Constraining the unexplored period between the dark ages and reionization with observations of the global 21 cm signal

Jonathan R. Pritchard and Abraham Loeb

Presentation by: Matthew McJunkin

Why Global?

- Simpler, lower cost
  - Single Dipole Experiment
- Higher redshifts
  - JWST, GMT, ELT, TMT may provide glimpses from z~12 to z~20

Absorption Signal

- For IGM gas temperature less than CMB temperature.
- Why do we see an absorption signal?
- How do we cool below CMB temperature?

Redshifted 21 cm

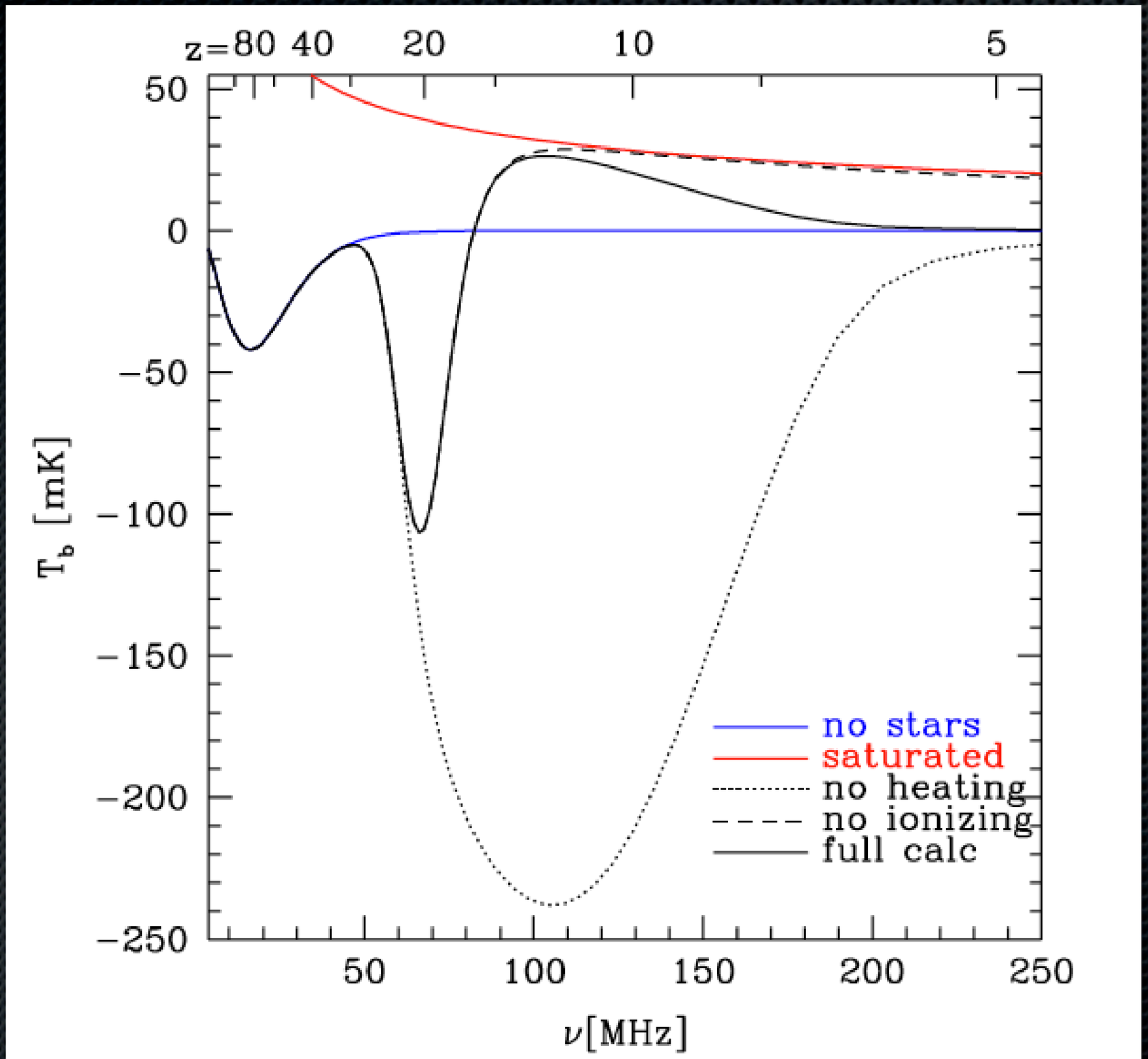
- The 1420 MHz signal is redshifted to a corresponding 50-200 MHz for z = 6-27.

