COSMIC REIONIZATION AND ITS SOURCES

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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").

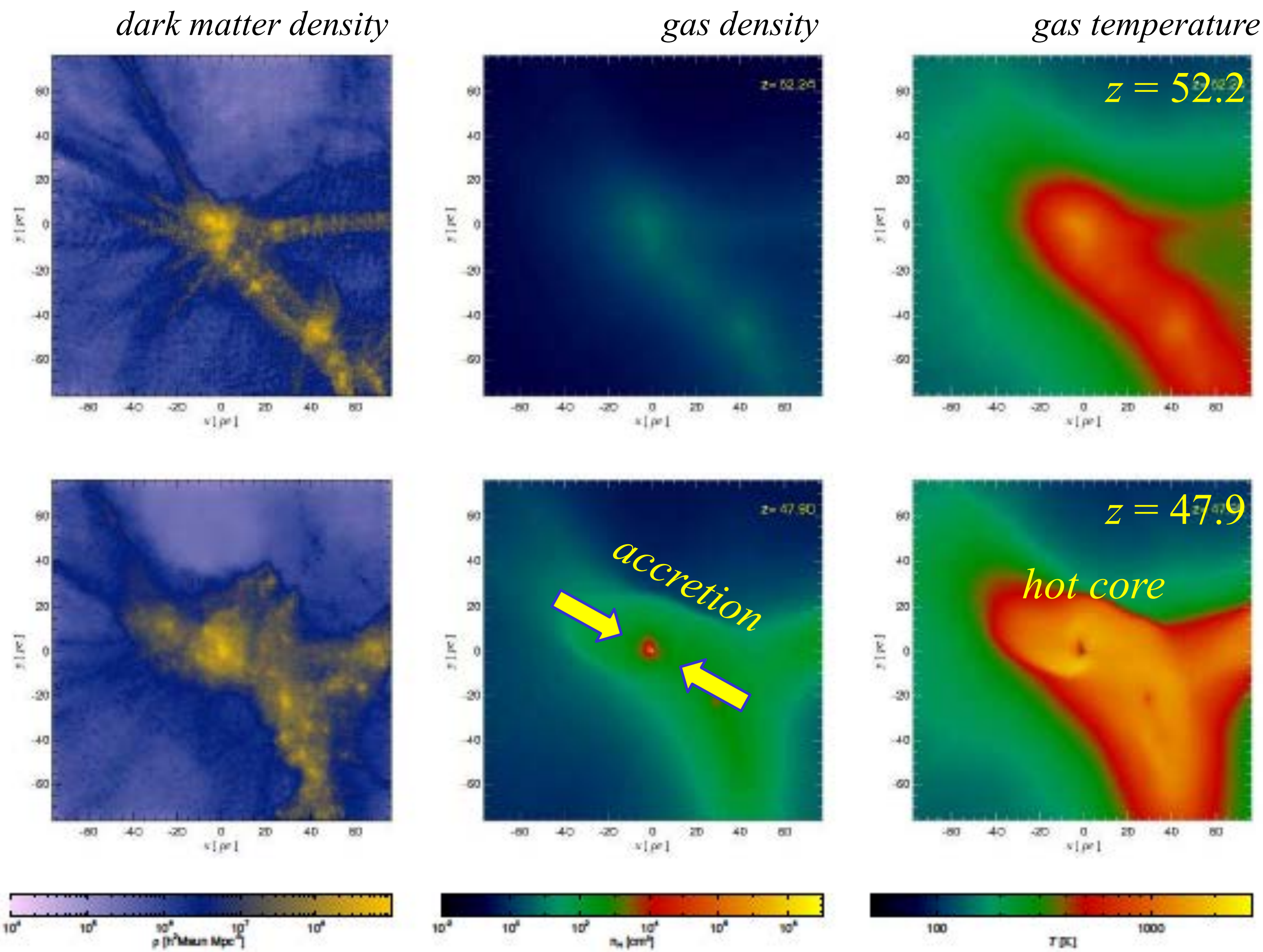
At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.

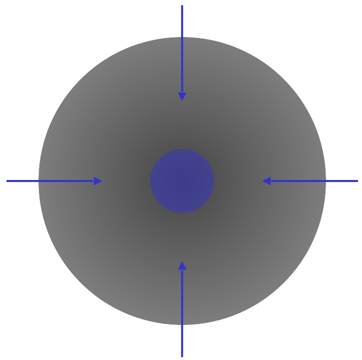
The first star

Gao+07

Halo mass = $2.2\times10^5\ M_\odot$



First stars are massive



- Run-away collapses produces a core + accreting envelope structure
- Initial conditions: $M_c \approx 10^{-3}\ M_\odot$, $M_{env} \approx 10^3\ M_\odot$

KEY POINTS

It takes only 70,000 years to build a 300 $M_\odot$ star

Was the Initial Mass Function of the first stars top-heavy?

Accretion rate

$$dM/dt \approx M_J / t_{ff} \propto \lambda_J^3 \rho / t_{ff} \propto c_s^3 \rho \ t_{ff}^2 \propto c_s^3\, G^{-1}$$

