Reconstructing the Reionisation History with the Cosmic Microwave Background

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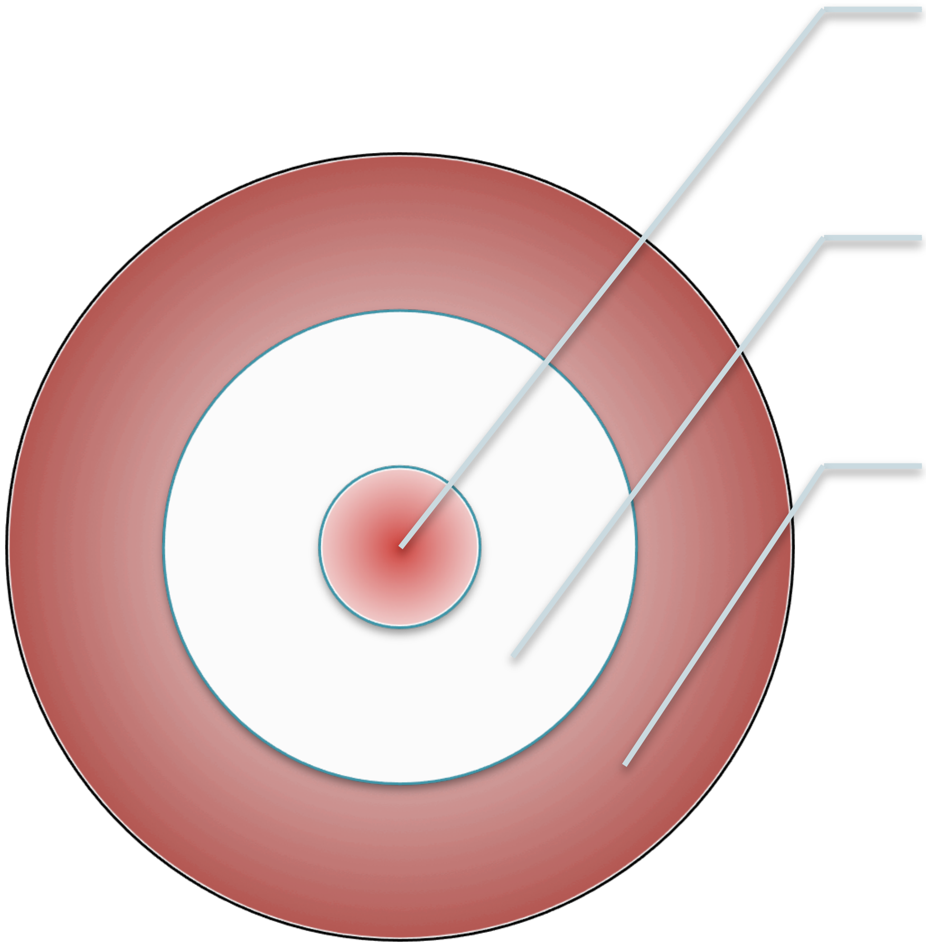
Effort of Planck WG 5: lead by Nabila Aghanim, Richard Battye, JW

Excellence Cluster Universe

The Transport of CMB Photons through a Ionised Universe

- 3 phases
  - tight coupling regime: $z > 1100$
    - photons and baryons are coupled and the Universe is opaque
  - free streaming regime: $1000>z>20$ (?)
    - Universe is neutral and the CMB photons stream freely through the medium
  - Ionized regime: $20>z$
    - photons couple again to free electrons

The Scattering Surfaces



Quantitative Prescription

- Imprint on CMB anisotropies governed by the visibility – or probability that a photon scatters out of the line of sight

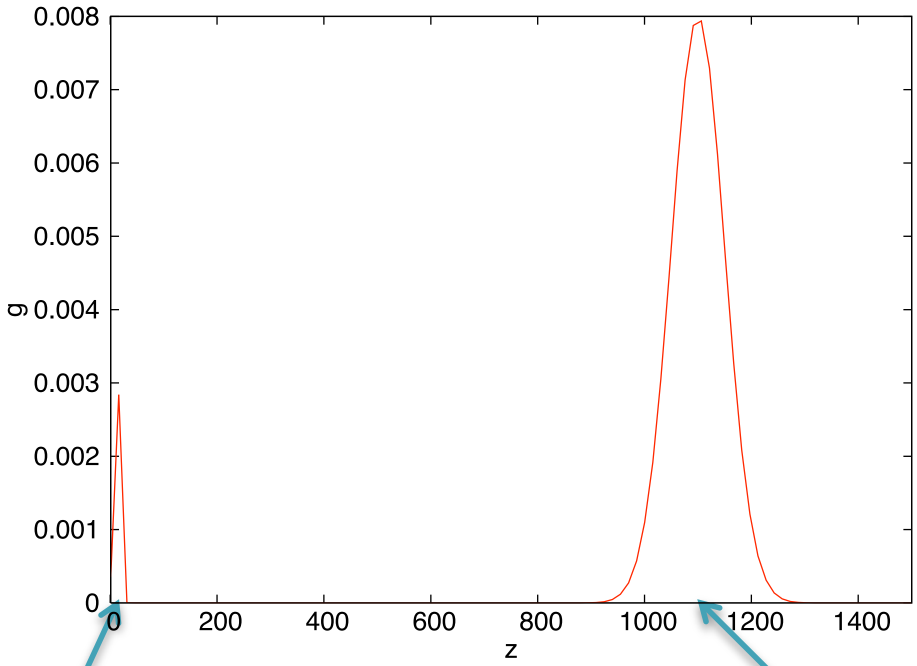
$$g = \dot{\tau} e^{-\tau}$$

- τ is the optical depth given by

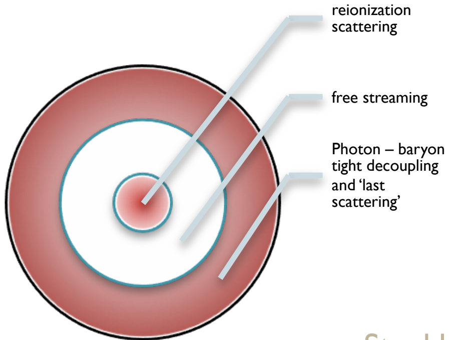
$$\dot{\tau} = x_e n_H \sigma_T$$

wih $x_e n_H$ the number density of free electrons

Example for Visibility



artificially enhanced reionisation scattering



'Last Scattering'

Imprint on CMB Anisotropies

- For simple analytical argument assume for a moment a visibility made of two delta-functions

