The first stars, high-redshift 21-cm absorption, and dark matter.

Jordi Miralda Escudé
ICREA Professor
Institut de Ciències del Cosmos,
Universitat de Barcelona.
miralda@icc.ub.edu

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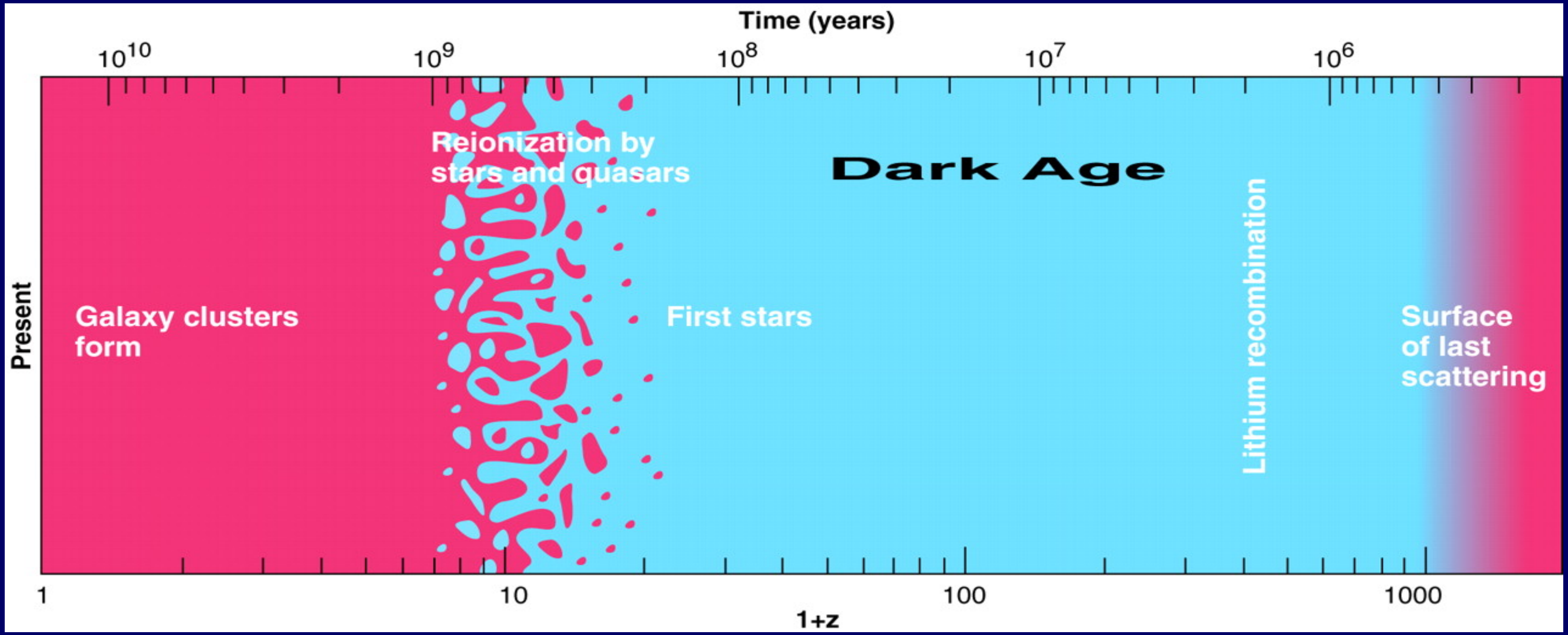
History of recombination and reionization



The 21-cm emission or absorption by hydrogen occurs in the epoch when most baryons are in atomic form. There is emission when atoms are hotter than the CMB, and absorption when they are colder. But what matters for this is the spin temperature.

$$\frac{n_1}{n_0} = 3\, e^{-T_*/T_s} \,, \qquad T_* = \frac{E_{21}}{k_B} = 0.07\,\mathrm{K}$$

