

# Reionization Physics

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**Pune**



NCRA • TIFR

**Frontiers in 21 cm Cosmology**  
**Kodaikanal Solar Observatory, India**  
**10 December 2018**

# Studying the epoch of reionization

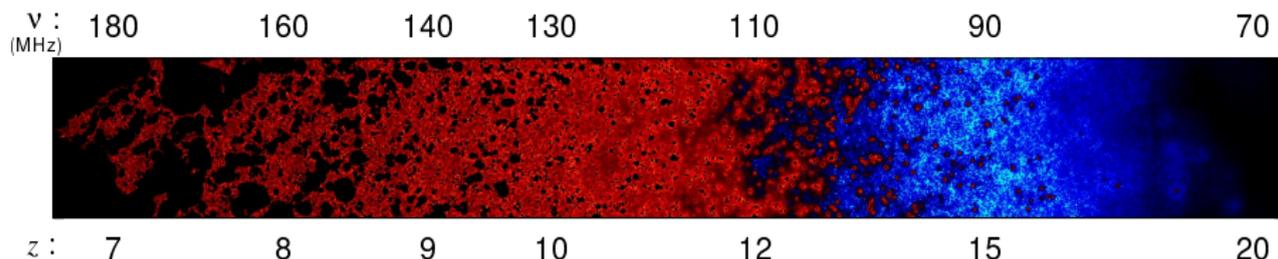


Figure courtesy Raghunath Ghara

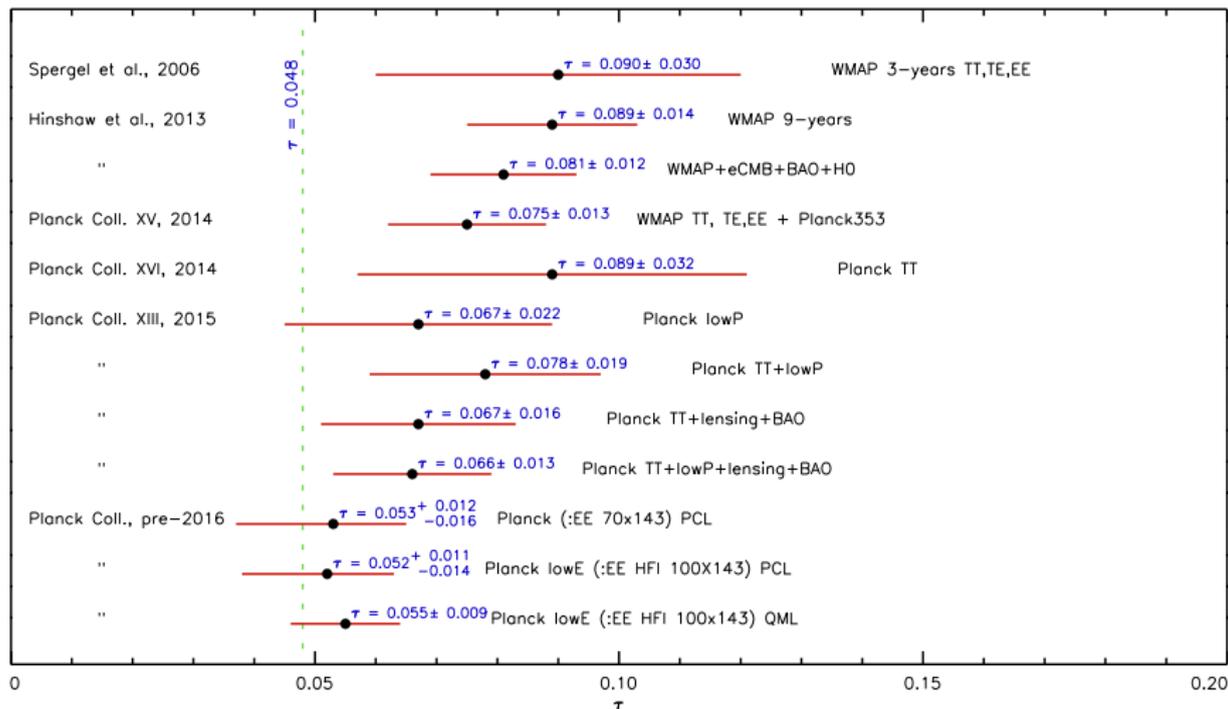
- ▶ universe getting ionized by the first stars
- ▶ aim is to study the neutral hydrogen fraction  $x_{\text{HI}}(\mathbf{x}, z)$  as it decreases from  $\sim 1$  to  $\sim 0$
- ▶ get insights on the nature of the first stars

# Thomson scattering $\tau_{\text{el}}$ from CMB



$$\tau_{\text{el}} = \sigma_T C \int_0^{z[t]} dt n_e (1+z)^3$$

Planck Collaboration (2016)

