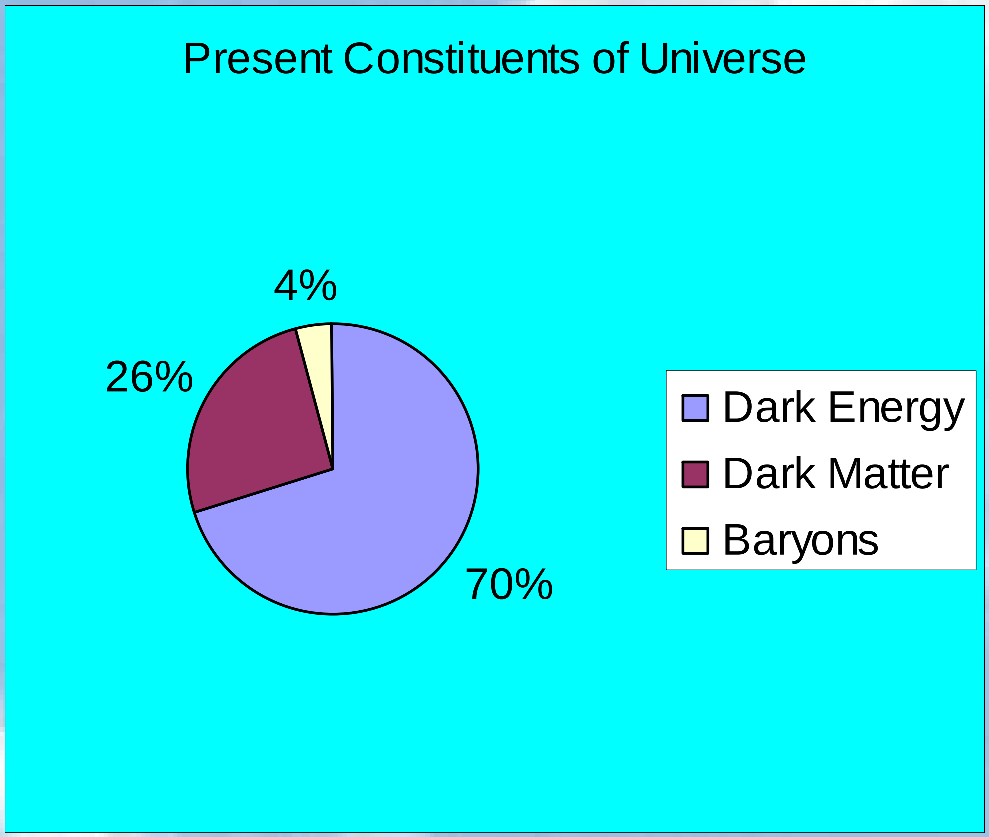
Reionization

Somnath Bharadwaj
Physics and CTS
IIT Kharagpur


Of what?

Constituents of the Universe



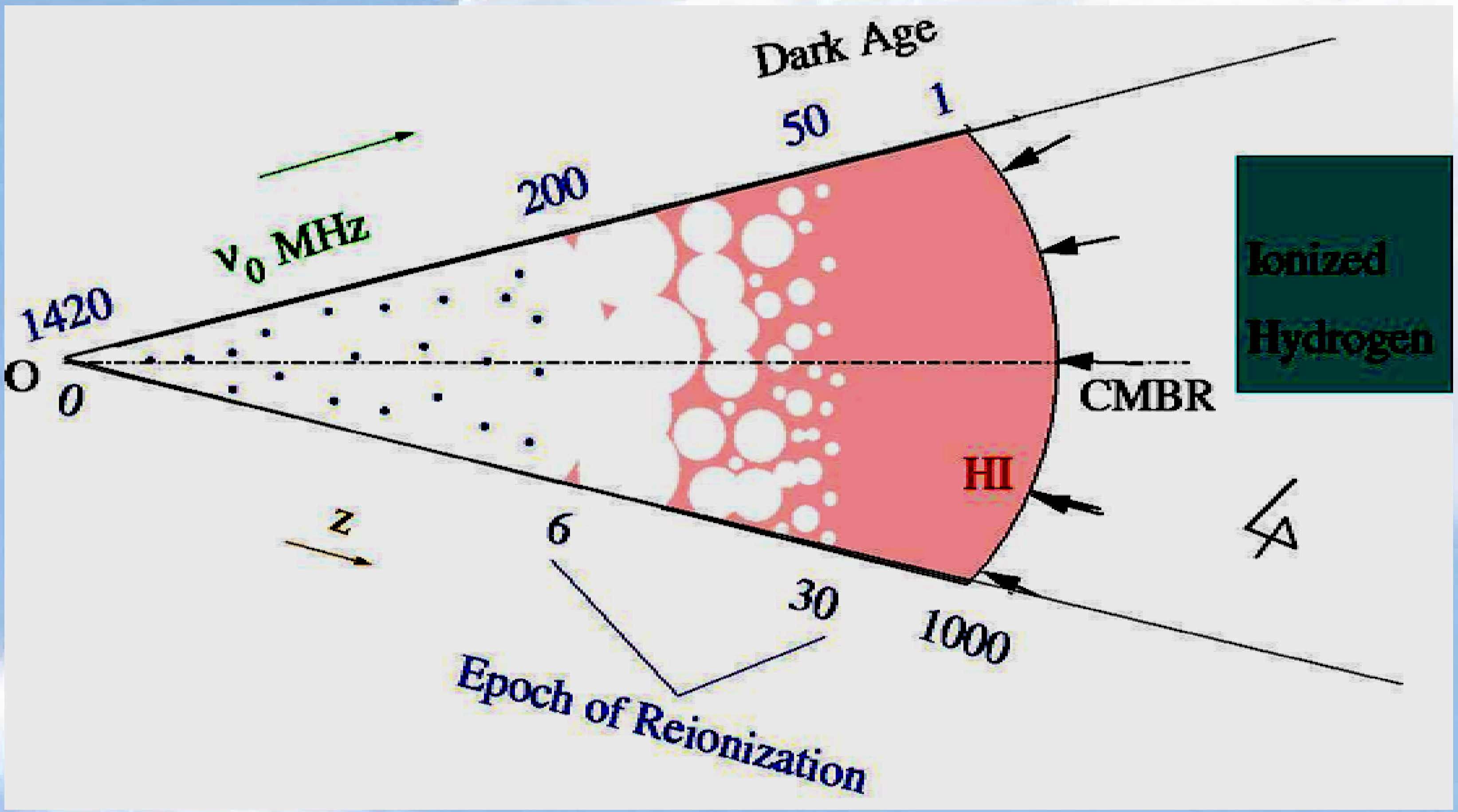
Of what?

Baryons

75 % Hydrogen

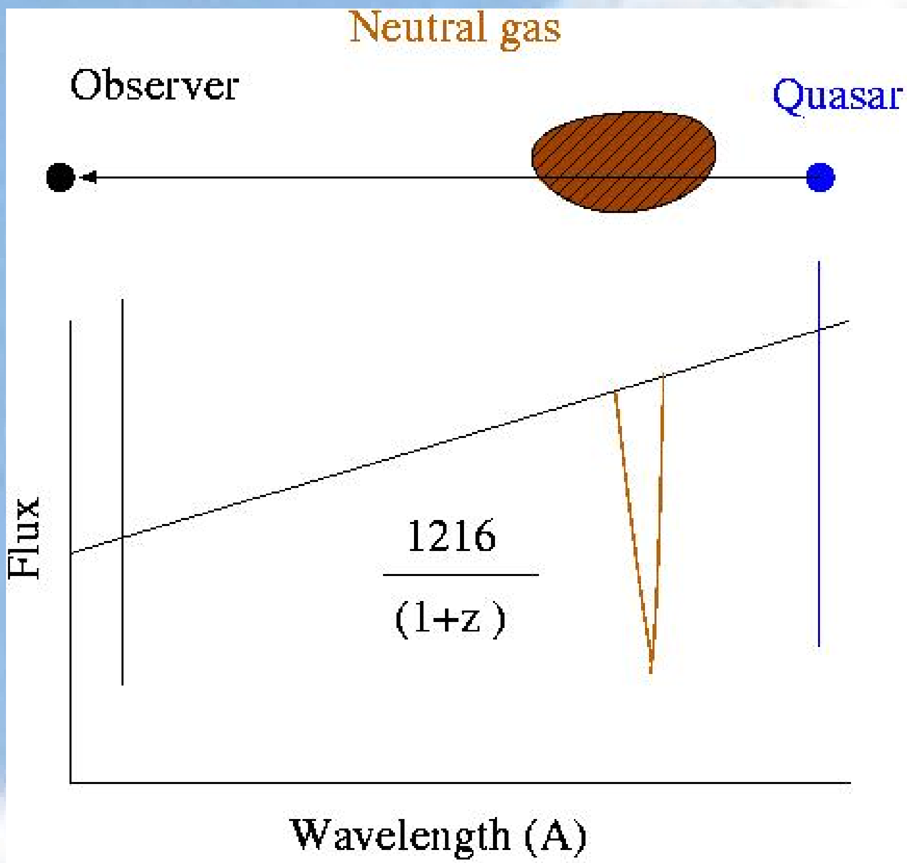
25% Helium

Summary

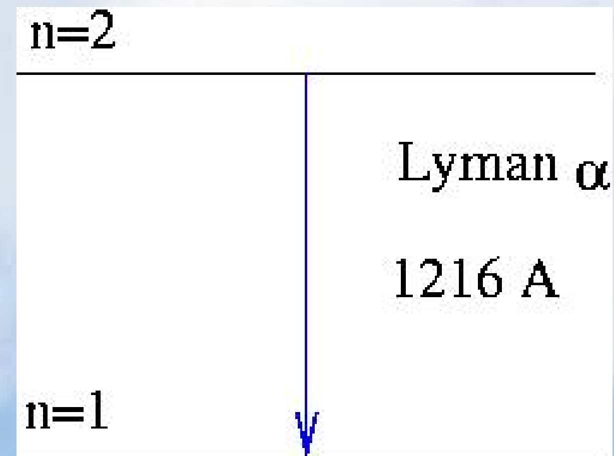


Dark Age
1
50
200
ν_0 MHz
1420
O
0
z
6
30
1000
Epoch of Reionization
CMBR
HI
Ionized
Hydrogen

