FERMILAB-PUB-10-373-A-T

Confirmation of the Copernican principle at Gpc radial scale and above from the kinetic Sunyaev Zel'dovich effect power spectrum

Pengjie Zhang[1] and Albert Stebbins[2]

[1]*Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Nandan Road 80, Shanghai, 200030, China; pjzhang@shao.ac.cn*

[2]*Fermilab Theoretical Astrophysics, Box 500, Batavia, IL 60510; stebbins@fnal.gov*

The Copernican principle, a cornerstone of modern cosmology, remains largely unproven at Gpc radial scale and above. Violations of this type will inevitably cause a first order anisotropic kinetic Sunyaev Zel'dovich (kSZ) effect. Here we show that, if large scale radial inhomogeneities have amplitude large enough to explain the "dark energy" phenomena, the induced kSZ power spectrum will be orders of magnitude larger than the ACT/SPT upper limit. This single test rules out the void model as a viable alternative to dark energy to explain the apparent cosmic acceleration, confirms the Copernican principle on Gpc radial scale and above and closes a loophole in the standard cosmology.

PACS numbers: 98.80.-k; 98.80.Es; 98.80.Bp; 95.36.+x

Introduction.—The Copernican principle has been a fundamental tenet of modern science since the 16^{th} century and is also a cornerstone of modern cosmology. It states that there should be no special regions in the universe and hence our universe should be homogeneous at sufficiently large scales. Cosmic microwave background (CMB) observations verify the statistical homogeneity in angle on our celestial sphere [1]. Galaxy surveys verify the radial homogeneity up to the Gpc scale [2]. However, radial homogeneity at larger scales remains unproven.

Testing the Copernican principle is of crucial importance for fundamental cosmology. If the Copernican principle is violated such that we live in or near the center of a large void as described by a Lematre-Tolman-Bondi (LTB) space-time [3] in which the matter distribution is spherically symmetric, the apparent cosmic acceleration [4, 5] can be explained without cosmological constant, dark energy or modifications of general relativity [6]. Various tests of the Copernican principle have been proposed [7–12] and joint analysis has been performed (e.g. [13]). Here we propose a powerful single test which confirms the Copernican principle at Gpc scales and above.

The kSZ test.— A generic consequence of violating the Copernican principle is that some regions will expand faster or slower than others and as photons transit between these regions there will be a relative motion between the matter comoving frame[1] and CMB. When relative motions between free electrons and photons exist the inverse Compton scattering will induce a shift of the brightness temperature of CMB photons via the kinetic Sunyaev Zel'dovich (kSZ) effect [14]. This temperature shift will be anisotropic on our sky tracing the anisotropy of the projected free electron surface density. This test of the Copernican principle has been applied to cluster kSZ observations [7, 11, 15], where the electron surface density is high. However this effect applies to all free electrons which exist in great abundance everywhere in the universe up to the reionization epoch at redshift $z \sim 10$, whereas clusters are rare above $z \sim 1$. So one can expect a more sensitive test from blank field CMB anisotropy power spectrum measurements than from cluster measurements as has been demonstrated for the "dark flow" induced small scale kSZ effect [16]. The amplitude of the effect is much larger for the proposed LTB models and in conflict with recent observations. Furthermore this power spectrum test limits flows on a much larger range of redshifts than cluster measurements can.

When the Copernican principle is violated, the electron peculiar motion $\vec{v}$ has two components. $\vec{v}_H$ is the relative motion between the matter comoving frame and CMB and $\vec{v}_L$ is the local motion of electrons with respect to the comoving frame. Correspondingly the induced kSZ temperature fluctuation [14, 16] has two contributions,

$$\Delta T(\hat{n}) \ = \ \Delta T_L(\hat{n}) + \Delta T_H(\hat{n}) \ . \tag{1}$$

The first term on the r.h.s is the conventional kSZ effect,

$$\Delta T_L(\hat{n}) = T_{\rm CMB} \times \int [1+\delta_{\rm e}(\hat{n},z)] \frac{\vec{v}_L(\hat{n},z)\cdot\hat{n}}{c} d\tau_e \ . \tag{2}$$

