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Cosmological Reionisation

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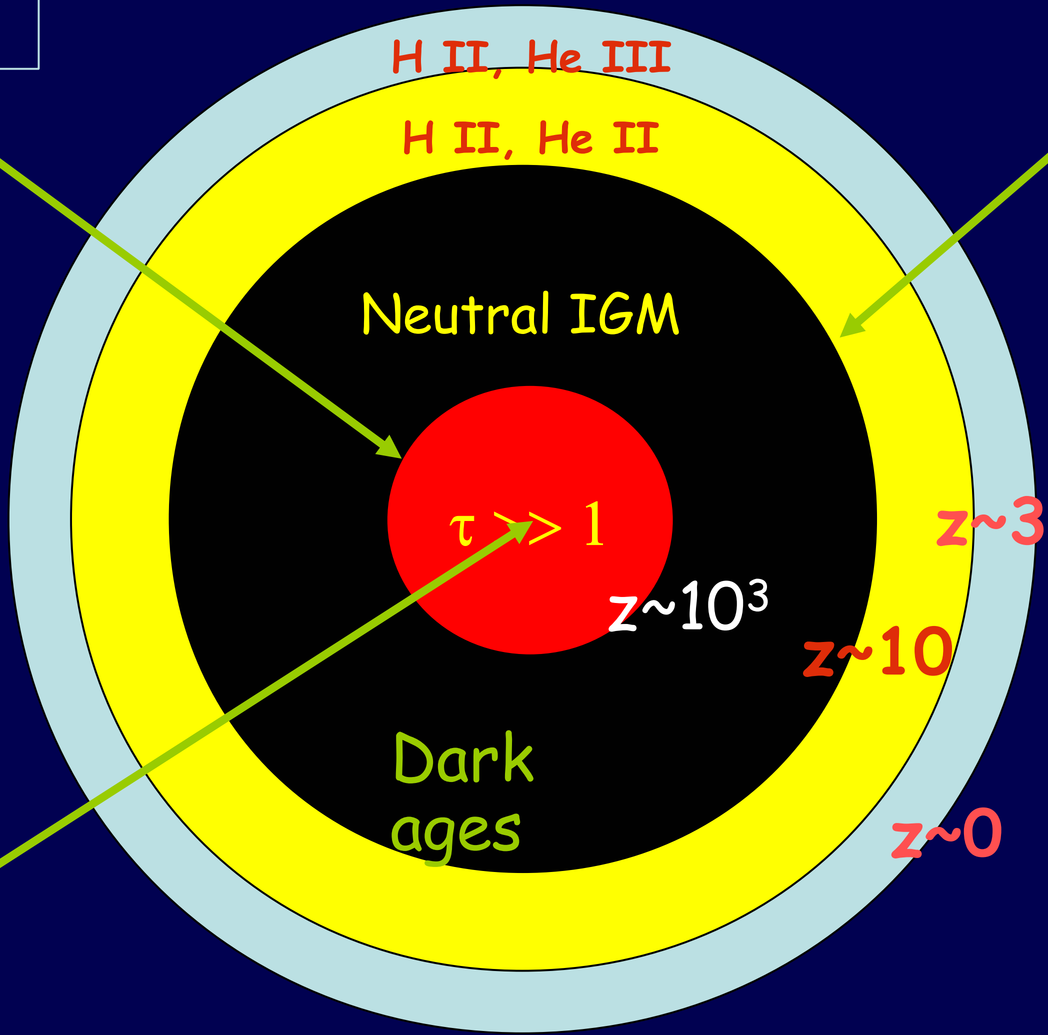
Overview

I. Introduction
II. What do we know? WMAP polarisation data , high-z QSO's, IGM temp.
III. Do the data suggest a coherent picture?
IV. How could the universe reionised so early?
V. The Future: 21 cm measurements (LOFAR, PAST, ...)
VI. Summary

Thermal History Of The Universe

Recombination



Reionization process is probably complicated and extends over large z range

Inflation

What do we know?

The high z end: CMB and reionisation

- Thomson Scattering of CMB photons off free electrons produced during reionisation suppresses the CMB temp. fluctuations angular power spectrum on large scales and enhances their polarisation.
- On small scales there are also effects on both the CMB temp. and polarisation power spectra, this will be measured by future missions.
- Secondary CMB (SZ & VO effects)

Reionisation affects both T & Polar. CMB data.

