The Diffused Polarized ALPs (Axion-like Particles) Power Spectrum in the Microwave Sky

arXiv:2405.08879 (Published in JCAP)

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CMB-S4 Summer Collaboration Meeting
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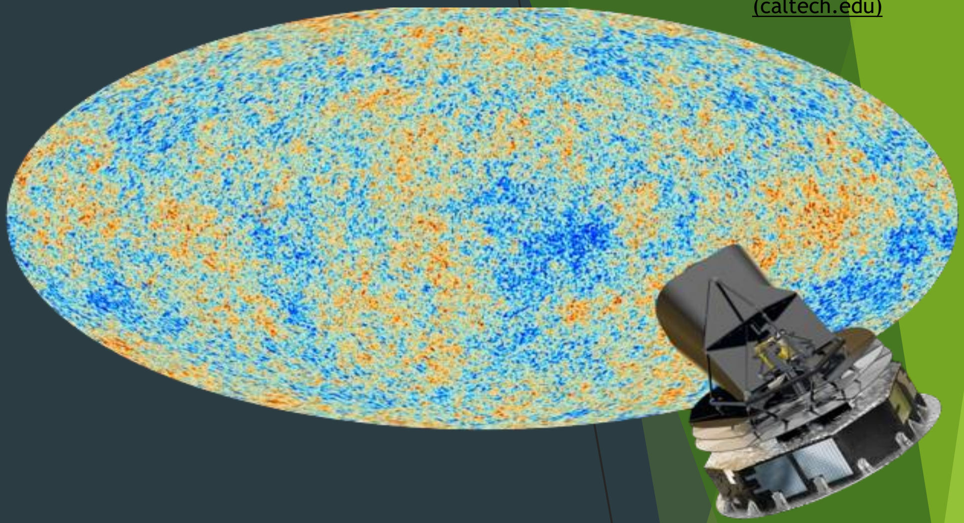
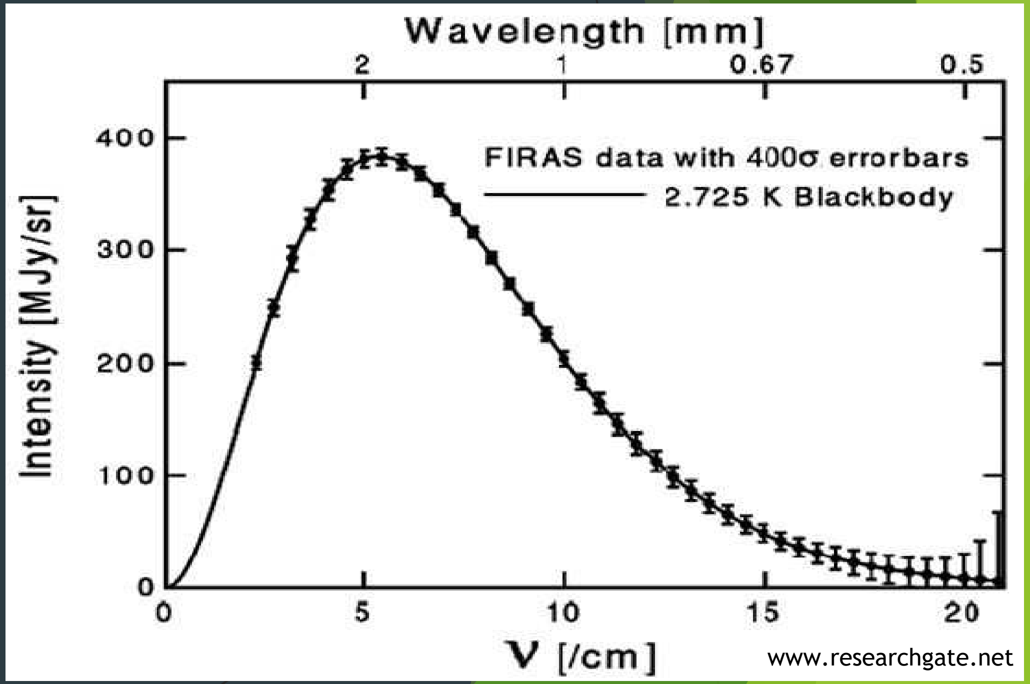
Probing Axions with CMB-S4 using spatial anisotropic spectral distortion

Planck | IPAC (caltech.edu)



Nasa.gov

- *Axions 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 axions.*

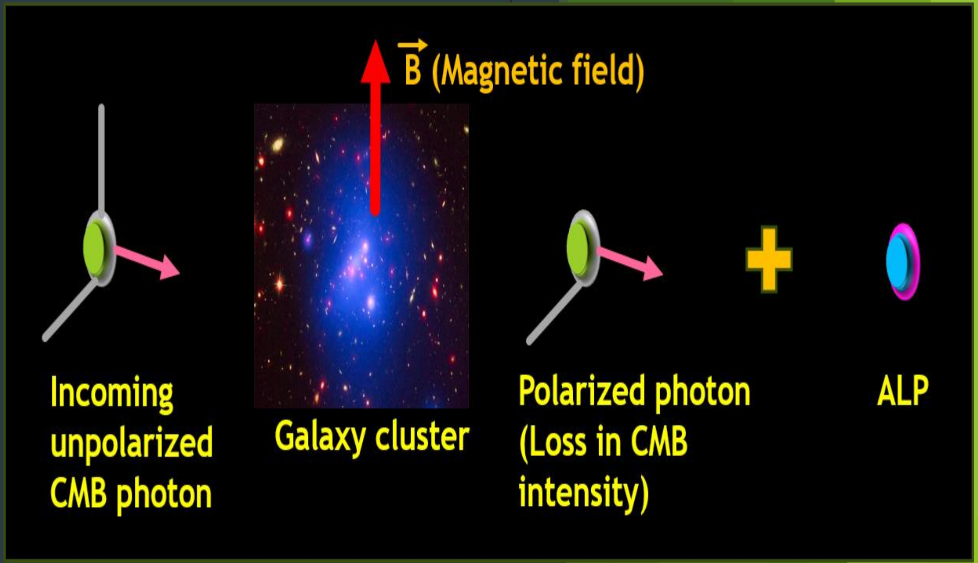


CMB photon-ALP resonant conversion

- *How it happens?*

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

$$\mathcal{L}_{int} = -\frac{g_{a\gamma}}{4} aF_{\mu\nu}\widetilde{F^{\mu\nu}} = g_{a\gamma} E \cdot B_t \, a \, ,$$



- *Where it happens?*

  Resonant condition:

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

- *How strong is it?*

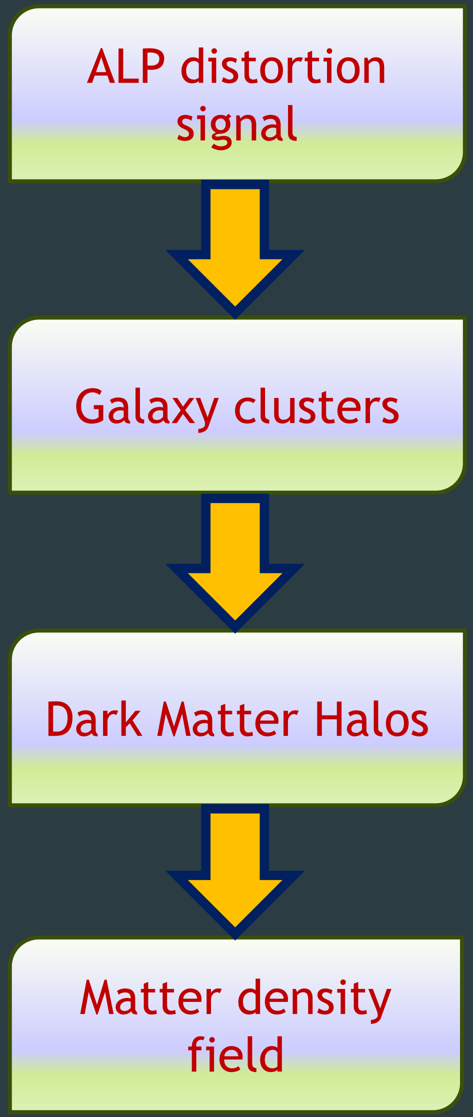
  The probability of conversion at a location in a galaxy cluster:

