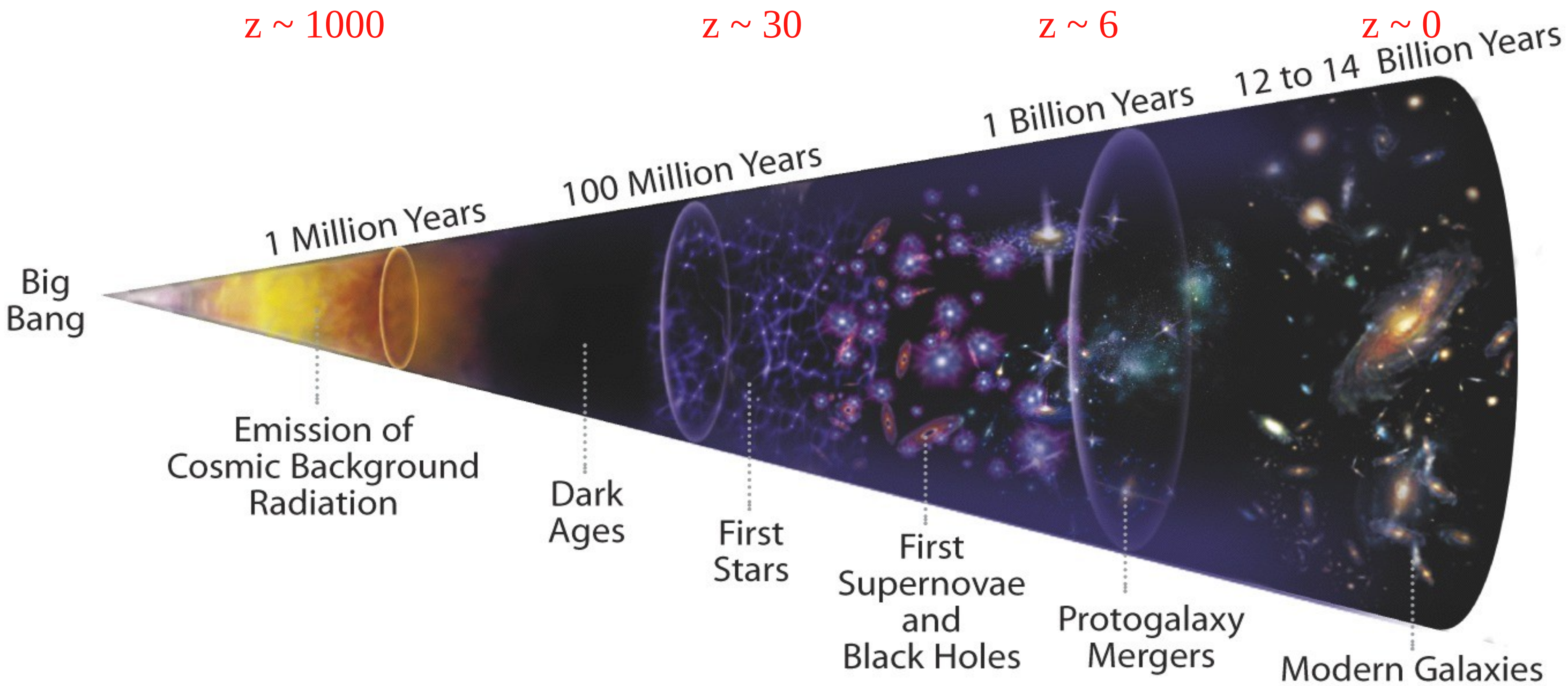
The 21cm signature of the First Stars

Xuelei Chen
National Astronomical Observatory of China
(Beijing, China)

LOFAR workshop
Landal Parc Sundur, Emmen, Netherland, April 26 , 2006

The Cosmic History



The first stars

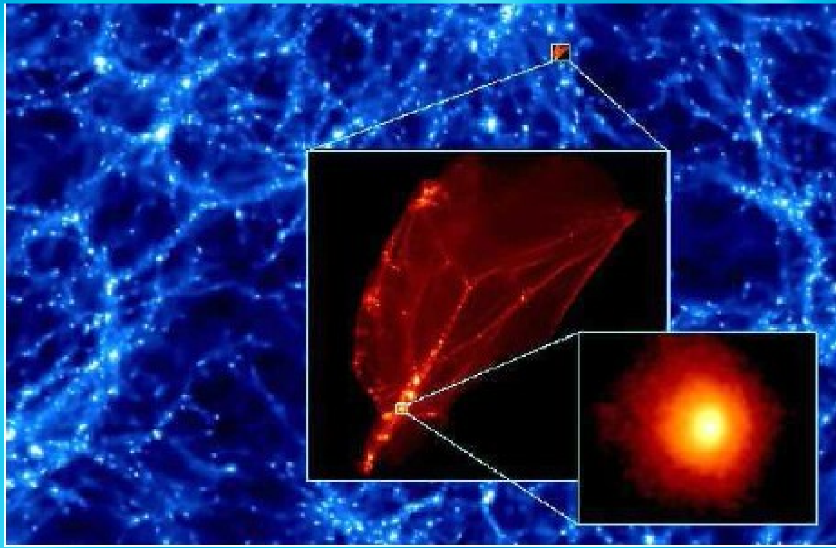
- collisionless dark matter collapse to halos

- if gravity exceeds gas pressure gas can fall into halos (Jeans mass)

- gas in the halo can cool

- molecule H cooling ~10^{2-3} K

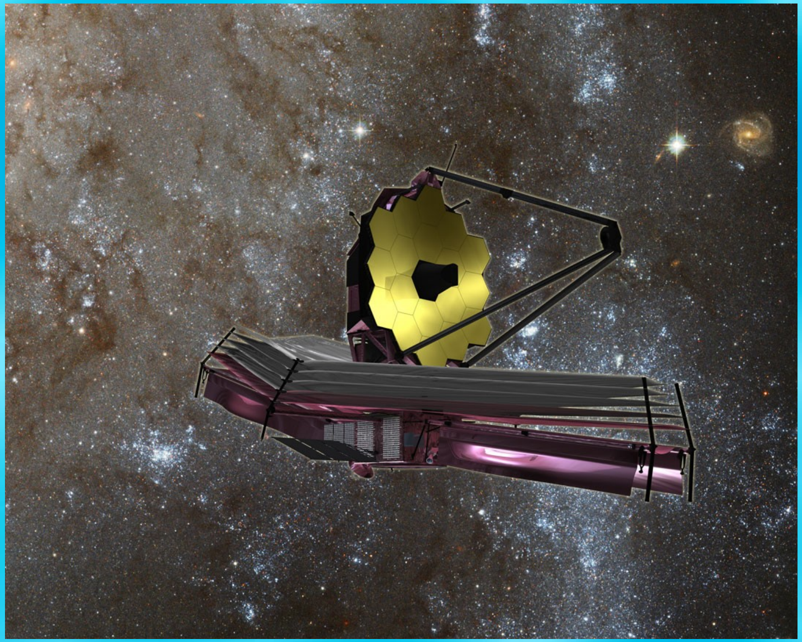
- atomic cooling ~ 10^4 K



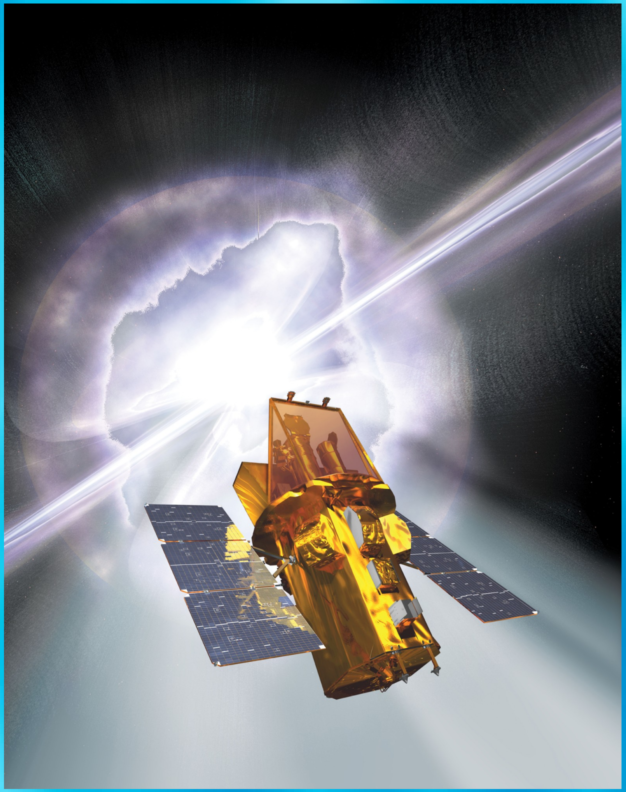
Simulations (Abel 2000, Bromm 2000) indicate first star may form in halos of 10^{5-6} solar mass, one or a few per halo, with masses of a few hundred solar.

$$M_J \simeq 700 M_\odot \left(\frac{T}{200\ \mathrm{K}}\right)^{3/2} \left(\frac{n}{10^4 \mathrm{cm}^{-3}}\right)^{-1/2}$$

Observational Signature



IR (JWST?)