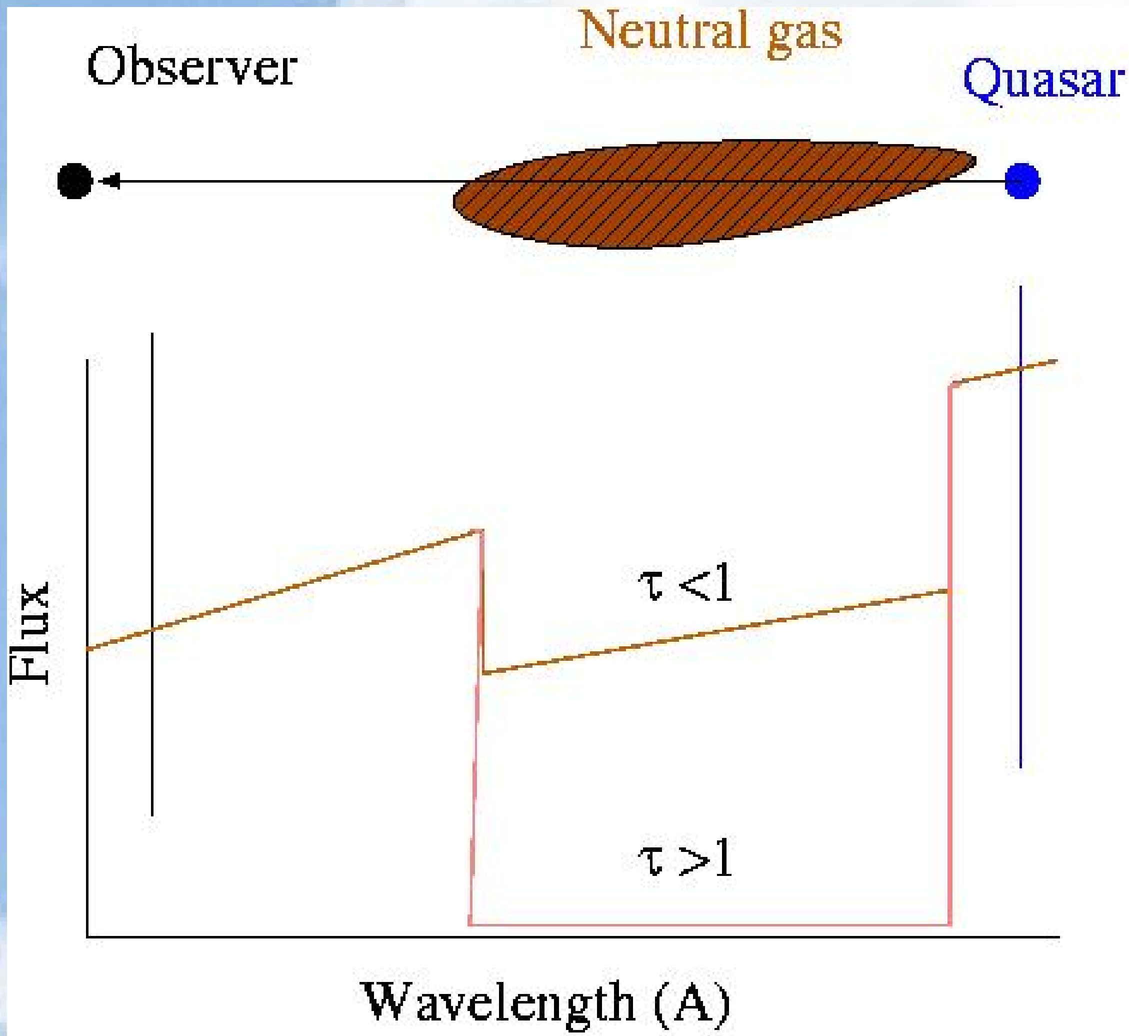
Quasar Spectra



Neutral Hydrogen



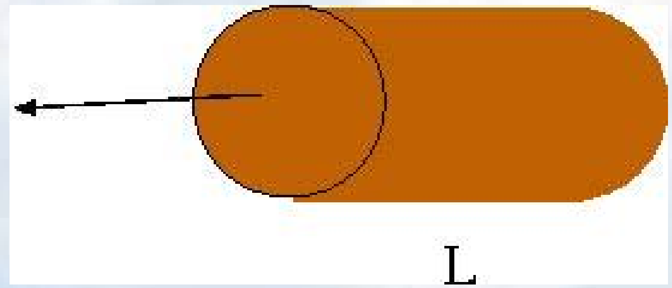
Diffuse Gas



Optical Depth τ

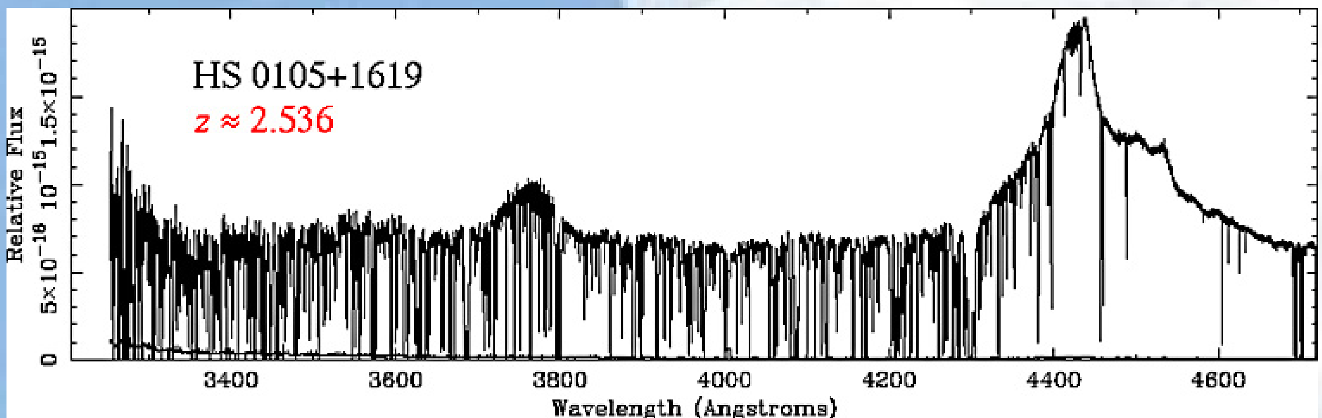
$I = I_0 \, e^{-\tau}$

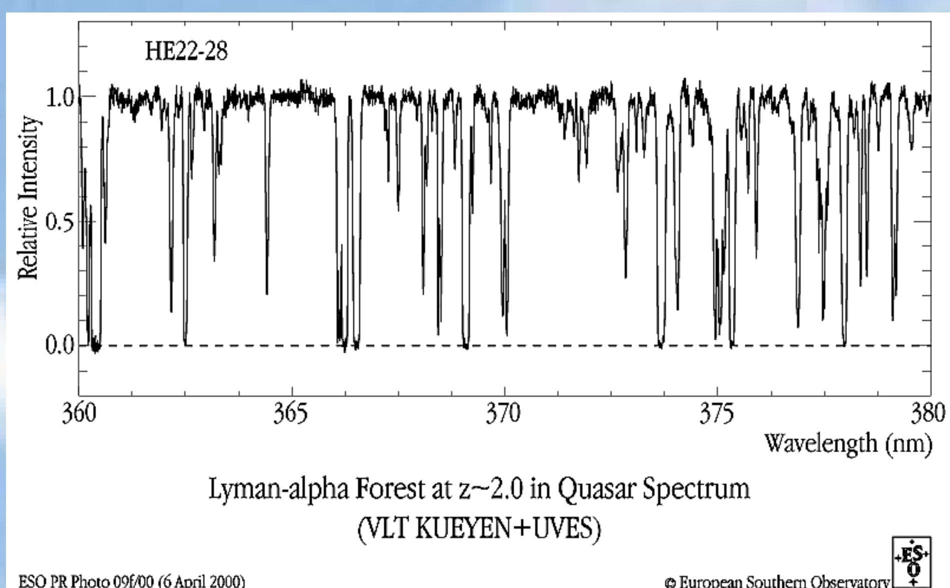
$\tau = n \, L \, \sigma$



$$\tau_{\mathrm{GP}}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{\mathrm{HI}}}{n_{\mathrm{H}}}\right)$$

