Foregrounds for observations of the high-redshift global 21-cm signal

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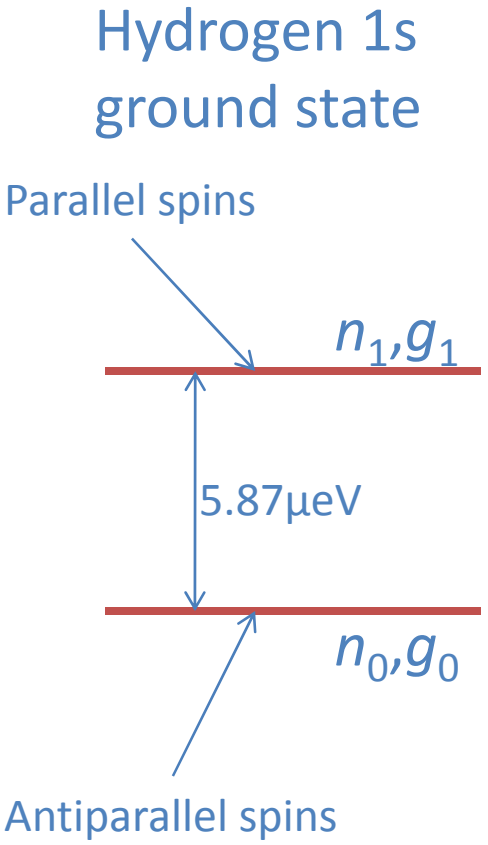
The hydrogen 21cm line

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

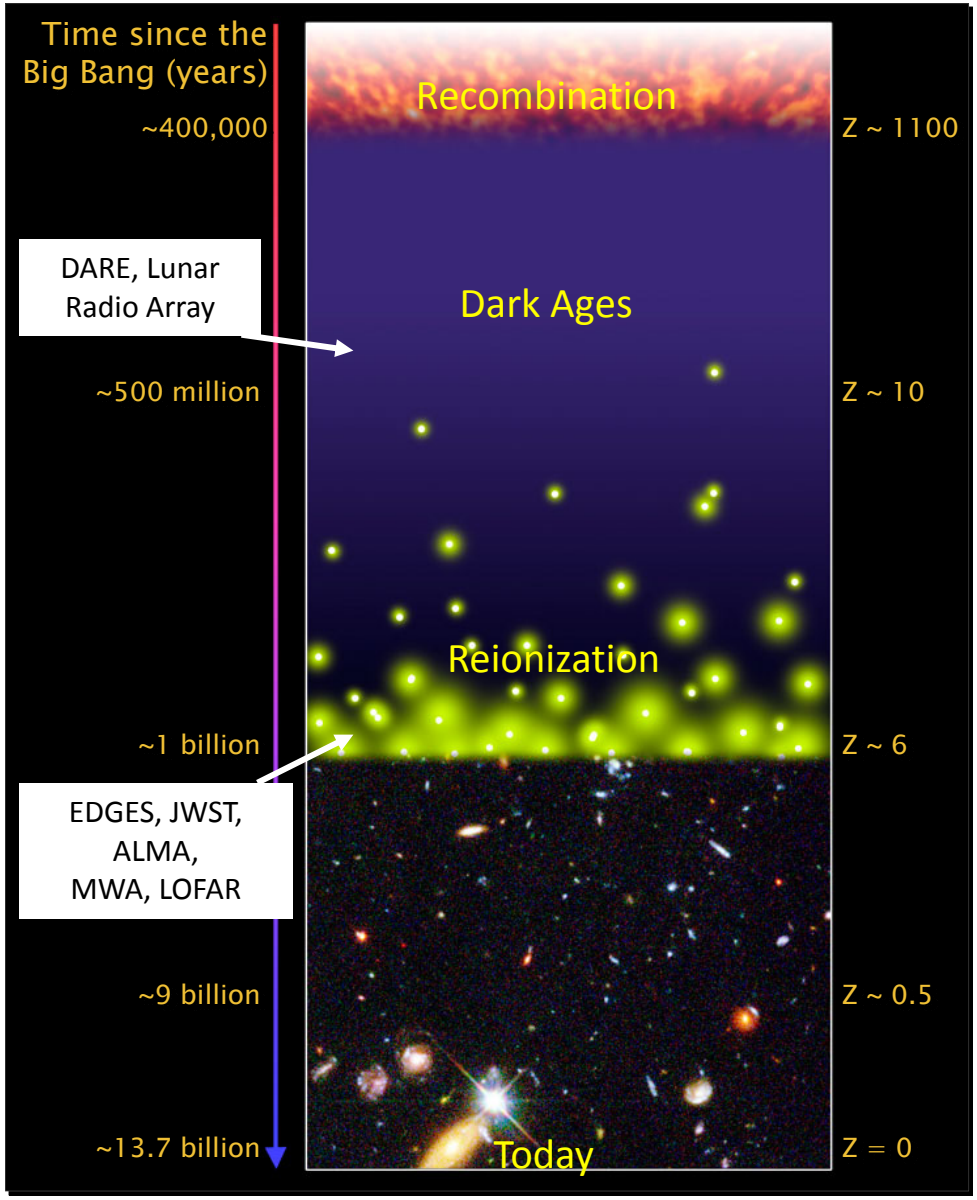
$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \mathrm{e}^{-T_*/T_{\mathrm{spin}}}$$

(T_* = 0.068K)