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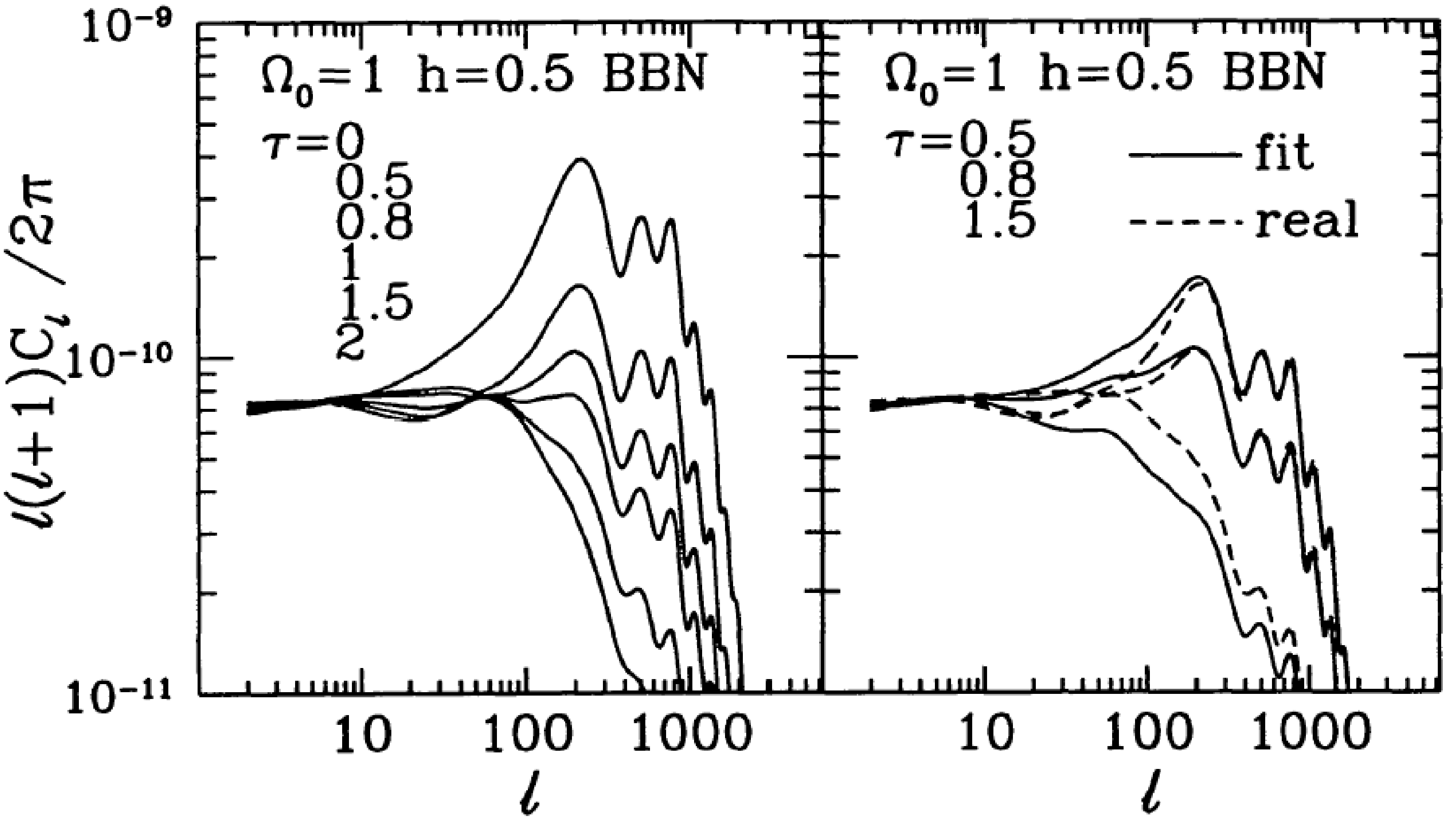
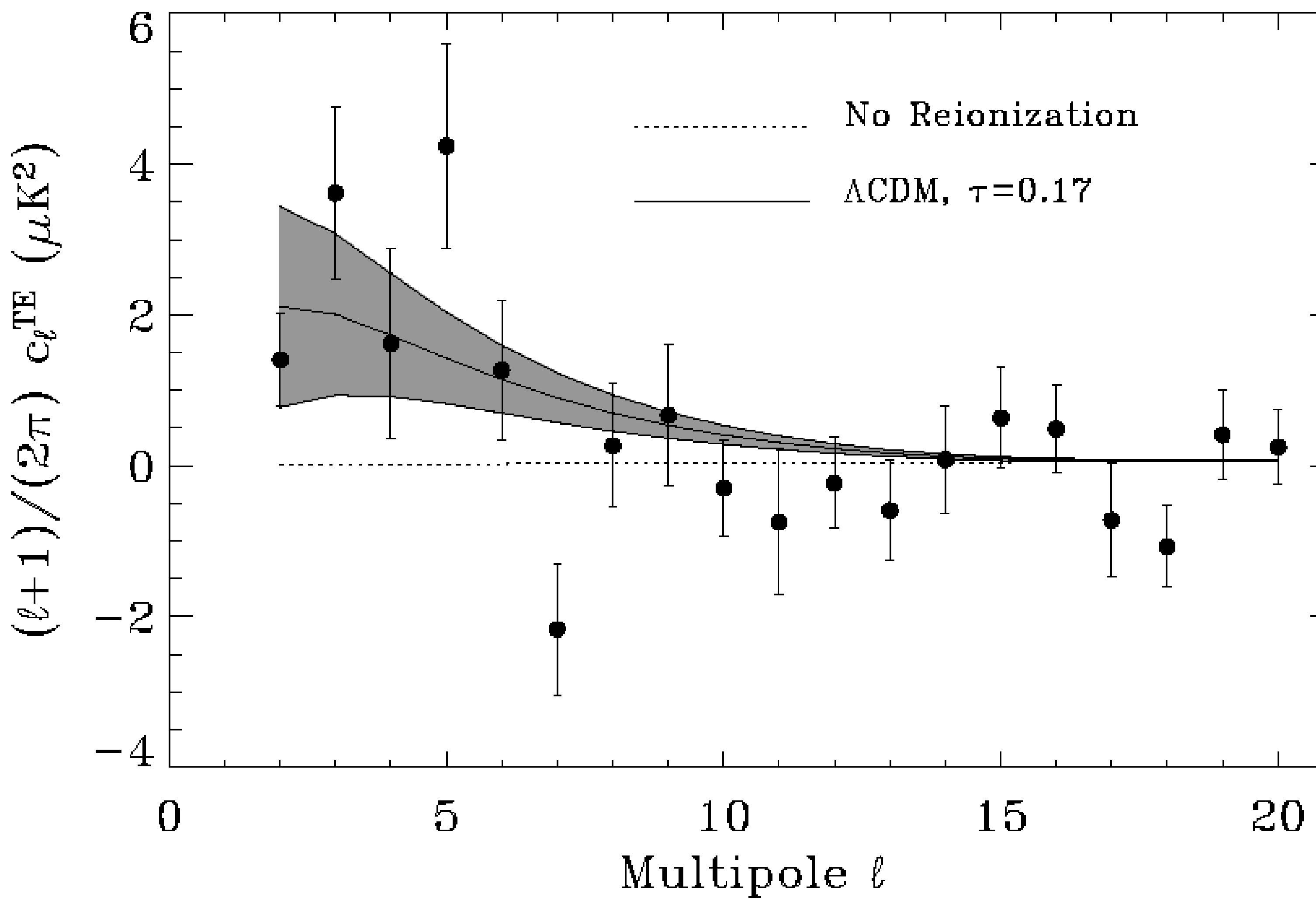
Sugiyama, Silk & Vittorio 93

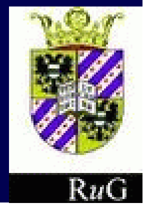


Suppression

Kogut at al. 2004

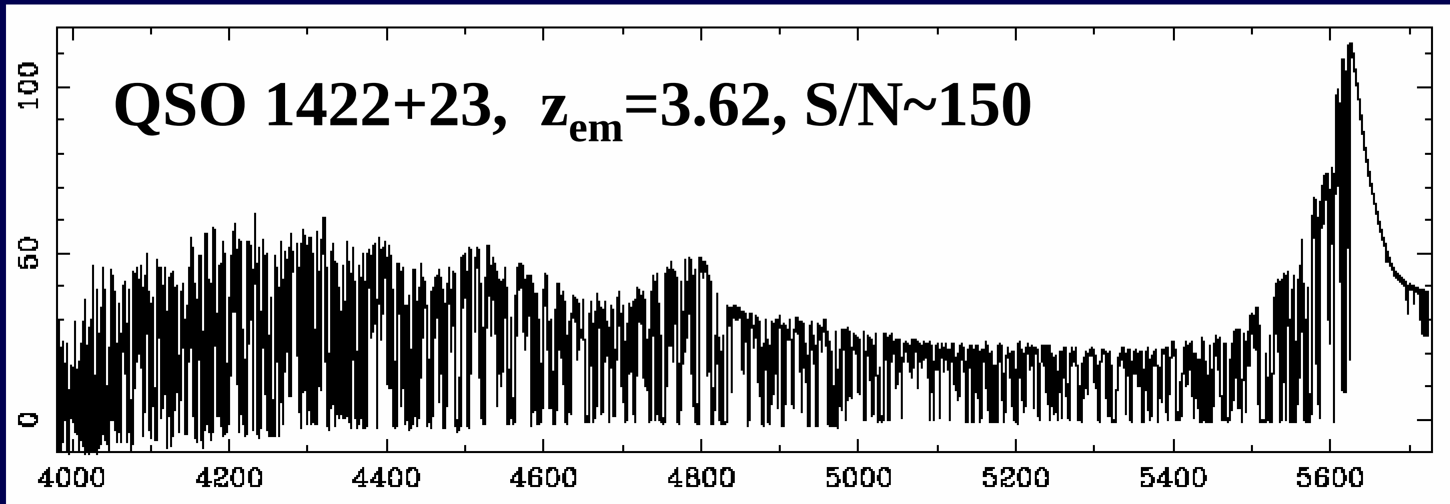


- WMAP measures optical depth of 0.17



The low z end: The Lyman-α Forest

Absorption features bluewards of the Lyman-α emission line in quasar spectra (Bahcall & Salpeter 65).