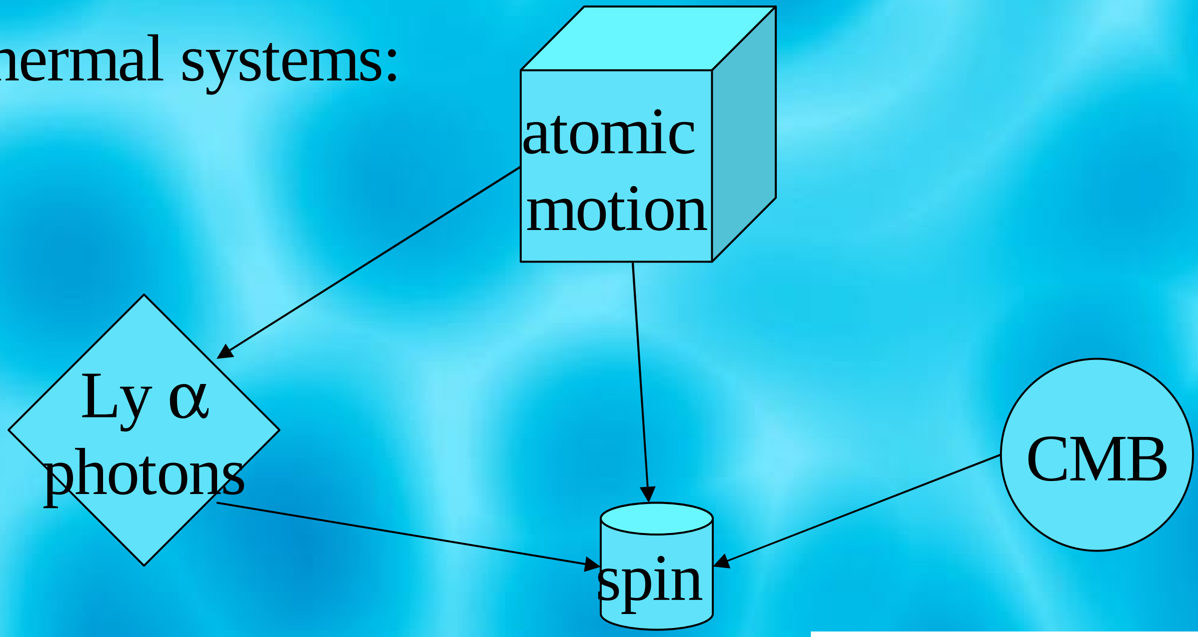
GRB (SWIFT?)


LOFAR

Spin Temperature determines 21cm signature

$$\frac{n_1}{n_0} = 3e^{-\Delta E/k_B T_S} = 3e^{-T_*/T_S}$$

Thermal systems:



Ly α

collision

$$T_\alpha = T_k$$

$$T_S = \frac{T_{CMB} + y_\alpha T_\alpha + y_c T_k}{1 + y_\alpha + y_c} ,$$

The role of Lyman alpha photons

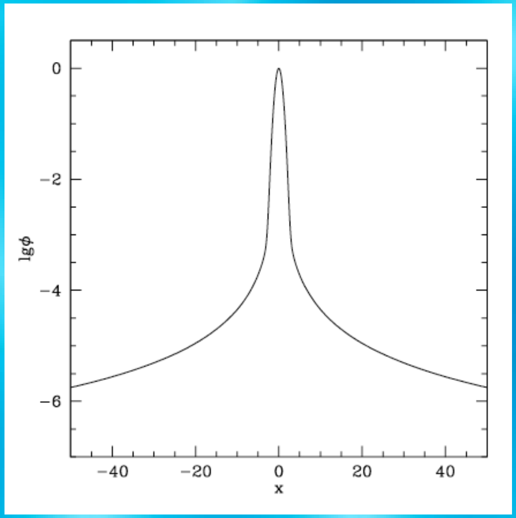
- injected photons: photons emitted/scattered at Ly alpha frequency, produced by recombination

- Continuum photons: UV photon between Ly alpha and Ly beta, redshift to Ly alpha frequency

- Once enter Ly alpha frequency (Doppler core), resonant scattering & confined locally. At Ly alpha frequency, color temperature equals to kinetic temperature

- leaking by 2 photon process

- higher Lyman series



The temperature of gas

Heating of the neutral IGM:

- Shock
- UV ionizing radiation (confined to Stromgren sphere)
- Lyman alpha? No
(Chen & Miralda-Escude 2004, Hirata 2006, chuzhoy & Shapiro 2006, Rybicki 2006, Meiksen 2006, Pritchard & Furlanetto 2006)
- X-ray

