The Gravitational Lensing of Pregalactic 21 cm Radiation

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Abstract

Low-frequency radio observations of neutral hydrogen during and before the epoch of cosmic reionization will provide ~ 1000 quasi-independent source planes, each of precisely known redshift, if a resolution of ~1 arcminutes or better can be attained. These planes can be used to reconstruct the projected mass distribution of foreground material. Significant power is expected down to sub-arcsecond scales. This structure can, in principle, be used to make mass images with a formal signal-to-noise per pixel exceeding 10, even for pixels as small as an arc-second. With an ideal telescope, both resolution and signal-to-noise can exceed those of even the most optimistic idealized mass maps from galaxy lensing by more than an order of magnitude. Individual dark halos similar in mass to that of the Milky Way could be imaged with high signal-to-noise out to z~10.

Even with a much less ambitious telescope, a wide-area survey of 21 cm lensing would provide very sensitive constraints on cosmological parameters, in particular on dark energy. These are up to 20 times tighter than the constraints obtainable from comparably sized, very deep surveys of galaxy lensing although the best constraints come from combining data of the two types. Any radio telescope capable of mapping the 21cm brightness temperature with good frequency resolution (~ 0.05 MHz) over a band of width > 10 MHz should be able to make mass maps of high quality. The planned Square Kilometer Array (SKA) should be capable of mapping the mass with a resolution of a few arcminutes depending on the reionization history of the universe and our success in subtracting foreground sources. The Low-Frequency Array (LOFAR) might be able to measure an accurate projected matter power spectrum.

Imaging Dark Matter

When low-frequency radio telescopes become sufficiently powerful to map the signal from high-redshift 21 cm emission/absorption within ~10 or more statistically independent bands, the data will necessarily be good enough to map the foreground mass distribution. The background of this poster shows what such a map would look like with a resolution similar to that of SKA. Objects as small as 2x10^{13} M$_{¤}$ would be clearly visible. This noise level is called the irreducible level because it is limited only by the number of statistically independent redshift slices of 21 cm emission that are mapped. The 21 cm emission is correlated at relevant level of below ~0.05 MHz on 1 arcmin scales so decreasing the bandwidth below this level produces no Improvement in the lensing noise.

In the near term the telescopes will not reach the irreducible noise limit because of noise and foreground subtraction. Figure 1 shows the estimated signal- to-noise for an SKA-like telescope after 90 days of observing when noise is added. Reasonably high fidelity maps should be possible with resolution of a few arc-minutes. Exceptional regions such as around large galaxy clusters would have higher fidelity down to smaller scales. It has been assumed for figure 1 that the universe very rapidly reionized at z=7 and that the frequency range of the observations goes down to ~0.1 GHz or z=13. Reionization could increase the signal or decrease it depending on how and when it occurs.

Increasing the collecting area of the telescope by a factor of two would reduce the noise to close to the irreducible limit. Increasing the resolution of the telescope would *reduce* the irreducible noise both because of the number of statistically independent redshift slices increases and because the number of independent patches on the sky increases. If a resolution of ~6 arcsec (fwhm) could be achieved, every halo more massive than the Milky Way's would be clearly visible back to z~10.

21 cm lensing surveys could be cross-correlated with any other survey of foreground objects including galaxy lensing surveys to get tomographic information. Images of the mass distribution through nearly the entire depth of the observable universe would be of enormous value for the study of cosmology and galaxy formation, and a very direct test for the existence of dark matter.

