Researches on 21cm cosmology

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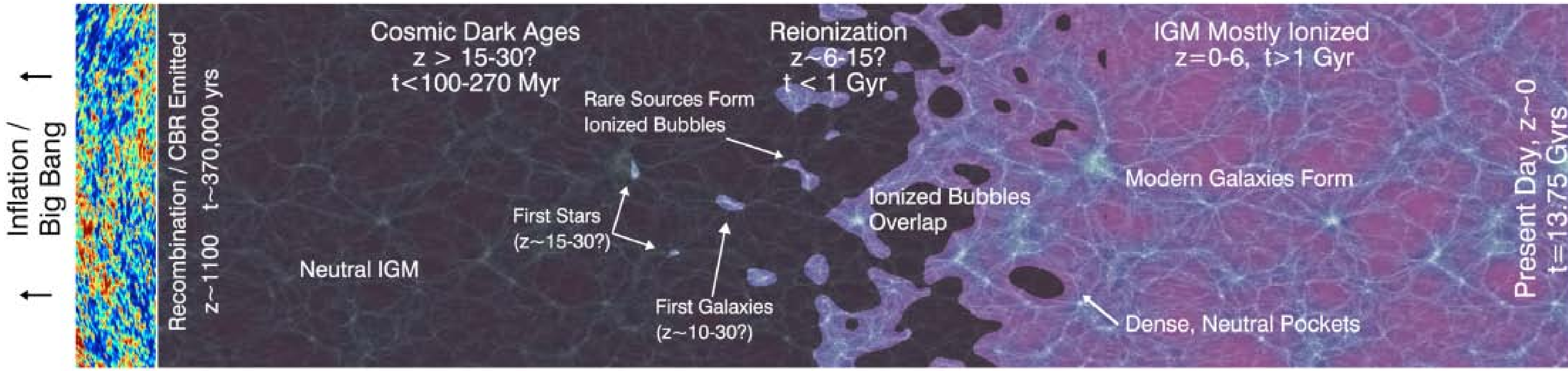
5th KIAS workshop on cosmology and large scale structrue
2012.11.1

Neutral Hydrogen (HI) in the universe



coutesy B.E. Robertson et al., Nature

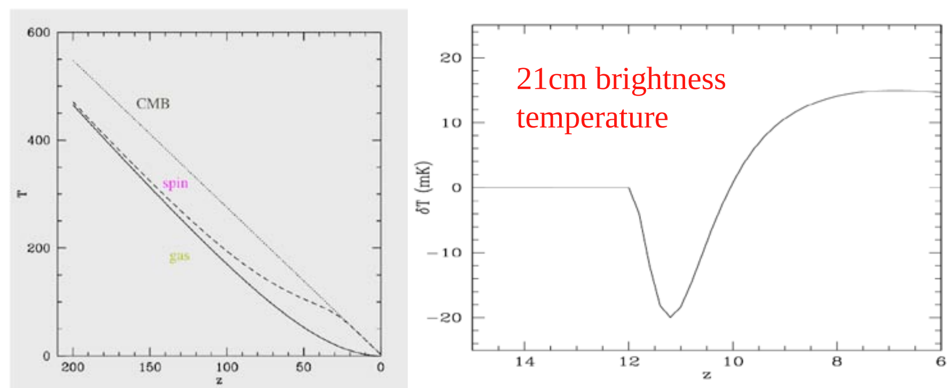
- interstellar medium

- nearby galaxies, kinematics (dark matter, Tully-Fisher relation determined distance), gas accretion

- large scale structure

- epoch of reionization

- dark age



Chen & Miralda-Escude 2004

21cm Cosmology
The observable Universe in comoving scale

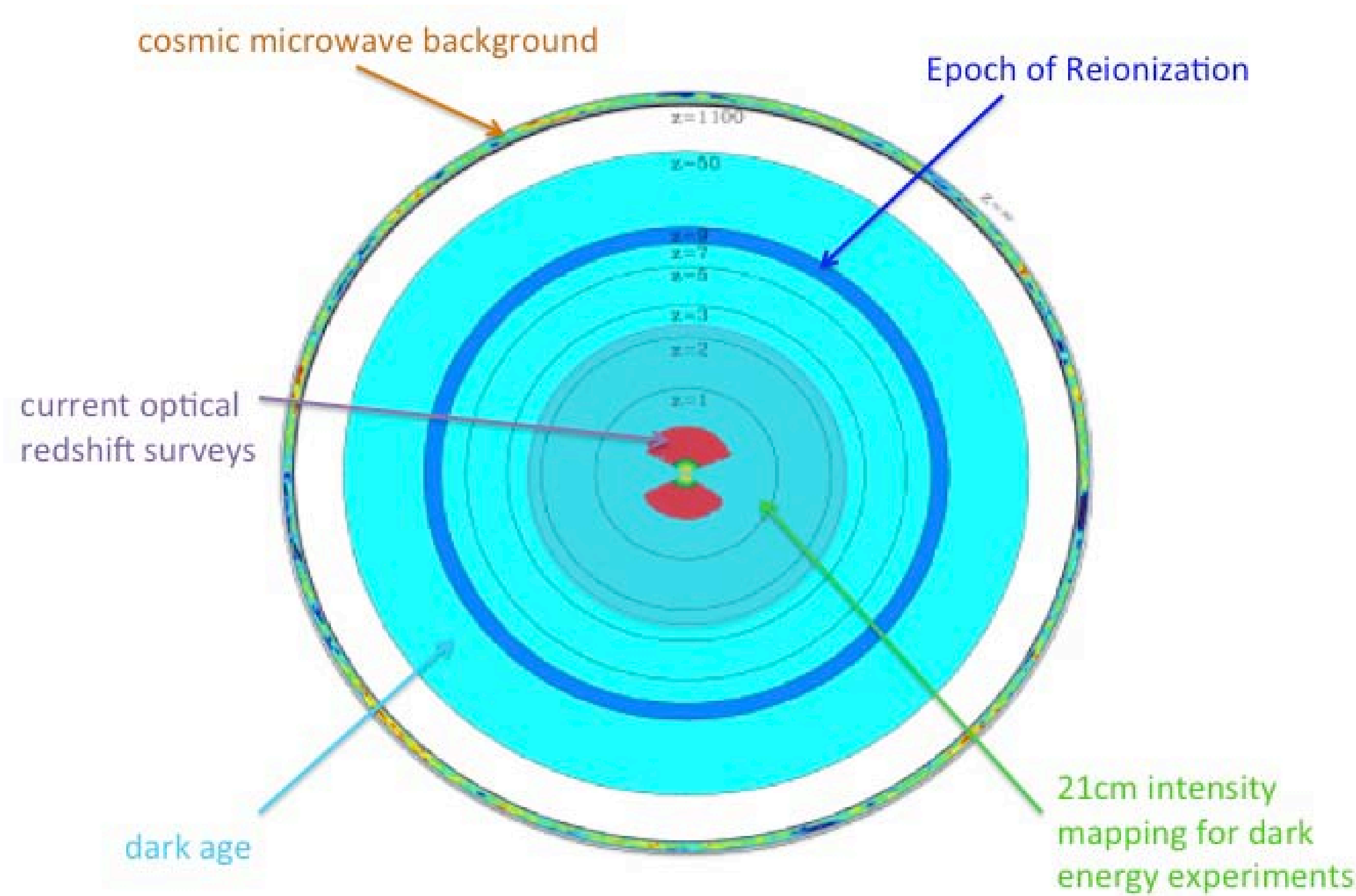
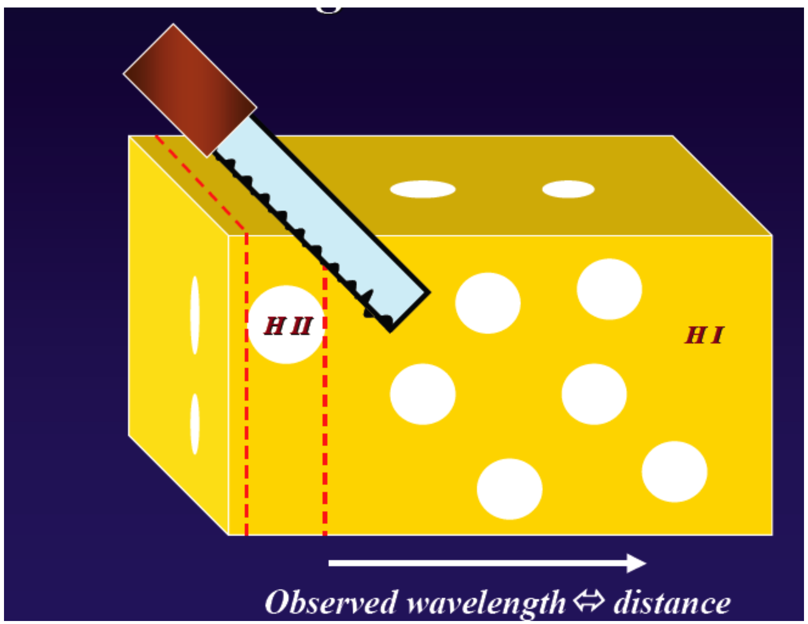


