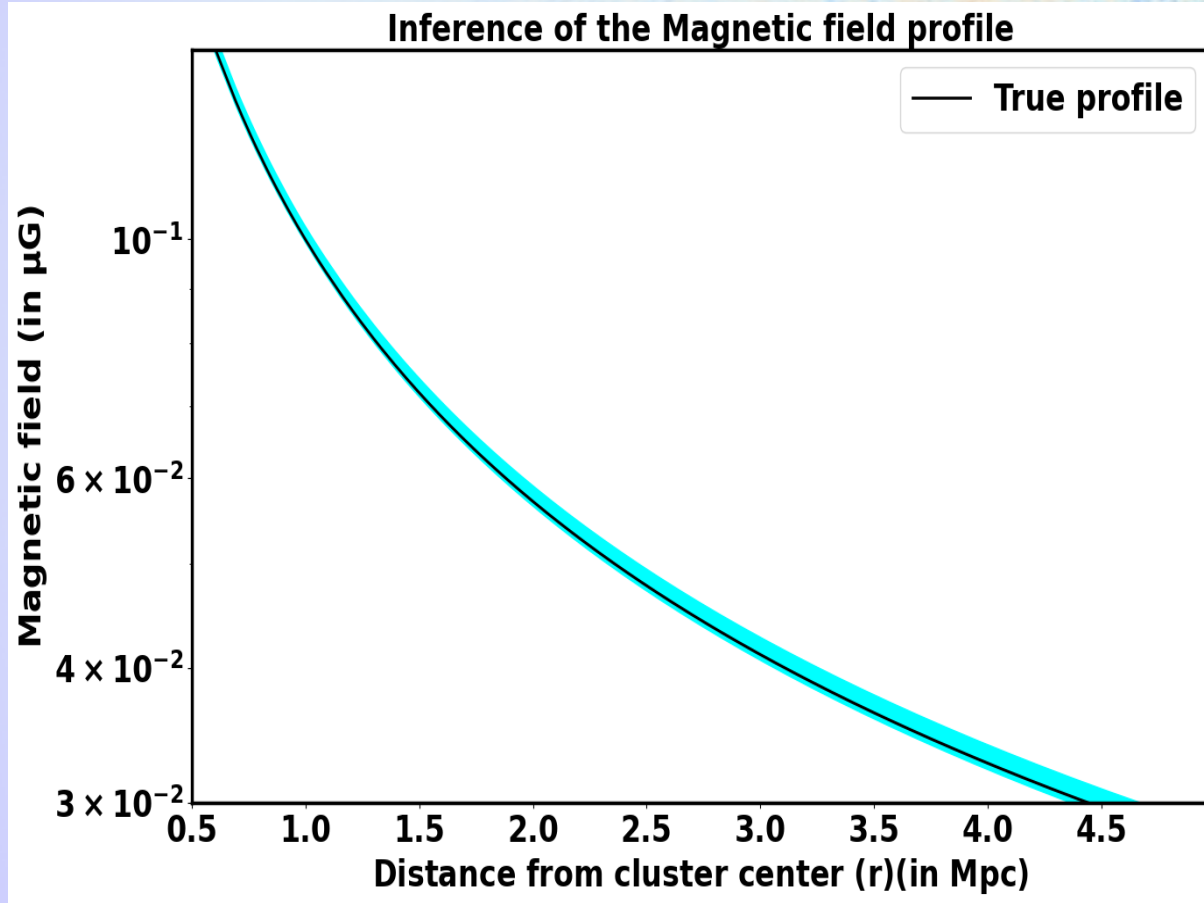


Contaminated map



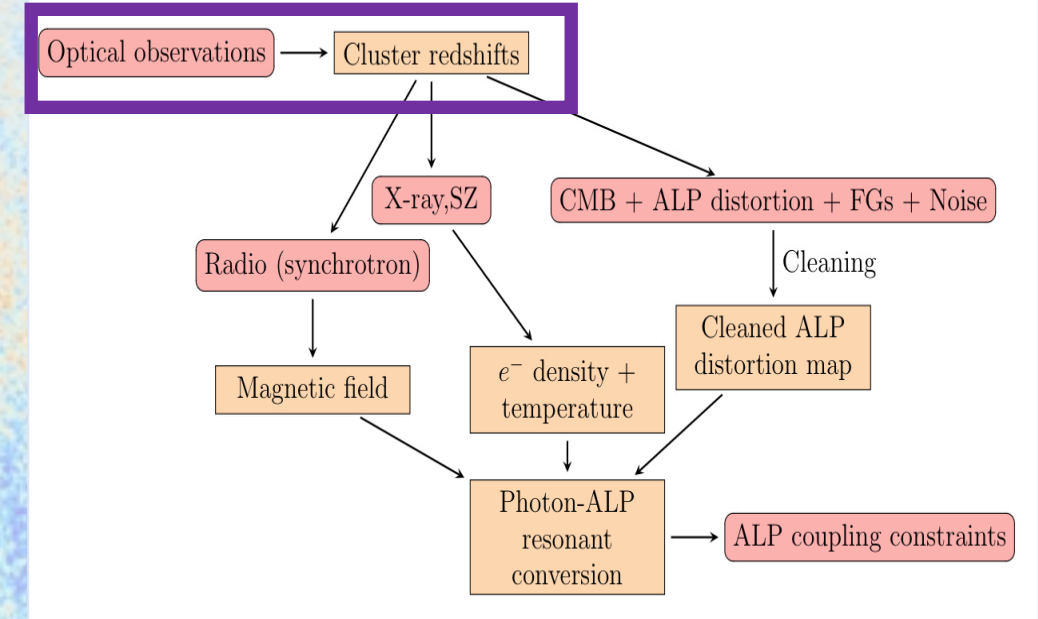
Masked map

PROFILE INFERENCE

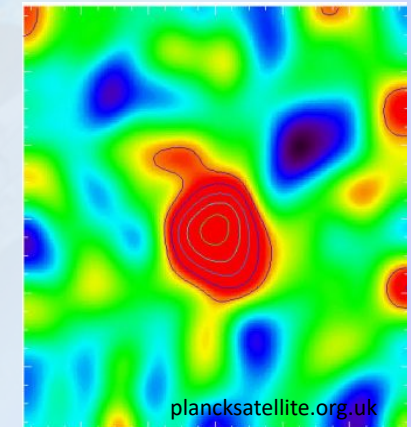
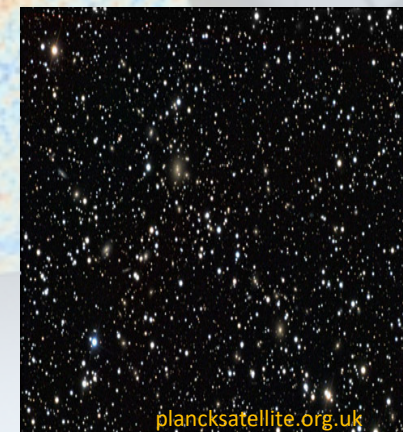