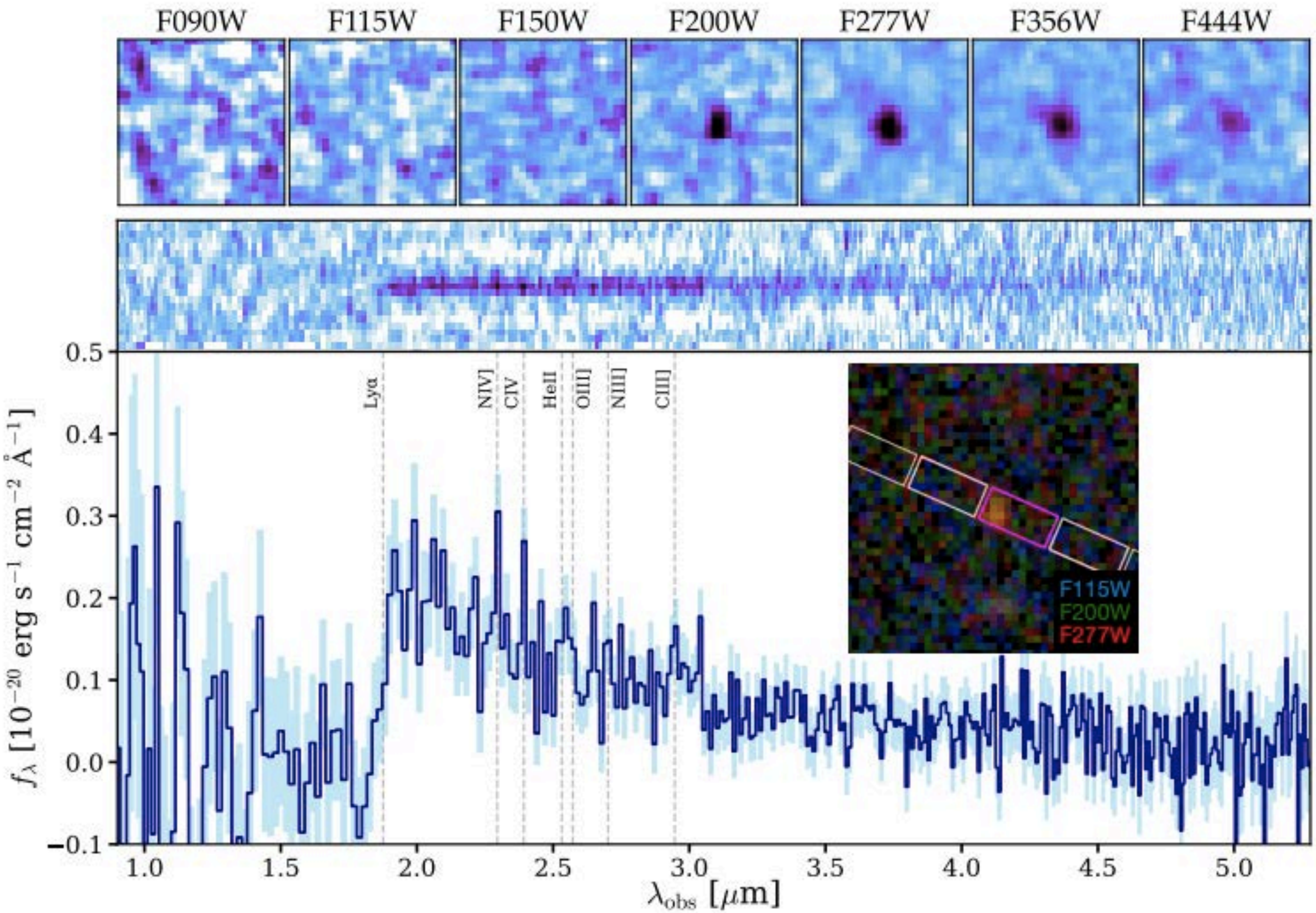
Numerical estimate

$$dM/dt \approx 4.4 \times 10^{-3}\ M_\odot/\mathrm{yr} \qquad (T = 1600\ \mathrm{K})$$

The most distant galaxy

Naidu+25

MoM-z14 (z=14.44)



Key physical ingredients

Constrained by Luminosity Functions

Lyman continuum escape fraction

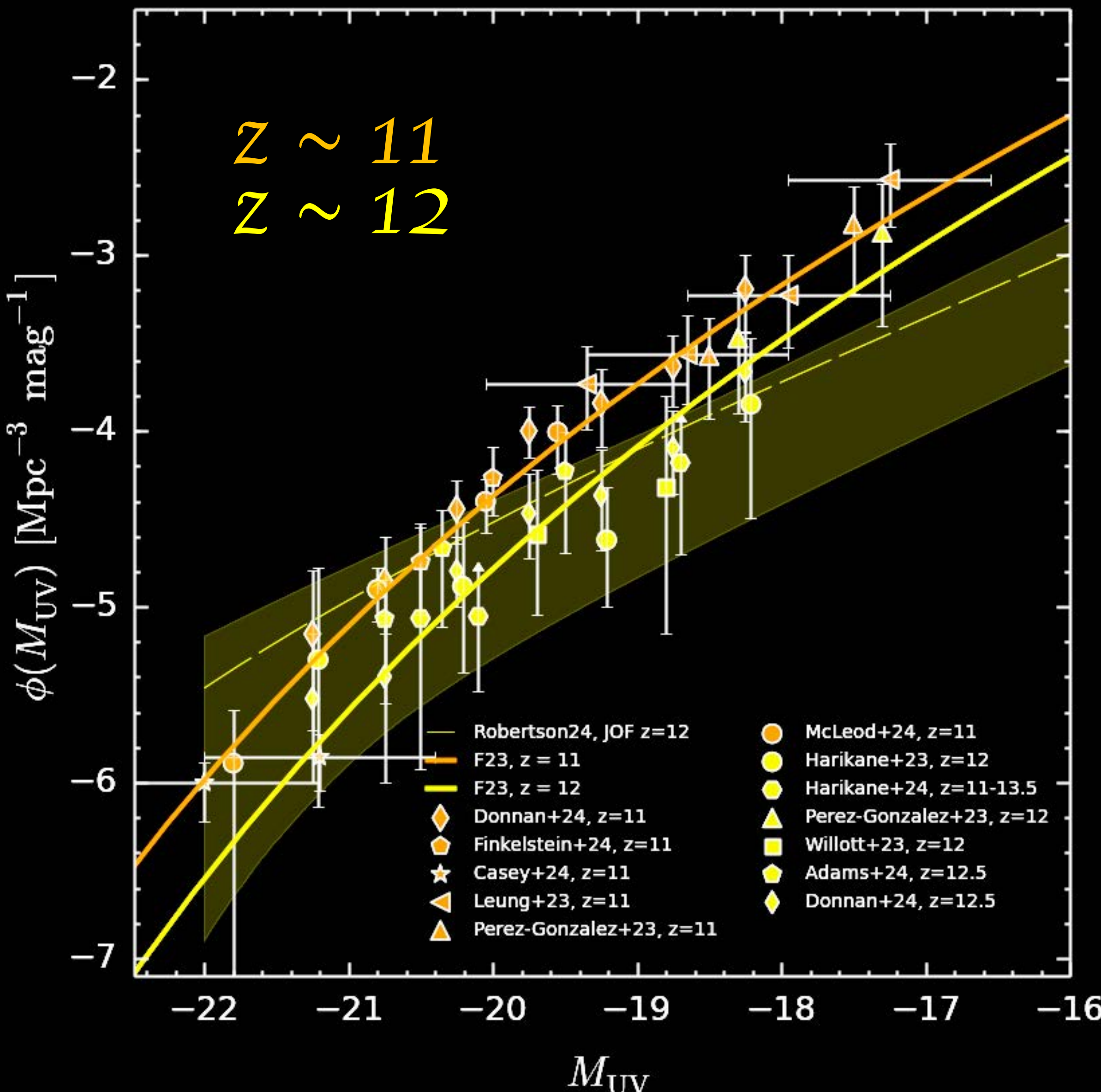
$$\dot{n}_{ion}(z) = \rho_{\mathrm{UV}}(z)\xi_{ion}(z)f_{esc}(z)$$

