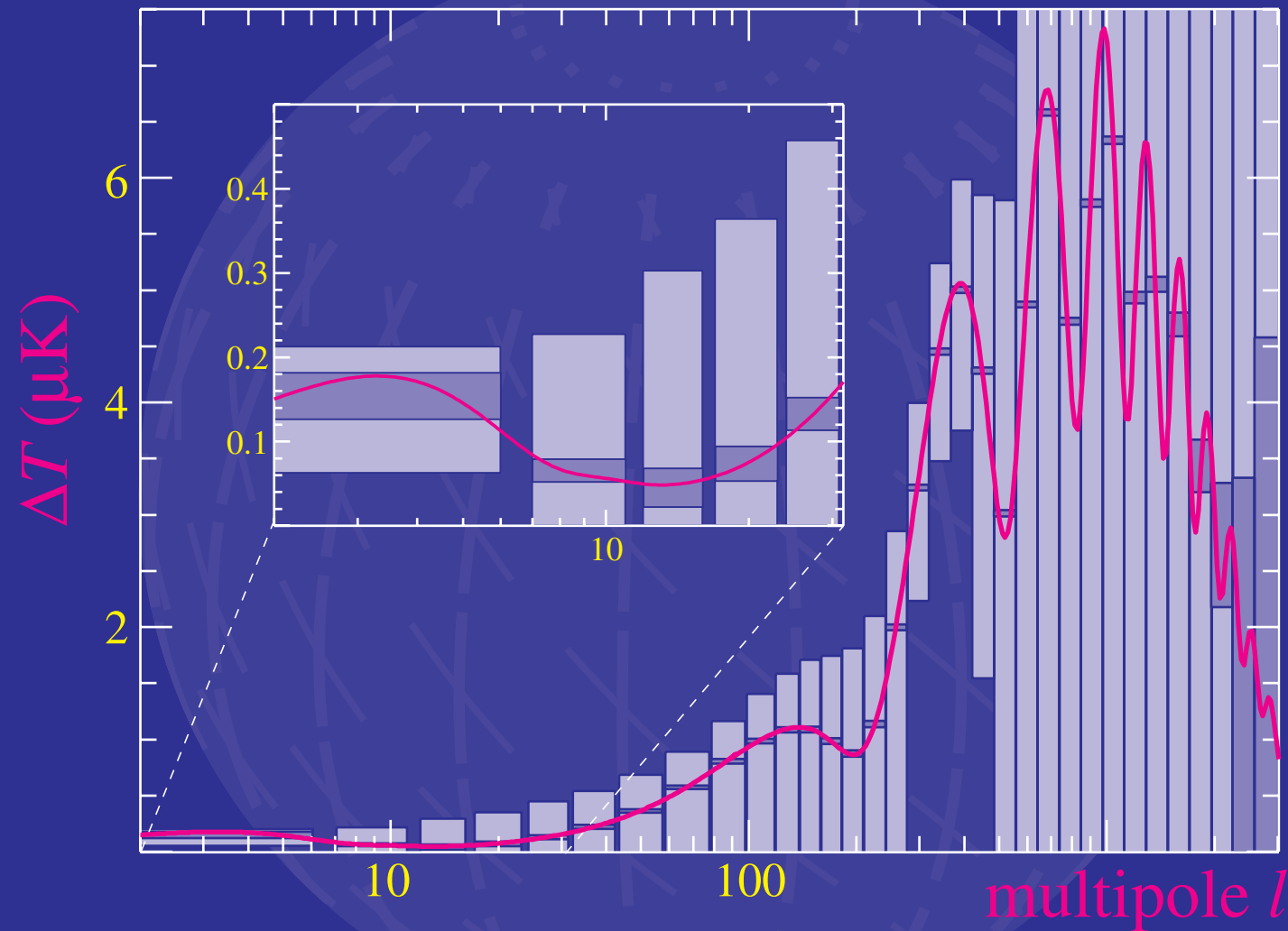
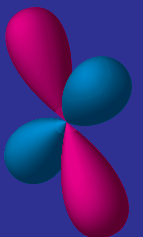
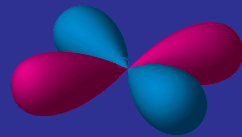
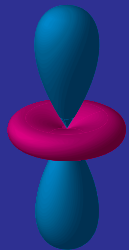


The Physics of CMB Polarization



Wayne Hu



Why Measure the Polarization?

- Virtues of polarization
 - unlike temperature anisotropies, generated by scattering only
 - tensor field on the sky; carries more info than scalar temperature

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 - verify the gravitational instability paradigm: fluctuations present during last scattering (outside horizon \Rightarrow inflation)
 - probe the reionization epoch: remove a leading source of ambiguity (degeneracy) in the temperature power spectrum
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 - get higher statistics on the acoustic peaks and their underlying parameters
 - reconstruct the scalar, vector, tensor nature of the perturbations and hence the cosmology even if ab initio models are wrong
 - test inflationary models by measuring the gravity wave amplitude: energy scale and shape of inflaton potential

Polarization from Thomson Scattering

- Differential cross section depends on polarization and angle

Polarization from Thomson Scattering

- Isotropic radiation scatters into unpolarized radiation

Polarization from Thomson Scattering

- Quadrupole anisotropies scatter into linear polarization

aligned with
cold lobe

Isotropization by Scattering

- **Rock:** polarization **generated** by Thomson scattering
- **Hard Place:** Thomson scattering **destroys** quadrupole source

