Reionization

In a State of Grace

(in the Roman Catholic Church) having been forgiven by God for the wrong or evil things you have done (Oxford Dictionary)

using the most modern or advanced techniques or methods; as good as it can be at the present time (Oxford Dictionary)

Naoshi Sugiyama

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Reionization

(Confusion)

ing @ Paris

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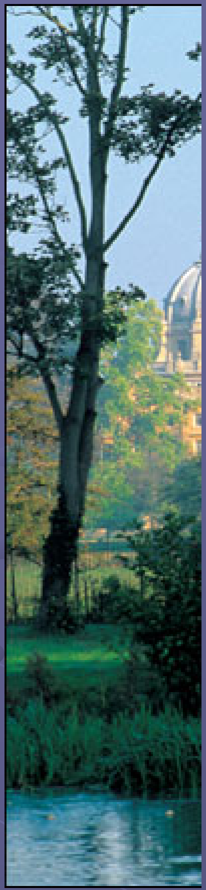
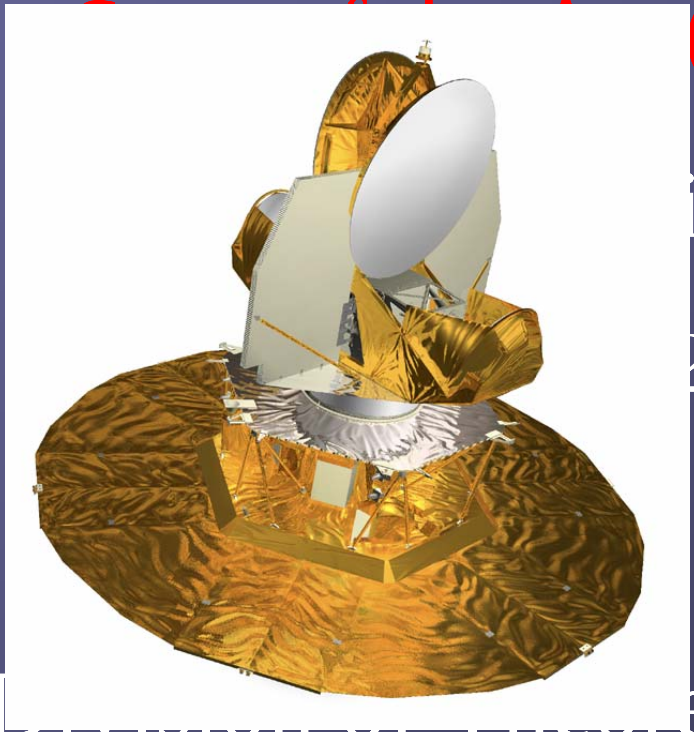




etical Astrophysics

National Astronomical Observatory

Naoshi Sugiyama

1st CM

@Oxfo

§ 1. Early Reionization of the Universe

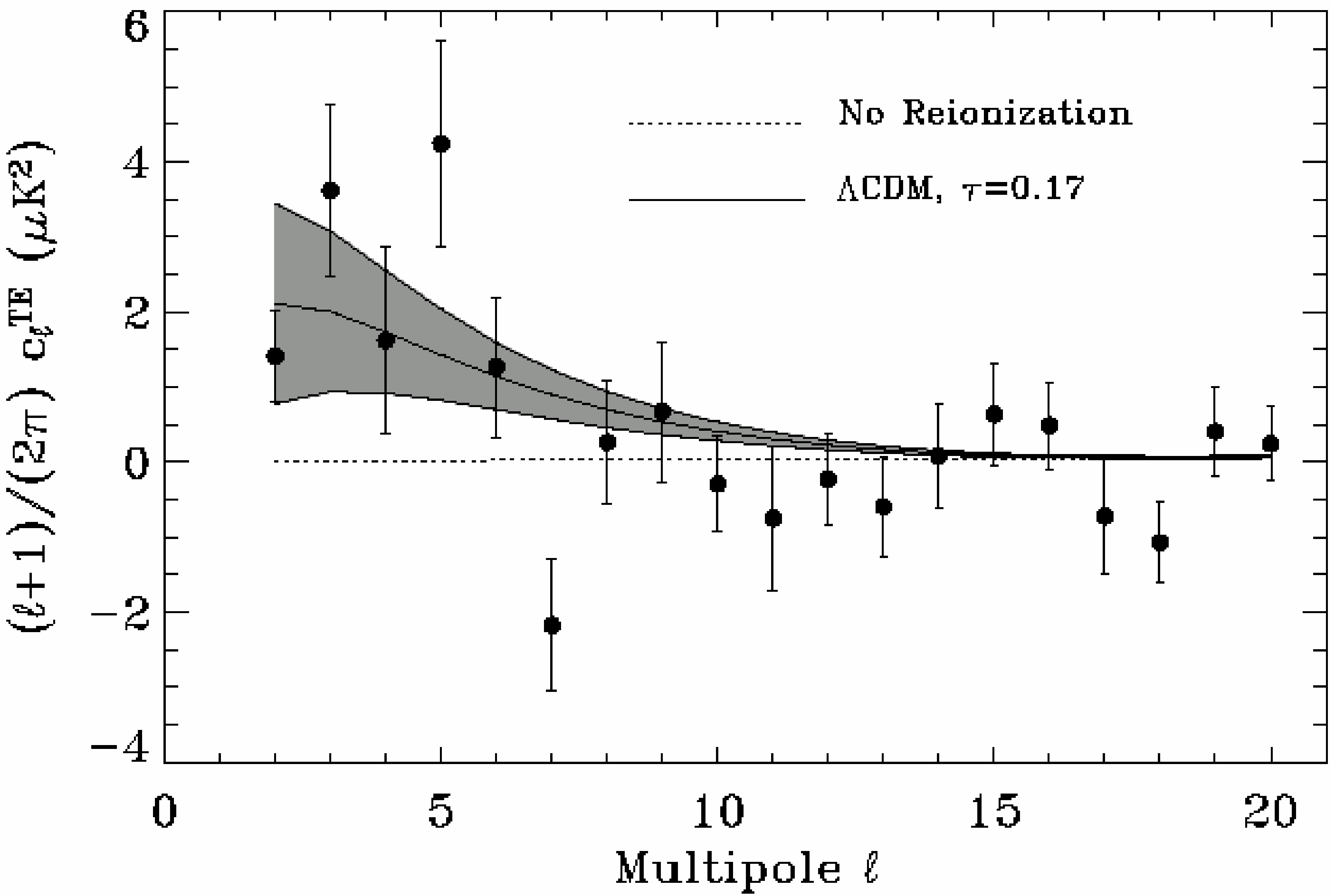
WMAP

- Reionization
  - $\tau = 0.17$
    - Corresponds to (best fitted WMAP parameters)

z = 17.8 no He reionize

z = 16.9 HeI->HeII reionization

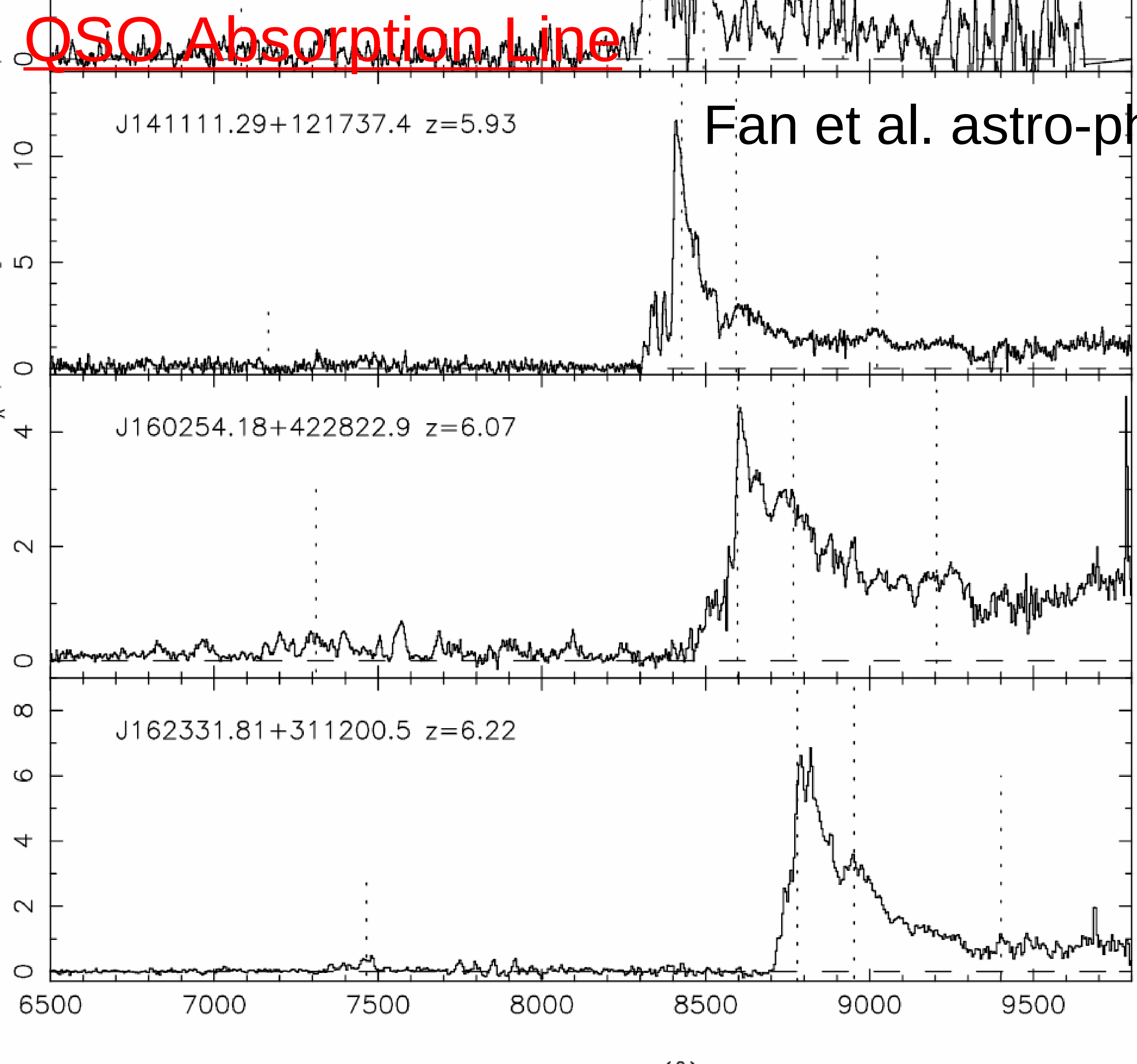
z = 16.1 all He reionize

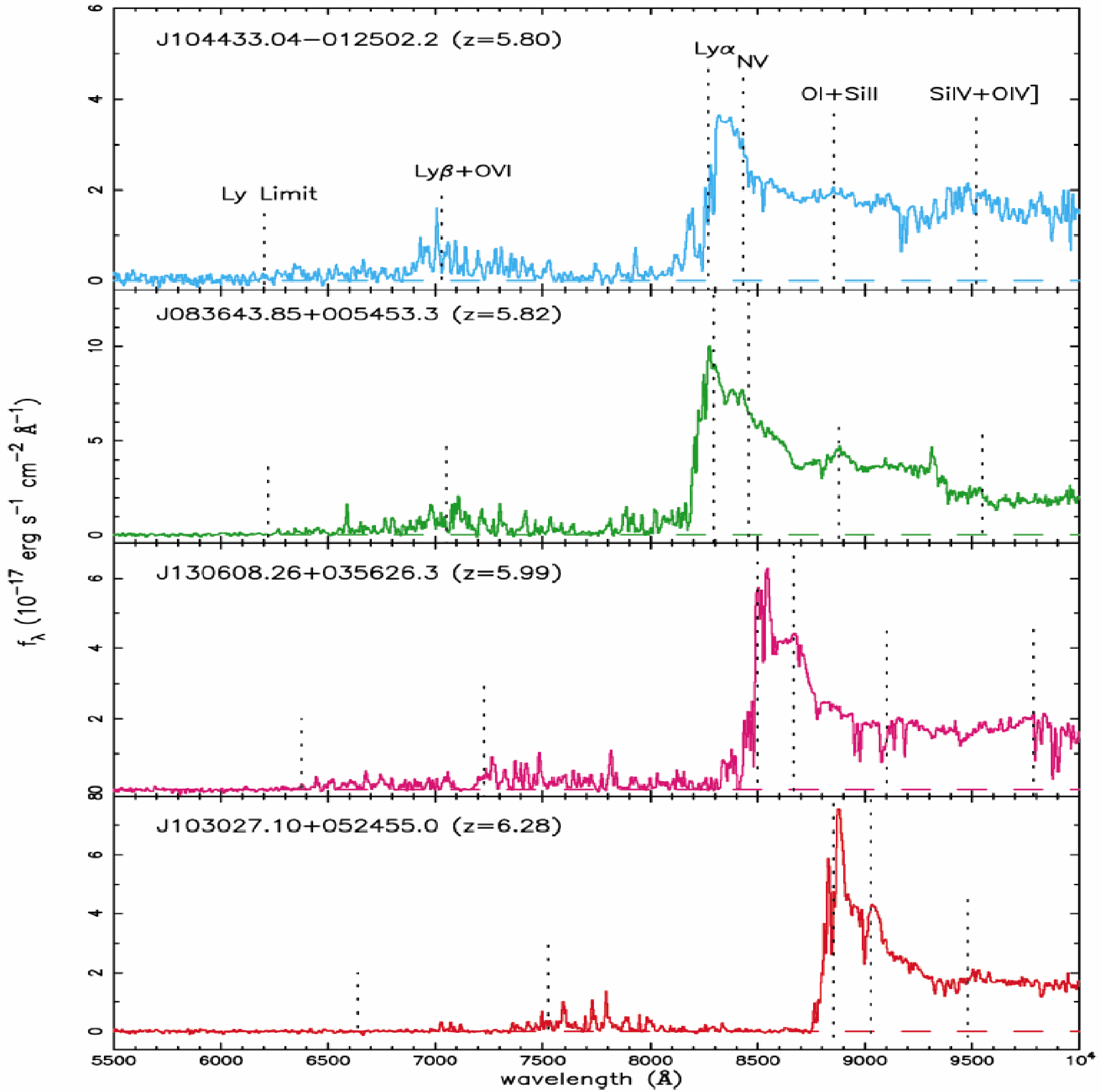


No Reionization
ΛCDM, τ=0.17
$(\ell+1)/(2\pi)\ c_\ell^{TE}\ (\mu K^2)$
Multipole ℓ

