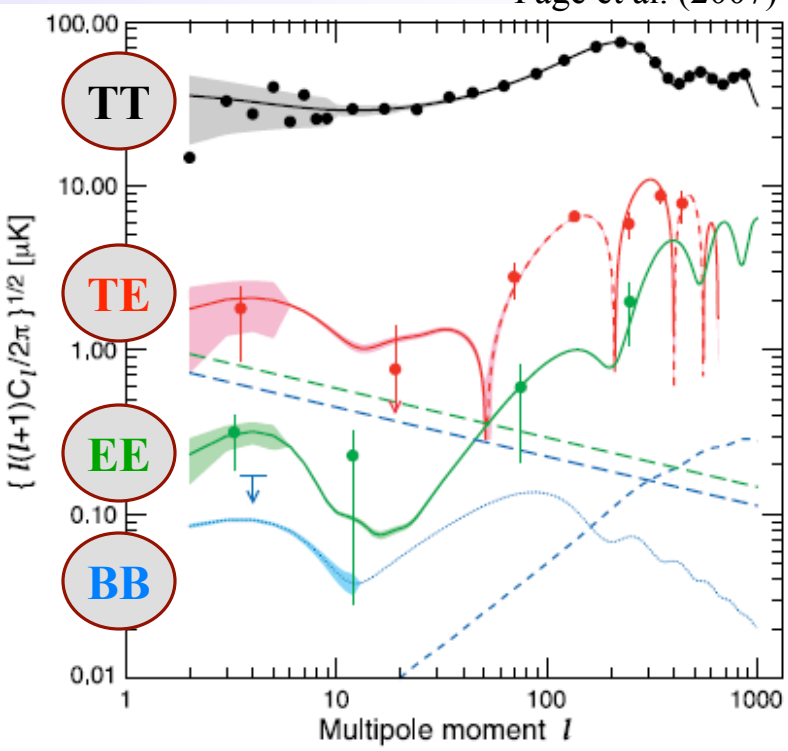
The Reionization History from WMAP5 and Beyond

Michael Mortonson

Kavli Institute for Cosmological Physics
University of Chicago

UC Berkeley Cosmology Seminar
April 22, 2008

Page et al. (2007)



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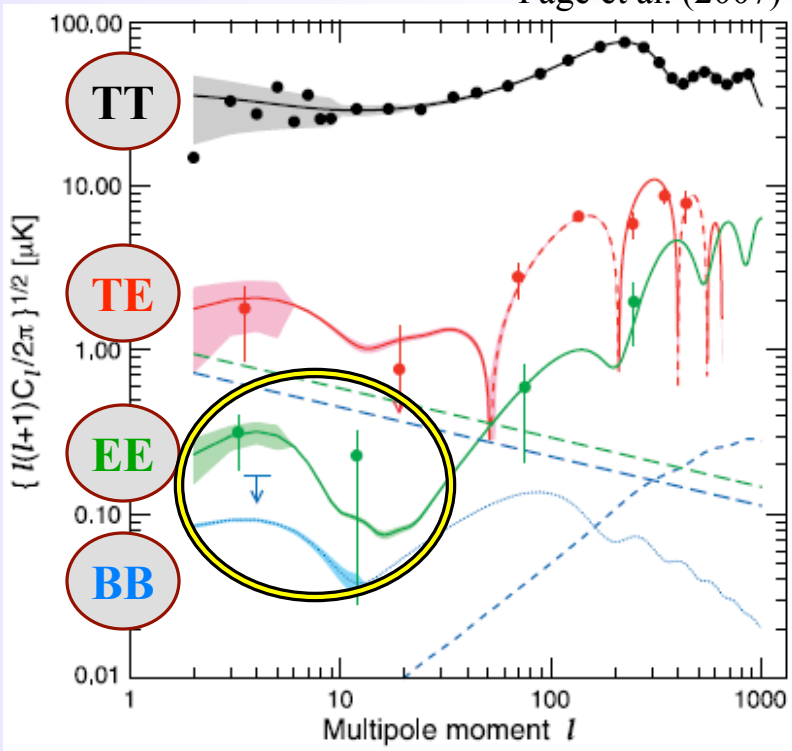
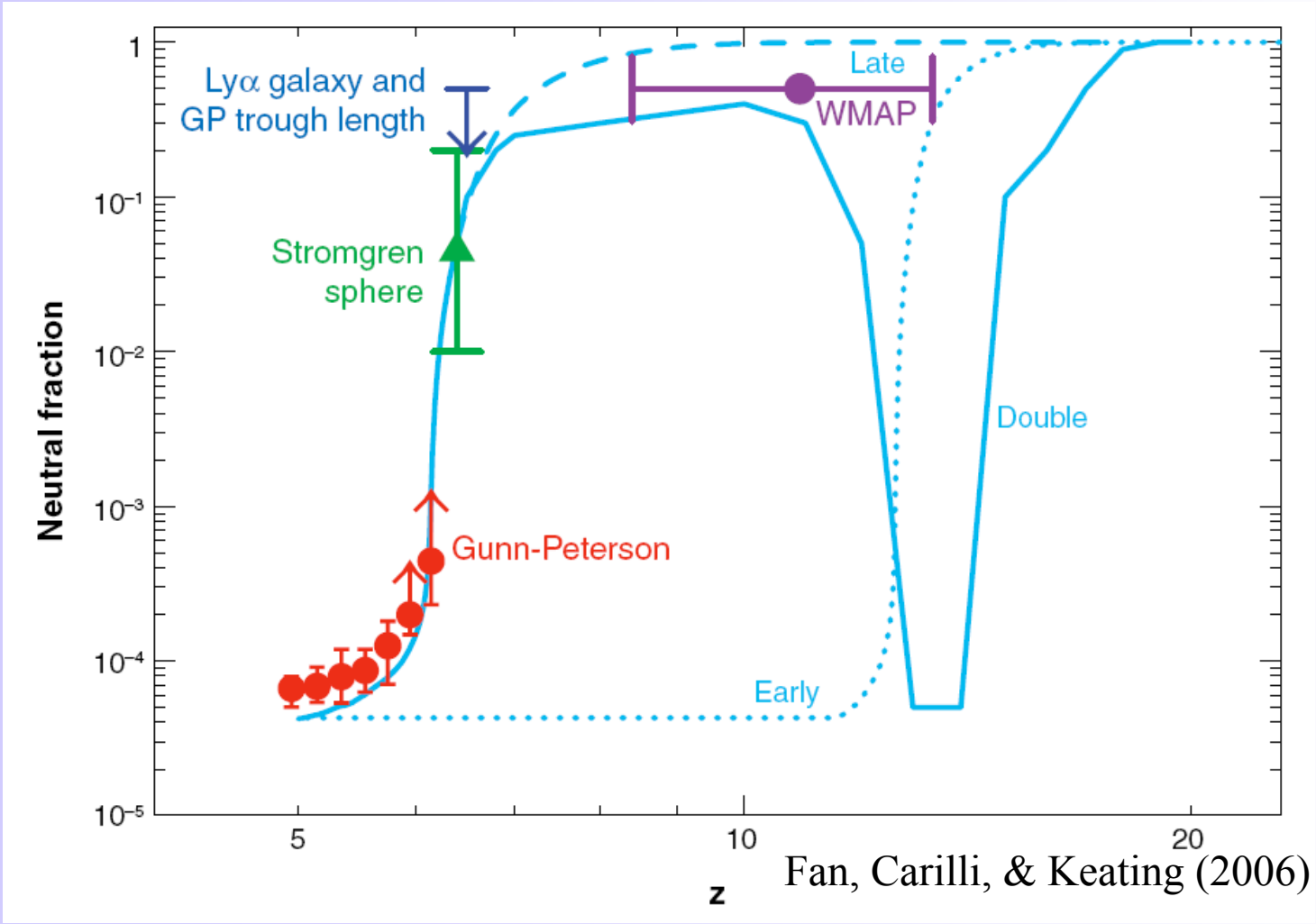


Outline

- Overview of reionization and CMB polarization
- Principal component decomposition of the reionization history (describe general $x_e(z)$ with small number of parameters)
- MCMC constraints from WMAP5 and simulated CV-limited data:
  - total optical depth to reionization (without assuming a specific model)
  - optical depth from high z (> 15-20) vs. low z
- Applications to tensor BB spectrum – degeneracy with inflationary parameters

Reionization



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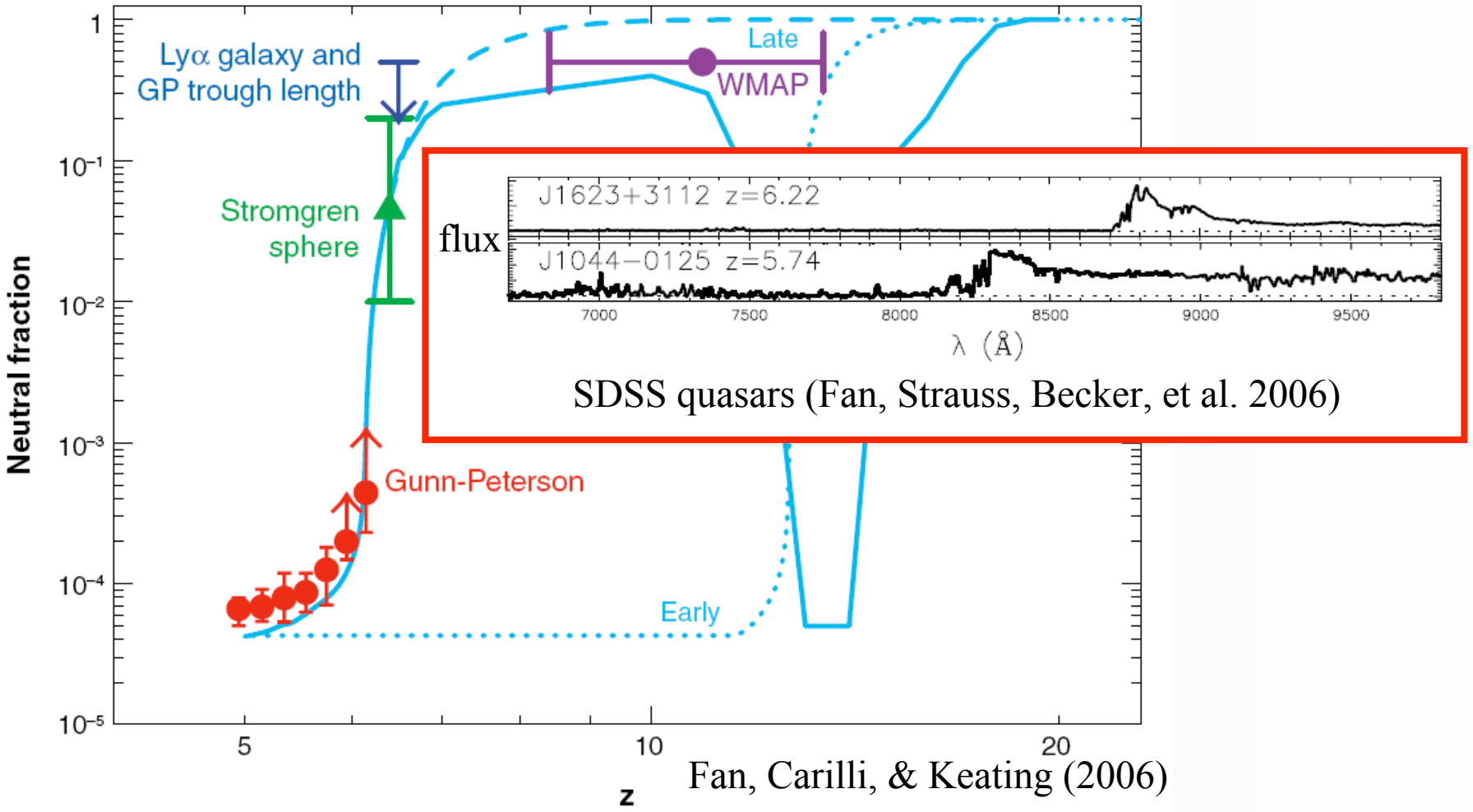

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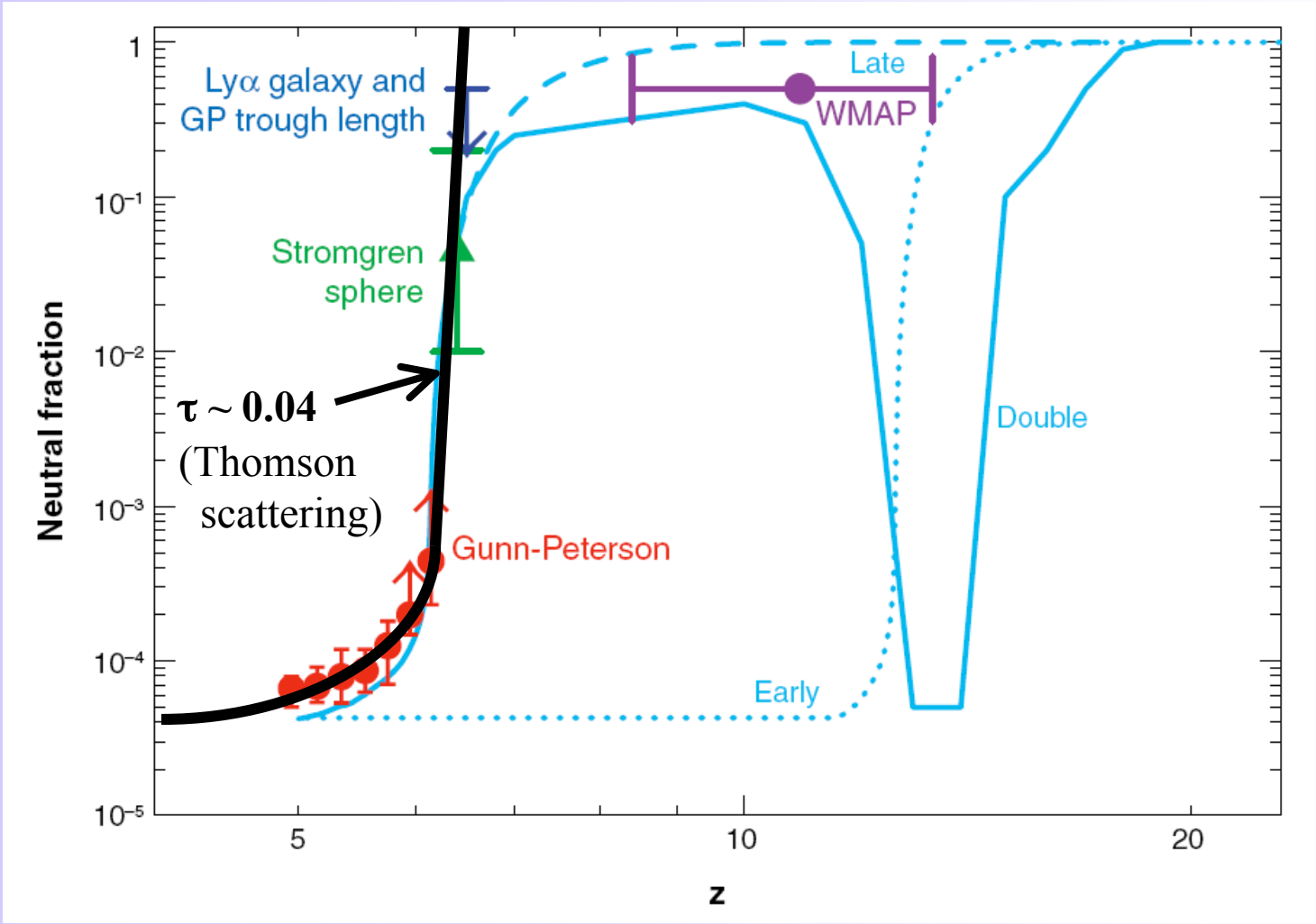

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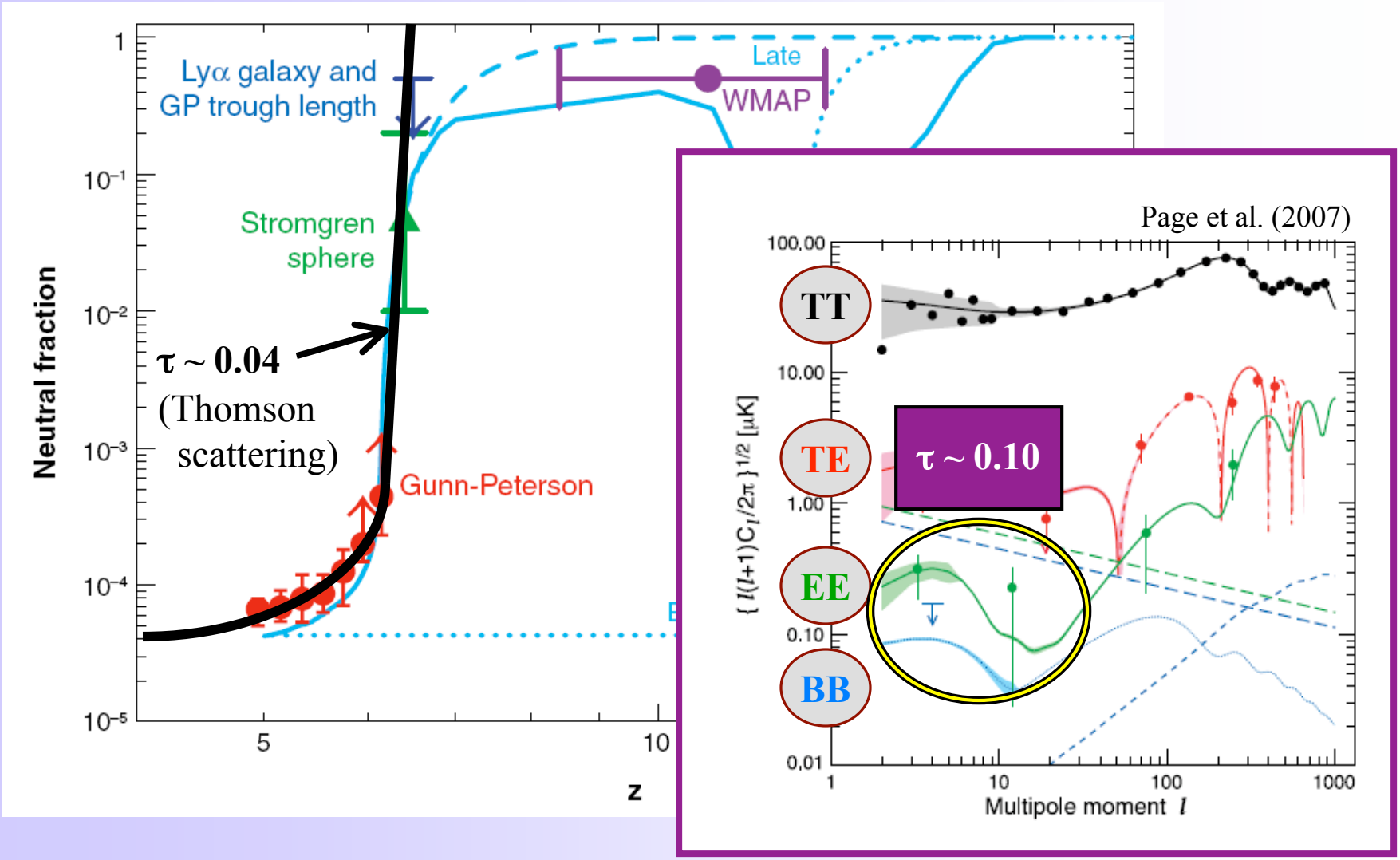

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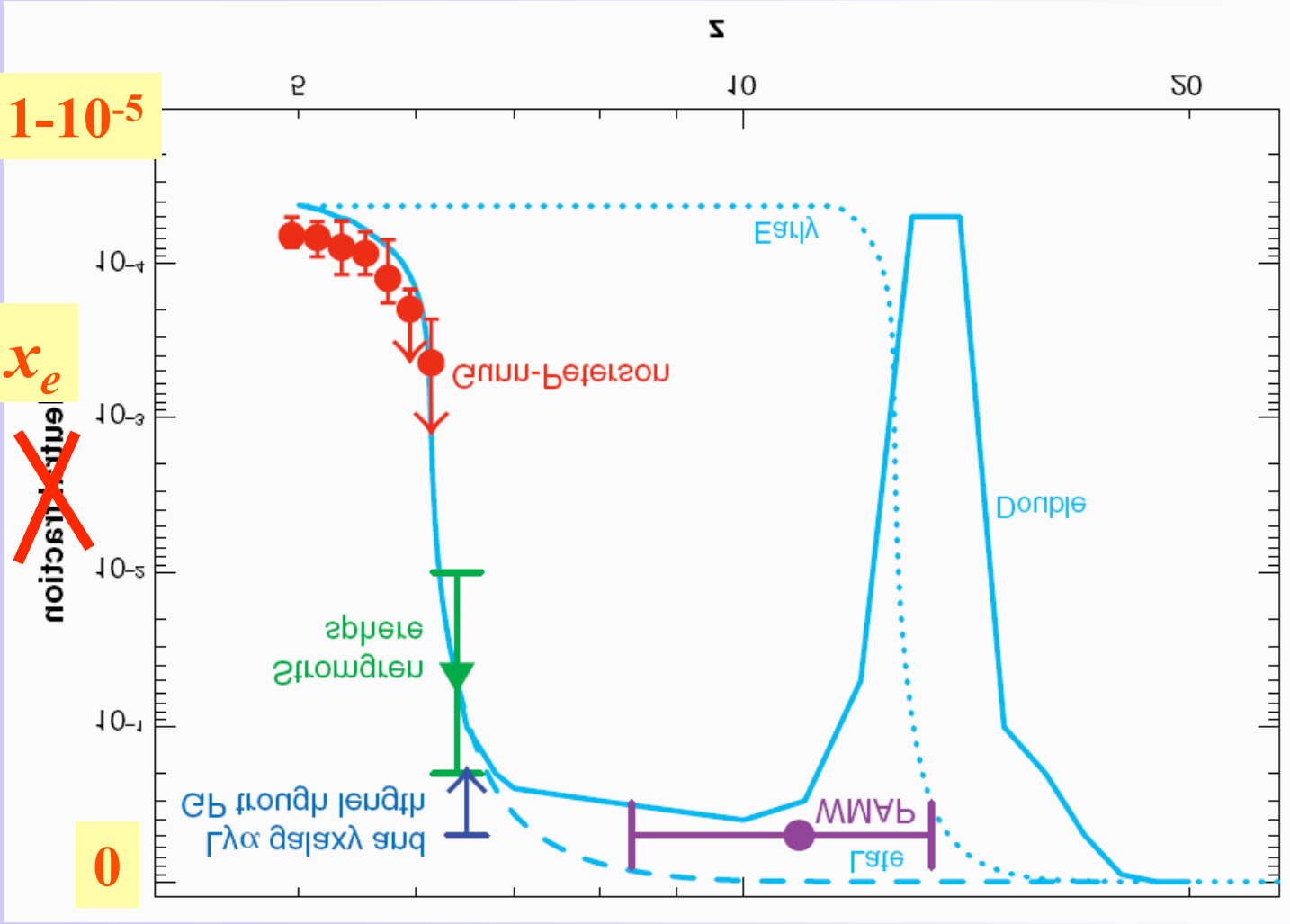