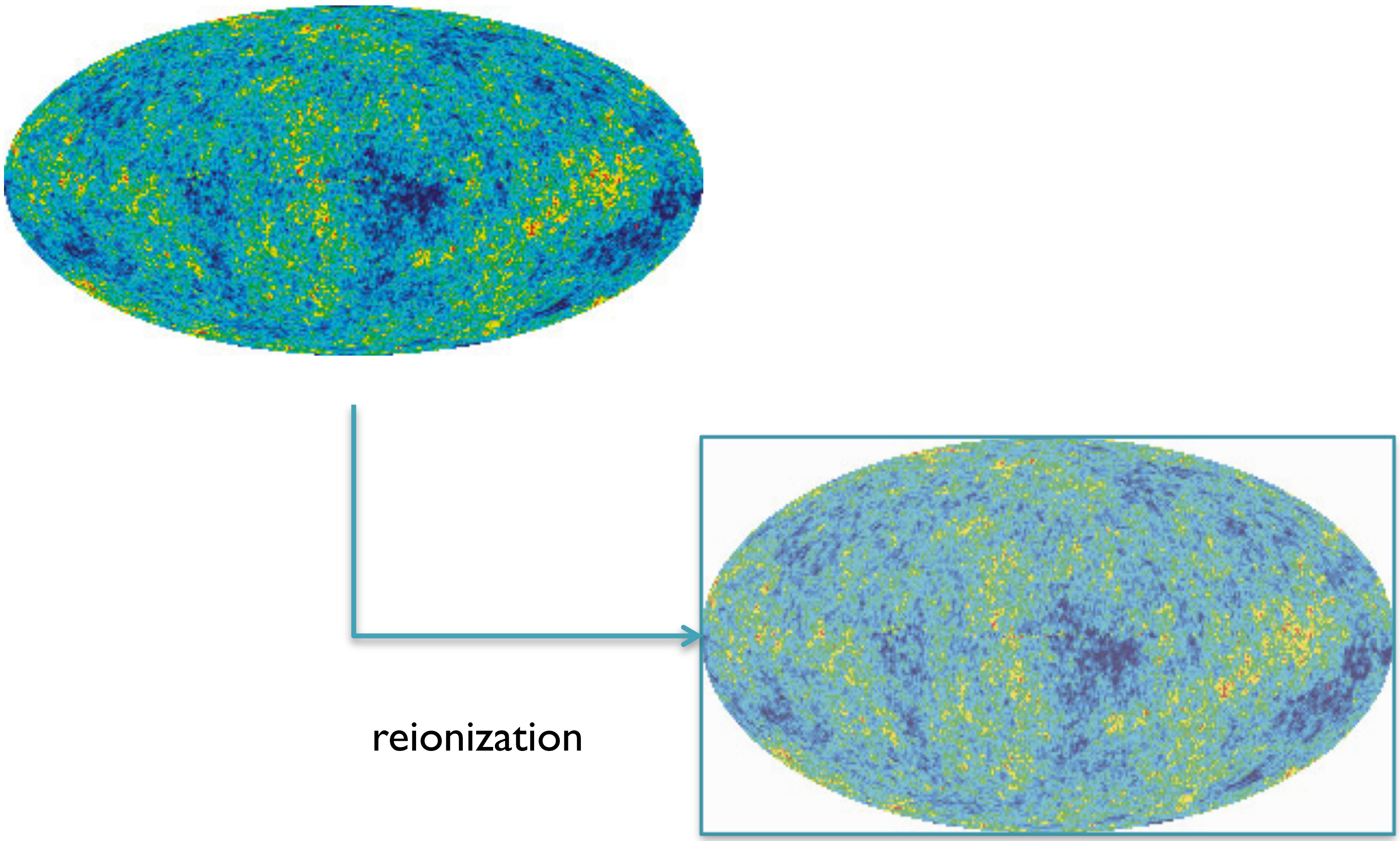
$$g(z) = e^{-\tau(z_r)}\delta(z - z_{rec}) + (1 - e^{-\tau(z_r)})\delta(z - z_r)$$

- In this case the CMB temperature anisotropy is given by three contributions

$$\Delta_l = e^{-\tau(z_r)} F_l(z_{rec}) + \left[1 - e^{-\tau(z_r)}\right] F_l(z_r) + ISW$$

- For astrophysical reionisation scenarios ('low' reionisation redshift and low optical depth) the second term is usually negligible
- Hence: Damped temperature anisotropy

Damped Temperature Fluctuations



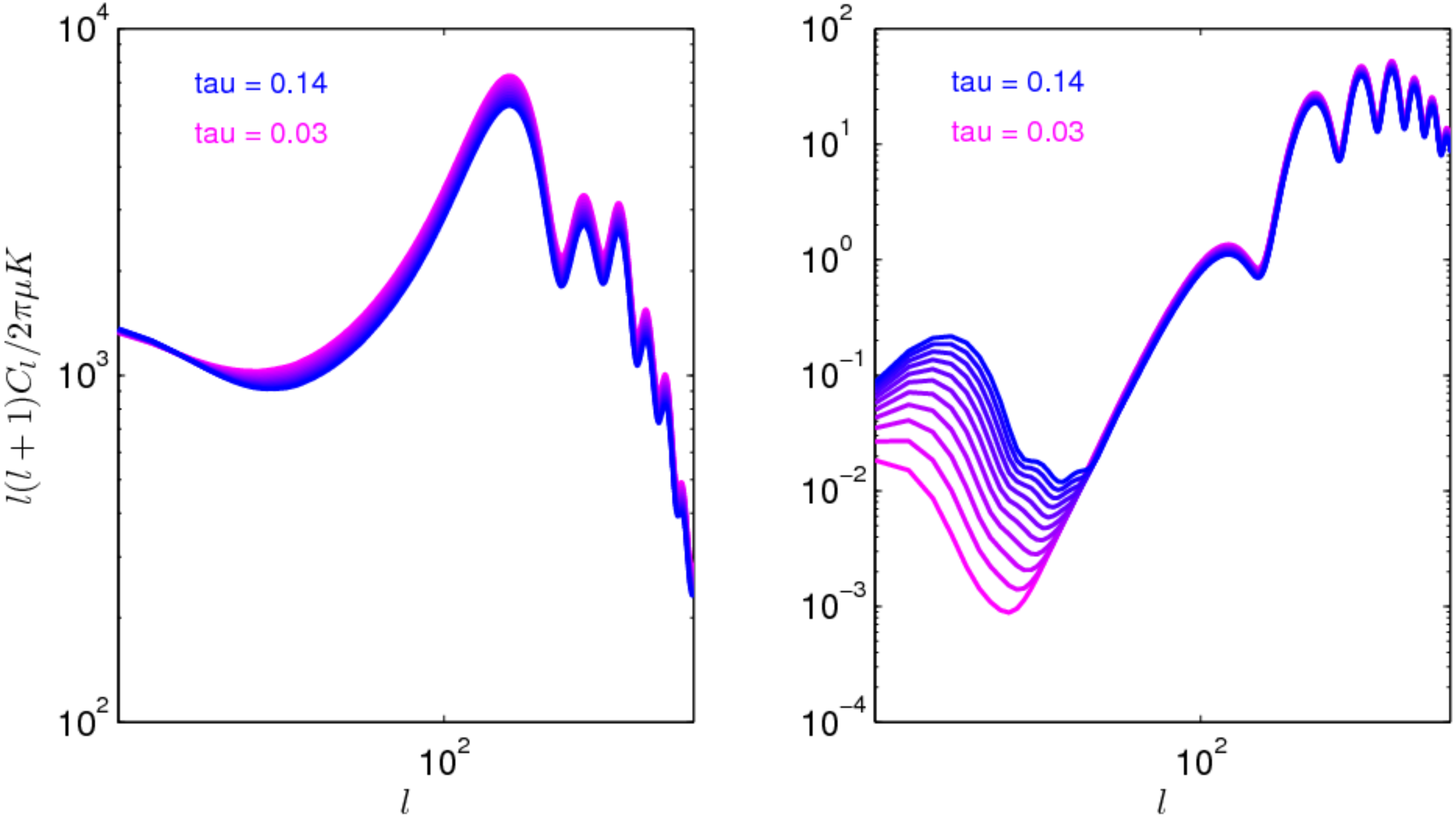
Imprint on Polarization Anisotropies

- Two contributions

$$E_l \propto \left[e^{-\tau(z_r)} P(z_{rec}) \varepsilon_l \{ z_{rec} \} + \left(1 - e^{-\tau(z_r)}\right) P(z_r) \varepsilon_l \{ z_r \} \right]$$

