



21 cm: Reionization

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What is the Reionization Era?

A Schematic Outline of the Cosmic History

Time since the Big Bang (years)

~ 300 thousand

~ 500 million

~ 1 billion

~ 9 billion

~ 13 billion



← The Big Bang

The Universe filled with ionized gas

← The Universe becomes neutral and opaque

The Dark Ages start

Galaxies and Quasars begin to form
The Reionization starts

The Cosmic Renaissance
The Dark Ages end

← Reionization complete, the Universe becomes transparent again

Galaxies evolve

The Solar System forms

Today: Astronomers figure it all out!

Brightness Temperature

- Brightness temperature is equivalent to intensity.
- So when we measure T_b , we can picture it like absorption or emission in the intensity.
- Idea is to measure T_b of high-redshift hydrogen clouds against the CMB.

Brightness Temperature

$$T'_b(\nu) = T_s (1 - e^{-\tau_\nu}) + T'_\gamma(\nu) e^{-\tau_\nu}$$

- Here T_s is defined as the spin temperature like so

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} e^{-E_{10}/k_B T_s} = 3e^{-T^*/T_s}$$

- T'_γ is the temperature of the CMB

[Brightness Temperature]

- T'_b is defined at the cloud, thus we need to correct for redshift by dividing by $(1+z)$.
- We see that T_b contains contributions from both the cloud and CMB.
- We want only the cloud's T_b so we subtract with the brightness temperature of the CMB.

Differential Brightness Temperature

$$\delta T_b(\nu) = \frac{T_s(1 - e^{-\tau_\nu}) + T_\gamma(\nu)e^{-\tau_\nu} - T_\gamma(\nu)}{1+z} = \frac{T_s - T_\gamma(z)}{1+z}(1 - e^{-\tau_\nu}) \approx \frac{T_s - T_\gamma(z)}{1+z}\tau_{\nu 0}$$

$$\approx 9x_{HI}(1+\delta)(1+z)^{1/2} \left[1 - \frac{T_\gamma(z)}{T_s} \right] \left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right] \text{ mK}$$

- Note that x_{HI} is the neutral hydrogen fraction
- We can measure this explicitly if $T_s \gg T_\gamma$
- In other words, in emission
- Whether we see a signal depends on T_s

[Spin Temperature]

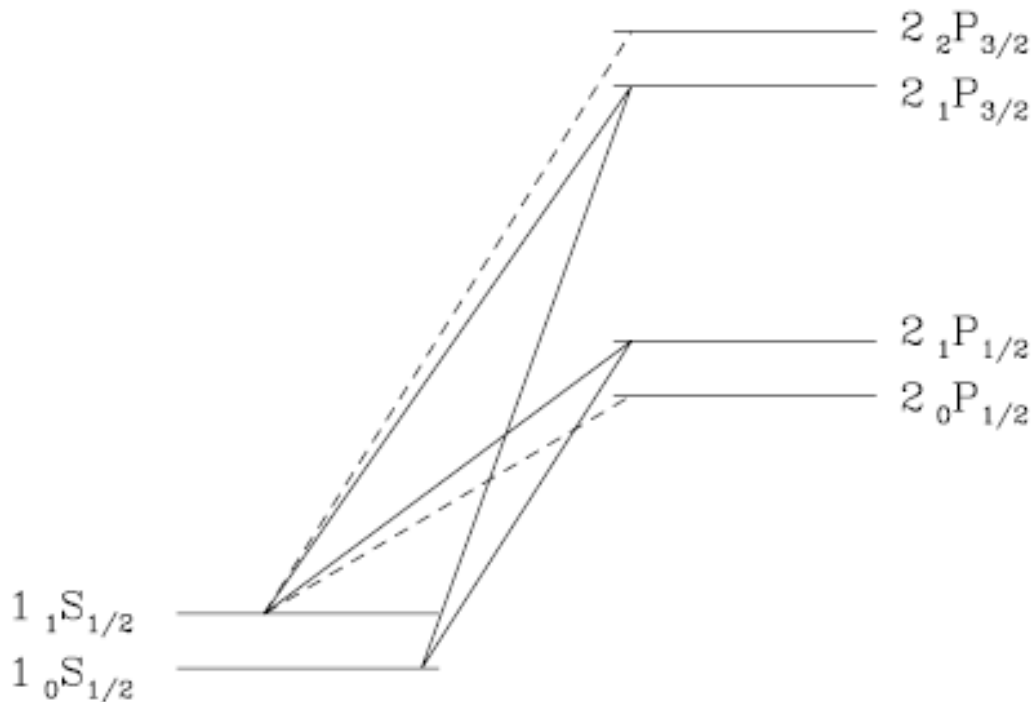
- Three processes that determine T_s
- Absorption of CMB photons
- Collisions with other hydrogen atoms, free electrons, and protons
- Scattering of UV photons

