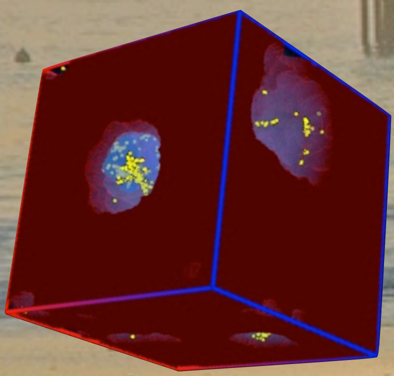
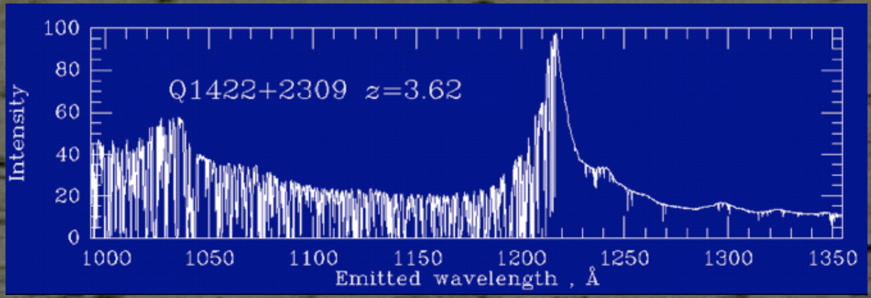
Radiative Transfer in a Clumpy Universe: the UVB

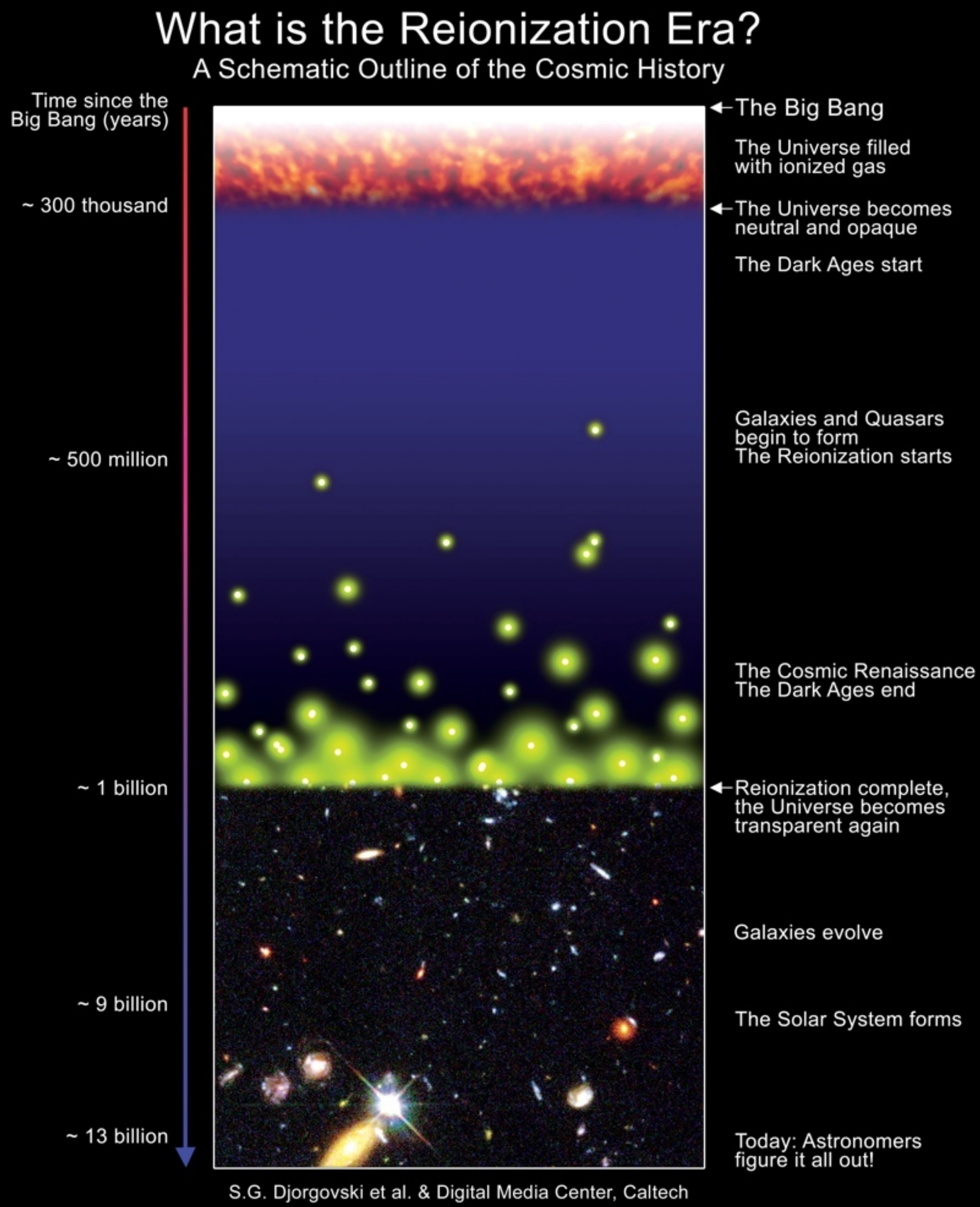




Piero Madau
UC Santa Cruz

The cosmic UVB originates from the integrated emission of star-forming galaxies and QSOs. It determines the thermal and ionization state of the IGM, the repository of most of the baryons in the Universe at high redshift.

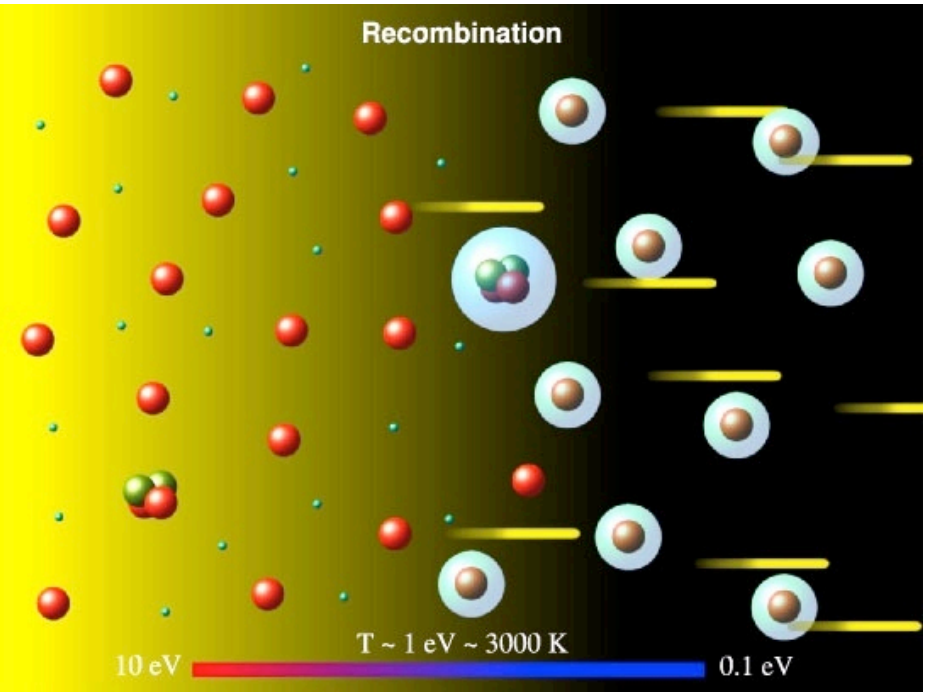
It is a crucial yet most uncertain input parameters for cosmological simulations of LSS and galaxy formation, for interpreting QSO absorption-line data and derive information on the distribution of primordial gas -- traced by HI, HeI, HeII transitions -- and of the nucleosynthetic products of star formation -- CIII, CIV, SiIII, SiIV, OVI, etc.



Outline

Hydrogen recombination
The dark ages
Cosmic structure formation
The reionization equation
Quasars or galaxies?
The Gunn-Peterson trough
Quasar absorbers along the LOS
Effective optical depth of the Universe
Cosmological radiative transfer
CUBA (the code)

Hydrogen recombination



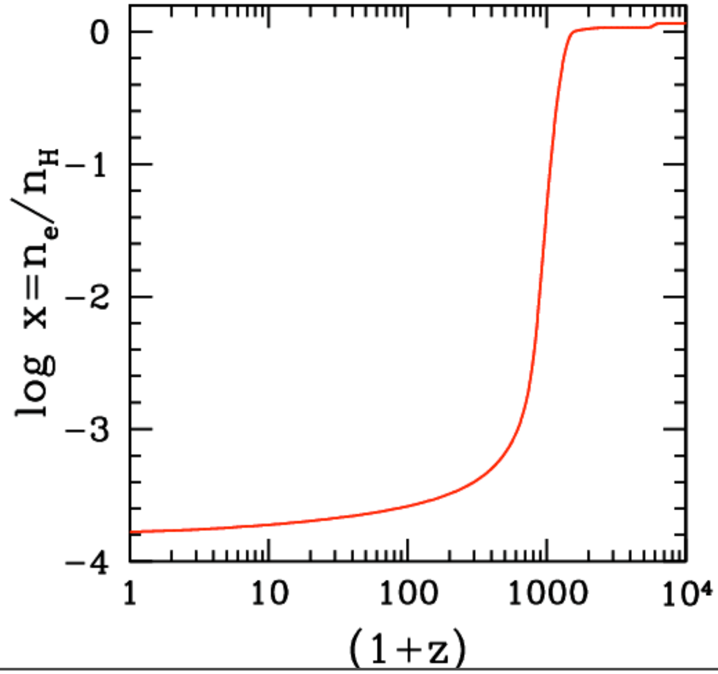
$e^- + p \rightarrow H + \gamma$ @ $z=1100$

marks the end of the plasma era

equilibrium (Saha) eq. for $x \equiv n_e/n_H$

$$\frac{x^2}{1-x} = \underbrace{2.5\times10^6 \eta^{-1}}_{\textit{big coefficient}} \left(\frac{I}{k_B T}\right)^{3/2} \exp\left(-\frac{I}{k_B T}\right)$$

$I=13.6eV$ $\eta^{-1} \equiv n_\gamma/n_b$

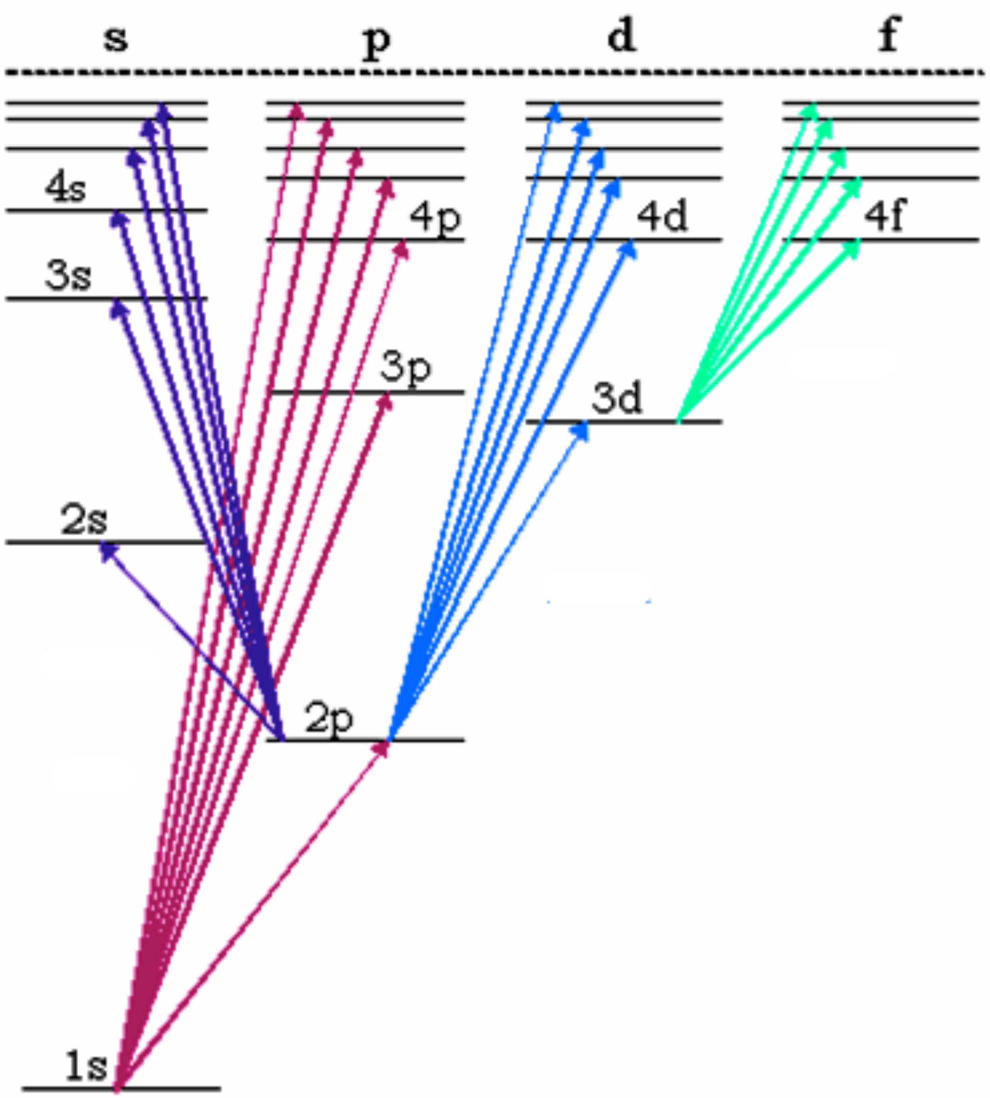


Two factors delay recombination:

(1) $\eta^{-1}=1.5\times10^9 \gg 1$

(2) inability to mantain equilibrium as $H^{-1} \ll t_{\rm rec} \equiv x/\dot{x}$

Hydrogen recombination (a digression)



Zeldovich, Kurt, Sunyaev 1968
Peebles 1968

When an e^- is captured to the ground state of HI, it produces a photon that *immediately ionizes another atom*, leaving no net change.

When it is captured to an excited state, the allowed decay to the ground state produces a resonant Lyman series photon, which has a large capture cross-section → *puts another atom in a high energy state that is easily photoionized again*, thereby annulling the effect.