21-cm emission and absorption

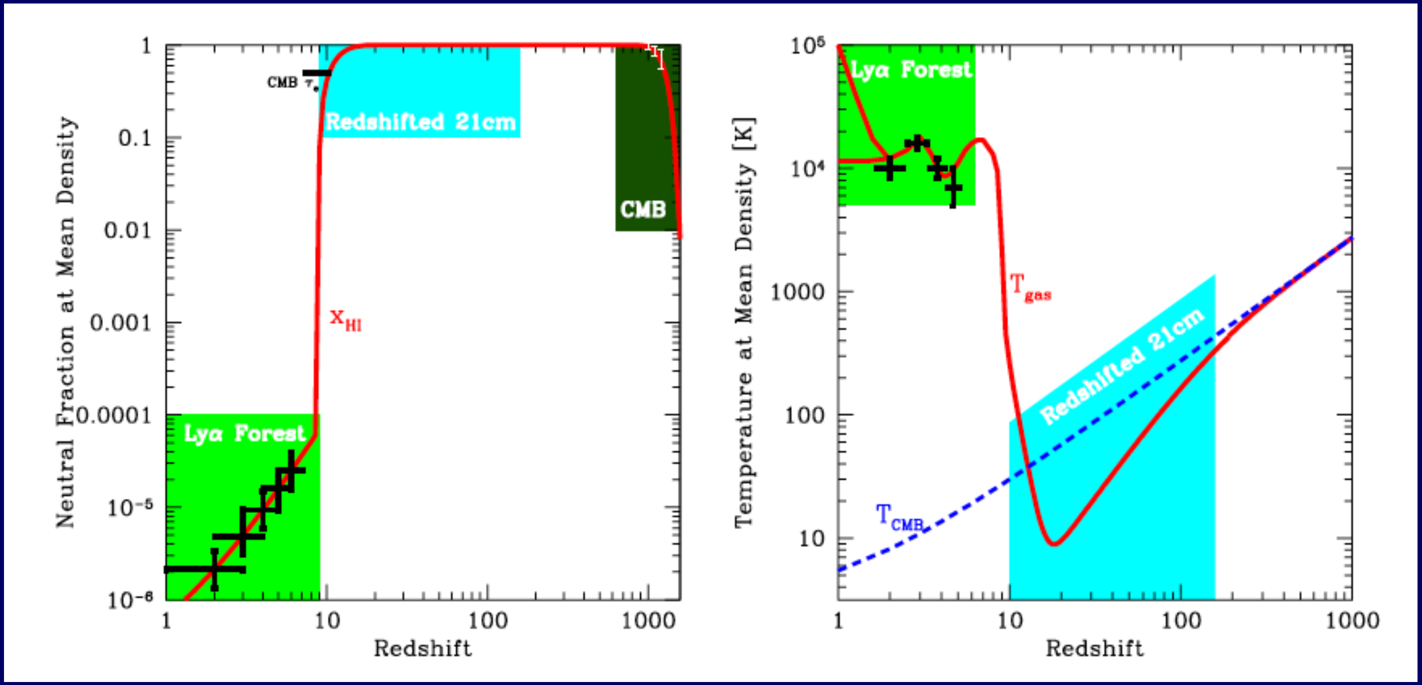
- 21-cm emission on the CMB: $$\delta T = \frac{T_s - T_{\rm CMB}}{1+z}\left(1 - e^{-\tau}\right) \simeq$$

$$\simeq (0.025\,{\rm K}) \frac{T_s - T_{\rm CMB}}{T_s} \frac{\rho_{\rm HI}}{\bar{\rho}_{\rm HI}} \left(1 + H^{-1}(z)\frac{dv_\parallel}{dr_\parallel}\right)^{-1} \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{\Omega_b h}{0.03}\right) \left(\frac{0.3}{\Omega_m}\right)^{1/2}$$

- The spin temperature must be different from T_{CMB} to make HI observable in 21-cm, by coupling it to the kinetic temperature T_k, either collisionally or through Lyman alpha photons (e.g., Madau, Meiksin, & Rees 1997).

$$T_s = \frac{T_{CMB} + (y_\alpha + y_c) T_k}{1 + y_\alpha + y_c}$$

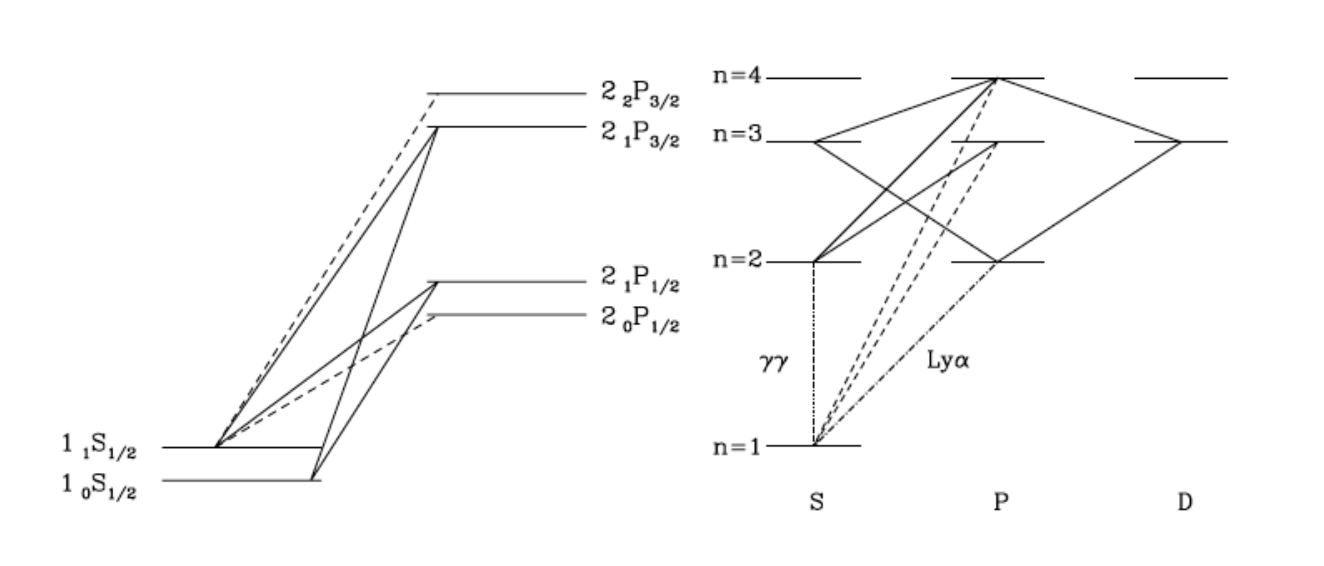
Reionization and thermal evolution of the IGM



