Weak Lensing with 21 cm Intensity Mapping

Ripples in the Cosmos

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21 cm at High Redshift

The 21 cm line is the hyperfine transition of neutral hydrogen or HI.

brightness temperature $$\delta T_b \simeq 9\,\frac{\rho_{HI}}{\bar{\rho}}(1+z)^{1/2}\left(1-\frac{T_{\rm CMB}(z)}{T_s}\right)\left(\frac{H(z)/(1+z)}{dv_{\|}/dr_{\|}}\right)\ {\rm mK}$$

Three interesting epochs:

- Dark Ages before reionization

  The neutral hydrogen fraction is high but foregrounds and noise are high and resolution is a limited.

Zahn & Zaldarriaga 2008, Metcalf & White 2008

- EoR (Epoch of Reionization)

- After reionization

  The neutral hydrogen fraction is much lower (~ 1 % today), but the foregrounds and noise are also lower.

21 cm Intensity Mapping

The 21 cm emission is treated as a diffuse source without attempting to detect individual objects.

Foregrounds are removed by filtering in frequency. The HI density, and thus its emission, has more structure on small scales than the foregrounds.

The result is a three dimensional map of the HI density with frequency indicating the redshift or radial direction.

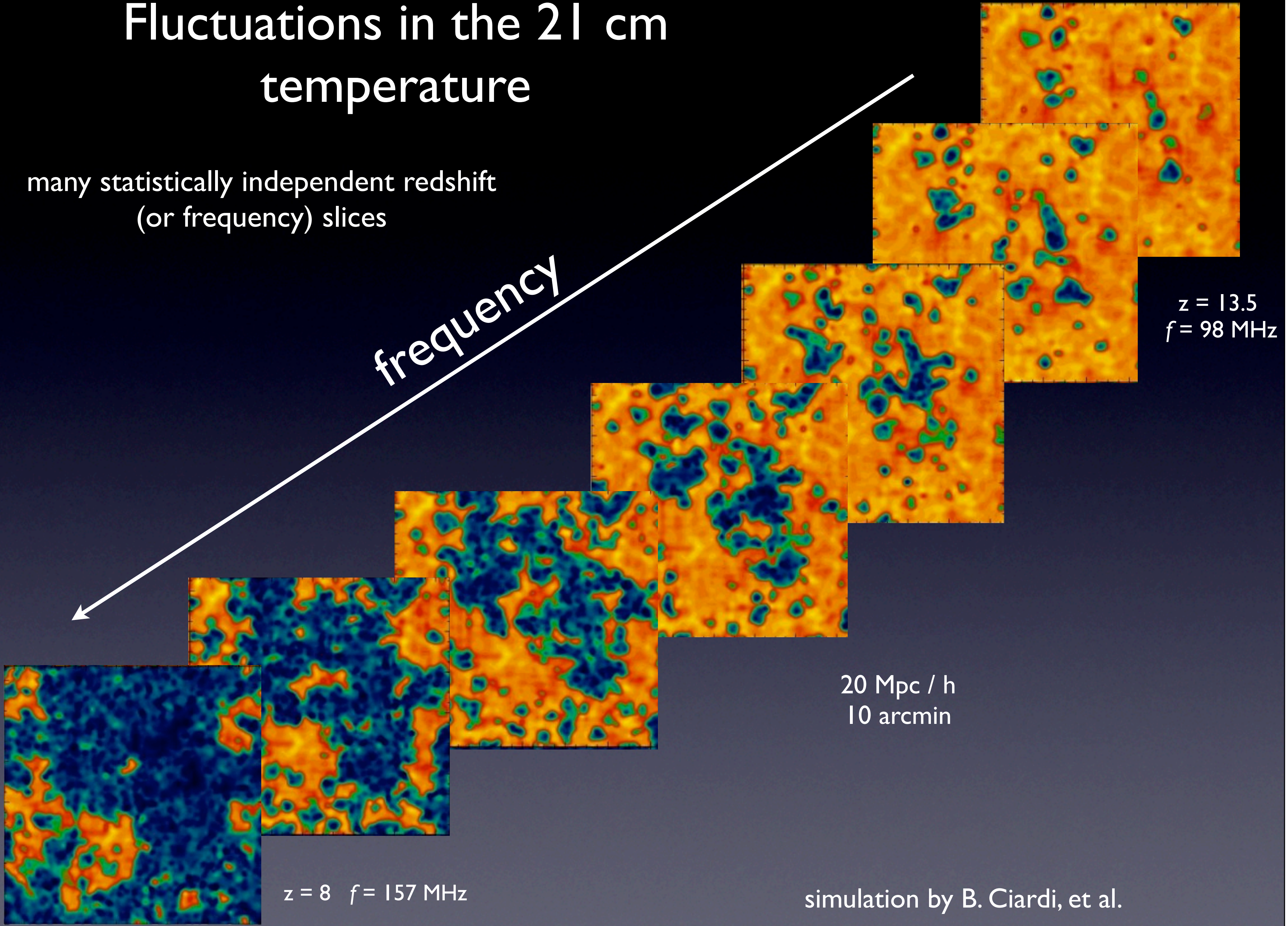
This is being used to probe the EoR:
MWA, GMRT, PAPER, 21CMA, LOFAR, SKA

And for measuring baryon acoustic oscillations (BAO) at z <~ 1:
BAOBAB, BAORadio, BINGO, CHIME, TianLai, GBT

