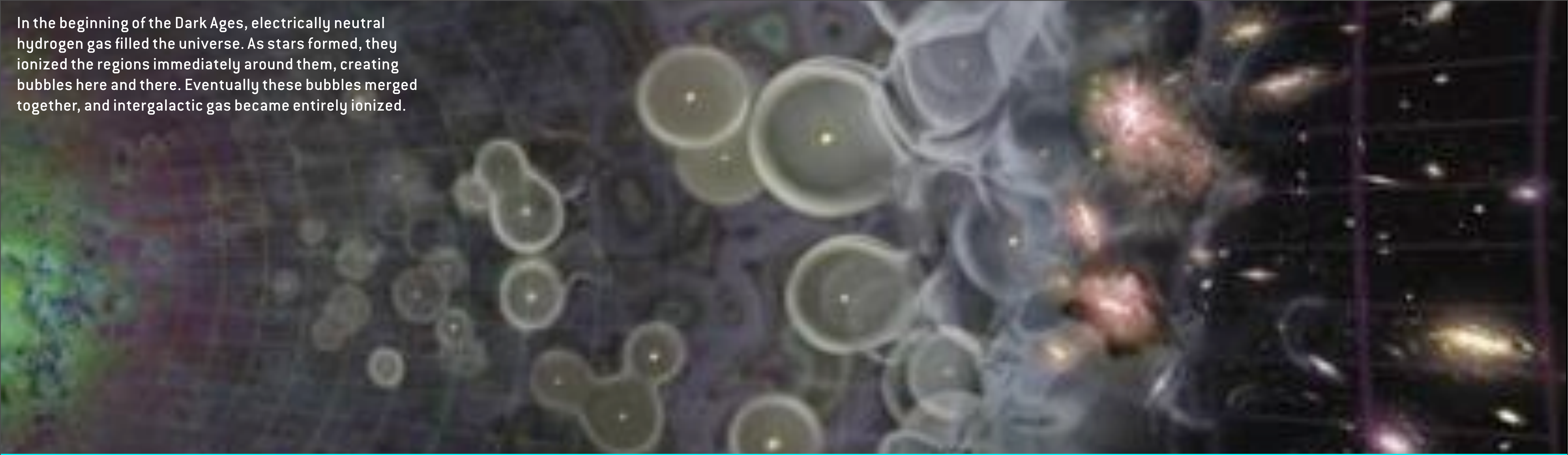
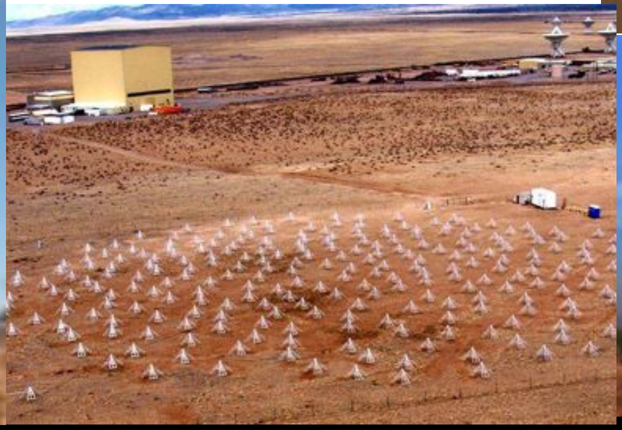


In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Exploring the dawn of structure with the 21 cm line

Jonathan Pritchard
Hubble-ITC Fellow
CfA



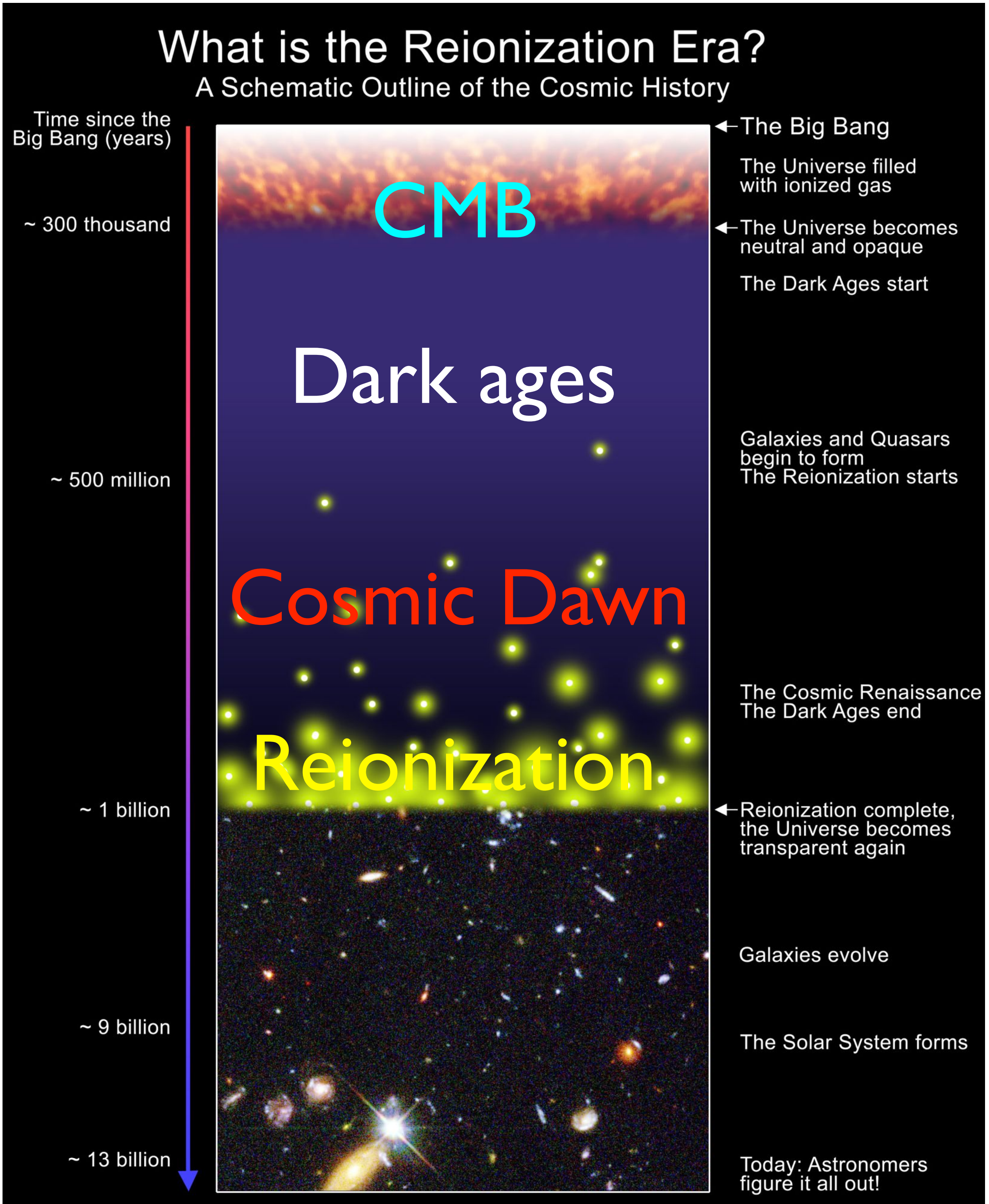
Avi Loeb (CfA)
Hy Trac (CMU)

Steve Furlanetto (UCLA)
Alex Amblard (Ames)

Stuart Wyithe (Melbourne)
Renyue Cen (Princeton)

Mario Santos (Portugal)
Asanthe Cooray (UCI)

The first billion years

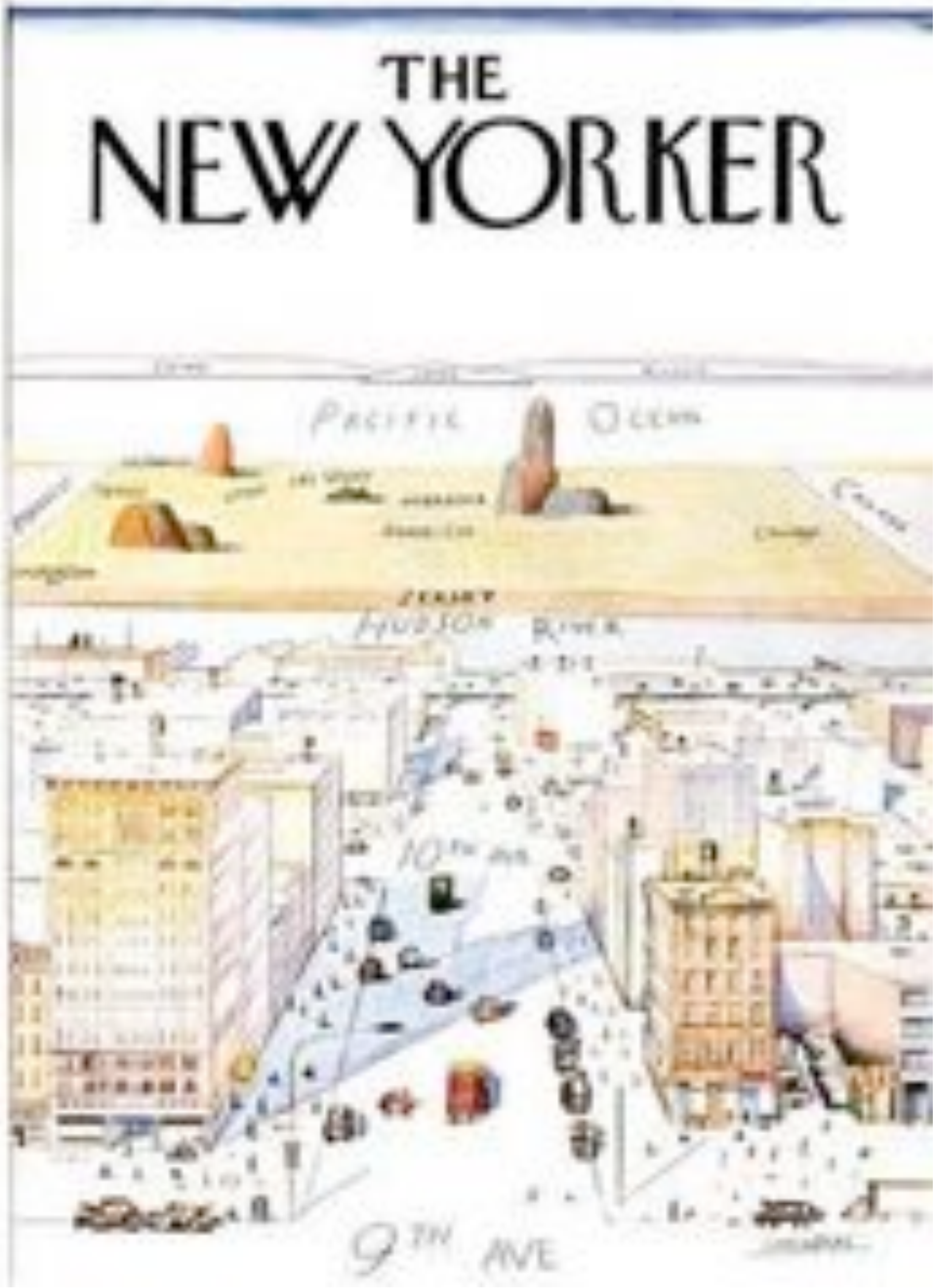


S.G. Djorgovski et al. & Digital Media Center, Caltech

Reionization marks the limits of current observations

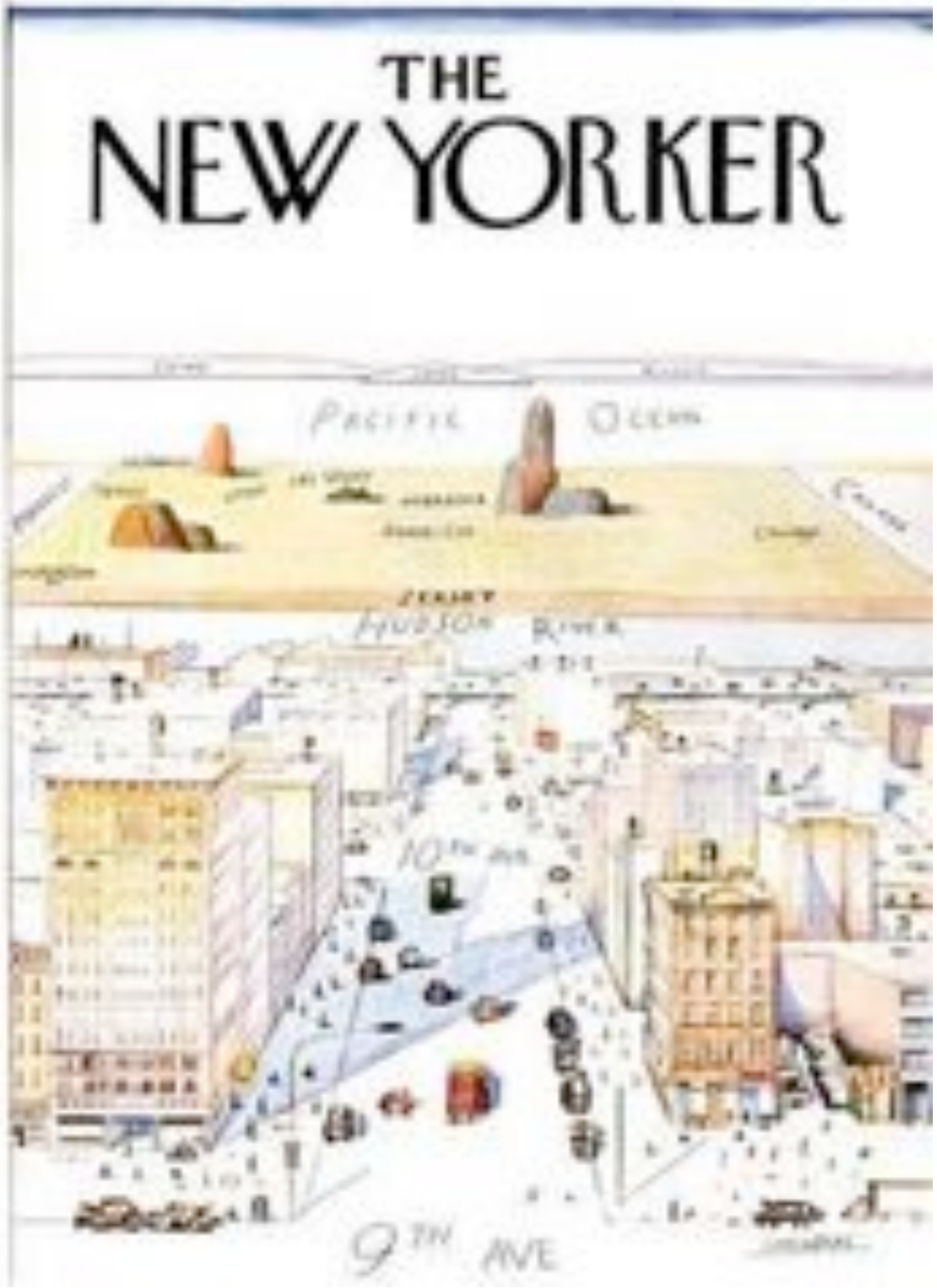
- Probes of reionization
- 21 cm basics
- 21 cm global signal
- 21 cm fluctuations

The next ten?



Things far off look simple!

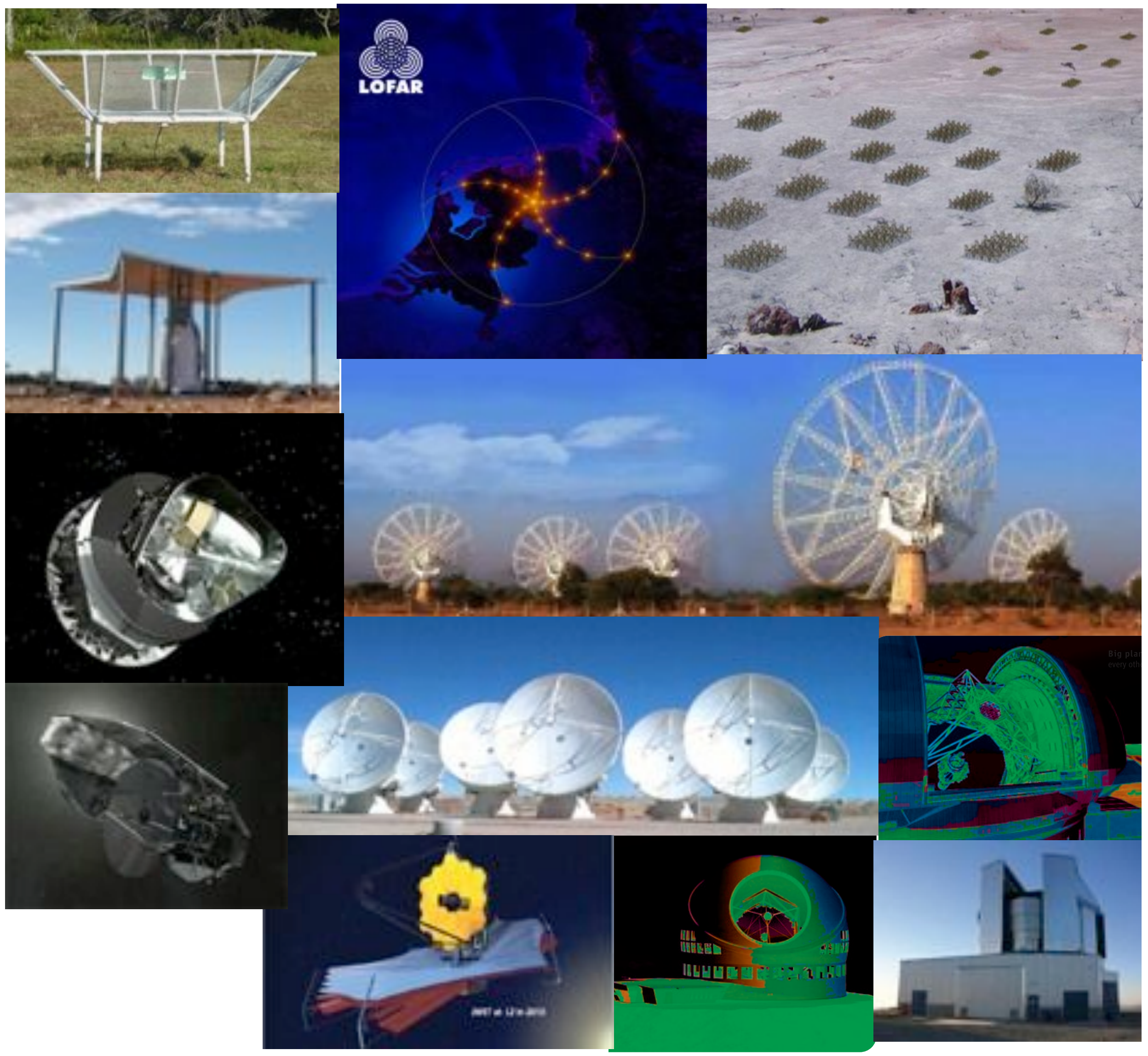
The next ten?



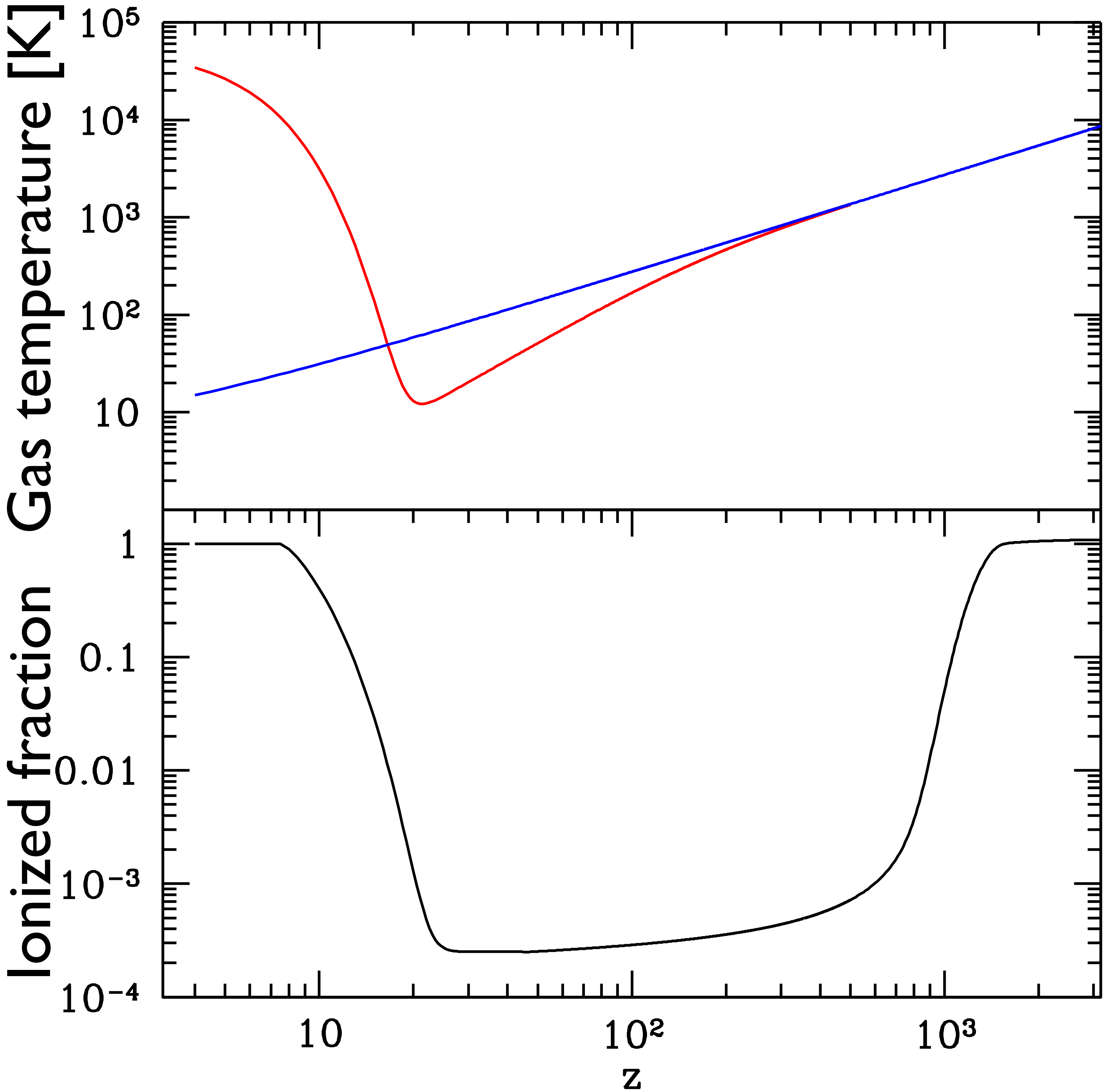
Things far off look simple!

> It's tough to make predictions, especially about the future.
>
> -Yogi Berra

Next decade will be ripe in new observations



Known unknowns



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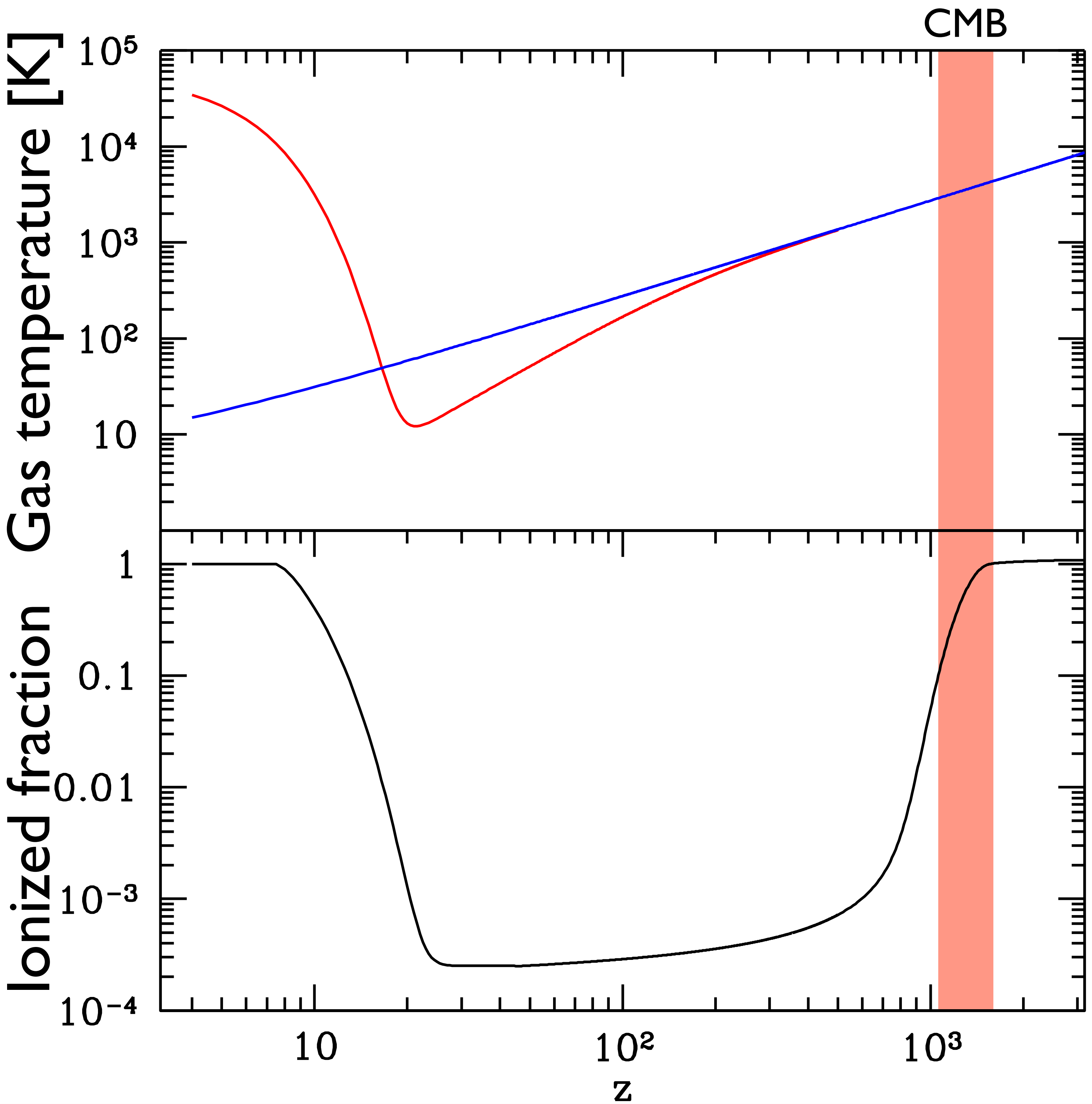

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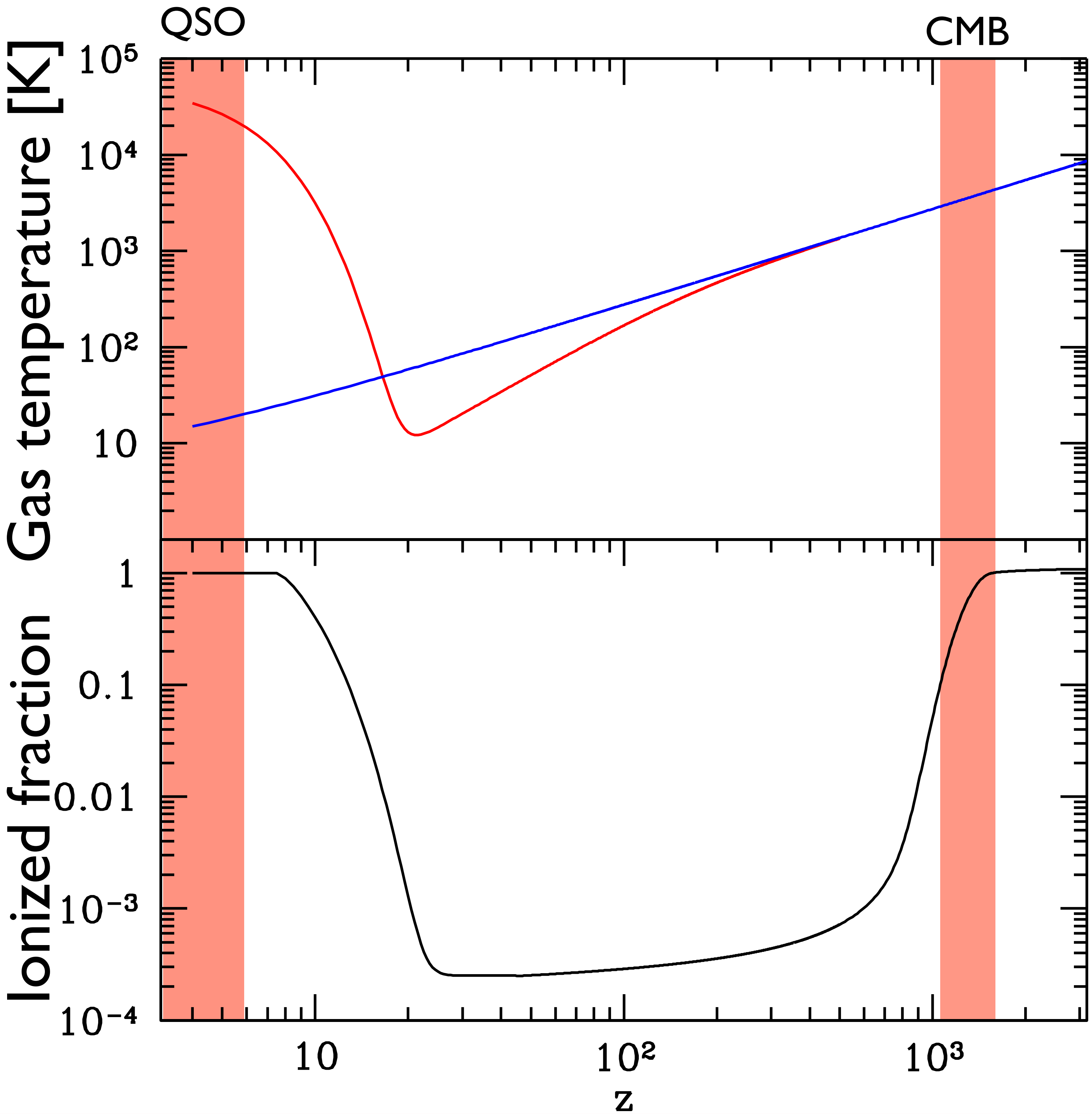

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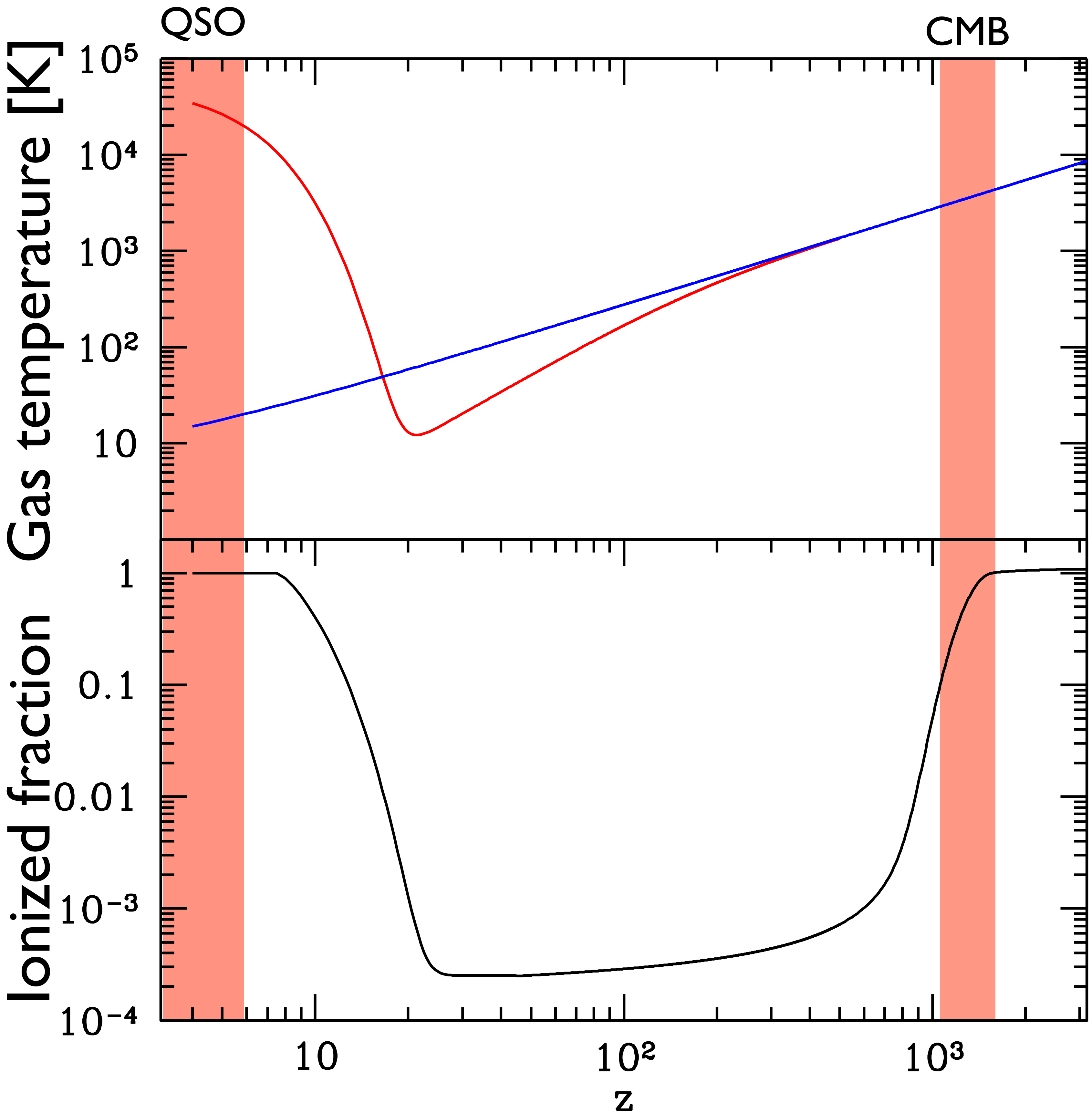
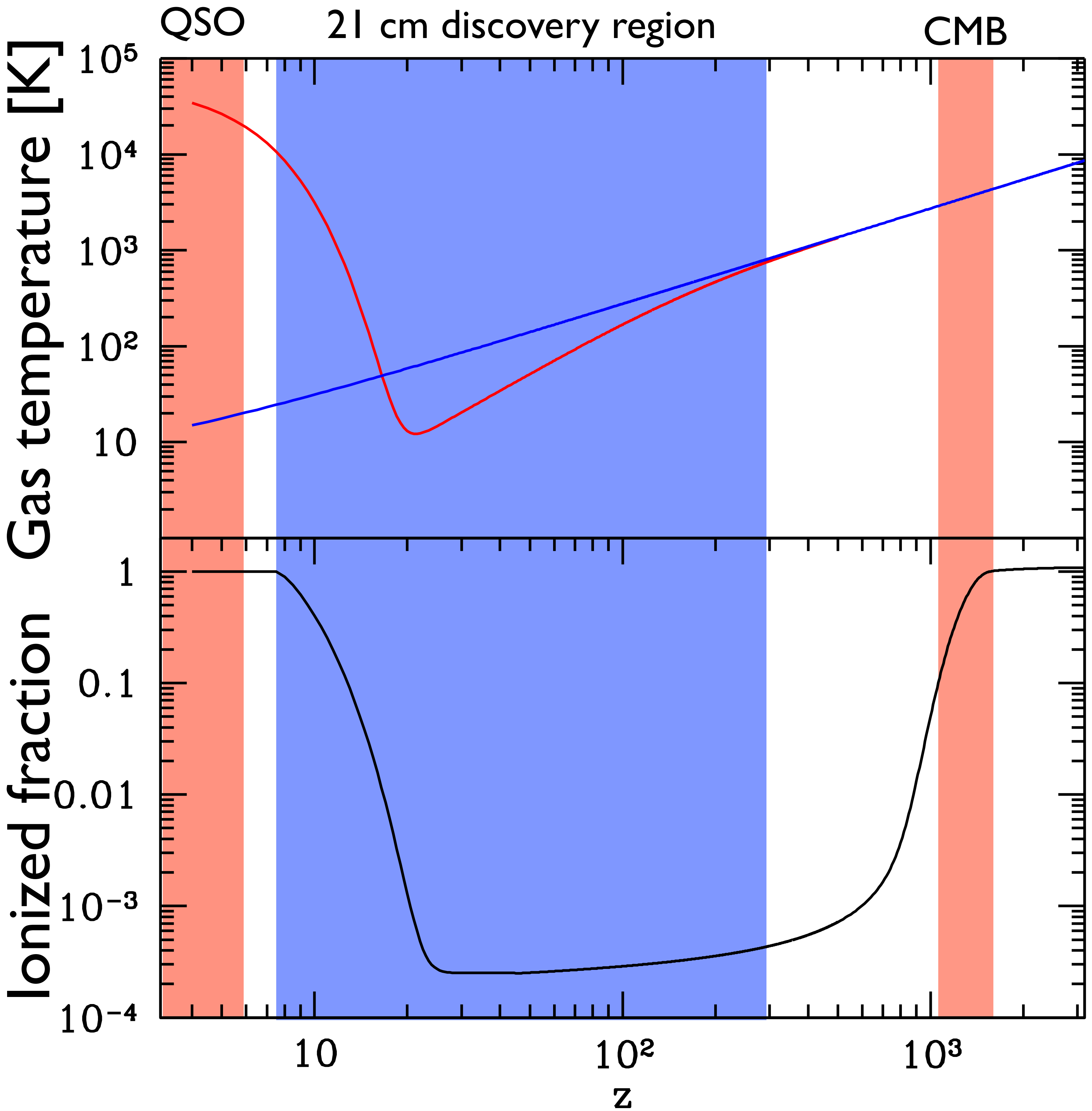


