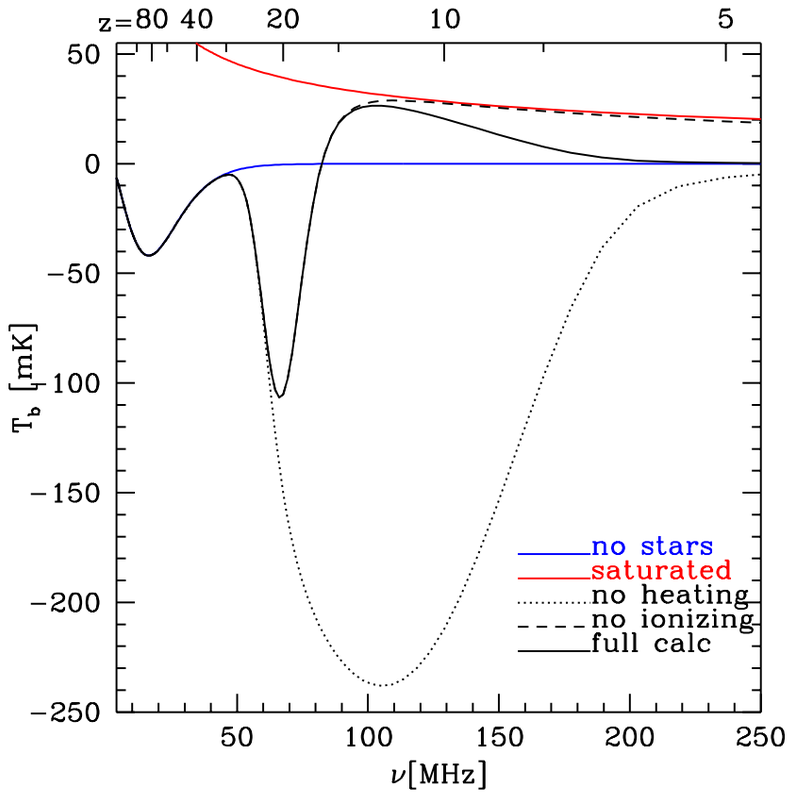
In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

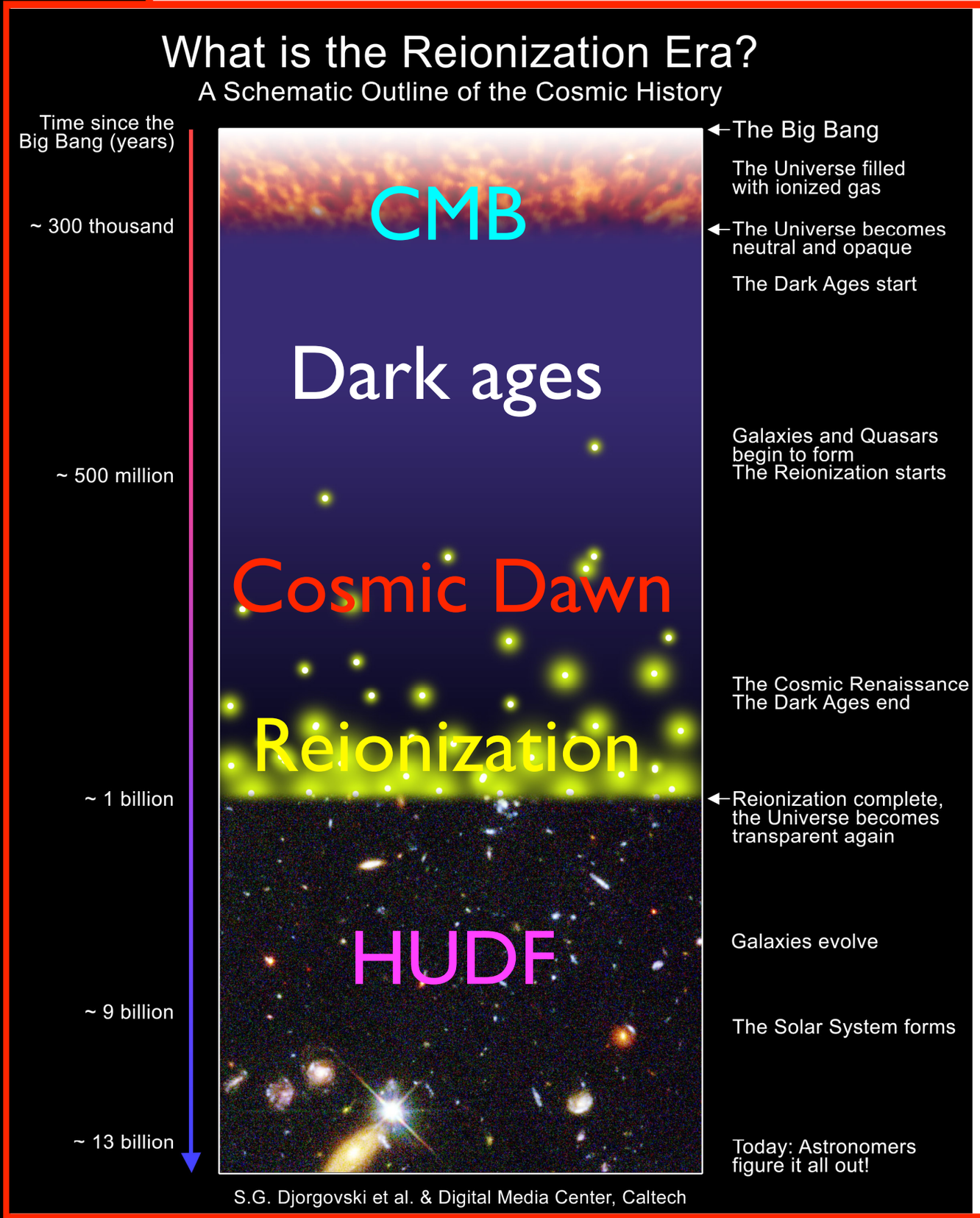
The Global 21 cm Signal

Jonathan Pritchard
Hubble-ITC Fellow
CfA

Robotic science from the moon



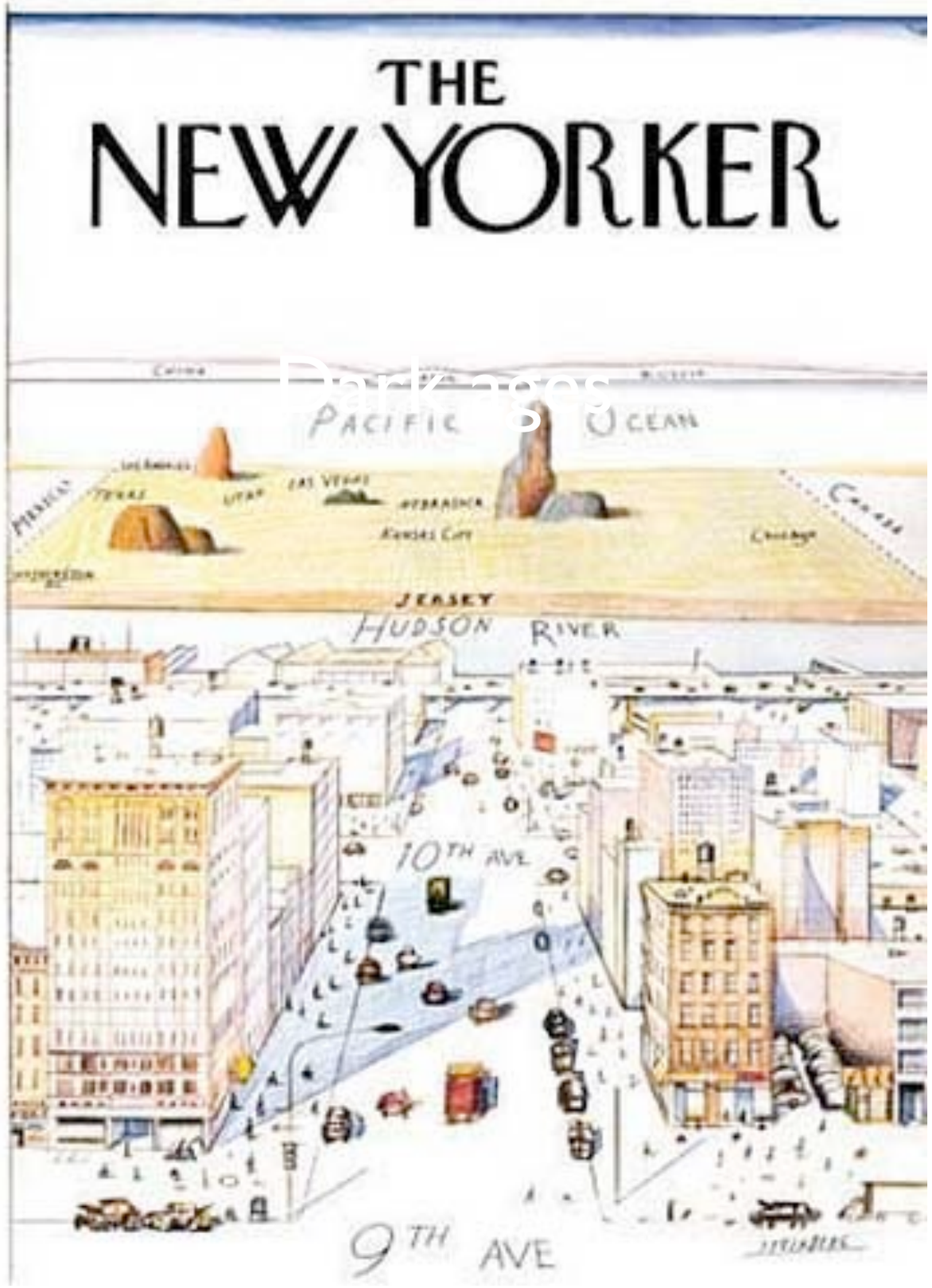
The first billion years



Reionization marks the limits of current observations

- 21 cm basics
- Reionization
- First galaxies

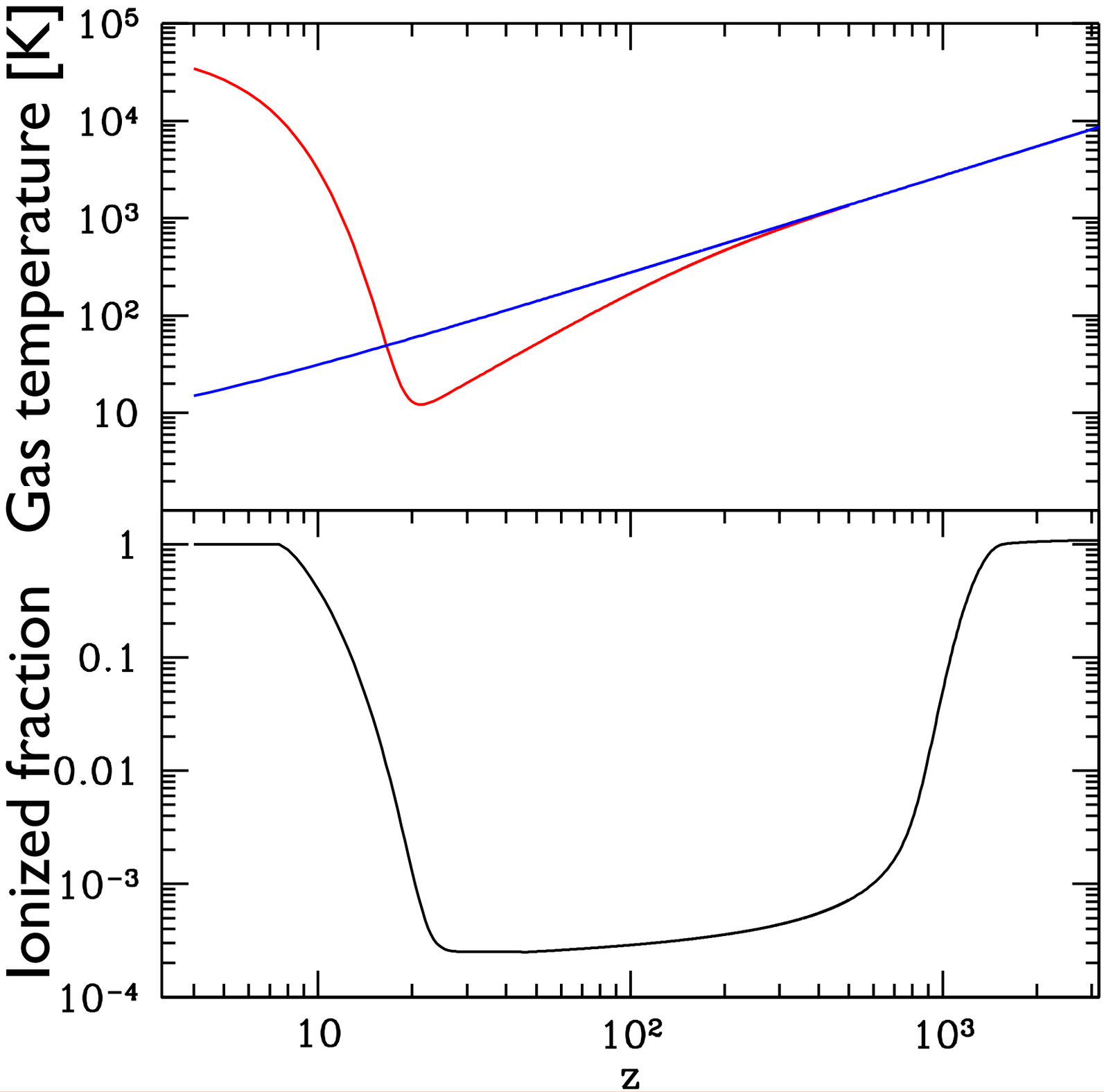
The first billion years



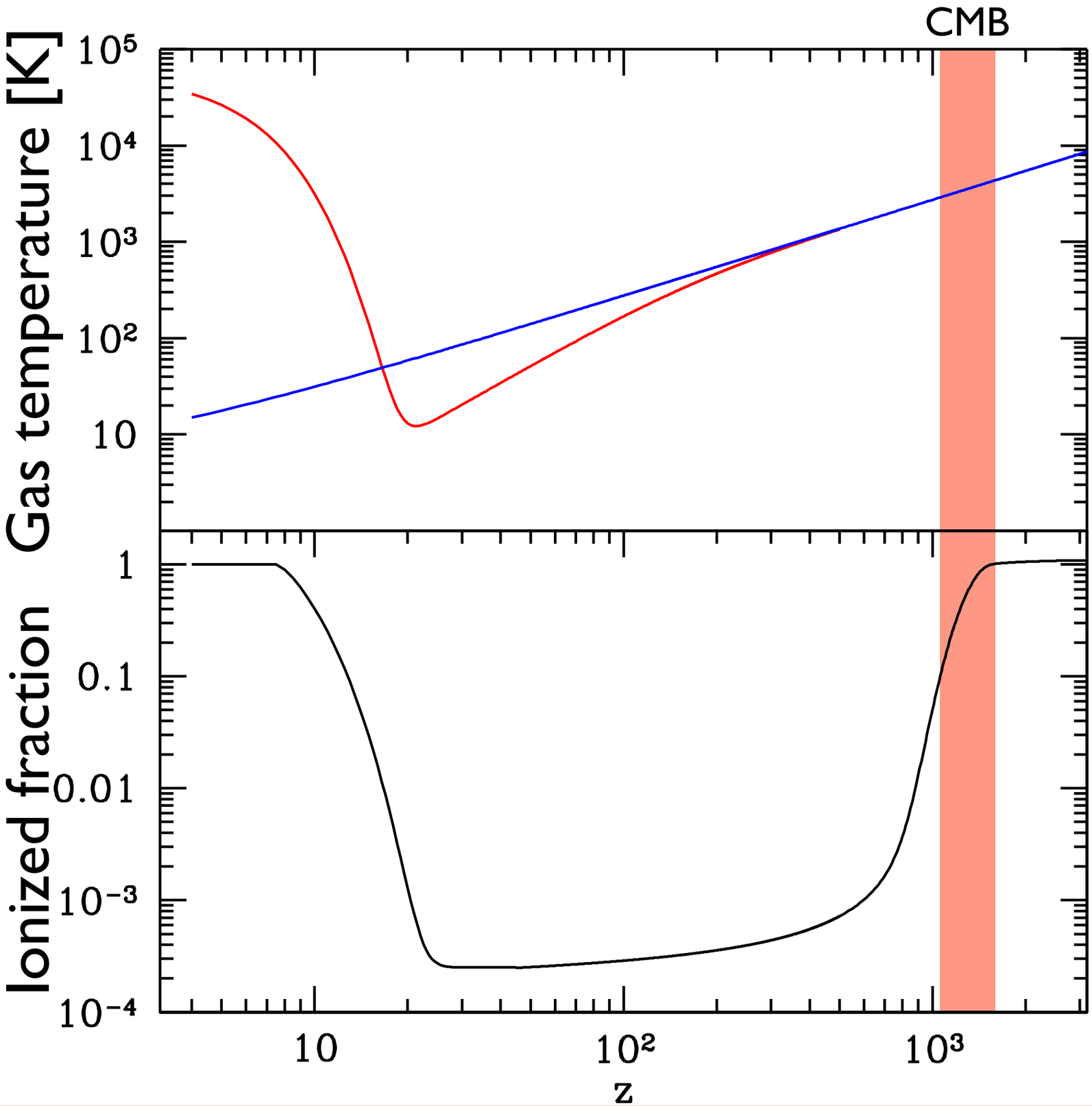
Things far off look simple!

