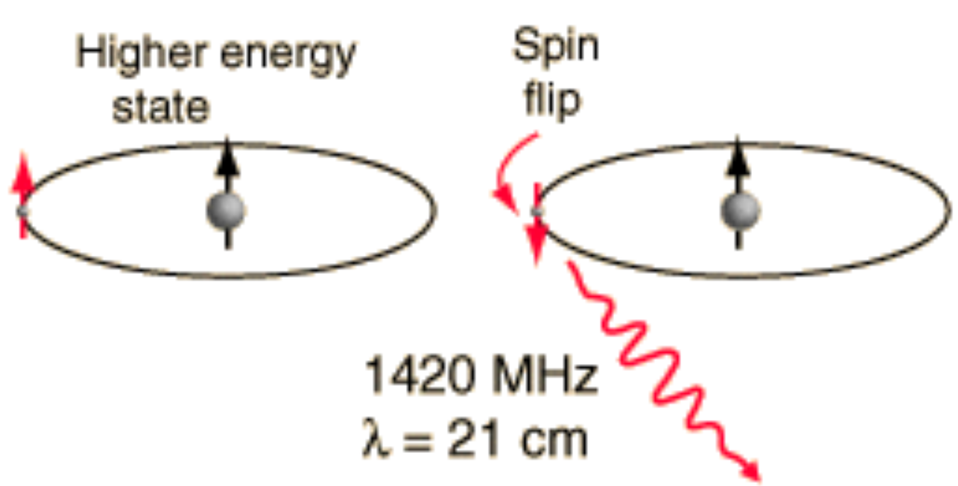
The physics of the HI 21cm line
Observing the early Universe

Marta B. Silva
Kapteyn Astronomical Institute
University of Groningen, The Netherlands

6ª Escola Avançada de Astrofísica do INPE
Cosmologia de 21 cm no século 21



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html

The HI 21cm line
The first light in the Universe

Lecture 1

i) The 21 cm line

ii) CMB Formation

iii) The mean 21cm line signal

Lecture 2

iV) Cosmic Dawn/ The First Stars

V) Reionization

Vi) Observing the EoR

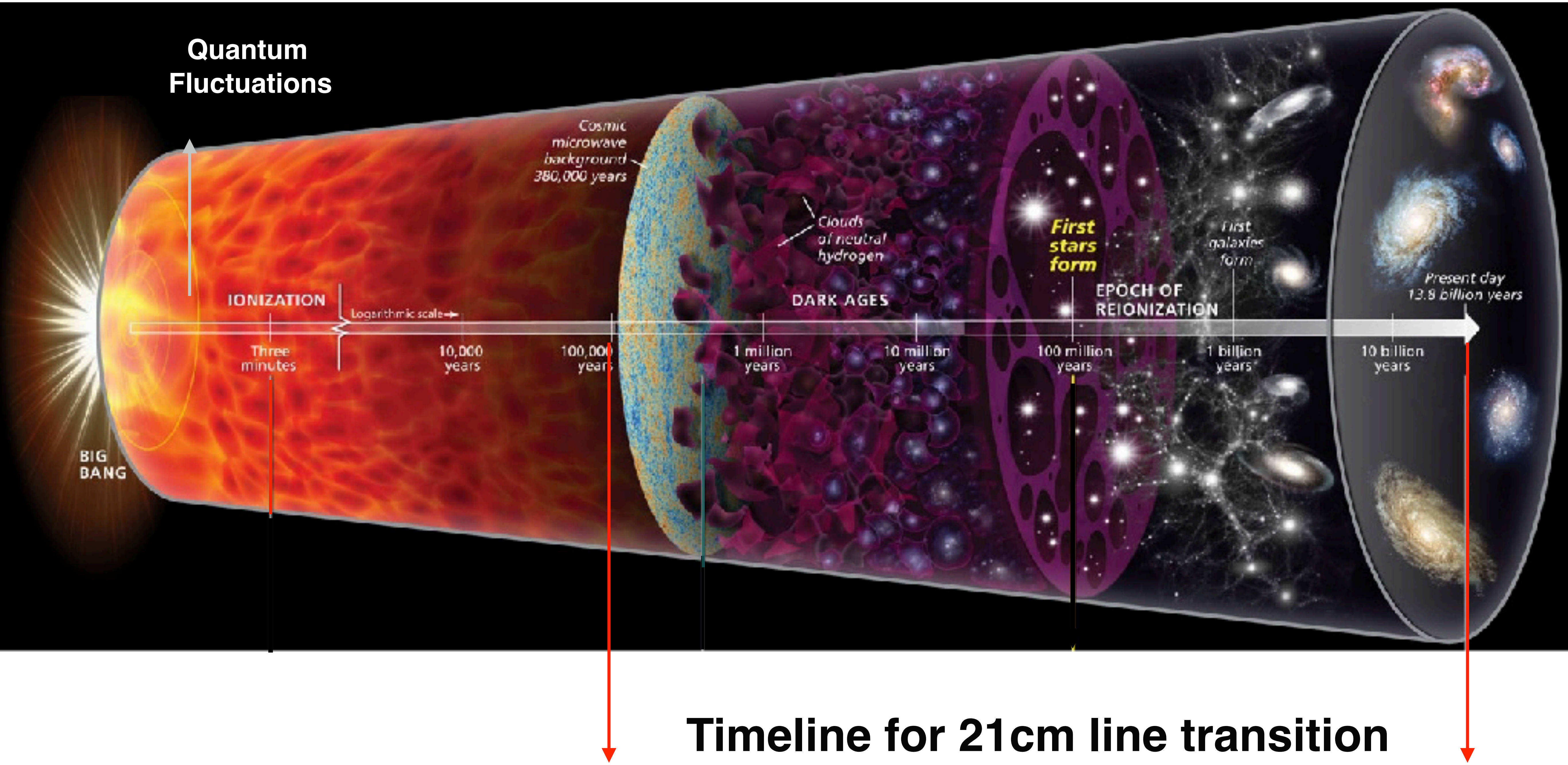
Lecture 3

Vii) Impact of the EoR on the CMB

Viii) Other probes of the EoR

ViV) 21cm line in the post EoR

Highlights Lecture 1



Timeline for 21cm line transition

Credit - http://discovermagazine.com/~/media/Images/Issues/2014/April/21-centimeter-cosmology.jpg

Highlights Lecture 1

21 cm line Brightness Temperature

$$\delta T_b \approx 28\mathrm{mK}(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Astrophysics

Cosmology

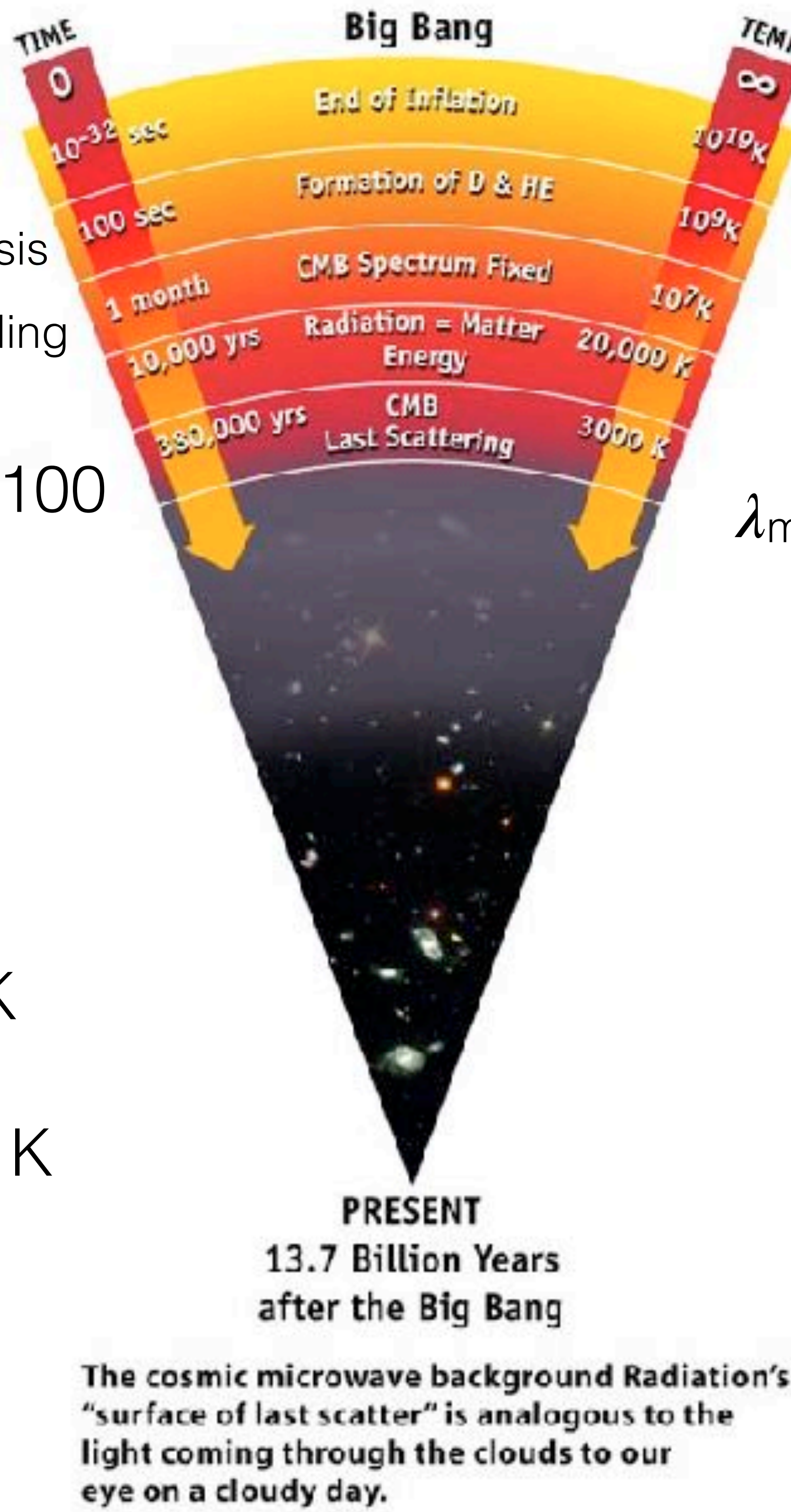
Highlights Lecture 1: The origin of the CMB

Planck Epoch

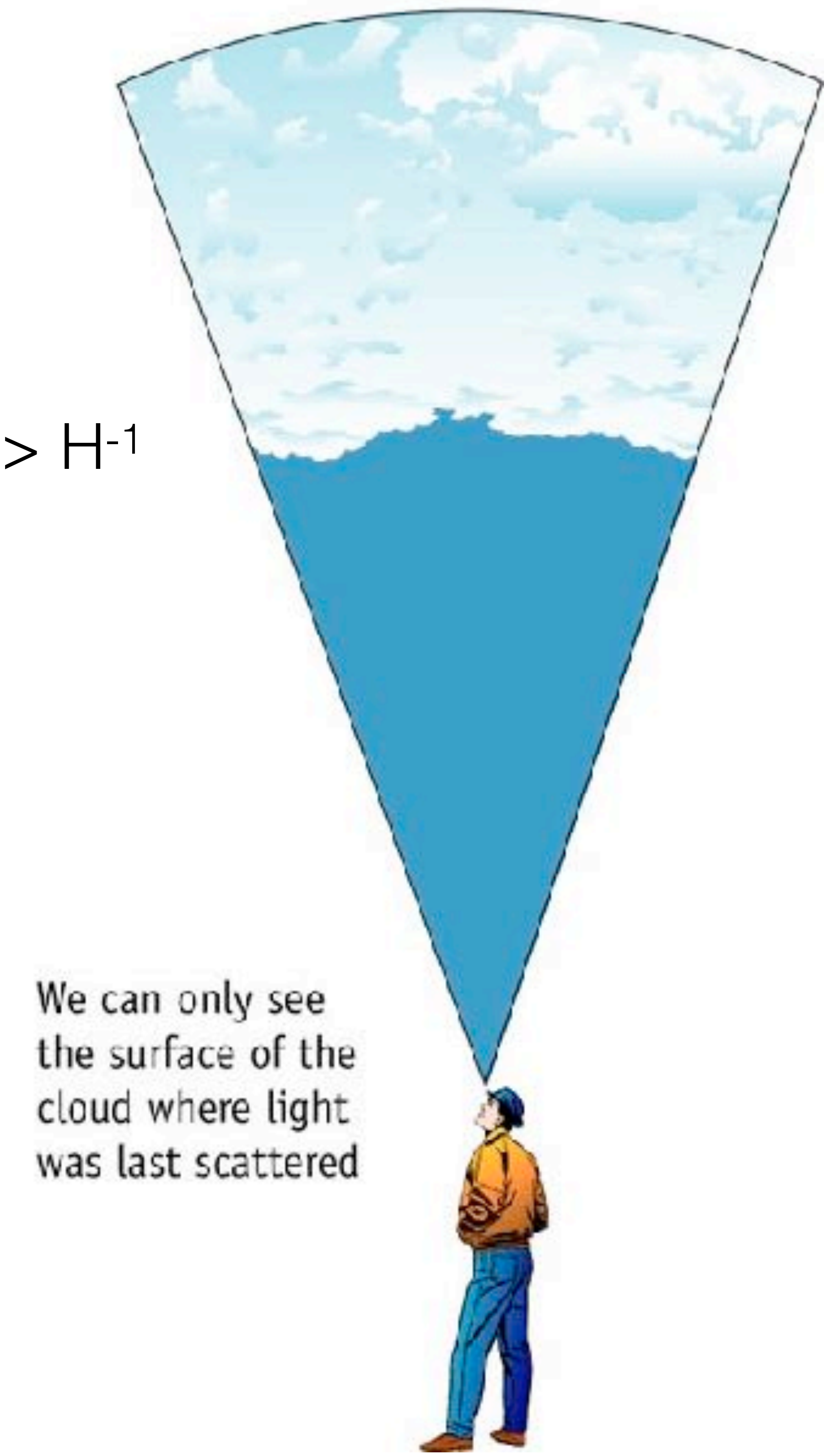
Nucleosynthesis

Decoupling

z~1100



$\lambda_{mfp} > H^{-1}$

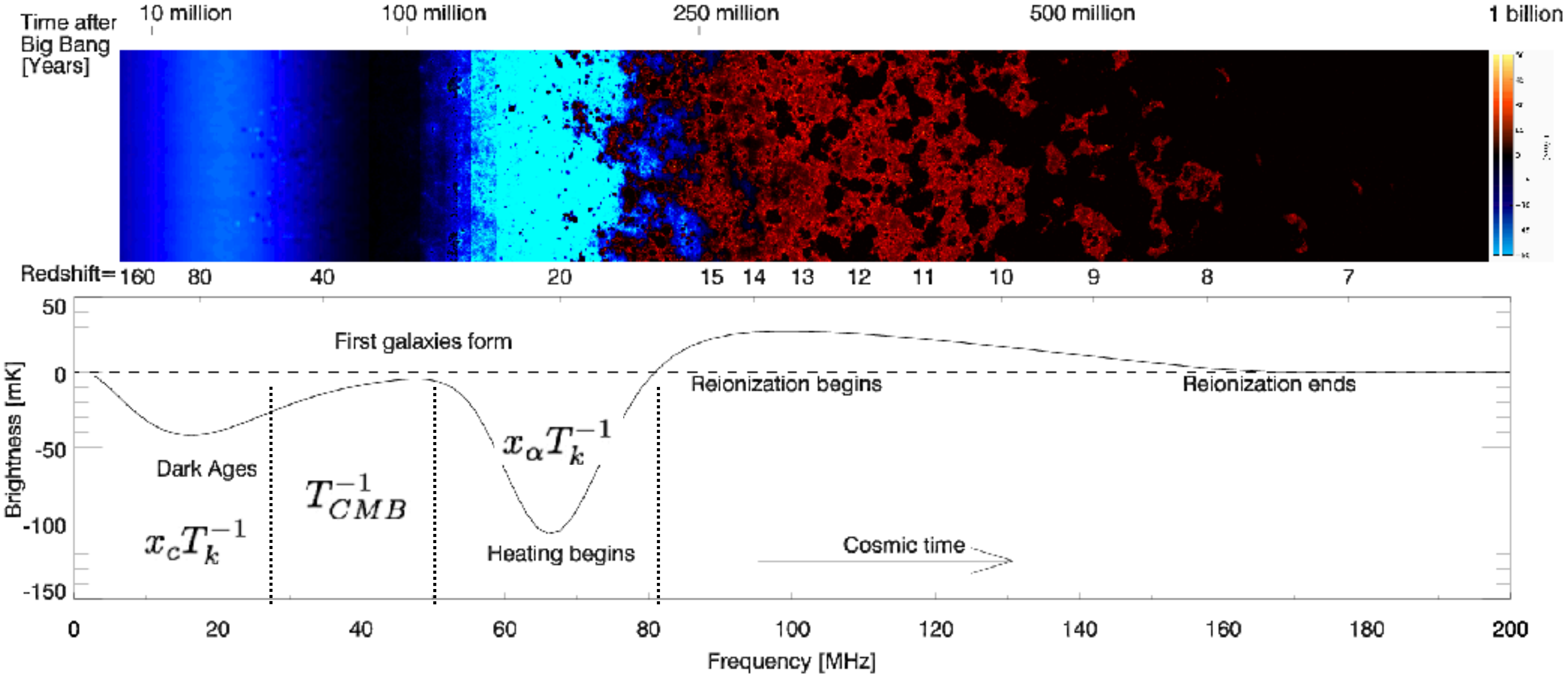


$$T_{\rm CMB} \propto (1+z)$$

$T_{CMB,z} = 3000(1+\Delta z)^{-1}$ K

$T_{CMB,0} = 3000(1+1100)^{-1}$ K
$= 2.725$ K

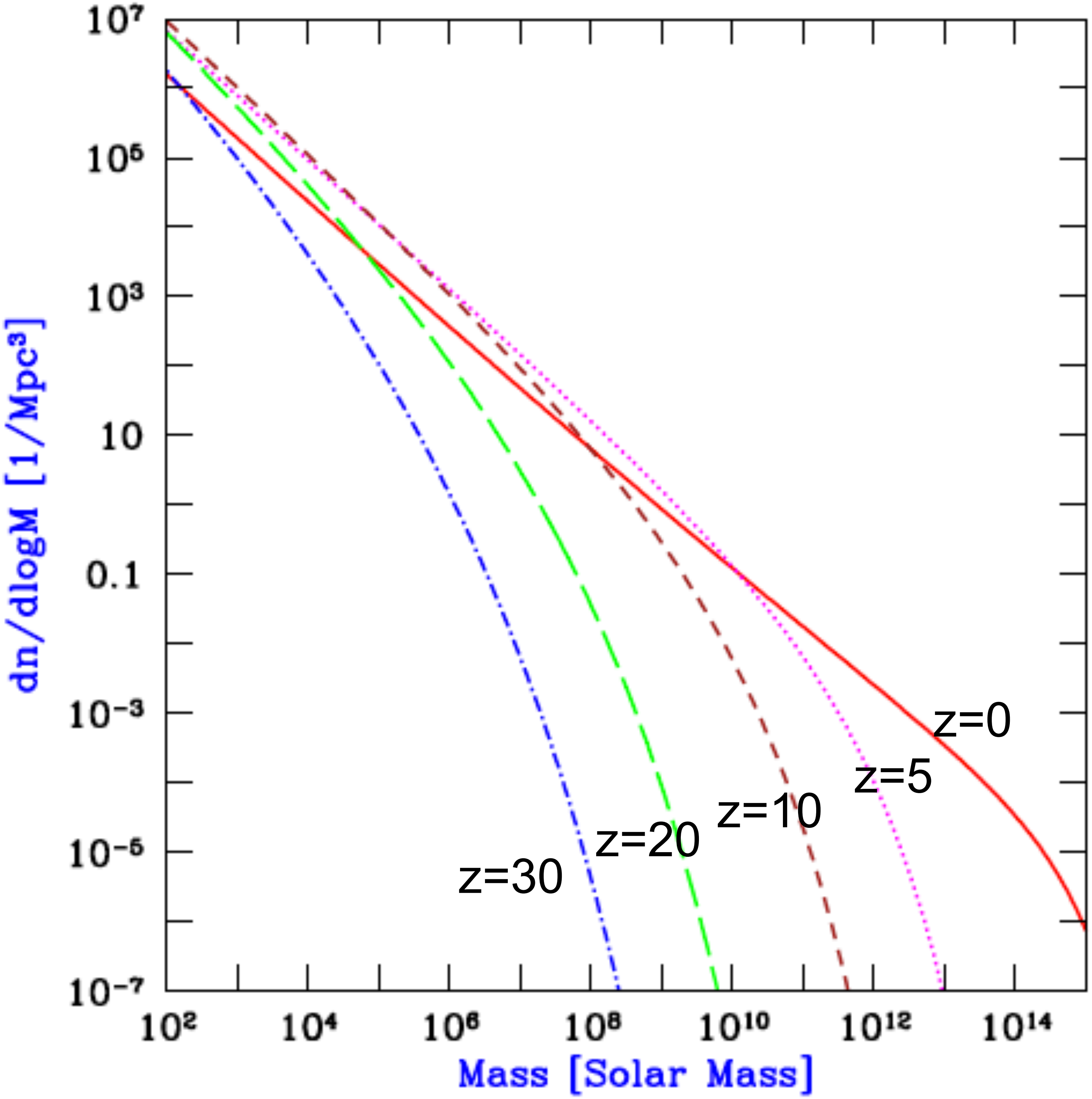
Highlights Lecture 1: Tb evolution



$$\delta T_{\rm b} = \propto \frac{T_S - T_{\rm CMB}}{T_S}$$

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

Dark Matter Halo Formation



Spherical collapse:

Press & Schechter Formalism

$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}}\,\frac{\rho_m}{M}\,\frac{-d(\ln\sigma)}{dM}\,\nu_c\, e^{-\nu_c^2/2}$$

$$\nu \equiv \frac{\delta_{\rm crit}}{\sigma(M)}$$

Credit: Barkana & Loeb 2001

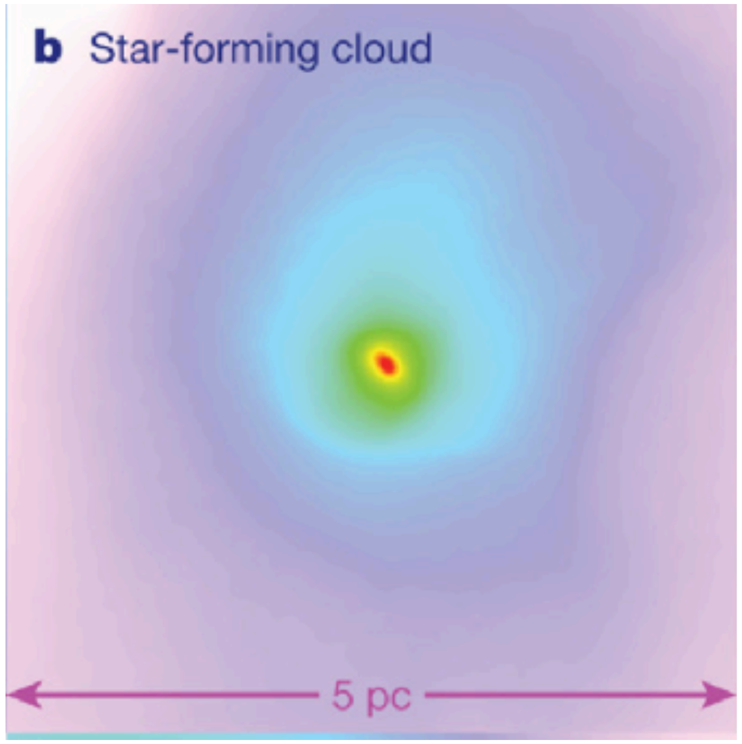
Stellar Formation in a Halo: Gas collapse and cooling

Stability of spherical gas cloud: Jeans criterion

(Gravity vs Pressure)

$$M_J \approx 5 \times 10^3 \mathrm{M}_\odot \left(\frac{\Omega_\mathrm{m} h^2}{0.14}\right)^{-1/2} \left(\frac{\Omega_\mathrm{b} h^2}{0.022}\right)^{-3/5} \left(\frac{z+1}{10}\right)^{3/2}$$

If $\mathrm{M} < \mathrm{M}_\mathrm{J}$ the gas expands



Bromm *et al.* 2009

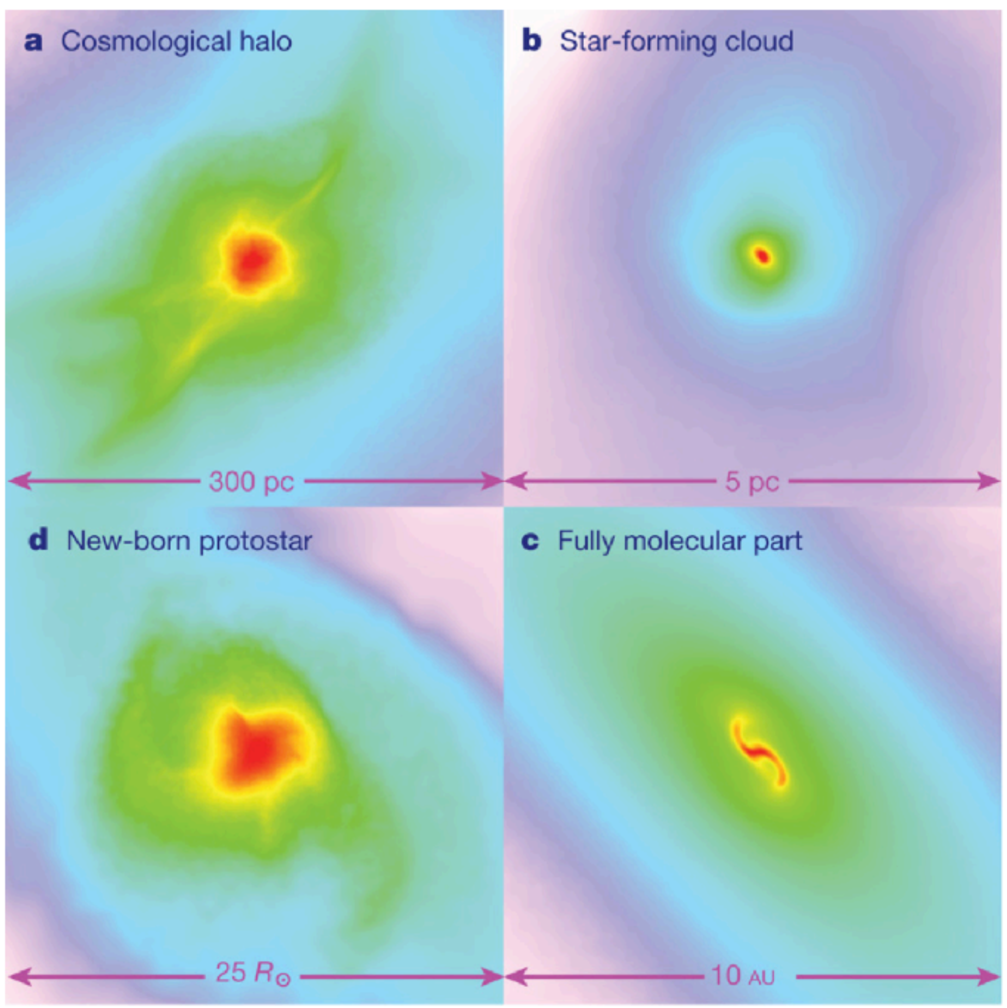
The gas needs not only to be bound but also to cool to form stars

$$M_\mathrm{cool} \approx 6 \times 10^5 \mathrm{M}_\odot\, h^{-1} \Omega_\mathrm{m}^{-1/2} \left(\frac{\mu}{1.22}\right)^{-3/2} \left(\frac{z+1}{10}\right)^{3/2}$$

If $\mathrm{M} < \mathrm{M}_\mathrm{cool}$ the gas does not cool sufficiently fast (within a Hubble time)

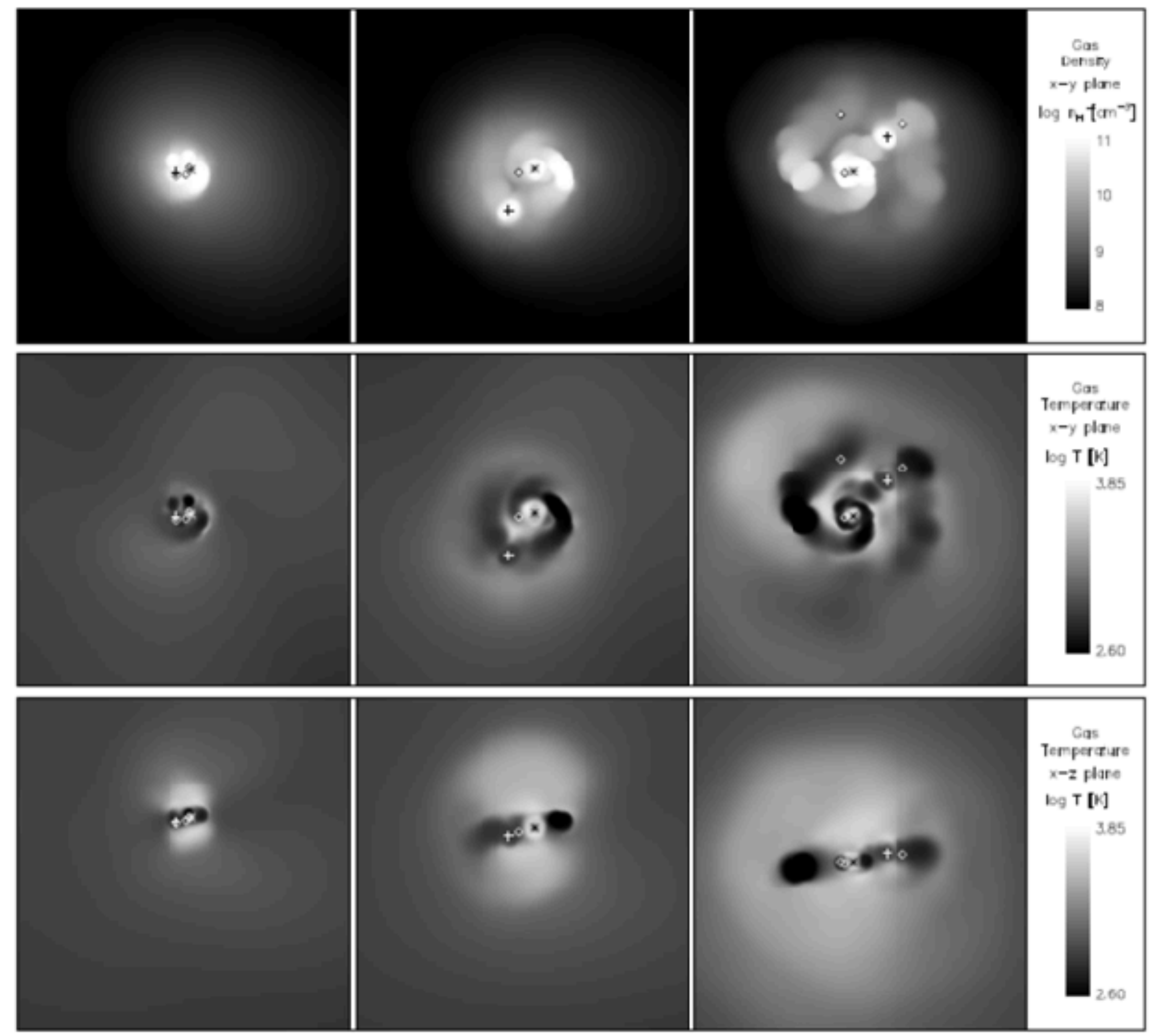
For $z < 40$ $M_\mathrm{cool} > M_J \Rightarrow$ Many halos do not form stars

Stellar Formation in a Halo: Fragmentation



Projected gas distribution around a primordial protostar.

