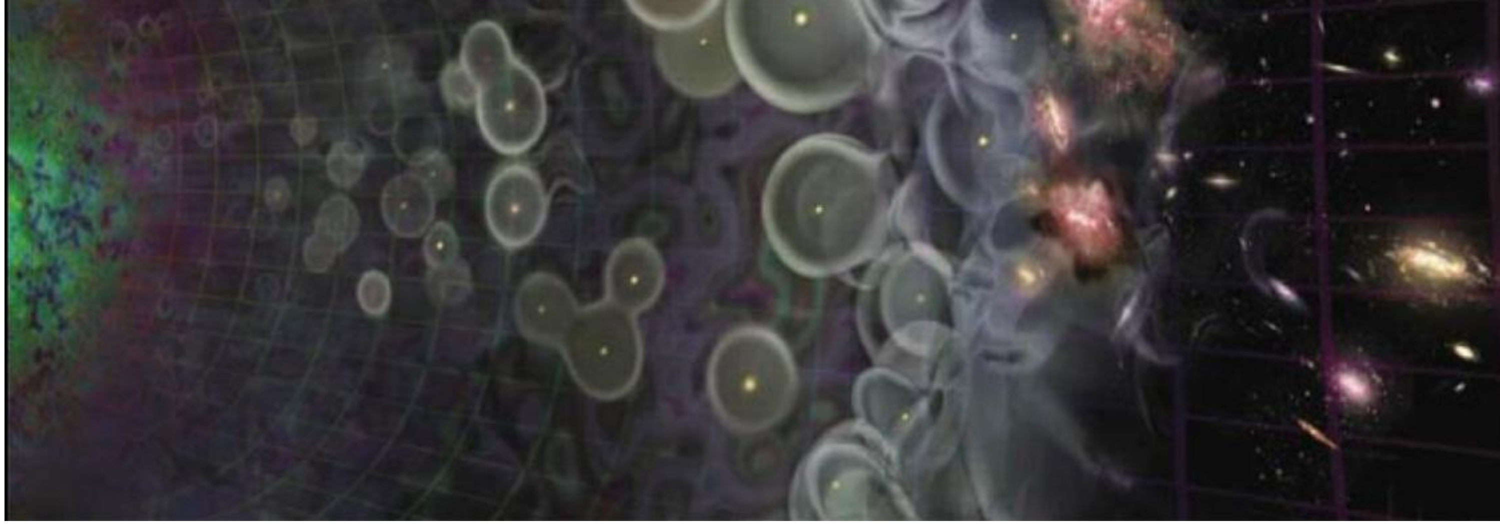
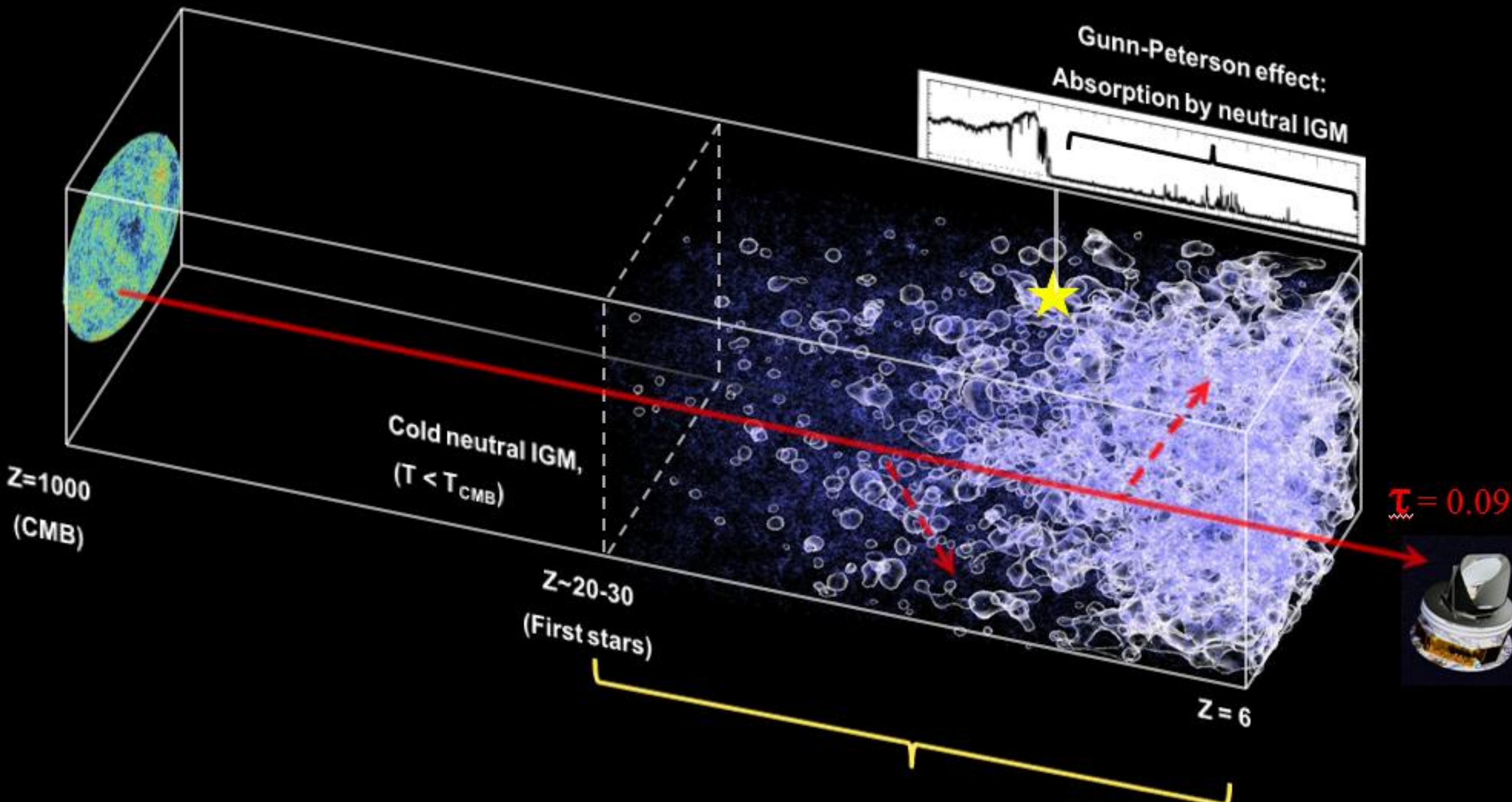


Physics of the Epoch of Reionization

Françoise Combes

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

The epoch of reionization:

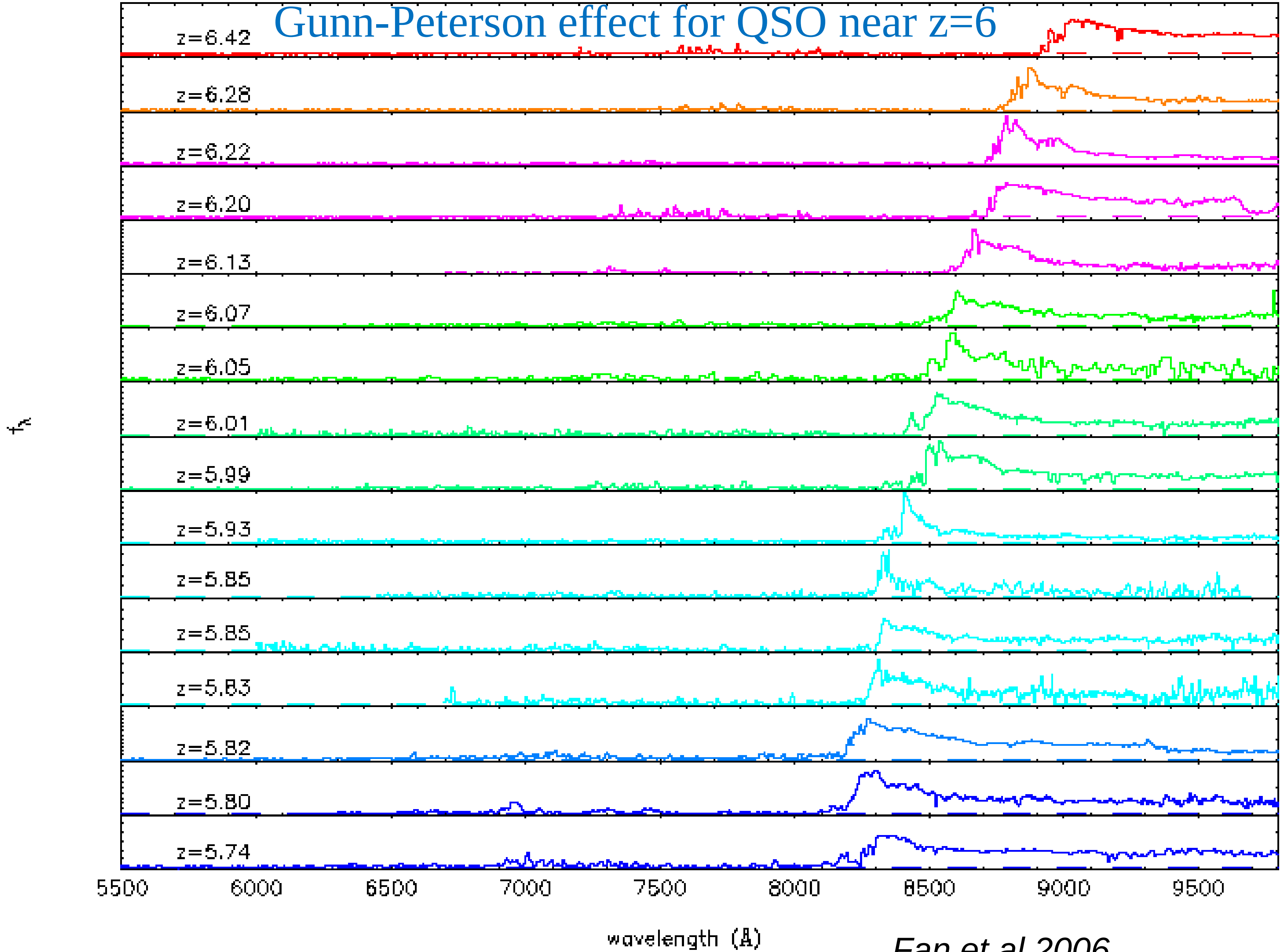


21 cm tomography =>

LOFAR (2013) SKA (2020)

- Source nature
- Luminosity fonction
- Cosmological constraints
- …

Gunn-Peterson effect for QSO near z=6



Fan et al 2006

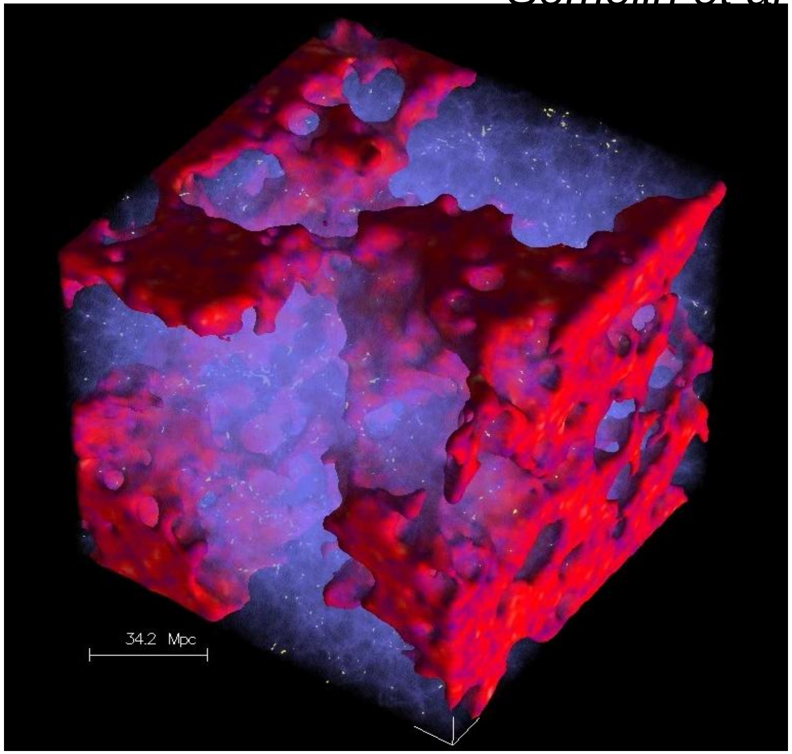
EoR: when?