Lyman α Forest

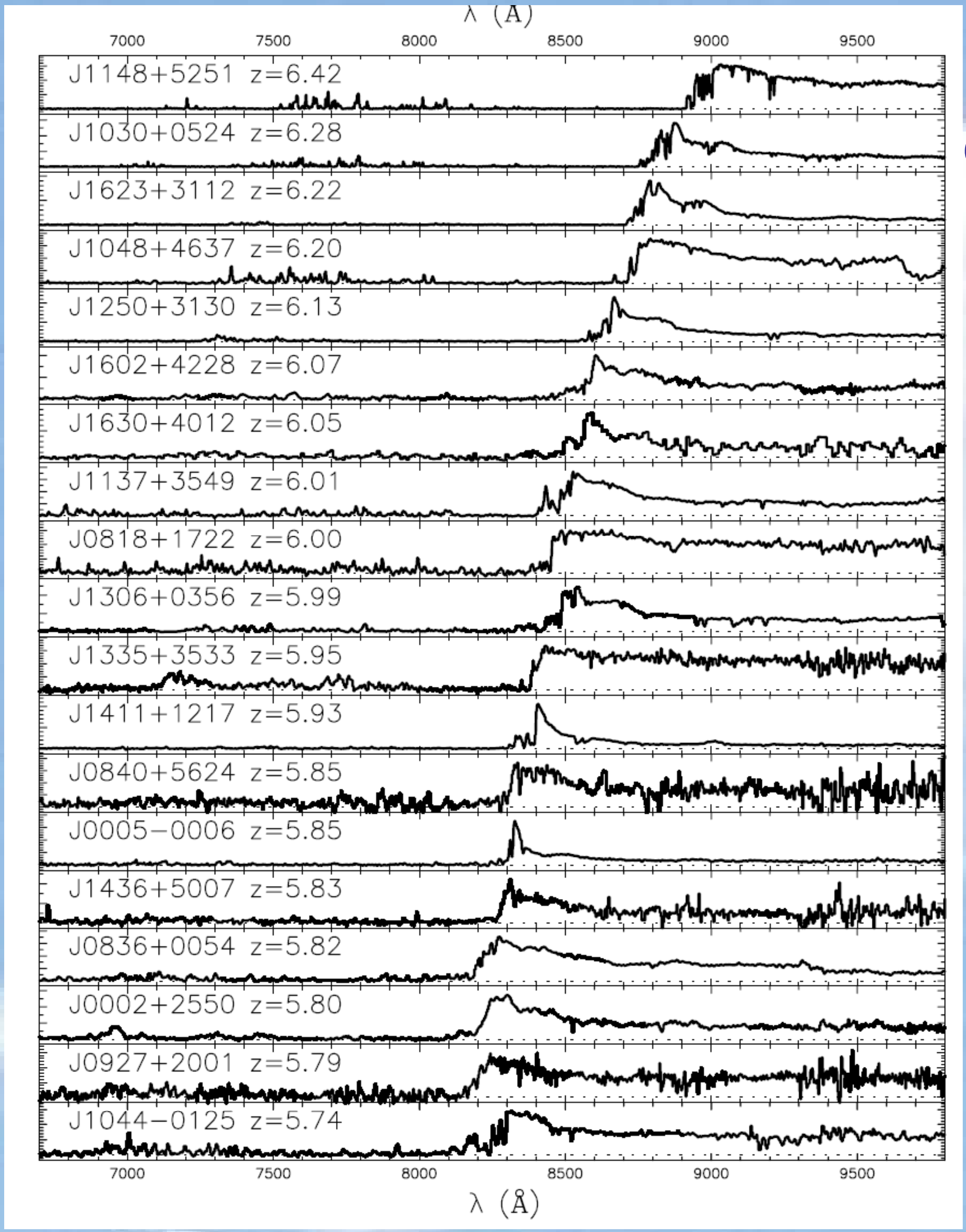




z < 4 $\tau < 1$

Neutral fraction

Below 10^{-5}



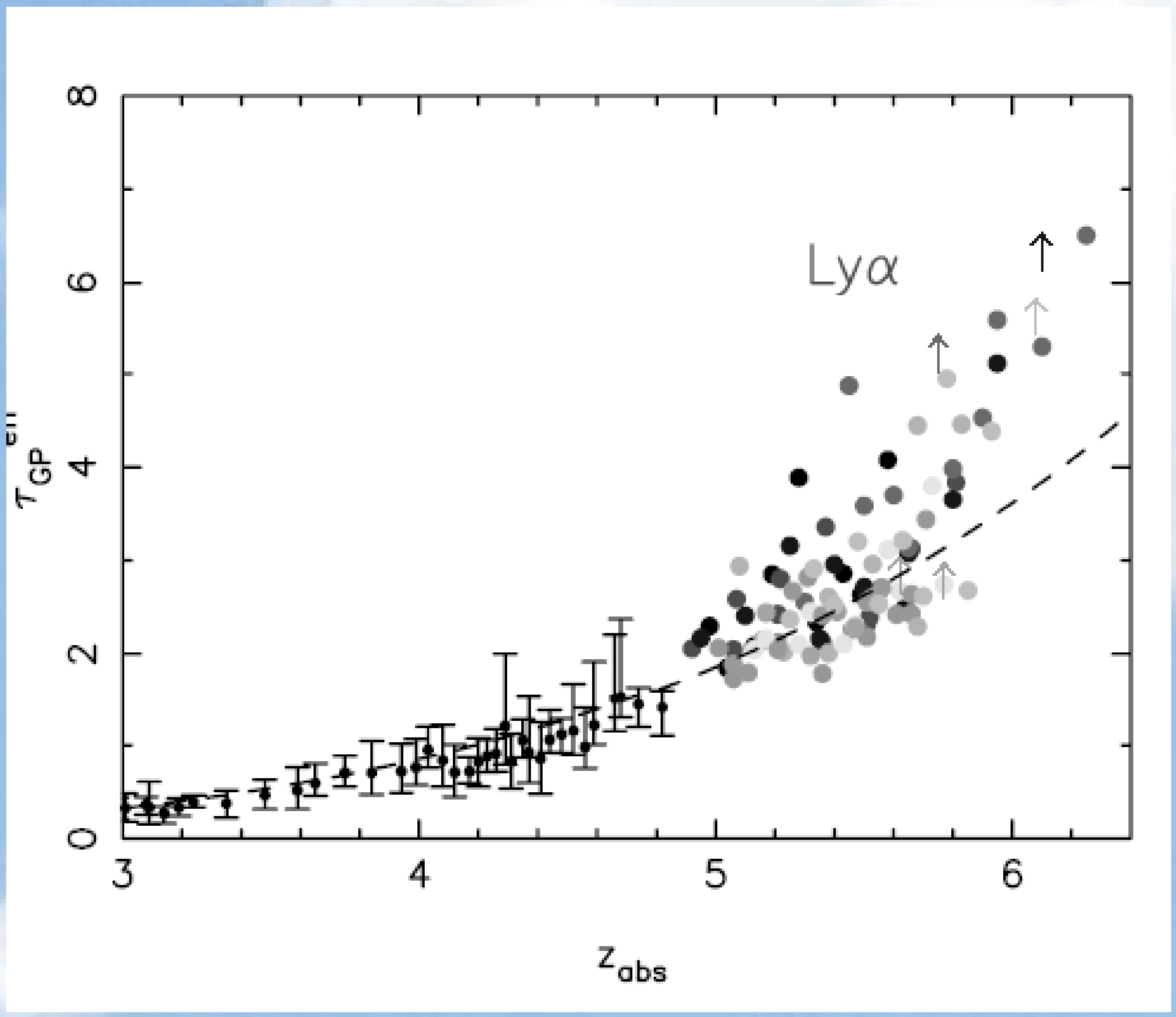
asars

19 SDSS quasars
5.74 < z < 6.42

Ly-aTransmission
~1% to 20%

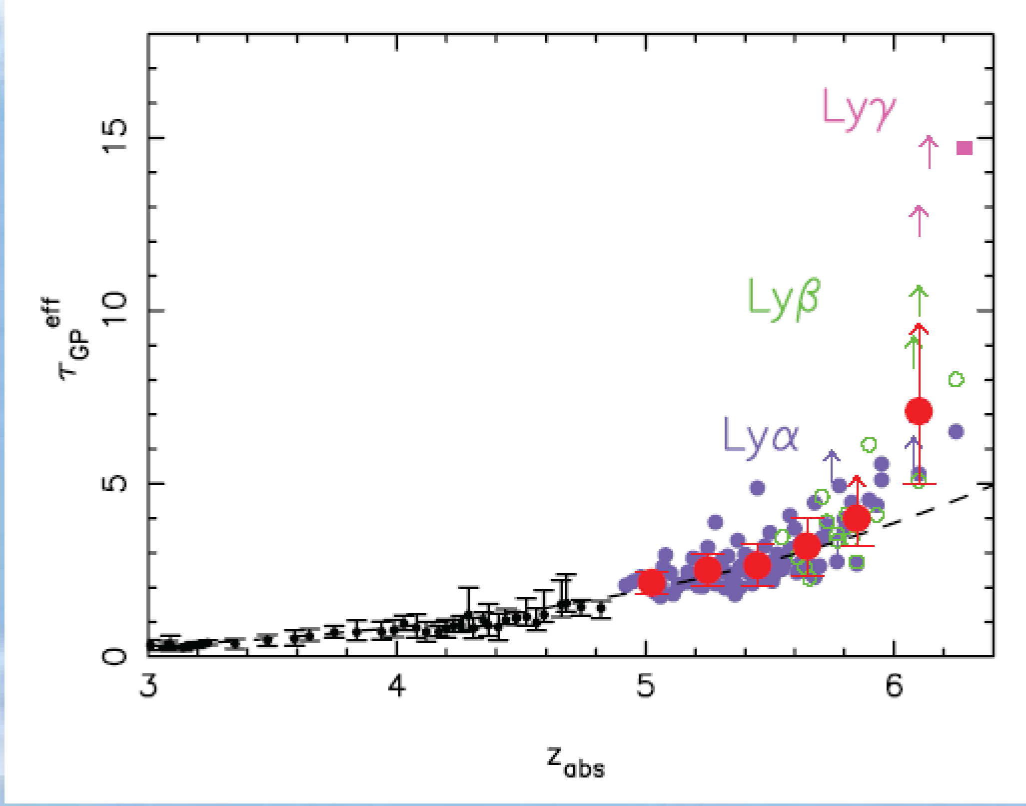
Fan et al. 2006, AJ, 132, 117

Lyα Optical Depth Evolution

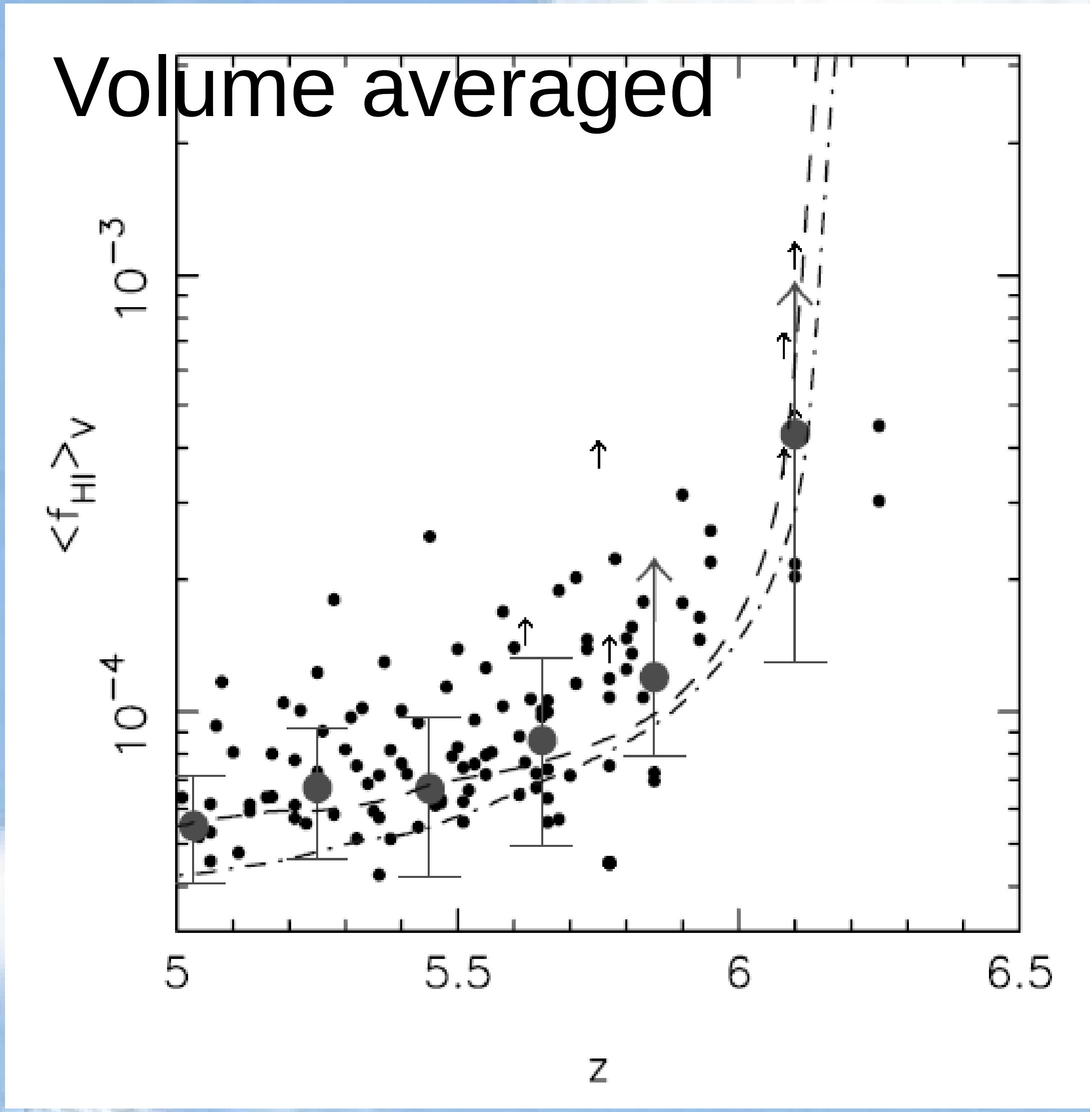


Lyα, Lyβ, Lyγ

For same HI density Lyβ and Lyγ optical depth are 6.2 and 17.9 times smaller



Hydrogen Neutral Fraction

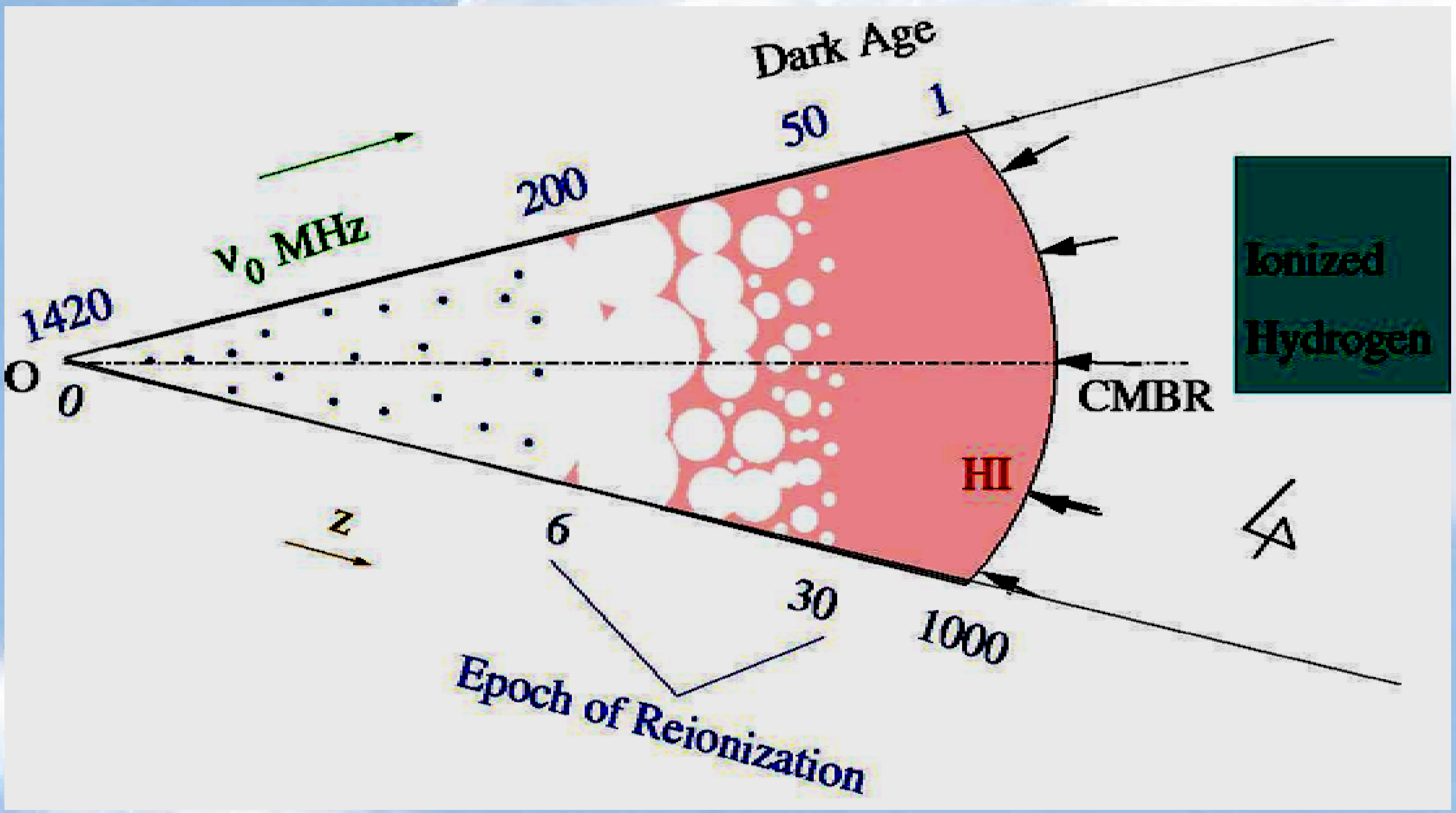


Mass Averaged

2.8×10^{-3} (z~5.7)

0.04 (z~6.4)

Summary


Dark Age
1
50
200
ν_0 MHz
1420
O
0
z
6
30
1000
Epoch of Reionization
HI
CMBR
Ionized
Hydrogen

CMBR

Thomson Scattering of CMBR from electrons

Suppresses CMBR anisotropies at scales
Below the Horizon at Epoch of Reionization

Polarize the CMBR Large Scale TE and EE

WMAP3 Spergel et al. 2007, ApJS, 170, 377

Thomson Scattering τ

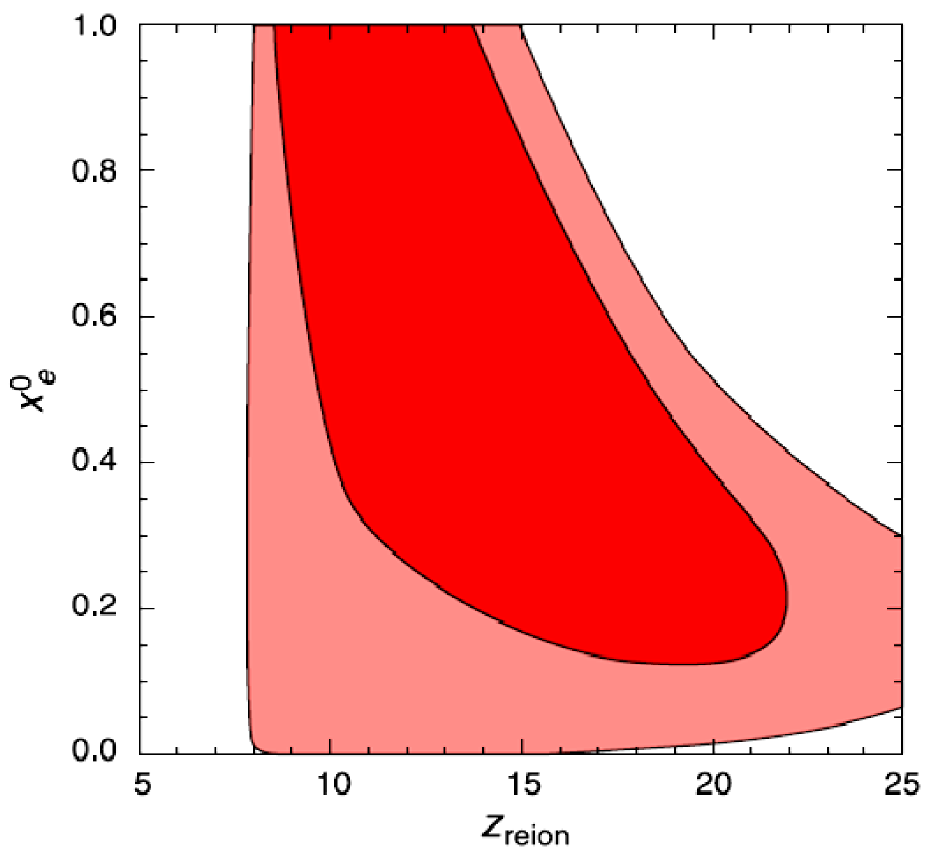
τ~0.1 error ~30%

Power-Law ΛCDM Model Parameters and 68% Confidence Intervals

Parameter	First-Year Mean	WMAPext Mean	3 Year Mean (No SZ)	3 Year Mean	3 Year + ALL Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.229 ± 0.073	2.186 ± 0.068
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	$0.1277^{+0.0080}_{-0.0079}$	$0.1324^{+0.0042}_{-0.0041}$
H_0	72^{+5}_{-5}	73^{+3}_{-3}	73.5 ± 3.2	$73.2^{+3.1}_{-3.2}$	$70.4^{+1.5}_{-1.6}$
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	$0.088^{+0.029}_{-0.030}$	0.089 ± 0.030	$0.073^{+0.027}_{-0.028}$
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017	0.958 ± 0.016	0.947 ± 0.015
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035	0.241 ± 0.034	0.268 ± 0.018
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05	$0.761^{+0.049}_{-0.048}$	$0.776^{+0.031}_{-0.032}$
Parameter	First-Year ML	WMAPext ML	3 Year ML (No SZ)	3 Year ML	3 Year + ALL ML
$100\Omega_b h^2$	2.30	2.21	2.23	2.22	2.19
$\Omega_m h^2$	0.145	0.138	0.125	0.127	0.131
H_0	68	71	73.4	73.2	73.2
τ	0.10	0.10	0.0904	0.091	0.0867
n_s	0.97	0.96	0.95	0.954	0.949
Ω_m	0.32	0.27	0.232	0.236	0.259
σ_8	0.88	0.82	0.737	0.756	0.783

Notes.—The 3 Year fits in the columns labeled "No SZ" use the likelihood formalism of the first-year paper and assume no SZ contribution, $A_{SZ} = 0$, to allow direct comparison with the first-year results. Fits that include SZ marginalization are given in the last two columns of the upper and lower parts of the table and represent our best estimate of these parameters. The last column includes all data sets.

