UTAP/RESCEU seminar 2012/02/02 Toshiya Namikawa

"Cosmology at low frequencies: The 21 cm transition and the high redshift Universe"

[Abstract]
In this seminar, I review about the Cosmology with the fluctuations of 21cm brightness temperature. I will also show the weak lensing effect on the 21-cm fluctuations.

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[Historical overview] S. Furlanetto et al, 2006

- At the 2nd World War --- van de Hulst calculated the photon's energy emitted by the hyper fine transition of hydrogen atom.
- 1951 --- 21cm line was detected by several groups. Then, the neutral hydrogen map in Galaxy was made and Galaxy was found to be a spiral galaxy.
- 1980s-90s ---- Several projects tried to detect the neutral hydrogen gas at z~3 which was predicted by the "Top-down scenario", but all of them could not have detected.
- Todays --- Observation of 21 cm line is considered as a probe of reionization history, interactions between galaxies and galactic intermedium and cosmology.

➢ 21cm brightness temperature

$$\delta T_b(\vec{r},z) \simeq \frac{3c^3\hbar A_{21}}{16\nu_0^2 k_B}\frac{[1-x_i(\vec{r},z)]n_p(\vec{r},z)}{(1+z)H(z)}\left[1-\frac{T_{CMB}(\vec{r},z)}{T_S(\vec{r},z)}\right]\left[1-\frac{1+z}{H(z)}\frac{dV_r}{dr}(\vec{r},z)\right]$$

➢ Fluctuations of 21cm brightness temperature

1) $\delta_{HI} \ll 1$

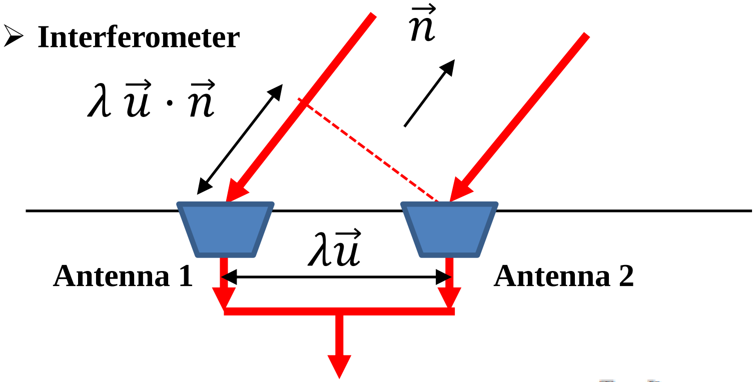
$$\delta_{21} \simeq -\delta_i + \delta_p + \frac{1}{\bar{T}_s - \bar{T}_{CMB}}(\bar{T}_s\delta T_s - \bar{T}_{CMB}\delta T_{CMB}) - \delta v$$

2) $\delta_{HI} \ll 1$ and $T_s \gg T_{CMB}$

$$\delta_{21} \simeq -\delta_i + \delta_p - \delta v$$

Observation of 21 cm line

➢ **Interferometer**



[FIG.3] CG image of interferometer. SKA will start to observe 21 cm line from 2016, with a few thousand of a few ten meter antenna located inside the area with 100,000 m^2