Two main routes to the production of atomic hydrogen:

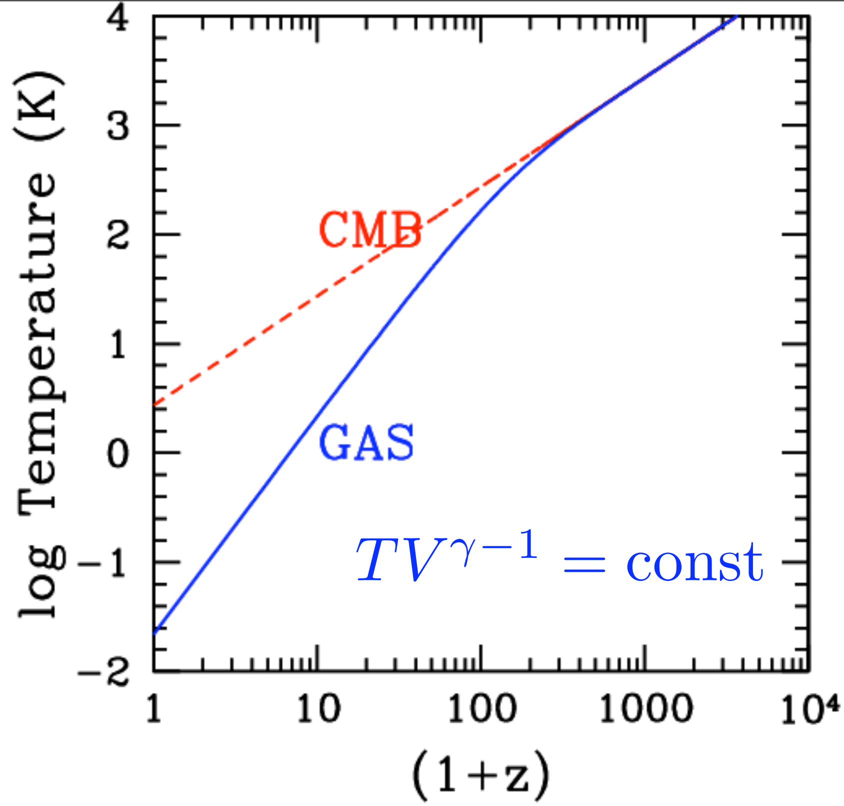
1) two-photon decay from the 2s level to *1s*.
2) loss of Lyα resonance photons by the cosmological redshift.

The "dark ages"...

Timescale for relaxation of matter temperature is

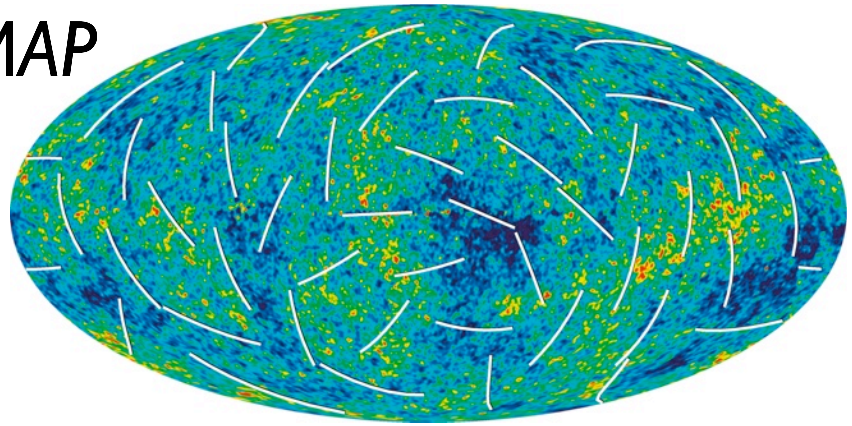
$$t_{\rm comp} = \frac{3m_e c}{4\sigma_T a_B T^4}\,\frac{1+x}{2x}$$

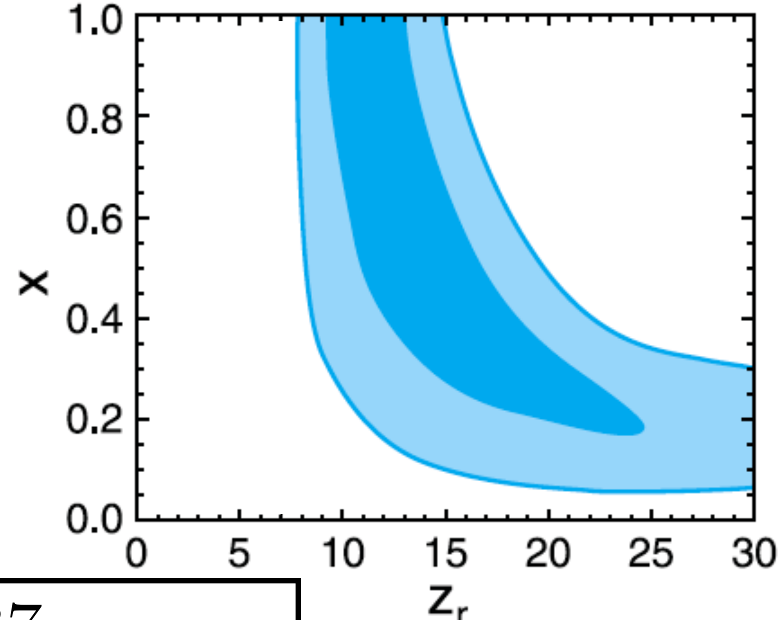
→ $z_{\rm th} \simeq 580(\Omega_b h^2)^{2/5} \simeq 130.$



..and their end

WMAP





$\tau_T(z) = \int_0^z n_e(z)\sigma_T |c\,dt/dz|\,dz = 0.087$

→ Universe becomes semi-opaque after reionization

The "dark ages"...

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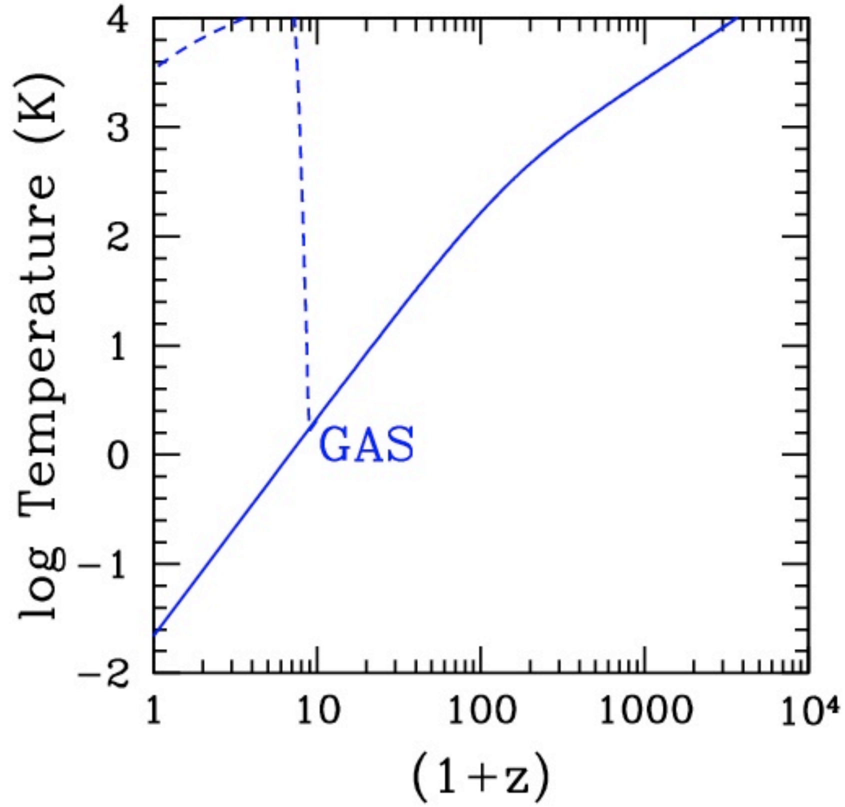
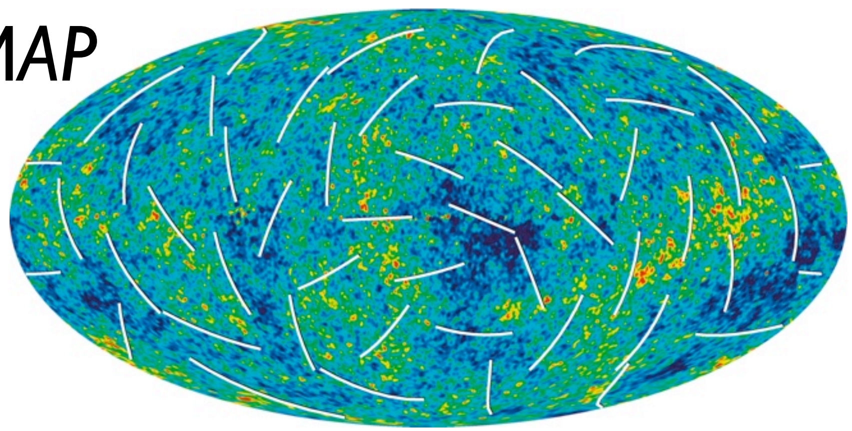
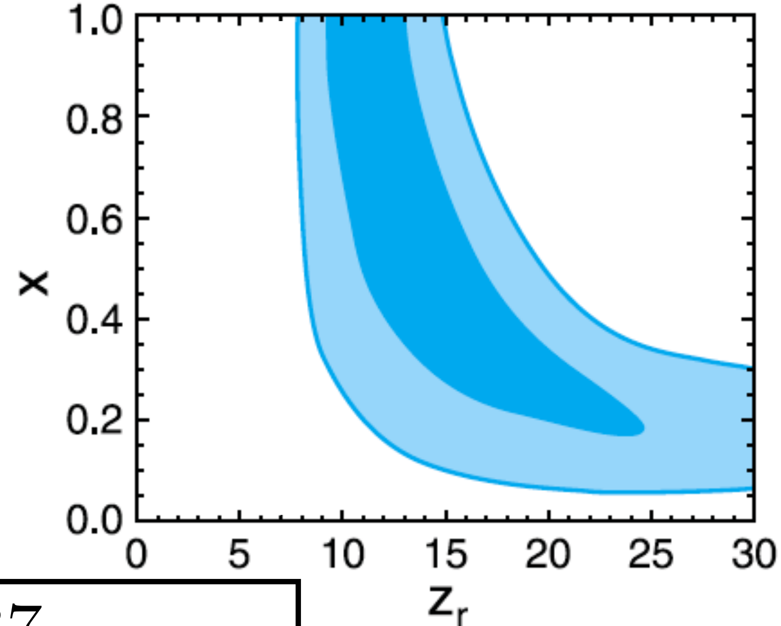


..and their end

WMAP





$\tau_T(z) = \int_0^z n_e(z) \sigma_T |c\,dt/dz|\,dz = 0.087$

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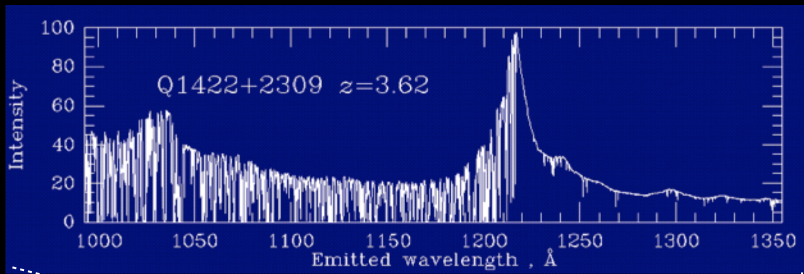
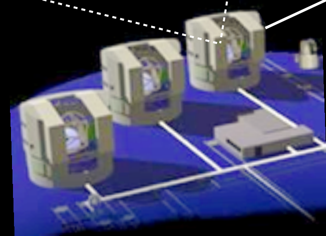
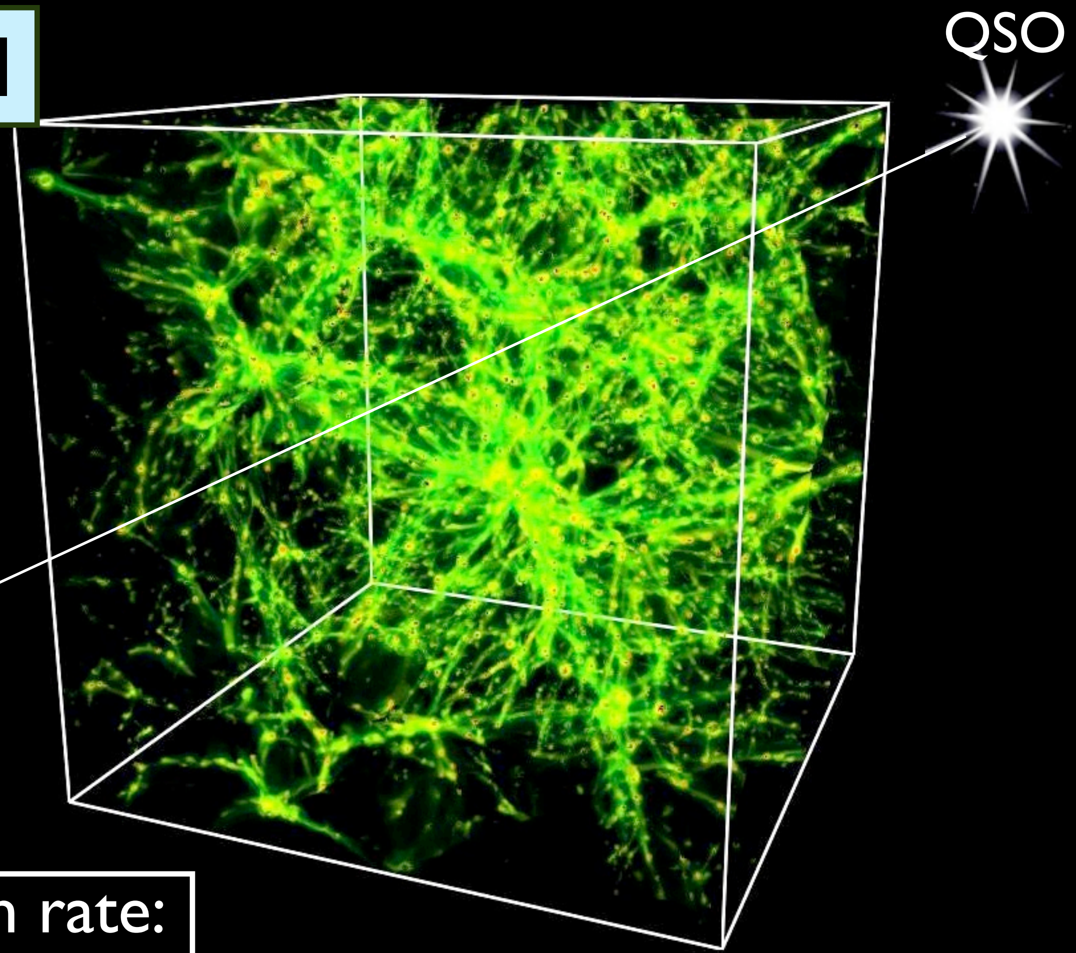
Cosmic structure formation: I







Clumpiness boosts H recombination rate:

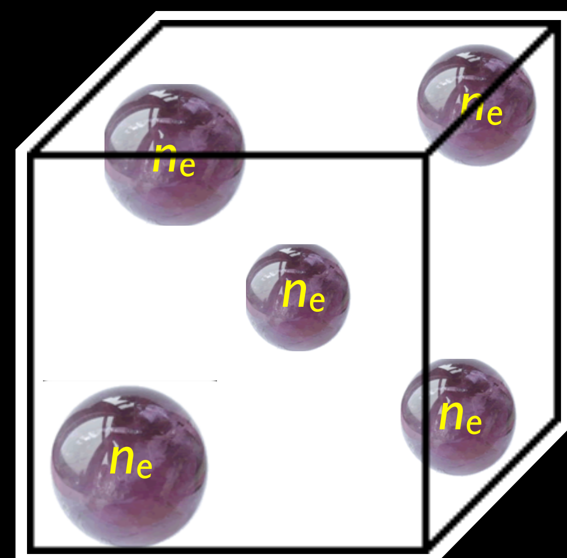
$$\langle n_e n_p \rangle \alpha_B(T) = C \langle n_p \rangle^2 \alpha_B(T)$$

$$t_{\rm rec} = (n_p \alpha_B C)^{-1}$$

Example: ionized gas of density n_e filling uniformly a fraction f of the available volume, rest is empty space. Then

$$\langle n_e^2 \rangle = f n_e^2; \quad \langle n_e \rangle = f n_e$$

$$\rightarrow \langle n_e^2 \rangle = \langle n_e \rangle^2 / f \rightarrow C = 1/f$$

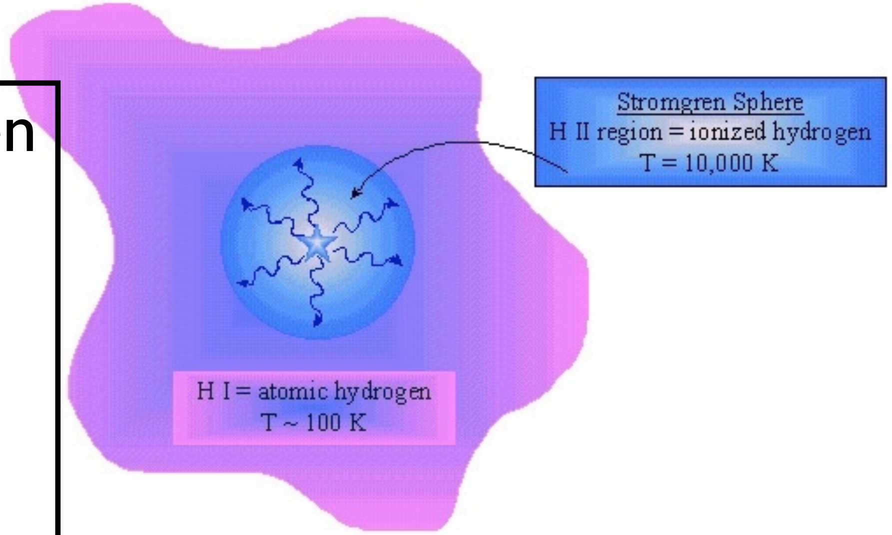


Cosmic structure formation: II

HII region in homogeneous ISM (Stromgren analysis):

$$n_H \frac{dV}{dt} = \dot{N}_\gamma - V \alpha_B n_H^2$$

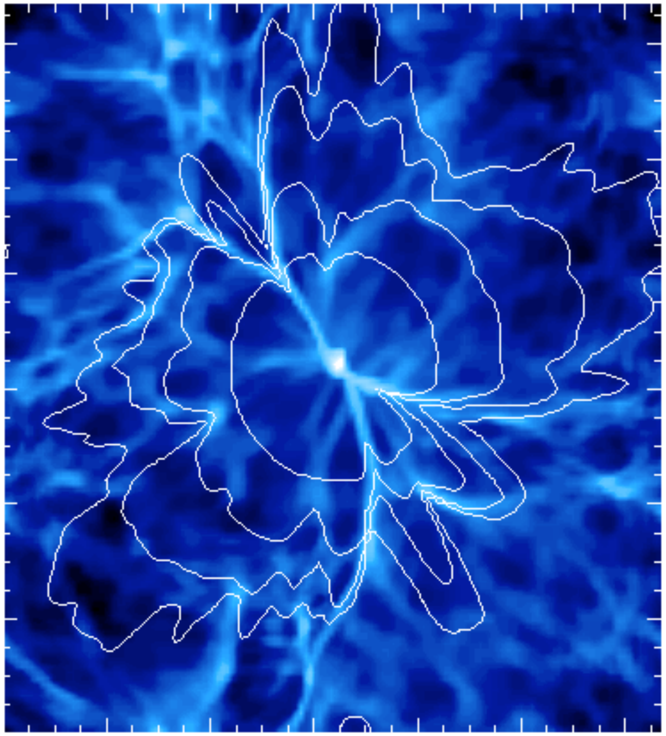
$$\rightarrow V = \frac{\dot{N}_\gamma t_{\rm rec}}{n_H}(1 - e^{-t/t_{\rm rec}})$$



HII region in expanding clumpy IGM (Shapiro & Giroux 1987):

$$n_H(t)(\frac{dV}{dt} - 3HV) = \dot{N}_\gamma - V\alpha_B \langle n_H(t)\rangle^2 C$$

V=proper volume



The reionization equation

Reionization @ milliFLOP speed (PM, Haardt, & Rees 1999)

$Q_I(t)$= volume filling factor of HII regions at t

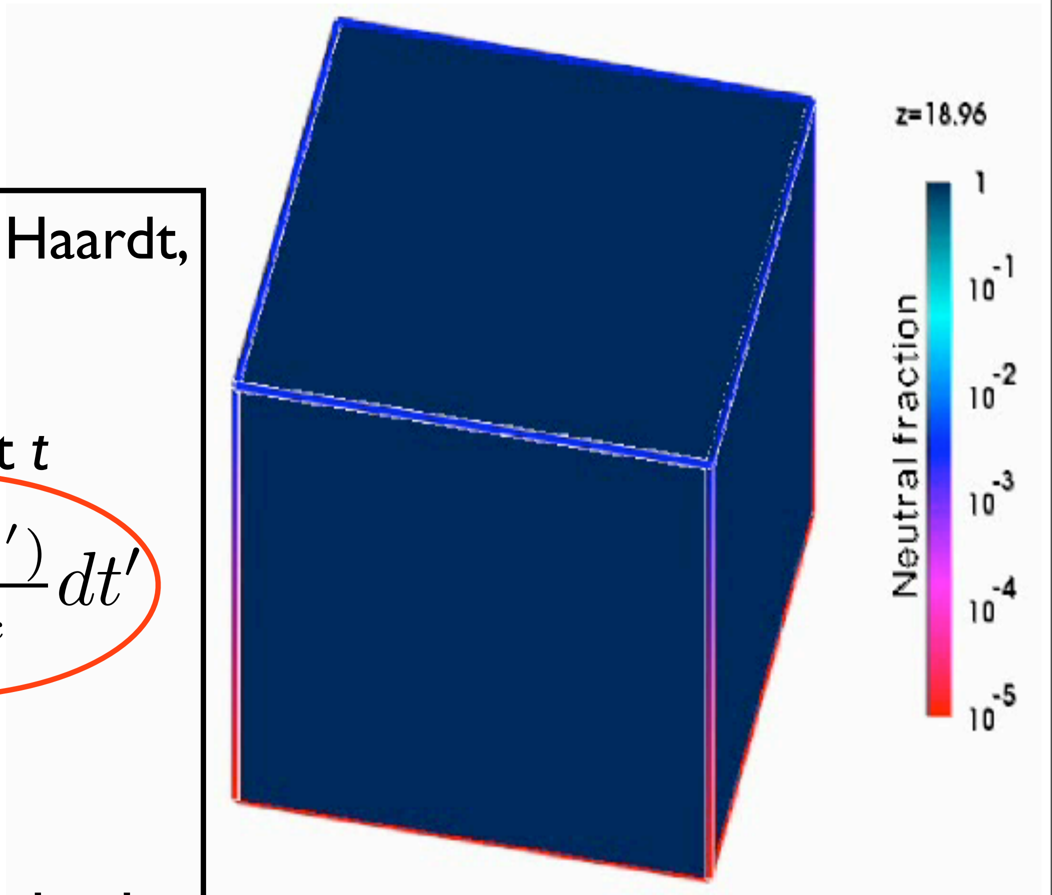
$$Q_I(t) = \int_0^t \frac{\dot{n}_\gamma(t')}{\langle n_H(t')\rangle} dt' - \int_0^t \frac{Q_I(t')}{t_{\rm rec}} dt'$$

source sink

(no redshifting, ionizing photons assorbed locally). Differentiating:

$$\frac{dQ_I}{dt} = \frac{\dot{n}_\gamma}{\langle n_H \rangle} - \frac{Q_I}{t_{\rm rec}}$$

simple diff. eq. statistically describes transition from a neutral Universe to a fully ionized one!



Contrary to the static case, cosmological HII regions will always percolate in an expanding universe with constant comoving ionizing emissivity....

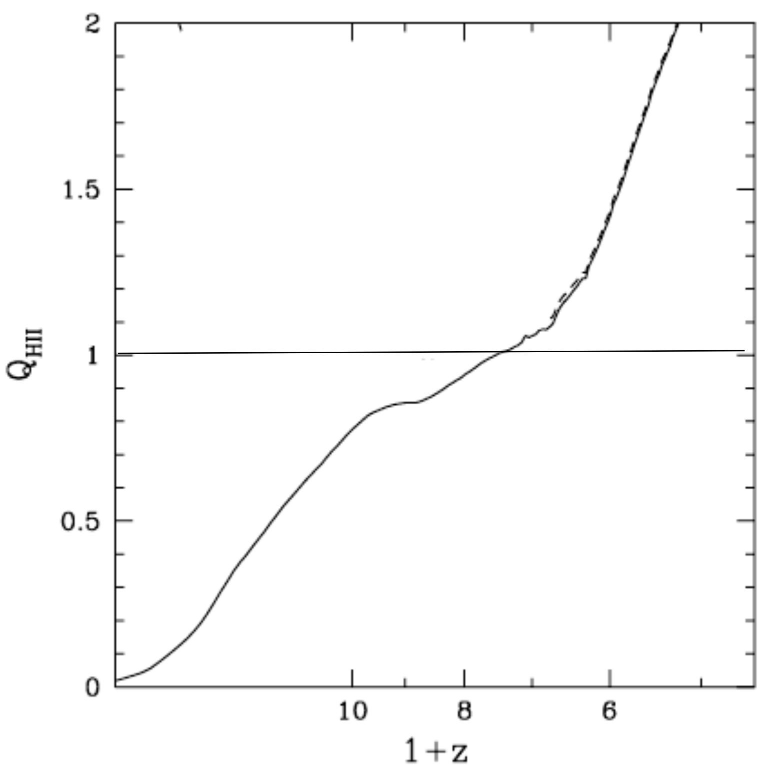
The reionization equation

$$t_{\rm rec} \ll t \rightarrow Q_I \approx \frac{\dot{n}_\gamma}{\langle n_H \rangle} t_{\rm rec}$$

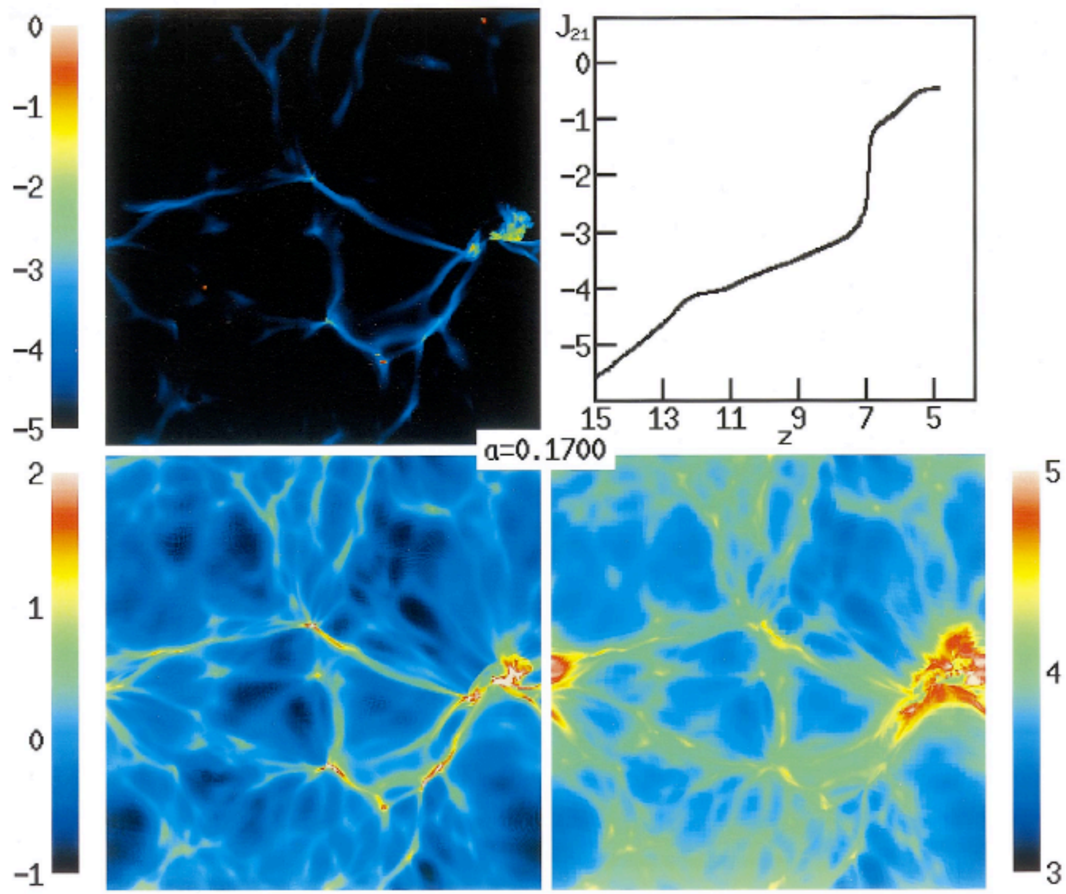
Because of hydrogen recombinations, only a fraction t_{rec}/t of the photons emitted above 13.6 eV is actually used to ionize new IGM material.