Ionization rate (controls reionization)

Ionizing photons/UV luminosity (IMF dependence)

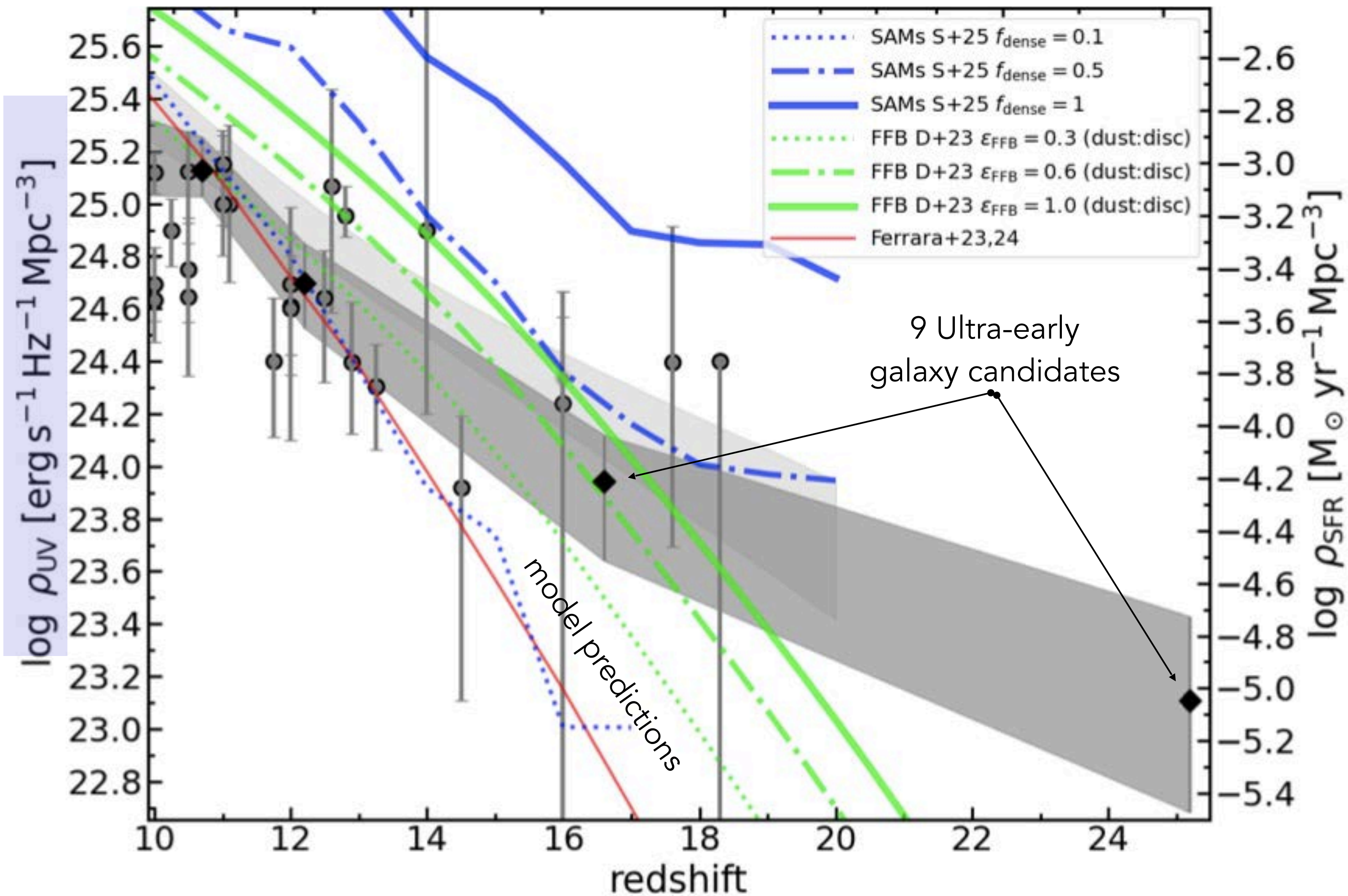
UV LF OF BLUE MONSTERS

Ferrara+23
Ferrara24



A FLAT LUMINOSITY DENSITY?