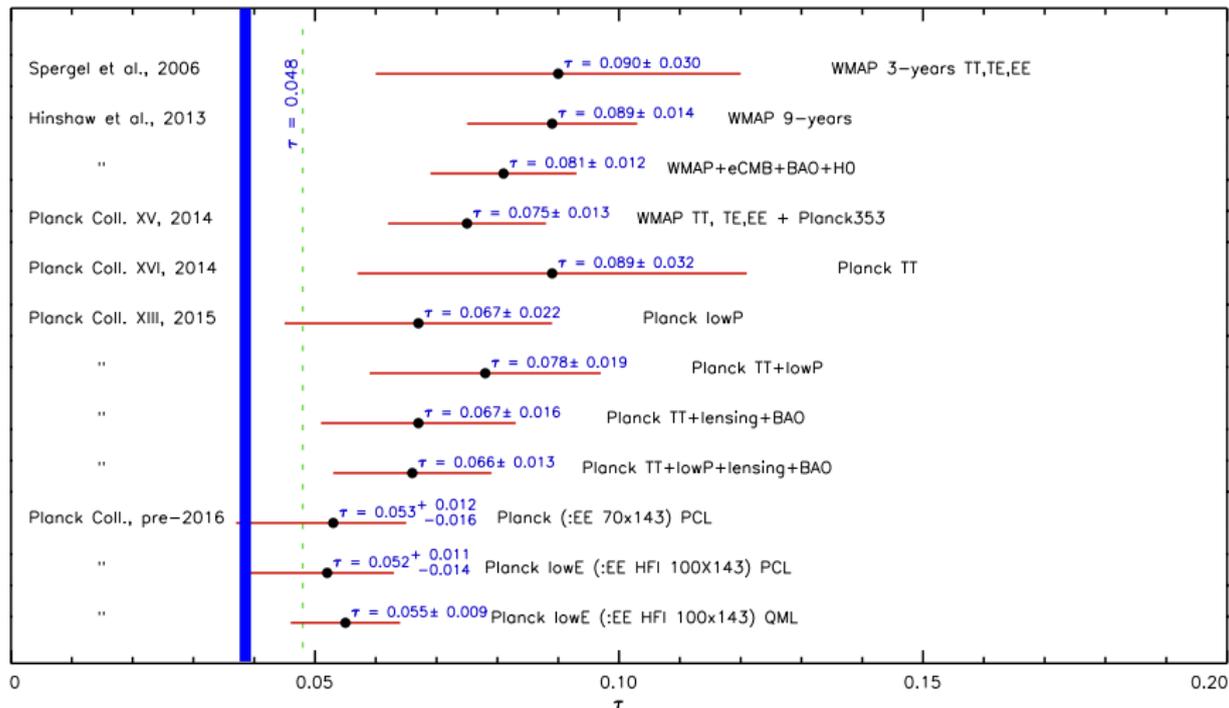


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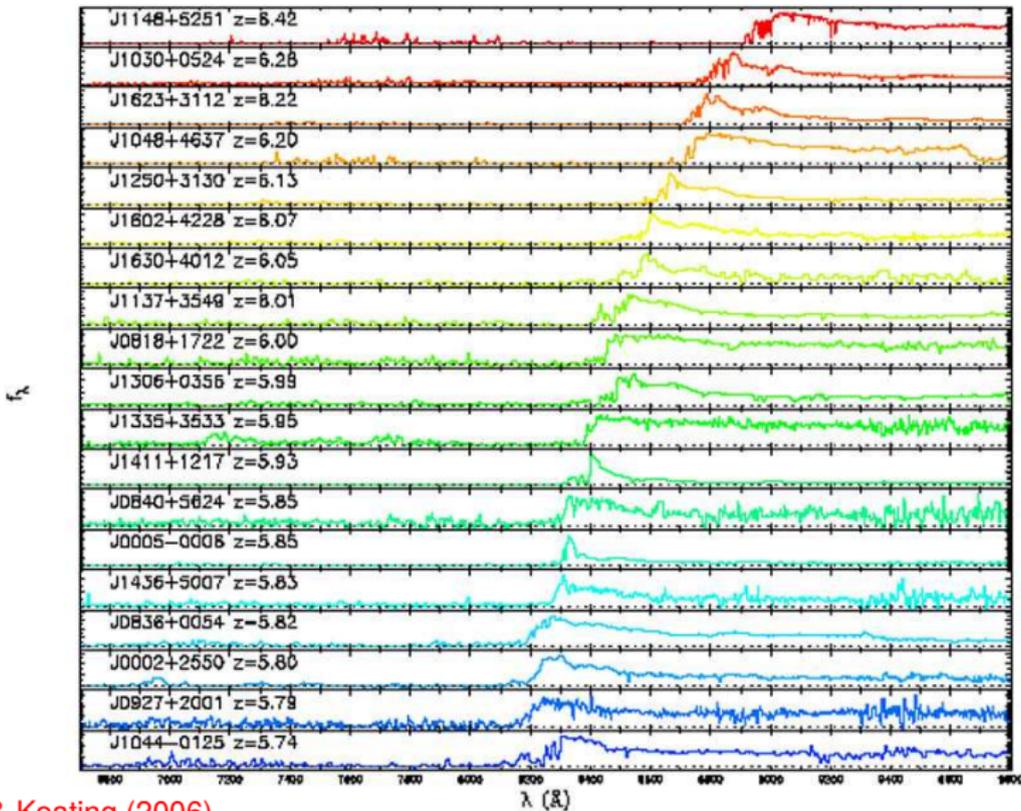