- Quadrupole P(z) grows significantly after recombination. For polarization second term is NOT negligible
- ε_l (Bessel function) peaks for angular scales of last scattering and reionisation

Anisotropy Power Spectra

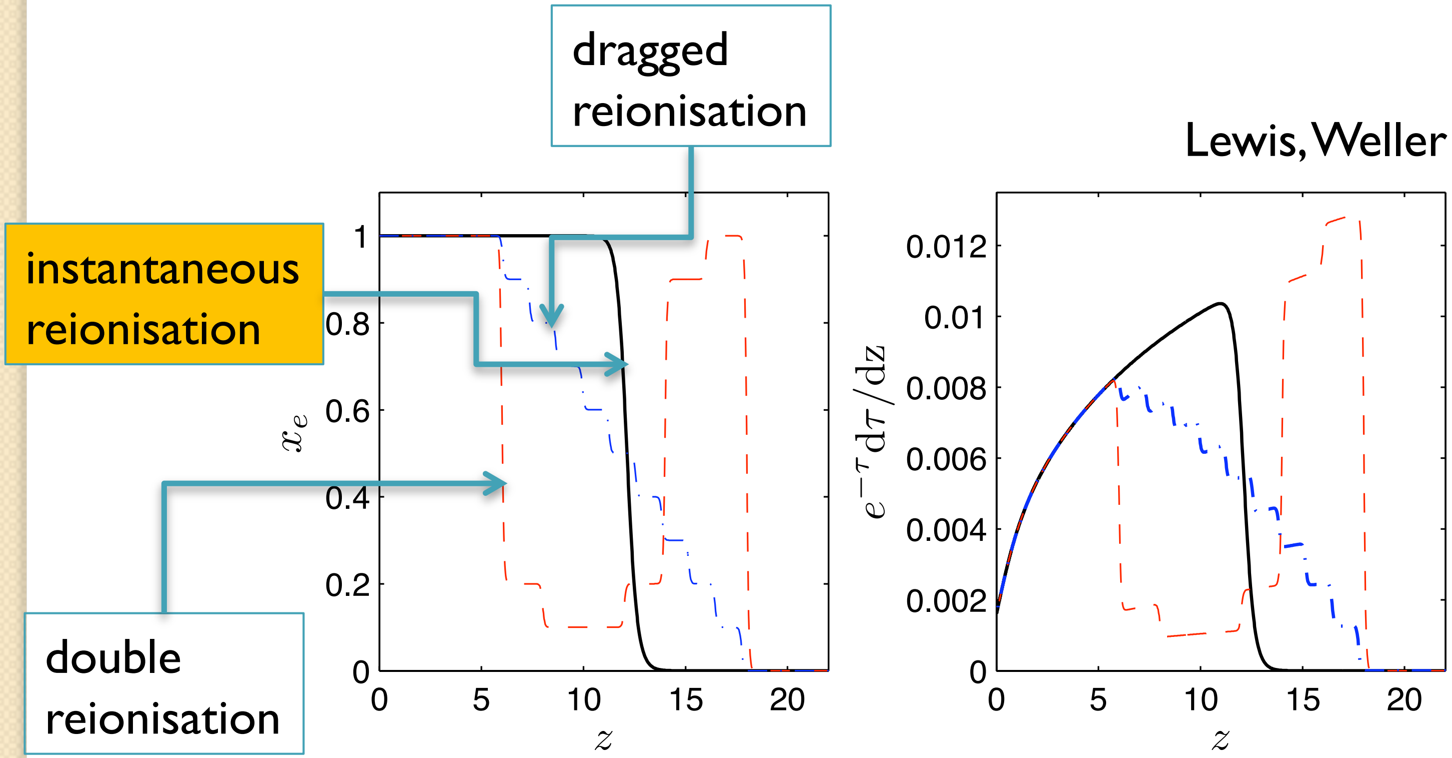


From previous talk by A. Lewis

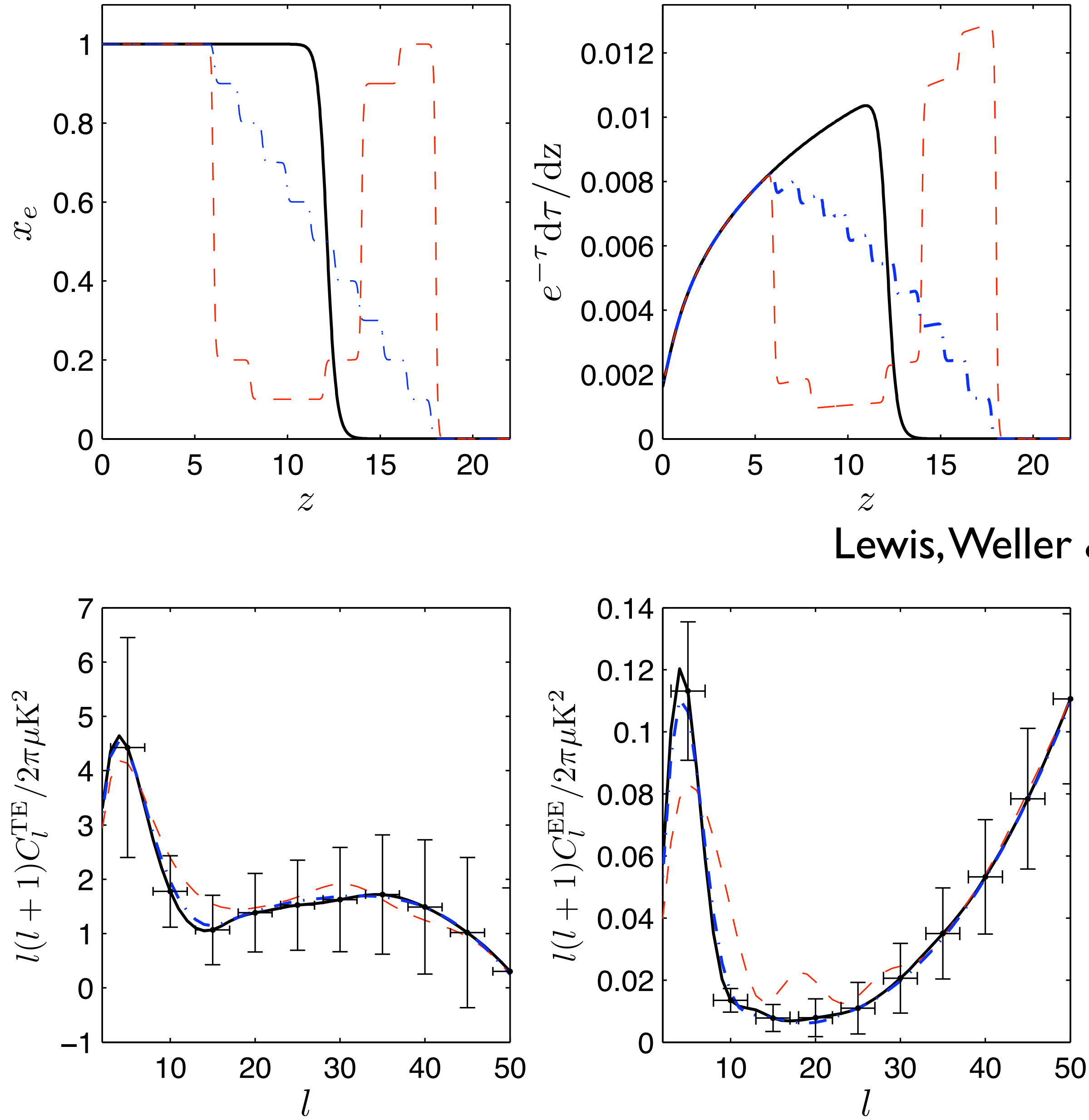
Build up to Include 'Realistic' Reionisation Histories

