Feedback During Early Reionization and the Shapes of Quasar HII Regions

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Jun Zhang, Shiv Sethi
Greg Bryan, Lam Hui

Outline of Talk

1. Feedback During Early Stages of Reionization

   Andrei Mesinger, Roban Kramer, Greg Bryan

2. Diagnostics of Stellar vs Quasar Reionization

   Shiv Sethi, Roban Kramer, Jun Zhang, Lam Hui

Conclusions

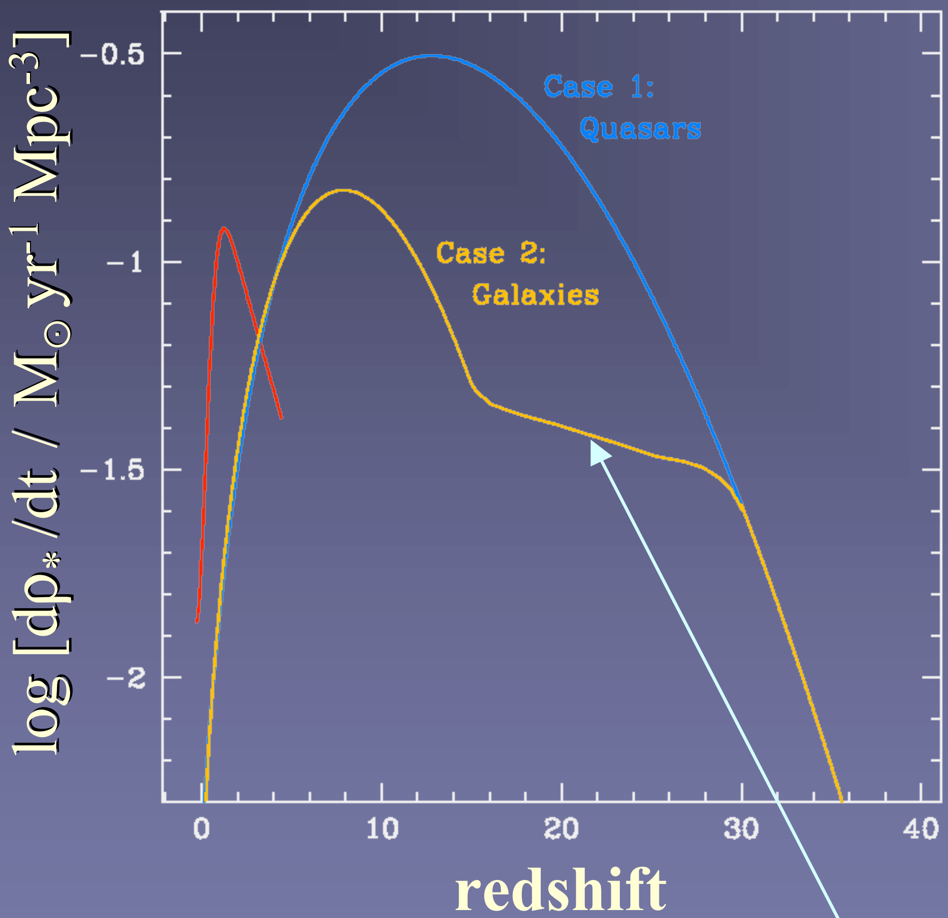
- WMAP τ_e~0.09 $\rightarrow$ mini-halos suppressed by factor of ~10
- **J(LW) $\gtrsim$ 0.01-0.001** and **J(UV) $\gtrsim$ 0.1** for negative feedback
- Clustering boosts feedback, helps to reduce τ_e

♣

- QSOs induce few % anisotropy in 21cm power spectrum
- QSO HII front thickness detectable in 21cm (not in Lyα,β ?)
- Large-scale 21cm power spectra $\rightarrow$ spectral hardness
- OI pumping $\rightarrow$ CMB distortion at ~600μm up to y~10^{-7}

SF/Reionization History Self-Regulates?

Haiman, Abel & Rees (2000)



Case 1 : No net feedback

- reionization completed early
- small halos
- closely spaced
- smooth
- He/H close in time

Case 2 : Negative feedback

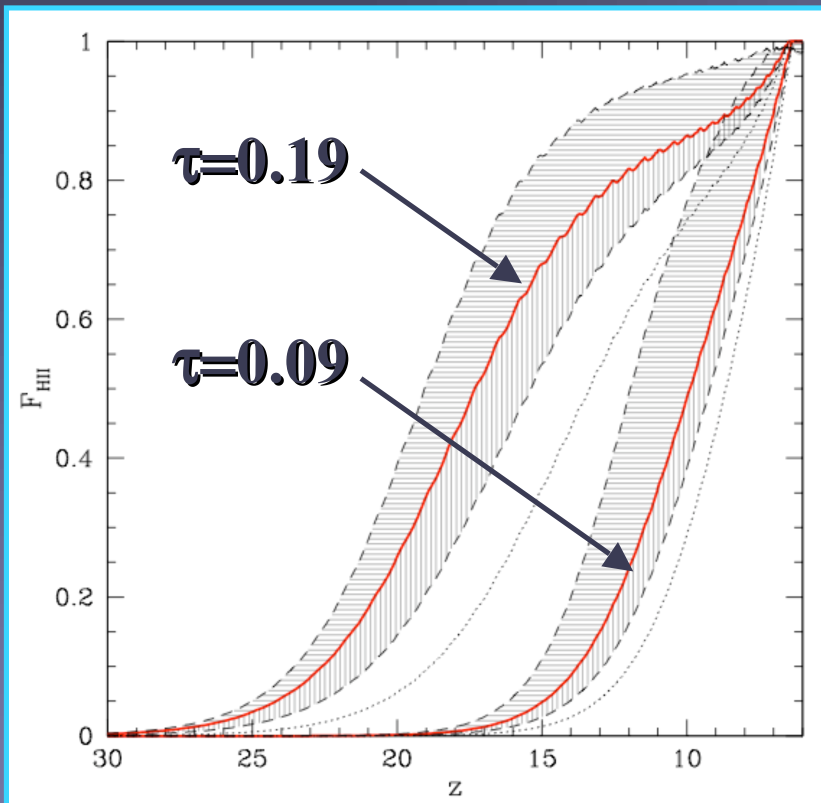
- reionization completed later
- larger halos,
- farther spaced
- more patchy
- He/H farther in time

IF feedback regulates reionization history, then there will be a period with a robust 'steady state' solution for the star formation history - need to know $J_{crit}(M_{halo},z)$

Evidence for Feedback from WMAP

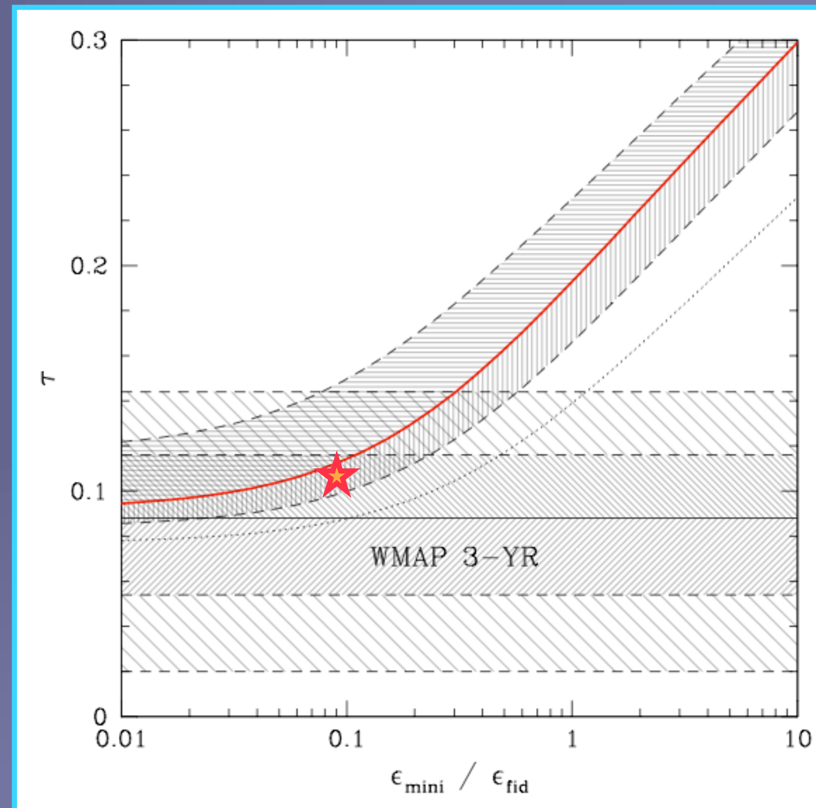
Haiman & Bryan (2006)

ionized volume fraction



redshift

Optical depth



efficiency

Minihalo contribution suppressed by a factor of ~10

Typical Early Halo Exposed To:

- **EARLY COSMIC BACKGROUNDS:**
  - soft UV (11-13.6 eV) photo-dissociates H_2
  - soft X-rays (~1 keV) catalyze H_2 formation
- **UV FLUX OF NEARBY SOURCES (>13.6 eV):**
  - photo-evaporation (minihalos with $\sigma < 10$ km/s)
  - photo-dilution (halos with 10 km/s $< \sigma <$ 50 km/s)
- **PAST ACTIVITY IN FOSSIL HII REGION:**
  - gas retains heat ("entropy floor")
  - extra free electrons from incomplete recombination

OTHER EFFECTS:

- SN blast waves, metal pollution (pop III $\rightarrow$ pop II)
- Internal feedback inside the mini-galaxies

Do most minihalos fail to form stars or black holes?