CROSS-MATCHING WITH OPTICAL SURVEYS

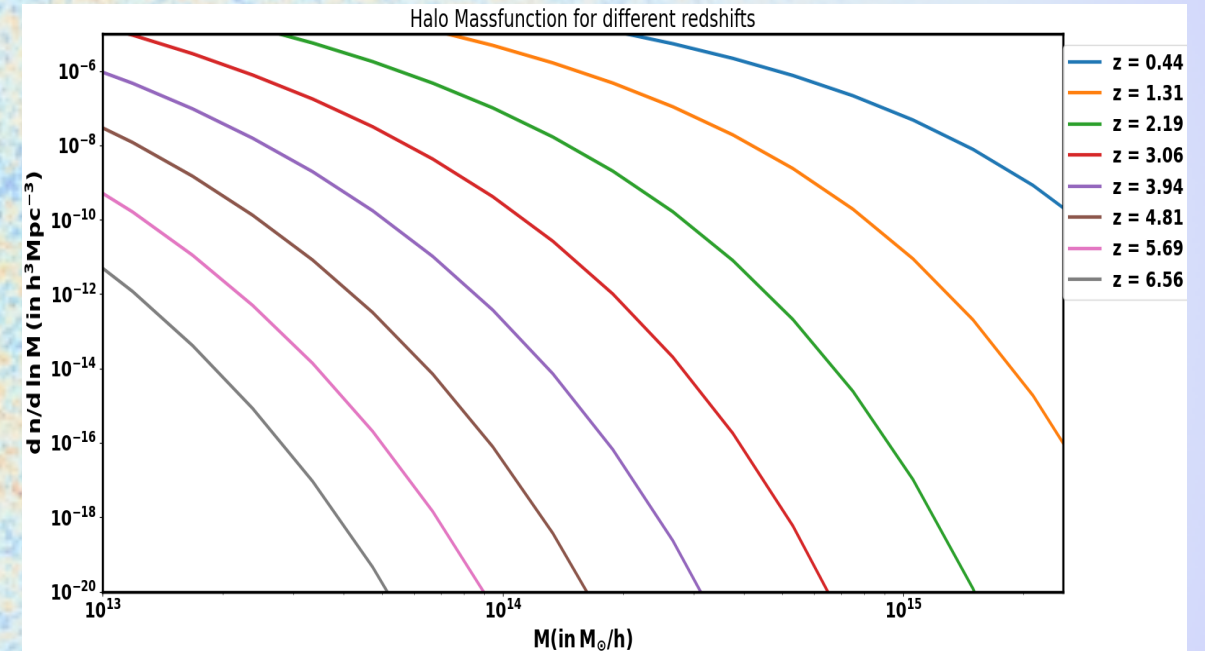
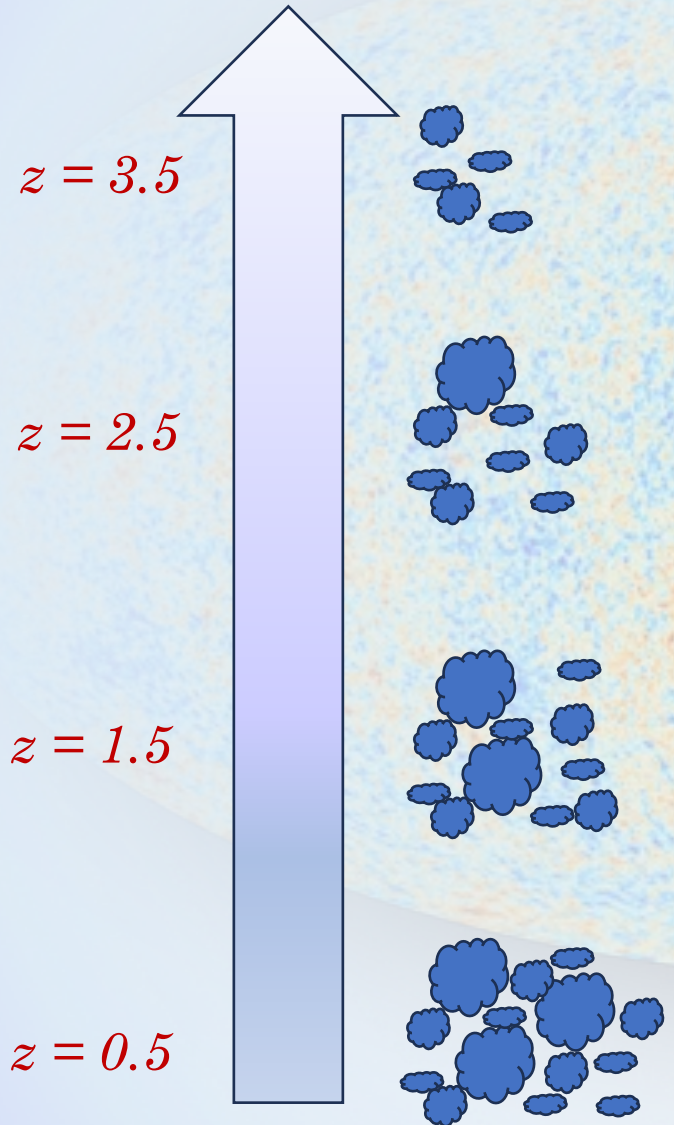
- *Galaxy cluster detection methods: Red Sequence method or the BCG method*
- *Redshift measurements are obtained using spectroscopic or photometric measurements*
- *Photo-z errors considered: Up to 10% in the analysis*
- *The clusters are cross matched with optical surveys to obtain the redshift measurements*
- *The redshift distribution of clusters is used for binning them*