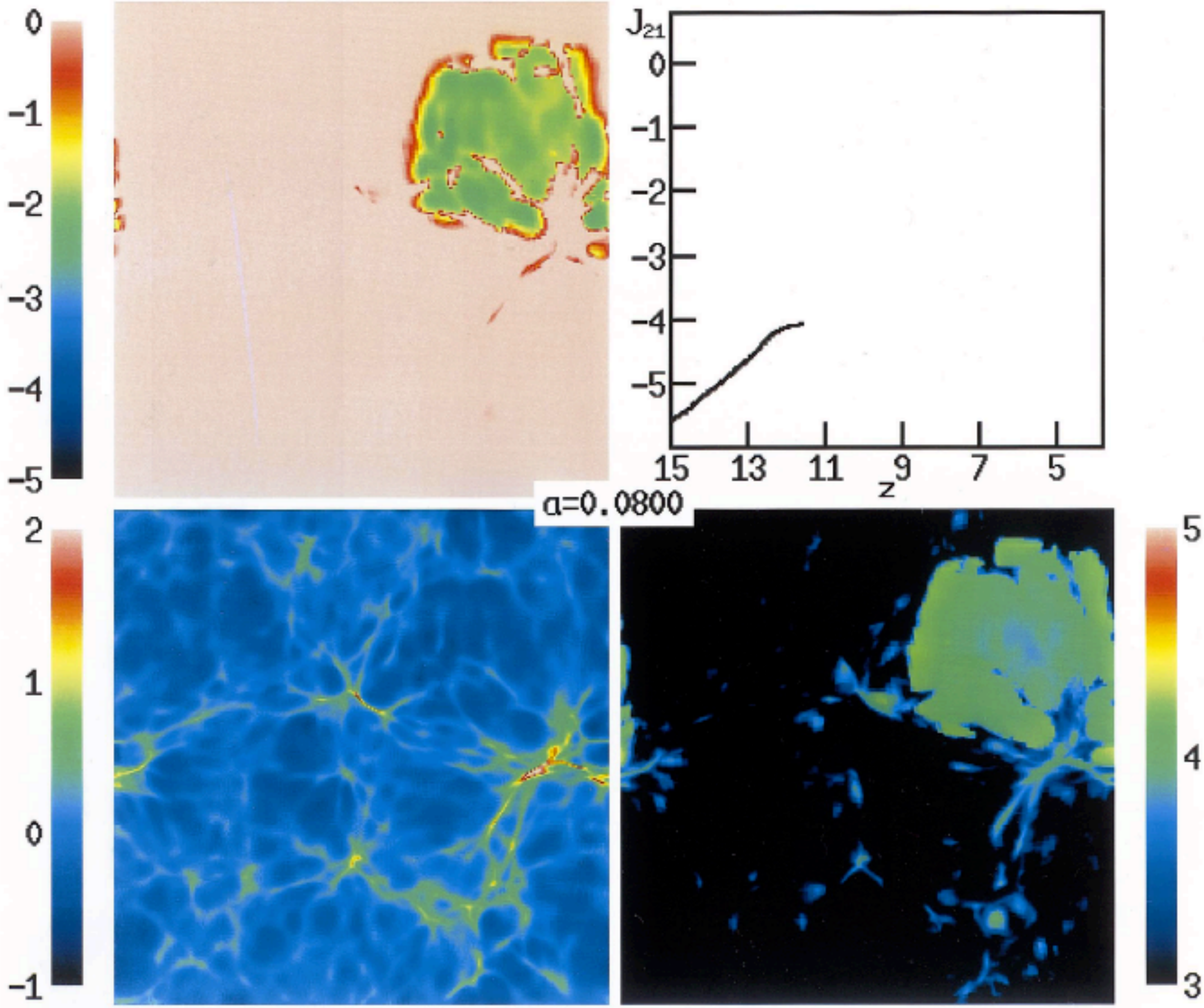
The universe is completely reionized when Q_I=1, i.e. when

$$\dot{n}_\gamma t_{\rm rec} = \langle n_H \rangle$$

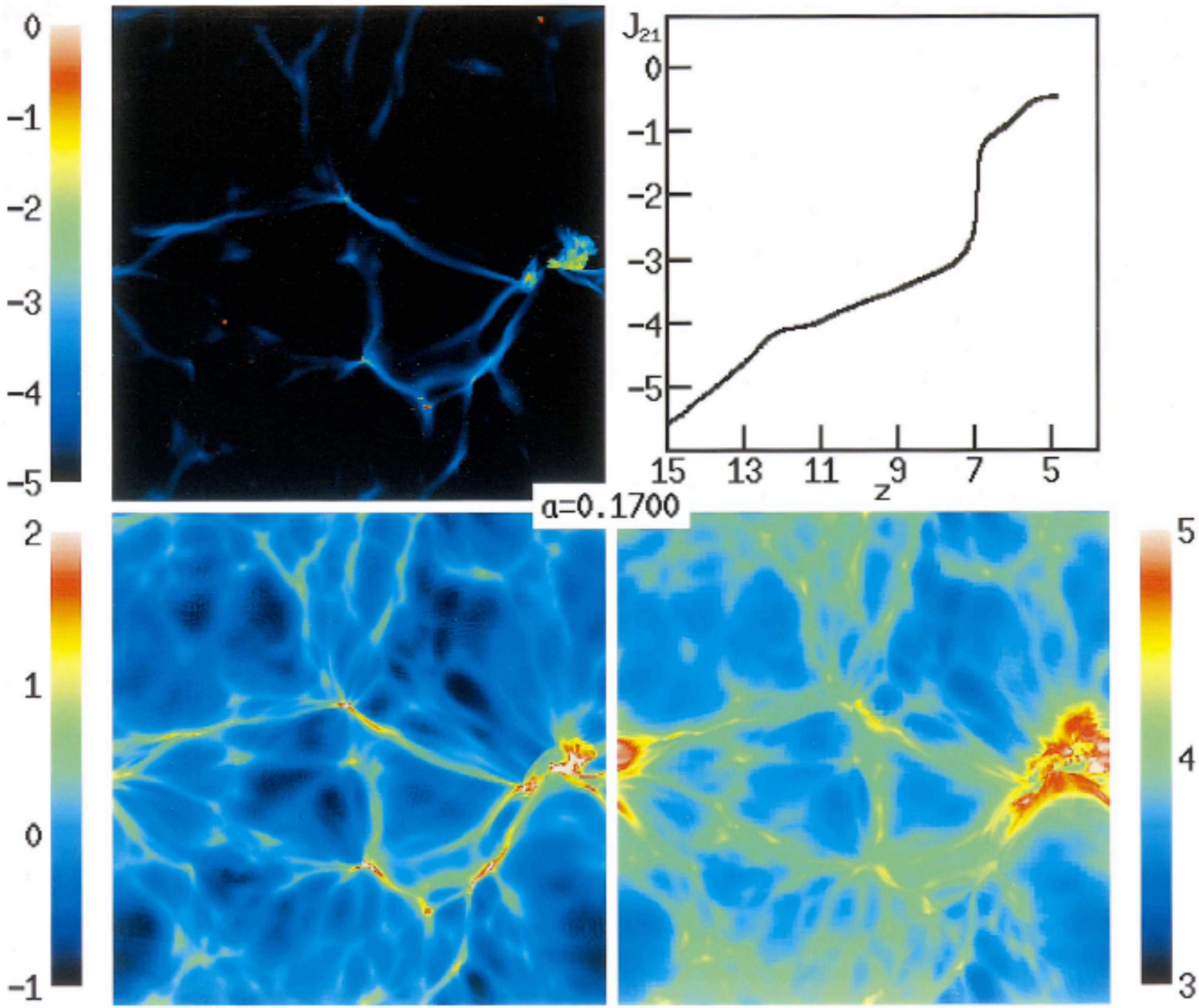


Numerical simulation of stellar reionization (Gnedin 2000)



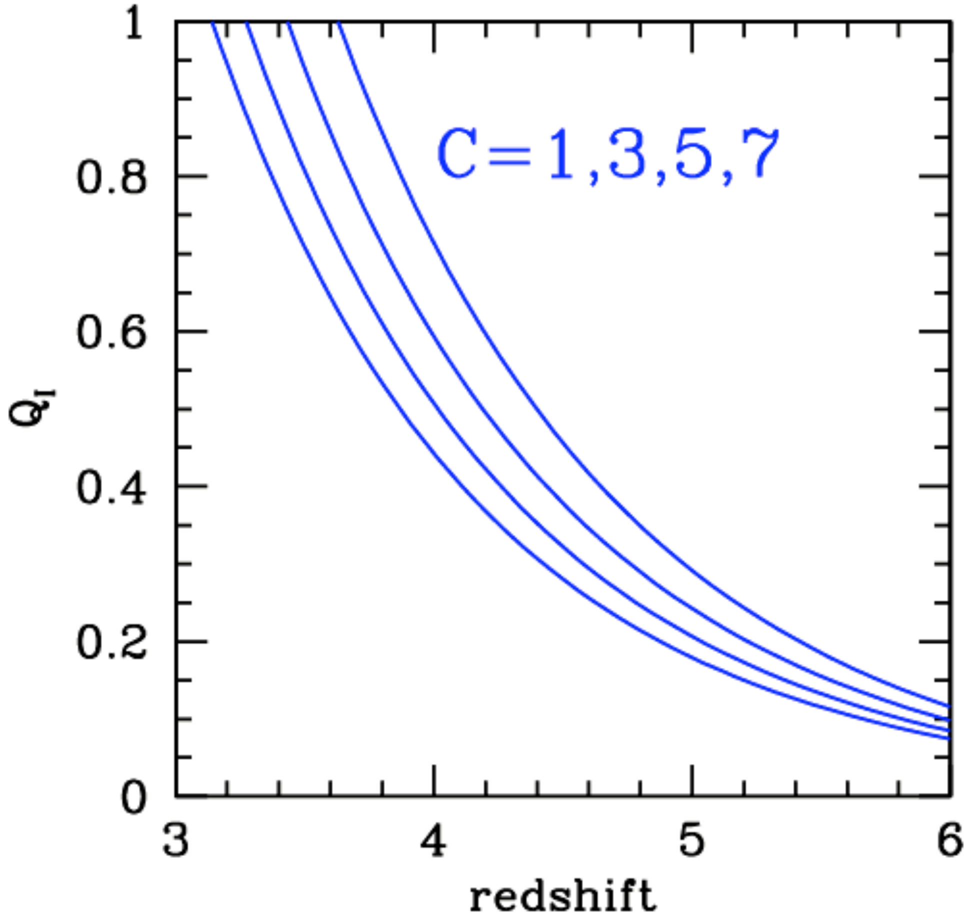


Wednesday, August 4, 2010

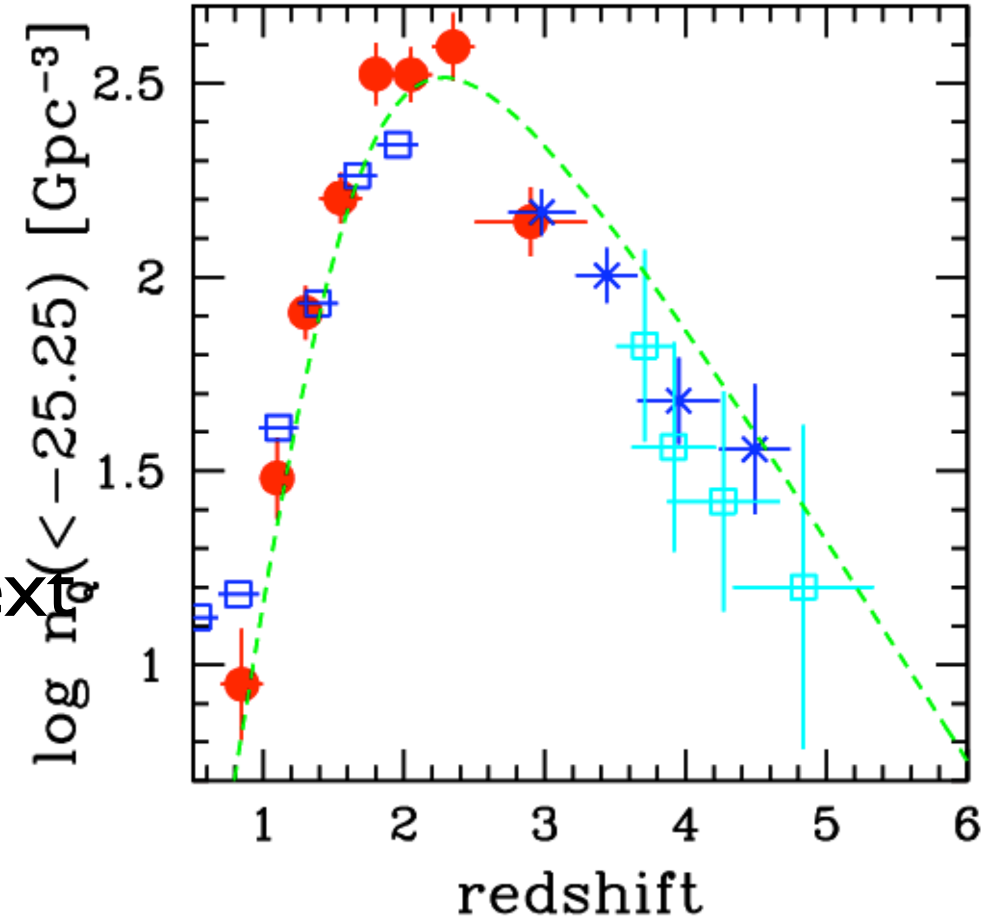


0
−1
−2
−3
−4
−5
J_{21}
0
−1
−2
−3
−4
−5
15
13
11
9
7
5
z
a=0.1700
2
1
0
−1
5
4
3

Quasars or galaxies?

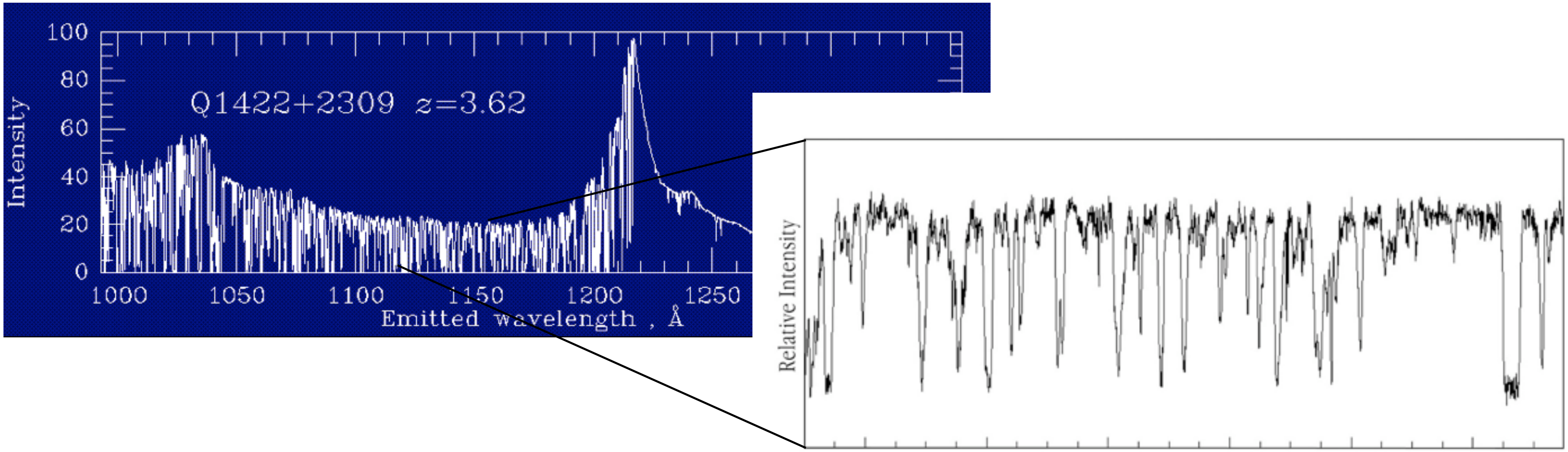


Text



(Bright) QSOs are not responsible for the reionization of cosmic hydrogen!