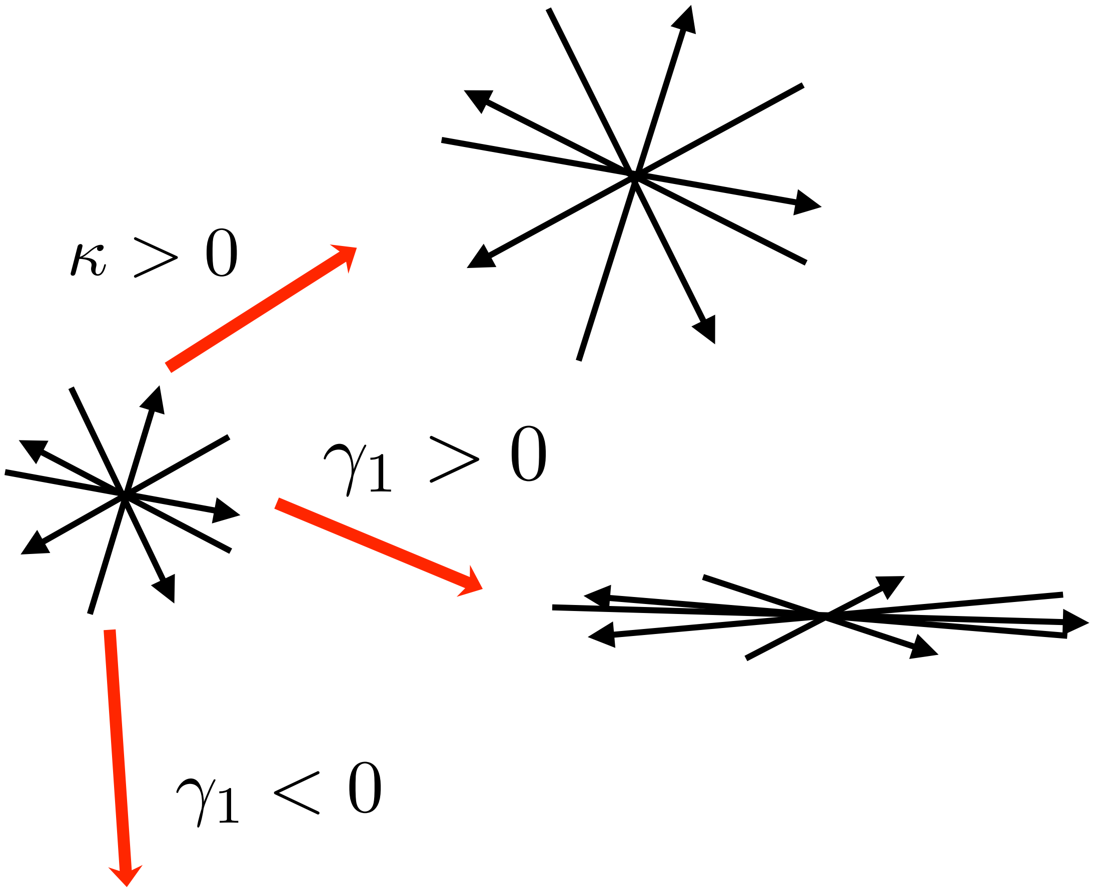
z	frequency	$D = \lambda/1$ arcmin
2	473 MHz	2.2 km
8	148 MHz	6.5 km
10	129 MHz	7.9 km
15	89 MHz	11.5 km

