Early Universe cosmology with the Sunyaev Zel'dovich effect

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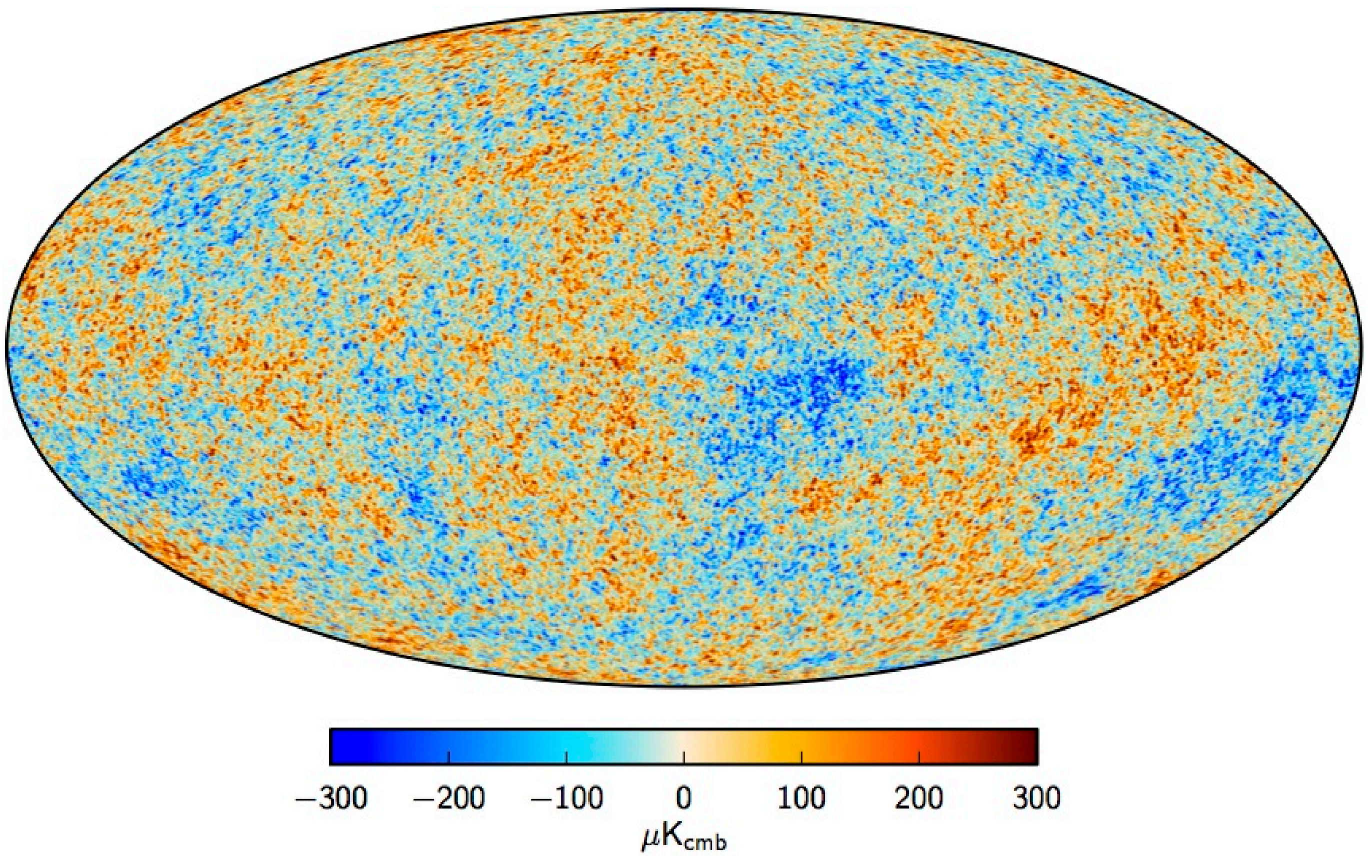
The primary CMB



(Planck 2015 Temperature)

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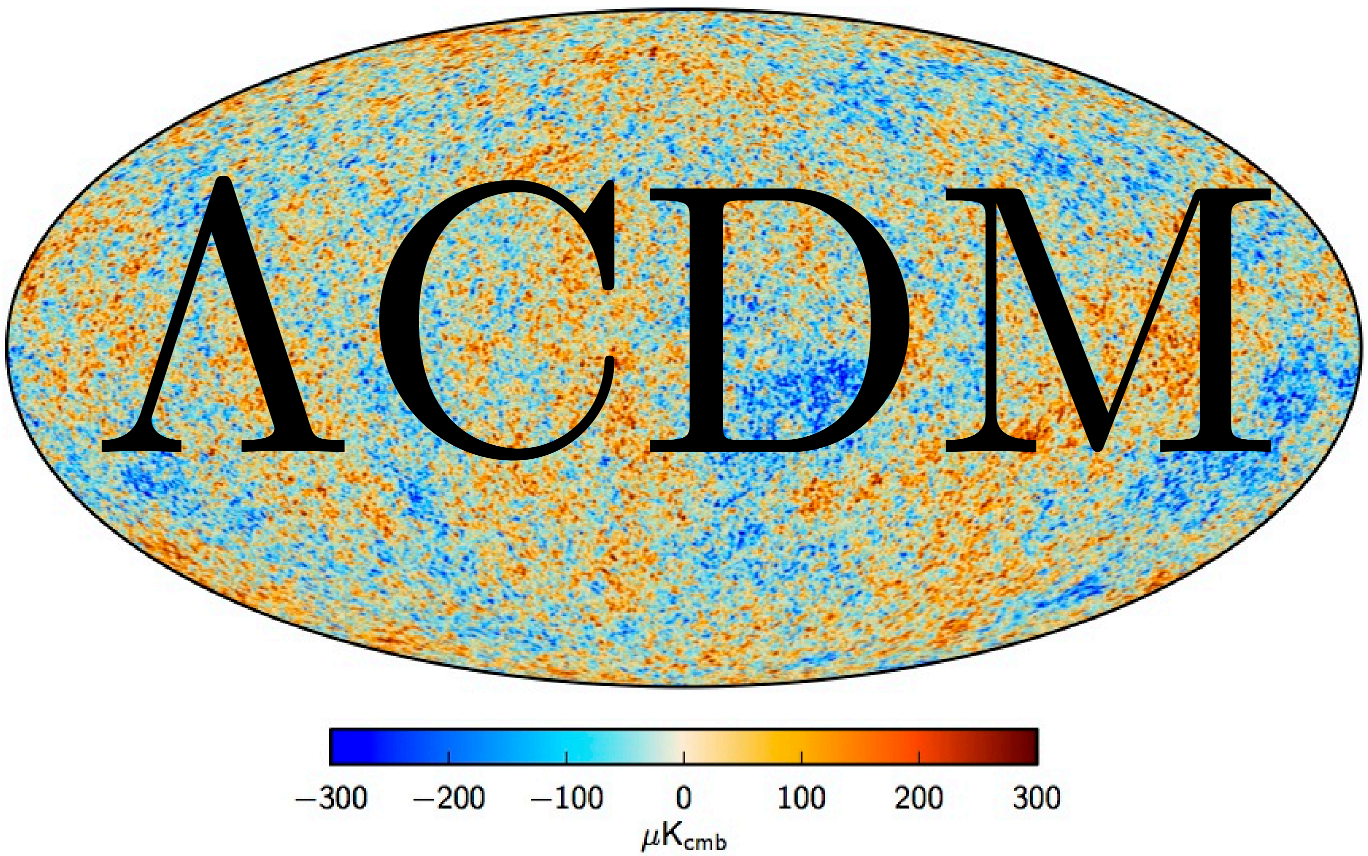
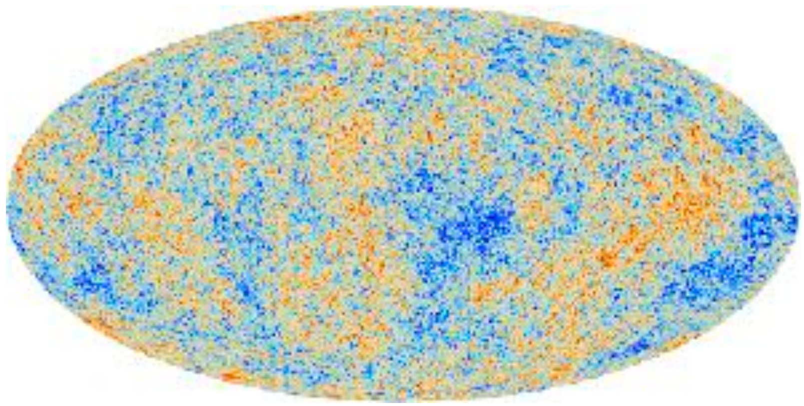
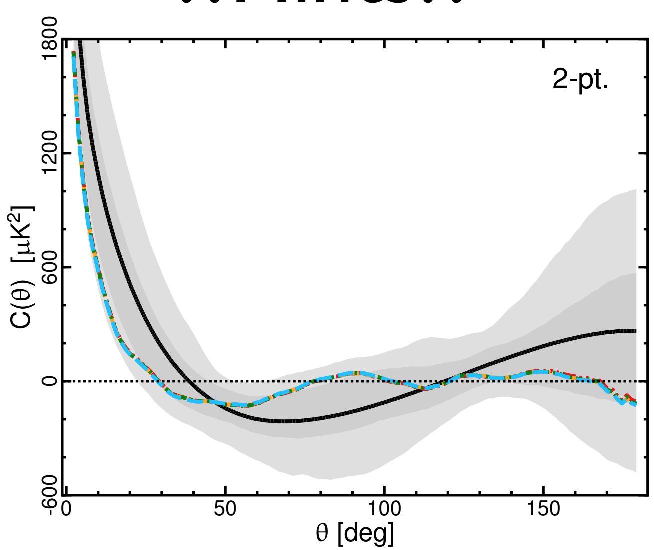