Here, $\hat{n}$ is the radial direction on the sky. $\tau_{\rm e}$ is the mean Thomson optical depth to the corresponding redshift and $\delta_{\rm e}$ is the fractional fluctuation in the free electron number density. Both $\vec{v}_L$ and $\delta_{\rm e}$ fluctuate about zero, and cancellations along the line-of-sight cause the small scale anisotropy power spectrum to be dominated by terms cubic and higher in the amplitude of the inhomogeneities [17, 18]. The last term in Eq. 1 is new and does not vanish in a non-Copernican universe,

$$\begin{aligned} \Delta T_H(\hat{n}) \ &= \ T_{\rm CMB} \times \int [1+\delta_{\rm e}(\hat{n},z)] \frac{\vec{v}_H(\hat{n},z)\cdot\hat{n}}{c} d\tau_e \\ &= \ 9.1\mu{\rm K} \left[\int \frac{\vec{v}_H\cdot\hat{n}}{10^4{\rm km/s}} \frac{\delta_{\rm e}(\hat{n},z)}{0.1} \frac{d\tau_e}{0.001} \right] \ . \end{aligned} \tag{3}$$

[1] The matter comoving frame coincides with the background defined in synchronous gauge ($g_{00}=-1$, $g_{0i}=0$), which reads $ds^2 = dt^2 - (\partial R(r,t)/\partial r)^2 dr^2/(1+2E(r)) - R^2(r,t)d\Omega$.

The last expression neglects the $\int \vec{v}_H \cdot \hat{n} d\tau_e$ term, which has no direction dependence in LTB models in which we live at the center, and is therefore not observable. $\vec{v}_{\rm H}$ varies slowly along radial direction and does not suffer the cancellation of $\vec{v}_L$ in the conventional kSZ effect. The small scale anisotropy power spectrum will be quadratic in the amplitude of $\delta_{\rm e}$ (which does fluctuate about zero) so we can say that $\Delta T/T$ is first order in the density fluctuations. Throughout this paper, unless otherwise specified, we will focus on this *linear* kSZ effect. We restrict ourselves to adiabatic voids in which the initial matter, radiation, and baryon densities track each other. This is what one would expect if baryogenesis and dark matter decoupling occurs after the process which generates the void inhomogeneity. Non-adiabatic voids can in some case suppress v_H [19]. We also restrict ourselves to small voids outside of which both matter and radiation are homogeneous. Adding additional inhomogeneities will generically lead to larger values of v_H.

To explain the dimming of SNe-Ia and hence the apparent cosmic acceleration without dark energy and modifications of general relativity, we shall live in an underdense region (void) of size $\gtrsim 1h^{-1}$Gpc, with a typical outward velocity $v_{\rm H} \gtrsim 10^4$ km/s (e.g. [11]). Given the baryon density $\Omega_{\rm b}h^2 = 0.02\pm0.002$ from the big bang nucleosynthesis [20], $\tau_{\rm e} > 10^{-3}$. Scaling the observed weak lensing rms convergence $\kappa \sim 10^{-2}$ at ~ 10 arcminute scale [22], the rms fluctuation in $\delta_{\rm e}$ projected over Gpc length is $\gtrsim 0.1$ at the same angular scale. Hence such a void generates a kSZ power spectrum $\Delta T^2_{\rm H} \gtrsim 80\mu$k^2 at these angular scales. This is in conflict with recent kSZ observations. The South Pole telescope (SPT) collaboration [23] found $\Delta T^2 < 13\mu$K^2 (95% upper limit) at multipole $\ell = 3000$ (~ 7 arcminutes). The Atacama cosmology telescope (ACT) collaboration [24, 25] found $\Delta T^2 < 8\mu$K^2 (95% upper limit) at the same angular scale. This simple order of magnitude estimation demonstrates the discriminating power of the kSZ power spectrum measurement. It implies that a wide range of void models capable of replacing dark energy are ruled out. This also demonstrates how purely empirical measurements of CMB anisotropies and the large scale structure (e.g. weak lensing) can in principle be combined to limit non-Copernican models without any assumptions of how the inhomogeneities vary with distance.