Perez-Gonzalez+2025



Cosmic reionization

Cosmic hydrogen is ionized by UV light from first stars/galaxies

Electron scattering Optical Depth

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

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

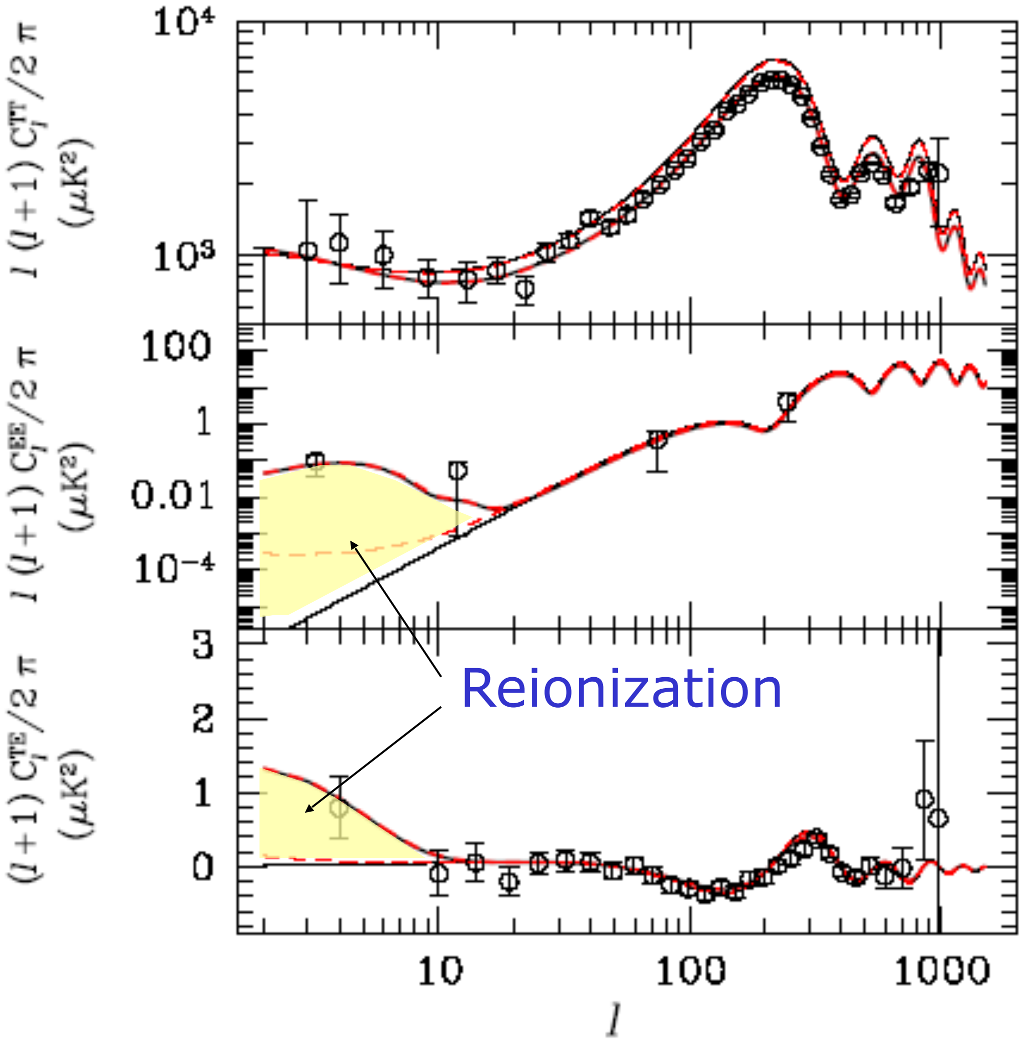
Effects on the CMB

Reionization affects CMB in three ways:

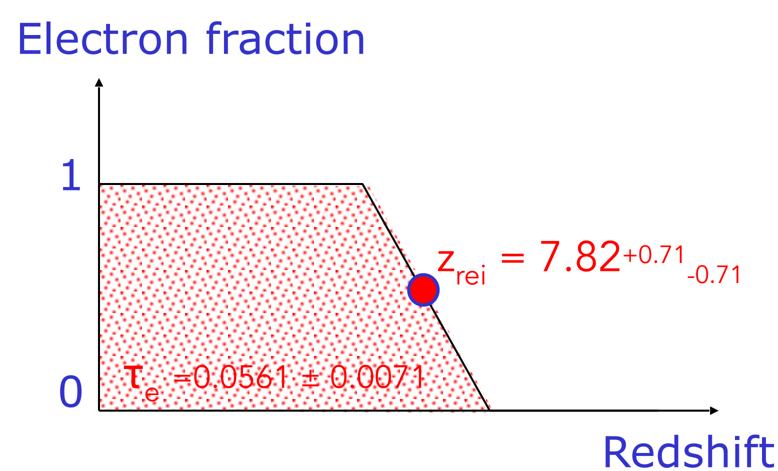
1. Damping of primary anisotropies on all scales
2. Small scale secondary anisotropies (patchy reionization)
3. Large scale ($\ell < 10$) polarization signal