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

[Collisional Coupling]

- The most known is hydrogen-hydrogen collisions.
- Electron interactions causes a spin exchange, causing the hydrogen atom to either jump up or down into the hyperfine levels.
- Can also occur with free electrons, bare protons, deuterium atoms, helium atoms or ions, or other trace elements.

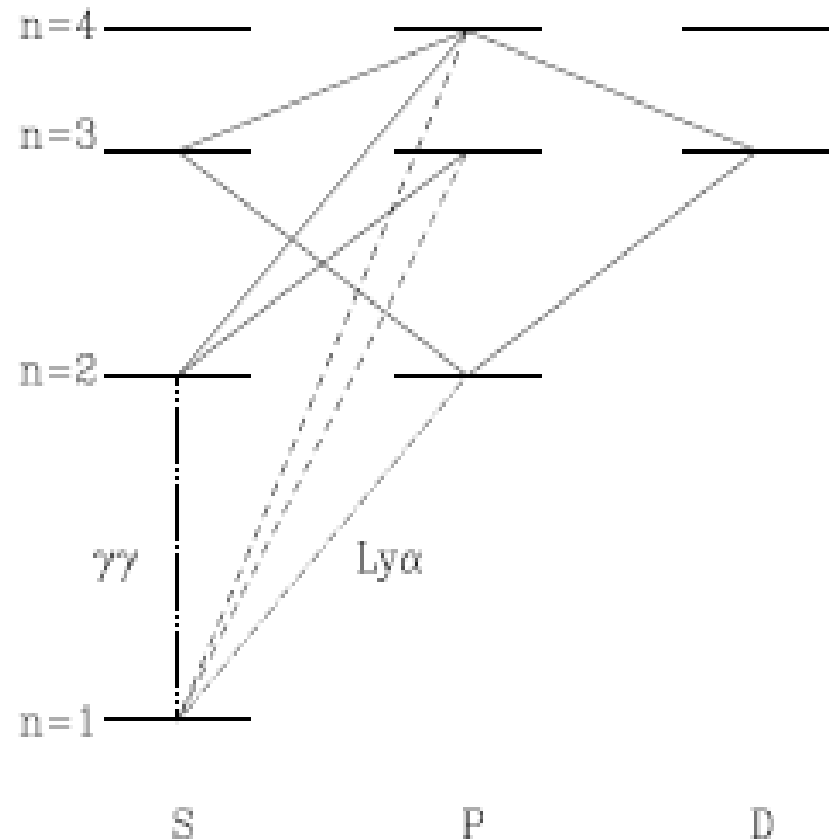
[Wouthuysen-Field Effect]



- Electric dipole selection rules allow certain atomic transitions that make it transition to one of central P states.
- But it allows it to decay into the hyperfine triplet level.

[Wouthuysen-Field Effect]

