Early Reionization and its Cosmological Implications

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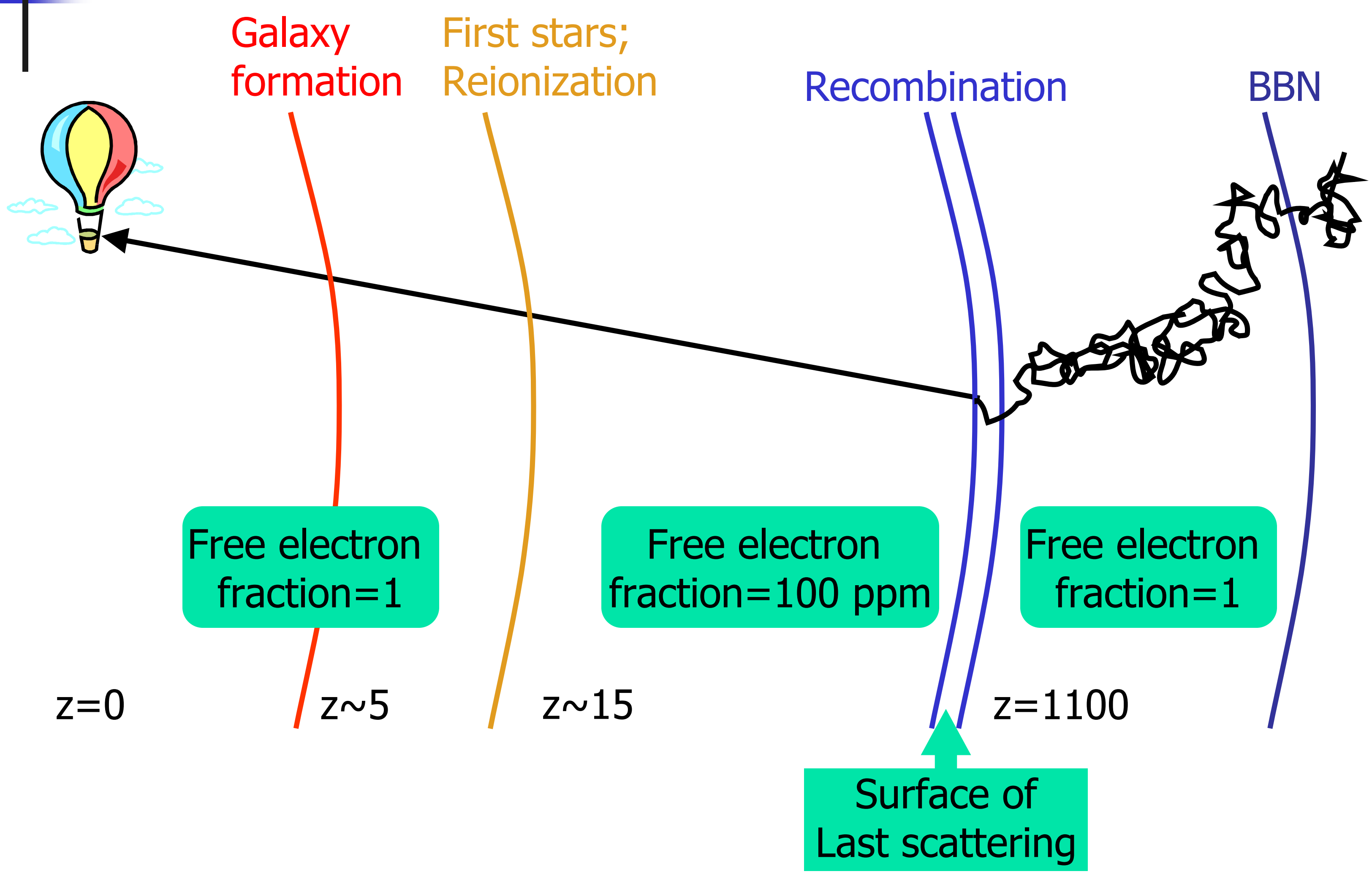
