Reionization of the Universe
&
Kinetic SZ Effect

Probing Dark Ages by CMB

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§1. Early Reionization of the Universe

WMAP

- Reionization
  - τ = 0.17: based on Temperature-Polarization Correlation

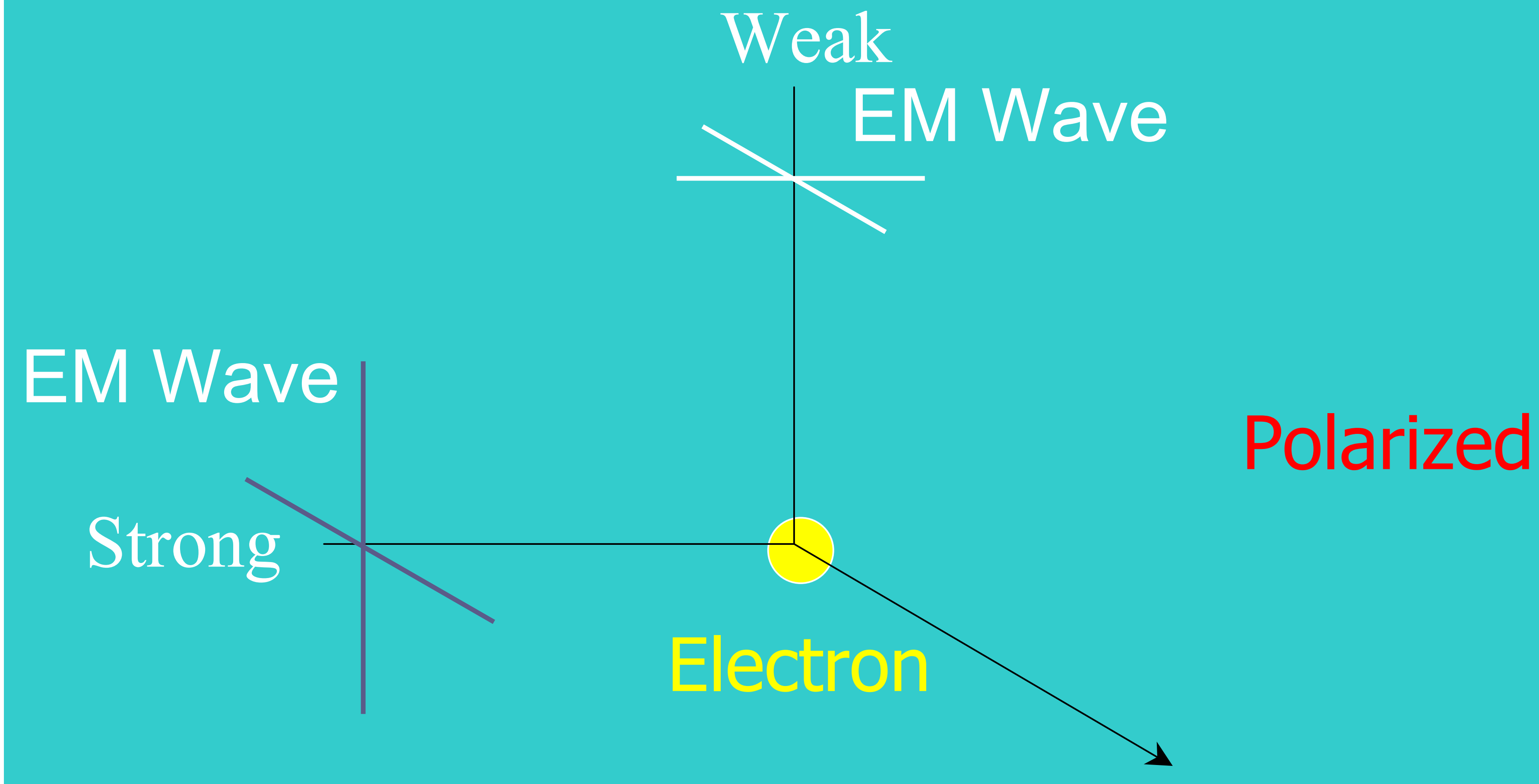
    $\tau \equiv \int n_e \sigma_{Thomson} dt$: Thomson Optical depth

- Corresponds to (best fitted WMAP parameters)

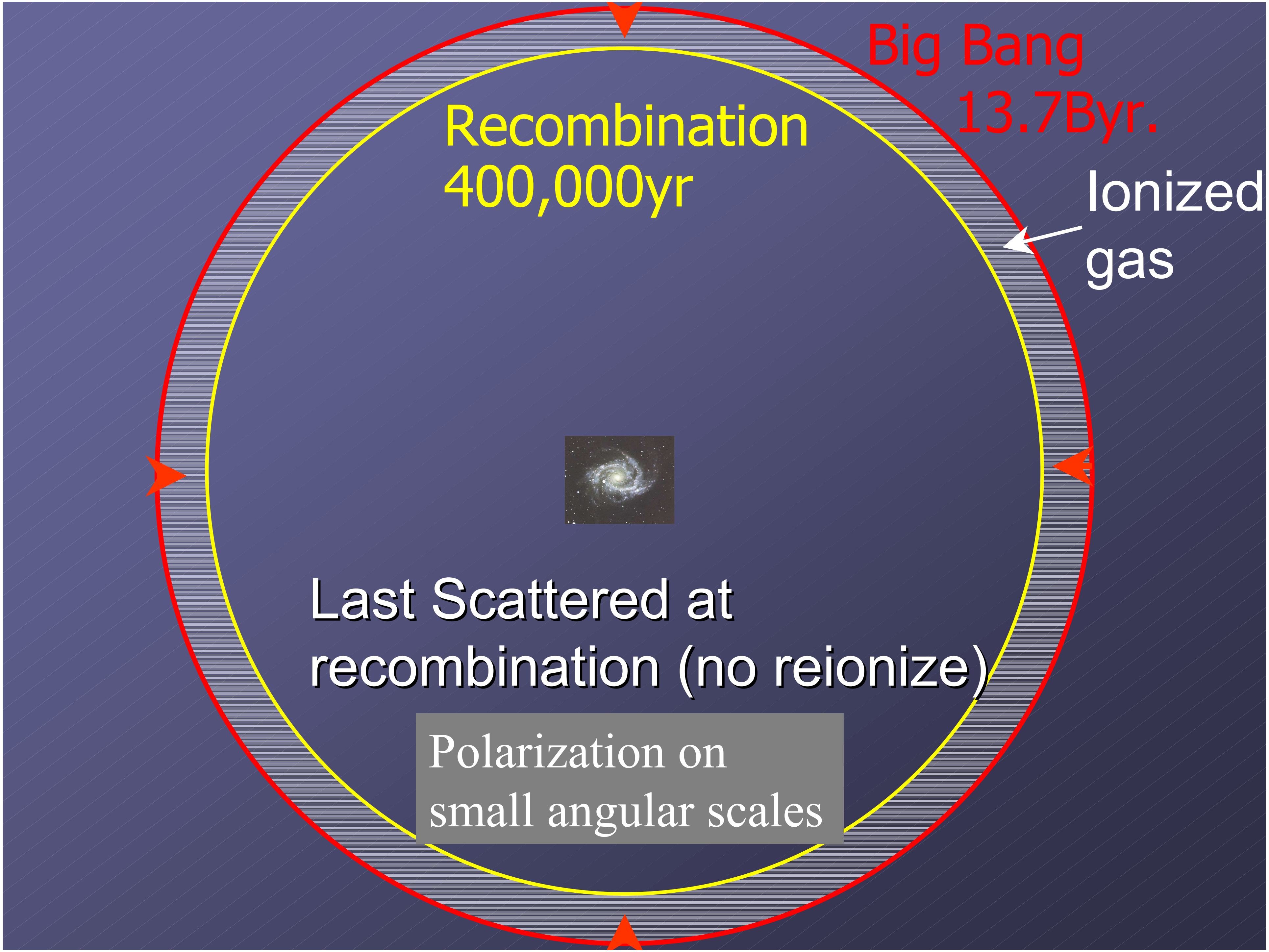
  z = 17.8 no He reionize

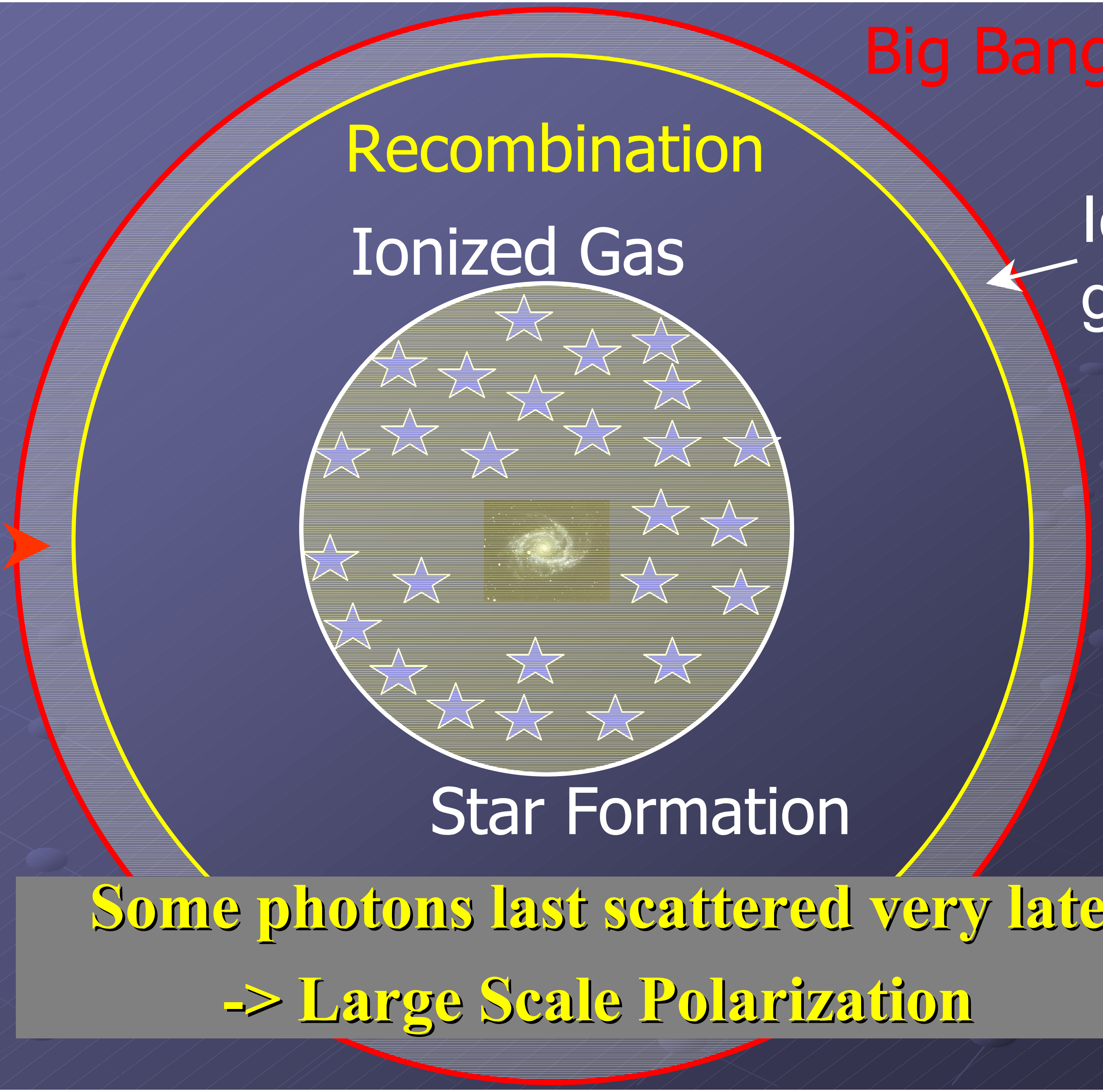
  z = 16.9 HeI->HeII reionization

  z = 16.1 all He reionize



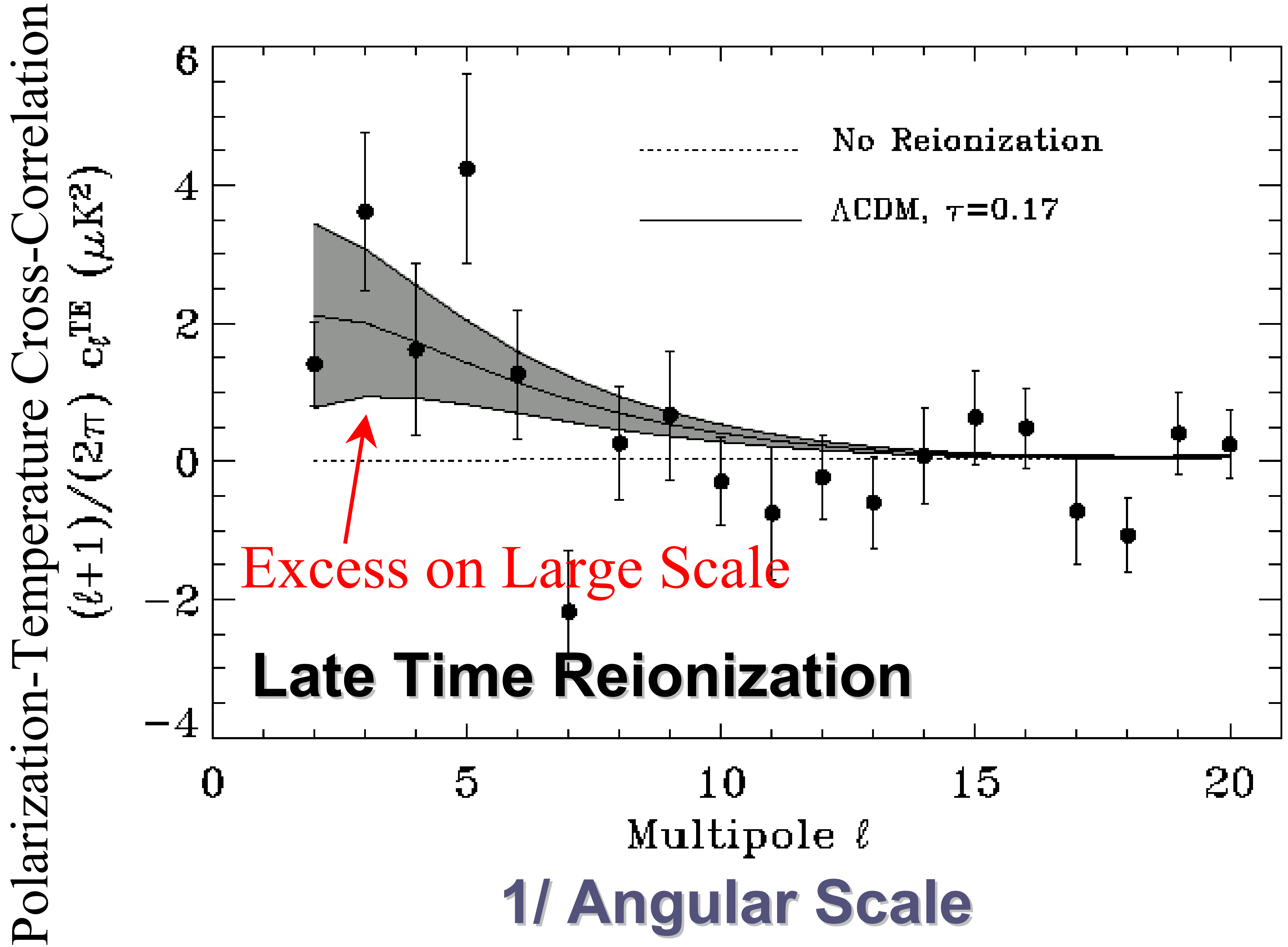
Scattering with Quadrupole Anisotropies of CMB produce polarization


Big Bang
13.7Byr.
Recombination
400,000yr
Ionized
gas
Last Scattered at
recombination (no reionize)
Polarization on
small angular scales



