21-cm Emission and Absorption by the Intergalactic Medium: What can we learn on Dark Matter Particle Candidates?

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21-cm emission and absorption

- 21-cm emission on the CMB:

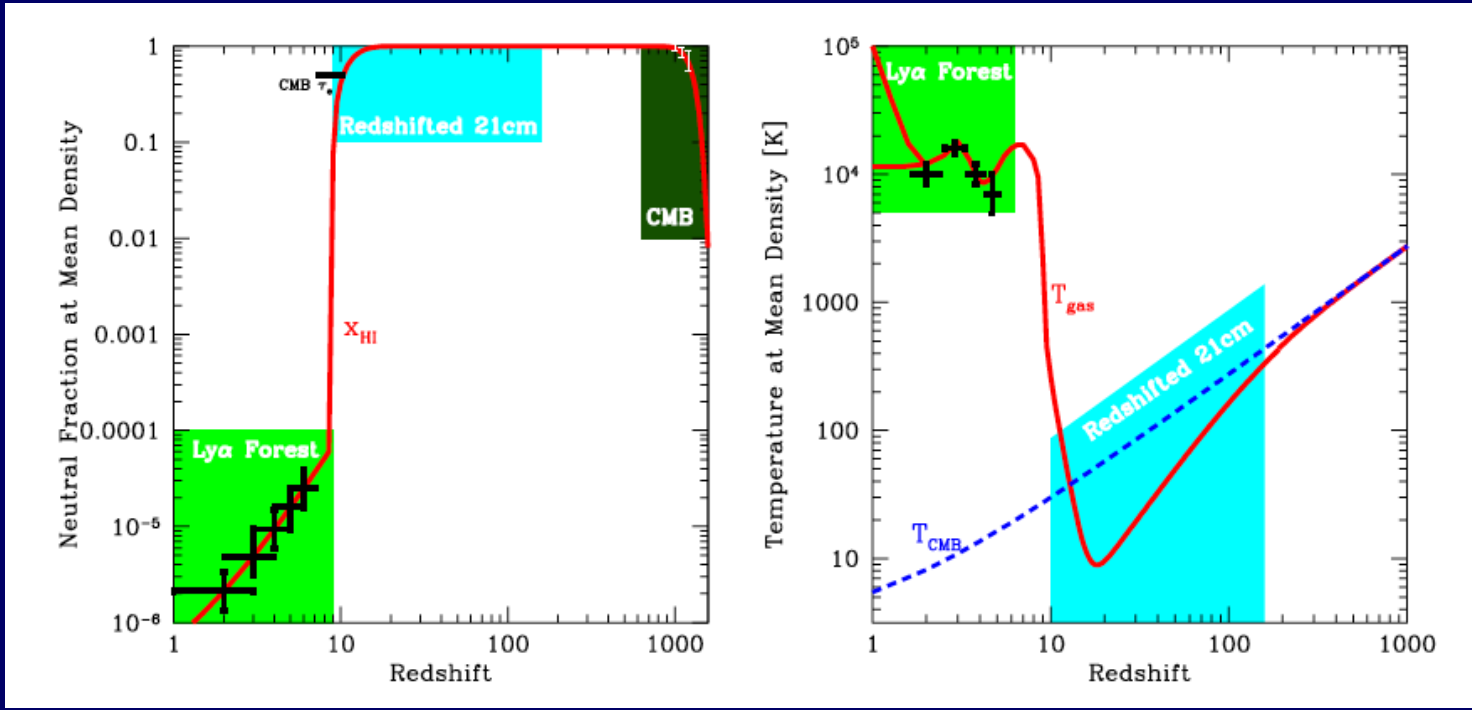
$$\delta T = \frac{T_s - T_{\rm CMB}}{1+z}\left(1 - e^{-\tau}\right) \simeq$$

