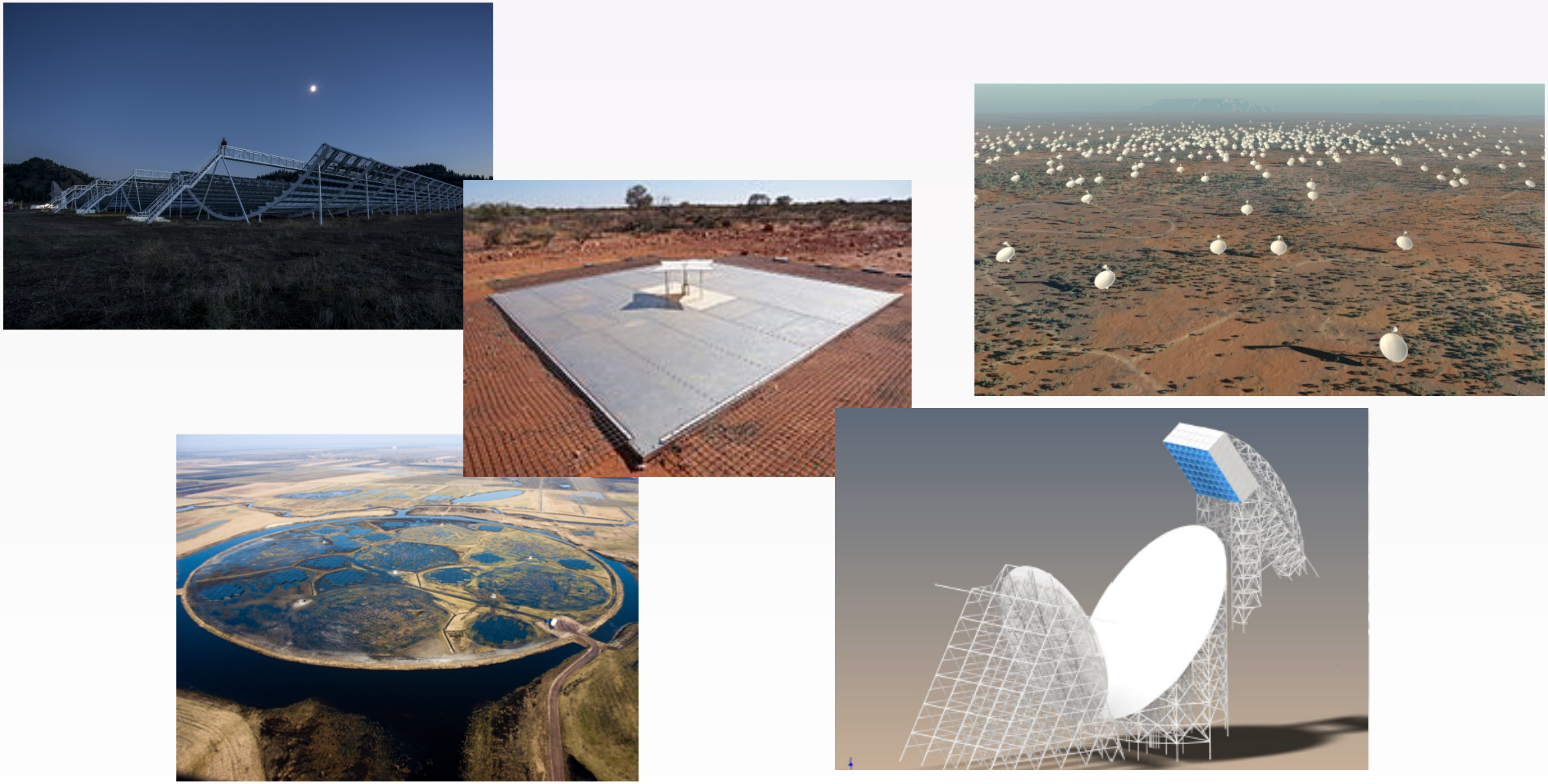
21cm as a cosmological probe!



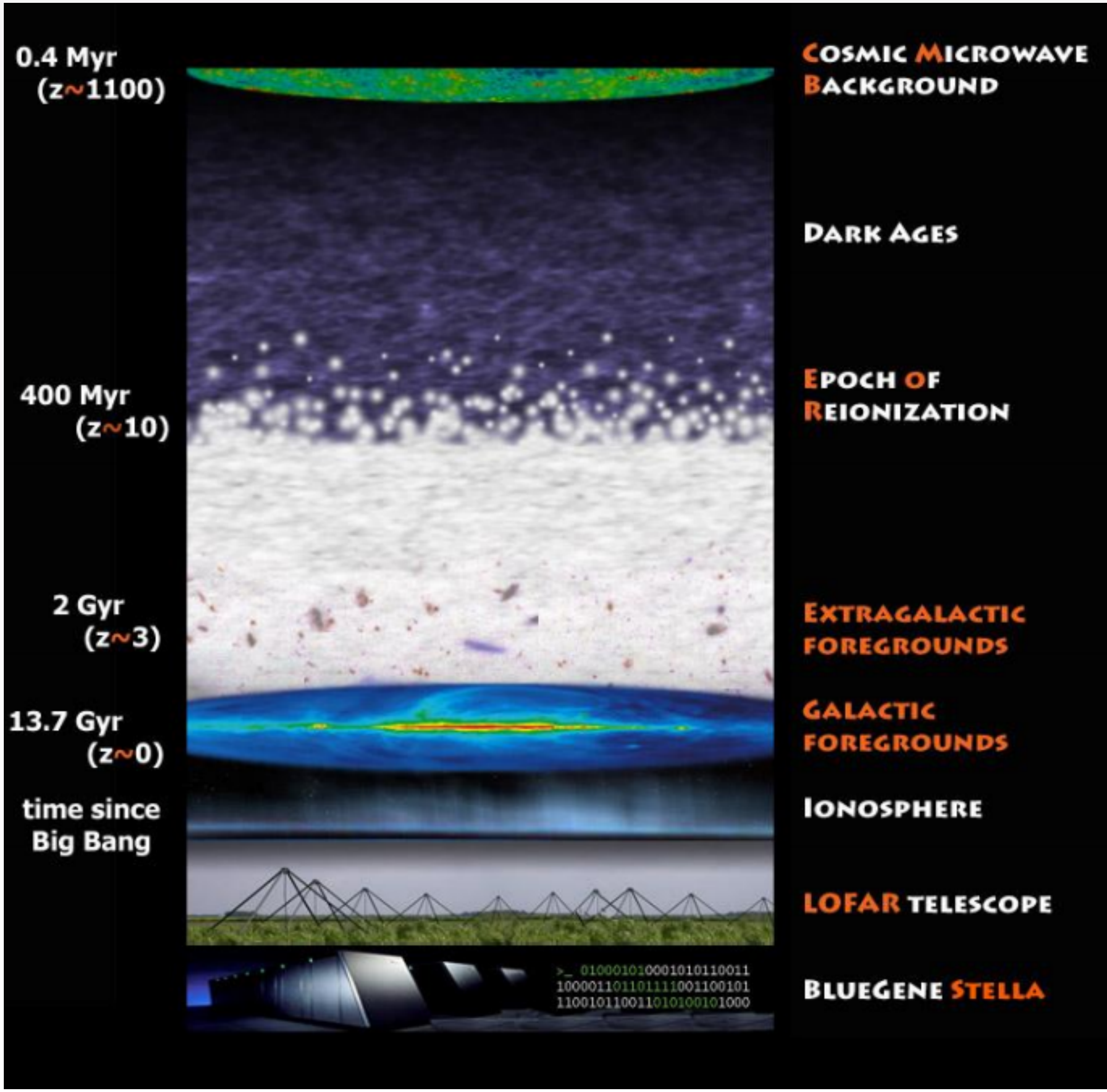
Filipe B. Abdalla

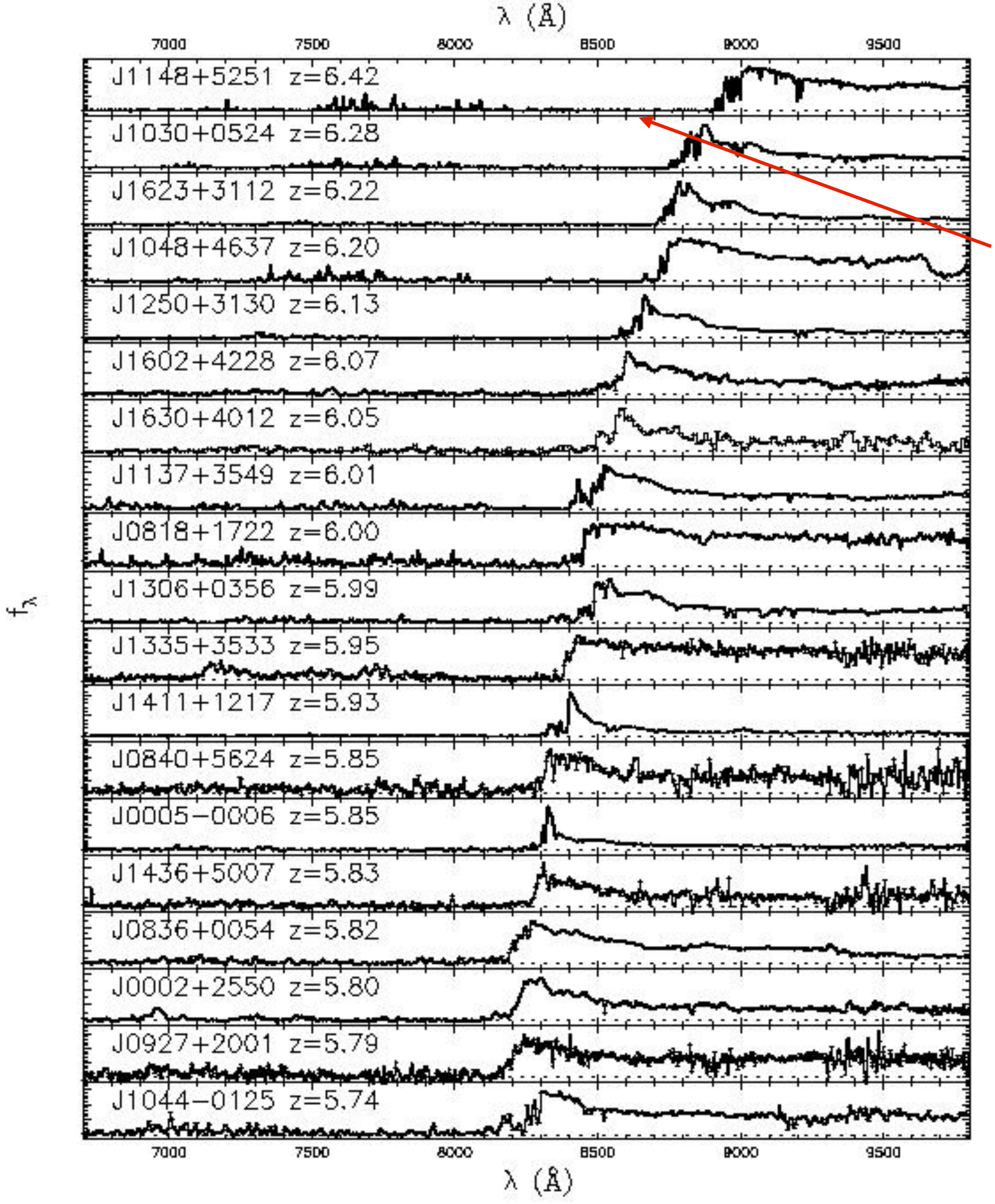
Outline:

- Background of the 21cm: EoR and IM
- Current status on IM.
- One of the main problems: Foreground subtraction.
- Looking forward

The History of our Universe.