Some photons last scattered very late

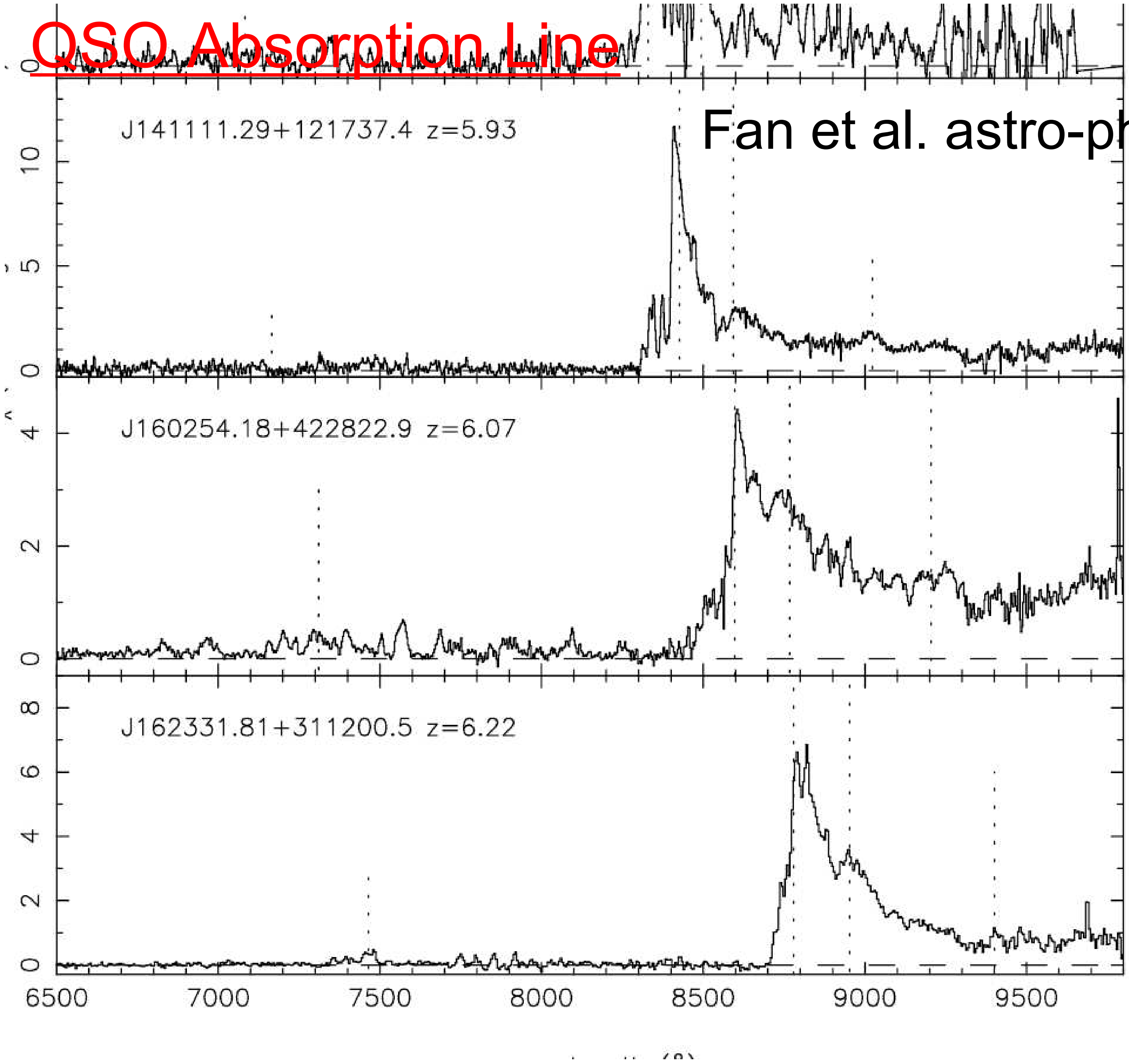
-> Large Scale Polarization



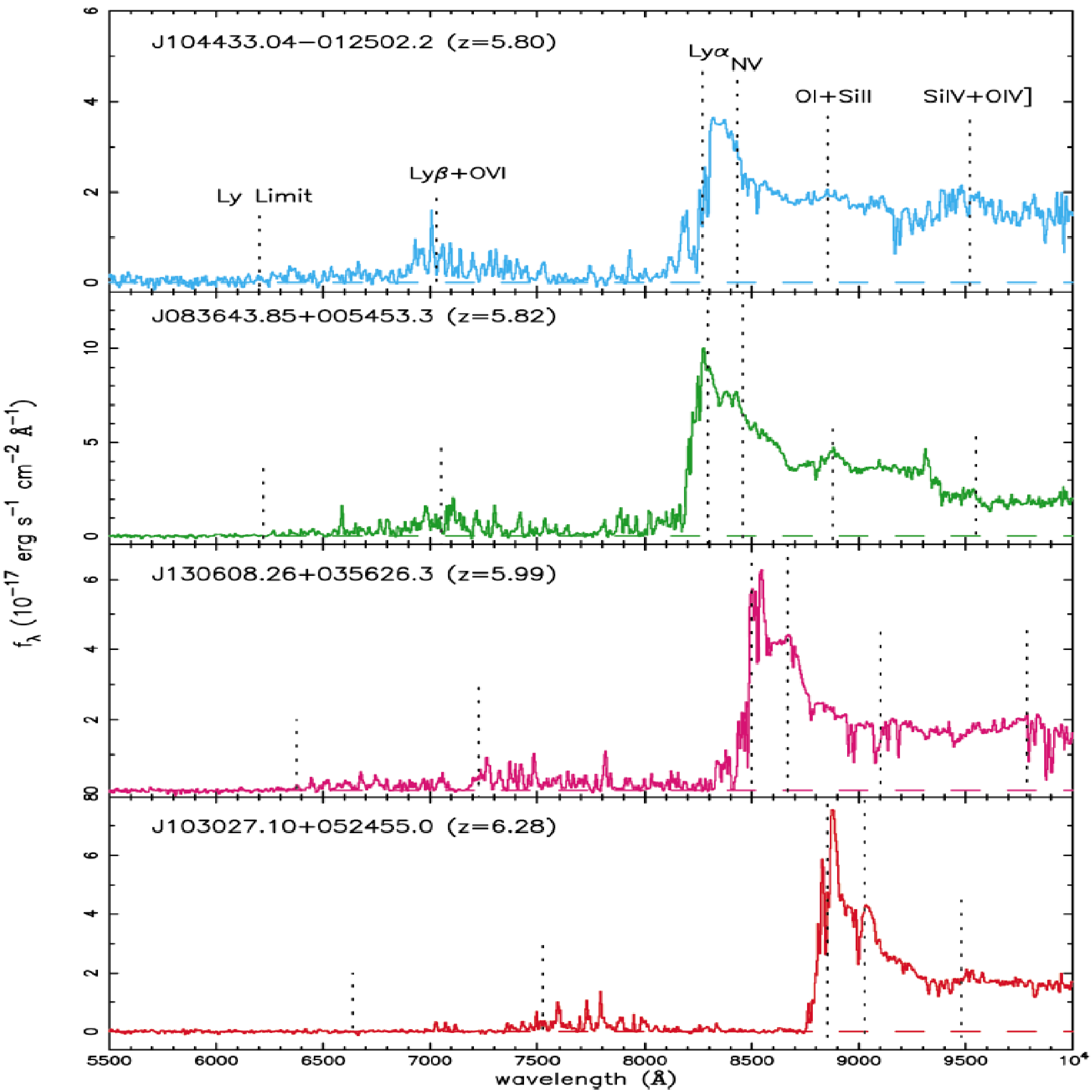
Polarization-Temperature Cross-Correlation
$(\ell+1)/(2\pi)\ c_\ell^{TE}\ (\mu K^2)$
No Reionization
ΛCDM, τ=0.17
Excess on Large Scale
Late Time Reionization
Multipole ℓ
1/ Angular Scale

QSO Absorption Line

Fan et al. astro-ph/0405138



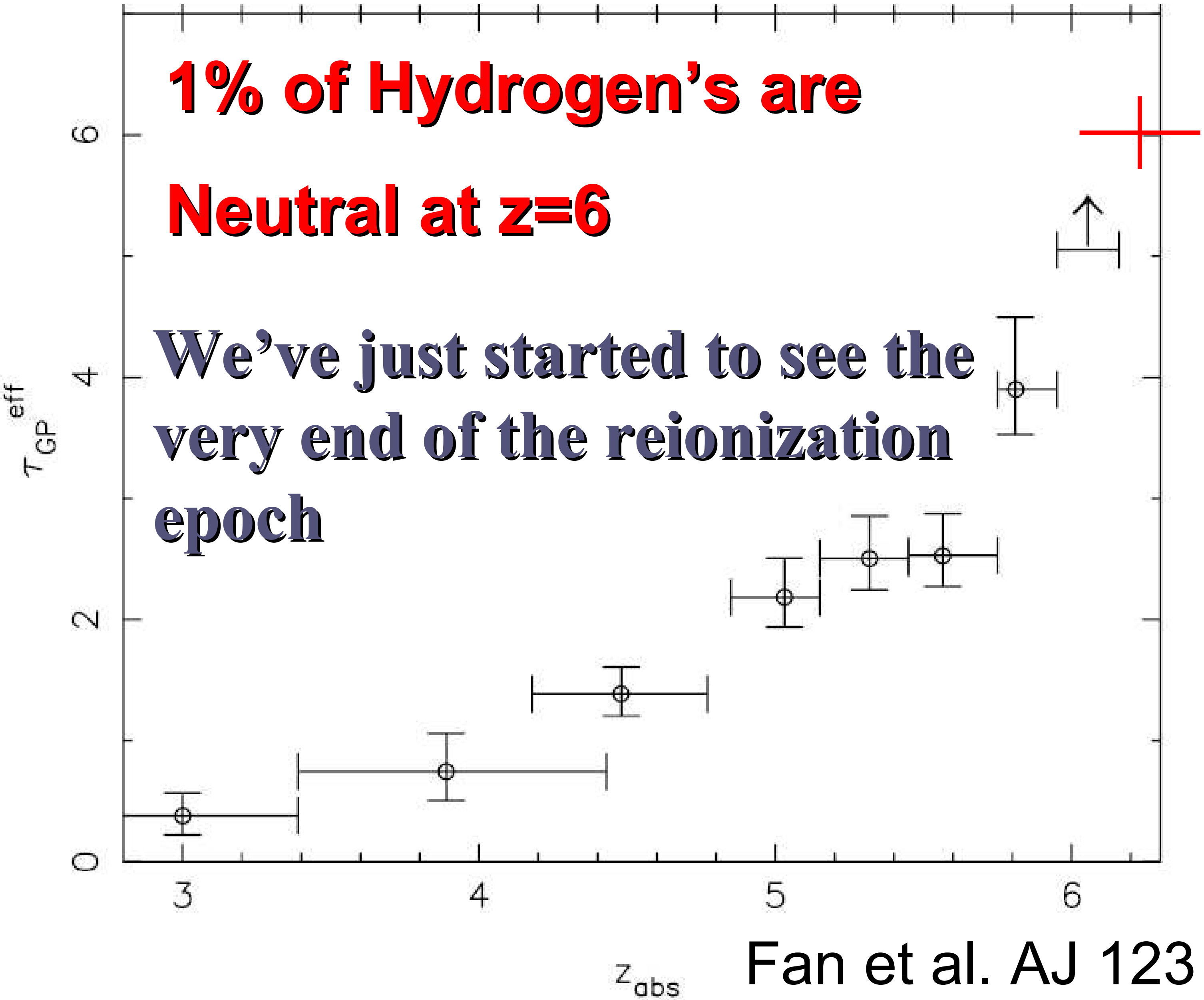
Becker et al. AJ122, 2850



1% of Hydrogen's are

Neutral at z=6

We've just started to see the very end of the reionization epoch



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

    $\tau=0.17$ but stars form from z=35

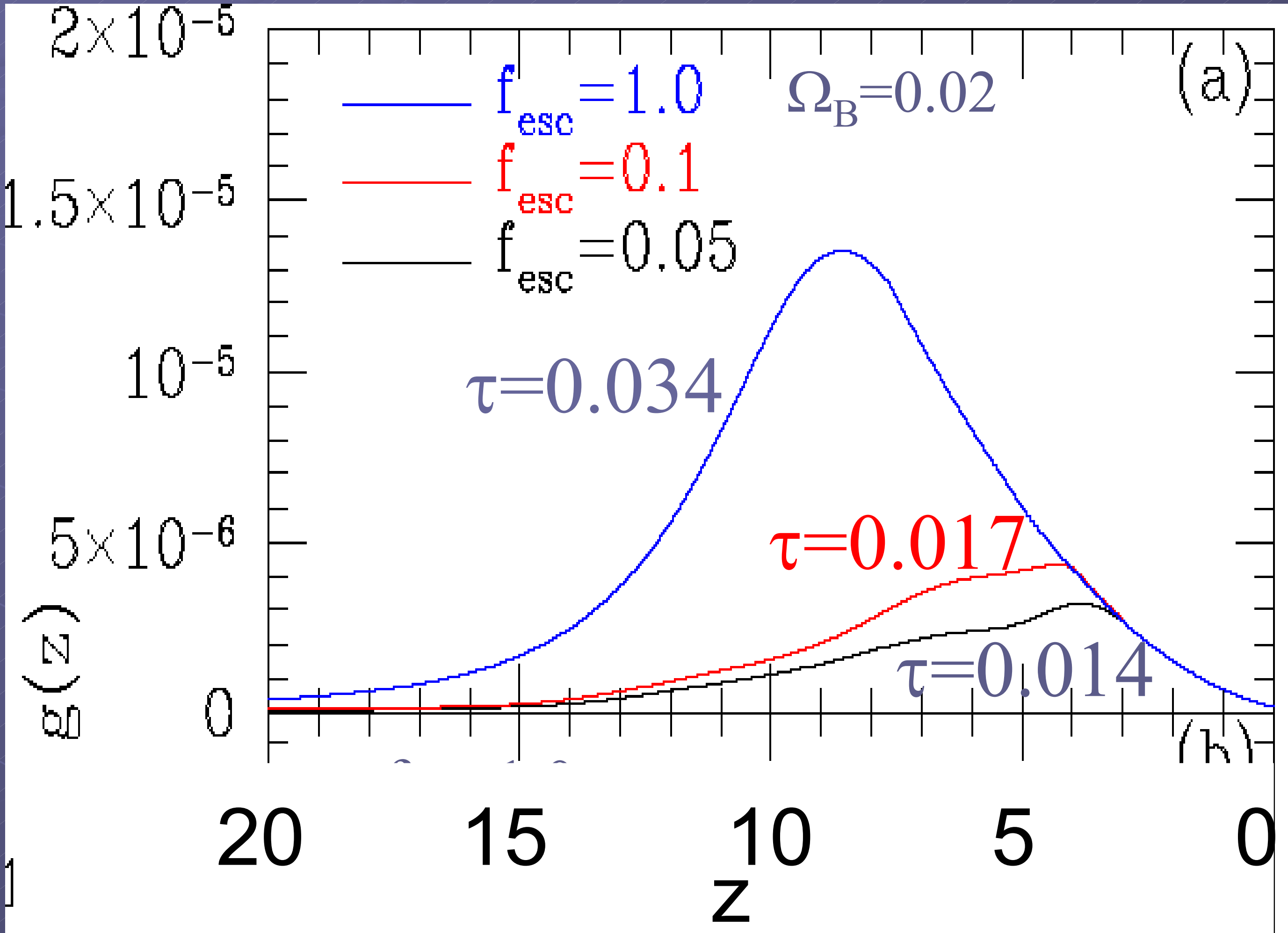
    realistic $z_{reio}=10$
  - Ciardi, Ferrara, White (Post-WMAP)