We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

We know little or nothing about galaxies at z>10

Known unknowns



We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

We know little or nothing about galaxies at z>10

Out in the fields

Density

↓

Galaxies

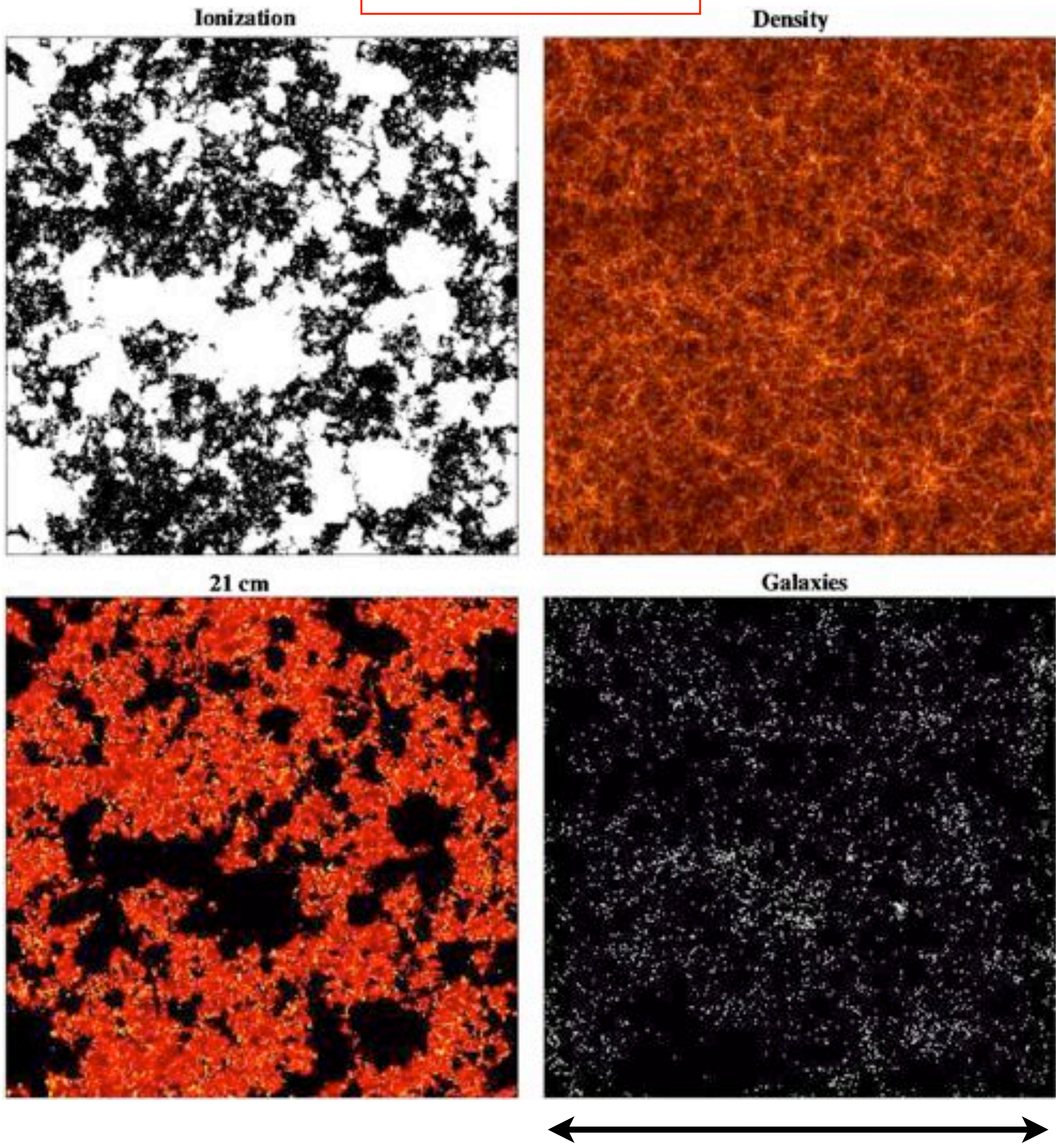
↓

Ionization

↓

21 cm

$z=7.32 \quad x_i=0.54$



130/h Mpc=1.2 deg

Lidz+ 2009

▪ HUDF

🟥 GOODS

Hyper Suprime-Cam
~1.5 deg^2

MWA FoV
~800 deg^2

SKA FoV
~200 deg^2

Out in the fields

$z=7.32 \quad x_i=0.54$

Density

↑

Galaxies

↓

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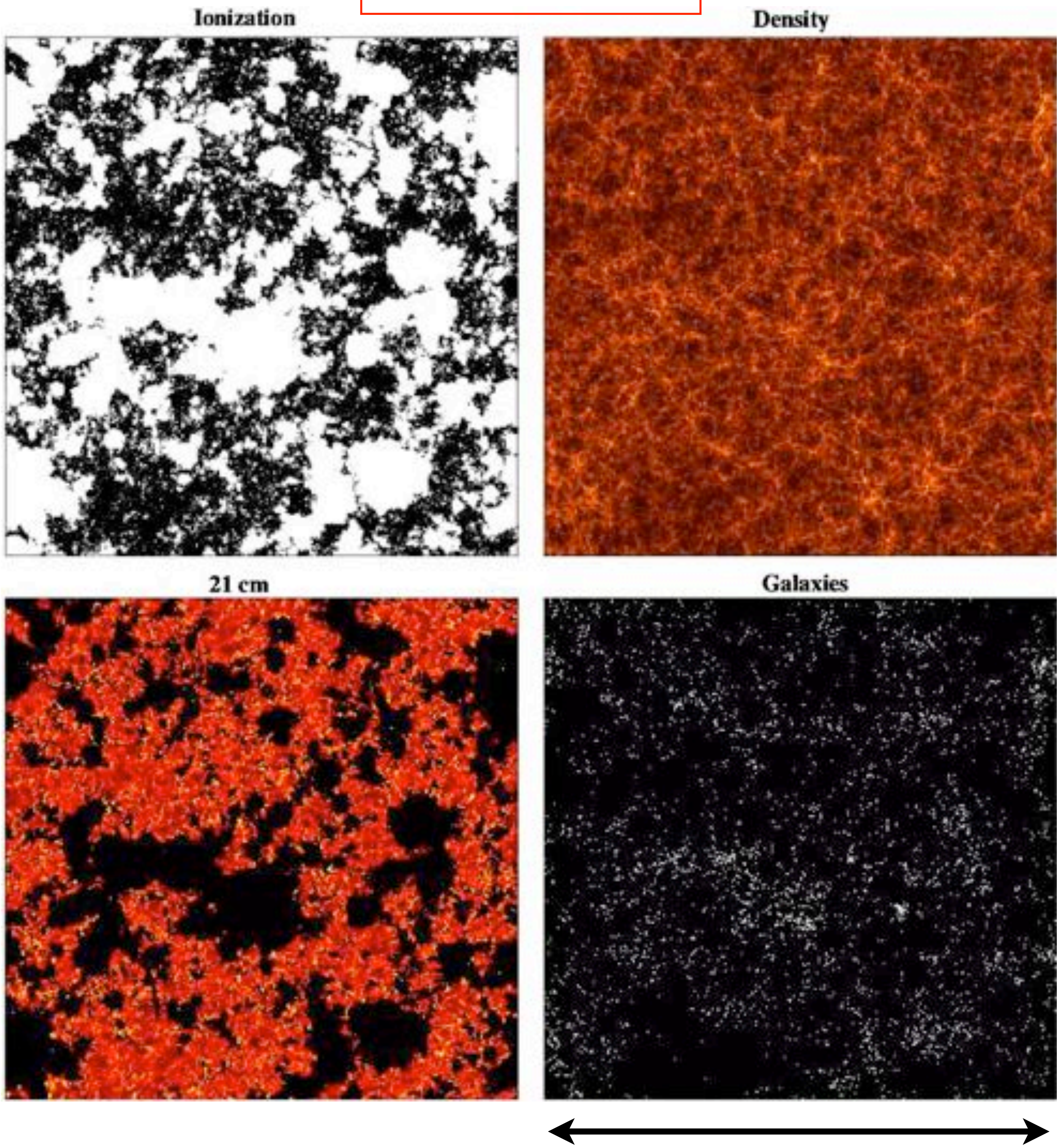
↑

21 cm



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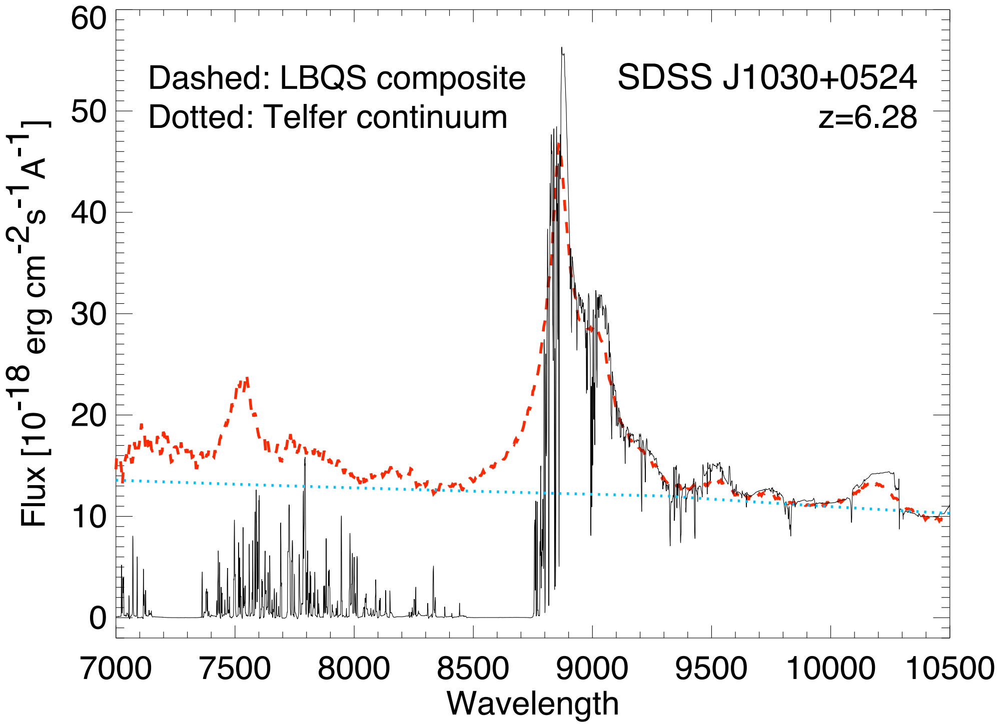
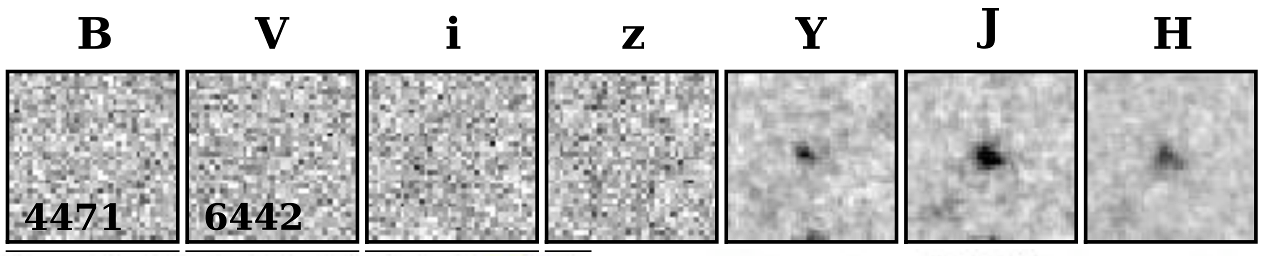
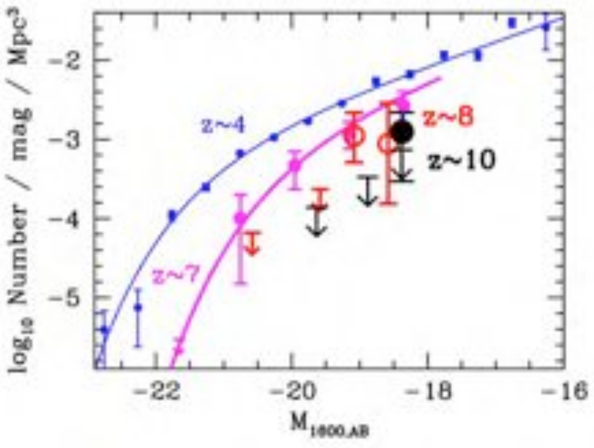
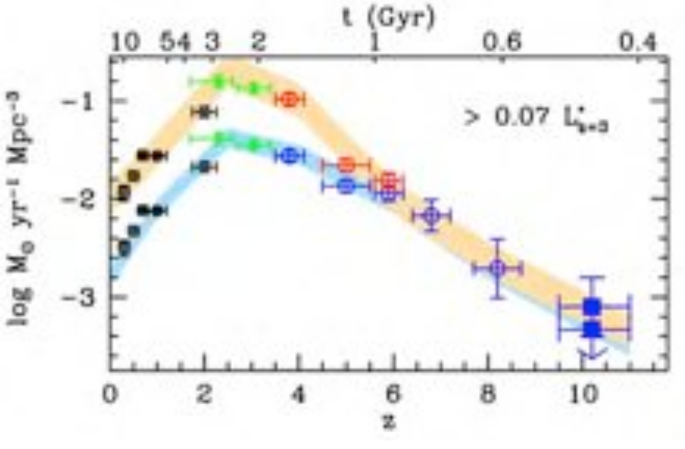


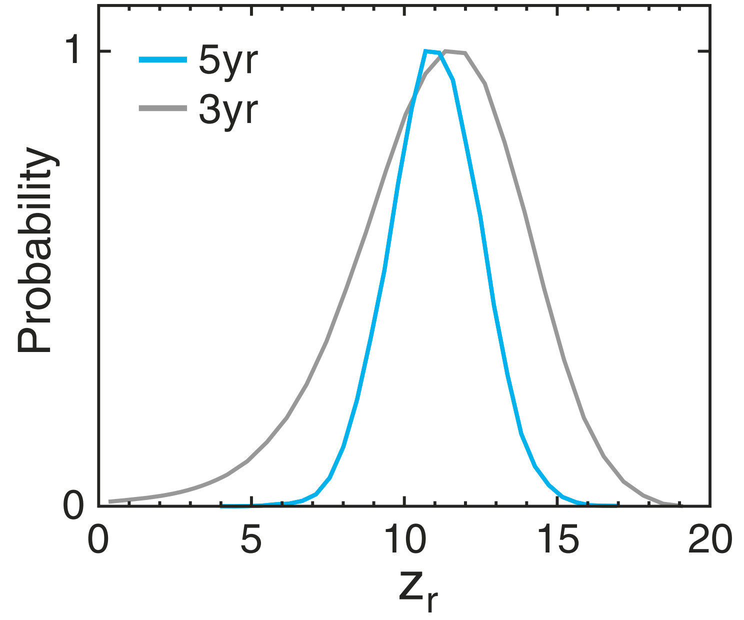






Probes of the epoch of reionization

$$\tau_{\rm CMB} = 0.087 \pm 0.017$$



Cosmic microwave background

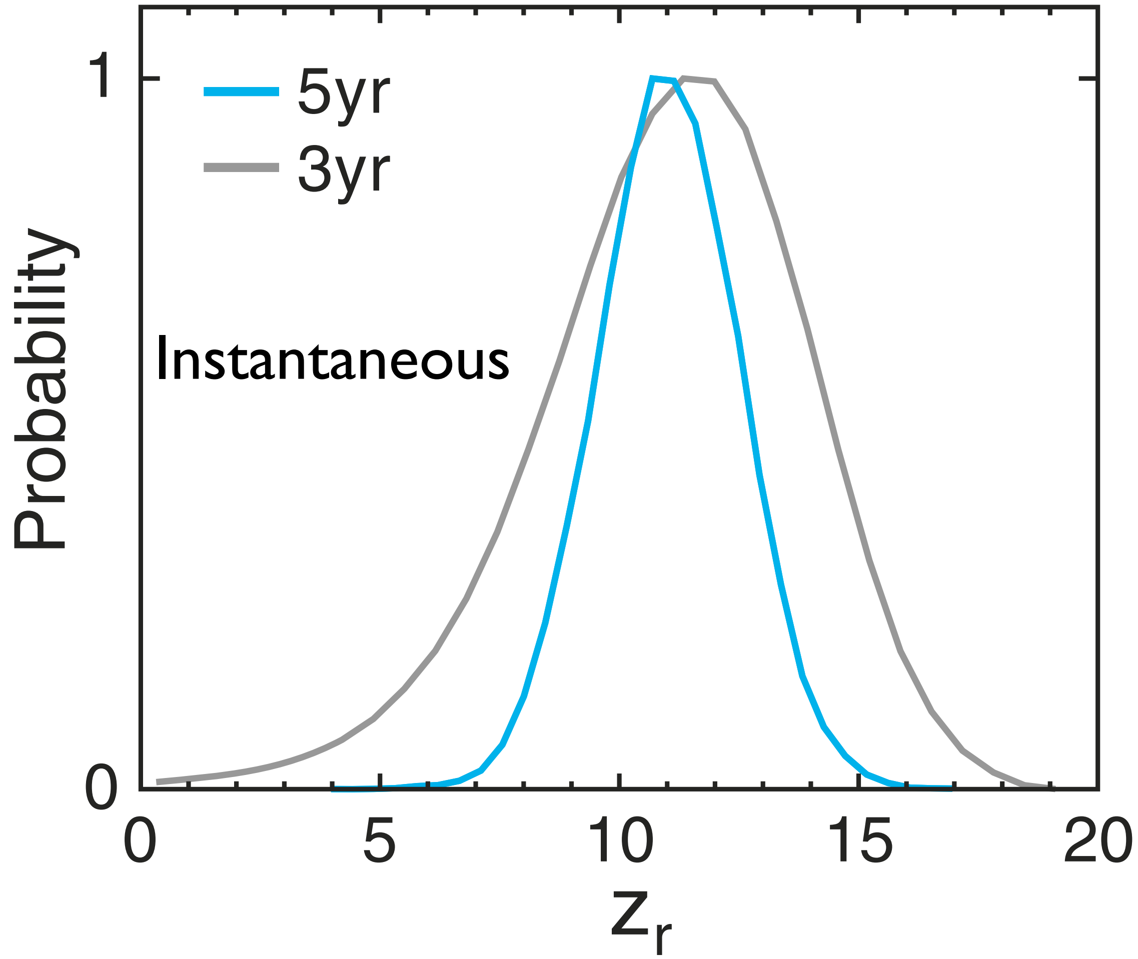
- CMB polarisation constrains scattering by ionized plasma

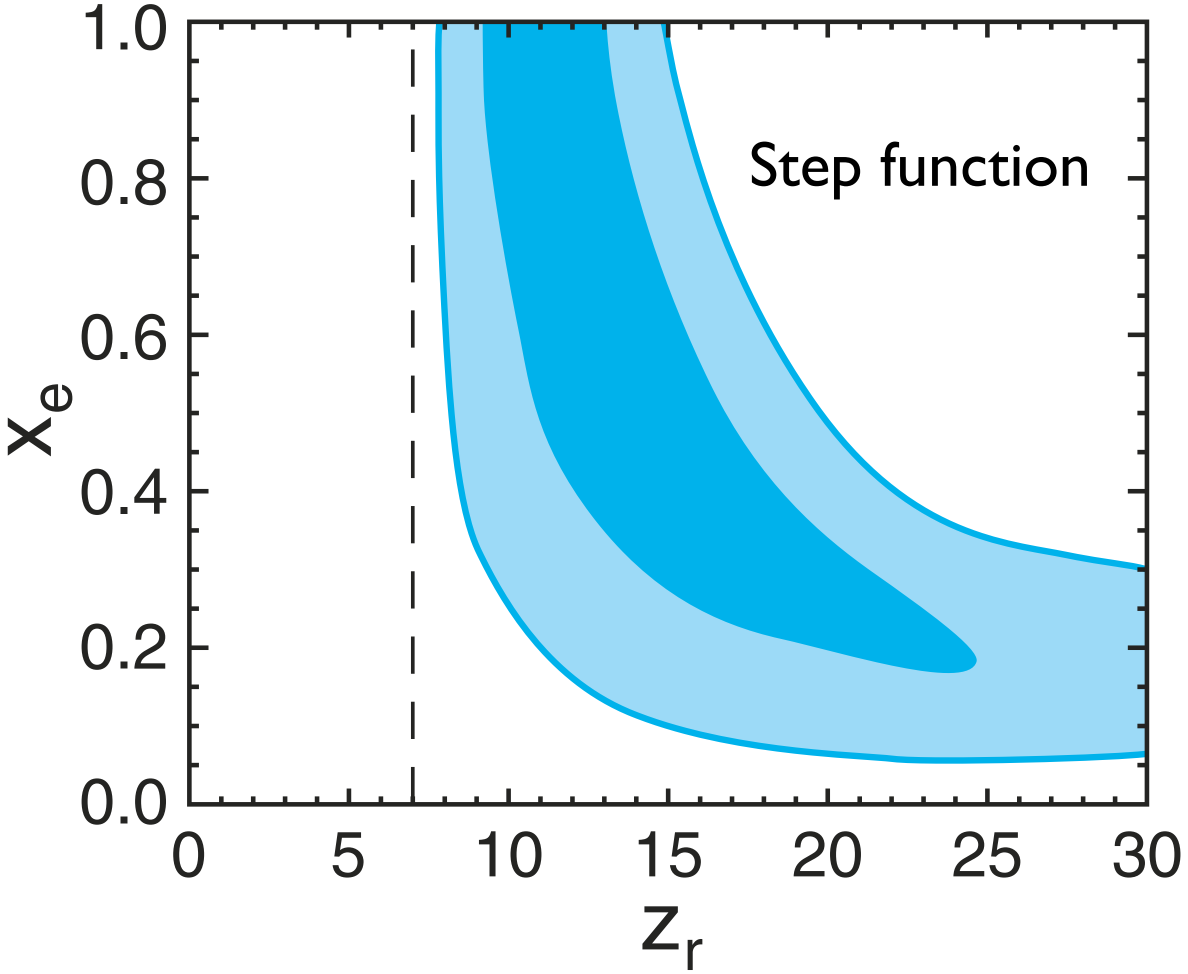
$$\tau_{\rm CMB} = 0.087 \pm 0.017$$

Dunkley+ 2009

$$\sigma_\tau^{\rm Planck} = 0.005$$

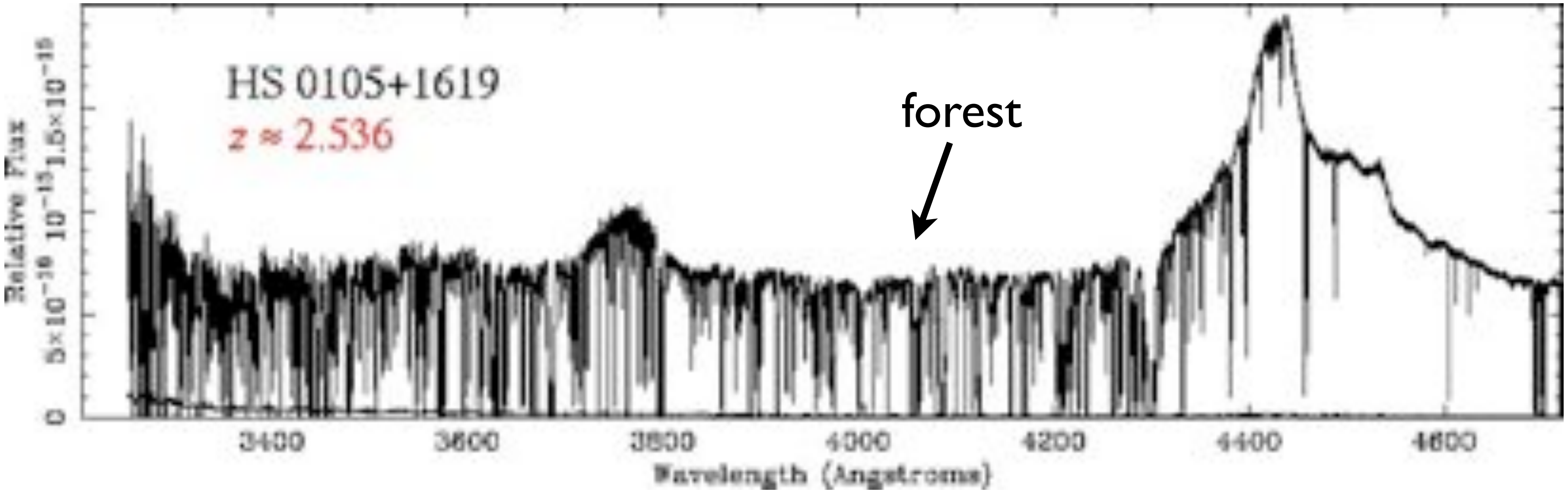
Tegmark+ 2000





- Tau gives integral constraint on ionization history
- Detailed shape gives a little more information

Lyman alpha forest



transmittance

ionizing background

rate sources produce ionizing photons

$$\tau_{\rm eff} \longrightarrow \Gamma_{-12} \longrightarrow \dot{N}_{ion}$$

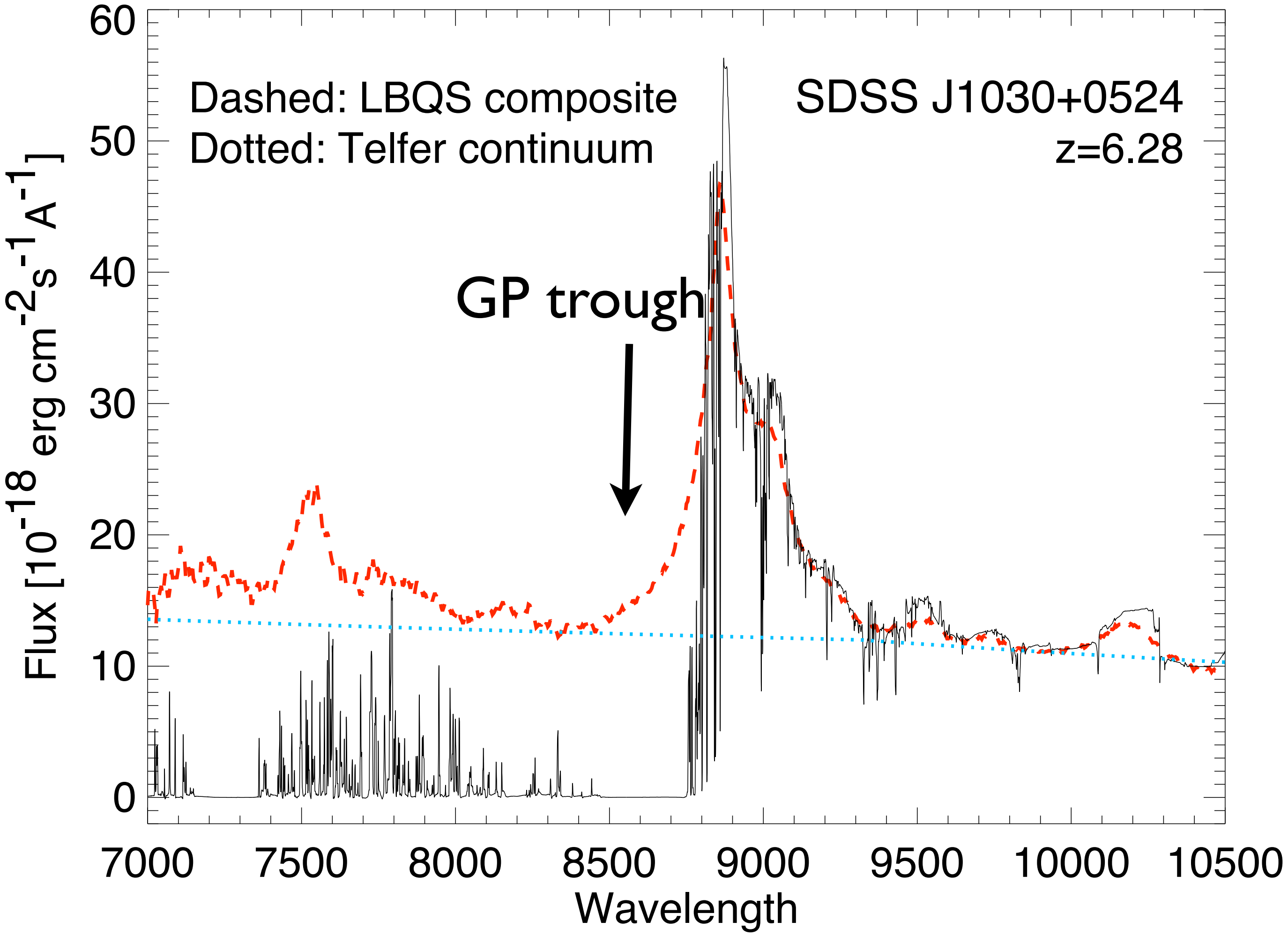
+ temperature -density relation
+ density pdf

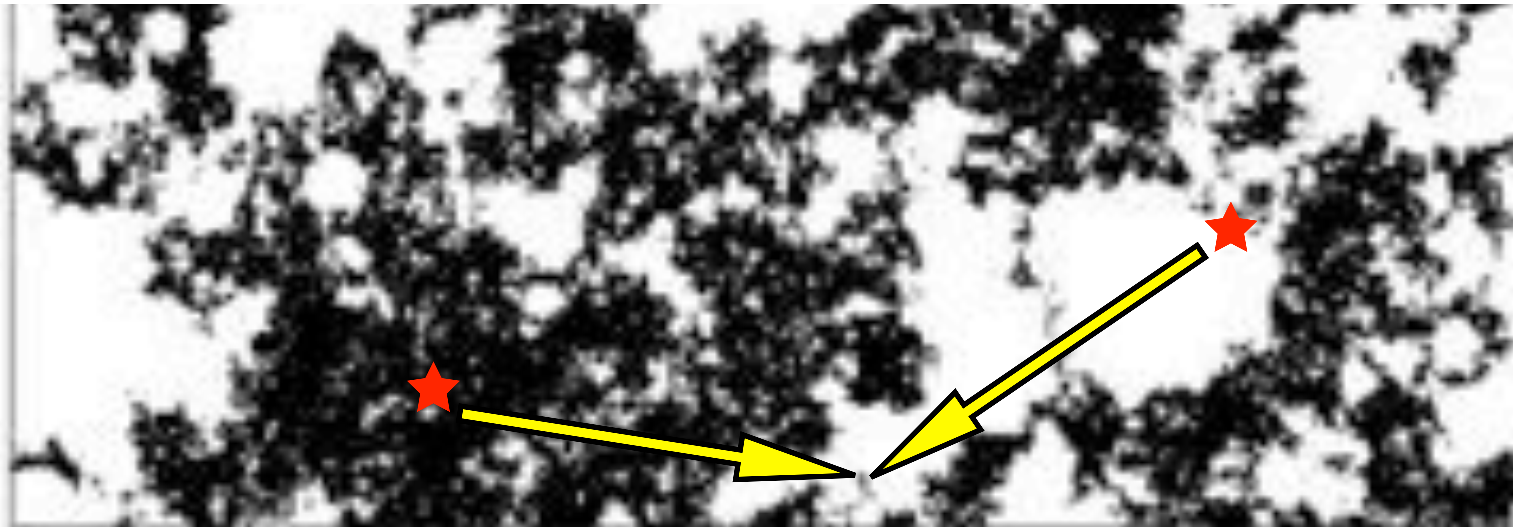
+ photon mfp
+ column density dist.
+ source spectrum

e.g. Fan+ 2002, Bolton & Haehnelt 2007, Faucher-Giguere+ 2008

If same sources at z<6 as z>6 can use forest to calibrate sources

Gunn-Peterson trough





Absorption by neutral hydrogen along skewer to quasar

Total absence of flux just shy of Lyman alpha line = GP trough

Gunn-Peterson trough constrains neutral fraction at z~6.5 to be $x_H>10^{-3}$

inhomogeneity makes statistics important...

Inference

Bayesian inference of parameters

$$\boxed{p(w|D,M) = \frac{p(D|w,M)p(w|M)}{p(D|M)},}$$

ionization rate

recombinations

Filling fraction of ionized regions

$$\frac{\mathrm{d}Q_{\rm HII}}{\mathrm{d}t} = \boxed{\frac{\dot{N}_{\rm ion}}{n_H(0)}} - \boxed{Q_{\rm HII}C_{\rm HII}n_H(0)(1+z)^3\alpha_A(T).}$$

↑

Lyman alpha forest at z<6

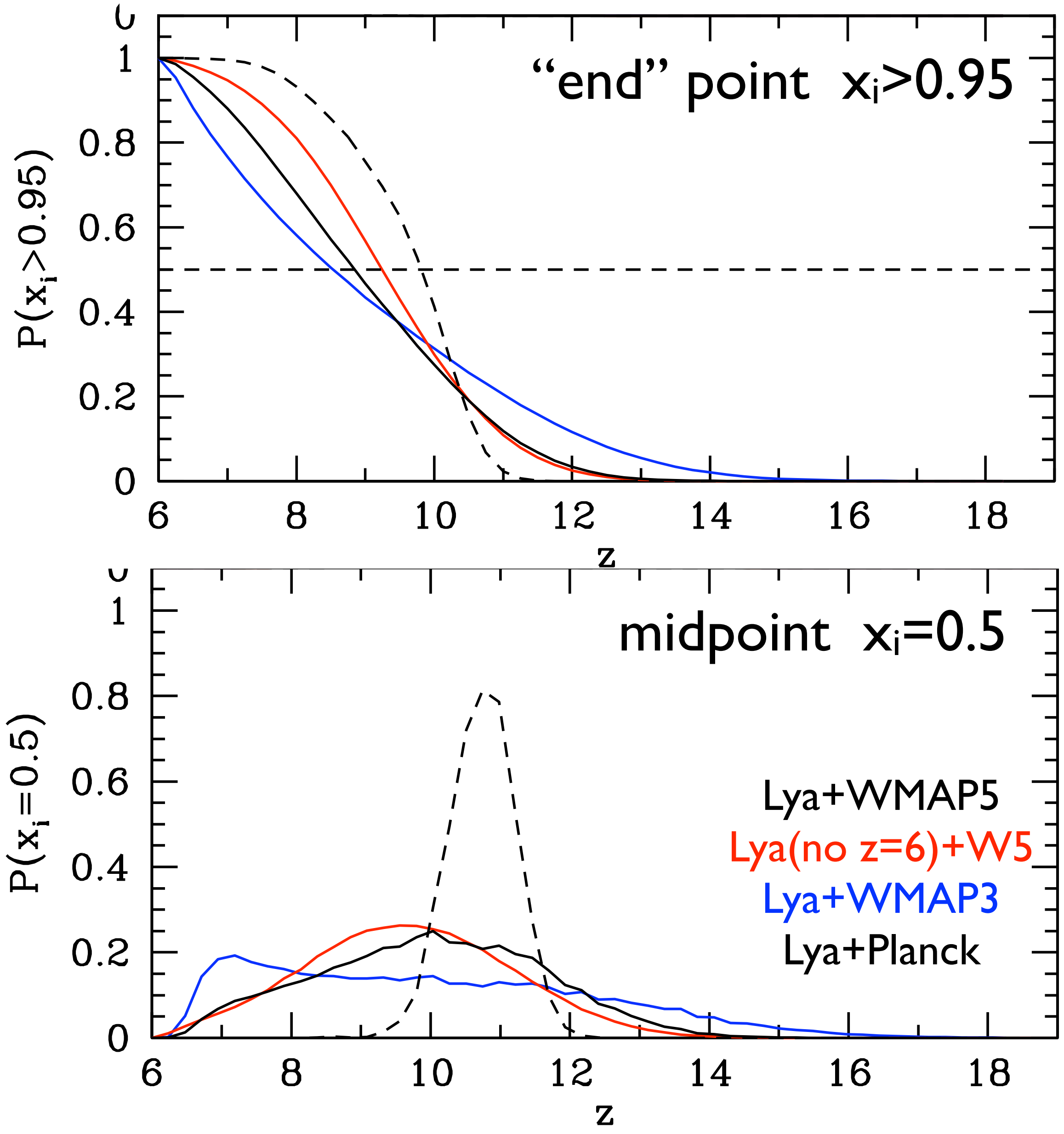
CMB optical depth

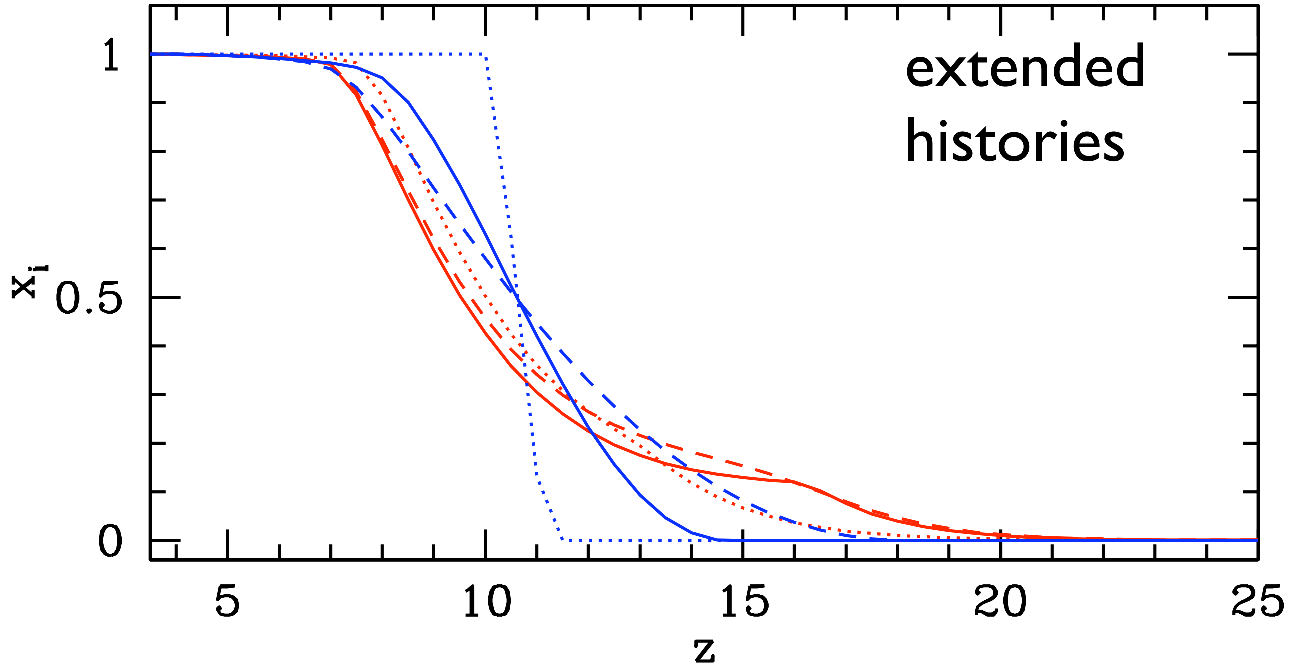
$$\boxed{\tau_{\rm CMB} = \int_0^{z_{\rm CMB}} \mathrm{d}z \, \frac{\mathrm{d}t}{\mathrm{d}z} x_e(z) n_H(z) \sigma_T .}$$

Pritchard, Wyithe, Loeb 2010

Constraining reionization

Use CMB+Lya to constrain analytic model

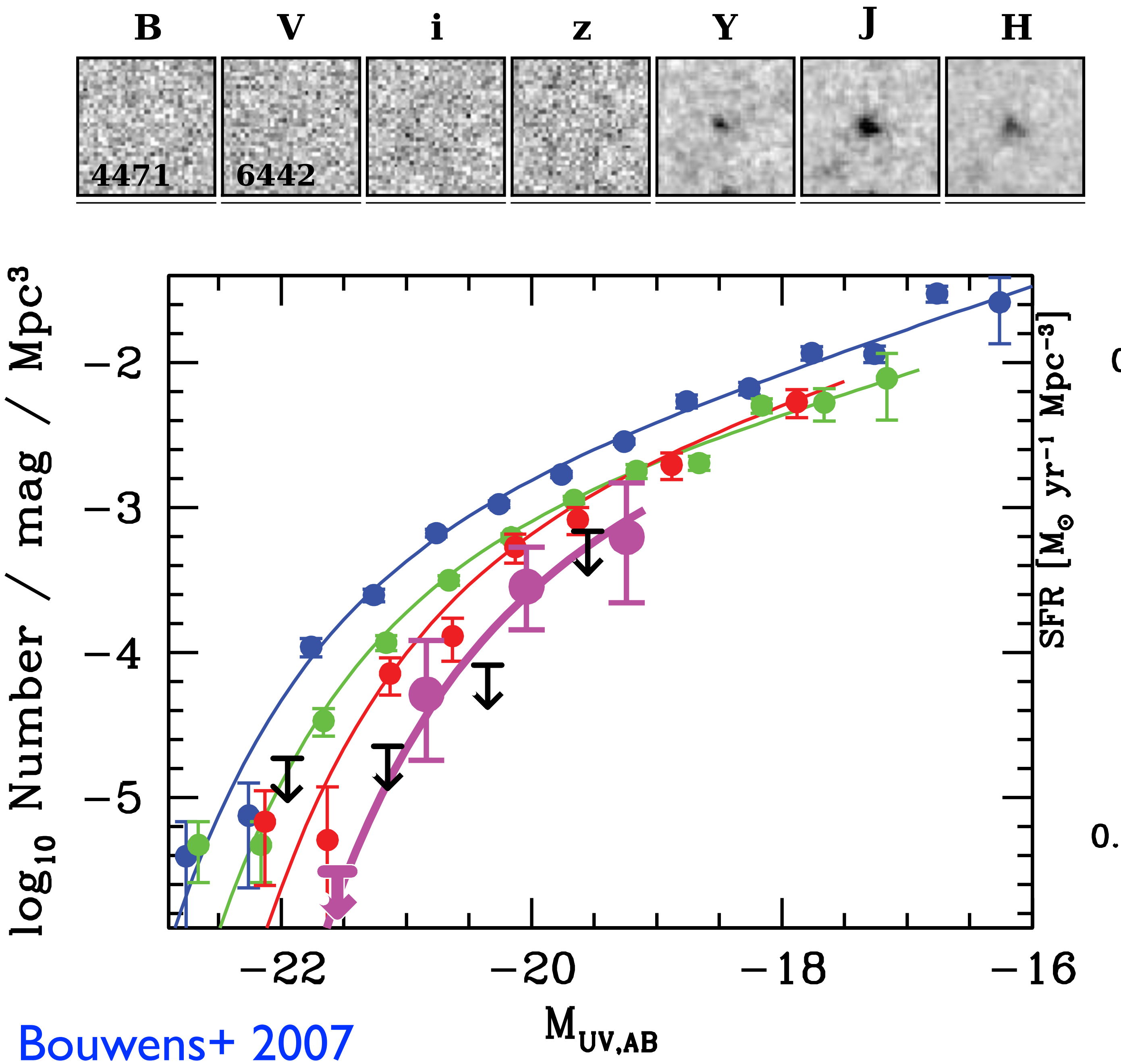




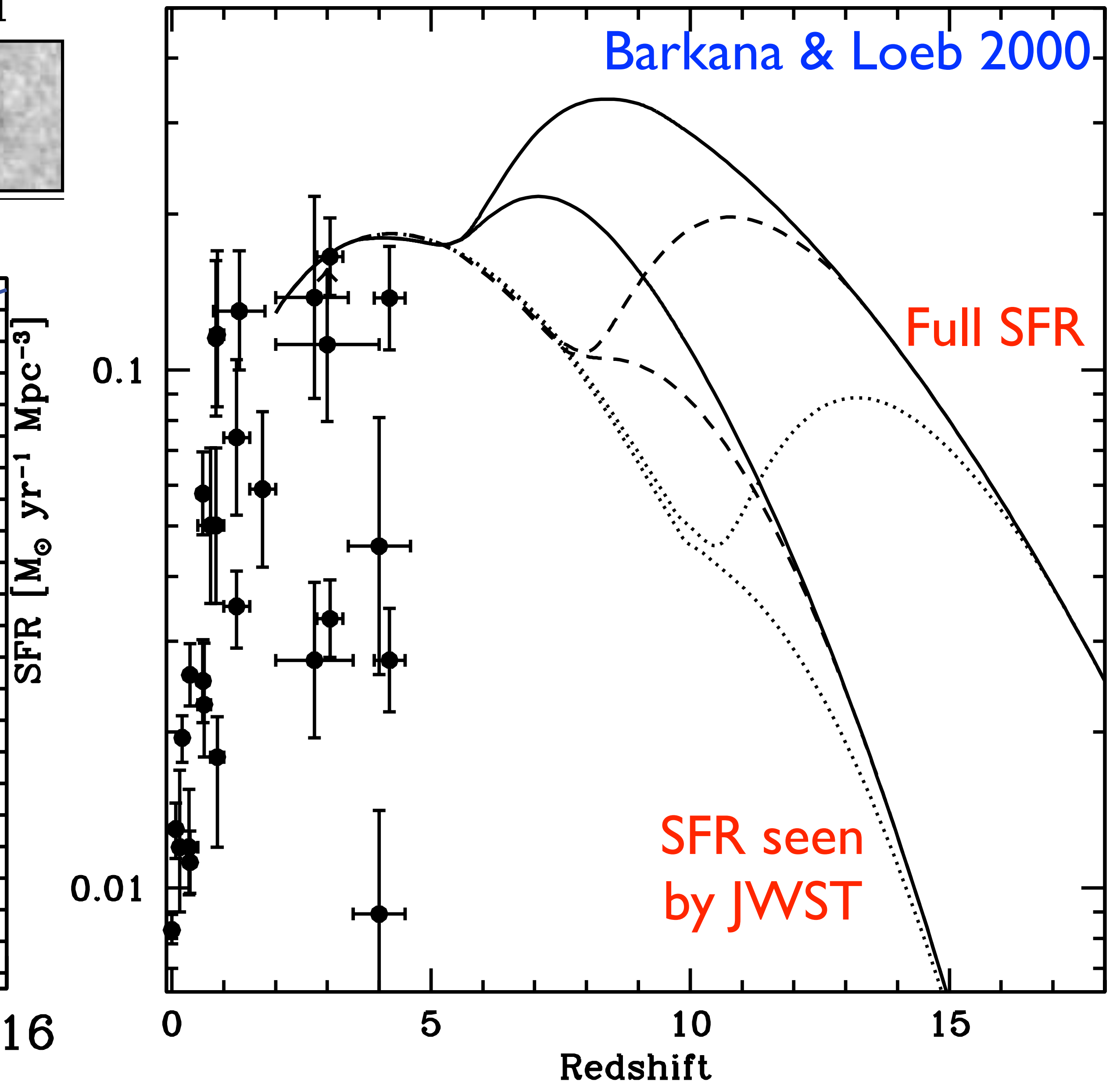
- Universe most likely ionized by z=8
- Mid-point of reionization typically occurs around z=9-11
- Reionization is extended

combining data sets consistently is important
for calibrating models and fully exploiting observations

