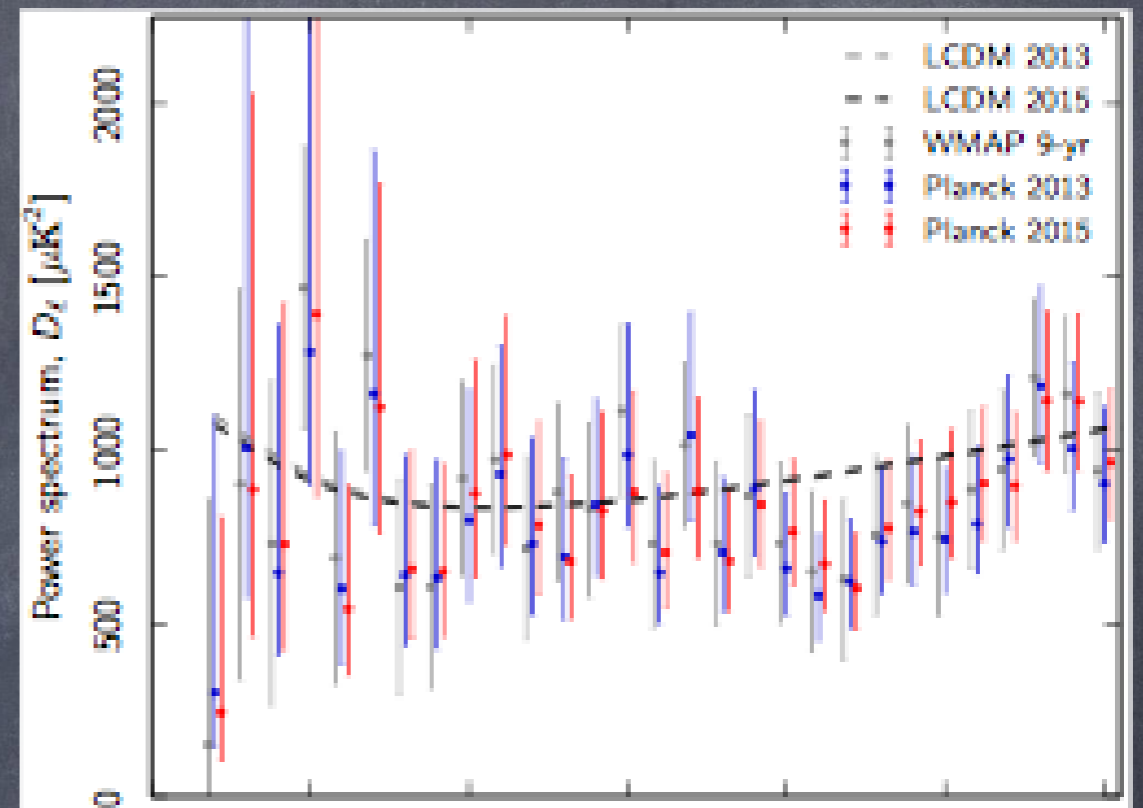


Reconstruction of large-scale CMB
temperature anisotropies with
primordial CMB induced Polarization
in galaxy cluster

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Tamkang University
IWARA 2018
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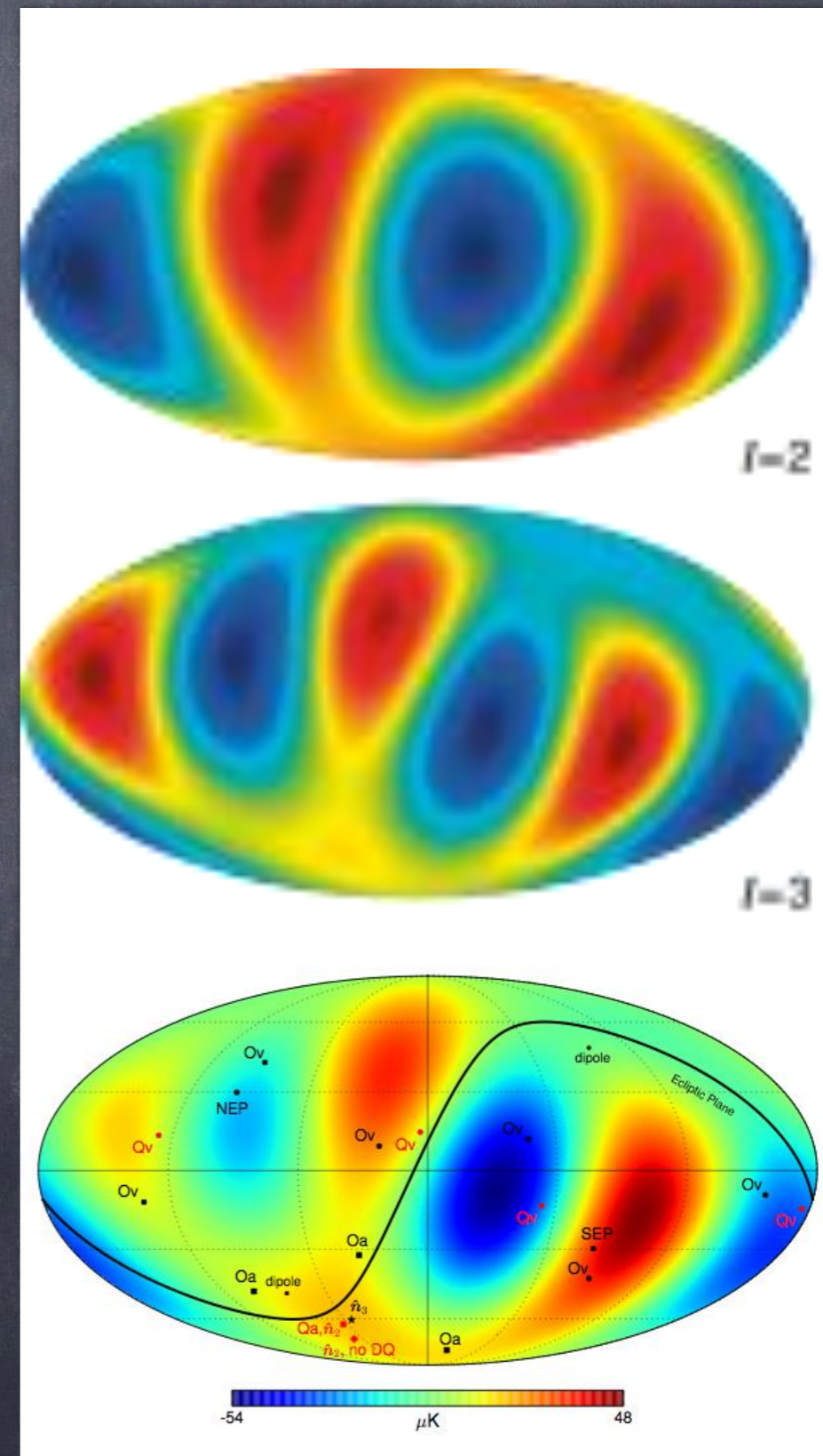
CMB Anomalies

- Low quadrupole problem:
 - Smallness of the quadrupole moment: ($p < 0.5\%$ [Planck Collaboration 2015](#))
- Alignment of low multipole moments:
 - Quadrupole and octopole planes are aligned with each other (p -value $< 1.5\%$ [Planck Collaboration, 2013 XII](#), [Copi et al. 2015](#), [Rassat et al. 2013](#))
- Hemisphere Power Asymmetry:
 - power is larger in one hemisphere than the other ($p < 0.1\%$ [Eriksen et al. 2004](#); [Planck Collaboration 2013 XXIII](#))
- Cold Spot:
 - unusual cold spot with radius around 10 degrees ($p < 1\%$ [Vielva](#)



CMB Anomalies

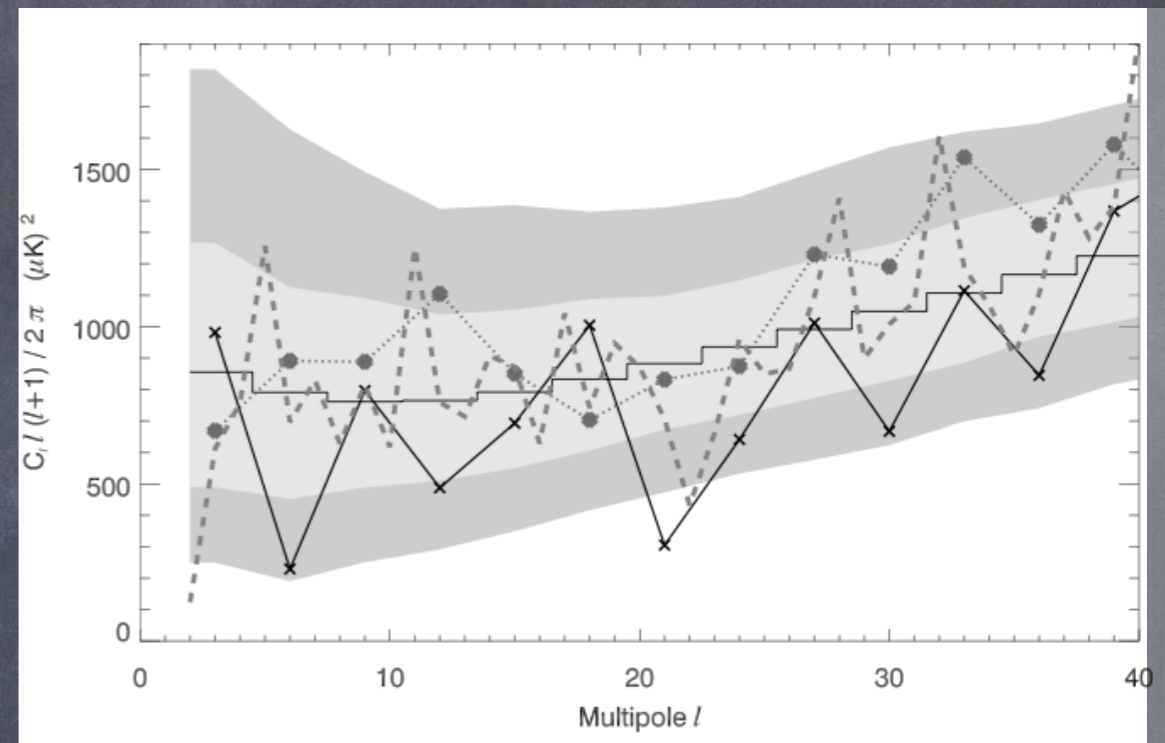
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Copi et al. 2015