(Planck 2015 Temperature)

The primary CMB: some hints?



??Hints??



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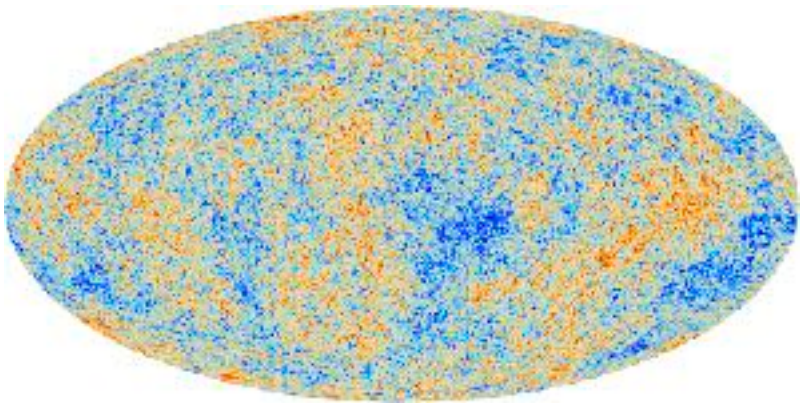

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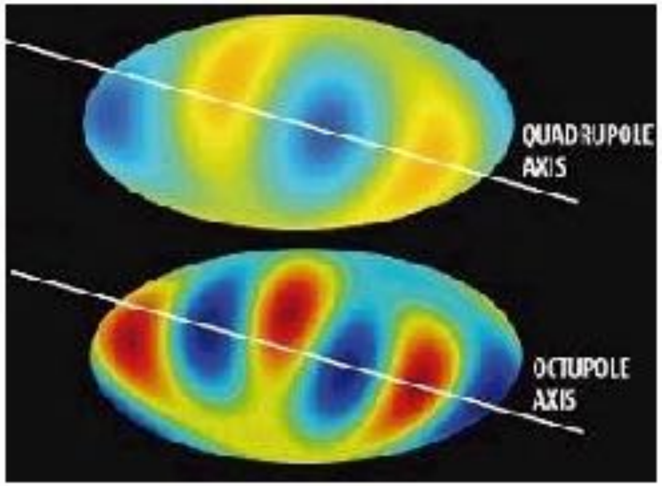

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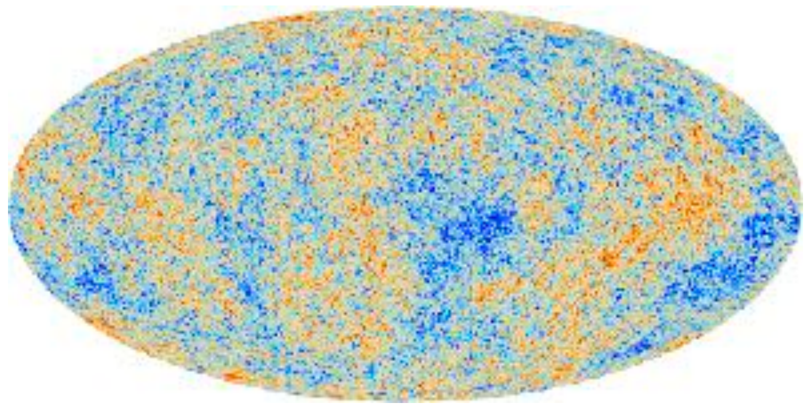

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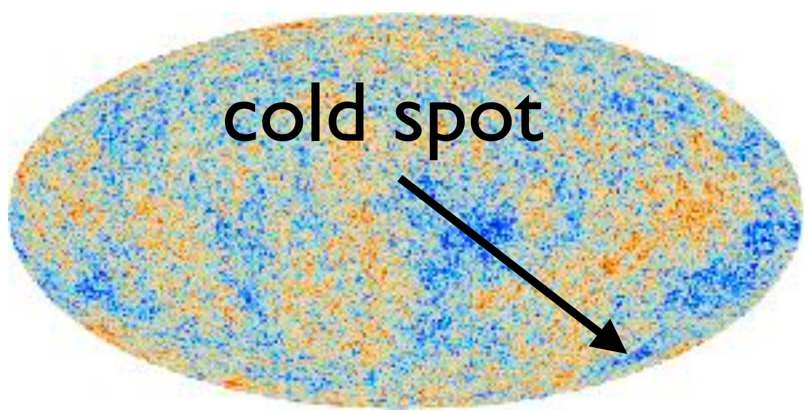

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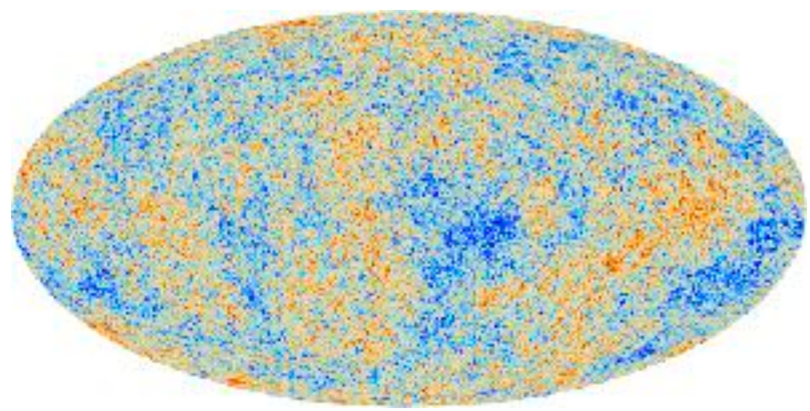