High redshift galaxies



Bouwens+ 2007

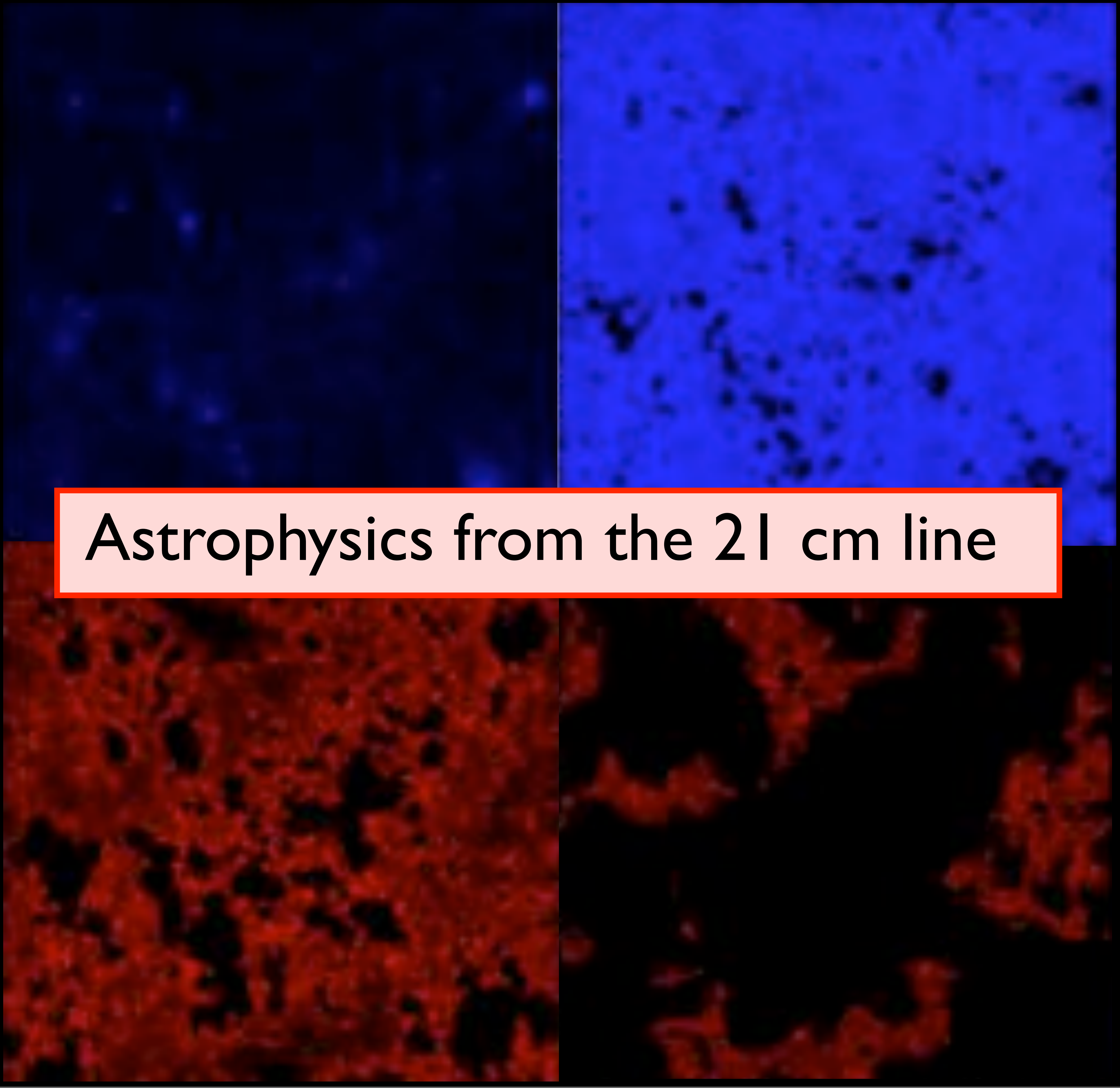


High-z surveys constrain galaxy luminosity function
e.g. HST+WFC3
=> JWST

Bunker+ 2009, Bouwens+2009

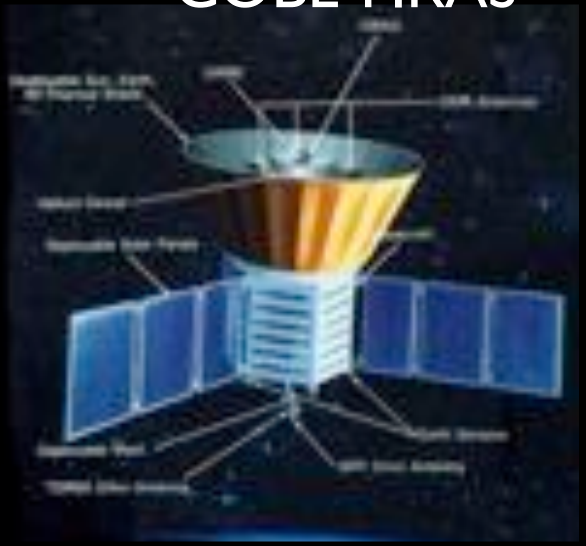
Even JWST will miss faintest galaxies at high redshifts

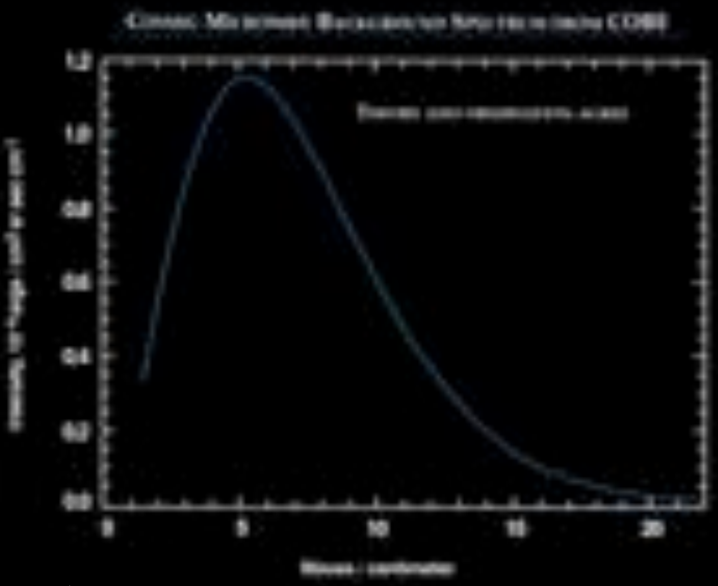
Astrophysics from the 21 cm line



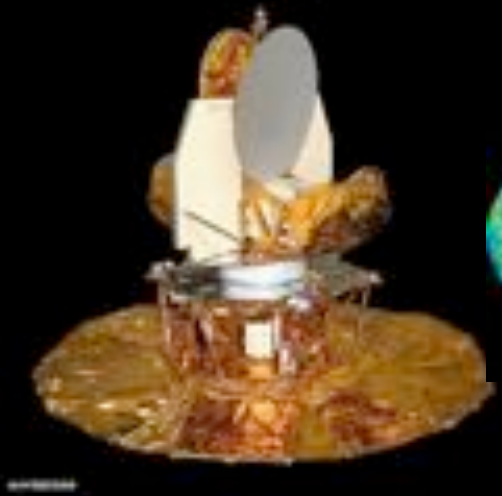
Global vs Fluctuations

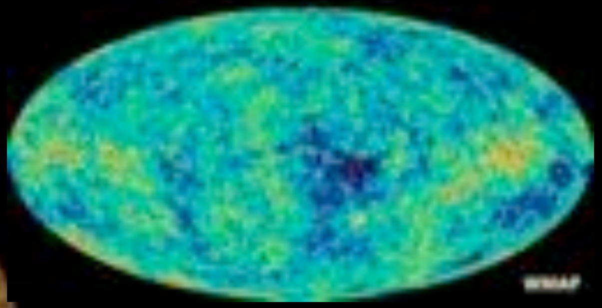
COBE-FIRAS



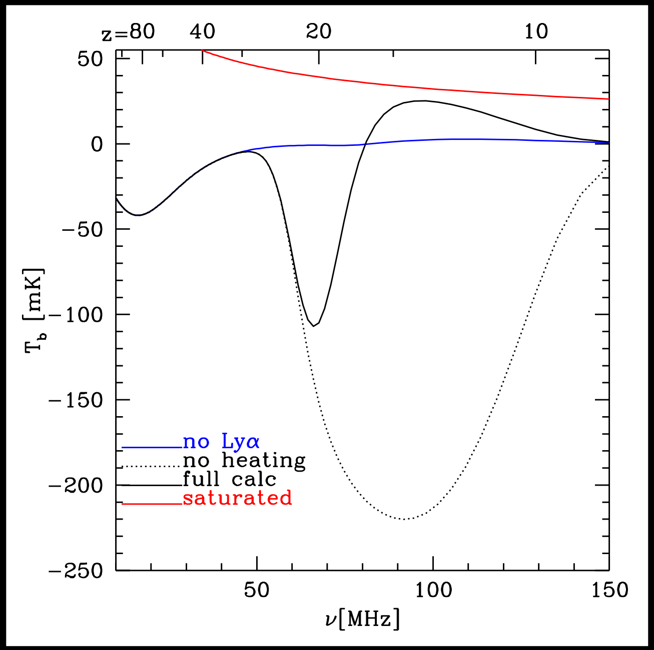


WMAP

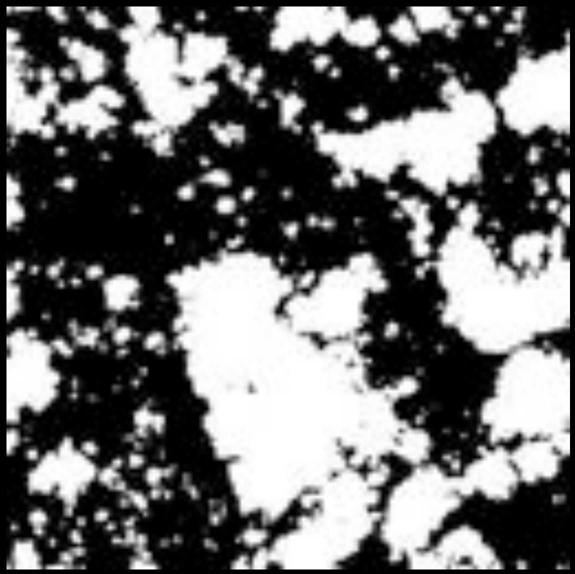




EDGES



MWA

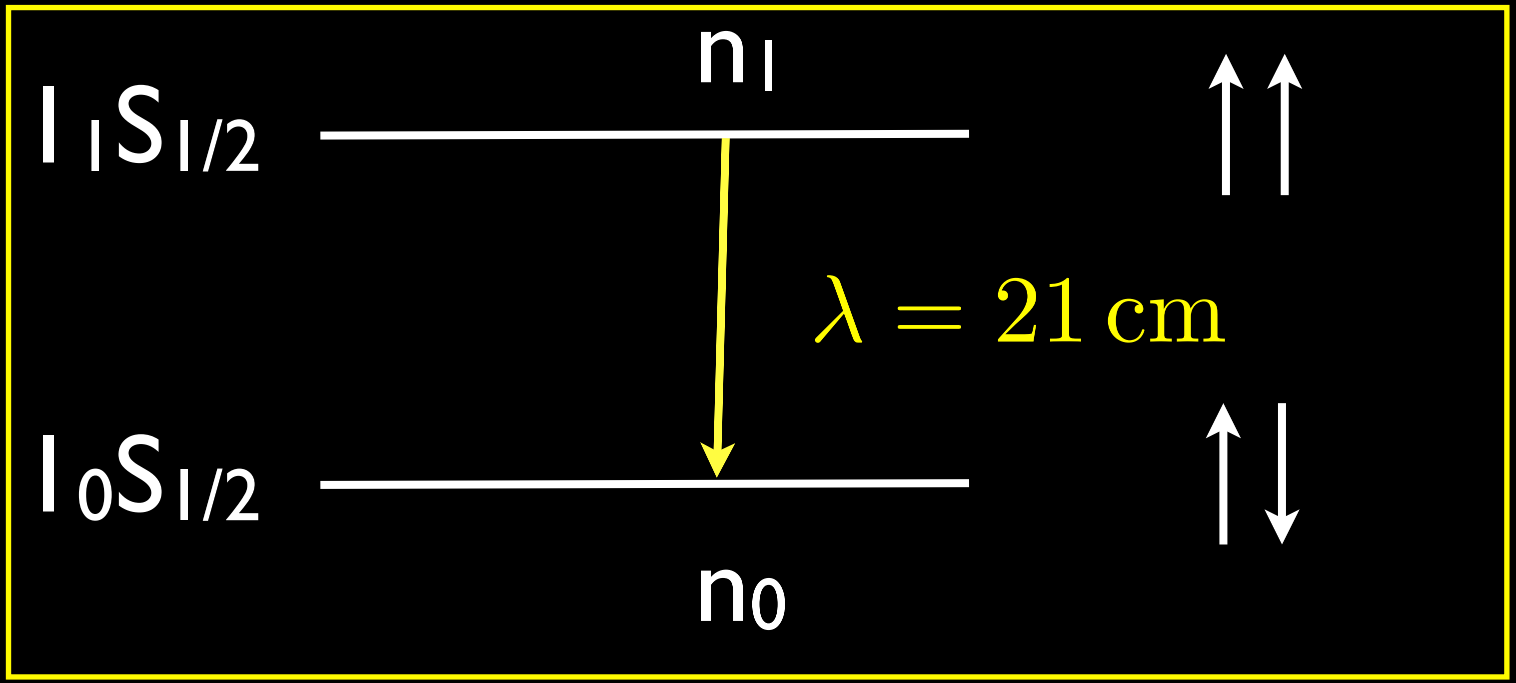


21 cm basics

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

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

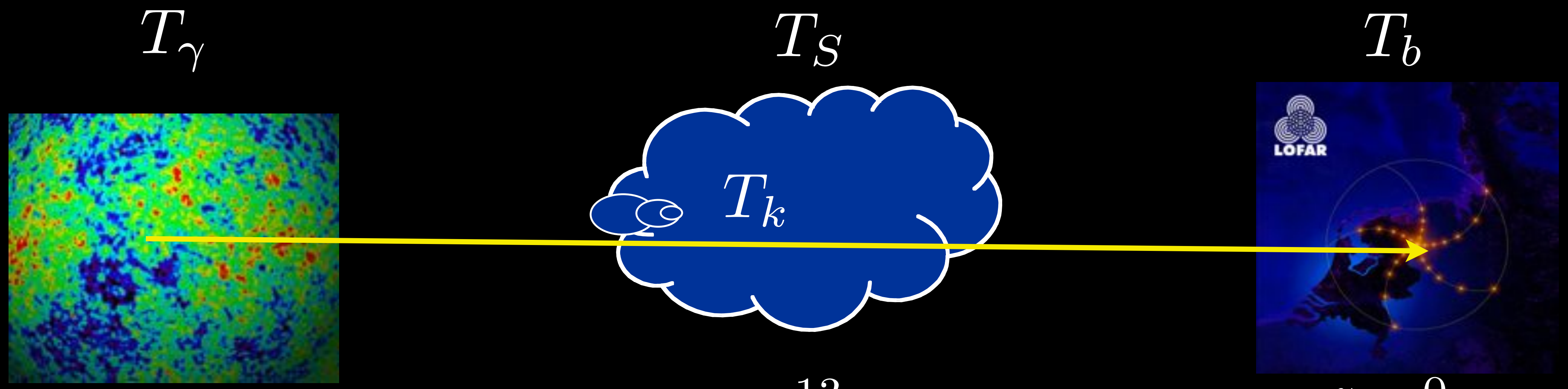
Useful numbers:

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

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

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

21 cm line in cosmology



$z = 13$

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

$z = 0$

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

CMB acts as
back light

Neutral gas
imprints signal

Redshifted signal
detected

brightness temperature

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

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

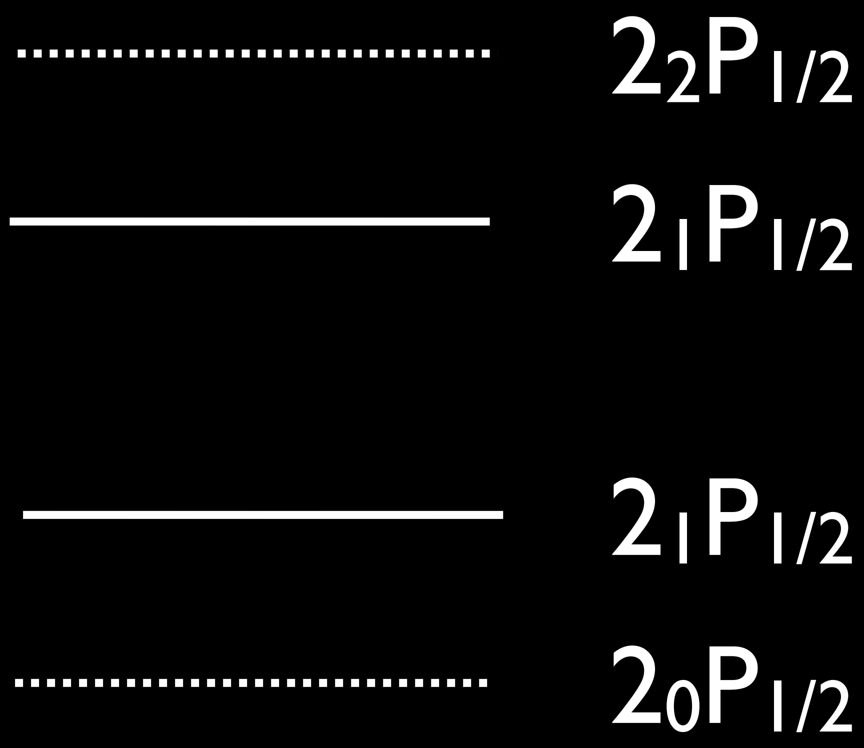
Wouthysen-Field Effect

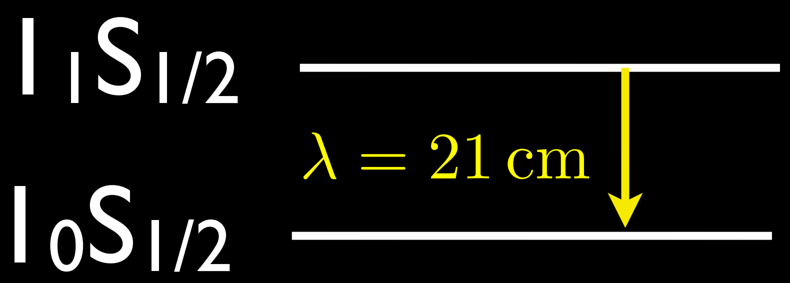
Hyperfine structure of HI

Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux

$$\overset{\text{spin}}{T_S} \underset{\substack{\uparrow \\ \text{W-F}}}{\sim} \overset{\text{colour}}{T_\alpha} \underset{\substack{\uparrow \\ \text{recoils}}}{\sim} \overset{\text{gas}}{T_K}$$





Wouthysen 1959

Field 1959

Wouthysen-Field Effect

Hyperfine structure of HI

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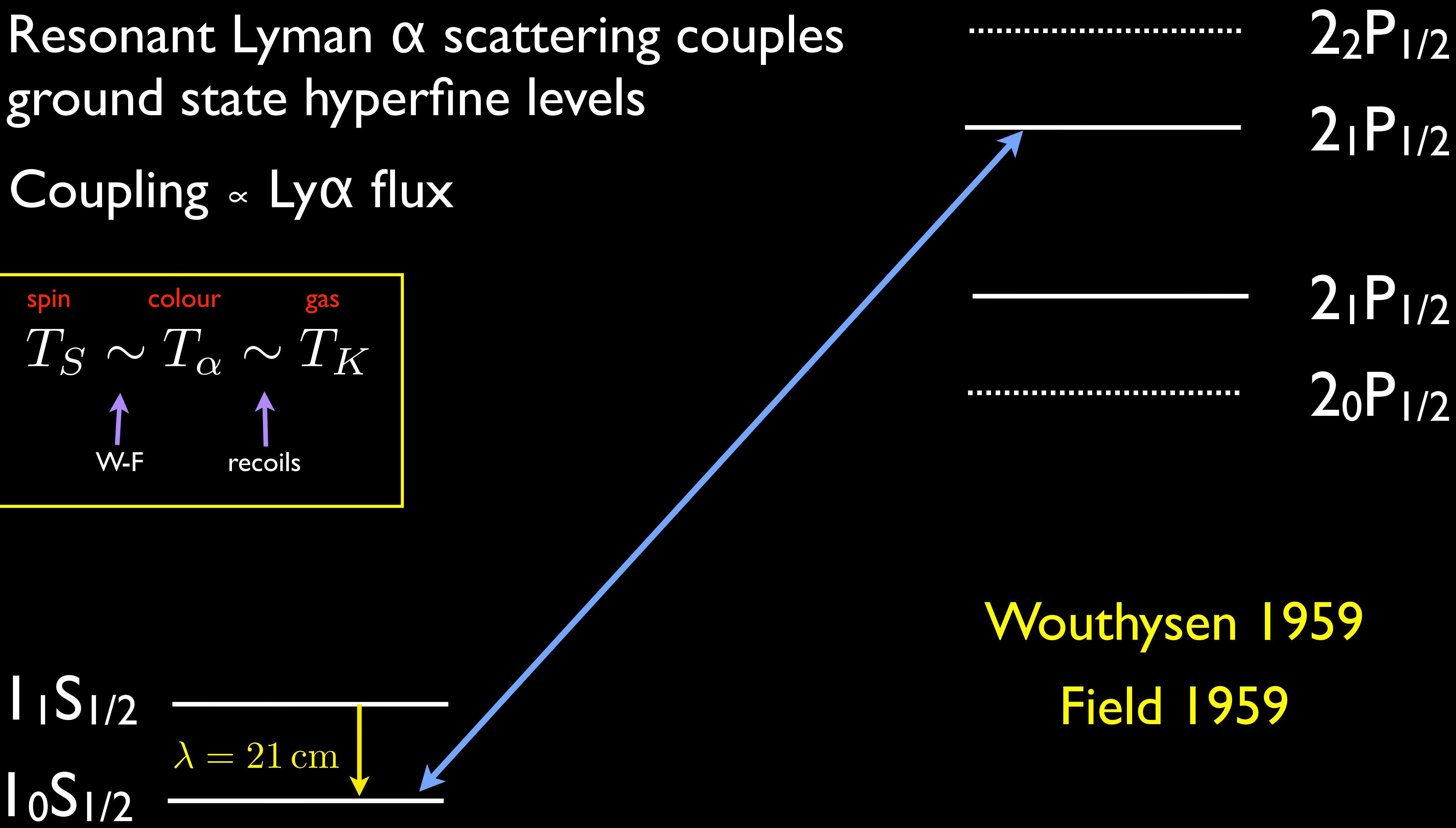
Coupling ∝ Lyα flux

spin colour gas

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

↑ W-F ↑ recoils



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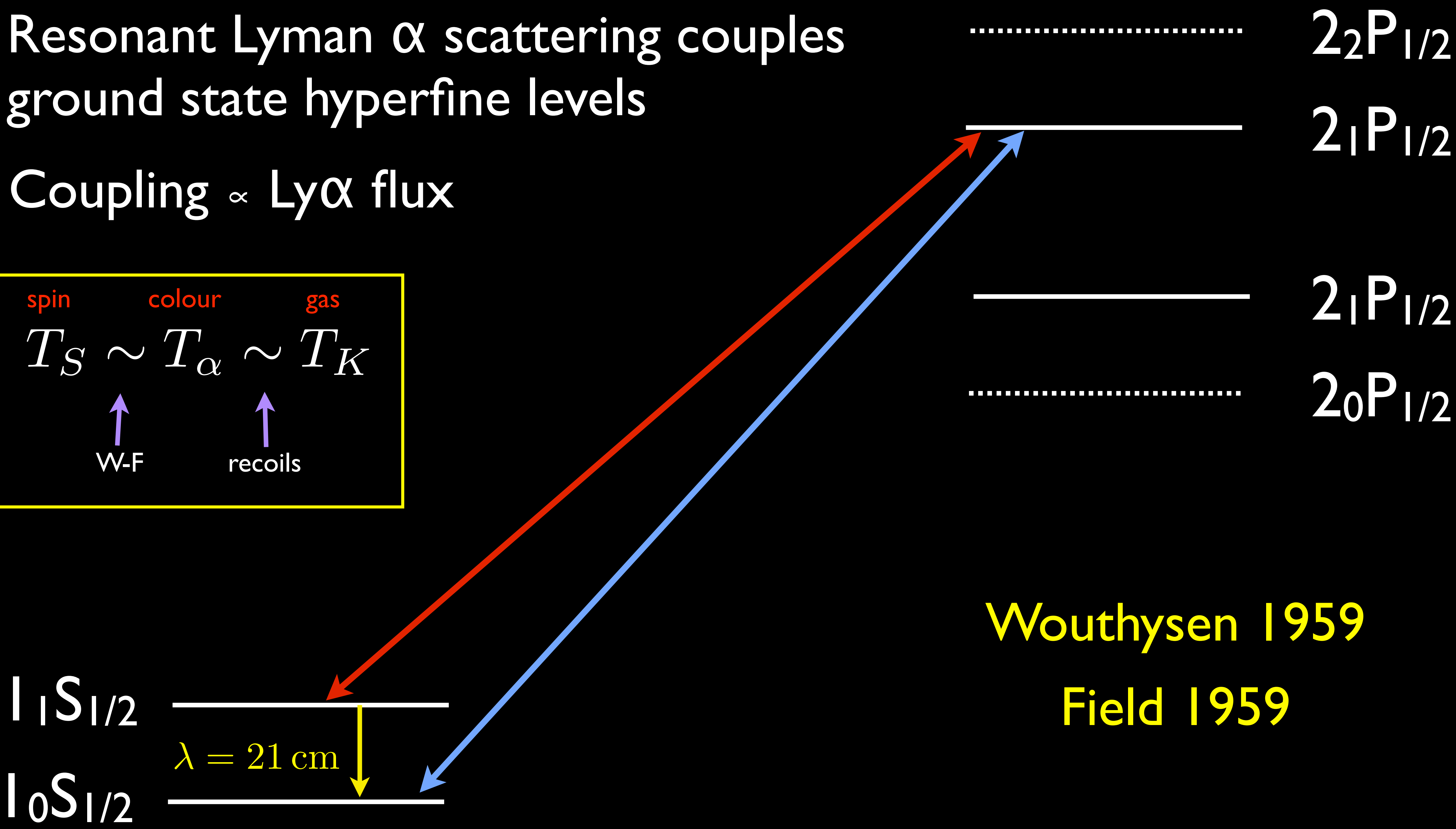

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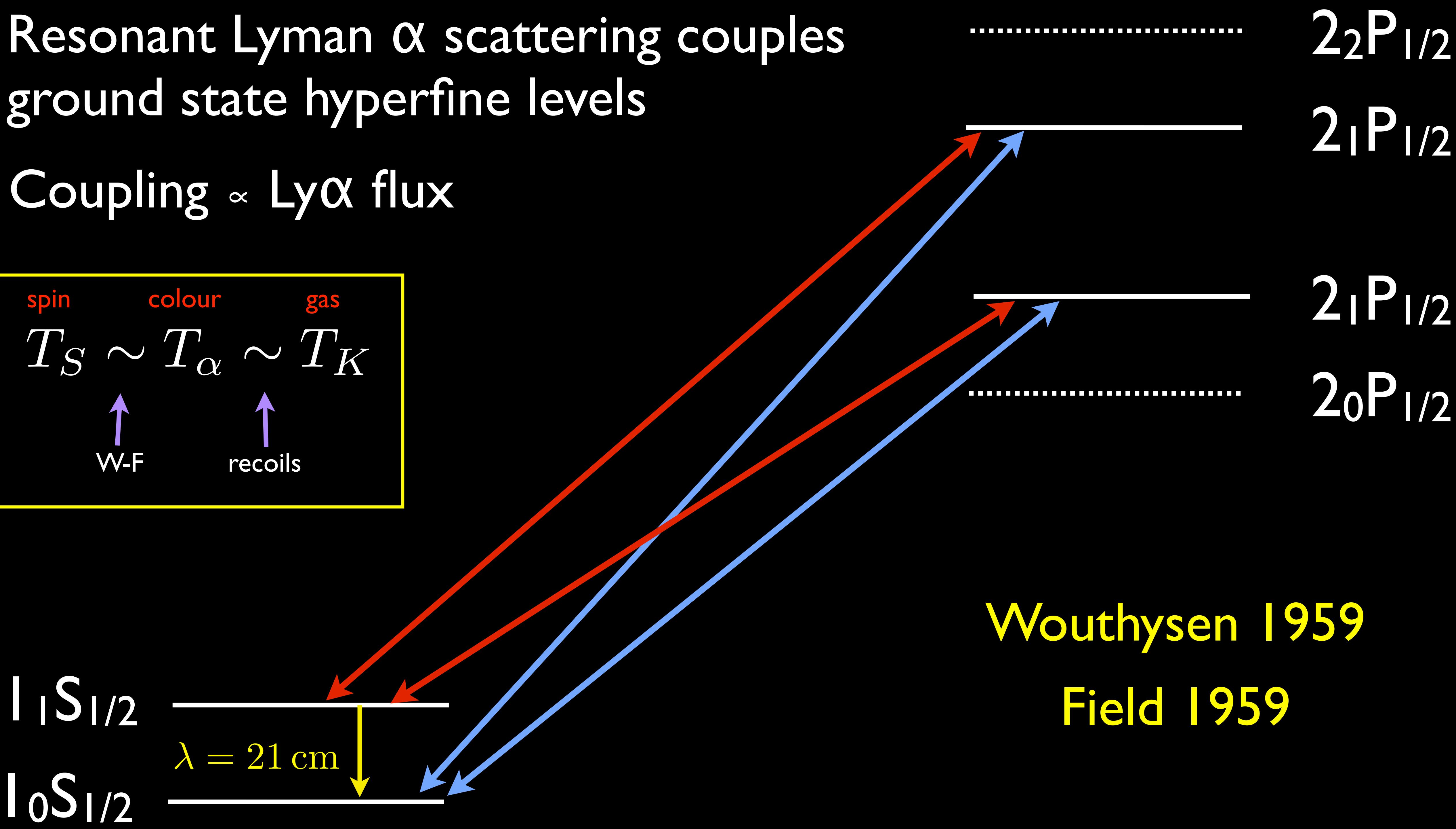


Wouthysen 1959

Field 1959

Thermal history

- X-rays likely dominant heating source in the early universe
  - (also Lya heating but inefficient)

X-ray binary

SNR

mini-quasar

- Only weak constraints from diffuse soft X-ray background

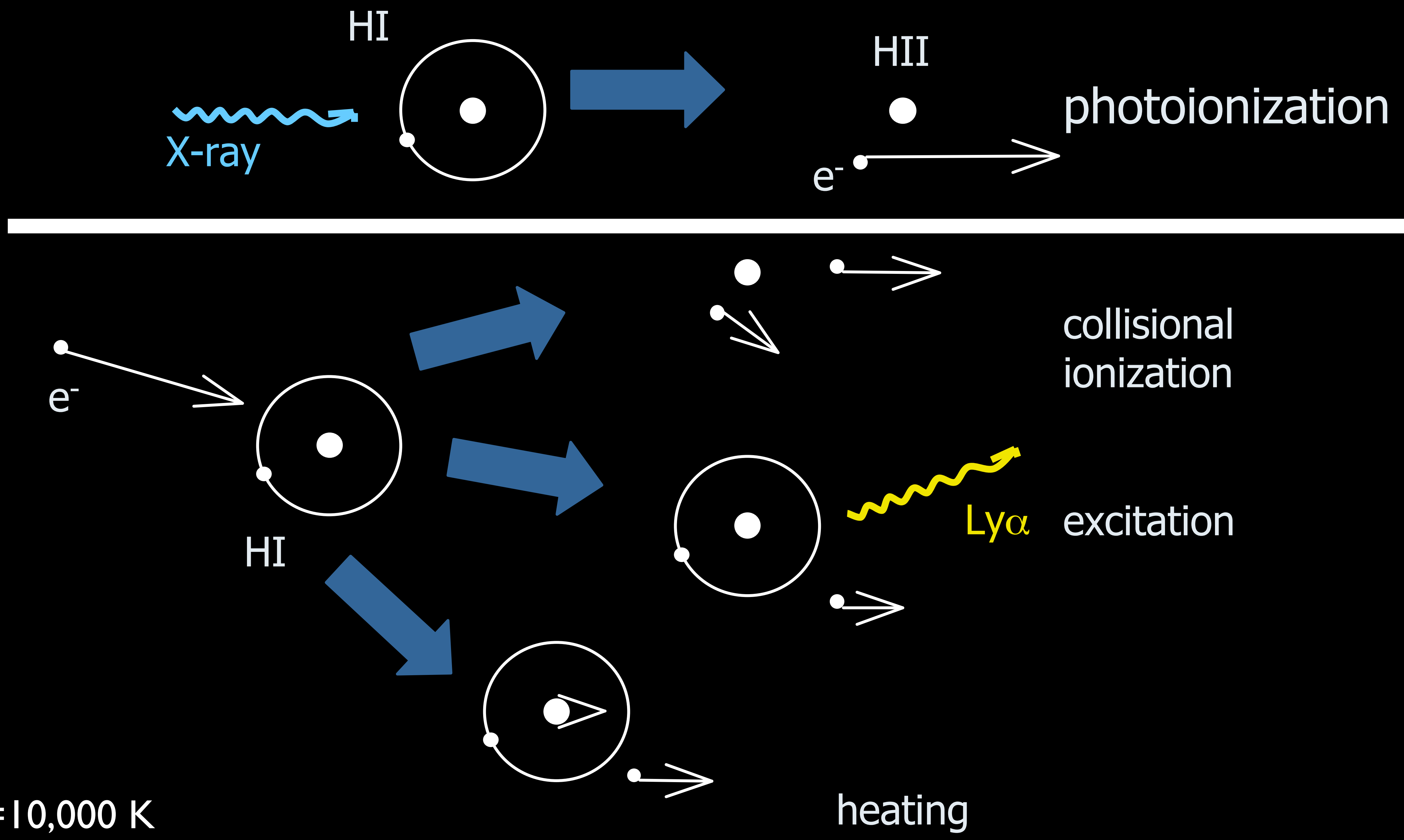
Dijkstra, Haiman, Loeb 2004

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

  ~1 keV per baryon in stars

X-ray heating

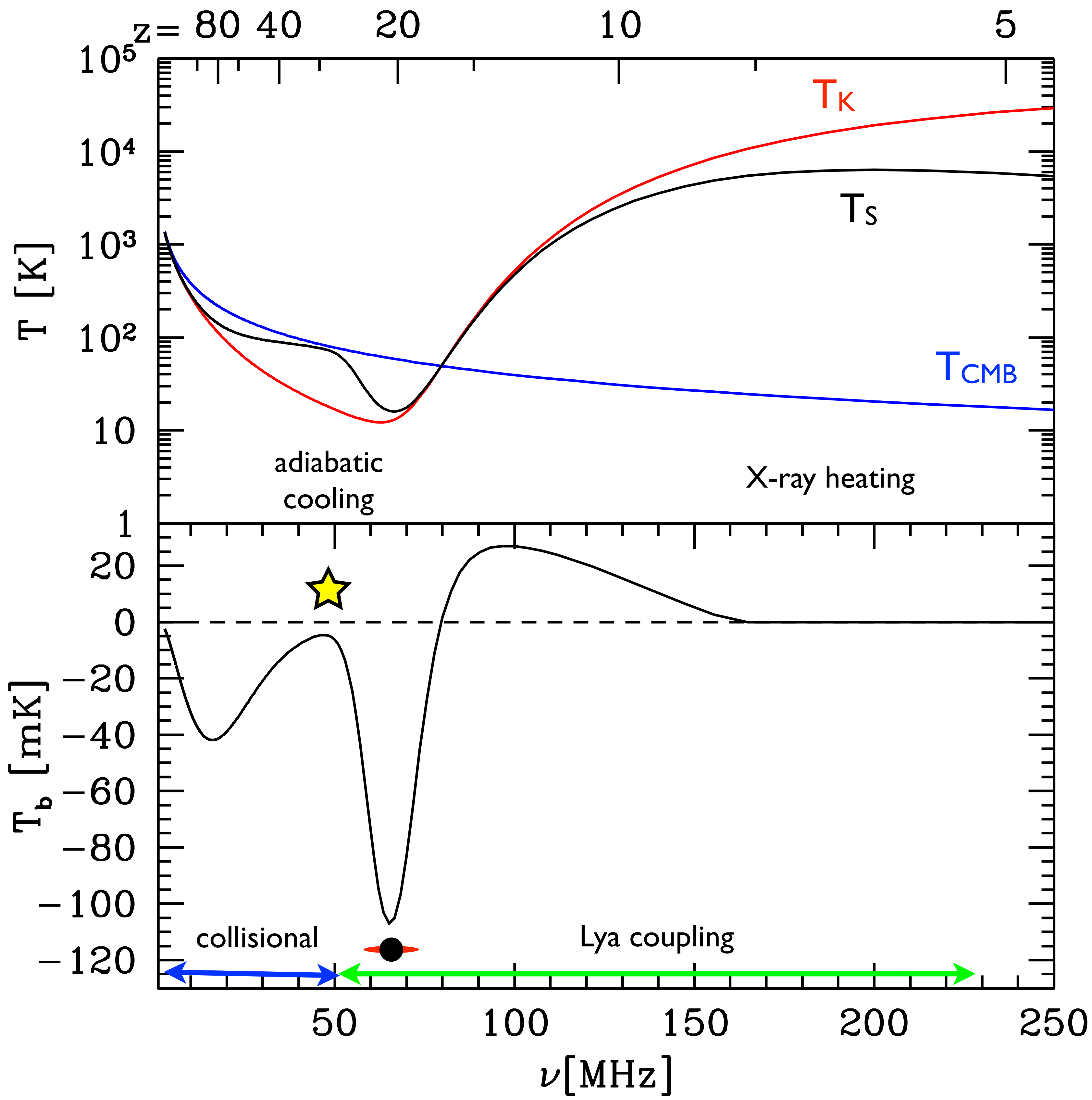
- X-ray energy partitioned



1eV=10,000 K

Shull & van Steenberg 1985, Furlanetto & Johnson 2010

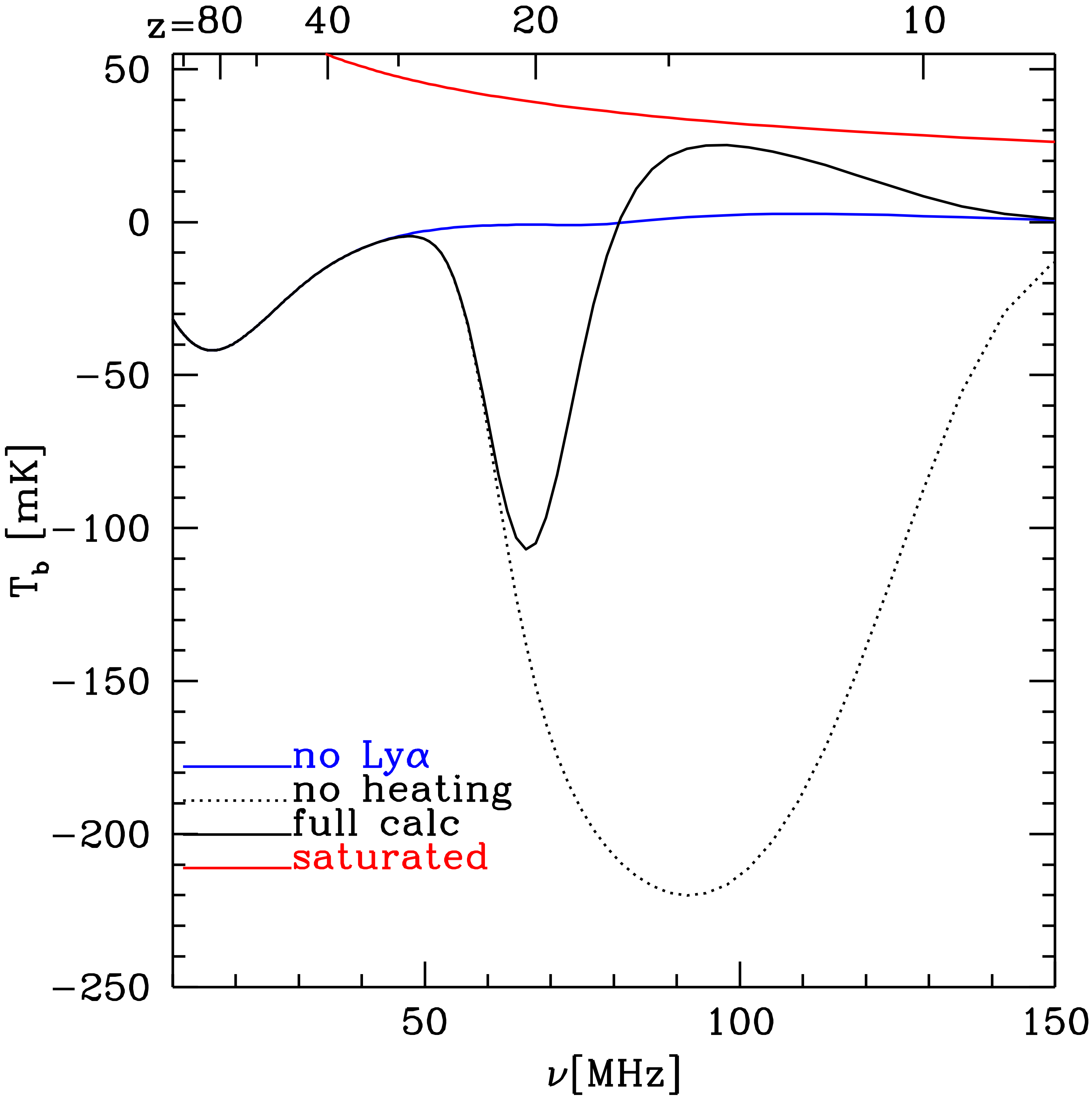
21 cm global signal



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

Furlanetto 2006
Pritchard & Loeb 2010

Alternative scenarios



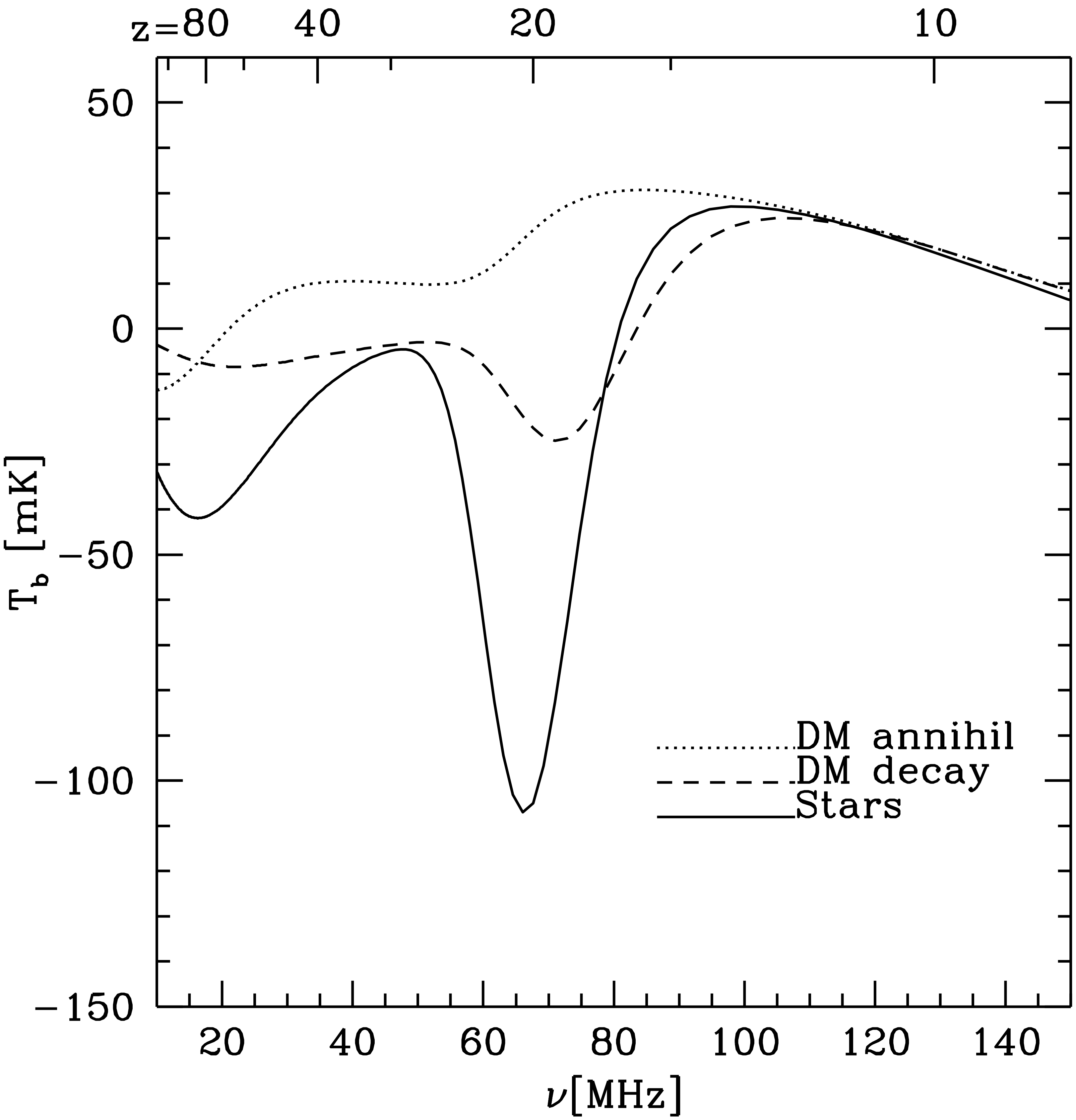
Maybe there was no
X-ray heating?