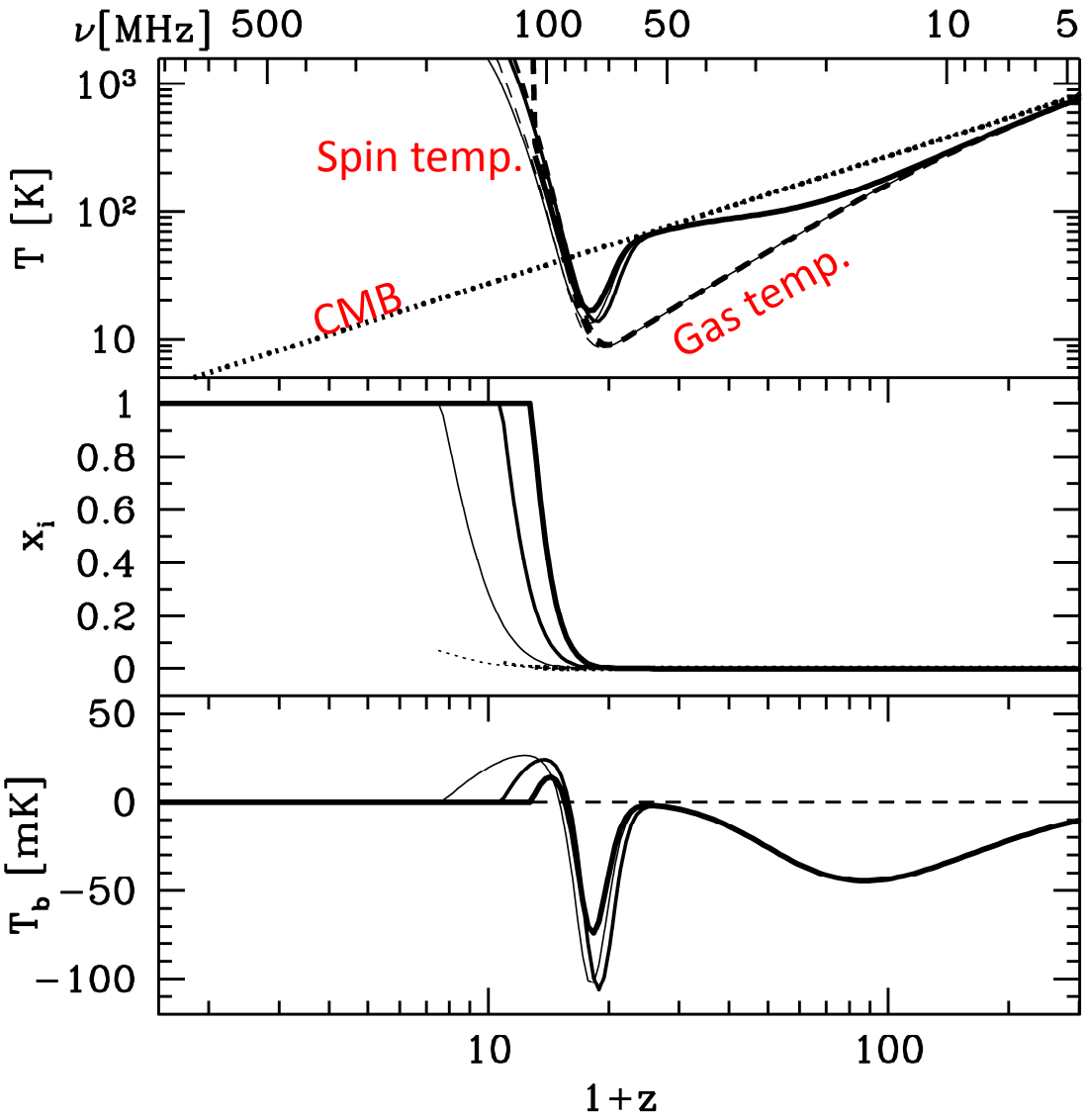
Major epochs in cosmic history, from recombination onwards

- Pre-reionization:
  - Evolution covered by simple physics
  - Good for cosmology
  - 21-cm line may be the only probe.
- Reionization:
  - Upcoming instruments see the tip of the iceberg
  - 21-cm measurements can probe the integrated effects of all the sources.
- Post-reionization:
  - Most remaining neutral hydrogen is in dense clumps.