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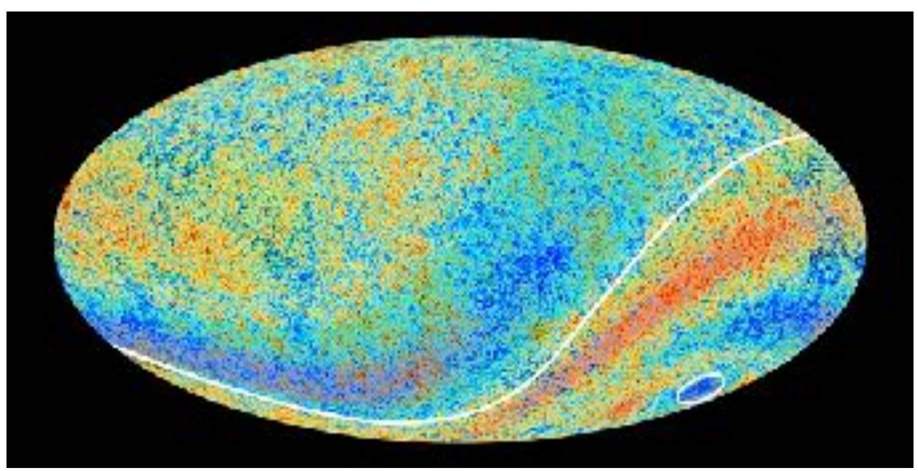

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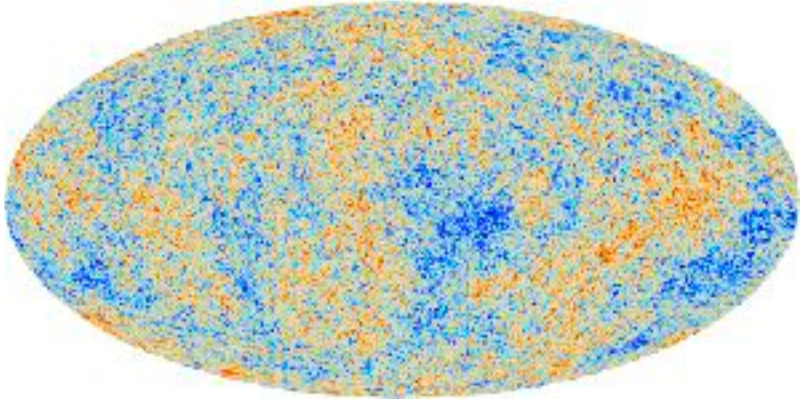

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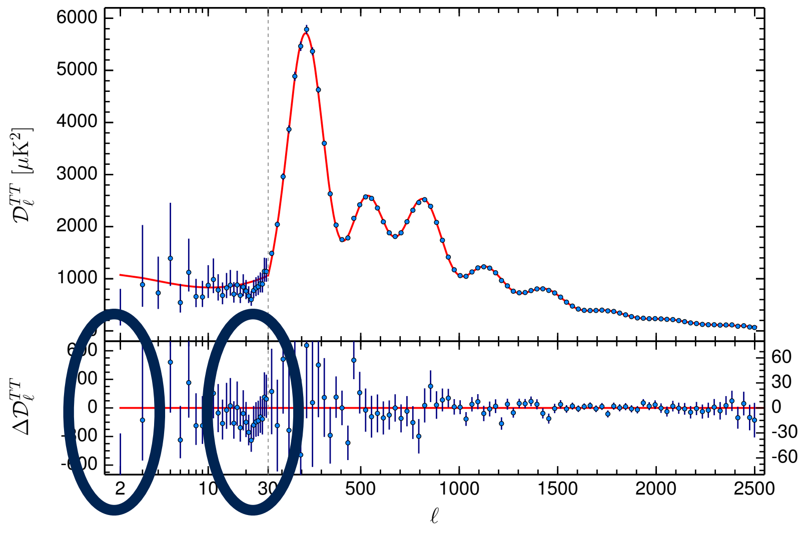
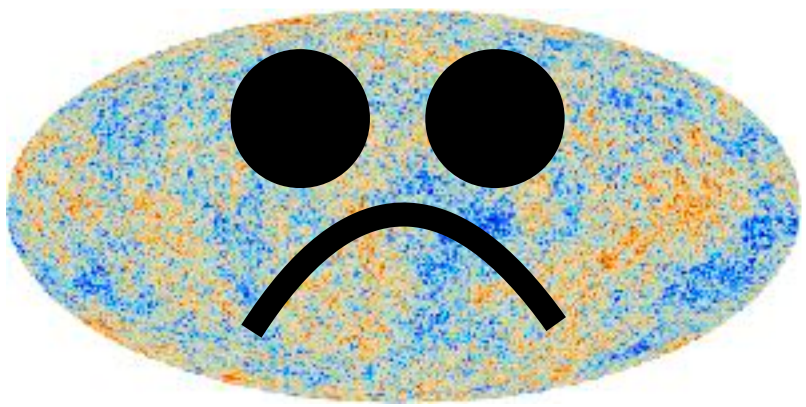


The primary CMB: what's next?

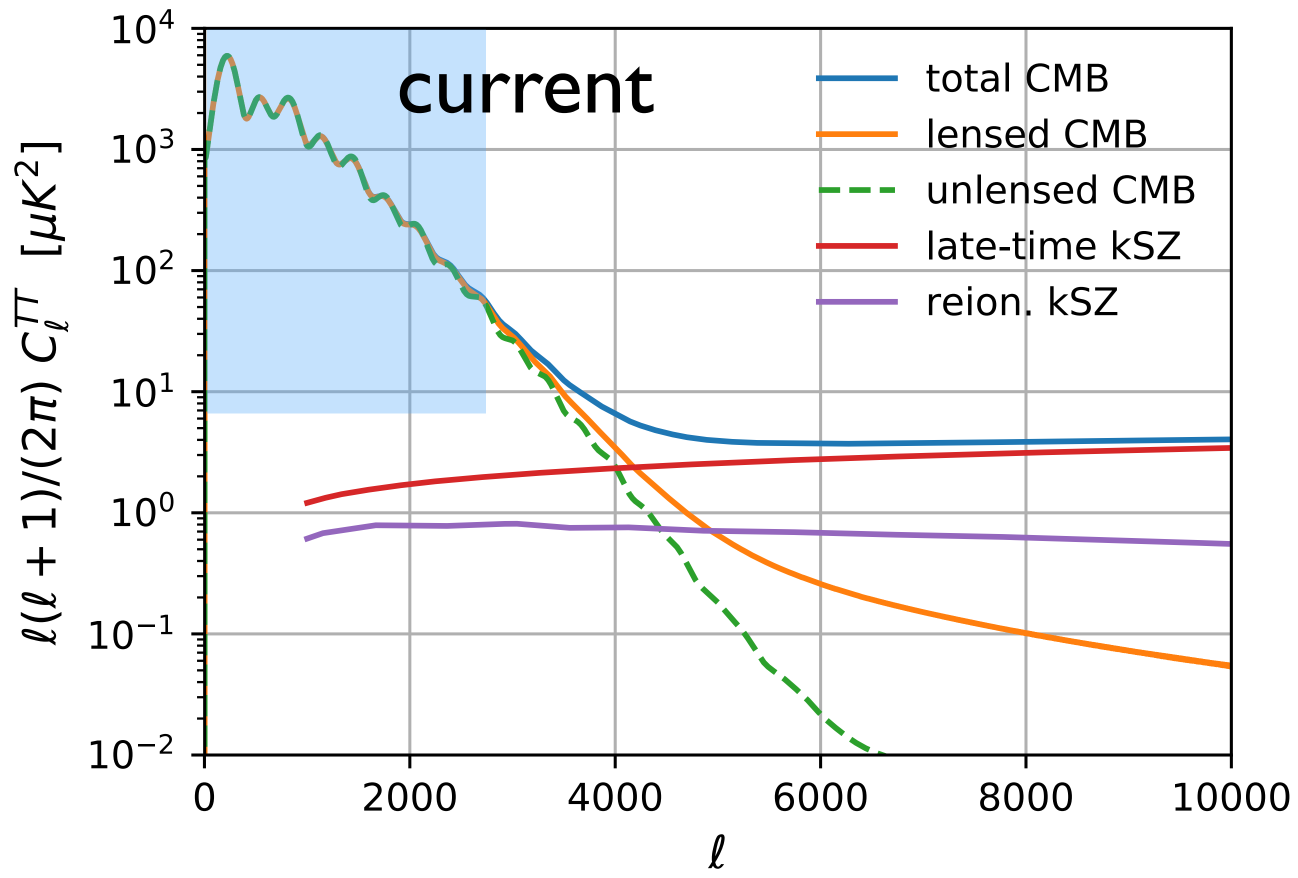
Sadly, the primary CMB will not teach us much more**.