Maybe shocks heat the IGM
long before X-ray sources
exist?

Maybe Lya photons don't
escape their host halos?

Observations could answer
any of these questions

Exotic physics



Exotic energy injection before first stars switch on

Possibilities:
DM annihiliation
DM decay
Excited DM relaxation
Evaporating primodial BH
Cosmic string wakes
...

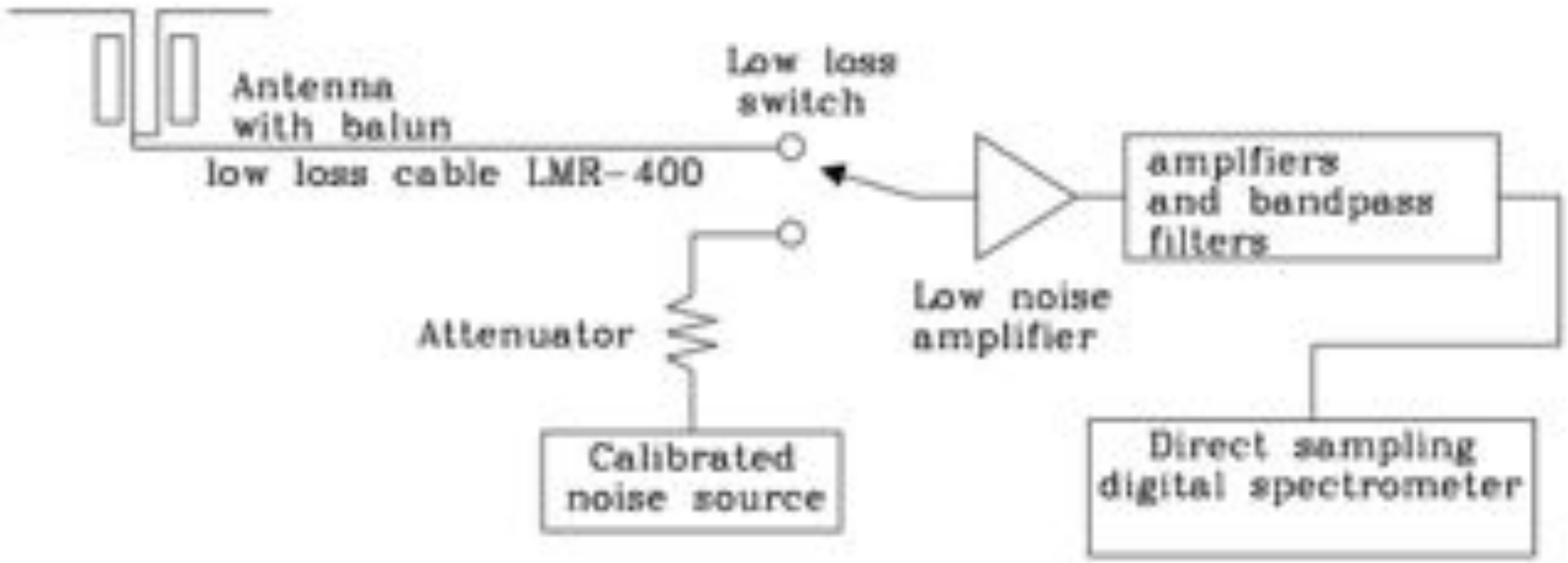
Very sensitive thermometer

Furlanetto+ 2006
Valdes+ 2007
Finkbeiner+ 2008
Mack+ 2008

Experiments

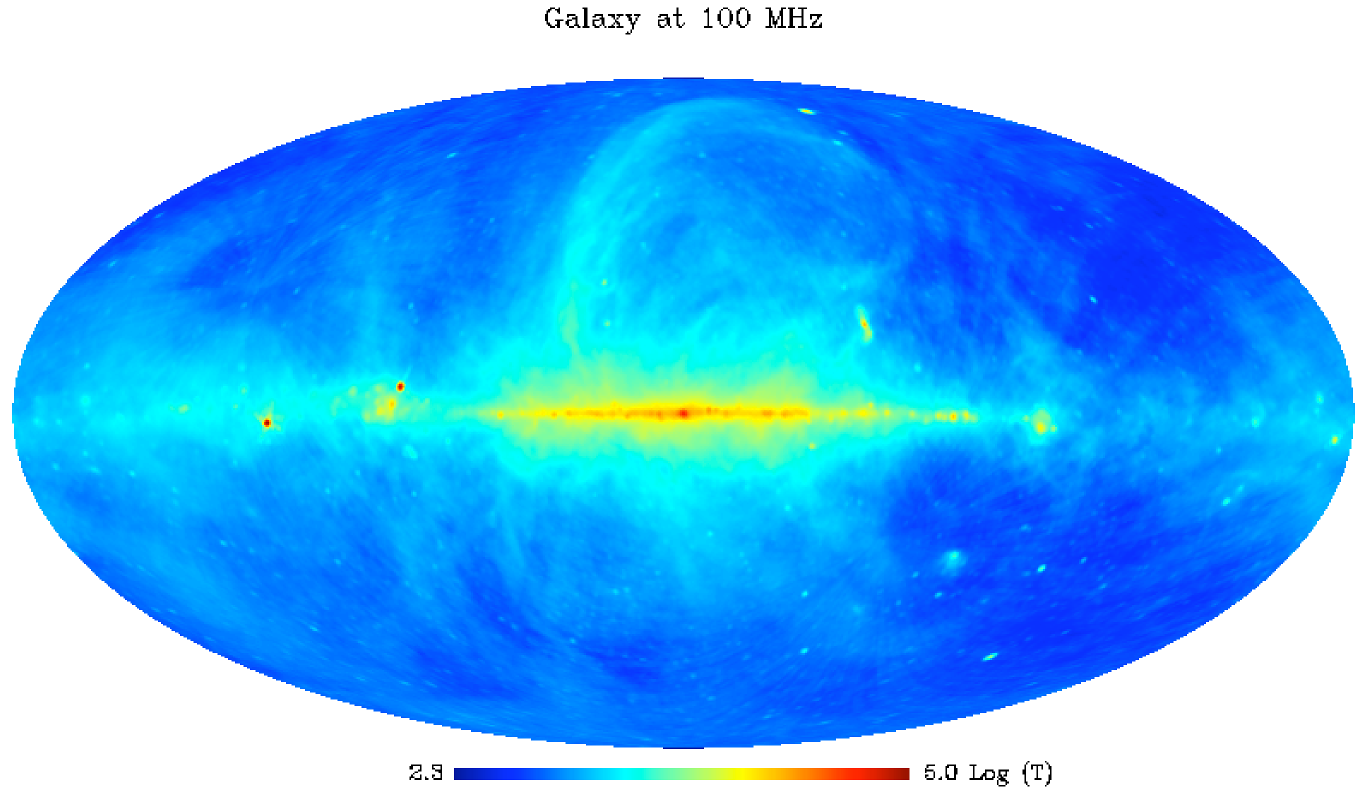

Bowman & Rogers 2008

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



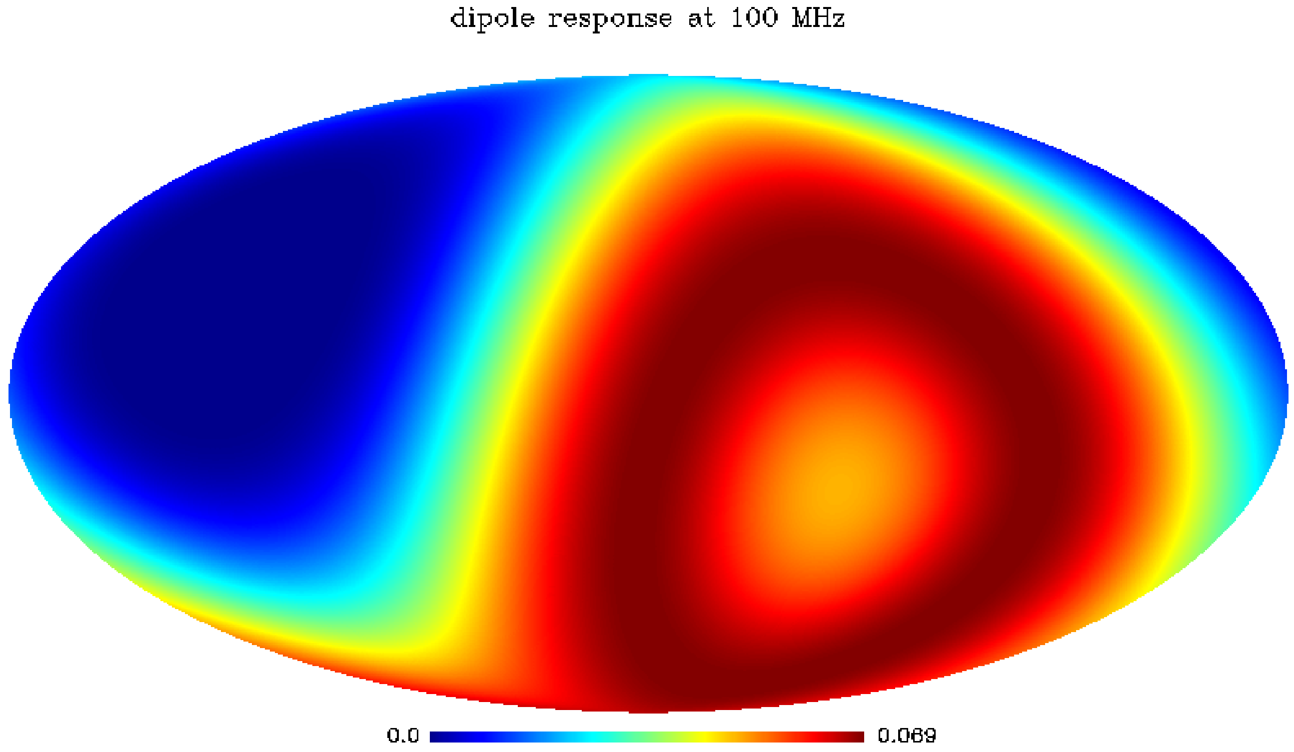
Switch between sky and calibrated reference source

Foregrounds



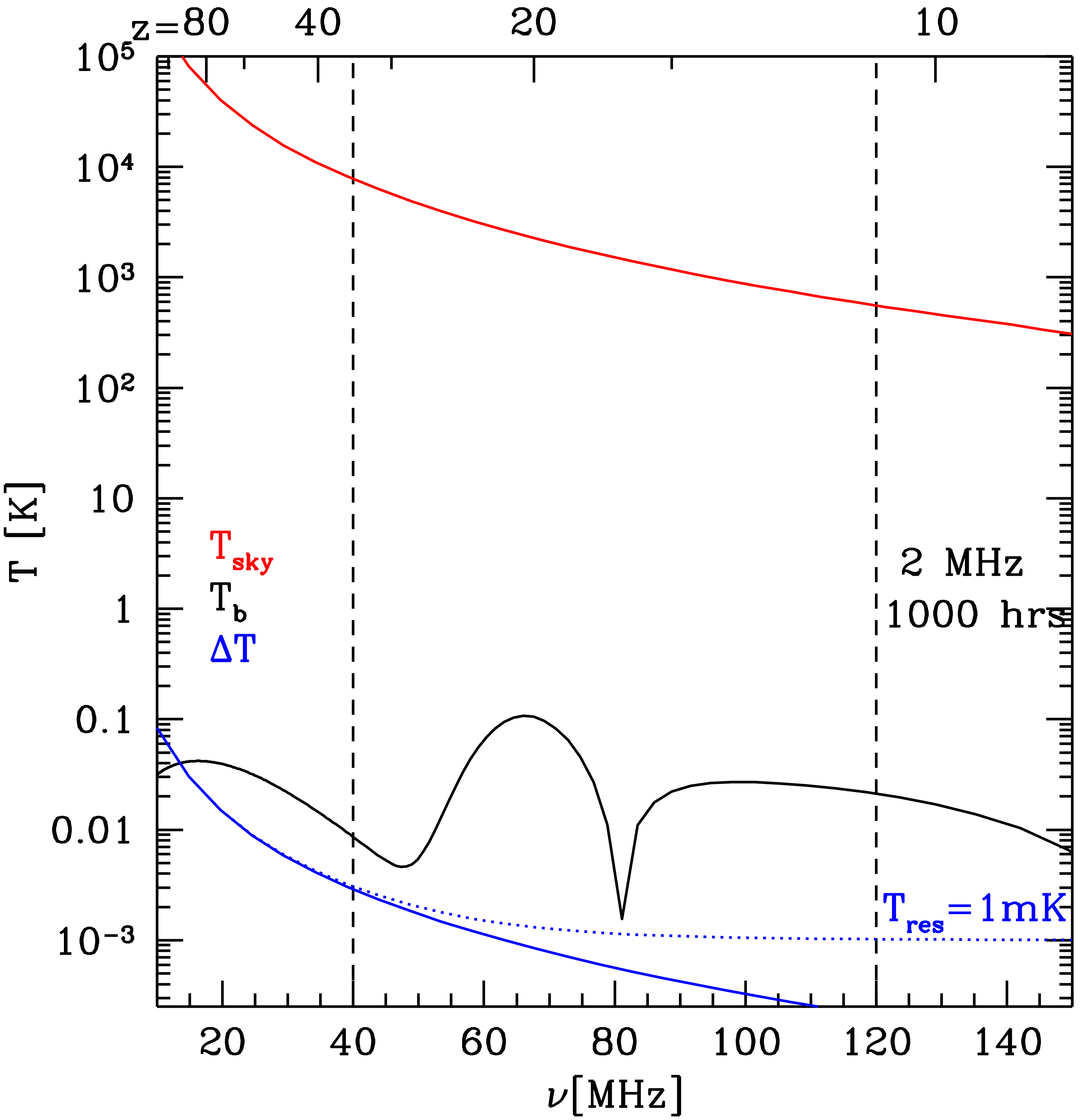
Sky at 100 MHz dominated by galactic foregrounds

de Oliveira-Costa+ 2008



Response of ideal dipole
at MWA site averaged over a day

Foregrounds vs Signal

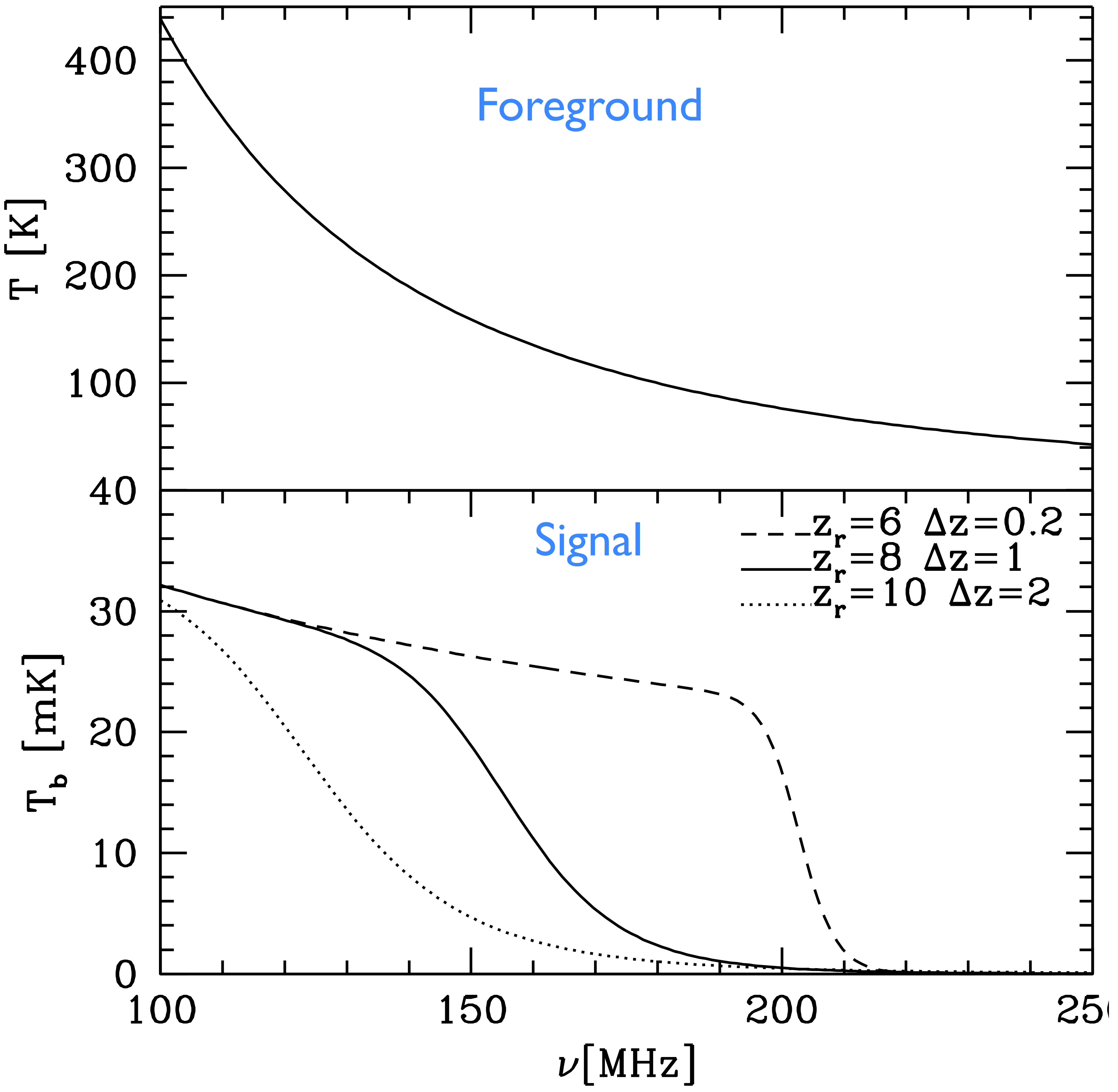


Foregrounds smooth
Signal has structure
Separation possible...

Dynamic range >10^5 needed

$$\Delta T = \frac{T_{\rm sky}}{\sqrt{\Delta\nu t_{\rm obs}}}$$

Frequency subtraction



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

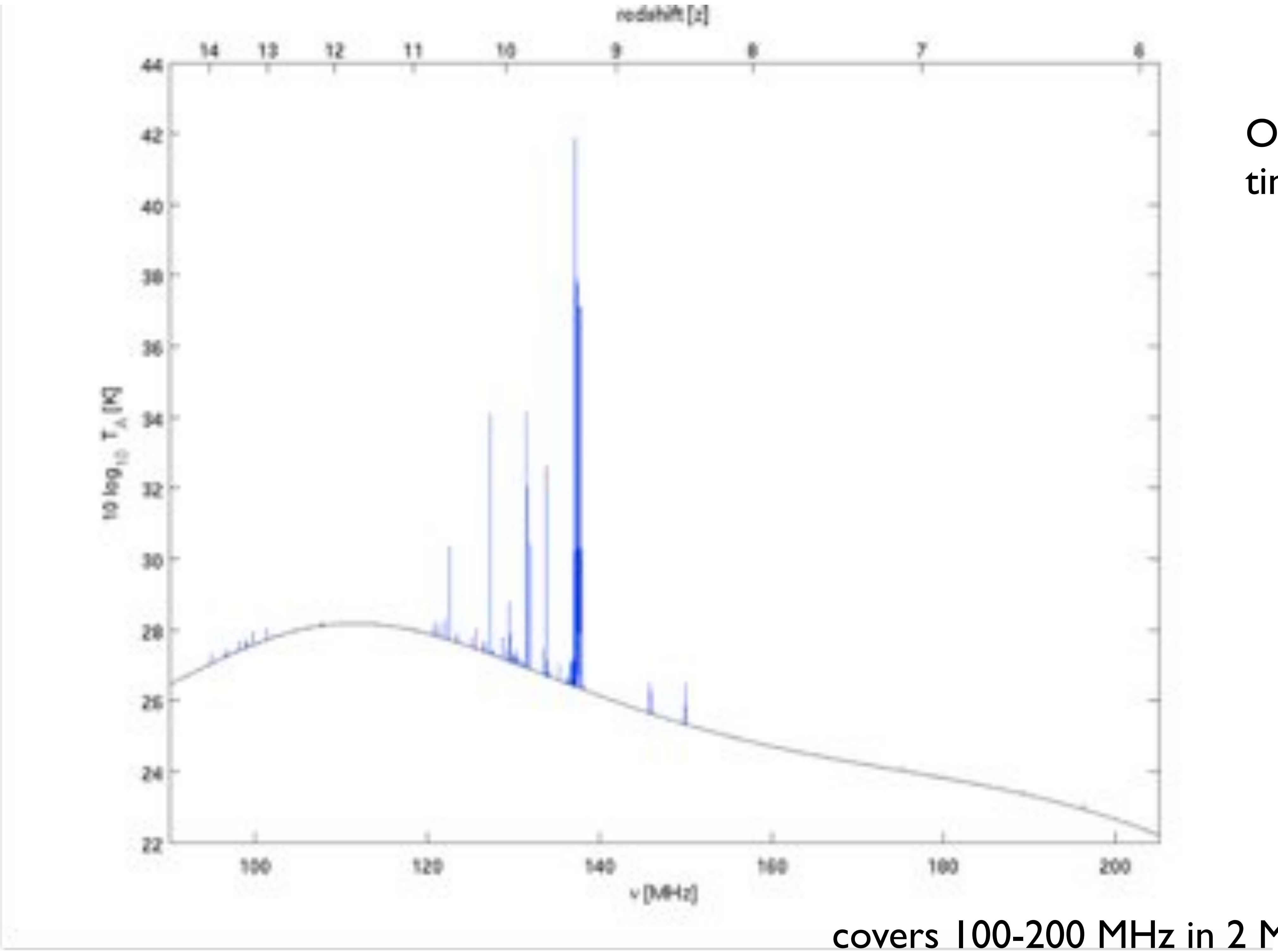
Look for sharp 21 cm signal against smooth foregrounds
Shaver+ 1999

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

TS>>TCMB
no spin temperature dependence

Extended reionization histories closer to foregrounds

EDGES observations



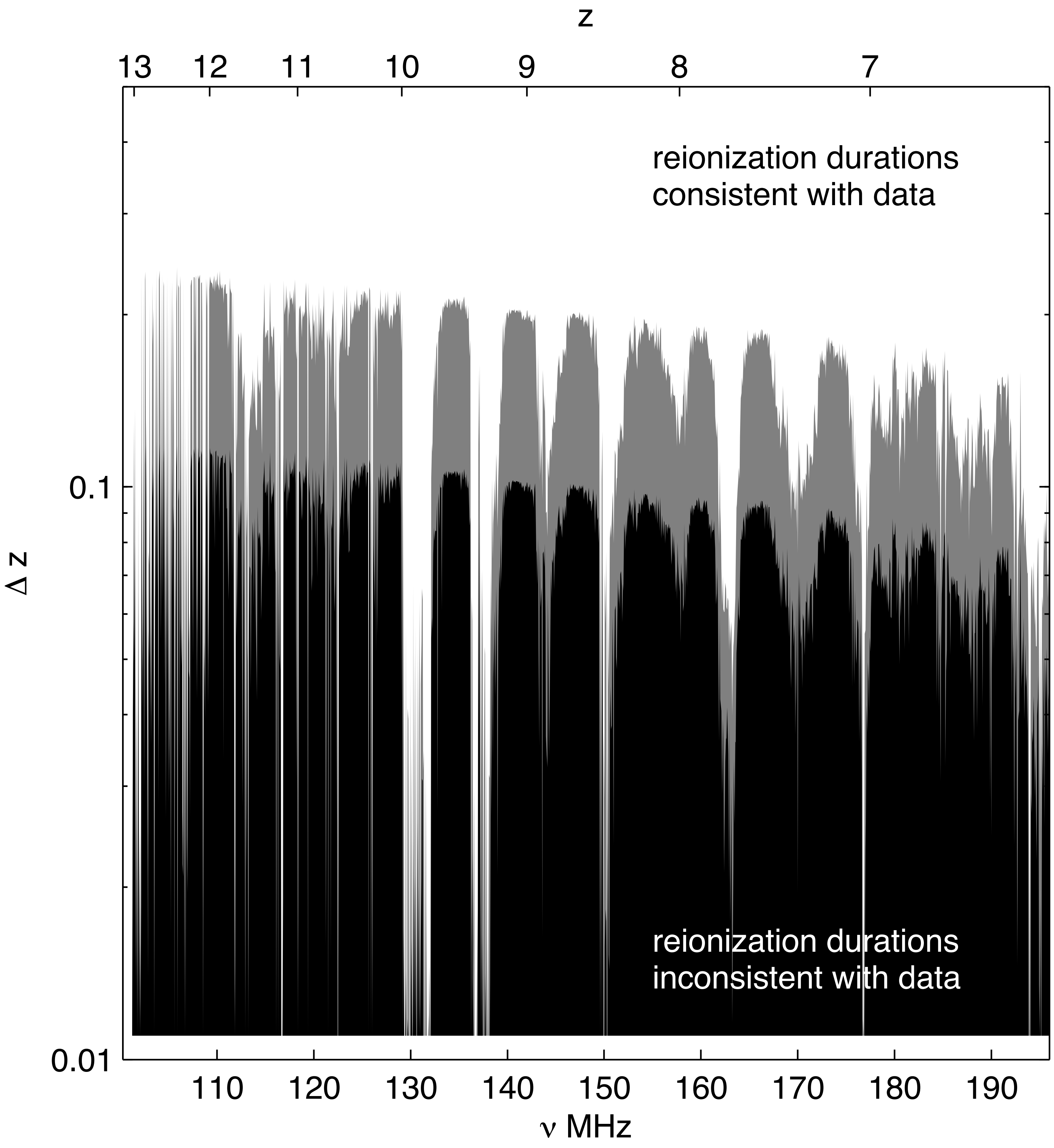
Observed sky
tint=50 hours

covers 100-200 MHz in 2 MHz channels

Foregrounds convolved with
instrumental response - calibration

Bowman & Rogers 2008

Reionization constraints



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

Some channels lost to RFI

Bowman+ 2010

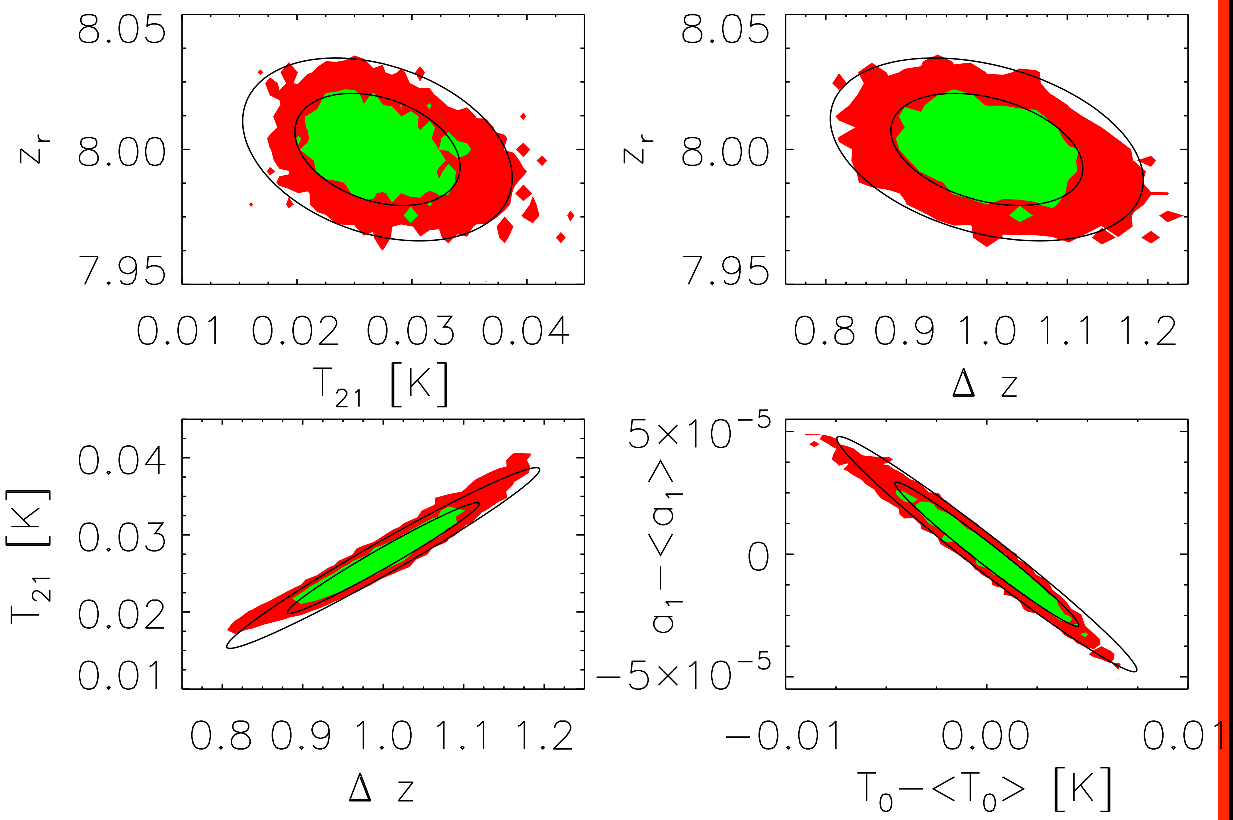
Making predictions

Assume full sky experiment covering range [numin,numax]
in N channels of width B and integrating for tint

Thermal noise $$\sigma_i^2 = \frac{T_{\rm sky}^2}{Bt_{\rm int}}$$

Sky model $$T_{\rm sky} = T_{\rm fg} + T_b.$$

Fisher matrix $$F_{ij} = \sum_i (2+Bt_{\rm int}) \frac{{\rm d}\log T_{\rm sky}}{{\rm d}p_i} \frac{{\rm d}\log T_{\rm sky}}{{\rm d}p_j}$$

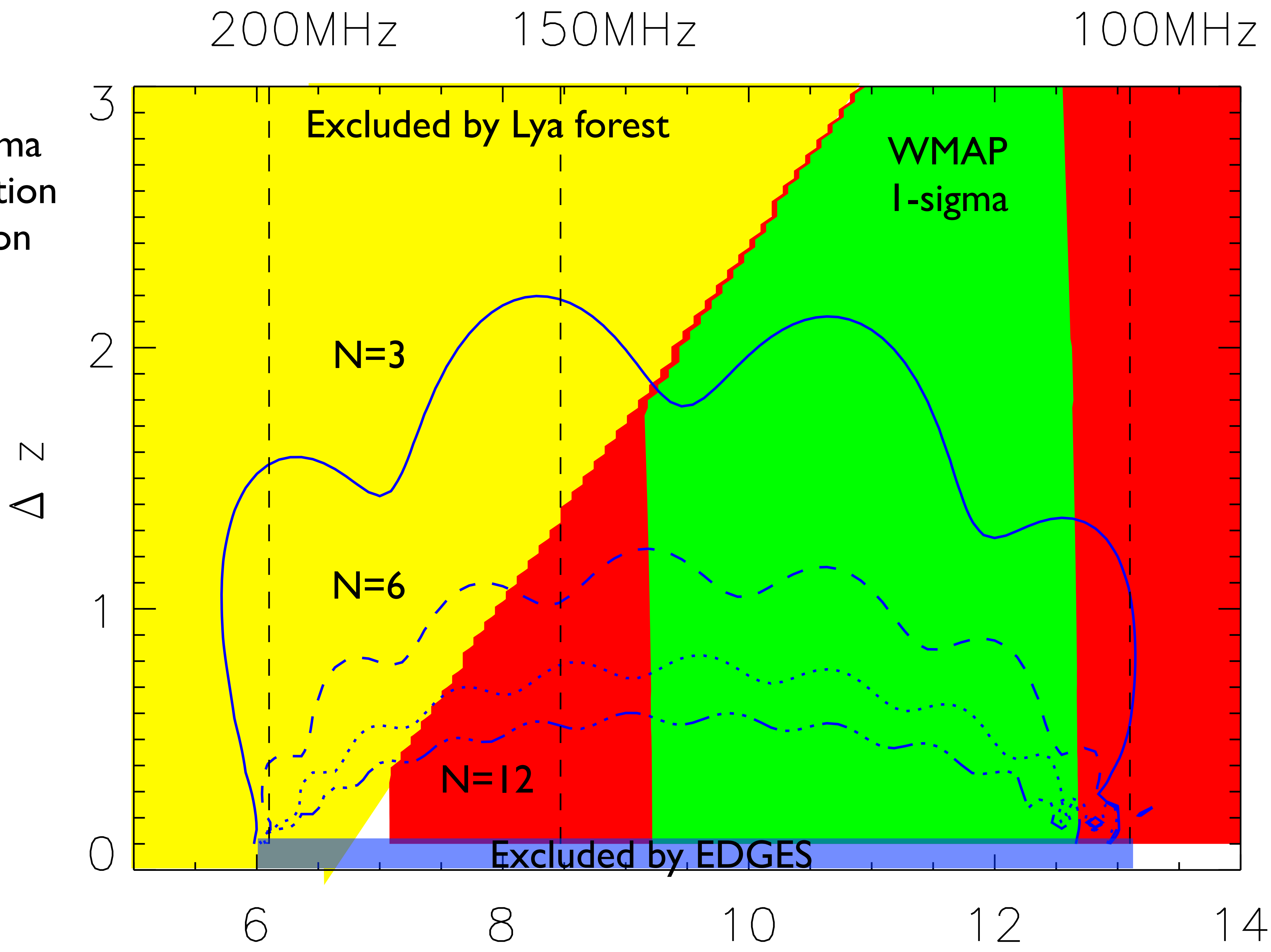


Compare with least squares fitting of model
to 10^6 realisations of thermal noise: Good agreement

tint= 500hrs, 50 channels spanning 100-200MHz, 3rd order polynomial Pritchard & Loeb 2010

Reionization detection region

2-sigma
detection
region



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

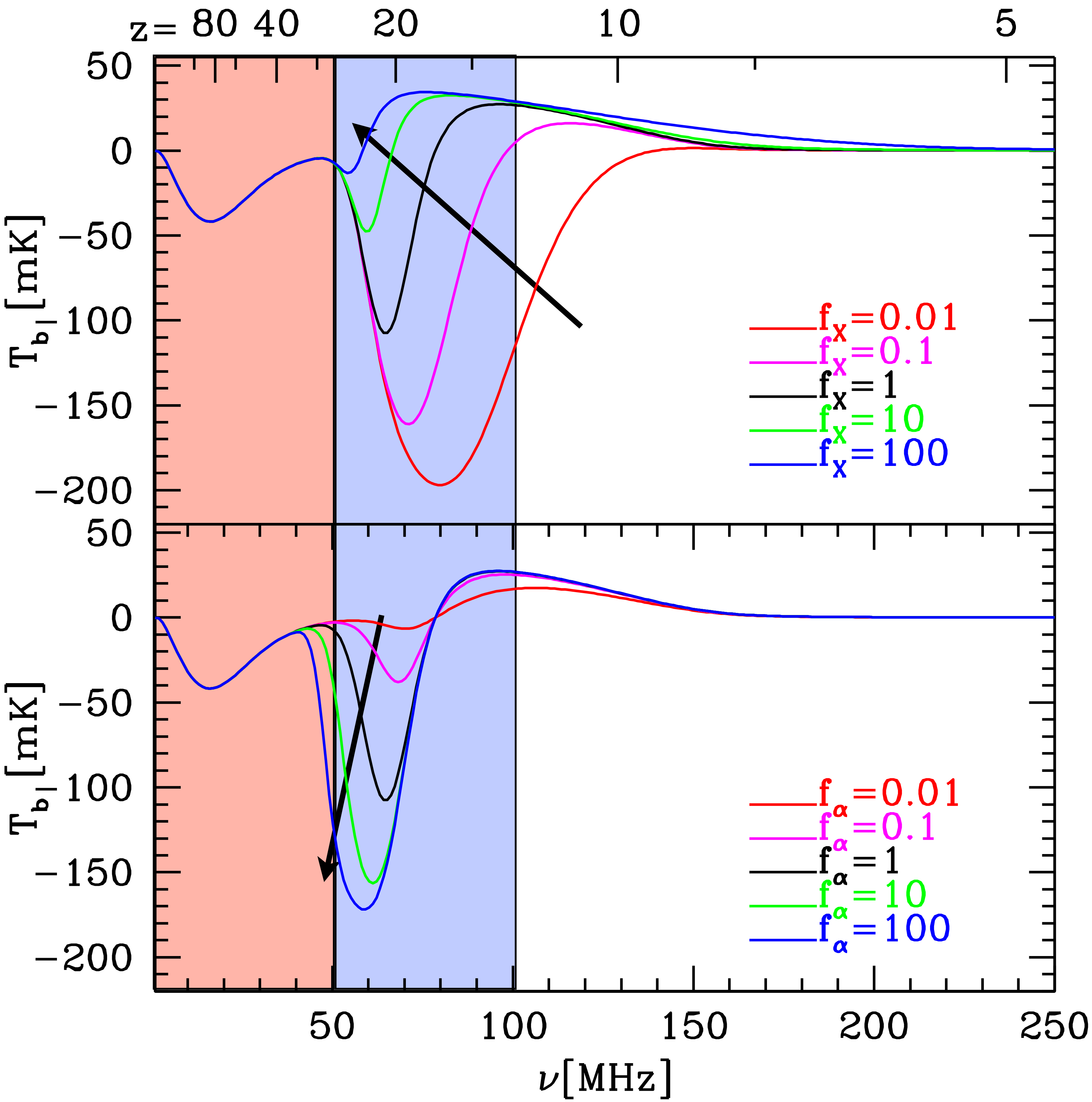
tint= 500hrs,
50 channels spanning 100-200MHz

