“The 21 cm Signature of the First Stars”

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Today's Show is Brought to You By the Letter

$$\alpha$$

Outline

- Population III Stars
- Physics of the 21 cm Line
- Lyman α Spheres around the First Stars
- Pesky Backgrounds
- Feasibility

Pop III Stars

- Form from gas of primordial composition (X=0.76, Y=0.24)--> $M_J \approx 10^3 M_\odot$. Pulsational Instability/Line Driven Wind not problems.
- Z=0-> Hydrogen burning starts on pp chain-- $T_c \approx 10^{8.1} K$ Triple α kicks in eventually. Pre-enrichment to $Z \approx 10^{-9}$-- CNO burning
- Radiation Pressure Dominated--Due to High Mass and Temperature.

$$L \approx L_{edd} = 1.25 \times 10^{38} ergs^{-1} \frac{M}{M_\odot}$$

- Reasonable to use n=3 polytrope (Bromm, Kudritzki, &Loeb 2001)

$$T = 1.1 \times 10^5 \left(\frac{M}{100 M_\odot}\right)^{0.025} K \qquad L = 10^{4.5} \frac{M}{M_\odot} L_\odot$$

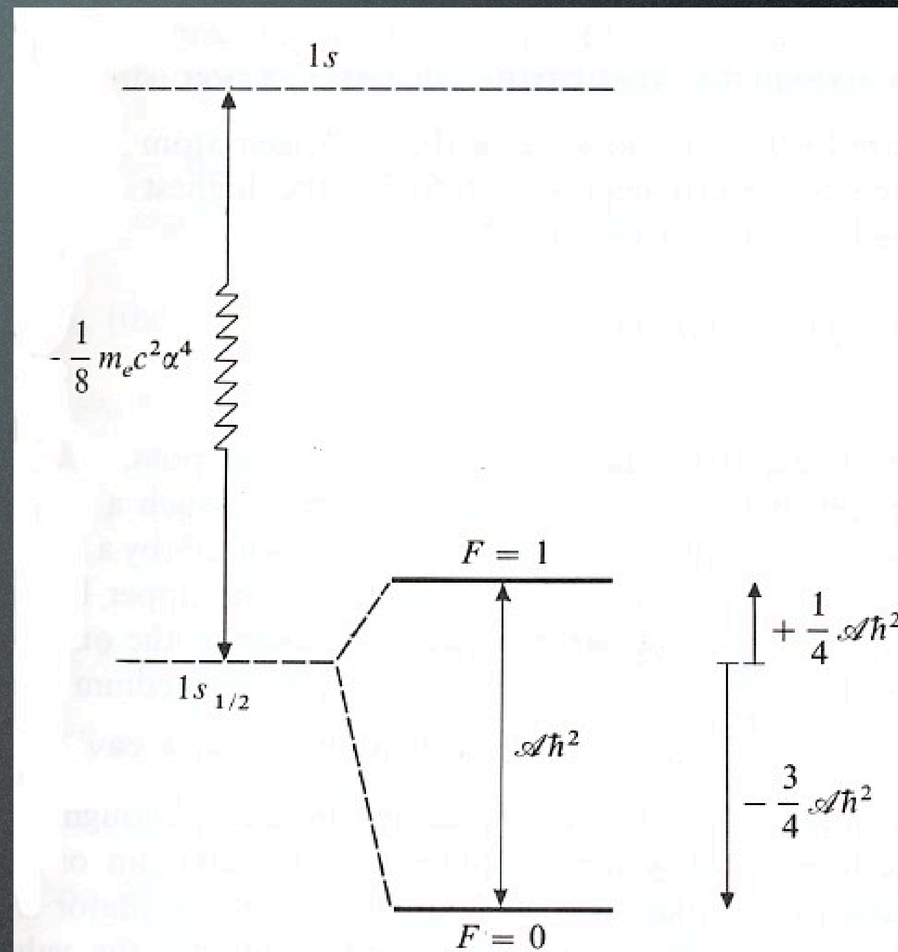
- Roughly Blackbody Spectrum

Physics of the 21 cm line:

Hyperfine Splitting in Neutral Hydrogen.

- Fine Structure: SO and SR lower energy of HI ground state.
- Hyperfine splitting: F=1 state less affected by SO interaction, higher energy than F=0 state.
- Magnetic dipole transition (21 cm)
  $\nu = 1420.405751768 \pm 1 Mhz$
- Radiative Transfer:

$$T_B = \frac{(T_s - T_{CMB})}{1+z}\tau$$



We're going to pump you (the F=1 hyperfine state of Hydrogen) up!