Cosmic Variance:
Projection of 3D field.
Few modes on large scales/finite volume.

CMB secondaries

- CMB secondaries: CMB photons scattered from mass or charges.



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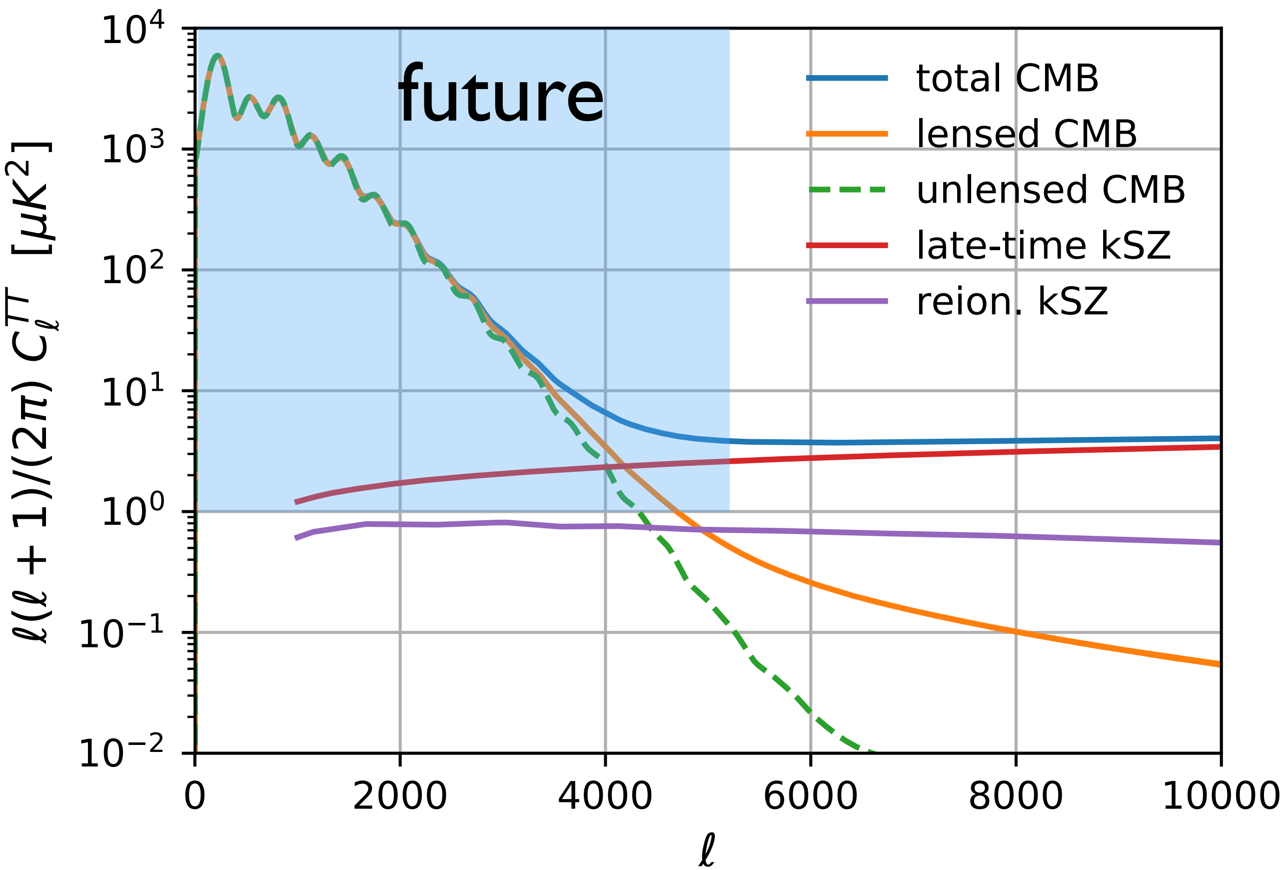


At the resolution/sensitivity frontier!

CMB secondaries

- CMB Lensing: scattering from mass.

$$\Delta T_{\mathrm{lensed}} = \nabla T_{\mathrm{unlensed}} \cdot \nabla \phi$$

- Can infer ϕ from temperature and polarization measurements.

- We're now in the 'lensing era', with exciting constraints on cosmology emerging from on-going experiments.

(See Mat Madhavacheril's talk tomorrow)

CMB secondaries

- Sunyaev Zel'dovich (SZ) effect: scattering from free electrons after reionization.

  - Kinetic SZ (kSZ) effect: temperature anisotropies due to scattering from bulk motion of free electrons (preserves blackbody).

$$\Delta T_{\rm kSZ} \sim \tau(\hat{n}) v_{\rm eff}(\hat{n})$$

  - Polarized SZ (pSZ) effect: polarization anisotropies due to scattering from quadrupole seen by free electrons (preserves blackbody).

$$\Delta E, B_{\rm pSZ} \sim \tau(\hat{n}) q_{\rm eff}^{E,B}(\hat{n})$$

The kinetic Sunyaev Zel'dovich (kSZ) effect

The induced temperature anisotropies are given by a line of sight integral:

$$\left.\frac{\Delta T}{T}\right|_{\rm kSZ}(\hat{\mathbf{n}}_e) = -\sigma_T \int_0^{\chi_{\rm re}} d\chi_e \; a_e(\chi_e) \; \bar{n}_e(\chi_e) \; (1+\delta(\hat{\mathbf{n}}_e,\chi_e)) \sum_{m=-1}^{1} v_{\rm eff}^m(\hat{\mathbf{n}}_e,\chi_e) Y_{1m}(\hat{\mathbf{n}}_e).$$

The kSZ effect depends on the moments of the CMB dipole field:

$$v_{\rm eff}^m(\hat{\mathbf{n}}_e,\chi_e) = \int_\Omega d^2\hat{\mathbf{n}} \; \Theta(\hat{\mathbf{n}}_{\mathbf{e}},\chi_e,\hat{\mathbf{n}}) Y_{1m}^*(\hat{\mathbf{n}})$$