CMB POLARIZATION

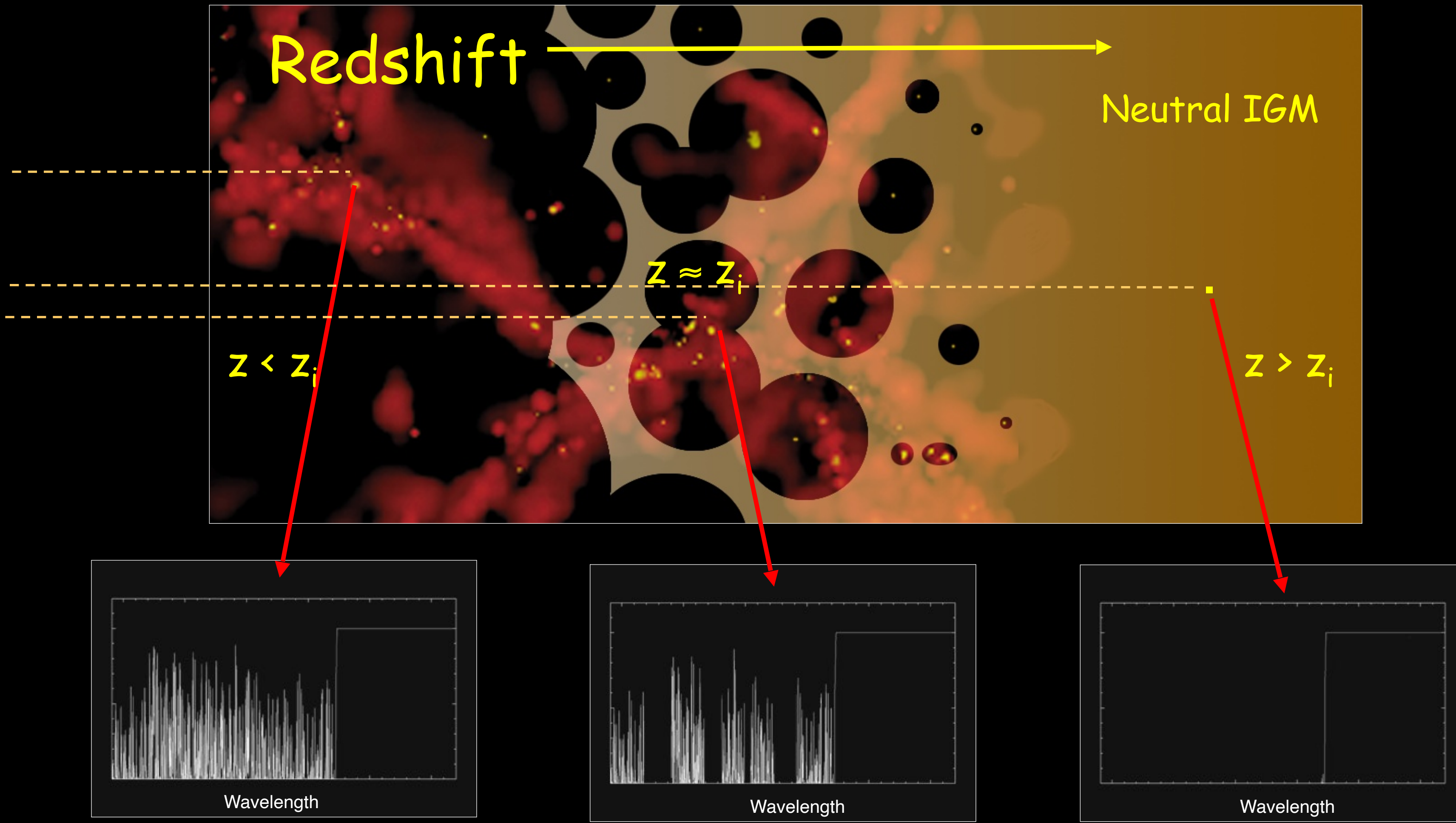
Planck Collaboration 2018



PLANCK+Lensing+BAO



GUNN-PETERSON EFFECT



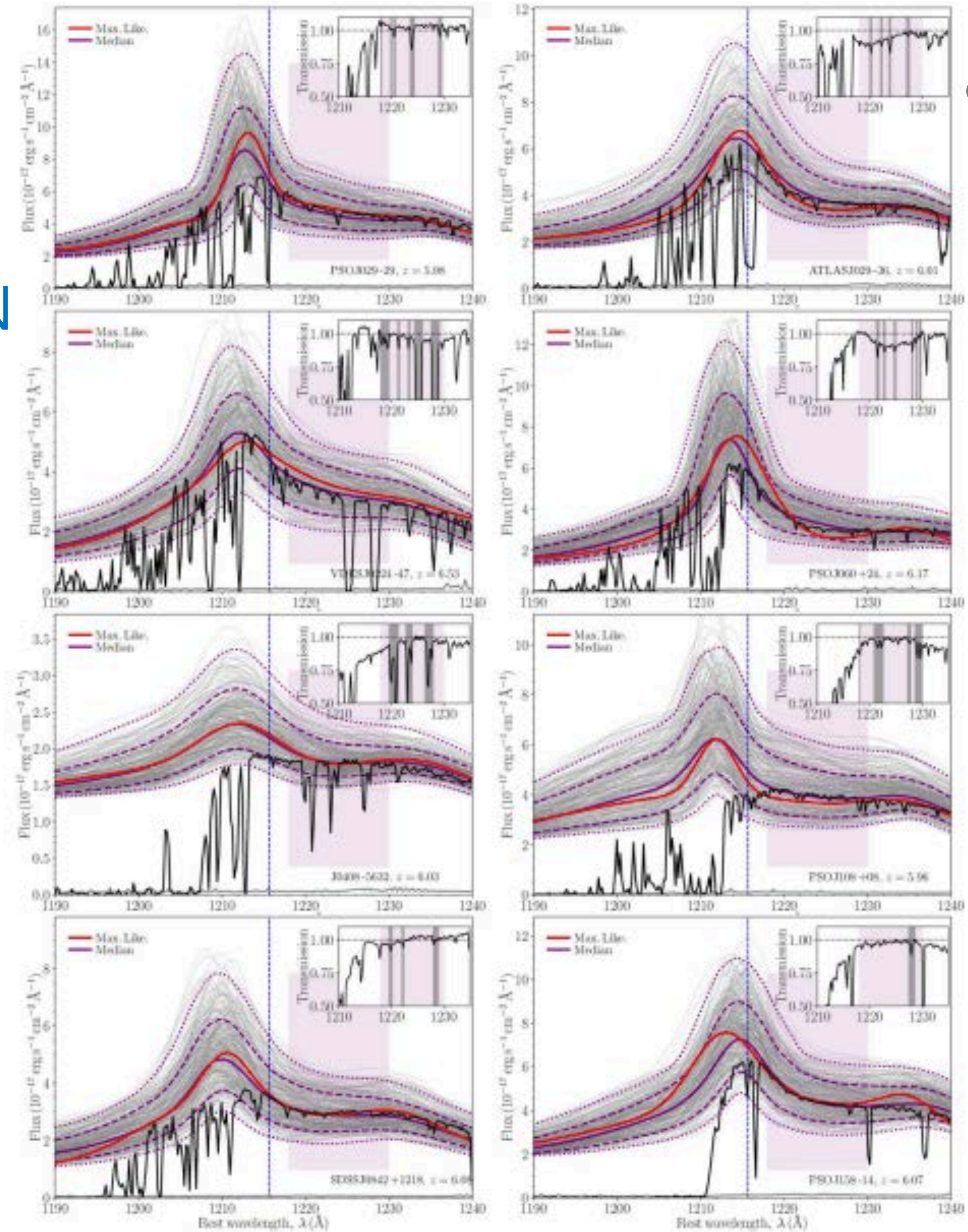
Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