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

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

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

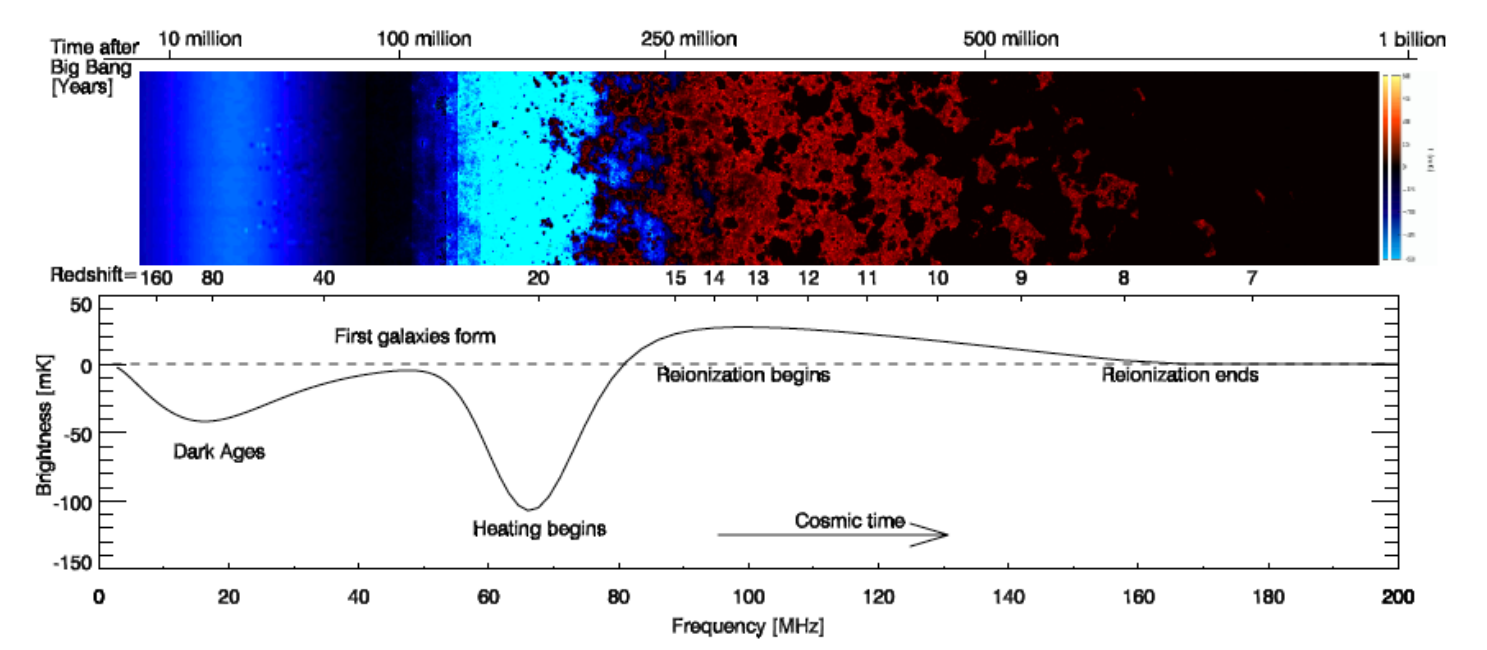
Reionization and thermal evolution of the IGM



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. X-rays from the first stars heat the neutral medium, until it is reionized completely and heated to ~ 10^4 K. Later, HeII reionization and galaxy winds can further heat the diffuse IGM.