Quadrupoles at Recombination's End

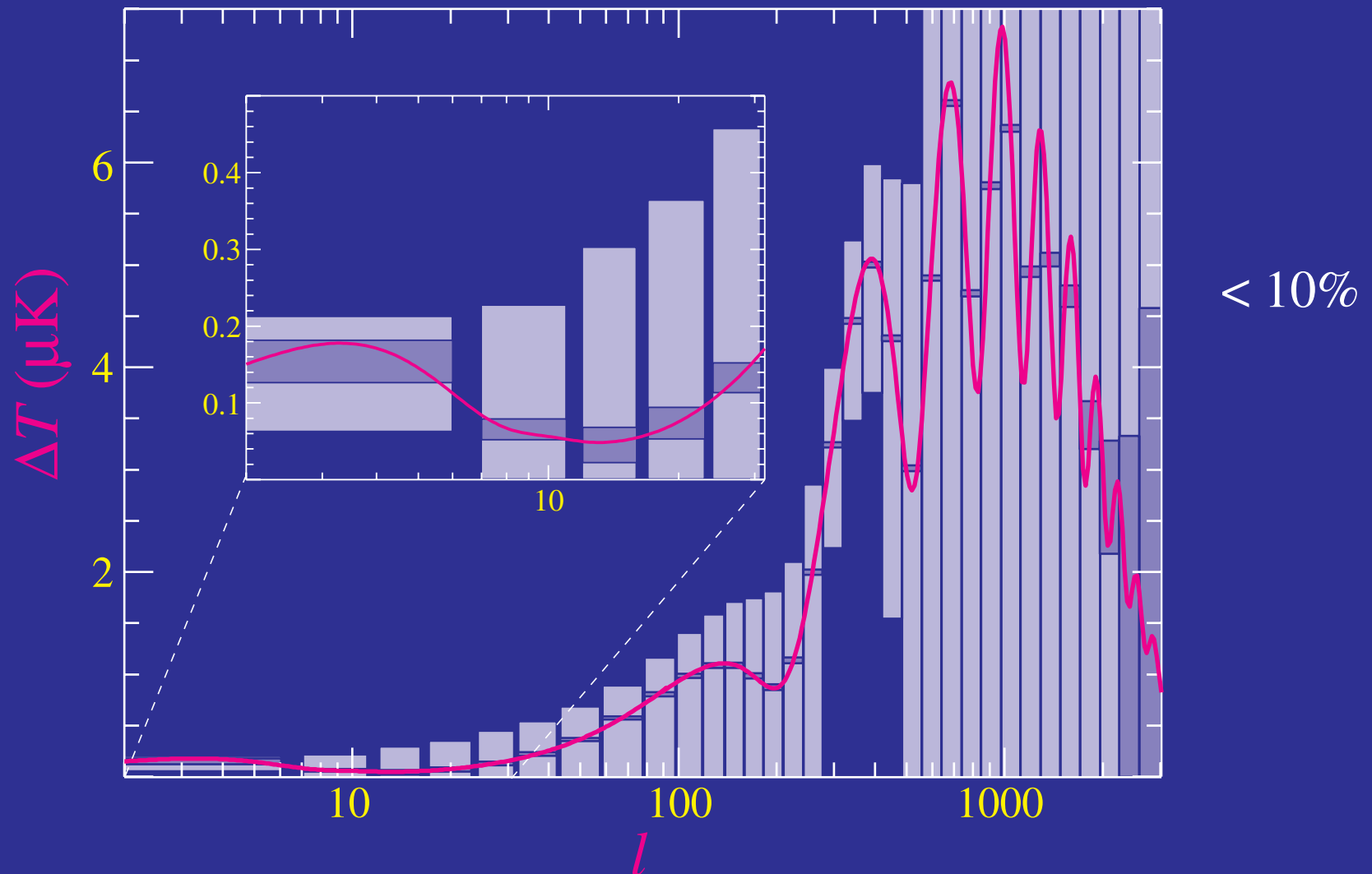
- Acoustic inhomogeneities become anisotropies by streaming/diffusion

Quadrupoles at Recombination's End

- Electron "observer" sees a quadrupole anisotropy
- Polarization pattern is a projection quadrupole anisotropy

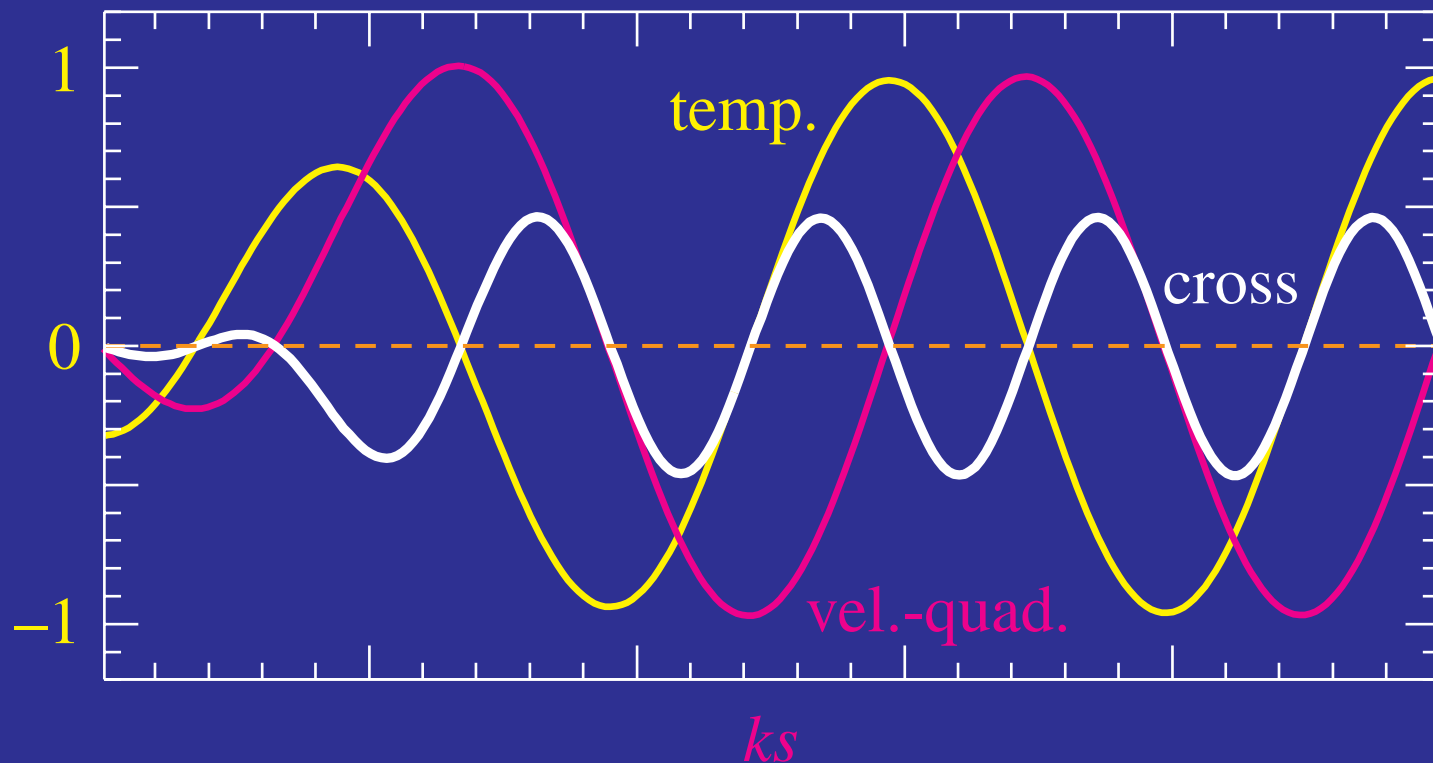
Polarization Power Spectrum

- Quadrupole generation on **diffusion scale** (optically thin regime)
- Primary peak coincides with beginning of **damping tail** $l \sim 1000$
- Secondary peak coincides with horizon scale at **reionization** $l < 10$

