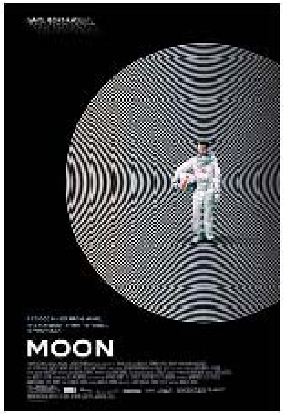
Moon

January 27 @ 7:00pm

Free Admission

At Fiske Planetarium

In HD Blue Ray and Surround Sound



Sam Bell is the sole occupant of a lunar base, employed by Lunar Industries to supply Earth with Helium-3 from the moon's surface. Contact with Earth is limited to occasional recorded transmissions from his wife; his only real-time interaction is with a computer assistant named GERTY. With two weeks remaining on his three-year contract, Sam begins to experience hallucinations, and suffers an accident as a result. In the aftermath, he makes a discovery that changes everything he thought he knew.

This movie is rated R

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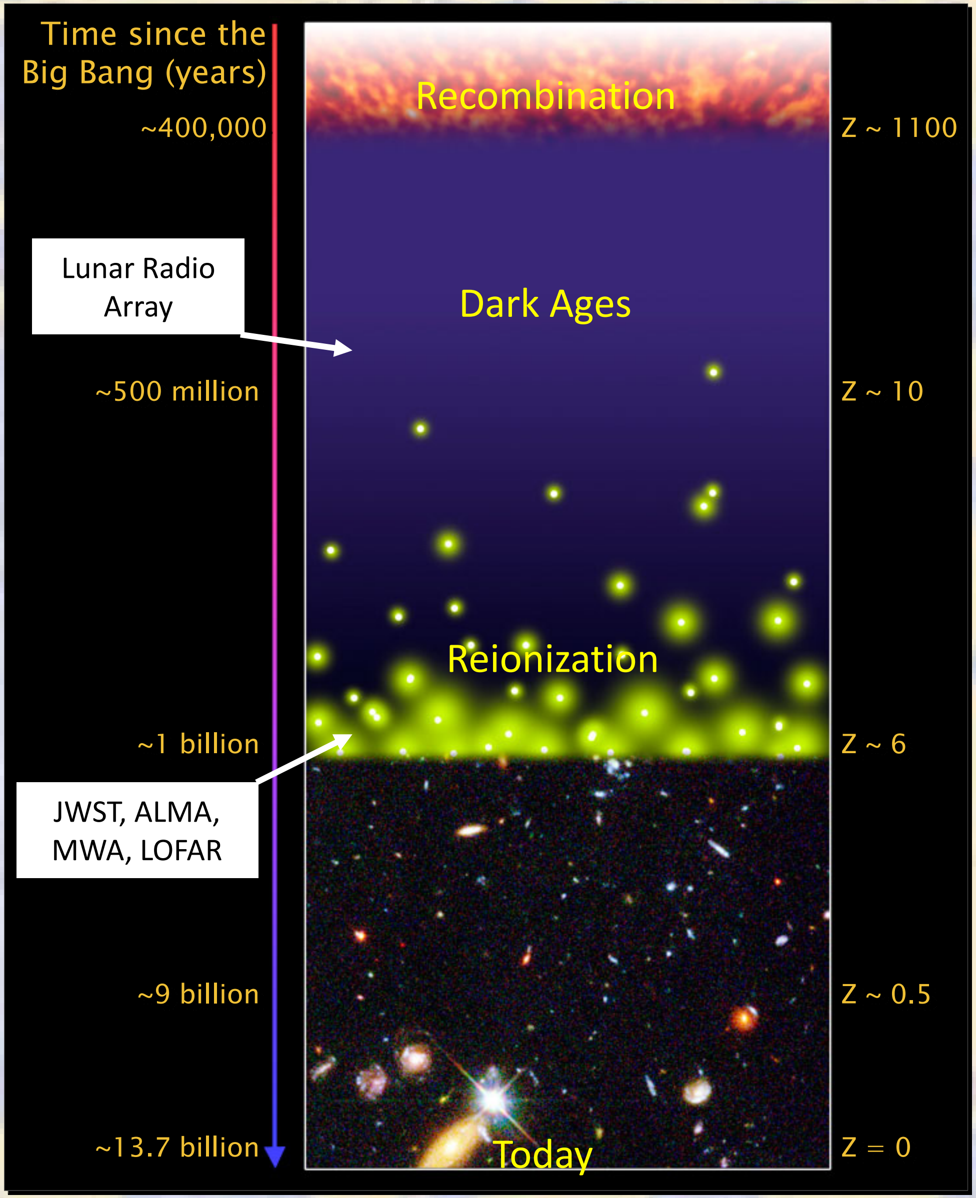
Evolution of the 21cm signal throughout cosmic history

A review of Pritchard & Loeb (2008)

Geraint Harker
Interdisciplinary Lunar Science Seminar
Tuesday 26th Jan. 2010

Major epochs in cosmic history since recombination

- Recombination leads to production of the cosmic microwave background (CMB), which peaks at 160.2 GHz.
- Structure formation leads to objects in the low-redshift Universe observed at a range of wavelengths.
- Current observations, mostly at z<0.3, only cover roughly 0.1% of the volume of the Universe.
- How to get at the rest…?



Physics and cosmology from 21cm measurements (examples)

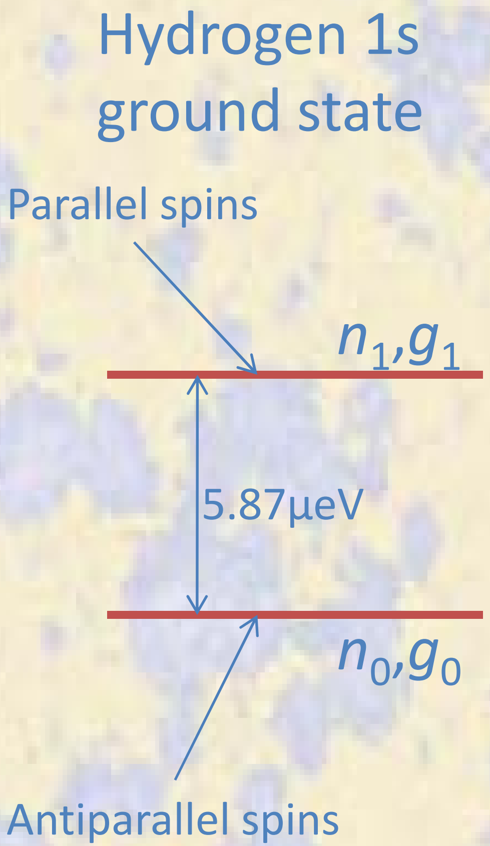
- The post-reionization epoch and the dark ages may be the cleanest from the point of view of learning about cosmology (though the epoch of reionization may yield the most interesting astrophysics).
- Cosmological parameters may be constrained very tightly, e.g. a good knowledge of the expansion history and the growth of structure may tell us about dark energy.
- Accurate measurement of density fluctuations give us the shape of the power spectrum and may lead to tests of non-Gaussianity (and hence models of inflation).
- Decaying dark matter may heat or ionize material before the first astrophysical sources switch on.
- Measurements of neutrino mass or other exotic components may come from looking at small-scale density fluctuations.