Bromm *et al*. 2009



Stacy et al 2009

Lecture 2

i) Cosmic Dawn/The First Stars (POP III)

ii) Galaxy Formation (POP II stars)

iii) Reionization

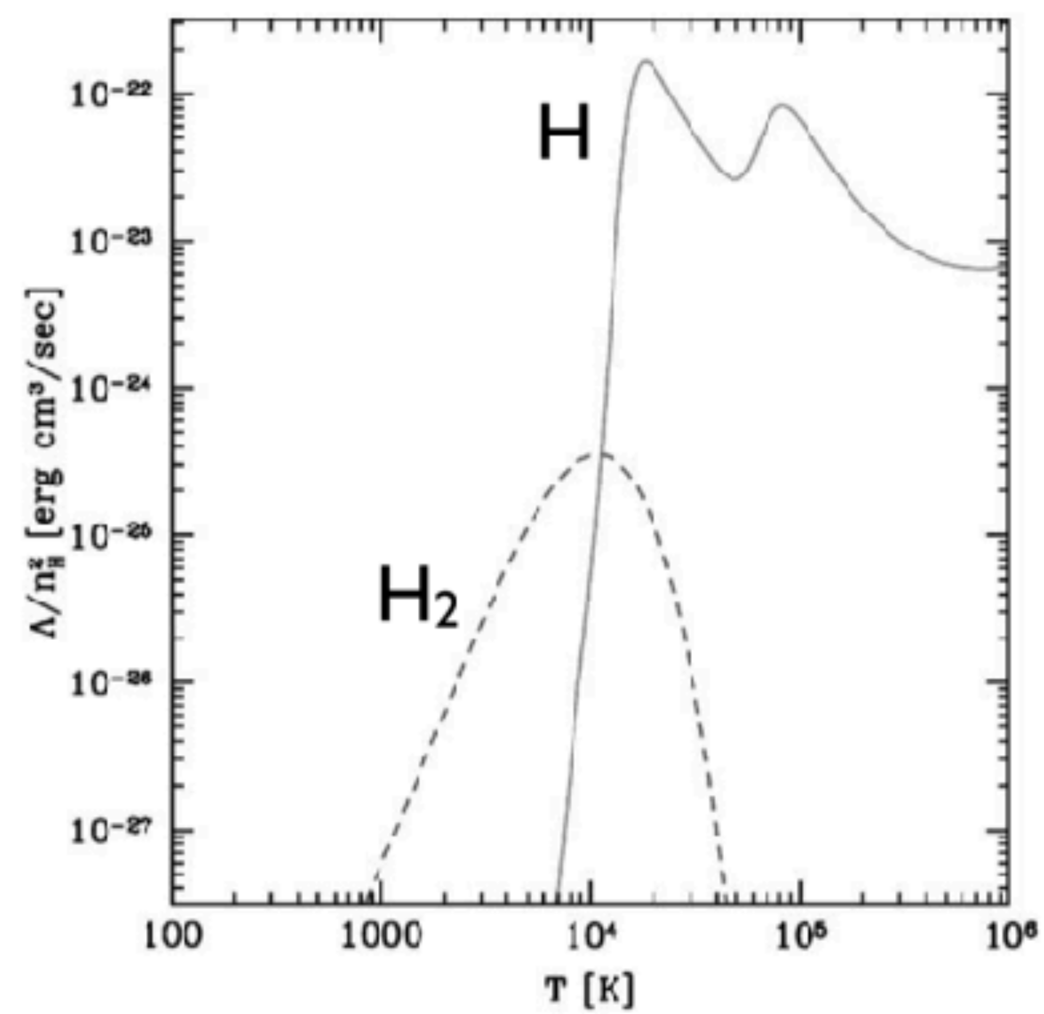
iV) Observing the EoR

First star formation: POP III stars

- Formation sites: minihaloes / atomic cooling haloes: 10^5 - 10^7 $M_\odot$
- IMF is highly uncertain, stellar mass range: 0.1 - 1000 $M_\odot$
- Cooling:
  - $T > 10^4$ K : atomic hydrogen
  - $T > 200$ K : molecular hydrogen
    - Direct formation: forbidden
    - Formation via H- channel:

$$H + e^- \rightarrow H^- + h\nu$$

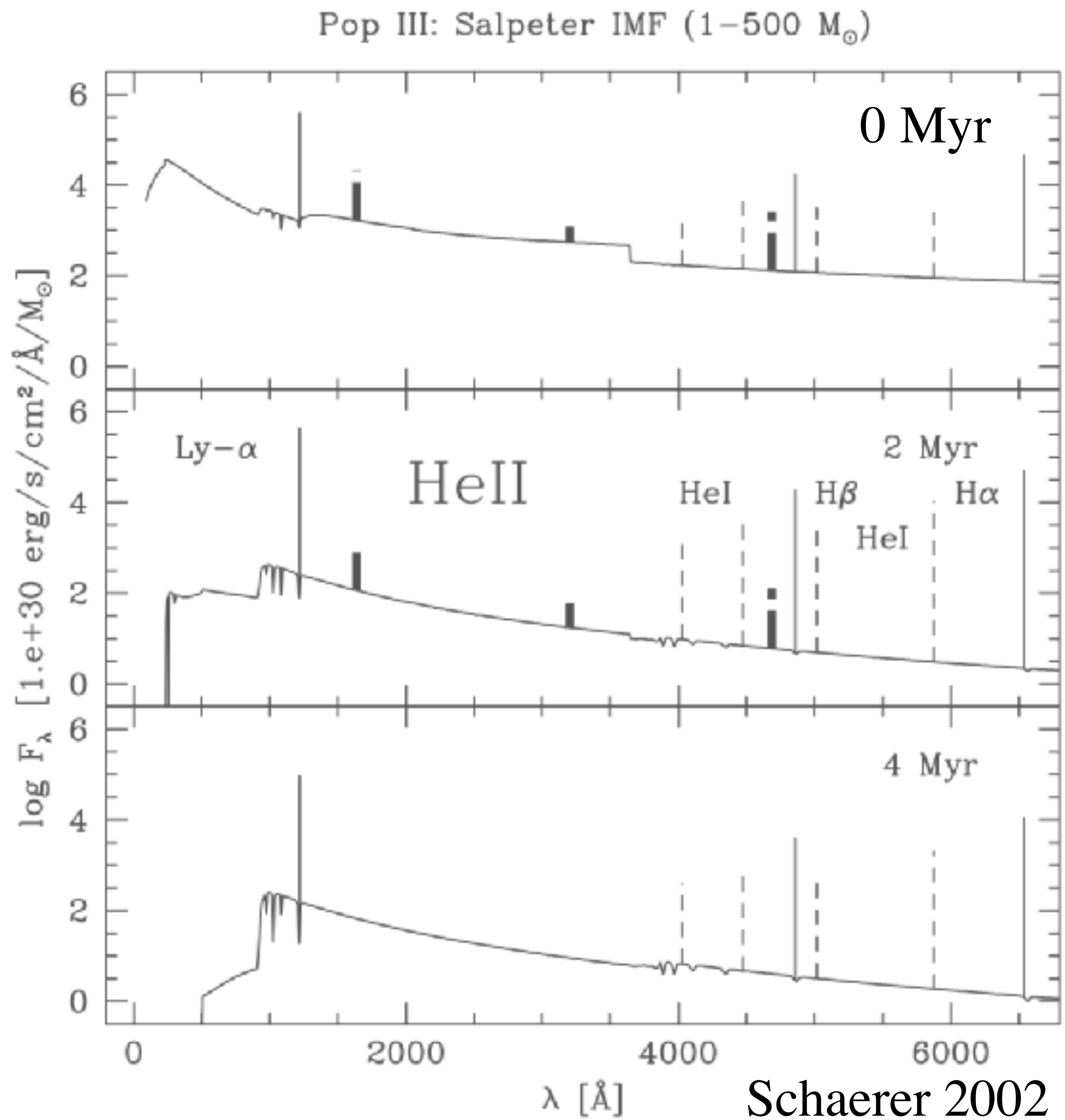
$$H^- + H \rightarrow H_2 + e^-$$



Barkana & Loeb 2001

POP III stars: spectra and lifetime

$M_{\rm ini}$	lifetime
1000.	
500.00	1.899E+06
400.00	1.974E+06
300.00	2.047E+06
200.00	2.204E+06
120.00	2.521E+06
80.00	3.012E+06
60.00	3.464E+06
40.00	3.864E+06
25.00	6.459E+06
15.00	1.040E+07
9.00	2.022E+07
5.00	6.190E+07



Schaerer 2002

POP III stars

Characteristics:

0.1-1000 solar masses
Massive stars have short life's

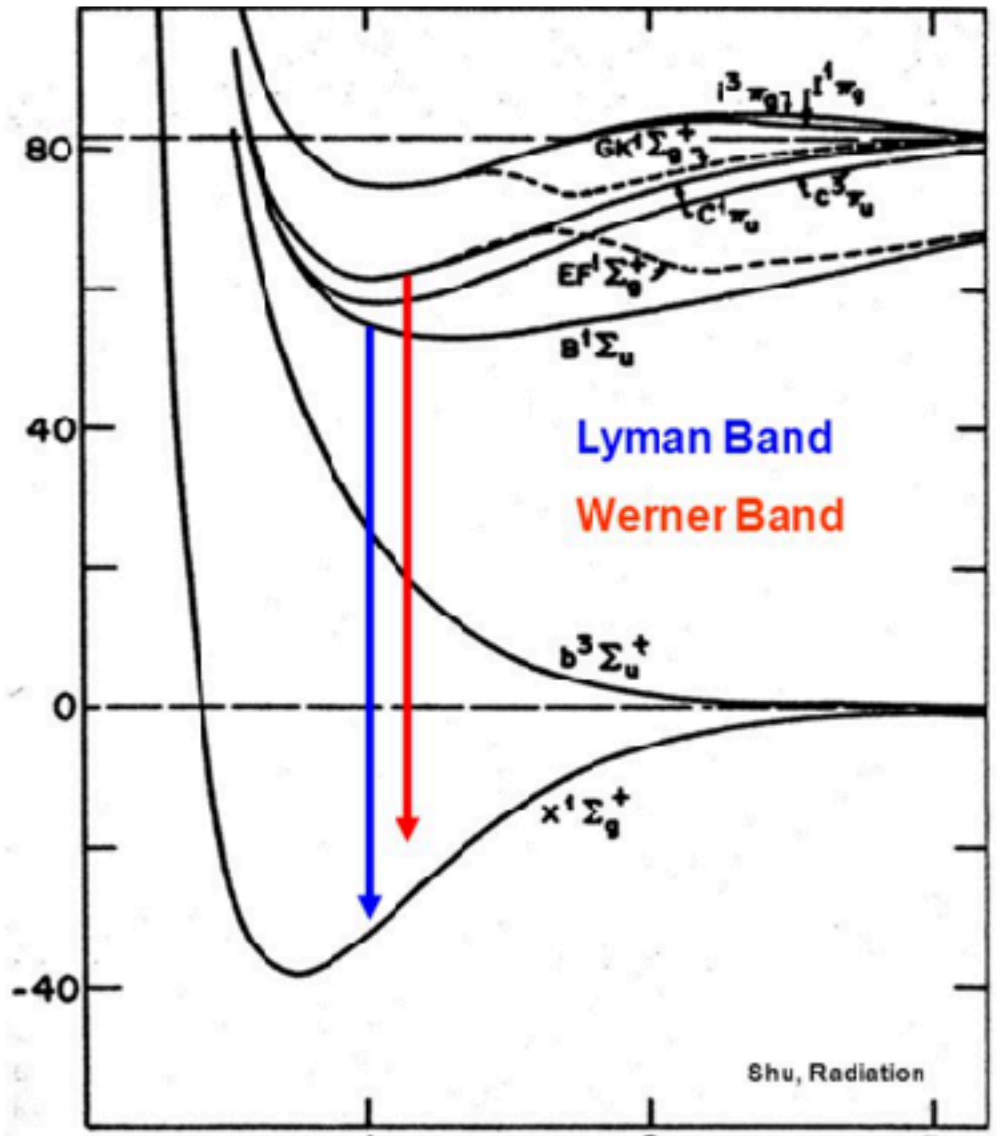
Galaxies become stable when atomic cooling is possible $T_{virial} = 10^4 K$

First metals produced in the cores of these stars

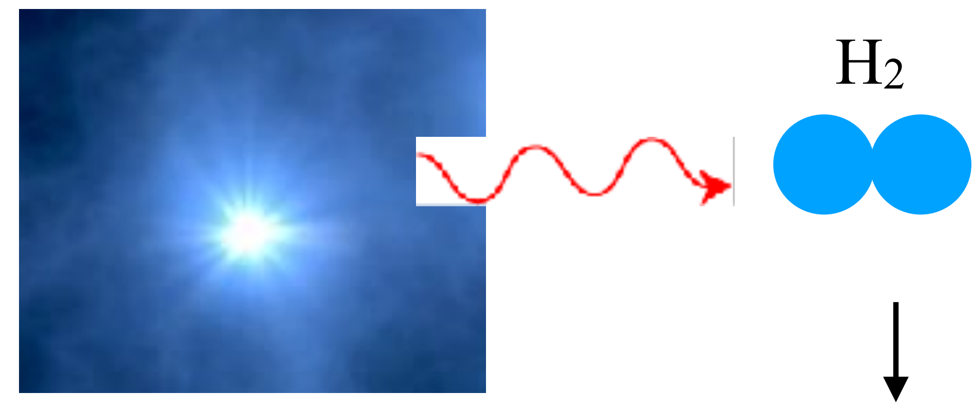
Impact on the IGM:

1. Production of Lyman-Werner photons (11.2 to 13.6 eV)
2. Ionisation of its surroundings
3. Heat and contaminate the IGM with metals after they SN explode

1) The Lyman-Werner photons:



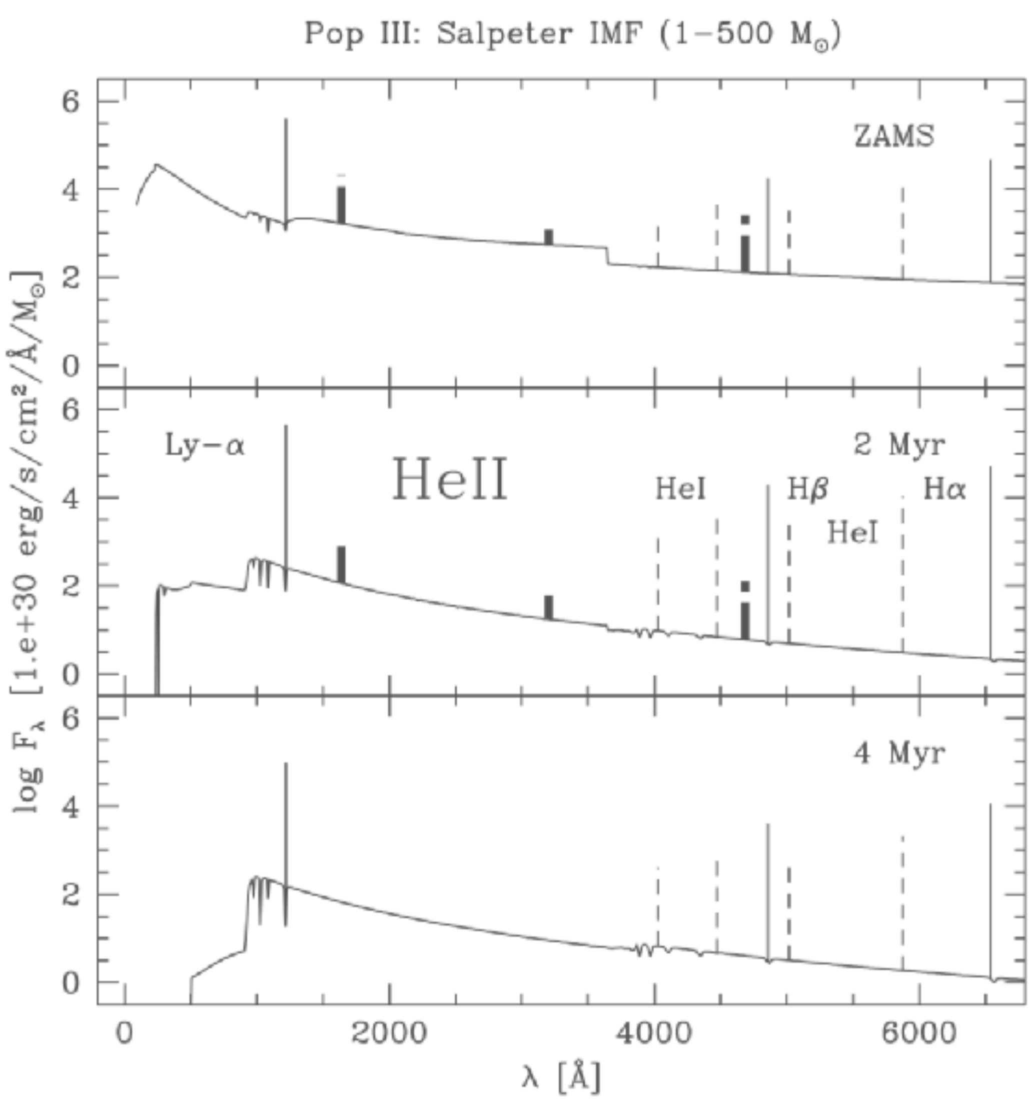
UV Electronic Transitions: H_2



H_2 gets excited and often vibrates and breaks into H + H

- Lyman-Werner photons destroy H_2 ⇒ No more SF in small halos
- Regions with a high Lyman-Werner background only form stars by atomic cooling ⇒ stable SF at $T_{vir} = 10^4$ K

2) Ionization of the stellar surroundings



Hydrogen ionising energy
E_{ion} =13.6 eV

Not enough stars to ionise the IGM

After stars stop producing ionizing photons the gas recombines

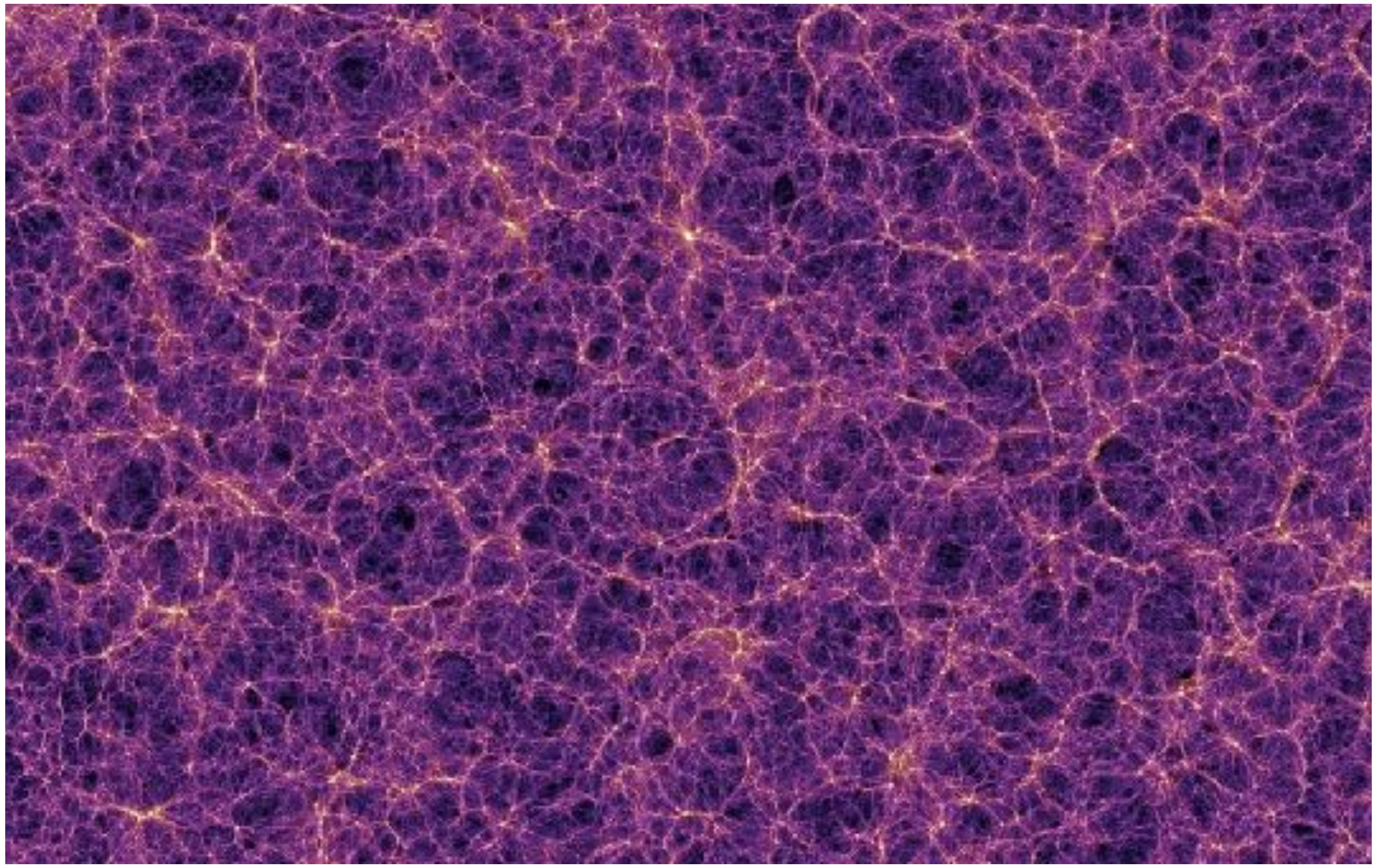
3) Heat and contaminate the IGM with metals after they SN explode

SN explosion

X-rays heat, ionise and excite the IGM

Metals produced in the start ejected into the IGM

POP II stars
(Formed with metals)

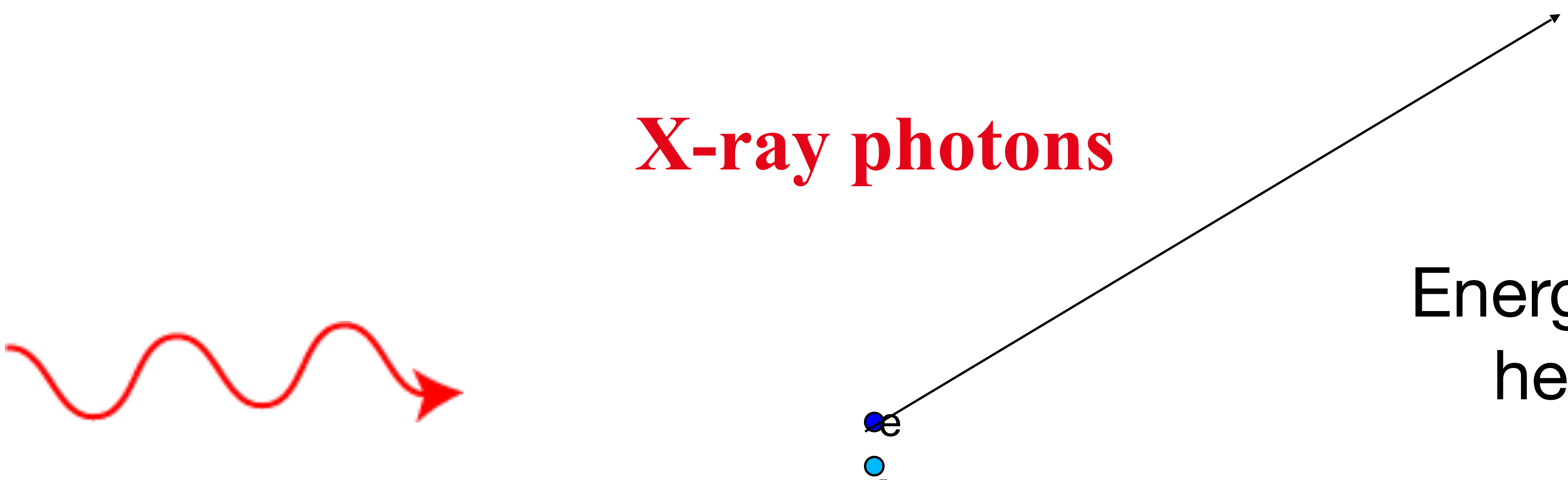


UV photons

Almost all energy goes into ionising the gas

Large cross section but ejected electron has low energy

X-ray photons



Energy goes into ionisations, heating and excitations 1:1:1

Low cross section but ejected electron has high energy

The impact of the first stars on the IGM

Mean free path

$$\langle l_E \rangle \approx \frac{1}{n_H \sigma_H(E)}$$

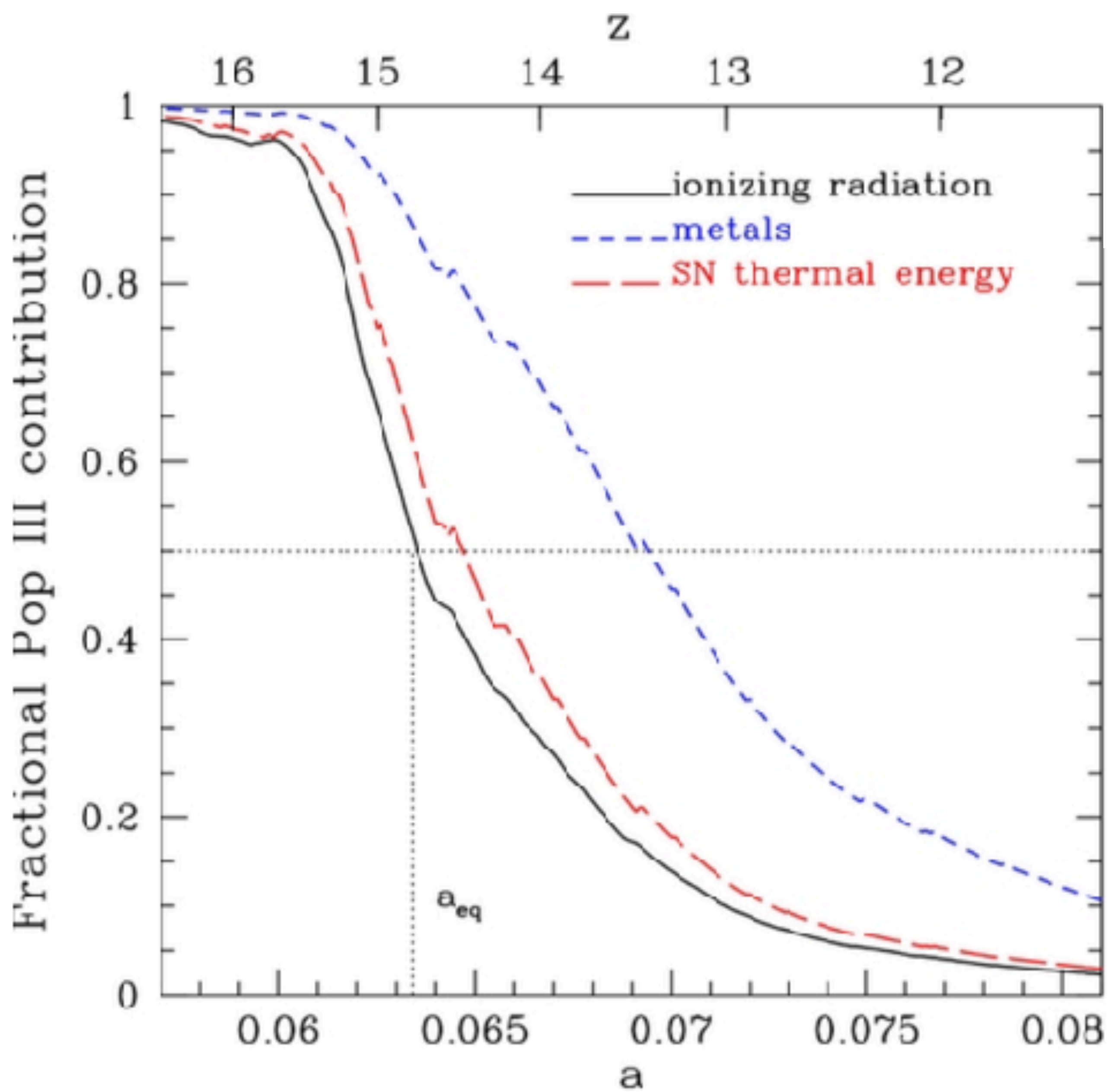
Bound-free
Cross section

$$\sigma_H(E) = \sigma_0 \left(E_0/E\right)^3$$

$\boldsymbol{n_H} = 2.2 \times 10^{-7}\ \mathrm{cm}^{-3}\ (1+z)^3$
$\sigma_0 = 6 \times 10^{-18}\ \mathrm{cm}^2$
$E_0 = 13.6\ eV$

At $z = 20$: For $E = E_0$ $\langle l_E \rangle \approx 0.22$ kpc comoving
For $E = 1$ keV $\langle l_E \rangle \approx 0.1$ Mpc comoving

The impact of the first stars on the IGM



Muratov, OG et al. (2013)

The duration of Pop III era is less than 100-200 Myr in a given galaxy

The impact of the first stars on the IGM

Mean free path $\langle l_E \rangle \approx \frac{1}{}$

POP III stars emit UV radiation which only ionises its surroundings

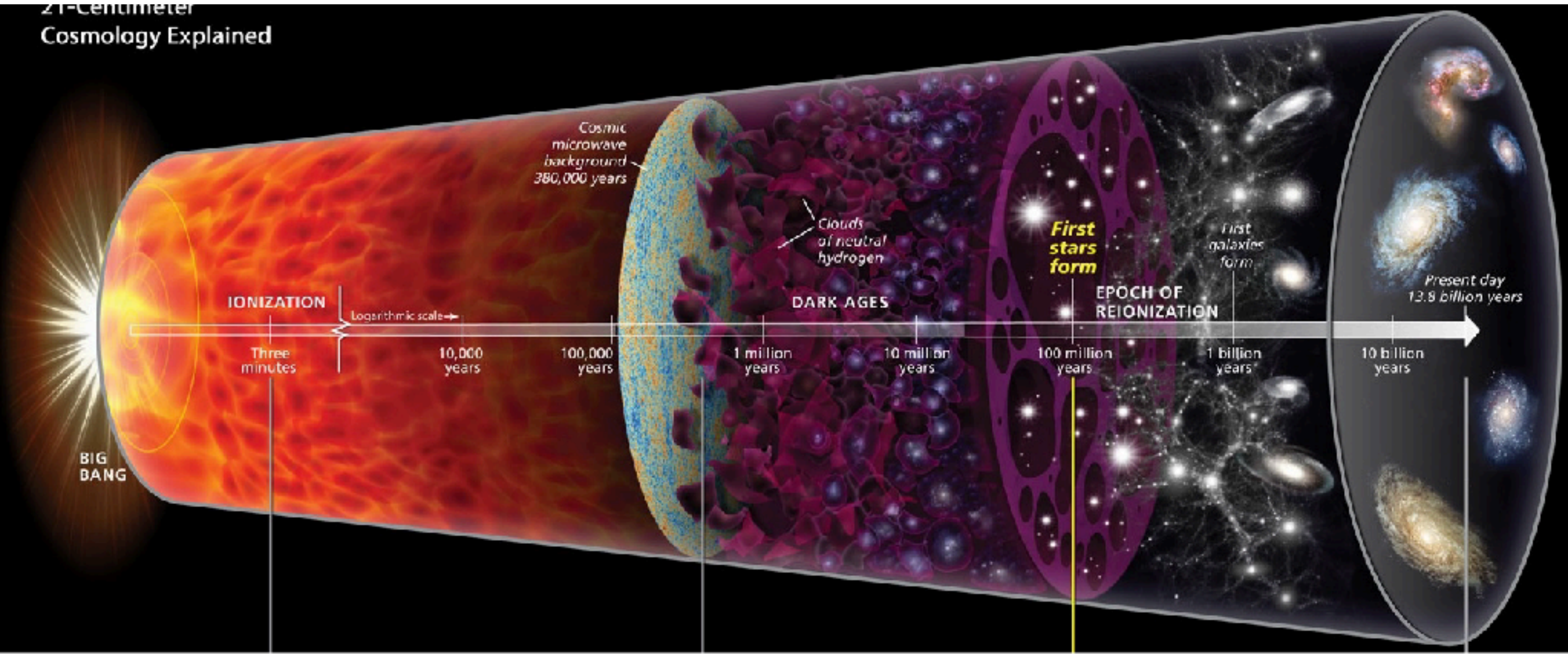
When this stars turn into SN x-rays heat the IGM up to large distances

$E_0 = 13.6\ eV$

At $z = 20$: For $E = E_0$ $\langle l_E \rangle \approx 0.22$ kpc comoving

For $E = 1$ keV $\langle l_E \rangle \approx 0.1$ Mpc comoving

The formation of the first galaxies and the reionization of the IGM



21 cm line Brightness Temperature

$$\delta T_b \approx 28\mathrm{mK}(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

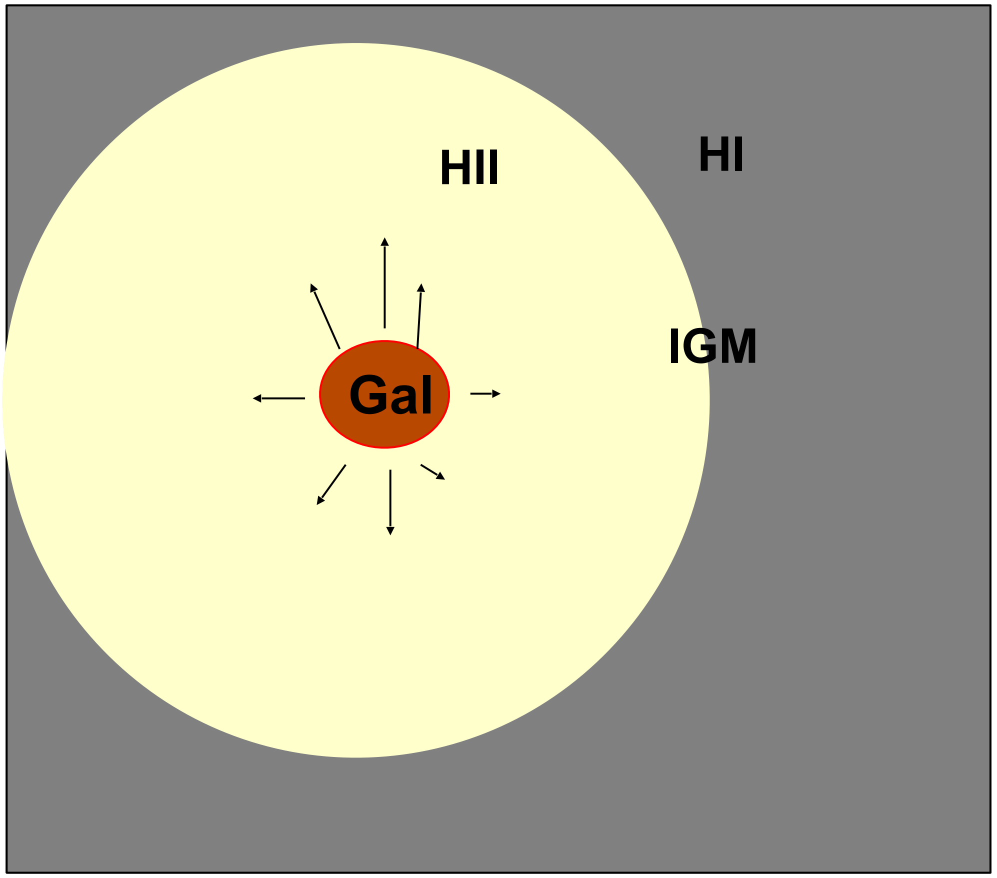
Astrophysics

Cosmology

Ionisation of the IGM: What do we want to know?

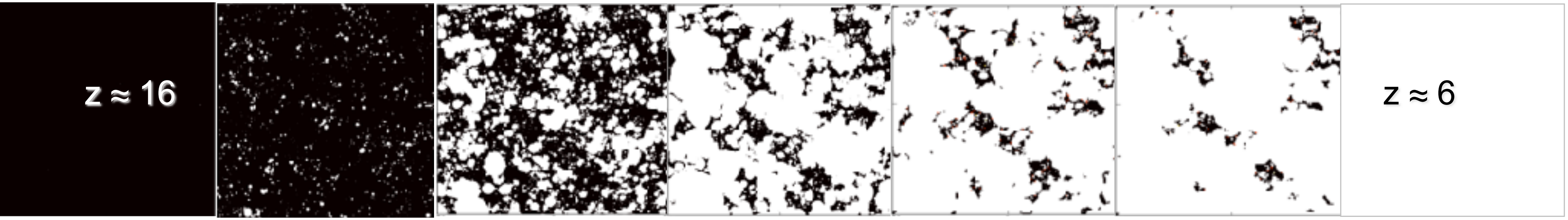
What were the main sources?