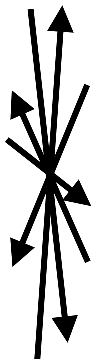
Fluctuations in the 21 cm temperature

many statistically independent redshift (or frequency) slices



21 cm Lensing





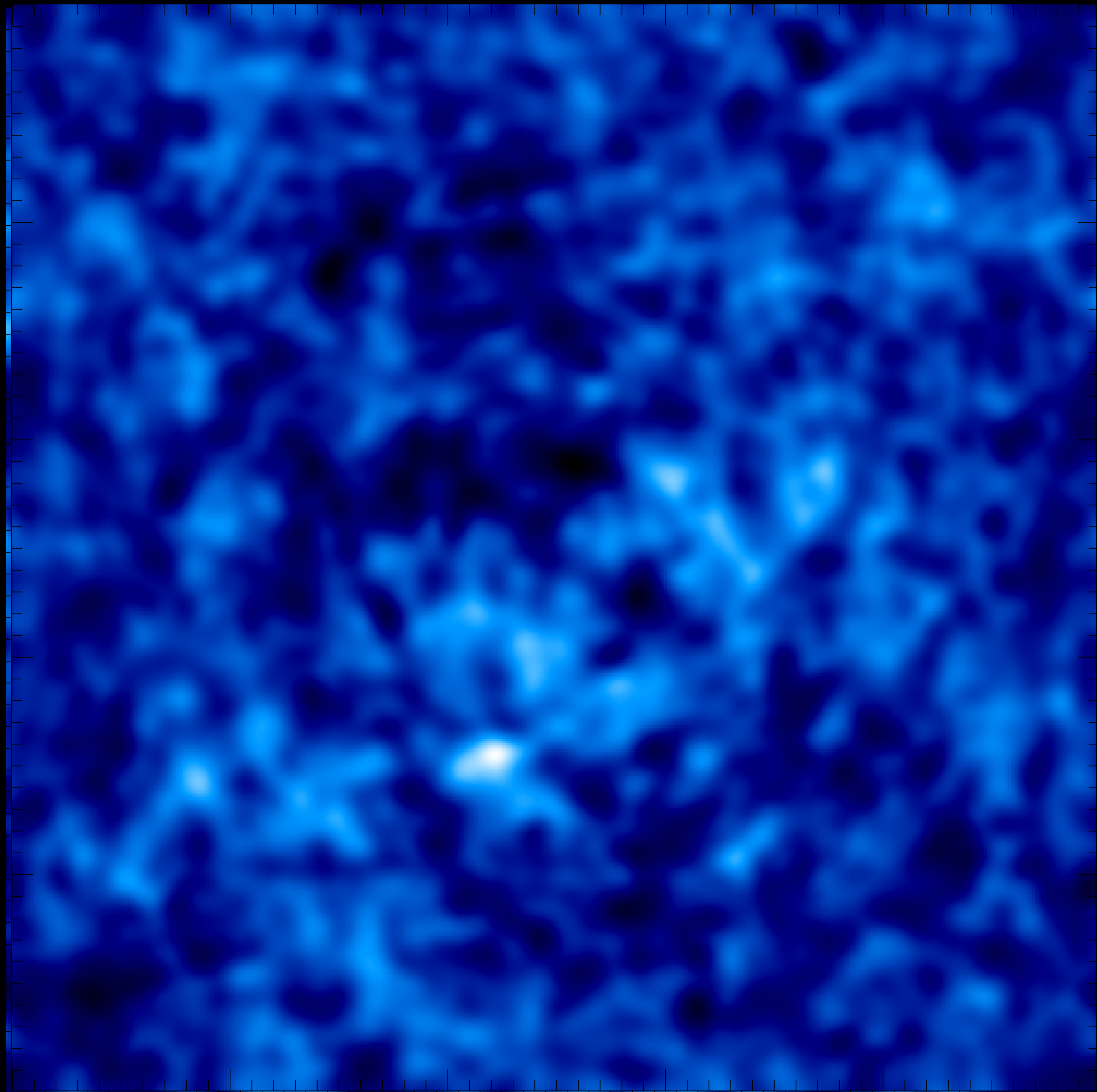
$\vec{\gamma}(\vec{x})$ shear

$\kappa(\vec{x})$ convergence

$$\kappa = \int_0^{z_s} dz\, W(z, z_s)\delta(z)$$

assumption: redshift or frequency slices are statistically independent

limitations: number of independent redshift slices
observations are hard



Estimator for the foreground surface density

Fourier-space quadratic convergence (surface density) estimator

filter

$$\kappa(\mathbf{u}) = \sum_{\nu} \int d^2u' \; \chi(\mathbf{u}, \mathbf{u}', \nu) V(\mathbf{u}', \nu) V(\mathbf{u}' - \mathbf{u}, \nu)$$

sum over frequency (redshift)

visibilities

Second order in brightness temperature.

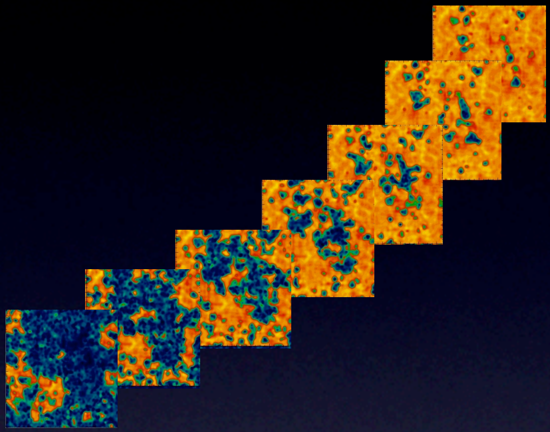
Based on Hu & Okamoto 2002 method for measuring lensing of the CMB, but extended to multiply frequencies (Zhan & Zaldarriaga 2008, Metcalf & White, 2008, Metcalf & White 2009) .

Two Sources of Noise in the Lensing Measurement

Intrinsic Noise -

Property of 21 cm emission distribution

Depends on:
- frequency range (number of redshift slices)
- telescope resolution
- ionization history of the universe
- distribution of gas in and outside of galaxies



Reached when the brightness temperature is accurately mapped within each band.

Foreground Noise -

Noise from instrumental and foreground sources. Noise is dominated by galactic syncrotron radiation for z >~ 3.

Depends on:
- collecting area of telescope
- observation time

Results at z = 8 before reionization

- Assume abrupt reionization at $z = 8$ ($\nu = 158\,\mathrm{MHz}$). Neutral hydrogen fraction $f_{HI} = 1$.
- $\bar{T}(z) = 180\,\Omega_{HI}(z)\,h\,(1+z)^2/(H(z)/H_0)$ mK
- Telescope noise $C_\ell^N = \frac{(2\pi)^3 T_{\mathrm{sys}}^2}{B t_0 f_{\mathrm{cover}}^2 \ell_{\mathrm{max}}^2}$
- SKA-like telescope:

$D_{\mathrm{tel}} = 2$ km, $A_{\mathrm{coll}} = 0.56\ \mathrm{km}^2$

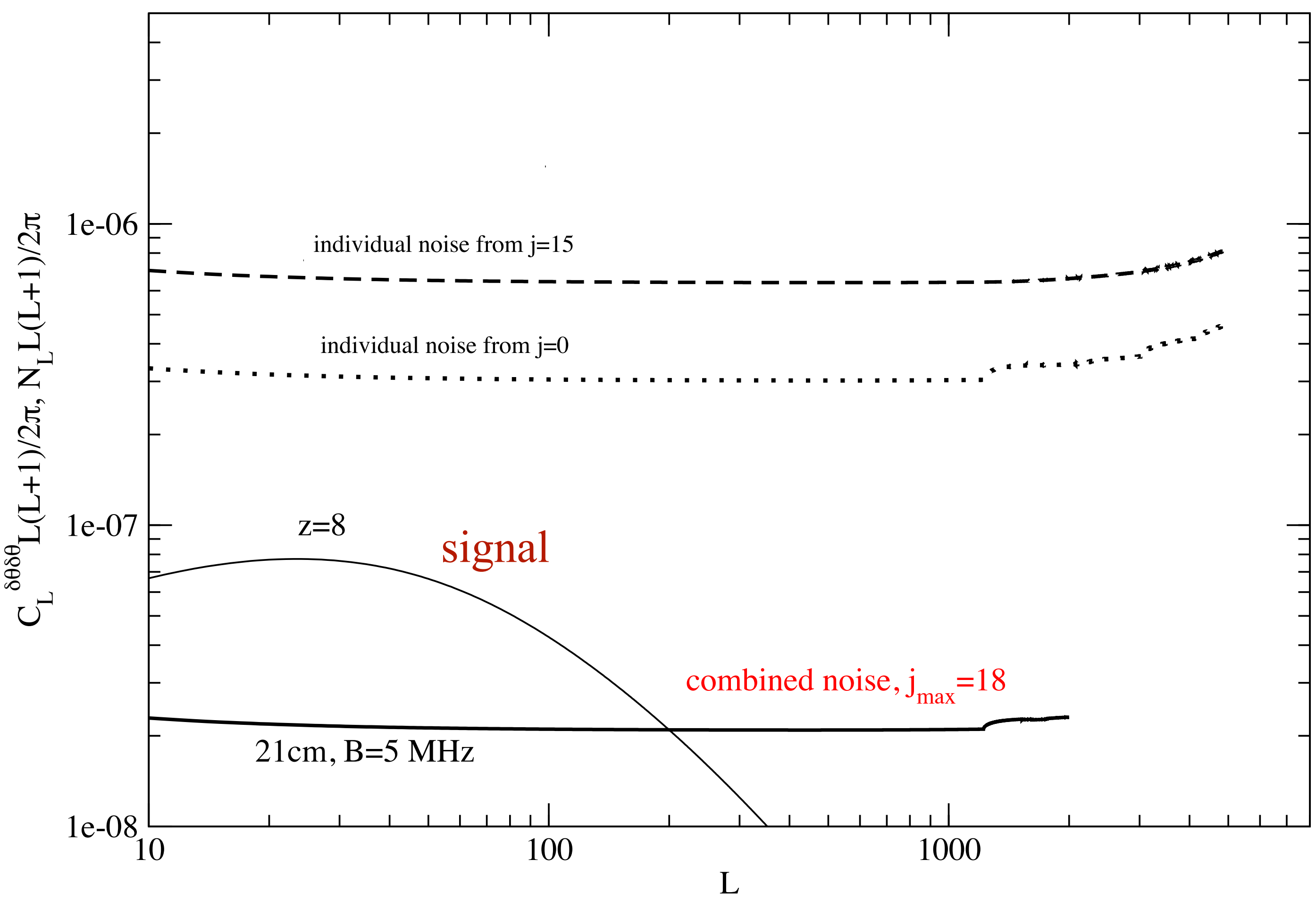
$f_{\mathrm{cover}} = \frac{A_{\mathrm{coll}}}{\pi(D_{\mathrm{tel}}/2)^2}$, $\ell_{\mathrm{max}} = \frac{2\pi D_{\mathrm{tel}}}{21(1+z)}$