Uncertain high redshift sources

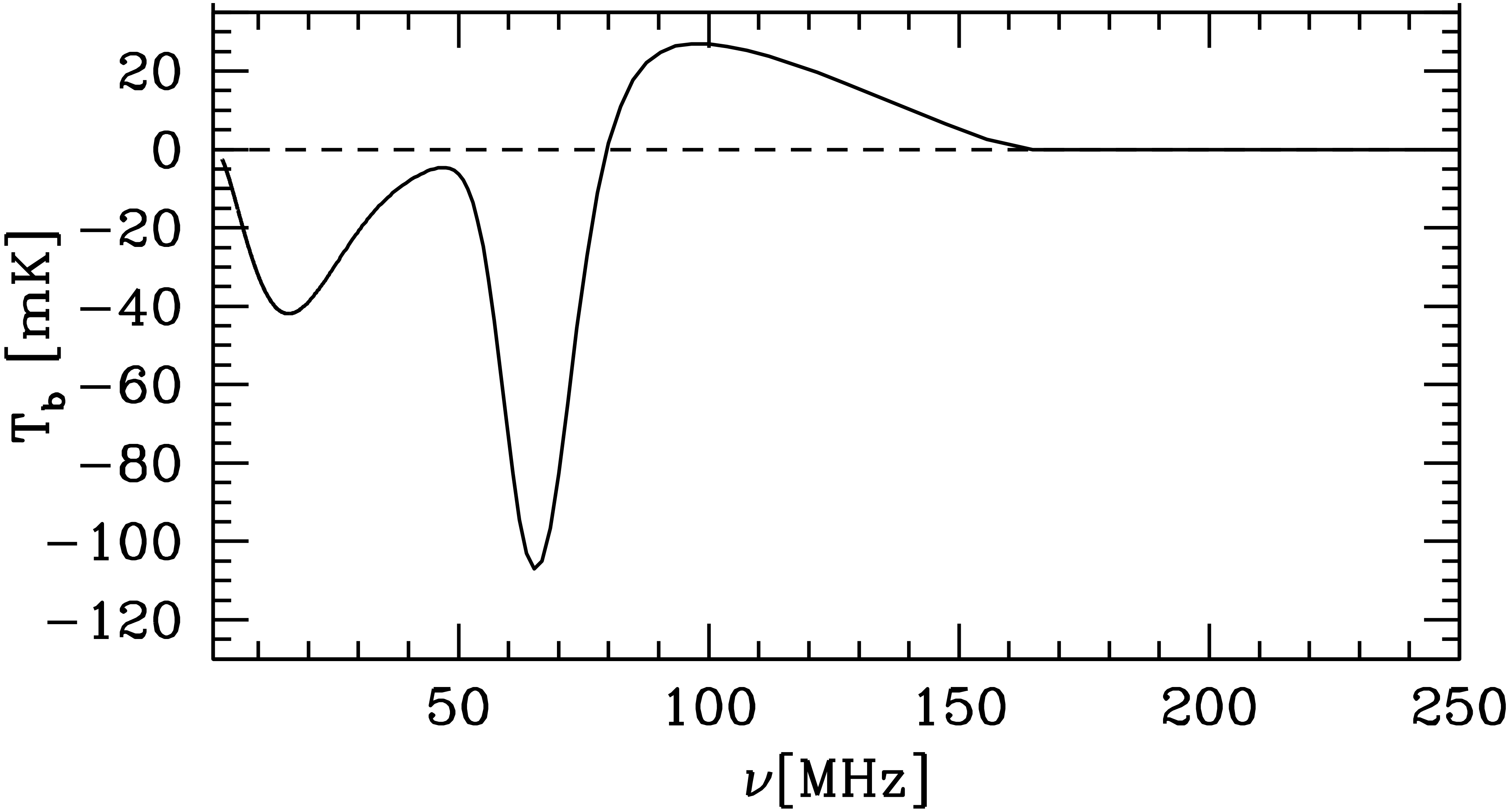
Properties of first galaxies are very uncertain

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

Below ~50 MHz ionosphere and RFI probably a killer on earth



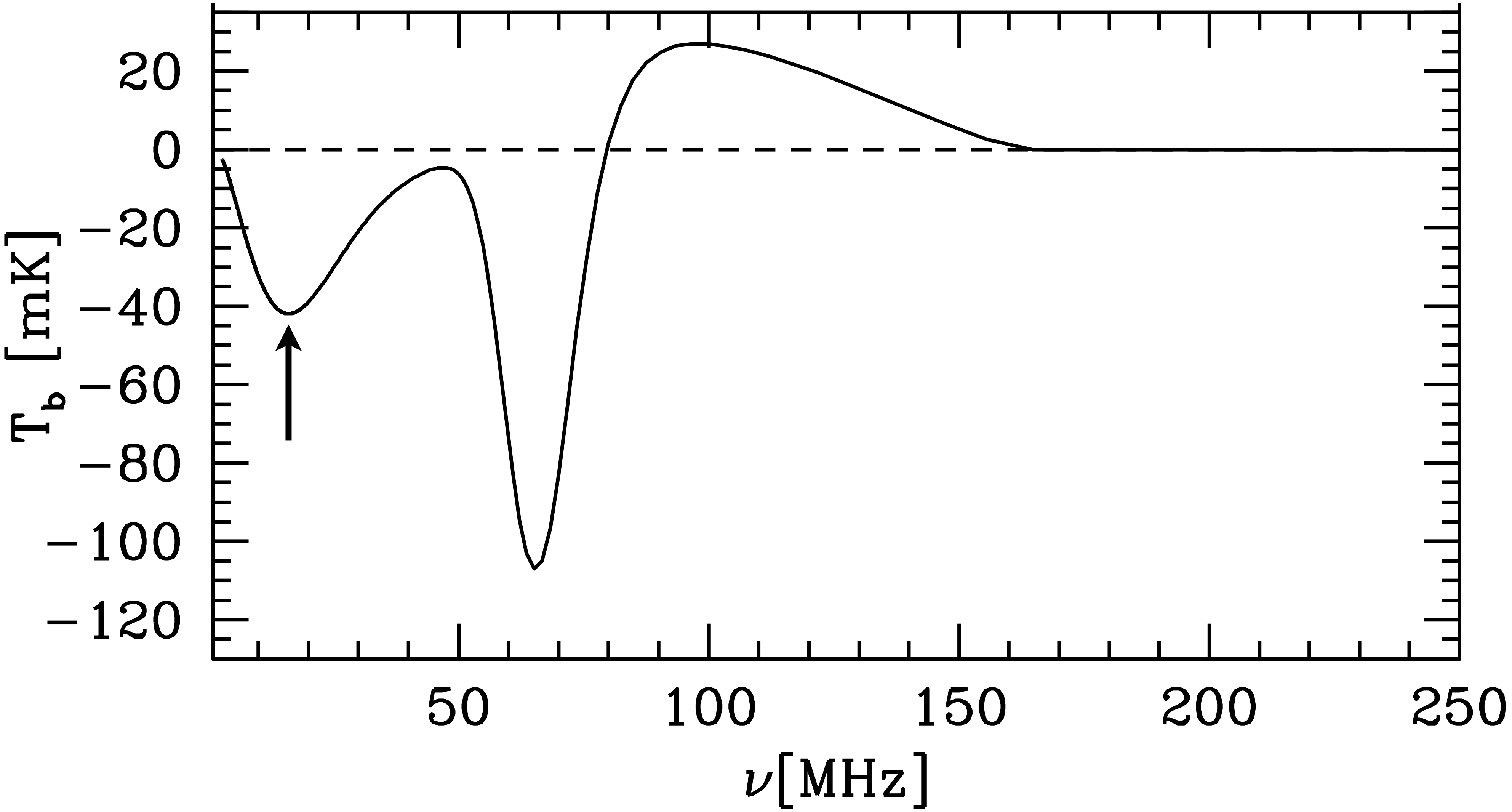
Features in the global signal



five key features

focus on turning points

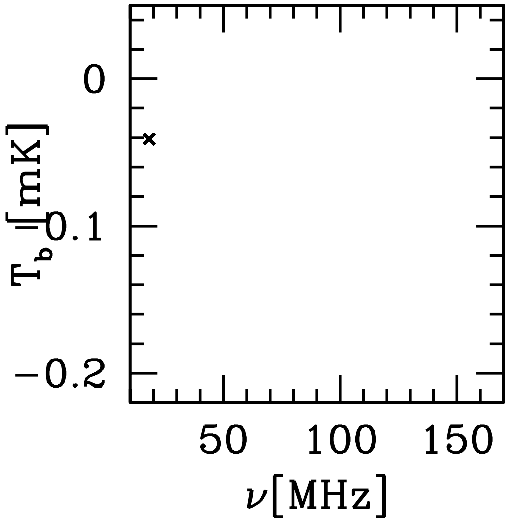
Features in the global signal



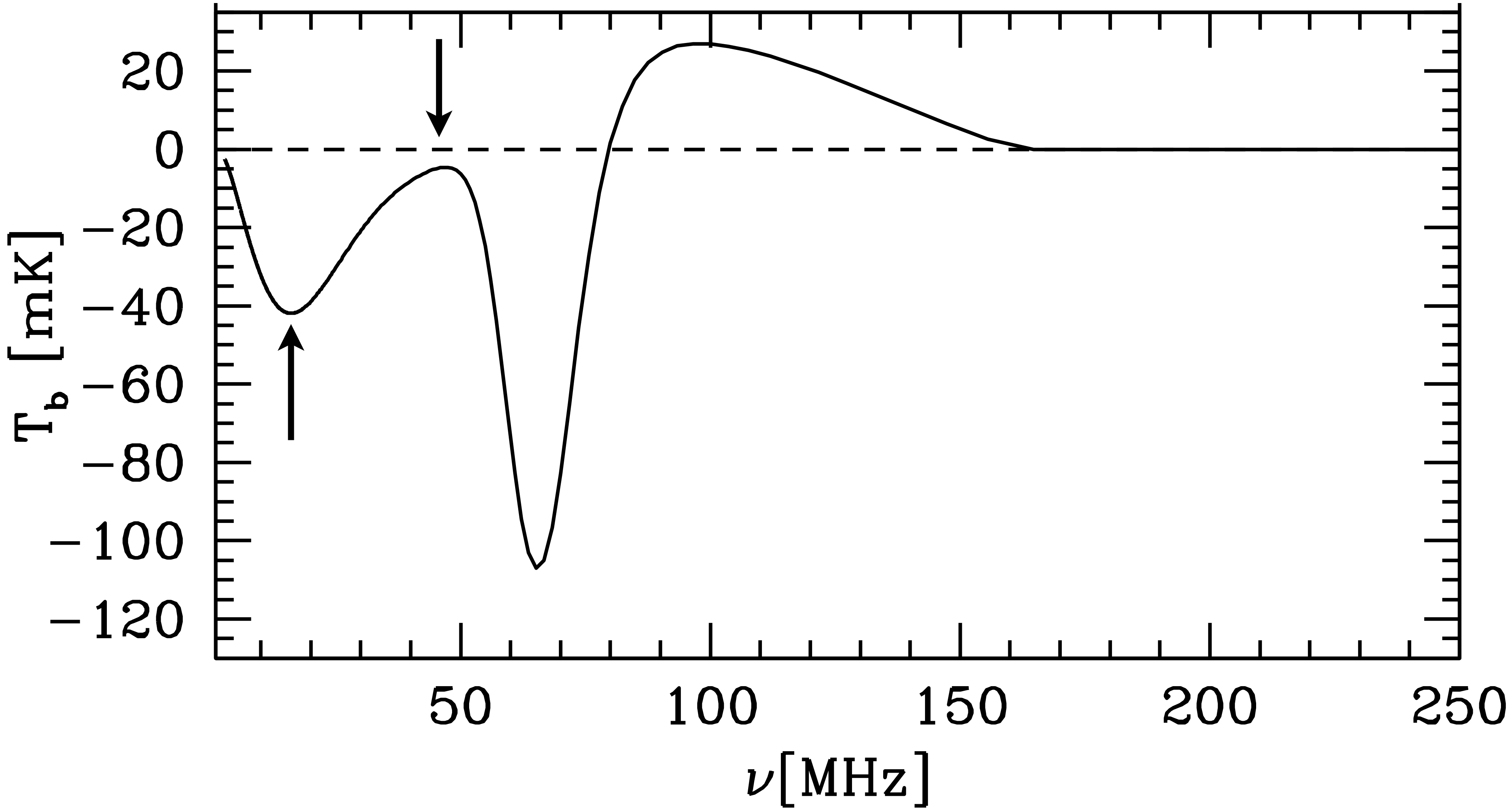
five key features

focus on turning points

Collisions fail



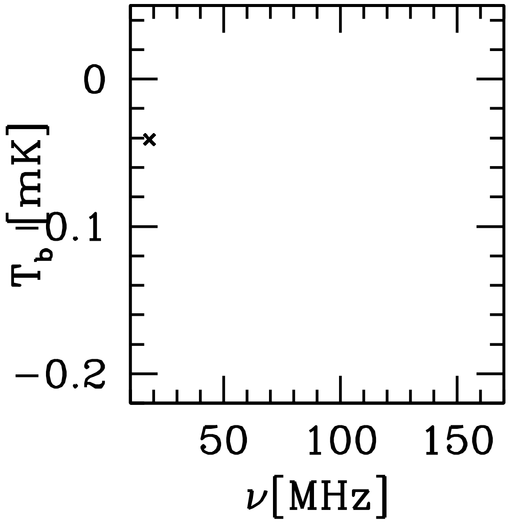
Features in the global signal



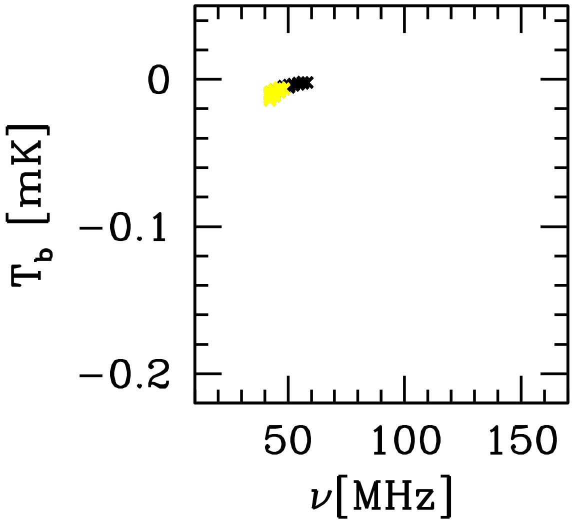
five key features

focus on turning points

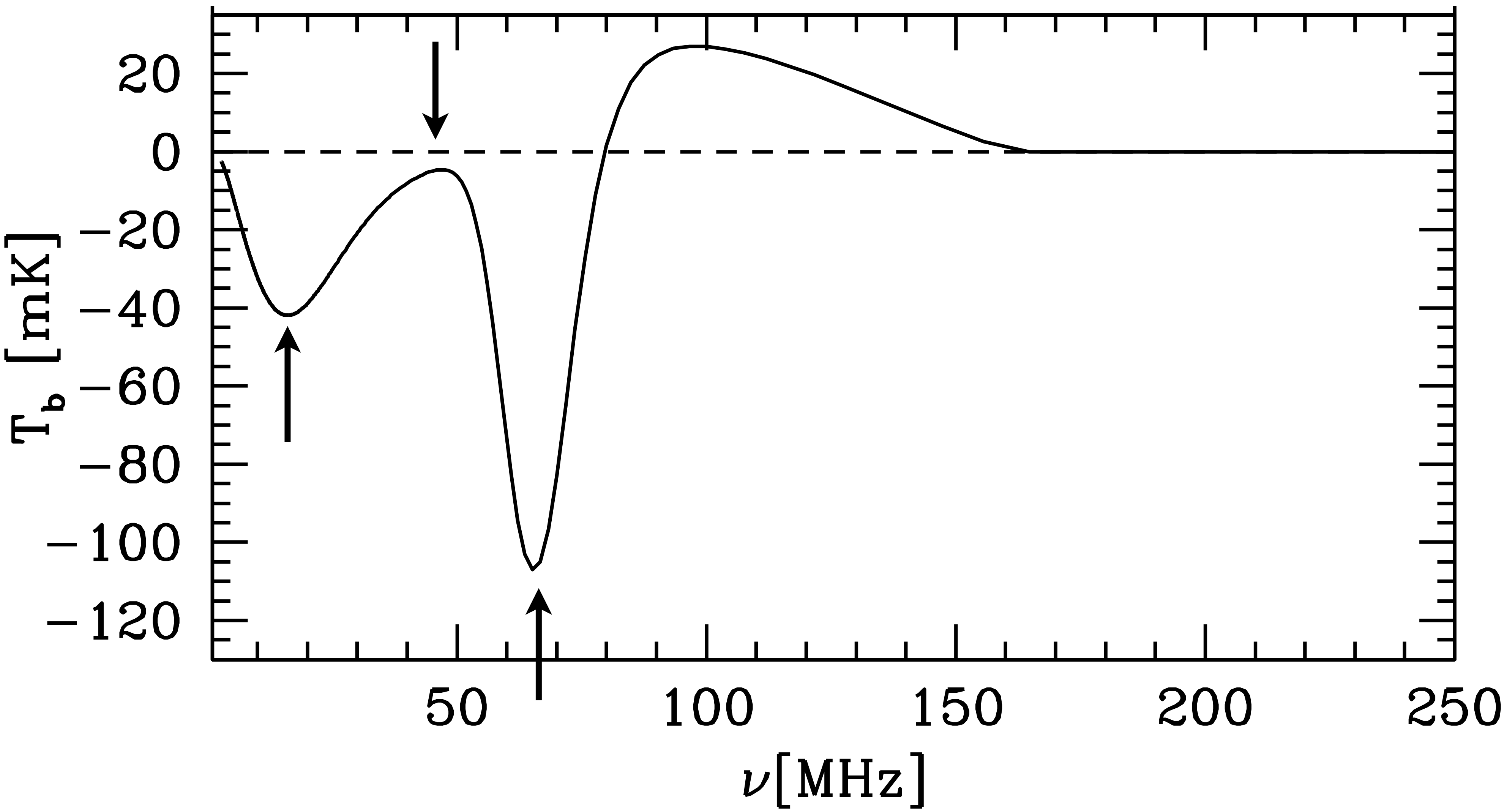
Collisions fail



Lya begins



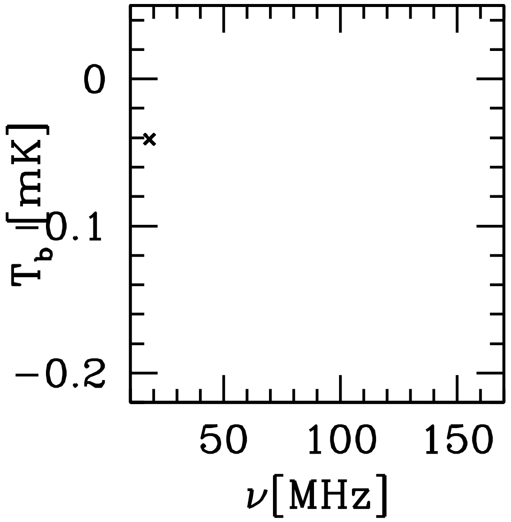
Features in the global signal



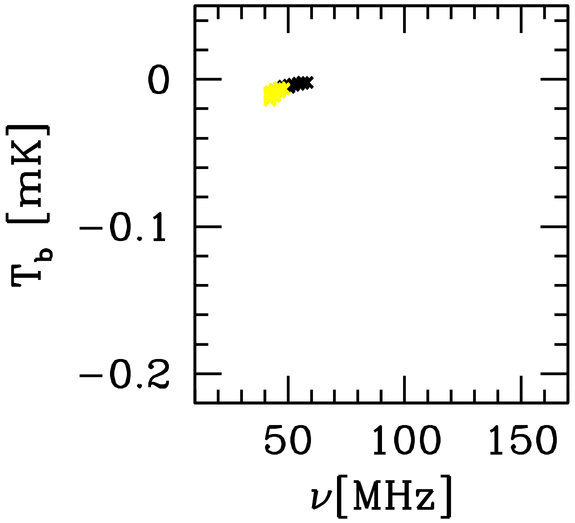
five key features

focus on turning points

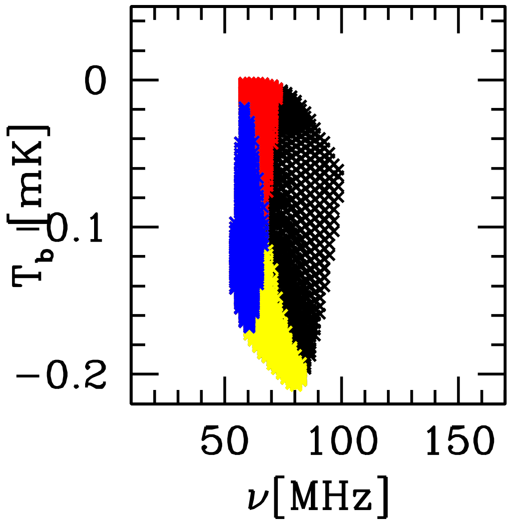
Collisions fail



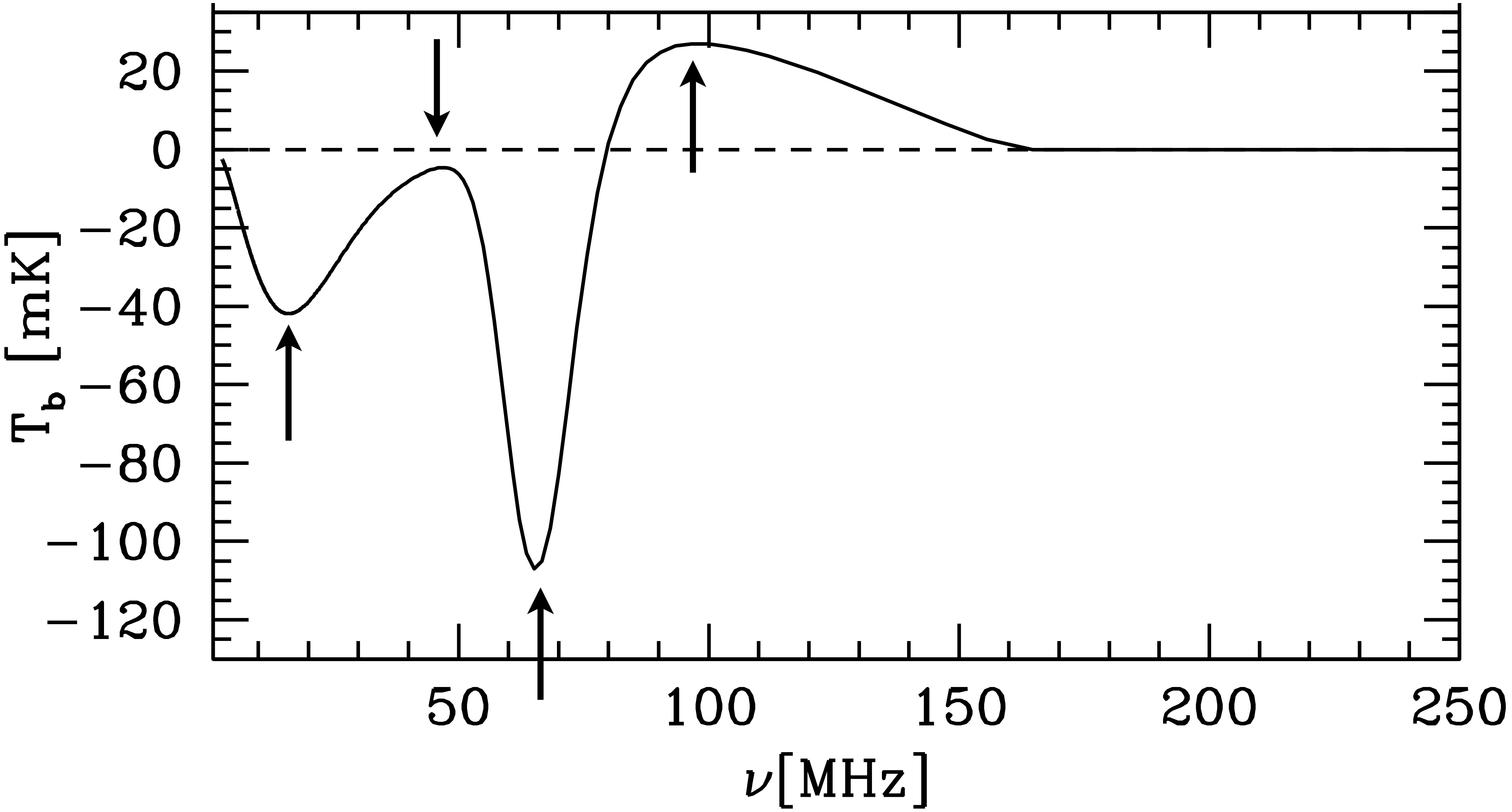
Lya begins



heating begins

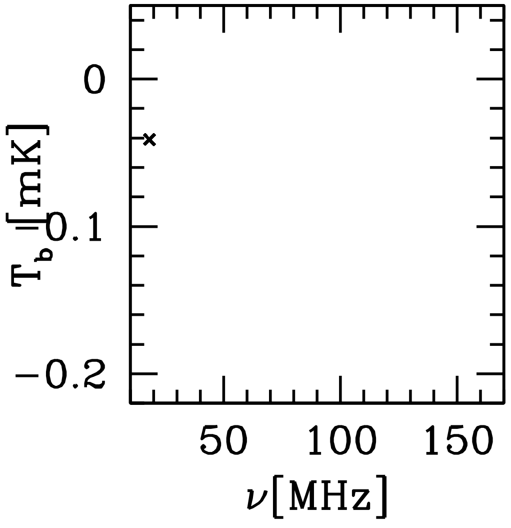


Features in the global signal

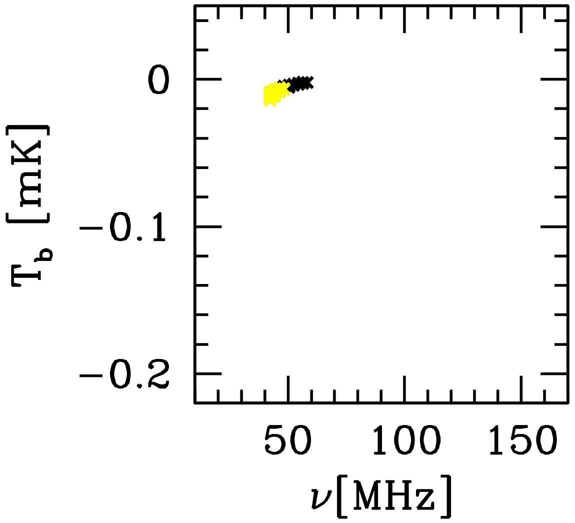


five key features

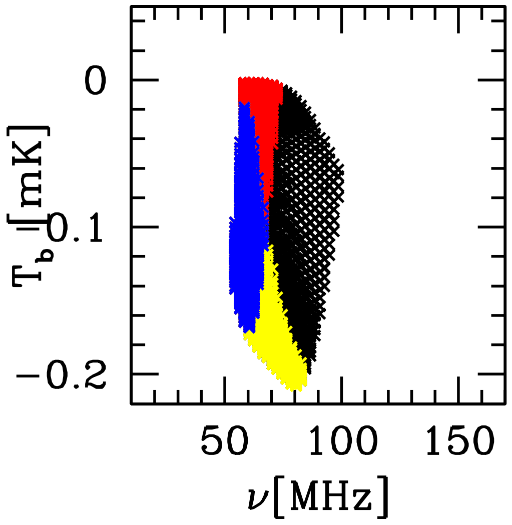
focus on turning points



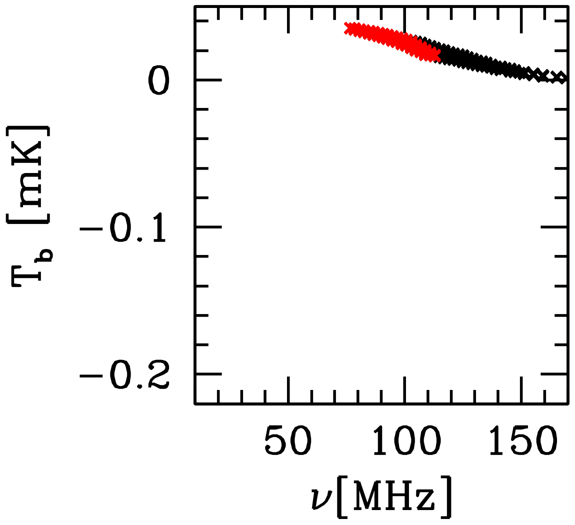
Collisions fail



Lya begins

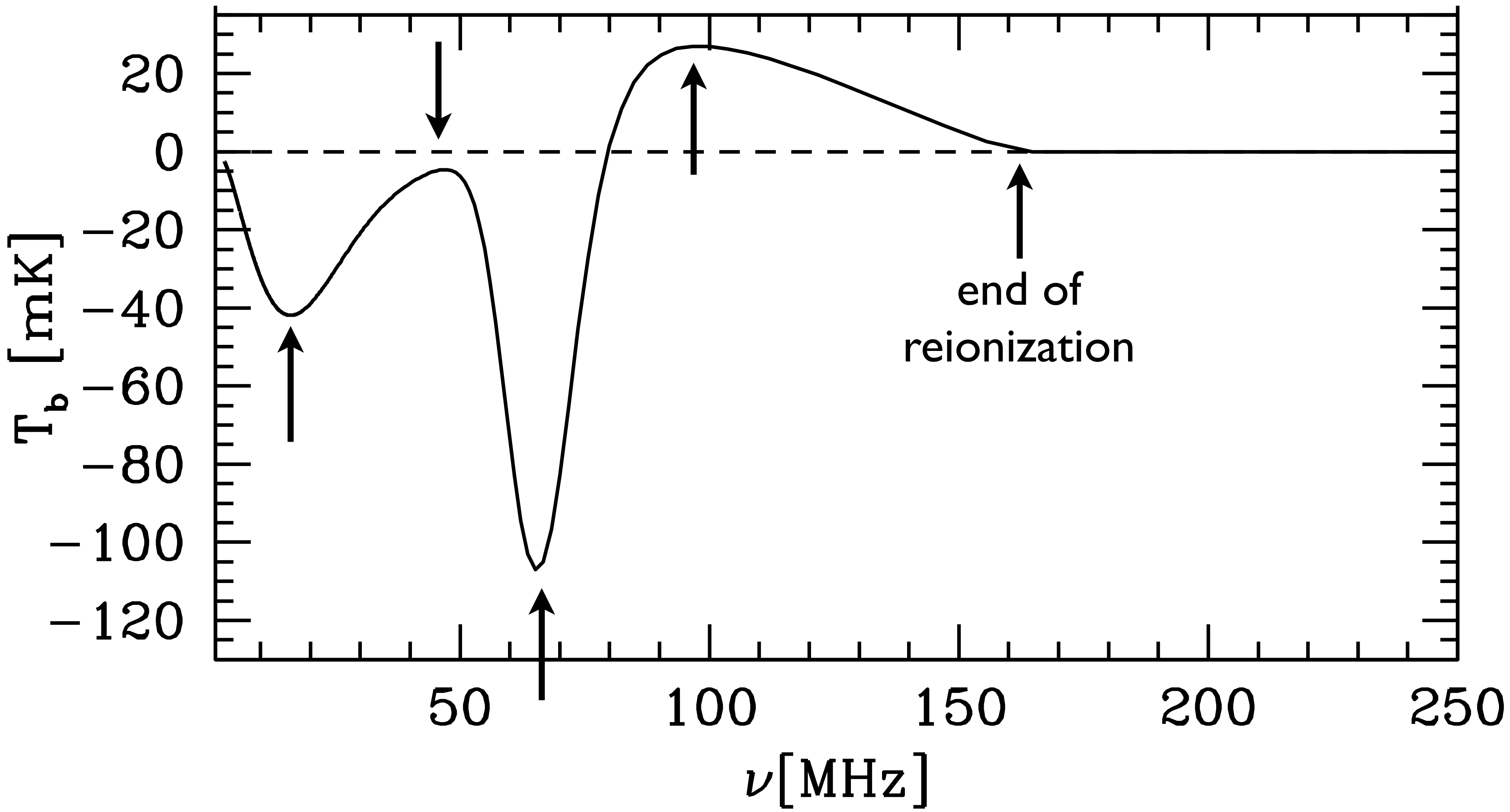


heating begins



signal saturates

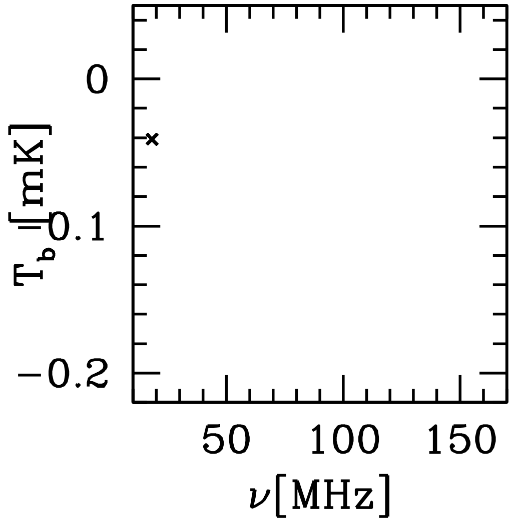
Features in the global signal



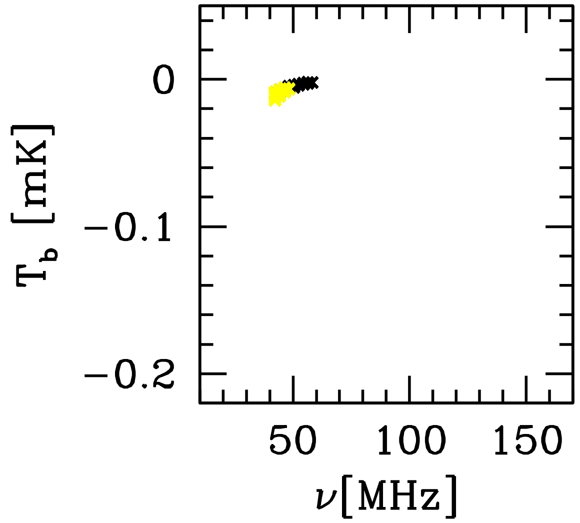
five key features

focus on turning points

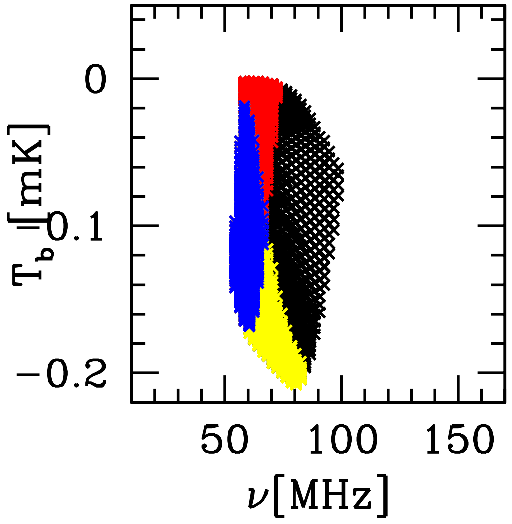
Collisions fail



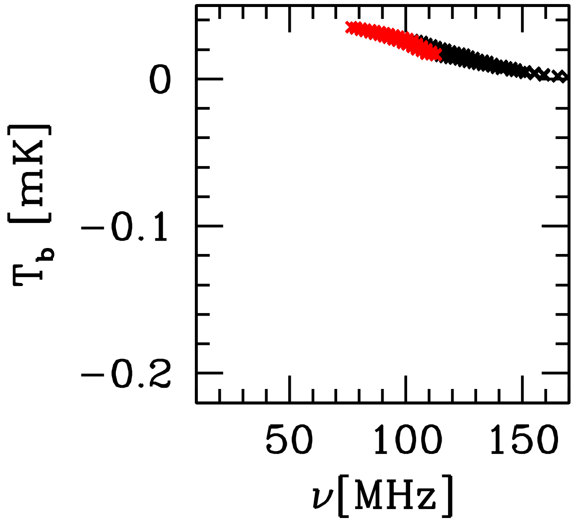
Lya begins



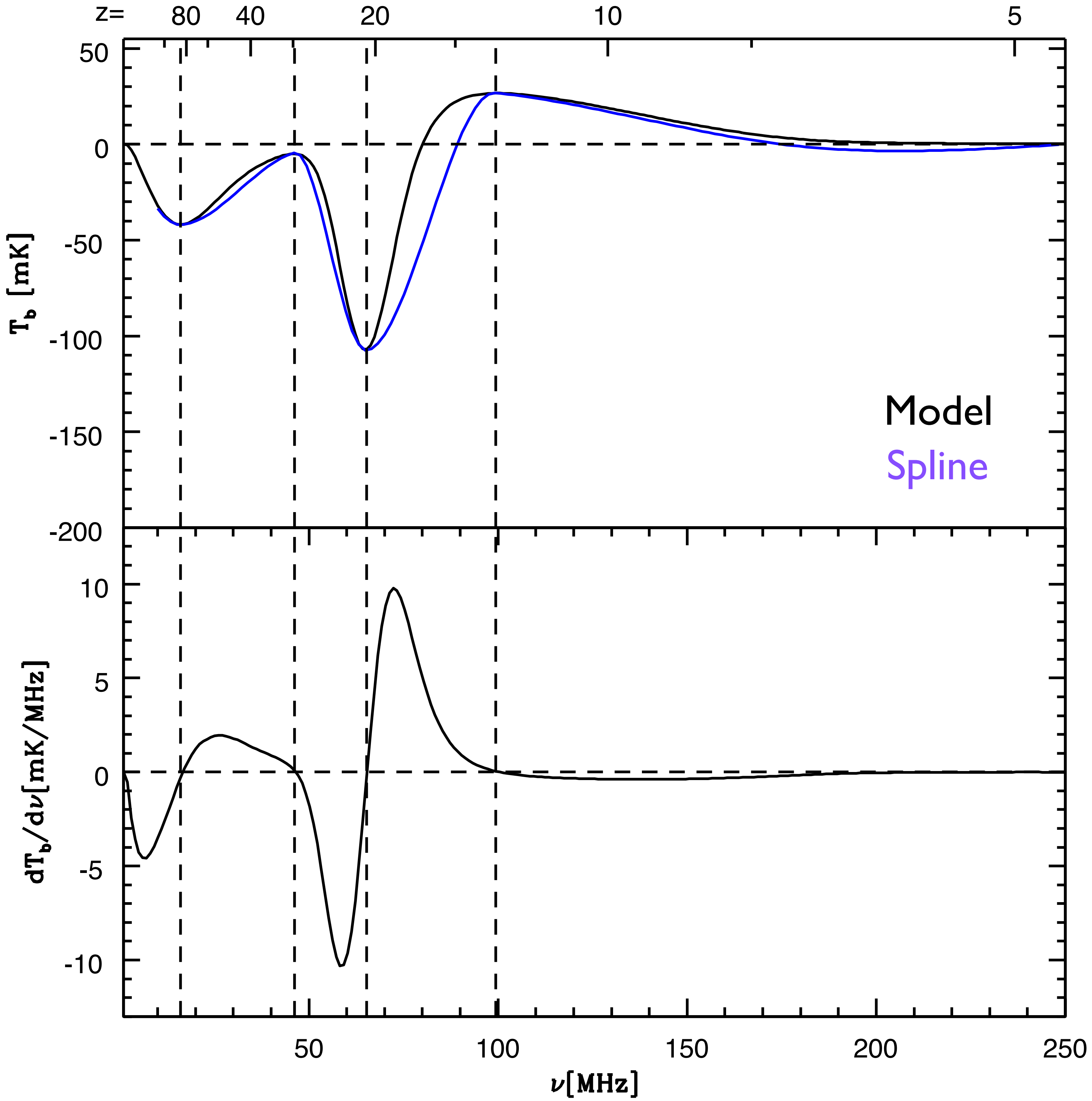
heating begins



signal saturates



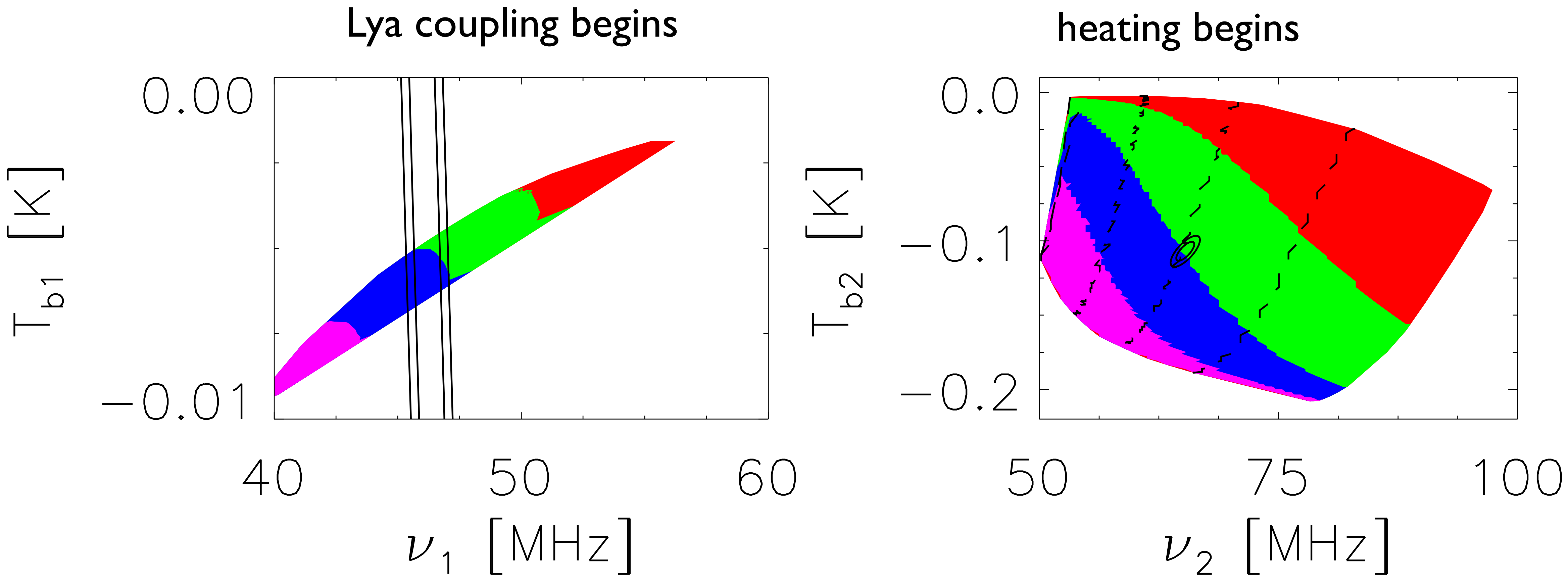
Modeling global signal

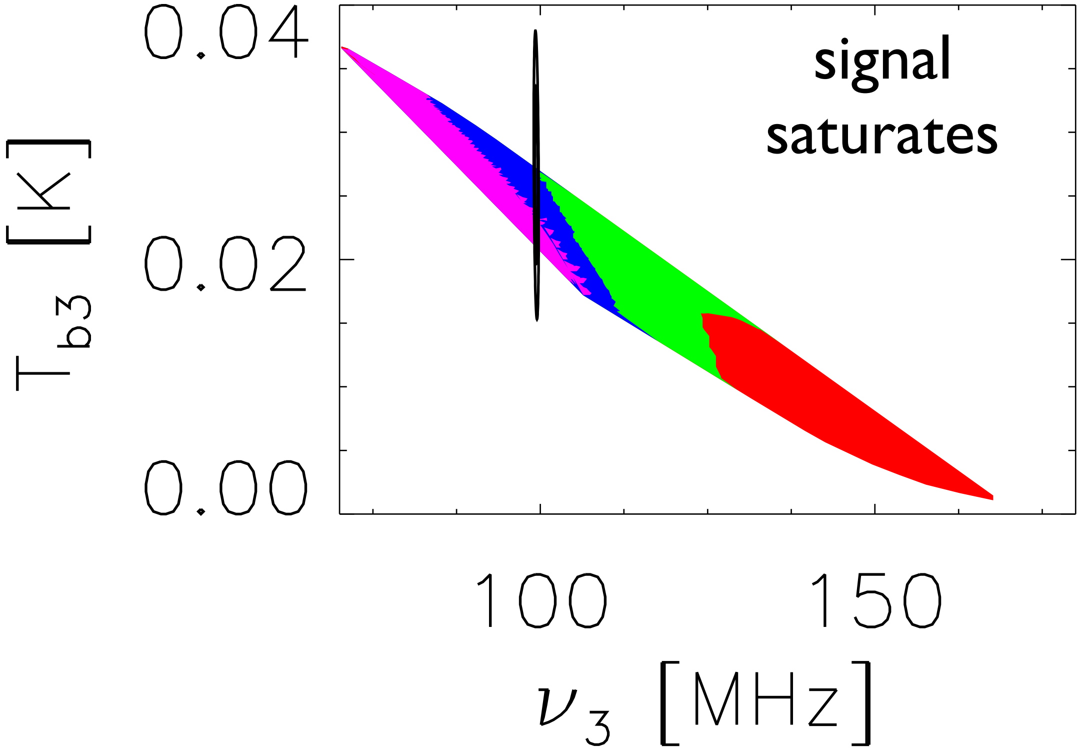


Modelling probably only good in broad brush terms

Physical features are the positions and amplitudes of maxima and minima
-> spline using extrema