Evolution of global spin temperature

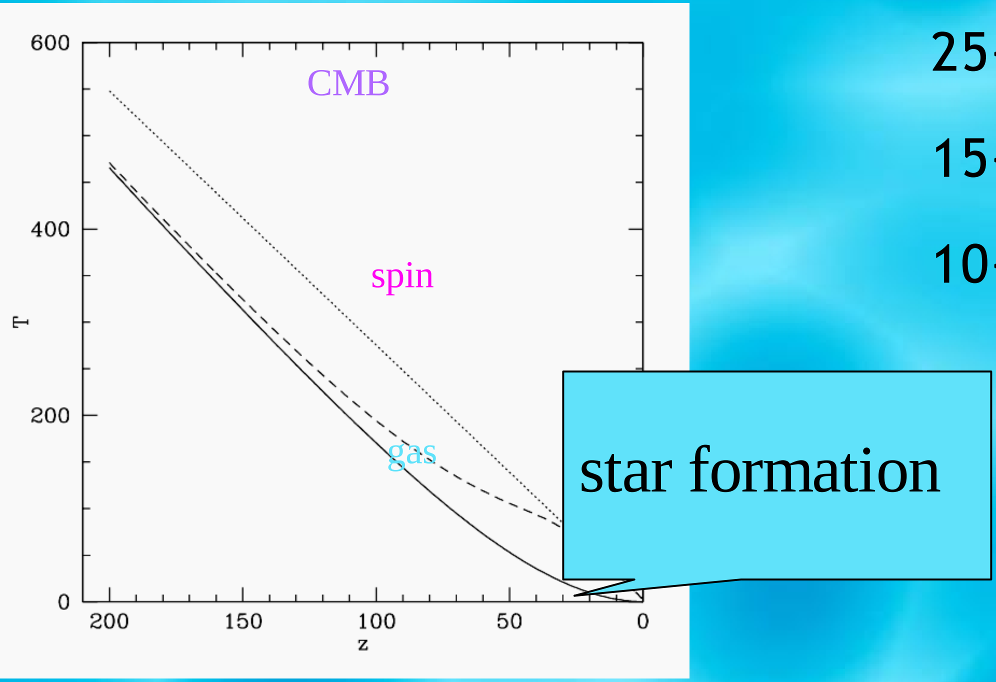
$z>150$: $T_k=T_{cmb}=T_s$

$50<z<150$: $T_s=T_k<T_{cmb}$ collisional coupling

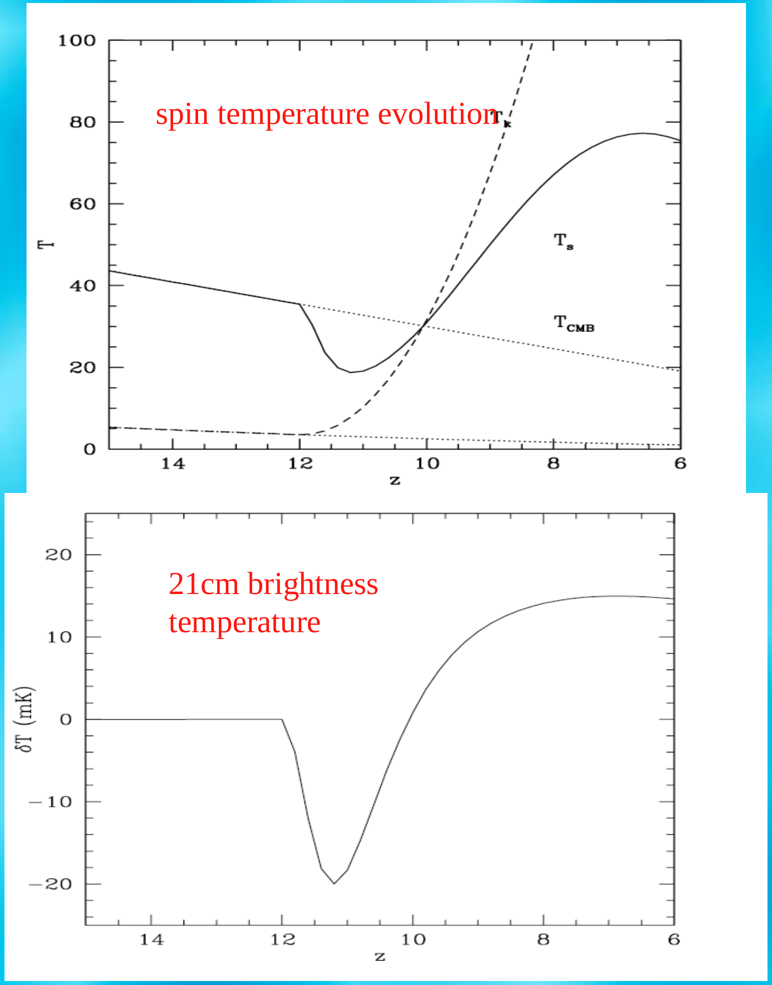
$25<z<50$: $T_k<T_s=T_{cmb}$ no coupling

$15<z<25$: $T_k<T_s<T_{cmb}$ Ly alpha coupling

$10<z<15$: $T_k>T_s>T_{cmb}$ Ly alpha coupling



Evolution of global spin temperature



$z>150$: $T_k=T_{cmb}=T_s$

$50<z<150$: $T_s=T_k<T_{cmb}$ collisional coupling

$25<z<50$: $T_k<T_s= T_{cmb}$ no coupling

$15<z<25$: $T_k<T_s <T_{cmb}$ Ly alpha coupling

$10<z<15$: $T_k>T_s >T_{cmb}$ Ly alpha coupling

Chen & Miralda-Escude, 2004, ApJ 602, 1 (2004)

Modulation of 21cm signal

$$\delta T \simeq (0.025\,\mathrm{K}) \left(\frac{\Omega_b h_0}{0.03}\right) \left(\frac{0.3}{\Omega_{m0}}\right)^{1/2} \left(\frac{1+z}{10}\right)^{1/2} \frac{\rho_{HI}}{\bar{\rho}_H} \frac{T_s - T_{CMB}}{T_s}$$

- density (cosmic web, minihalo)
- ionization fraction (galaxy, cosmic HII region)
- spin temperature:
  temperature,
  density,
  Ly alpha flux

The absorption signatures

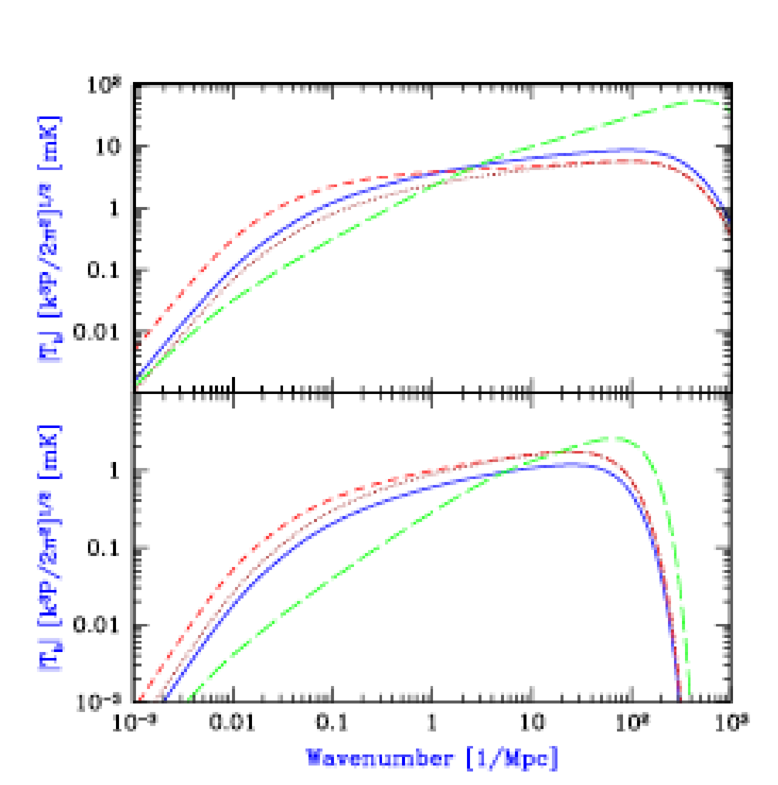
- z>200, CMB and gas has about the same temperature, no 21cm signal

- 200>z>40, gas temperature < CMB temperature, absorption modulated by density (but if DM decays, can also have Lyman alpha coupling)

- z<40, before the presence of Lyman alpha background: absorption, density modulation in mini-halos

- Lyman alpha modulation, temperature modulation, density modulation, ionization modulation...

large scale Lyman alpha fluctuations



Barkana & Loeb 2004

Lyman alpha sphere around first stars

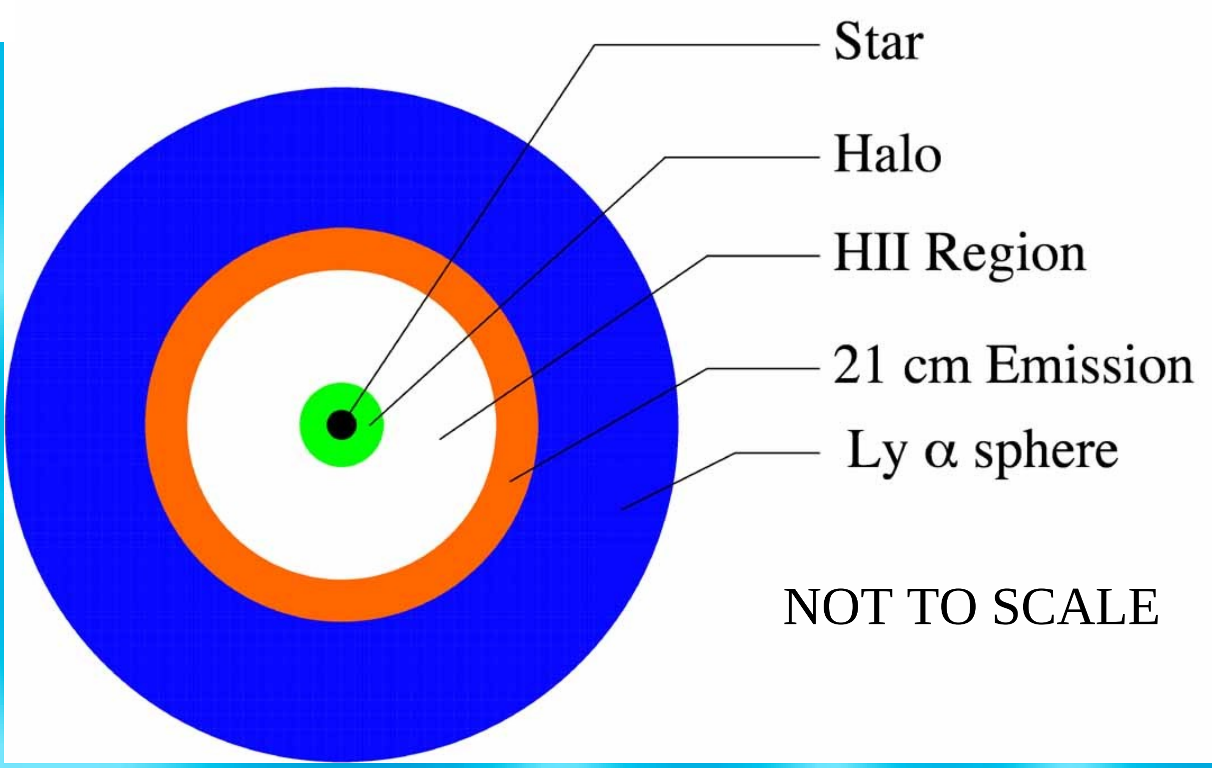
first stars: 100 solar mass metal free star radiating at Eddington limit (Bromm et al 2001)

