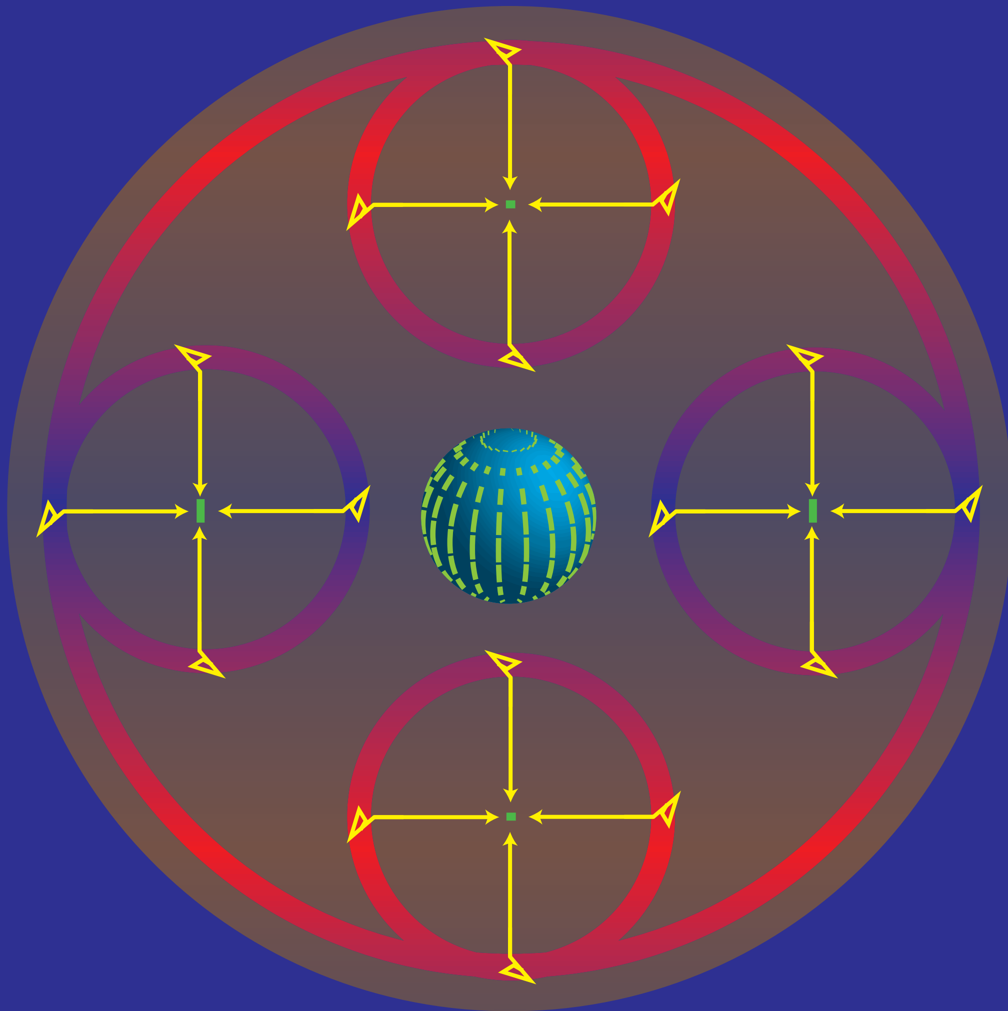
CMB Polarization Theory



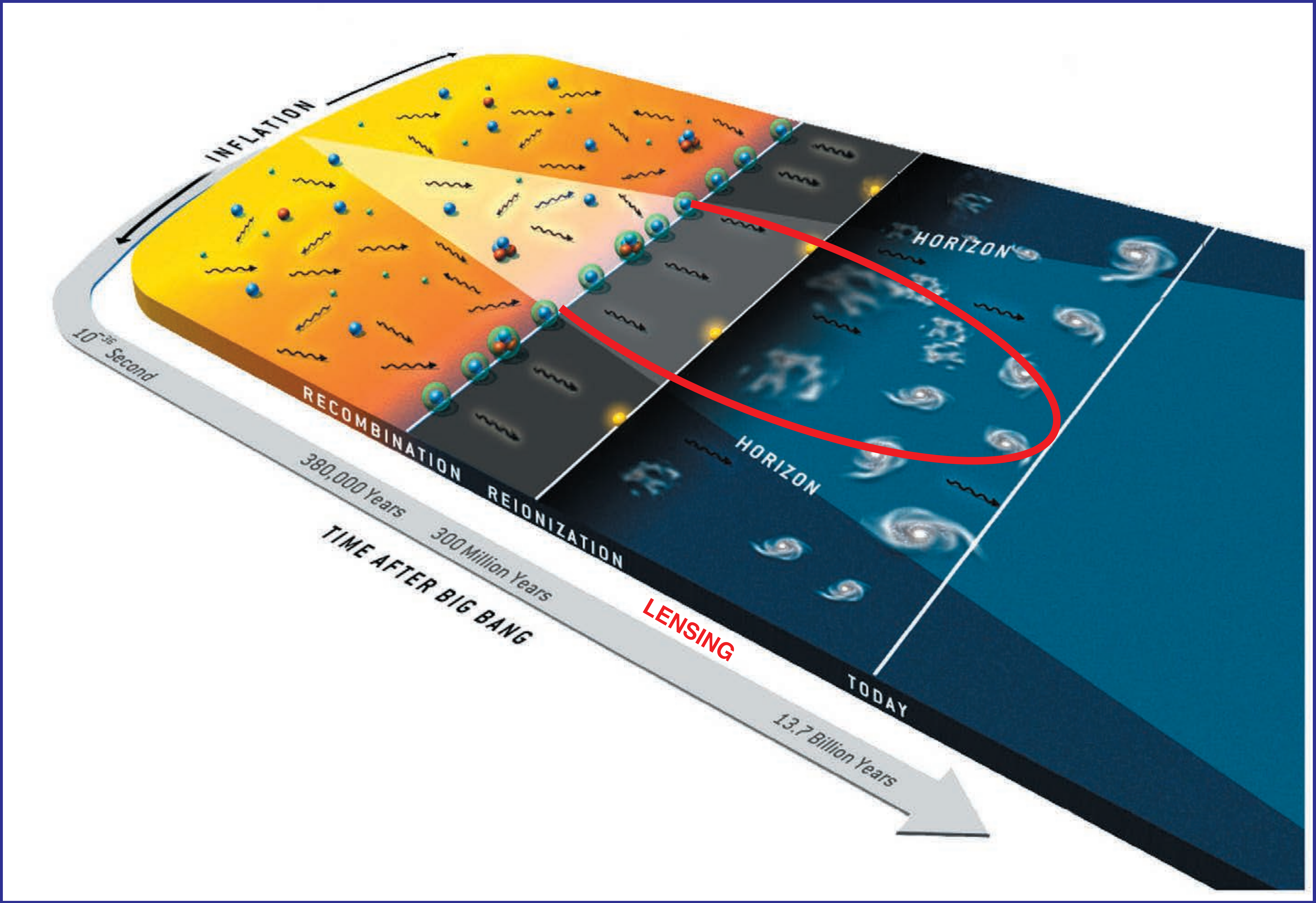
Wayne Hu

Varenna, July 2017

Polarization Trinity

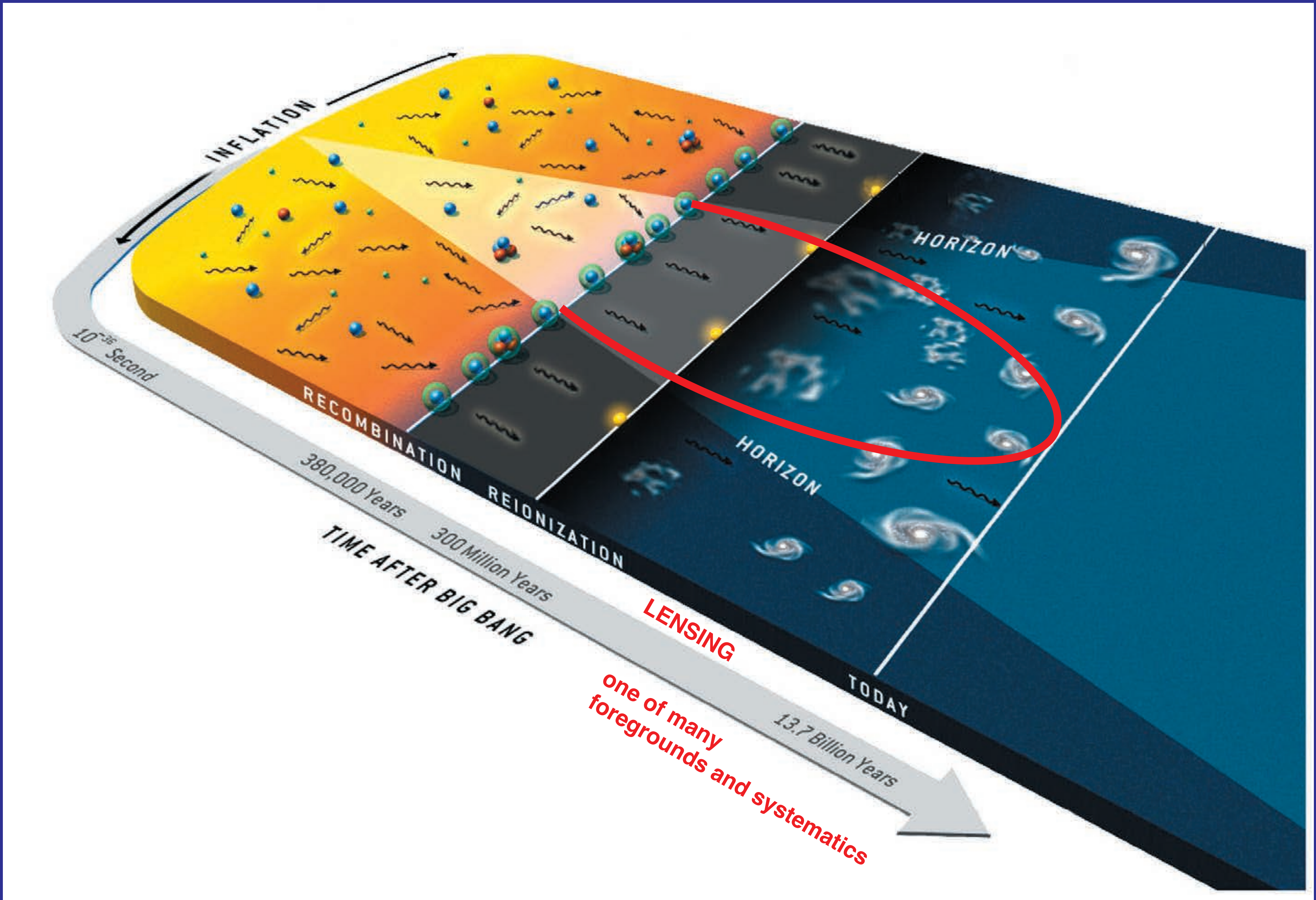
Isolating Three Cosmological Epochs

Polarization 4 Noble (Nobel?) Truths



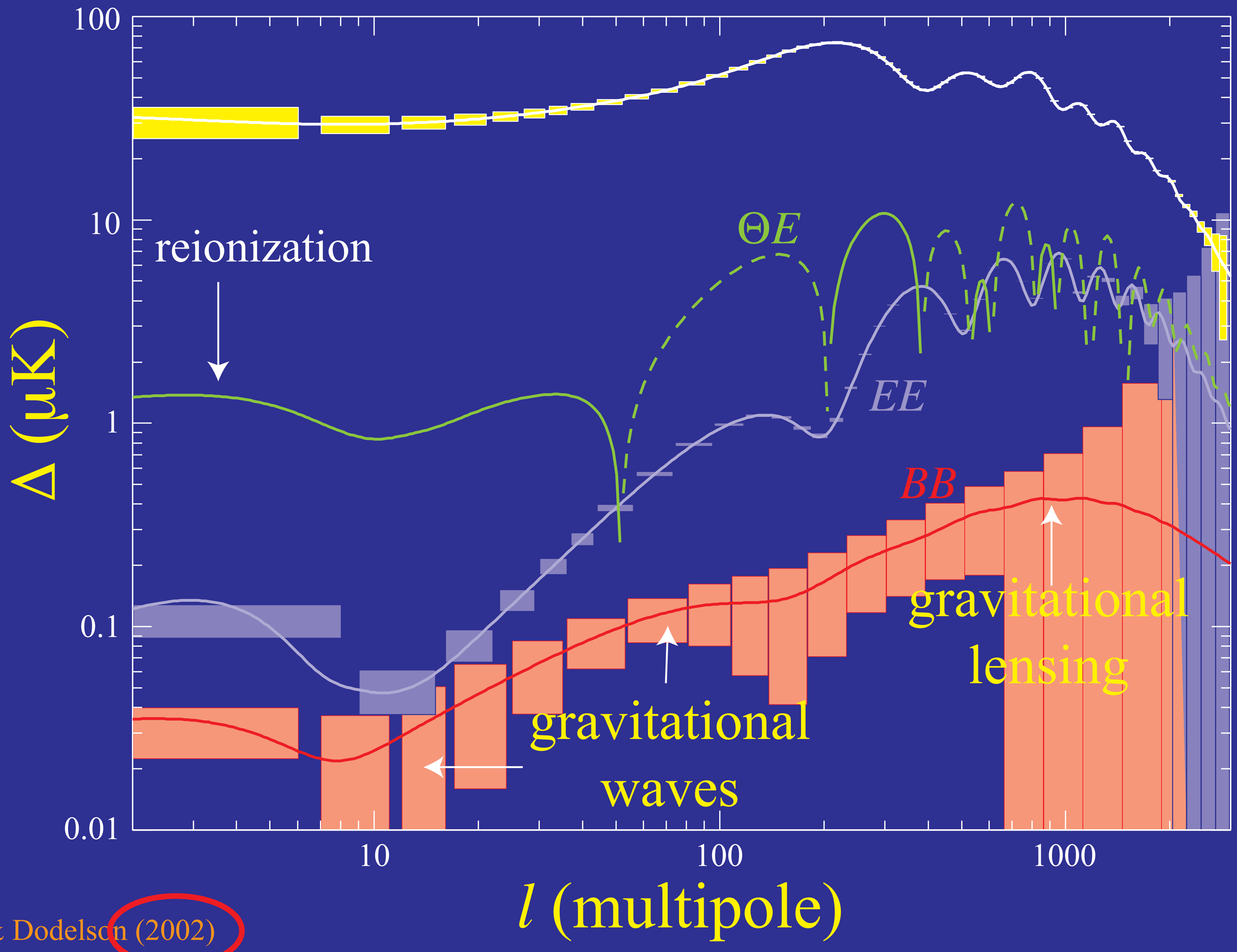
And one integrated probe

Polarization 4 Noble (Nobel?) Truths



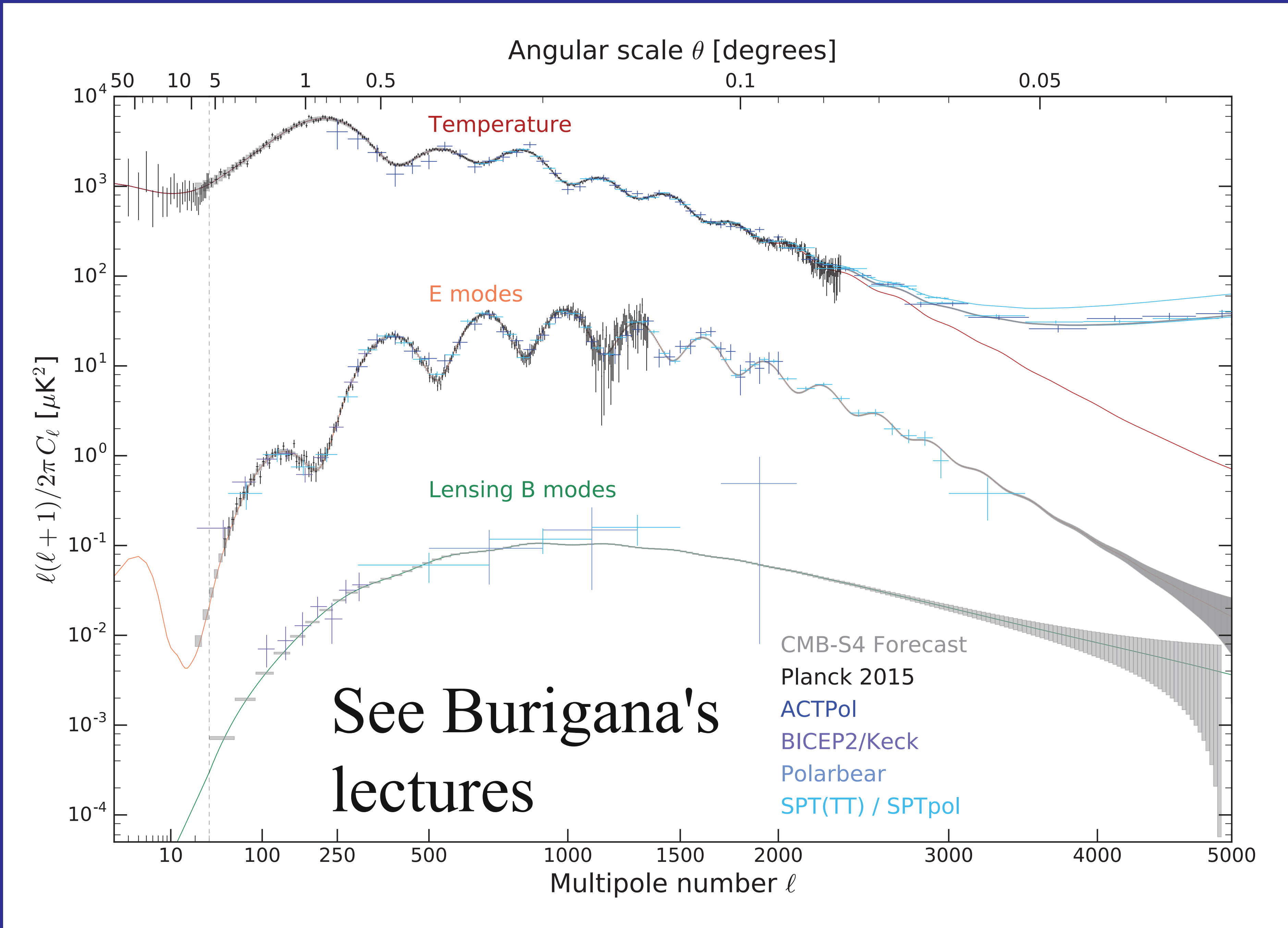
polarization is suffering... but cessation of suffering is nirvana

Polarized Landscape

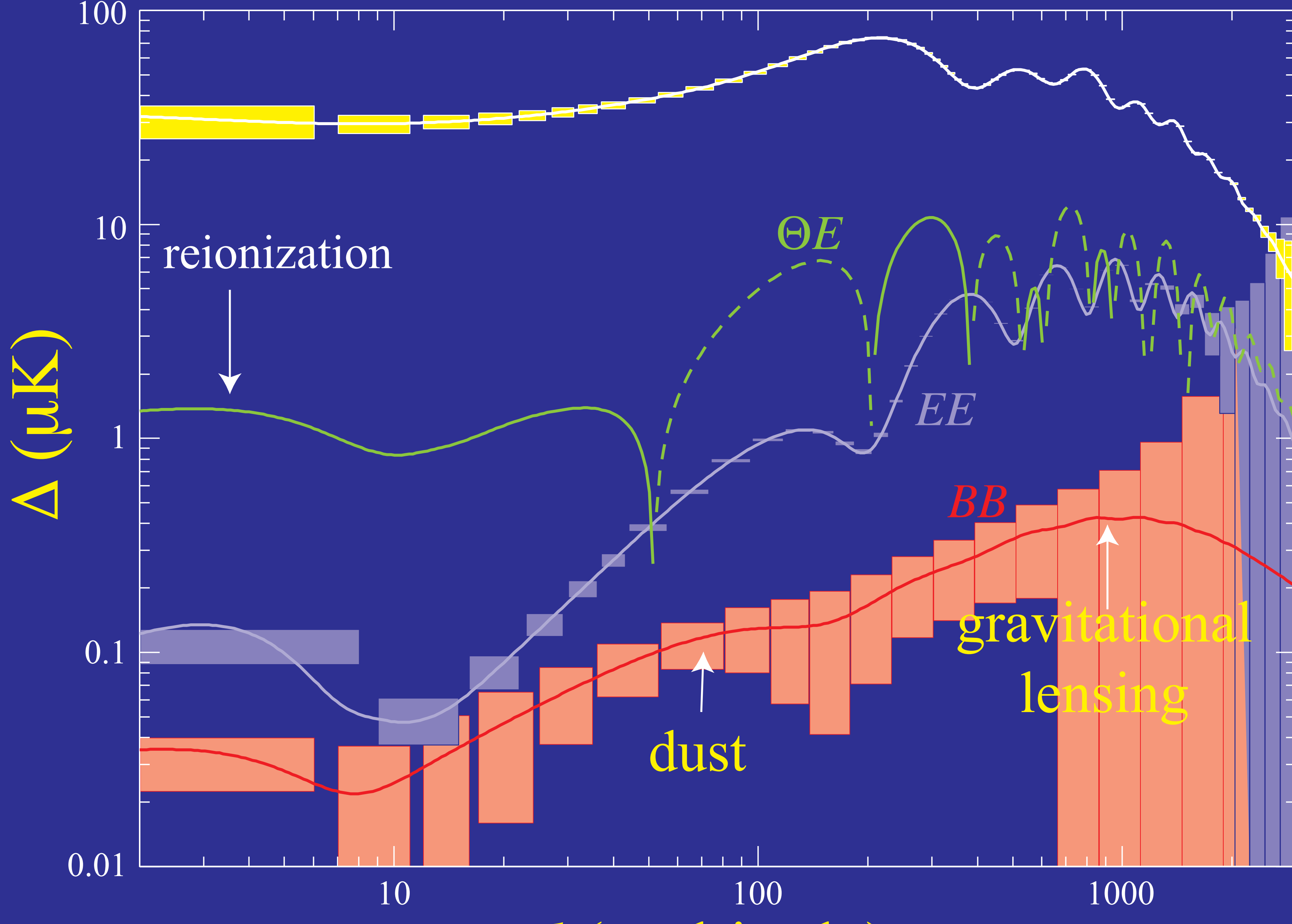


Hu & Dodelson (2002)

CMB Power Spectra Measurements



Polarized Landscape

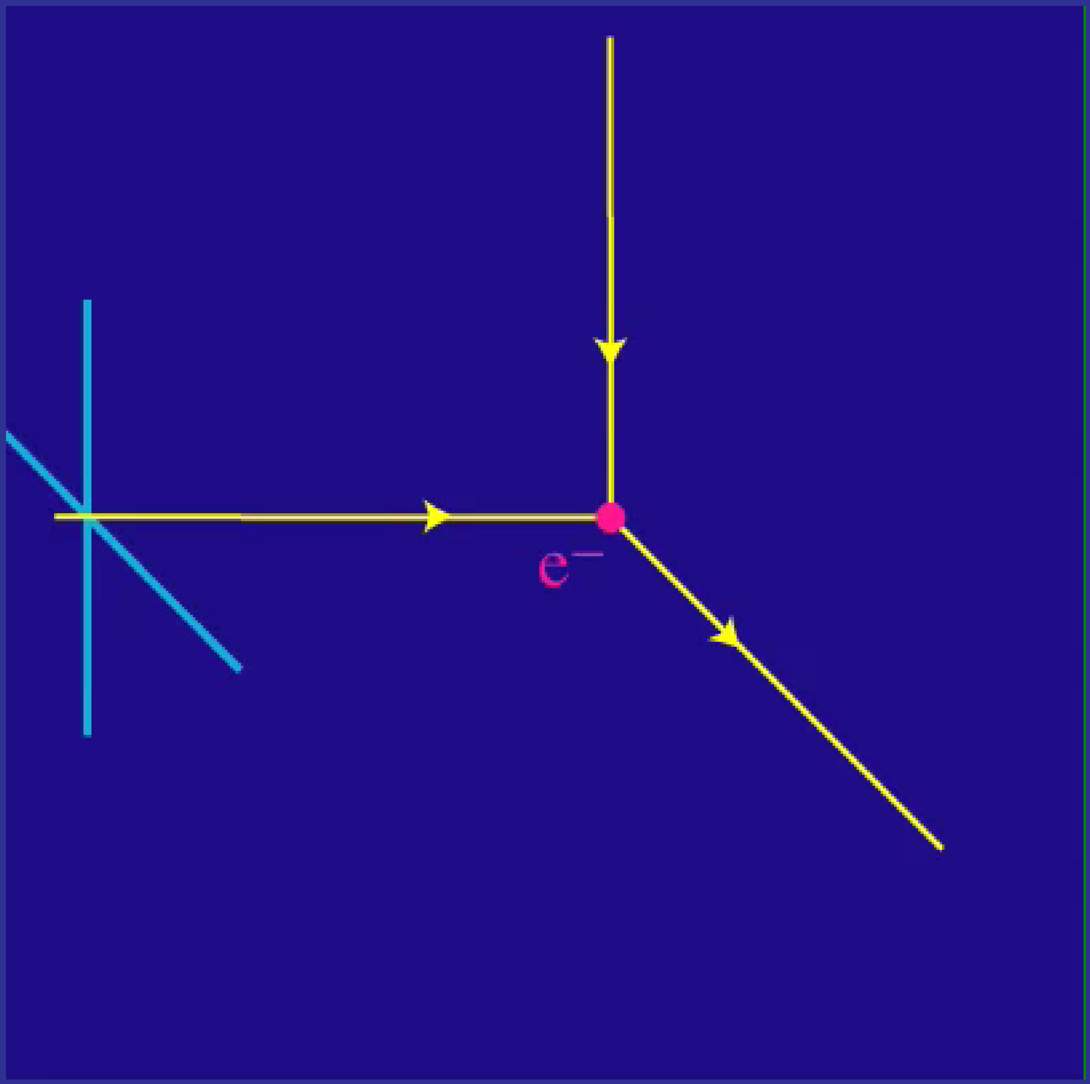


Hu & Dodelson (2002)

Why is the CMB polarized?

Polarization from Thomson Scattering

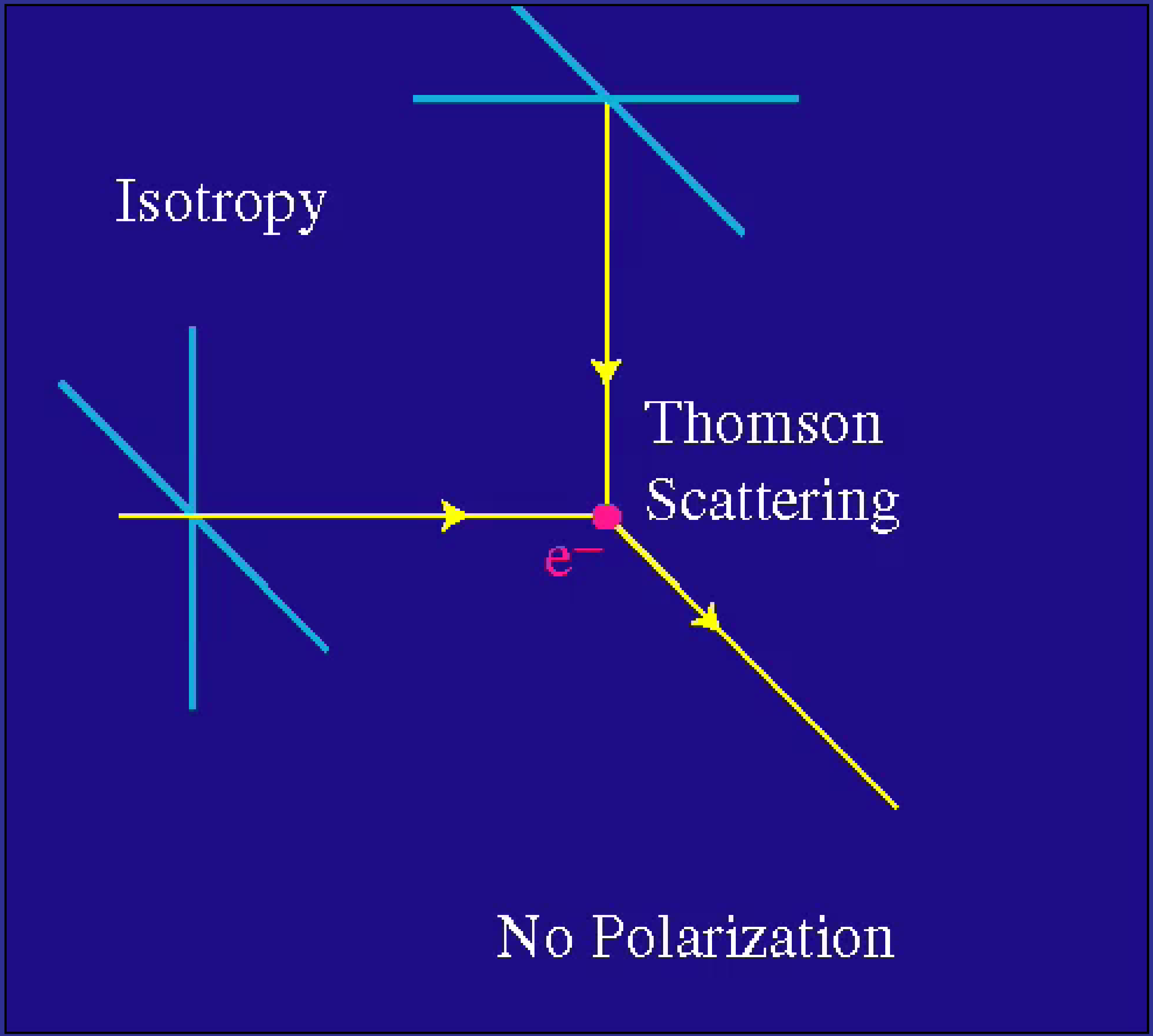
- Differential cross section depends on polarization and angle



$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}|\hat{\varepsilon}' \cdot \hat{\varepsilon}|^2 \sigma_T$$

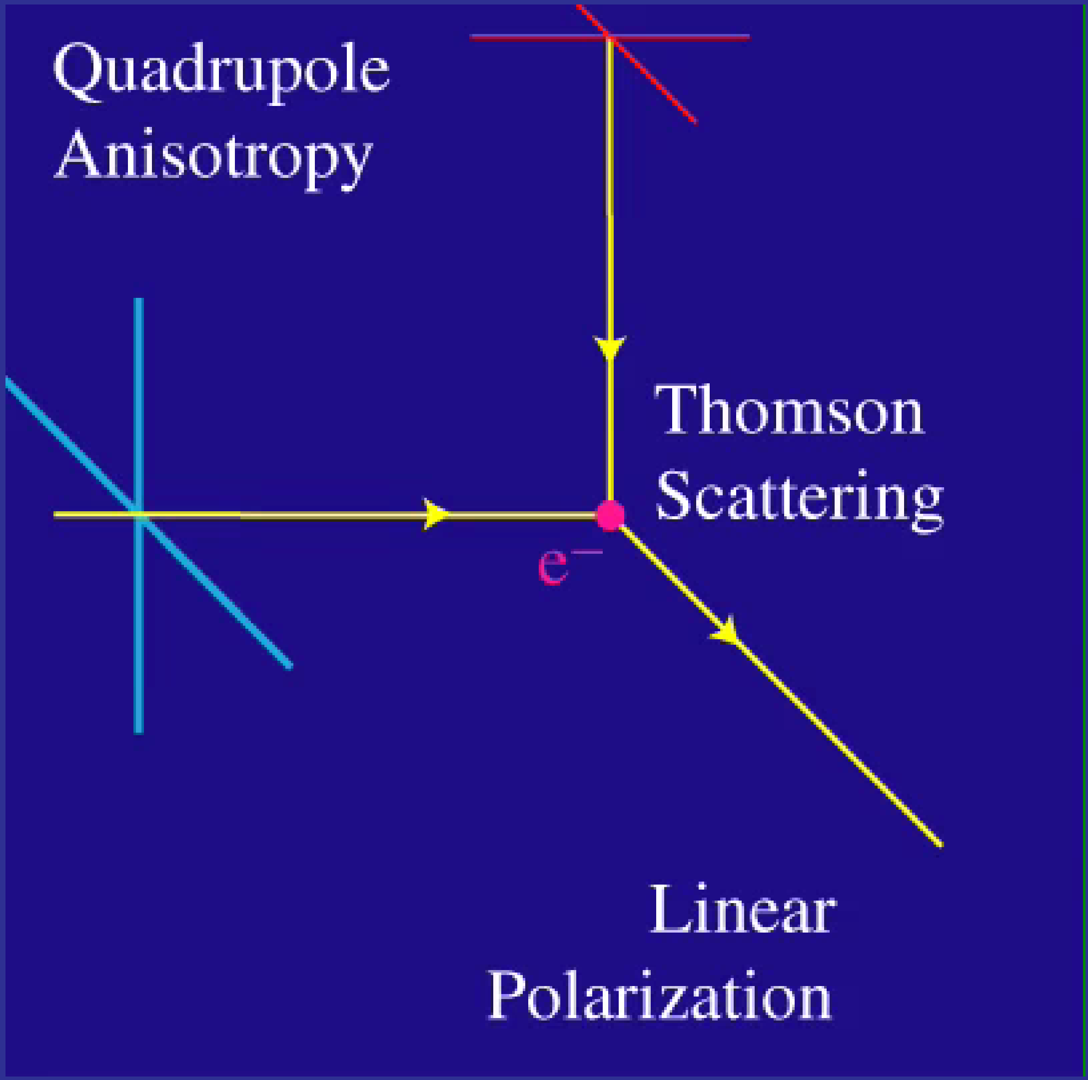
Polarization from Thomson Scattering

- Isotropic radiation scatters into unpolarized radiation



Polarization from Thomson Scattering

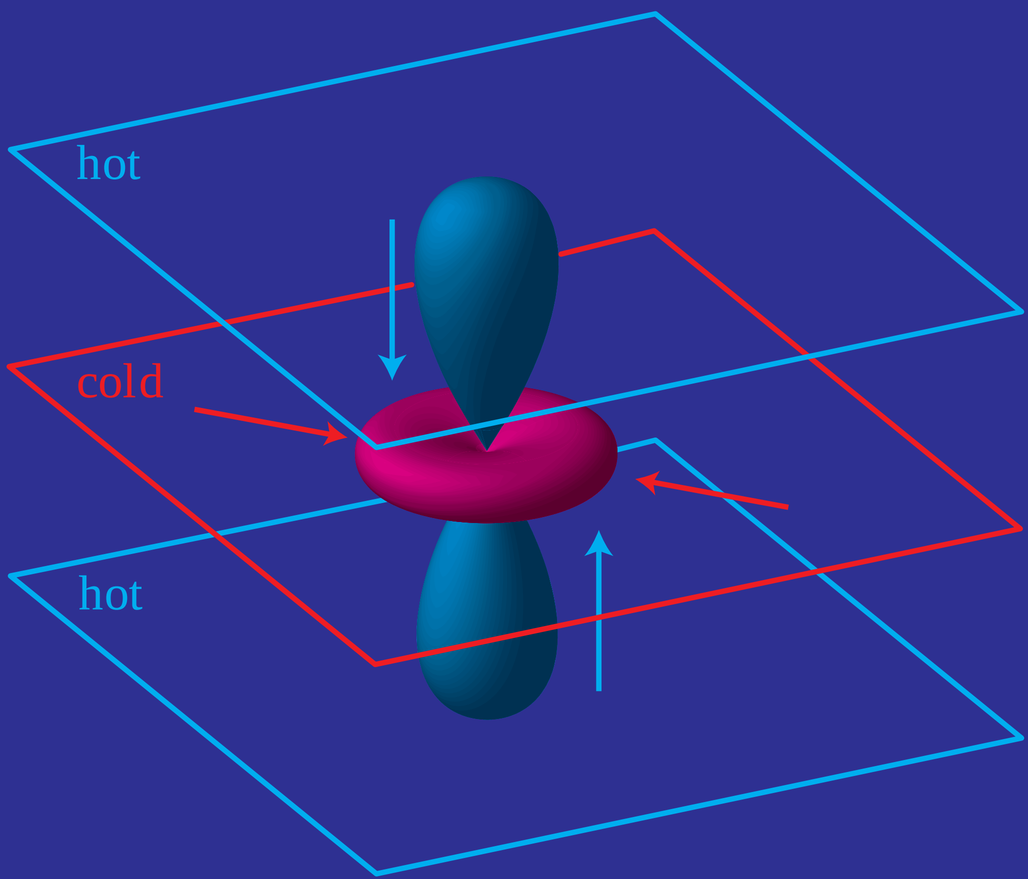
- Quadrupole anisotropies scatter into linear polarization



aligned with
cold lobe

Whence Quadrupoles?