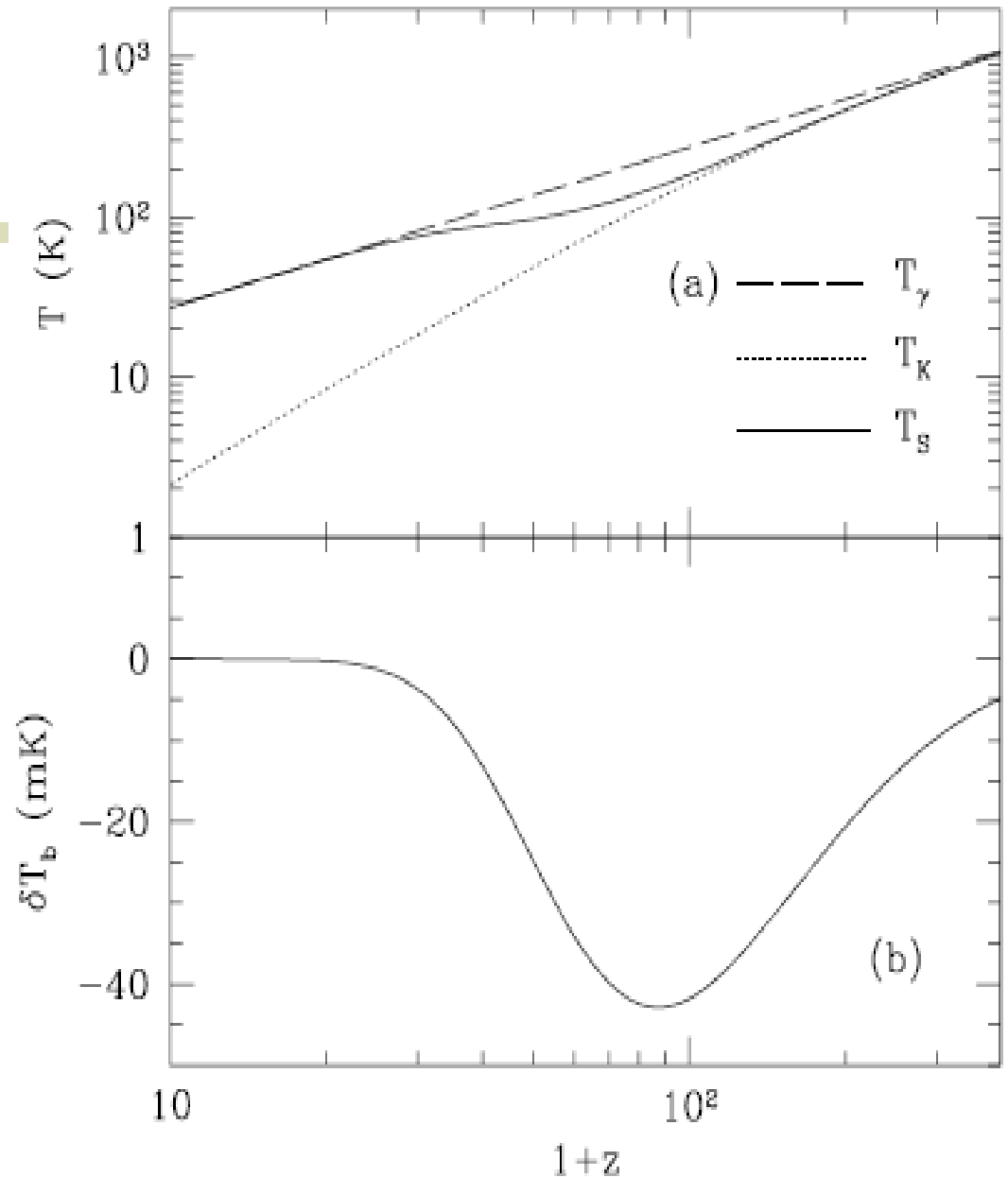
- Also important for non Lyman alpha photons, in particular for any Lyman continuum photon.
- Except for Lyman Beta.



Global Evolution of IGM

- There are only three temperatures we care about, T_K T_s T_γ
- The previous collisional coupling and W-field effect both couple T_s to T_k
- At the beginning of universe, all three were coupled due to Compton scattering between CMB and residual electrons
- But CMB temperature cooled off like $(1+z)$
- While the kinetic temperature cooled off like an adiabatic gas $(1+z)^2$

