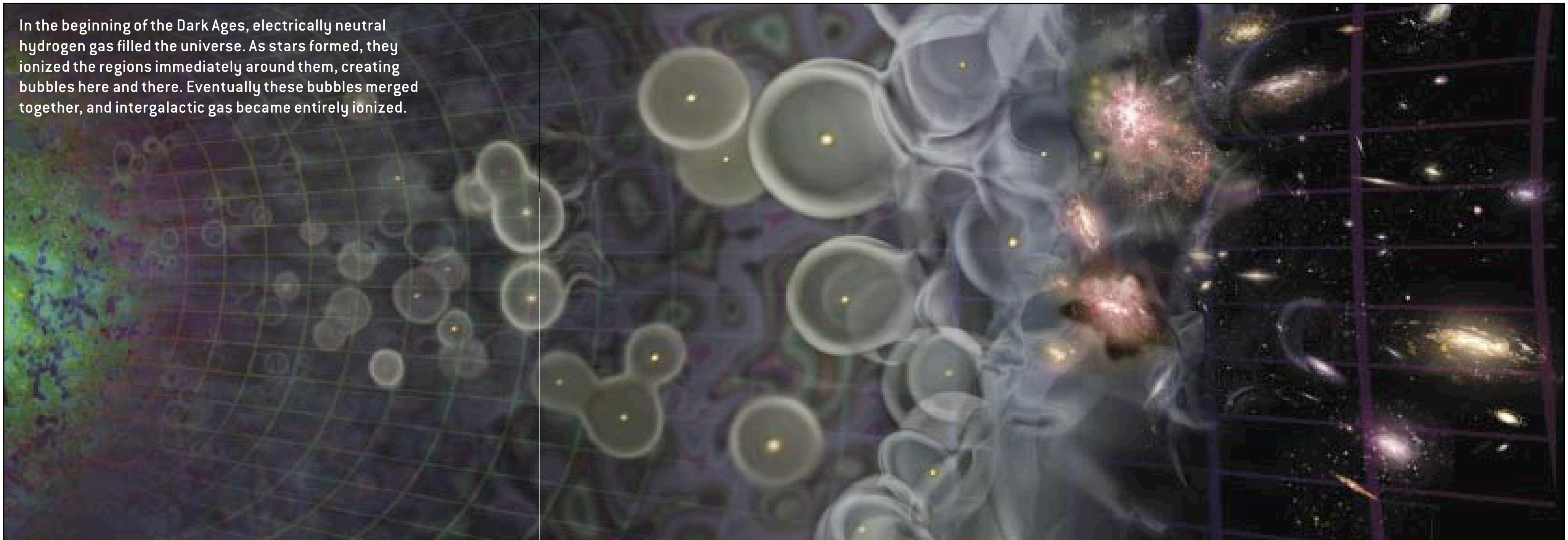
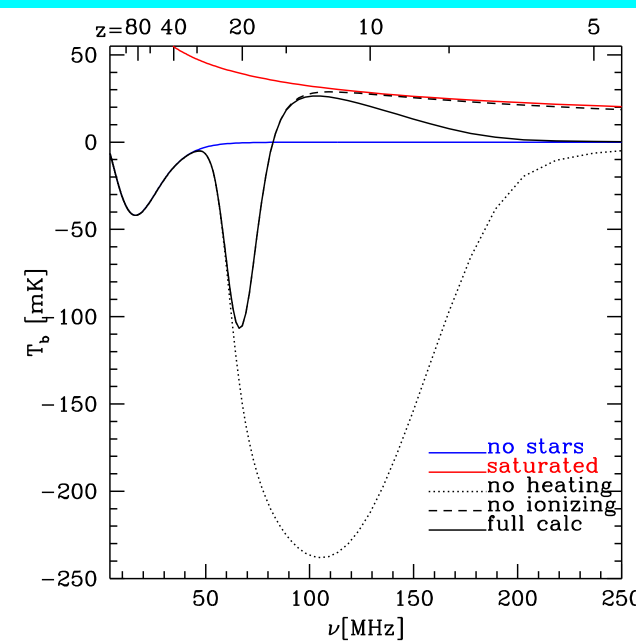


Lessons from constraining the global 21 cm signal in the presence of foregrounds

Jonathan Pritchard
Hubble Fellow
CfA

KISS Workshop
The first billion years



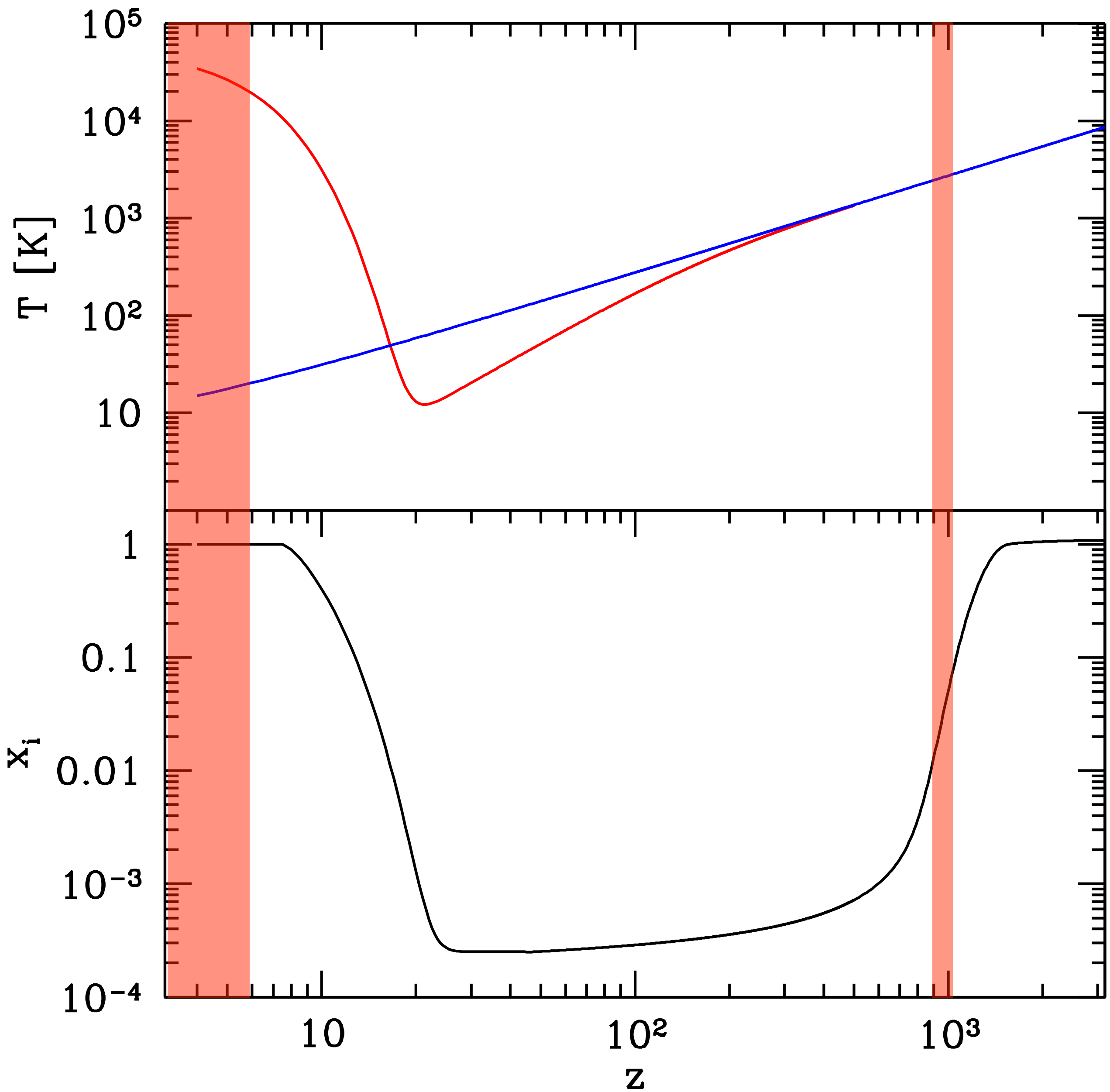
Overview

- 21 cm global signal - physics
- Foregrounds and experiments
- Reionization
- First galaxies

Assume perfect calibration. What information survives foreground removal?

Pritchard & Loeb 2010

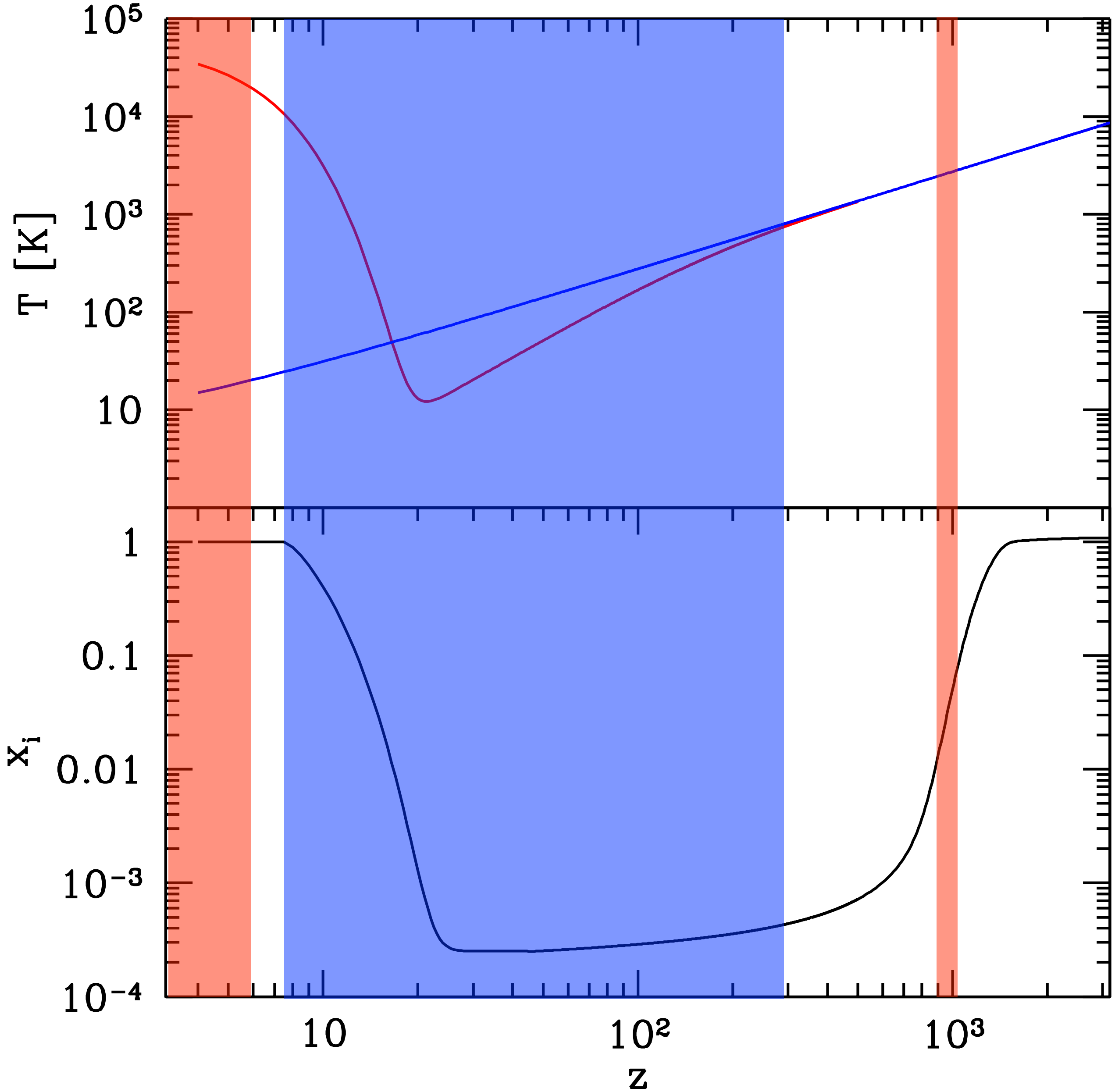
Known unknowns...