IGM emission/absorption at 21cm for 6<z<30:
➔Tomography with SKA

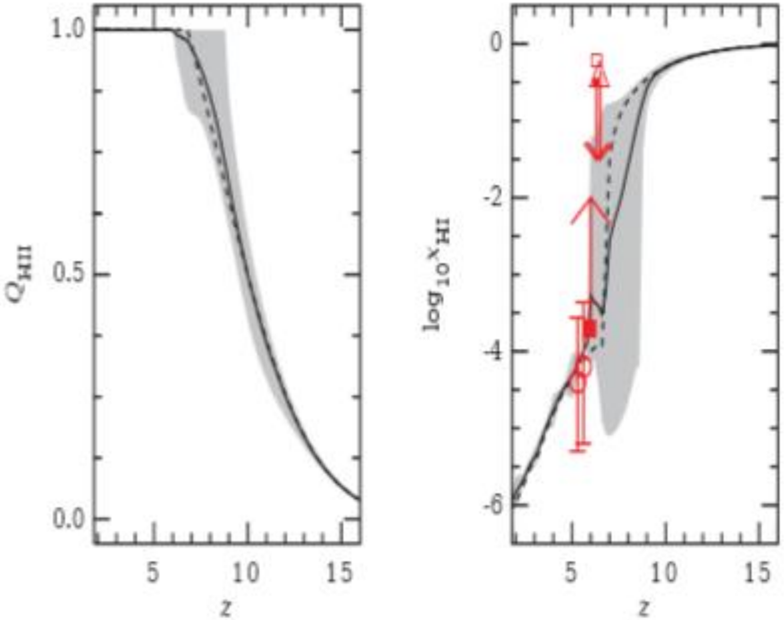
$$\tau = \int dt\, c\, \sigma_{\rm T}\, n_{\rm e} = \int \frac{dz}{H(z)(1+z)} c\, \sigma_{\rm T}\, n_{\rm e}(z)$$

Constraints from the CMB, WMAP, Planck, and QSO

Semelin et al

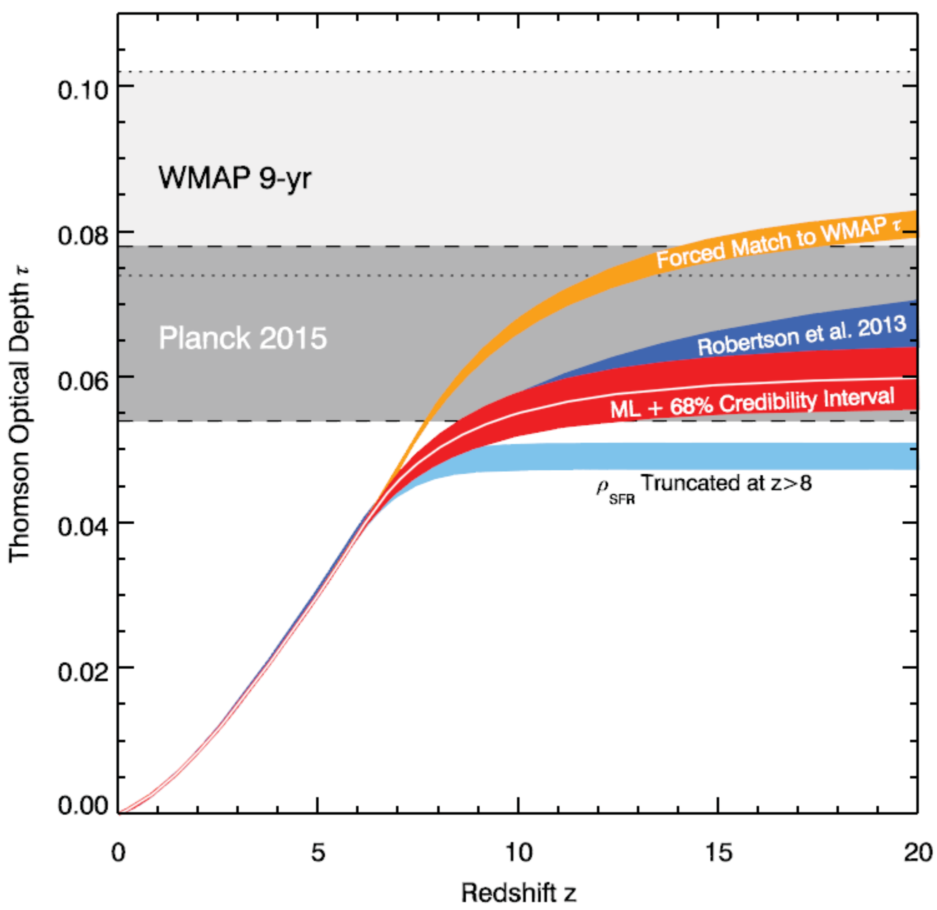


τe= 0.09 EoR between z=15 and 6



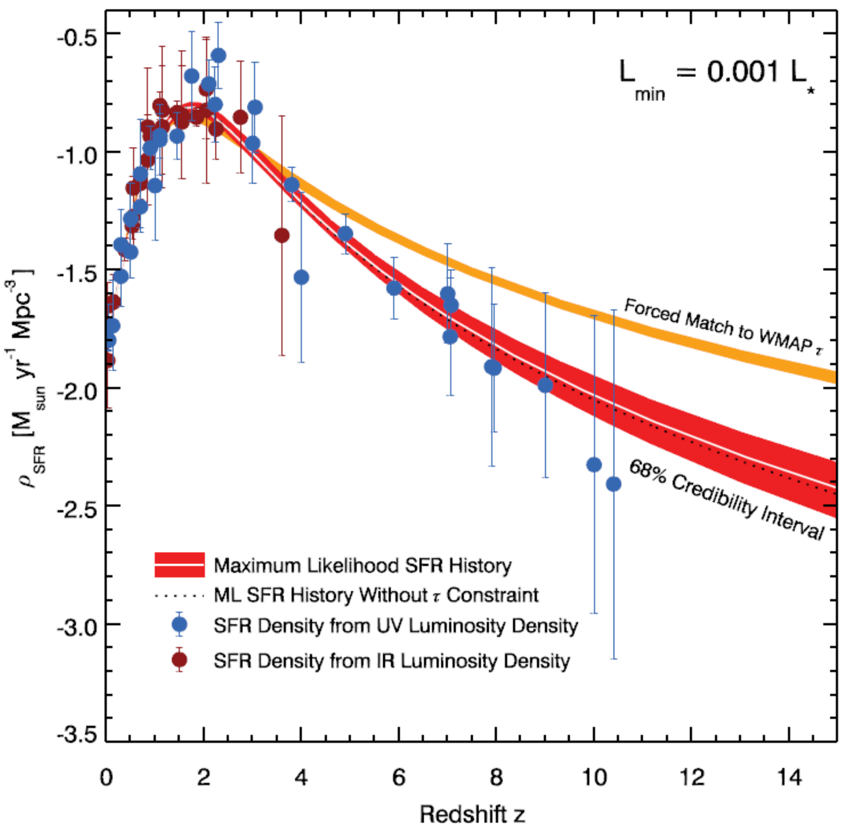
Mitra 2014

New opacity from Planck



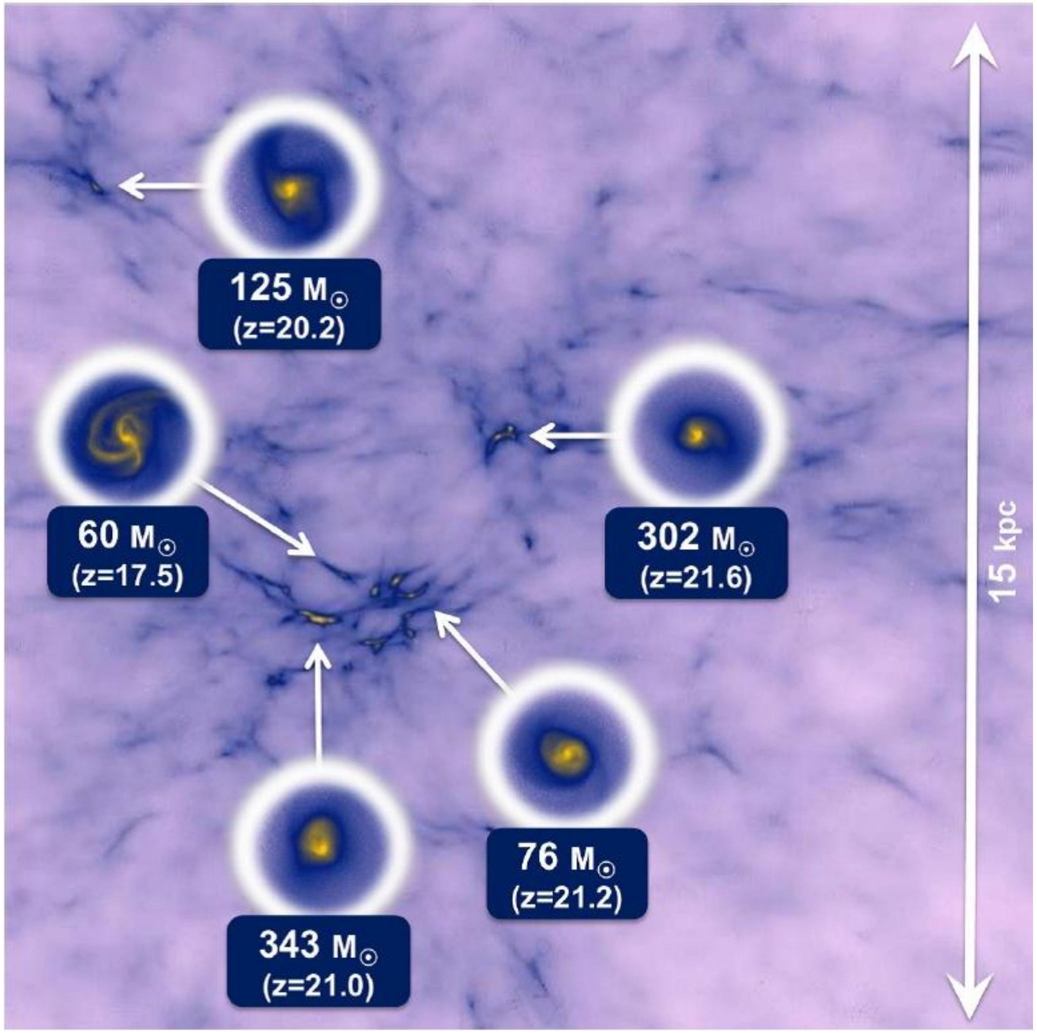
τ= 0.066±012

Requires less galaxies at z>8



Robertson et al 2015

Star formation in the early universe



Dark ages z=200-30 ??
From space

Cosmic Dawn z=30-15
First stars, the HI Tb will be
a mixture of density and Ts

EoR z=15-6 Bubbles around the
first galaxies, percolate

Hirano et al 2014

Main equations

$$T_b = T_{CMB} e^{-\tau} + T_S(1 - e^{-\tau}) \quad \Rightarrow \quad \delta T_b = T_b - T_{CMB} \approx \frac{T_s - T_{CMB}}{1+z} \tau$$

$$\tau_{\nu_0} = \frac{3}{32\pi} \frac{hc^3 A_{10}}{k_B T_S \nu_0^2} \frac{x_{\rm HI} n_H}{(1+z)\,(\mathrm{d}v_{||}/\mathrm{d}r_{||})}$$

$$\approx 0.0092\,(1+\delta)\,(1+z)^{3/2} \frac{x_{\rm HI}}{T_S} \left[\frac{H(z)/(1+z)}{\mathrm{d}v_{||}/\mathrm{d}r_{||}}\right]$$