    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

$$g(z) \equiv \frac{d\tau}{dz}\exp(-\tau)$$ Probability of last scattering



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

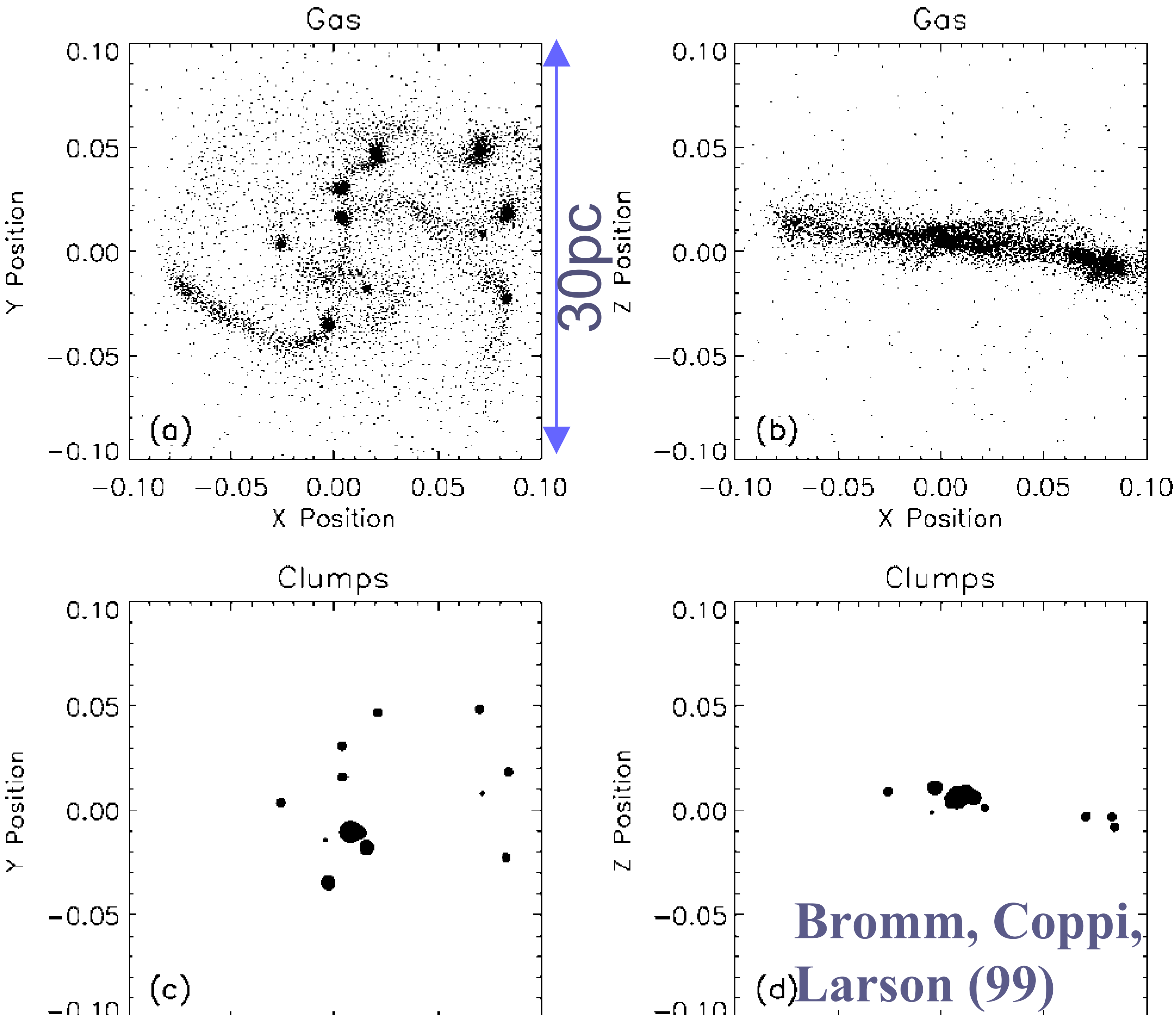
Assuming ΛCDM Cosmogony

- 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

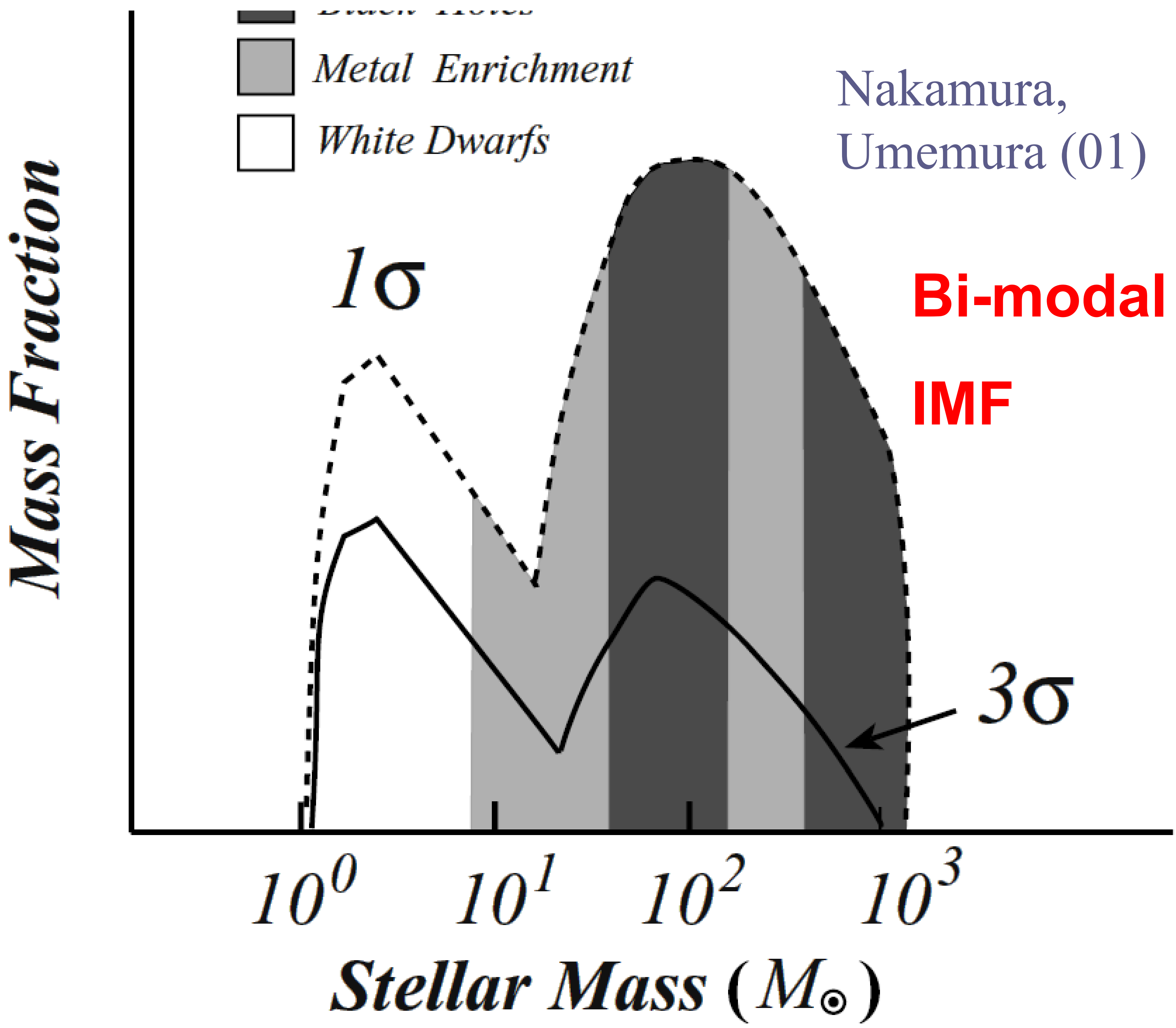


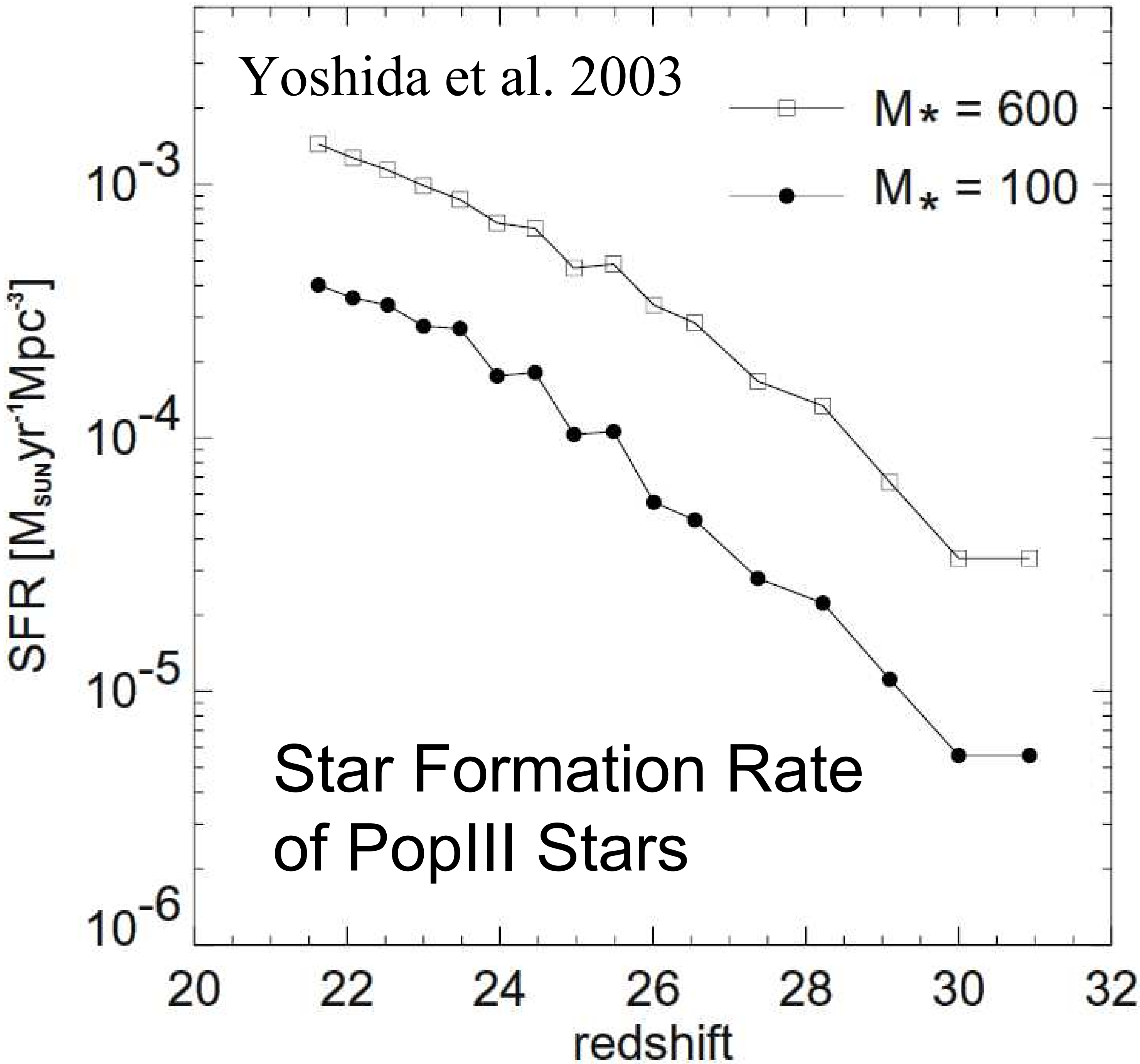
Bromm, Coppi, Larson (99)

Nakamura, Umemura (01)

Bi-modal

IMF




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
  - τ = 0.17
    - Corresponds to (best fitted WMAP parameters)

z = 17.8 no He reionize

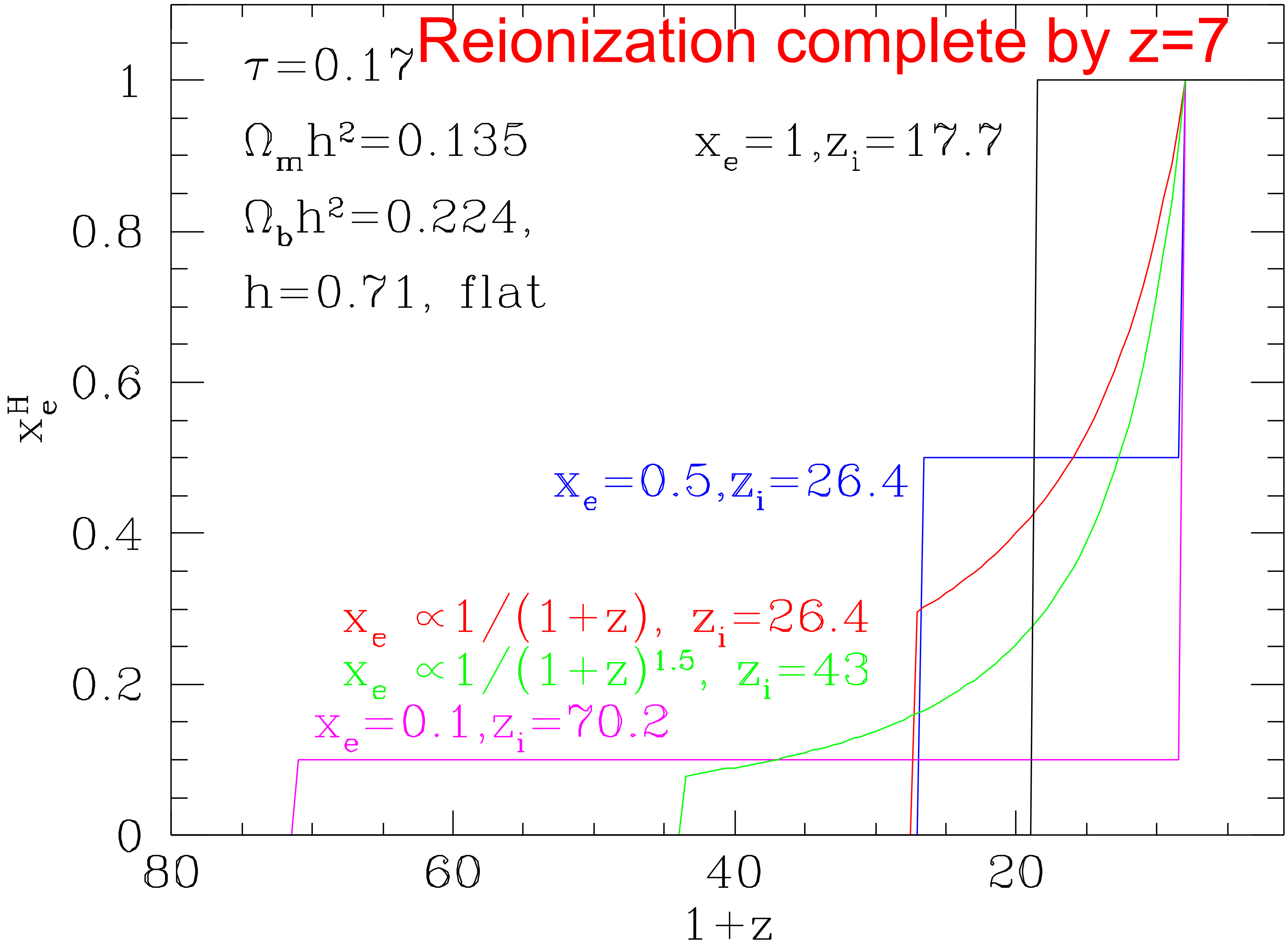
instantaneous reionization was assumed

z = 16.9 HeI->HeII reionization

z = 16.1 all He reionize

Rather, gradual reionization is likely!