- 21 cm basics
- Reionization
- First galaxies

Known unknowns



Known unknowns



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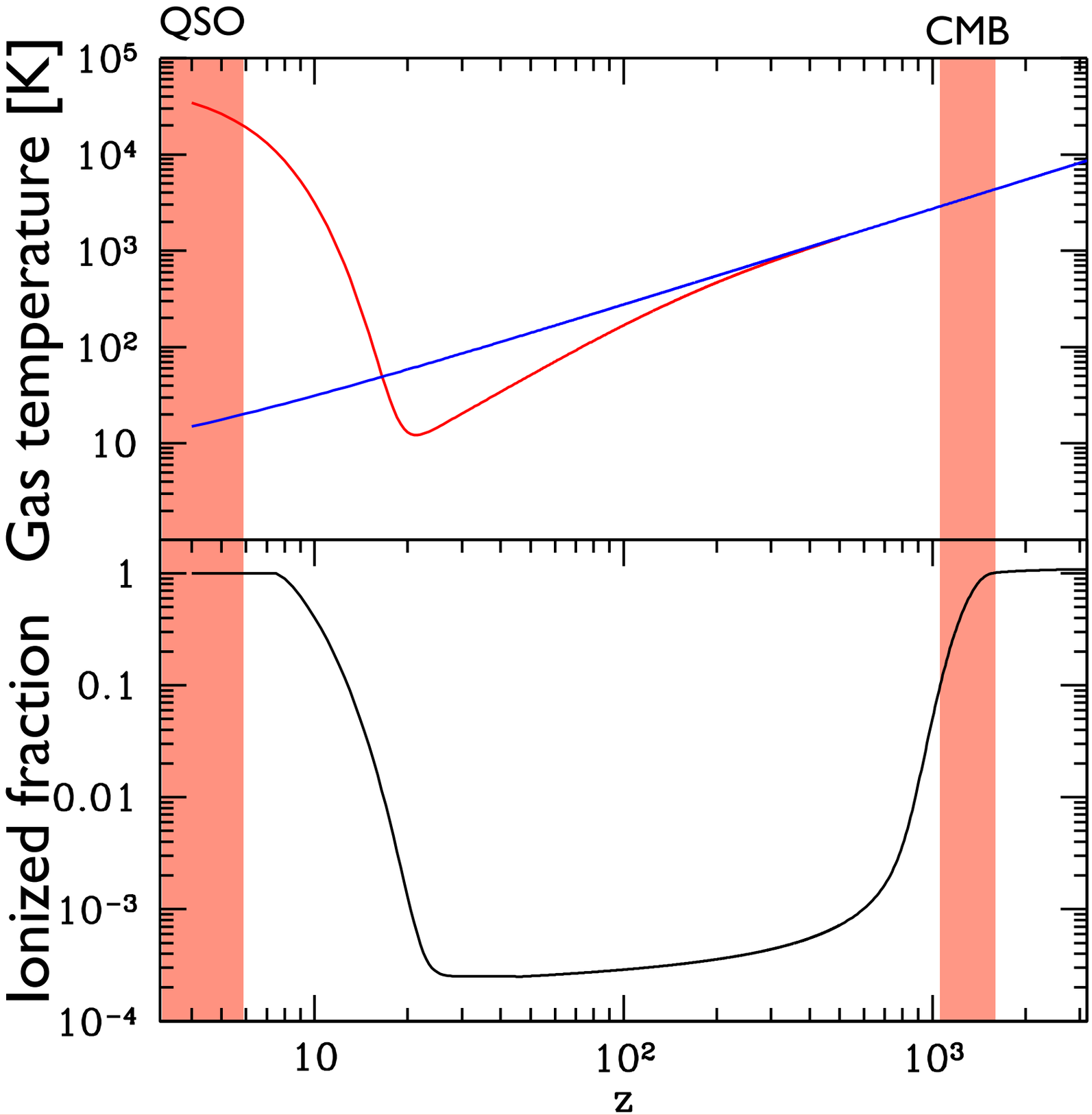

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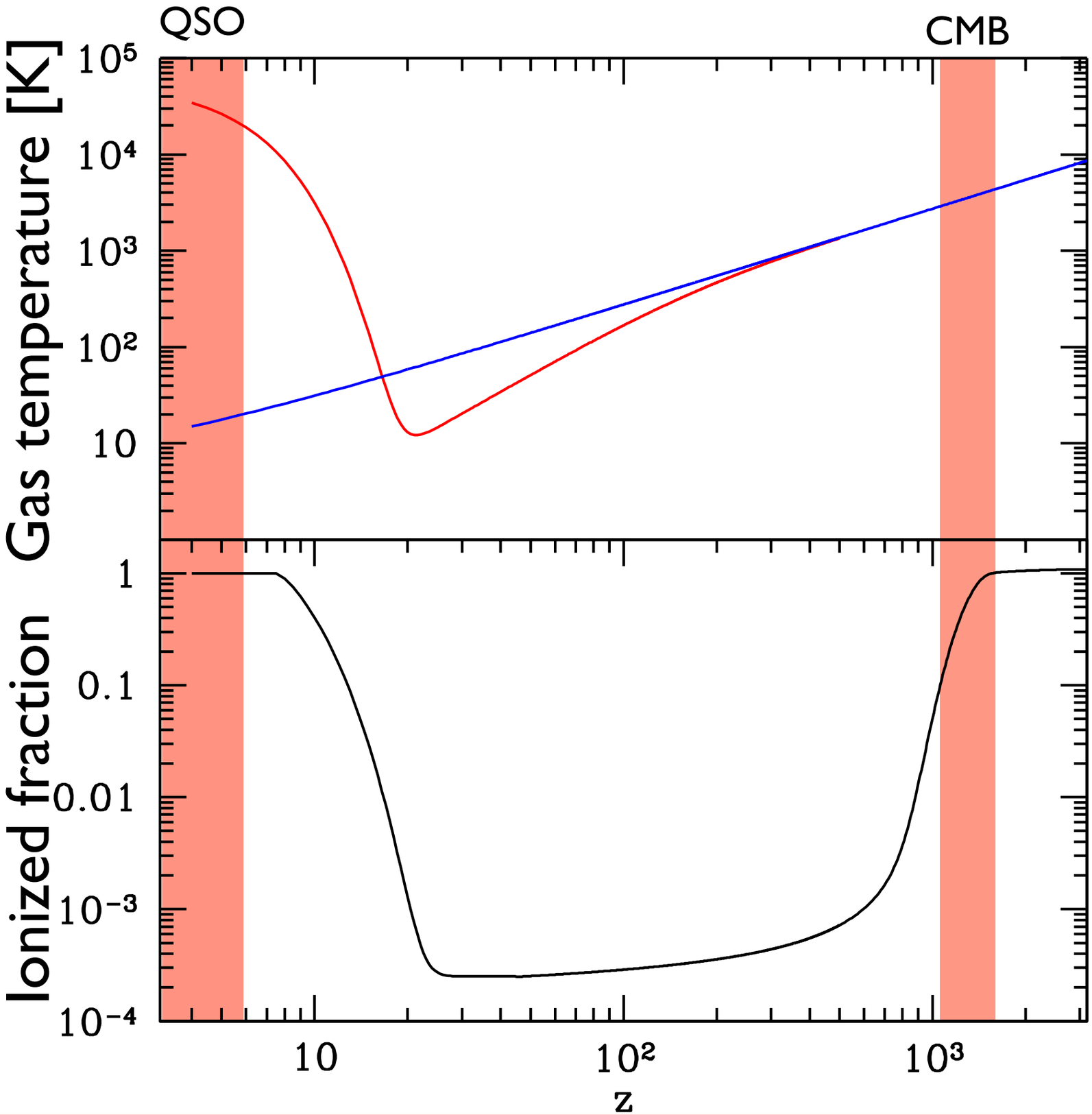
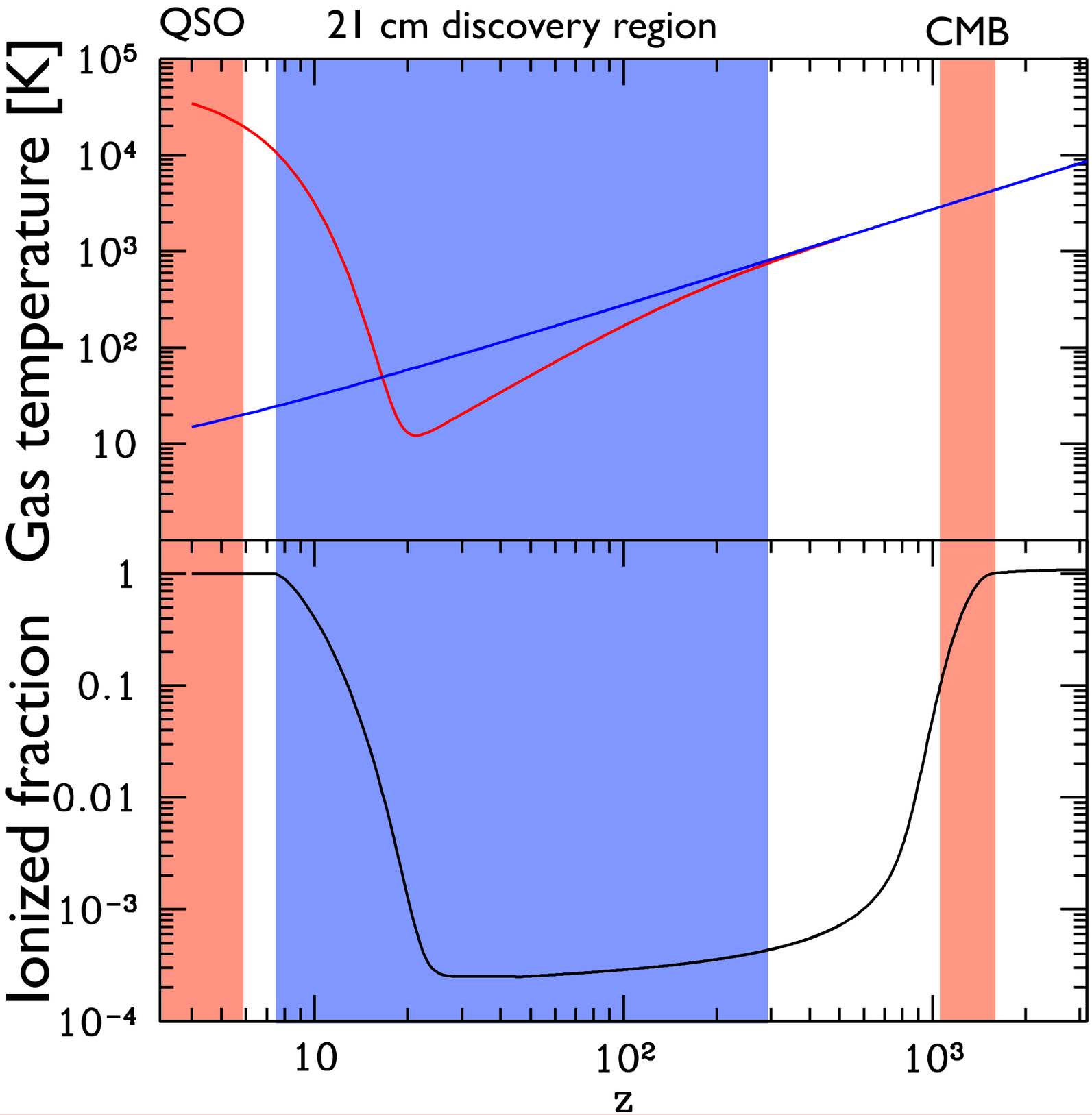


We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

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

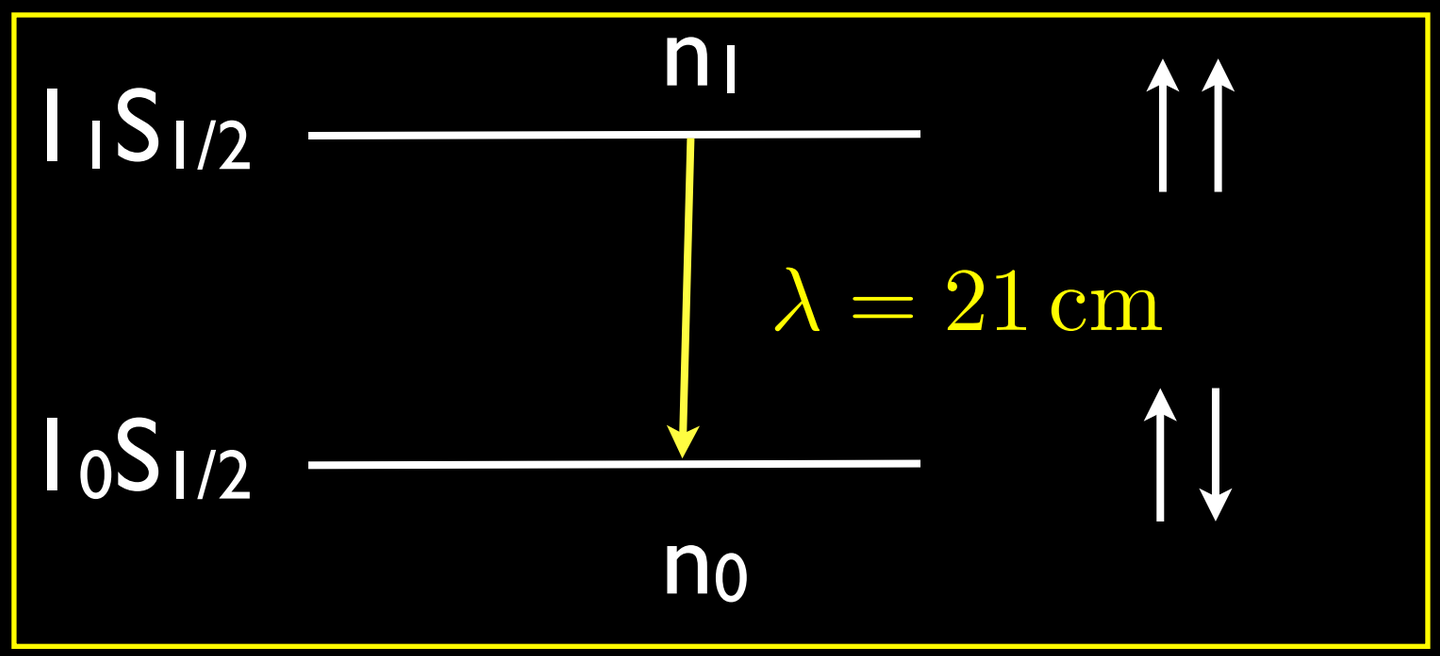
We know little or nothing about galaxies at z>10

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



Useful numbers:

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

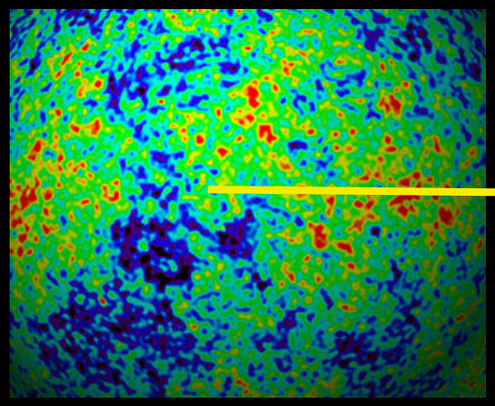
$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$
$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$
$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$

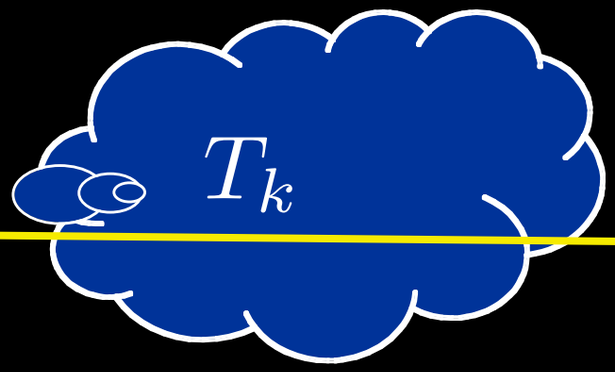
Spin temperature describes relative occupation of levels