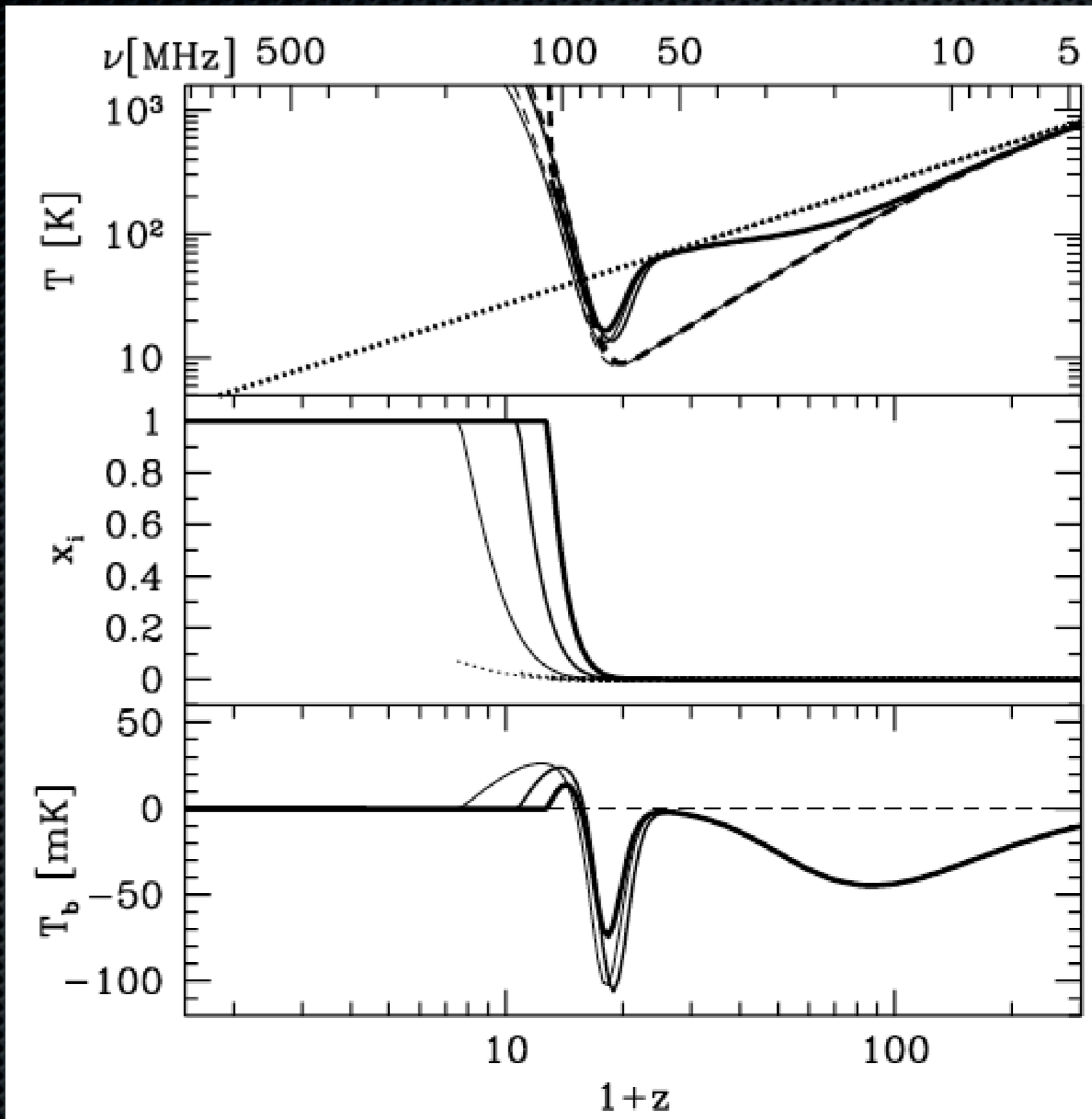
$$T_b \approx 27 x_H \left(\frac{T_s - T_\gamma}{T_s} \right) \left(\frac{1+z}{10} \right)^{1/2}$$

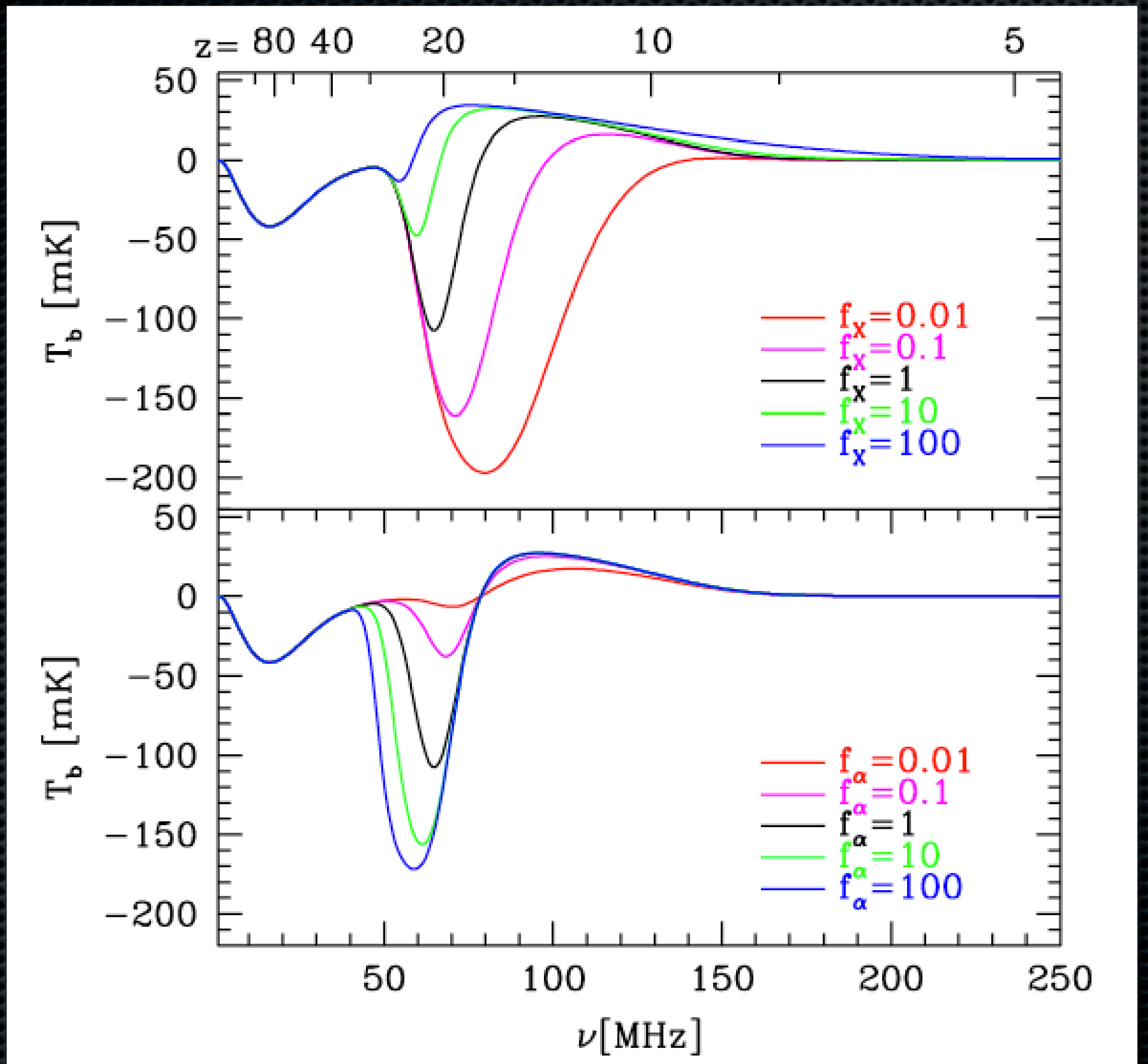
- Why neglect the fluctuation terms?