Abell 2319 cross matching

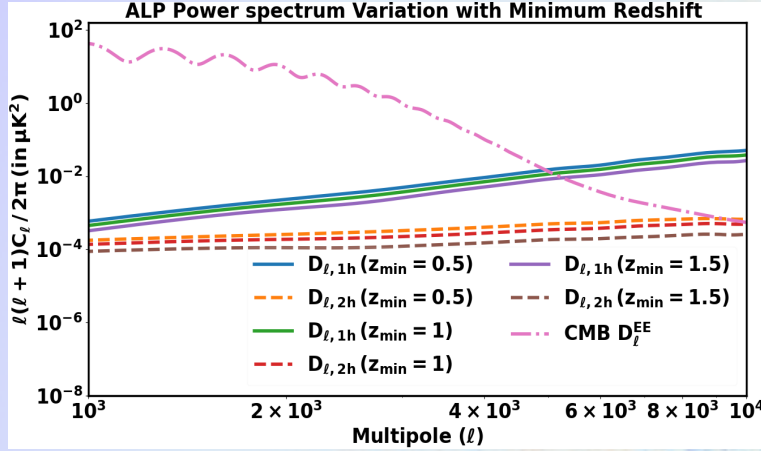


DISTRIBUTION OF HALOS

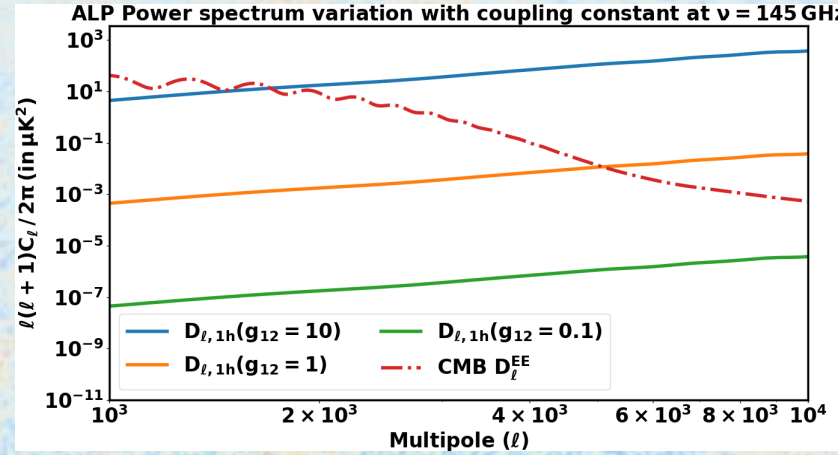


Cosmological Variations

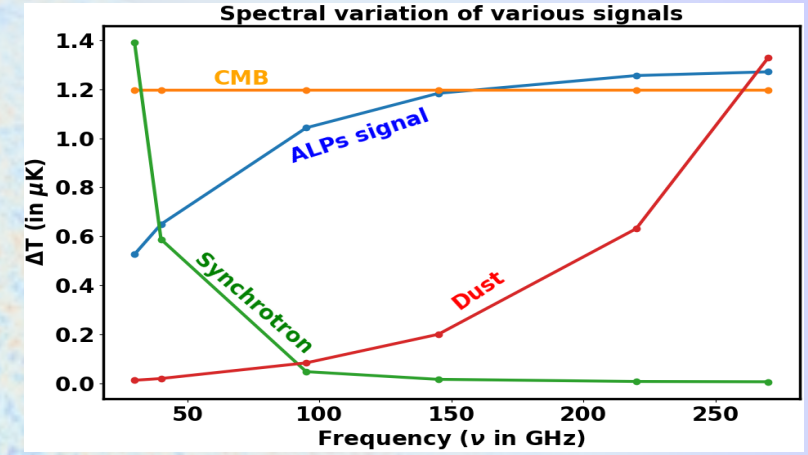
$$P(\gamma \rightarrow a) \propto \gamma = \left| \frac{2 g_{a\gamma}^2 B_t^2 v(1+z)}{\nabla \omega_p^2} \right|$$