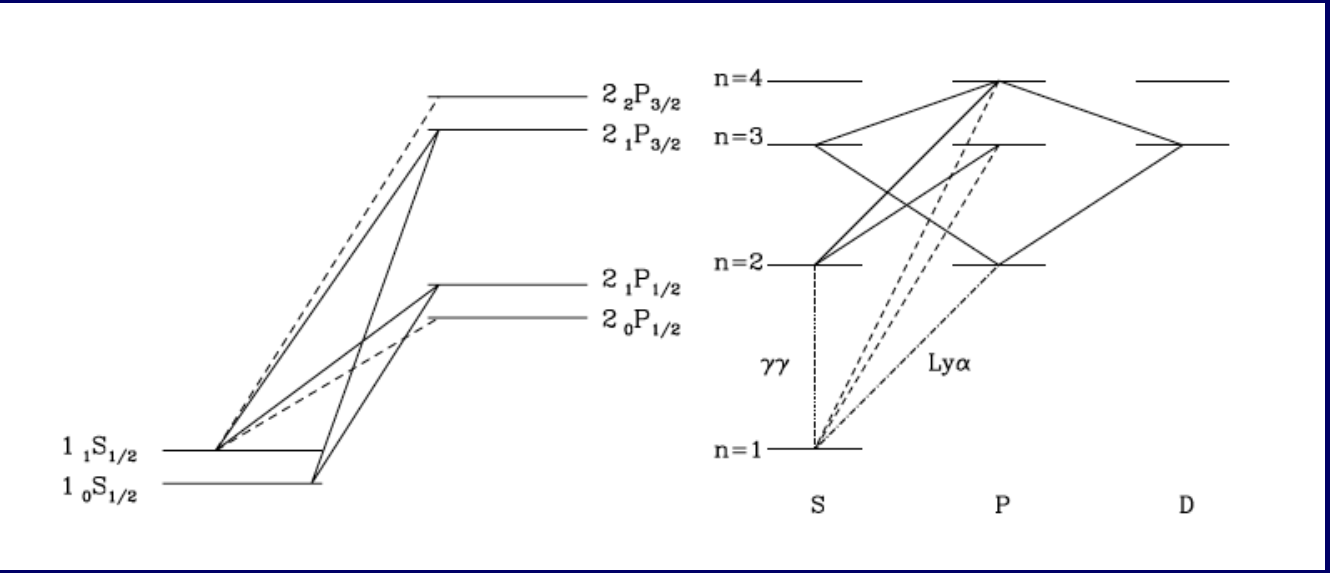
Evolution of the spin temperature



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 emission.
- Reionization results in emission from low-density neutral regions, and at late times emission from DLAs in high-density regions.

Lyα coupling: Woythuysen-Field effect

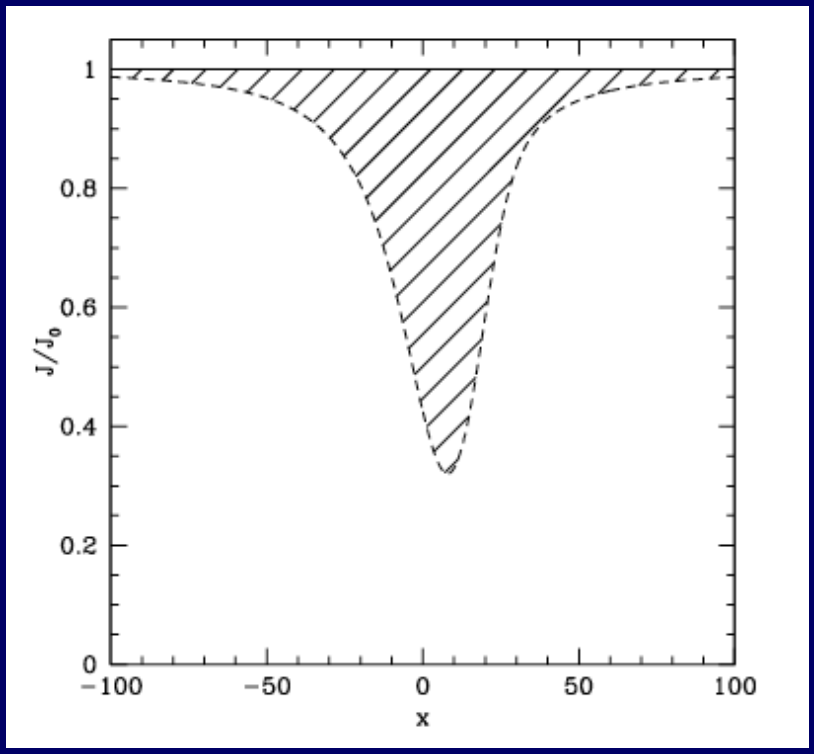


Pritchard & Loeb (2011)

- 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.