Five events in 21 cm history

- Collisional coupling becoming ineffective.
- Lyα coupling becoming effective.
- Heating occurring
- Reionization beginning
- Reionization ending


z=80 40 20 10 5
50
0
−50
−100
−150
−200
−250
T_b [mK]
50 100 150 200 250
ν[MHz]
no stars
saturated
no heating
no ionizing
full calc

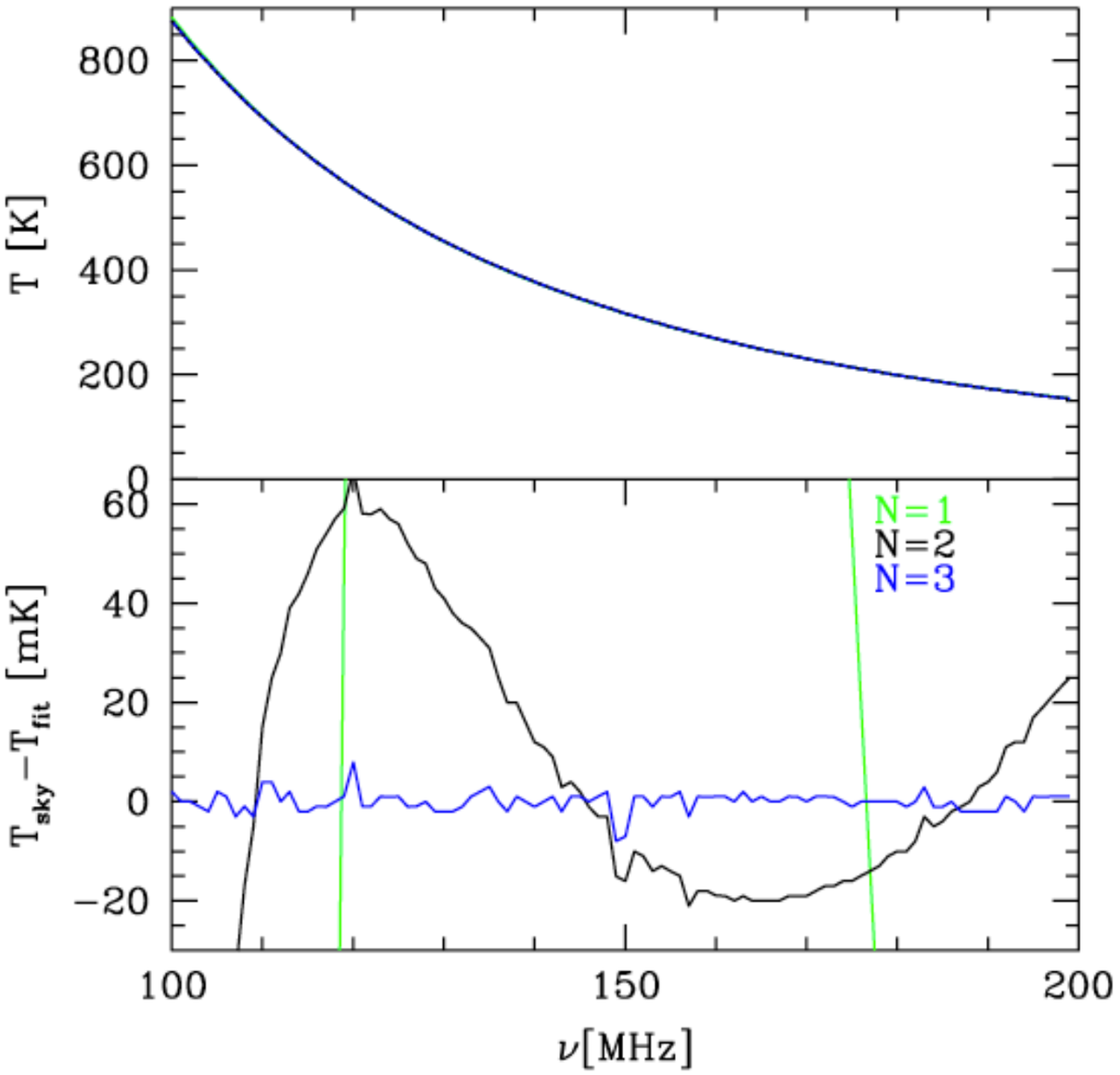

ν[MHz]
500
100
50
10
5
10³
10²
10
T [K]
1
0.8
0.6
0.4
0.2
0
x_i
50
0
−50
−100
T_b [mK]
10
100
1+z