- Obtain ionisation history in terms of reionisation fraction
- and calculate visibility
- same total optical depth for all models: τ =0.1

Lewis, Weller & Battye 2006



Response in Polarization Spectra



Lewis, Weller & Battye 2006

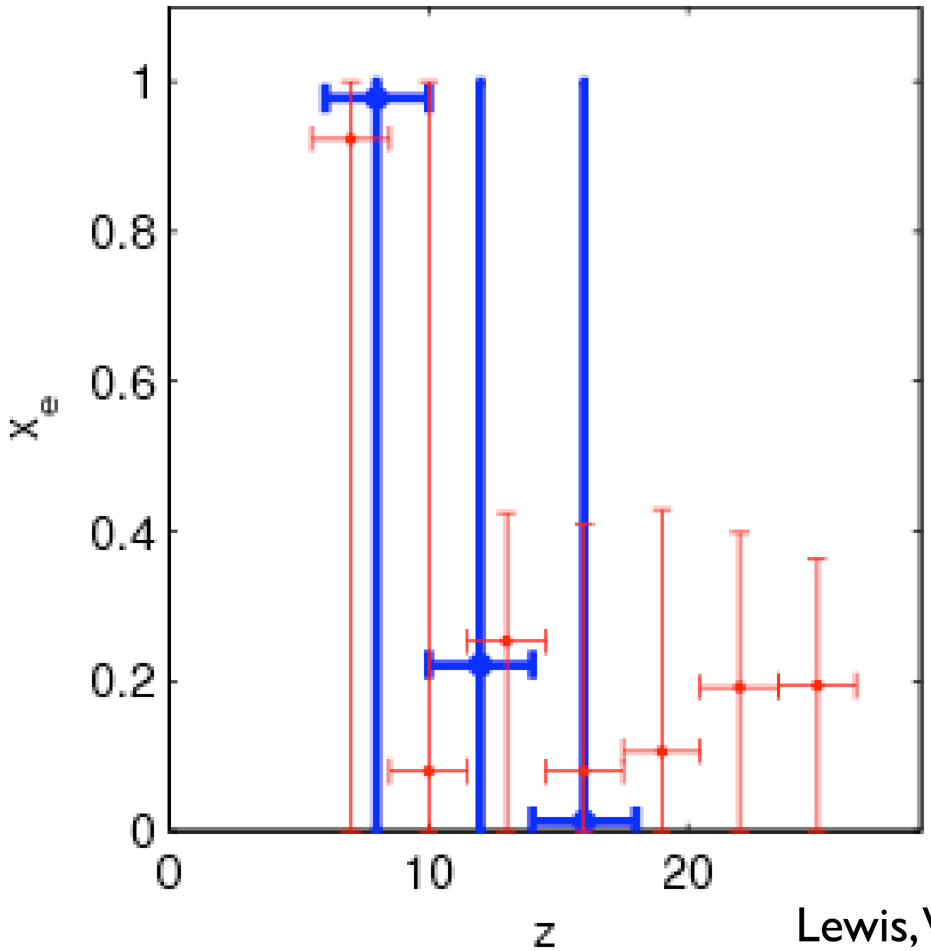
Reconstructing the Reionisation History

- Ionization fraction in bins:

$$x_e(z) = x_i \qquad z_i - \frac{\Delta z}{2} < z < z_i + \frac{\Delta z}{2}$$

- maximum redshift above, which ionisation fraction follows std. recombination history
- minimum redshift below, which ionisation is complete (here z=6)

Result for WMAP3



Lewis, Weller & Battye 2006

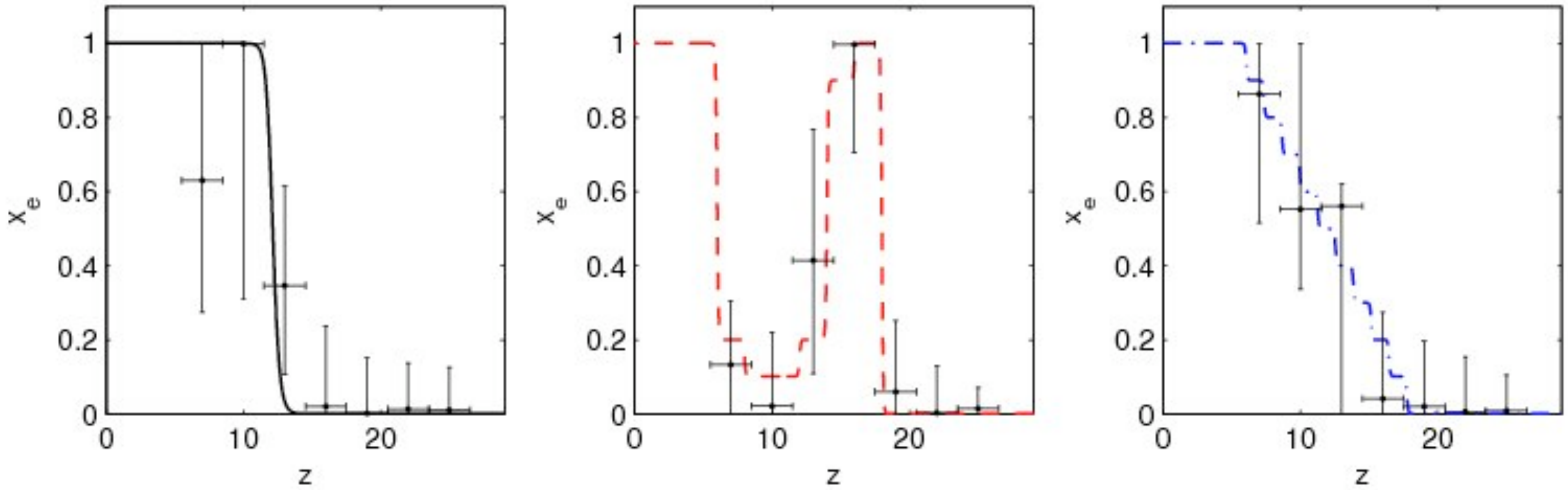
Three vs. 7 bins;