Constraining Reionization

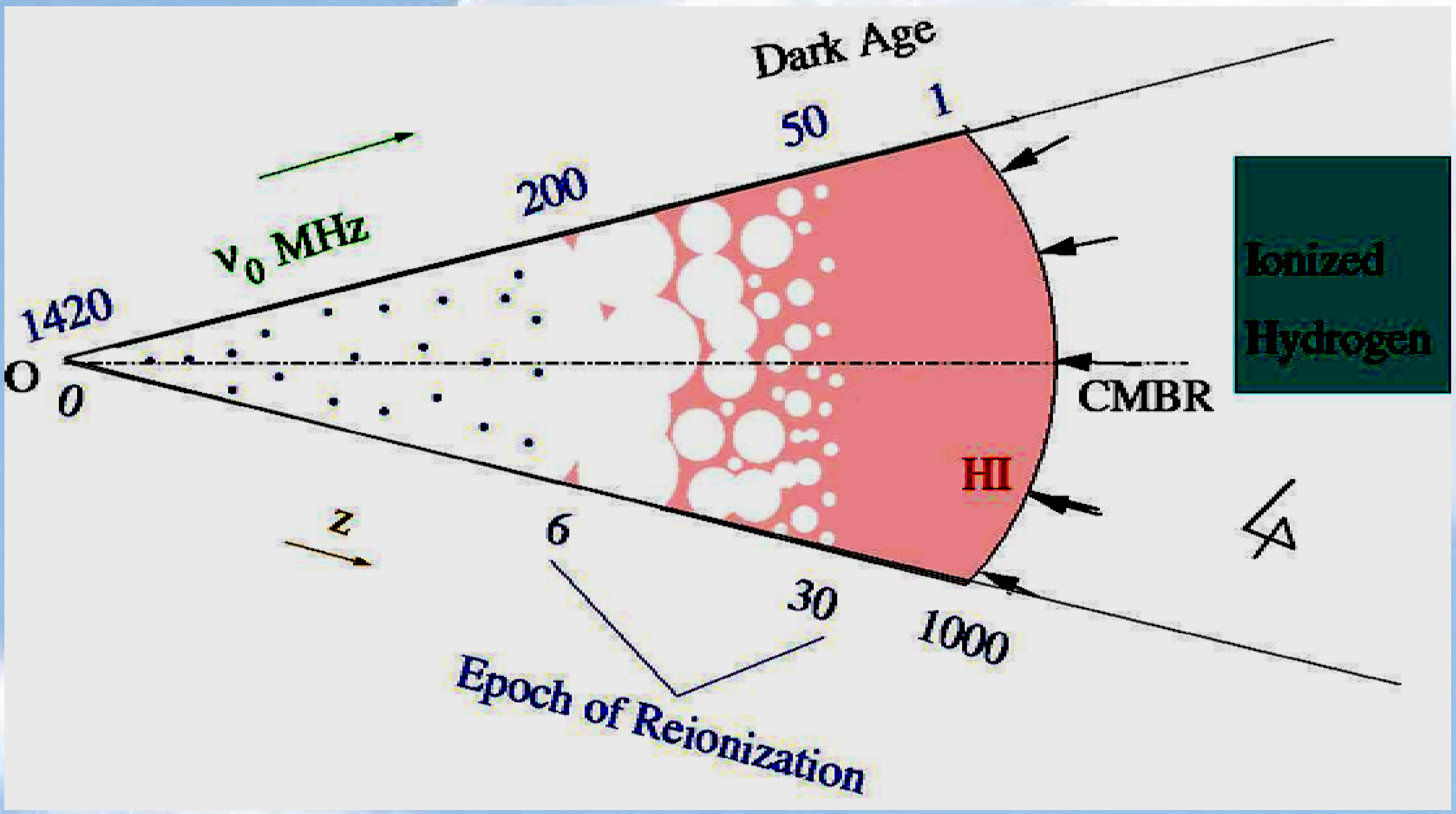


68% and 95% joint 2D marginalized confidence level contours

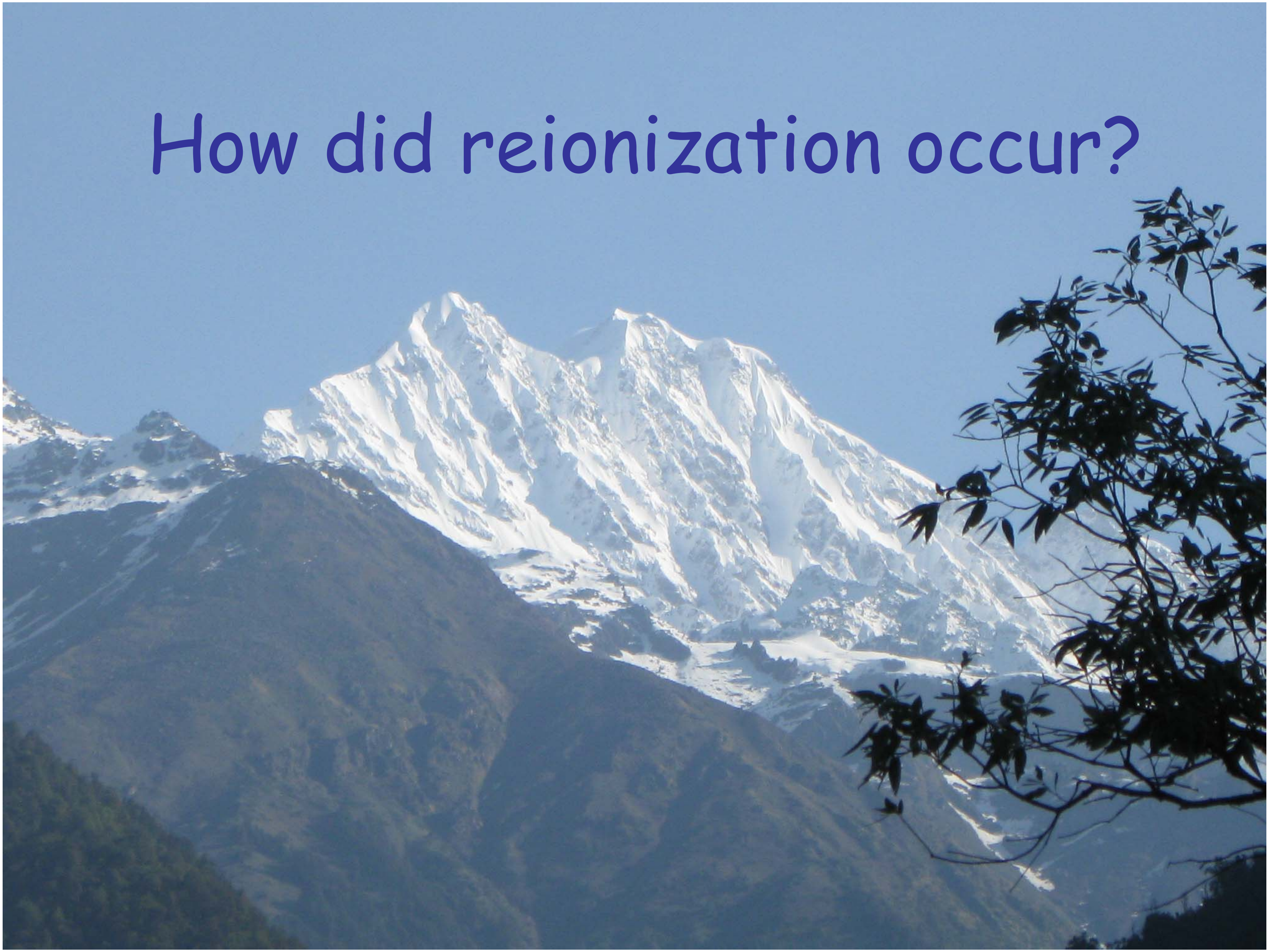
$$x_e = \begin{cases} 0, & z > z_{\rm reion}, \\ x_e^0, & z_{\rm reion} > z > 7, \\ 1, & z < 7. \end{cases}$$

$z_{reion=}$=11.3 if x_e=1

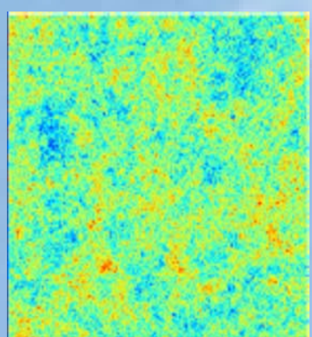
Summary

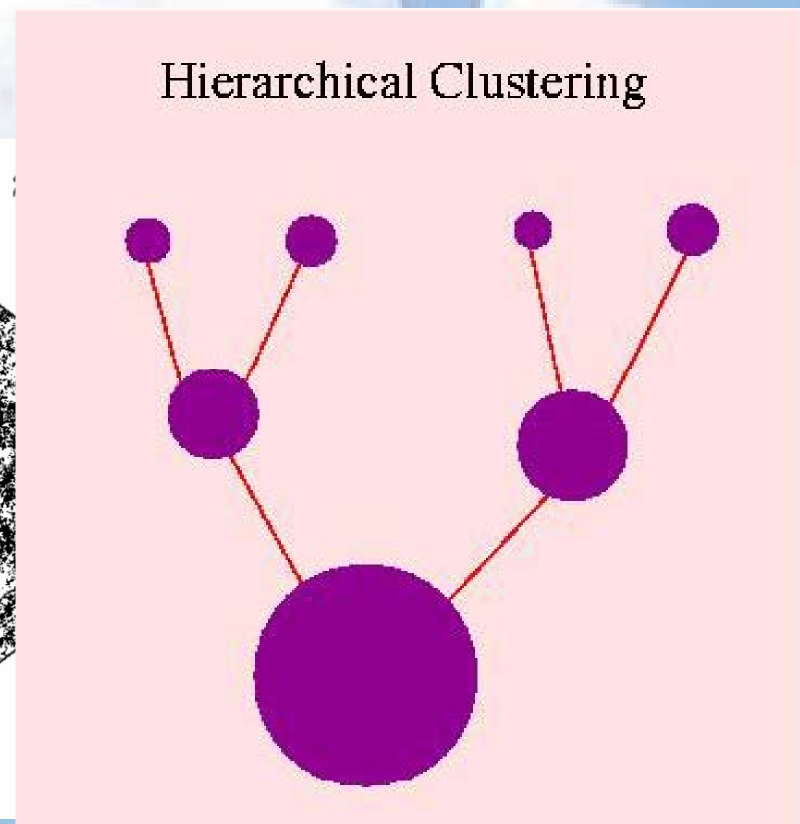


Dark Age
1
50
200
ν_0 MHz
1420
O
0
Ionized
Hydrogen
CMBR
HI
z
6
30
1000
Epoch of Reionization


How did reionization occur?

Structure Formation





Gravitational Instability

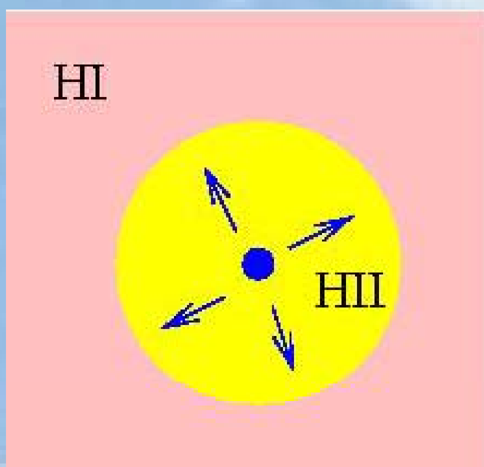
Dark matter dominates the dynamics

Rionization

Dark Matter Halos
Baryons Condense Within Halos

Galaxies

Photoionization   First Luminous Objects z~30



Massive Stars
Quasars - Accreting Black Holes
Emit Photons with E > 13.6 eV
Bubbles of Ionized Gas - HII Regions
Bubbles Grow - Overlap
Reionization Complete by z ~ 6

30 >z > 6

Reionization Sources

- Quasars - not enough photons to reionize
- Stars in galaxies

Star/Galaxy Formation

- Metal Free - Pop III stars - very massive
- Chemical Enrichment
- Pop II stars
- Star formations and quasars heat the IGM
- Chemical and thermal feedback on star formation in halos