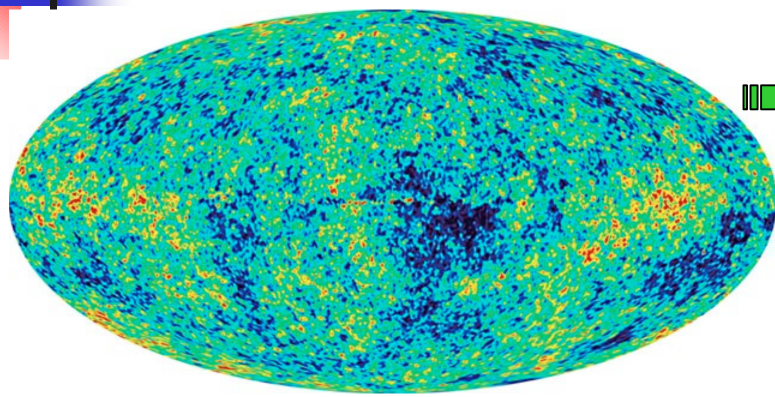
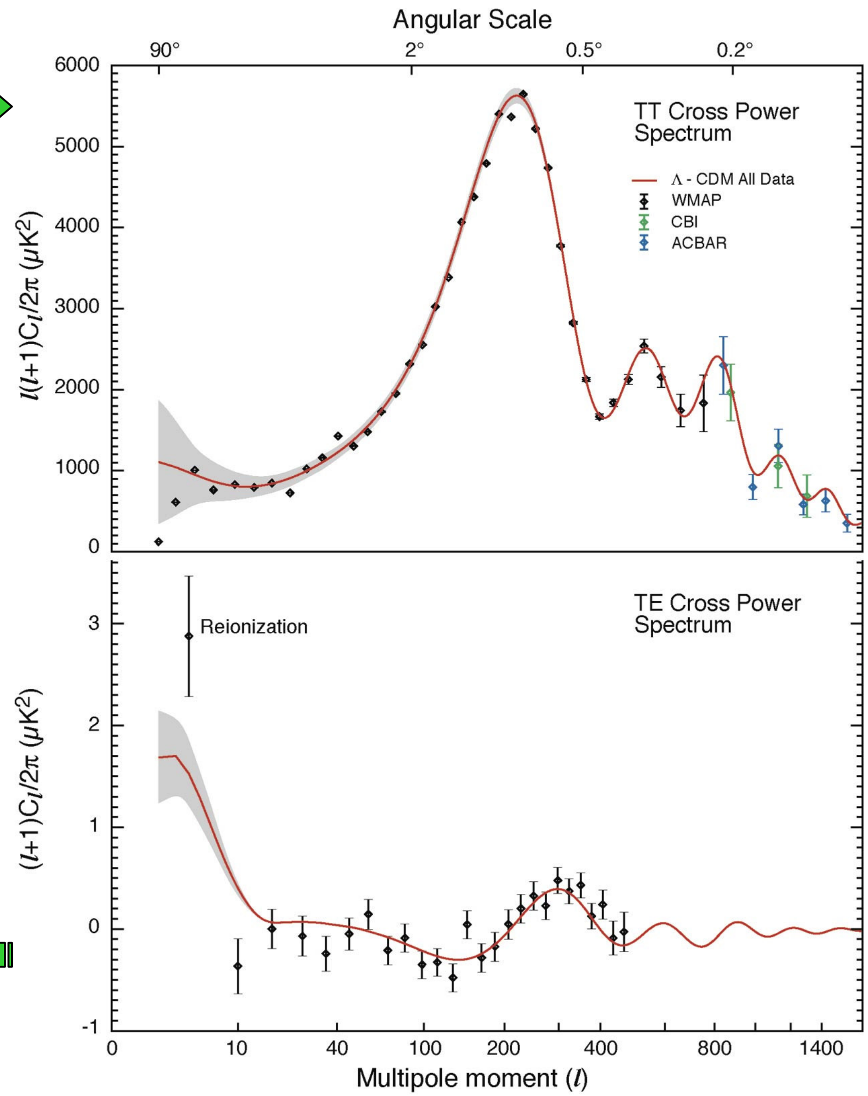
"Photonic" Thermal History