The Gunn-Peterson trough



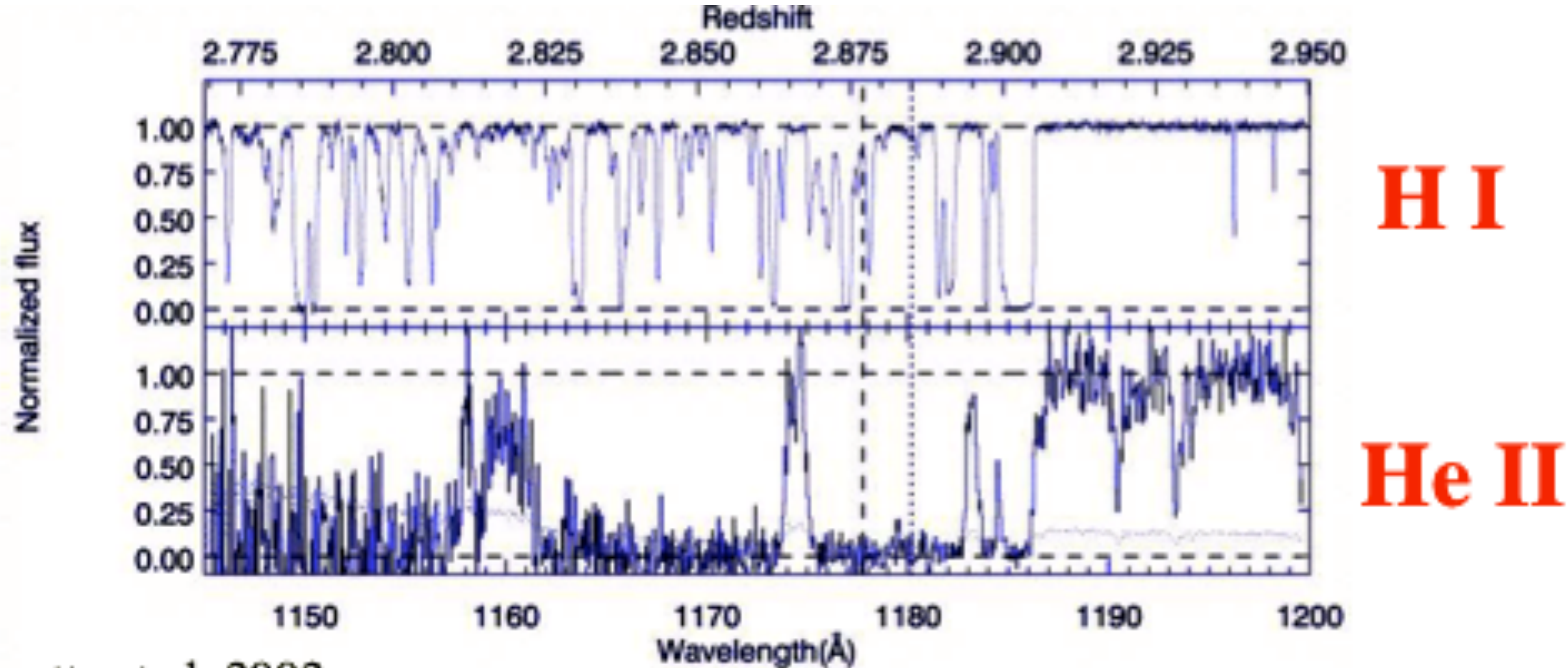
radiation emitted at ν_e and z_e becomes resonant (Lyα) at $(1+z) = (1+z_e)\,\nu_\alpha/\nu_e$ ➔ scattered off the los with cross-section:

$$\sigma(\nu) = \frac{\pi e^2}{m_e c} f\,\phi(\nu)$$

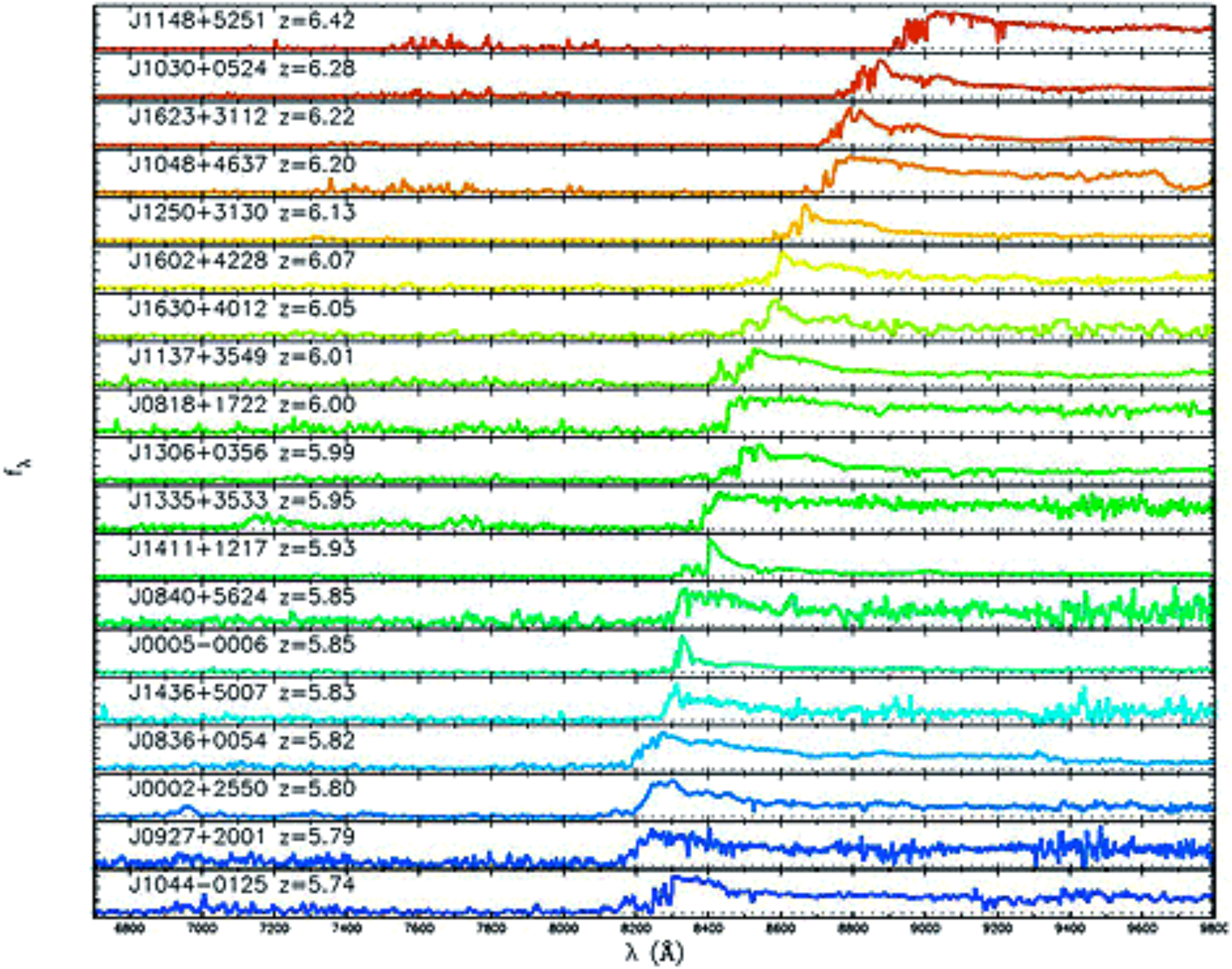
total optical depth for resonant scattering (Gunn-Peterson)

$$\tau_{\rm GP}(z_e) = \int_0^{z_e} \sigma n_{\rm HI}(z)|c\,dt/dz|dz = \left(\frac{\pi e^2 f}{m_e \nu_\alpha}\right) \frac{n_{\rm HI}}{H}.$$

Hydrogen is highly ionized at z<5.7

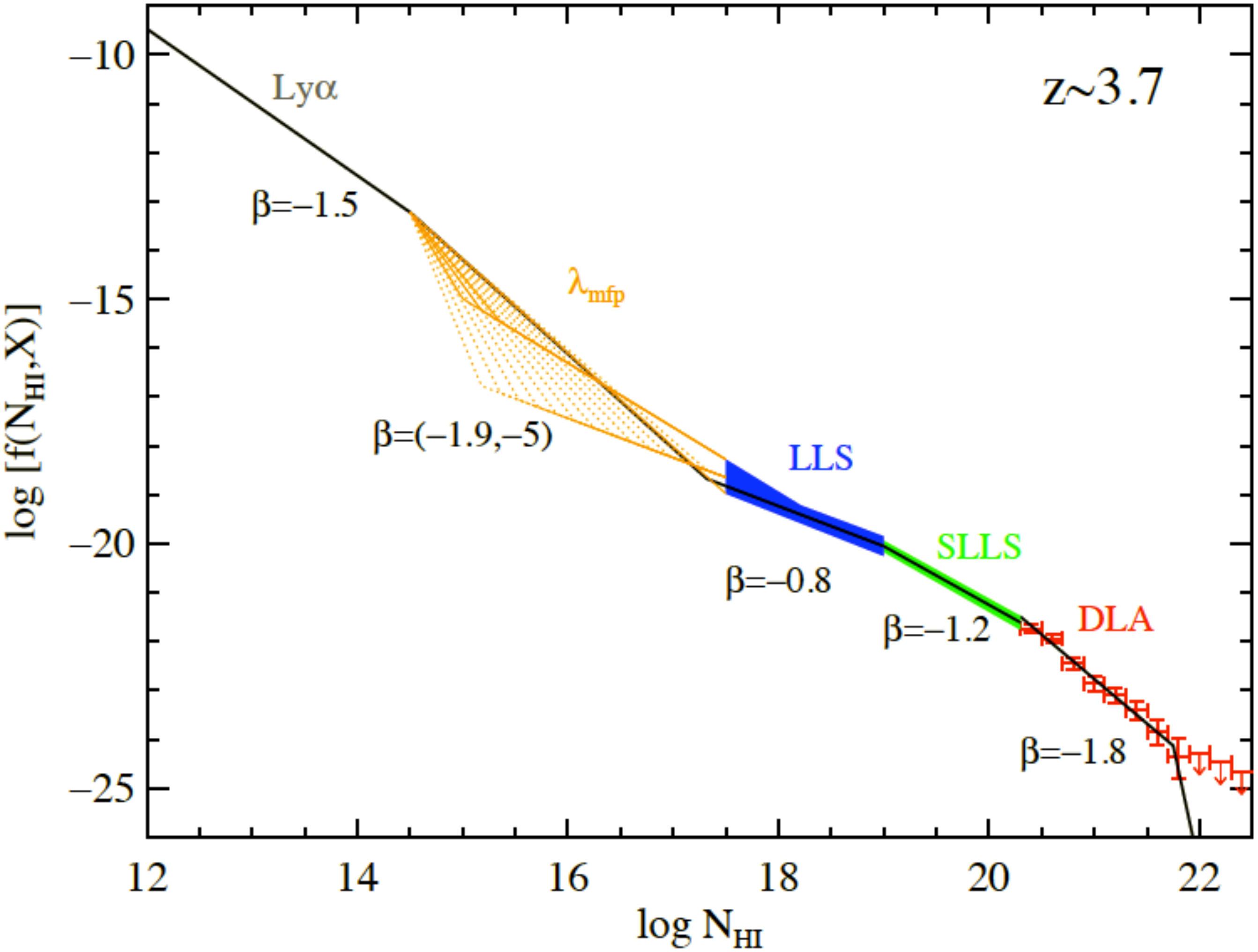


Smette et al. 2002



J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J1602+4228 z=6.07
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J1335+3533 z=5.95
J1411+1217 z=5.93
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
f_λ
6800
7000
7200
7400
7600
7800
8000
8200
8400
8600
8800
9000
9200
9400
9600
λ (Å)

Quasar absorbers along the LOS



f(N

$f(N_{HI},z)$ defined by the probability dP that a los intersects an absorber with column density N_{HI} in the range dN_{HI}, at redshift z in the range dz,

$$dP = f(N_{\rm HI}, z)dN_{\rm HI}dz$$

We can now quantify the degree of attenuation of UV radiation in a clumpy Universe by introducing the concept of an effective continuum optical depth τ_{eff} along the line-of-sight to redshift z: $\langle e^{-\tau} \rangle = e^{-\tau_{\rm eff}}$ where the average is taken over all lines-of-sight.

Effective optical depth

Assume random distribution of absorbers in column density and redshift space, then:

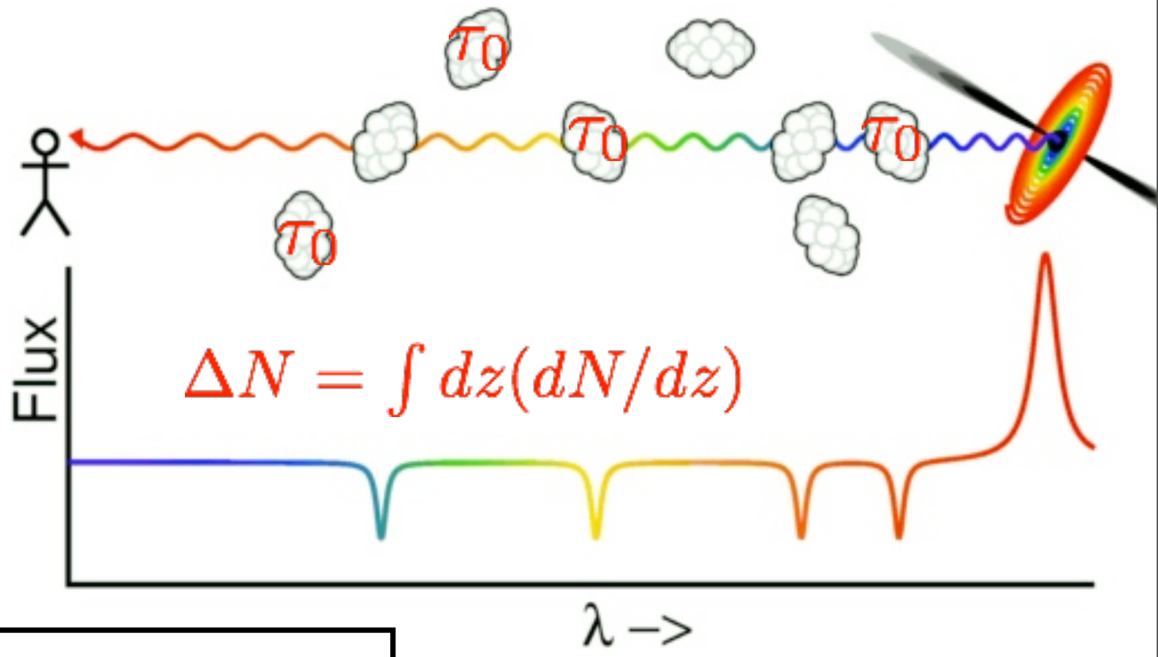
$$\tau_{\rm eff}(\nu_o, z_o, z) = \int_{z_o}^{z} dz' \int_0^\infty f(N_{\rm HI}, z)(1 - e^{-\tau})$$

$$\tau = N_{\rm HI}\sigma_{\rm HI}(\nu) \quad [... + N_{\rm HeI}\sigma_{\rm HeI} + N_{\rm HeII}\sigma_{\rm HeII}]$$

$$\nu = \nu_0(1+z)/(1+z_0); \quad \sigma_i = \text{photoionization cross section}$$

➔ Poissonian probability of encountering a total optical depth $k\tau_0$ is:

$$p(k\tau_0) = e^{-\Delta N} \Delta N^k / (\tau_0 k!)$$



$$\langle e^{-\tau} \rangle = e^{-k\tau_0} p(k\tau_0) = \exp[-\Delta N(1 - e^{-\tau_0})]$$

$$\langle \tau \rangle = \Delta N \tau_0 > \tau_{\rm eff} = \Delta N(1 - e^{-\tau_0})$$