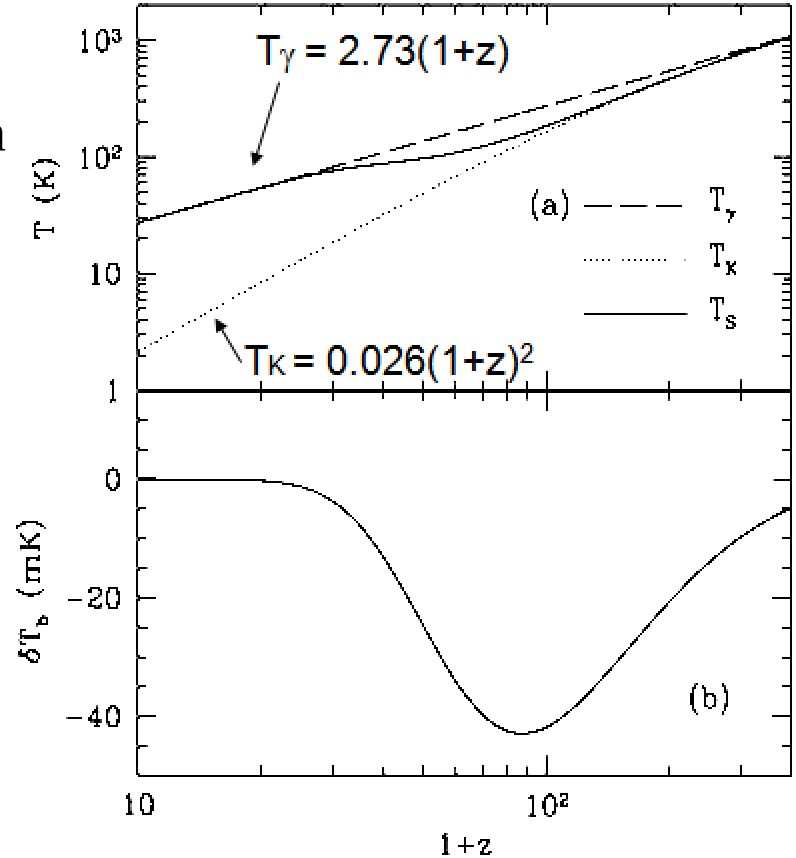
$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}(1 - e^{-\tau_{\nu_0}}) \approx \frac{T_S - T_\gamma(z)}{1+z}\,\tau_{\nu_0}$$

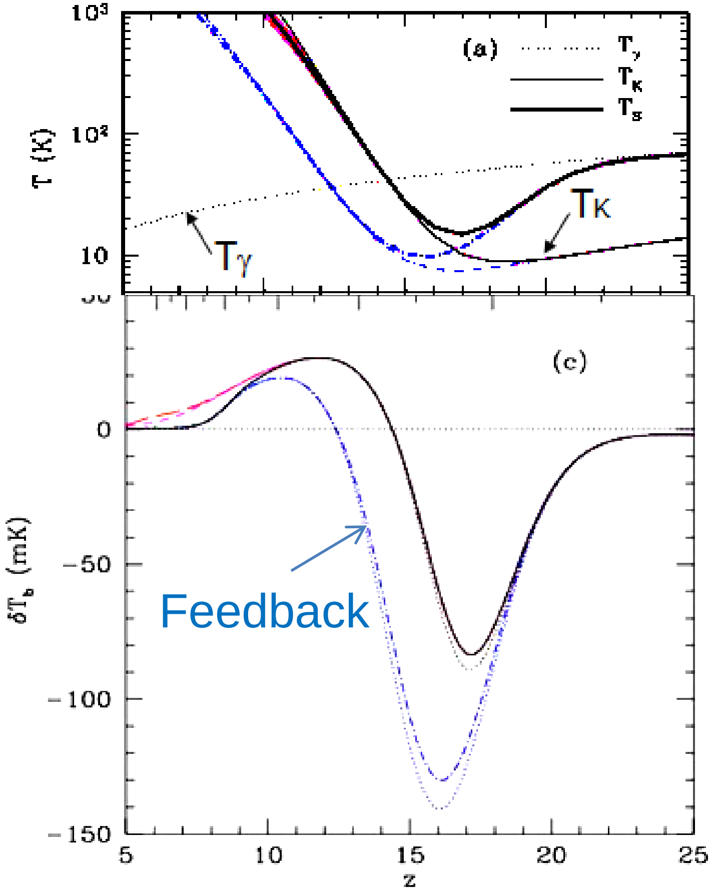
$$\approx 9\, x_{\rm HI}(1+\delta)(1+z)^{1/2} \left[1 - \frac{T_\gamma(z)}{T_S}\right] \left[\frac{H(z)/(1+z)}{\mathrm{d}v_{||}/\mathrm{d}r_{||}}\right] \ \mathrm{mK}.$$

LSS: Neutral fraction / Cosmic density / Temperature: Spin, CMB

Dark Ages HI 21cm signal

- $z > 200$: $T_\gamma = T_K = T_s$ due to collisions + Thomson scattering ➔ No signal
- $z \sim 30$ to 200: T_K decouples from T_γ, but collisions keep $T_s \sim T_K$ ➔ absorption signal
- $z \sim 20$ to 30: Density drops $T_s \sim T_\gamma$ ➔ No signal





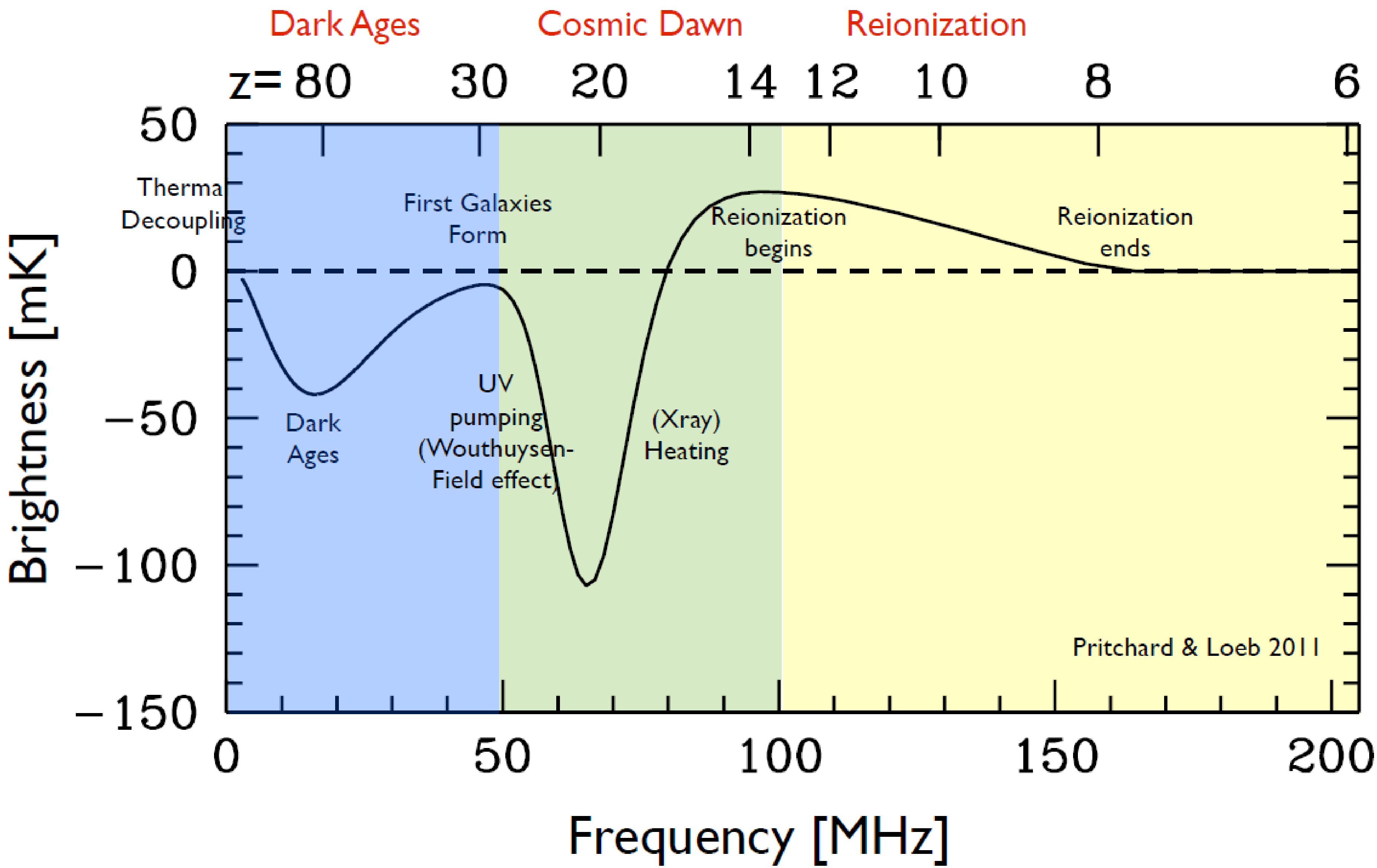
First luminous sources

- $z \sim 15$-20: $T_s \sim T_K$ via Lyα, $T_K < T_\gamma$ ➔ abs
- $z \sim 6$ -15: heating (Xrays, Lya, shocks), partially ionized ➔ emission
- $z < 6$: IGM fully ionized