CMB Anomalies

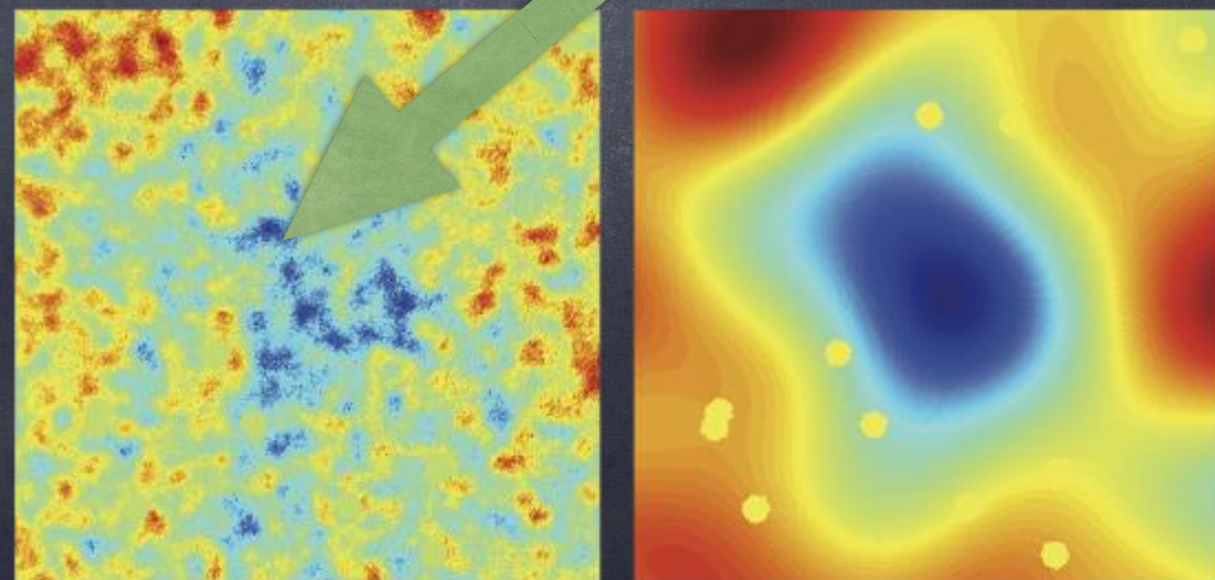
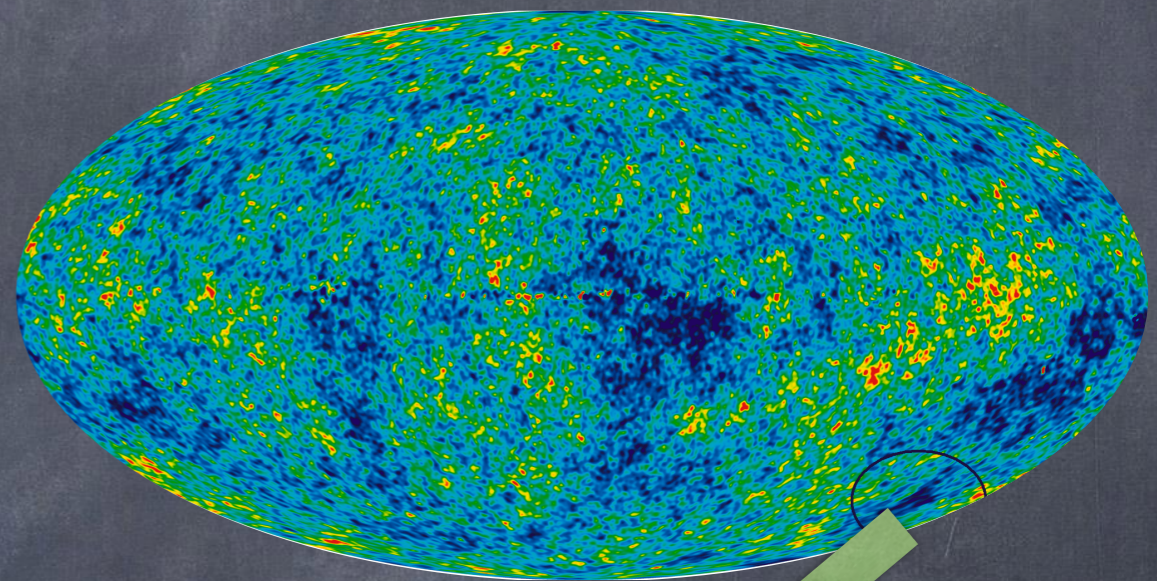
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Original evidence of power asymmetry by [Eriksen et al. 2004](#)

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Possible Sources of Anomalies

- Cosmology
 - Alternative inflation model violating scale invariance (e.g. [Boyanovsky et al. 2006](#), [Powell and Kinney 2007](#))
 - Alternative inflation model violating isotropy (e.g. [Gordon et al. 2005](#), [Grishchuk & Zeldovich 1978](#), [Turner 1991](#))
 - Super void in the direction of cold spot ([Marcos-Caballero et al. 2016](#); [Naidoo et al. 2016](#))
- systematics or foreground contamination (e.g. [Solar & Seljak 2004](#), [Copi et al. 2006](#), [Copi et al. 2015](#), [Mertsch & Sarkar 2013](#))

Any independent measurement to study these anomalies?

Primordial CMB Polarization

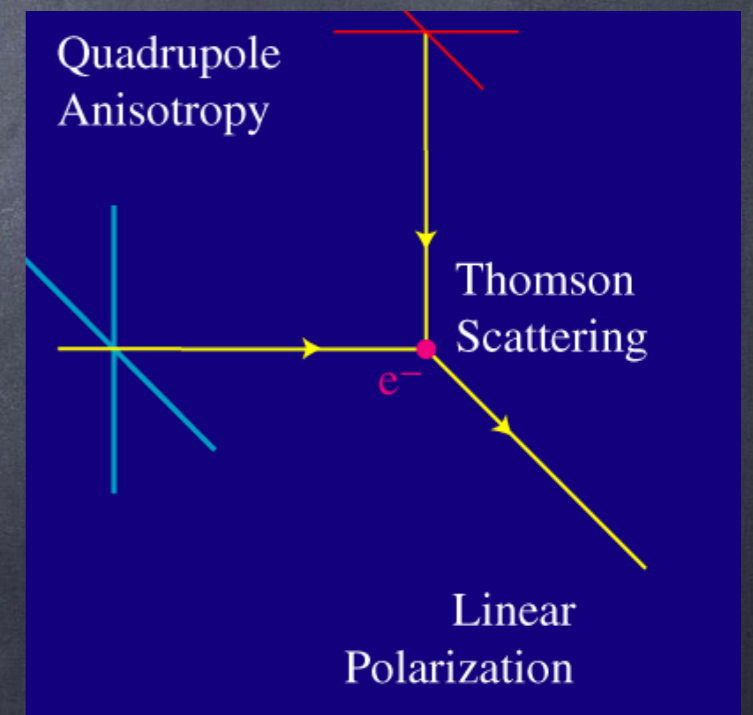
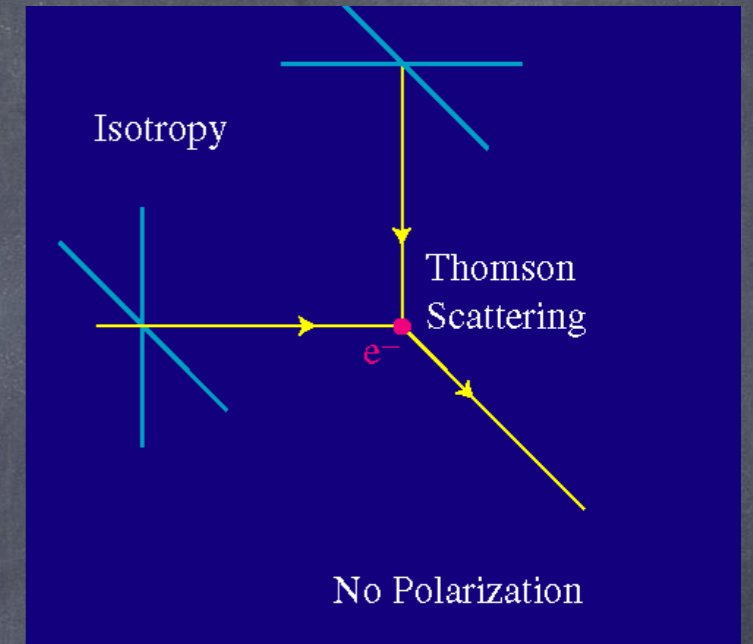
- CMB polarization is generated through Thomson scattering recombination, reionization, hot gas cloud
- temperature anisotropies (**quadrupole component**) are sources of polarization
- homogeneous hot gas: primordial polarization
perturbed hot gas: secondary polarization

Stokes parameters

$$Q = \frac{3S_T}{16\rho} \int I_{in}(q, f) \sin^2 q \cos 2f dW$$

$$-U = \frac{3S_T}{16\rho} \int I_{in}(q, f) \sin^2 q \sin 2f dW$$

z-axis as the propagating direction of scattered light

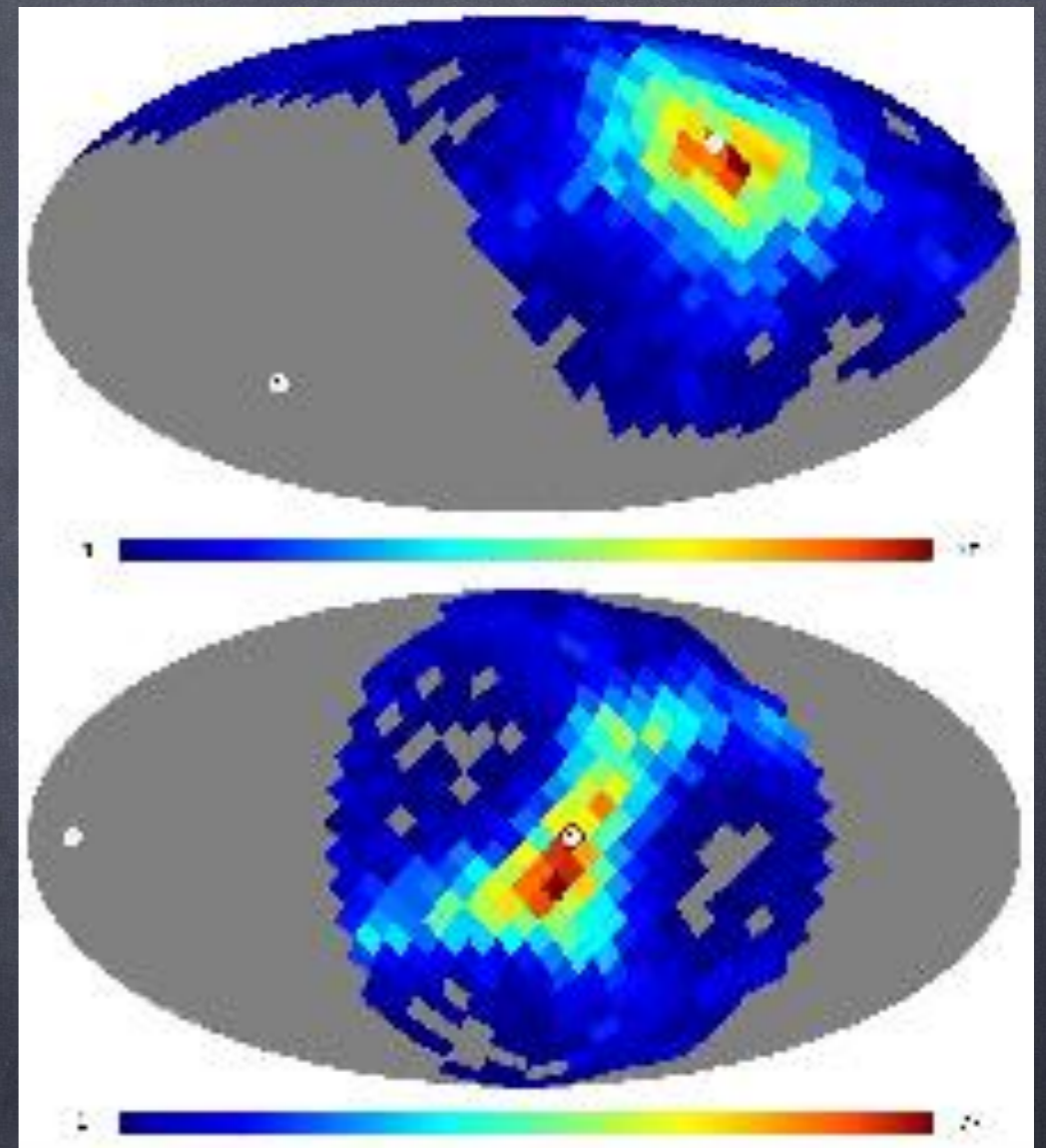


W. Hu

Anomalies with Polarization

- axis of evil(Frommert & Ensslin 2010):
 - separate the polarization into P_{corr} and P_{uncorr}
 - octopole of P_{uncorr} changes alignment
- cold spot(Vielva et al. 2011):
 - big uncertainty due to the bad sensitivity for polarization.