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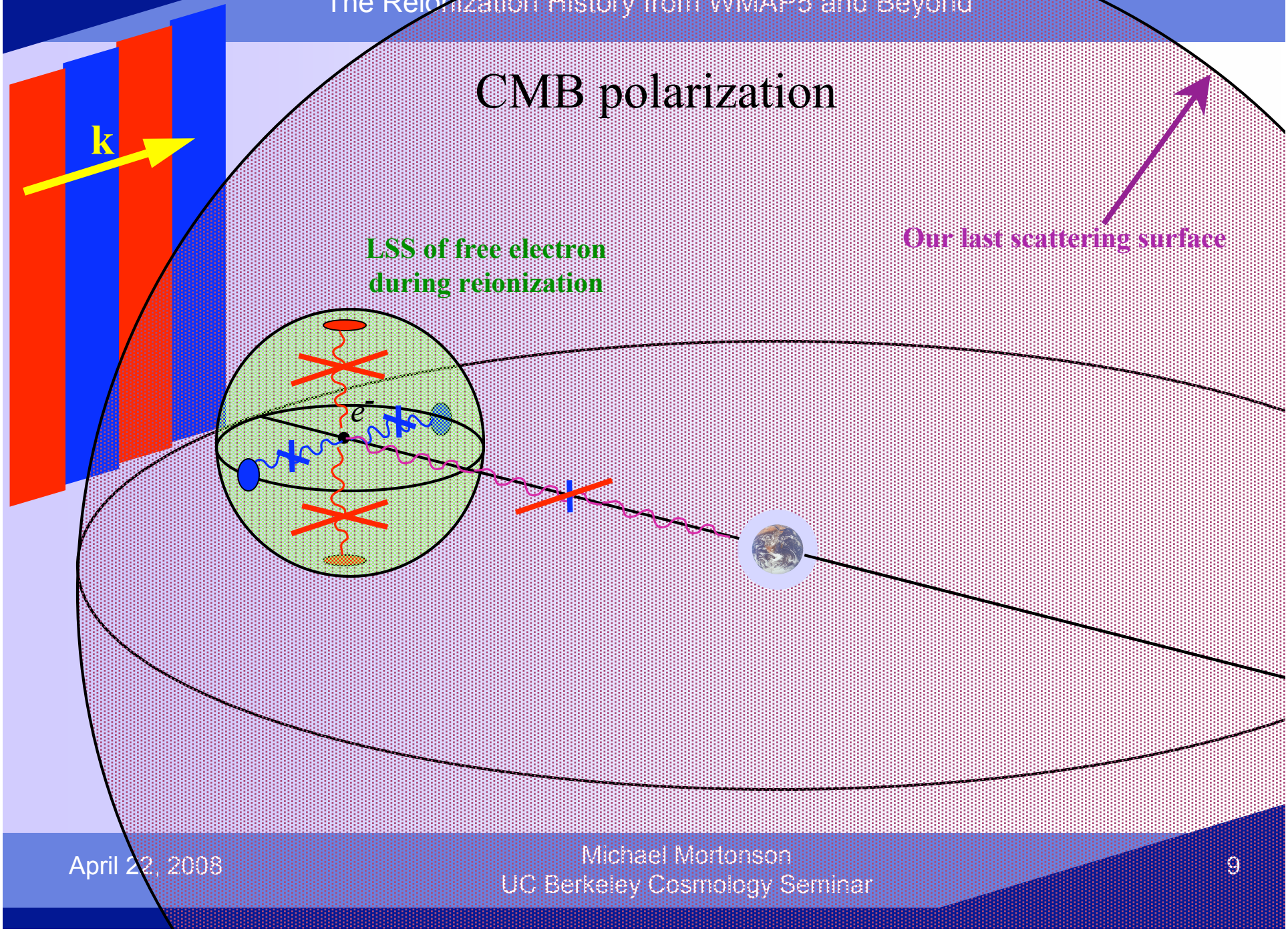
CMB polarization



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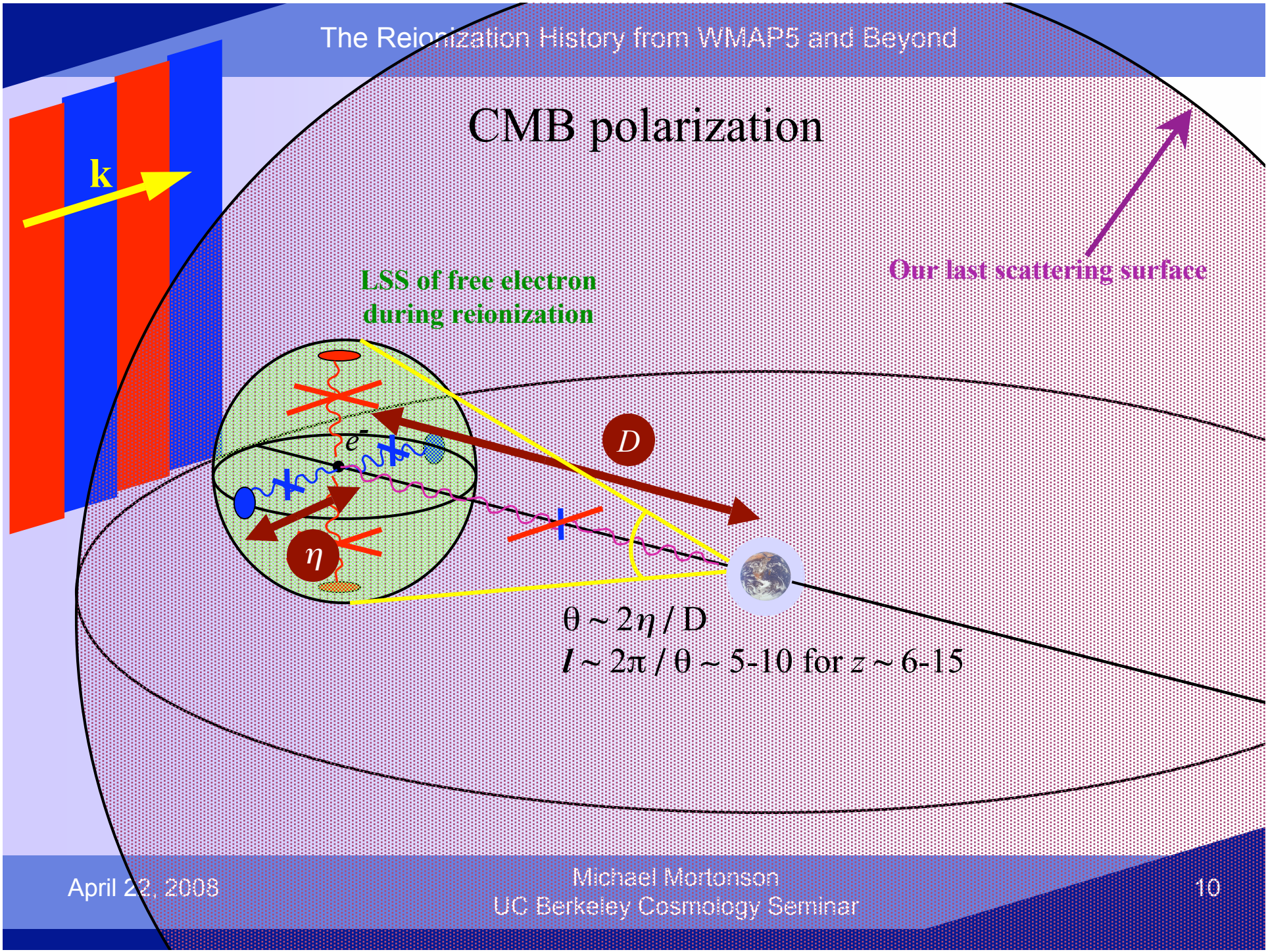
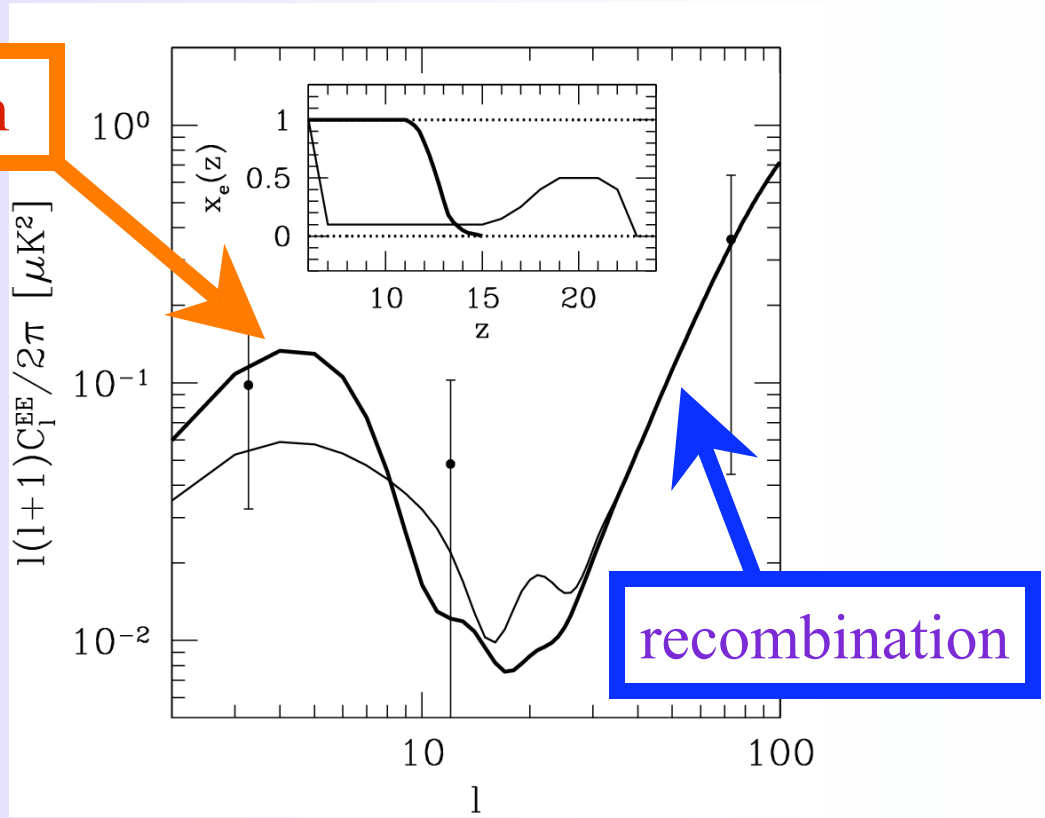


CMB polarization

- Ionization at higher z
  → EE power at higher l
- Reionization history imprinted on large-scale EE spectrum
- Can have same τ but different EE shapes



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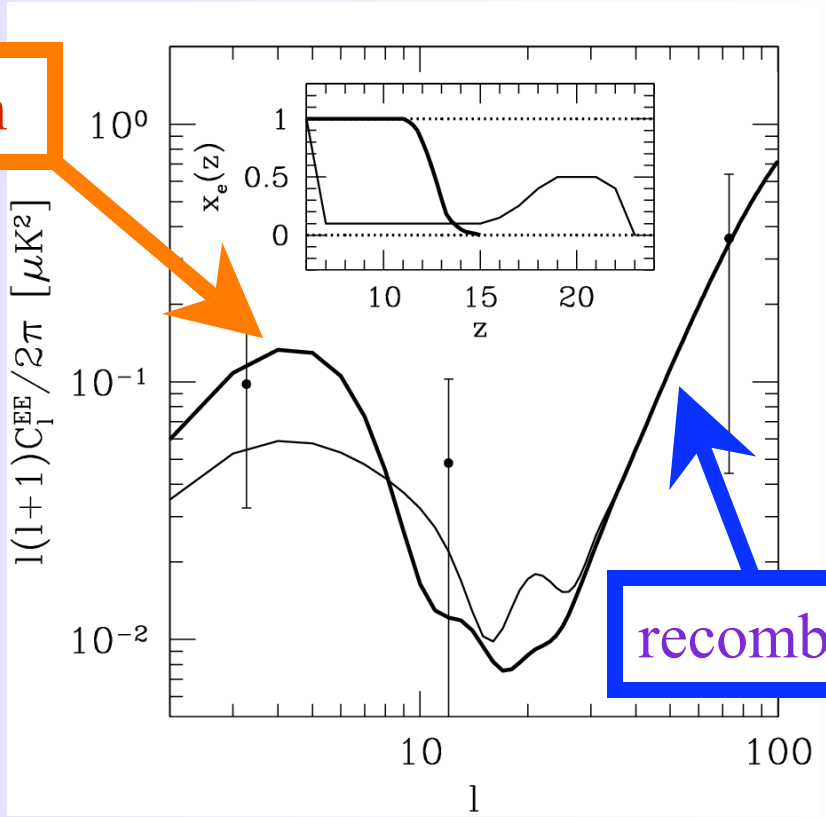

Other reionization effects (arcmin scales): kSZ/OV – CMB temperature (~μK), patchy reionization – E and B polarization (~nK)

Outline

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    (without assuming a specific model)
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Usual approach to constrain optical depth from the reionization peak:

Assume a simple form for $x_e(z)$
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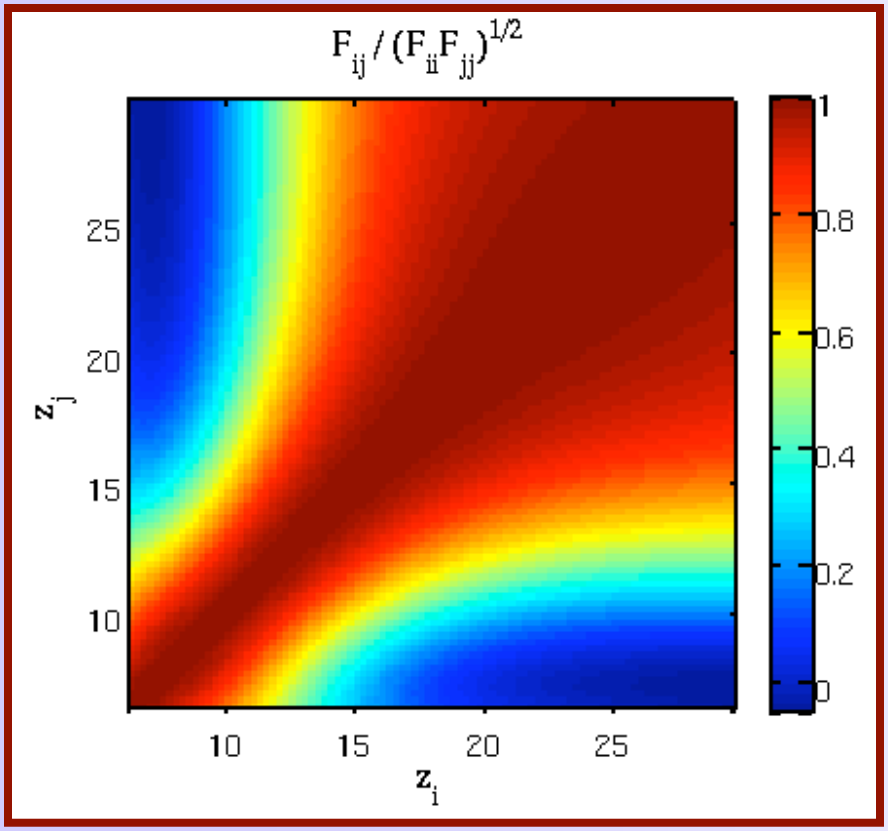
Future

- larger biases
- losing information about reionization from shape of EE spectrum

Model-independent observables (Hu & Holder 2003)

- Principal component analysis of $x_e(z)$ → orthogonal modes, ranked by variance
- PCs are eigenmodes of the Fisher matrix:



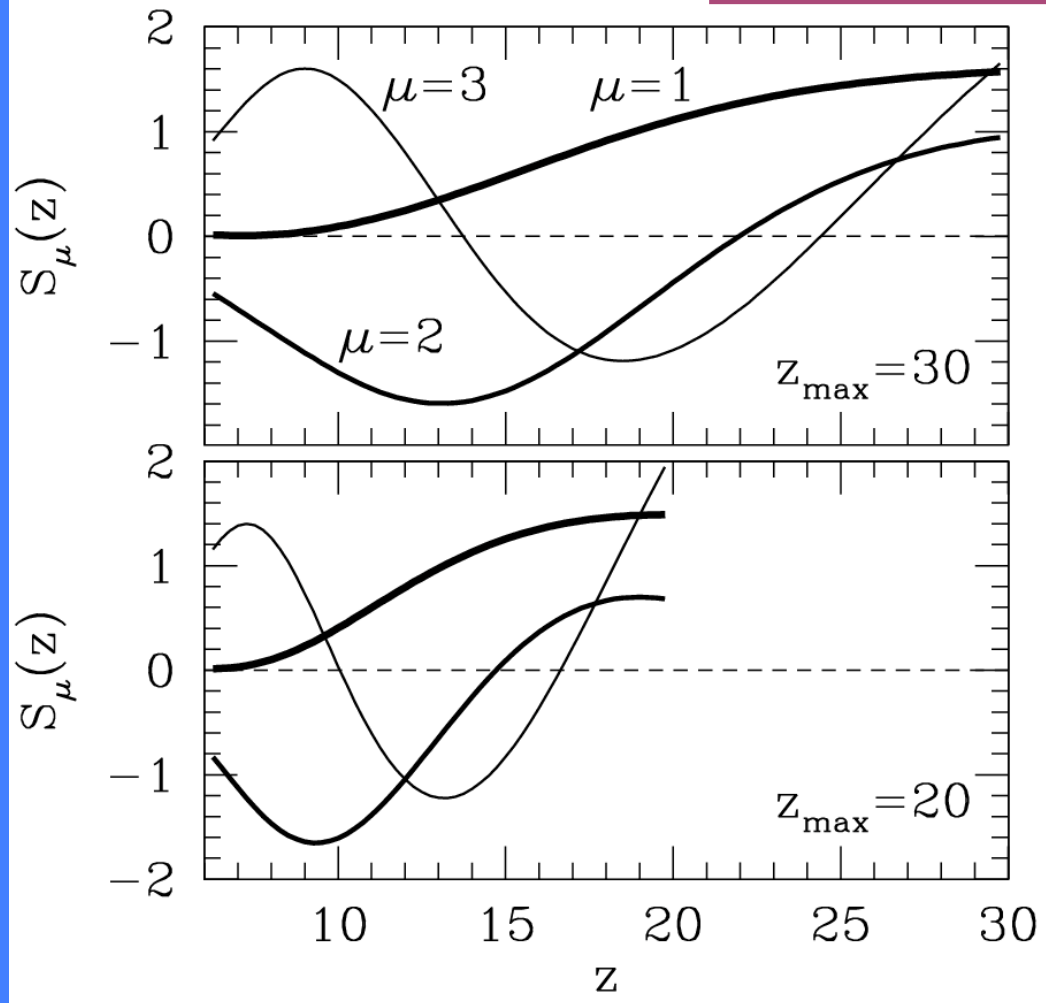
$$F_{ij} = \sum_{\ell=2}^{\ell_{\rm max}} \left(\ell + \frac{1}{2}\right) \frac{\partial \ln C_\ell^{EE}}{\partial x_e(z_i)} \frac{\partial \ln C_\ell^{EE}}{\partial x_e(z_j)}$$

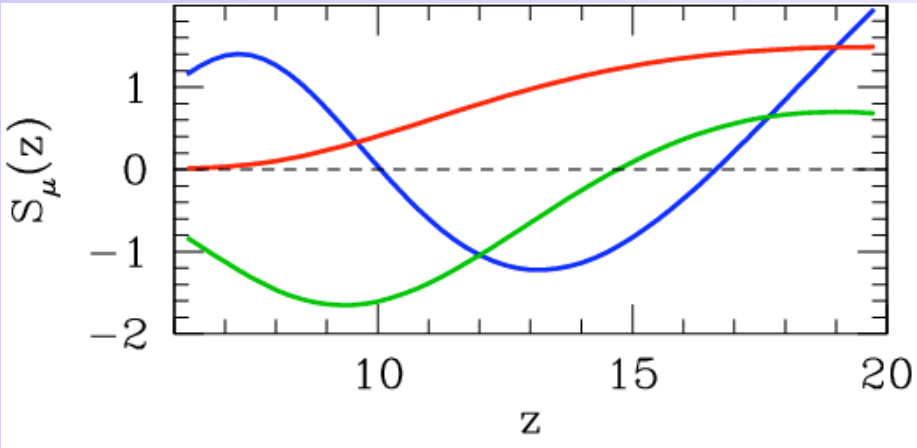
$$= (N_z+1)^{-2} \sum_{\mu=1}^{N_z} S_\mu(z_i) \sigma_\mu^{-2} S_\mu(z_j)$$

(variance)$^{-1}$

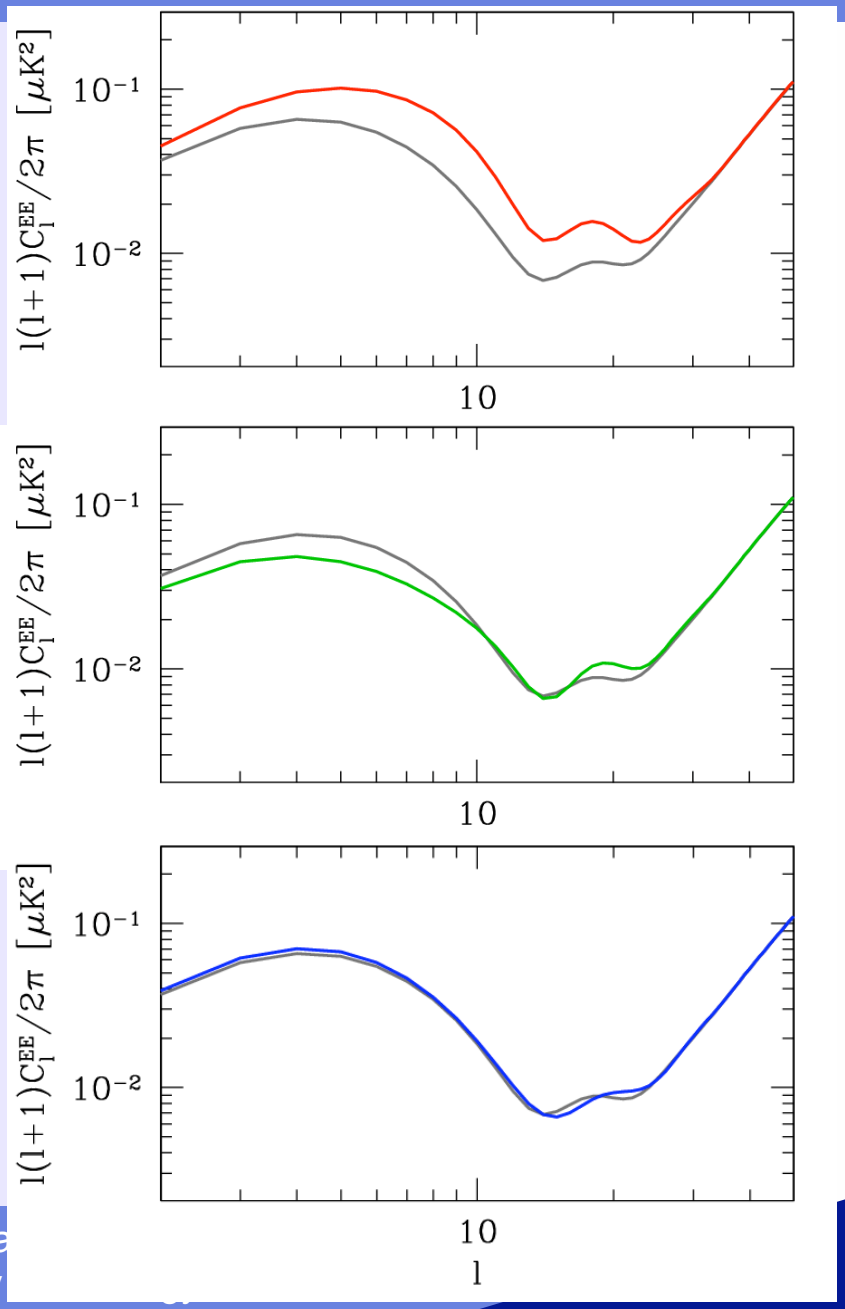
principal components

$$x_e(z) = x_e^{\rm fid}(z) + \sum_\mu m_\mu S_\mu(z)$$





$$m_1 = m_2 = m_3 = 0.15$$



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PCs are general:

- construct arbitrary $x_e(z)$ (within $z_{\rm min} < z < z_{\rm max}$)