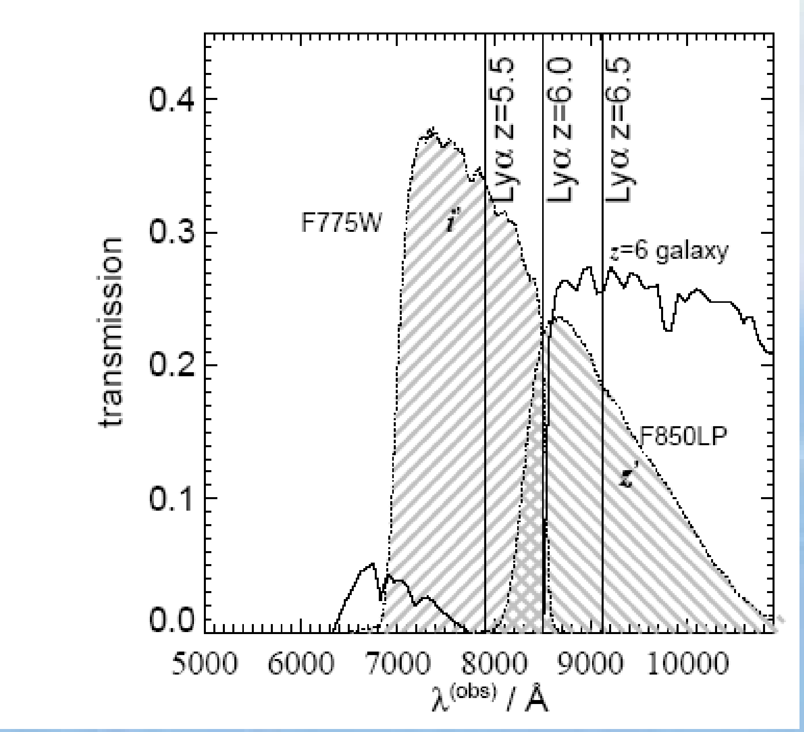
Bagla et al.,2009,arXiv.0902.0853
Metal Enrishment and Reionization Constrants
On Early Star Formation

High z galaxies and reionization

Bunker at a. 2009, arXiv.0909.1565

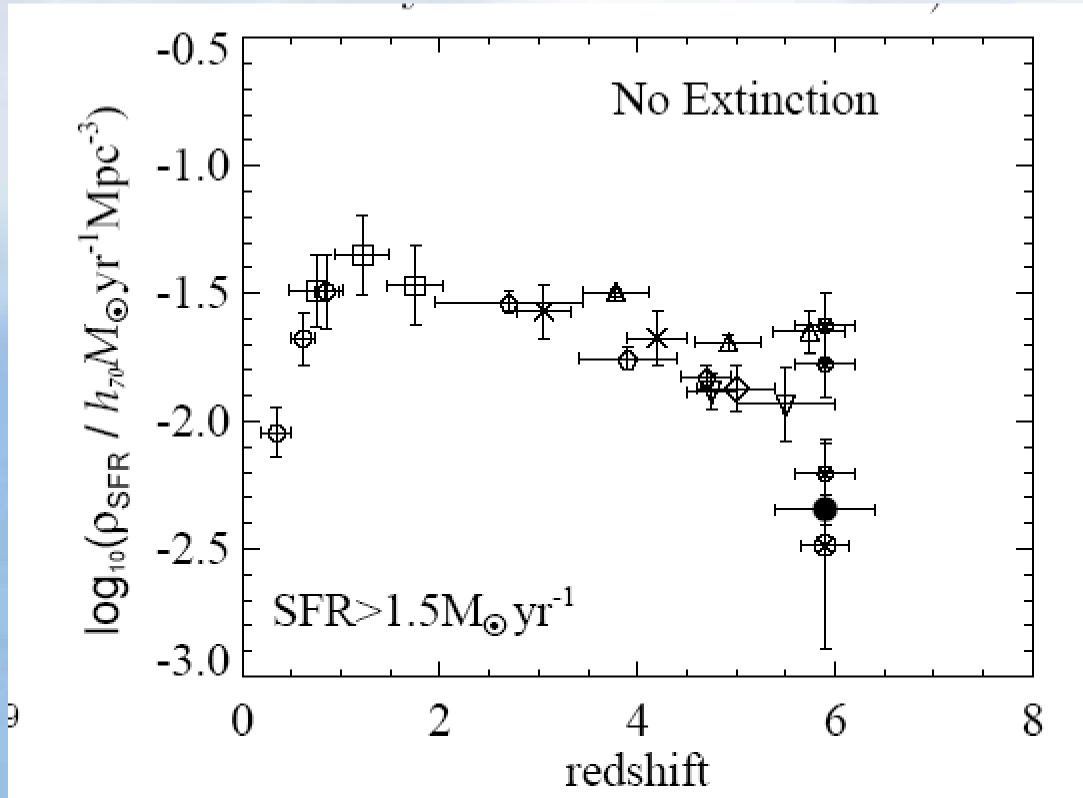
Photometric redshift i’ band dropout
z~6 Zero flux λ < 1216 A (1+z)
z’ band 9000A,
i’ band 8000A

HST ACS



High z galaxies and reionization

HUDF comoving volume averaged star formation rate



Implication for reionization

Measured SFR at z~6is 5 times smaller than needed if bulk of reionization occurred at z~6

3.6-8 μm
Spitzer/IRAC

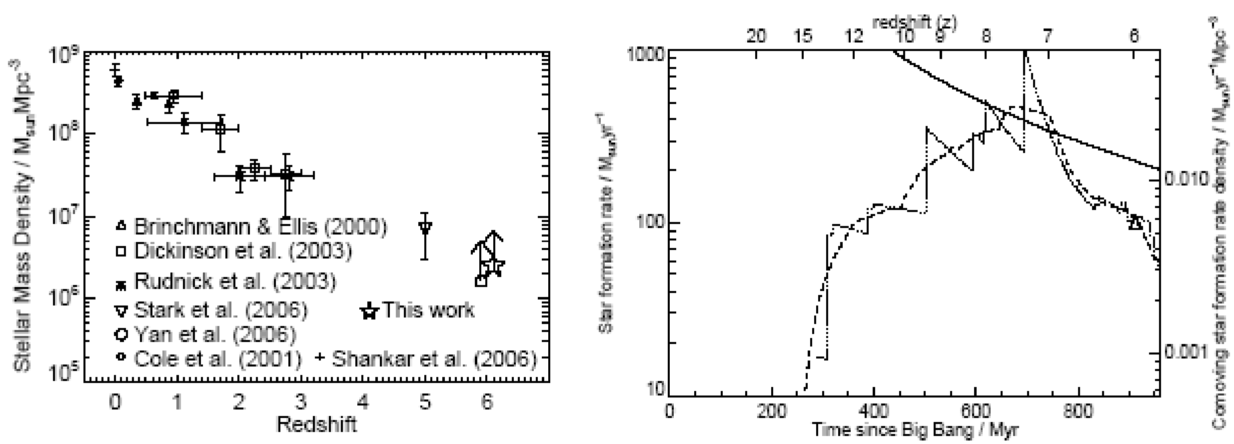


Figure 5. **Left:** The evolution of the stellar mass density – see Eyles et al. (2007) for details of this compilation and references to the literature. Our measurement from the i'-drop galaxies at $z \approx 6$ is marked by a star. **Right:** The sum of the past star formation rates for our i'-drop sample (dotted curve, and smoothed over 100 Myr for dashed curve). The requirement for reionization is the solid curve (from Madau, Haardt & Rees 1999) – if the escape fraction is high, there is sufficient UV flux from star formation to achieve reionization at $z \geq 7$ (Eyles et al. 2007).

Some more issues

Sources are clustered

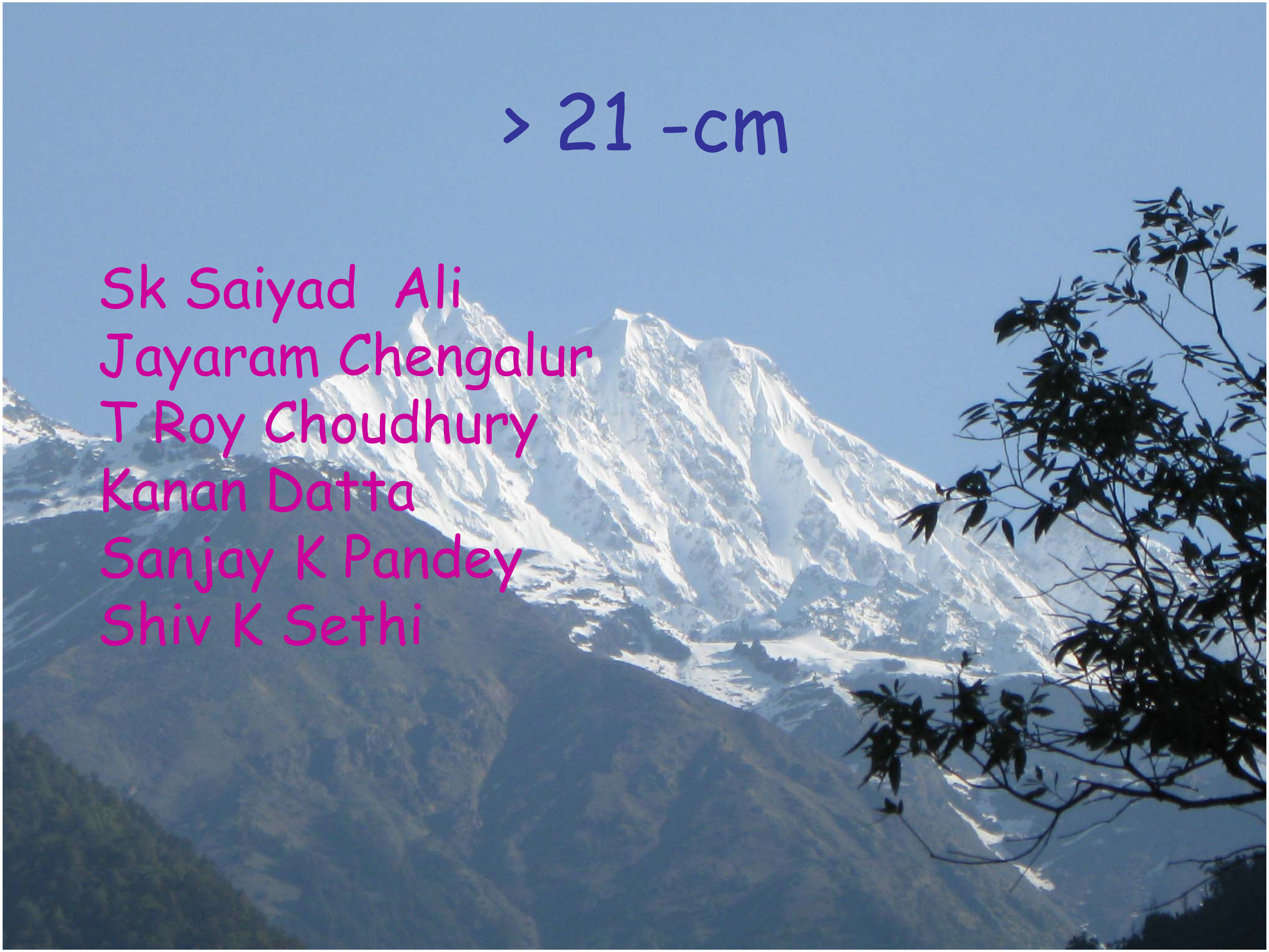
Radiative Transfer

Hydrogen density not uniform

$$\frac{dx}{dt} = \Gamma_{\rm HI}\ (1 - x) - \alpha\ x^2\ n_{\rm H}$$

Choudhury, T. Roy 2009, arXiv0904.4596

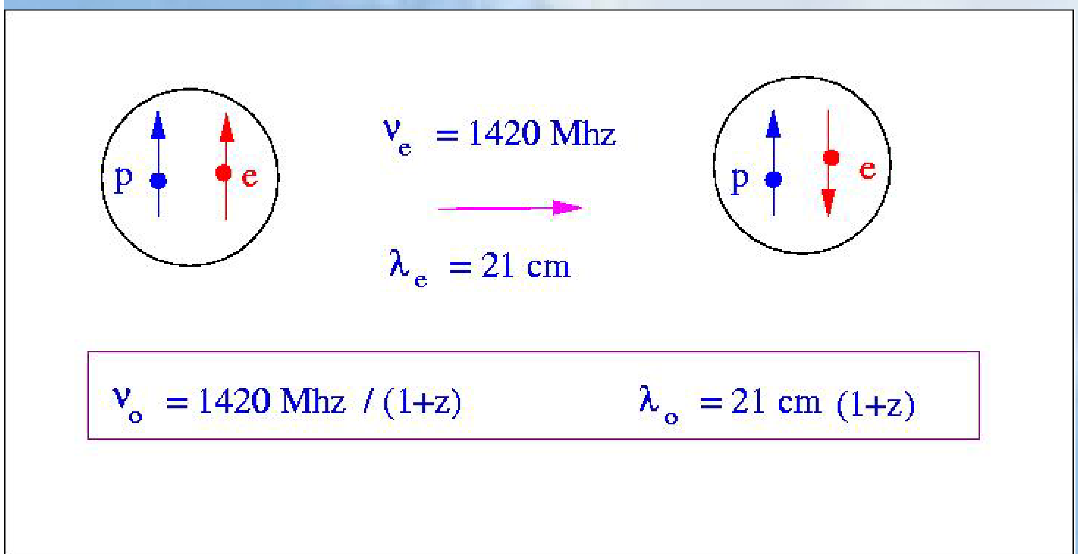
Simulations


> 21 -cm
Sk Saiyad Ali
Jayaram Chengalur
T Roy Choudhury
Kanan Datta
Sanjay K Pandey
Shiv K Sethi

