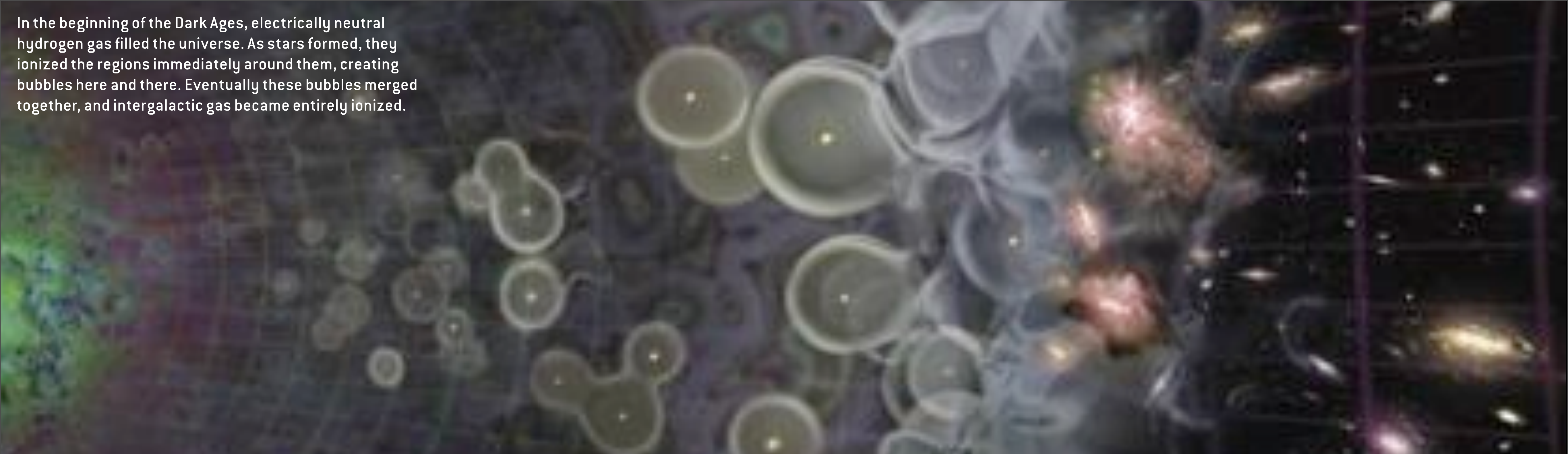
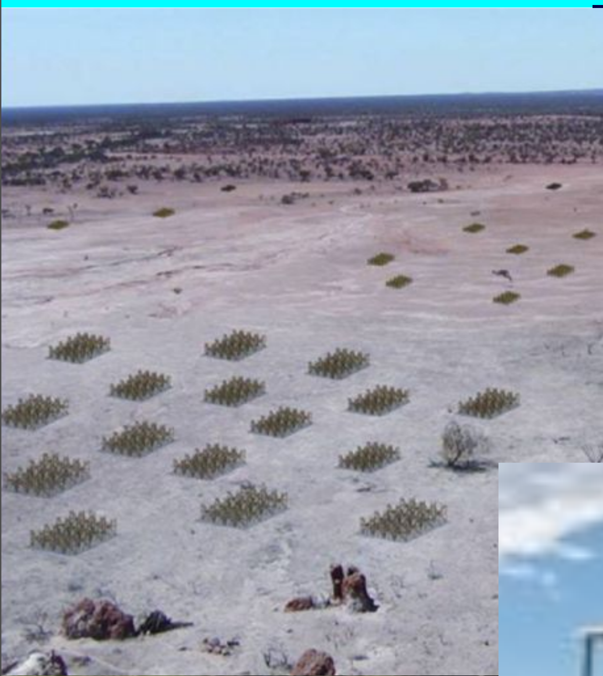
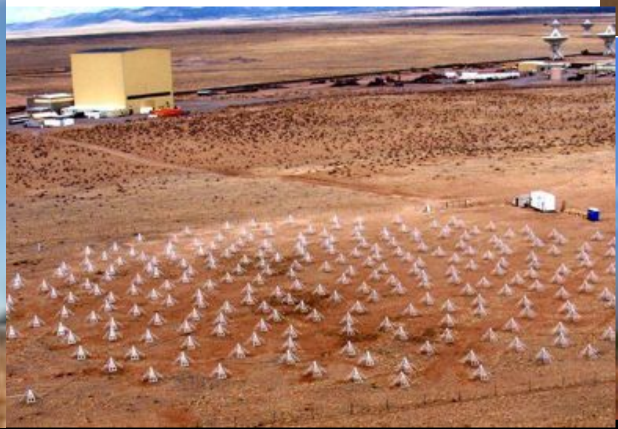


HI across cosmic time




Jonathan Pritchard
Hubble-ITC Fellow
CfA



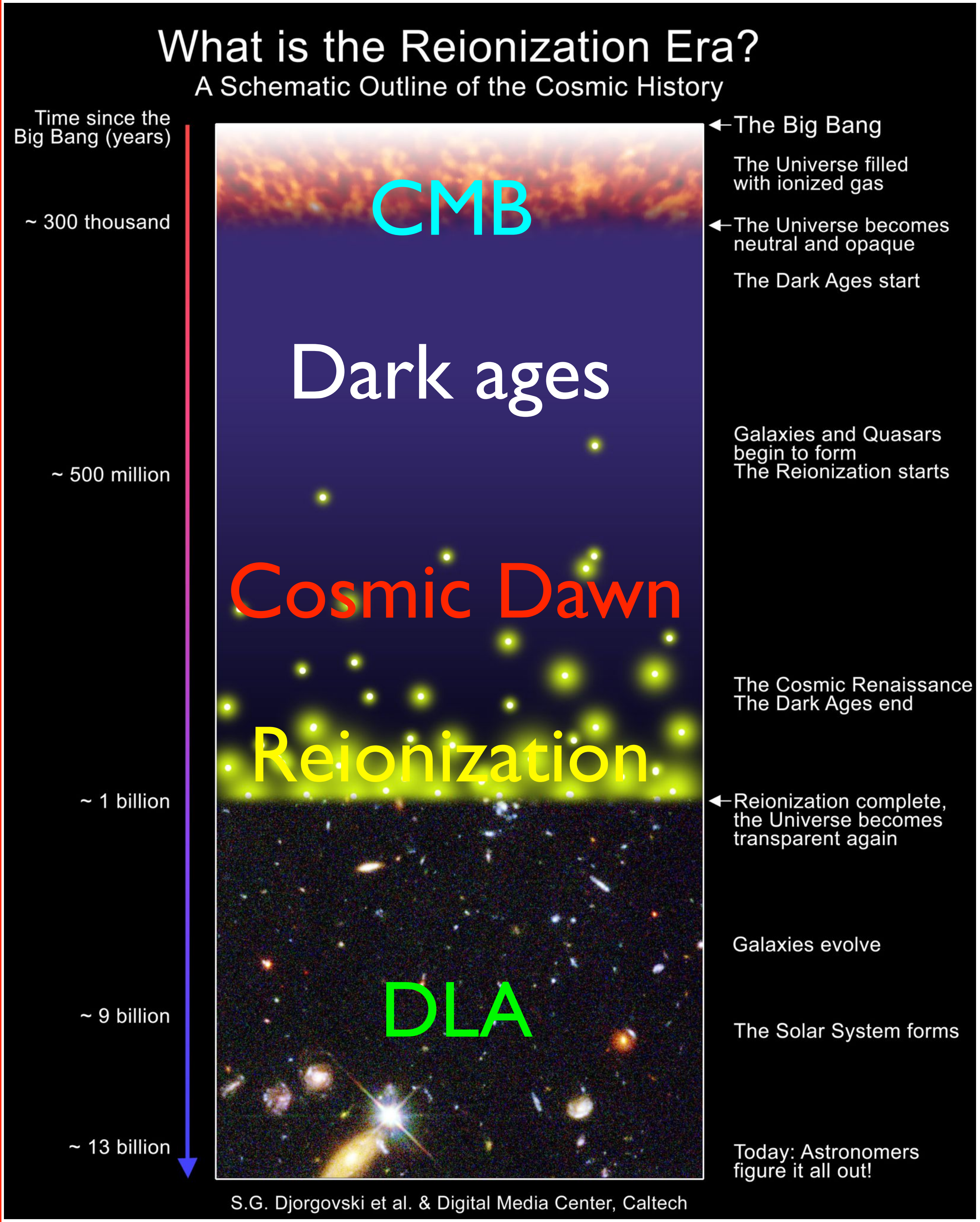

Avi Loeb (CfA)
Hy Trac (CMU)

Steve Furlanetto (UCLA)
Alex Amblard (Ames)

Stuart Wyithe (Melbourne)
Renyue Cen (Princeton)

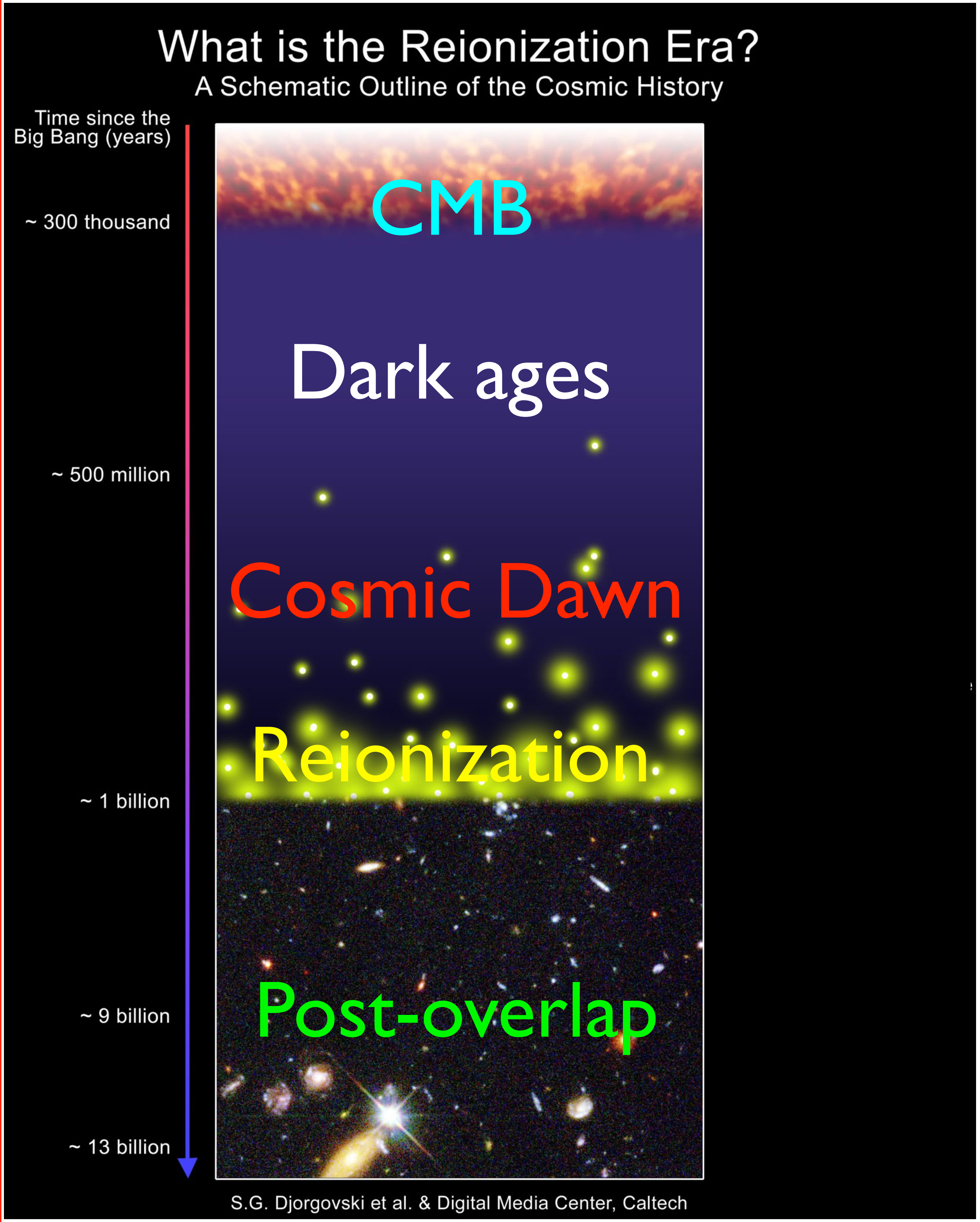
Mario Santos (Portugal)
Asanthe Cooray (UCI)