Neutral Hydrogen

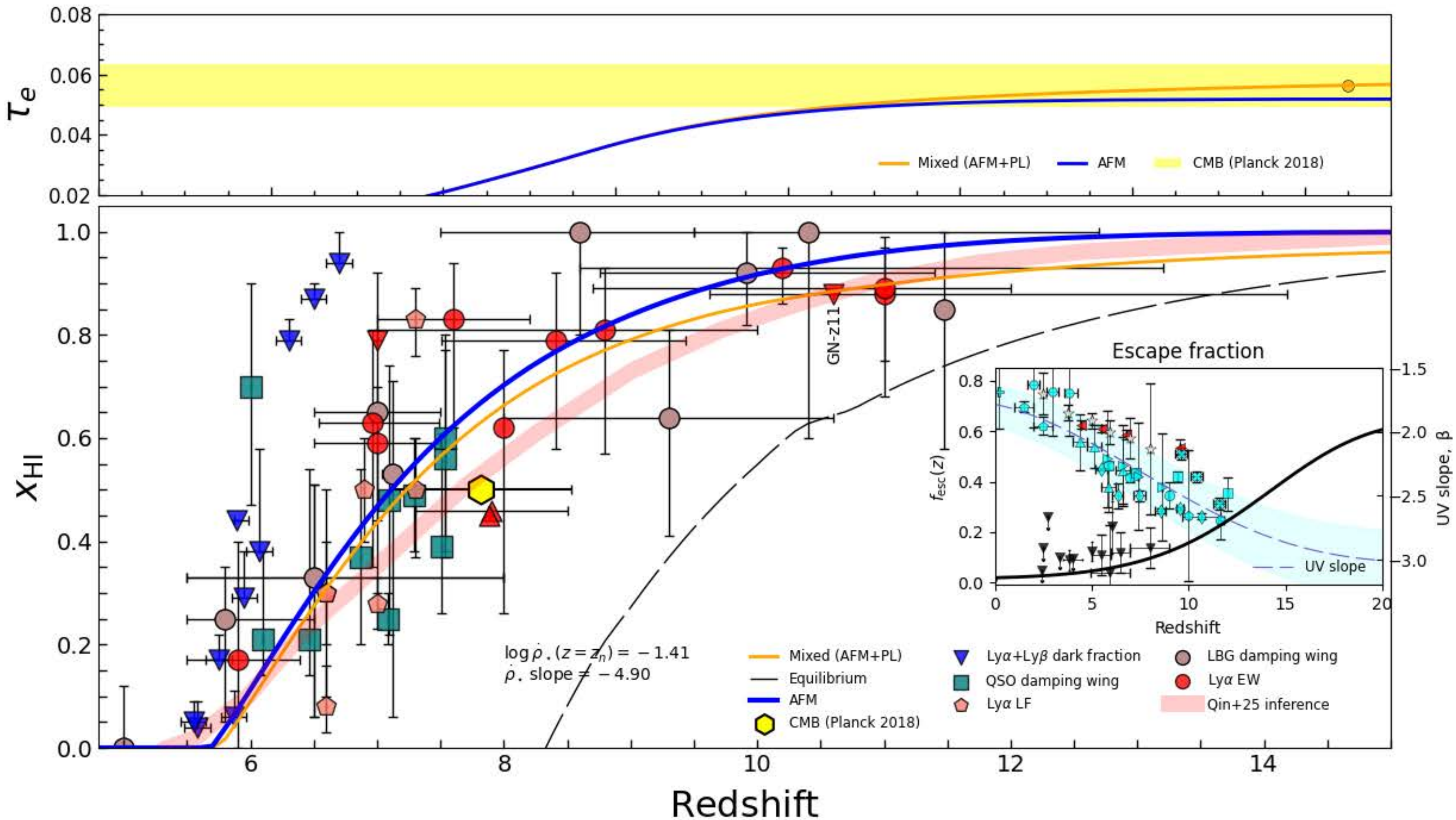
Measuring the HI from Gunn-Peterson damping wing in quasars and galaxies in the Epoch of Reionization



Greig+24

REIONIZATION HISTORY

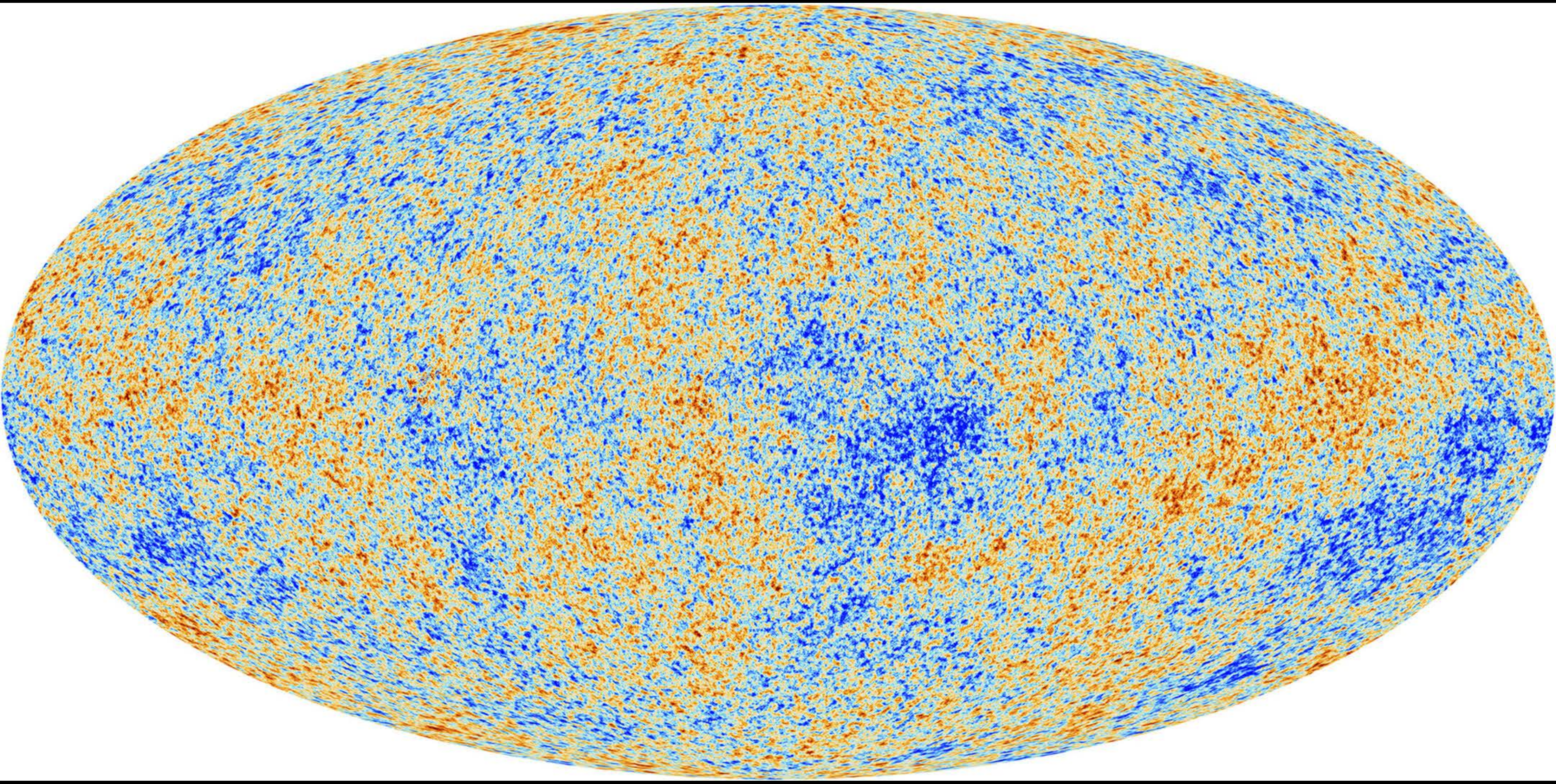
Ferrara+25, in prep.