Early Reionization : WMAP Observations





Universe is close to being spatially FLAT.

95% of the universe is DARK! The rest (5%) is Baryonic.

First stars formed when the Universe was about 1/20th the present size.

What does it take to reionize the universe?

- $E_{nuc} \sim n_B f_* (28.3\ \mathrm{MeV}/4) = 7\, n_B f_*\ \mathrm{MeV}$
- $E_{ion} \sim 7\, n_B f_* f_{>13.6\ eV}\ \mathrm{MeV}$
- $E_{ion} / \langle \varepsilon_{ion} \rangle \sim n_H$
- $\rightarrow f_* \sim 10^{-6} / f_{>13.6\ eV}$
- (One ionizing photon for every H atom.)
- $100\ M_\odot \rightarrow 10^5$ K Blackbody spectrum

- However:
- Recombinations Happen.
- Recombination rate / Expansion rate $\simeq [(1+z)/11]^{1.5}$
- (Ionizing photon rate must offset this.)

- (Effect of clustering not included above.)

Ionizing Sources

- Stars, Quasars
- Requirements: (1) Ionize all H. (2) Keep it ionized.

- Ionizing photon production rate depends on:
  - Rate for gas to ionizing sources conversion.
  - IMF of ionizing source population.
  - Photon production rate per baryon (n_{phot}).
  - Fraction of photons escaping into the IGM (f_{esc}).
  - Clumping factor (C).

- Important inputs:
  - $n_{phot} = 10^4$ (Venkatesan et al, astro-ph/0206390)
  - $f_{esc} = 1$; $C=20$
  - F_{coll} ($T_{vir} > 10^4$) : Press-Schechter

Observing reionzation: Gunn-Peterson trough

- Spectrum of z=6.3 quasar in the Sloan Digital Sky Survey showed the Gunn-Peterson trough. (Becker et. al. AJ, 122, 2850, 2001; Fan et. al. AJ, 123, 1247, 2002.)
- Implication: something dramatic was happening around z=6.3. It could be that the universe went from neutral to ionized at z=6.3. It could also be that the universe went from 99% ionized to 100% ionized at z=6.3.

$$\tau(z) = 3.8\times 10^{5}\; x_{\mathrm{HI}} \frac{\Omega_{\mathrm{B}}\mathrm{h}^{2}}{0.02}\sqrt{\frac{0.15}{\Omega_{\mathrm{M}}\mathrm{h}^{2}}}\left(\frac{1+z}{7.3}\right)^{1.5}$$

- Out to z=5.8, $x_{HI} < 10^{-6}$ (Fan et. al. AJ, 120, 1167, 2000).

Observing reionization: CMB

- CMB is sensitive to reionization through the (integrated) Thomson scattering optical depth.