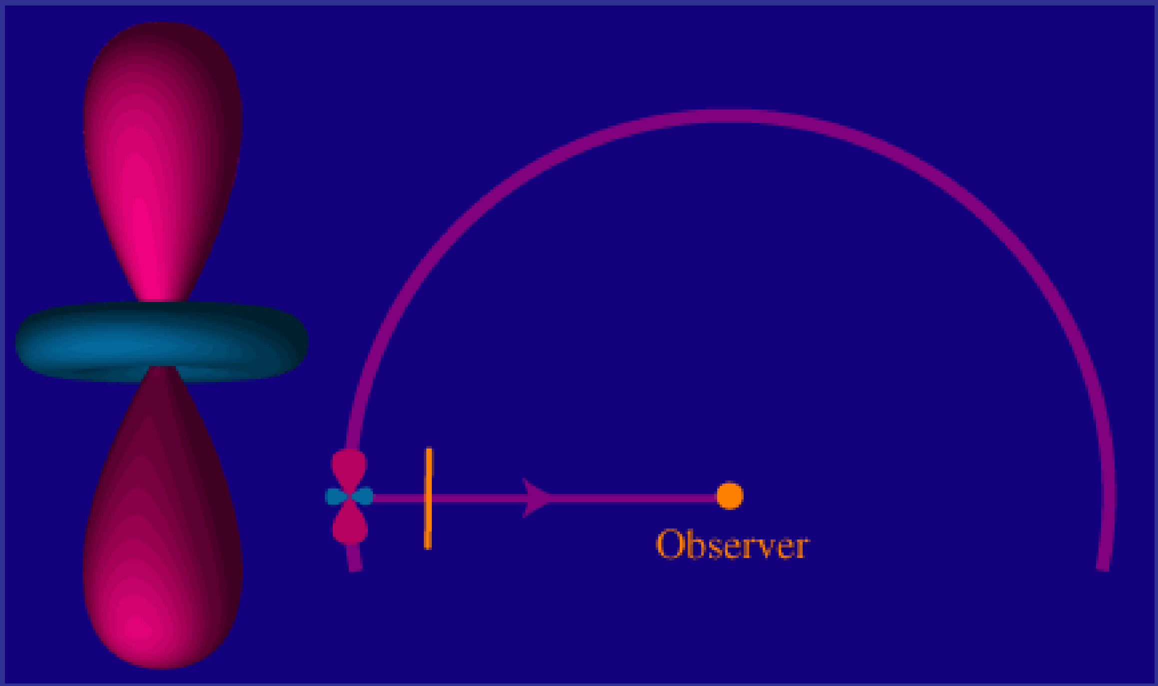
- Temperature inhomogeneities in a medium
- Photons arrive from different regions producing an anisotropy



(Scalar) Temperature Inhomogeneity

Whence Polarization Anisotropy?

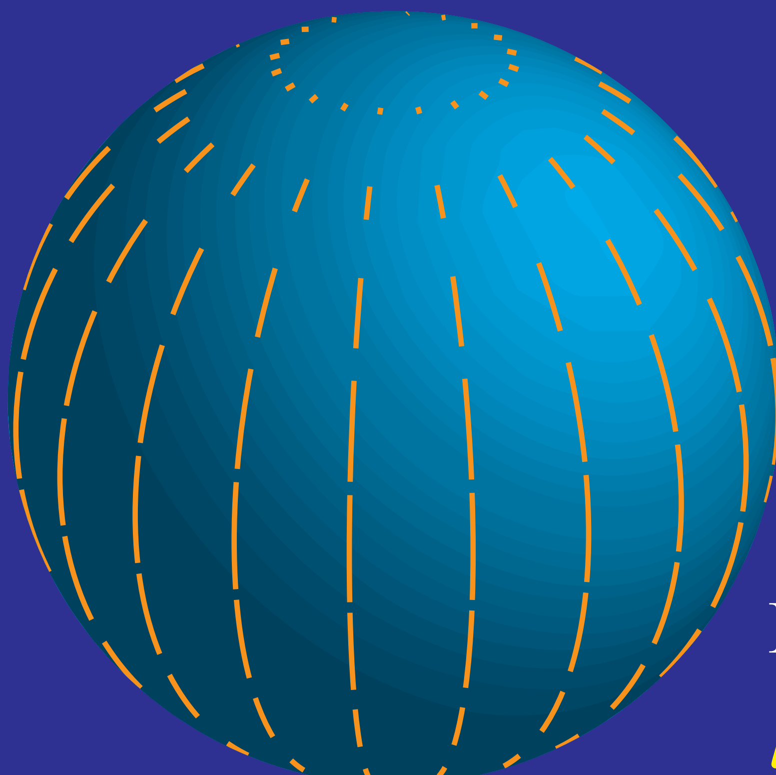
- Observed photons scatter into the line of sight
- Polarization arises from the projection of the quadrupole on the transverse plane



E and B Modes

Polarization Multipoles

- Mathematically pattern is described by the tensor (spin-2) spherical harmonics [eigenfunctions of Laplacian on trace-free 2 tensor]
- Correspondence with scalar spherical harmonics established via Clebsch-Gordan coefficients (spin x orbital)
- Amplitude of the coefficients in the spherical harmonic expansion are the multipole moments; averaged square is the power



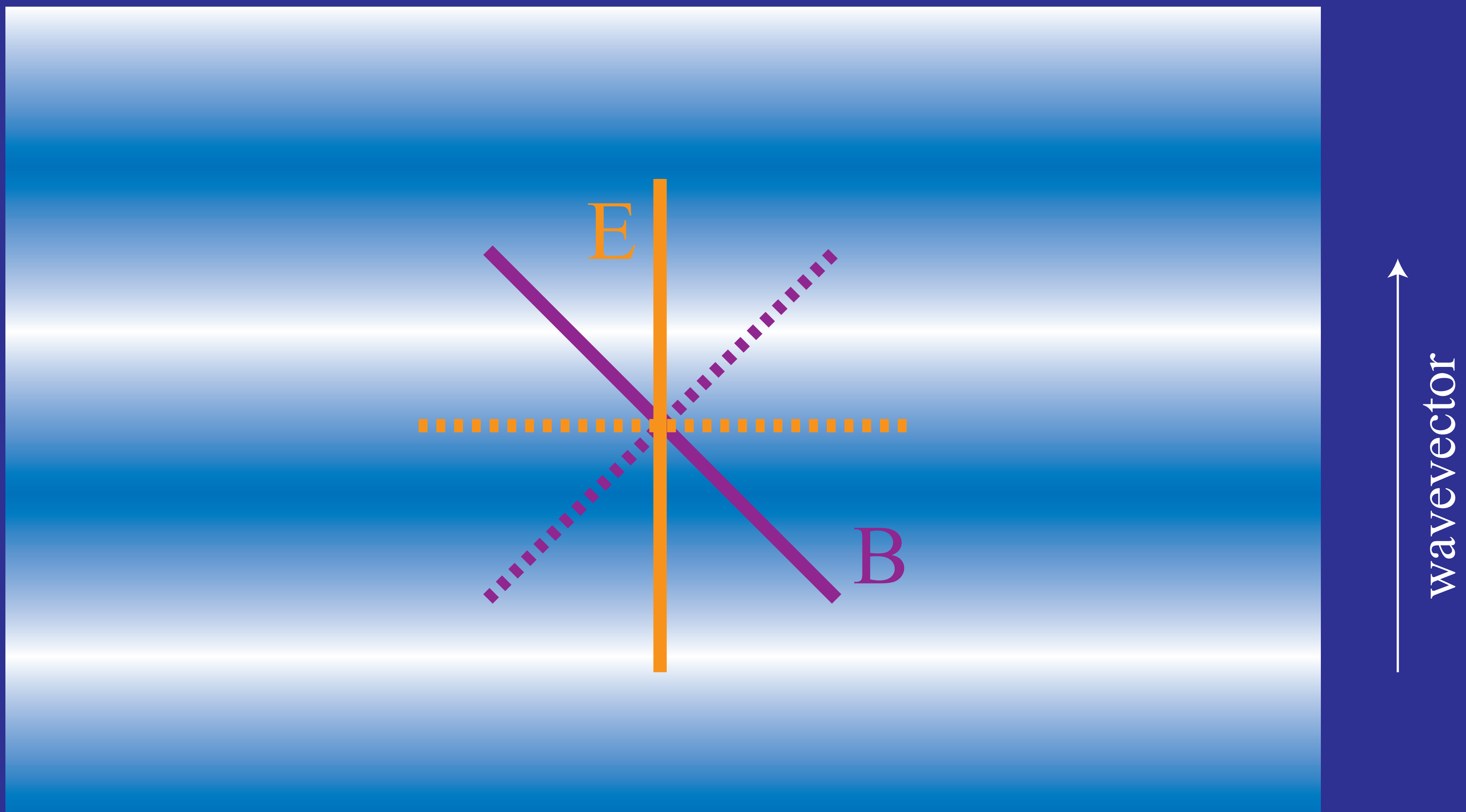
Amplitude varies along direction

E-tensor harmonic

$l=2$, $m=0$

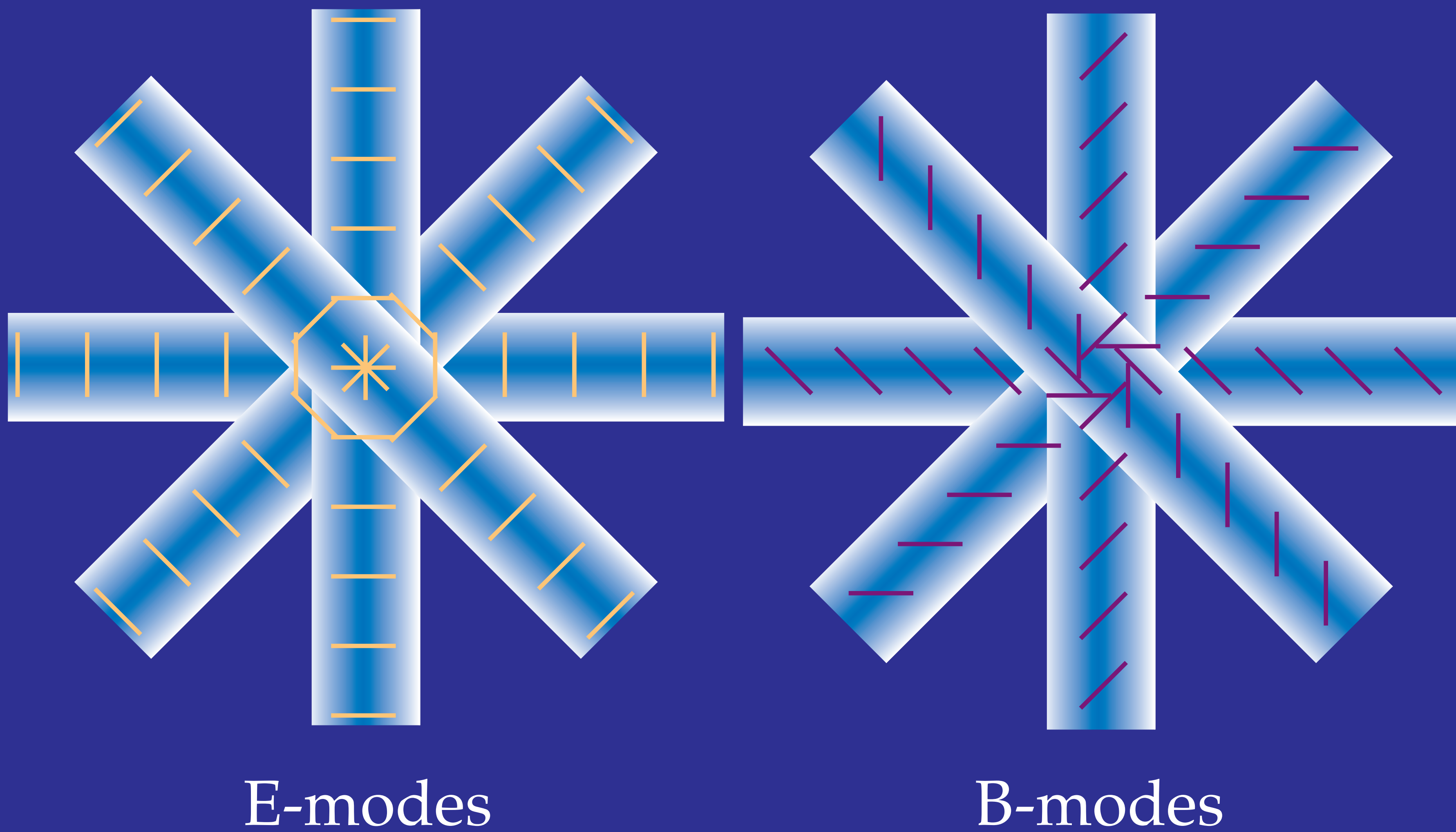
E and B modes

- E-modes are Stokes Q polarization in wavenumber basis
- B-modes are Stokes U polarization



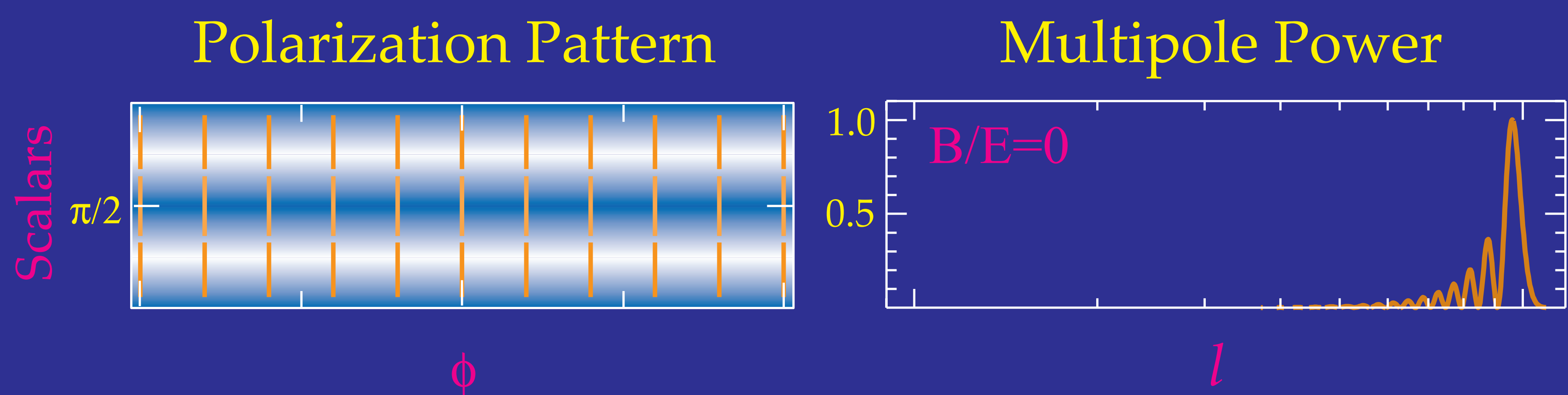
E and B modes

- Superimposing wavevectors
- B-modes have handedness or odd parity



Modulation by Plane Wave

- Amplitude modulated by plane wave → higher multipole moments
- Direction detemined by perturbation type → E-modes

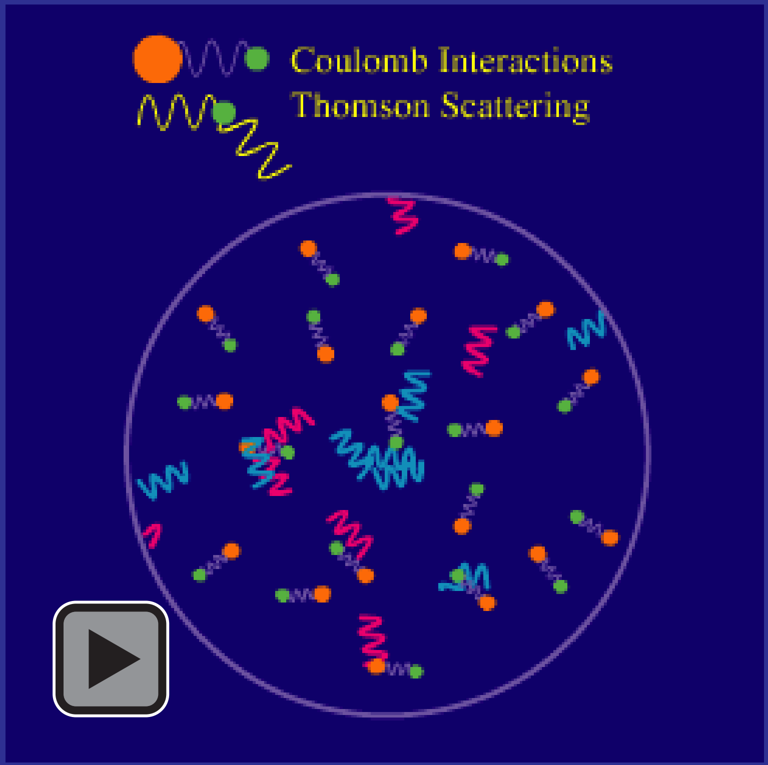


edge on orientation dominates:
nearly single l per k

Polarization Peaks

A Catch-22

- Polarization is generated by scattering of anisotropic radiation
- Scattering isotropizes radiation
- Polarization only arises in optically thin conditions: reionization and end of recombination
- Polarization fraction is at best a small fraction of the 10^{-5} anisotropy: $\sim 10^{-6}$ or μK in amplitude



Pros:
Polarization
Isolates
Scattering
Epoch

Acoustic Polarization

- Perfect fluid: no anisotropic stresses due to scattering isotropization; baryons and photons move as single fluid
- Fluid imperfections are related to the mean free path of the photons in the baryons

$$\lambda_C = \dot\tau^{-1} \quad \text{where} \quad \dot\tau = n_e \sigma_T a$$

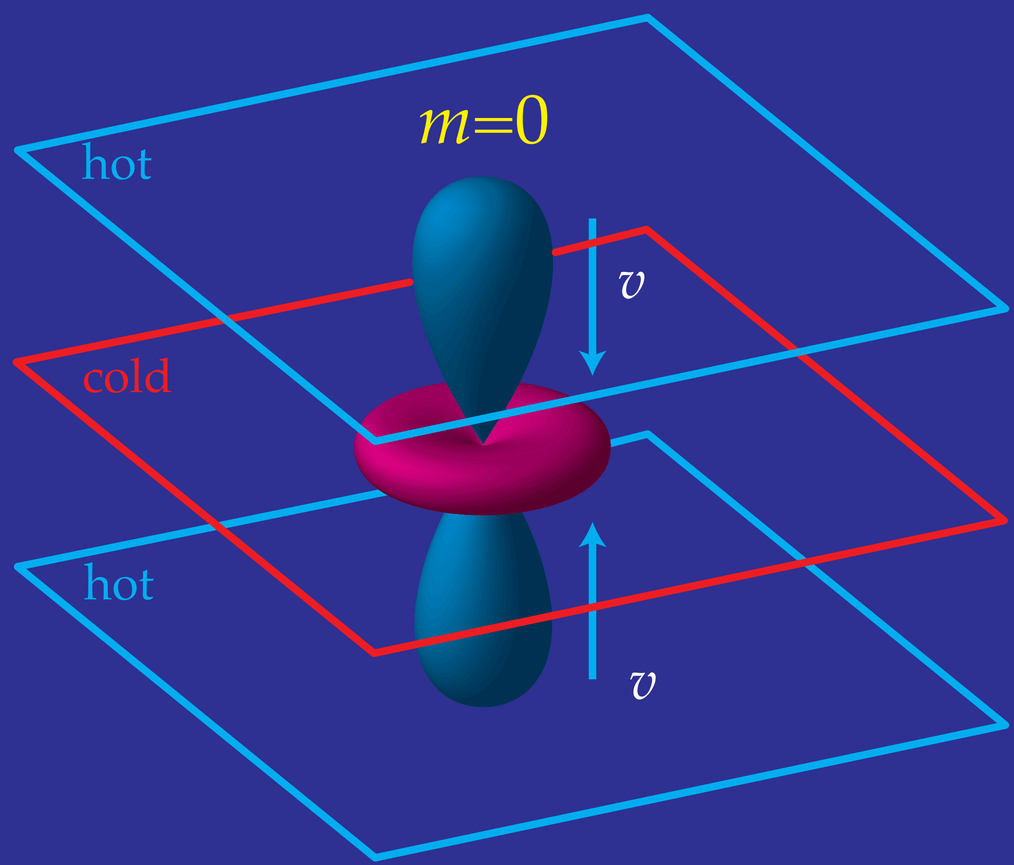
  is the conformal opacity to Thomson scattering
- Dissipation is related to the diffusion length: random walk approximation

$$\lambda_D = \sqrt{N}\lambda_C = \sqrt{\eta/\lambda_C}\,\lambda_C = \sqrt{\eta\lambda_C}$$

  the geometric mean between the horizon and mean free path
- $\lambda_D/\eta_* \sim$ few %, so expect the peaks >3 to be affected by dissipation

Viscosity & Heat Conduction

- Both fluid imperfections are related to the gradient of the velocity kv_γ by opacity $\dot{\tau}$: slippage of fluids $v_\gamma - v_b$.
- Viscosity is an anisotropic stress or quadrupole moment formed by radiation streaming from hot to cold regions



Back of the Envelope

- Viscosity= quadrupole anisotropy that follows the fluid velocity

$$\pi_\gamma \approx \frac{k}{\dot\tau} v_\gamma$$

- Mean free path related to the damping scale via the random walk $k_D = (\dot\tau/\eta_*)^{1/2} \to \dot\tau = k_D^2 \eta_*$
- Damping scale at $\ell \sim 1000$ vs horizon scale at $\ell \sim 100$ so $k_D \eta_* \approx 10$
- Polarization amplitude rises to the damping scale to be $\sim 10\%$ of anisotropy

$$\pi_\gamma \approx \frac{k}{k_D}\frac{1}{10} v_\gamma \qquad \Delta_P \approx \frac{\ell}{\ell_D}\frac{1}{10}\Delta_T$$

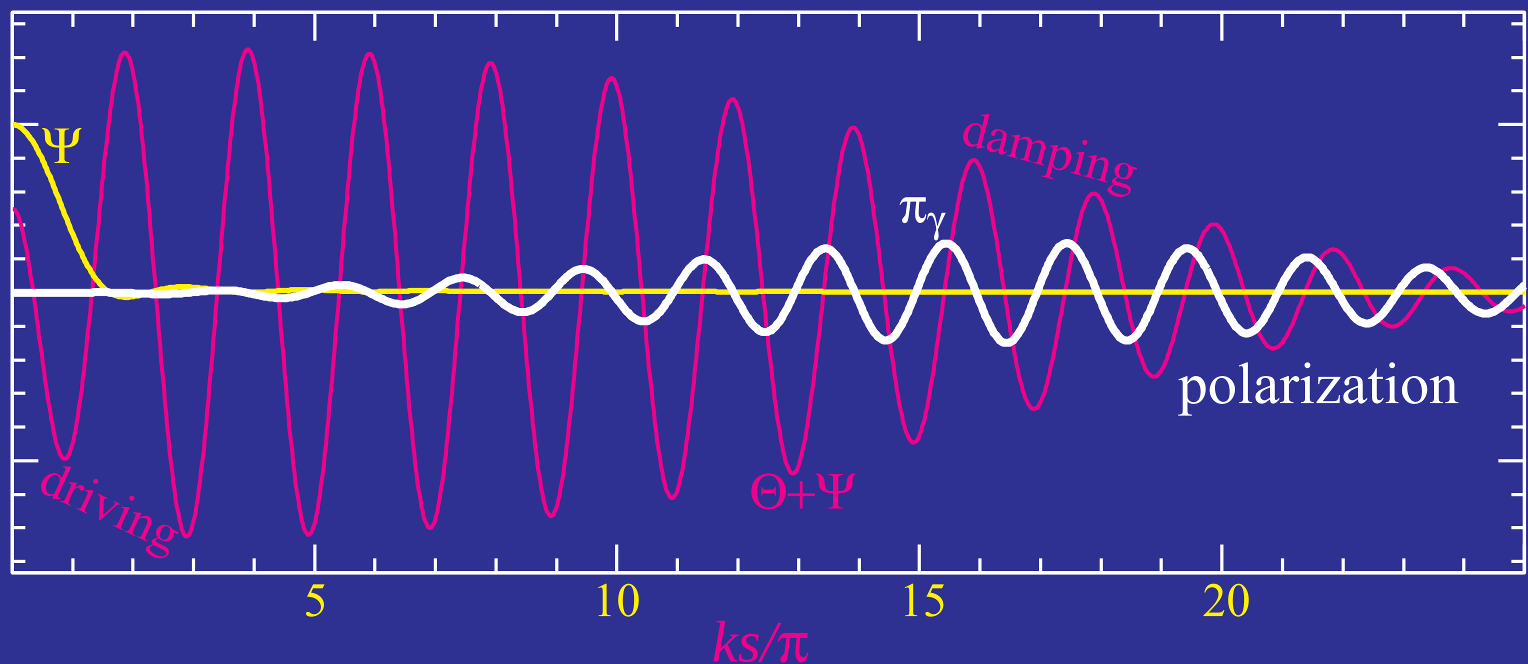
- Polarization phase follows fluid velocity

Damping & Polarization

- Quadrupole moments:

  damp acoustic oscillations from fluid viscosity
  generates polarization from scattering

- Rise in polarization power coincides with fall in temperature power – $l \sim 1000$



Acoustic Polarization

- Gradient of velocity is along direction of wavevector, so polarization is pure E-mode
- Velocity is 90° out of phase with temperature – turning points of oscillator are zero points of velocity:

$$\Theta + \Psi \propto \cos(ks); \quad v_\gamma \propto \sin(ks)$$

- Polarization peaks are at troughs of temperature power

Cross Correlation

- Cross correlation of temperature and polarization

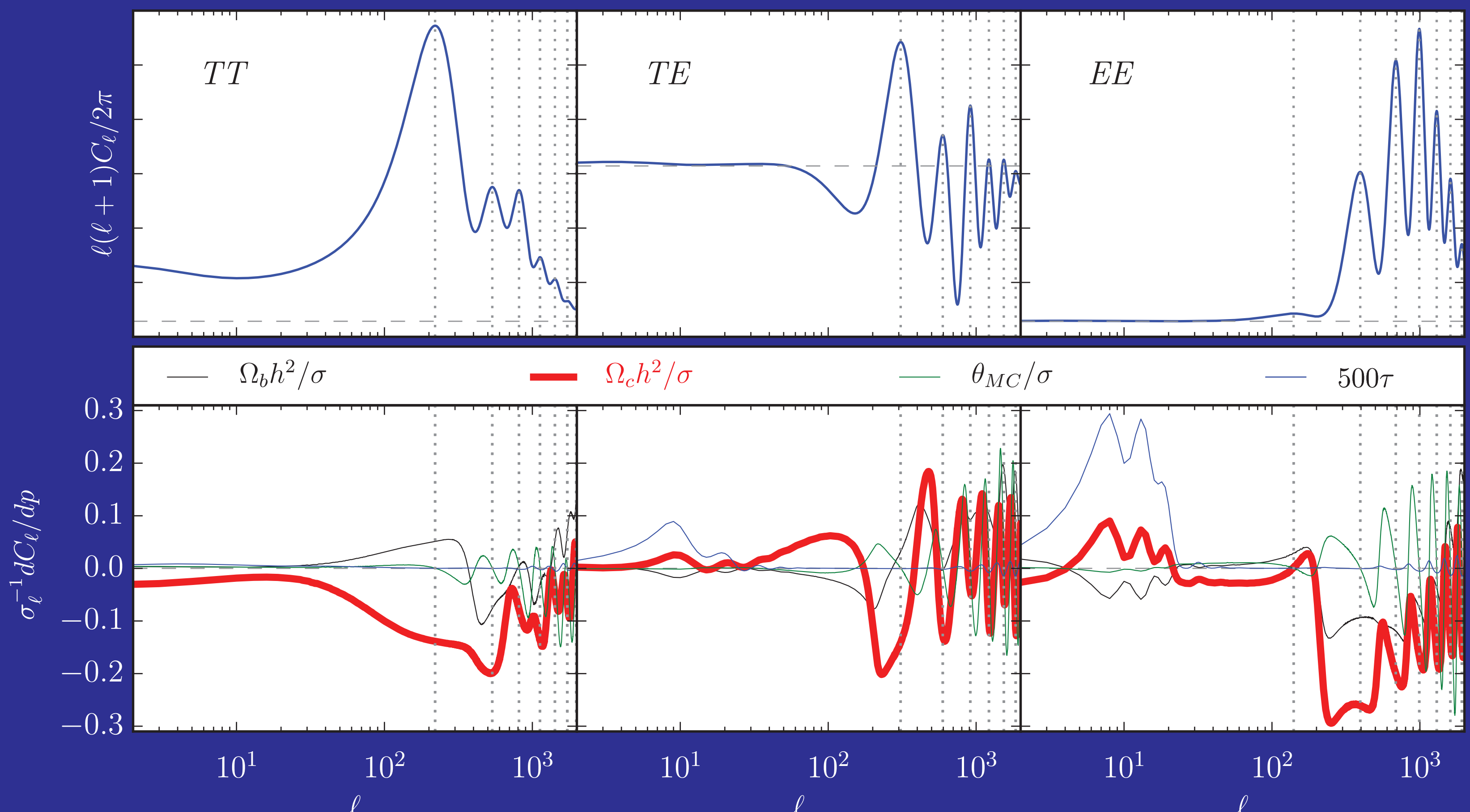
$$(\ \mathrm{T}\ )(v_\gamma) \propto \cos(ks)\sin(ks) \propto \sin(2ks)$$

- Oscillation at twice the frequency
- Correlation: radial or tangential around hot spots
- Partial correlation: easier to measure if polarization data is noisy

- Good check for systematics and foregrounds
- Comparison of temperature and polarization is proof against features in initial conditions mimicking acoustic features
- Polarization isolates scattering leading to reduced projection effects

Polarization and H_0

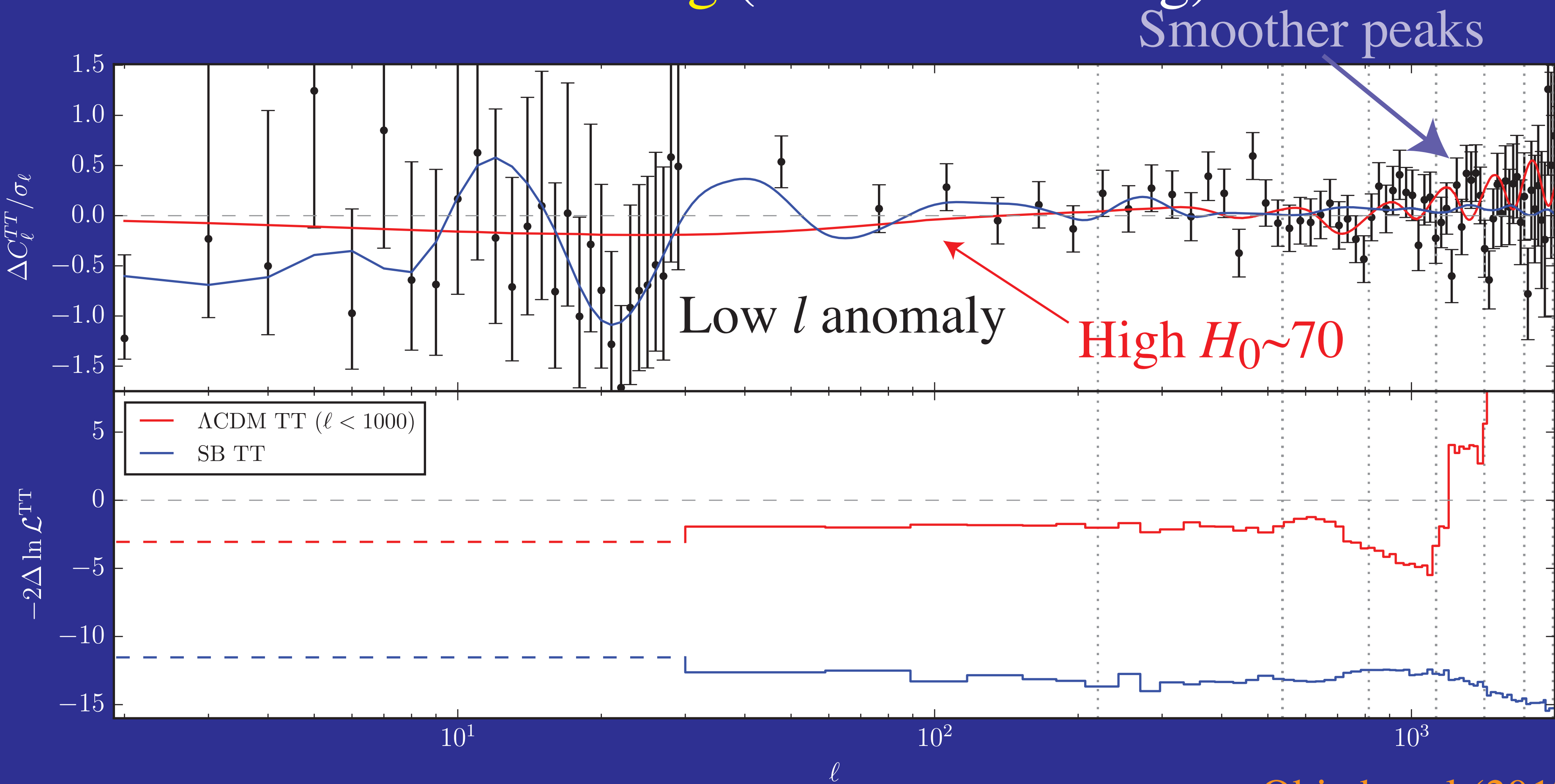
- Shift to lower H_0 from changes in the shape of peaks indicating more CDM relative to radiation
- Increased angular scale of sound horizion compensated by larger distance to recombination through lower H_0



Polarization and H_0

- Residuals from the best fit H_0~67km/s/Mpc ΛCDM solution
- High H_0 at l<1000 driven by low l anomaly
- Low H_0 at l>1000 driven by smoother peaks from less radiation driving (and more lensing)