Cosmological radiative transfer

The equation of cosmological radiative transfer describes the time evolution of the space- and angle-averaged monochromatic intensity J_ν:

$$\left(\frac{\partial}{\partial t} - \nu H \frac{\partial}{\partial \nu}\right) J_\nu + 3H J_\nu = -c\kappa_\nu J_\nu + \frac{c}{4\pi}\epsilon_\nu$$

$$* \quad J_{\nu_o}(z_o) = \frac{c}{4\pi}\int_{z_o}^{\infty} |dt/dz| dz \frac{(1+z_o)^3}{(1+z)^3}\epsilon_\nu(z) e^{-\tau_{\rm eff}}$$

$$\tau_{\rm eff}(\nu_o, z_o, z) = \int_{z_o}^{z} dz' \int_0^\infty f(N_{\rm HI}, z)(1 - e^{-\tau})$$

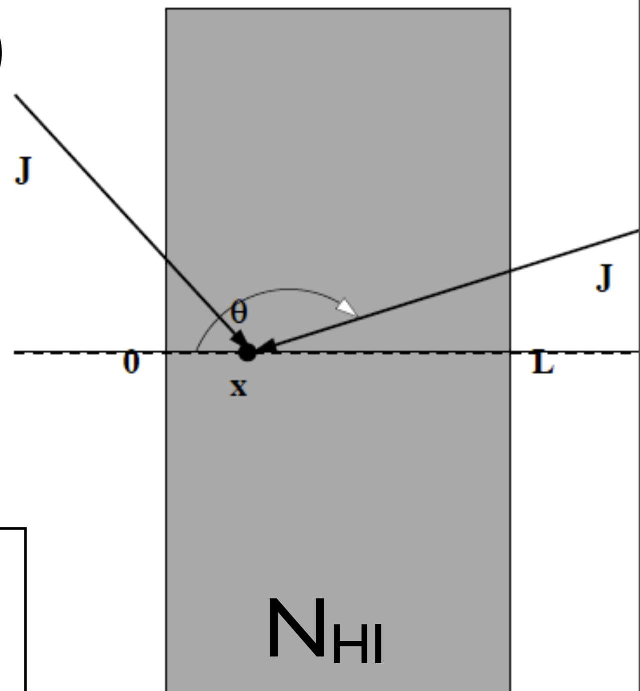
$$\tau = N_{\rm HI}\sigma_{\rm HI}(\nu) \quad [\ldots + N_{\rm HeI}\sigma_{\rm HeI} + N_{\rm HeII}\sigma_{\rm HeII}]$$

$$\nu = \nu_0(1+z)/(1+z_0)$$

$$\sigma_i = \text{photoionization cross section}$$

observed ($N_{\rm HI}$)

must be modeled ($N_{\rm HeI}$, $N_{\rm HeII}$)



☛equation * must be solved by iteration since $\tau = \tau(J)$

Two important effects must be included:

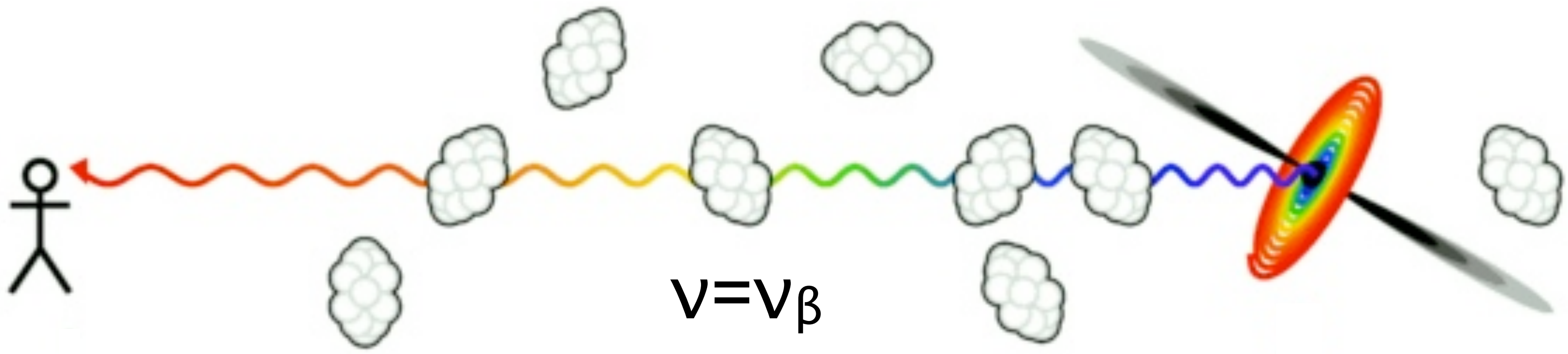
1) absorbers are not only sinks but also sources of ionizing radiation. In particular, HeII reprocesses soft X-rays He-ionizing photons into UV H-ionizing ones.

$$\epsilon(\nu, z) = \epsilon_{\rm QSO} + \epsilon_{\rm Gal} + \epsilon_{\rm rec}$$
$$\epsilon(z) = (1+z)^3 \int dL L \phi(L.z)$$

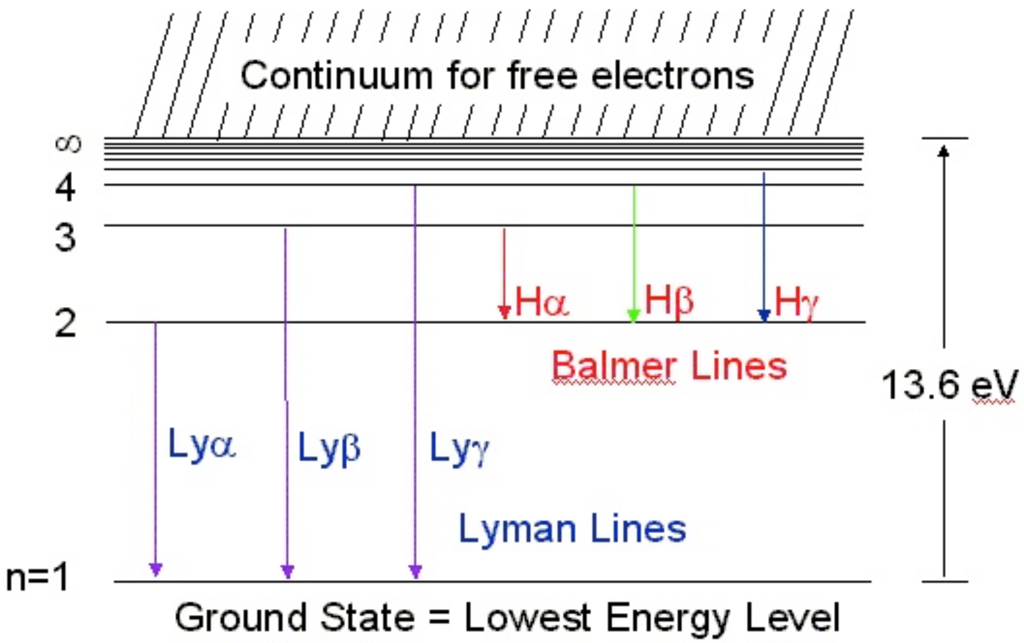
Ionizing recombination radiation includes:

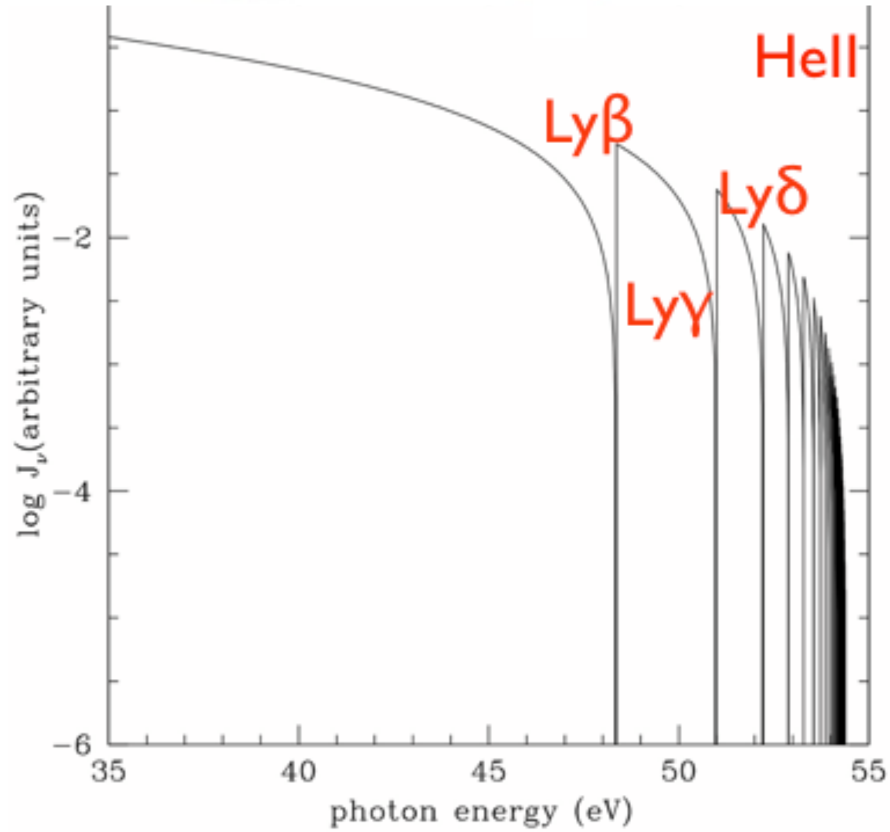
- recombinations to ground state of HI, HeI, HeII
- HeII Balmer and 2-photon continuum
- HeII Lyman-alpha

2) besides photoelectric absorption, resonant absorption by H and He Lyman series will produce a sawtooth modulation of the spectrum.