Simulating the Combined Effects

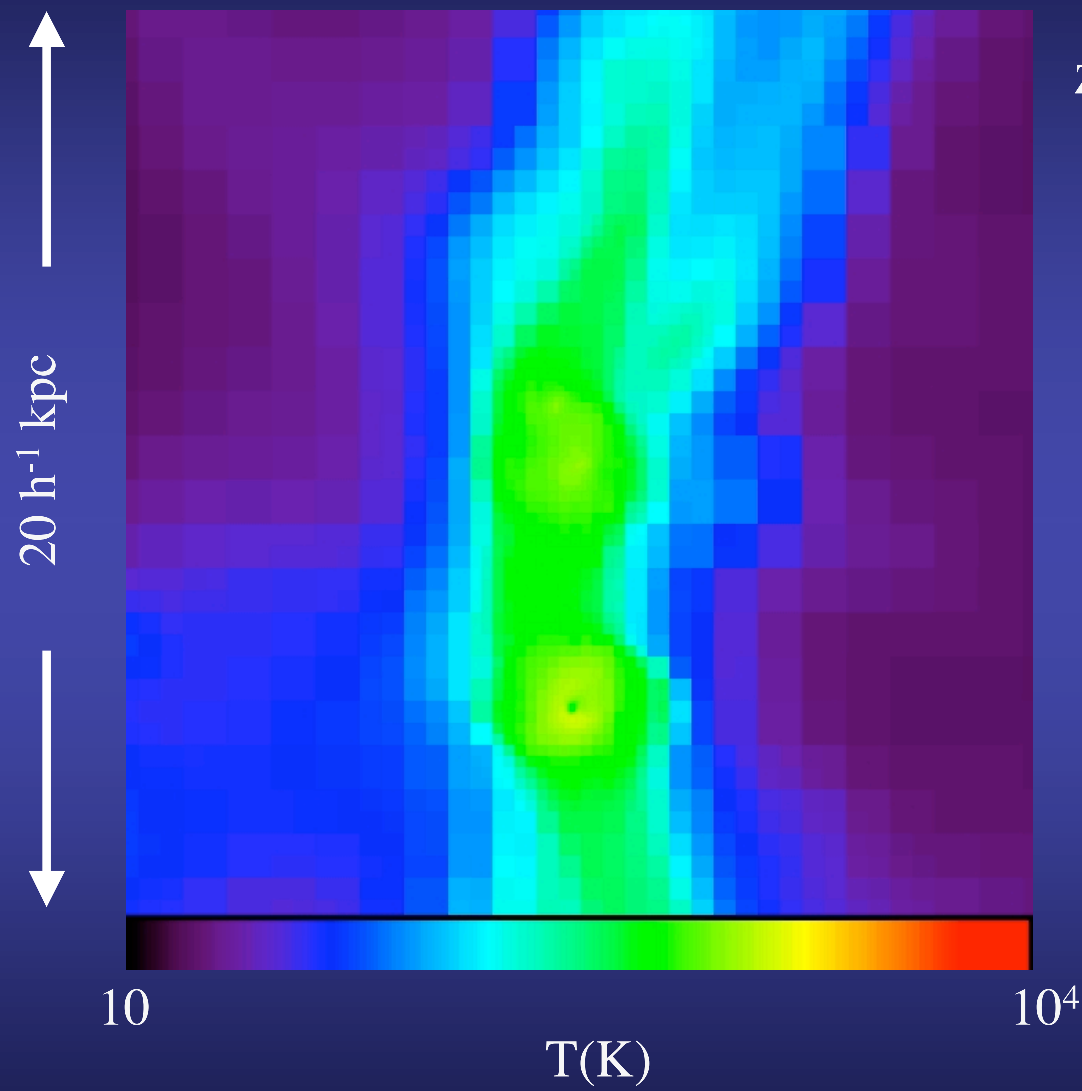
Mesinger, Bryan & Haiman (2006)

- **AMR Simulations with Enzo**
  - $(1\ h^{-1}\ \mathrm{Mpc})^3$, 128^3 root grid, run from z=99 to z=18
  - re-simulate inner $(0.25\ h^{-1}\ \mathrm{Mpc})^3$
  - 10 levels of refinement - 0.36 h^{-1} pc resolution at z=20
  - biased (2.4σ) region, yields several hundred DM halos in mass range of $10^5 M_\odot < M < 10^7 M_\odot$

- **Examine Effects of Transient Photoheating**
  - J(UV) = 0 (test run)
  - Flash ionization **(c.f. O'Shea et al. 2006)**
  - J(UV) = 0.08 or 0.8 on at z=25 for $\Delta t = 3\times10^6$ yr (opt.thin)

- **Examine Effect of adding LW background**
  - $10^{-3} < J(LW) < 10^{-1}$ added to J(UV)=0.8 run