http://www.skatelescope.org/

TABLE 1

The Parameters that We Adopt for MWA, LOFAR, and SKA

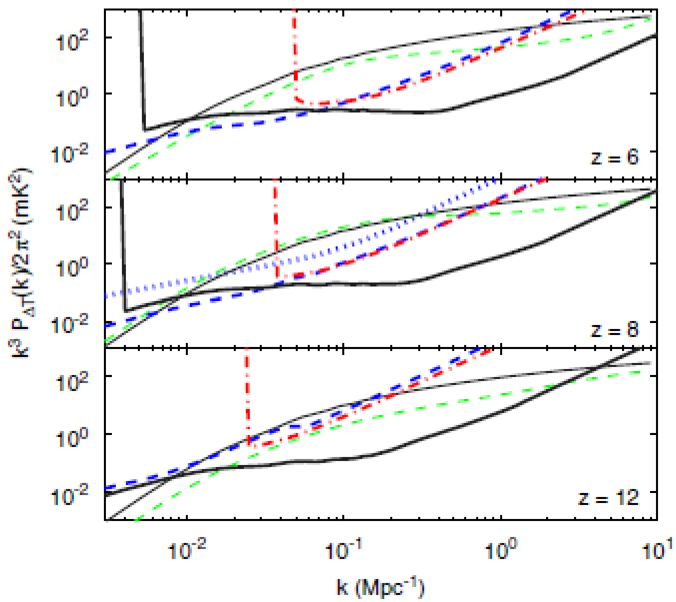
Array	N_{ant}	$N_{ant} A_e$ (m^2) $z = 6$	$z = 8$	$z = 12$	FOV (deg^2 at $z = 8$)	S_{cut}[a] (μJy)	Minimum Baseline (m)	Cost (10^6 dollars)
MWA	500	4500	7000	9000	$\pi 16^2$	180	4	~10
LOFAR	64	3.5×10^4	4.2×10^4	7.2×10^4	$4 \times \pi 2.0^2$	30	100	~100
SKA[a]	5000	3.6×10^5	6.0×10^5	12.5×10^5	$\pi 5.6^2$	2	10	~1000

➢ **Observable**

$$S(\vec{K}) = \int d^3X \; A(\vec{X}) \delta T_b(\vec{X}) \exp[-2\pi i \, \vec{K} \cdot \vec{X}]$$

➢ **Detector Noise**

$$N(\vec{X}) = \frac{\lambda^2 T_{sys}}{A\sqrt{\Delta\nu \, N_b(\vec{u}) t(\vec{u})}}$$



[FIG.1] Signal and Noise power spectrum.

M. McQuinn et al, 2006

Cosmological implications from 21 cm observations

M. McQuinn et al, 2006

TABLE 2

Errors on Cosmological Parameter Estimates When Density Fluctuations Dominate the 21 cm Signal

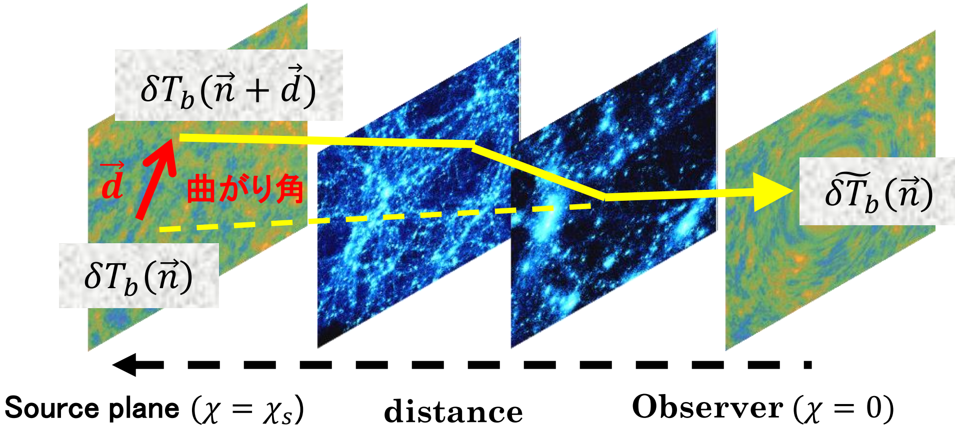
Interferometer	Parameters τ	Ω_w	w	$\Omega_m h^2$	$\Omega_b h^2$	n_s	$\delta_H \times 10^5$[a]	α_s	Ω_ν	$\bar{x}_{\rm H}$
Assumed value	0.1	0.7	−1.0	0.14	0.022	1.0	3.91	0.0	0.0	1.0
LOFAR	...	0.07	...	0.11	0.03	0.11	5.0	...	...	...
MWA	...	0.06	...	0.09	0.02	0.09	4.2	...	...	...
MWA5000	...	0.005	...	0.008	0.002	0.03	0.37	0.010	0.007	...
SKA	...	0.005	...	0.009	0.002	0.06	0.51	0.016	0.015	...
CCMB	0.060	0.084	...	0.017	0.0014	0.072	0.29	0.039	0.12	...
CCMB + LOFAR	0.057	0.050	...	0.010	0.0012	0.027	0.22	0.022	0.02	0.2
CCMB + MWA	0.056	0.046	...	0.009	0.0011	0.021	0.22	0.022	0.02	0.2
CCMB + MWA5000	0.048	0.005	...	0.003	0.0009	0.013	0.18	0.005	0.004	0.06
CCMB + SKA	0.048	0.005	...	0.003	0.0009	0.014	0.18	0.005	0.007	0.06
Planck	0.0050	0.029	0.09	0.0023	0.00018	0.0047	0.026	0.008	0.010	...
Planck + MWA5000	0.0046	0.017	0.06	0.0009	0.00012	0.0033	0.018	0.003	0.003	0.03
Planck + SKA	0.0046	0.021	0.08	0.0008	0.00012	0.0034	0.018	0.003	0.004	0.04

