A Theorist's Radio Sky

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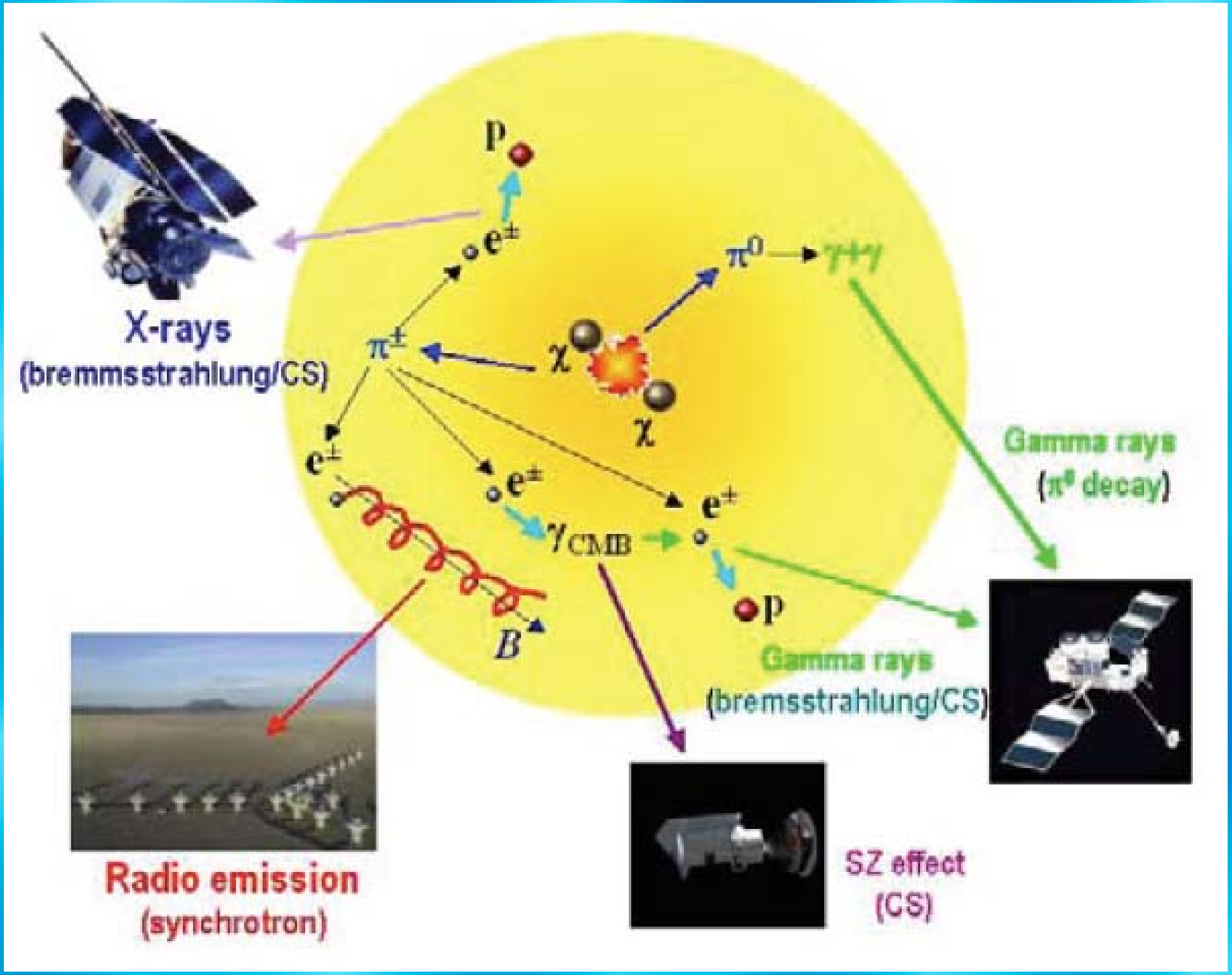
Outline

radio detection of dark matter

21cm signature of first stars

21cm forest

DM annihilation signals



S. Colafrancesco, IoP/RAS Meeting 2007

Electron & Positron Diffusion in magnetic field

$$n_e(E,r) = [Q_e(E,r)\tau_{loss}] \cdot \frac{V_{source}}{V_{source} + V_{diffusion}} \cdot \frac{\tau_D}{\tau_D + \tau_{loss}}$$

$\tau_{loss} \gg \tau_D$

$$n_e(E,r) = [Q_e(E,r)\tau_{loss}] \cdot \frac{V_{source}}{V_{diffusion}} \cdot \frac{\tau_D}{\tau_{loss}}$$

Possible local DM annihilation sources

Annihilation rate $\propto \rho^2$

- **Galactic Center**

  nearest and densest region

  but with numerous astrophysical activities

- **Nearby galaxies cluster: Coma**

cluster as the largest bound containers of DM

- **Dwarf galaxies: dwarf spheroidal galaxies**

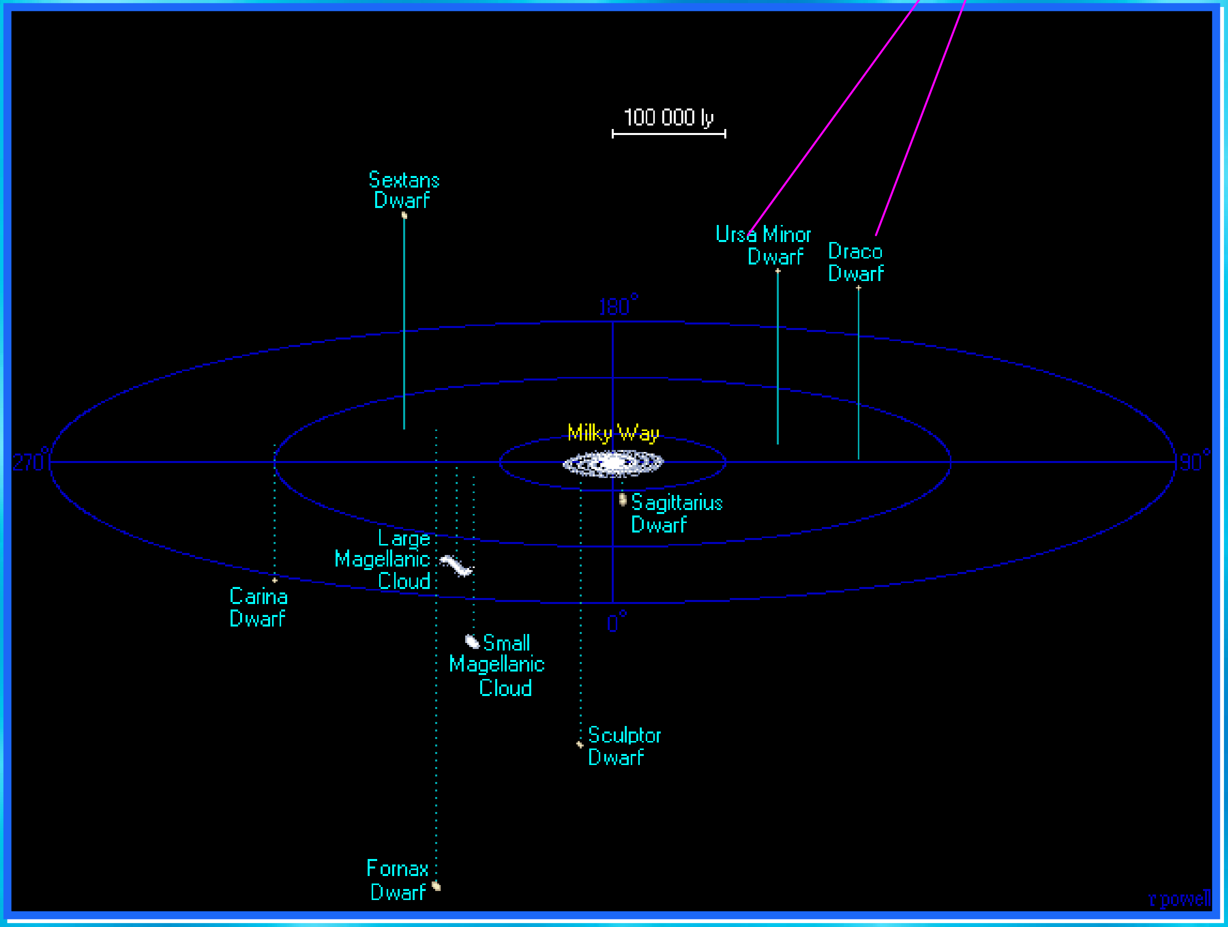
  dominated by DM both in central regions and outskirts;

  close to be a *pure* dark halo;