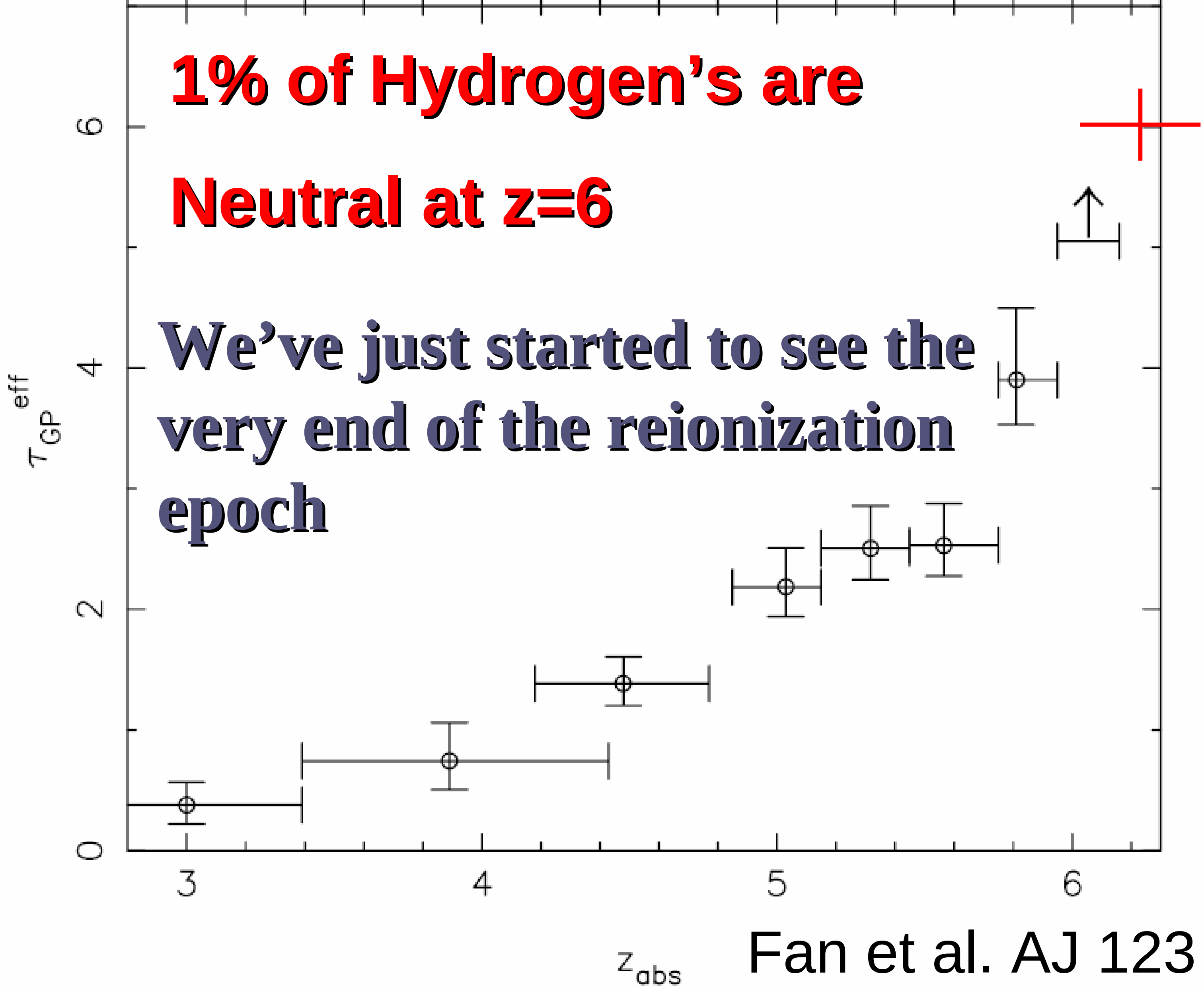
QSO Absorption Line

Fan et al. astro-ph/0405138





Becker et al. AJ122, 2850



Fan et al. AJ 123 1247

FIG. 1.—Evolution of Lyα absorption based on the observations of four quasars at $z > 5.7$ in Fan et al. (2001c), Becker et al. (2001), and Paper III. The results at $z_{abs} < 5.6$ are averaged over four lines of sight, and the error

Reionization

What we have known so far are

- Complete by $z \sim 6$
- $\tau = 0.17$

We don't know yet

- How it occurs
- How long it takes
- How the ionized region evolves

Questions:

1) Is it really possible to have $\tau=0.17$?

- Standard method: CDM, only stars (no QSO)
  - Benson, Nusser, Sugiyama, Lacey (pre-WMAP)

    Semi-analytic galaxy formation + N-body

    $\tau < 0.04$
  - Fukugita & Kawasaki: assume Scalo IMF (Post-WMAP)

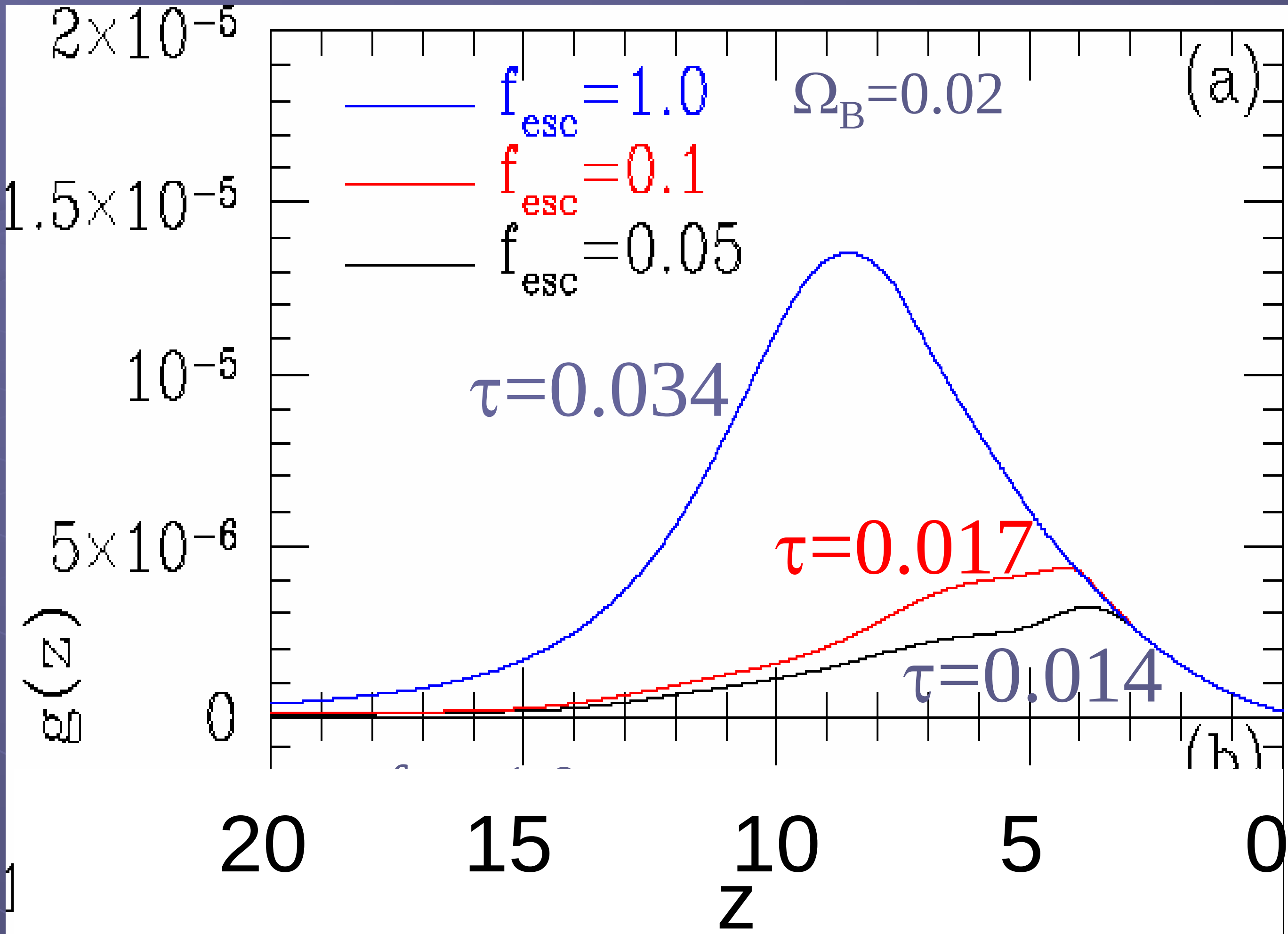
    Maximum $z_{reio} = 13.5$, 100% Escape of Ionizing Photons

    realistic $z_{reio}=10$
  - Ciardi, Ferrara, White (Post-WMAP)

    Scalo IMF+ moderate escape fraction: $\tau=0.10$

    Top Heavy IMF or high escape fraction for $\tau=0.17$

Visibility Function: peak corresponds to reionization epoch



Liu, Benson et al.

Any Papers which say, it is possible to have reionization with τ=0.17 **after WMAP** is,

Suspicious

To have τ=0.17

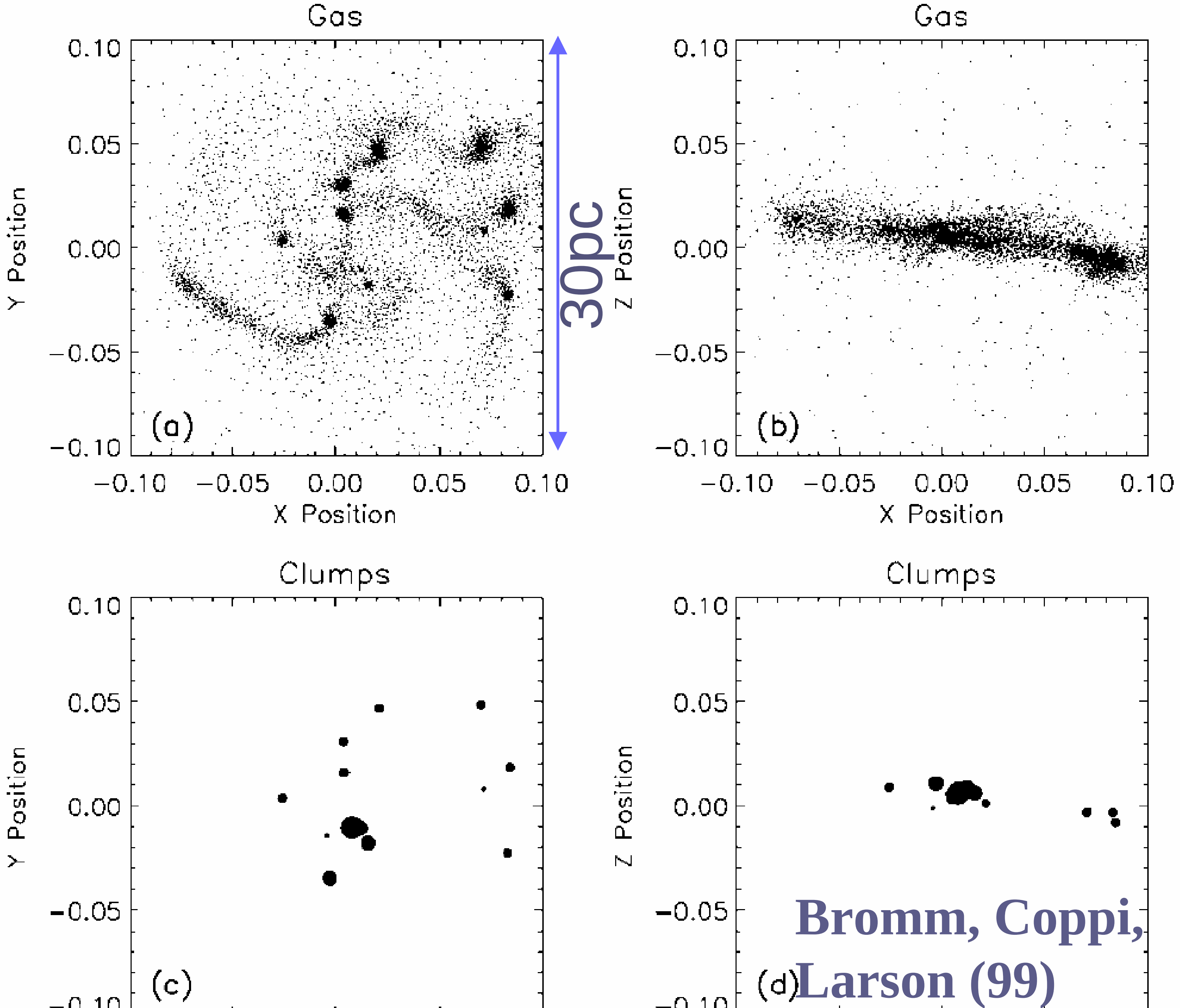
Assuming ΛCDM Cosmogony

- Top Heavy IMF **Plausible!** **But Unkonwn!**
  - H_2 Molecular Cooling, Accretion?
- Very Large Escape Fraction of Ionizing photons from the galaxy **Unknown!**