Heating of the IGM after first stars start the reionization

- Scattering of Lyα photons causes a dip in the background spectrum, with a color temperature that couples to the kinetic temperature.
- The first stars that produce ionizing radiation and Lyα photons are also likely to lead to X–ray emission, which can penetrate the neutral medium and heat it through Coulomb scattering of energetic electrons generated by ionization.
- Once the temperature of the neutral medium increases beyond the CMB temperature, 21-cm absorption turns to 21-cm emission from atomic regions.
- At the end of reionization, 21-cm with negative bias from voids should flip to positive bias from self-shielded DLAs.



$$x = c/(2kT_k/m_H)^{1/2}\,(\nu/\nu_\alpha - 1)$$

Normalized background spectrum around Lyα line, showing the dip caused by Lyα scattering (Chen & M.-E. 2004).

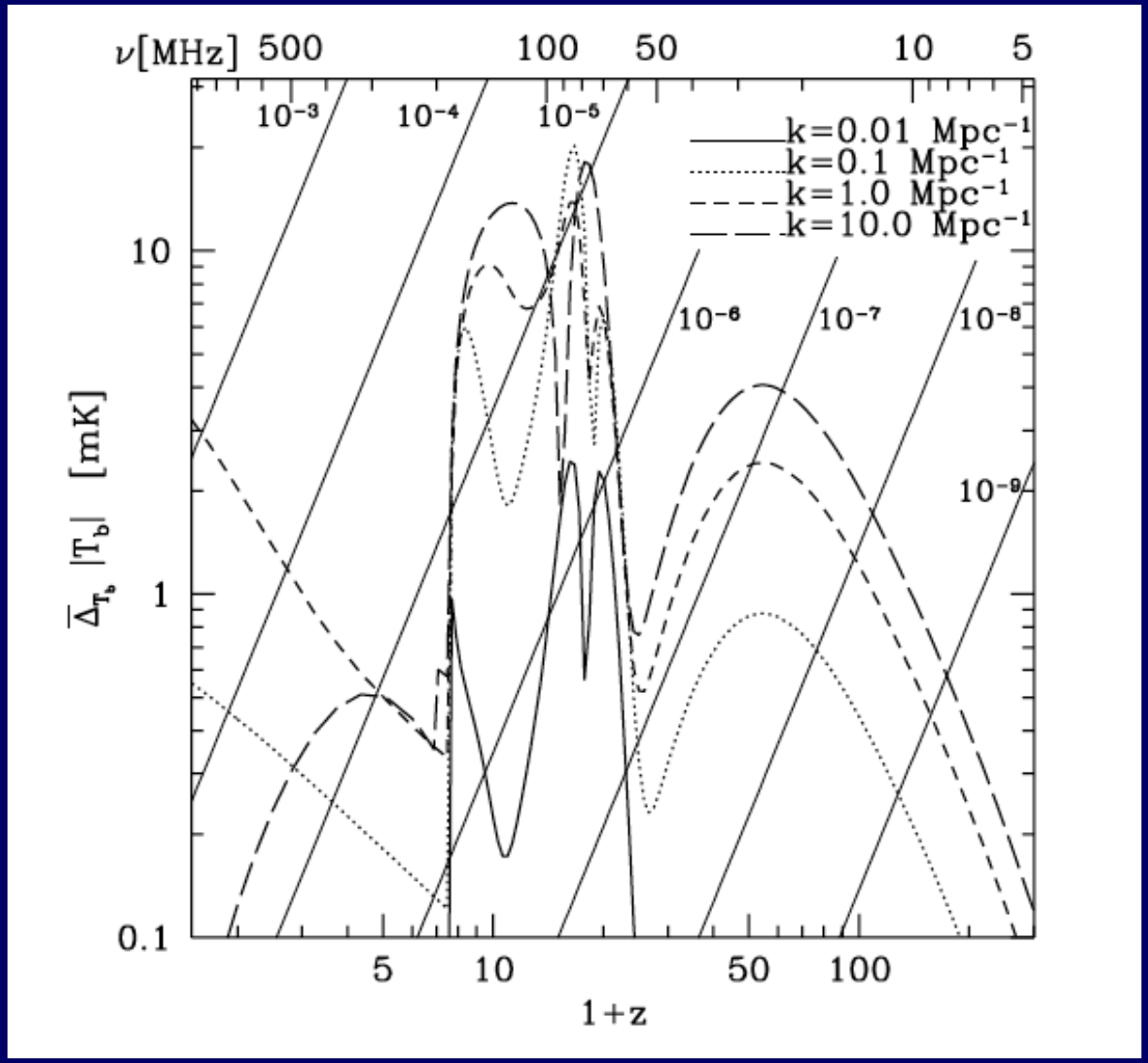
Impact of dark matter composition on 21-cm