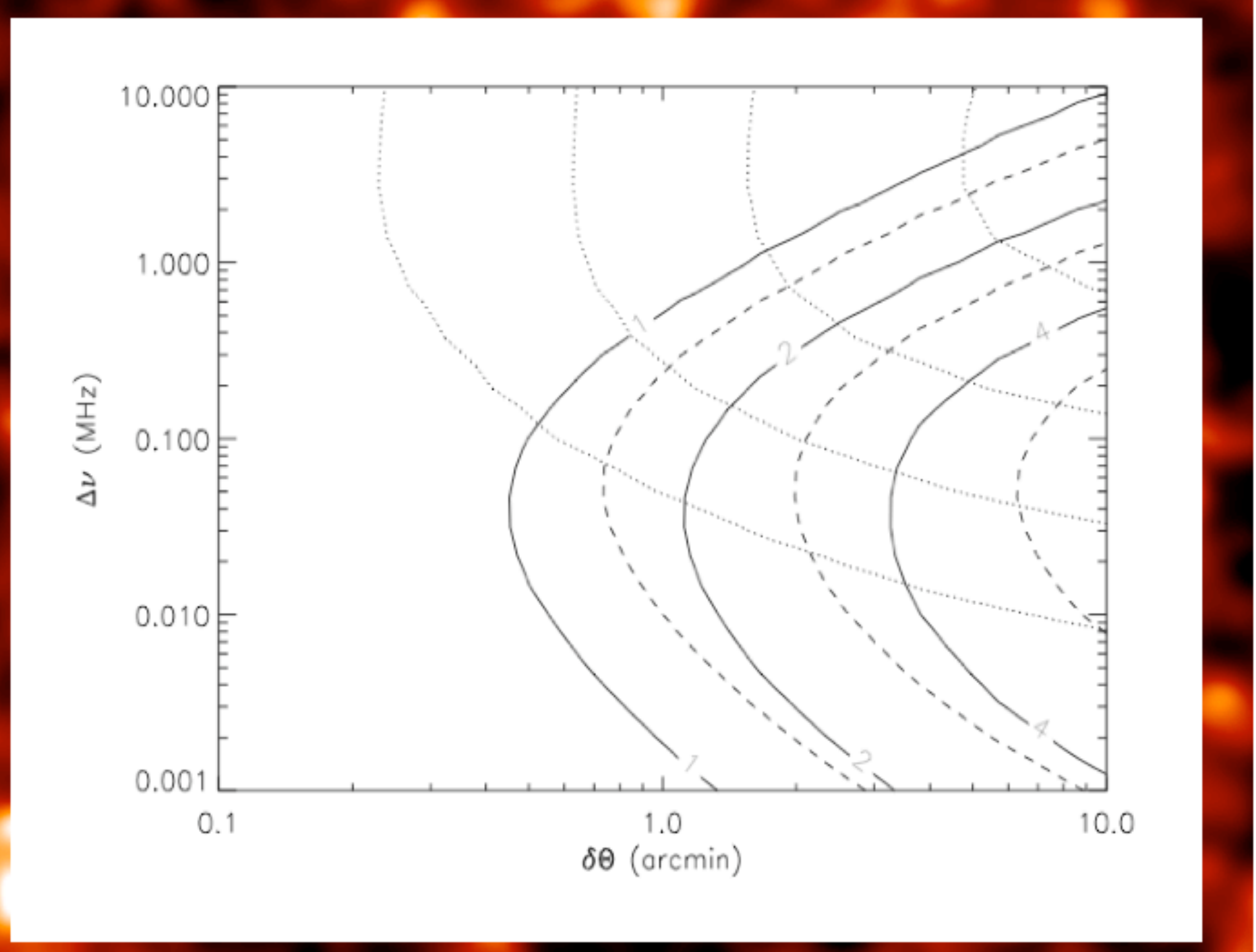


Figure 1. The signal to noise or fidelity of a convergence map $(\sigma_k/\sigma_{noise})$ for an SKA-like telescope after 90 days of observations. The horizontal axis is the radius of the smoothing kernel and the vertical is the bandwidth. The core array diameter is taken to be 6 km. The solid curve is for a collecting area that covers 0.025 of the total array area and dashed contours are for 0.018. You can see that there is an optimal bandwidth. The dotted contours are the signal-to-noise for fluctuations in the 21 cm brightness temperature within one band.

The system temperature is approximated T=180 K (ν/180 MHz)$^{-2.6}$ as appropriate for galactic synchrotron radiation in quite parts of the sky.