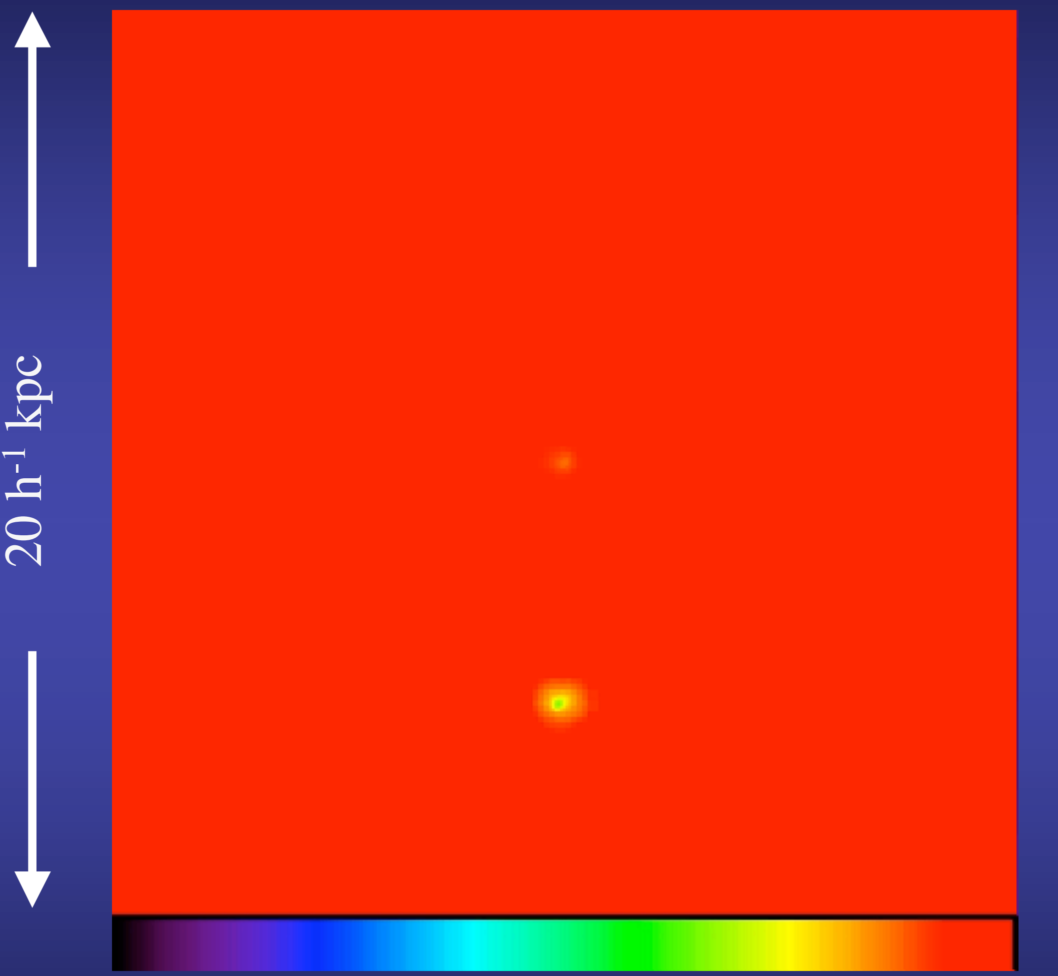
Gas Temperature



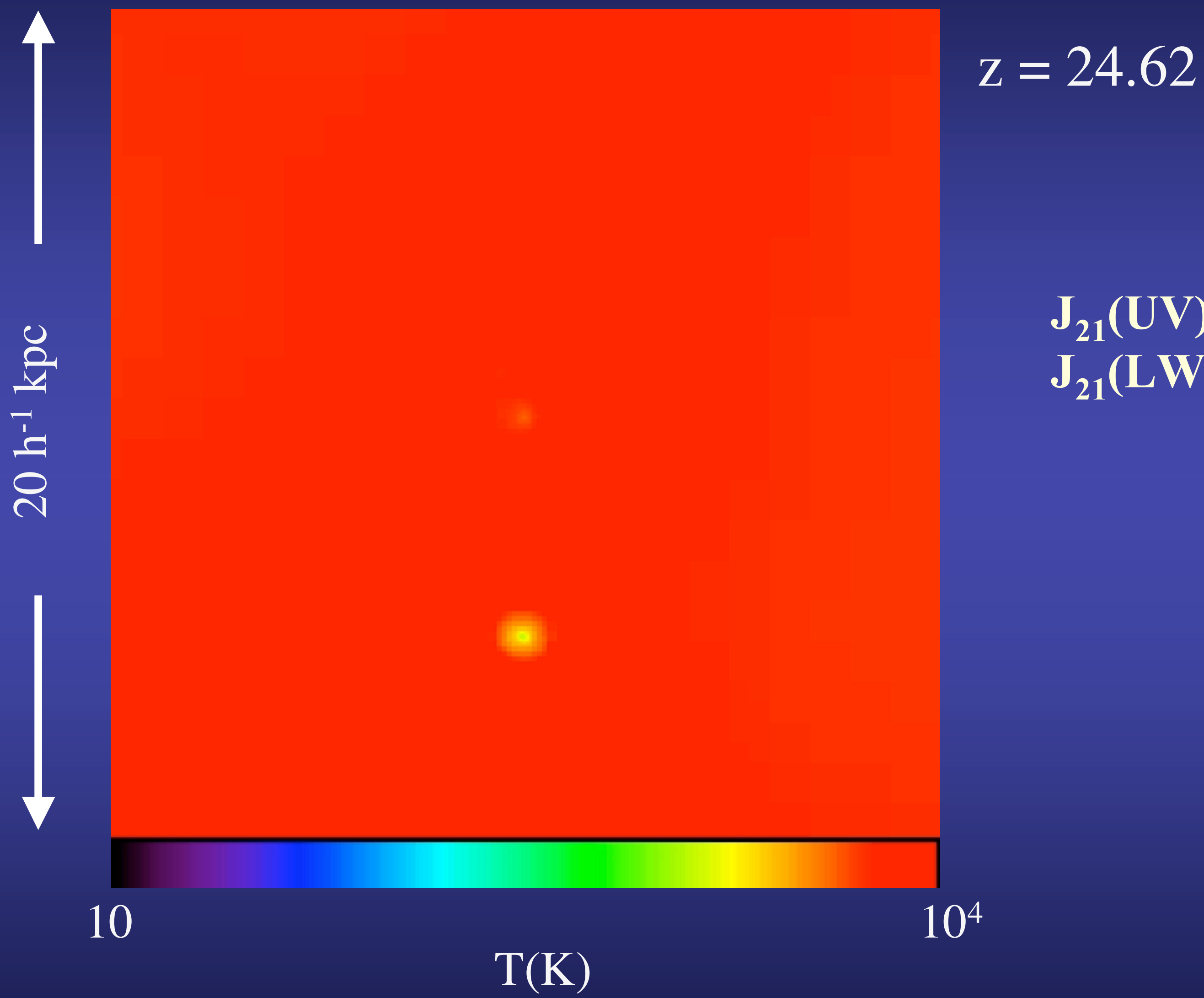
z = 25

J_{21}(UV)= 0.08
J_{21}(LW)= 0

Gas Temperature



Gas Temperature



J_{21}(UV)= 0.08
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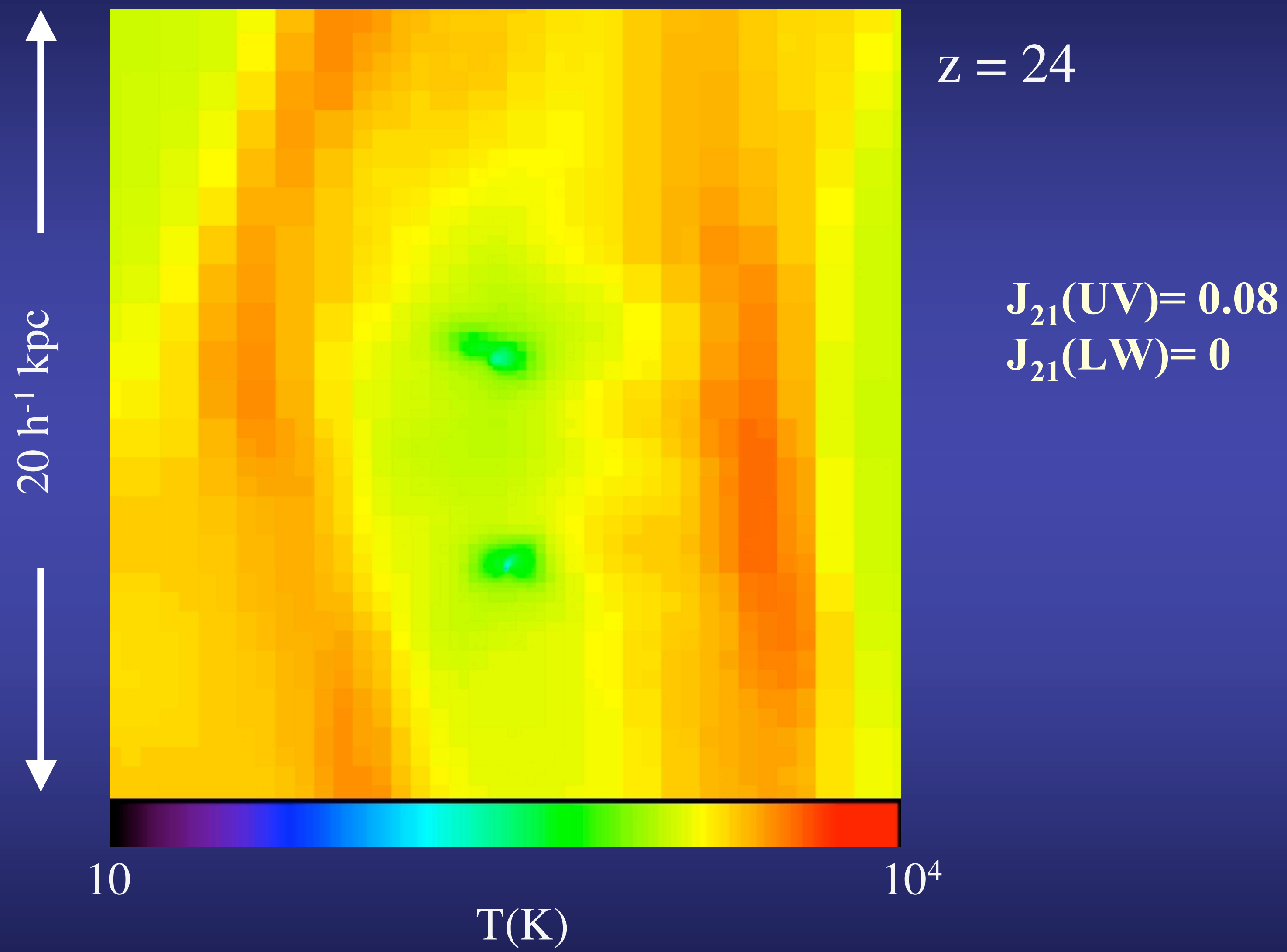
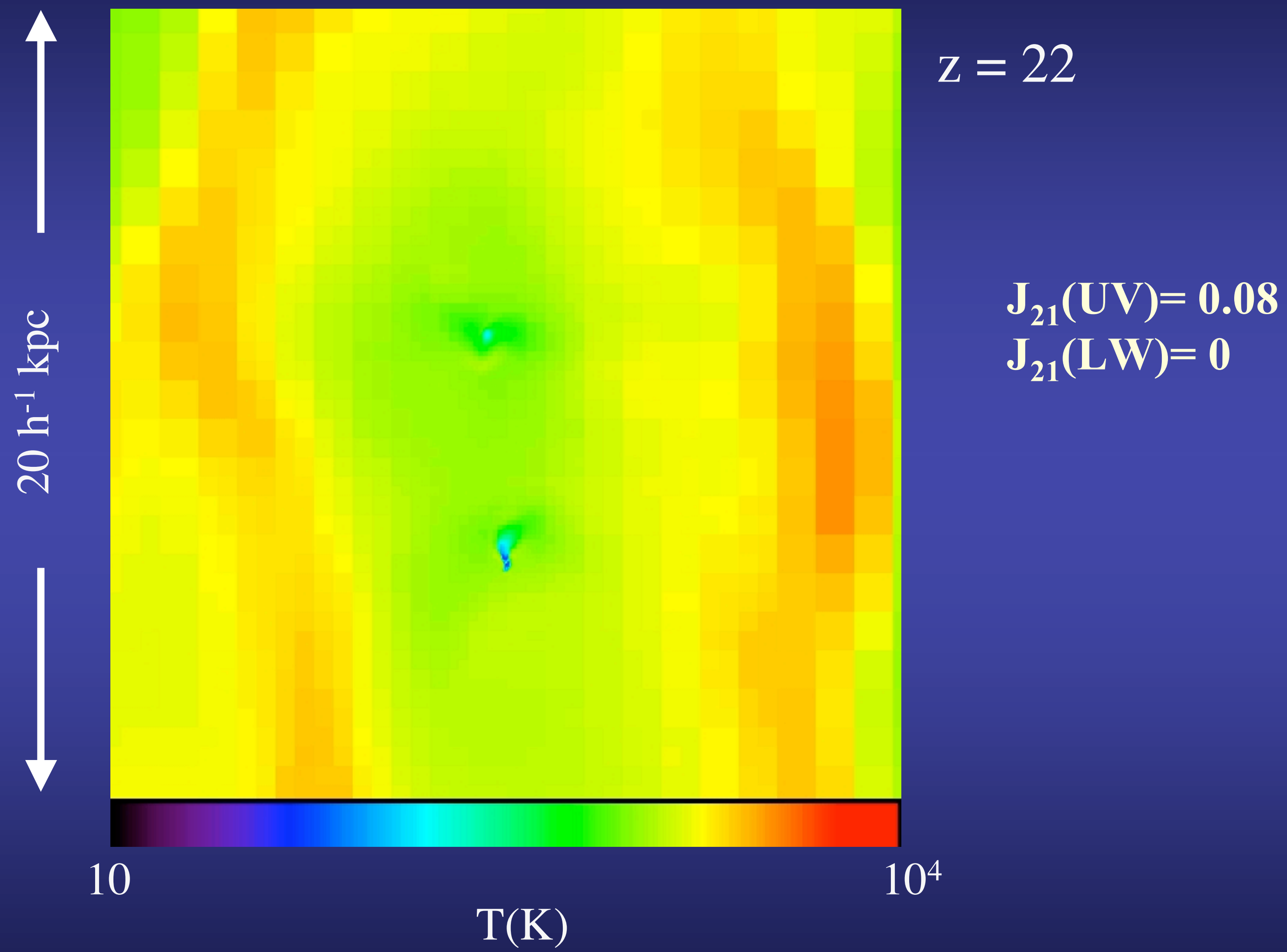
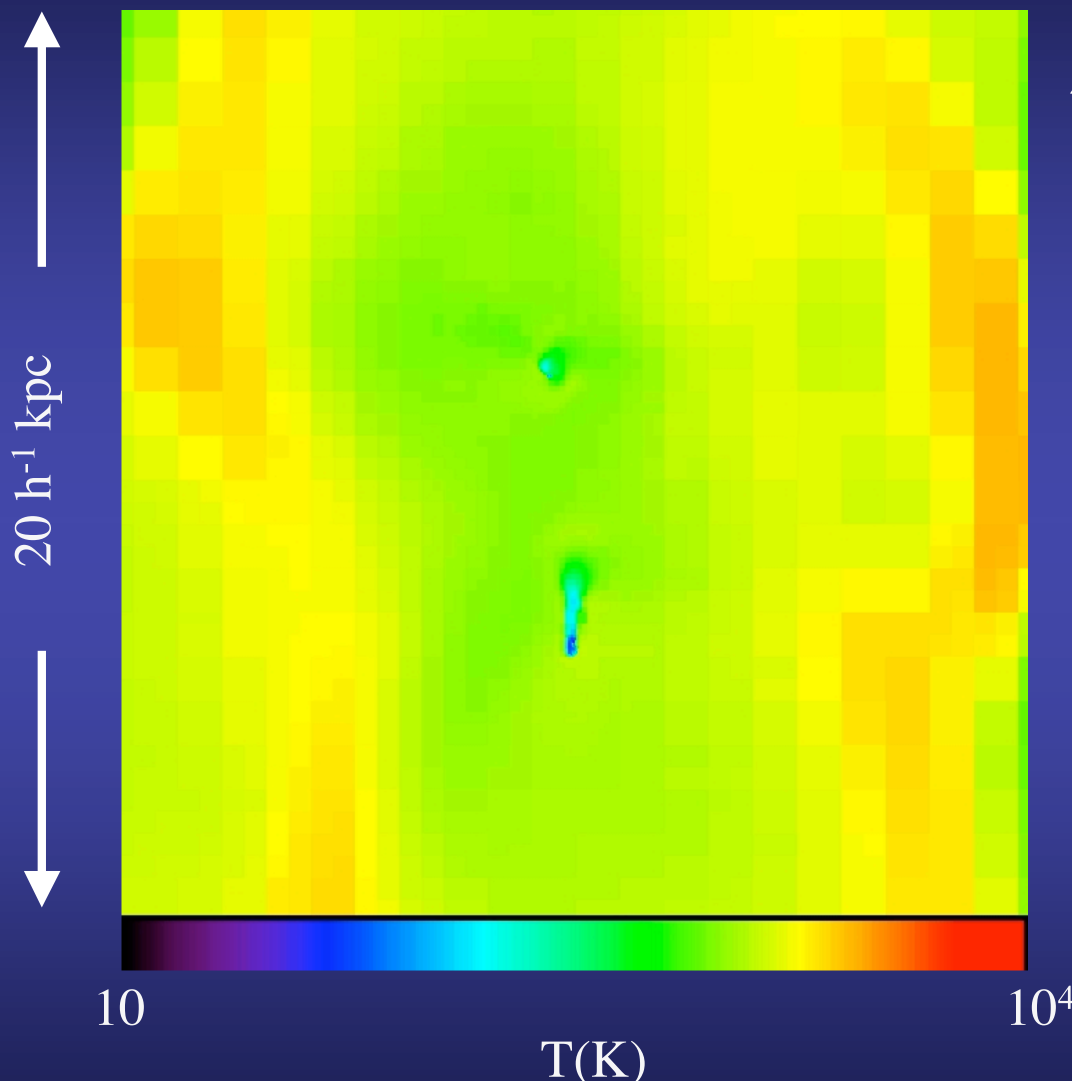