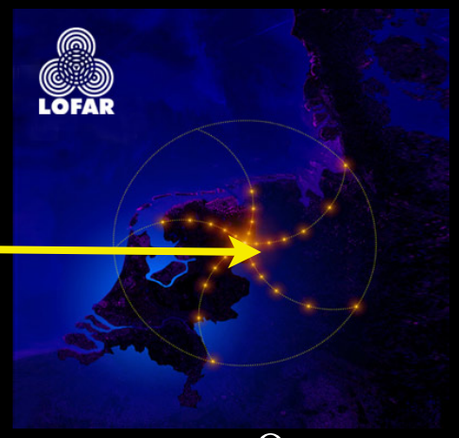
$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

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

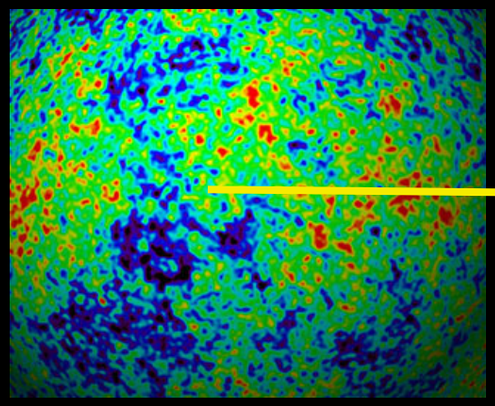
$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\,\mathrm{mK}$$

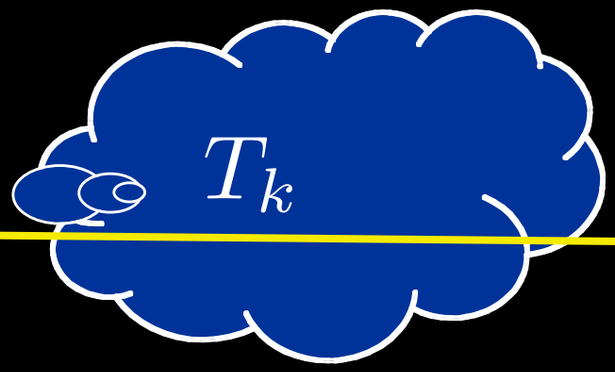
spin temperature set by different mechanisms:

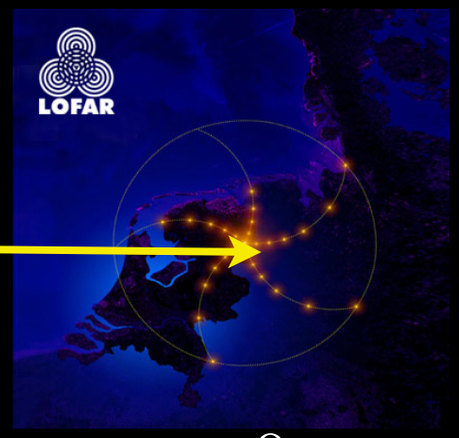
Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

21 cm line in cosmology

T_γ T_S T_b







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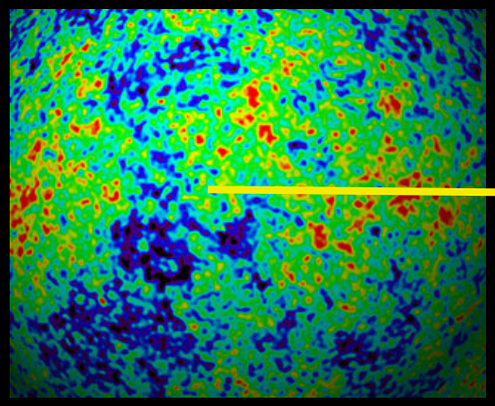

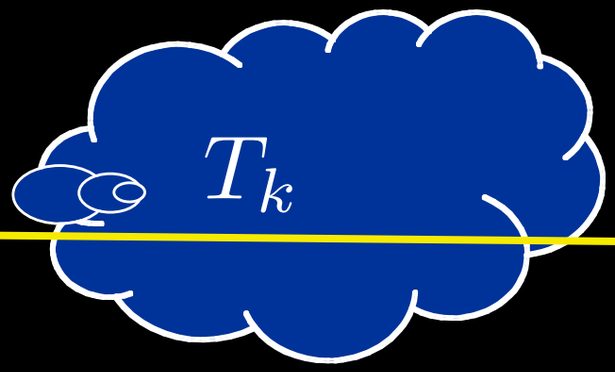

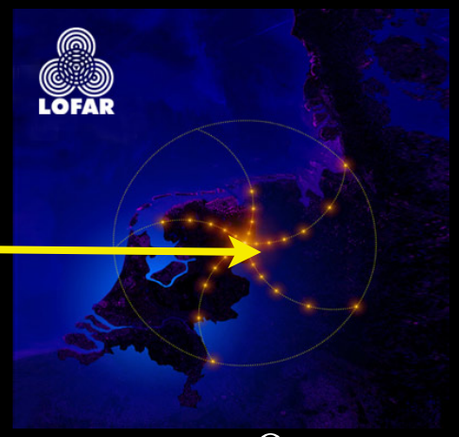

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baryon density

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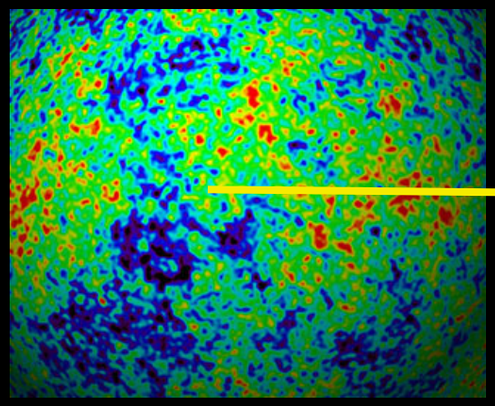

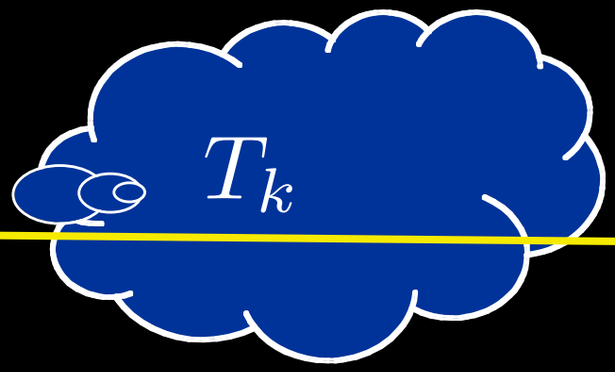

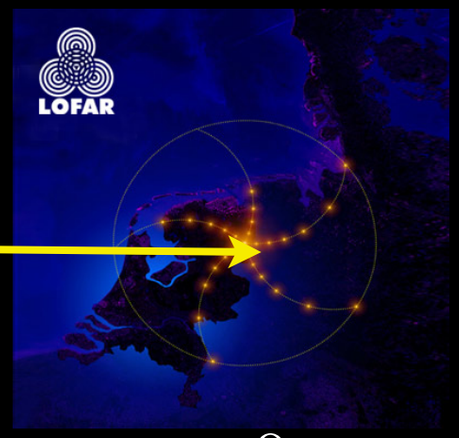

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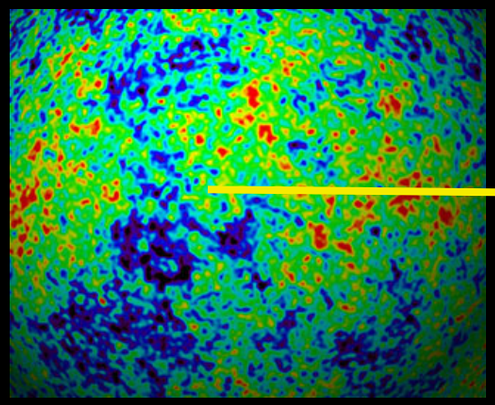

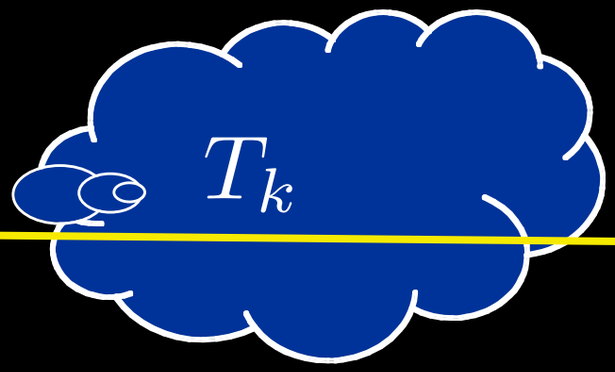

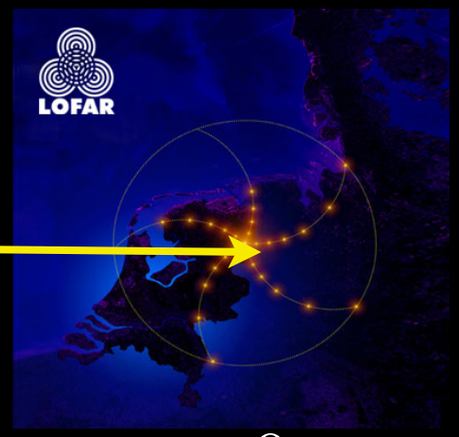

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neutral fraction

baryon density

spin temperature

peculiar velocities

spin temperature set by different mechanisms:

Radiative transitions (CMB)
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Wouthysen-Field Effect

Hyperfine structure of HI

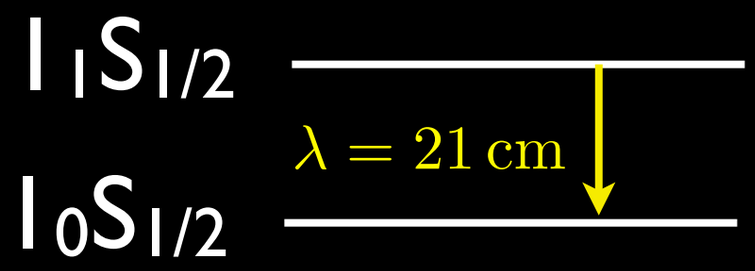
Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux

spin colour gas

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

W-F recoils



Wouthysen 1959

Field 1959

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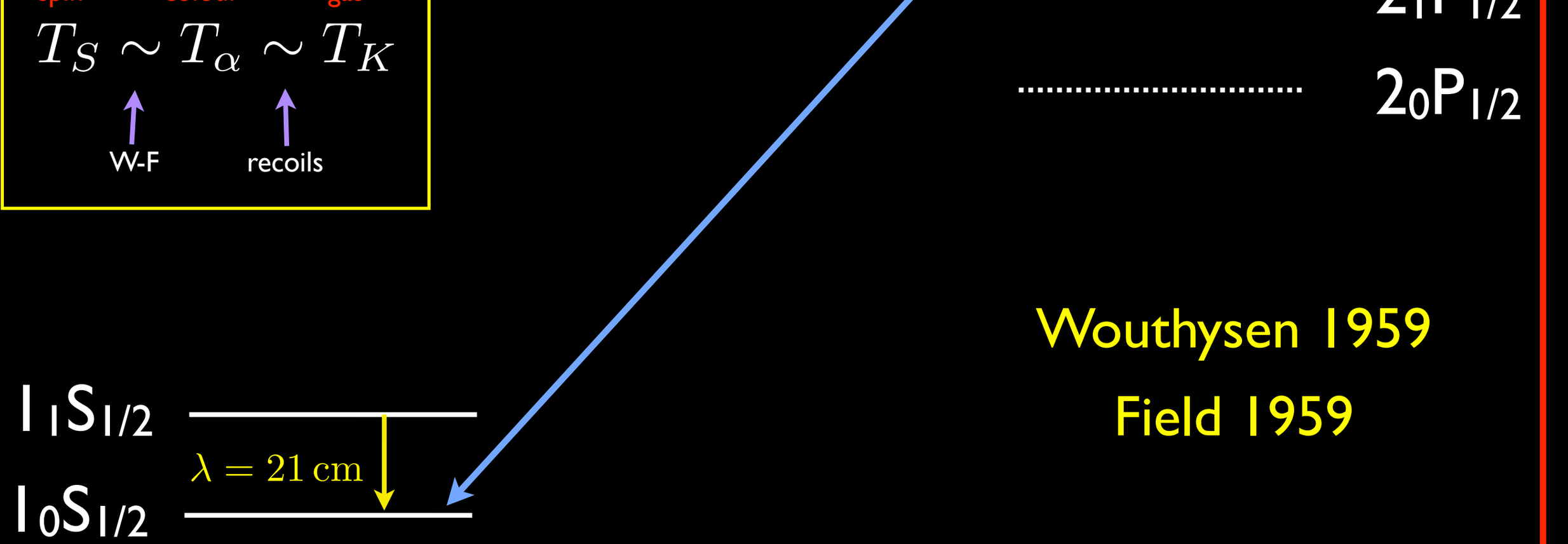

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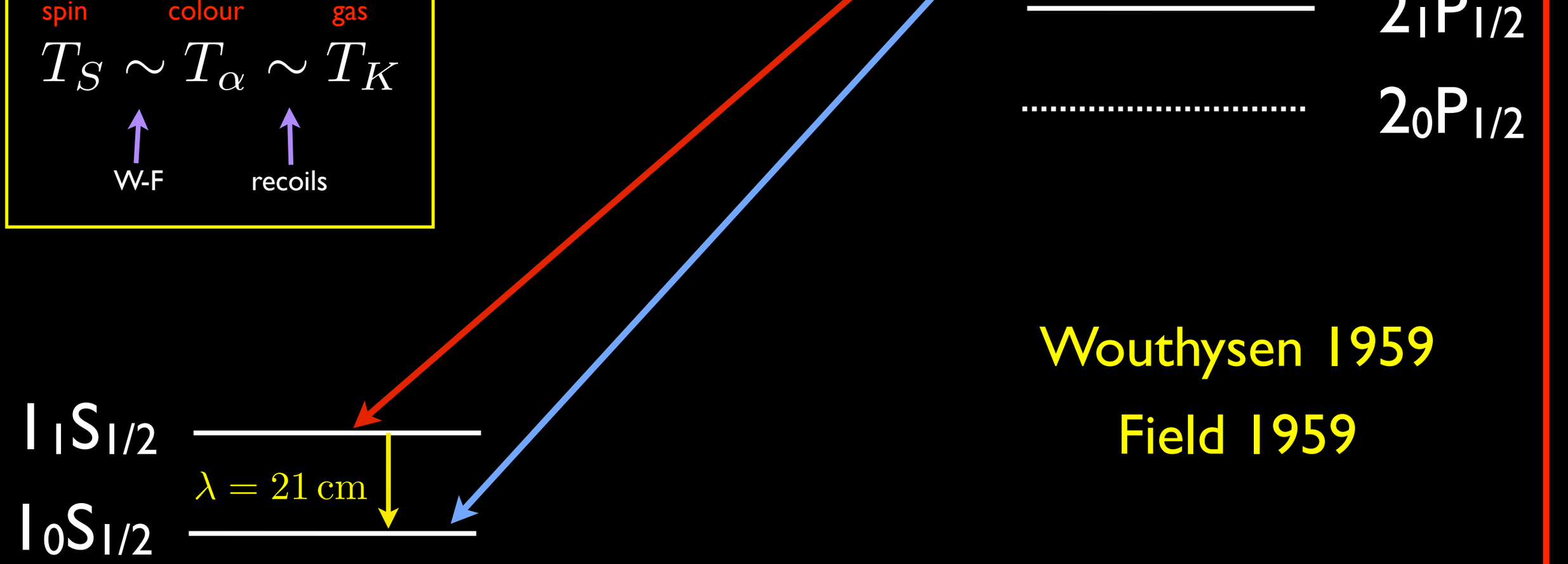

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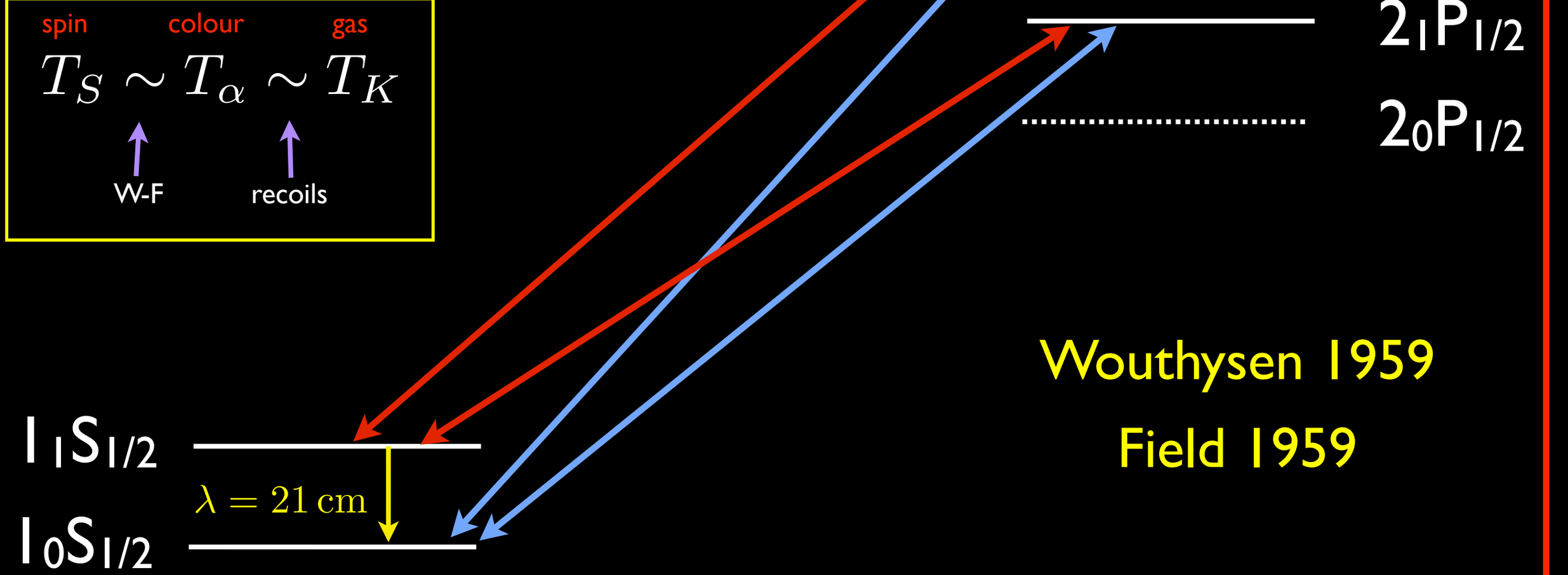


Wouthysen 1959

Field 1959

Nature of first galaxies?