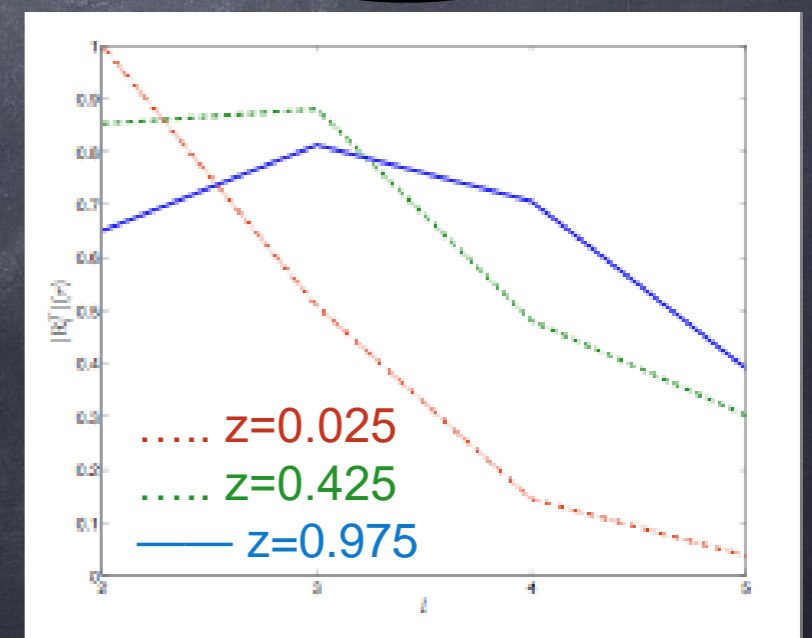
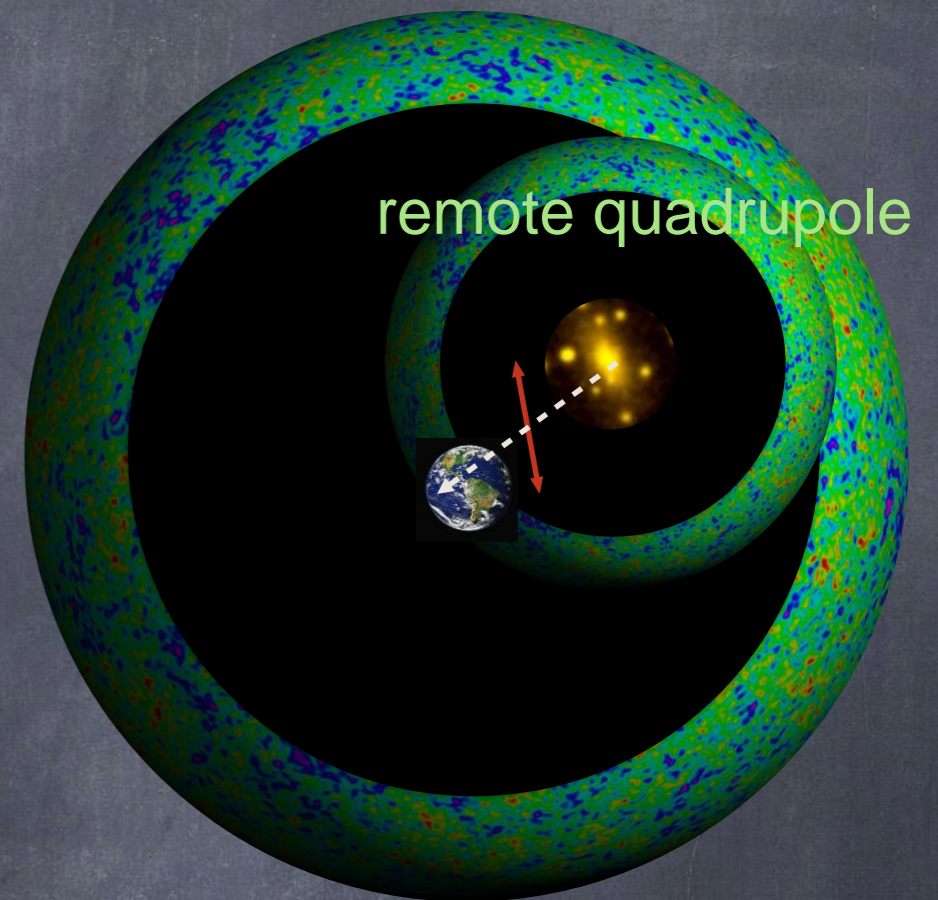
Preferred Quadrupole and Octopole of P_{uncorr}



Frommert & Ensslin 2010

CMB Induced Polarization in Galaxy Cluster

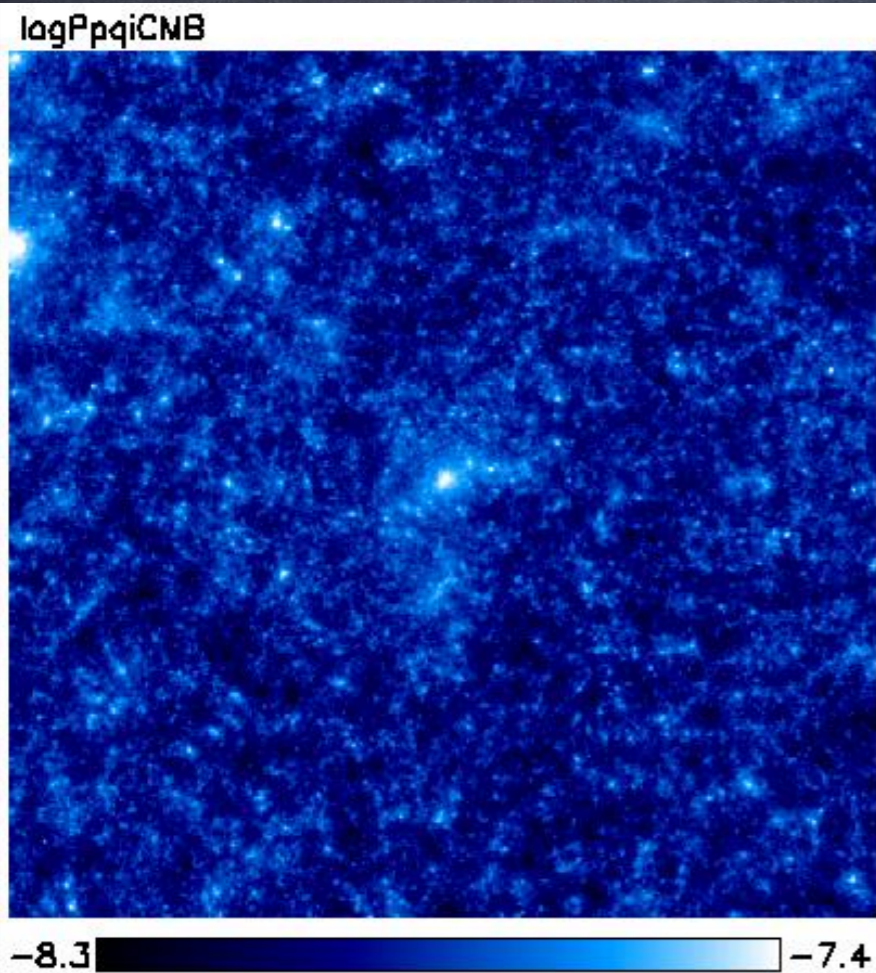
- Primordial CMB induced polarization
 - CMB quadrupole from LSS seen by cluster (Zeldovich & Sunyaev 1980)
 - polarization degree $P \sim Q_{\text{cmb}} \tau$,
 $\tau = \int n_e \sigma_T dl$
- Primordial CMB quadrupole has long coherence length
 - strong correlation between remote quadrupole and local CMB (Hall & Challinor 2014)



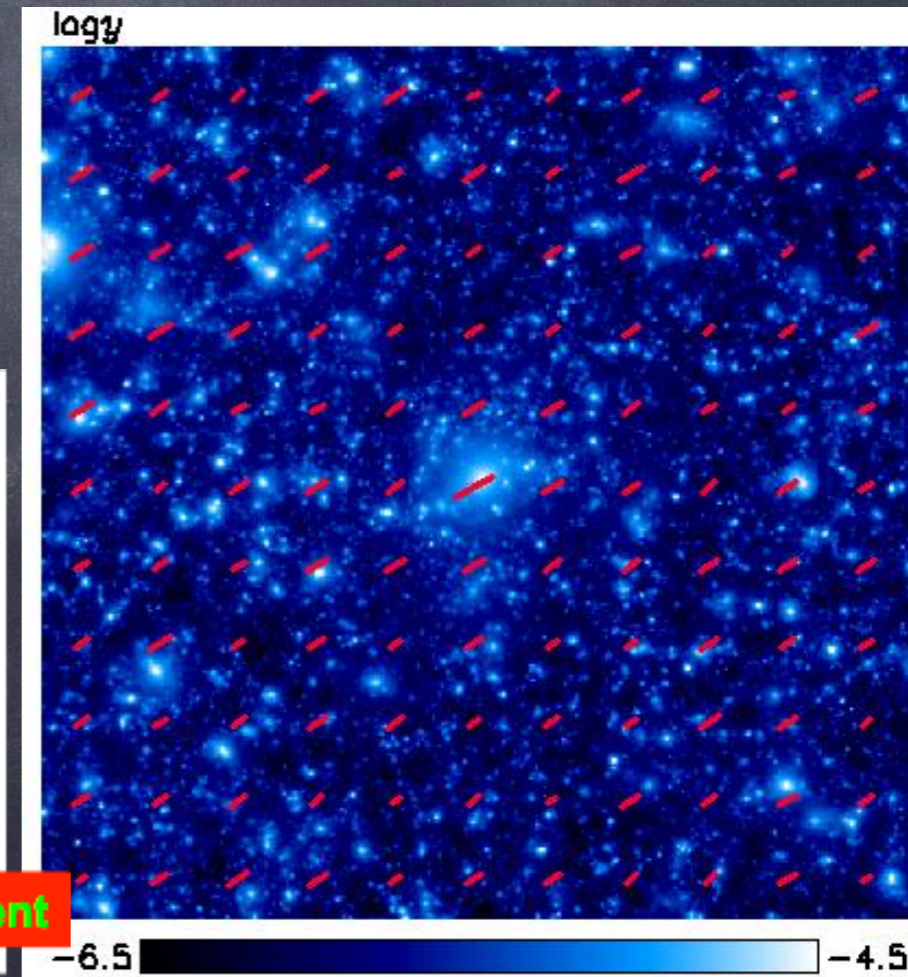
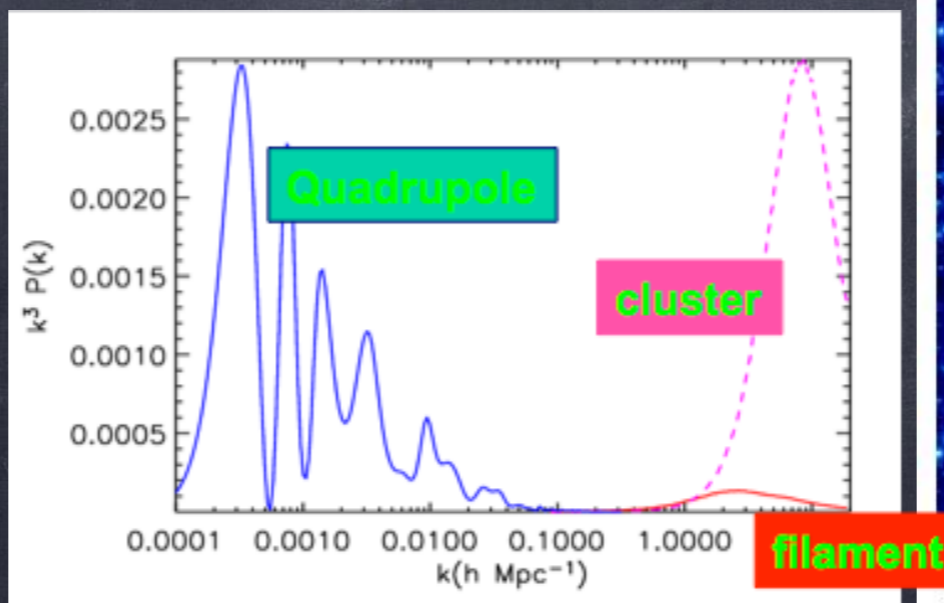
Simulated Sky Maps