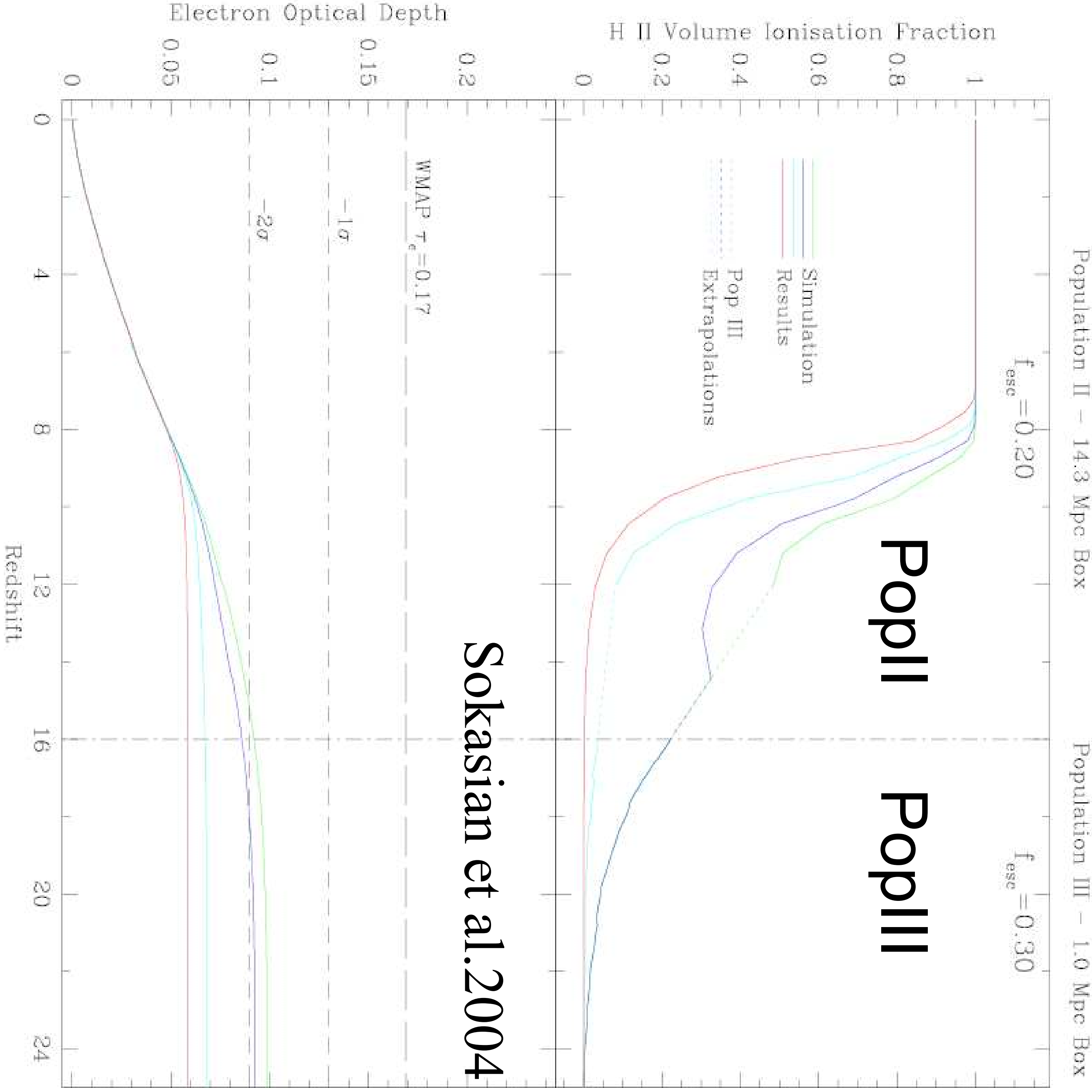
Consistent with SDSS QSOs



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
1
0.8
0.6
0.4
0.2
0
80
60
40
20
1+z
xeH

Optical Depth τ

Vol. frac. of Ionized H

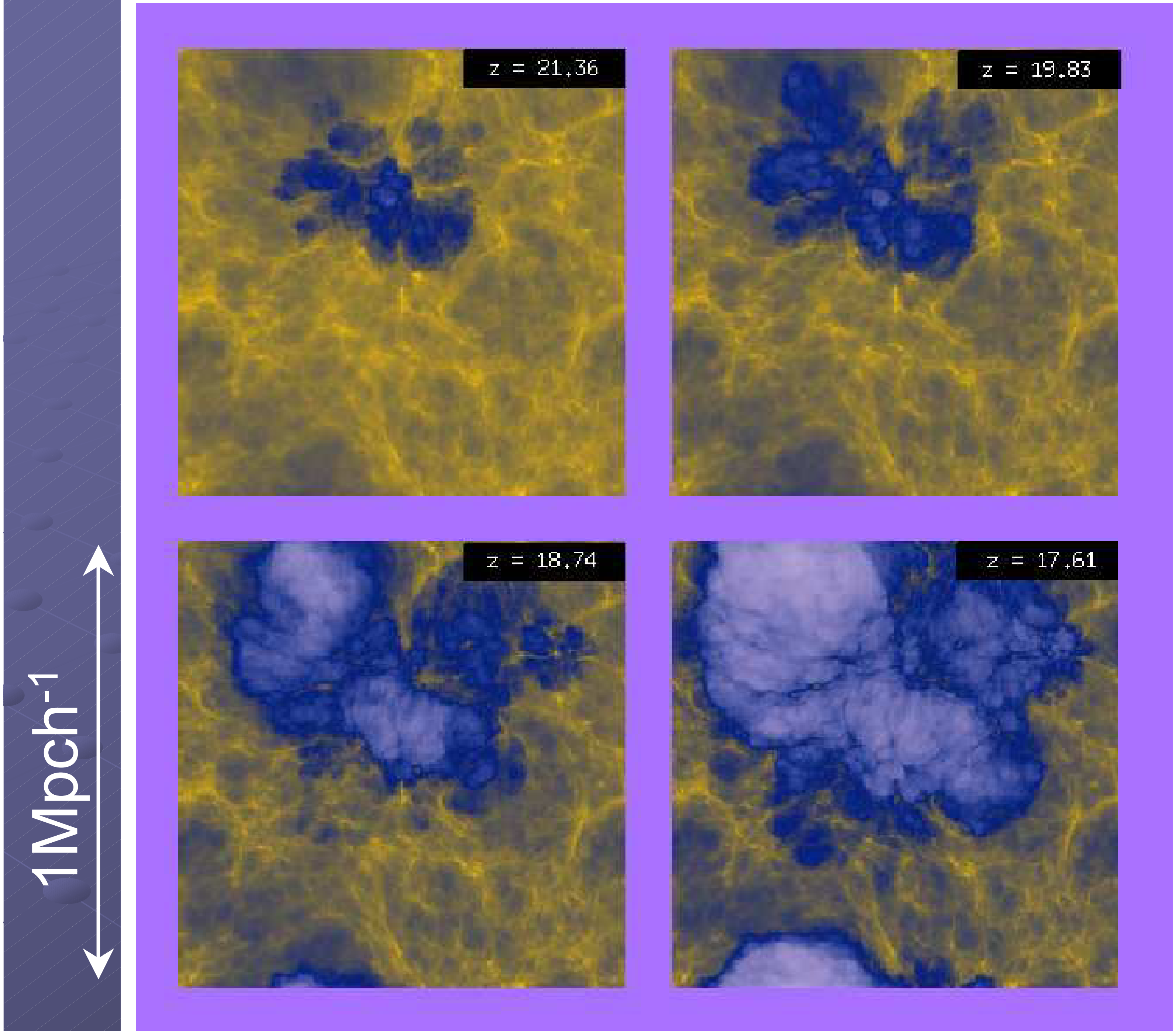


3) How does the ionized region evolve?

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



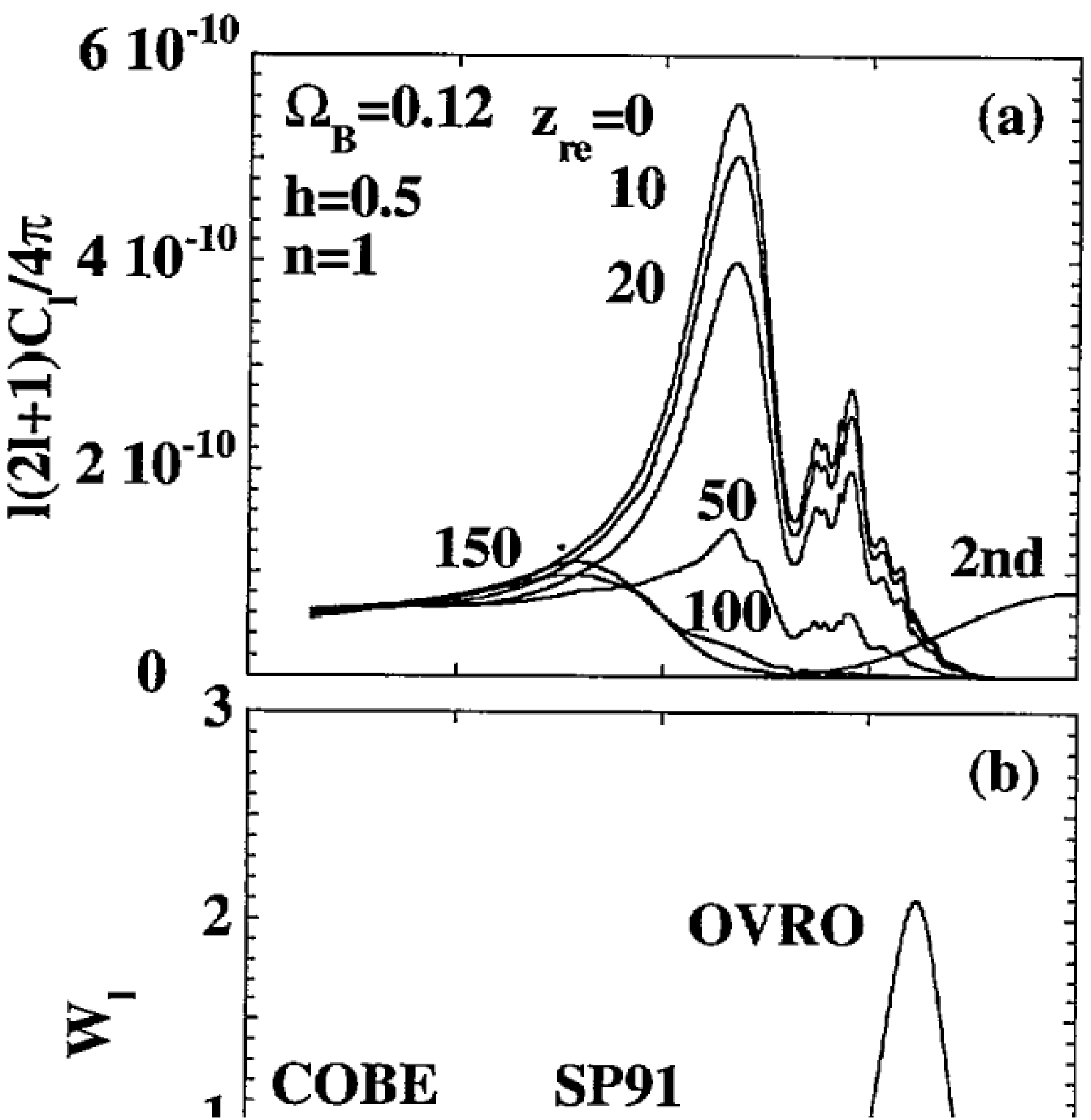
Ray Casting Method

Sokasian et al. 04

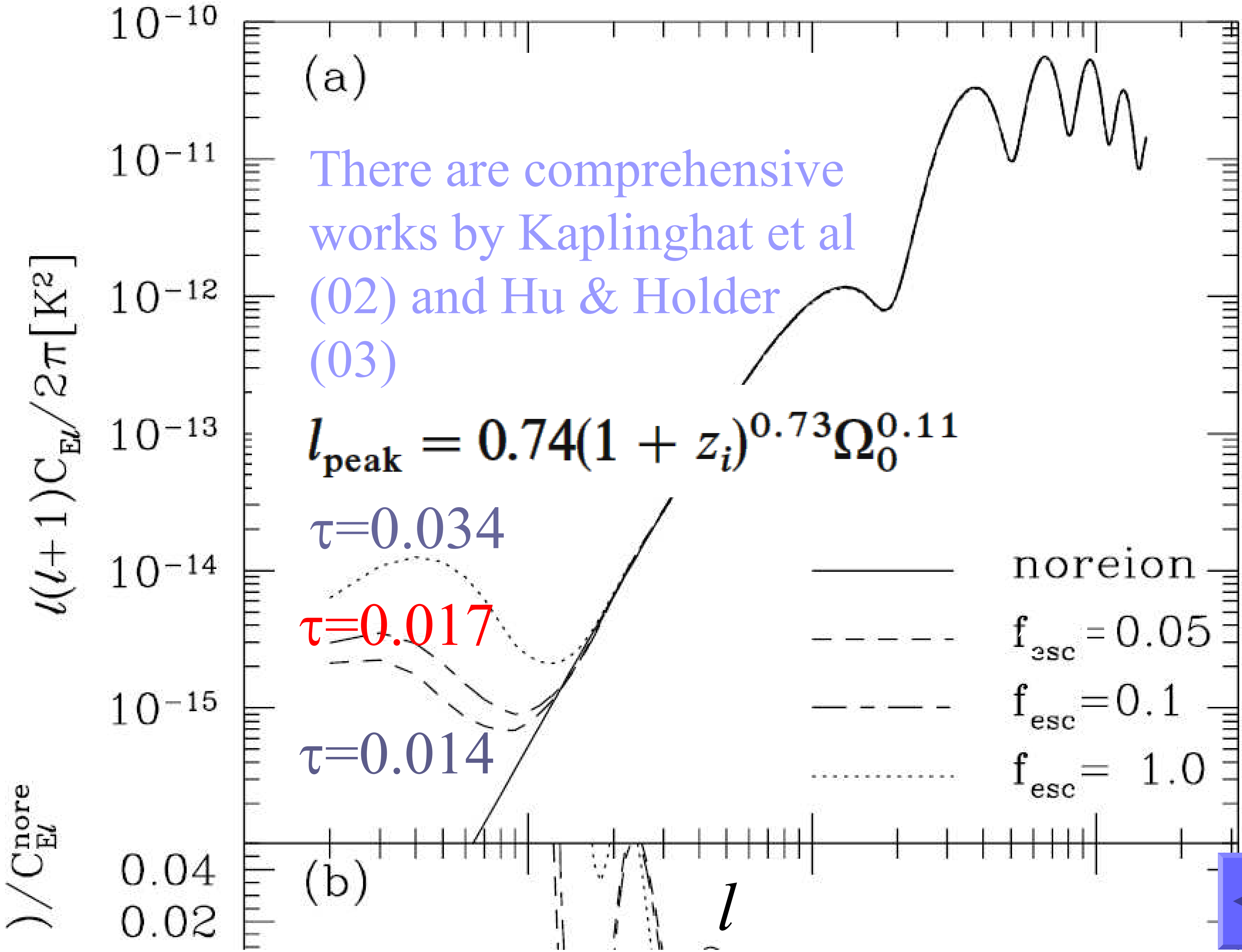
§ 2. How can we investigate reionization **by CMB?**

- 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(OVE)