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

Discovery space

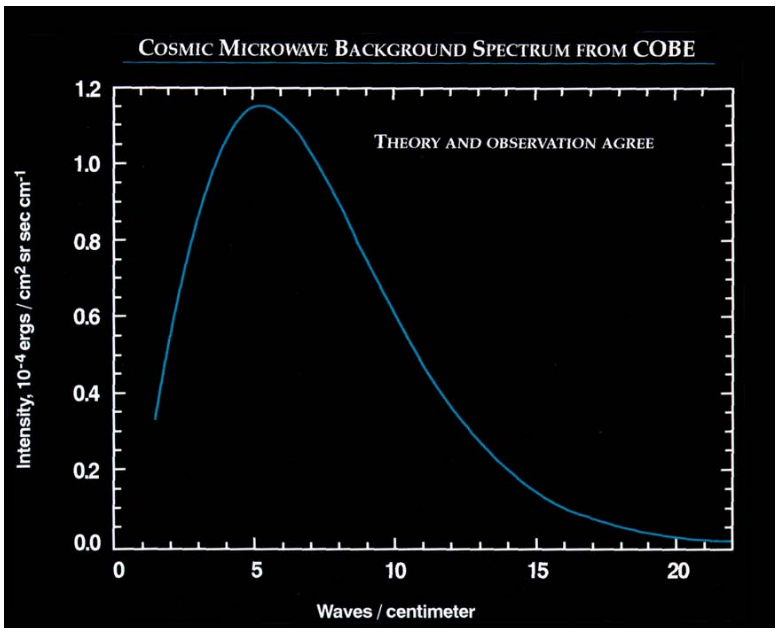


We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

We know little or nothing about galaxies at z>10

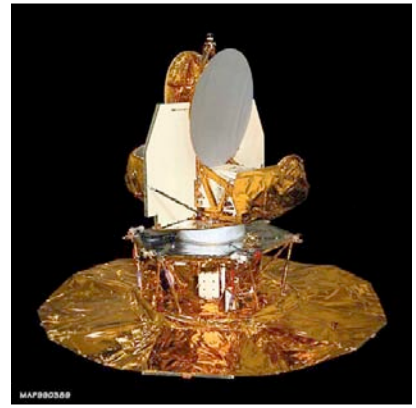
CMB

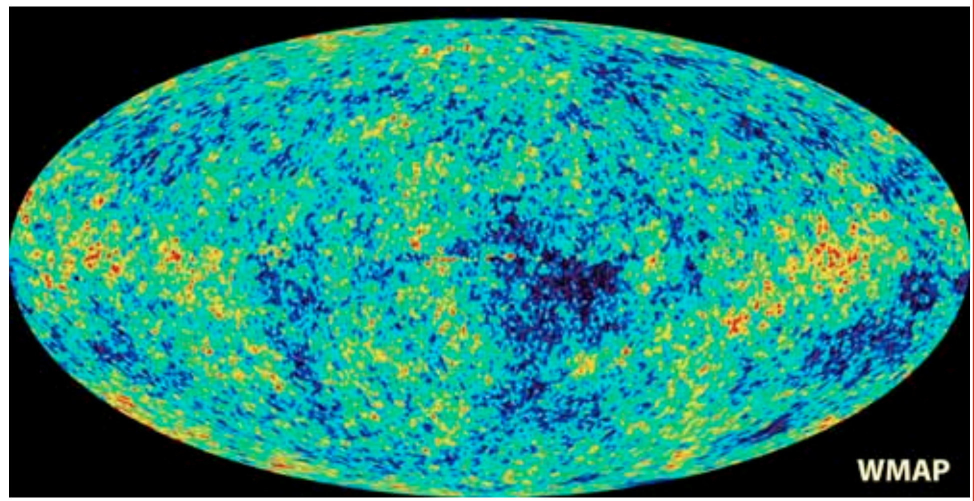
COBE-FIRAS



black body

WMAP

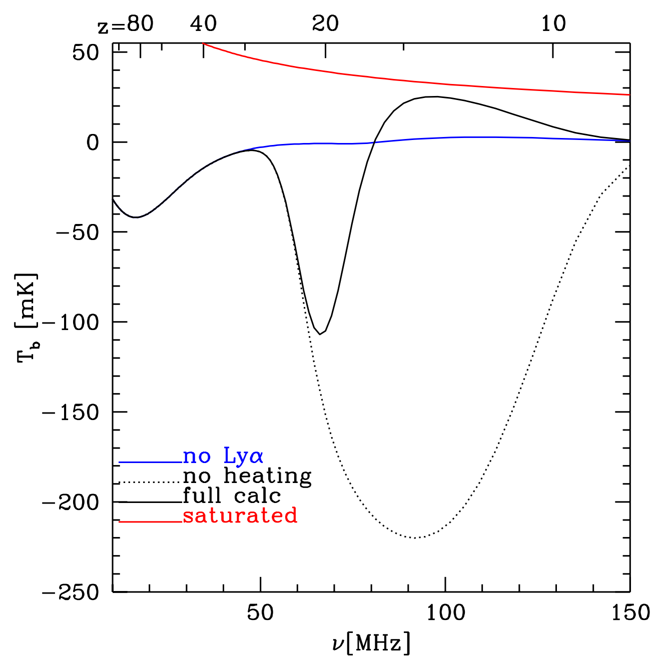




anisotropies

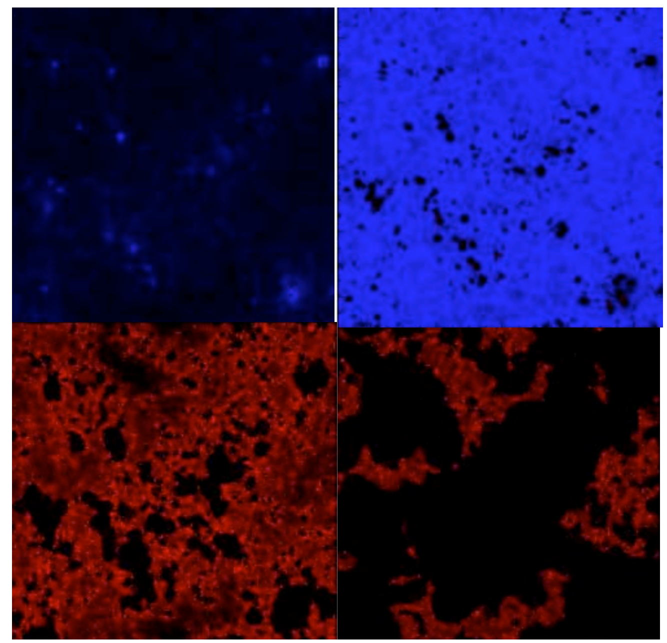
21cm

EDGES



global signal

LOFAR MWA



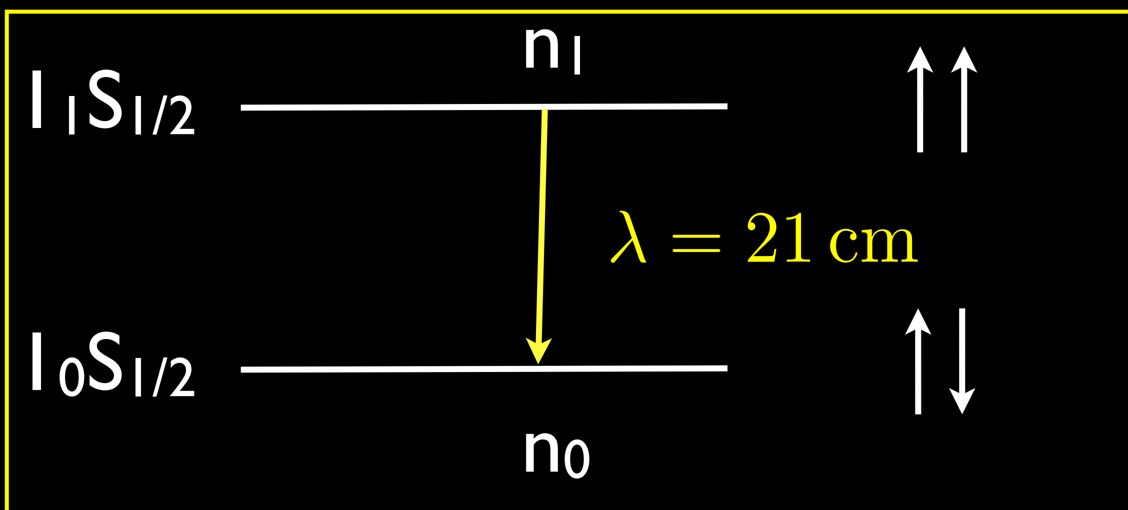
Fluctuations

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:

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

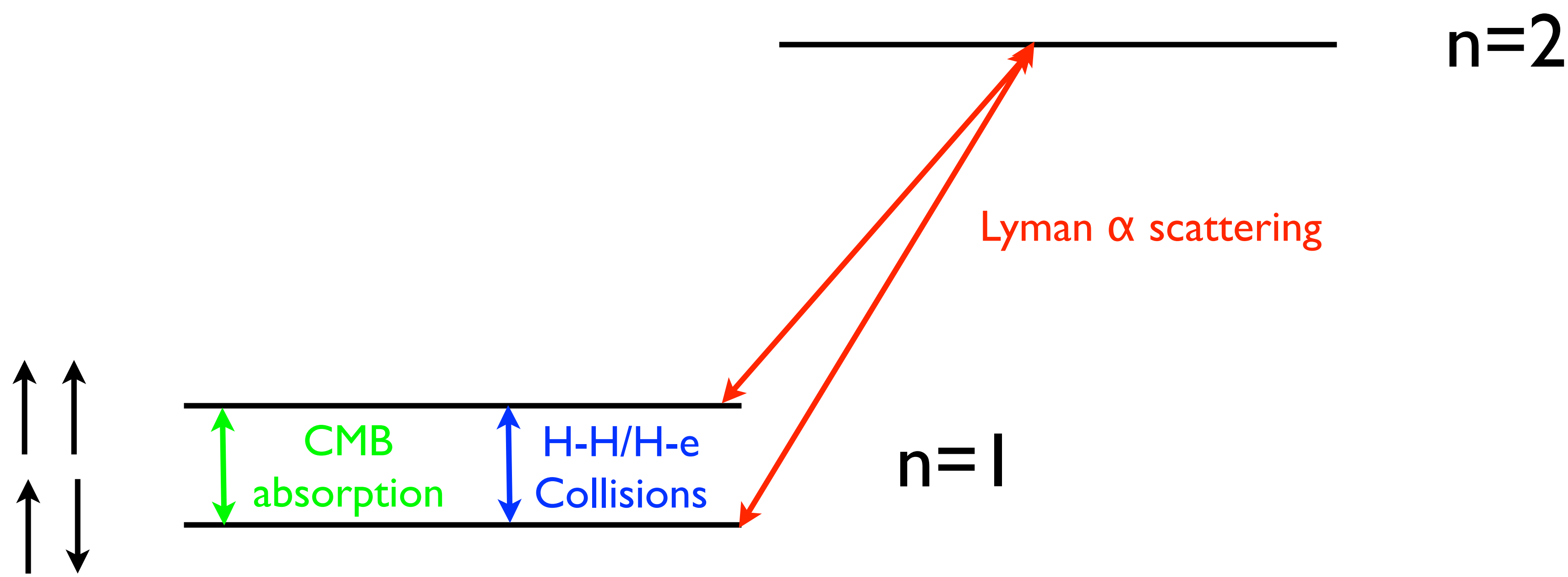
$$t_{\mathrm{Age}}(z=6) \approx 1\ \mathrm{Gyr}$$
$$t_{\mathrm{Age}}(z=10) \approx 500\ \mathrm{Myr}$$
$$t_{\mathrm{Age}}(z=20) \approx 150\ \mathrm{Myr}$$

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

Spin temperature

- After z~200 CMB and gas out of thermal equilibrium => two temperature scales

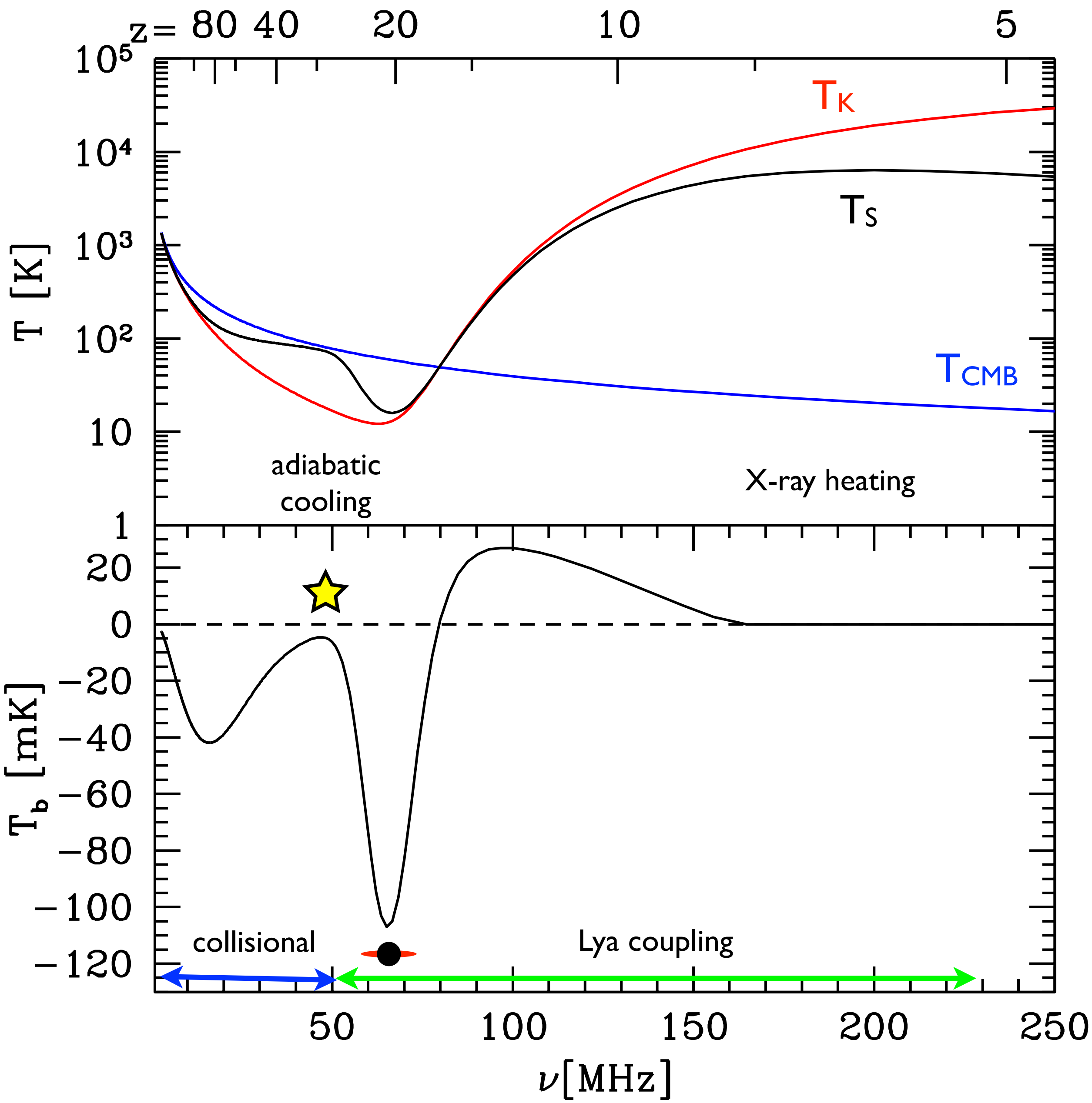
- 21 cm spin temperature interpolates between the two depending on the strength of coupling