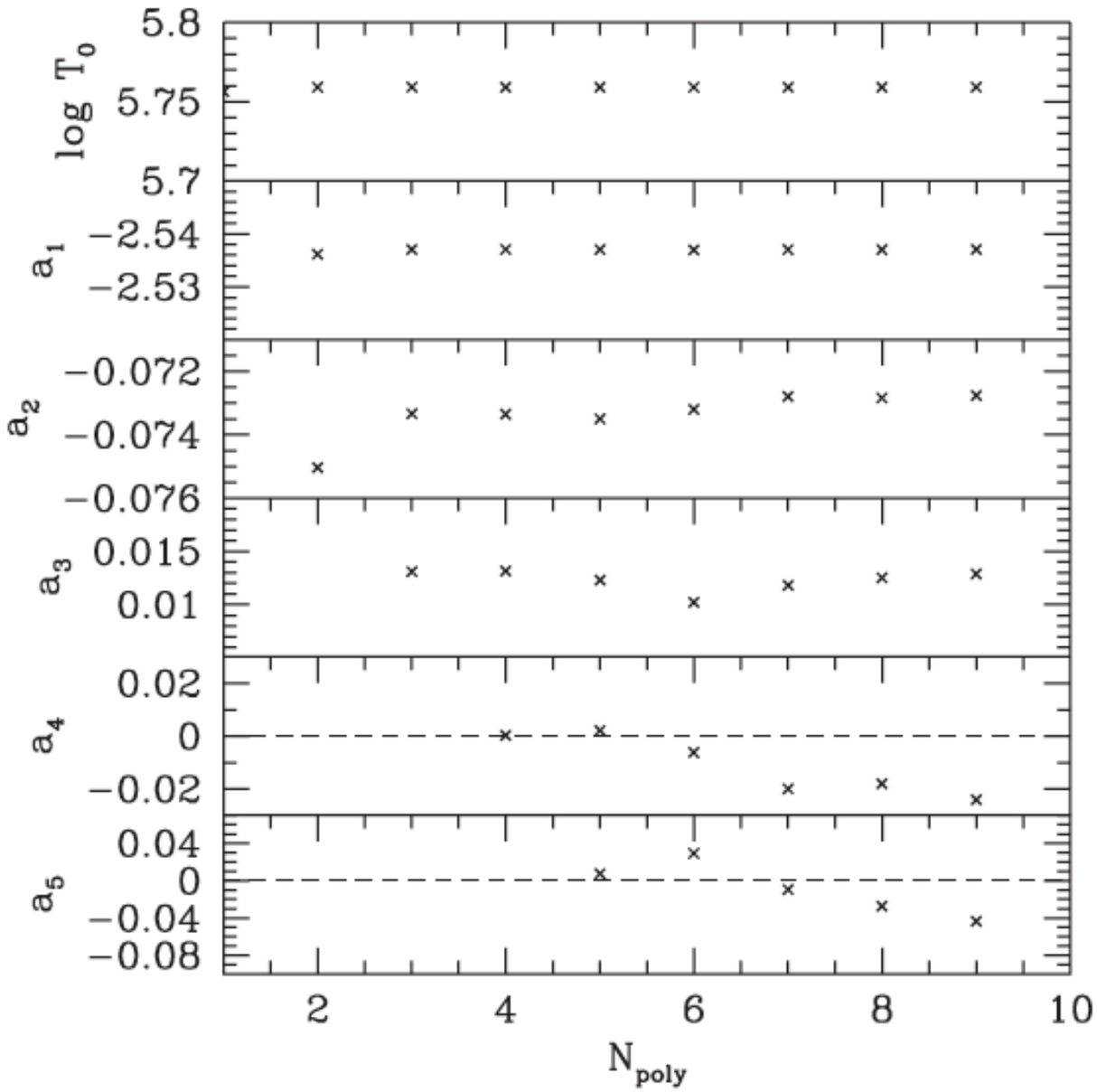

z= 80 40 20 10 5
50
0
−50
−100
−150
−200
T_b [mK]
f_x=0.01
f_x=0.1
f_x=1
f_x=10
f_x=100
50
0
−50
−100
−150
−200
T_b [mK]
f_α=0.01
f_α=0.1
f_α=1
f_α=10
f_α=100
50
100
150
200
250
ν[MHz]

Foregrounds

- In tomography, inhomogeneities fluctuate rapidly.
  - Only the largest modes of signal are in danger of being removed.
- In global signal, the smoothness of the signal makes it a concern when throwing out the foreground.