Figure inspired by Yi Mao & Max Tegmark

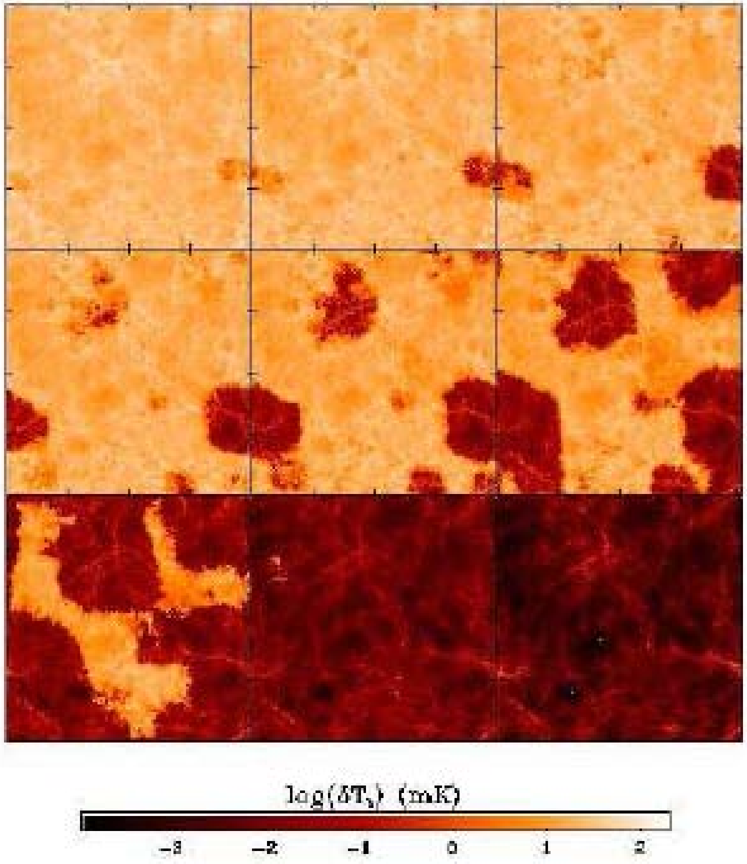
21cm tomography

By observing different frequency, can reveal 3D distribution



coutesy Avi Loeb

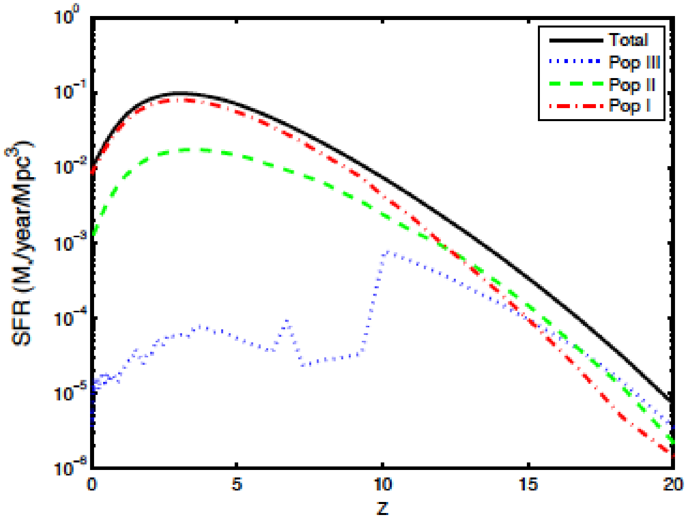
redshift

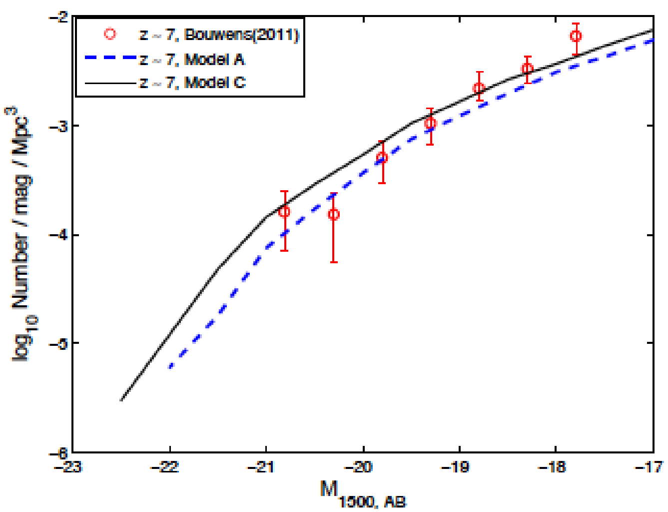


Furlanetto, Sokasian, Hernquist 2003

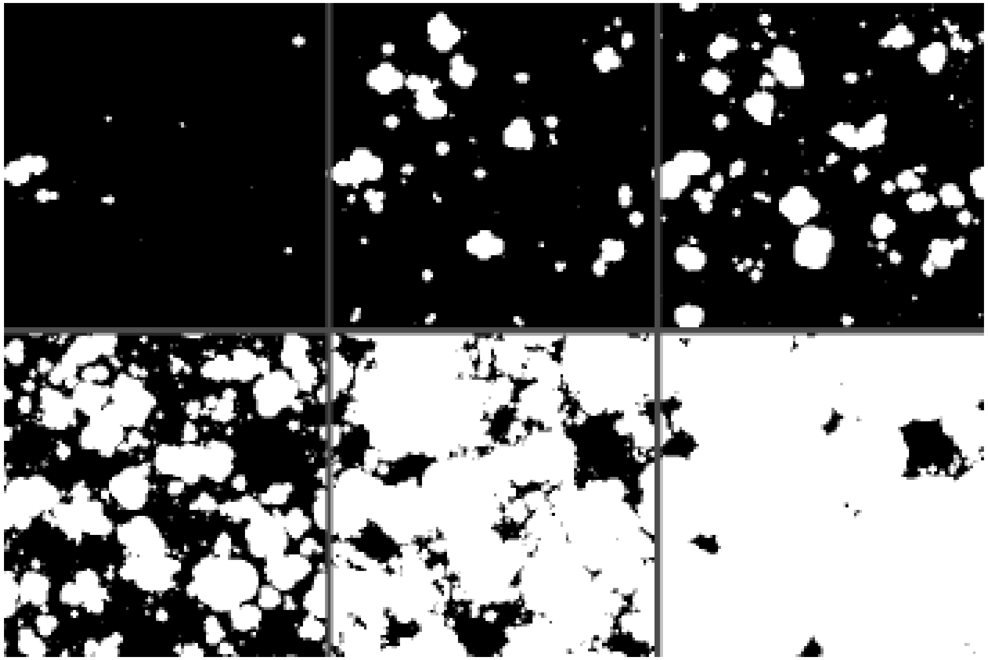
Model of Reionization

SFR given by Millenium II based semi-analytical model (Q. Guo et al 2010)



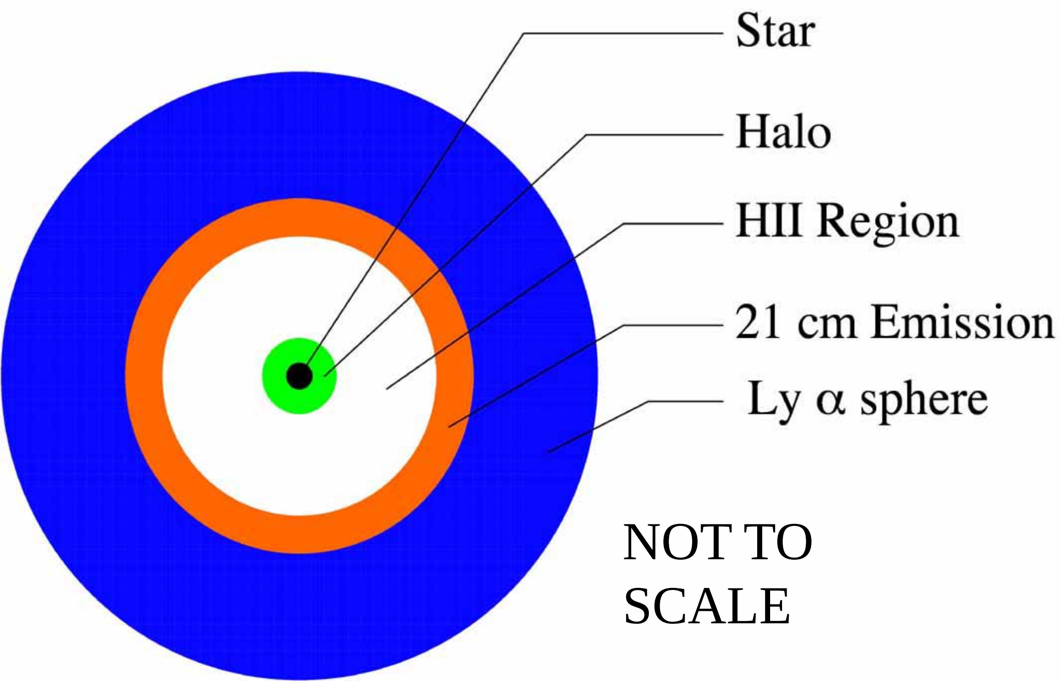


Semi-Numerical Model of Reionization



J. Zhou et al., to appear soon

First Stars and Galaxies



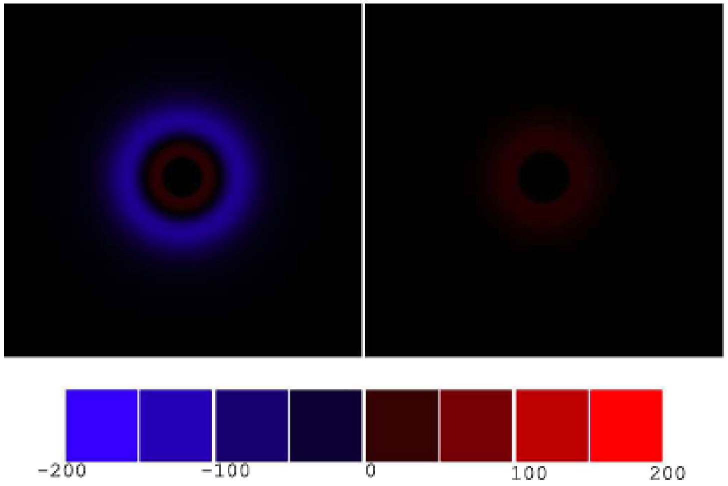


Fig. 12.— A cross section map for a star of 200 $M_\odot$ and age 1.5 Myr at redshift 20(left) and 15(right). The box size is 40 kpc across (physical distance), and unit of temperature scale is mk.

Chen & Miralda-Escude, 2008, ApJ 684, 18.

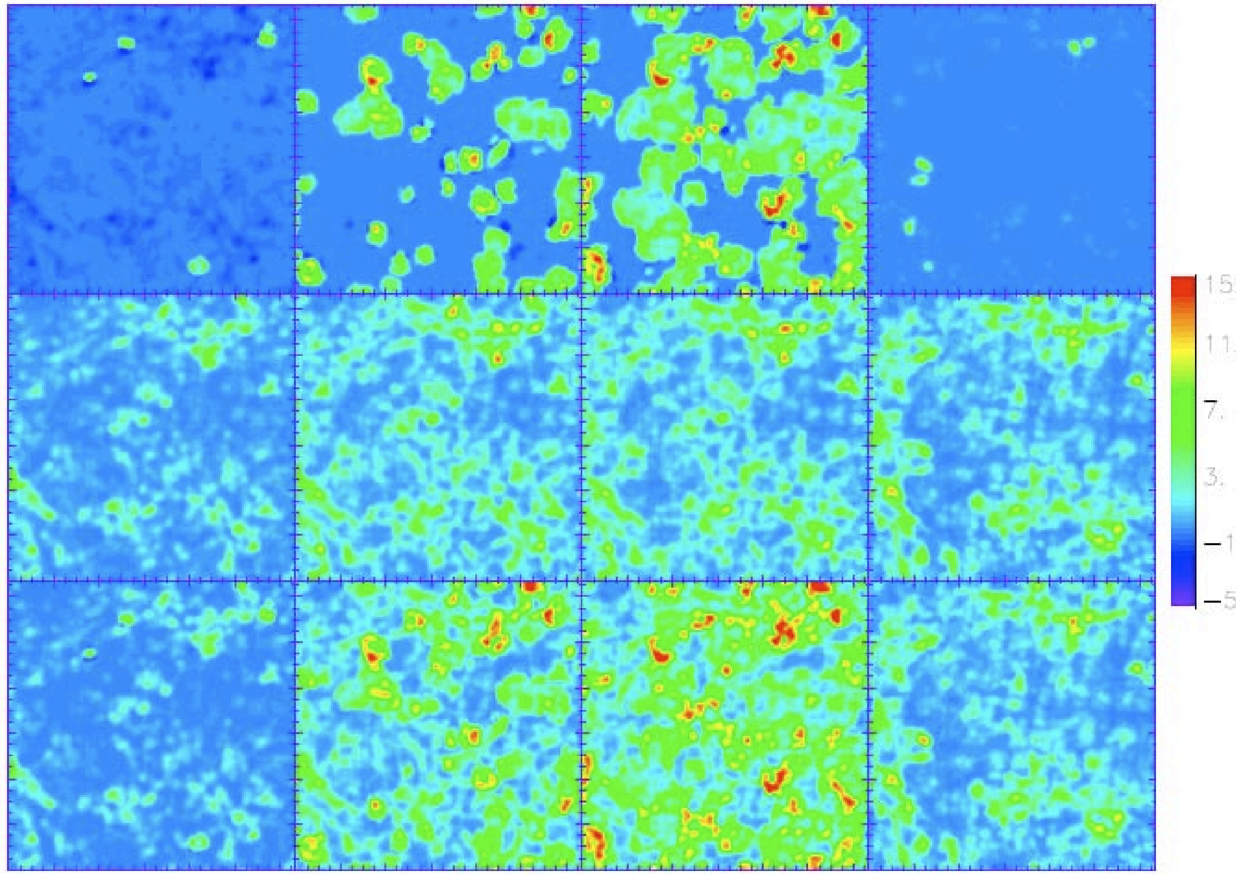
21cm map

B. Yue et al., 2009, MNRAS 398, 2122

IGM

minihalo

total



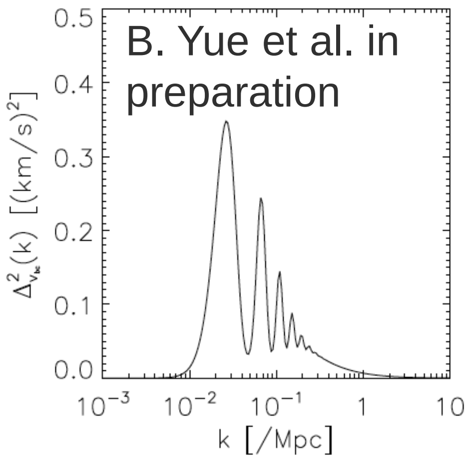
18.5 14.6 12.8 10.6

Velocity Acoustic Oscillation (VAO)