- Absorption couples (Field-Wouthuysen) T_s and T_α
- Collisions Couple T_s and T_k
- Resonant Scattering (Field 1959): $T_\alpha = T_k$
- By Detailed Balance:

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

$$y_\alpha = \frac{P_{10}T_*}{A_{10}T_k} \qquad y_c = \frac{C_{10}T_*}{A_{10}T_k}$$

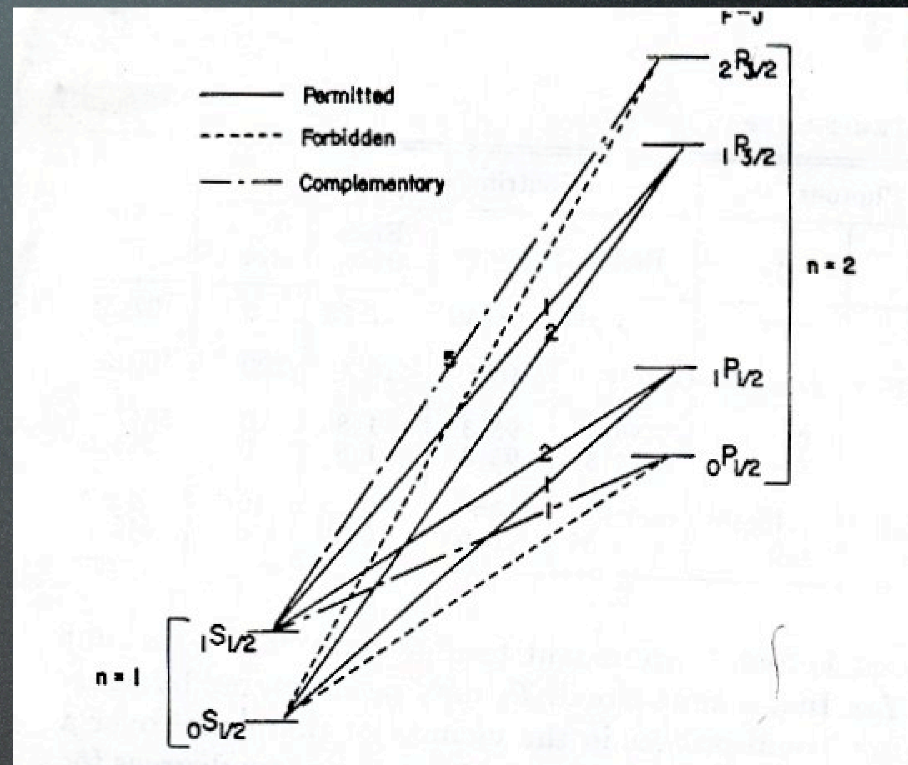


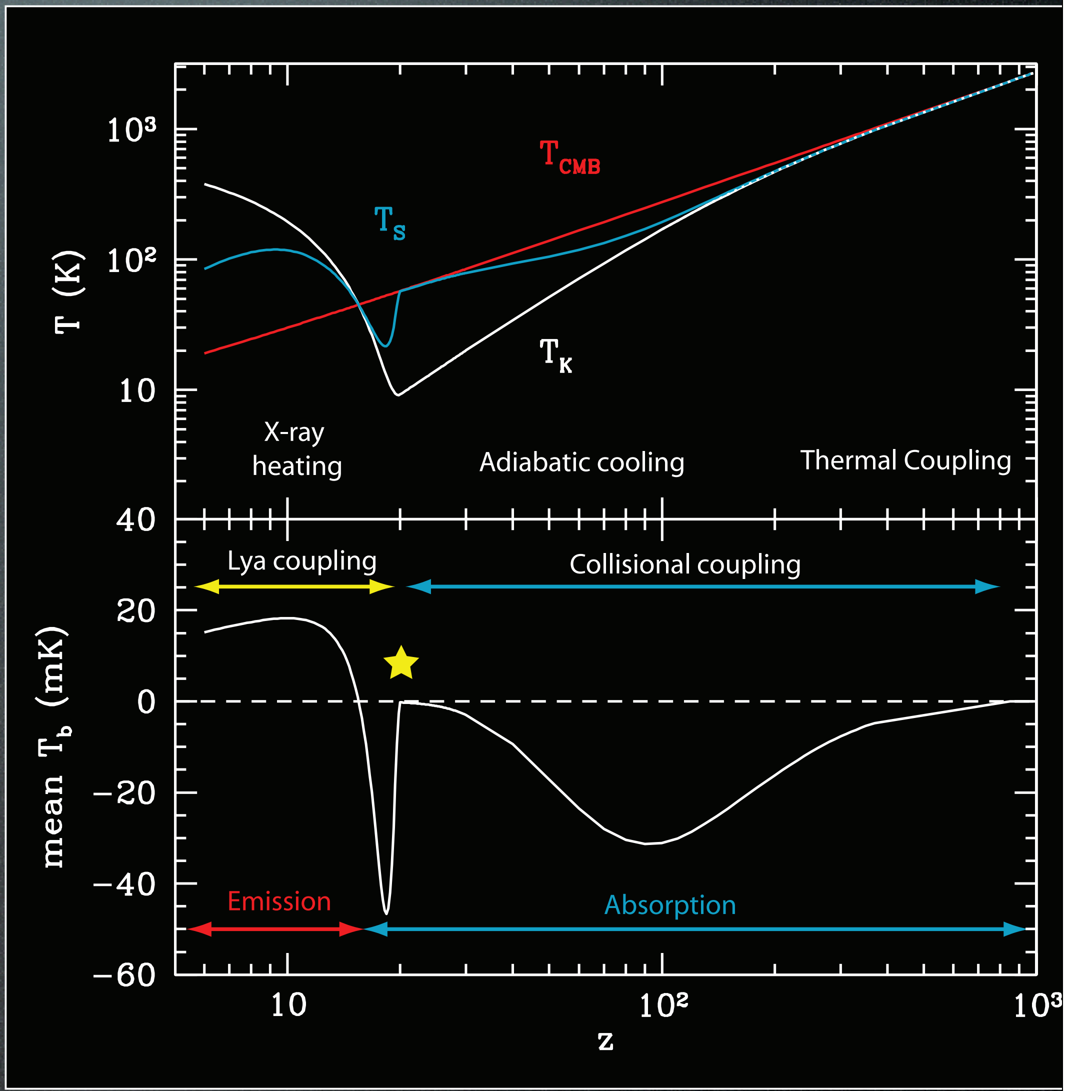
Fig. 3—The 1S and 2P levels of hydrogen, showing the particular transitions in the $L\alpha$ line which excite the triplet (dark lines). The numbers in the center are relative strengths.

$$P_{10} = \frac{4}{27} H \tau_{GP} \frac{S_c J_c + S_i J_i}{J_0} \qquad J_0 = \frac{c n_H}{4\pi \nu_\alpha}$$

Global Evolution of T_s

(Attractive plot courtesy of J. Pritchard)

- Residual e^- lock
  $T_k \rightarrow T_{CMB}$ until $z \approx 200$
- When Pop III stars, QSOs turn on, T_k increases
- Until collisions freeze-out,
  $T_s = T_k$
- After freeze-out:
  $T_s \rightarrow T_{CMB}$