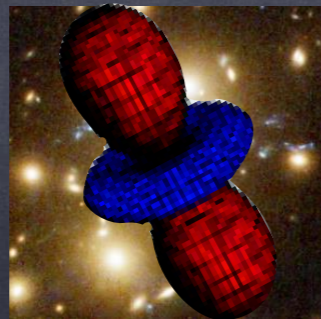
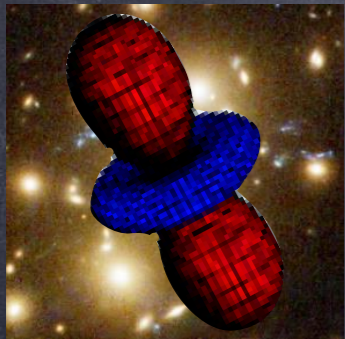
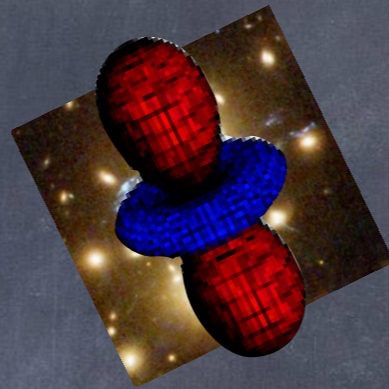
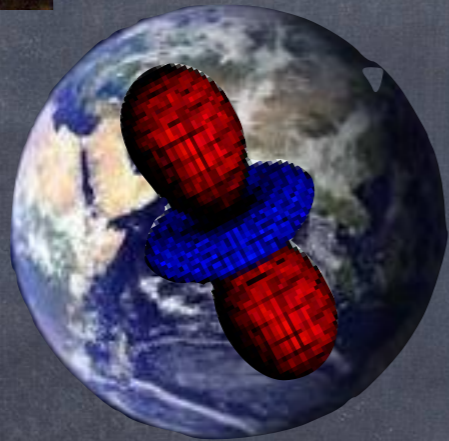
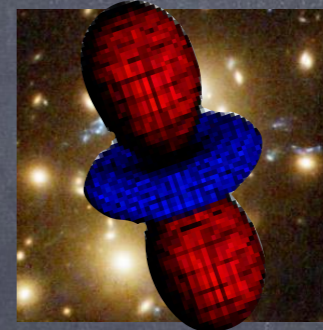
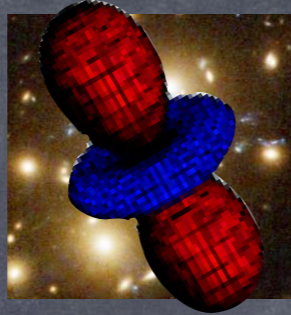
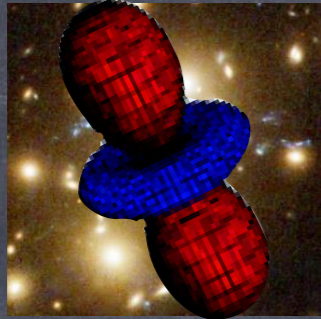
- polarization vectors align uniformly
- polarization degree follows the local distribution of gas

$$y = \int \frac{kT_e}{m_e c^2} n_e S_T dl$$



Ramos, da Silva, Liu 2013

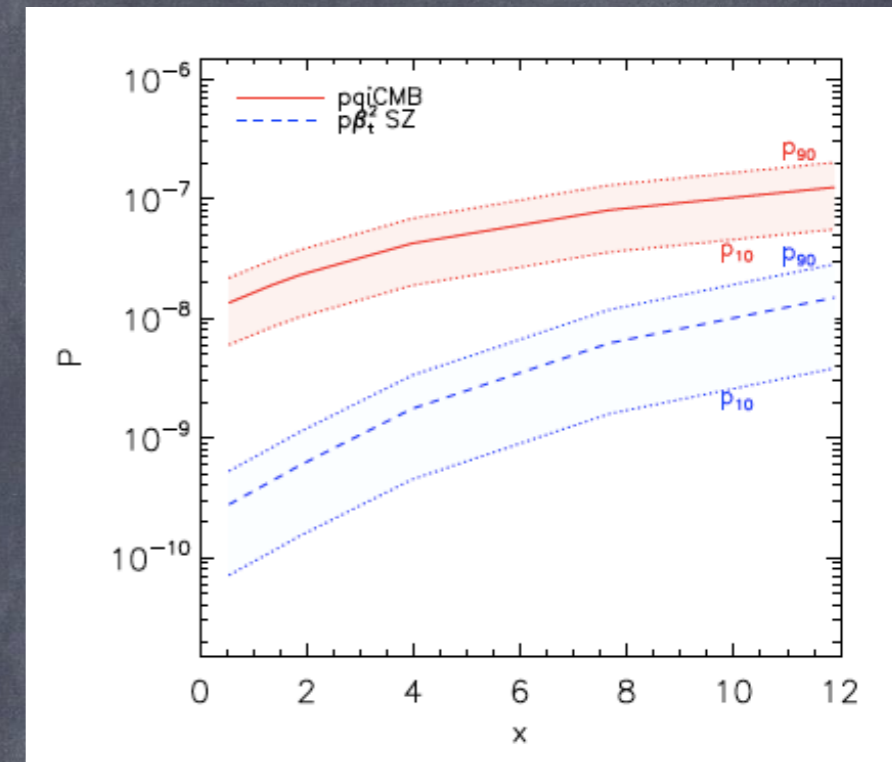




Other Sources of secondary CMB polarization

- kinematic quadrupole induced polarization

- ionized gas cloud moves w.r.t the rest frame of CMB. The quadrupole results from the relativistic Doppler effect. (Zeldovich & Sunyaev 1980)
- polarization signal $P \sim \beta_t^2 T$
- polarization direction is perpendicular to the transverse velocity of ionized gas
- Separable by multi-freq. obs.



Ramos, da Silva, Liu 2013

- double scattering

- due to non-symmetrical optical depth (Sunyaev & Zeldovich 1980)
- CMB acquires an anisotropy due to thermal and kinematic SZ effect.
- polarization degree $P \propto T_e \tau^2$ (thermal) and $\beta_t \tau^2$ (kinematic)

(Sazonov & Sunyaev 1999 Lavayssier et al 2004)

Initial Perturbations

Spherical harmonics coefficients of CMB

$$a_{X,lm} = (-i)^l 4\pi \int d^3\mathbf{k} Y_{lm}^*(\hat{\mathbf{k}}) \Delta_{Xl}(\mathbf{k}, \eta_0)$$

X: T, E

Induced Polarization in distant cluster

direction of cluster

$$(Q_T + iU_T)(\hat{\mathbf{n}}) = \frac{2\sqrt{6}\pi}{5} \tau \int d^3\mathbf{k} e^{i\mathbf{k}\cdot\mathbf{x}} \Delta_{T2}(\mathbf{k}, \eta) \sum_m Y_{2m}^*(\hat{\mathbf{k}}) \mp 2 Y_{2m}(\hat{\mathbf{n}})$$

time evolution of transfer function is indep. on direction of wave -mode

$$D_{Tl}(\mathbf{k}, h) = y(\mathbf{k}) D_{Tl}(k, h)$$

primordial gravitation potential:
origin of CMB and induced polarization

Statistics of initial perturbations

$$\langle y(\mathbf{k}_1) y(\mathbf{k}_2) \rangle = P_y(k) d(\mathbf{k}_1 + \mathbf{k}_2) = A k^{n-4} d(\mathbf{k}_1 + \mathbf{k}_2)$$

Estimate the Primordial Potential

Bayes' Theorem

$$P(\mathbf{y} | \mathbf{d}) \propto P(\mathbf{d} | \mathbf{y}) P(\mathbf{y})$$

likelihood \nearrow prior \nwarrow

$$P(\mathbf{y}) = e^{-\frac{1}{2} \sum_k \frac{(\mathbf{y}(\mathbf{k}))^2}{P_y(k)}}$$

minimizing the function

$$f = \sum_{j=1}^{n_c} \frac{(\hat{Q}_{T,j} - Q_{T,j})^2}{2\sigma_{Q_T}^2} + \sum_{j=1}^{n_c} \frac{(\hat{U}_{T,j} - U_{T,j})^2}{2\sigma_{U_T}^2} + \sum_{k=1}^{n_k} \frac{\psi_k^2}{2P_\psi}$$