(a) Variation with redshift

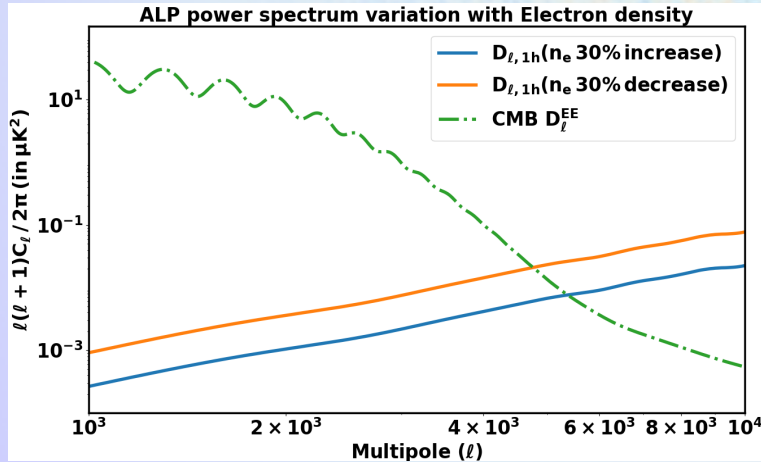


(b) Variation with Coupling constant

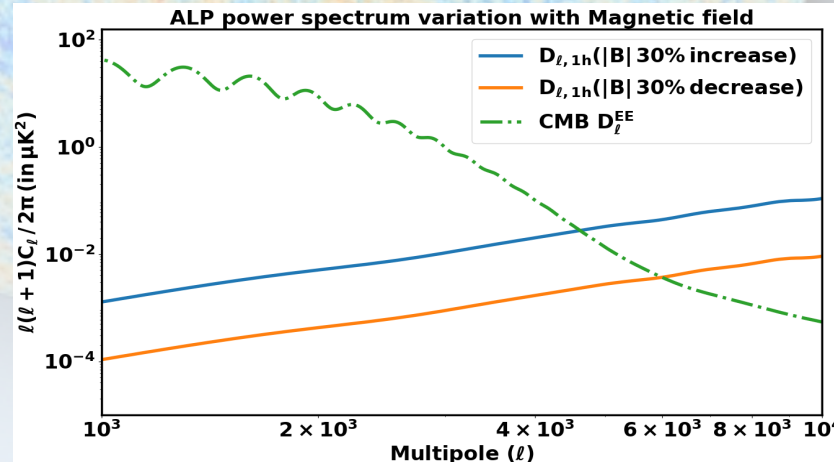


(c) Variation with frequency

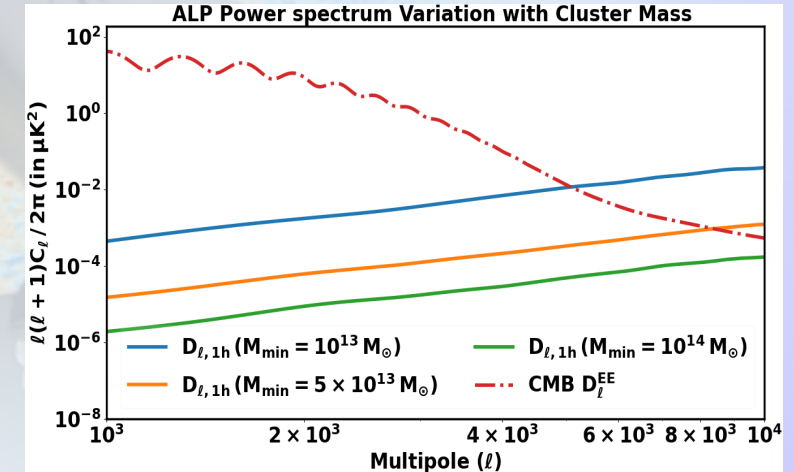
Astrophysical Variations



(a) Variation with Electron density strength



(b) Variation with Magnetic field steepening

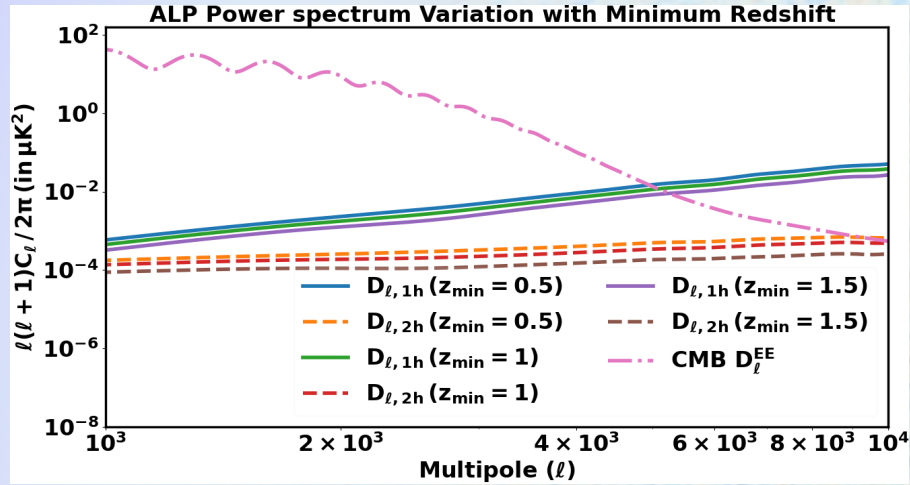


(c) Variation with Cluster Mass