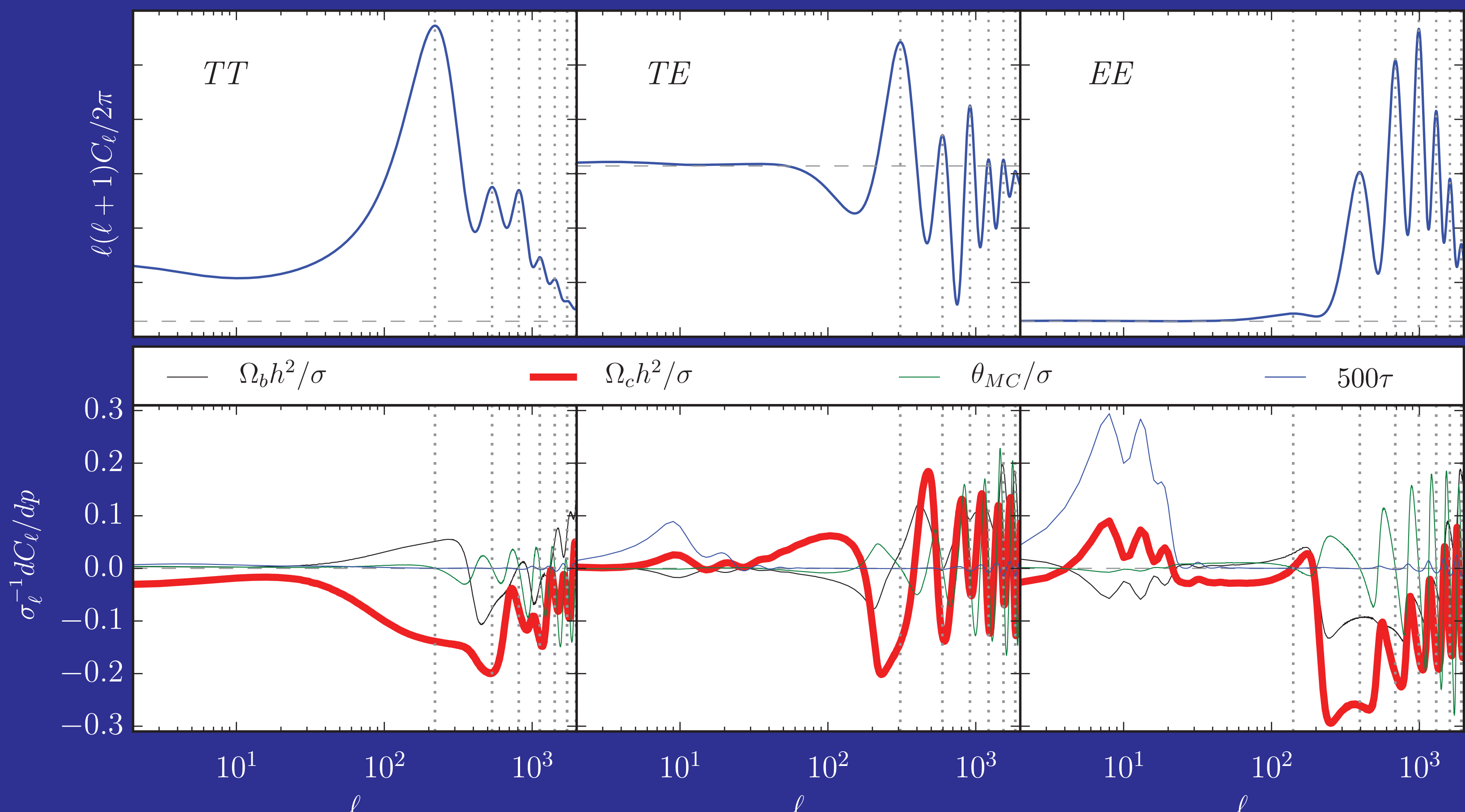
Addison et al (2015)
Aghanim et al (2016)



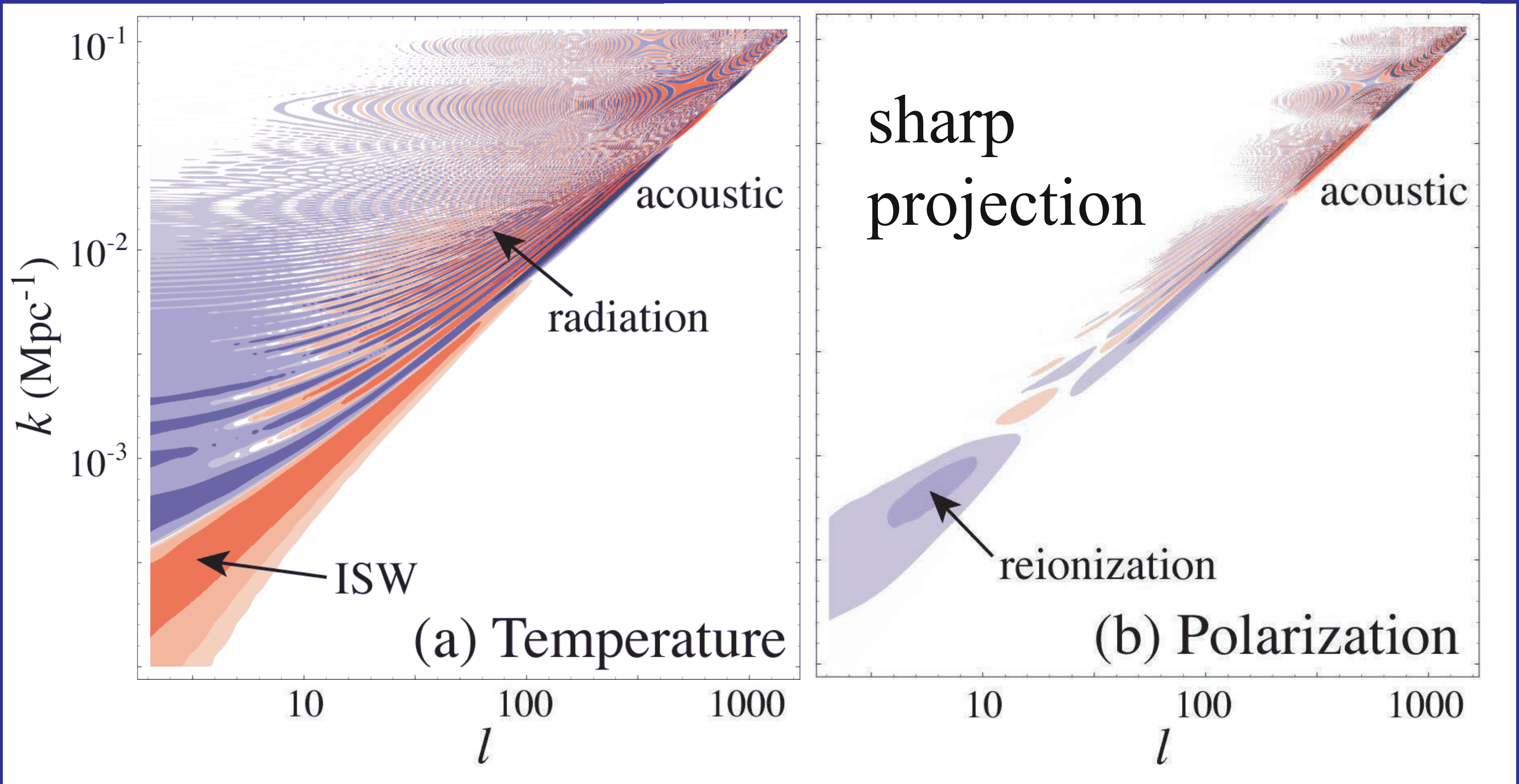
Obied et al (2017)

Polarization and H_0

- Polarization response to parameter shifts very sharp around first temperature peak: no intervening ISW sources, geometry of projection
- Powerful cross check in a different observable and scale



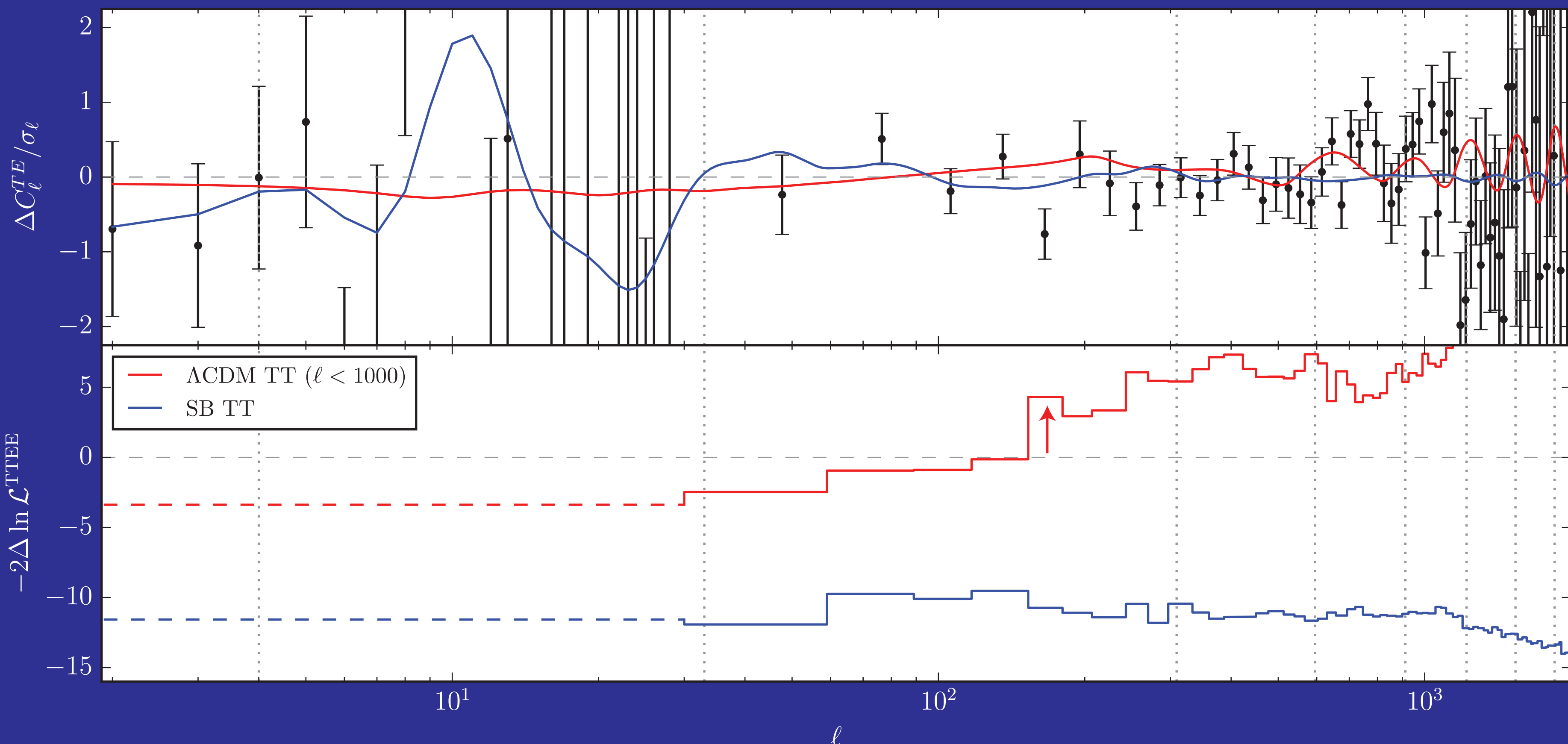
Transfer of Initial Power



Hu & Okamoto (2003)

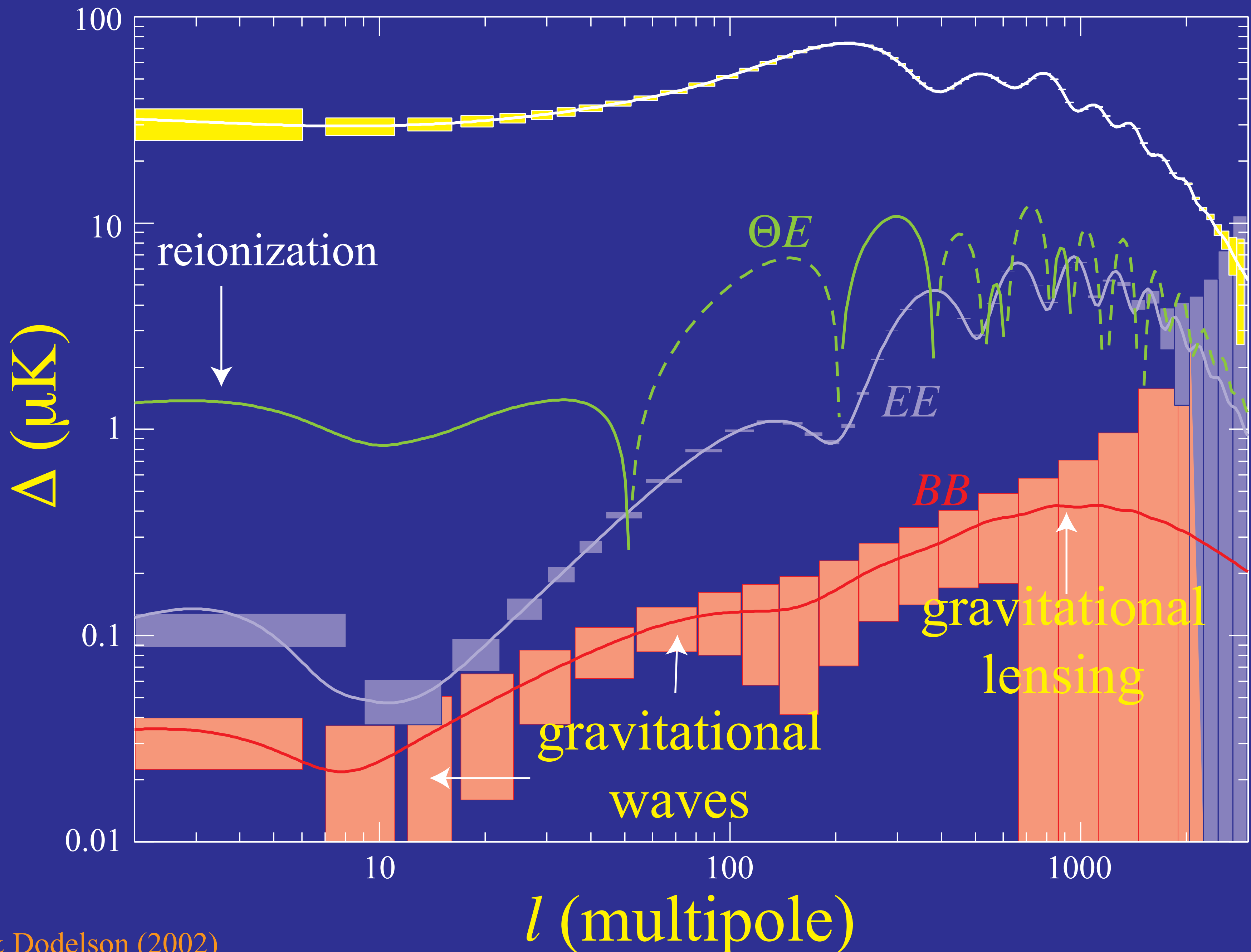
Polarization and H_0

- TE residuals favor H_0~67km/s/Mpc but at l<1000
- As sensitive as all of TT
- Anomalous sensitivity from a 2σ outlier at l~165 near the first polarization trough



Obied et al (2017)

Polarized Landscape

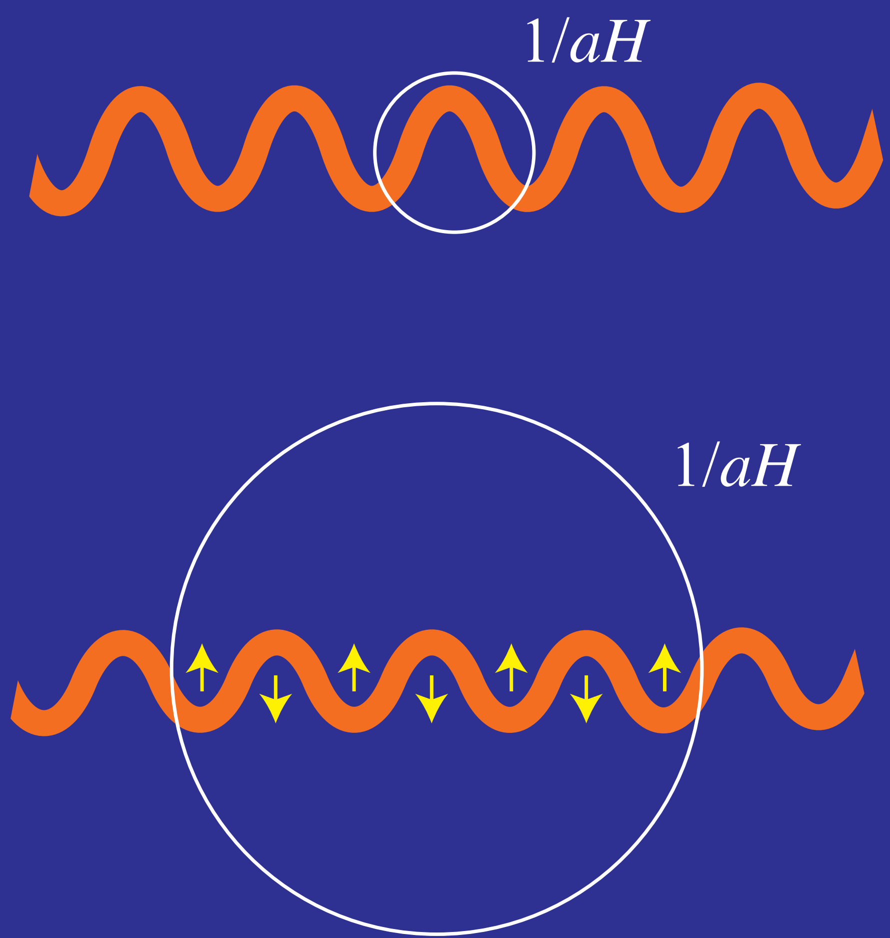


Hu & Dodelson (2002)

Gravitational Waves

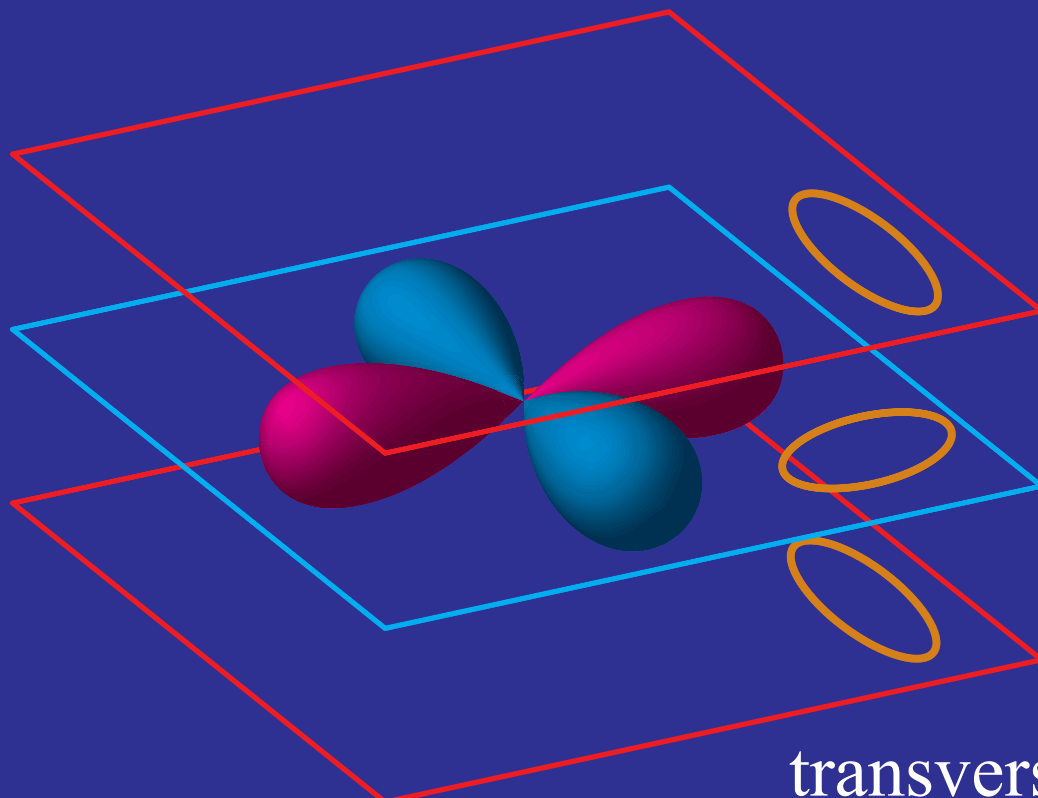
Gravitational Waves in Cosmology

- During deceleration epoch gravity waves are frozen outside the horizon
- Oscillate inside the horizon and decay or redshift as radiation



Quadrupoles from Gravitational Waves

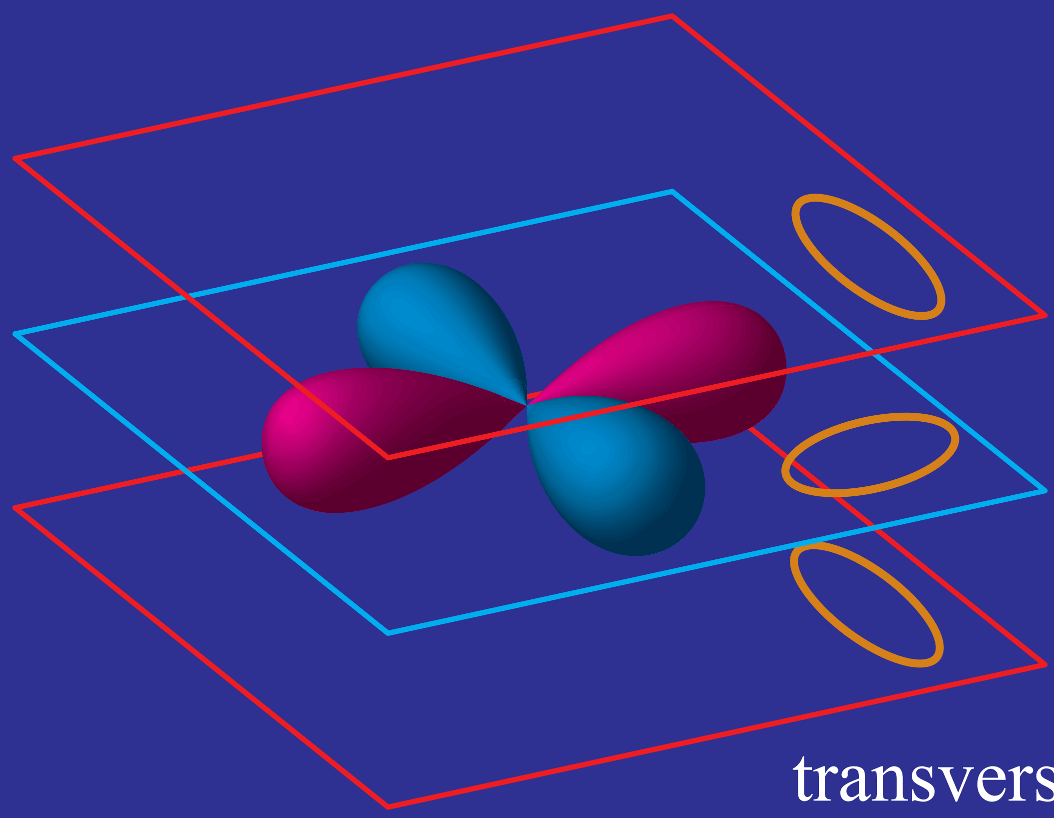
- Changing transverse traceless distortion of space, aka gravitational waves, creates quadrupole CMB anisotropy
- Gravitational waves are frozen when larger than the horizon and oscillate and decay as radiation inside horizon



transverse-traceless
tensor distortion

Quadrupoles from Gravitational Waves

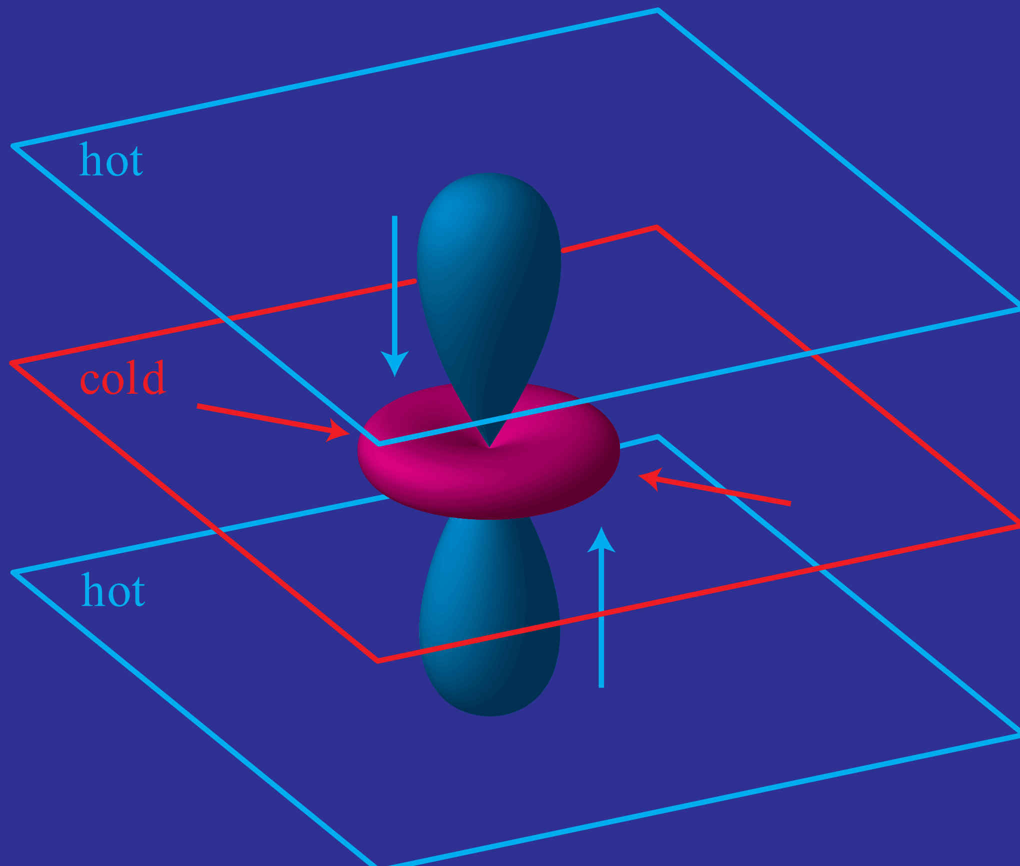
- Transverse-traceless distortion provides temperature quadrupole
- Gravitational wave polarization picks out direction transverse to wavevector



transverse-traceless distortion

How do Scalars Differ?

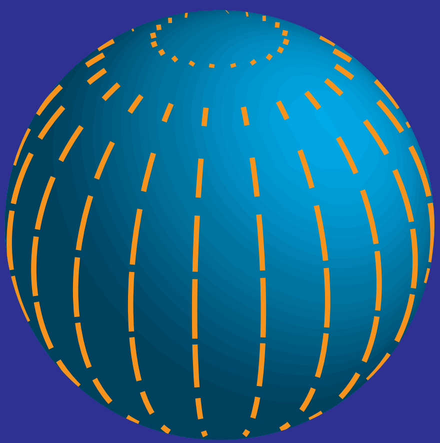
- Temperature inhomogeneities in a medium
- Photons arrive from different regions producing an anisotropy



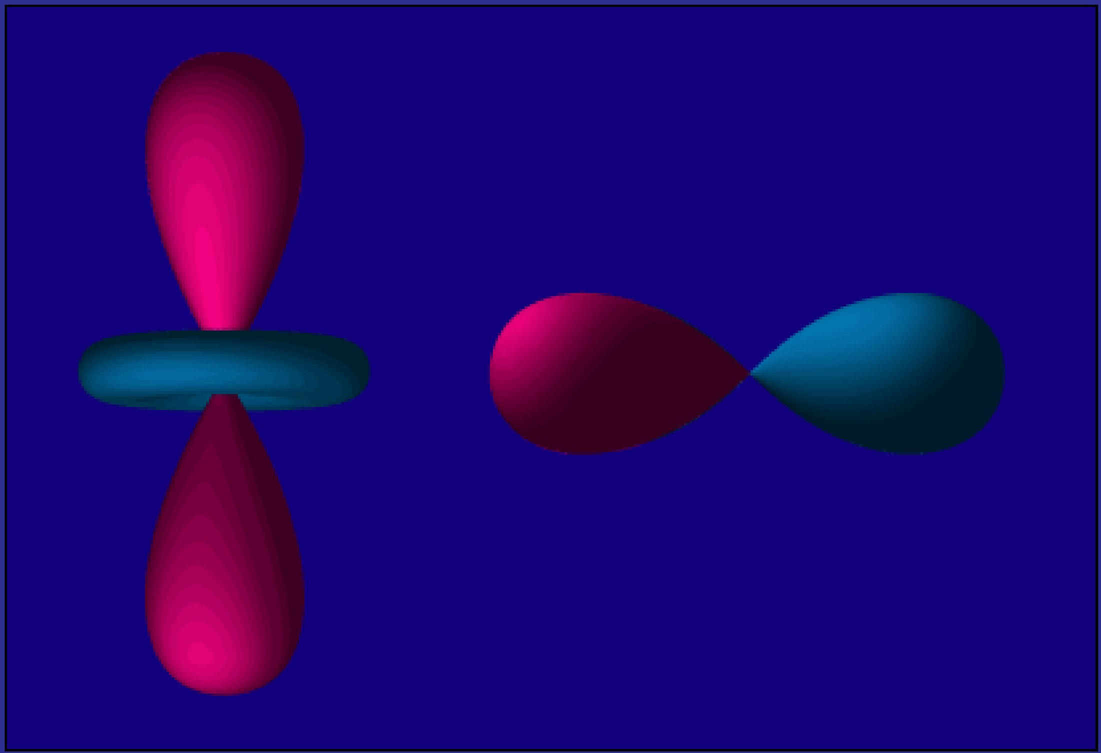
Azimuthally symmetric around wavevector

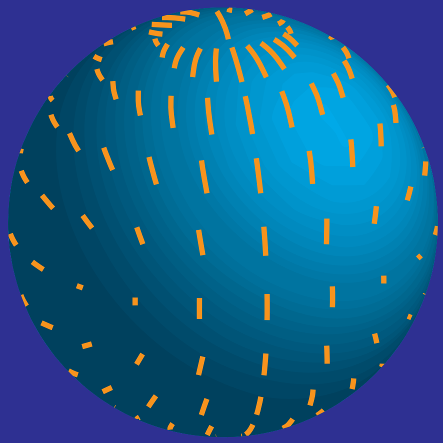
Gravitational Wave Pattern

- Projection of the quadrupole anisotropy gives polarization pattern
- Transverse polarization of gravitational waves breaks azimuthal symmetry



