Overture

Sequence of events

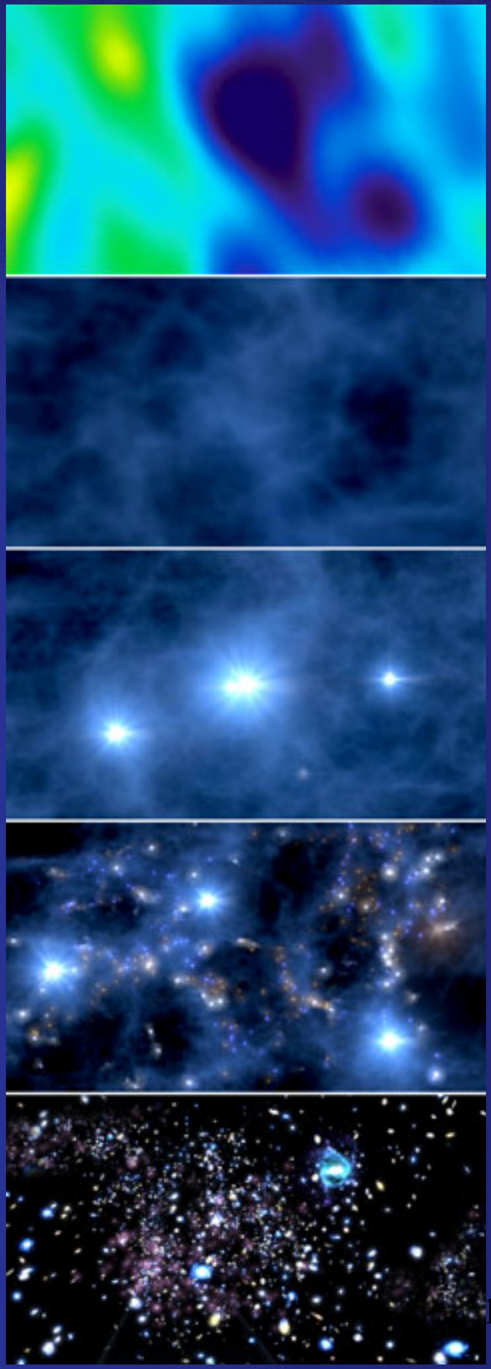
At z=1000 the Universe has cooled down to 3000 K. Hydrogen becomes neutral ("Recombination").

At z < 40 the first "PopIII" star (clusters)/small galaxies form.

At z ~ 6-15 these gradually photo-ionize the hydrogen in the IGM ("Reionization").

At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.



Time

Lecture #1

Cosmic Reionization

Andrea Ferrara
Scuola Normale Superiore, Pisa, Italy

"Historical" material

- Barkana, R. & Loeb, A. 2001, *Phys. Rep.*, **349**, 125
- Ciardi, B. & Ferrara, A. 2006, *SSRv,* **116**, 625 (updated: Apr 2008)

Recent material

- Ferrara, A. 2008, Saas-Fee Advanced Courses, 36. p. 161-258
- Choudhury, T. 2009, Current Science 97, 841
- Meiksin, A. 2009, Rev. Mod. Phys., 81:1405
- Ferrara, A. & Pandolfi, S. 2014, Varenna School arXiv1409.4946

COSMOLOGICAL I-FRONTS PROPAGATION

Single source

Physical coordinates

$$\bar{n}_H \left(\frac{dV_p}{dt} - 3HV_p \right) = \frac{dN_\gamma}{dt} - \alpha_B \left\langle n_H^2 \right\rangle V_p \, .$$

clumping factor

$$C = \left\langle n_H^2 \right\rangle / \bar{n}_H^2 \, .$$

Comoving coordinates

$$\frac{dV}{dt} = \frac{1}{\bar{n}_H^0} \frac{dN_\gamma}{dt} - \alpha_B \frac{C}{a^3} \bar{n}_H^0 V$$

$$V(t) = \int_{t_i}^{t} \frac{1}{\bar{n}_H^0} \frac{dN_\gamma}{dt'} e^{F(t',t)} dt' \, ,$$

where

$$F(t',t) = -\alpha_B \bar{n}_H^0 \int_{t'}^{t} \frac{C(t'')}{a^3(t'')} dt'' \, .$$

COSMOLOGICAL I-FRONTS PROPAGATION

Statistical approach

volume filling factor

$$Q_{\rm HII} = V_{\rm HII} / V$$

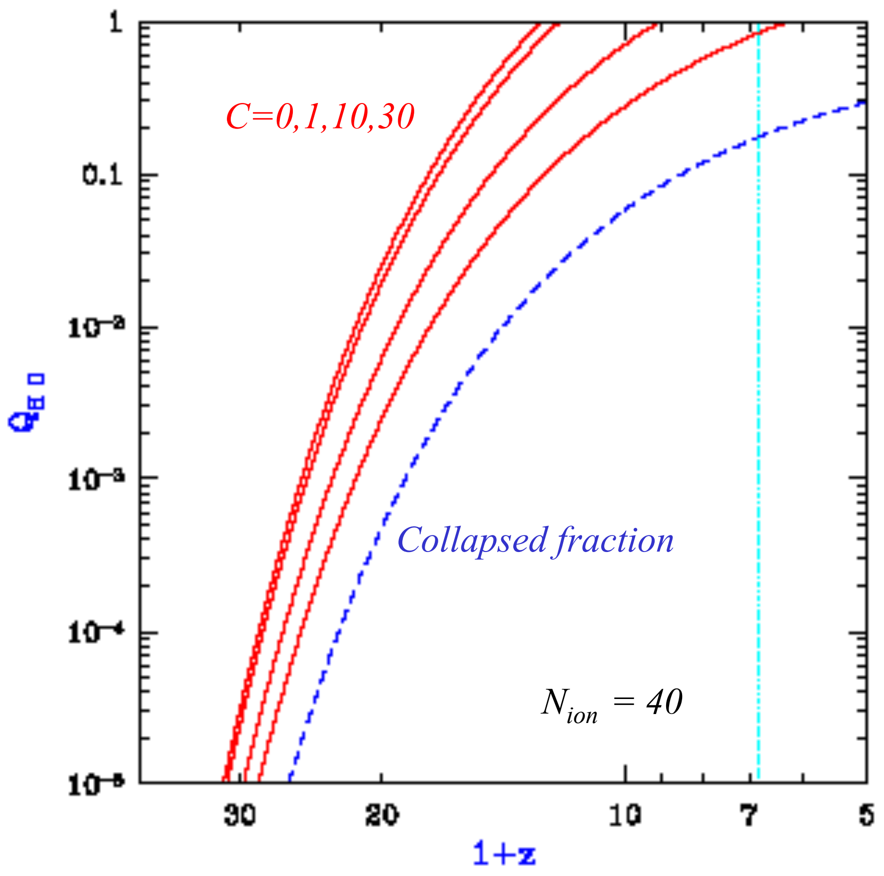
$$\frac{\bar{n}_\gamma}{\bar{n}_b} = N_{\rm ion} F_{\rm col}$$

$$N_{\rm ion} \equiv N_\gamma \, f_{\rm star} \, f_{\rm esc}$$

$$\frac{dQ_{\rm H\ II}}{dt} = \frac{N_{\rm ion}}{0.76} \frac{dF_{\rm col}}{dt} - \alpha_B \frac{C}{a^3} \bar{n}_H^0 Q_{\rm H\ II} \ ,$$

$$Q_{\rm H\ II}(t) = \int_0^t \frac{N_{\rm ion}}{0.76} \frac{dF_{\rm col}}{dt'} e^{F(t',t)} dt' \ ,$$

“HELLO WORLD!” REIONIZATION MODEL



COSMOLOGICAL RADIATIVE TRANSFER

$J_\nu = J\,(t, \mathbf{x}, \boldsymbol{\omega}, \nu)$

$$\dot{J}_\nu \equiv \frac{\partial J_\nu}{\partial t} - H(t)\nu\frac{\partial J_\nu}{\partial \nu} = -3H(t)J_\nu - c\kappa_\nu J_\nu + \frac{c}{4\pi}\epsilon_\nu$$

redshifting dilution absorption emission

Formal solution $$J_\nu(t) = \frac{c}{4\pi}\int_0^t \mathrm{d}t'\epsilon_{\nu'}(t')\frac{a^3(t')}{a^3(t)}e^{-\tau(t,t',\nu)}$$

$$\tau \equiv c\int_{t'}^{t}\mathrm{d}t''\kappa_{\nu''}(t'')$$

$$\nu'^{('')} = \nu\frac{a(t)}{a(t'^{('')})}$$

$\kappa_\nu \gg H/c$ *(Local approximation)*

$$J_\nu(t) \approx \frac{\epsilon_\nu(t)}{4\pi\kappa_\nu(t)}$$

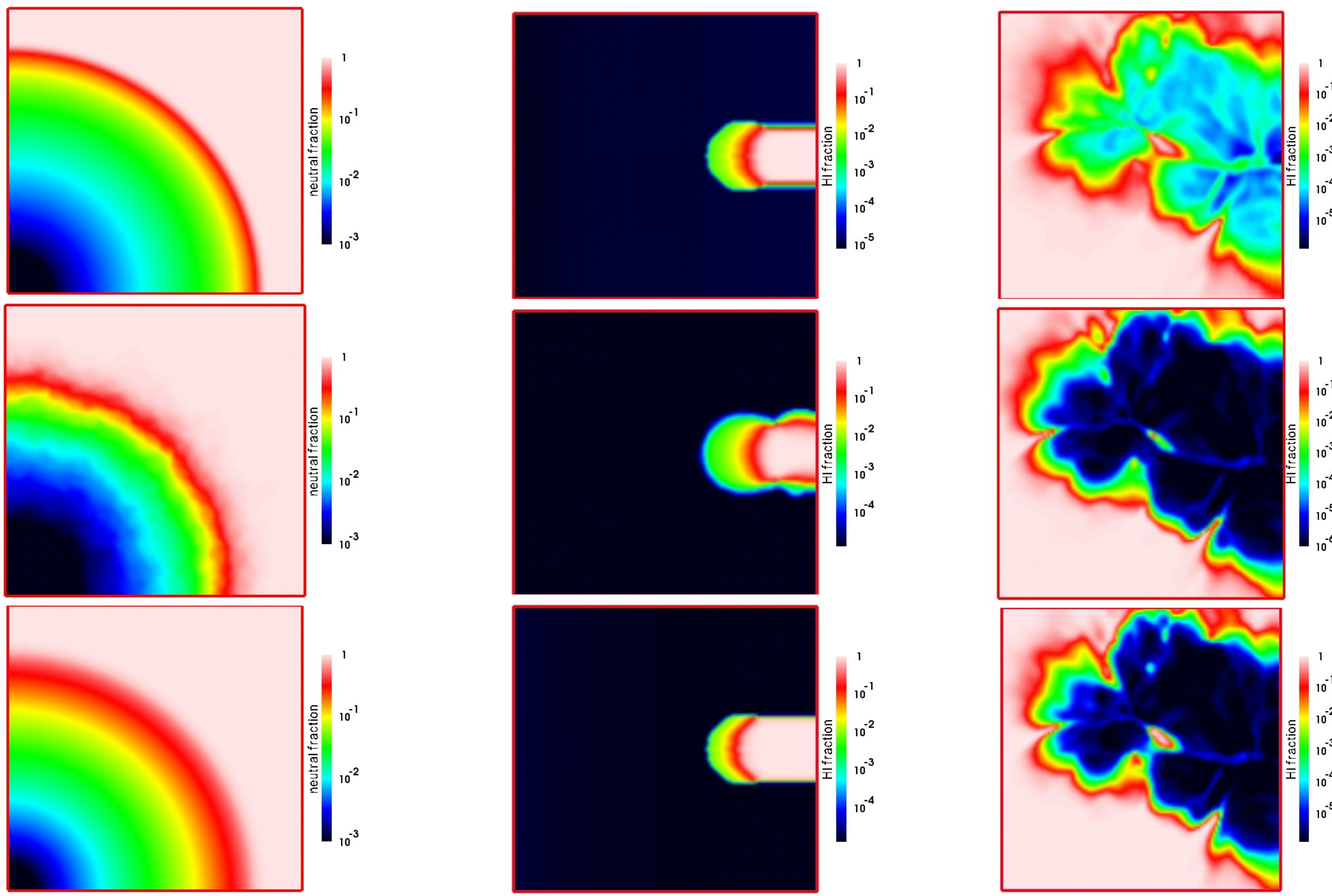
NUMERICAL SOLUTION TECHNIQUES

- Ray Tracing/Long characteristics *Abel, Norman & Madau 1999; Razoumov & Scott 1999; Sokasian, Abel & Hernquist 2001; Razoumov etal 2002*
- Ray Tracing/Short characteristics *Umemura etal 1999; Rijkhorst etal 2005*
- Flux-Eddington tensor *Gnedin & Abel 2001*
- Flux-limited diffusion *Turner & Stone 2001; Whitehouse & Bate 2004*
- Fourier transforms *Cen 2002*
- Unstructured grids *Ritzerveld etal 2004*
- Statistical (MC) methods *Ciardi etal 2001; Maselli, Ferrara & Ciardi 2003*