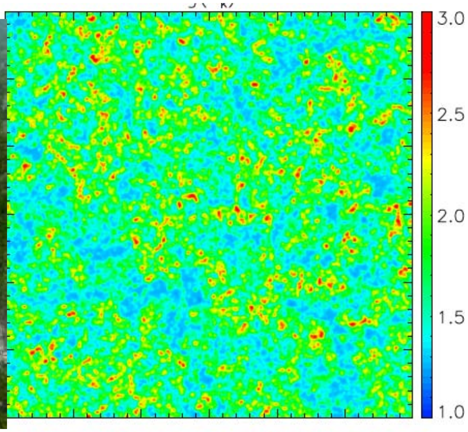
• Significant relative velocity (30km/s) between DM and Baryons at the end of Recombination (Tseliakhovich & Hirata 2010, Dalal et al. 2010)

• This "wind" against DM halos could still significantly modulate the formation of first stars, modulation on 10^2 Mpc, comparable to BAO

• an interesting FAST science case



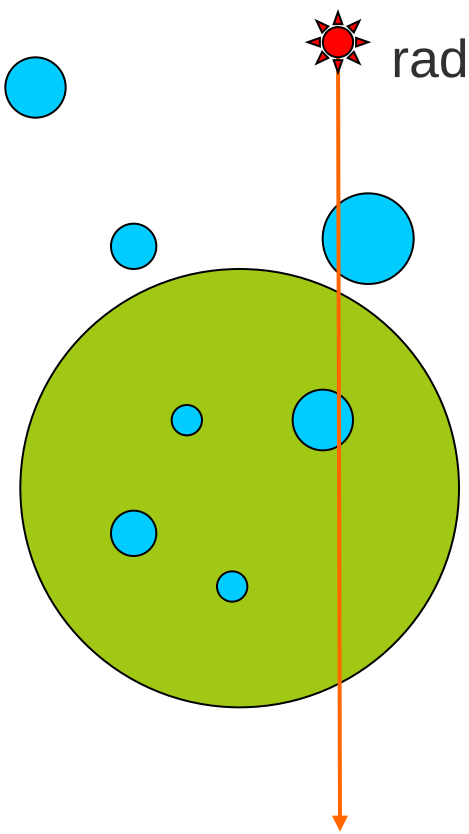
FAST



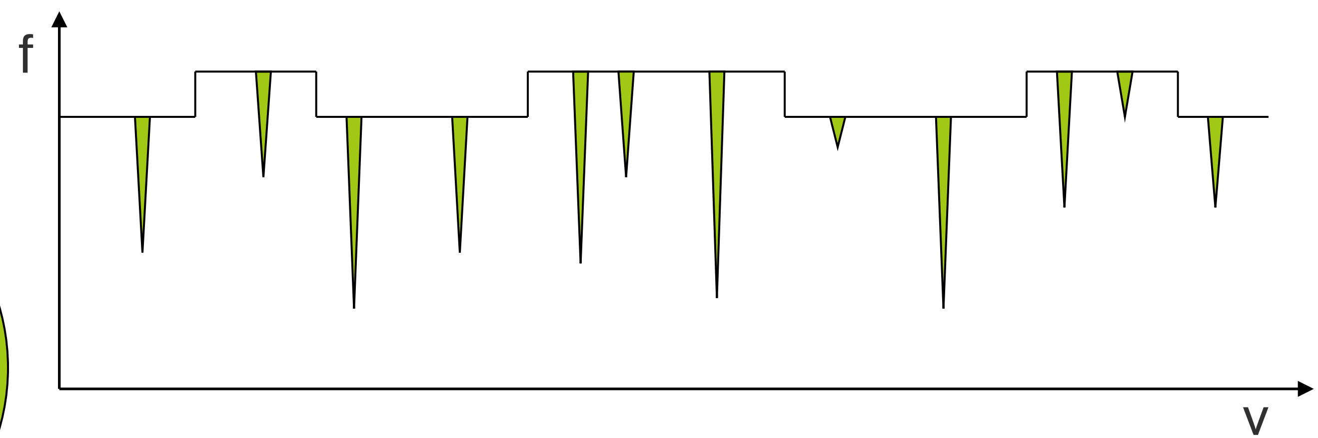
21cm Forest

limitation of 21cm tomography: insensitive to Ts when Ts >> Tcmb

$$\delta T \simeq (0.025\,\mathrm{K}) \left(\frac{\Omega_b h_0}{0.03}\right) \left(\frac{0.3}{\Omega_{m0}}\right)^{1/2} \left(\frac{1+z}{10}\right)^{1/2} \frac{\rho_{HI}}{\bar{\rho}_H} \frac{T_s - T_{CMB}}{T_s}$$



21cm forest: break degeneracy

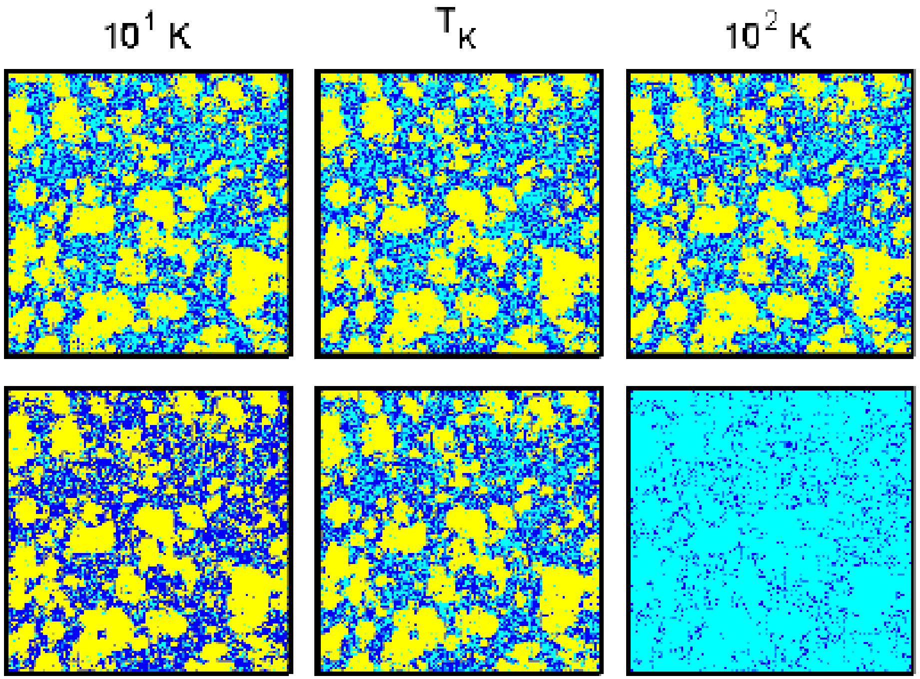


$$\tau_{\nu_0}(z) = \frac{3}{32\pi} \frac{h_p c^3 A_{10}}{k_B \nu_0^2} \frac{x_{\mathrm{HI}} n_H(z)}{T_S (1+z)(d v_\parallel / d r_\parallel)}$$

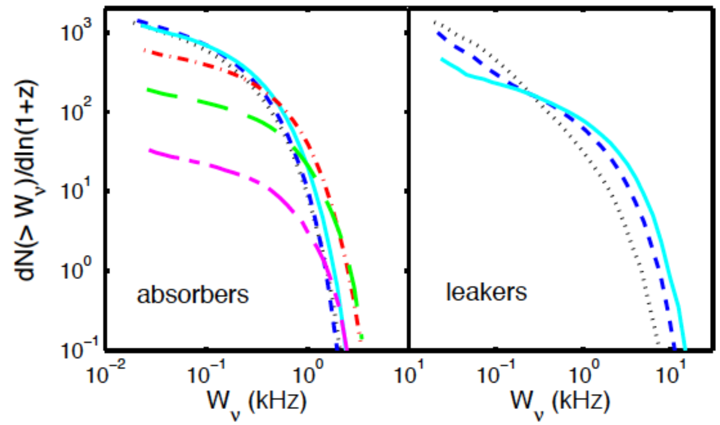
$$\approx 0.009 (1+\delta)(1+z)^{3/2} \frac{x_{\mathrm{HI}}}{T_S} \left[\frac{H(z)/(1+z)}{d v_\parallel / d r_\parallel}\right],$$

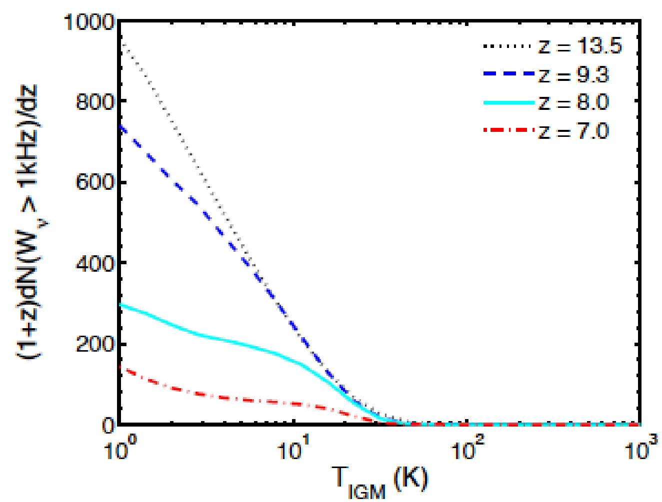
21cm forest as probe of reionization and temperature