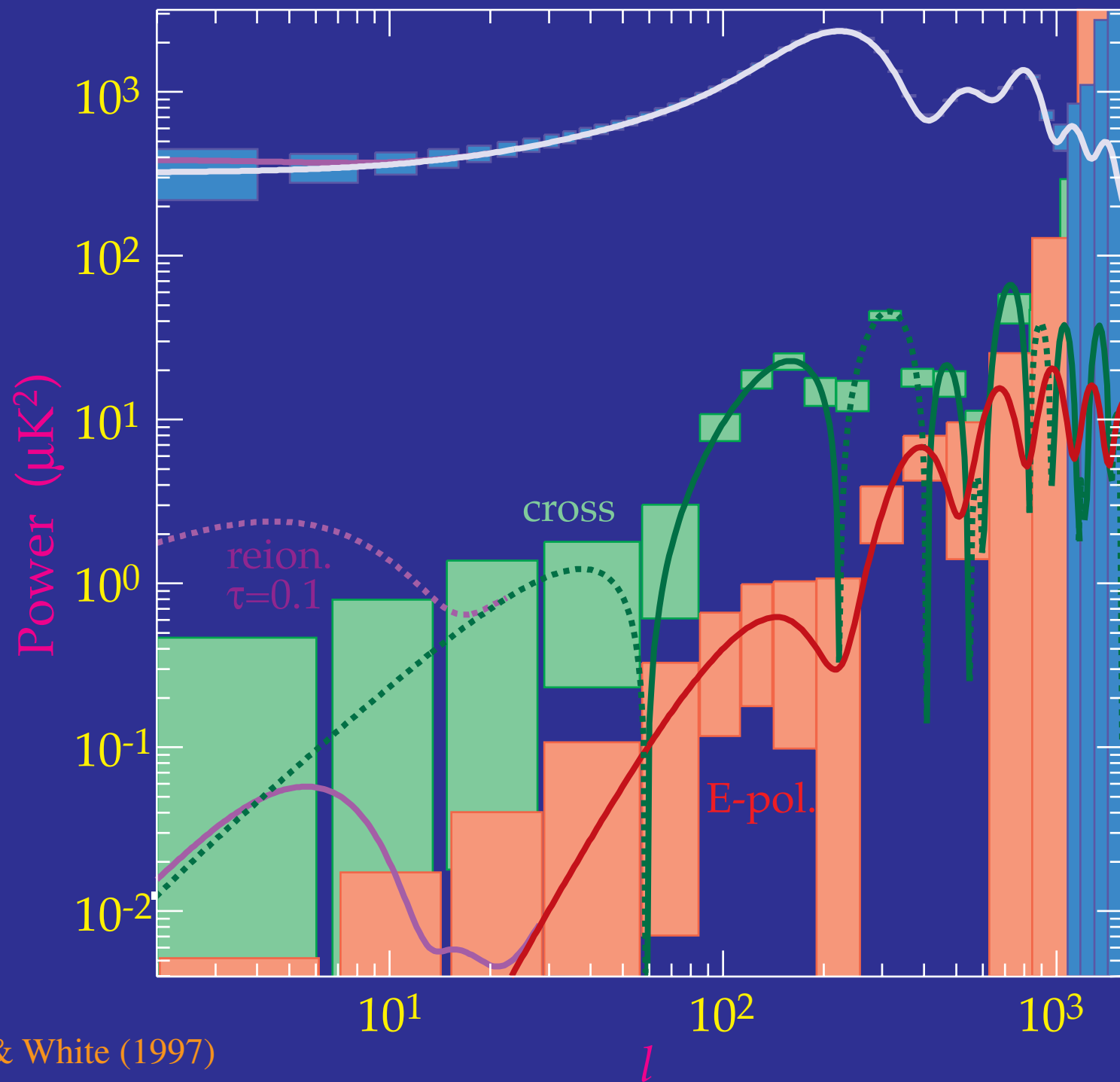


Acoustic Peaks in the Polarization

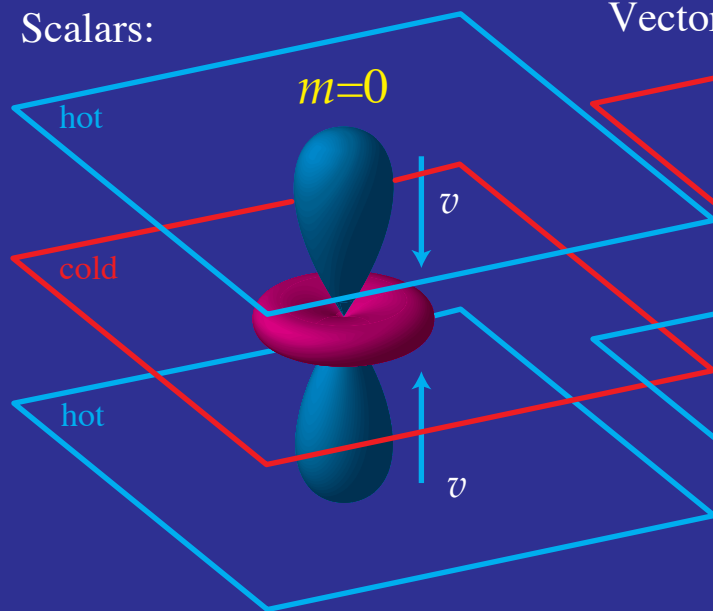
- **Scalar** quadrupole follows the velocity perturbation
- **Acoustic velocity** out of phase with acoustic temperature
- **Correlation** oscillates at twice the frequency



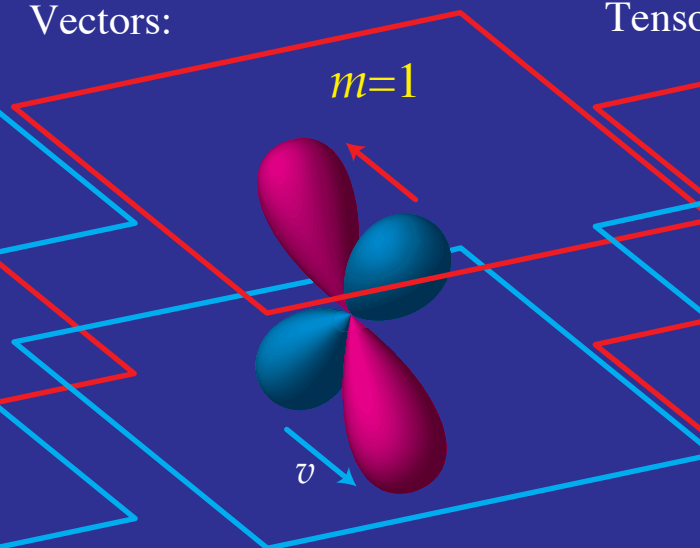
Scalar Power Spectra



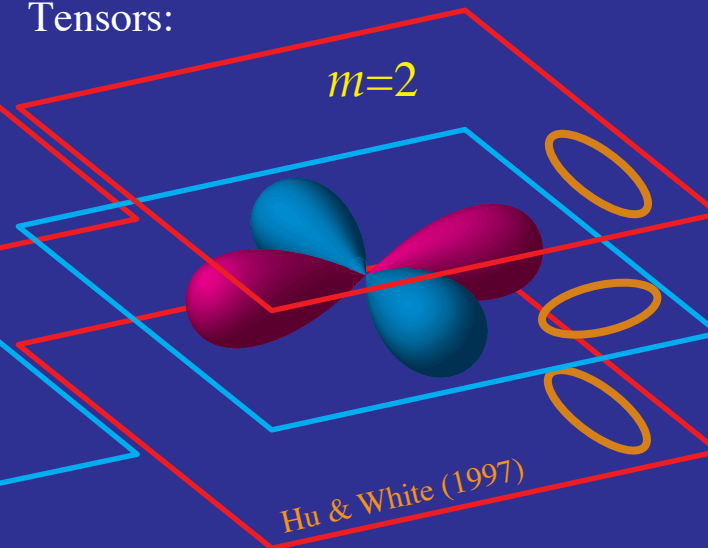
Scalars:



Vectors:



Tensors:

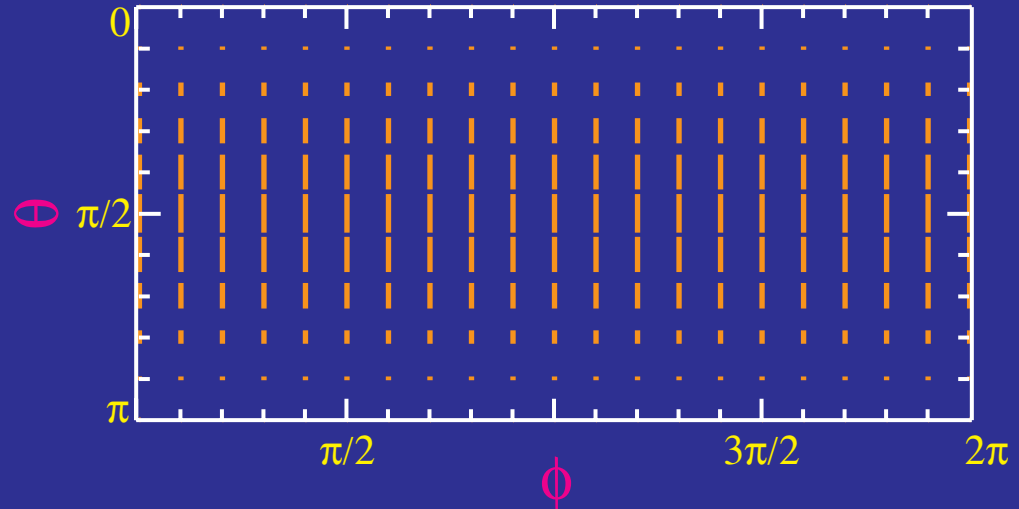
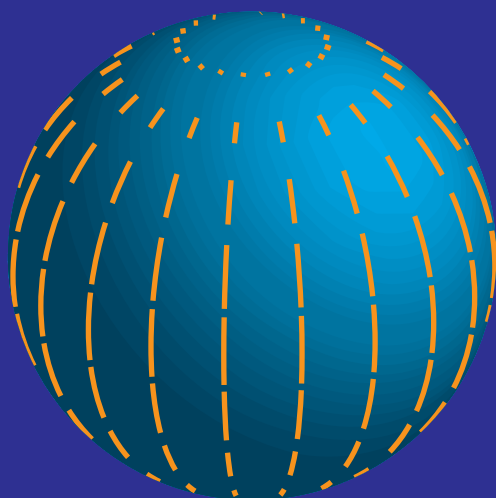
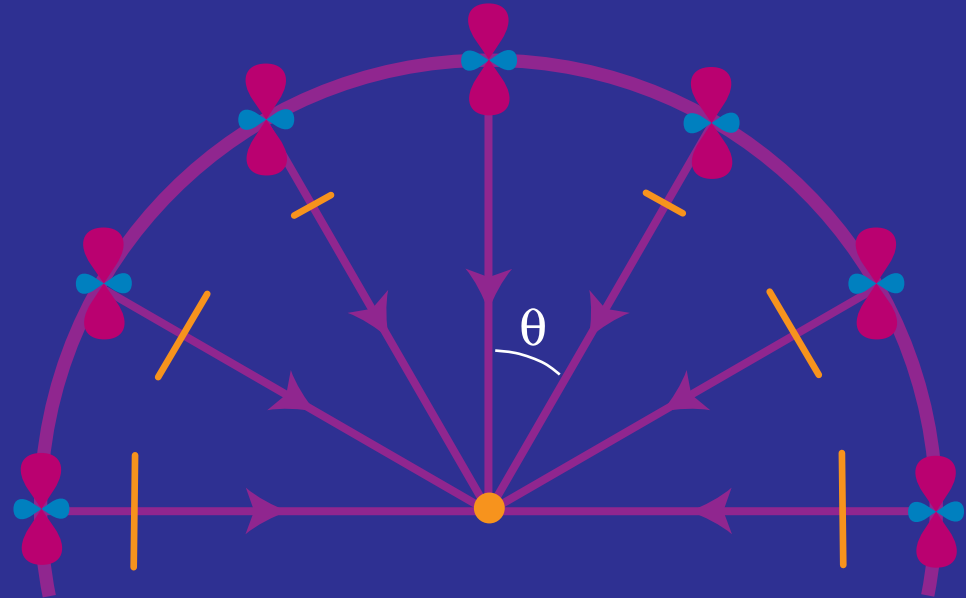
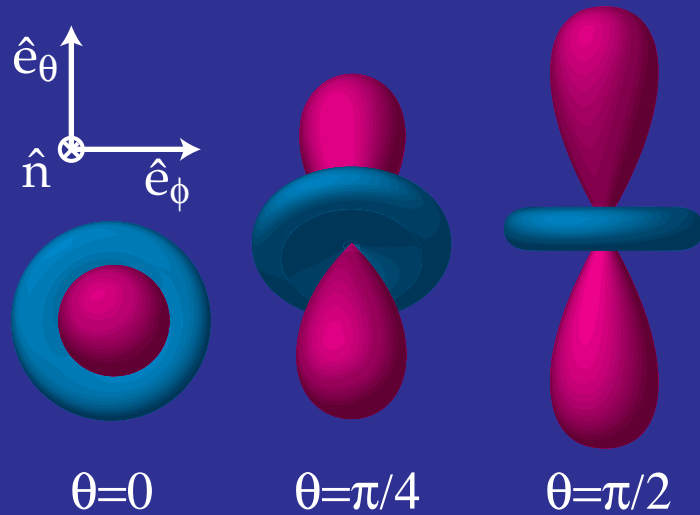


Polarization on the Sphere

- Polarization direction oriented with the cold lobe of the quadrupole
- A local observer will see a $\sin^2\theta$ pattern of Q -polarization: spin-spherical harmonic: $l=2, m=0, s=2$: ${}_2Y_2^0$.

Polarization on the Sphere

- **Polarization** is a projection of the quadrupole moments



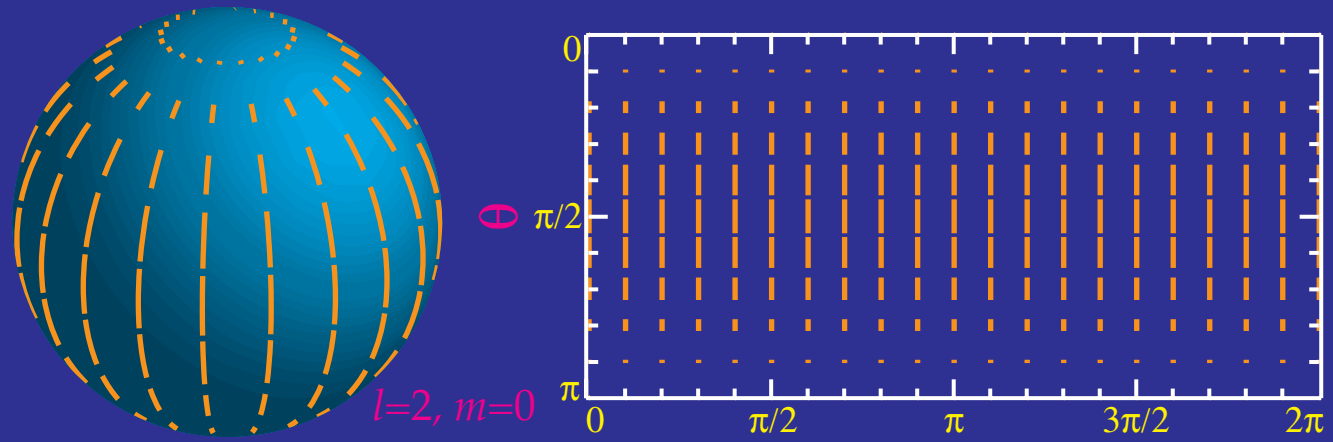
Polarization on the Sphere

- Polarization due to gravitational waves follows similarly
- $m=\pm 2$ quadrupole viewed at different angles