Lyman alpha photons originate from stars

Population II or III?

Star formation rate?

Thermal history

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

- Only weak constraints from diffuse soft X-ray background

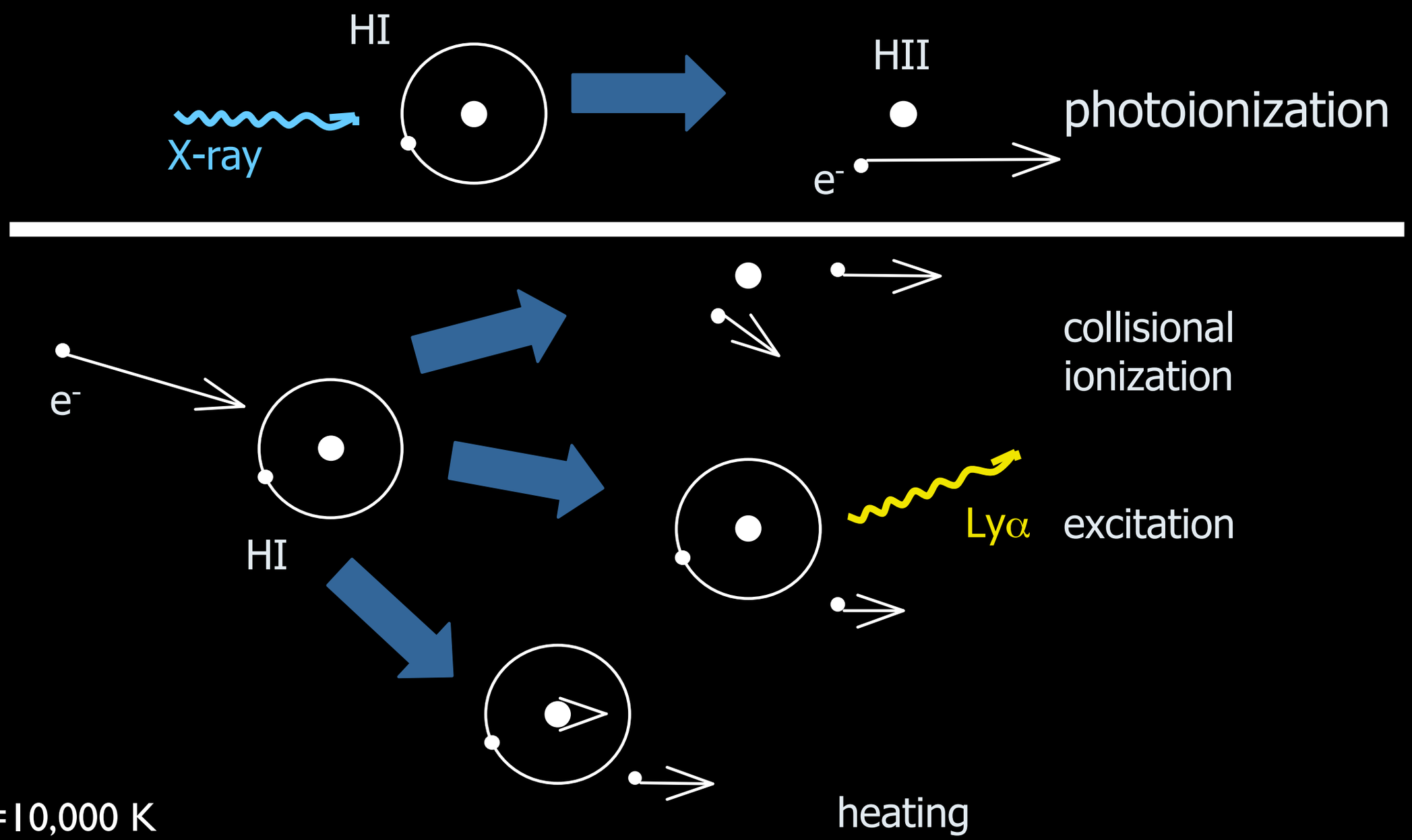
  Dijkstra, Haiman, Loeb 2004

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

  ~1 keV per baryon in stars

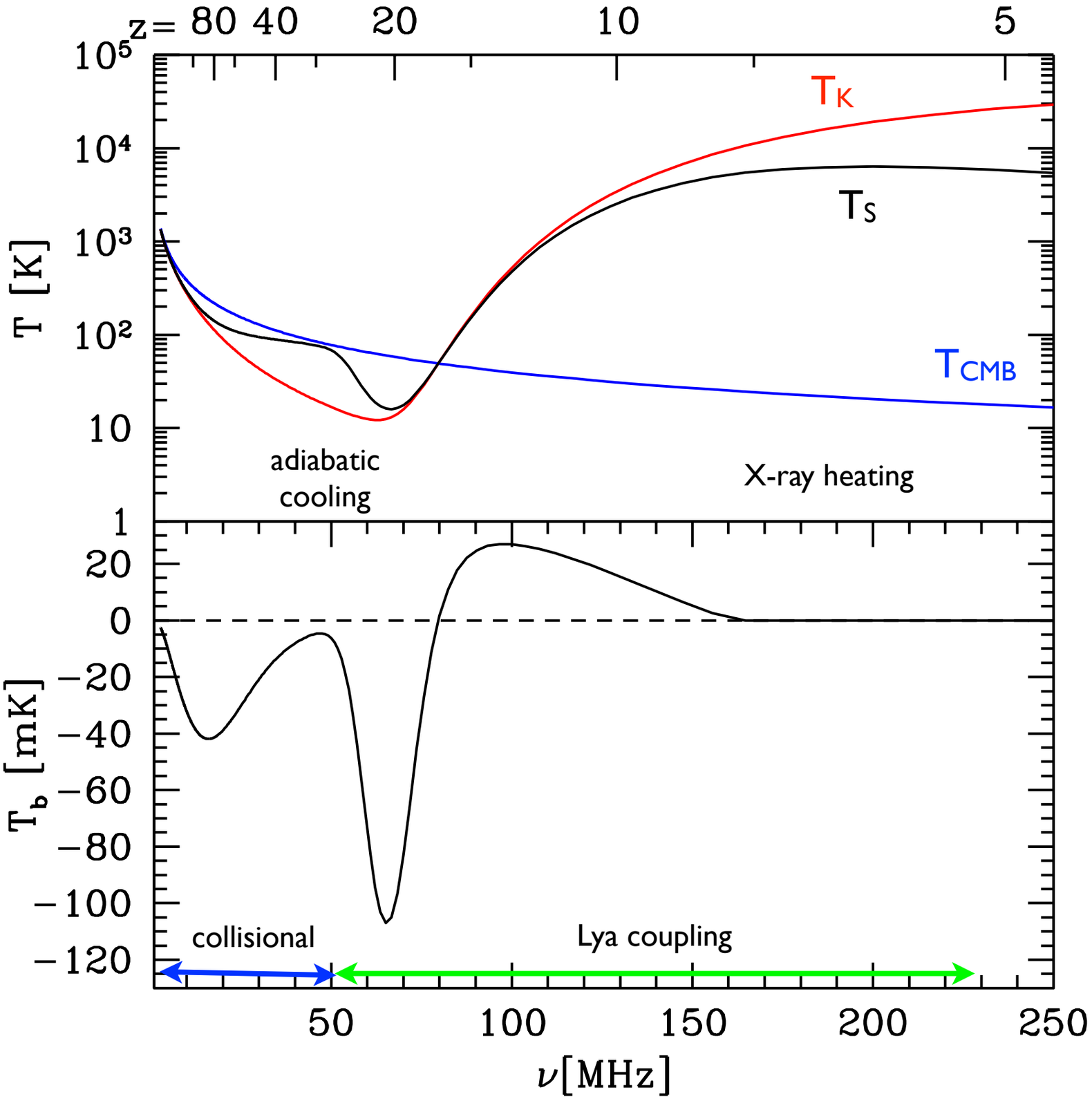
X-ray heating

- X-ray energy partitioned



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

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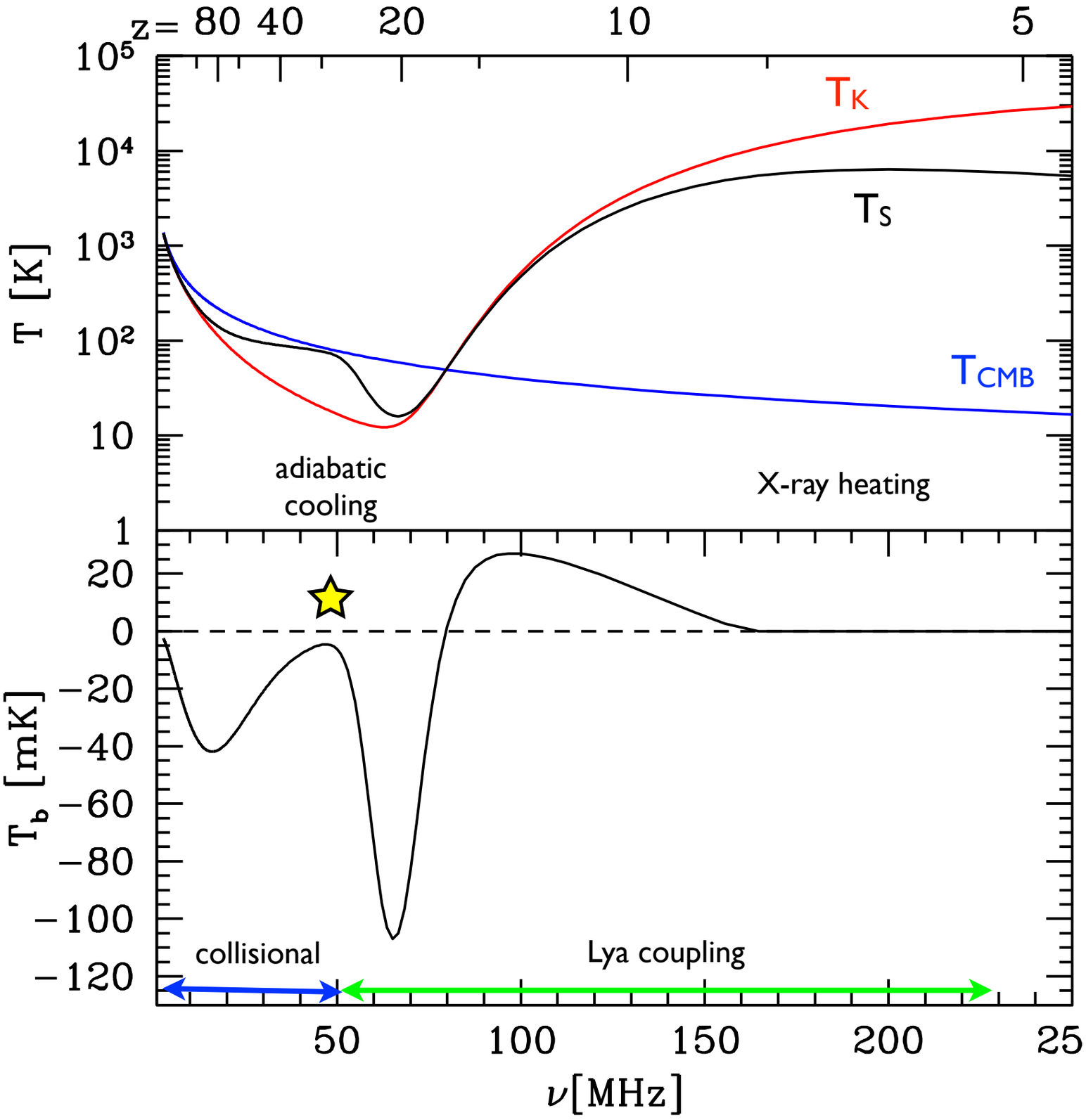

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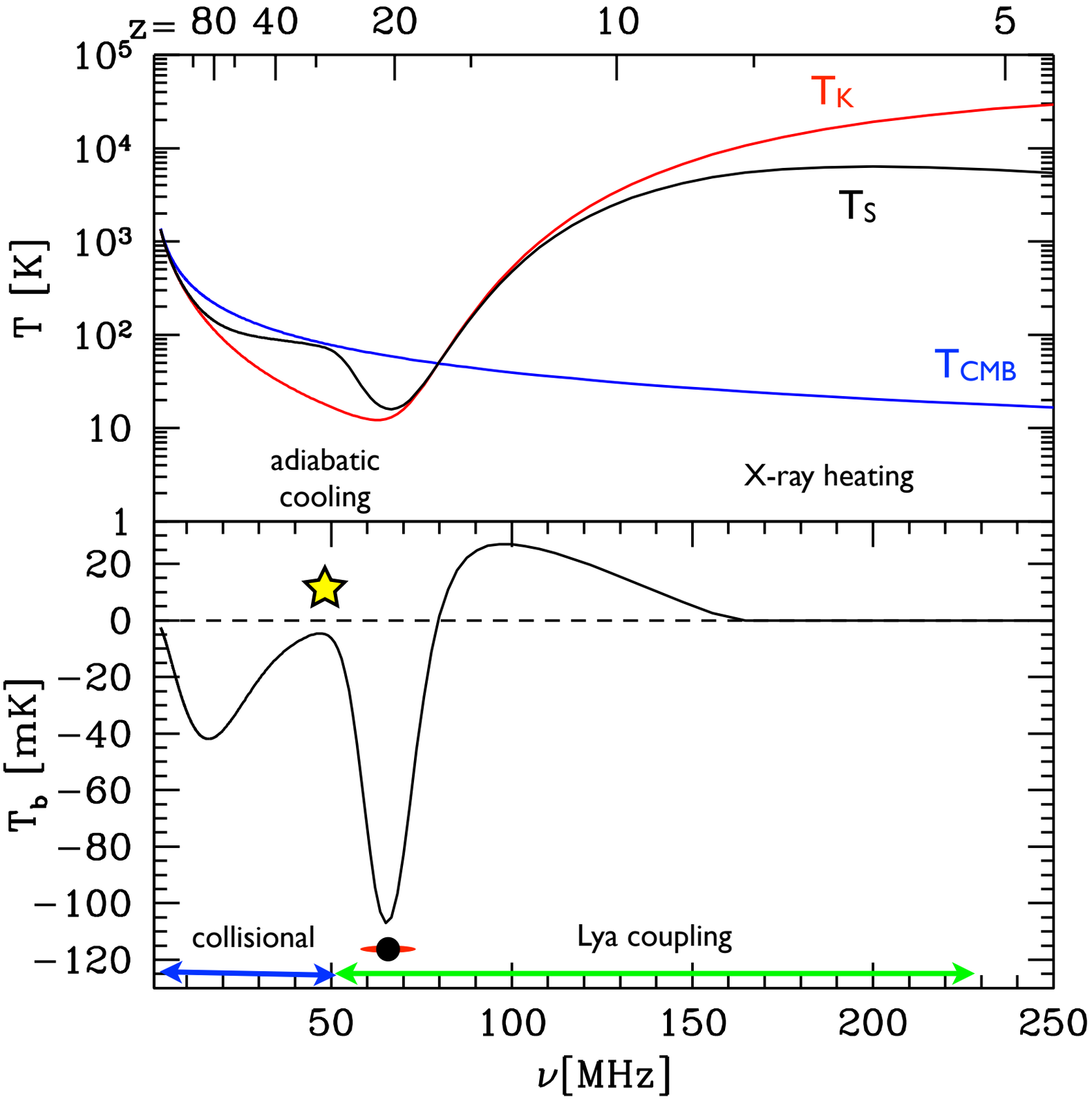