density perturbation

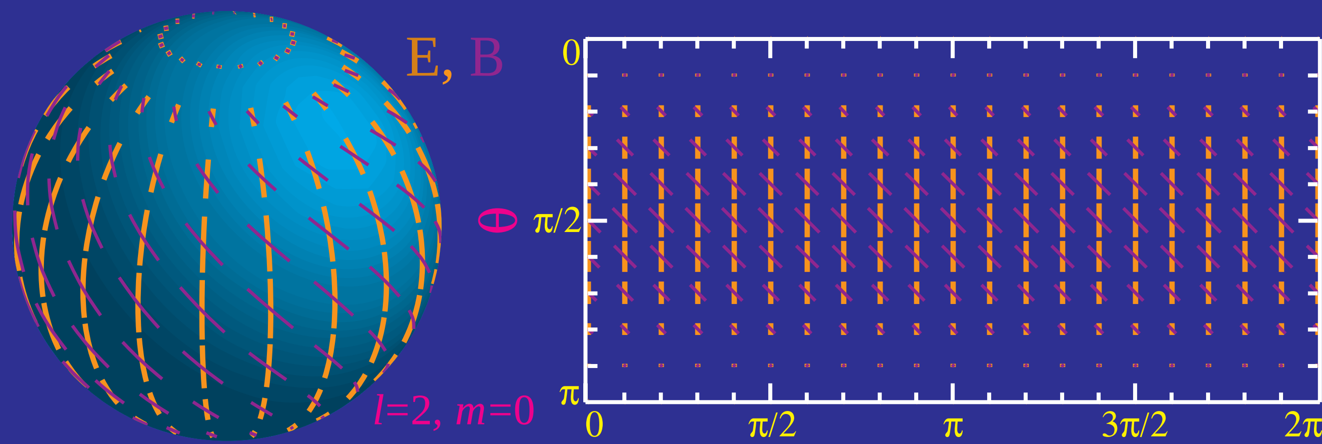




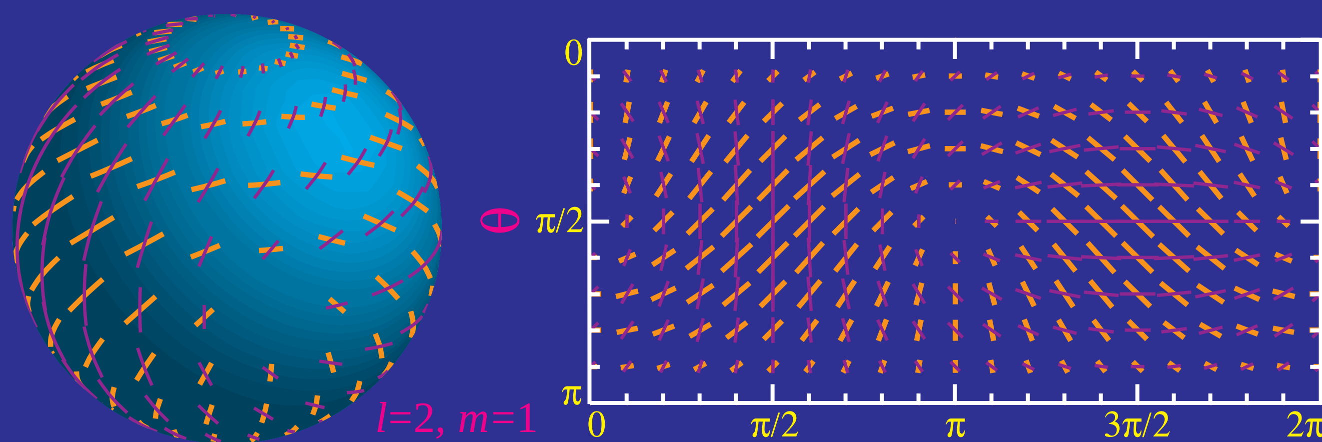
gravitational wave

Polarization Patterns

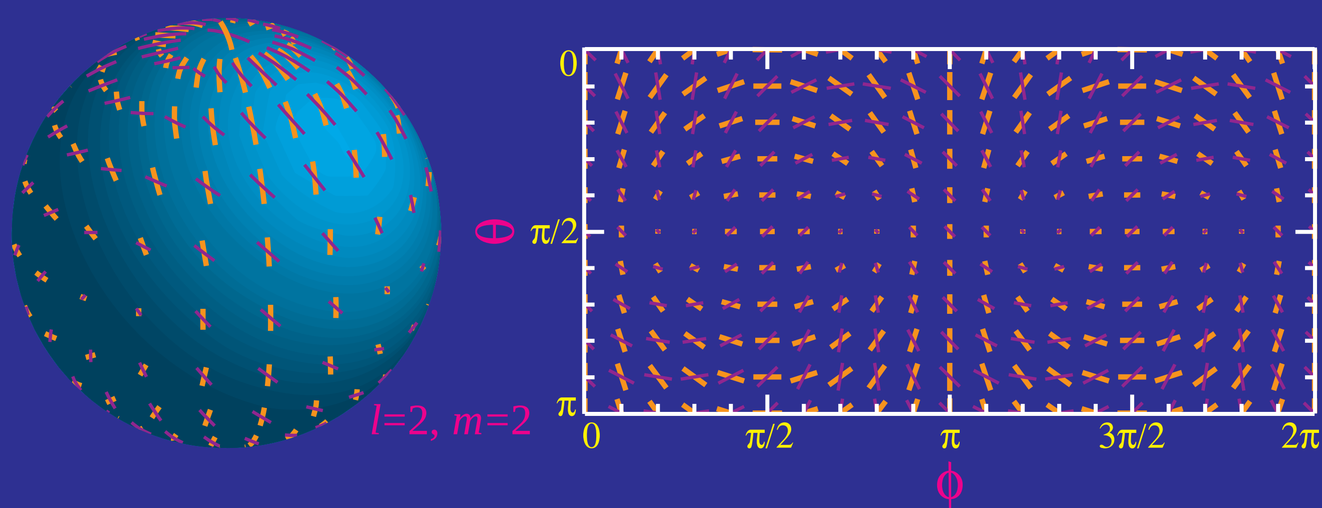
Scalars



Vectors

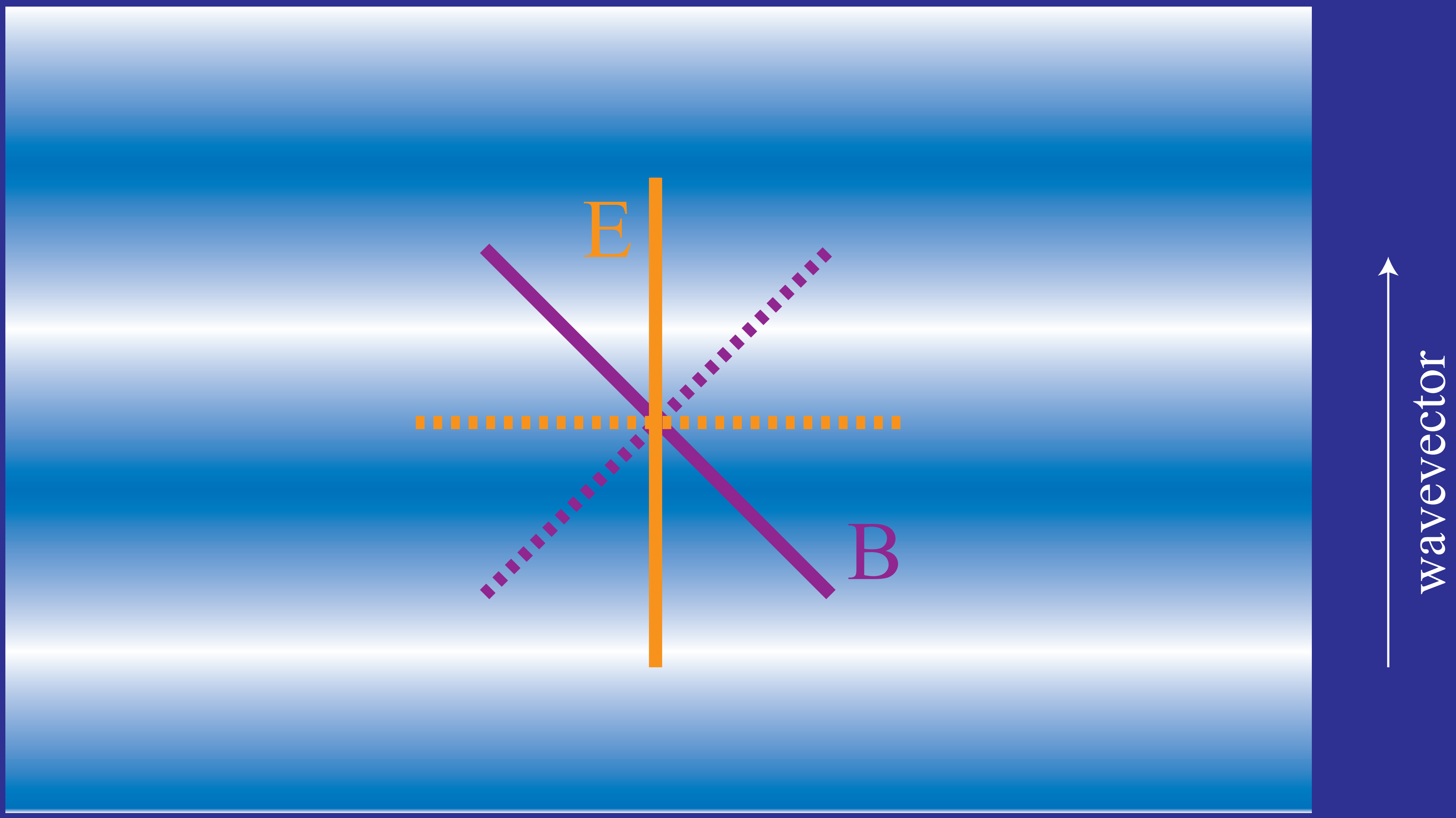


Tensors



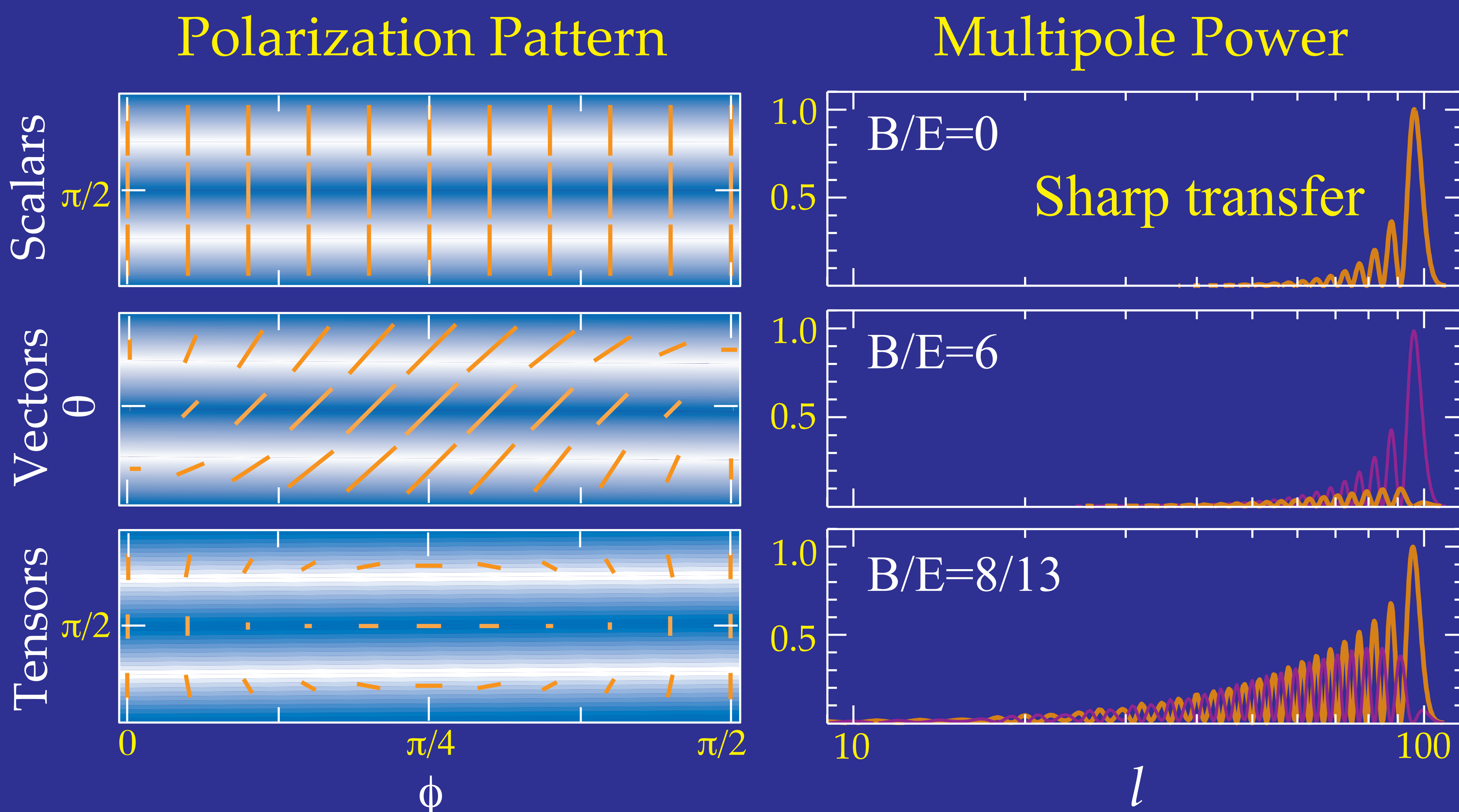
E and B modes

- E-modes are Stokes Q polarization in wavenumber basis
- B-modes are Stokes U polarization



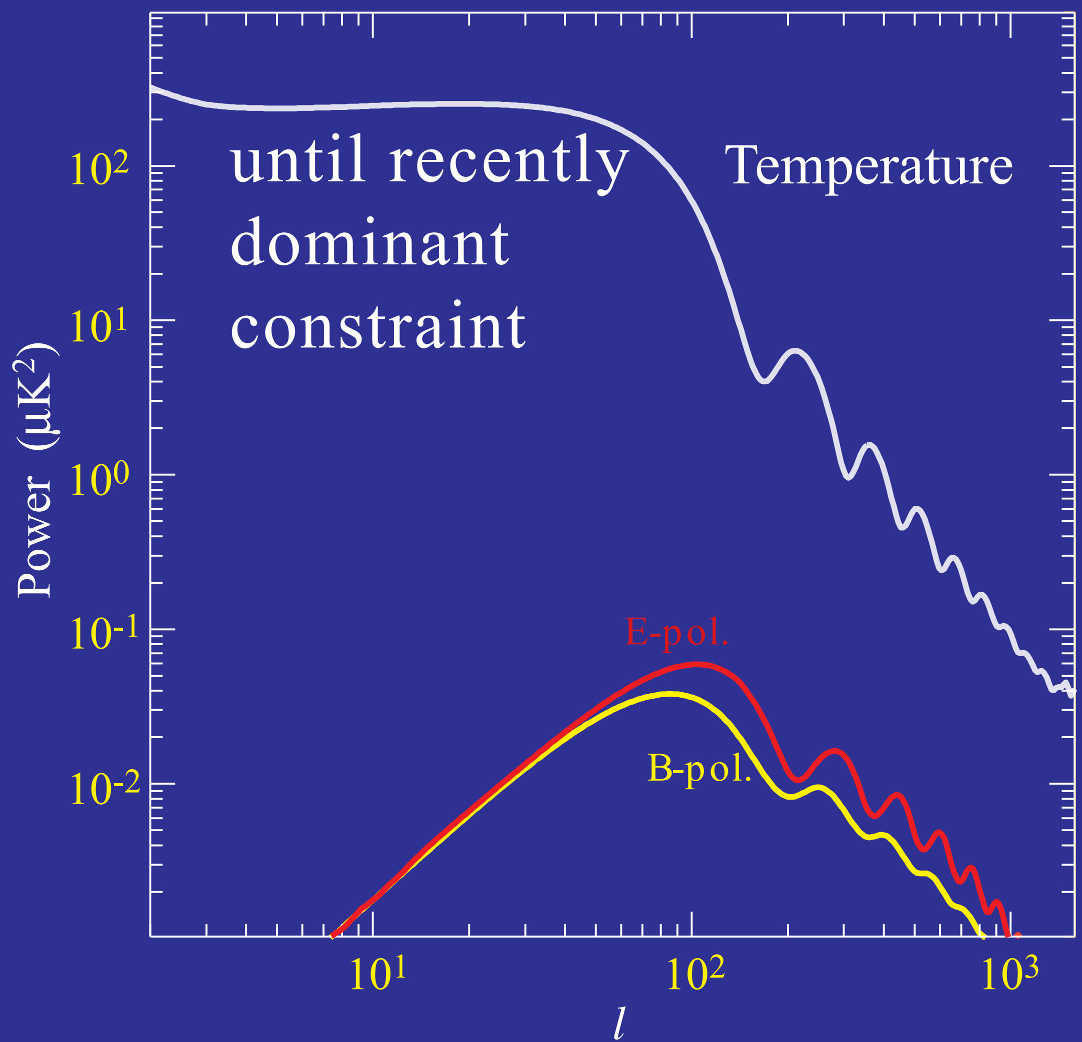
Patterns and Perturbation Types

- Amplitude modulated by plane wave → Principle axis
- Direction detemined by perturbation type → Polarization axis



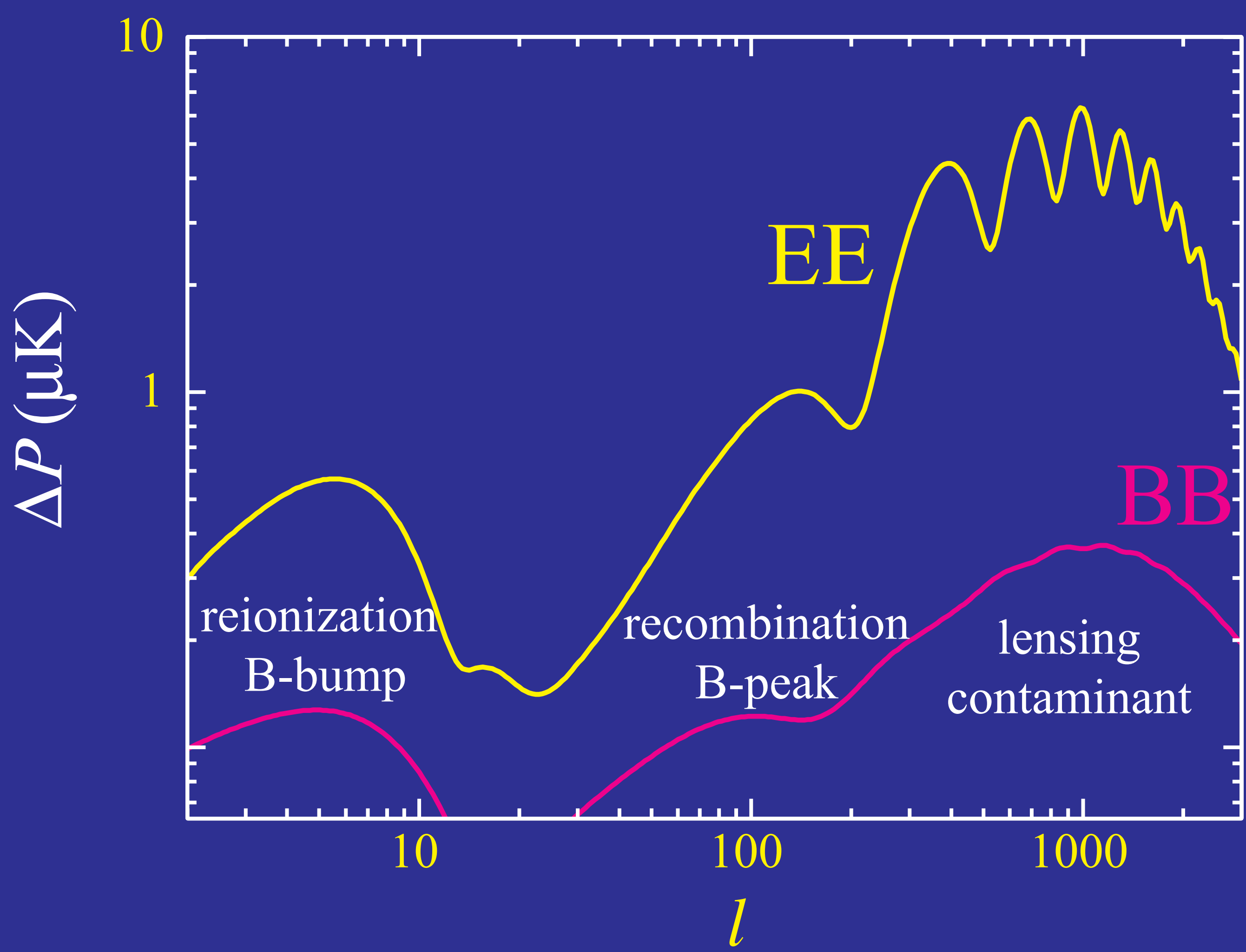
Recombination B-Modes

- Rescattering of quadrupoles at recombination yield a peak in B-modes



Polarized Landscape

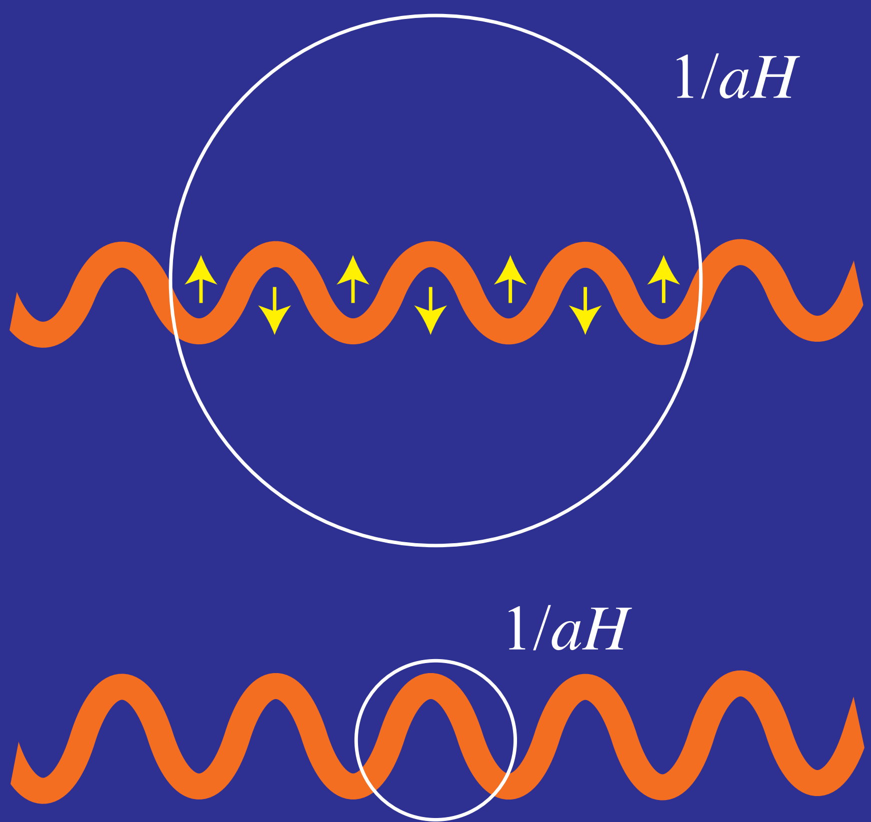
- Two scattering epochs: recombination and reionization leave two imprints on B-modes



Inflation

Gravitational Waves during Inflation

- During acceleration epoch gravity waves behave oppositely to deceleration epoch
- Oscillate inside the horizon and freeze when crossing horizon



Gravitational Waves

- Gravitational wave amplitude $h_{+,\times}$ satisfies same Klein-Gordon equation as scalars
- Just like inflaton ϕ, quantum fluctuations freeze out at horizon crossing with power per $\ln k$ given by the Hubble scale H

$$\Delta^2_{\delta\phi} = \frac{H^2}{(2\pi)^2}; \qquad \Delta^2_{+,\times} = \frac{2}{M^2_{\rm pl}} \frac{H^2}{(2\pi)^2}$$

- By the Friedmann equation

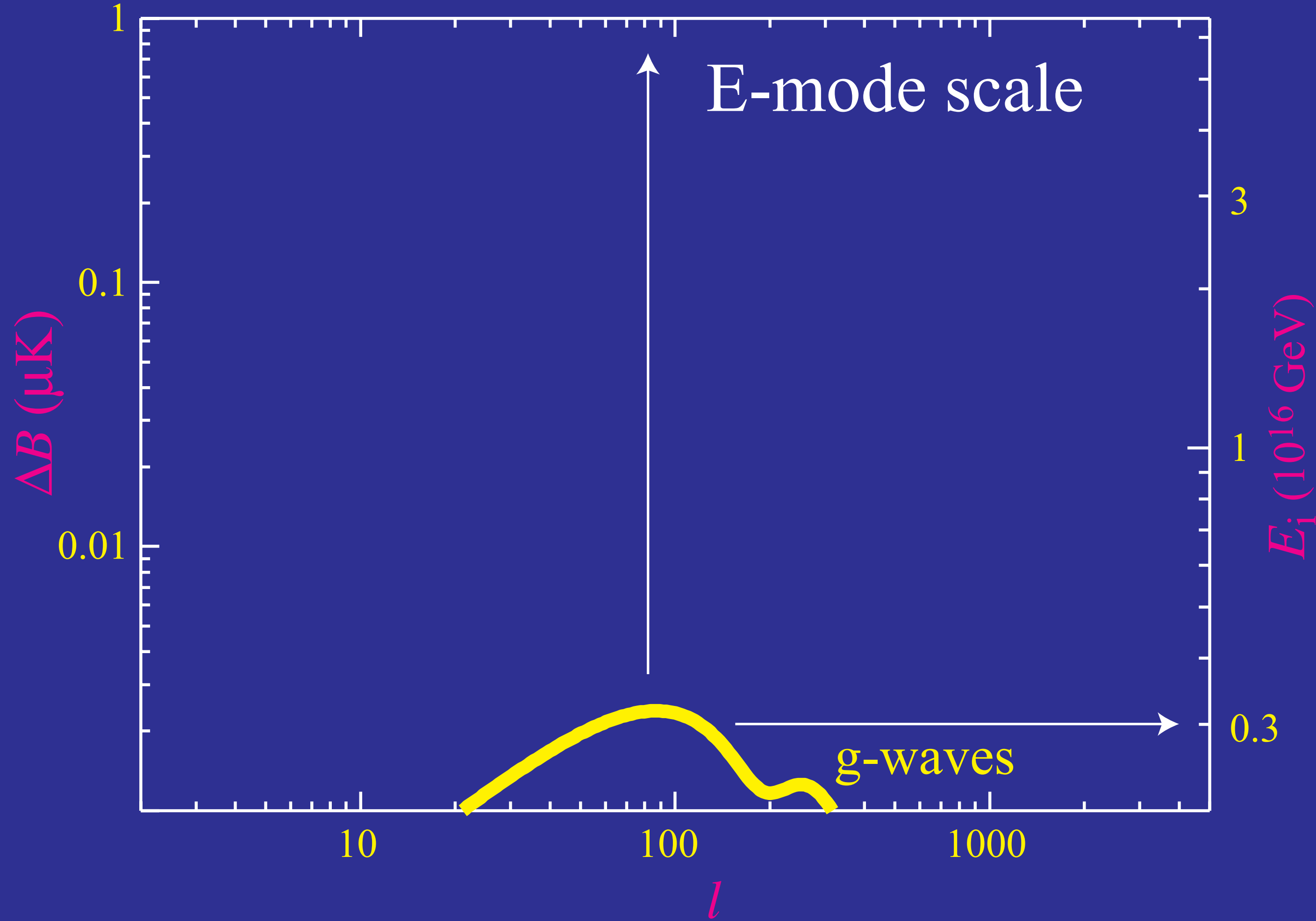
$$H^2 = \frac{\rho}{3M^2_{\rm pl}} \approx \frac{V(\phi)}{3M^2_{\rm pl}}$$

Measurement of B-modes determines energy scale $E_i = V^{1/4}$

$$B_{\rm peak} \approx 0.024 \left(\frac{E_i}{10^{16}{\rm GeV}} \right)^2 \mu{\rm K}$$

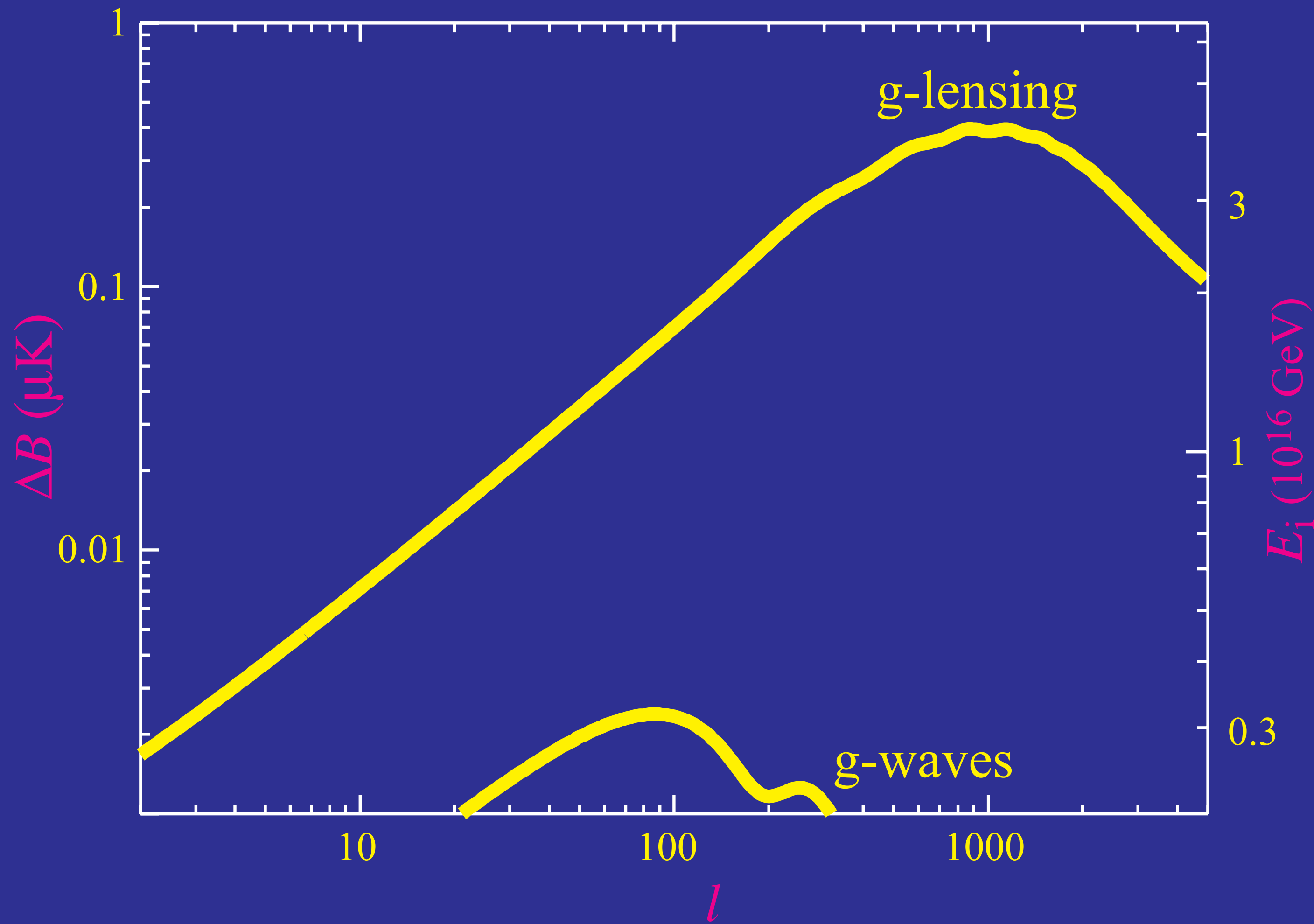
Scaling with Inflationary Energy Scale

- RMS B-mode signal scales with inflationary energy scale squared E_i^2



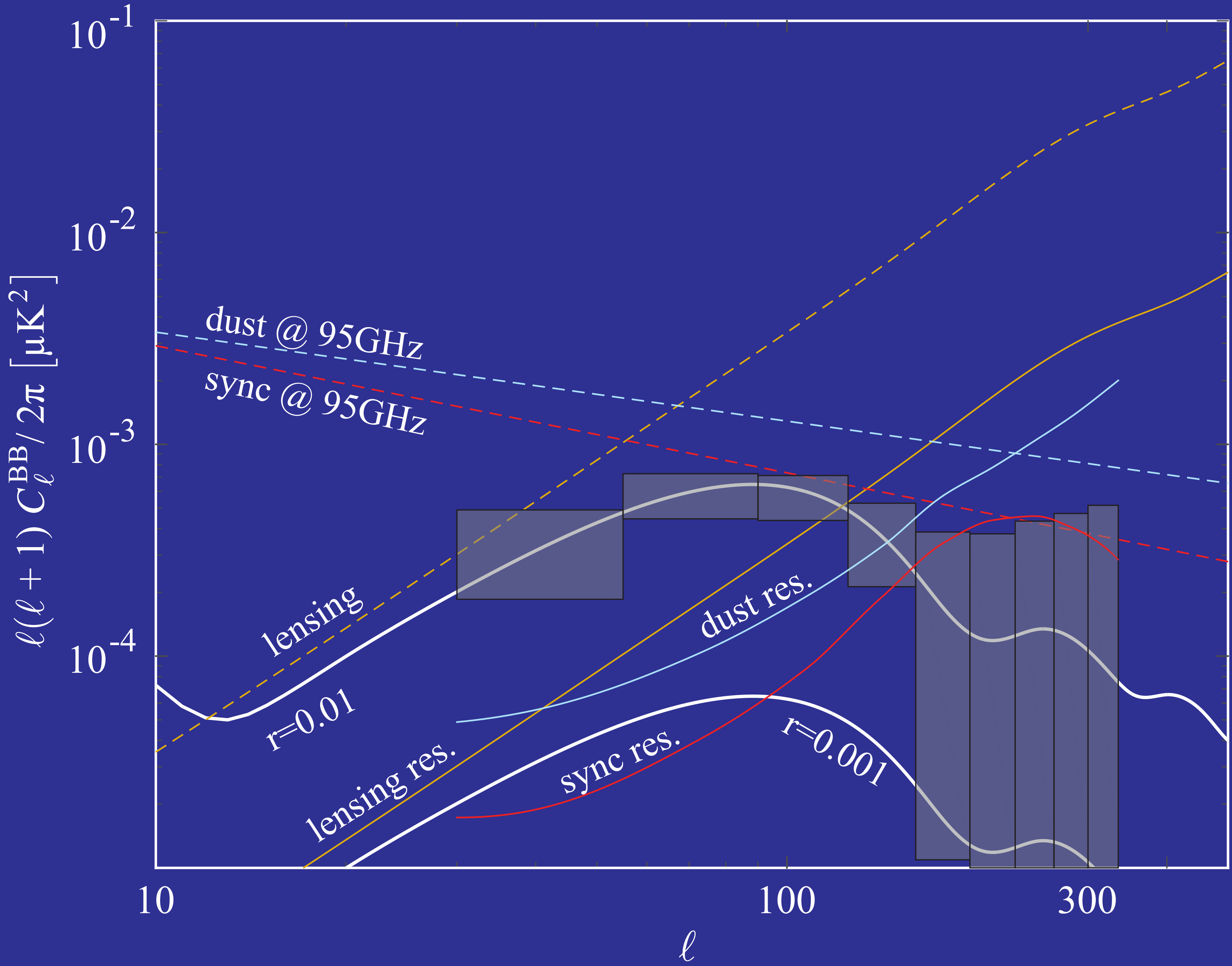
Contamination for Gravitational Waves

- Gravitational lensing contamination of B-modes from gravitational waves cleaned to $E_i \sim 0.3 \times 10^{16}$ GeV



Polarized Foregrounds

- Dust and synchrotron



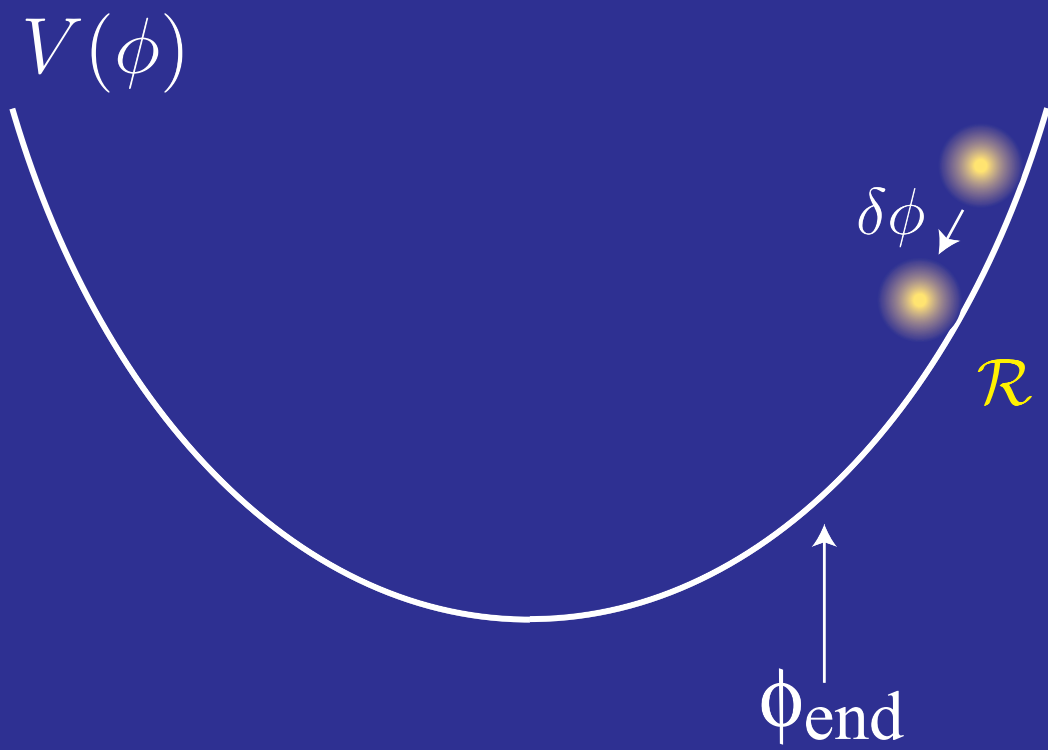
See Burigana's lectures

CMB S4 Science Book

Tensor-Scalar Ratio

- Unlike gravitational waves, inflaton fluctuations determine when inflation ends in a given patch, changing the scale factor or curvature
- Curvature power is enhanced by the slowness of the roll

$$\varepsilon = \frac{\dot{\phi}^2}{2H^2 M_{\rm pl}^2} \qquad \Delta_{\mathcal{R}}^2 = \frac{H^2}{8\pi^2 M_{\rm pl}^2 \varepsilon}$$



$$\mathcal{R} = -\frac{\delta a}{a} = -H\frac{\delta\phi}{\dot{\phi}}$$

Tensor-Scalar Ratio

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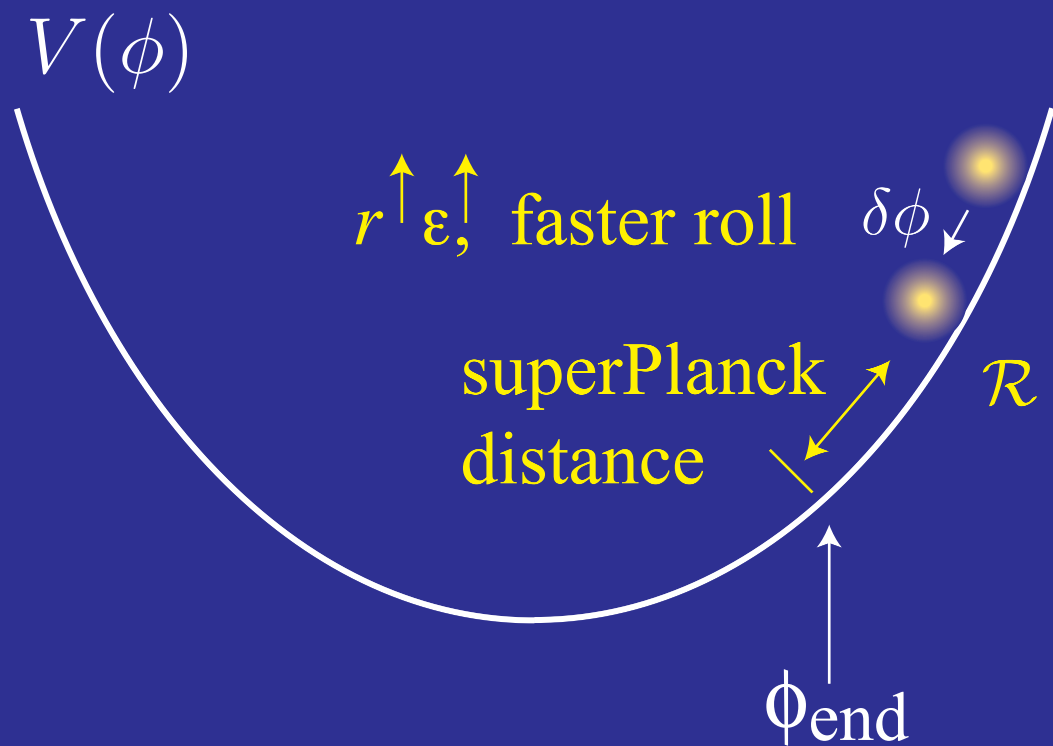


$$\mathcal{R} = -\frac{\delta a}{a} = -H\frac{\delta\phi}{\dot\phi}$$

Tensor-Scalar Ratio

- Tensor-scalar ratio r

$$r \equiv 4\frac{\Delta_+^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon$$