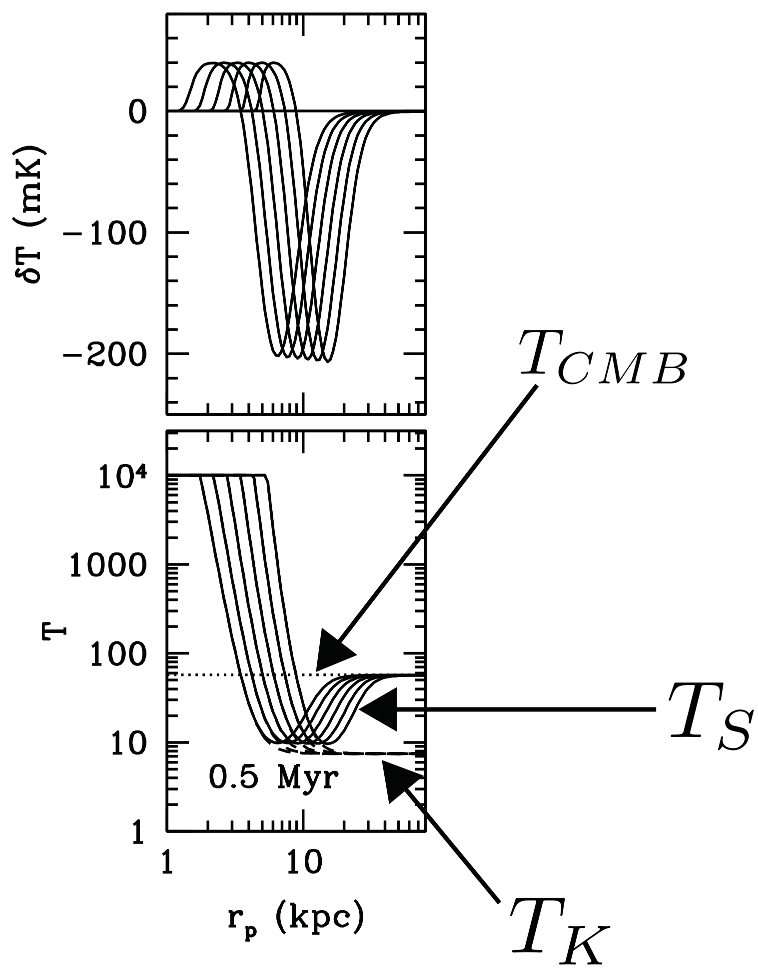
The Lyman α Sphere

- Region in which $T_s \neq \langle T_s \rangle$, larger than Strömgren sphere.
- First Source of Ly photons: Redshifted stellar photons between Ly_α and Ly_β. ``Continuum” $\rightarrow J_c$.
- Second Source of Ly photons: Soft ``X-Rays” ionize H, recombination -> $Ly_\alpha$ photons. ``Injected”$\rightarrow J_i$.
- Third Source of Ly photons: Redshifted photons between Ly_β and Ly continuum->Excited Ly series--> cascades that release more Ly_α photons $\rightarrow J_i$. These lead to a few % correction to $\rightarrow J_i$ (Pritchard et al. 2005). Ignored by these authors.

The Lyman α Sphere

- #2 Dominates #1 around Pop III stars!
- Ionization Equilibrium Equations Solved around Pop III Star to obtain $x_{HI}, x_{HeI}, x_{HeII}$, Recombination ignored here.
- Fraction Γ of photo-electron energy converted to heat (rate η) from Shull/van Steenberg (1981) Monte Carlo-> integrate over fluxes/cross sections to get heating rate $J_i^X = \dfrac{c\eta_\alpha \Gamma}{4\pi h H \nu_\alpha^2}$
- J_i^{Ly} from radiative transfer/resonant scattering ignored.
- Atomic Recoils: Gas is Heated. X-ray heating dominates over Ly α.

21 cm signal from the Lyman α Sphere



- Pop III Stellar spectrum heats surrounding IGM, setting T_k and y_c
- Stellar Flux processed $\rightarrow J_c$ and J_i, setting y_α
- Innermost Regions (still outside star): $T_k \rightarrow 10^4 K$ due to atomic cooling.
- Inner Regions: $T_s \rightarrow T_k$
- Outer Regions: $T_s \rightarrow T_{CMB}$
- Backgrounds neglected!
- Collisional coupling keeps $T_s < T_{CMB}$