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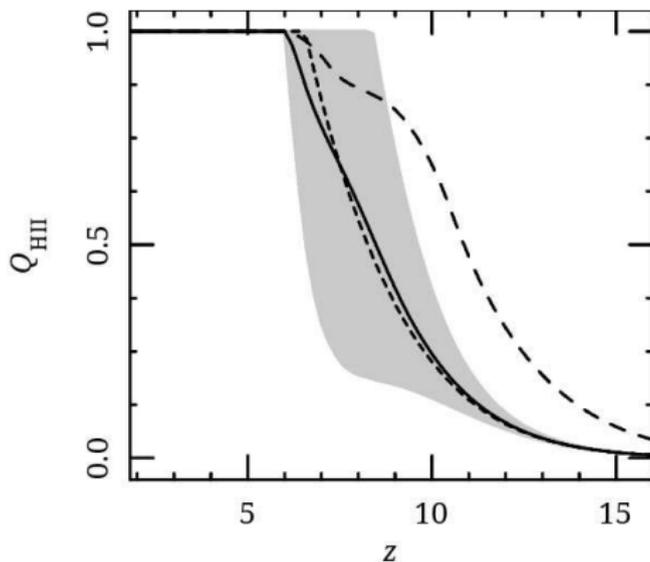
# Quasar absorption spectra at $z \gtrsim 6$



Fan, Carilli & Keating (2006)

$$F_{\text{obs}} = F_{\text{cont}} e^{-\tau_{\text{GP}}}, \quad \tau_{\text{GP}} \sim \left( \frac{X_{\text{HI}}}{10^{-5}} \right)$$

# Data constrained models



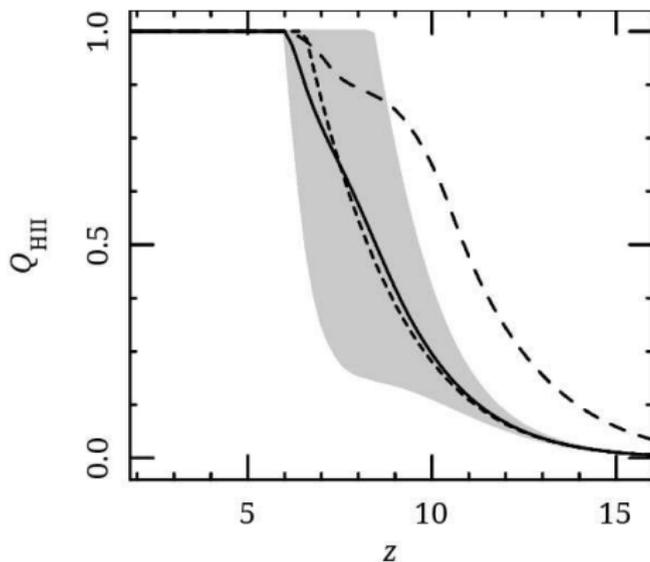
Mitra, **TRC** & Ferrara (2015)

Constraints based on

- ▶ Planck15 data on  $\tau_{\text{el}}$
- ▶ quasar absorption line measurements at  $z \lesssim 6$  (either  $\Gamma_{\text{HI}}$  or  $\langle \tau_{\text{eff}} \rangle$ )
- ▶ prior on  $x_{\text{HI}}$  at  $z \sim 5.5 - 6$  based on “dark pixel” fraction

McGreer, Mesinger & D’Odorico (2015)

# Data constrained models



Mitra, **TRC** & Ferrara (2015)

- ▶ reionization starts at  $z \sim 12 - 15$
- ▶ 50% ionized at  $z \sim 6 - 10$
- ▶ large uncertainties at  $7 \lesssim z \lesssim 10$

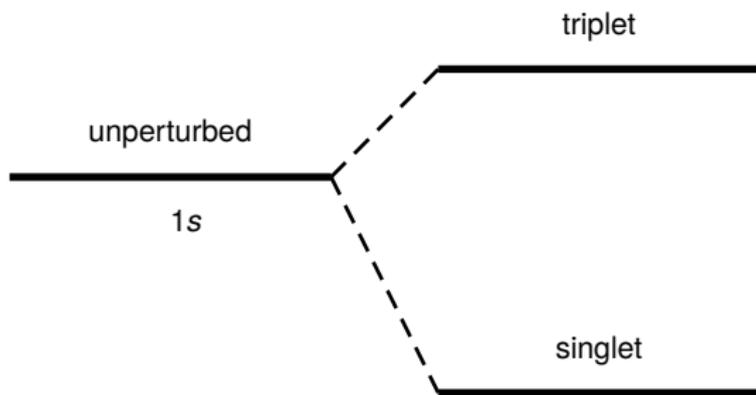
# Other probes of reionization



- ▶ Galaxy luminosity function: **uncertain escape fraction**
- ▶ Quasar absorption spectra (damping wings/near zones): **only a few quasars known till date**
- ▶ IGM temperature: **requires detailed modelling**
- ▶ Lyman- $\alpha$  emitters (number density and clustering): **systematics, model dependent constraints**