$B = 5$ MHz

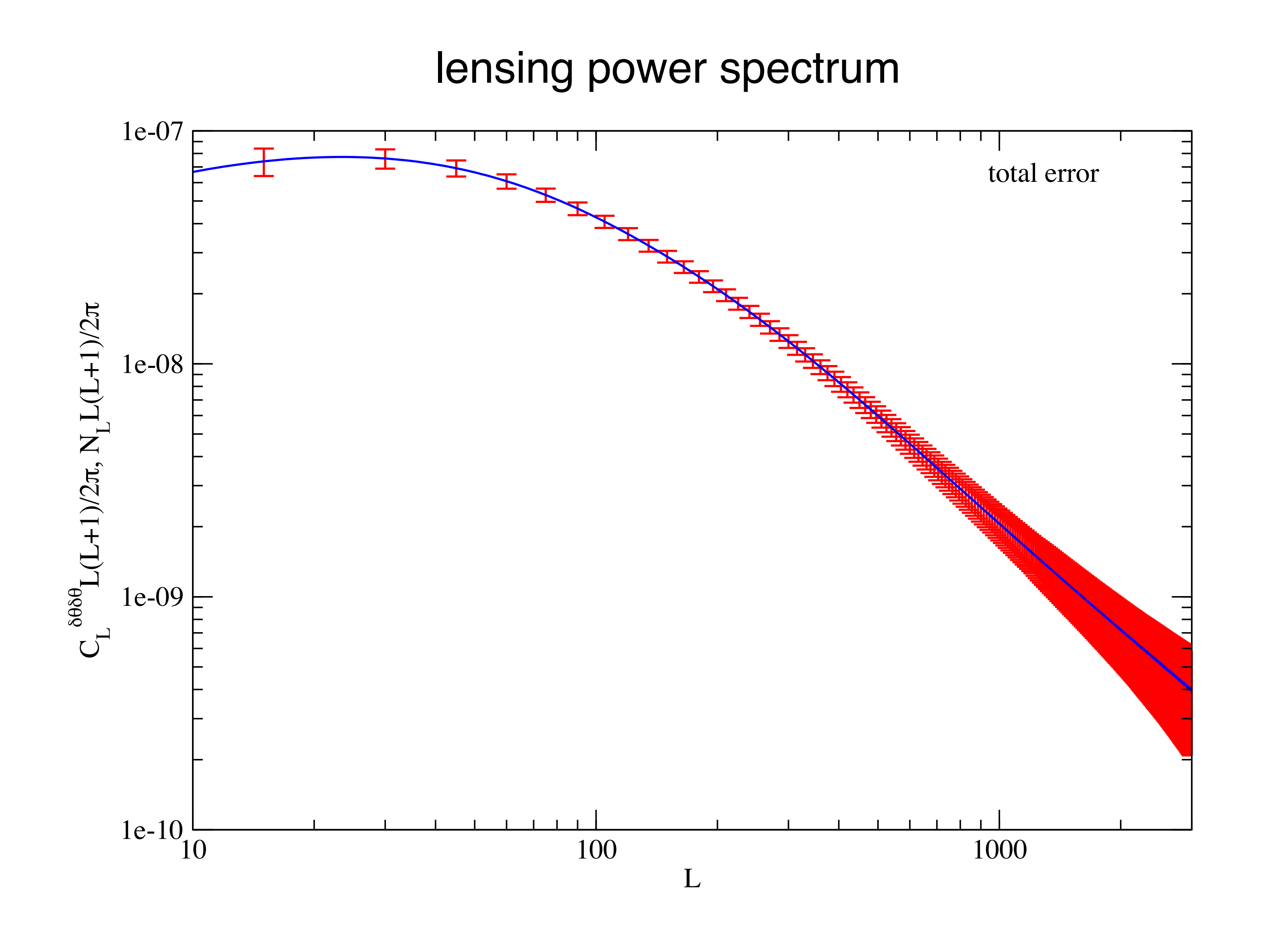
$T_{\mathrm{sys}} = 180\ \mathrm{K}\ (\nu/180\ \mathrm{MHz})^{-2.6}$ galactic synchrotron