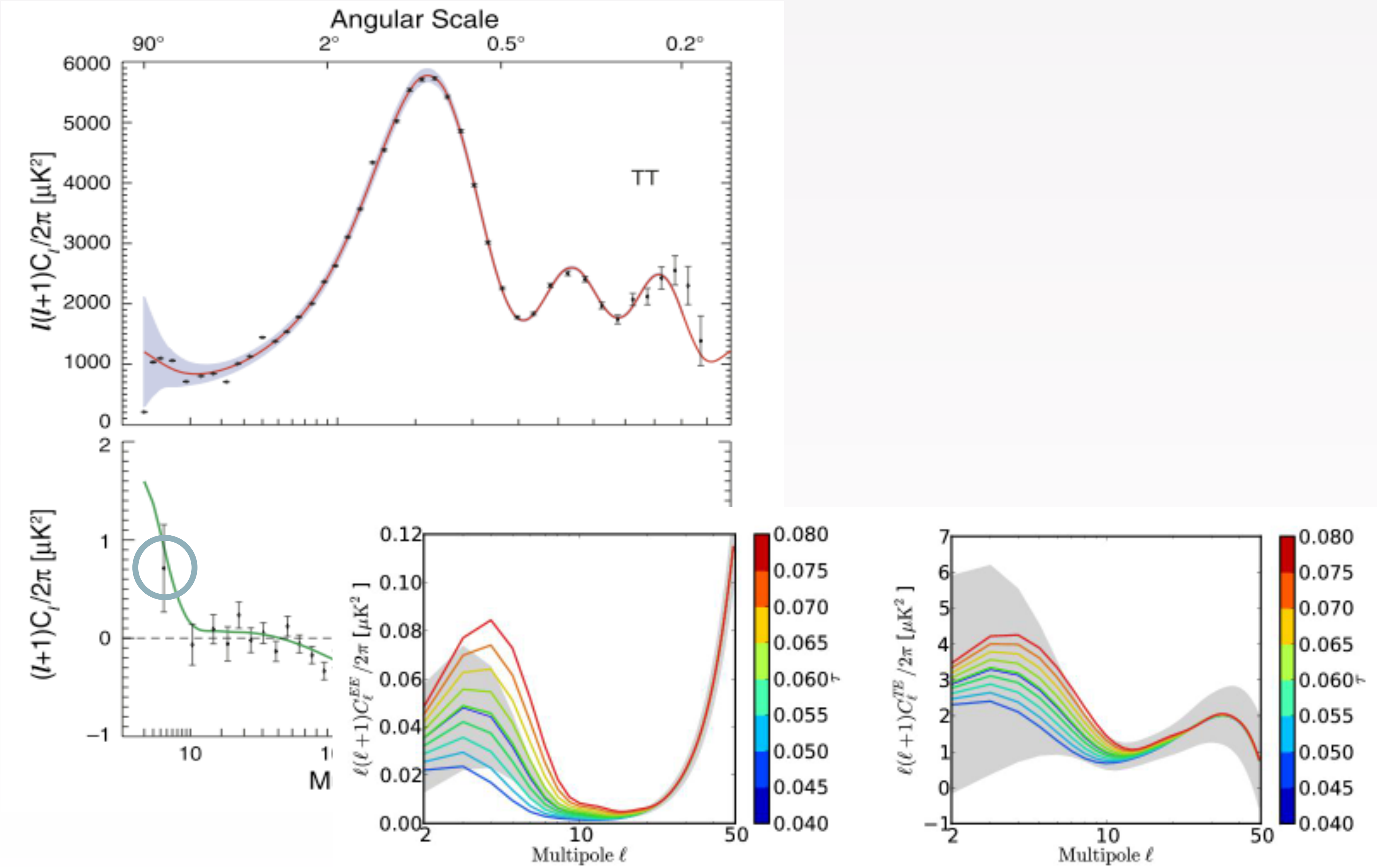
- We have a extremely well measured CMB sky.
- We are a long way measuring the LSS of the Universe near us.
- The EoR and the dark ages remain a mystery and unmeasured territory.



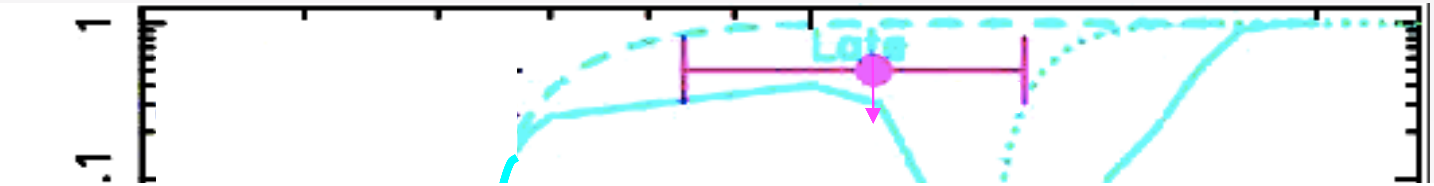


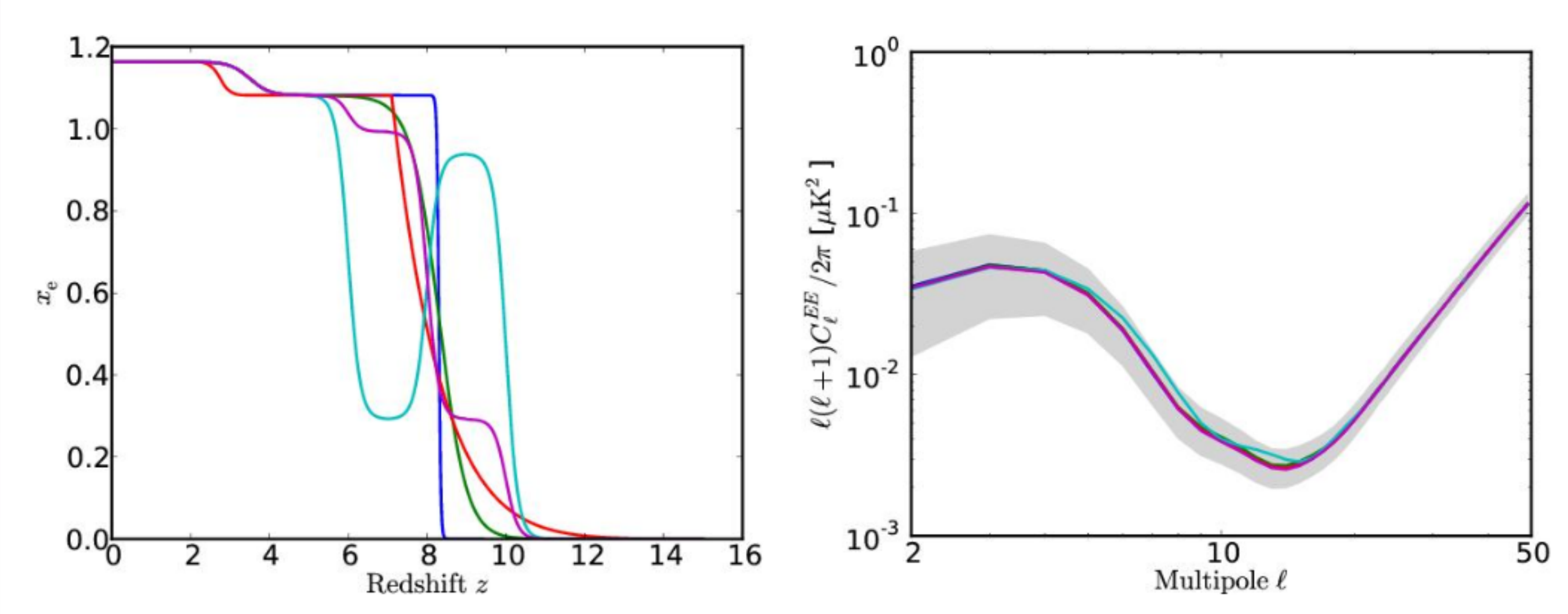
Gunn-Peterson Effect toward z~6 SDSS QSOs

Constraint: CMB large scale polarization WMAP



Combined CMB + GP constraints on reionization

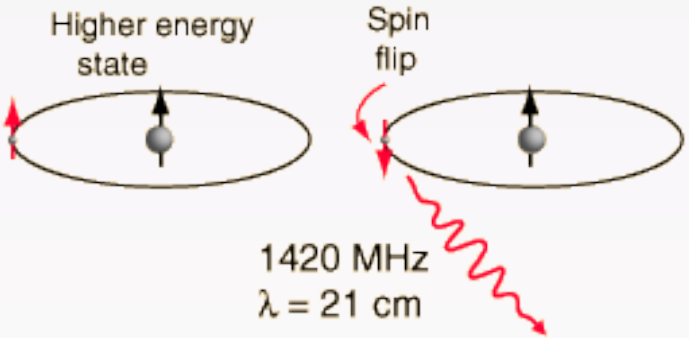




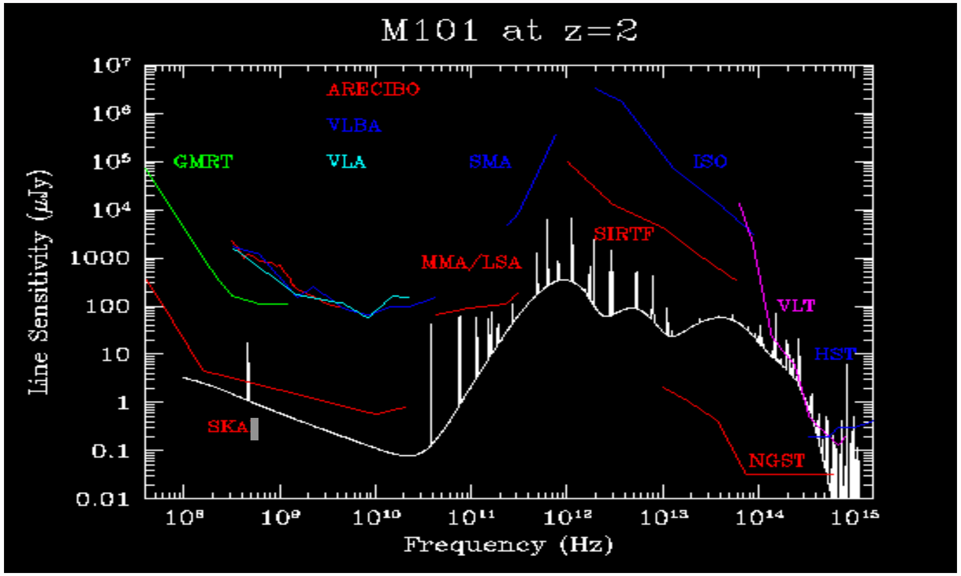
τ_e = integral measure to recombination=>