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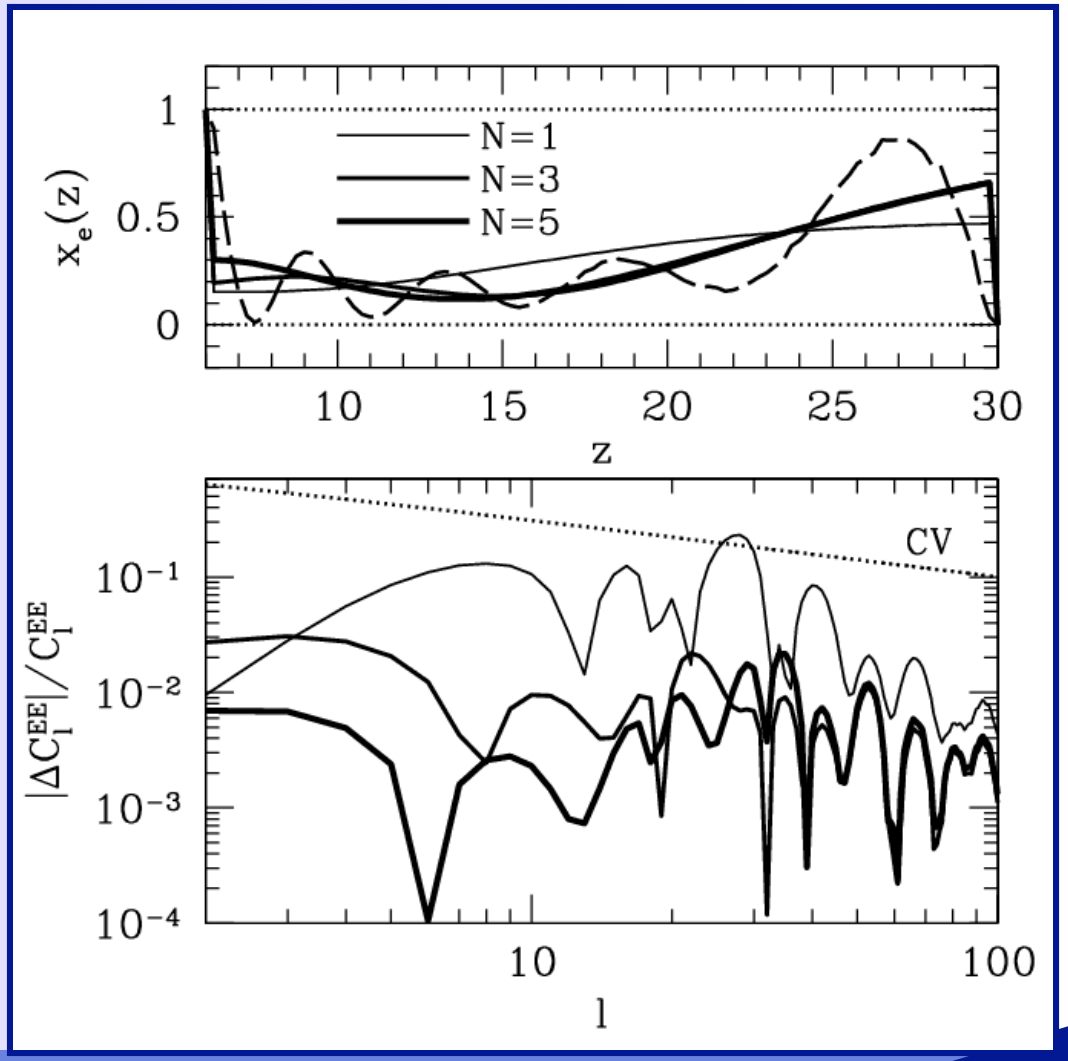
- **only the first few (lowest-variance) PCs affect $C_l^{\rm EE}$**



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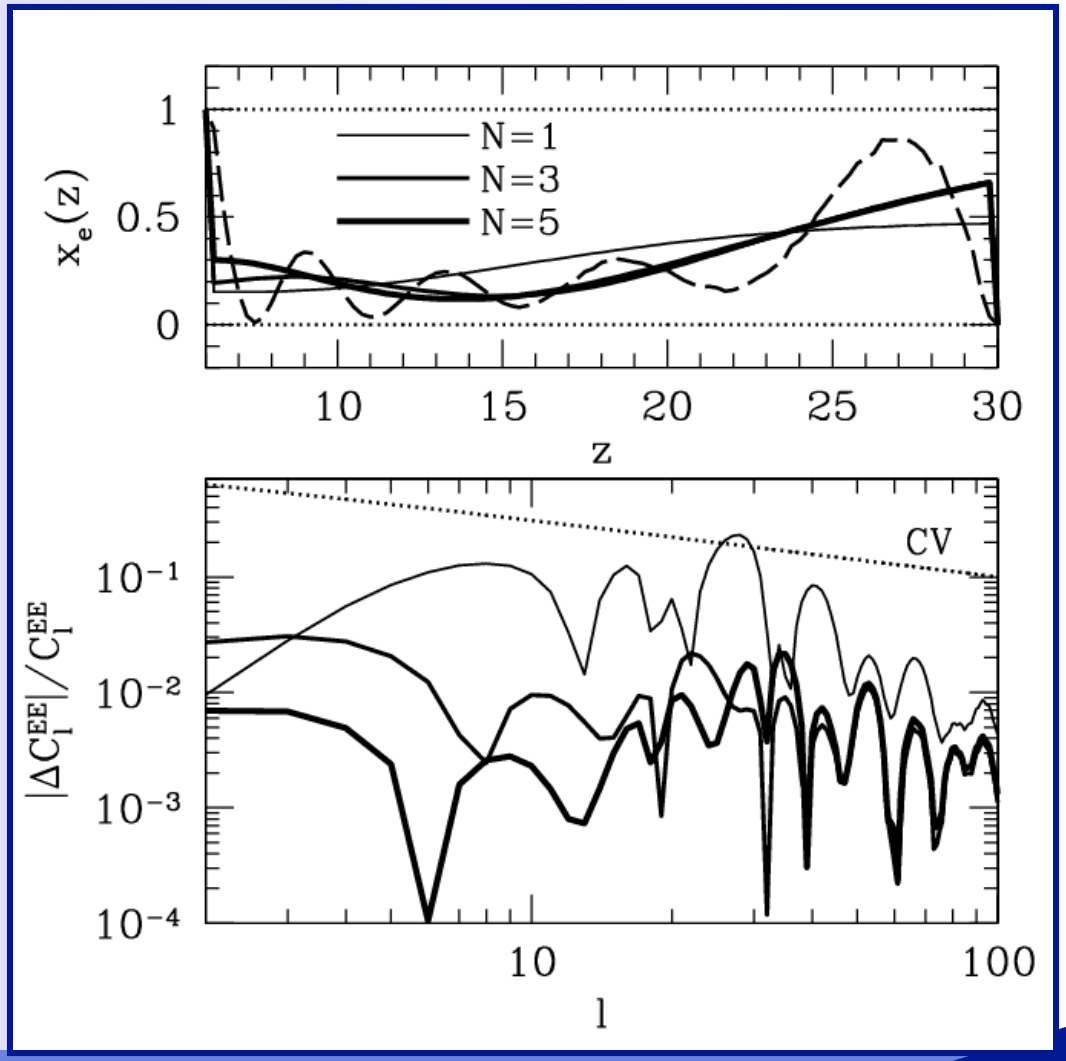
- small number of extra parameters (replace τ by 3-5 PCs)
- orthogonal



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With truncated set of PCs:

- we are not *reconstructing* the ionization history
- have to think about how to keep values of x_e physical

Physicality bounds: $0 < x_e < 1$

$$x_e(z) = \underbrace{x_e^{\rm fid}(z) + \sum_{\mu=1}^{N} m_\mu S_\mu(z)}_{\in [?,?]} + \sum_{\mu=N+1}^{\infty} m_\mu S_\mu(z)$$

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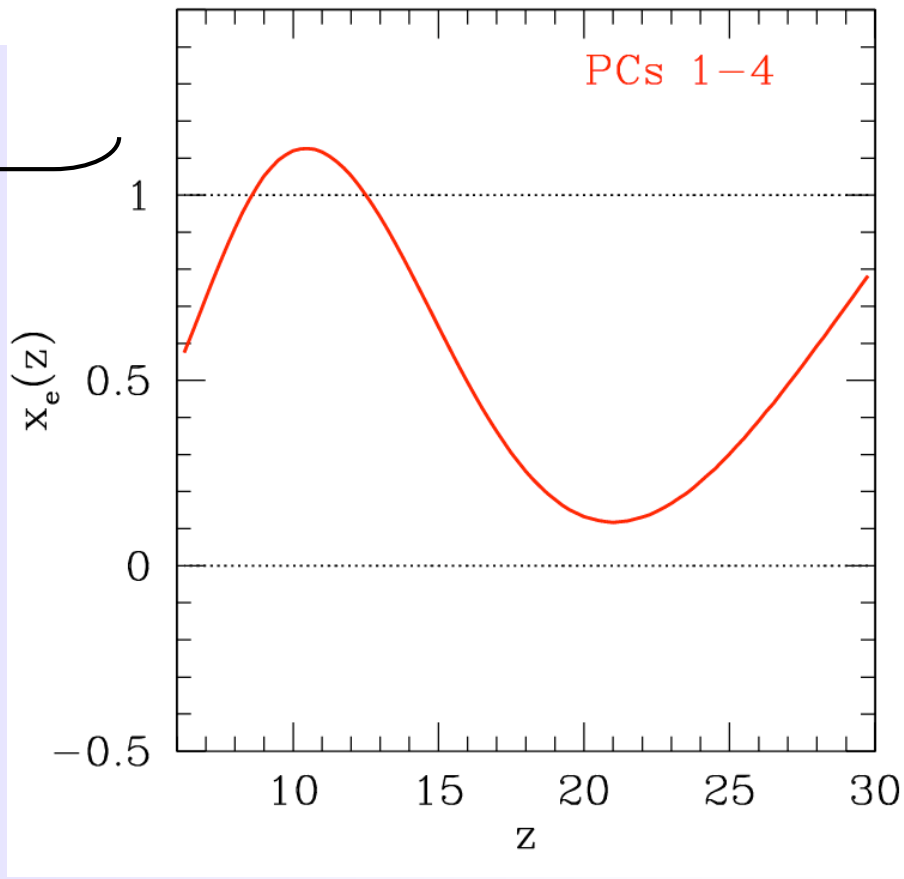

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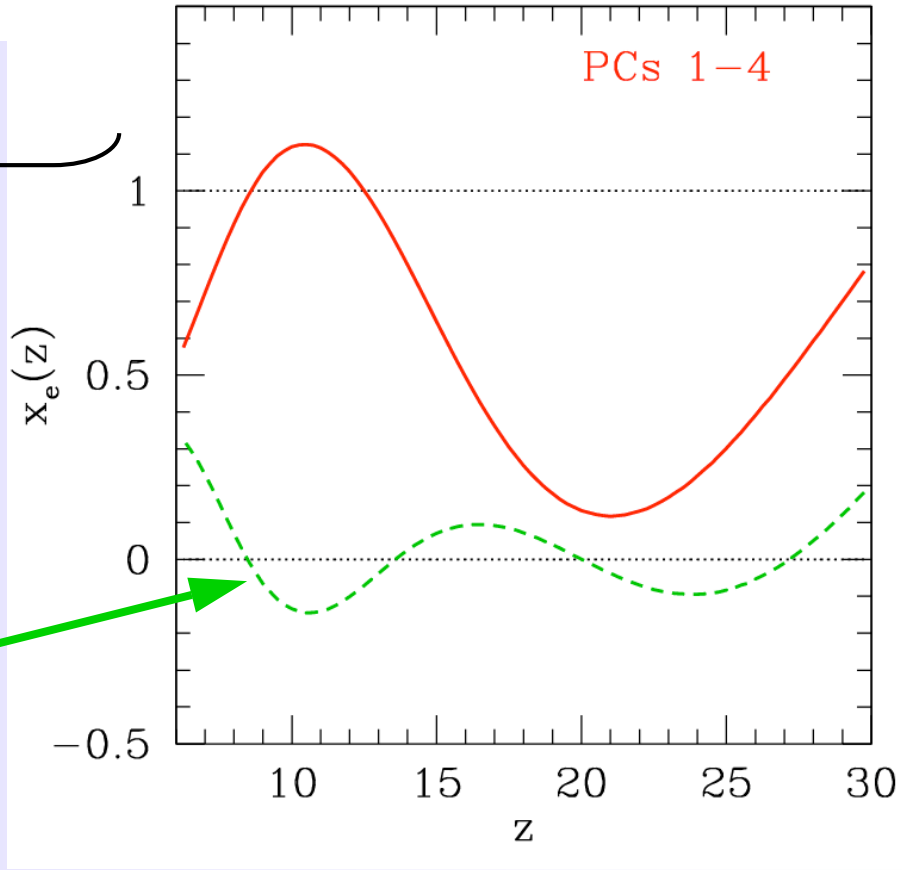

PC 5

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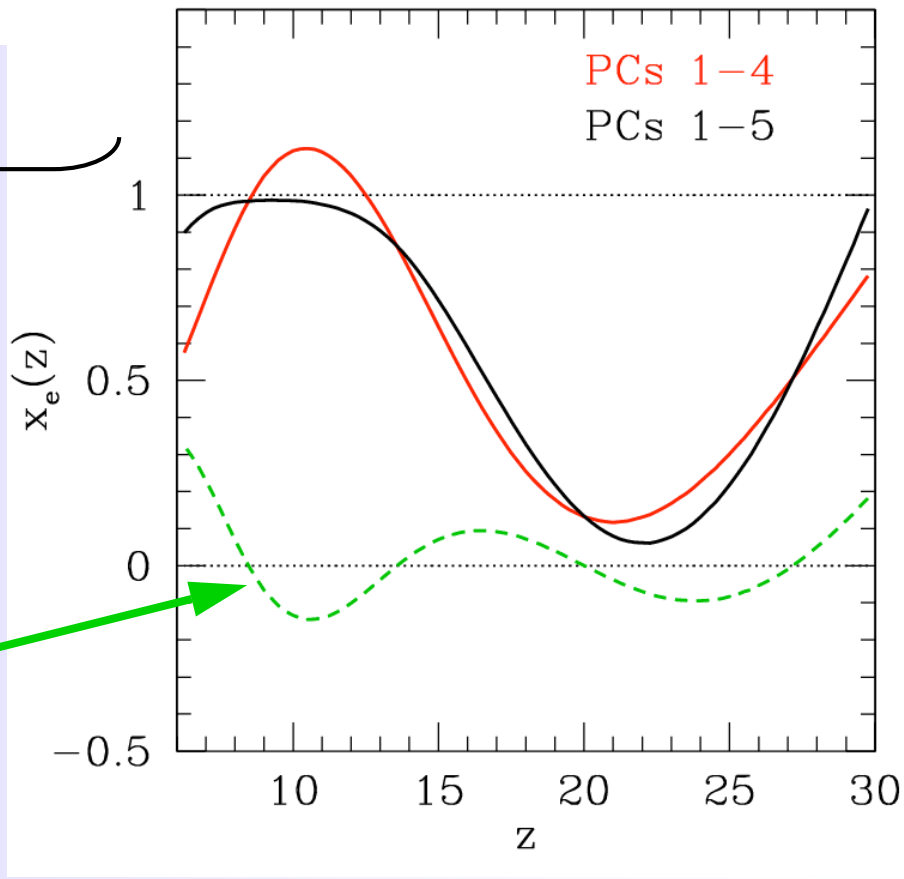

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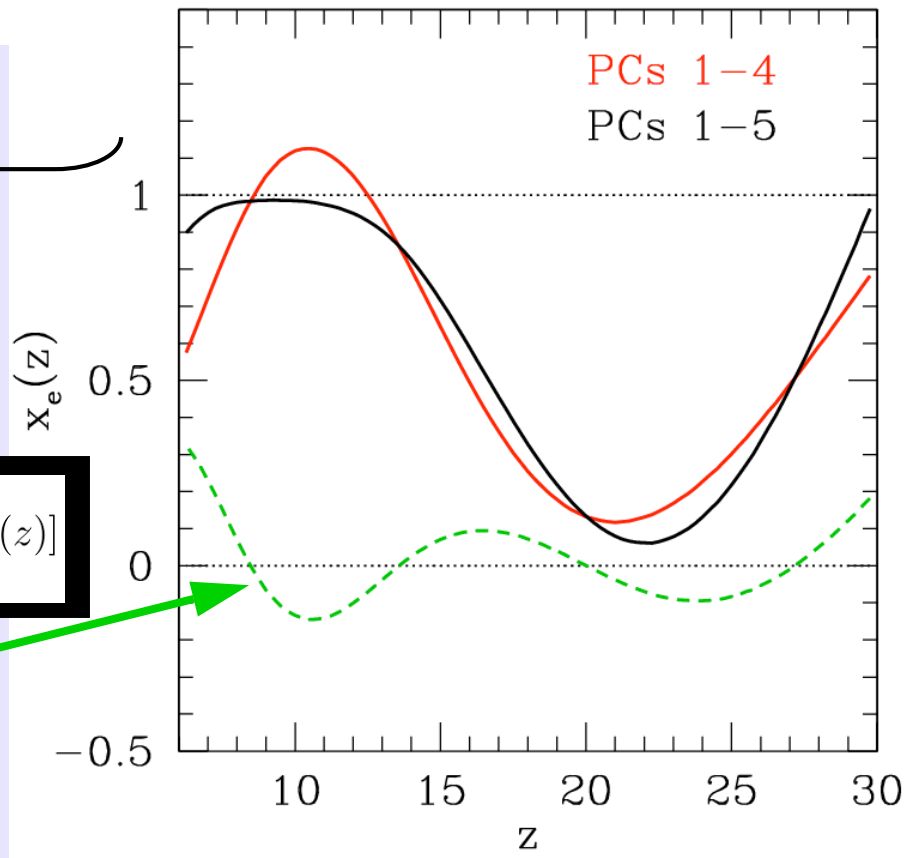

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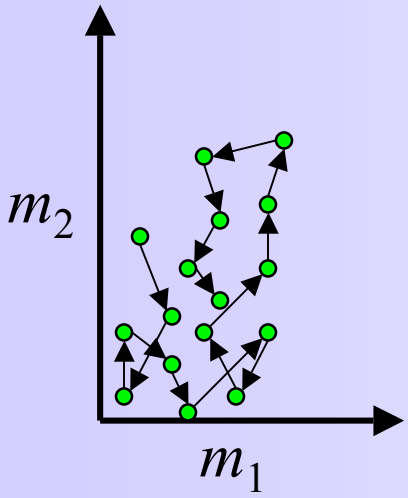
Markov Chain Monte Carlo

[CosmoMC]



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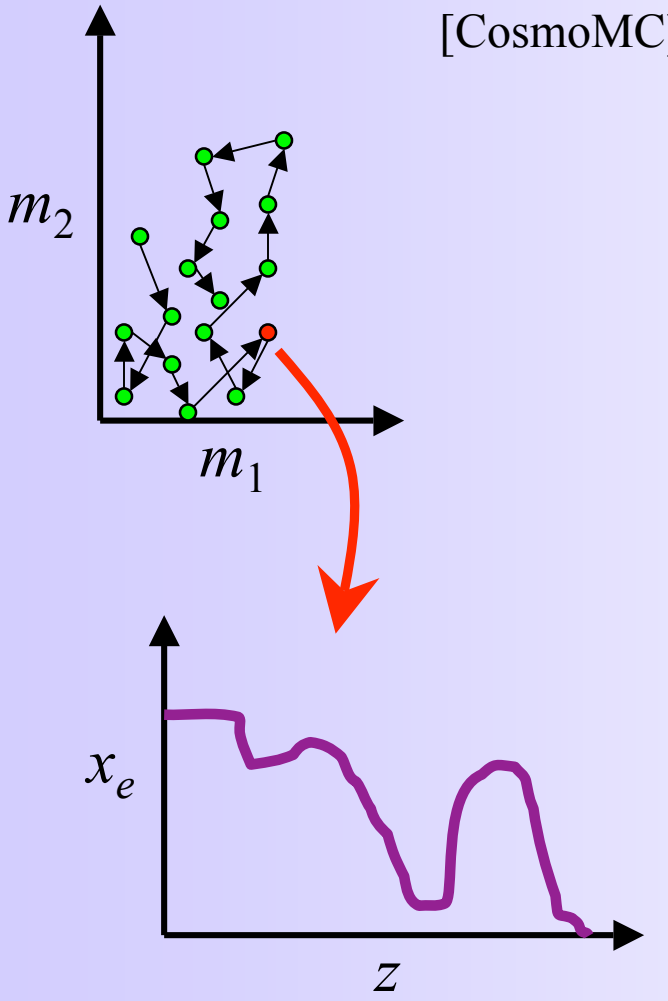

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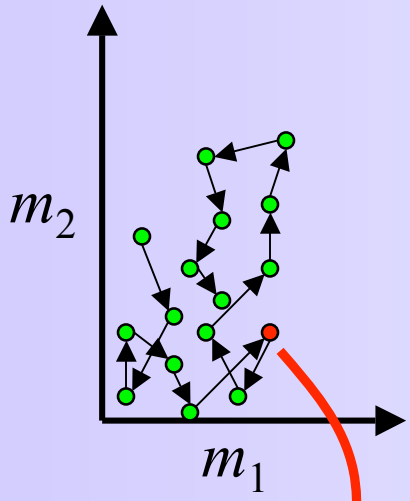
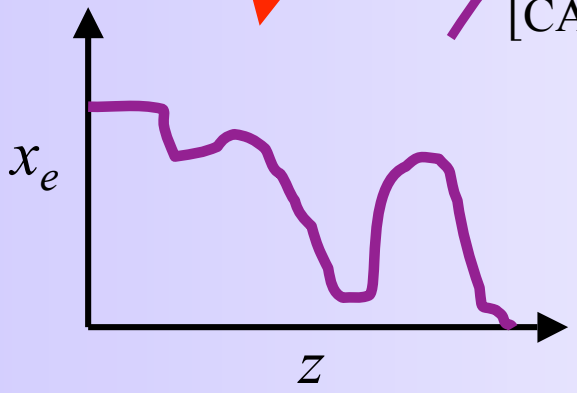
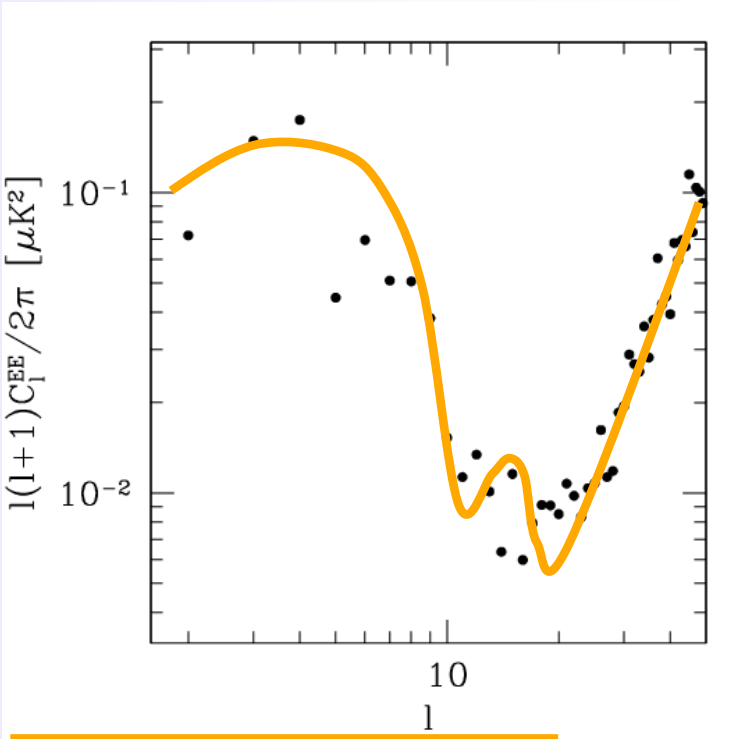


[CAMB]