21cm brightness temperature

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

21 cm global signal



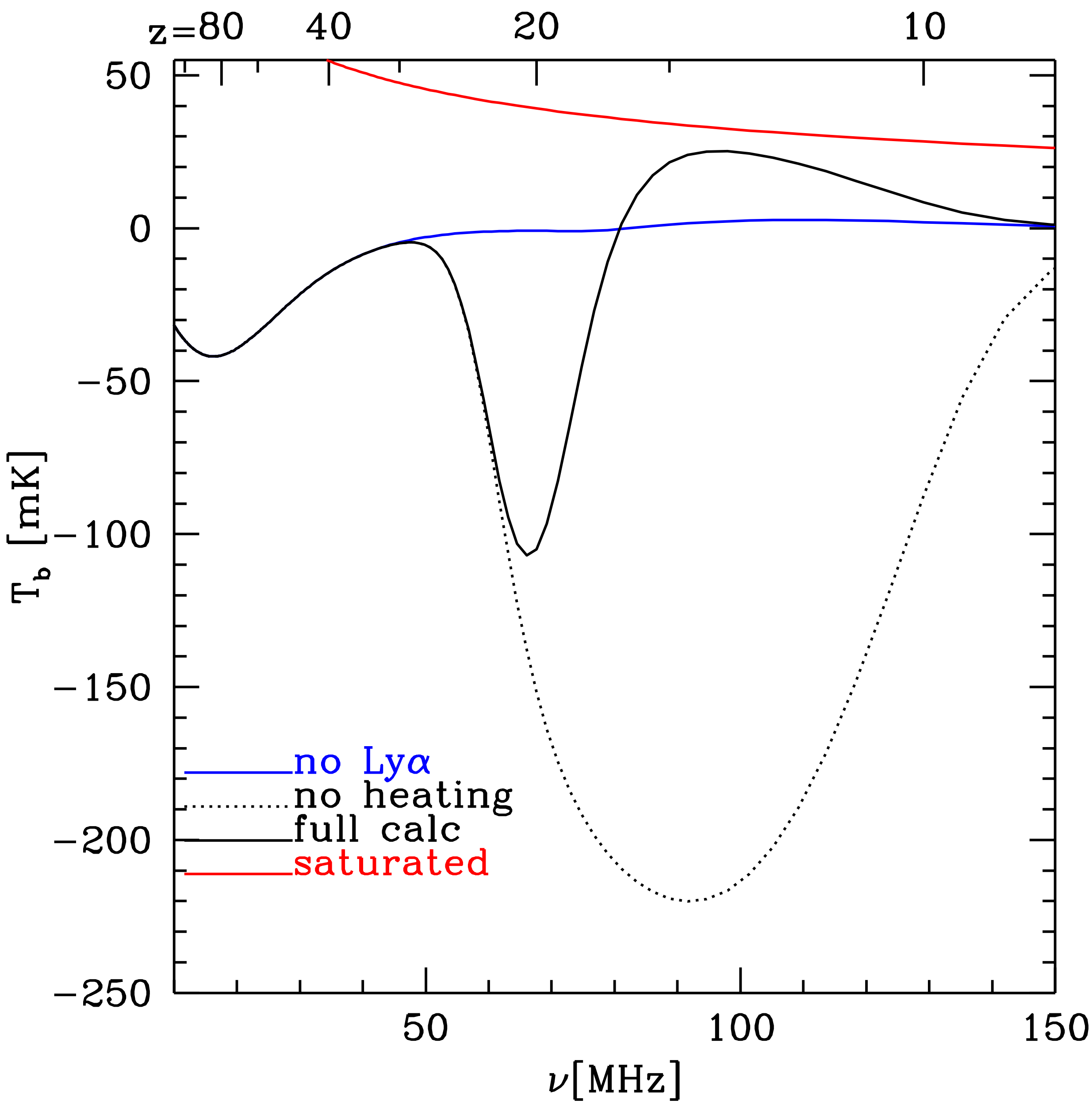
Main processes:

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

Furlanetto 2006

Pritchard & Loeb 2010

Alternative scenarios



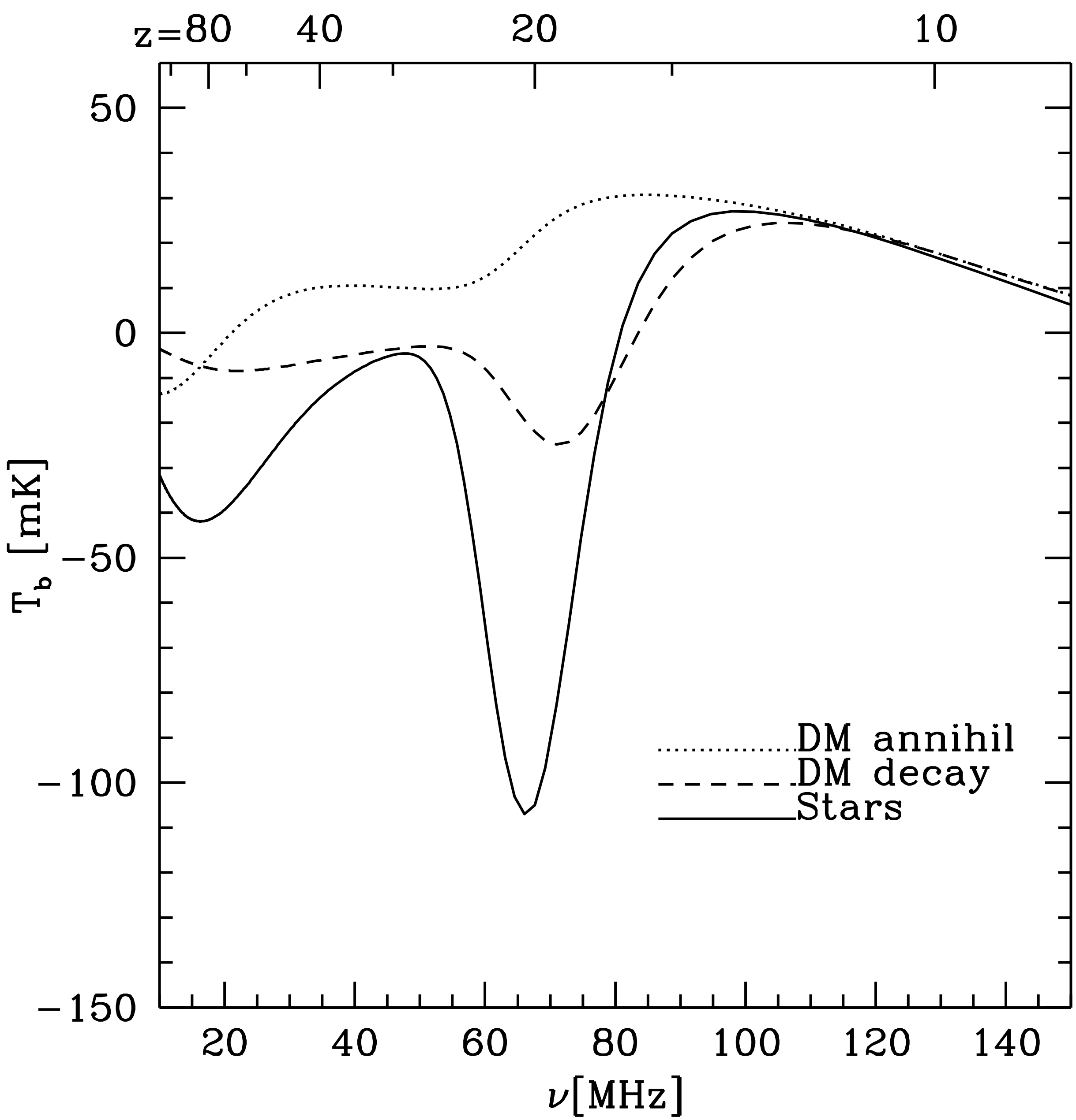
Maybe Lya photons don't escape their host halos?

Maybe there was no X-ray heating?

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

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
...

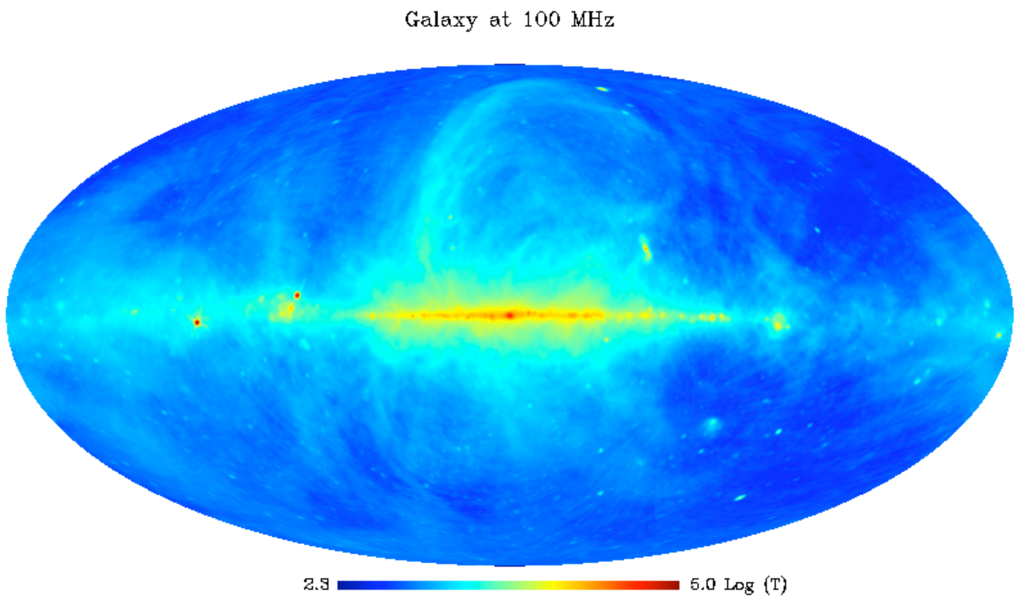
Very sensitive thermometer

Furlanetto+ 2006
Valdes+ 2007
Mack+ 2008

Shape of the signal

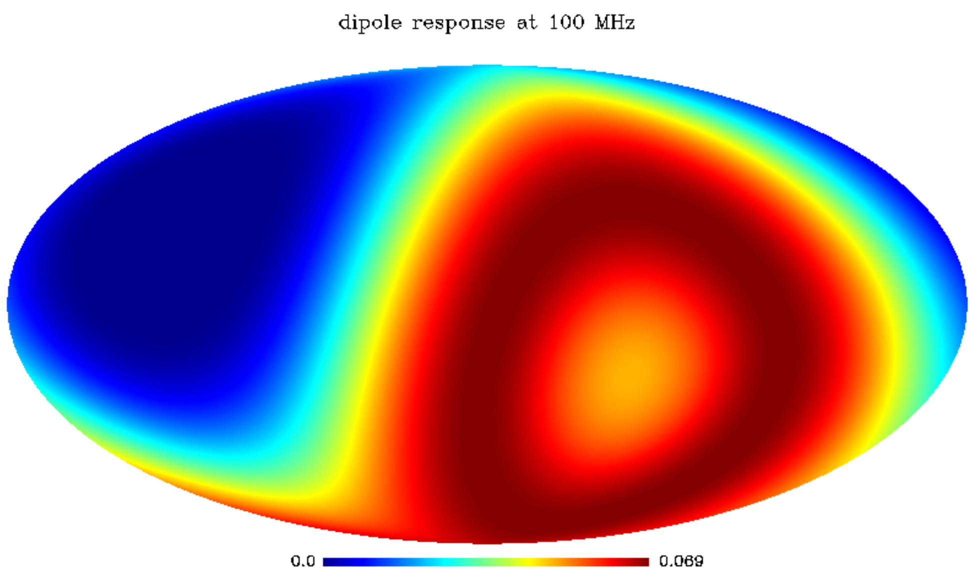
- 21 cm signal driven by coupling and heating
- Disentangling different physics requires shape details
- Much easier to pick out key features