McQuinn (2015)

The small ionized fraction left at recombination keeps first the IGM at the CMB temperature, until Thompson scattering cannot compensate for adiabatic cooling. Lyα photons from the first stars can couple spin and kinetic temperature, causing 21-cm absorption, but then X-rays heat the neutral medium and cause emission, until it is reionized completely and heated to ~ 10^4 K.

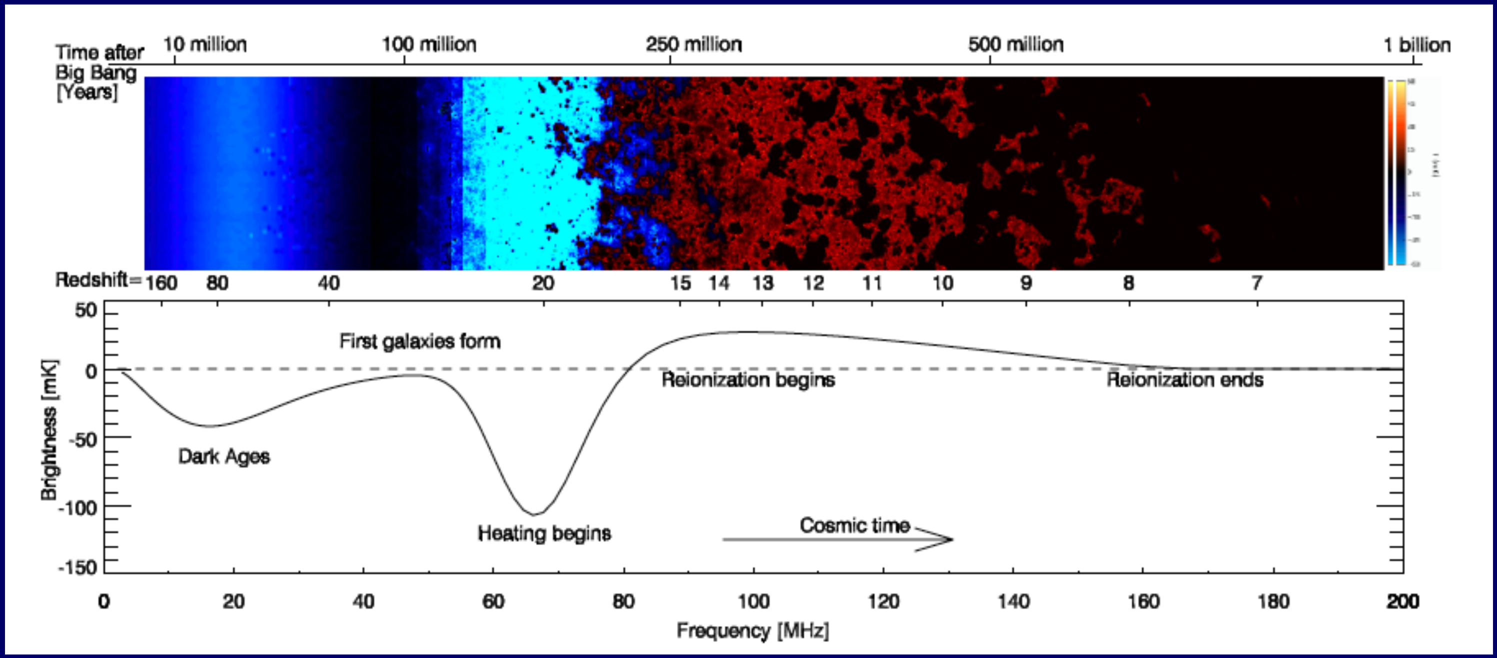
Lyα coupling: Woythuysen-Field effect



Pritchard & Loeb (2011)

- The Lyα photons scatter through the neutral medium, allowing for spin flips. This leads to a coupling of the gas kinetic temperature and the spin temperature.
- This was initially believed to also lead to rapid heating of the gas owing to the recoil of atoms when Lyα photons are scattered (Madau, Meiksin & Rees 1997), but this heating is actually very small (Chen & M.-E. 2004, Hirata 2006). The implication is that there may a substantial epoch of 21-cm absorption at high redshift.