The hydrogen 21cm line

- The hydrogen 21cm (1420MHz) transition is a forbidden transition between the two ground-level states of hydrogen.
- The proportion of electrons in each of these states defines a 'spin temperature', T_{spin}, through:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_{spin}}$$

($T_* = 0.068K$)



Excitation mechanisms

- Collisions
  - H-H collisions (electron exchange)
  - H-e collisions (important near early X-ray sources)
- Wouthuysen-Field effect ('Lyman alpha pumping')

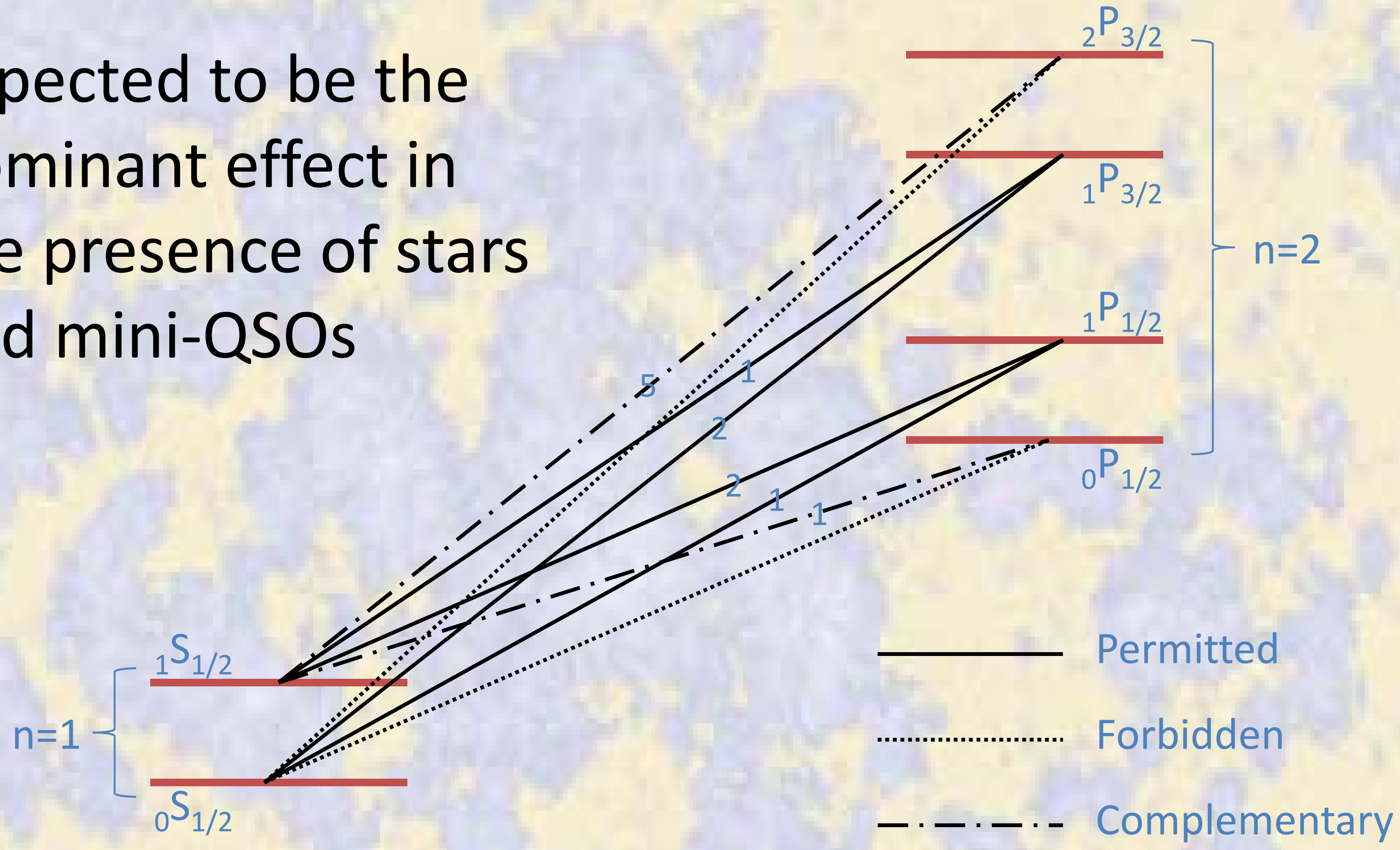
'Colour temperature', shown to be equal to T_{k} for the situation studied here

$$T_{\mathrm{spin}} = \frac{T_{\mathrm{CMB}} + y_\alpha T_\alpha + y_{\mathrm{c}} T_{\mathrm{k}}}{1 + y_\alpha + y_{\mathrm{c}}}$$

Field, 1958, Proc. IRE

Wouthuysen-Field effect

- Expected to be the dominant effect in the presence of stars and mini-QSOs



Differential brightness temperature

- To observe 21cm emission or absorption, the spin temperature needs to be decoupled from the CMB temperature.

$$\delta T_{\mathrm{b}} = \frac{T_{\mathrm{spin}} - T_{\mathrm{CMB}}}{1+z} \underbrace{\left(1 - \mathrm{e}^{-\tau_{\nu_0}}\right)}_{\approx \tau_{\nu_0}}$$

$$\tau_{\nu_0} = \frac{3}{32\pi} \frac{hc^3 A_{10}}{k_{\mathrm{B}} T_{\mathrm{spin}} \nu_0^2} \frac{x_{\mathrm{HI}} n_{\mathrm{H}}}{(1+z)(\mathrm{d}v_{\|}/\mathrm{d}r_{\|})}$$