Furlanetto et al. 2006

Brightness T_b at 21cm

$$T_s = \frac{T_{CMB} + (y_\alpha + y_c) T_k}{1 + y_\alpha + y_c}$$

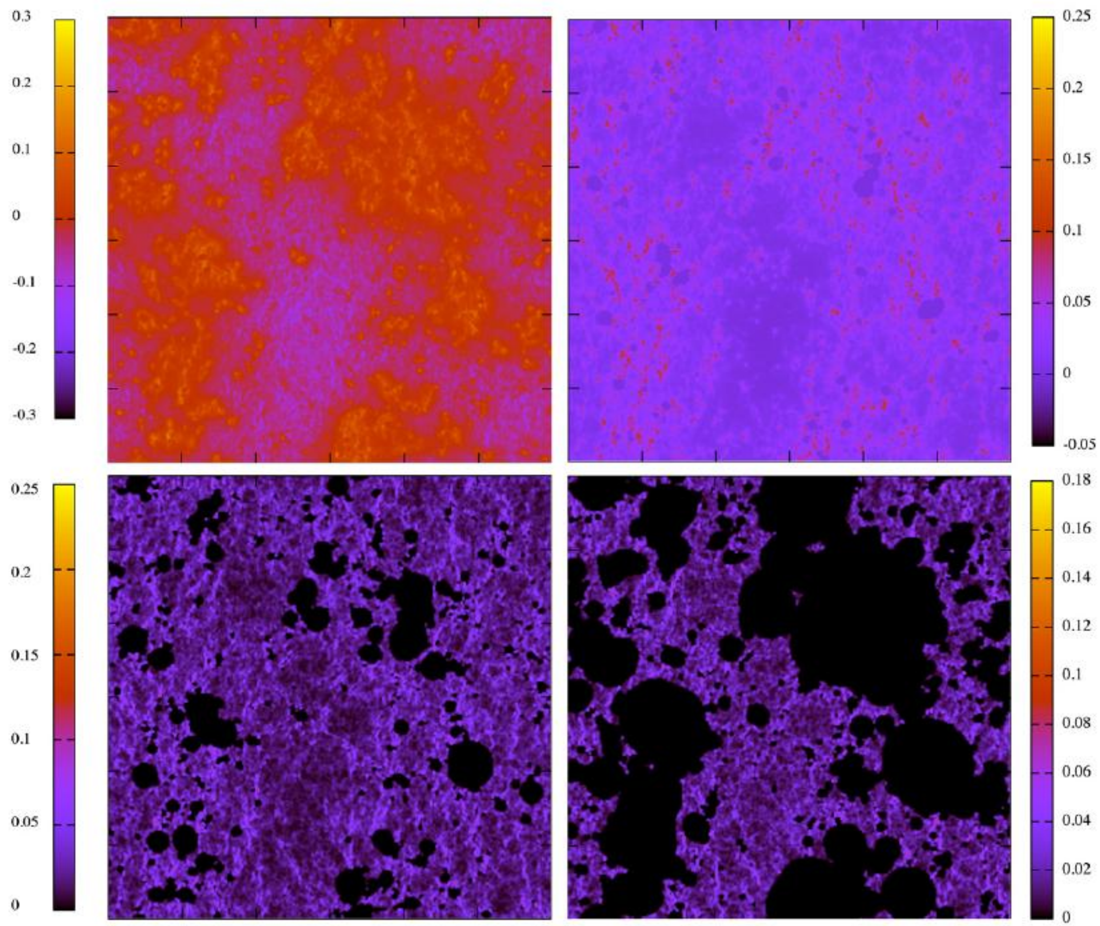


Semi-analytical models

300x300Mpc, Brightness temperature of 21cm line

z=14

z=12

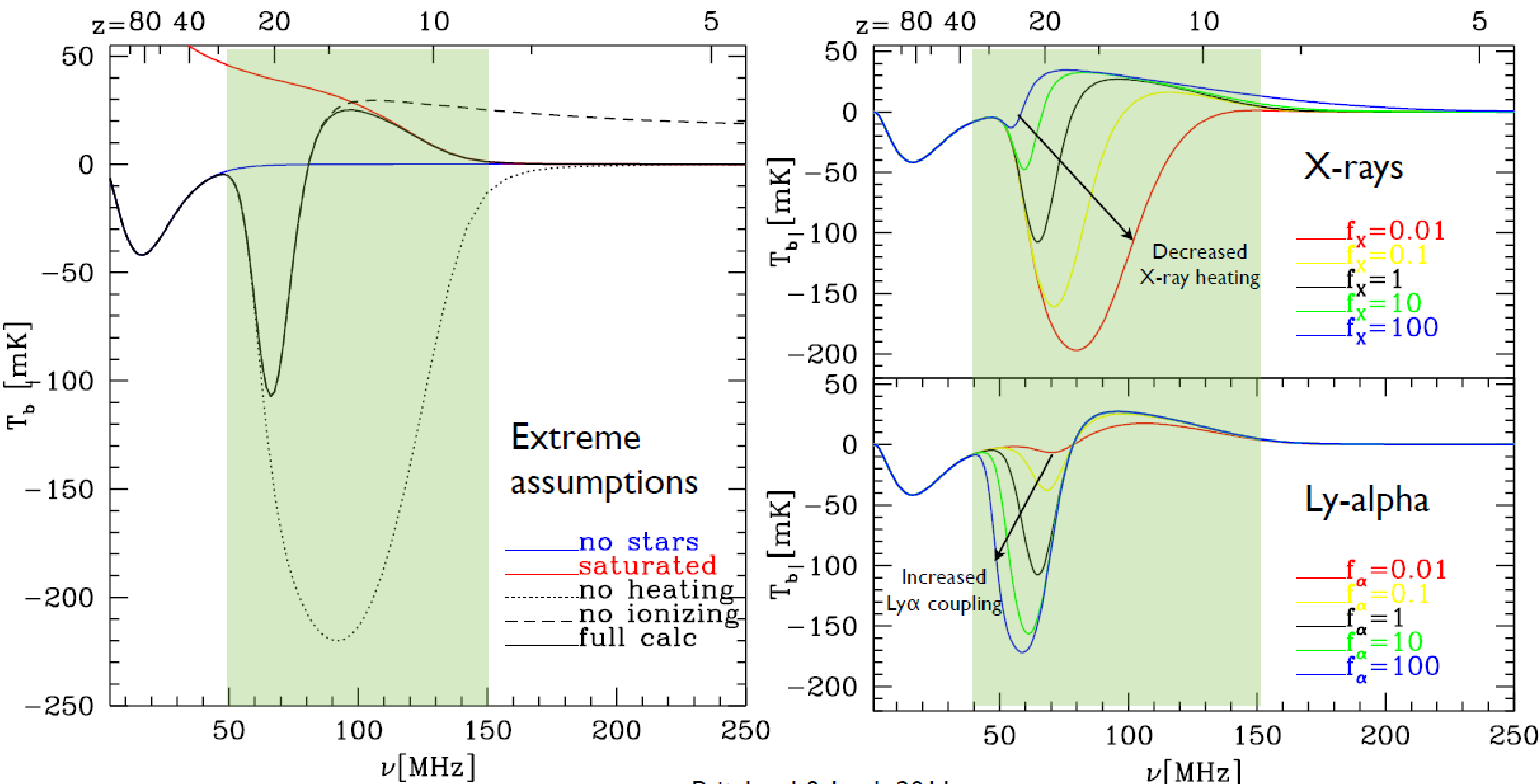


z=10

z=8

SIMFAST, Santos et al 2010

Variations due to SF, Lyα coupling (WF), X-ray heating…

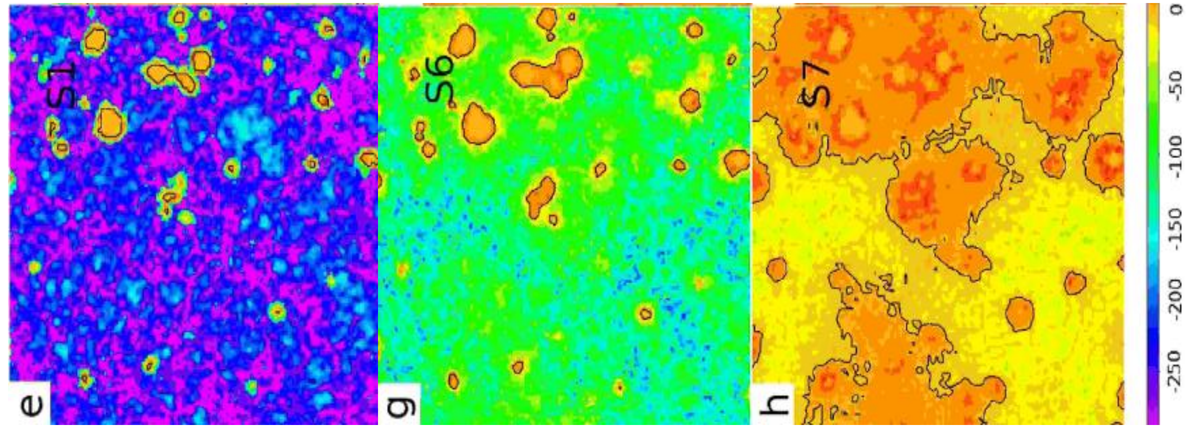


Pritchard & Loeb 2011

Simulations of radiative transfer

Baek et al 2009, 2010

Stars only Stars +QSO Stars + more QSO mK



Many simulations assume a very efficient coupling either from collisions, or from Lyα photons, through the Wouthuysen-Field mechanism ➔ $T_s = T_k$

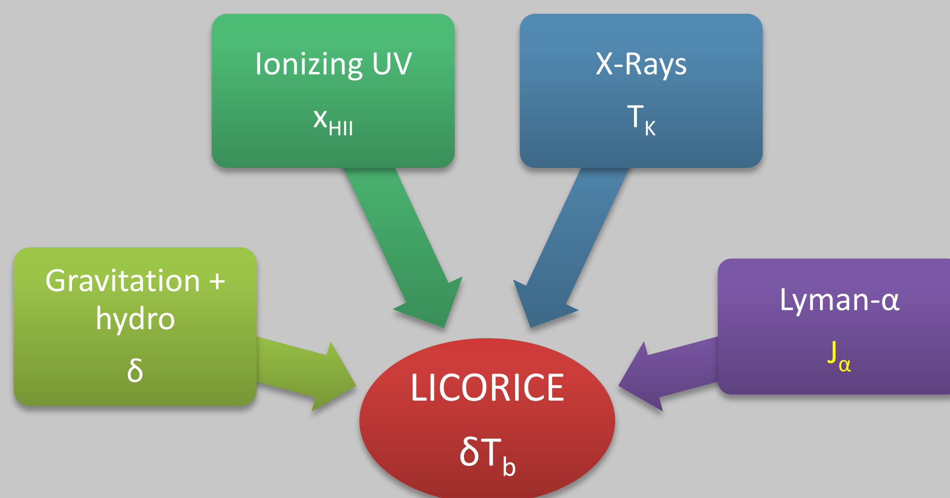
To compute the 21 cm signal:

$\delta,\ x_{HII},\ T_s(T_K, J_\alpha) \neq T_K$

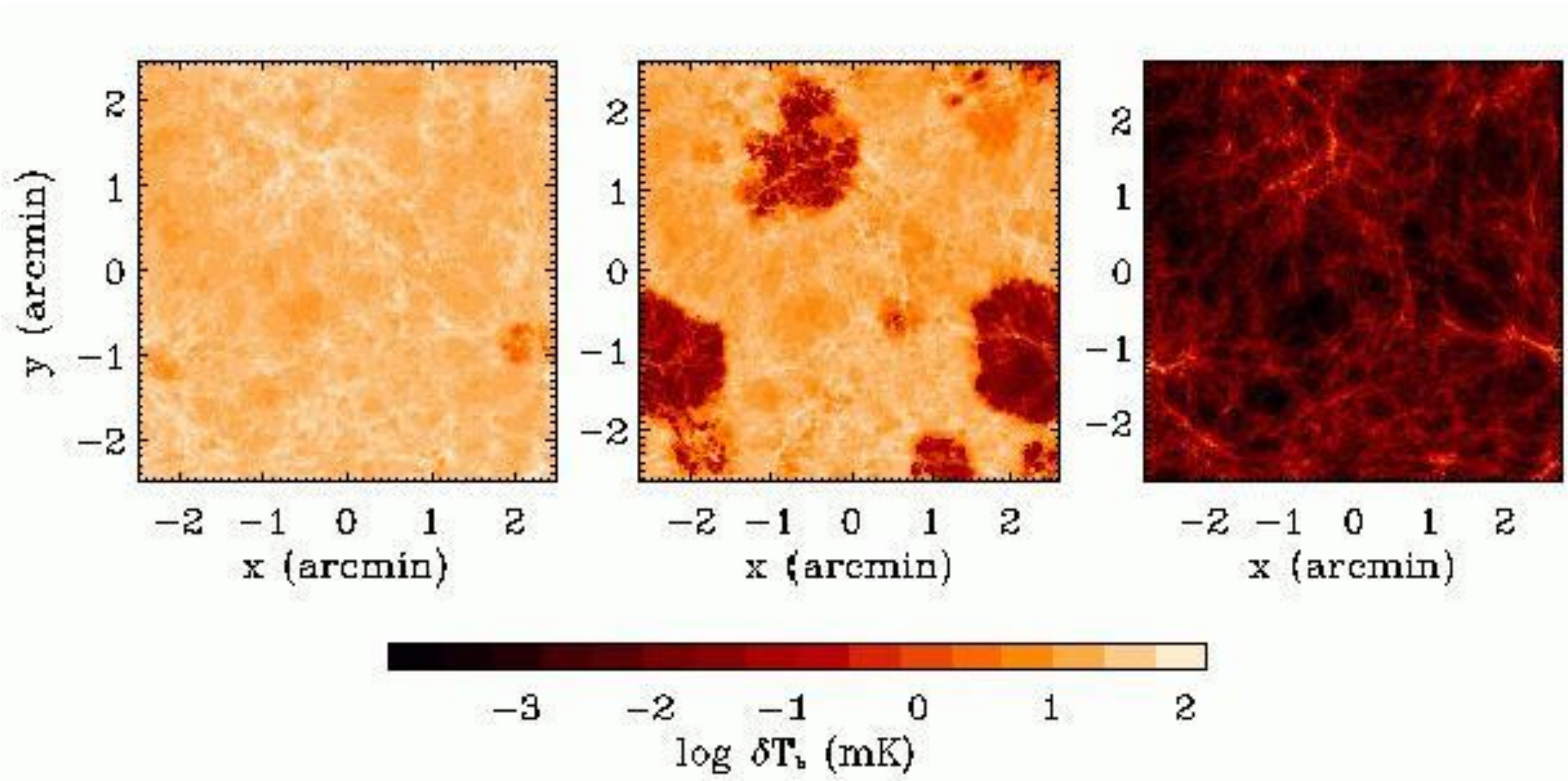
LICORICE:

a unique, validated code

(Semelin & Combes 2002, Semelin et al 2007, Iliev et al. 2009, Baek et al. 2010)