Evolution of 21-cm brightness

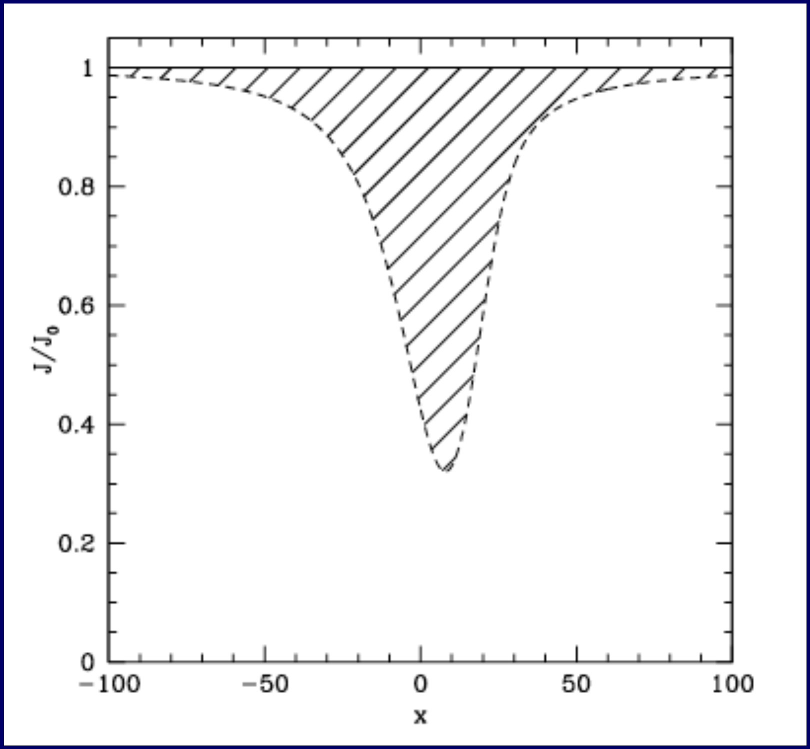


Pritchard & Loeb (2011)

- Dark ages: collisional coupling to adiabatically cooled gas causes 21-cm absorption, which declines as density goes down.
- First stars: Lyα coupling brings absorption back, with negligible heating.
- X-ray emission heats the medium and causes 21-cm emission.
- Reionization reduces the 21-cm emission.

Heating of the IGM after first stars start the reionization

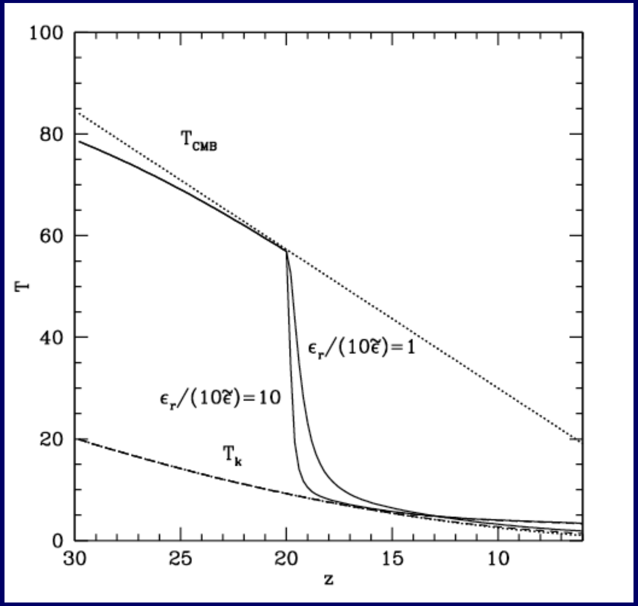
- Scattering of Lyα photons couples spin and kinetic temperatures, and causes a dip in the background spectrum.
- Heating of the gas from recoil effect is compensated by preferential scattering of photons moving against atoms. The resulting net heating rate is computed with a diffusion Fokker-Planck equation, and is very small.
- The most important heating is due to X–ray emission from the first accreting binaries or supernovae. X-rays penetrate the neutral medium and heat it by Coulomb scattering of the energetic electrons produced by ionization. Also, first cosmic rays can do the same.