Constraining turning points

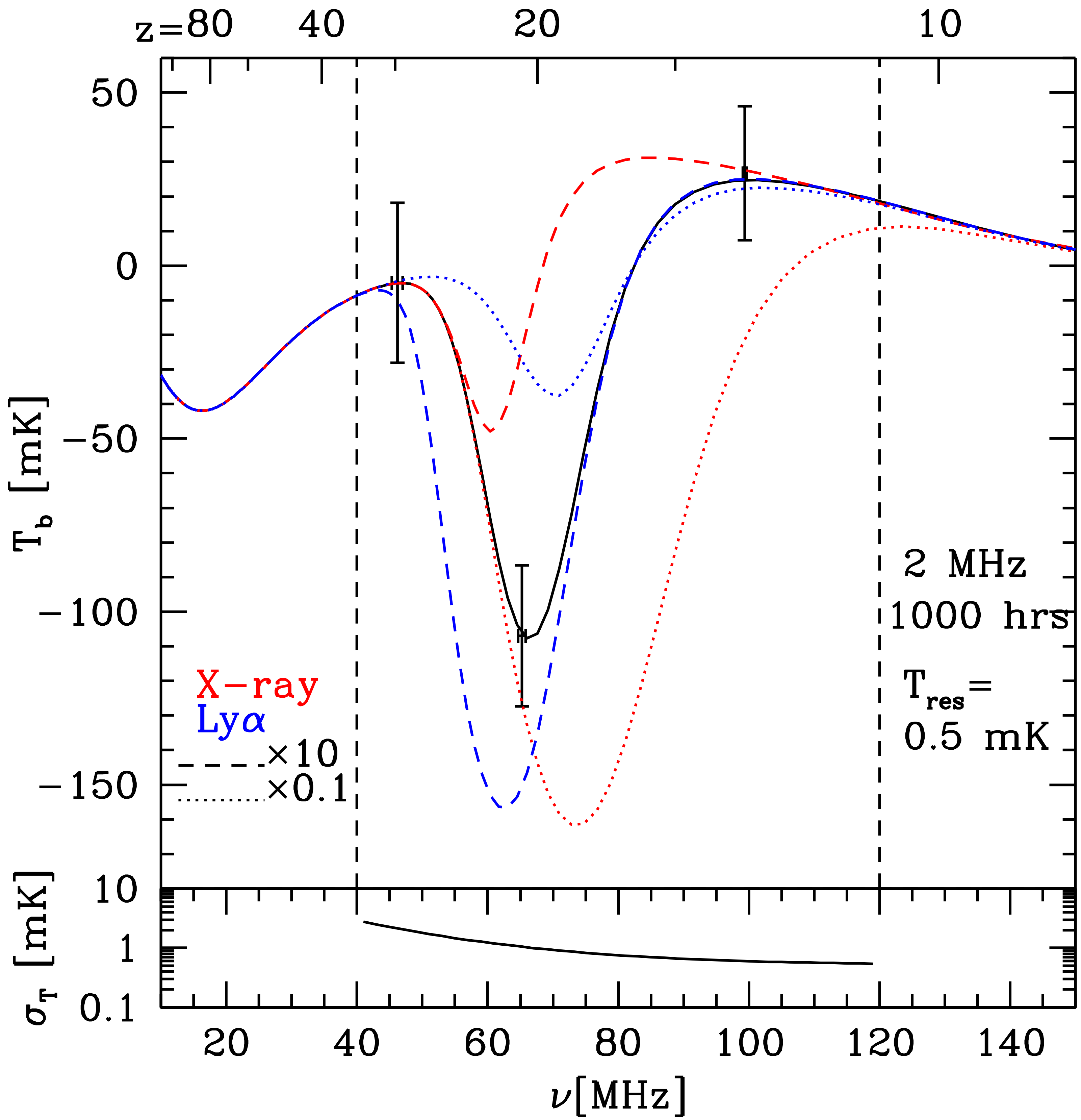




Npoly=3
tint= 500hrs,
50 channels spanning
40-140 MHz

Similar sensitivity as for reionization constrains deep absorption feature

First stars



z=80
40
20
10
50
0
−50
−100
−150
T_b [mK]
X−ray
Lyα
×10
×0.1
2 MHz
1000 hrs
T_res=
0.5 mK
10
1
0.1
σ_T [mK]
20
40
60
80
100
120
140
ν[MHz]

Dark Ages Radio Explorer

- DARE = Dark Ages Radio Explorer
  "EDGES in space"

- Lunar orbiting dipole experiment spanning 40-120 MHz

- To be proposed as small explorer mission
  (PI: Jack Burns)

- Advantages of going to the moon include:
  - Reduced RFI
  - No ionosphere
  - Use of the moon for calibration
  - Full sky coverage

21 cm global signal

- 21 cm global signal accessible with single dipole experiments

- Instrumental calibration and foreground removal are key to extracting astrophysics

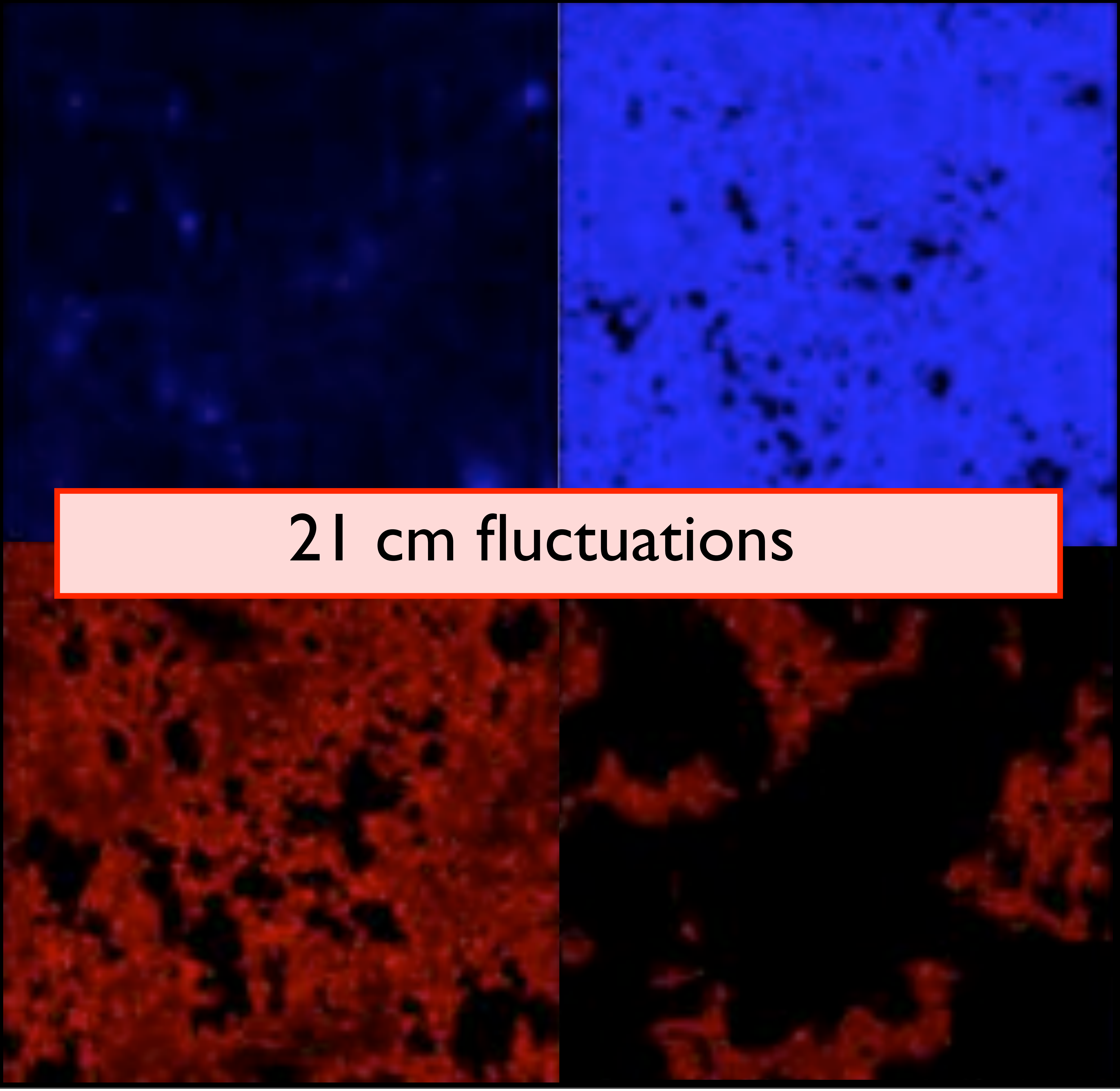
- Can potentially begin answering some fundamental questions about thermal and ionization history of universe

- Prospects for constraining basic properties of the first galaxies

- Lots of room for clever ideas in improving data collection and analysis

Pritchard & Harker in prep

21 cm fluctuations



Brightness Fluctuations

brightness temperature

density

neutral fraction

gas temperature

Lyman alpha flux

peculiar velocities

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

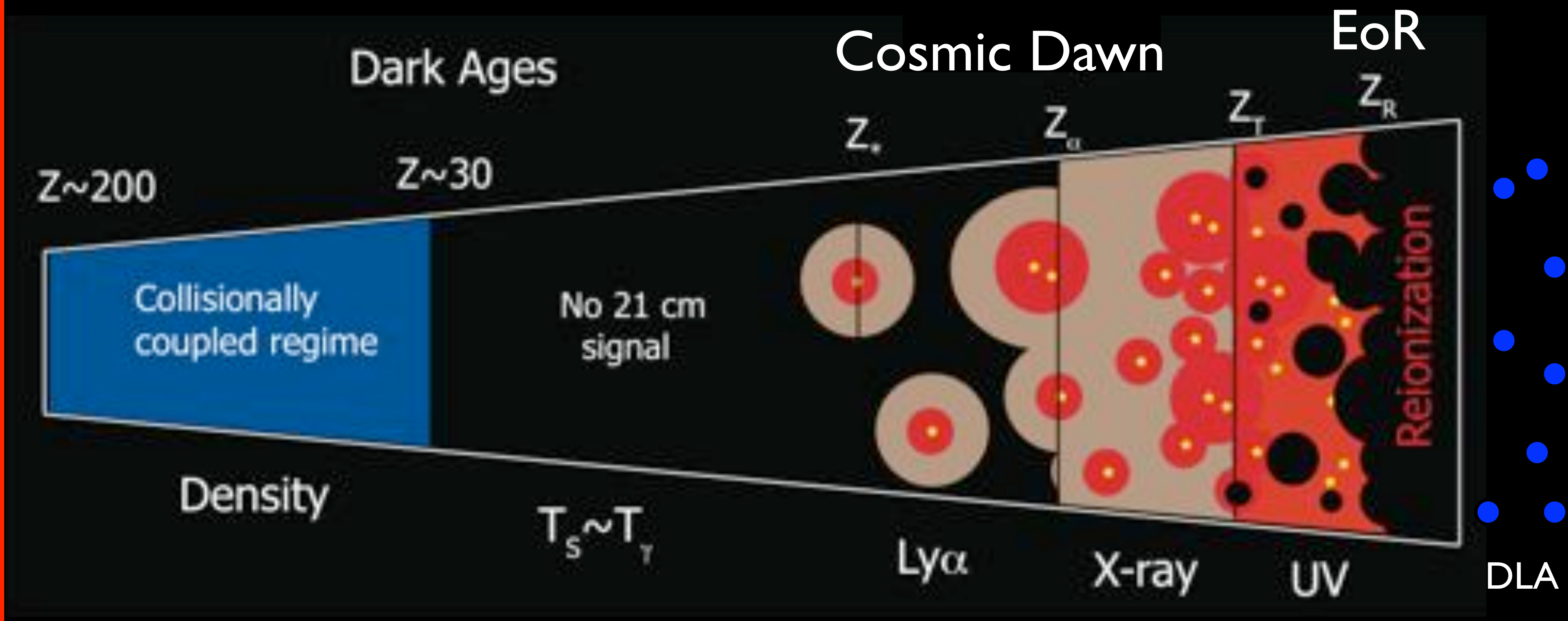
$$\underbrace{\text{cosmology} \qquad \text{reionization}}_{\text{Neutral hydrogen}} \qquad \underbrace{\text{X-ray heating} \qquad \text{Lya sources}}_{\text{spin temperature}} \qquad \text{cosmology}$$

Brightness Fluctuations

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

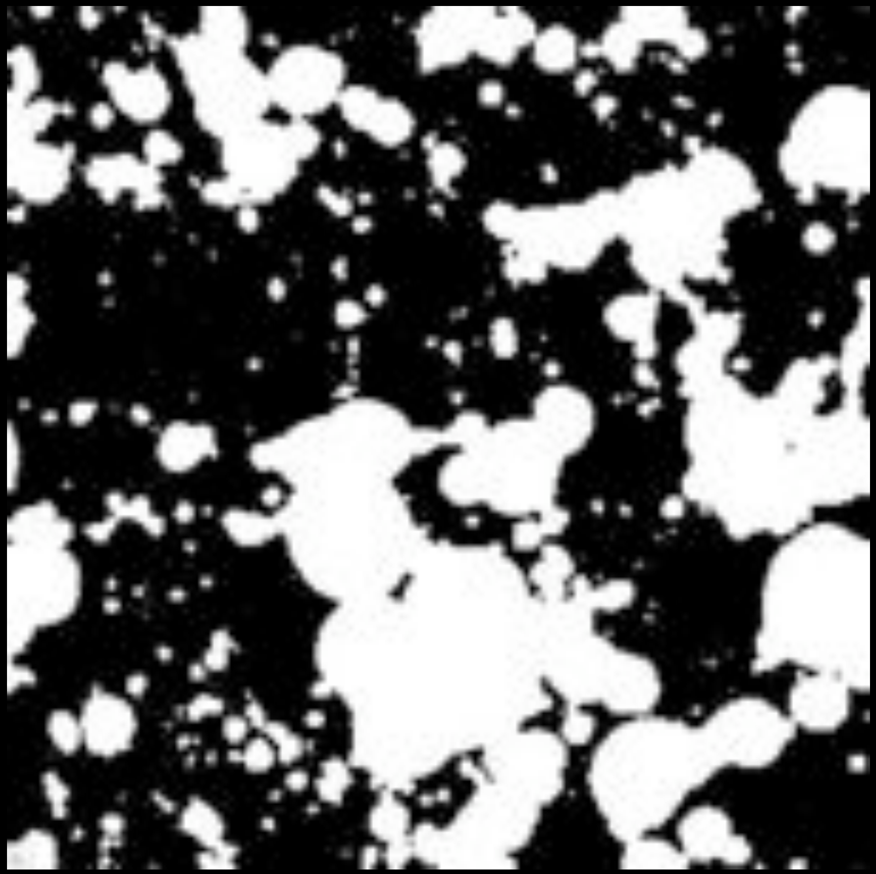
$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

cosmology
reionization
X-ray heating
Lya sources
cosmology

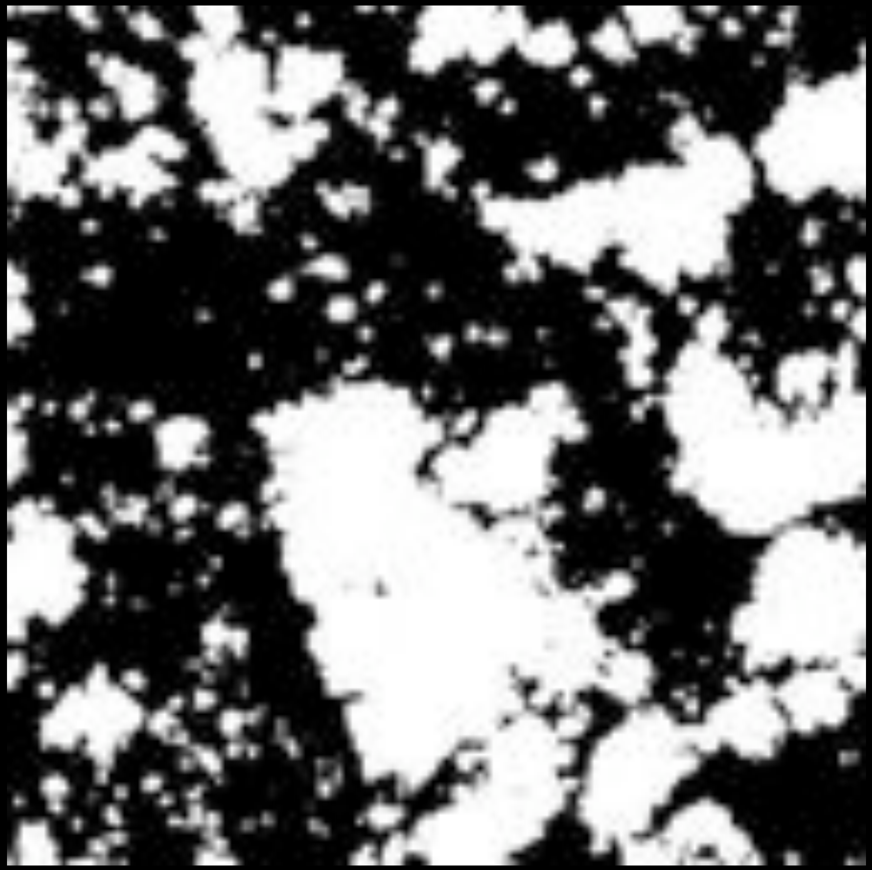


Semi-numerical modelling

Semi-numerical



Numerical



Initial conditions evolved using Zeldovich approximation to generate non-linearities

Ionization field calculated by filtering density field with self-ionization condition

Fast and accurate ionization maps can be created this way with many applications

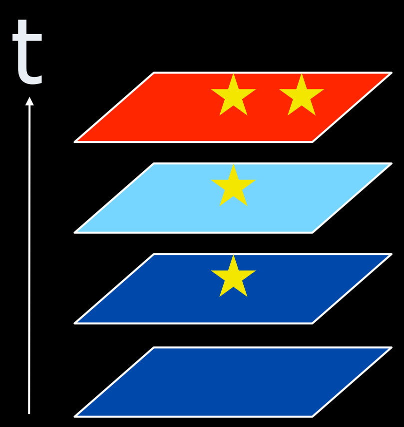
Zahn, Lidz, McQuinn+ 2006
Mesinger & Furlanetto 2007

Including other radiation fields

- Full radiative transfer calculation is very expensive for Lyman alpha and X-rays
- Implement analytic calculation of fluxes using SFR from N-body simulation

$$J_X(\boldsymbol{x},\ z,\ \nu) = \int d^3x' \frac{(1+z)^2}{4\pi|\boldsymbol{x}'|^2} \hat{\epsilon}_X(\boldsymbol{x}+\boldsymbol{x}',\ \nu'_n,\ z') e^{-\tau(z,\nu,\boldsymbol{x},\boldsymbol{x}')}$$

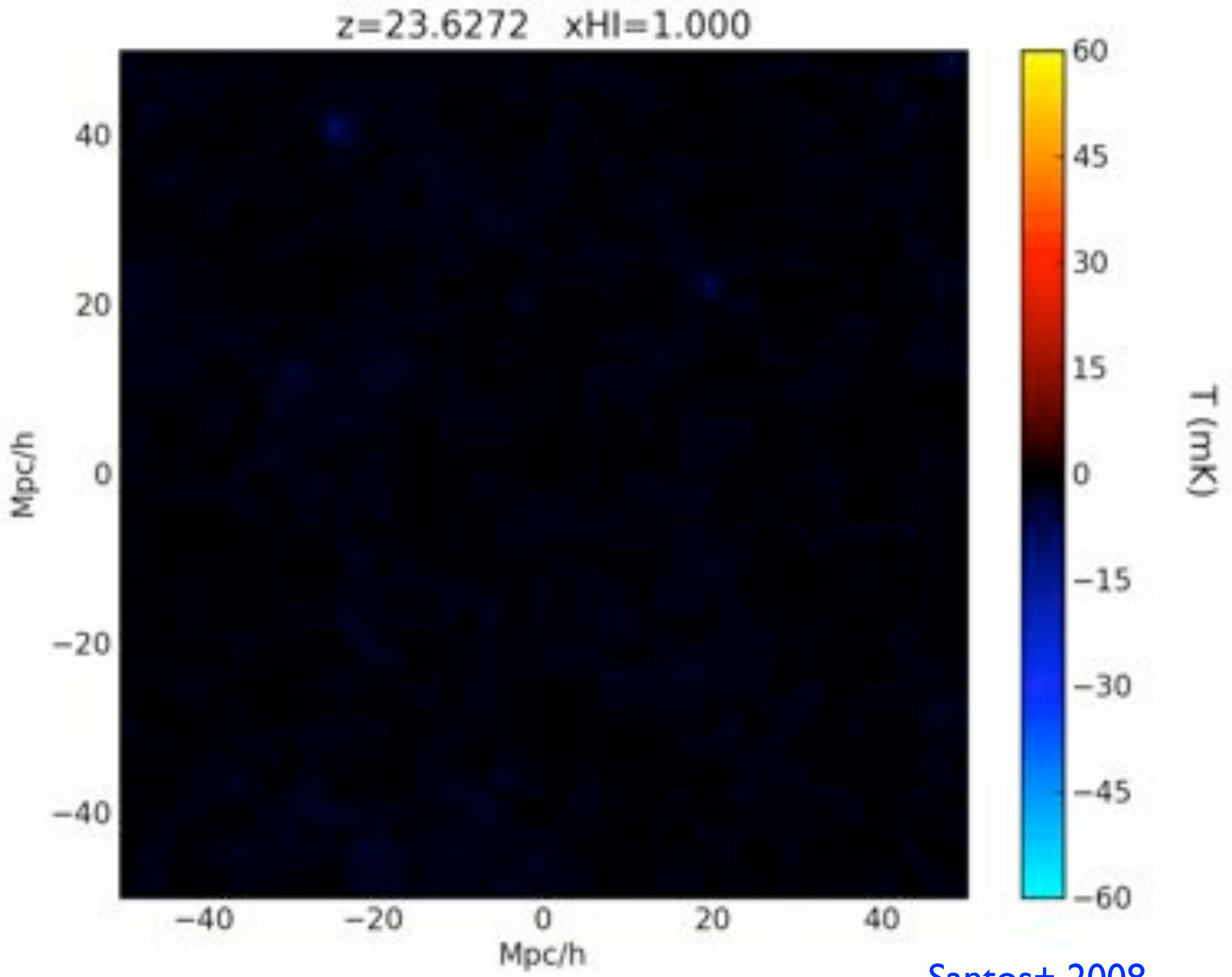
$$\hat{\epsilon}_X(\boldsymbol{x},\ z,\ \nu) = \hat{\epsilon}_X(\nu)\left[\frac{\mathrm{SFRD}(\boldsymbol{x},\ z)}{M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}}\right]$$



- Convolution can be evaluated relatively quickly
- Source parameters extrapolated from low-z sources
  - * Pop II+ III stars => reionization at z=6
  - * X-ray emission from SXRB in galaxies
- Calculate coupling and heating from fluxes

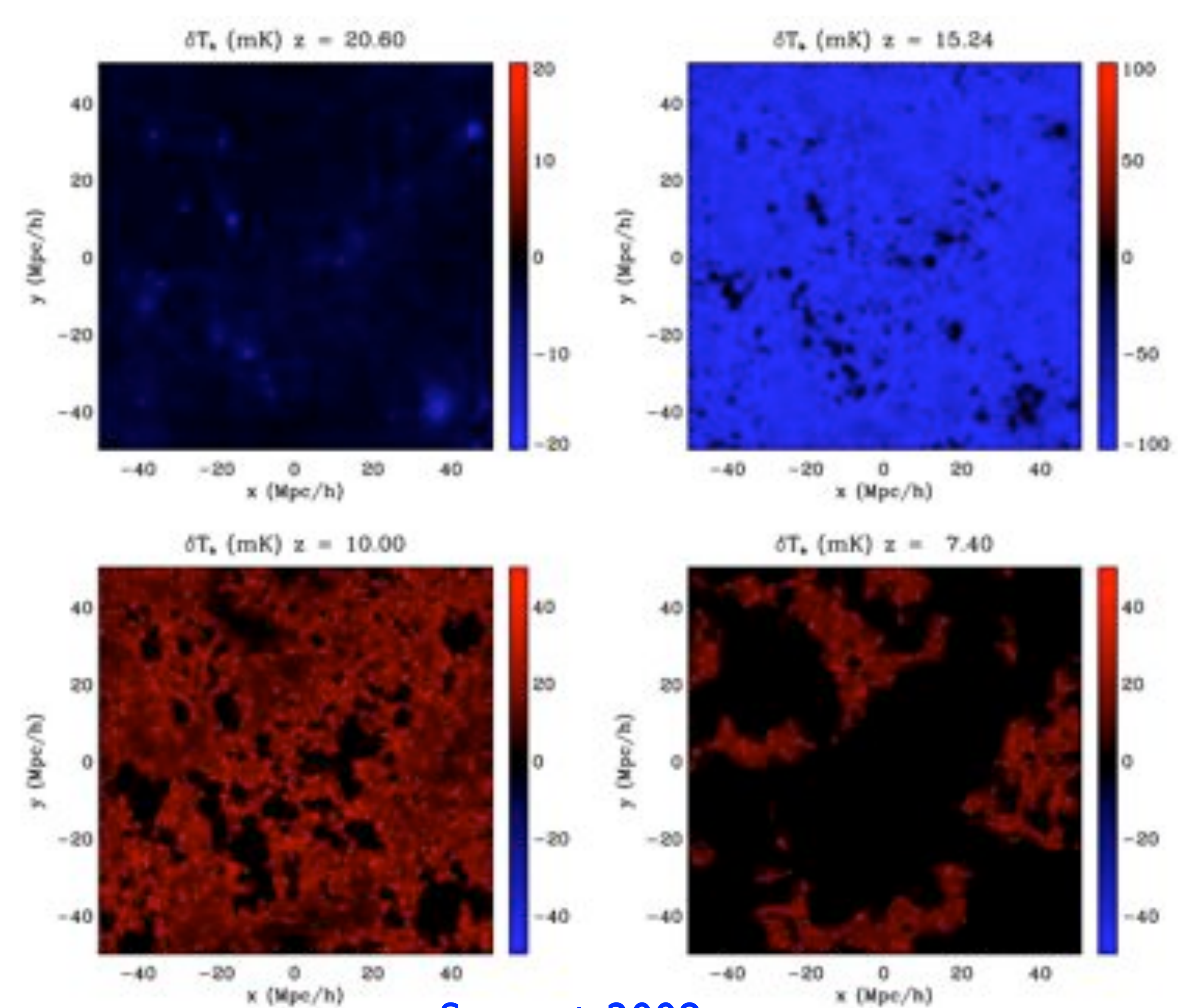
Barkana & Loeb 2004
Pritchard & Furlanetto 2007
Santos, Amblard, Pritchard+ 2008

Numerical simulation



Santos+ 2008

Numerical simulations



Santos+ 2008

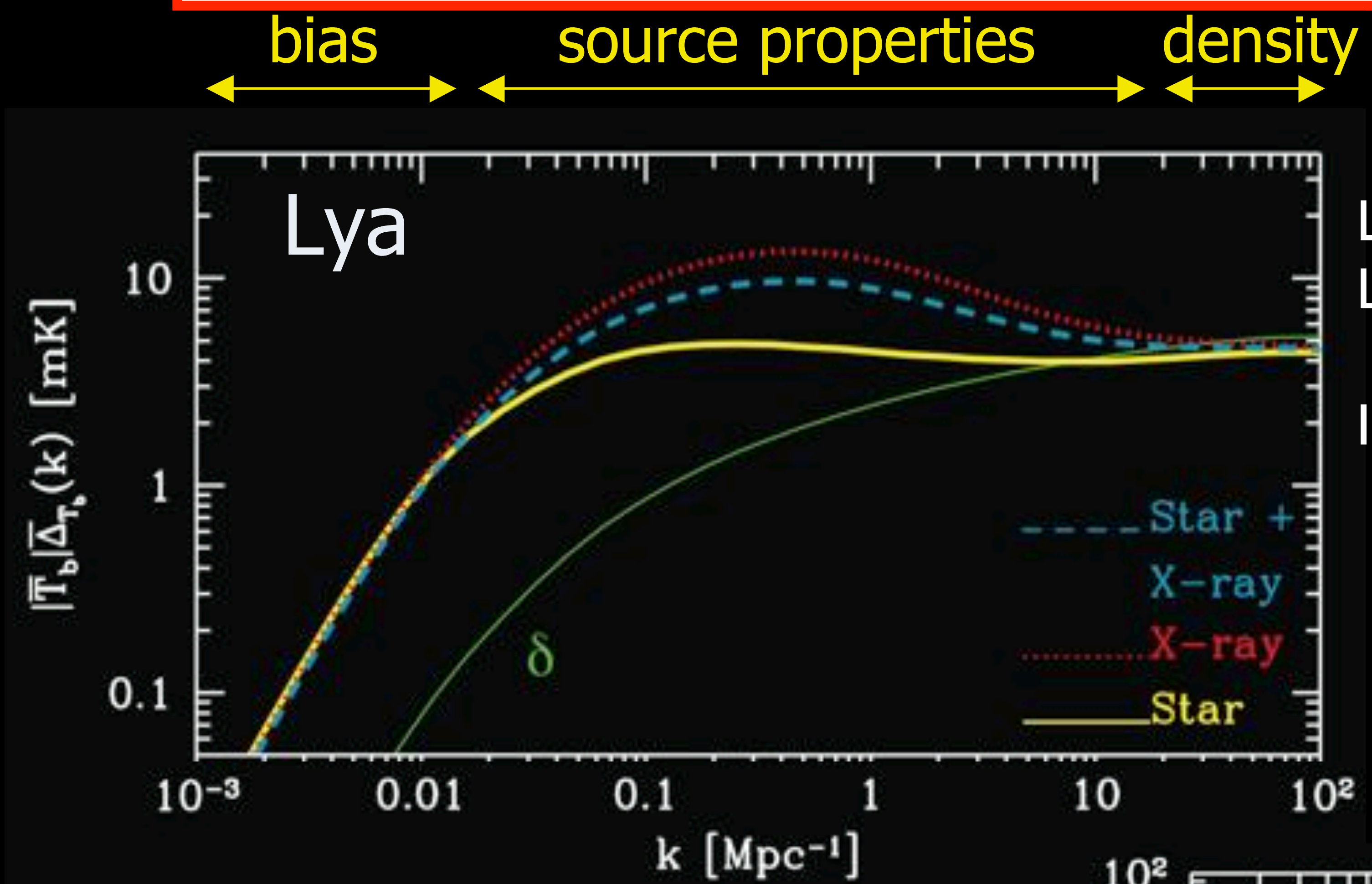
Basics of reionization simulation well understood
- dynamic range is hard

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

Size matters!

Power spectrum



Lya fluctuations add power on large scales

Largest scales give information on source bias

Intermediate scales on source spectrum

Barkana & Loeb 2004

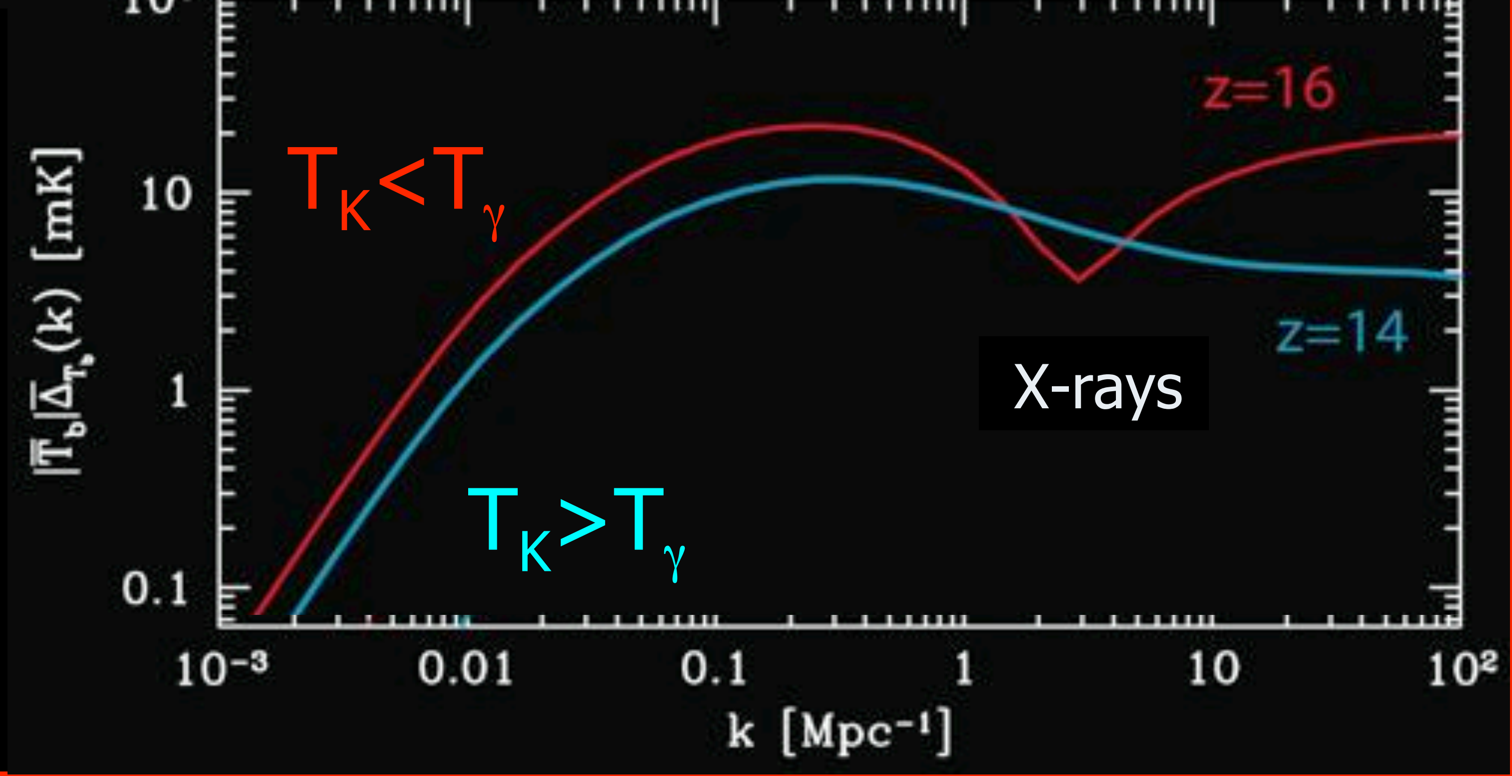
Chuzhoy, Alverez & Shapiro 2006

Pritchard & Furlanetto 2006

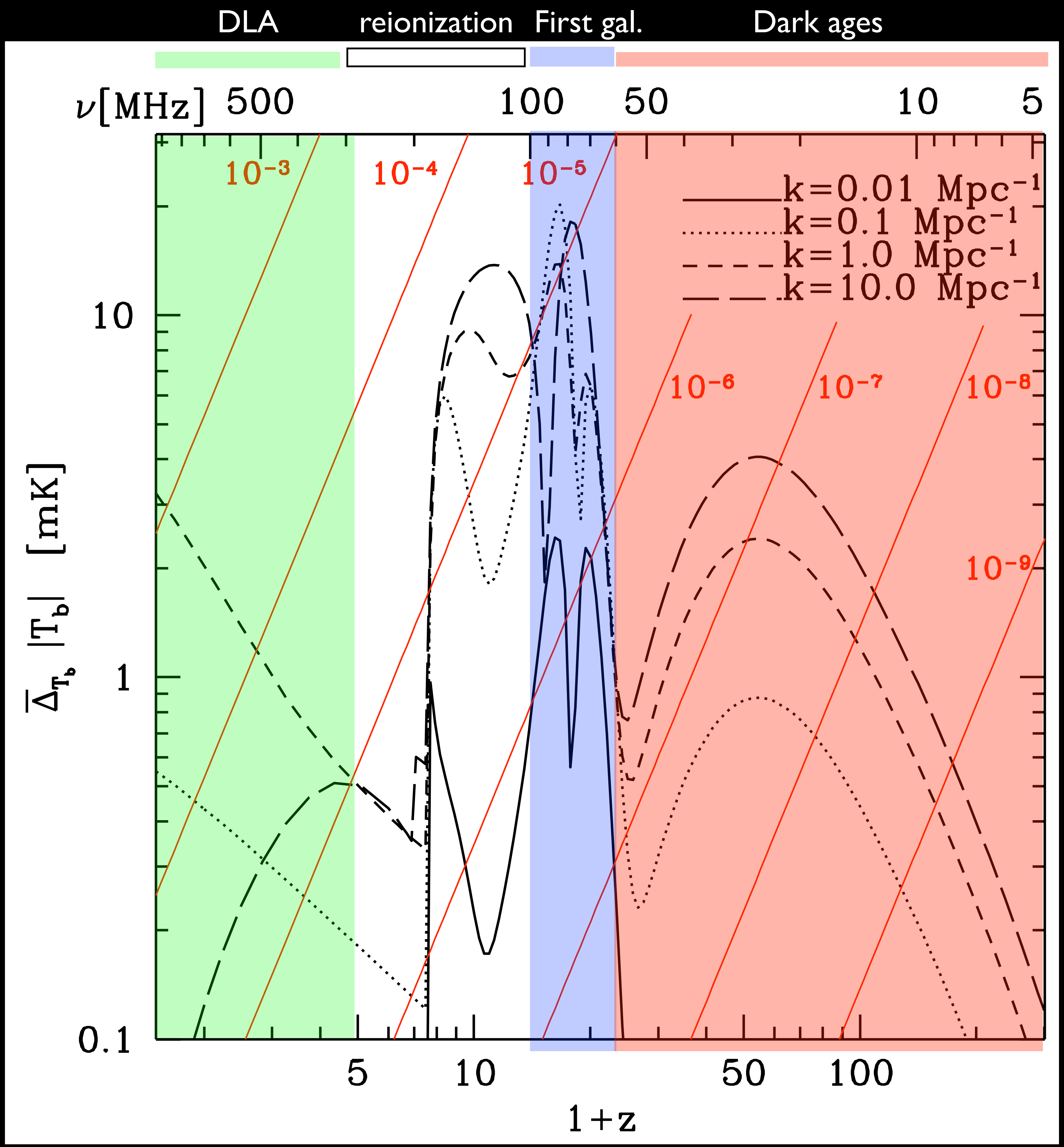
T fluctuations give information on thermal history

clustering/growth of mini-quasars could be very different

Pritchard & Furlanetto 2007



Evolution of power spectrum



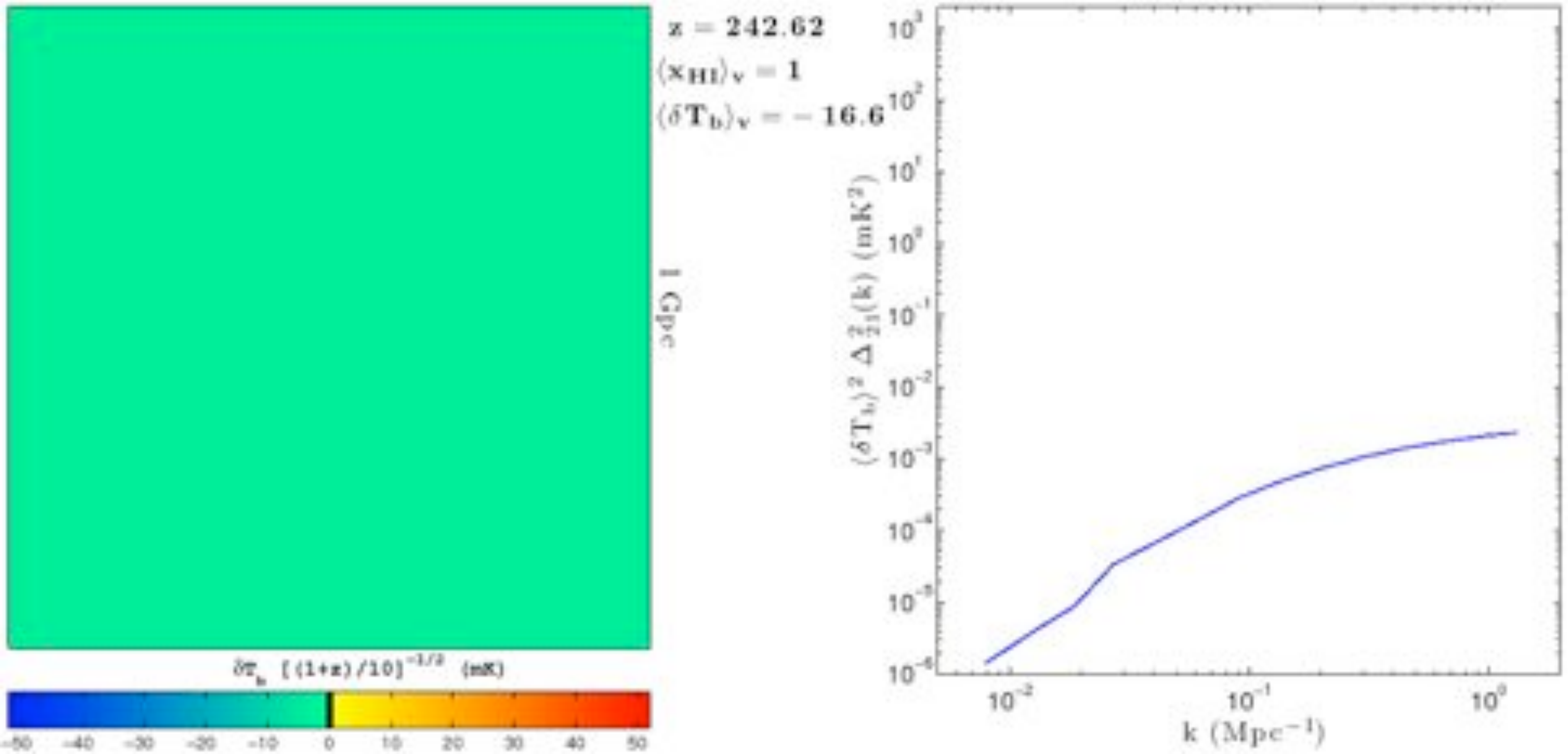
Evolution of signal means that detecting signal at z=20 not necessarily more difficult than at z=10

Distinguish different contributions via shape and redshift evolution

z=30-50 range much harder!