# 21 cm line

- ▶ Hydrogen 1s ground state split by the interaction between the electron spin and the nuclear spin.



$$\frac{1}{\sqrt{2}} [|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]$$

$$\nu = 1420 \text{ MHz}, \lambda = 21 \text{ cm}$$

$$\frac{1}{\sqrt{2}} [|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]$$

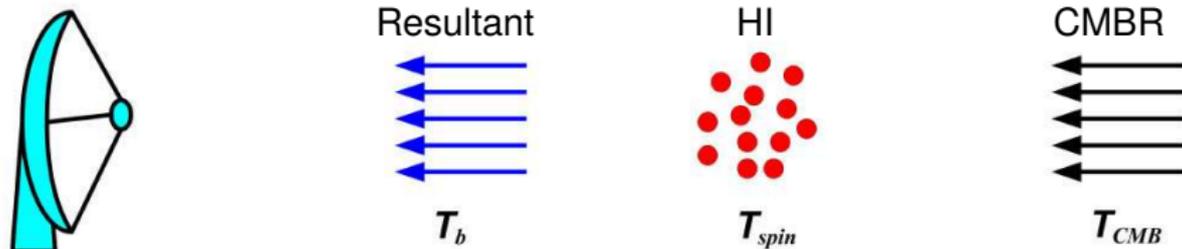
Line transition  $\Rightarrow$  a transition originating at  $z$  will be observed at a frequency  $\nu_{\text{obs}} = 1420/(1+z)$  MHz.

- ▶ It is a magnetic dipole transition, with transition probability  $A_{21} = 2.85 \times 10^{-15} \text{ s}^{-1} \Rightarrow$  an atom in the upper level is expected to make a downward transition once in  $10^7$  yr.

For Ly $\alpha$  transition, the corresponding coefficient is  $A_{21} \approx 6 \times 10^8 \text{ s}^{-1}$ .

# The 21 cm signal

Figure from Zaroubi (2013)

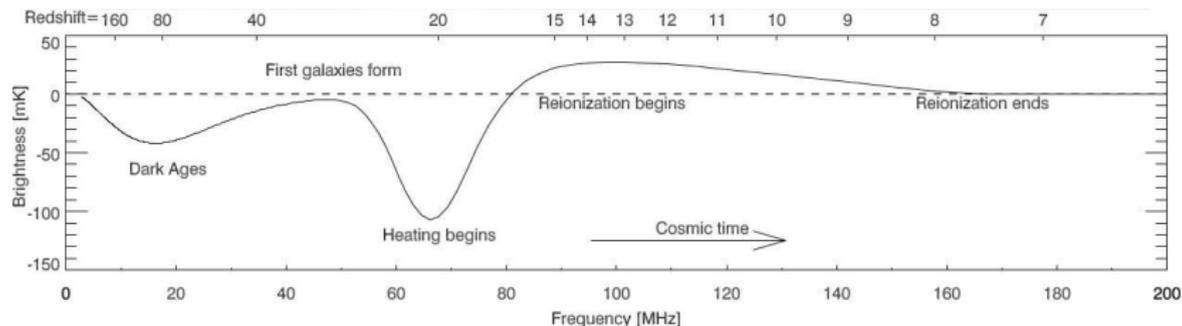


The signal: 
$$\delta I_\nu \propto \rho_{HI} \left( 1 - \frac{T_{CMB}}{T_{spin}} \right) \propto \rho_{HI} \text{ (if } T_{spin} \sim T_{gas} \gg T_{CMB} \text{)}$$

# Global 21 cm signature



$$\delta T_b \propto \frac{T_s - T_{\text{CMB}}(z)}{T_s} \rho_{\text{HI}}$$
$$T_s^{-1} = \frac{T_{\text{CMB}}^{-1} + X_C T_k^{-1} + X_\alpha T_k^{-1}}{1 + X_C + X_\alpha}$$