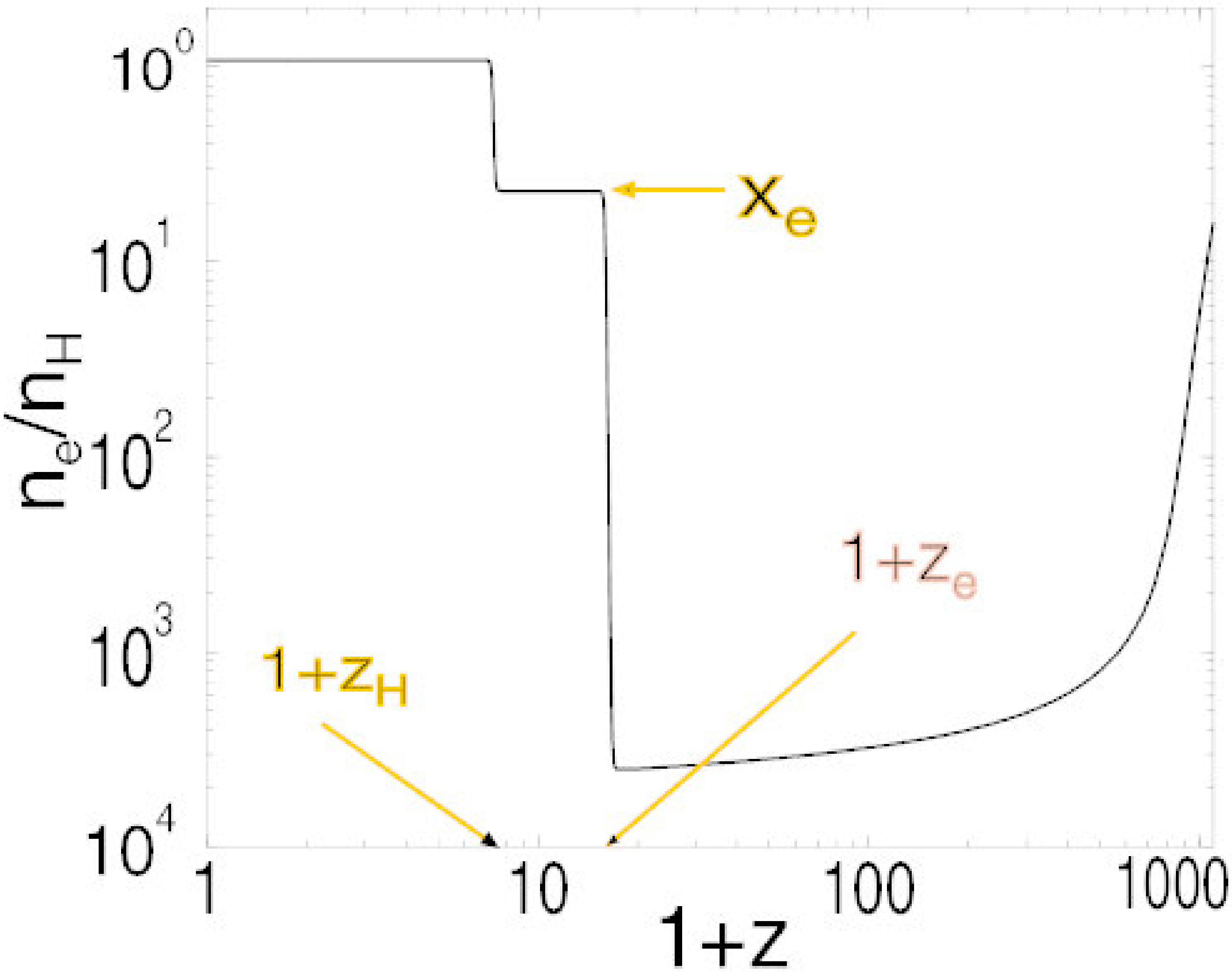
$$\tau_e(z) \approx 0.046\, x_e\, (1 - Y_P)\, \frac{\Omega_B h^2}{\sqrt{\Omega_M h^2}} (1+z)^{1.5}$$