- Ionizing photons sources:
- Stars: POP II + POP III
- Quasars +QSO's
- DM decay + annihilations



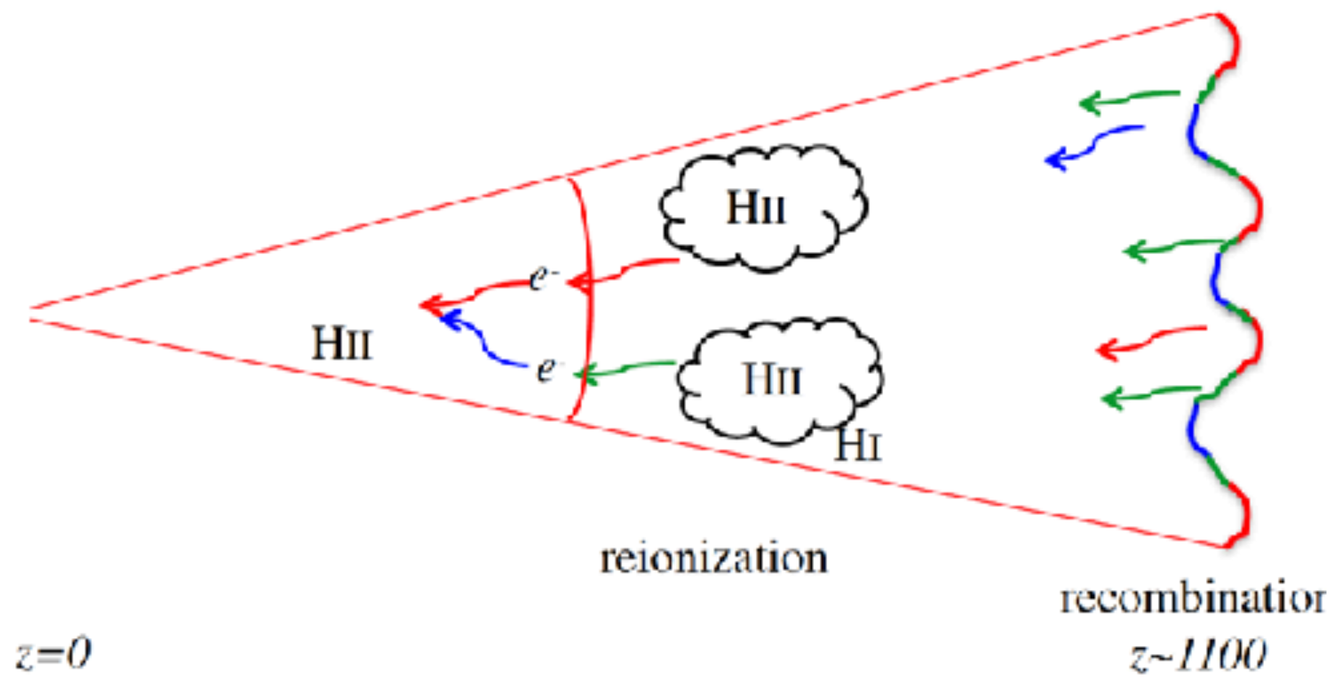
What was the topology?

What was the timeline?

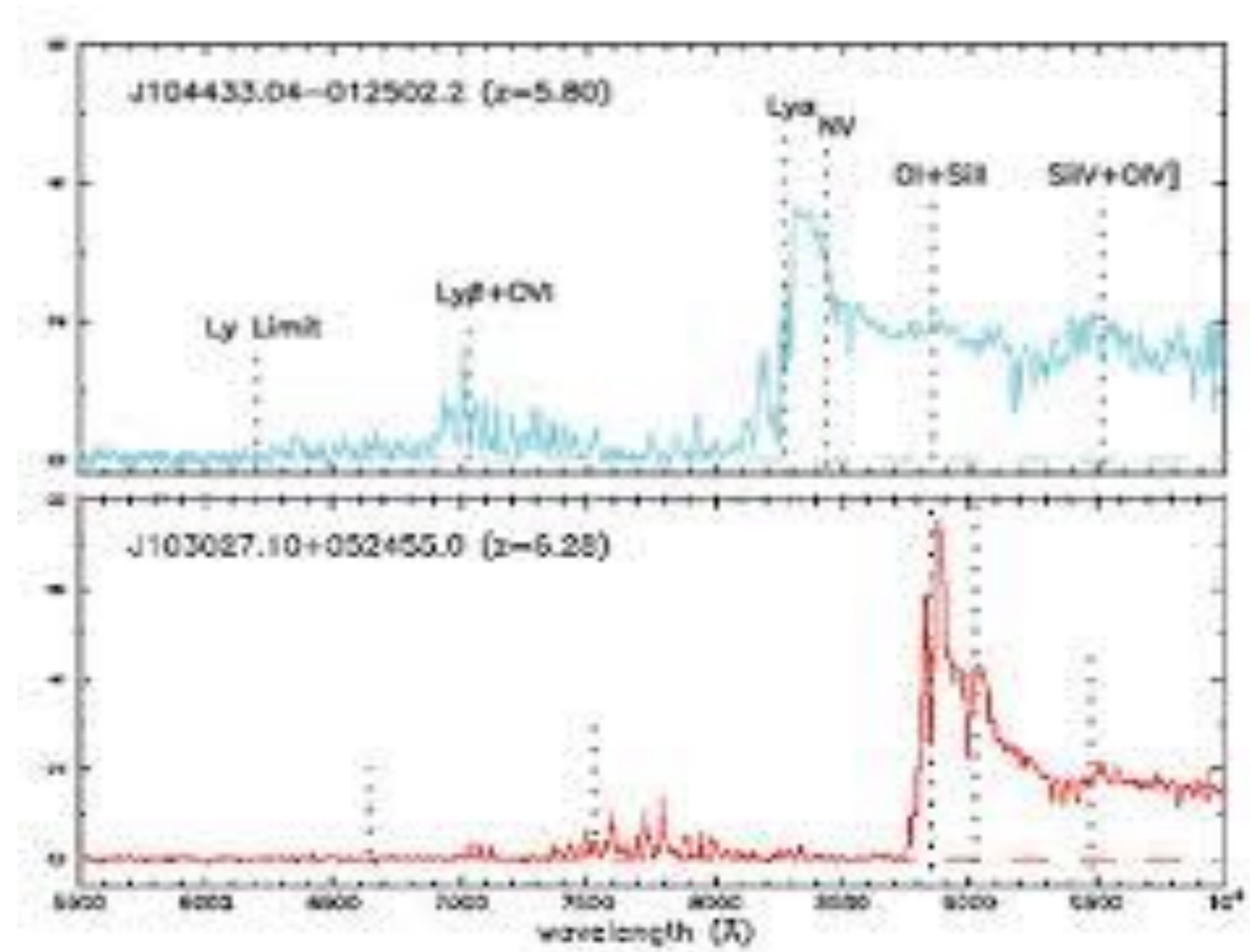


The Timeline: Optical depth + Lyα forest

Integral CMB constraints

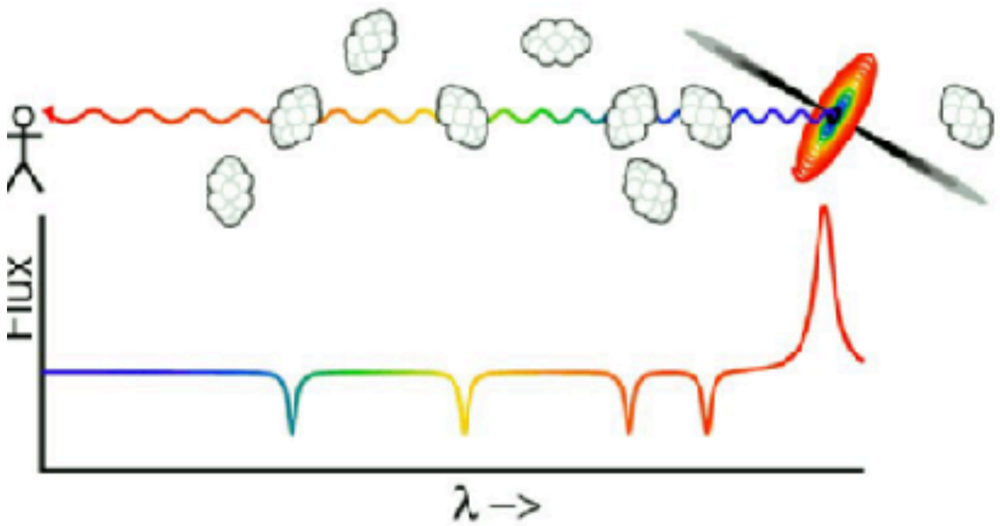


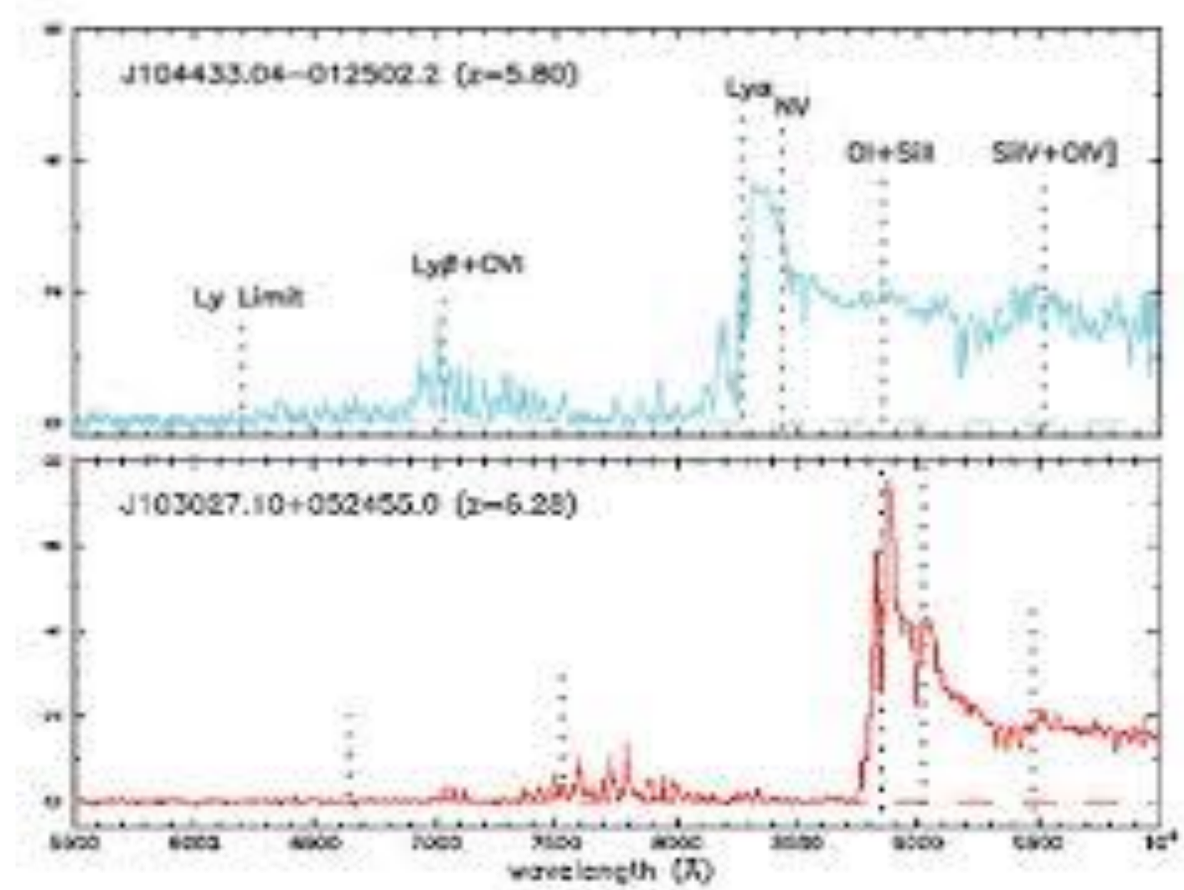
Quasars spectra:
Timing the end of the EoR



The Timeline: Lyα forest

Quasars spectra:
The end of the EoR

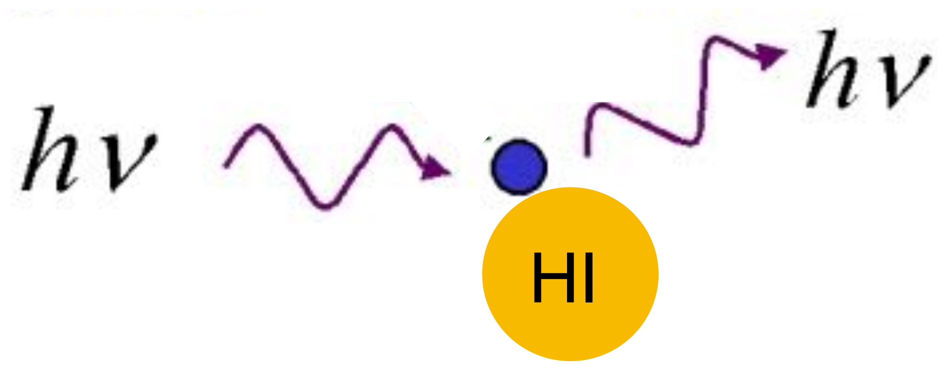




Absorption features due to Lyman-α in the IGM.

$$\tau_\alpha(\nu_0) = \int_{x_A}^{x_B} n_{HI}\sigma_\alpha dx/(1+z)$$

τ_α is the optical depth.x is the comoving radial distance. σ_α is the cross section & n_{HI} is the neutral hydrogen number density



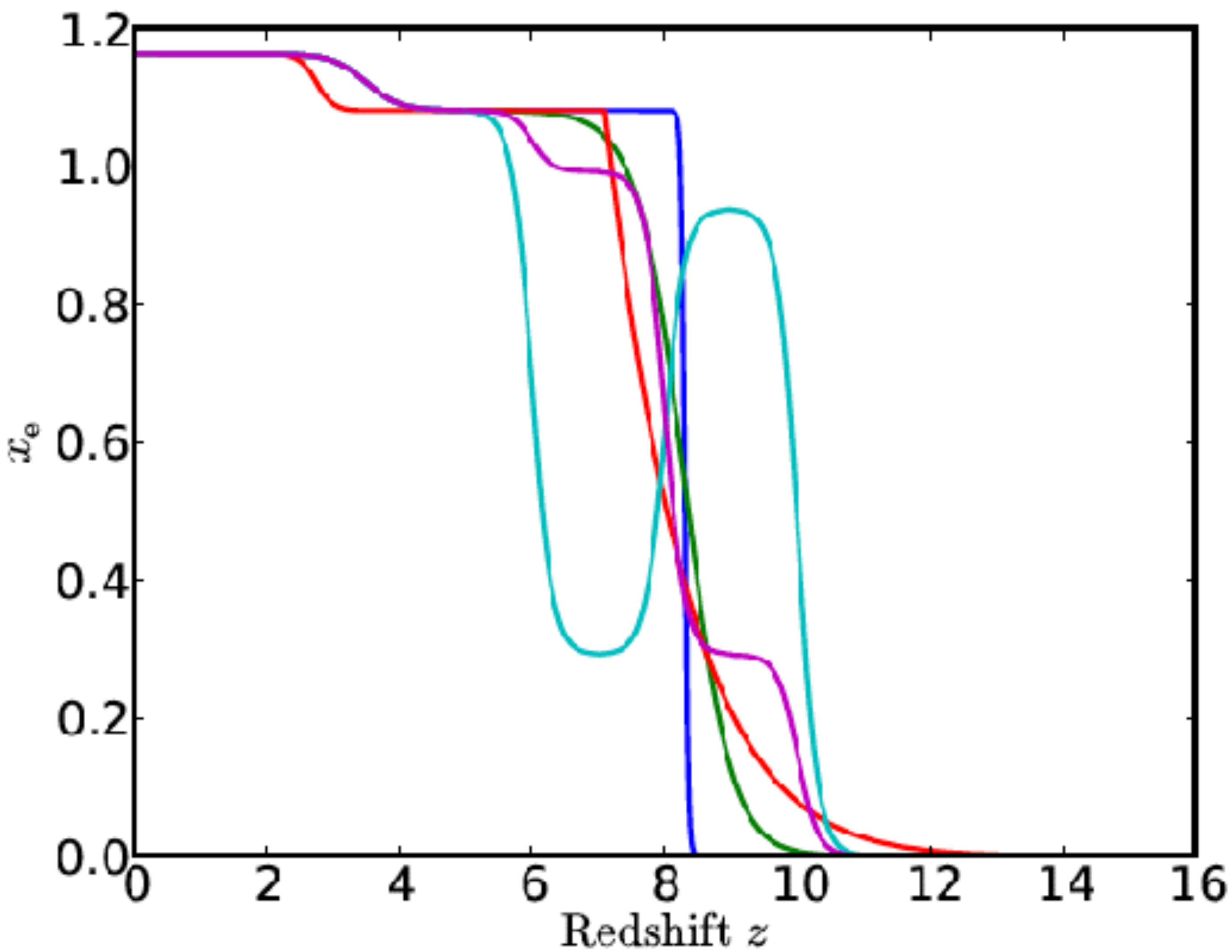
At mean density $x_{HI} = n_{HI}/n_H < 10^{-5}$ is enough to scatter Lyα

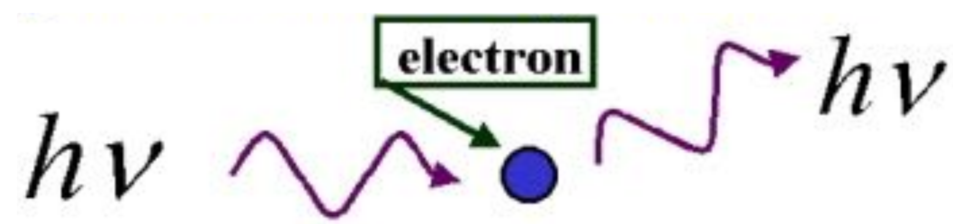
The Timeline: Optical depth to reionization

$$\tau_e(z_r) = \int_0^{z_r} n_e \sigma_T (1+z)^{-1} \, [c/H(z)] \, dz$$

Integral constrain

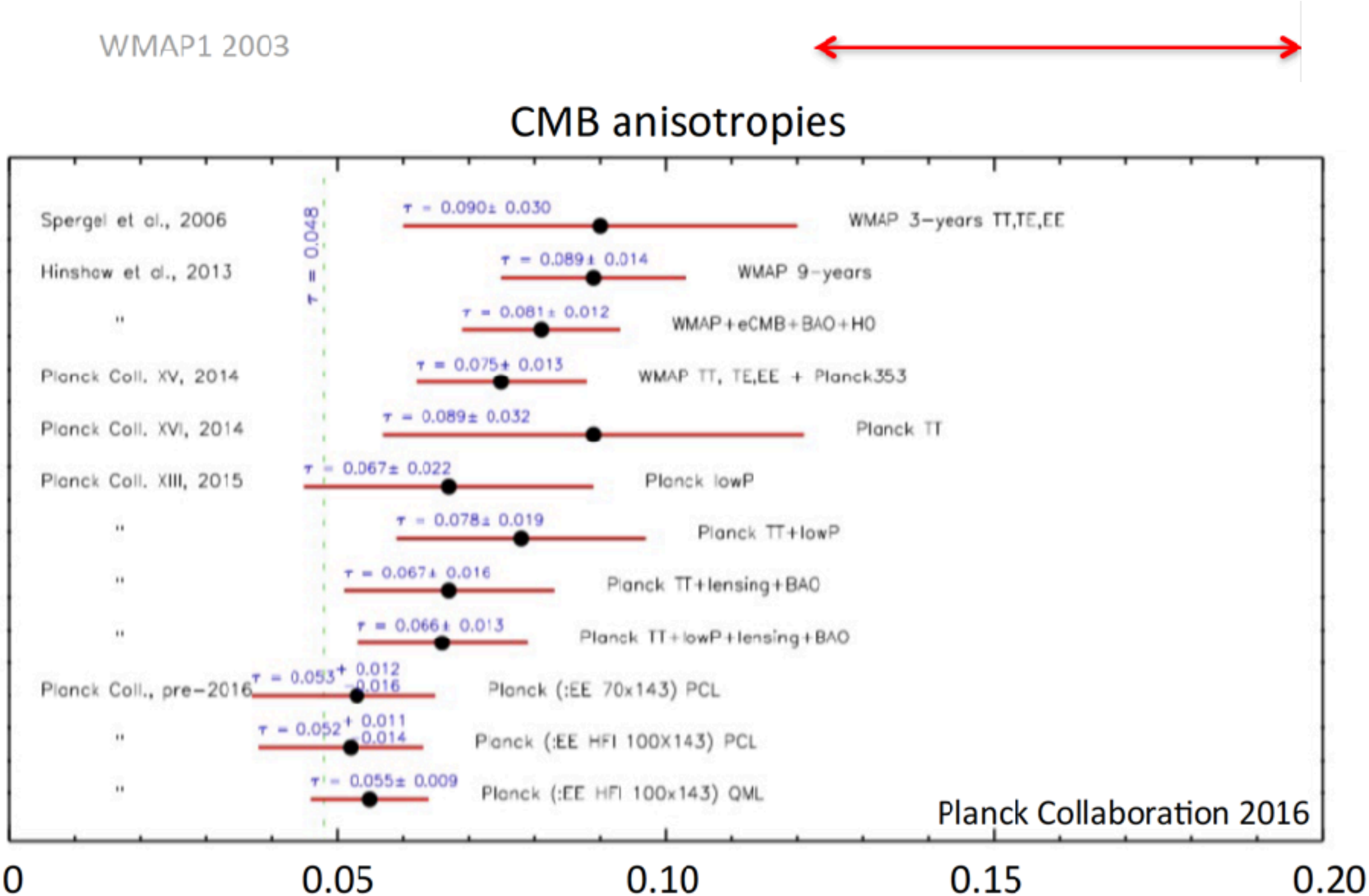
$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65 \times 10^{-25} \ \ \text{cm}^{-2}$$





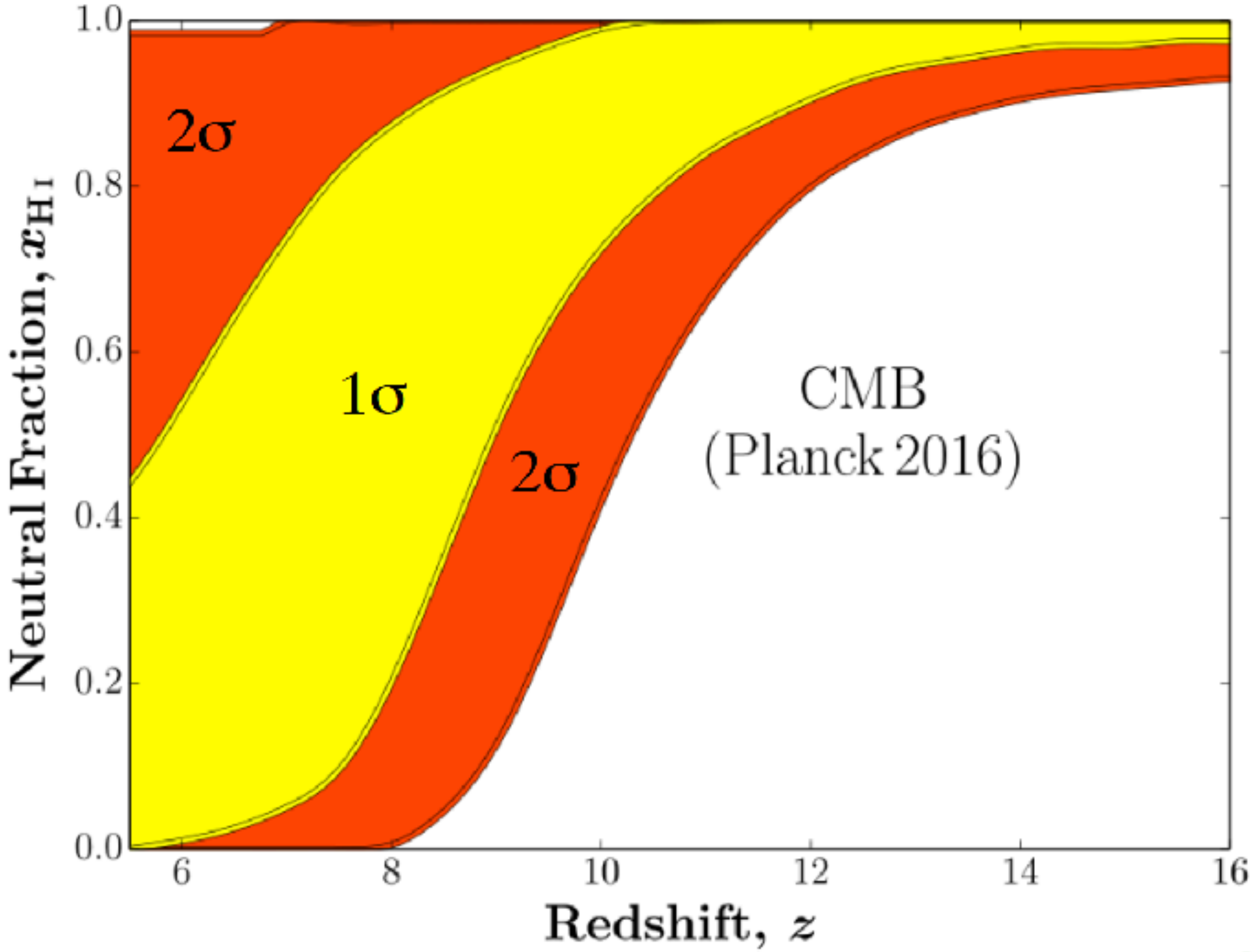
Thomson scattering of CMB photons (low energy photons) by free electrons

The Timeline: Optical depth to reionization



$\tau = 0.054 \pm 0.007$ Planck 2018

The Timeline: Optical depth



Greig & AM 2017

More constraints on the EoR timeline

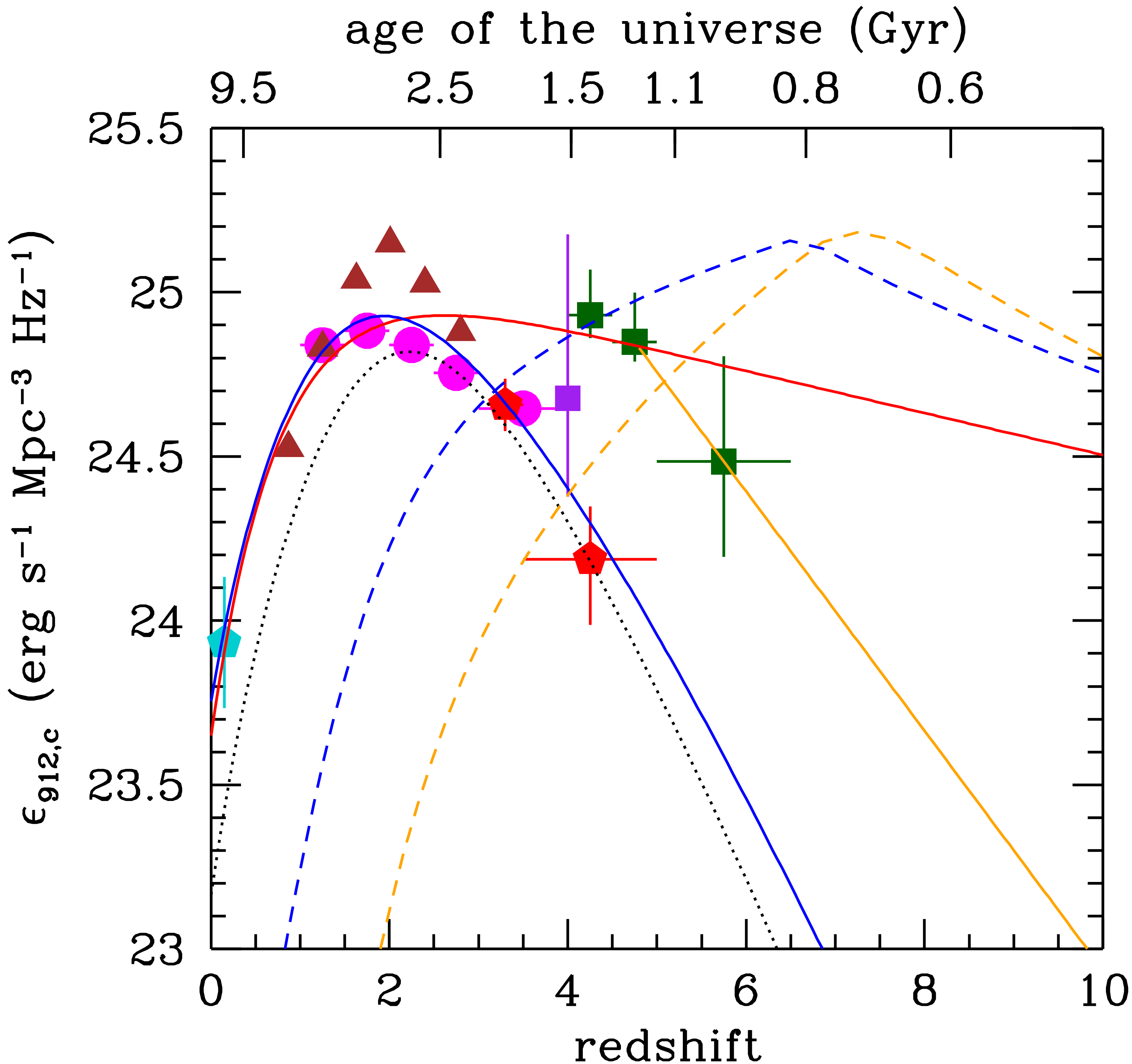
ex: Lyman break galaxies,

LAE

(To be discussed later)

Lets assume EoR from z~16 - 6

The sources of Reionization: Galaxies vs quasars emissivity



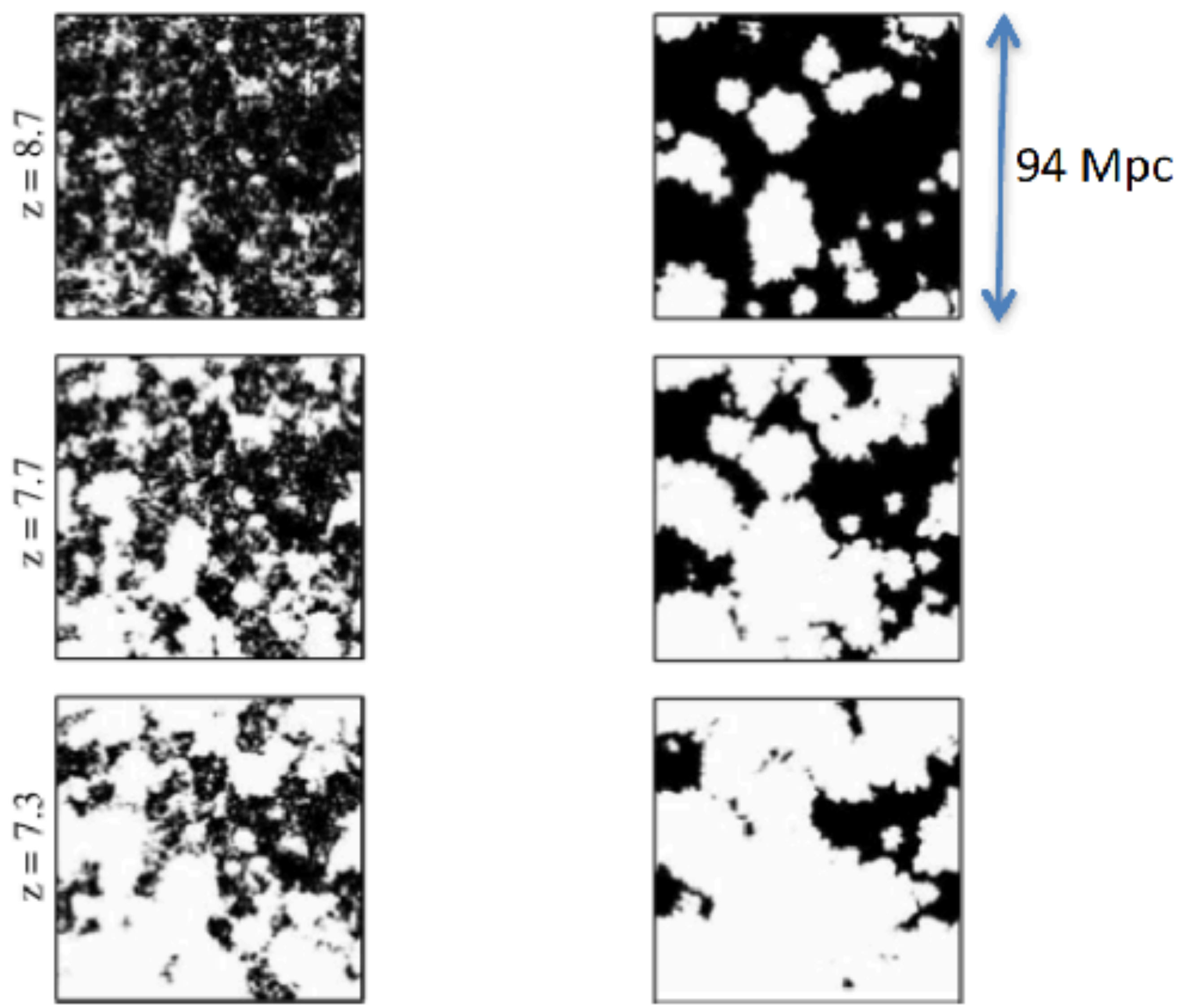
QSOs - Hard UVB
large-scale fluctuations

Stars/Galaxies - SOFT UVB
small-scale fluctuations

Puchwein2018

Reionization by Galaxies or quasars: Impact on Tb

- Galaxy clustering + stellar properties → *evolution of large-scale EoR/CD structures*