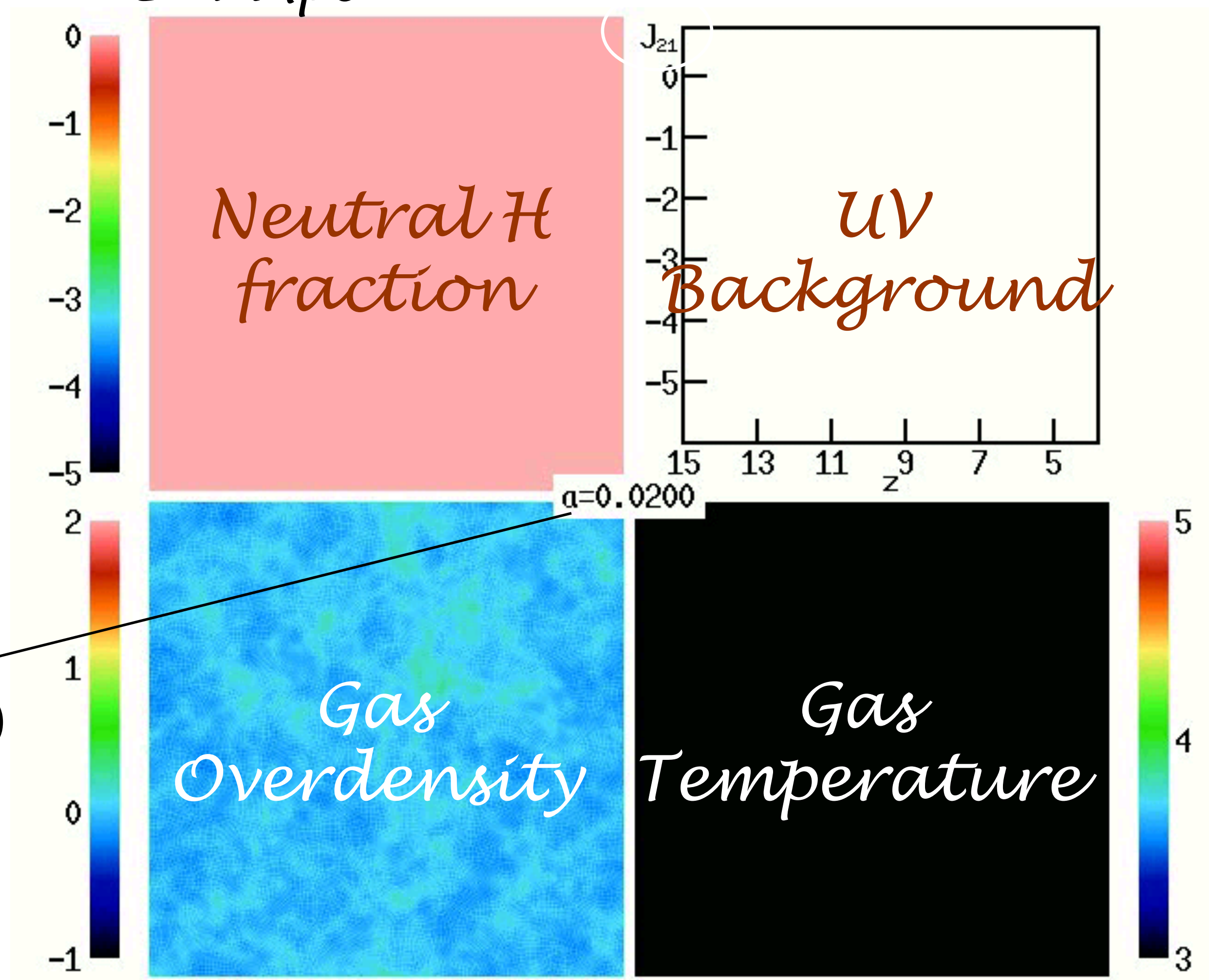
TSU³ CODE BENCHMARK

www.mpa-garching.mpg.de/**tsu3**/

Stromgren sphere | Dense clump | Cosmological field



L=4 Mpc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-1
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-3
-4
-5
Neutral H fraction
J21
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-2
-3
-4
-5
15
13
11
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7
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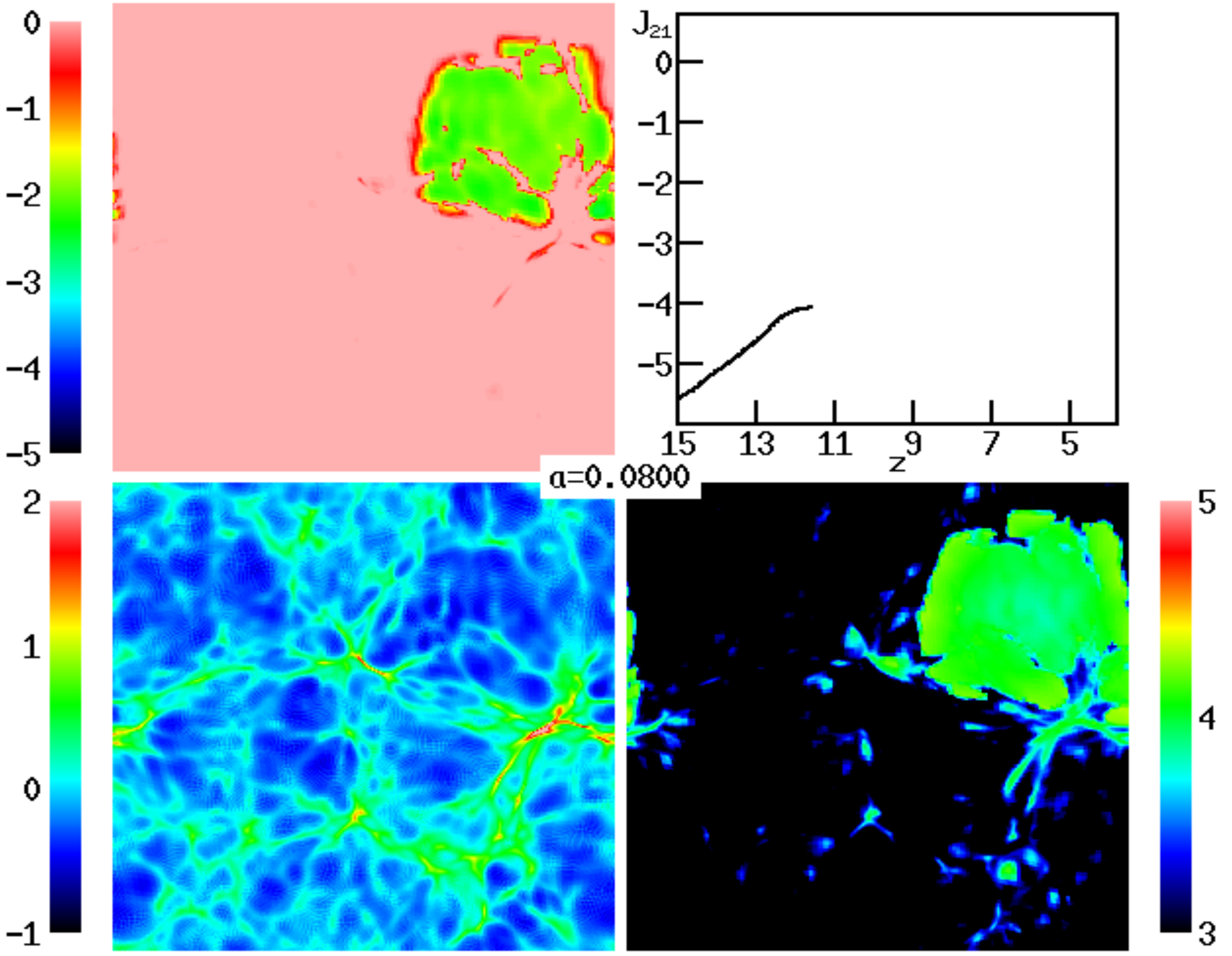
z
UV Background
a=0.0200
2
1
0
-1
Gas Overdensity
Gas Temperature
5
4
3

$a = 1/(1+z)$



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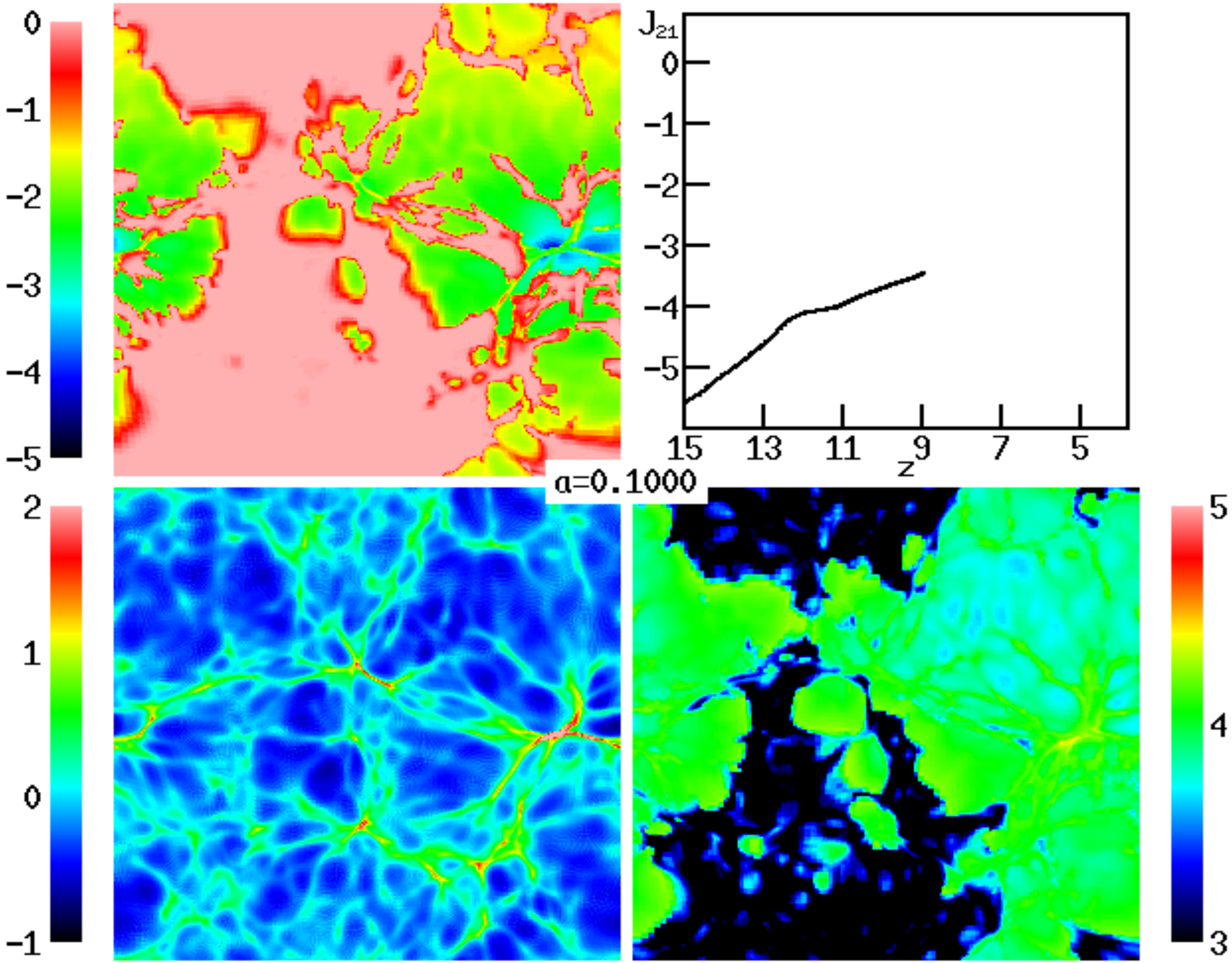

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a=0.1000
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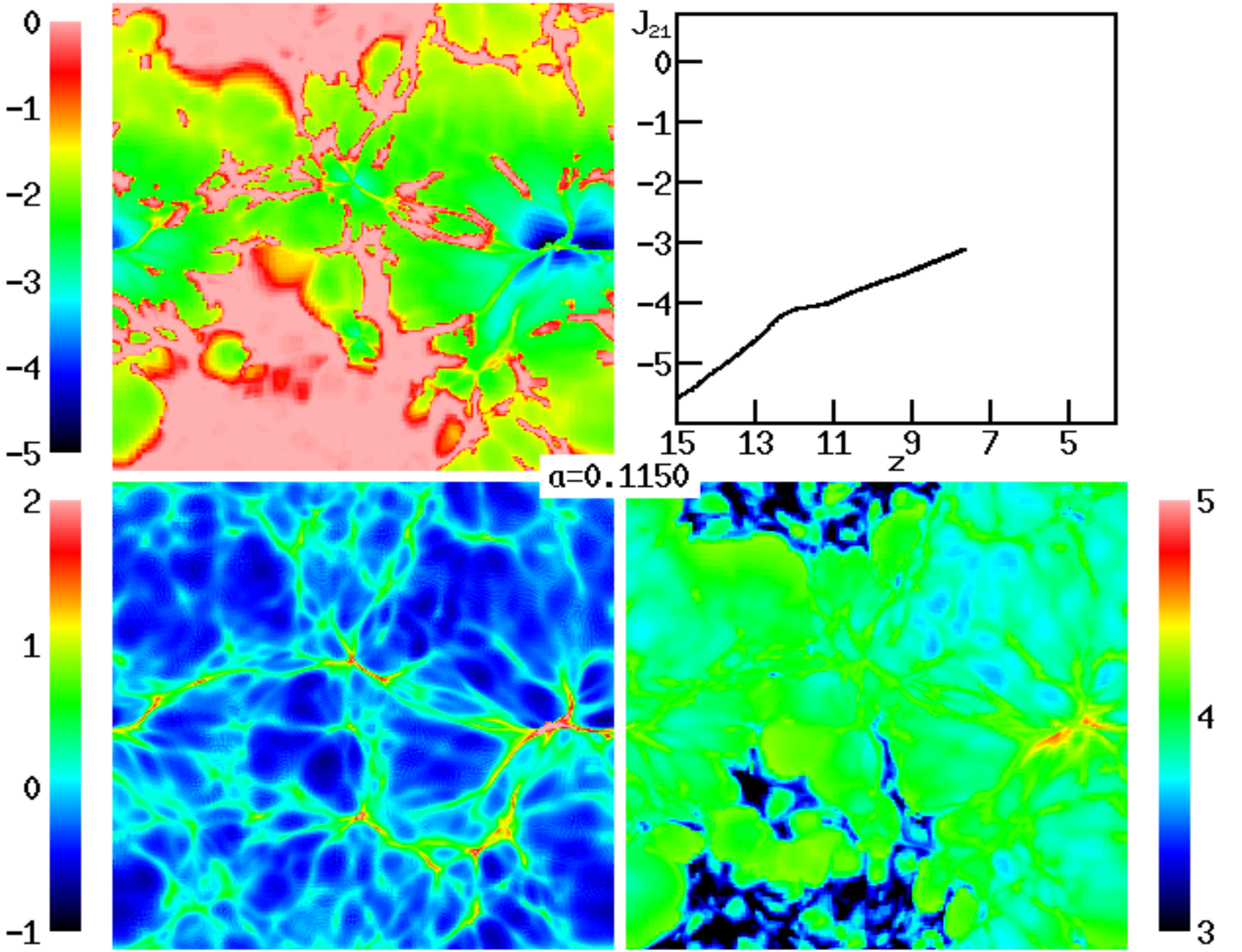

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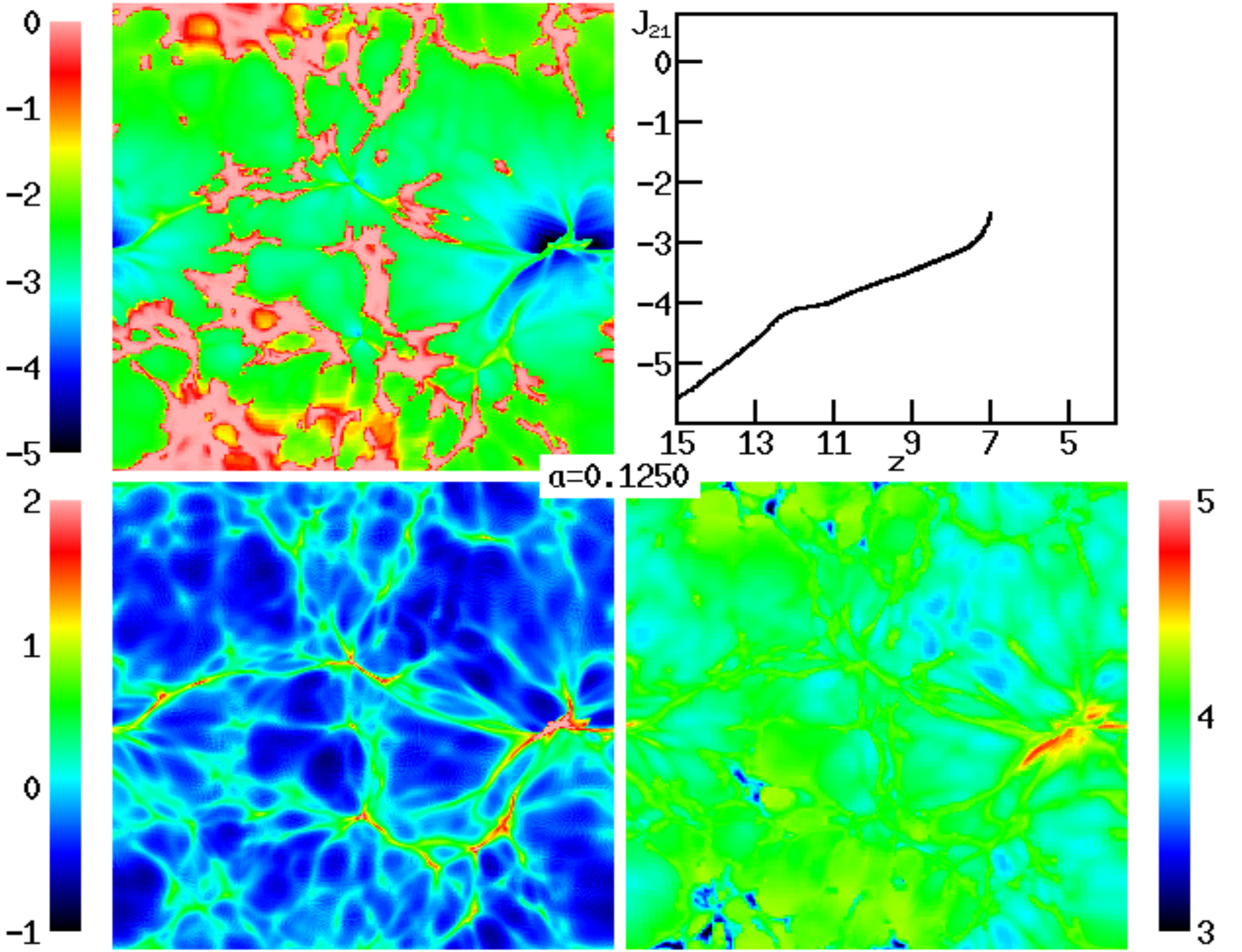

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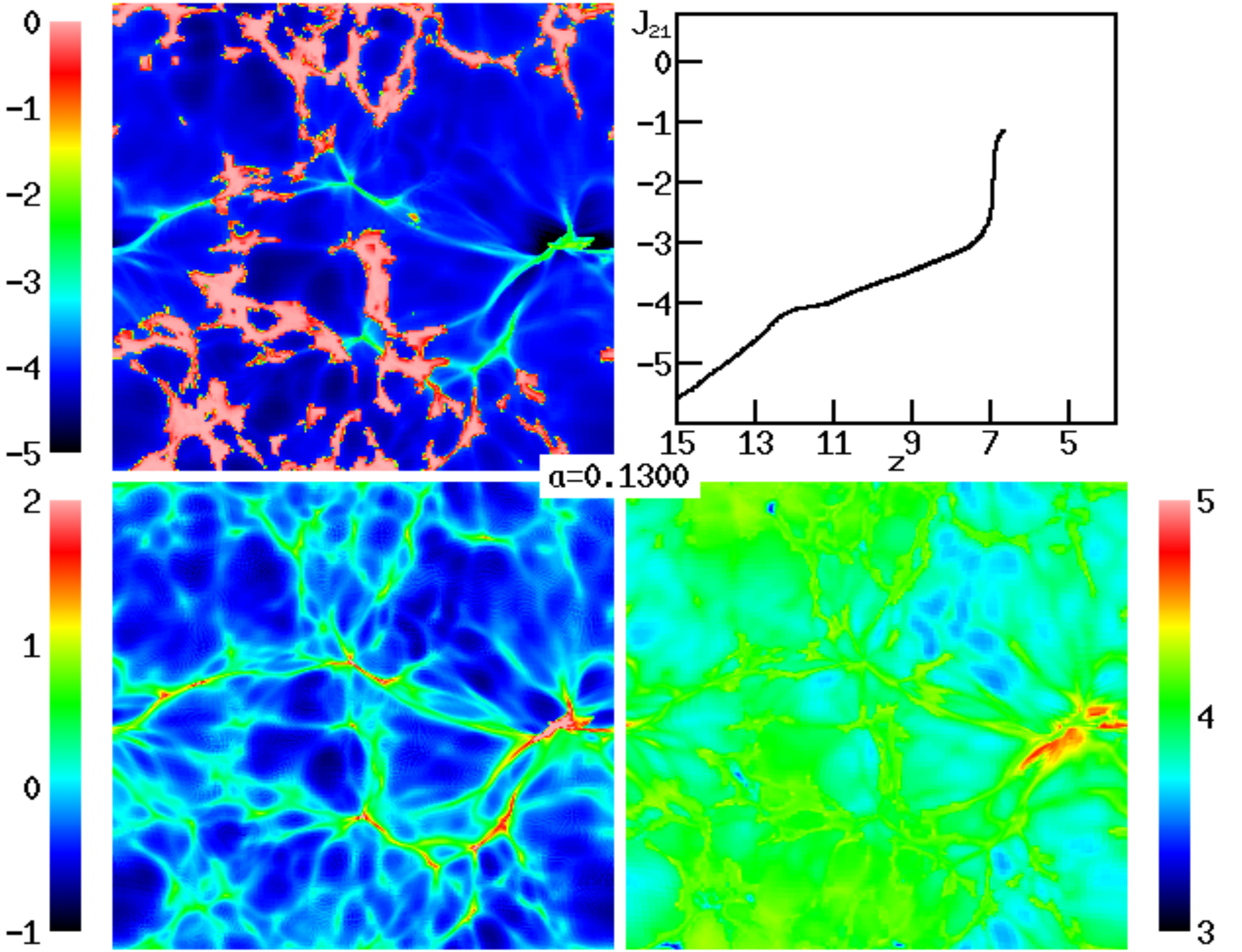