Reionization in the JWST era

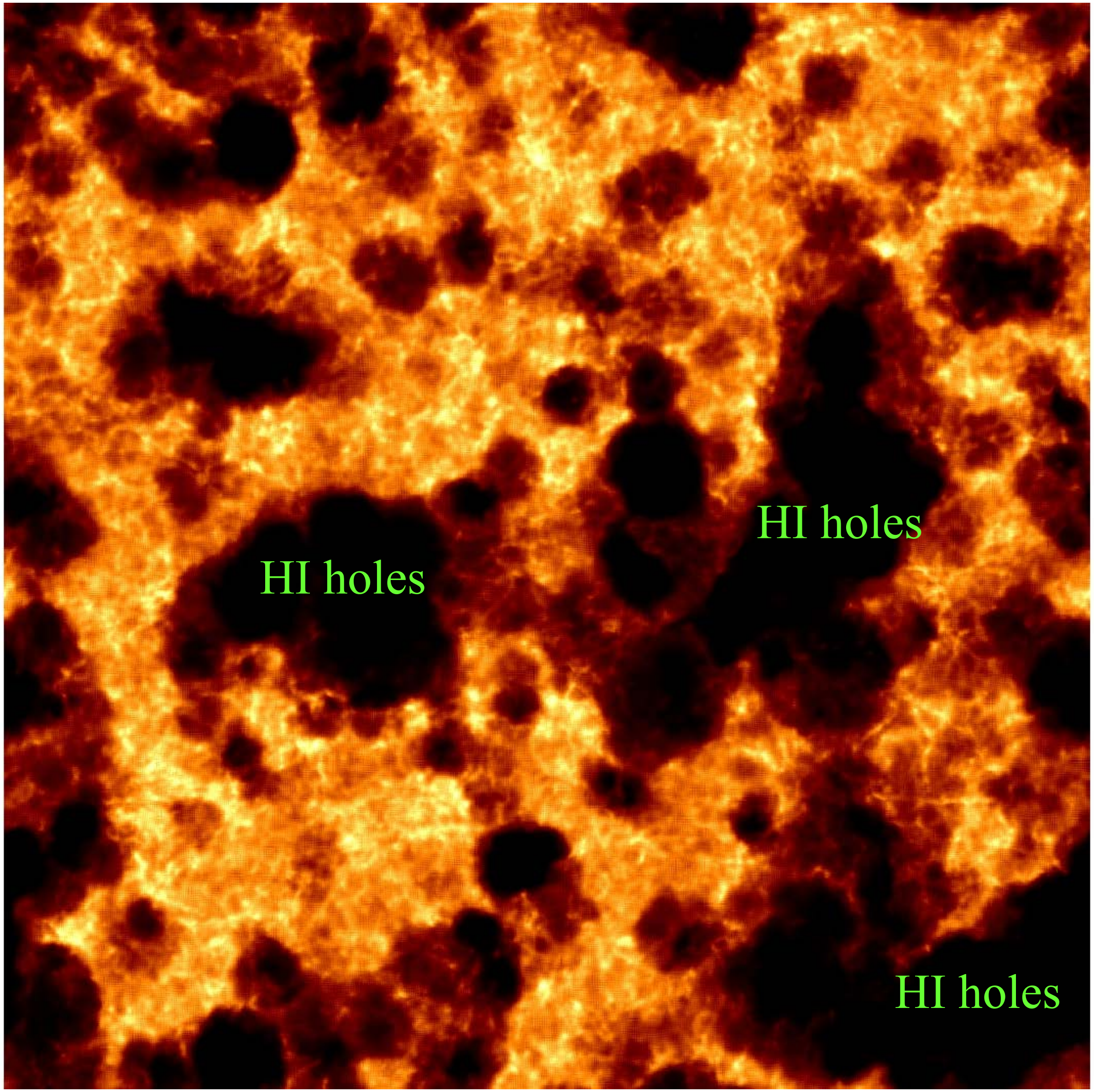
Open questions

1. When *exactly* did reionization start?
2. Can we model and detect Pop III stars?
3. What is their role in cosmic reionization?
4. Can we model the evolution of the LF at ultra-high redshifts?
5. Can we reliably compute the escape of UV photons?
6. How can we improve RT in extremely large volumes?
7. Oligarchic vs. democratic? Early or late?



HAPPY BIRTHDAY, CMB!