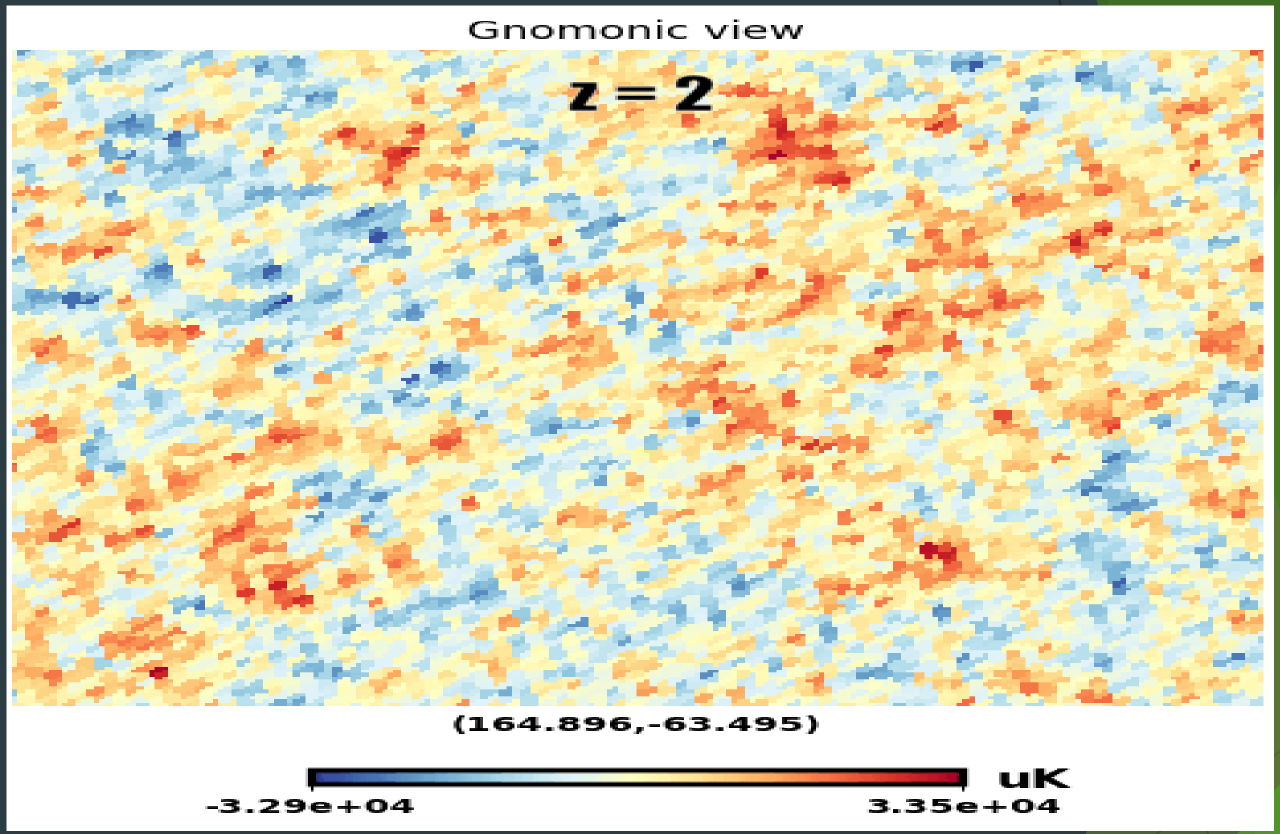
$$P(\gamma \to a) \approx \pi\gamma, \qquad \gamma = \left| \frac{2\, g_{a\gamma}^2\, {B_t}^2\, \nu(1+z)}{\nabla \omega_p^2} \right|$$

- *Observable effect:*

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

Background signal from Unresolved Galaxy clusters

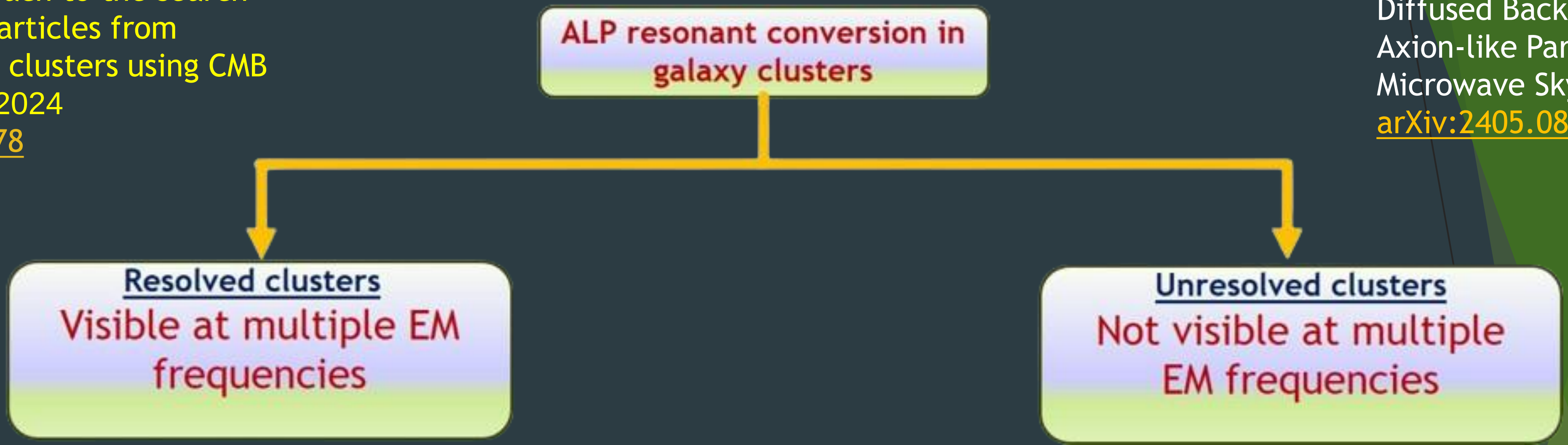




Galaxy clusters can be modelled as halos of mass range $10^{13} - 7.10^{15}\ M_{\odot}$