TABLE 4

Errors on Cosmological Parameter Estimates from 21 cm Observations When Only P_{μ^4} and P_{μ^6} Are Not Contaminated by Bubbles

Interferometer	Parameters τ	Ω_Λ	$\Omega_m h^2$	$\Omega_b h^2$	n_s	$\delta_H \times 10^5$	α_s	Ω_ν	$\bar{x}_{\rm H}$ $(z = 8)$
Assumed value	0.1	0.7	0.14	0.022	1.0	3.9	0.0	0.0	0.8
CCMB	0.060	0.084	0.017	0.0014	0.07	0.3	0.039	0.12	...
CCMB + MWA5000	0.058	0.066	0.011	0.0012	0.05	0.2	0.033	0.05	0.3
CCMB + SKA	0.057	0.062	0.011	0.0012	0.04	0.2	0.028	0.04	0.3
Planck	0.005	0.011	0.0023	0.00017	0.0047	0.03	0.007	0.010	...
Planck + MWA5000	0.005	0.011	0.0022	0.00017	0.0047	0.03	0.007	0.010	0.07
Planck + SKA	0.005	0.011	0.0022	0.00017	0.0047	0.03	0.007	0.010	0.07
Planck + MWA50K	0.005	0.010	0.0020	0.00017	0.0047	0.03	0.007	0.009	0.06