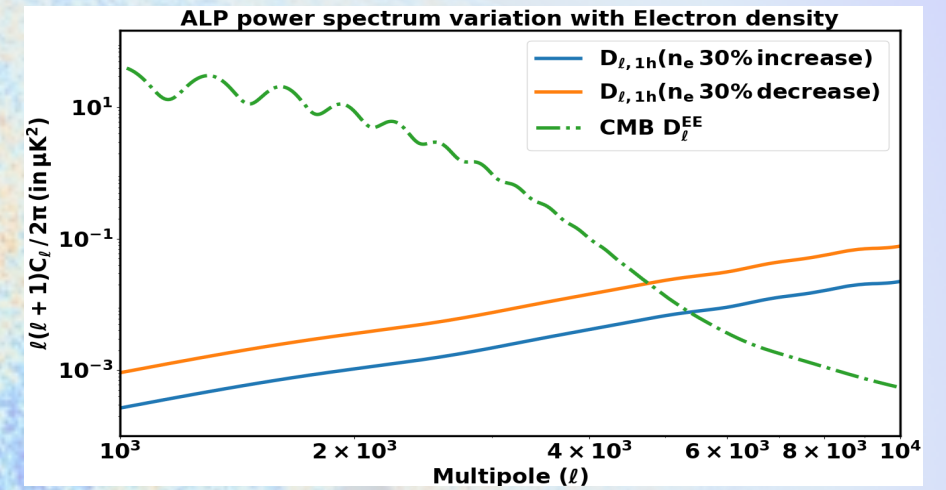
Cosmological

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

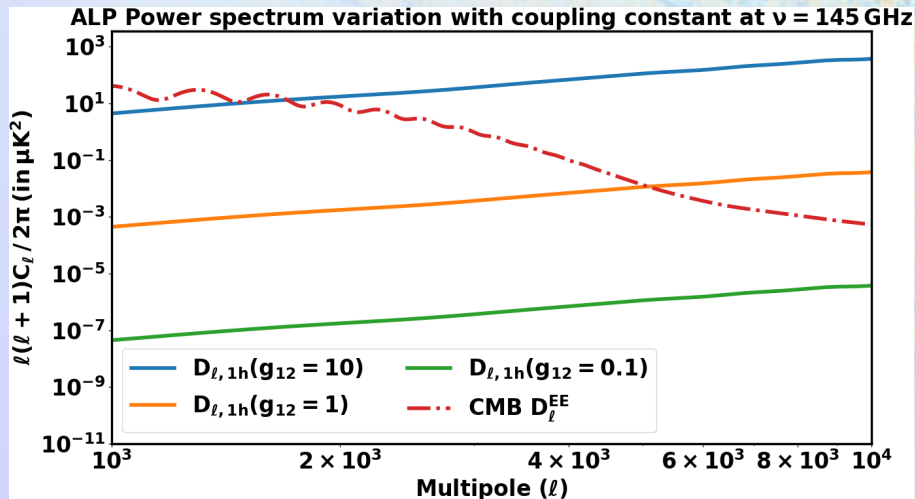
Astrophysical



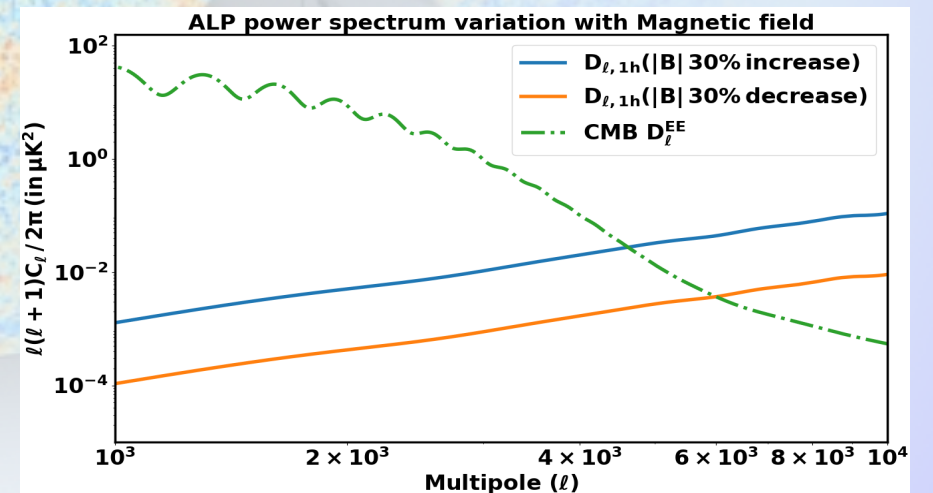
(a) Variation with redshift



(a) Variation with Electron density strength



(b) Variation with Coupling constant



(b) Variation with Magnetic field steepening

Simulation setup