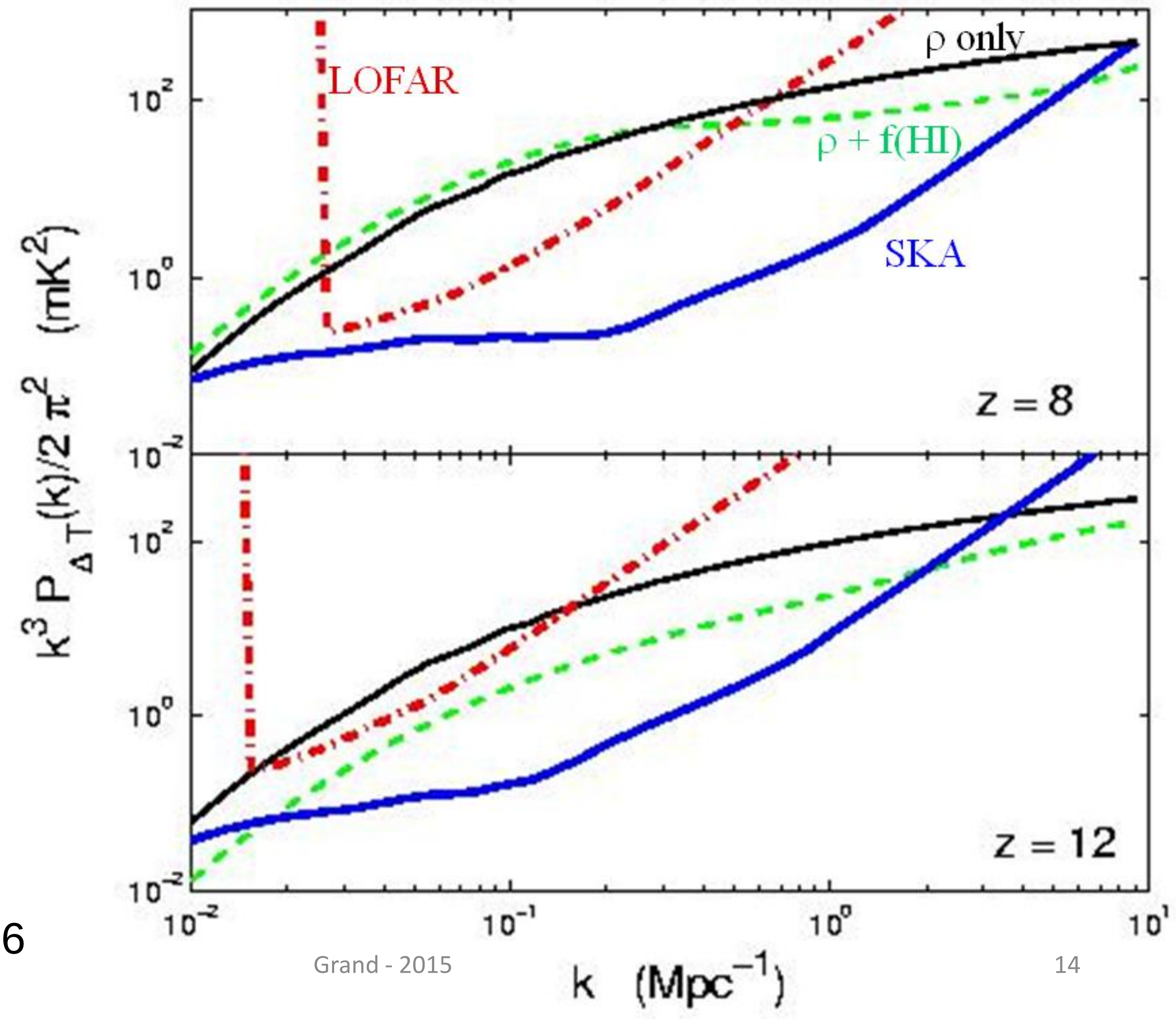


HI 21cm tomography



Zaldarriaga et al 2003

Power spectrum



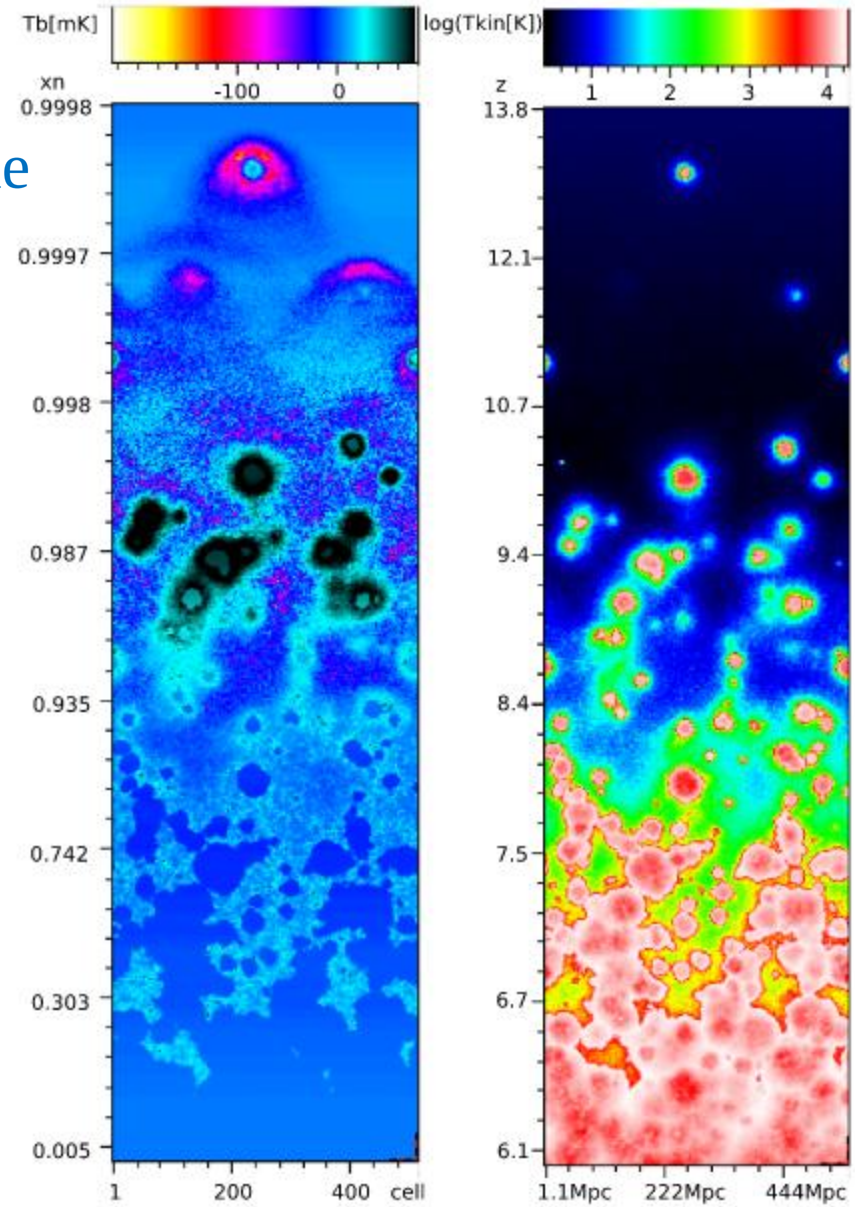
McQuinn + 06

Anisotropy detectable?

Anisotropy Space/time of the light cone
Might be detectable with SKA
Zawada, Semelin et al 2014

Different correlations along and perp los, when?
--overlap of ionized bubbles,
--the onset of mild heating by X-rays
--the onset of efficient Lymanα coupling

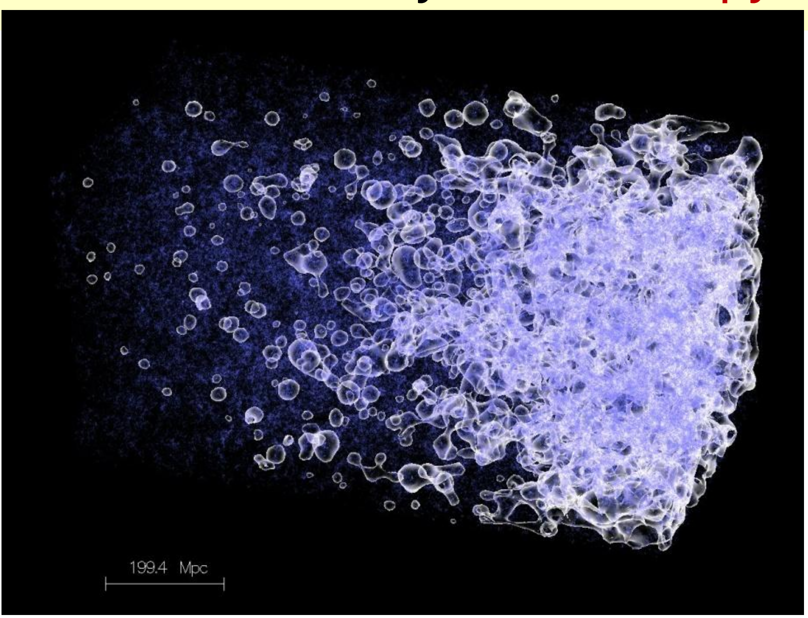
Predictions of maps at 21cm for 6<z<30:
➔Design of SKA



Light-cone effects

During overlap $\langle x_{HII} \rangle$ changes much in $\Delta z=1 \Leftrightarrow$ 200 Mpc/h.

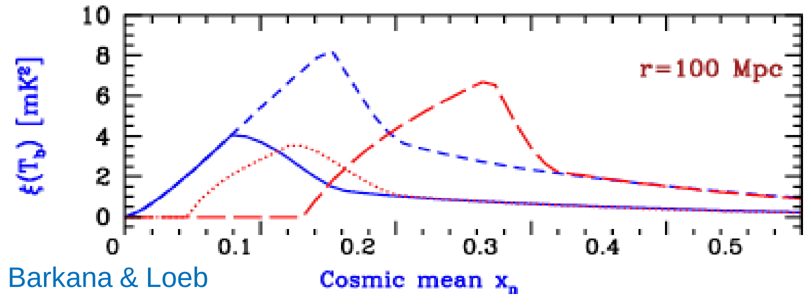
Large scale correlations will “detect” ionization history ➔ anisotropy.



Zawada et al. 2014

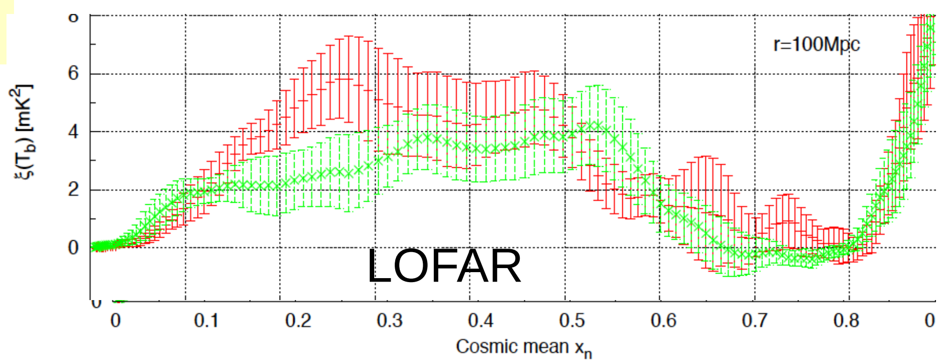
Correlation function: parallel vs perpendicular

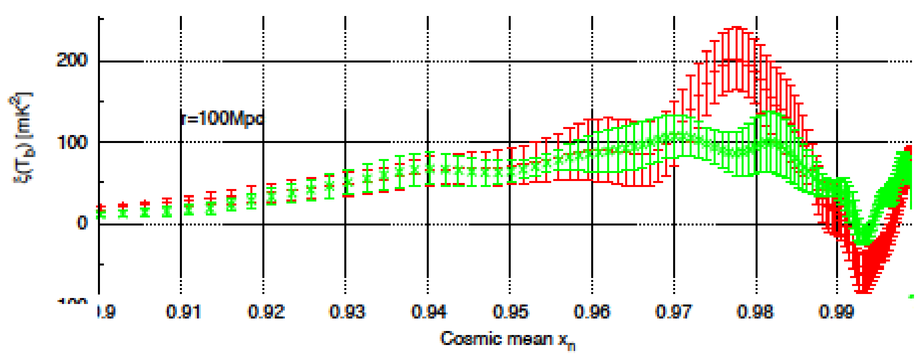
Theoretical toy model



Barkana & Loeb

Simulations: 400 Mpc/h box (512^3 particles)





Relative V between DM and gas

Tseliakhovich & Hirata 2010 vbc= V(baryons-CDM)