Gas Temperature



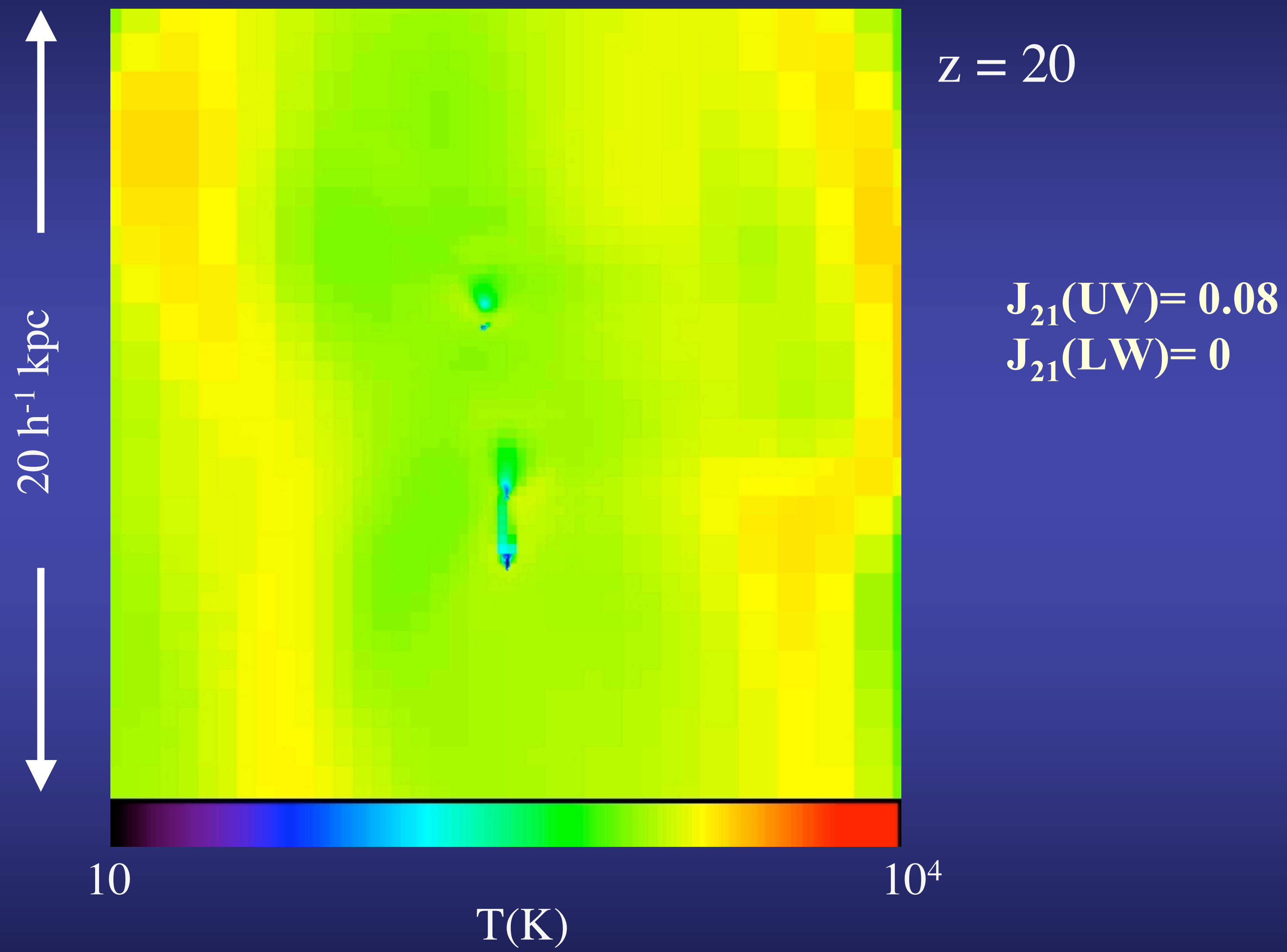
Gas Temperature



z = 21

J_{21}(UV)= 0.08
J_{21}(LW)= 0

Gas Temperature



Interpretation: Delayed Cooling

- **Cold gas develops in a cooling time**

$$\Delta t = t_{cool} \propto T / n_{gas}\, x_{H2}$$

T: little affected (initial Compton cooling)

n_{gas}: depressed by factor of ~ 40

x_{H2}: increased by factor of ~ 10

net delay: factor of ~4

- **Works on halo-by-halo basis - often near cancelation**
- **Statistics for the population as a whole?**