➤ *Axes being considered:*

$$\begin{aligned}\hat{z} &\rightarrow \cos\theta_z \\ \hat{x} &\rightarrow \sin\theta_z \cos\theta_x \\ \hat{y} &\rightarrow \sin\theta_z \sin\theta_x\end{aligned}$$

➤ *Local gradient in electron density:*

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

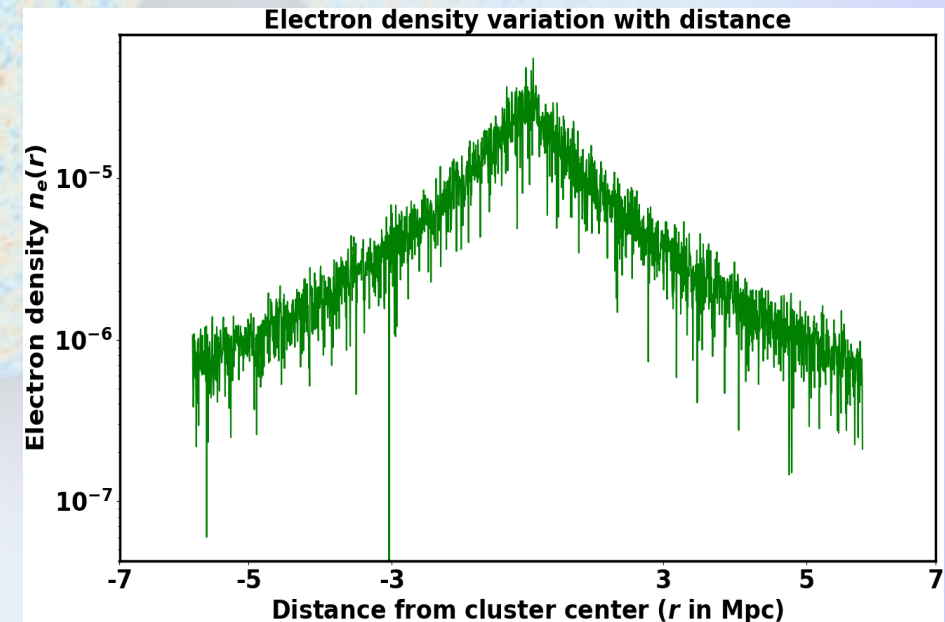
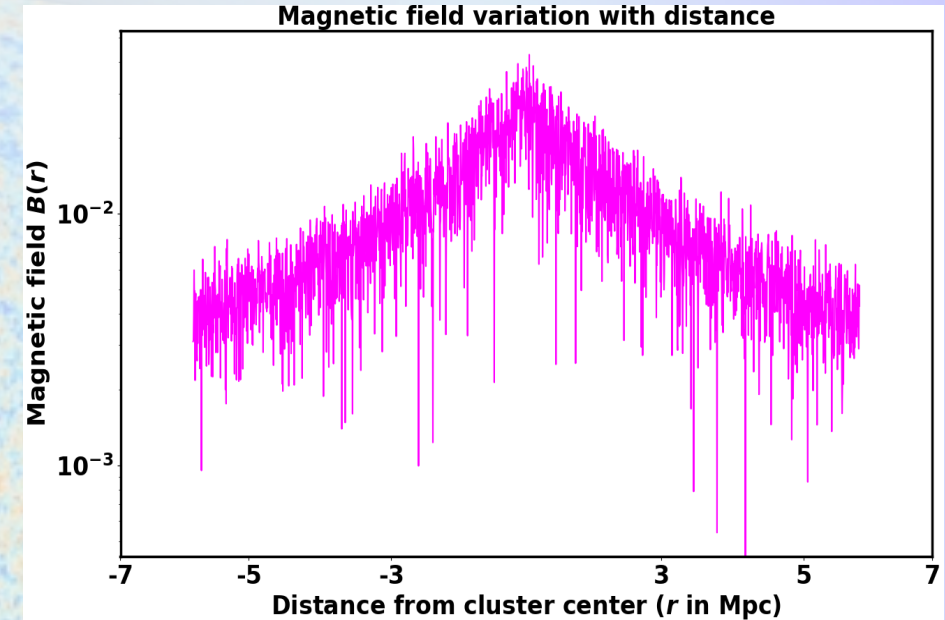
➤ *Profiles & Turbulence considered:*