Differential brightness temperature

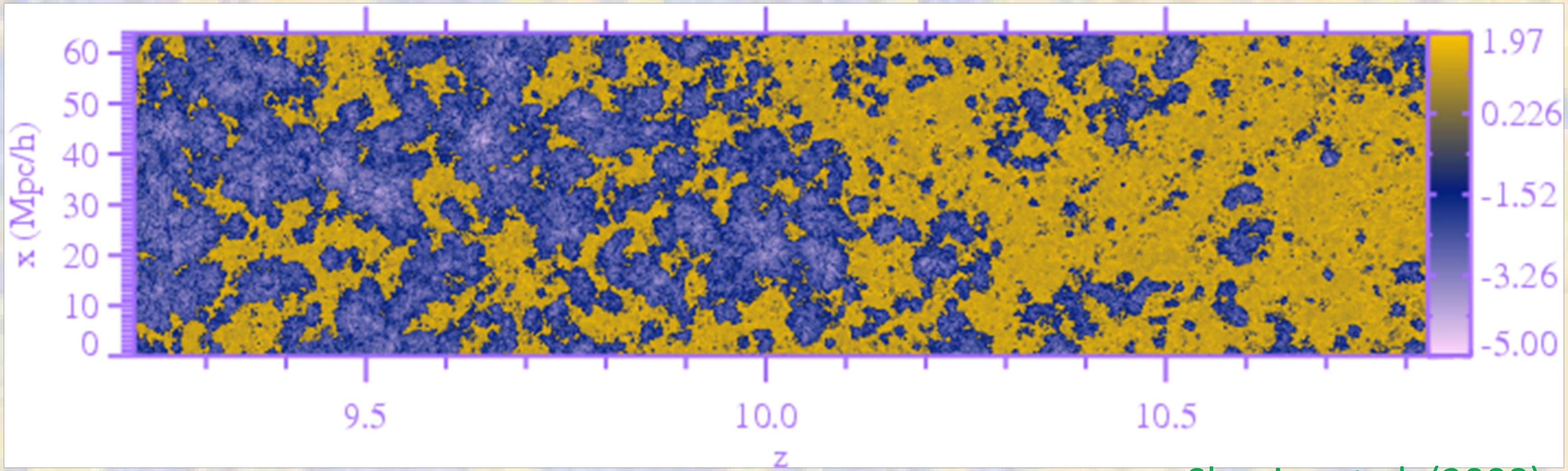
- δT_b depends on position and redshift, which in principle allows us to carry out tomography of high redshift neutral hydrogen.

$$\frac{\delta T_{\rm b}}{\rm mK} = 39h(1+\delta)x_{\rm HI}\left(1-\frac{T_{\rm CMB}}{T_{\rm spin}}\right)\left(\frac{\Omega_{\rm b}}{0.042}\right)\left[\left(\frac{0.24}{\Omega_{\rm m}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

- Contains information on:
  - the growth of structure (through $1+\delta$);
  - reionization (through x), e.g. growth of bubbles;
  - heating (through dependence on the spin temperature);
  - cosmology;
  - redshift-space distortions (through extra $\left[1-\frac{1+z}{H(z)}\frac{\partial v}{\partial r_v}\right]$ term).

Simulations of reionization: a 'slice of sight'

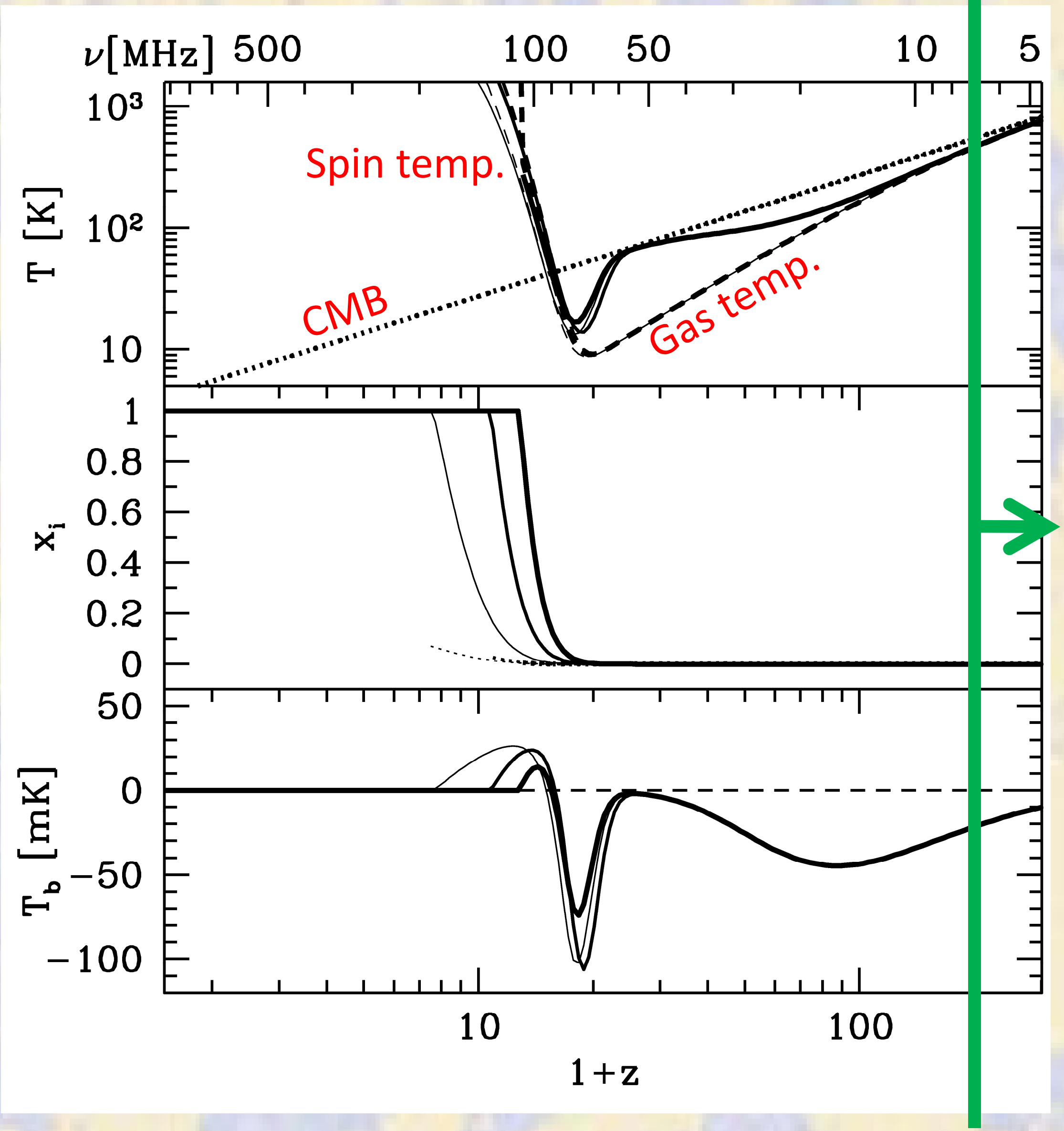
Mostly ionized ⟵ 'Swiss Cheese' ⟵ Mostly neutral



Shapiro et al. (2008)

Evolution of mean temperatures, ionization and signal

- z>200:
  - Gas temperature coupled to CMB temperature by Compton scattering.
- 50<z<200:
  - Gas cools adiabatically.
  - Spin temperature also reduced by collisional coupling.
- z_*<z<50:
  - Collisional coupling becomes ineffective.