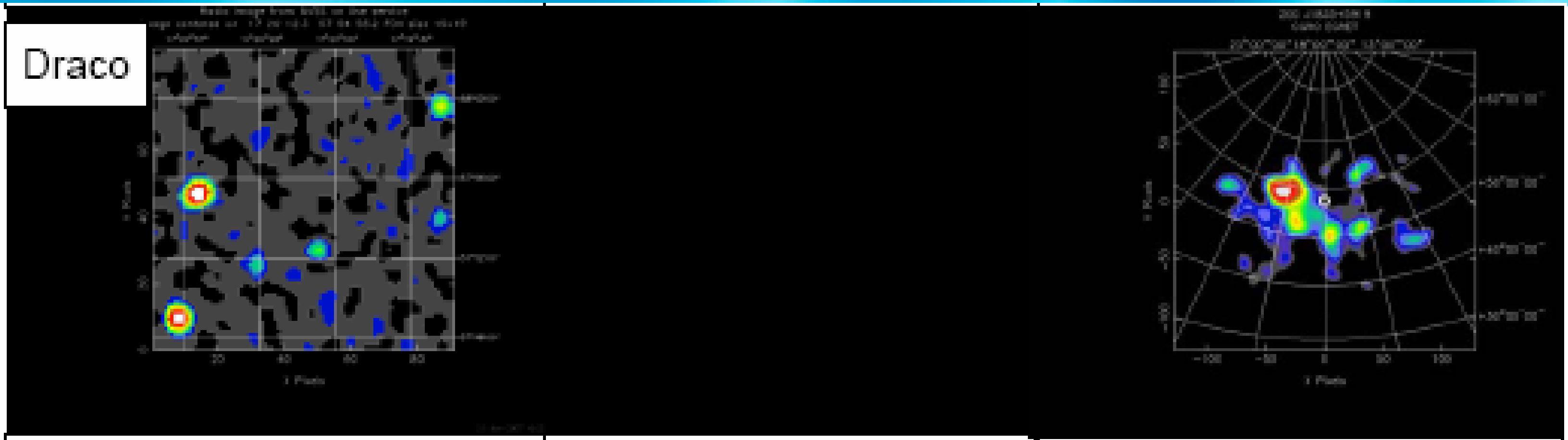
  local group satellites

Milk Way dSphs

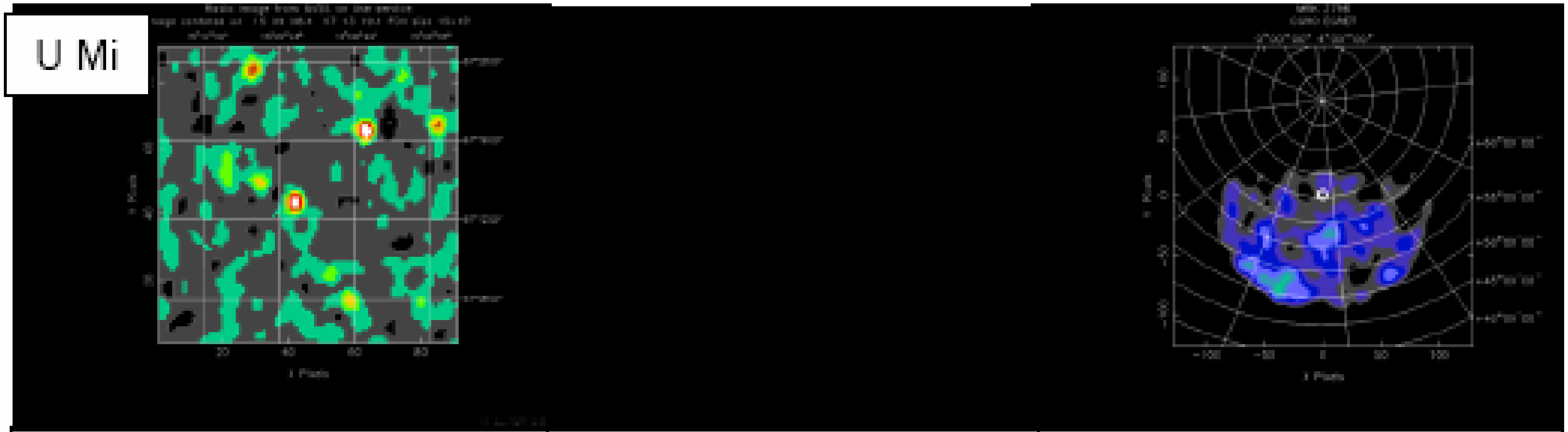
High latitude
Highest mass/light



Draco and Ursa Minor



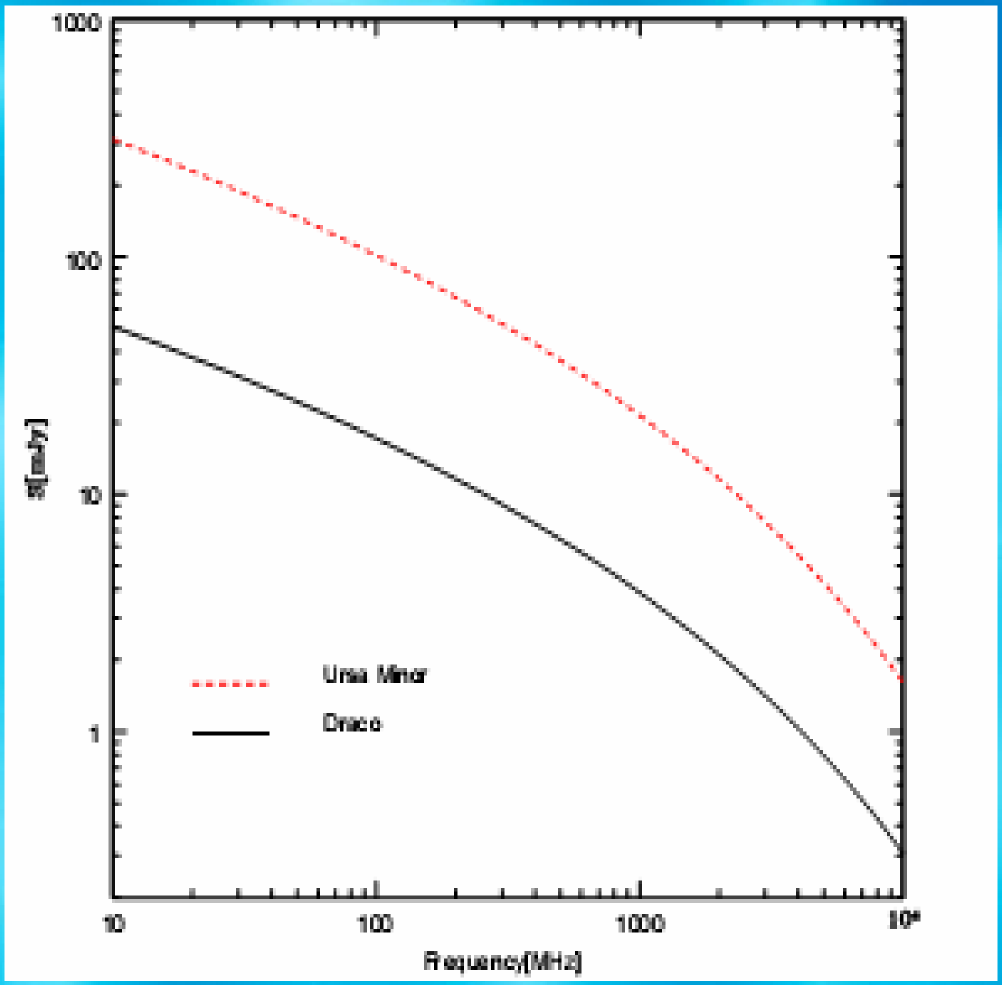
$F_{4.9} <$ 2 mJy	$F_{2keV} <$ 1.7e-14 erg/scm^2	S=1 pho; bkg=1 pho



$F_{1.4} <$ 3.5 mJy	$F_{2keV} <$	S=13 pho; bkg=11 pho

S.Colafrancesco,IoP/RAS Meeting 2007

Estimation of the radio emission:



1) Dark halo:

$$\rho_{NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

with two parameters determined
from the velocity dispersion of stars

2) Magnetic field:

$1\mu\mathrm{Gs.}$

3) neutralino:

$M_\chi = 100\mathrm{GeV}$

$< \sigma v > \simeq 2.0 \times 10^{-26}\ cm^3 s^{-1}$

Diffuse radio emission in dSphs

Table 2. Related results (θ: half of the angular diameter)

	Flux(mJy) from Draco			Flux(mJy) from Ursa Minor		
	4.89GHz	1.42GHz	0.7GHz	4.89GHz	1.42GHz	0.7GHz
$\theta = 6'$	0.2	0.7	1.1	0.4	1.5	2.7
$\theta = 30'$	0.8	2.9	5.1	4.4	15.9	28.6
$\theta = 60'$	0.9	3.2	5.7	6.2	22.8	40.9

1) About 90% of the total flux is from the central region of 2 degree of angular diameter and 50% is within central 50 arcmin region.
2) Fluxes increase greatly with the frequency decreases
3) Dependency on DM properties and the local magnetic field:

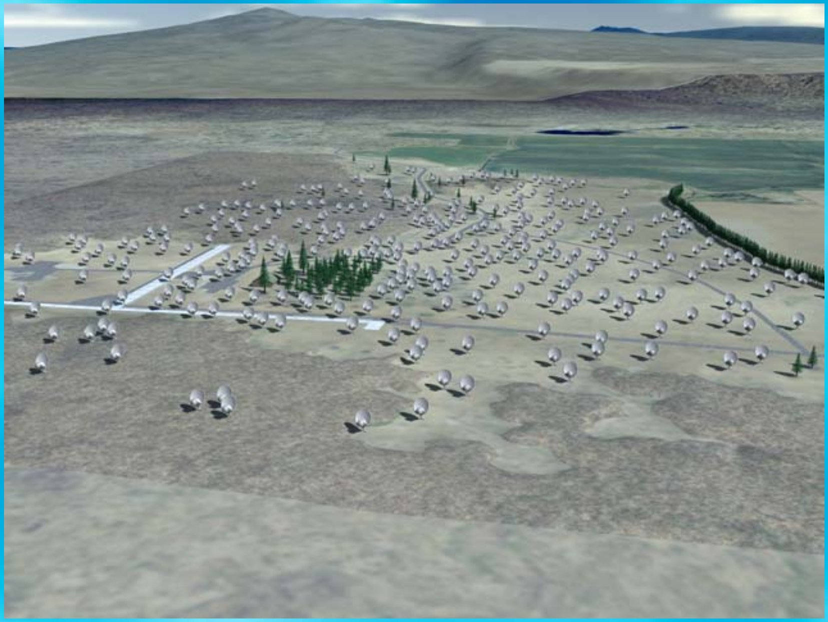
$$S[mJy] \approx 11.25 < \sigma v >_{26} B^{4.5}(1 - 0.3B + 0.022B^2)$$

Observation

•Previous radio continuum observation in the very center region

• No detectable radio emission at 3 σ noise level of 2mJy were found within 4arcmin of the galaxy centers (Fomalont et al with VLA at 4.885GHz in 1979)

Allen Telescope Array



- Large field of view (2.5 degrees at 1.4GHz)
- short baseline
- 42 working antenna

ideal for searchingdiffuse emission from nearby galaxies.

ATA proposal

Feng Huang, ZhiqiangShen, Xuelei Chen

Frequency: 1.4 GHz & 750 MHz
Effective Bandwidth: 103 MHz
Total Observing Time: 24 hr (half source/half blank field)
Expect: rms 0.05mJy/beam at1.42GHz

Non-detection: will constrain the particle properties of DM and the local environment.

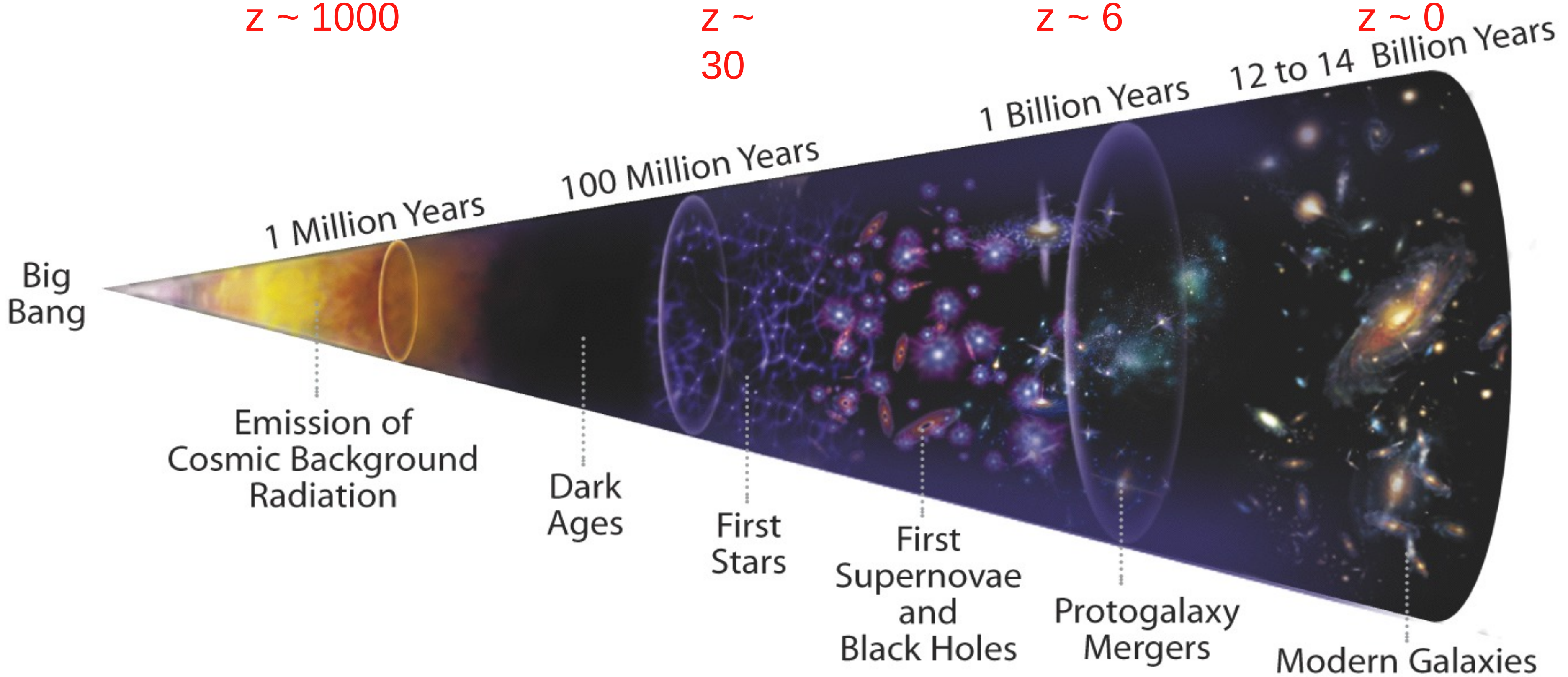
21cm signature of first stars
(X.C. &JordiMiralda-Escude)