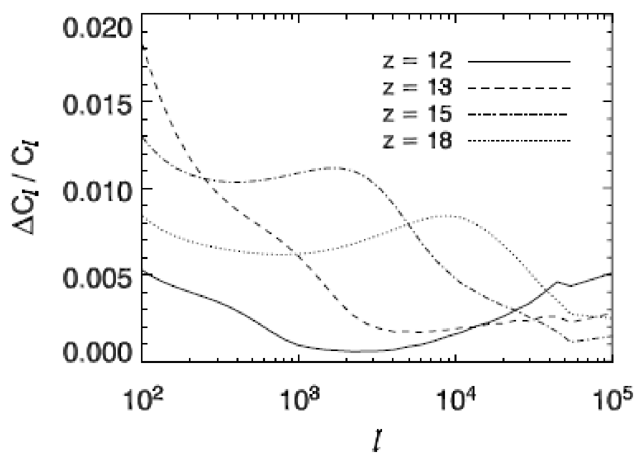
- **Lensing effect**

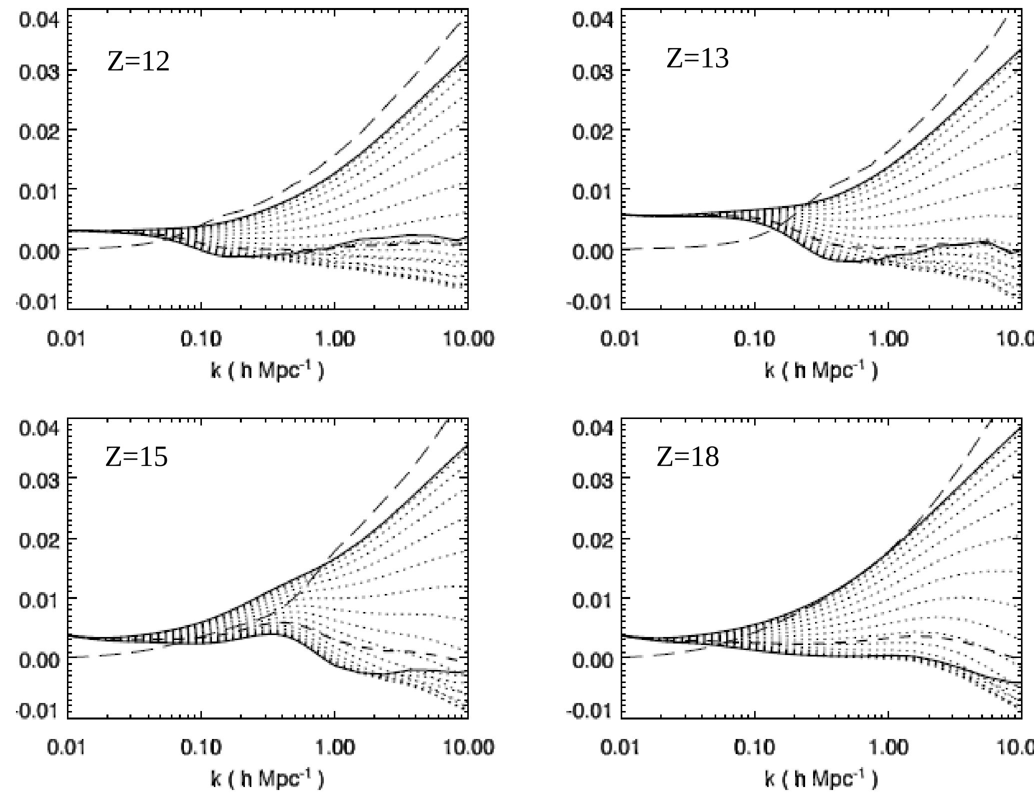


$$\widetilde{\delta T_b}(\vec{n}) = \delta T_b\left(\vec{n} + \vec{d}(\vec{n})\right)$$

$$= \delta T_b(\vec{n}) + \vec{d}(\vec{n}) \cdot \nabla \delta T_b(\vec{n}) + O(|d|^2)$$

$$\nabla\left(-2\int_0^{\chi_s} d\chi \frac{\chi_s - \chi}{\chi \chi_s} \underbrace{\psi(\eta_0 - \chi, \chi\vec{n})}_{\text{Gravitational potential}}\right)$$





[FIG.2] Lensing effect on angular power spectrum and 3D power spectrum.

K. Mandel & M. Zaldarriaga, 2006

Lensing reconstruction

O. Zhan & M. Zaldarriaga, 2006

- **Quadratic estimator**

$$N_L = \frac{1}{\sum_k N_{L,k}}$$

$$N_{L,k} = \int \frac{d^2\vec{\ell}}{(2\pi)^2}\left[\frac{C_\ell(k)\,\vec{L}\cdot\vec{\ell} + C_{|L-\ell|}(k)\,\vec{L}\cdot(\vec{L}-\vec{\ell})}{2C_\ell^{tot}(k)C_{|L-\ell|}^{tot}(k)}\right]^2$$

$$C_L(k) = \left(1+\mu_k^2\right)^2 \frac{P\left(\sqrt{(L/D_A)^2 + \left(k_j\right)^2}\right)}{D_A^2\Delta_{k\,j}}$$