$\nu = \nu_\alpha$





J-solution flow chart

ABSORBERS

SOURCES

HI distribution

QSO/GAL LF

SED

J-solution flow chart

ABSORBERS

HI distribution

SOURCES

QSO/GAL LF

SED

cosmological radiative transfer → J

J-solution flow chart

ABSORBERS

SOURCES

HI distribution

QSO/GAL LF

SED

local radiative transfer → H/He ionization state

cosmological radiative transfer → J

J-solution flow chart

ABSORBERS

SOURCES

HI distribution

QSO/GAL LF

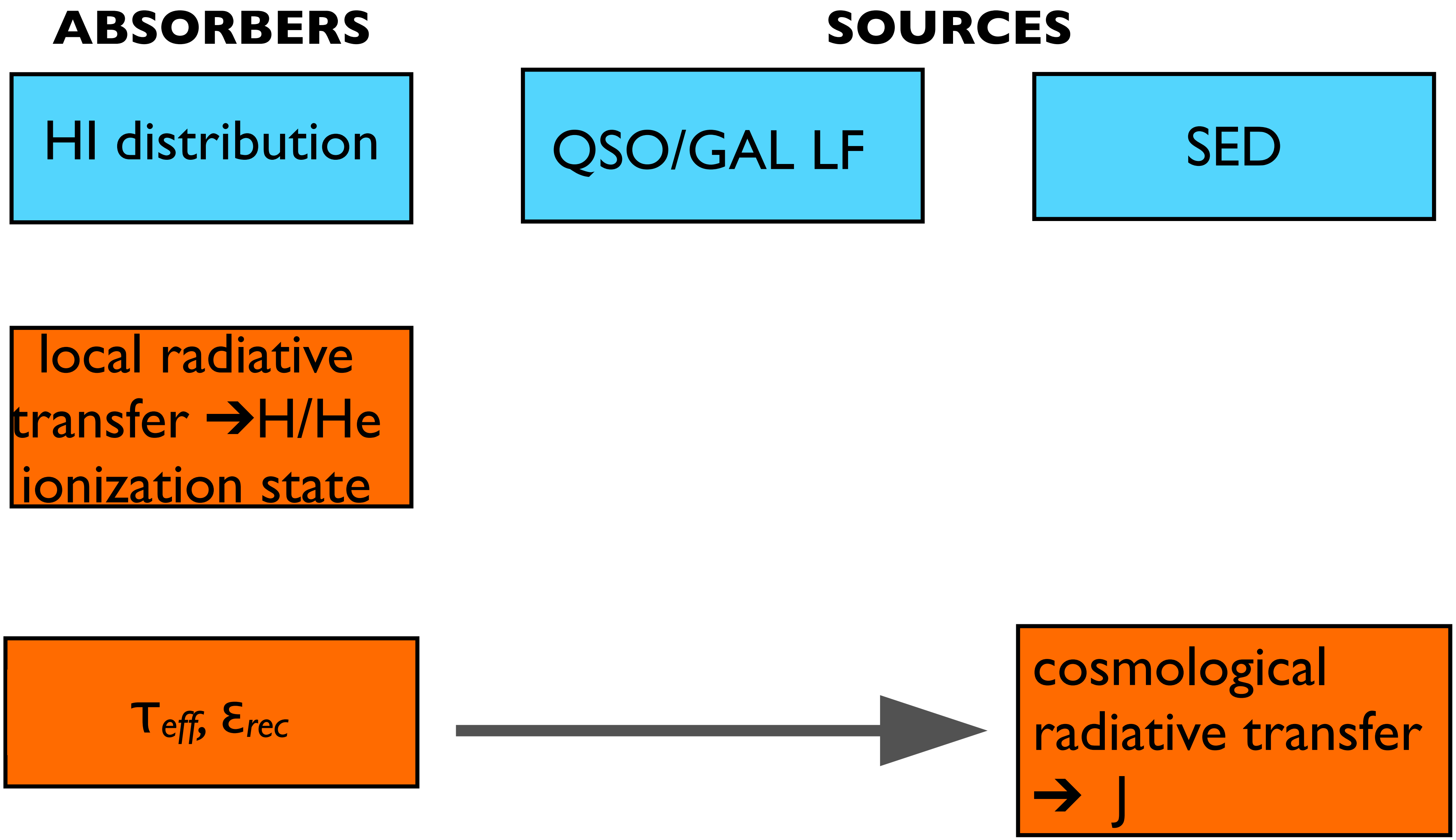
SED

local radiative transfer → H/He ionization state

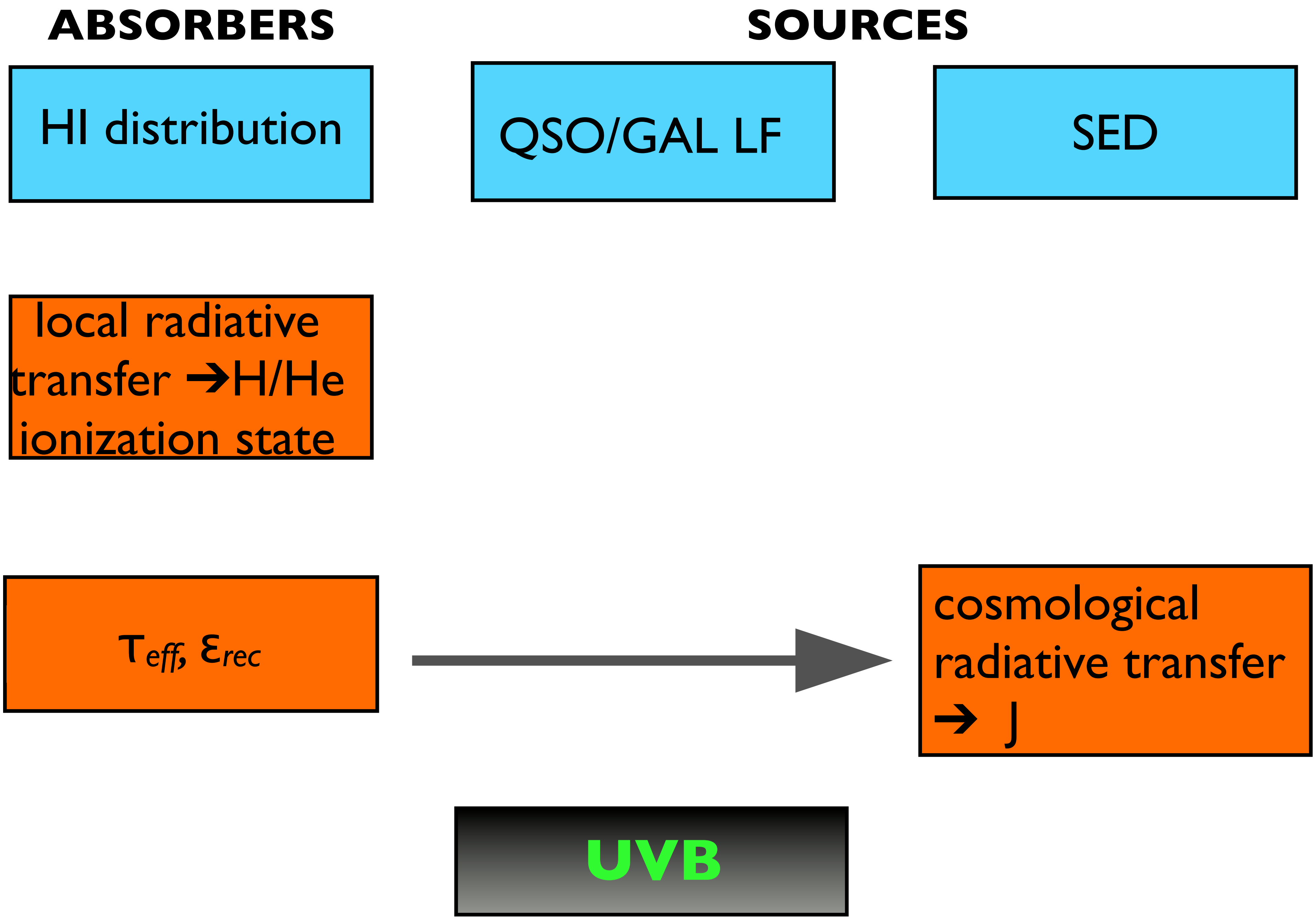
τ_{eff}, ε_{rec}

cosmological radiative transfer → J

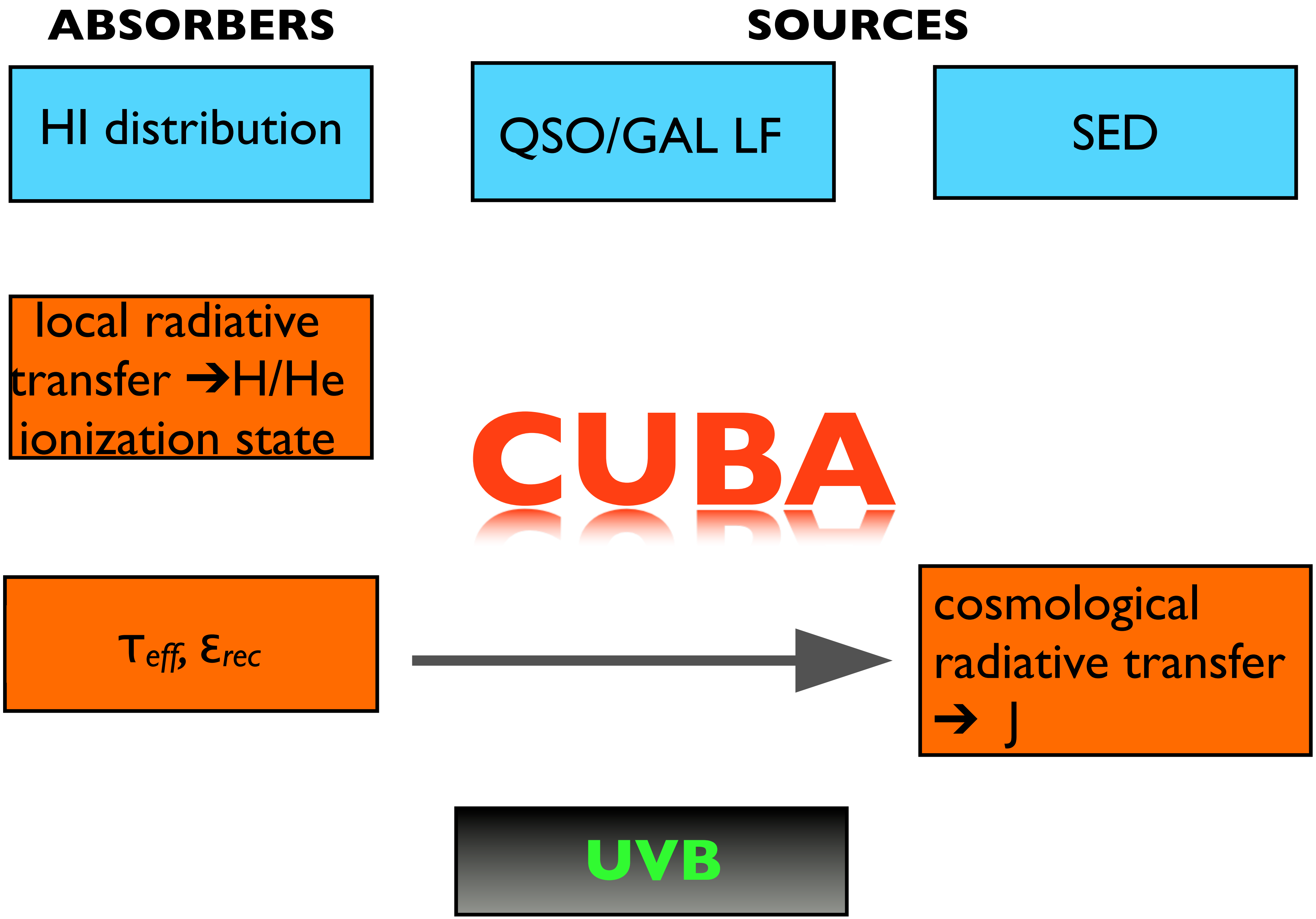
J-solution flow chart