allows many IGM histories …. Further constraints from kSZ…

21cm Radiation



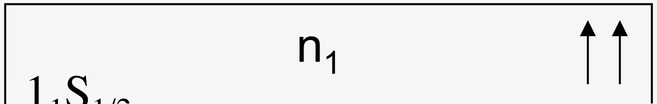
$$\lambda_{obs} = (1+z)\lambda_{21cm}$$



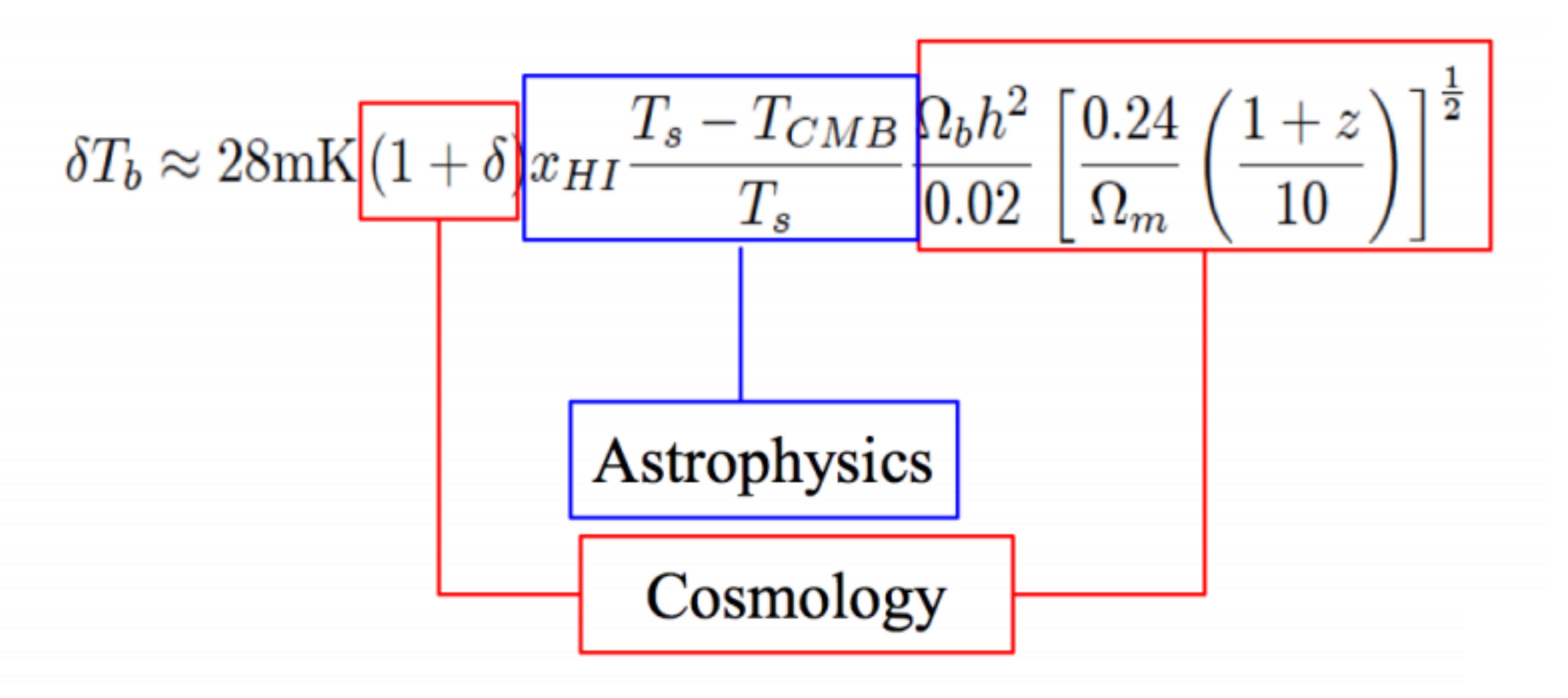
21 cm basics

- Use CMB backlight to probe 21cm transition

- HI hyperfine structure



$n_1/$



$$\delta T_b \approx 28\mathrm{mK}\,\boxed{(1+\delta)}\,\boxed{x_{HI}\frac{T_s - T_{CMB}}{T_s}}\,\boxed{\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}}$$

Astrophysics

Cosmology

0

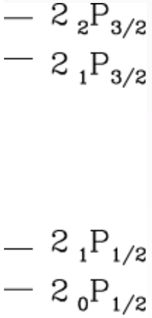
0 MHz

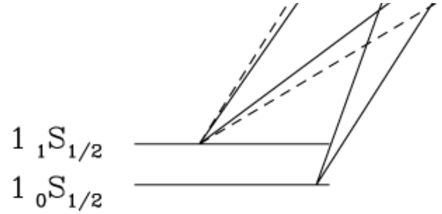
- 3D
- 21

T

- 21 cm spin temperature

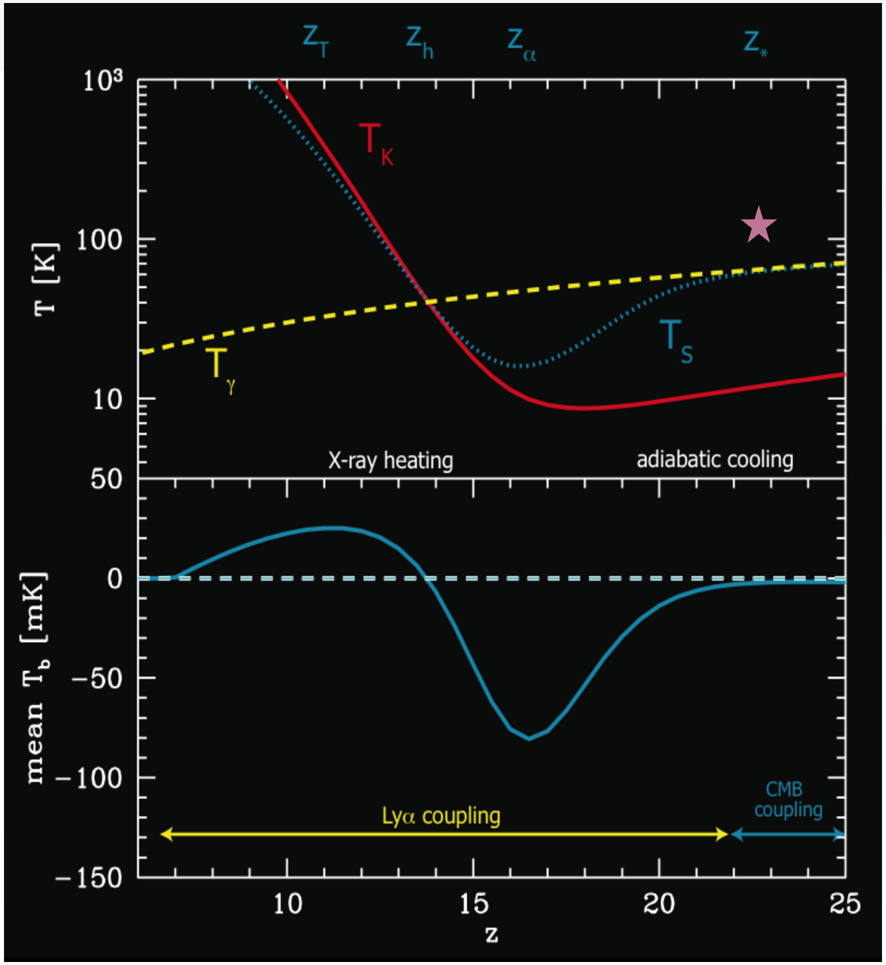
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



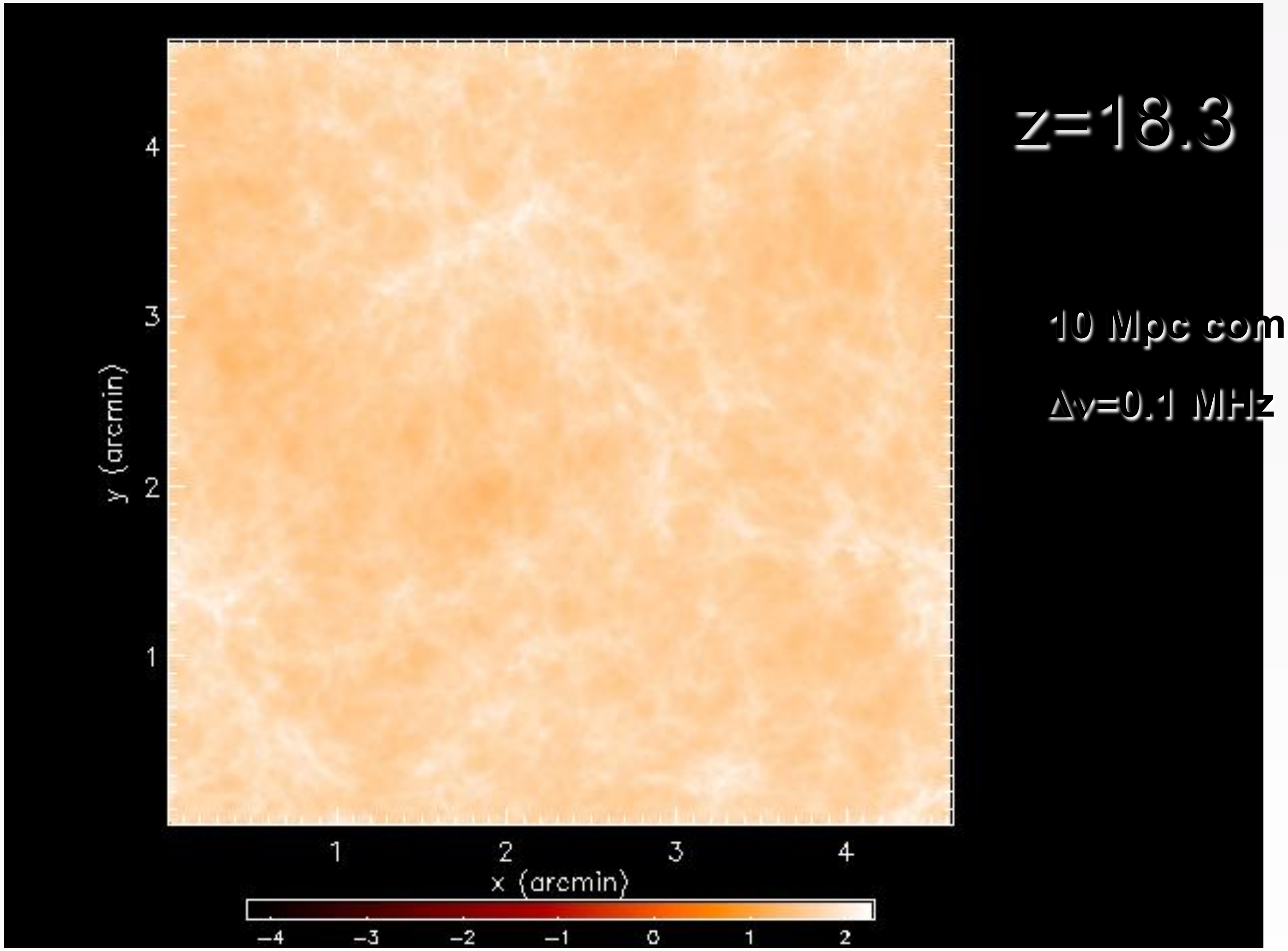


The global evolution of the spin temperature

- Ts is coupled to the CMB at high redsfhits.
- Collisional processes make the spin temperature decouple from the CMB temperature. At this stage we an observe a difference between both.
- At lower redfshits, the first sources produce Lyman alpha and heat the gas. This makes a temperature change and a signal in emission may be seen