The optical depth for absorption by the Lyman-α resonance line is:

$$\tau(\lambda_{obs}) = \int_{z_S}^{z_{obs.}} \underbrace{dz \frac{cdt}{dz}}_{\text{dl}} \; \underbrace{n_{HI}(z)}_{\text{HI number density}} \; \underbrace{\sigma_{\alpha}[\nu_{obs}(1+z)]}_{\text{Scattering cross-section through Ly-}\alpha\text{ resonance}}$$

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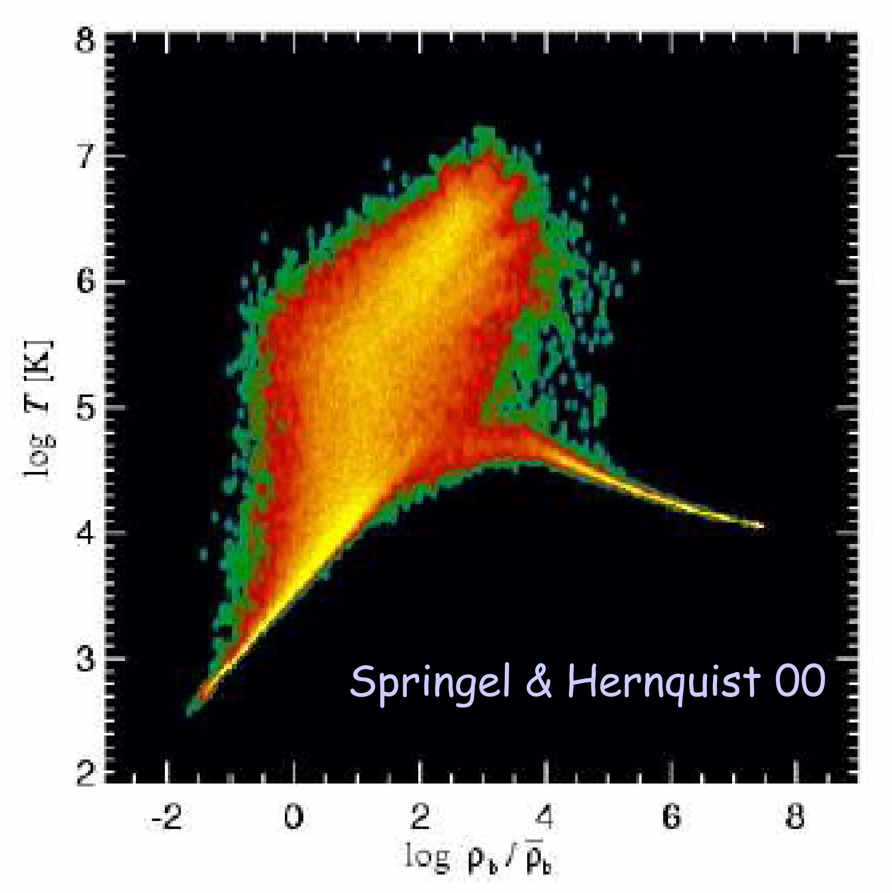
The balance between the IGM adiabatic cooling (due to expansion) and the UV background photo-heating introduces a tight relation between the IGM temperature and density (Hui & Gnedin 97).



$$T = T_0 \left(\frac{\rho}{\rho_0} \right)^{\gamma}$$

Temperature of the IGM

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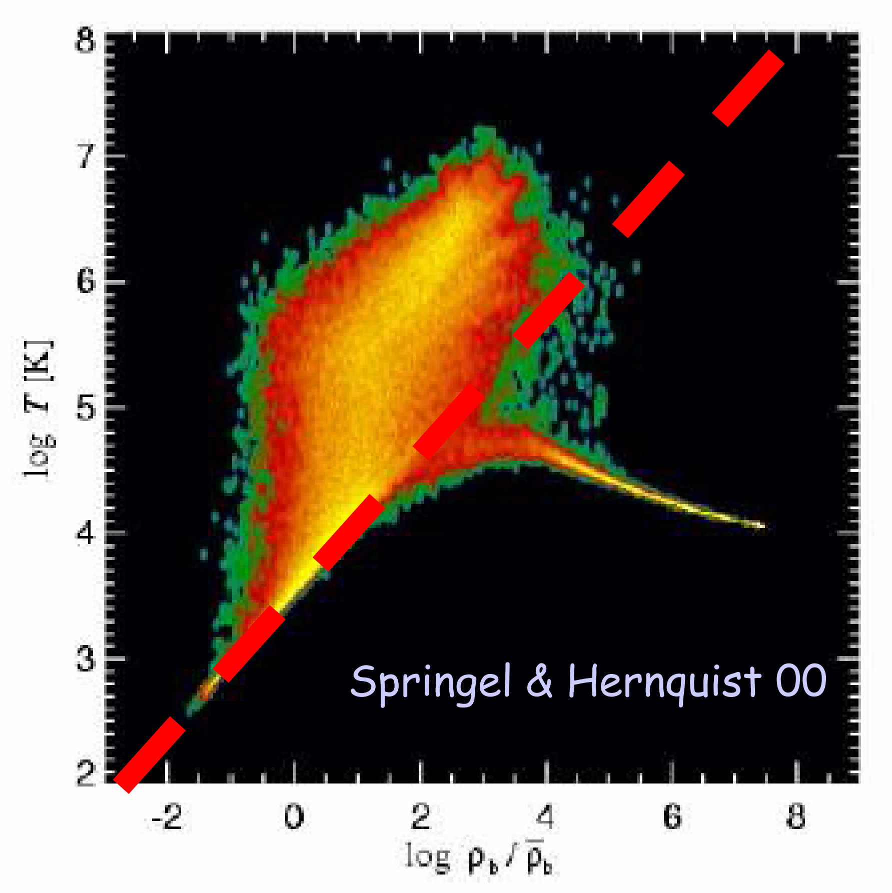

$$T = T_0 \left(\frac{\rho}{\rho_0} \right)^{\gamma}$$

Temperature of the IGM

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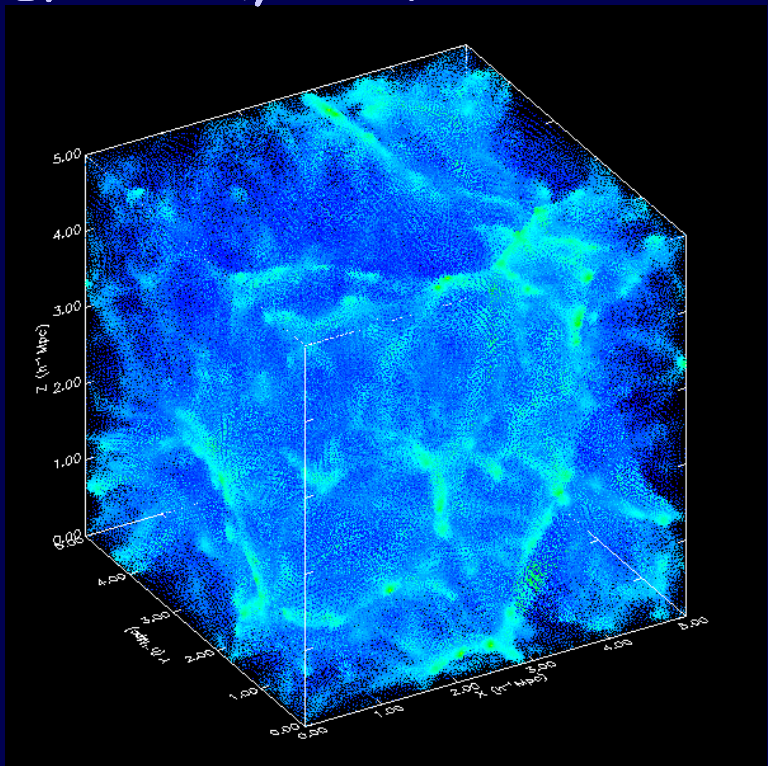
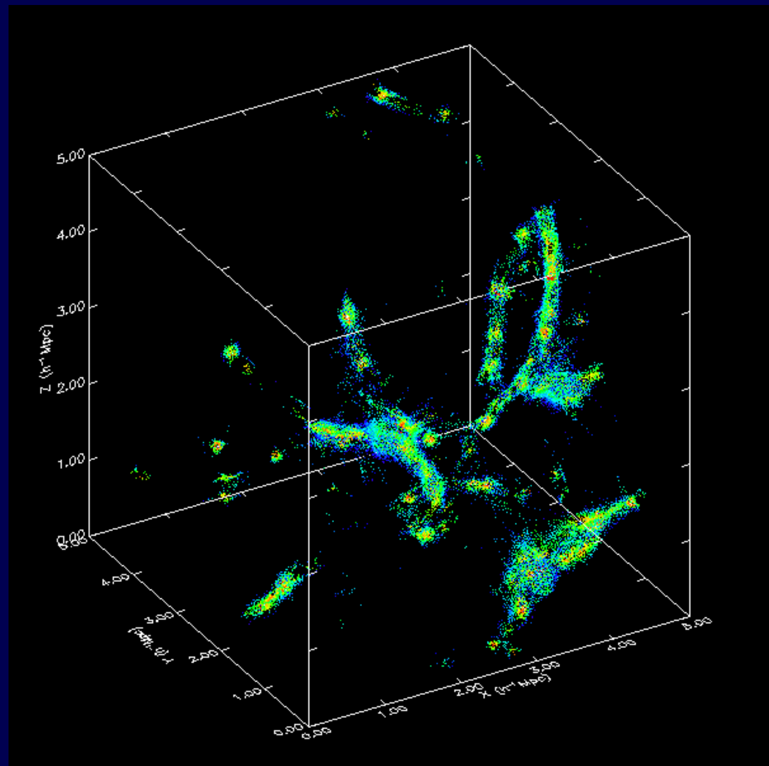
The Lyman-α forest is mainly produced by gas with