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 $\tau=0.24$, $z=21.5$

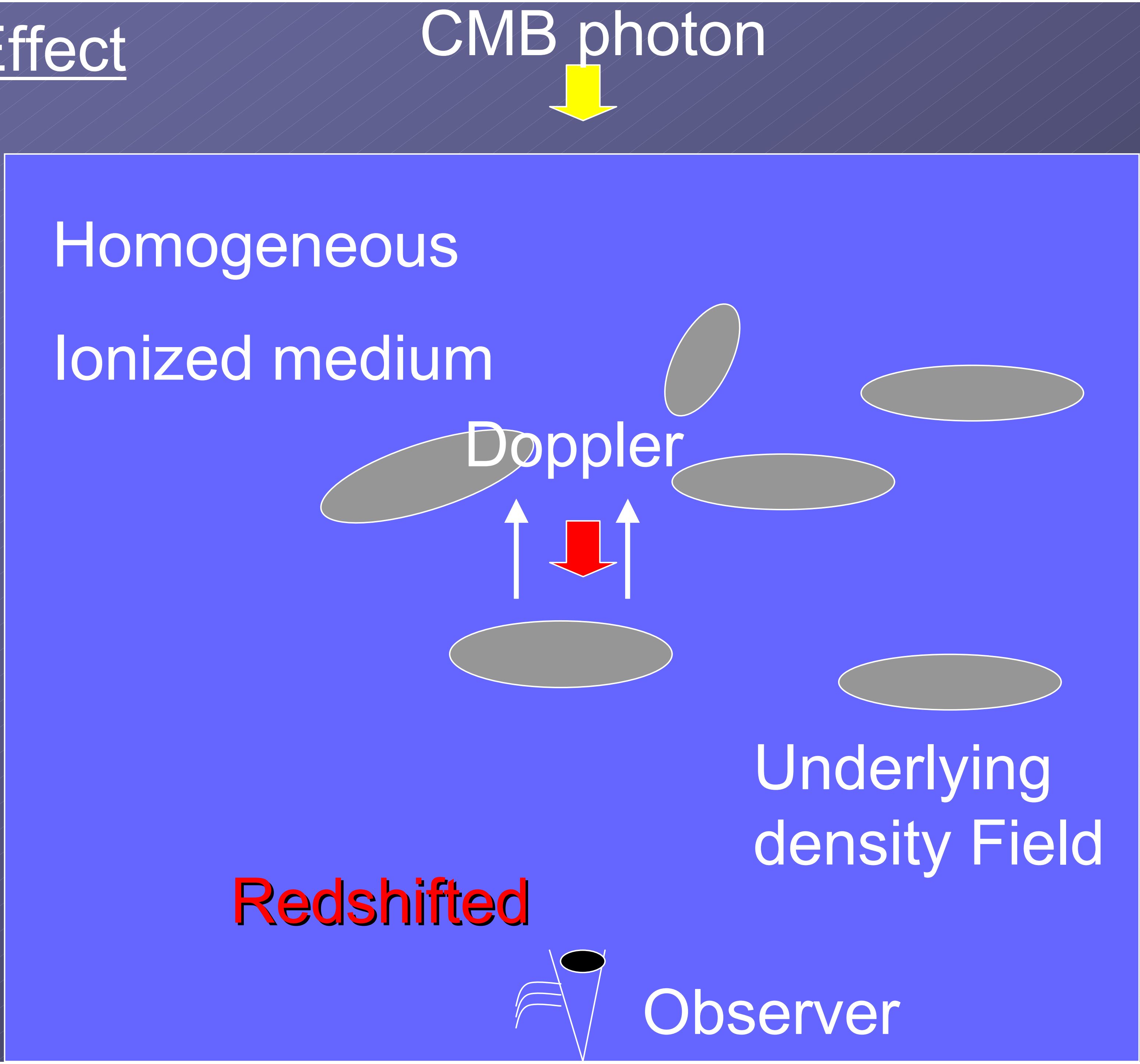
(3) The largest power law index $n=1.03$

(4) The largest small scale power

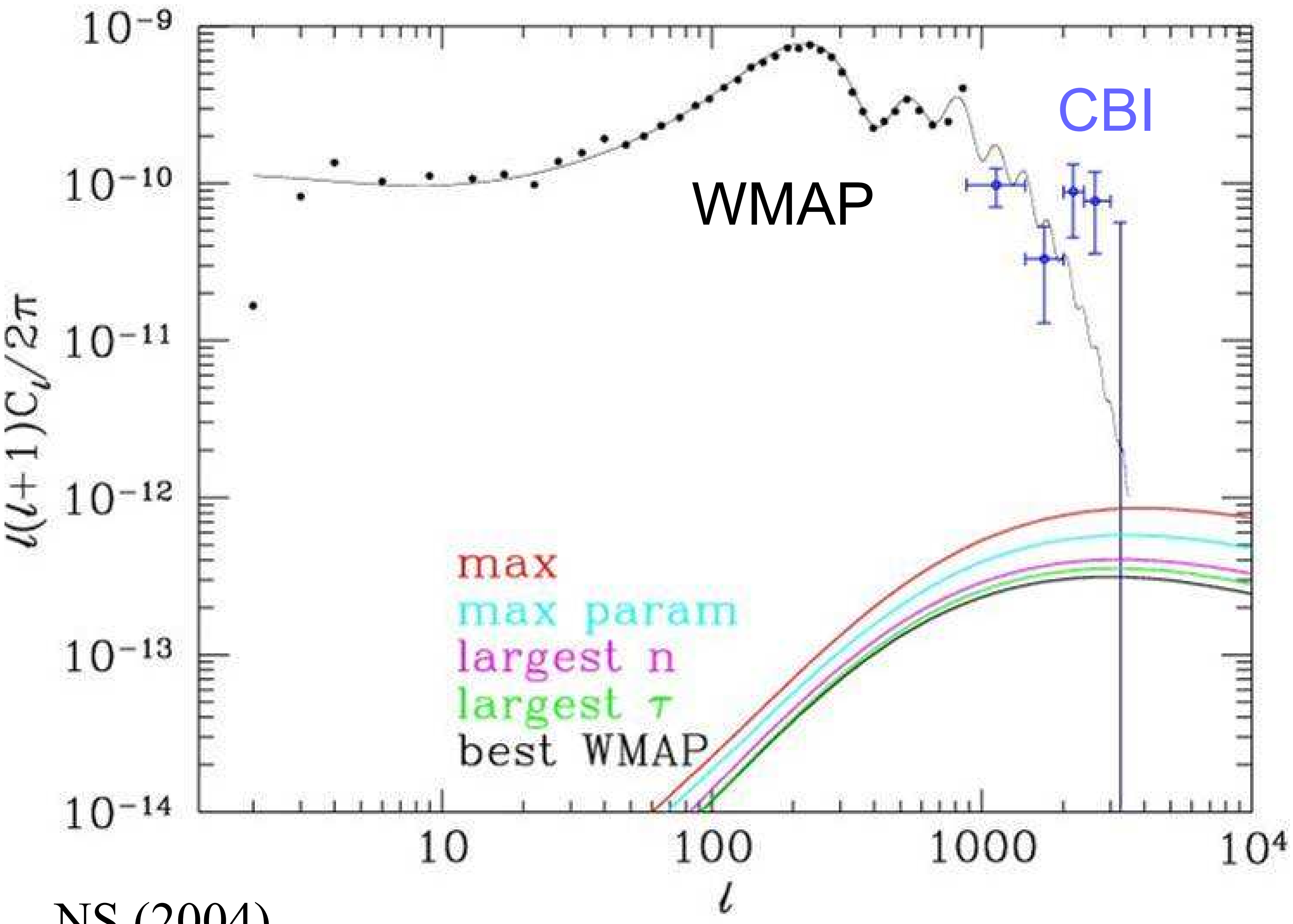
- Largest $\Omega_M h=0.23$, smaller $\Omega_B h^2=0.023$, $h=0.67$

(5) The largest OV effect

OV Effect



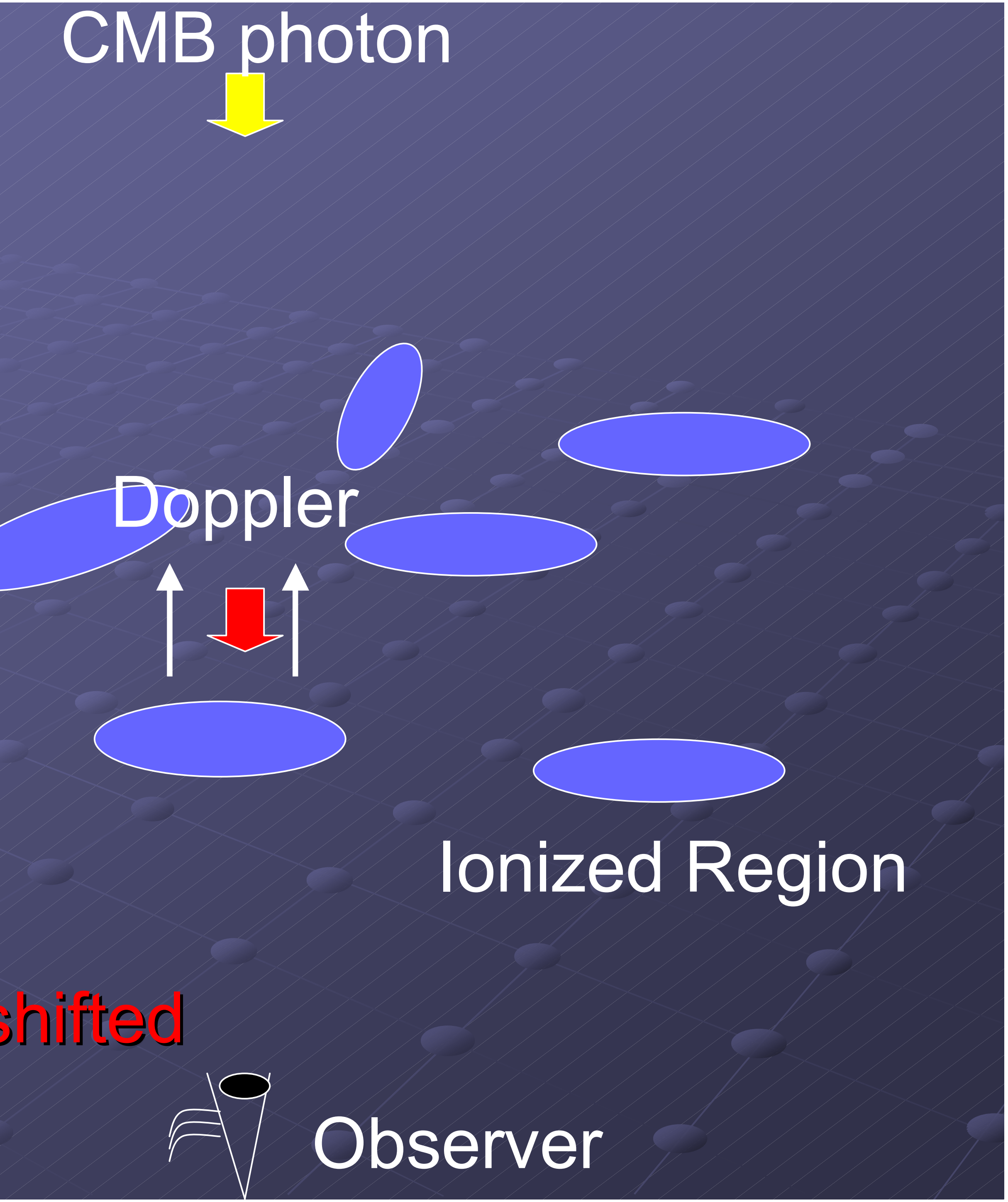
CMB photon
Homogeneous
Ionized medium
Doppler
Underlying
density Field
Redshifted
Observer



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

NS (2004)

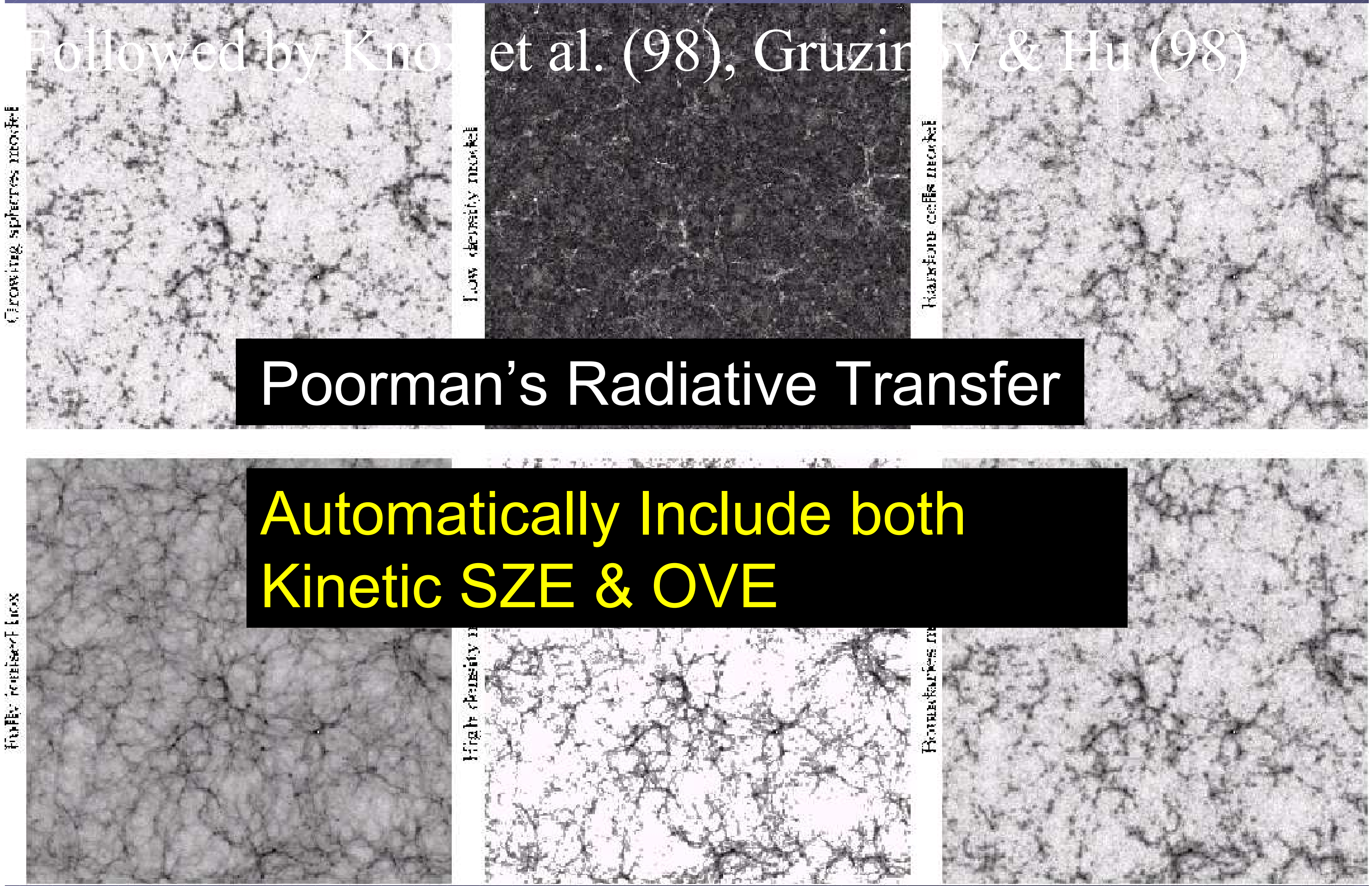
Kinetic SZ Effect



Pioneering works by; Aghanim et al. (96)