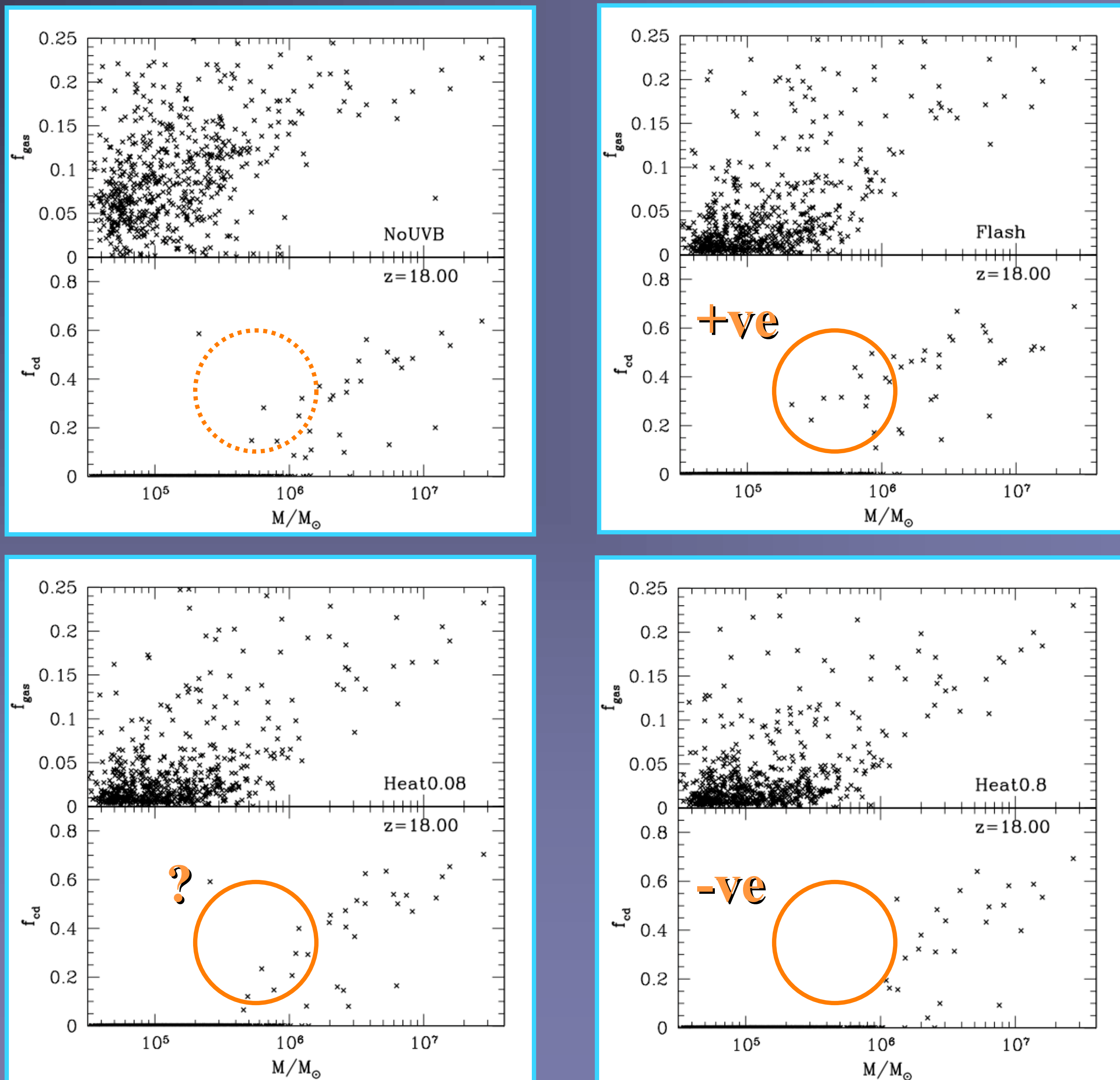
Gas Fractions at z = 18

No UV

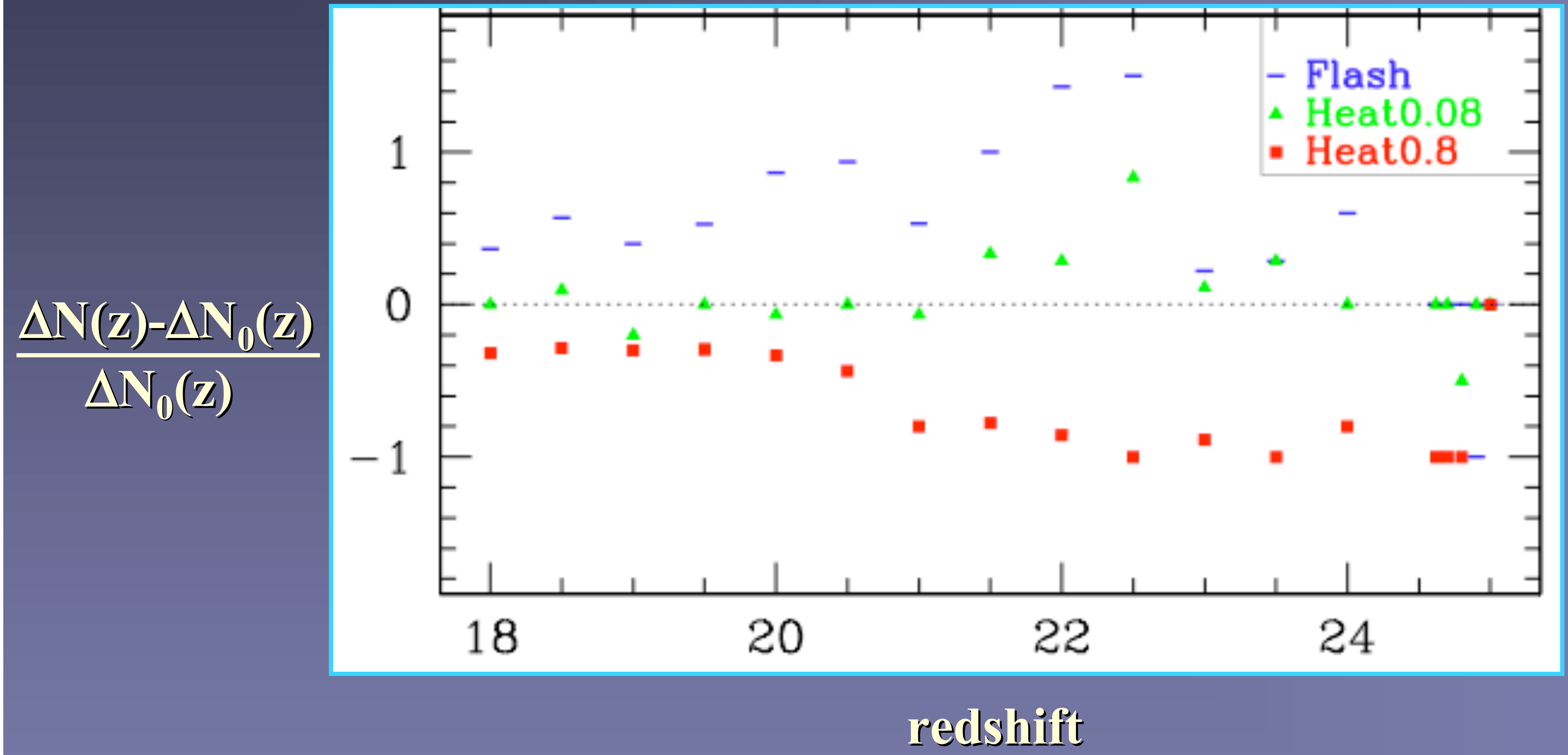
Flash

J=0.08

J=0.8



Population of Halos with Cold Dense Gas



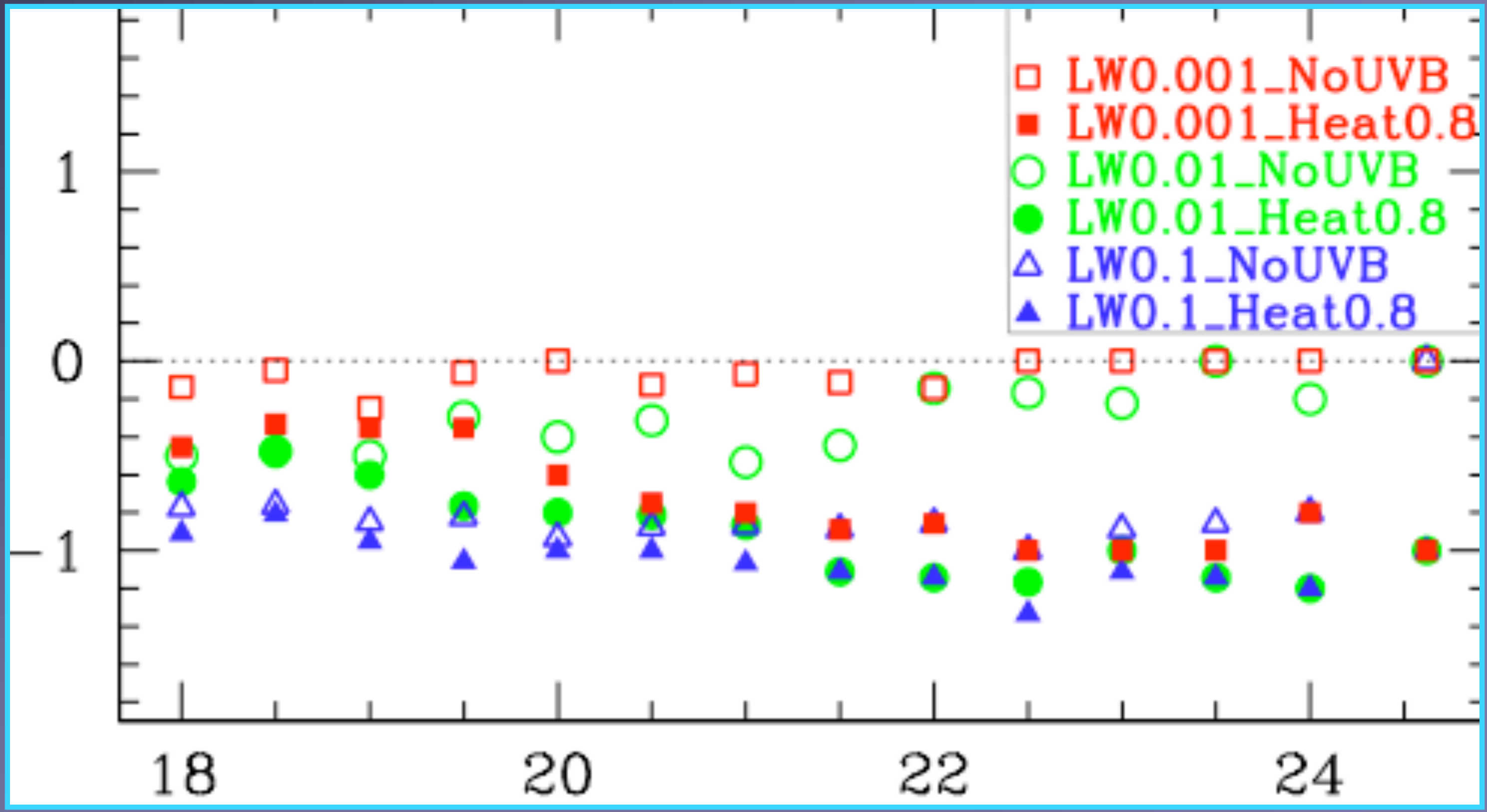
➔ strong effects persist for ~100 Myr, critical $J_{21} \approx 0.1$

➔ Only low-mass ($M \lesssim 10^6 M_\odot$) halos affected beyond 100 Myr

Results with Lyman-Werner Background

Suppression expected if H_2-diss time $t_{diss} \leq t_{cool}$

$$\frac{\Delta N(z)-\Delta N_0(z)}{\Delta N_0(z)}$$



redshift

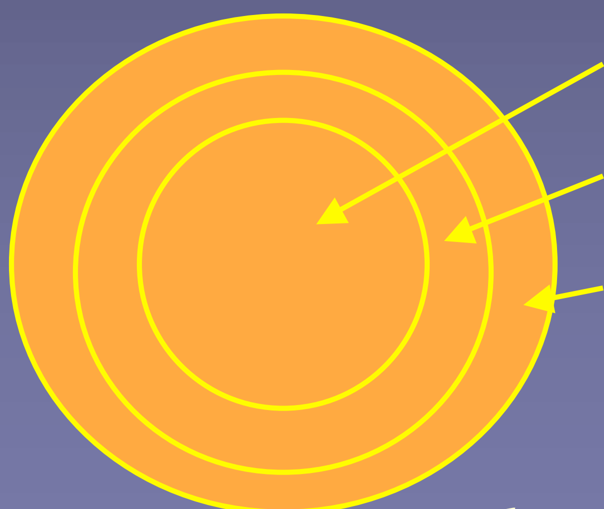
- ➔ Entropy floor reduces critical J(LW) from 0.01 to 0.001
- ➔ for J(LW) ≳ 0.01 strong suppression persists beyond 100 Myr

Feedback retards reionization when $f_{ion} \gtrsim$ 0.1-1%

Source Clustering Boosts Feedback

Kramer, Haiman & Oh (2006)

- important if bubble size < correlation length
- Difficult to model: bubble size depends on entire merger history - and history depends on feedback
- Approximate treatment modifying bubble model (Furlanetto, Zaldarriaga & Hernquist 2004)