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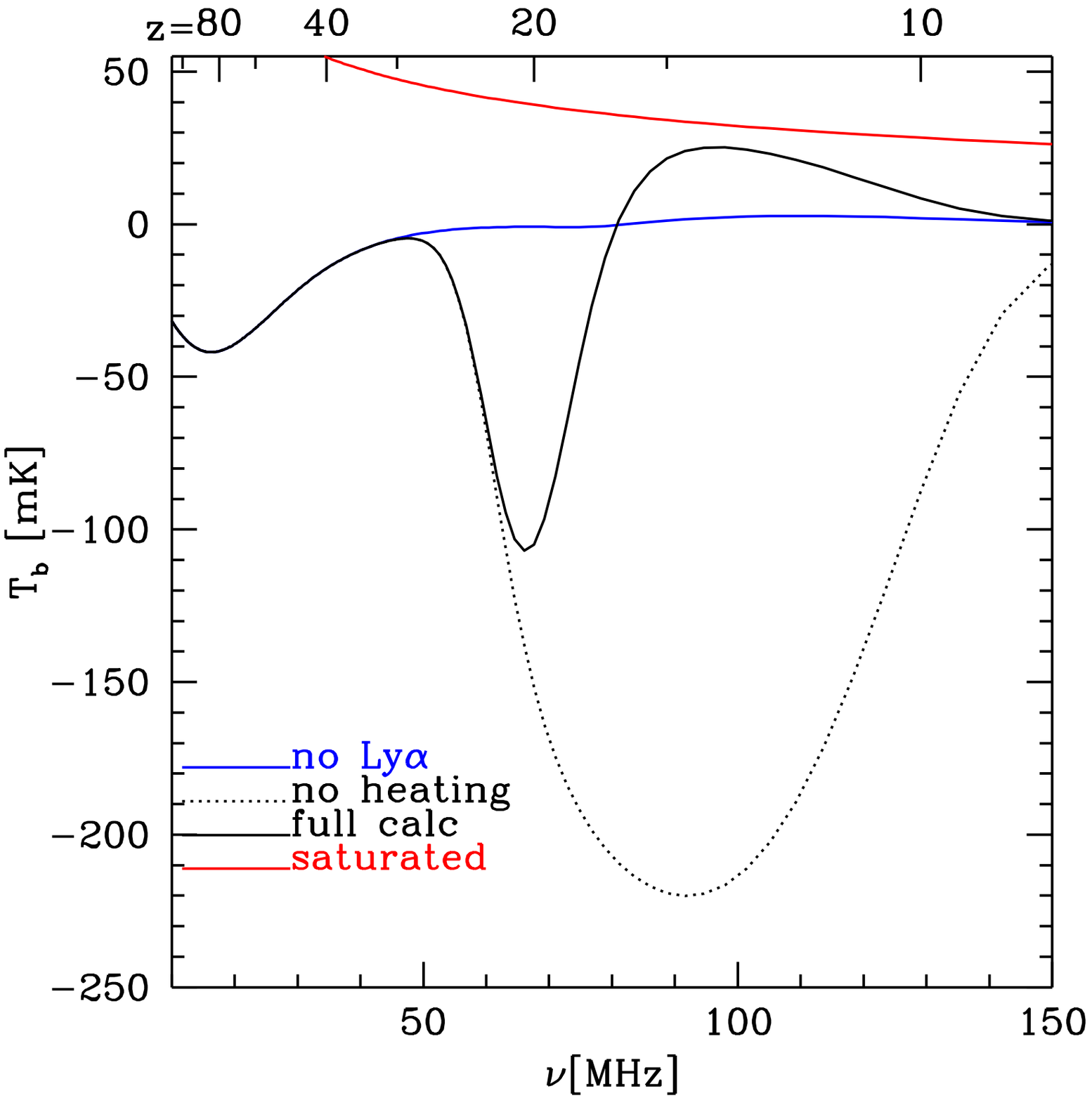
Alternative scenarios



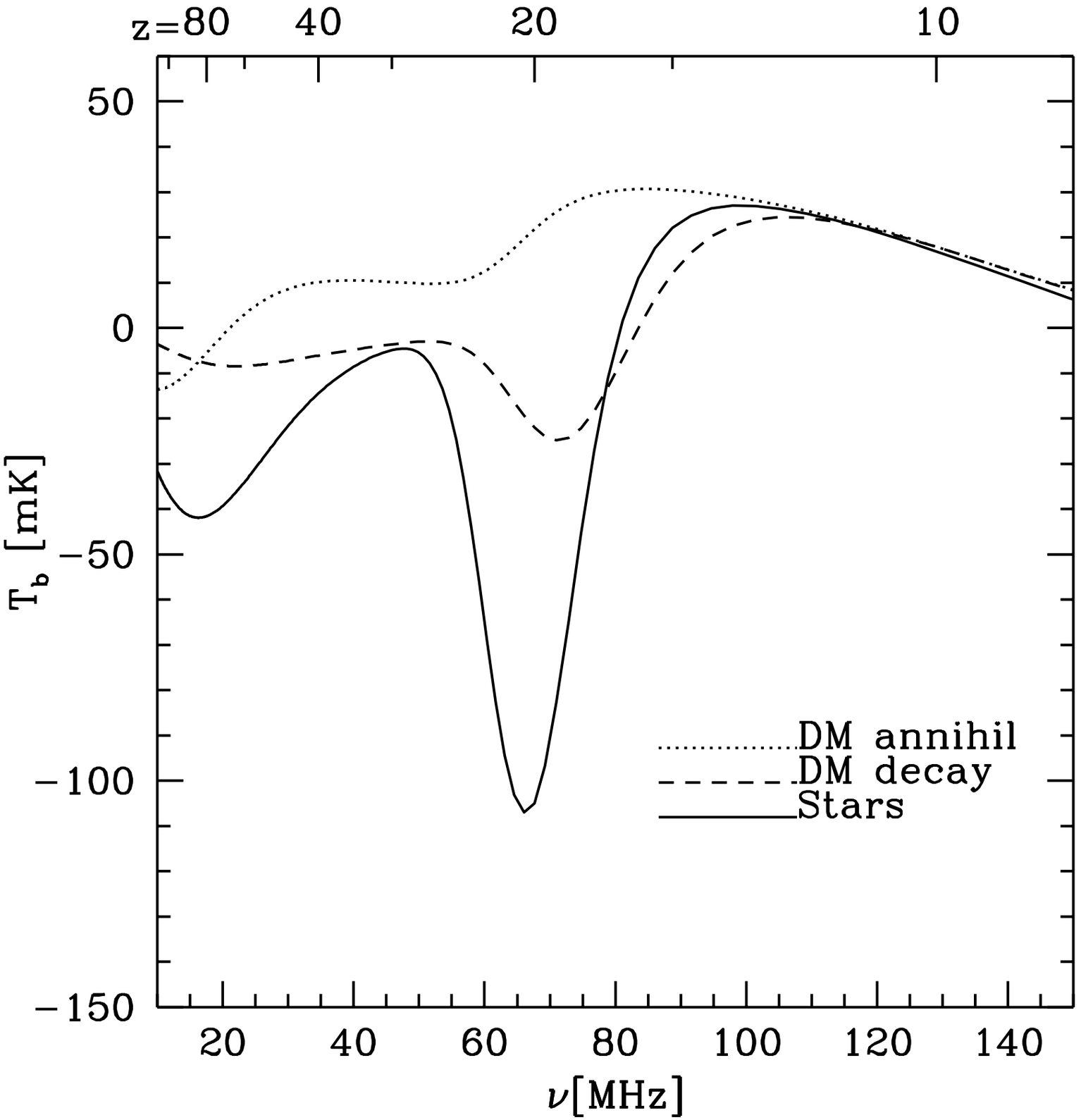
Maybe Lya photons don't escape their host halos?

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

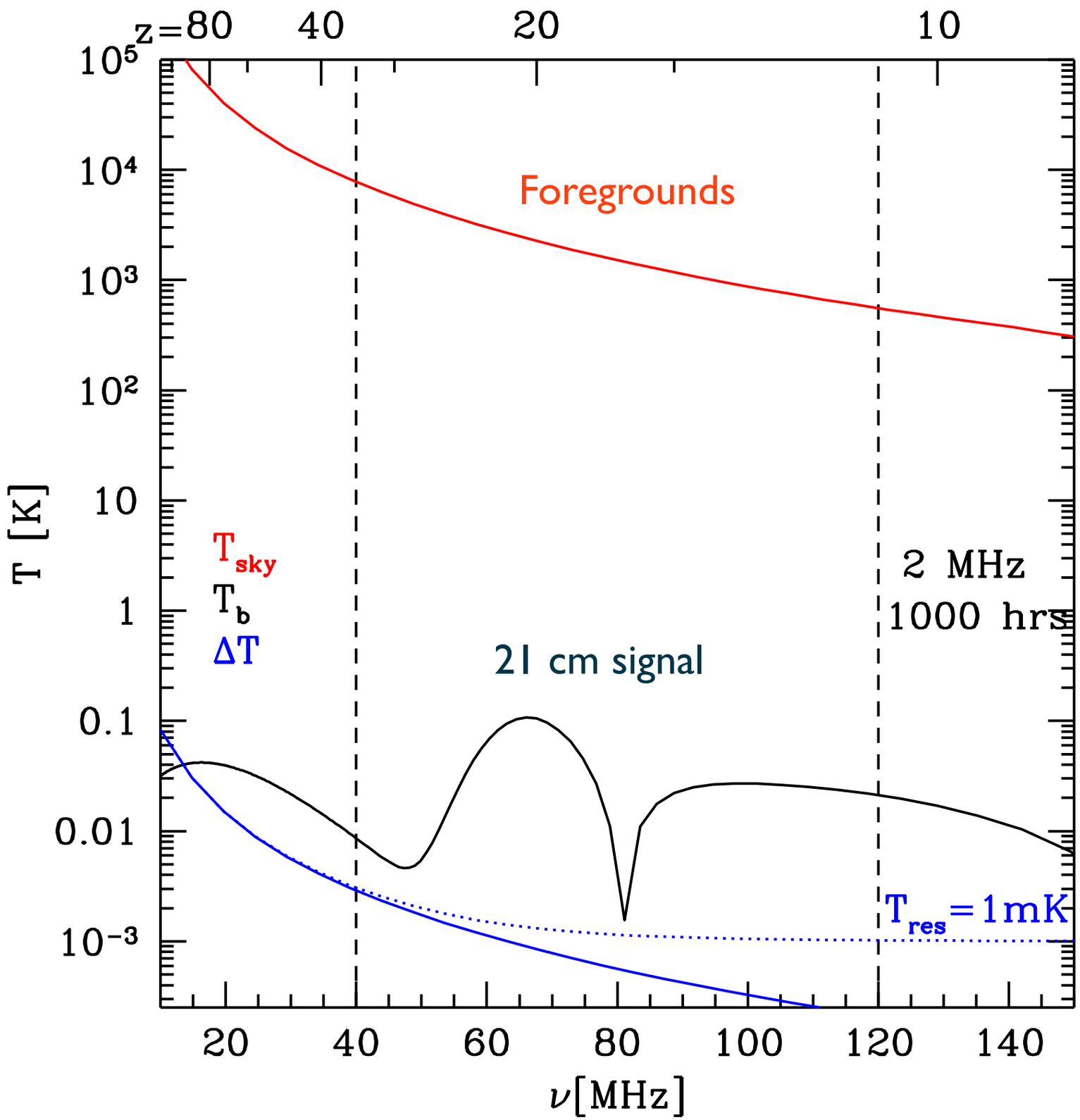


Exotic energy injection before first stars switch on

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

Very sensitive thermometer
Furlanetto+ 2006
Valdes+ 2007
Finkbeiner+ 2008
Mack+ 2008

Foregrounds vs Signal

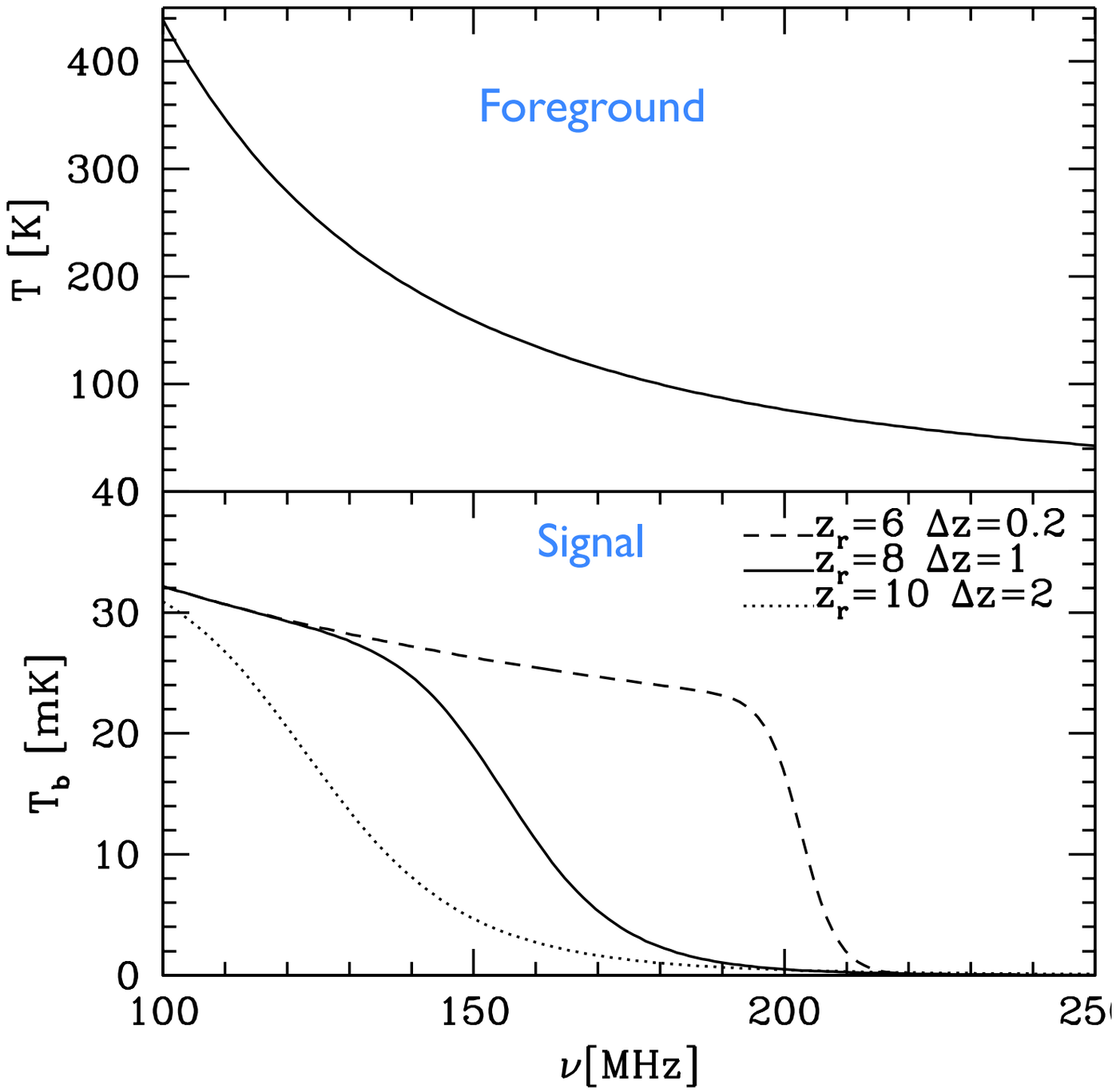


Foregrounds smooth
Signal has structure
Separation possible...