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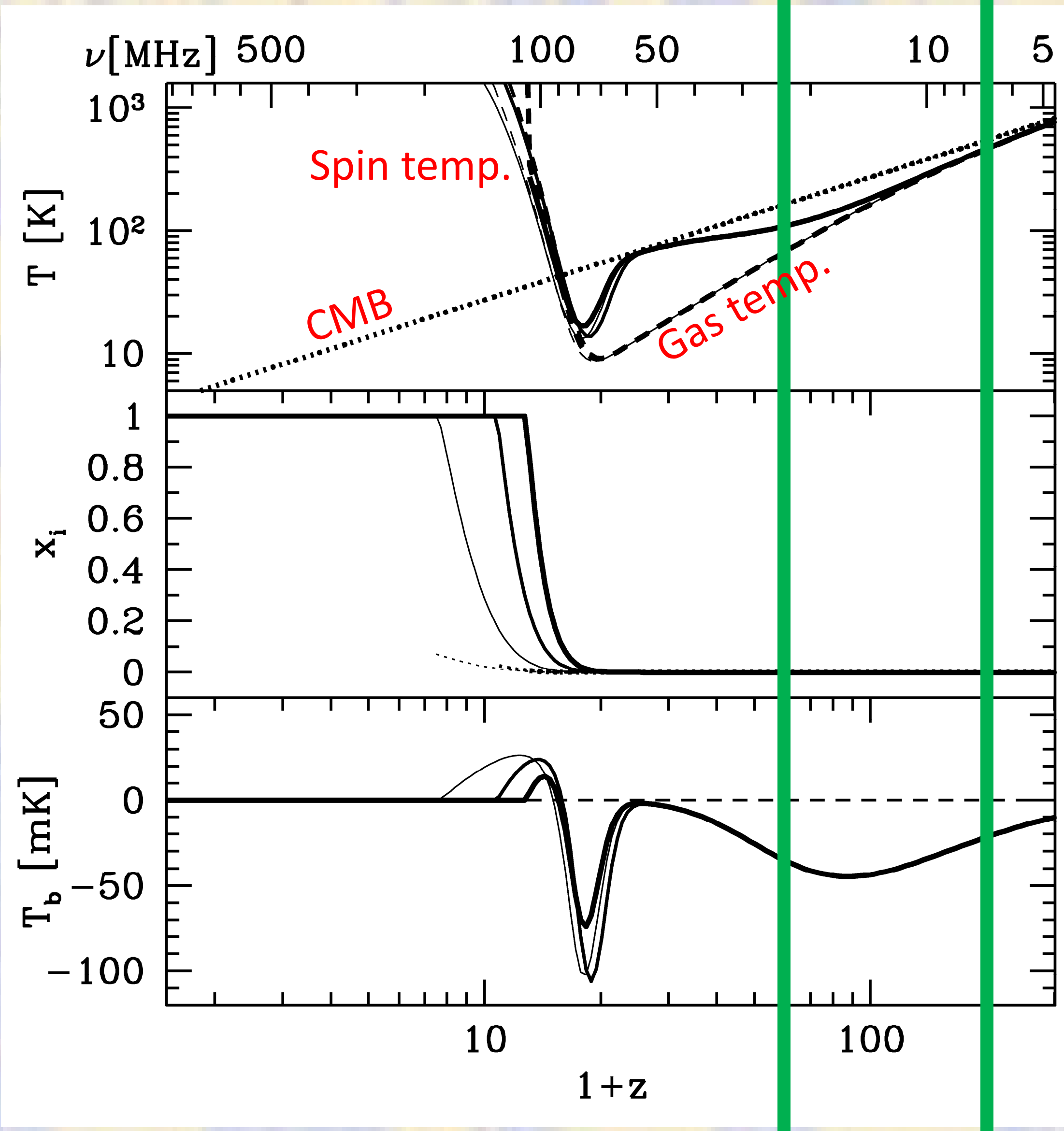