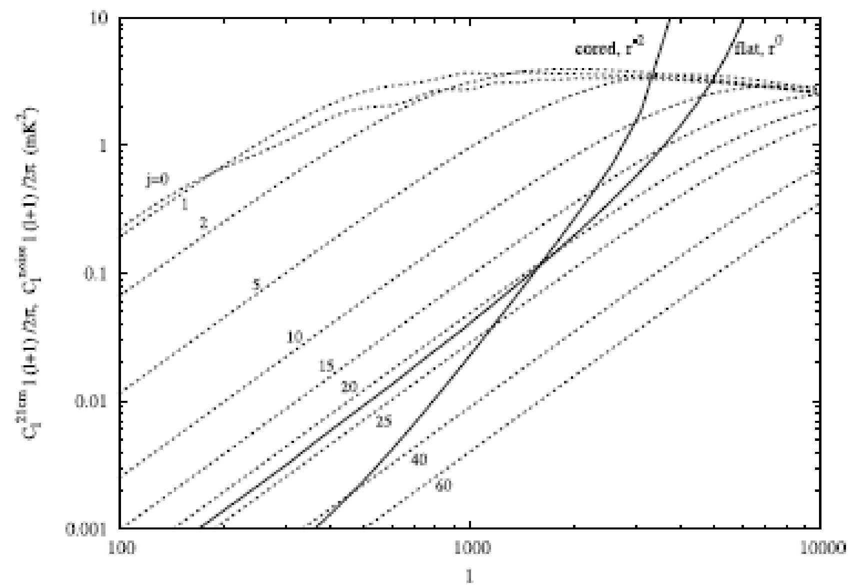


FIG. 3.— Dotted lines show the angular power spectrum for different $k_{\|,j} = j2\pi L^{-1}$, labeled by j. Going to higher values of j, the signal decays quickly below S/N = 1 and only the first 15 or so modes contribute to the final lensing estimator. This number depends of course on the thickness of the redshift interval probed (in this case $B = 5$ MHz, corresponding to $\Delta z = 0.286$ at $z = 8$). The thick and thin solid curves are for a flat and a cored antenna configuration of SKA, respectively (see the text).

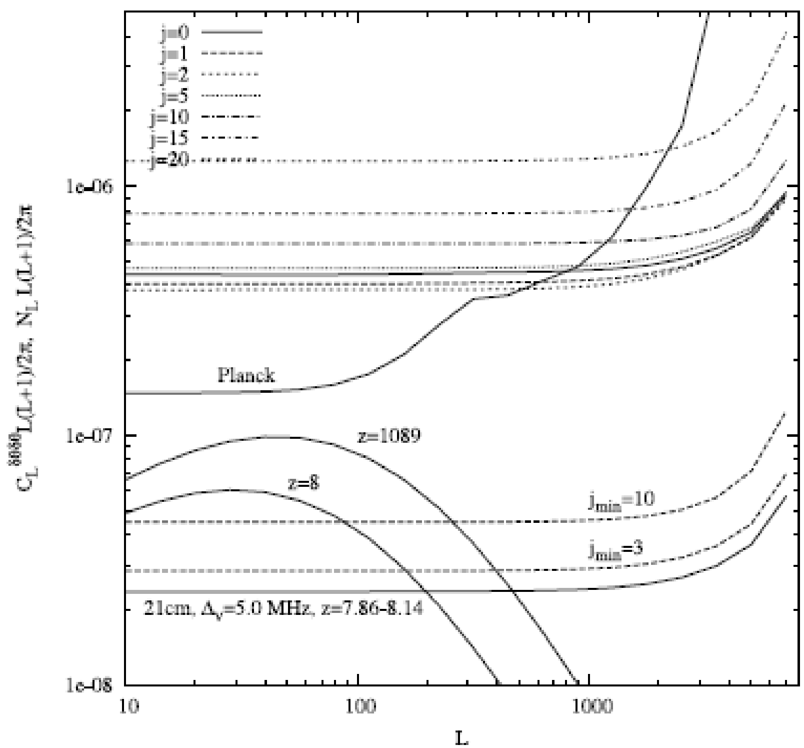


FIG. 4.— Lensing reconstruction noise N_L for one redshift interval centered at $z = 8$ corresponding to a bandwidth of 5 MHz. The curves labeled "$z = 8$" and "$z = 1089$" are the displacement field power spectra for 21 cm and CMB as source respectively. The thick solid curves labeled "*Planck*" and "21 cm" are the lensing reconstruction noises we find. The 21 cm noise is based on combining all $k_\|$ modes. The thin lines labeled "$j = $ 0-20" on the other side are the results for individual $k_\|$ modes. We see that from this redshift range alone the combined temperature and polarization information of *Planck* can be beaten. The necessity to substract foregrounds lessens the constraint from 21 cm somewhat. They effectively render the first few $k_\|$ modes useless for the reconstruction, see the text. The resulting noise levels are shown in the thick dashed curves labeled $j_{min} = 3$ and 10, for a less and more conservative assumption about the complexity of foreground contamination, respectively.

References

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