Y. Xu et al., 2009, ApJ 704, 1396



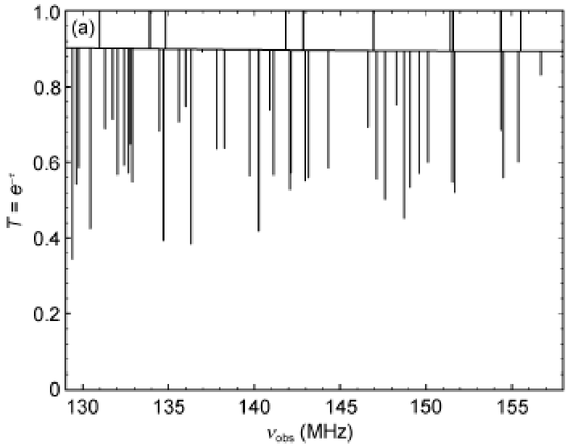
relative optical depth



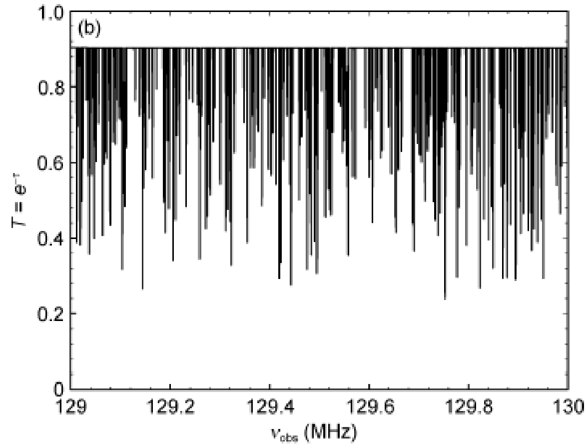


The earliest galaxies seen in 21cm forest

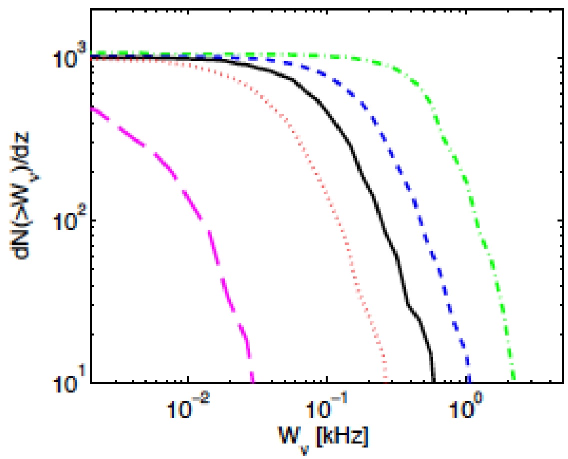
Y. Xu et al., 2010, Sci. China. G 53, 1124;
Y. Xu et al., 2011, MNRAS 410, 2025



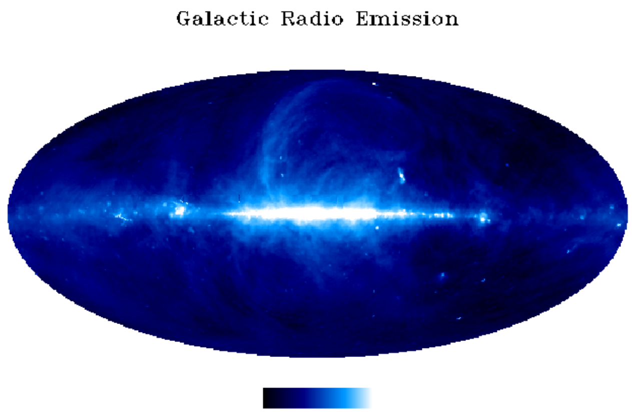
dwarf galaxies

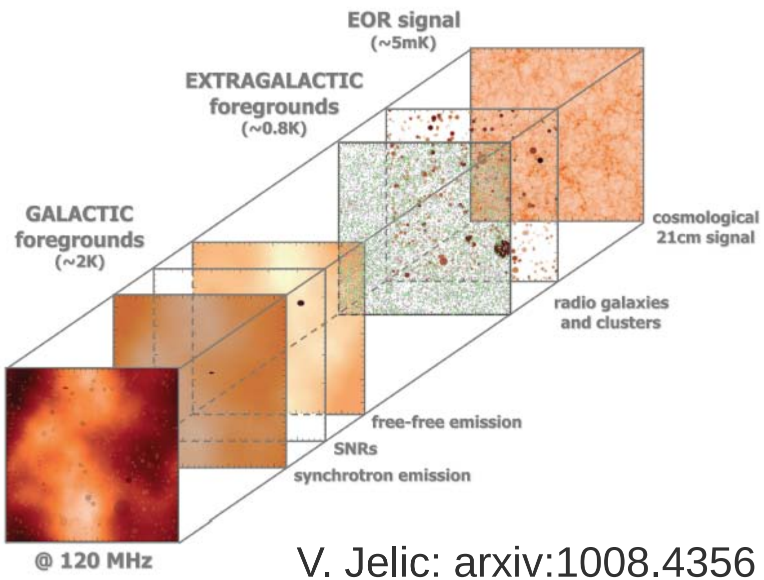


minihalos



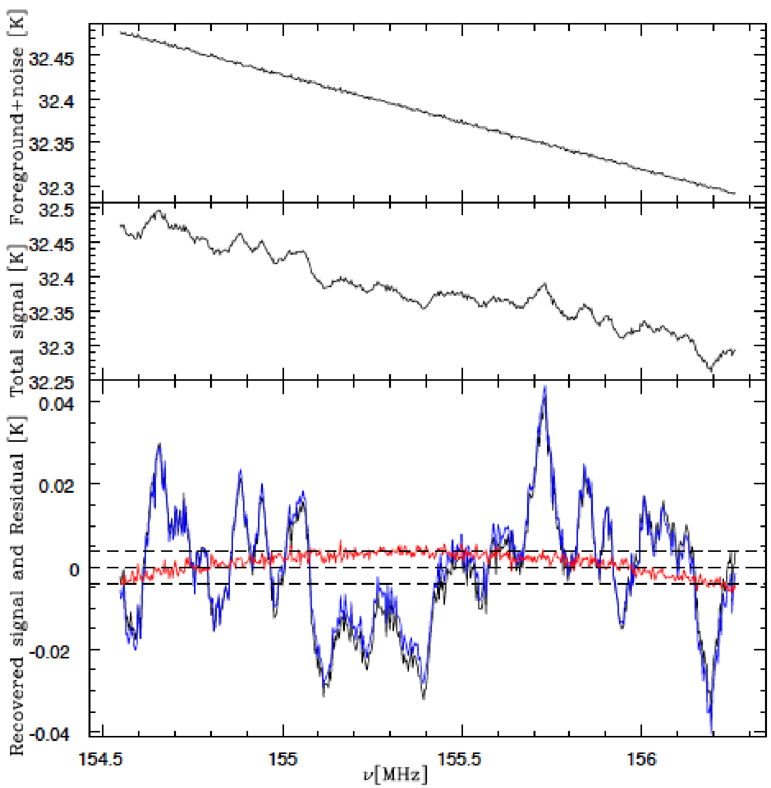
Foreground





V. Jelic: arxiv:1008.4356

Subtraction is possible in principle, but challenging:: the mode mixing problem



X. Wang et al astro-ph/0501081

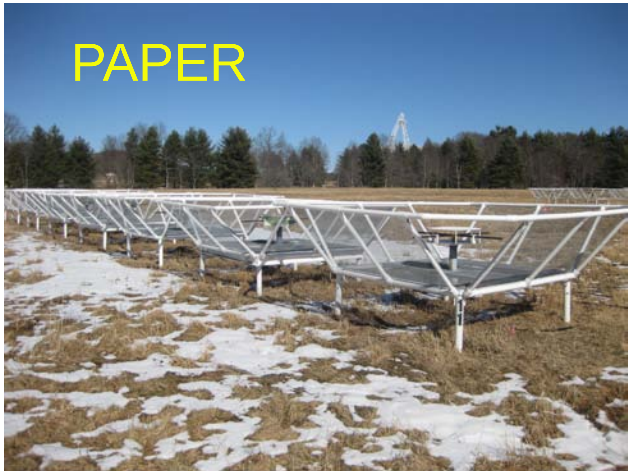
21cm observations: single dish

Arecibo (300m dish)

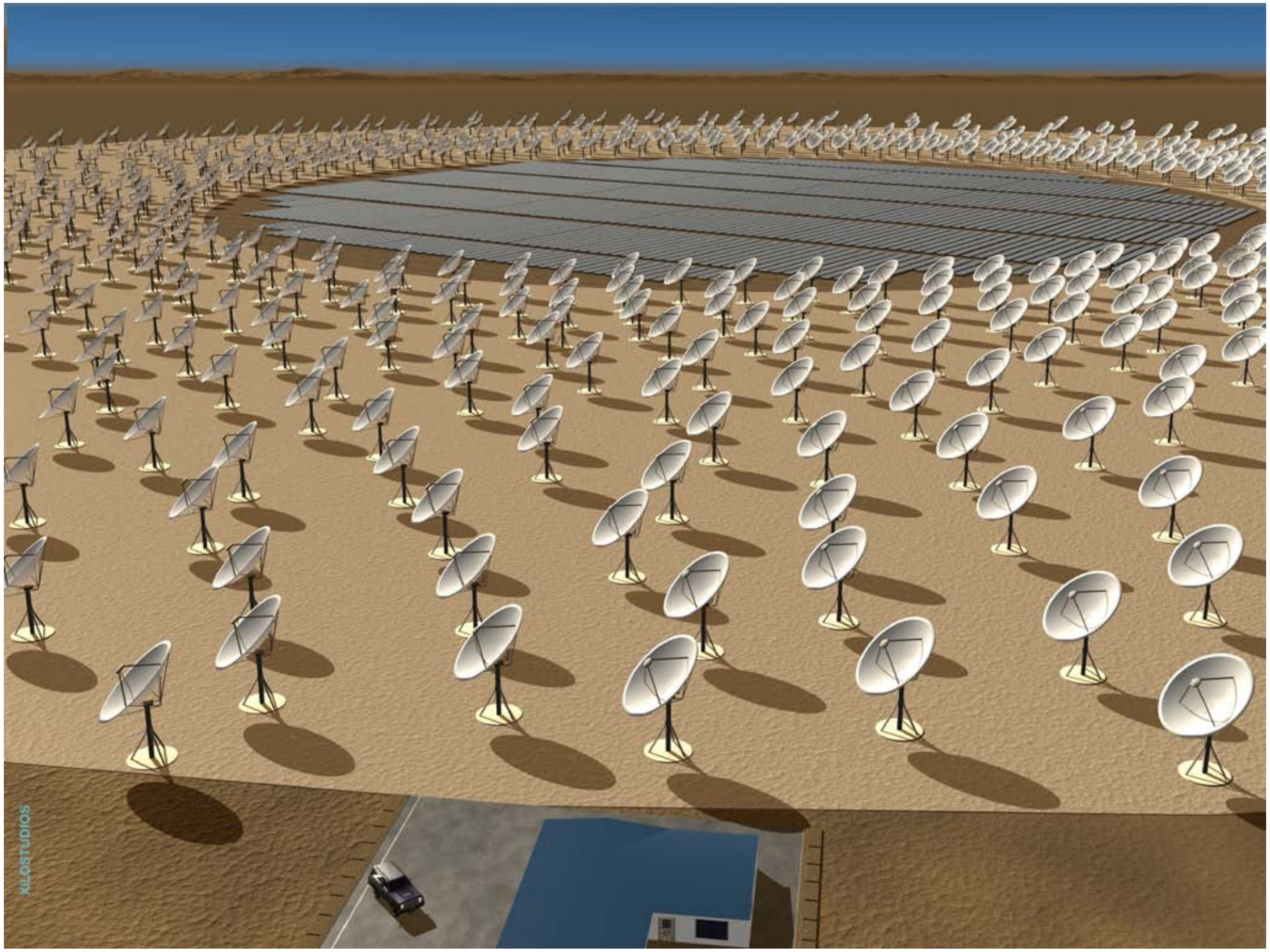
The GBT (110m dish): the 21cm intensity mapping experiment

- BINGO (50m multibeam dish)