3 months observation time

Results at z = 8 before reionization



Results at z = 8 before reionization



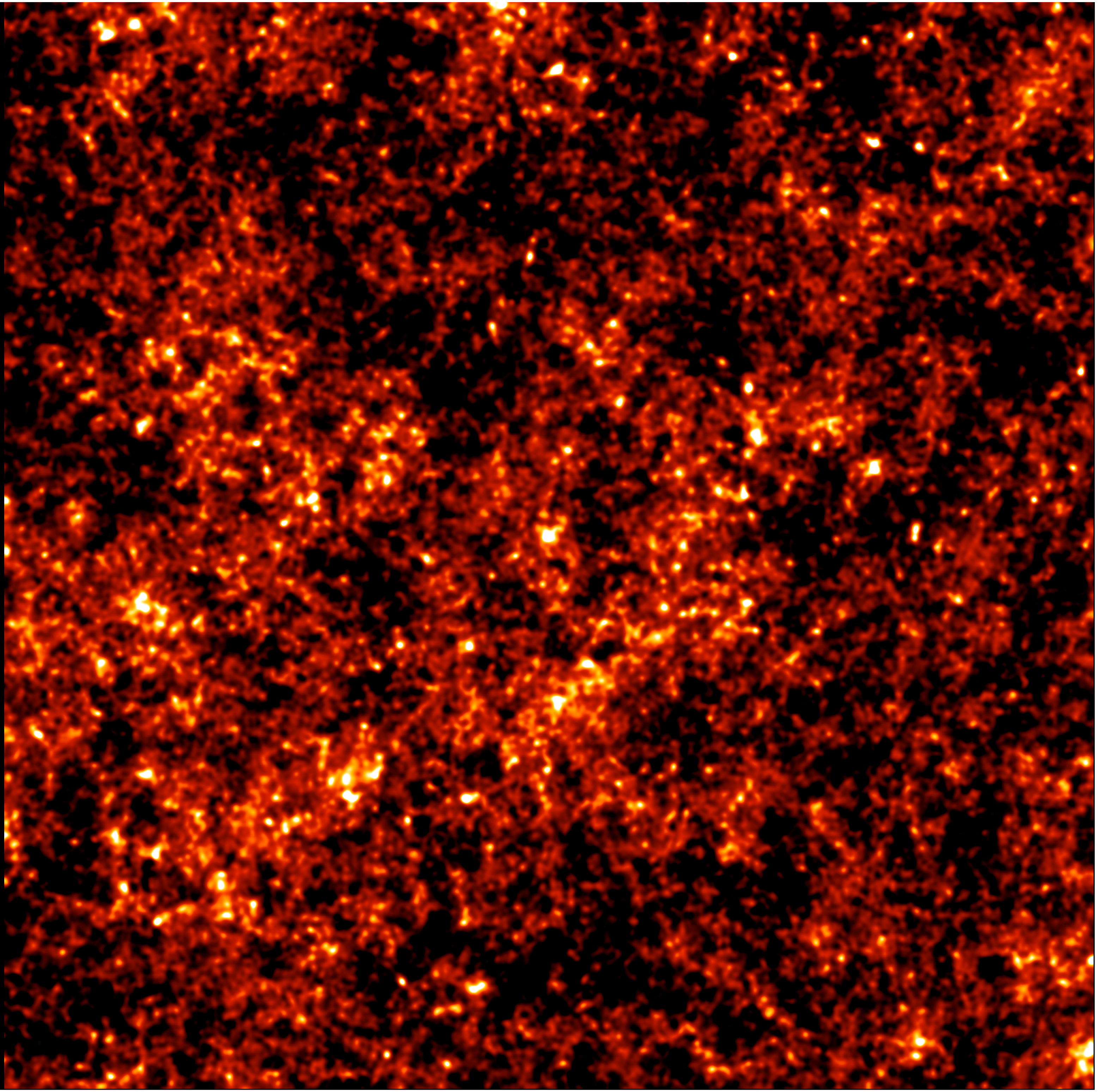
Metcalf & White, 2009

4 X 4 deg

Lensing through
The Millennium Simulation

21 cm Sources at z = 12
1′ pixels

Hilbert, Metcalf
& White (2008)



After Reionization

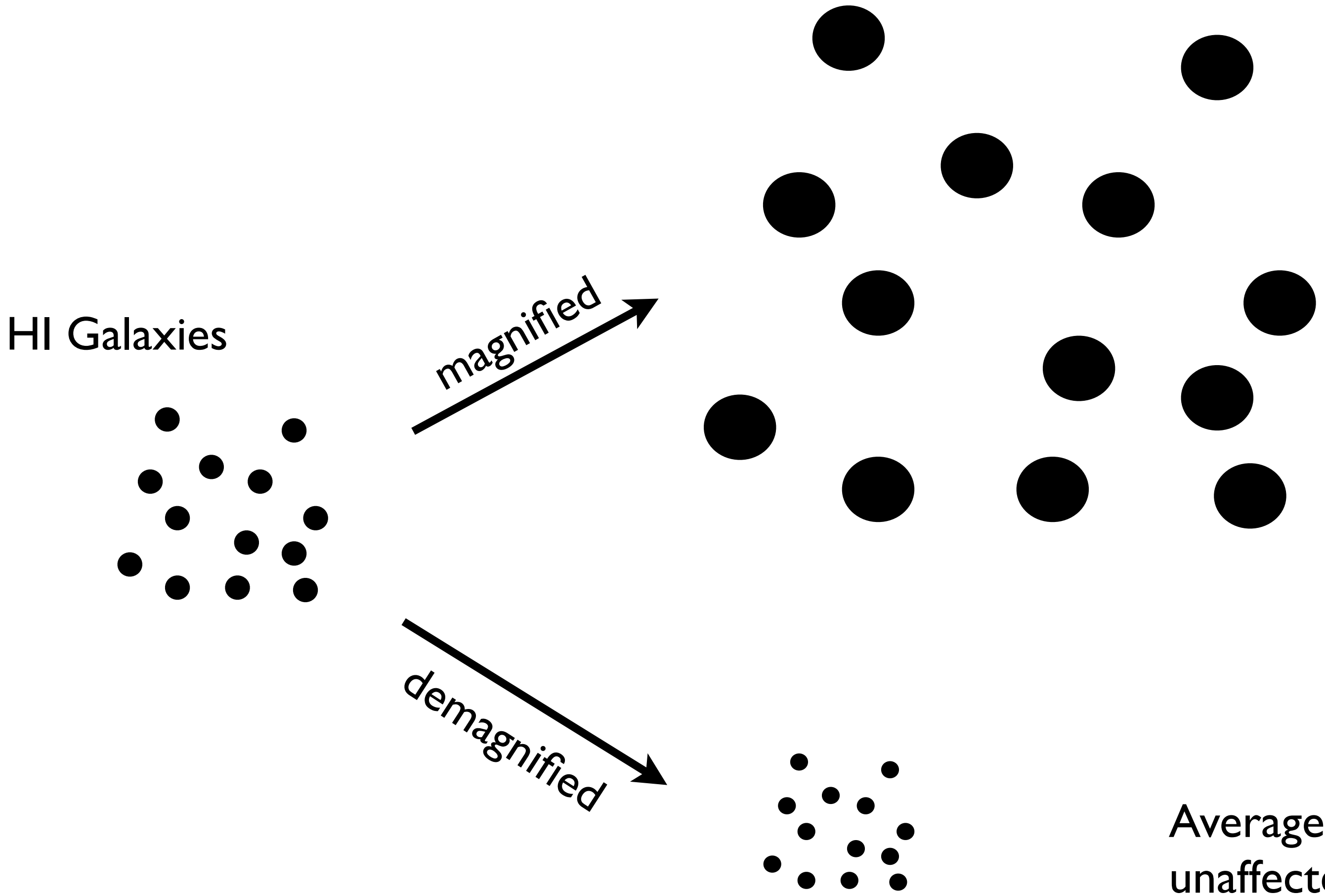
HI resides mostly in the galaxies.