A:Growing sphere C:Low density D:Random cells

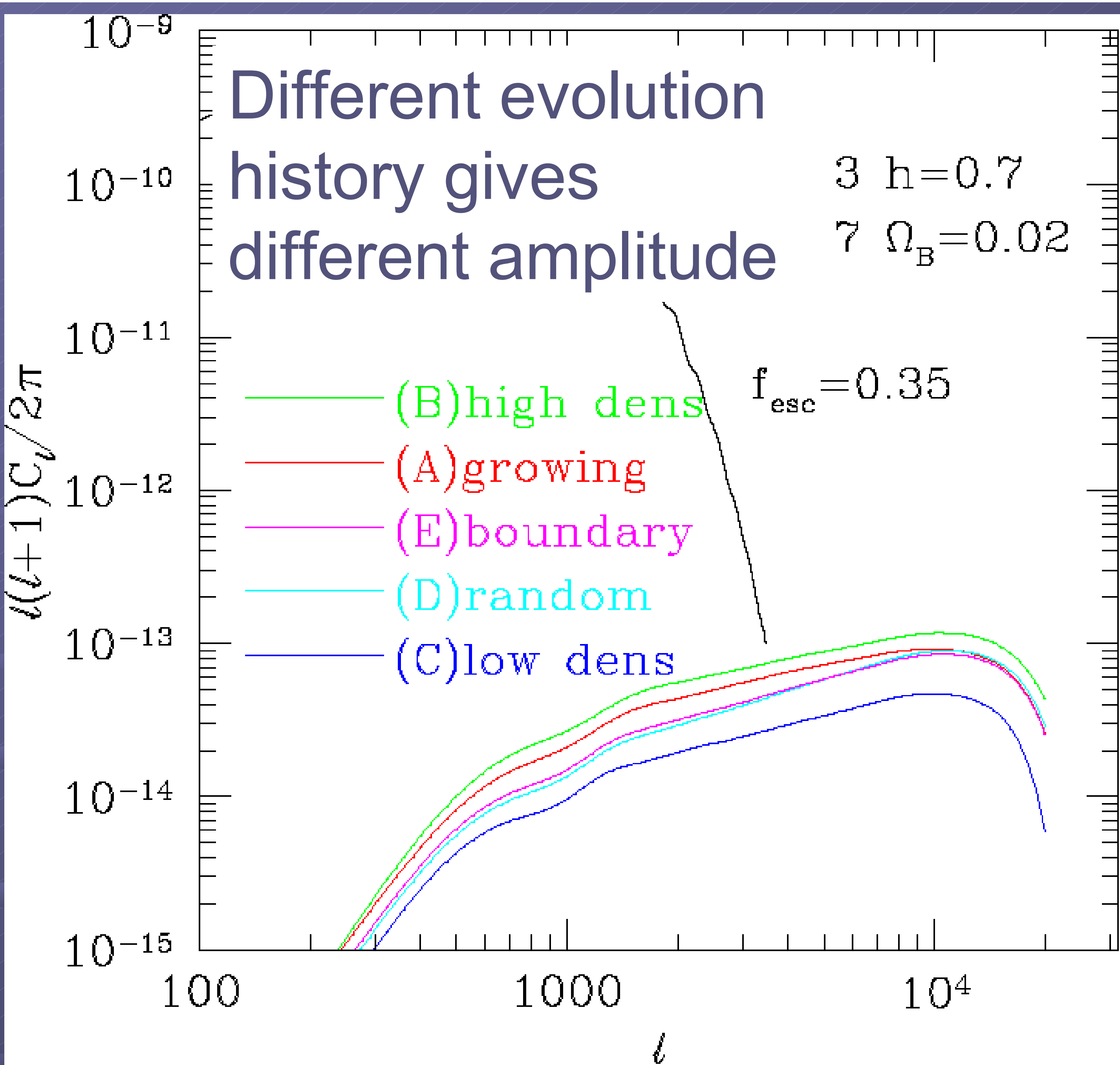
Followed by Knox et al. (98), Gruzinov & Hu (98)



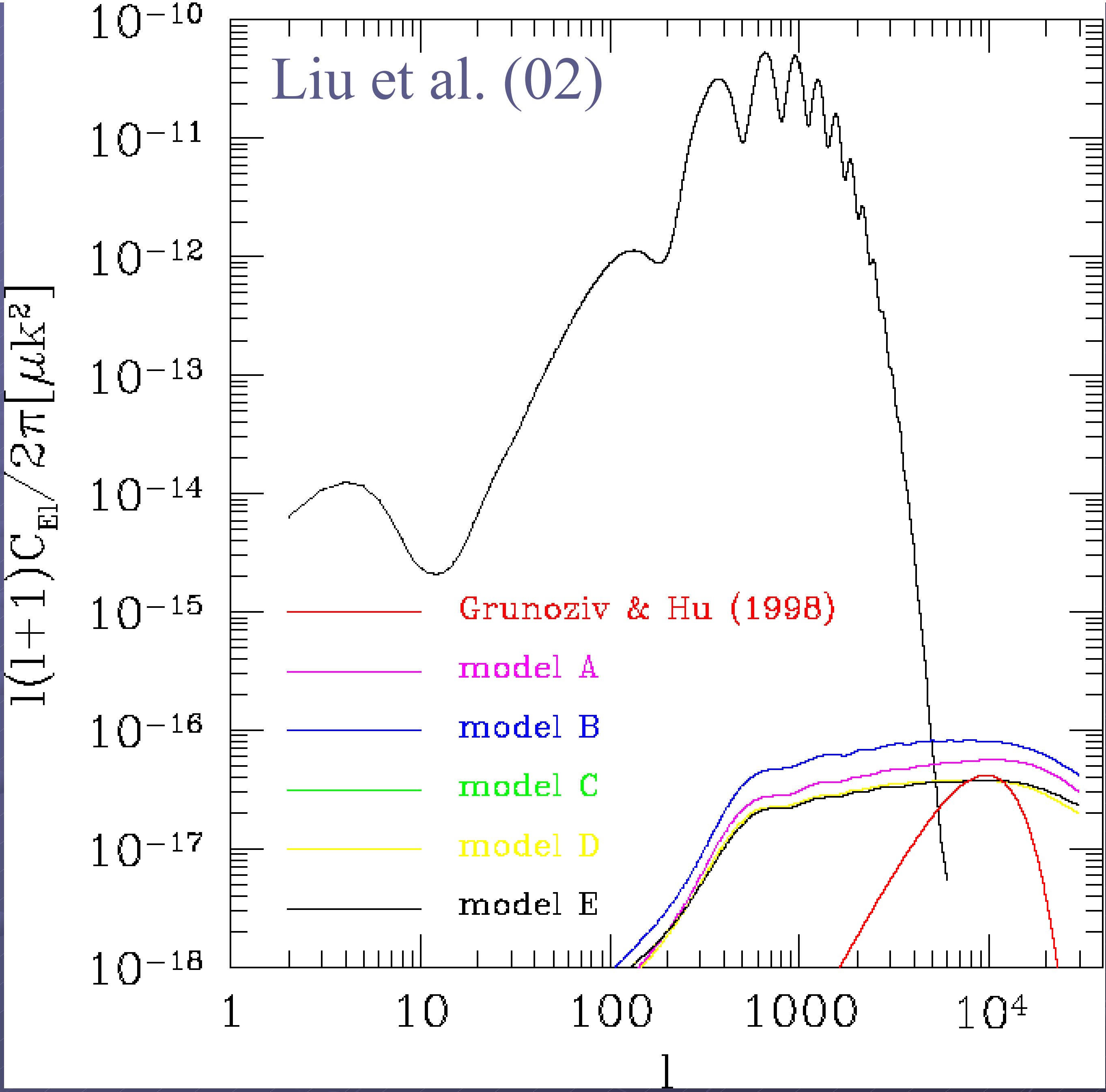
Poorman's Radiative Transfer

Automatically Include both Kinetic SZE & OVE

Density Field B:High density E:Boundary



Dependence on distribution of ionized region



Ionized region dependence

§ 3. Some Attempts of Early Reioniz.

- 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!**

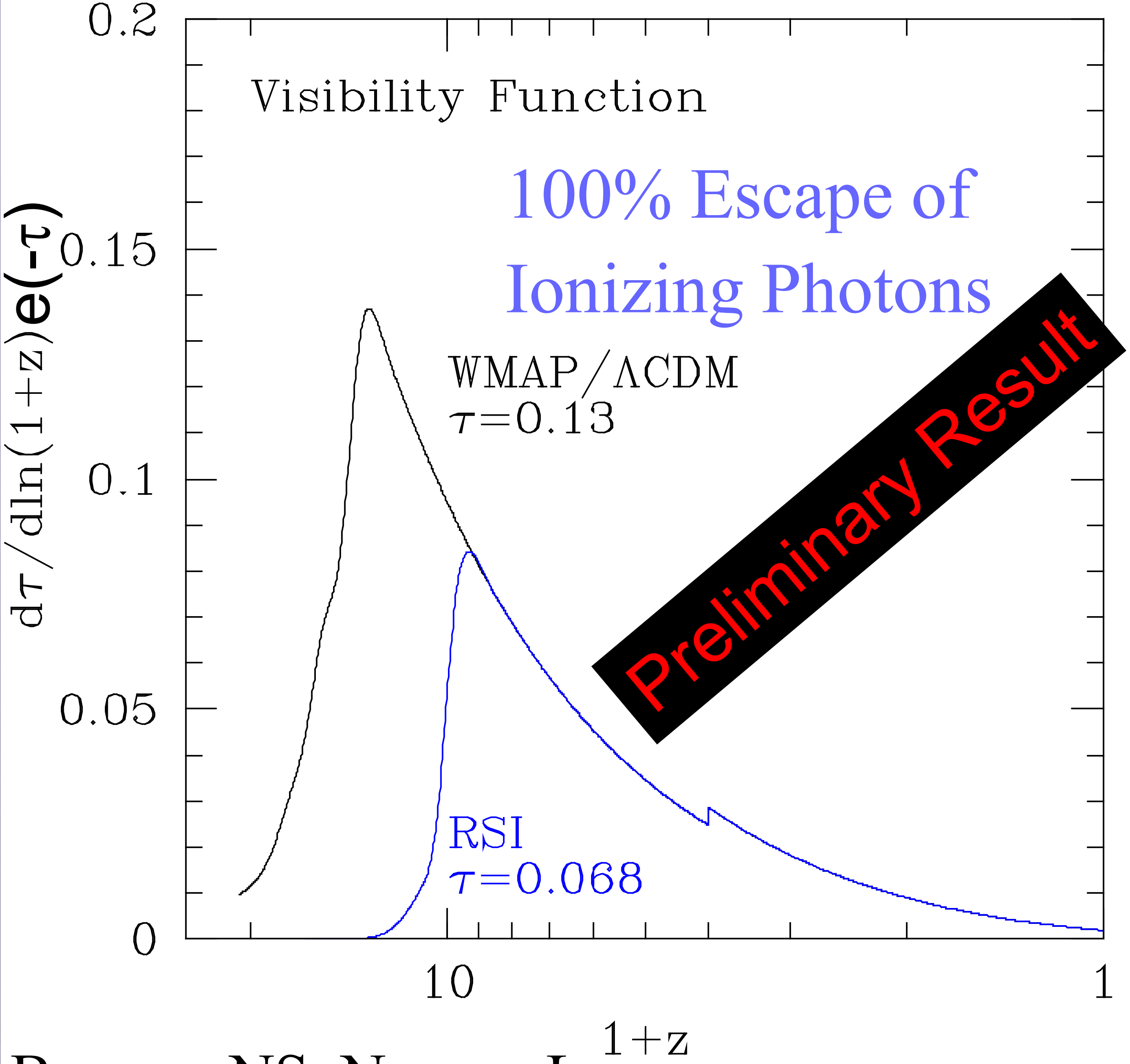
    ⇒ How is CMB affected?

Mimi-QSOs,

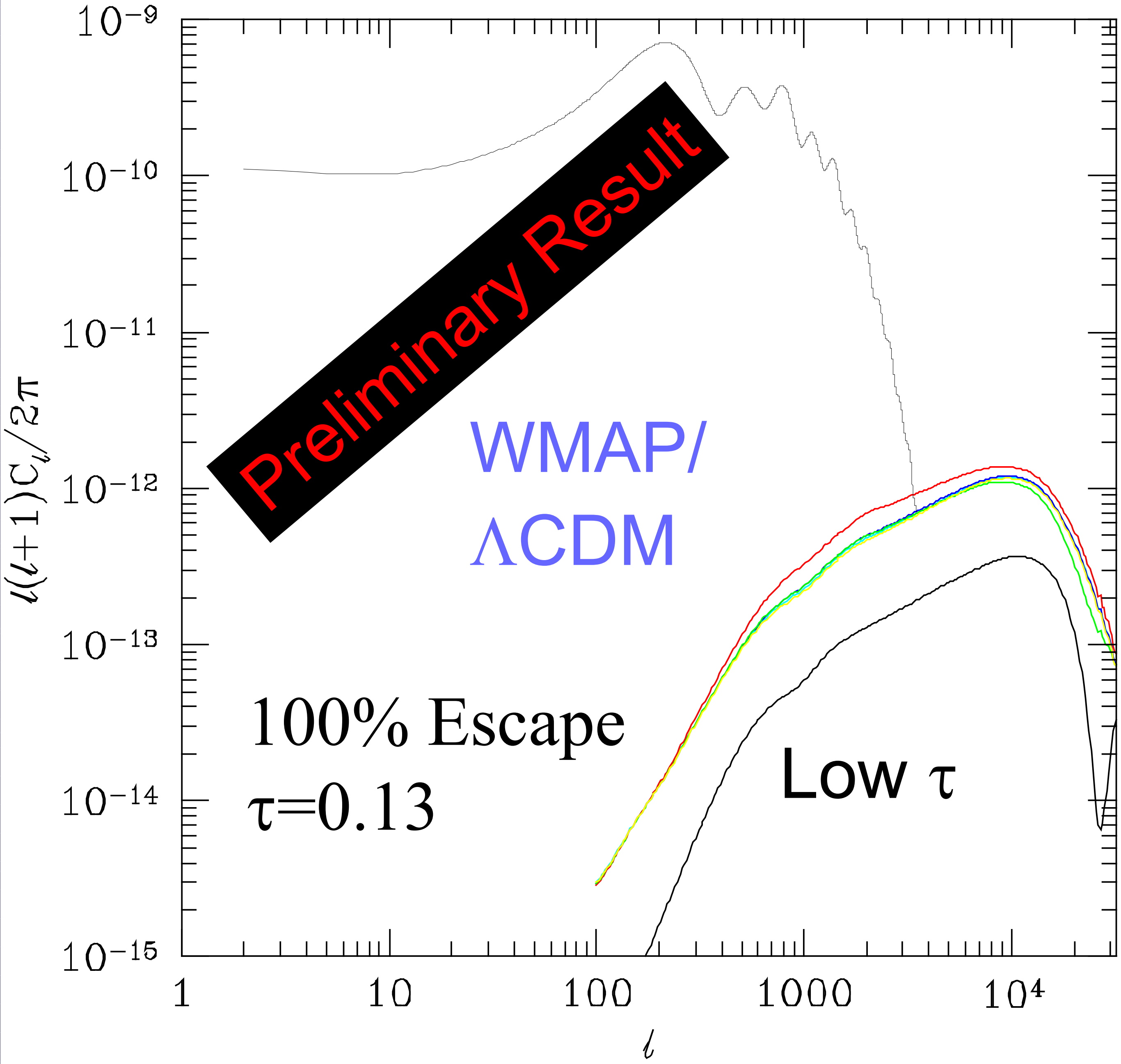
- Exotic Possibilities
  - CDM with isocurvature power spectrum

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

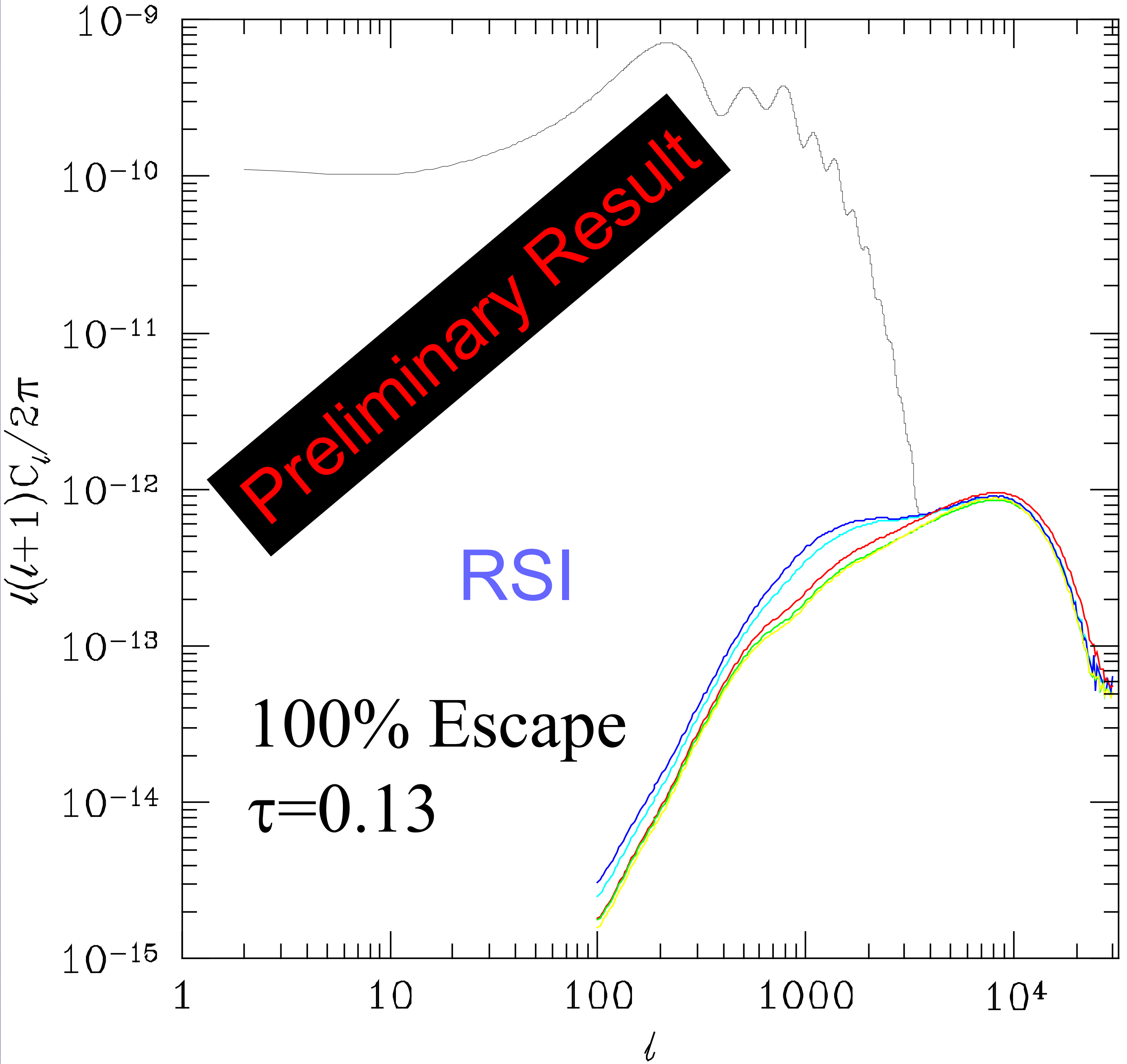
    Induce early structure formation
  - CDM with decaying particles
    - Radiation from the particles can reionize the universe