$$\frac{\delta\rho}{\langle\rho\rangle} \leq 10$$

Efstathiou, et al. 2000



z=3



T < 10^5K

T > 10^5K

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- The optical depth for Lyman-α absorption by the IGM at z=3 is about 10^5xThe neutral fraction of Hydrogen. This is the strongest evidence for ionised IGM below z~6.
- Probe the Matter distribution and Power spectrum.
- Measure the IGM Temp.

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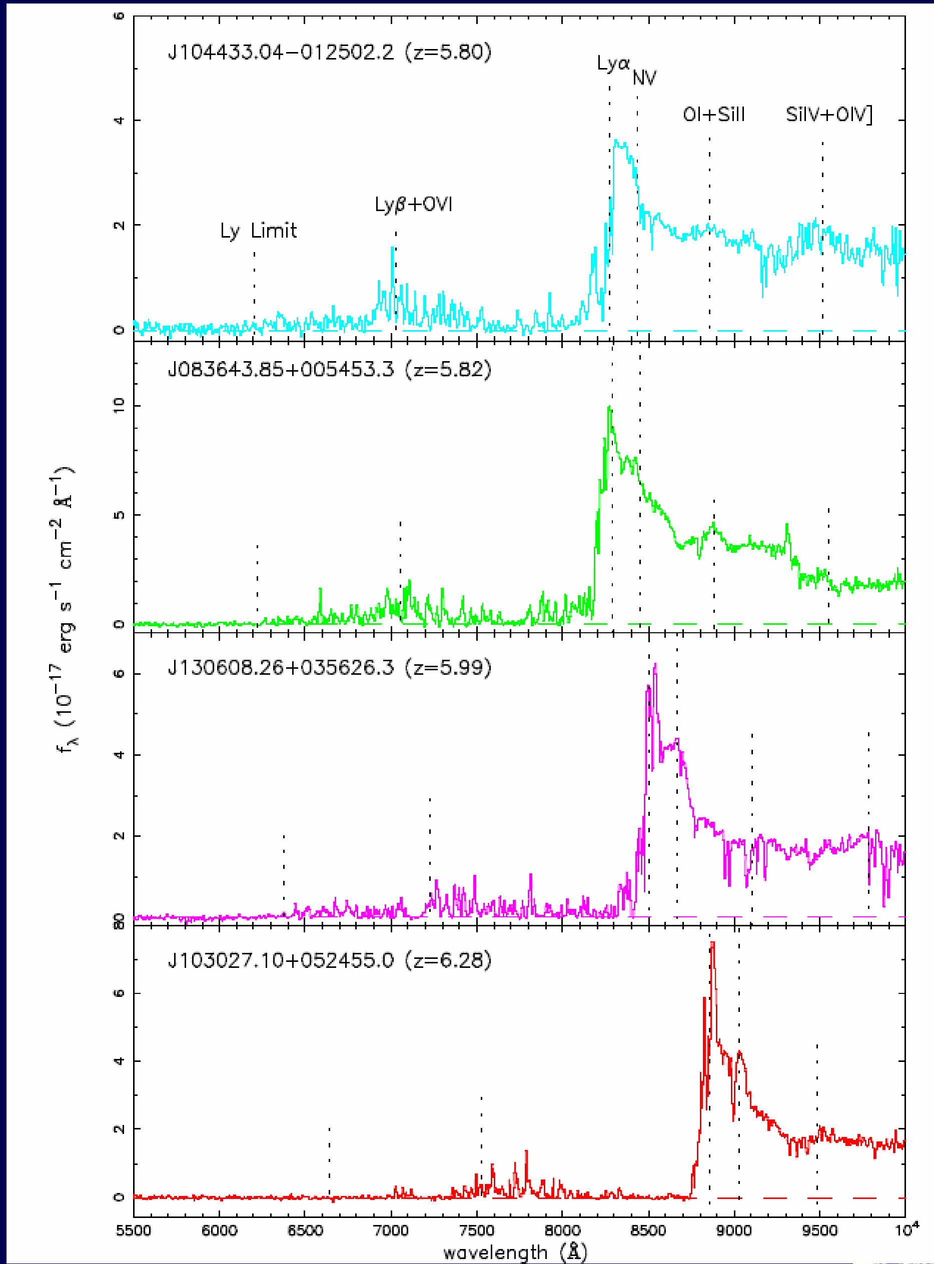
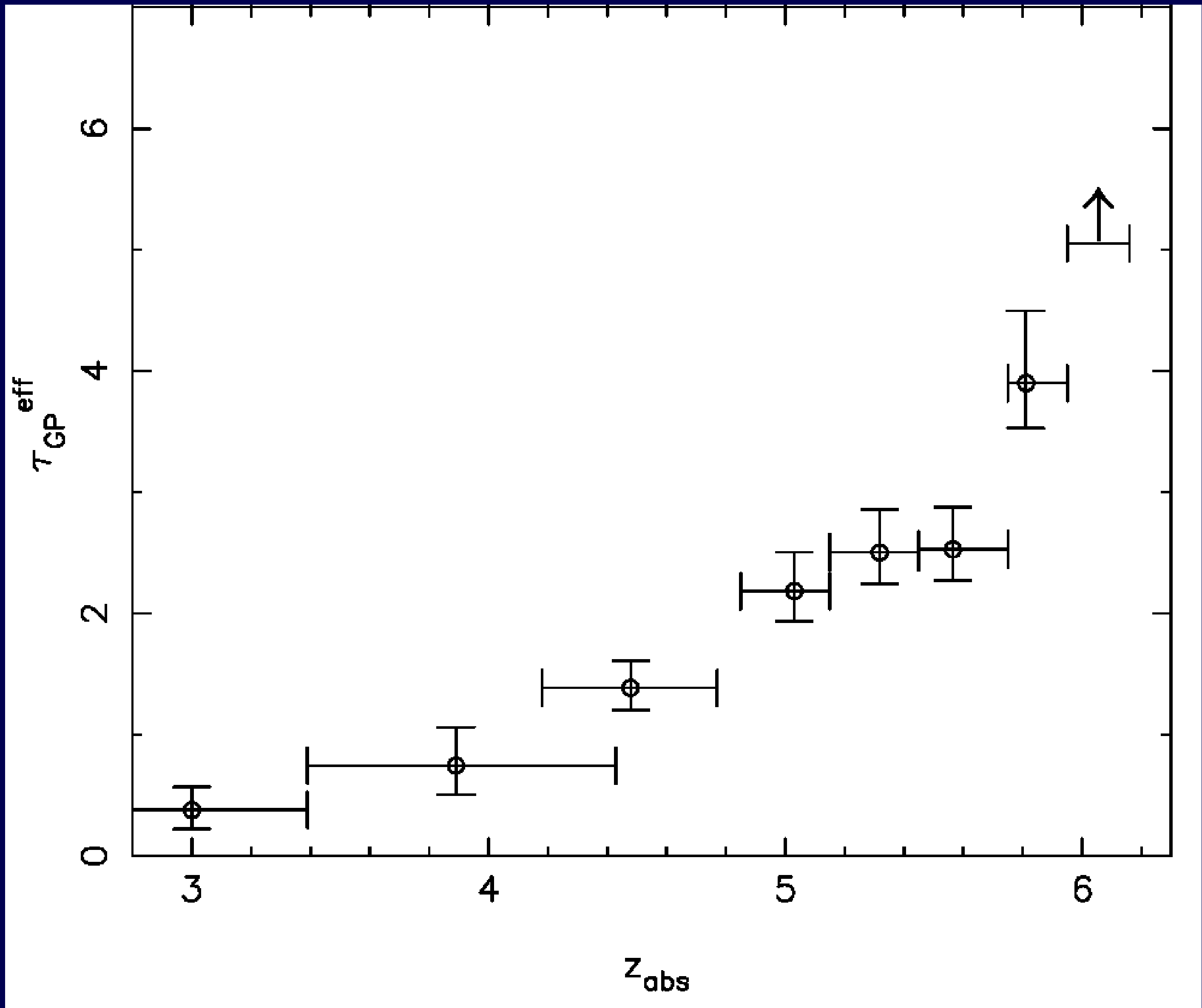
Becker et al. 01 and Djorkovski et al. 01, and Fan et al. (02 & 04) have detected sudden increase in the flux decrement bluewards of the Lyman-α emission of QSO spectra at z~6. This sharp increase indicates the observation of the "tail" of the reionization process.