Model the HI distribution as a Poisson distribution drawn from a Gaussian distribution representing the clustering of galaxies.

HI mass function is taken to be a Schechter function

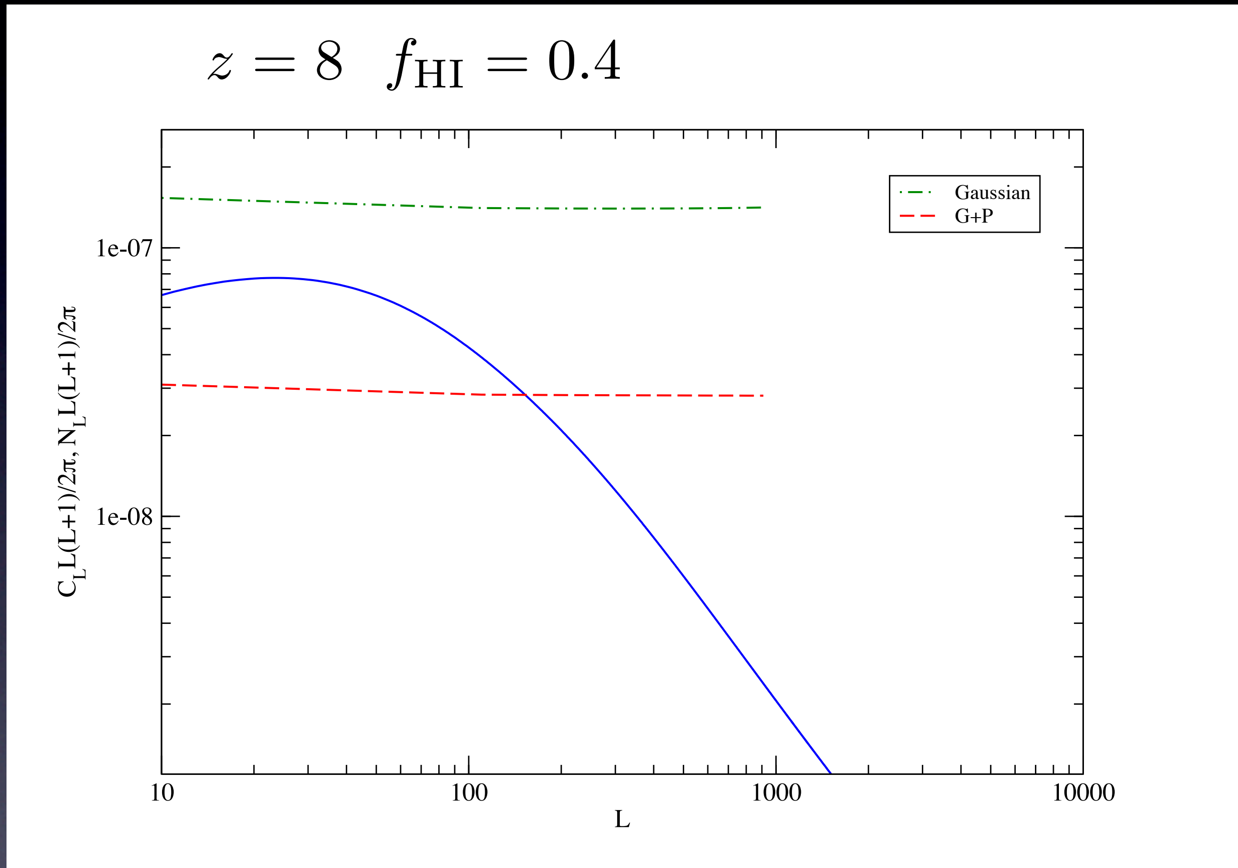
$$\frac{dn}{dM}dM = \phi^* \left(\frac{M}{M_*}\right)^\alpha \exp\left[-\frac{M}{M_*}\right]\frac{dM}{M_*}$$

(α, M_*, ϕ^*) Known in the local universe but not well constrained at high z



Average surface brightness is unaffected, but variance is changed.

After Reionization



Shot noise caused by the discreteness of the galaxies actually increases the signal-to-noise!