Sachs-Wolfe

$$\frac{1}{3}\Psi(\mathbf{r}_{\rm dec},\chi_{\rm dec})$$

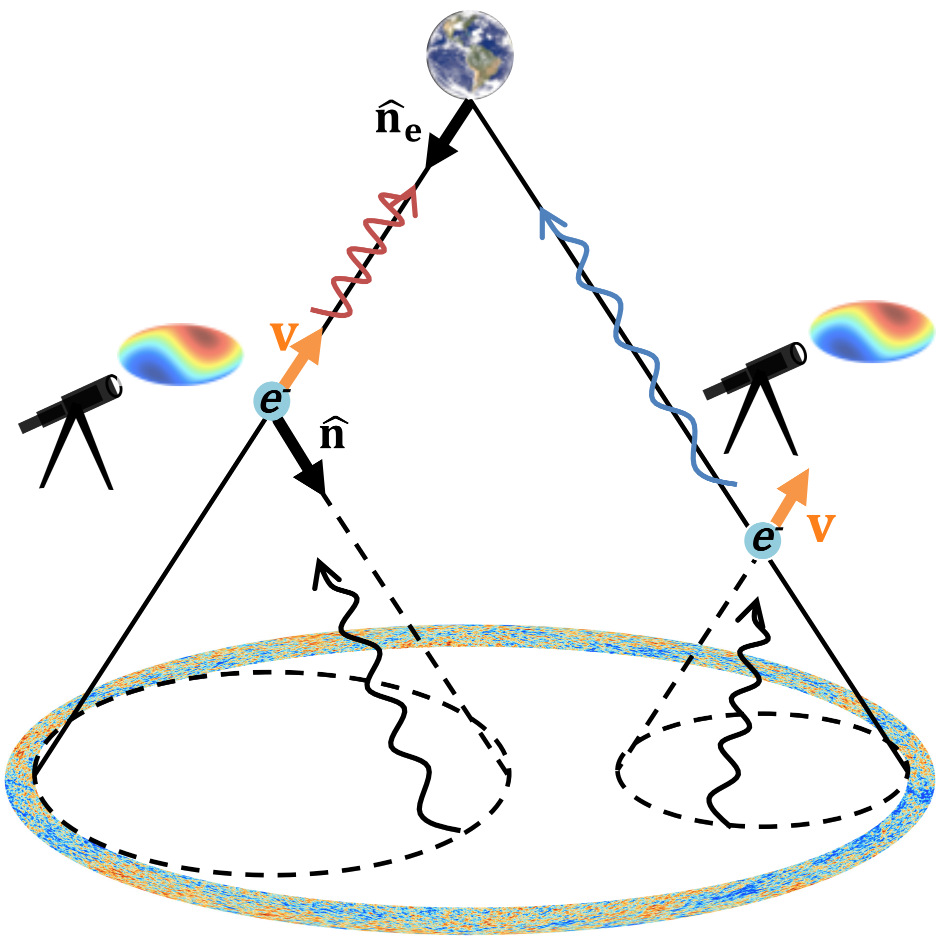
Integrated Sachs-Wolfe

$$2\int_{\chi_e}^{\chi_{\rm dec}} \frac{d}{d\chi}\Psi(\mathbf{r}(\chi),\chi)d\chi$$

Doppler

$$\hat{\mathbf{n}}\cdot[\mathbf{v}(\mathbf{r}_e,\chi_e)-\mathbf{v}(\mathbf{r}_{\rm dec},\chi_{\rm dec})]$$

The kinetic Sunyaev Zel'dovich (kSZ) effect

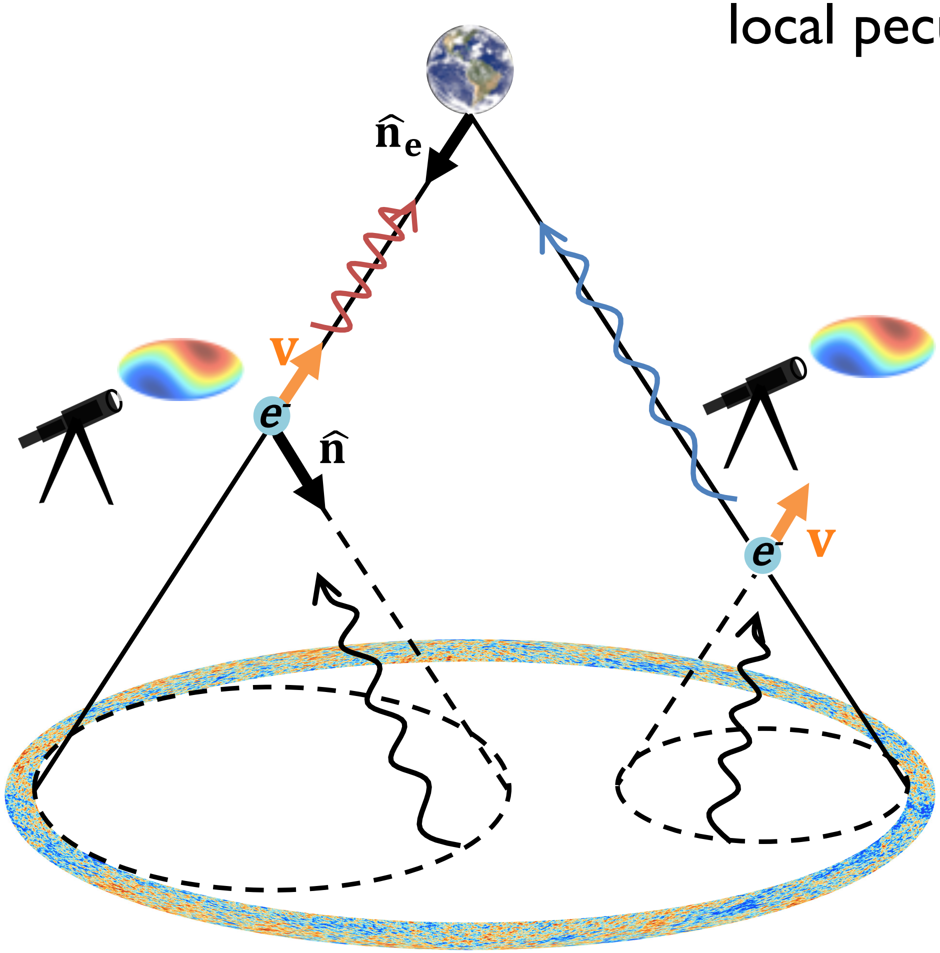


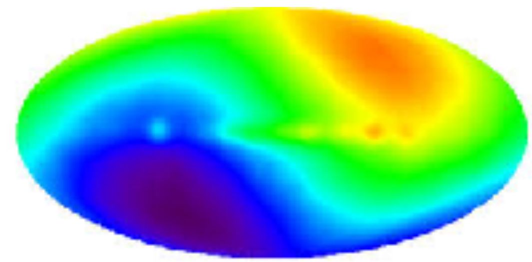
Provides a census of the locally observed CMB dipole at the location of each electron.

Provides information off of our past light cone - new information beyond CMB.