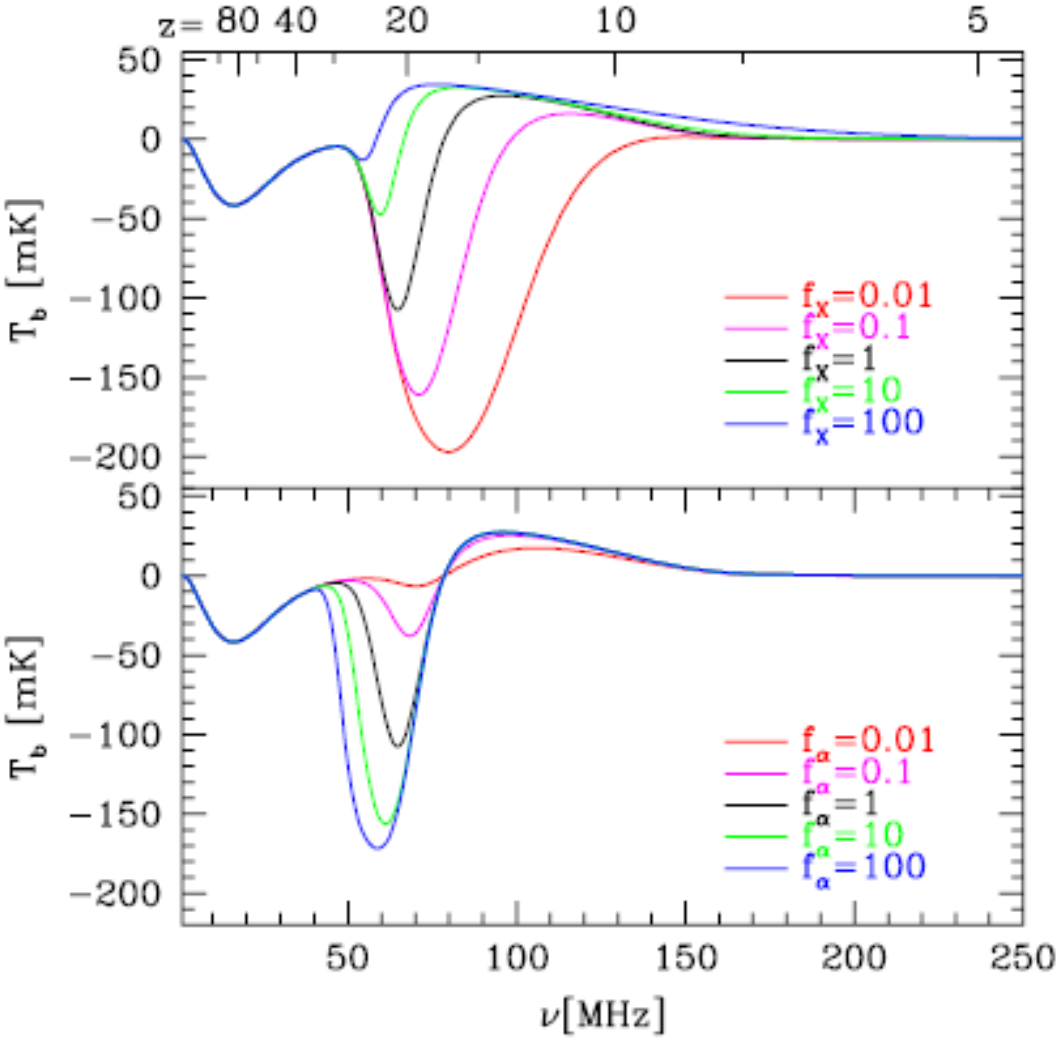
Evolution of the global ionization fraction, temperature, and 21-cm brightness temperature.

- Three different models, same basic features.
- 'Dark Ages': absorption from cold gas; collisional coupling.
- 'Cosmic twilight': absorption due to Lyman alpha coupling.
- Emission as gas is heated by UV and X-rays.
- Signal disappears when all the gas is ionized.



Pritchard & Loeb (2008)

Varying model parameters

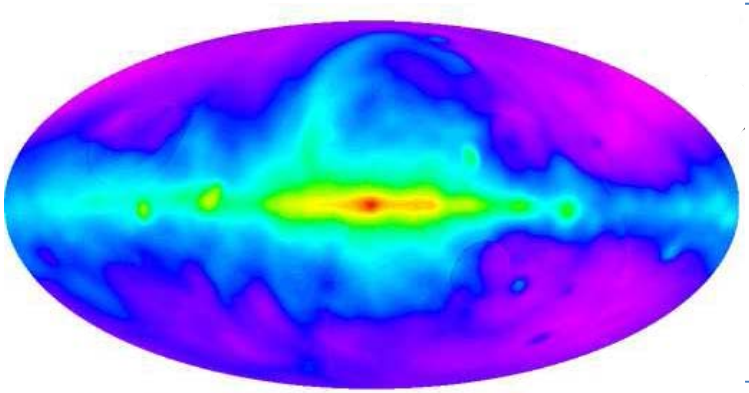


X-ray efficiency

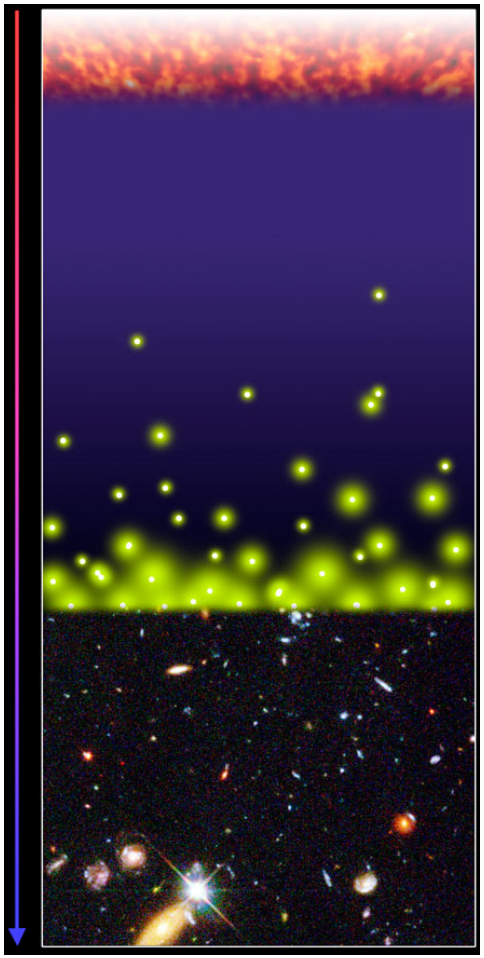
Lyman-α efficiency

Astrophysical foregrounds

- Synchrotron & free-free from our own galaxy.
- Extragalactic radio sources.
- The Sun & Jupiter.
- Radio recombination lines.