Interferometer 21cm experiments



Ultimately, SKA

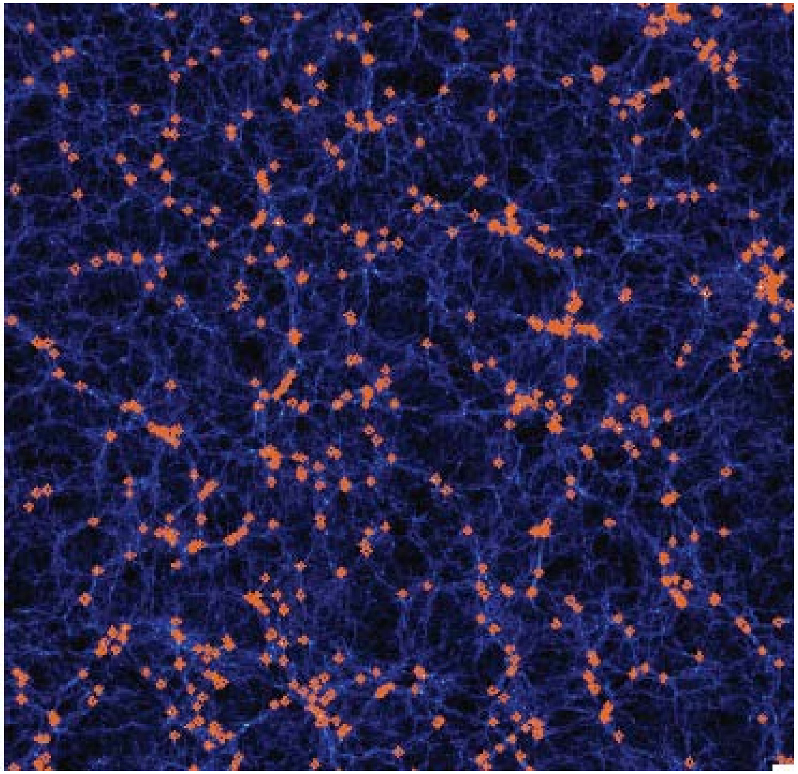


21cm as a probe of Large Scale Structure

many papers published on

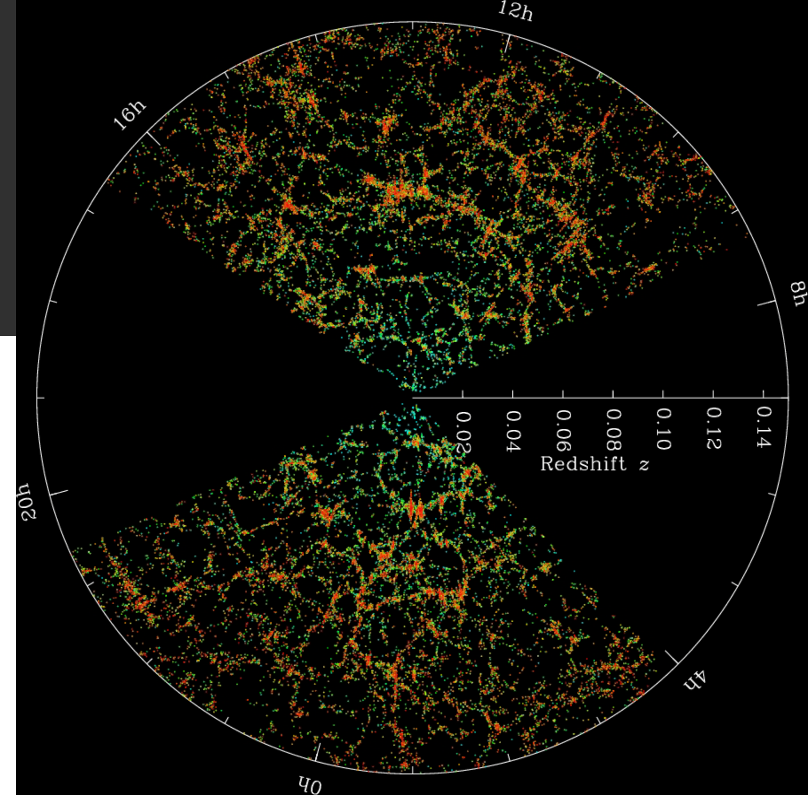
- dark energy
- power spectrum
- redshift distortion
- lensing
- non-Gaussianity
- topology
- modified gravity
- halo occupation model

...



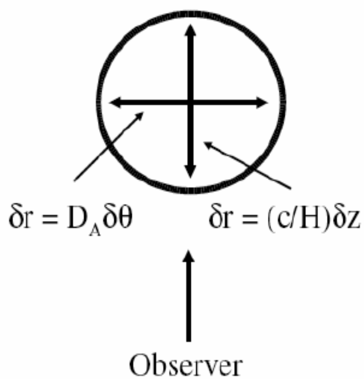
Baryon Acoustic Oscillation (BAO) as probe of dark energy

Baryon Acoustic Oscillation in large scale structure can be used to measure the Hubble expansion rate H(z) and angular diameter distance $d_A(z)$



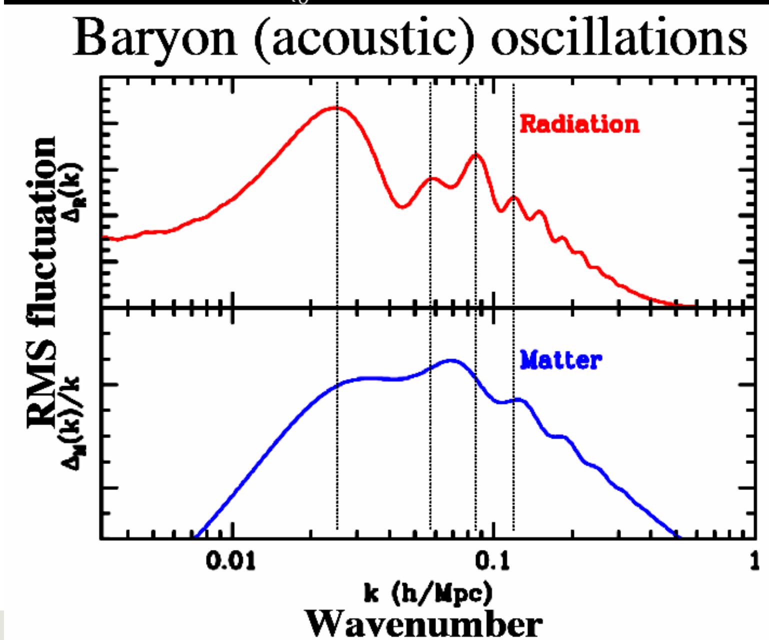
$$r_{||} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z)D_A(z)\Delta\theta$$

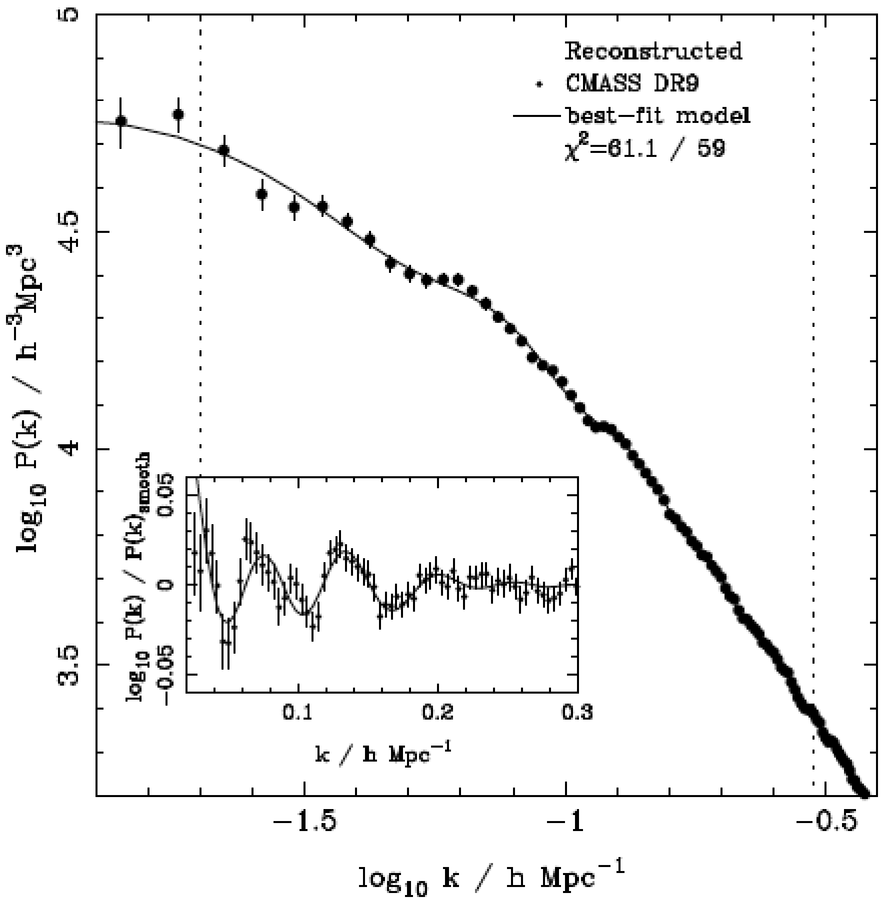


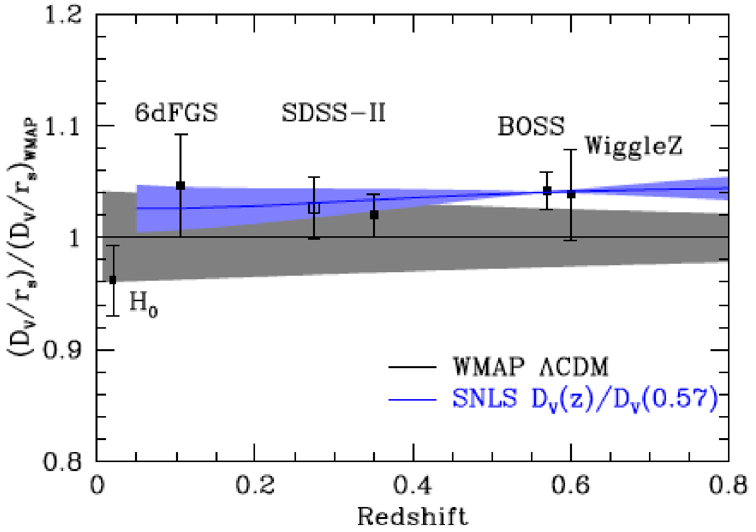
$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}$$

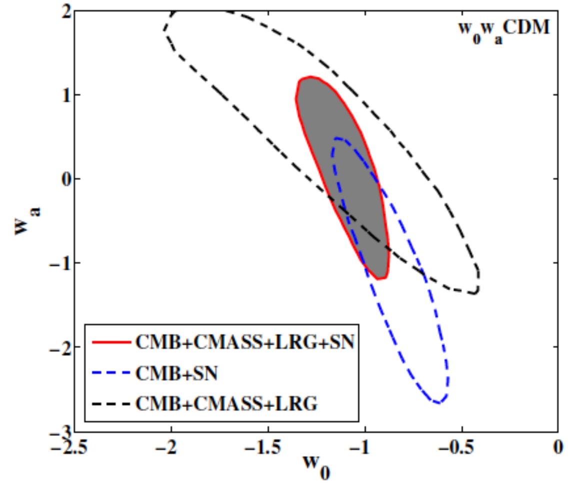
$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$