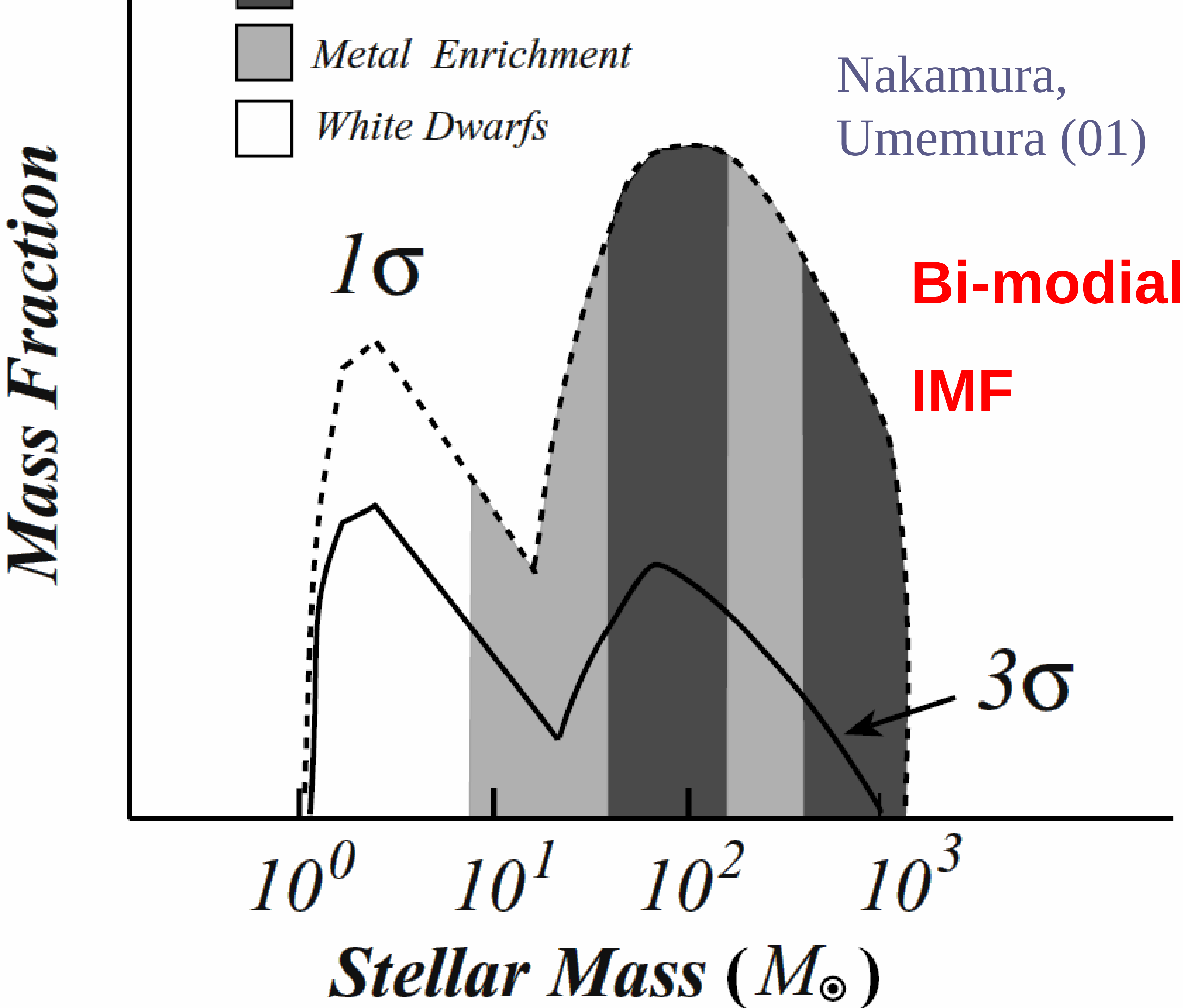
the lack of information: IMF, star formation efficiencies the effect of dust, complex gas inhomogeneity, gas dynamics, Shape of the (proto-)Galaxies

Something Exotic?

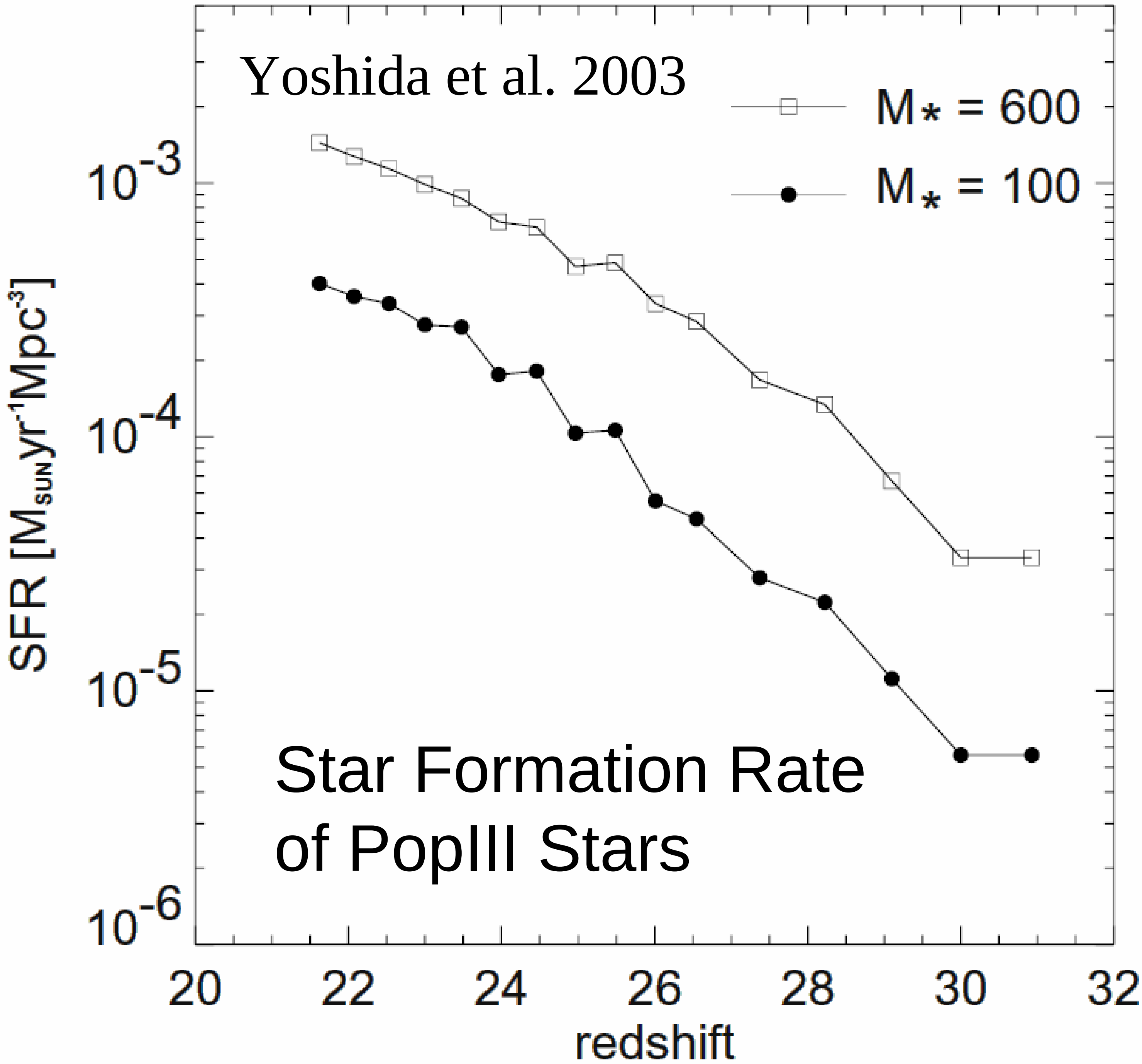
- Extra Power in the matter power spectrum
- Extra Ionizing Photons



Bromm, Coppi, Larson (99)



Metal Enrichment
White Dwarfs
Nakamura,
Umemura (01)
1σ
Bi-modial
IMF
3σ
Mass Fraction
10^0
10^1
10^2
10^3
Stellar Mass ($M_\odot$)



Yoshida et al. 2003
M* = 600
M* = 100
Star Formation Rate
of PopIII Stars
SFR [$M_{SUN} yr^{-1} Mpc^{-3}$]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
20
22
24
26
28
30
32
redshift

2) When did the reionization take place?

- Reionization
  - $\tau = 0.17$
    - Corresponds to (best fitted WMAP parameters)

$z = 17.8$ no He reionize

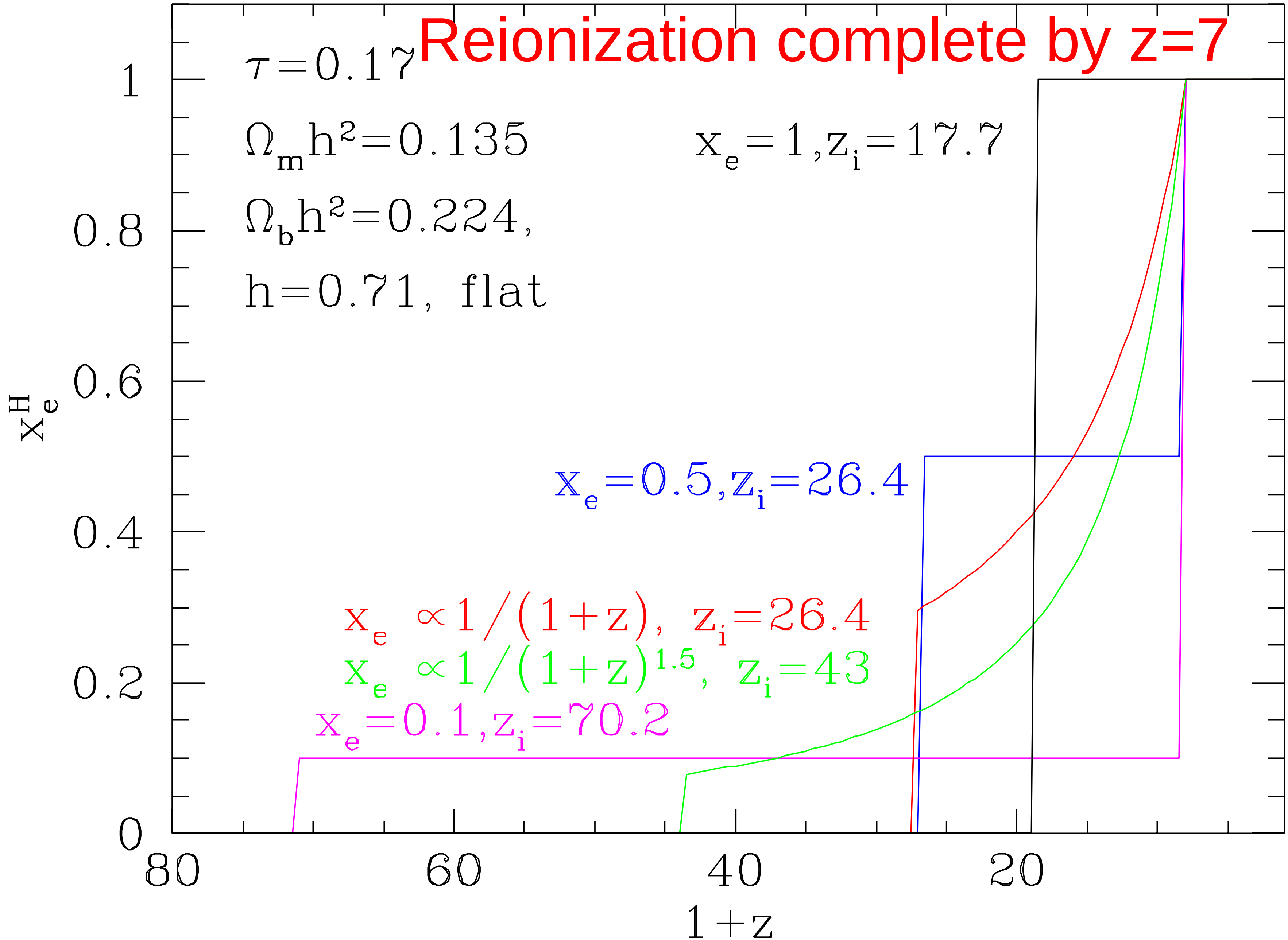
$z = 16.9$ HeI->HeII reionization

$z = 16.1$ all He reionize

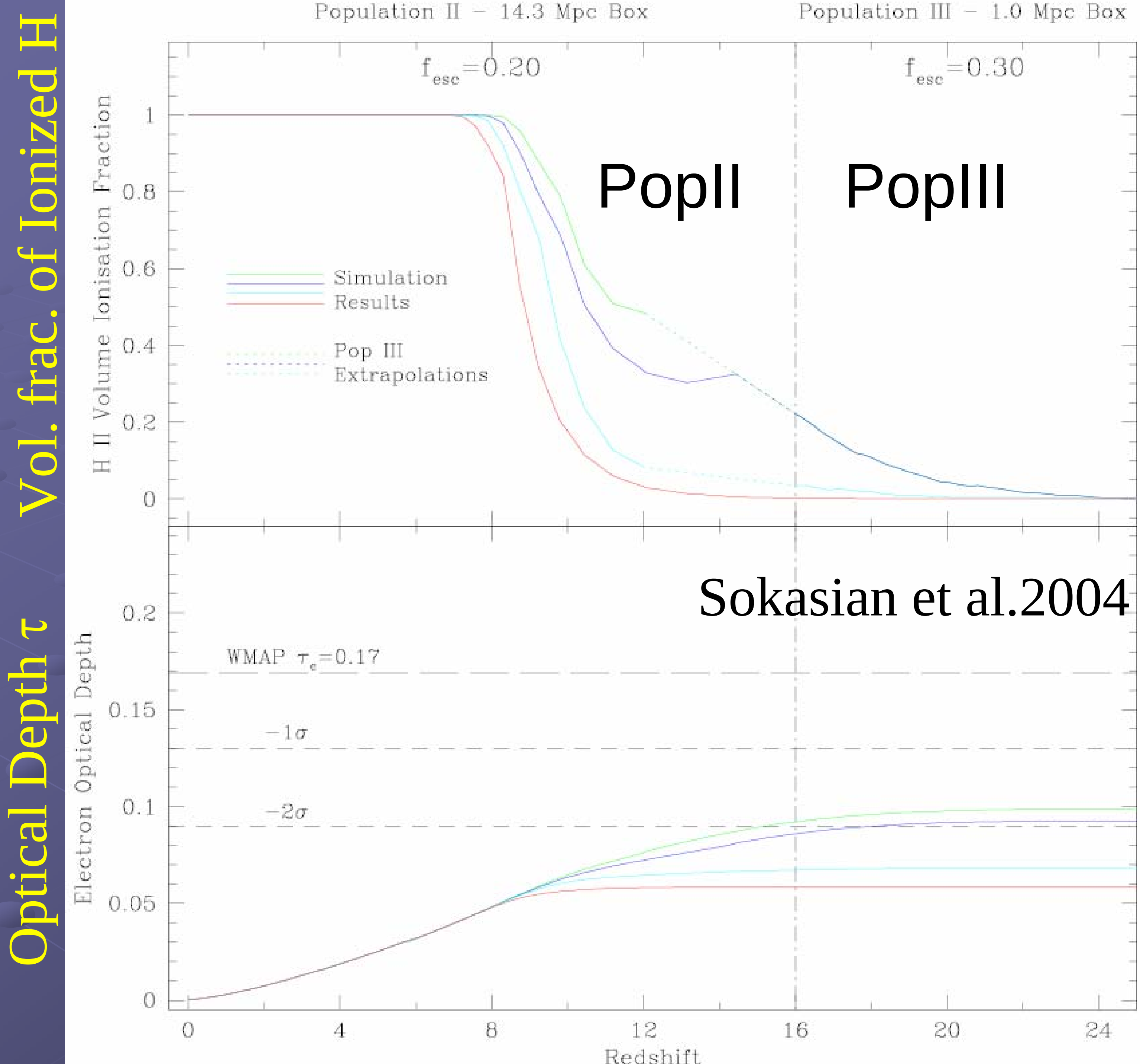
instantaneous reionization was assumed

Rather, gradual reionization is likely!