Relative supersonic motion gas - DM affects **10^4-10^8 M$_\odot$ halos**

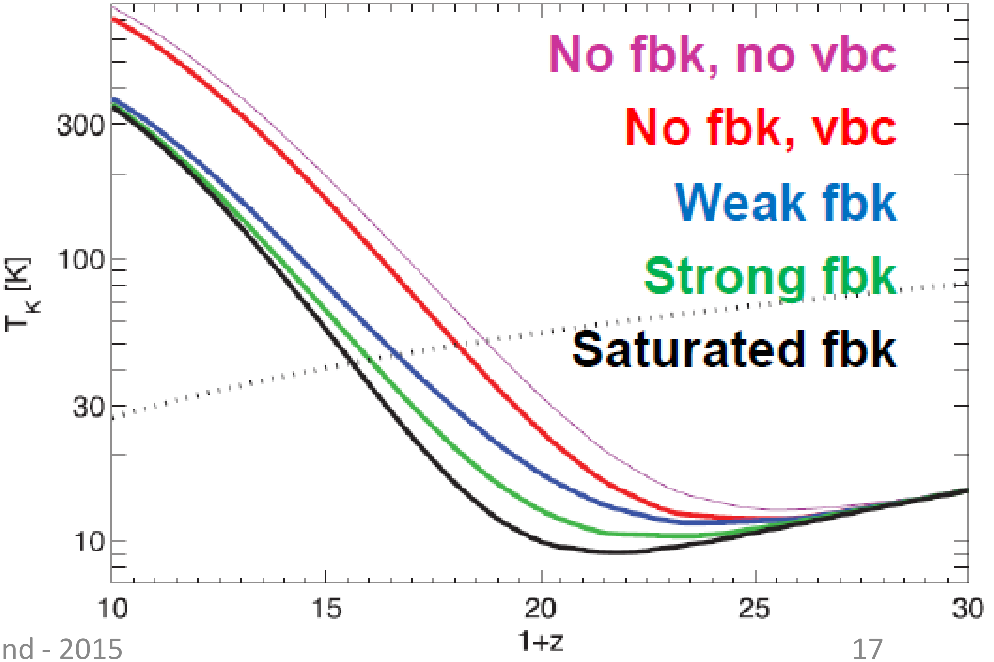
•Limits halo abundance

•Removes the gas

➔Delays star formation by $\Delta z \sim 5$

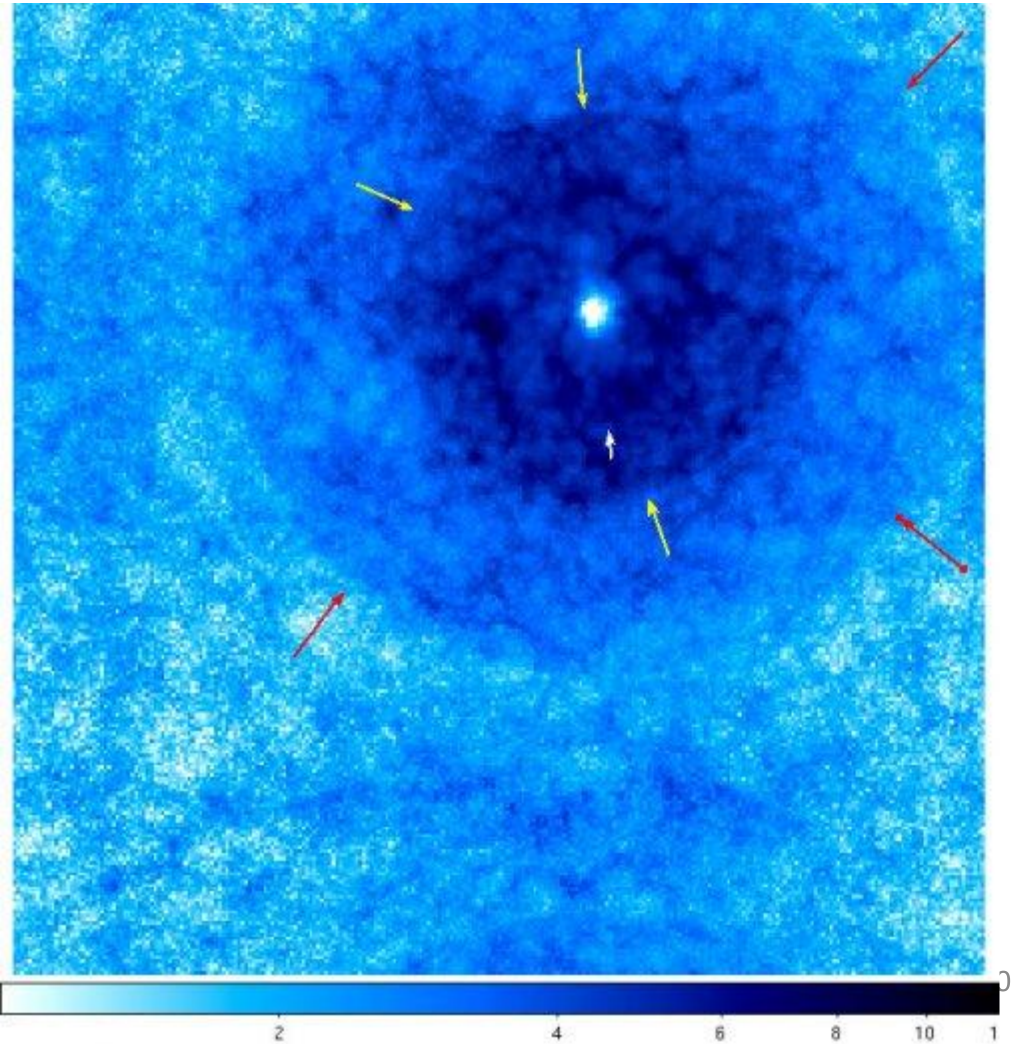
Equivalent to feedback, or to WDM

Fialkov et al 2013

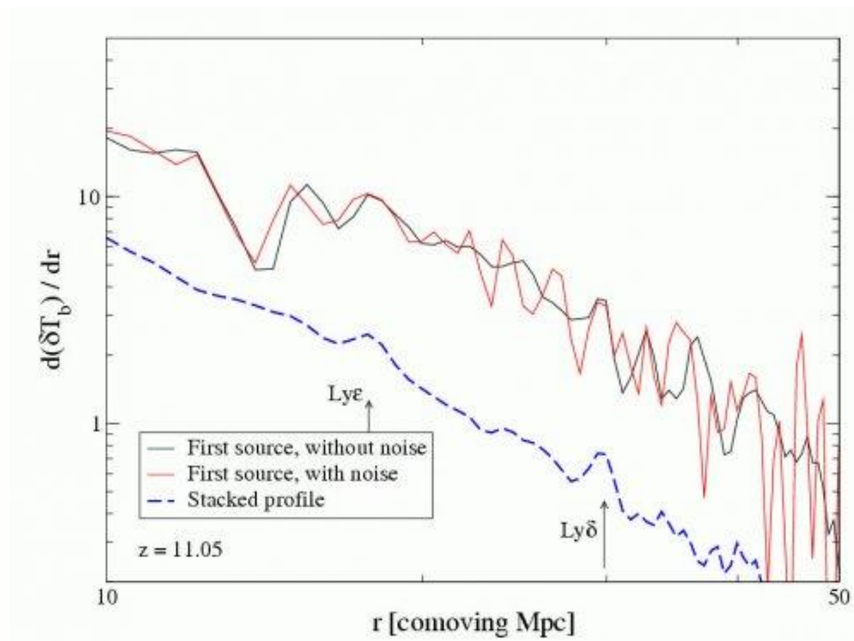


Rings in the 21cm signal

Concentric shells =Lyman horizons, that photons cannot overtake.
Around UV sources, the Lyα flux shows discontinuities at Lyman-series



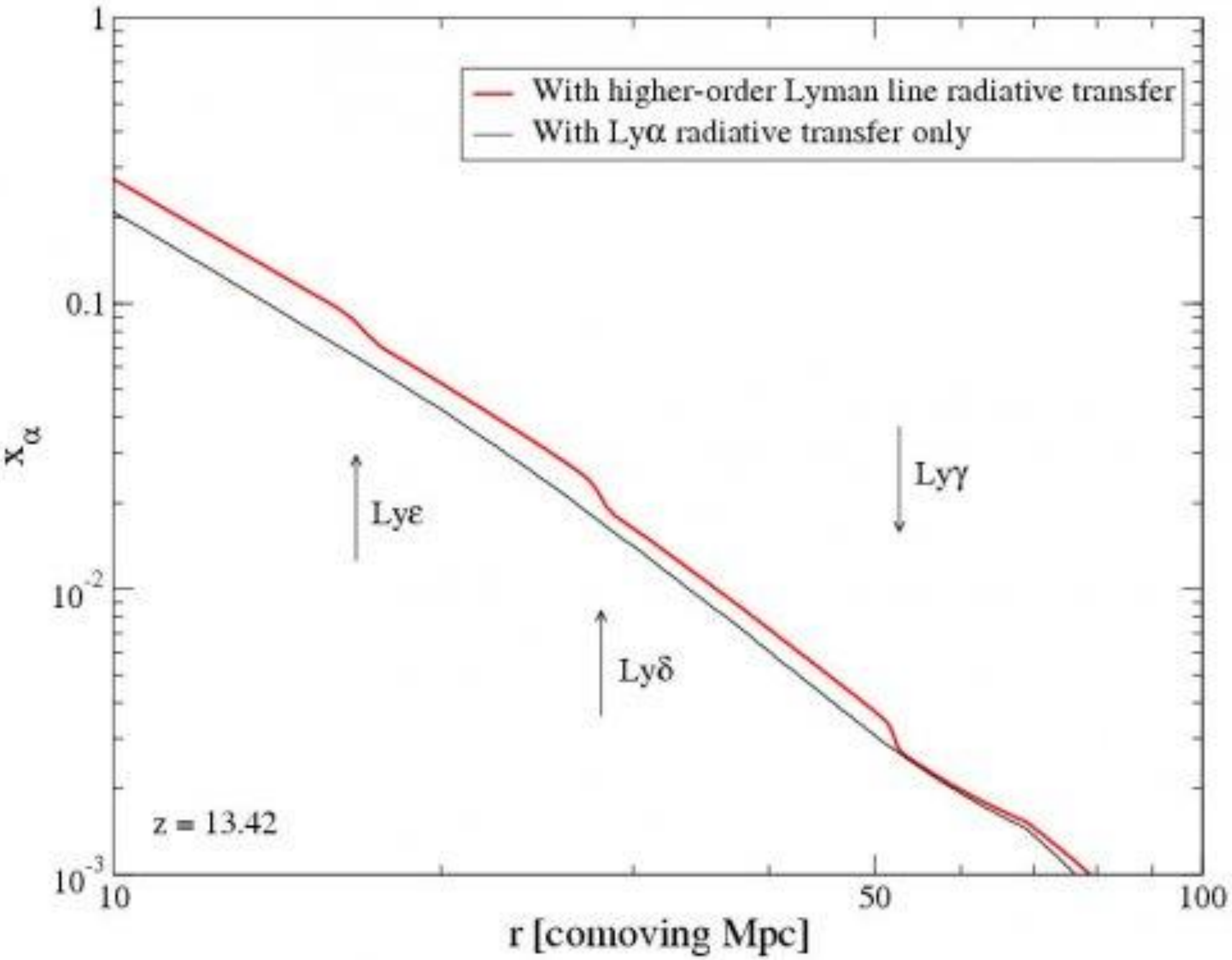
Visible in the 21cm signal



Vonlanthen et al 2011

Rings in the simulations

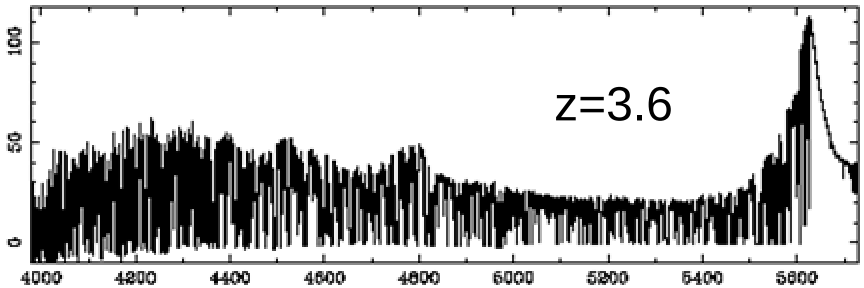
Coupling coefficient for Lyman-α excitation, x_α, at z=13.42
In red, a simulation showing the Lyman horizons, Ly-γ, Ly-δ, Ly-ε