The first billion years

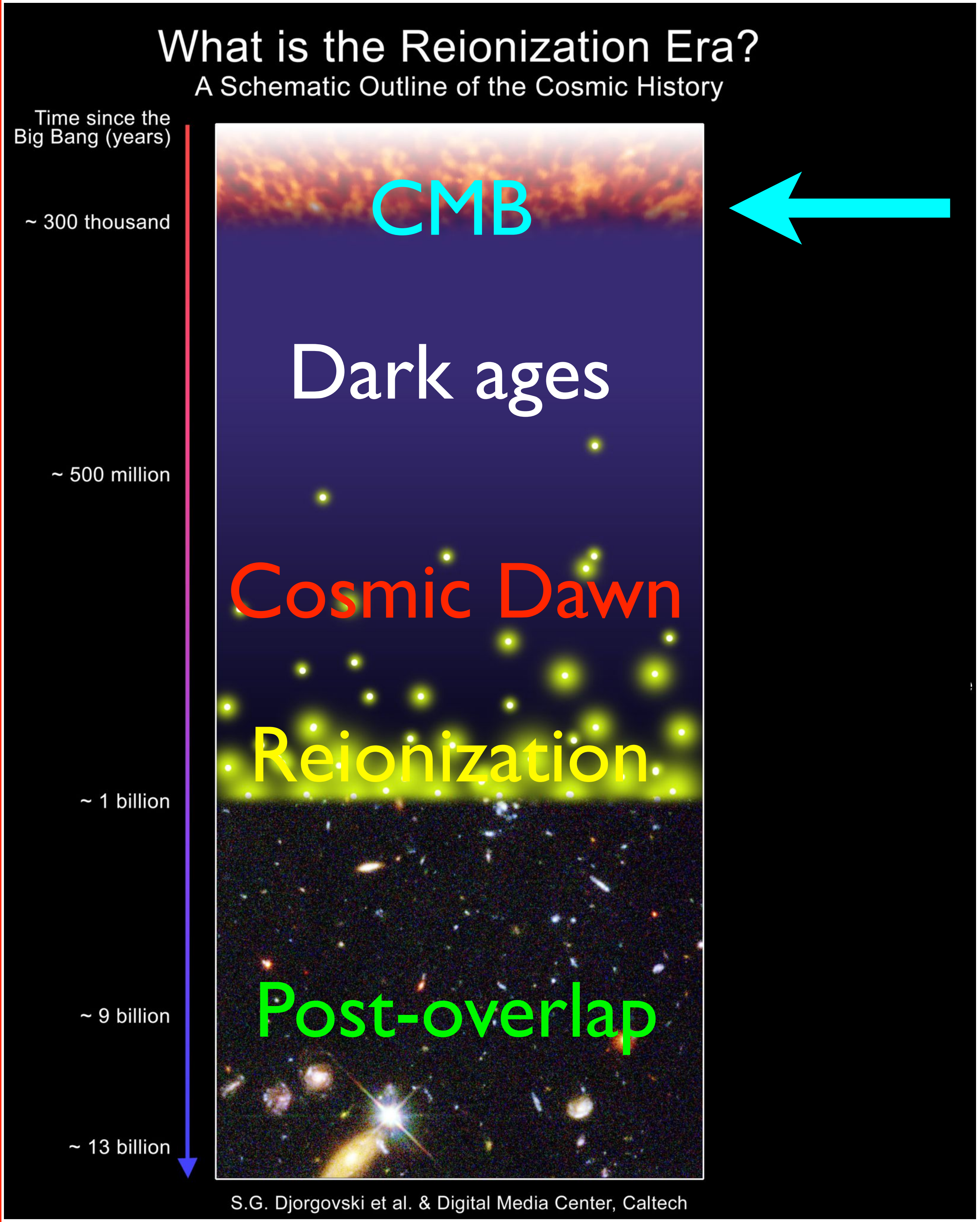


- Story of hydrogen
- 21 cm mean signal
- 21 cm fluctuations
- Intensity mapping

The first billion years

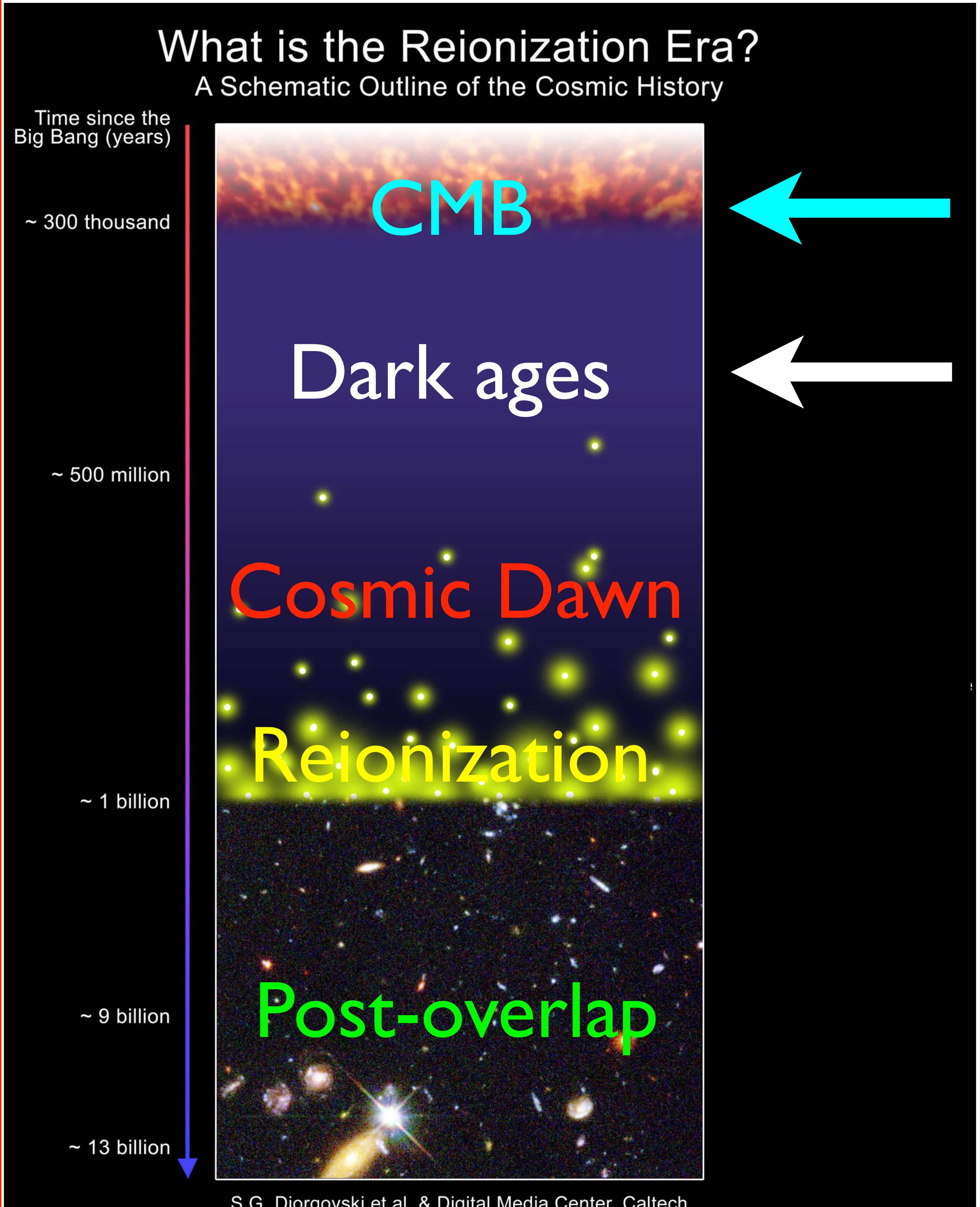


The first billion years



Recombination: hydrogen becomes neutral

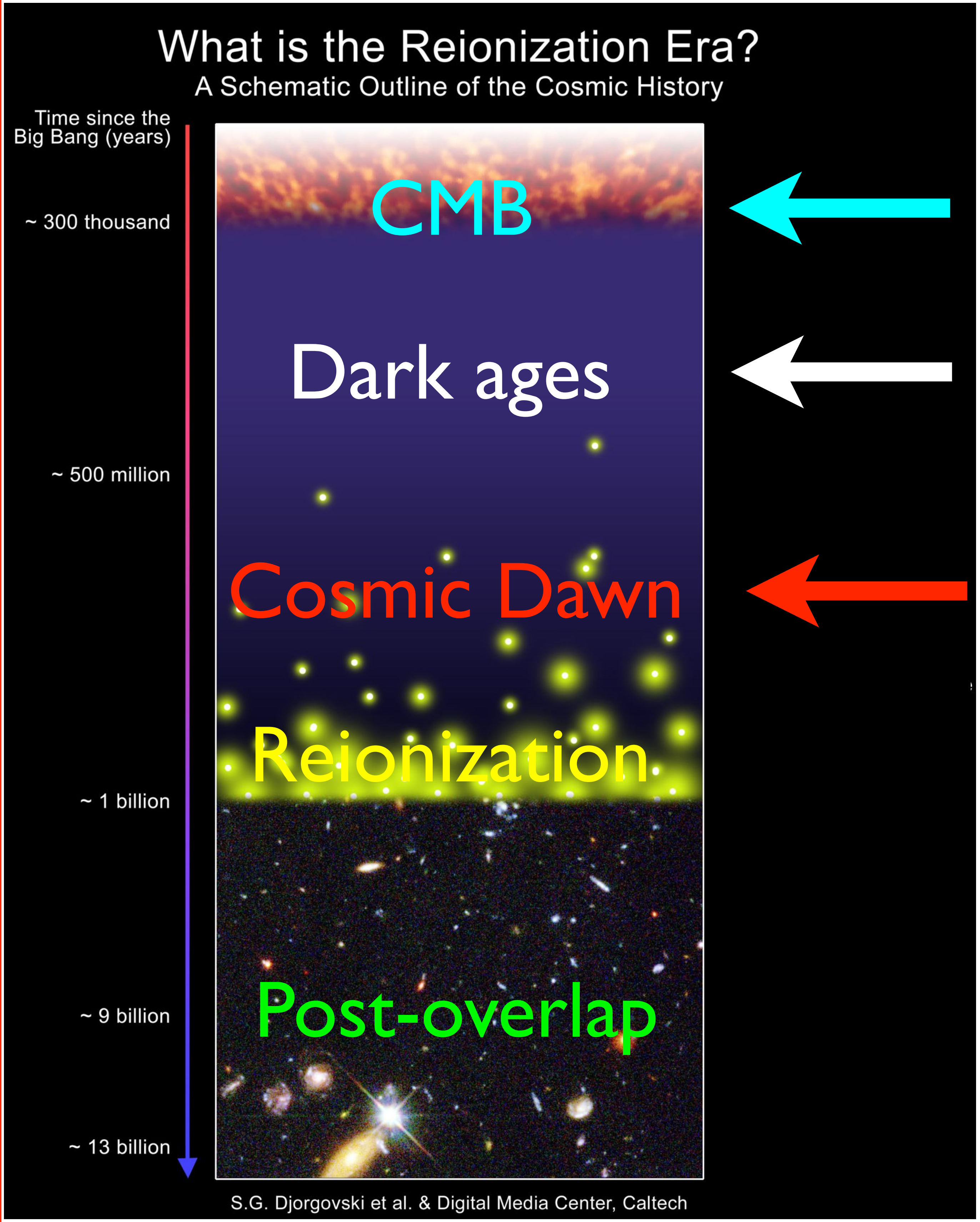
The first billion years



Recombination: hydrogen becomes neutral

Thermal decoupling: hydrogen cools

The first billion years

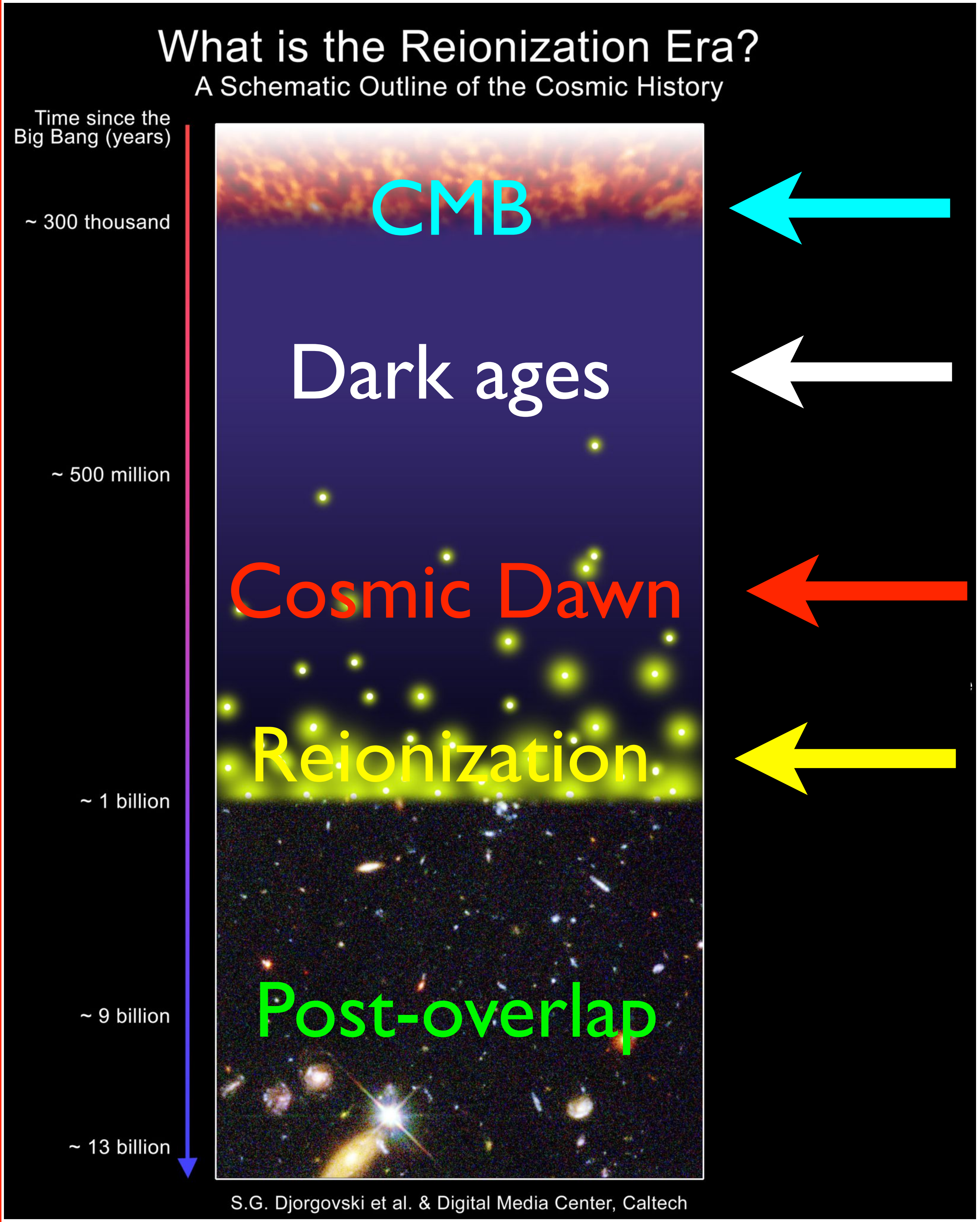


Recombination: hydrogen becomes neutral

Thermal decoupling: hydrogen cools

Structures form: hydrogen heated

The first billion years



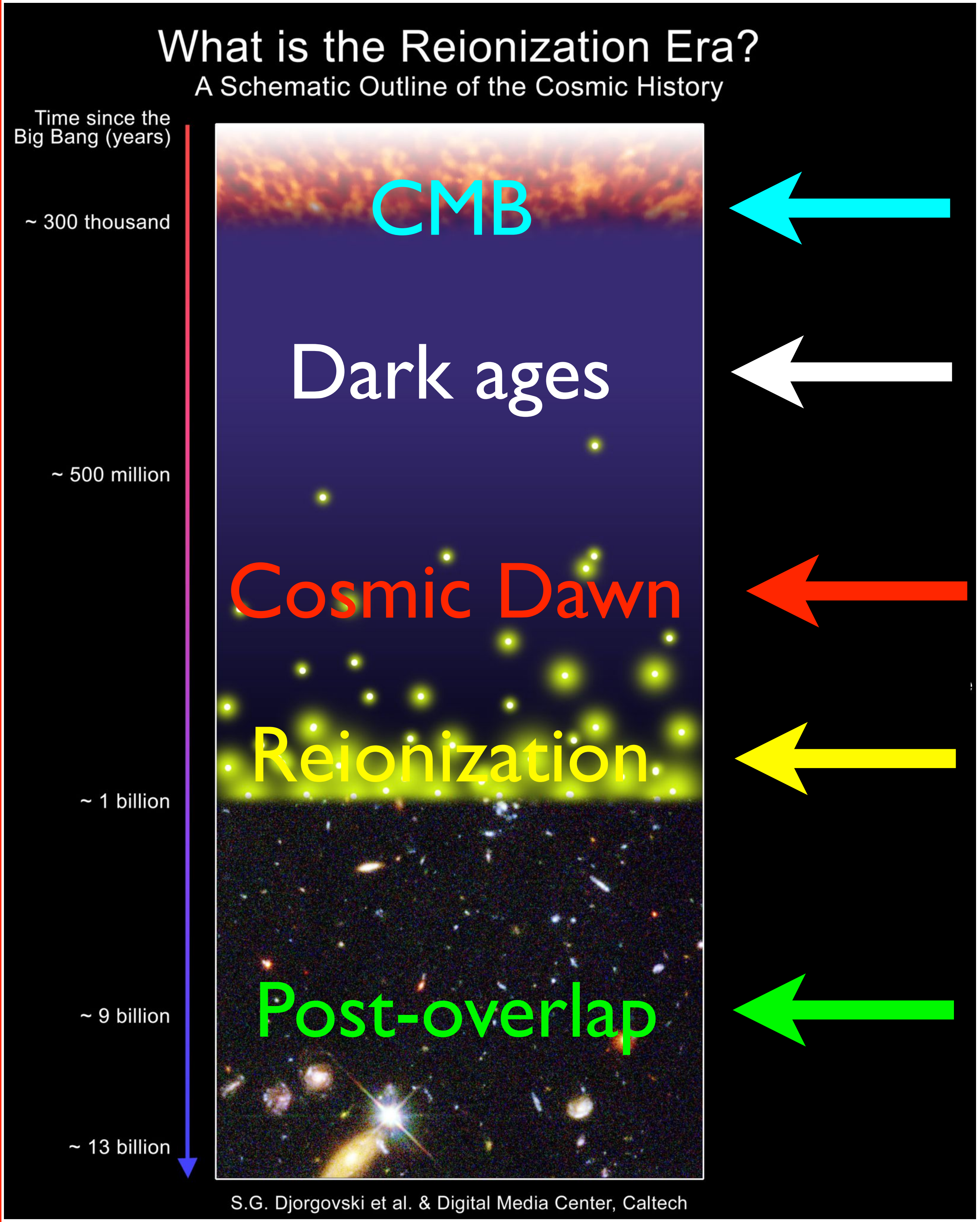
Recombination: hydrogen becomes neutral

Thermal decoupling: hydrogen cools

Structures form: hydrogen heated

Reionization: hydrogen ionized

The first billion years



Recombination: hydrogen becomes neutral

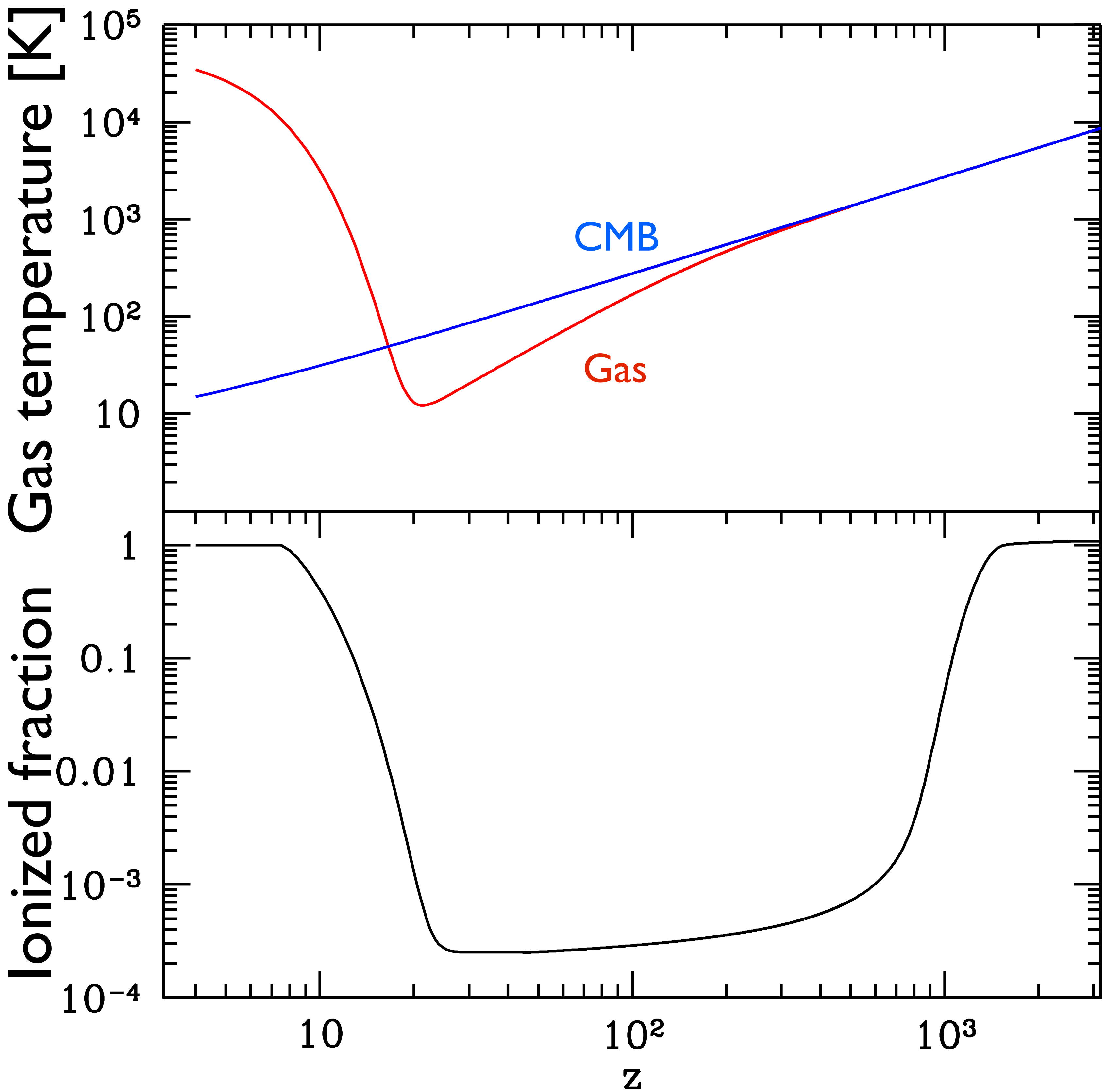
Thermal decoupling: hydrogen cools

Structures form: hydrogen heated

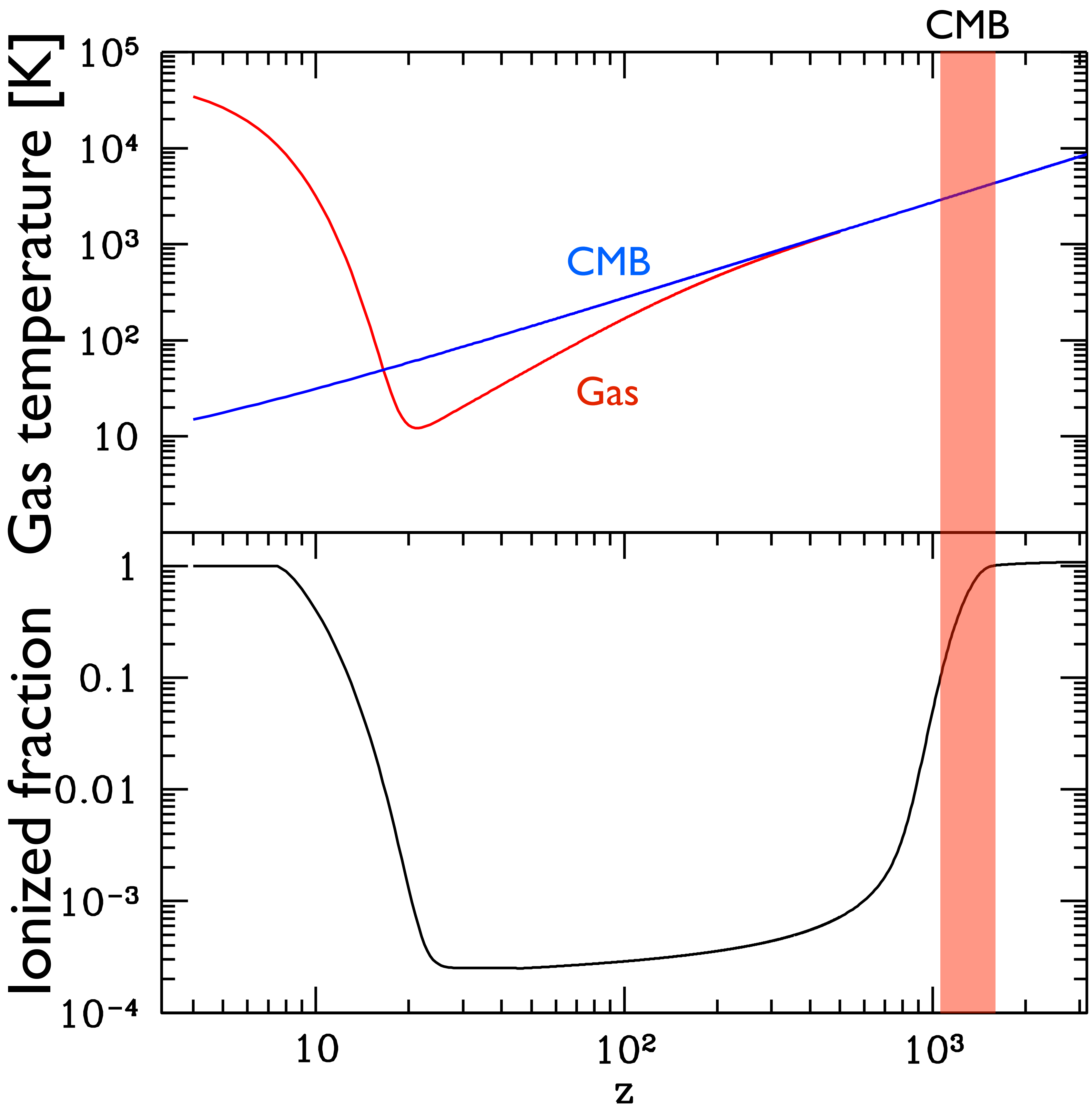