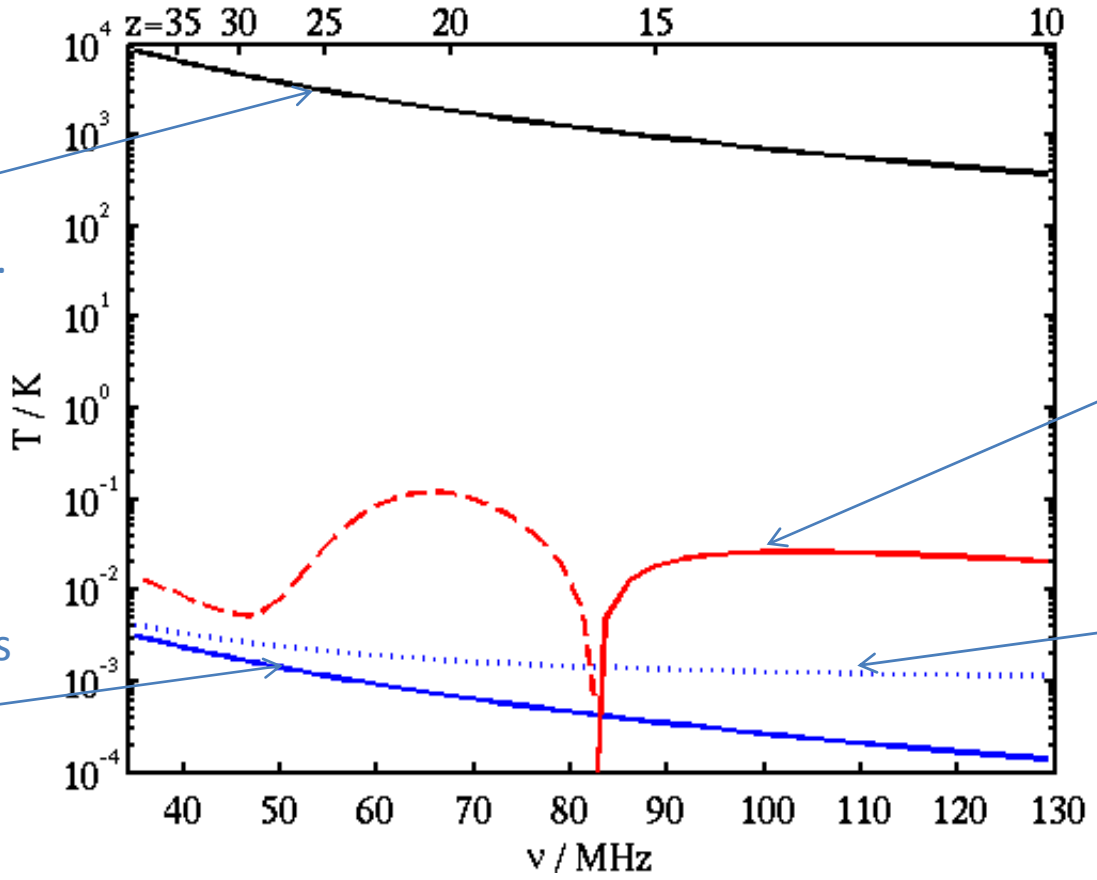


Ugh



Size of the foregrounds

Foregrounds in a cool area of sky, according to de Oliveira-Costa et al. (2008)