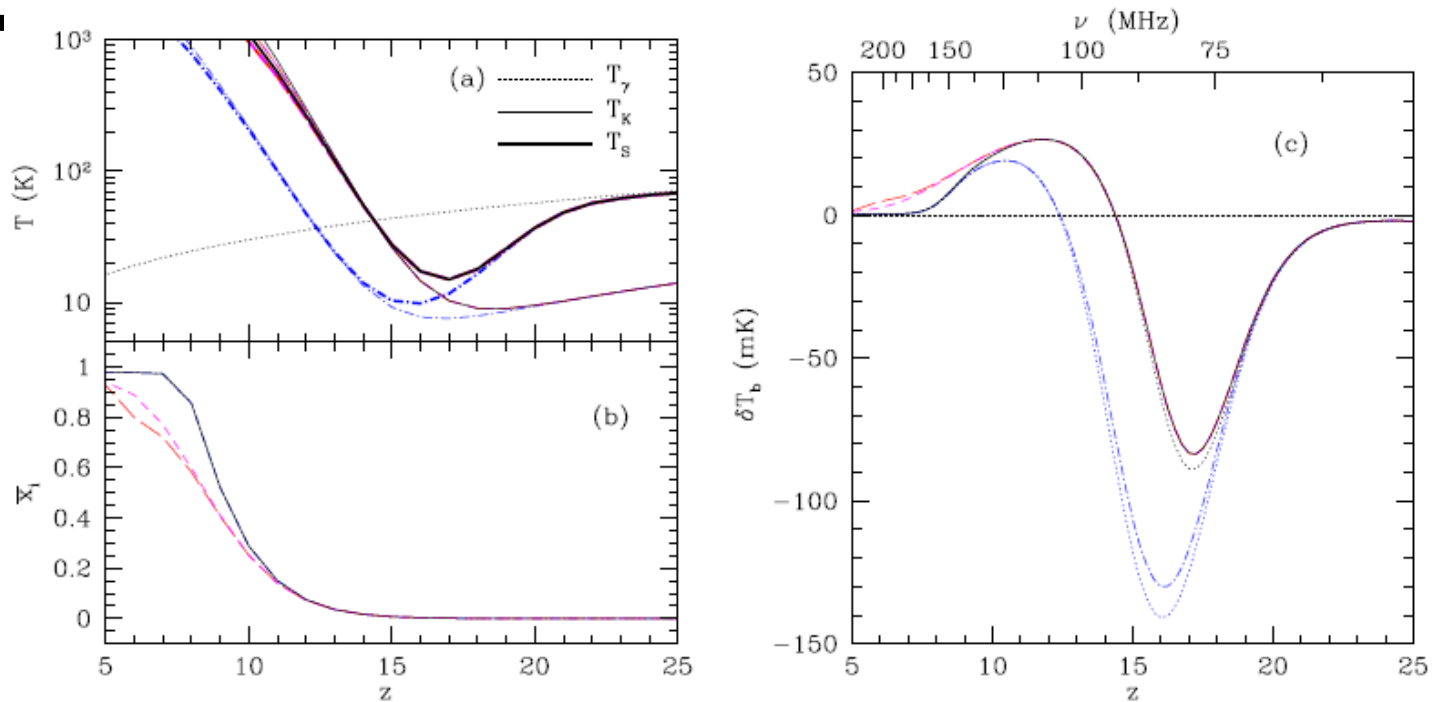
- Spin temperature is coupled to T_K because collisional coupling was still strong due to universe being dense