Consistent with SDSS QSOs



Reionization complete by z=7
τ=0.17
Ωmh²=0.135
Ωbh²=0.224,
h=0.71, flat
xe=1,zi=17.7
xe=0.5,zi=26.4
xe ∝1/(1+z), zi=26.4
xe ∝1/(1+z)^1.5, zi=43
xe=0.1,zi=70.2
x^H_e
1+z
1
0.8
0.6
0.4
0.2
0
80
60
40
20



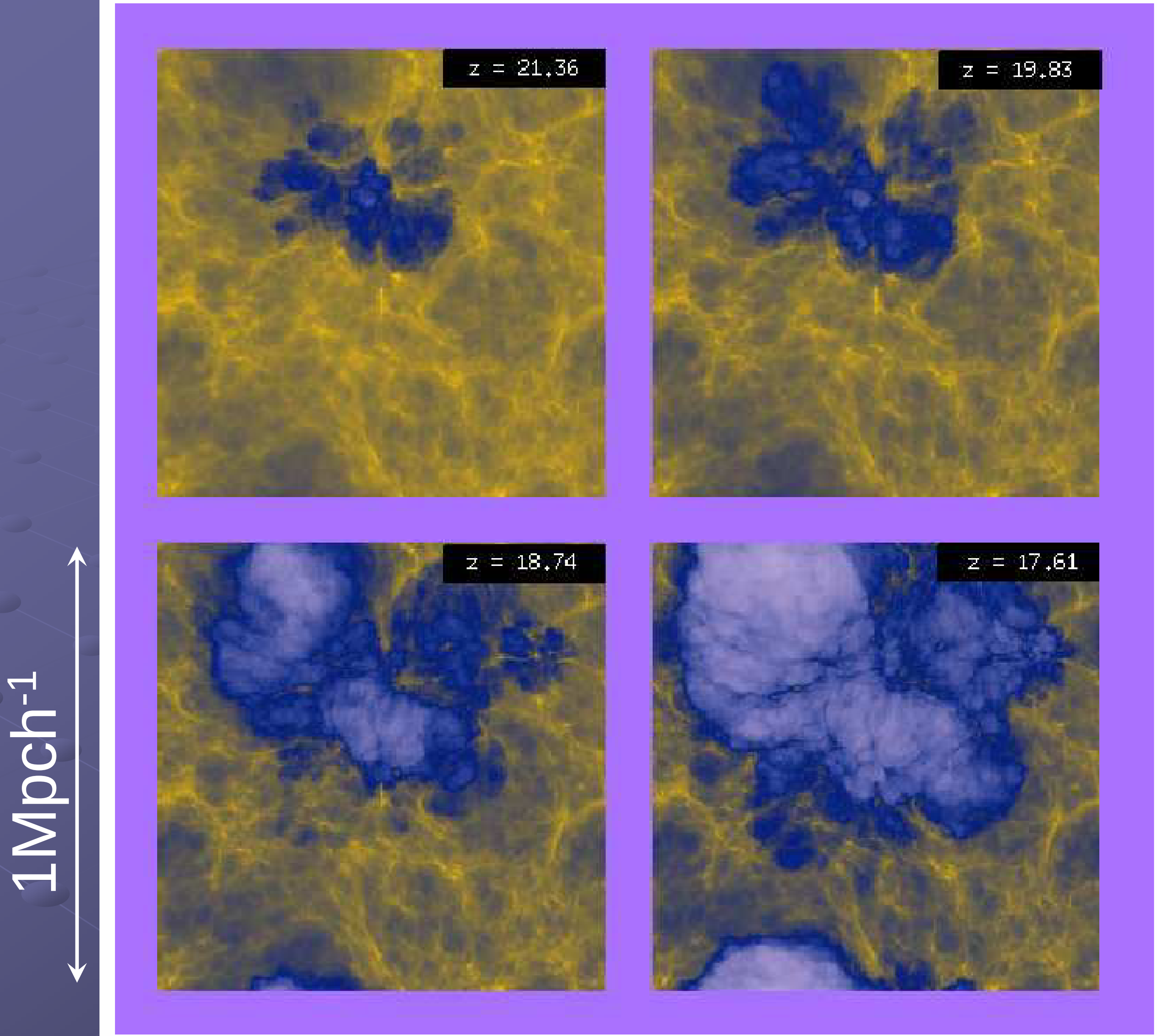
Vol. frac. of Ionized H
Optical Depth τ
Population II – 14.3 Mpc Box
Population III – 1.0 Mpc Box
f_esc=0.20
f_esc=0.30
PopII
PopIII
H II Volume Ionisation Fraction
Simulation
Results
Pop III
Extrapolations
Sokasian et al.2004
WMAP τ_e=0.17
−1σ
−2σ
Electron Optical Depth
Redshift

3) How does the ionized region evolve?

What we need are

- **High resolution 3D hydrodynamical simulations with radiative transfer**
- Inclusion of
  - •All Chemical Processes
  - •Feedback from SN,Stars (photo dissociation of H_2)
- Needed to know
  - •IMF
  - •Escape fraction of ionizing photons

People are busy: Gnedin 2000; Ciardi et al. 2000; Razoumov et al. 2002; Ciardi et al. 2003, Sokasian et al. 2003, 2004

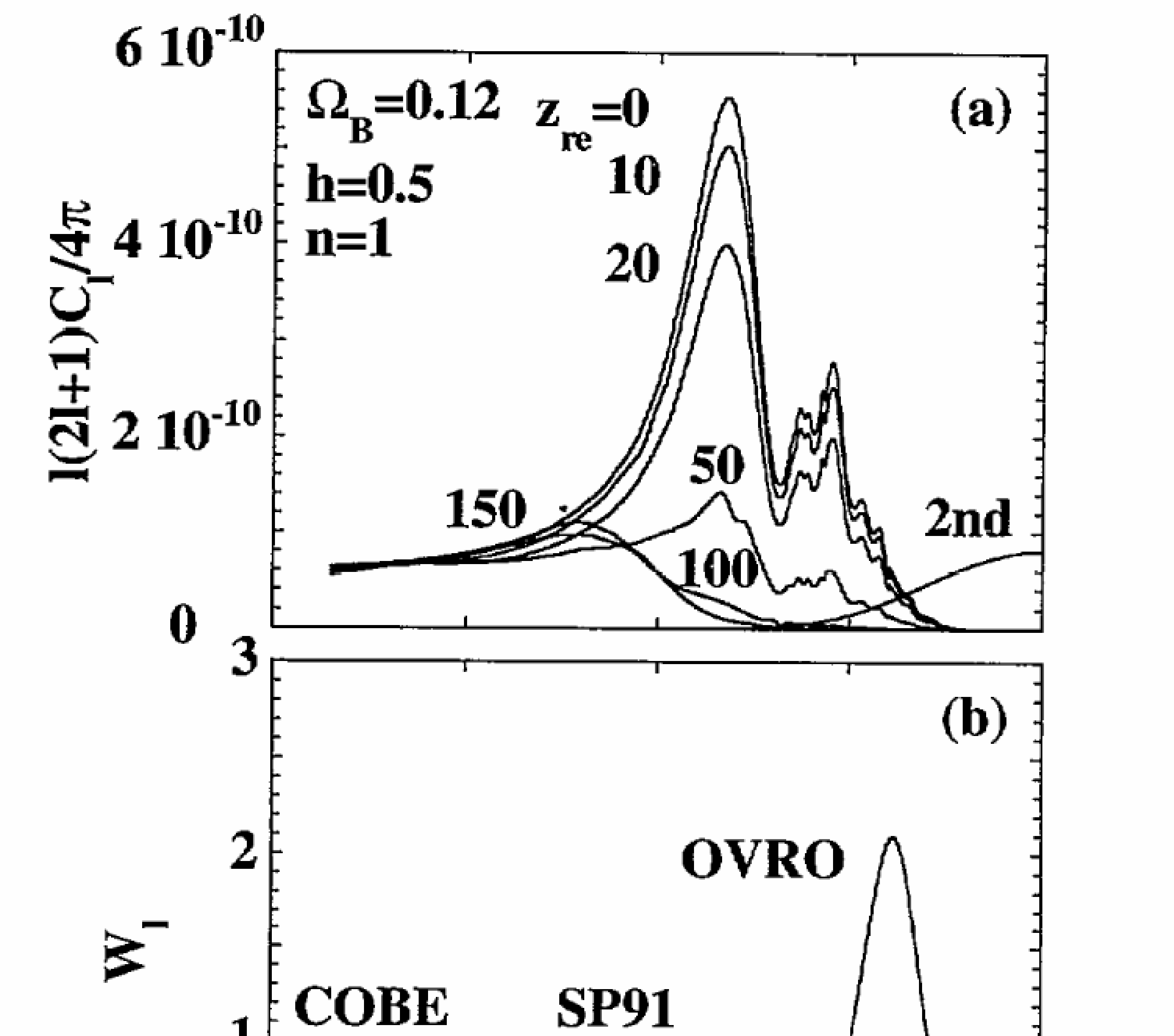


Sokasian et al. 04

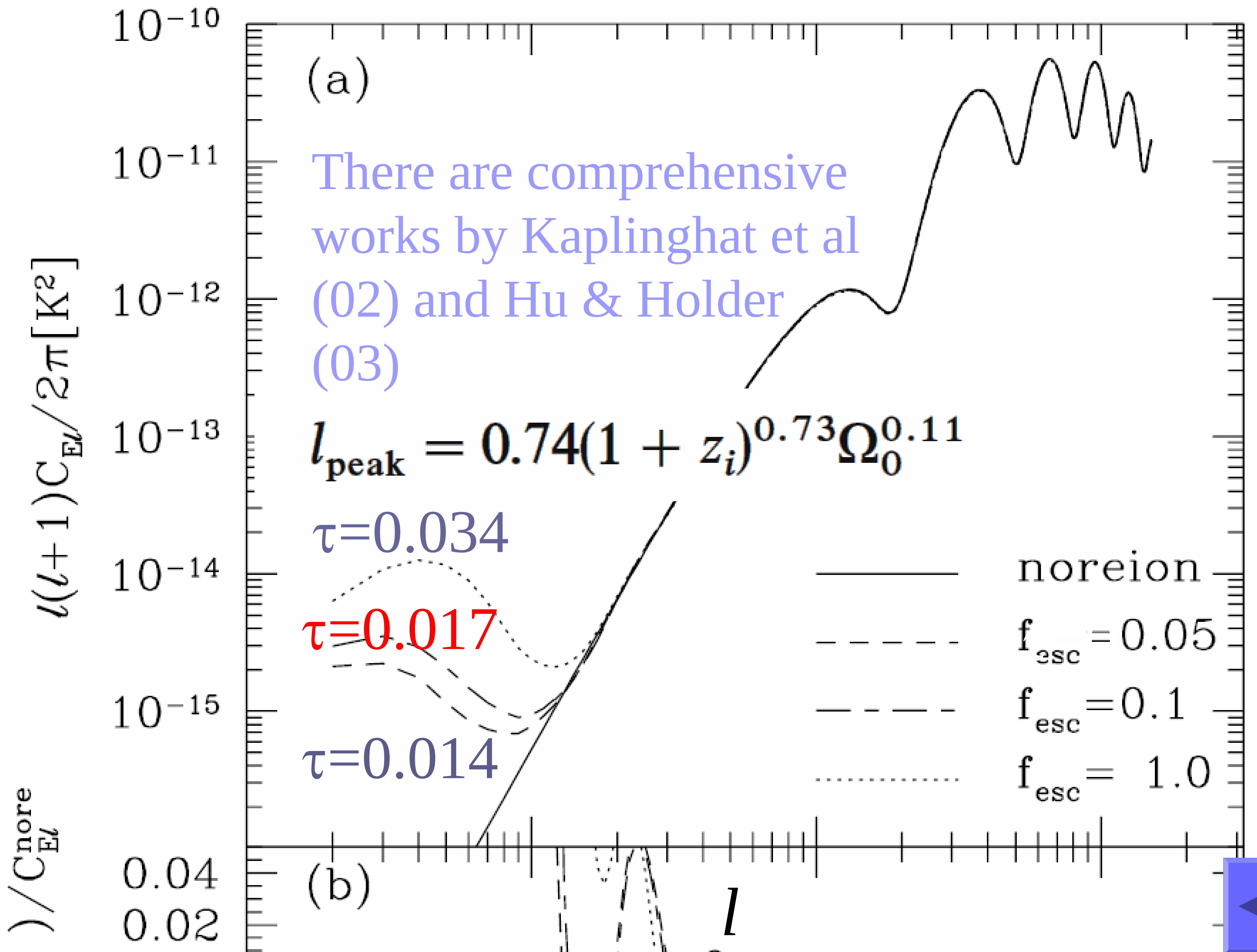
§ 2. How can we investigate reionization **by CMB?**

- CMB Primary Anisotropies: τ
- CMB Primary Polarization : τ, **duration**
- CMB Secondary Anisotropies:
  - Ostriker-Vishniac Effect: τ
  - Kinetic SZ Effect by Patchy Reionized Regions: τ, **topology of ionized regions**
- CMB Secondary Polarization: τ, **topology**

N.S., Silk, Vittorio, ApJL (1993), 419, L1



Liu, NS, Benson, Nusser, Lacey (01)



Ostriker-Vishniac effect

Homogeneous ionized IGM, density fluc.+velocity

- How large can OV effect be under WMAP?