- A large r implies a large ϵ and a large roll

$$\epsilon = \frac{1}{2M_{\rm pl}^2}\left(\frac{d\phi}{d\ln a}\right)^2$$

- Observable scales span $d\ln a = d\ln k \sim 5$ so

$$\Delta\phi \approx 5\frac{d\phi}{d\ln a} = 5(r/8)^{1/2}M_{\rm pl} \approx 0.6(r/0.1)^{1/2}M_{\rm pl}$$

- For $r = 0.2$ the field must roll by at least $M_{\rm pl}$
- Difficult to protect the flat potential across this large a range in field space

$n_S - r$ Plane

- Scalar power spectrum depends on both H and ε, so its tilt:

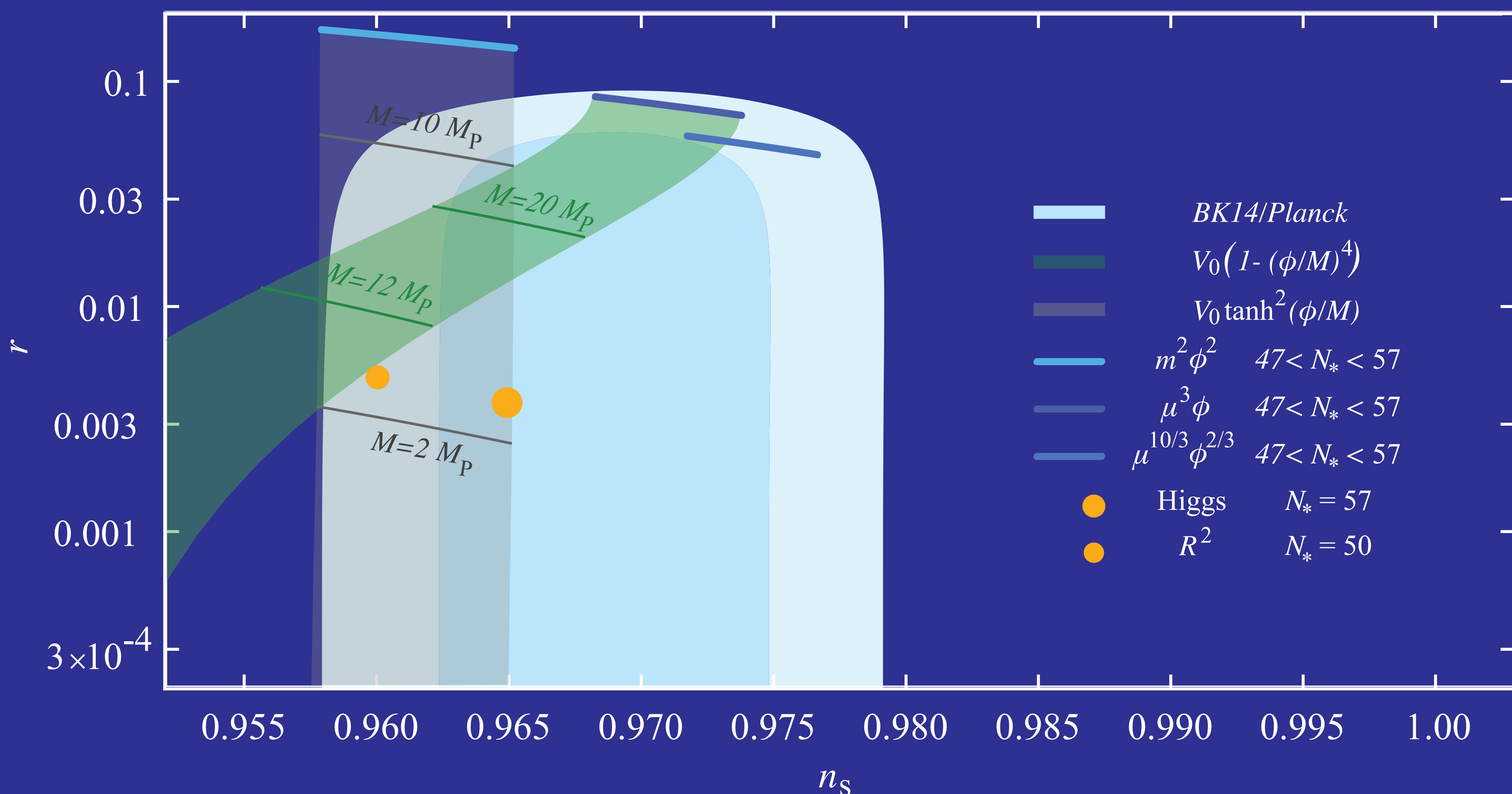
$$\frac{d\ln\Delta^2_{\mathcal{R}}}{d\ln k} \equiv n_S - 1$$
$$= 2\frac{d\ln H}{d\ln k} - \frac{d\ln\epsilon}{d\ln k} = -2\epsilon - \frac{d\ln\epsilon}{d\ln k}$$

- Measuring both $n_S - 1$ and r constrain the inflationary model
- In slow roll, related to derivatives of potential

$$\epsilon \approx \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$
$$\frac{d\ln\epsilon}{d\ln k} = 4\epsilon - 2M_{\rm pl}^2\frac{V''}{V}$$

r-n_s Trajectories and Constraints

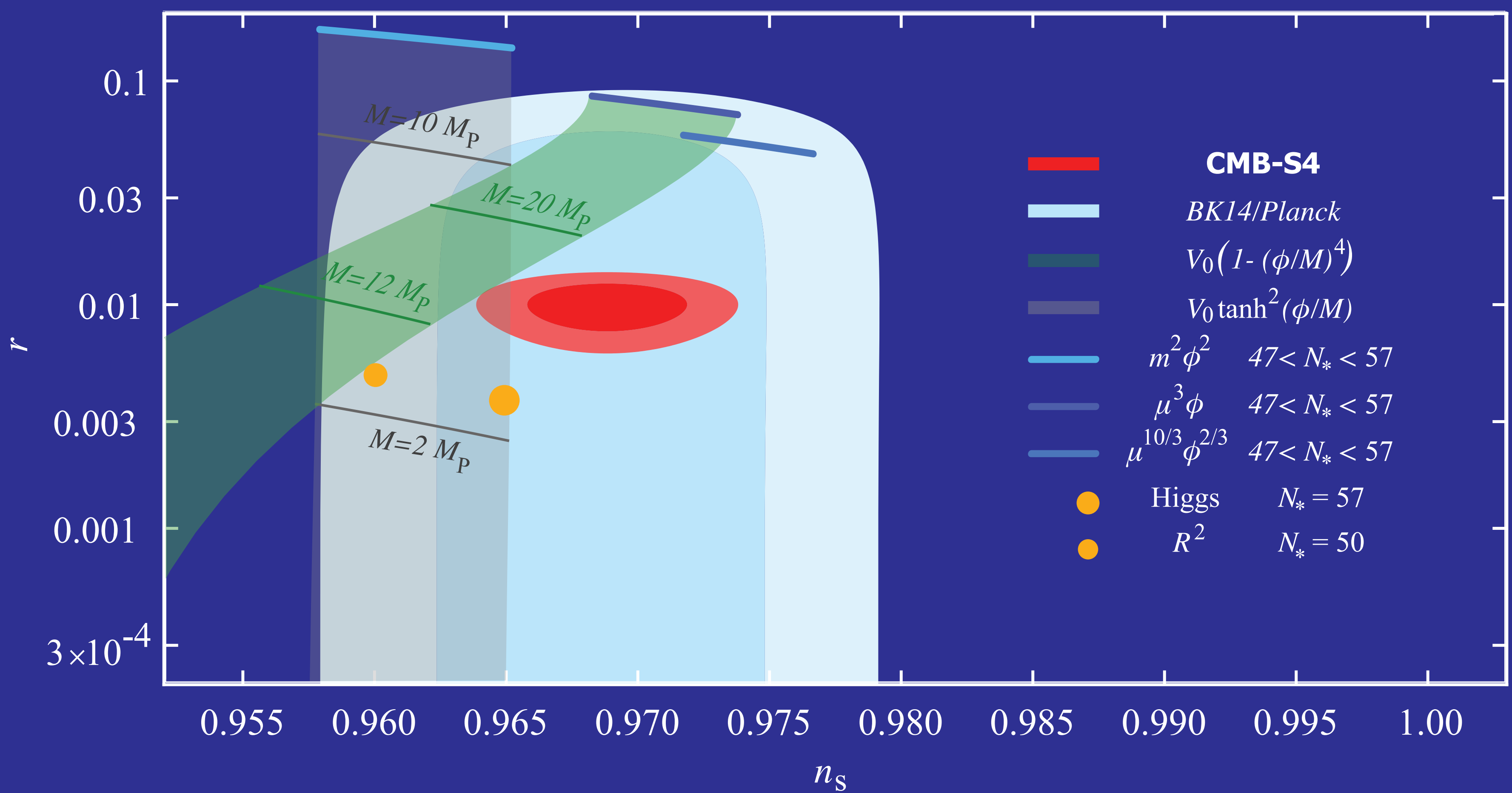
- Each inflationary model executes a trajectory in the plane
- Scale free models predict large tensors and large field excursions



CMB S4 Science Book

r-n_s Trajectories and Constraints

- Each inflationary model executes a trajectory in the plane
- Large improvements in r limits from B-modes, moderate improvement in n_s possible



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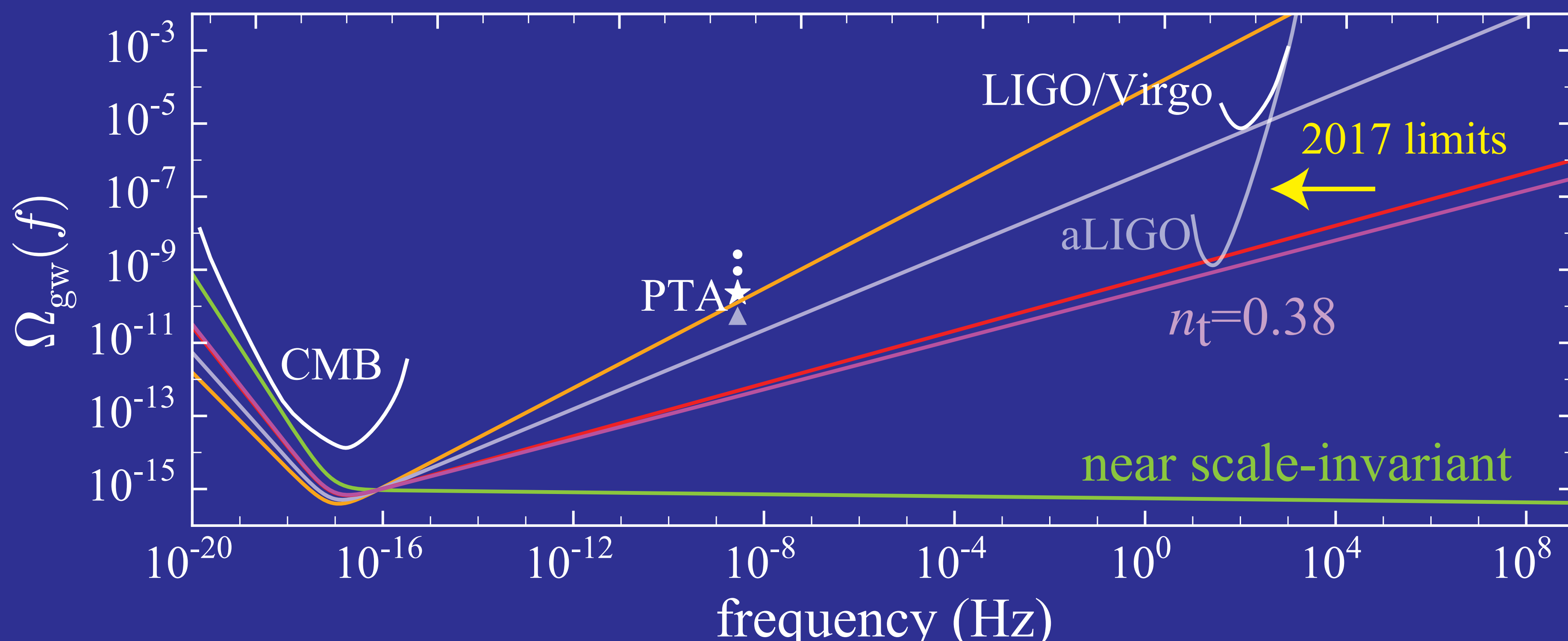
Inflationary GW Background

- Near scale invariant spectrum gives flat Ω contributions in radiation domination
- Blue tilted spectra directly constrained

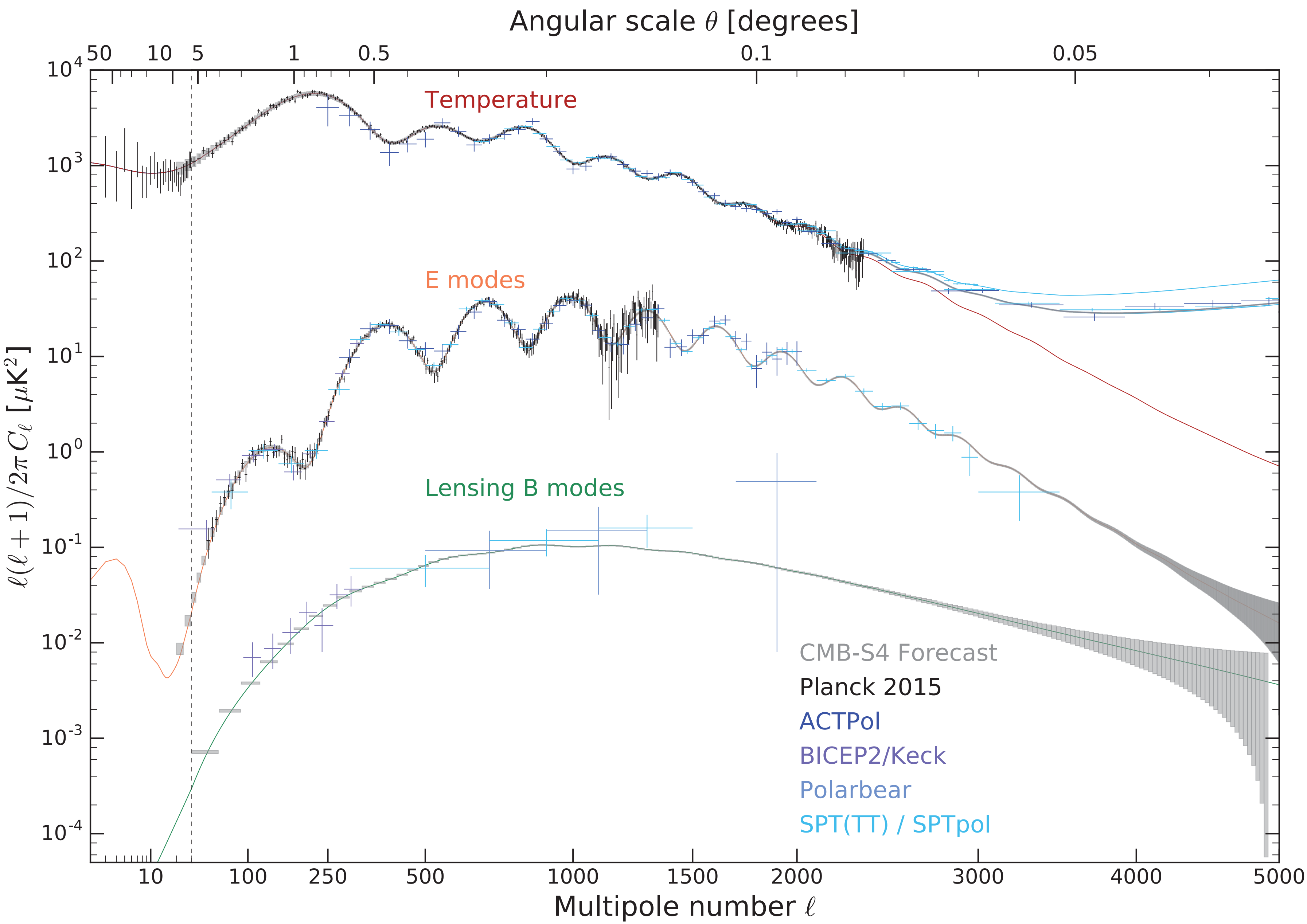


See Christensen's lectures

Lasky et al (2015)

Gravitational Lensing

CMB Power Spectra



Gravitational Lensing

- Lensing is a surface brightness conserving remapping of source to image planes by the gradient of the projected potential

$$\phi(\hat{\mathbf{n}}) = 2 \int \frac{dz}{H(z)} \frac{D_A(D_s - D)}{D_A(D)\, D_A(D_s)} \Phi(D_A \hat{\mathbf{n}}, D)\,,$$

  such that the fields are remapped as

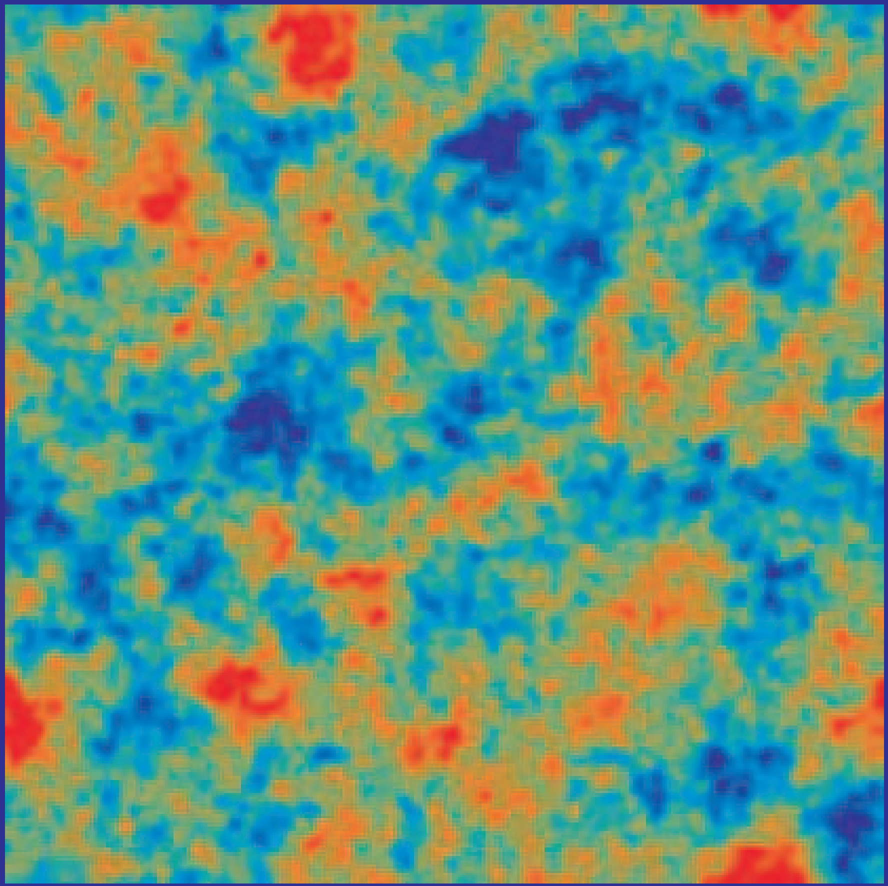
$$x(\hat{\mathbf{n}}) \to x(\hat{\mathbf{n}} + \nabla\phi)\,,$$

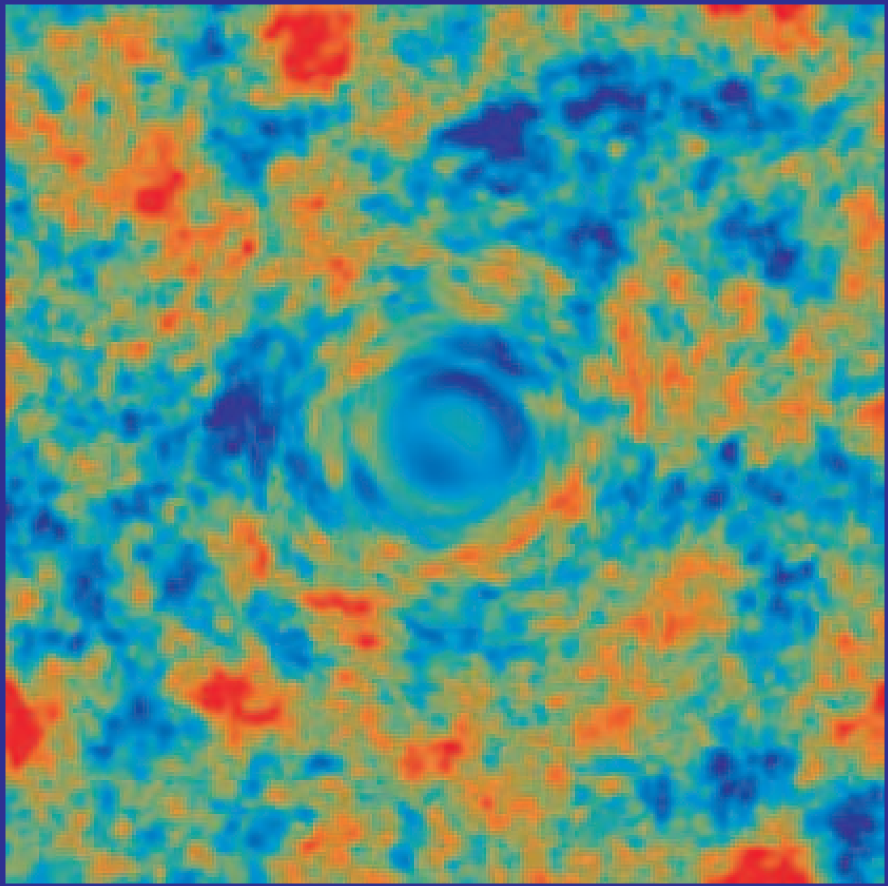
  where $x \in \{T, Q, U\}$ temperature and polarization.

- Taylor expansion leads to product of fields and Fourier mode-coupling
- Appears in the power spectrum as a convolution kernel for T and E and an $E \to B$.

Lensing of a Gaussian Random Field

- CMB temperature and polarization anisotropies are Gaussian random fields – unlike galaxy weak lensing
- Average over many noisy images – like galaxy weak lensing

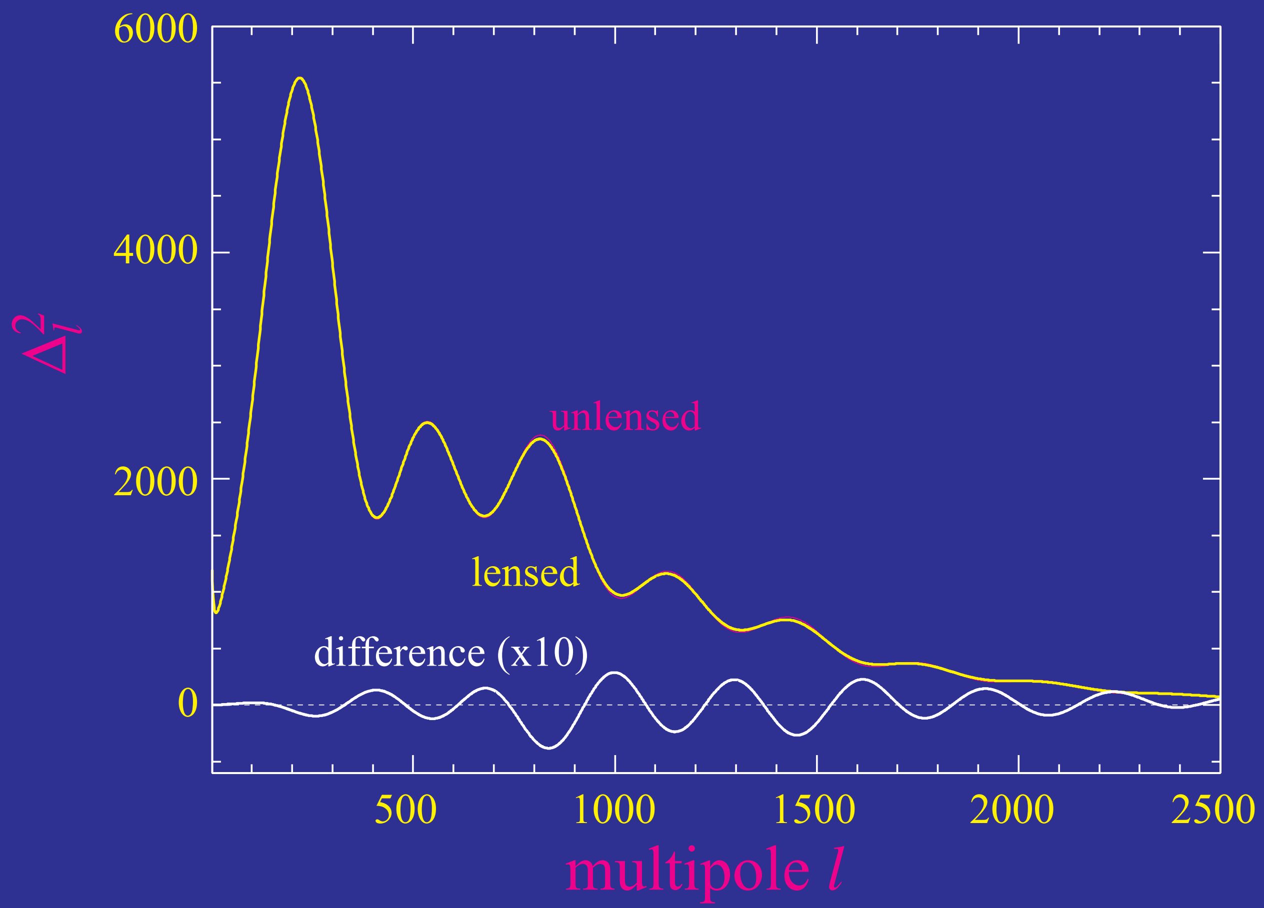




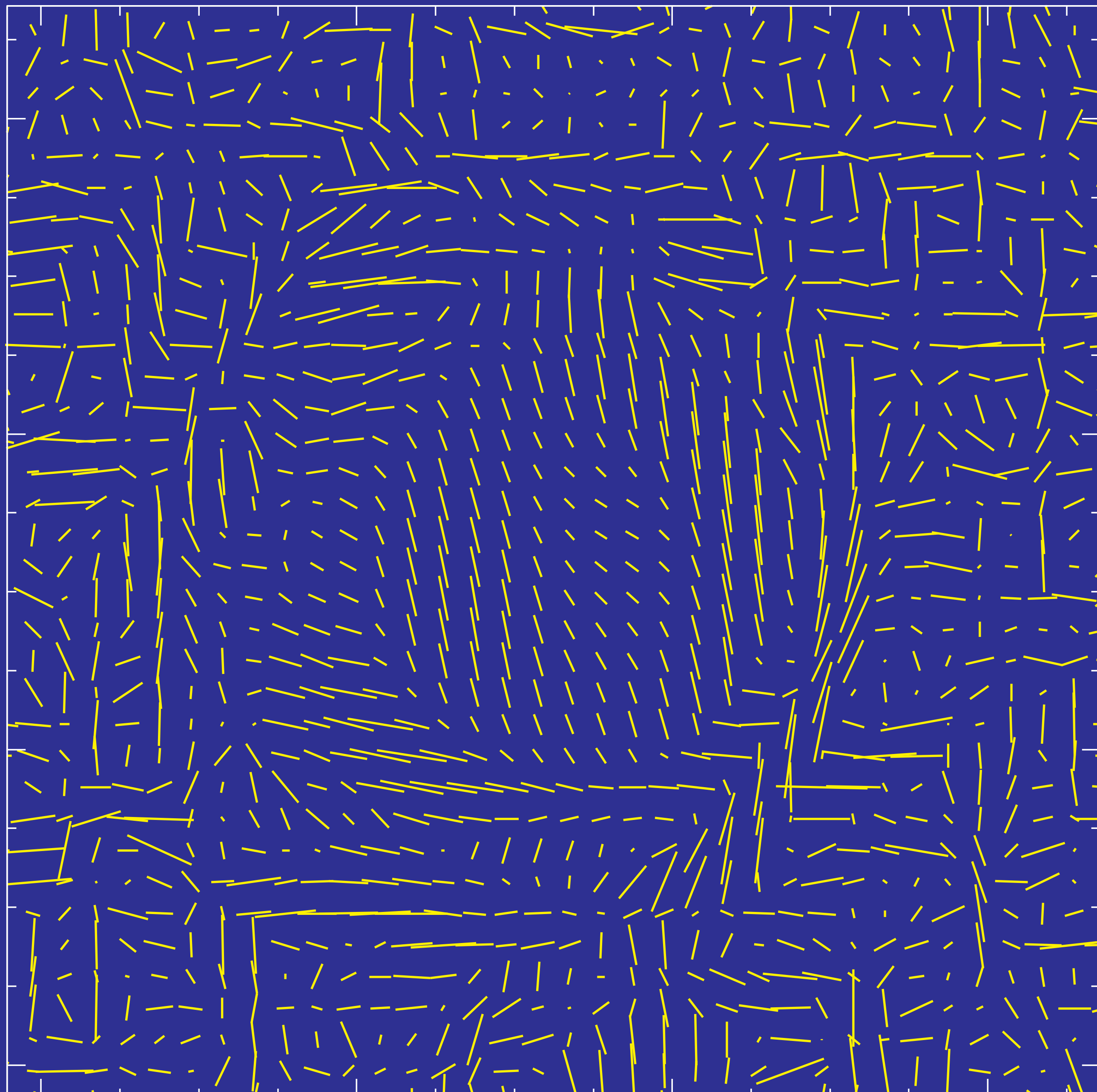
highly exaggerated: see Burigana's talk for realism

Temperature Power Spectrum

- Lensing acts to smooth temperature (and E polarization)peaks)
- Subtle effect reaches 10% deep in the damping tail
- Statistically detected at high significance

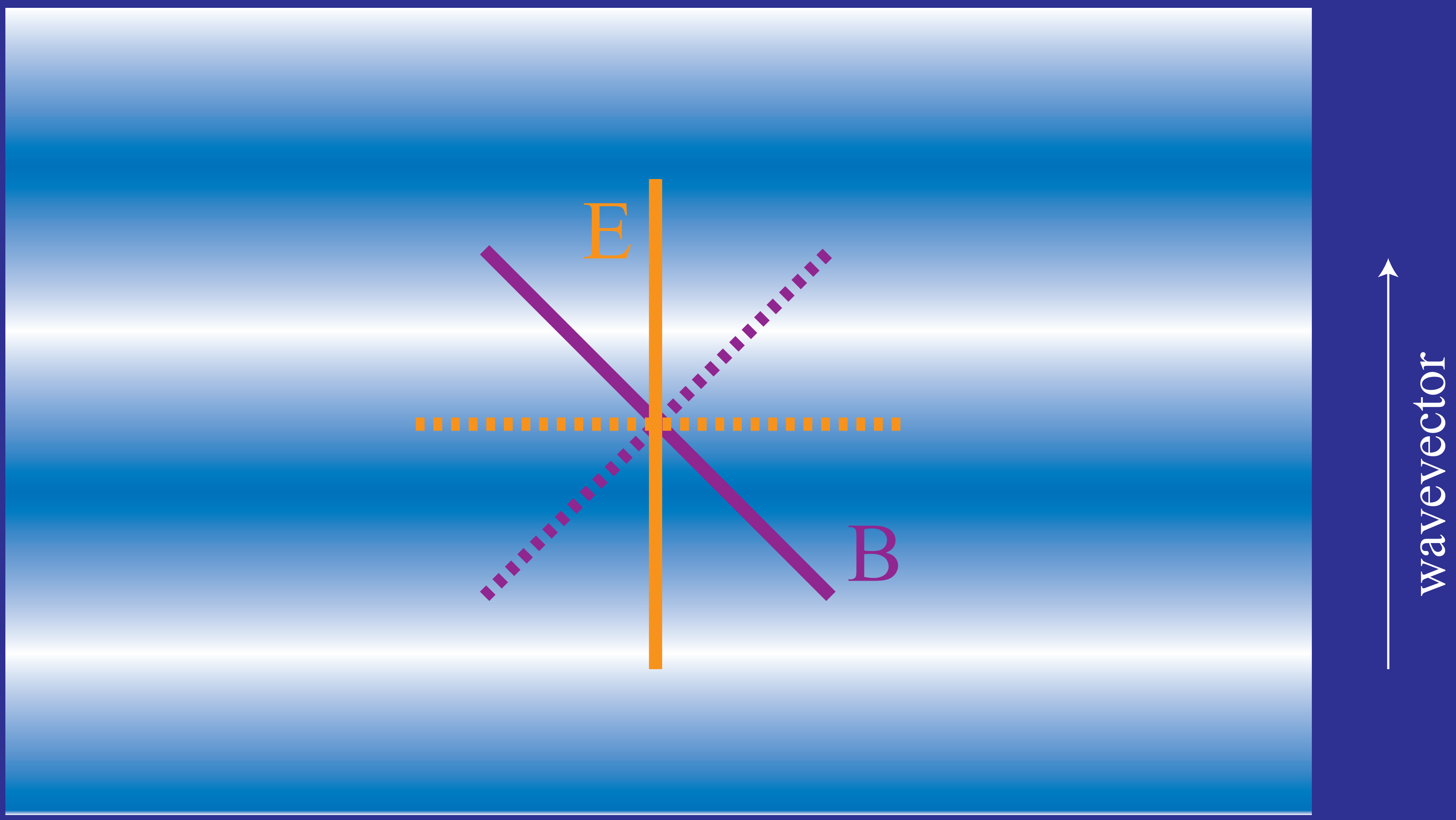


Polarization Lensing



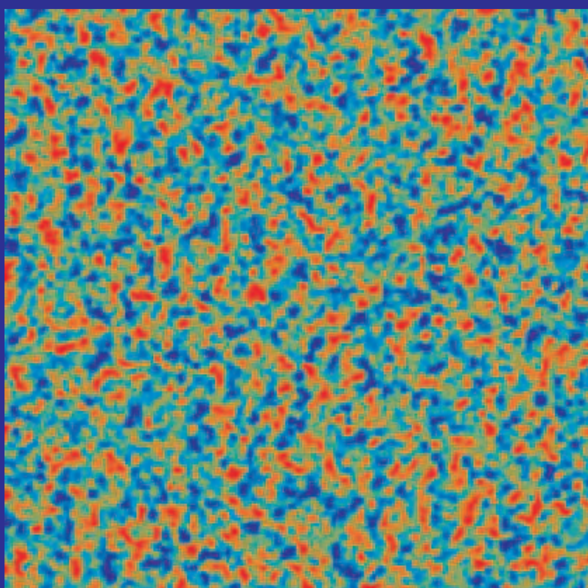
E and B modes

- E-modes are Stokes Q polarization in wavenumber basis
- B-modes are Stokes U polarization