Reionization: hydrogen ionized

only neutral hydrogen in dense clumps

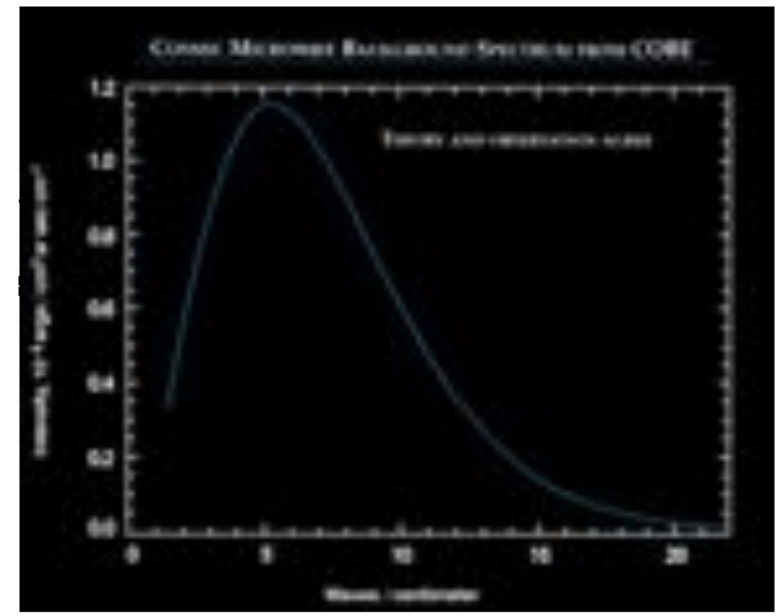
Known unknowns



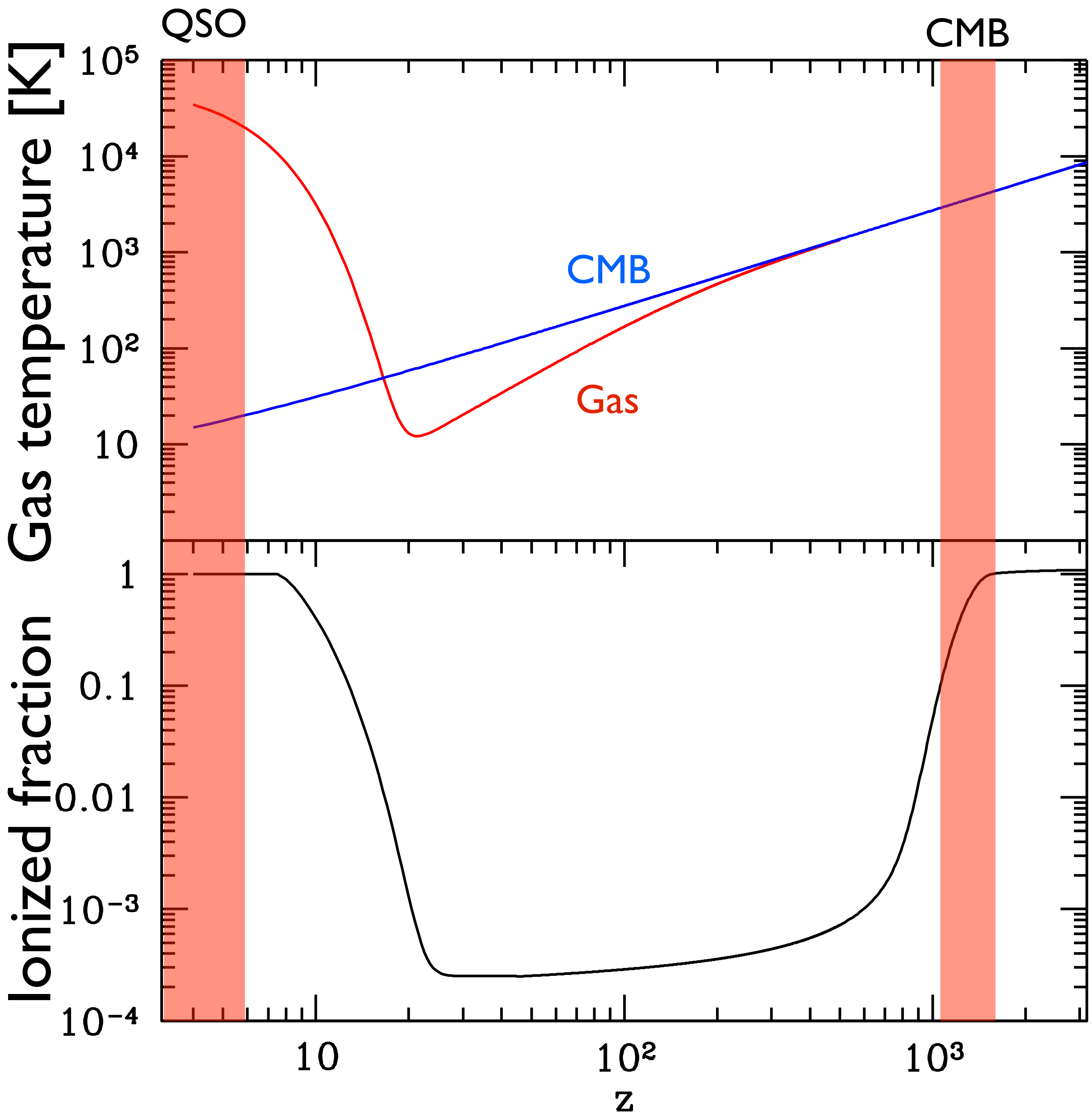
Known unknowns



Hydrogen was warm and neutral at z=1100



Known unknowns



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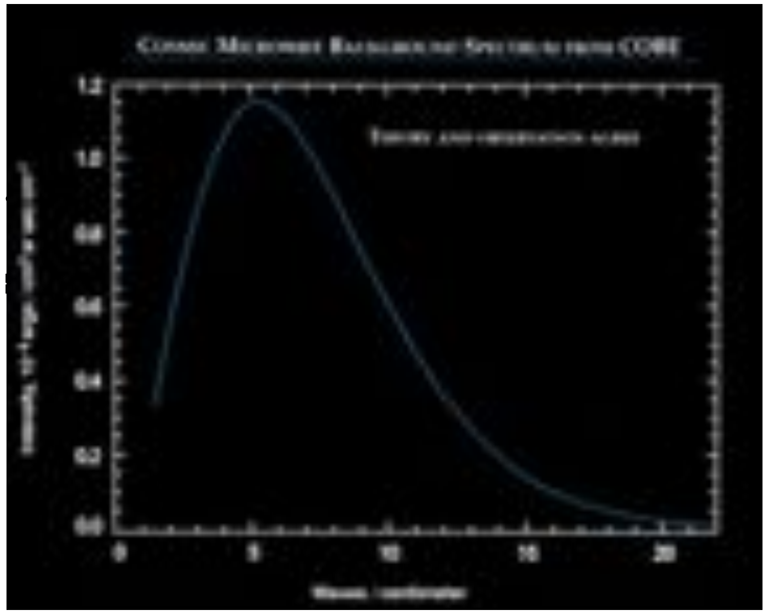
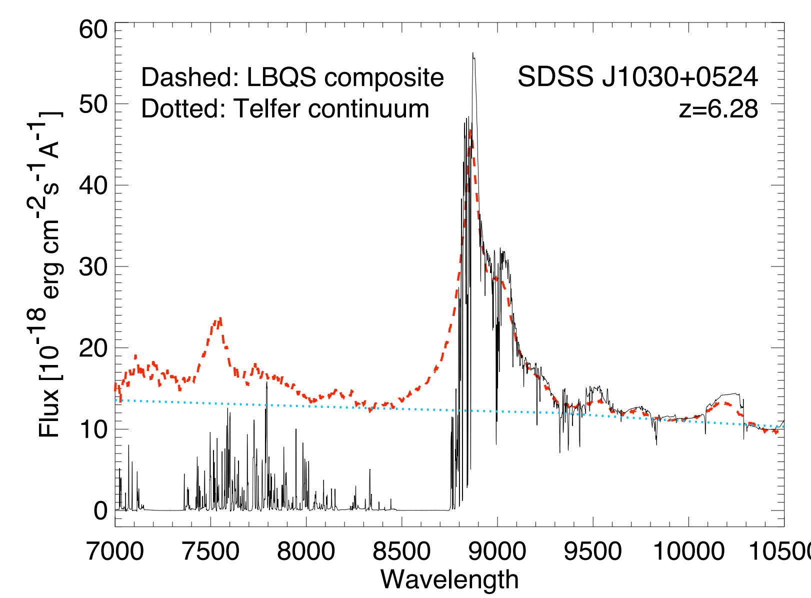
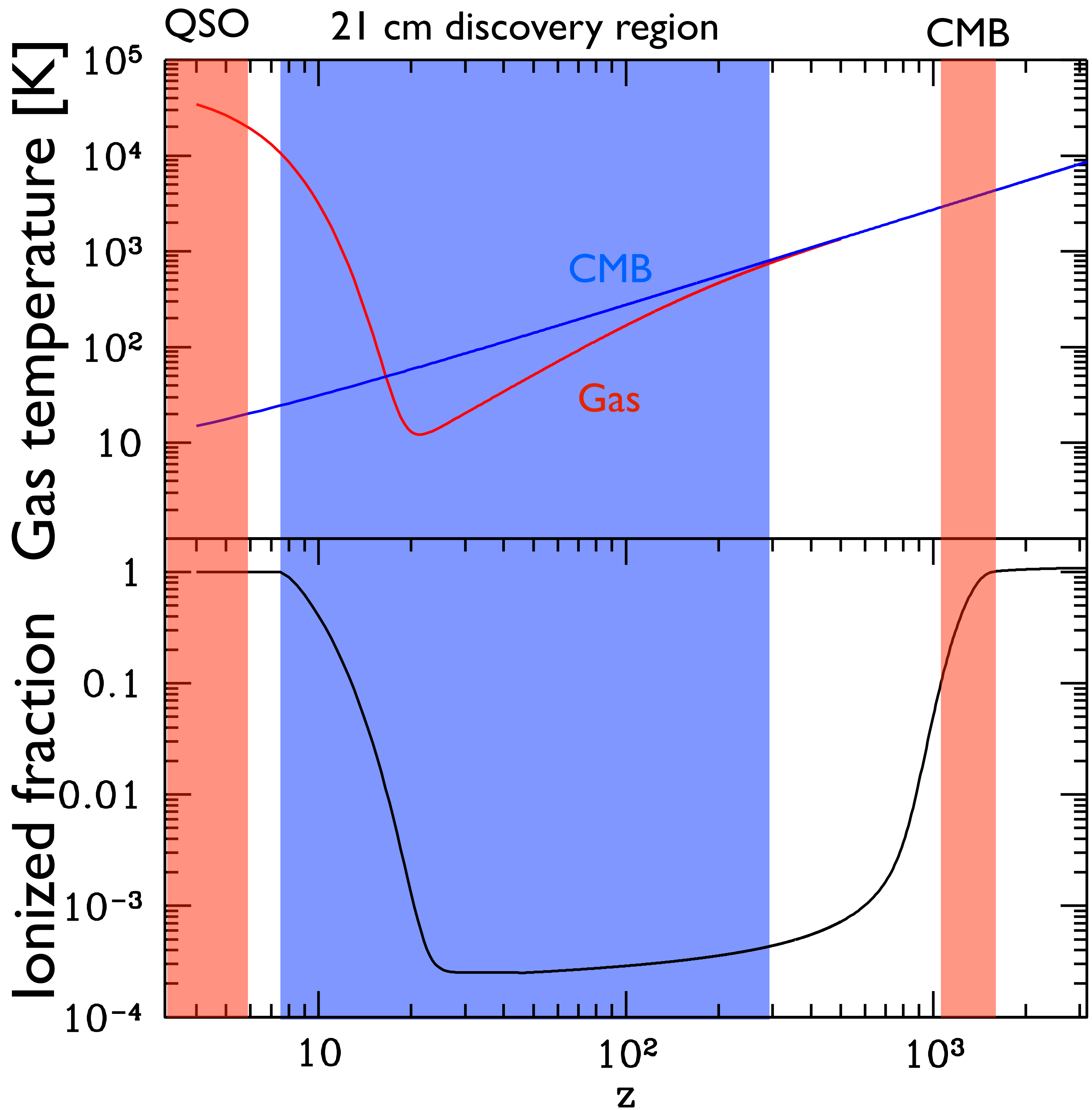


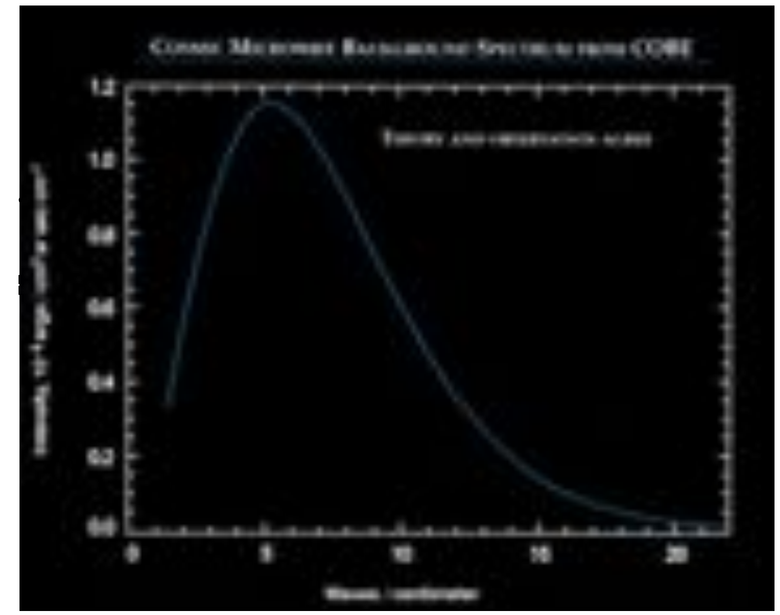
Hydrogen is hot and ionized at z<6



Known unknowns



Hydrogen was warm and neutral at z=1100



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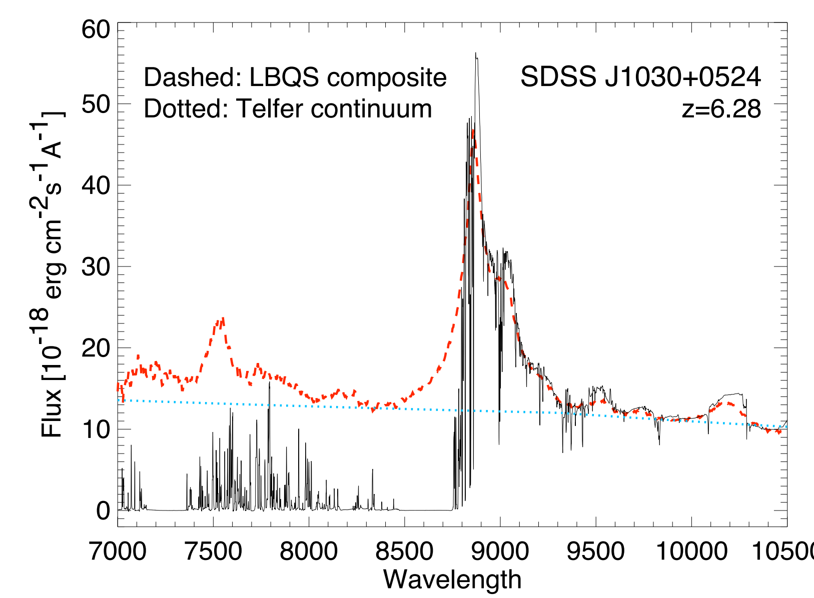

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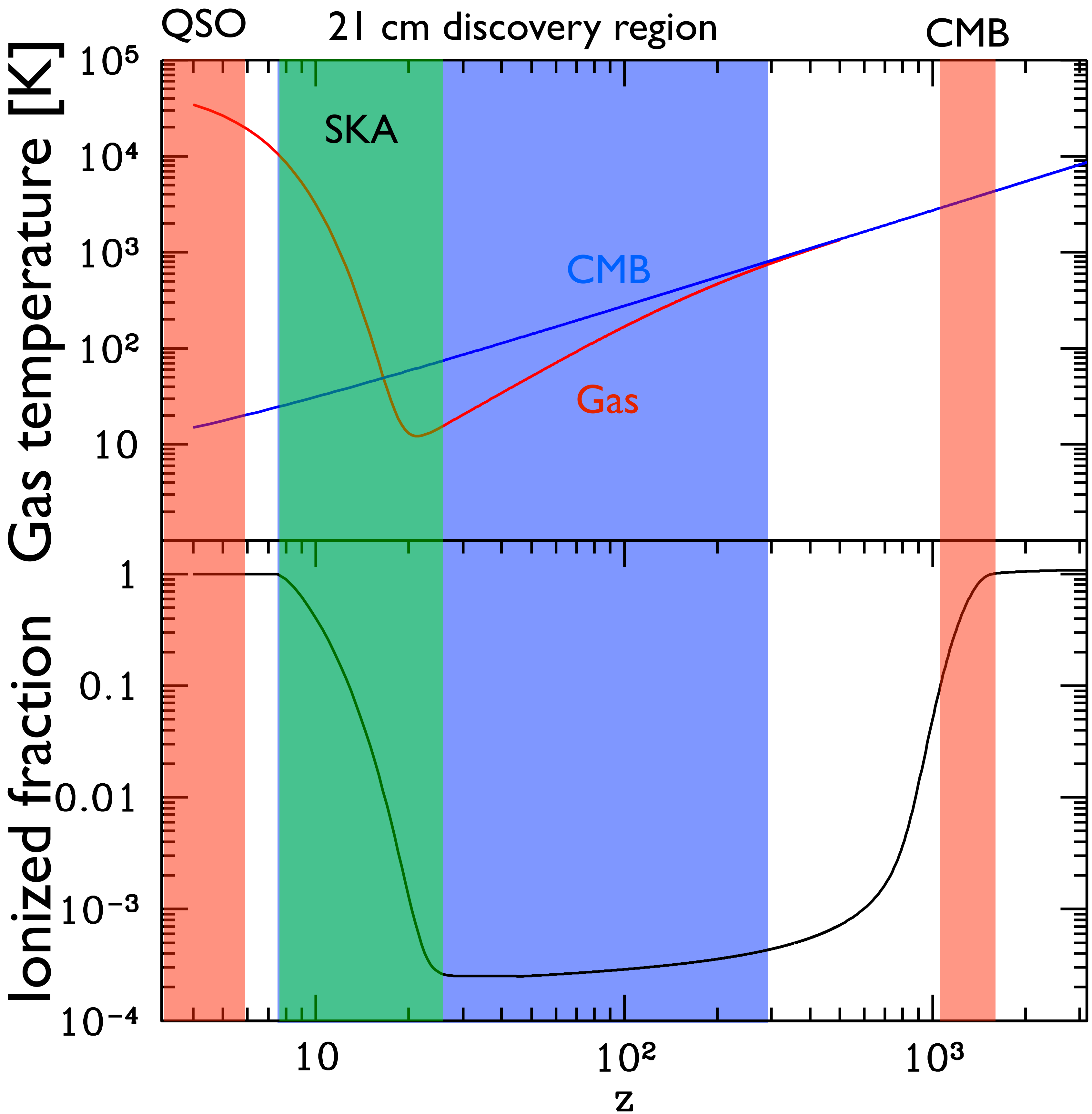

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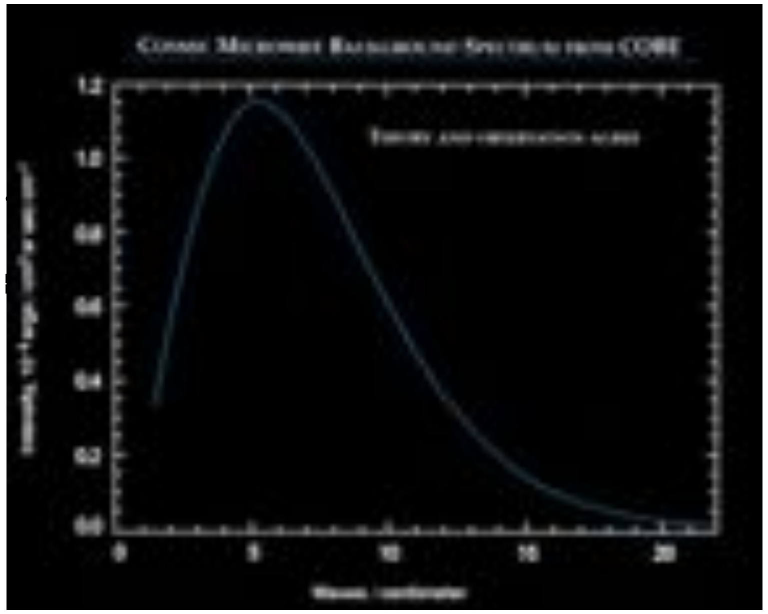

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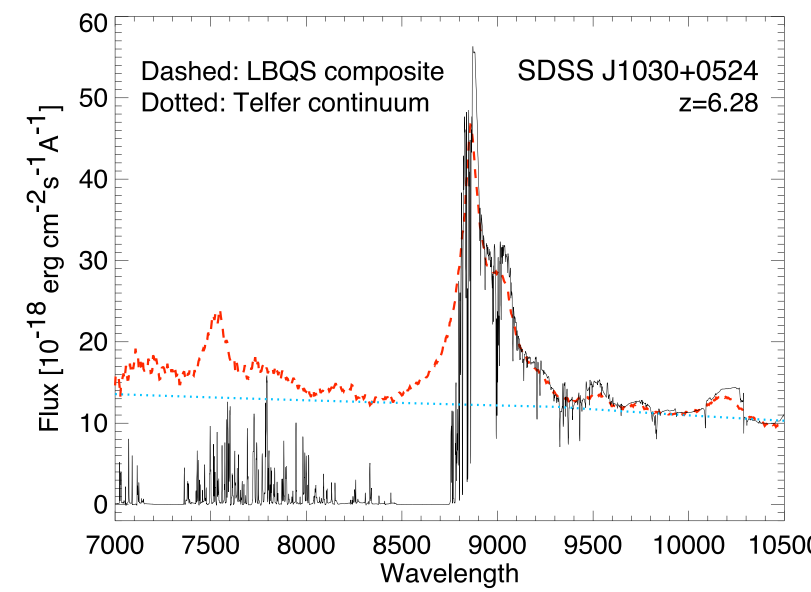


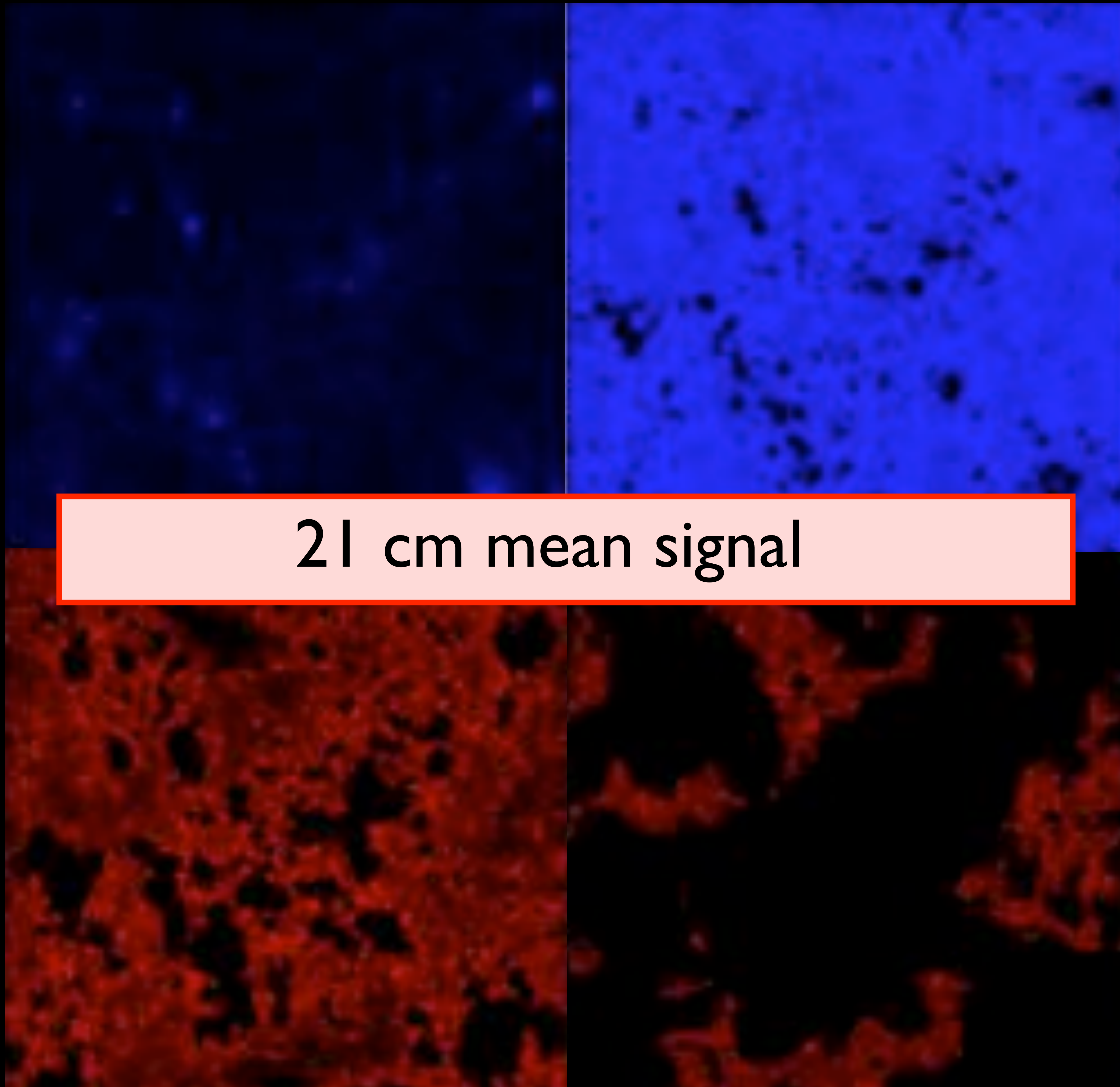
What do we know about reionization?