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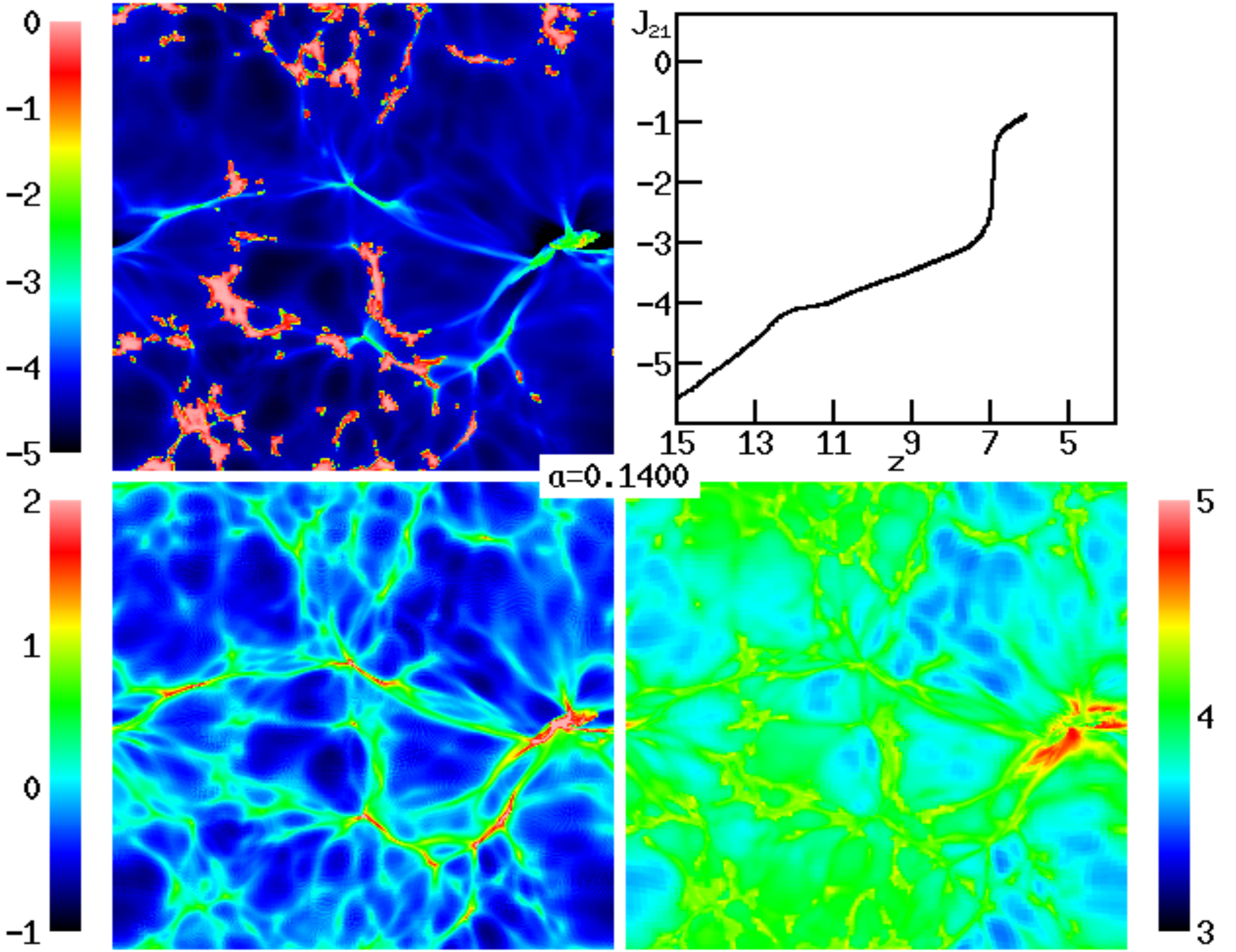

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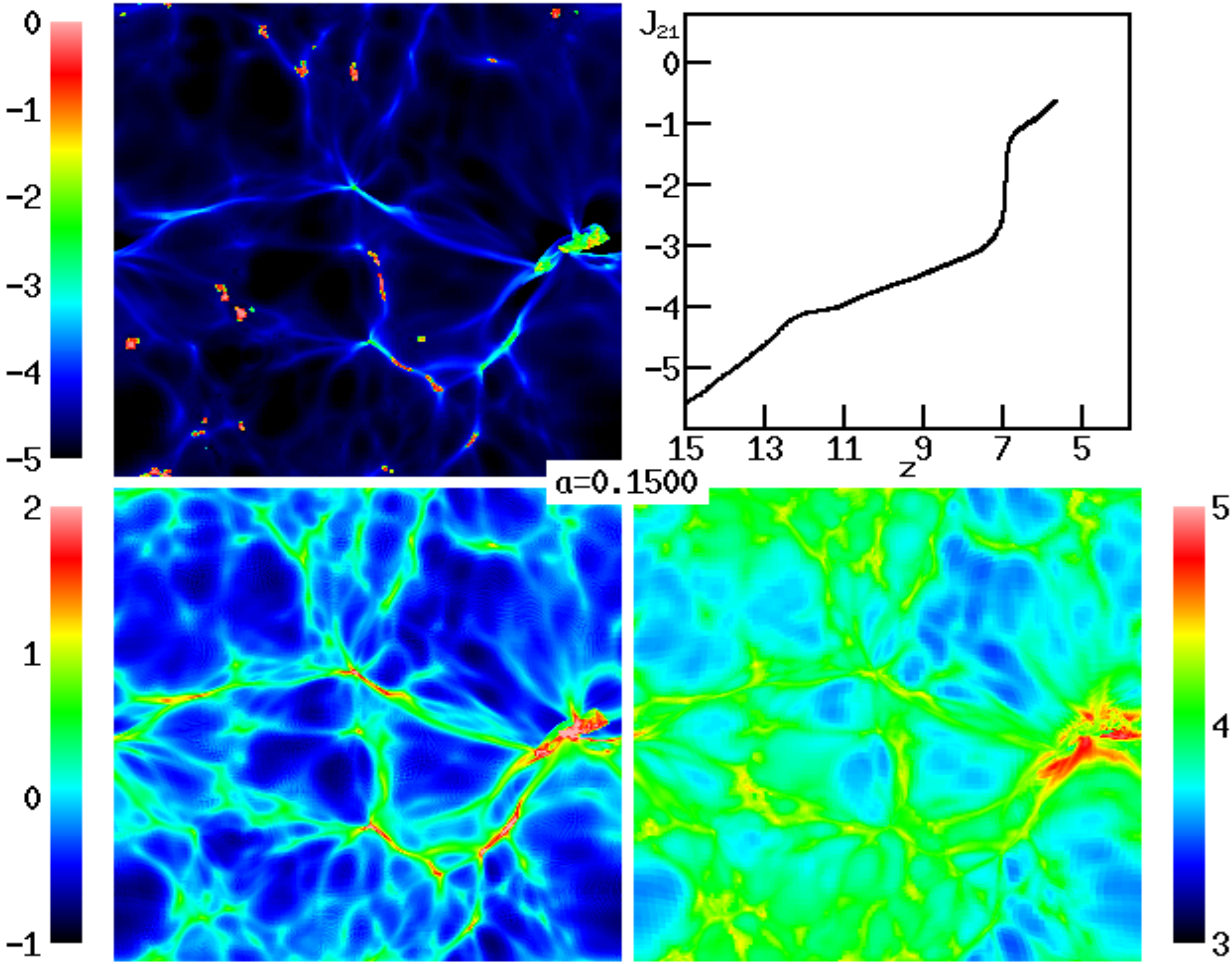
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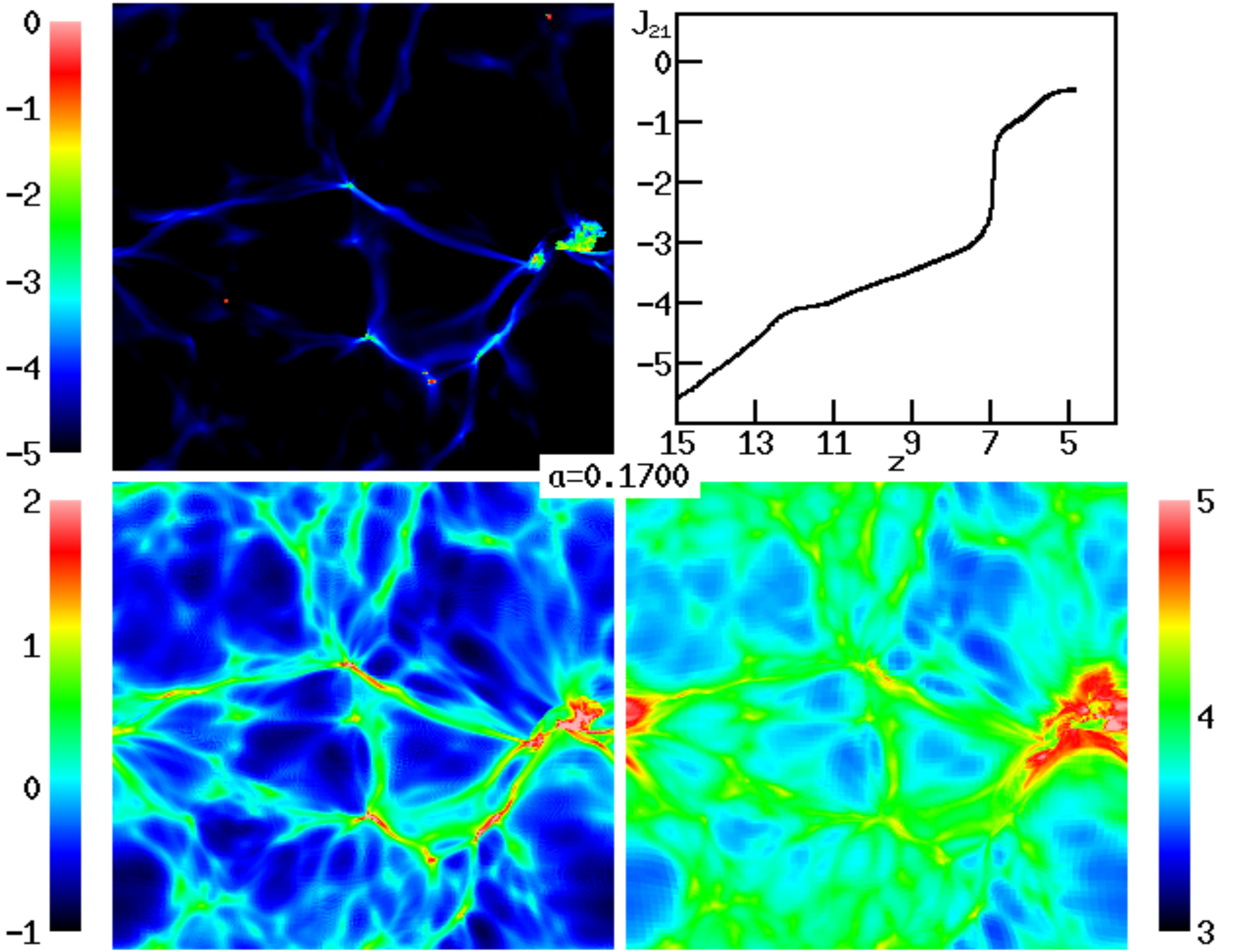

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J21
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z
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a=0.1700
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−1
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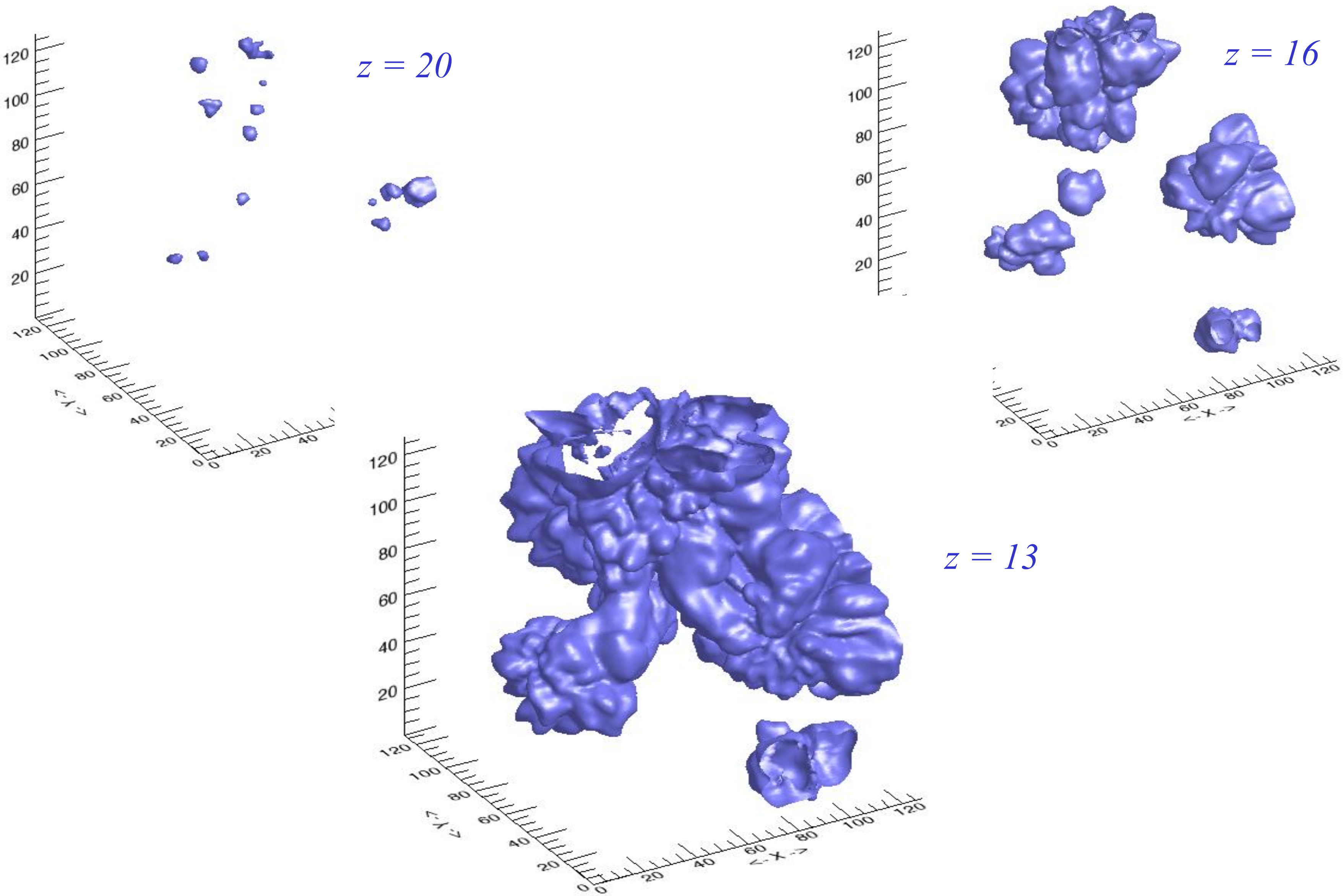
Reionization completed

Reionization Topology



Gunn and Peterson (1965)

NOTES

ON THE DENSITY OF NEUTRAL HYDROGEN IN INTERGALACTIC SPACE

Recent spectroscopic observations by Schmidt (1965) of the quasi-stellar source 3C 9, which is reported by him to have a redshift of 2.01, and for which Lyman-α is in the visible spectrum, make possible the determination of a new very low value for the density of neutral hydrogen in intergalactic space. It is observed that the continuum of the source continues (though perhaps somewhat weakened) to the blue of Ly-α; the line as seen on the plates has some structure but no obvious asymmetry. Consider, however, the fate of photons emitted to the blue of Ly-α. As we move away from the source along the line of sight, the source becomes redshifted to observers locally at rest in the expansion, and for one such observer, the frequency of any such photon coincides with the rest frequency of Ly-α in his frame and can be scattered by neutral hydrogen in his vicinity. The calculation of the size of the effect is very easily performed as follows:

BASIC FORMULAE

Historical formula

$$p = \int_0^{z_0} dp = \int_0^{z_0} n[t(z)]\,\sigma[\nu(1+z)]\,\frac{dl}{dz}\,dz.$$