Foregrounds





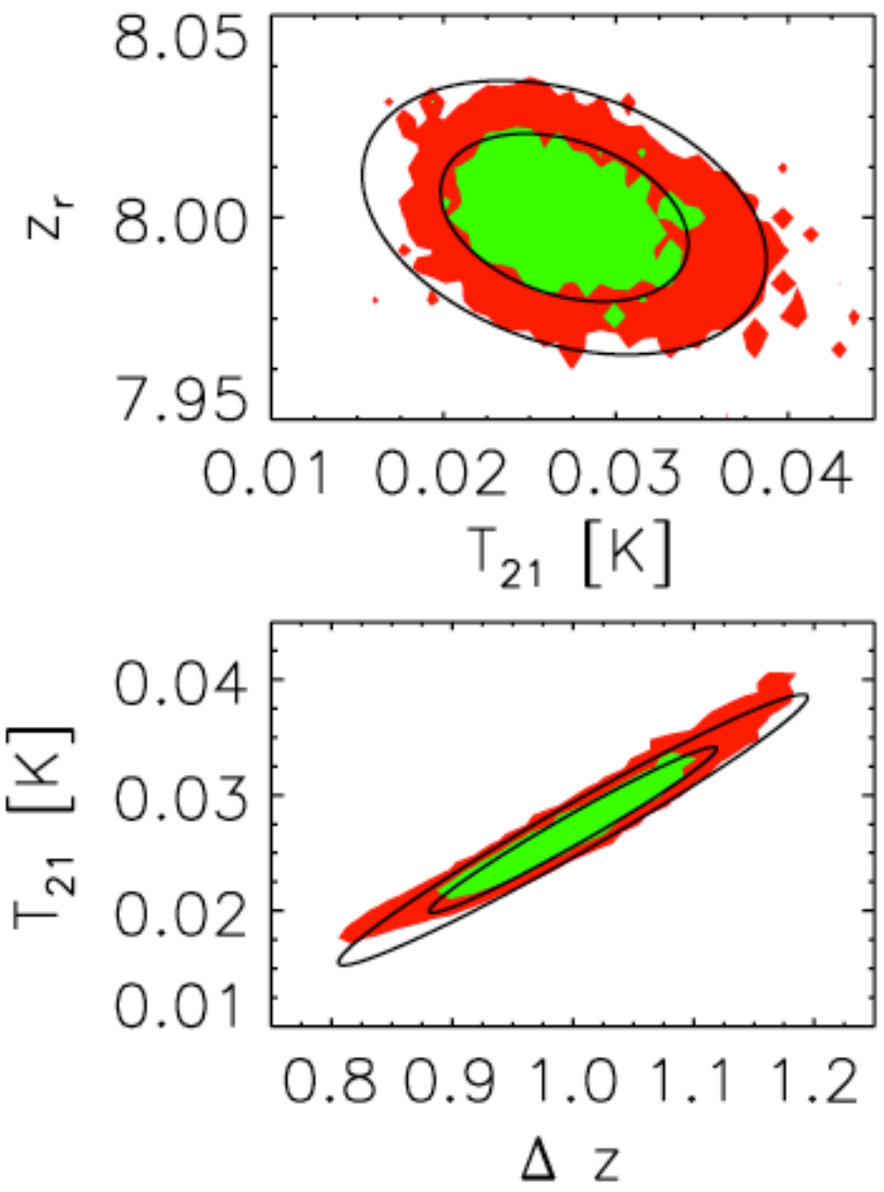
Fisher Matrix

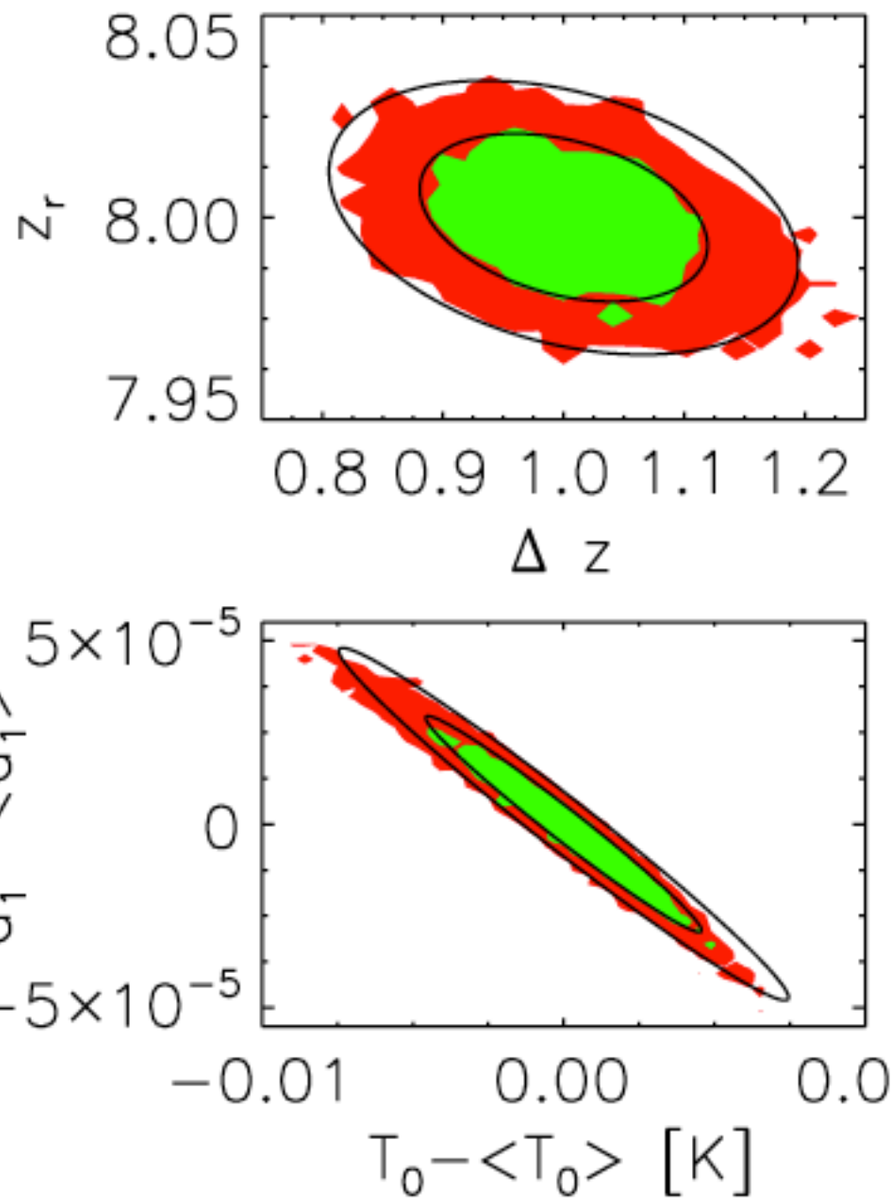
- Hard to quantify the ability of 21 cm measurements to constrain astrophysical parameters with Monte Carlo.
  - Large space of model parameters
  - Can use Fisher matrices if the likelihood is ~ Gaussian