Chen & Miralda-Escude, astro-ph/0605439 (ApJ accepted)

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

$$L_{total} = 10^{4.5} \frac{M}{M_\odot} L_\odot$$

- life time of the star ~ 3 Myr, Hubble time ~ 10^8 yr
- light propagation time ~ size of Lya sphere (10 kpc)
- halo virial radius ~ 0.1 kpc



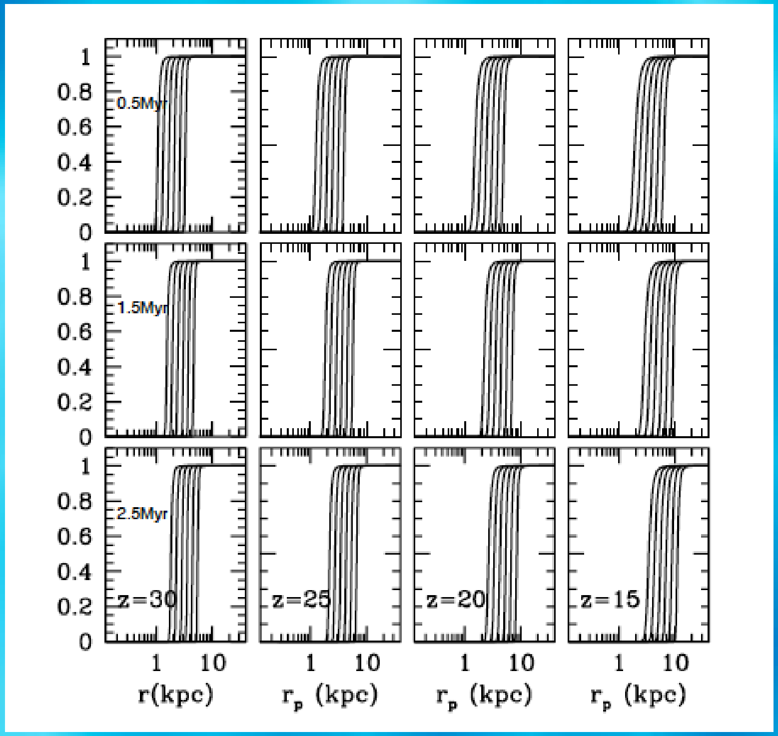
Radiative Transfer

1D (spherical) radiative transfer code

assume first star blackbody radiation

evolve photon spectrum

include helium

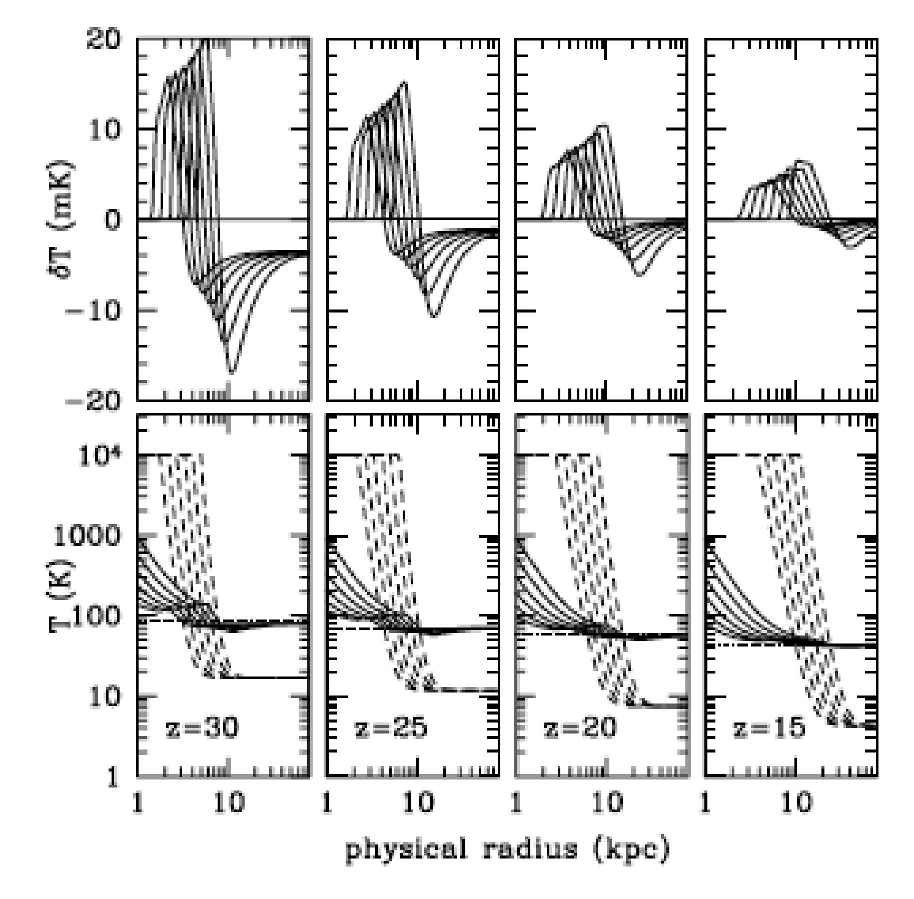


For stellar mass of 25, 50, 100, 200, 400, 800 Msun.

continuum Lyman alpha photons

- Line photons confined to HII region (or where it is produced) by resonance scattering

- continuum photon: decrease as r^{-2}



The secondary Lyman alpha photons

induction by X-ray photons:
recombination, excitation, cascade

photon production rate ~ energy rate/E_α

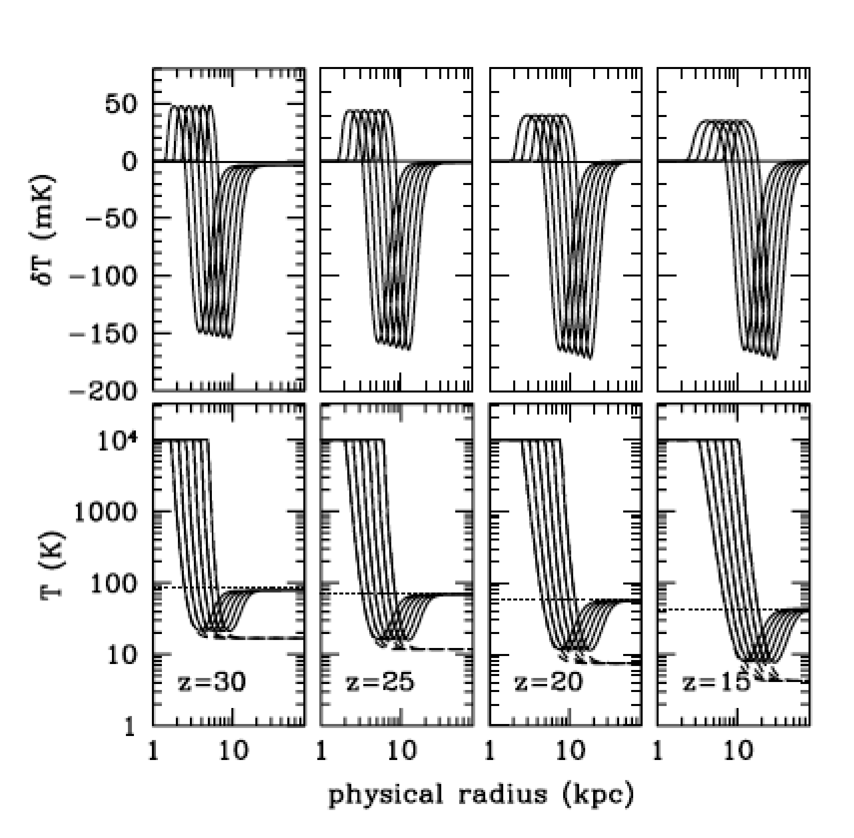
frequency shift rate ~ H ν_α

flux ~ photon production rate / frequency shift rate:

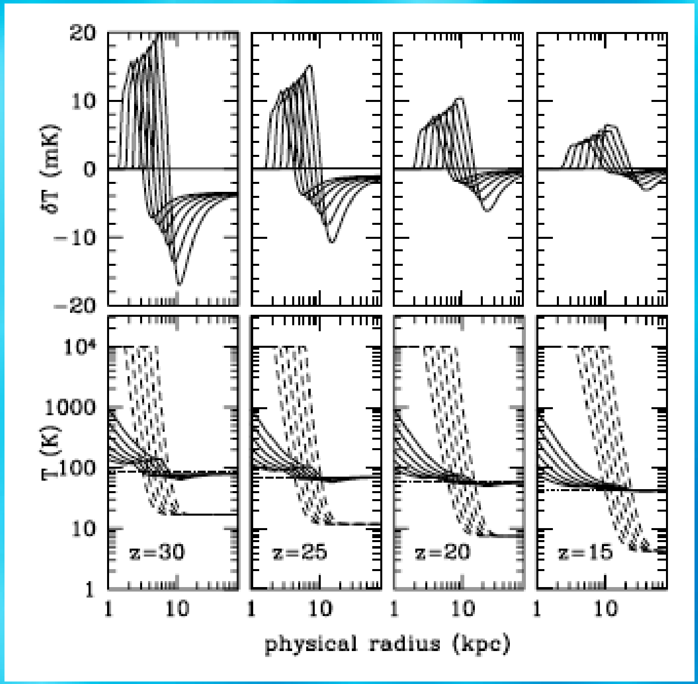
$$J_i = \frac{c\eta_\alpha \Gamma}{4\pi h H \nu_\alpha^2} \, .$$

Neglected order 1 correction factor and higher Lyman series

Ly α sphere profile

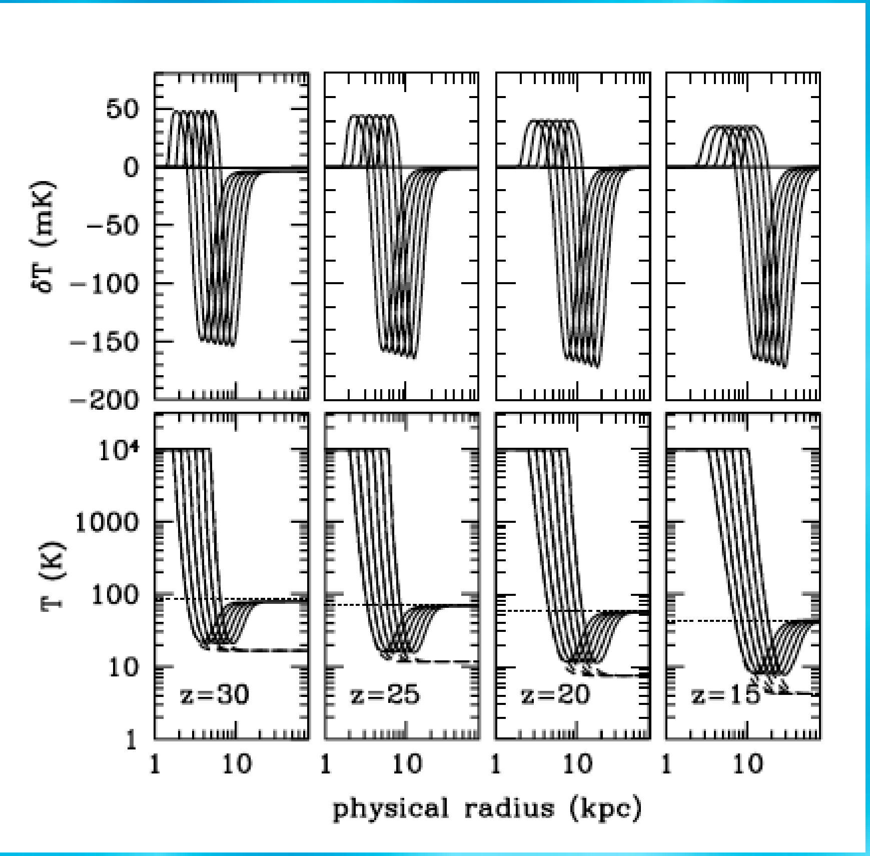


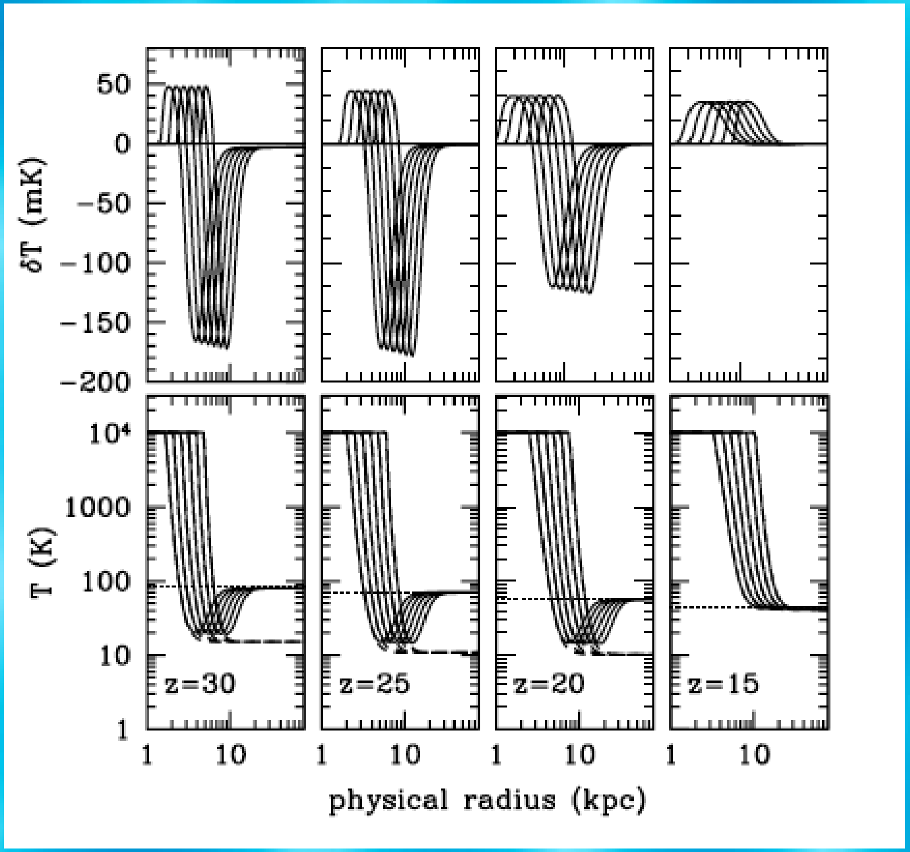
with injected Lyman photons
very strong absorption



with only continuum Ly photons, weak absorption

The profile of Lyman alpha sphere with X-ray background heating



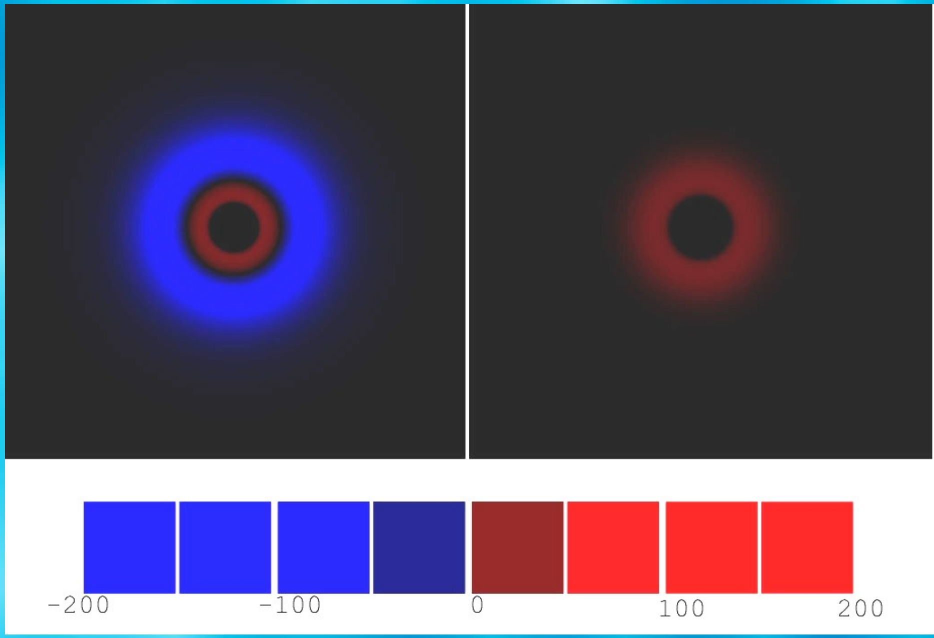


no heating

with heating

Cross Section Map

- Ly alpha background reduce contrast of Ly alpha sphere
- If gas heated above CMB, no absorption signal
- absorption signal much stronger than emission