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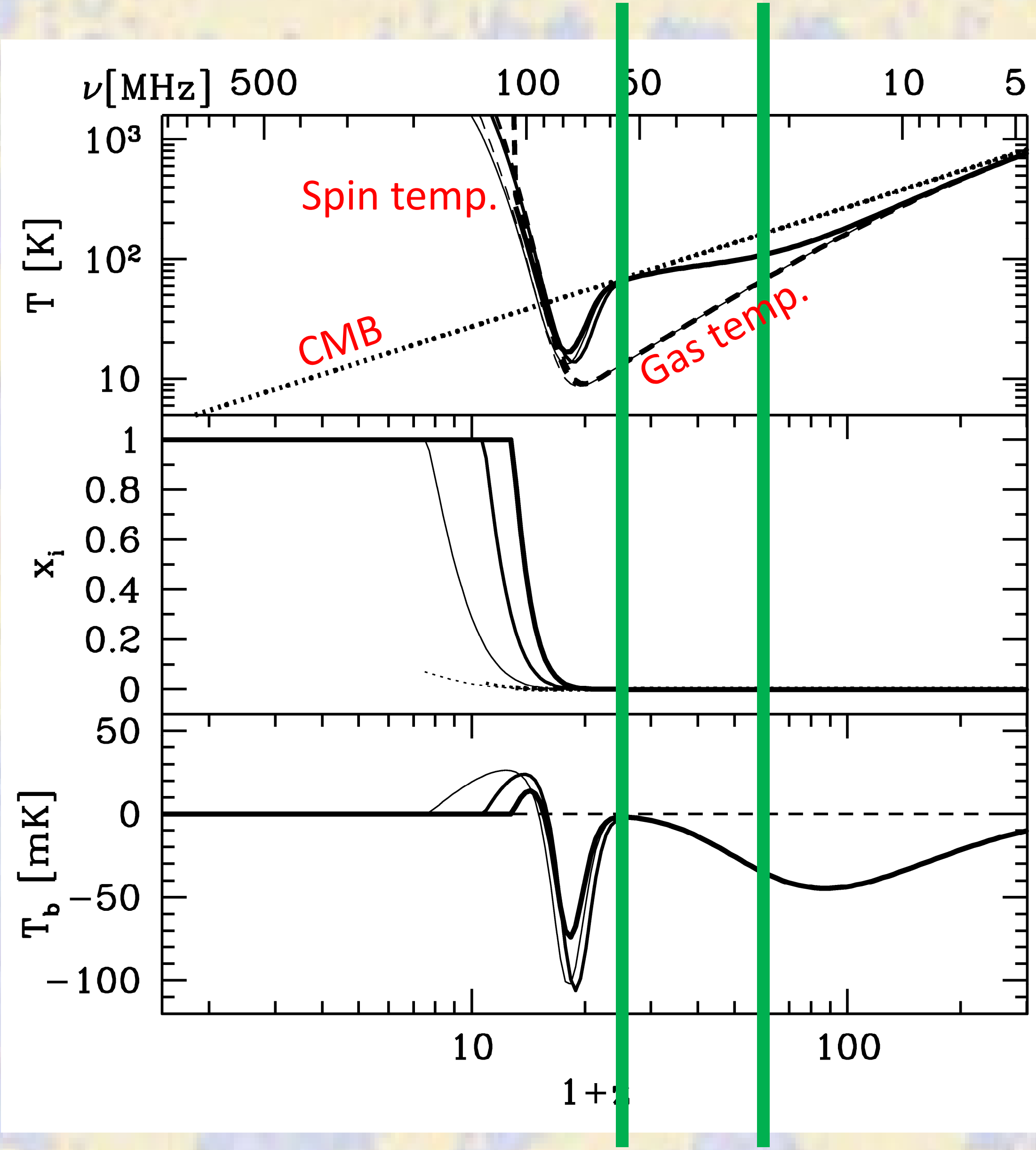
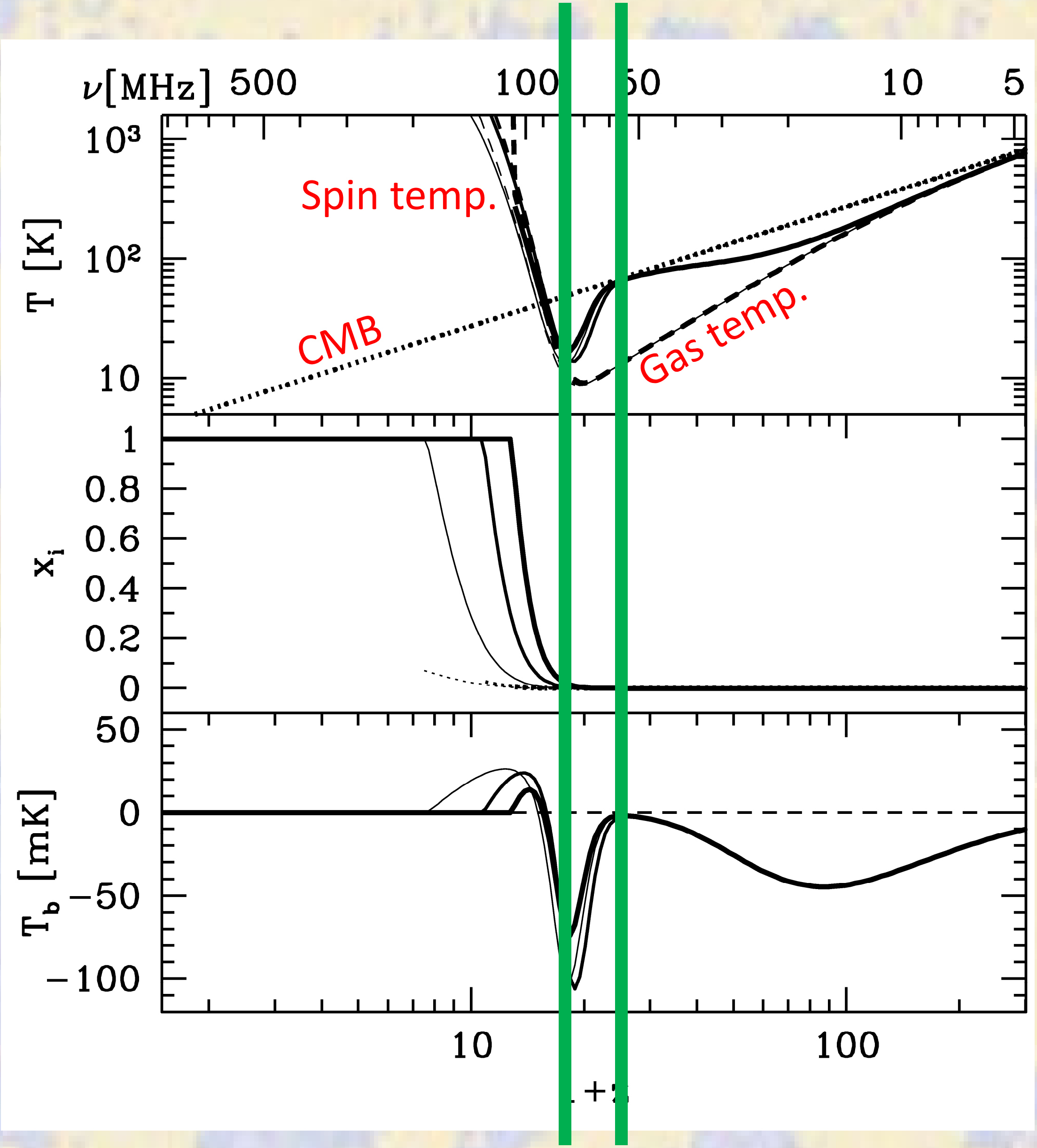


Evolution of mean temperatures, ionization and signal

- $z_\alpha < z < z_*$:
  - Lyman alpha from the first sources couples the spin temperature to the gas temperature again.
- $z_T < z < z_\alpha$:
  - Heating becomes effective.
  - Signal moves from absorption to emission.
  - Spin temperature eventually saturates.