Pritchard & Loeb 2008

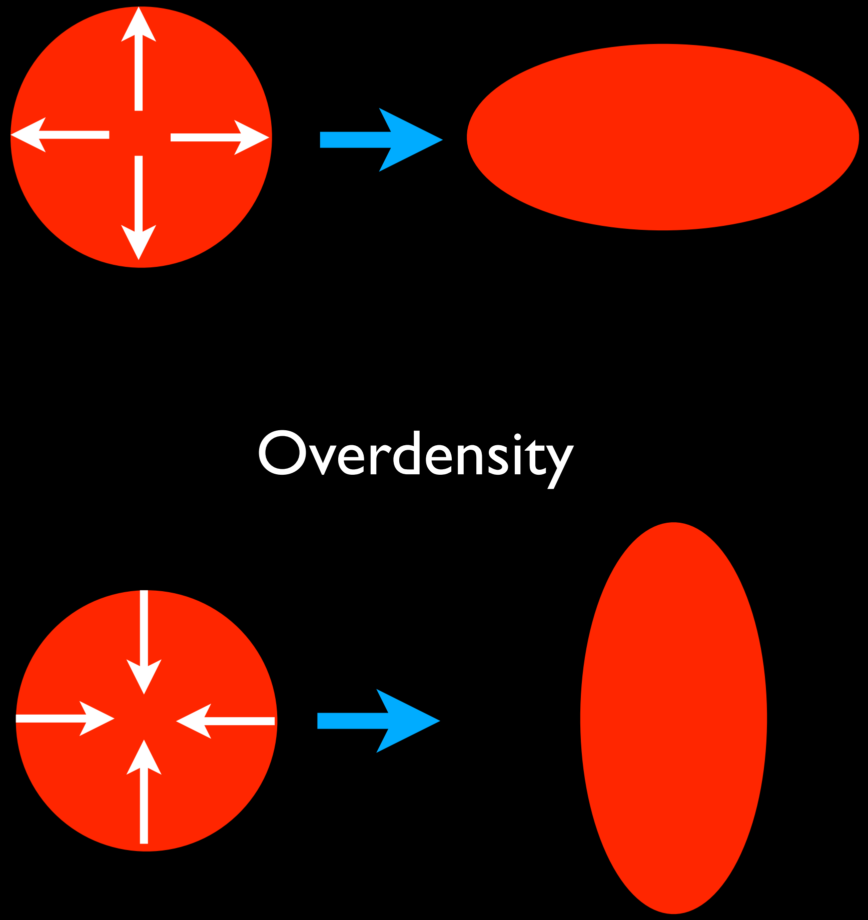
Evolution of the power spectrum



Mesinger+ 2010

Redshift distortions

$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$



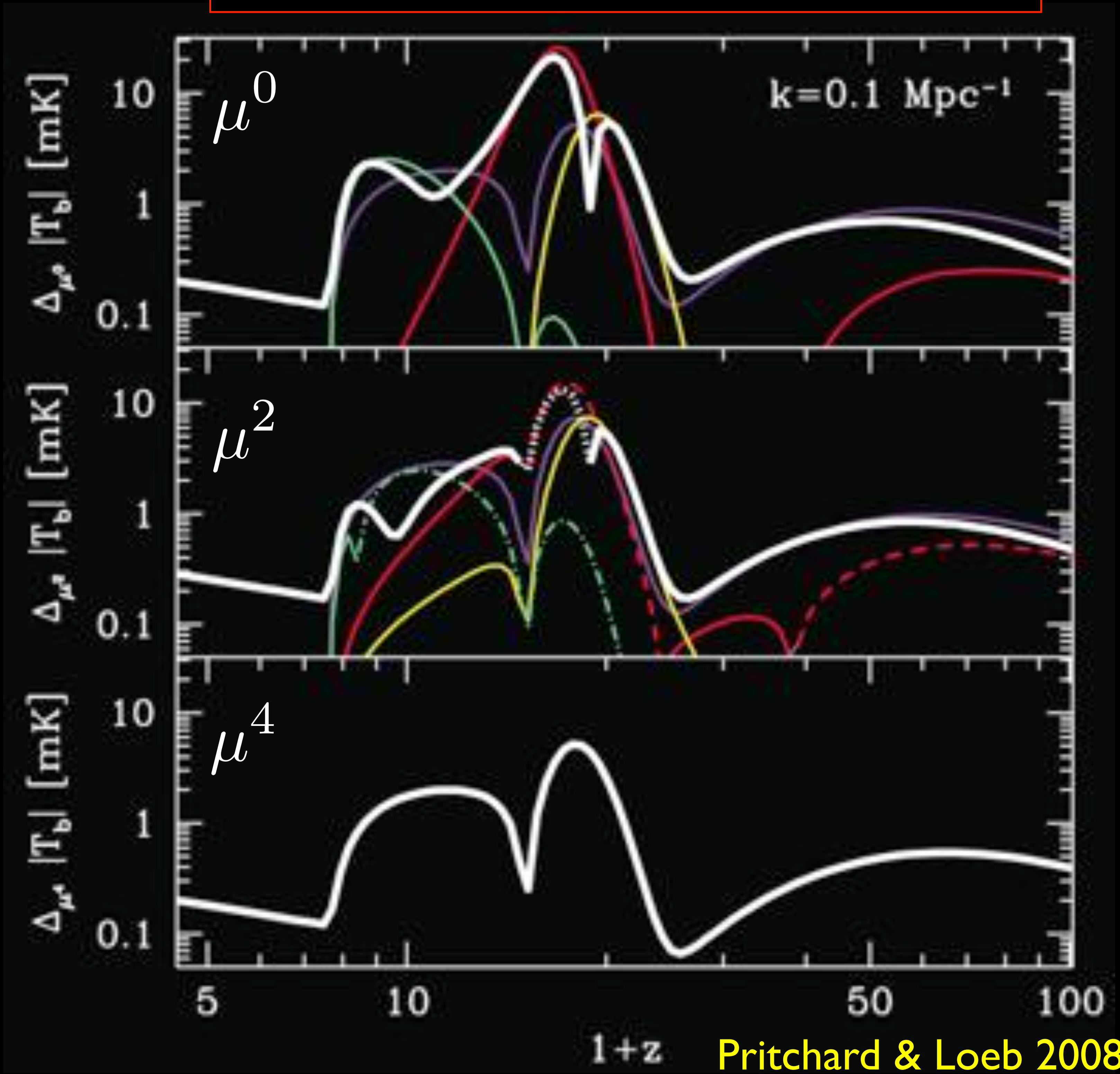
Underdensity

Overdensity

Real space

redshift space

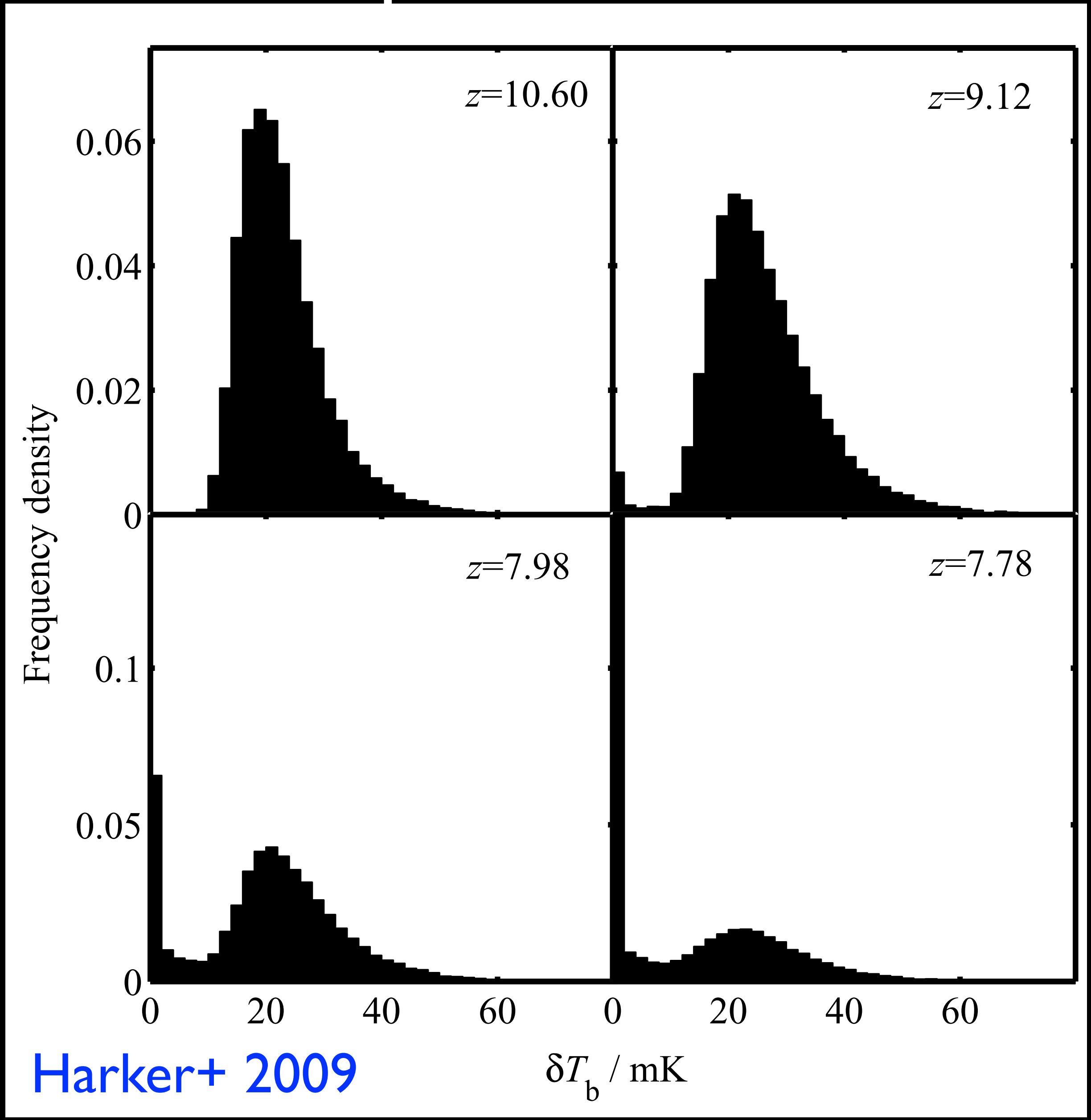
$$\delta_{\partial_r v_r}(k) = -\mu^2 \delta$$



Pritchard & Loeb 2008

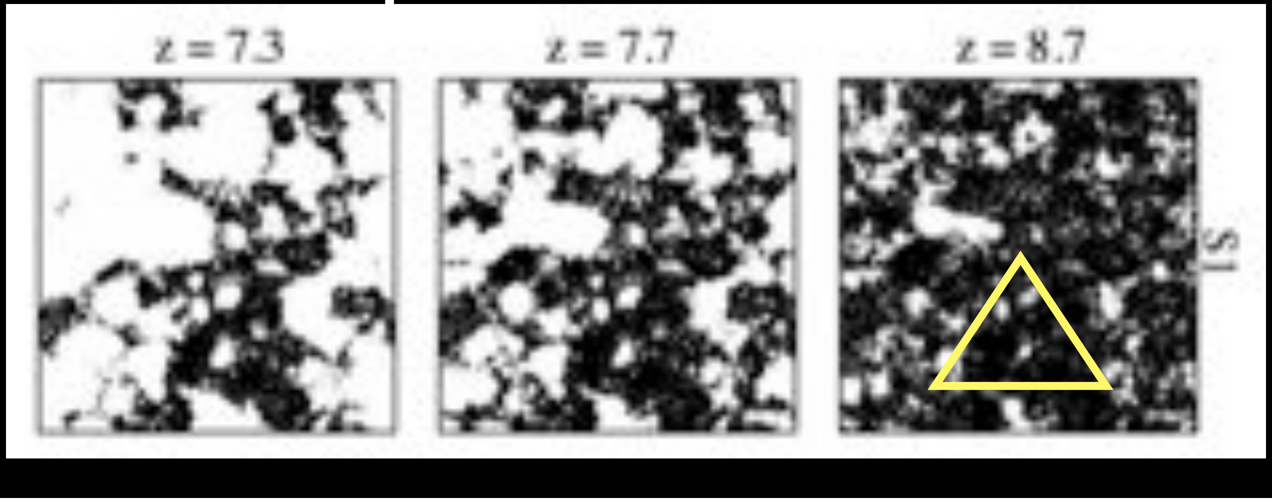
Non-Gaussianity

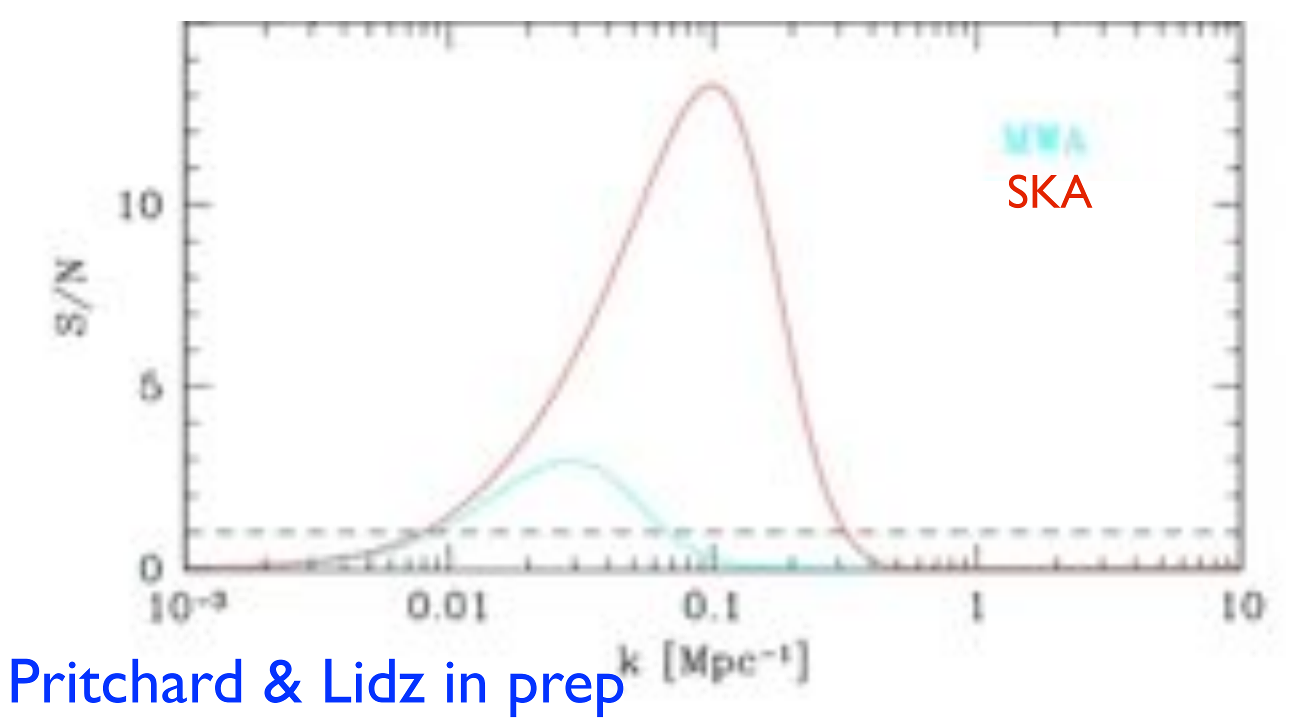
1-point function



Harker+ 2009

3-point correlations



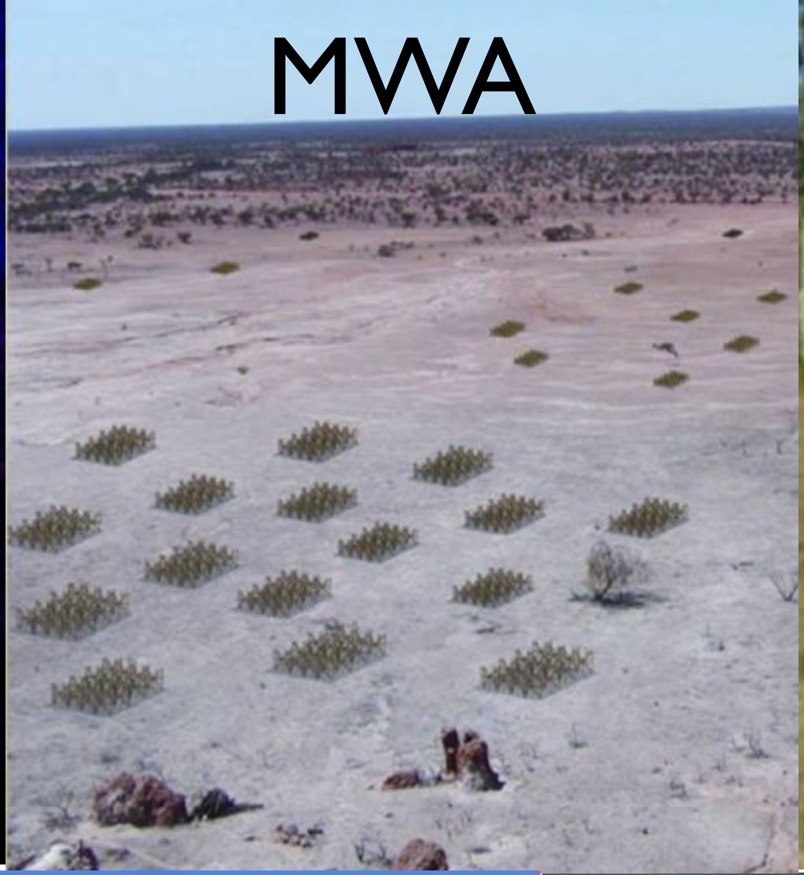


Pritchard & Lidz in prep

Ionization field is highly non-Gaussian => statistics beyond power spectrum are important

Important to explore new statistics that might be useful:
- skewness, bispectrum, wavelets, threshold statistics, ...?

21 cm experiments



Several interferometers under construction
data expected in the next few years
probe reionization (z<12)

Next generation required for probing fluctuations
from the first galaxies (z>12)
e.g. Square Kilometer Array (~2020)

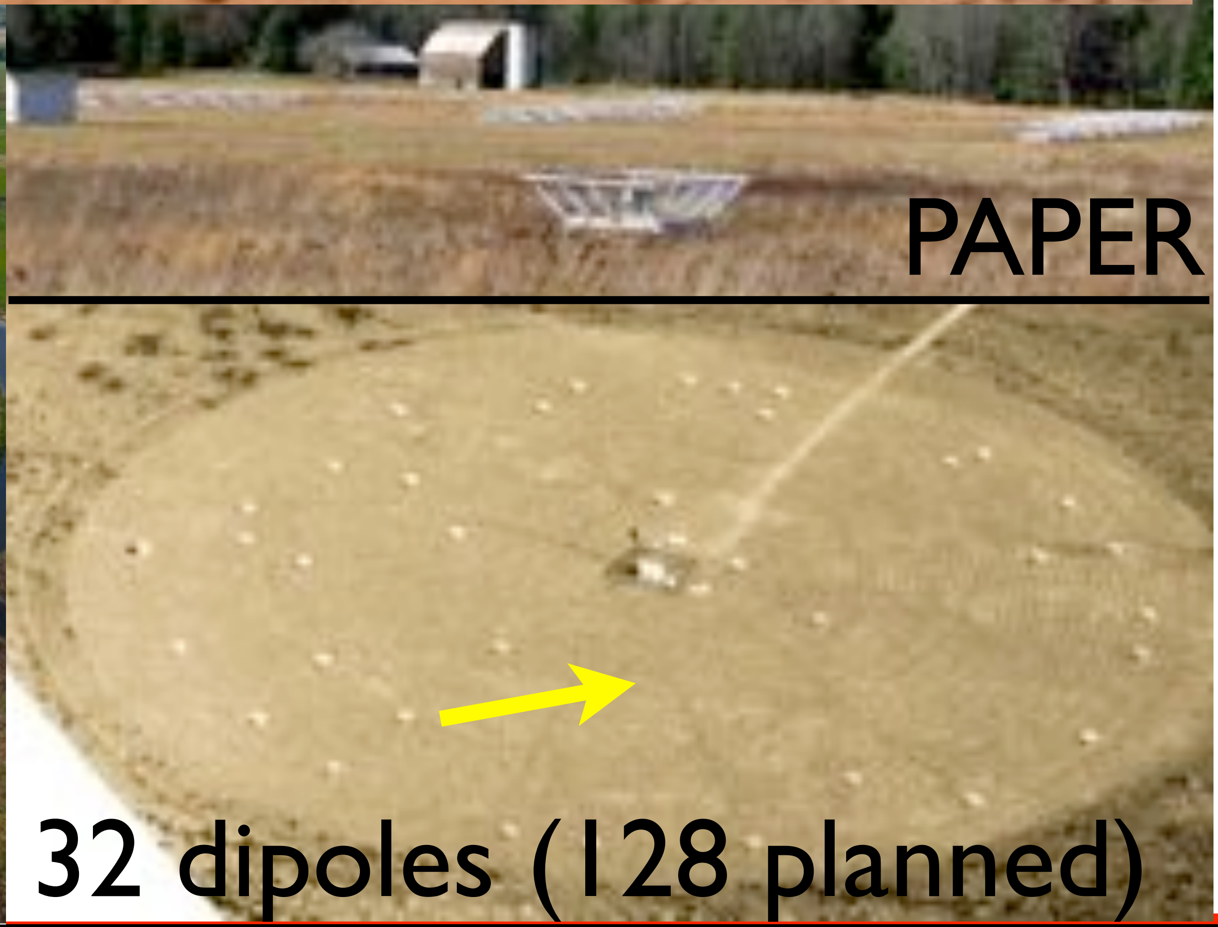
Under construction


MWA

32 tiles (512 tiles planned)

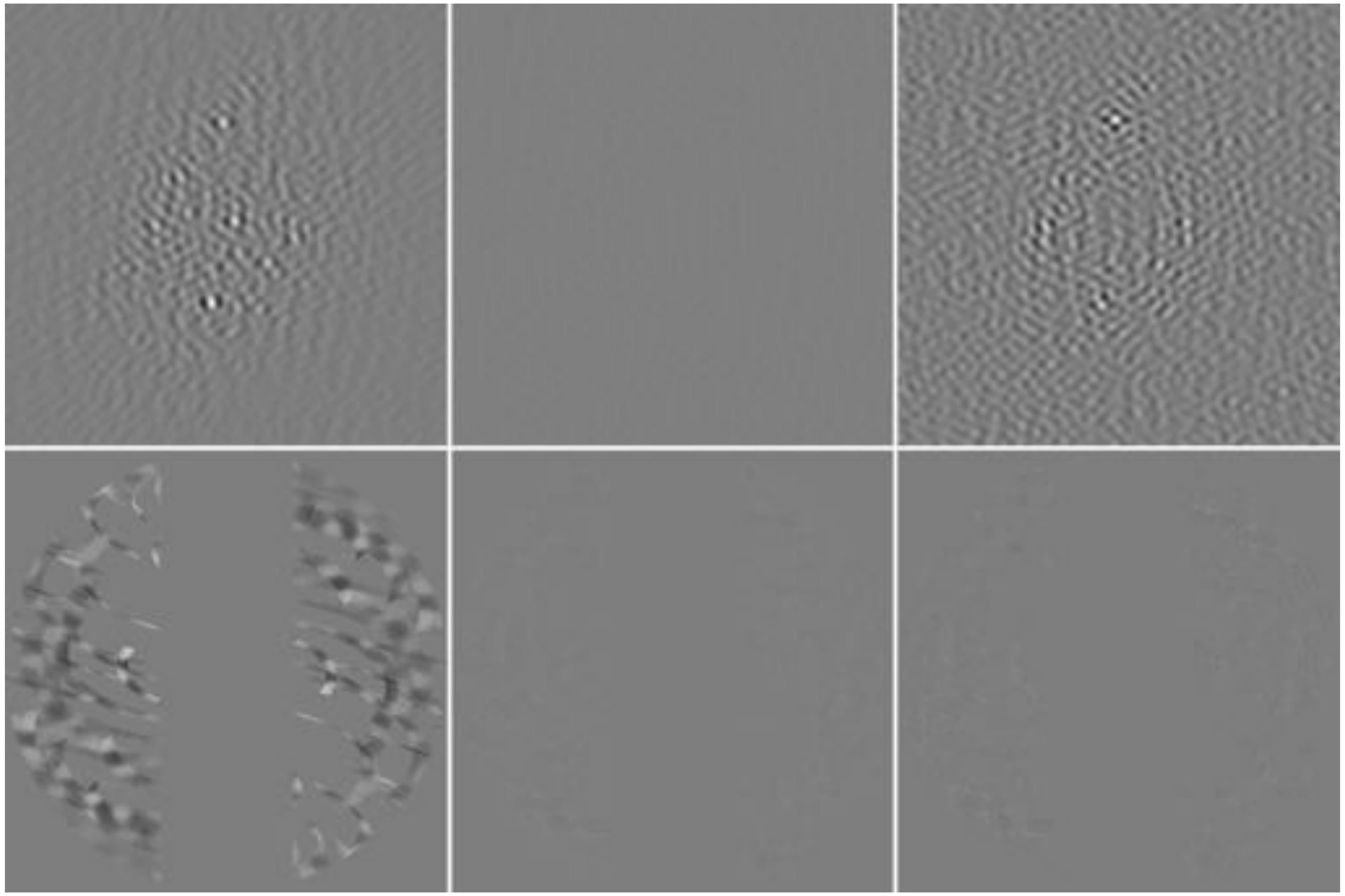

LOFAR

18 core stations
(24 planned)


PAPER

32 dipoles (128 planned)

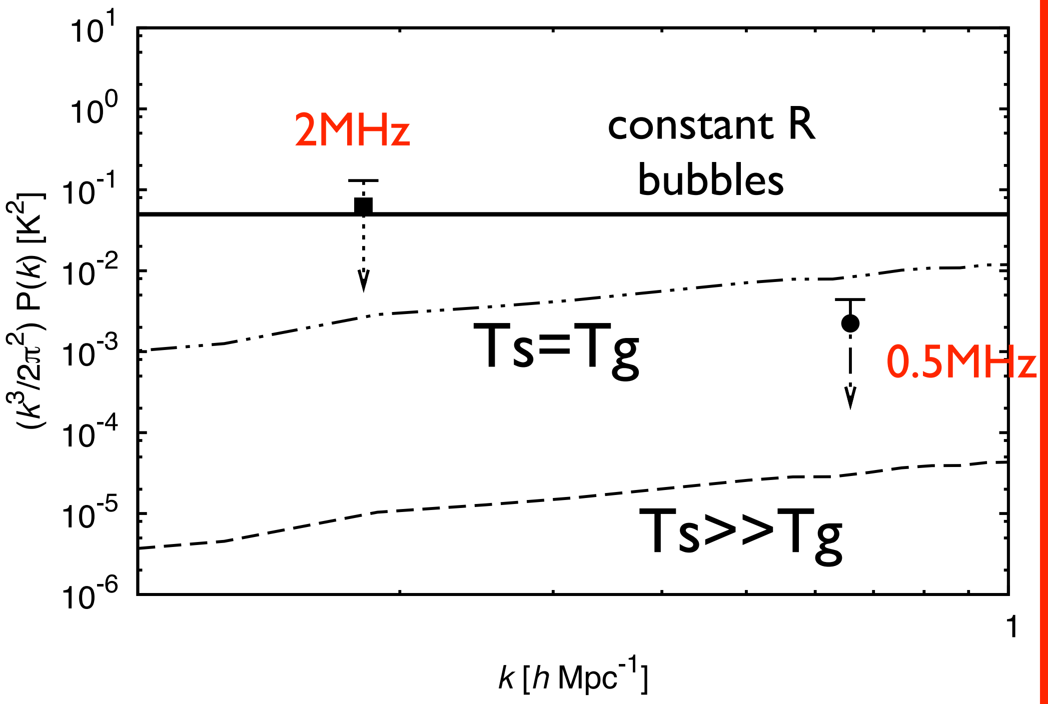
GMRT observations


Sky map

Sky map
- foregrounds

Sky map-foregrounds
zoom

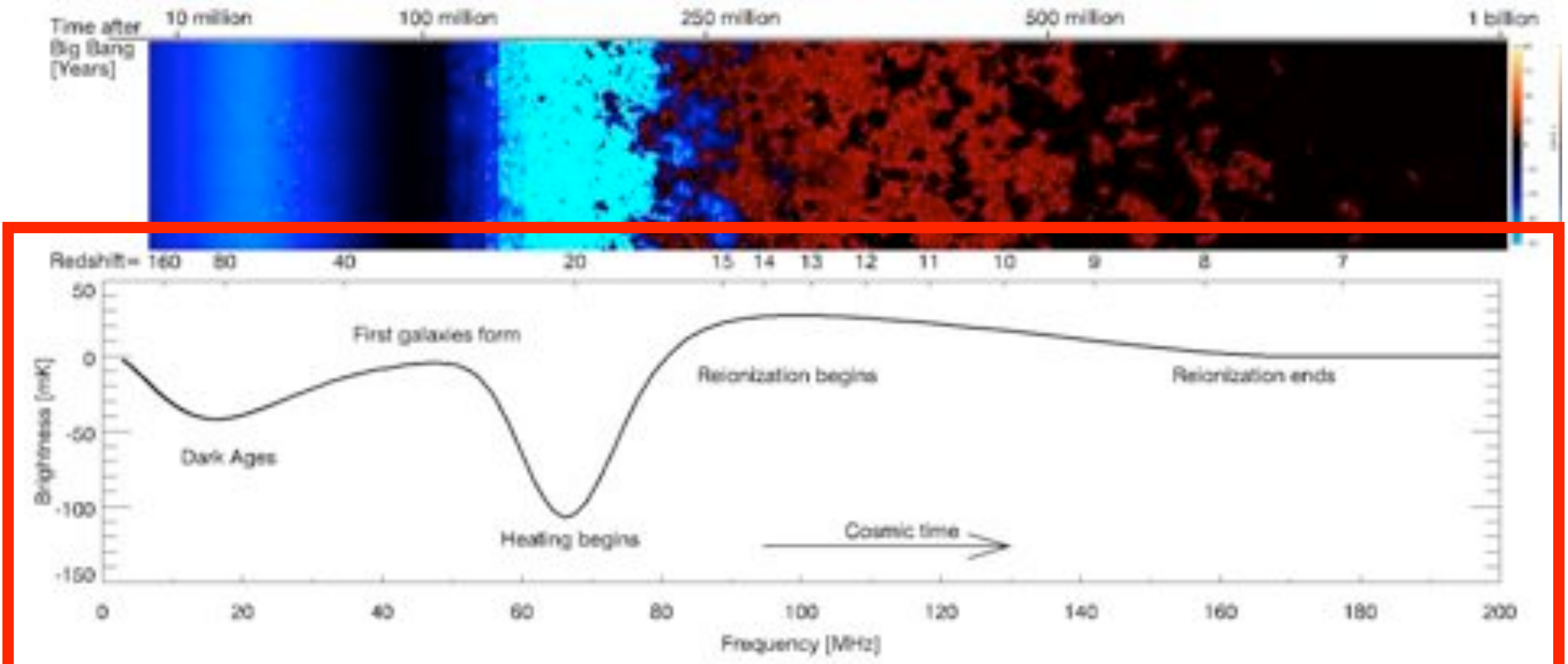
Upper limits
on power spectrum of
cold IGM



Data of the required sensitivity acquired with GMRT
=> first serious limits on 21 cm signal at z~8.5

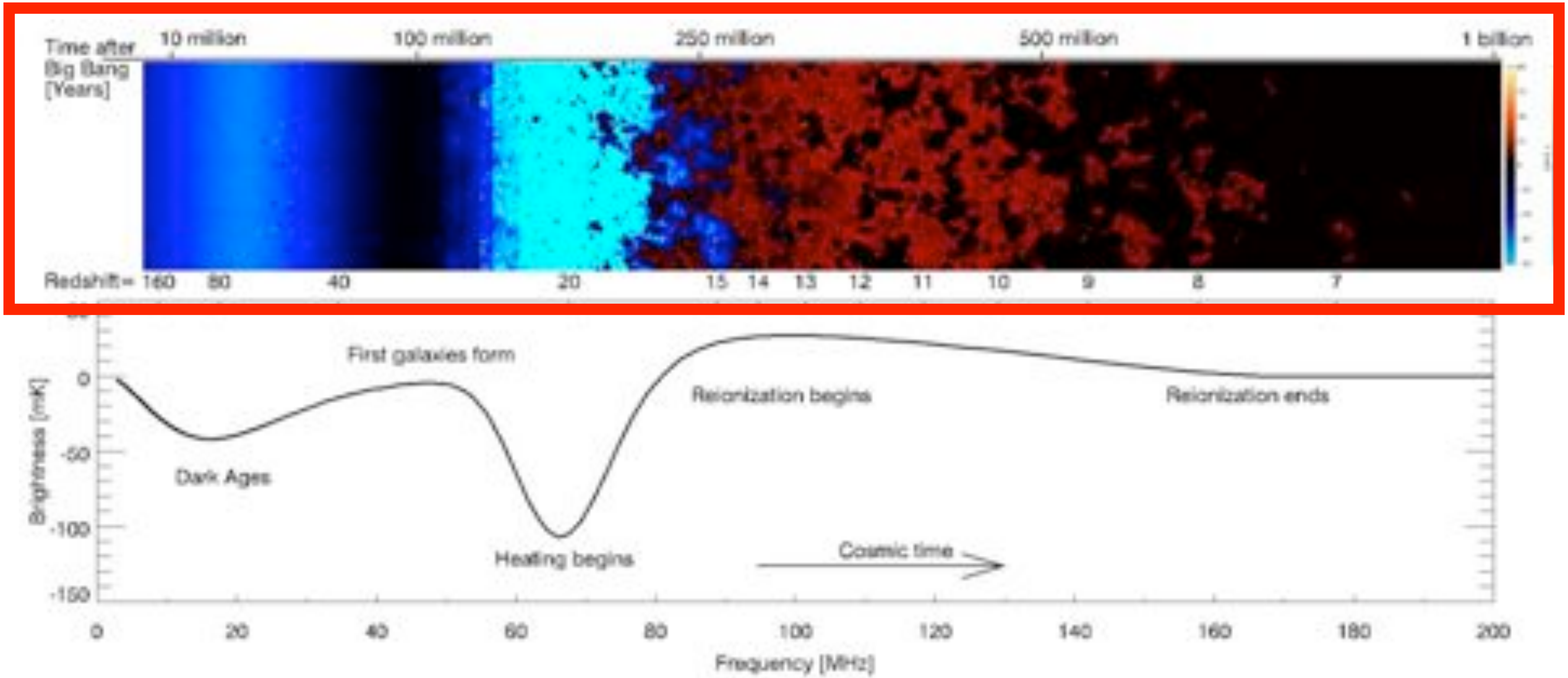
Paciga+ 2010

21 cm global signal



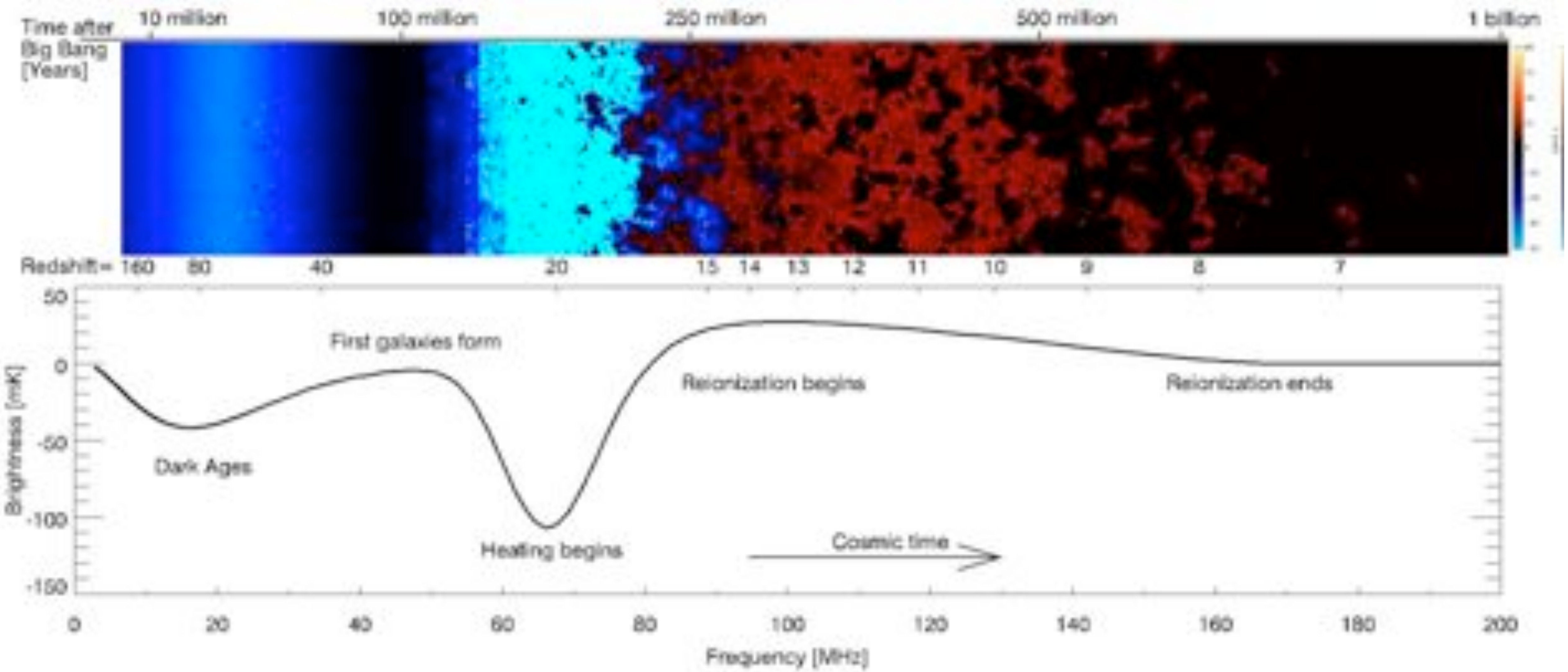
- 21 cm global signal is potentially a unique probe of the first galaxies
  - First instruments collecting data: calibration and foregrounds
  - Sensitive to sharp features in the global signal
  - Constrain basic features of reionization, thermal history, and first galaxies

21 cm fluctuations



- 21 cm fluctuations complement the global signal and contain wealth of information
  - Lyman alpha fluctuations => star formation rate and first galaxies
  - Temperature fluctuations => X-ray sources and first black holes
  - Neutral fraction fluctuations => topology of reionization

21 cm signal



- Pathfinder instruments: LOFAR, MWA, PAPER, GMRT, EDGES are in the process of proving the principle... first constraints from GMRT... more data coming soon!