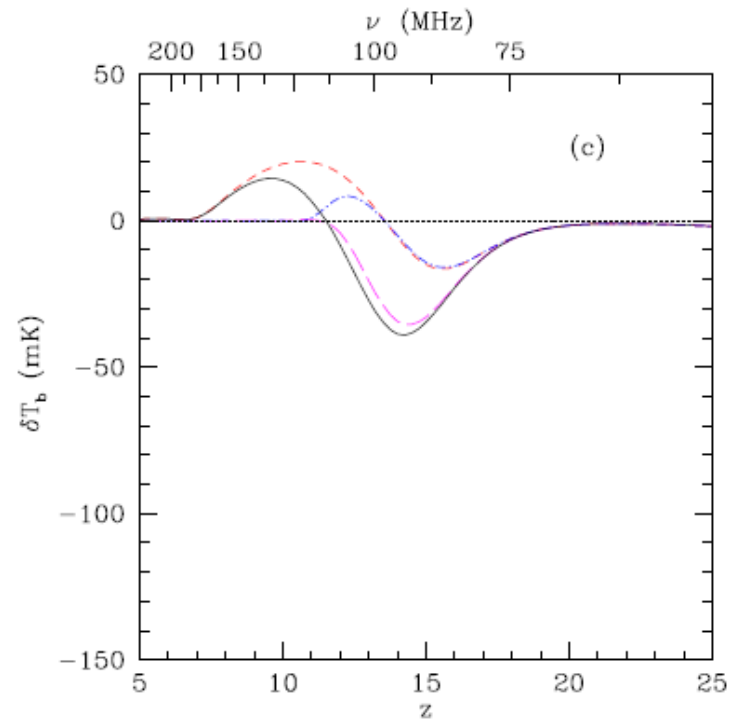
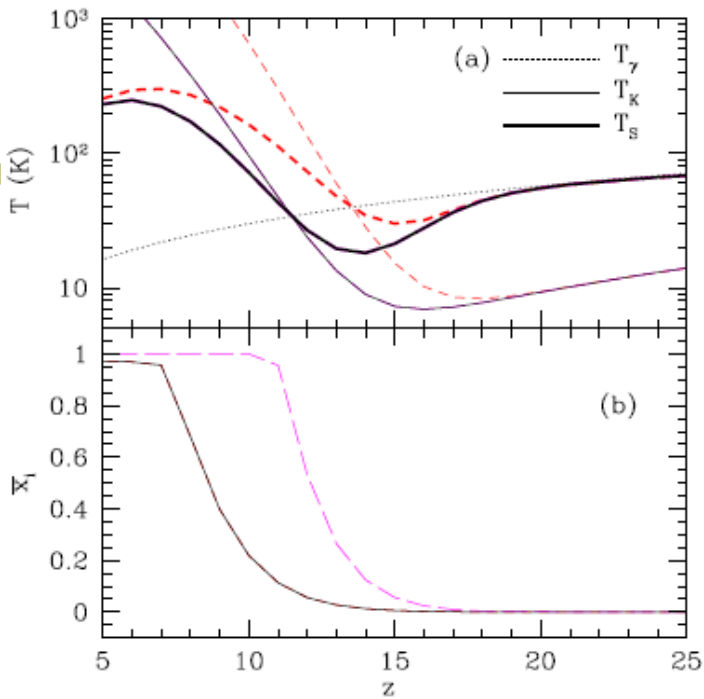
[Heating of the IGM]

- X-rays from inverse-Compton scattering off of relativistic electrons accelerated by supernovae
- Also from high-mass X-ray binaries, formed as soon as the first massive stars die.
- Heat the IGM through collisional ionizations, collisional excitations of HeI and HI, Coulomb collisions with free electrons.
- Lyman alpha can heat through atomic recoil, but negligible compared to X-rays

Representative Models



- Population II star parameters.
- Can see spin temperature coupled to kinetic temperature due to W-field effect
- Important to note that there are signals before reionization.



- Population III parameters
- Notice a smaller absorption peak due to less Lyman alpha photons generated
- Important points to note, z_h is where IGM is hotter than CMB and z_r W-field most efficiently couples spin temperature to kinetic temperature.

Reionization

$$\frac{d\bar{x}_i}{dt} = \zeta(z) \frac{df_{coll}}{dt} - \alpha C(z, \bar{x}_i) \bar{x}_i(z) n_e(z)$$

- First term is the source, with ionizing efficiency and collapse fraction
- Second term is sink, with the notoriously difficult-to-calculate clumping factor.

[Reionization]

- Two ways to model reionization, semi-analytical models and numerical simulations
- Semi-analytical glosses over the details by prescribing a simple clumping factor.
- This leads to good agreement with the general result of reionization, but doesn't provide insight to the intricate interactions between the dark matter, stars, gas, and the radiation field

[Reionization]

- Numerical simulations act to do this by incorporating codes to take into account every kind of physics including gas dynamics and three-dimensional radiative transfer.
- Most agree reionization starts at $z \sim 12$ and ends at $z \sim 6$