z ~ 1000

z ~ 30

z ~ 6

z ~ 0



The first stars

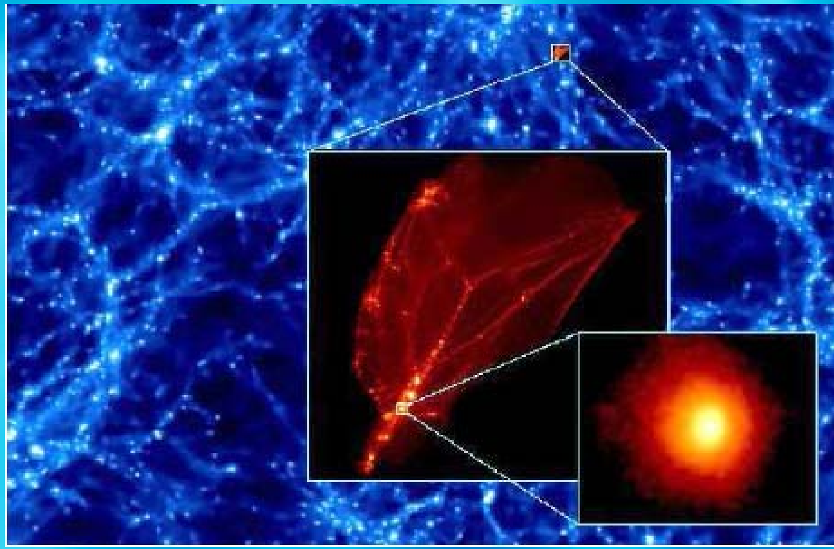
• collisionless dark matter collapse to halos

• 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



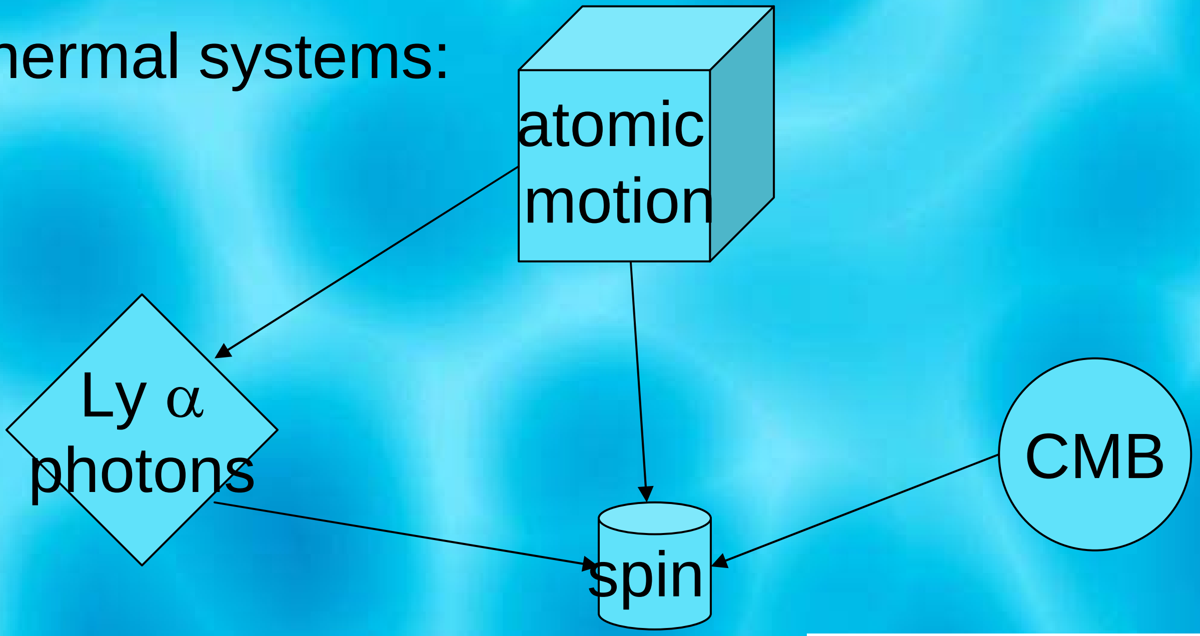
Simulations (Abel 2000, Bromm 2000) indicate first star may form in halos of 10^{5-6} solar mass, one or a few per halo, with masses of a few hundredsolar.

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

Spin Temperature determines 21cm signature

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

Thermal systems:



collision

Ly α

$$T_\alpha = T_k$$

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

The temperature of gas

Heating of the neutral IGM:

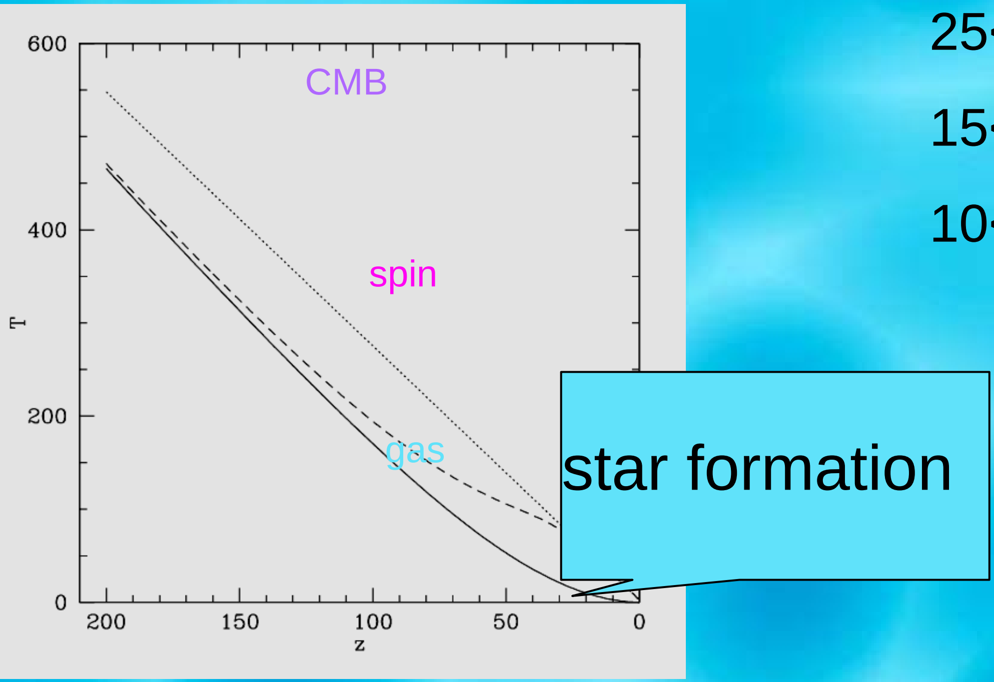
- Shock

- 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: $T_k = T_{cmb} = T_s$

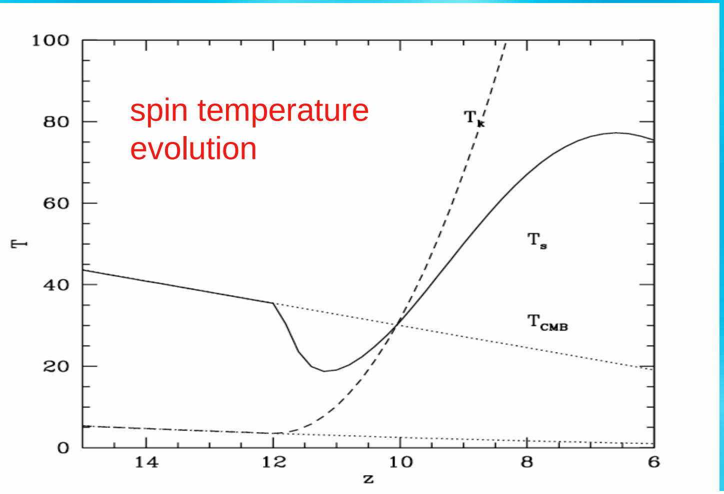
50<z<150: $T_s = T_k < T_{cmb}$ collisional coupling

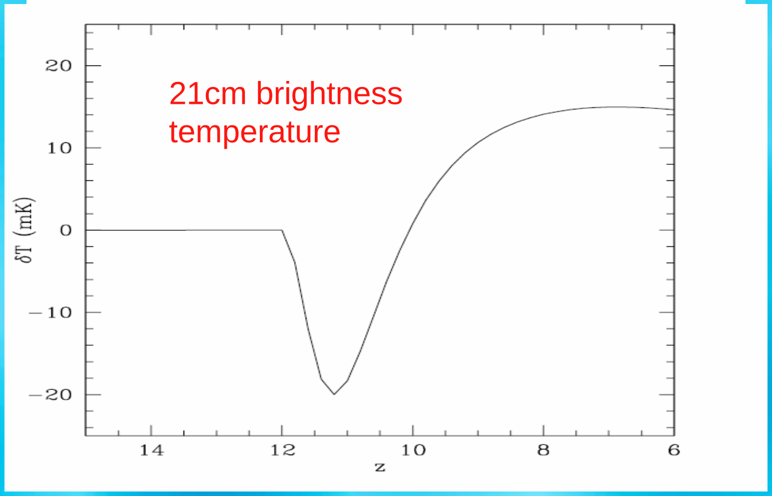
25<z<50: $T_k < T_s = T_{cmb}$ no coupling

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





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

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$25<z<50$: $T_k<T_s= T_{cmb}$ 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)

Lyman alpha sphere around first stars

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

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

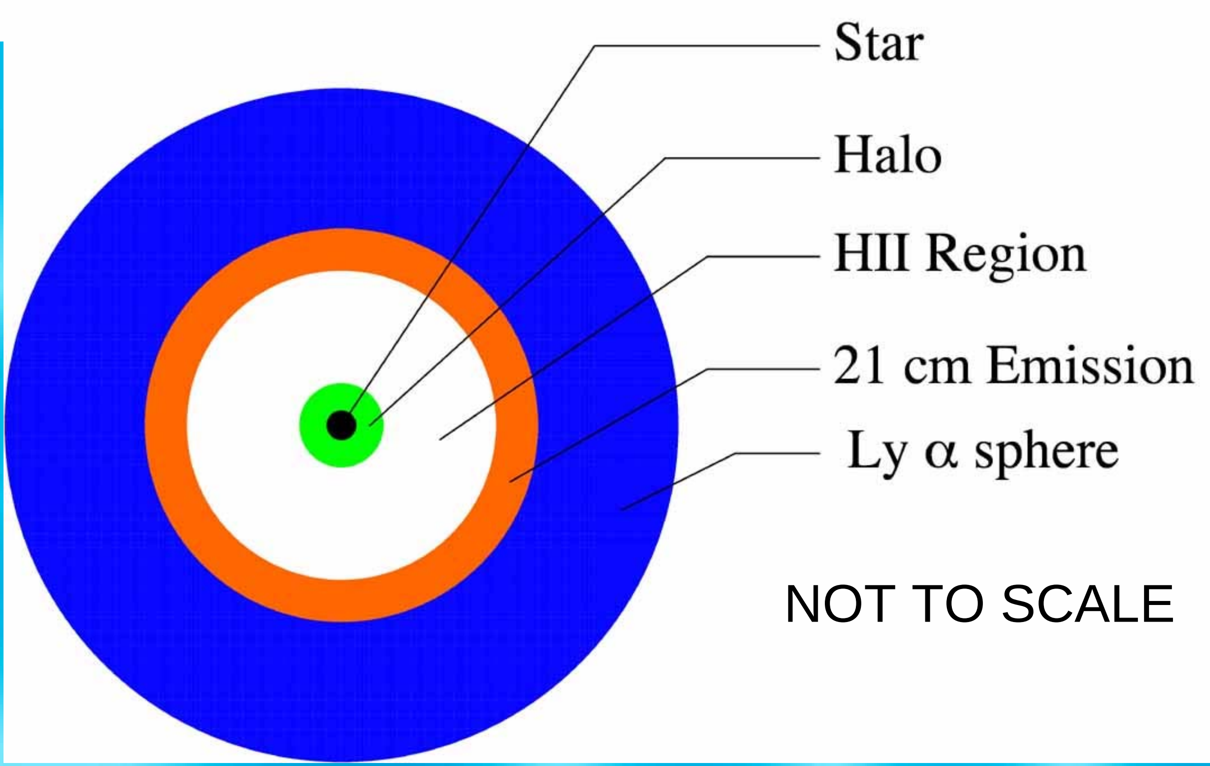
$$L_{total} = 10^{4.5} \frac{M}{M_\odot} L_\odot$$