assume very nice observation

$$\sigma_{Q_T} = \sigma_{U_T} = 10^{-9} \text{ K}$$

assume the optical depth is well measured by other observations

Algorithm

Simulate primordial potential $\psi(\mathbf{k})$

CMB maps

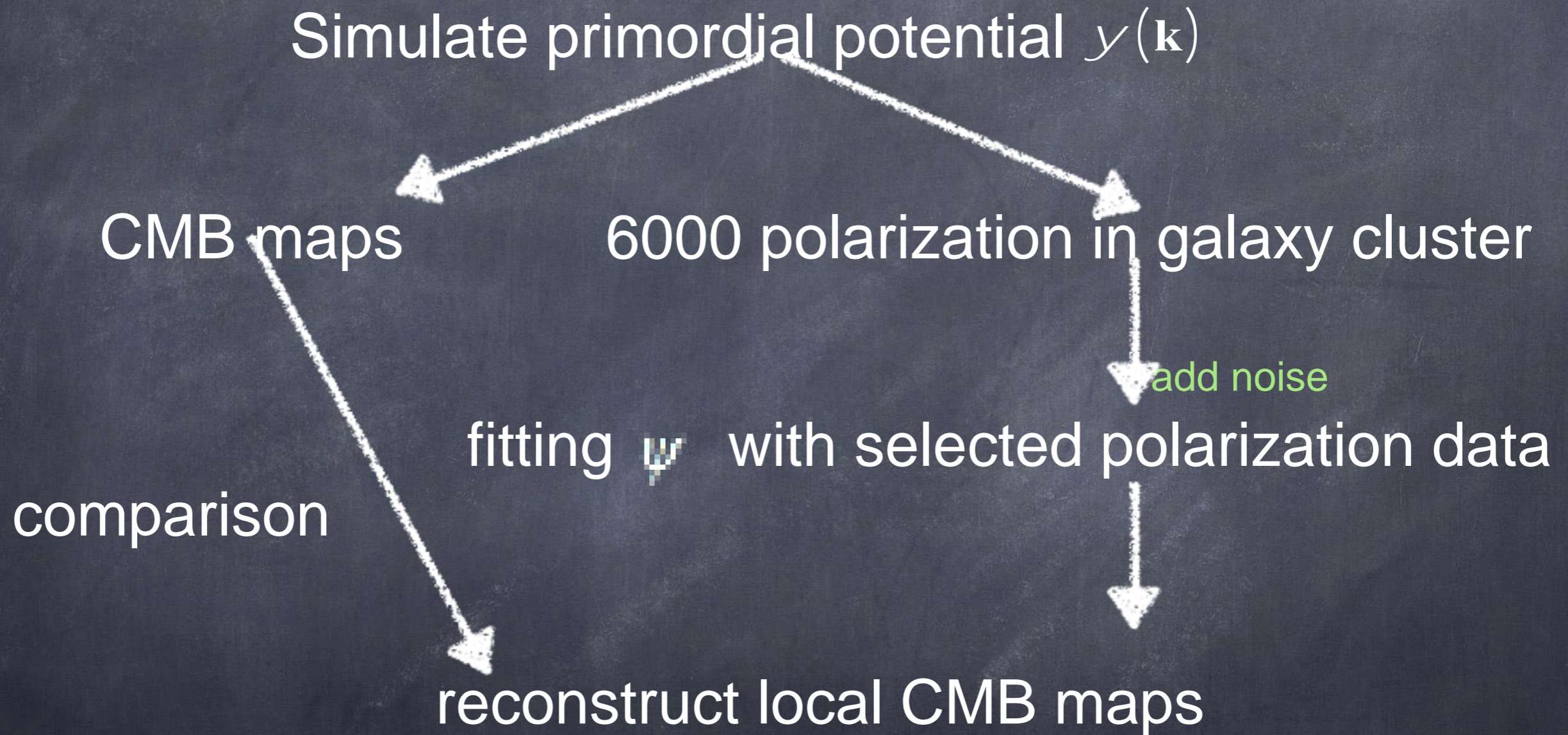
6000 polarization in galaxy cluster

add noise

fitting ψ with selected polarization data

comparison

reconstruct local CMB maps



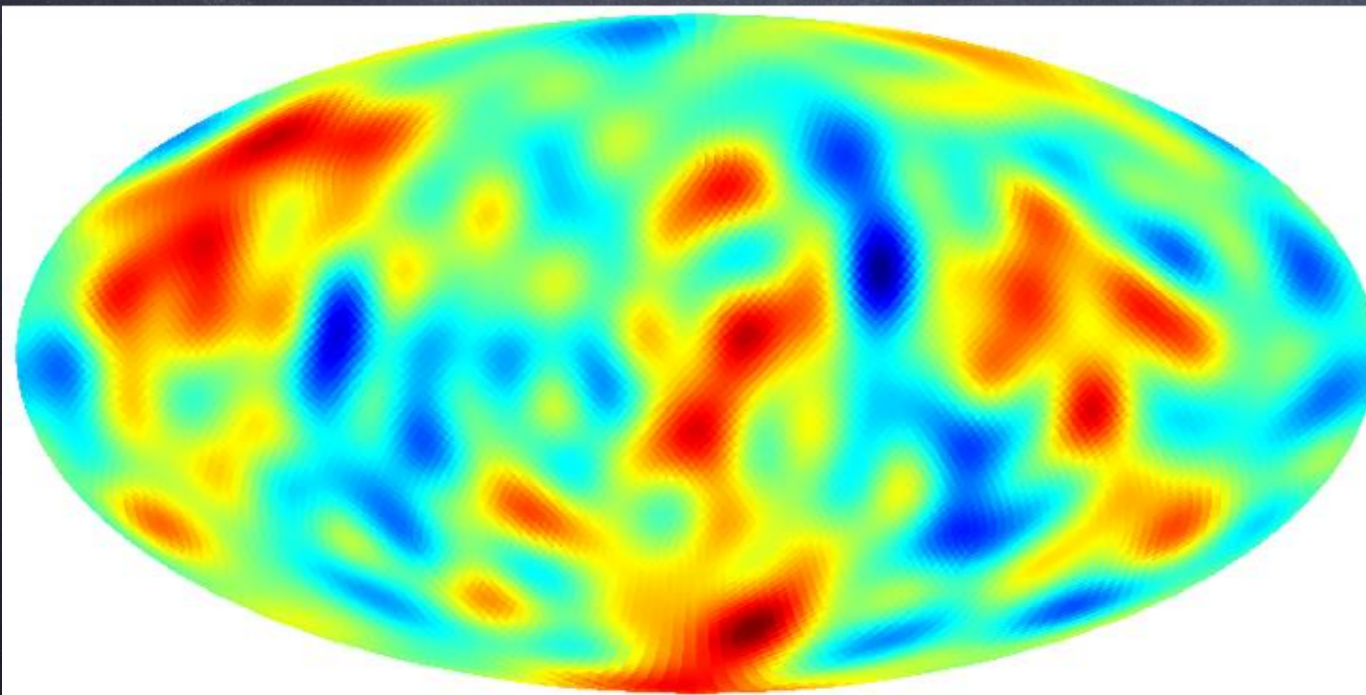
Reconstructed Temperature

Temperature Map by simulated perturbations

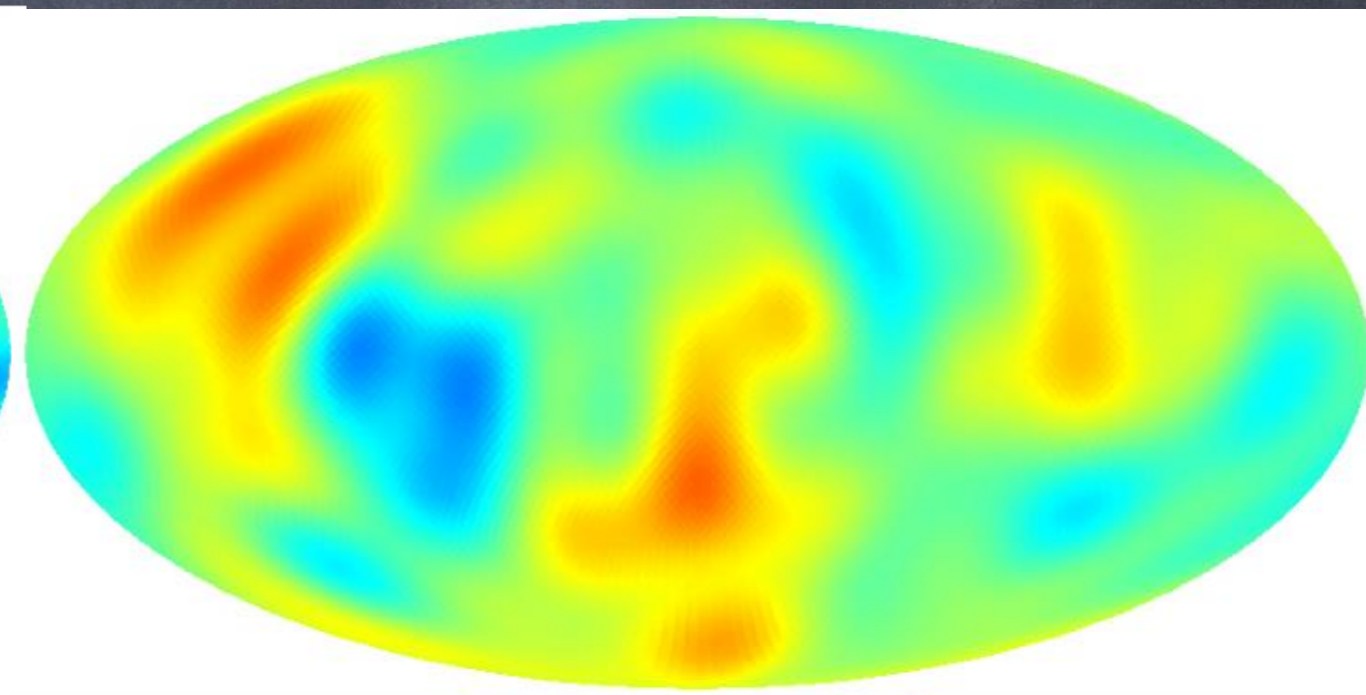
- $n_r=5$
- $n_k=240$
- $l_{\max}=16$

Reconstructed Map using remote quadrupole