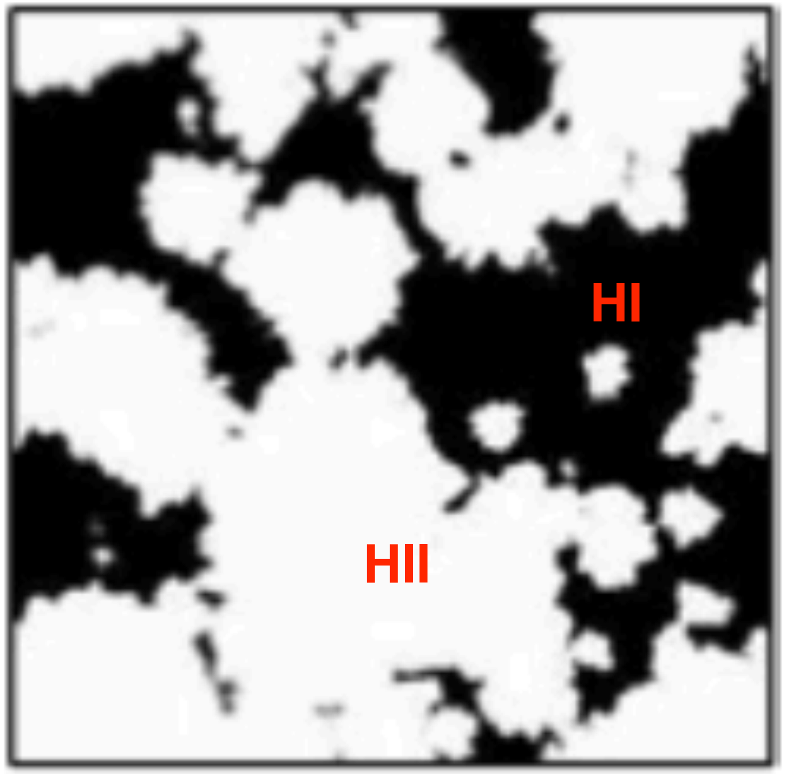
McQuinn+ 2007

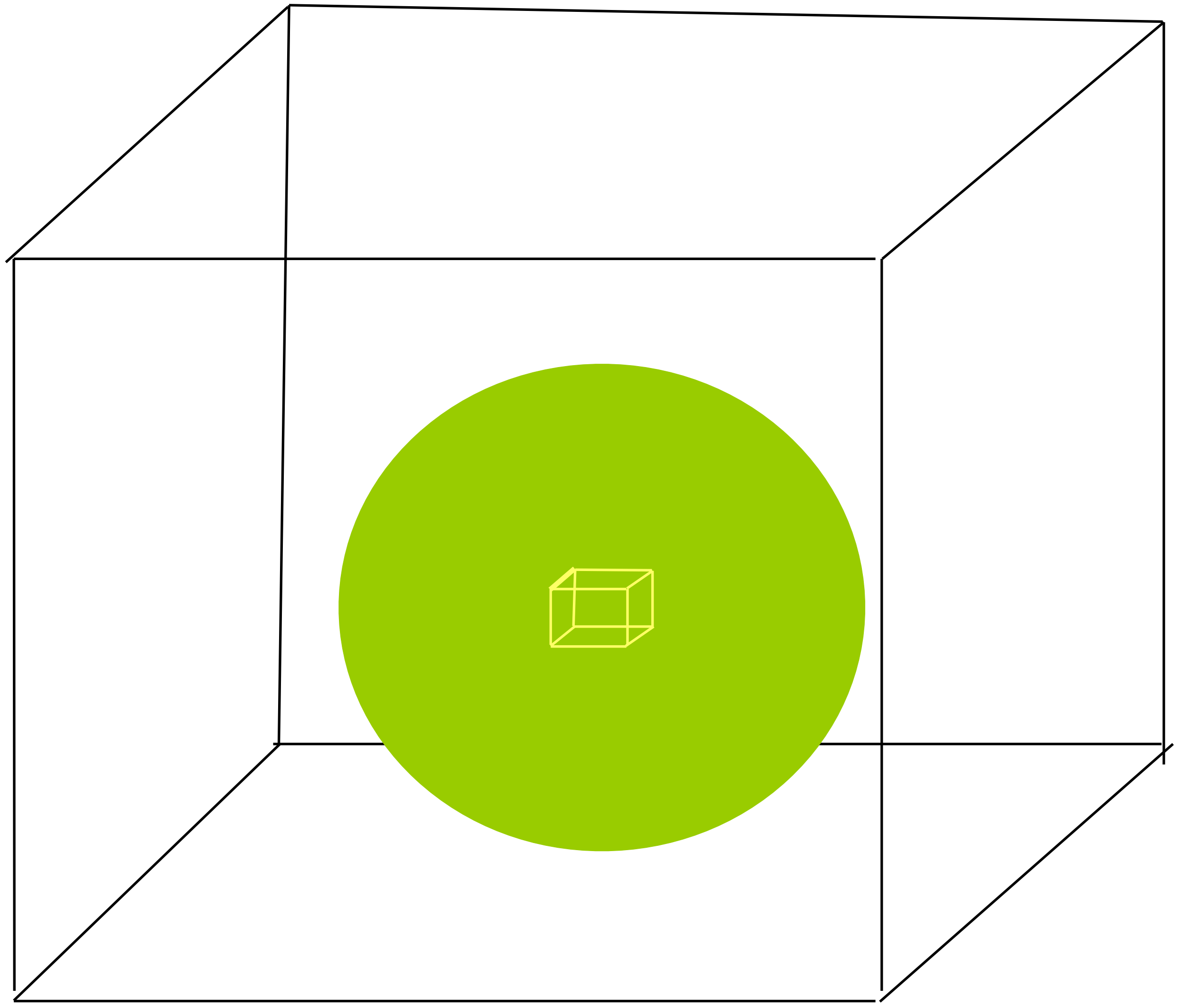
Abundant, faint galaxies vs **Rare, bright galaxies**

Modeling Reionization: Simulations

The evolution of the ionization field: determining $x_i = \langle n_{HII}/n_H \rangle$

Ionizing rate ≥ Recombination rate





Ionizing emissivity: Ionizing photons available to ionise the IGM

$$\dot{n}_{\rm ion} = A_{\rm He} \times SFRD \times Q_{\rm ion} \times f_{\rm esc}$$

He correction factor

Star formation rate density

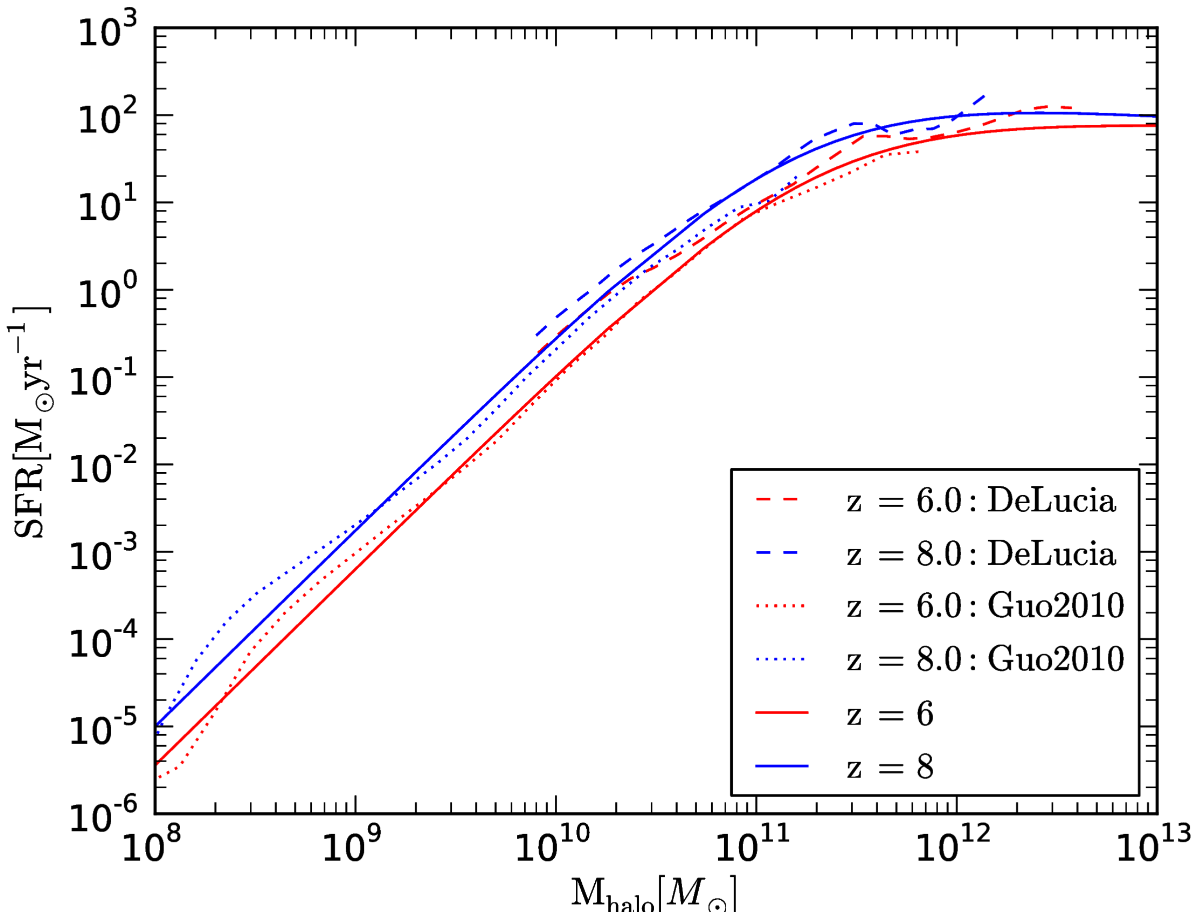
Nº of ionizing photons per solar mass in SF

Ionizing photons escape factor

These parameters depend on the stellar population (IMF) and on the galaxy SED

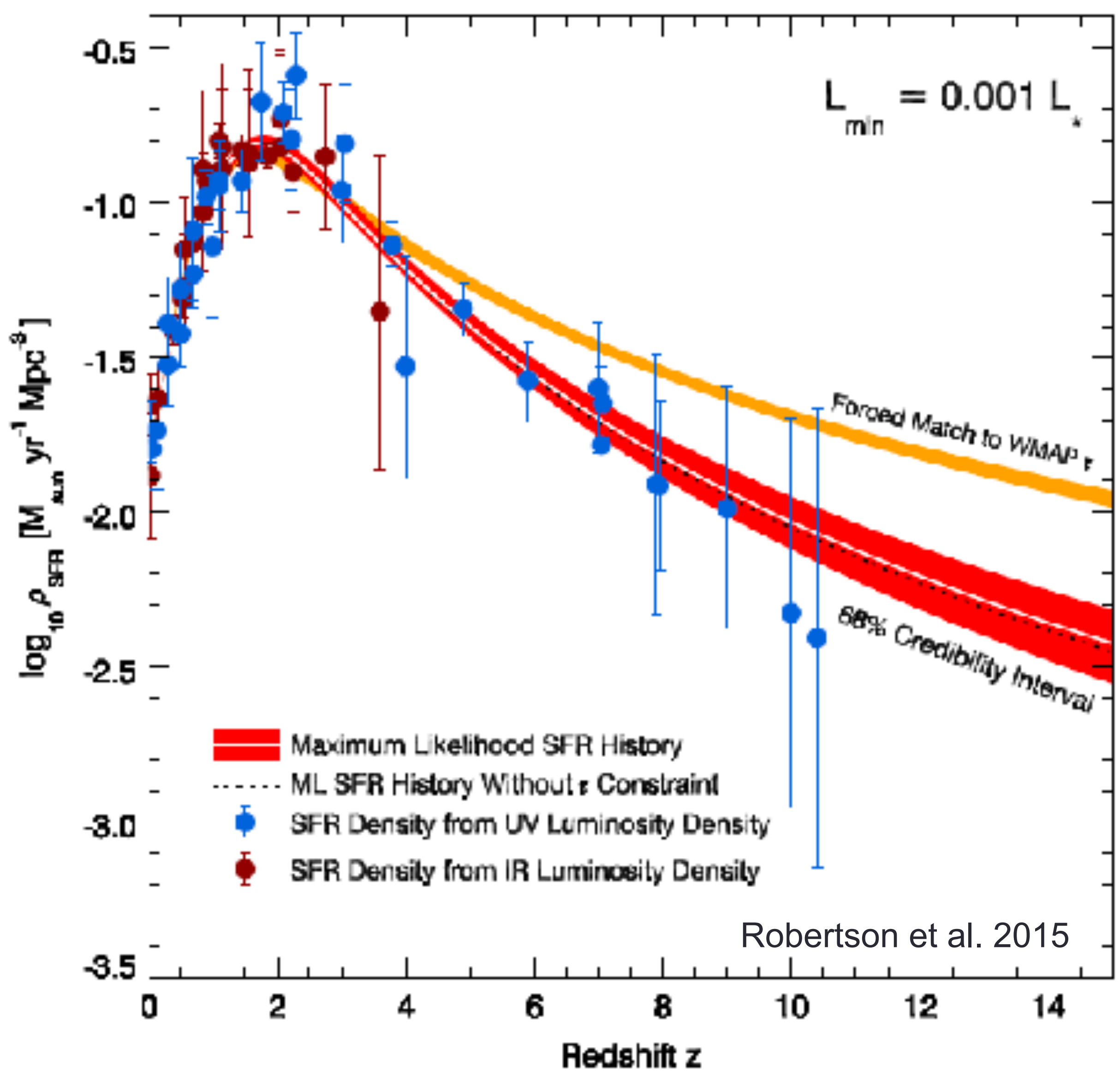
Note: In observations Nion is calculated by integrating over the galaxies luminosity function

Star Formation Rate and SFRD



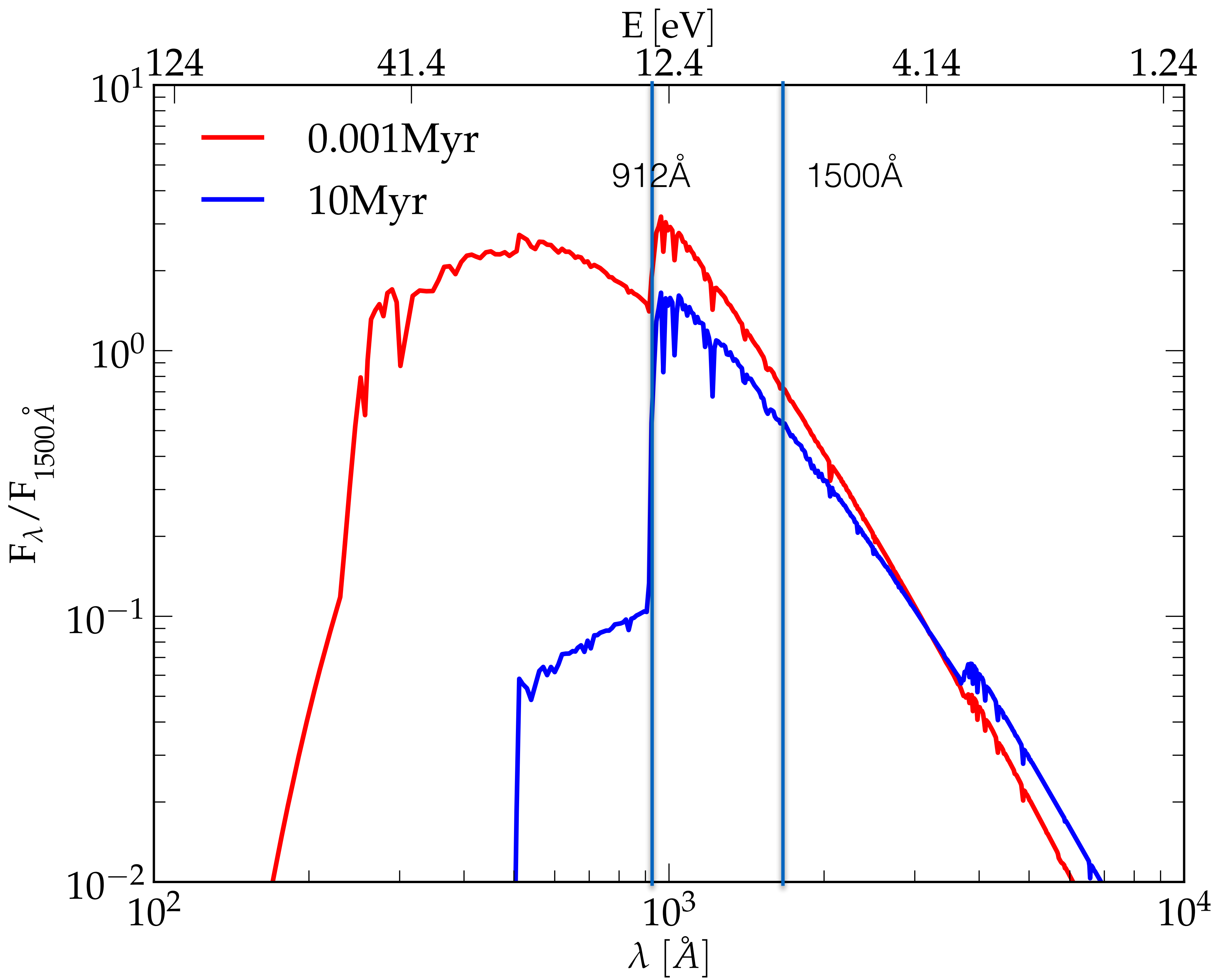
Fit to the galaxies properties from the simulated galaxy catalogs from:

DeLucia et Blaizot (2007) & Guo et al. 2011



UV - Young galaxies
IR - Old galaxies

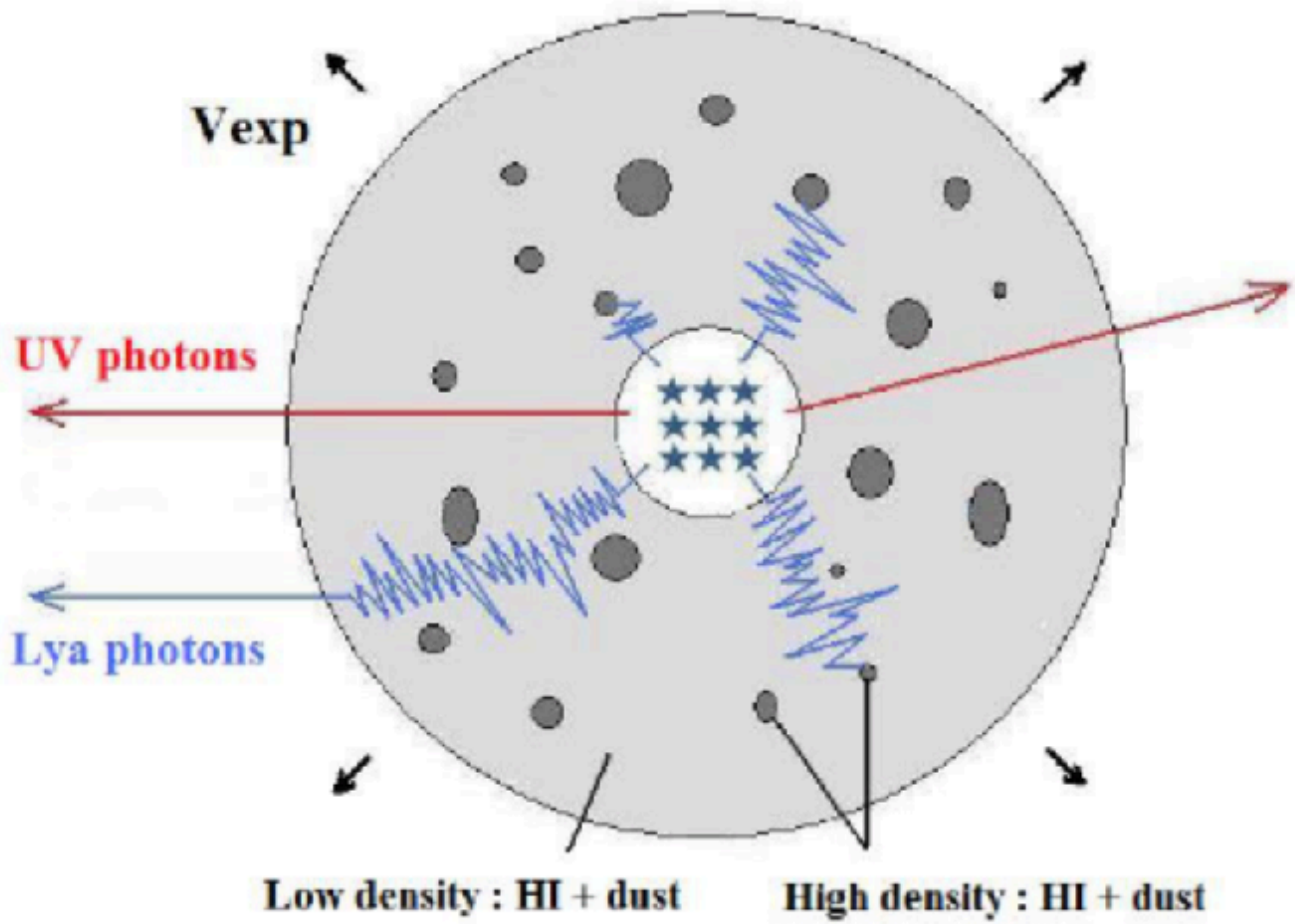
Galaxy Spectra (POP II stars): Calculating Qion



Qion = Nº of ionizing photons per Msun in SF

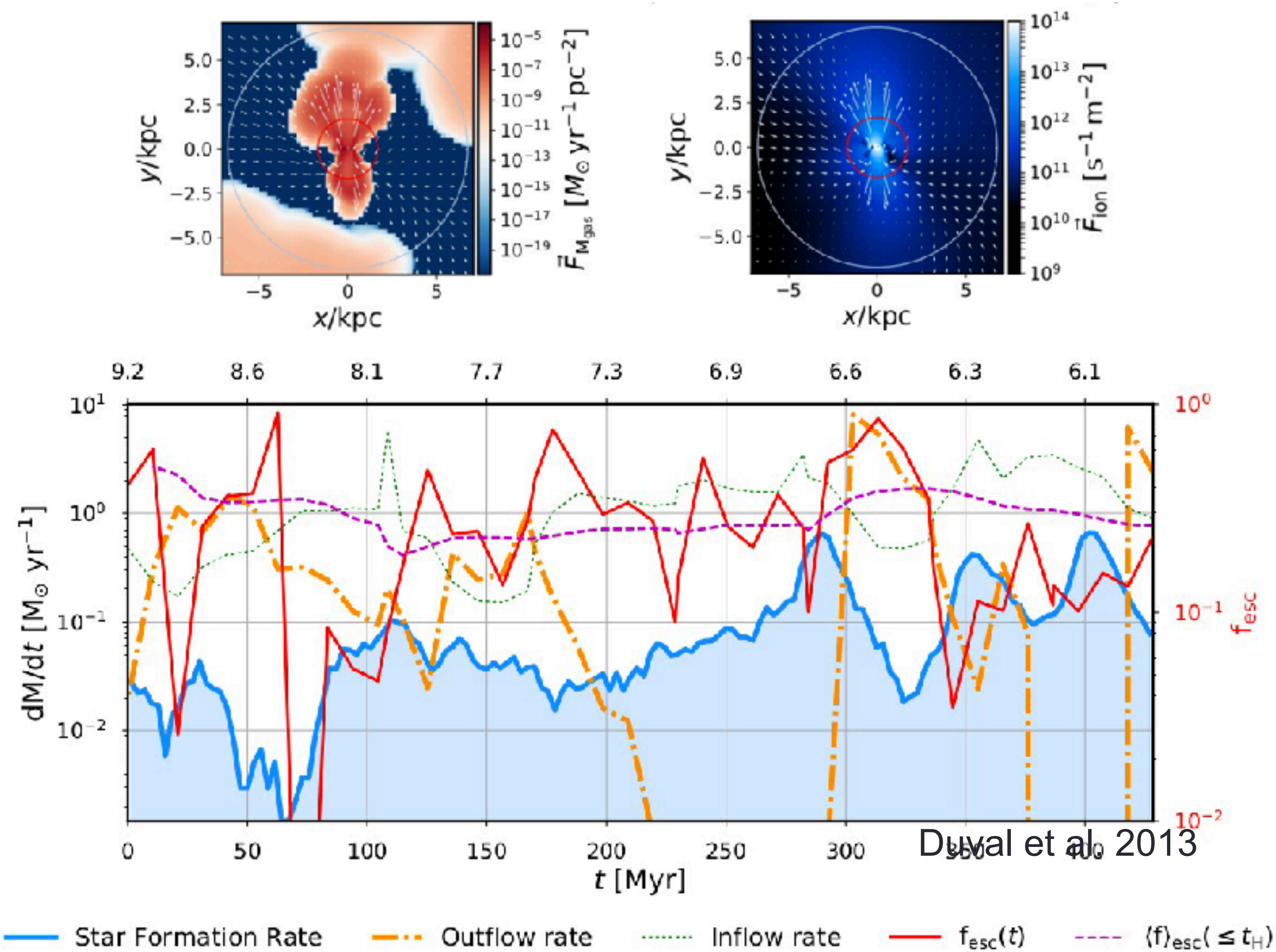
In observations the UV fluxes are usually measured at 1500 Å

Ionizing photons escape fraction



Duval et al. 2013

Ionizing photons escape fraction



Duval et al. 2013

Ionizing photons escape fraction

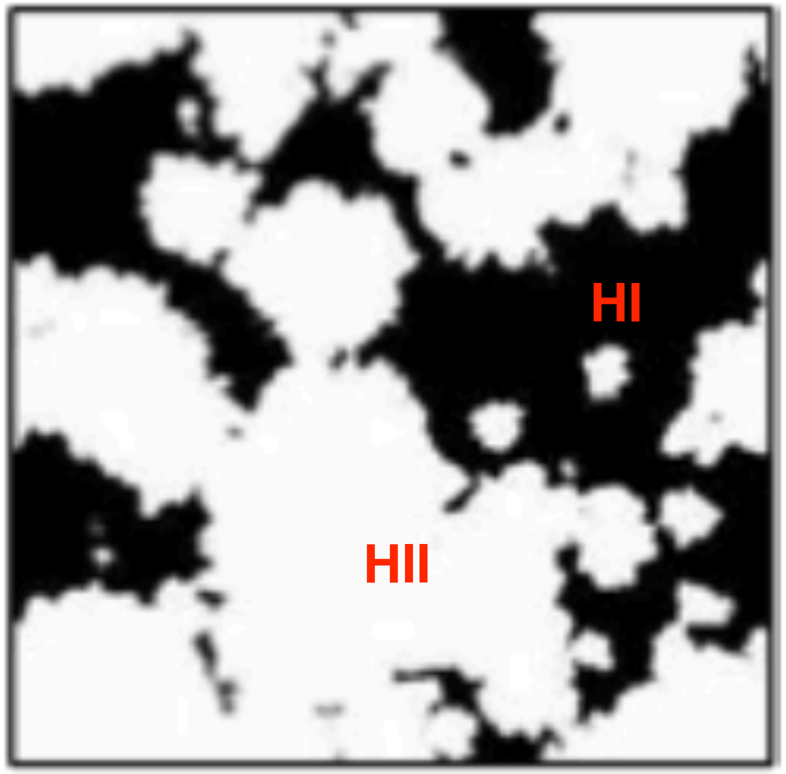
Reionization with galaxies requires fesc~0.1-0.2

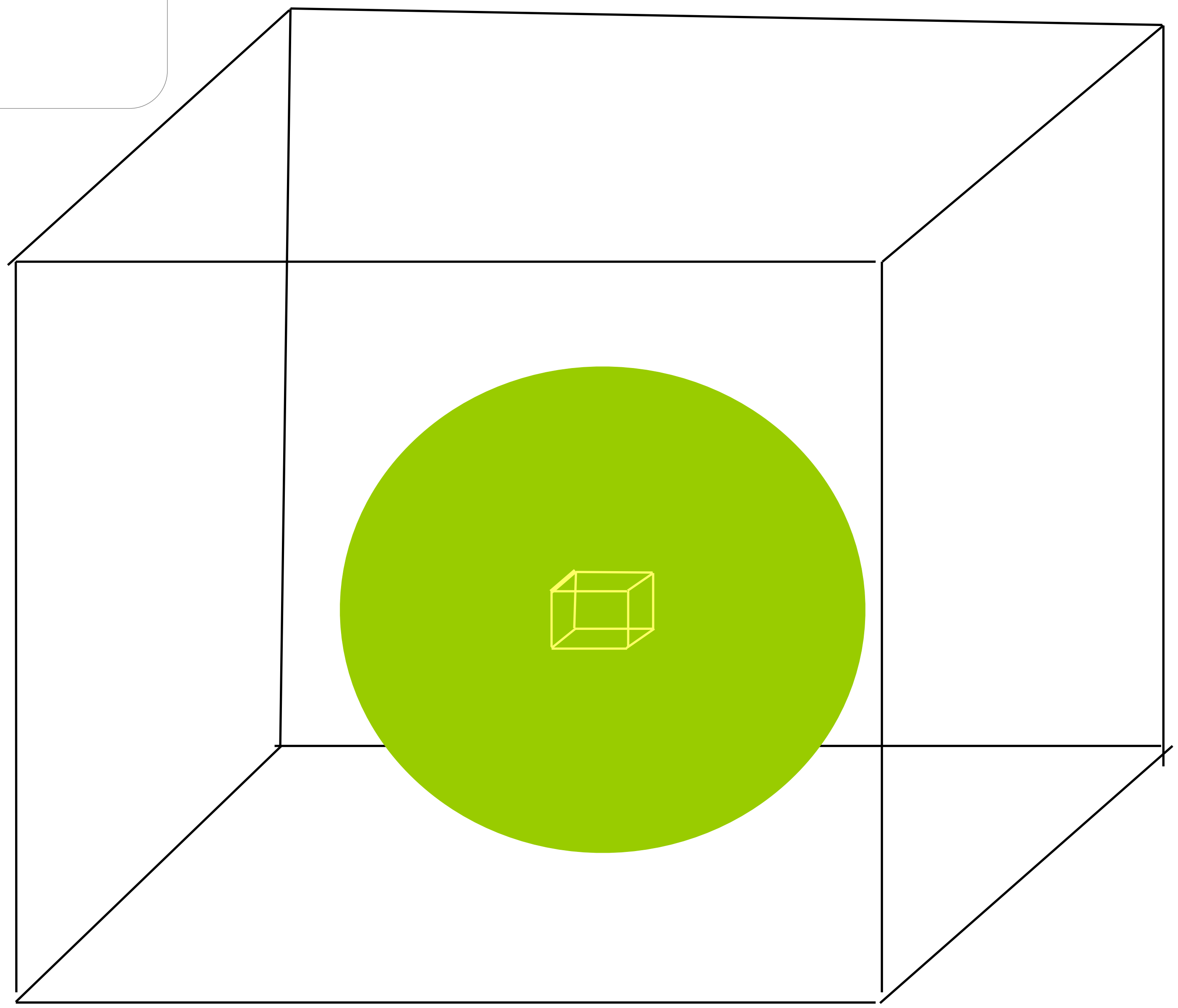
Observations at low redshift usually measure fesc~0.01 or less

Only a few galaxies were found with a large fest of the order of 6-13% (green pees)

The evolution of the ionization field: determining xi=$\langle n_{HII}/n_H \rangle$

Ionizing rate ≥ Recombination rate





Rate of recombinations

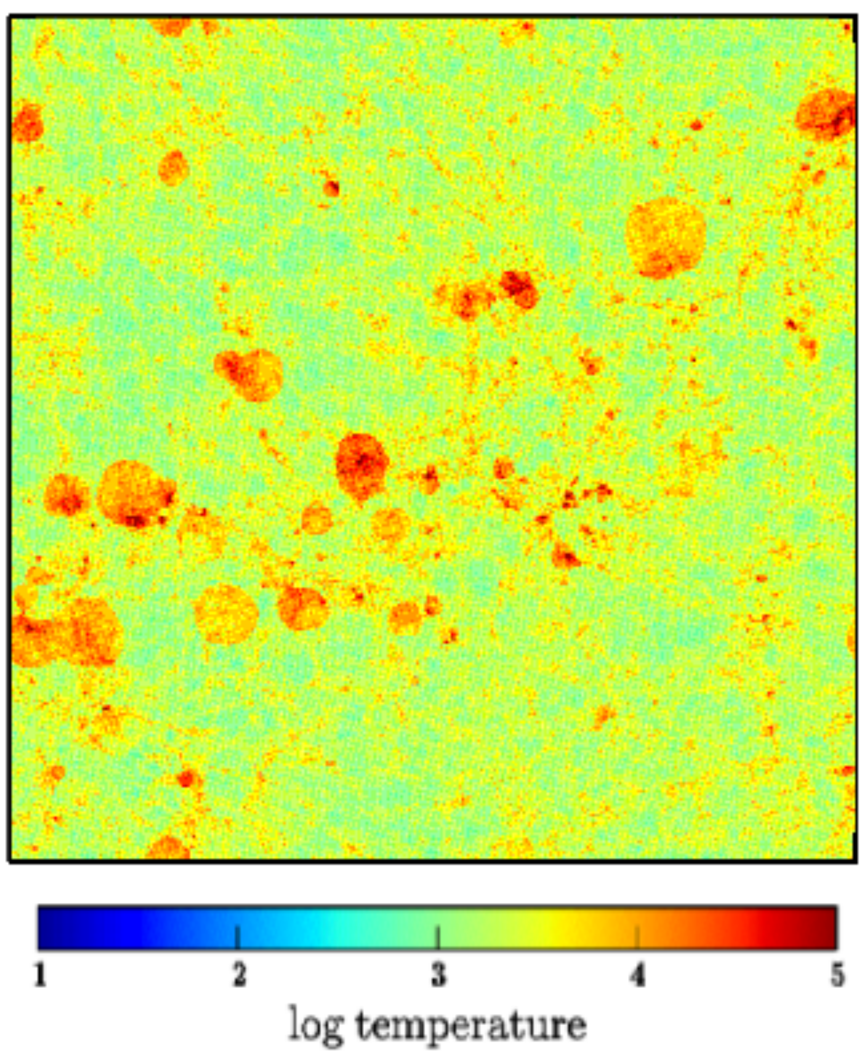
$$\dot{n}_{\rm rec} = \alpha_{\rm rec}(T_{\rm K}) \times C \times n_{\rm e} \times n_{\rm HII}$$