BAO measurements





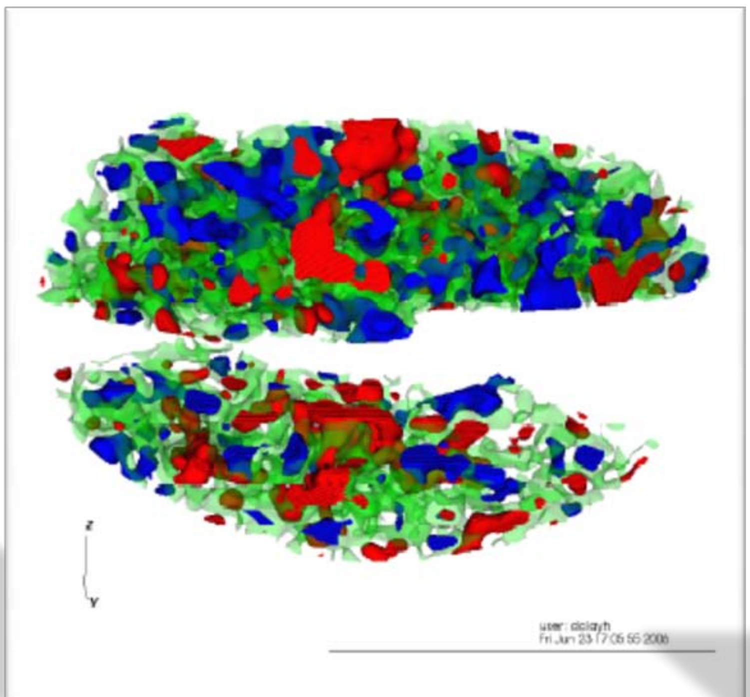


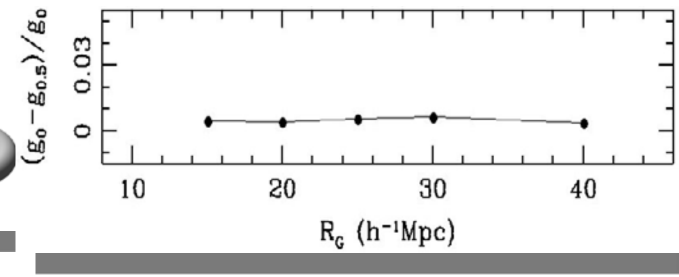
Anderson et al.(BOSS collab.), arxiv:1203.6594

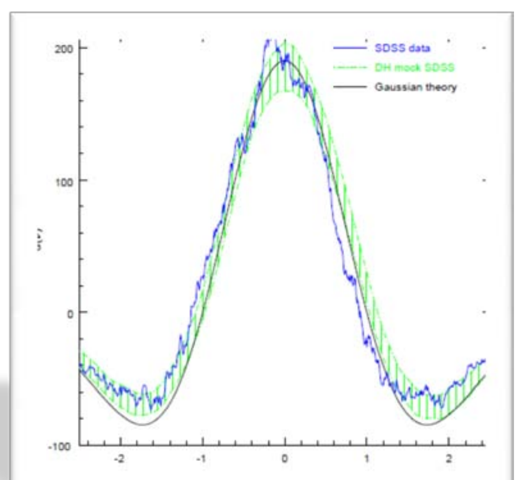
Another Example: density topology constraints

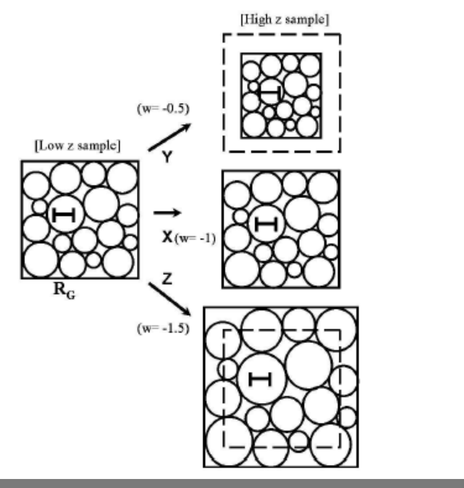
Wang, Chen & Park 2012, ApJ

$$\mathcal{G}(\nu) = \frac{g}{V}(\nu) = \mathcal{A}(1-\nu^2)e^{-\nu^2/2}, \qquad \mathcal{A} = \frac{1}{4\pi^2 3^{3/2}}\left(\frac{\int d^3k k^2 P(k) W(kR_G)}{\int d^3k P(k) W(kR_G)}\right)^{3/2},$$









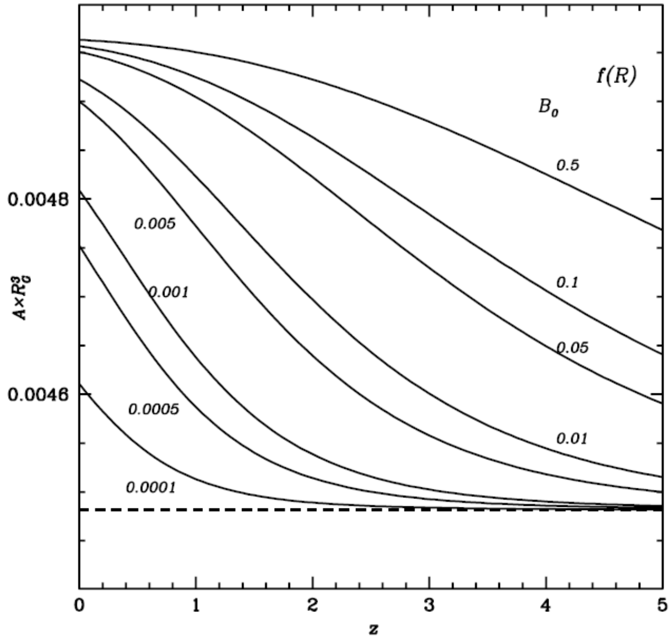
21cm constraint on f(R) gravity model

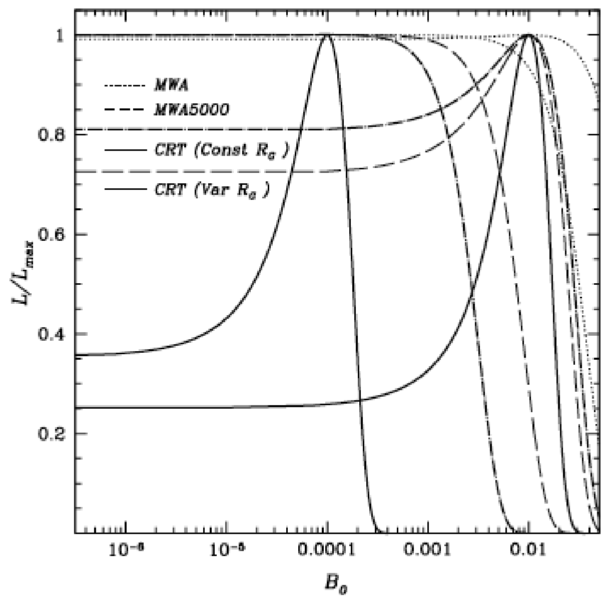
$$S = \int d^4x\sqrt{-g}\left[\frac{\mathcal{R} + f(\mathcal{R})}{16\pi G} + \mathcal{L}_m\right],$$

satisfy all expansion constraints
such as SNIa:

$$B(a) \equiv \frac{f_{\mathcal{R}\mathcal{R}}}{1 + f_{\mathcal{R}}}\mathcal{R}'\frac{H}{H'}$$

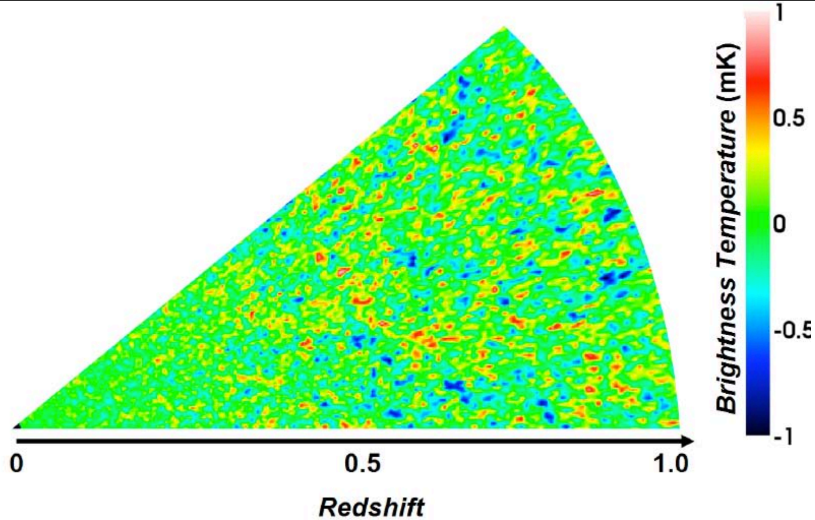
$$-f_{\mathcal{R}}(HH' + H^2) + \frac{1}{6}f + H^2 f_{\mathcal{R}\mathcal{R}}\mathcal{R}' = \frac{8\pi G}{3}\rho - H^2,$$

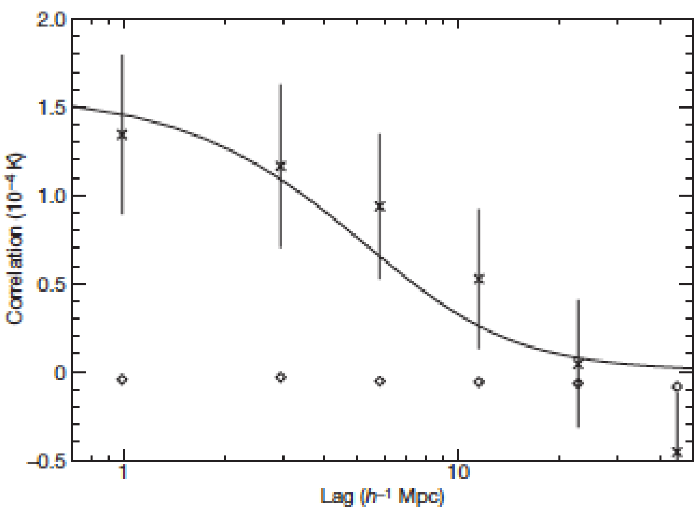




Map the 3D large scale structure

21 cm Intensity mapping: No need to resolve individual galaxies, map the density in large cells (T. Chang et al. 2008 PRL)





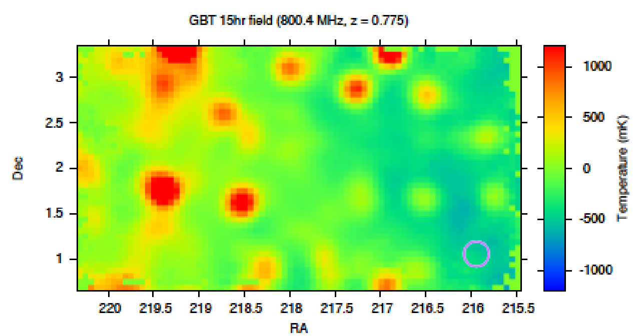
T. Chang et al., 2010, Nature

Cross-Correlation with Optical Galaxies (Wigglez)