- CMB optical depth => midpoint of reionization z~10
- Gunn-Peterson trough => universe mostly ionized at z<6
- Lyman alpha forest => ionizing background at z<6
- High redshift galaxies => ionizing background + star formation

Reionization complete by z~6.5

Midpoint of reionization z~9-11

Reionization extended, may begin z>15

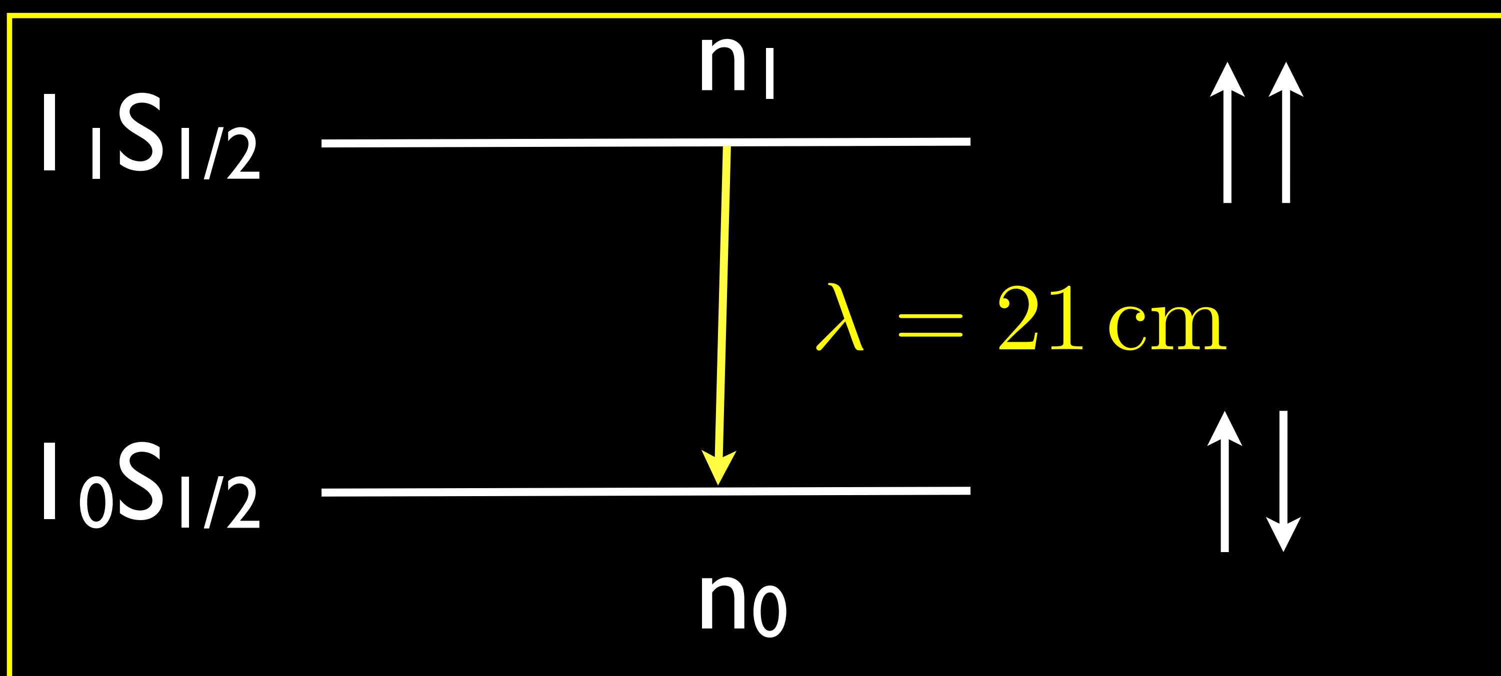

21 cm mean signal

21 cm basics

Precisely measured transition from water masers

$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\,\mathrm{Hz}$$

Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

Useful numbers:

$$200\,\mathrm{MHz} \rightarrow z = 6$$
$$100\,\mathrm{MHz} \rightarrow z = 13$$
$$70\,\mathrm{MHz} \rightarrow z \approx 20$$

$$t_{\mathrm{Age}}(z=6) \approx 1\,\mathrm{Gyr}$$
$$t_{\mathrm{Age}}(z=10) \approx 500\,\mathrm{Myr}$$
$$t_{\mathrm{Age}}(z=20) \approx 150\,\mathrm{Myr}$$

$$t_{\mathrm{Gal}}(z=8) \approx 100\,\mathrm{Myr}$$

21 cm line in cosmology

T_γ T_S T_b

$z = 13$

$\nu = 1.4\,\mathrm{GHz}$

$z = 0$

$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

brightness temperature

$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\ \mathrm{mK}$$

spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

Coupling mechanisms:
Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

Wouthysen-Field Effect

Hyperfine structure of HI

Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux

spin colour gas

$$T_S \sim T_\alpha \sim T_K$$

W-F recoils

$2_2P_{1/2}$

$2_1P_{1/2}$

$2_1P_{1/2}$

$2_0P_{1/2}$

$1_1S_{1/2}$

$\lambda = 21\,\mathrm{cm}$

$1_0S_{1/2}$

Wouthysen 1959

Field 1959

Wouthysen-Field Effect

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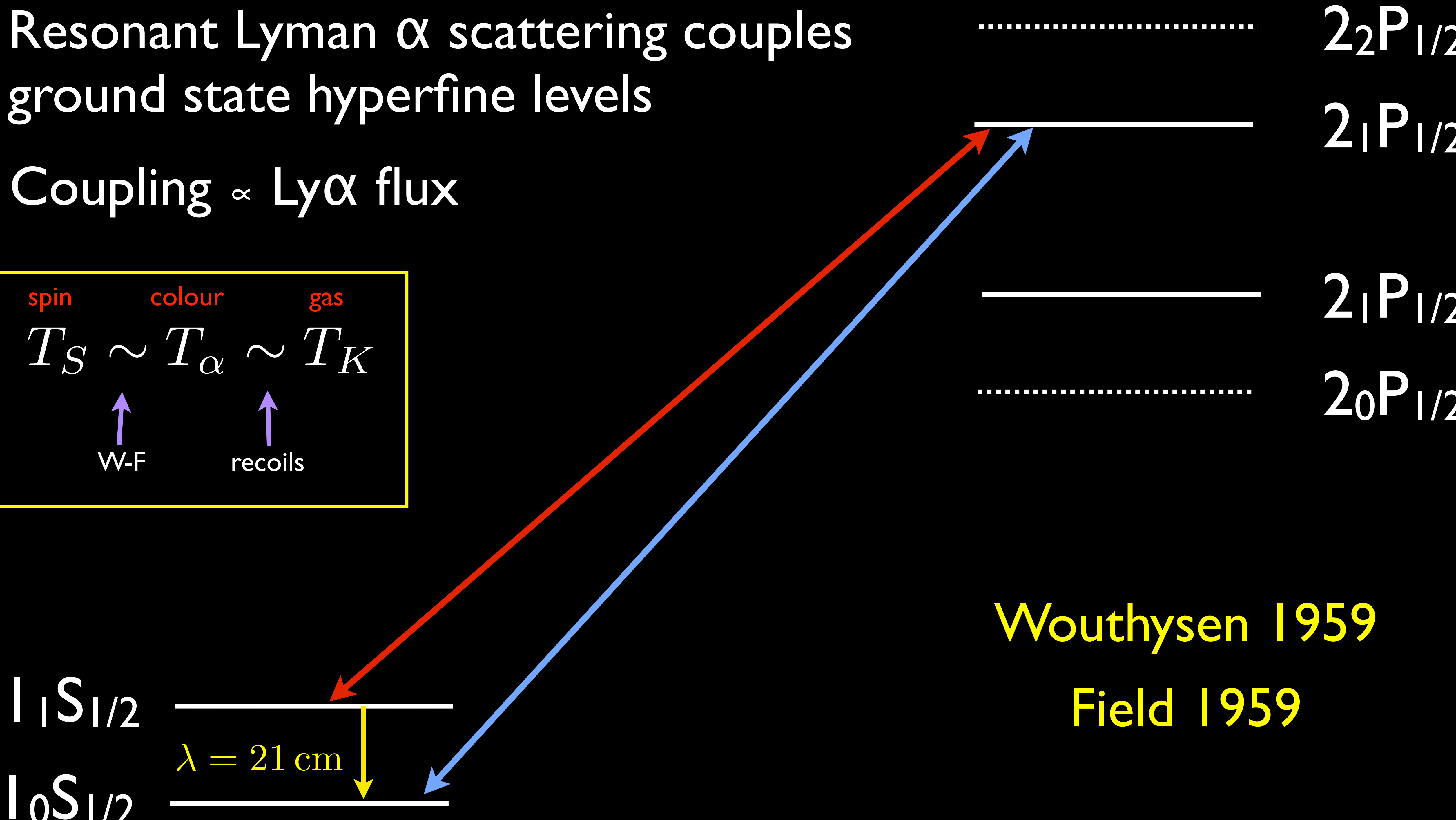

Wouthysen 1959

Field 1959

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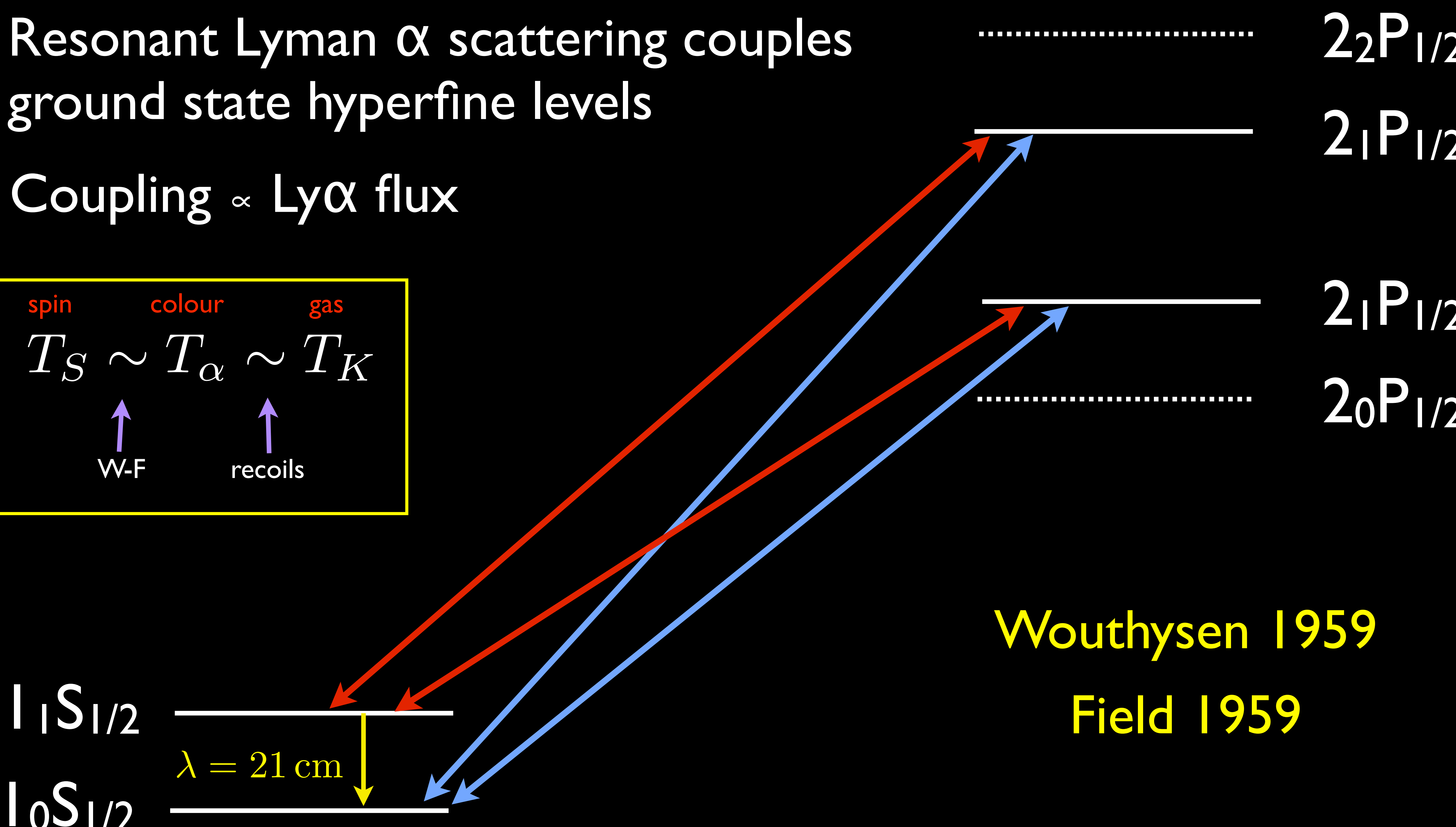


Wouthysen 1959

Field 1959

What did the first galaxies look like?

Lyman alpha photons originate from stars

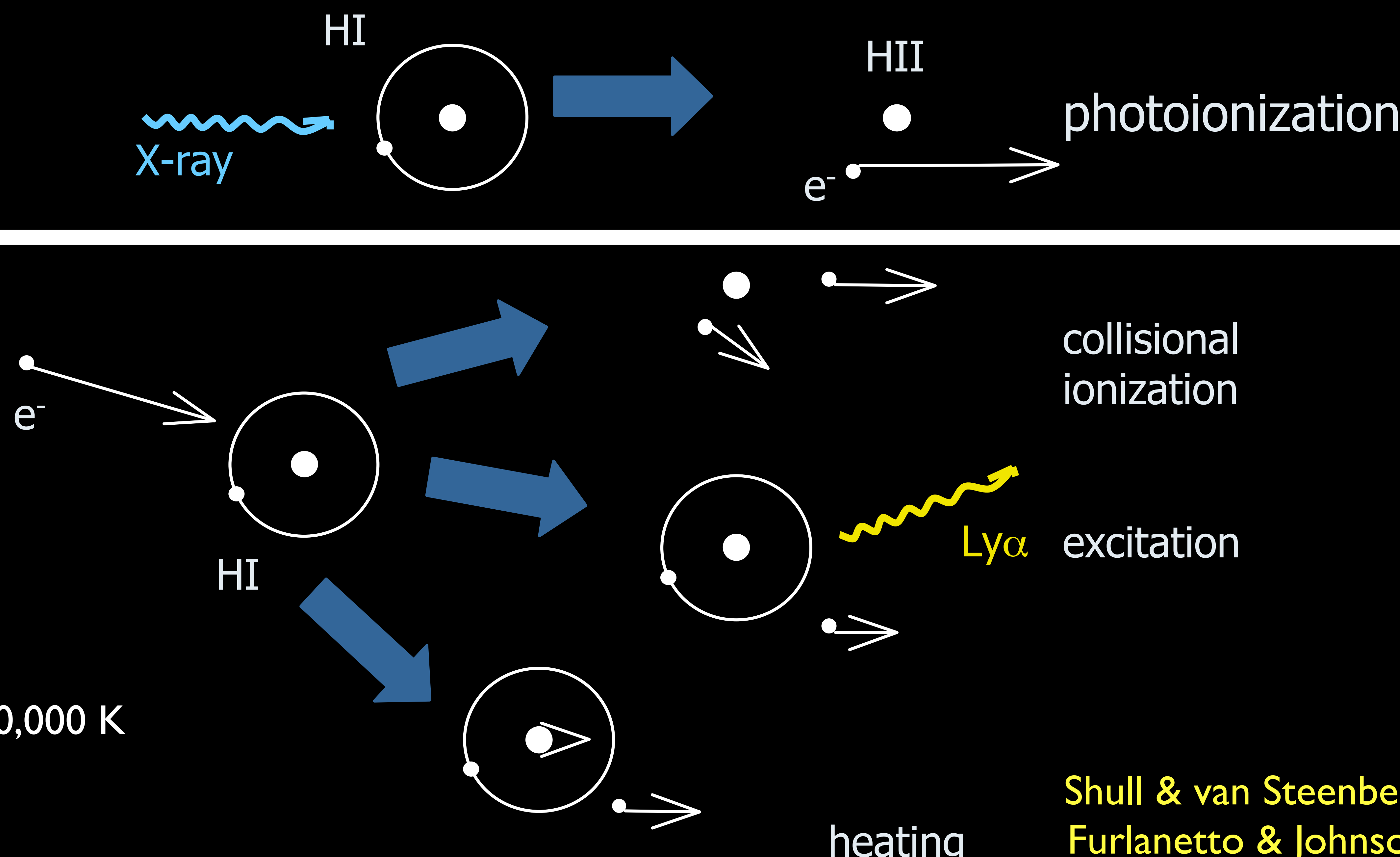
Population II or III?
(cooling by metals or hydrogen)

Star formation rate?
(feedback from radiation or heating)

Clustering properties?
(host halo mass)

Thermal history

- X-rays likely dominant heating source in the early universe
  - (Lya heating inefficient, uncertain shock contribution)
- Long X-ray mean free path allows heating far from source



1eV=10,000 K

Shull & van Steenberg 1985
Furlanetto & Johnson 2010

What were the first X-ray sources?

- Only weak constraints from diffuse soft X-ray background

Dijkstra, Haiman, Loeb 2004

- Fiducial model extrapolates local X-ray-FIR correlation to connect X-ray emission to star formation rate

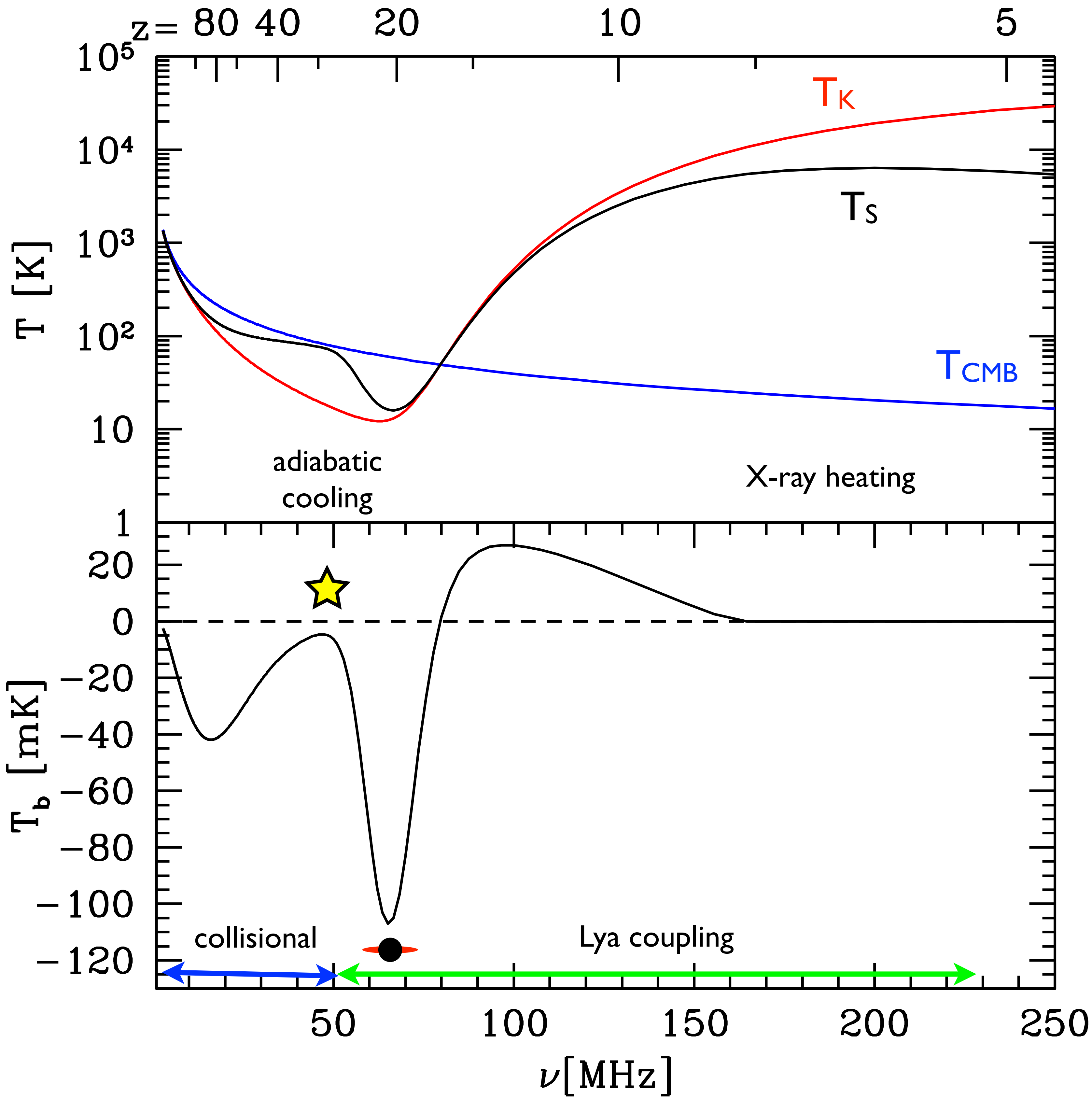
  ~1 keV per baryon in stars

Glover & Brand 2003

- Might track growth of black holes instead of star formation

Zaroubi+ 2007

21 cm mean signal



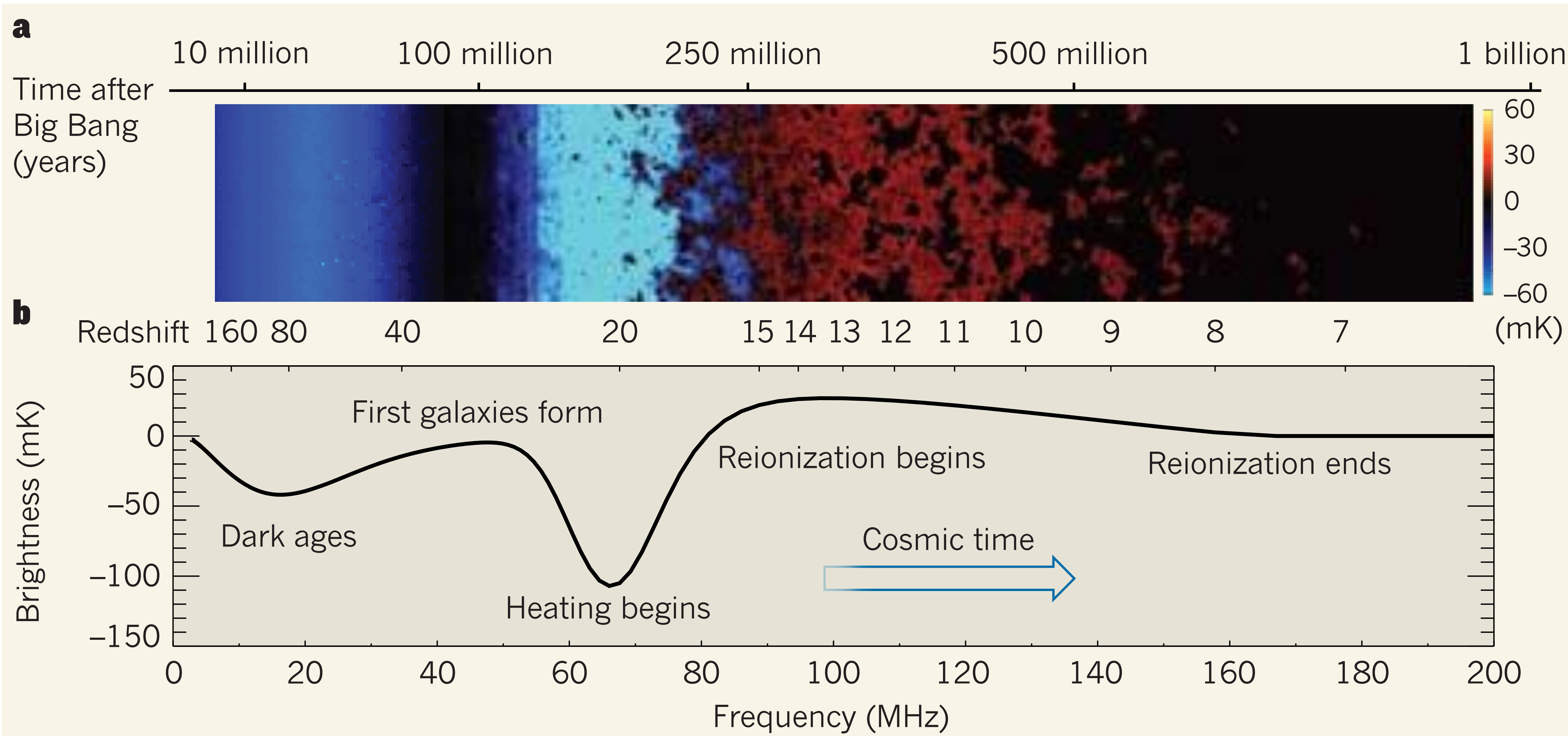
Main processes:

1) Collisional coupling
2) Lya coupling
3) X-ray heating
4) Photo-ionization

Furlanetto 2006

Pritchard & Loeb 2010

EoR signal



Pritchard & Loeb 2010

>100 MHz

>70 MHz

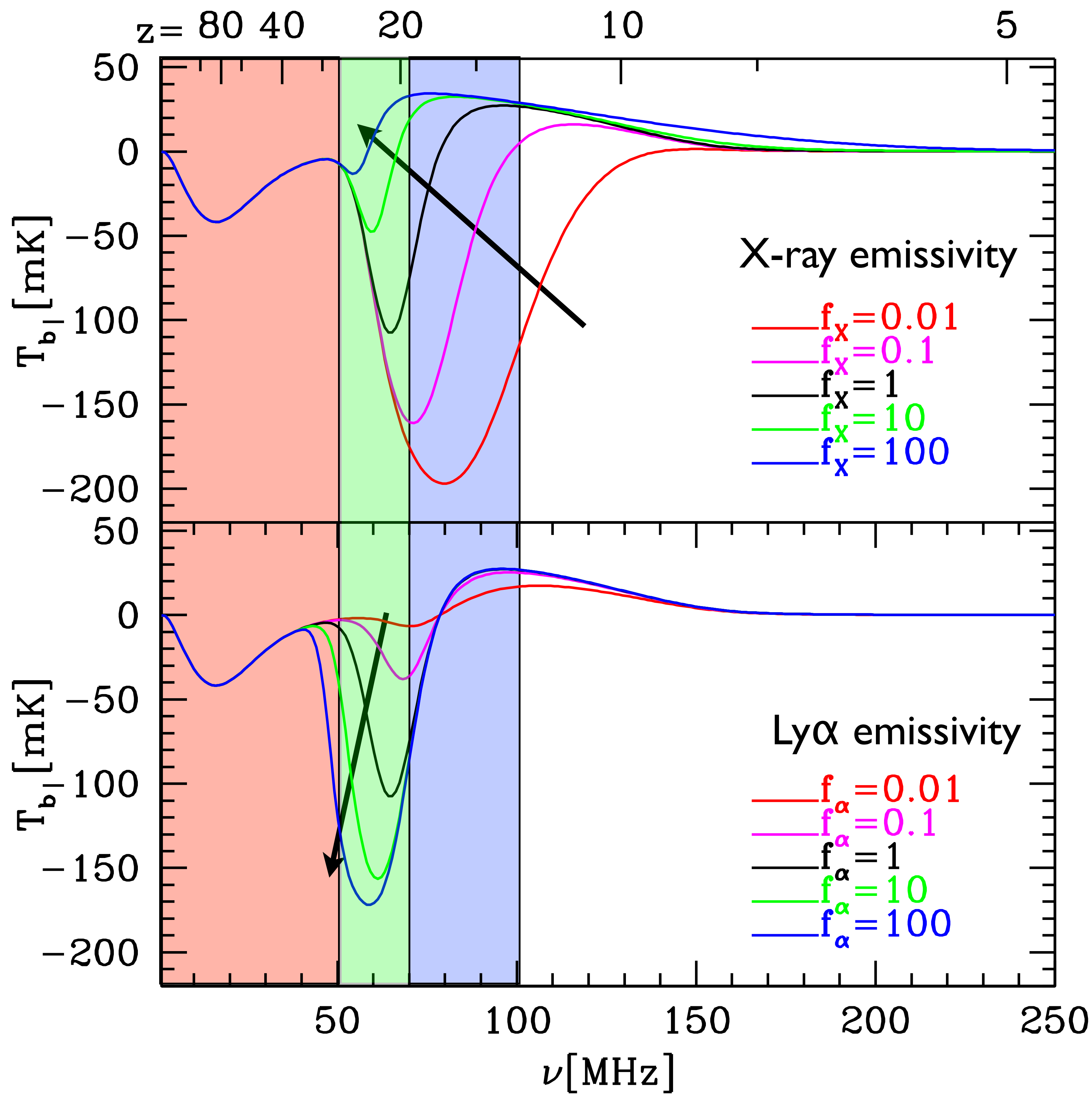
>50 MHz

Uncertain high redshift sources

Properties of first galaxies are very uncertain

Frequencies below 100 MHz probe period of X-ray heating & Lya coupling

Possibility of heating from shocks or exotic physics too

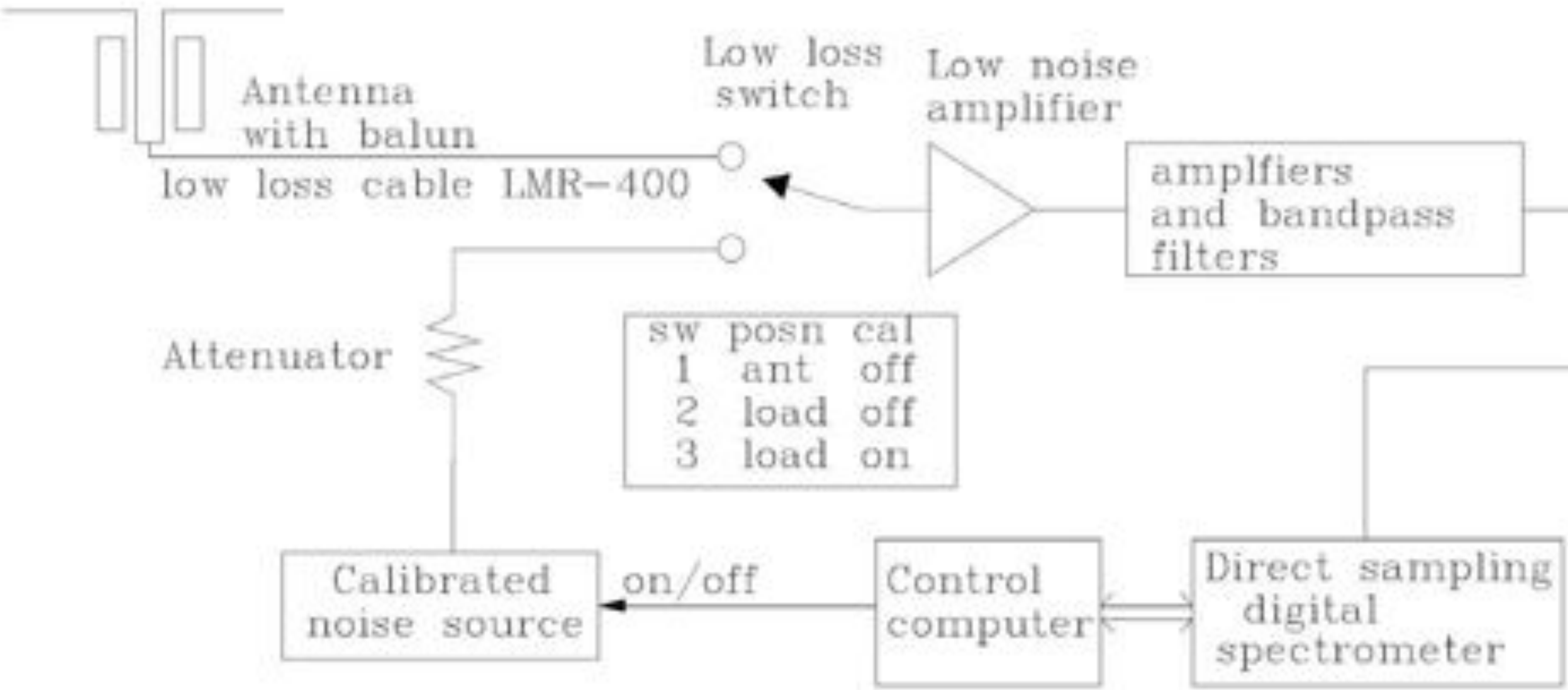


Pritchard & Loeb 2010

Global 21 cm experiments

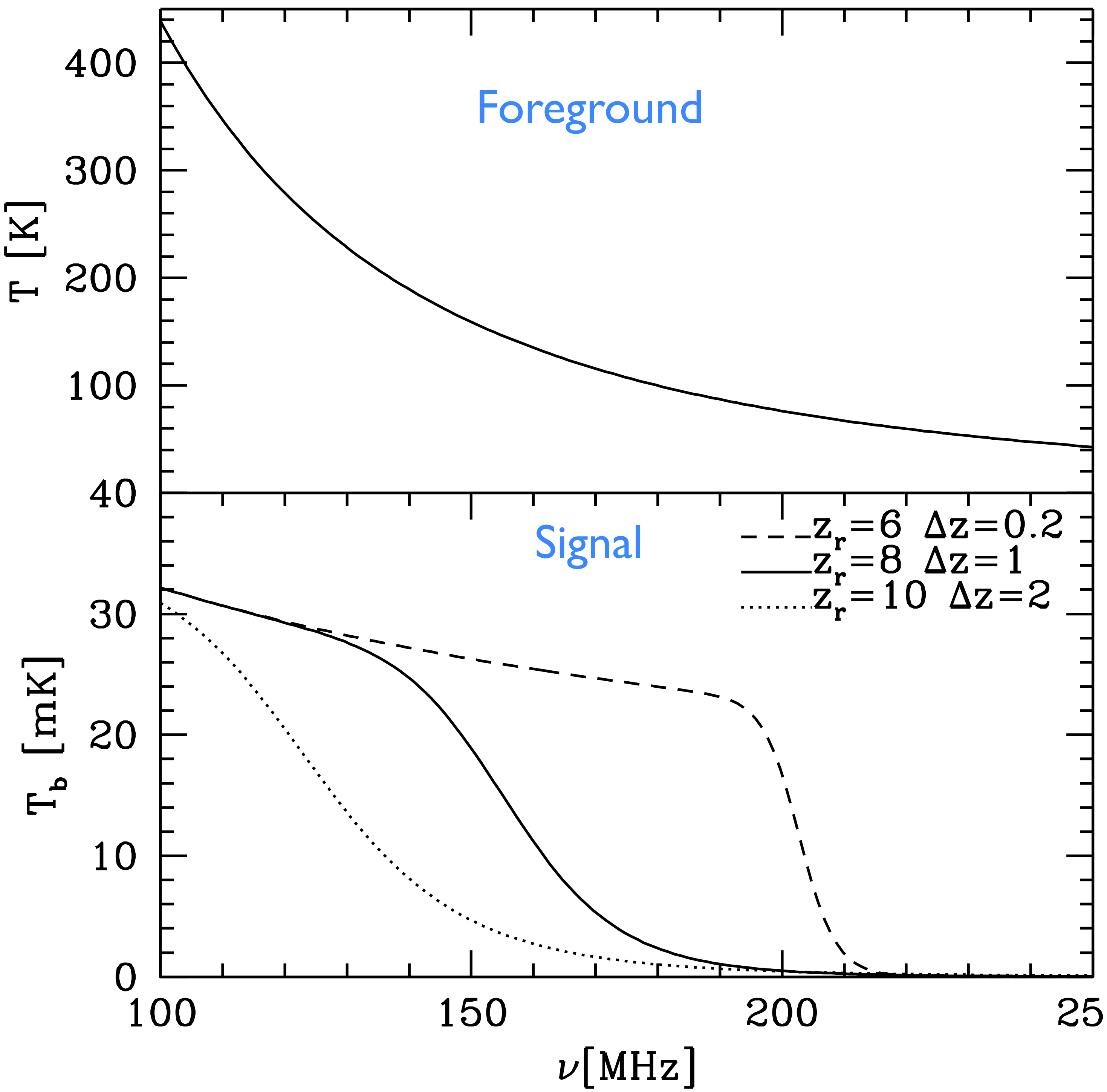
Global signal can be probed
by single dipole experiments
e.g. EDGES - Bowman & Rogers 2008
CoRE - Ekers+

Bowman & Rogers 2010
today's Nature



Switch between sky and calibrated noise source

Frequency subtraction



Look for sharp 21 cm signal against smooth foregrounds
Shaver+ 1999

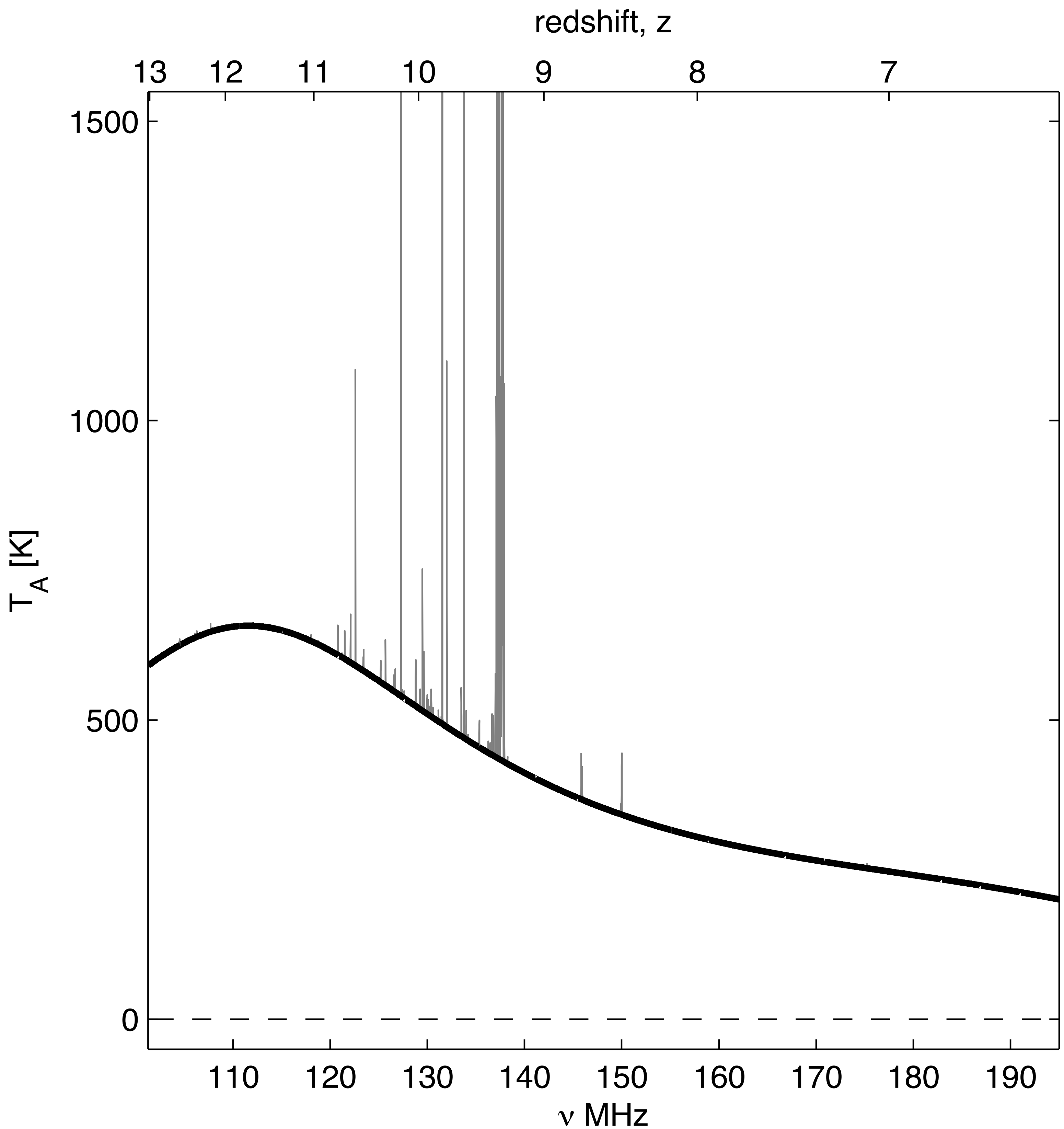
$$\log T_{\rm fit} = \sum_{i=0}^{N_{\rm poly}} a_i \log(\nu/\nu_0)^i.$$

TS>>TCMB
no spin temperature dependence

Extended reionization histories closer to foregrounds

$$T_b(z) = \frac{T_{21}}{2}\left(\frac{1+z}{10}\right)^{1/2}\left[\tanh\left(\frac{z-z_r}{\Delta z}\right)+1\right]$$

Latest results from EDGES



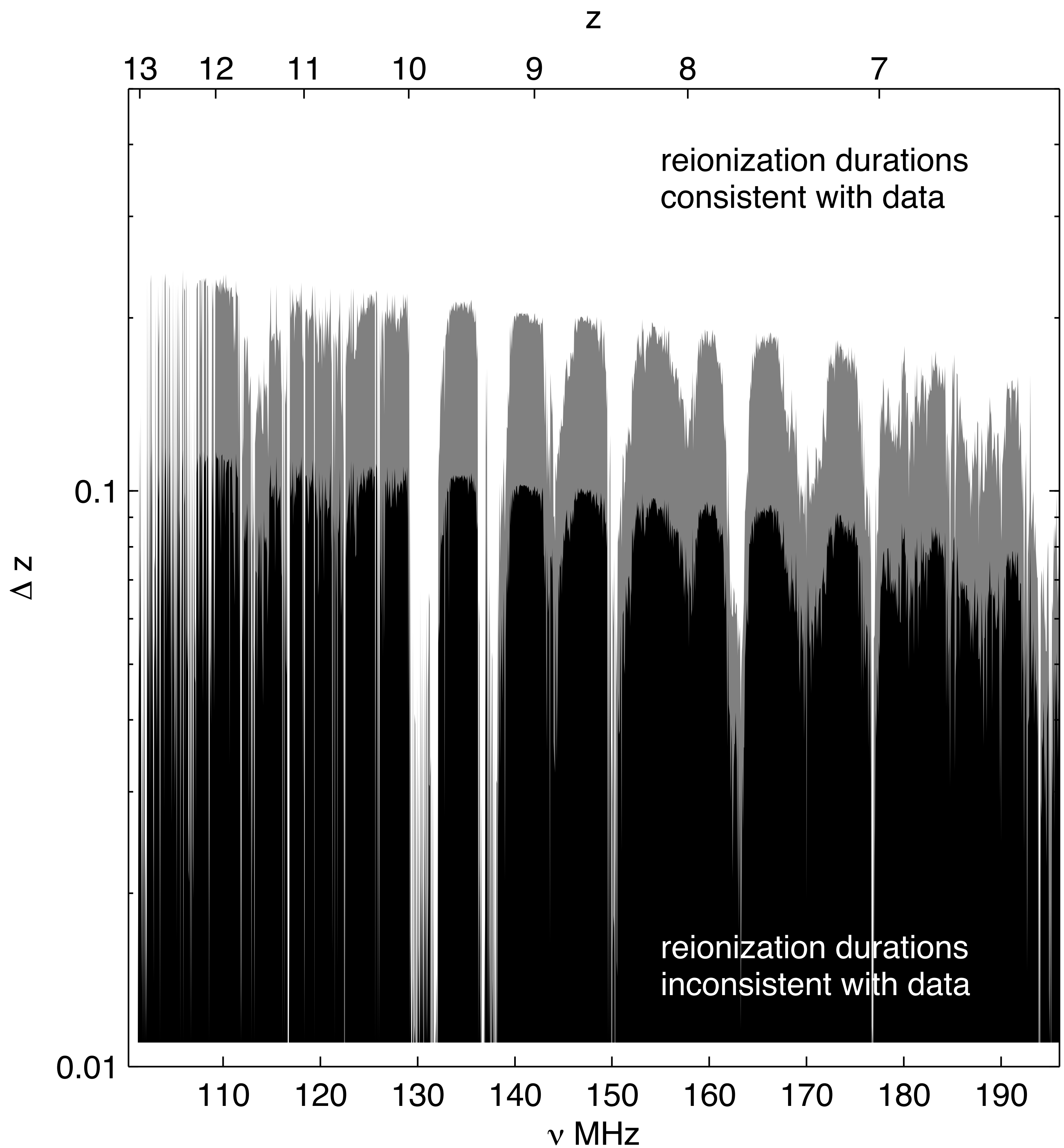
Bowman & Rogers 2010
today's Nature

Three months integration
at low duty cycle
at MWA site

Thermal noise ~ 6mK

Role off at edges of band
due to instrumental response

Reionization constraints

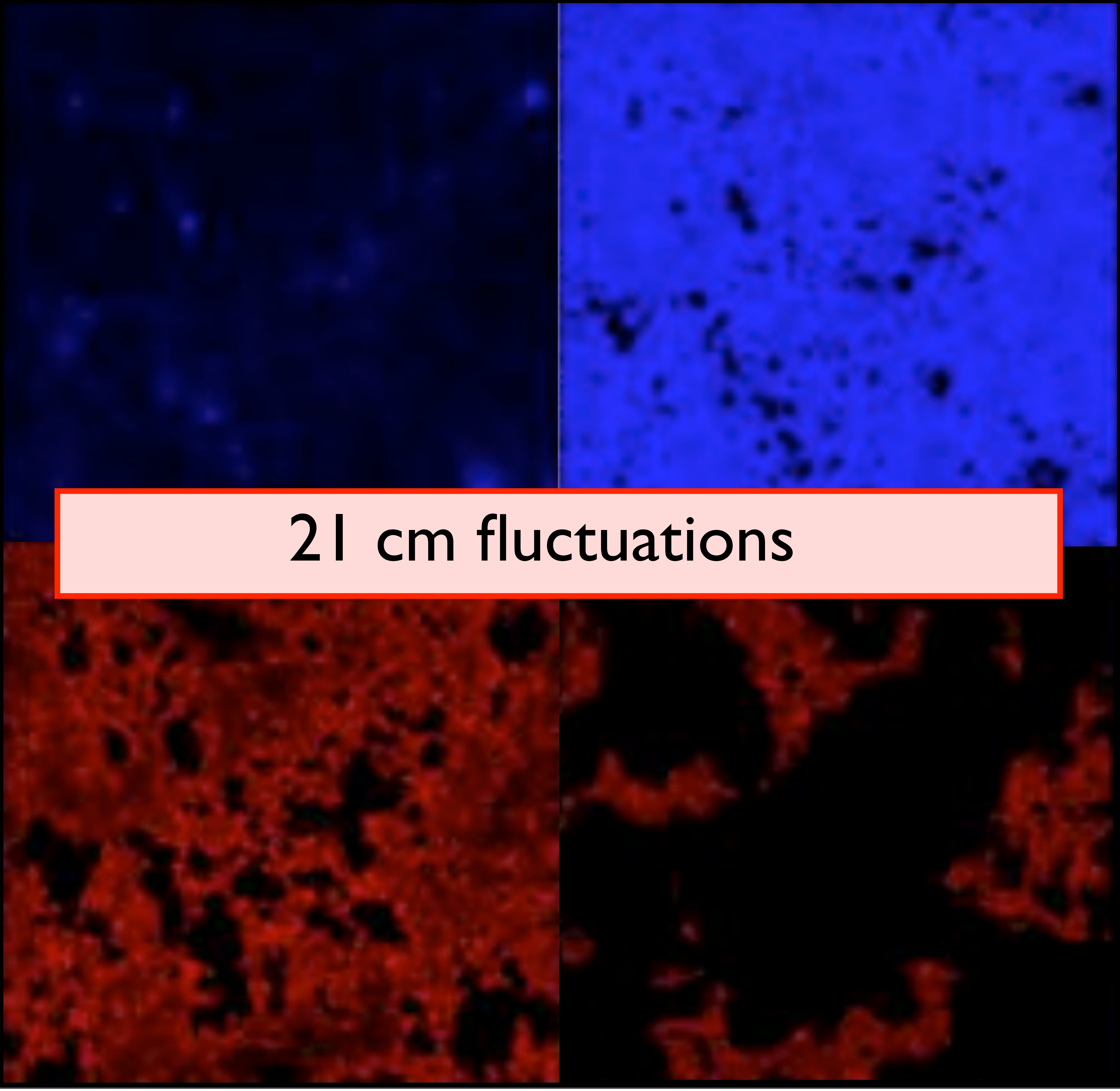


Bowman & Rogers 2010
today's Nature

marginalising over 12th order polynomial fit to foregrounds and instrument response