(M_1, δ_1) - bubble size at z_1

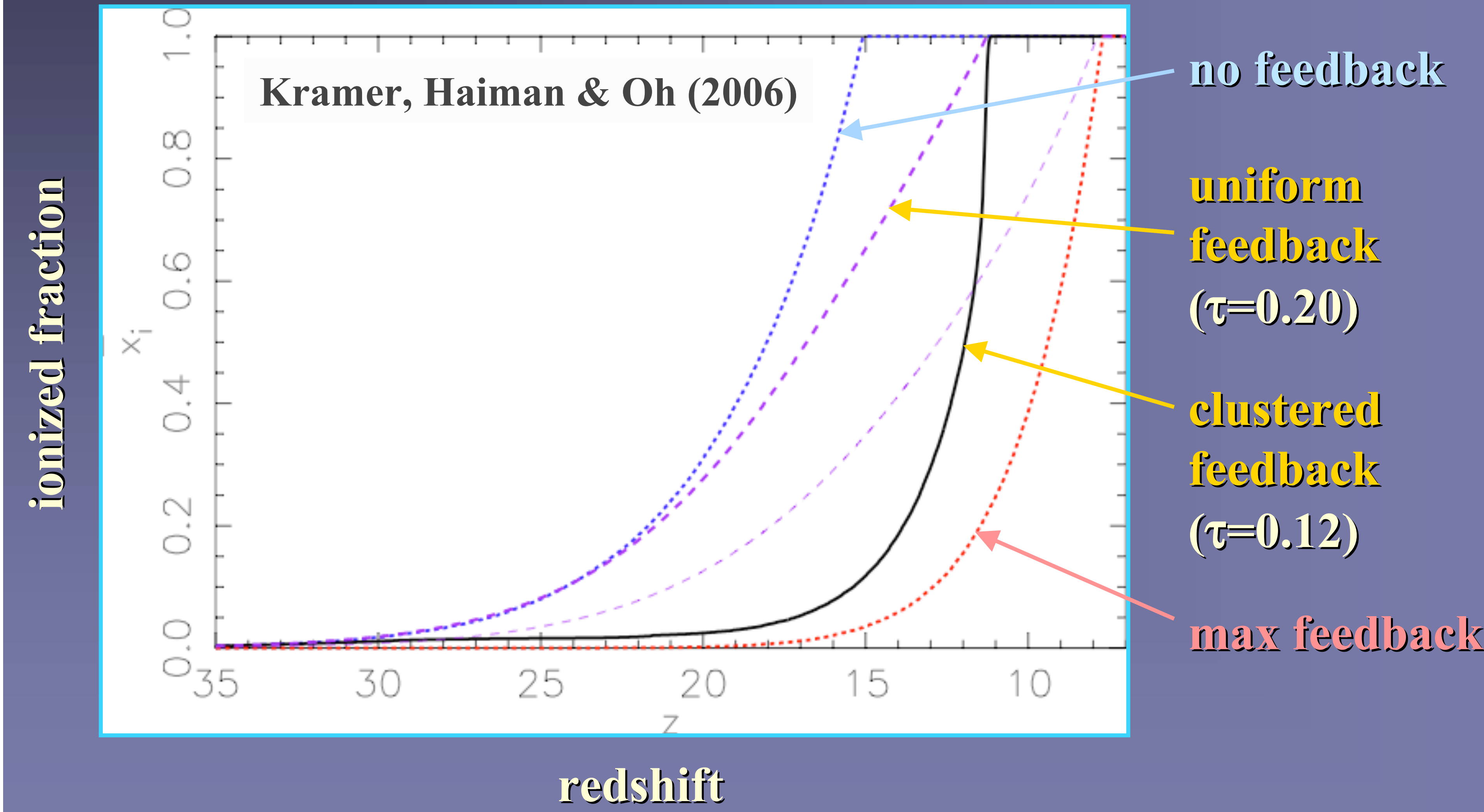
(M_2, δ_2) - bubble size at z_2

(M_3, δ_3) - bubble size at z_3

etc

hypothesis: just enough halos within each sphere to keep it fully ionized

Feedback from Clustered Sources Suppresses Early Reionization



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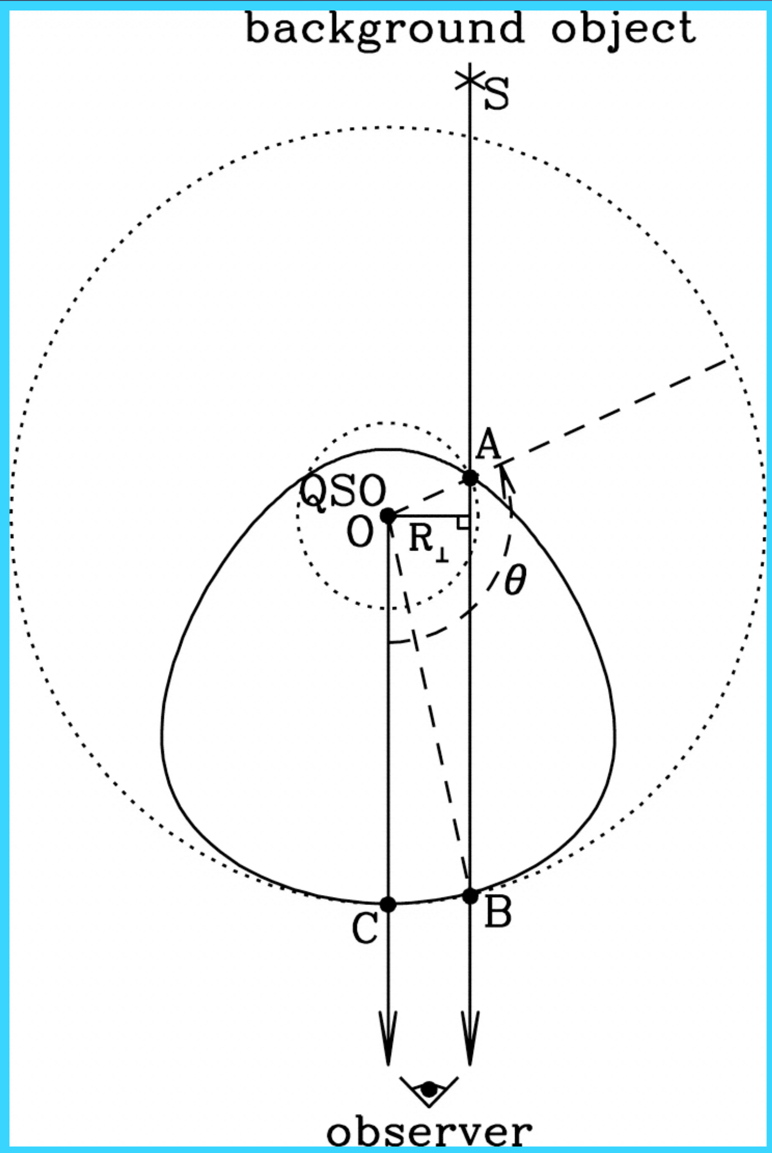
The Shapes of Quasar HII Regions



Finite speed of light distorts apparent shape of quasar HII region (Cen & Haiman 2000 Wyithe & Loeb 2004; Yu 2005):

$$t_A = t(z_Q) + R(t_A)\cos\theta / c,$$

Effect is large when spheres are large and expand at v ~ c (short-lived, bright quasars)

Asymmetry confirms quasar origin, and constrains a combination of (t_{Q}, t_{rec}, t_{nr}) and therefore (t_{Q}, x_{HI}, C)

Can We Detect The Distortion?

- 21cm is best bet, since it offers 3D tomographic information (another signature is modulation in the spatial distribution of Lyα emitters?)

- Has to be statistical, involving 100s of quasars, to average out intrinsic non-sphericities

- Effect is ~10 percent for quasars ~10 times less luminous than the SDSS quasars at z~6

- There could be up to ~10 such quasars deg^{-2} , ionizing up to ~10% of the IGM volume, consistent with observed LF, lensing, and XRB
  (Dijkstra, Haiman & Loeb 2005; Sbrinovsky & Wyithe 2007; Richards et al. 2006)

Quasar HII Region Shapes in 21cm

- Quasar HII region appears as a hole, surrounded by ring of emission, in the 21cm maps Tozzi et al. (2000)
- Imaging individual HII regions (although high S/N may require sensitivity of SKA) Wyithe, Loeb & Barnes (2005)
- Alternatives: statistical detection in the small-scale 21cm power spectrum, or by stacking? Sethi & Haiman (2007)
- Best case scenario: large quasar bubbles, expanding relativistically into a partially ionized IGM, fill a few percent of the IGM volume without overlapping significantly

21cm Power Spectrum Anisotropy

Sethi & Haiman (2007)

When $T_{spin} \gg T_{spin}$, 21cm emission given by local neutral hydrogen density:

$$T_0 = \frac{3}{32\pi}\frac{h\lambda^2 A_{21} n_b(z)}{kH(z)} \approx \quad (2)$$

$$\approx 40\left[\left(\frac{0.127}{\Omega_m h^2}\right)\left(\frac{\Omega_b h^2}{0.223}\right)^2\left(\frac{0.73}{h}\right)^2\left(\frac{1+z}{11}\right)\right]^{1/2} \text{mK},$$

and

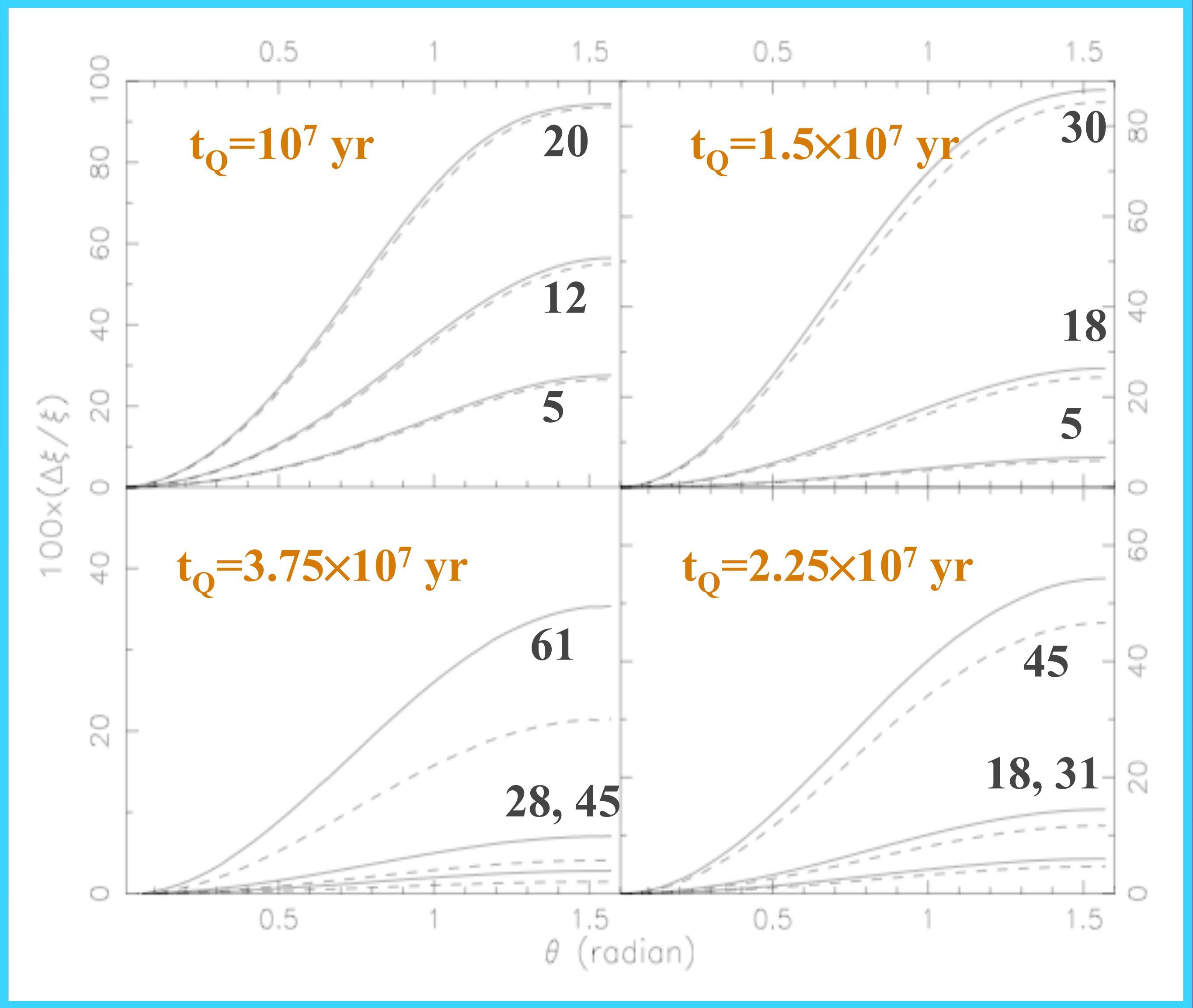
$$\psi = x_H(\mathbf{r})[1+\delta(\mathbf{r})], \quad (3)$$

We need correlation function ξ of x_{HI}:

$$C(r_{12},\theta) \equiv \langle \Delta T(\hat{n}_1, r_1)\Delta T(\hat{n}_2, r_2)\rangle =$$
$$= T_0(r_1)T_0(r_2)[\langle \psi(\hat{n}_1, r_1)\psi(\hat{n}_2, r_2)\rangle - \langle\psi\rangle^2]. \quad (6)$$

Model: randomly distributed distorted spheres

Expected Anisotropy in $\xi(r,\theta)$



Sethi & Haiman (2007)

$z=8$

$f_{ion} = 0.8$

$C=5-20$

$N=2\times10^{56}\ s^{-1}$

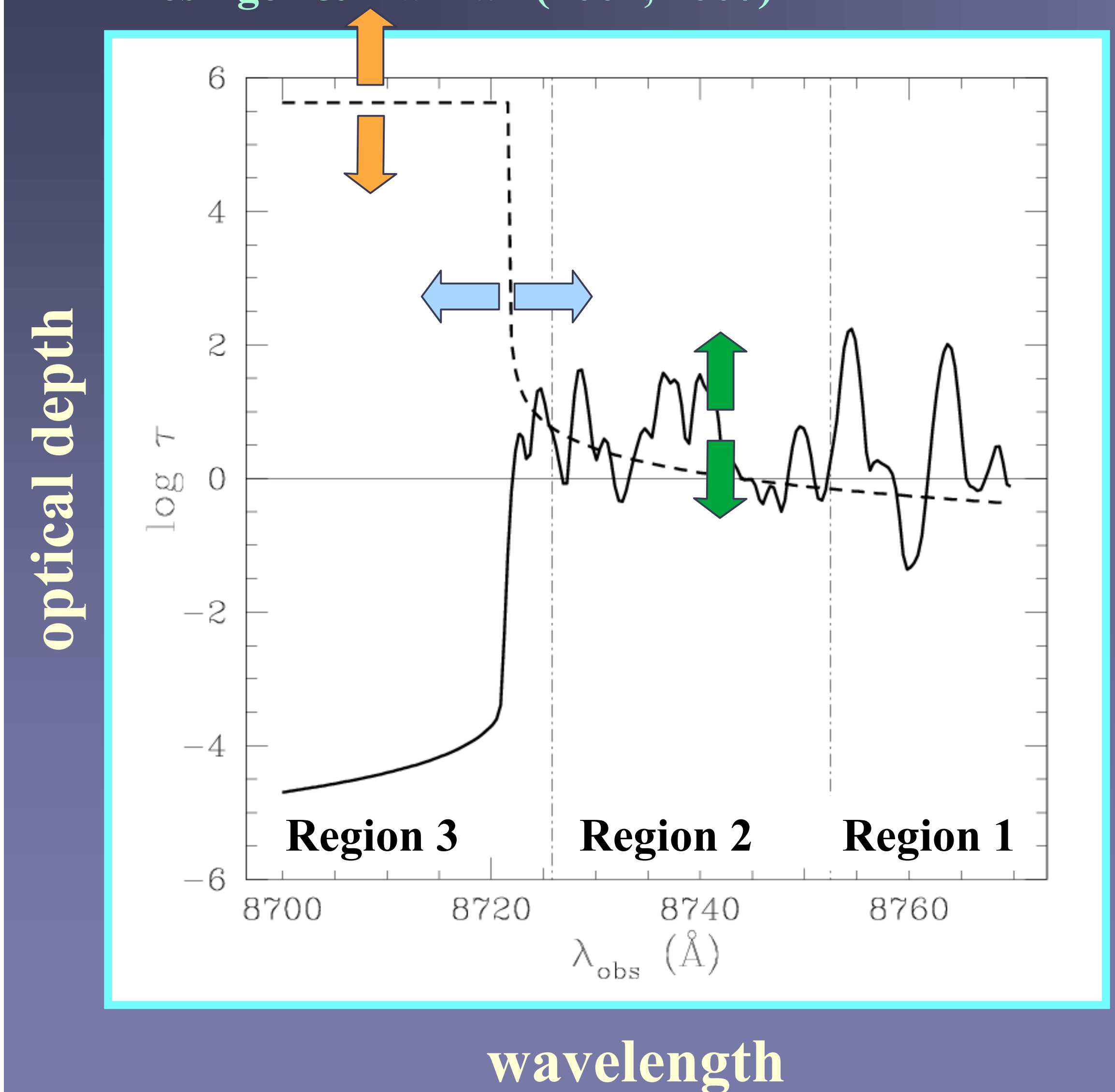
MWA can detect ~10% anisotropy in few days