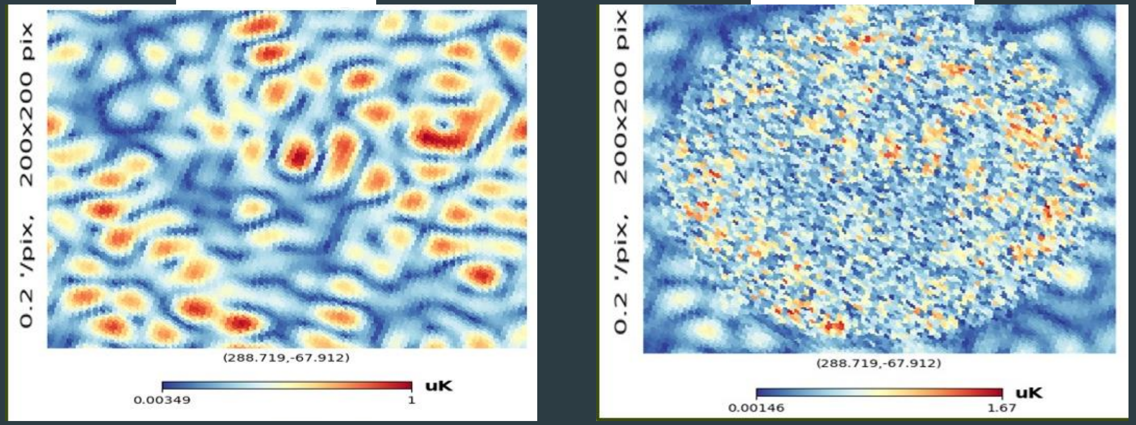
Mehta and Mukherjee, A power spectrum approach to the search for Axion-like Particles from resolved galaxy clusters using CMB as a backlight, 2024
arXiv:2405.08878

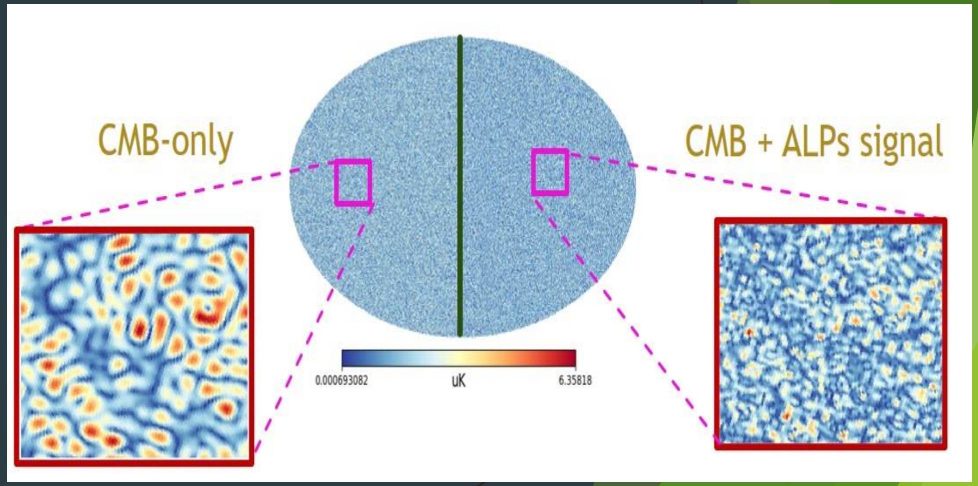
Mehta and Mukherjee, A Diffused Background from Axion-like Particles in the Microwave Sky, 2024
arXiv:2405.08879