We perform quantitative calculation for a popular void model, namely the Hubble bubble model ([8] and references therein). In this model, we live at the center of a Hubble bubble of constant matter density $\Omega_0 < 1$ embedded in a flat Einstein-de Sitter universe ($\Omega_m = 1$). The void extends to redshift $z_{\rm edge}$, surrounded by a compensating shell ($z_{\rm edge} < z < z_{\rm out}$) and then the flat Einstein-de Sitter universe ($z > z_{\rm out}$). The kSZ effect in this universe has two components, (1) the linear kSZ arising from the large angular scale anisotropies generated by matter (a) inside the void, (b) in the compensating shell, (c) outside the void; (2) the conventional kSZ effect quadratic in density fluctuation [18] and the kSZ effect from patchy reionization [26]. The contributions of each of these to the anisotropy power spectrum are uncorrelated. Hence the ACT/SPT measurements put an upper limit on the total. The later contributes at least 5μK^2 [27], so what is left for the first component is less than 3μK^2. However, we will test the Copernican principle in a conservative way, by requiring the power spectrum of the first component generated by matter *inside the void* to be below the ACT upper limit 8μK^2 at $\ell = 3000$.

For a general Hubble bubbles $\vec{v}_{\rm H}$ is determined by both Doppler and Sachs-Wolfe anisotropies generated by the void and depends qualitatively on the size of the void [8] . It is only small Hubble bubbles (technically $z_{\rm edge} < \frac{5}{4}$) which are consistent with both the SNe data and the spectrum of the CMB [8] and for these small Hubble bubbles a simple Doppler formula can be used [28]

$$v_{\rm H}(z) \approx [H_{\rm i}(z) - H_{\rm e}]\, \frac{D_{\rm A,co}(z)}{1+z} \qquad (4)$$

where, $H_{\rm i}(z)$ is the Hubble expansion rate inside the void as a function of redshift, $H_{\rm e}$ gives the Hubble expansion rate exterior to the void at the same cosmological time, $D_{\rm A,co}(z)$ is the comoving angular diameter distance to redshift z. The above expression is valid in the limit of $|v_{\rm H}| \ll c$. Later we will see that void models which pass the proposed kSZ test satisfies this condition.

The auto power spectrum at multipole ℓ generated by the linear KSZ effect inside of the Hubble bubble, using the Limber approximation, is

$$\begin{aligned} \Delta T^2_{\rm H}(\ell) \;=\; & (9.1\mu{\rm K})^2 \frac{\pi}{\ell} \int_0^{z_{\rm edge}} \left[\frac{v_{\rm H}(z)}{10^4{\rm km/s}}\right]^2 \qquad (5) \\ & \times \left[\frac{\Delta^2_{\rm e}(\frac{\ell}{D_{\rm A,co}(z)}, z)}{0.1^2}\right] \left[\frac{d\tau_e/dz}{0.001}\right]^2 \frac{cD_{\rm A,co}(z)}{H_{\rm i}[z]}\, dz \ . \end{aligned}$$

Here $\Delta^2_{\rm e}(k, z)$ is the electron number overdensity power spectrum (variance) at wavenumber k and redshift z. Henceforth we assume that $\Delta^2_{\rm e} = \Delta^2_{\rm m}$ where $\Delta^2_{\rm m}$ is the matter power spectrum (variance), which is a sufficiently good approximation at the scales of interest.

It is non-trivial to calculate $\Delta^2_{\rm m}$ in general LTB models, even at linear scales as locally the expansion rate is anisotropic so the inhomogeneities will have an anisotropic power spectrum (refer to [21] for a linear perturbation treatment). We take a minimalist's approach to circumvent this obstacle. The measured matter clustering and its evolution agree with the standard ΛCDM [22, 29–31] to $z \sim 1$, so do the galaxy clustering and evolution [32]. Hence the density inhomogeneities in any viable LTB models must be consistent with the ΛCDM prediction, within a factor of ~ 2 observational uncertainty. This allows us to approximate $\Delta^2_{\rm m}$ in the LTB models to be that of the standard ΛCDM model. We