Beware of Prior

- Conclusion: For more bins ionization fraction is lower at intermediate redshift
- Prior: Random amplitude in each bin
- If data is not strongly constraining there is a tendency to have a small contribution to the optical depth in each bin. This effect is getting stronger for a larger number of bins
- Way out? Include smoothness or more realistic prior

As Good as it Gets

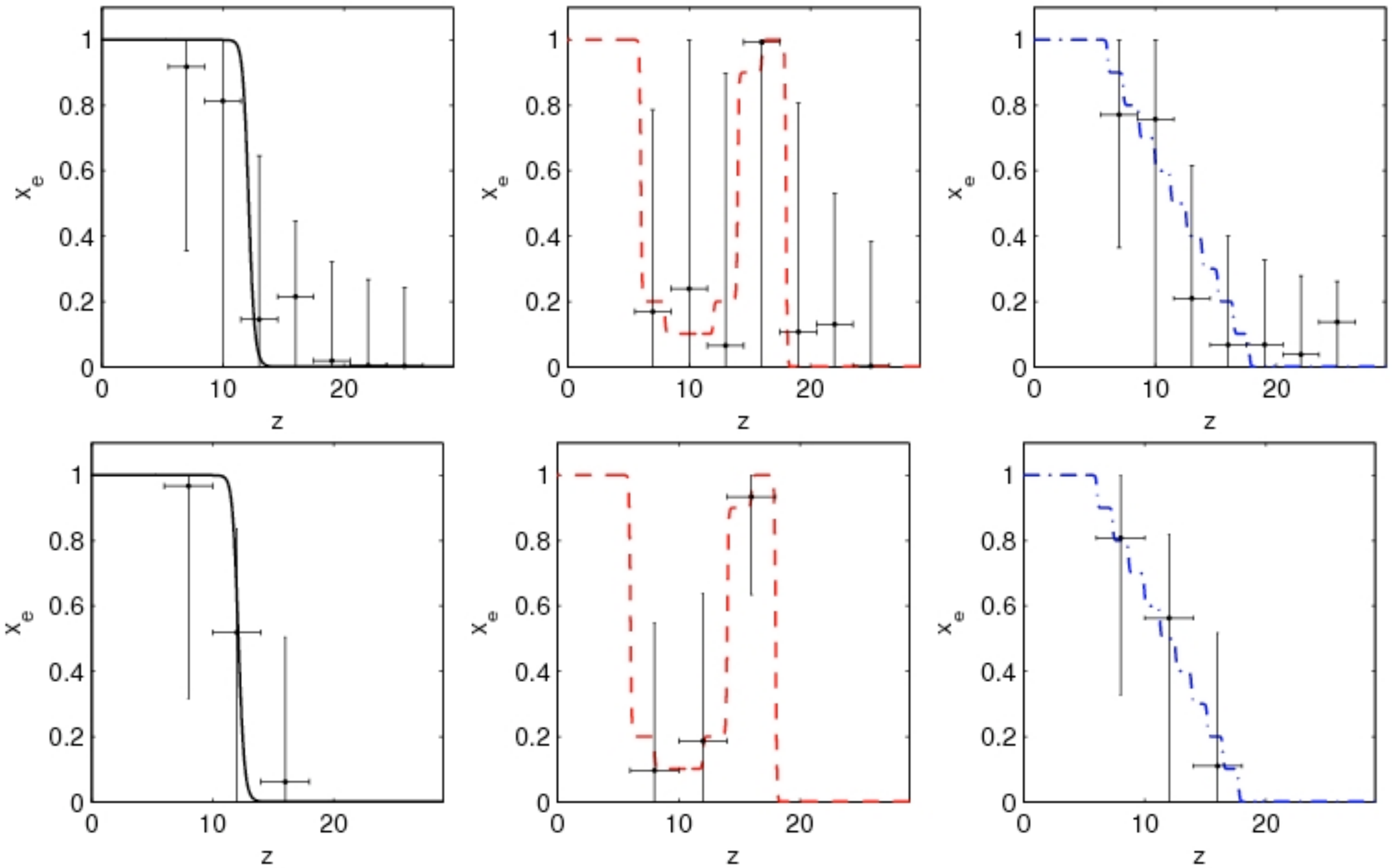
Lewis, Weller & Battye 2006



Perfect Situation: Fixed cosmological parameters; noise free

Forecasting Planck

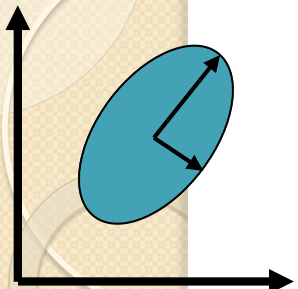
Lewis, Weller & Battye 2006



Including noise, marginalized over cosmological parameters

Conclusions so far

- Hard to distinguish the three fiducial models at the $2-\sigma$ level
- Planck can not resolve the start of reionization accurately to distinguish a high x_e followed by a low x_e from the case of two equal contributions
- 4 bins look better if maximum reionisation is fixed to z = 18
- The estimate of the total optical depth is robust for binning



Principal Component Approach

(Hu & Holder 2003; Mortonson & Hu 2007,2008)

- calculate Fisher matrix for leading order approximation of likelihood

$$F_{ij} = \left\langle \frac{\partial^2 \mathcal{L}}{\partial x_i^e \partial x_j^e} \right\rangle$$

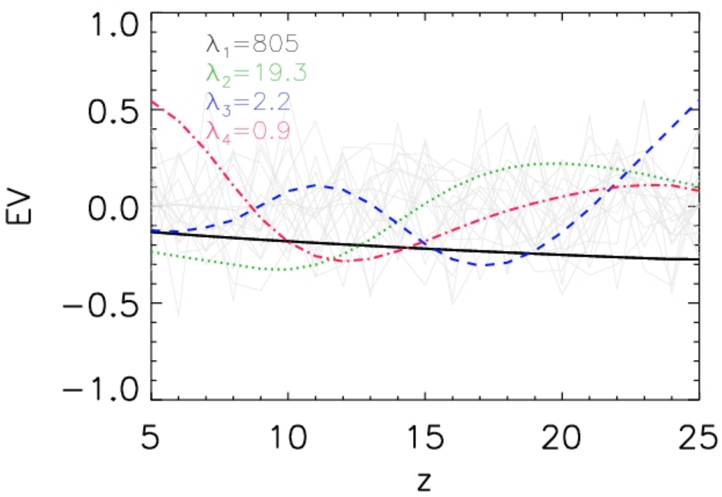
- Diagonalize Fisher matrix to establish independent modes