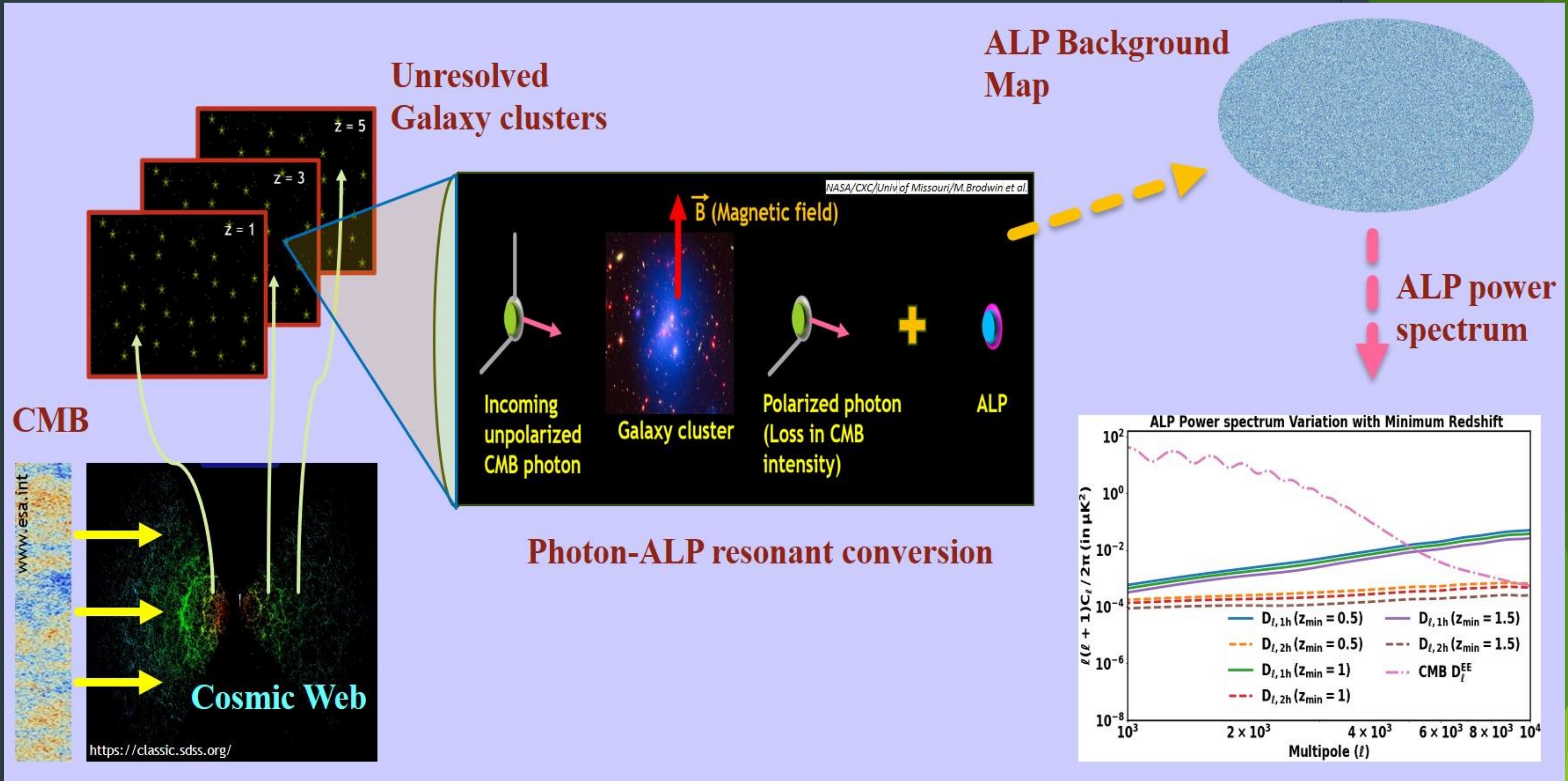
CMB only

CMB + ALP





The ALP diffused Background



The CMB power spectrum

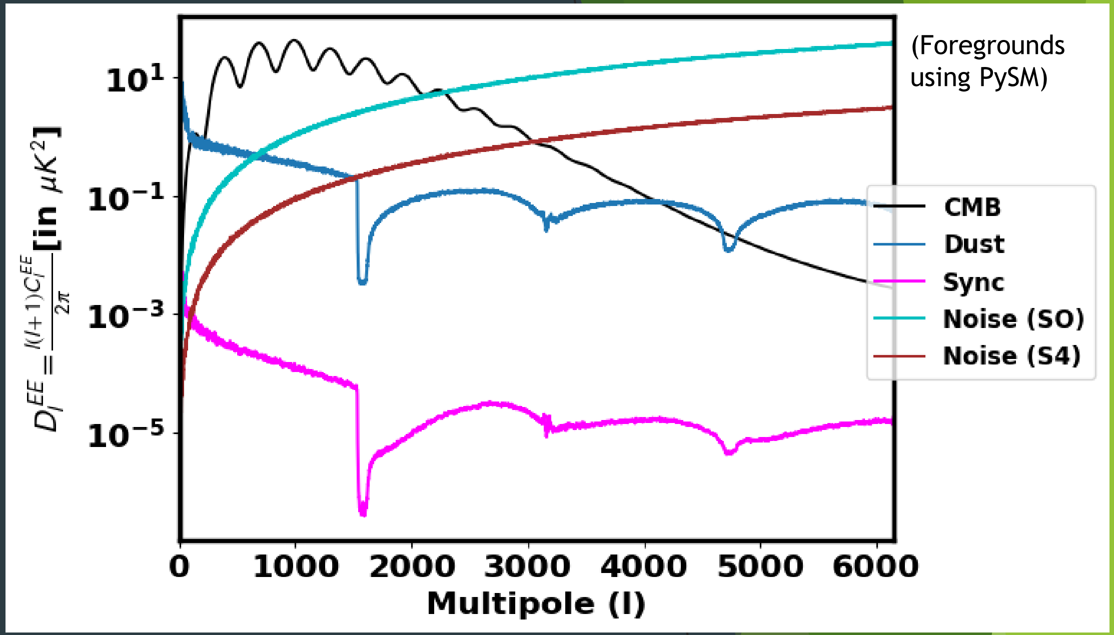
- *The Power spectrum is estimated as:*

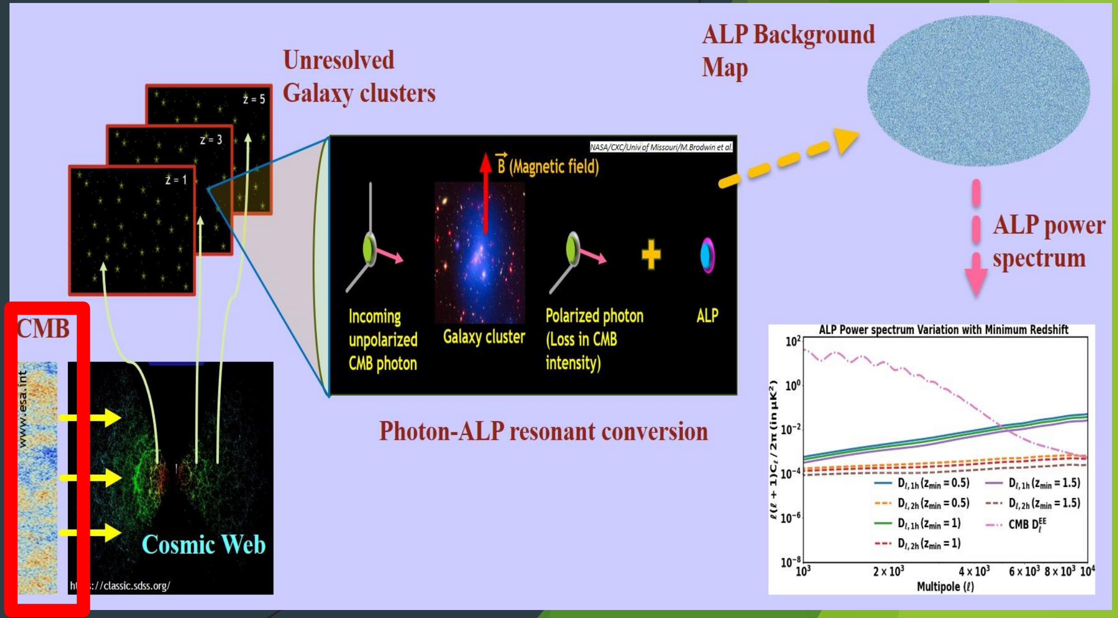
$$\widehat{C_\ell} = \frac{B_\ell^{-2}}{2\ell+1}\sum_{m=-\ell}^{\ell} \widetilde{a_{\ell m}}^{\,*}\,\widetilde{a_{\ell m}}$$

with B_ℓ being the beam function.

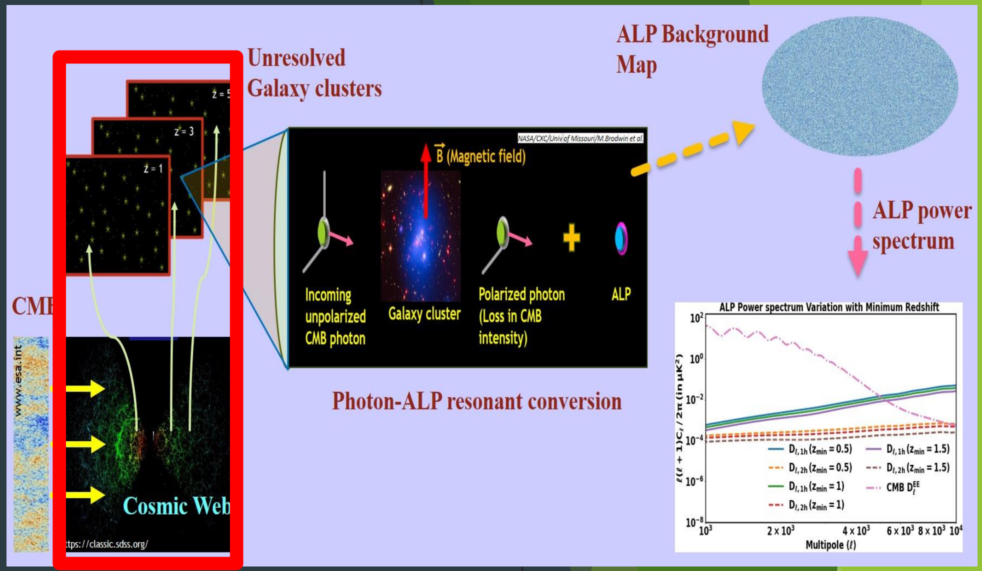
- *The CMB primary anisotropy is frequency independent*

- *Spatial and spectral variation can distinguish signals.*





Halo Modelling of the ALP distortion signal



- *ALP Power spectrum can be separated into one and two halo terms*

- *One halo: Correlations between locations within the same cluster*

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

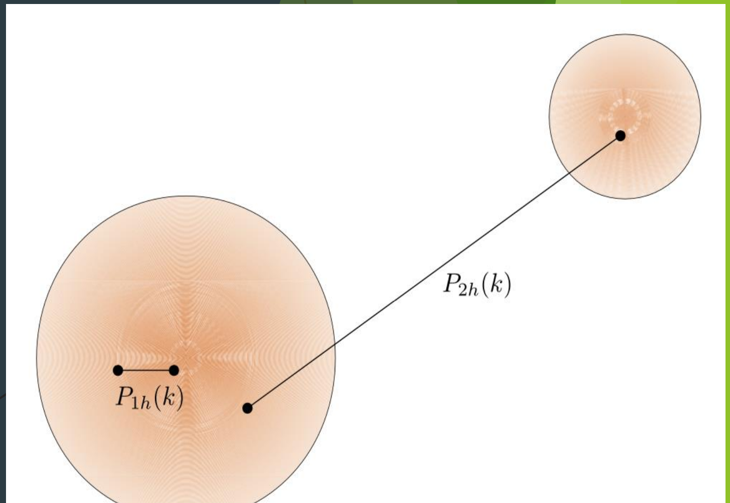
- *Two halo: Correlations between locations in different clusters*

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

(Relatively Weak)

where halo correlation has been used:

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



Dodelson Modern Cosmology

Modelling the $a_\ell' s$

- *The Electron density profile used for mock data :*

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

(Vikhlinin et al., 2006 arXiv:astro-ph/0507092)