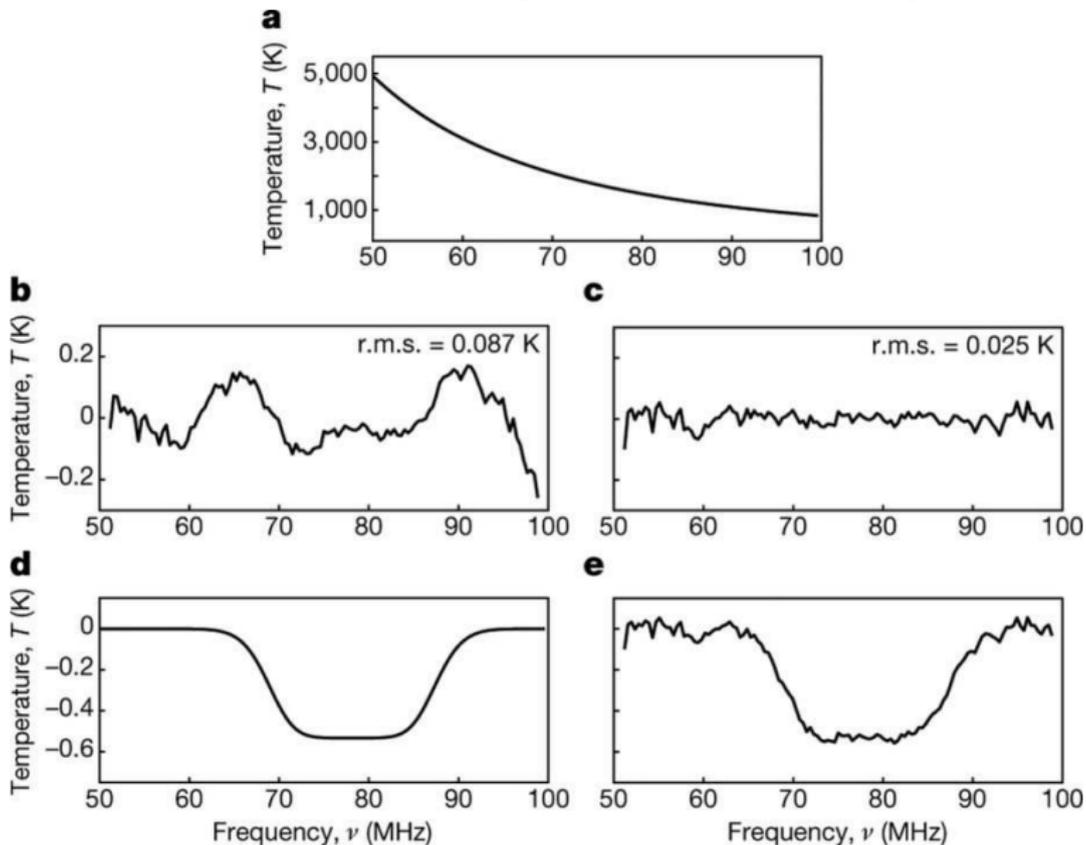


Pritchard & Loeb (2012)

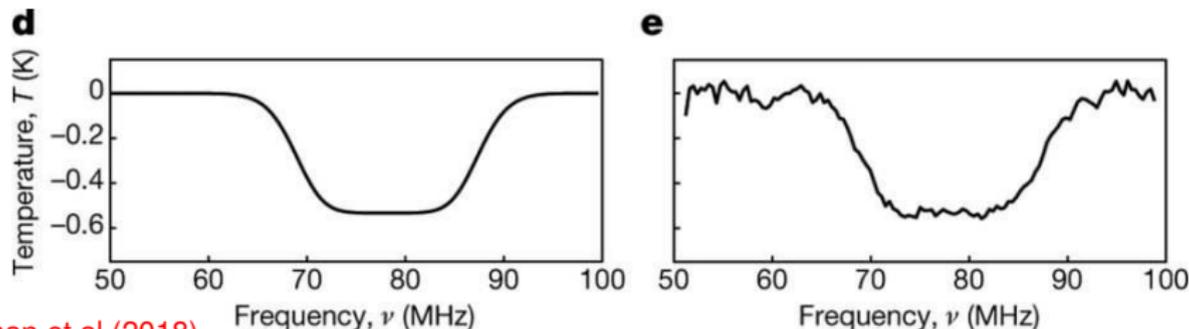
# Recent detection of the global 21 cm signal



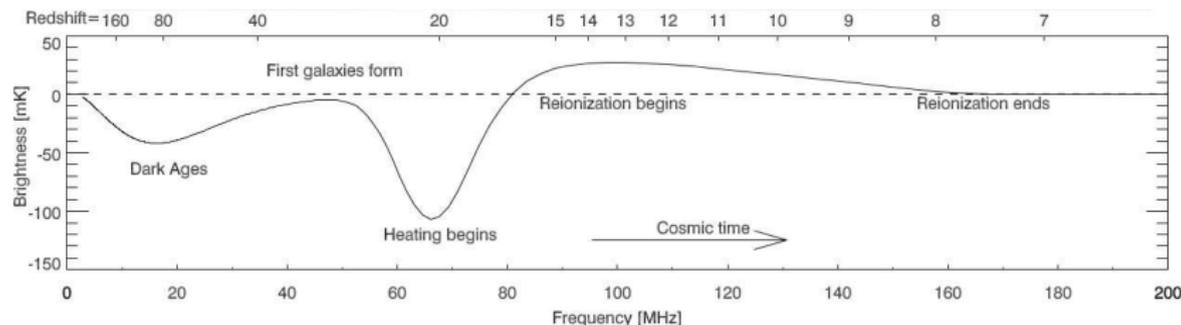
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# Consistent with standard calculations?