- $n_r=3$
- $n_k=60$
- $n_c=100$
- $l_{\max}=10$



-6.1e-05 5.4e-05

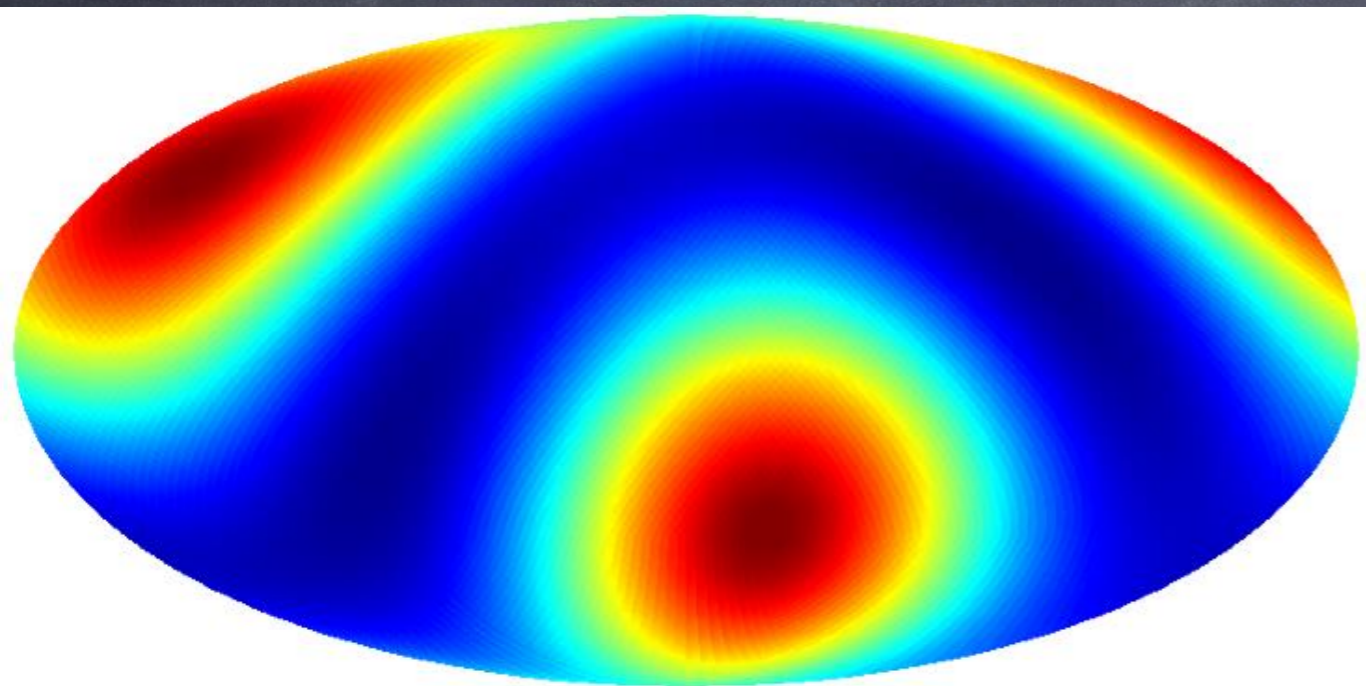


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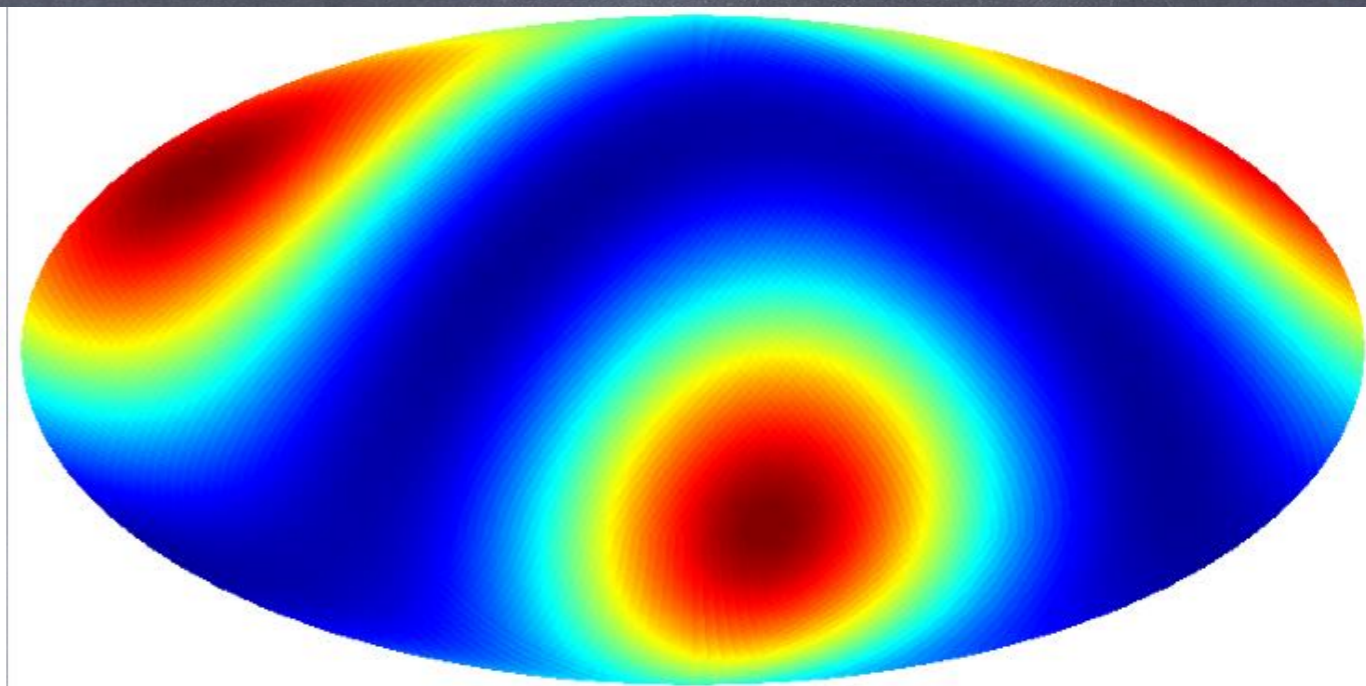
Reconstructed Quadrupole/Octopole

Simulated Temperature Maps

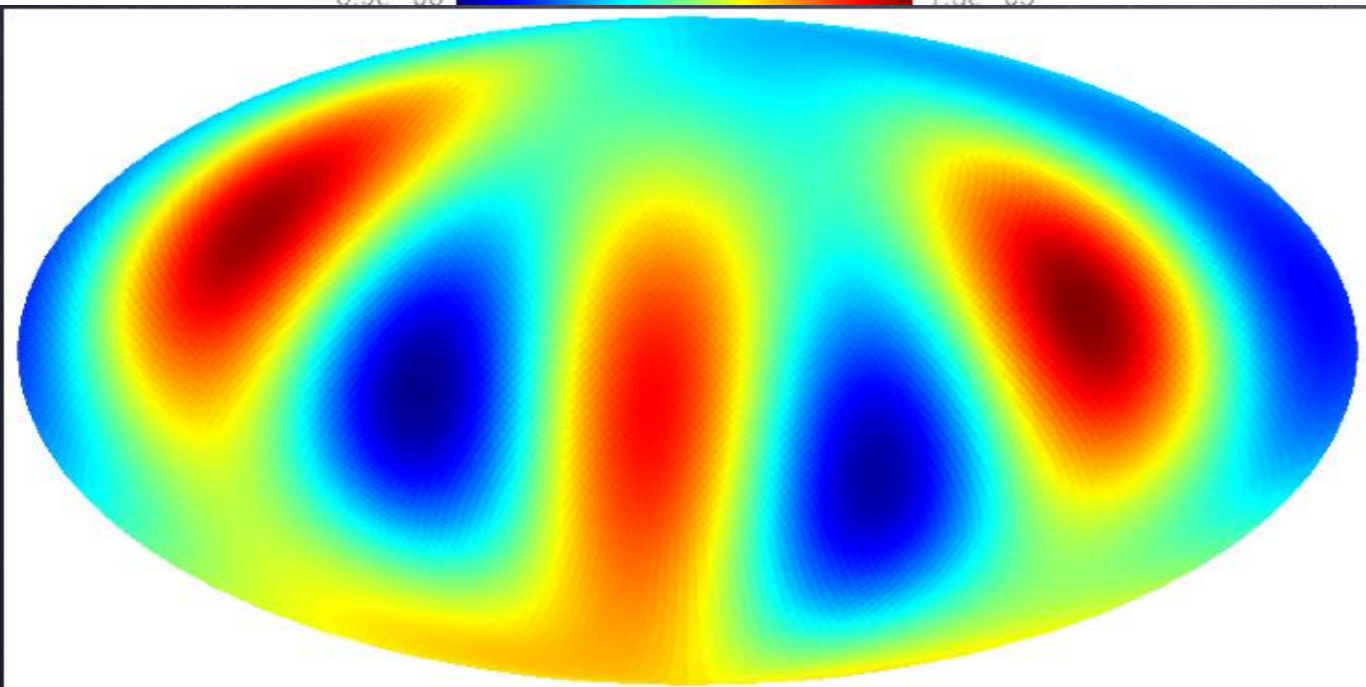
Reconstructed Temperature Maps



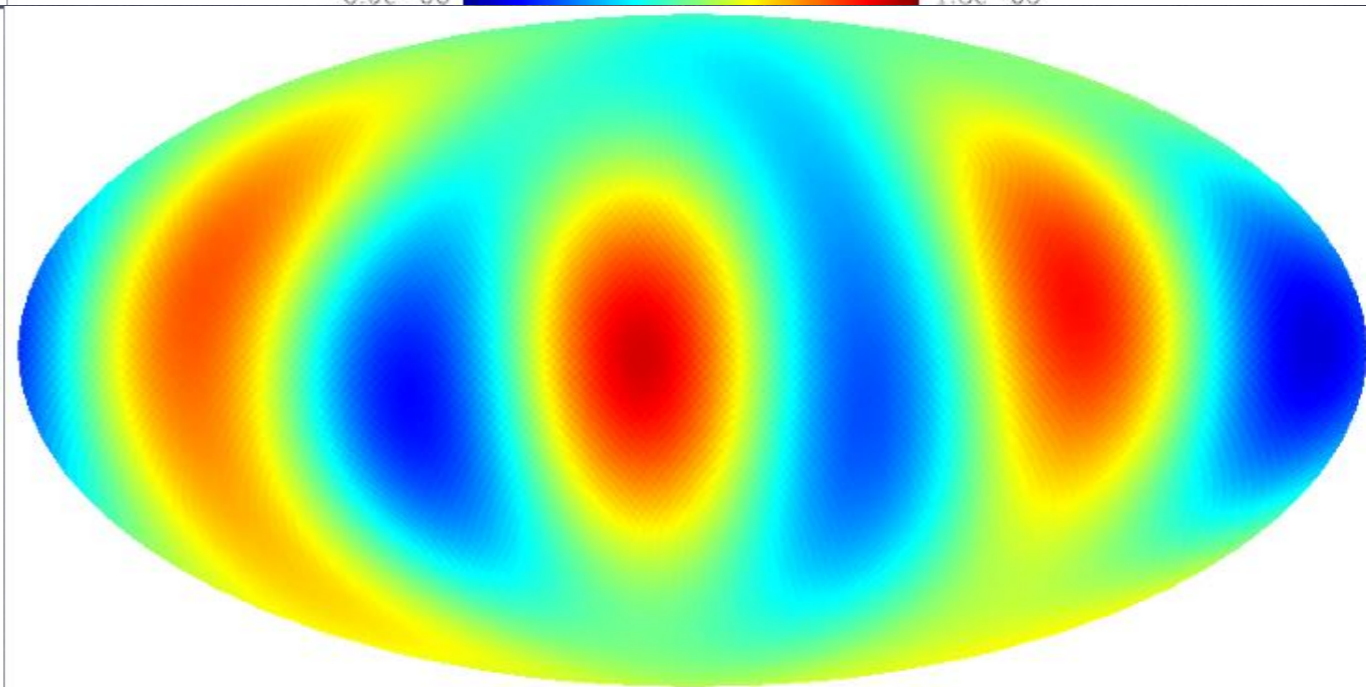
$-6.9e-06$ $1.3e-05$



$-6.9e-06$ $1.3e-05$



$-2.2e-05$ $2.2e-05$



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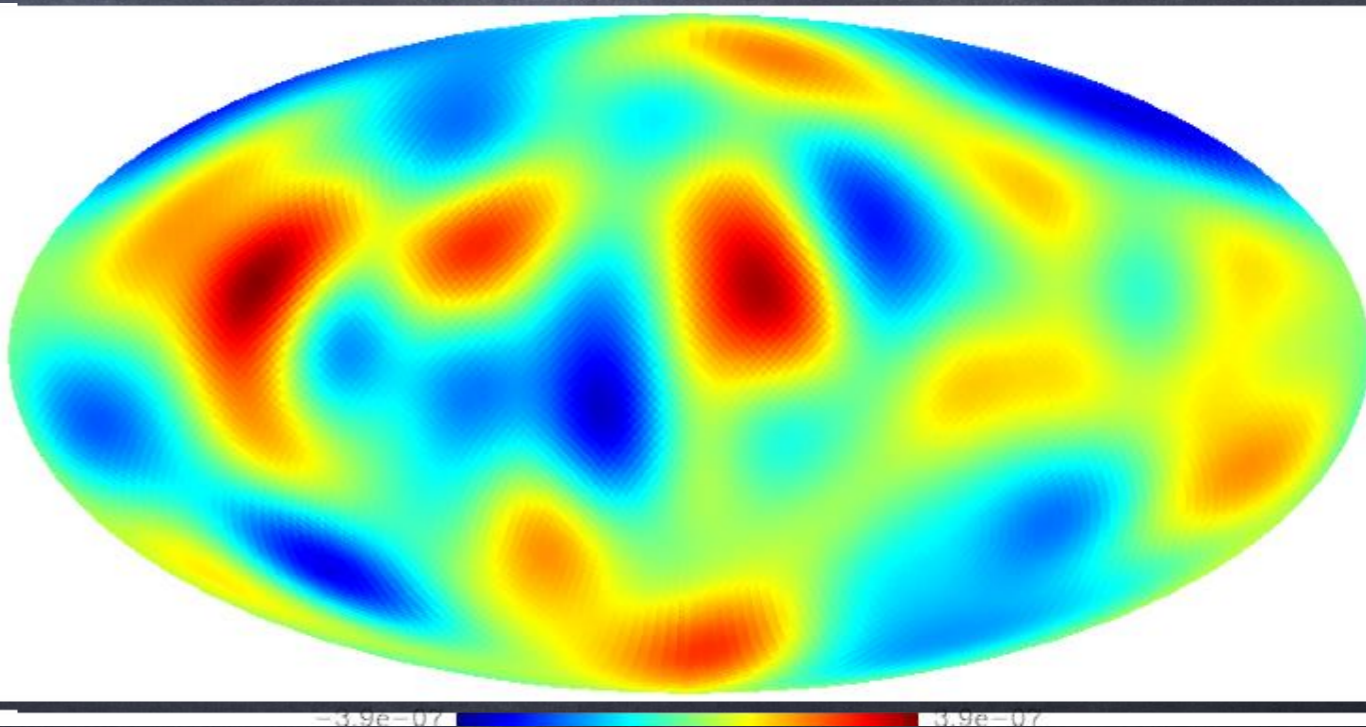
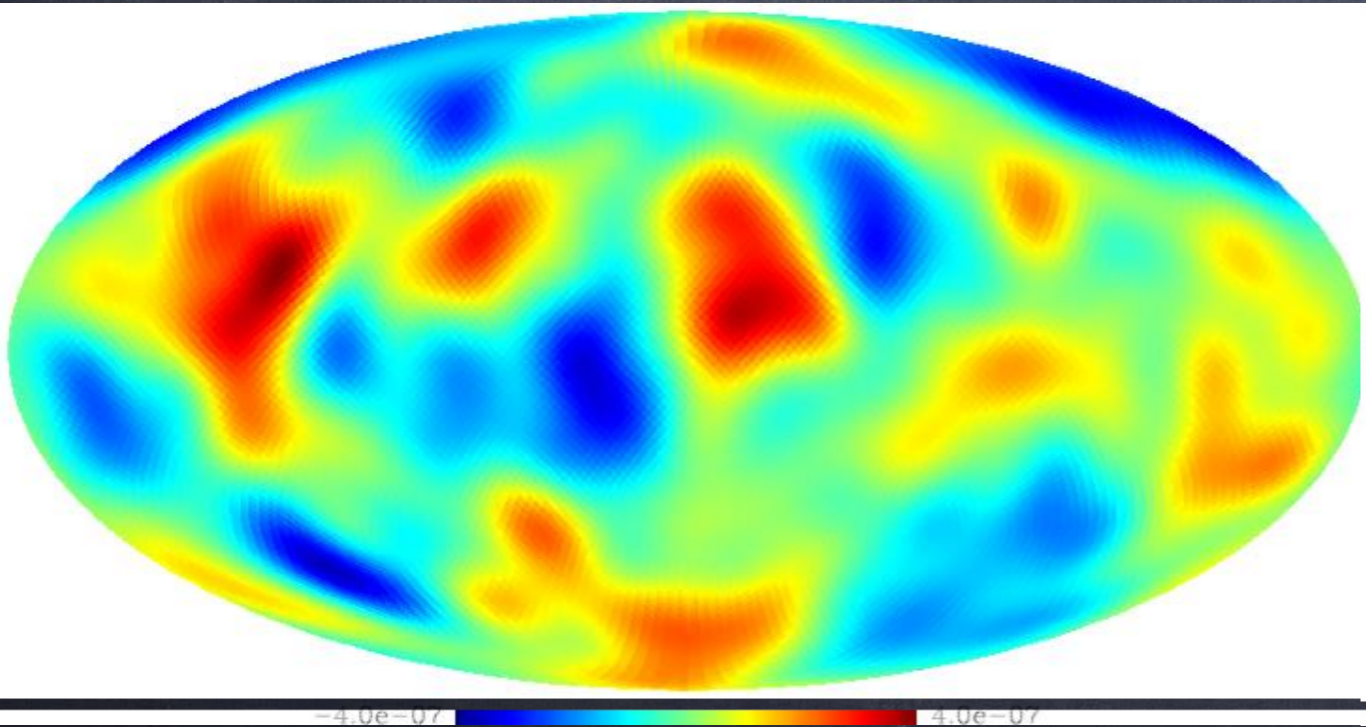
Reconstruction of CMB Polarization