Some channels lost to RFI

$\Delta z<0.06$ excluded at 95% level



21 cm fluctuations

Brightness Fluctuations

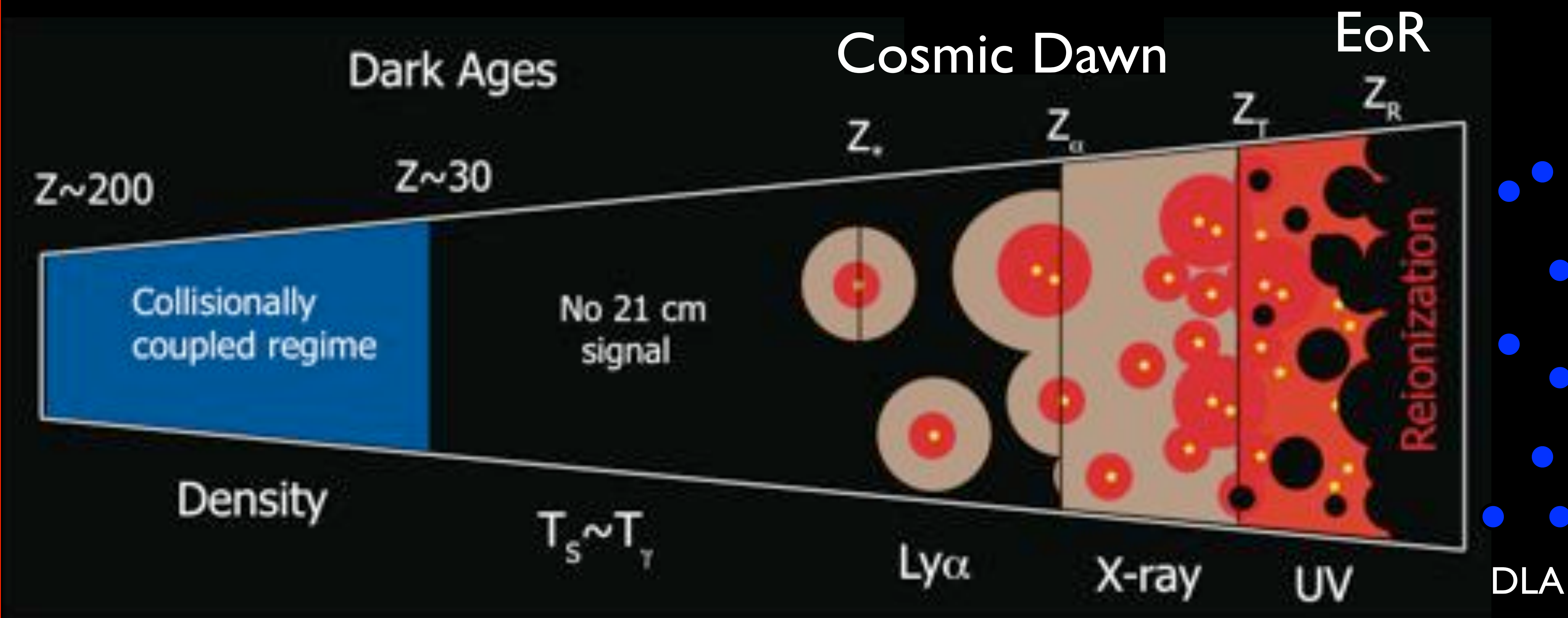
$$\underset{\text{brightness temperature}}{\delta_{T_b}} = \underbrace{\underset{\text{cosmology}}{\overset{\text{density}}{\beta\delta_b}} + \underset{\text{reionization}}{\overset{\text{neutral fraction}}{\beta_x \delta_{x_{HI}}}}}_{\text{Neutral hydrogen}} + \underbrace{\underset{\text{X-ray heating}}{\overset{\text{gas temperature}}{\beta_T \delta_{T_k}}} + \underset{\text{Lya sources}}{\overset{\text{Lyman alpha flux}}{\beta_\alpha \delta_\alpha}}}_{\text{spin temperature}} - \underset{\text{cosmology}}{\overset{\text{peculiar velocities}}{\delta_{\partial v}}}$$

Brightness Fluctuations

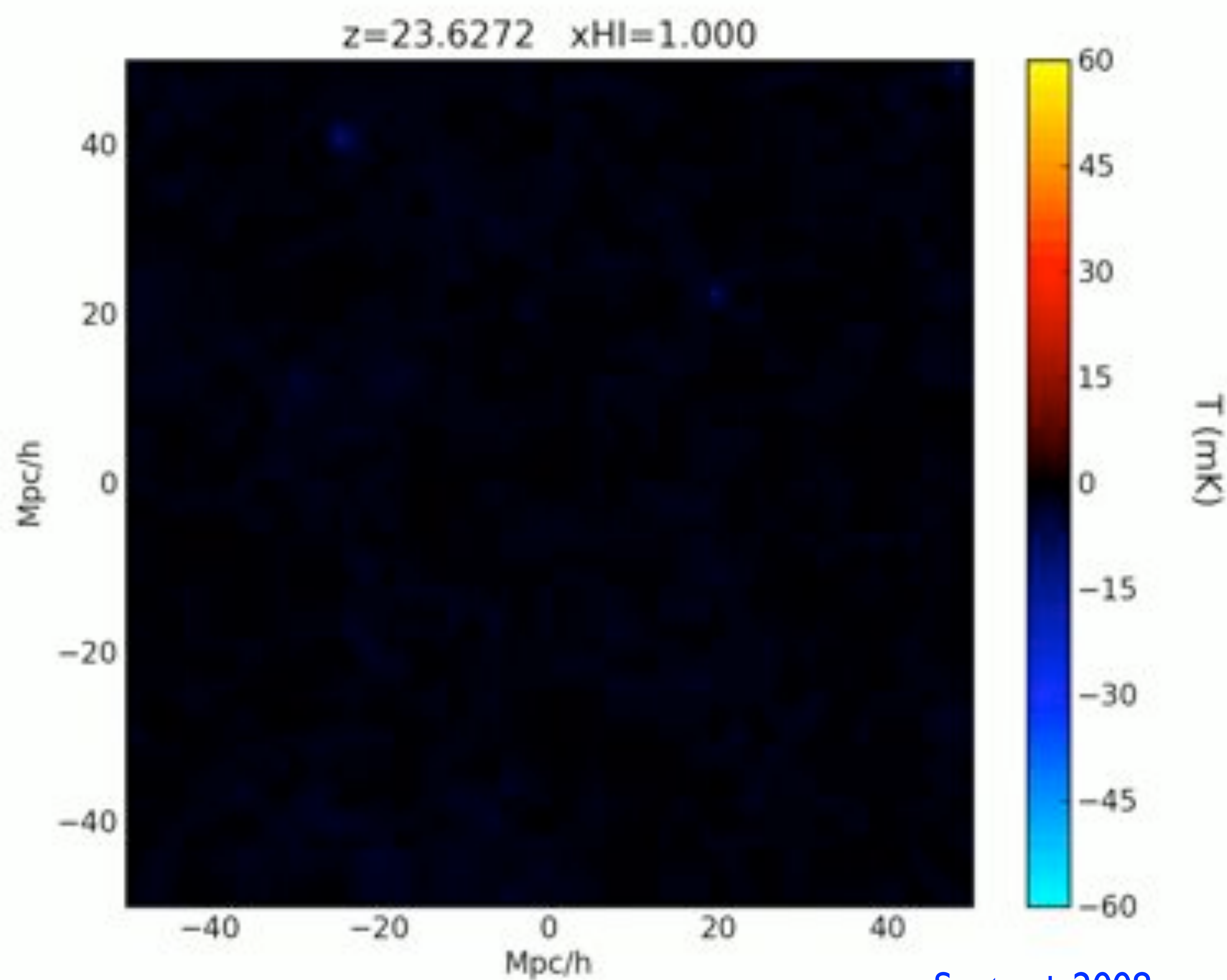
brightness temperature	density	neutral fraction	gas temperature	Lyman alpha flux	peculiar velocities

$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

cosmology	reionization	X-ray heating	Lya sources	cosmology

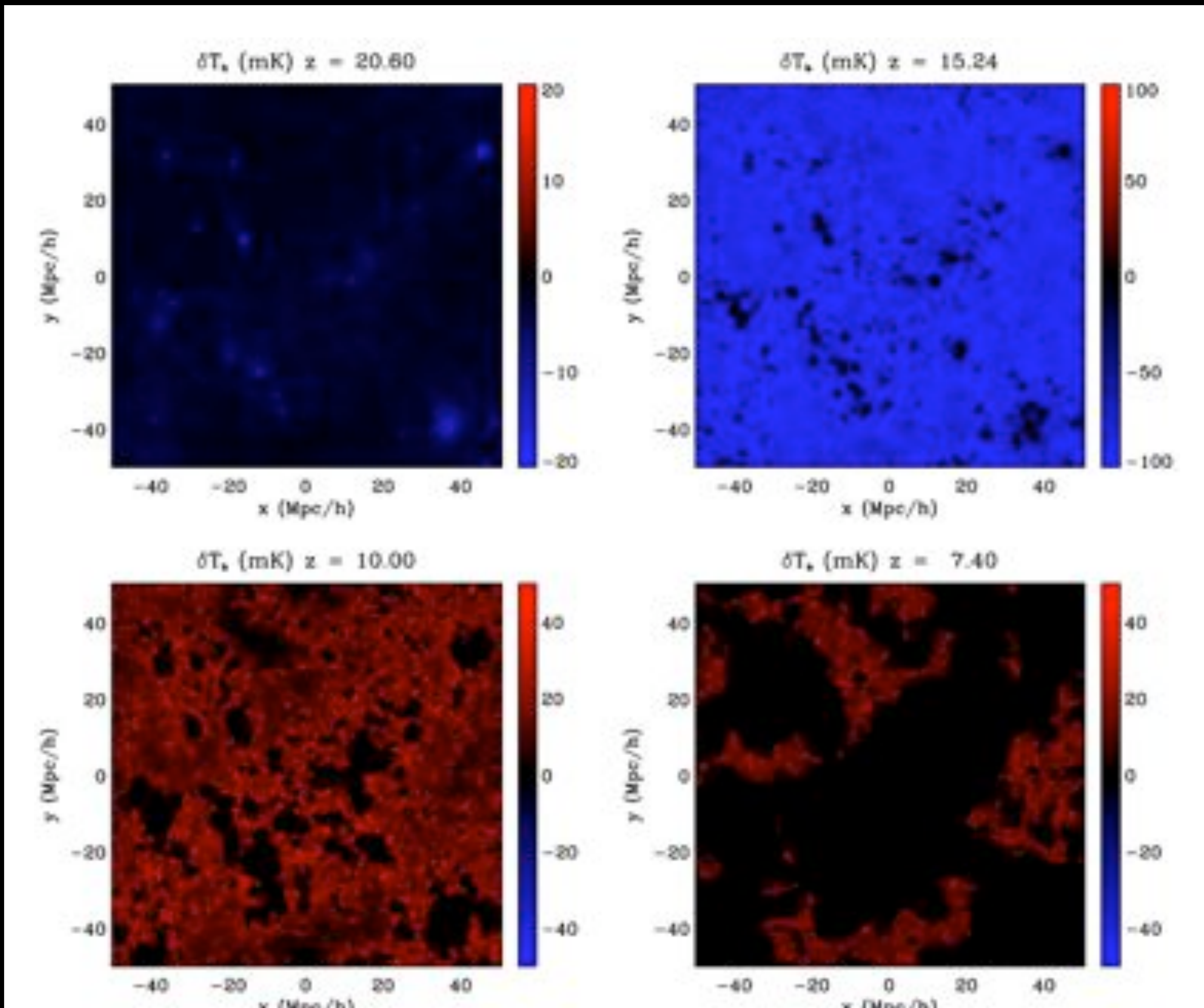


Numerical simulation



Santos+ 2008

Numerical simulations



Santos+ 2008

100/h Mpc ~ 1 deg @z=7.4

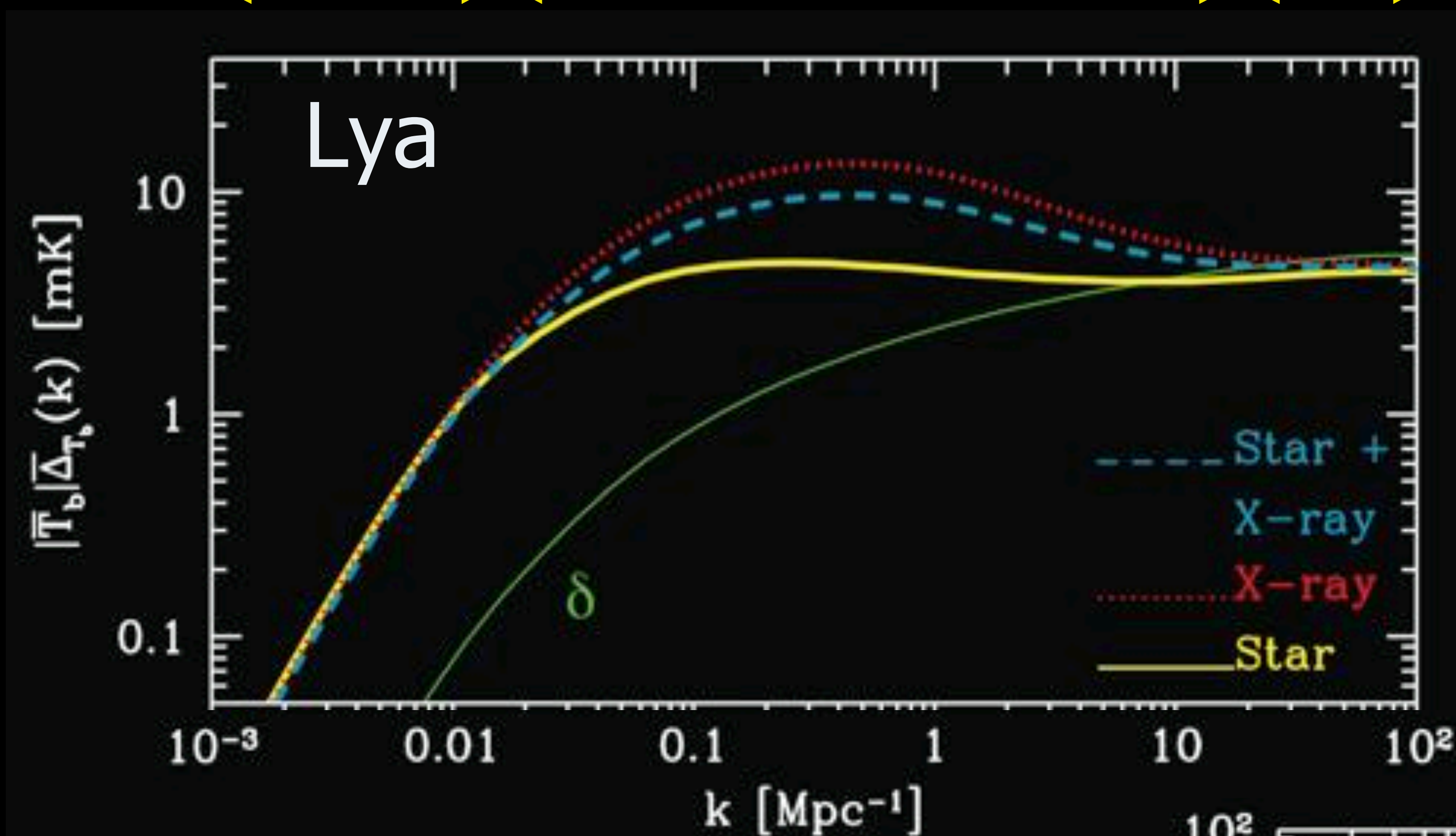
Basics of reionization simulation well understood
- dynamic range is hard

Fast approximate schemes being developed:
- Santos+ 2009 "Fast21CM"
- Mesinger+ 2010 "21cmFast"
- Thomas+ 2010 "BEARS"

Detailed numerical simulation including spin temperature limited but underway:
- Baek+ 2008, 2010

Power spectrum

bias — source properties — density



Lya fluctuations add power on large scales

Largest scales give information on source bias

Intermediate scales on source spectrum

Barkana & Loeb 2004

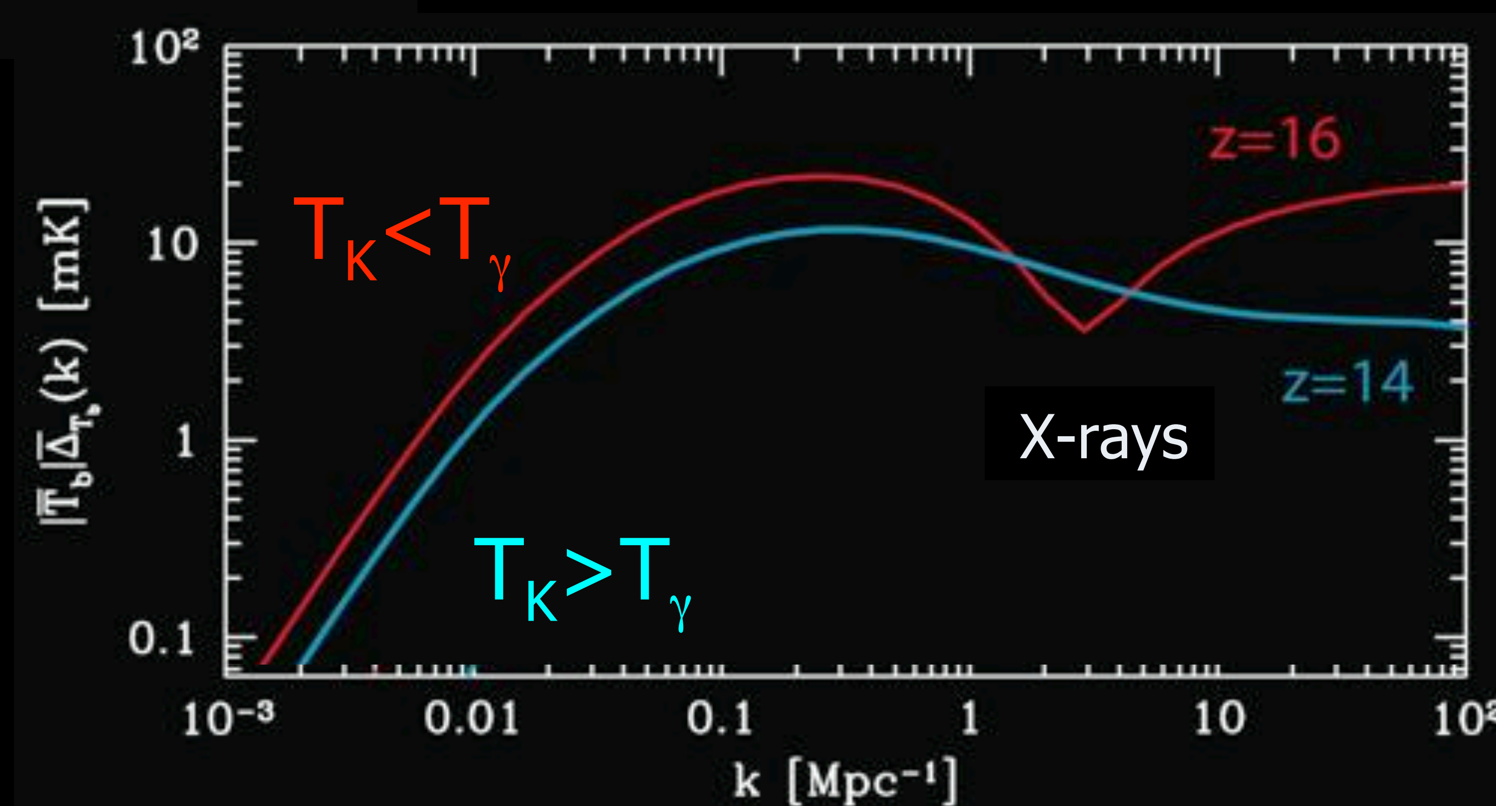
Chuzhoy, Alverez & Shapiro 2006

Pritchard & Furlanetto 2006

T fluctuations give information on thermal history

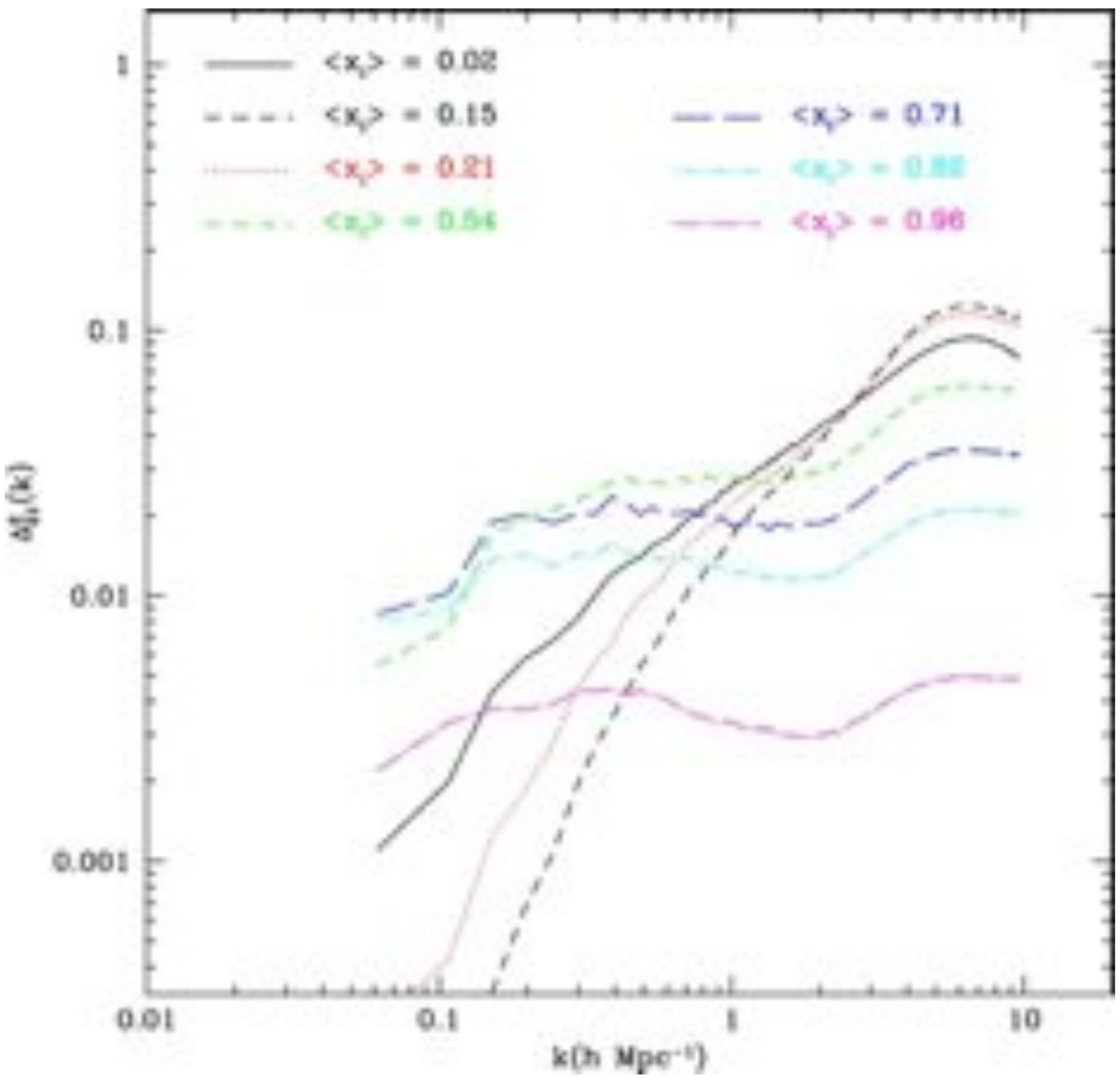
clustering/growth of mini-quasars could be very different