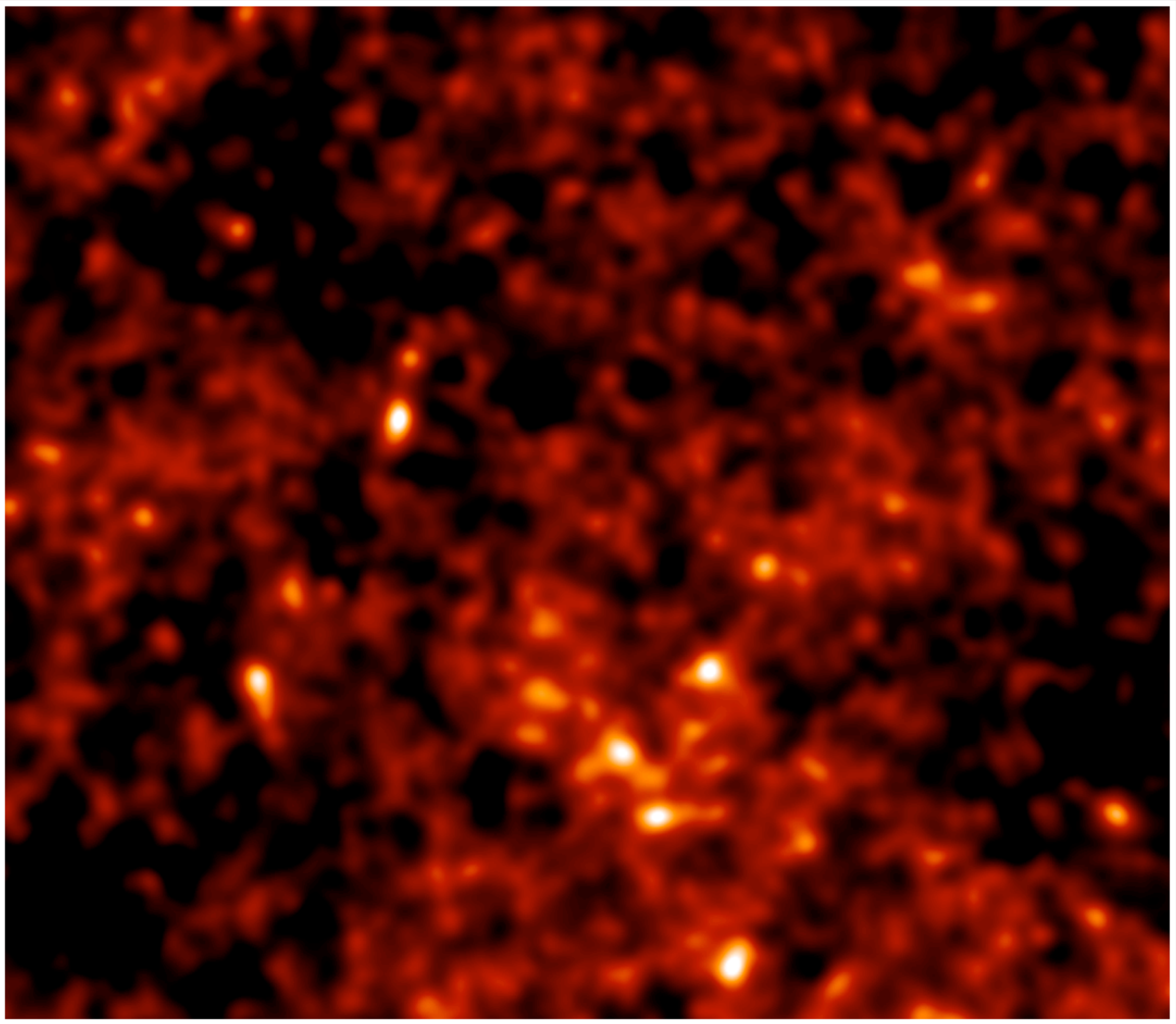


Figure 4. A small section of a simulated convergence map made by ray-shooting through the Millennium Simulation (Springel et al. 2005). The resolution is 1”. Noise at the irreducible level has been added. The whole poster is 4 degrees from top to bottom. The map has very high fidelity at the smallest resolved scales meaning that almost every feature represents real structures. Nearly as good a map might be possible with SKA.

Measuring Cosmological Parameters

21 cm lensing is capable of measuring the matter power spectrum and its evolution. Cross-correlating the convergence maps from 21 cm lensing at different redshifts and with galaxy lensing surveys provides information on the evolution of structure formation. Any cosmological parameters that affect the power spectrum and/or its evolution can be probed in this way. Dark energy is of particular interest and 21 cm lensing would provide a unique probe of its behavior at redshifts above 1 as well as substantially constricting the constraints on it below z=1.