- Annihilations or decay of dark matter may give rise to gamma-rays or leptons at high redshift producing cascades and heating the medium.
- Free-streaming of dark matter particles (warm dark matter, neutrinos) or effective pressure terms may result in smoothing of the power spectrum, resulting in reduced star formation at the highest redshifts.
- Elastic scattering of dark matter particles with baryons can cool the medium before Lyα coupling starts, if cold dark matter is colder than baryons.
- Effects on the BAO shape in the power spectrum could be measured, although foregrounds are severe.

Difficulties:

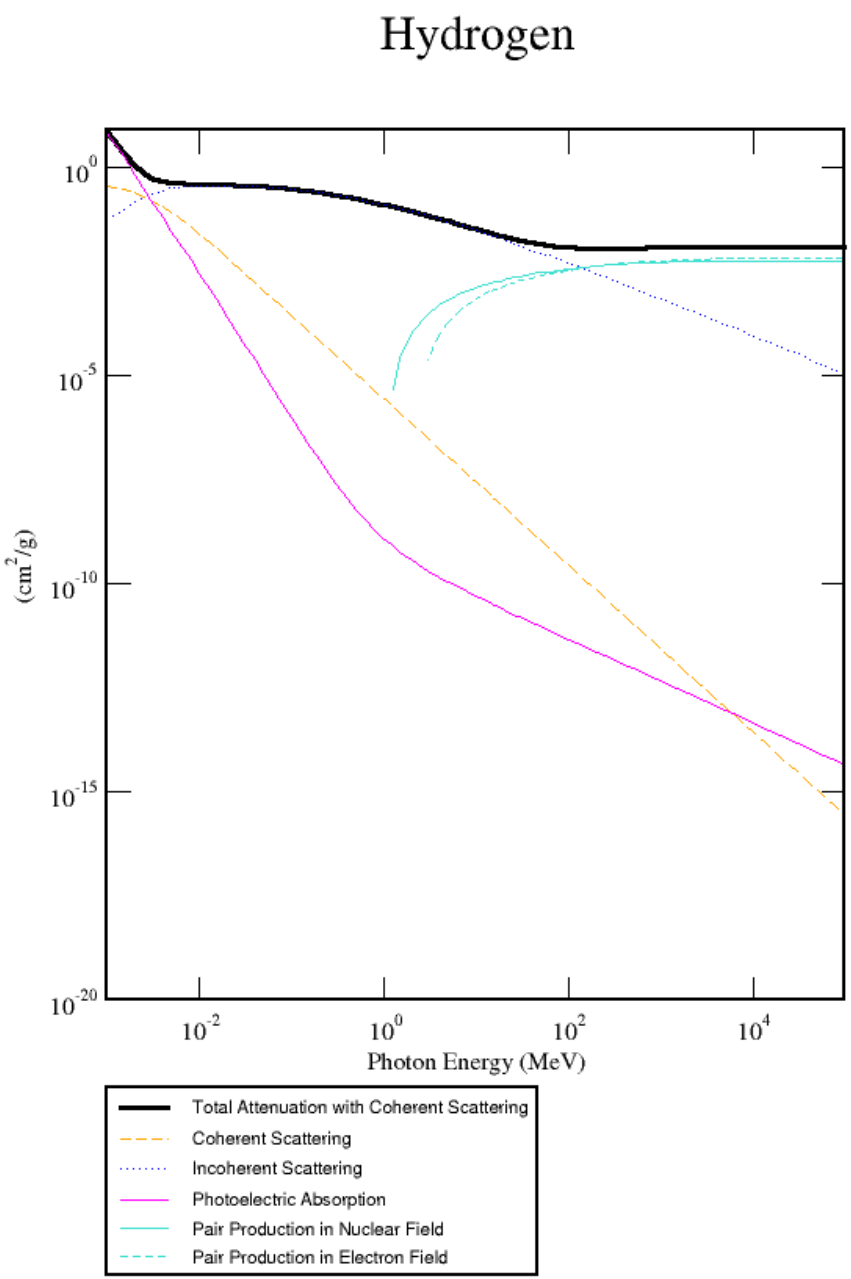
- The power spectrum has complex contributions from many physical effects: density, neutral fraction, kinetic temperature, Lyα intensity, spin temperature, peculiar velocities.
- Diffuse and point source foreground contamination is severe.
- How can we interpret detected signals?