(1) The best fitted WMAP value

- $\Omega_\Lambda=0.73$, $\Omega_M=0.27$, $\Omega_B h^2=0.02$, $h=0.72$

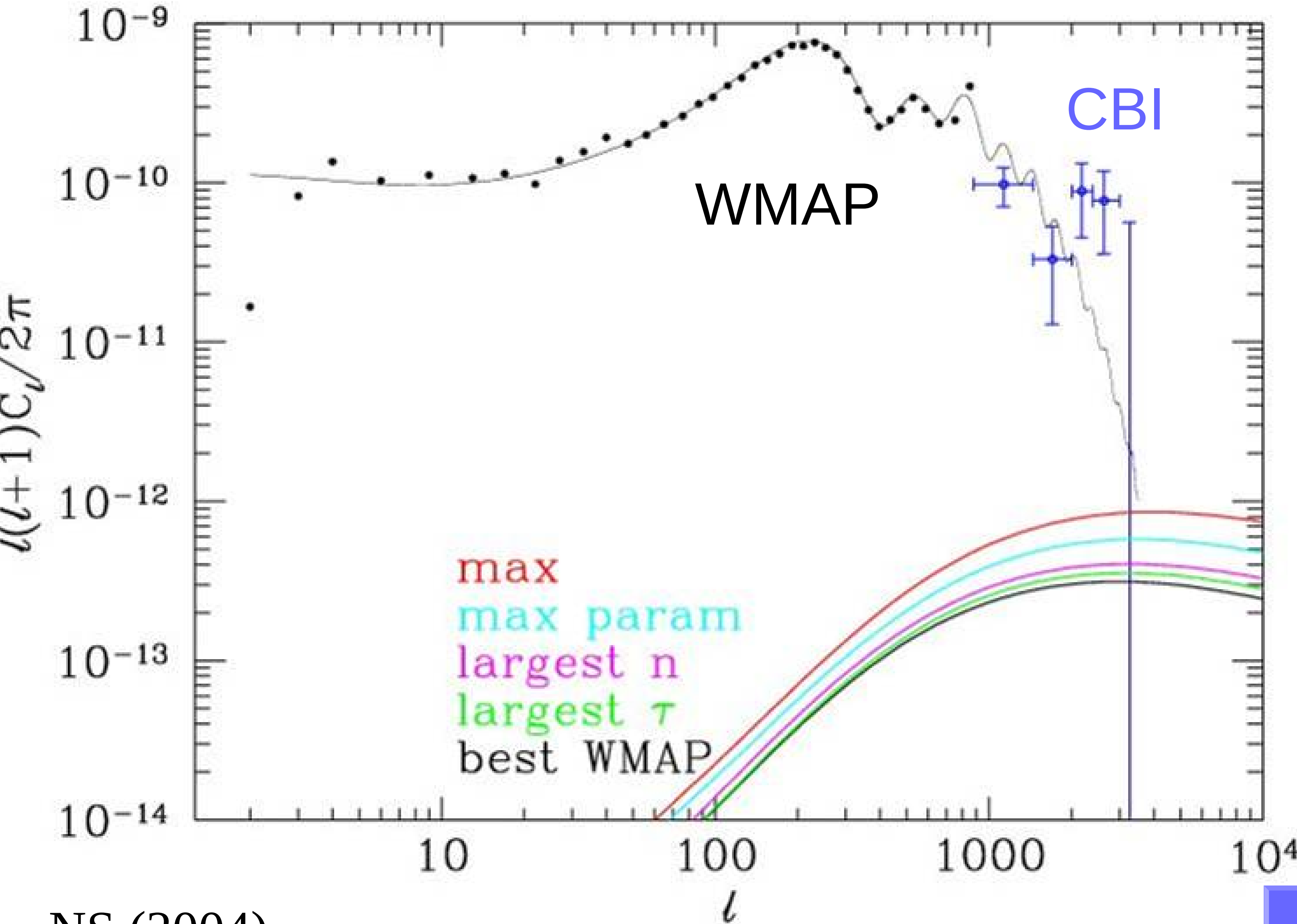
(2) The largest optical depth $\tau=0.24$, $z=21.5$

(3) The largest power law index $n=1.03$

(4) The largest small scale power

- Largest $\Omega_M h=0.23$, smaller $\Omega_B h^2=0.023$, $h=0.67$

(5) The largest OV effect

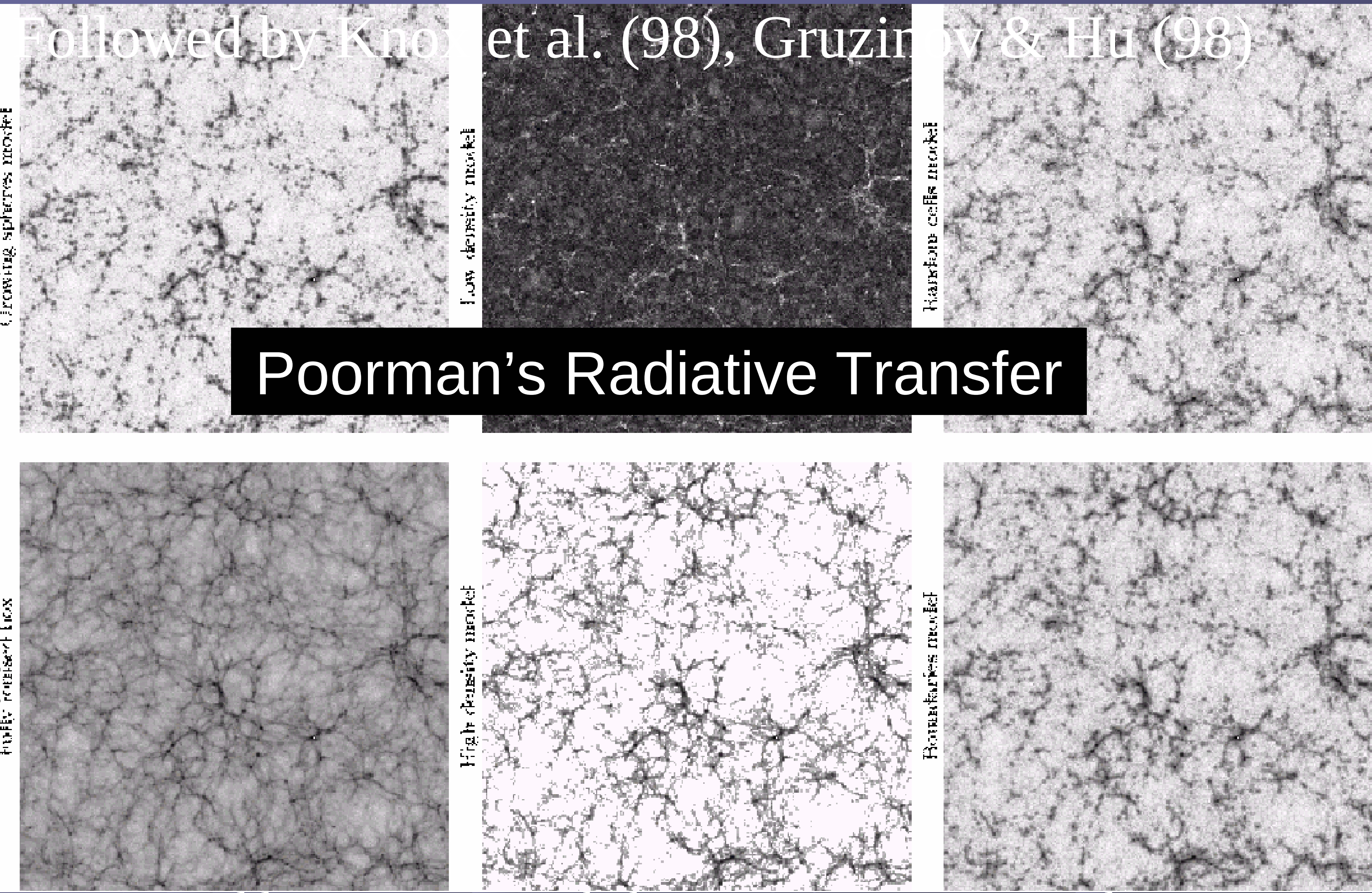


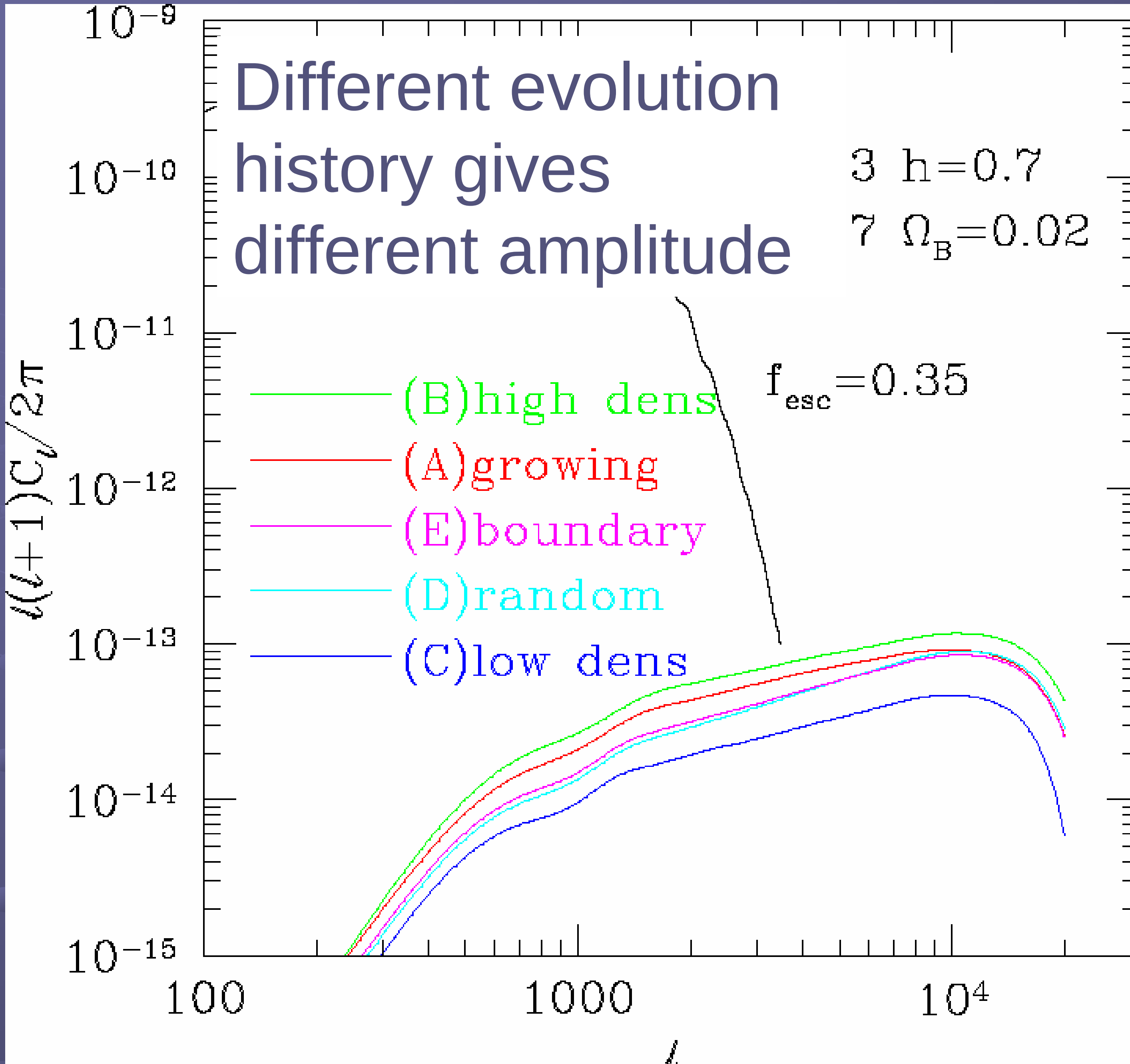
CBI
WMAP
max
max param
largest n
largest τ
best WMAP
$\ell(\ell+1)C_\ell/2\pi$
ℓ
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10
100
1000
10^4

NS (2004)

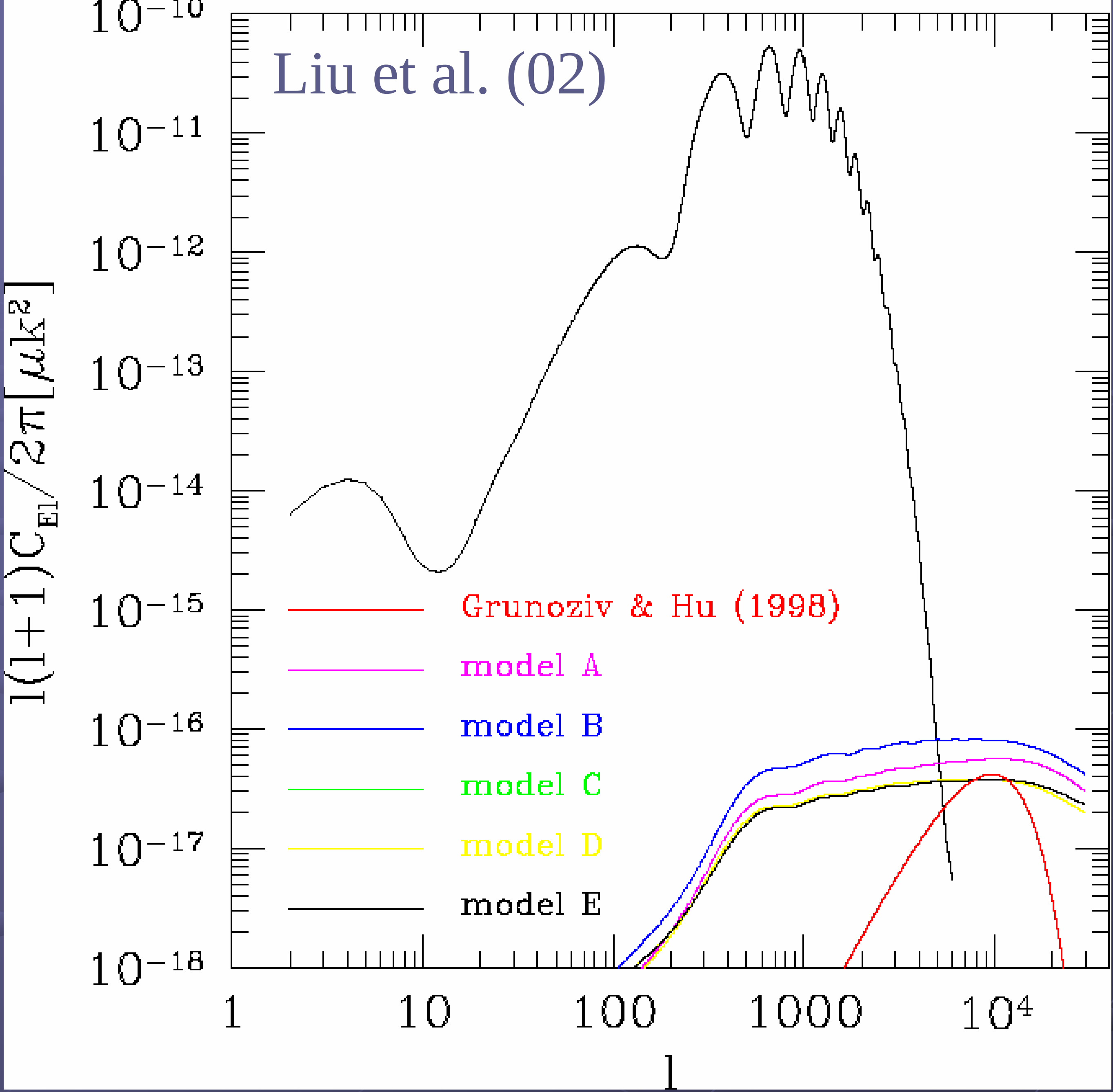
Pioneering works by; Aghanim et al. (96)