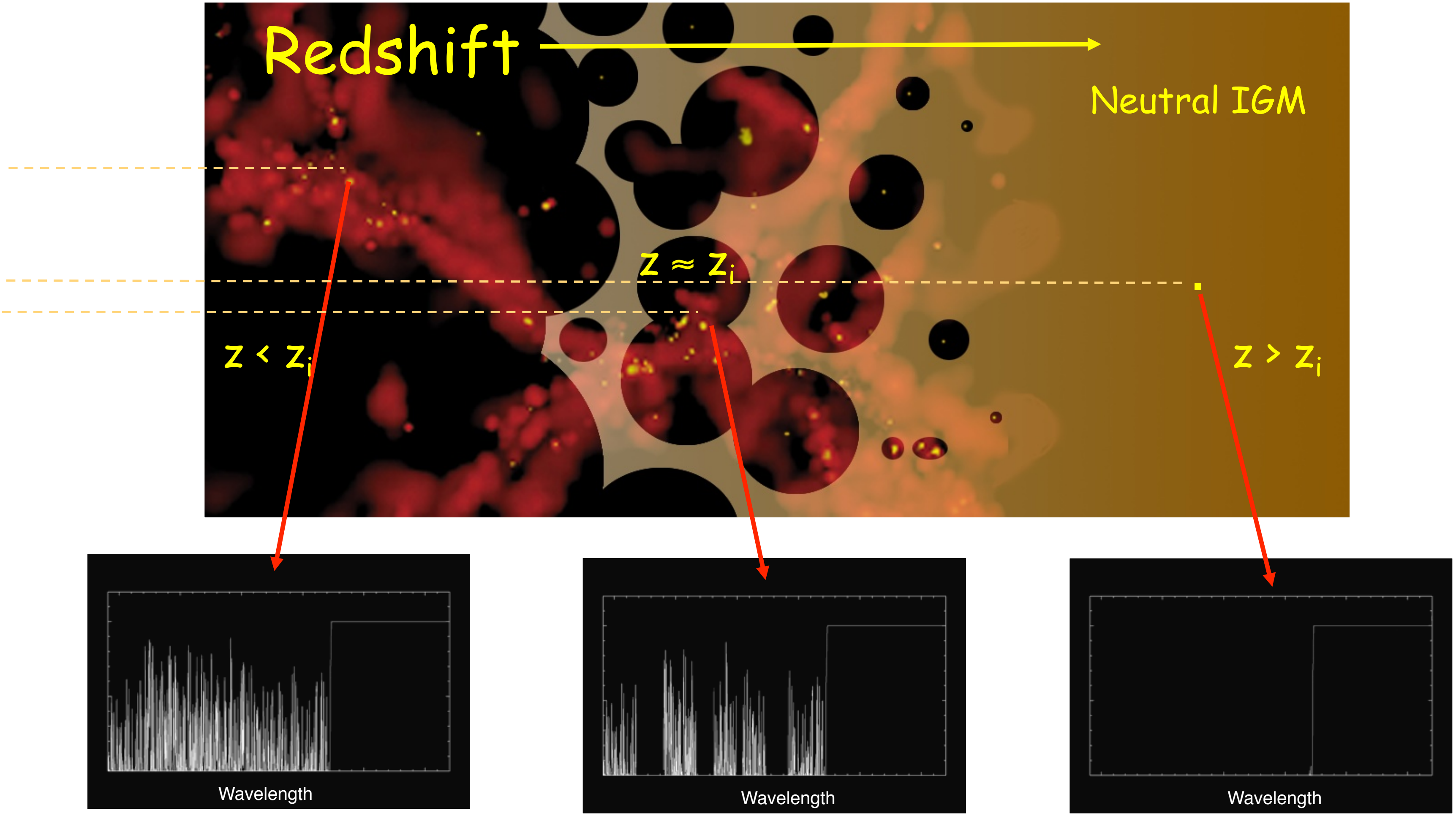
$$\sigma(\nu) = \frac{\pi e^2}{mc} f g(\nu - \nu_\alpha),$$

$$\tau_{\mathrm{GP}} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\mathrm{HI}}$$

Modern formula

$$\tau_{\mathrm{GP}}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{\mathrm{HI}}}{n_{\mathrm{H}}}\right)$$

A neutral fraction $x_{HI} \approx 10^{-4}$ gives rise to complete GP absorption



Lyman Forest Absorption

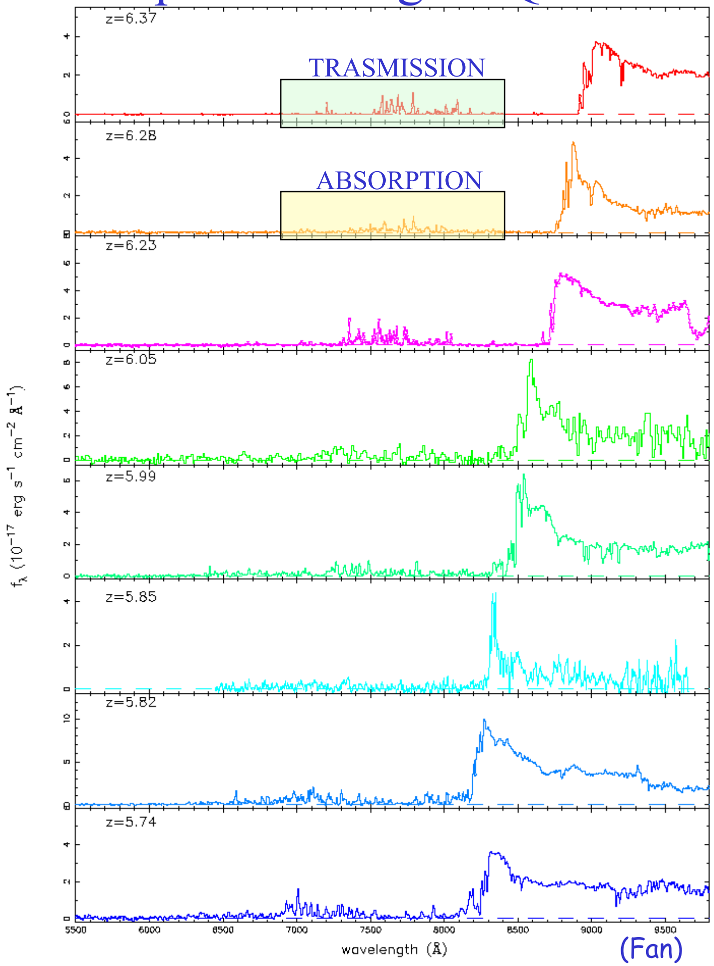
Patchy Absorption

Black Gunn-Peterson trough

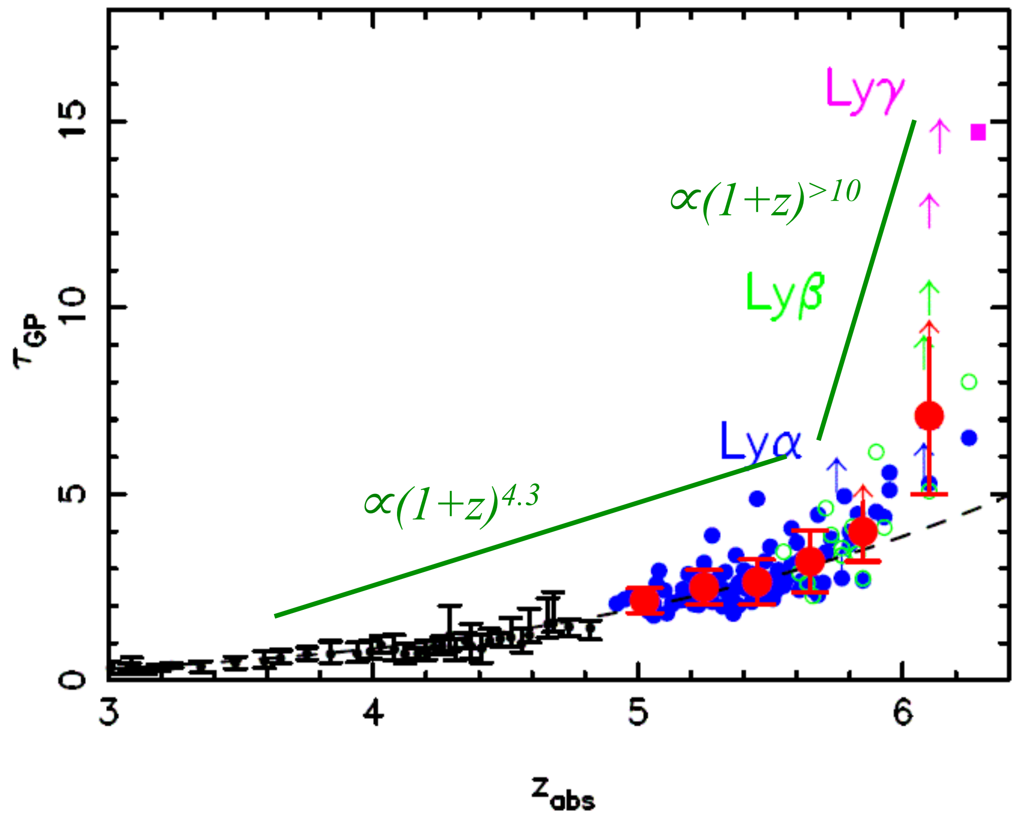
Fan 2006

GUNN-PETERSON EFFECT

Spectra of high-*z* QSOs



Lyα optical depth



SOURCE LIST

- Stars: Pop II and/or (massive) Pop III

  In what proportion ? (4, 30, 100)×10^3 phot/baryon into stars

- Quasars

  Too rare, too late; key sources for HeII reionization

- Supernova explosions

  Filling factor too small; Compton-y limited

- Dark Matter: decays/annihilations

  Light particles (LDM, sterile neutrinos) can produce a $\tau_e < 0.01$
  Heavy particles (neutralinos, gravitinos) totally negligible

- Mini-quasars

  Limited by unresolved SXRB
  Only 3 phot/baryon in IGM in 10 Salpeter times

- Structure formation

  Important for HeII reionization, bremsstrahlung has $f_{esc} \approx 1$!

CMB

Reionization affects CMB in three ways:

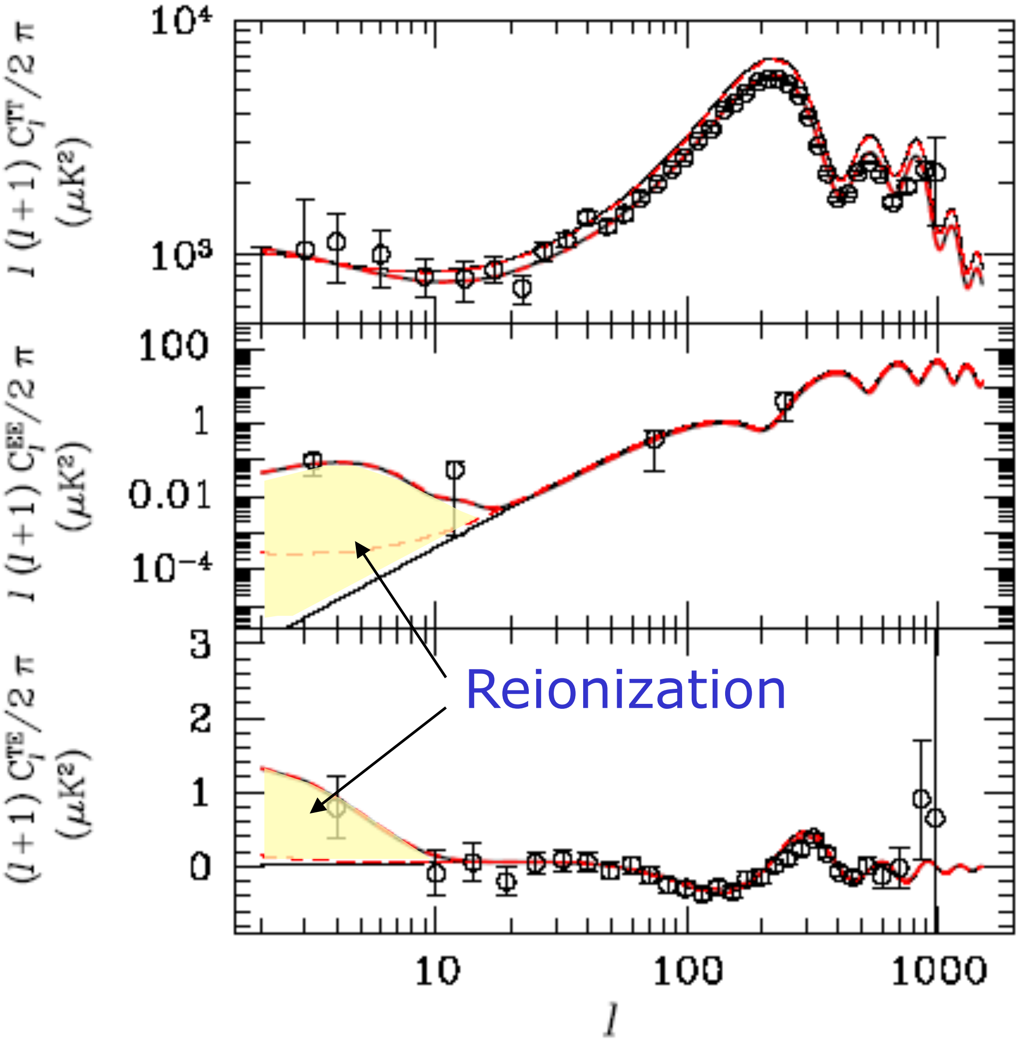
1. Damping of primary anisotropies on all scales
2. Small scale secondary anisotropies (patchy reionization)
3. Large scale polarization signal

ELECTRON SCATTERING OPTICAL DEPTH

$$\tau_e(z_{\rm rei}) = \int_0^{z_{\rm rei}} n_e \sigma_T (1+z)^{-1} \left[c/H(z) \right] dz$$

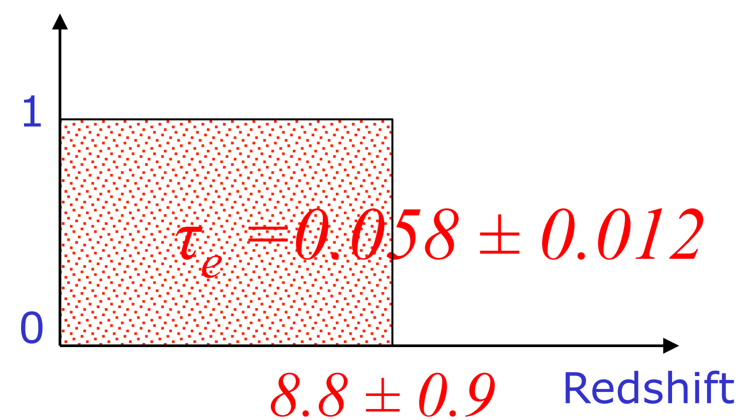
$$\tau_e(z_{\rm rei}) \approx \left(\frac{c\,\sigma_T}{H_0}\right) \left(\frac{2\Omega_b}{3\Omega_m^{1/2}}\right) \left[\frac{\rho_{\rm cr}(1-Y)(1+y)}{m_H}\right] (1+z_{\rm rei})^{3/2} \approx (0.0521) \left[\frac{(1+z_{\rm rei})}{8}\right]^{3/2}$$

CMB POLARIZATION



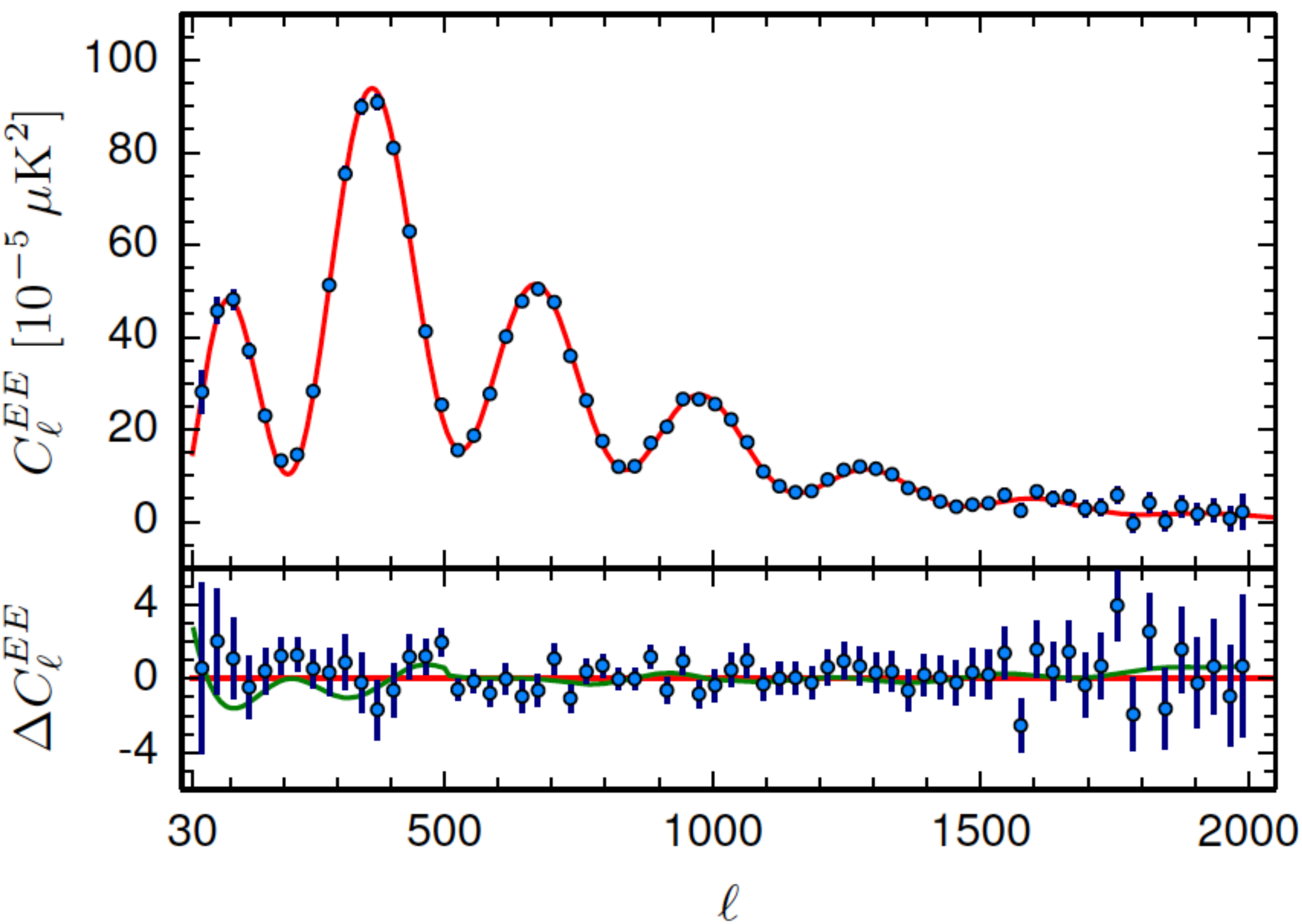
PLANCK XLVII (2016)