21 cm signal in the Lyman α Sphere

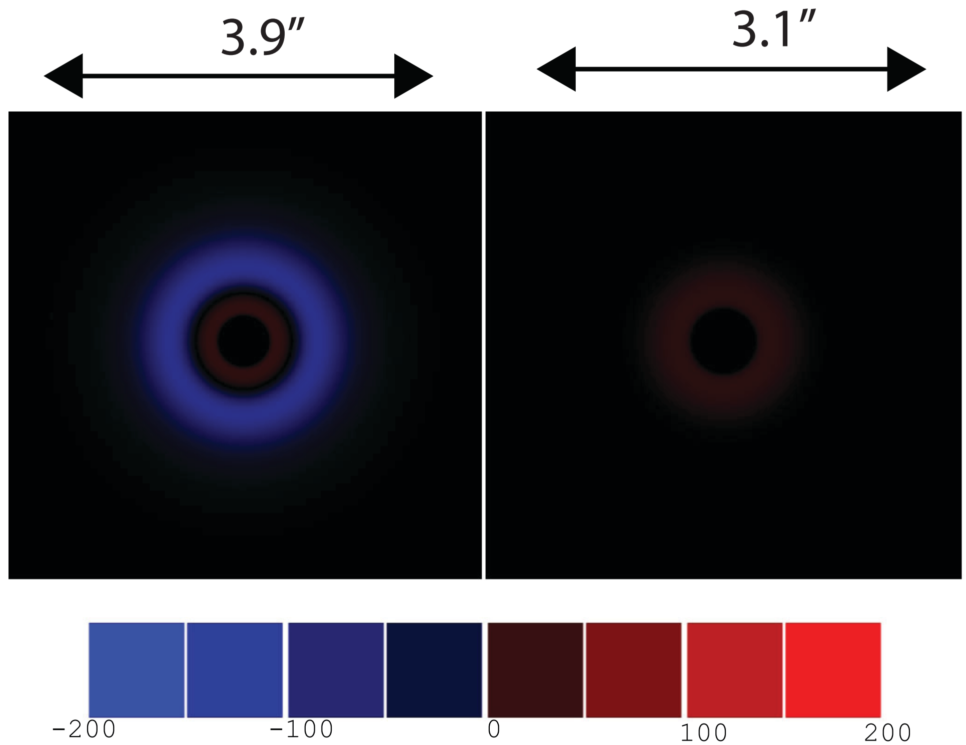


Fig. 12.— A cross section map for a star of 200 $M_\odot$ and age 1.5 Myr at redshift 20(left) and 15(right). The box size is 40 kpc across (physical distance), and unit of temperature scale is mk.

Effect of Stellar Mass/Redshift

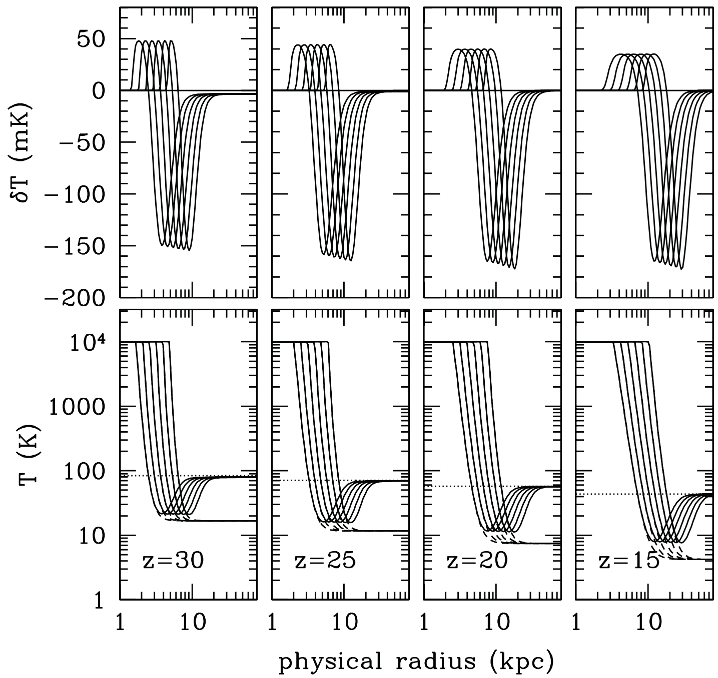
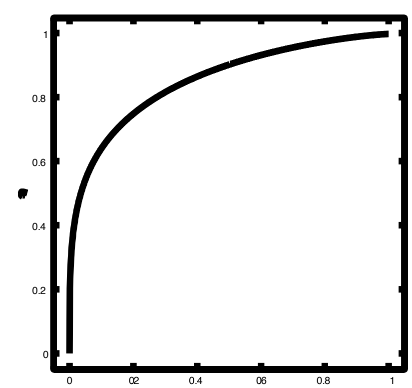


Fig. 2.— Brightness and temperature profiles of Lyα spheres, at a time $t = 1.5$ Myr and the indicated redshifts. *Bottom panels:* T_k (dash lines), T_{CMB} (dotted line), and T_S (solid lines). The six curves are for a star mass M = 25, 50, 100, 200, 400, and 800 $M_{\odot}$. *Top panel*: 21cm brightness temperature fluctuation on the CMB at time $t = 1.5$ Myr.

- More Massive, Luminous Pop III stars-- T_K drops less quickly
- Denser gas at high z, smaller HI sphere. Neutral fraction higher at given radius, heating more efficient (S-vSberg MC).