χ^2 → accept/reject step

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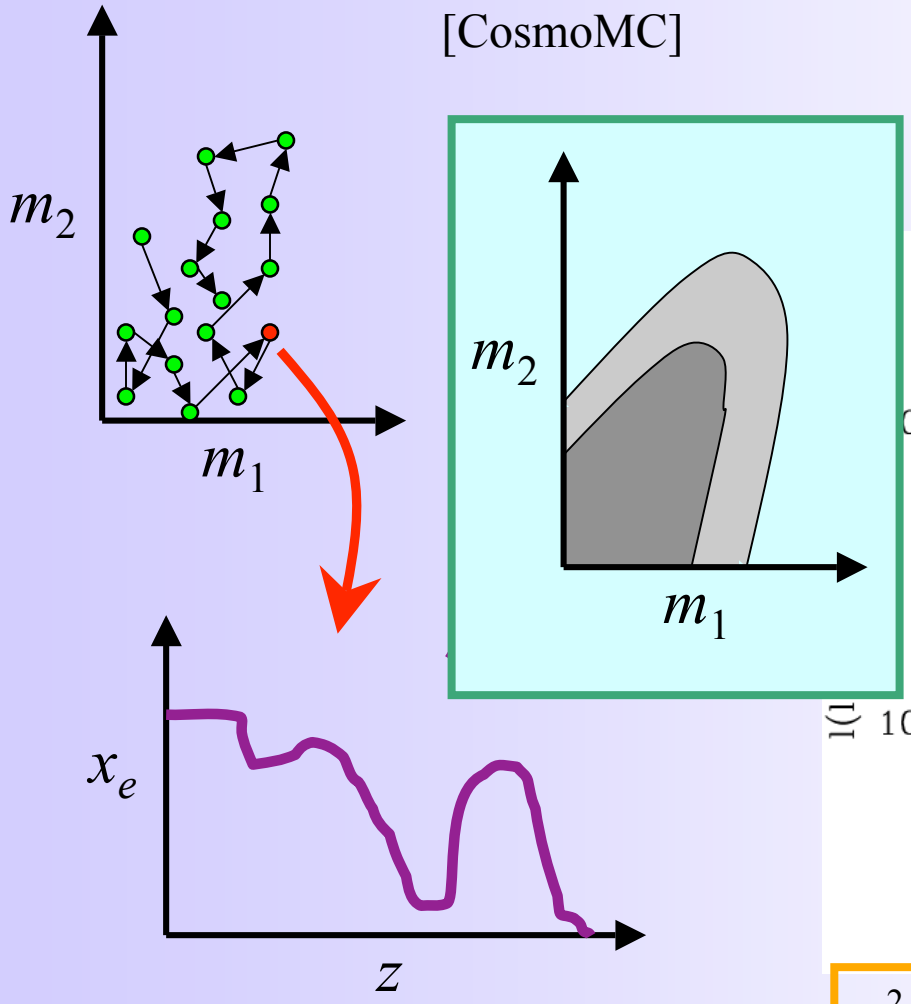
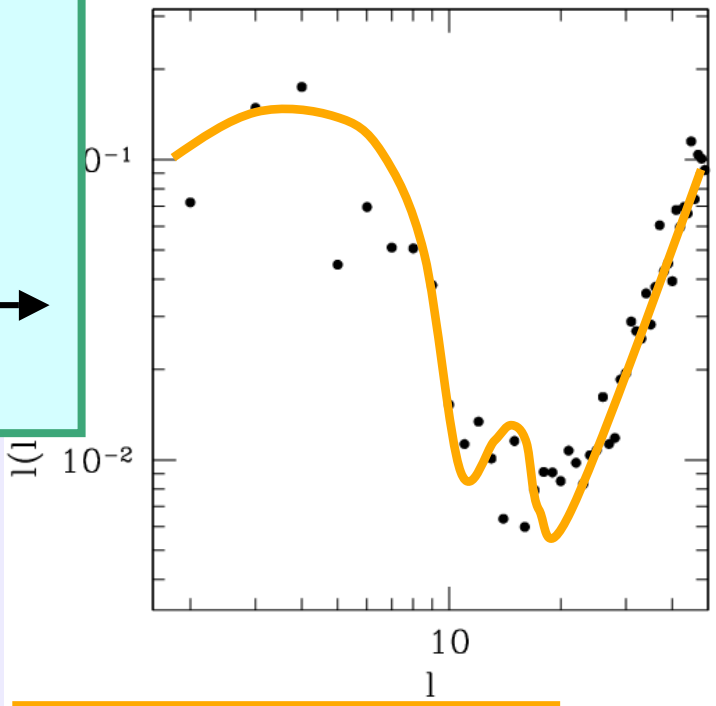
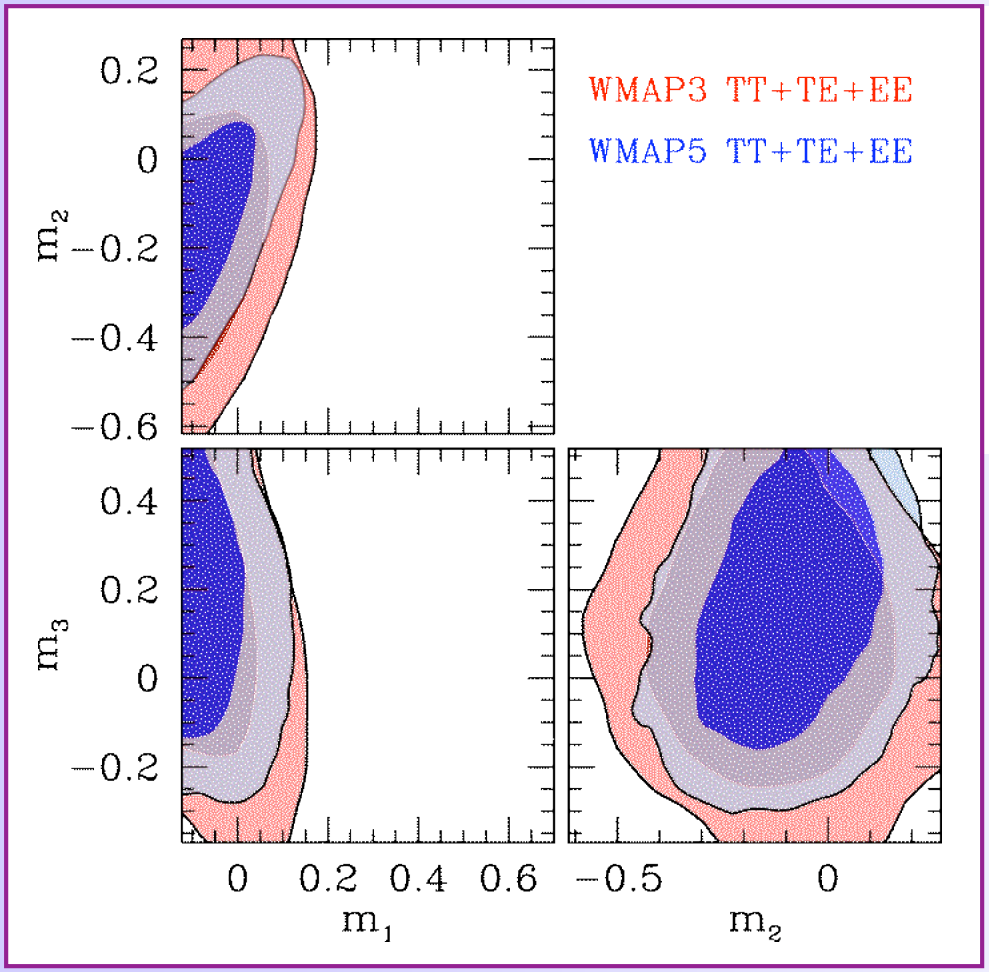
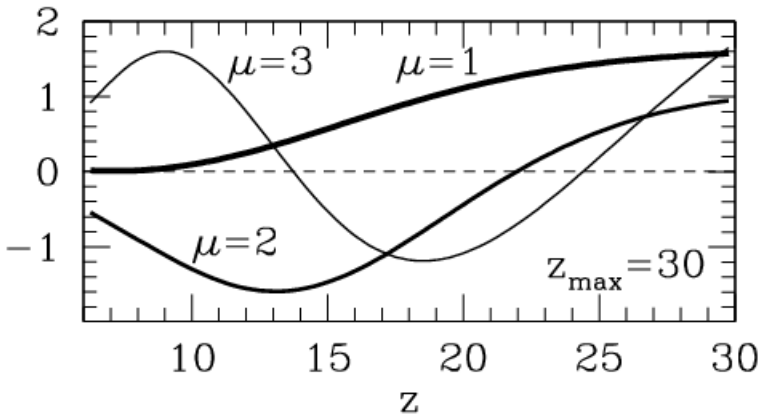




$\chi^2 \rightarrow$ accept/reject step

5-year WMAP constraints





PCs are defined with respect to constant $x_e = 0.15$ at $6 < z < 30$

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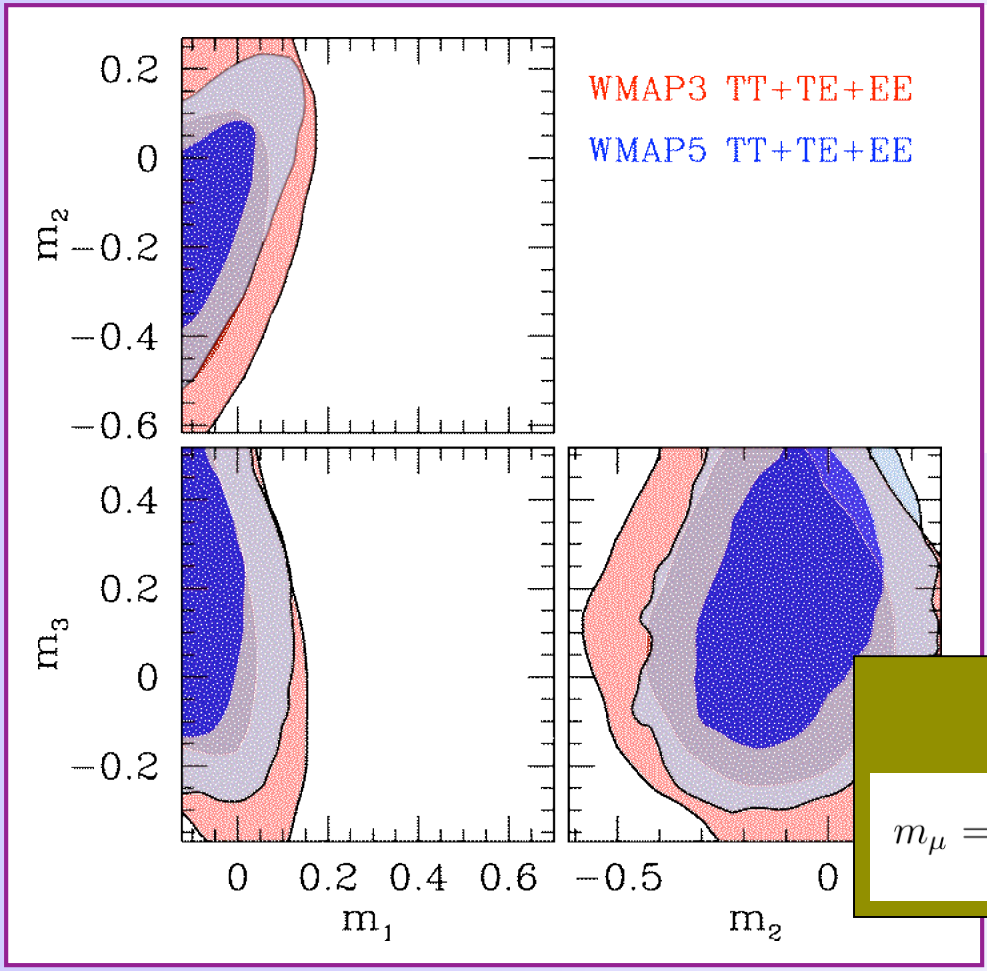

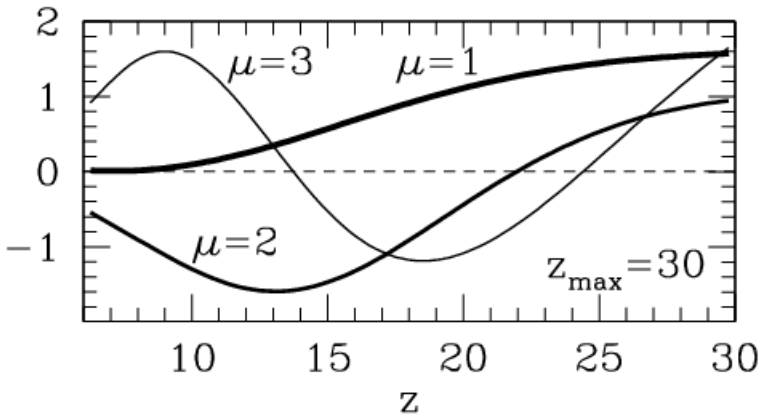

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Model testing with PCs:

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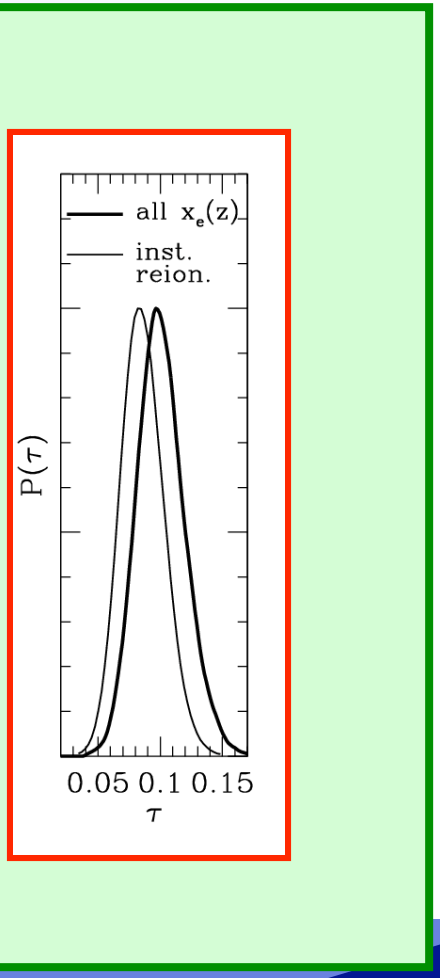
5-year WMAP constraints: optical depth

WMAP5 constraint on total optical depth with model-independent approach remains $\sigma_\tau = 0.017$

(WMAP3: $\sigma_\tau = 0.03$)



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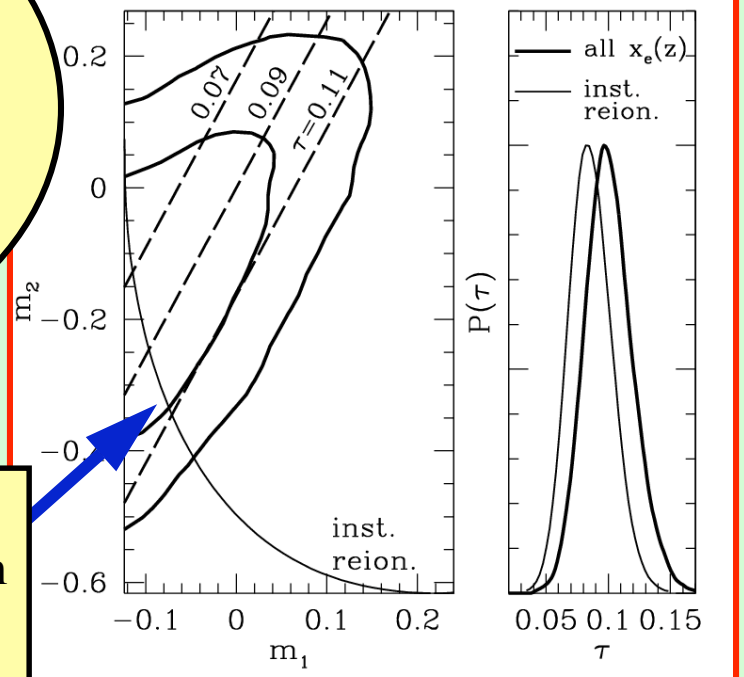

Instantaneous reionization models pass through max. likelihood region

Current constraints are fairly weak → insensitive to choice of model

Slightly larger mean optical depth

($n_s = 1$ not as strongly disfavored by just WMAP)

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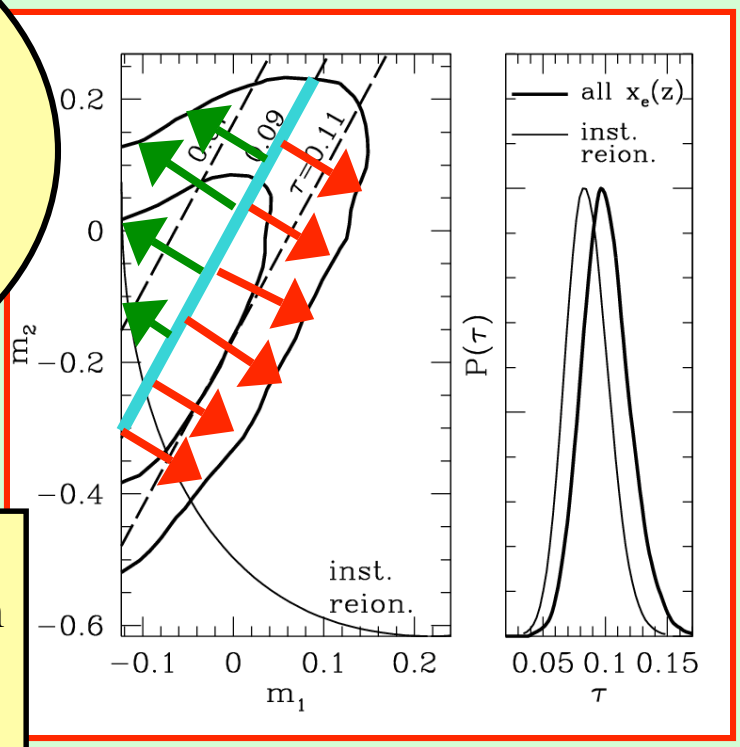

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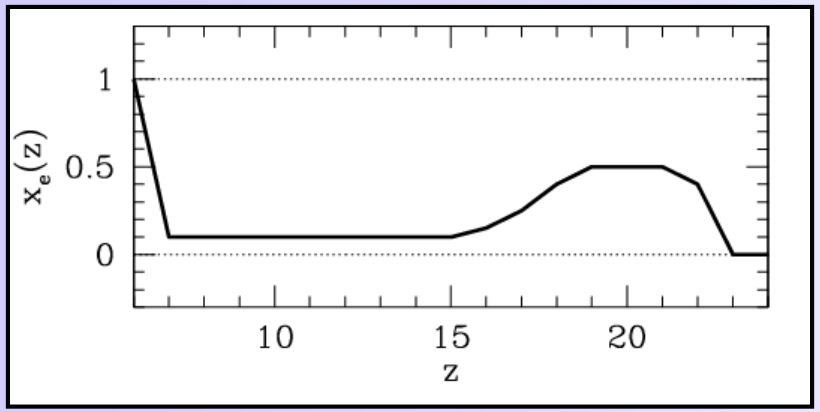
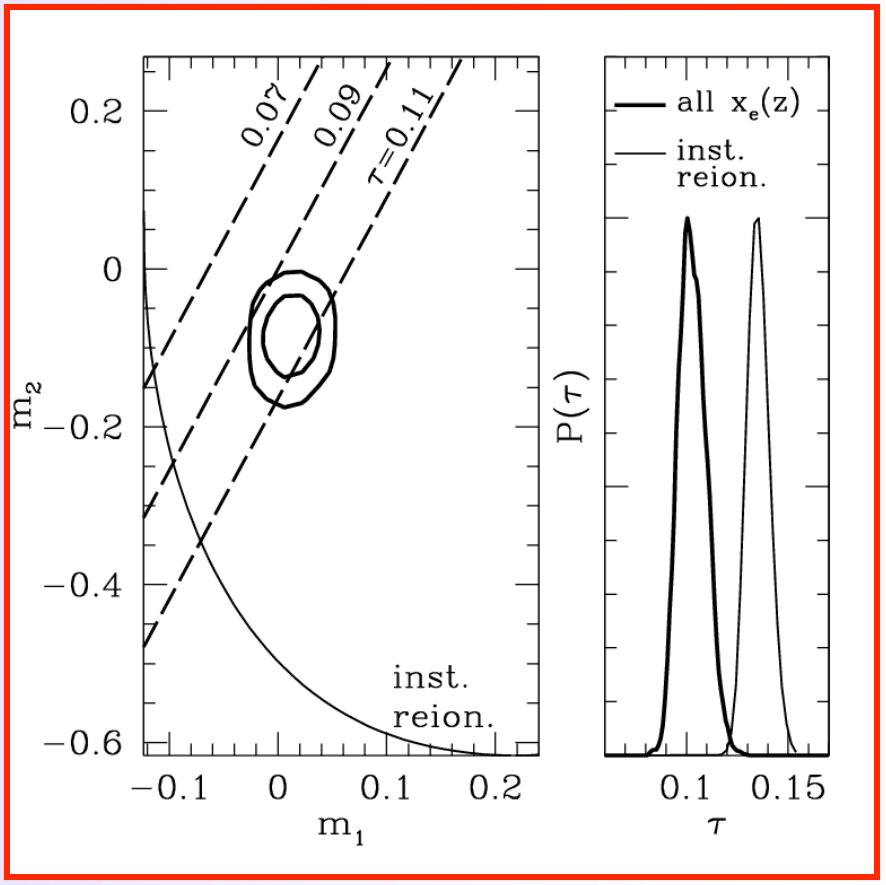
Model independence is important for **future** constraints on τ



CV-limited simulated data



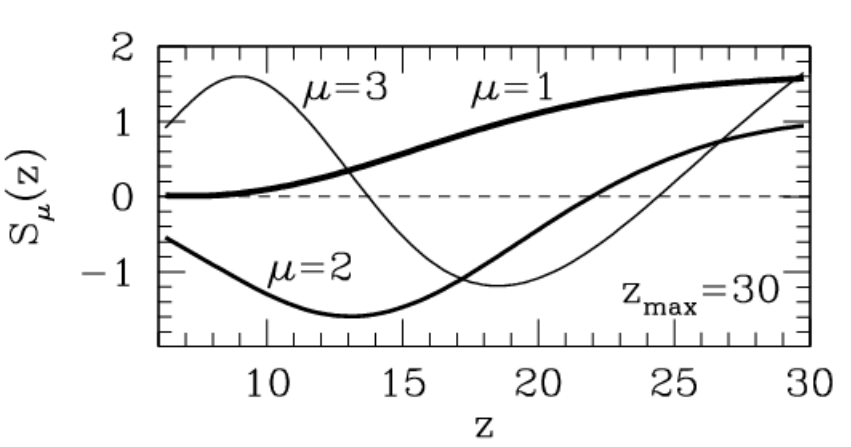
Going beyond optical depth: constraints on a second parameter

Best constrained quantity:

$m_1 \rightarrow \tau$

Next best constrained:

$m_2 \rightarrow ?$



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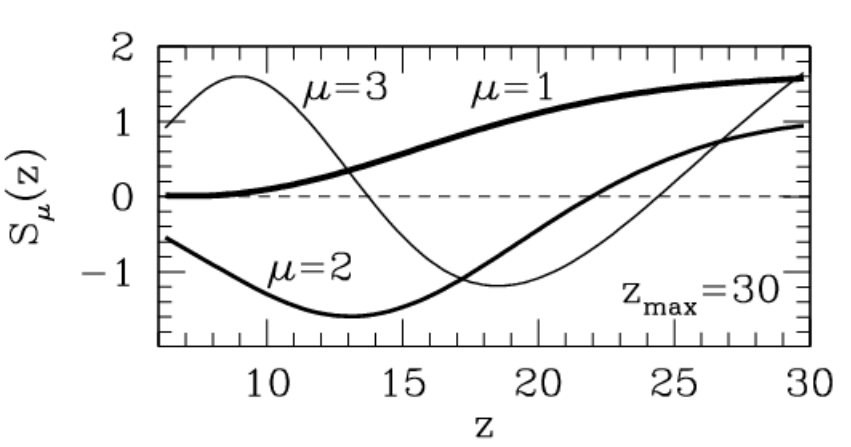

$$\tau(z_1, z_2) = 0.0691(1 - Y_p)\Omega_b h \int_{z_1}^{z_2} dz \frac{(1+z)^2}{H(z)/H_0} x_e(z)$$