Dynamic range >10^5 needed

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

Reionization step



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

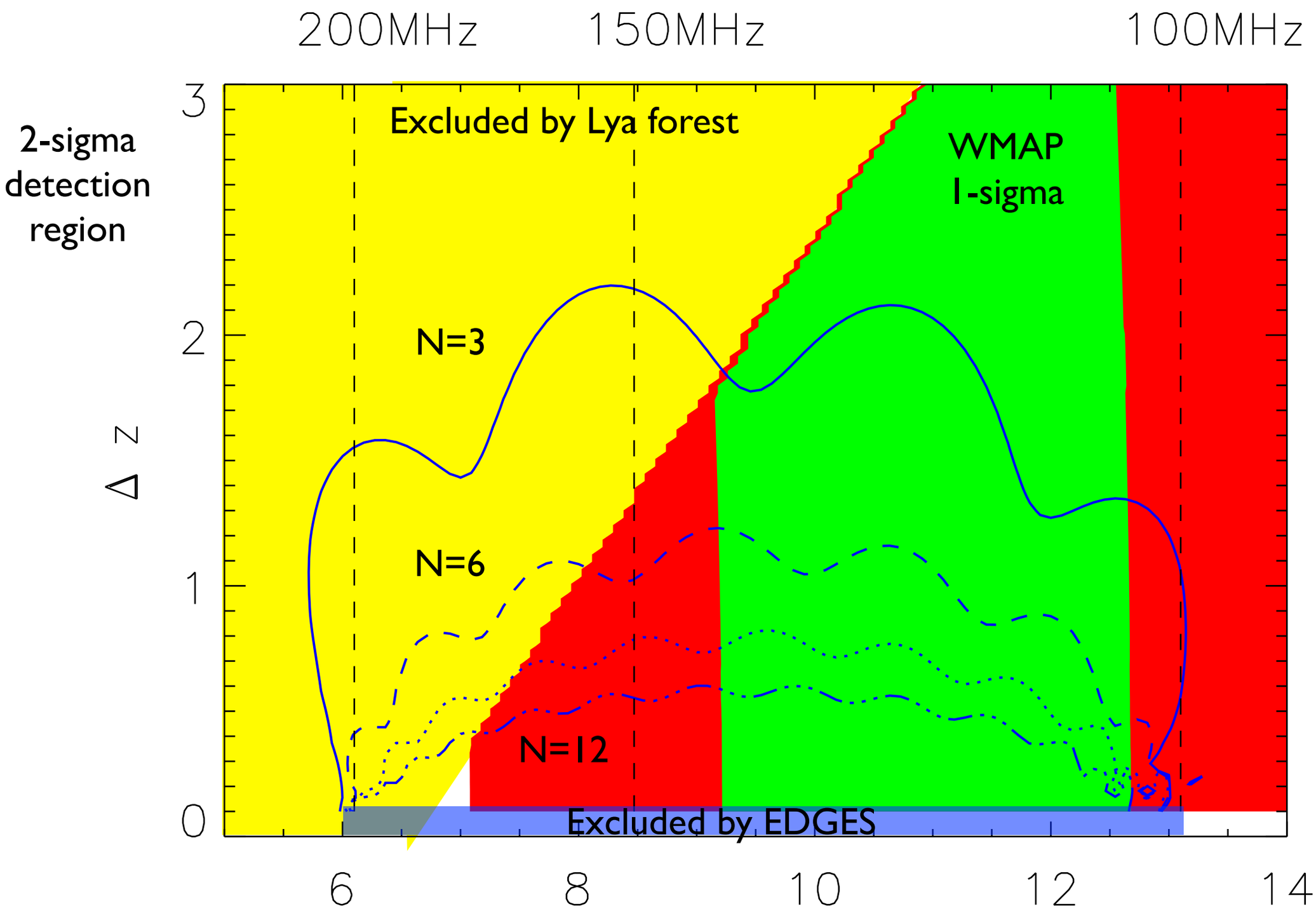
TS>>TCMB
no spin temperature dependence

Extended reionization histories closer to foregrounds

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

Reionization detection region

Pritchard & Loeb 2010



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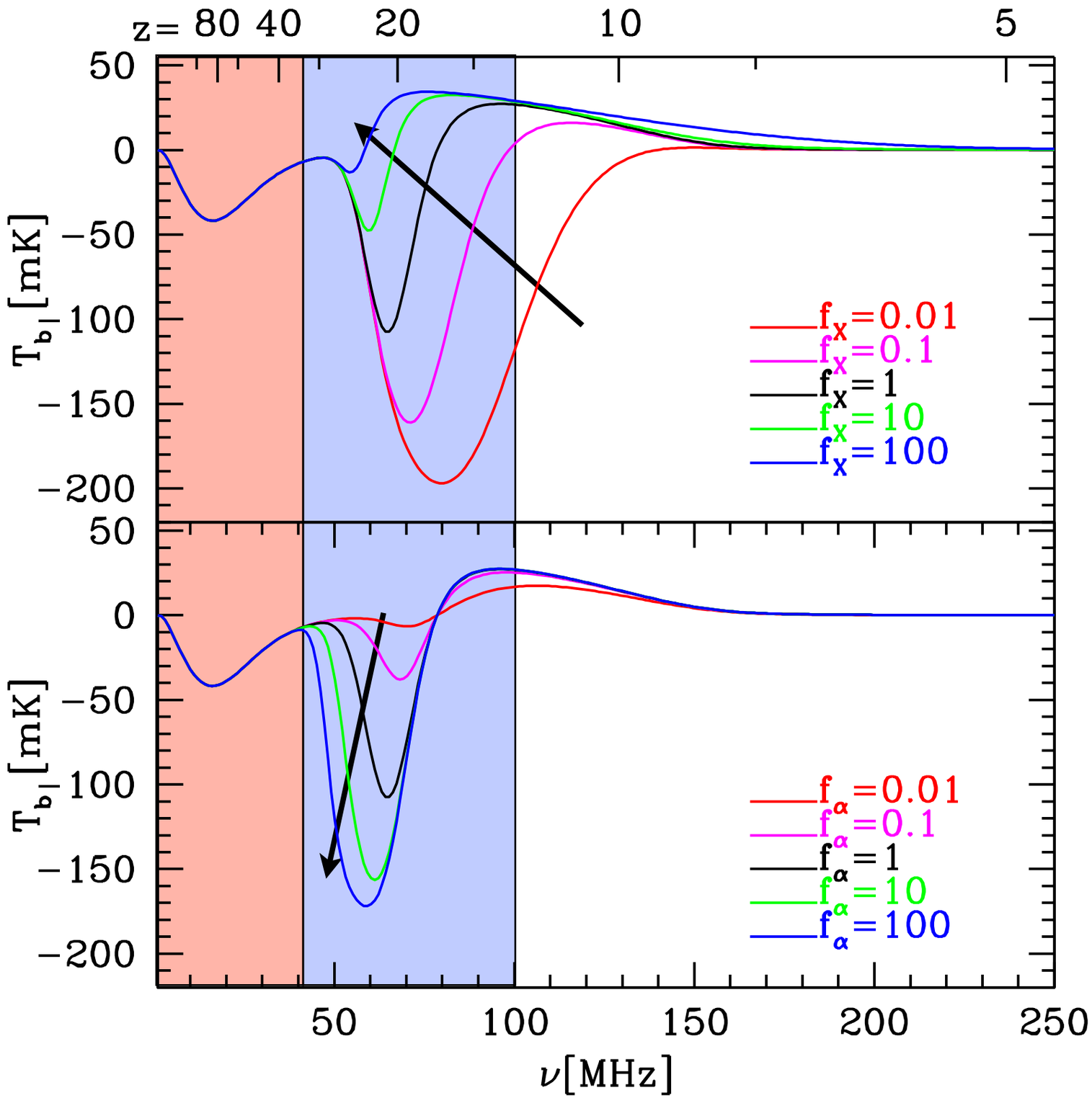
tint= 500hrs,
50 channels spanning 100-200MHz

Uncertain high redshift sources

Properties of first galaxies are very uncertain

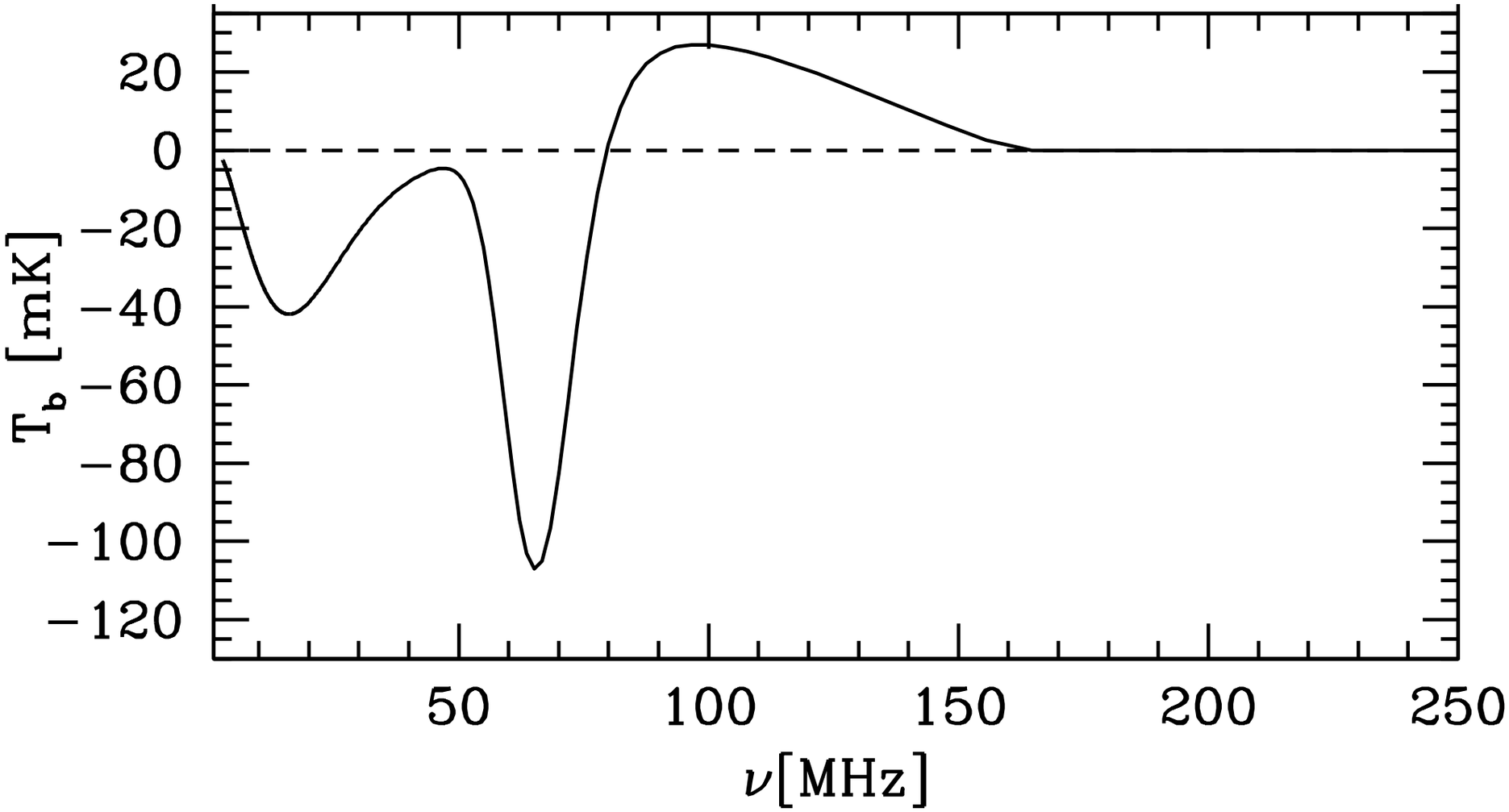
Frequencies below 100 MHz probe period of X-ray heating & Lya coupling