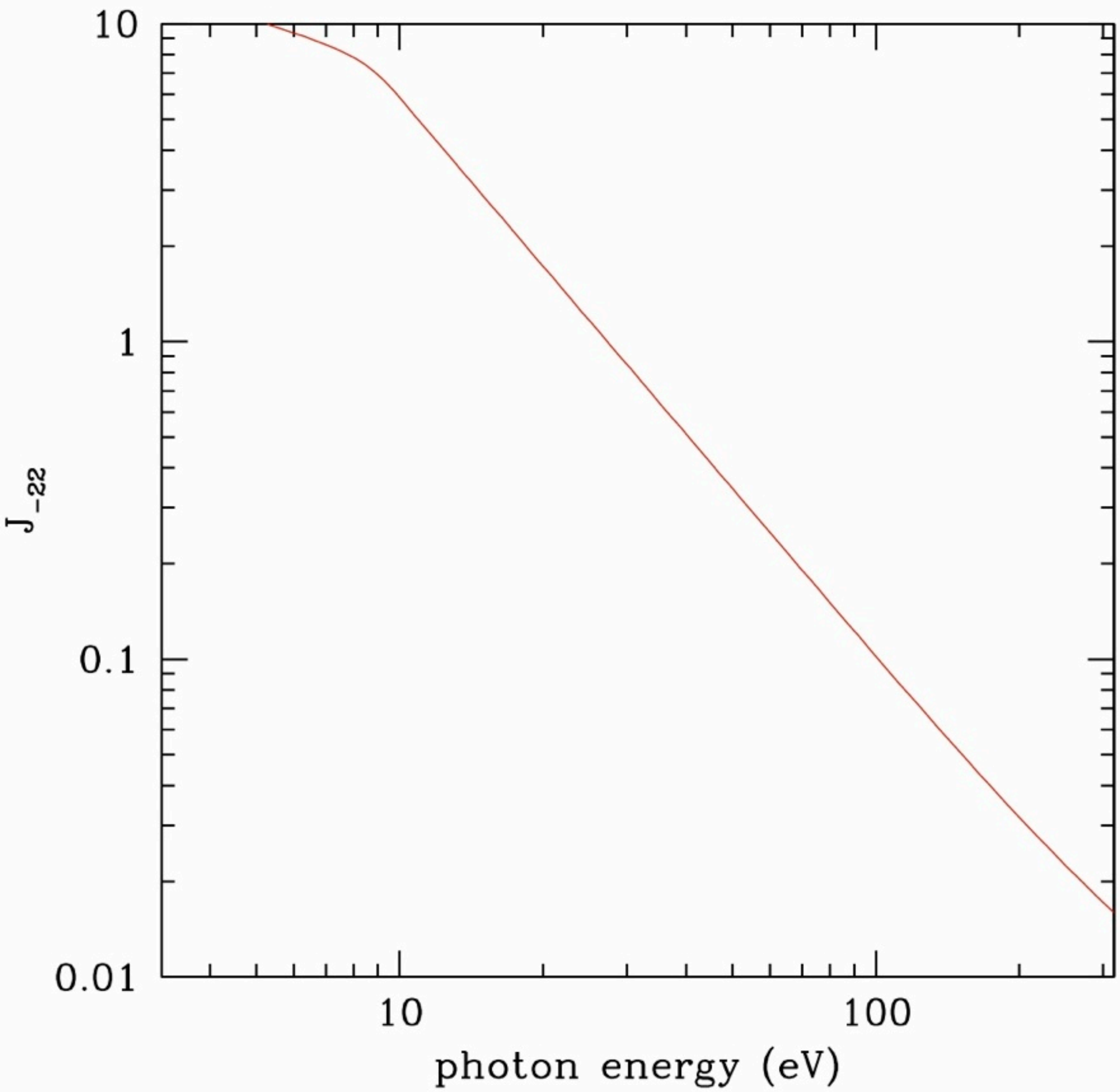


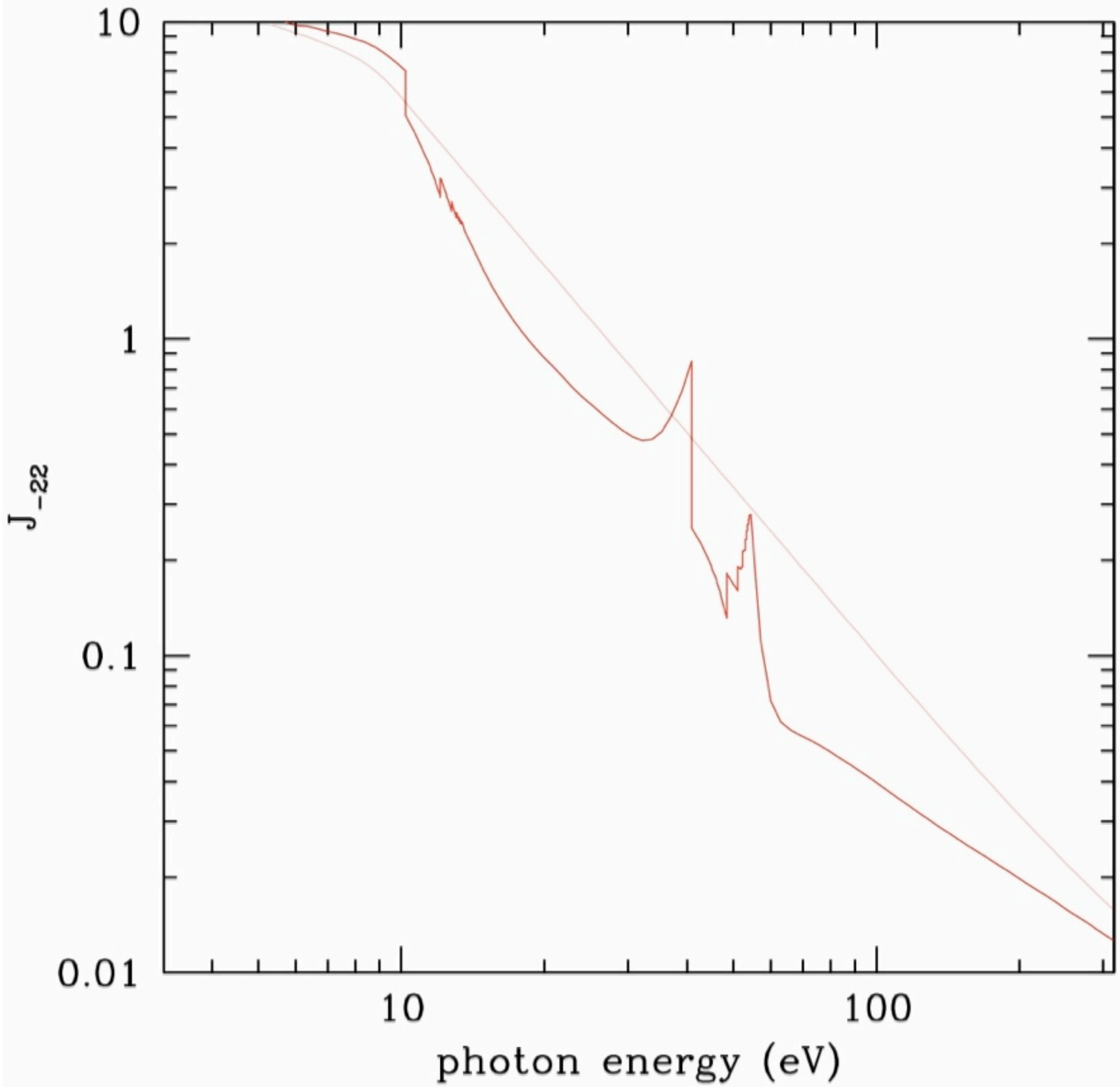
J-solution flow chart



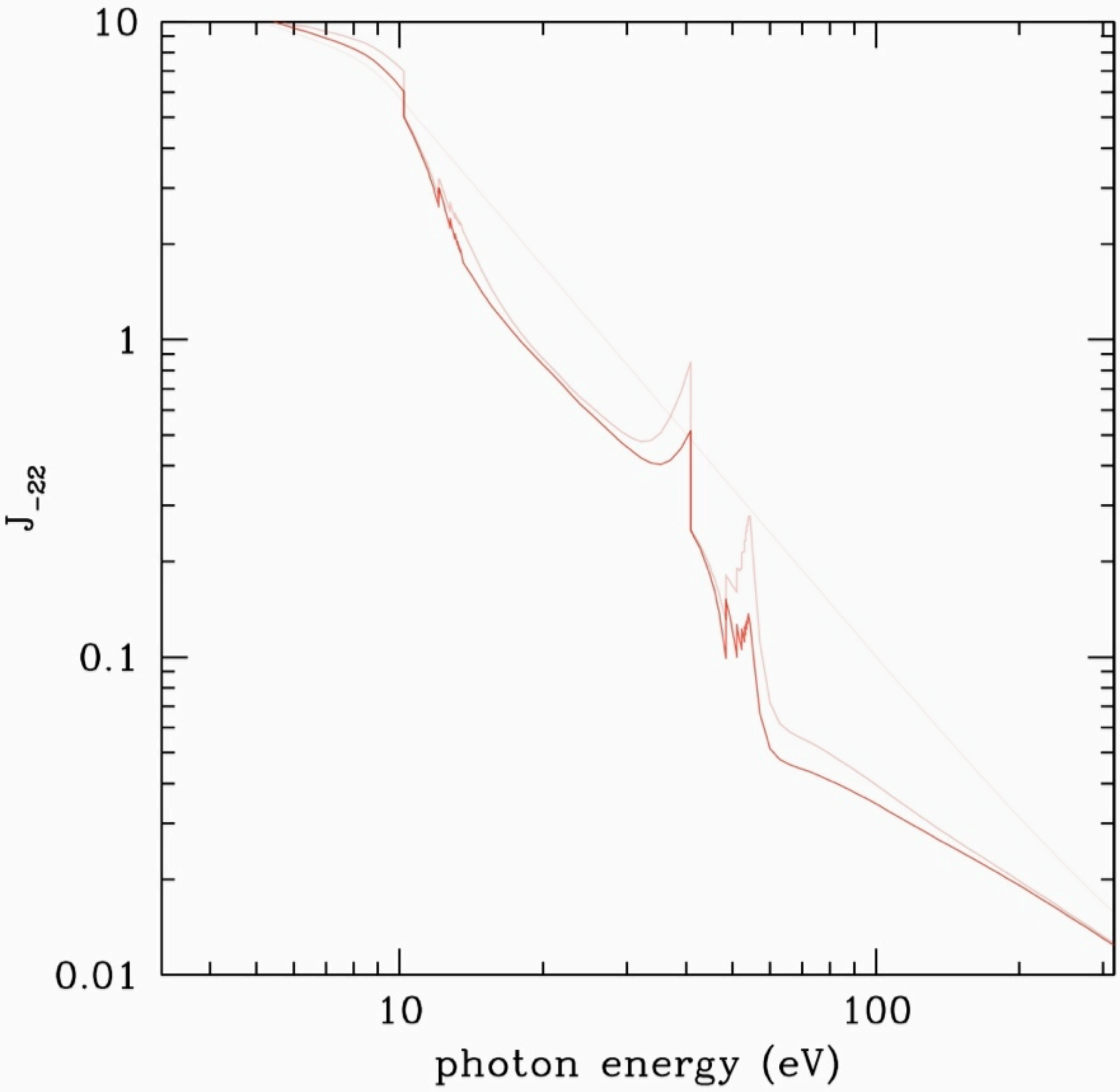
J-solution flow chart

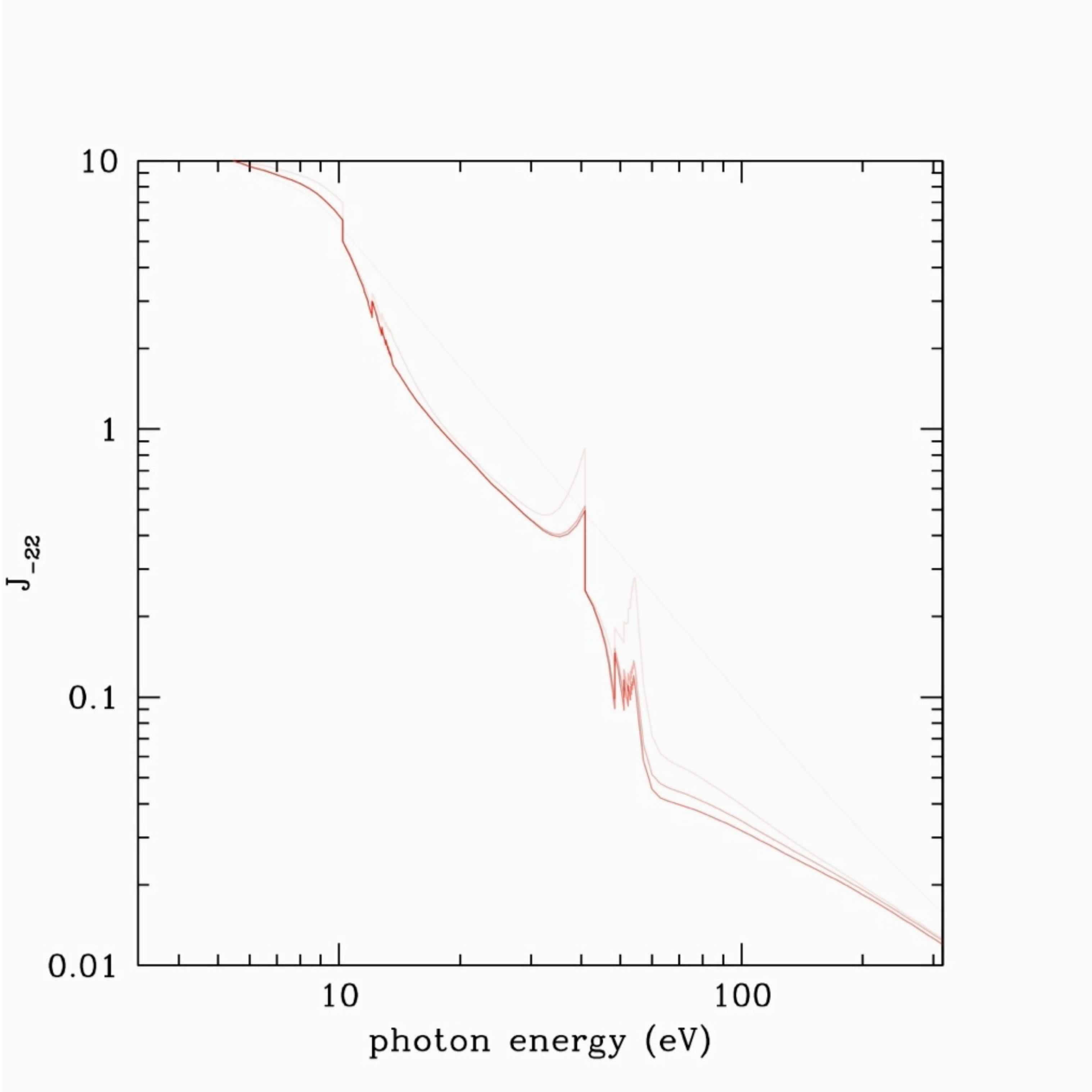



10
1
0.1
0.01
J_{-22}
10
100
photon energy (eV)

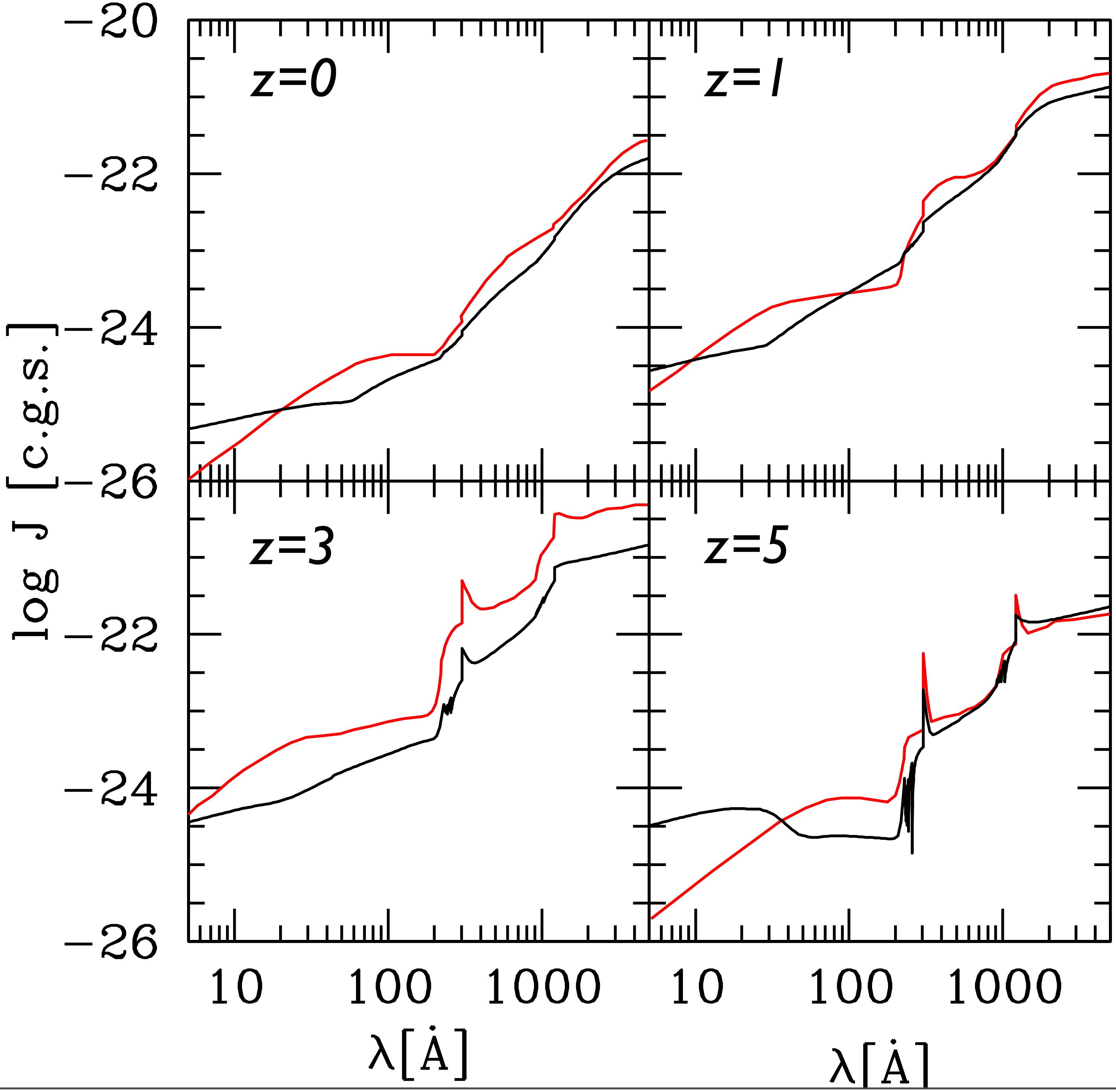


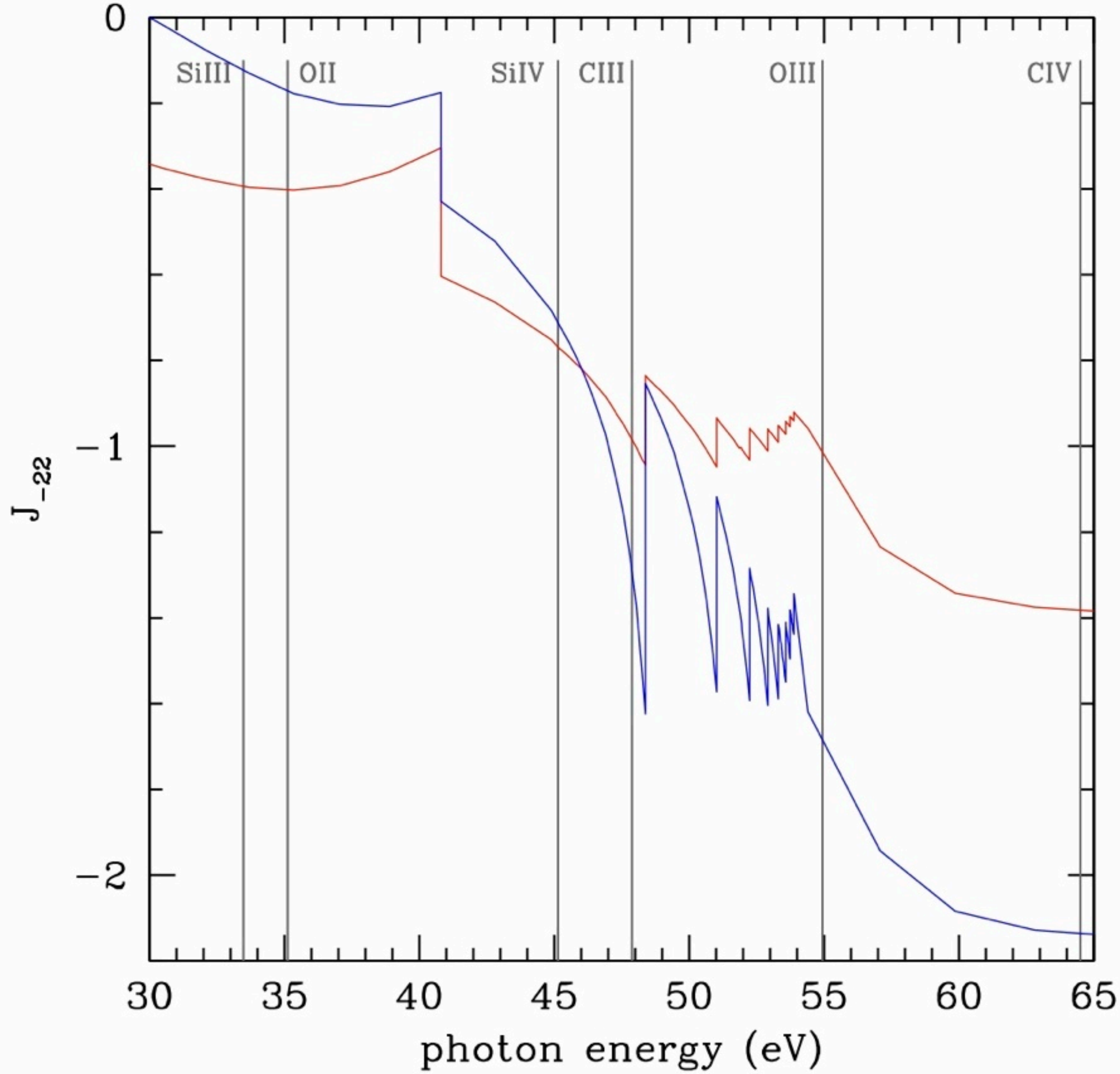
10
1
0.1
0.01
10
100
photon energy (eV)
J_{-22}


10
1
0.1
0.01
J_{-22}
10
100
photon energy (eV)



10
1
0.1
0.01
J_{-22}
10
100
photon energy (eV)


z=0
z=1
z=3
z=5
−20
−22
−24
−26
−22
−24
−26
log J [c.g.s.]
10
100
1000
10
100
1000
λ[Å]
λ[Å]



SiIII
OII
SiIV
CIII
OIII
CIV
0
−1
−2
J_{-22}
30
35
40
45
50
55
60
65
photon energy (eV)

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THE END