Time Evolution

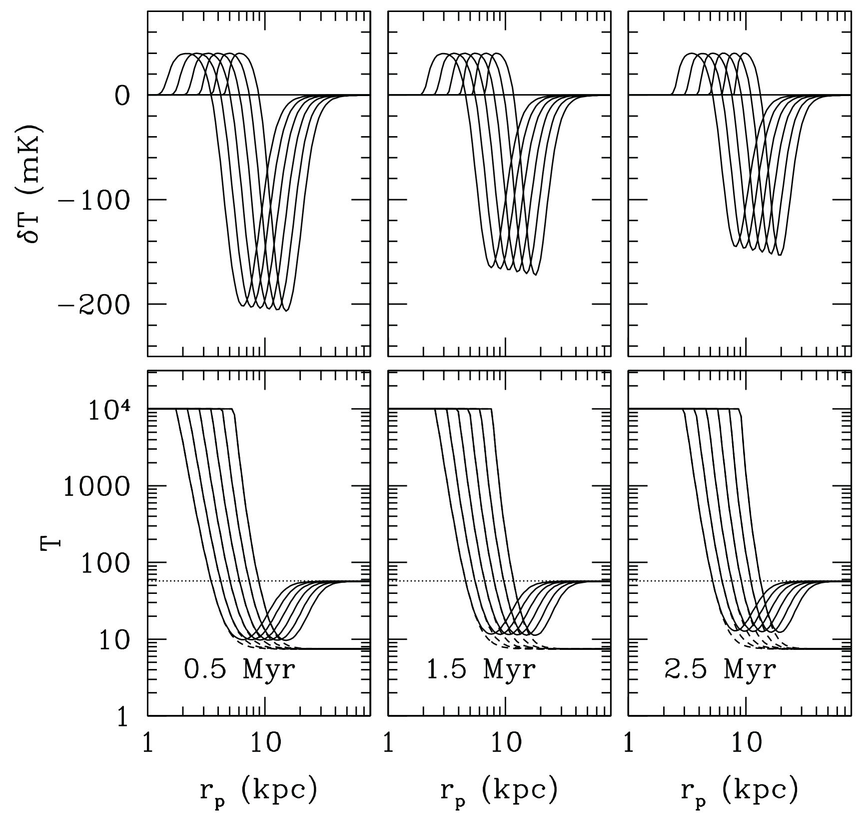


Fig. 3.— Brightness profile of Lyα spheres at $z = 20$, for the three indicated ages after the star birth.

- Ionization/Heating fronts move outward--Absorption Region moves outward
- Heating becomes more important . T_k falls less before $y_\alpha \ll 1$. Shallower Absorption Feature.

Star Formation and the Abundance of First Stars

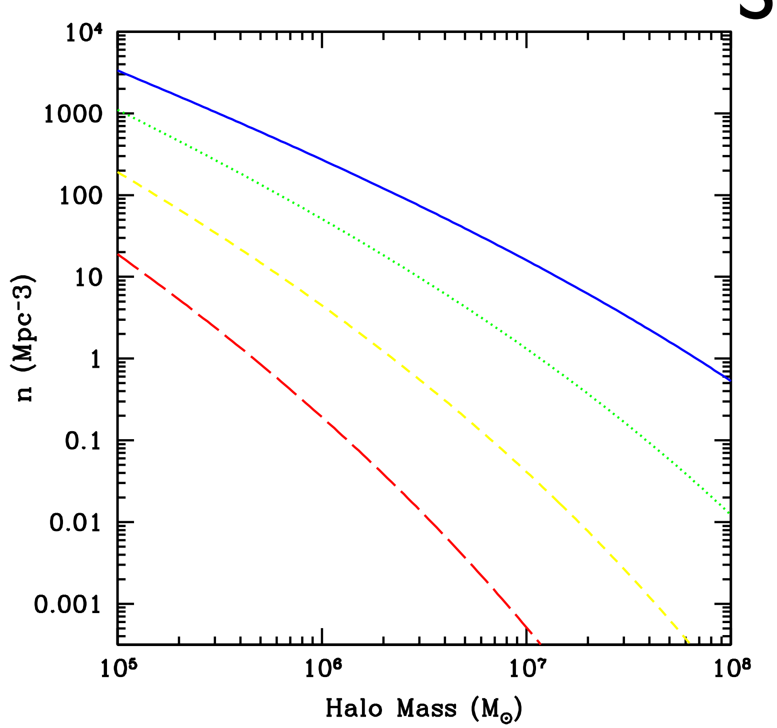


Fig. 4.— Number density of star-harboring halos of mass m per comoving Mpc^{-3} per $\log m$. The four curves are at $z = 15$ (solid, blue curve), $z = 20$ (dotted green curve), $z = 25$ (short-dash yellow curve), and $z = 30$ (long-dash red curve).

- Assuming H_2 cooling, can calculate minimum mass of star-forming halo.
- Use ST/PS mass function to calculate density of these Halos, assuming lifetime t_*.
- Mergers/feedback become important at low z; this breaks down.

$$M_{min}(z) = 1.17 \times 10^6 \left(\frac{\Omega_m h^2}{0.147}\right)^{-1/2} \left[\frac{(1+z)}{21}\right]^{-3/2} \frac{T_{vir}}{2000K}$$

How many neighbors?