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

• 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



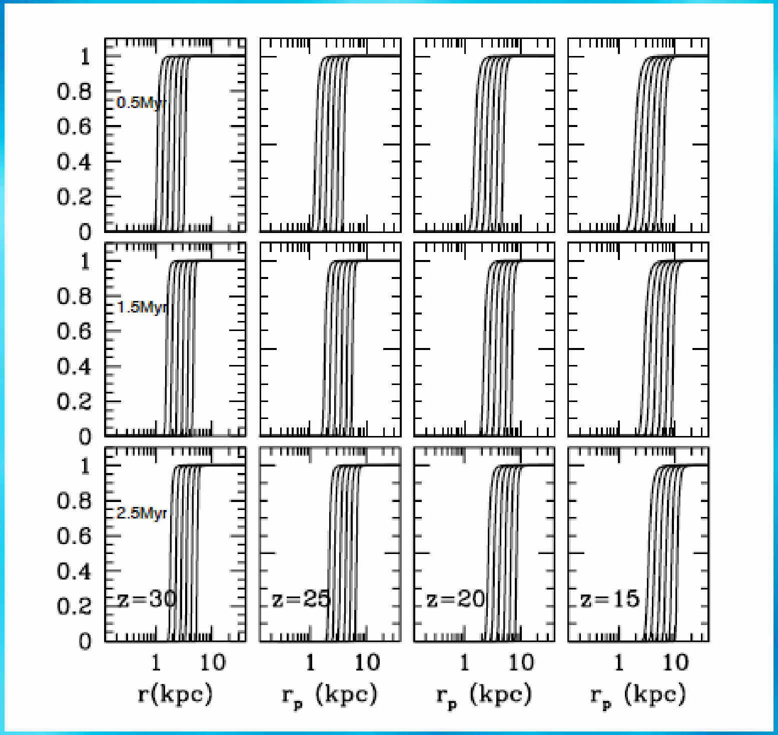
Radiative Transfer

1D (spherical) radiative transfer code

assume first star blackbody radiation

evolve photon spectrum

include helium

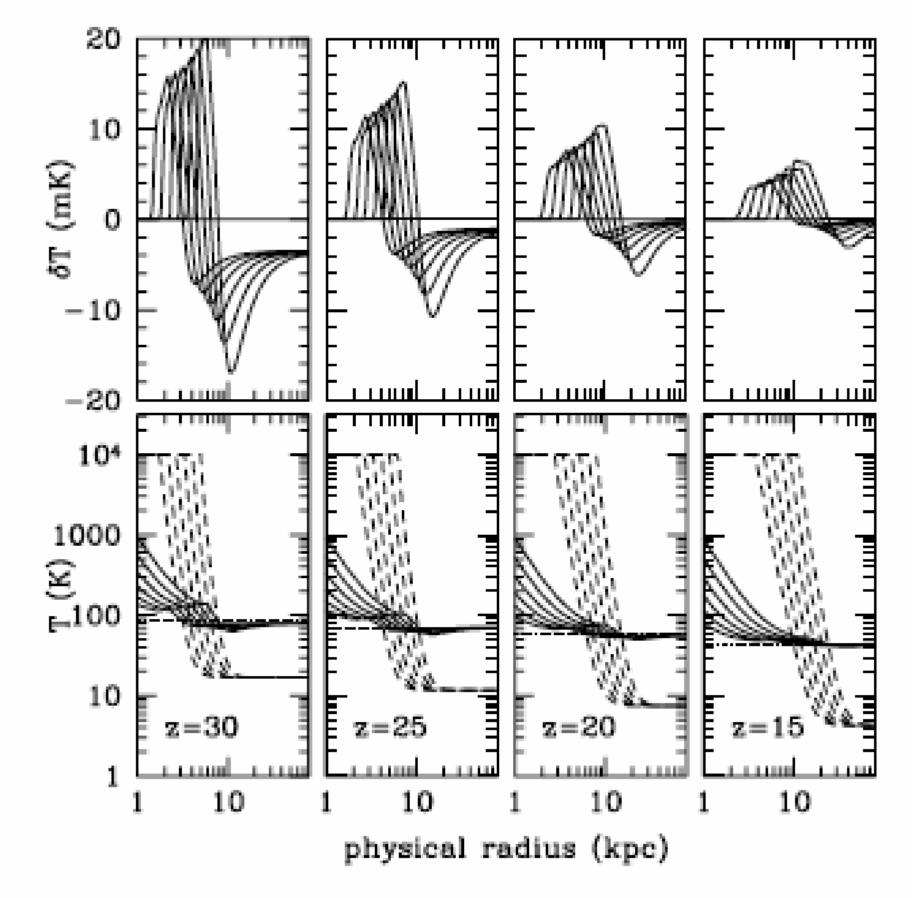


For stellar mass of 25, 50, 100, 200, 400, 800 Msun.

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

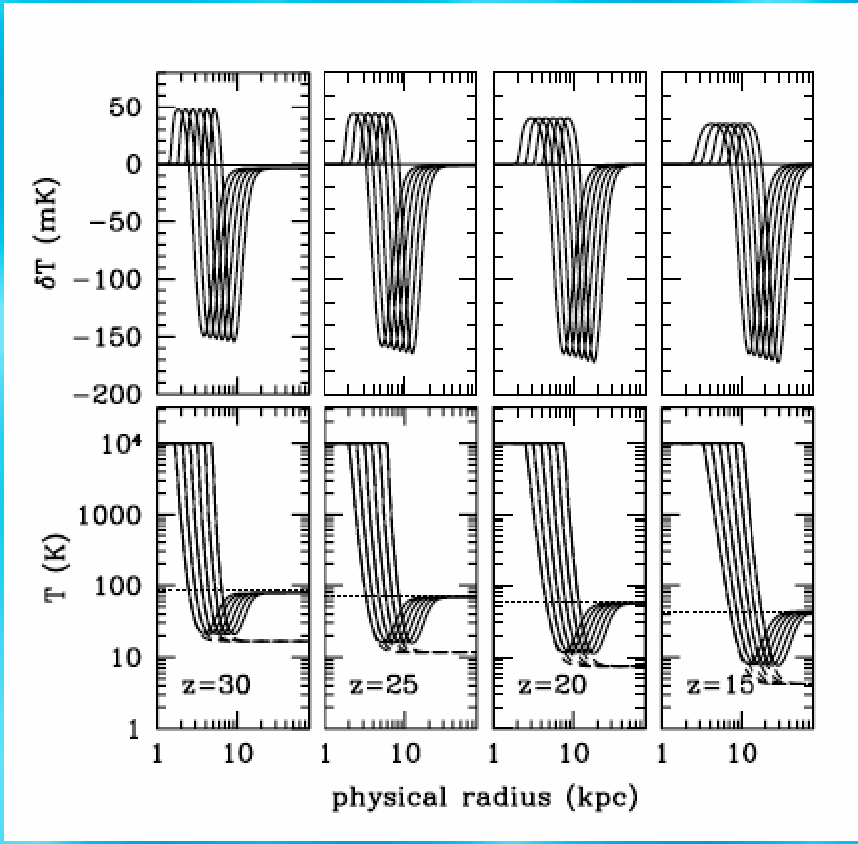
frequency shift rate ~ H ν_α

flux ~ photon production rate / frequency shift rate:

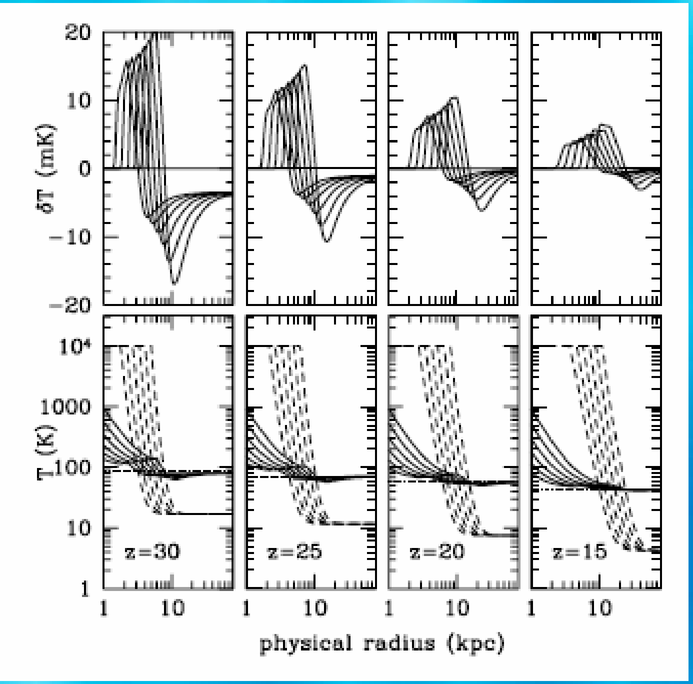
$$J_i = \frac{c\eta_\alpha \Gamma}{4\pi h H \nu_\alpha^2} \ .$$