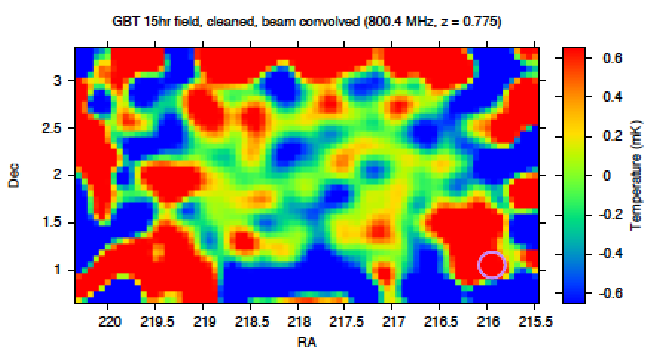
K. Masui et al., arxiv:1208.0331

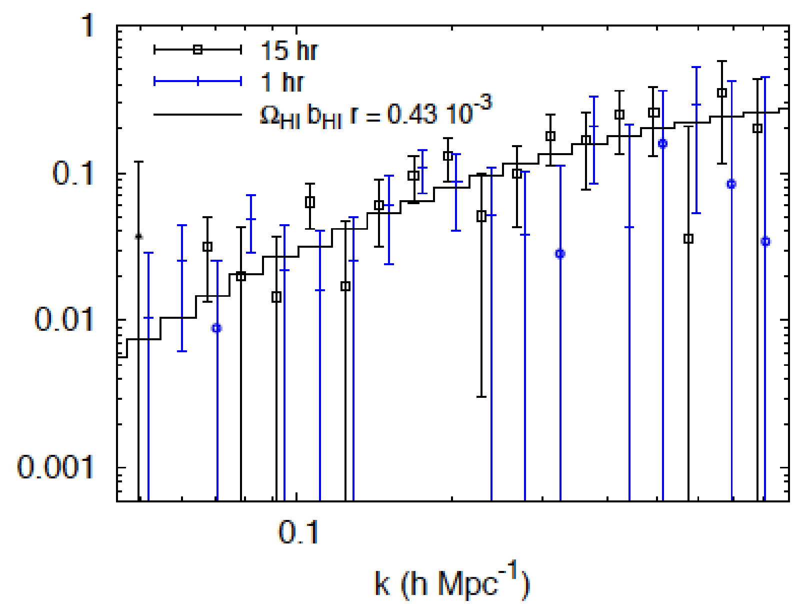
GBT survey map

original



foreground modes subtracted





Advantage of 21cm for intensity mapping

Y. Gong et al. (ApJL 2011)

Intensity mapping may be contaminated by different spectral lines:

$$(1 + z_1)\lambda_1 = (1 + z_2)\lambda_2.$$

The low frequency 21cm does not have significant contaminants, we considered OH 18cm line. In such contamination, incoherent superposition (power spectra adds)

Thompson, Moran & Swenson (2001)

TABLE 1.1 Some Important Radio Lines

Chemical Name	Chemical Formula	Transition	Frequency (GHz)
Deuterium	D	$^2S_{\frac{1}{2}}, F = \frac{3}{2} \to \frac{1}{2}$	0.327
Hydrogen	H I	$^2S_{\frac{1}{2}}, F = 1 \to 0$	1.420
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 1 \to 2$	1.612[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 1 \to 1$	1.665[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 2 \to 2$	1.667[a]
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{3}{2}, F = 2 \to 1$	1.721[a]
Methyladyne	CH	$^2\Pi_{\frac{1}{2}}, J = \frac{1}{2}, F = 1 \to 1$	3.335
Hydroxyl radical	OH	$^2\Pi_{\frac{1}{2}}, J = \frac{1}{2}, F = 1 \to 0$	4.766[a]
Formaldehyde	H_2CO	$1_{10} - 1_{11}$, six F transitions	4.830
Hydroxyl radical	OH	$^2\Pi_{\frac{3}{2}}, J = \frac{5}{2}, F = 3 \to 3$	6.035[a]
Methanol	CH_3OH	$5_1 \to 6_0 A^+$	6.668[a]
Helium	$^3He^+$	$^2S_{\frac{1}{2}}, F = 1 \to 0$	8.665
Methanol	CH_3OH	$2_0 \to 3_{-1} E$	12.179[a]
Formaldehyde	H_2CO	$2_{11} \to 2_{12}$, four F transitions	14.488
Cyclopropenylidene	C_3H_2	$1_{10} \to 1_{01}$	18.343
Water	H_2O	$6_{16} \to 5_{23}$, five F transitions	22.235[a]
Ammonia	NH_3	$1, 1 \to 1, 1$, eighteen F transitions	23.694
Ammonia	NH_3	$2, 2 \to 2, 2$, seven F transitions	23.723
Ammonia	NH_3	$3, 3 \to 3, 3$, seven F transitions	23.870
Methanol	CH_3OH	$6_2 \to 6_1, E$	25.018
Silicon monoxide	SiO	$\upsilon = 2, J = 1 \to 0$	42.821[a]
Silicon monoxide	SiO	$\upsilon = 1, J = 1 \to 0$	43.122[a]

$$\bar{I}_{\rm OH}(z) = f_{\rm OH}\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} f_{\rm IR}(M)\frac{L_{\rm OH}(M,z)}{4\pi D_L^2} y(z) D_A^2$$

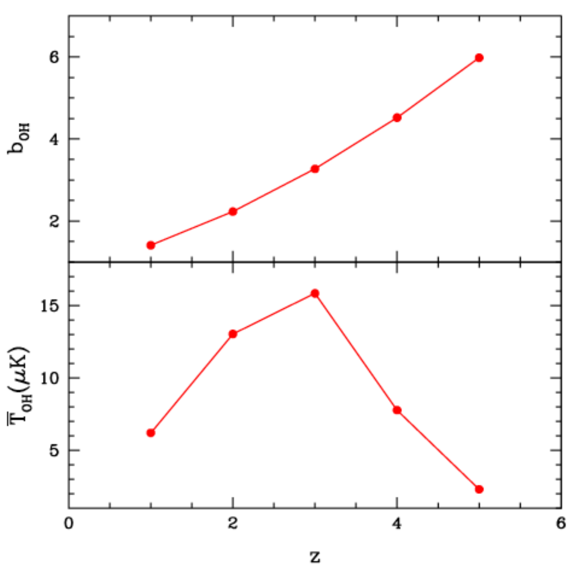
OH –IR relation (Darling & Giovanelli 2002):

$$\log L_{\rm OH} = (1.2 \pm 0.1)\log L_{\rm IR} - (11.7 \pm 1.2).$$

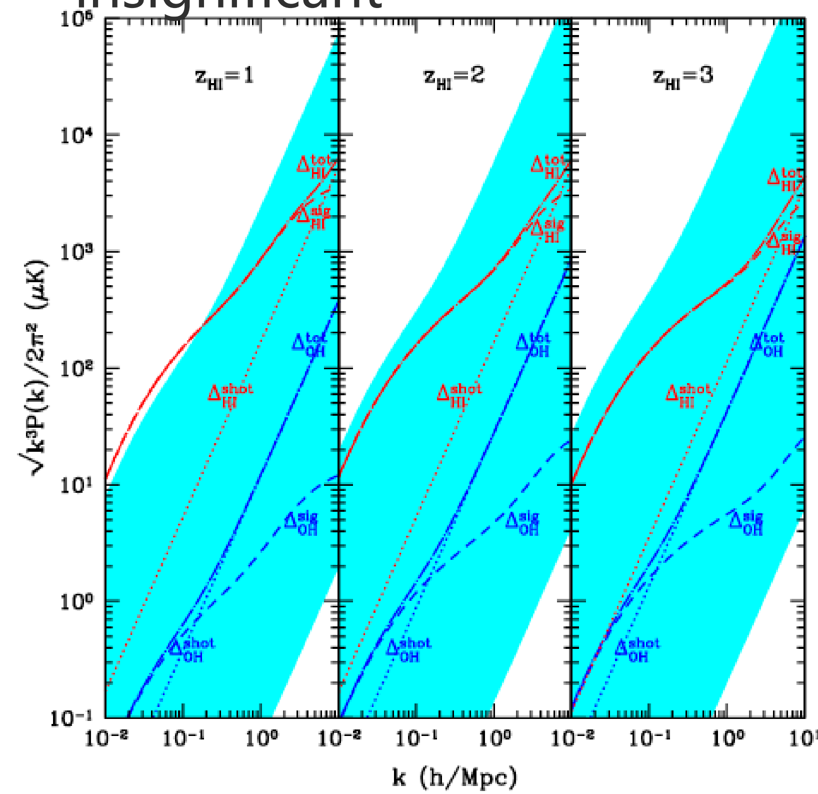
IR-SFR relation (Magnelli et al. 2011)

$$L_{\rm IR}\ [L_\odot] = 5.8\times 10^9\ {\rm SFR}\ [{\rm M_\odot yr^{-1}}].$$

Using SKA sky simulation model to obtai
(Obreschkow et al. 2009)



The OH power is several orders of magnitude smaller than the 21cm power, so the contamination is insignificant



The Tianlai（天籁, Heavenly Sound) Project:
21cm intensity mapping experiment in China

The concept of "tianlai" (the cosmic sound) was introduced by Taoist philosopher
Chuang-Tzu (369BC-286BC)

The Collaboration:

Academic: NAOC(Chen), CITA(Pen), CMU(Peterson), LAL/U. Paris-Sud (Ansari), U. Wisconsin (Timbie), Fermilab, ASIAA(Chang), Peking U., Hangzhou Dianzi U.,

Industry: CETC-54, Institute of Automation

Design Considerisions

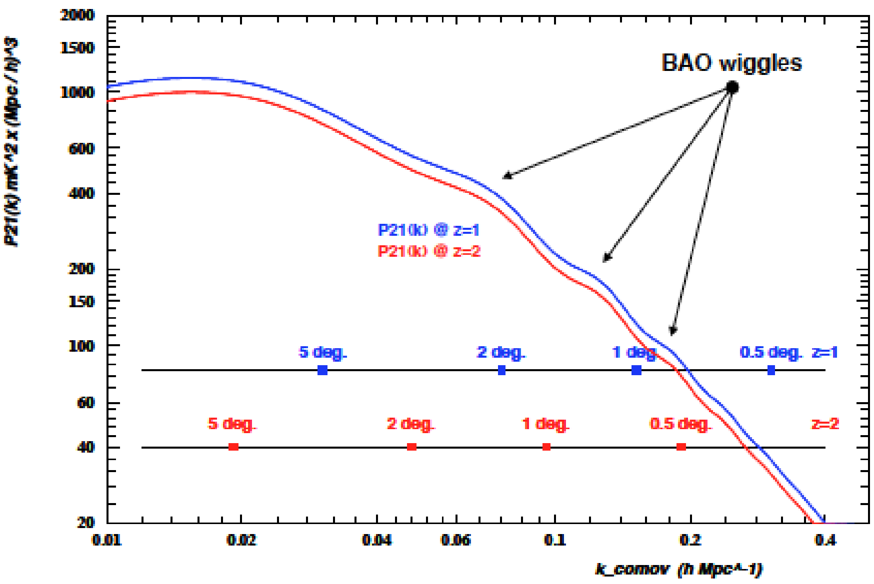
• Drift Scan (less cost, more stable)

• 0<z<3, first probably z=1 (sensitive to dark energy, avoids cell phone band at 850-950 MHz), alternatively z=0.2-0.3 (better optical coverage, smaller antenna)