- *Magnetic field profile used for mock data:*

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

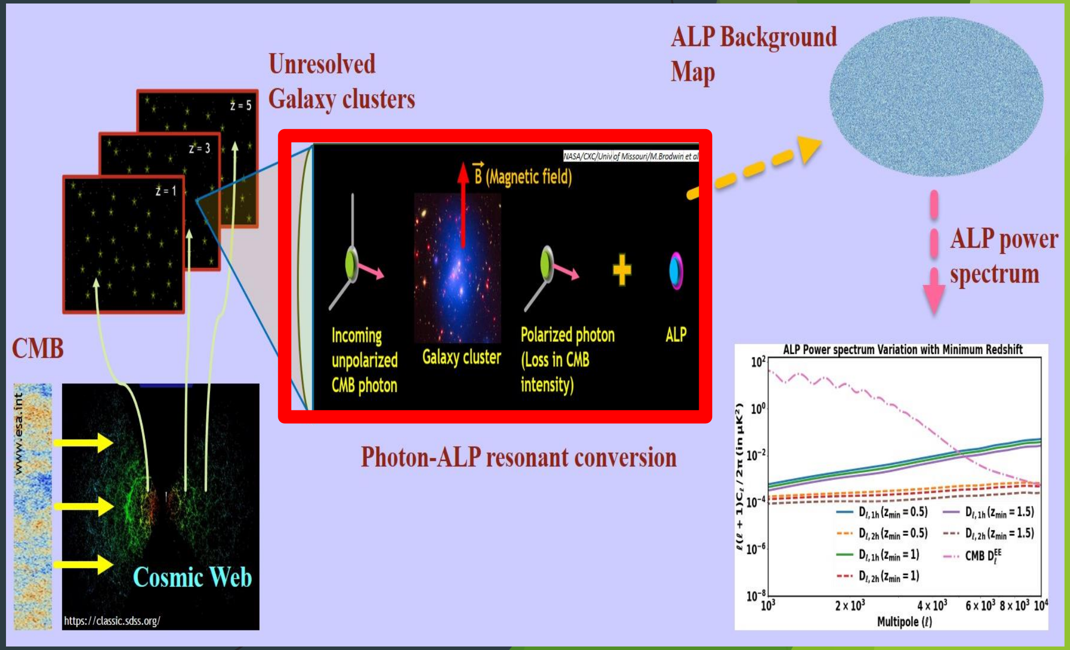
(Bonafede et al., 2010 arXiv:1009.1233)

- *Random profiles have been used*

- *ALP Mass range:* $10^{-15} - 10^{-11}$ eV

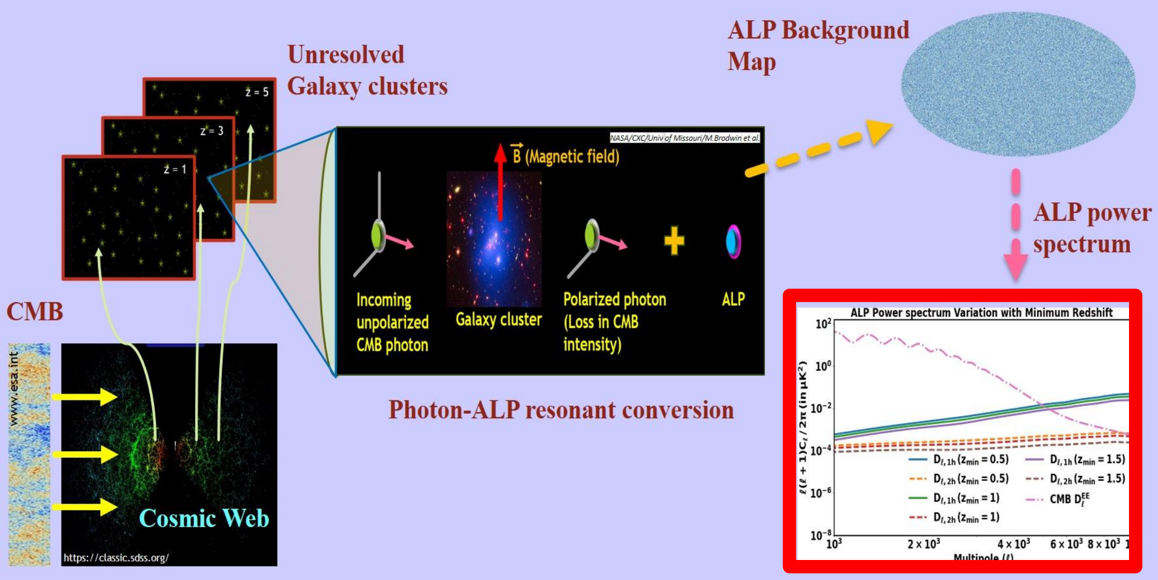
- *Coupling constant* $g_{a\gamma}$ *range*: $10^{-14} - 10^{-11}$ GeV $^{-1}$

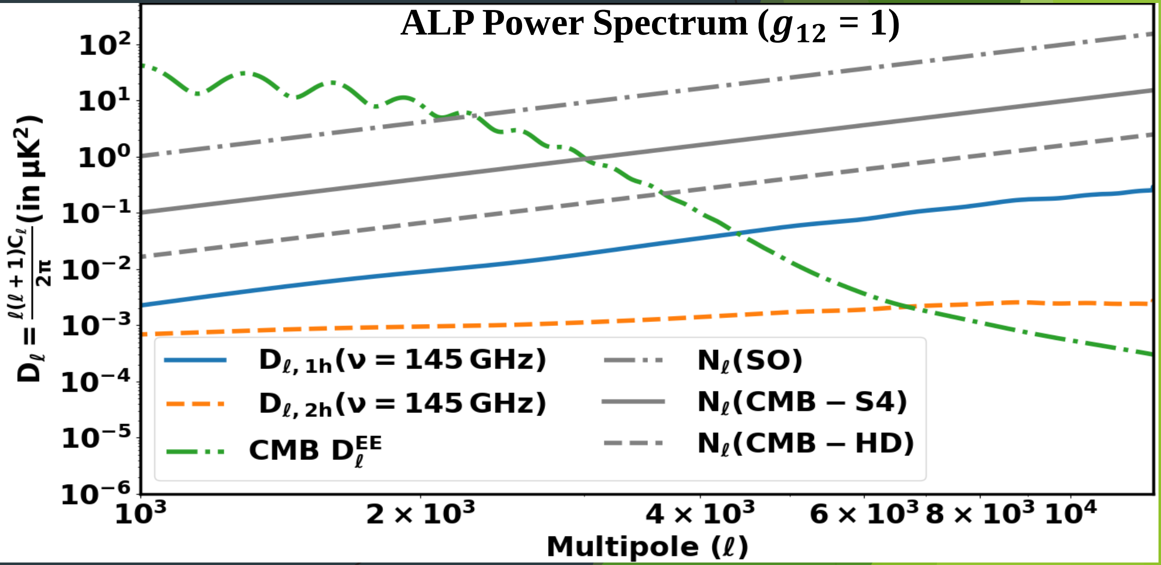
  (Value used in the plot $g_{a\gamma} = 10^{-12}$ GeV $^{-1}$ *)*



How does the ALP background spectrum look like?