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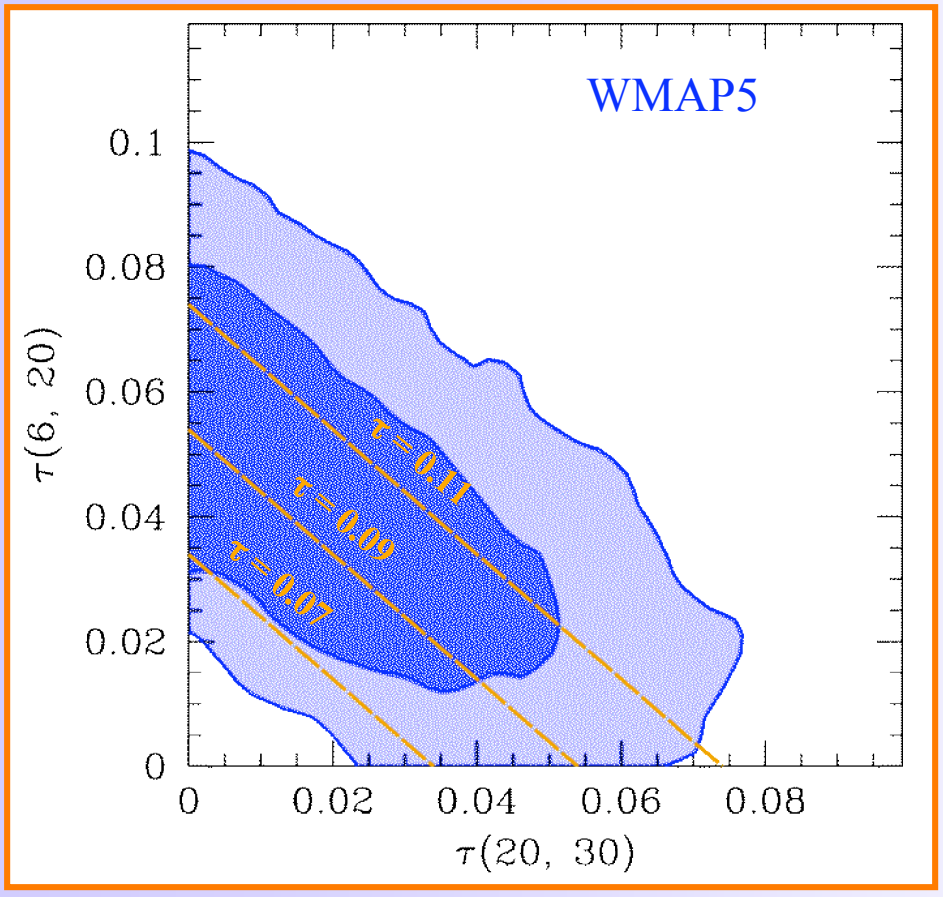

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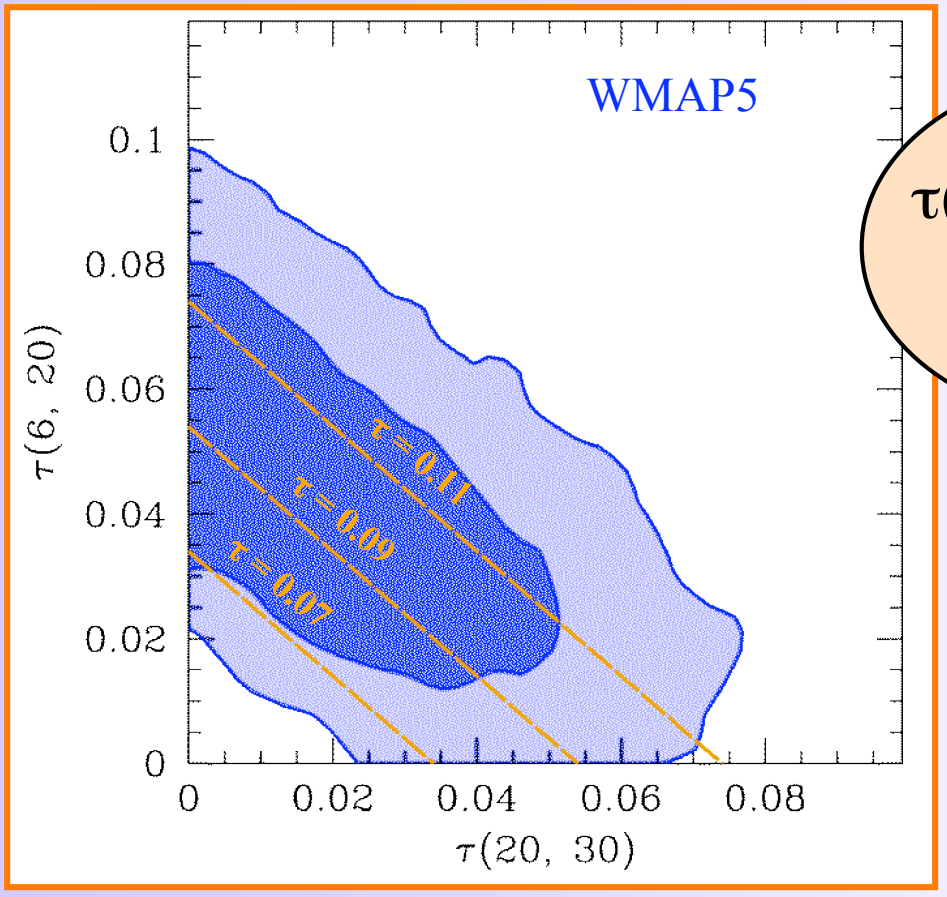

$\tau(z>20) < 0.07$

(95% CL)

(WMAP3: $\tau(z>20) < 0.08$)

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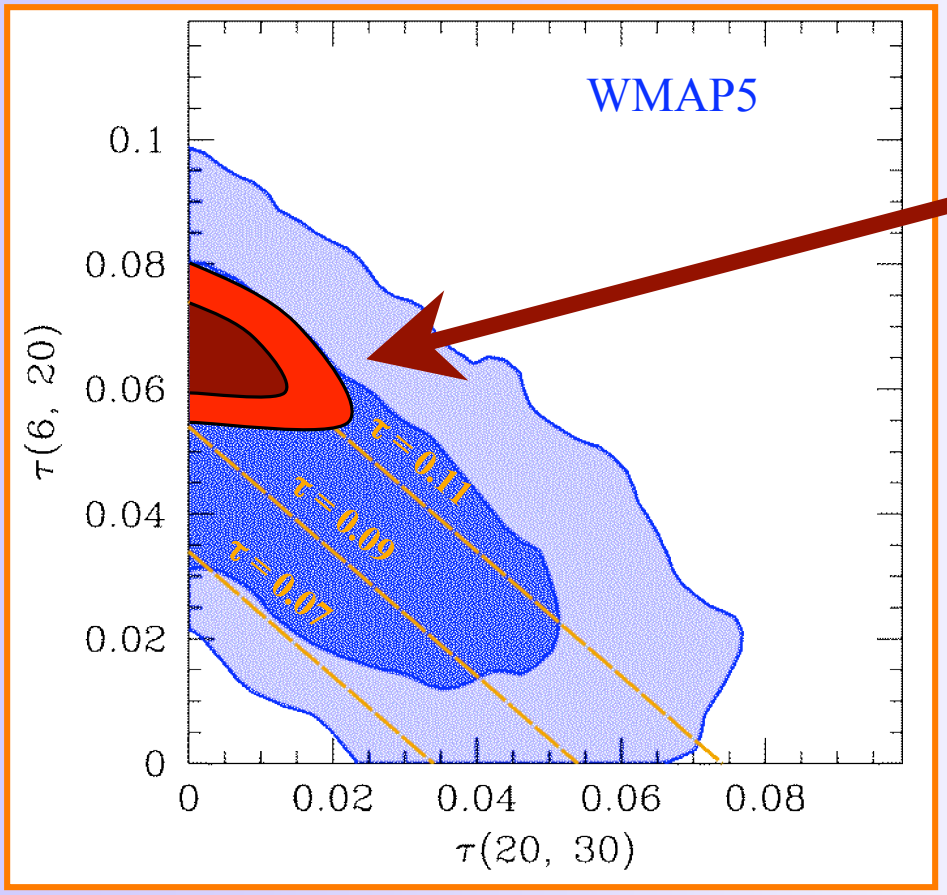
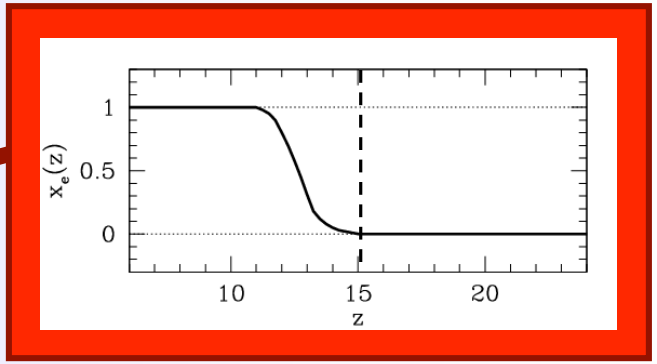
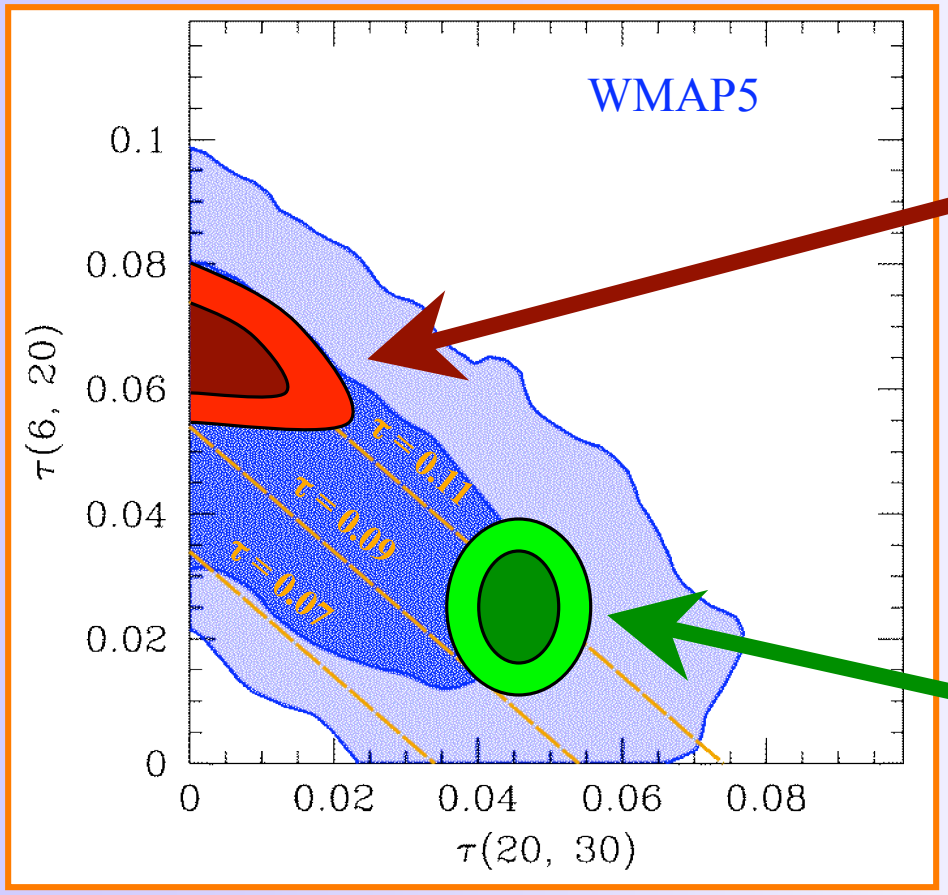