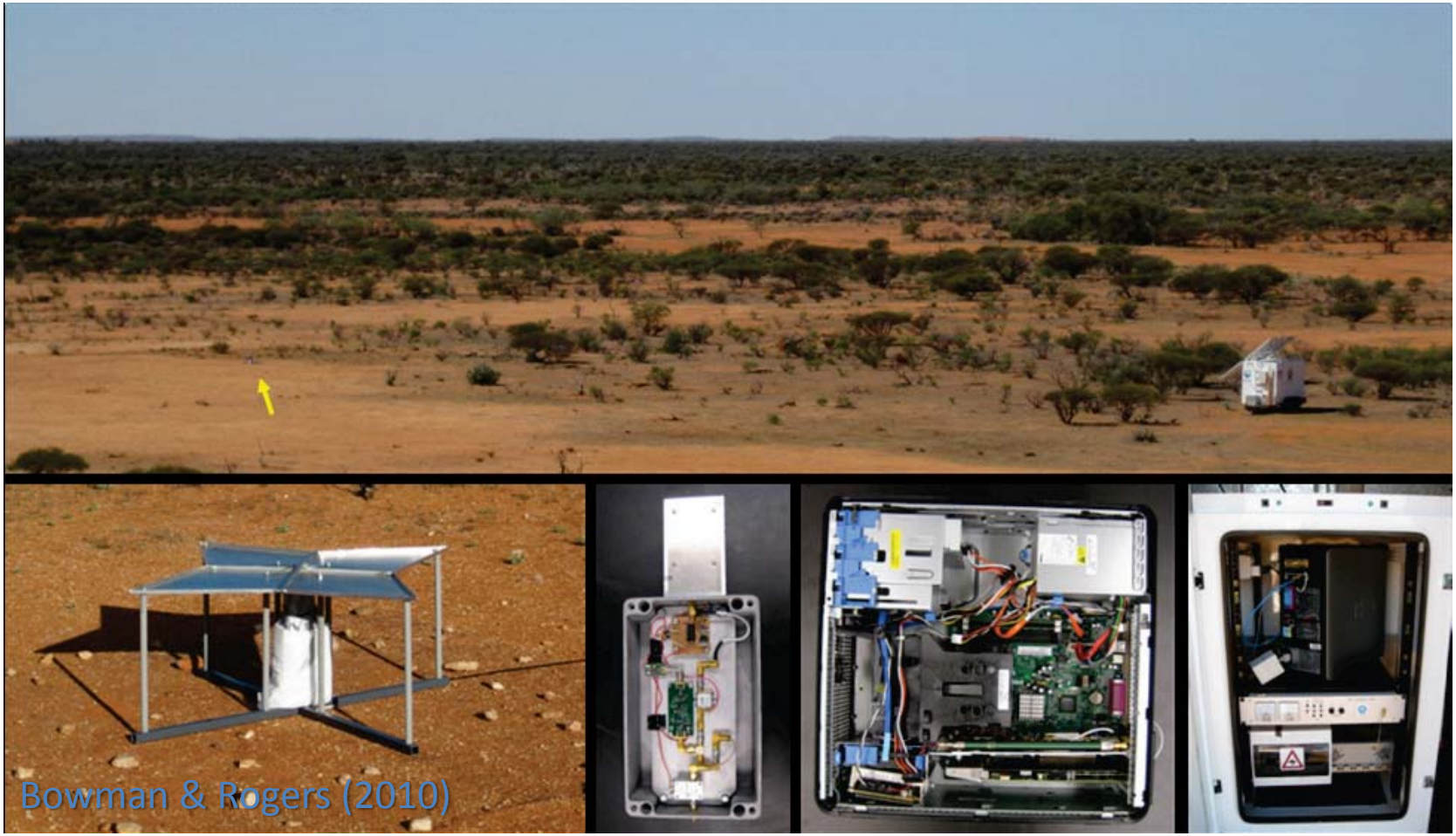


Signal

Noise plus a systematic error

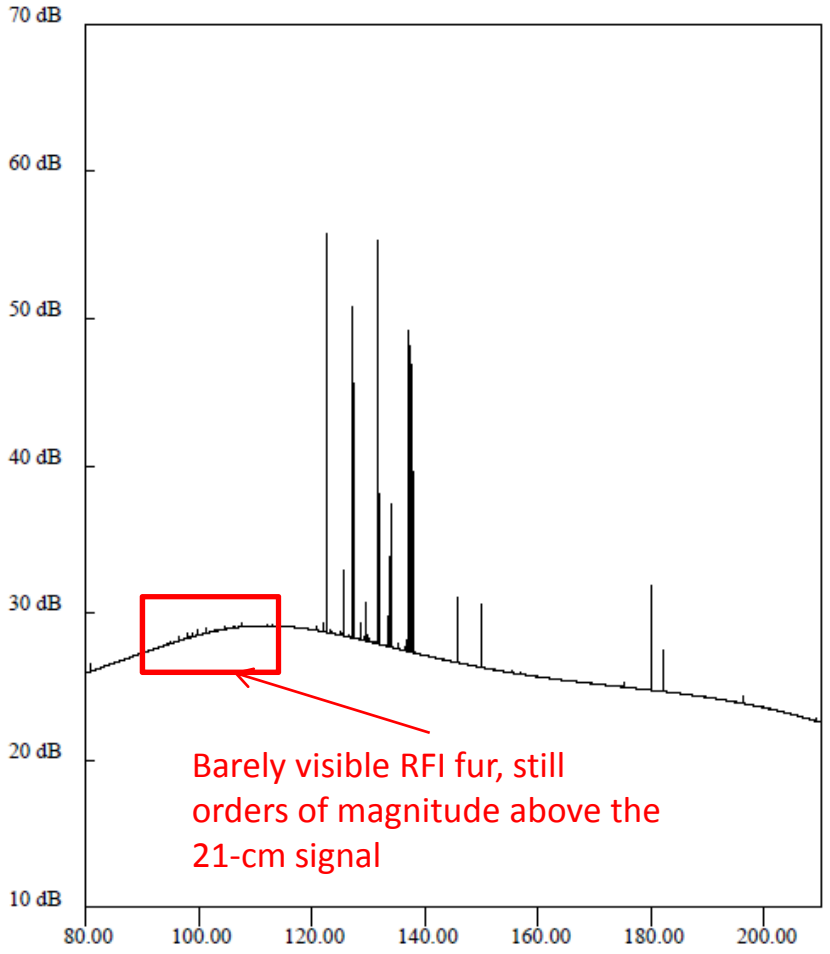
Noise after 1000hrs of observation, binned into 2MHz channels

EDGES (Experiment to Detect the Global EoR signal)