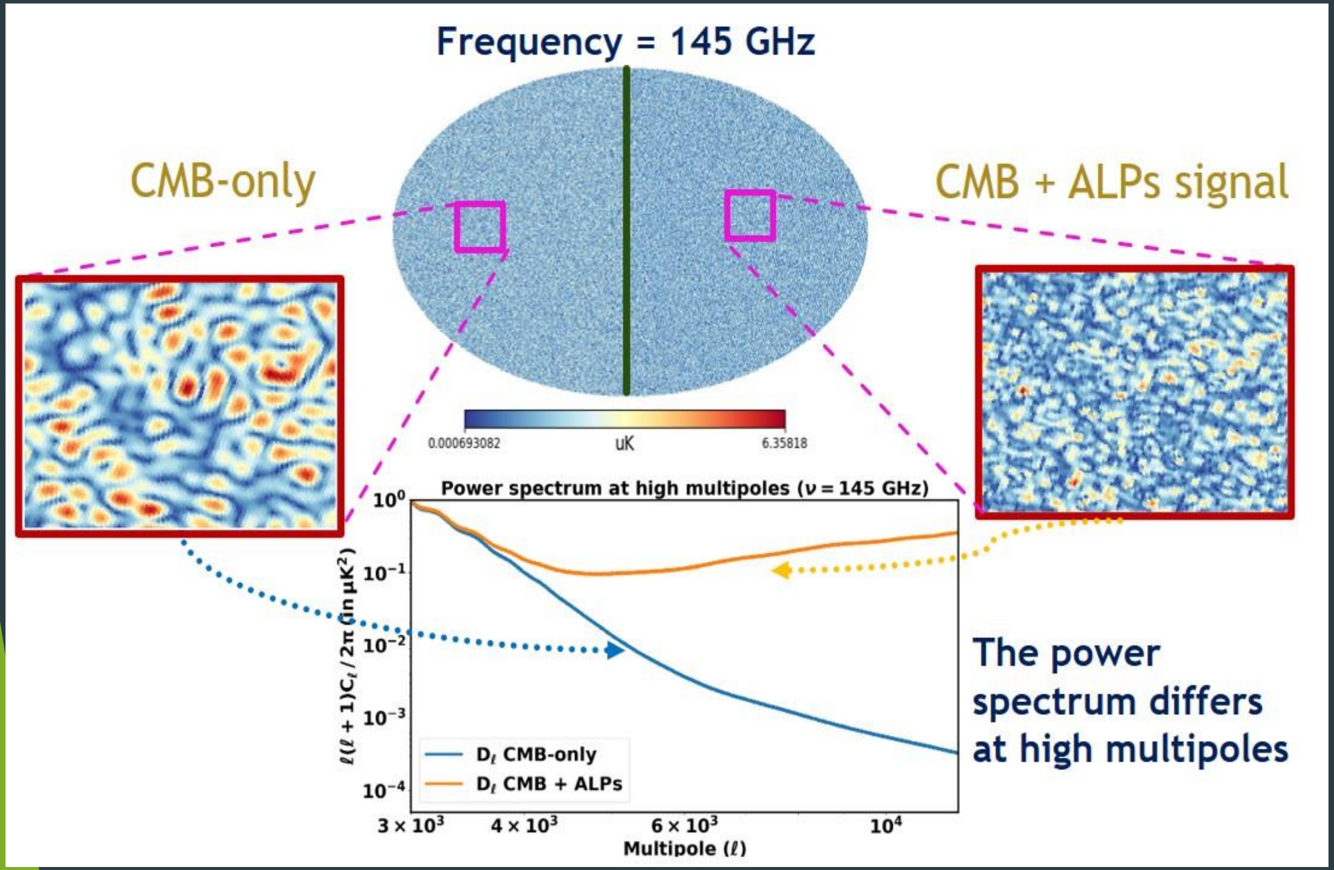
- *Two halo: Increases at low multipoles ($20 < \ell < 100$) and then decreases*
- *One halo: Dominates at high mulitpoles*
- *Power spectrum shape independent of strength at high multipoles*

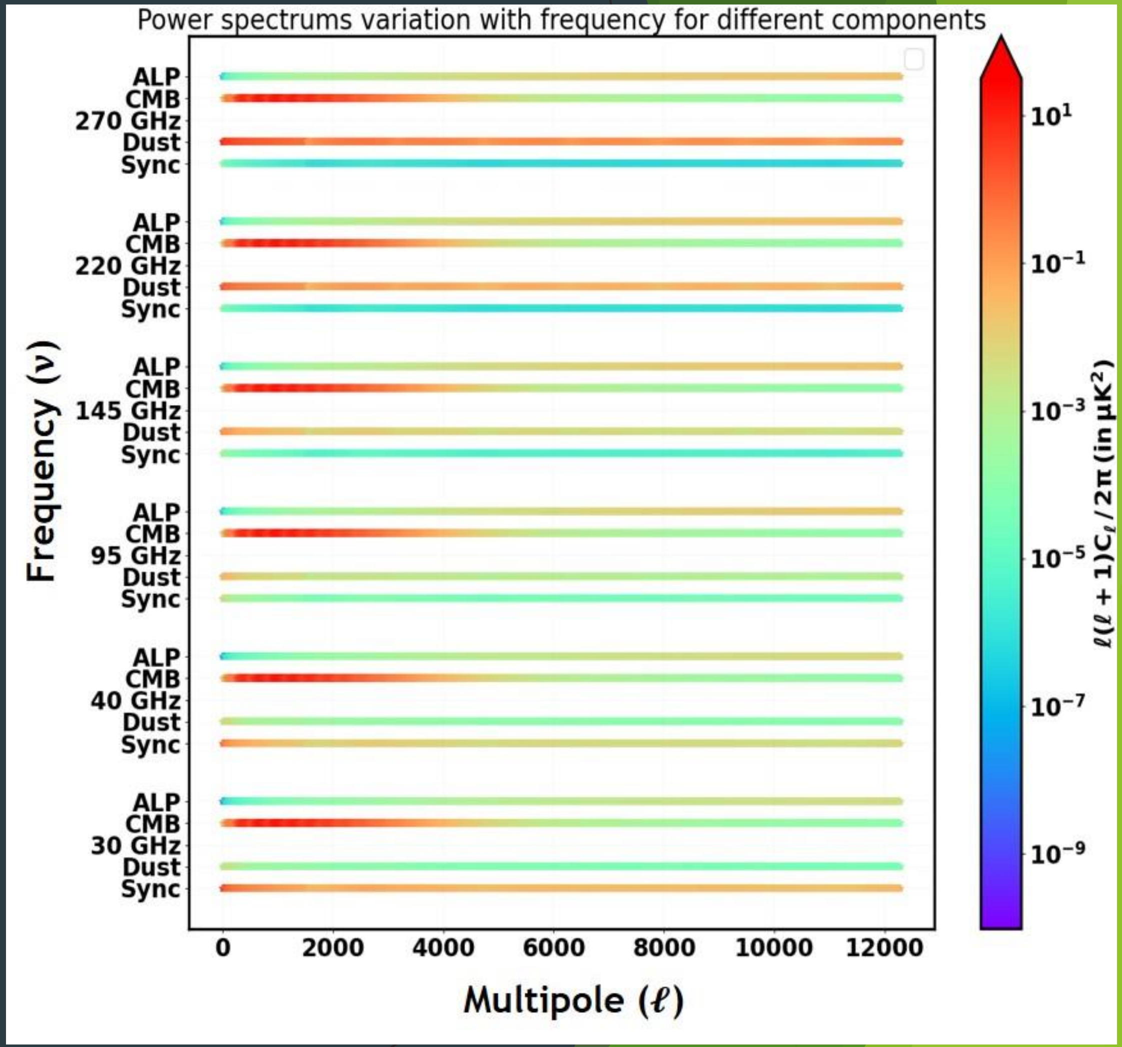




How is the ALP signal different from other signals?