Foregrounds



Sky at 100 MHz dominated by galactic foregrounds

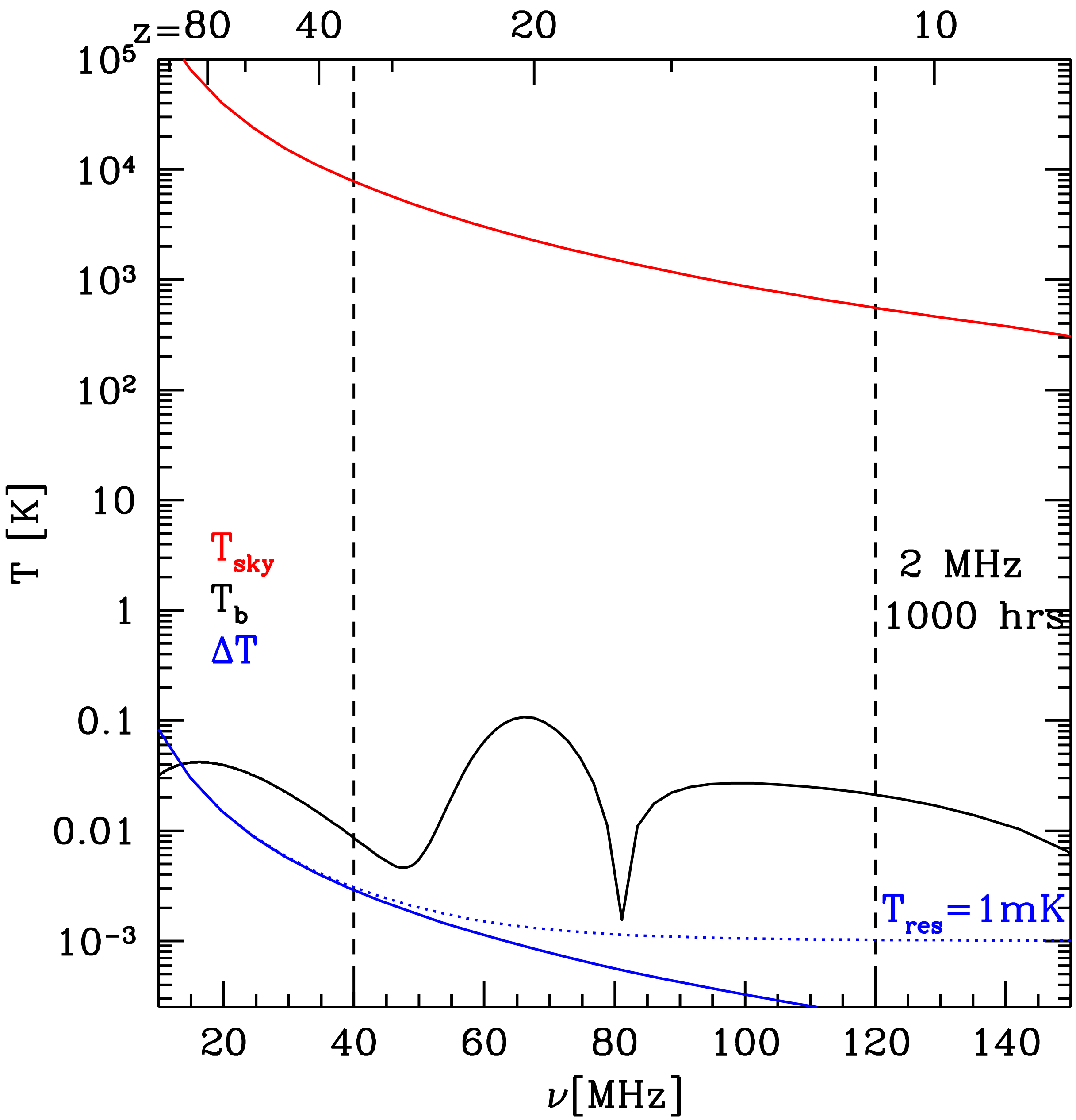
de Oliveira-Costa+ 2008



Response of ideal dipole at MWA site averaged over a day

Few independent pixels on the sky but possibly can exploit

Foregrounds vs Signal



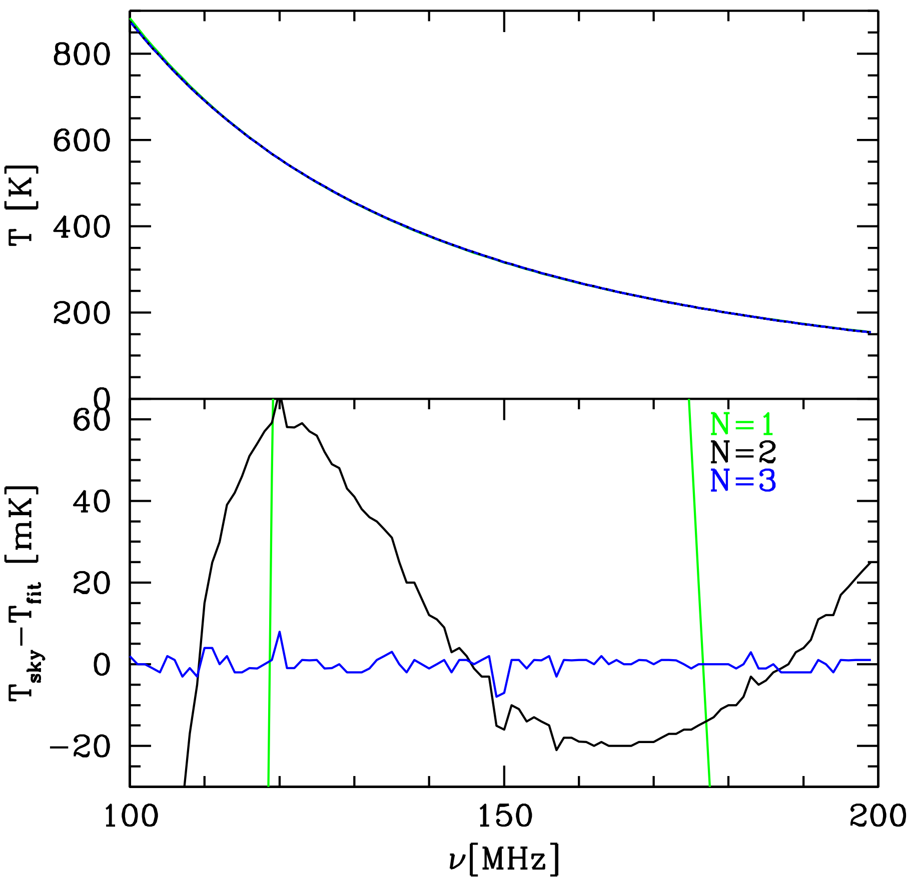
Foregrounds smooth
Signal has structure
Separation possible...