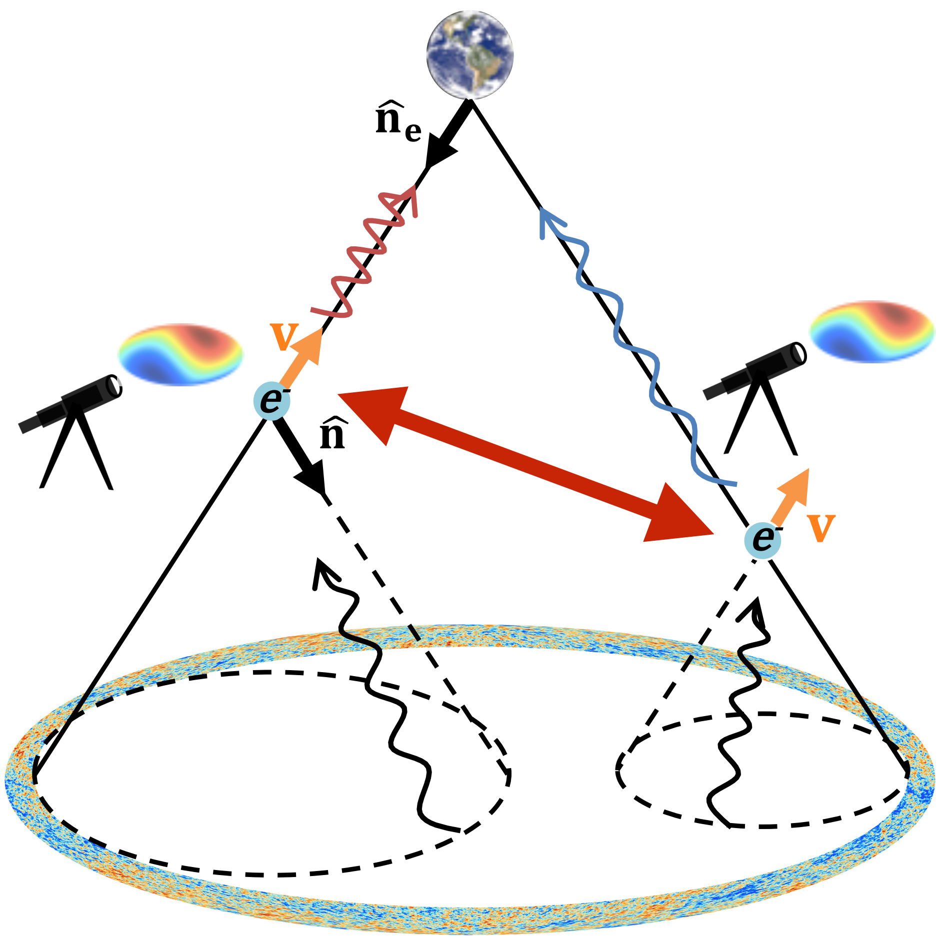
The kinetic Sunyaev Zel'dovich (kSZ) effect

CMB dipole at a point is mostly from local peculiar velocities





The kinetic Sunyaev Zel'dovich (kSZ) effect



'primordial' information encoded in long-range (in angle or redshift) correlations of the dipole field.

kSZ Tomography

$$\Delta T_{\rm kSZ} \sim \tau(\hat{n}) v_{\rm eff}(\hat{n})$$

- Given a tracer of the electron density field (e.g. a galaxy survey), can derive a quadratic estimator for the dipole field:

$$\bar{v}^{\alpha}_{\rm eff}(\hat{n}) = QE\left[\Delta T(\hat{n}), \delta^{\alpha}(\hat{n})\right]$$

- Get a coarse-grained dipole field, averaged over each tomographic redshift bin α

Preserves long-range correlations, small-scale peculiar velocities cancel.

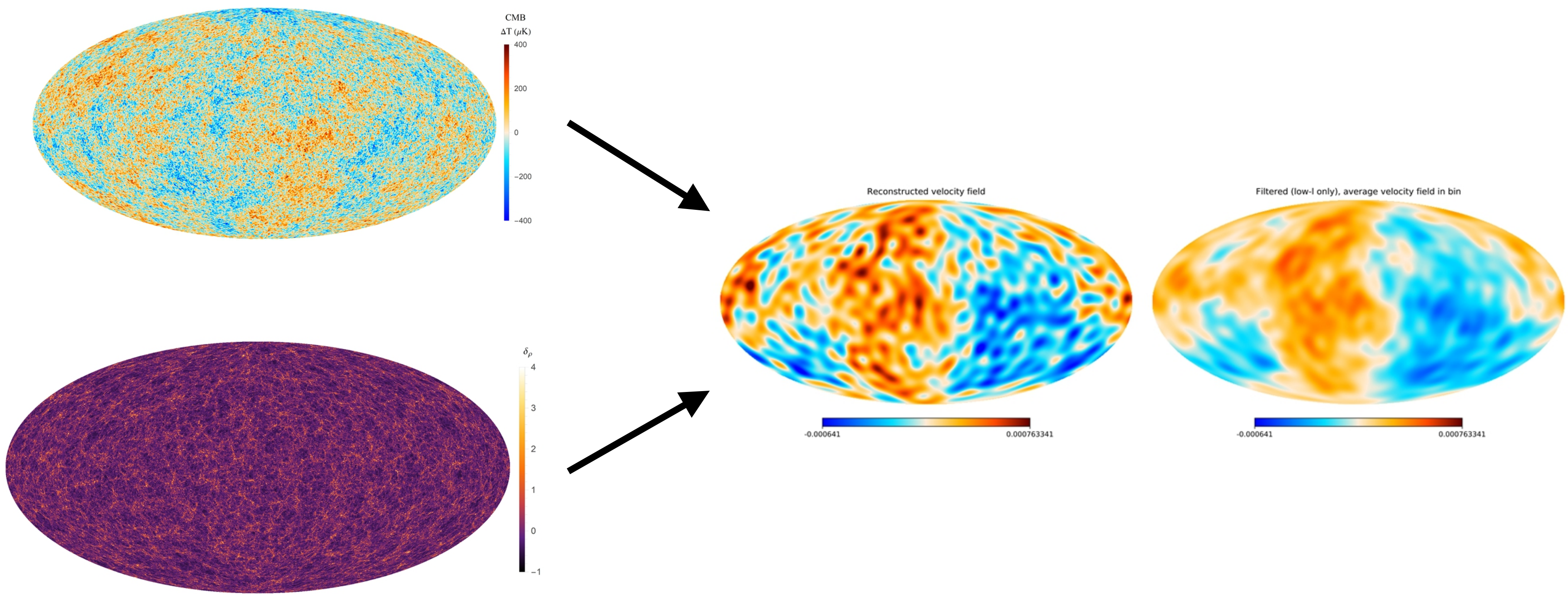
→ Excellent probe of very large scales!

[Zhang and Stebbins, Zhang '10, Terrana, Harris, MCJ '16]

kSZ Tomography

- Proof-of-concept with N-body simulations:

(See James Mertens' talk tomorrow)



The polarized Sunyaev Zel'dovich (pSZ) effect

The induced polarization anisotropies are given by a line of sight integral:

$$(Q \pm iU)^{\rm pSZ}(\hat{\mathbf{n}}_e) = -\frac{\sqrt{6}\,\sigma_T}{10} \int d\chi_e \; a_e \bar{n}_e(\chi_e)(1+\delta_e(\hat{\mathbf{n}}_e,\chi_e)) \sum_{m=-2}^{2} q^m_{\rm eff}(\hat{\mathbf{n}}_e,\chi_e) \; {}_{\pm 2}Y_{2m} \; (\hat{\mathbf{n}}_e)$$

The pSZ effect depends on the components of the local CMB quadrupole:

$$q^m_{\rm eff}(\hat{\mathbf{n}}_e,\chi_e) = \int_\Omega d^2\hat{\mathbf{n}} \; \left[\Theta(\chi_e,\hat{\mathbf{n}}_e,\hat{\mathbf{n}}) + \Theta^T(\chi_e,\hat{\mathbf{n}}_e,\hat{\mathbf{n}})\right] \; Y^*_{2m}(\hat{\mathbf{n}})$$