Bowman et al (2018)



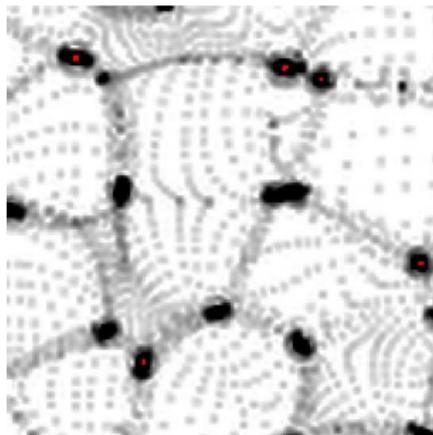
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$$\delta T_b = 0.023 \text{ K } x_{\text{HI}} \left( \frac{T_s - T_{\text{CMB}}(z)}{T_s} \right)$$

# Reionization model ingredients



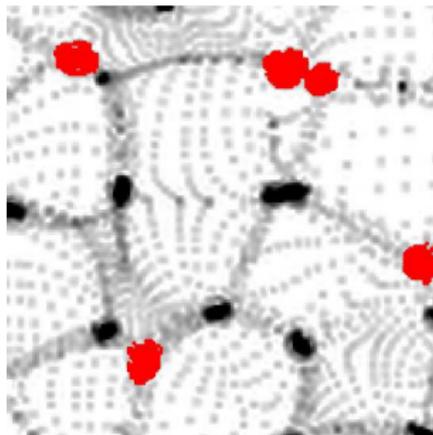
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Analytical: Press-Schechter/Sheth-Tormen formalism  
Simulations: DM only  $N$ -body codes



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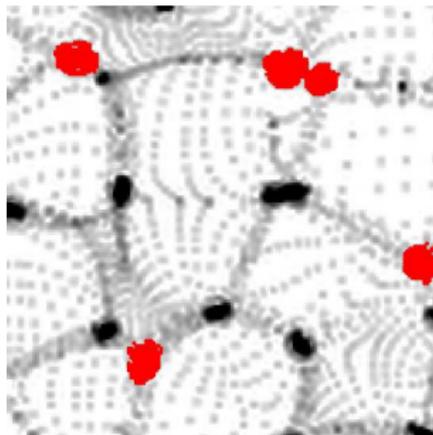
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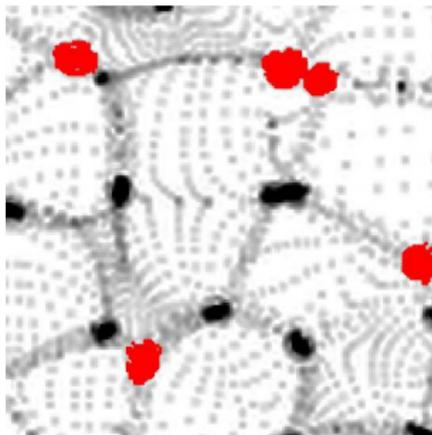
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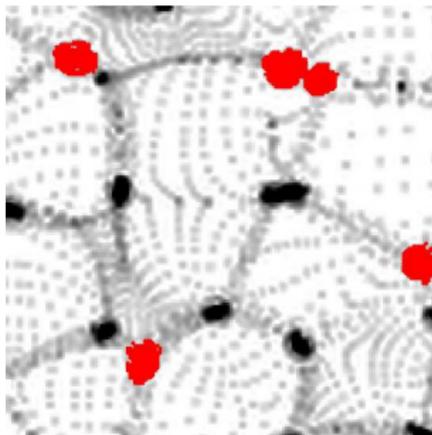
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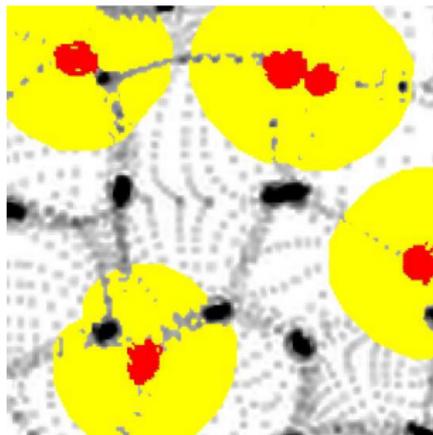
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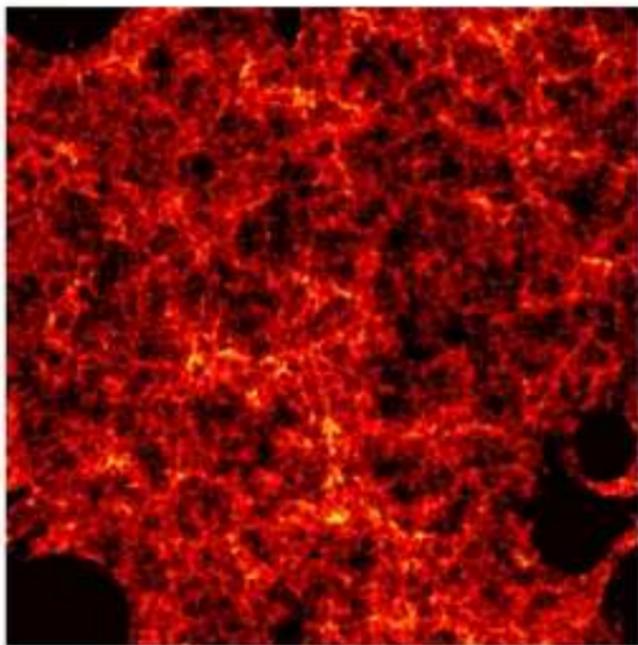
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  - ✗ **Escape of photons  $f_{\text{esc}}$ :** neutral hydrogen within the host galaxy
- ✗ **Radiative transfer in the IGM:** evolution of ionization fronts  
Simulations, semi-numerical, analytical