Below ~40 MHz exploring dark ages before first galaxies



Furlanetto 2006
Pritchard & Loeb 2010

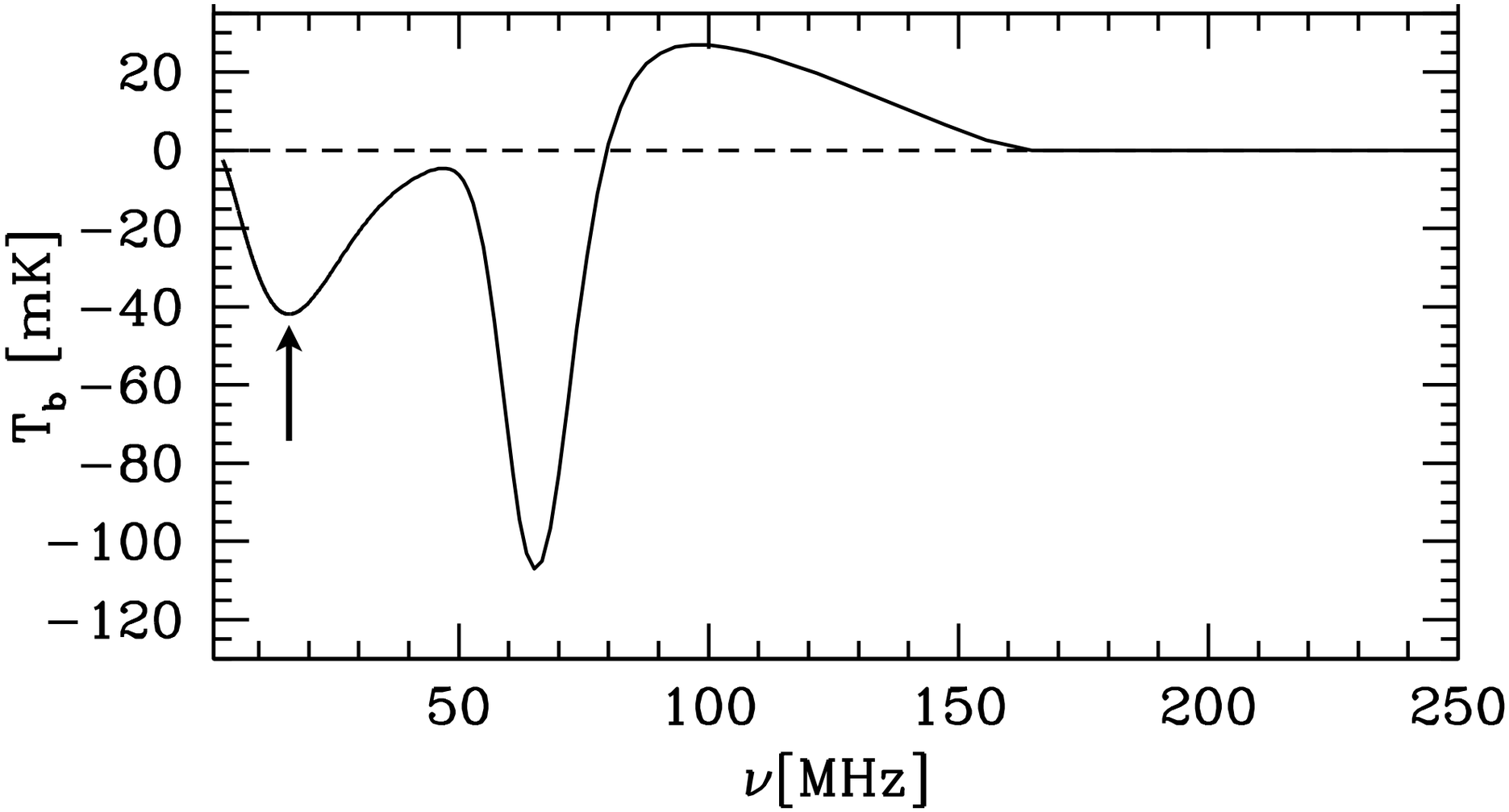
Features in the global signal



five key features

focus on turning points

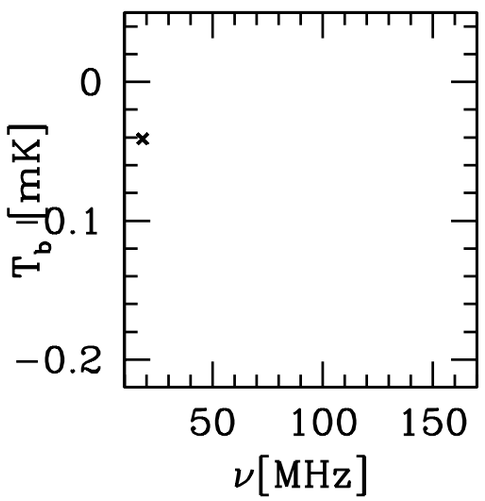
Features in the global signal



five key features

focus on turning points

Collisions fail



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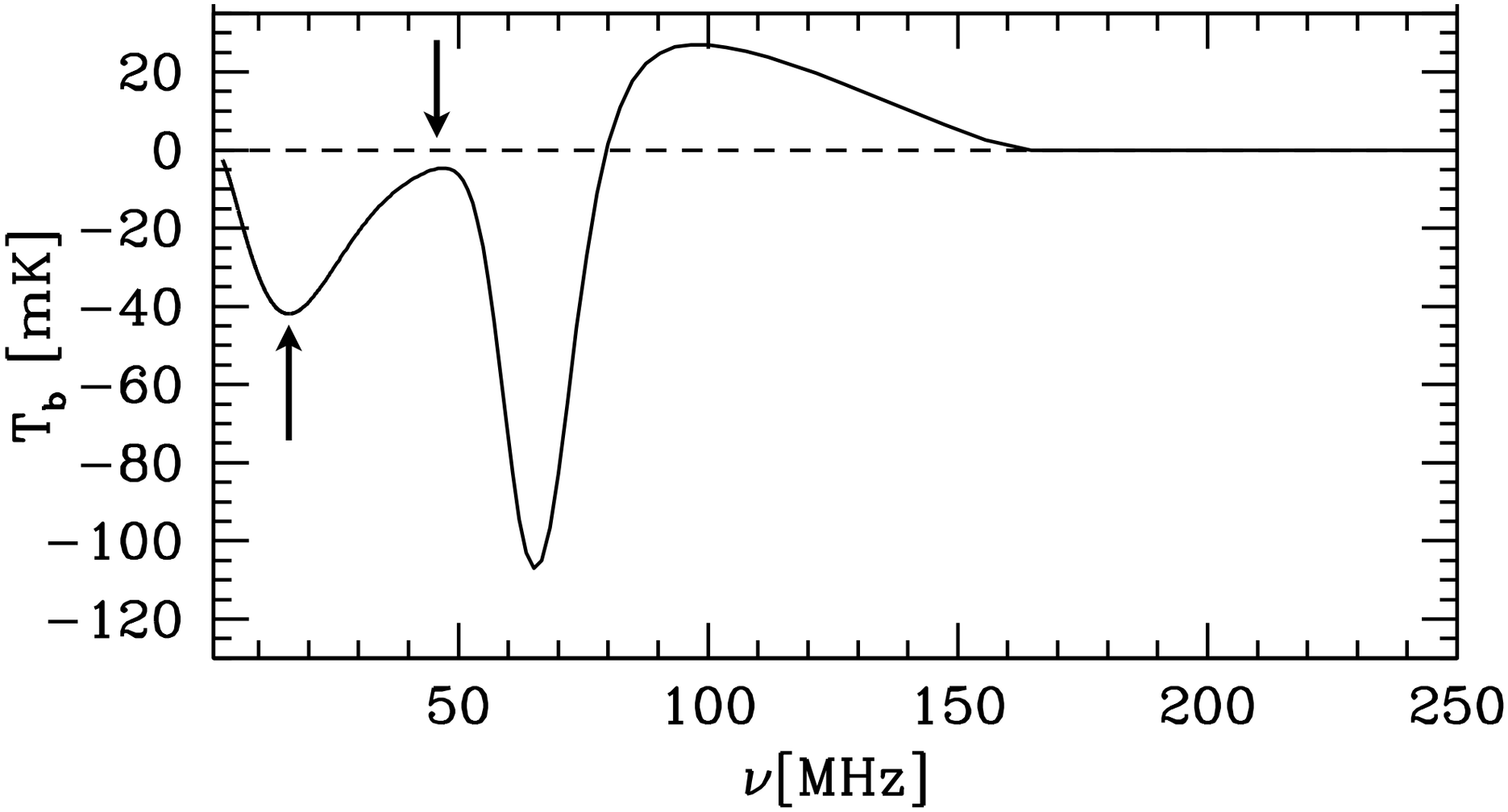

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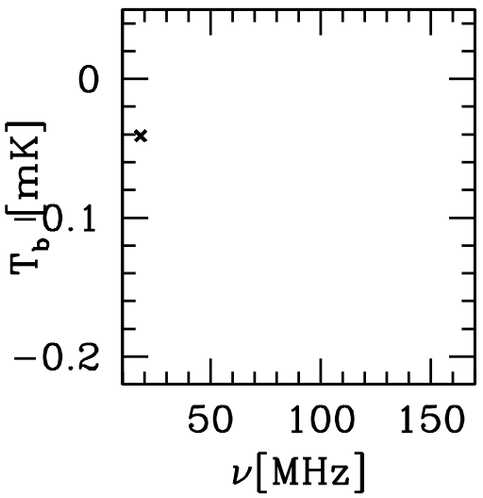
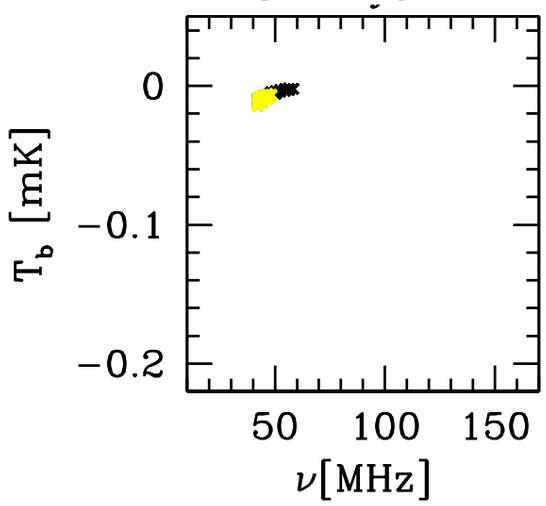
focus on turning points

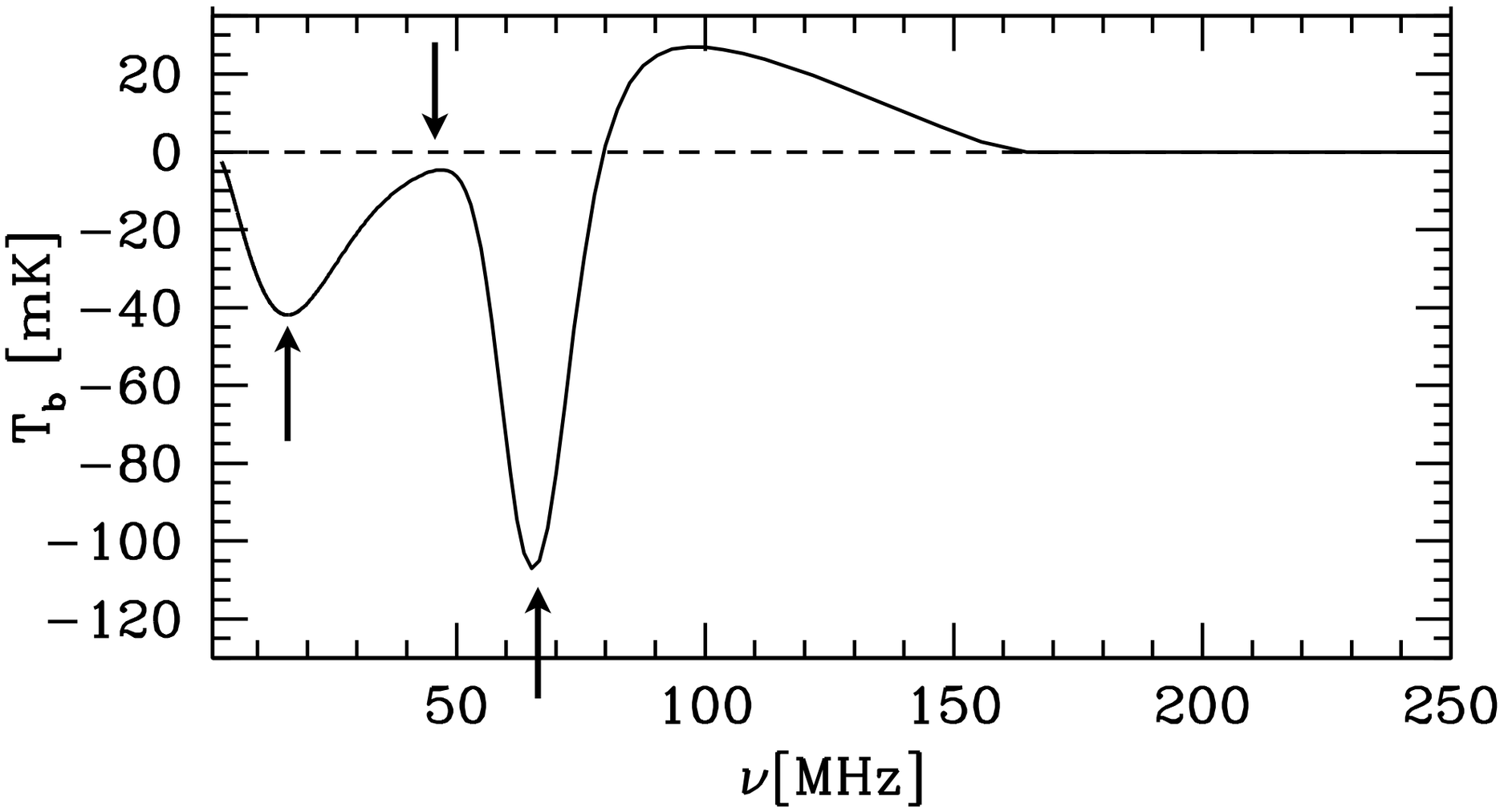
Collisions fail



Lya begins

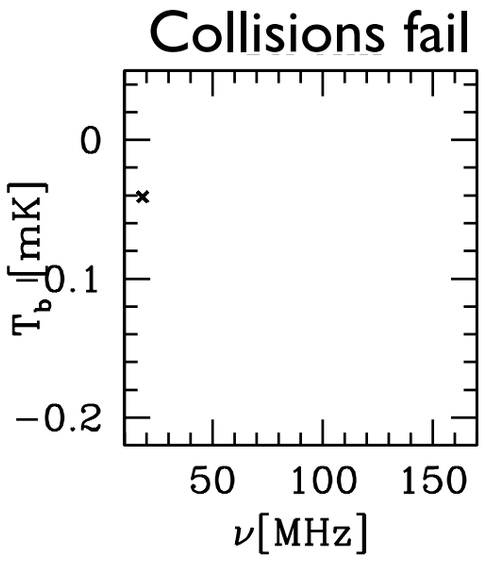


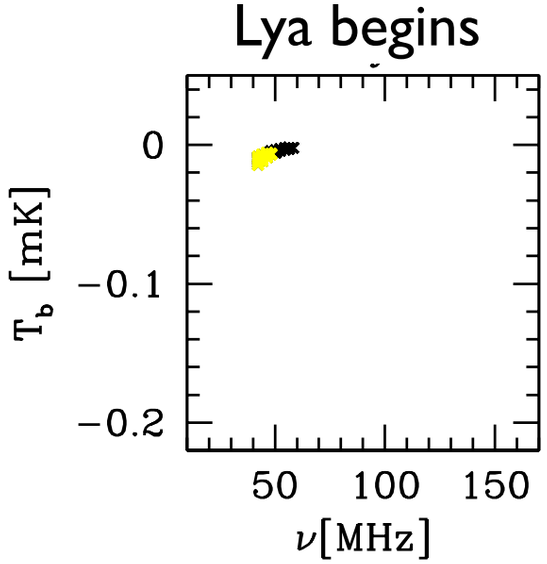
Features in the global signal

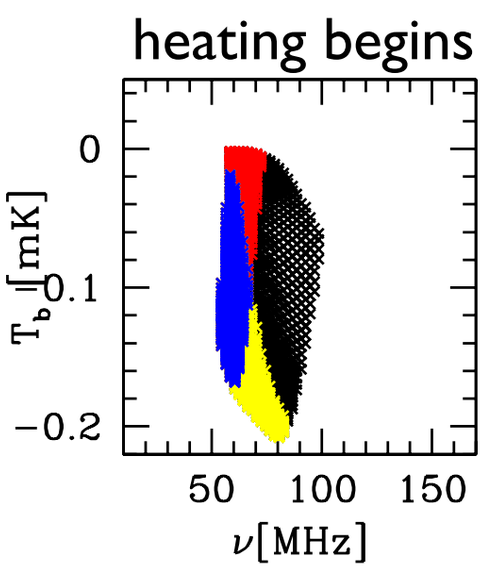


five key features

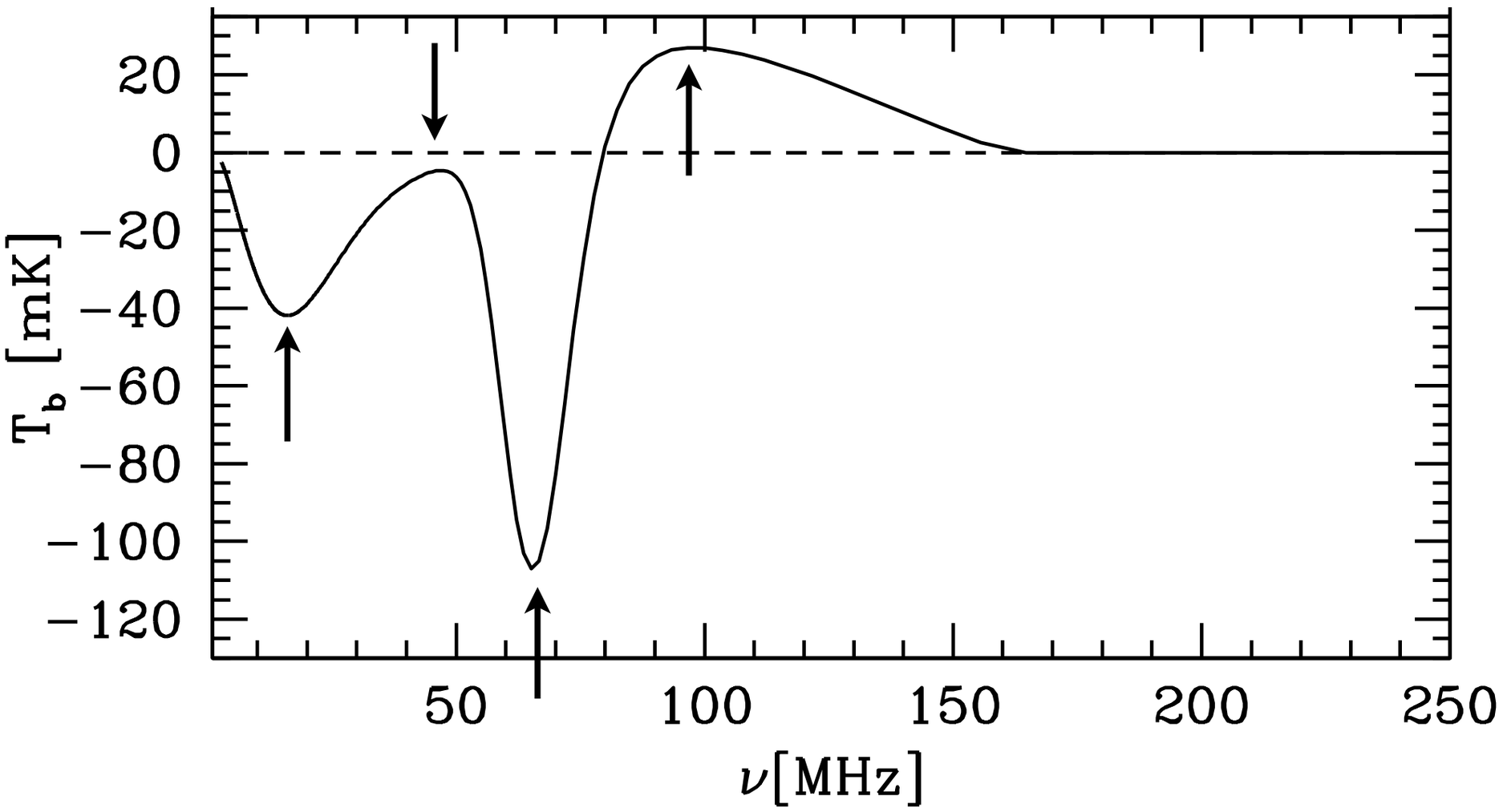
focus on turning points







Features in the global signal



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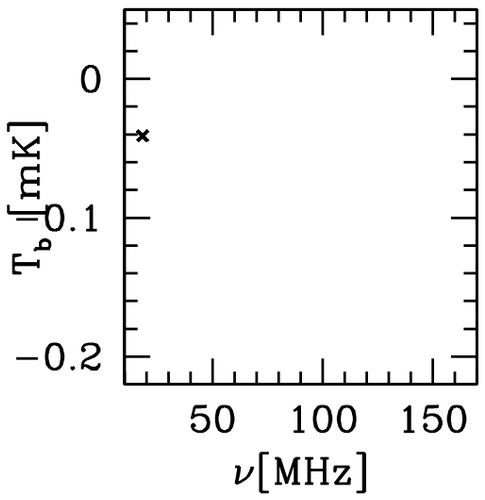
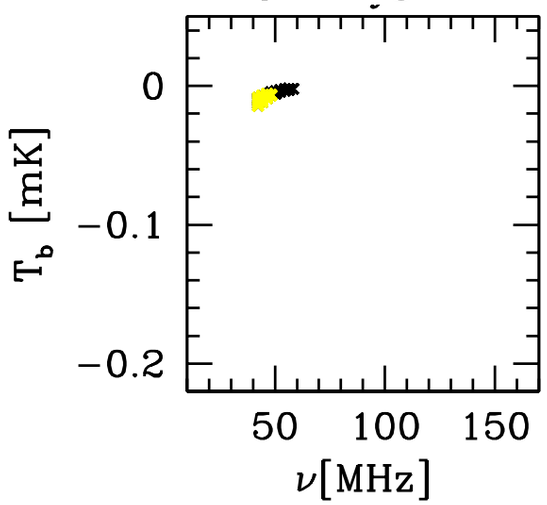
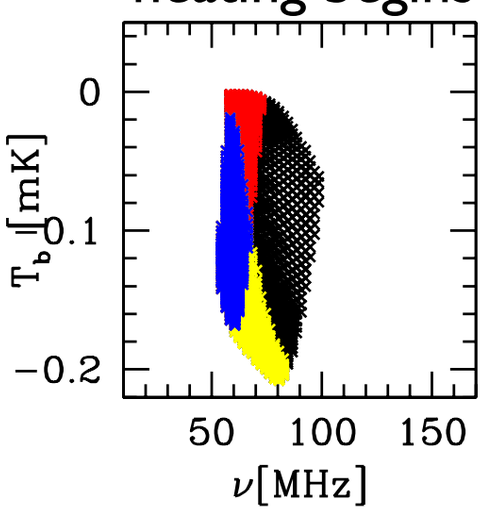