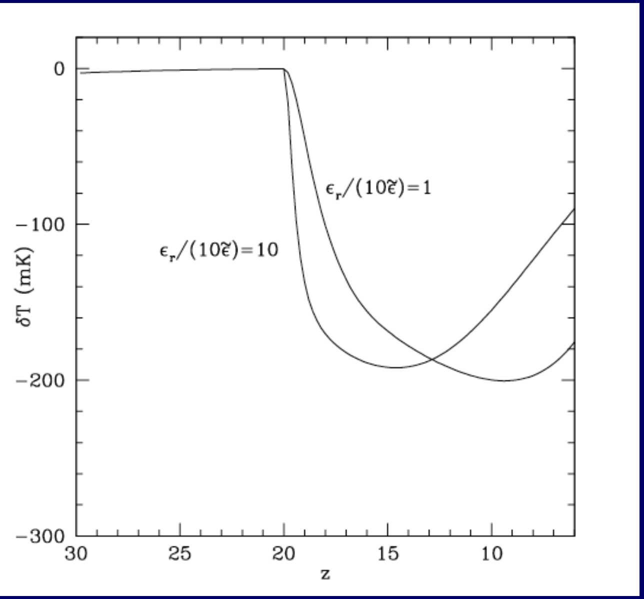


- Cosmic spectrum of star light in narrow range around Lyα line, with dip caused by Lyα scattering (Chen & M.-E. 2004).

Robust prediction: a maximum 21-cm absorption of ~ 0.2 K.

- In the absence of X-ray heating, we predict the maximum possible absorption: spin temperature is perfectly coupled to kinetic temperature, as determined by adiabatic cooling of recombining gas, and the small amount of Lyα heating.
- This maximum absorption is a very robust prediction: only an extraordinary modification in cosmology could violate it, such as a new dark matter strong interaction with baryons (Barkana) that can cool the gas.

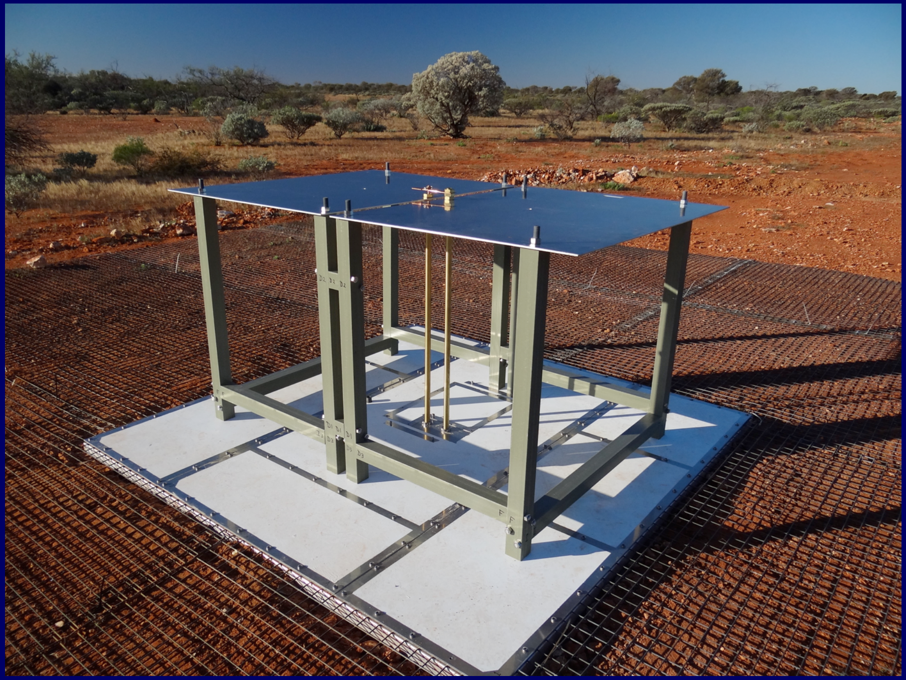




Chen & JM-E (2004)