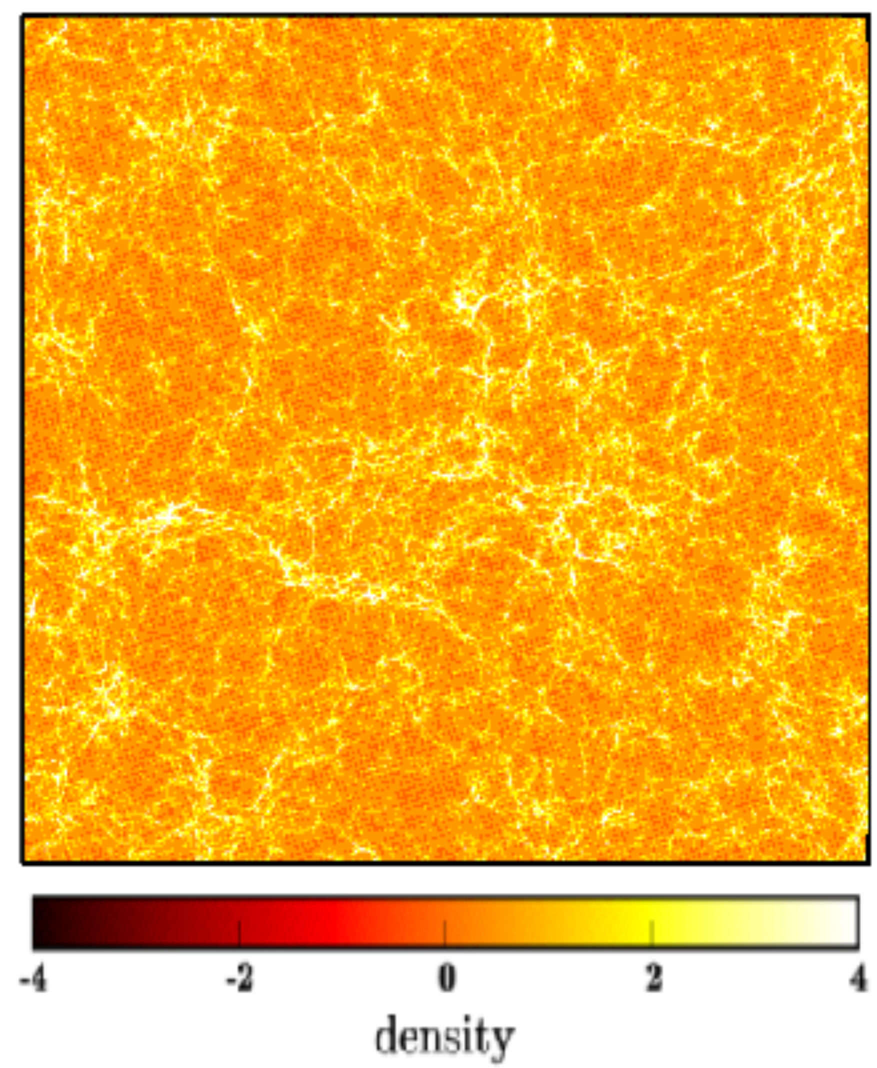
Recombination coefficient

IGM Clumping factor

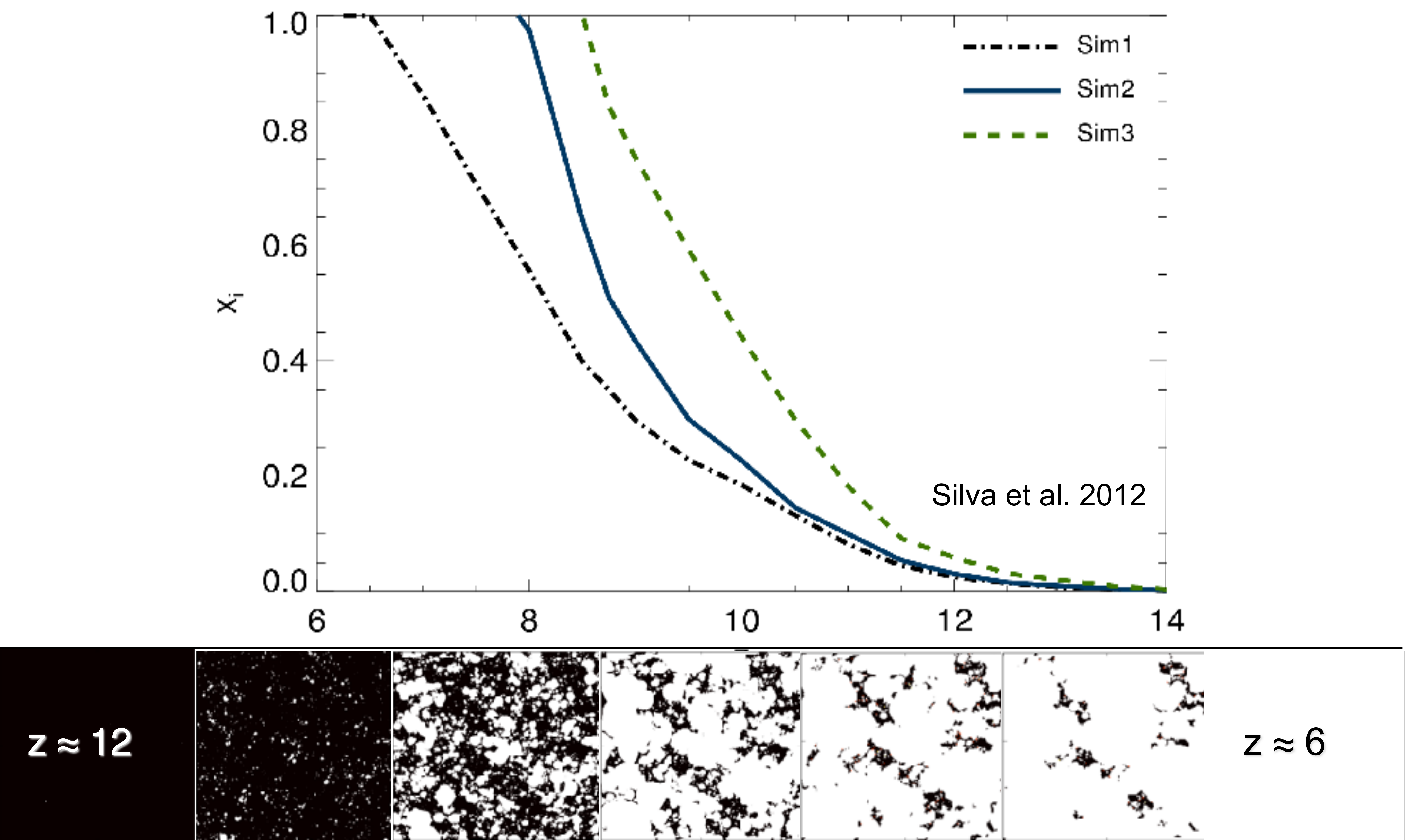
Nº density of free electrons

Nº density of HII

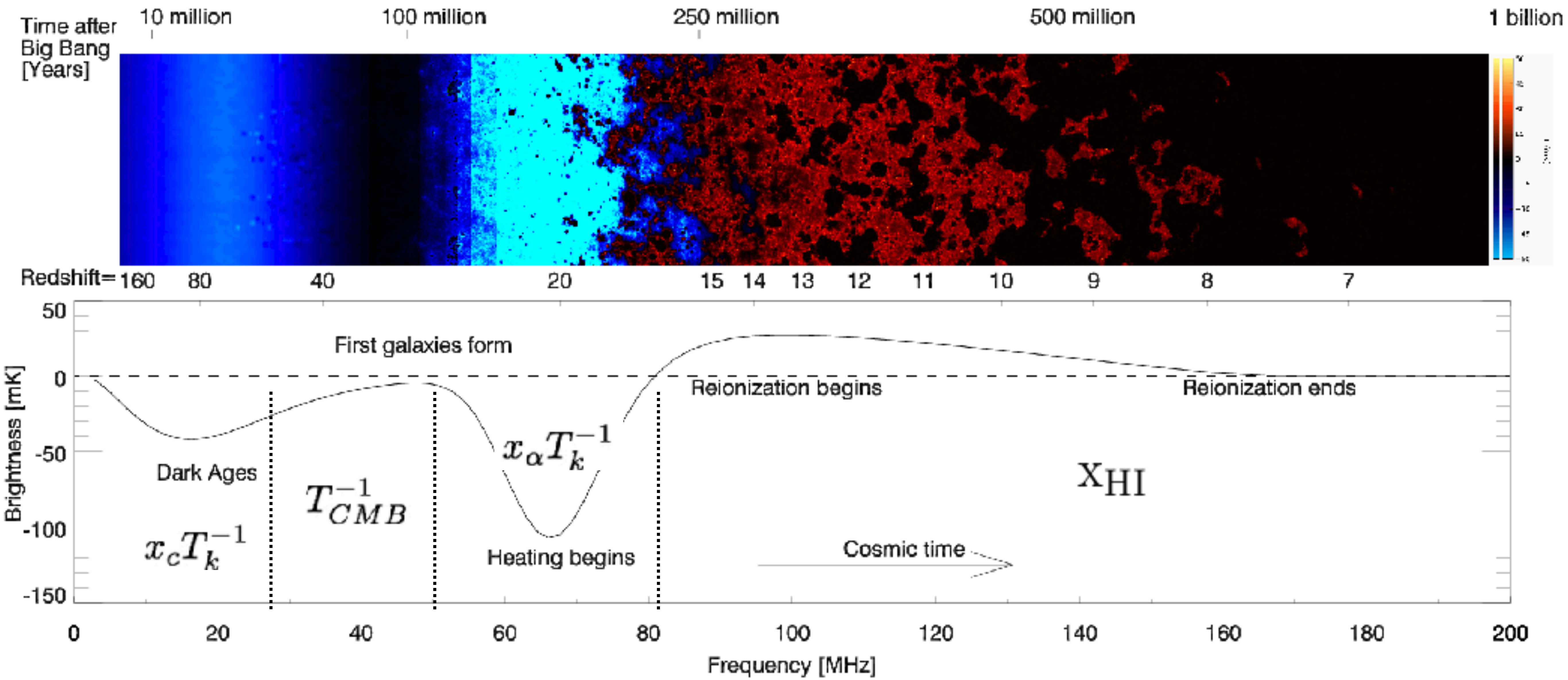




The evolution of the ionisation field



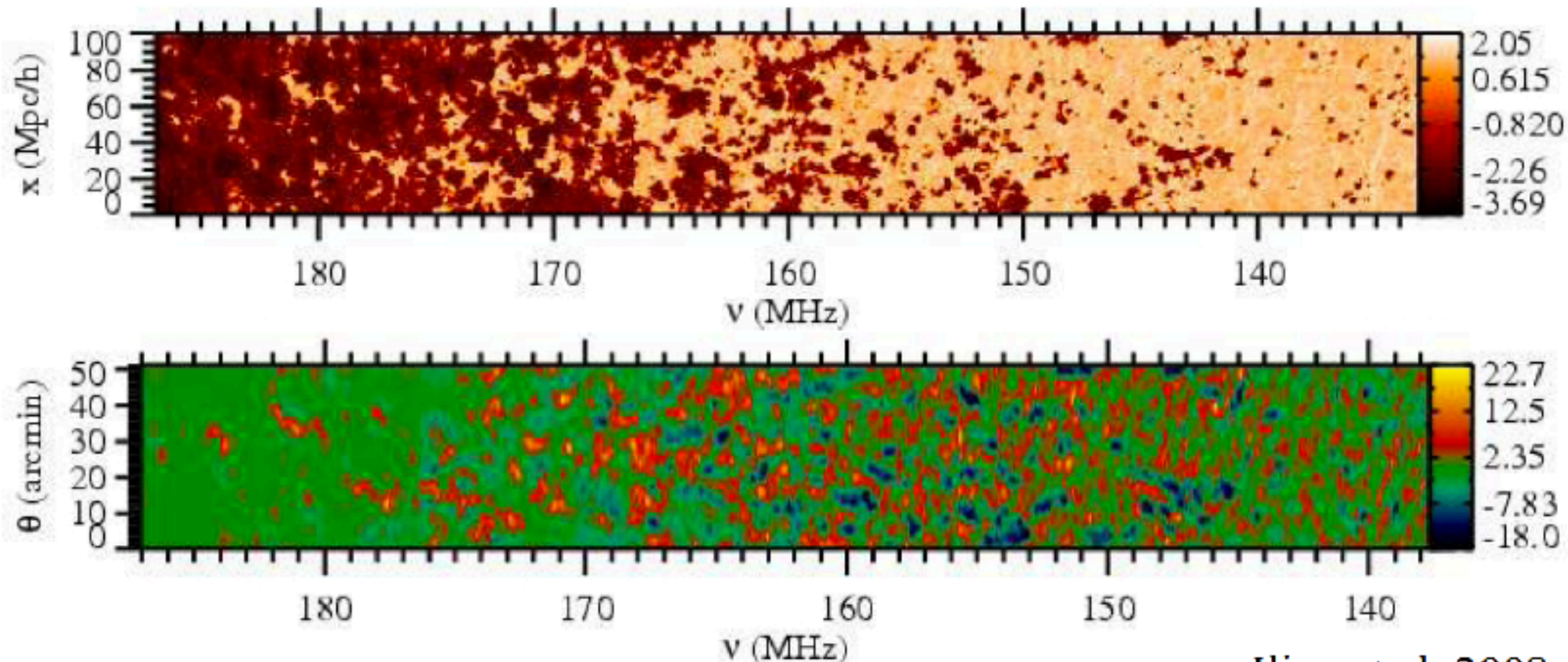
The evolution of the Tb



$$\delta T_b(z) = C(z)(1+\delta)\left(\frac{1}{1+H(z)dv_r/dr}\right) x_{HI}\left(\frac{T_S - T_{CMB}}{T_S}\right)$$

Simulations of the EoR

Results from 3D RT

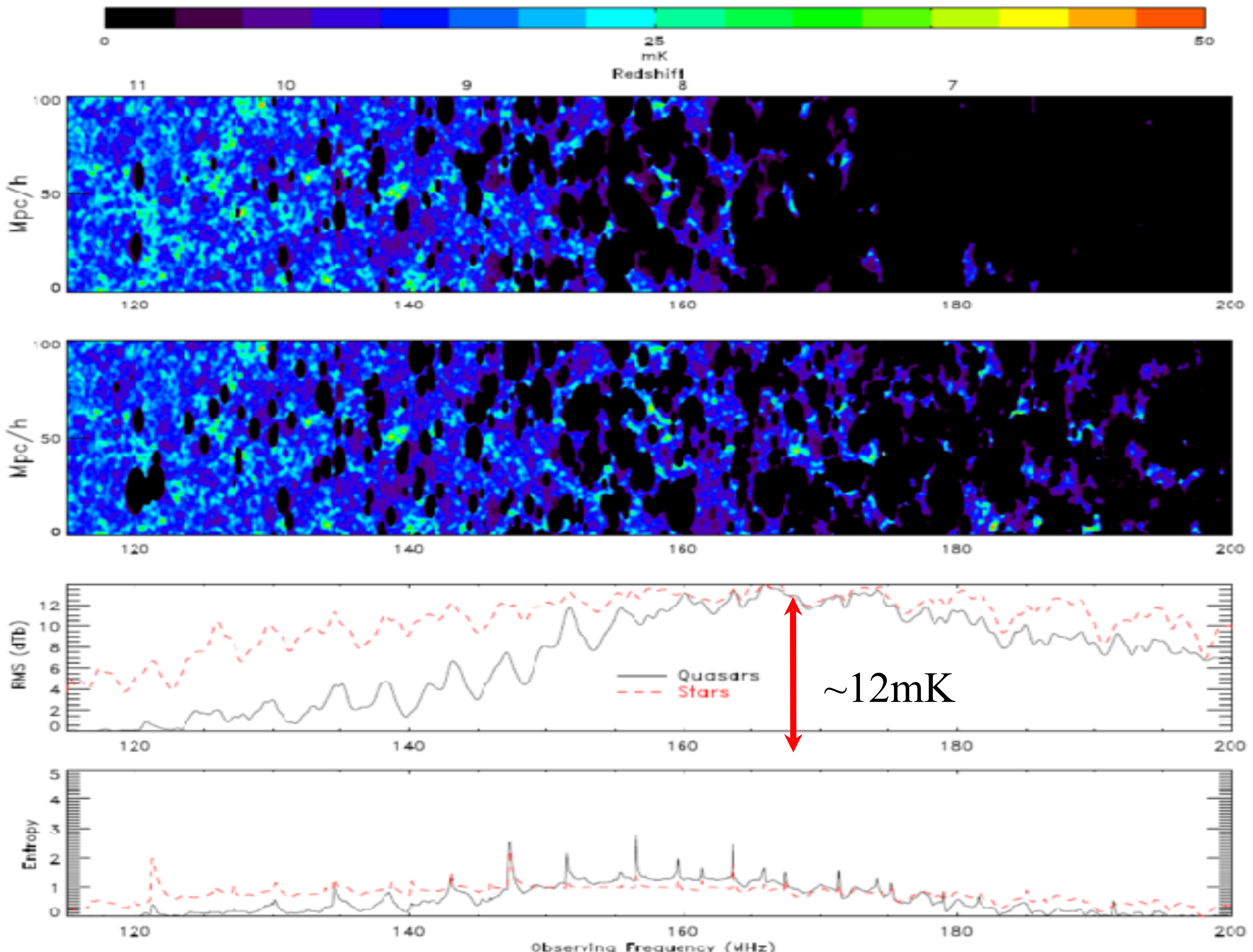


Iliev et al. 2008

At half ionization the signal rms is about 8mK

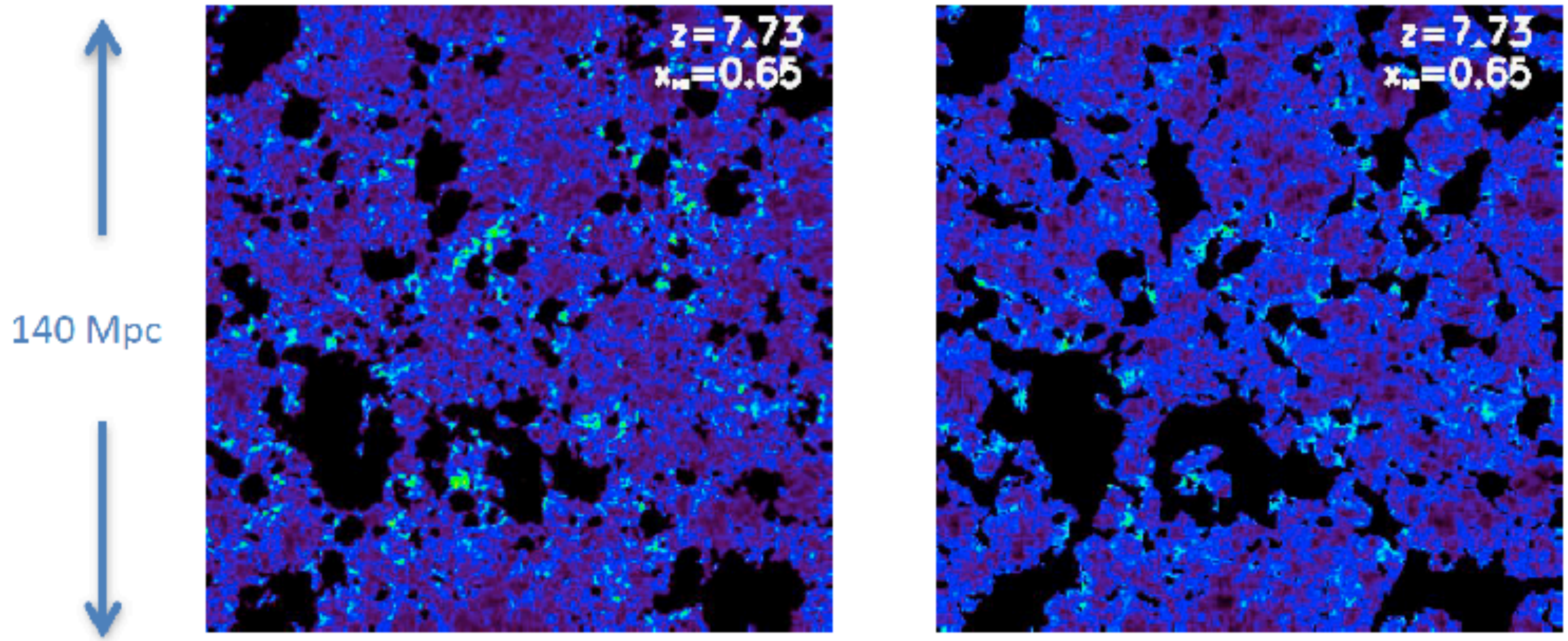
$$\delta T_b \approx 28\mathrm{mK}\,(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Semi-numerical simulations



Thomas & zaroubi 2008

Full vs. approximate simulations



~ 1 week on 1536 cores

~ few min on 1 core

e.g. Mesinger+2011 (also Zahn+2007; Furlanetto&AM2007; Santos+2011)

Uses:

- quickly explore the large astrophysical parameter space
- easily create mock data-sets for large FoV cosmological observations (e.g. 21-cm)

From theory to observations

How can we image reionization?

Line Intensity Mapping

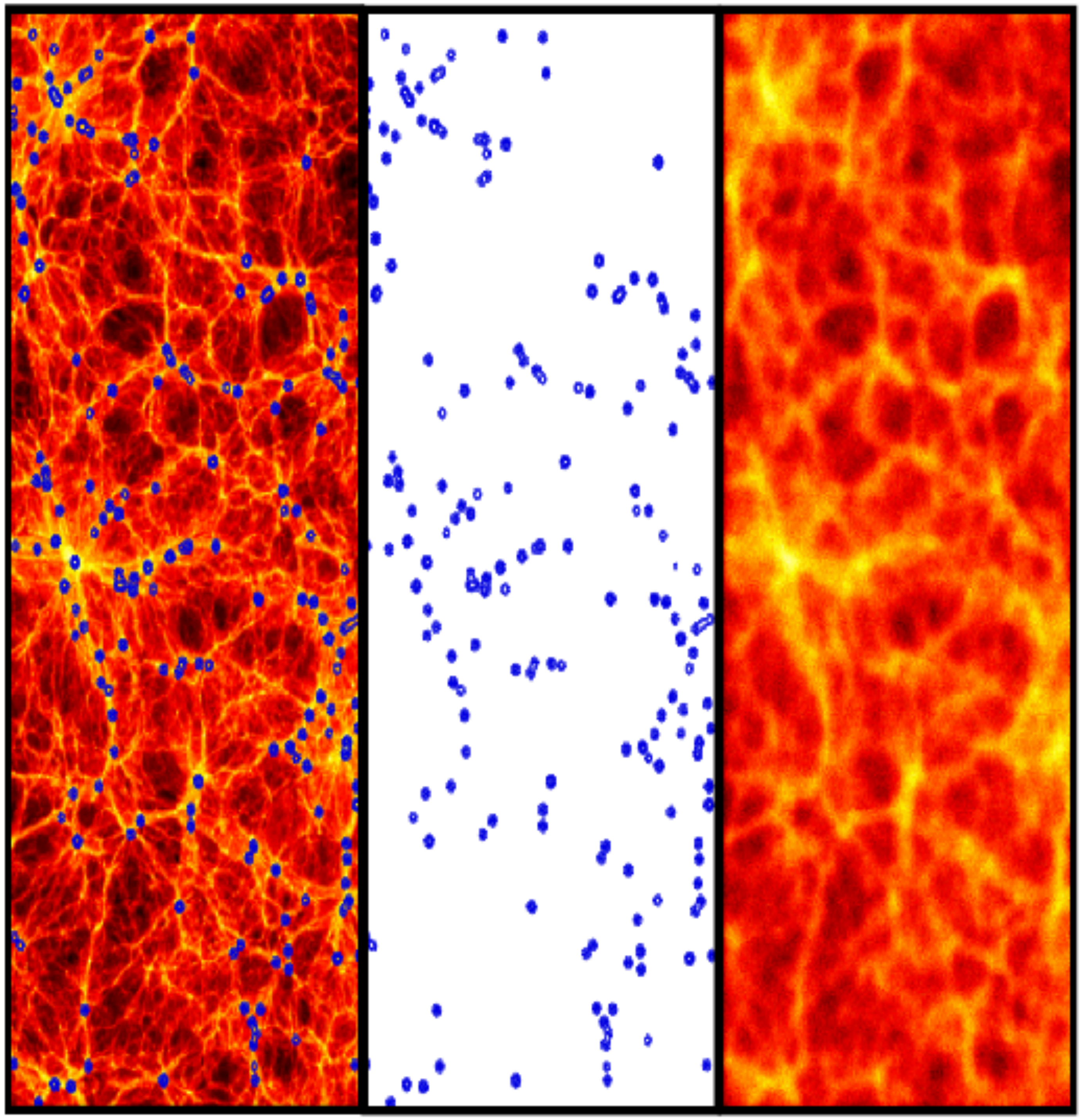
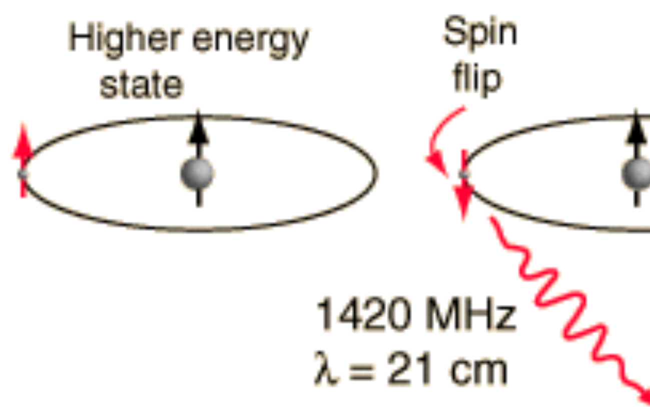
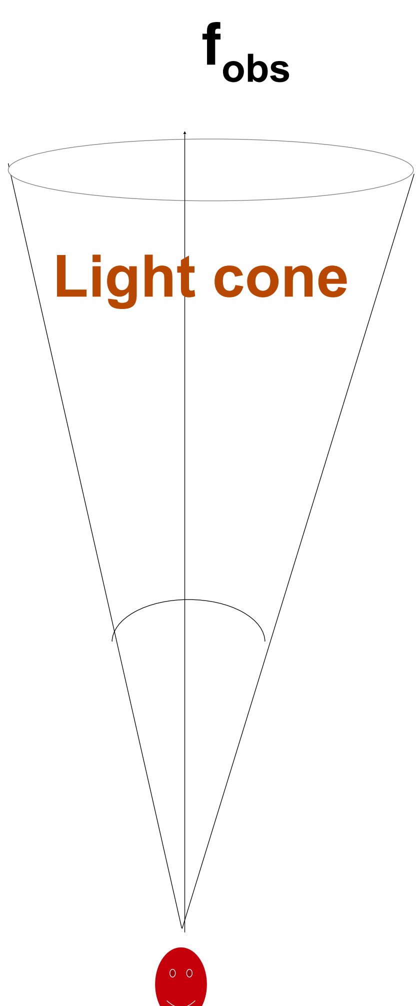


Image from
Dore & Bock 2014

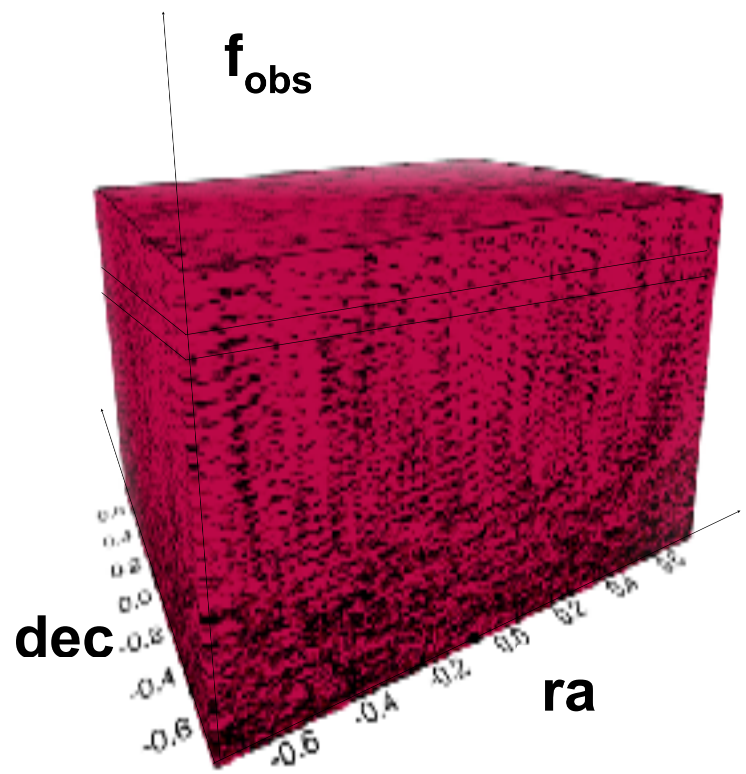
The intensity mapping technique



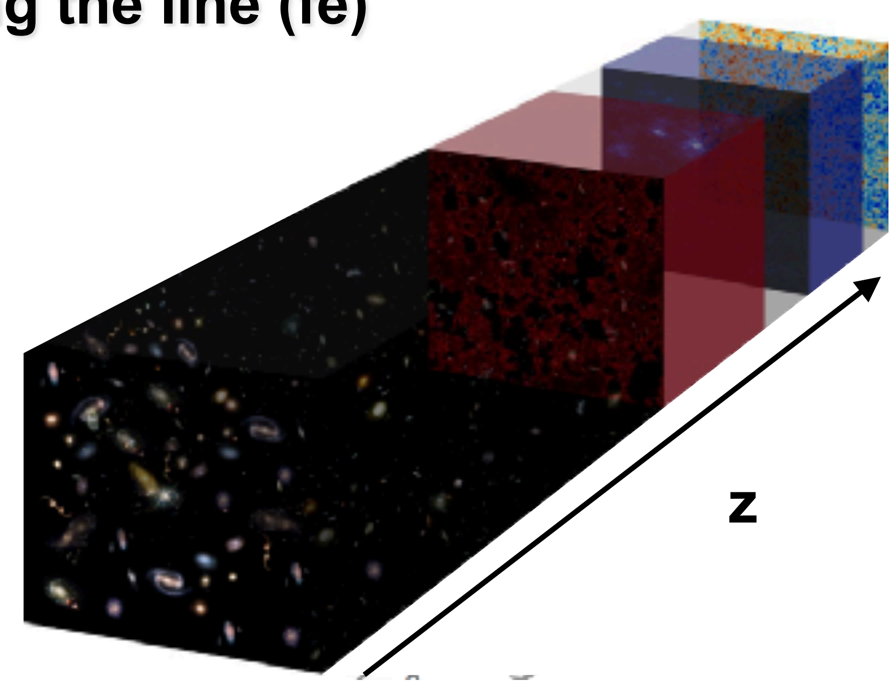
$$f_{\rm obs} = \frac{f_{\rm e}}{1+z}$$



Ex: f_{obs}=(70-90)MHz



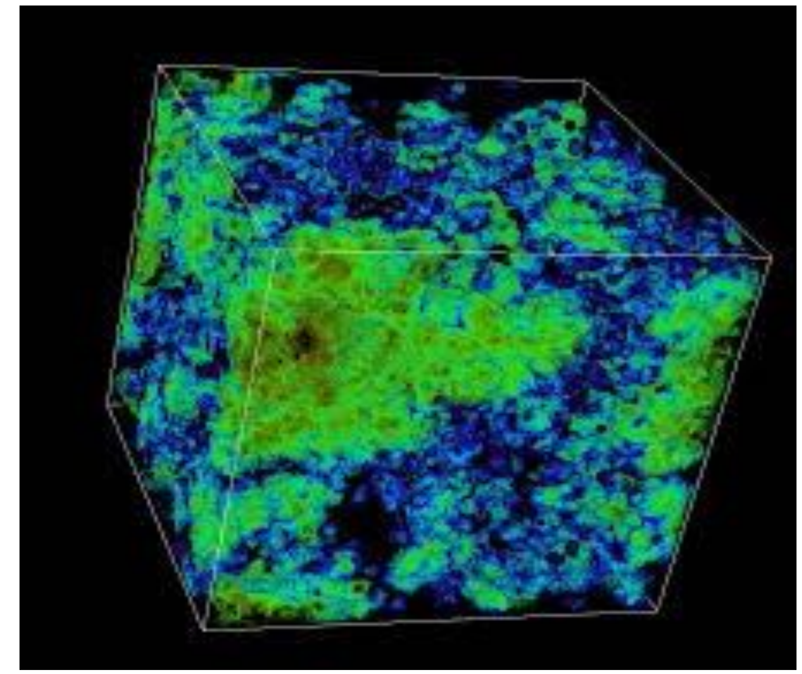
Fixing the line (fe)



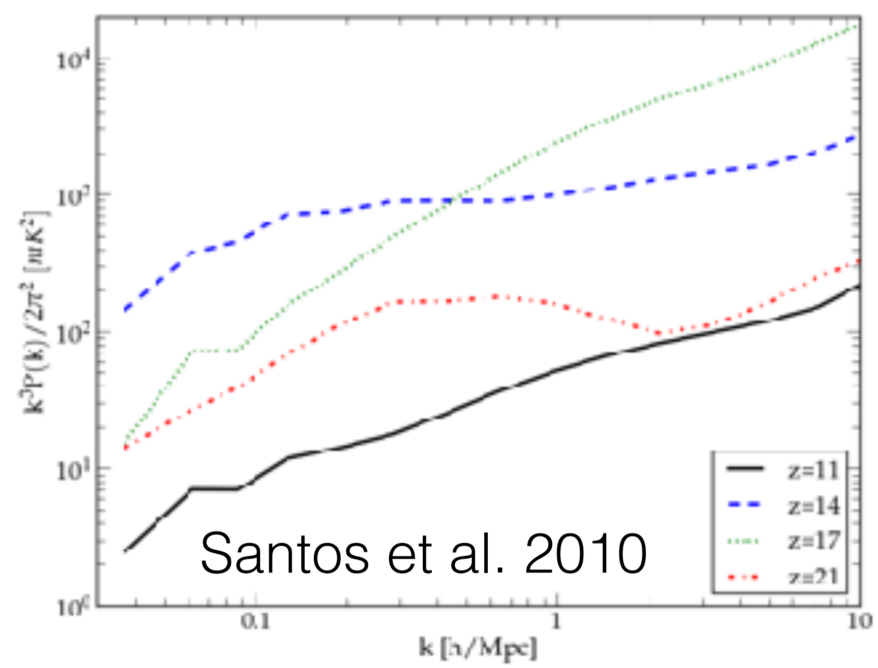
For f_e: 1420MHz it correspondents to:16 < z < 20

The Line-IM Technique

- **Integrated line intensity**
  - Detects emission from faint sources
  - Redshift information
- **High volumes / low resolution**
  - Fast
- **Constraints on:**
  - Cosmology
  - Global astrophysical quantities



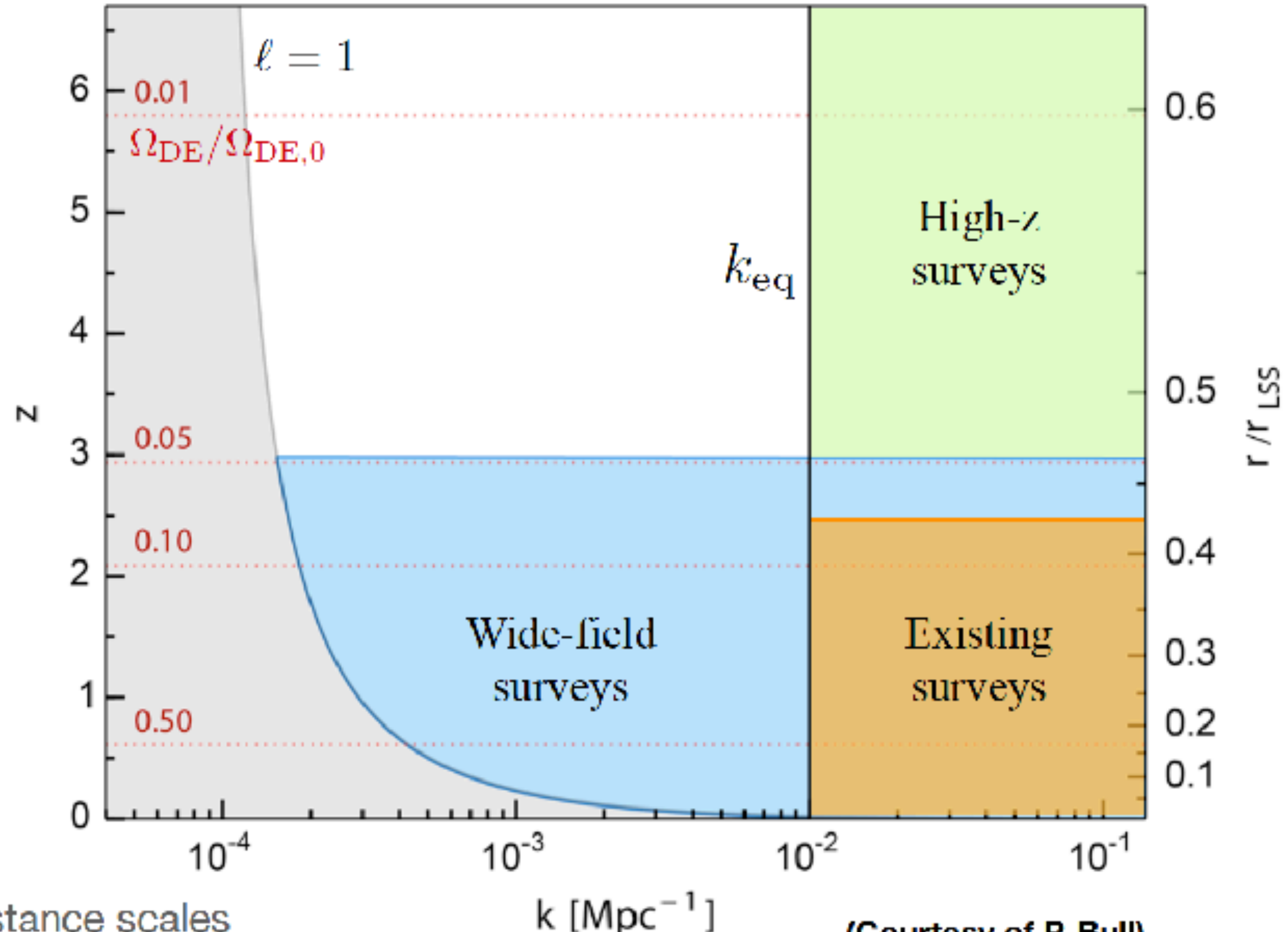
CEA-Irfu



- High S/N ➜ Tomography
- Low S/N ➜ Statistical detection
  (no need to be well above noise)

The reach of future surveys

LIM is highly competitive with galaxy surveys on *large scales* and at *high redshift*!