21-cm radiation

Neutral Hydrogen - HI

Ground state



Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_\star / T_s}$$

$$T_\star = h_p \nu_e / k_B = 0.068 \text{ K}$$

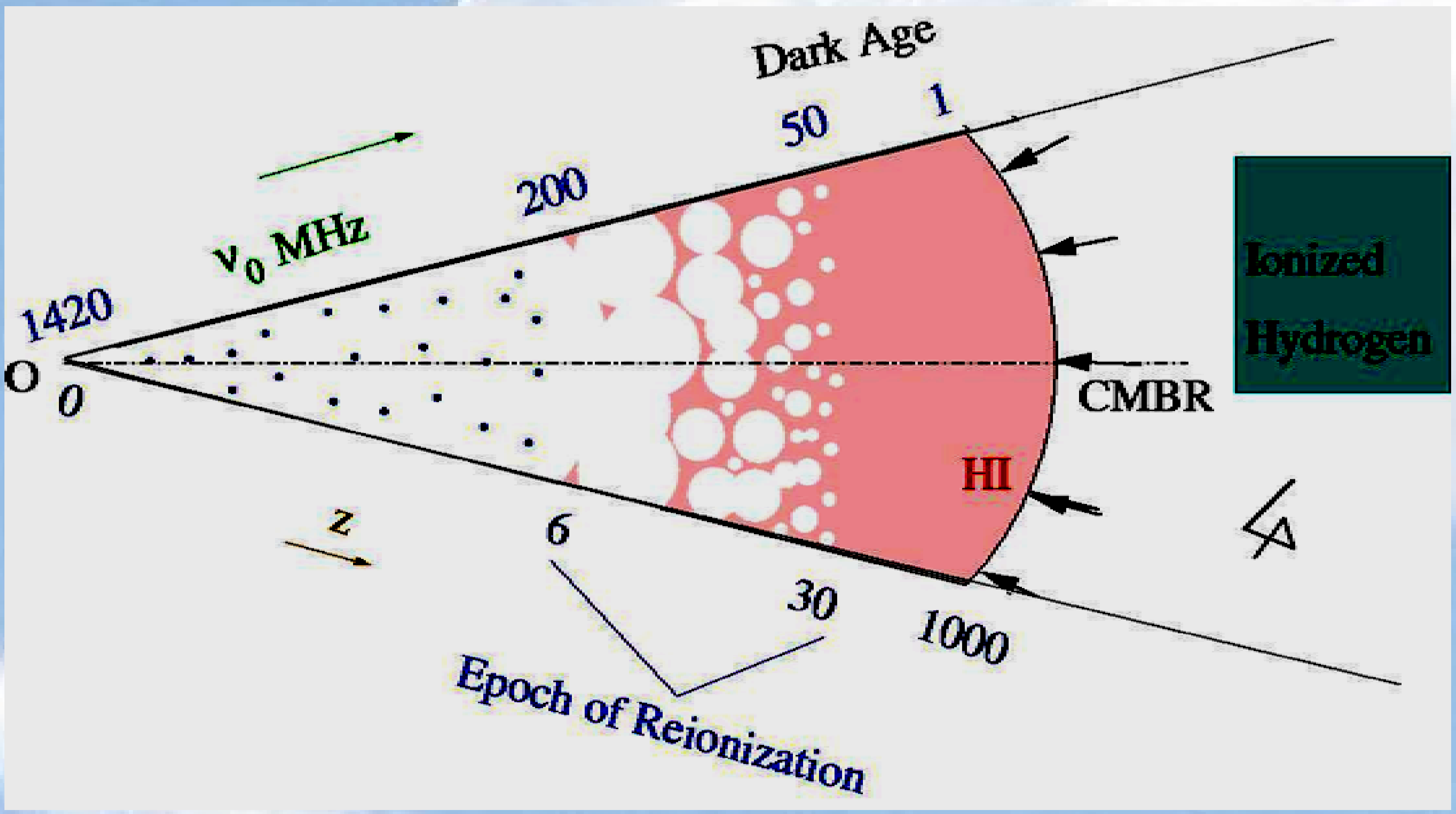
21-cm signal

$$\tau = \frac{3\bar{n}_{\rm H} h_{\rm p} c^3 A_{10}}{32\pi k_{\rm B} T_{\rm s} \nu_{\rm e}^2 H(z)} \left[1 + \Delta_{\rm H} - \frac{1}{H(z)a(z)} \frac{\partial v}{\partial r} \right]$$

$$\delta T_{\rm b}(\boldsymbol{n}, \nu) = \bar{T} \left[\left(1 - \frac{T_\gamma}{T_{\rm s}} \right) \left(\Delta_{\rm H} - \frac{1}{Ha} \frac{\partial v}{\partial r} \right) + \frac{T_\gamma}{T_{\rm s}} s \Delta_{\rm H} \right]$$

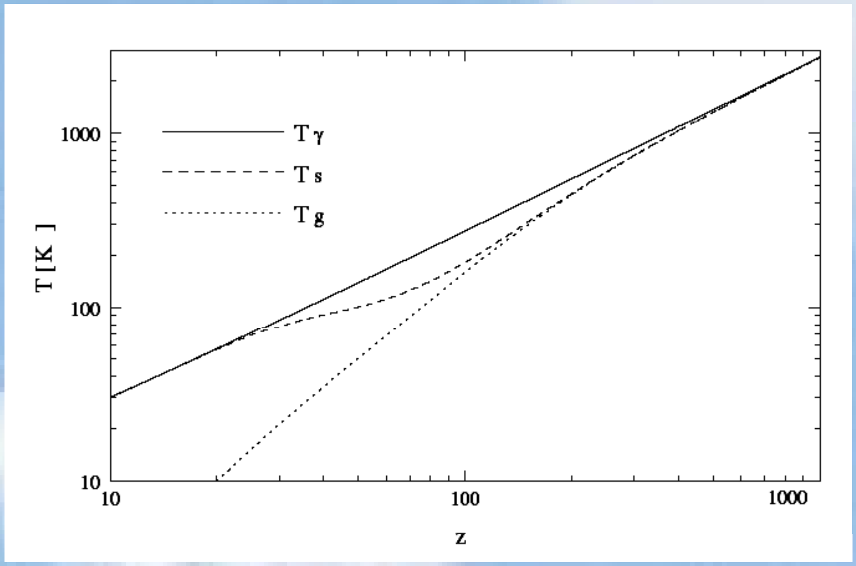
$$\bar{T} = 2.67 \times 10^{-3} \mathrm{K} \ \ \frac{\Omega_{\rm b} h^2}{0.02} \frac{(1+z)^{1/2}}{\Omega_{\rm m0}^{1/2} h}$$

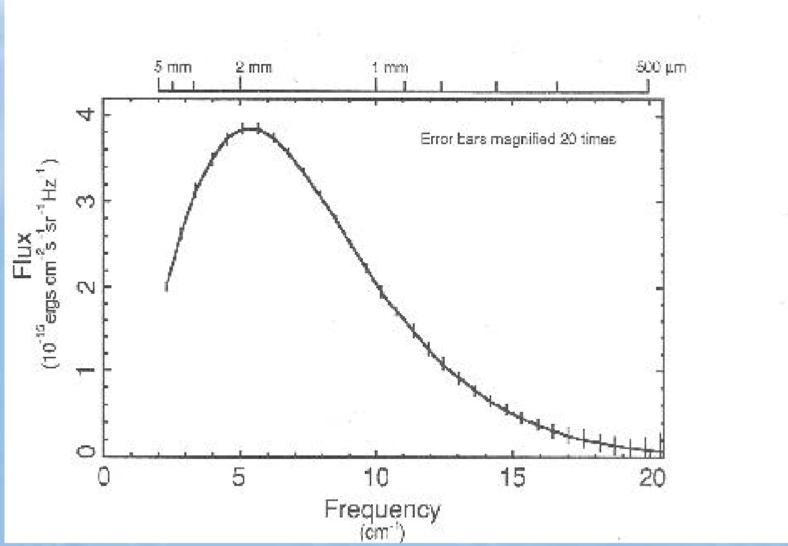
HI Evolution



The Dark Ages

No luminous sources
HI traces dark matter
Will be seen in absorption against CMBR 200 > z > 30





$T_s < T_\gamma$

Statistical Signal

$$a_{lm}(\nu) \;=\; \int \mathrm{d}\Omega \, Y^*_{lm}(\hat{\mathbf{n}})\, T(\nu, \hat{\mathbf{n}})$$

$$C_l(\nu_1, \nu_2) \equiv \langle a_{lm}(\nu_1)\, a^*_{lm}(\nu_2) \rangle$$

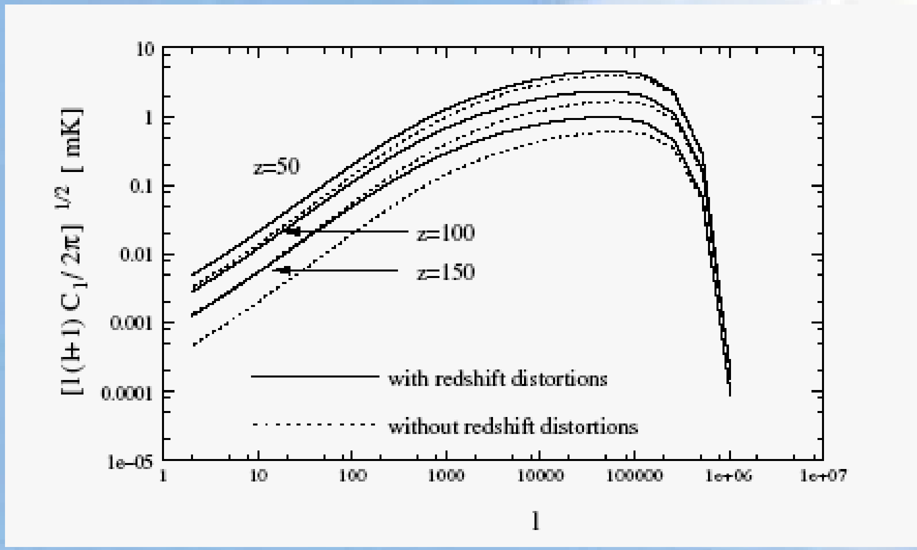
MAPS

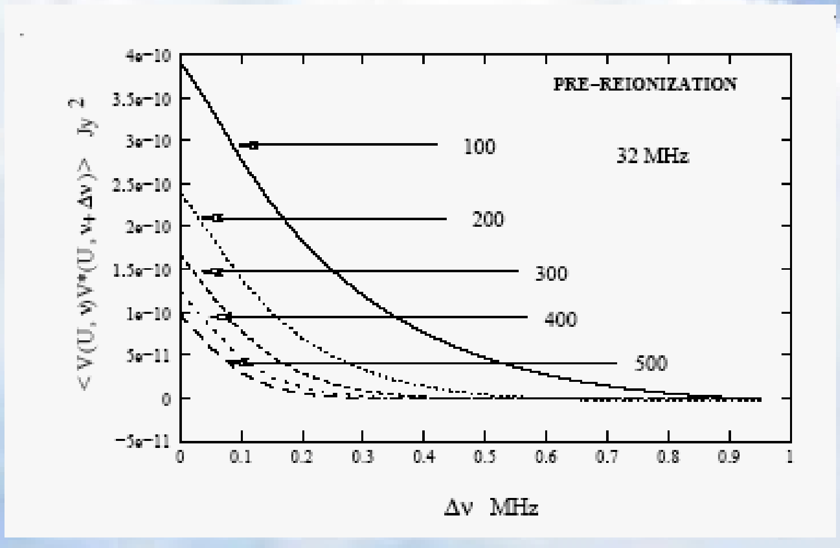
$$C_l(\Delta\nu) \equiv C_l(\nu, \nu + \Delta\nu)$$

$$\kappa_l(\Delta\nu) \equiv \frac{C_l(\Delta\nu)}{C_l(0)}$$

$$C_l^{\mathrm{flat}}(\Delta\nu) = \frac{\bar{T}^2}{\pi r_\nu^2} \int_0^\infty \mathrm{d}k_\parallel \, \cos(k_\parallel r'_\nu \Delta\nu)\, P_{\mathrm{HI}}(\mathbf{k})$$

Prereionization Signal





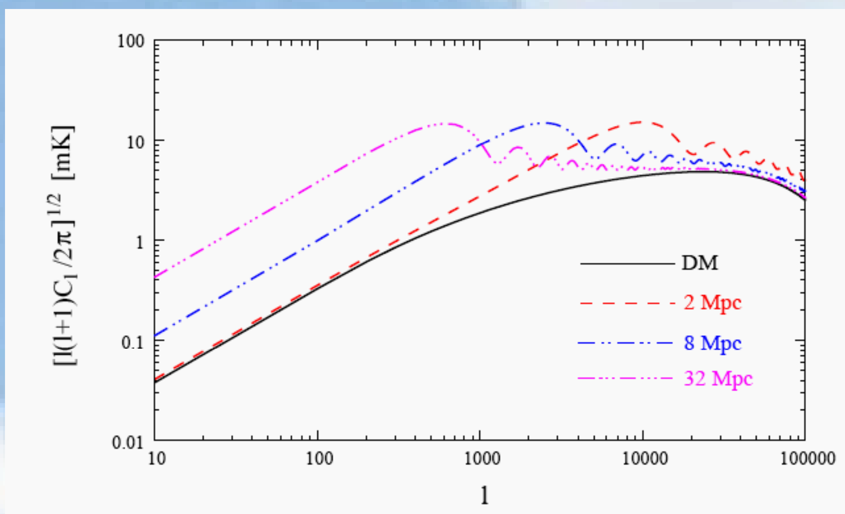
Very sensitive probe of the dark matter power spectrum