Optical depth Fan et al. 2002

Summary of direct data!

- The Reionisation is completed by redshift of 6.
- $\tau=0.17$ (WMAP)
- Open questions:
  a. How did it occur? Ionisation sources
  b. When did it occur? And how long did it take?
  c. How did it evolve?

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Cosmological Fluctuations

- Large scale structure properties are determined by the mass density fluctuations Power Spectrum, $P^{3D}(k)$ (Fourier trans. of the 2-point correlation function).
- Gaussian Random Fields are completely determined by their power spectrum
- $P^{3D}(k)$ is a function of a handful of cosmological parameters.

$$P^{3D}(k) = Ak^{n_s} T^2(k; \Omega_m, \Omega_\Lambda, \Omega_b, h, S/T)$$

- Instead of A, the practice is to use the rms fluctuations within 8 Mpc/h spheres, σ_8.

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Can ionising sources produce $\tau=0.17$ in standard ΛCDM

- Can one get an optical depth of 0.17? This value came as a surprise as most theoretical studies before expected a lower value (*e.g.*, Benson et al. 02). Even post WMAP studies produce this value but with some uncomfortable assumptions.

In General the fluctuations power spectrum should have a high amplitude. σ_8 should be approx. 0.9 or larger.

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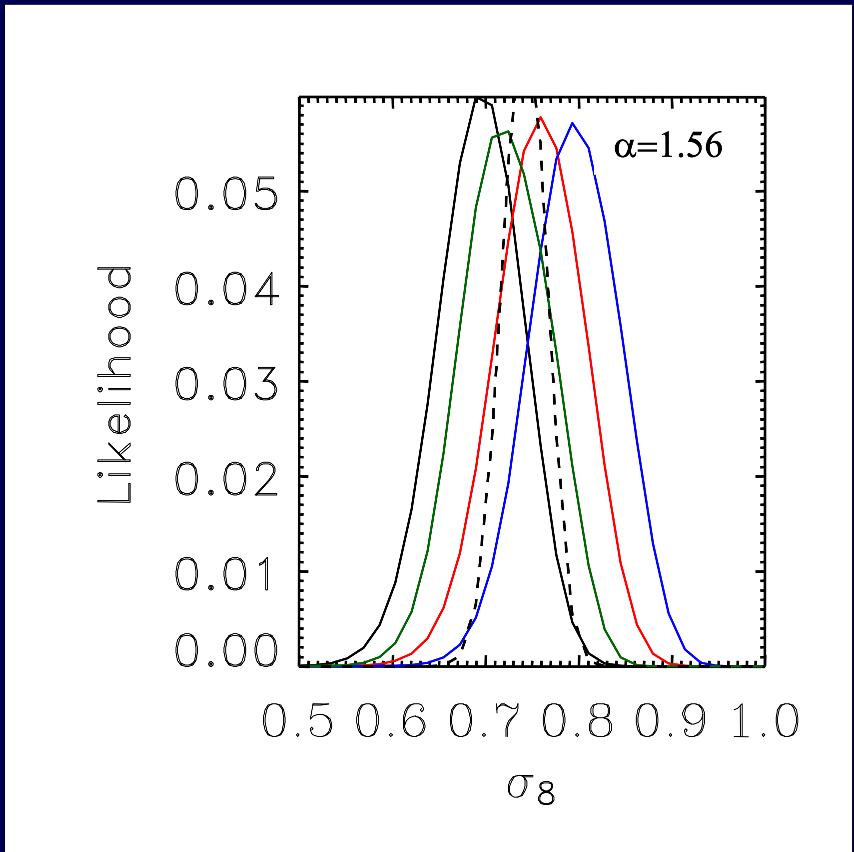
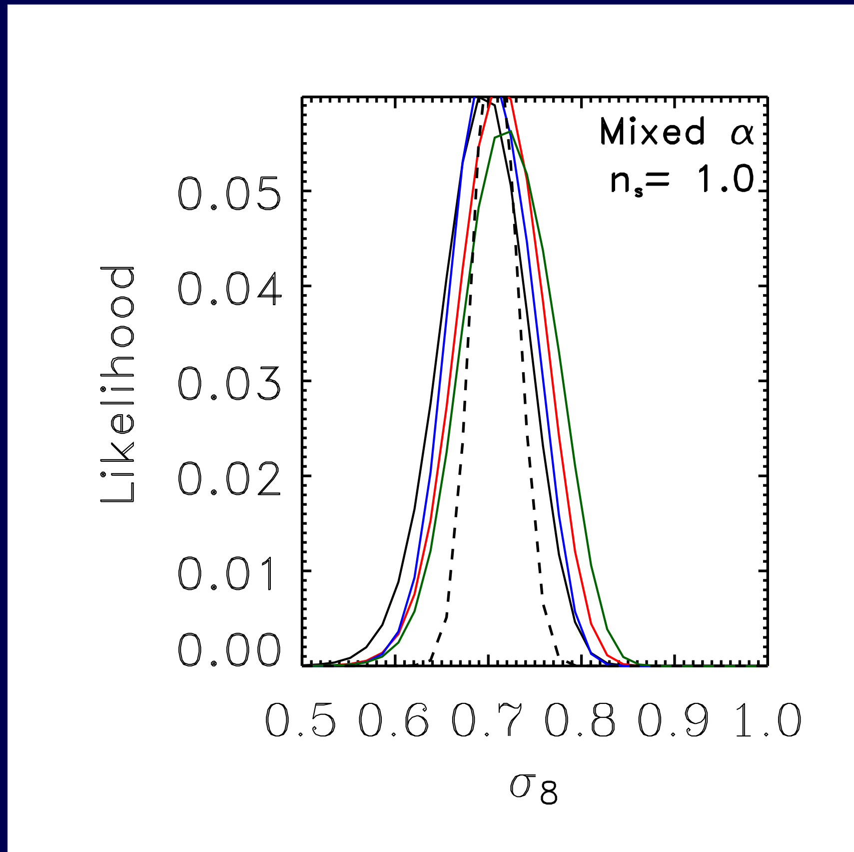
PS amplitude

From about 30 high resolution Lyman-alpha VLT spectra. (LUQAS data) .