Electron fraction



Planck Collaboration 15

PLANCK POLARIZATION DATA



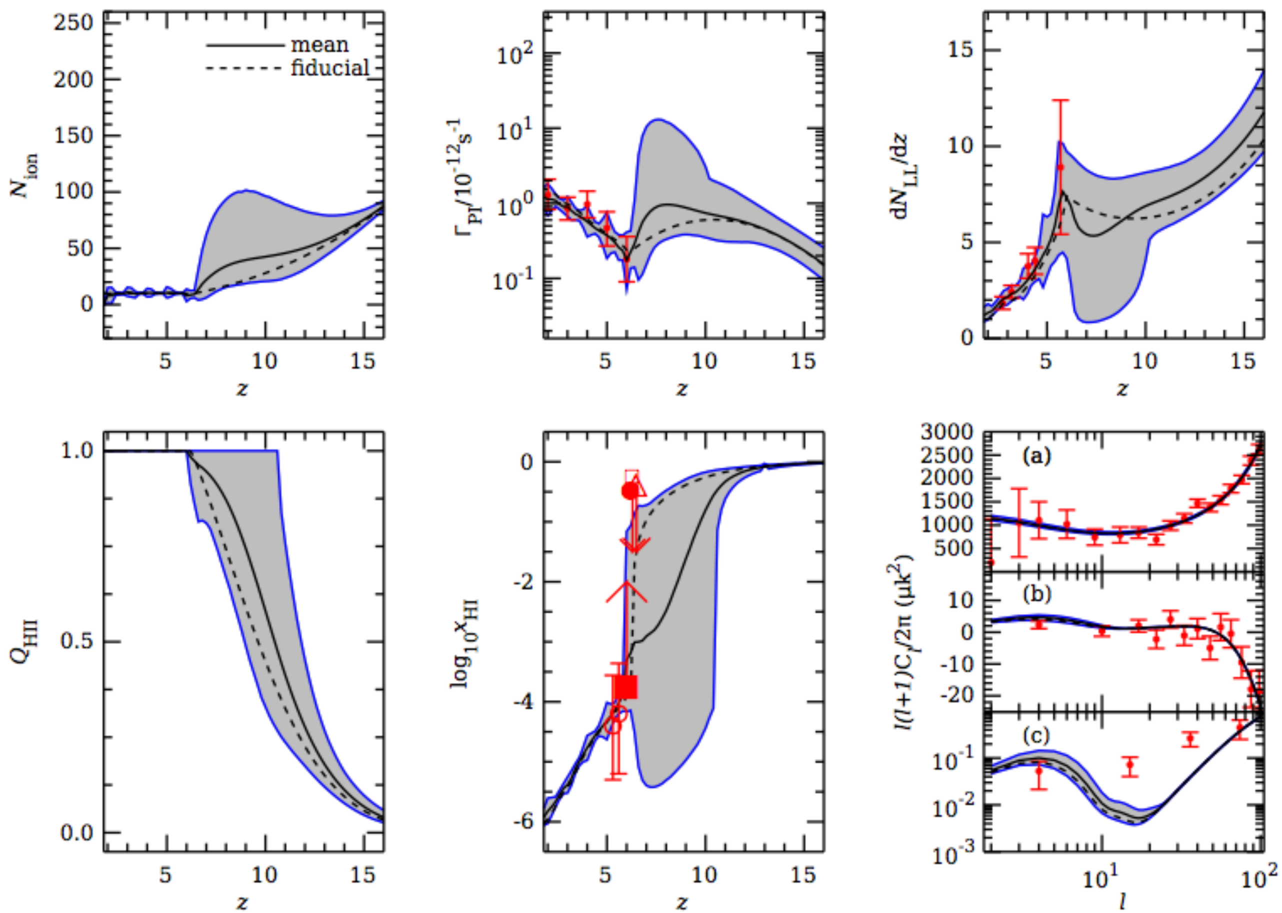
EXPERIMENTAL CONSTRAINTS

- Lyα Gunn-Peterson opacity
- Electron scattering optical depth
- Lyβ Gunn-Peterson opacity
- UV Background intensity
- Redshift evolution of Lyman Limit Systems
- IGM Temperature evolution
- IGM Metallicity
- Cosmic star formation history
- High-z galaxy counts
- Near Infrared Background

CONSTRAINING REIONIZATION

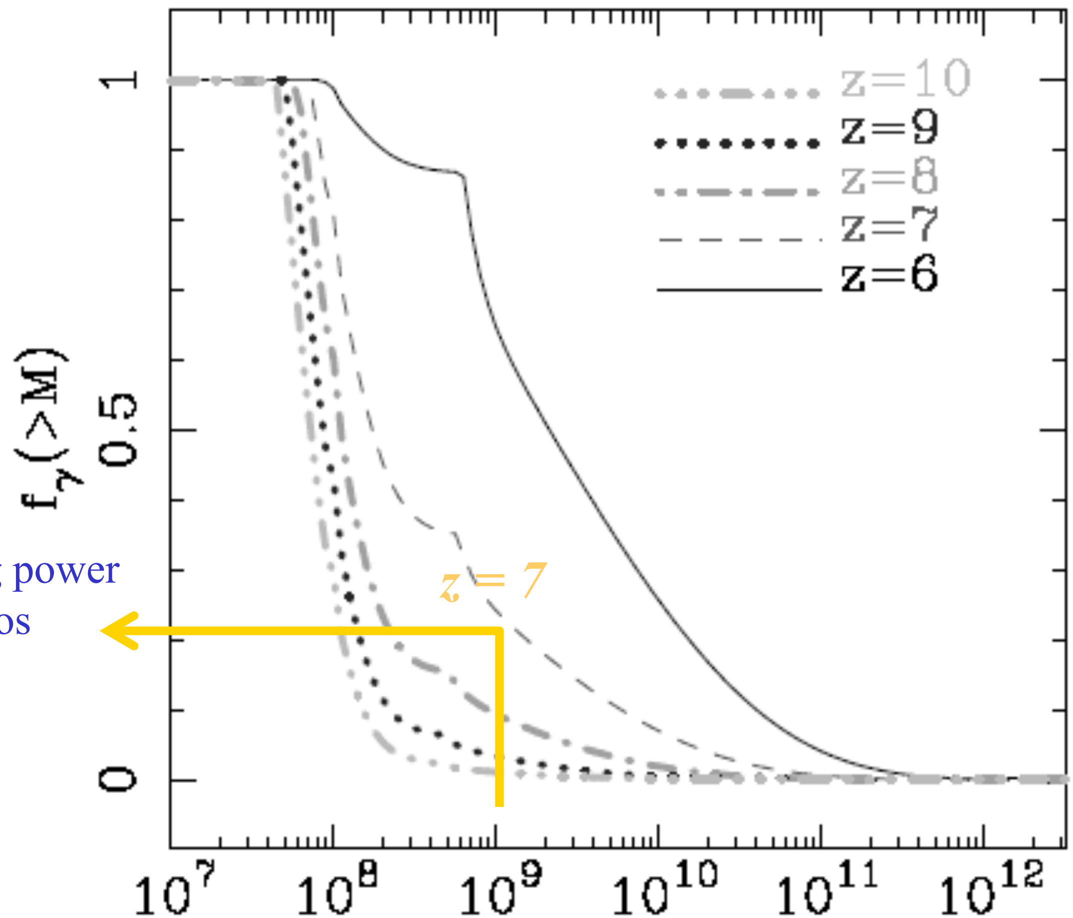
PCA/MCMC Constraints

Effective Ion. photons/baryon | Photoionization rate | Lyman Limit Systems



Porosity factor | Neutral hydrogen fraction | CMB spectra

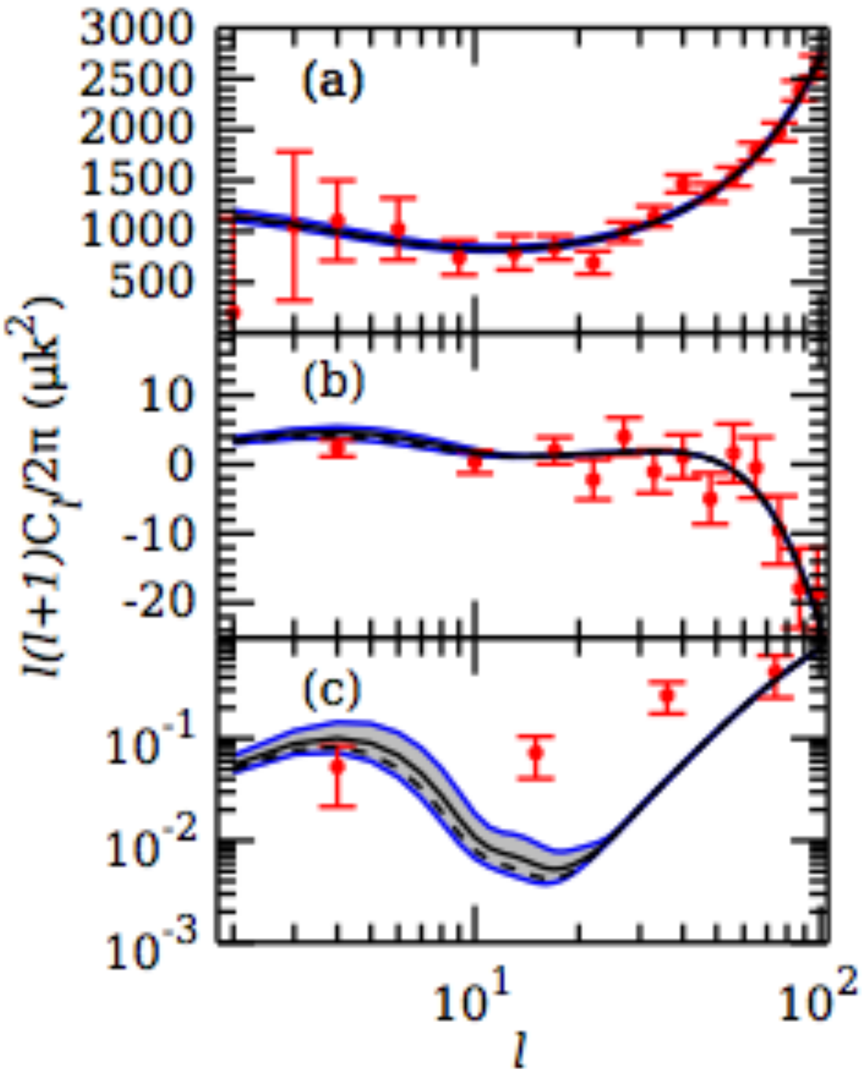
IONIZING PHOTON BUDGET



$f_\gamma > 80\%$ of the ionizing power from $M < 10^9\ M_\odot$ halos

Halo Mass [$M_\odot$]

CONSTRAINING REIONIZATION



IMPACT ON PARAMETERS

Principal components

$$x_e(z) = x_e^f(z) + \sum_\mu m_\mu S_\mu(z),$$

$$m_\mu = \frac{1}{z_{max} - z_{min}} \int_{z_{min}}^{z_{max}} dz\; S_\mu(z) \delta x_e(z)$$

PC amplitudes

IMPACT ON PARAMETERS

Principal Component + MCMC Analysis

Parameter	WMAP7	WMAP7 + PC	WMAP7 + ASTRO
Ω_m	0.266 ± 0.029	0.243 ± 0.032	0.273 ± 0.027
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02321 ± 0.00076	0.02183 ± 0.00054
h	0.710 ± 0.025	0.735 ± 0.033	0.698 ± 0.023
n_s	0.963 ± 0.014	0.994 ± 0.023	0.958 ± 0.013
σ_8	0.801 ± 0.030	—	0.794 ± 0.027
τ_e	0.088 ± 0.015	0.093 ± 0.010	0.080 ± 0.012
$z_r{}^*$	10.5 ± 1.2	—	6.7 ± 0.6

Lecture #2

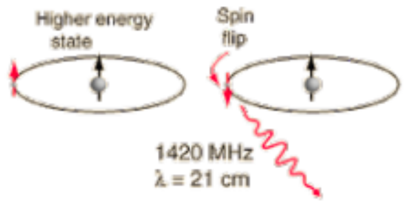
HI 21 cm line intensity mapping

DRAWBACKS

- Lya line powerful probe of reionization but the GP opacity is enormous
- CMB probes only provide integrated measurements of the electron scattering optical depth, i.e. no sensitivity to specific redshift

Spin-flip (hyperfine) transition of neutral hydrogen
[due to electron-proton magnetic interactions]

LINE RADIATIVE TRANSFER



$$\frac{dI_\nu}{d\ell} = \frac{\phi(\nu)h\nu}{4\pi}\left[n_1 A_{10} - (n_0 B_{01} - n_1 B_{10}) I_\nu\right]$$

- I_ν: specific line intensity
- $\phi(\nu)$: line profile
- A_{ij}, B_{ij} : Einstein coefficients

Line frequency ν_{21}=1420.4057 MHz or λ_{21}=21.1061 cm

LINE RADIATIVE TRANSFER

$$\left(\frac{n_1}{n_0}\right) = \left(\frac{g_1}{g_0}\right) \exp\left\{\frac{-T_*}{T_S}\right\}$$

- $g_1/g_0 = 3$ (spin degeneracy factors)
- $T_* = E_{10}/k_B = 68$ mK
- T_S : spin temperature

Usually $T_* << T_S,\ T_\gamma$ hence $n_1 = 3n_0$

[stimulated emission is important]

BRIGHTNESS TEMPERATURE

Effective temperature required by a black body radiator such that

$$I_\nu = B_\nu(T_b)$$

At radio-frequencies, we work in the Raleigh-Jeans approximation. Hence

$$T_b(\nu) \approx I_\nu c^2 / 2k_B \nu^2$$

The RT equation can be casted in terms of the *brightness temperature*

$$T_b'(\nu) = T_S(1 - e^{-\tau_\nu}) + T_R'(\nu) e^{-\tau_\nu}$$

- $T_b(\nu) = T'_b(\nu)/(1+z)$ is the *observed* brightness temperature
- $T'_b(\nu)$ is the brightness temperature in the cloud framework
- $T'_R(\nu)$ is the brightness of the background radiation field along the l.o.s.