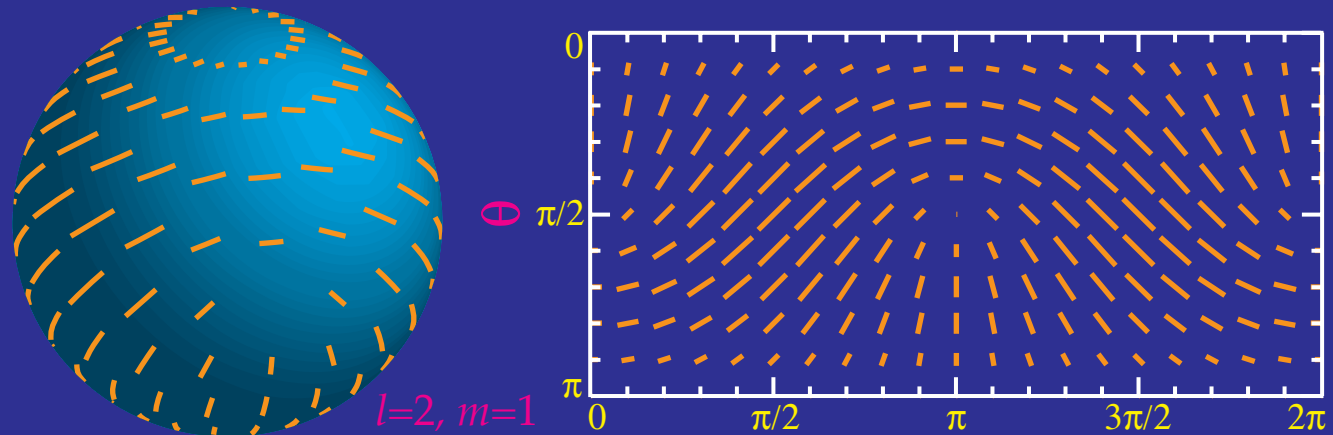
- Difference: no symmetry – Q and U polarization
- Coordinate independent description of polarization