21 cm Observations: Emission

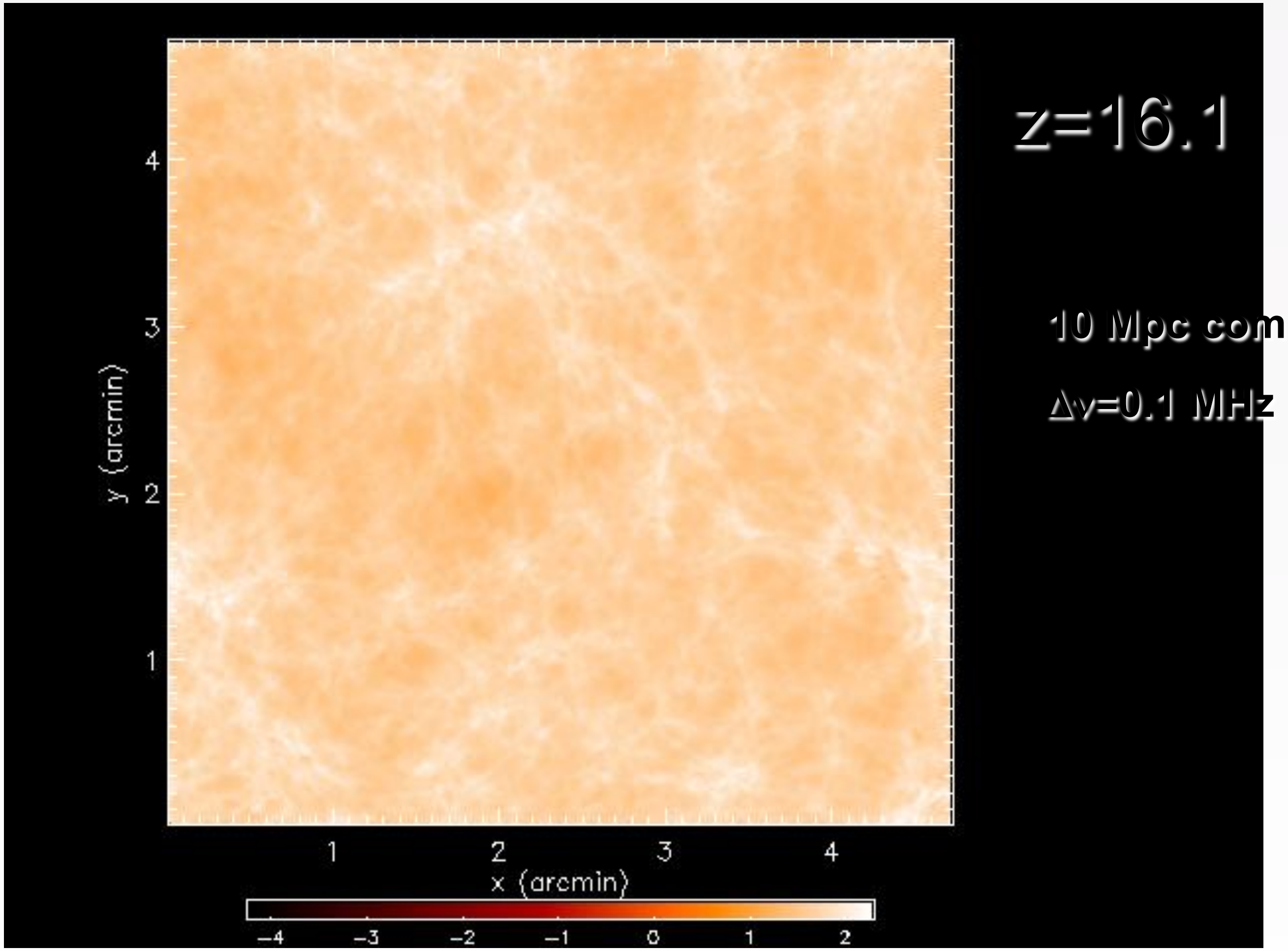


10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



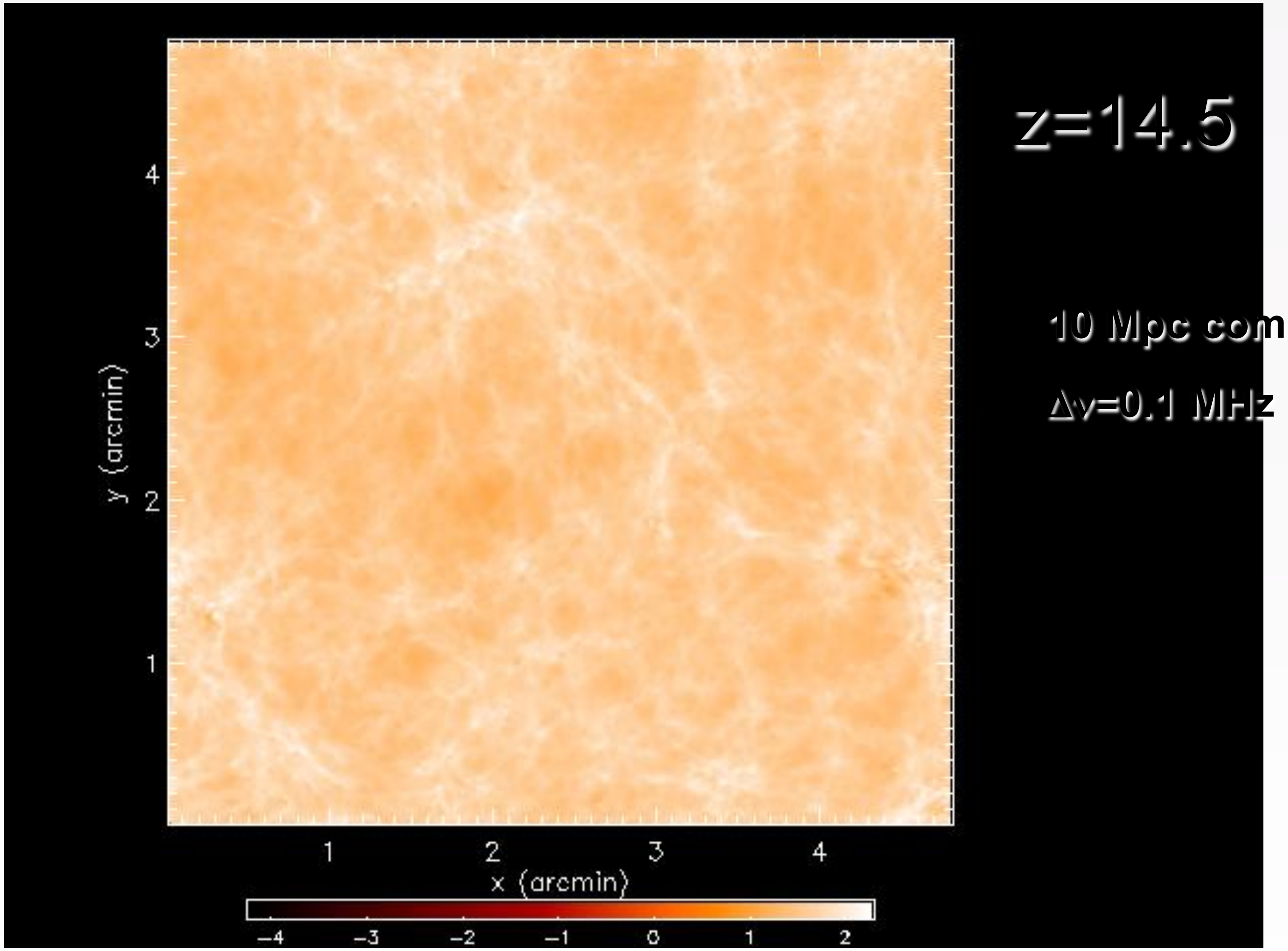
z=16.1

10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



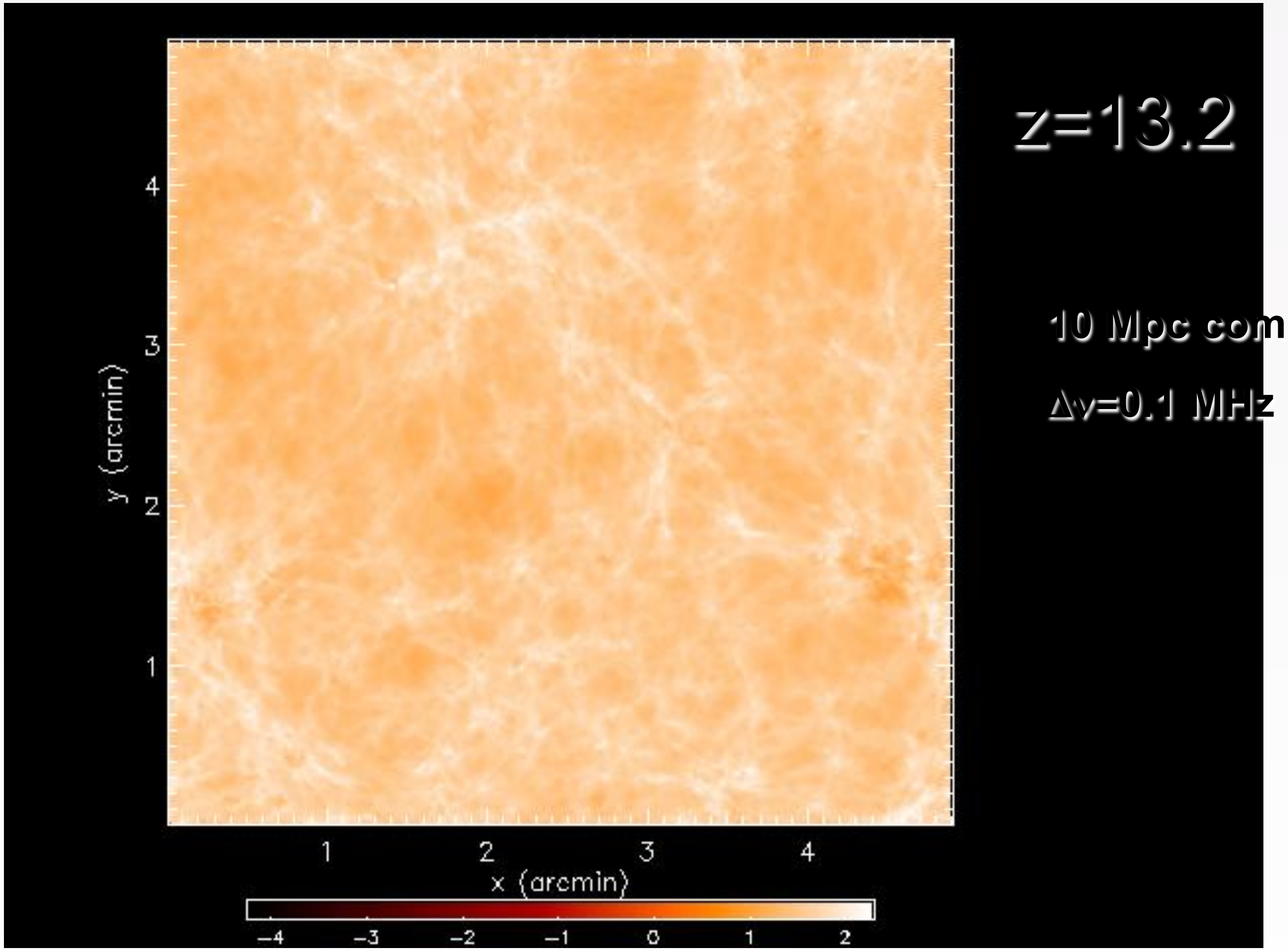
z=14.5

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



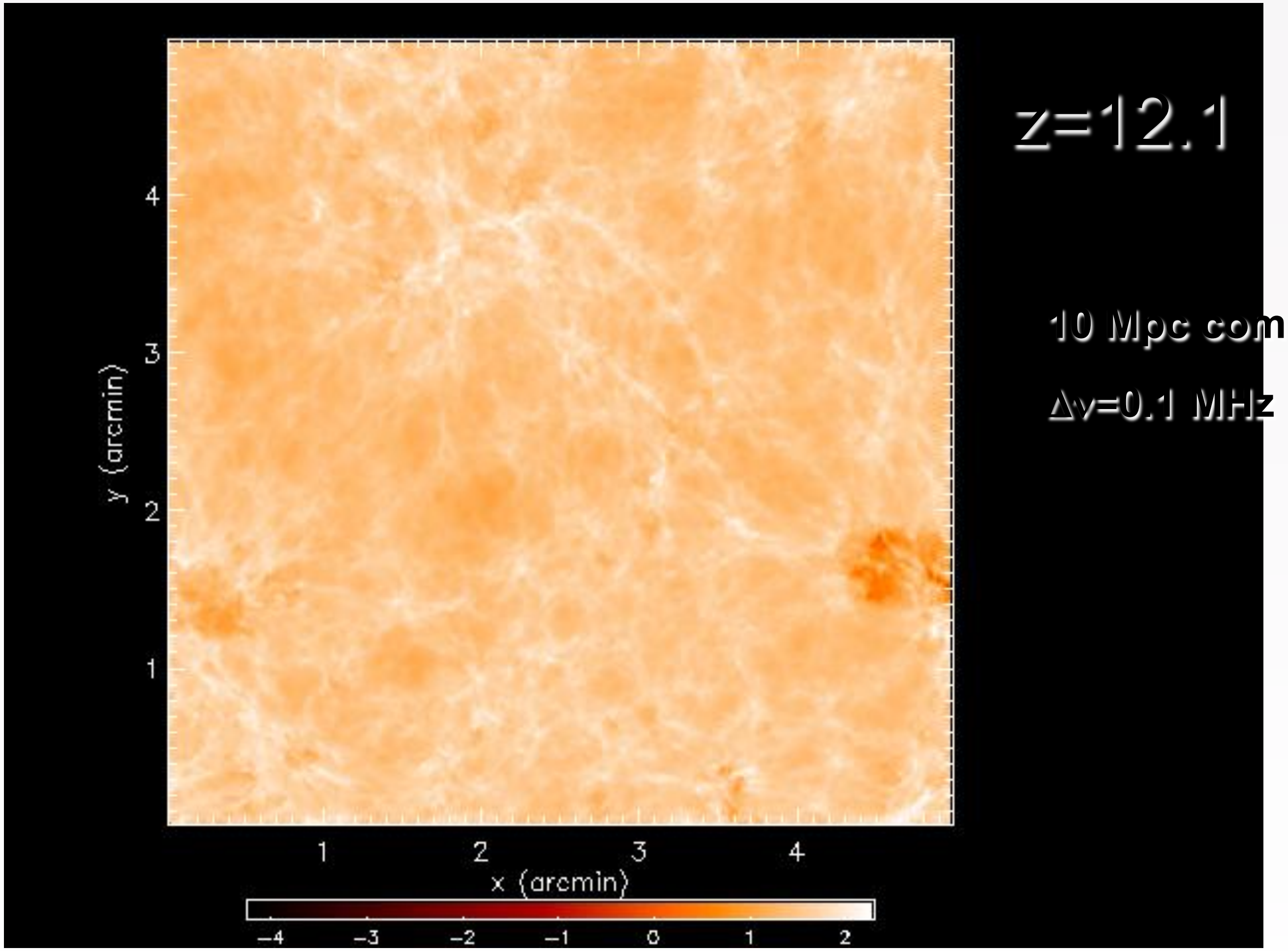
z=13.2

10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission

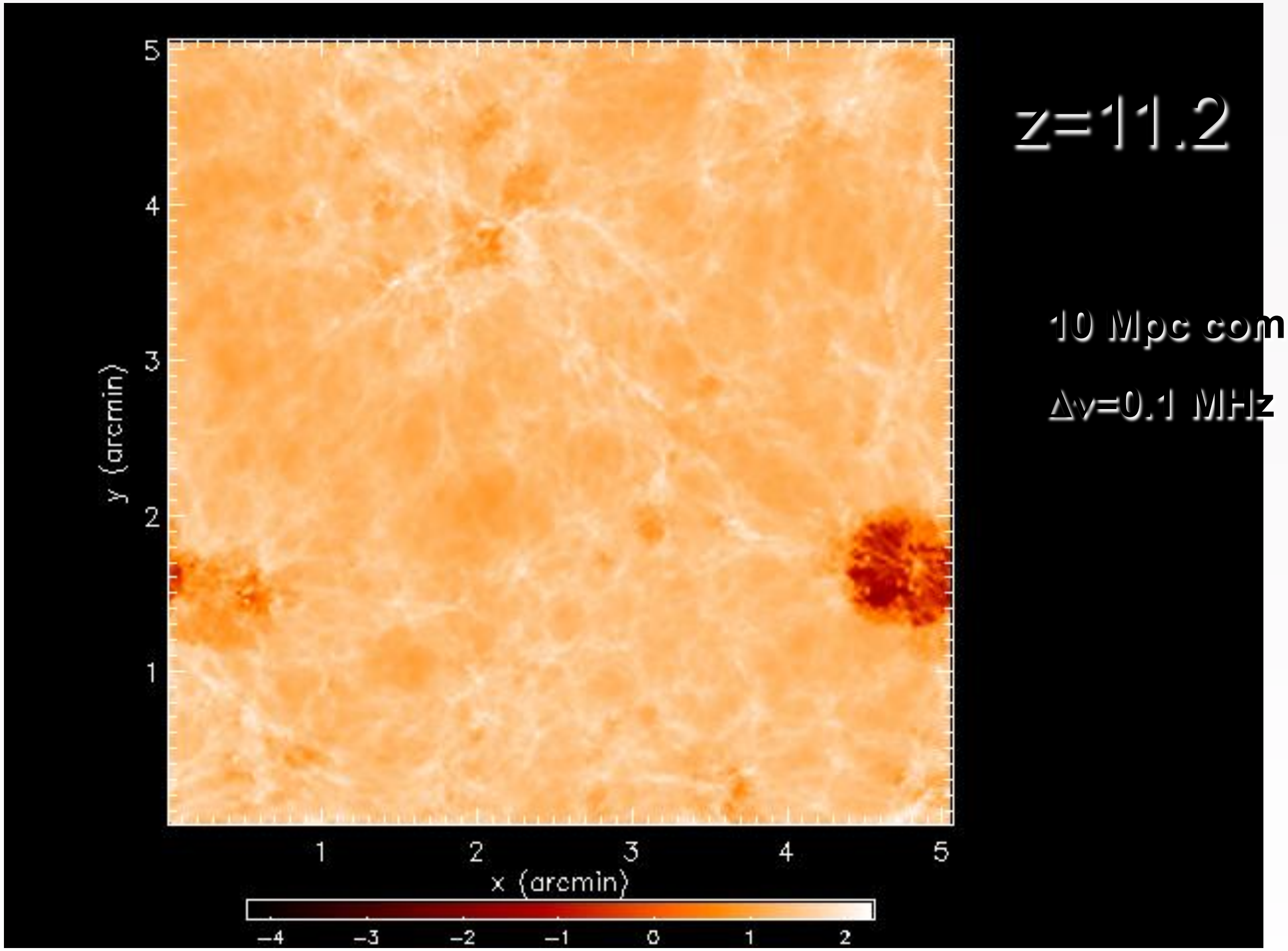


10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



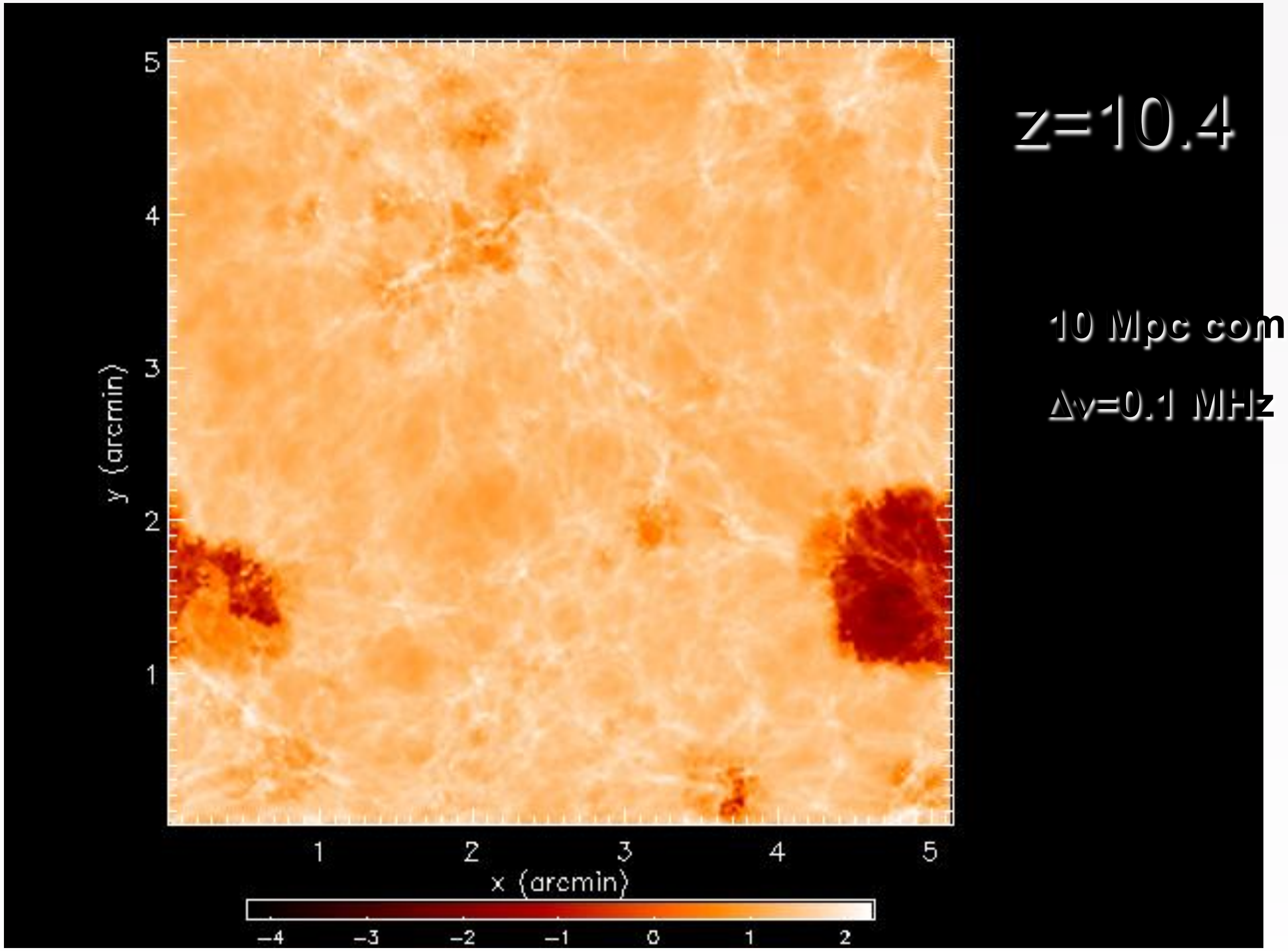
z=11.2

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



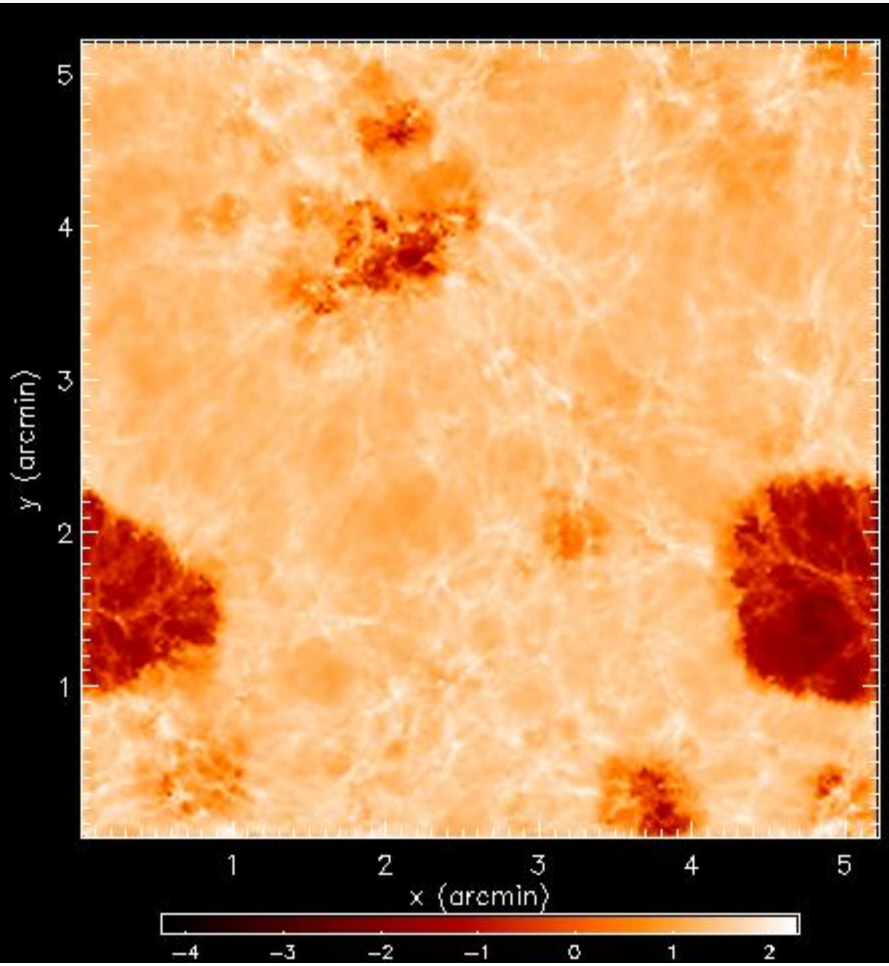
z=10.4

10 Mpc comoving

$\Delta\nu=0.1$ MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



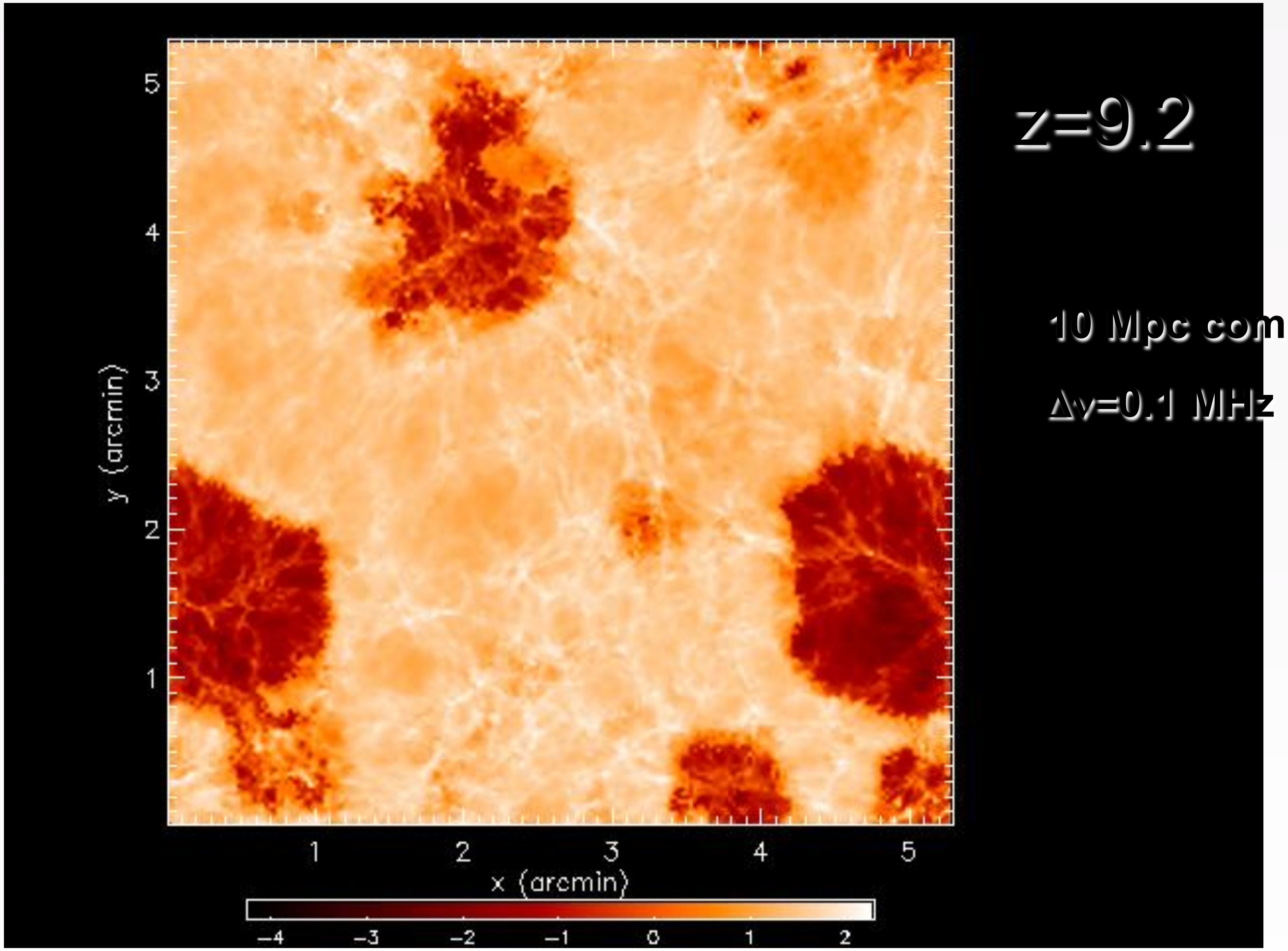
z=9.8