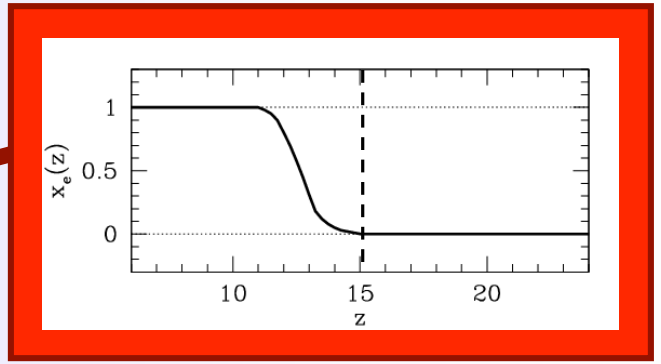
CV-limited, simulated data

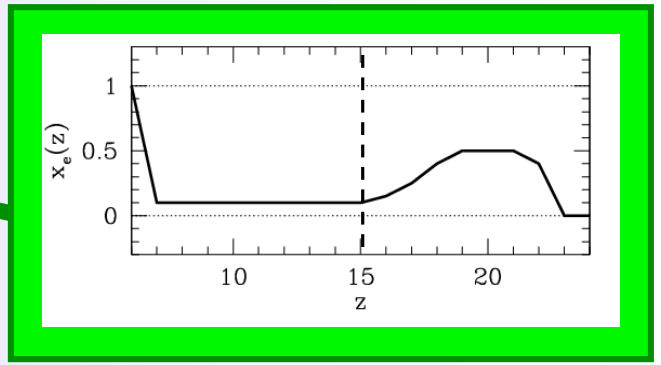


Going beyond optical depth: constraints on a second parameter

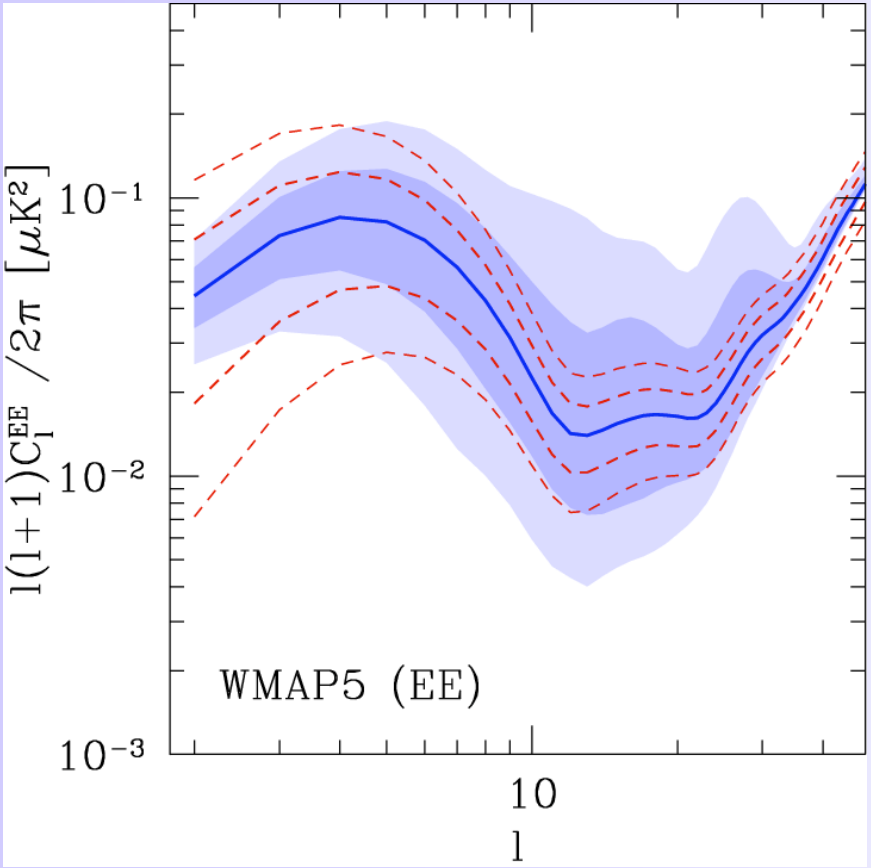


CV-limited, simulated data

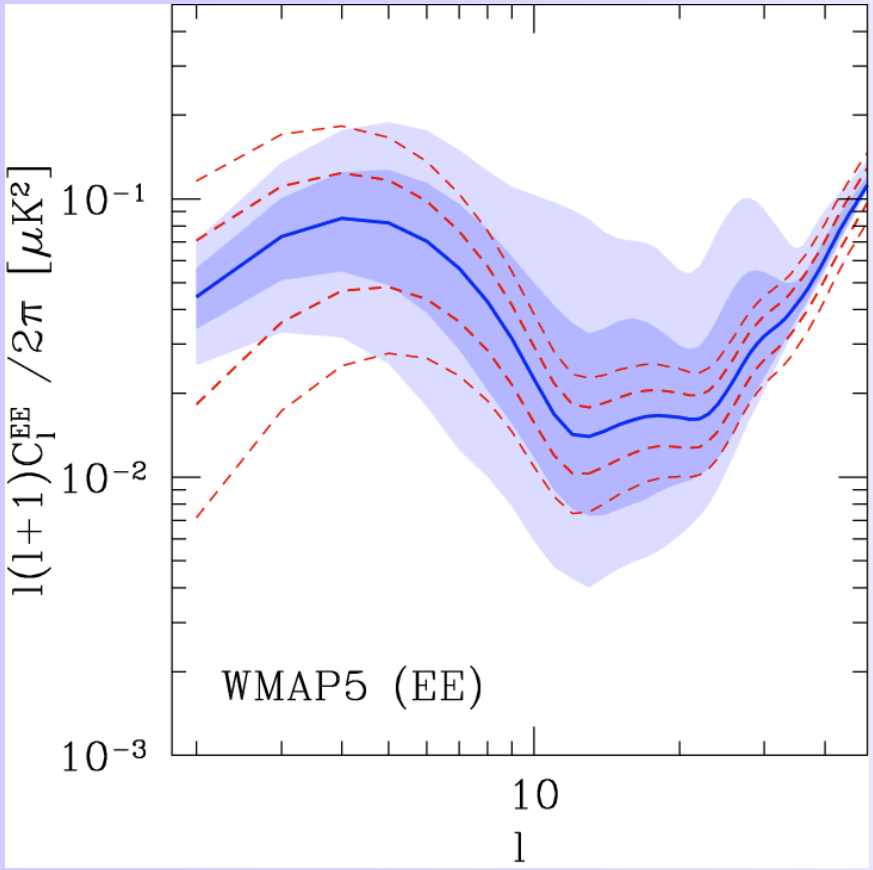


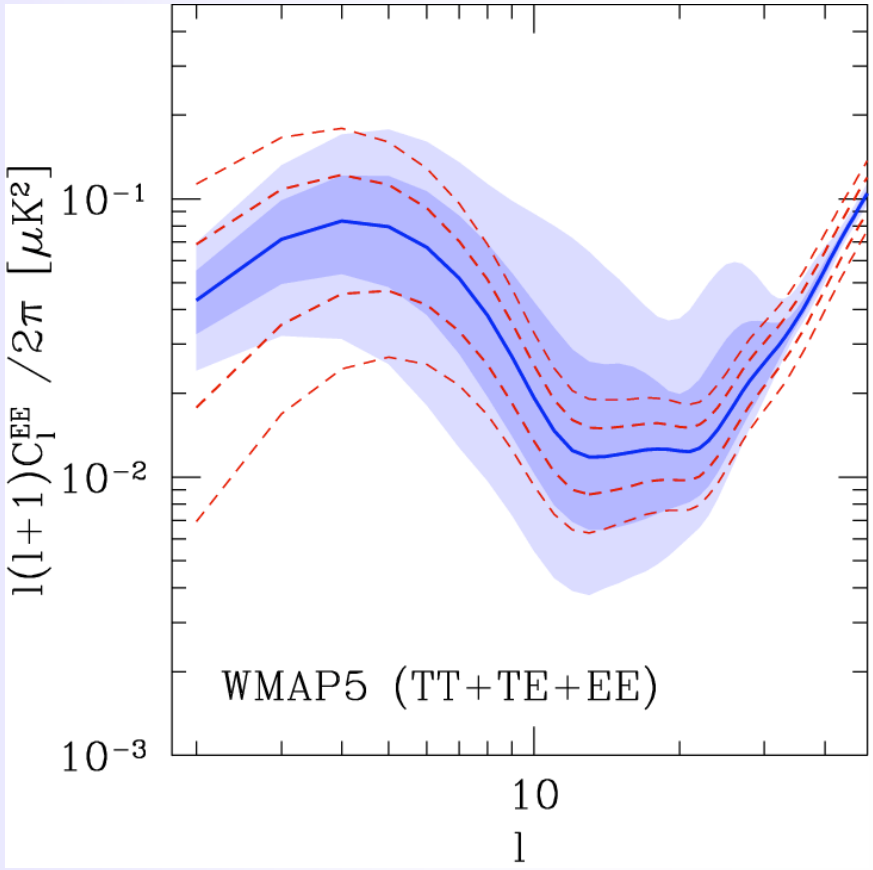


WMAP5: power spectra for allowed models

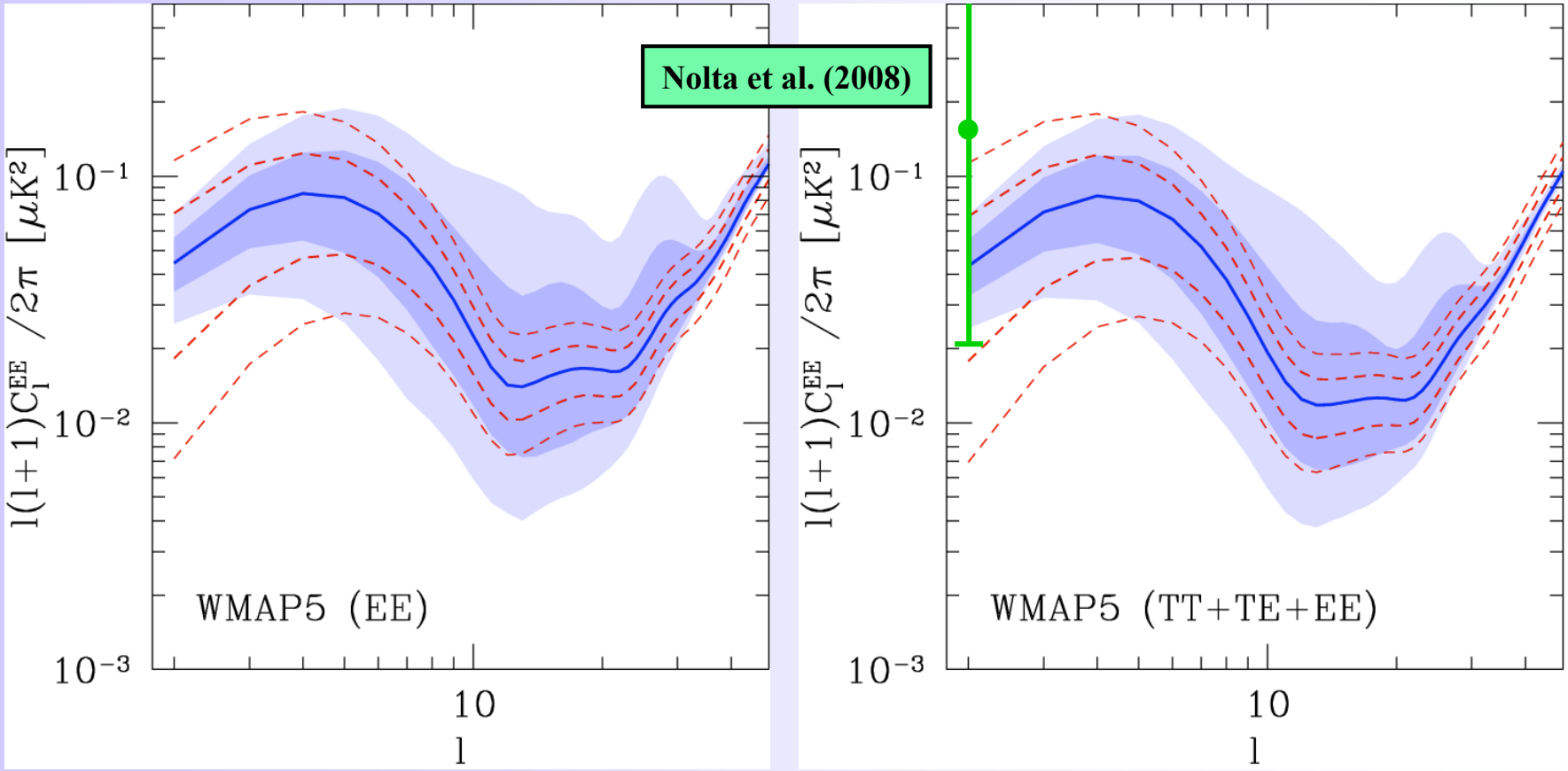


WMAP5: power spectra for allowed models

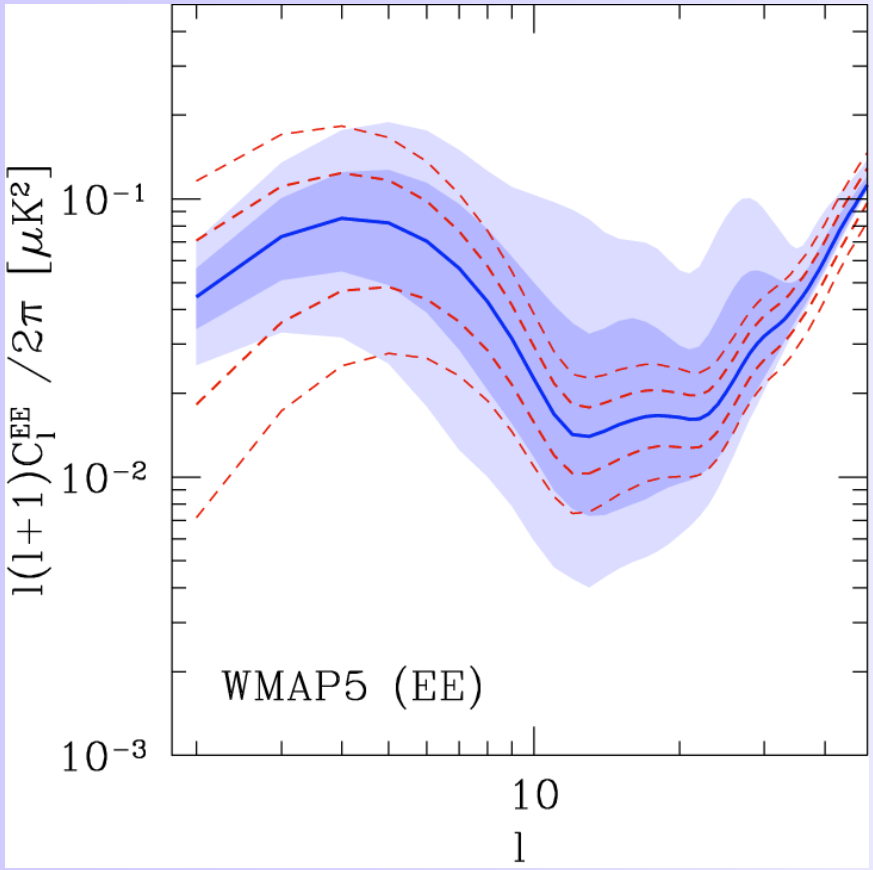


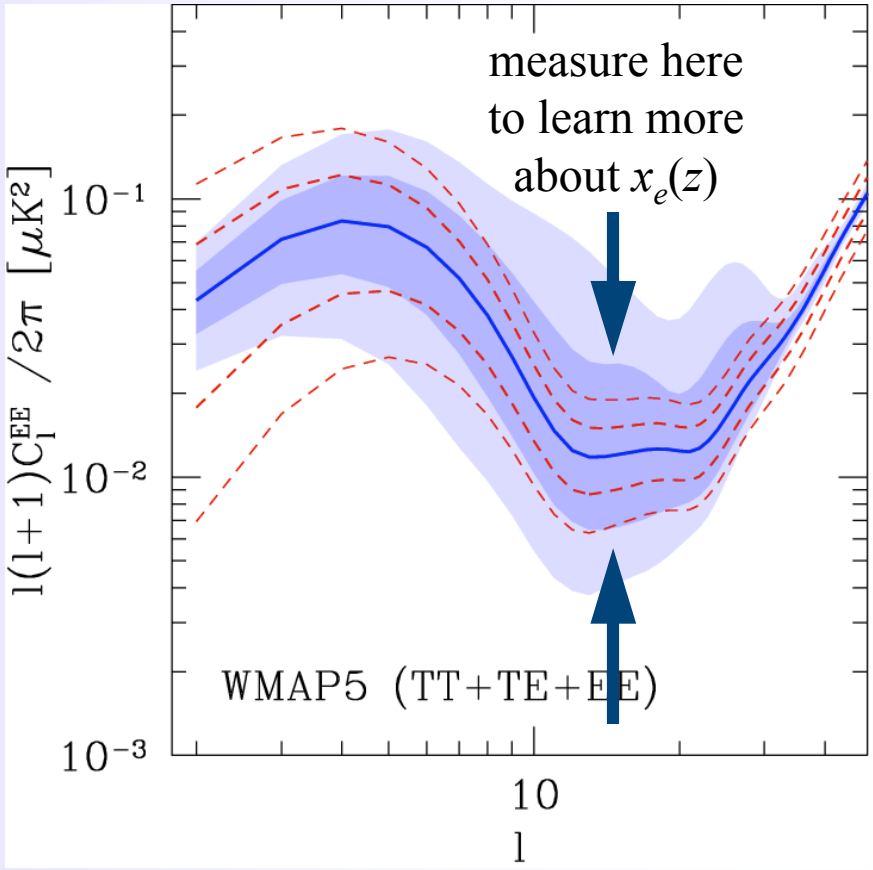


WMAP5: power spectra for allowed models



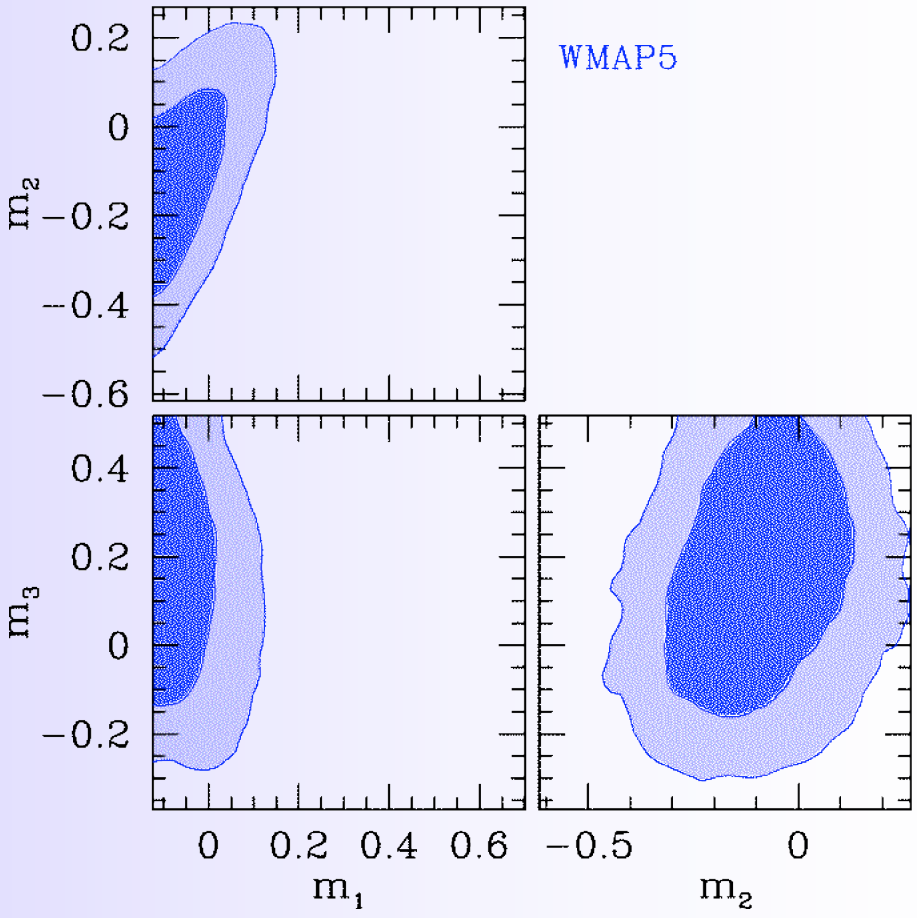
WMAP5: power spectra for allowed models





Future data forecasts

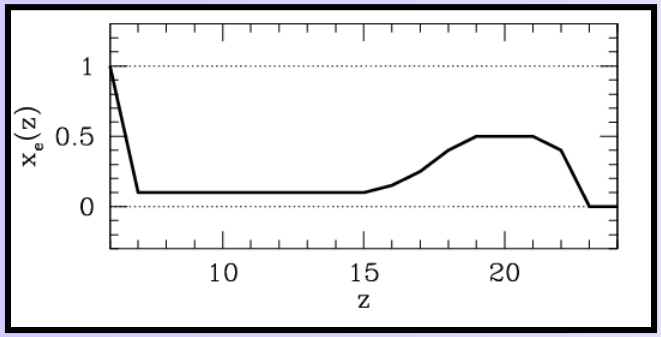
$\sigma_\tau = 0.017$

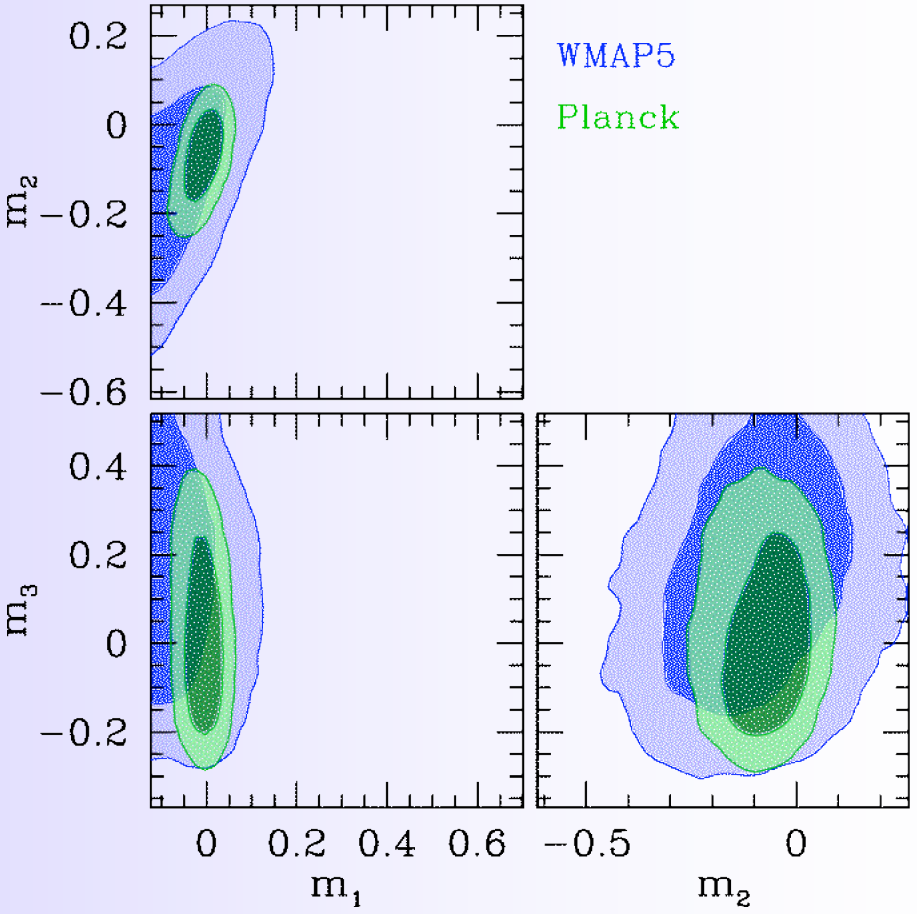


Future data forecasts

$\sigma_\tau = 0.017$

$\sigma_\tau = 0.009$



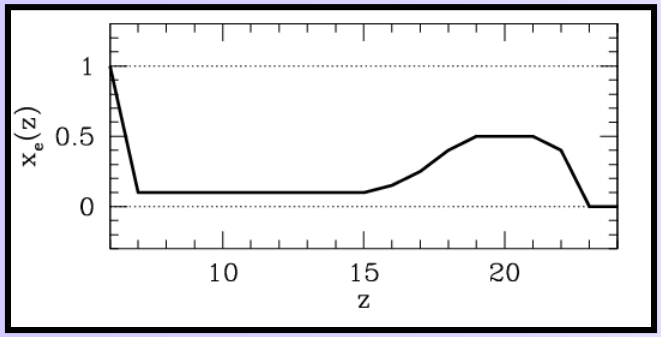


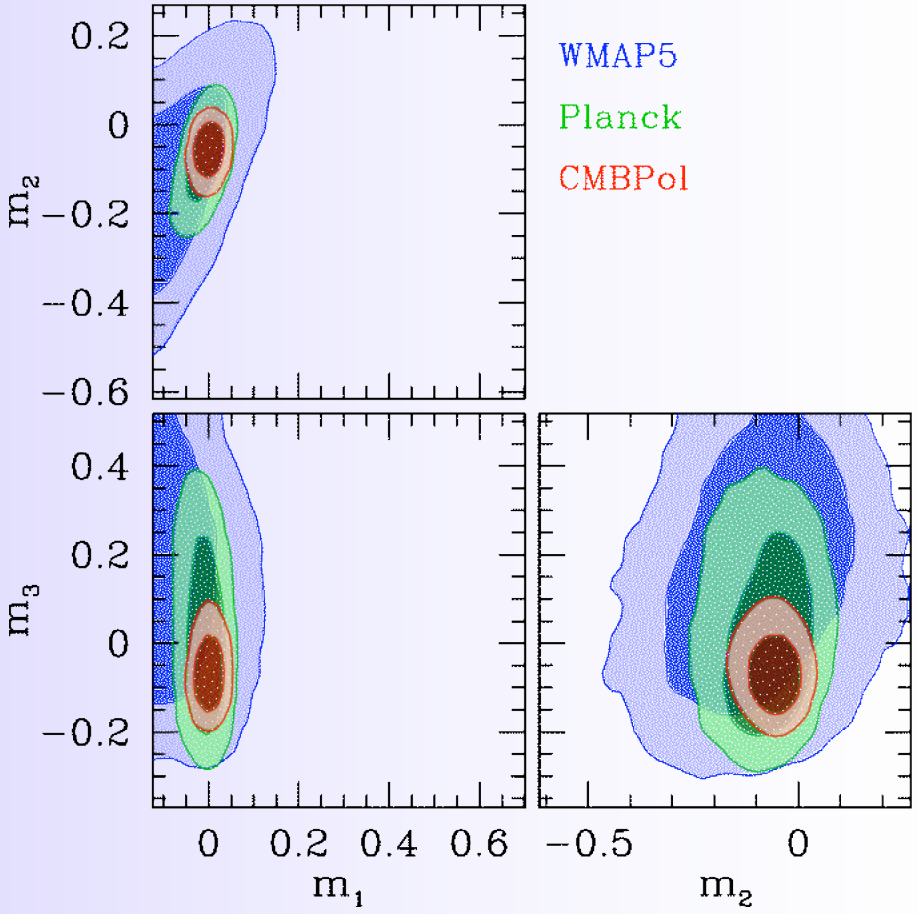
Future data forecasts

$\sigma_\tau = 0.017$

$\sigma_\tau = 0.009$

$\sigma_\tau = 0.007$





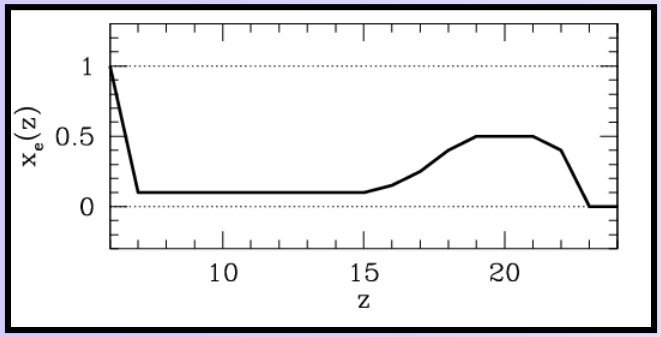
Future data forecasts

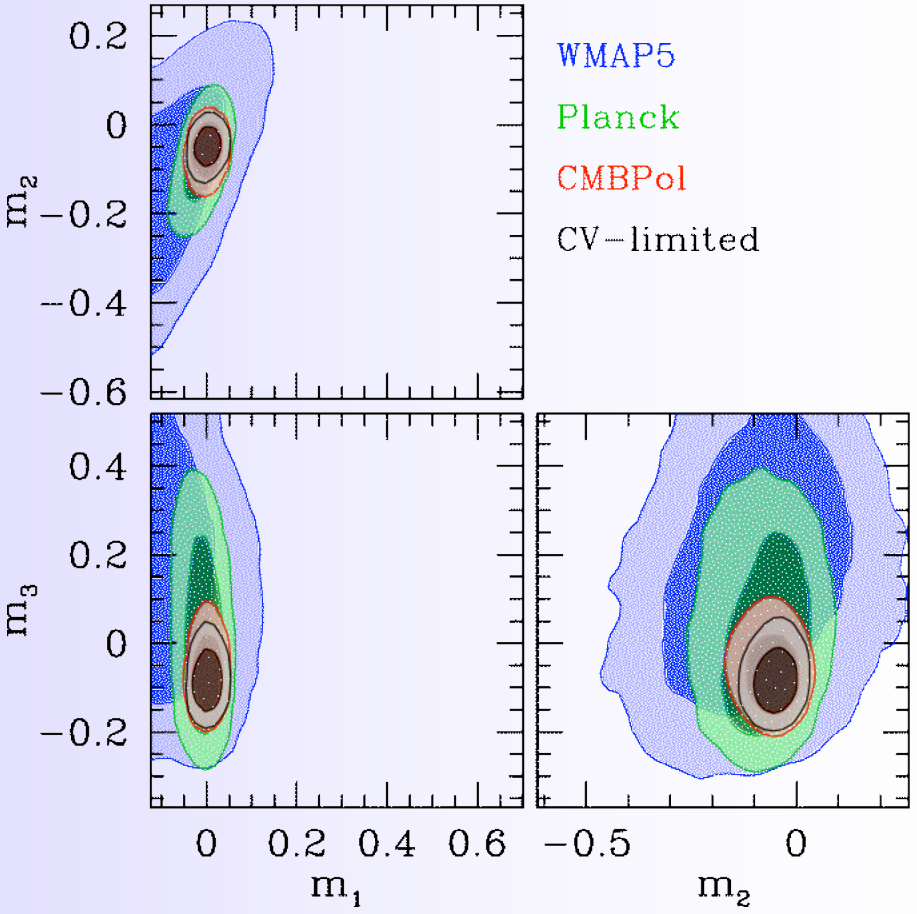
$\sigma_\tau = 0.017$

$\sigma_\tau = 0.009$

$\sigma_\tau = 0.007$

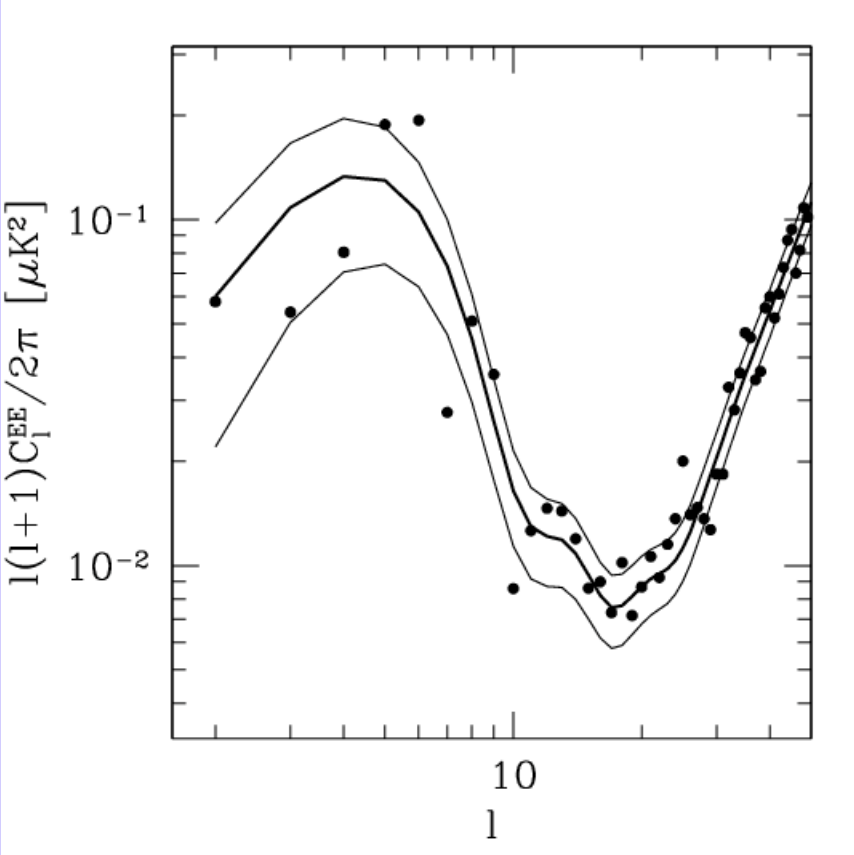
$\sigma_\tau = 0.005$

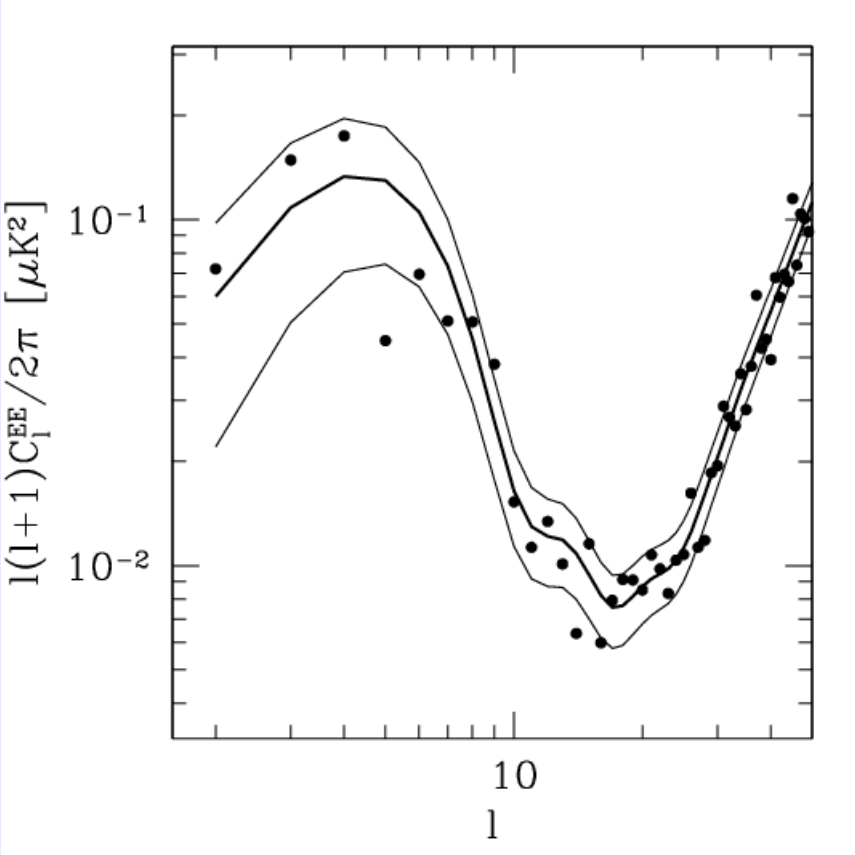




Cosmic variance and PC constraints

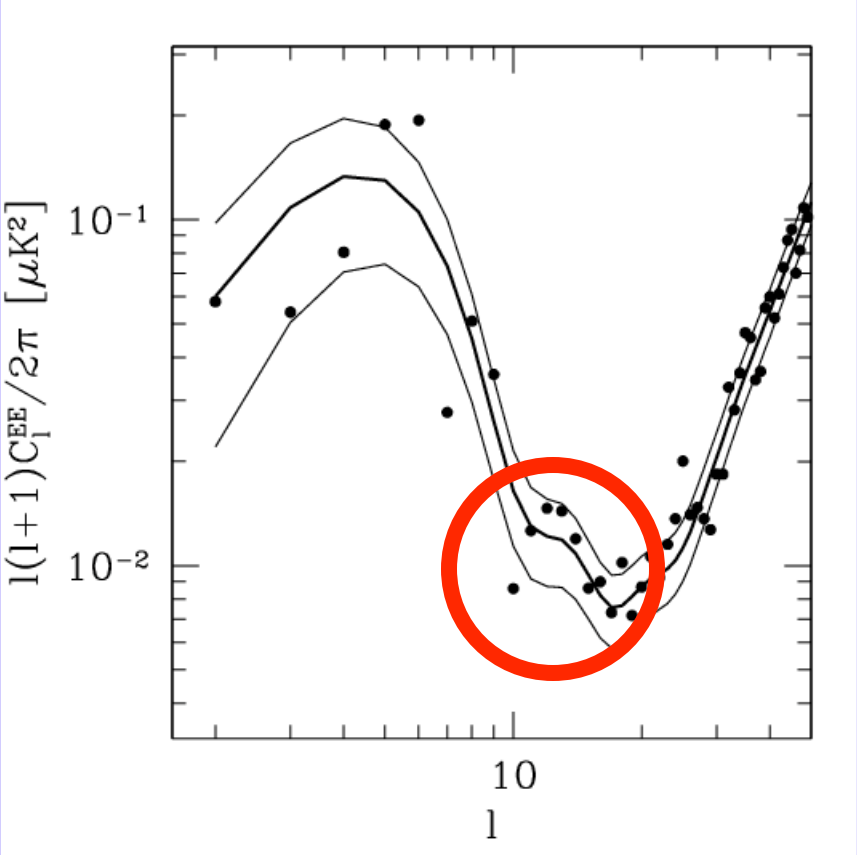
2 random draws of C_l^{EE} with same $x_e(z)$:

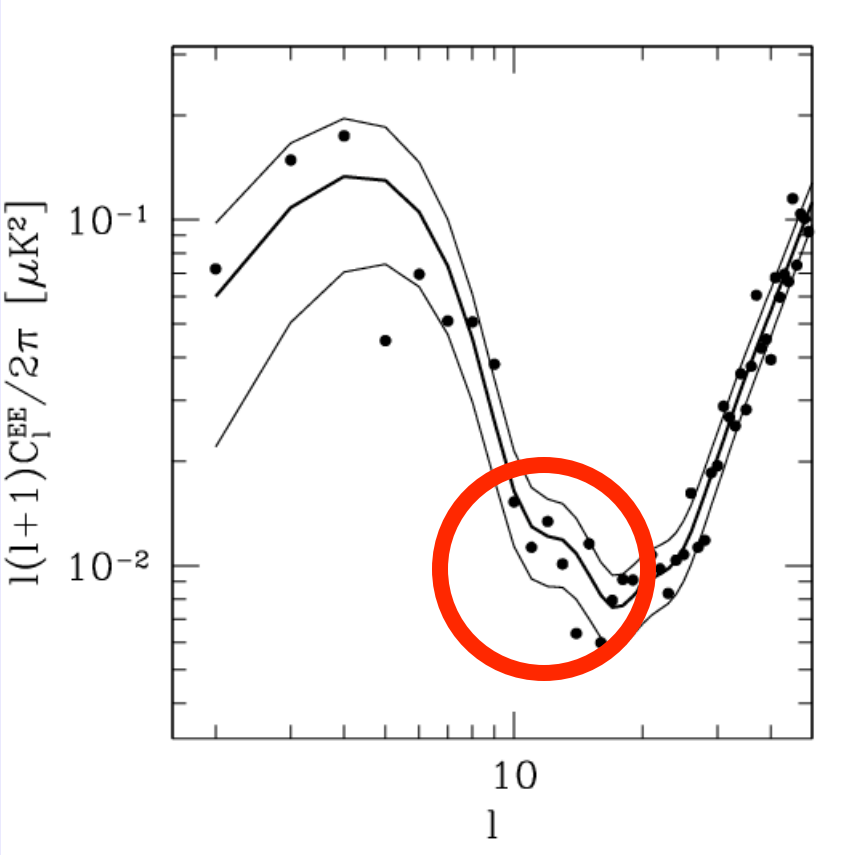




Cosmic variance and PC constraints

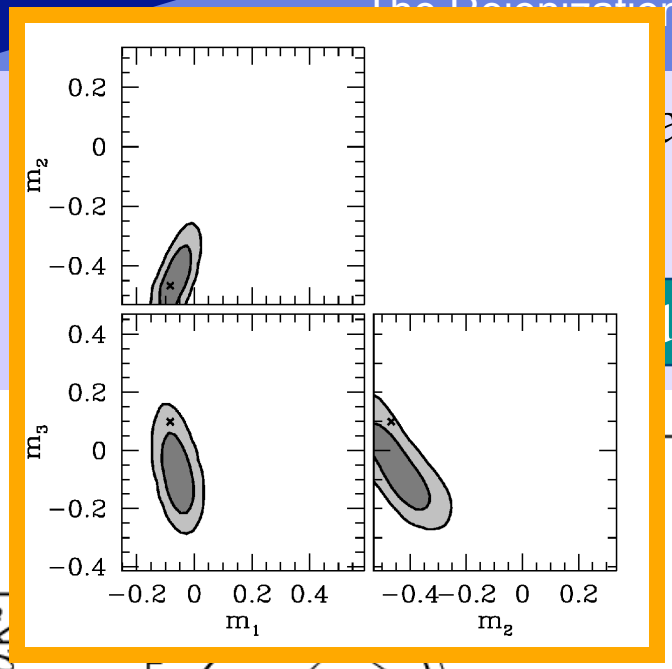
2 random draws of C_l^{EE} with same $x_e(z)$:

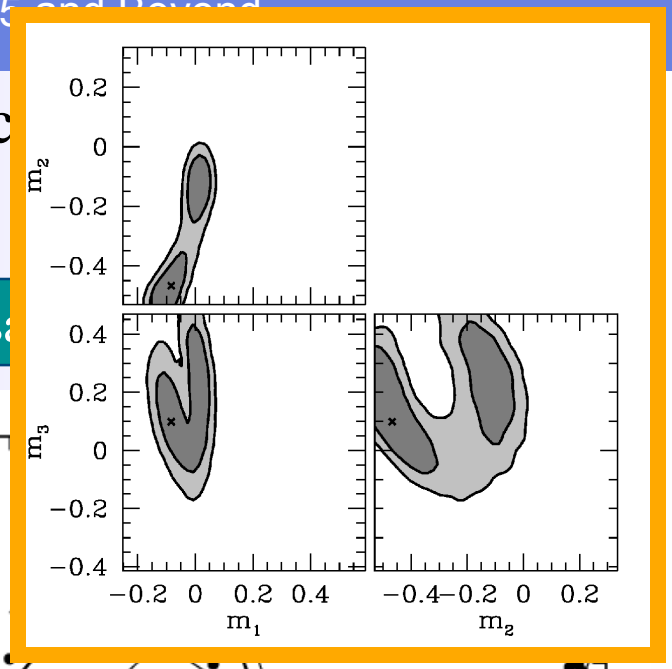


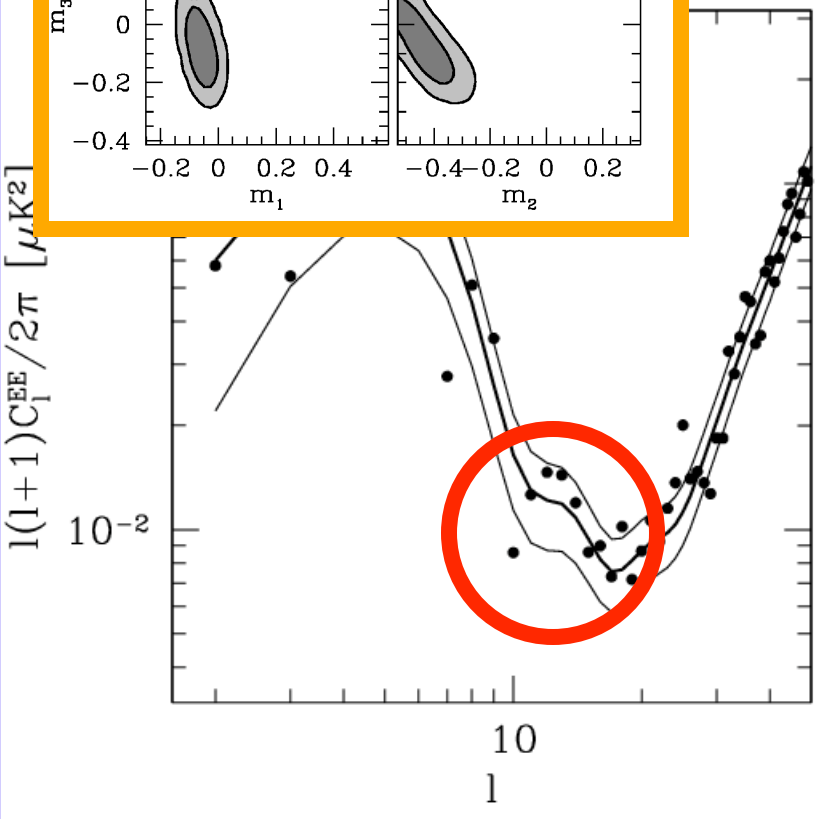


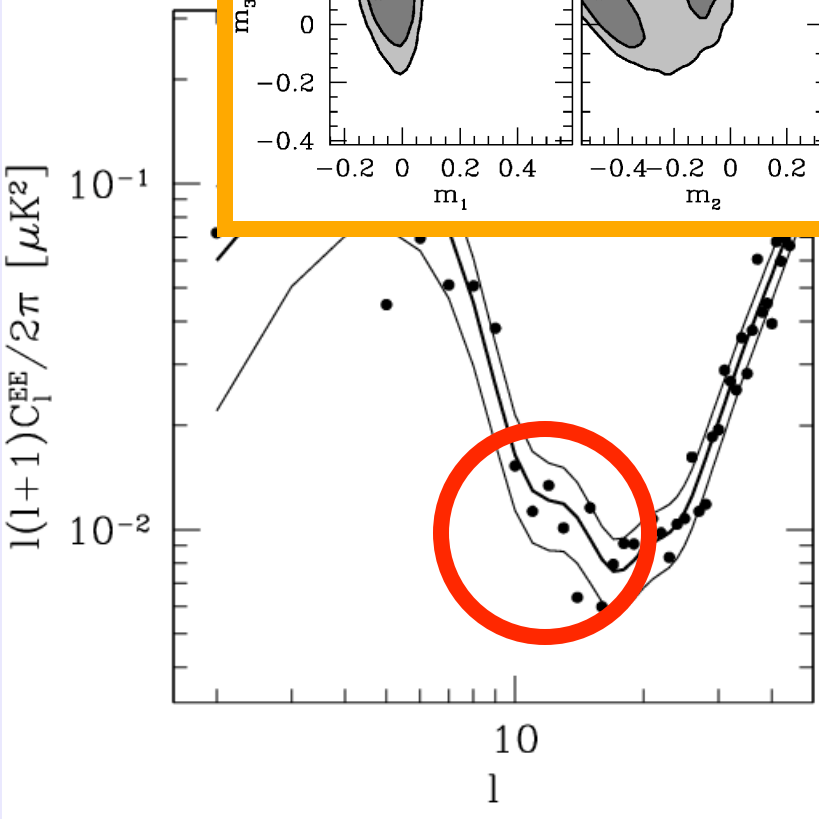
ariance and PC c

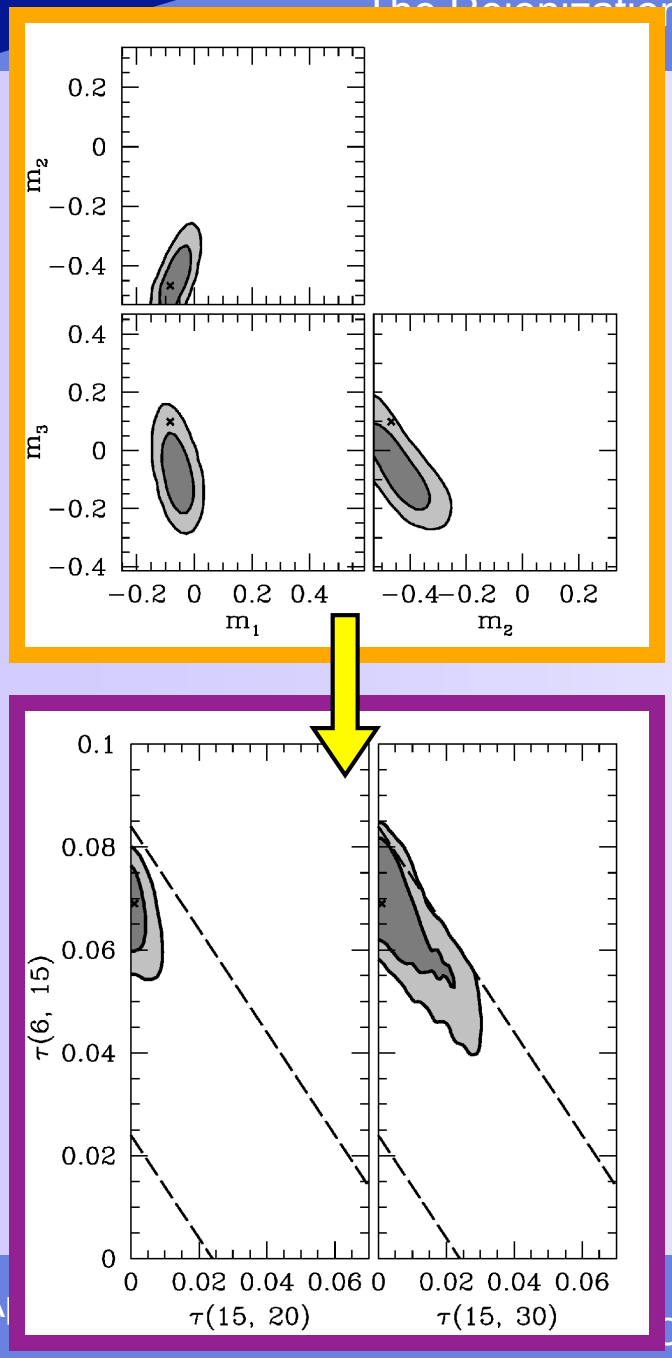
raws of C_l^{EE} with s

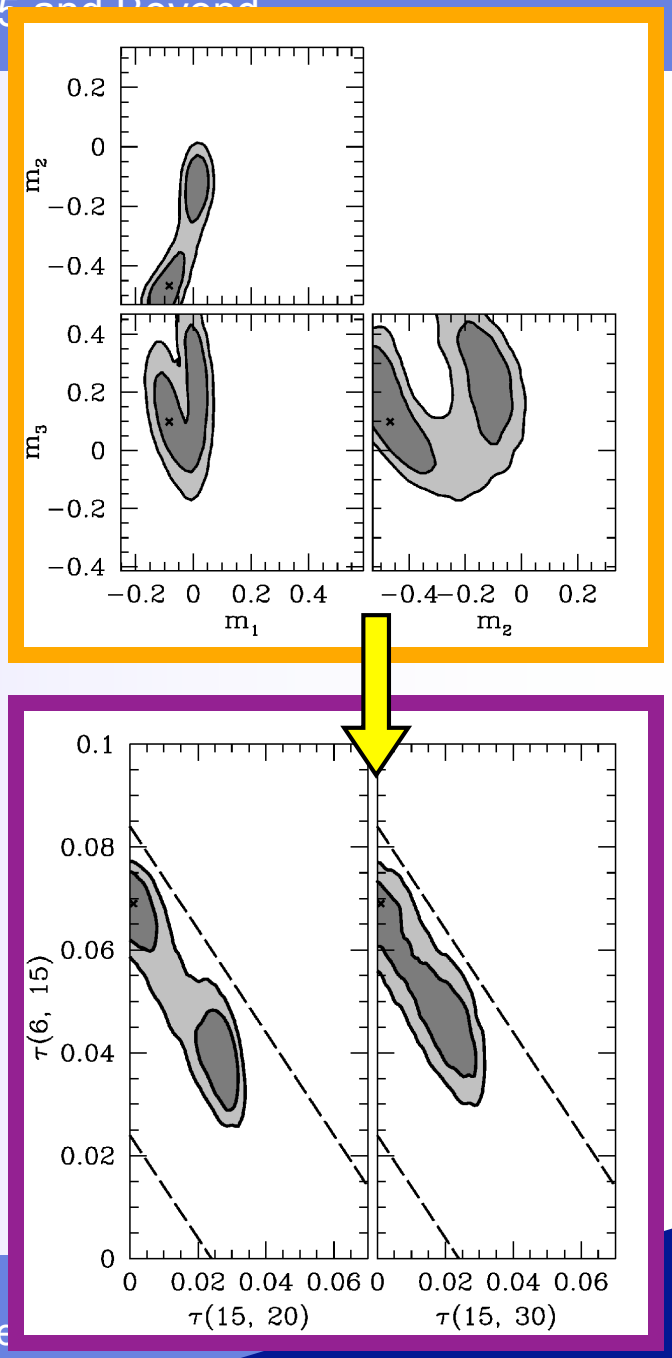









0.2
0
−0.2
−0.4
m2
0.4
0.2
0
−0.2
−0.4
m3
−0.2 0 0.2 0.4
m1
−0.4 −0.2 0 0.2
m2
0.1
0.08
0.06
0.04
0.02
0
τ(6, 15)
0 0.02 0.04 0.06
τ(15, 20)
0 0.02 0.04 0.06
τ(15, 30)


0.2
0
−0.2
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m2
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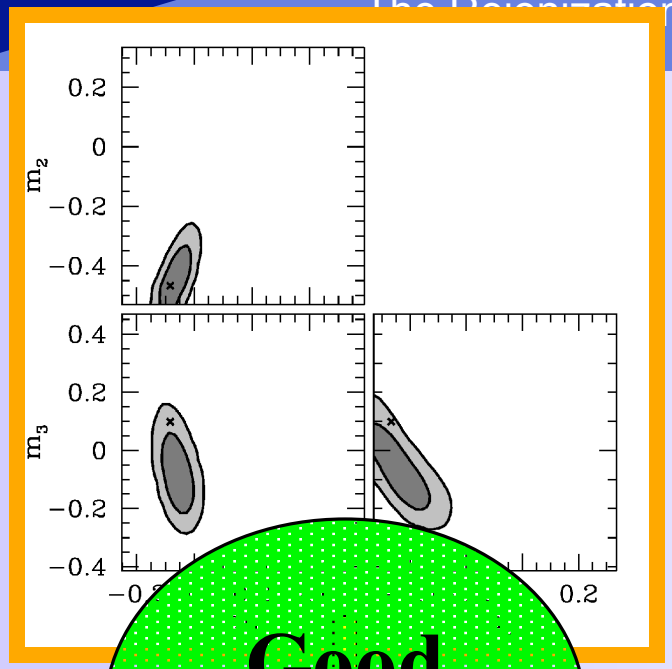
0
−0.2
−0.4
m3
−0.2 0 0.2 0.4
m1
−0.4 −0.2 0 0.2
m2
0.1
0.08
0.06
0.04
0.02
0
τ(6, 15)
0 0.02 0.04 0.06
τ(15, 20)
0 0.02 0.04 0.06
τ(15, 30)


0.2
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m2
0.4
0.2
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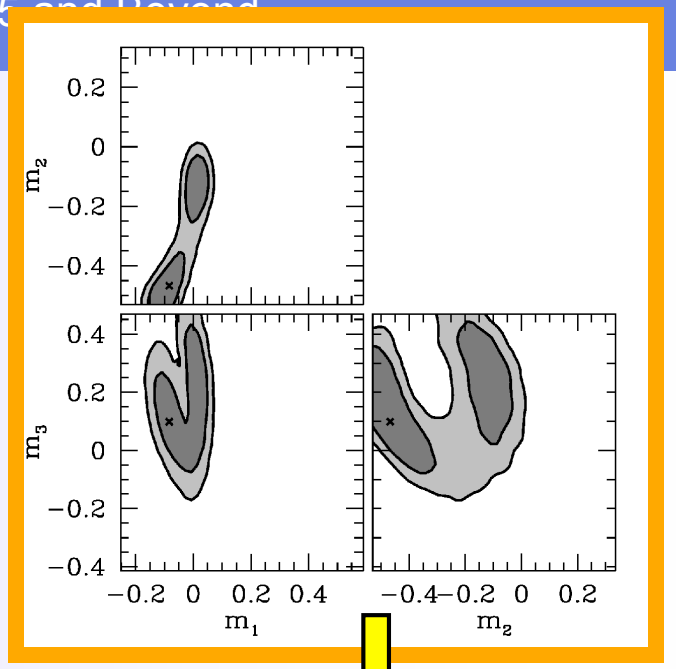
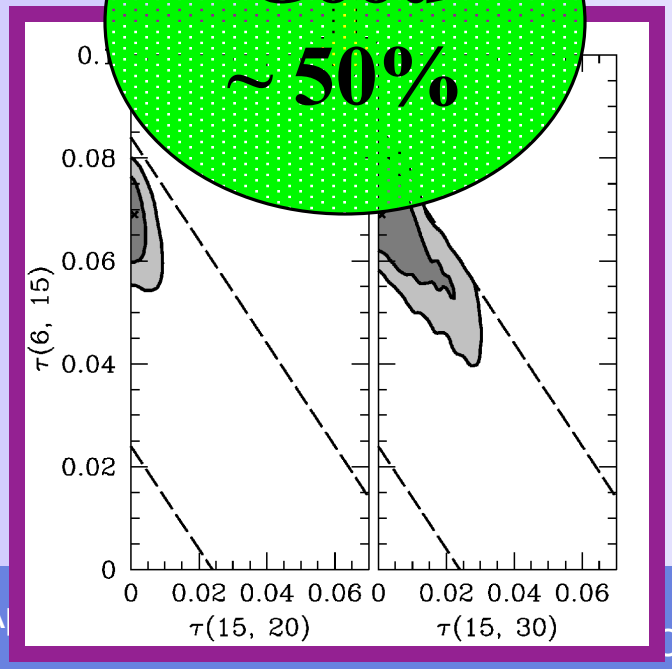
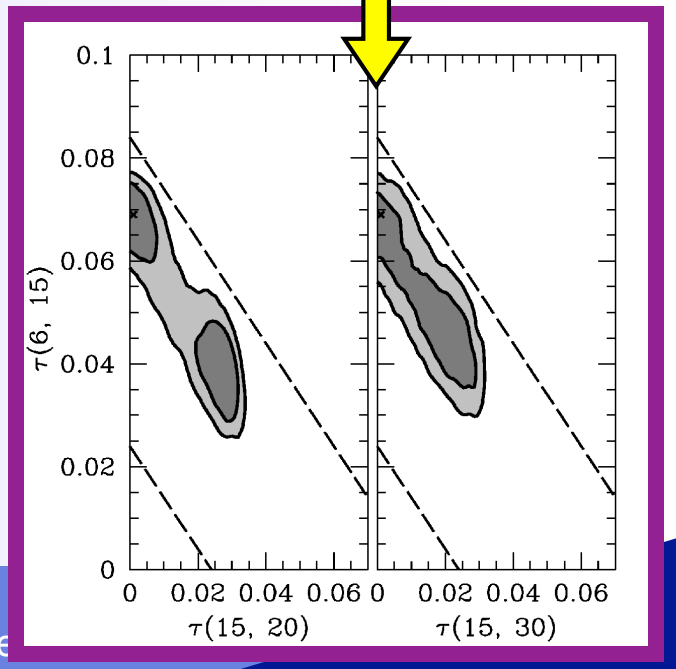
−0.2
−0.4
m3
−0
0.2


0.2
0
−0.2
−0.4
m2
0.4
0.2
0
−0.2
−0.4
m3
−0.2 0 0.2 0.4
m1
−0.4 −0.2 0 0.2
m2

Good
~50%


0.1
0.08
0.06
0.04
0.02
0
τ(6, 15)
0 0.02 0.04 0.06
τ(15, 20)
0 0.02 0.04 0.06
τ(15, 30)