Followed by Knox et al. (98), Gruzinov & Hu (98)





Dependence on distribution of ionized region



Ionized region dependence

§ 3. Some Attempts on having Early Reionization

- Orthodox Approach
  - CDM with Top Heavy IMF
  - CDM with High Escape Fraction of Ionizing Photons

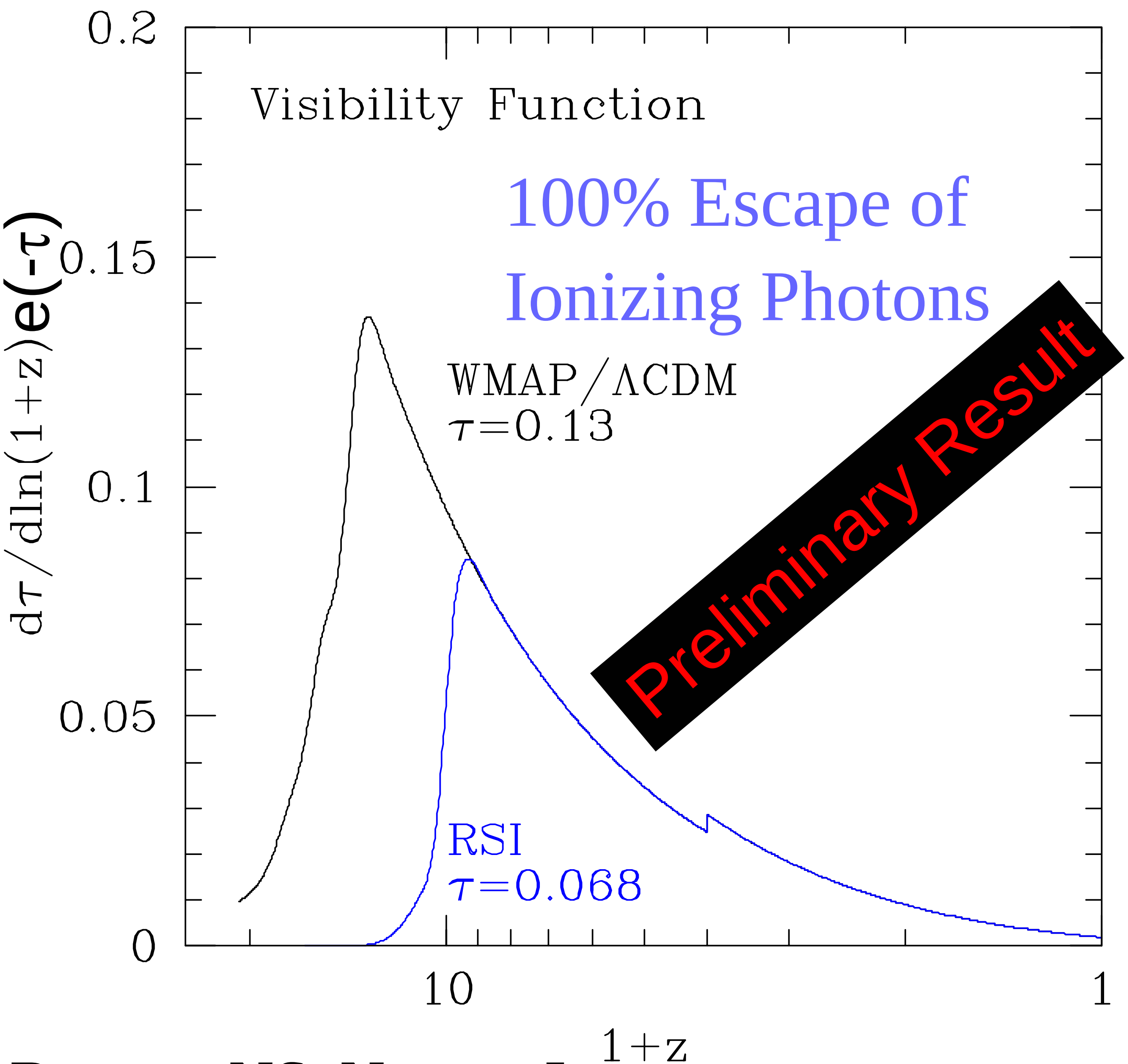
    They've Worked, **sort of.** **But not for RSI model!**

    ⇒ How is CMB affected?

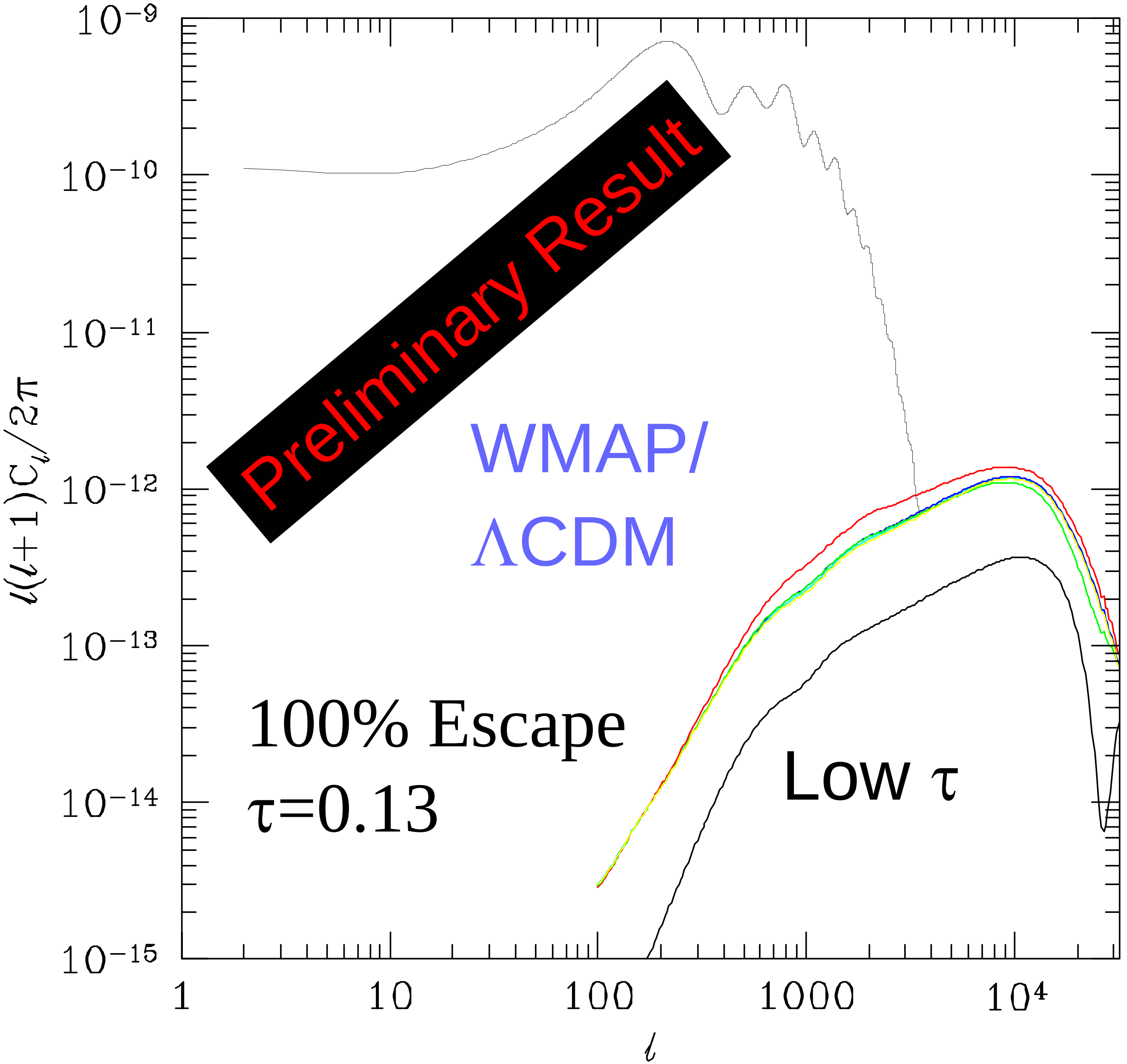
- Exotic Possibilities
  - CDM with isocurvature power spectrum

    Can be consistent with Ly-alpha and reionization
  - CDM with non-Gaussian fluctuations

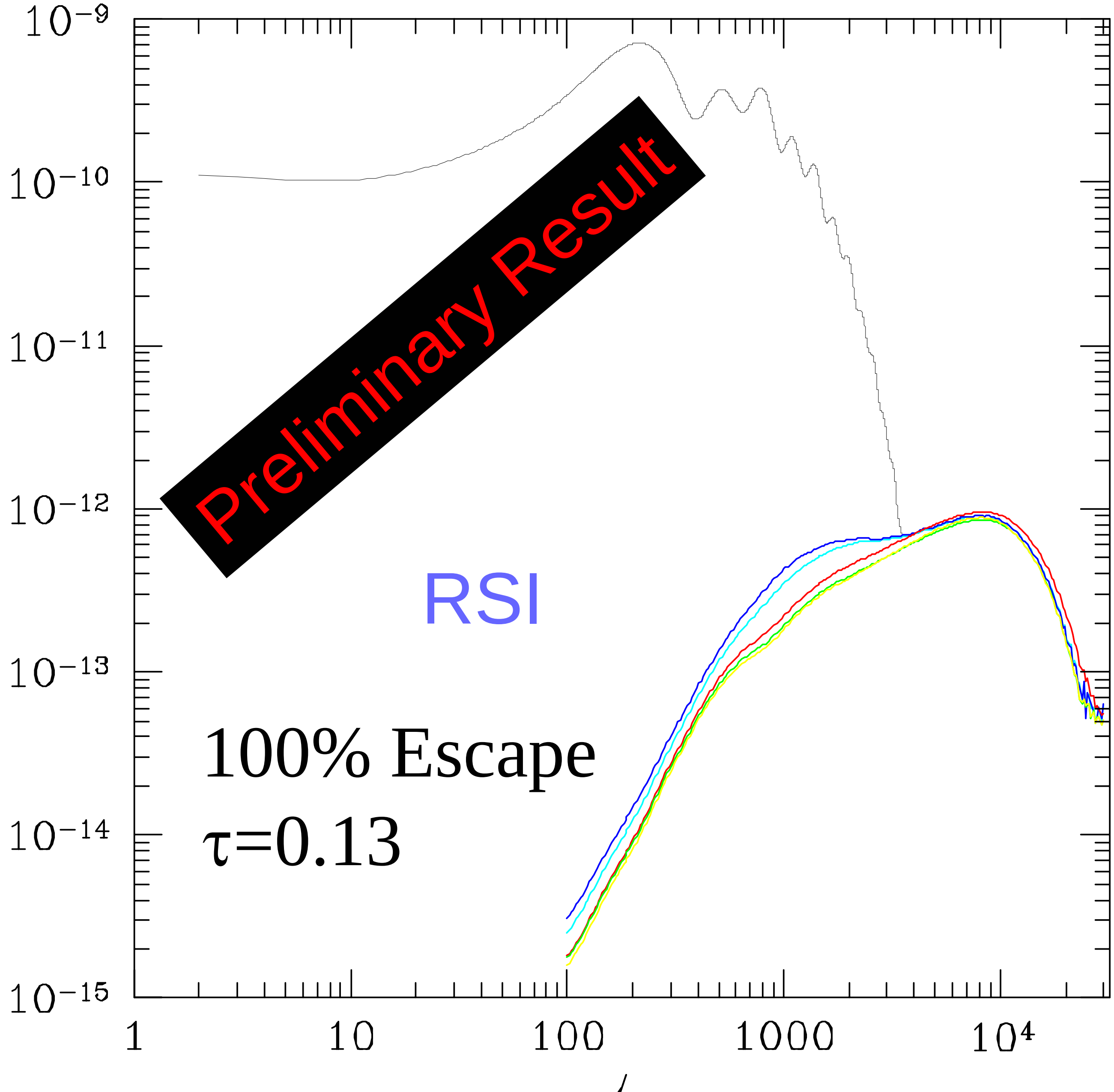
    Induce early structure formation
  - CDM with decaying particles
    - Radiation from the particles can reionize the universe



Benson, NS, Nusser, Lacey:



Benson, NS, Nusser, Lacey



Benson, NS, Nusser, Lacey

CDM adiabatic +Isocurvature modes

with Zaroubi, Silk

Requirements:

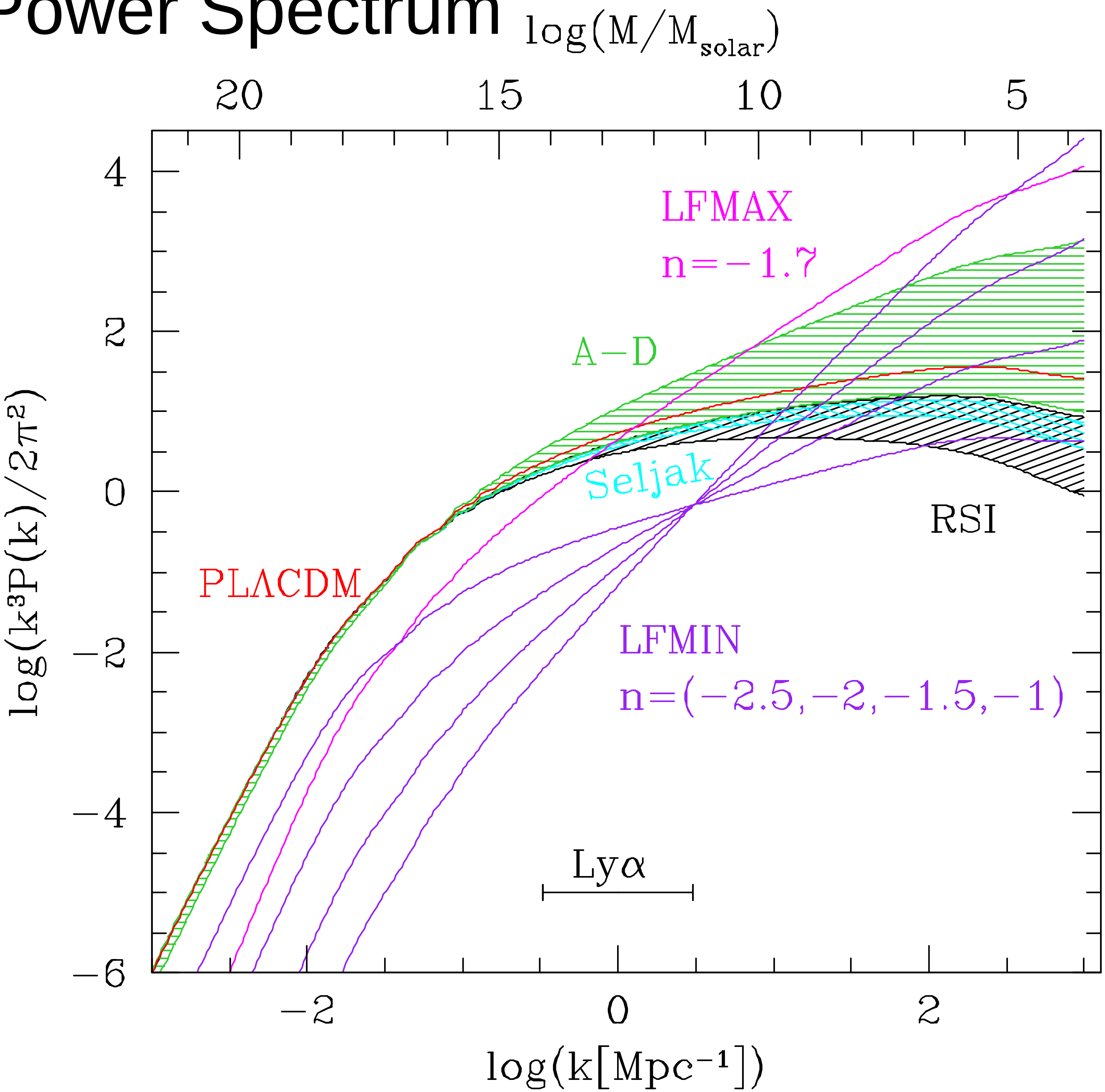
- To be consistent with Ly-alpha forest power spectrum
- Early enough reionization

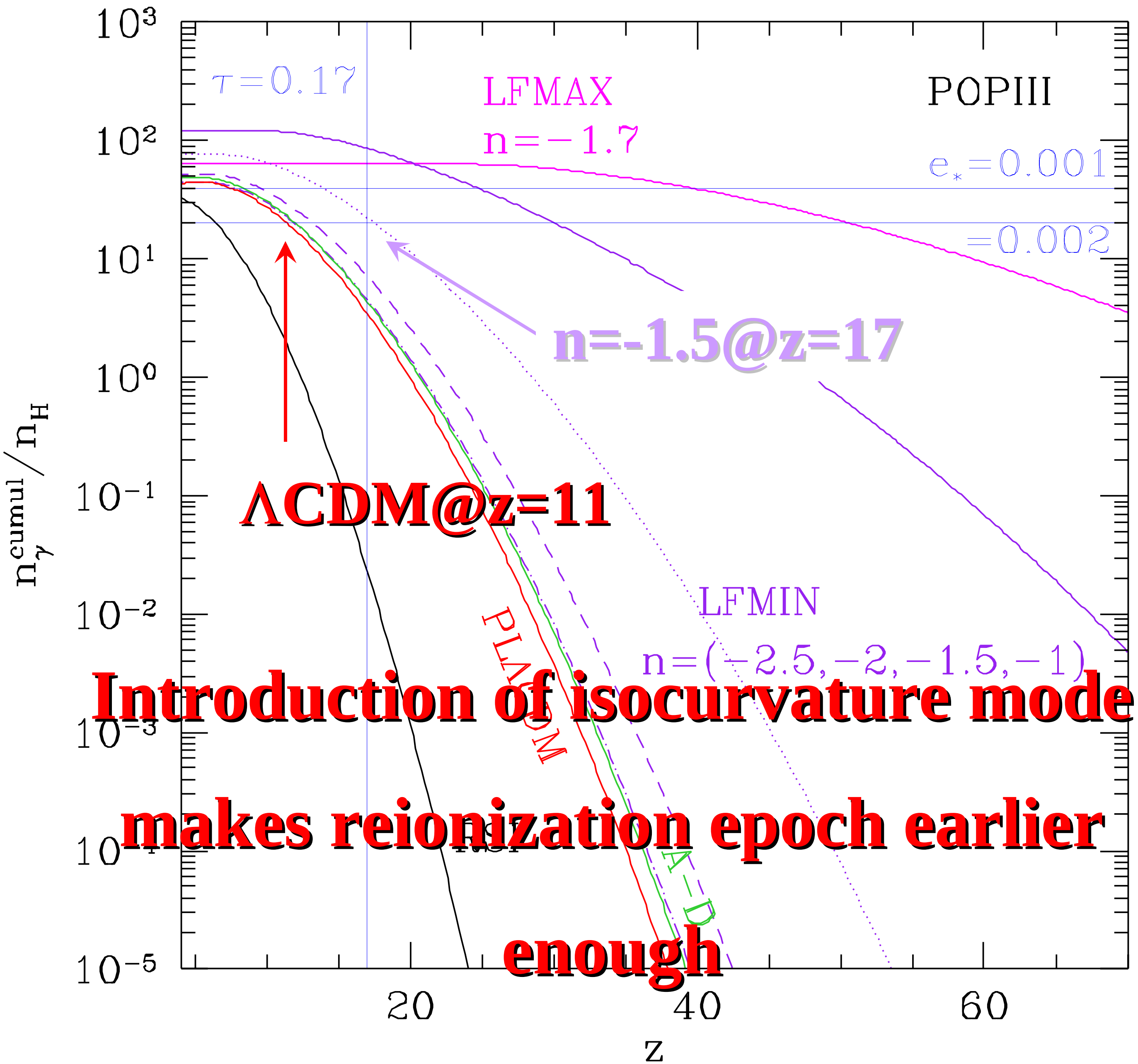
Plotted here are n_γ/n_H: translate into Iionization fraction, need to be devided by $f_{esc} f_{ion}/C_{clump}$~10 to 20

f_{esc}: esc.frac, f_{ion}: # of ioniz per UV photon

C_{clump}: Clumping factor

Power Spectrum





Introduction of isocurvature mode makes reionization epoch earlier enough

Number of Ionizing Photons per H atom

CDM with non-Gaussian Fluc.

Chen, Cooray, Yoshida, N.S. MNRAS (2003) 346, 31

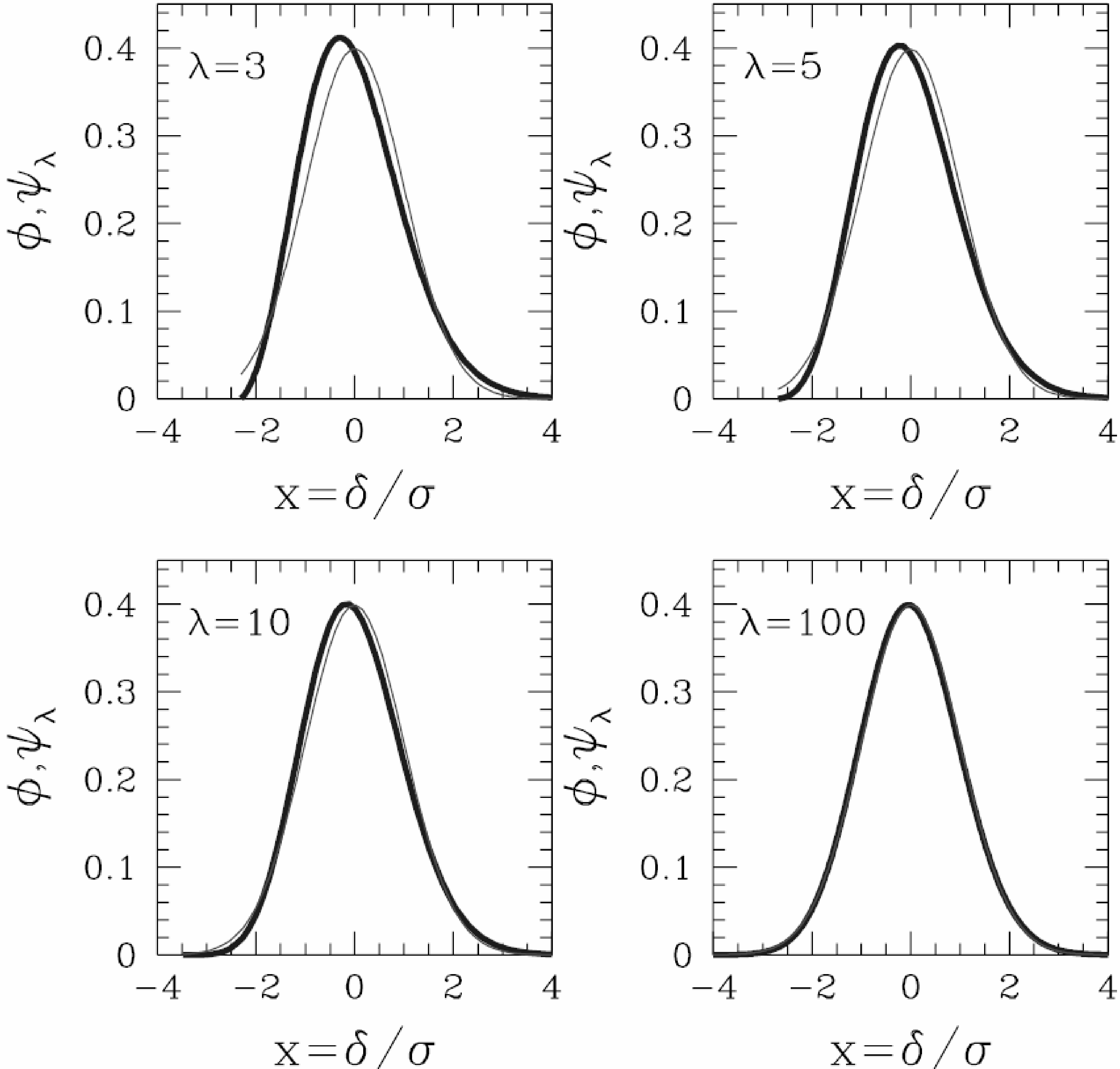
- Perhaps the least exotic model…?

$$\psi(x) = 2A \frac{\lambda^{\sqrt{\lambda}x+\lambda+0.5} e^{-\lambda}}{\Gamma(\sqrt{\lambda}x+\lambda+1)},$$

$\lambda \to \infty$: Gaussian

Willick (00)

$\lambda \approx D(z)/6\varepsilon$: D(z) Growth Rate



λ=3
λ=5
λ=10
λ=100
φ, ψλ
x=δ/σ
0.4
0.3
0.2
0.1
0
−4
−2
0
2
4

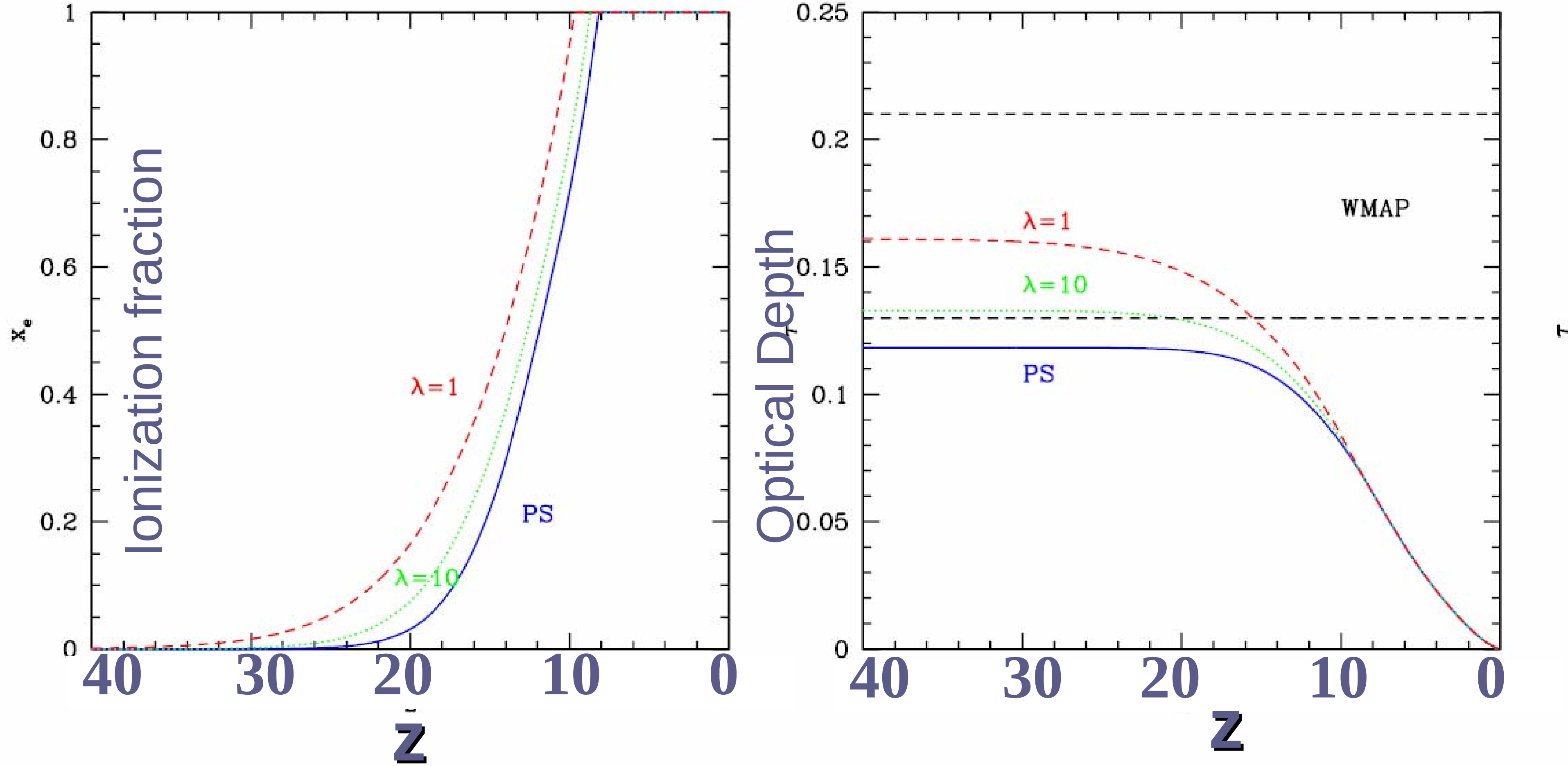


Figure 2. *Left:* The volume ionized fraction, $x_e(z) \equiv F_{\mathrm{HII}}(z)$ as a function of redshift. *Middle* scattering. The models are based on "ordinary" star-formation in Type I halos only. The Press-S depth with a value of 0.097 while the non-Gaussian mass functions lead to values of 0.11 and The two black das he range of the first year V plot, but with σ_8

$$\psi(x) = 2A \frac{\lambda^{\sqrt{\lambda}x+\lambda+0.5} e^{-\lambda}}{\Gamma(\sqrt{\lambda}x+\lambda+1)},$$