Formation Rate of first stars

- Minimal mass requirement:

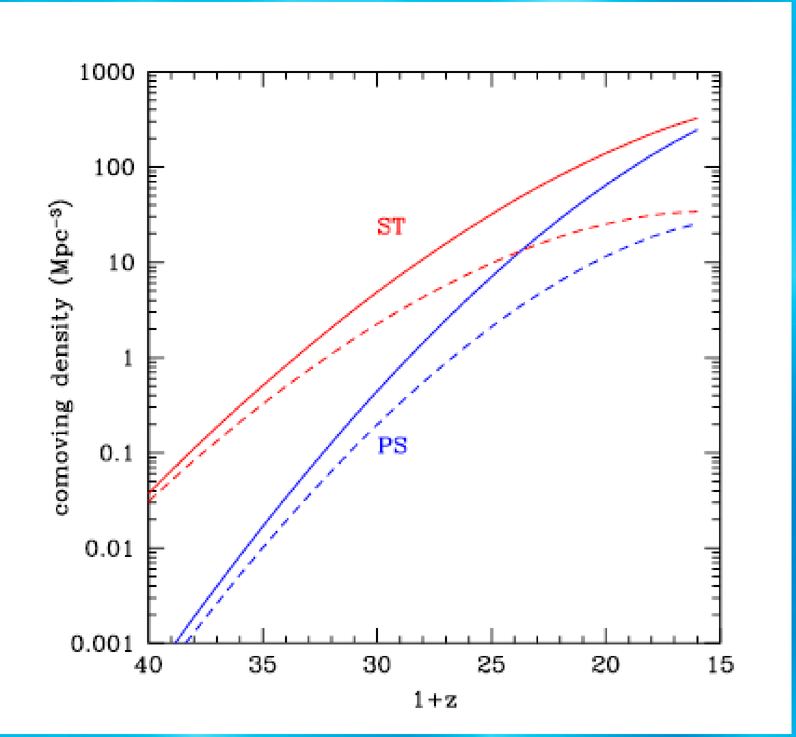
  $T_{vir} > 2000$ K

- One star formed per halo

- Star died after 3 Myr, so exist only in halos just formed

$$n_* = \int_z^{z_a} dz \int_{M_{min}(z)}^{\infty} dm \, \frac{\partial N(m,z)}{\partial z} \, ,$$

$$n_* \approx (1+z) H(z) t_* \int_{M_{min}(z)}^{\infty} dm \, \frac{\partial N(m,z)}{\partial z}$$



This breaks down at low redshift: (1) halo destruction (2) feed back

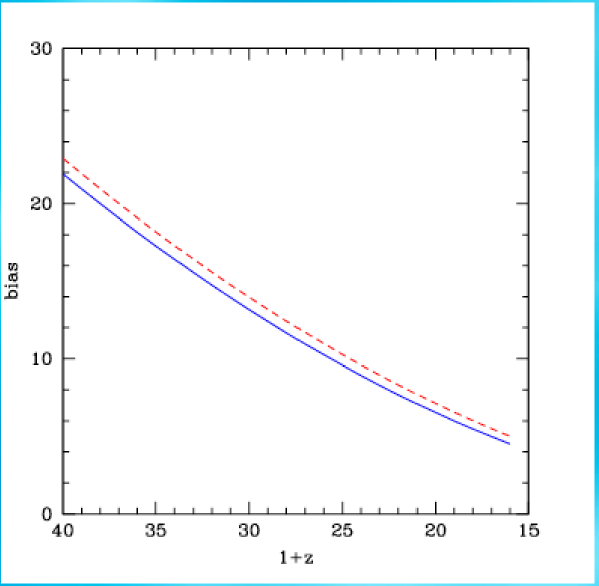
Biase & correlation function of halos (not stars)

PS

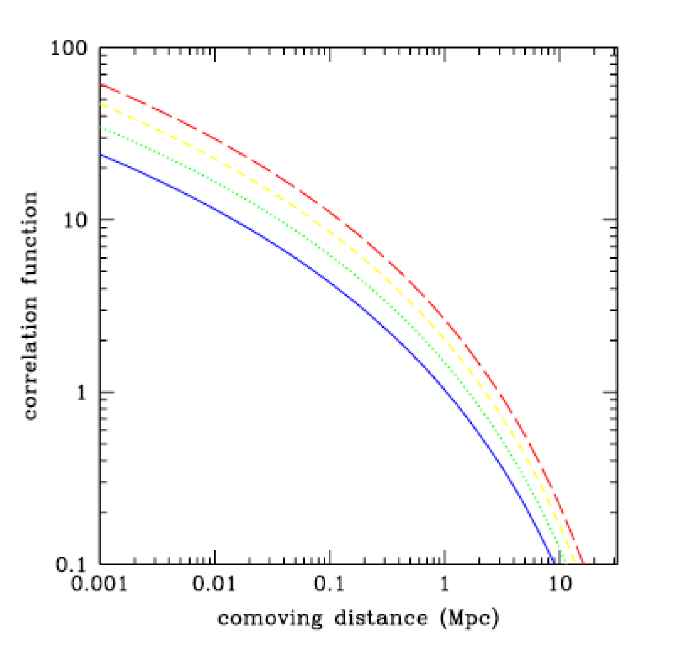
$$b = 1 + \frac{\nu(M,z) - 1}{\delta_c(0)}$$

ST

$$b = 1 + \frac{1}{\delta_c(0)}\left[s' + 0.5 s'^{0.4} - \frac{s'^{0.6}/0.84}{s'^{0.6} + 0.14}\right]$$