Electron density:

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

Magnetic field:

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



ALP DISTORTION IN TEMPERATURE & POLARIZATION

➤ *ALP signal in temperature:*

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

➤ *ALP signal in polarization:*

$$\Delta I_Q(\gamma \rightarrow a) = \frac{\pi}{2} \sum_{i=1}^N \gamma_{\text{ad},i} (\cos 2\theta_x)_i I_0,$$

$$\Delta I_U(\gamma \rightarrow a) = \frac{\pi}{2} \sum_{i=1}^N \gamma_{\text{ad},i} (\sin 2\theta_x)_i I_0,$$

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

➤ *The signal is decomposed to spherical harmonics:*

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

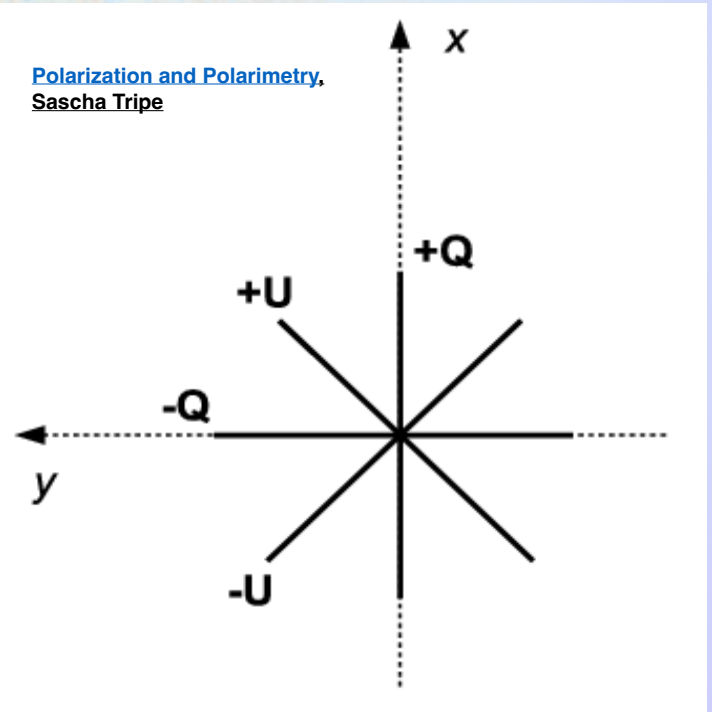
➤ *The multipoles can be approximated as:*

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

➤ *The power spectrum is given as:*

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

Harsh Mehta



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:*

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

- *The signal is affected by beam:*

$$\tilde{a}_{\ell m}^{ax} = B_\ell a_{\ell m}^{ax}$$

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

- *The power spectrum is given as:*

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

- *The ALP power spectrum is estimated as:*

$$\hat{C}_\ell^{ax} = \frac{B_\ell^{-2}}{2\ell + 1} \sum_{m=-\ell}^{\ell} \tilde{a}_{\ell m}^{ax} * \tilde{a}_{\ell m}^{ax}$$