(Courtesy of P. Bull)

- horizontal: distance scales
- vertical: redshift / distance to LSS.

Power spectrum of line-intensity fluctuations

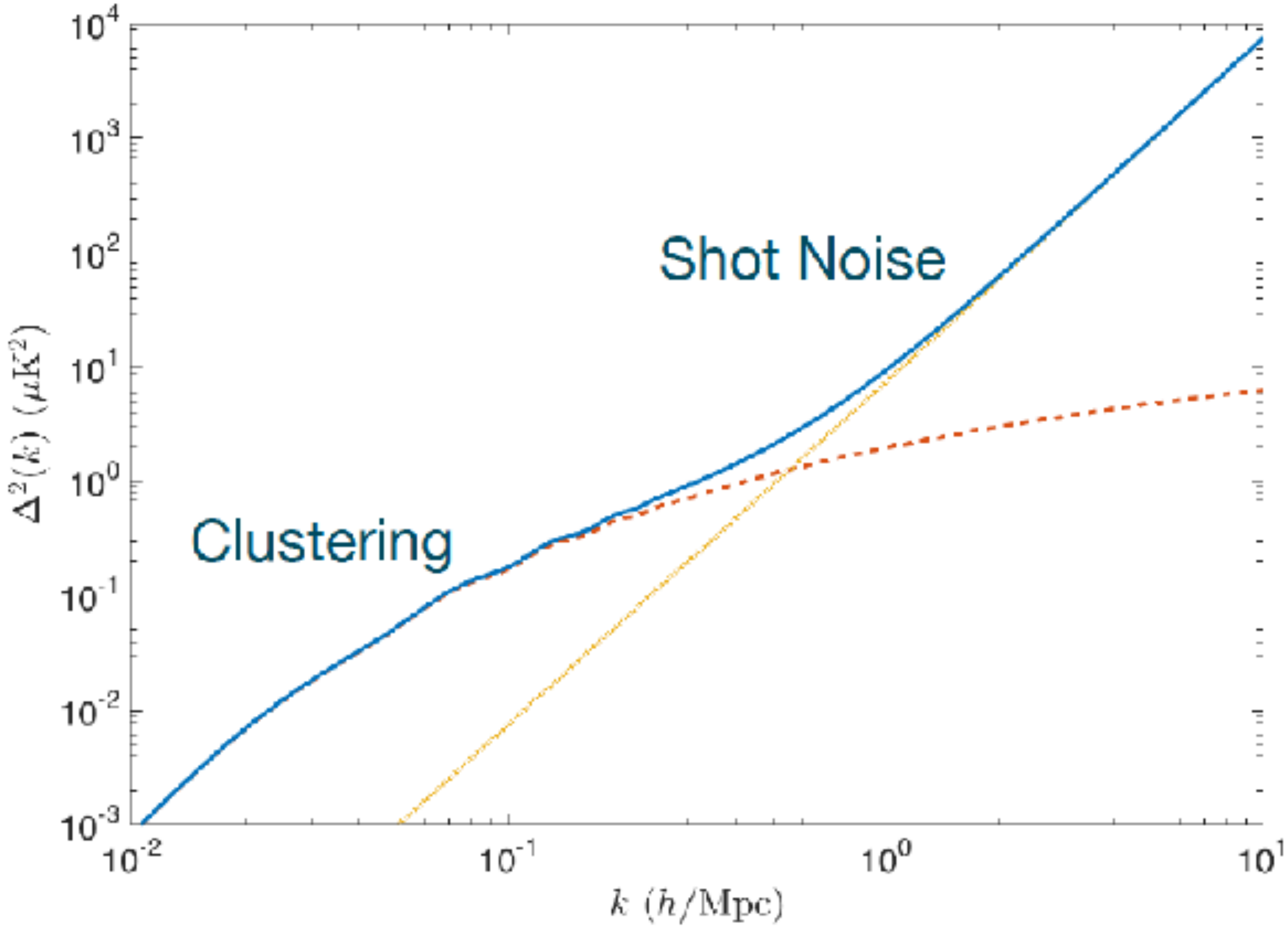
$$P_{\rm line}(k,z) = \langle I_{\rm line}(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

Luminosity function

$$\langle I_{\rm line}(z)\rangle \propto \int L \frac{dn(z)}{dL} dL$$

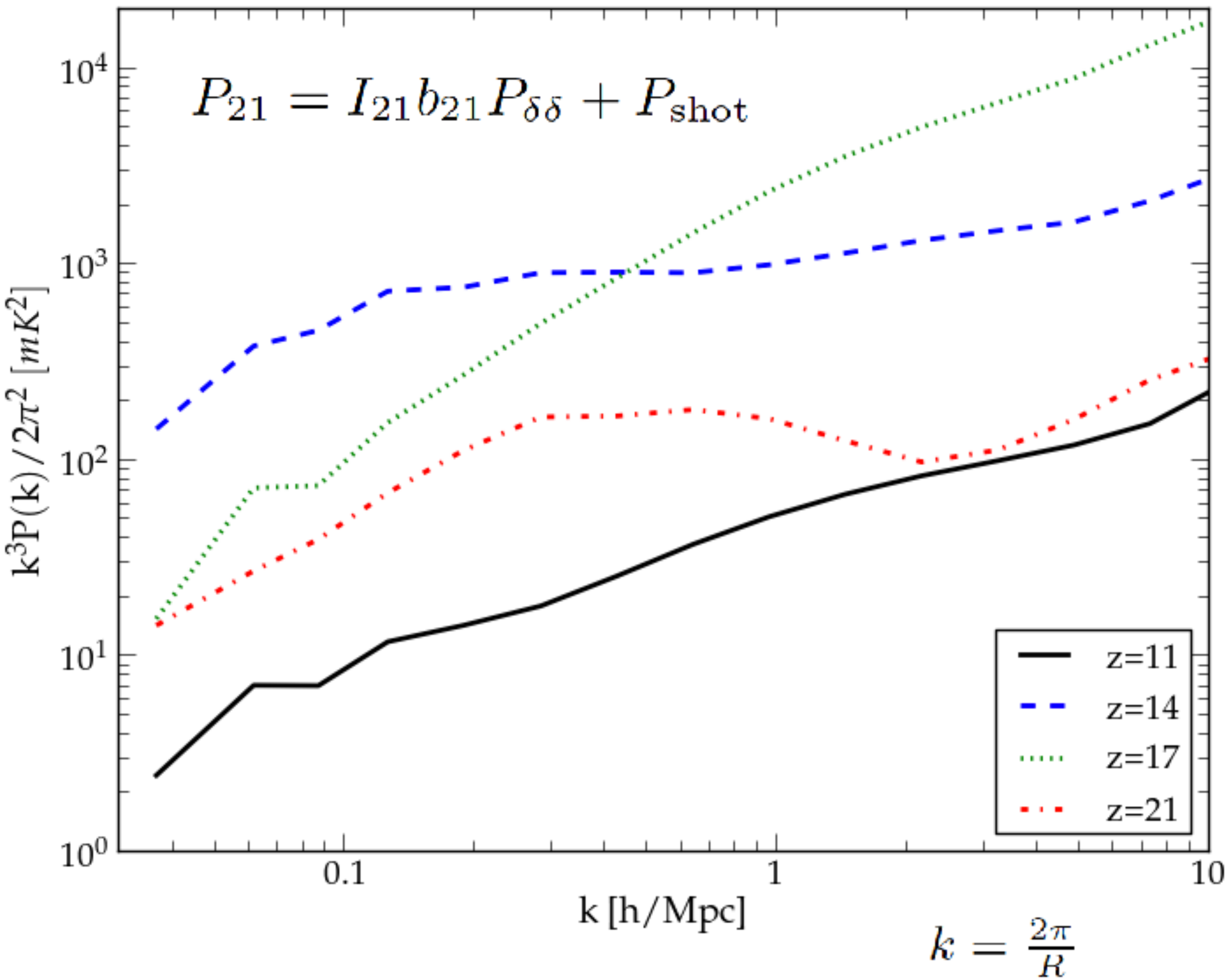
$$P_{\rm shot}(z) \propto \int L^2 \frac{dn(z)}{dL} dL$$

$$k = \frac{2\pi}{R}$$

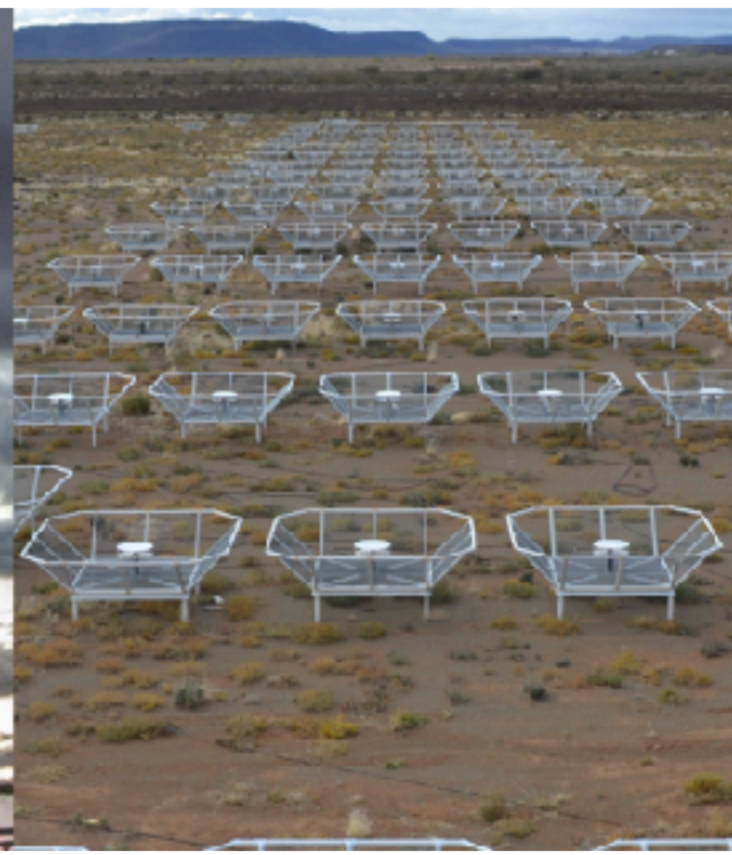


(Credit: Ely Kovetz)

The Power spectra of the 21 cm line



21cm line IM surveys

Hera — **South Africa**

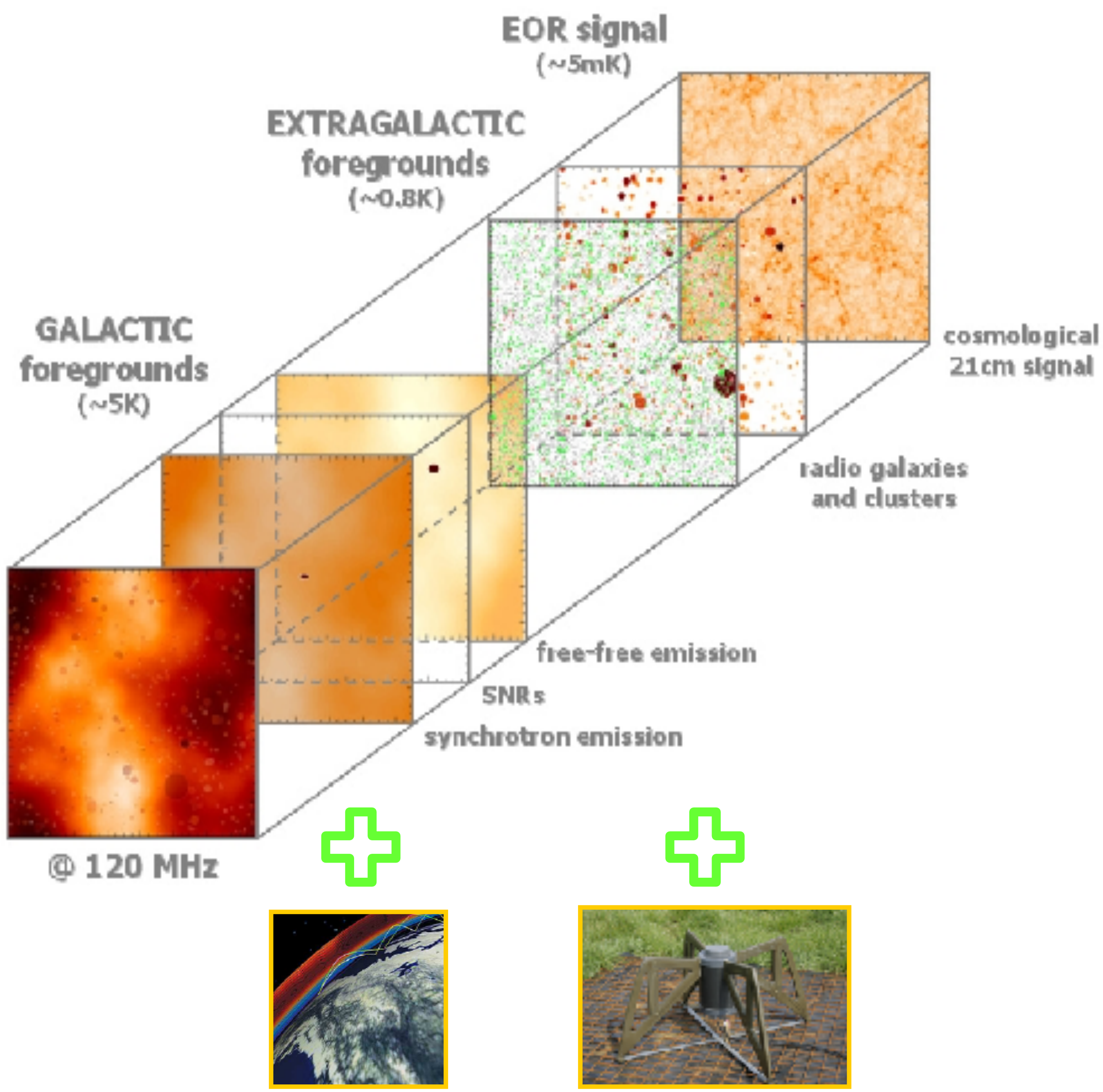
Paper — **South Africa + USA**

MWA — **USA**

Lofar — **Europe**

Future ➜ SKA in Australia

Measuring Redshifted HI: Challenges

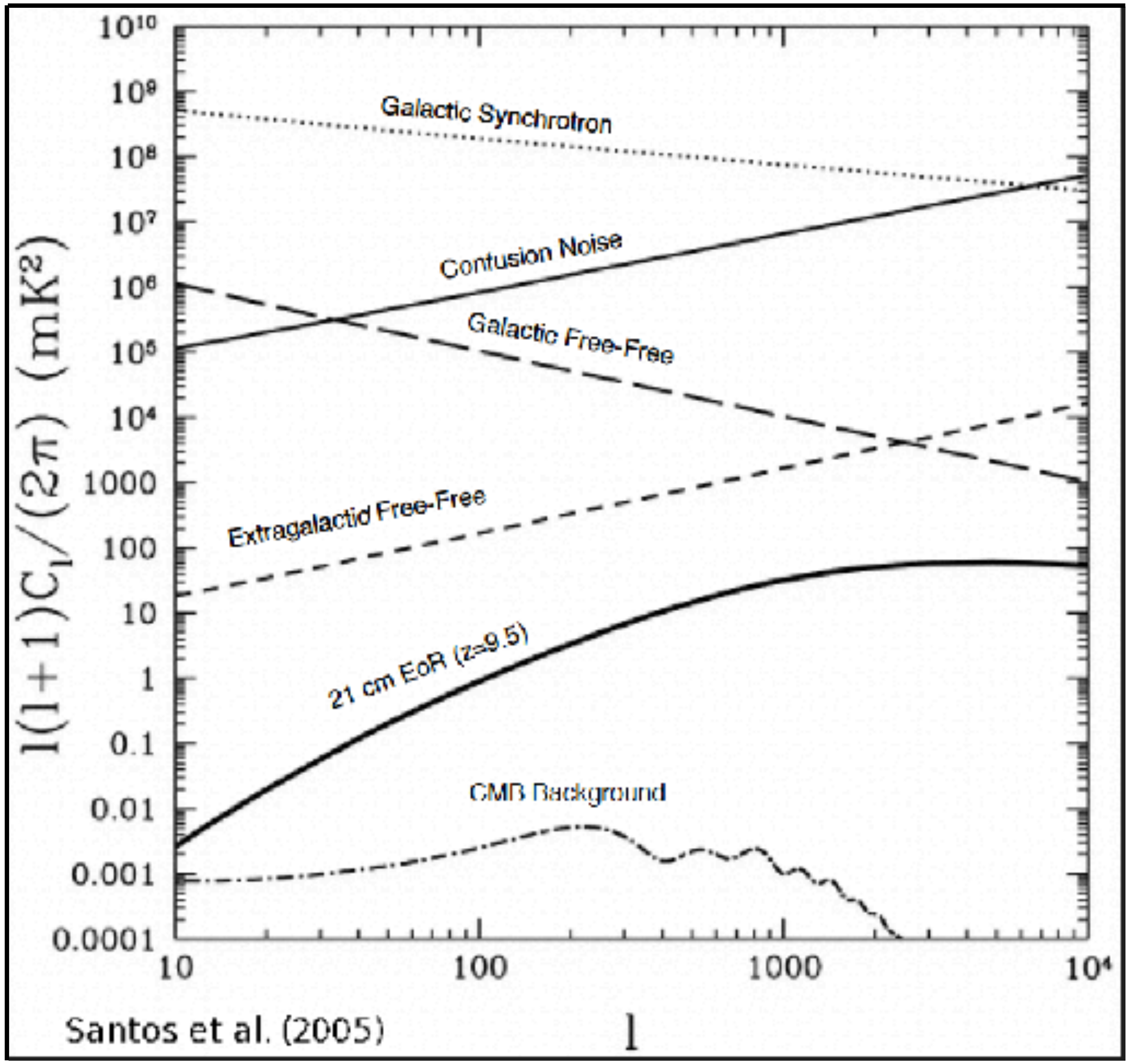


1. Astrophysical Challenges
   1. Foregrounds: total intensity
   2. Foregrounds: polarized
   3. Ionosphere
   4. Etc.
2. Instrumental challenges
   1. Beam stability
   2. Calibration
   3. Resolution
   4. uv coverage
   5. Etc.
3. Computational challenges
   1. Multi petabyte data set
   2. Calibration
   3. inversion

Measuring Redshifted HI: Challenges

The Foregrounds are
9 orders of magnitude in mK^2

- 70% of the foregrounds are galactic.
  - Synchrotron (the most dominant)
  - Diffuse Bremsstrahlung
  - Individual supernovae remnants
- 30% Extra-galactic
  - Radio galaxies
  - Radio clusters



The foregrounds are very complex across the sky but very smooth along the frequency

Extraction of the EoR Signal: The LOFAR case

@150 MHz, 3arcmin

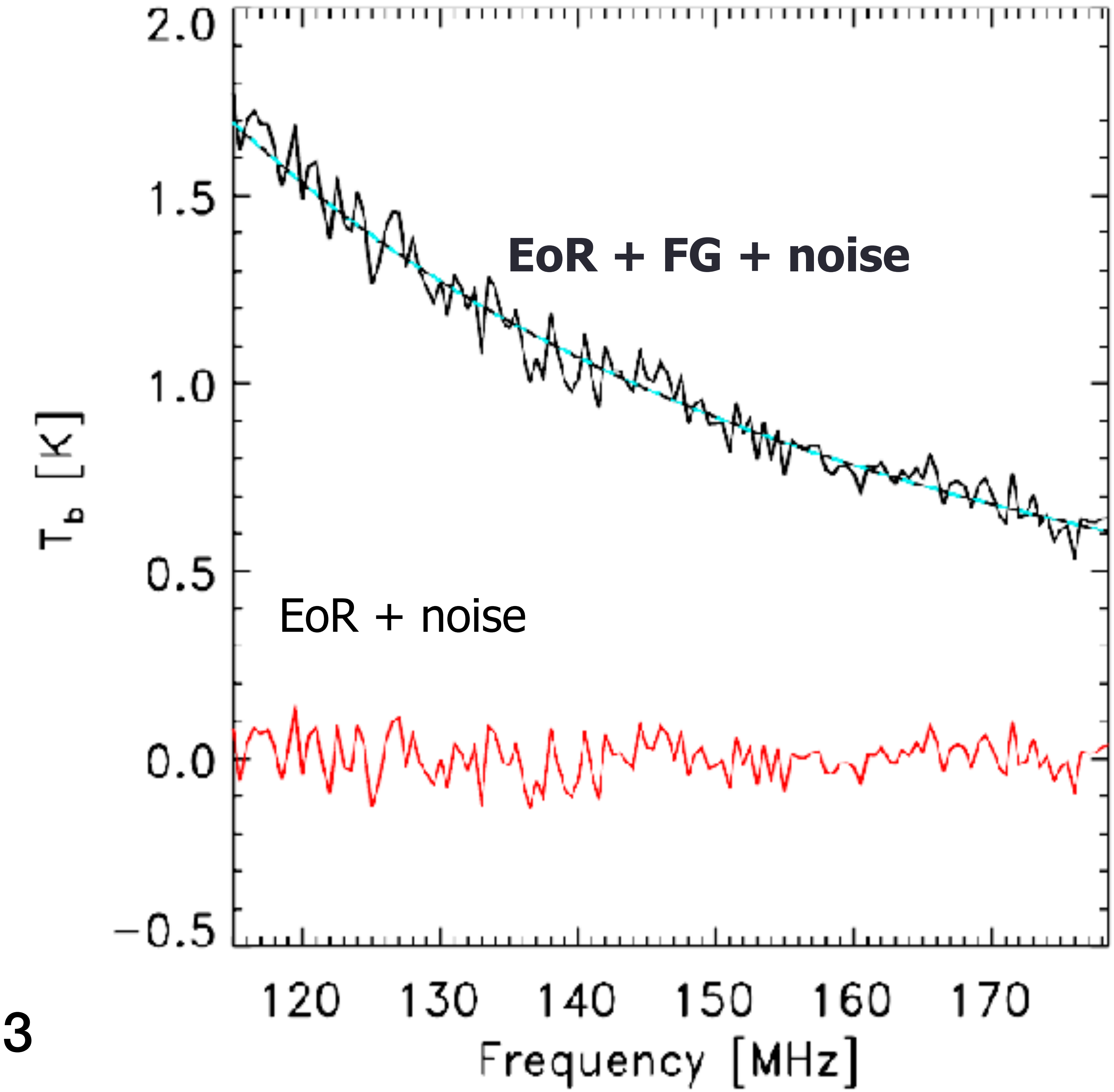
T_{EoR} ~ 5 mK

T_{FG} ~ 2 K

T_{noise} ~ 78 mK

Parametric fitting
(polynomial fitting)
Jelic et al. 2008

Non-parametric fitting
(Wp smoothing, ICA,..)
Harker et al. 2009
Chapman et al. 2012,2013



Current (large) 21-cm Power-Spectrum Detection Experiments

Specs
- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- z = 8.1-9.2

Paciga et al. 2013

Specs:
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s, Decl.(J2000) = −30° 0′ 0″
- high-band of 30.72 MHz, centered at 182 MHz i.e. 6.2 < z < 7.5

Dillon et al. 2015

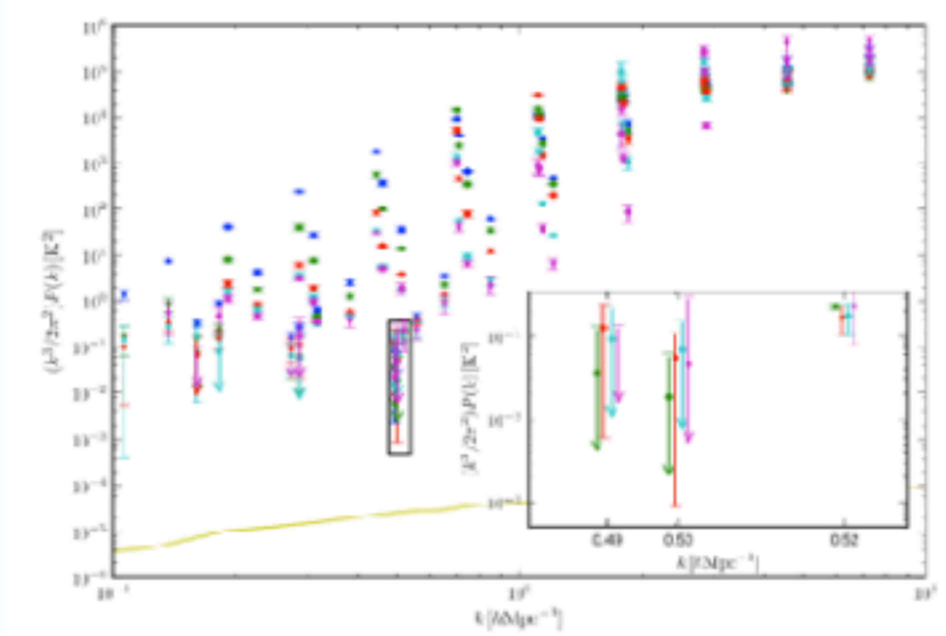
Specs:
- 1148 hrs of data (8/11/2012 to 23/3/2013)
- 100 to 200 MHz, 1024 chan
- visibility integr.: 10.7 seconds

Ali et al. 2015

Specs:
- 13 hrs of data; - Feb11/12 2013
- R.A.(J2000) = 0h 0m 0s, Decl.(J2000) = 90° 0′ 0″
- high-band of 115-189 MHz

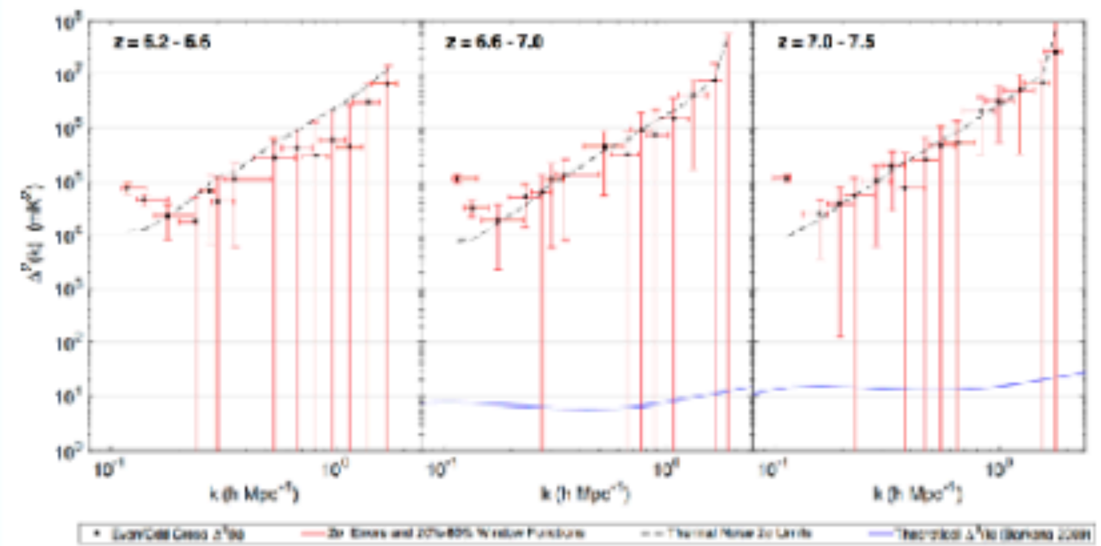
Patil et al. 2017

Current 21-cm Power-Spectrum Detection Experiments



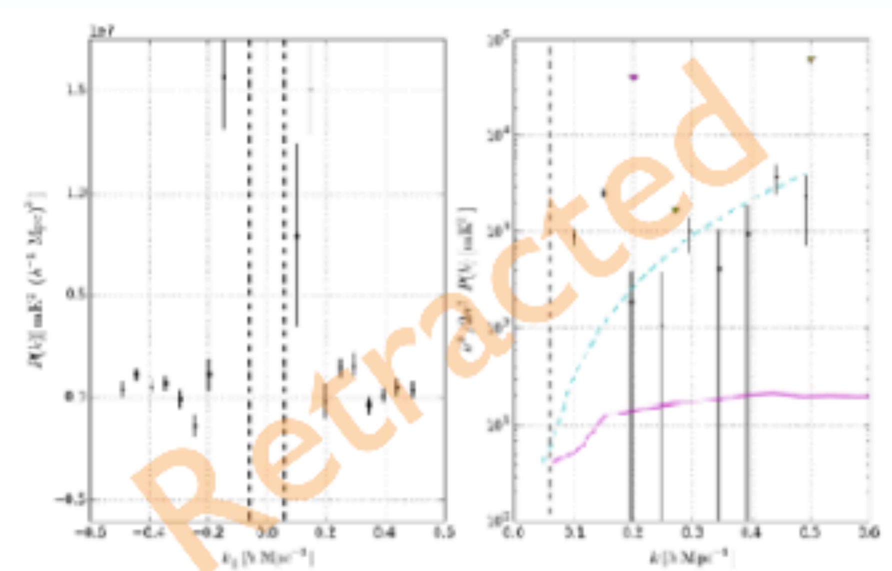
GMRT: Measurement of a 2σ upper limit of $\Delta(k) < 248$ mK for k = 0.50 h Mpc^{-1} at z = 8.6.

Paciga et al. 2013



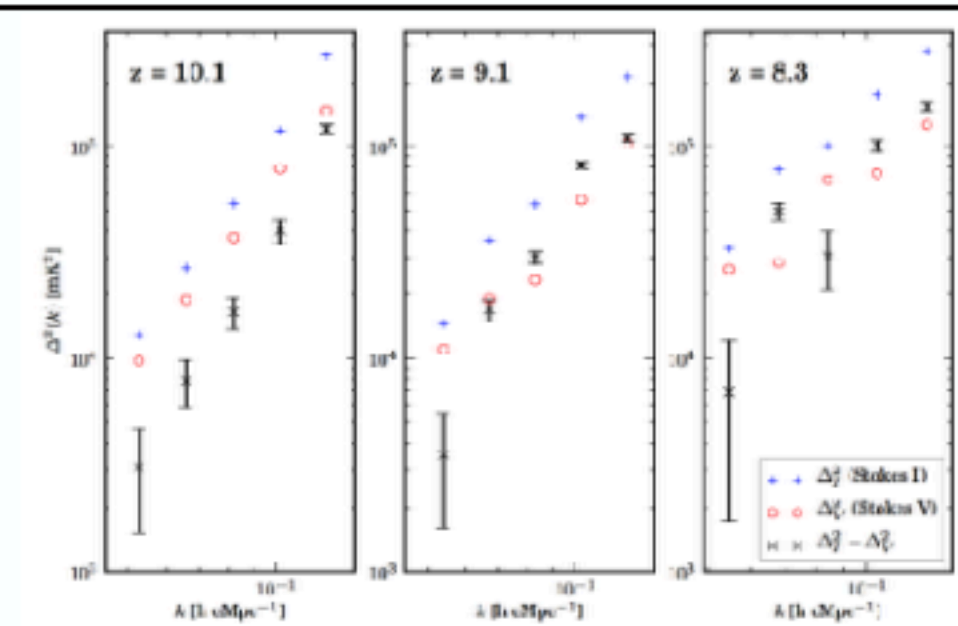
MWA-128T: Upper limits on the power spectrum from z = 6.2 to z = 7.5. The lowest limit is $\Delta(k) < 192$ mK at 95% confidence at a co-moving scale k = 0.18 Mpc^{-1} at z = 6.8.