• Angular Resolution: 15arcmin, to resolve the high order BAO peaks

• An array of about 100m size

• For 1st BAO peak, the array can be smaller

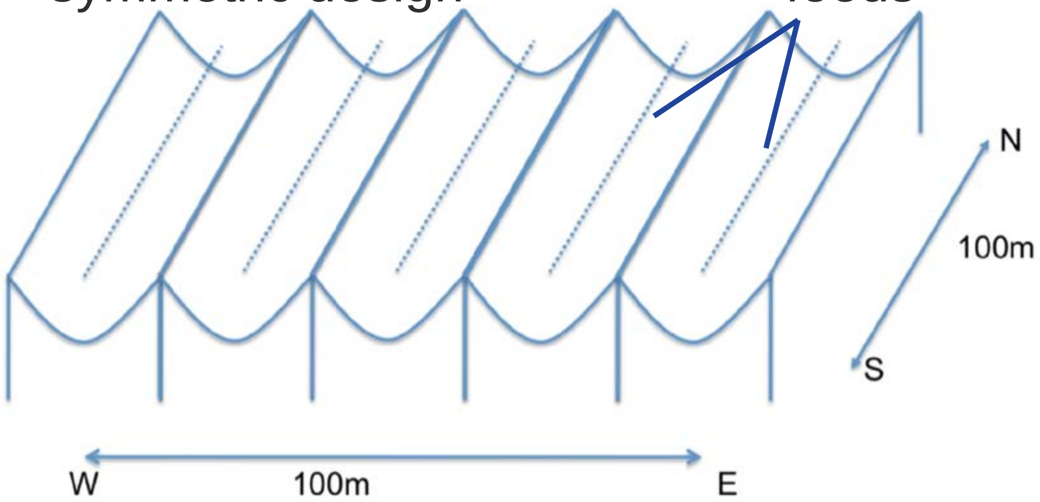


Ansari et al., 1108.1474

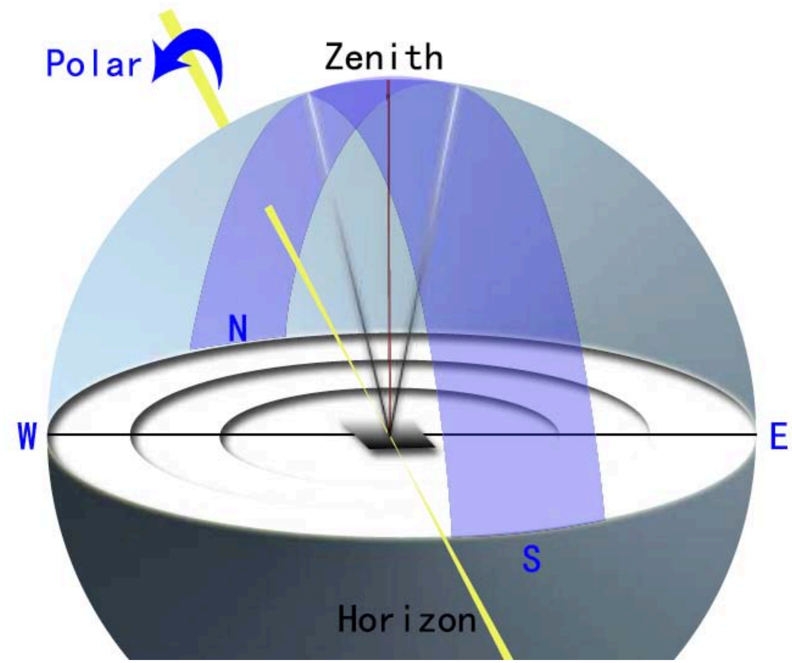
Cylinder Radio Telescope

symmetric design

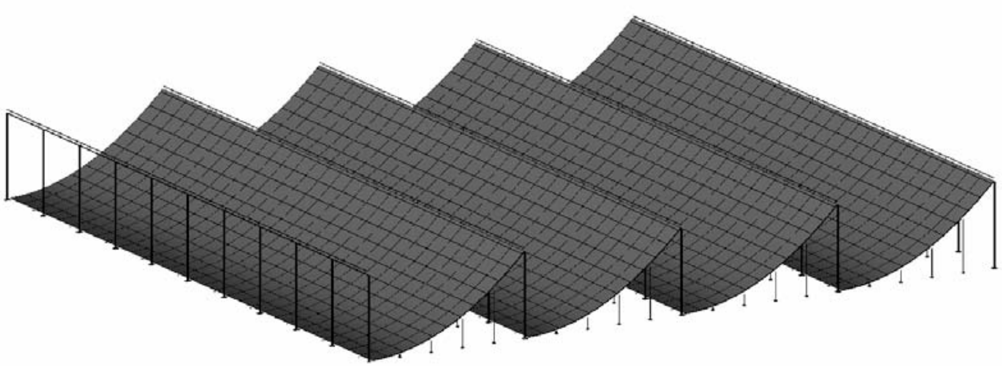
feeds



Jeff Peterson et al. 2006



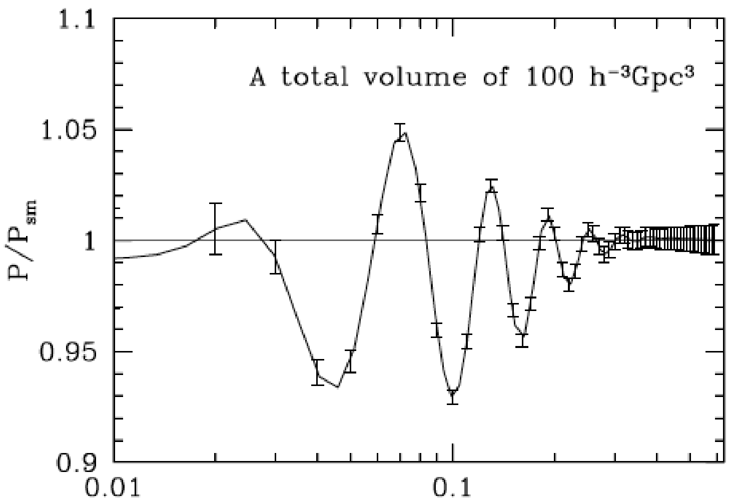
asymmetric design



instant field of view

Experimental Design Study

H. Seo et al. 2009



X. Wang & X. Chen, in preparation

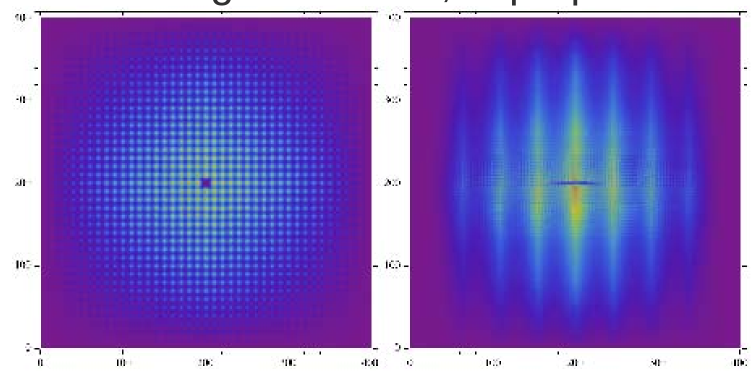
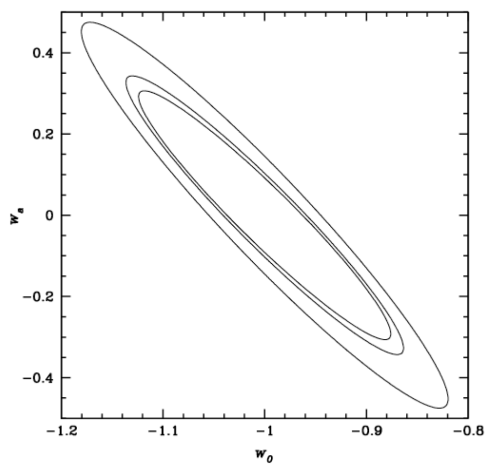


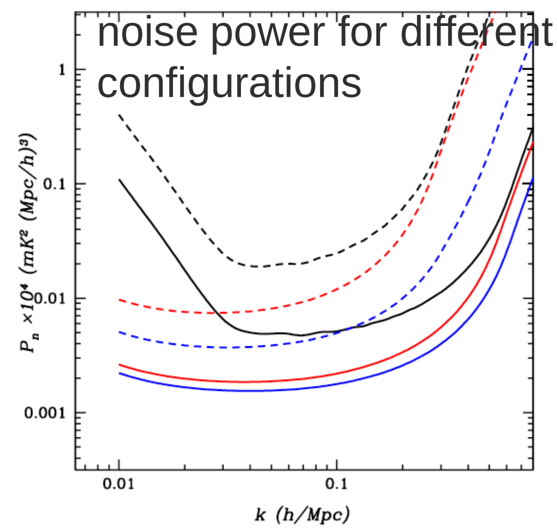
Fig. 4.— u-v coverage of natural map for both dishes (*left*) and cylinder(*right*).

dish vs cylinder

X. Wang & X. Chen, in preparation



noise power for different configurations

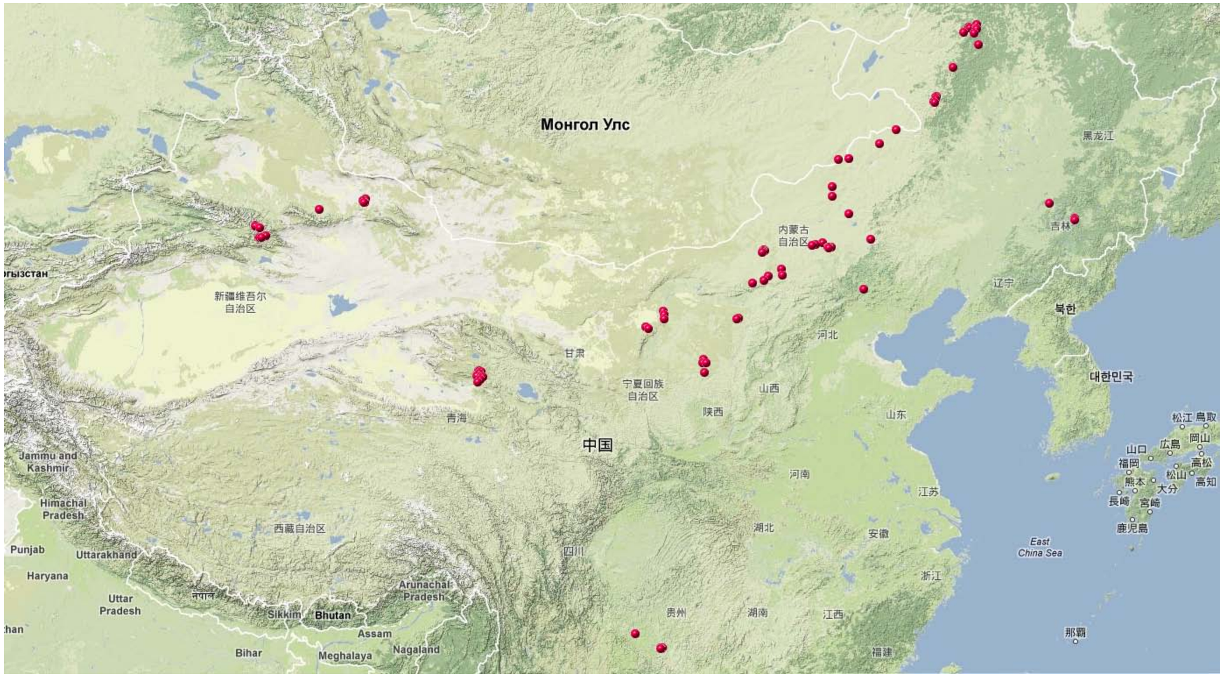


Pilot Experiment

- A small pilot experiment to check the basic principles and designs, find out potential problems
- 3x15x40m cylinders (can expand if additional fund available)
- 4 years
- allow using later technology at the full scale experiment
- whole project: about 8-10 years
- Alternative: instead of cylinders, use small dishes (about 5-10m)

Site Surveys in China

- Low RFI (low population density, shielded by mountains)
- wide open terrain
- convenience in logistics, electricity,communication




新疆和静县大山口站址

Thanks