$\Delta T_B = 2.2K$

$\Delta\xi = 5\times10^{-6}K^2$

Quasar HII Regions II: Blurred Boundary?

Mesinger & Haiman (2004, 2007)



- sharpness of ionization front is expected to be of order the mean free path of the typical ionizing photon (~1 Mpc for ~200 eV)

- properties of Lyα,Lyβ transmission in "near zone" suggests sharp transition if $R_\alpha \approx R_\beta$

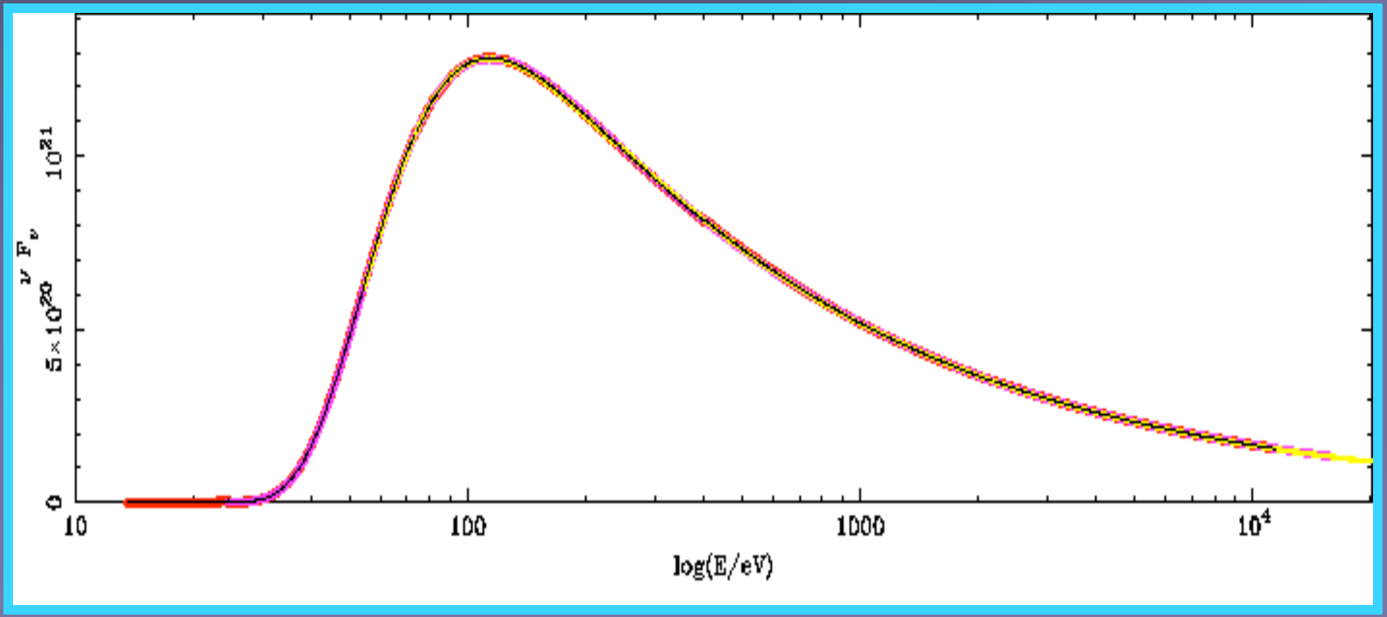
- may be testable in 21cm

  Zaroubi & Silk (2005)

Toy Model for Absorbed Spectrum

Spectrum can be hard if:

- **steep power-law extends to E>0.2 keV**
- **soft X-ray excess**
- **source is absorbed:**



$F_\nu \propto \nu^{-1.5}$

$N_{HI}=5\times10^{18}$ cm^{-2}

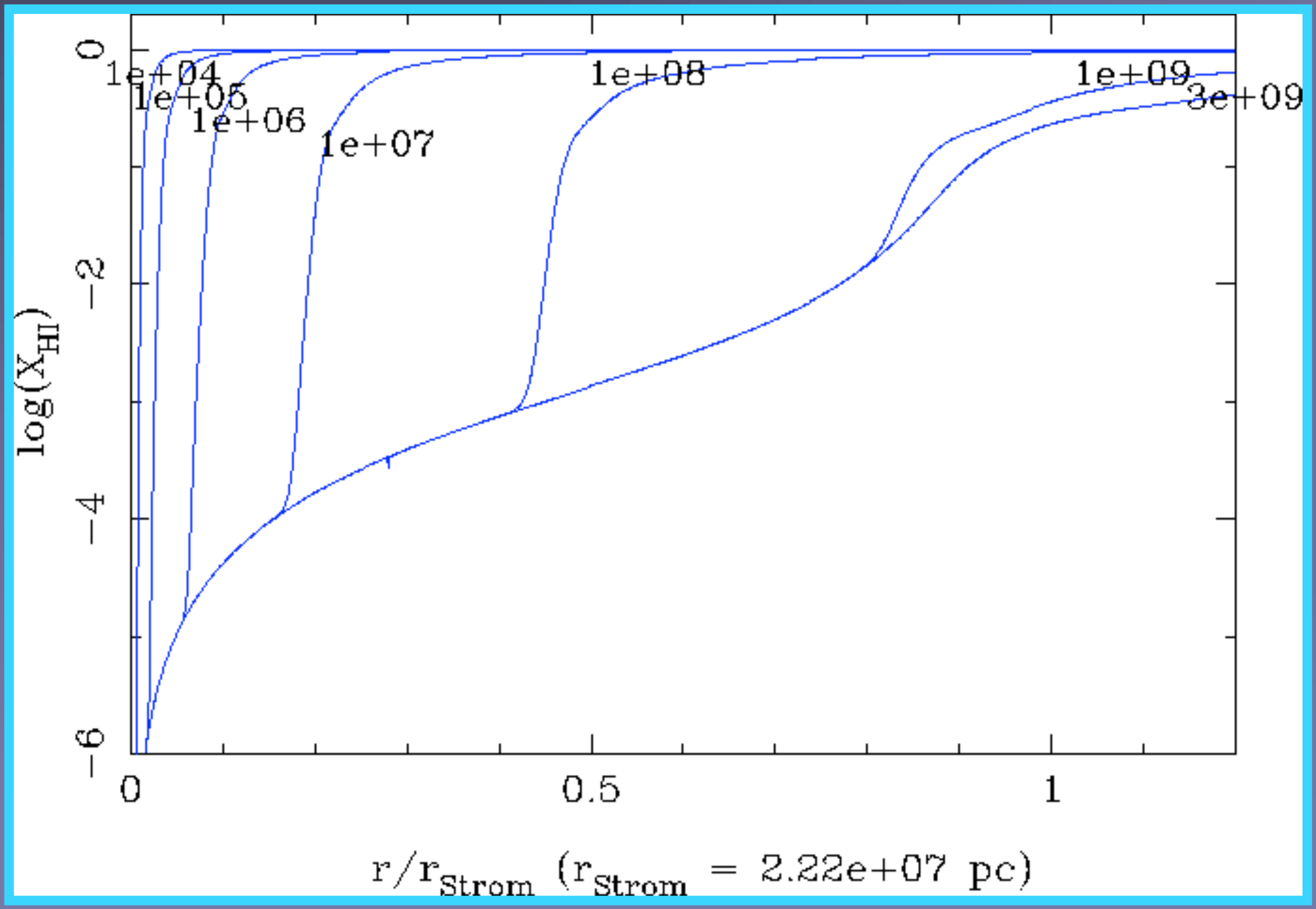
Energy of mean ionizing photon <E> ~ 200 eV

Kramer et al. (2007)

Expected Ionization Profile

Kramer & Haiman (2007)

$z=7$ $x_{HI}=1.0$ $C=1$ $N=2\times10^{57}\ s^{-1}$



- Ionization front is sharp and not in equilibrium at $t_Q \sim 10^7$ years
- profile is sharp at low $x_{HI} \lesssim 10^{-3}$ relevant to Lyα, β
- finite thickness due to secondary ionizations + HeI at $x_{HI} \gtrsim 0.1$ detectable in 21cm

A Perturbation Theory of Reionization

Zhang, Hui & Haiman (2007)

- Power spectrum of fluctuations (HII, HII) will be smoothed on scales below the mean free path of ionizing photons leaking into the IGM
- We will need parameterized model to fit to future data (e.g. kSZ or 21cm power spectra) that probe the ionization topology
- On large scales ($k \lesssim 0.1\ Mpc^{-1}$), linear perturbation theory should be adequate
- Linear perturbation theory solves ionization balance and radiative transfer, and can predict power spectra as a function of parameters
- Example: typical spectral slope $\beta = -\ d\ lnF_{\nu} / d\ ln\nu$