LINE OPTICAL DEPTH

$$\tau_\nu \equiv \int ds\, \alpha_\nu$$

The absorption coefficient depends on the Einstein coefficients

$$\alpha = \phi(\nu)\frac{h\nu}{4\pi}(n_0 B_{01} - n_1 B_{10})$$

Derivation similar to GP opacity. Use $\phi(\nu) \approx (\Delta\nu)^{-1}$

$$\tau_{10} = \frac{3}{32\pi}\frac{hc^3 A_{10}}{k_B T_S \nu_{10}^2}\frac{x_{\rm HI} n_{\rm H}}{(1+z)(dv_\parallel/dr_\parallel)}$$
$$\approx 0.0092\,(1+\delta)\,(1+z)^{3/2}\,\frac{x_{\rm HI}}{T_S}\left[\frac{H(z)/(1+z)}{dv_\parallel/dr_\parallel}\right]$$

OBSERVED SIGNAL

We observe the *contrast* T_b-T_R between cloud and background, i.e. CMB

Small optical depth limit, $\tau_\nu << 1$

$$T_b(\nu) \approx \frac{T_S - T_\gamma(z)}{1+z}\,\tau_{\nu_0}$$

$$\approx \quad 9\,x_{\rm HI}(1+\delta)\,(1+z)^{1/2}\left[1-\frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{dv_\parallel/dr_\parallel}\right]\,{\rm mK}$$

Note that

- If $T_S > T_\gamma$ the signal appears in emission
- If $T_S < T_\gamma$ the signal appears in absorption
- In emission the signal saturates; in absorption it can become arbitrarily large

SPIN TEMPERATURE

Determined by

- Interactions with CMB photons [drive $T_S = T_\gamma$]
- Particle collisions [drive T_S away from T_γ]
- Scattering of UV photons [drive T_S away from T_γ]

Detailed balance

UV photons CMB-stimulated

$$n_1 \left(C_{10} + P_{10} + A_{10} + B_{10} I_{\rm CMB} \right) = n_0 \left(C_{01} + P_{01} + B_{01} I_{\rm CMB} \right)$$

collisions spontaneous

SPIN TEMPERATURE

In the Rayleigh-Jeans regime the detailed balance eq. reads

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha},$$

where, by definition,

kinetic temperature

$$\frac{C_{01}}{C_{10}} = \frac{g_1}{g_0} e^{-T_\star/T_K} \approx 3\left(1 - \frac{T_\star}{T_K}\right)$$

color temperature

$$\frac{P_{01}}{P_{10}} \equiv 3\left(1 - \frac{T_\star}{T_c}\right)$$

Most often, $T_c \approx T_K$ in which case

$$1 - \frac{T_\gamma}{T_S} = \frac{x_c + x_\alpha}{1 + x_c + x_\alpha}\left(1 - \frac{T_\gamma}{T_K}\right)$$

COUPLINGS

Collisional coupling

$$x_c^i \equiv \frac{C_{10}^i}{A_{10}} \frac{T_\star}{T_\gamma} = \frac{n_i \kappa_{10}^i}{A_{10}} \frac{T_\star}{T_\gamma}$$

i = hydrogen atoms, electrons

Critical overdensity at which x_c=1 for H-H collisions

$$1+\delta_{\rm coll} = 0.99 \left[\frac{\kappa_{10}(88\ {\rm K})}{\kappa_{10}(T_K)}\right] \left(\frac{0.023}{\Omega_b h^2}\right) \left(\frac{70}{1+z}\right)^2$$

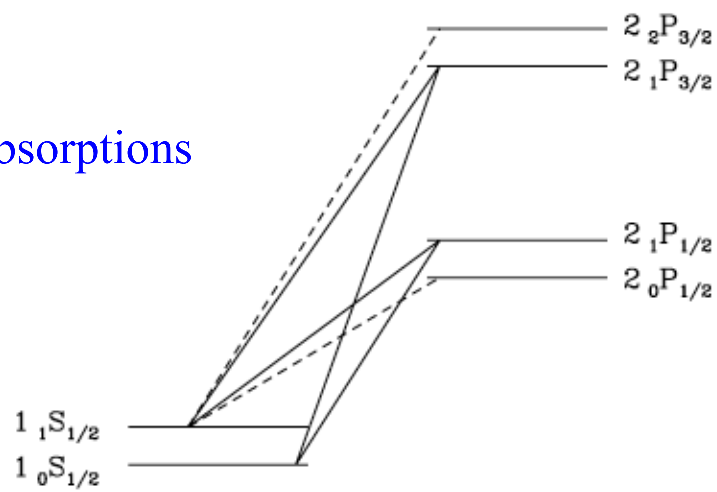
At z < 70, x_c becomes very small and hence $T_S \approx T_\gamma$

By z ≈ 30 the IGM would become invisible

COUPLINGS

UV coupling [Wouthuysen-Field effect]

Lya photon absorptions



Hyperfine splittings of the 1S and 2P levels. The solid lines label transitions that mix the ground state hyperfine levels, while the dashed lines label complementary allowed transitions that do not participate in mixing.

$$x_\alpha = \frac{4P_\alpha}{27A_{10}} \frac{T_\star}{T_\gamma}$$

$$P_\alpha = 4\pi\sigma_0 \int d\nu \, J_\nu(\nu)\phi_\alpha(\nu)$$

POWER SPECTRUM

Define the fractional perturbation to the brightness temperature

$$\delta_{21}(\mathbf{x}) \equiv [T_b(\mathbf{x}) - \bar{T}_b]/\bar{T}_b \qquad \text{(zero mean field)}$$

Perform its Fourier transform: $\tilde{\delta}_{21}(\mathbf{k})$

The 21cm power spectrum, $P_{21}(\mathbf{k})$ is defined by

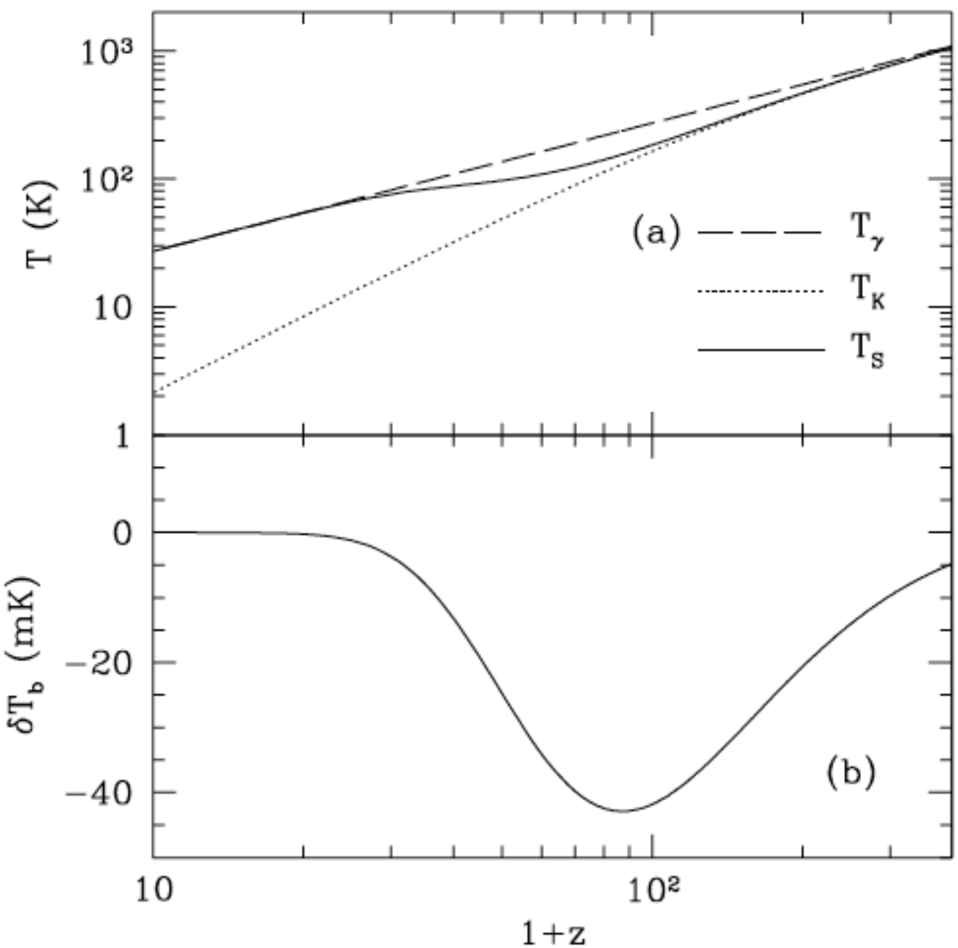
$$\left\langle \tilde{\delta}_{21}(\mathbf{k}_1)\,\tilde{\delta}_{21}(\mathbf{k}_2) \right\rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_1 - \mathbf{k}_2) P_{21}(\mathbf{k}_1)$$

kinetic temperature

Dirac-delta

Dimensionless version $\Delta^2(\mathbf{k}) = (k^3/2\pi^2)P(\mathbf{k})$

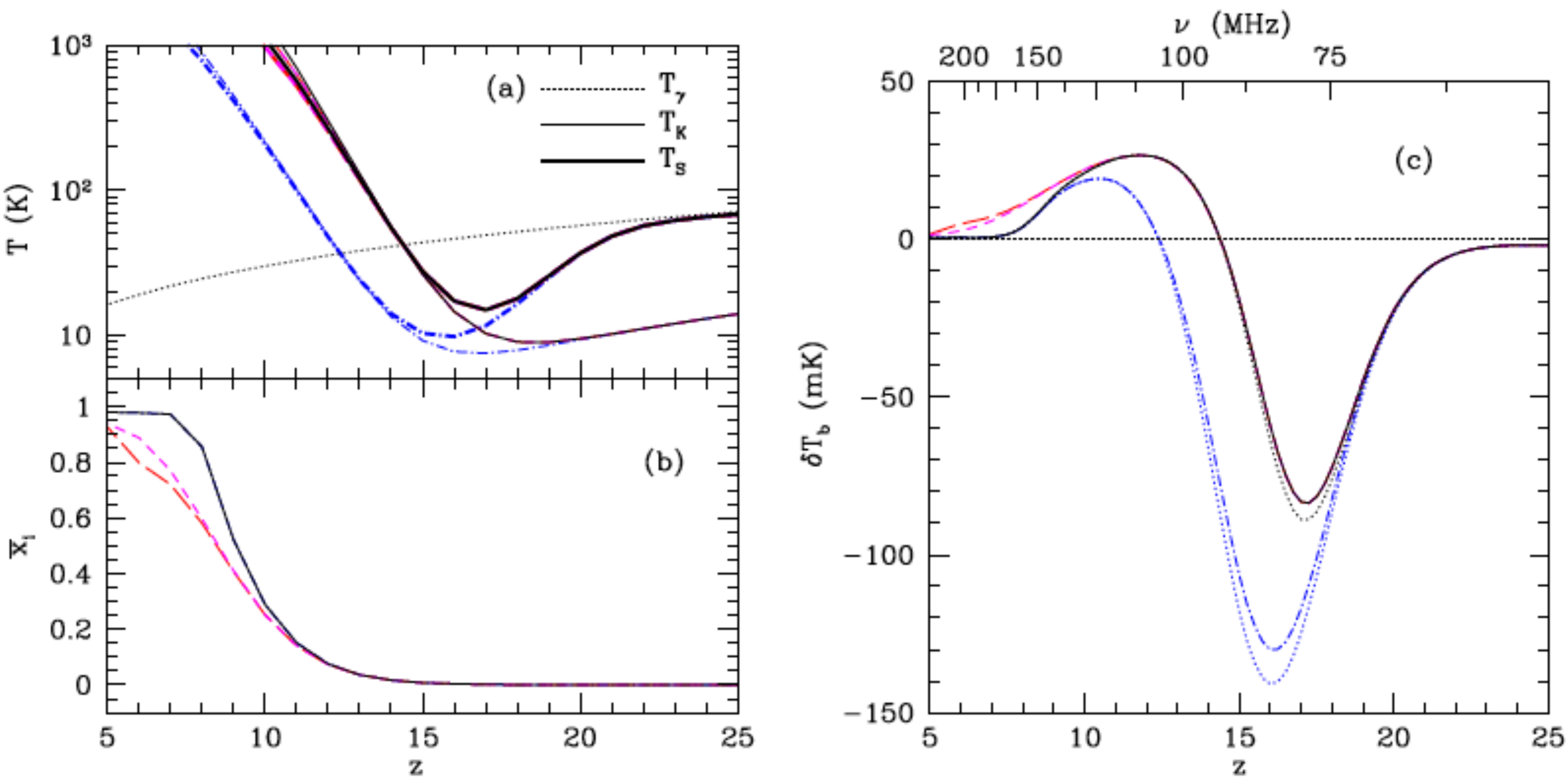
GLOBAL HISTORY (NO HEATING)



IGM temperature evolution including only adiabatic cooling and Compton heating. The spin temperature includes only collisional coupling.

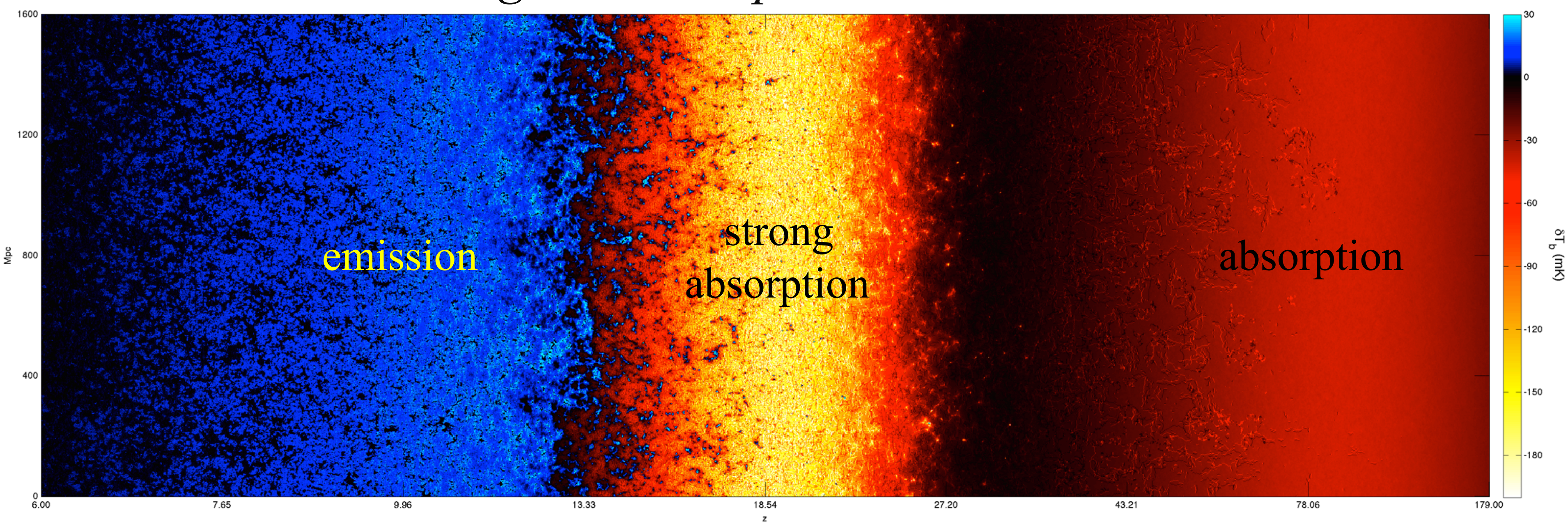
Corresponding differential brightness temperature against the CMB