- SKA/HERA-II/III would image at lower redshifts and sensitive to power spectrum out to z<20

- Possibility of doing cosmology once signal better understood: dark matter decay, isocurvature, neutrino mass, ...

Conclusions

- Over next decade new observations will transform our understanding of reionization

- Need to understand both sources and IGM => 21 cm observations key

- Currently know very little about reionization history

- 21 cm global signal is potentially a powerful probe of the first galaxies
  - First instruments collecting data: calibration and foregrounds
  - Sensitive to sharp features in the global signal
  - Constrain basic features of reionization, thermal history, and first galaxies

- 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

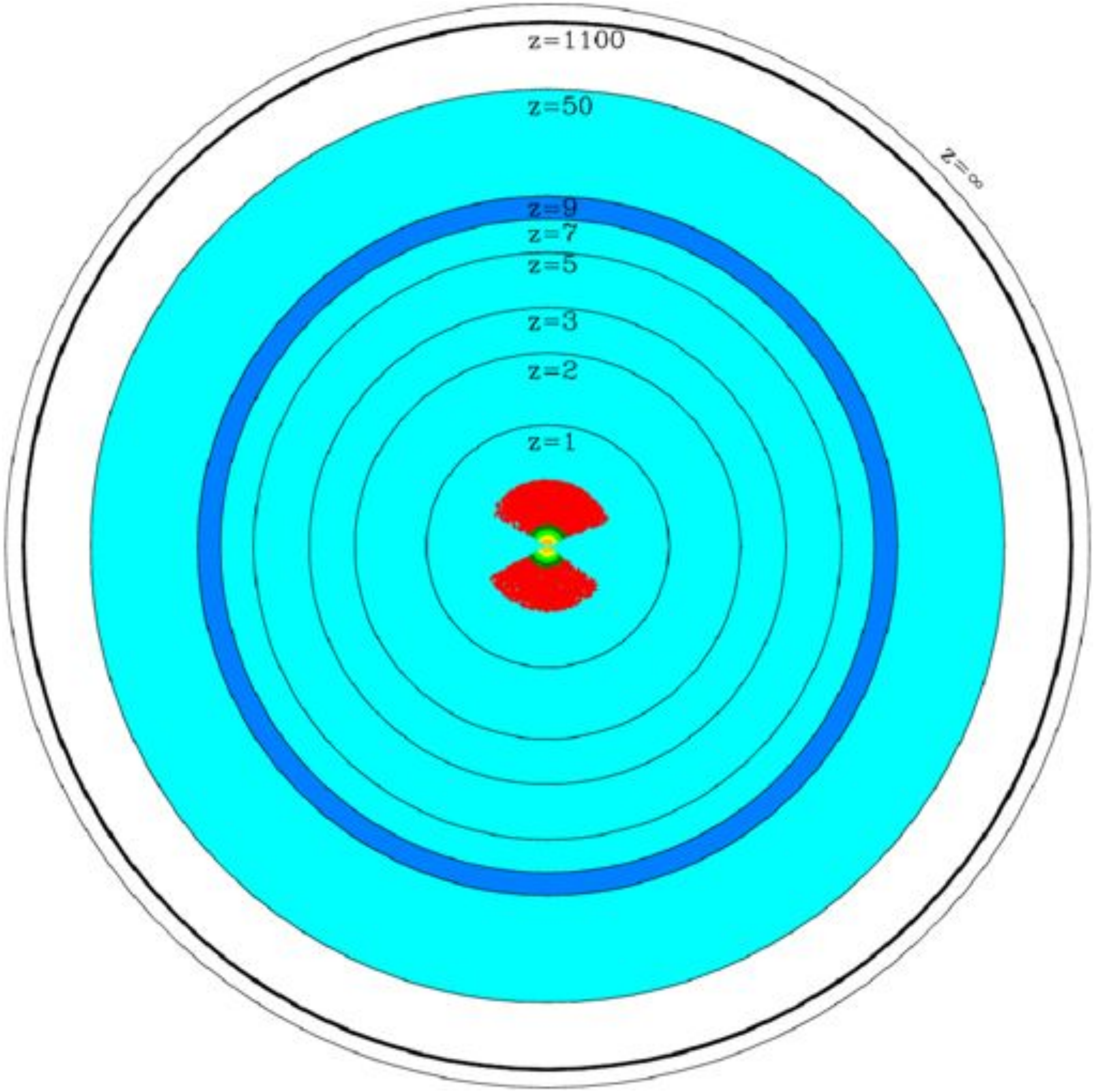
- Pathfinder instruments: LOFAR, MWA, PAPER, GMRT, EDGES are in the process of proving the principle...

- SKA/HERA-II/III would image at lower redshifts and sensitive to power spectrum out to $z<20$

- Possibility of doing cosmology once signal better understood: dark matter decay, isocurvature, neutrino mass, ...

Bonus material

Fundamental physics



Mao+ 2008

- Current constraints on cosmological parameters come from a small fraction of the observable Universe

- **If** astrophysics understood or high redshifts probed 21 cm observations can dramatically improve constraints:
  - Inflationary tilt and running
    Adshead+ 2010, Mao+ 2008
  - Isocurvature
    Gordon & Pritchard 2009
  - Neutrino mass
    Pritchard & Pierpaoli 2008

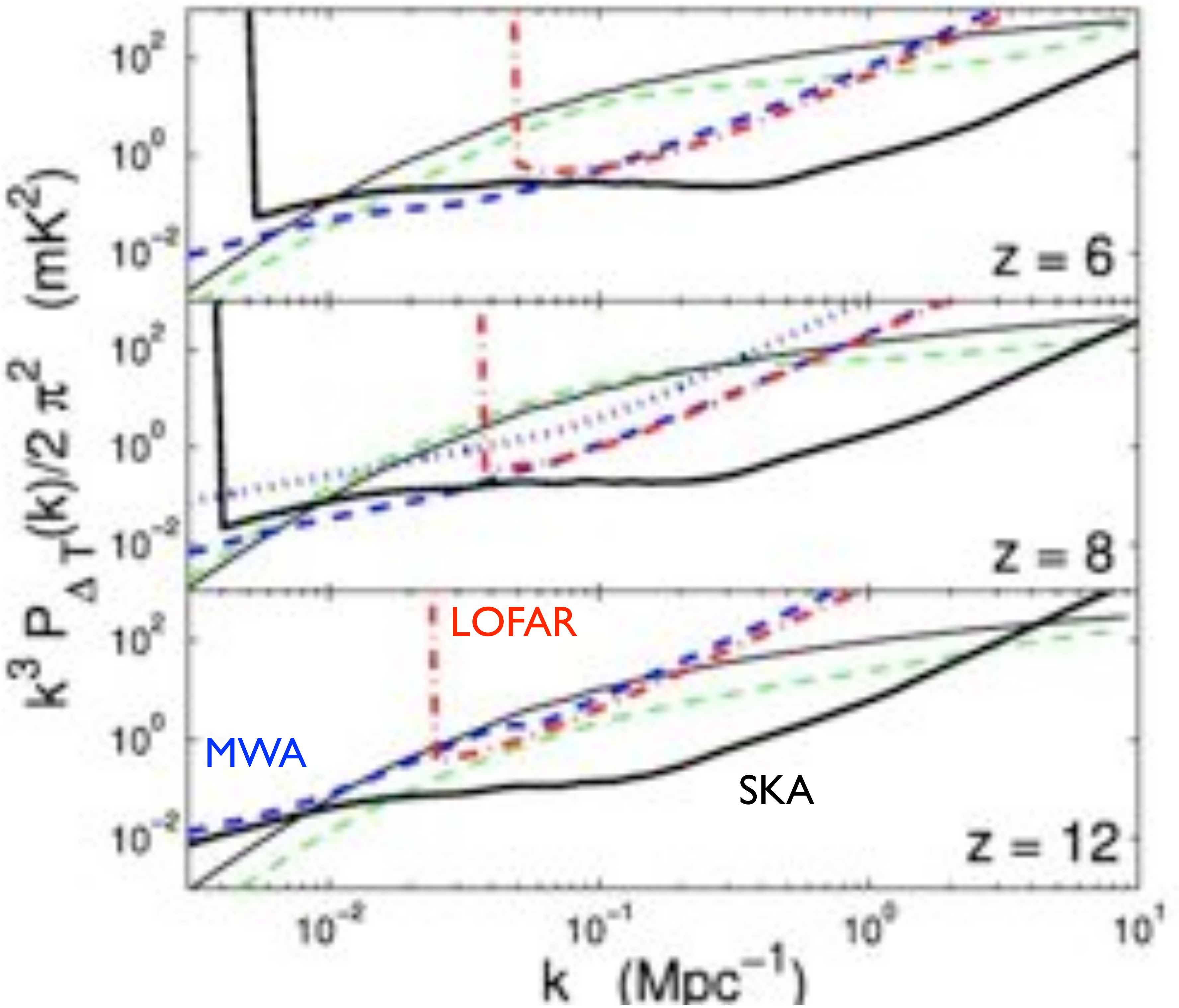
- Extracting information from small scales will be key for improving many cosmological constraints c.f. galaxies, Lyman alpha forest,...

Exciting decade ahead

- Over next decade new observations will transform our understanding of the first billion years
- Currently know very little about reionization history and first galaxies
- Need to understand both sources and IGM => 21 cm observations key
- Important to improve modelling of galaxies and reionization to connect observables

+ many more

Power spectrum sensitivity



Pathfinder instruments sensitive to about a decade in wavenumber

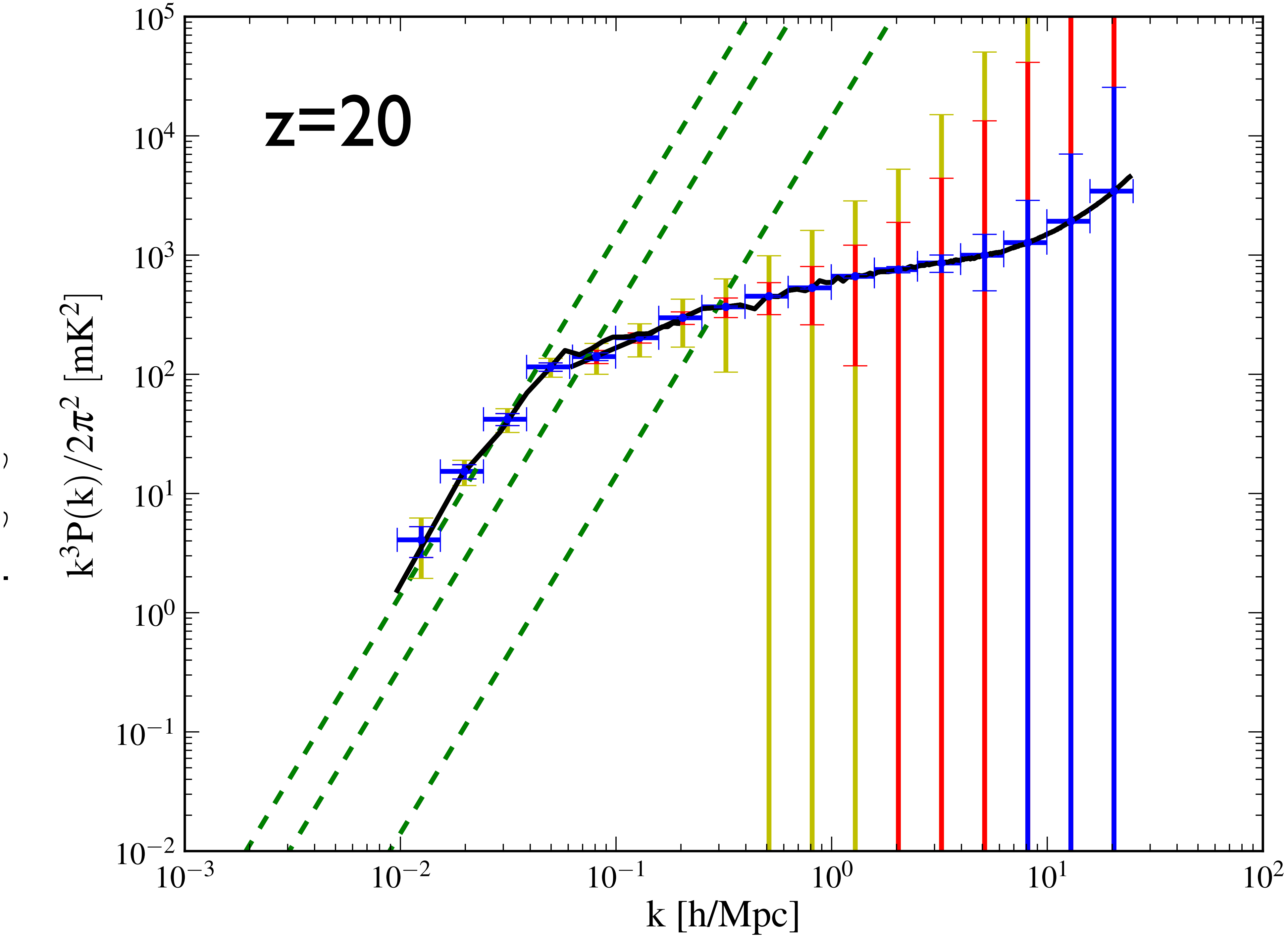
=> evolution of tilt and amplitude of power spectrum

Lidz+ 2008

SKA can measure shape of power spectrum

McQuinn+ 2006

21 cm sensitivity



10% SKA

20% SKA

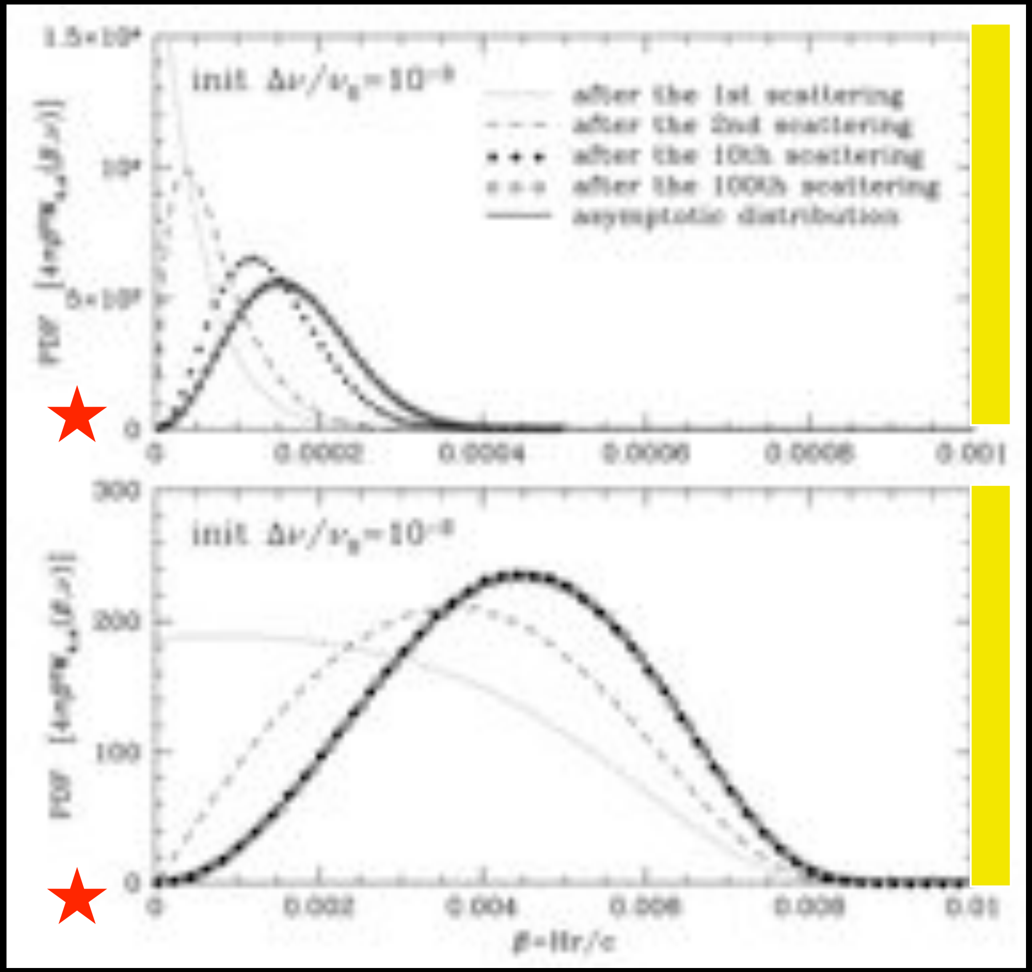
Full SKA

Higher redshifts need second generation instruments

Santos, Silva, Pritchard+ 2010

Simplifications

- Propogate in mean density IGM to simplify radiative transfer
- Ignore effects of shock heating
- Propogate Lyman photons until they redshift to line center

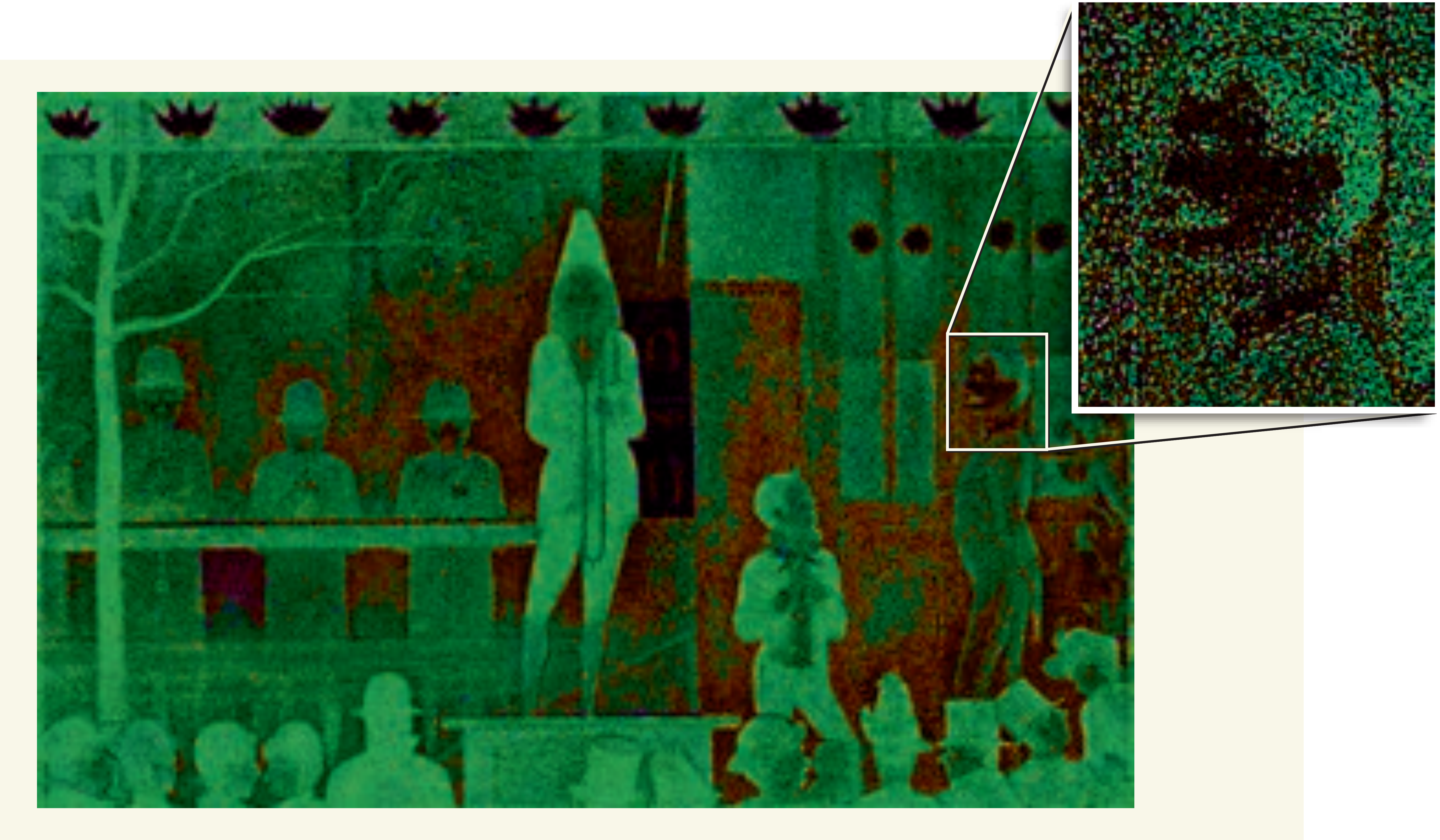


Scattering in wings tends to steepen radial dependence of flux

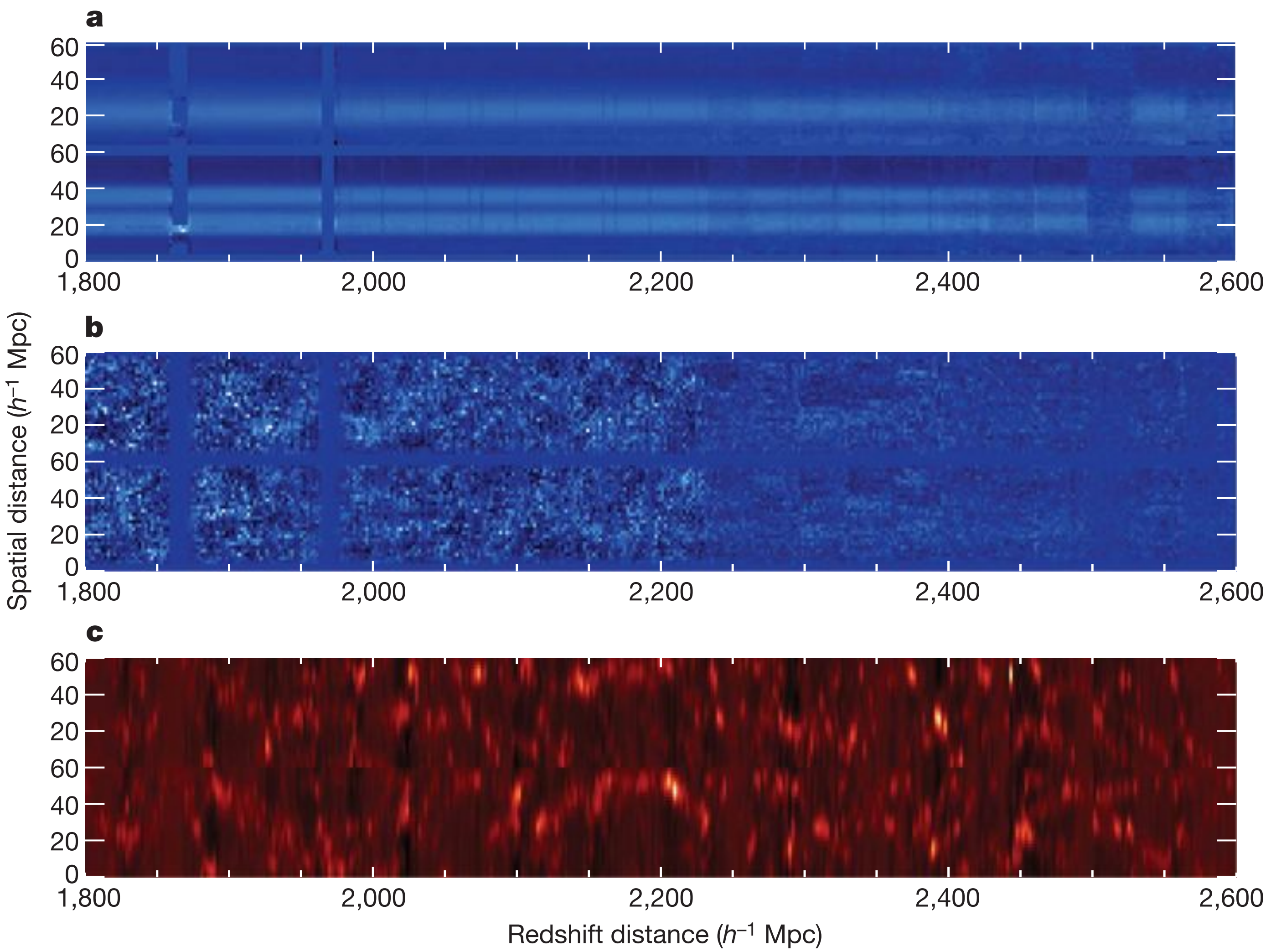
Semelin, Combes, Baek 2007
Chuzhoy & Zheng 2007
Naoz & Barkana 2007

Including correct physics will tend to increase power on small scales

Intensity Mapping in outline



Intensity mapping results



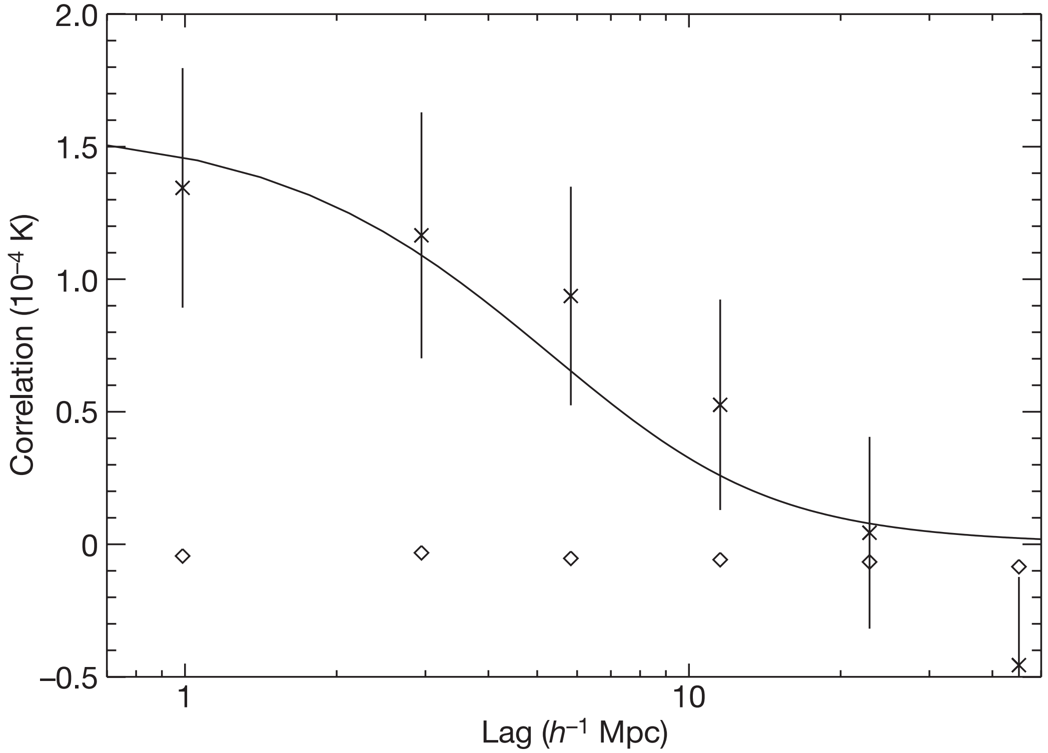
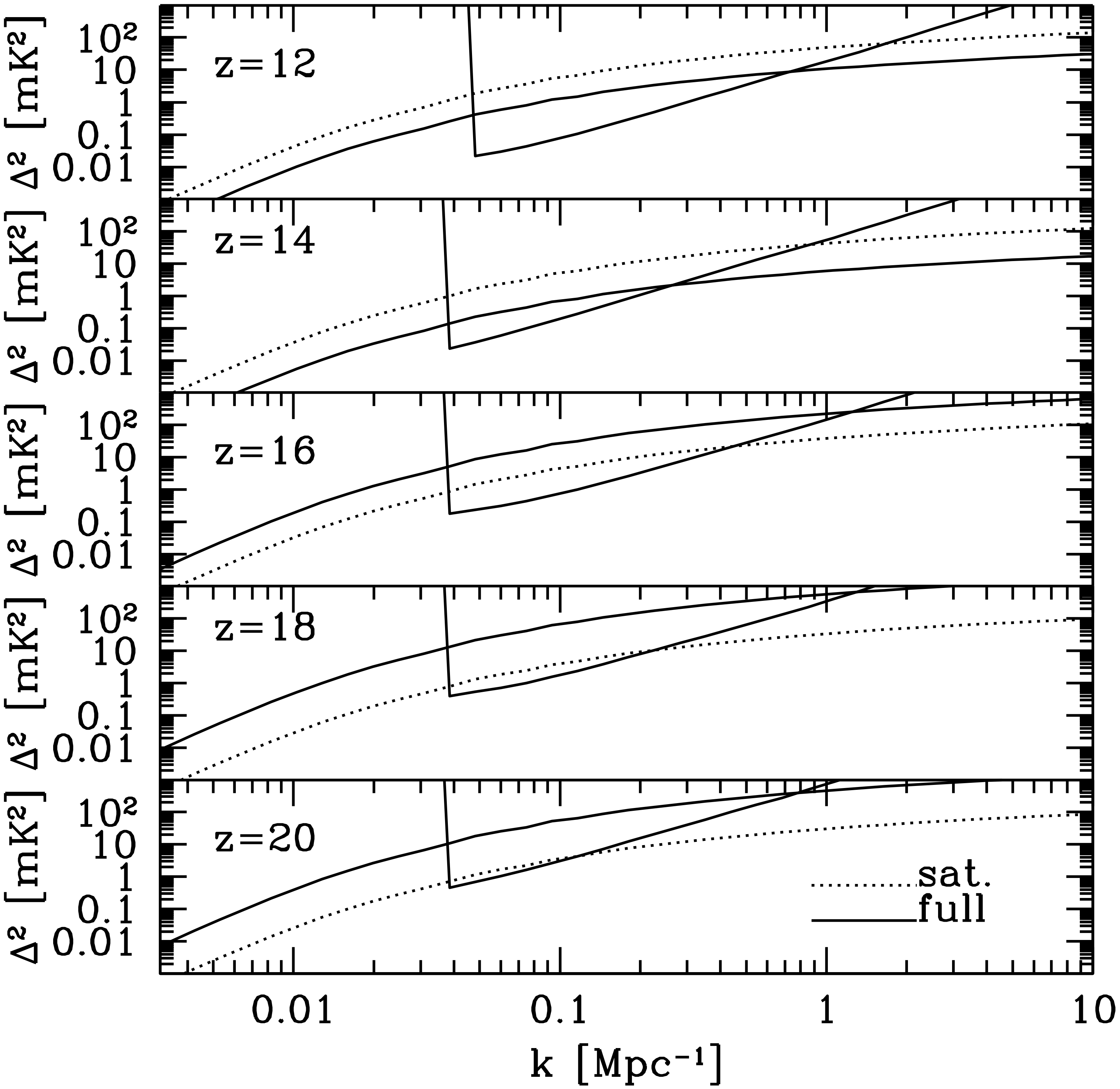


Figure 2 | The cross-correlation between the DEEP2 density field and GBT H I brightness temperature. Crosses, measured cross-correlation temperature. Error bars, 1σ bootstrap errors generated using randomized optical data. Diamonds, mean null-test values over 1,000 randomizations as described in Supplementary 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

Rise and fall of T_b



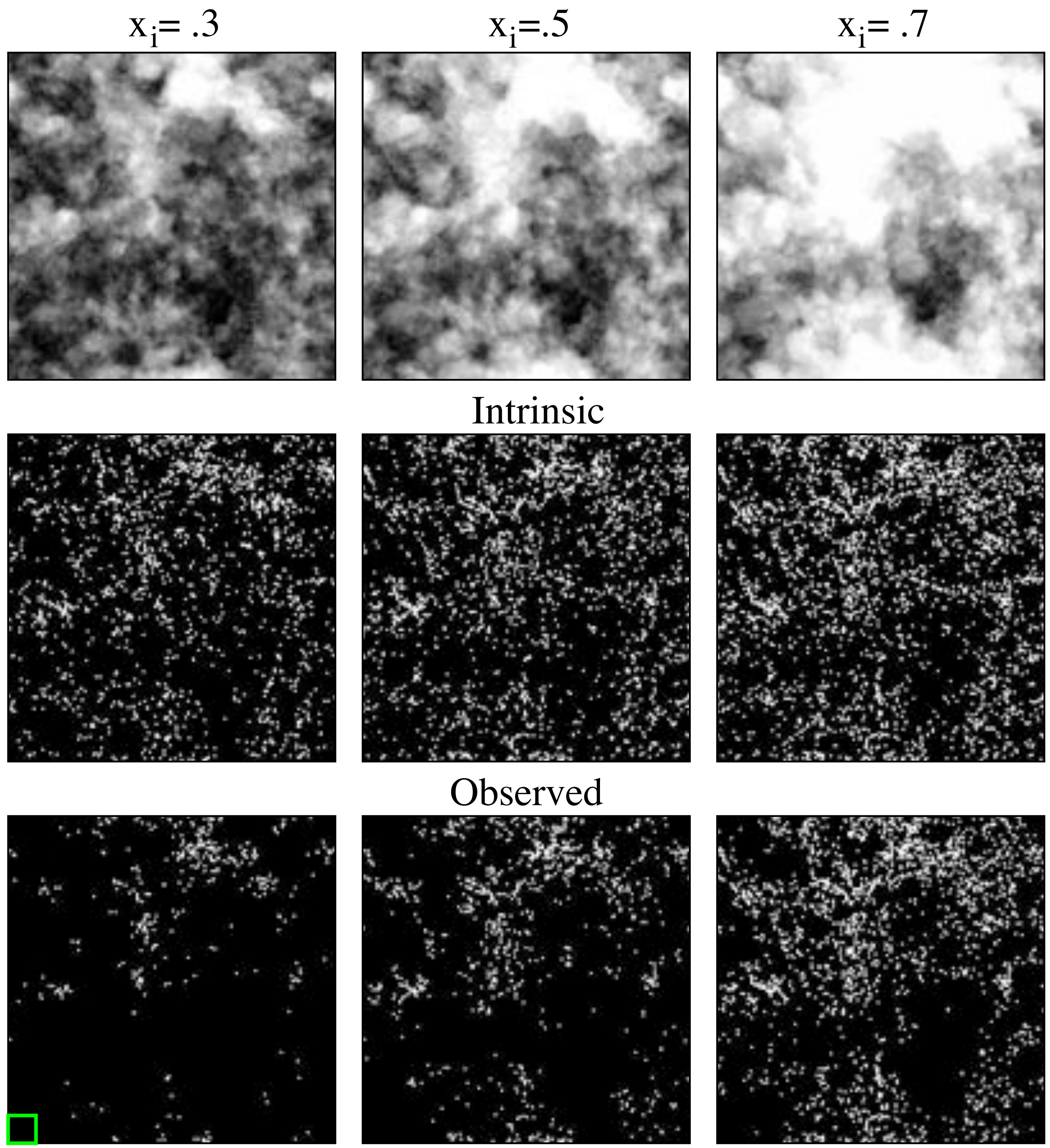
With full calculation of Tb signal amplitude varies with redshift and can become larger

SKA can track this rise and fall

fluctuations add extra power making detection easier...

SKA strawman with
30% antennae in 1 km
and 20 % in 6km rings
8 MHz channels for 1000 hrs

LAE

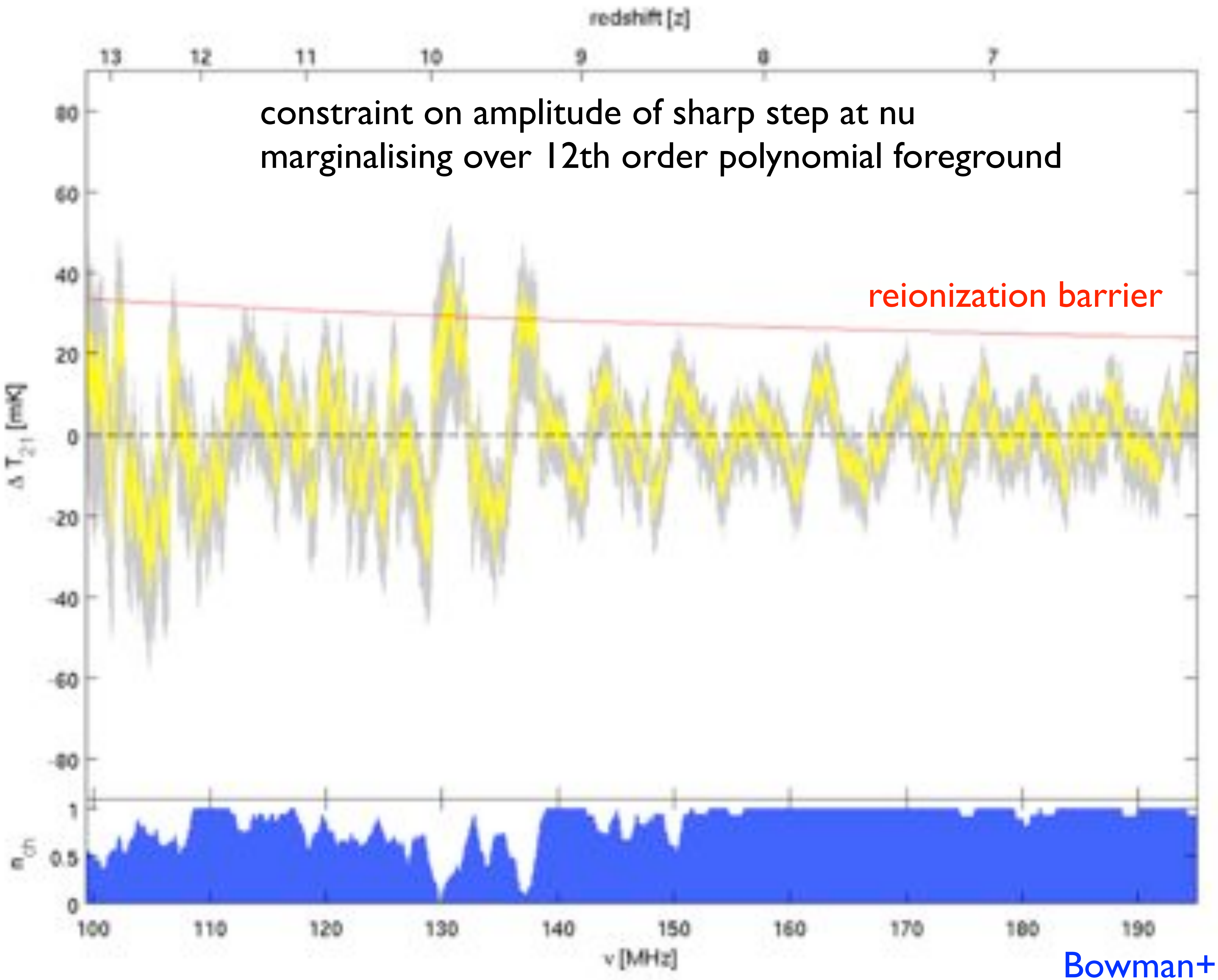


Evolution of LAE LF probes evolution of neutral fraction

Galaxy distribution seen through neutral HI "mask" that enhances clustering

From ground done through narrow windows by surveys like Subaru, VISTA,...

Residuals



constraint on amplitude of sharp step at nu
marginalising over 12th order polynomial foreground

reionization barrier

Bowman+ 2010