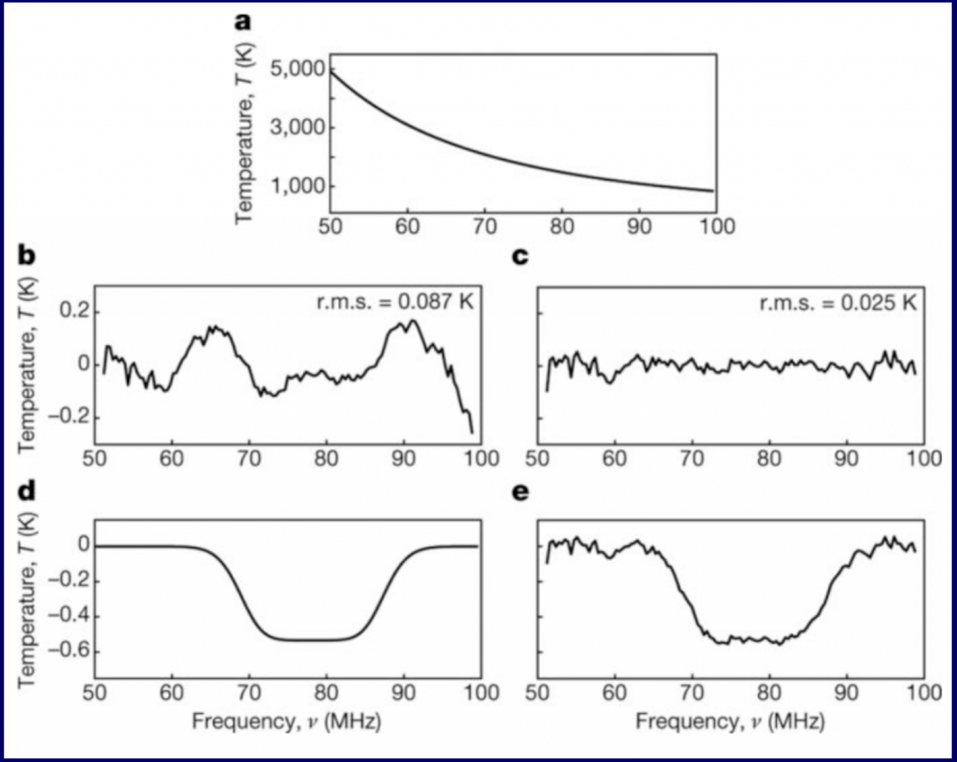
EDGES observatory:

- Observe the global spectrum (monopole) of radio background in the region 50-100 MHz where we should have the 21-cm absorption from the cold IGM with the spin temperature cooled by first Lyman alpha photons.



What is observed: the global spectrum with a huge synchrotron foreground.

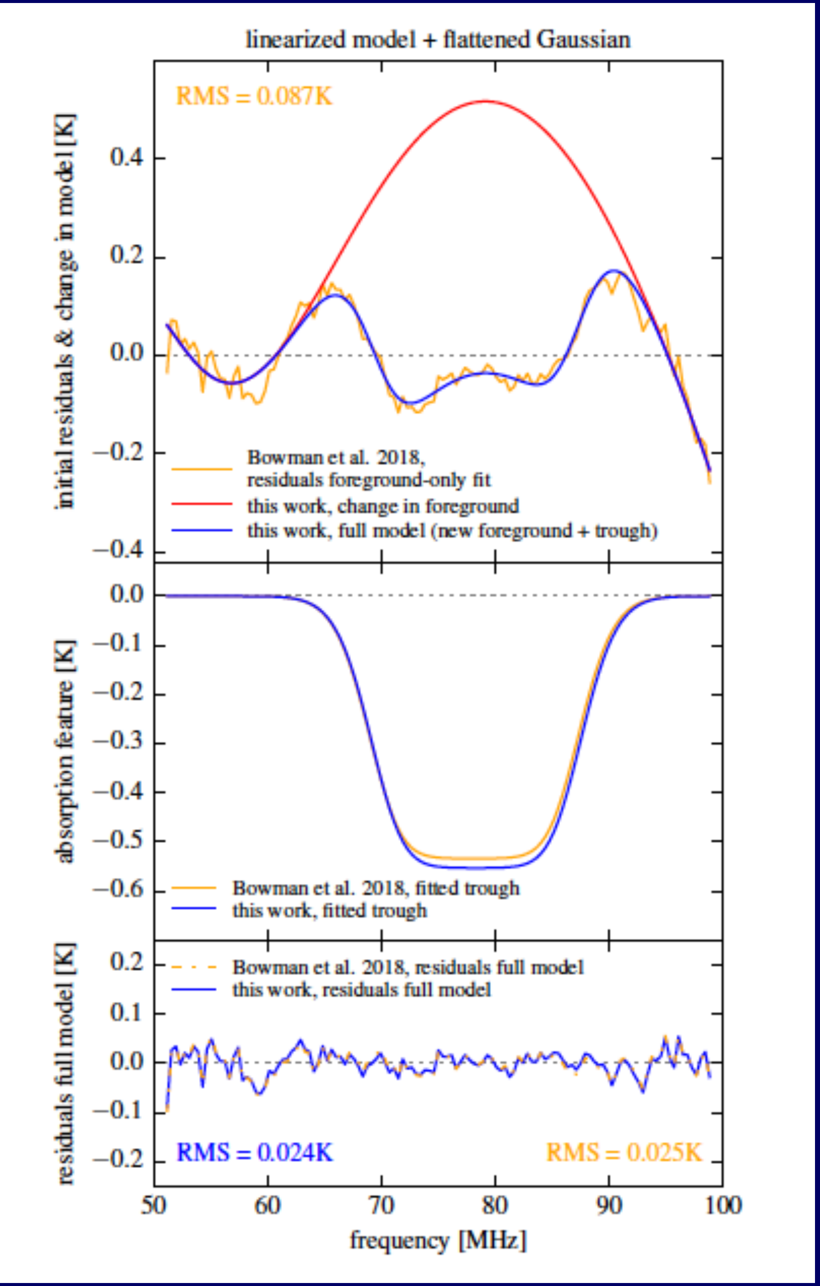
- Search for 0.2K dip in spectrum around 70 MHz.
- Model the synchrotron foreground to subtract it to 10^{-4} relative accuracy
- The shape of the dip is not predicted by theory.
- The synchrotron (and other stuff) model is not predicted by theory.