- New peaks in the CMB polarization power spectra at low multipoles. (Zaldarriaga, PRD 55, 1822, 1997.)

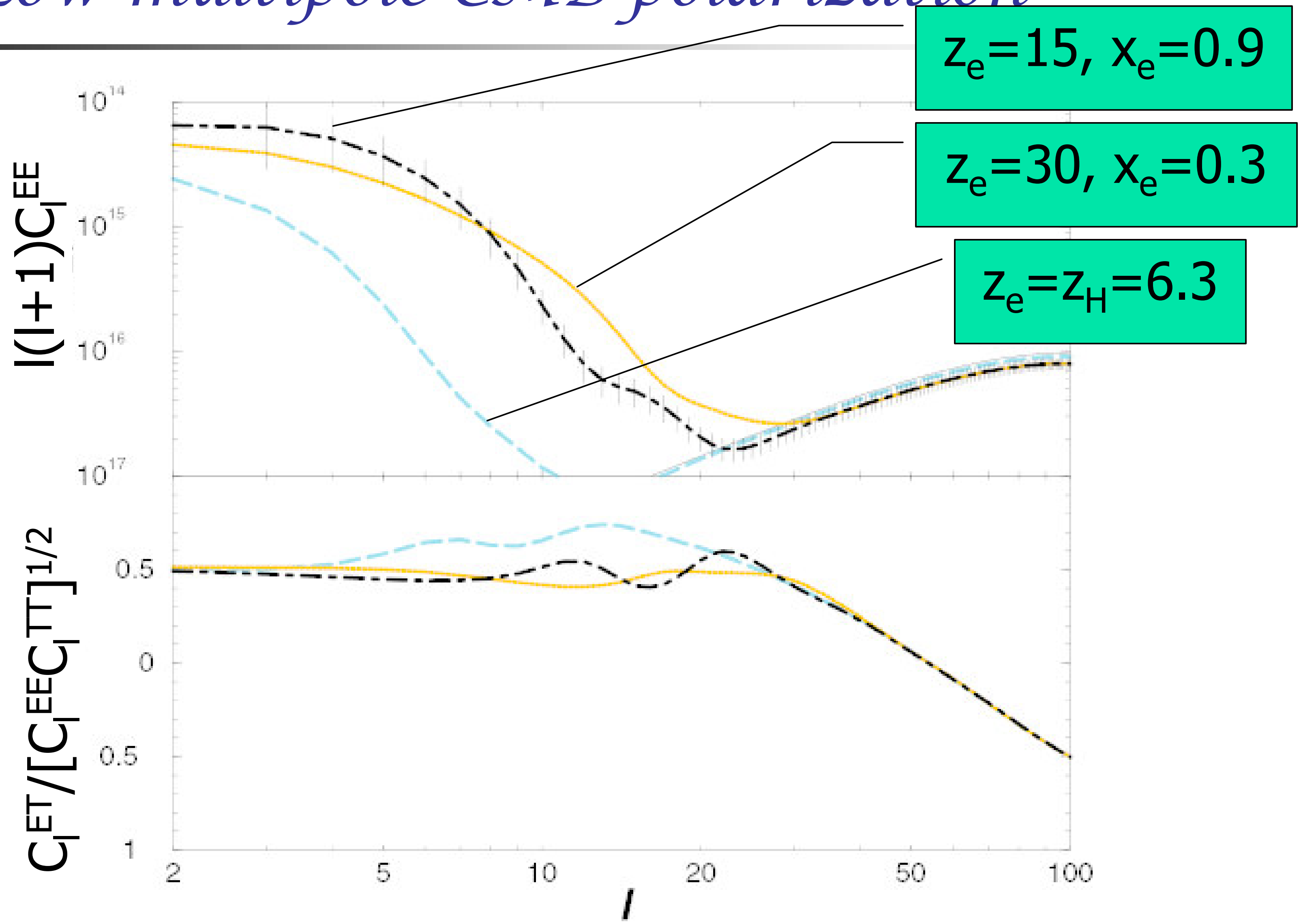
Reionization features in CMB polarization