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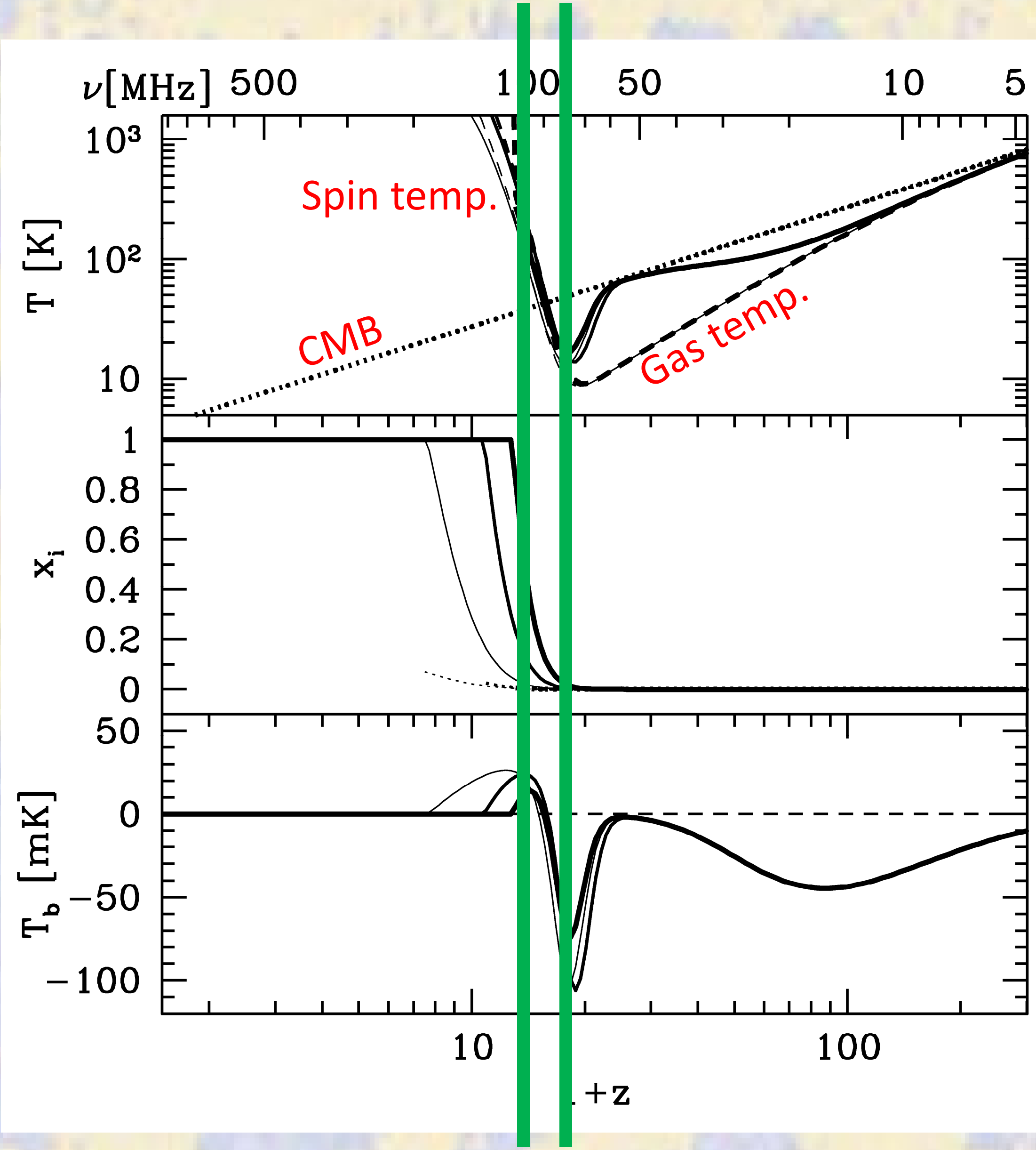
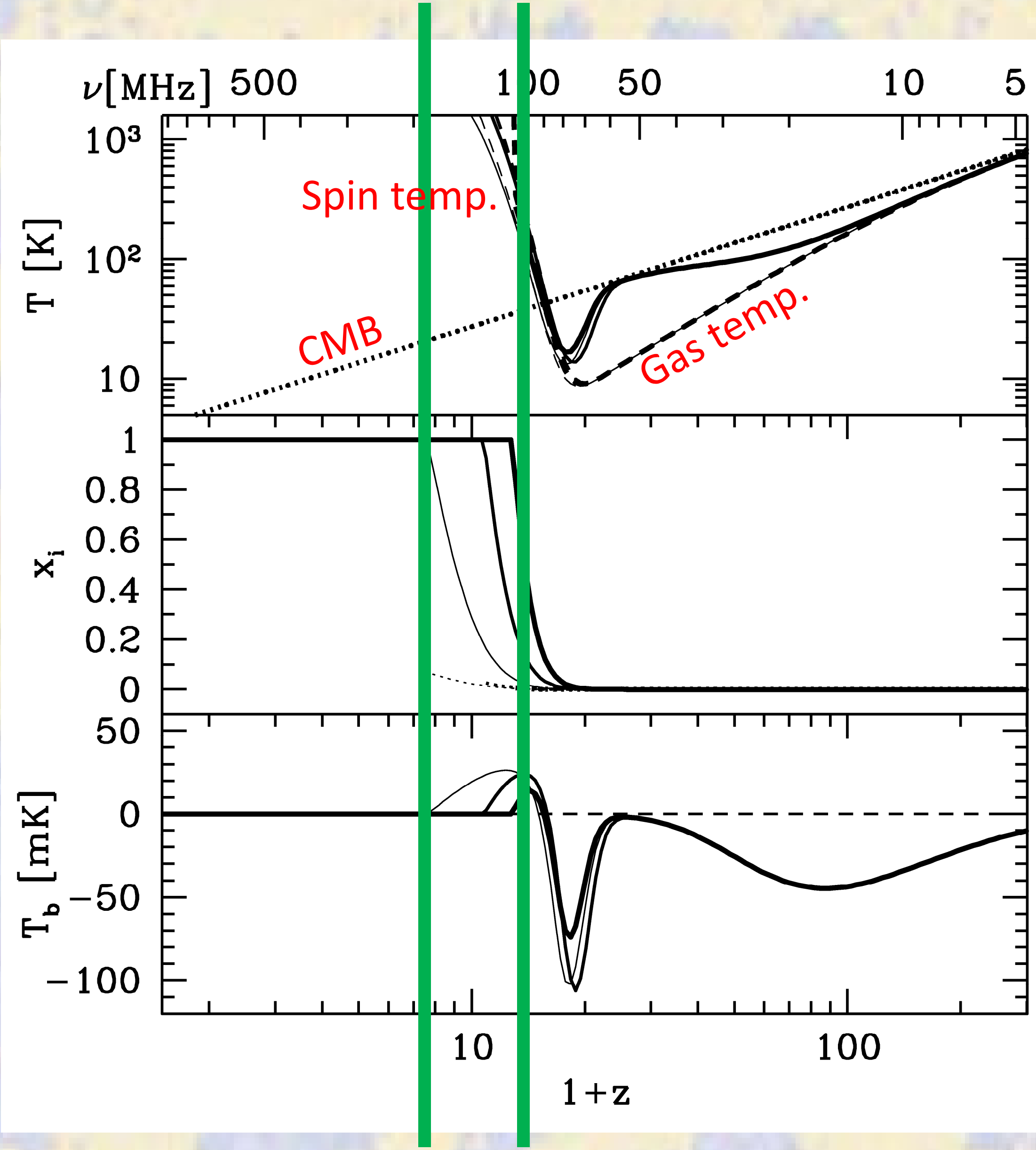