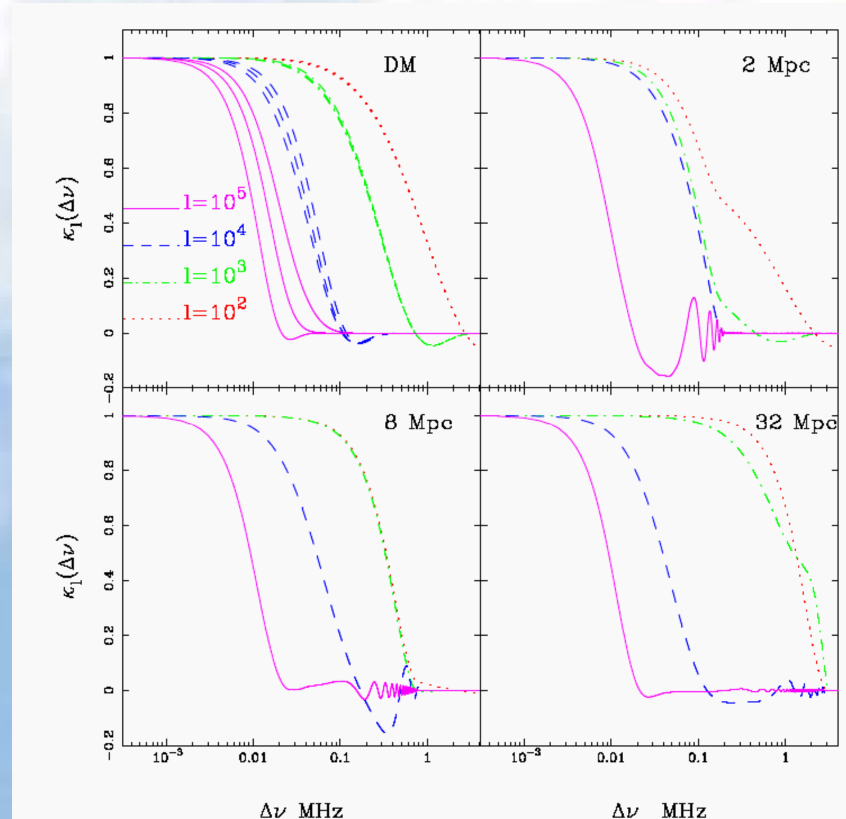
Epoch of reionization

- Luminous sources produce UV/X-ray
- Ionize and heat IGM
- $T_s > T_\gamma$
- 21-cm signal is in emission
- HI distribution is patchy
- ionized bubbles around luminous sources

Reionization Signal

X=0.5, z=10

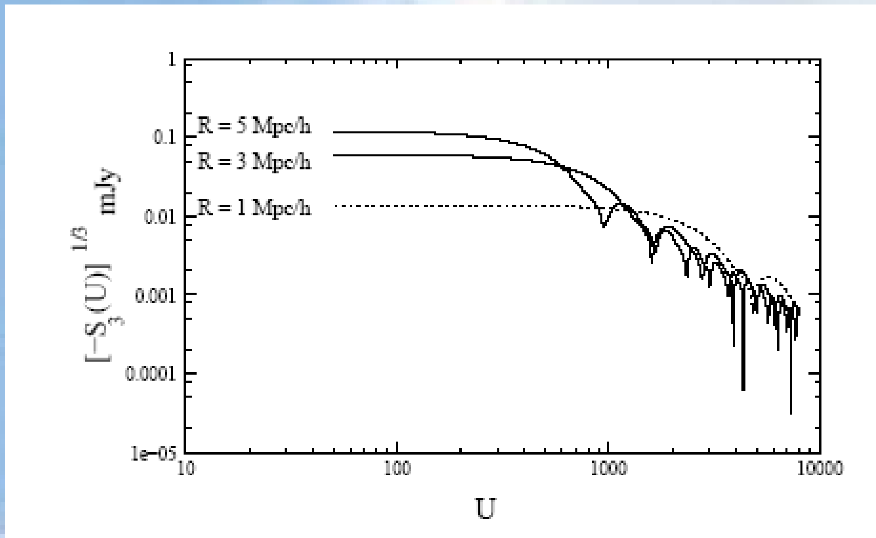


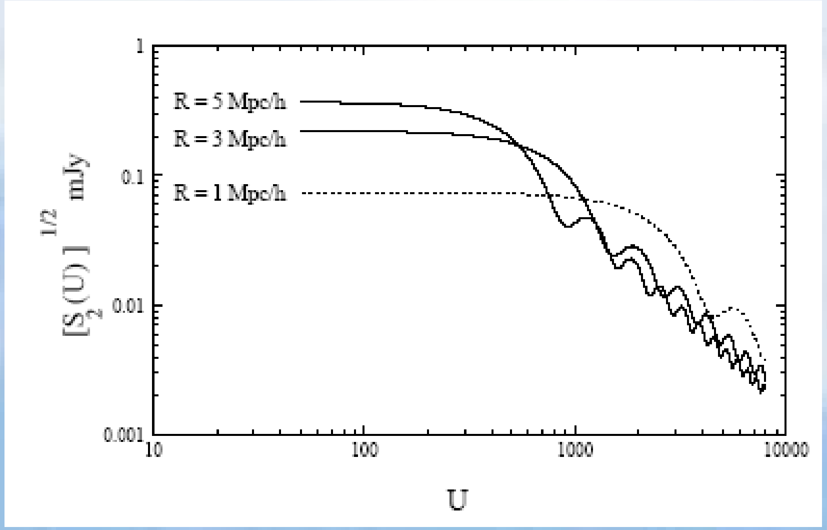


Non-Gaussian

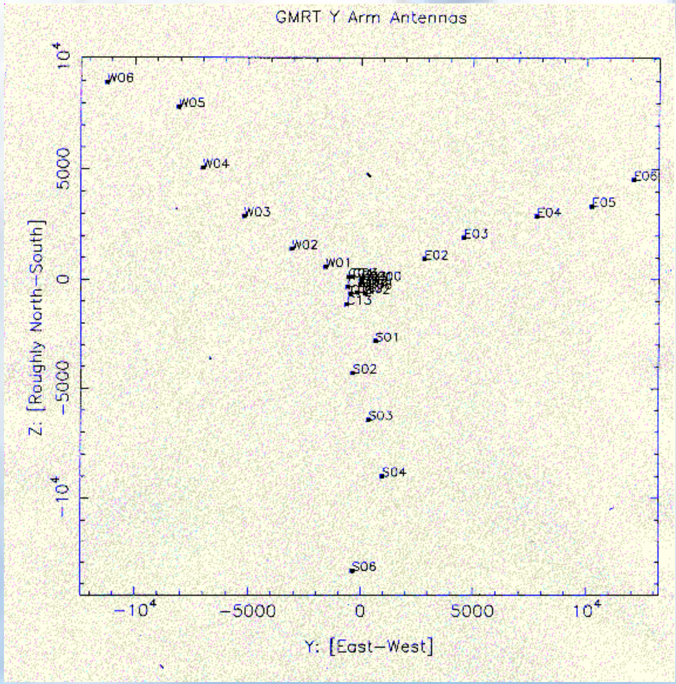
Bispectrum

Power spectrum





Radio Interferometric Arrays



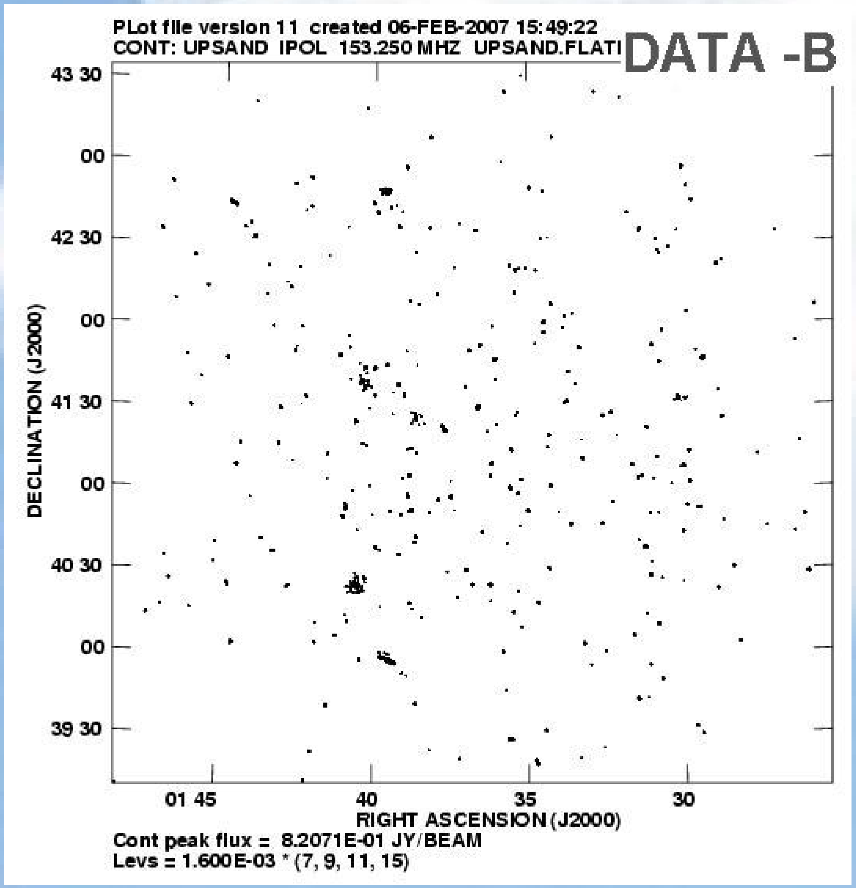
GMRT

30 antennas 45 diameter

Frequency MHz	153	235	325	610	1420
z	8.3	5.0	3.4	1.3	0

32 MHz bands with 128 separate channels

14 hrs GMRT Observations



RA 01 36 46 DEC 41 24 23

Results GMRT Observations

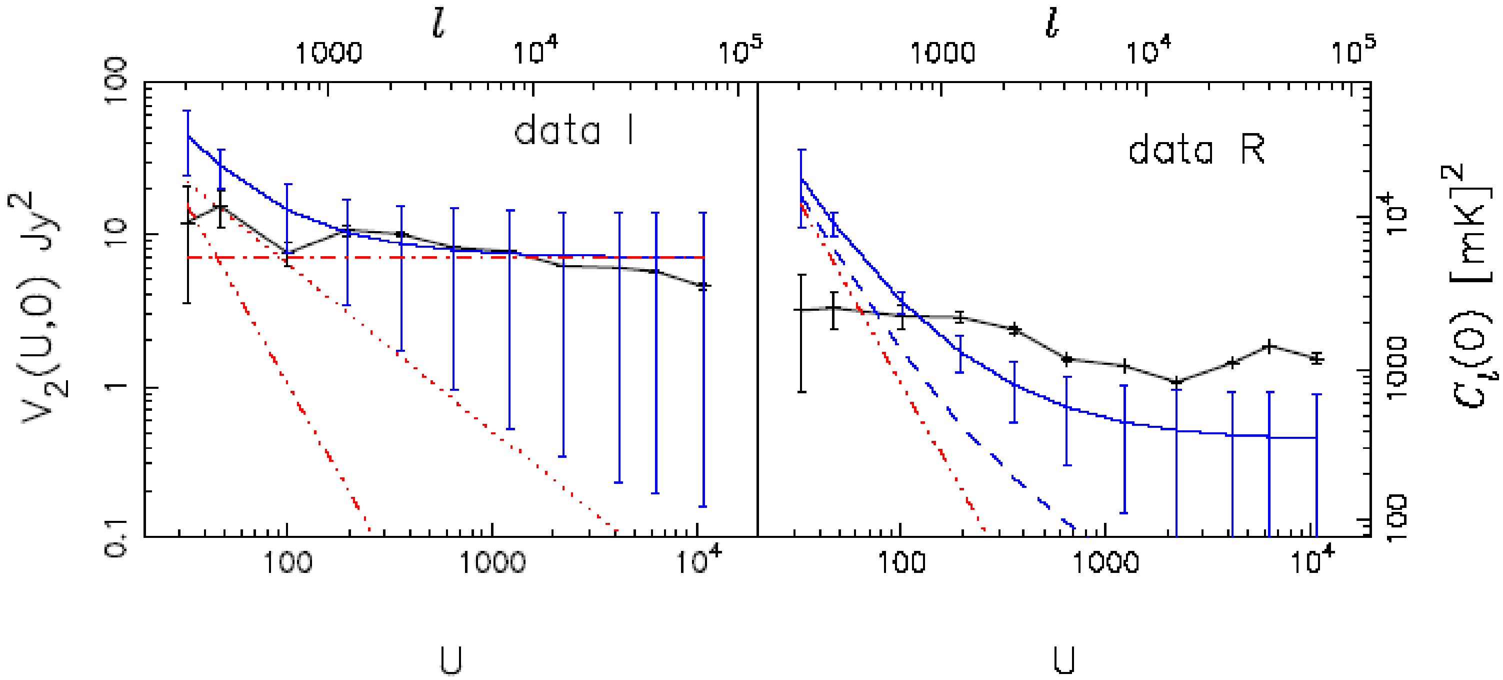


Figure 6. The thick solid line shows the real part of the observed visibility correlation $V_2(U, 0)$ as a function of U for the two data-sets indicated in the figure. As shown here, this may also be interpreted as $C_l(0)$ as a function of l. For **data I** the thin solid line shows the total model prediction for $S_c = 900\,\mathrm{mJy}$. Also shown are the contributions from point source Poisson (dash-dot), point source clustering (dot) and Galactic synchrotron (dash-dot-dot-dot). For **data R** the thin solid line shows the total model predictions for $S_c = 100\,\mathrm{mJy}$ and and the long dashed line for $10\,\mathrm{mJy}$. The dash-dot-dot-dot curve shows the Galactic synchrotron contribution.