HI density map in a 400 cMpc box @ z=8



Baek & AF 12

SOURCE LIST

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

  In what proportion ? $N\gamma = (4, 30, 100)\times10^3$ 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

COSMOLOGICAL I-FRONTS PROPAGATION

Single source

Physical coordinates

$$\bar{n}_{\rm H}\left(\frac{{\rm d}V_p}{{\rm d}t} - 3HV_p\right) = \frac{{\rm d}N_\gamma}{{\rm d}t} - \alpha_{\rm B}\langle n_{\rm H}^2\rangle V_p$$

Comoving coordinates

$$\frac{{\rm d}V}{{\rm d}t} = \frac{1}{\bar{n}_{\rm H}^0}\frac{{\rm d}N_\gamma}{{\rm d}t} - \alpha_{\rm B}\frac{C}{a^3}\bar{n}_{\rm H}^0 V$$

clumping factor

$$C = \langle n_{\rm H}^2\rangle/\bar{n}_{\rm H}^2$$

$$V(t) = \int_{t_i}^{t}\frac{1}{\bar{n}_{\rm H}^0}\frac{{\rm d}N_\gamma}{{\rm d}t'}\,{\rm e}^{F(t',t)}\,{\rm d}t' \ ,$$

where

$$F(t',t) = -\alpha_{\rm B}\bar{n}_{\rm H}^0\int_{t'}^{t}\frac{C(t'')}{a^3(t'')}\,{\rm d}t''$$

COSMOLOGICAL I-FRONTS PROPAGATION

Statistical approach

volume filling factor

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

Effective photon/baryon ratio

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

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

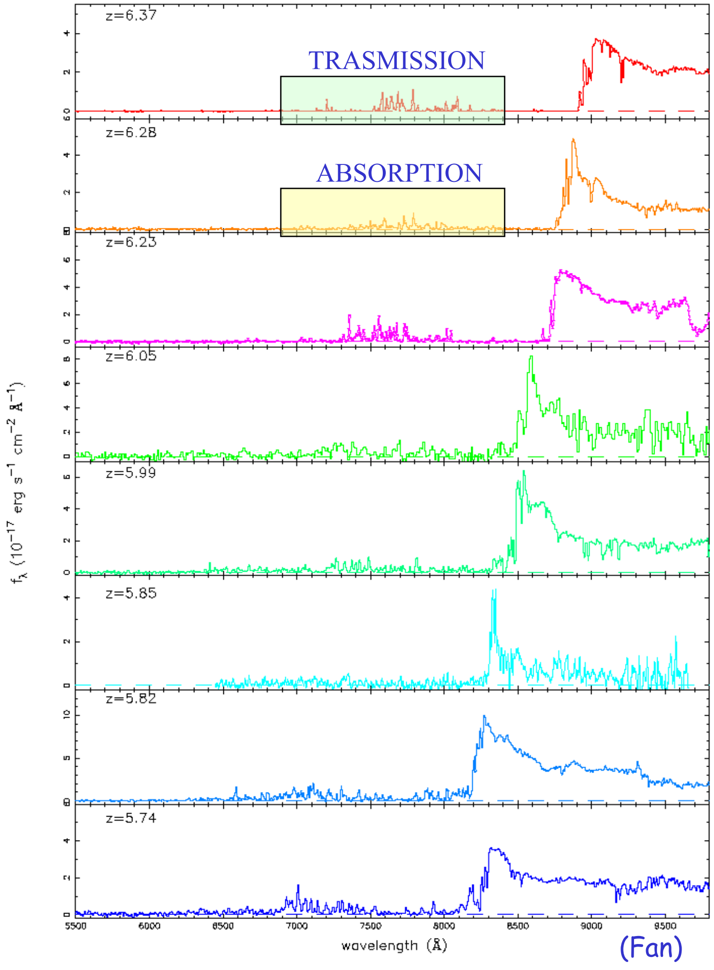
$$\frac{dQ_{H\ II}}{dt} = \frac{N_{ion}}{0.76}\frac{dF_{col}}{dt} - \alpha_B \frac{C}{a^3}\bar{n}_H^0 Q_{H\ II}$$

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

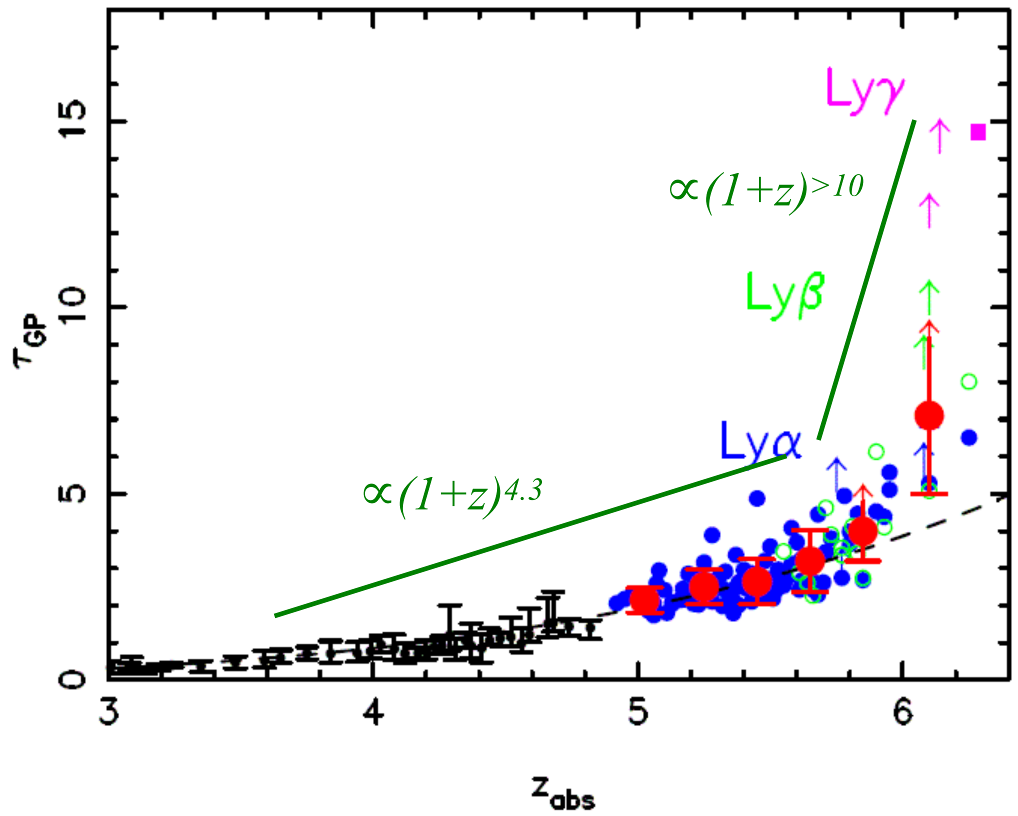
Fan 2006

GUNN-PETERSON EFFECT

Spectra of high-*z* QSOs



Lyα optical depth



Wise & Cen 2009

ESCAPE FRACTION EVOLUTION