$$D = XFX^T$$

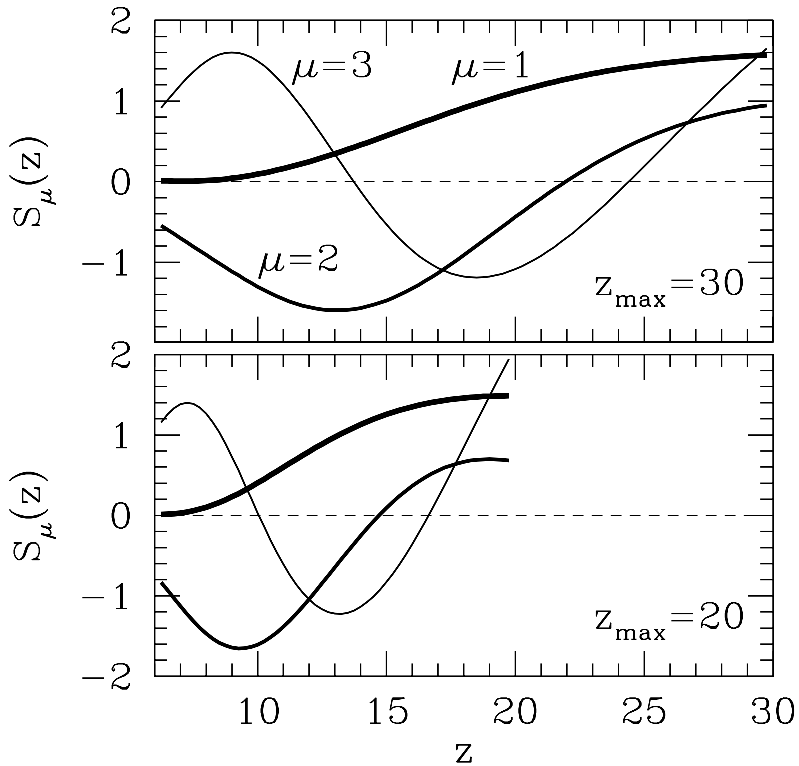
$$x_e(z) = x_e^{fid}(z) + \sum_{j=1}^{N} \alpha_j e_j(z)$$

- Inverse Eigenvalue is measure of uncertainty in Eigenmode $\Delta\alpha_j = \lambda_j^{-1/2}$

Eigenmodes in the Reionisation Fraction

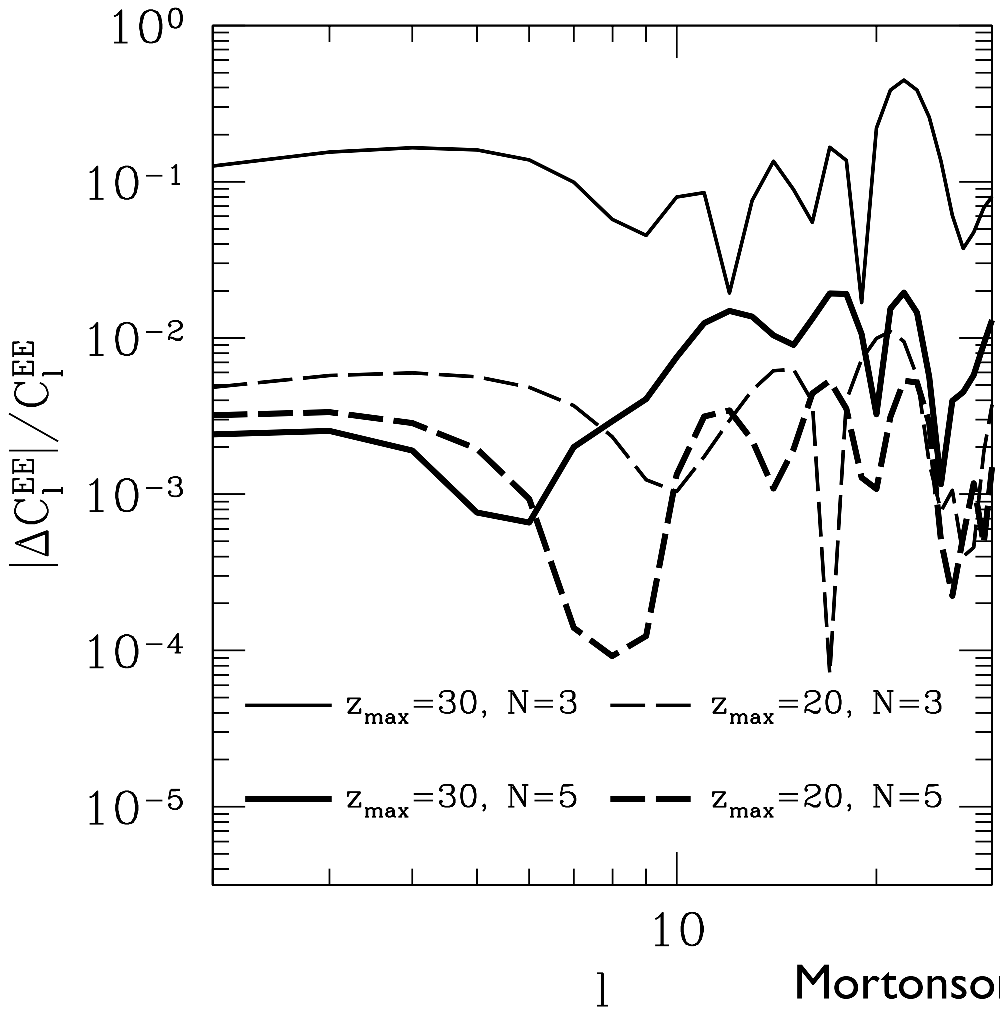


just E and cosmic variance
z_{min}=6; Δ z = 0.25; z_{max} = 25



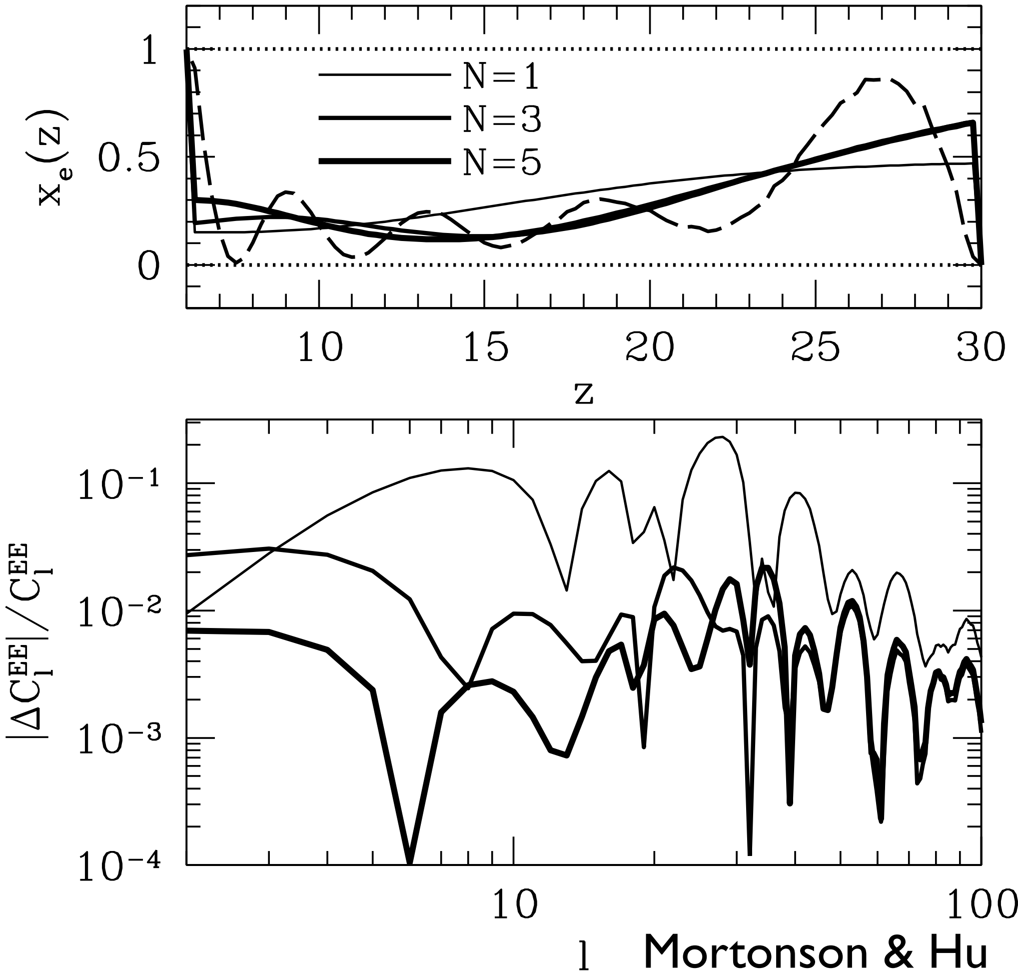
Mortonson & Hu 06
(different normalization !)