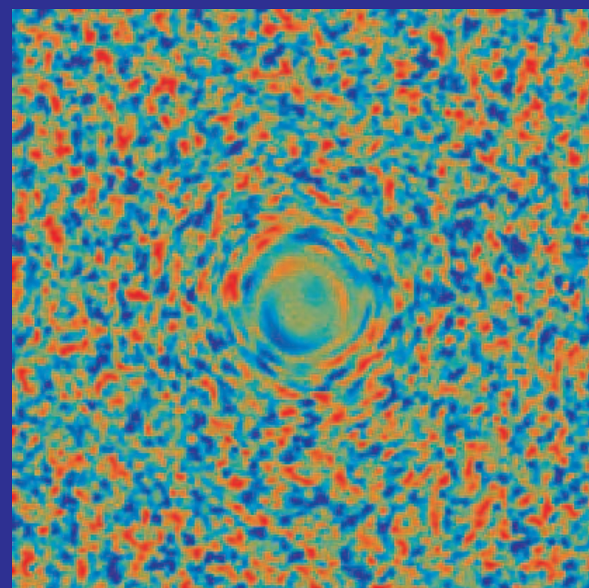


Polarization Lensing

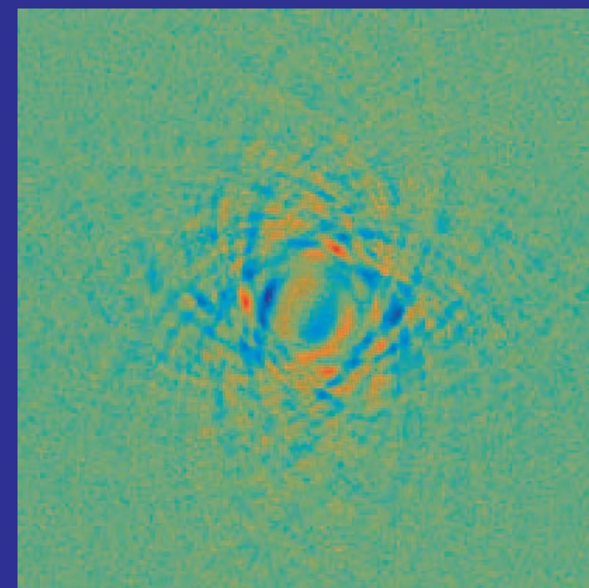
- Since E and B denote the relationship between the polarization amplitude and direction, warping due to lensing creates B-modes



Original



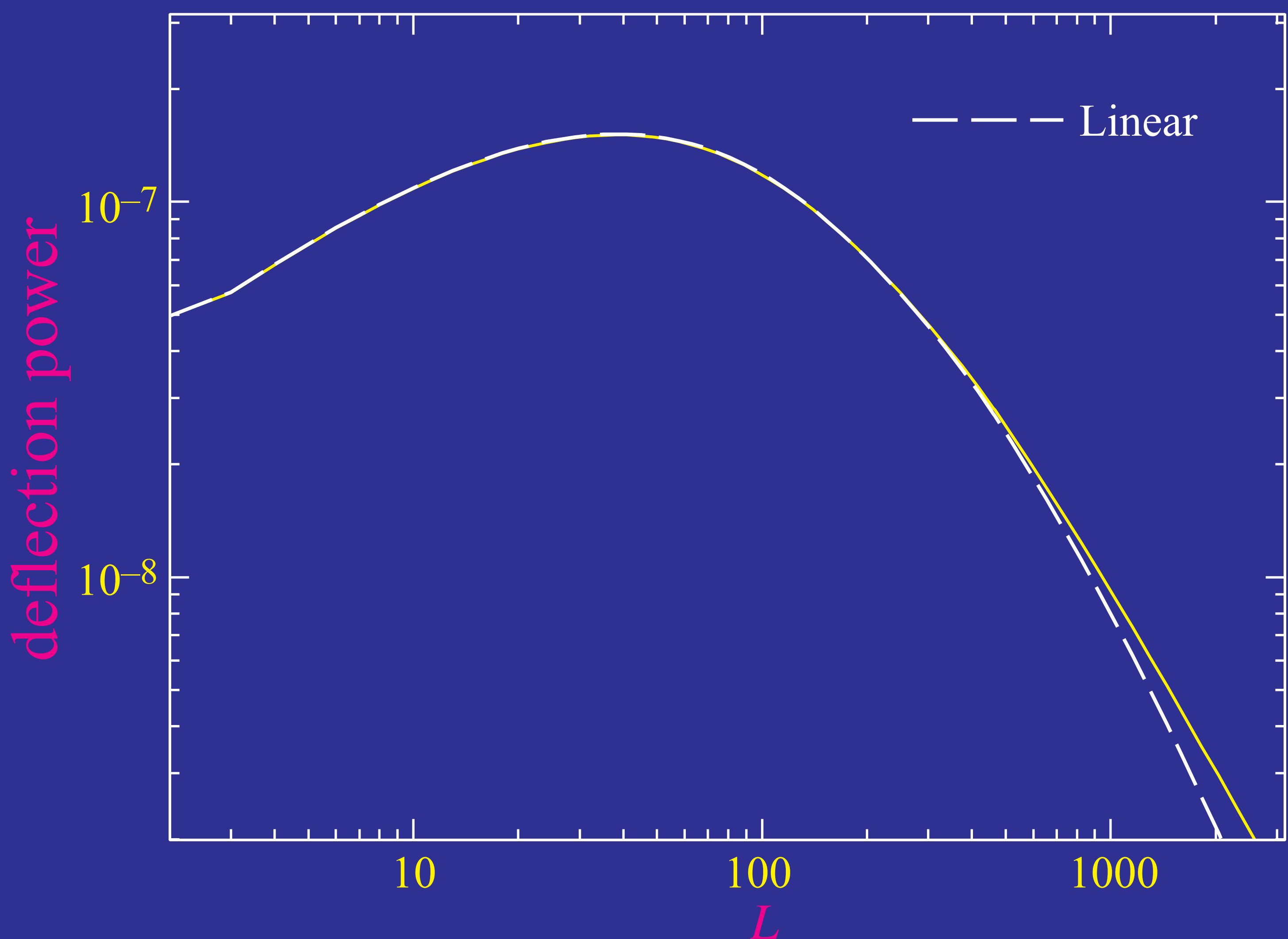
Lensed E



Lensed B

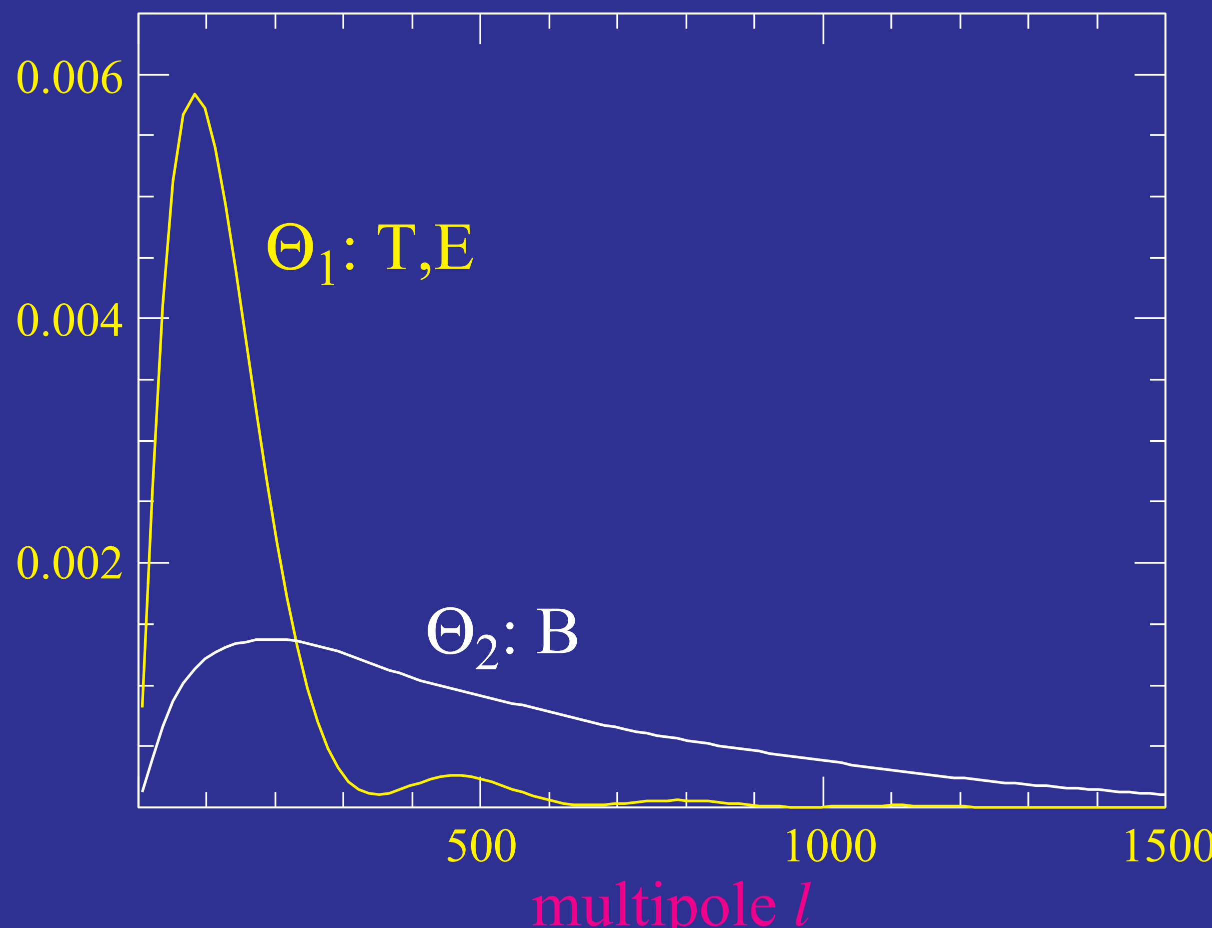
Deflection Power Spectrum

- Fundamental observable is deflection power spectrum (or convergence / l^2)
- Nearly entirely in linear regime



Lensed Power Spectrum Observables

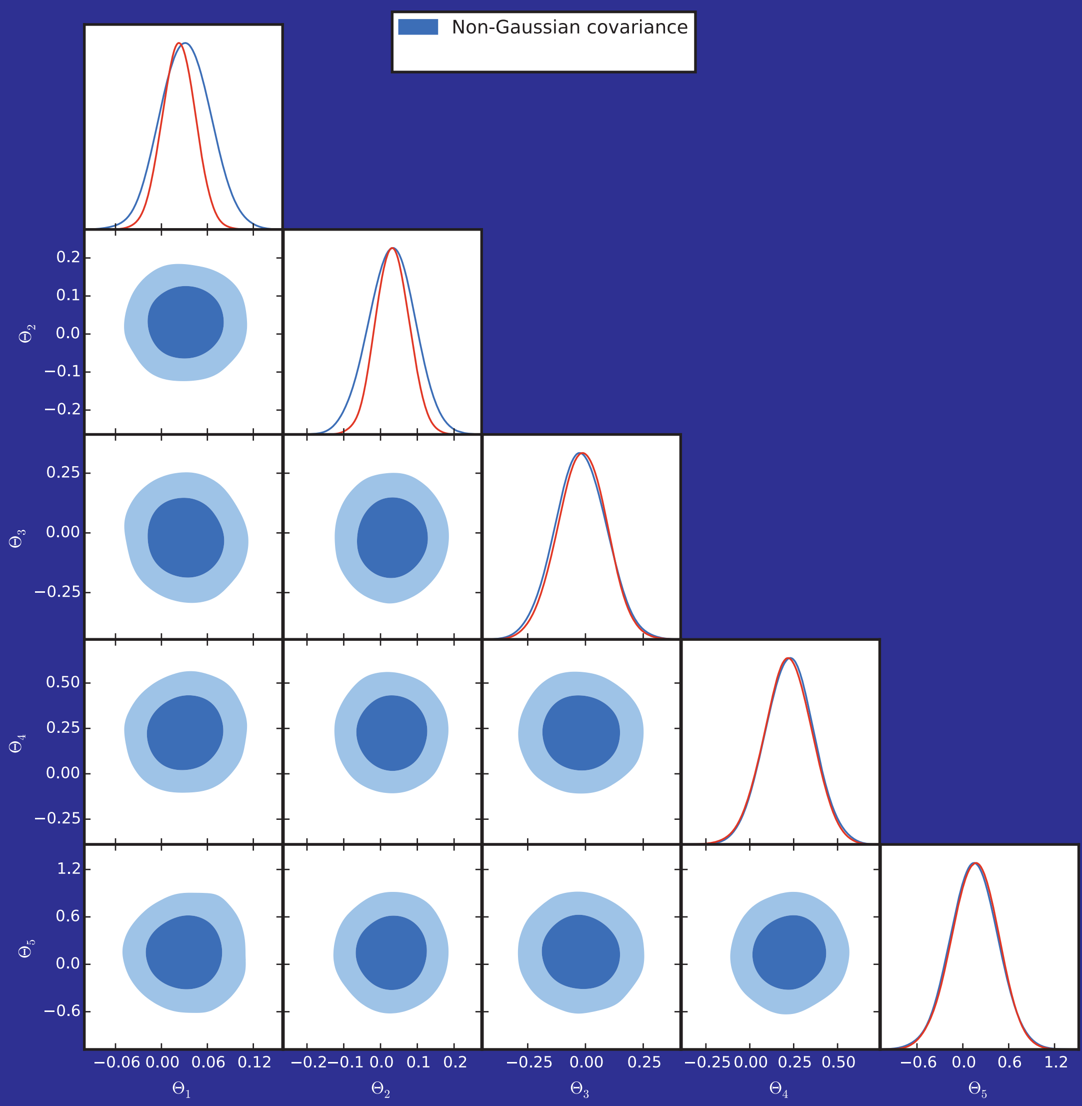
- Principal components show two observables in lensed power spectra
- Temperature and E-polarization: deflection power at *l*~100
  B-polarization: deflection power at *l*~500
- Normalized so that observables error = fractional lens power error



Smith, Hu & Kaplinghat (2006)

Principal in Practice

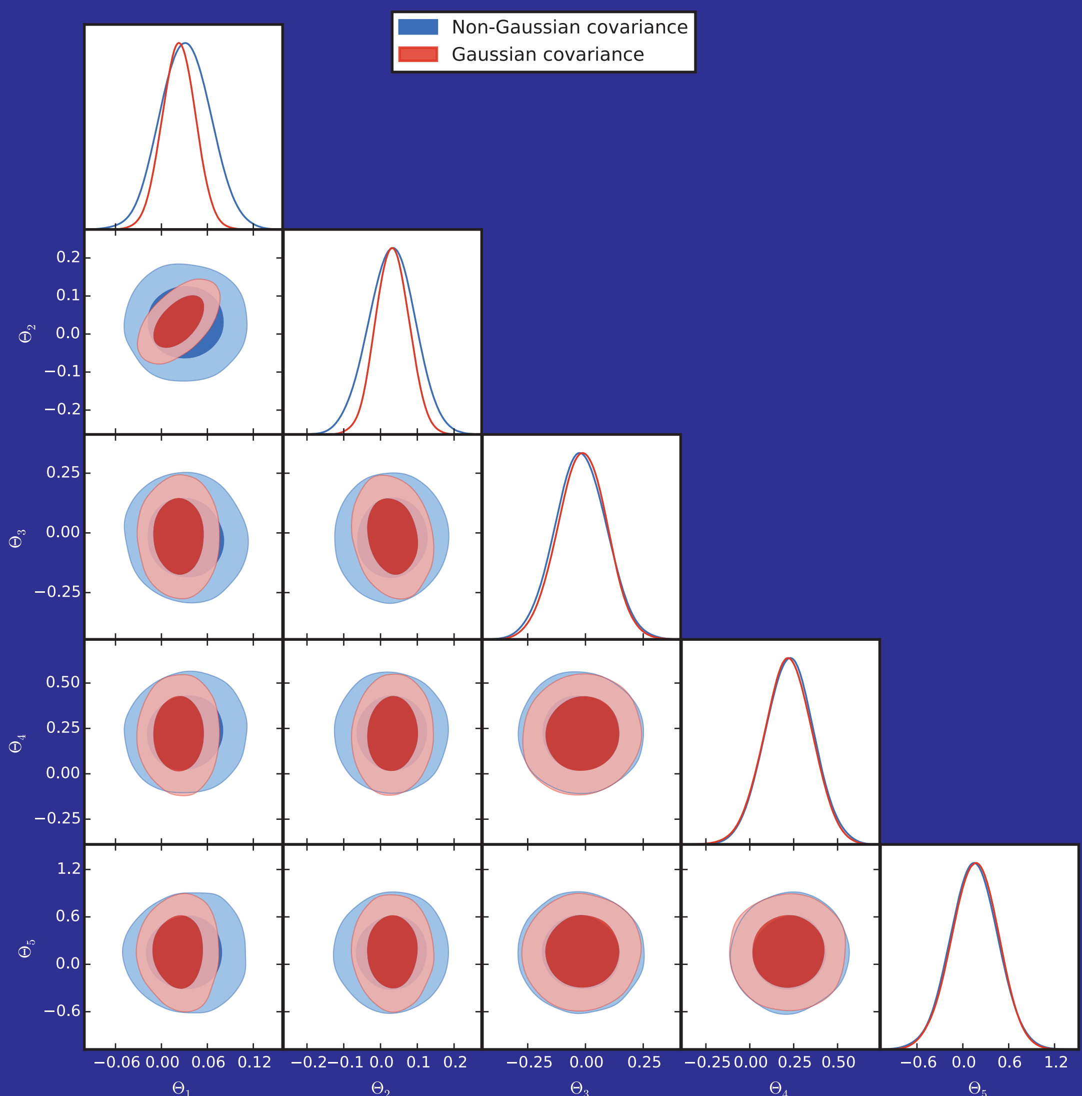
- Extracting principal components from LensPix simulated CMB temperature and polarization maps



Motloch & Hu (2017)

Principal in Practice

- Treating CMB maps as Gaussian leads to overly tight constraints and potentially misleading tension



Motloch & Hu (2017)

Mass Reconstruction

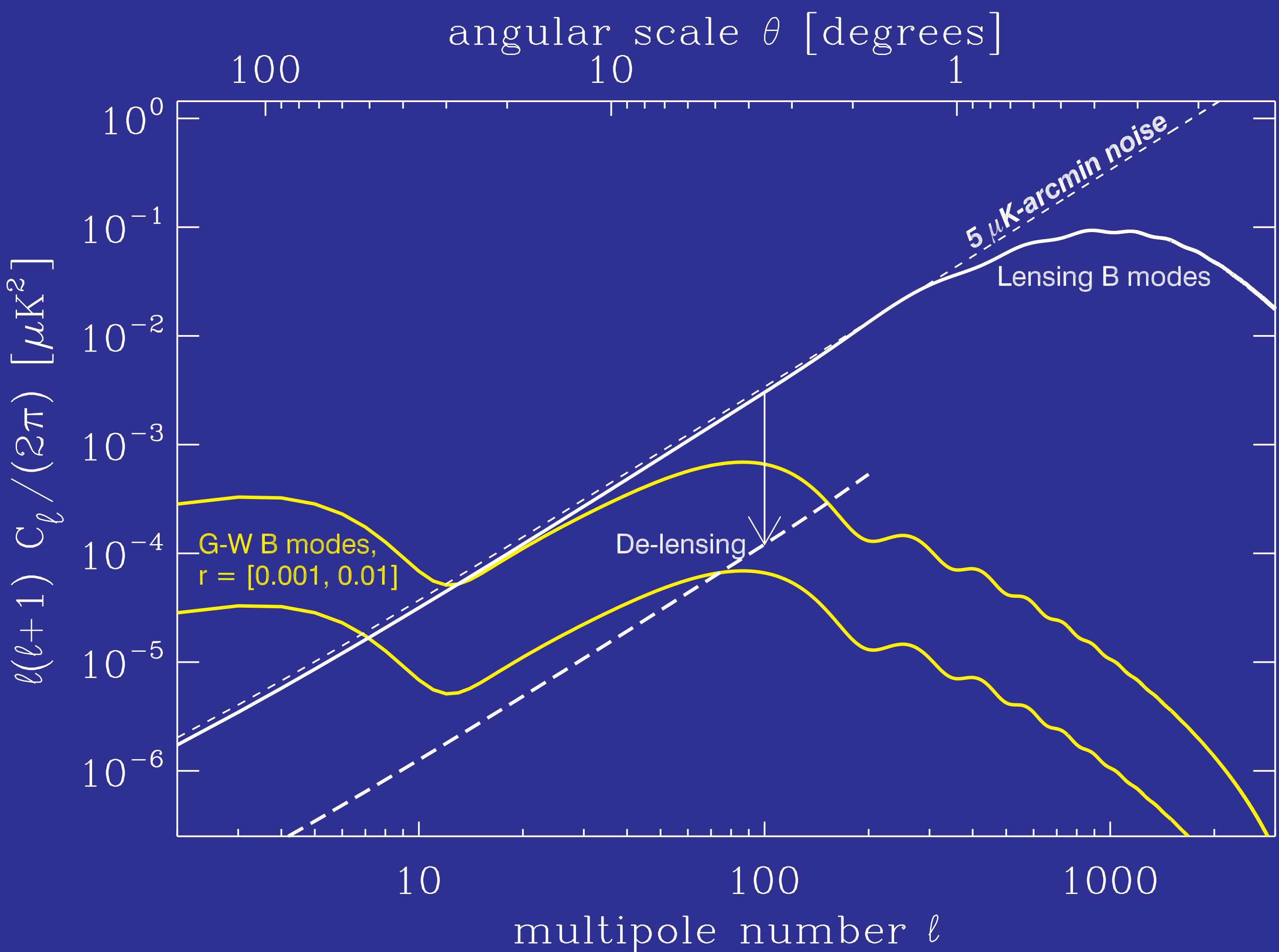
Why Care

- Gravitational lensing sensitive to amount and hence growth of structure
- Examples: massive neutrinos - $d\ln C_\ell^{BB}/dm_\nu \approx -1/3\mathrm{eV}$, dark energy - $d\ln C_\ell^{BB}/dw \approx -1/8$
- Mass reconstruction measures the large scale structure on large scales and the mass profile of objects on small scales
- Large scale delensing of the gravitational wave
- Lensing by high-z dark matter halos: mass calibration of clusters and cosmography (same lens, different sources)

See Simon White's Lectures

Lensing Contamination

- Lensing acts as cosmic noise that isn't Gaussian - delensing



Quadratic Estimator

- Taylor expand mapping

$$
\begin{aligned}
T(\hat{\mathbf{n}}) &= \tilde{T}(\hat{\mathbf{n}} + \nabla\phi) \\
&= \tilde{T}(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\tilde{T}(\hat{\mathbf{n}}) + \ldots
\end{aligned}
$$

- Fourier decomposition $\rightarrow$ mode coupling of harmonics

$$
\begin{aligned}
T(\mathbf{l}) &= \int d\hat{\mathbf{n}}\, T(\hat{\mathbf{n}}) e^{-il\cdot\hat{\mathbf{n}}} \\
&= \tilde{T}(\mathbf{l}) - \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} (\mathbf{l}-\mathbf{l}_1)\cdot\mathbf{l}_1\, \tilde{T}(\mathbf{l}_1)\phi(\mathbf{l}-\mathbf{l}_1)
\end{aligned}
$$

- Consider fixed lens and Gaussian random CMB realizations: each pair is an estimator of the lens at $\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$:

$$
\langle T(\mathbf{l})T'(\mathbf{l}')\rangle_{\mathrm{CMB}} \approx \left[\tilde{C}_{l_1}^{TT}(\mathbf{L}\cdot\mathbf{l}_1) + \tilde{C}_{l_2}^{TT}(\mathbf{L}\cdot\mathbf{l}_2)\right]\phi(\mathbf{L}) \quad (\mathbf{l} \neq -\mathbf{l}')
$$

Reconstruction from the CMB

- Generalize to polarization: each quadratic pair of fields estimates the lensing potential

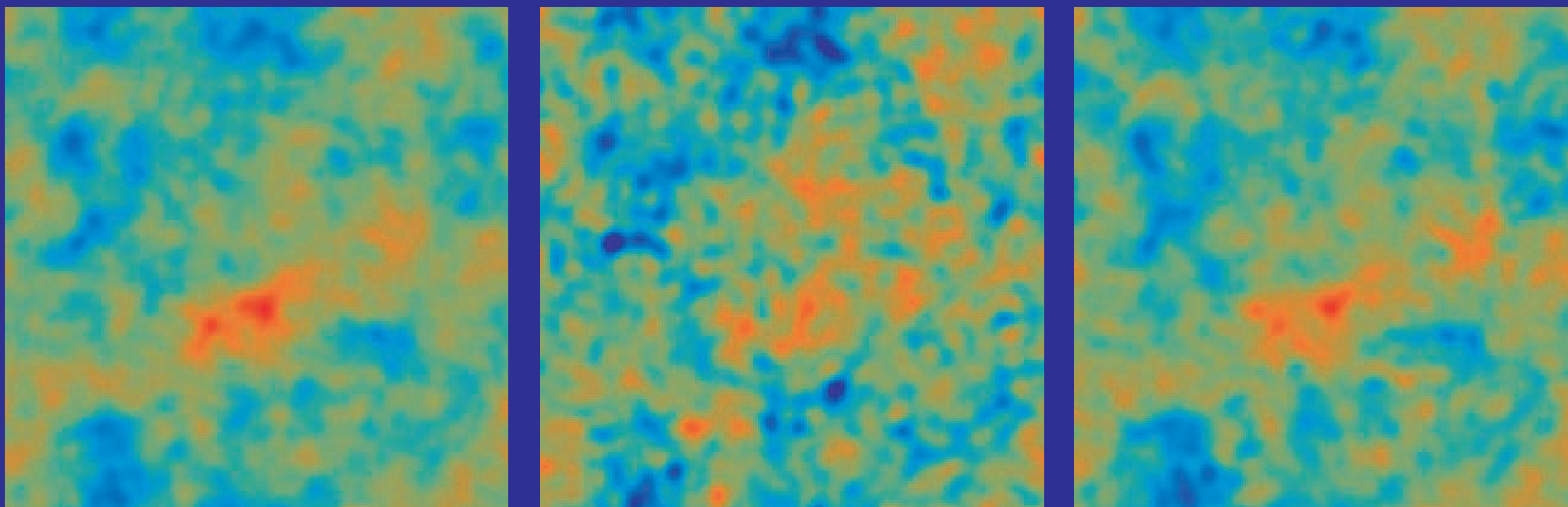
$$\langle x(\mathbf{l})x'(\mathbf{l}')\rangle_{\rm CMB} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(\mathbf{l}+\mathbf{l}')\,,$$

  where $x \in$ temperature, polarization fields and f_α is a fixed weight that reflects geometry

- Each pair forms a noisy estimate of the potential or projected mass - just like a pair of galaxy shears
- Minimum variance weight all pairs to form an estimator of the lensing mass
- Generalize to inhomogeneous noise, cut sky and maximum likelihood by iterating the quadratic estimator

High Signal-to-Noise B-modes

- Cosmic variance of CMB fields sets ultimate limit for T,E
- B-polarization allows mapping to finer scales and in principle is not limited by cosmic variance of E



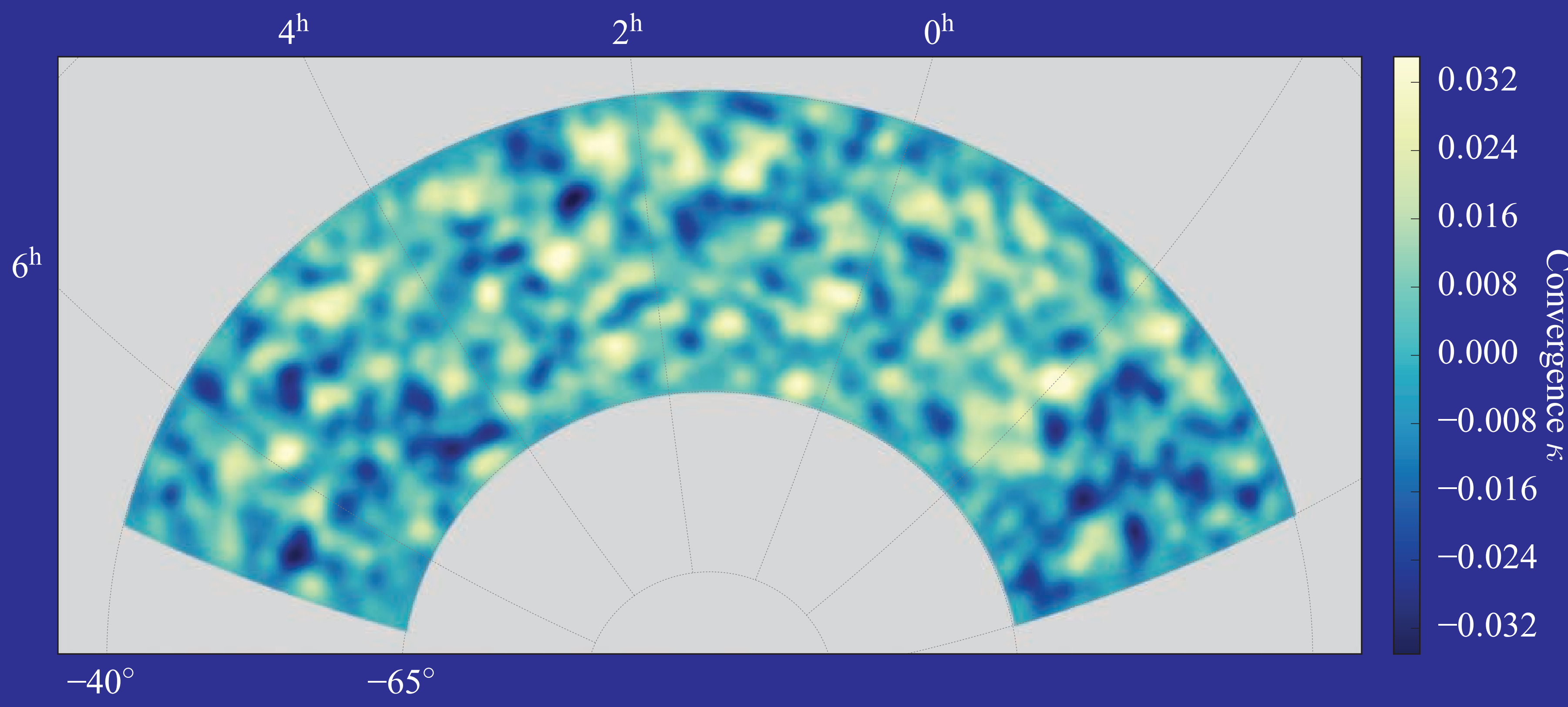
mass   temp. reconstruction   EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2001)

Lensing Reconstruction

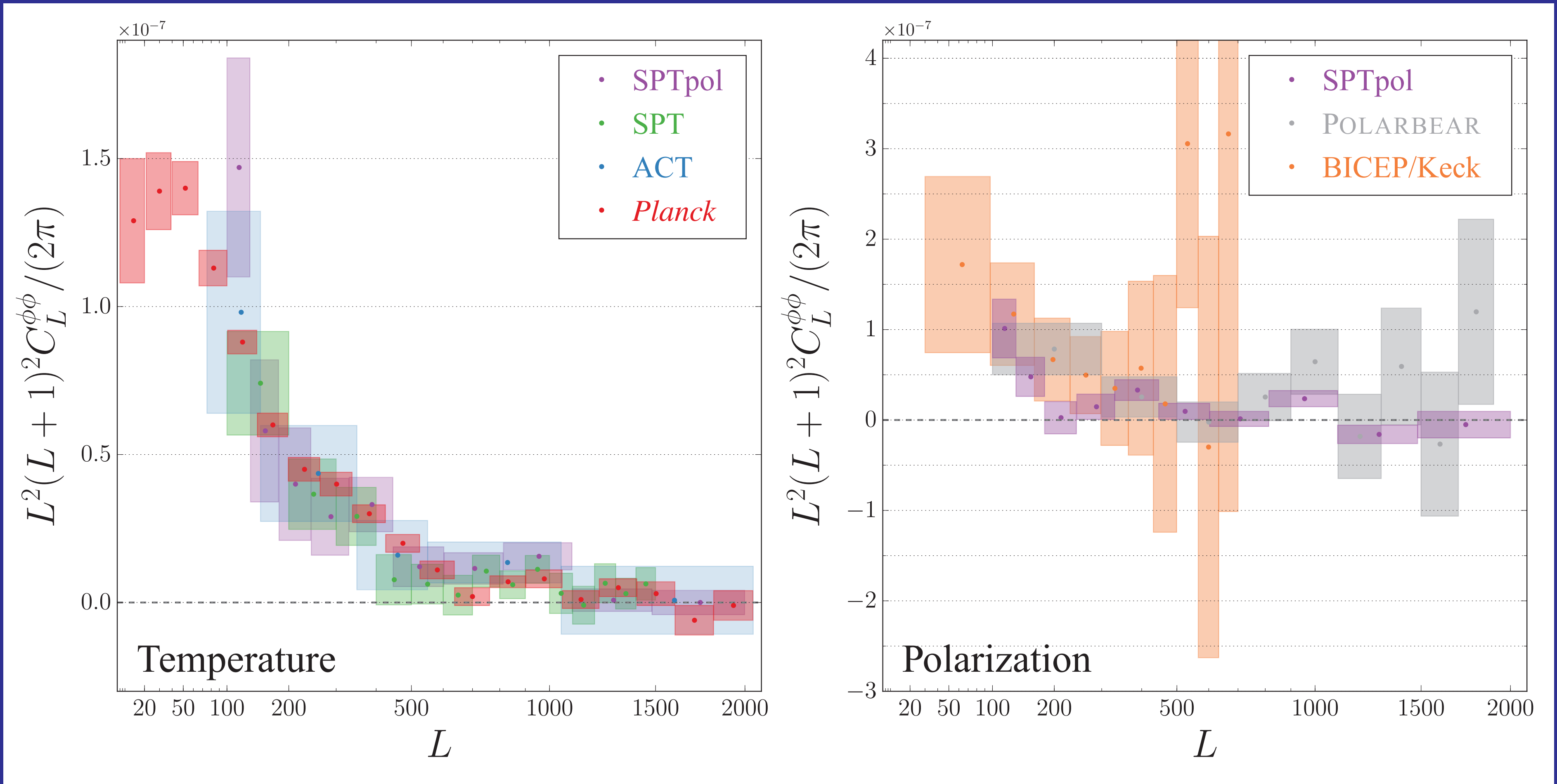
- SPT+Planck example



Omori et al (2017)