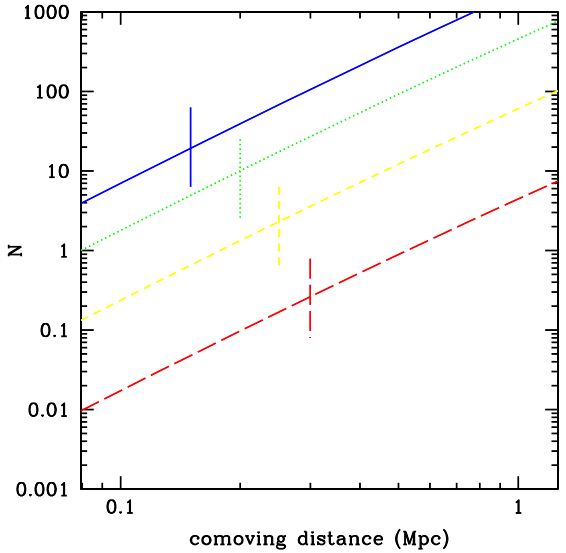


Fig. 8.— Expected number of star-forming halos as a function of distance. The four curves are $z = 15$ (solid, blue curve), $z = 20$ (dotted green curve), $z = 25$ (short-dash yellow curve), and $z = 30$ (long-dash red curve). A physical distance of 10 kpc (the approximate size of the Lyα spheres) is marked at each redshift.

- Using ST bias formula, ξ_{lin} , n(z), can get N(R).
- At low z, several star-forming halos within Ly_α sphere of single star.

The Lyman α Background: Show's over at $z \approx 25$?

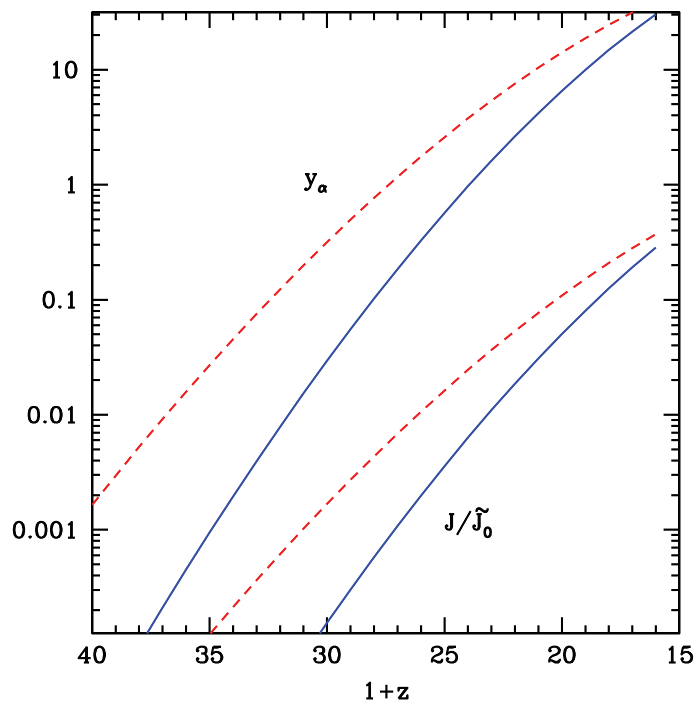


Fig. 9.— Ratio $J/\tilde{J}_0$ (lower curves) and y_α (upper curves) as a function of redshift. Solid curves are for the Press-Schechter mass function, dashed curves are for the Sheth-Tormen mass function.

- Only continuum photons can contribute.
- Use ST/PS Mass function to get J, y_α
- Global absorption after $z \approx 25$,local feature unobservable -> FIRST Stars!

The X-Ray Background: Show's Over at ?