Impact of Maximum Redshift



Mortonson & Hu 07

Completeness from Modes



Mortonson & Hu 07

How to Decide the Number of Modes

- Fix a priori (Mortonson & Hu use 6)
  - from convergence arguments
- Use Evidence
  - evidence measures three effects in fitting
    - goodness of fit
    - degradation of errorbars due to increased number of parameters
    - bias between true underlying model and fiducial model

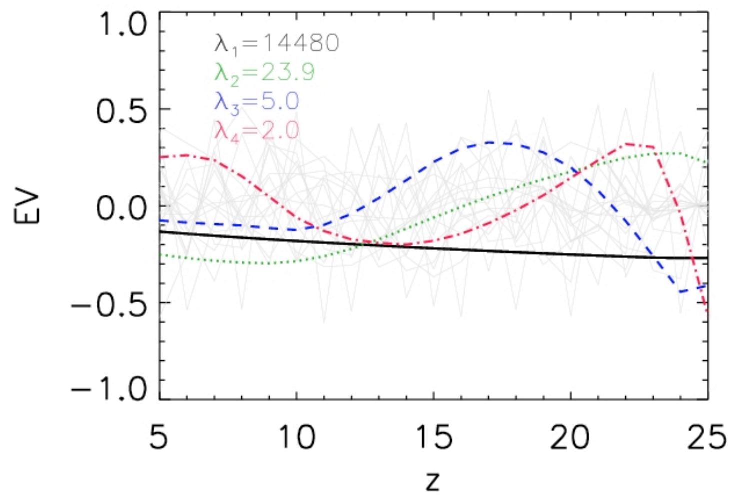
$$\mathcal{E} = P(D|H) \approx \underbrace{P(D|\theta_L, H)}^{\text{best fit}} \underbrace{\exp(-C)}_{\text{bias: prior-true}} \underbrace{\left(\frac{|F+P|}{|P|}\right)^{-1/2}}_{\text{Occam's razor}}$$

Simple Rule of Thumb

- Rough guide for significant Eigenmodes is $N\lambda_i > 100$
  - under simplifying Gaussian assumptions
  - neglect bias
- However, taking only low number of Eigenmodes creates bias wrt to true model

Forecasted Eigenmodes for Planck

- Use instantaneous reionization as fiducial model (τ =0.09)



Using T, E, TE and noise

- Improvement only on first mode: τ
- 4 modes significantly constraint

Priors – Again !

- PCA leads to negative (unphysical) ionization fraction
- Constraint on possible amplitudes

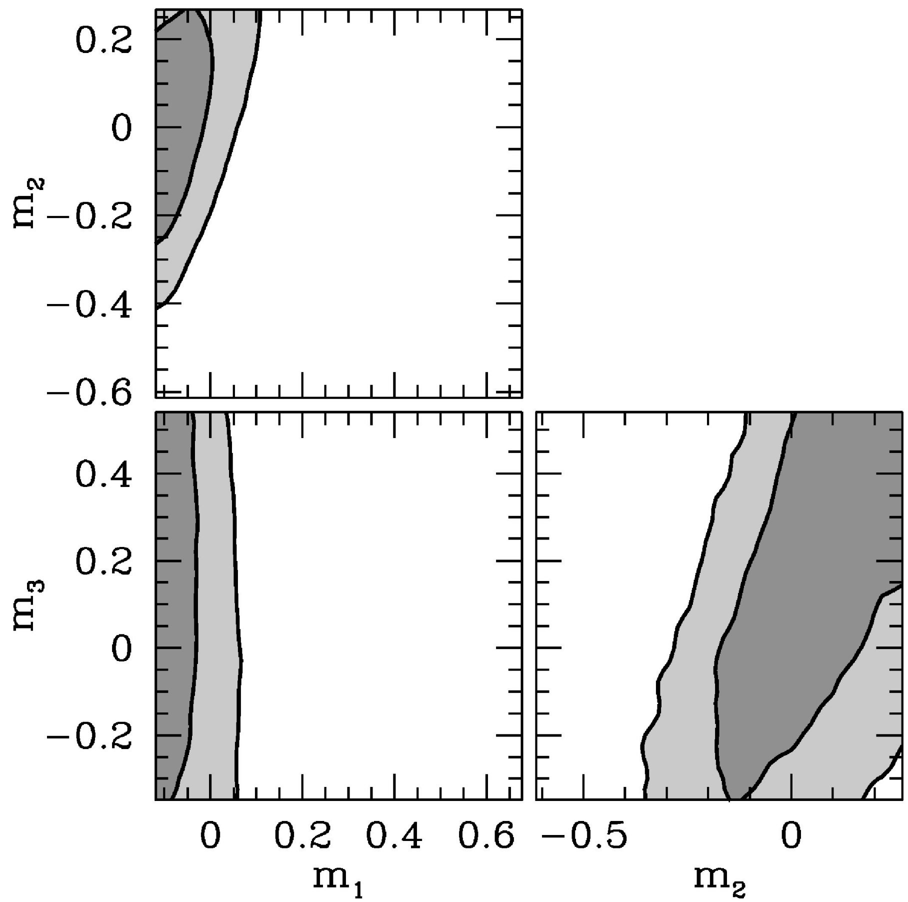
$$\alpha_i^{(\pm)} = \int_{z_{min}}^{z_{max}} dz \frac{e_i(z)[1-2x_e^{fid}(z)] \pm |e_i(z)|}{2(z_{max}-z_{min})}$$