For estimating cosmological parameters the requirements on resolution and frequency range are not as demanding as for imaging, but survey area is of greater importance. At the irreducible noise level the uncertainties in the cosmological parameters are dominated by sample variance if 10s of independent redshift slices are used. Even for SKA sample variance should be the most important source of error for multipole number l < 2000 ($l \sim \pi/\theta$ =1.08x10^4 arcmin / θ). This can be seen in figure 3. Where the noise is below the expected signal the sample variance will dominate the power spectrum measurement. The noise in the power spectrum estimate on these scales can only be reduced by increasing the area of the survey. For comparison, an ambitious galaxy lensing survey would reach the sample variance limit at l of a few hundred. For the proposed radio interferometer the survey area depends primarily on information storage and processing speed which should improve over time. The table shows some estimates of the constraints that might be possible and compares them to an idealized galaxy lensing survey.

The power spectrum of the projected mass density or convergence could also be measured. Estimates of the errors in these measurements are shown in figures 2 and 3.

$\sigma_{\Omega_m} \simeq 2\times10^{-4}$	$\sigma_{\Omega_m} \simeq 3.0\times10^{-3}$
$\sigma_{\Omega_\Lambda} \simeq 3\times10^{-4}$	$\sigma_{\Omega_\Lambda} \simeq 0.01$
$\sigma_{\Omega_b} \simeq 7\times10^{-4}$	$\sigma_{\Omega_b} \simeq 0.005$
$\sigma_w \simeq 0.003(0.0006)$	$\sigma_w \simeq 0.04(0.03)$
$\sigma_{w_a} \simeq 0.02$	$\sigma_{w_a} \simeq 0.09$
$\sigma_A \simeq 0.01A$	$\sigma_A \simeq 0.06A$
$\sigma_n \simeq 0.001$	$\sigma_n \simeq 0.01$
21 cm lensing + galaxy lensing survey	galaxy survey alone

Table of estimated constraints on some cosmological parameters. The parameters are in order: the matter density, the present density of dark energy, the density of baryons, the equation of state parameter at z=5 (pressure/energy density), the derivative of the equation of state parameter with respect to the expansion parameter, the normalization of the power spectrum and the logarithmic slope of the primordial power spectrum. All errors have been marginalized over the other parameters in this set. The galaxy survey has 35 galaxies per arc minute and covers the whole sky as is expected for the next generation of ground a space based surveys (LSST, PanSTARRS, DUNE, etc.). Tomographic information has been used. No photo-z errors are included. The 21 cm survey is for two redshift slices centered on z=10 and 15. All errors scale as the one over the square root of the fraction of the sky covered. The errors in parentheses are for the case of constant w (w_a=0).

Conclusions:

Cross-correlating several redshift slices with each other and with galaxy lensing surveys over a significant portion of the sky would begin a new era of very high precision cosmology.