10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



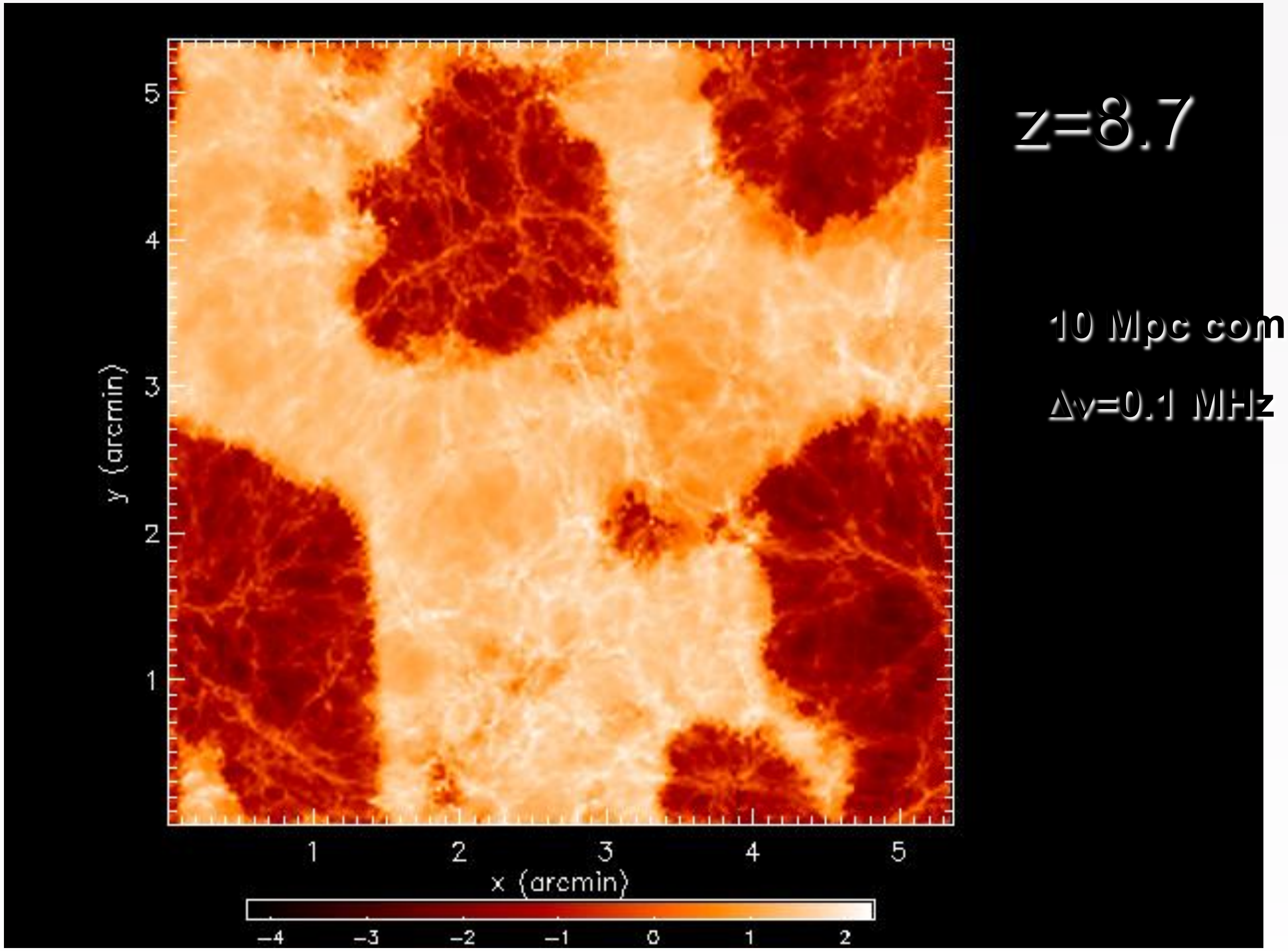
$z=9.2$

10 Mpc comoving

$\Delta\nu=0.1$ MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



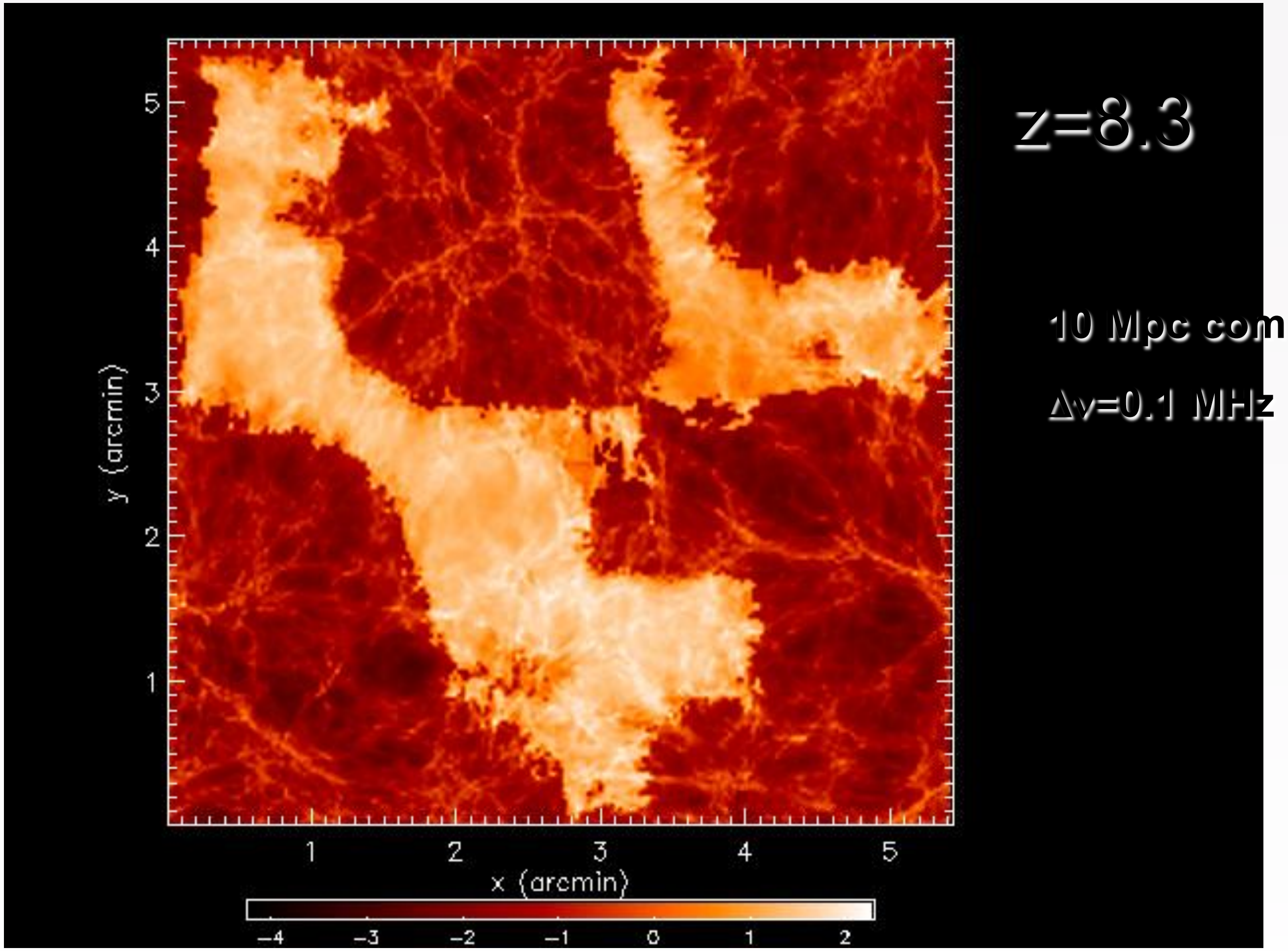
$z=8.7$

10 Mpc comoving

$\Delta\nu=0.1$ MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



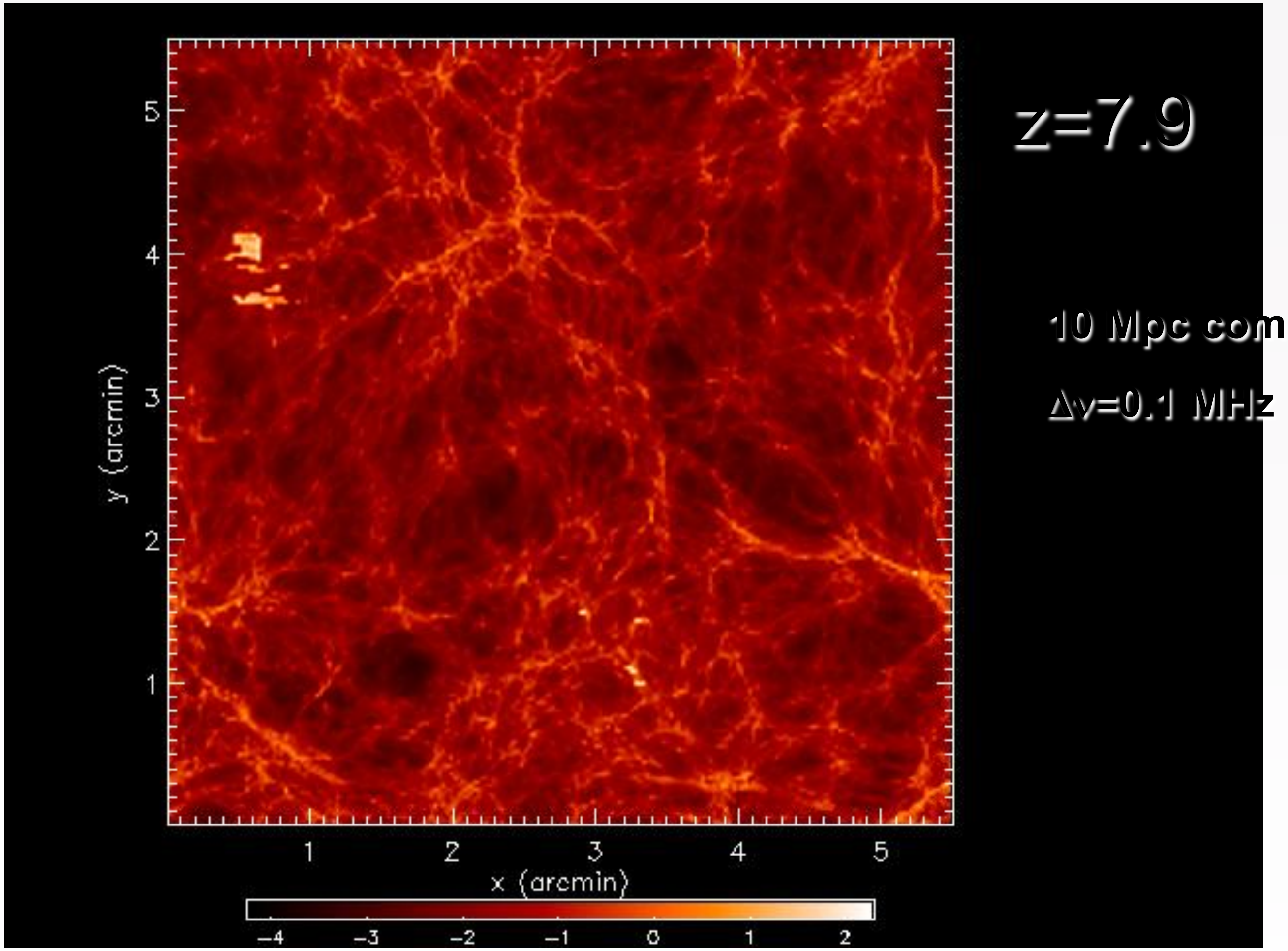
$z=8.3$

10 Mpc comoving