Dillon et al. 2015



PAPER 64-antenna: A best 2σ upper limit of $\Delta(k) < 22$ mK for k = 0.15-0.5 h Mpc^{-1} at z = 8.4.

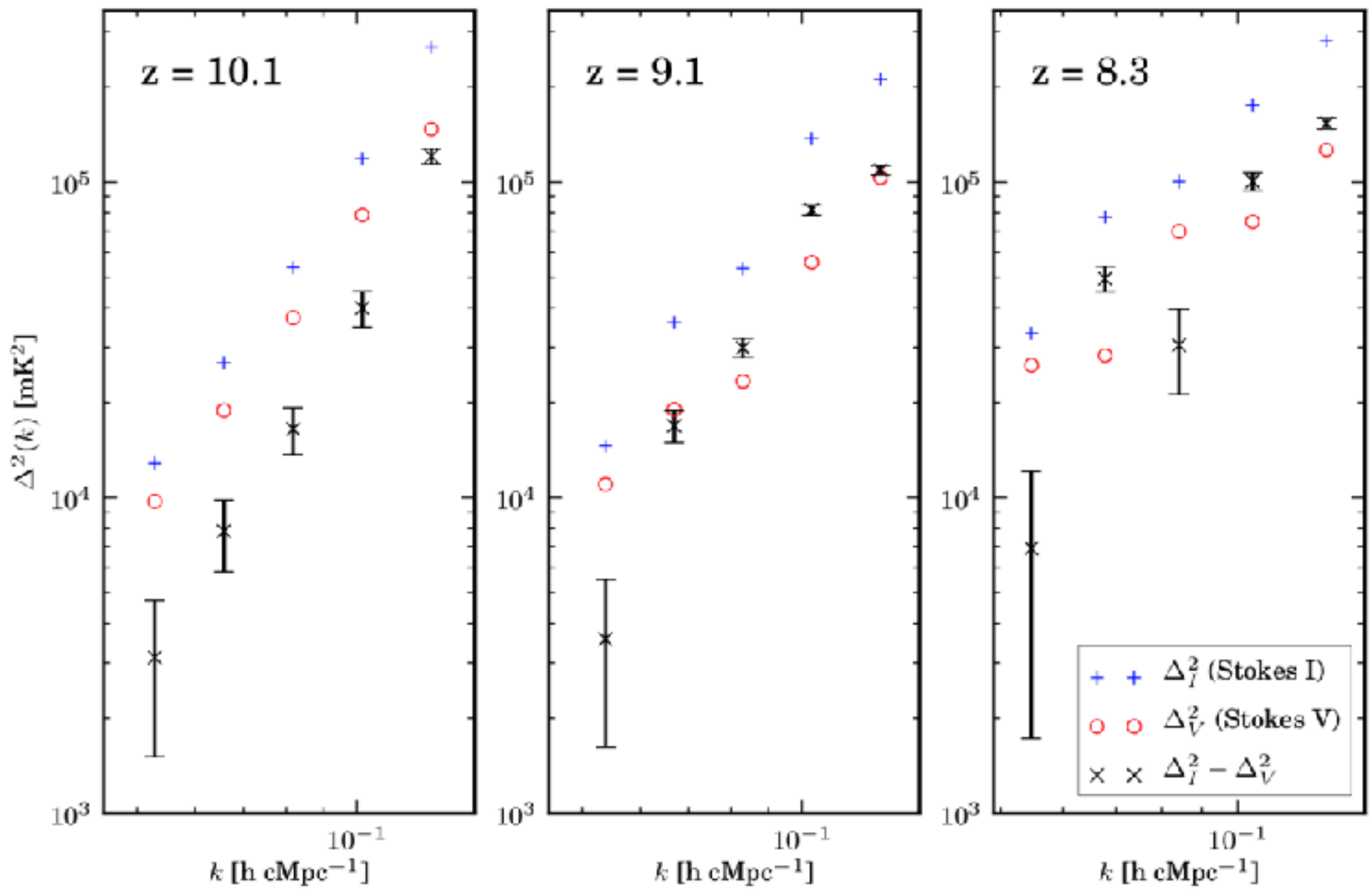
Ali et al. 2015



LOFAR: Measurement of a 2σ upper limit of $\Delta(k) < 80$ mK for k = 0.05 h Mpc^{-1} at z = 10.1.

Patil et al. 2017

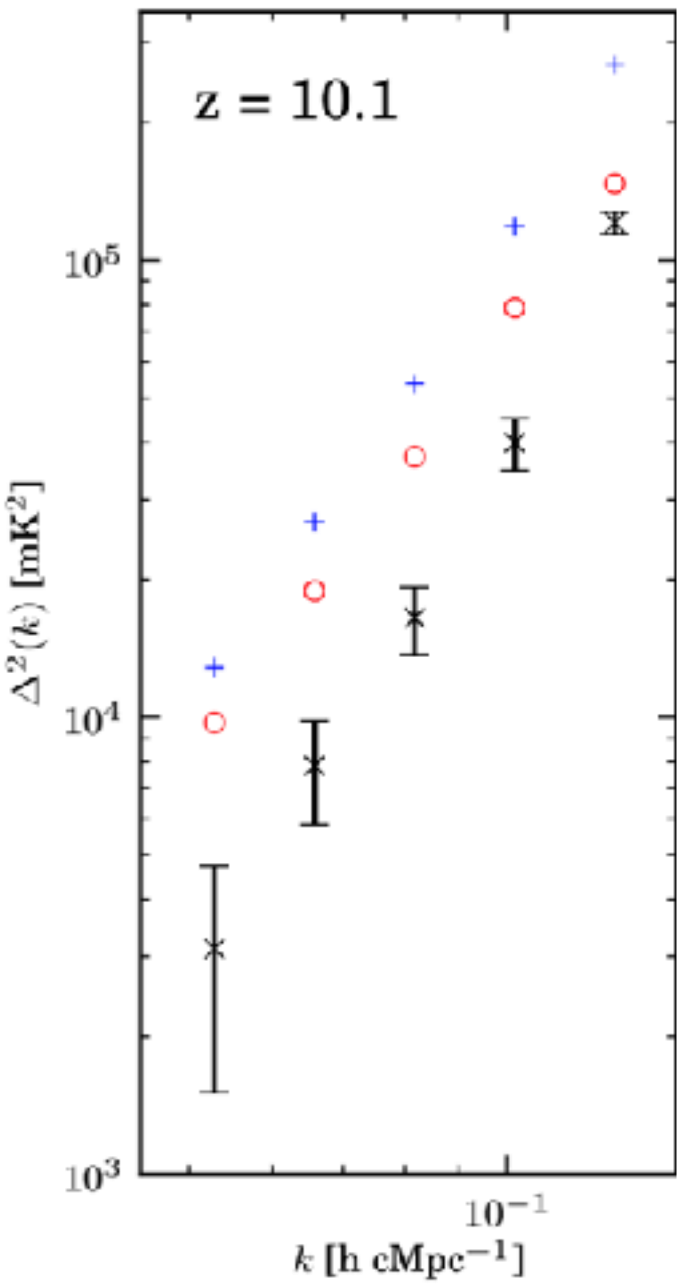
The LOFAR upper limit

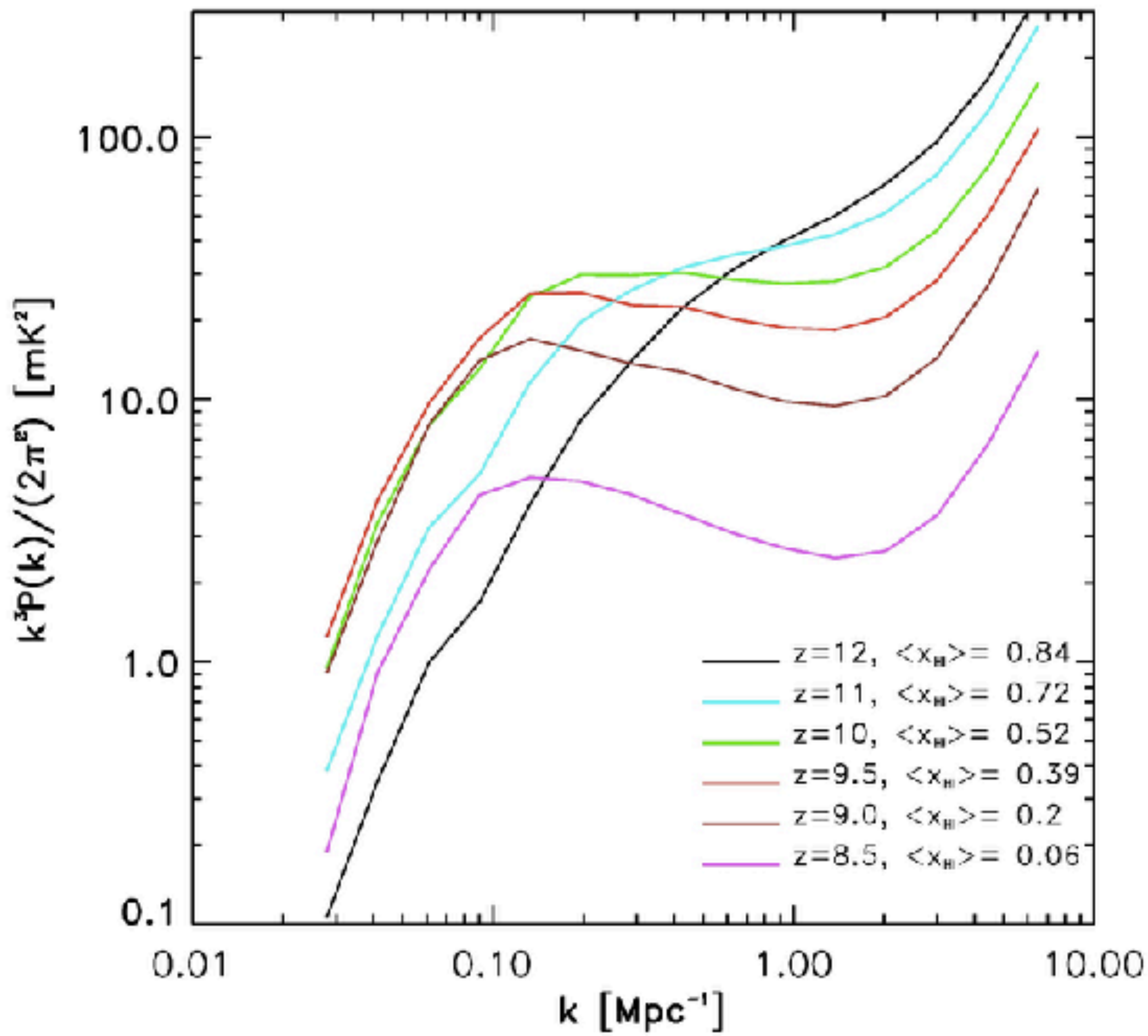


LOFAR: Measurement of a 2σ upper limit of $\Delta(k) < 80$ mK for $k = 0.05$ h Mpc^{-1} at $z = 10.1$.

Patil et al. 2017

The LOFAR upper limit





Patil et al. 2017

LOFAR: Measurement of a 2σ upper limit of

Δ(k) < 80 mK for k = 0.05 h Mpc^{-1} at z = 10.1.

The 21cm signal is highly non-Gaussian

Using only the power spectrum wastes a lot of information!!!

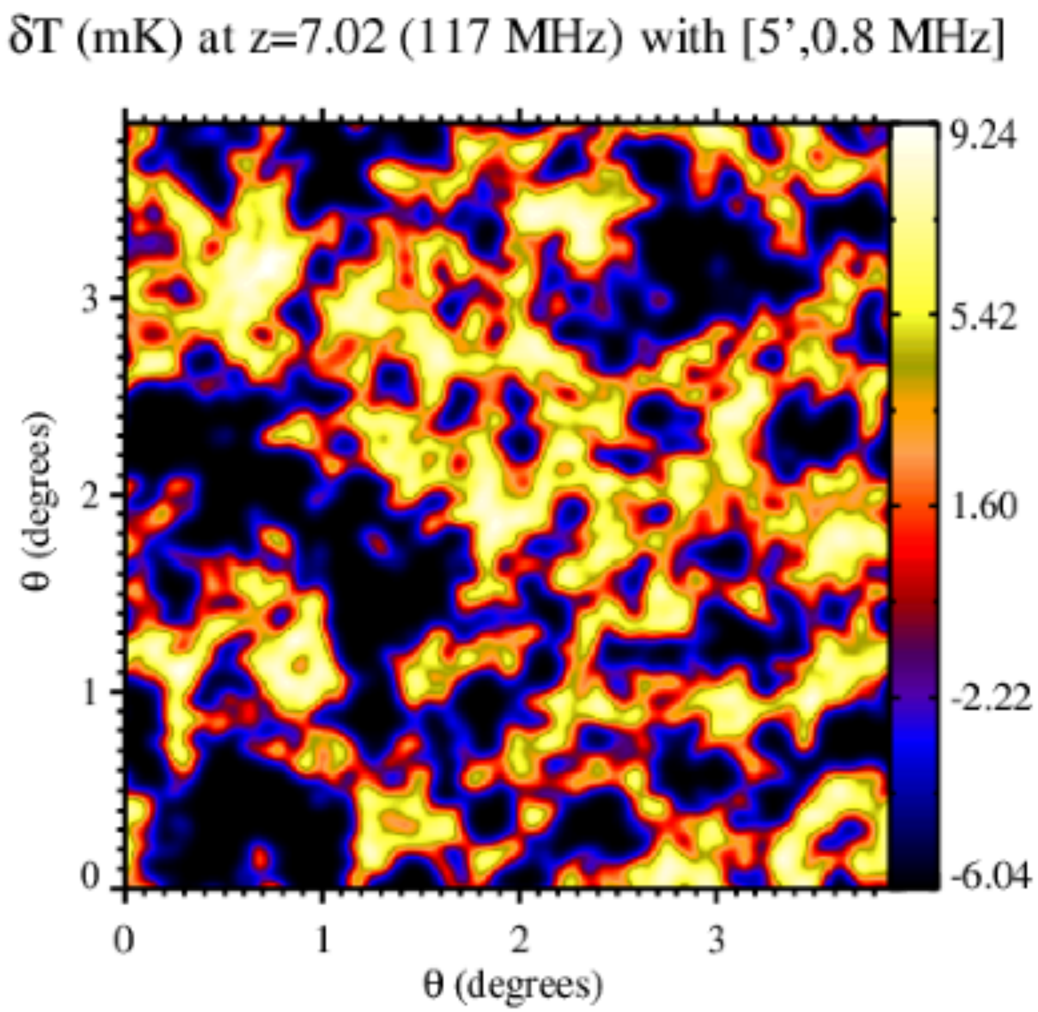
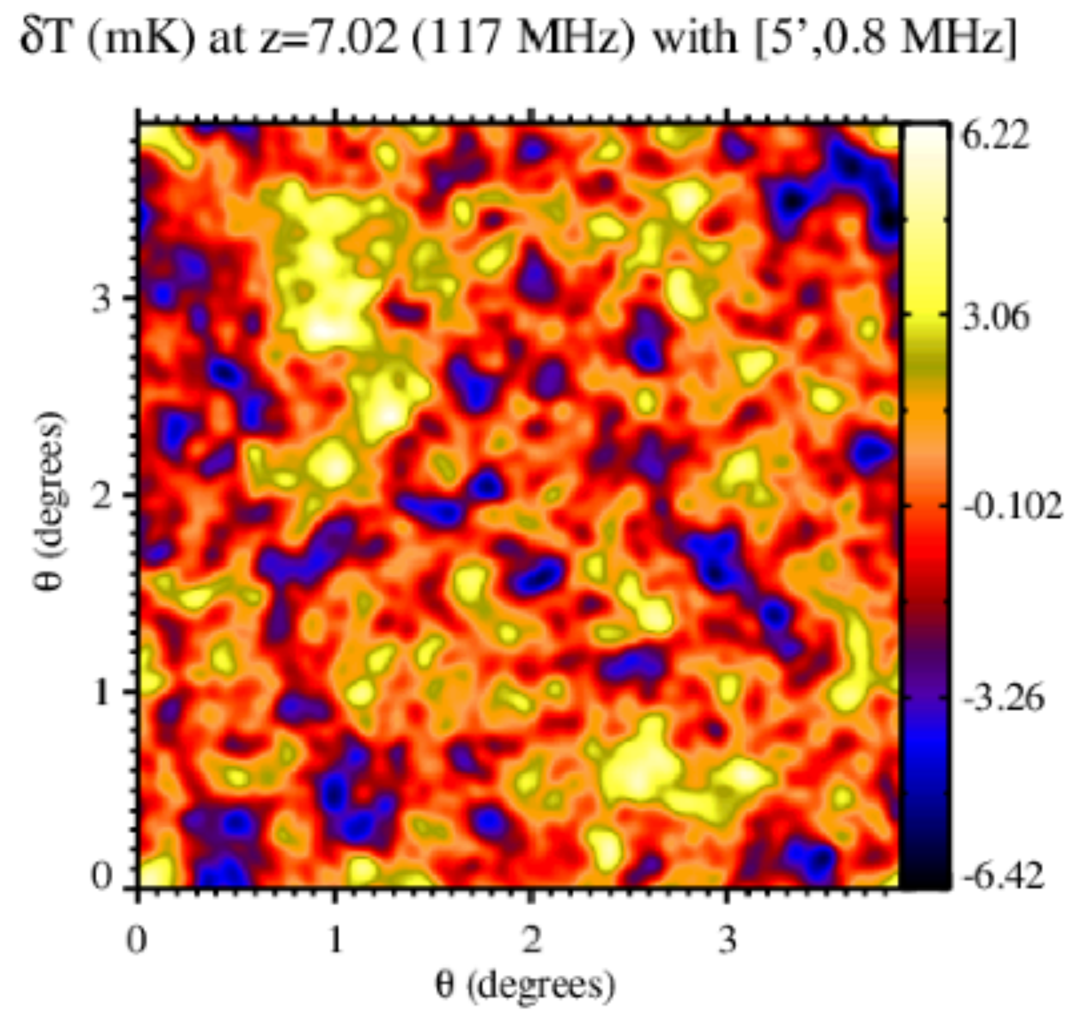


Image from an EoR simulation



Gaussian field with identical PS

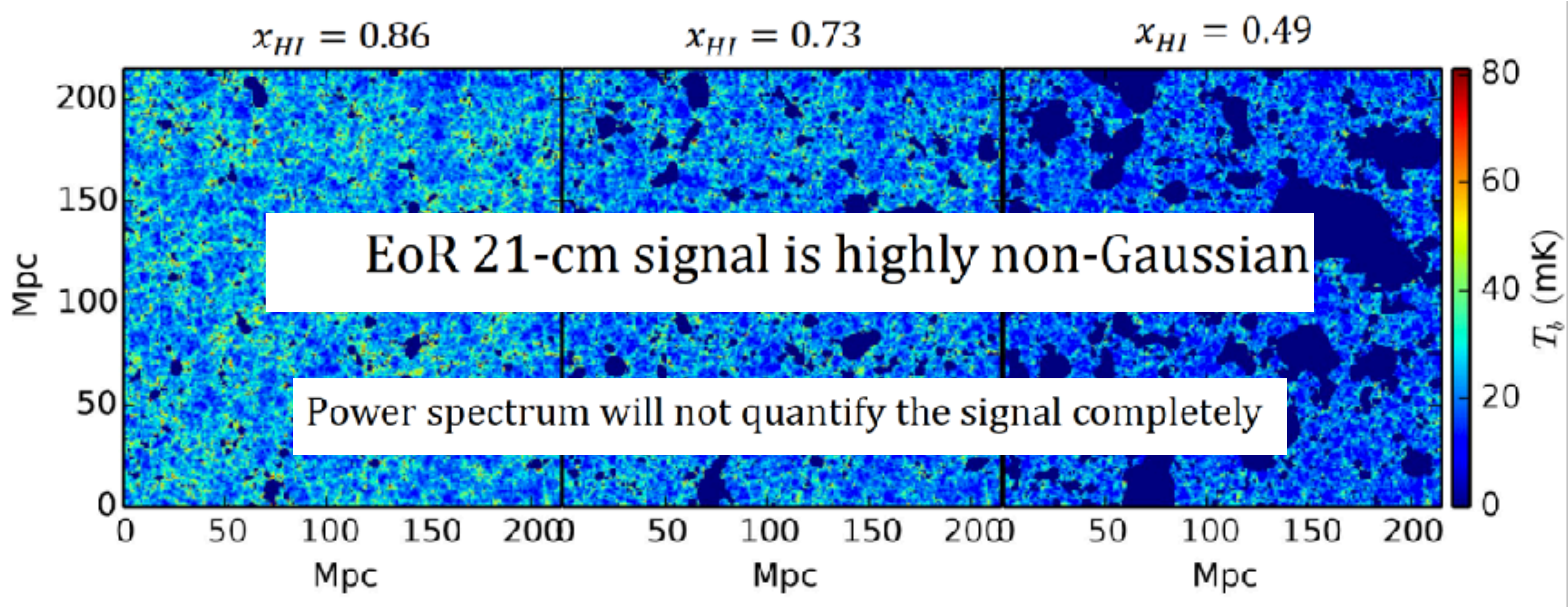
Mellema+2015

Analysis of IM data besides the 2 point statistics (power spectrum) can be done using:

Higher order statistics

Redshift space distortions

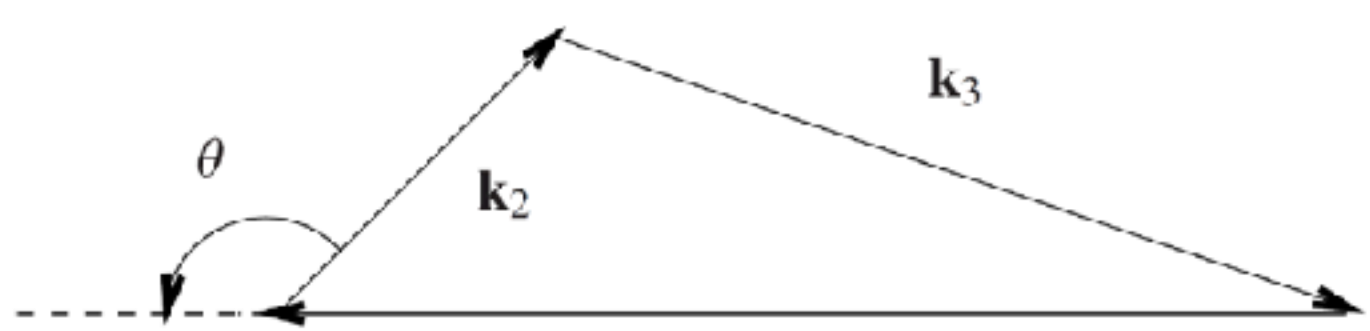
Bispectrum



EoR 21-cm signal is highly non-Gaussian

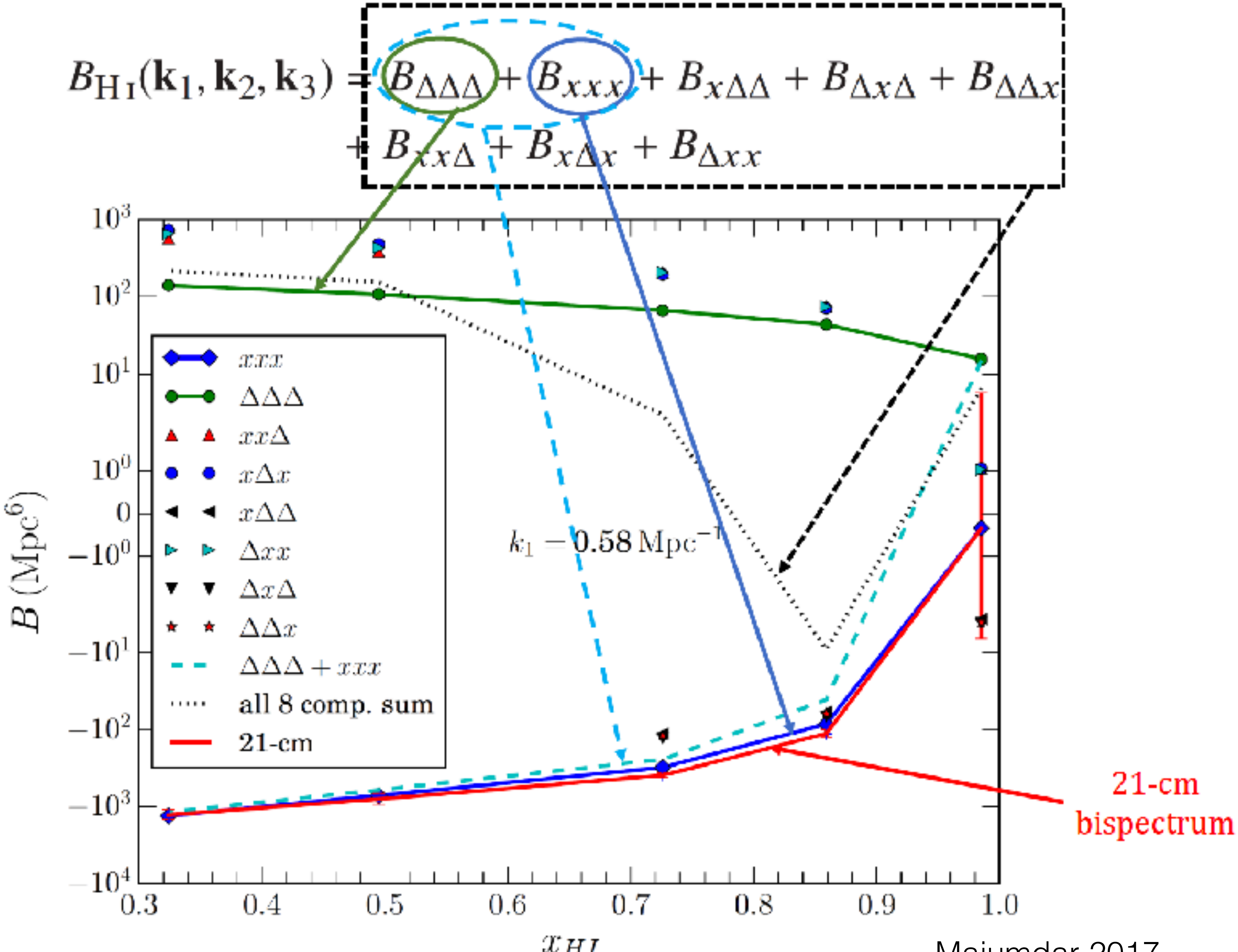
Power spectrum will not quantify the signal completely

Bispectrum: $\langle \Delta_b(\mathbf{k}_1)\Delta_b(\mathbf{k}_2)\Delta_b(\mathbf{k}_3)\rangle = V\delta^{K}_{\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3,0}\, B_b(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$



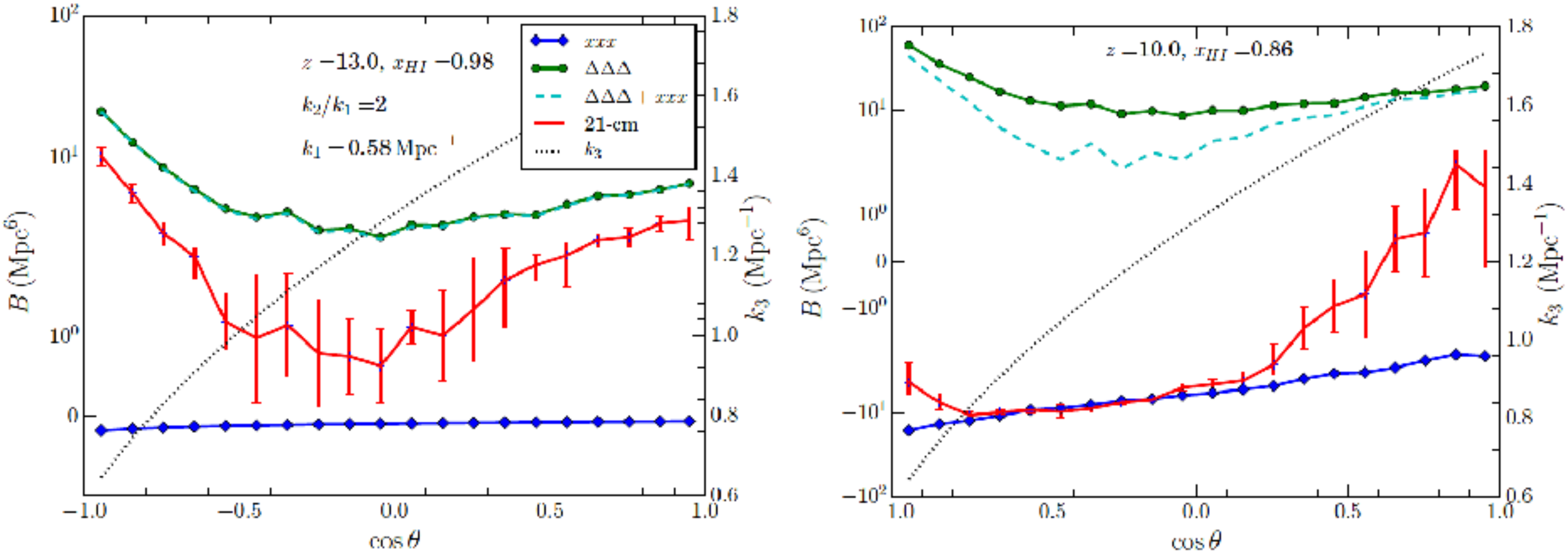
Majumdar, Pritchard, Mondal, Watkinson et al., arXiv:1708.08458

EoR 21 cm Bispectrum: Componentes



Majumdar 2017

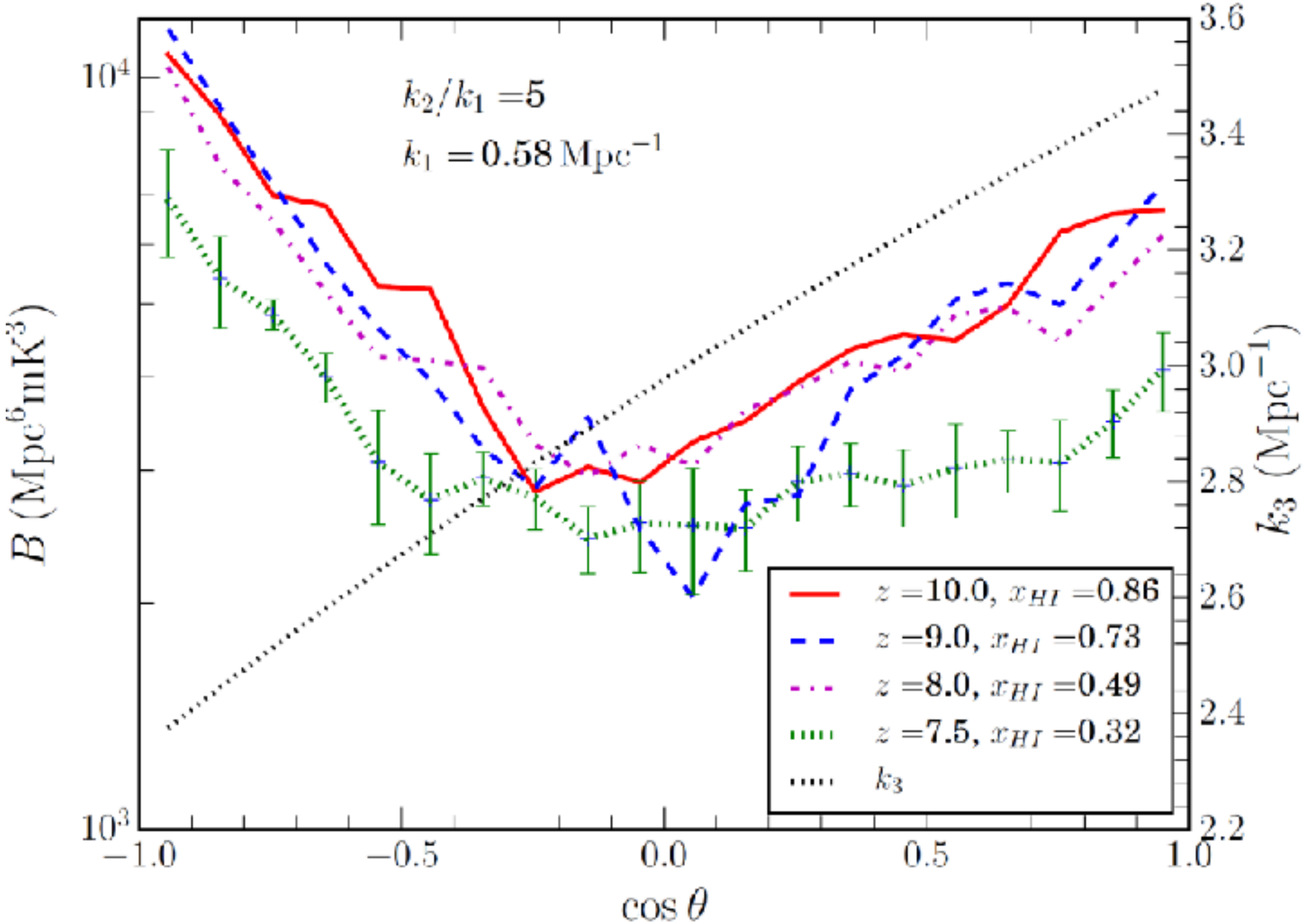
EoR 21 cm Bispectrum: Dominant component



- dominated by ionization and density fields at different stages and configurations…
- also a powerful discriminant for astrophysics?