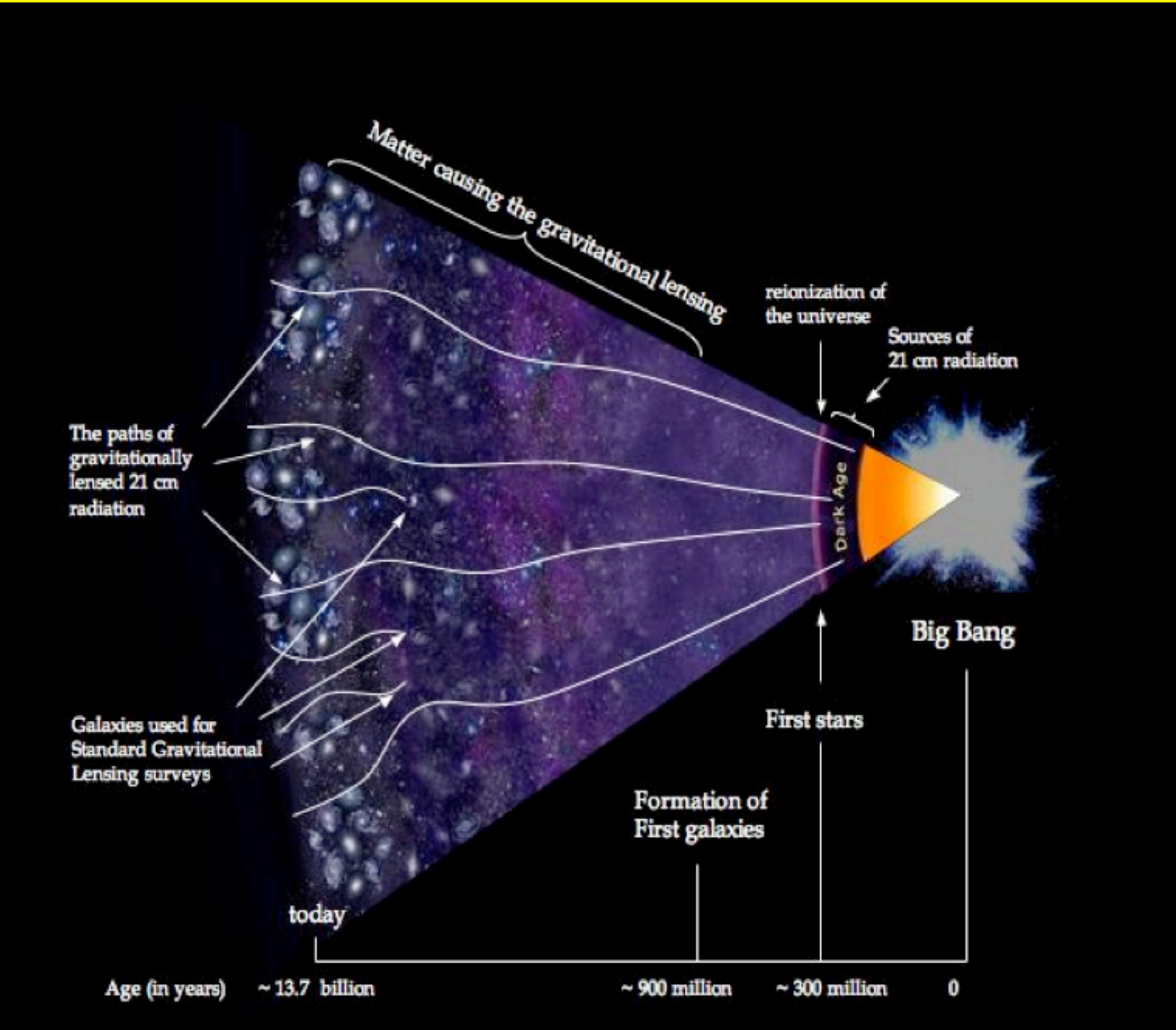
Much will depend on future instrument design and the as yet unknown characteristics of the 21 cm absorption and emission, particularly around the epoch of reionization. If reionization happens unexpectedly early there may not be a large enough range of redshift within the observed frequency range. Despite this, the planned specifications for SKA might enable it to make high fidelity maps of the matter distribution and if enough area can be surveyed very good statistical information might be possible. Realistic upgrades to the collecting area and array size would greatly improve its sensitivity to lensing.

Further Reading:

Metcalf, R.B. & White, S.D.M., 2006, accepted for publication in MNRAS, astro-ph//0611862

Hilbert, S., Metcalf, R.B. & White, S.D.M., 2007, astro-ph/0703337

Metcalf, R.B. & White, S.D.M., 2007, in preparation.



Schematic diagram showing the history of the universe. The pregalactic 21 cm radiation originates from a period when most of the hydrogen in the universe was neutral before most of the galaxies formed and emitted ionizing radiation. This is often called the dark ages. At z~1100 the universe cooled to the extent where nearly all of the hydrogen became neutral. We know this from the spectrum of the CMB. Some time between z=6.5 and z=30 most of the hydrogen in the universe reionized. We know this from quasar spectra. The 21 cm line comes from the hyperfine splitting of the ground state of hydrogen (coupling between the spin of the electron and proton). It is redshifted to several meters when it reaches us.

The path length for lensing greatly exceeds that for galaxies making the expected signal ~ 3.3 times larger on 1 acminute scales and because of the many independent regions of 21 cm emission the statistical errors can be much smaller then those for galaxy lensing.