After Reionization $z = 2 \ (\nu = 473 \text{ MHz})$

No evolution in the HI fraction since z = 0

$$\alpha = -1.3, \ M_* = 3.47 \times 10^9 \, h^{-2} M_\circ, \ \phi^* = 0.0204 \, h^3 \, Mpc^{-3}$$

$f_{\rm HI} = 0.014$ HIPASS survey Zwaan et al. 2003

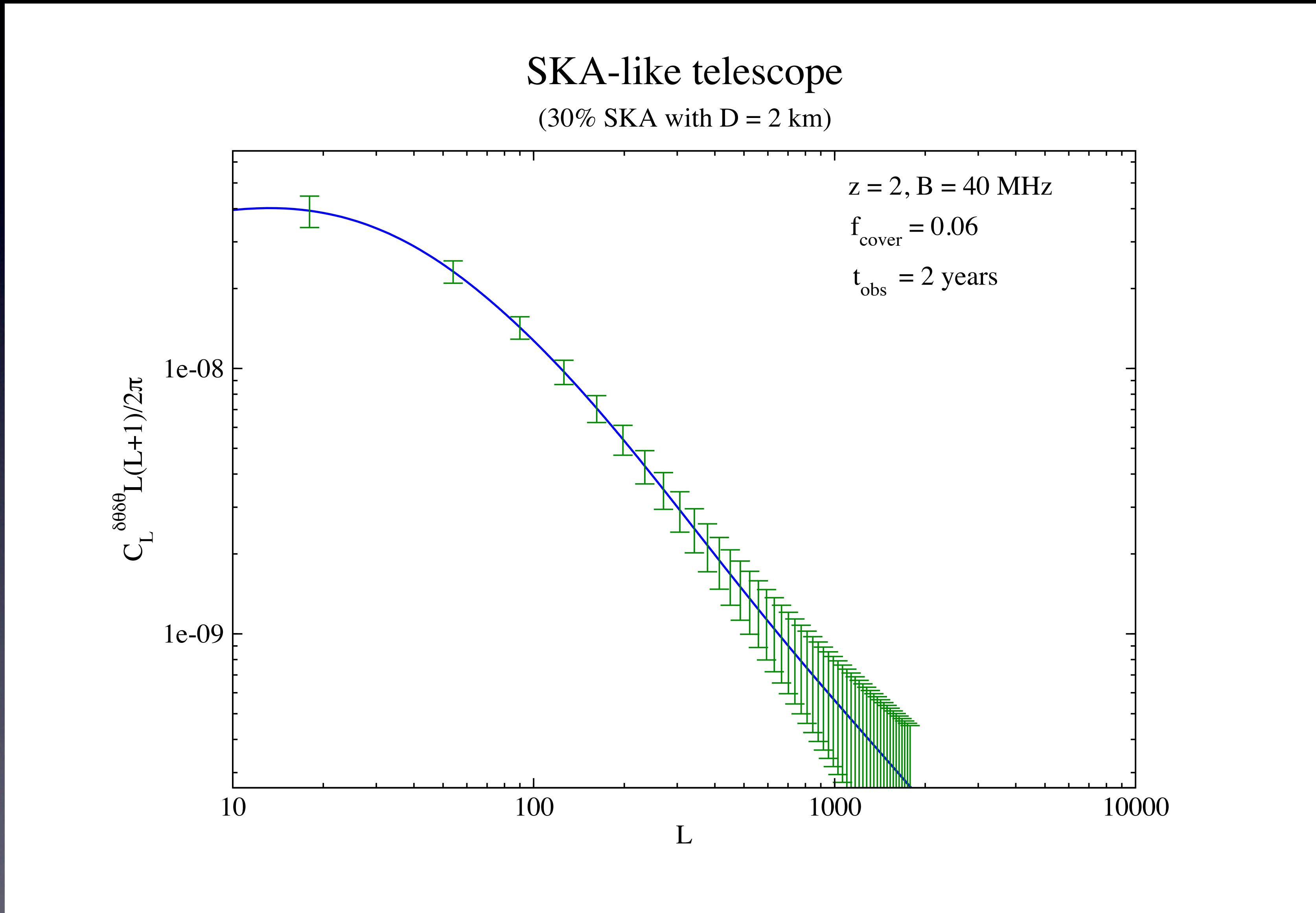
SKA - like telescope

collecting area $A_{coll} = 0.19 \text{ km}^2$ (30% of SKA)
maximum baseline $D_{max} = 2$ km
sky coverage $f_{\rm sky} = 0.2$

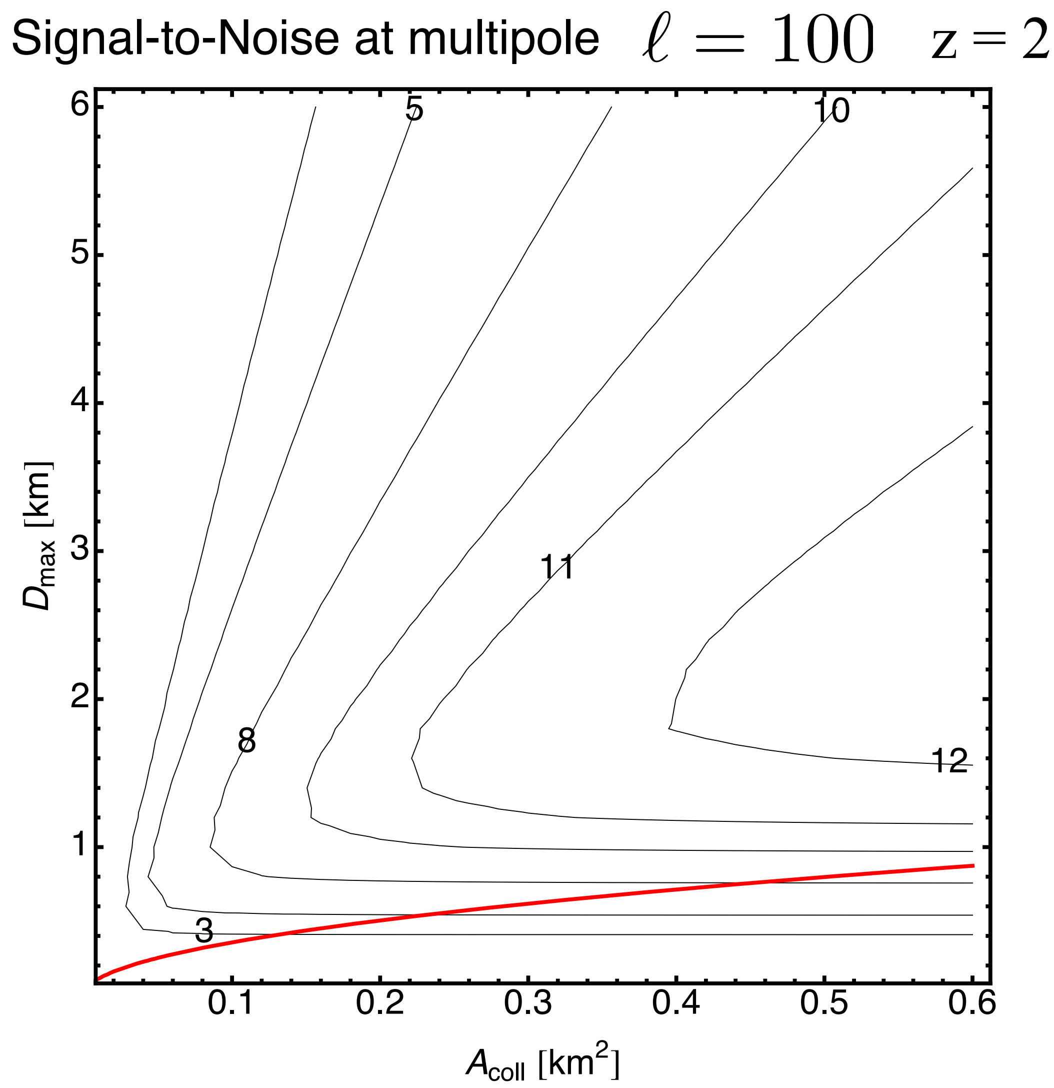
Noise system temperature $T_{\rm sys} = T_{\rm receiver} + T_{\rm synchrotron}$