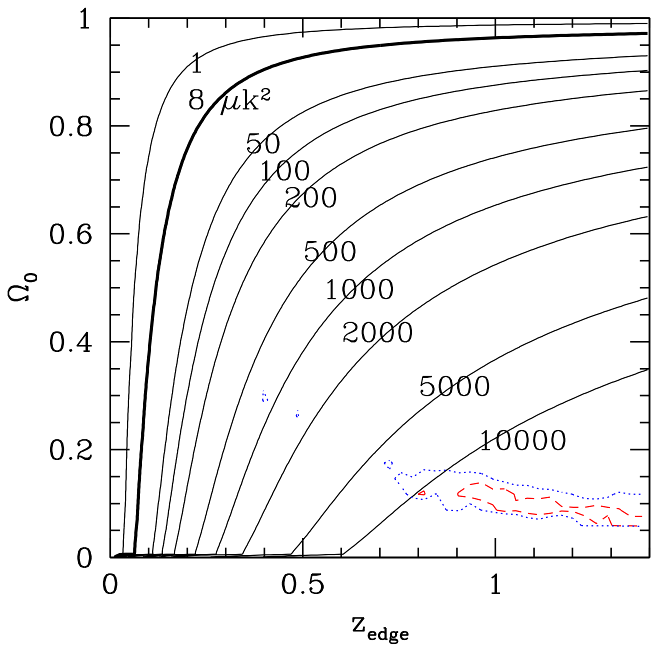

FIG. 1: The kSZ power spectrum (black curves having constant ΔT_H^2) at multipole $\ell = 3000$ in the Hubble bubble universe. The thick black line highlights the ACT 95% upper limit, $\Delta T^2 < 8\mu\mathrm{K}^2$ [25]. The kSZ test alone rules out large voids with low density and strongly supports the Copernican principle at Gpc scale and above. The dashed and dotted contours are the 2-σ and 3-σ constraints from the UNION2 supernova data [35]. The kSZ test robustly excludes the void model as a viable alternative to dark energy.

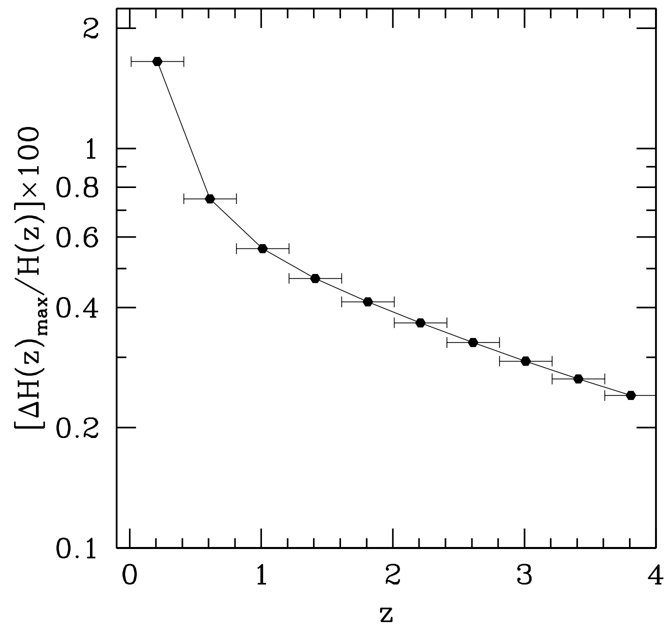

FIG. 2: The maximal deviation from the overall expansion allowed by the ACT observation, for each mass shell of $\Delta z = 0.4$, which corresponds to $1h^{-1}$Gpc at $z \sim 0$, $0.7h^{-1}$Gpc at $z \sim 1$ and $0.5h^{-1}$Gpc at ~ 2.

adopt $\Omega_{\mathrm{m}} = 0.27$, $\Omega_\Lambda = 1 - \Omega_{\mathrm{m}}$, $\Omega_{\mathrm{b}} = 0.044$, $\sigma_8 = 0.84$ and $h = 0.71$ and calculate the linear density clustering using the CMBFAST package [33], the nonlinear clustering from the halofit formula [34] and the kSZ power spectrum from Eq. 5. In this procedure, we have assumed that these LTB models agree with existing matter clustering measurements. Certainly they may not. So the proposed kSZ test is a conservative test of the Copernican principle.

Constraints on the void model.— The ACT/SPT upper limit rules out large voids with low density (Fig. 1). Only those voids either with $\Omega_0 \to 1$ ($\Omega_0 \gtrsim 0.8$) or $z_{\mathrm{edge}} \to 0$ ($z_{\mathrm{edge}} \lesssim 0.2$, corresponding to void radius $\lesssim 0.6h^{-1}$Gpc) survive this test (Fig. 1). This is by far the most stringent *single* test of the void models and the Copernican principle at Gpc scale and above.