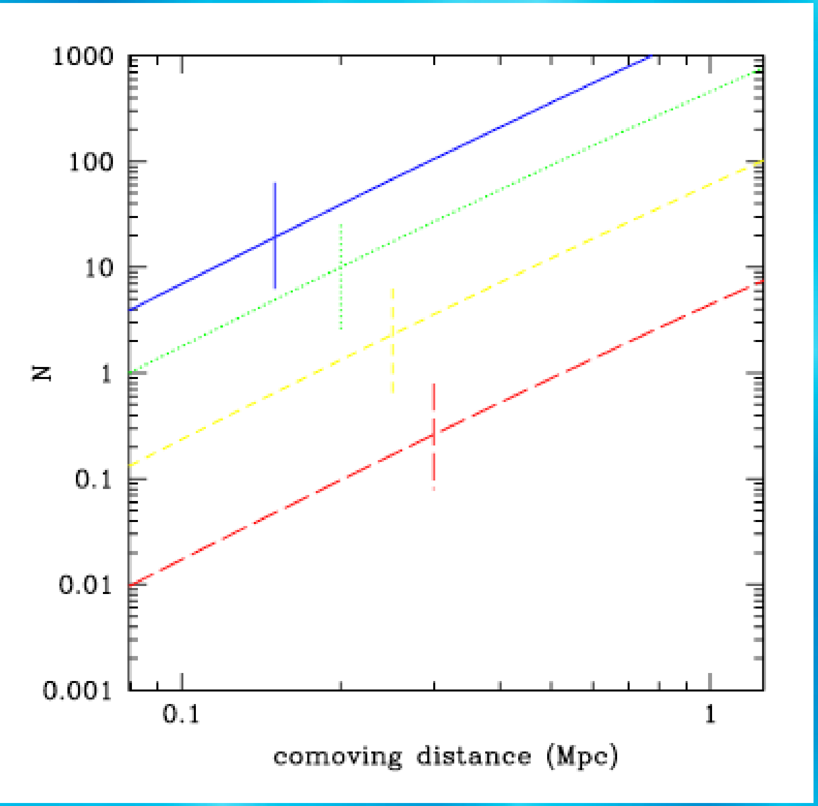


$$\xi_{hh}(r,z) \approx b^2 \xi_{lin}(r,z) \ ,$$



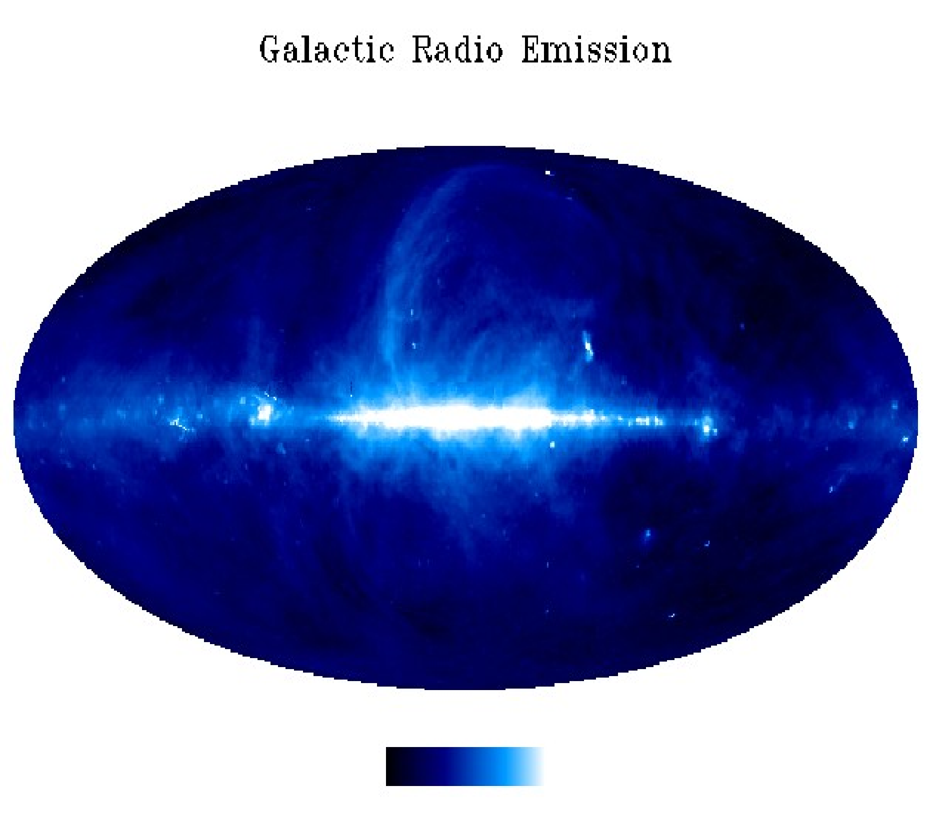
Overlap of Lyman alpha spheres

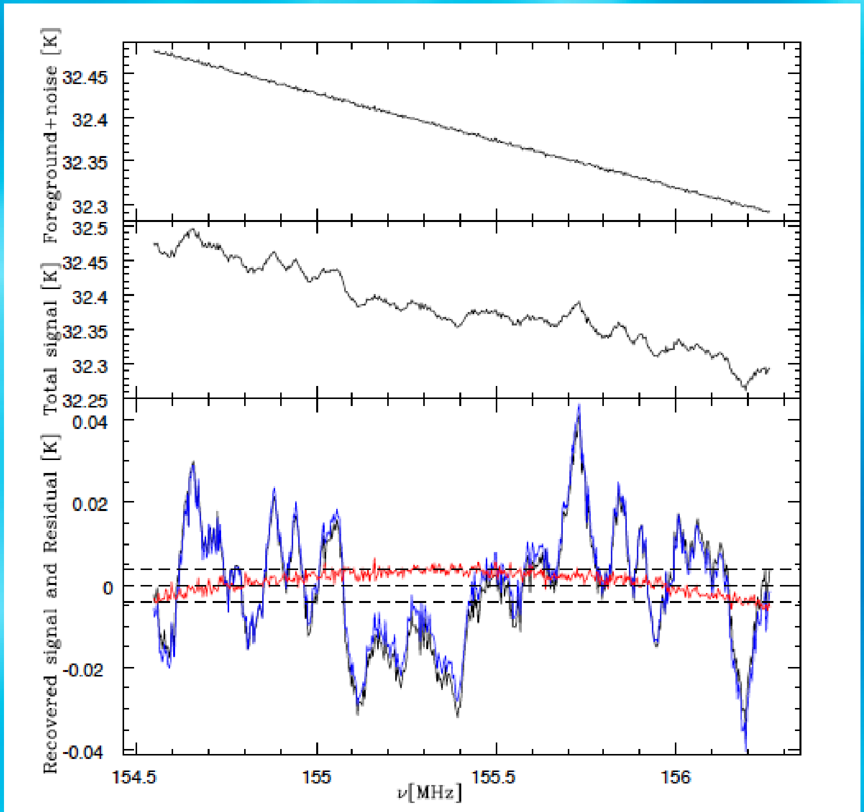
- cumulative number of halos within a certain distance
- caveat: may not form at the same time
- first star clusters: bigger Lyman alpha sphere
- the shape of Ly alpha sphere may be irregular due to nearby first star and density fluctuation



$$\bar{N}(R) = \bar{n}(z) \int_0^R d^3r \, [1 + \xi(r)] \ ,$$

Foreground





X. Wang et al astro-ph/0501081

Observablity

measurement error

$$\Delta T \sim \frac{T_{sys}}{f_{cov}\sqrt{\delta\nu t}} ,$$

system temperature dominated by galactic foreground:

$$T_{sys} \simeq 2000\mathrm{K} \left(\frac{1+z}{21}\right)^{2.5} .$$

covering factor

$$f_{cov} = N_{dish} A_{dish} / A_{total}$$

signal to noise ratio

$$\mathrm{SNR} = \sqrt{\Delta\nu t} f_{cov} \frac{\delta\hat{T}}{T_{sys}} .$$

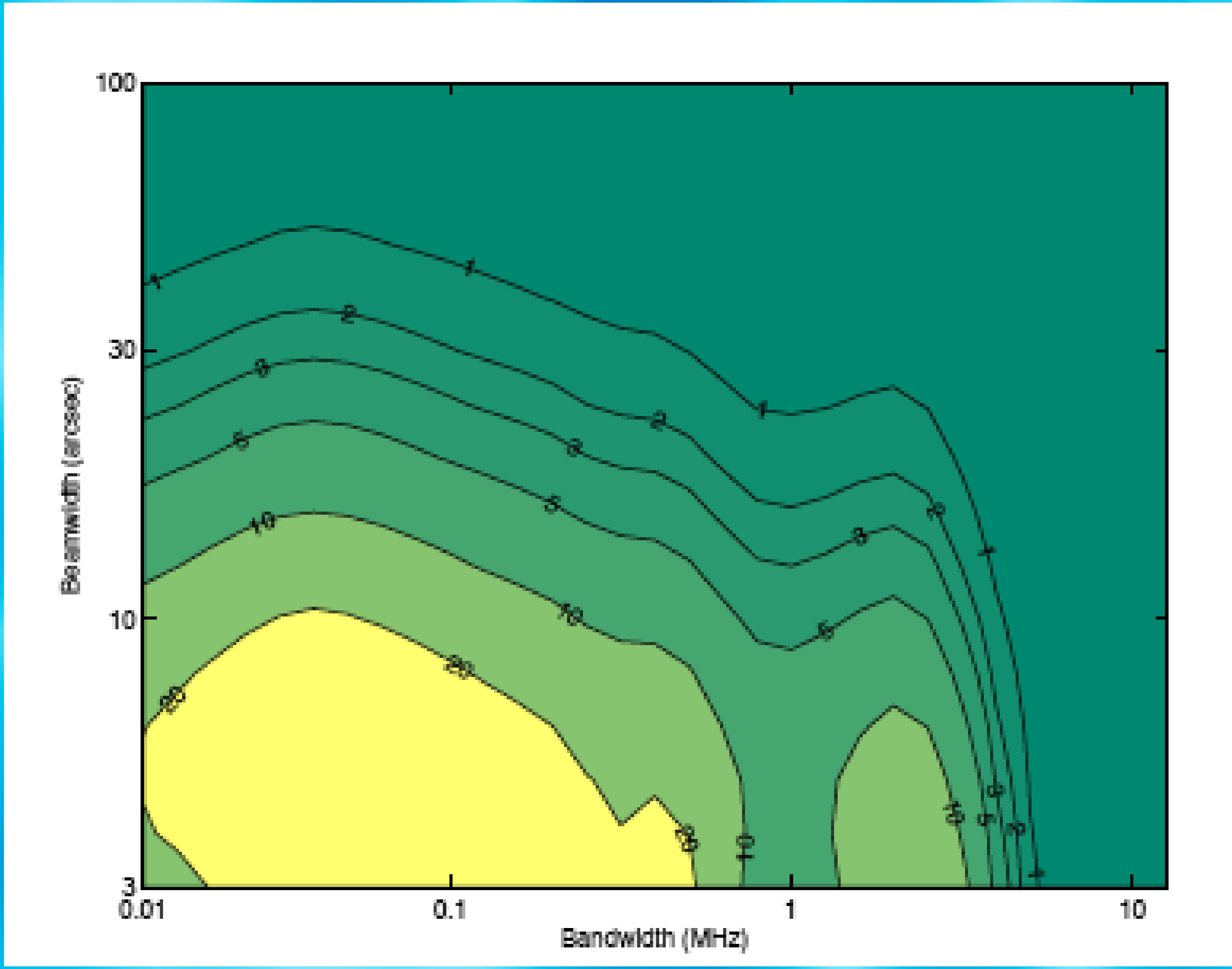
Observablity

difficult to achieve high SNR:
require almost-filled array

$$\mathrm{SNR} = \sqrt{\Delta\nu t}\, f_{cov} \frac{\delta\hat{T}}{T_{sys}}.$$

10^5 1 10^{-5}

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



Beamwidth (arcsec)
Bandwidth (MHz)
100
30
10
3
0.01
0.1
1
10

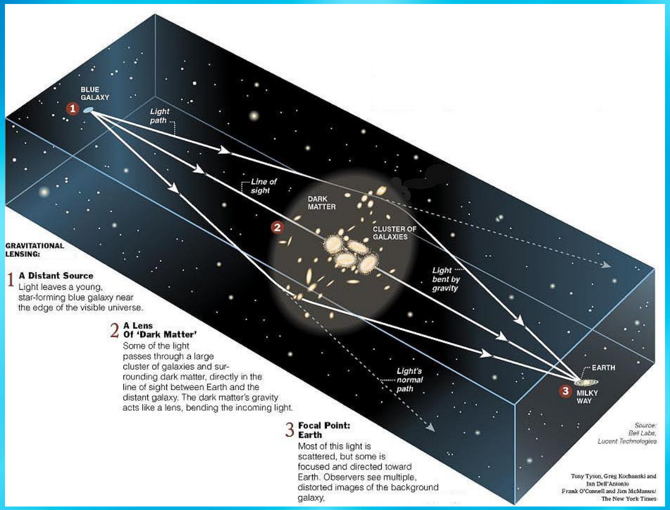
Some Numbers

Very Challenging, far beyond the capability of current generation 21cm experiments.

baseline	bandwidth	beamwidth	SNR
45 km	30 kHz	20 arcsec	5
65 km	30 kHz	14 arcsec	10
91 km	30 kHz	10	20

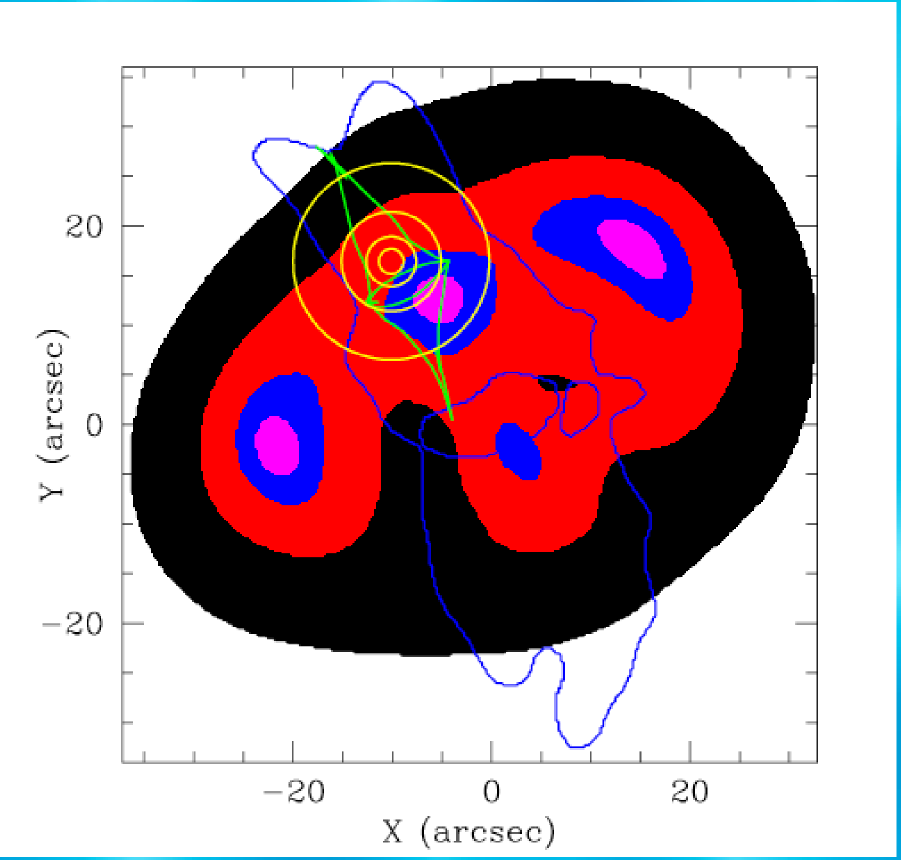
Strong gravitational lensing

- Lensing strong near caustics
- cluster strongly lensed region ~ 10 arcsec size
- significantly increases the size of the image



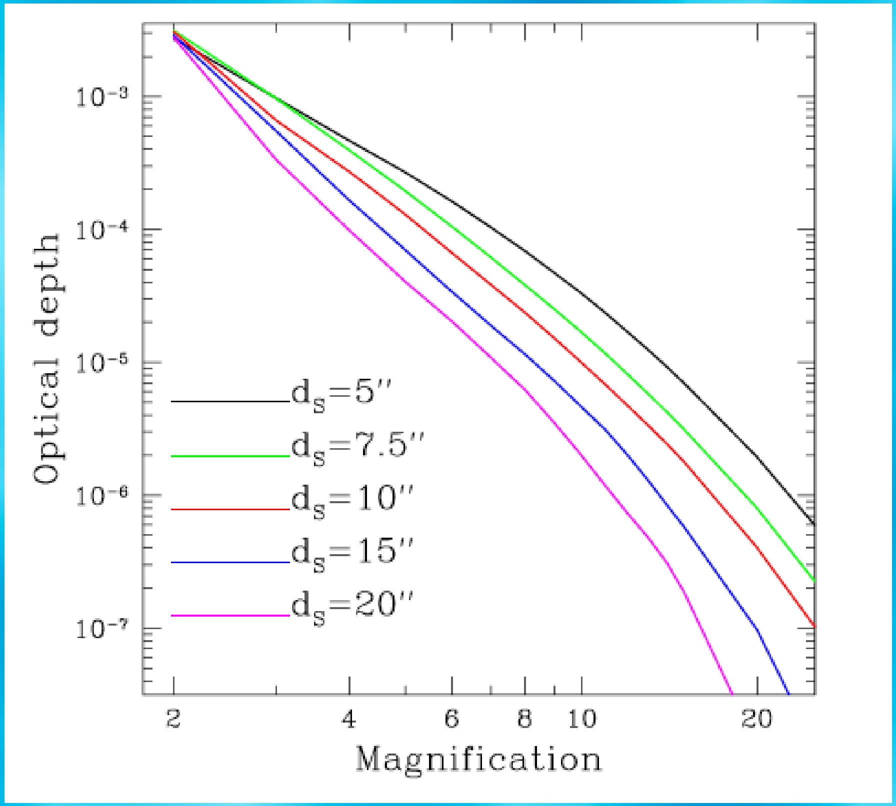
$$\tau = \frac{1}{4\pi {D_{\rm s}}^2} \int_0^{z_{\rm s}} dz\, \overline{\sigma}(z)(1+z)^3 \frac{dV_{\rm p}(z)}{dz},$$

Can lensing enhance 21cm signal?



G. Li, P. Zhang & XC, astro-ph/0701492, ApJ accepted

optical depth for different size of LYA sphere



Estimates

Total number of LYA spheres (whole sky) 10^{11-13}

optical depth 10^{-6}, a total of 10^{5-7} strongly lensed

The original LYA sphere requires A ~ 1000 km^2 , with lensing, reduce to A ~ 100 km^2, still larger than SKA, but there are proposals on constructing such telescopes cheaply (U. Pen & J. Peterson)

Summary

- The 21cm signal is determined by spin temperature, for low spin temperature strong "absorptional" signal can be achieved

- spin temperature is modulated by Lyman alpha photons. Around strong sources, there could be "Lyman alpha spheres" visible in 21cm

- X-ray from first stars maybe important in heating and in creating "injected Lyman alpha photons", enhancing the signal. This may be used to distinguish different models of first objects.

- For detecting true individual first stars, need very large effective area (1000 km^2), this factor could be reduced by a factor of 10.

Thanks