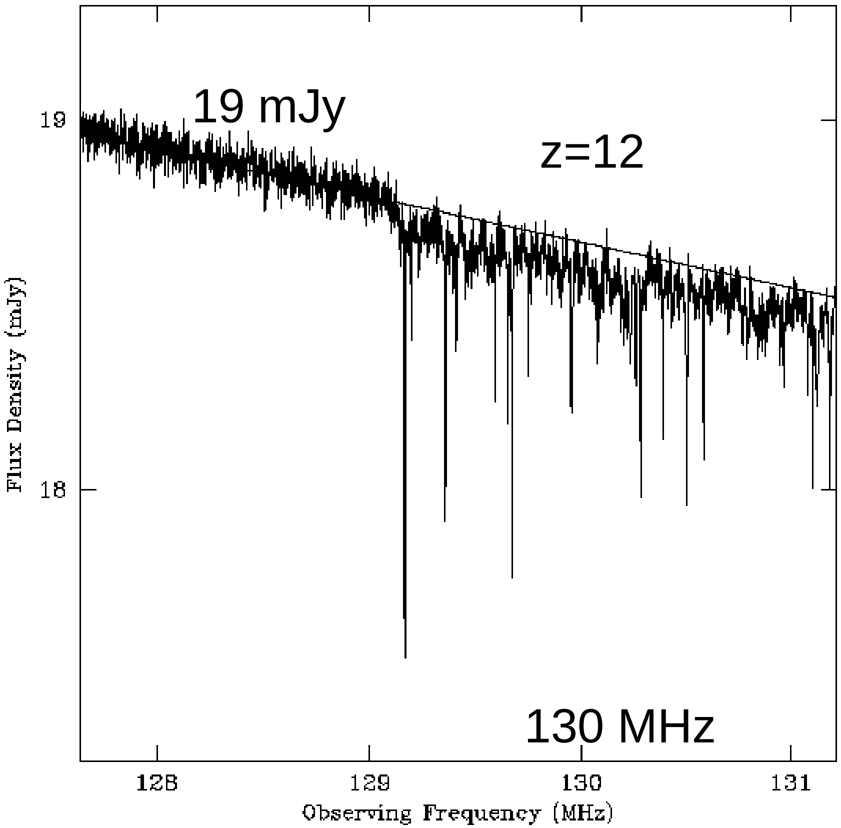
Visible between z=14 and 10

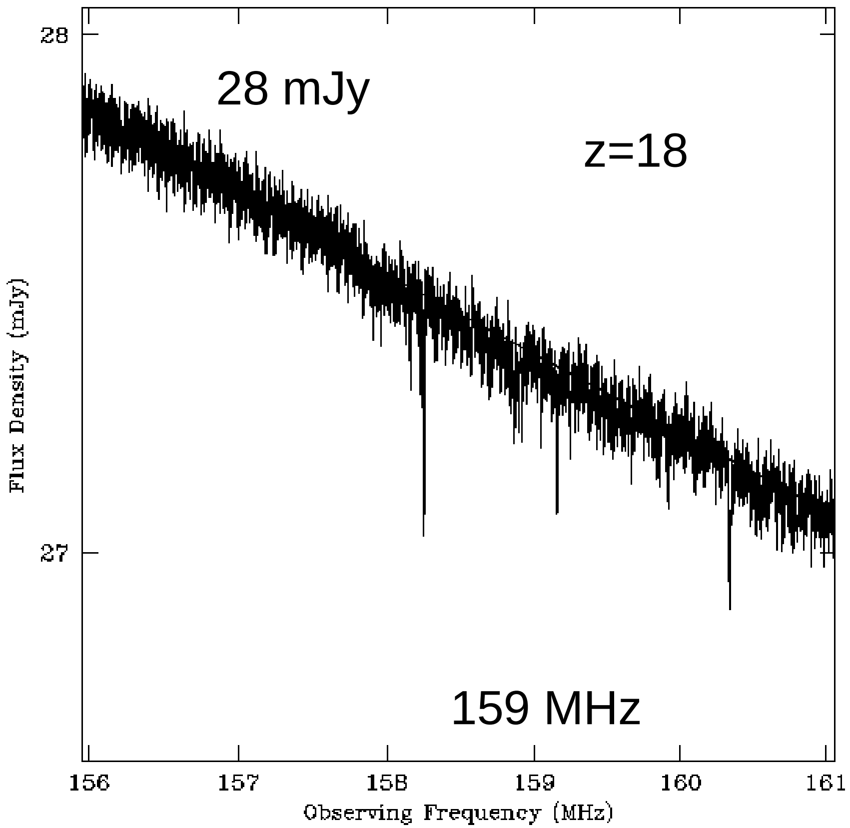
Vonlanthen et al 2011

21cm forest



Analogy with Lyα forest



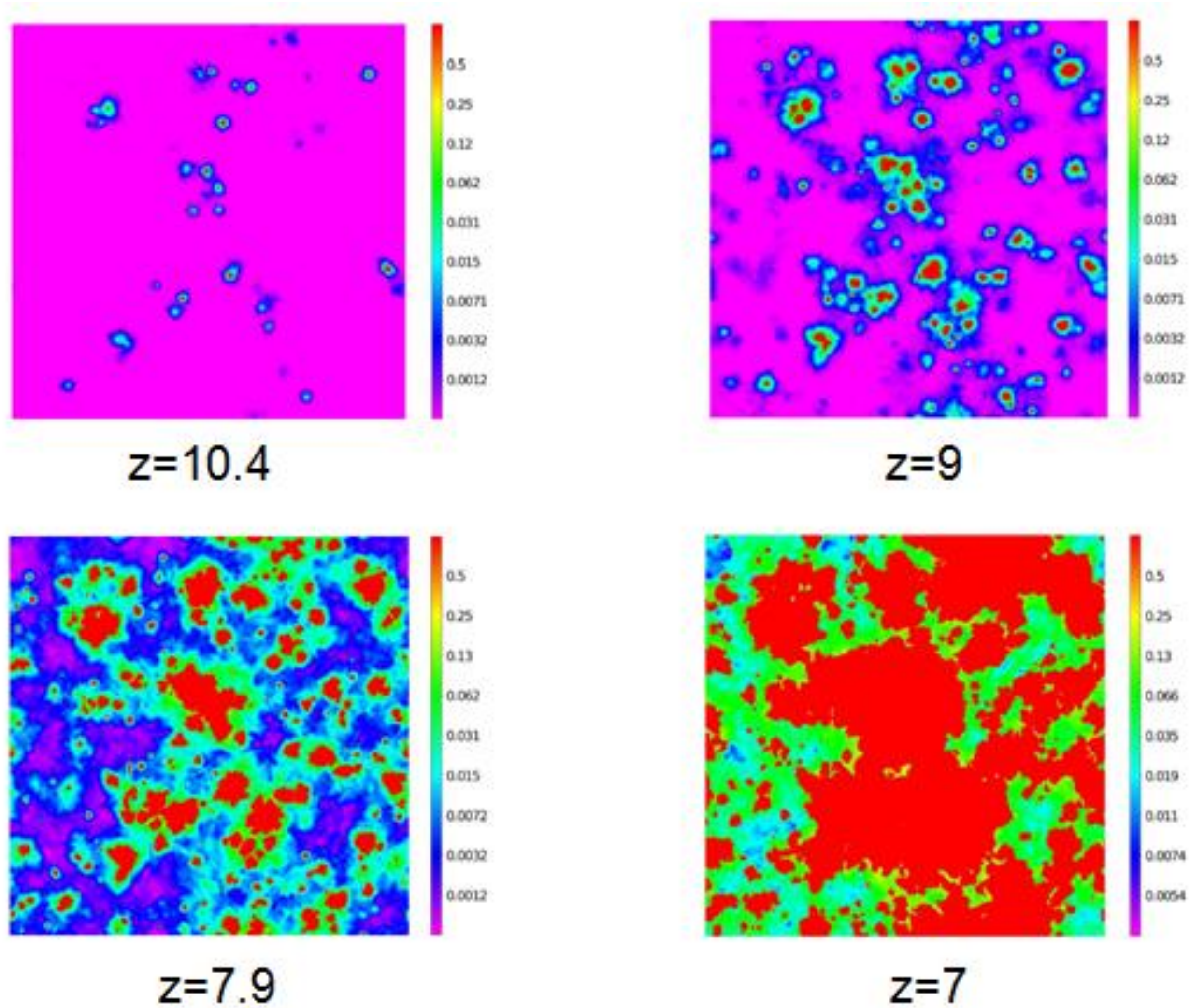


Carilli 2004

Ionization Fraction

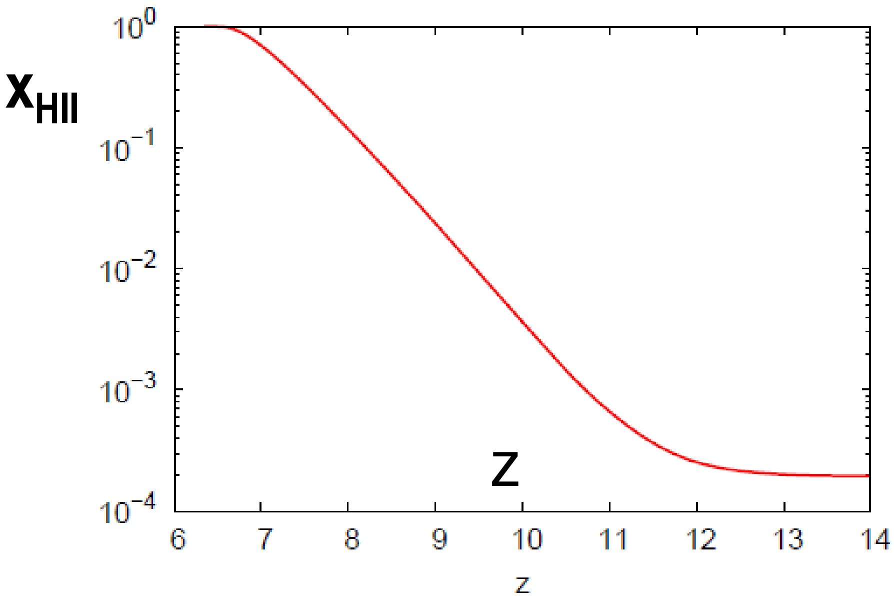
Simulation AMR
RAMSES
Transfer ATON
(moments)
GPU code
2 bands, UV, X

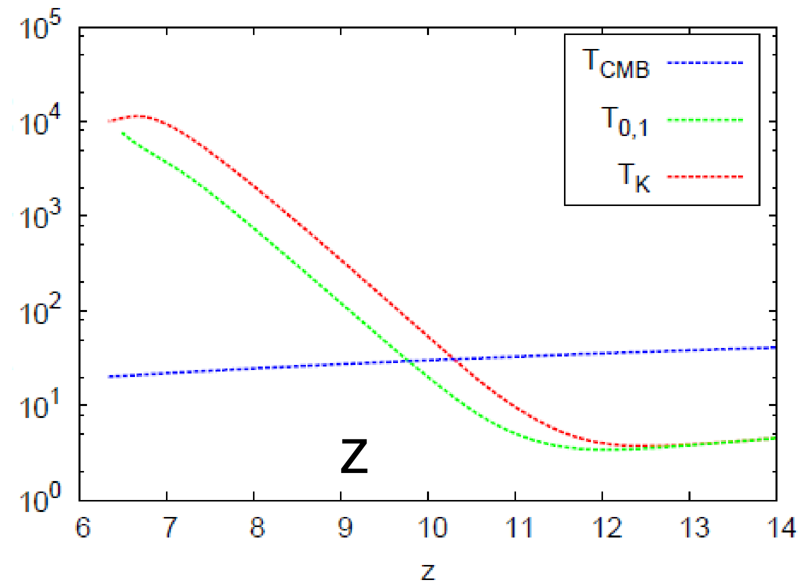
300 Mpc^3
2048^3



Semelin et al 2015

Evolution of x_{HII}, T_{emp}





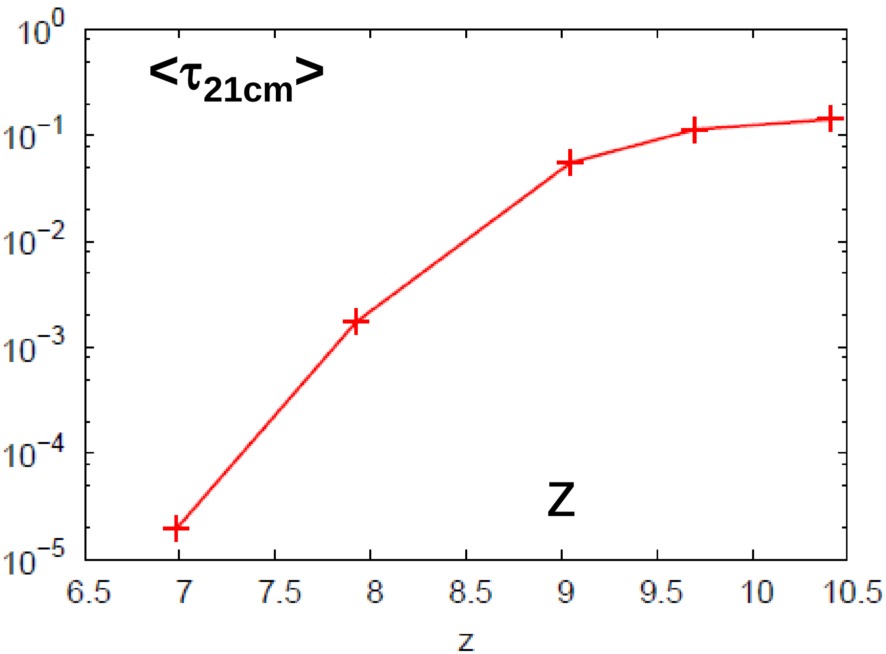
$T_{0.1}$ is the average over regions of $x_{HII} < 0.1$