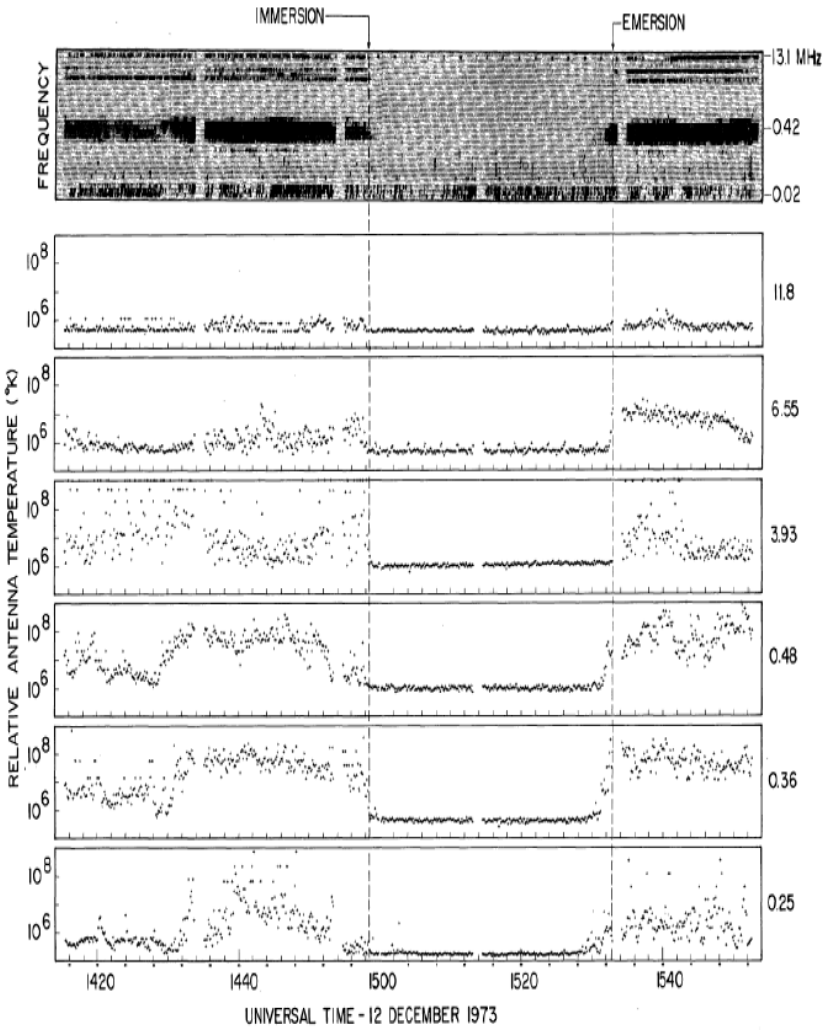


Raw EDGES spectrum

- Overall shape from the spectrum of the sky multiplied by the instrument response.
- Huge RFI spikes (→ dynamic range problem) + many tiny spikes.
- This site is many orders of magnitude quieter than the VLA site…



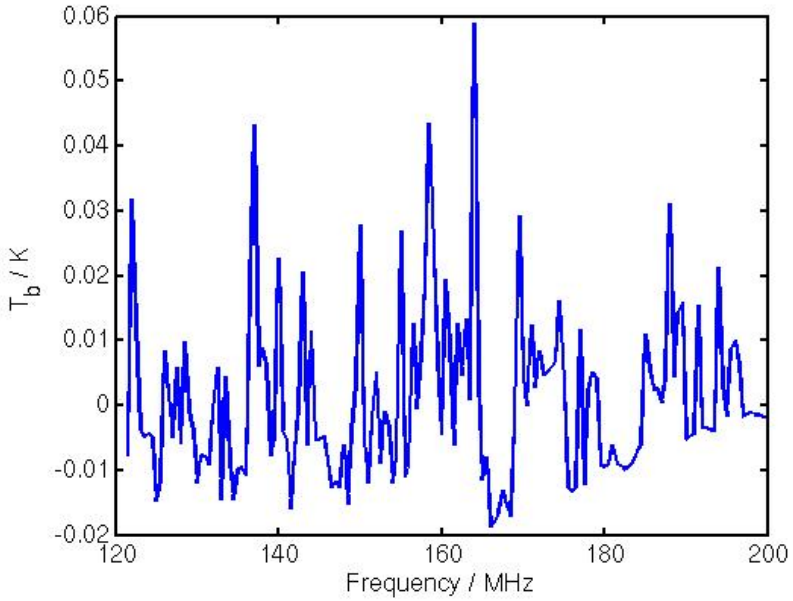
- One site in the inner solar system is shielded from terrestrial RFI: the lunar farside.
  - What's needed is EDGES in space!
- Proposed DARE satellite would go to lower frequencies than EDGES, to probe the cosmic dawn and the start of the EoR.
- Astrophysical foregrounds at these frequencies are even worse!



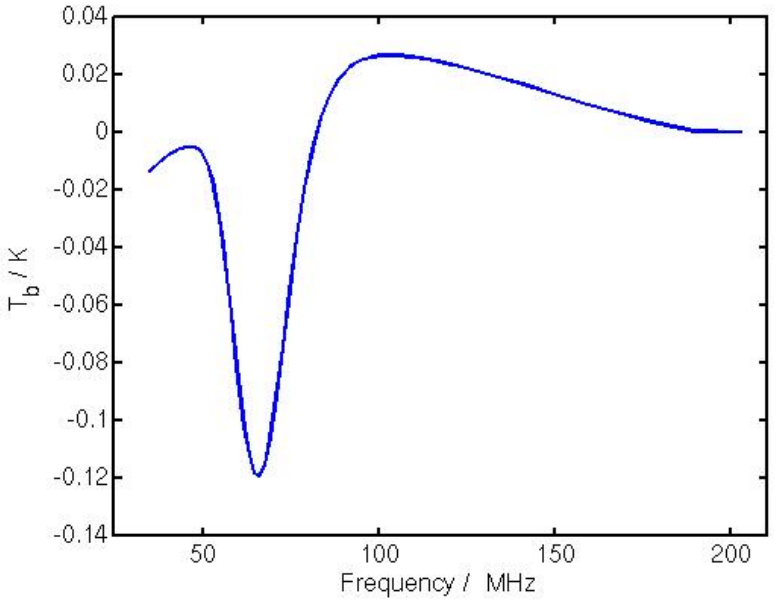
Alexander et al. (1975)

Removing foregrounds: can we learn from the interferometric case?