Foregrounds

- 4 to 5 orders of magnitude larger than signal
- Galactic Synchrotron, Extragalactic Radio Sources
- Continuum Sources
- Expected to be correlated across large frequency separations ~5 MHz
- HI Signal decorrelates faster with $\Delta\nu$

Frequency Decorrelation

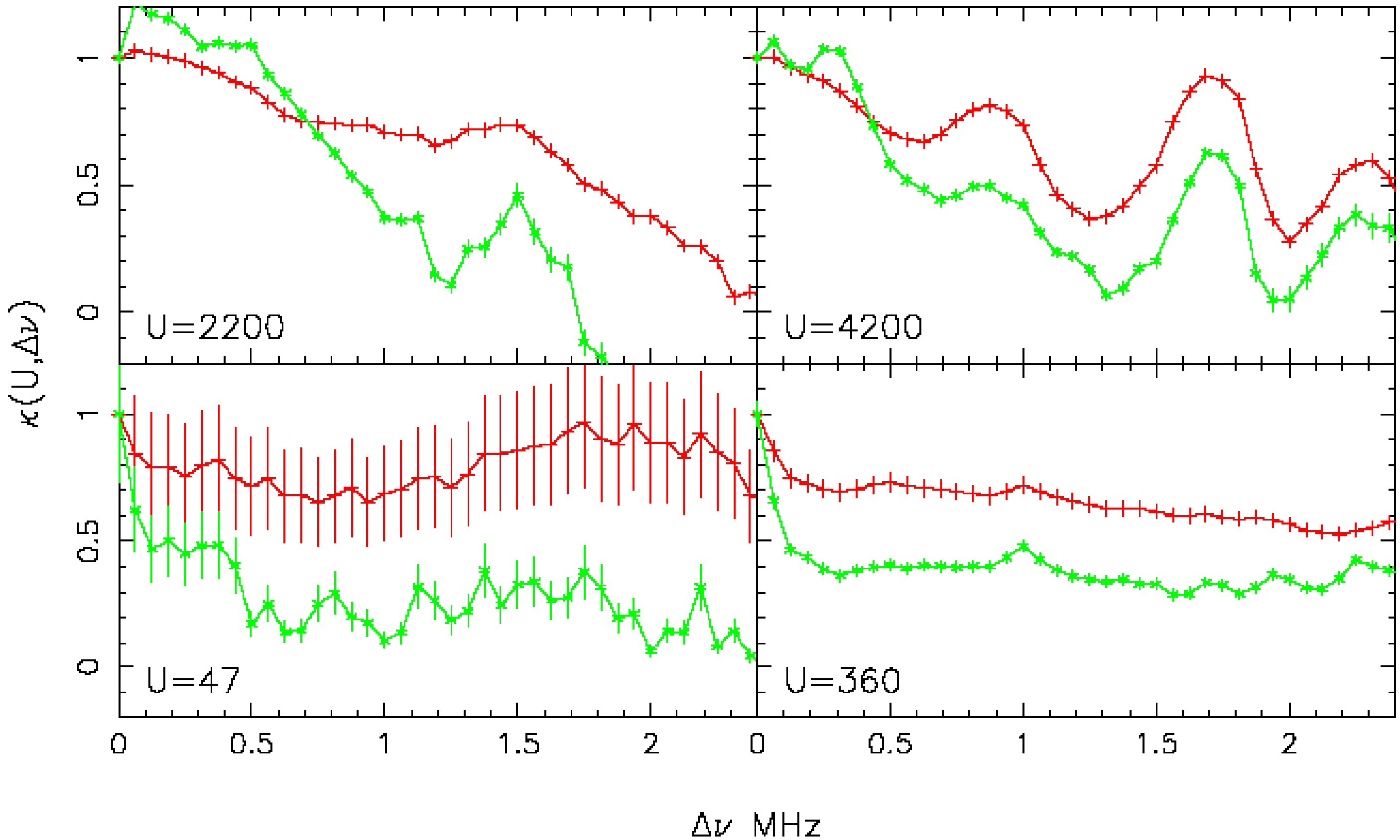
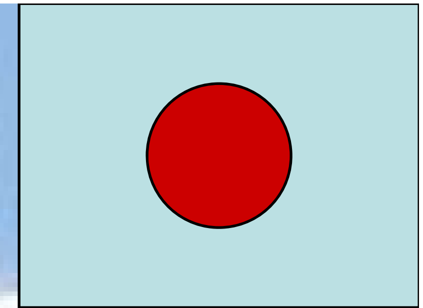


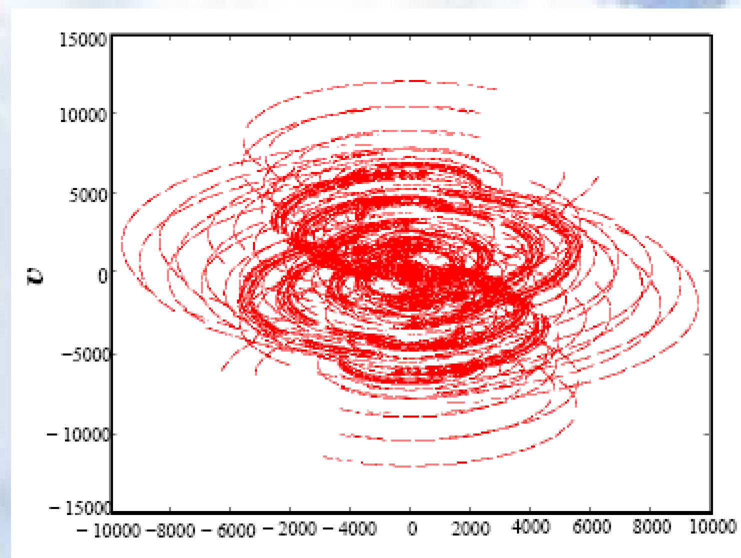
Figure 7. This shows $\kappa(U, \Delta\nu)$ as a function of $\Delta\nu$ for the different U values shown in the figure. The upper curve (at large $\Delta\nu$) shows data **I** while the lower shows data **R**.

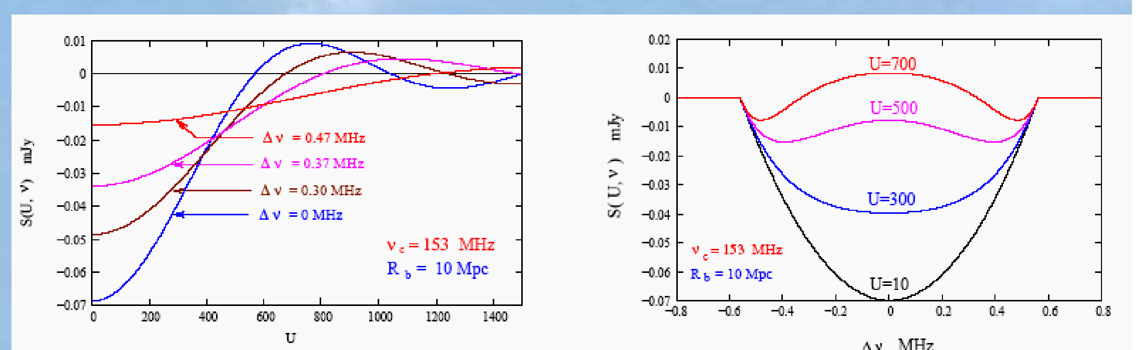
Detecting Ionized Bubbles



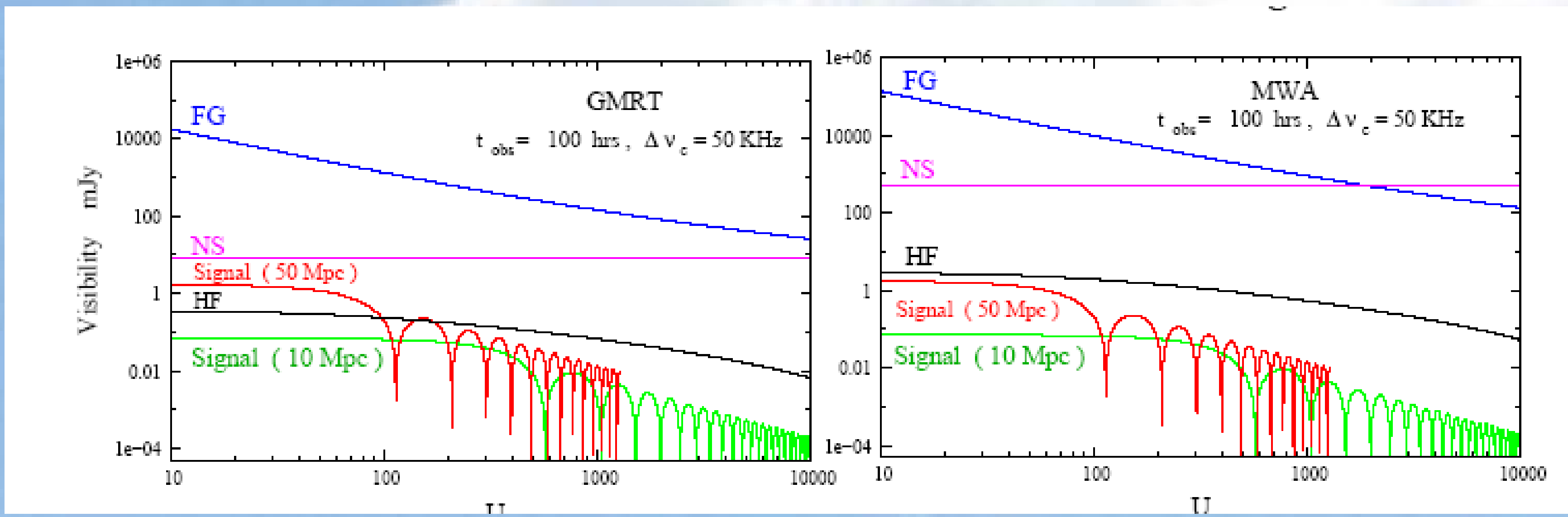
Visibility based

Noise in each visibility
Is independent





Other contributions

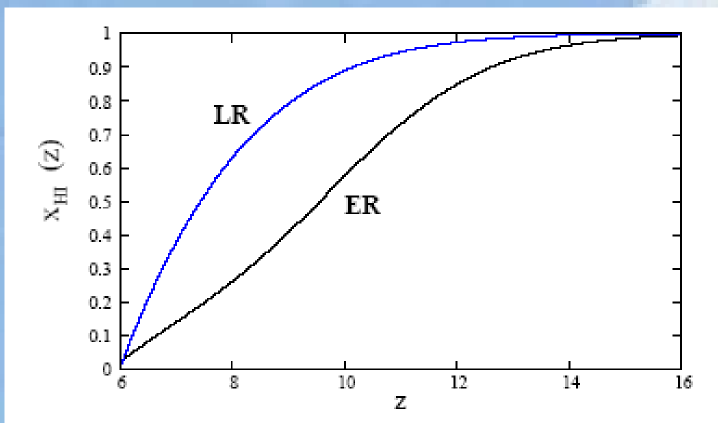


Matched Fiter

$$\hat{E} = \left[\sum_{a,b} S_f^*(\vec{U}_a, \nu_b) \hat{V}(\vec{U}_a, \nu_b) \right] / \left[\sum_{a,b} 1 \right]$$

Optimize Signal to Noise ratio
Minimize Foreground contribution

Prospects

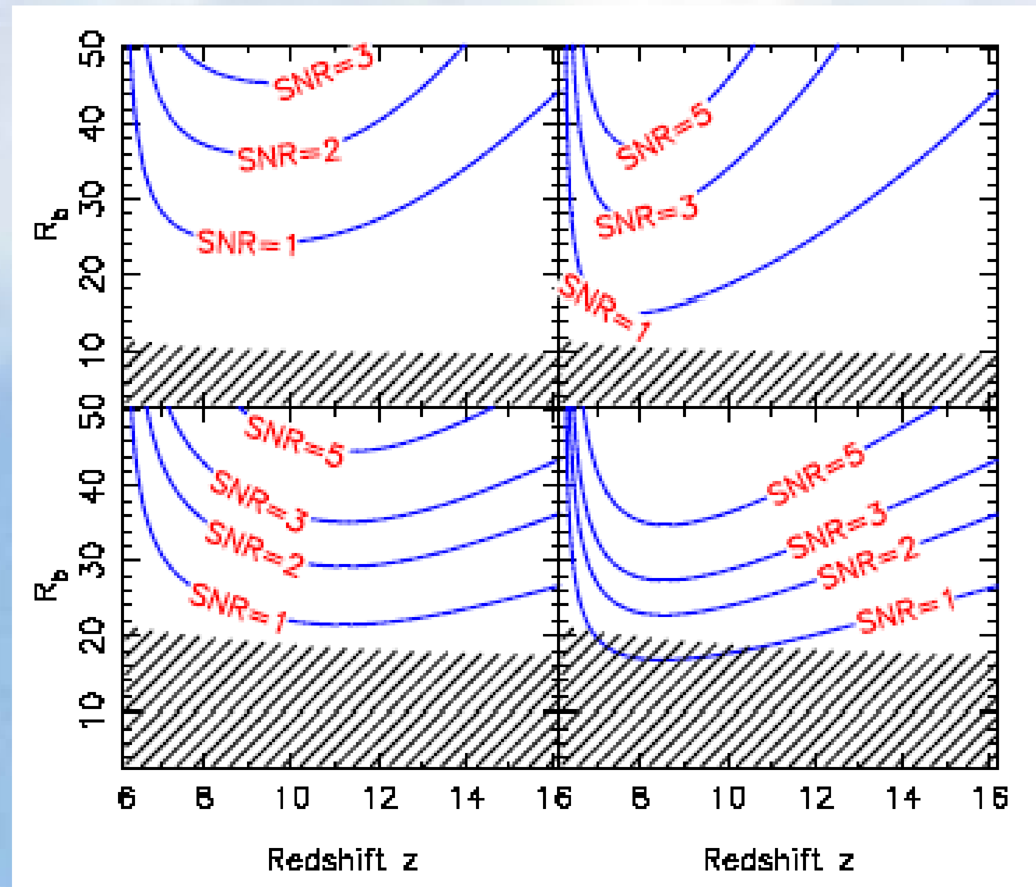


1000 hrs

ER LR

GMRT

MWA



Concluding Remarks

21 cm - important cosmological probe

GMRT + upcoming MWA, LOFAR,...

Concluding Remarks

- Probe Dark Ages, First Luminous Objects, reionization, post-reionization

- Potential Probe of Dark Energy