Power spectrum models of 21-cm



Pritchard & Loeb (2011)

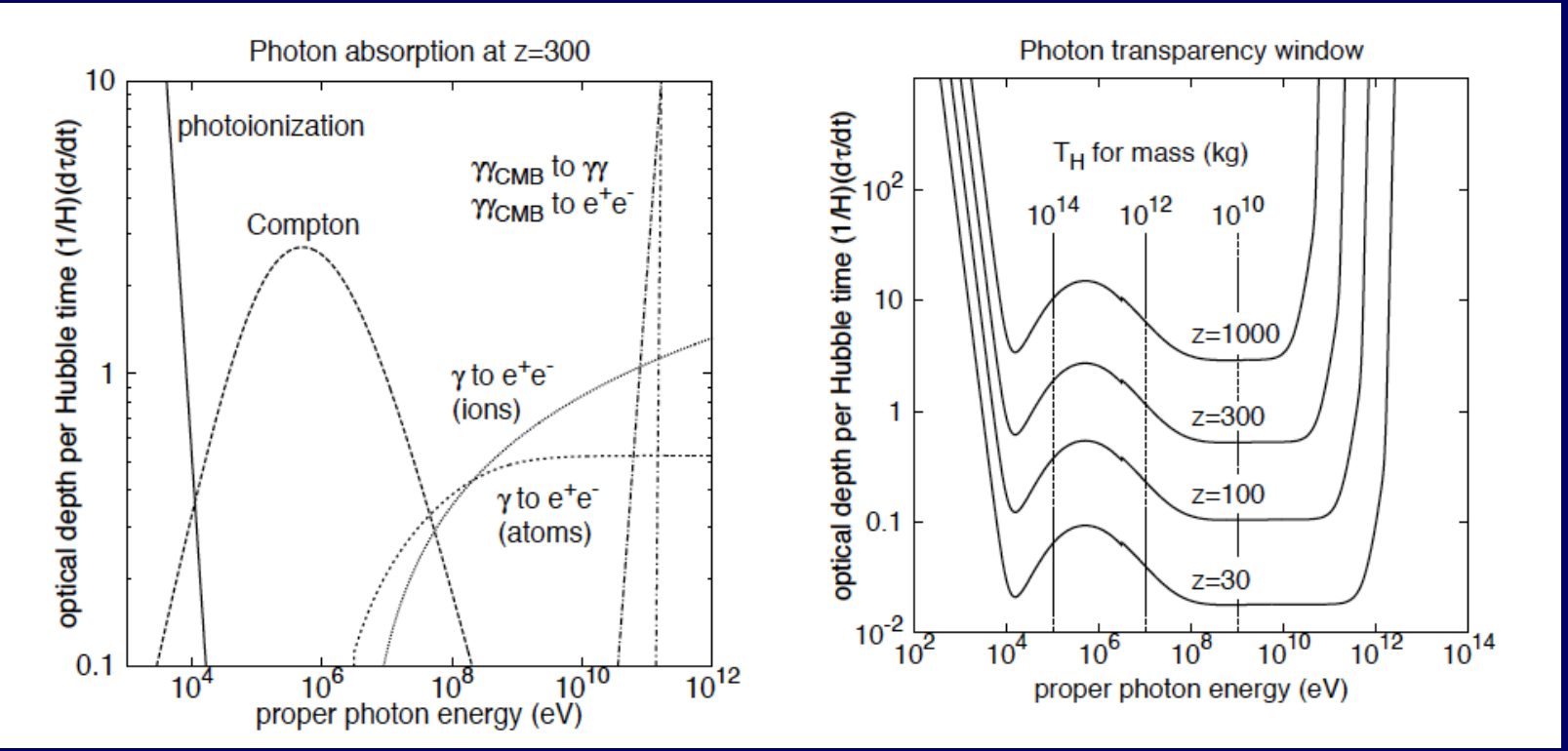
- Uncertain theoretical predictions of complex processes.
- High foreground contamination.
- Possible sources of frequency-dependent fluctuations: radio recombination lines; scattering of polarized, Faraday-rotated radio emission.
- How shall we interpret detected signals?