Neglected order 1 correction factor and higher Lyman series

Ly α sphere profile

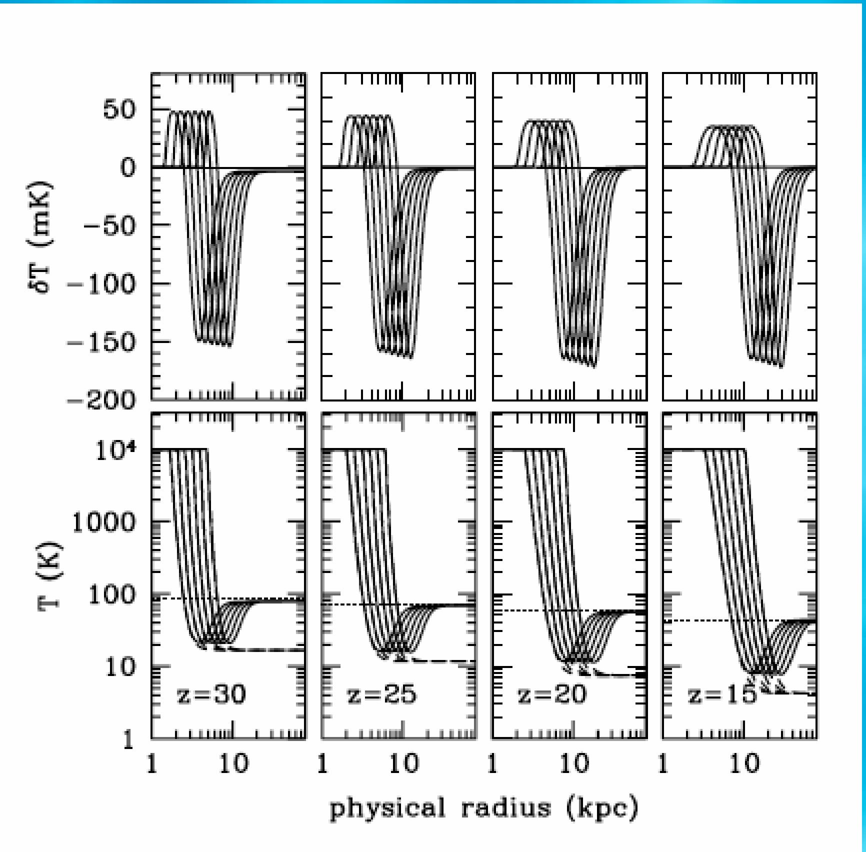


with injected Lyman photons
very strong absorption

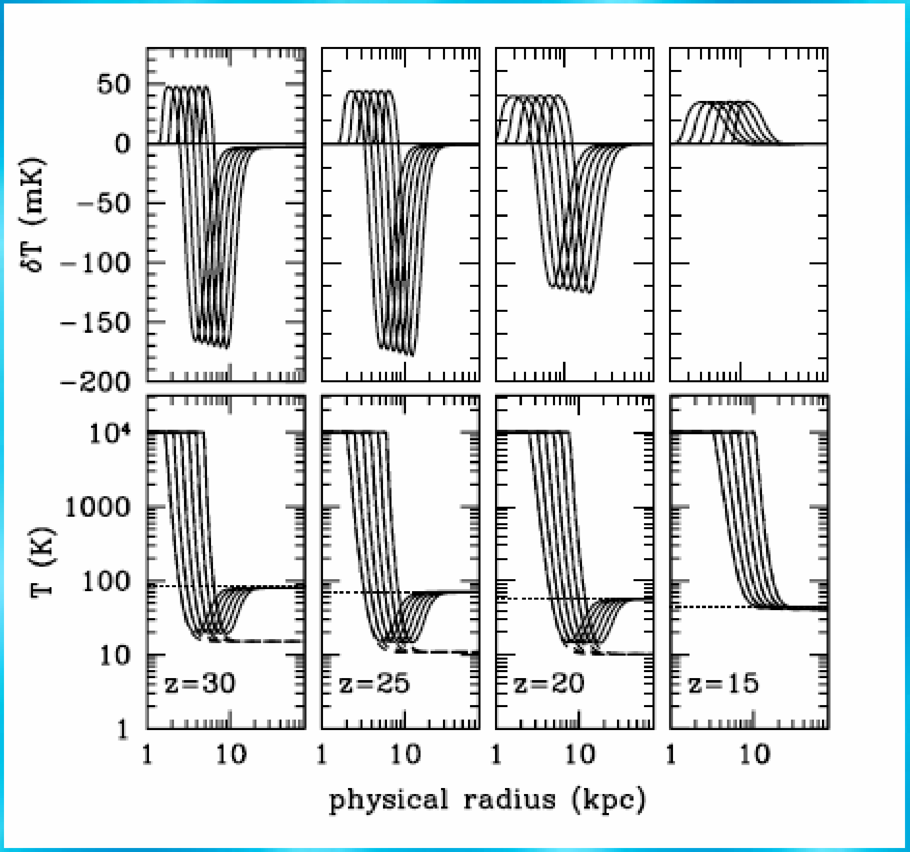


with only continuum Ly
photons, weak absorption

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



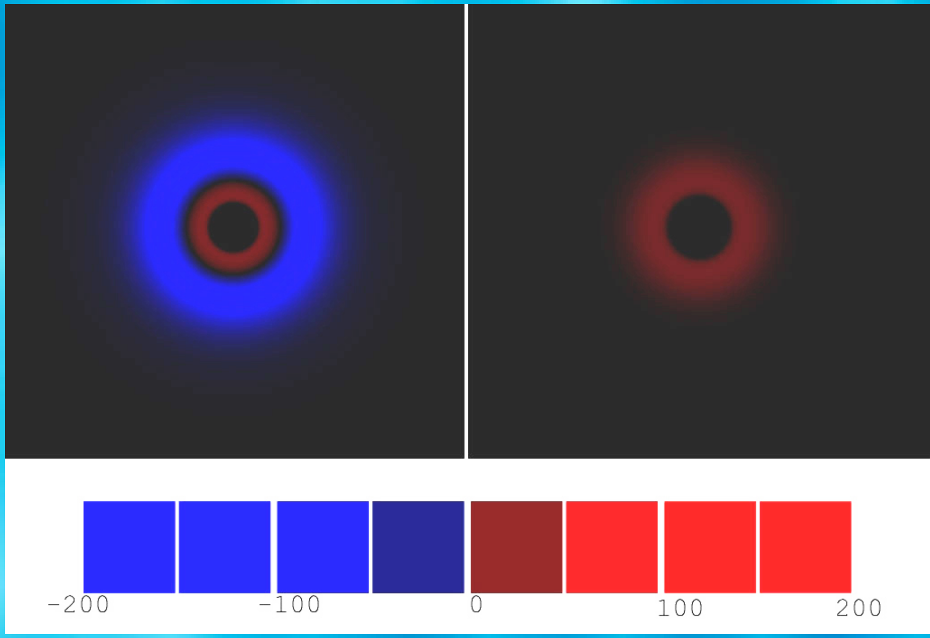
no heating



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:

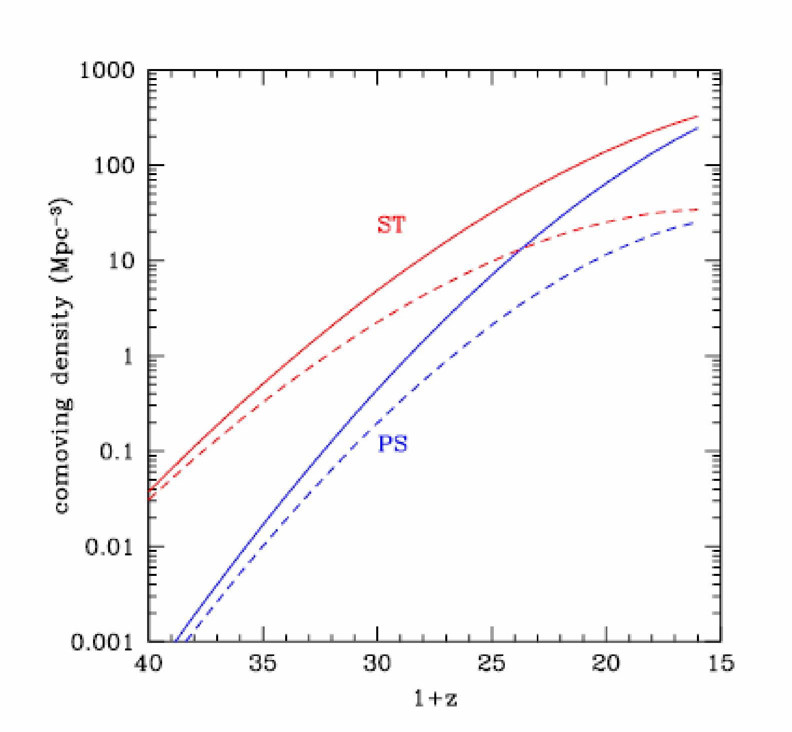
  $T_{vir} > 2000$ K

- One star formed per halo

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

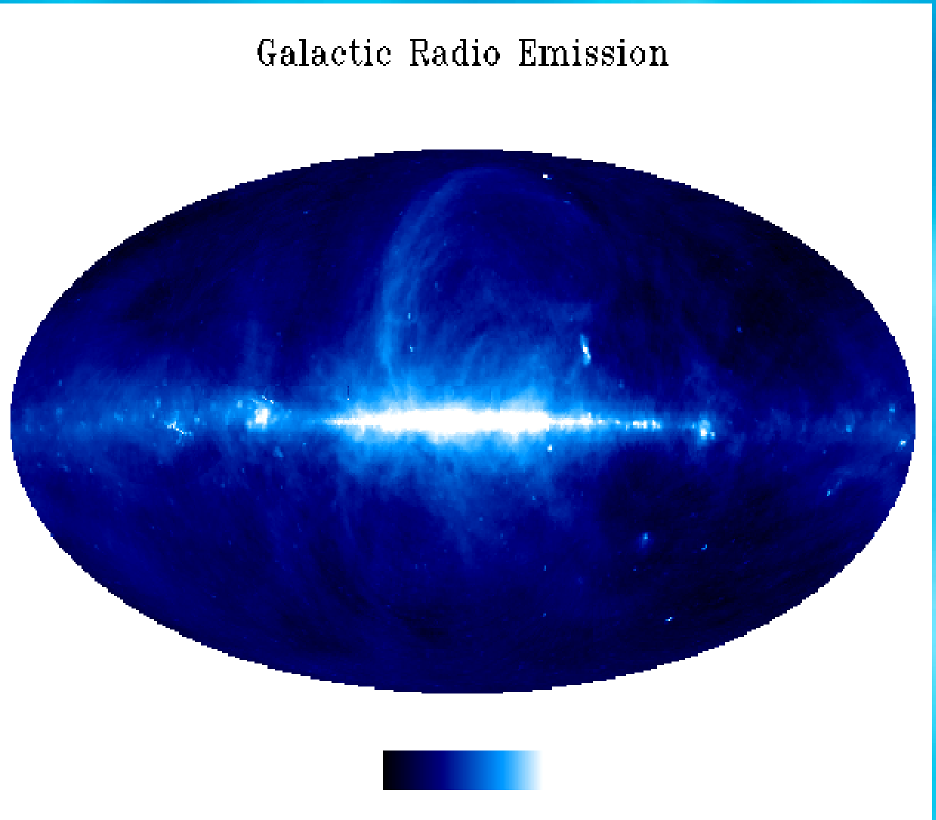
$$n_* = \int_z^{z_a} dz \int_{M_{min}(z)}^{\infty} dm \, \frac{\partial N(m,z)}{\partial z} \, ,$$