# Hydrogen reionization by stars

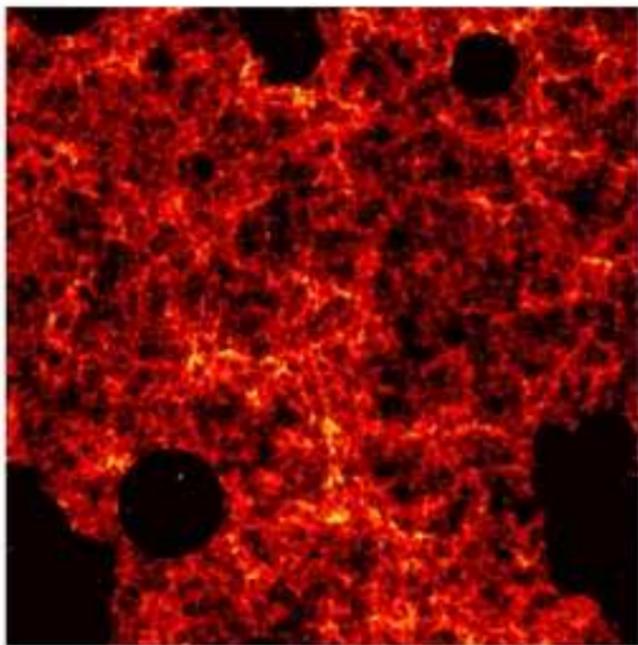


*N*-body simulations (GADGET) + Semi-numerical radiative transfer

TRC, Haehnelt & Regan (2009)

Figure courtesy Aditya Chowdhury

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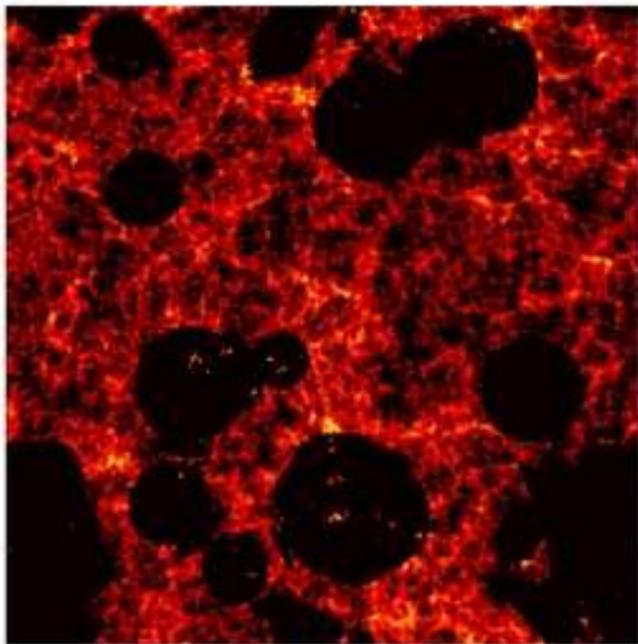


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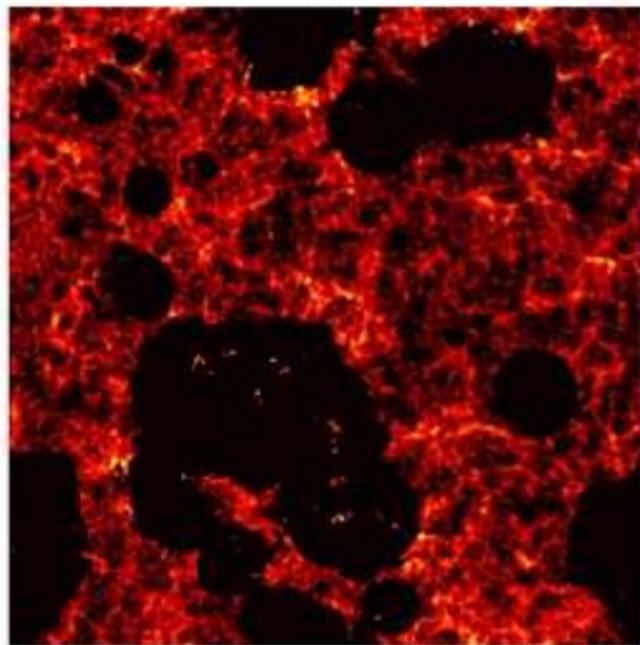