Heating by gamma-rays from dark matter

- Dark matter may annihilated or decay, producing photons and electrons that can heat the IGM.
- Much of the energy goes to Compton up-scattering and ionization, but some goes to IGM heat.

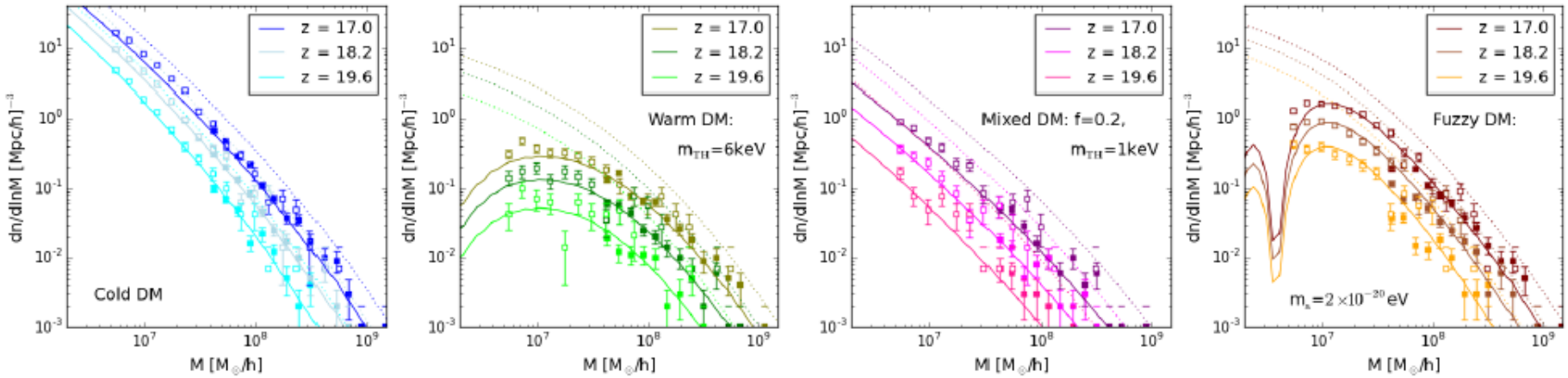
IGM optical depth to gamma-rays



Mack & Wesley (2008)

- The gamma-ray heating can suppress small-mass halos, reduce 21-cm absorption, and contribute to the gamma-ray background.