Lens Power Spectra

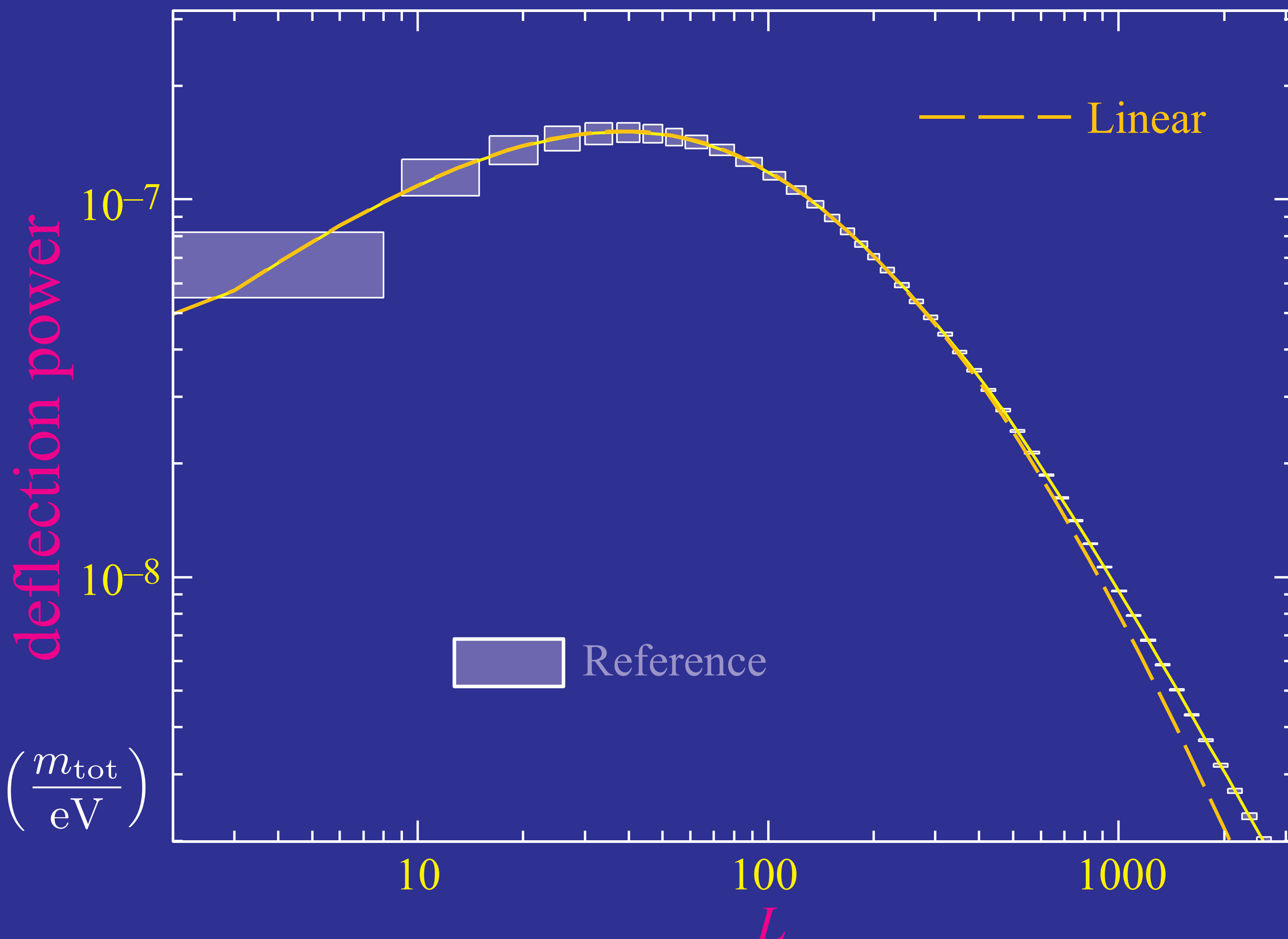
- Temperature and polarization reconstruction



CMB S4 Science Book

Matter Power Spectrum

- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime 0.002< k < 0.2 h/Mpc

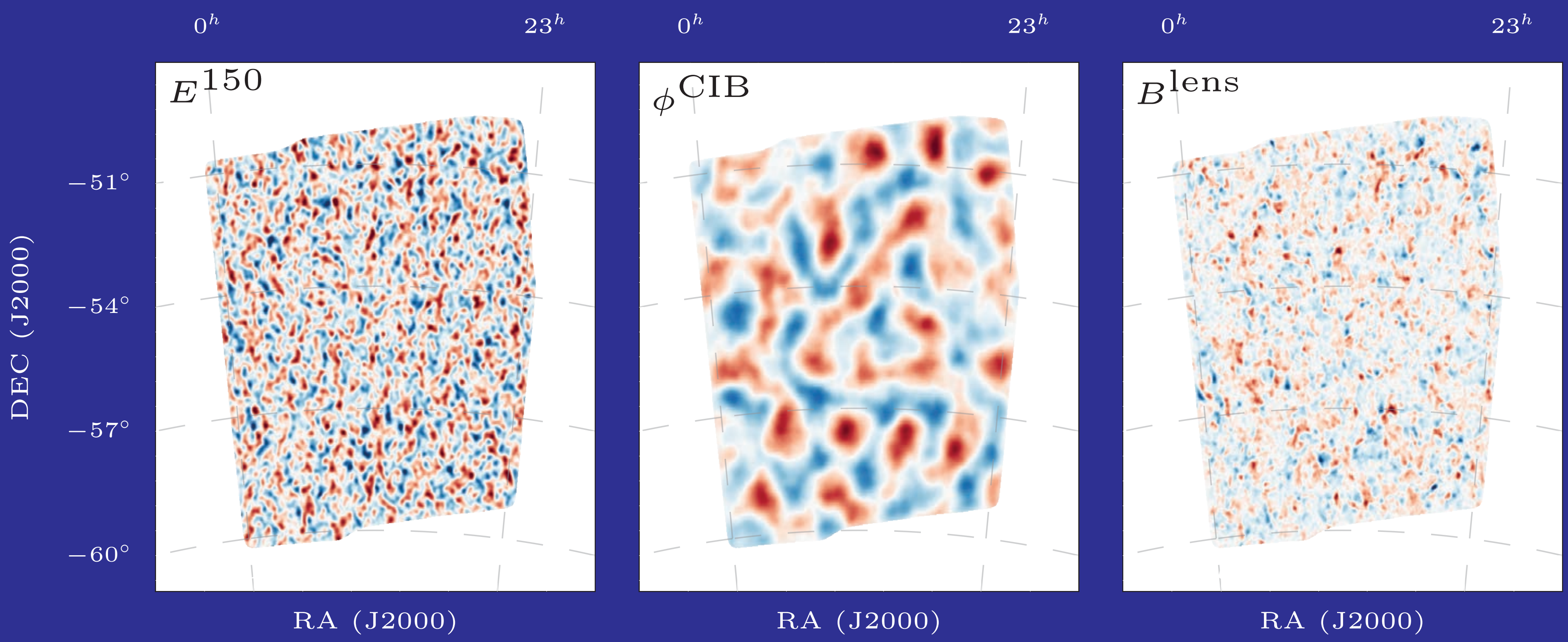


$$\frac{\Delta P}{P} \approx -0.6 \left(\frac{m_{\rm tot}}{\rm eV} \right)$$

Hu & Okamoto (2001)

Delensing with External Template

- Herschel CIB data as tracer of lensing
- Predict and subtract B-mode contamination - SPT example



Manzotti et al (2017)

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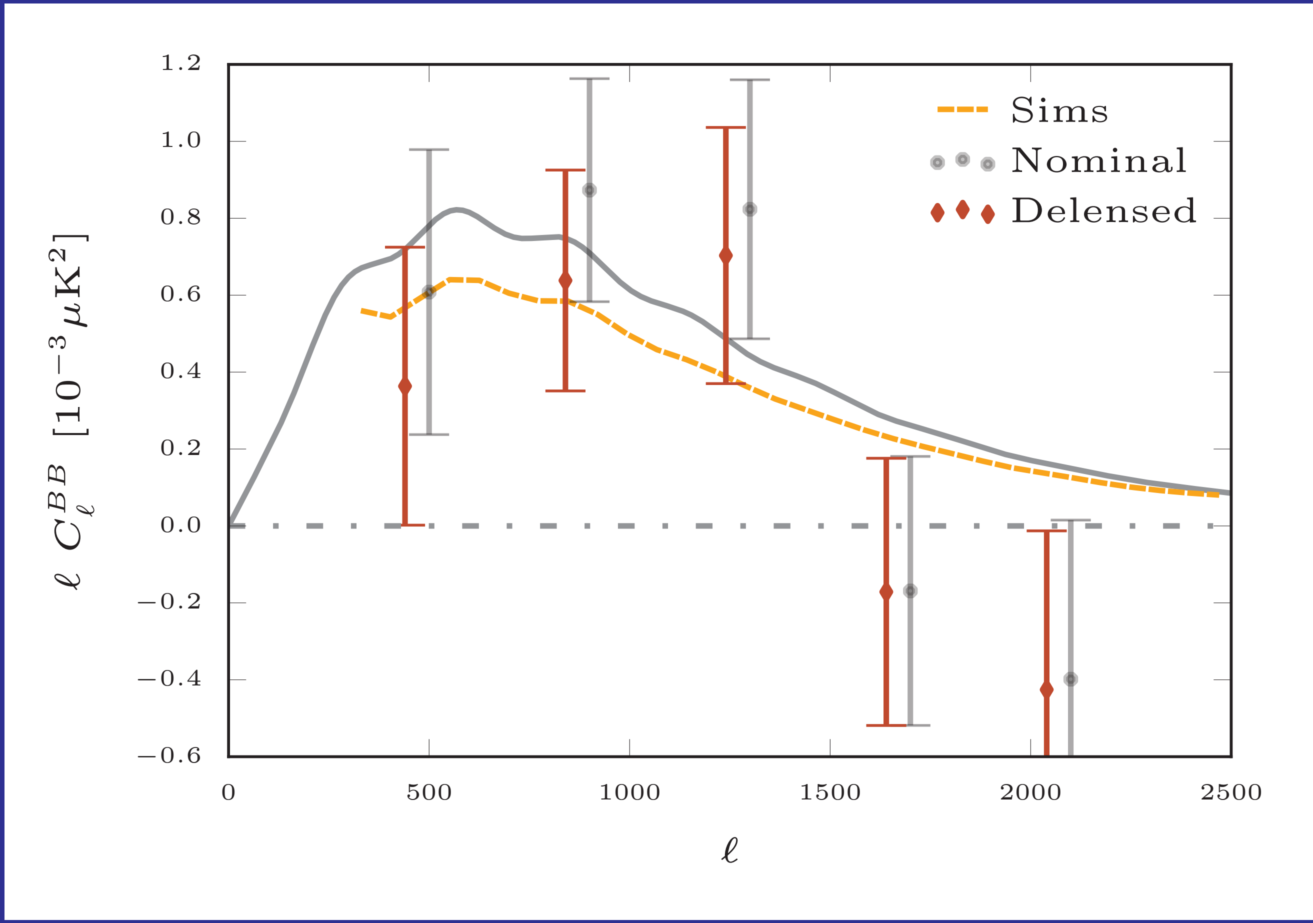
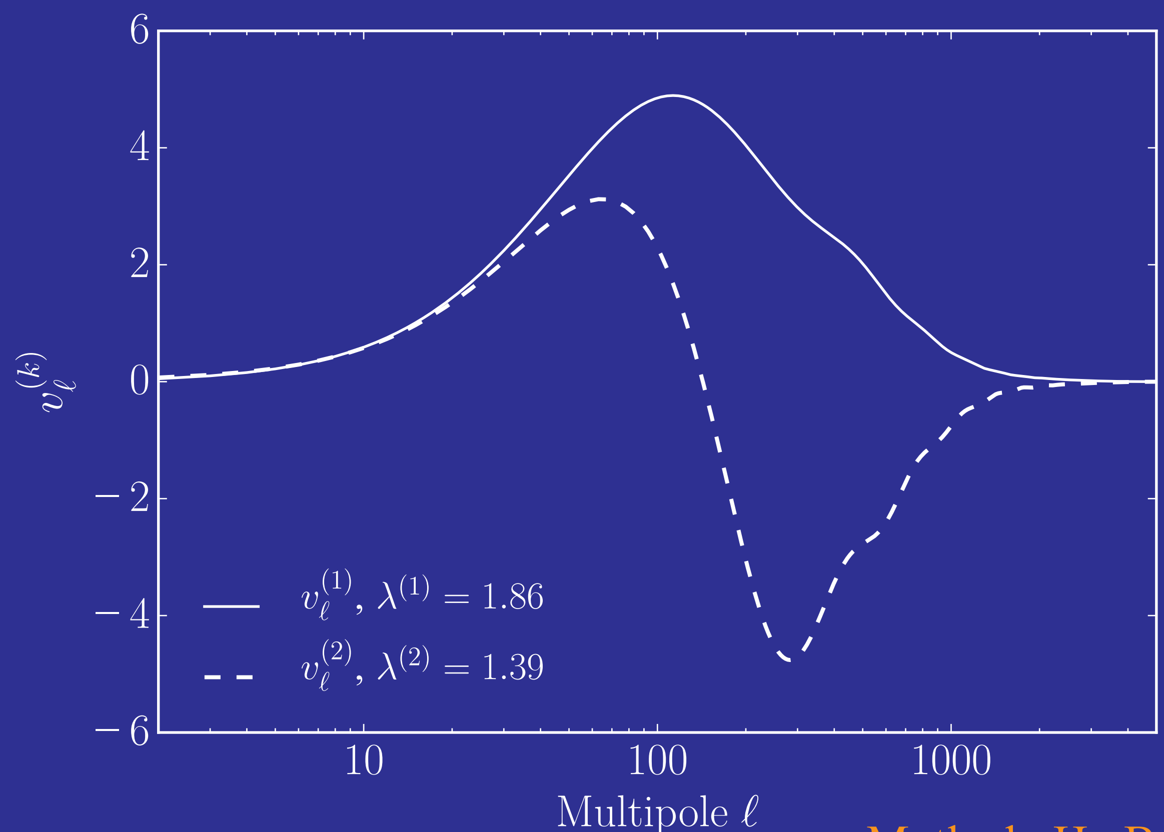


Manzotti et al (2017)

Consistency in Lens Observables

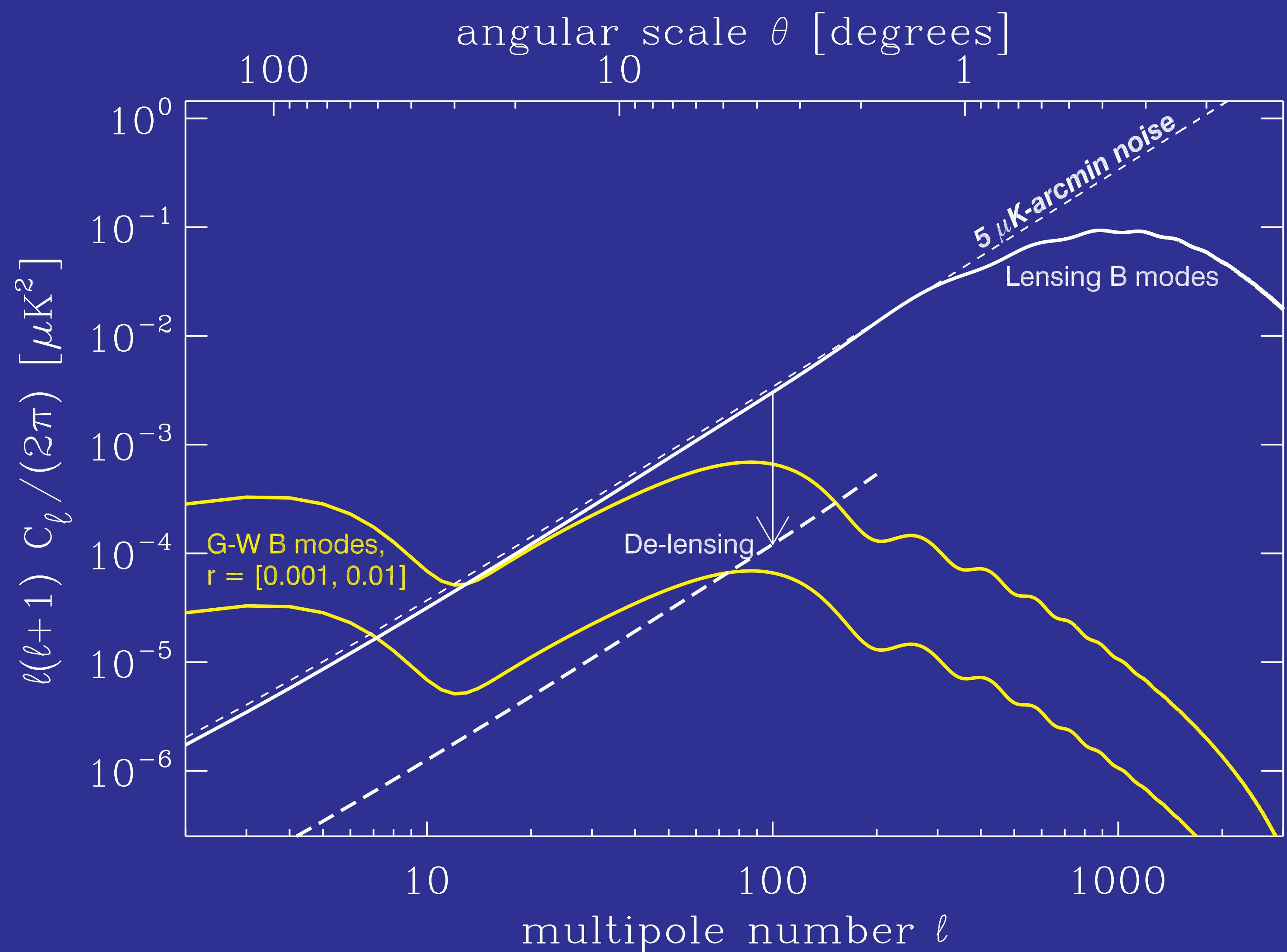
- Consistency between lensed CMB power spectra and lensing reconstruction critical for delensing
- Compare directly lens power spectrum information in model independent and nearly sample variance free way (consistency modes: a more precise A_{lens} test)



Motloch, Hu,Benoit-Levy (2017)

Delensing Goals

- Lensing noise isn't Gaussian, may be removed to uncover *r*

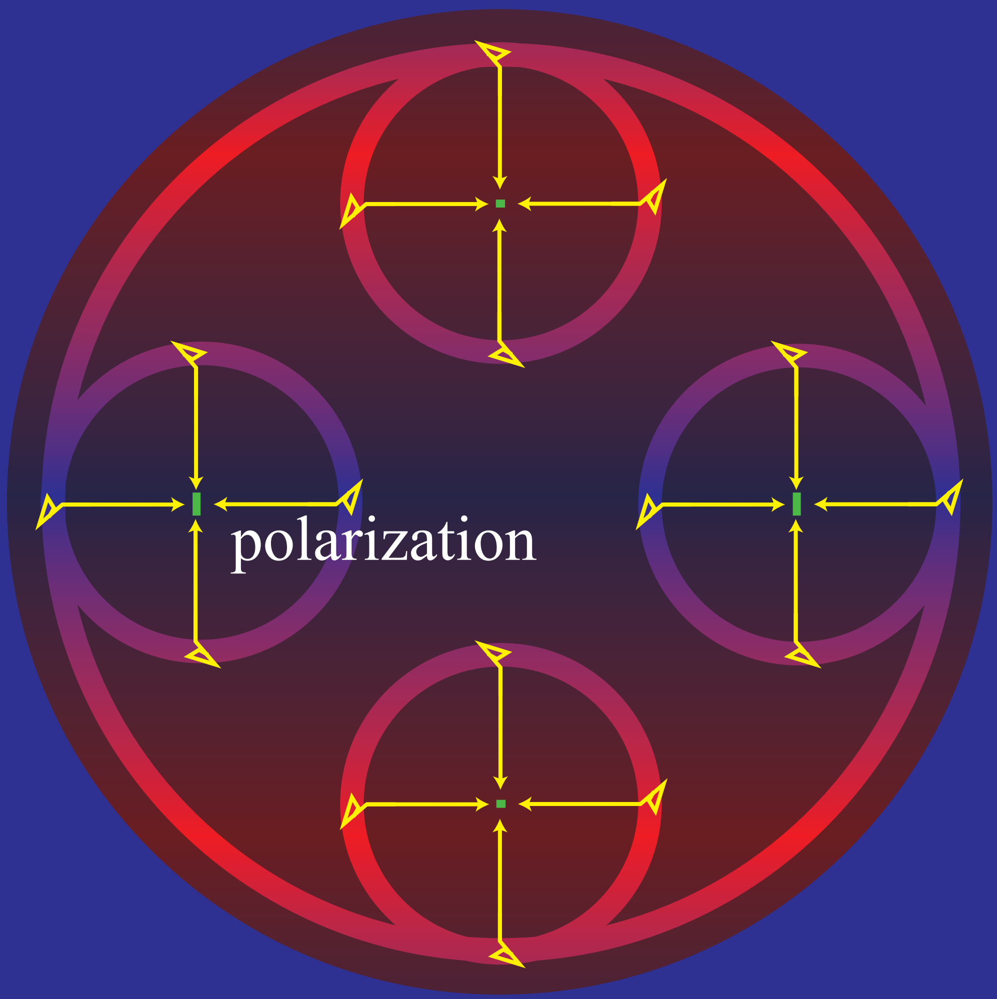


CMB S4 Science Book

Reionization

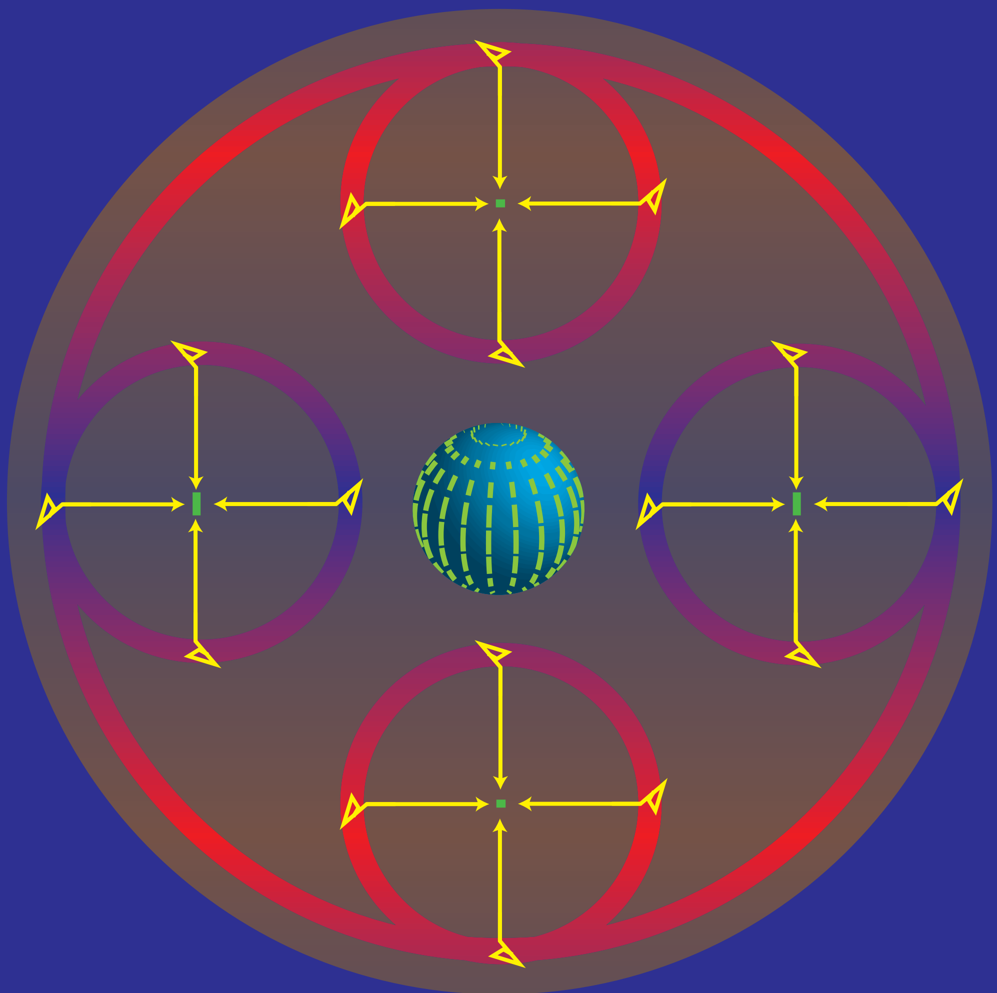
Polarization Anisotropy

- Electron sees the temperature anisotropy on its recombination surface and scatters it into a polarization



Temperature Correlation

- Pattern correlated with the temperature anisotropy that generates it; here an m=0 quadrupole



Why Care?

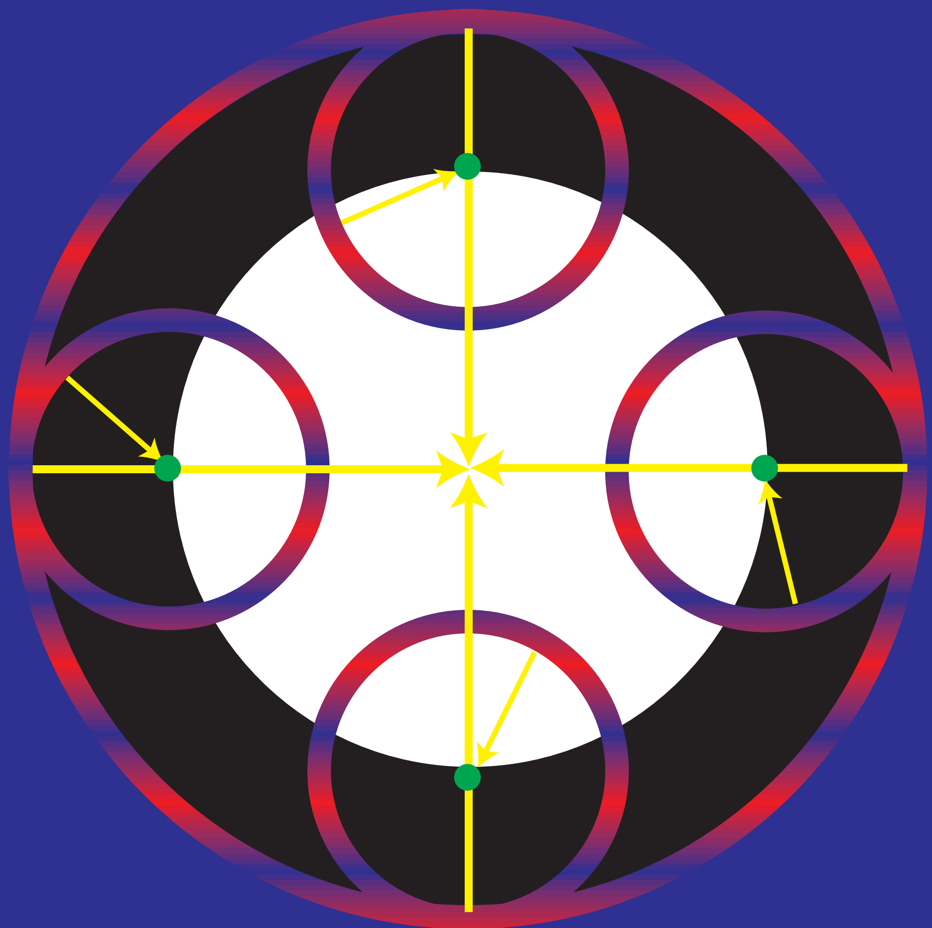
- Early ionization would imply more exotic astrophysics (Pop-III stars) or physics (dark matter annihilation)

- Reionization screens temperature anisotropy on small scales making the true amplitude of initial fluctuations larger by e^{τ}
- Measuring the growth of fluctuations is one of the best ways of determining the neutrino masses and the dark energy
  limits lensing information if not substantially better than 1%

- Offers an opportunity to study the origin of the low multipole statistical anomalies
- Presents a second, and statistically cleaner, window on gravitational waves from the early universe

Anisotropy Suppression

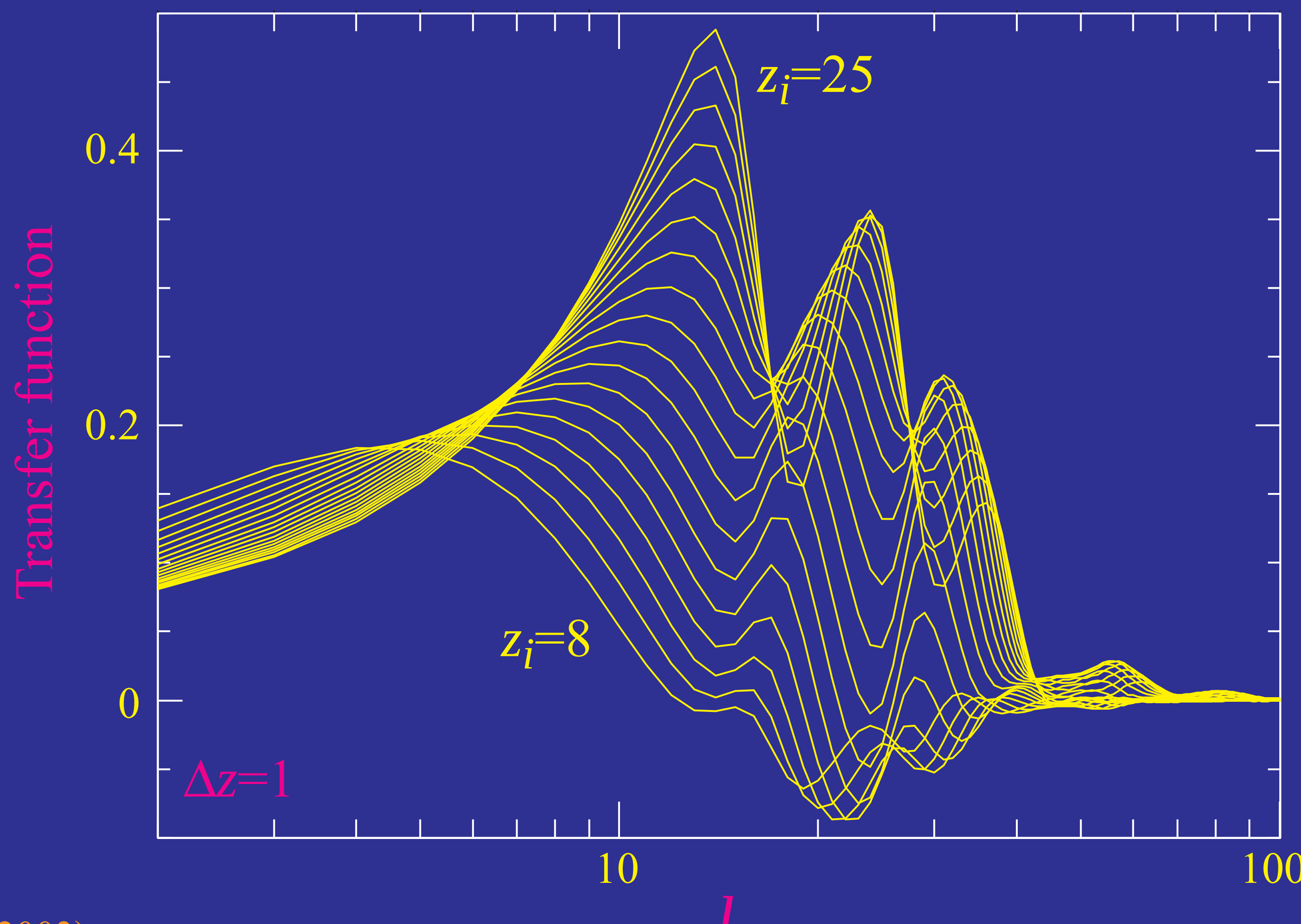
- A fraction τ of photons rescattered during reionization out of line of sight and replaced statistically by photon with random temperature flucutuation - suppressing anisotropy as $e^{-\tau}$



Transfer Function

- Linearized response to delta function ionization perturbation

$$T_{\ell i} \equiv \frac{\partial \ln C_\ell^{EE}}{\partial x(z_i)}\,, \qquad \delta C_\ell^{EE} = C_\ell^{EE} \sum_i T_{\ell i} \delta x(z_i)$$

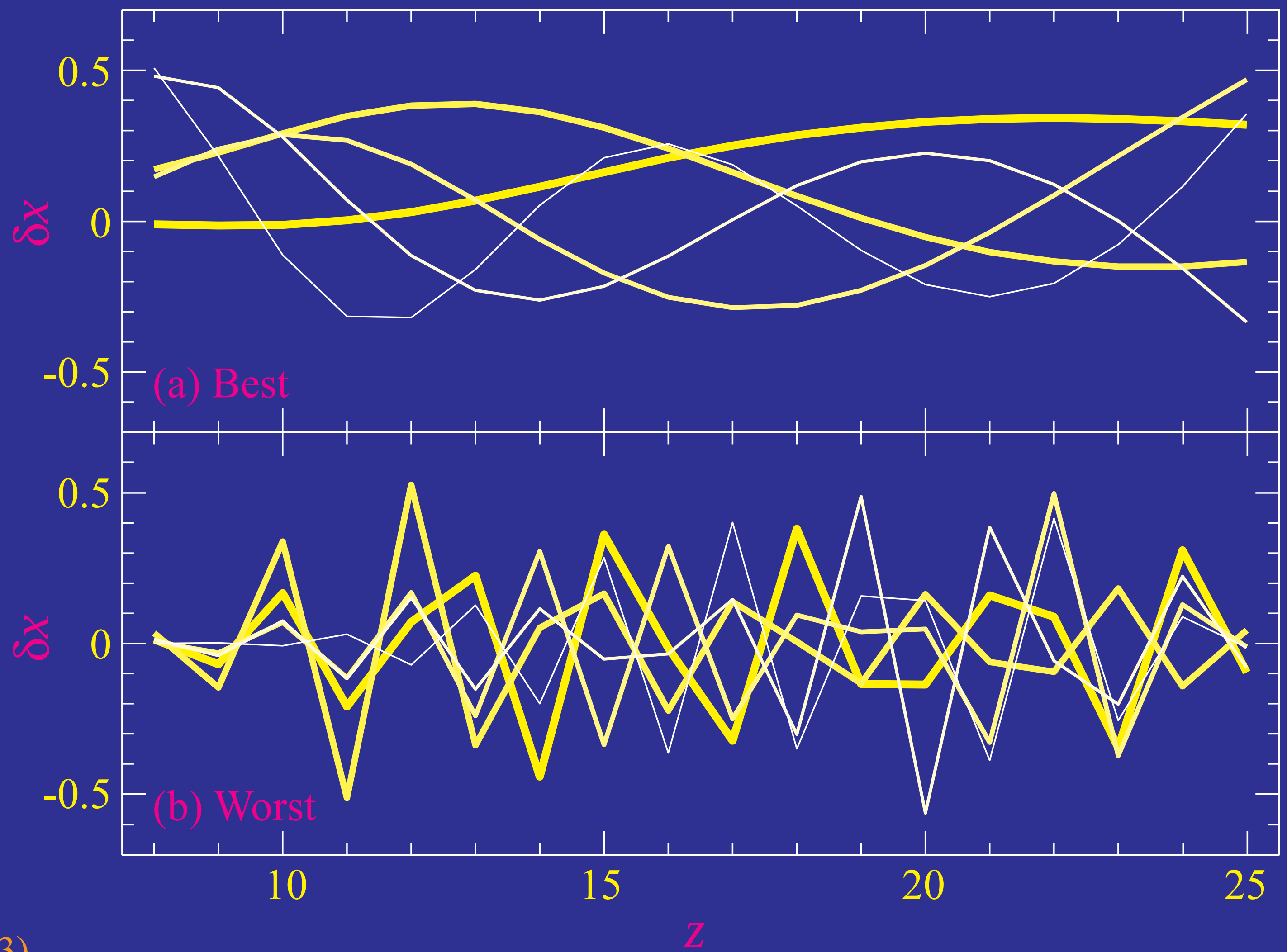


Hu & Holder (2003)