GLOBAL SIGNAL: ADD REIONIZATION



SIMULATED SIGNAL

Brightness Temperature Evolution



6 — *15* — *27* — *redshift*

Epoch of Reionization

- *IGM warmer than CMB*
- *Strong $T_s - T_k$ coupling*

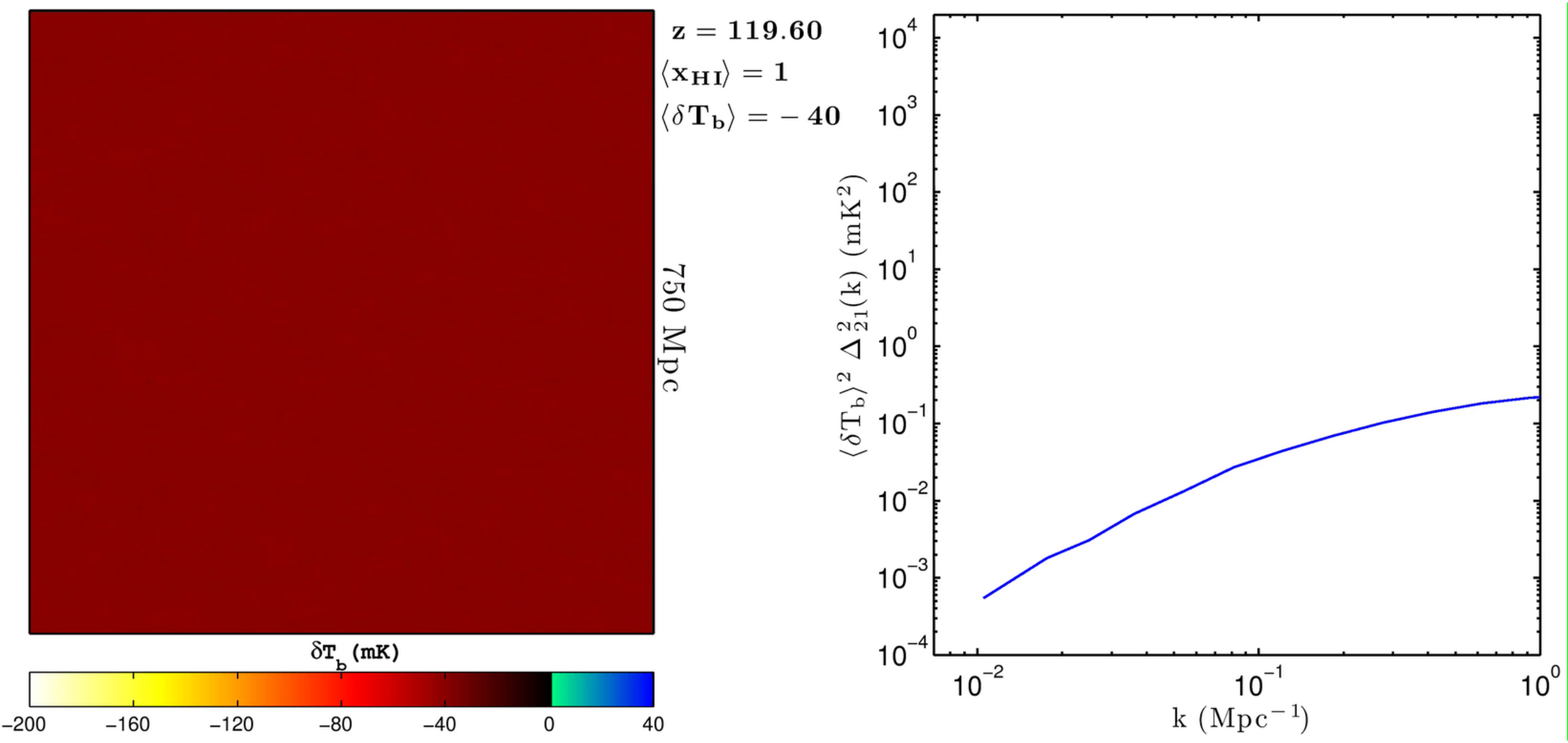
Cosmic Dawn

- *IGM colder than CMB*
- *Lya coupling (WF effect)*
- ***X-ray preheating***

Dark Ages

- *IGM colder than CMB*
- *Weak $T_s - T_k$ coupling*

SIMULATED POWER SPECTRUM

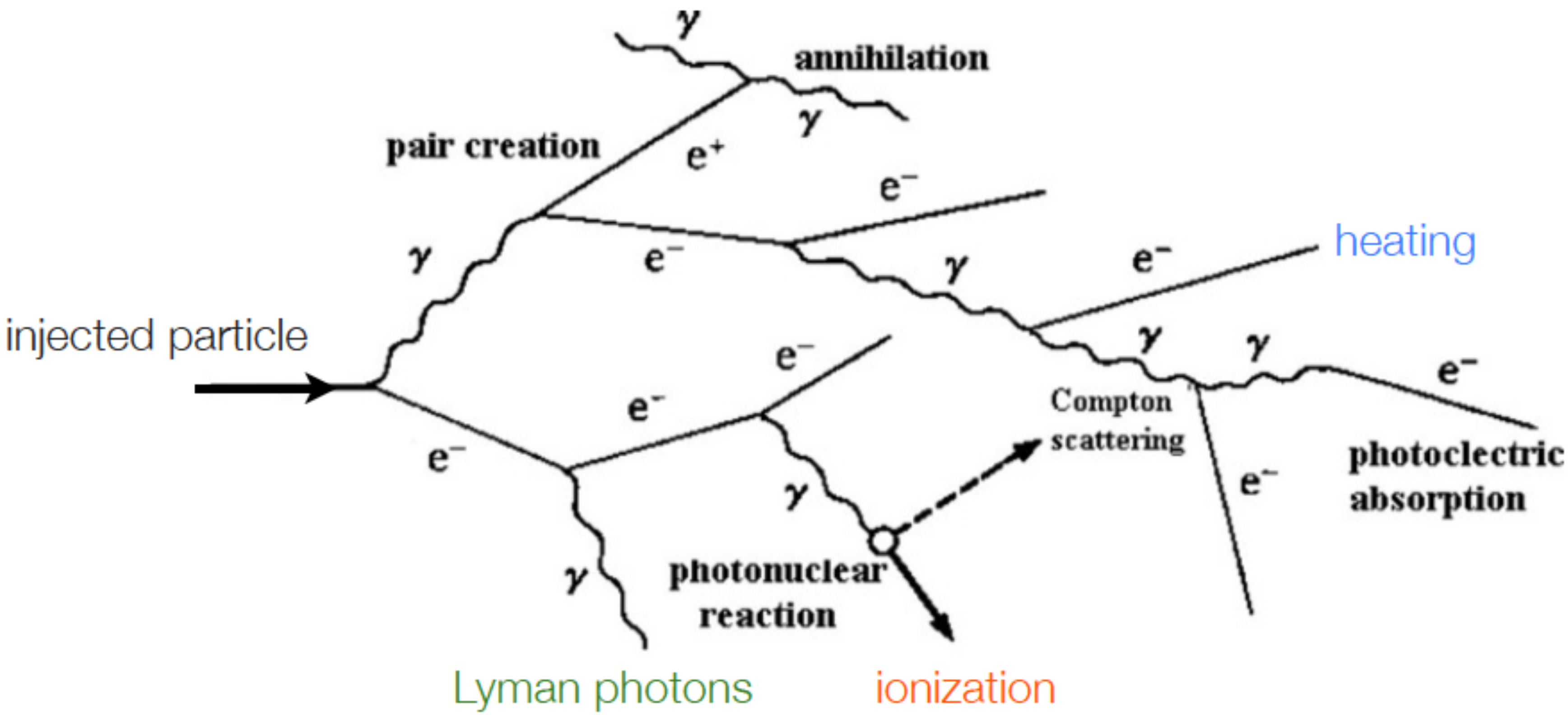


HEATING PROCESSES

- X-ray heating from astrophysical sources
- Lya heating
- Dark matter annihilation/decay heating
- Shock heating

Valdes & AF 09; Mapelli+10; Evoli+12

DARK MATTER HEATING



Evoli, Mesinger & AF+14

IONIZATION AND HEATING

IONIZATION EQUATION

$$\frac{dx_e}{dz} = \frac{dt}{dz}\left[\Gamma_{\rm ion} - \alpha_{\rm B} C x_e^2 n_b f_{\rm H}\right] \ ,$$

$$\frac{dT_K}{dz} = \frac{2T_K}{1+z} + \frac{2T_K}{3n_b}\frac{dn_b}{dz} - \frac{T_K}{1+x_e}\frac{dx_e}{dz} + \frac{2}{3k_B(1+f_{He}+x_e)}\frac{dt}{dz}\sum_p \epsilon_p$$

ENERGY EQUATION

Compton heating
Astrophysical X-ray sources
Dark matter annihilations

DARK MATTER HEATING

HEATING RATE

$$\mathcal{E}_\chi = \frac{1}{n_b}\frac{dE}{dtdV}(z) = (1+z)^3 \frac{\Omega_\chi^2}{\Omega_b}\rho_{c,0}[1+B(z)]m_p c^2 \frac{\langle \sigma v \rangle}{m_\chi}$$

STRUCTURE FORMATION BOOST

$$B(z) = \frac{b_h}{(1+z)^\delta}\mathrm{erfc}\left(\frac{1+z}{1+z_h}\right)$$

Average DM density enhancement from collapsed structures

MINIMUM HALO MASS

$M_{h,min}$ [$M_\odot$]	b_h	z_h	δ
10^{-3}	1.6×10^5	19.5	1.54
10^{-6}	6.0×10^5	19.0	1.52
10^{-9}	2.3×10^6	18.6	1.48

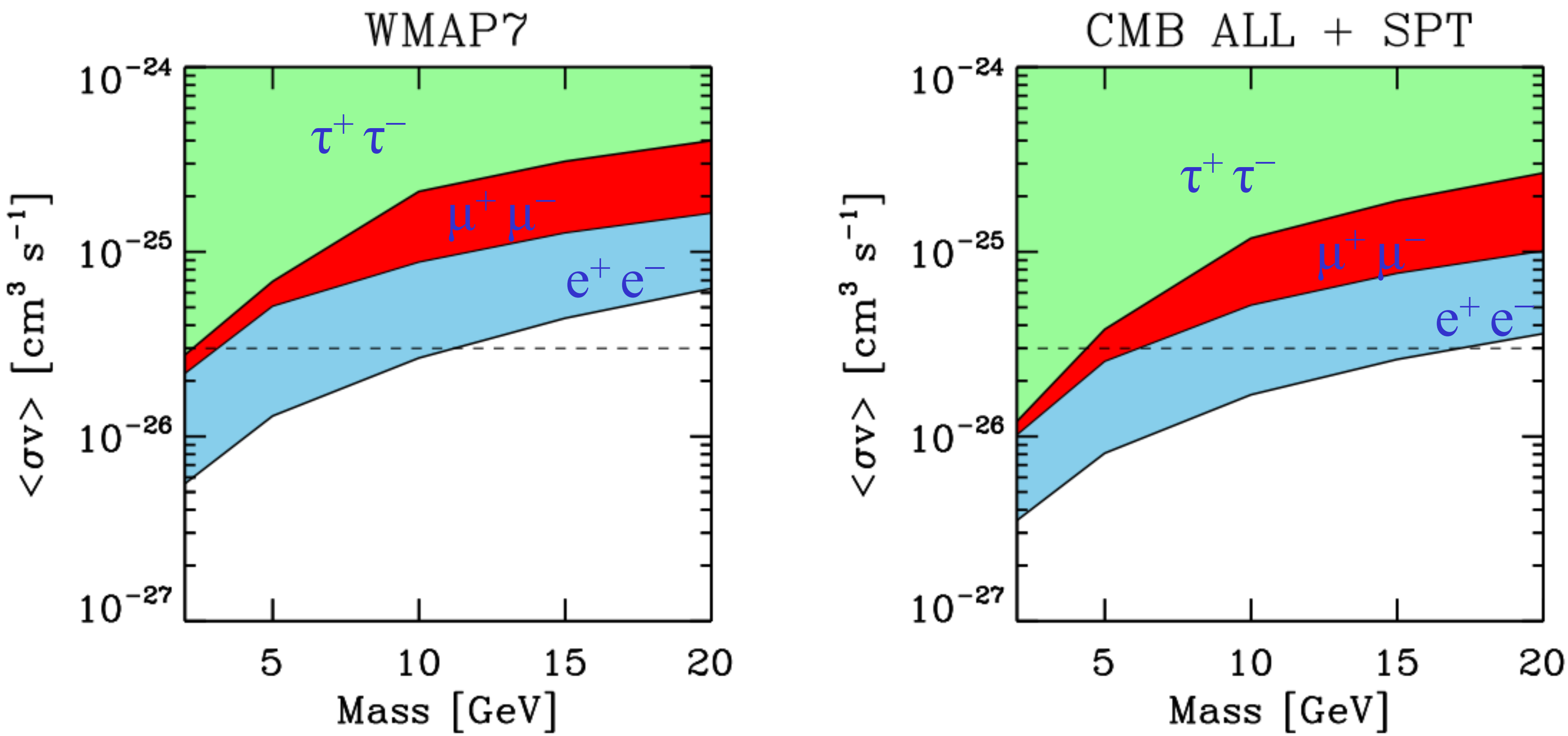
FIDUCIAL CDM CANDIDATE

Light WIMP particle: $m_X = 10$ GeV
Annihilating into $\mu^+\mu^-$
Annihilation cross-section $\langle\sigma v\rangle \leq 4.3\times10^{-26}$ cm^3 s^{-1}

EXPLAINS

- Signal from Galactic Center
- Low-energy signals from direct detections
- Cross-section compatible with combined Planck, WMAP9, ACT, SPT data

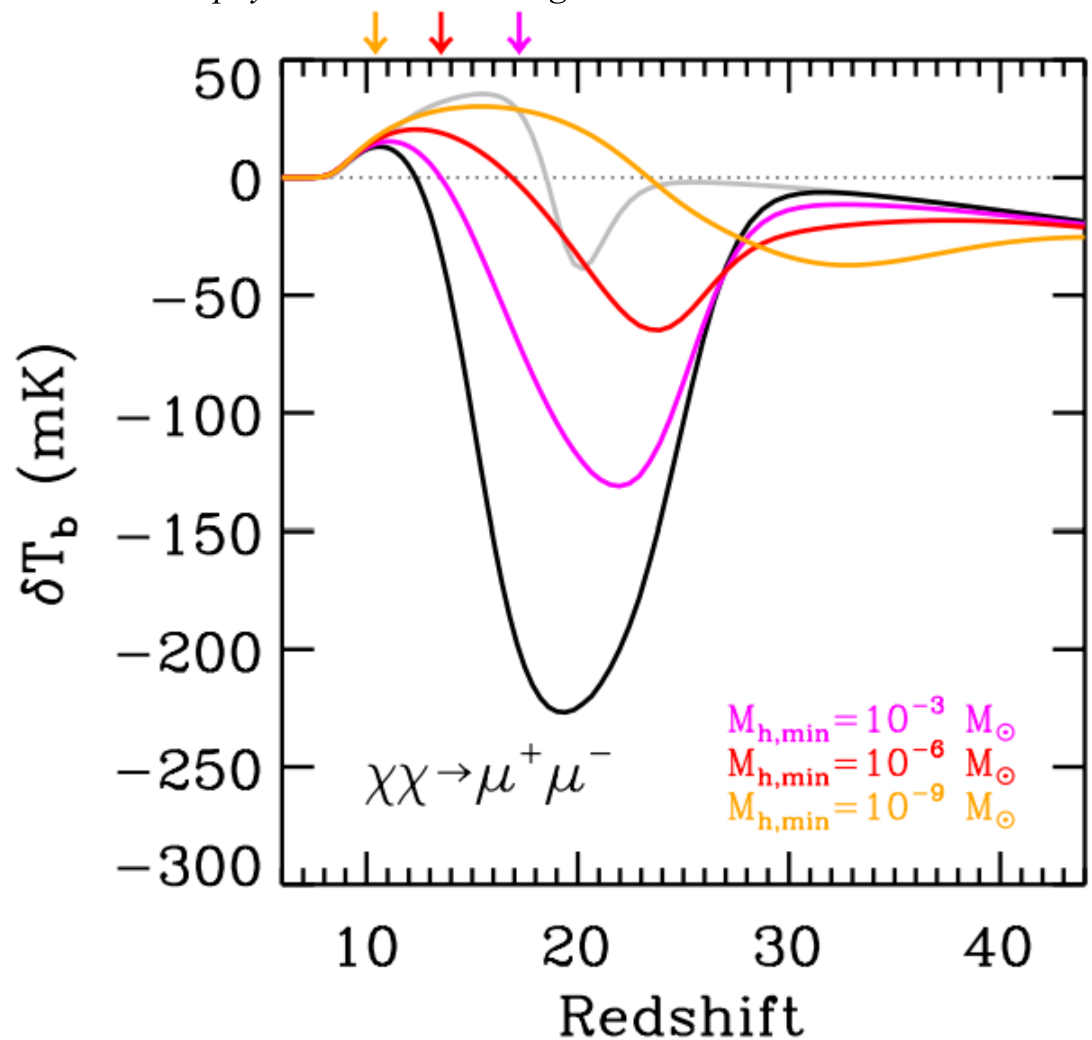
CMB CONSTRAINTS



Evoli, Mesinger & AF+14

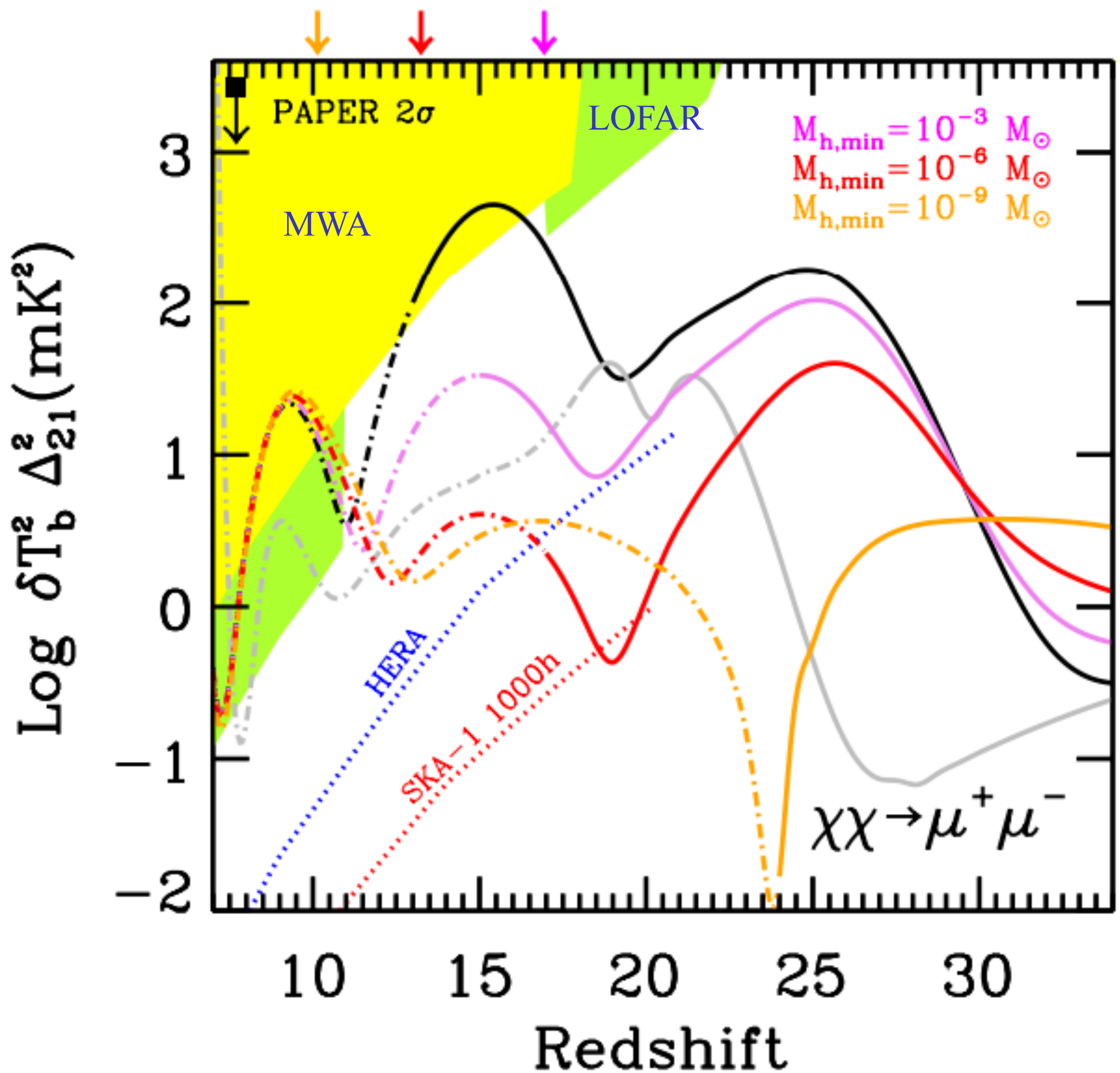
GLOBAL SIGNAL

Transition from DM to astrophysical source heating



Evoli, Mesinger & AF+14

POWER SPECTRUM



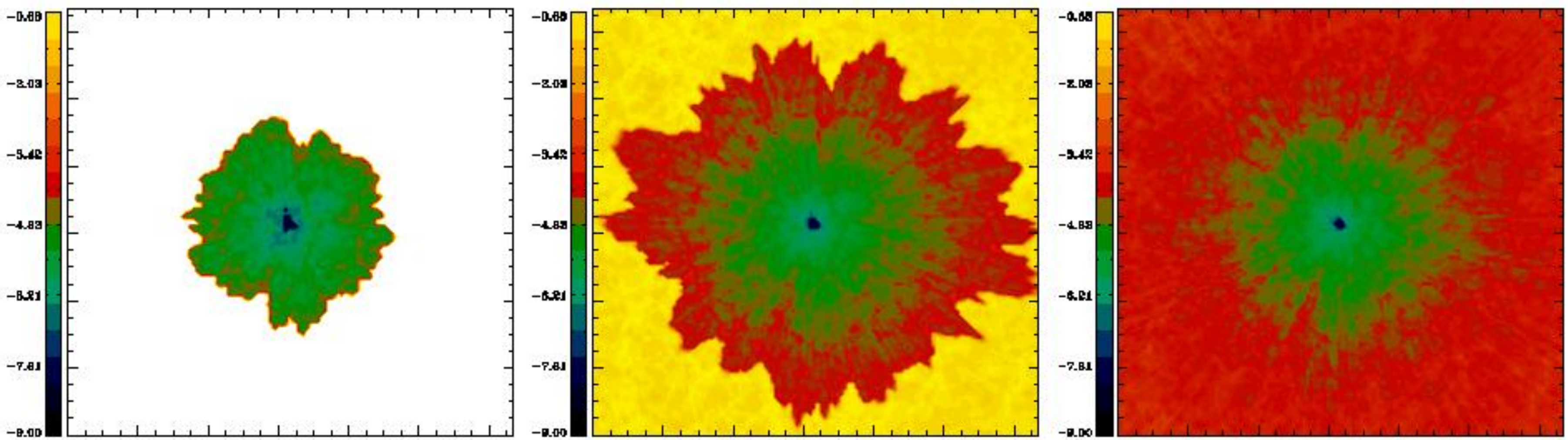
SUMMARY OF DM HEATING EFFECTS

- Depressed second (heating) peak of the power spectrum
- The second peak occurs while the signal is in *emission*
- Such feature *cannot* be produced by astrophysics
- If DM dominates heating, $\delta T_b = 0$ before X-ray sources appear
- A null detection at very high-z would indicate DM *pre-heating*