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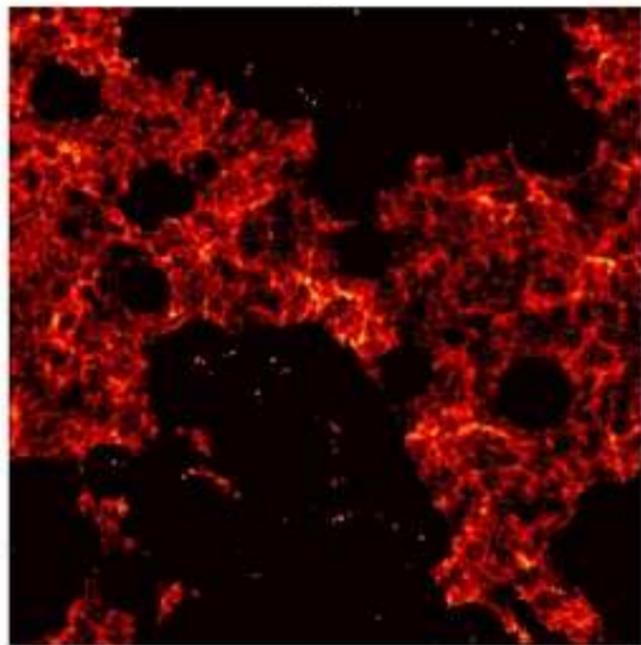


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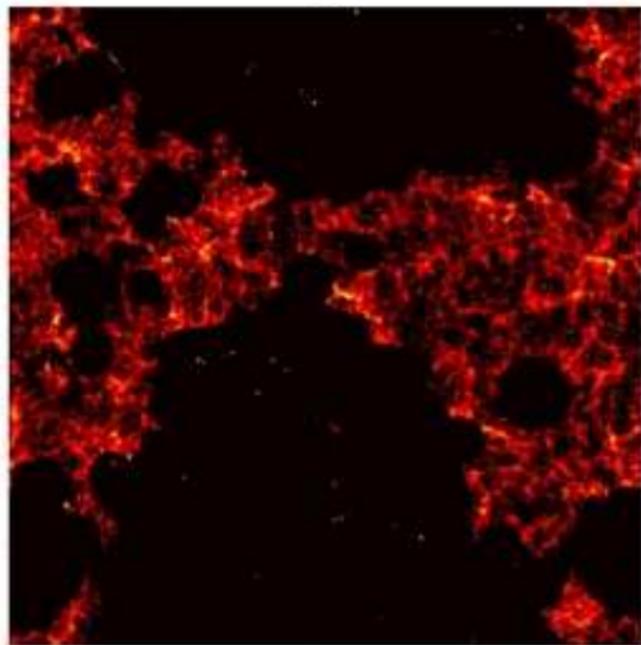


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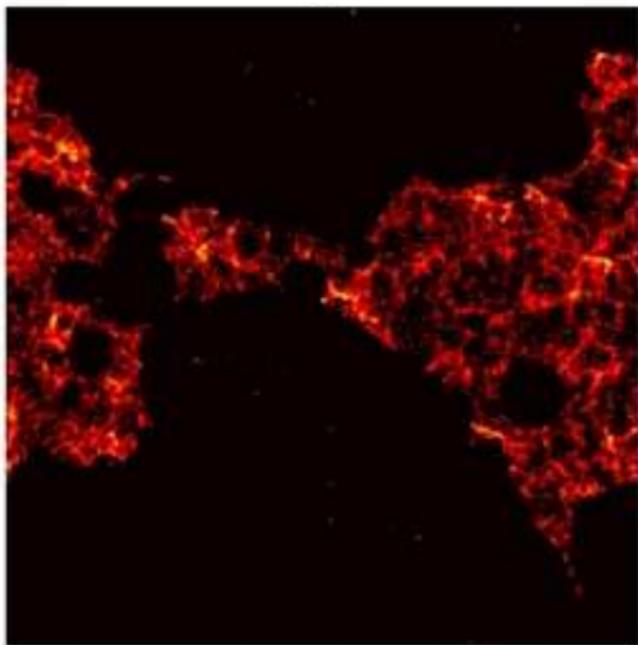


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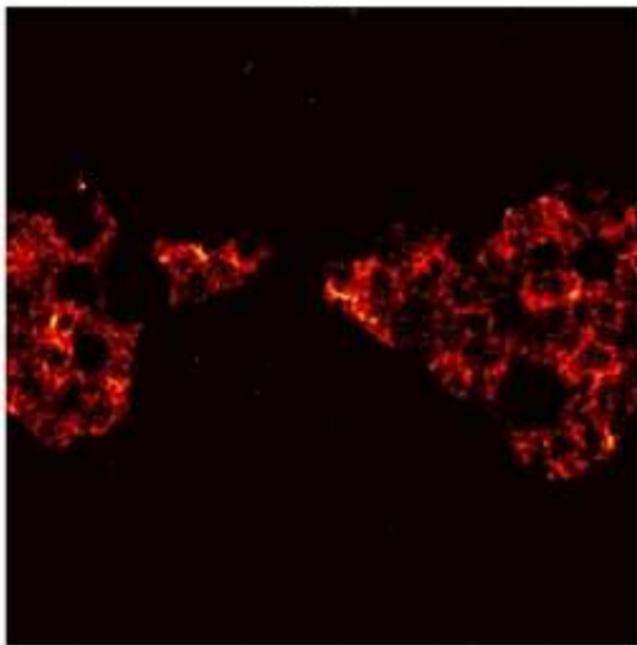


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