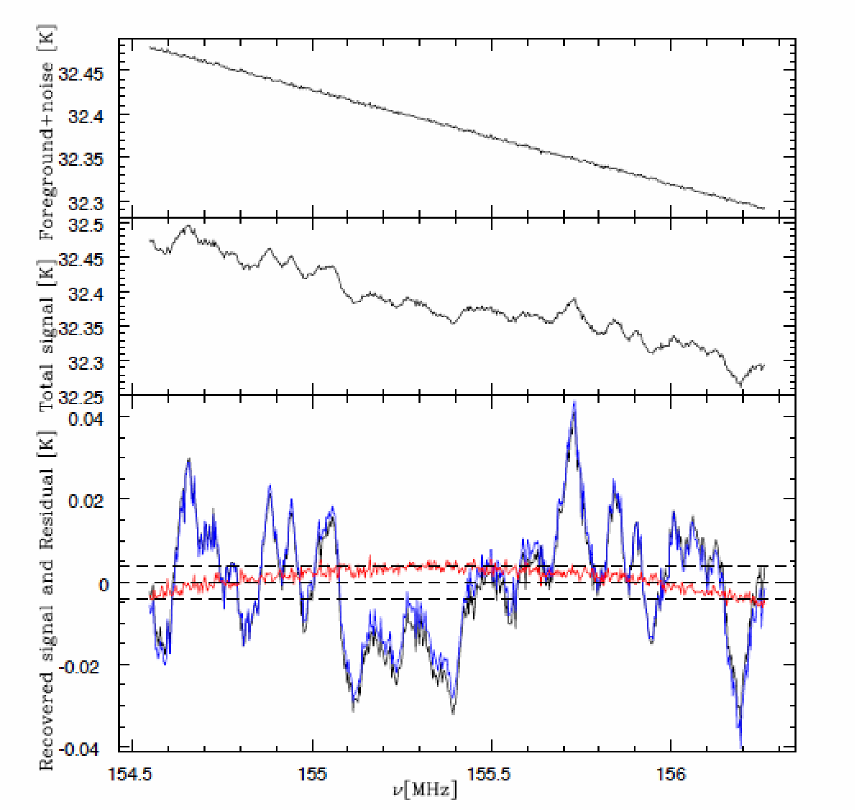
$$n_* \approx (1+z)H(z)t_* \int_{M_{min}(z)}^{\infty} dm \, \frac{\partial N(m,z)}{\partial z}$$



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

Foreground





X. Wang et al astro-ph/0501081

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}

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

Some Numbers

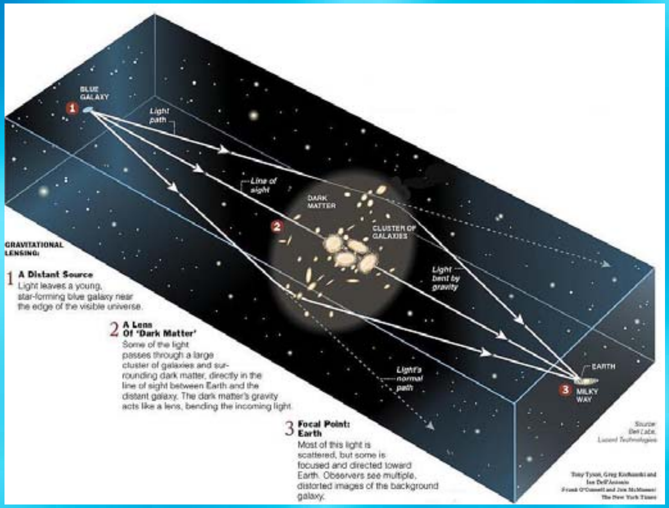
Very Challenging, far beyond the capability of current generation 21cm experiments.

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

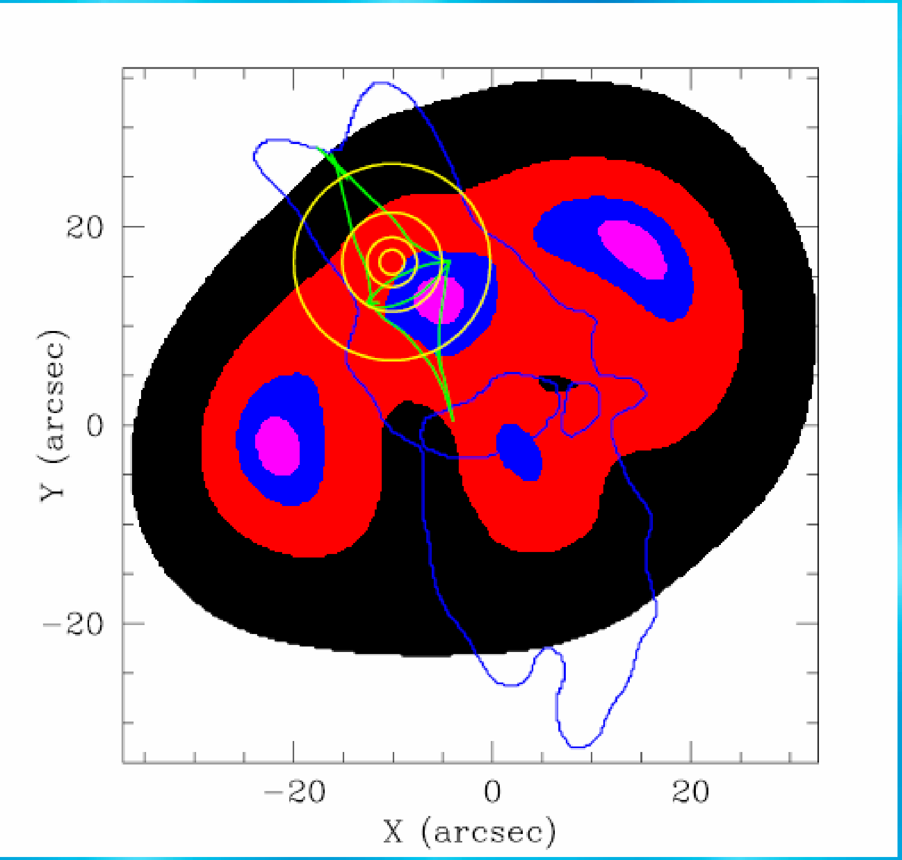
Guoliang Li, Pengjie Zhang, X.C.

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



$$\tau = \frac{1}{4\pi {D_s}^2}\int_0^{z_s} dz\, \overline{\sigma}(z)(1+z)^3\,\frac{dV_p(z)}{dz},$$

Can lensing enhance 21cm signal?



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

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)

Two aspects in the 21 cm observations

the 21 cm tomography

$$\delta T_b(\nu) \approx 8\, x_{HI}\, (1+\delta)(1+z)^{1/2} \left[1 - \frac{T_\gamma(z)}{T_s}\right] \left[\frac{H(z)/(1+z)}{dv_{||}/dr_{||}}\right] \mathrm{mK}.$$

the “21 cm forest” (YidongXu, X.C., Zuhui Fan, HyTrac, RenyueCen, work in progress)

$$\tau_\nu(z) = \frac{3 h_p c^3 A_{10}}{32\pi k\, \nu^2} \int_{-\infty}^{+\infty} dr\, \frac{n_{HI}}{T_s \sqrt{\pi}\, b(T_k)} \exp\left[-\frac{u^2(\nu)}{b^2(T_k) + v^2}\right]$$

The simulation

- reionizationsimulation by (Shin, Trac&Cen 2007)

- The ionization slices
  - f_{HI}<= 0.5 – black
  - f_{HI}> 0.5 – white

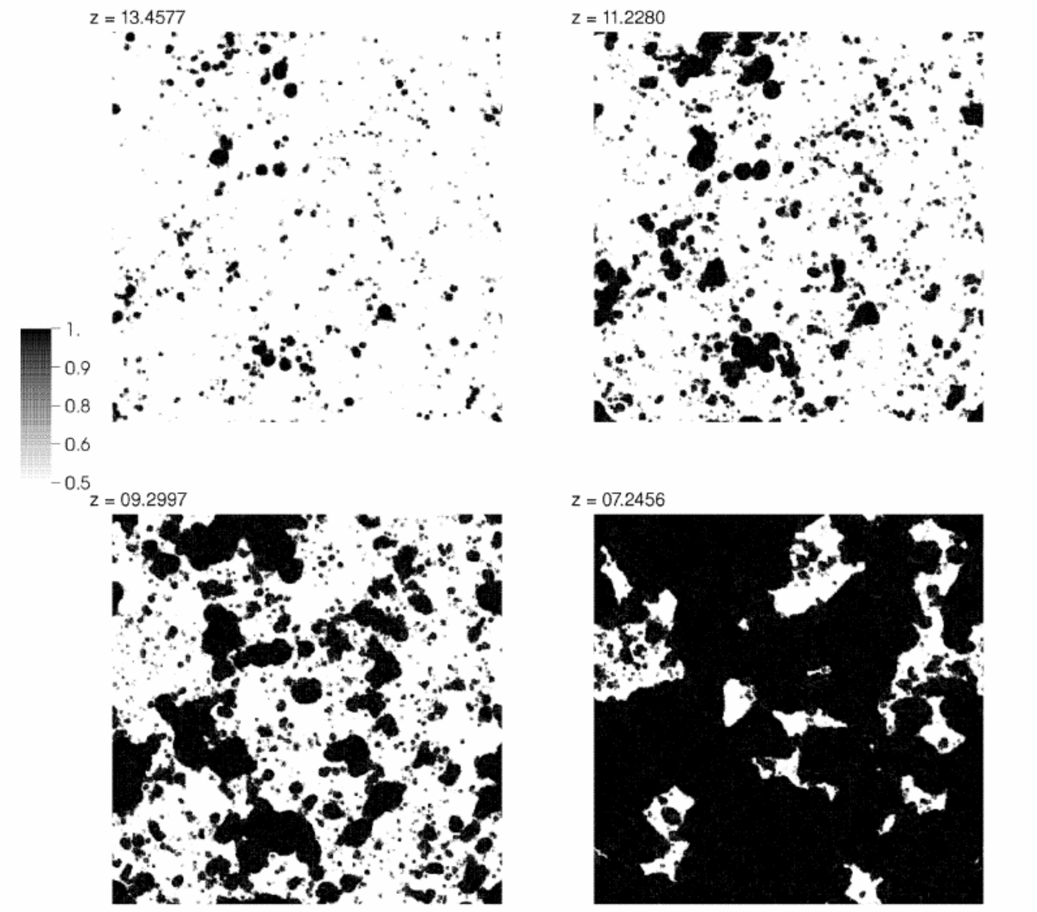
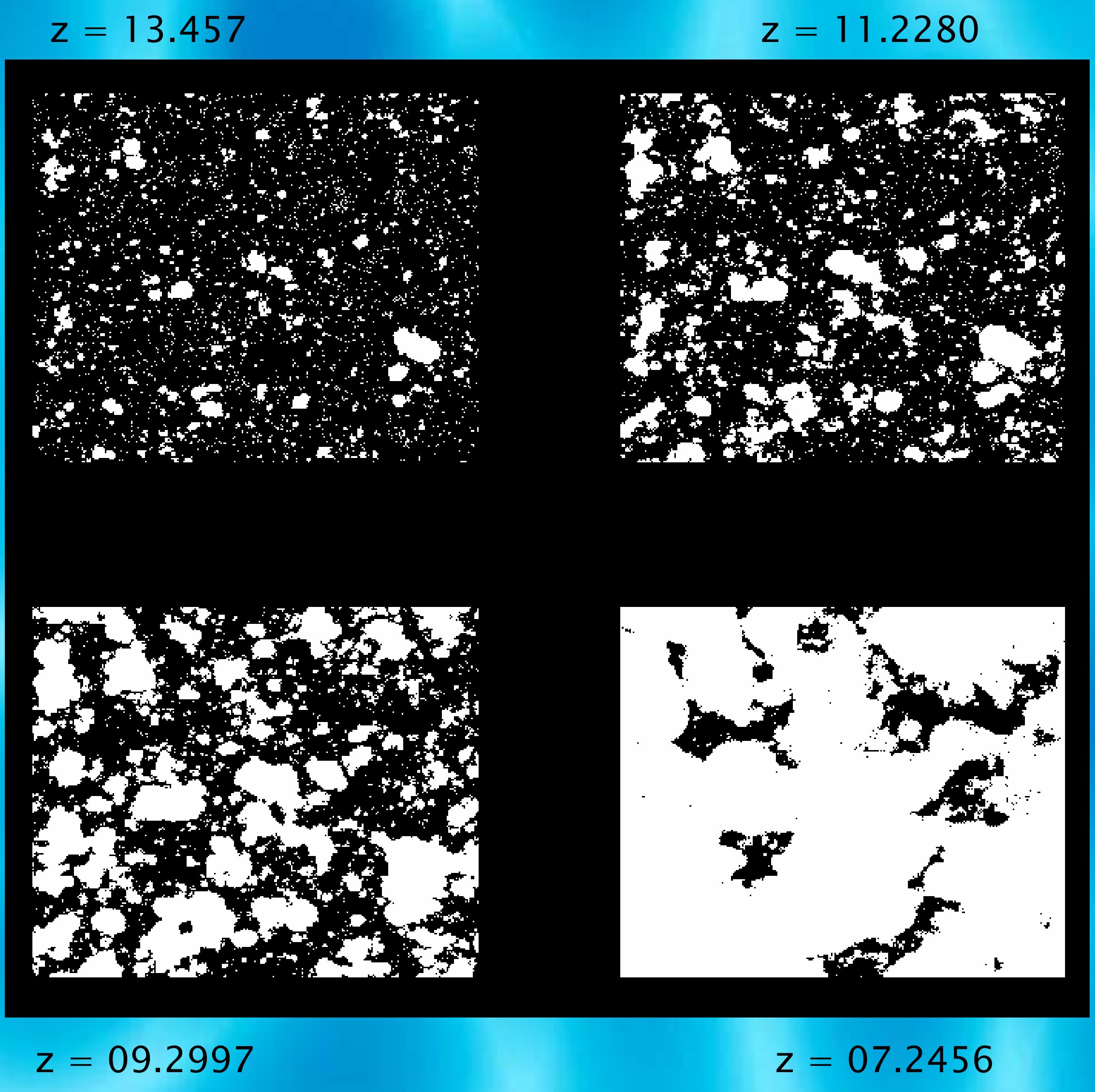