More reionization tests

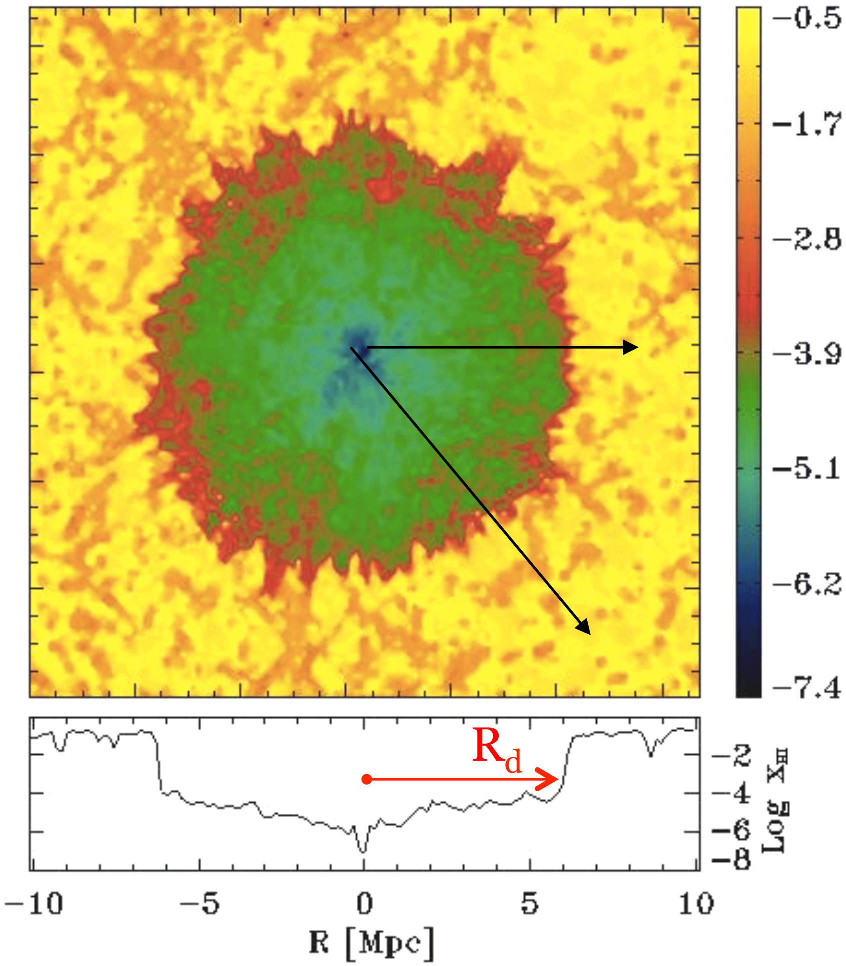
QSO HII REGIONS

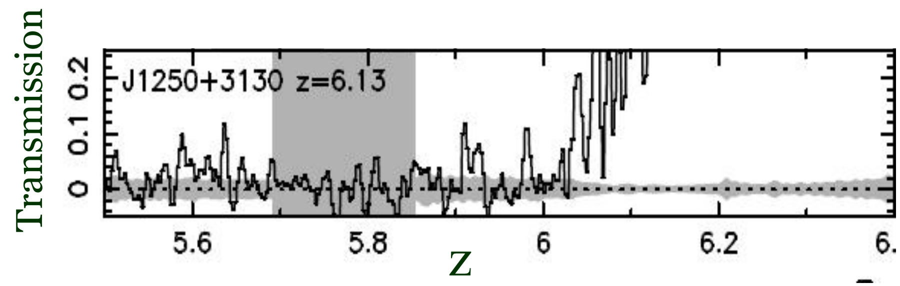
$\langle x_{HI} \rangle = 1.0$ $\langle x_{HI} \rangle = 0.1$ $\langle x_{HI} \rangle = 2.3 \times 10^{-4}$



$$R_d \approx \left(\frac{3\dot{N}_\gamma t_Q}{4\pi n_{\rm H} x_{\rm HI}} \right)^{1/3}$$

QSO HII REGIONS

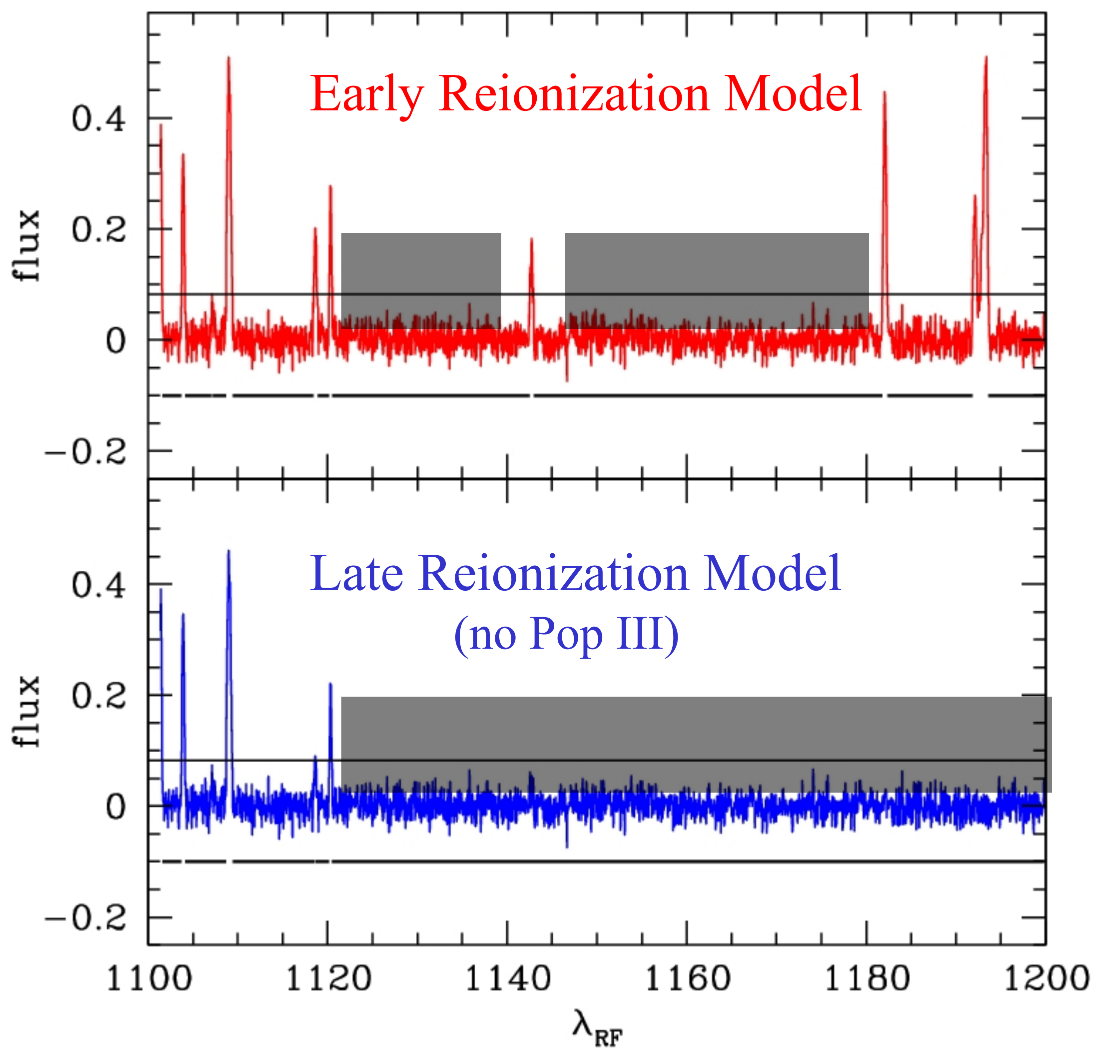




x_{HI}<0.06 @ z=6.13

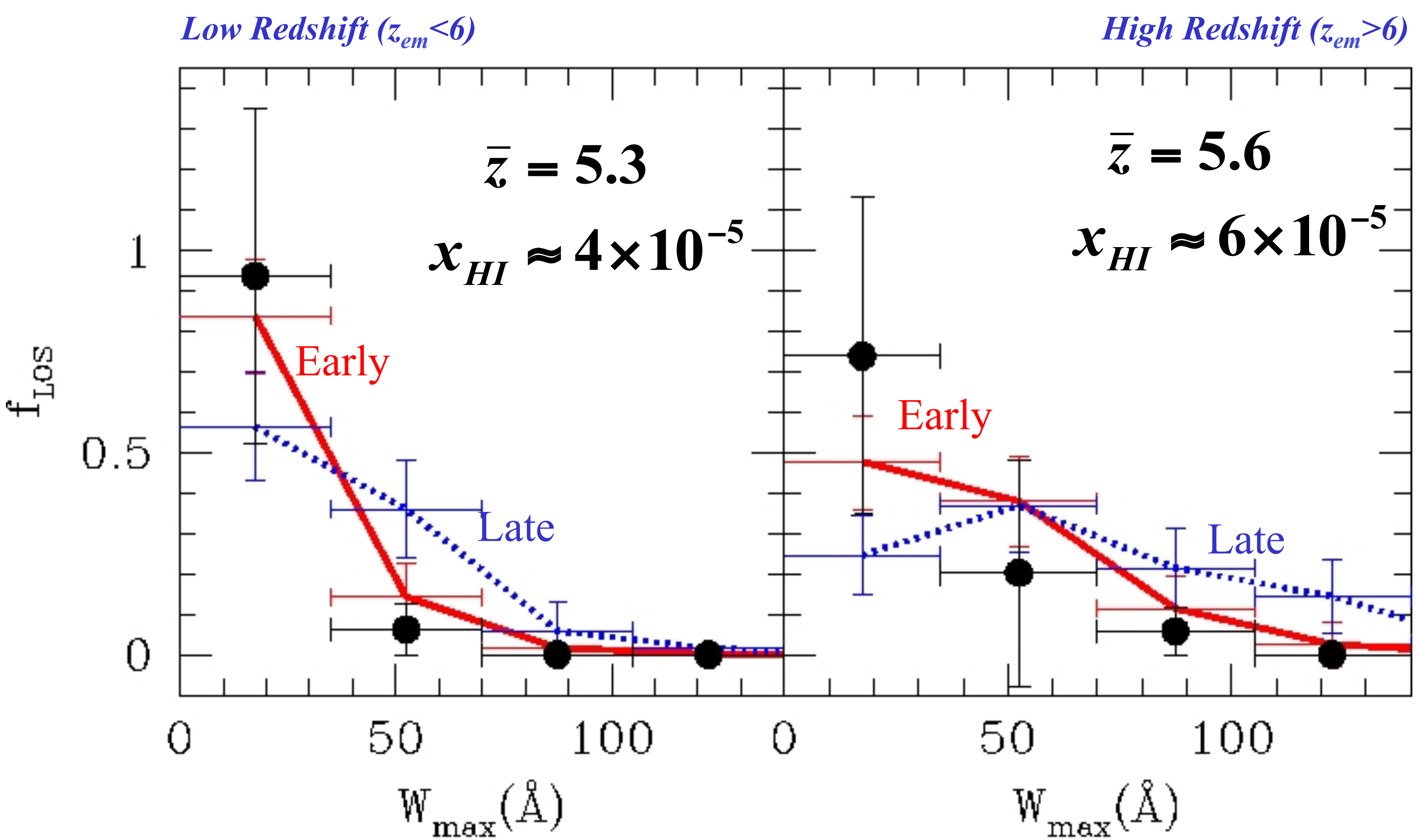
based on the analysis of Fan (2006) QSO sample

GAP STATISTICS



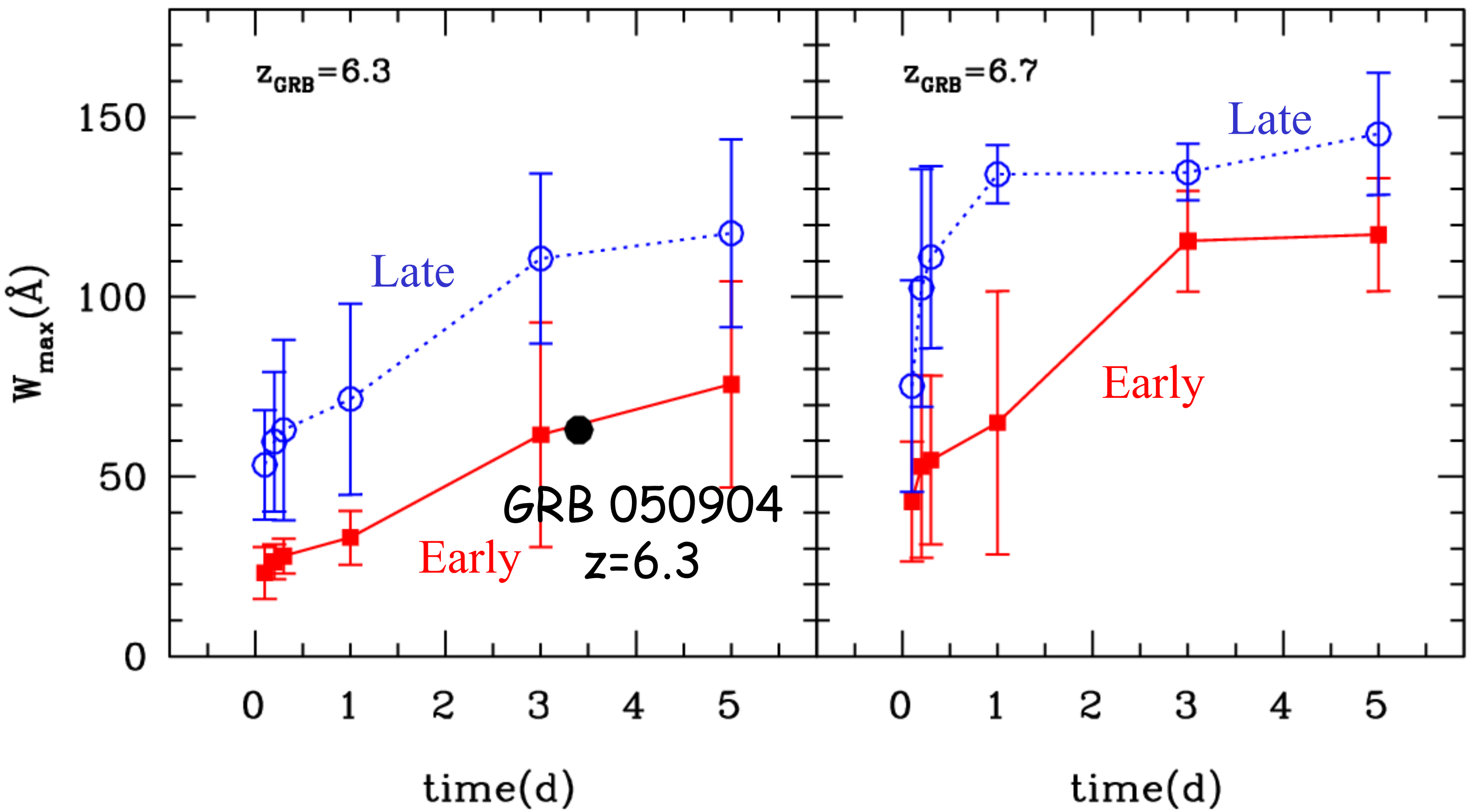
GAPS

GAP STATISTICS



$x_{HI}<0.36$ @ $z=6.3$

GAPS IN GRB AFTERGLOWS



FOUR BASIC FACTS

- Reionization started by metal-free stars @ z=20; 90% complete @ z=8
- Early Reionization ($z > 7$) not in contrast with any QSOAL test (GP, Gaps, HII regions)
- $f_\gamma > 80\%$ of the ionizing power at $z \geq 7$ from halos of $M < 10^9\ M_\odot$
- Bulk of reionization sources not observed yet. Need JWST.