Dynamic range $>10^5$ needed

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

Foreground fitting

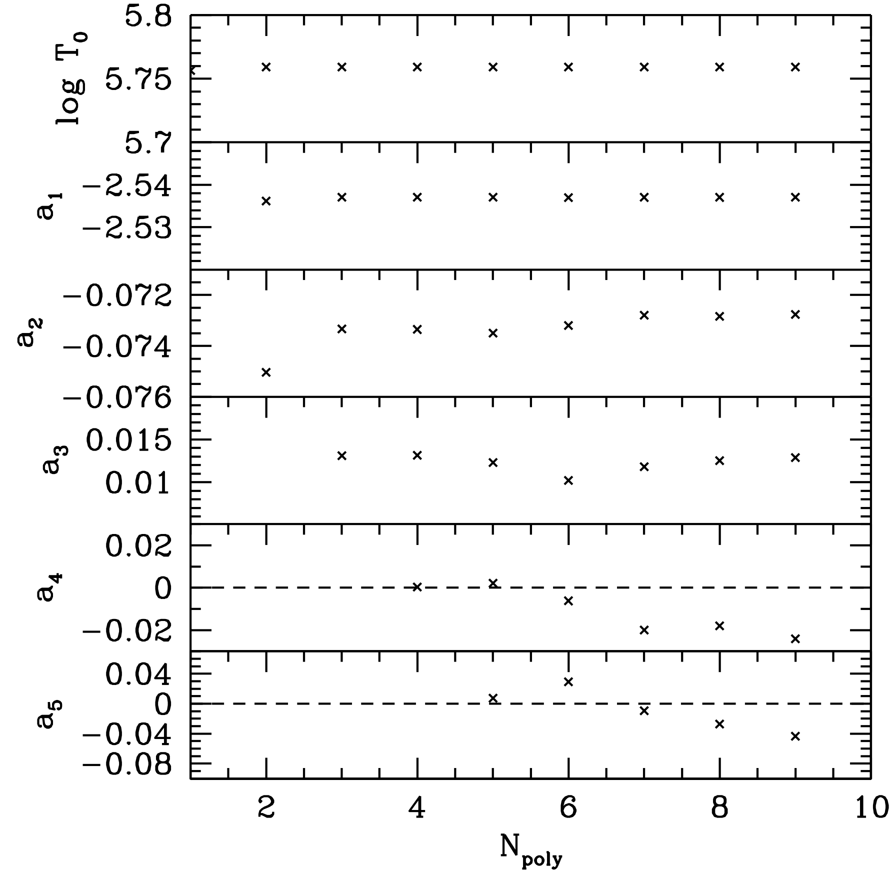
Fitting residuals



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

Minimum third order polynomial needed

Fitting coefficients



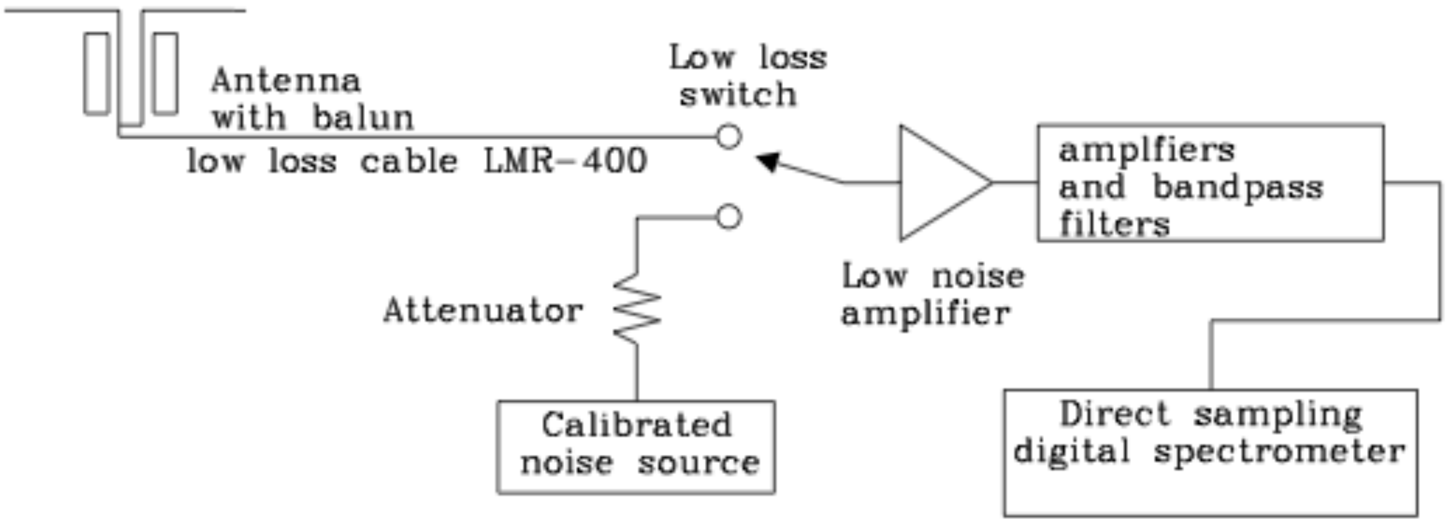
$\nu_0 = 150\,{\rm MHz}$

$T_0 = 320\,{\rm K},\ \ a_1 = -2.54,$

$a_2 = -0.0736,\ a_3 = 0.0127$

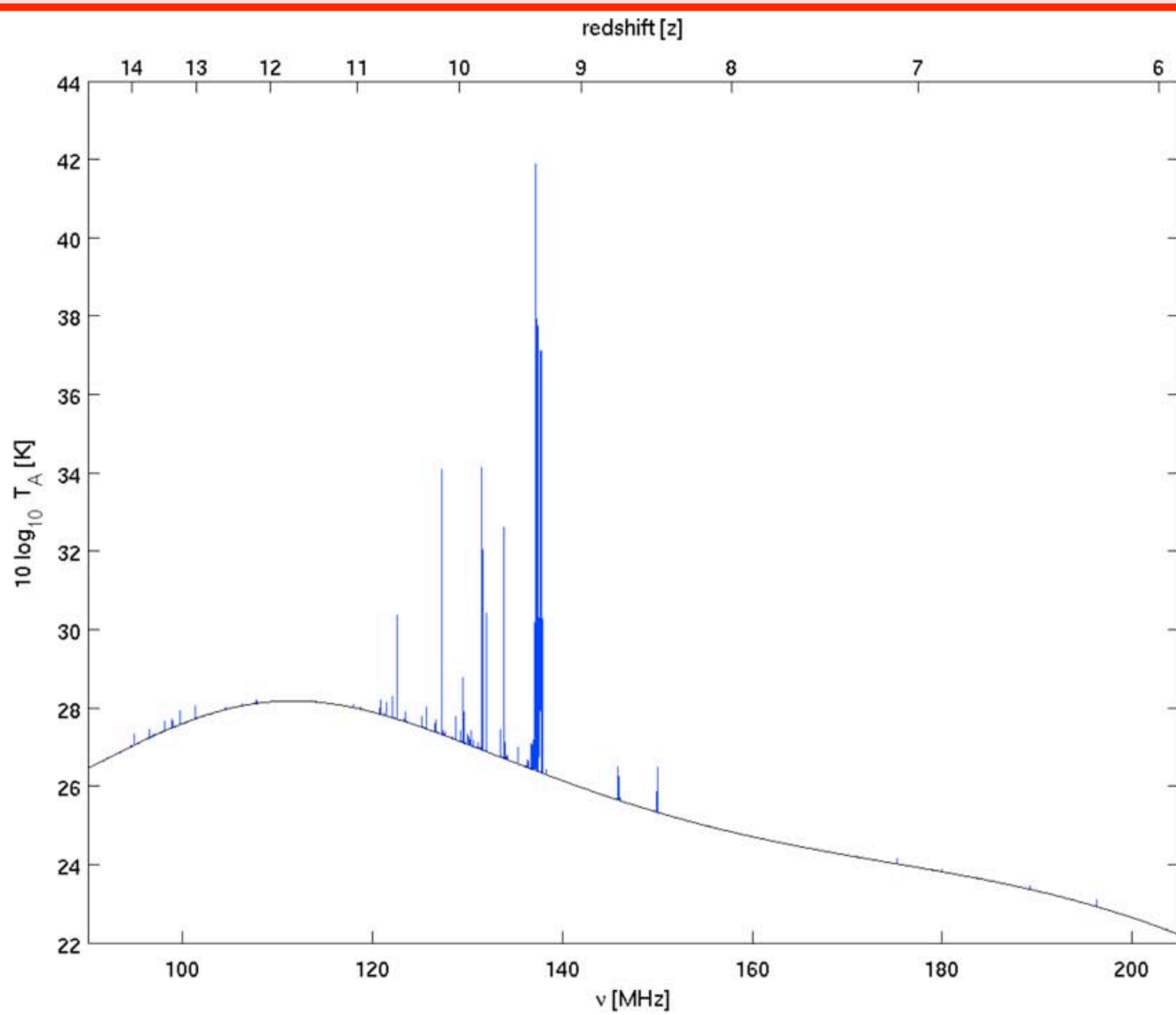
EDGES

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



Switch between sky and calibrated reference source

Observations



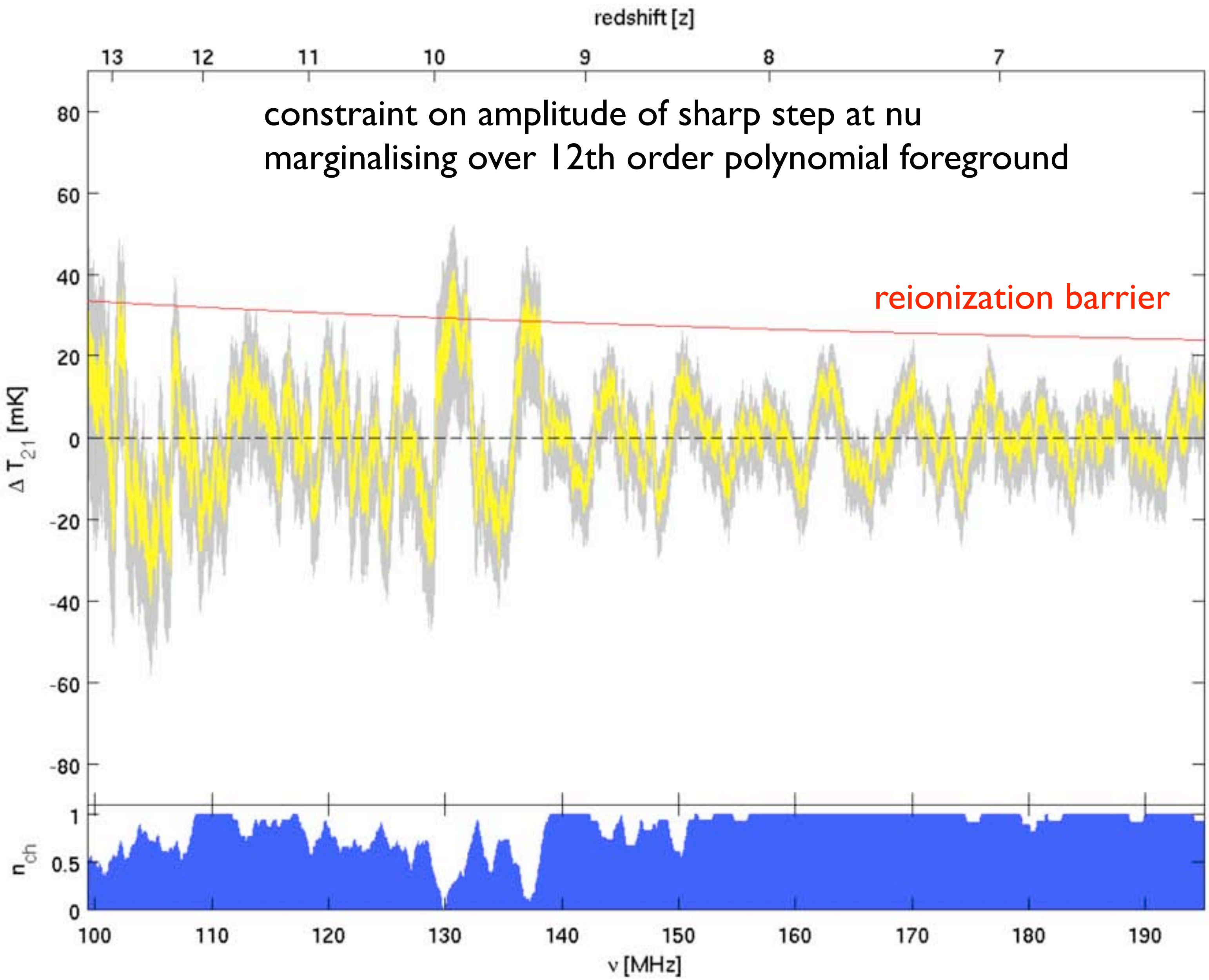
Observed sky
tint=50 hours

covers 100-200 MHz in 2 MHz channels

Foregrounds convolved with
instrumental response - calibration

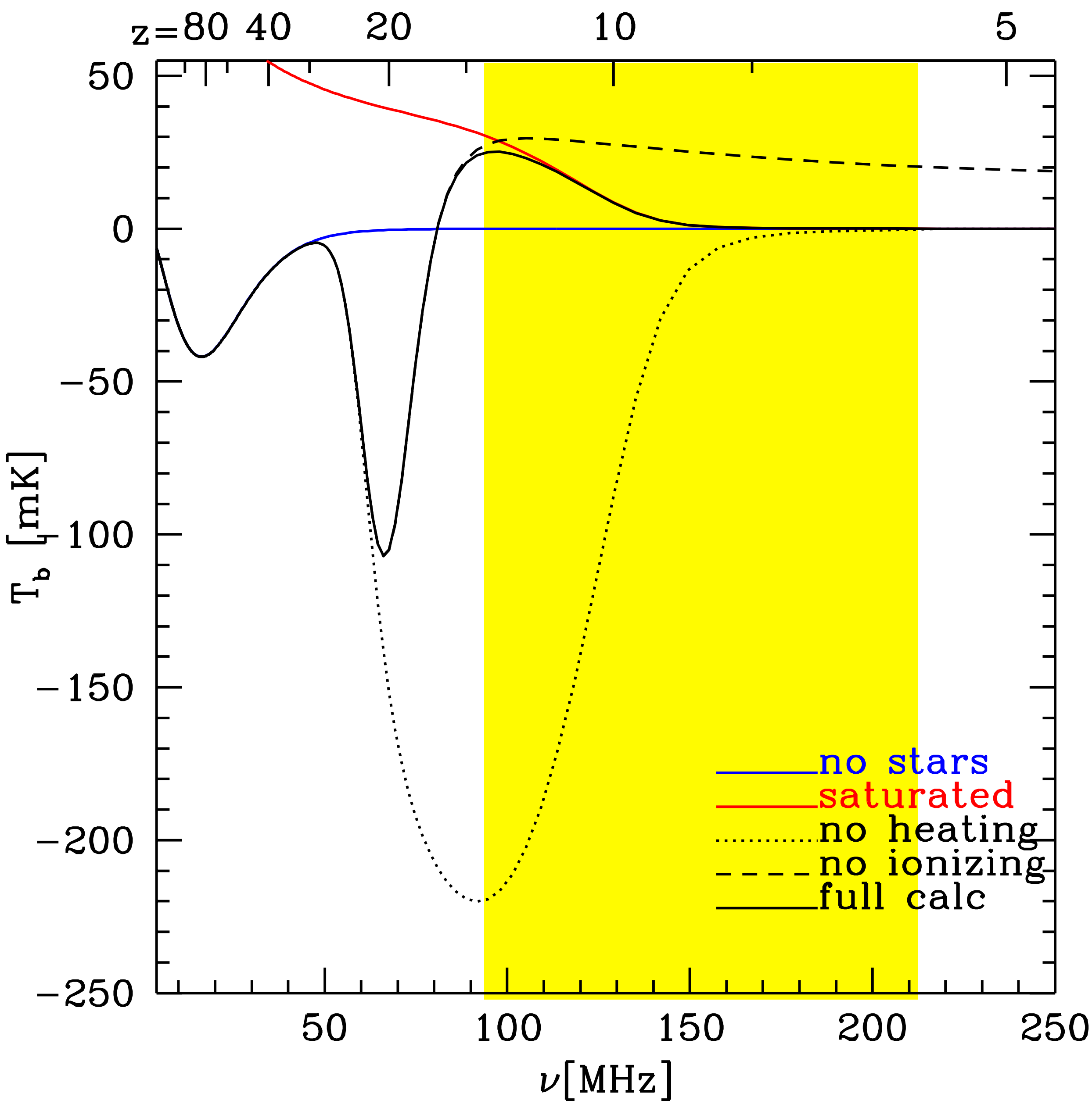
Bowman & Rogers 2008

Residuals

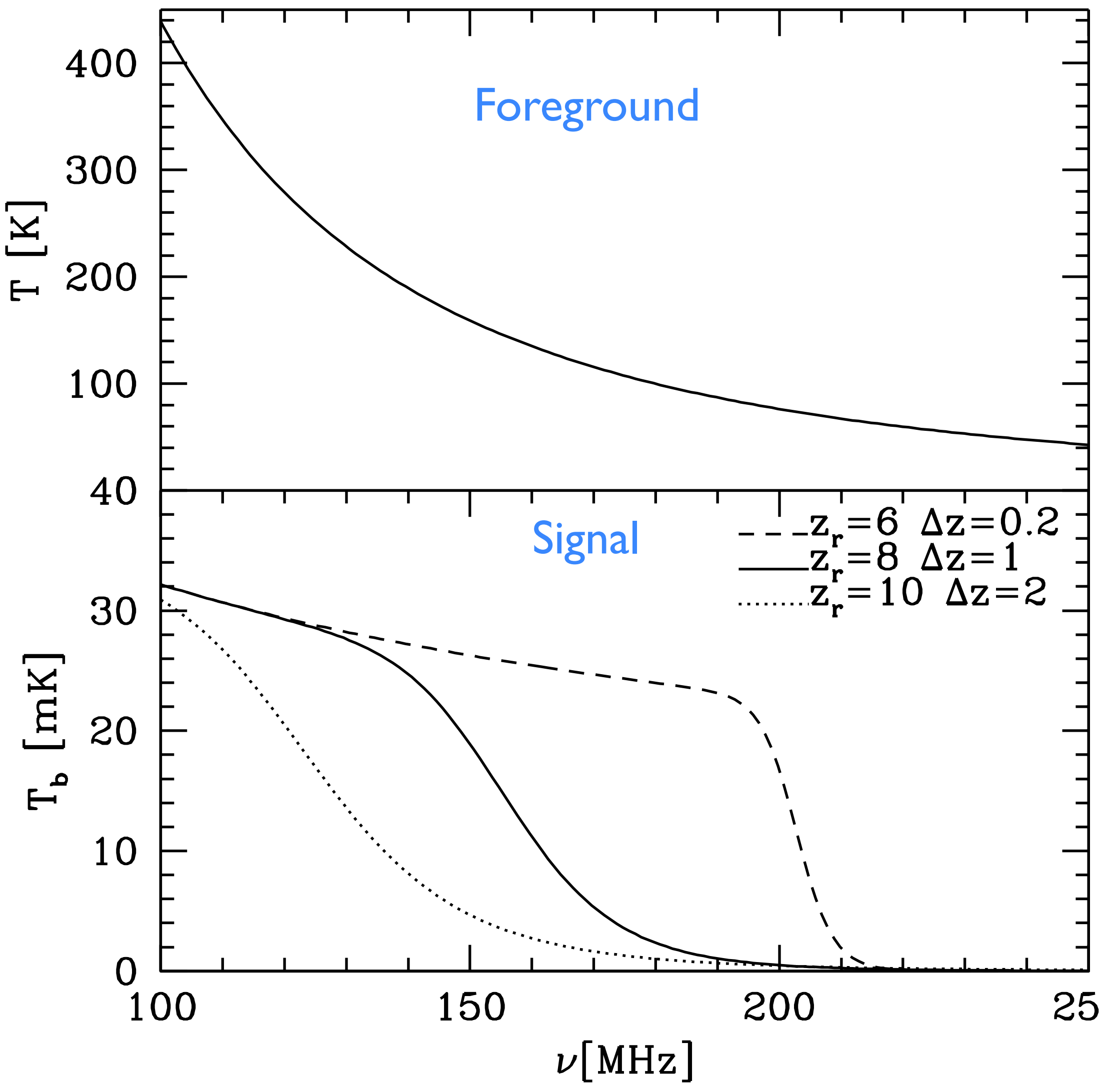


redshift [z]
13
12
11
10
9
8
7
constraint on amplitude of sharp step at nu
marginalising over 12th order polynomial foreground
reionization barrier
80
60
40
20
0
-20
-40
-60
-80
Δ T21 [mK]
nch
1
0.5
0
100
110
120
130
140
150
160
170
180
190
ν [MHz]