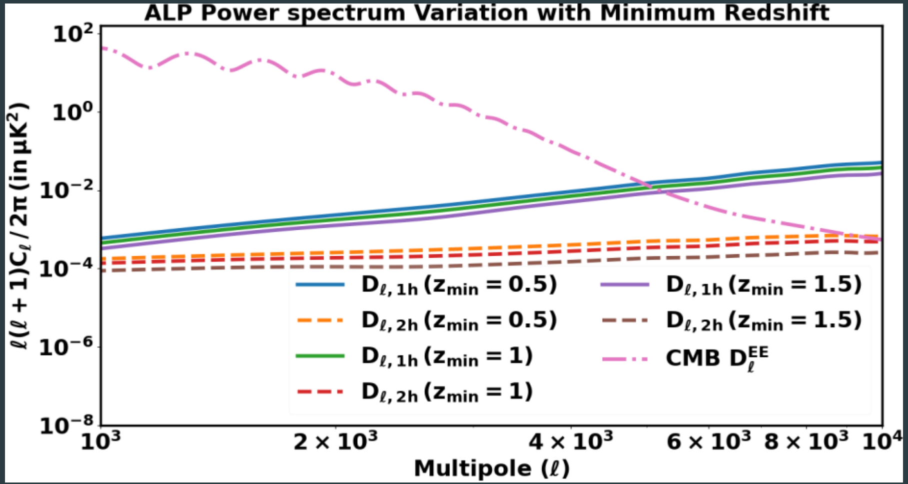
Can be distinguished in pixel, spectral and spatial domain



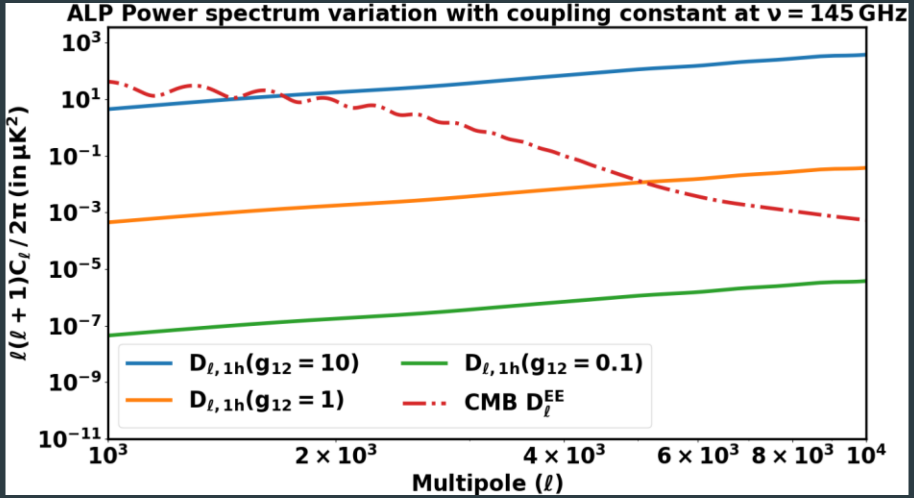


$$P(\gamma \rightarrow a) \propto \gamma = \left| \frac{2\, g_{a\gamma}^2\, B_t^{\,2}\, \nu(1+z)}{\nabla \omega_p^2} \right|$$

Cosmological

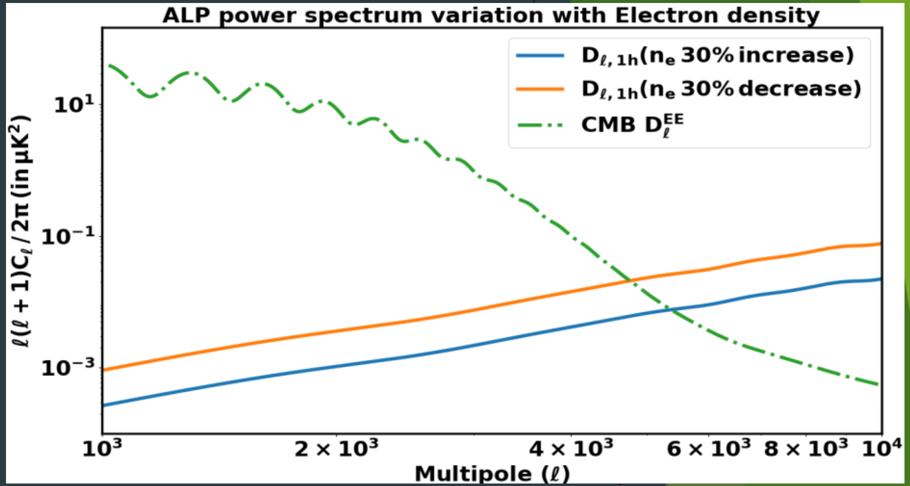


(a) *Variation with redshift*

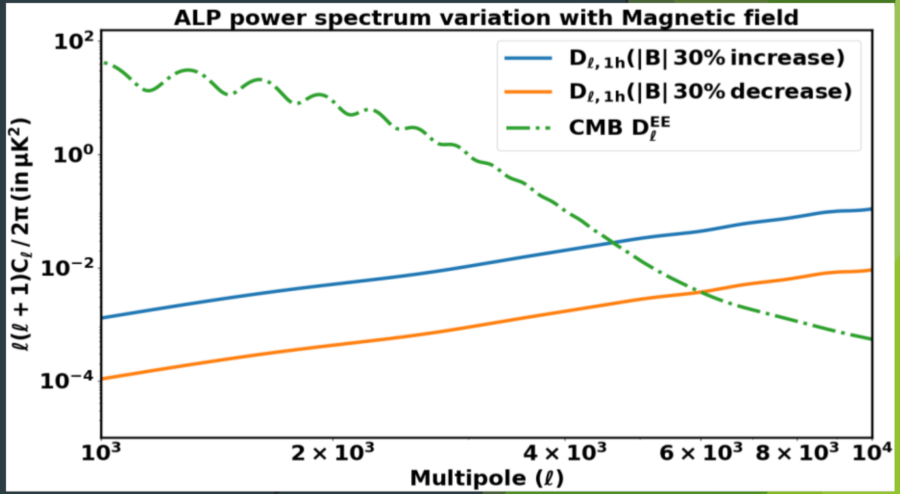


(b) *Variation with Coupling constant*

Astrophysical



(a) *Variation with Electron density strength*



(b) *Variation with Magnetic field steepening*

Future CMB experiments can constrain $g_{a\gamma}$ better than Particle Physics experiments