Polarization Map by simulated perturbations

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- $n_r=5$
- $n_k=240$

Polarization Map using remote quadrupole

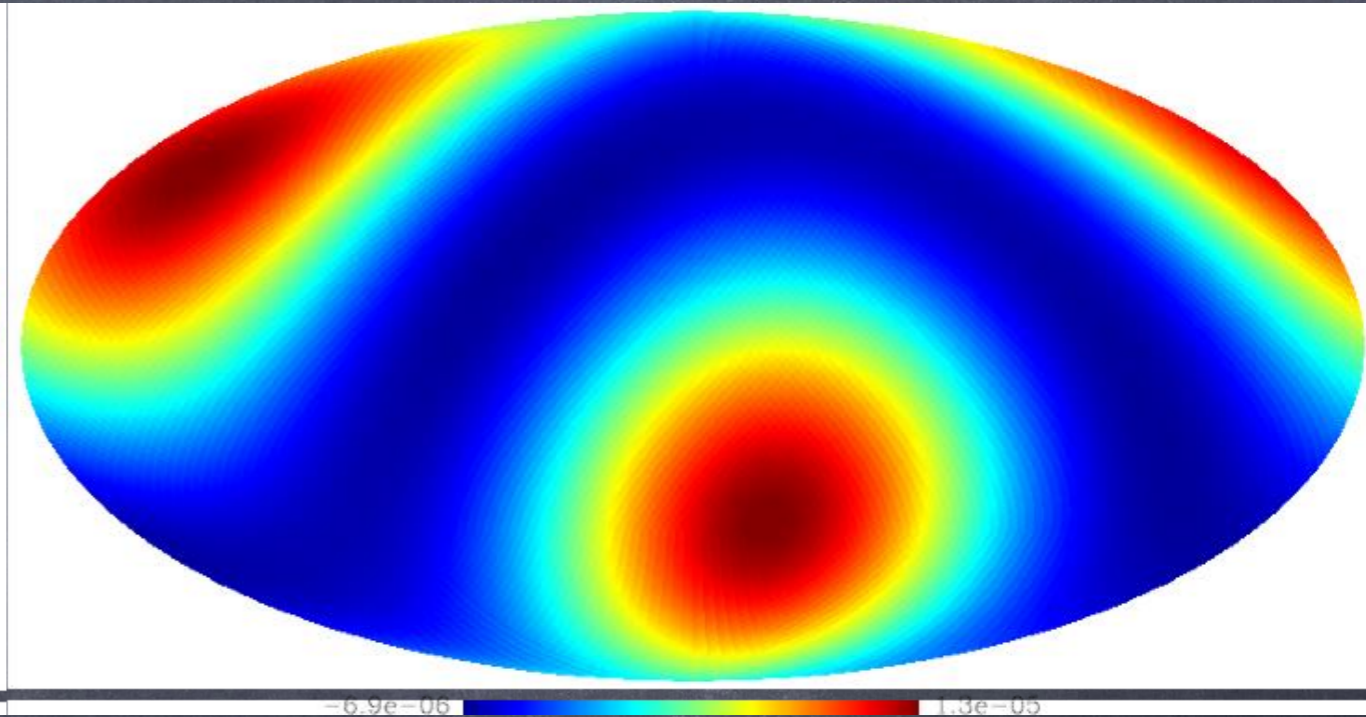
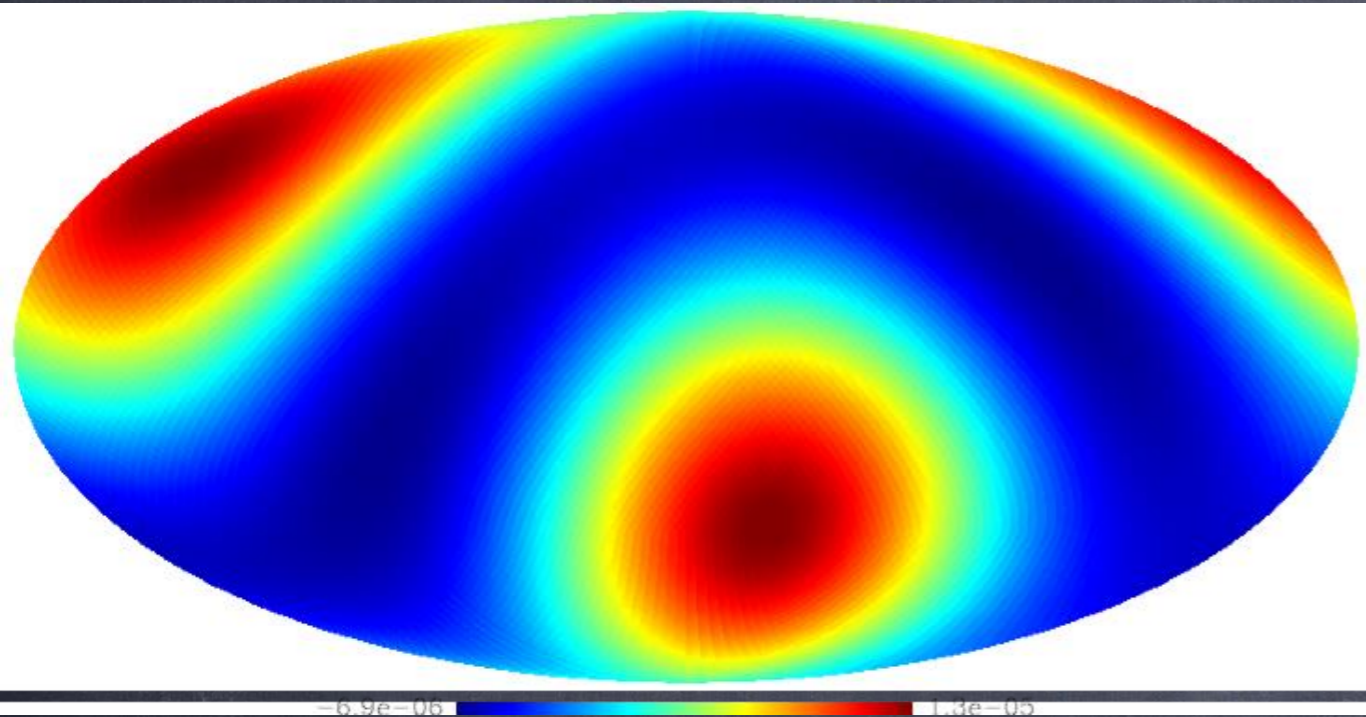
- $l_{\text{max}}=10$
- $n_r=3$
- $n_k=60$
- $n_c=100$