Principal Components

- Eigenvectors of the Fisher Matrix

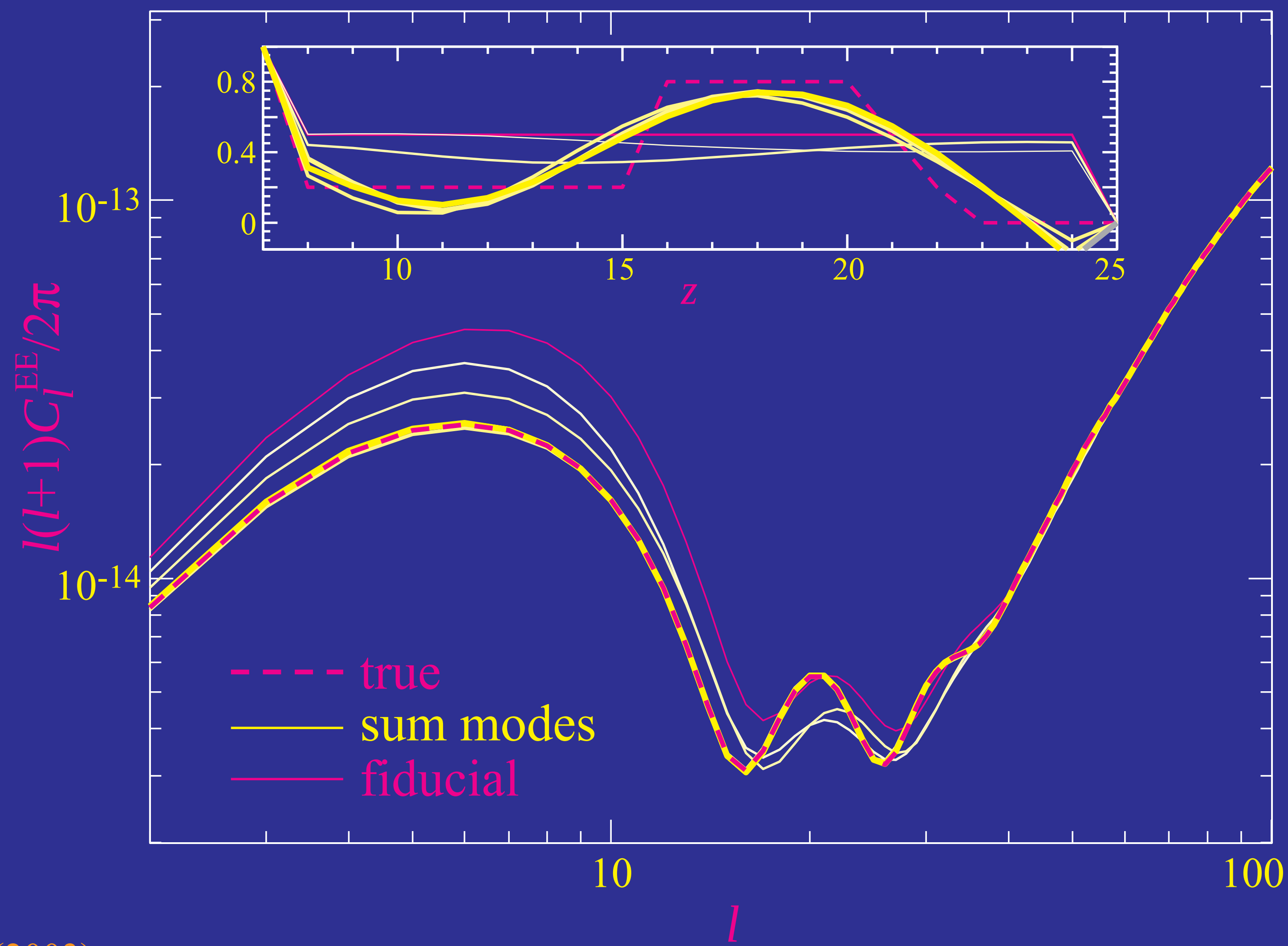
$$F_{ij} \equiv \sum_\ell (\ell + 1/2) T_{\ell i} T_{\ell j} = \sum_\mu S_{i\mu} \sigma_\mu^{-2} S_{j\mu}$$



Hu & Holder (2003)

Representation in Modes

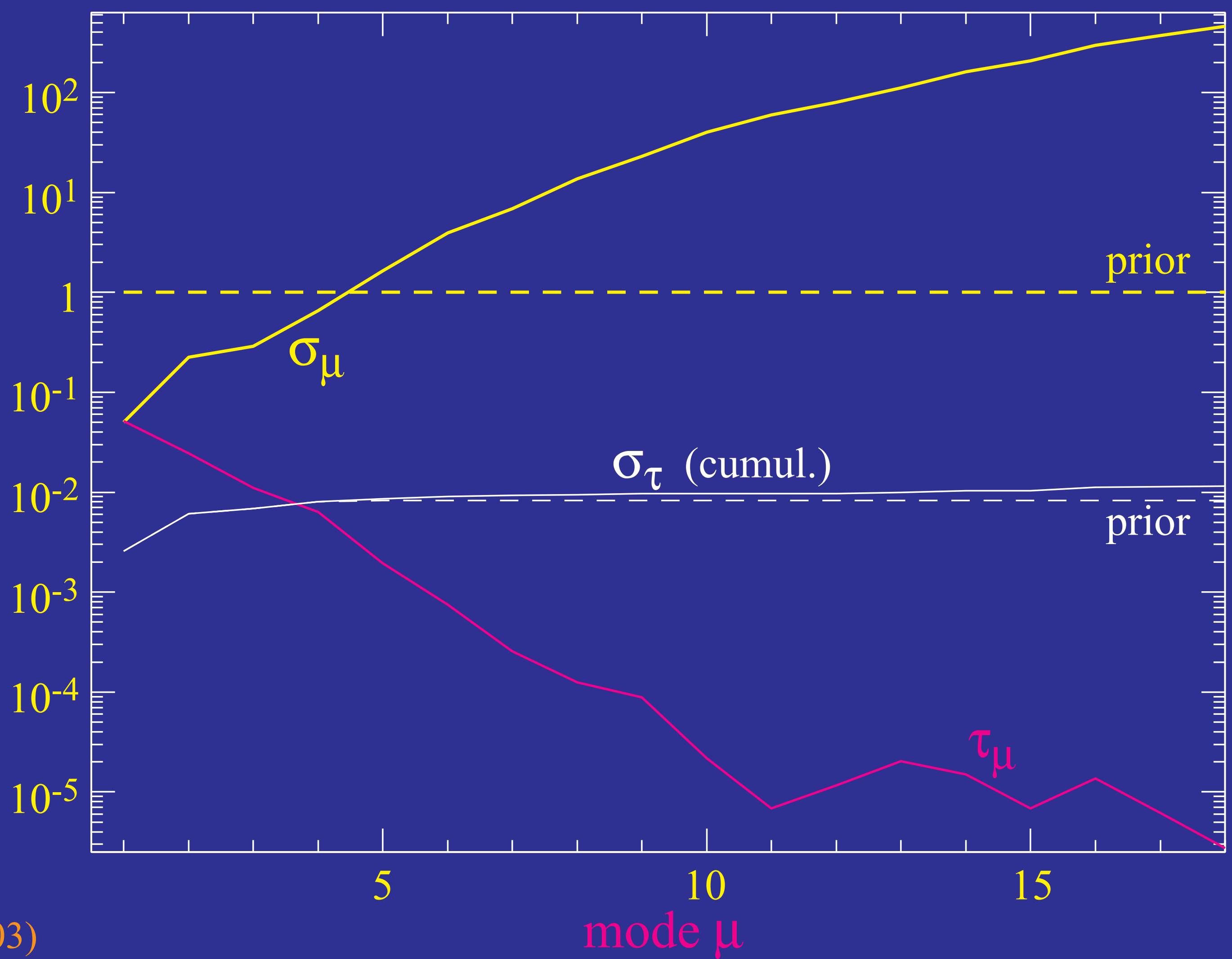
- Reproduces the power spectrum with sum over >3 modes more generally 5 modes suffices: e.g. total τ=0.1375 vs 0.1377



Hu & Holder (2003)

Total Optical Depth

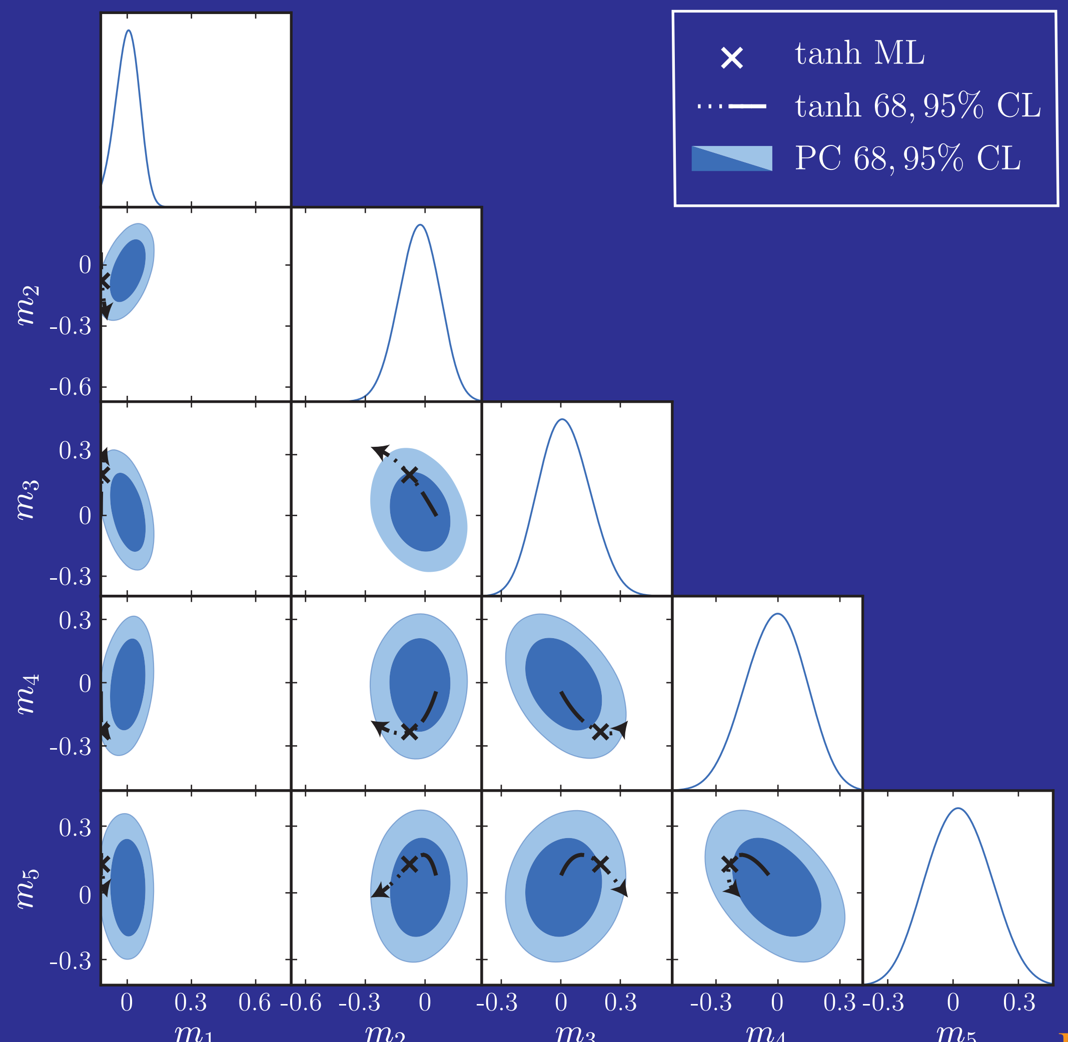
- Optical depth measurement unbiased
- Ultimate errors set by cosmic variance here 0.01
- Equivalently 1% measure of initial amplitude, impt for dark energy



Hu & Holder (2003)

Complete Planck 2015 Reionization

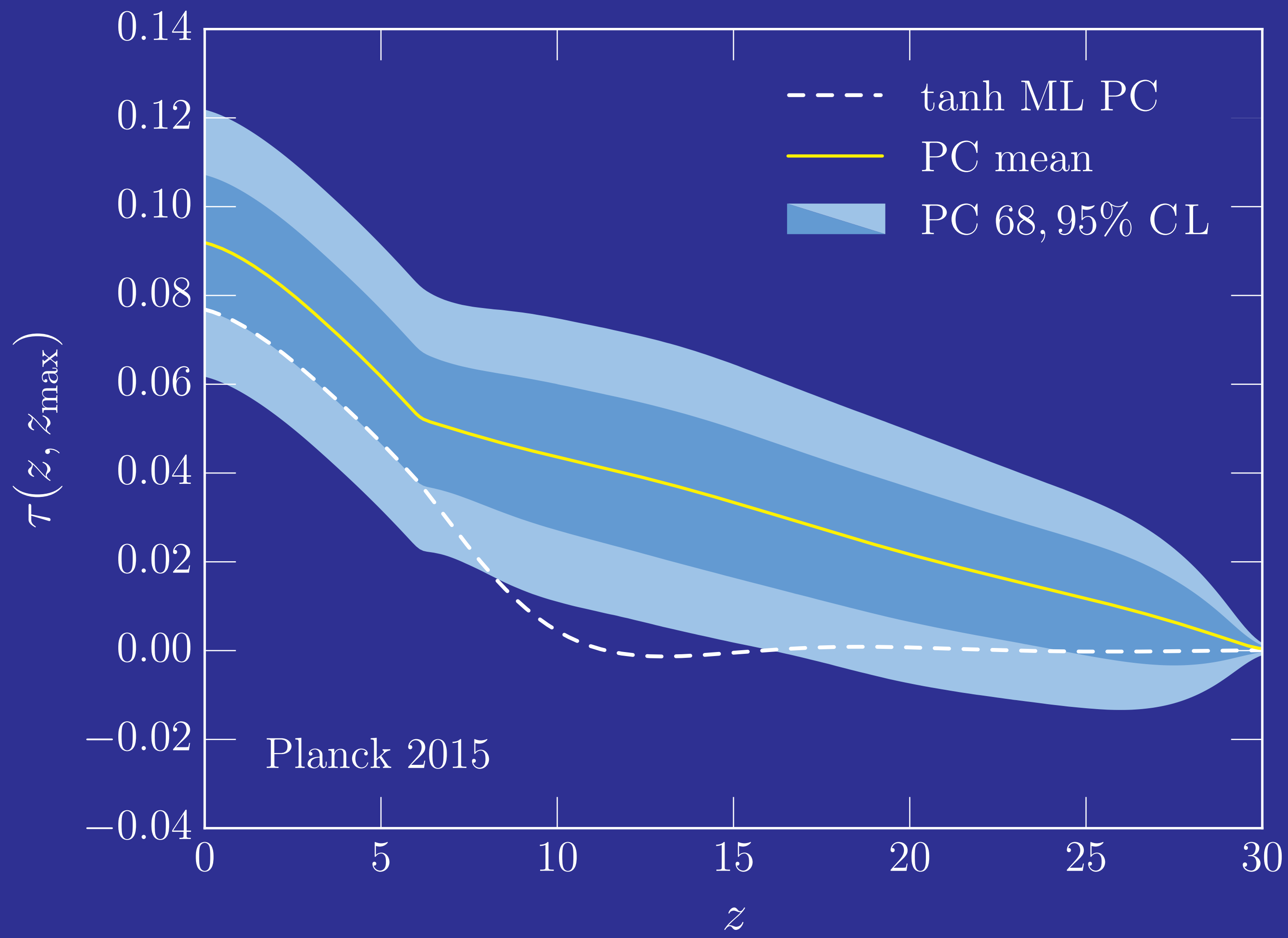
- 5PCs completely span $z<30$ reionization observables
- Step function models only skirt the favored regions



Heinrich, Miranda, Hu (2016)

Complete Planck 2015 Reionization

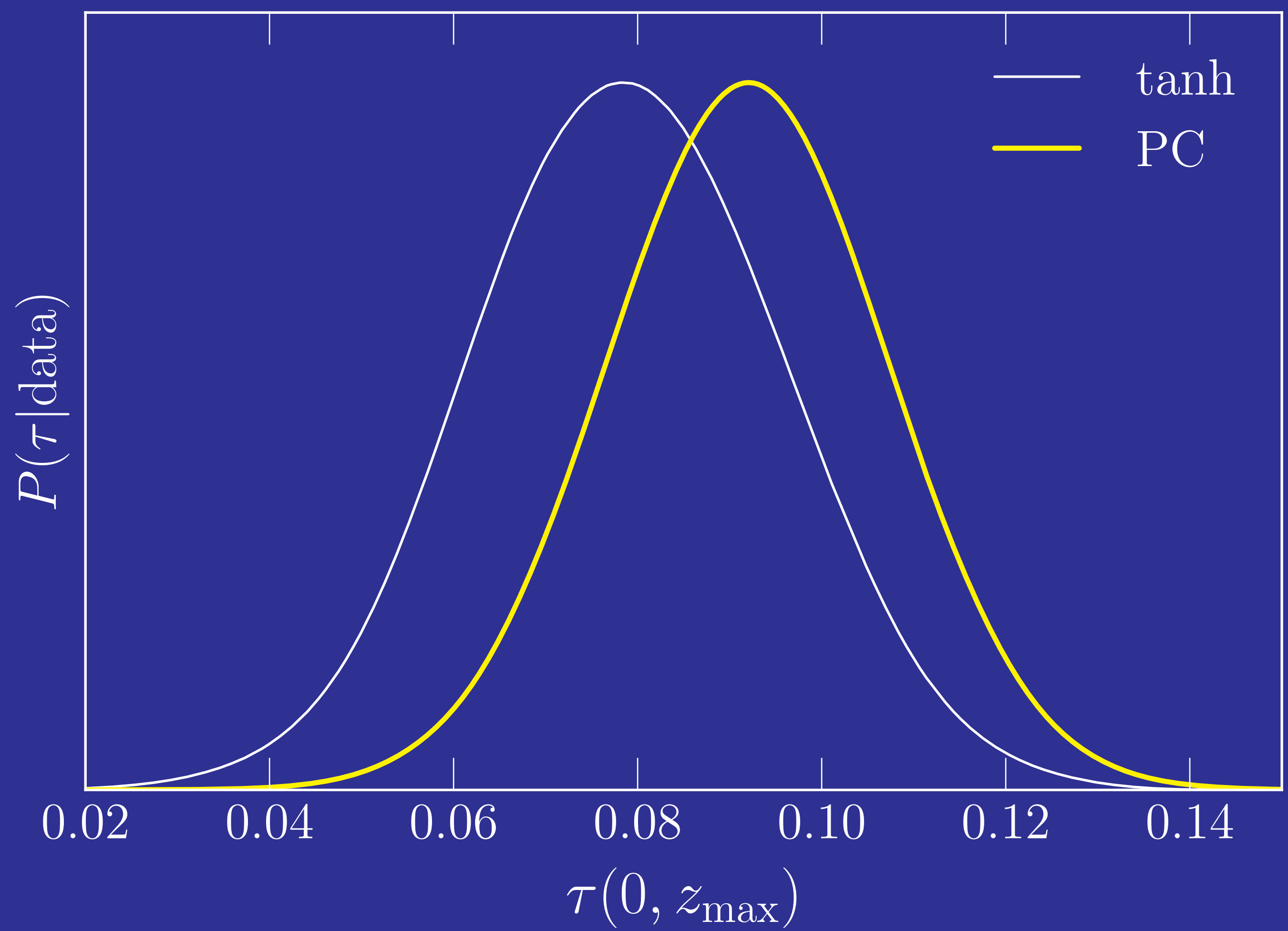
- Allows for a high redshift component of ionization



Heinrich, Miranda, Hu (2016)

Complete Planck 2015 Reionization

- Shifts optical depth higher



Heinrich, Miranda, Hu (2016)

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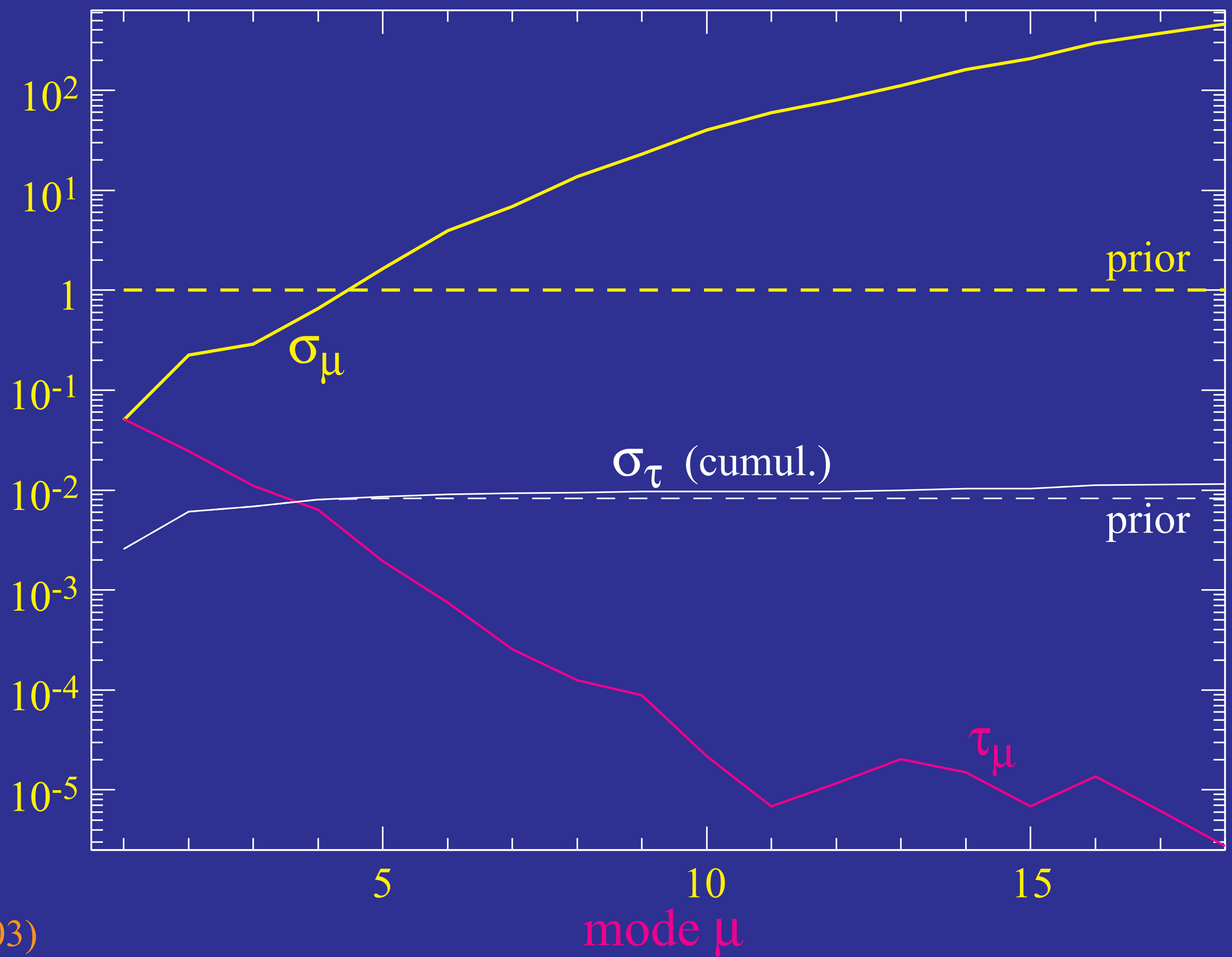
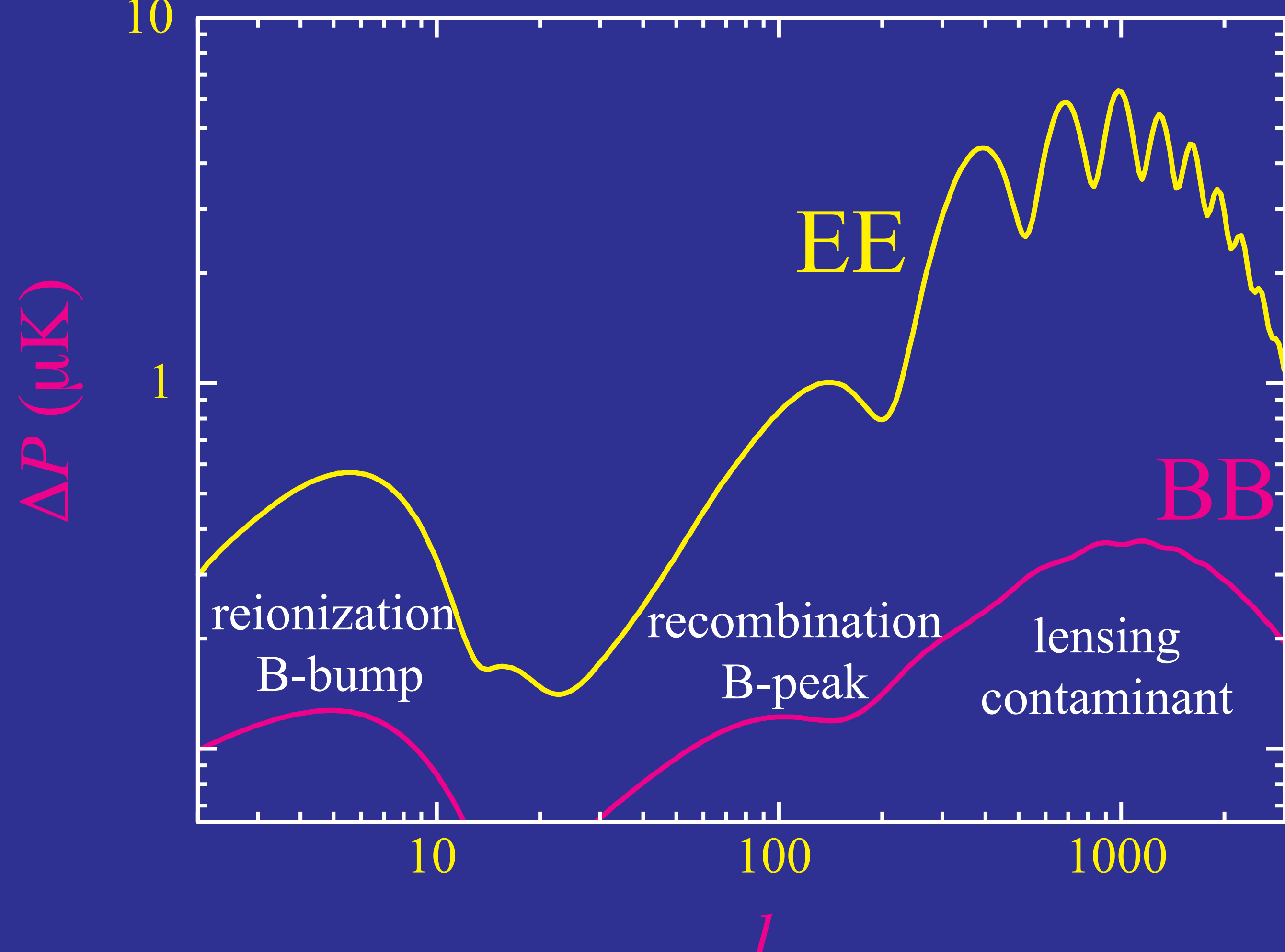


Hu & Holder (2003)

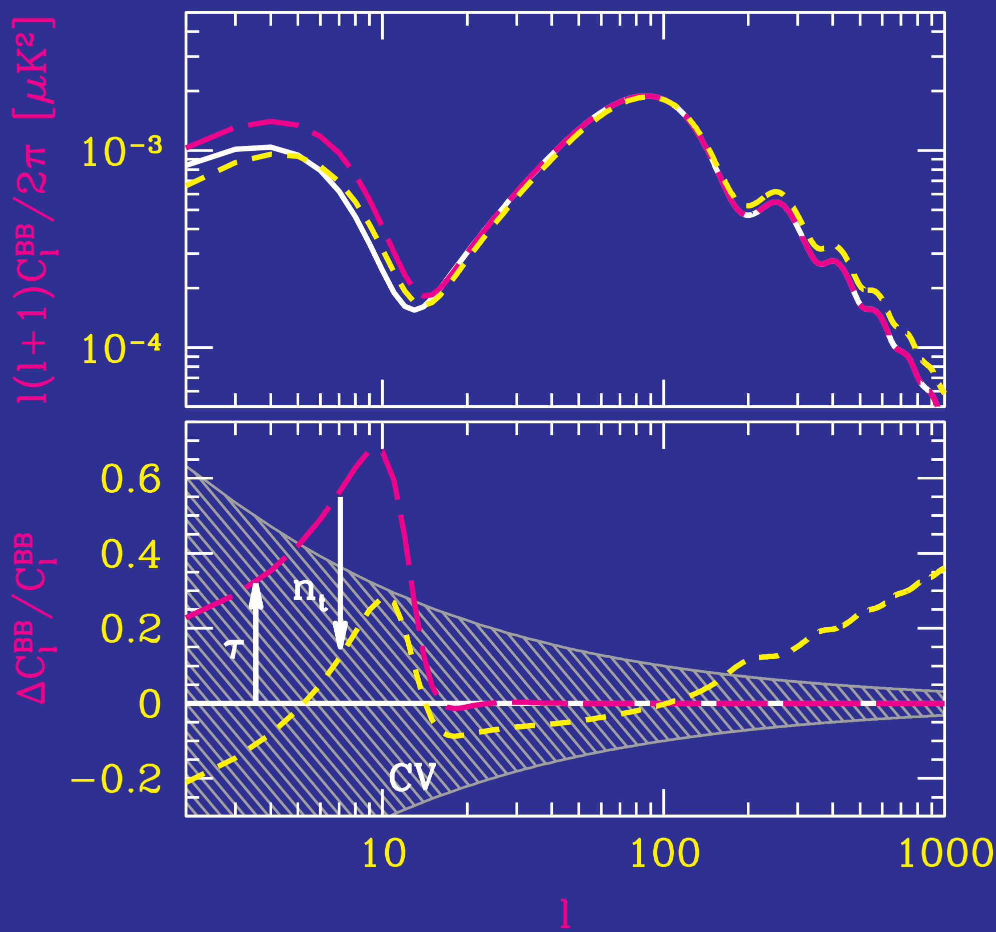
The B-Bump

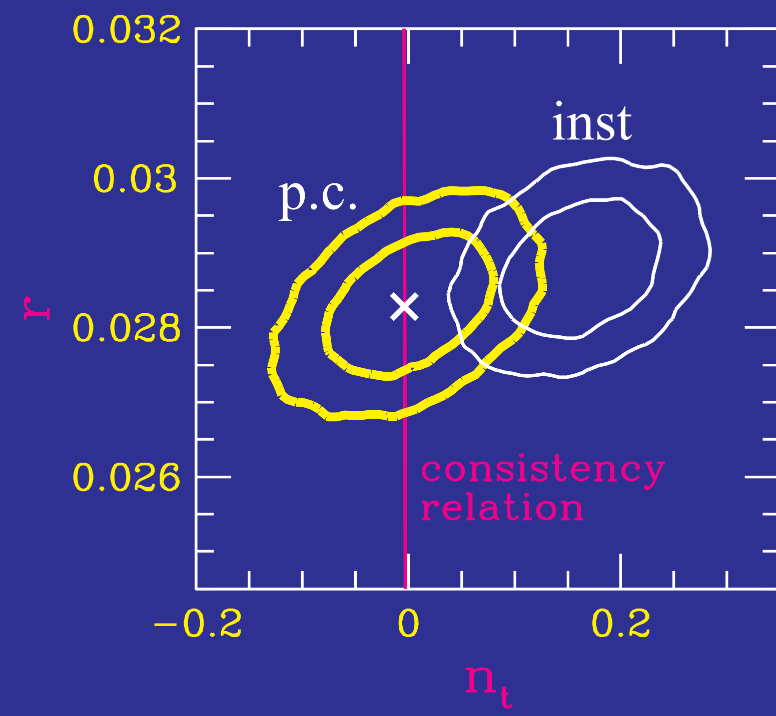
- Rescattering of gravitational wave anisotropy generates the B-bump
- If r is near current upper limit, motivates next generation satellite
- Potentially enables test consistency test of canonical inflation



Slow Roll Consistency Relation

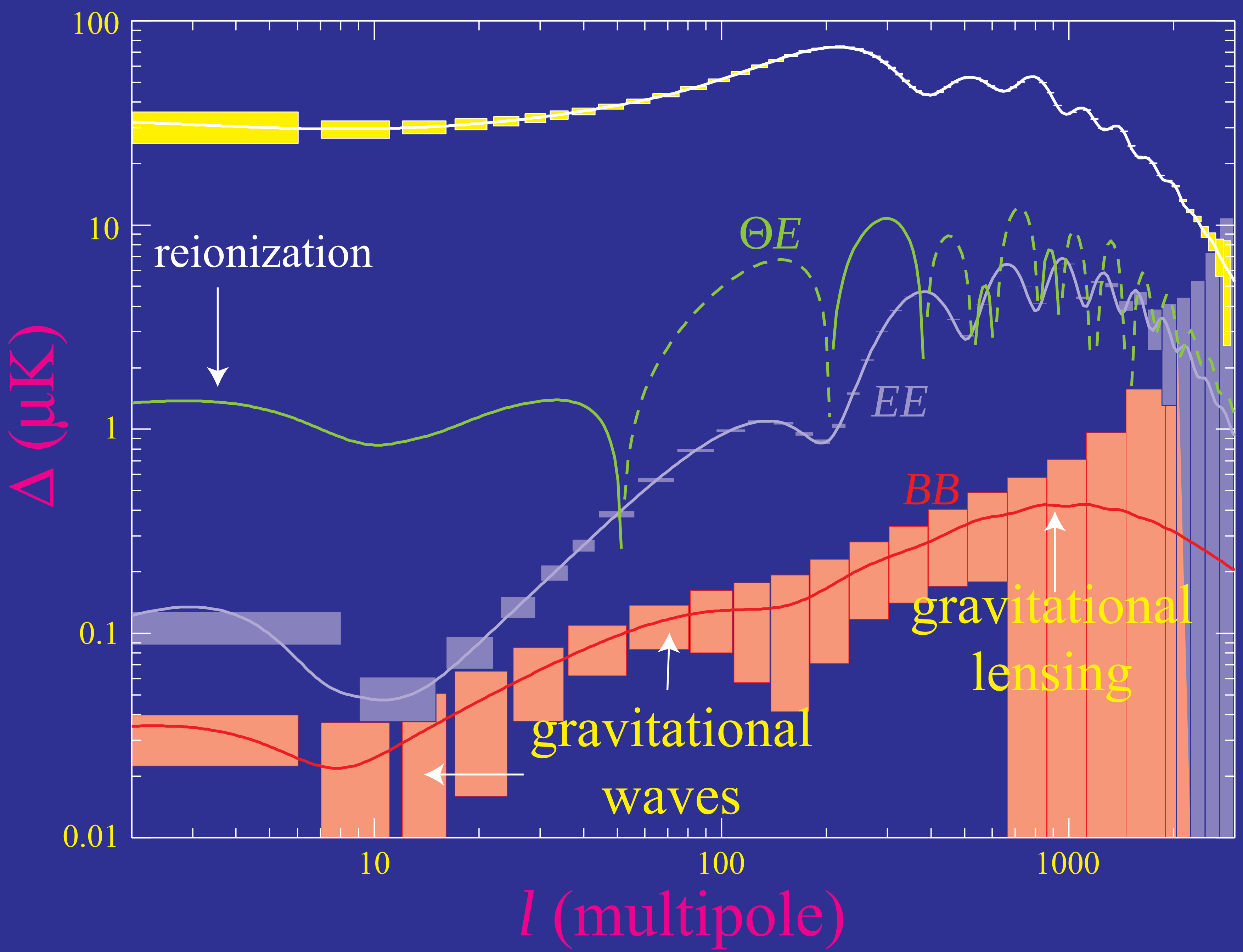
- Consistency relation between tensor-scalar ratio and tensor tilt $r = -8n_t$ tested by reionization
- Reionization uncertainties controlled by a complete p.c. analysis





Mortonson & Hu (2007)

Temperature and Polarization Spectra



Summary

- CMB polarized by Thomson scattering of quadrupole anisotropy: isolates recombination, reionization with little projection effects in transfer
- Linear scalar fluctuations generate E-modes where polarization direction (anti)aligned with amplitude change
- Linear tensor fluctuations also generate B-modes where polarization direction (anti)crossed with amplitude change
- B-mode gravitational wave amplitude measures the inflation energy scale: if observably large imply superPlanckian roll
- Beyond linear theory, scalar fluctuations generate B-modes
- Gravitational lensing B-modes measure amplitude of structure at $z{\sim}2$, neutrino mass and can be quadratically reconstructed
- Delensing of the CMB can enable measurements to $r{\sim}10^{-3}$

Ciao!