FIG. 3.— Distributions of ionization fraction at redshifts z ~ 13.5, 11.2, 9.3, and 7.2. Highly ionized regions are represented by blac while ionization fraction below 50 percent is shown as white. This is a plot of one slice in the simulation box. Each side of the plot is 10 Mpc/h. The global ionization fractions are ~ 10, 30, 50, and 90 percents for z ~ 13.5, 11.2, 9.3, and 7.2, respectively.

⊙The optical depth slices

- τ –slices with relative threshold trace xi–slices well, and insensitive to the IGM temperature.

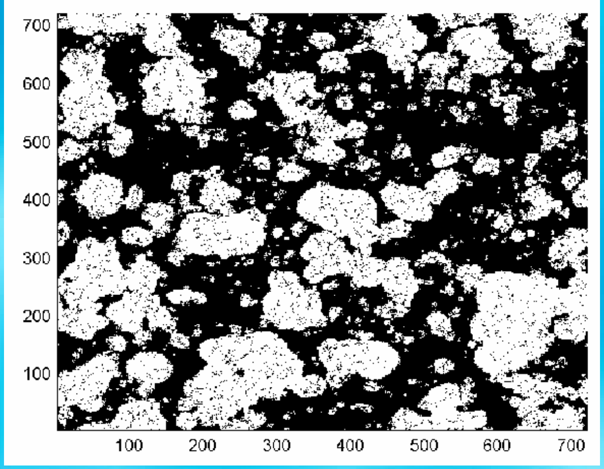


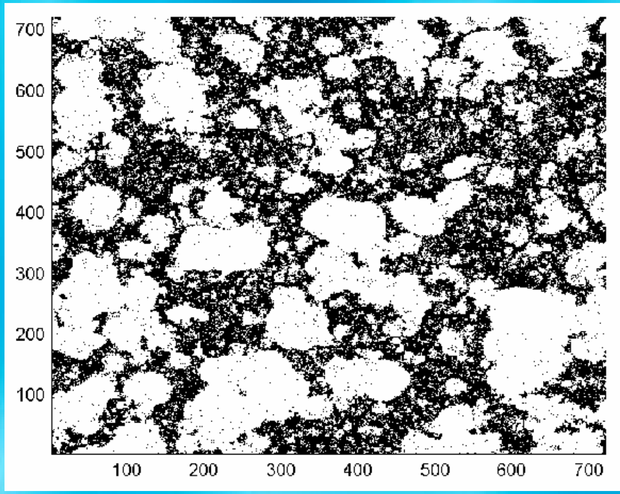
◉ The optical depth slices with absolute threshold:

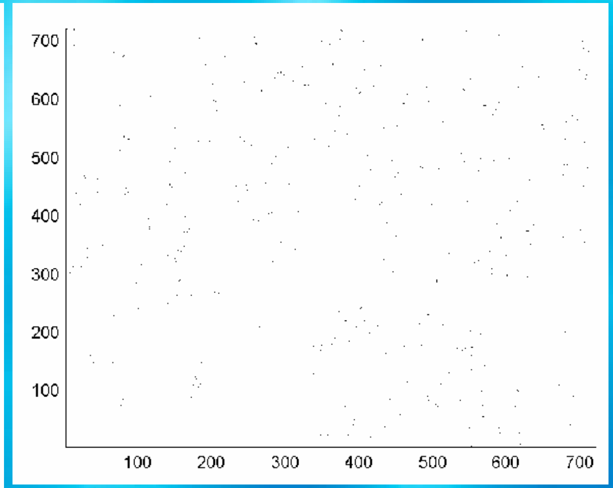
T_{IGM} = 10^1 K

T_{IGM} = "real" temperature from simulation (~ 27 K for z = 8.9)

T_{IGM} = 10^2 K

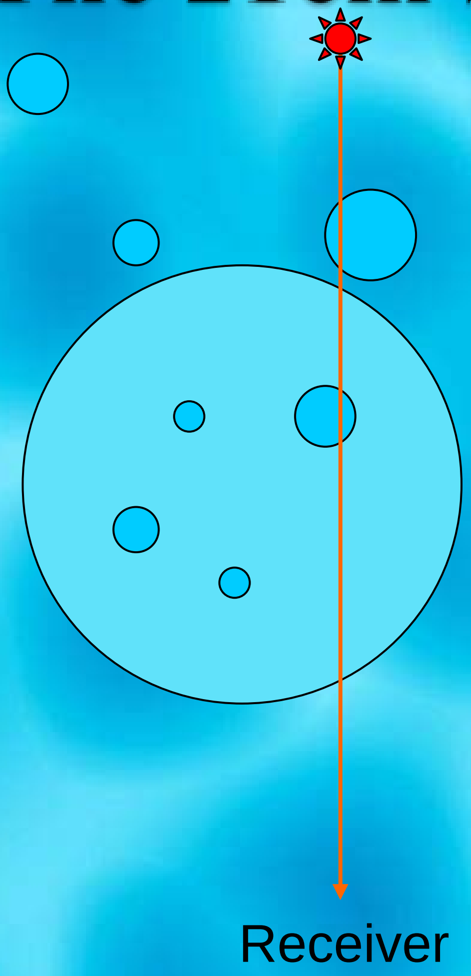


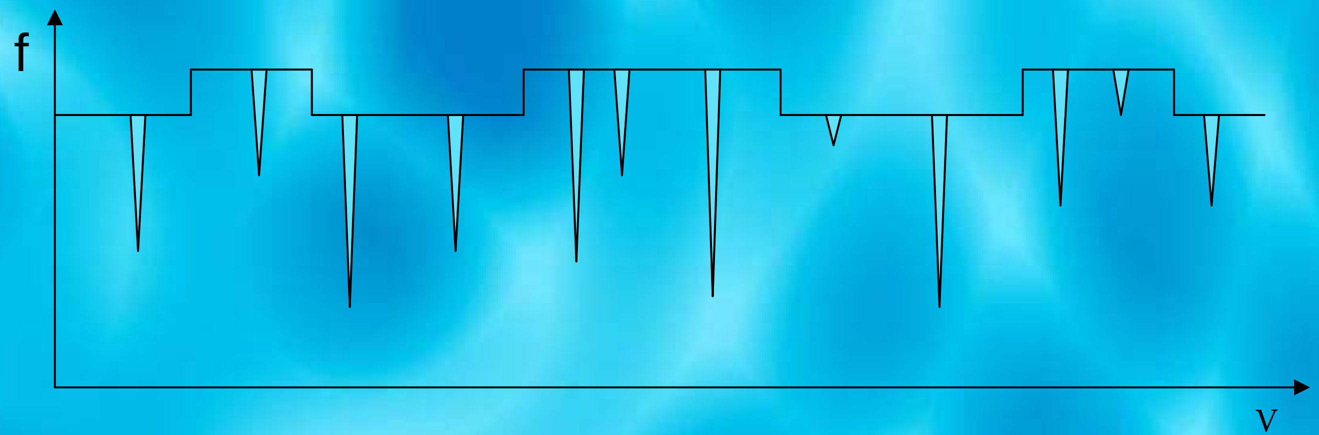


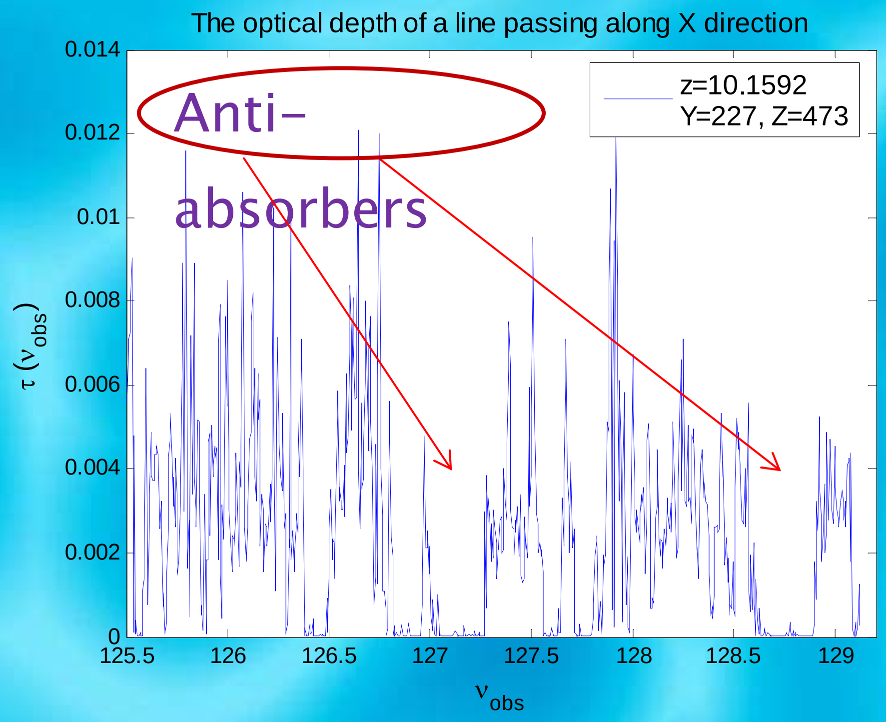


- τ -slices with absolute threshold are sensitive to the IGM temperature.