Effects of warm dark matter and various models for suppressing small-scale power

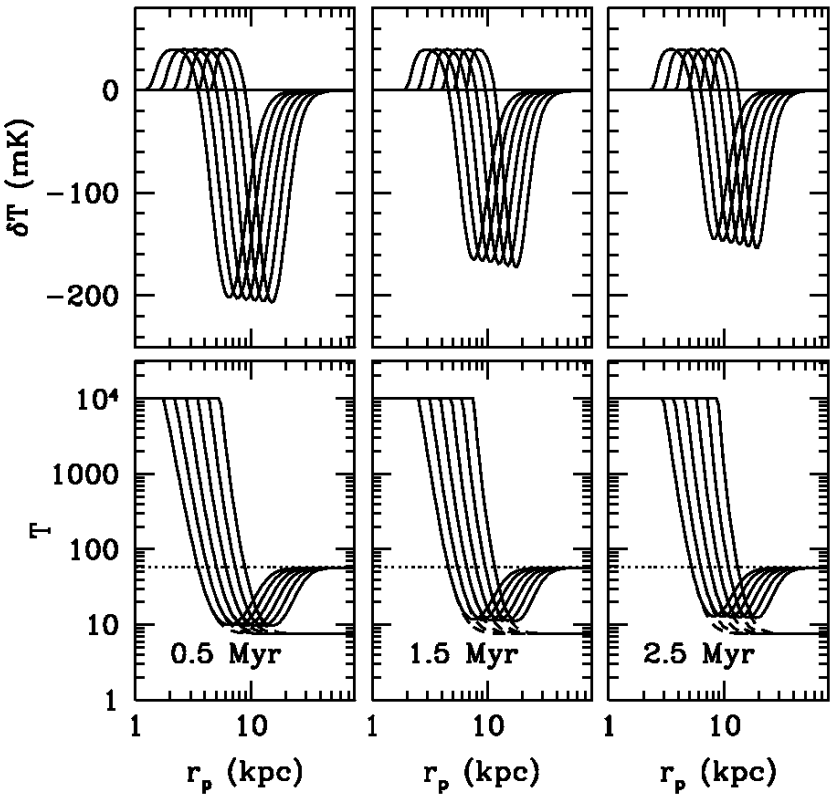


Schneider 2018)

- The suppression of low mass halos generally means that the 21-cm absorption epoch is delayed.
- Other astrophysical methods based on nearby dwarfs can constrain any suppressed small-scale power (Stacy et al. 2018)

Temperature and 21cm profiles of first stars

- Around a first star, the inner ionized, 21-cm region should be surrounded by an outer region affected by Lyα coupling with 21-cm absorption (Chen & M.-E. 2008). This could probe the IGM temperature before any stars are formed.
- This requires far greater resolution and S/N compared to planned 21-cm observatories.



Conclusions

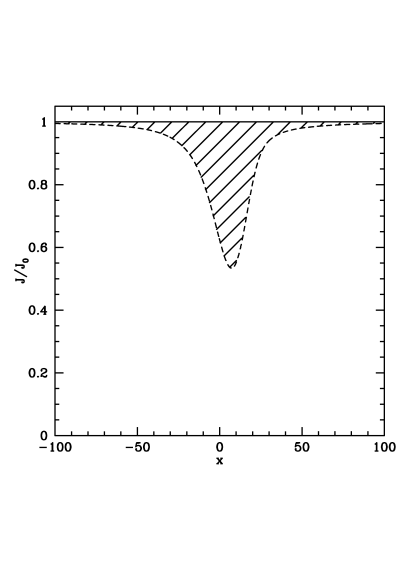
- The theory on the reionization and heating of the intergalactic medium predicts an initial epoch of 21-cm absorption from collisional coupling before stars were formed, a second epoch of absorption with Lyα coupling, and then an epoch of 21-cm emission due to X-ray heating. Fluctuations arise from a combination of Lyα intensity, spin temperature, ionization and density.
- Dark matter can impact on 21-cm observations through heating and cooling, and effects on the matter power spectrum. Foreground subtraction and interpretation of the complex signal will likely be hard. Cross-correlations with galaxies will be crucial.

Heating due to the scattering of Lyα photons itself is negligible

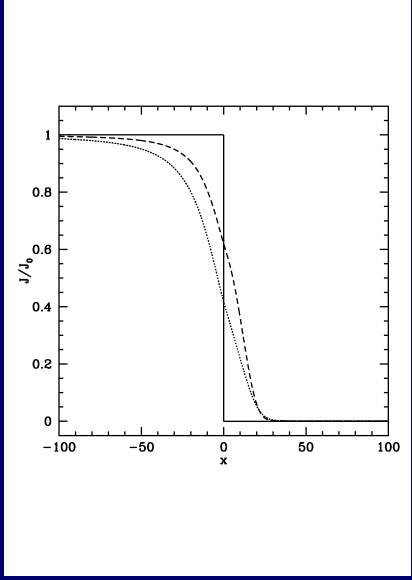
- Heating rate:

$$\frac{\Gamma}{Hn_H k_B} = \sqrt{2TT_*}\,\frac{J_\alpha}{\dfrac{cn_H}{4\pi\nu_\alpha}}\,I$$

Continuum photons:



Injected photons:



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 ~ $c_s M/R \sim c_s^3/G$
- 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).