Reionization



Frequency subtraction



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

Extended reionization histories closer to foregrounds

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

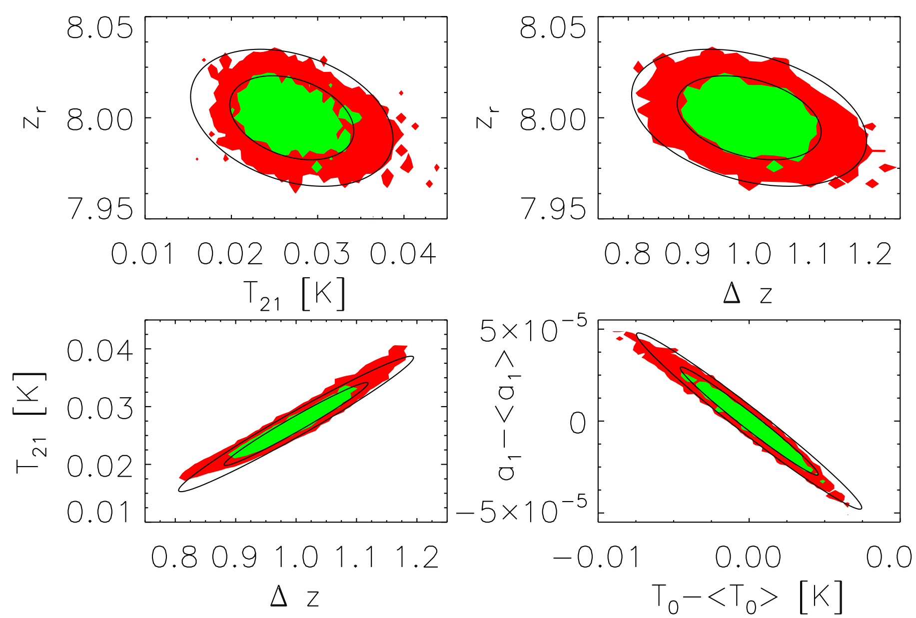
Fisher matrix

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



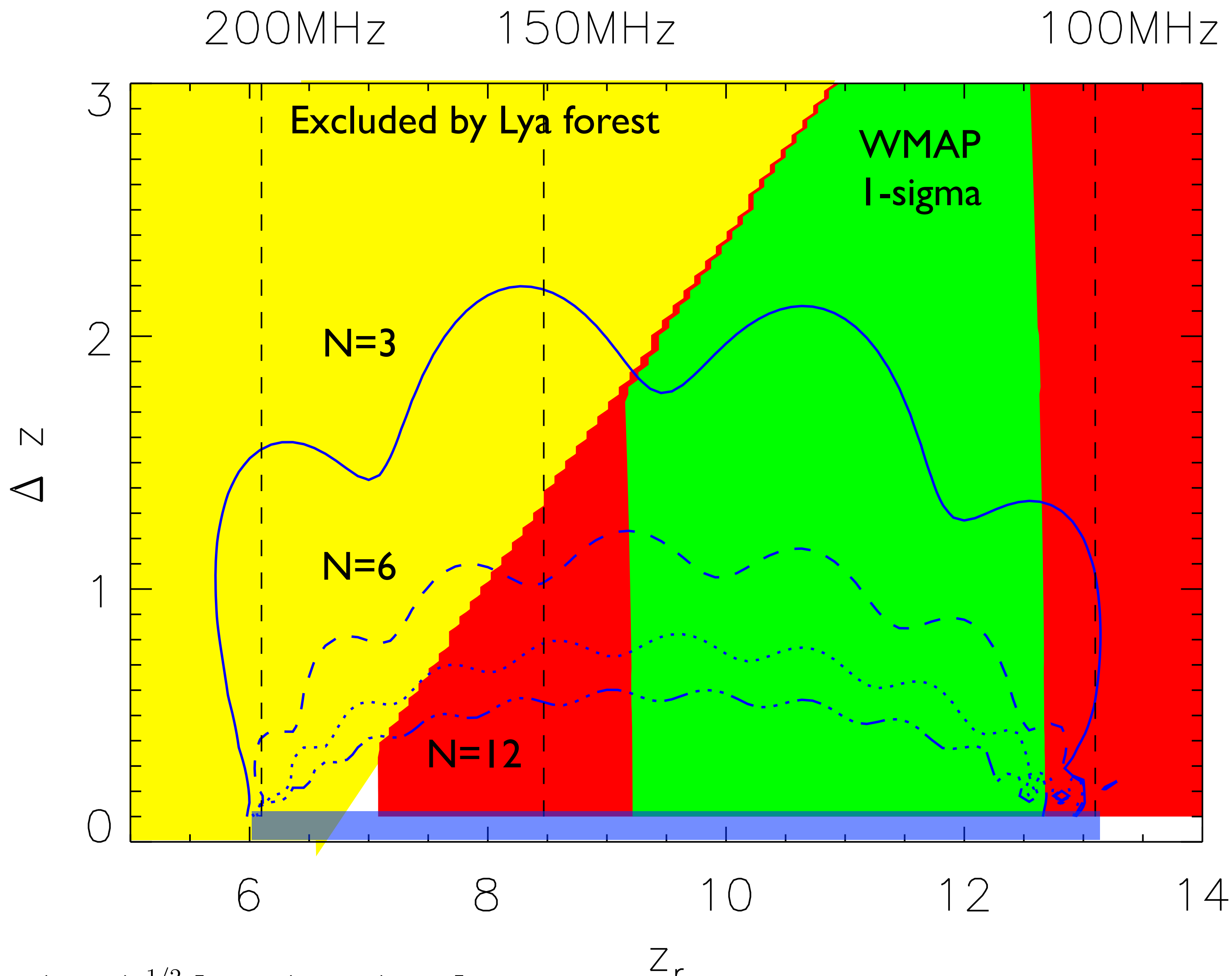
Compare with least squares fitting of model
to 10^6 realisations of thermal noise: Good agreement

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

Pritchard & Loeb 2010

Reionization detection region

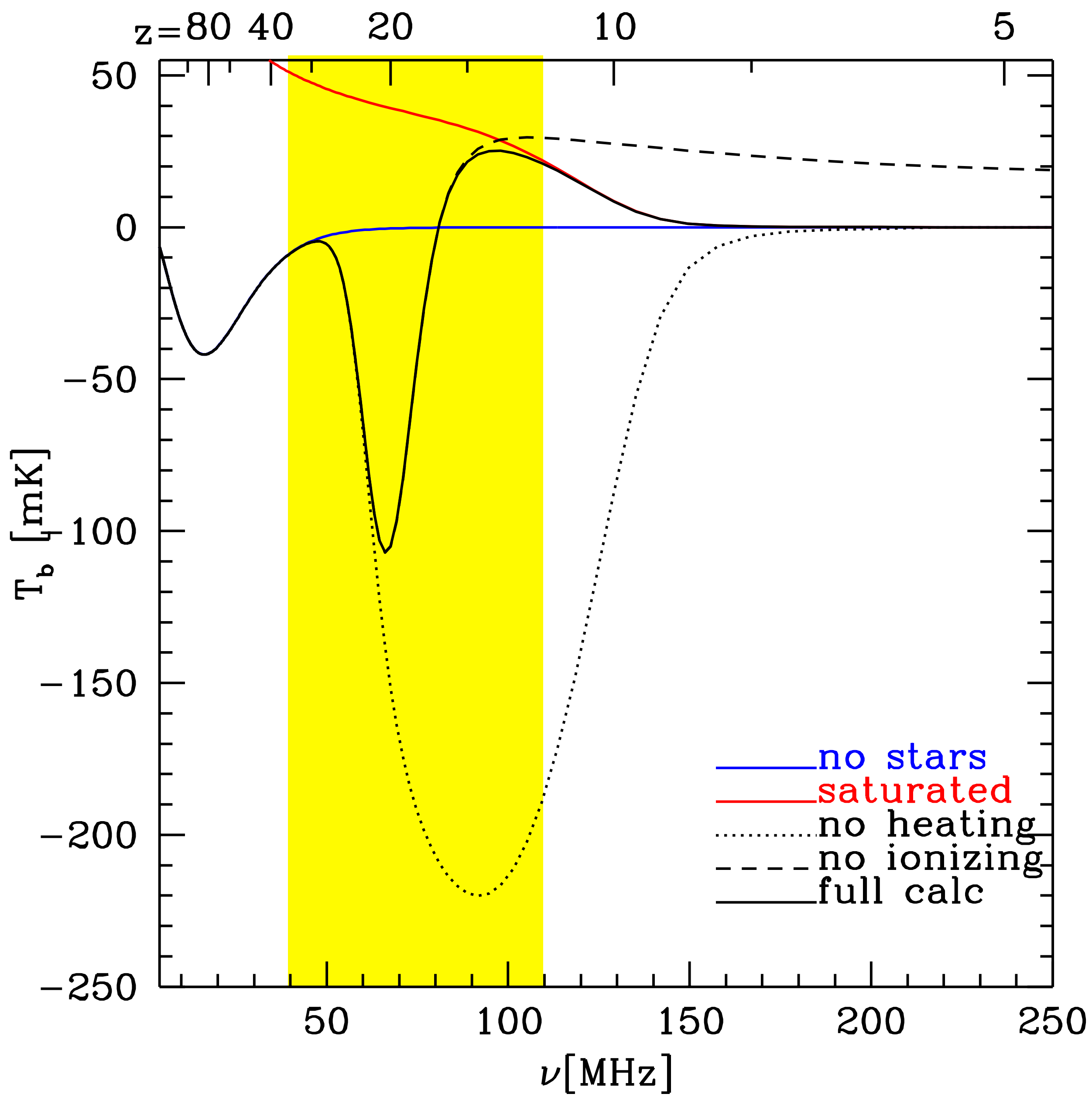
2-sigma detection region



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

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

Spin temperature evolution

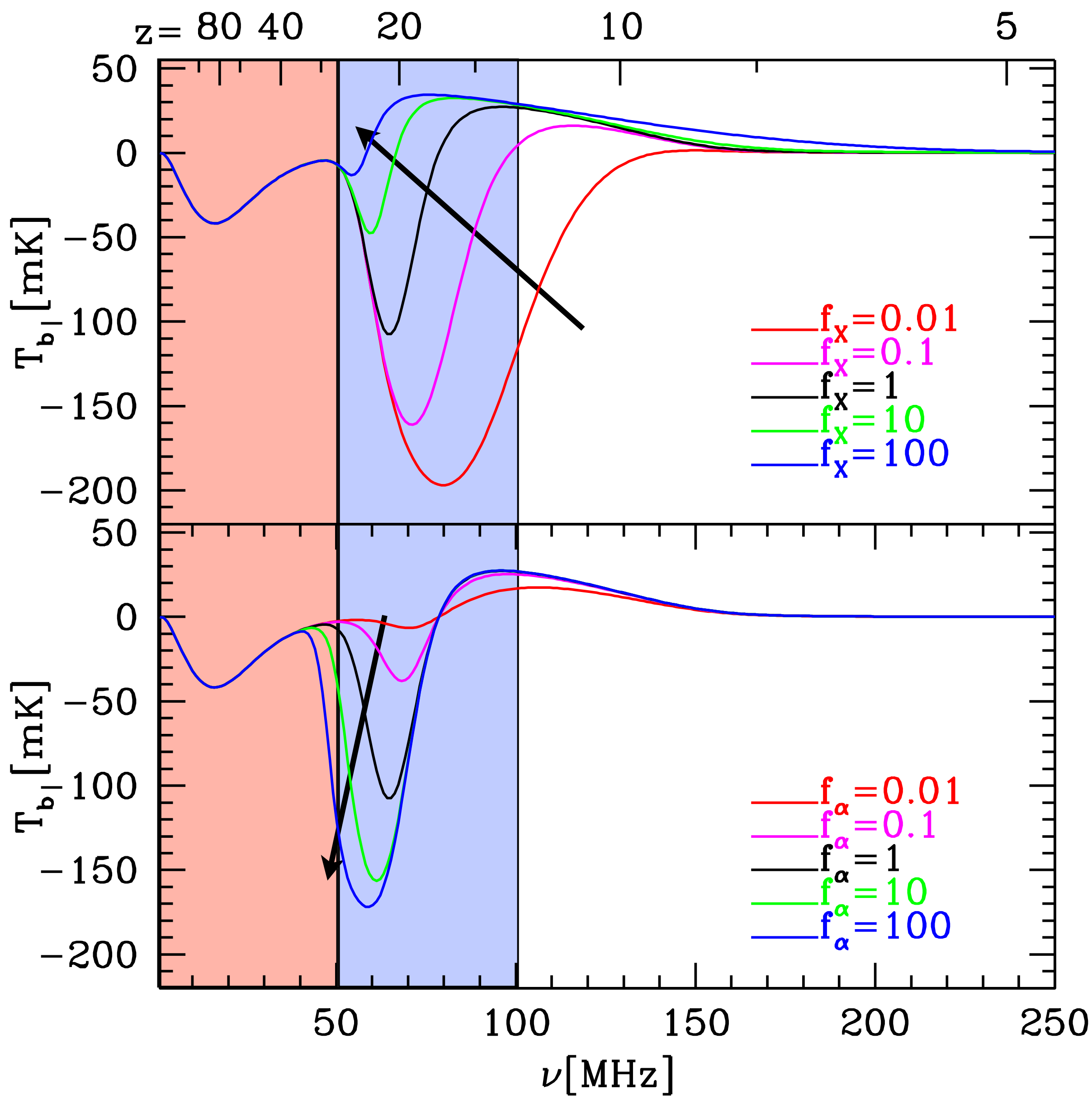


Uncertain high redshift sources

Properties of first galaxies are very uncertain

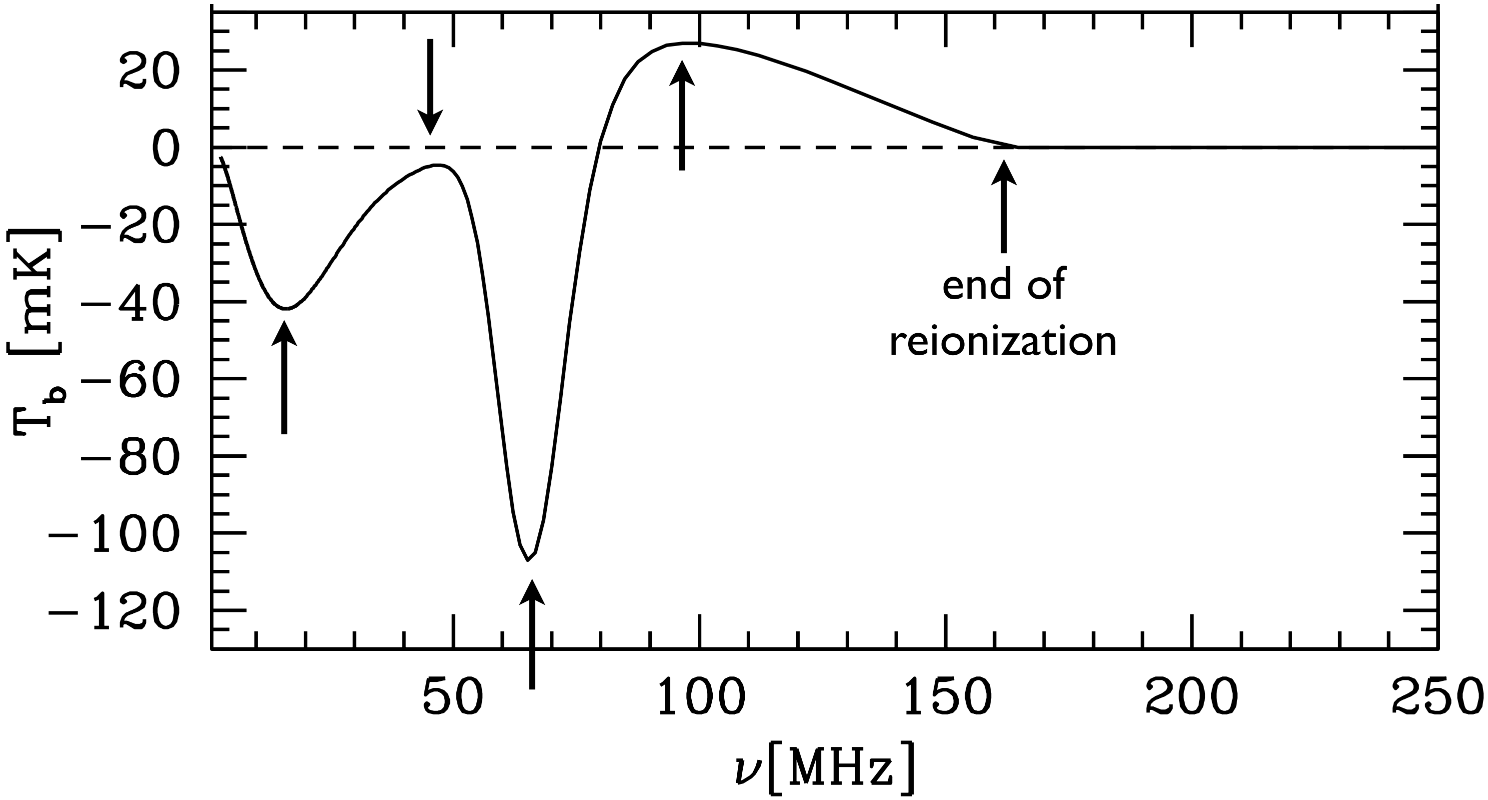
Frequencies below 100 MHz probe period of X-ray heating & Lya coupling