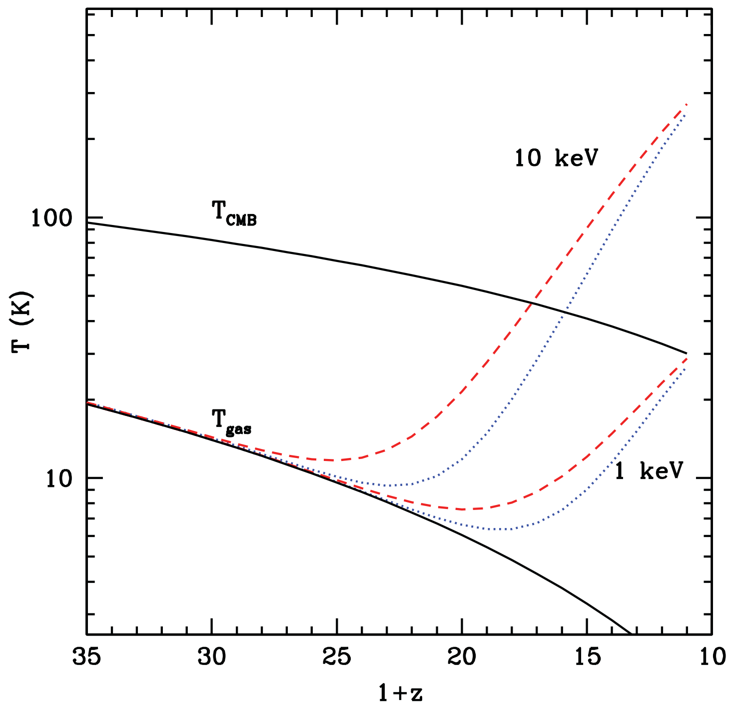


Fig. 10.— Temperature evolution of the IGM. Solid curves show T_{CMB} and the adiabatically evolved gas temperature. Short and long-dash curves show the IGM heated by X-rays, with the PS (short dash) and ST (long dash) model calculations. Two sets of curves are plotted, for $\epsilon = 1\,\mathrm{keV}$ and $10\,\mathrm{keV}$ respetively.

- Hard X-rays have long MFP, heat IGM globally.
- Estimate ϵ_x per stellar baryon, assume η_{eff} (heating efficiency of X-rays), f_*.
- Assume MF from before to count baryons in halos with stars.
- Other heat sources (supernovae, QSO) neglected.

More on the X-Ray Background

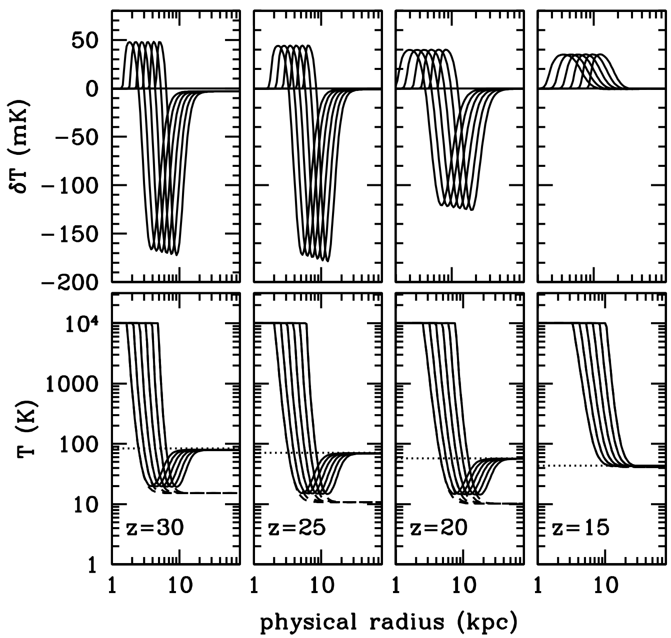


Fig. 11.— Brightness and temperature profiles of Lyα spheres, as in Fig. 2 except with X-ray heating of 10 keV per baryon.

- As X-rays heat IGM at low z, IGM floor is hotter and $|\Delta T_b|$ shrinks
- At low enough z, star appears only in emission.

Is this nuts?

- Baselines:

$$d = 10kpc \rightarrow \theta \approx 5.3^{"}, \Delta\nu = 9.2kHz \text{ at z =30}$$

$$L = 910km \left(\frac{1+z}{21}\right)\left(\frac{\theta}{1''}\right)^{-1} km$$

- $$SNR \approx 3 f_{cov} \left(\frac{1+z}{21}\right)^{-2.5} \left(\frac{\Delta\nu t}{10kHz yr}\right)^{1/2} \left(\frac{\delta T}{10mK}\right)$$

For SNR of 5, with complete coverage and 1 year of continuous observing, and looking for a $400 M_{\odot}$ star,
optimal bandwidth is $\Delta\nu \approx 30kHz$ and optimal baseline is $\Delta\theta \approx 45km$

•Need full coverage with this baseline for this SNR-
-1600 km^2 of collecting area fully covered! (Next Generation)