$$F_{ij} = \frac{1}{2}\mathrm{Tr}\left[C^{-1}C_{,i}C^{-1}C_{,j} + C^{-1}\left(\mu_{,i}\mu_{,j}^{T} + \mu_{,j}\mu_{,\mathrm{i}}^{T}\right)\right]$$

Fisher Matrix

- Covariance matrix is taken to be diagonal. Why?
- Best parameter constraints are given by the Cramer-Rao inequality. Which is?


8.05
8.00
7.95
z_r
0.01 0.02 0.03 0.04
T_{21} [K]


8.05
8.00
7.95
z_r
0.8 0.9 1.0 1.1 1.2
Δ z

0.04
0.03
0.02
0.01
T_{21} [K]
0.8 0.9 1.0 1.1 1.2
Δ z

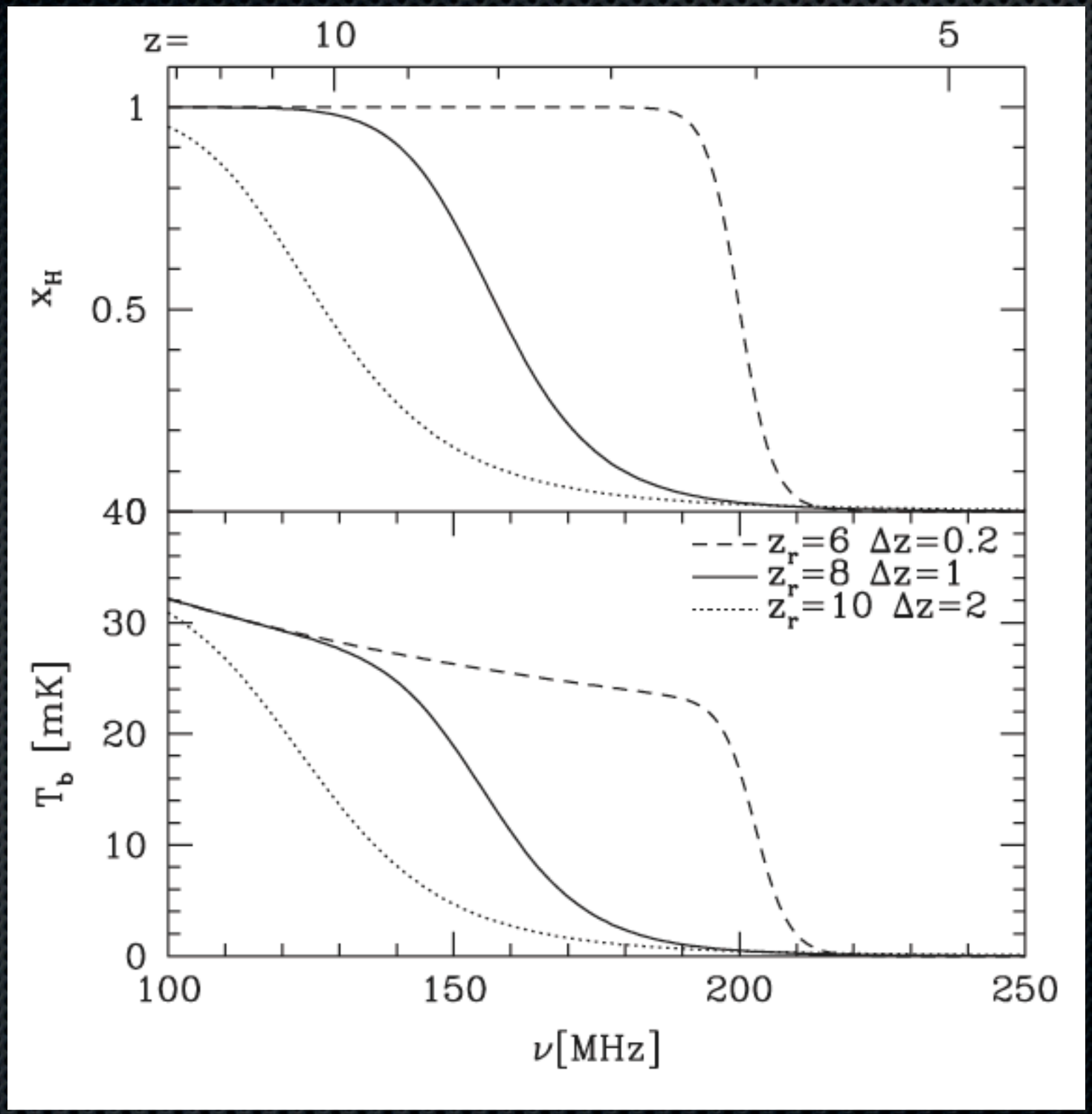
5×10^{-5}
0
-5×10^{-5}
$a_1-\langle a_1\rangle$
−0.01 0.00 0.01
$T_0-\langle T_0\rangle$ [K]