Sachs-Wolfe

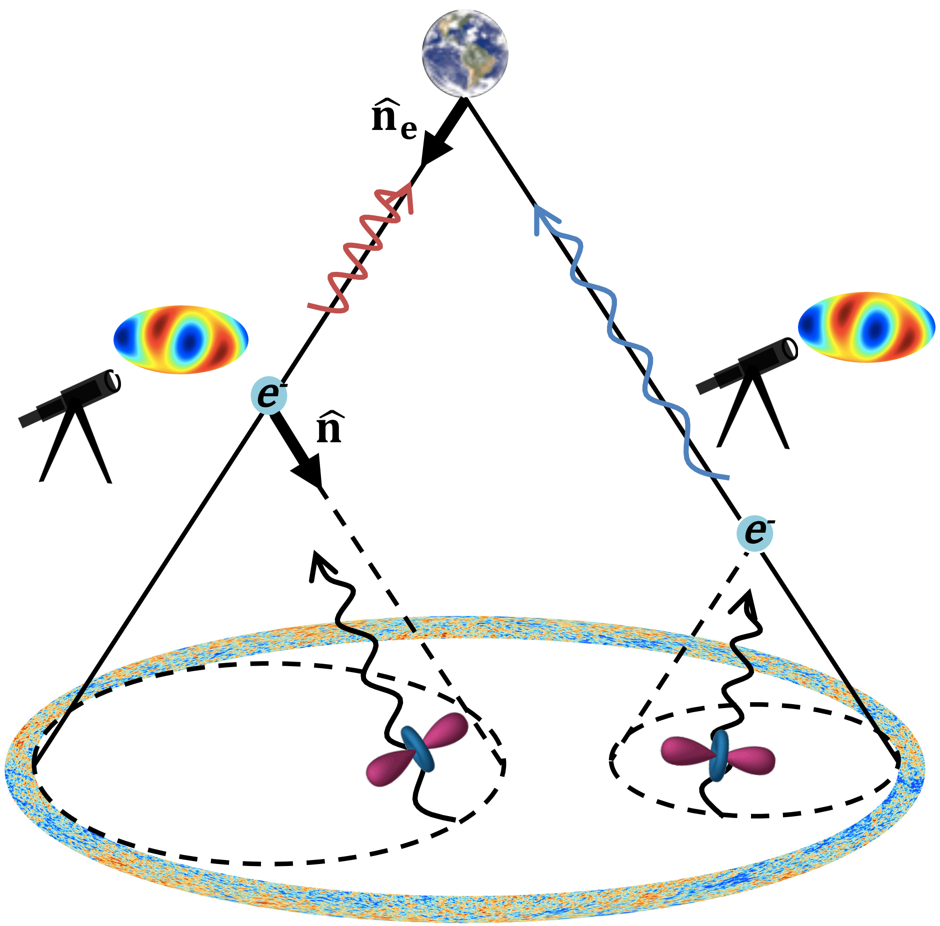
Integrated Sachs-Wolfe

Doppler (local part doesn't contribute)

$$\int_{\chi_e}^{\chi_{\rm dec}} \frac{dh_{+,\times}}{d\chi} d\chi$$

[Kamionkowski, Loeb '97, Alizadeh, Hirata '12, Deutsch, Dimastrogiovanni, MCJ, Münchmeyer, Terrana '17]

The polarized Sunyaev Zel'dovich (pSZ) effect



Provides a census of the locally observed CMB quadrupole at the location of each electron.

Provides information off of our past light cone - new information beyond CMB, different information from kSZ.

All 'primordial' unlike kSZ.

pSZ Tomography

$$\Delta E, B_{\mathrm{pSZ}} \sim \tau(\hat{n}) q_{\mathrm{eff}}^{E,B}(\hat{n})$$

- Given a tracer of the electron density field (e.g. a galaxy survey), can derive a quadratic estimator for the quadrupole field:

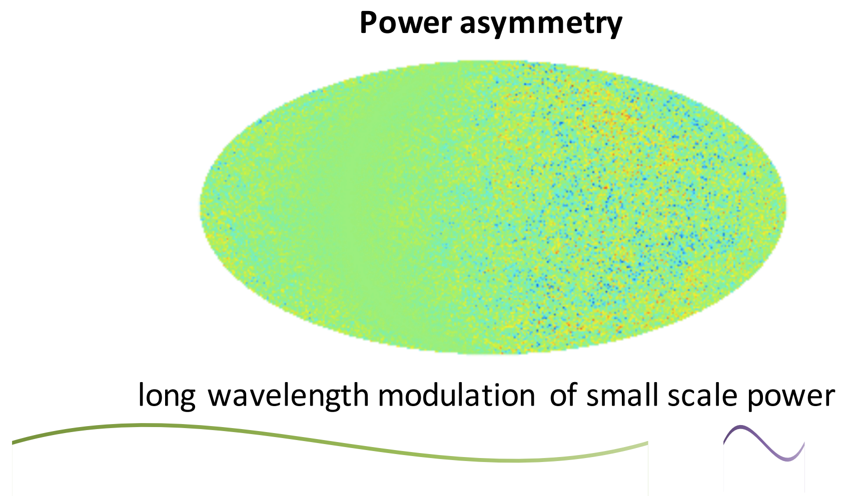
$$q_{\mathrm{eff}}^{\alpha,E}, q_{\mathrm{eff}}^{\alpha,B} = QE^{E,B}\left[E(\hat{n}), B(\hat{n}), \delta^{\alpha}(\hat{n})\right]$$

- Get a coarse-grained quadrupole field, averaged over each tomographic redshift bin α
- E-mode quadrupole: scalar+tensor
- B-mode quadrupole: only tensor

New cosmological observables

- CMB + LSS enables the construction of new cosmological observables from CMB secondaries:

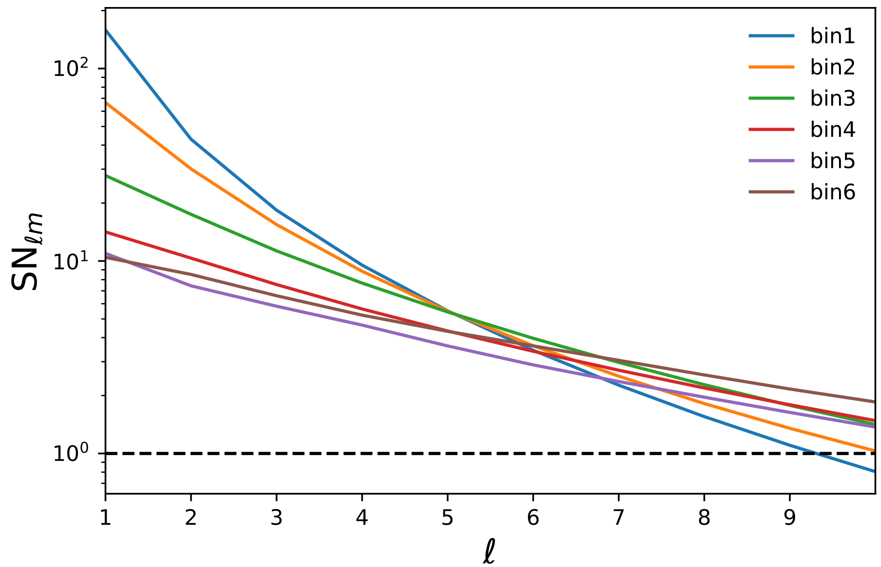
$$\phi(\hat{n}) \quad \bar{v}^{\alpha}_{\rm eff}(\hat{n}) \quad \bar{q}^{\alpha,E}_{\rm eff}(\hat{n}) \quad \bar{q}^{\alpha,B}_{\rm eff}(\hat{n})$$