0.1
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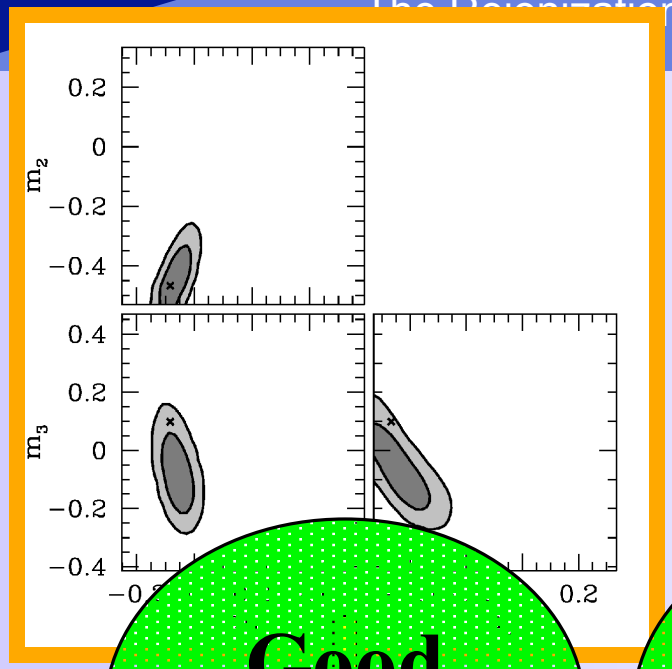
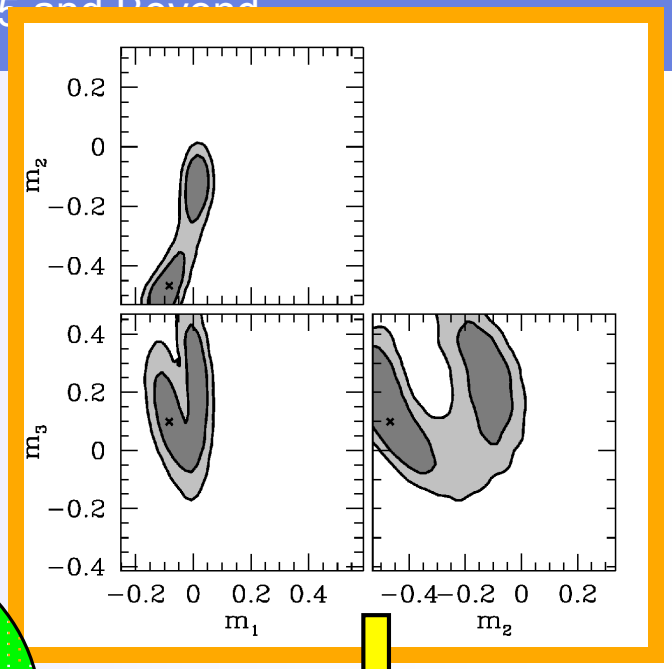
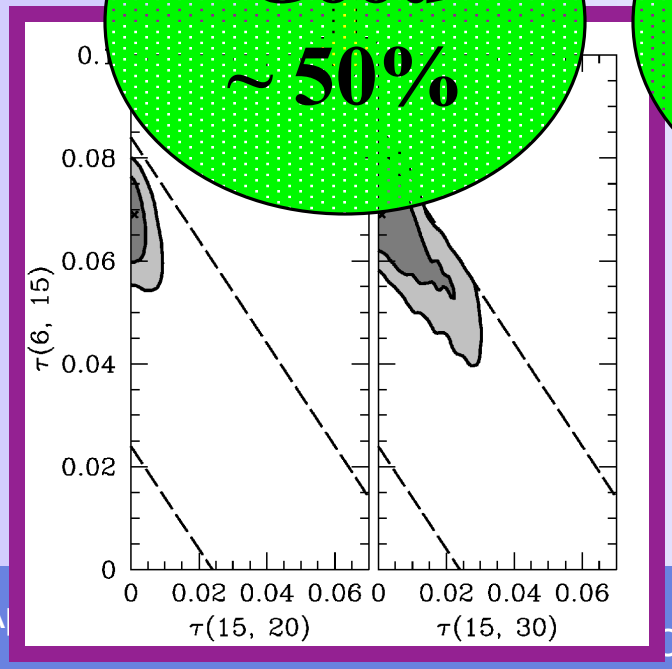
0.06
0.04
0.02
0
τ(6, 15)
0 0.02 0.04 0.06
τ(15, 20)
0 0.02 0.04 0.06
τ(15, 30)

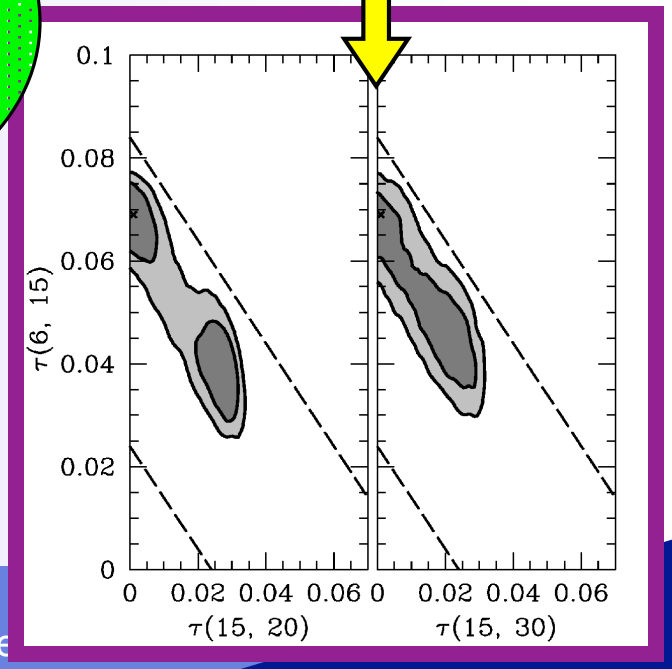


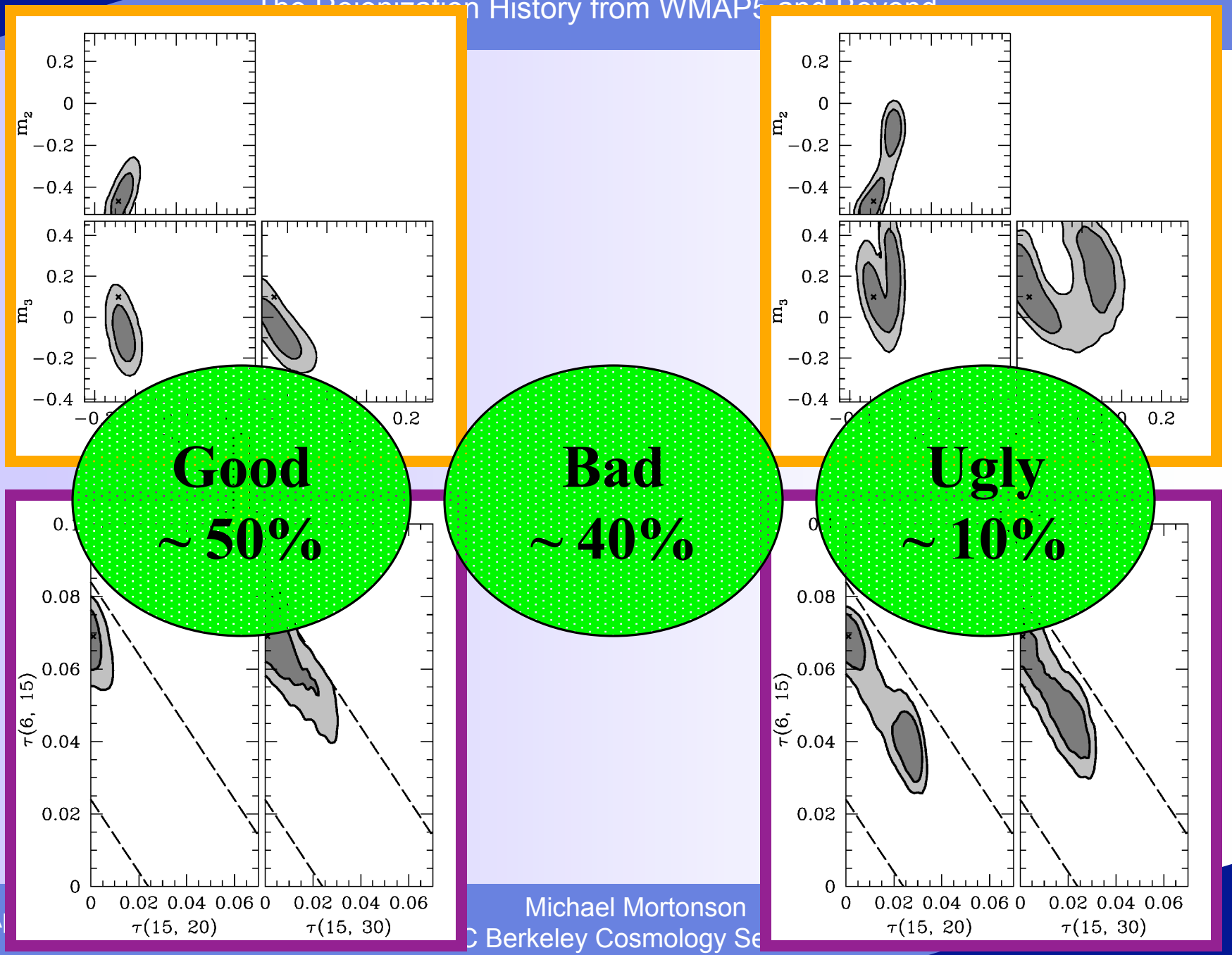


Good
~50%

Bad
~40%






Good
~ 50%
Bad
~ 40%
Ugly
~ 10%
m2
m3
τ(6, 15)
τ(15, 20)
τ(15, 30)

Outline

- Overview of reionization and CMB polarization

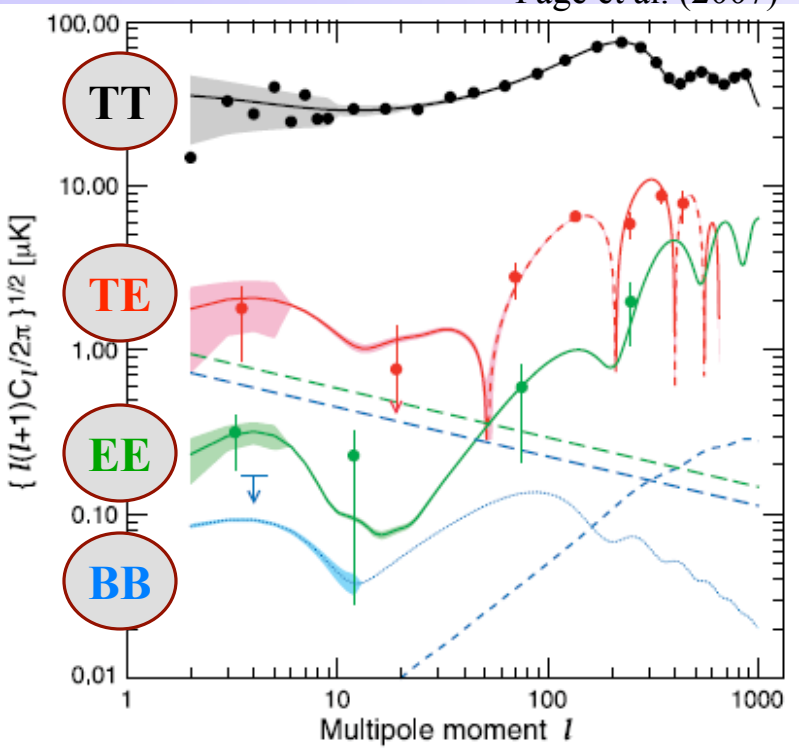
- Principal component decomposition of the reionization history (describe general $x_e(z)$ with small number of parameters)

- MCMC constraints from WMAP5 and simulated CV-limited data:
  - total optical depth to reionization
    (without assuming a specific model)
  - optical depth from high z (> 15-20) vs. low z

Applications to tensor BB spectrum – degeneracy with inflationary parameters

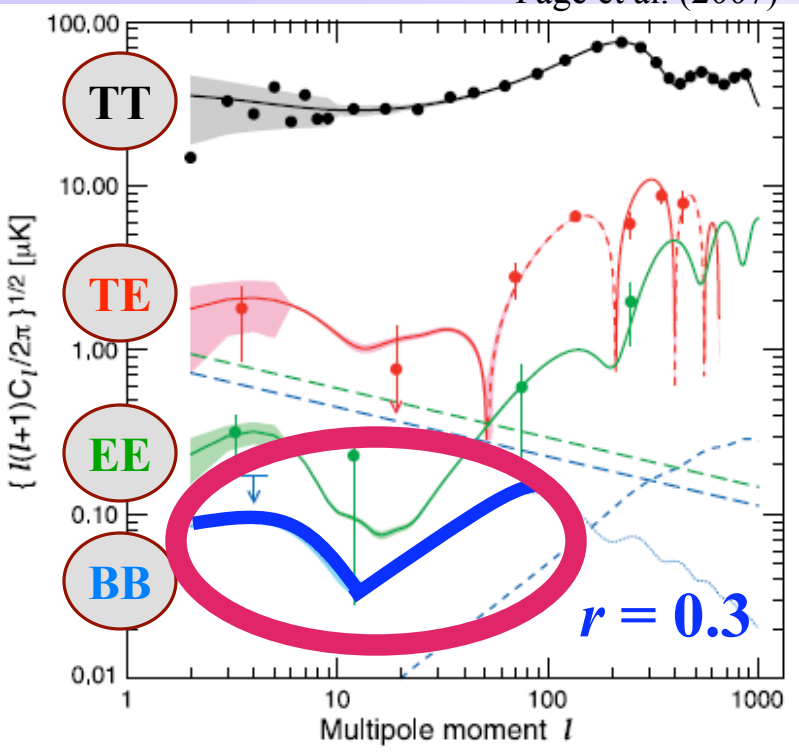
Large scale B-modes and reionization

Page et al. (2007)



Large scale B-modes and reionization

Page et al. (2007)



Large scale B-modes and reionization

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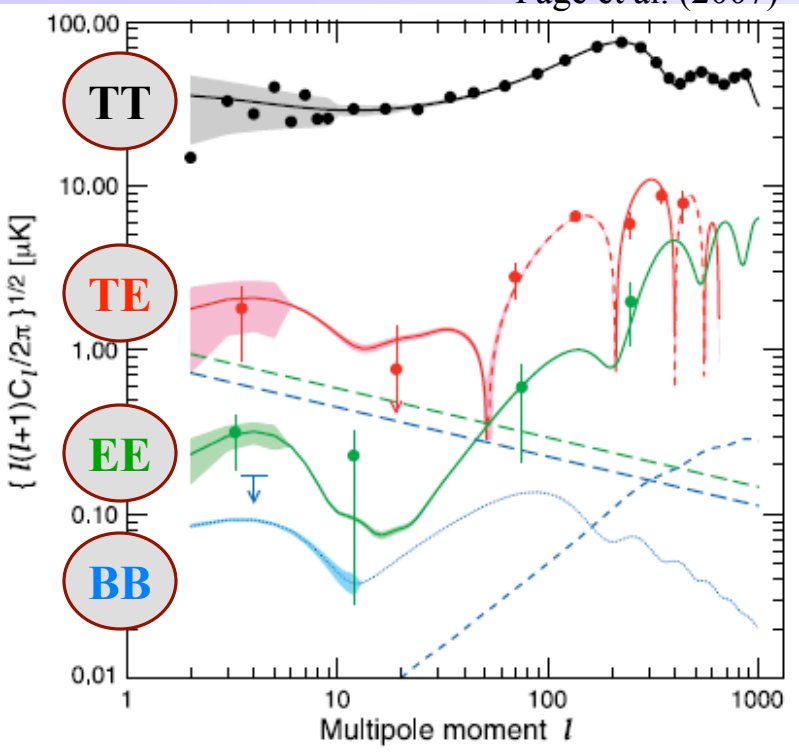
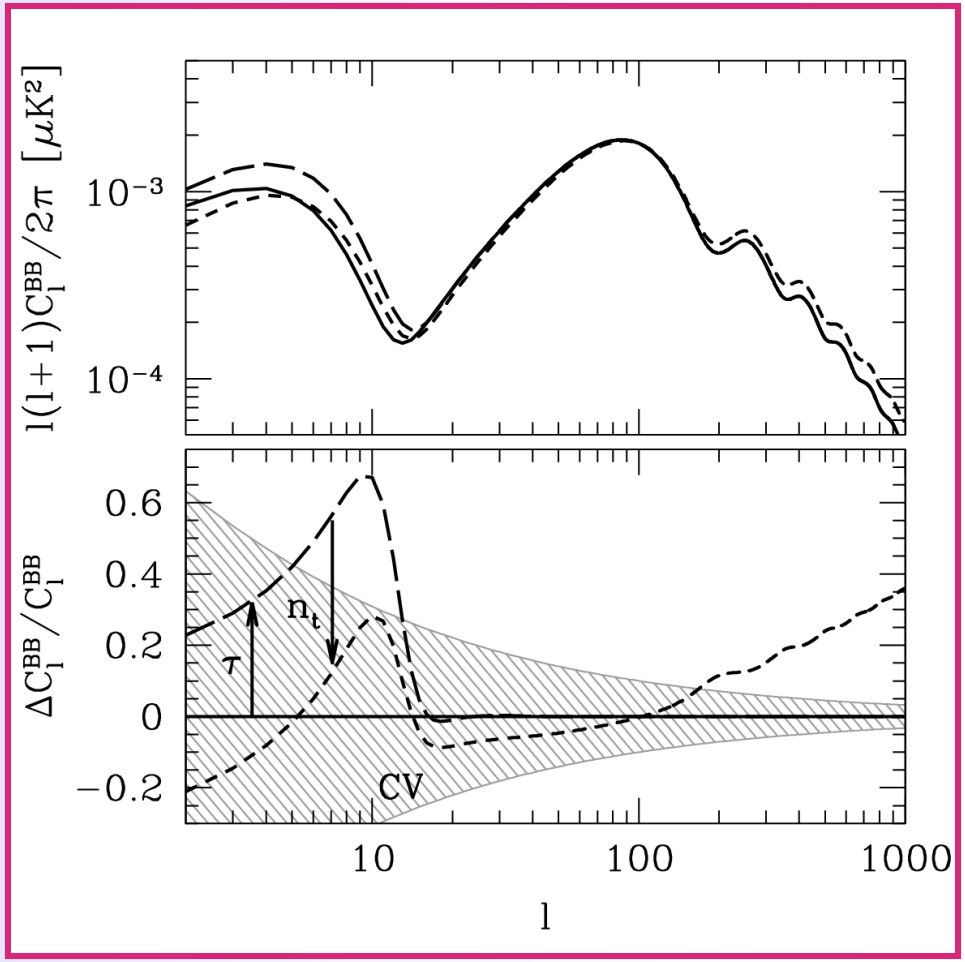
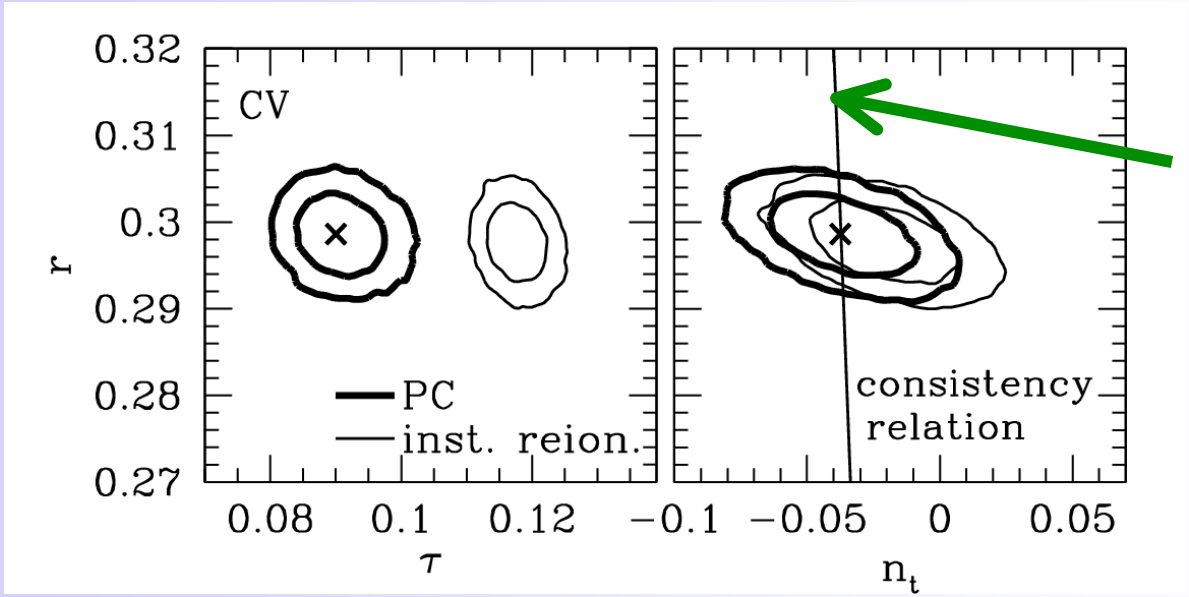
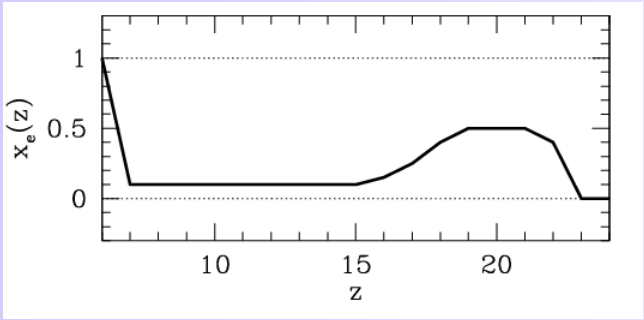




Large scale B-modes and reionization

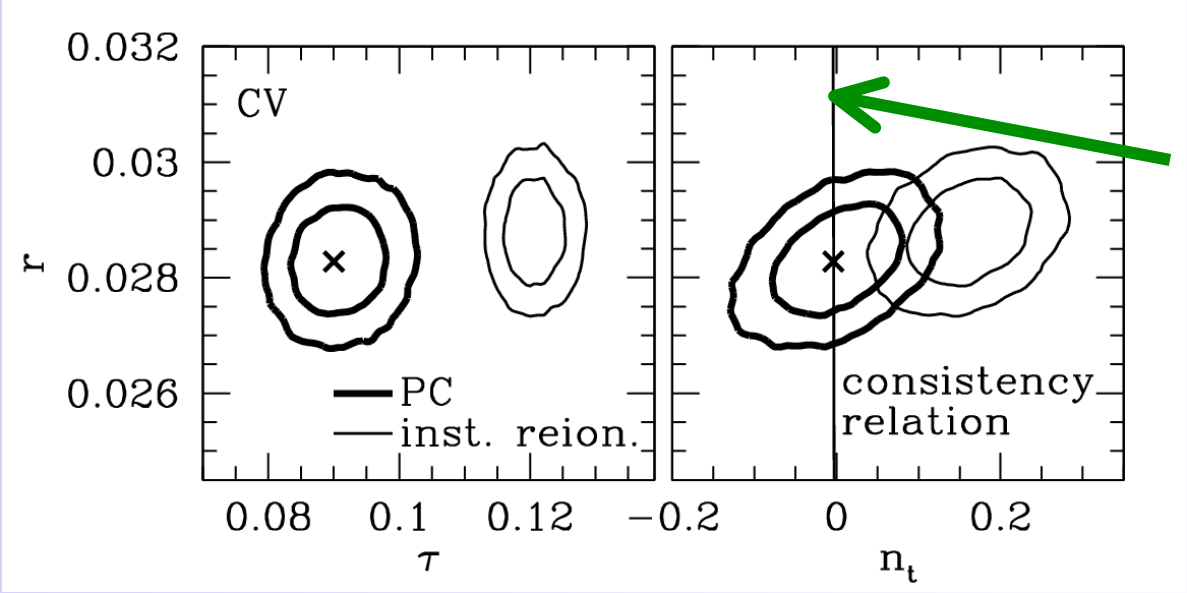


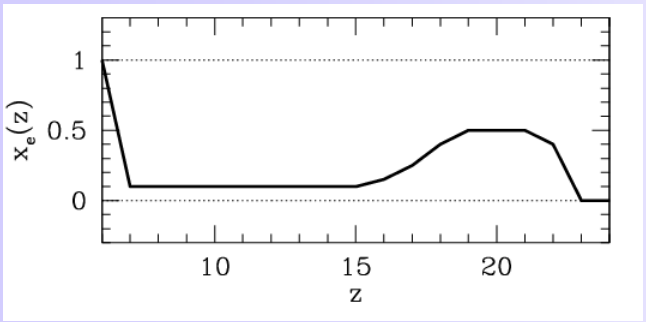


MCMC with EE + BB spectra, including scalar and tensor (***r* = 0.3**) perturbations

(no CV in "data" – ensemble average)

Large scale B-modes and reionization





MCMC with EE + BB spectra, including scalar and tensor (***r* = 0.03**) perturbations

(no CV in "data" – ensemble average)

Summary

- Using PCs of $x_e(z)$, model-independent analysis of large-scale CMB polarization is possible with only a few new parameters
- Expanding the space of models leaves current constraints on τ unchanged, but is crucial to avoid bias with future data
- Shape of reionization peak can constrain parameters besides τ
- PC constraints from MCMC provide framework for model testing and analysis of other data where reionization matters (e.g., low-l BB)

E-modes: Mortonson & Hu (2008), ApJ, 672, 737, arXiv: 0705.1132
B-modes: Mortonson & Hu (2008), PRD, 77, 043506, arXiv: 0710.4162
WMAP5 update: Mortonson & Hu, arXiv: 0804.2631