The kSZ test is highly complementary to other tests such as the supernova test.[2] We have improved the SNe Ia constraints in [8] by using the UNION2 data with 557 SNe Ia [35]. The minimum χ^2 is 605.4. Hubble bubble models within 3σ contour have typical $\Delta T_{\mathrm{H}}^2 > 10^3\mu\mathrm{K}^2$ at $\ell = 3000$, two orders of magnitude larger than the ACT upper limit $8\mu\mathrm{K}^2$ [25], so they are robustly ruled out. On the other hand, Hubble bubble models consistent with the ACT result have $\Delta\chi^2 > 195$ ($\chi^2 > 800$) for the SNe Ia test and hence fail too. Thus in combination with SNe Ia observations, all Hubble bubble models are ruled out.

The above numerical calculation performed for the Hubble bubble model justifies our previous order of magnitude estimation on void models in general. This leads to a general conclusion that adiabatic void models capable of explaining the supernova Hubble diagram generate too much power in the kSZ sky to be consistent with the ACT/SPT upper limit. This conclusion is robust against various uncertainties in the kSZ modeling and measurement. Hence we rule out the possibility to explain the apparent cosmic acceleration by these voids. This confirms that the observed apparent cosmic acceleration is indeed real and has to be caused by either an unknown dark energy component or modification of general relativity.

[2] Another complementary test is the structure growth test. Hubble bubble models consistent with the ACT result predict $f \equiv d\ln D/d\ln a > 0.98$ at $z = 0.7$-0.8, contradicting with recent measurements [29, 31]. Here, D is the linear density growth rate.

Constraints on the Hubble flow.— Still, violation of the Copernican principle less dramatic than the above void models can in principle exist. For example, there could be large scale density modulation on the ΛCDM background. As long as the amplitude of the modulation is sufficiently small, it can pass the supernova test and the structure growth rate test. However, if unaccounted, it could bias the dark energy constraint. The kSZ test is able to put interesting constraint on this type of violation. We take a model independent approach and parameterize the violation of the Copernican principle by $\Delta H(z)$, the deviation of the Hubble expansion of a mass shell of size Δz centered at redshift z from the overall expansion of the background universe. The ACT result constrains $|\Delta H(z)/H(z)| \lesssim 1\%$ for each mass shell of radial width $\sim 1h^{-1}$Gpc (Fig. 2). This estimation neglect contributions from other mass shells so the actual constraint is tighter. This test can be carried out on each patch of the sky to test the isotropy of the Hubble flow.

The above test is not able to determine at which redshift a violation of the Copernican principle occurs, since the kSZ power spectrum is the sum over all contributions along the line-of-sight and hence has no redshift information. This problem can be solved with the aid of a survey of the large scale structure (LSS) with redshift information.

The basic idea is the same as the one proposed by [16] to probe the dark flow through the kSZ-LSS density distribution two point cross correlation. This cross correlation is non-zero only in non-Copernican Universes, since the velocity $\vec{v}_{\rm H}$ varies slowly over the clustering length of the LSS and since the linear kSZ effect is linear in density. Since the cross correlation vanishes for the conventional kSZ effect, a non-vanishing cross correlation signal can serve as a smoking gun of violation of the Copernican principle. The thermal SZ (tSZ) contaminates the measurement. However, it can be largely removed by spectral fitting or observing at its null: 217 GHz. Since the redshift surveys can map the LSS with much higher S/N than kSZ measurements, this cross correlation can achieve much higher S/N than the kSZ auto-correlations. We thus expect that small scale CMB anisotropy surveys, such as ACT and SPT, in combination with deep LSS surveys [36] will be able to put more stringent constraints on violations of the Copernican principle at each redshift and each direction of the sky.

Acknowledgment.— We thank U. Pen, J. Fry, C. Clarkson and S. Das for useful discussions. PJZ was supported by the NSFC grant No. 10821302 & 10973027, the CAS/SAFEA International Partnership Program for Creative Research Teams and the 973 program grant No. 2007CB815401. A.S was supported by the DOE at Fermilab under contract No. DE-AC02-07CH11359.