$\Delta\nu=0.1$ MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



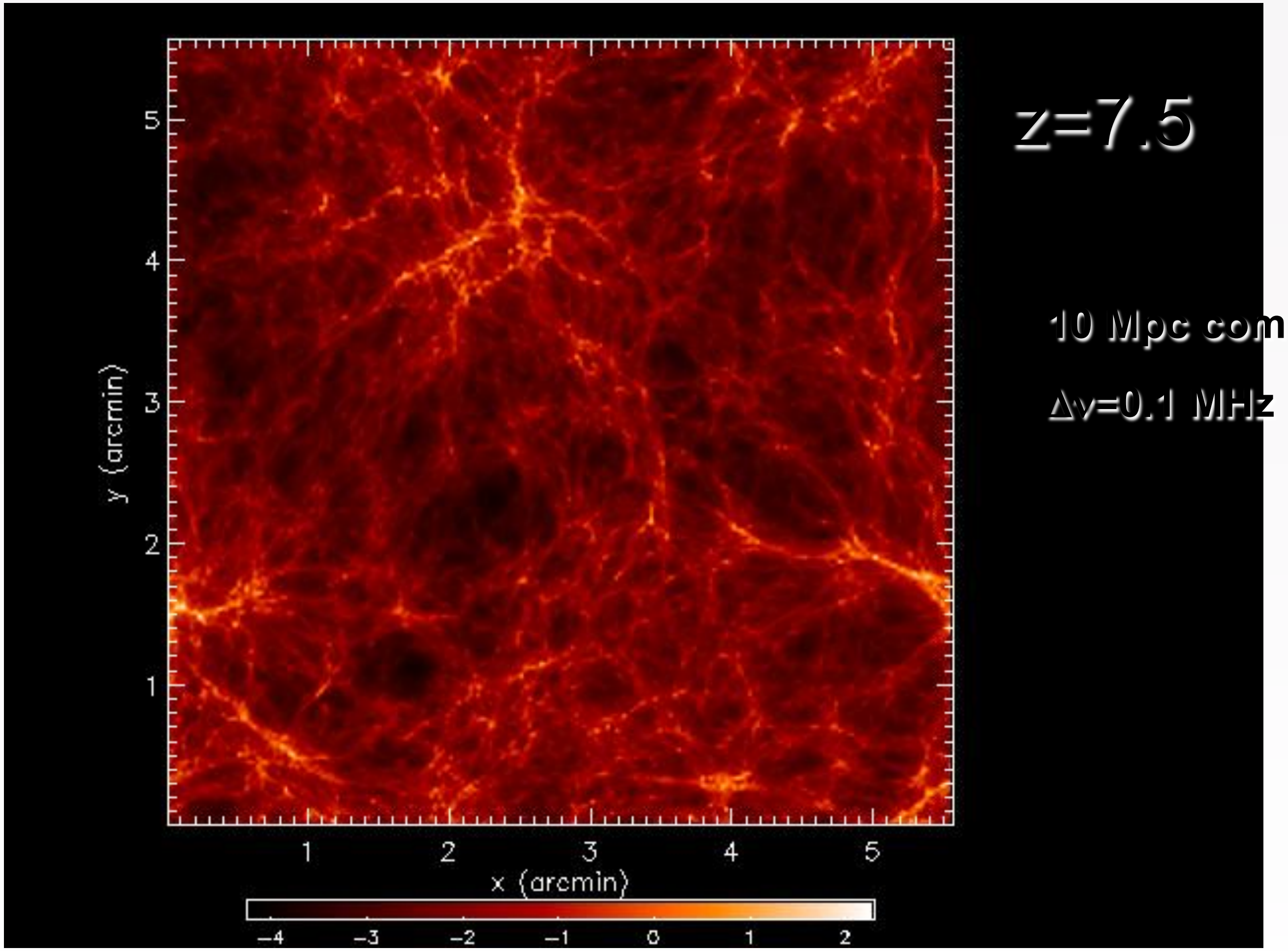
z=7.9

10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission

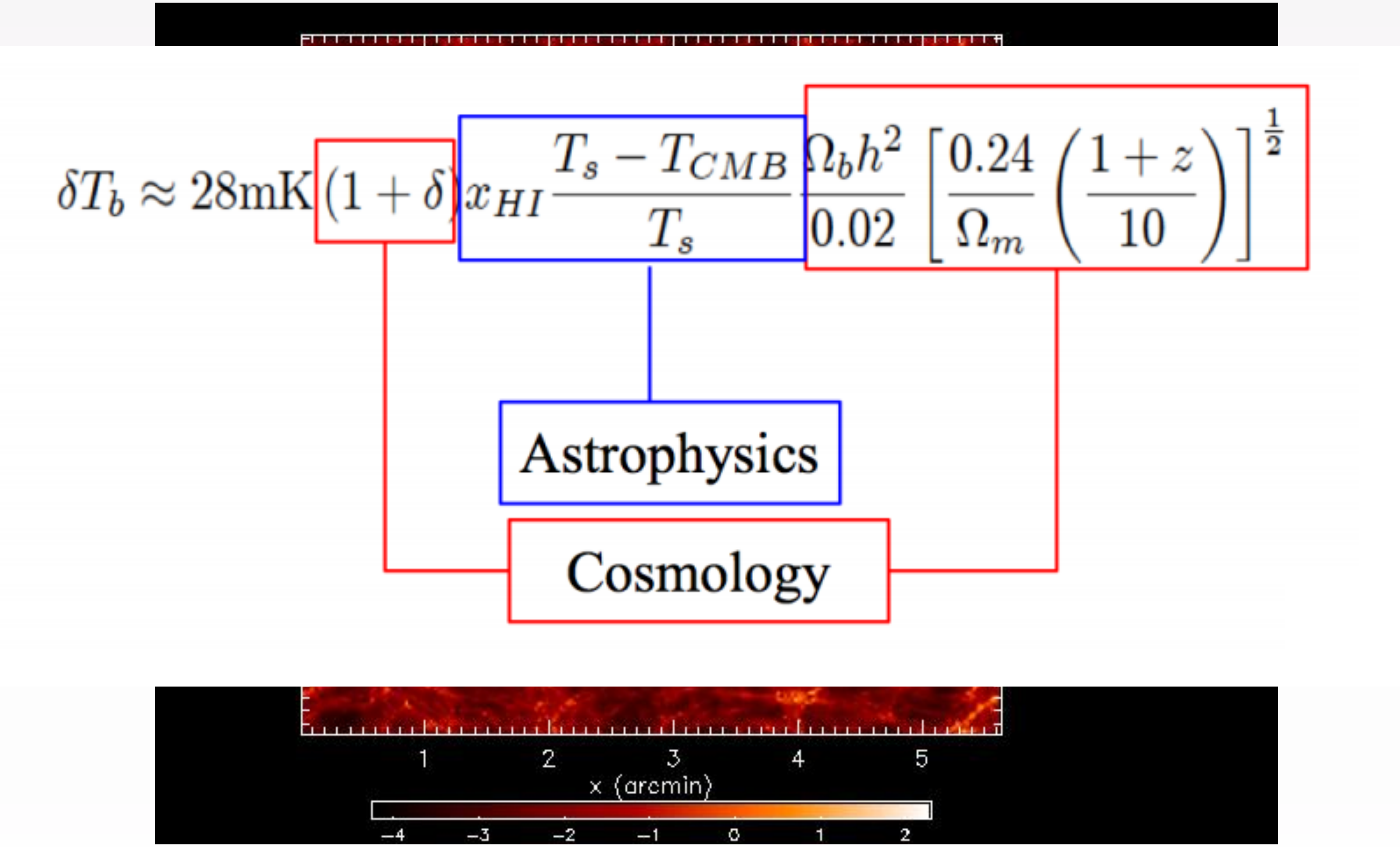


10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



$$\delta T_b \approx 28\mathrm{mK}\boxed{(1+\delta)}\boxed{x_{HI}\frac{T_s - T_{CMB}}{T_s}}\boxed{\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}}$$