Evolution of mean temperatures, ionization and signal

- $z_r < z < z_T$:
  - Epoch of reionization
  - Brightness temperature reduced because the amount of neutral hydrogen is reduced.
- $z < z_r$:
  - Post-reionization epoch.
  - Any remaining signal comes from dense, collapsed structures.



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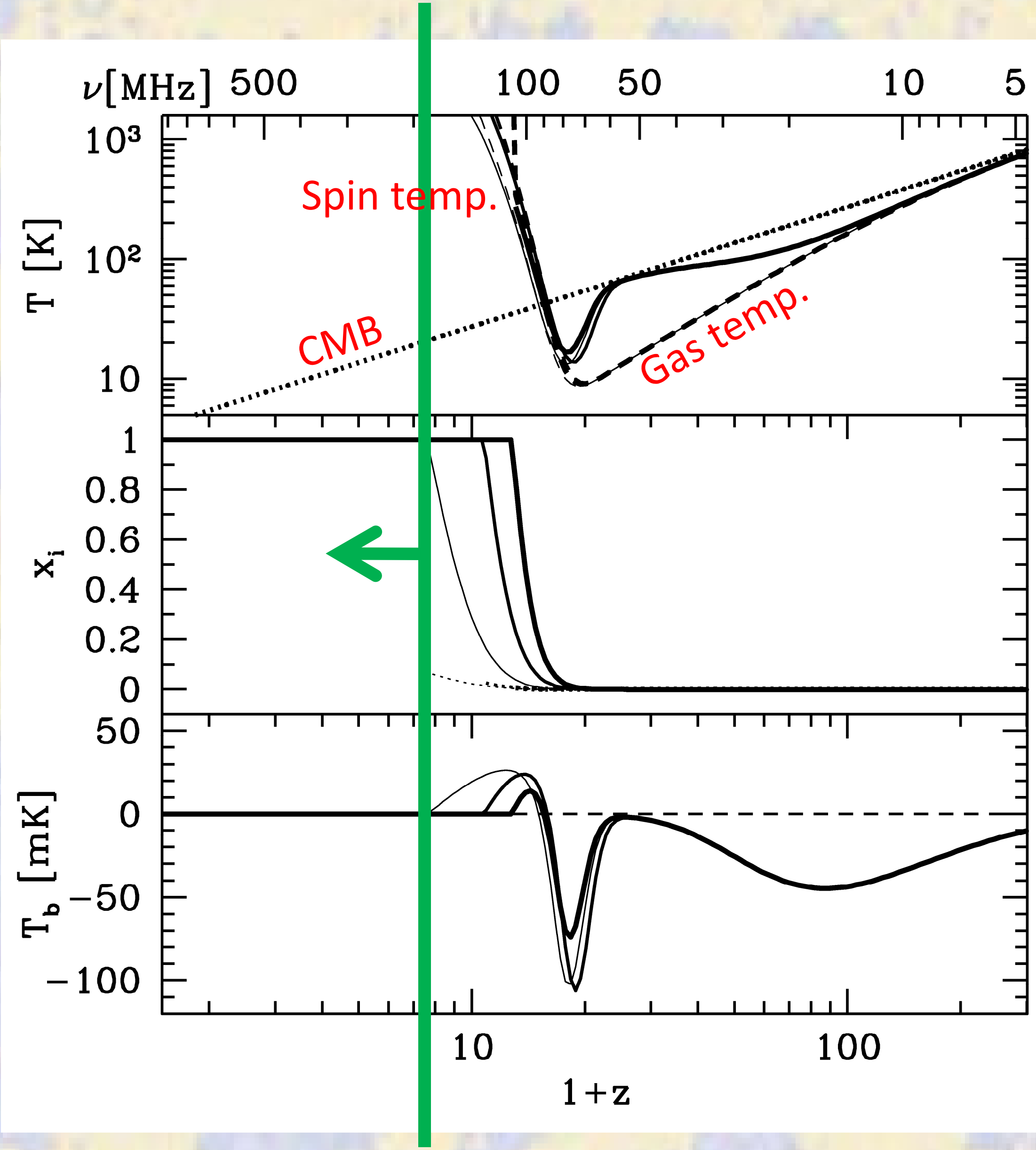