Majumdar, Pritchard, Mondal, Watkinson et al., arXiv:1708.08458

EoR 21 cm Bispectrum: Redshift evolution



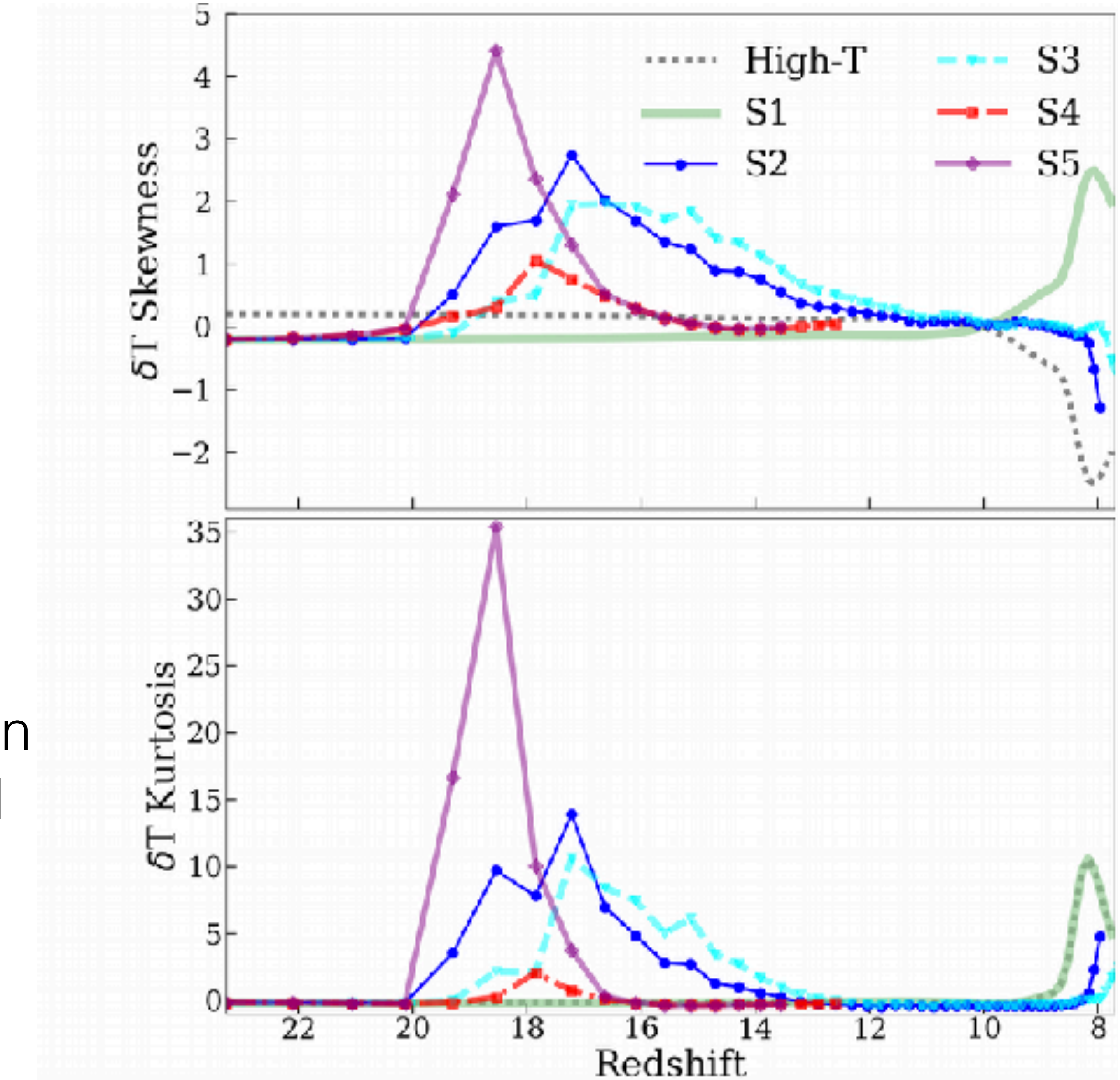
$|k_2| = 5\,|k_1|$ | Asymmetric triangles

Majumdar, Pritchard, Mondal, Watkinson et al., arXiv:1708.08458

EoR 21 cm: Skewness and Kurtosis

$$\text{Skewness}(y) = \frac{1}{N}\frac{\sum_{i=0}^{N}(y_i - \overline{y})^3}{\sigma^3}$$

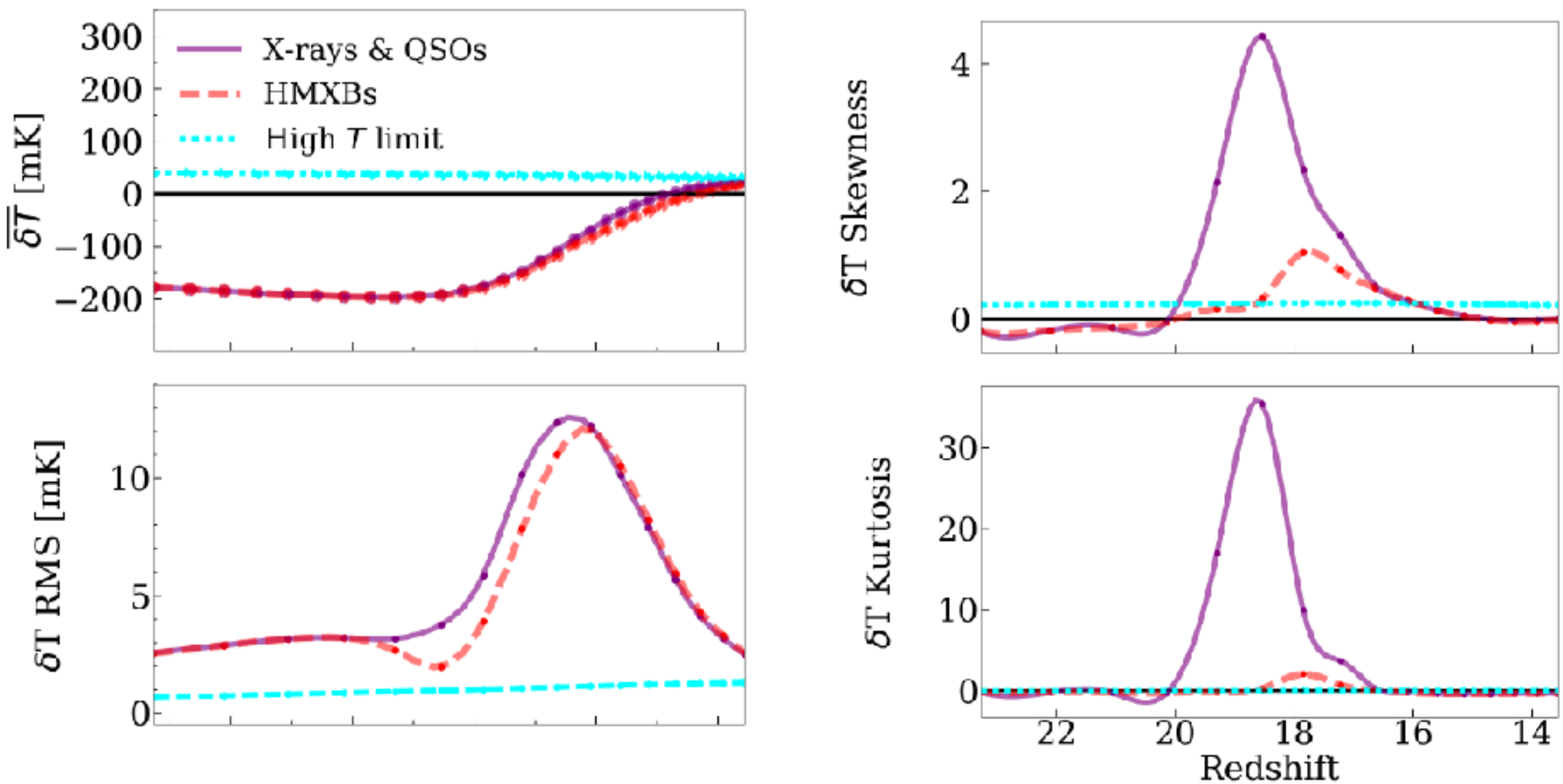
$$\text{Kurtosis}(y) = \frac{1}{N}\frac{\sum_{i=0}^{N}(y_i - \overline{y})^4}{\sigma^4}.$$



Skewness: symmetry in a distribution
Kurtosis: Measure of the combined size of the two tails

Ross et al.
arxiv 1808.03287 2018

Statistics of the EoR 21cm signal



Ross et al.
arxiv 1808.03287 2018

Redshift Space effect

$$P^{\mathrm{s}}(k,\mu) = \overline{\delta T_b}^2(z)\left[P_{\rho_{\mathrm{H\,I}},\rho_{\mathrm{H\,I}}}(k) + 2\mu^2 P_{\rho_{\mathrm{H\,I}},\rho_{\mathrm{M}}}(k) + \mu^4 P_{\rho_{\mathrm{M}},\rho_{\mathrm{M}}}(k)\right]$$

astrophysics

Velocities alone which give clean probe of cosmology

$$\mathbf{s} = \mathbf{r} + \frac{1+z}{H(z)} v_{\parallel} \hat{r}$$

r = real space position

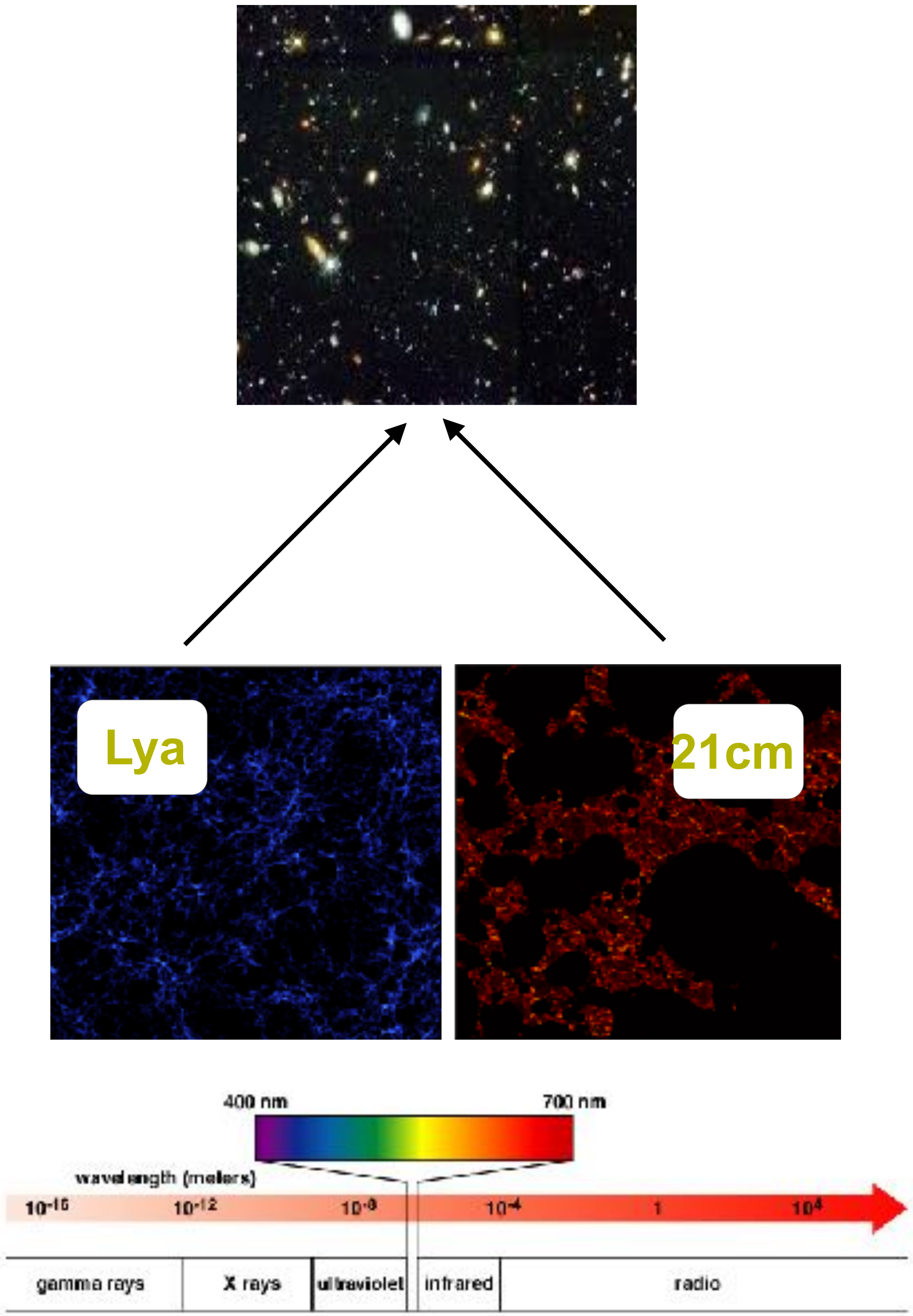
s = apparent redshift position

$v_{||}$ = line-of-sight peculiar velocity of the emitter

How to confirm a statistical detection?

Cross correlations

Cross correlations as a way to avoid foregrounds



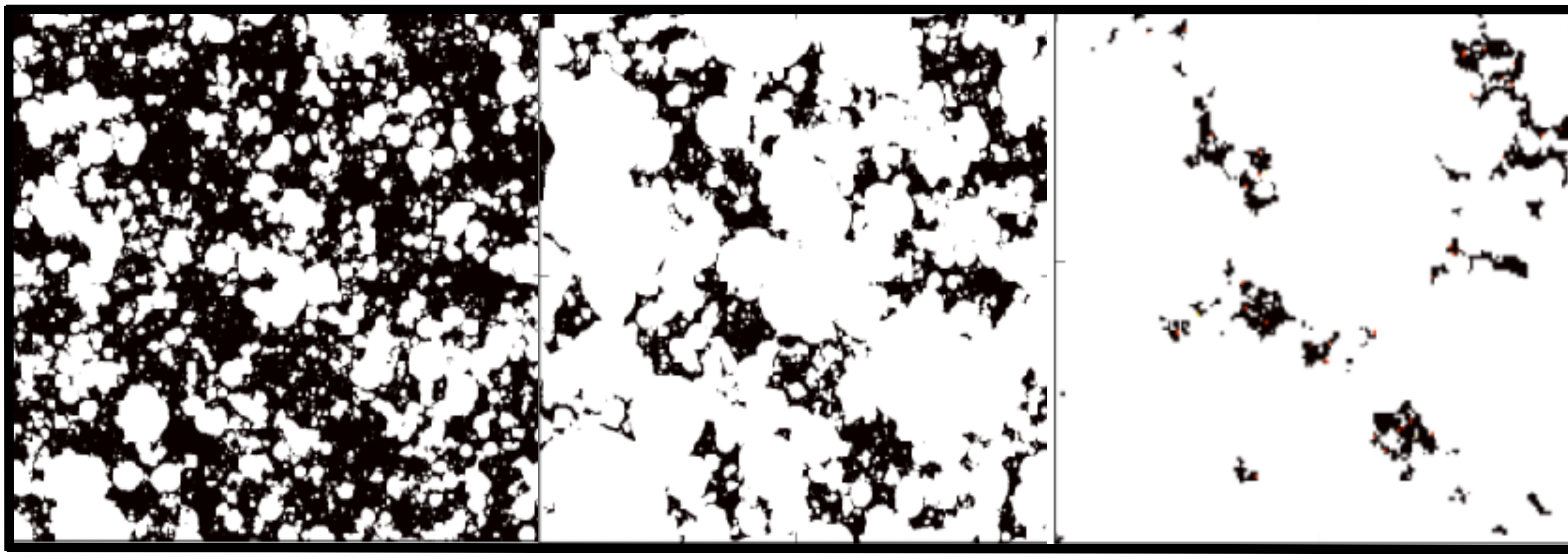
Possible cross correlations with galaxies or IM of other lines

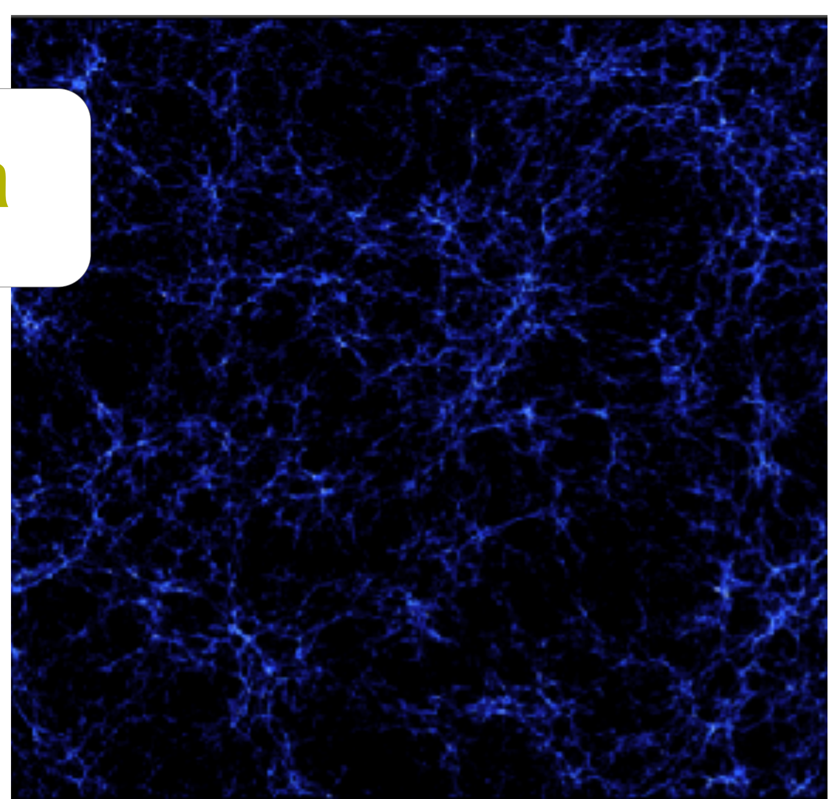
The idea is:

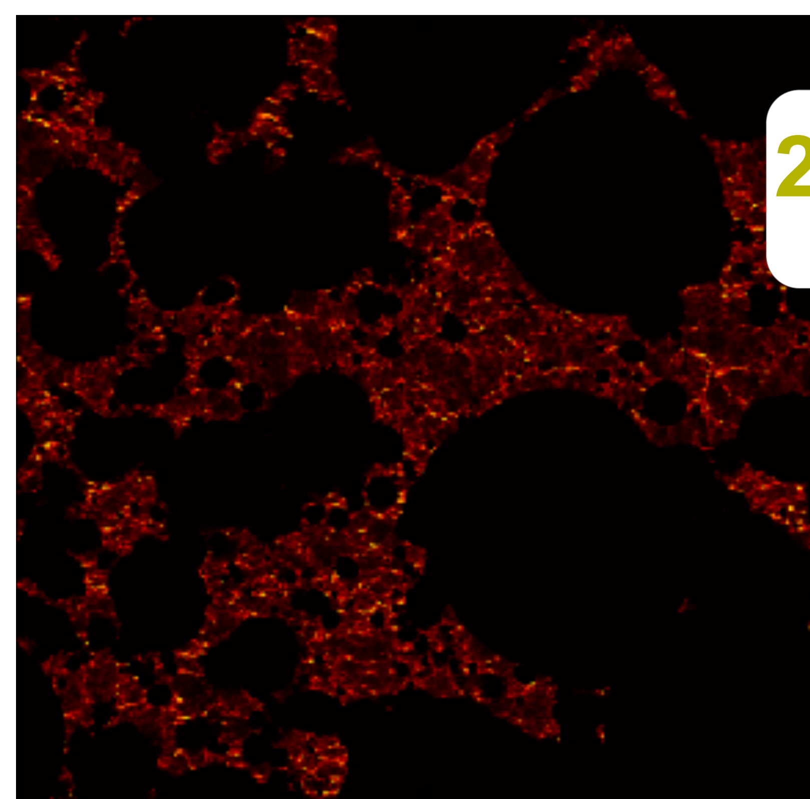
Two independent observations of the same volume in space will be to first order free of foregrounds

≠ observations are made in ≠ freq. bands so they have ≠ foregrounds

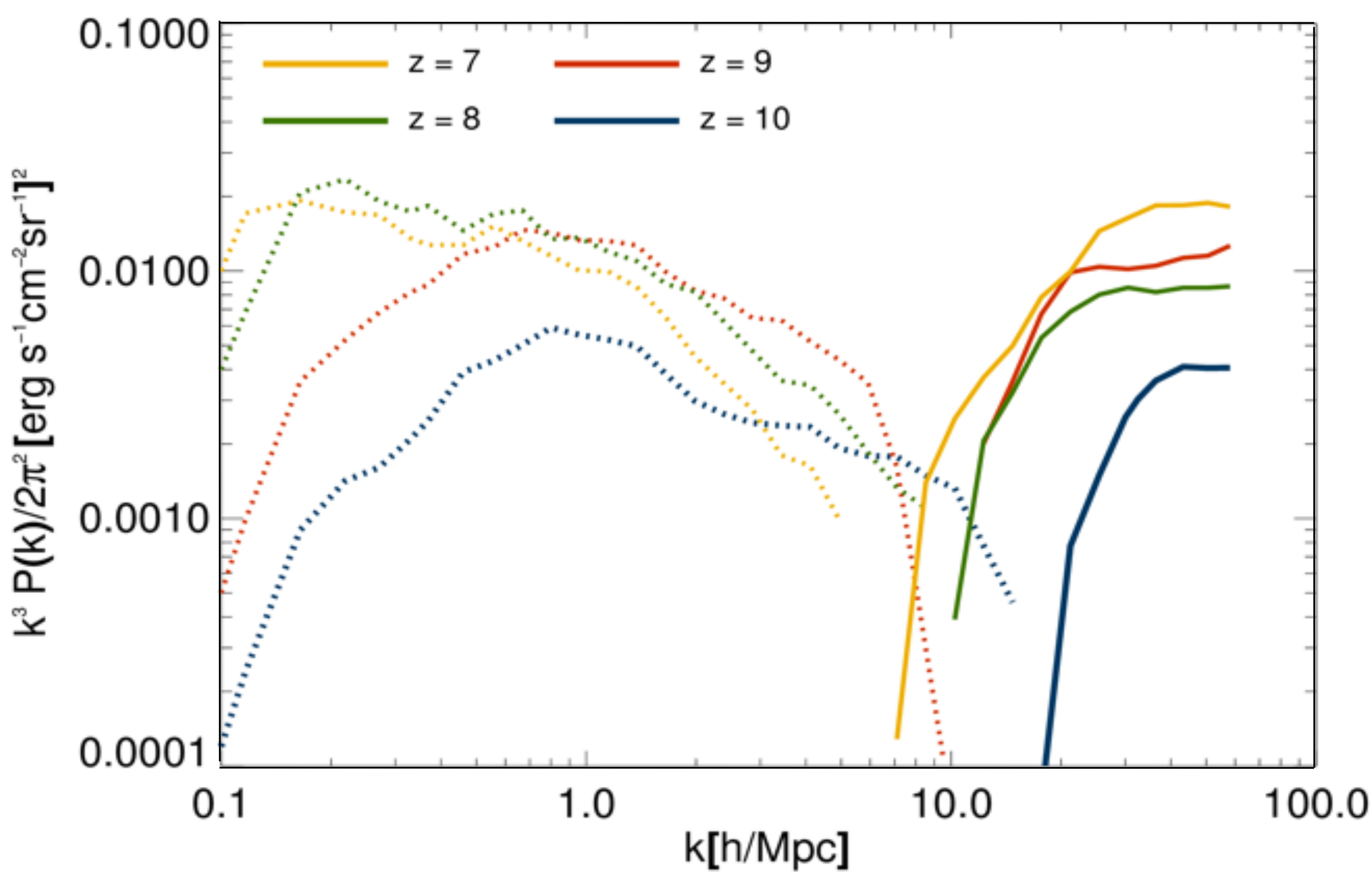
Cross correlation with Lyα IM



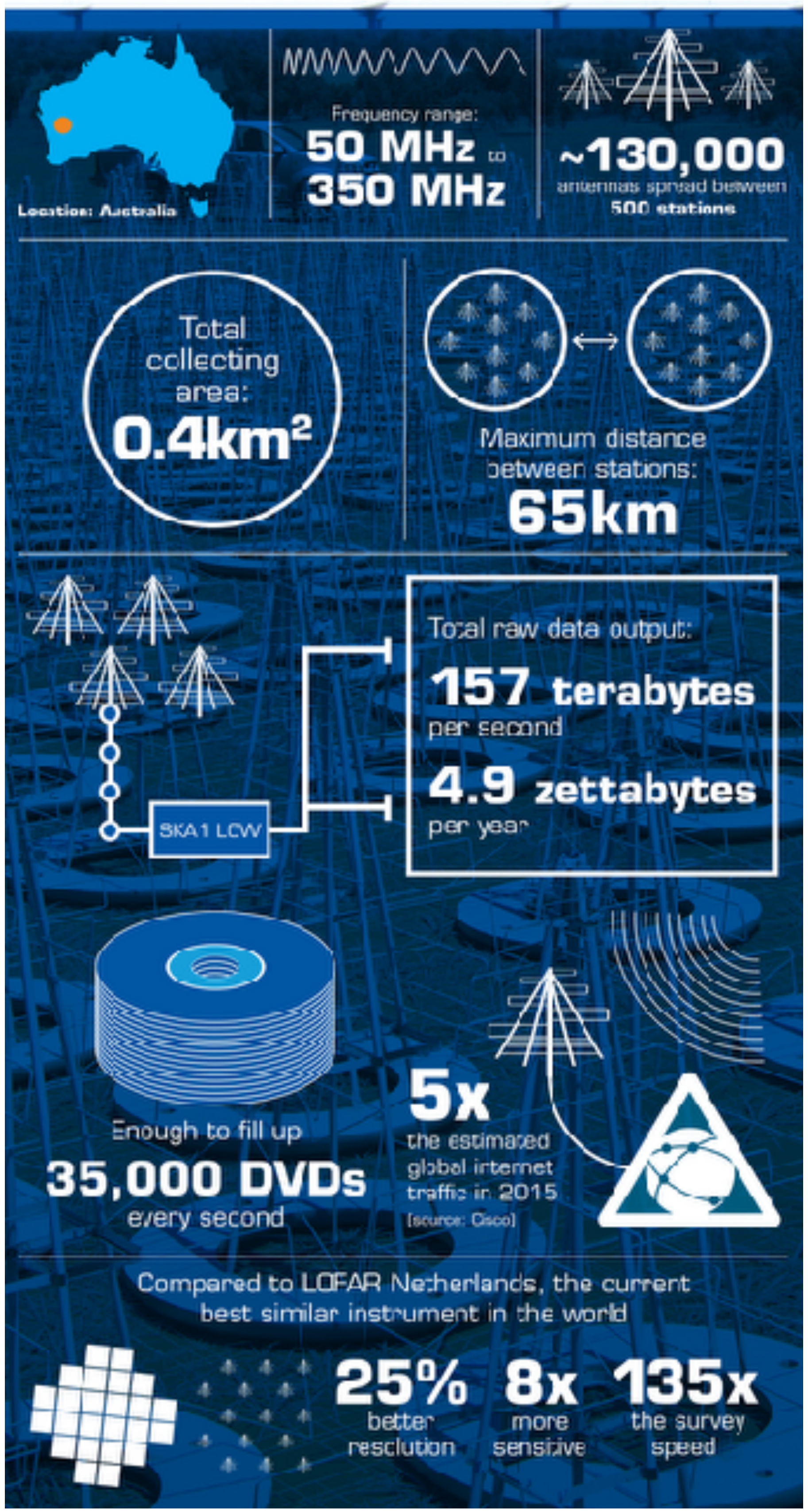


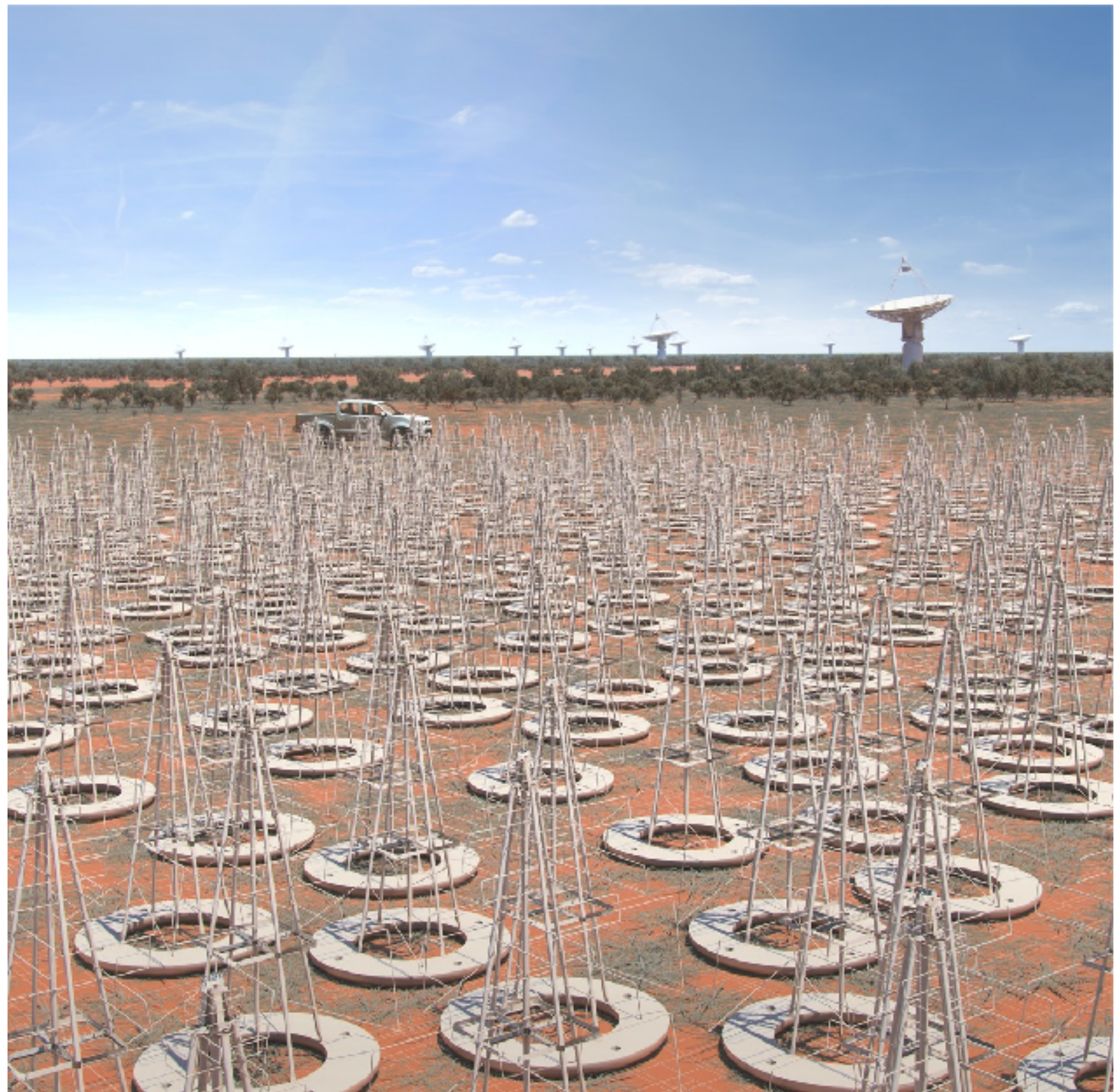


21cm/Lyα cross correlation

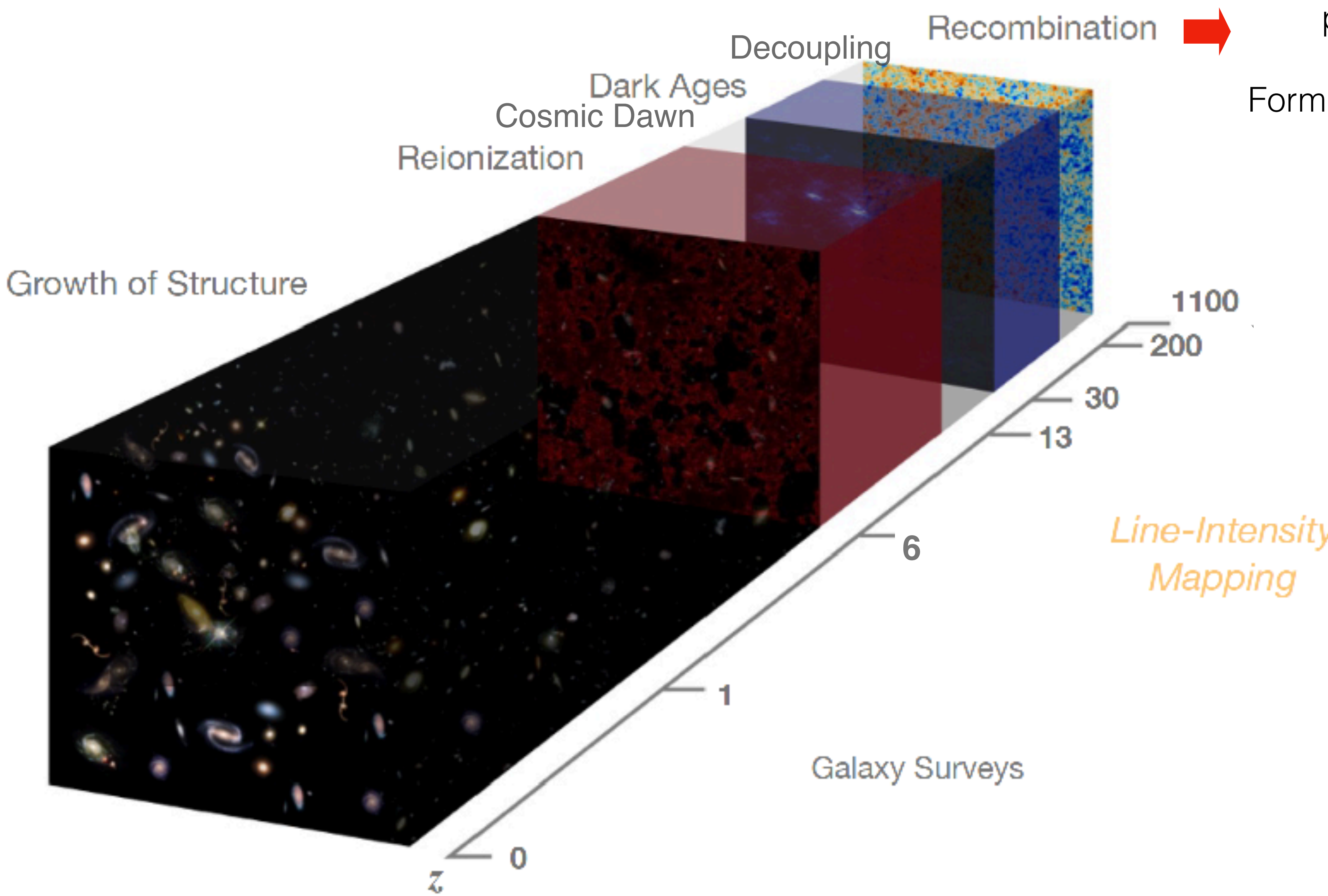


The Future: SKA





Tomography of 21cm line emission during the EoR



p + e⁻

Formation of HI

Credit: E. Kovetz