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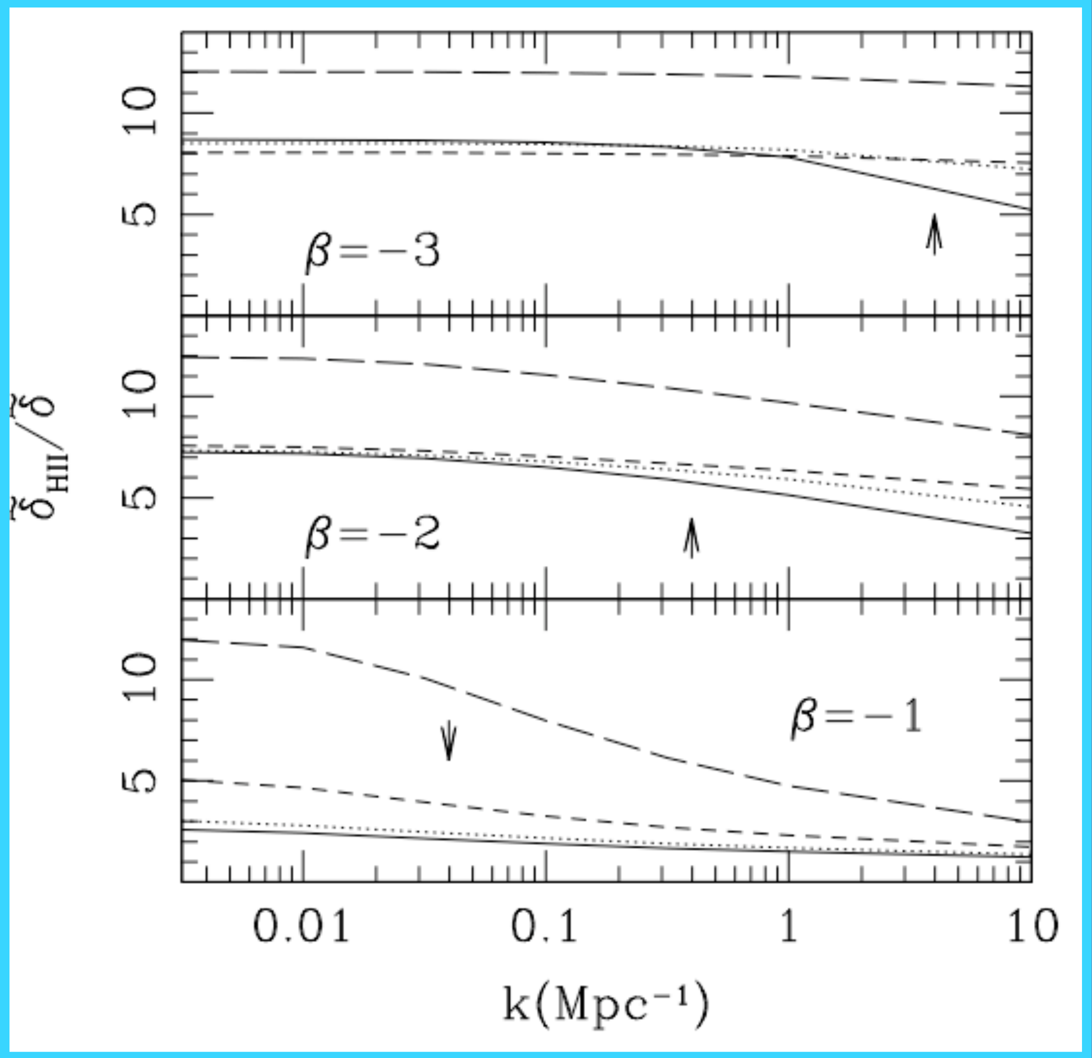
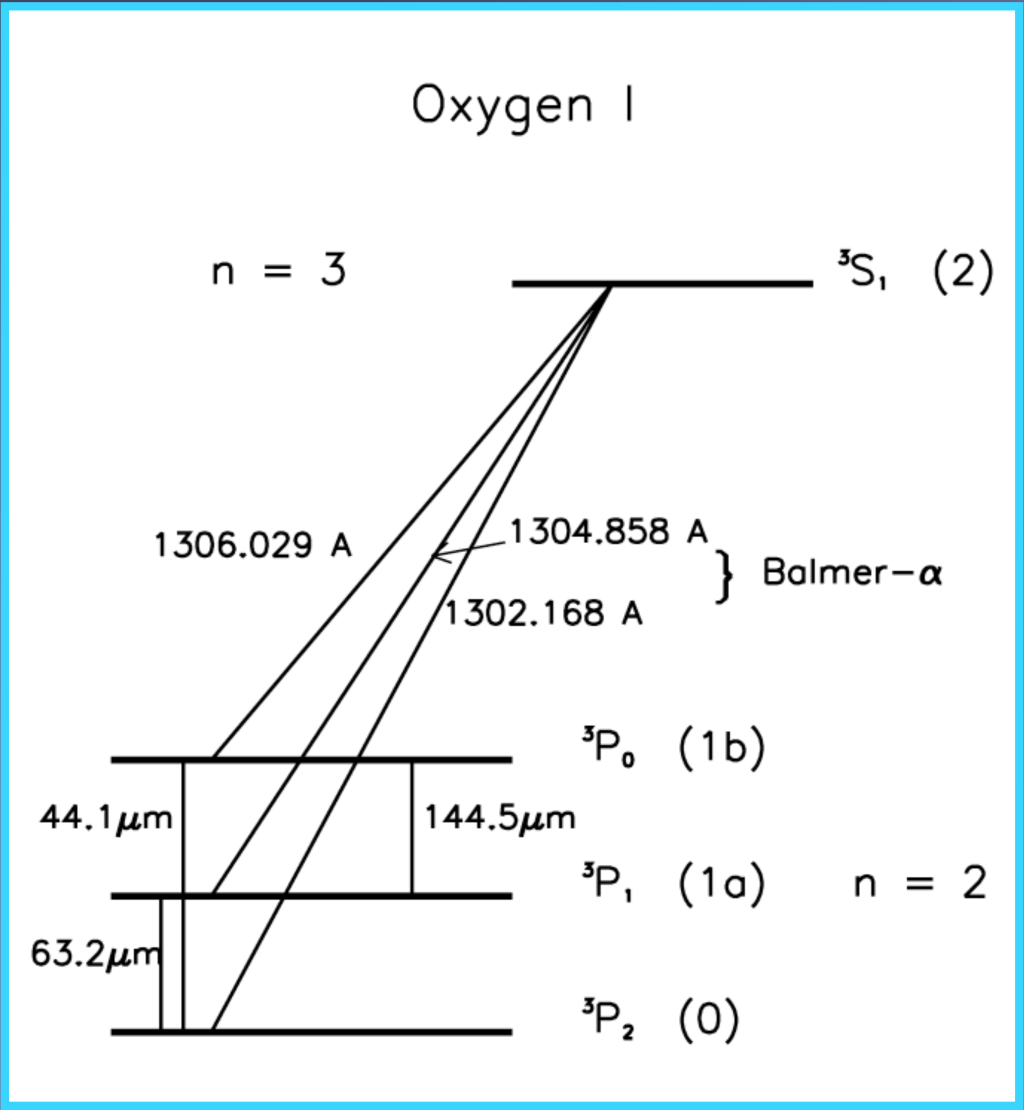


Soft spectrum

Hard spectrum

Oxygen Pumping

Hernandez-Monteagudo, Haiman, Jimenez & Verde (2007)



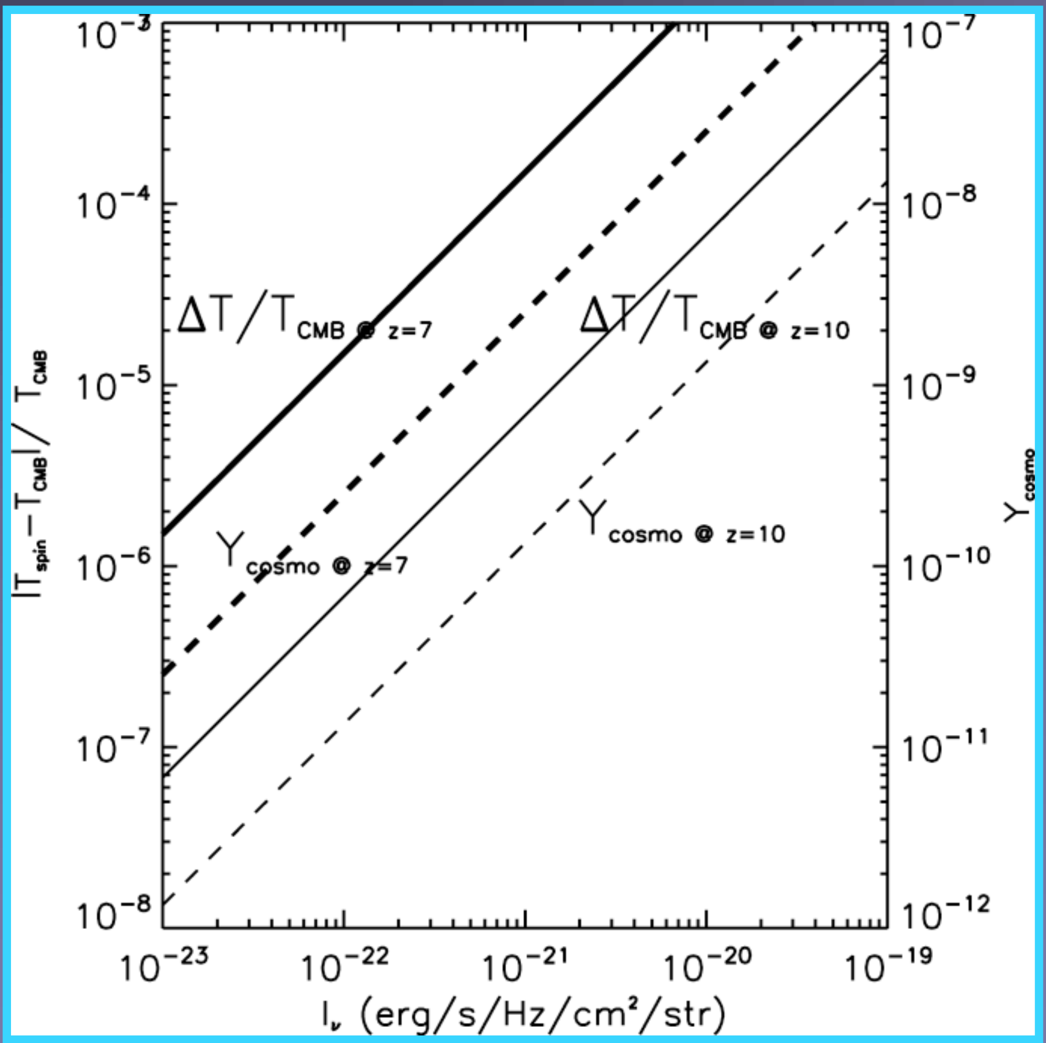
Can pumping analogous to Wouthuysen-Field process work for some metal line?

1. Abundant metal in right ionization state
2. Spin transition at right frequency, small A coeff
3. UV pumping at λ>1215Å
4. Large enough UVB flux

Direct probe of IGM metal pollution at early stages of reionization

Distortion of CMB Spectrum

Hernandez-Monteagudo, Haiman, Jimenez & Verde (2007)



$y \approx 10^{-7}$ is produced if OI abundance is ~$10^{-2.5}$ solar at z=7, and J(1300Å)~10

$y \approx 10^{-7}$ achievable with state-of-the art technology and with improvements over FIRAS detector and design

(Fixsen & Mather 2002)

Fluctuations may be easier to detect?

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