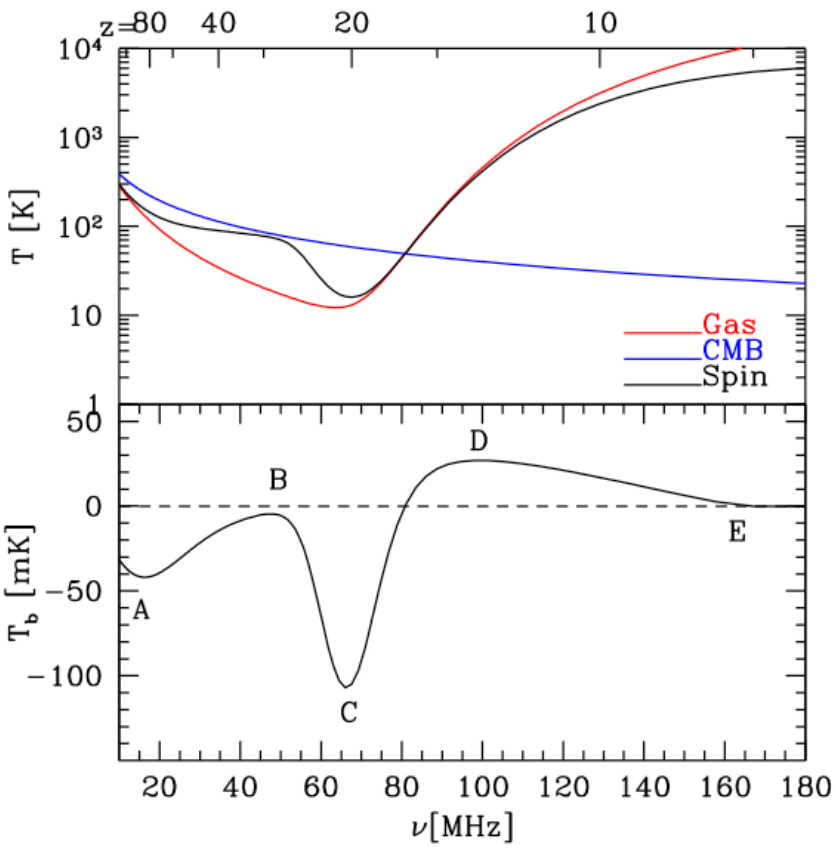
Signal for one resolution element of LOFAR



Signal for one 'resolution element' of a global 21-cm signal experiment.



Approaches to removing foregrounds: fit parametrized models



- Signal has turning points A,B,C,D,E with frequency and amplitude.
- Parametrize logT_{FG} of the diffuse foregrounds as a polynomial in logν.
- Treat instrumental frequency response as a low-order polynomial.
- Fit other parameters as necessary: solar spectrum, other aspects of the antenna…

More on the instrumental response

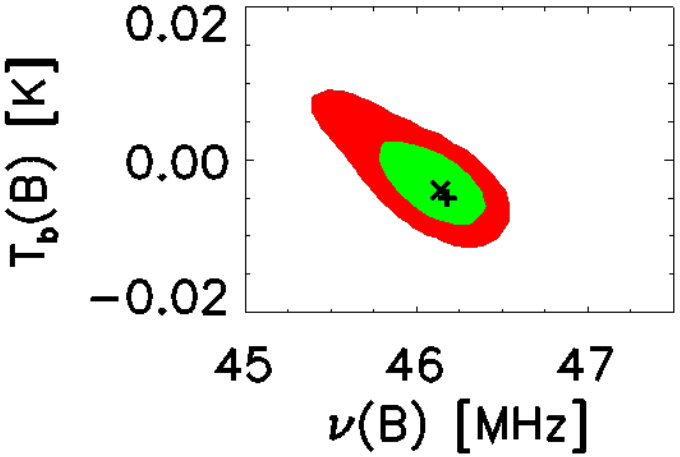
$$T_{\rm ant}(\nu) = \left[1 - |\Gamma(\nu)|^2\right] T_{\rm sky}(\nu) + \left[2\varepsilon|\Gamma|\cos(\beta) + \varepsilon^2|\Gamma|^2\cos^2(\beta) + (1-\varepsilon)^2|\Gamma|^2\right] T_{\rm rcv}(\nu) + \ldots$$

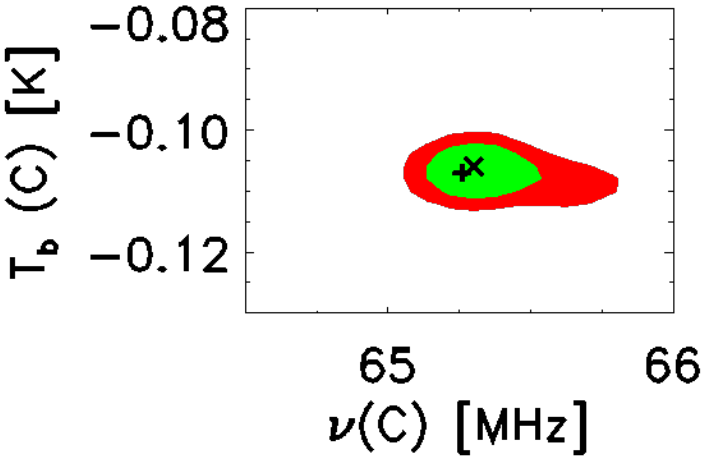
(Rogers & Bowman 2010)