λ→∞: Gaussian

CDM with decaying particles

Kasuya, Kawasaki, N.S., PRD (2003) 69 3512

- Here we include:
  decaying particles+Stars+QSO
- Can gradually reionize the universe from high z
- Shape of EE spectrum is very different

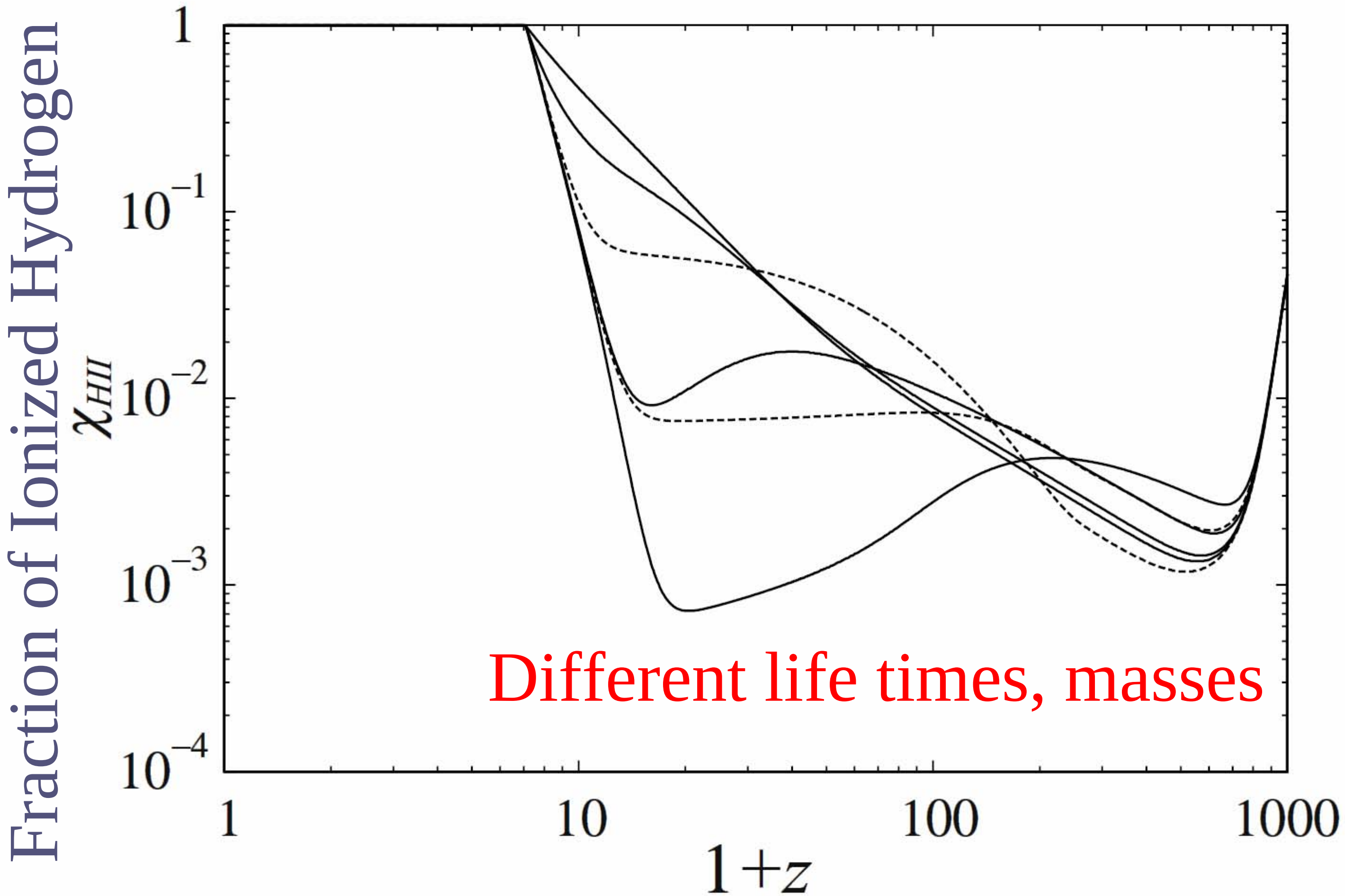


FIG. 1: Ionization histories of hydrogen (HII). We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}$, 10^{15}, 10^{16}, and 10^{18} sec in solid lines from the bottom to the top (at $z \sim 20$), while lower and upper dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively.

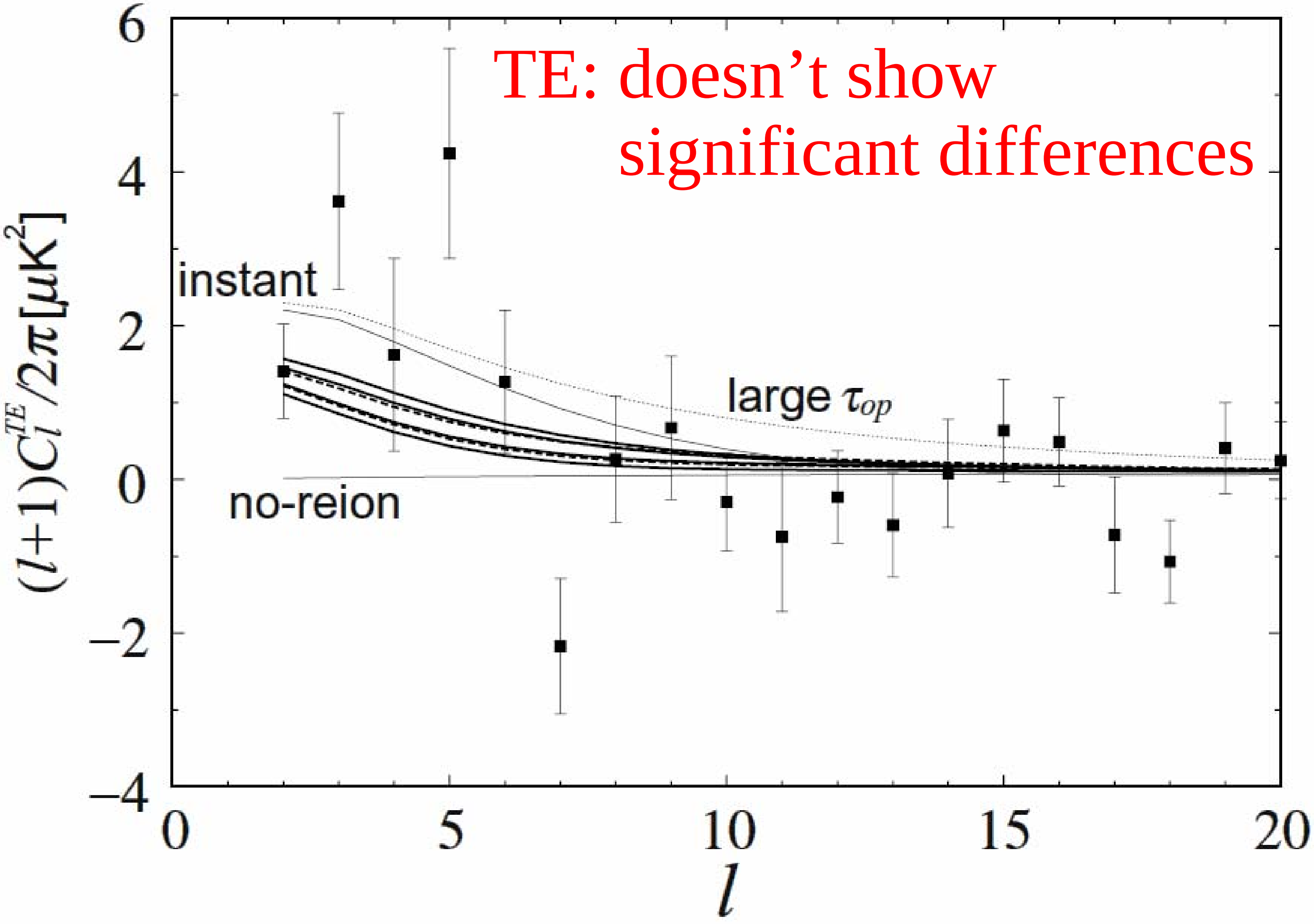


FIG. 5: TE spectrum for various ionization histories. We plot for $E_{...} = 15$ eV for $\tau_{...} = 10^{14}$, 10^{15}, 10^{16}, and 10^{18}

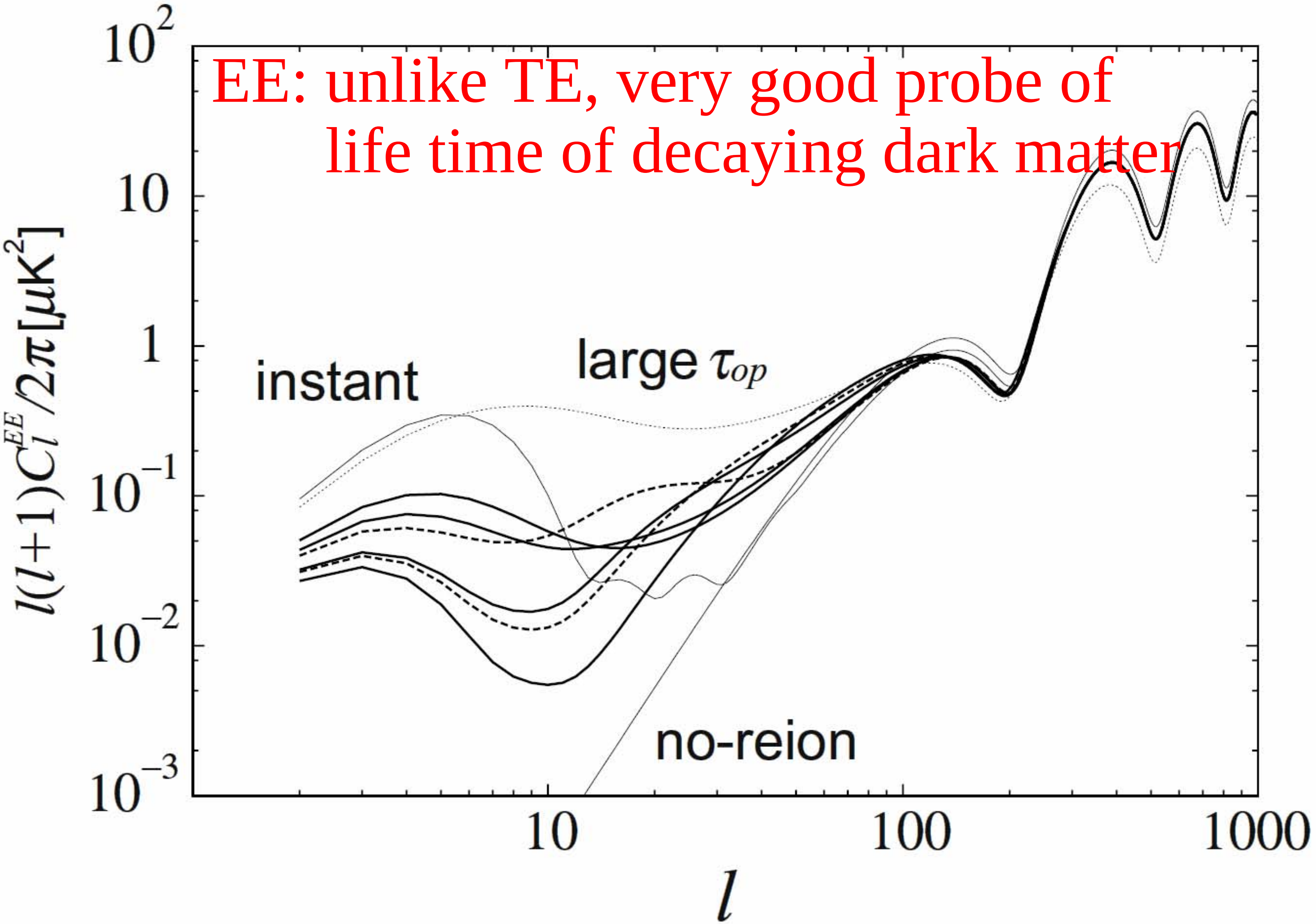


FIG. 6: EE spectrum for various ionization histories. W

Reionization

- To get τ=0.17, we need
  - Top heavy IMF, High Escape Fraction of Ionizing Photons, or Something Exotic
- We are eagerly awaiting for
  - EE Spectrum by WMAP, PLANCK and more
    - Accurate τ

    - Epoch of reionization
    - Duration of Reionization
  - Observations of Small Angular Scale CMB Temperature Fluctuations by
    - Consistency Check of τ
    - Topology of ionized regions