Zaroubi et al. 2005

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How Could the universe ionise so early?

- Form favourably very massive stars very early on. Plausible but poorly understood!
  - First stars are completely different creatures from the ones we see in the local universe: H_2 cooling probably produces very massive stars.
  - Can production of this population be maintained. Unknown!
  - Efficiency of producing stars!! In our environment the main question is why star formation is inefficient. Unknown!
- Very efficient use of the ionising photons. Unknown!!

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How Could the universe ionise so early?

- Black holes as sources (x-ray). Plausible but poorly understood.
  - At z~6 we observe black holes with $10^9 M_{sun}$
- Other exotic physics:
  - Different power spectrum, *e.g.*, isocurvature (Sugiyama, Zaroubi & Silk 04)
  - Non Gaussian fluct. (Avelino & Liddle 04)
  - Decaying particles (Kasuya, Kawasaki & Sugiyama 03, Hansen & Haiman 04)
  - Decaying string loops.

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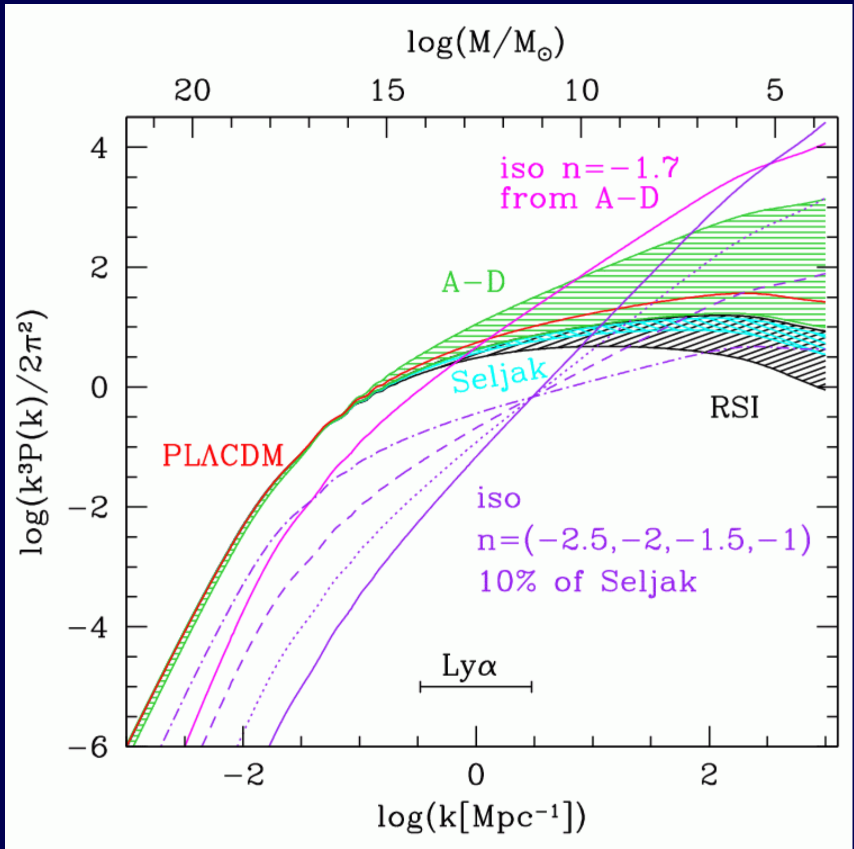
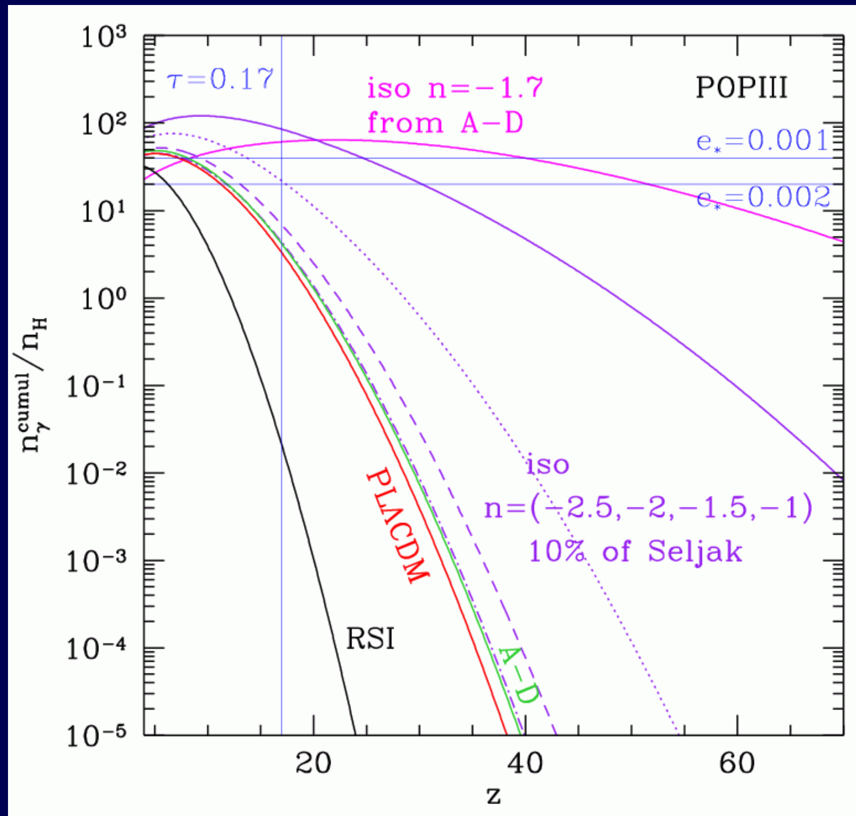
Adiabatic + Isocurvature fluctuations





Sugiyama, Zaroubi & Silk 2004

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Evidence for complicated reionisation process