Polarization Patterns

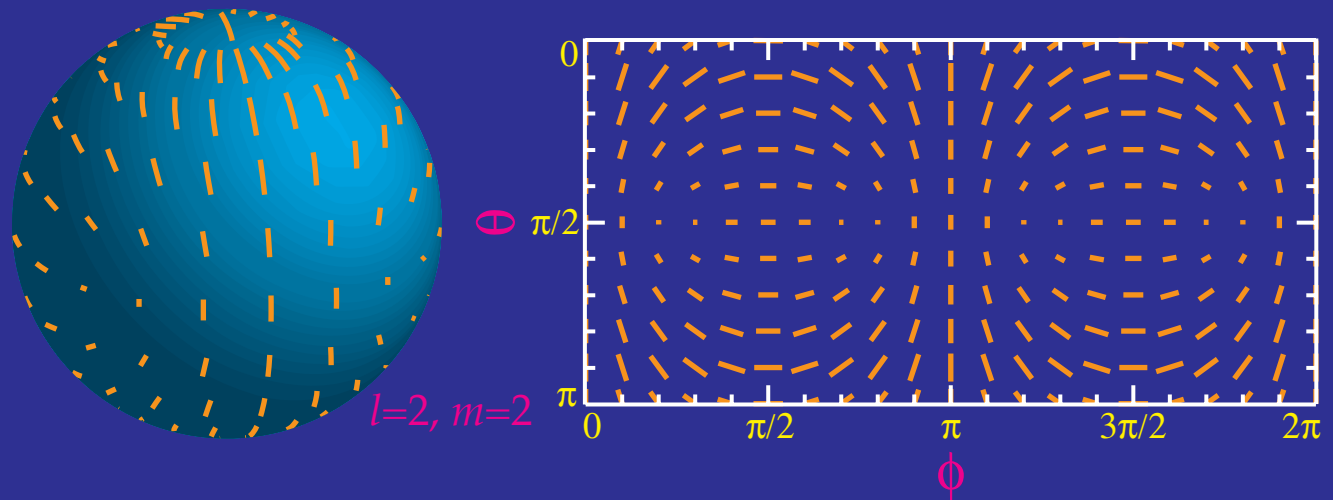
Scalars



Vectors



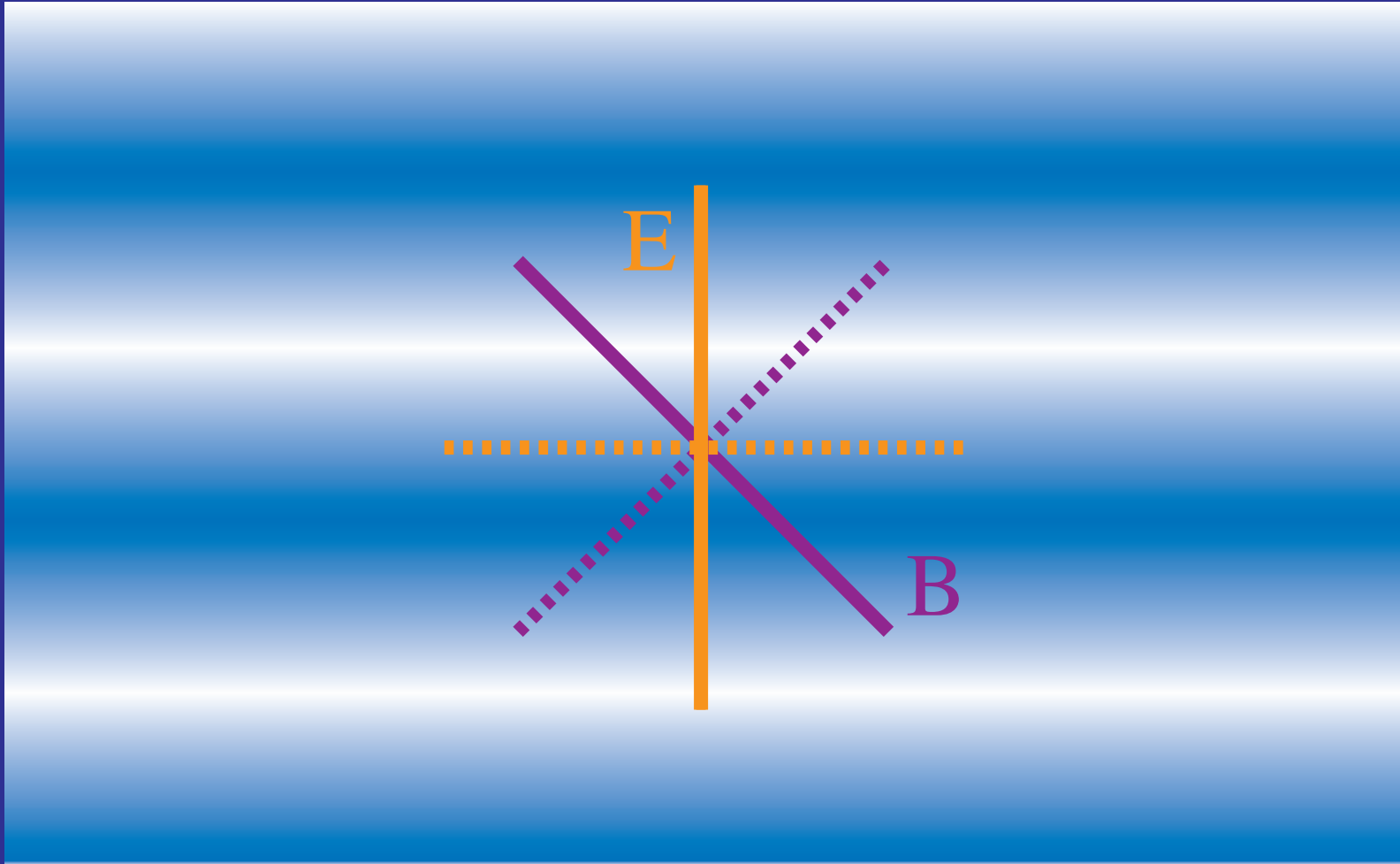
Tensors



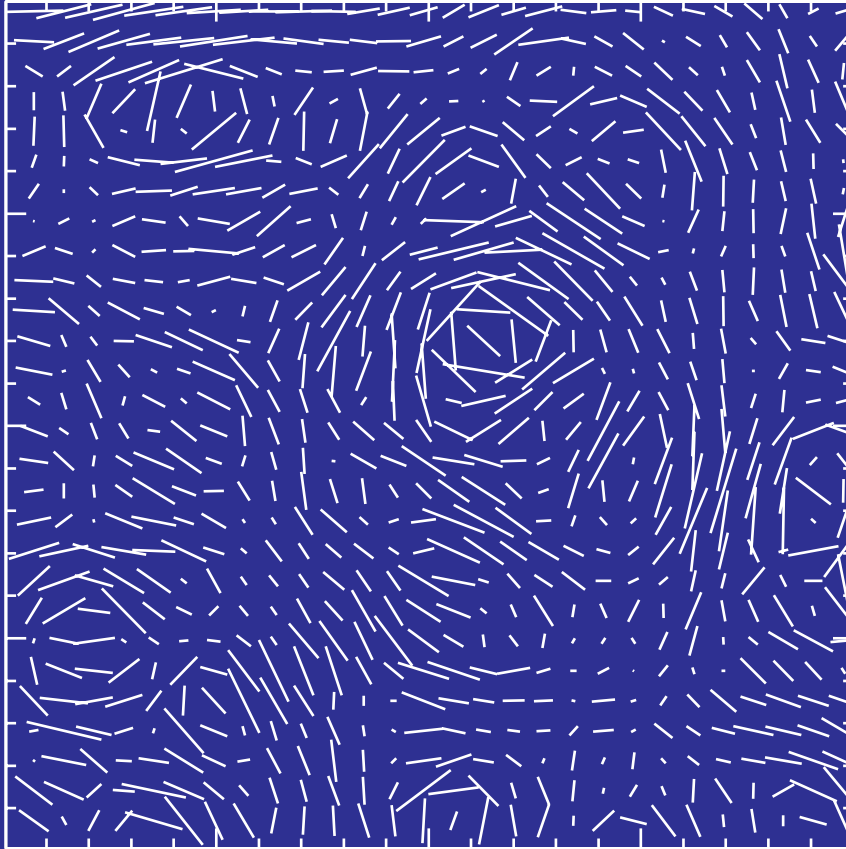
Electric & Magnetic Polarization

(a.k.a. gradient & curl)

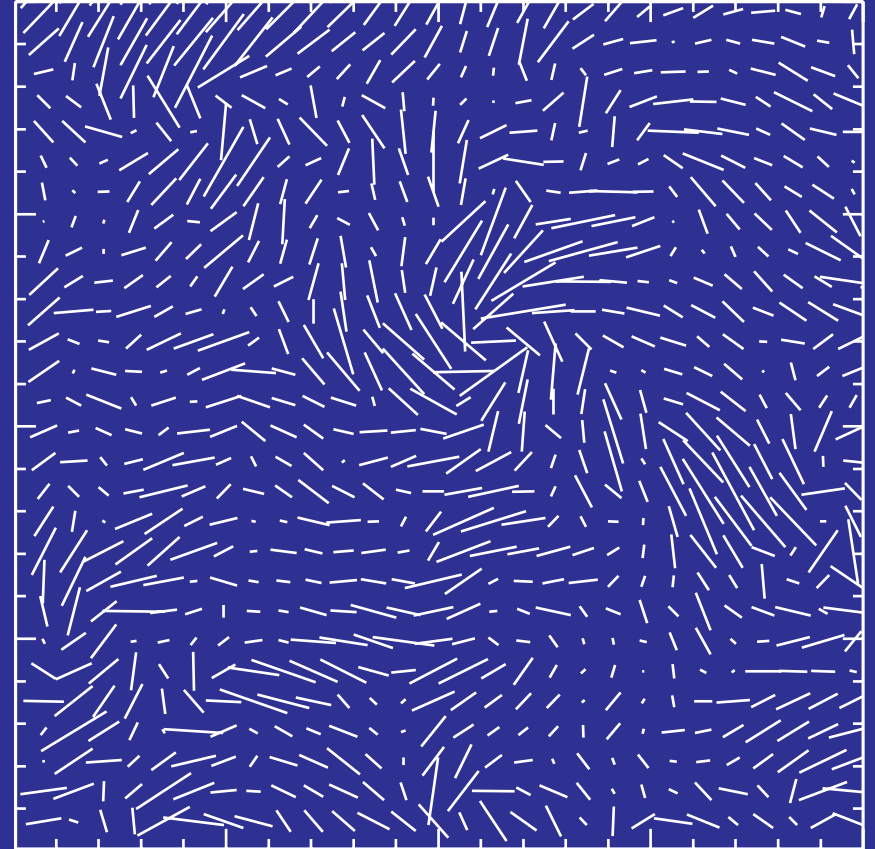
- Alignment of principal vs polarization axes
(**curvature** matrix vs **polarization** direction)