Benson, NS, Nusser, Lacey:



Benson, NS, Nusser, Lacey



Benson, NS, Nusser, Lacey

CDM adiabatic +Isocurvature modes

with Zaroubi, Silk

Requirements:

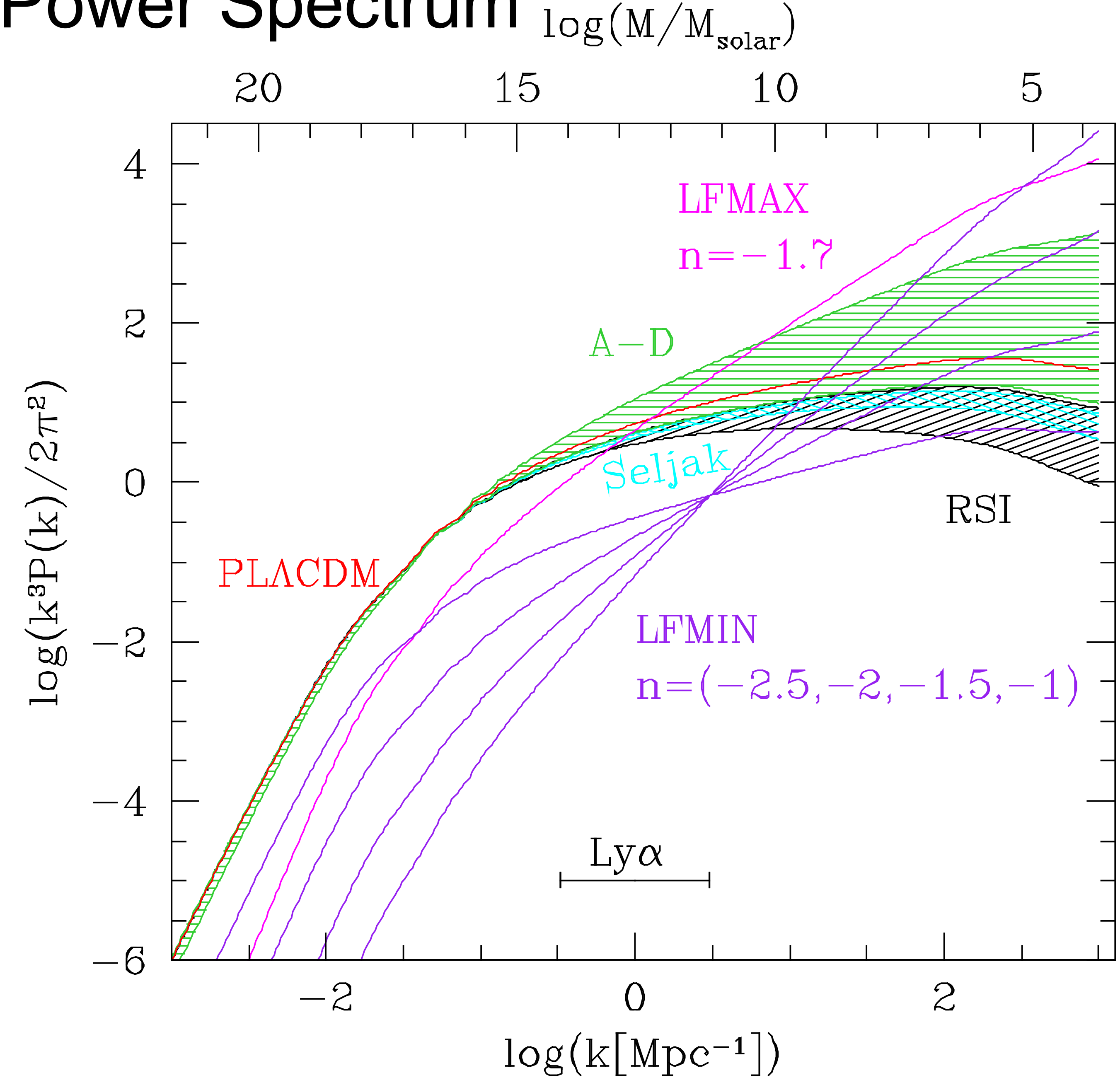
- To be consistent with Ly-alpha forest power spectrum
- Early enough reionization

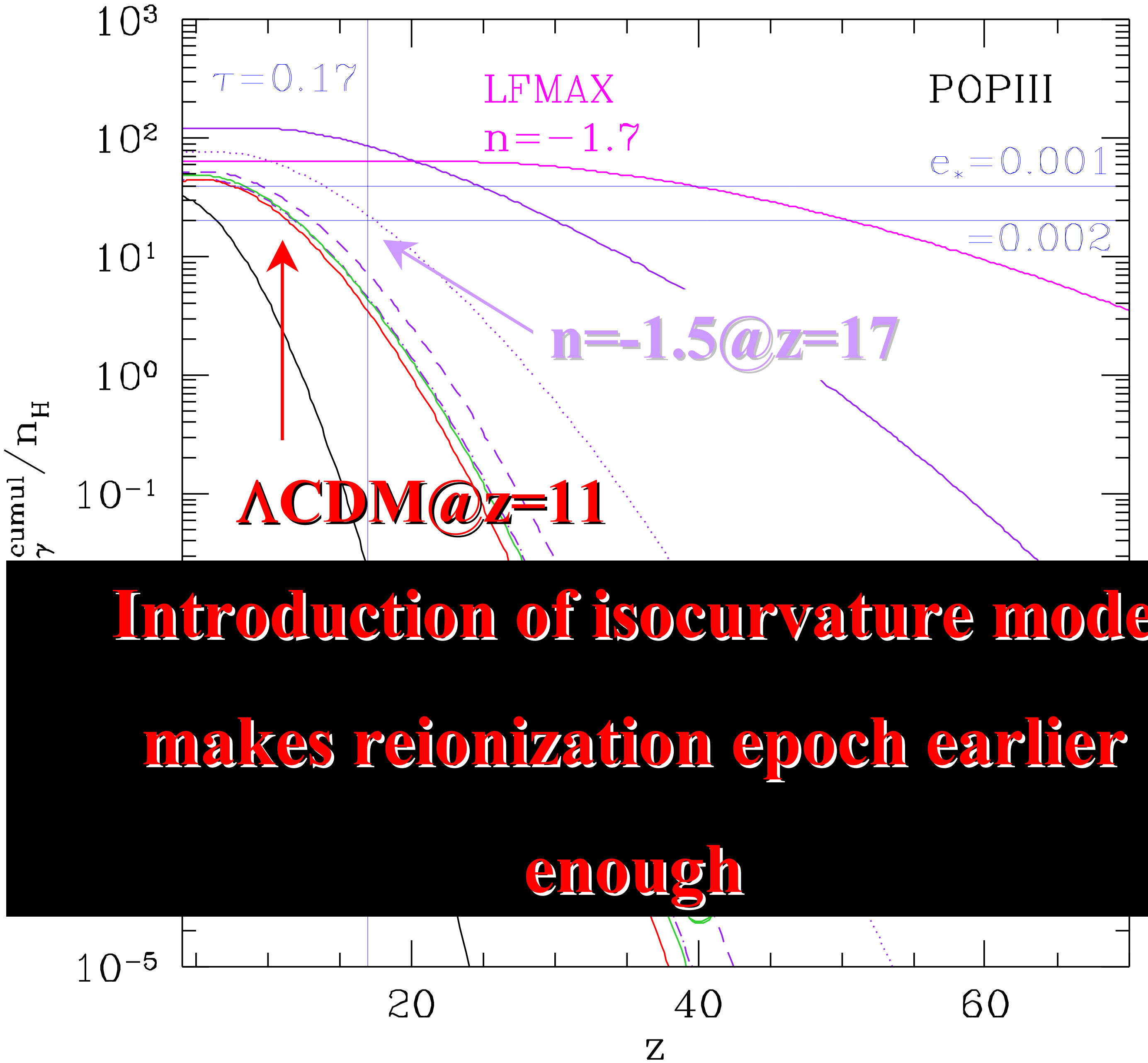
Plotted here are n_γ/n_H: translate into lionization fraction, need to be divided by $f_{esc}f_{ion}/C_{clump}$~10 to 20

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…?

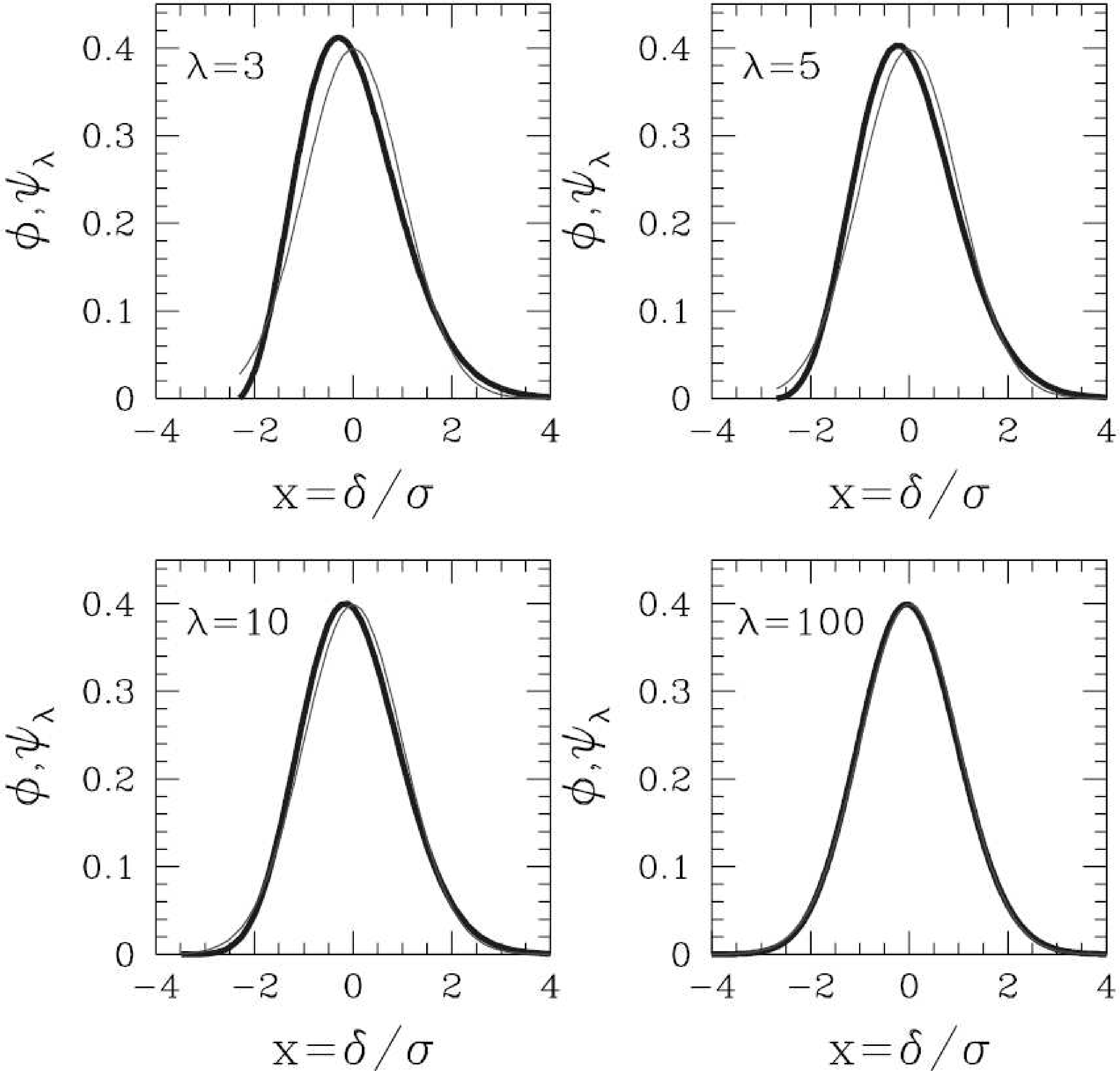
$$\psi(x) = 2A \frac{\lambda^{\sqrt{\lambda}x+\lambda+0.5} e^{-\lambda}}{\Gamma(\sqrt{\lambda}x+\lambda+1)},$$

$\lambda \to \infty$: Gaussian

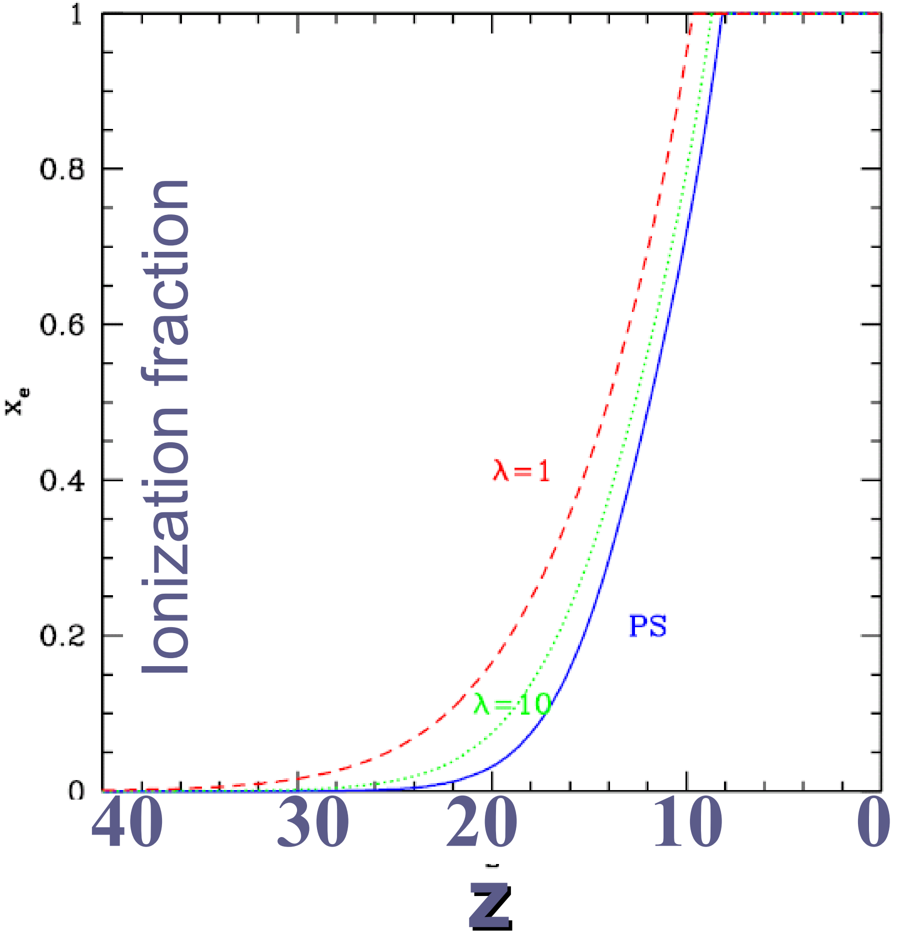
$\psi(x) = 2A\exp(-x^2/2)$

Willick (00)