[1] A. Hajin & T. Souradeep, T., Phys. Rev. D , 74, 123521 (2006)
[2] D.Hogg et al., ApJ, 624, 54 (2005)
[3] H. Bondi, MNRAS, 107, 410 (1947)
[4] A. Riess et al., AJ, 116, 1009 (1998)
[5] S. Perlmutter et al., Astrophys. J. , 517, 565 (1999)
[6] e.g. J. W. Moffat and D. C. Tatarski, Astrophys. J. 453, 17(1995); M.N. Celerier, Astron. Astrophys., 353, 63 (2000); R.K. Barrett, and Clarkson, C.A.Class. Quant. Grav.,17, 5047 (2000); K. Tomita, K., MNRAS, 326, 287 (2001); K. Tomita, Prog. Theor. Phys., 106, 929 (2001); H. Iguchi, T. Nakamura, and K.I. Nakao, Prog. Theor. Phys.,108, 809 (2002); J. W. Moffat, JCAP 0605, 001 (2006)
[7] J. Goodman, Phys. Rev. D , 52, 1821 (1995)
[8] R. R. Caldwell, A. Stebbins, Phys. Rev. Lett. , 100, 191302 (2008)
[9] C. Clarkson, B. Bassett, and T. H.-C. Lu, T. H.-C., Phys. Rev. Lett. , 101, 011301 (2008)
[10] T. Clifton, P. G. Ferreira, and K. Land, Phys. Rev. Lett. , 101, 131302 (2008)
[11] J. García-Bellido, and T. Haugbølle, Journal of Cosmology and Astro-Particle Physics, 9, 16 (2008)
[12] J. Uzan, C. Clarkson and G. Ellis. Phys.Rev.Lett., 100, 191303 (2008)
[13] A. Moss, J.P. Zibin, and D.Scott., arXiv:1007.3725 (2010)
[14] R. A. Sunyaev, and Y. B. Zeldovich, Comments on Astrophysics and Space Physics, 4, 173 (1972); R. A. Sunyaev, and Y. B. Zeldovich, MNRAS, 190, 413 (1980)
[15] Chul-Moon Yoo, Ken-ichi Nakao, Misao Sasaki. arXiv:1008.0469 (2010)
[16] P.J. Zhang, MNRAS, 407, L36 (2010). [arXiv:1004.0990]
[17] J.P. Ostriker, and E. T. Vishniac, ApJ, 306, L51 (1986)
[18] E. T. Vishniac, Astrophys. J. , 322, 597 (1987)
[19] Chris Clarkson, Marco Regis. arXiv:1007.3443 (2010)
[20] S. Burles, K. M. Nollett, and M. S. Turner, ApJ, 552, L1 (2001)
[21] C. Clarkson, T. Clifton, S. February. JCAP, 06, 025 (2009). [arXiv:0903.5040]
[22] L. Fu et al. AAP, 479, 9 (2008)
[23] N. R. Hall, et al., arXiv:0912.4315 (2009)
[24] S.Das, et al. arXiv:1009.0847 (2010)
[25] J. Dunkley, et al. arXiv:1009.0866 (2010)
[26] M. G. Santos et al., Astrophys. J. , 598, 756 (2003)
[27] P.J. Zhang, U.-L. Pen, and H. Trac, MNRAS, 347, 1224 (2004)
[28] K. Van Acoleyen, Journal of Cosmology and Astro-Particle Physics, 10, 28 (2008)
[29] L. Guzzo et al., Nature (London) , 451, 541 (2008)
[30] T. Schrabback et al. arXiv:0911.0053 (2009)
[31] C. Blake et al., arXiv:1003.5721 (2010)
[32] M. Tegmark, et al., Astrophys. J. , 606, 702 (2004); A. L. Coil et al., Astrophys. J. , 644, 671 (2006); Z. Zheng, A. L. Coil, and I. Zehavi, Astrophys. J. , 667, 760 (2007)
[33] U. Seljak, U., M. Zaldarriaga, M., Astrophys. J. , 469, 437 (1996)
[34] R. E. Smith et al., MNRAS, 341, 1311 (2003)
[35] R. Amanullah et al. ApJ, 716, 712 (2010)
[36] e.g. BigBOSS: D. Schlegel et al., arXiv:0904.0468 (2009); DES: J. Annis et al., arXiv:astro-ph/0510195

(2005); KDUST: G.B. Zhao, et al. arXiv:1005.3810 (2010); LSST: P. Abell et al., arXiv:0912.0201 (2009); 21cm intensity mapping: T. Chang, et al. Phys.Rev.Lett.100:091303 (2008)