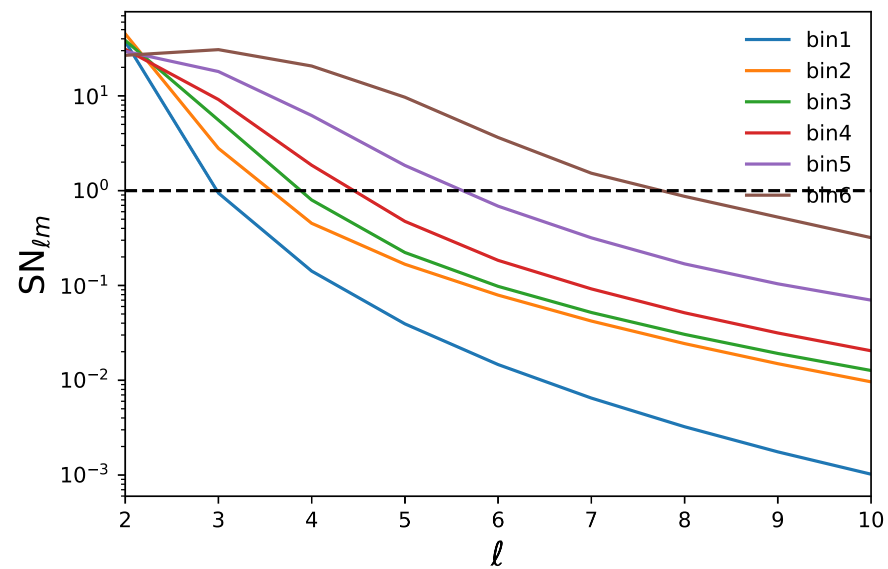
- All are indirectly determined from statistics of small-scale fluctuations: ideally suited for resolution/sensitivity frontier.

Can we detect it?

- Reconstruction of the bin-averaged dipole field via quadratic estimator.



kSZ $\bar{v}_{\mathrm{eff},\ell m}$



pSZ $a^{q,E}_{\ell m}(\chi)$

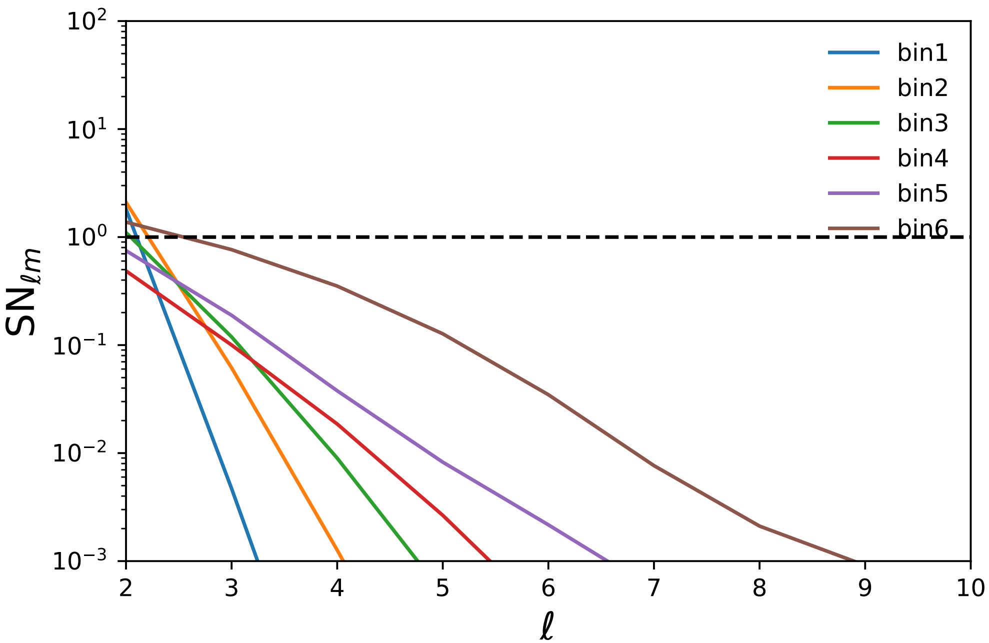
Per-mode signal to noise assuming no foregrounds, full sky, CMB-S4 like CMB experiment, LSST-like galaxy survey.

[Terrana, Harris, MCJ '16, Deutsch, Dimastrogiovanni, MCJ, Münchmeyer, Terrana '17]

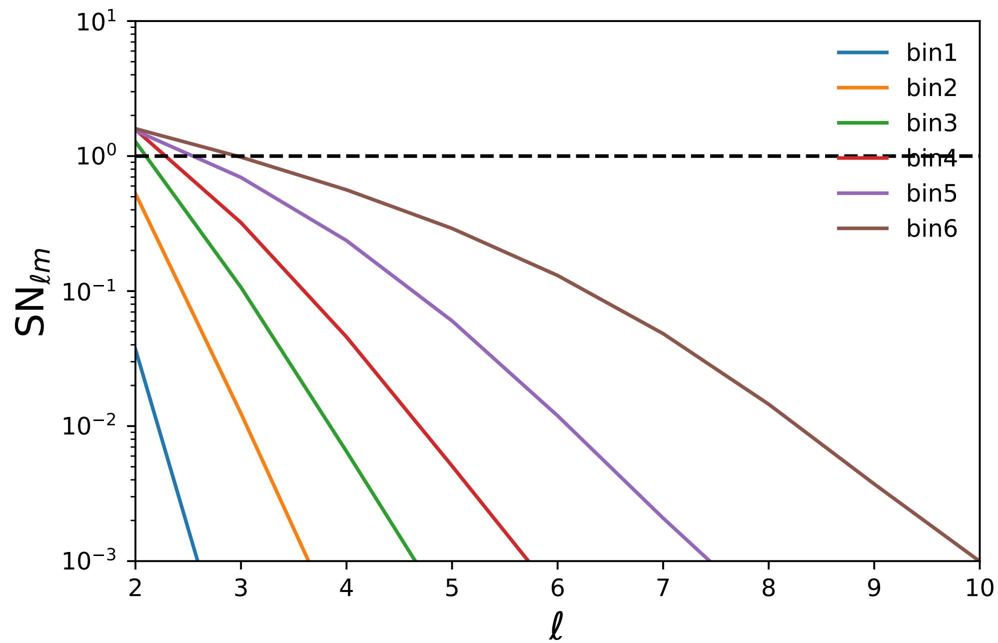
Can we detect it?

- Reconstruction of the E-mode and B-mode tensor quadrupole field via quadratic estimator using both E-mode and B-mode polarization.

Forecast for r = 0.1



E-mode tensor modulation



B-mode tensor modulation

[Alizadeh, Hirata '12, Deutsch, Dimastrogiovanni, MCJ, Münchmeyer, Terrana '17]

Can we detect it?

- In principle, yes! There is a signal to go after.
- Resolution and sensitivity requirements of next-generation CMB (e.g. CMB S4) are in the ballpark of what would be required.
- Massive galaxy surveys such as LSST, Euclid, SKA are in the ballpark of what would be required.
- Still, won't be easy: foregrounds, partial sky coverage, non-gaussian and non-uniform instrumental noise, other systematics, etc.

Important point: This technique is not cosmic variance limited, and improvements can be made!

What would we learn?

- Intrinsic CMB dipole. [Cayuso,MCJ, Mertens]
- Primordial non-gaussianity: factor of ~2 improvement on CMB or LSS alone. [Ferraro,Giri,MCJ,Madhavacheril,Münchmeyer,Smith]
- Dark energy: competitive constraints to g-g lensing, different degeneracies. [Cayuso,MCJ, Mertens]
- Models of low-l CMB anomalies: improved constraints on e.g. power suppression on large-scales, power asymmetry, alignment of multipoles….. [Cayuso,MCJ, Mertens]
- Tensors: new constraints on r, nt, chirality…

  [Deutsch, Dimastrogiovanni, MCJ, Münchmeyer]

The best part

This science can be done with planned/funded CMB experiments and galaxy redshift surveys.

There is in principle lots of progress to make using these techniques in the future.

Thanks!