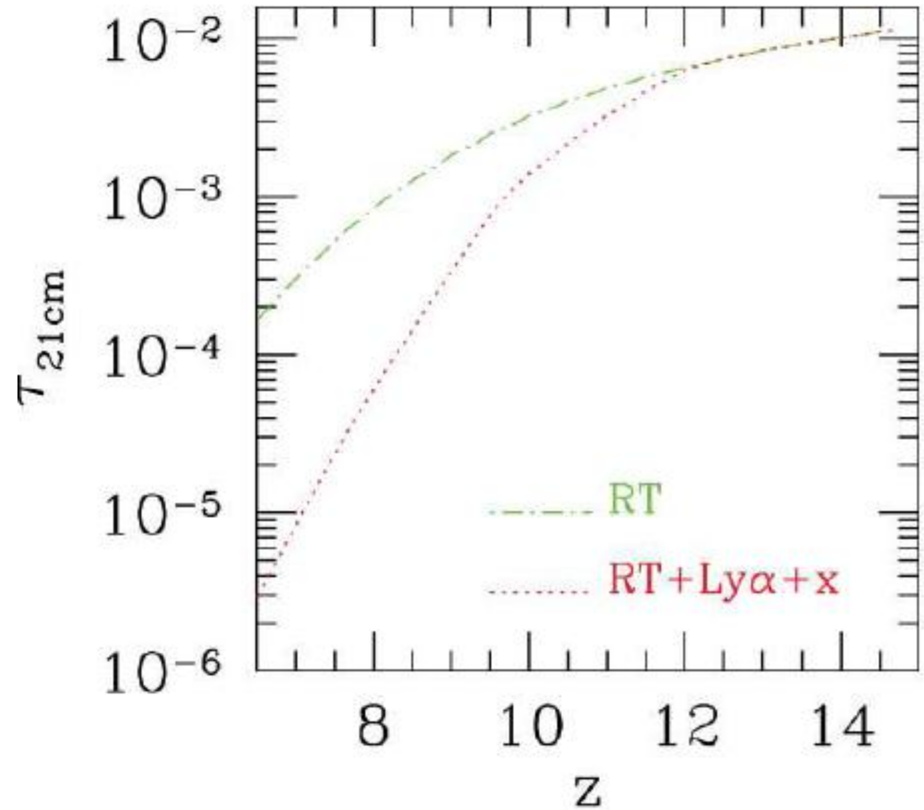
➔Represents the HI regions temperature

While T_K is averaged over the whole simulation volume

Semelin et al 2015

Evolution of 21cm optical depth





Higher τ_{21cm} than previous results

Simulation ε1.2-α3 de Ciardi et al 2013

Coupling Ts=Tk (green curve)

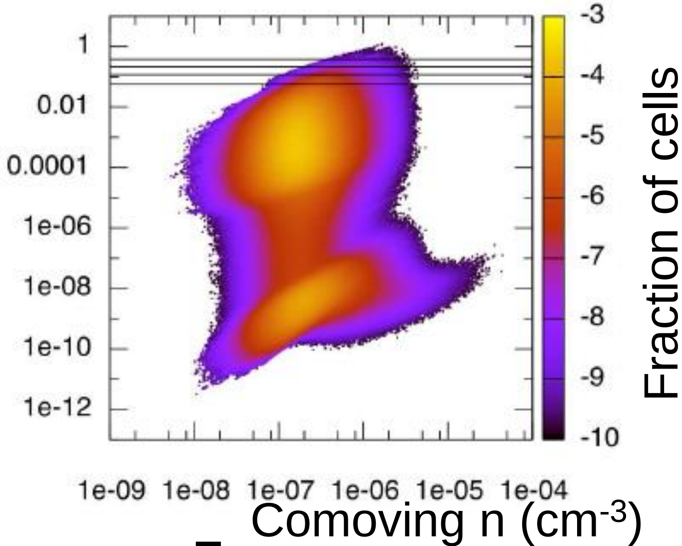
Ts= max (Tk, results with Lyα +X) red

Semelin et al 2015

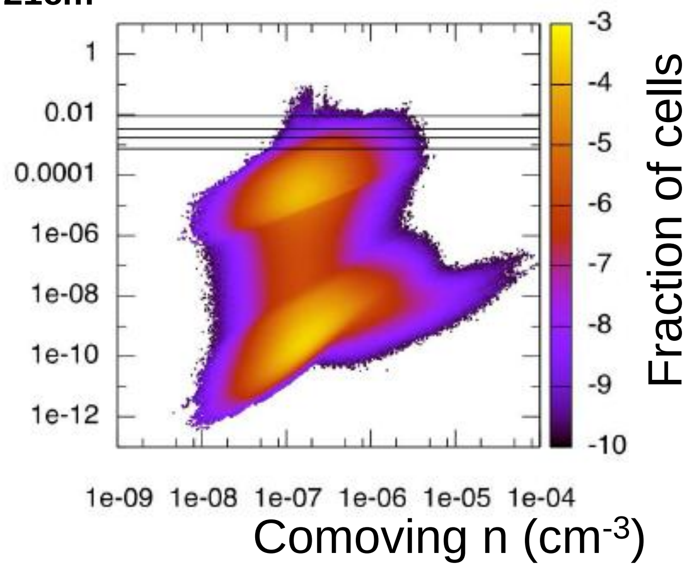
Ciardi et al 2013

Optical depth-density

$<\tau_{21cm}>$ z=7.9



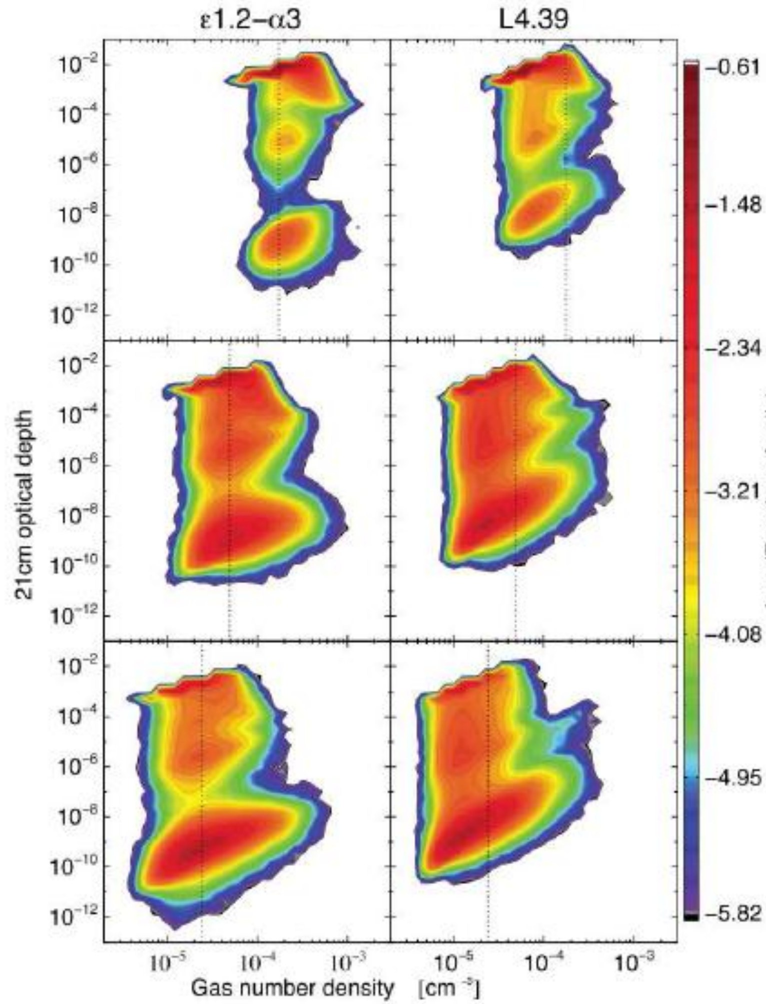
$<\tau_{21cm}>$ z=7



z=14

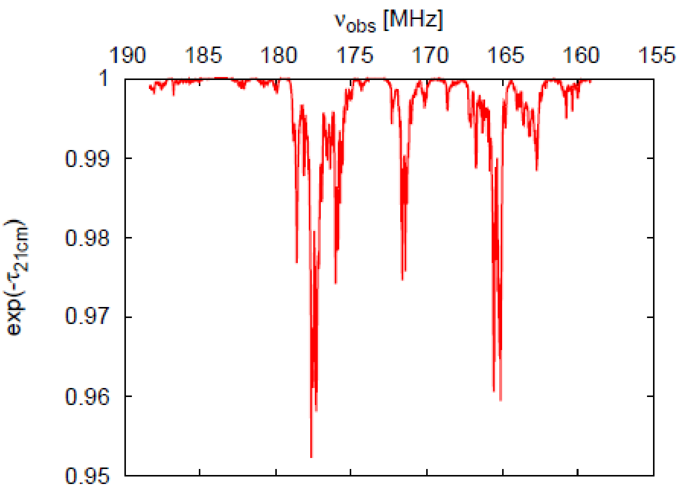
z=9

z=7

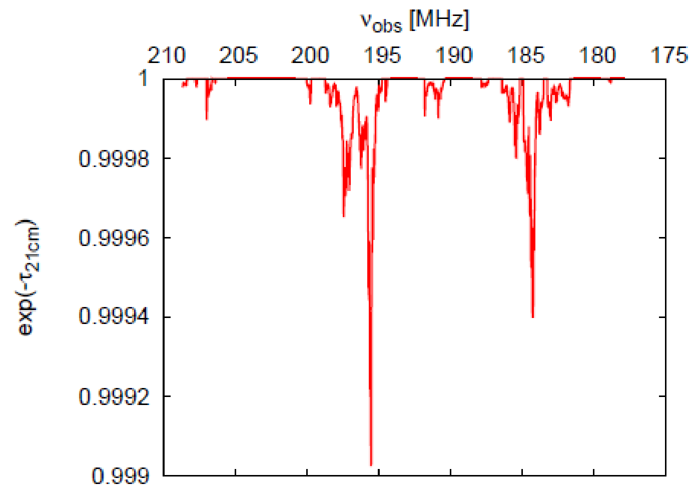


Ciardi et al 2013

Expected spectra



z=7.9

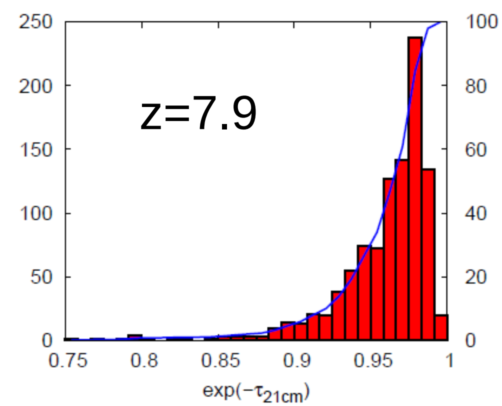


z=7

$<\tau_{21cm}>$ ~ 0.05 at z=7.9, and ~0.001 at z=7

➔Not detectable at z=7
but may be at z=7.9 in 10% of cases

Number of abs



%

Semelin et al 2015

Conclusions

EoR is a privileged domain to test the universe history
And cosmological models

Signals at 21cm are of several kinds:

➔ Tb versus redshift (dark age, cosmic dawn, reionization epoch)
➔ 21cm tomography (2D planes)
➔ Power spectra (k) LSS
➔ 21cm forest (small scale structure)
➔ Stromgren sphere around powerful quasars