- Free-streaming from last scattering surface
- Quadrupole at reionization
- Low multipole polarization
- $l_{ri} \sim (\eta_0 - \eta_{ri})/\eta_{ri}$ (Hu and White, ApJ 479, 568, 1997)
- $l(l+1)C_l^{EE} \propto \tau^2$ (Kaplinghat, Knox and Skordis, ApJ, 578, 665, 2002)

Reionization history



Low multipole CMB polarization

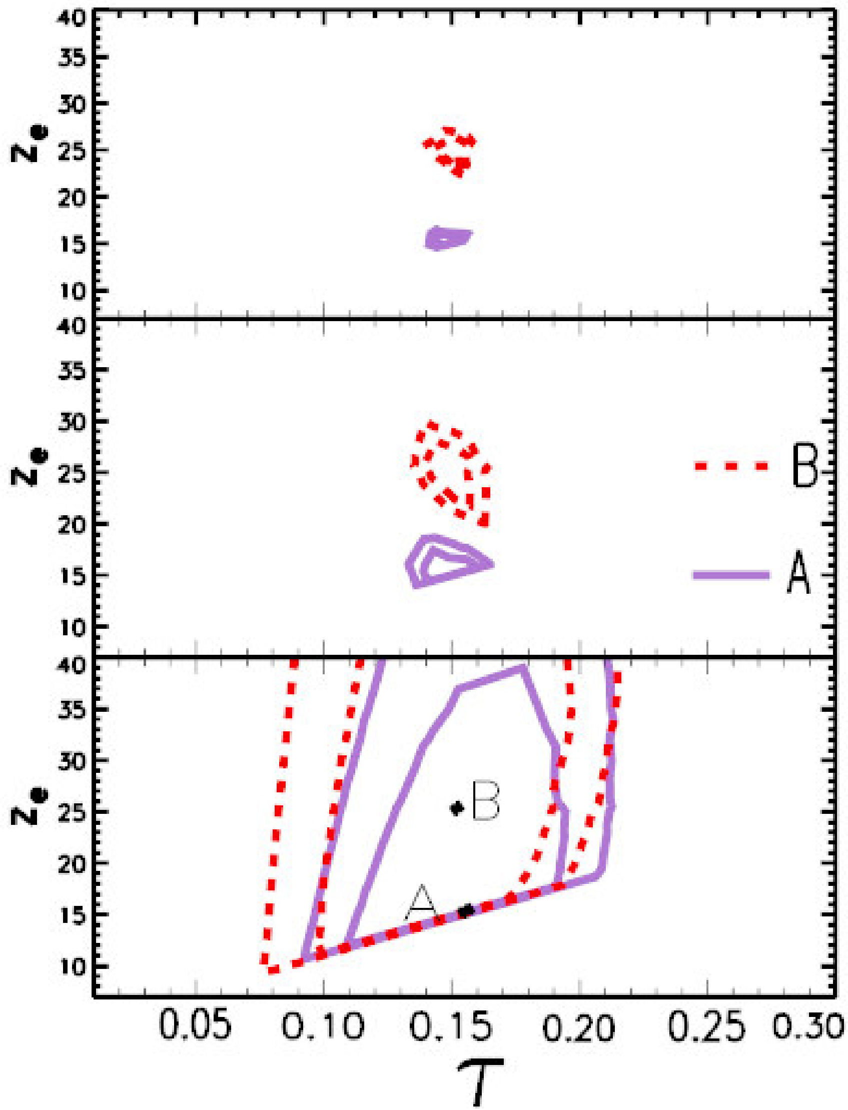


Probing reionization history

CMBpol

Planck

MAP



Summary (story so far)

- Dark ages ended with reionization. The universe was neutral after last scattering (also called recombination) and (almost) completely ionized after about $z \sim 6$.
- Redshift when neutral hydrogen atoms first appear $z_H = 6.3$. (Observation of Gunn-Peterson trough.)
- Redshift when free electrons (ionized H) first appear $z_e \sim 15$. (Low multipole/large angle power in CMB polarization.)
- Coming up…
- Cosmological implications.

Cosmological implications 1: Inflation

- Measurement of optical depth and the amplitude of scalar power spectrum are correlated.
- Primary CMB measures Amplitude x exp(-2 τ) extremely well.
- σ(Amplitude) / Amplitude = 2 $\sigma(\tau)$
- Planck can measure optical depth to about $\sigma(\tau)$=0.01
  (Kaplinghat et al Ap.J. 583 (2003) 24, Holder and Hu, Phys. Rev. D68 (2003) 023001.)
- Primordial scalar power spectrum amplitude can be measured to an accuracy of about 2%.
- Practically this is important for low redshift probes of the matter power spectrum (example lensing of the CMB).

Cosmological implications 2: Inflation

- Just like the E-mode polarization power spectra, the B-mode power spectrum will also show a distinct reionization "bump".

- This can be vital to measuring the B-mode power spectrum and hence the energy scale of inflation.

- On large scales (where the reionization bump shows up), there is no contamination from gravitational lensing of the CMB. On smaller scales, lensing contamination limits how well B-mode signal can be measured. (Knox and Song, PRL, 2002; Kesden, Cooray and Kamionkowski, PRL 2002.)

- Including the B-mode reionization bump, detectability of tensors (at 3σ) is limited to $T/S > 10^{-5}$ or $E_{inf} > 1.7 \times 10^{15}$ GeV. (Kaplinghat, Knox and Song, PRL, 2003.)

Cosmological implications 3: Structure

- High optical depth seems to require more collapsed structures or (unnaturally) large efficiencies.

- Perhaps this is pointing to primordial non-gaussianity (or a large scale dependent isocurvature contribution)…

  (Chen et al MNRAS 346 (2003) L31; Sugiyama et al astroph/0310593.)

- Primordial non-gaussianity: $\Phi_L = \Phi_L + f_{NL}\,\Phi_L^2$

- Constant f_{NL} models won't do the job. Scale-dependent non-gaussianity from inflationary models is an interesting possibility and a test of non-standard inflationary dynamics.

  (Chen et al MNRAS 346 (2003) L31; Kaplinghat, Santos and Haiman, 2004.)

Observations

- Non-negligible power at large angles in CMB polarization is due to the formation of anisotropy during reionization and hence it can provide valuable constraints on reionization history.

- 21 cm absorption and emission can trace the state of the IGM during reionization. The anisotropic 21 cm signal resulting from the patchiness of the reionization process will help us better understand early structure formation.

- Direct detection (by James Webb Space Telescope) of sources at $z \sim 20$.

- We can expect exciting results about the reionization history and early universe inflation from future observations.