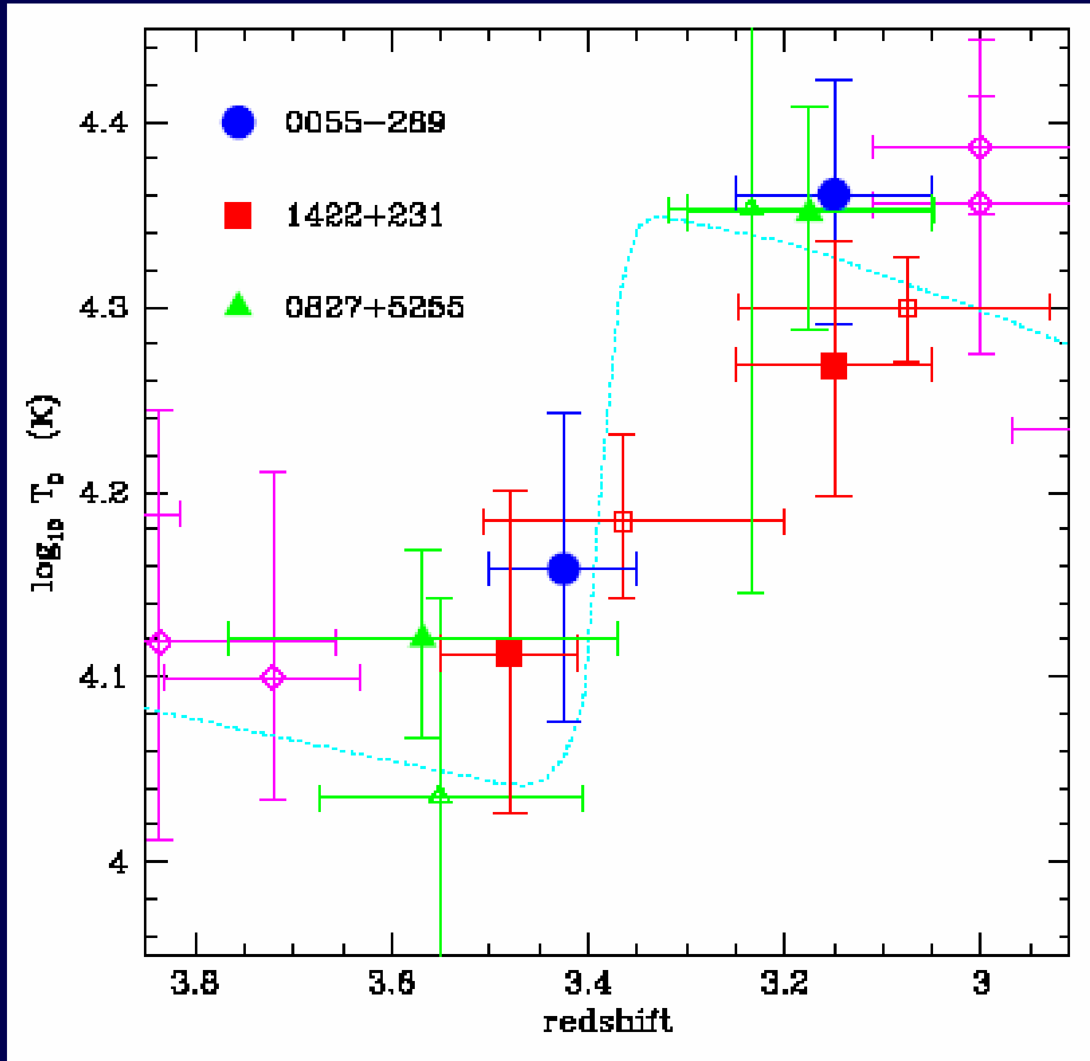
- Many authors have argued that this increase in flux decrement could be caused by a very slight increase in the H I neutral fraction. However, based on the size of the Gunn-Peterson trough Wyithe & Loeb 04 have argued that the neutral fraction at z~ 6.3 is significantly larger than 0.1. (see also M

- The IGM Temperature at low redshifts

- Other probes.

Temperature at the mean density T_0 versus redshift.

Closed Symbols are from Theuns, Zaroubi, et al 02, and Open symbols are from Schaye et al. 2000.



$$\Delta T/T_{before} = 60\% \pm 14\%$$

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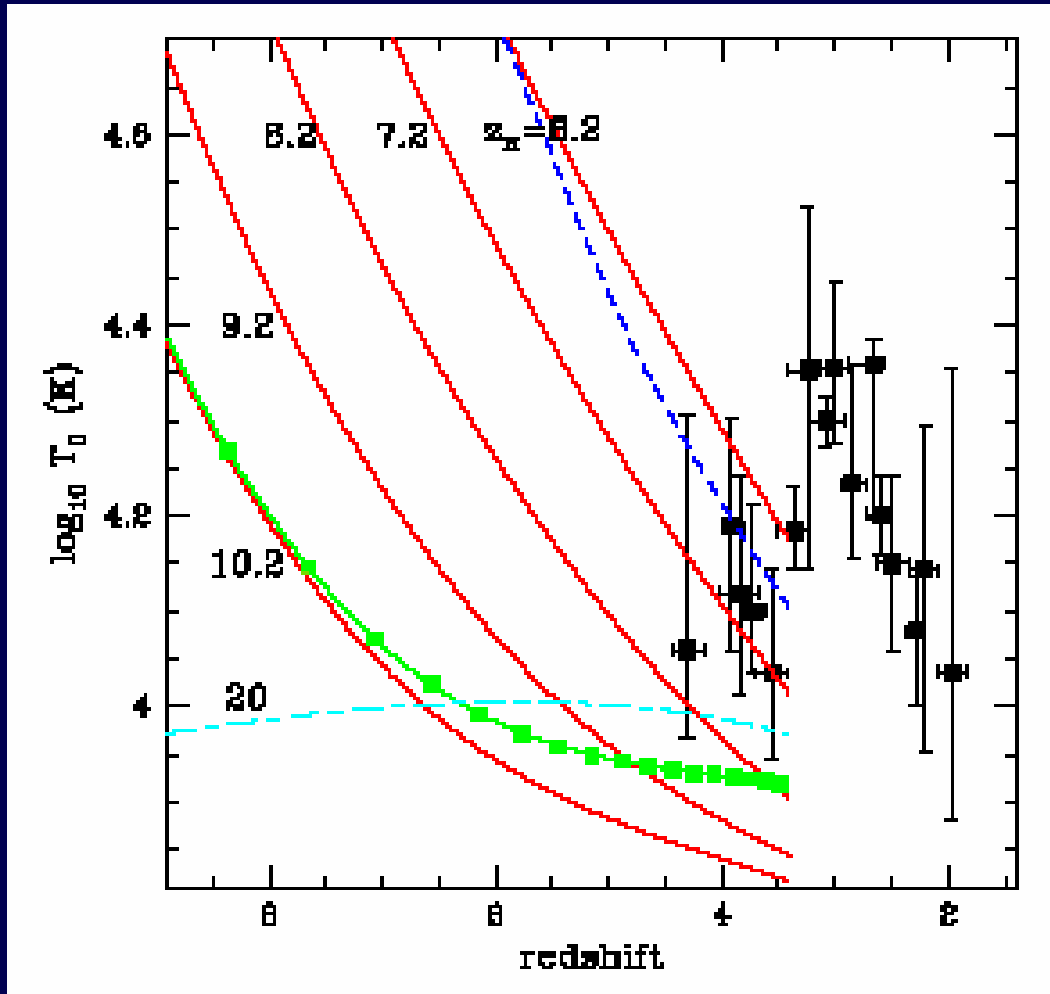
- Interpolate the Temp. back in time.
- After H I reionisation $T_0=6\times10^4$K & $\Gamma_{H\,I}=10^{-13}s^{-1}$.



In light of the WMAP polarization results this indicates that the reionization process is complicated and probably has happened in distinct phases (see also Hui & Haiman 2003)