The 21cm Signals





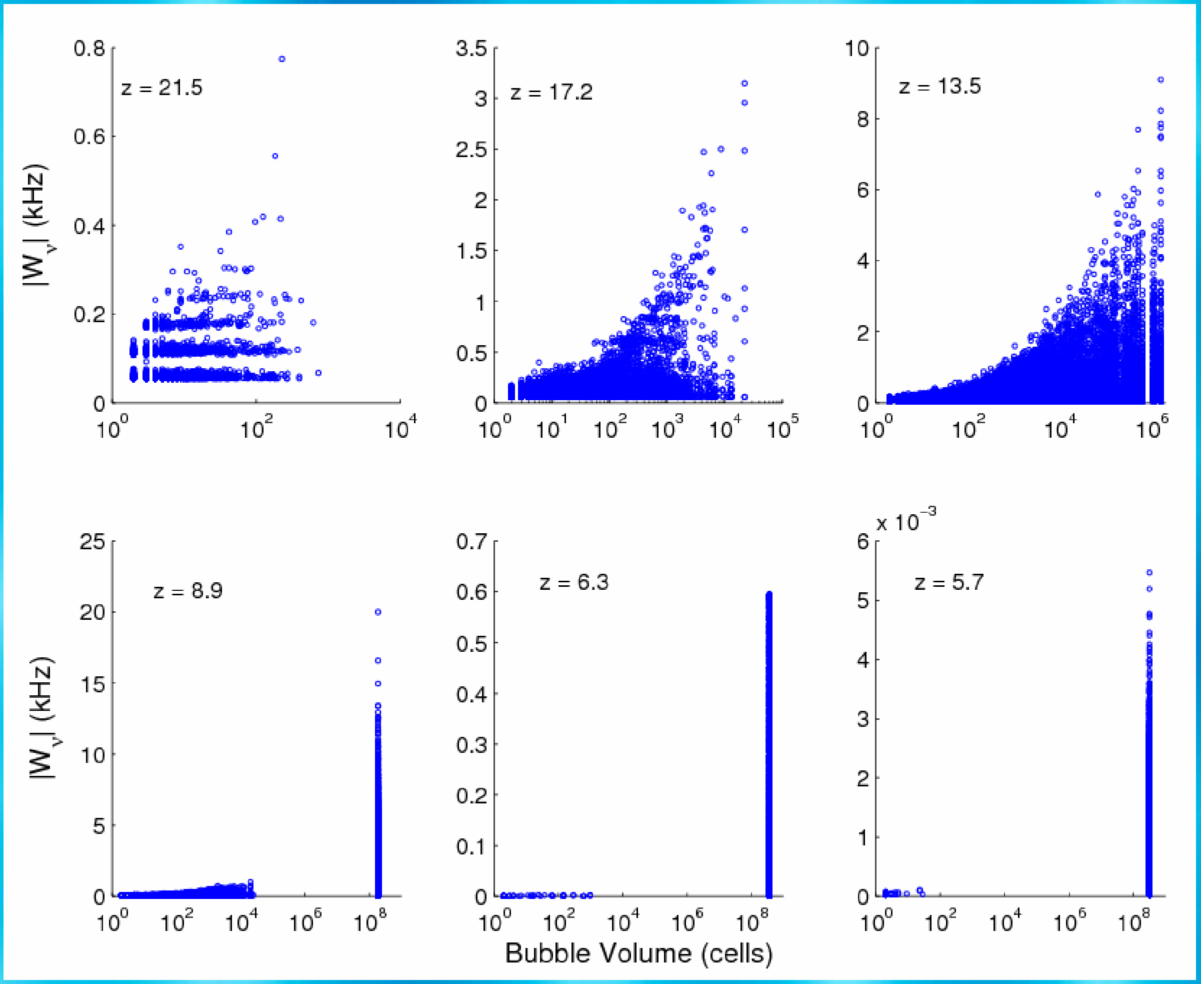


simulation data from (Shin Trac & Cen 2007)

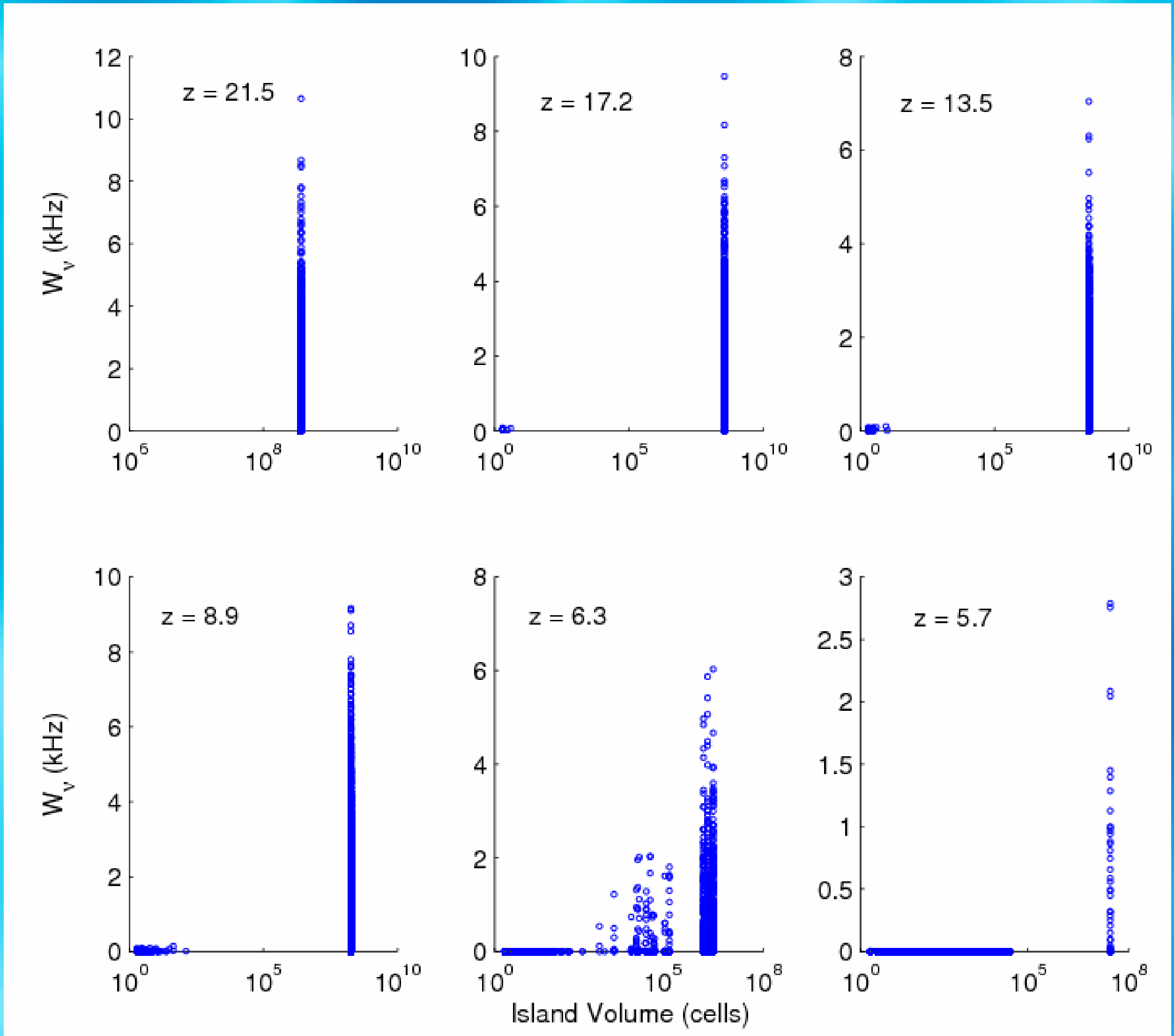
Equivalent width and bubble volume

- 400 random lines of sight through each side of the simulation box
- Periodic boundary condition is considered
- The threshold:

$$(\tau_0 - \tau_\nu)/\tau_0 \geq 0.5$$

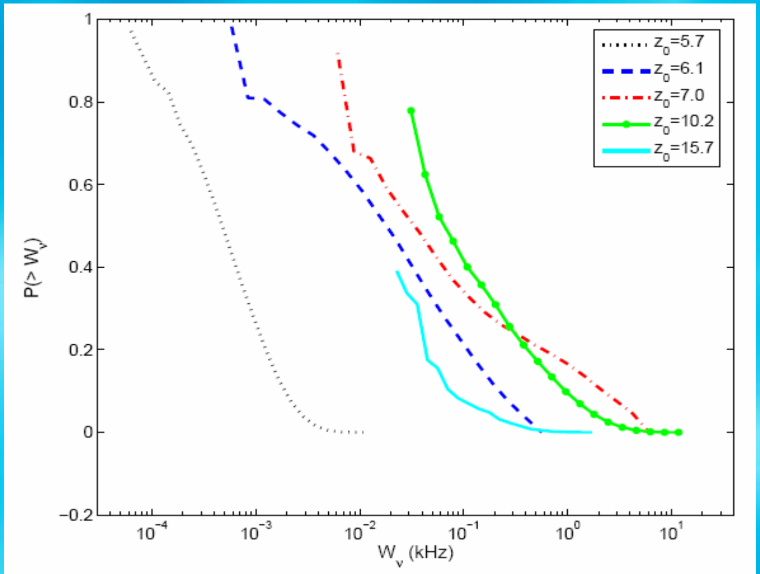


Equivalent width and island volume



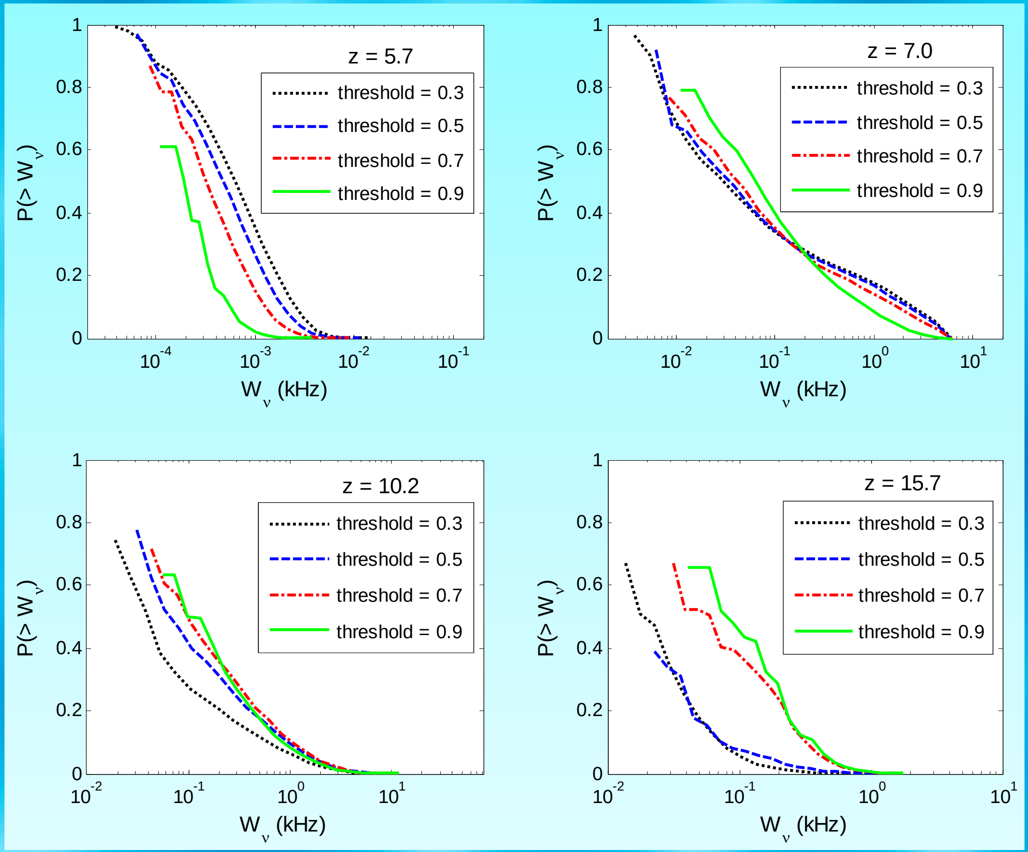
The "21 cm forest" from simulation

- The cumulative probability distribution (CPD) of the equivalent widths for several redshifts.



Show evolution!

- The different thresholds for anti-absorber definition



Thanks