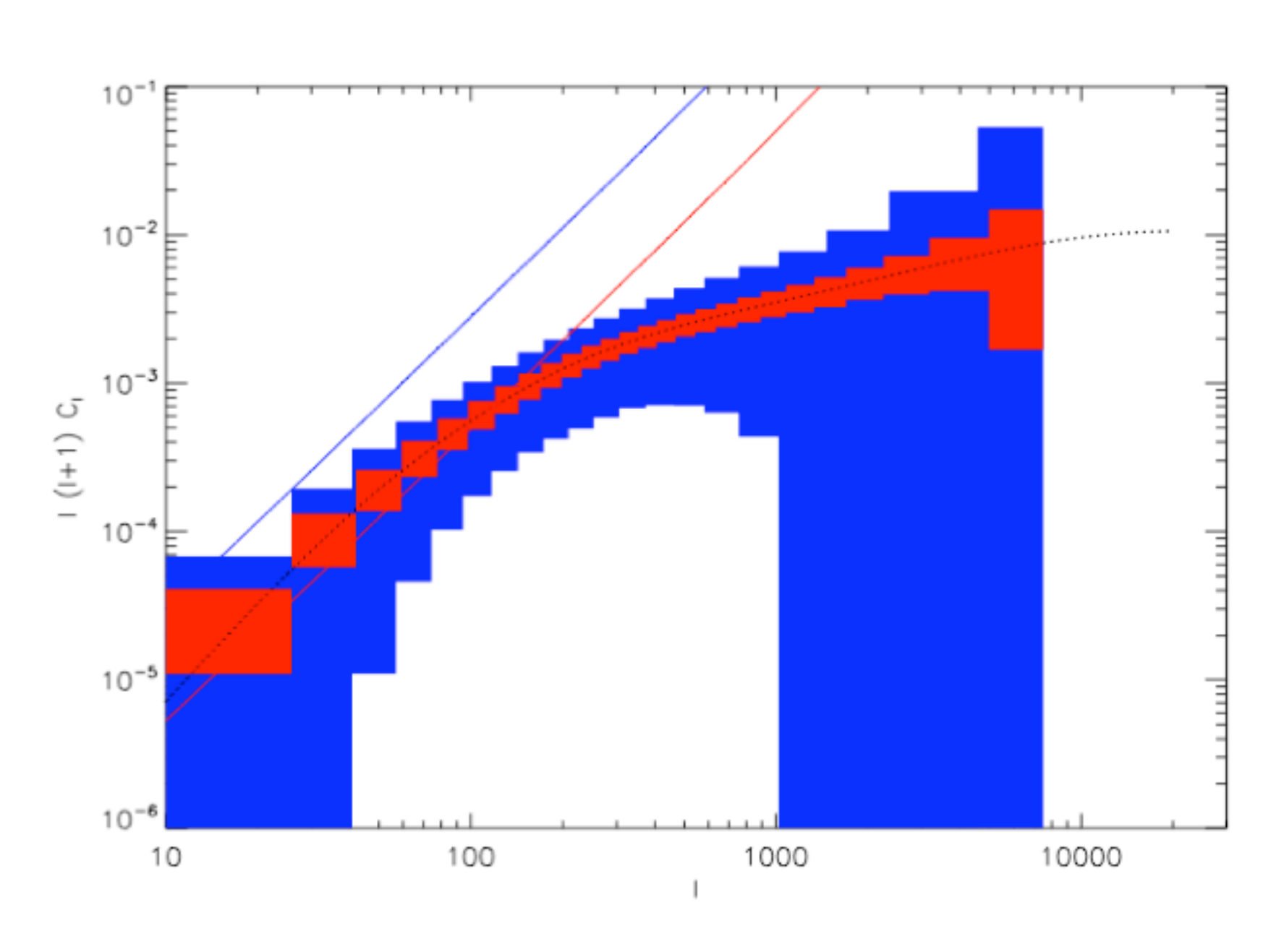


Figure 2. The 1 s errors on the convergence (~ projected density) power spectrum for a telescope like the core of LOFAR after 30 days (blue) and 90 days (red) of observing. The solid colored curves are the noise per mode. It is assumed that 10% of the sky is observed (the noise scales as fsky-1/2.). The dotted curve is the expected power spectrum. The bins are much larger than the l-space resolution and uncorrelated. Where the noise per mode curve is below the signal curve cosmic variance will dominate and mapping with some fidelity will be possible. As seen here, mapping is unlikely for LOFAR. (The core telescope diameter is 2 km, the collecting area is 1.6% of the array areas and reionization happens instantaneously at z=7.)