Below ~50 MHz ionosphere and RFI probably a killer

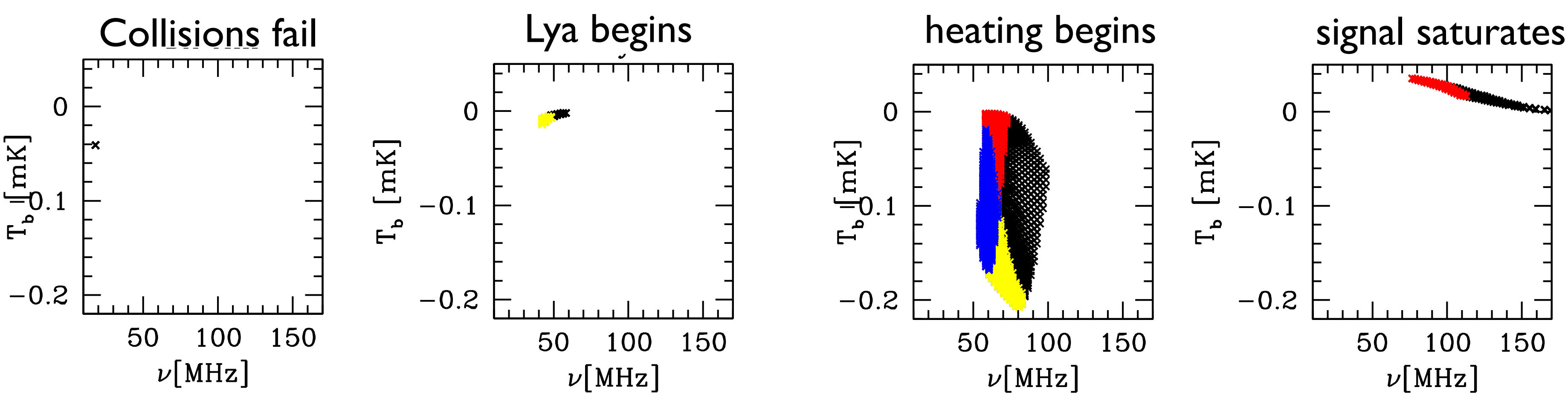


Furlanetto 2006
Pritchard & Loeb 2010

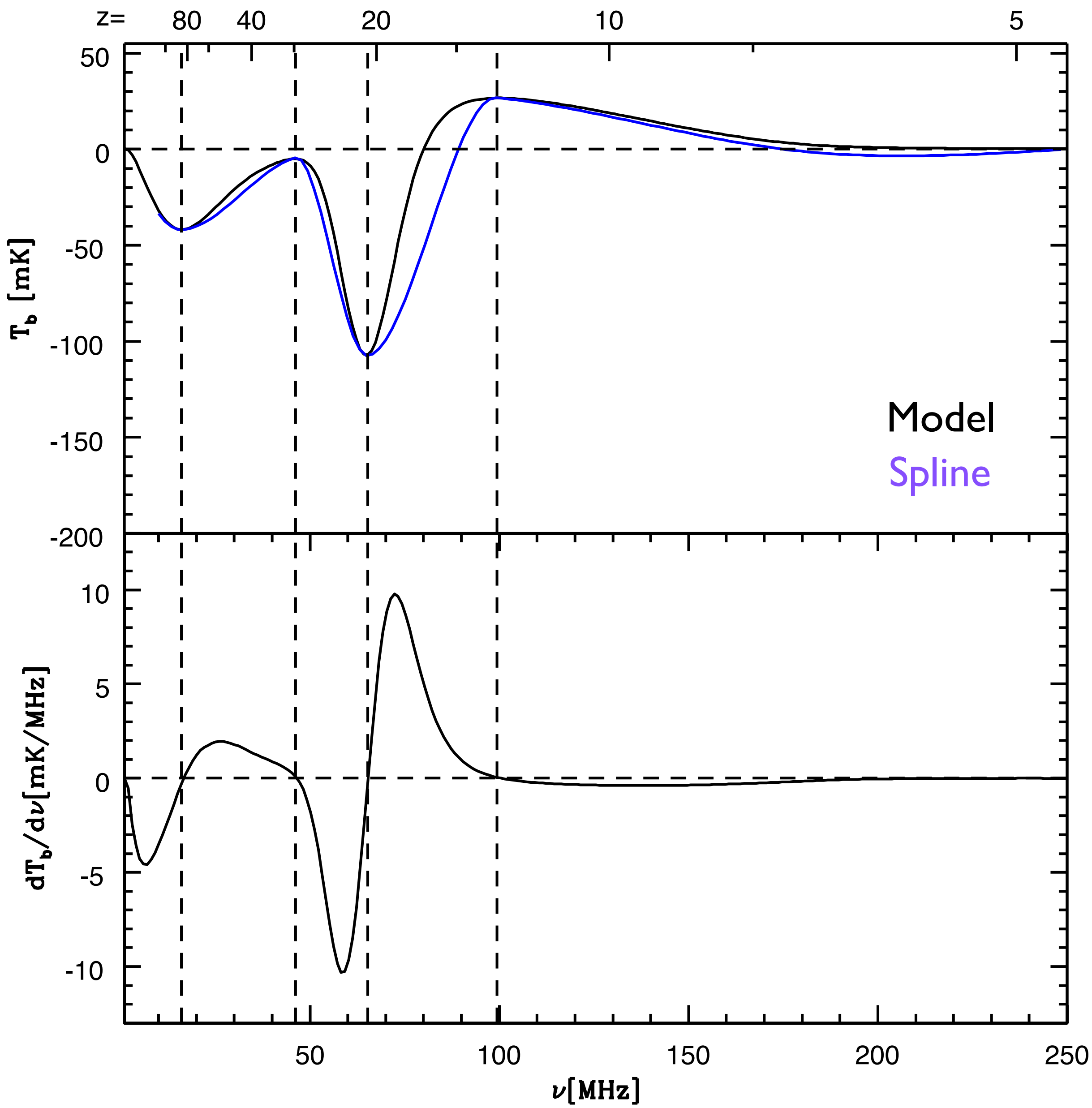
Features in the global signal



five key features



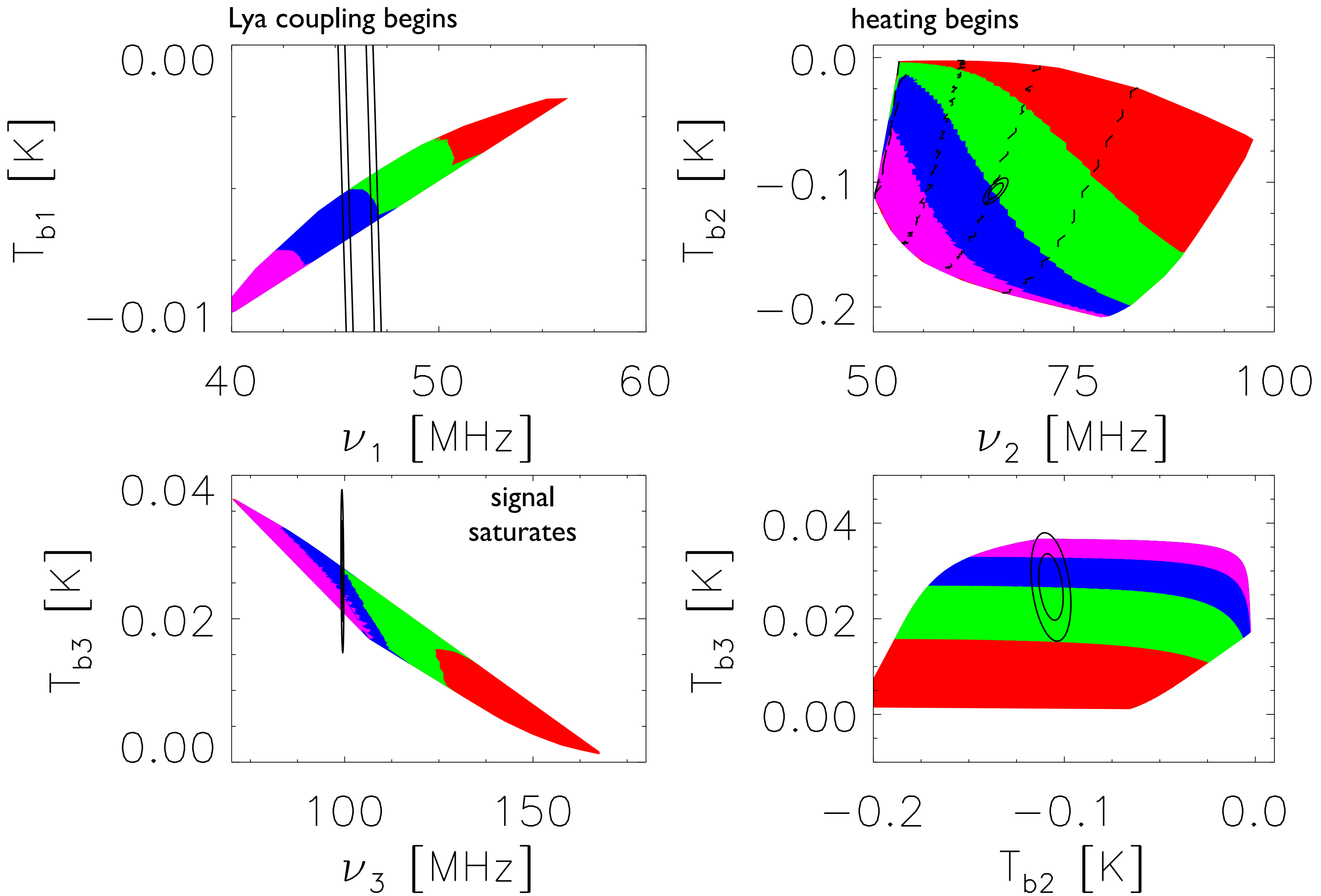
Modeling global signal



Modelling probably only good in broad brush terms

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

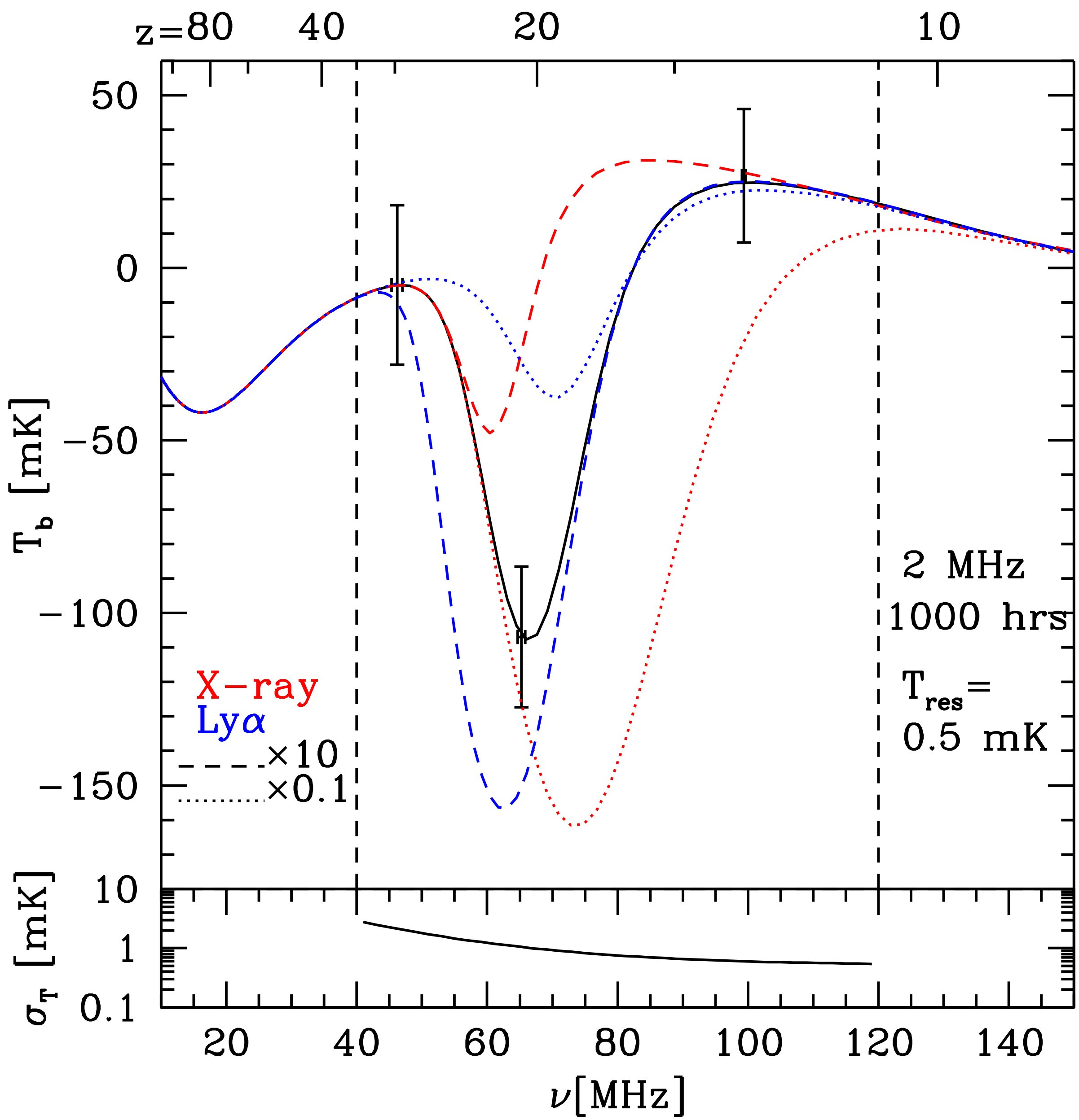
Constraining turning points



Similar sensitivity as for reionization constrains deep absorption feature

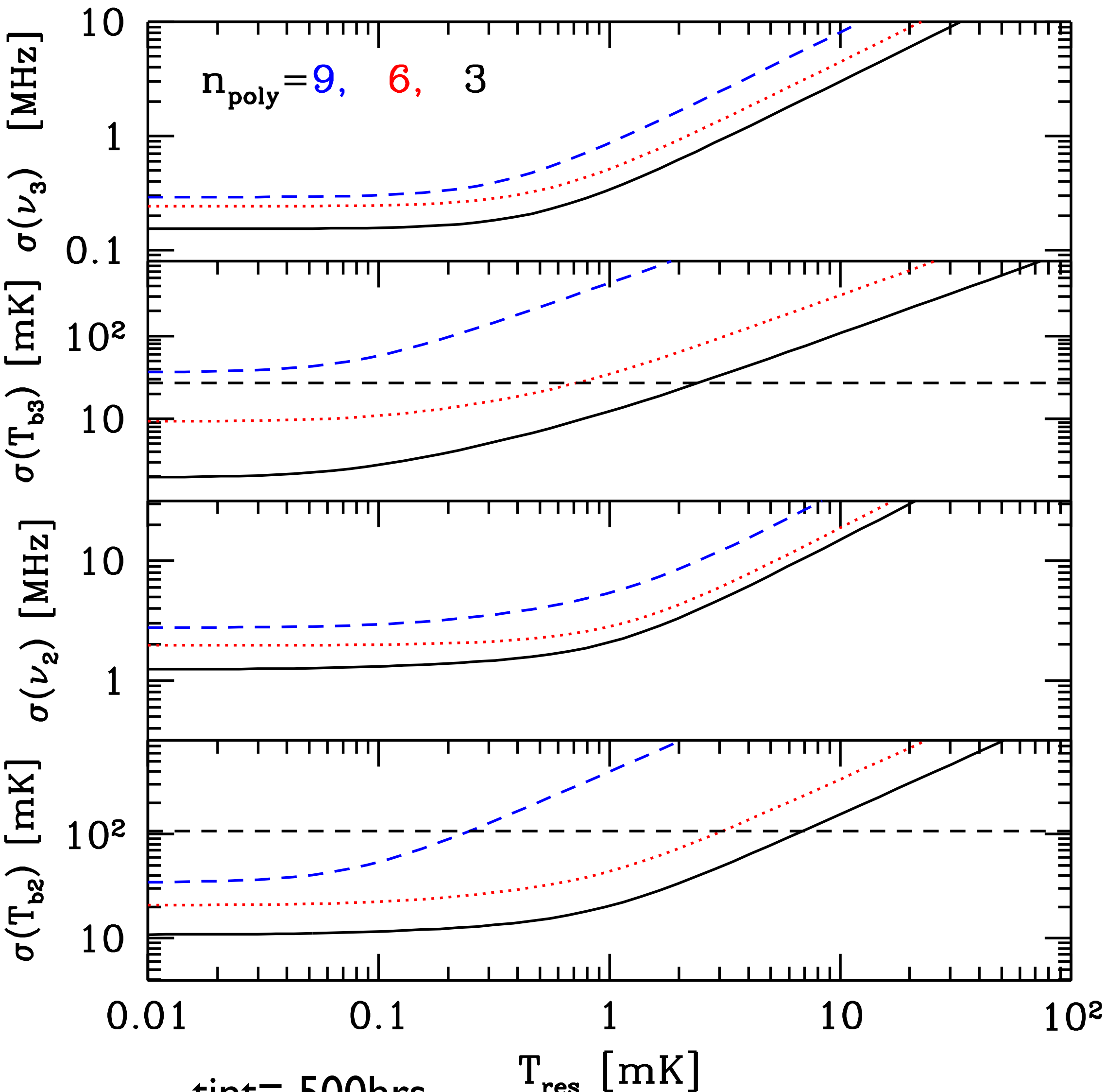
Npoly=3
tint= 500hrs,
50 channels spanning 40-140 MHz

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]

Experimental requirements



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

Need Npoly<9 to even have a chance

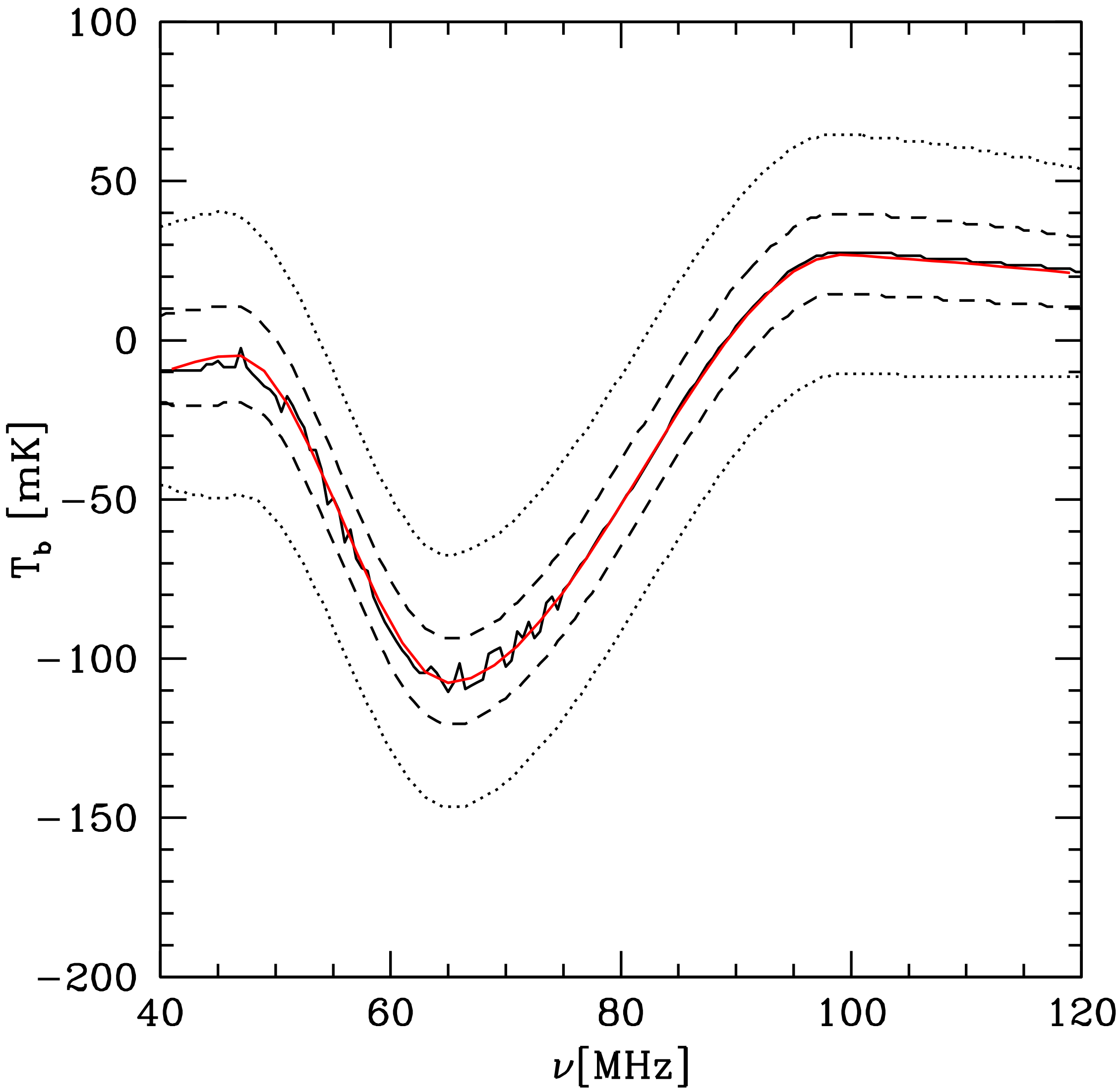