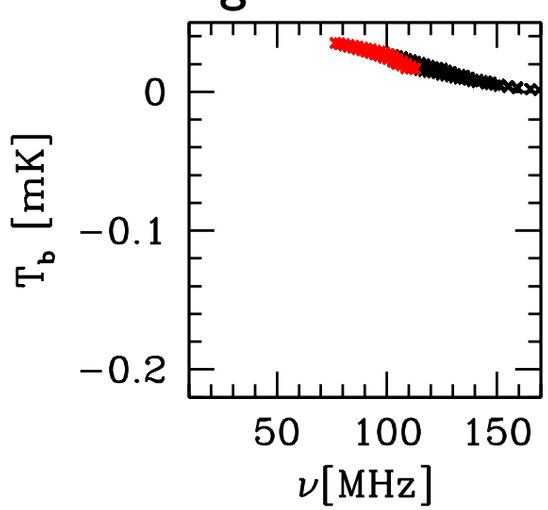
Lya begins



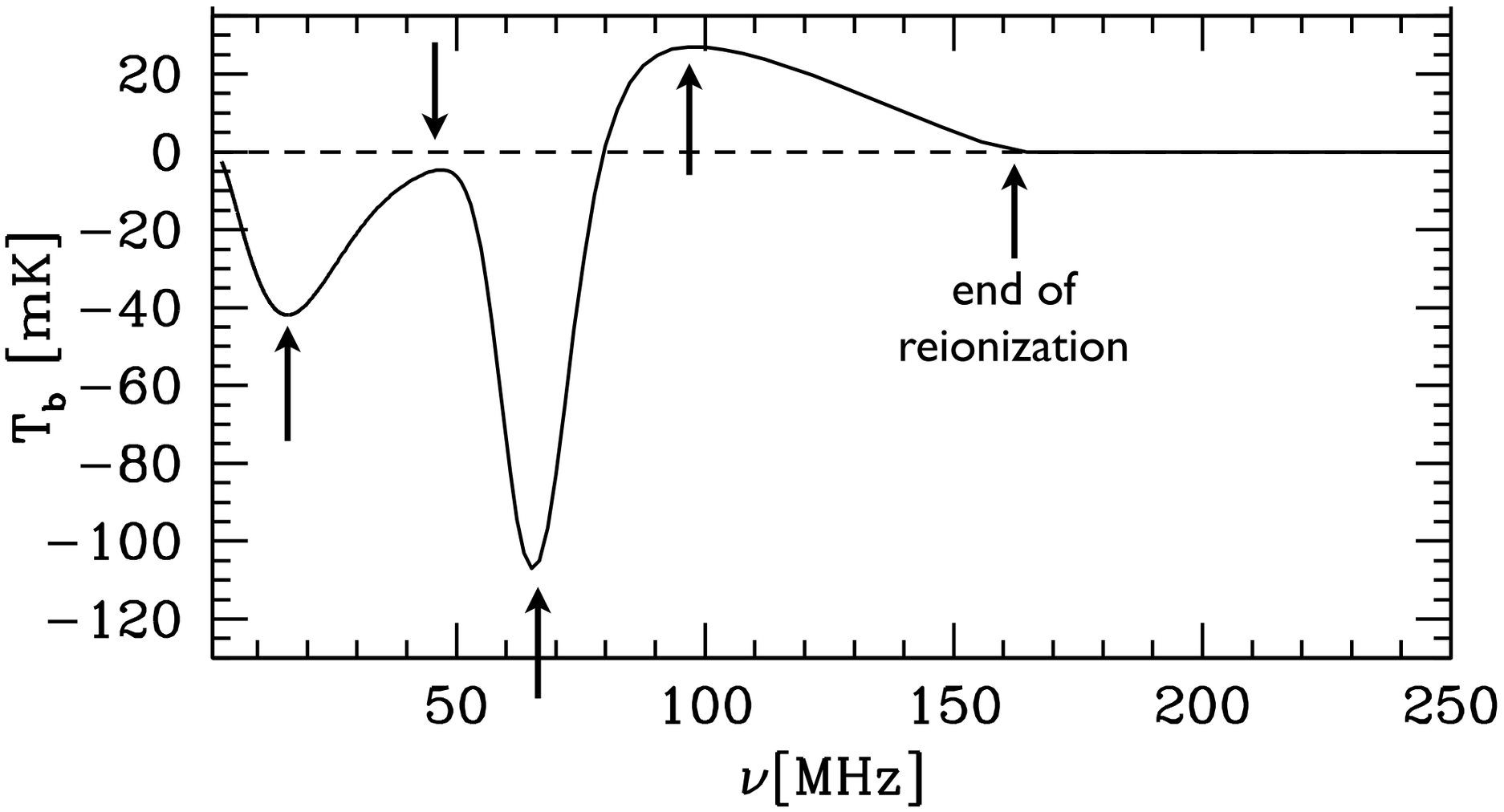
heating begins



signal saturates



Features in the global signal



five key features

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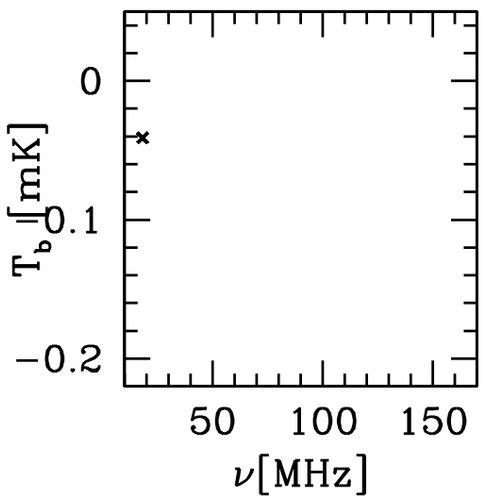
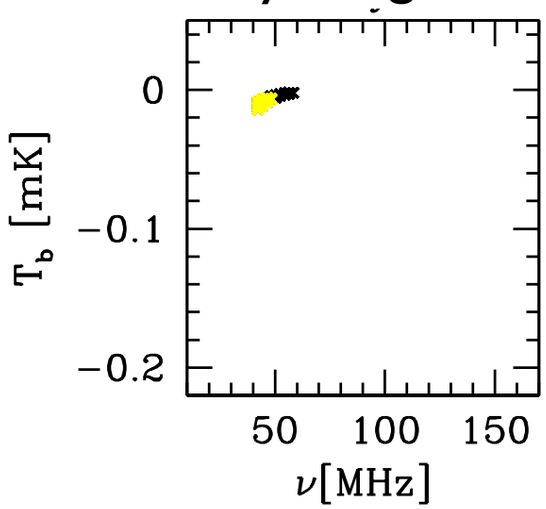
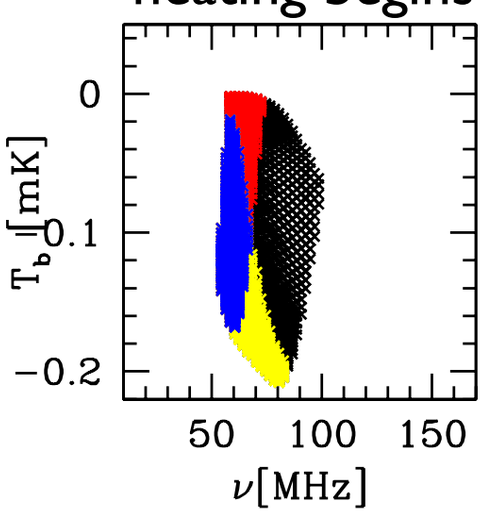
Collisions fail



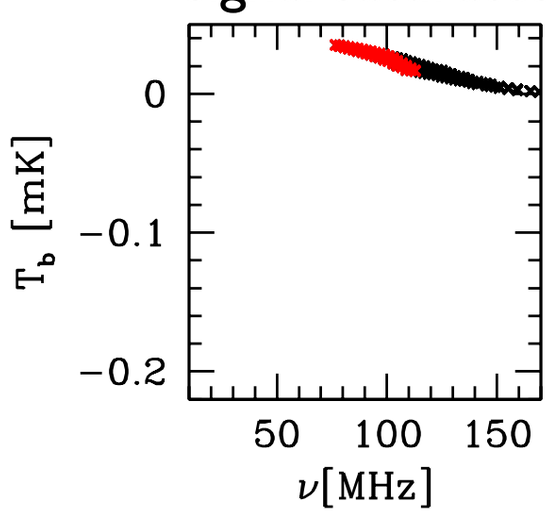
Lya begins



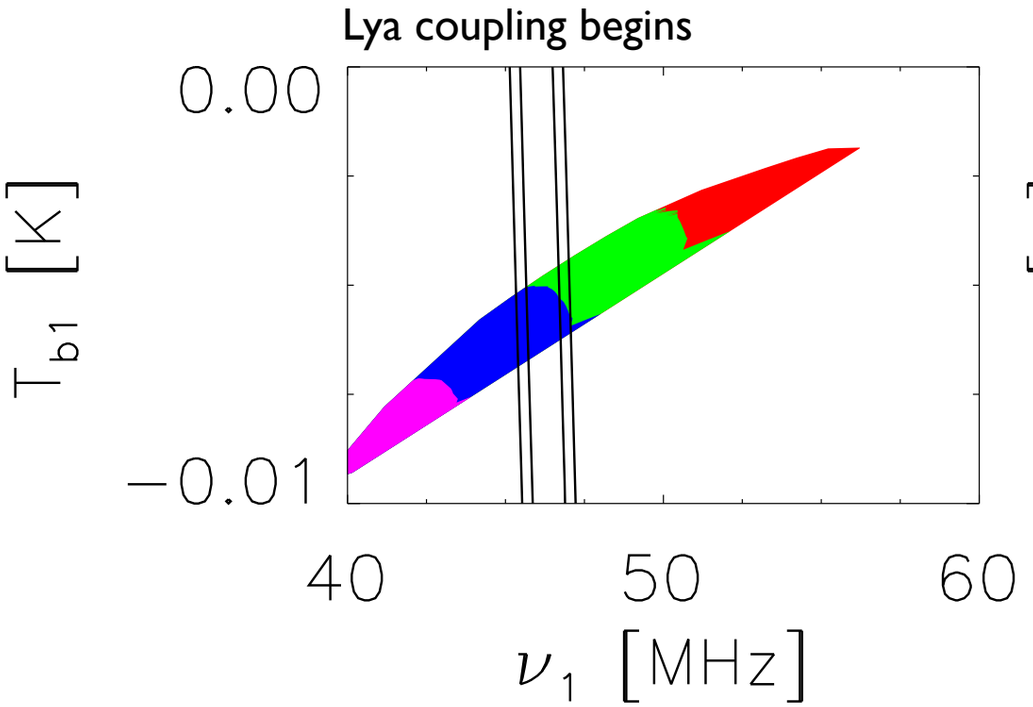
heating begins

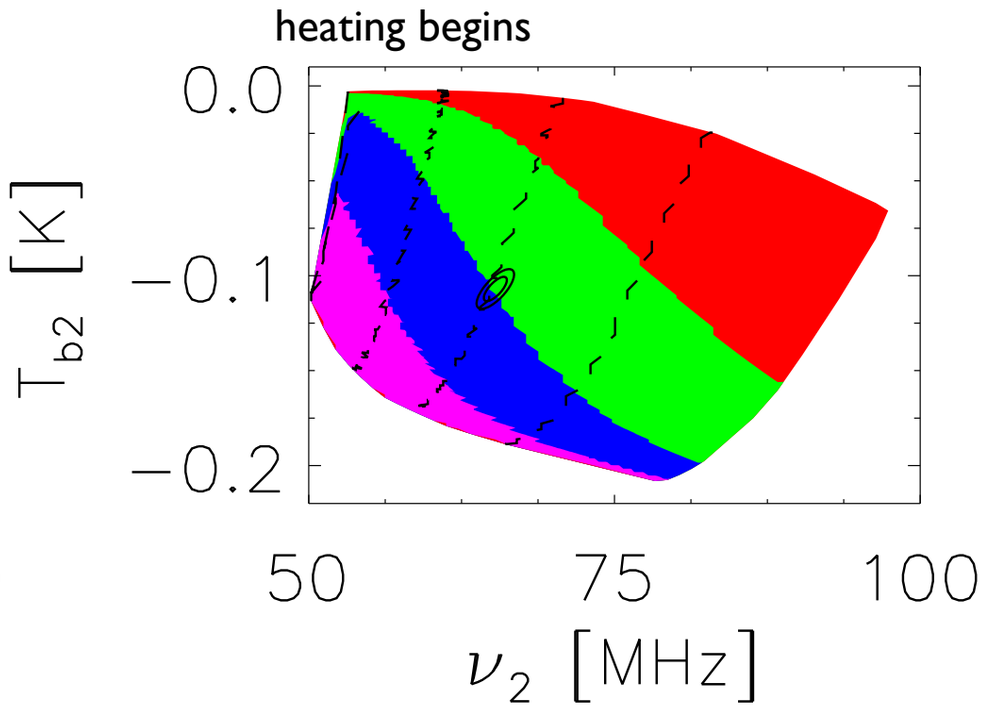


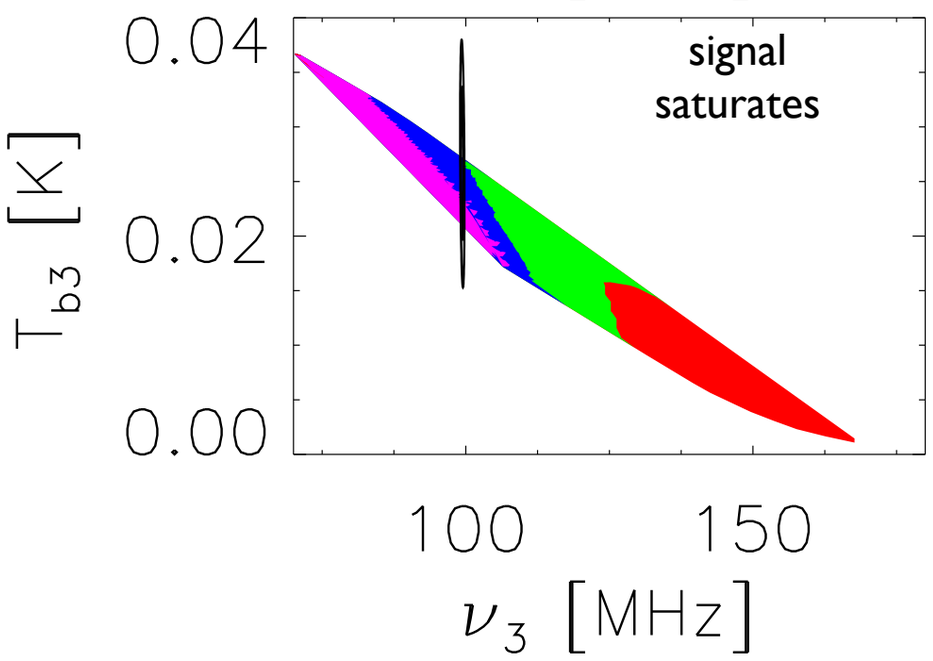
signal saturates



Constraining turning points







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

Similar sensitivity as for reionization
constrains deep absorption feature

Conclusions

- 21 cm global experiments can potentially access the full redshift range of star formation and constrain the first galaxies

- Sensitivity to sharp reionization histories

- Evolution of spin temperature
  - Lya coupling => star formation rate
  - Gas temperature => X-ray sources

- Position and amplitude of turning points useful parametrization

- Plenty of experimental challenges: foregrounds!

- Lots of potential...

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