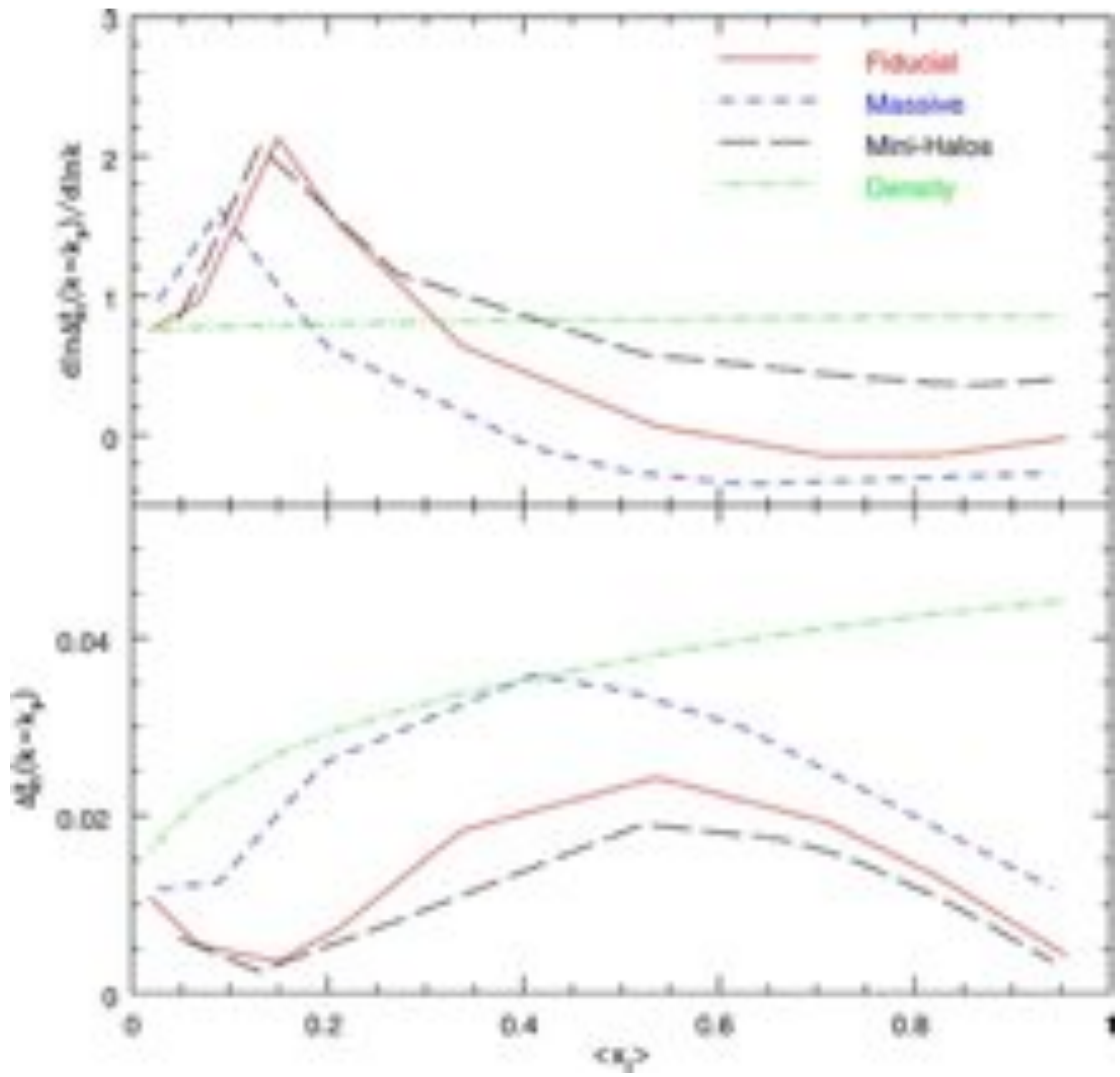
Pritchard & Furlanetto 2007



Amplitude and Tilt

Lidz+ 2008





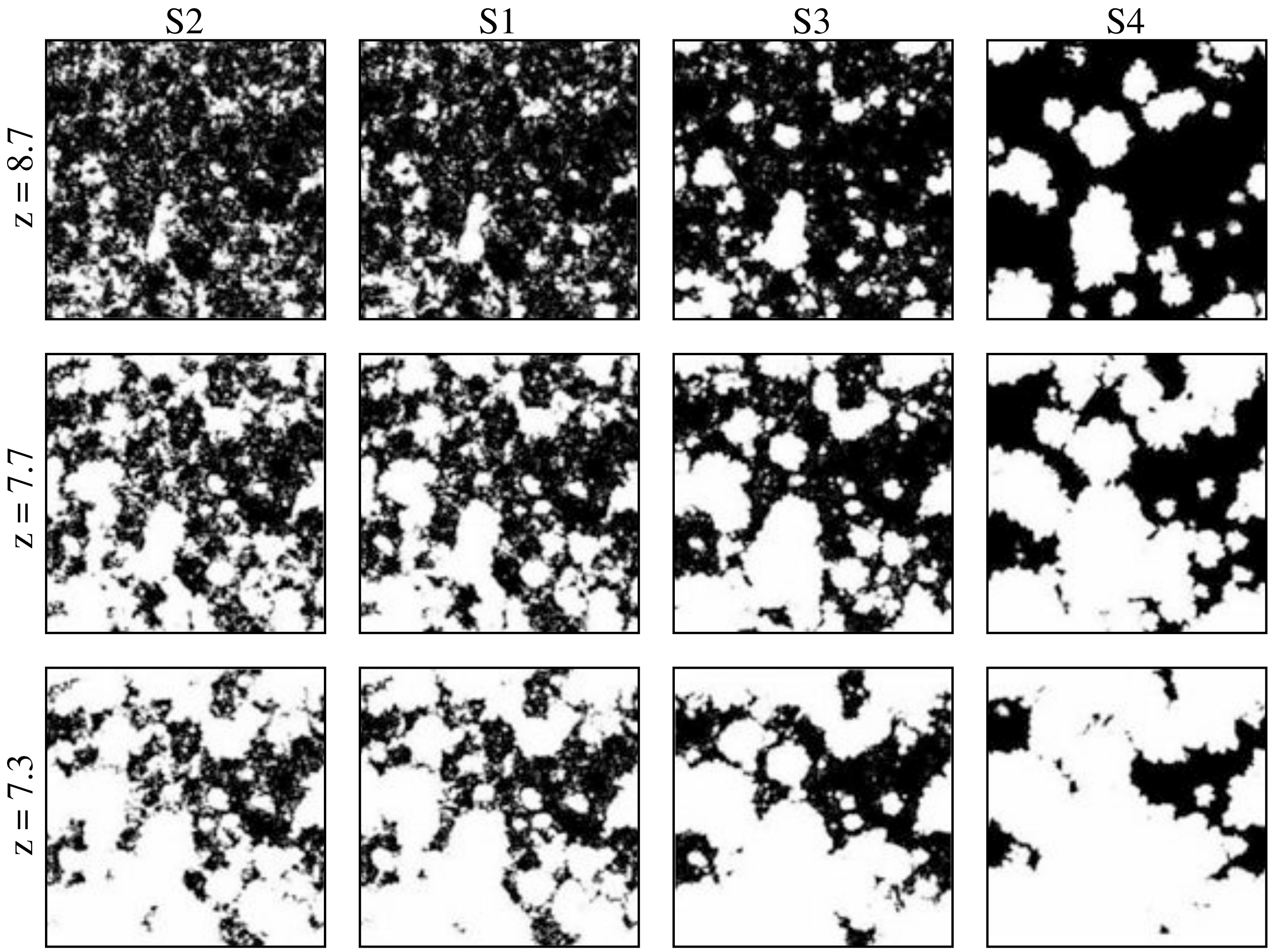
Power spectrum flattens and drops as reionization proceeds

MWA/LOFAR probably limited to amplitude and slope
-> neutral fraction measurement at 10% level at several redshifts

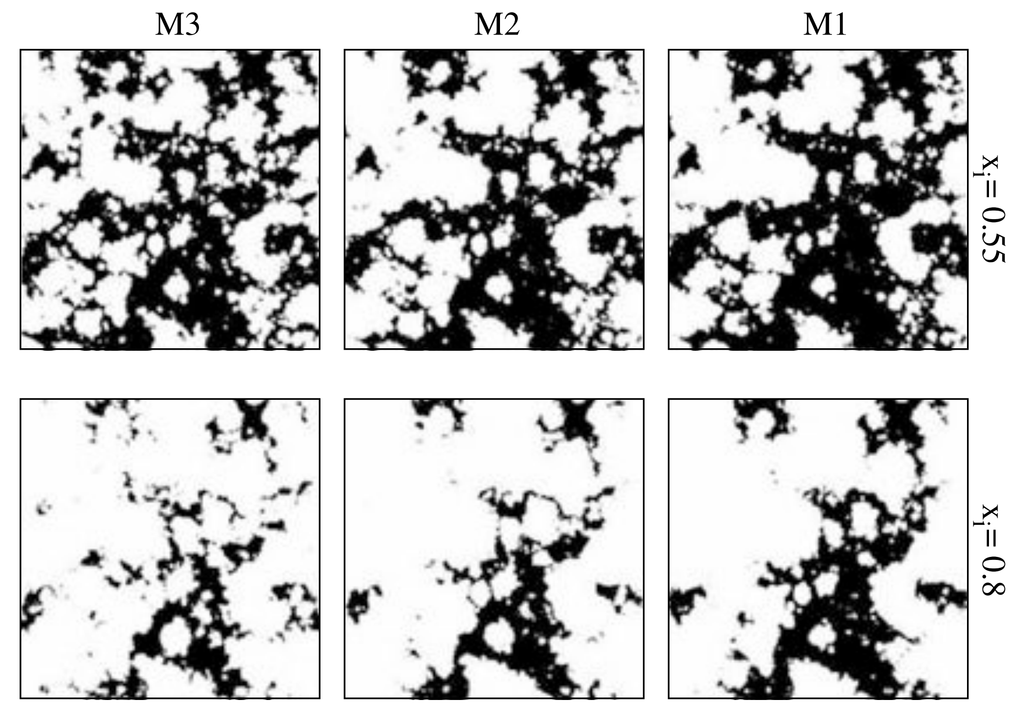
HII region morphology

More massive sources dominate

$L \propto m^{1/3}$ $L \propto m$ $L \propto m^{5/3}$ $m > 4\times 10^{10} m_\odot$



Minihaloes less important



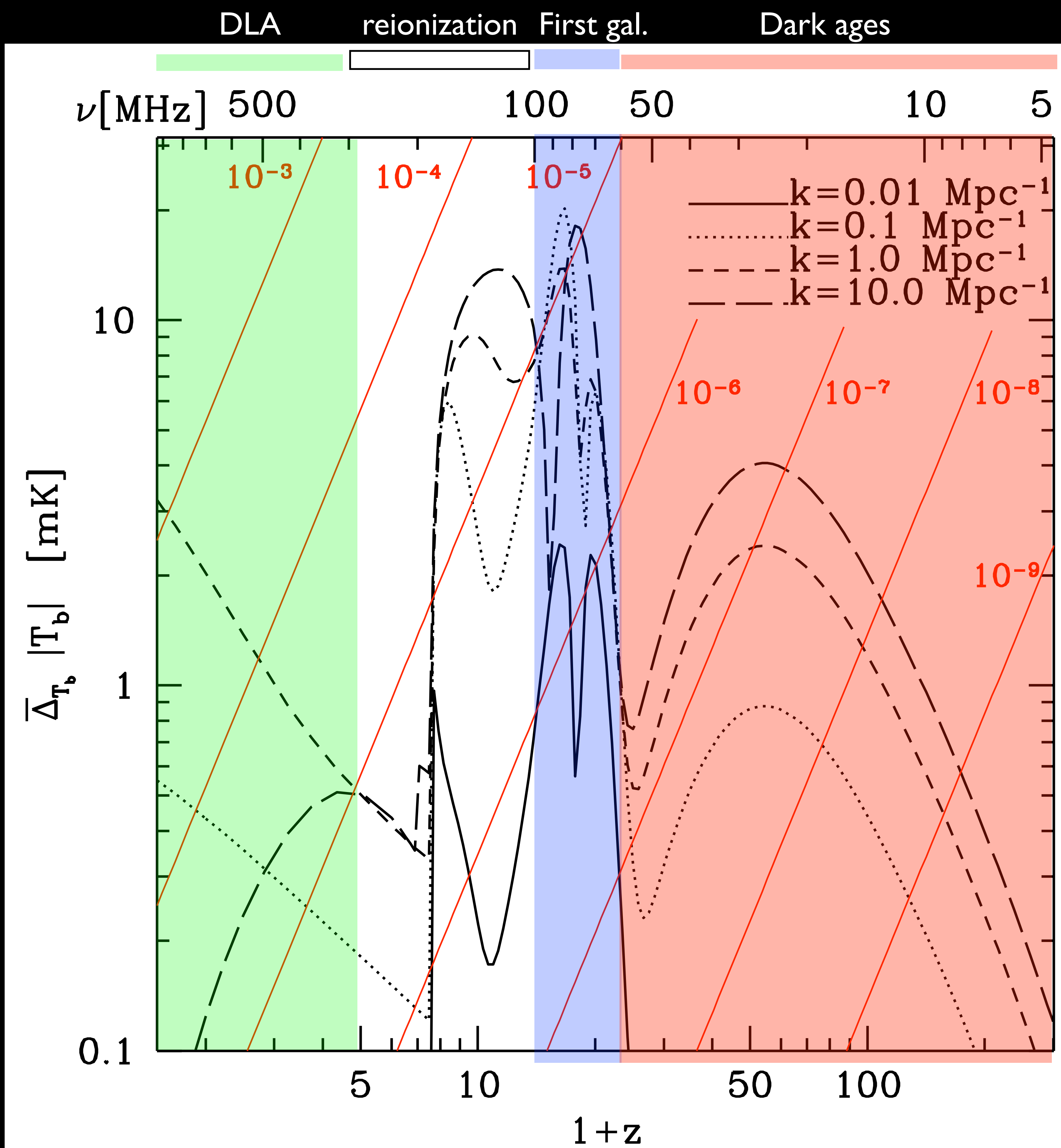
McQuinn+ 2007

HII region morphology determined primarily by:

1. neutral fraction
2. Sources
3. Sinks
4. Thermal feedback

Precise power spectrum measurements can distinguish these different scenarios

Evolution of power spectrum



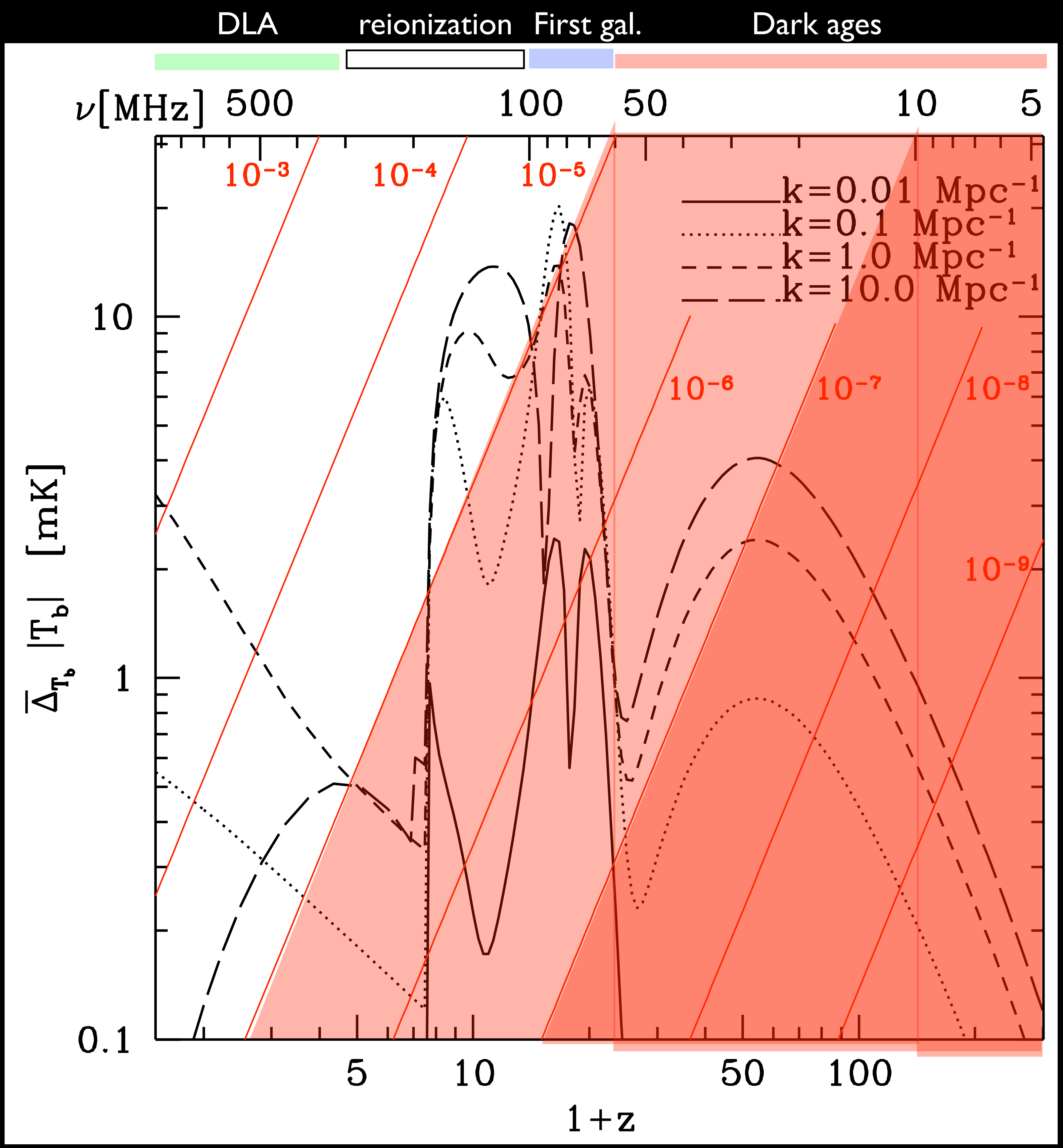
Evolution of signal means that detecting signal at z=20 not necessarily more difficult than at z=10

Distinguish different contributions via shape and redshift evolution

z=30-50 range much harder!

Pritchard & Loeb 2008

Evolution of power spectrum



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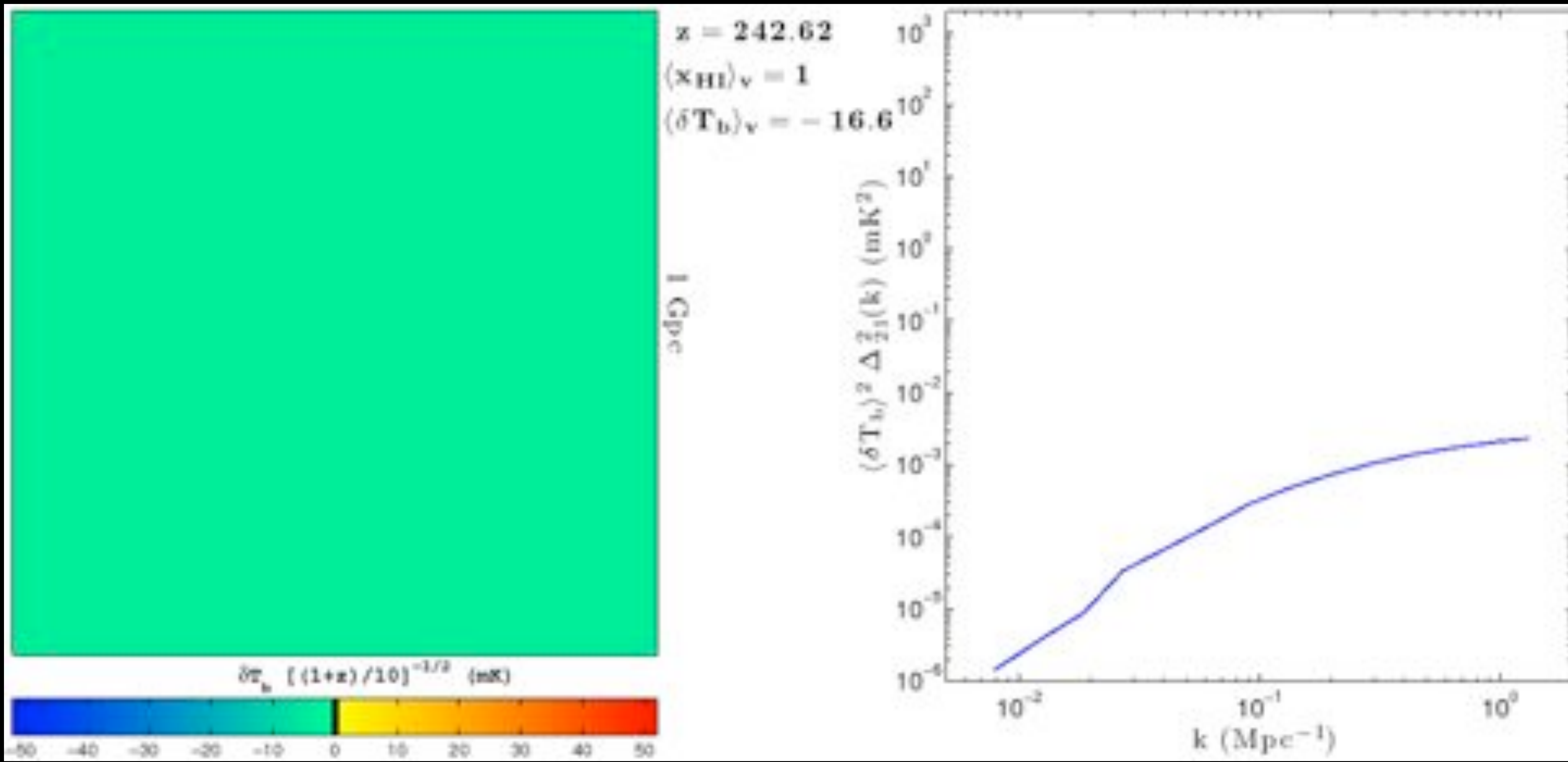
Pritchard & Loeb 2008