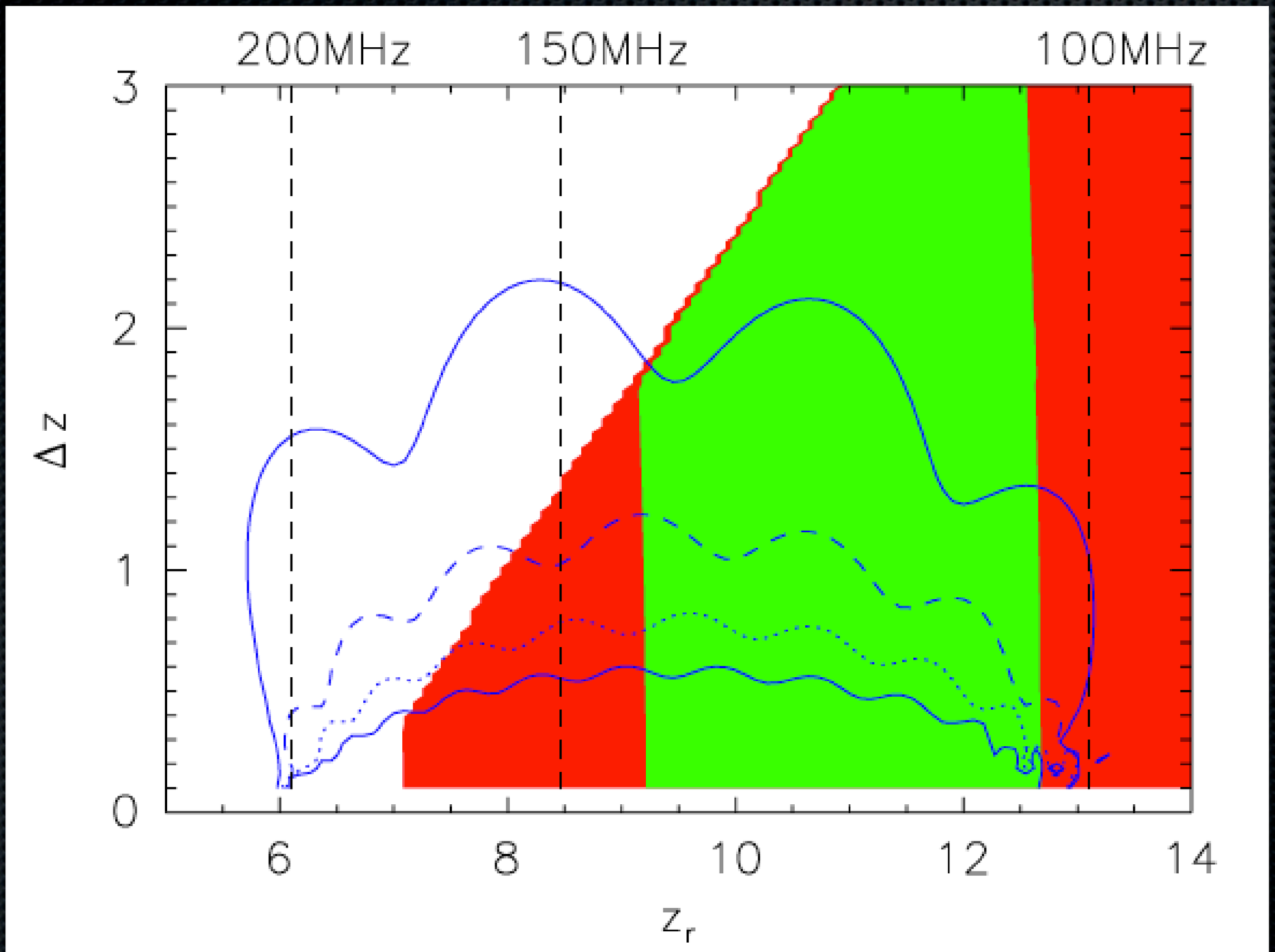
Reionization

- Want to constrain the evolution of x_H
- Have constraints from Ly**α** forest and CMB optical depth. How?
- Reionization is expected to be relatively extended
- Toy model: tanh with midpoint z_r and duration **Δ**z.
- Assume: 21 cm spin temperature is saturated. Valid?