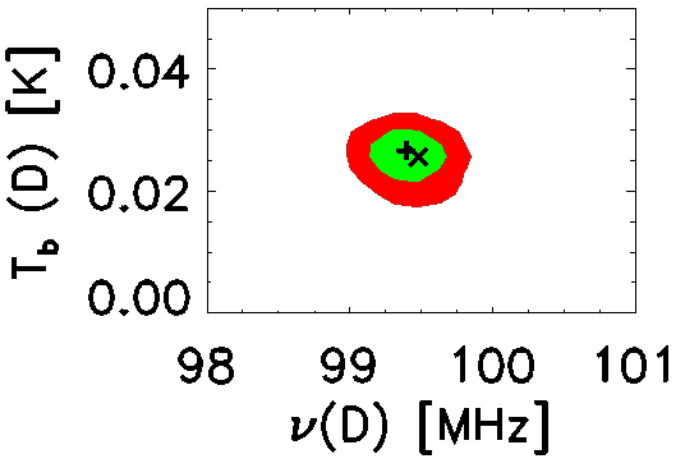
- $T_{\rm ant}$: antenna temperature, calibrated by switching between loads
- $T_{\rm sky}$: sky temperature (large!)
- $T_{\rm rcv}$: temperature of receiver noise propagated back towards the antenna
- $|\Gamma|^2$: power reflection coefficient between antenna and receiver
- β : phase shift due to electrical path length
- ε : voltage correlation coefficient

Preliminary results (using MCMC to find parameter likelihoods)

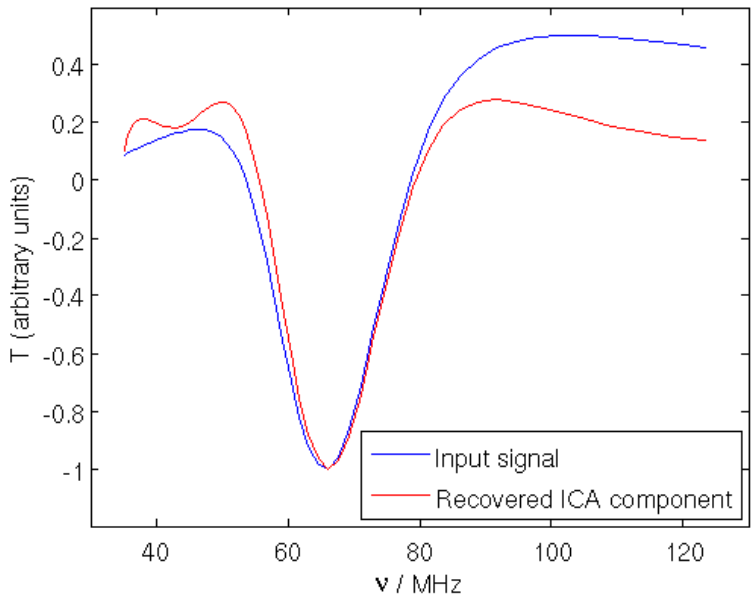
Four independent pointings for a total of 3000 hours. Doesn't yet include the Sun, the Moon, Jupiter or the instrument!

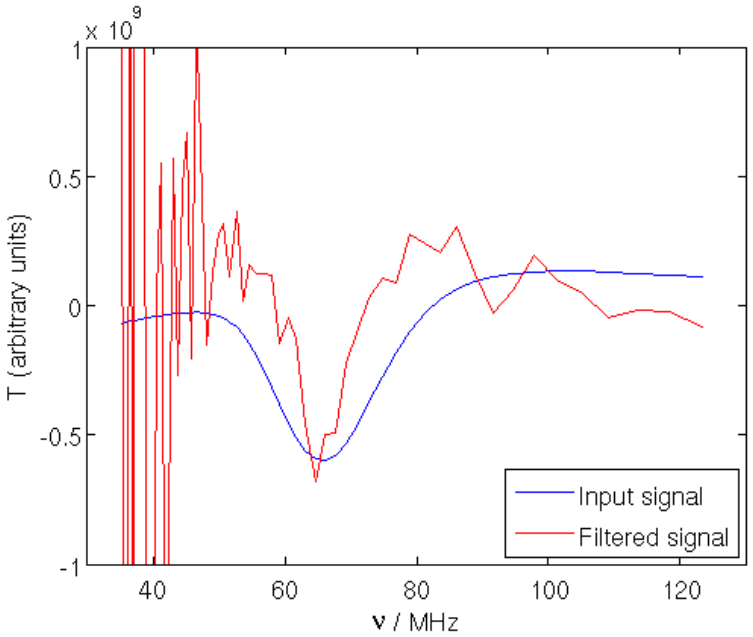






Approaches to removing foregrounds: ICA and optimal filtering





- Independent component analysis: a non-parametric signal separation technique.
- Finds statistically independent components (from physically independent components)

- Matched filtering: works nicely for finding signals in noise.
- Can it be adapted to non-stochastic noise?
- May work best for an initial detection.

Summary

- Global 21-cm experiments can go to high redshift with a single low-frequency radio antenna, by probing the integrated effect of all sources on the IGM.
- The main challenge to extracting that signal is removing foregrounds which are $\sim 10^{4\text{-}6}$ times larger.
  - These interact with inaccuracies of the calibration and modelling of the instrument.
- Use the fact that the signal is spatially constant but has spectral features, while the foregrounds are spatially varying but are spectrally smooth.
- There are some lessons from interferometric experiments, but the global case seems more awkward in some ways.
- There are some promising statistical techniques to remove the foregrounds, but the best approach is still unclear.