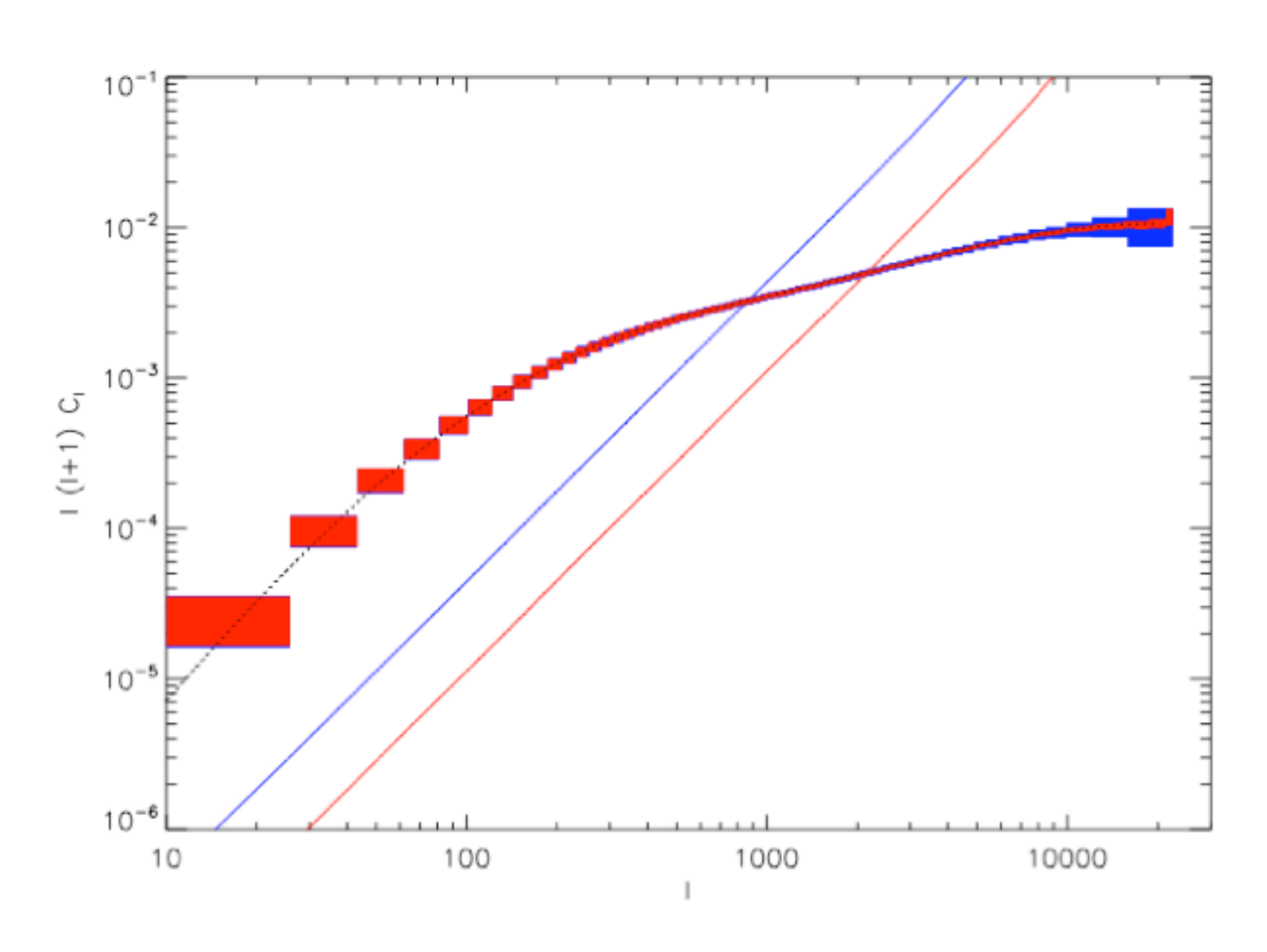


Figure 3. The same as in figure 2 only for the core of an SKA-like telescope. Here cosmic variance dominates and imaging will be possible for l <~ 2500 or q >~ 4.3 arcmin in agreement with figure 1. The binning in l is a matter of choice. Wider bins would give smaller errors, but less l-space resolution (scales like Dl-1/2).