Polarization Patterns

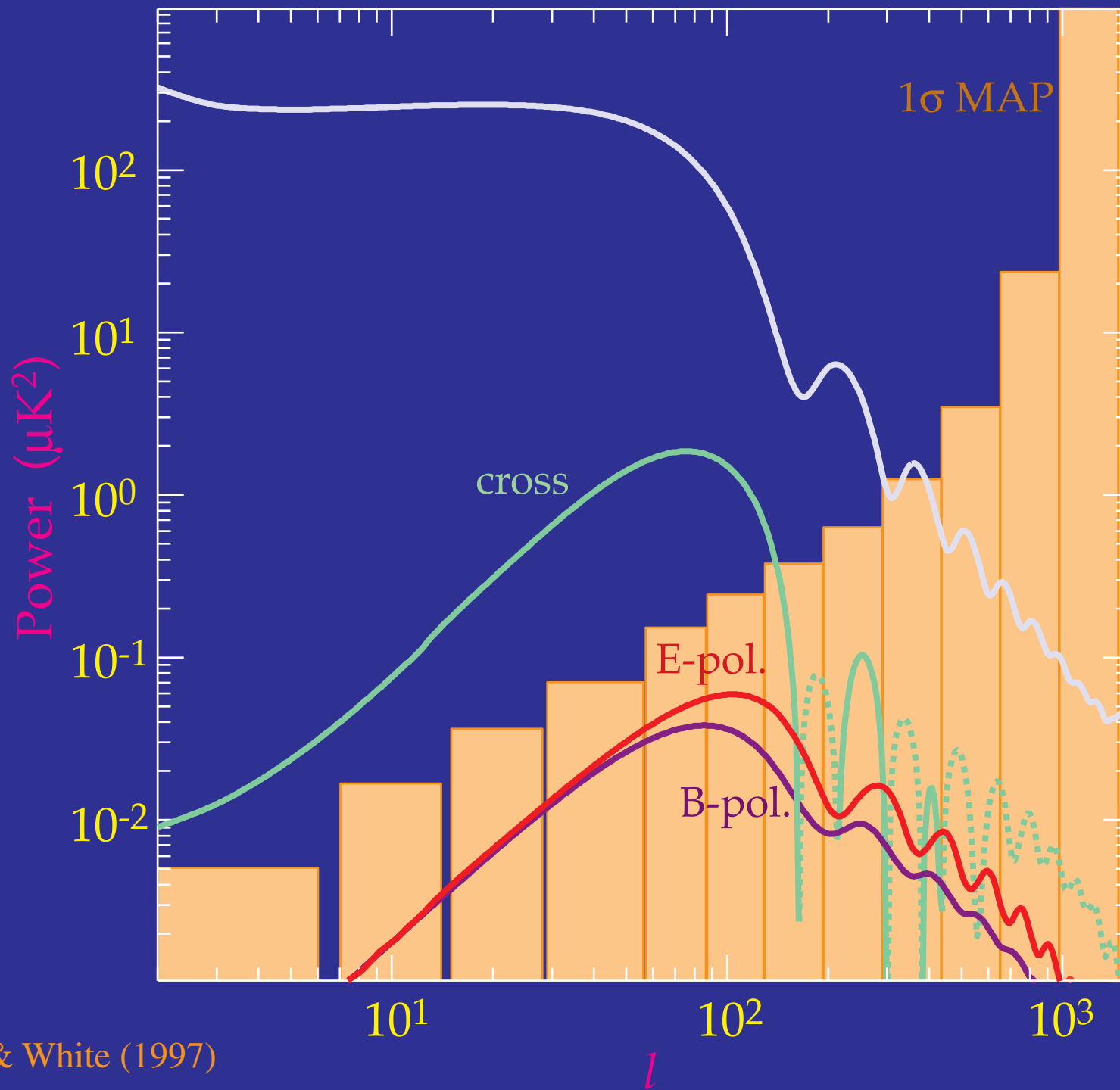


E-polarization



B-polarization

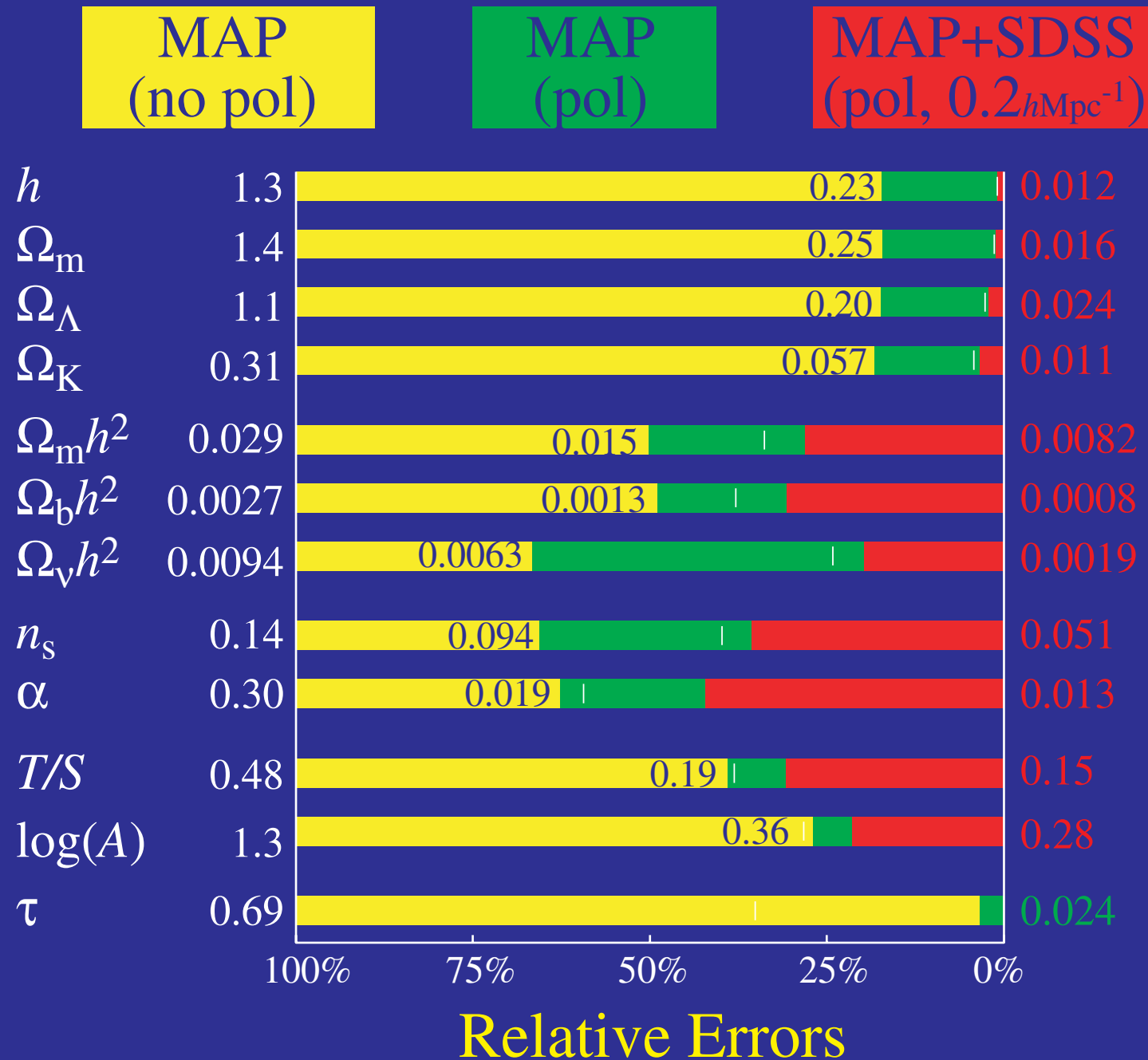
Tensor Power Spectra



Reionization and Gravitational Waves

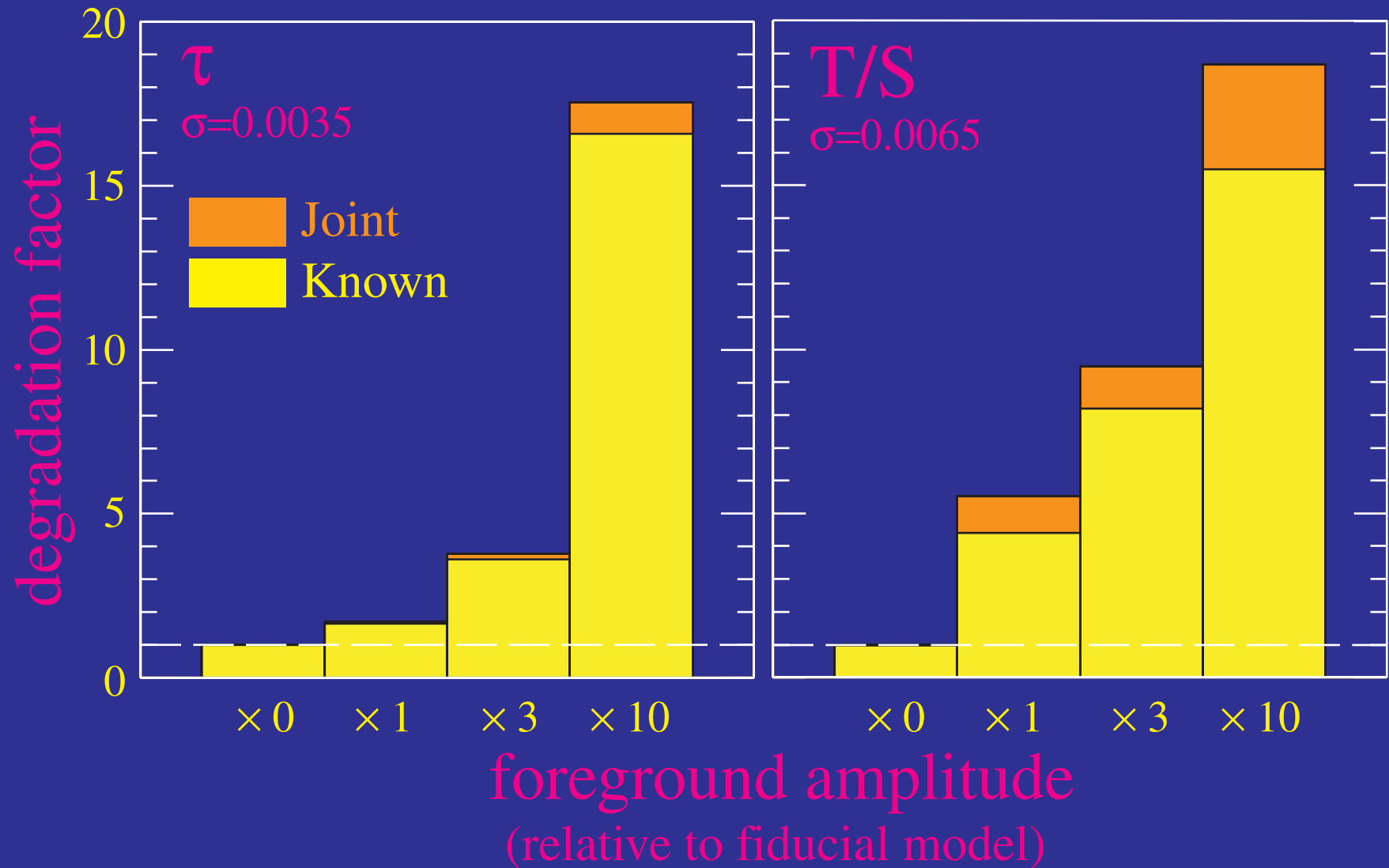
- Distinguished by polarization power spectrum (B-modes)

Polarization and Parameter Estimation



Foregrounds & Parameter Estimation

Planck



B-modes from Secondaries

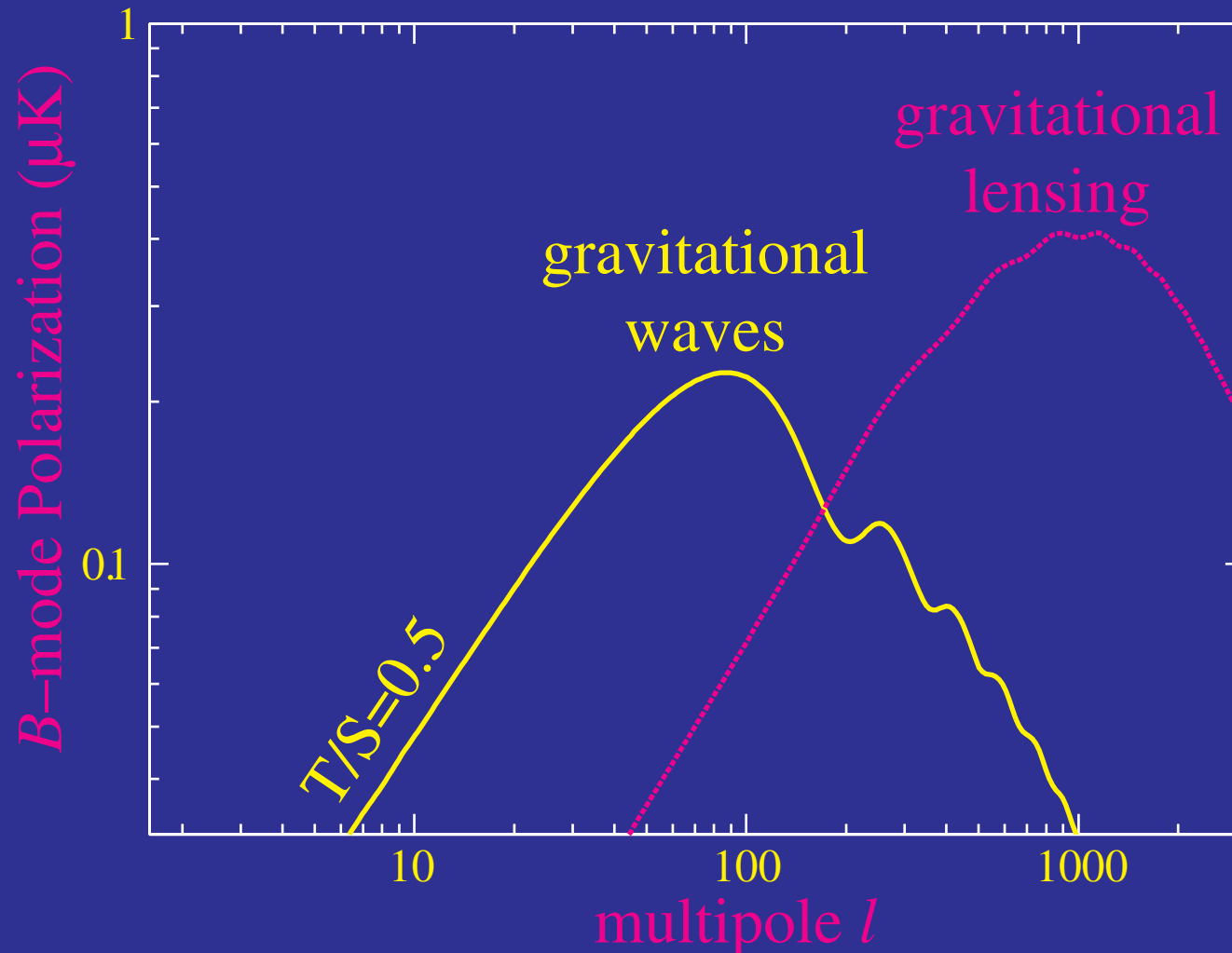
- Beyond linear theory, density fluctuations generate B-modes
- Secondary gravitational and scattering processes

B-modes from Secondaries

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B-modes from Secondaries

- Gravitational lensing is a foreground for gravitational waves
- B-modes can be used to map the dark matter



Summary

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- Power Spectra
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- Patterns
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Details & Outtakes

<http://background.uchicago.edu>