At z ~ 3 the receiver noise becomes dominant.
We will take $T_{\rm sys} = 50$ K at z = 2.

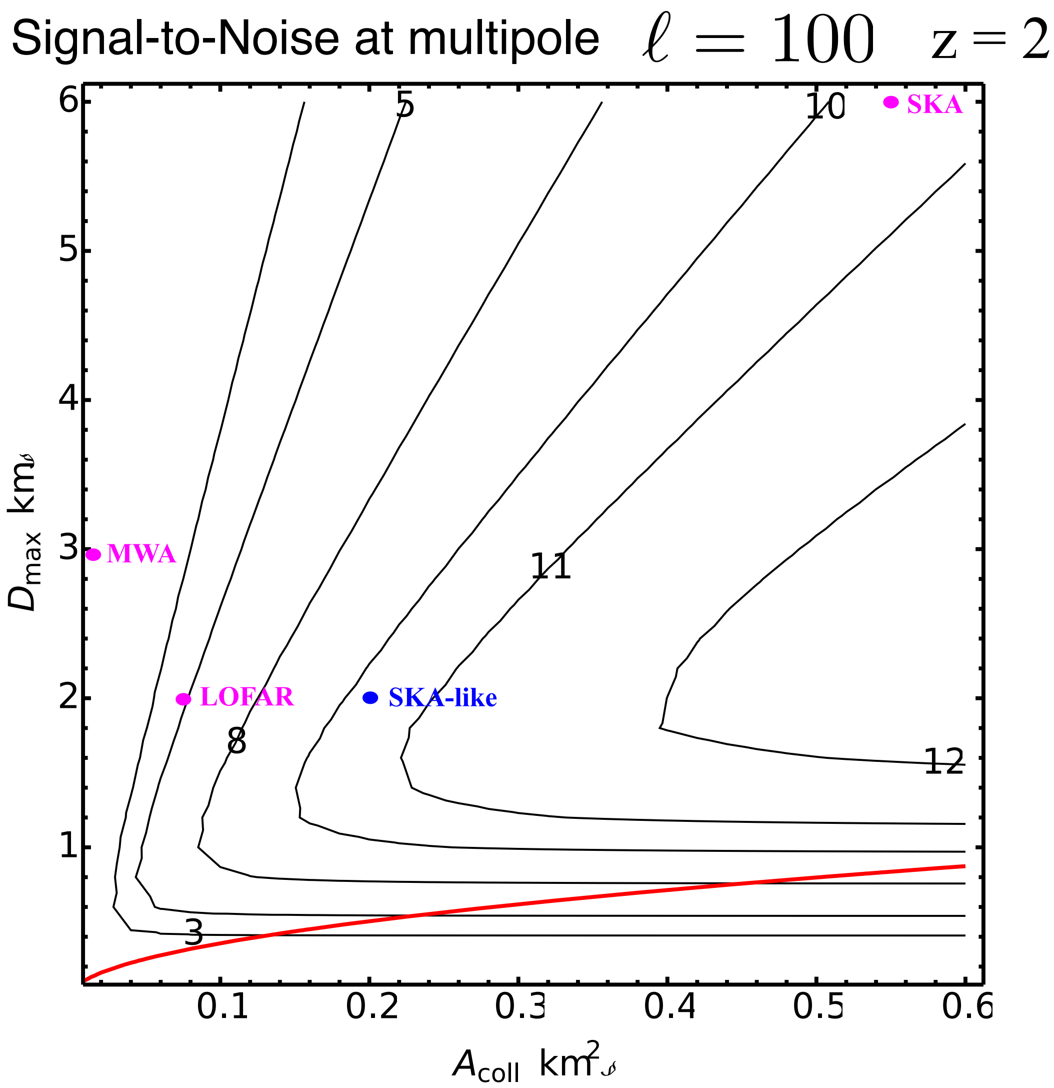
After Reionization $z = 2 \ (\nu = 473 \text{ MHz})$



After Reionization



After Reionization



But MWA and LOFAR are not at the right frequency for 21 cm at z = 2.

Conclusions

-- 21 cm intensity mapping could be used to measure gravitational lensing over a wide range of redshift.

-- This would extend weak lensing measurements to higher redshift than is accessible with conventional galaxy lensing surveys.

-- Early dark energy and modifications to gravity could require such a high redshift probe.

-- Cross correlations between galaxy lensing surveys and 21 cm lensing would increase the sensitivity to the equation of state at high redshift.

-- Shot noise from the discreteness of the galaxies contributes to both the noise and the signal in the lensing measurement - in most cases increasing the signal-to-noise.

-- This require telescope arrays with collecting areas ~ 0.1 km^2 spread over a region of diameter ~ 1 km.