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



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



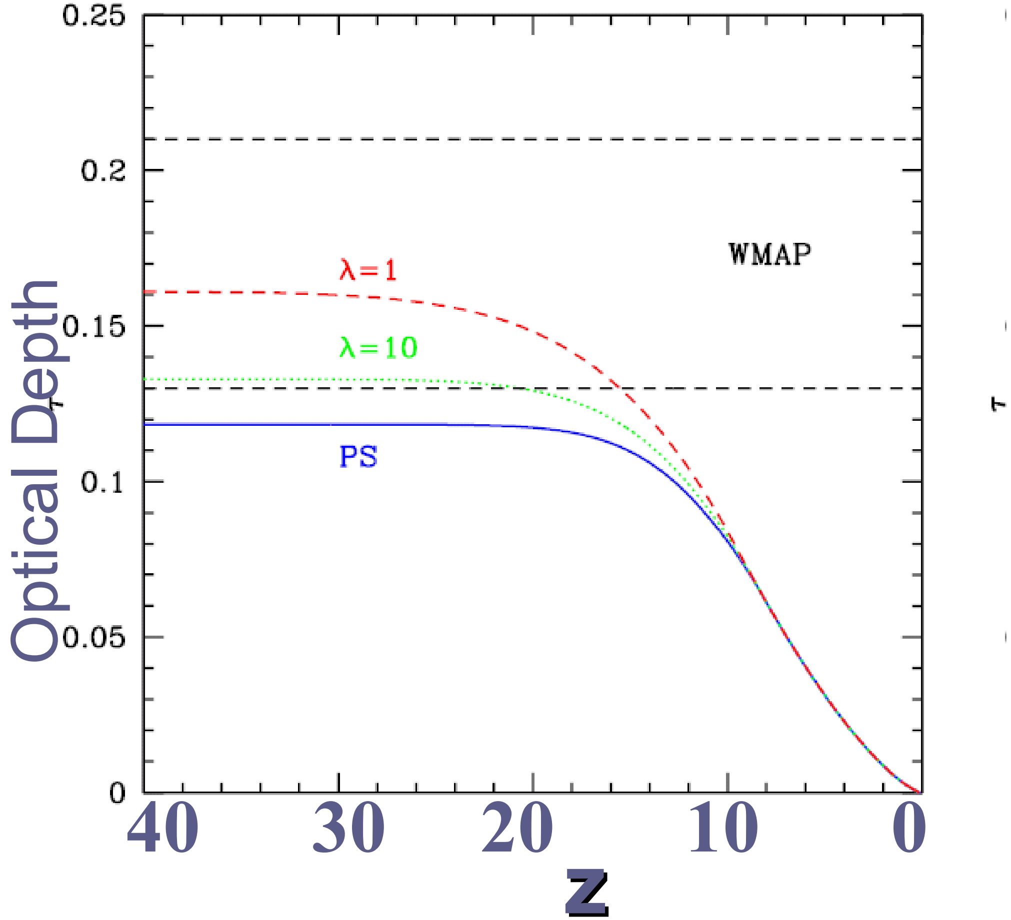


Figure 2. *Left:* The volume ionized fraction, $x_e(z) \equiv F_{\rm HII}(z)$ as a function of redshift. *Middle.*
scattering. The models are based on "ordinary" star-formation in Type I halos only. The Press-S
depth with a value of 0.097 while the non-Gaussian mass functions lead to values of 0.11 and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

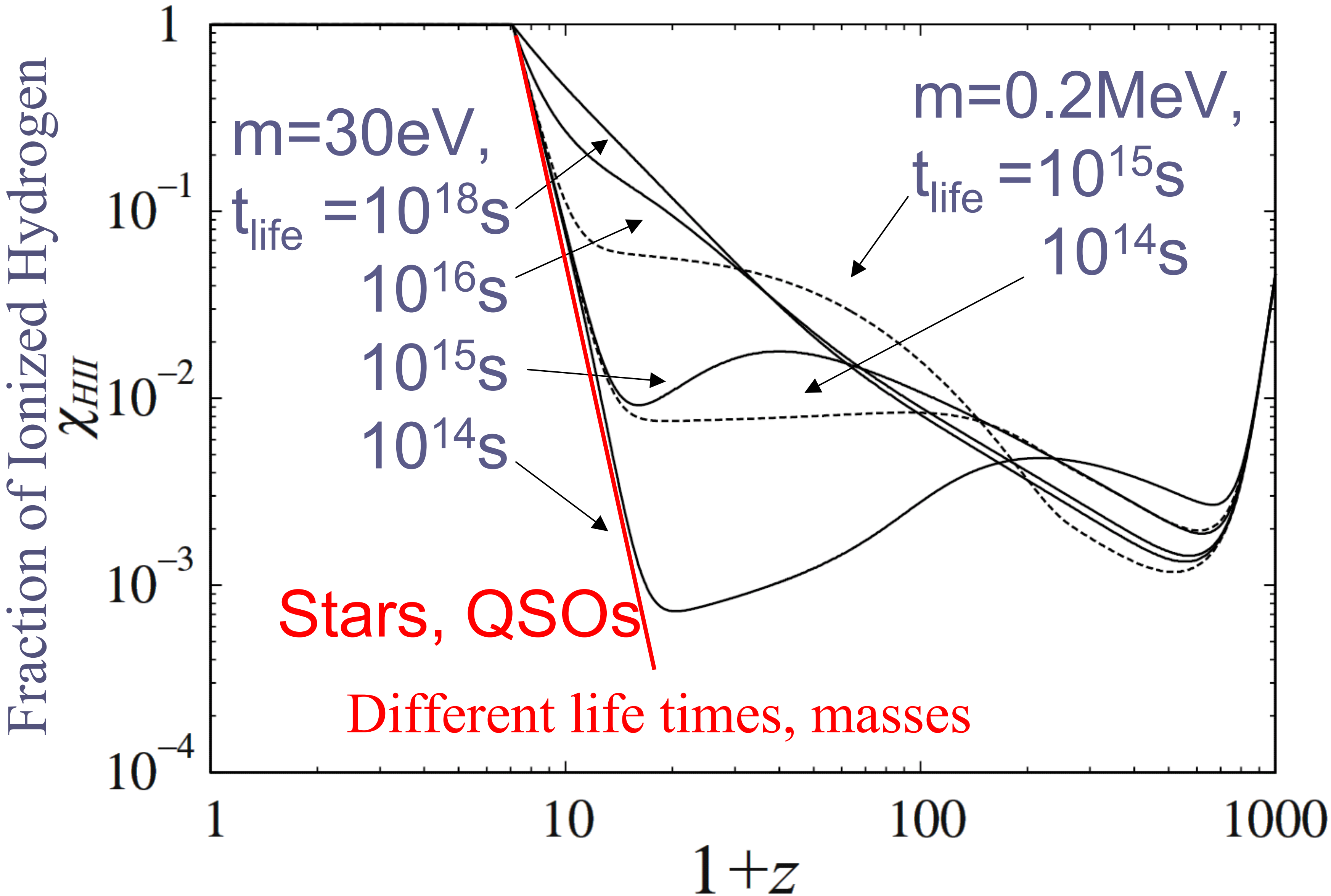


FIG. 1: Ionization histories of hydrogen (HII). We plot for $E_{\gamma} = 15$ eV for $\tau_{\phi} = 10^{14}$, 10^{15}, 10^{16}, and 10^{18} sec in solid

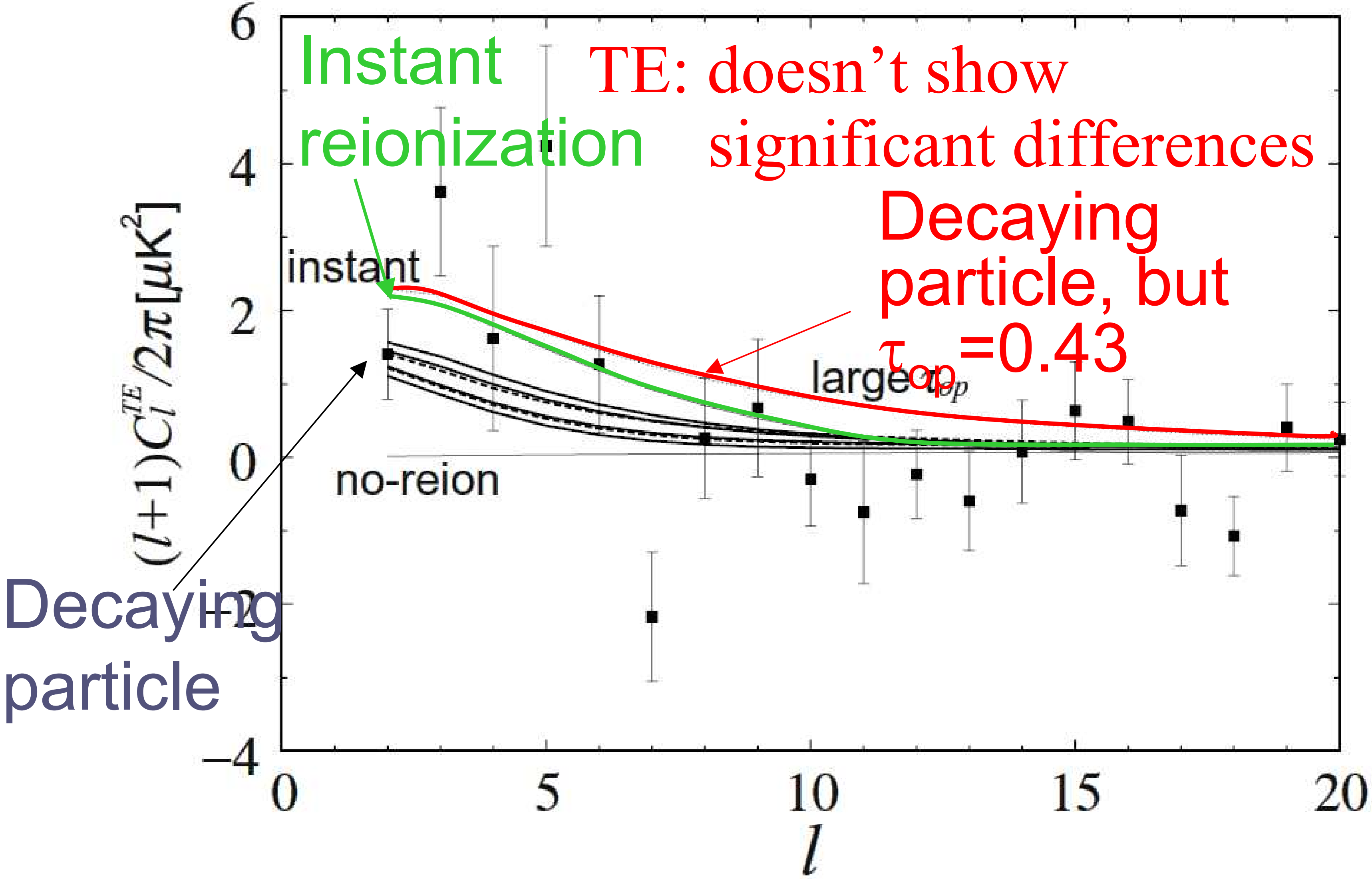


FIG. 5: TE spectrum for various ionization histories. We plot for $E = 15$ eV for $\tau_d = 10^{14}, 10^{15}, 10^{16}$ and 10^{18}

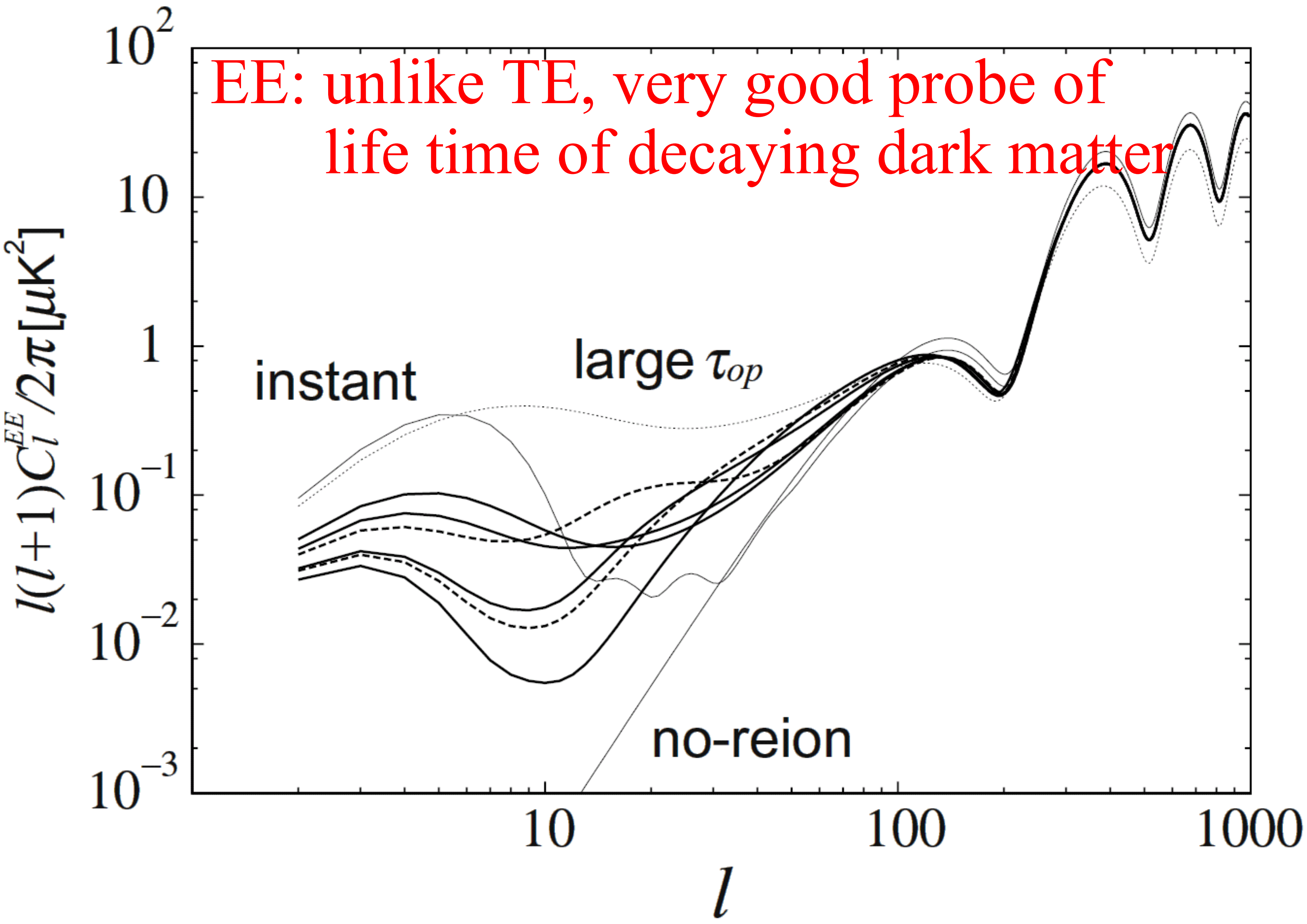


FIG. 6: EE spectrum for various ionization histories. We

Reionization

- To get τ=0.17, we need
  - Top heavy IMF, High Escape Fraction of Ionizing Photons, or Something Exotic

Physics are there

  - EE Spectrum by WMAP, PLANCK and more

CMB Shines the Dark Ages

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