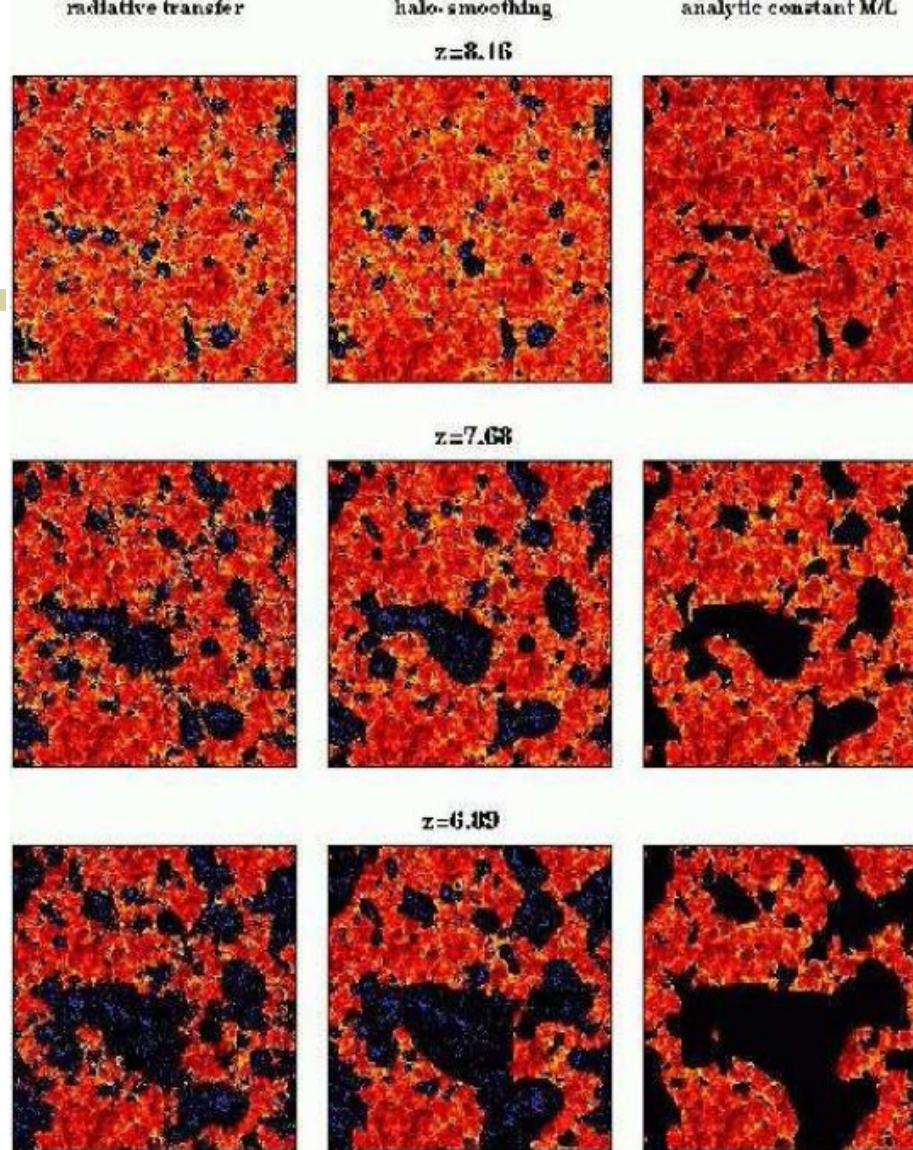


Fig. 16. Slices through a simulation of reionization at $z = 8.16, 7.68,$ and 6.89 (top to bottom); these have $\bar{x}_i = 0.13, 0.35,$ and $0.55,$ respectively. The colorscale is proportional to the HI density. The slice is $65.6h^{-1}$ comoving Mpc across and $0.25h^{-1}$ Mpc deep. The left column uses a radiative transfer code; the right column applies a slightly modified version of [341] to the same density field. The middle column applies that ionization criterion to the overdensity of bound halos. The points inside the HII regions in the left and middle columns identify the ionizing sources. From [109].

[Conclusion]

- 21 cm is a very promising probe into the Dark Ages and reionization epochs.
- Can do tomography, that is find where the neutral and ionized gas was distributed at a given redshift, an actual 3-D picture
- Extremely difficult to see signal at such low frequencies and high foreground noise
- First generation of 21 cm experiments are being made right now, for example PaST in China.