Three models

Ionizing photons reaching the IGM per baryon in stars

Lyα photons produced per baryon in stars

Relative X-ray energy per baryon in stars

Star formation efficiency

Redshift of reionization

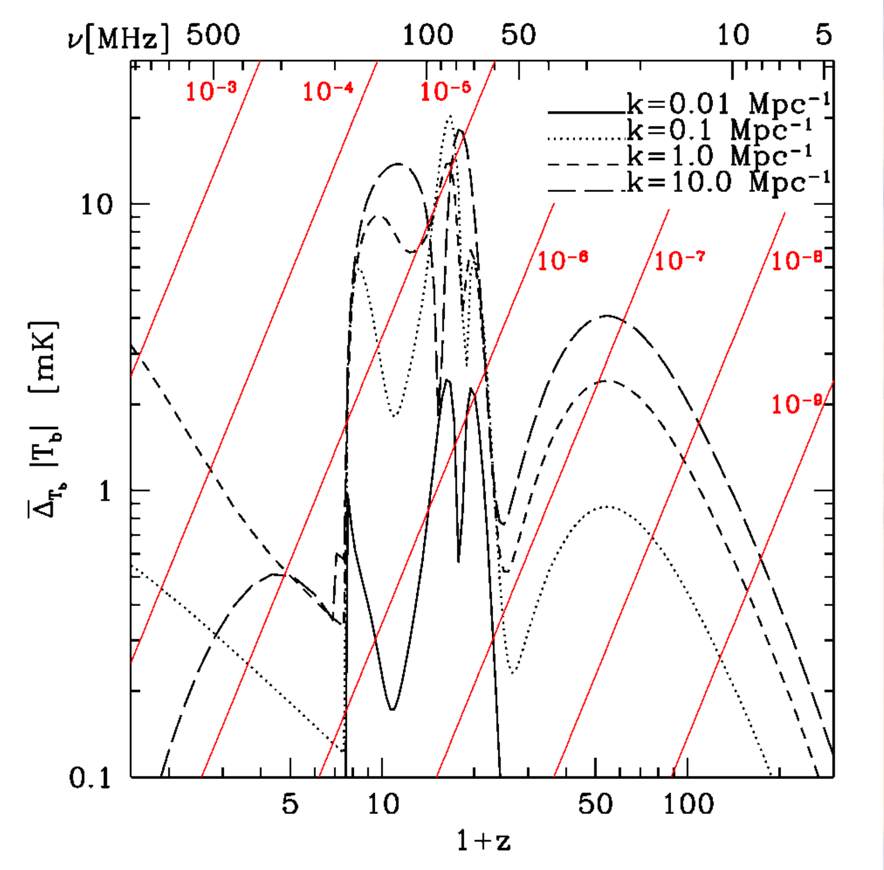
Electron-scattering optical depth

	A	B	C
$N_{ion,IGM}$	200	600	3000
f_α	1	1	0.46
f_X	1	0.1	1
f_*	0.1	0.2	0.15
z_r	6.47	9.76	11.76
τ	0.063	0.094	0.115

Parameters of a fully analytic reionization model

Power spectrum results

- This plot shows model A: earlier reionization tends to squash things together.
- Red lines are intended to show the accuracy of foreground subtraction required.
- Three regimes, the highest redshift of which is maybe the most interesting for a lunar array.



When do Lyα coupling, X-ray heating and ionization become important?

- Redshift at which fluctuations due to Lyα and X-rays become comparable to density fluctuations depends only logarithmically on model parameters (exponential growth of collapsed fraction dominates the transition).
- For stellar sources, it is very unlikely that heating becomes important before Lyα coupling.
- Reionization almost certainly occurs well after both these transitions.

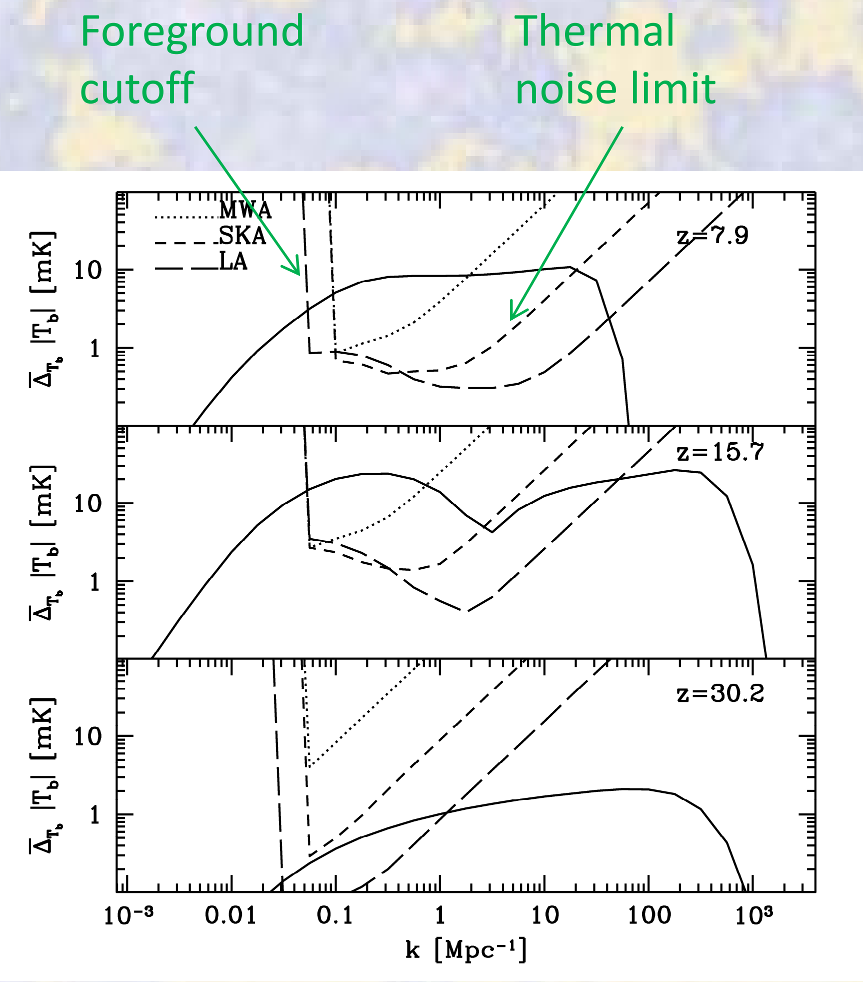
Hypothetical instruments

- Each assumed to be optimally configured at each redshift.
- Meant to illustrate different cases rather than 'real' instruments.

TABLE I. Low-frequency radio telescopes and their parameters. We specify the number of antennae N_a, total collecting area A_{tot}, bandwidth B, and total integration time t_{int} for each instrument.

Array	N_a	$A_{tot}(10^3\ m^2)$	B (MHz)	t_{int} (hr)
MWA	500	7.0	6	1000
SKA	5000	600	6	1000
LA	7800	3600	8	12000

Sensitivity to the power spectrum (optimistic)



- Similar sensitivity at low *k* and low *z* because of cosmic variance.
- Only the lunar array is able to probe trough at intermediate redshift or anything at high redshift.
- In practice, MWA and SKA may not go to such low frequencies anyway…

Summary

- An analytic model of the dark ages and reionization allows us to explore different models without the expense of full simulations (of currently uncertain physics).
- Signal at $z>25$ likely to be a clean probe of cosmology (dark energy, inflation…), and only accessible with a lunar array, in all likelihood.
- Lower redshift signal very complicated! Separation of powers may help disentangle things.
- Helps that the absorption signal can be much larger than the emission signal.
- Calculations like this may allow an array to be optimised (somewhat) for the expected signal.