Reconstruction with more information from CMB Polarization

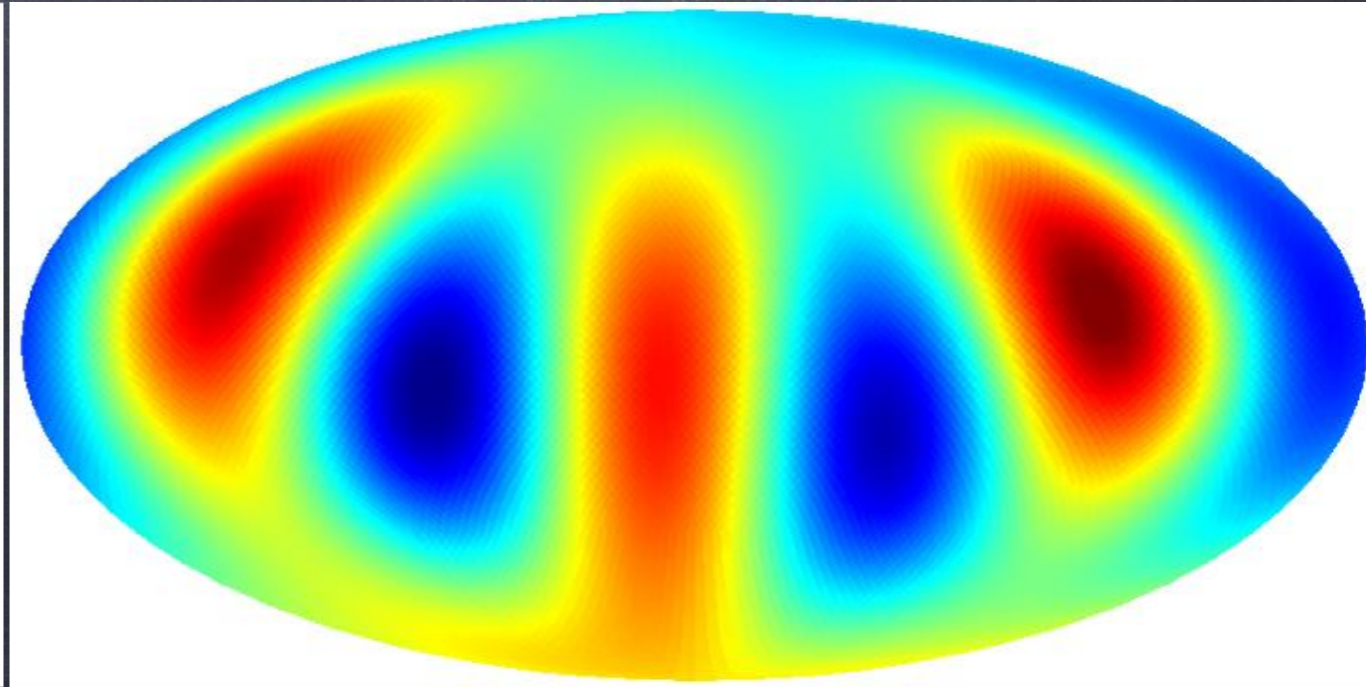
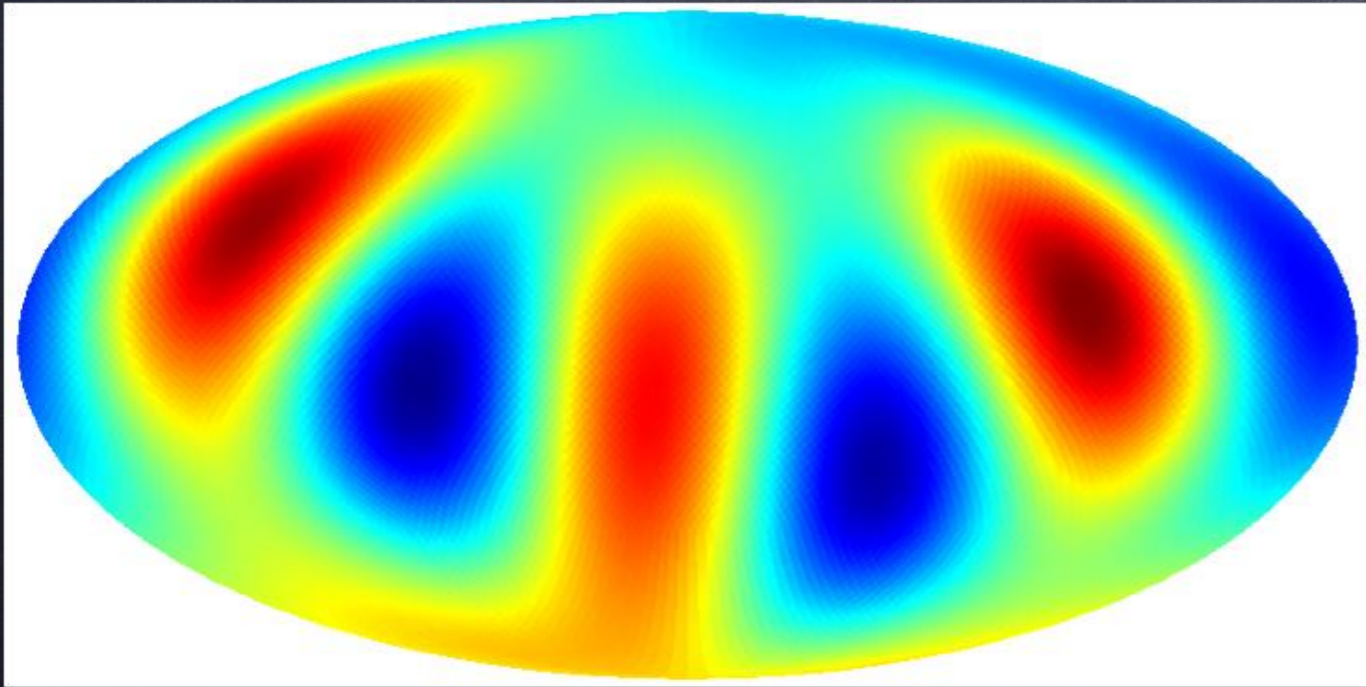
Simulated Temperature Maps

Reconstructed Temperature Maps



$-6.9e-06$ $1.3e-05$

$-6.9e-06$ $1.3e-05$



$-2.2e-05$ $2.2e-05$

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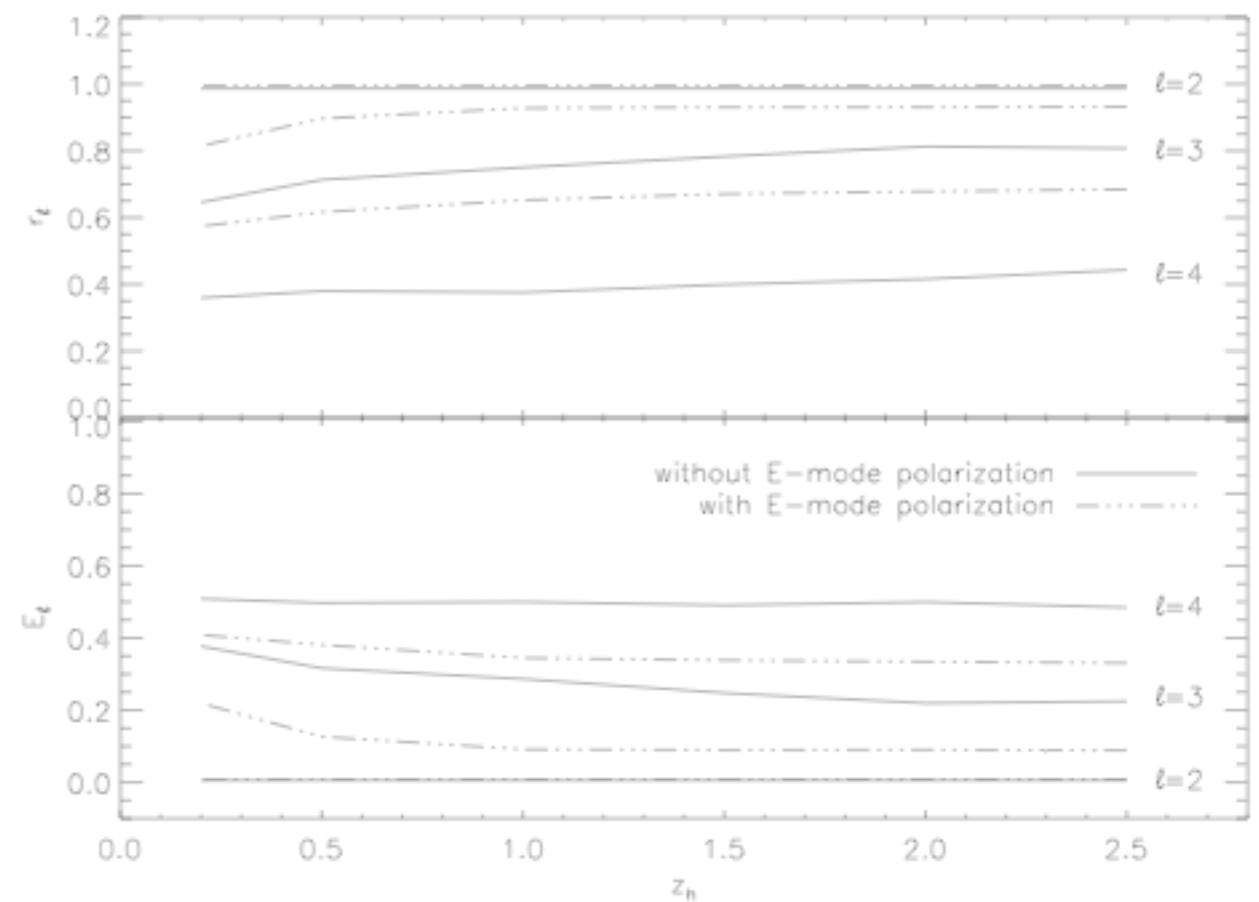
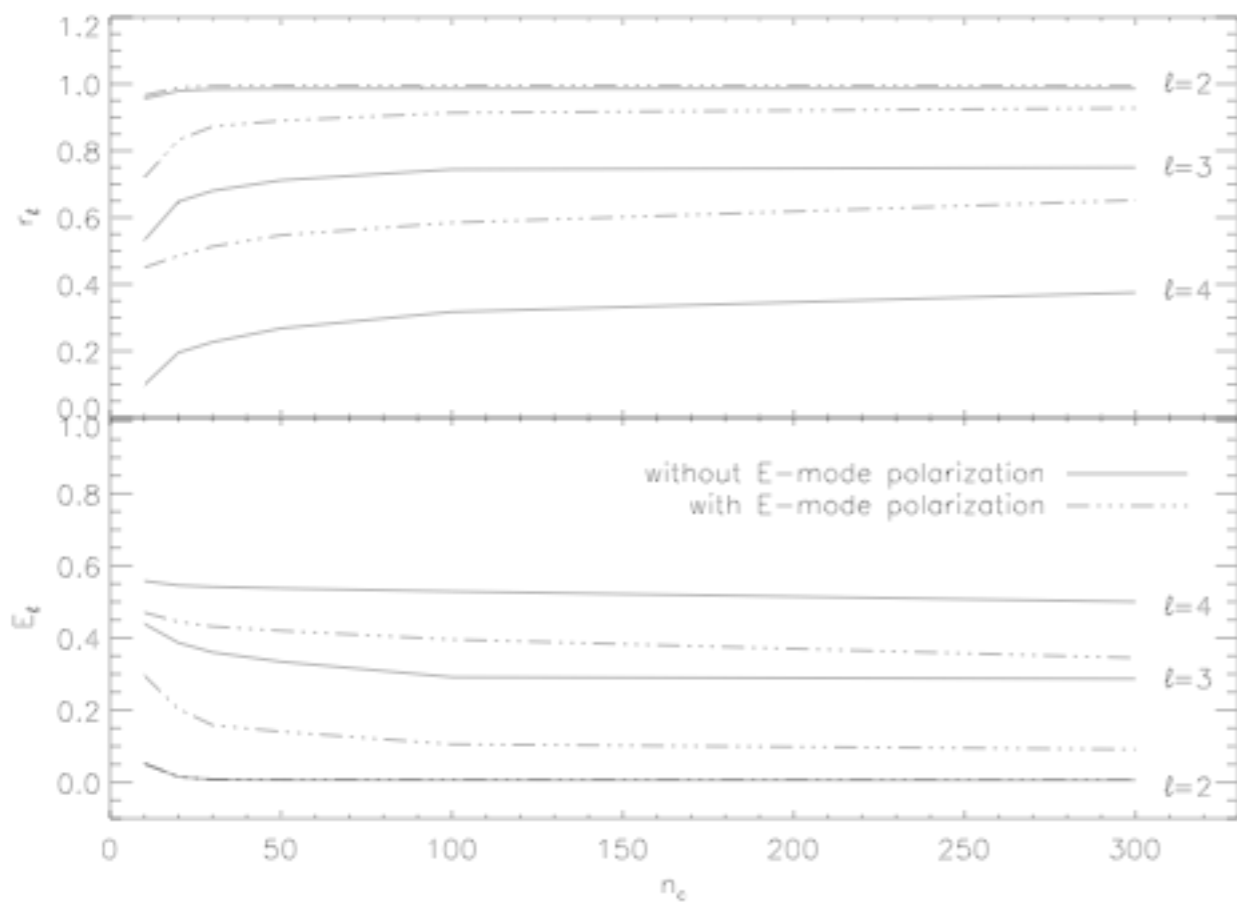
Forecase

$$r_l = \frac{\sum_m a_{T,lm} \hat{a}_{T,lm}}{(2l+1) \sqrt{C_l \hat{C}_l}}$$

$$0 < z < 1$$

$$E_l = \frac{\sum_m (\hat{a}_{T,lm} - a_{T,lm})^2}{(2l+1) C_l}$$

$$nc=300$$



Conclusion

- induced polarization in distant galaxy clusters can be the independent measurement to study the low quadrupole and alignment anomalies
- we may not need to scan large area of sky, just focus on galaxy clusters with low contamination