- additional

$$\sum_i e_i^2(z) < max[(x_e^{fid})^2, (1-x_e^{fid})^2]$$

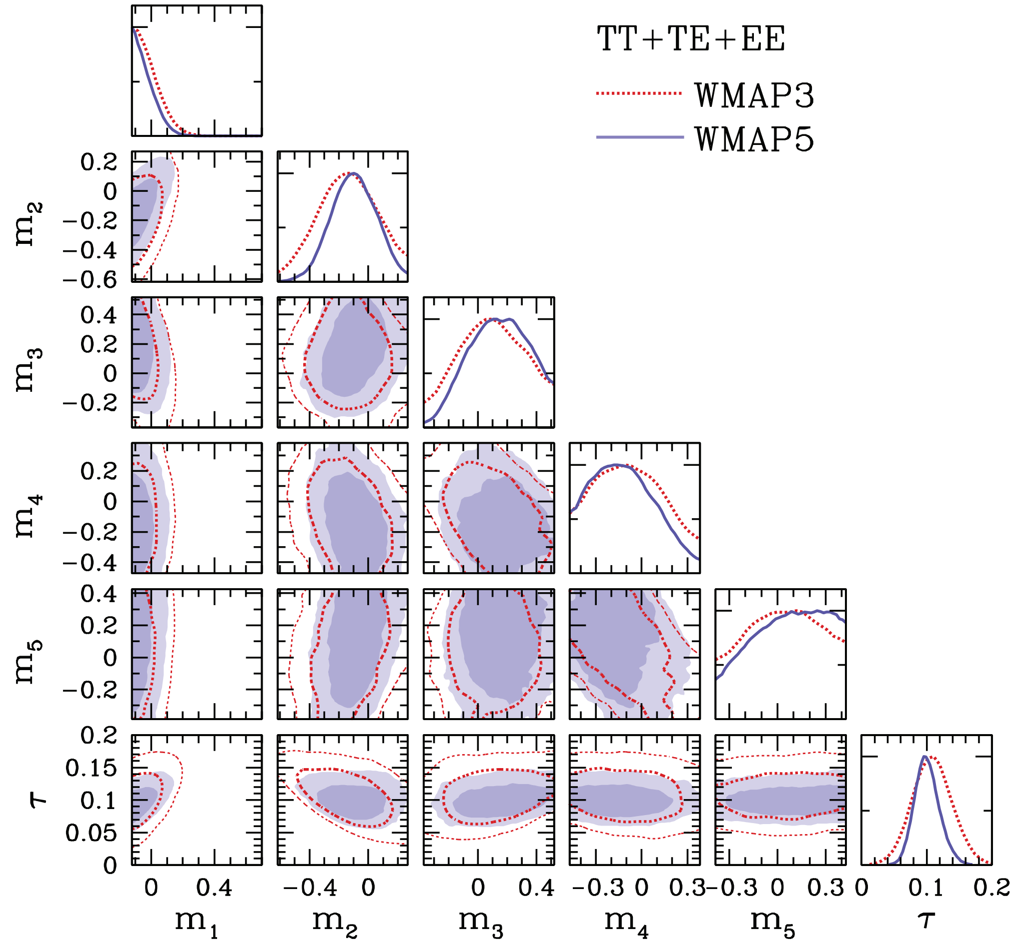
- Too restrictive for finite set of Eigenmodes; in practice prior on optical depth τ required

Modes from WMAP3



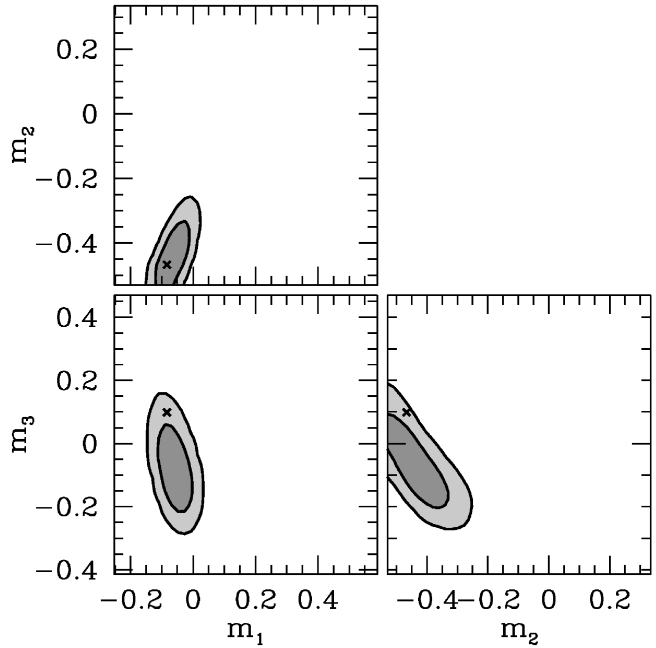
Mortonson & Hu 07

Result for WMAP5

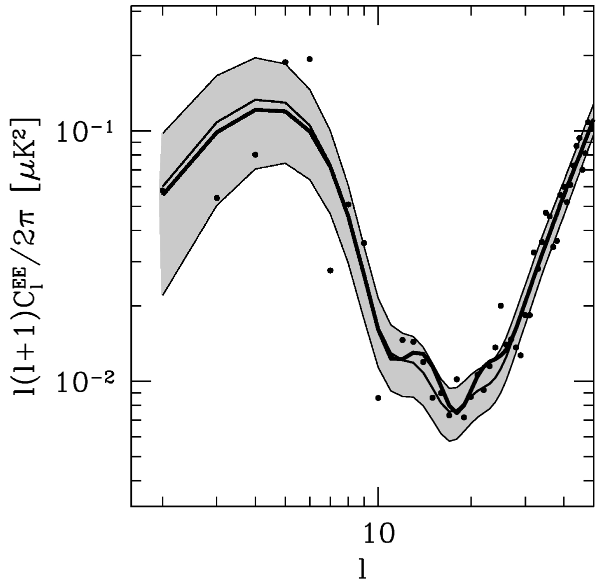


Mortonson & Hu 08

Cosmic Variance Limited Case



Mortonson & Hu 07

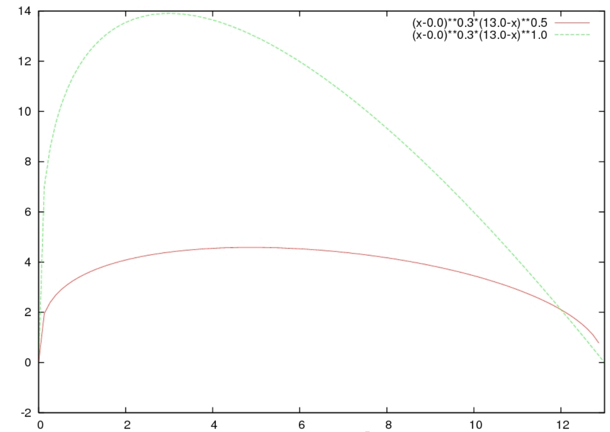


A Better Approach: Reconstructing the Visibility Function

- $x_e(z)$ bins not too well constrained
- CMB directly sensitive to visibility $\dot{\tau}e^{-\tau}$
- Probability that photon gets scatter out of line of sight

$$v = \dot{\tau}e^{-\tau} = N(z - z_1)^n (z_2 - z)^m$$

- A lot of models captured by this; allows non-Gaussian scatter probability



not normalized

Conclusion

- Currently reionisation history constraints from CMB deliver ‘only’ the optical depth
- Binning approach is versatile
- PCA shows that possibly 3-4 modes can be constrained with Planck
  - Polarization foregrounds on large scales ?
- Careful about priors and physicality
- Direct constraint of visibility function is most likely a bit better