Bowman et al. 2018

Absorption feature depends on foreground model (Hills et al. 2018)

- Adding the presumed 21-cm absorption feature requires a larger and unphysical modification of foreground model.
- Changing the foreground model or the frequency fitting range changes conclusions on 21-cm absorpiton.



Hills et al. 2018

Conclusions

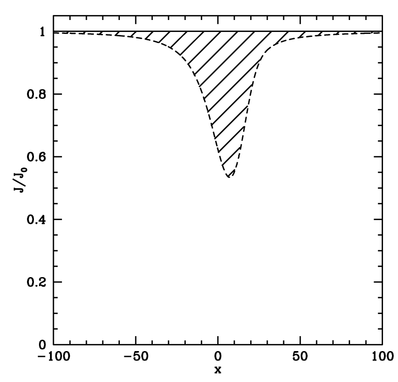
- The theory on the reionization and heating of the intergalactic medium predicts an initial epoch of 21-cm absorption from collisional coupling before stars were formed, a second epoch of absorption with Lyα coupling, and then an epoch of 21-cm emission due to X-ray heating.
- Robust physics of thermal evolution of IGM imply a maximum absorption of ~ 200 mK around z ~ 20. Larger absorption would have extraordinary consequences (cooling by dark matter strong interaction with baryons).
- The EDGES observations cannot be considered a detection of 21-cm absorption until foreground ambiguities are resolved.

Heating due to the scattering of Lyα photons itself is negligible

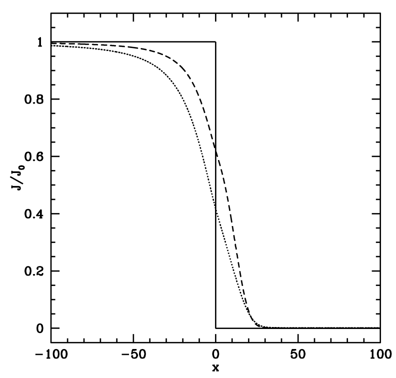
- Heating rate:

$$\frac{\Gamma}{H n_H k_B} = \sqrt{2TT_*}\,\frac{J_\alpha}{\frac{c n_H}{4\pi \nu_\alpha}} I$$

Continuum photons:



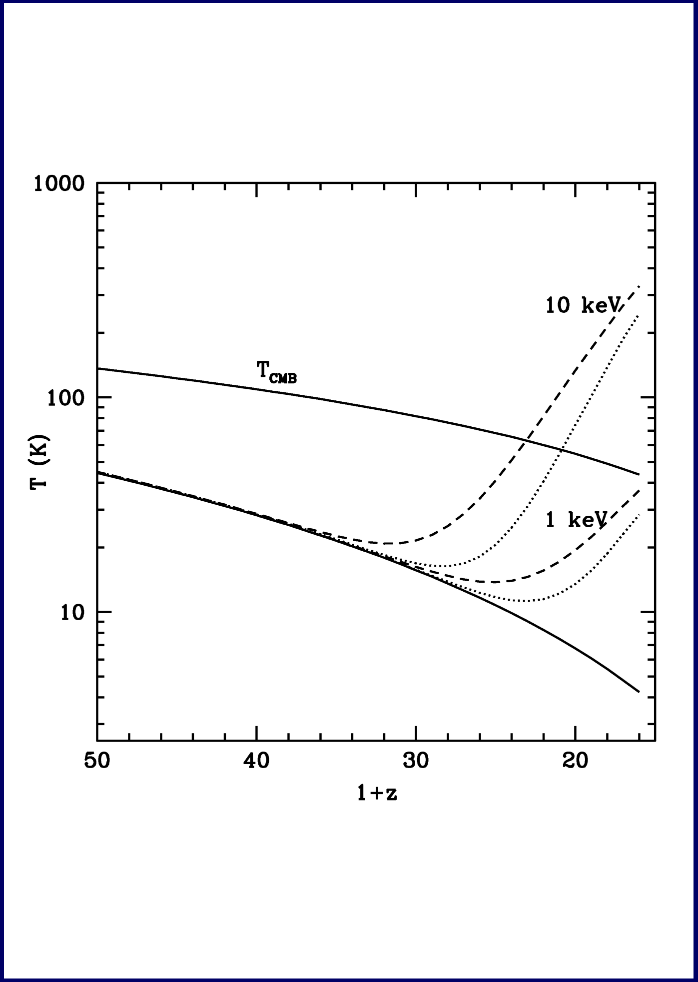
Injected photons:



First sources of X-rays

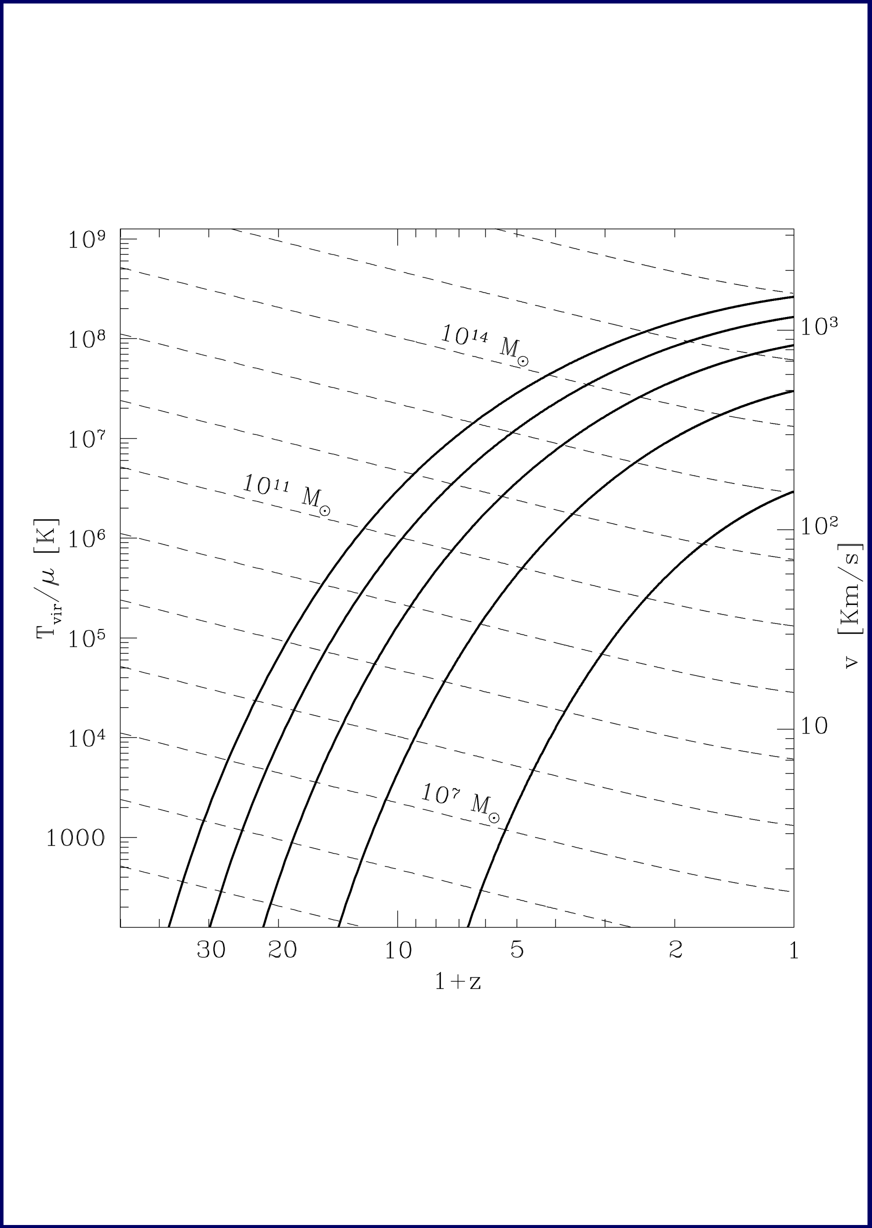
- Typical X-ray emission of local starbursts:

  1 keV per baryon.
- Possible early sources of X-rays:
  - Photospheres of massive stars
  - Coronae of massive stars
  - Early X-ray binaries
  - Early AGN from the first black holes.



What were the first sources of reionization and heating?

- Cooling of gas first took place from molecular hydrogen, at z~30 in halos of mass ~ 10^6 M_{sun} . Gas cools only to ~ 200 K.
- Accretion rate ~ $c_s M/R$ ~ c_s^3/G
- Massive (M~100 M_{Sun}), metal-free stars were made.
- The most metal-poor stars show independent evidence that most first stars were massive (e.g., Tumlinson 2007).



Evolution of kinetic temperature

- The principal heating mechanism for the atomic medium, outside the HII regions in the vicinity of sources, are X-rays.
  - $E < 0.1$ keV: absorbed locally (near HII regions)
  - 0.1 keV $< E < 1$ keV: absorbed far away, heat atomic medium
  - $E > 1$ keV: redshifted (universe is effectively transparent)
- High-energy electrons produced by X-rays give rise to secondary ionizations, excitations, and heating by Coulomb interactions.
- X-ray emission will determine a transition from 21-cm absorption to 21-cm emission