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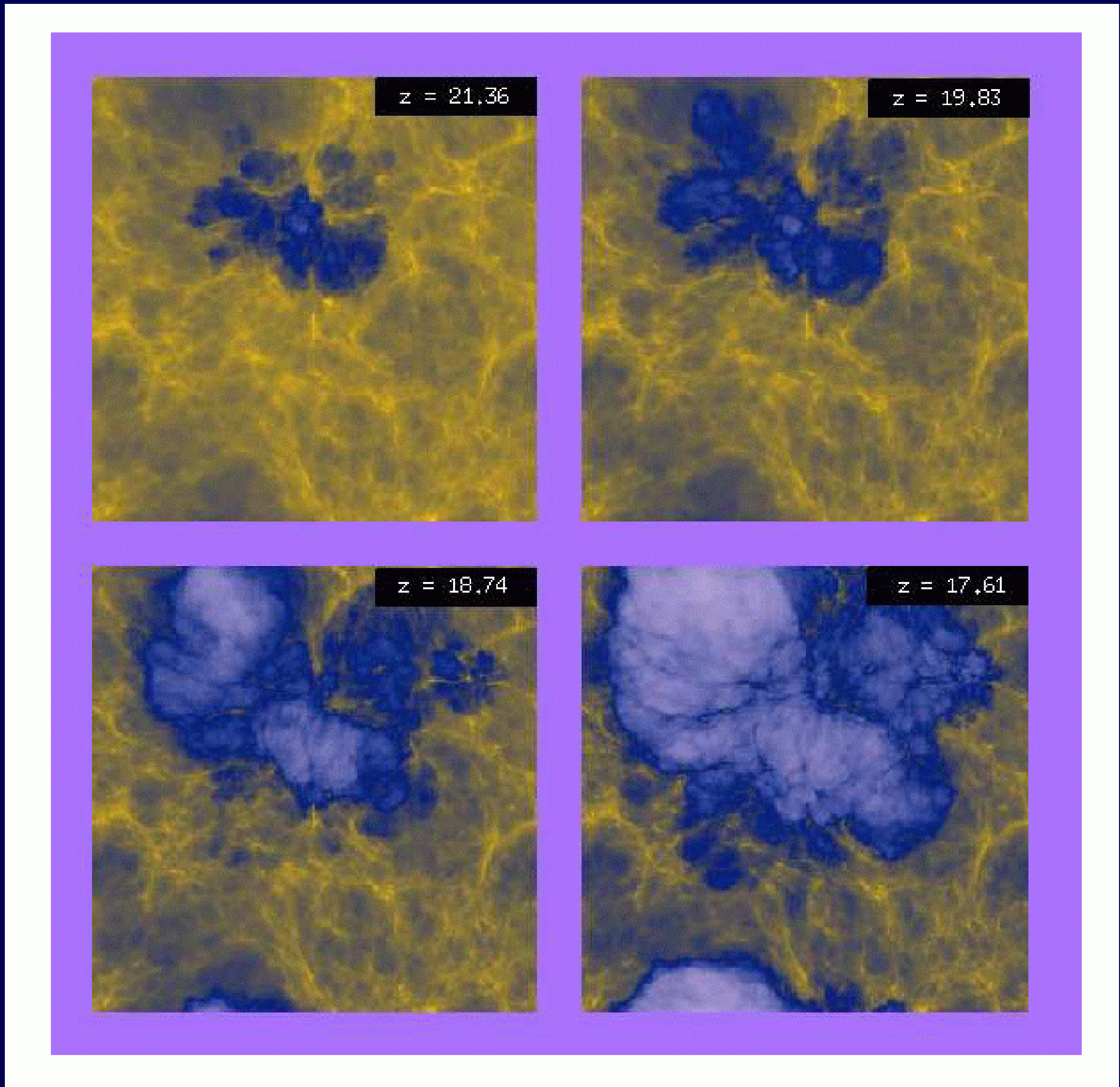
When did it happen? summary.

- For sudden reionisation models the WMAP data implies a reionisation redshift of ~ 16. This assumption however is not consistent with low redshift observations.
- More likely the reionisation happened gradually or in multiple phases (e.g., double reionisation).

How did it evolve?



Is this pictures realistic?

Which regions of the IGM ionised first, low density regions (outside-in) or the high-density regions (inside-out)?

Sokasian et al. 2004

LOFAR: The Epoch of Reionisation project

- The 21 cm hyperfine transition is a forbidden transition between the two $1^2S_{1/2}$ ground level states of hydrogen. The transition lifetime is ~10^7 years. The two states differ in their electron plus proton spins (⊥ and ||).

- The relative population of the two states is given by the spin temp. T_s, i.e.,

$$g_0 n_1 / g_1 n_0 = \exp(-E_{01}/kT_s).$$

- Could be measured in absorption or emission.

$$\delta T(\nu) \approx 16\mathrm{mK}\ (1+\delta) x_{HI} \left(\frac{T_s - T_{CMB}(z)}{T_s}\right)\left(\frac{\Omega_b h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left(\frac{h}{0.7}\right)^{=1}$$

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LOFAR: The Epoch of Reionisation project

- There are few mechanisms that decouple T_s from T_{CMB}: Lyman-alpha bumping, collisional excitation.
- LOFAR will be able to detect this line in the redshift range z=6-11.5
- Unless the reionization has occurred suddenly and in "one go" LOFAR will provide a unique window into the physical processes that reionized the universe (UV sources, hardness of spectra, ….)

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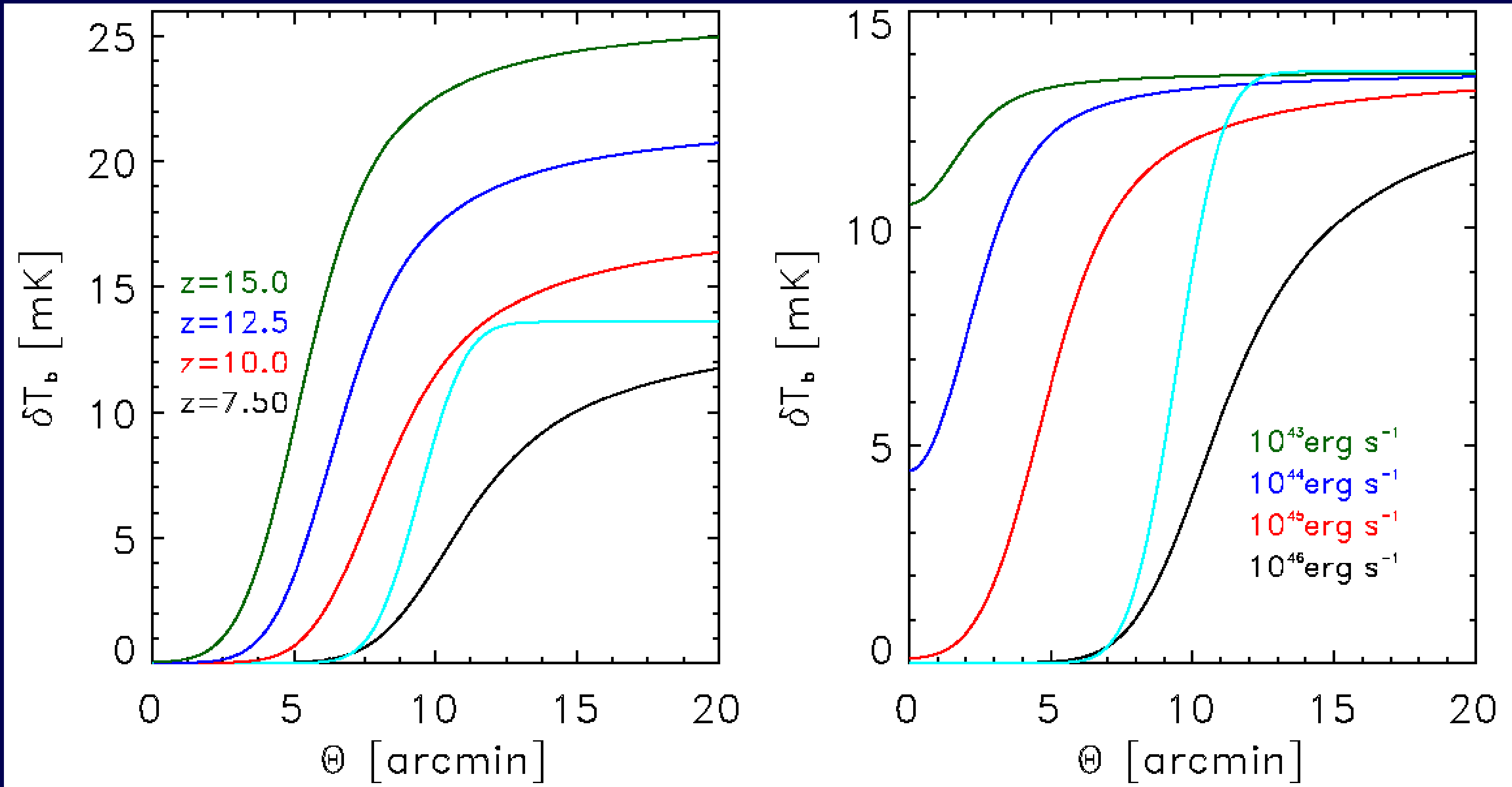

Zaroubi & Silk 2005

Probing the pre-reionisation IGM

- With LOFAR and similar telescopes one can get a very pristine view of the IGM and probe the fluctuations PS and PDF with very high accuracy.
- This will also enable basic properties of the Universe (Dark energy).

Eagerly awaiting the WMAP second year results!