Evolution of the power spectrum

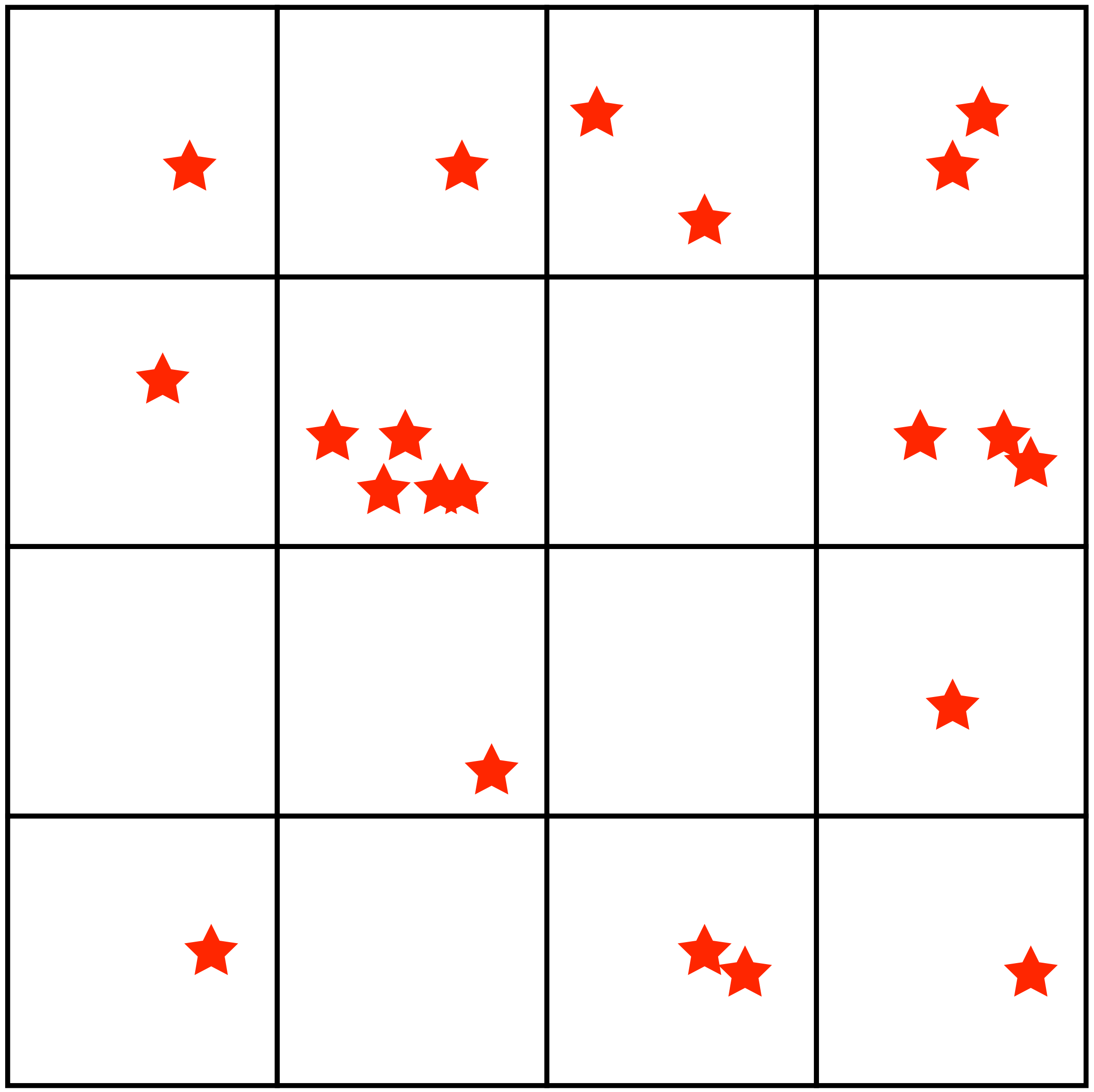


Mesinger+ 2010

More from Santos next...

Intensity mapping in outline

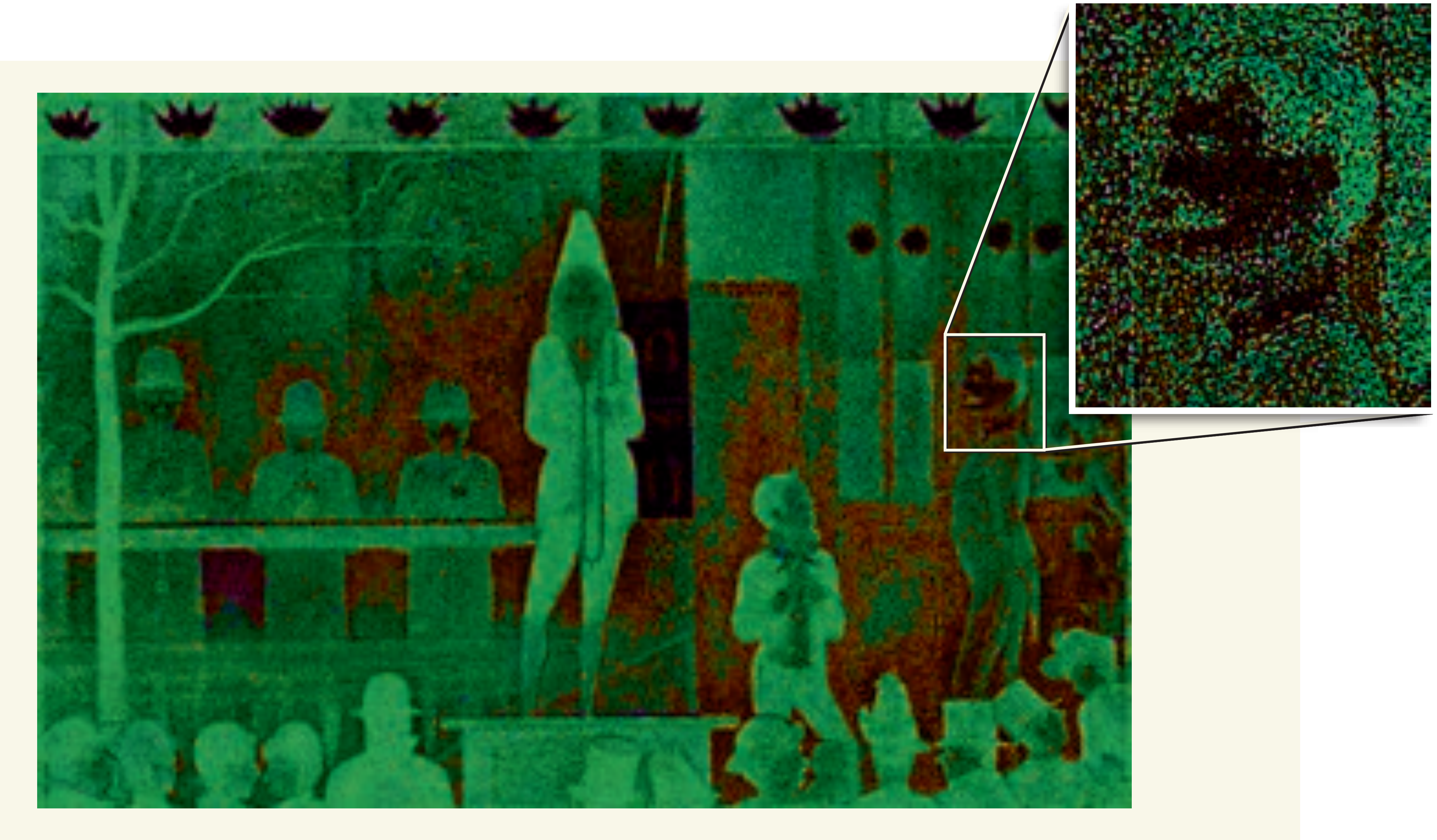
Can also target neutral hydrogen after reionization out to z~3 with instruments at frequencies > 350 MHz



Measure power spectrum of galaxies by integrating 21 cm flux
=> big picture of distribution of galaxies without spending time on resolving details

Intensity mapping in outline

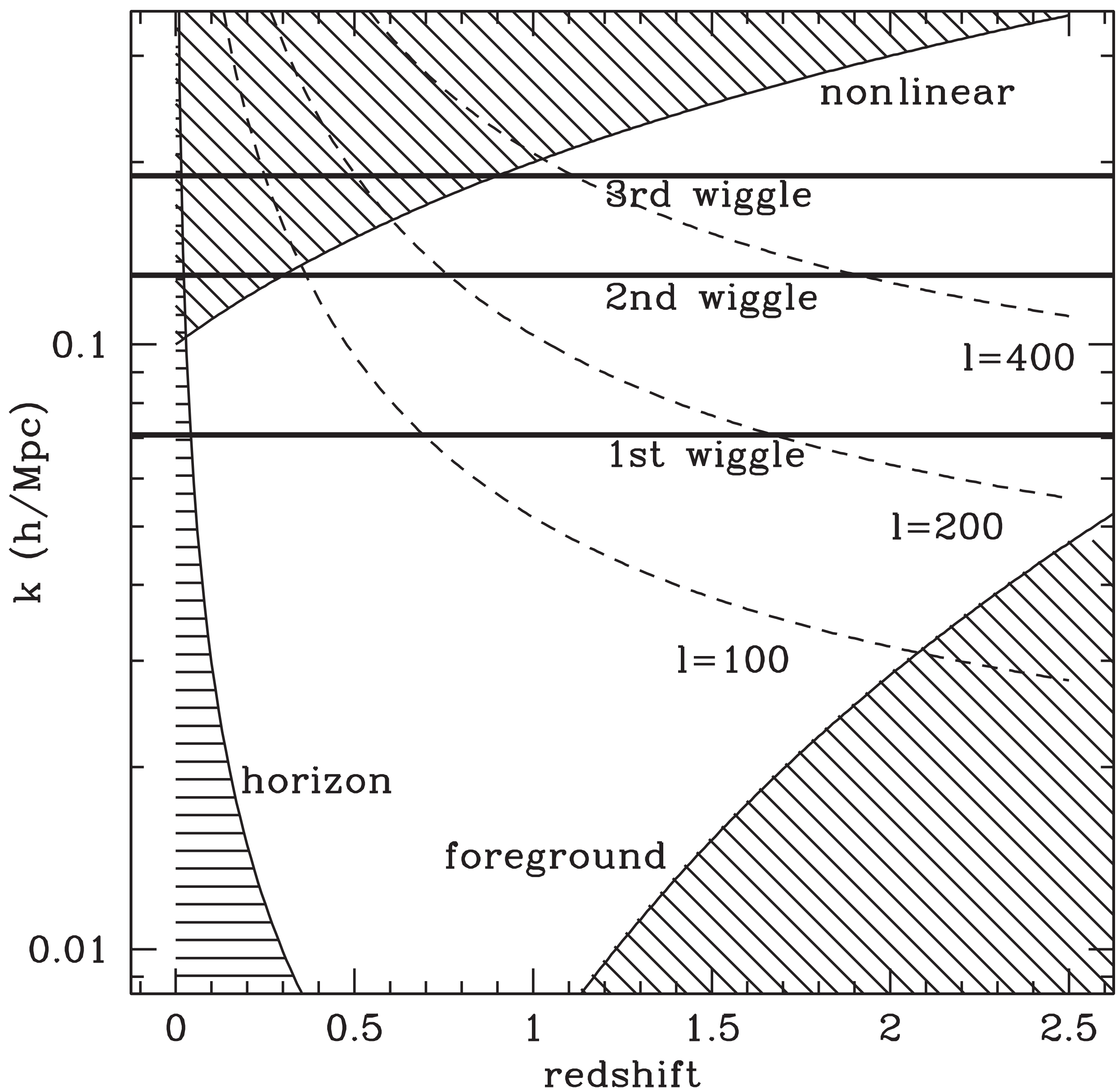
Can also target neutral hydrogen after reionization out to z~3 with instruments at frequencies > 350 MHz

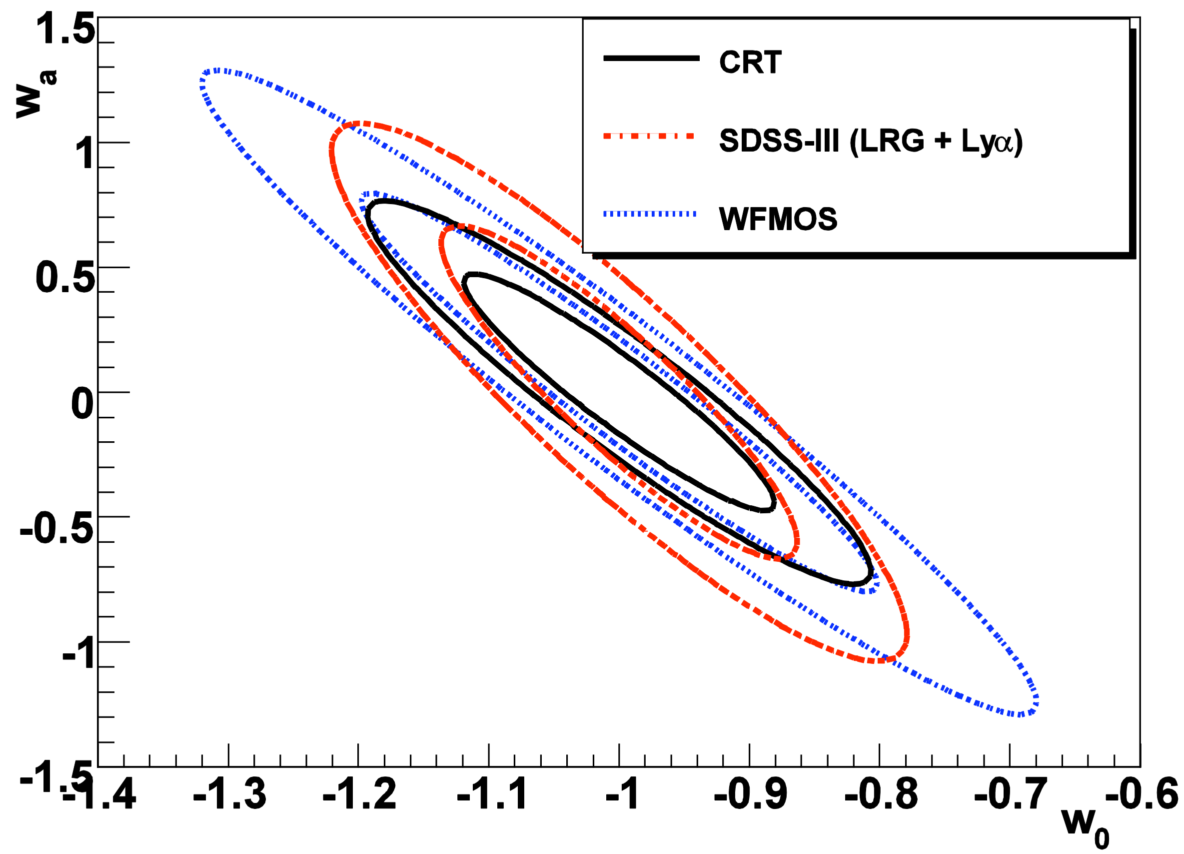


Carilli 2010

Measure power spectrum of galaxies by integrating 21 cm flux
=> big picture of distribution of galaxies without spending time on resolving details

Intensity mapping and dark energy





Cylinder Radio Telescope ~ 10,000 m^2

BAO first peak ~130 h^{-1} Mpc

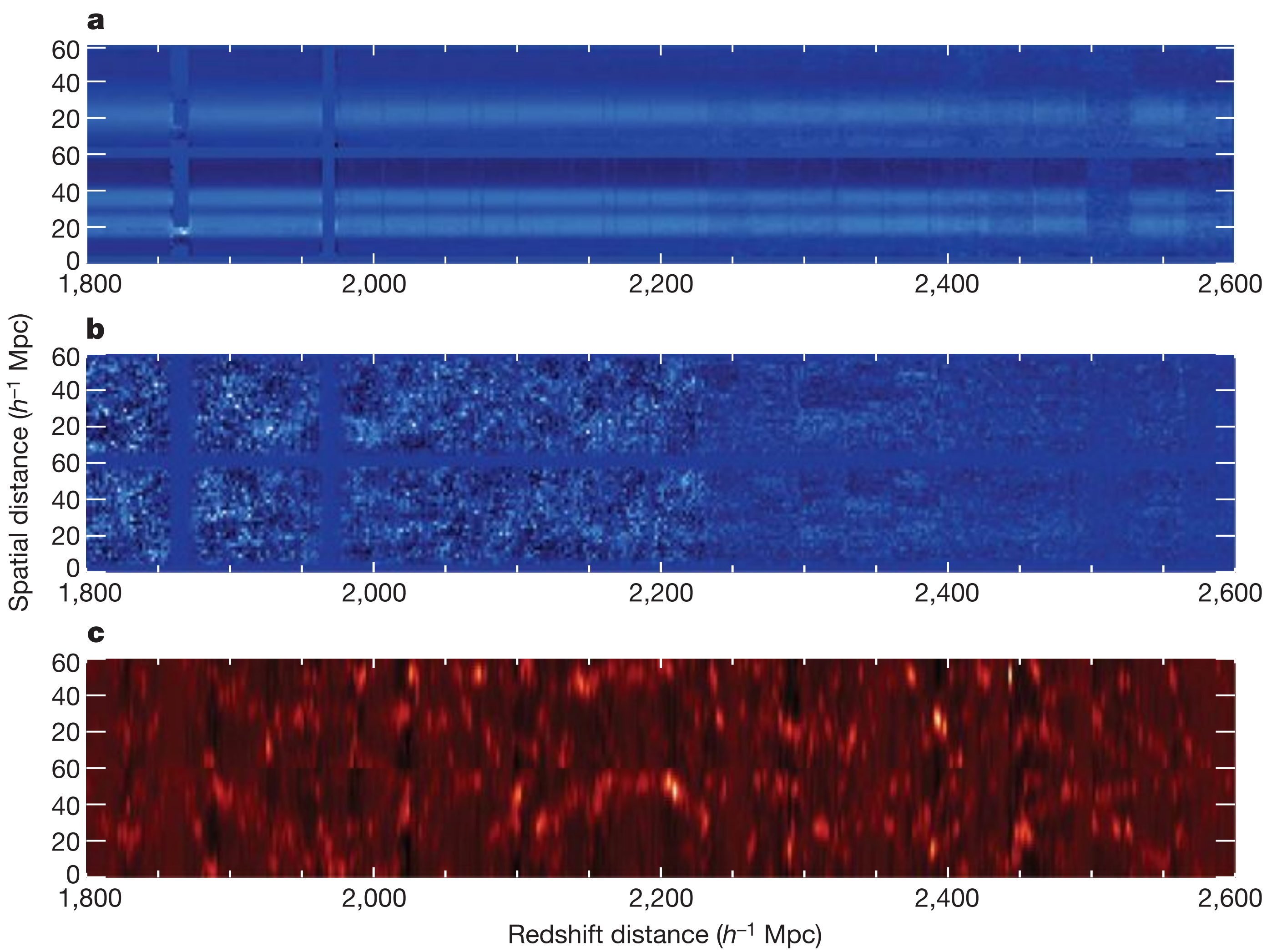
Covering large volumes allows strong constraints on dark energy and geometry

BAO third peak ~ 35 h^{-1} Mpc corresponds to ~20 arcmin

Also learn about Ω_{HI}

Chang, Pen, Bandura & Peterson 2010

Intensity mapping results



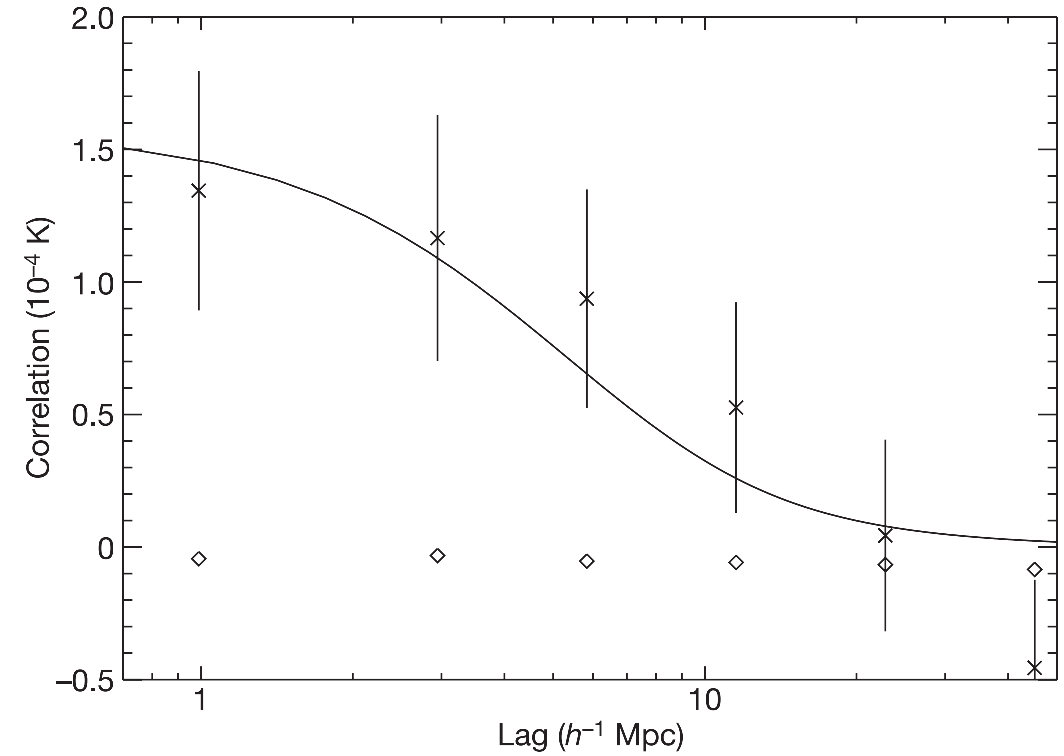


Figure 2 | The cross-correlation between the DEEP2 density field and GBT H I brightness temperature. Crosses, measured cross-correlation temperature. Error bars, 1σ bootstrap errors generated using randomized optical data. Diamonds, mean null-test values over 1,000 randomizations as described in Supplementary Information. The same bootstrap procedure performed on randomized radio data returns very similar null-test values and error bars. Solid line, a DEEP2 galaxy correlation model, which assumes a power law correlation and includes the GBT telescope beam pattern as well as velocity distortions, and uses the best-fit value of the cross-correlation amplitude.

Chang, Pen, Bandura & Peterson 2010

Observations at 0.5<z<1 showing cross-correlation between radio and galaxy signal

Conclusions

- Currently know very little observationally about reionization history
- Need to understand both sources and IGM => 21 cm observations with SKA-low key
- 21 cm global experiments capable of constraining broad-brush properties of signal
- 21 cm fluctuations complement the global signal and contain wealth of information
  - Lyman alpha fluctuations => star formation rate
  - Temperature fluctuations => X-ray sources
  - Neutral fraction fluctuations => topology of reionization
- For specified assumptions can begin to calculate 21 cm signal including all relevant physics
  - still large uncertainties in what assumptions about first galaxies are reasonable
- Spatial and redshift information are critical to separating the different contributions to the 21 cm signal
- SKA_1 and SKA_2 potentially sensitive to very first galaxies at lowest frequency range
- 21 cm intensity mapping provides a powerful alternative to galaxy surveys that should be explored