- *Internal Linear Combination method (ILC) weights are given as:*

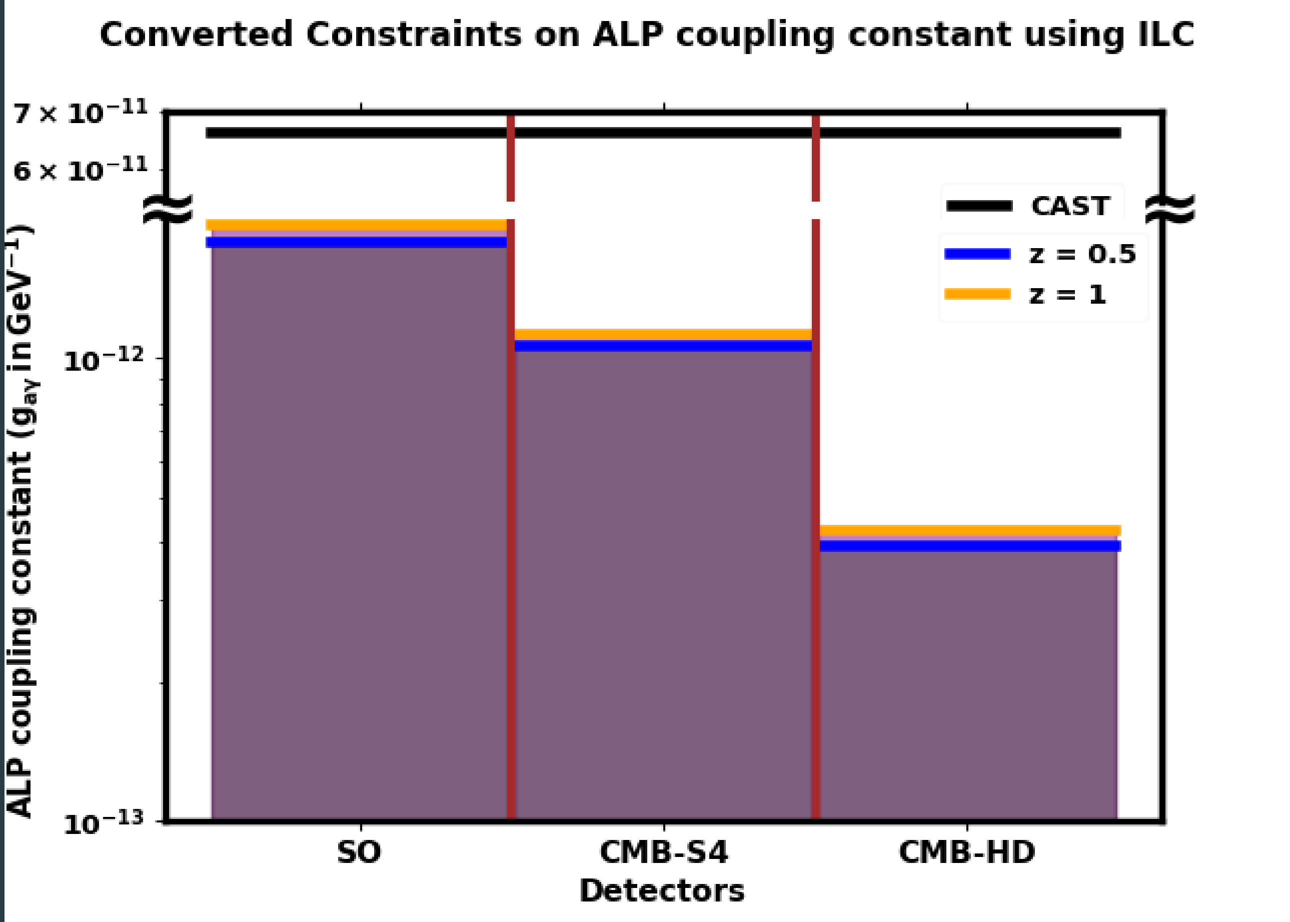
$$w_{a\gamma}=C_S^{-1}f_{a\gamma}\left(f_{a\gamma}^T C_S^{-1} f_{a\gamma}\right)^{-1}$$

Here $f_{a\gamma}$ is the ALP distortion spectrum

- *Residual = Data – Fiducial*

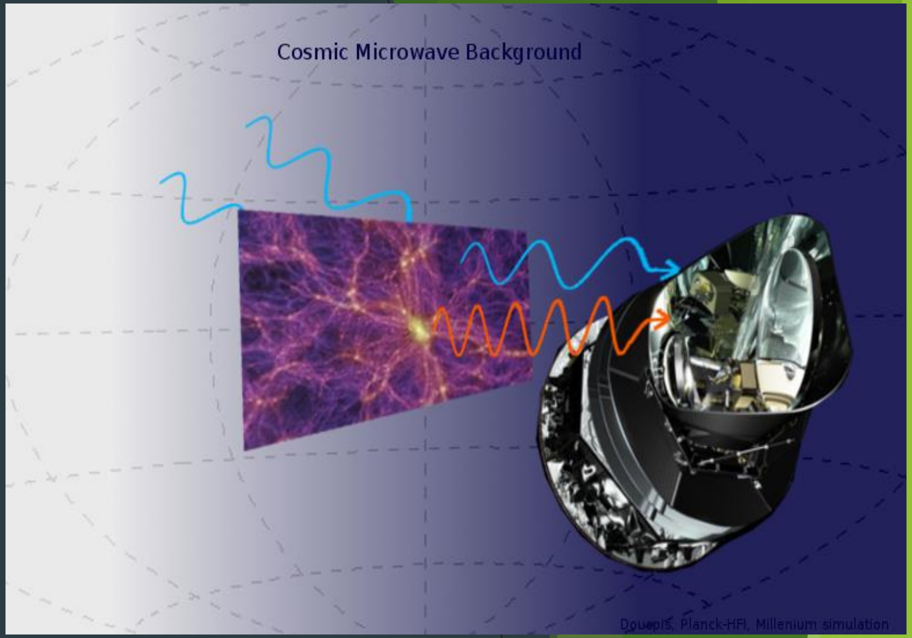
- *The bound on the ALP contribution in the residual is set by the covariance of the estimator*

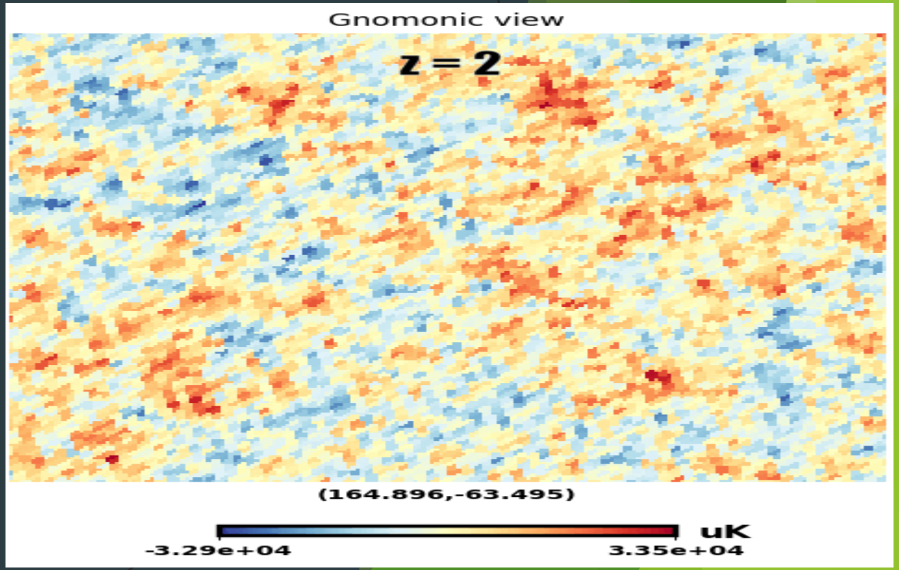
- *The bounds using various detectors using mock data are obtained as follows:*
  - *CMB-S4:* $g_{a\gamma} < 1.1 \times 10^{-12}$ GeV^{-1}
  - *Simons Observatory:* $g_{a\gamma} < 1.9 \times 10^{-12}$ GeV^{-1}
  - *CMB-HD:* $g_{a\gamma} < 4.2 \times 10^{-13}$ GeV^{-1}



Conclusion

- *The ALP background signal will follow the distribution of galaxy clusters in the universe.*
- *The ALP power spectrum will differ from those of other signals.*
- *The ALP power spectrum dominates at low angular scales and increases with frequency.*
- *CMB-S4 can improve the constraints on coupling constant by more than an order from current bounds.*





Thank you!!

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