Also need for residuals after fitting to be less than ~mK

Depends upon small scale structure of foregrounds at level currently unknown

Conclusions

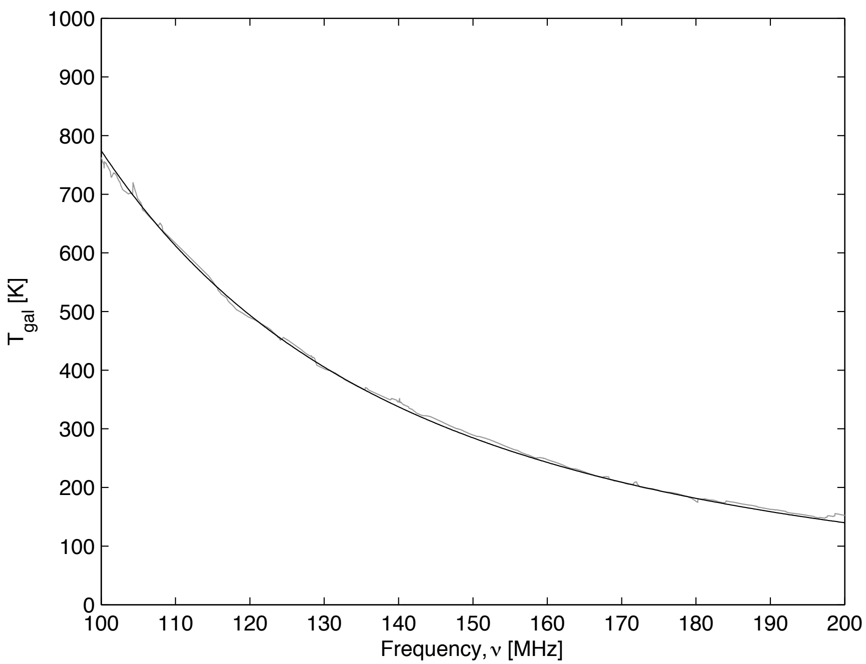
- Global experiments sensitive to sharp reionization histories
- Lower frequencies access onset of X-ray heating
- Performance very sensitive to order of polynomial needed to fit foregrounds and level of residuals
- Position and amplitude of turning points useful parametrization
- Much cheaper than interferometers!
- Key challenges: Calibration and RFI
- Plenty of scope for improved analysis techniques

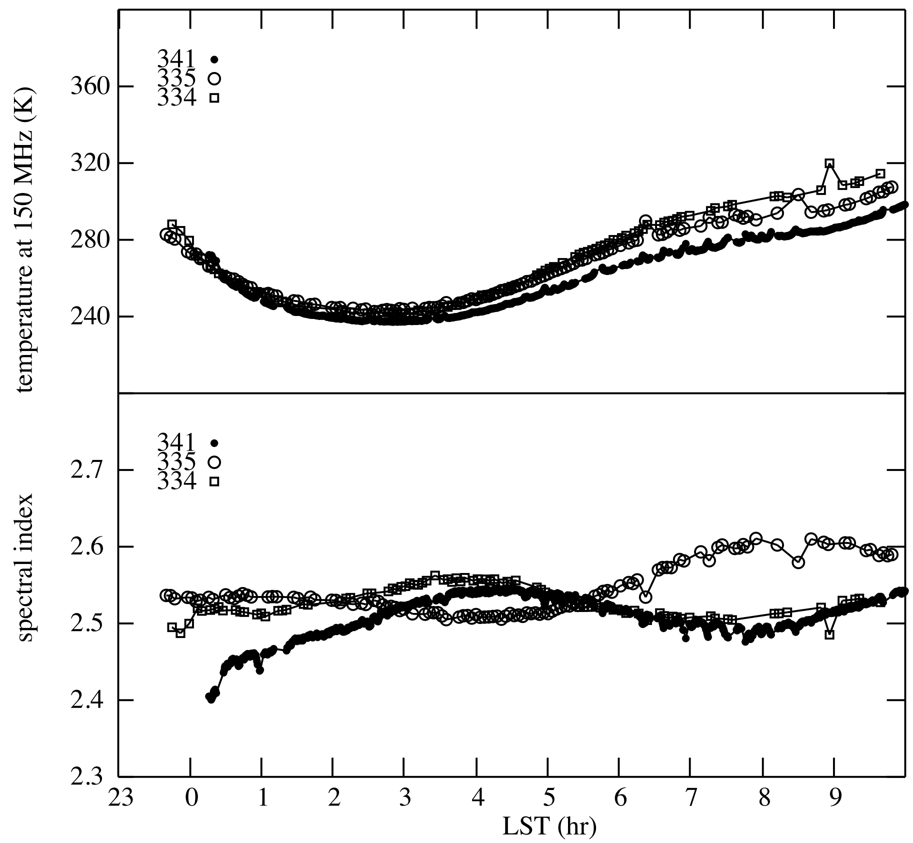
Signal errors



Foreground observations

$$T_{gal}(\nu) = T_{150}\left(\frac{\nu}{\nu_{150}}\right)^{-\beta}$$





Single dipole sky measurements

$$\beta_{100-200} = 2.5 \pm 0.1.$$

Rogers & Bowman 2008