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

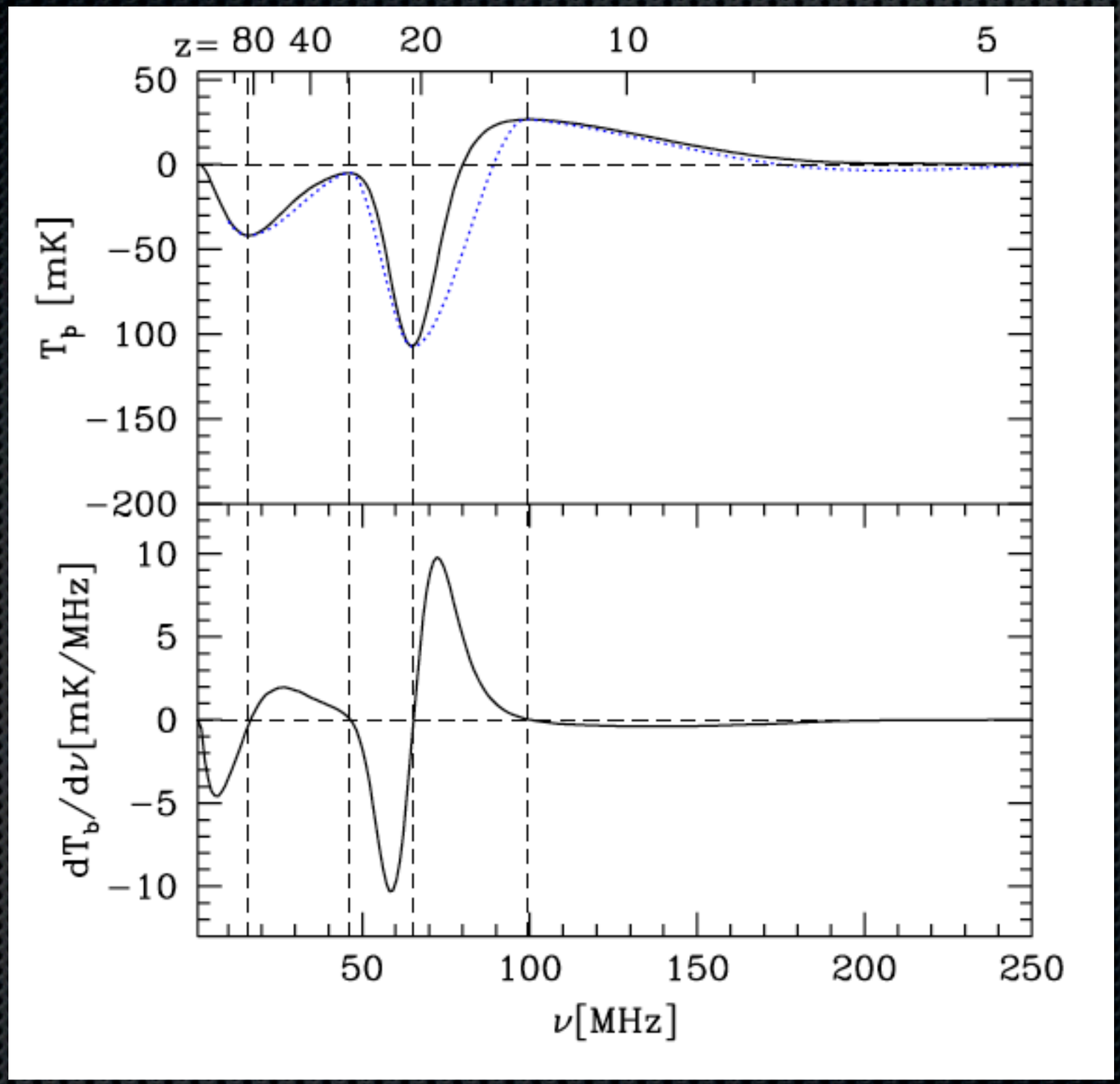
Tanh reionization models




200MHz
150MHz
100MHz
3
2
1
0
Δz
6
8
10
12
14
z_r

First Sources

- This region in z-space is unconstrained by existing observations.
- Parametrize by the turning points in the evolution
  - Minimum from ineffective collisional coupling
  - Maximum from Lyα pumping
  - Minimum as heating becomes important
  - Maximum from saturation


z= 80 40 20 10 5
50
0
−50
−100
−150
−200
T_b [mK]
10
5
0
−5
−10
$dT_b/d\nu$[mK/MHz]
50 100 150 200 250
ν[MHz]

First Sources

- Only the turning point corresponding to the heating has a large area in T_b-ν space.
- Other turning points are constrained by cosmology choice, and emissivities.
- This makes observations constraining this point extremely helpful to constrain different models and parameter spaces.

Dark Ages

- At these low frequencies, global measurements are more feasible than tomographic measurements.
- Easier to launch a single dipole experiment than the large area of interferometers.
- Would still need ~1000 hrs of integration time to get 4 mK sensitivity with one dipole

Conclusions

- Global measurements are cheaper and simpler than tomographic measurements.
- 21 cm signal is a sensitive thermometer.
- Galactic foreground fitting takes at least 3rd order poly.
- Fisher matrix formalism works very well.
- Deepest absorption trough provides best observational target.
- Detecting absorption in dark ages requires long integration times.