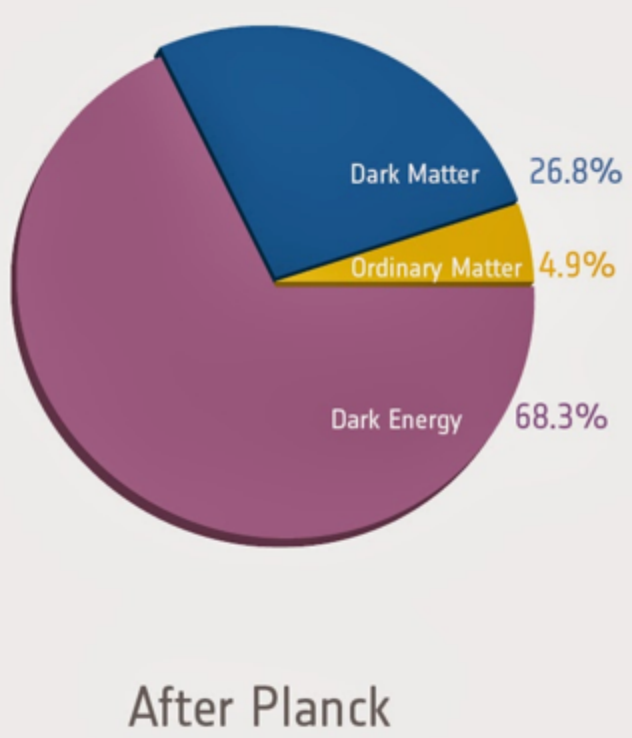
Astrophysics

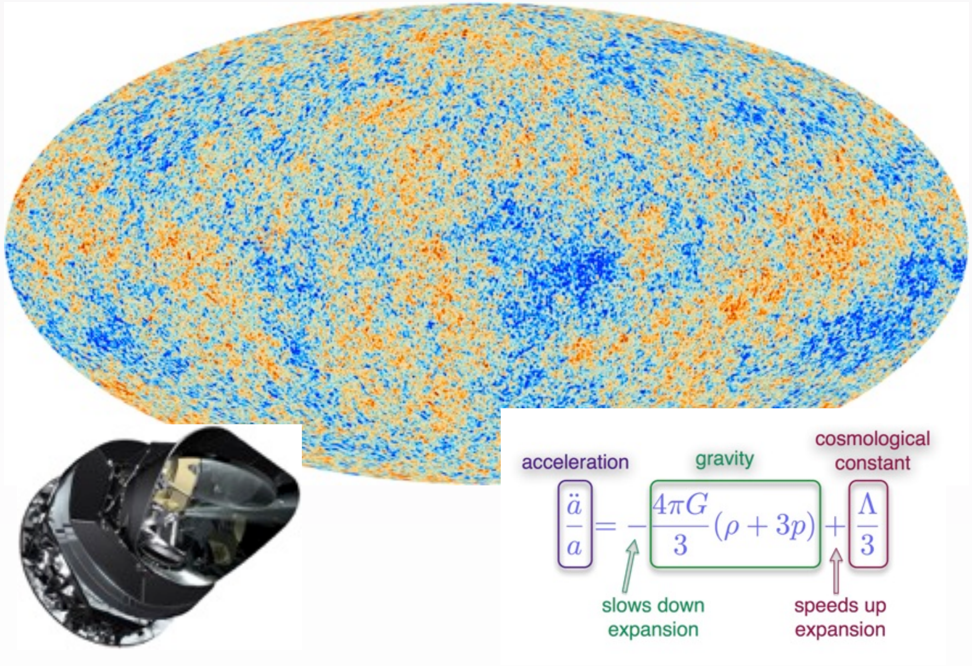
Cosmology

Furlanetto et al. (2003)

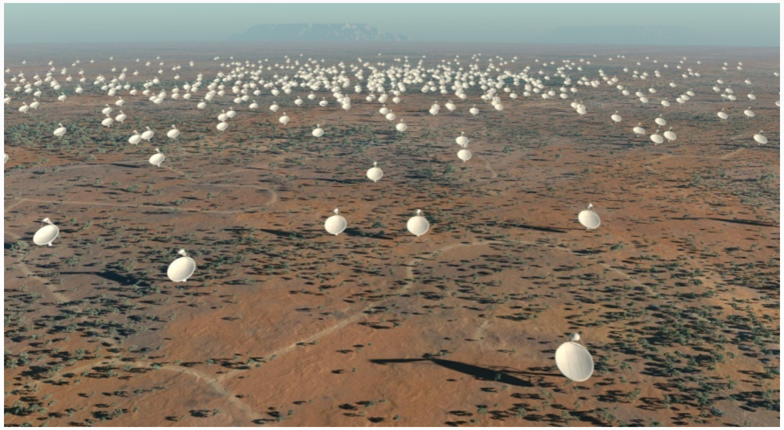
Era of precision cosmology

- Cosmology is now in a golden area
  - Standard ΛCDM model appears to be the best descripton so far!
- But still major questions remain!
  - Inflation ($t<10^{-32}$ s)
  - Dark energy





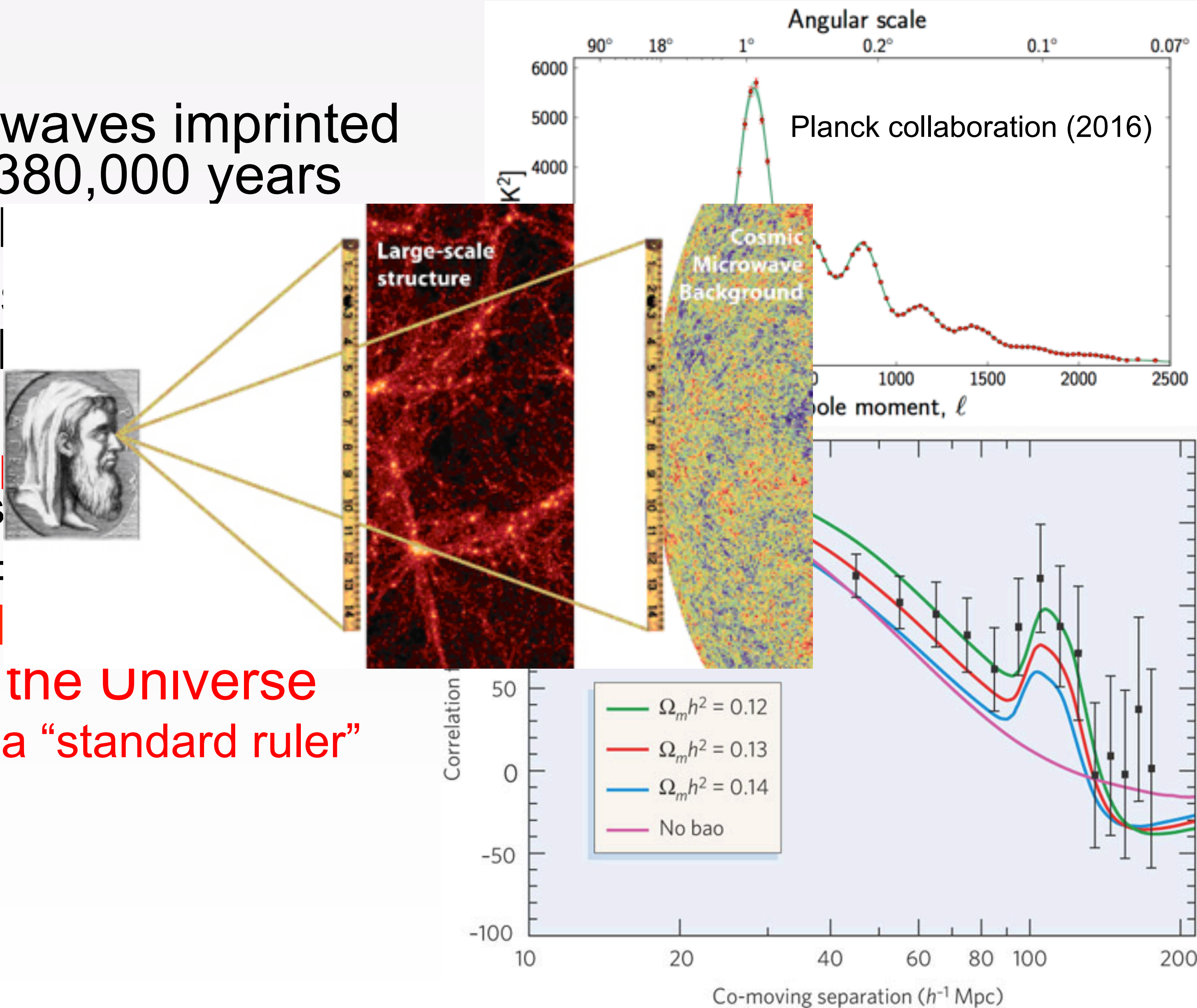
$$\boxed{\frac{\ddot{a}}{a}} = -\boxed{\frac{4\pi G}{3}(\rho + 3p)} + \boxed{\frac{\Lambda}{3}}$$



CMB map from Planck collaboration et al. (2016)

Baryon Acoustic Oscillations (BAOs)

- Acoustic waves imprinted on CMB 380,000 years after Big
- Acoustic
  distance
  that time
  - Known
    power s
  - D=149
- BAO scal
  matter in the Universe
  - Use as a “standard ruler”



Planck collaboration (2016)

Alternative to optical BAO: HI Intensity mapping

Use relatively large beam on the sky

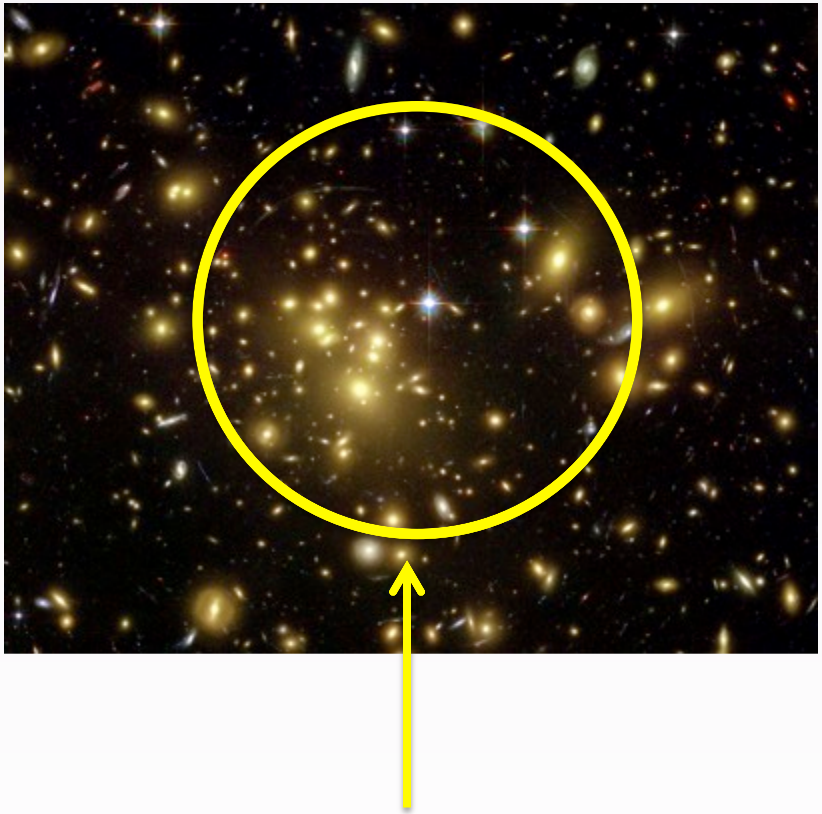
- ☐ Measure HI *fluctuations*
- ☐ Similar to CMB, using

$$\Delta T_{HI} = \Delta T_{HI}(\theta, \phi, z)$$

$$\Delta T_{CMB} = \Delta T_{CMB}(\theta, \phi, z = 1100)$$

- ☐ HI intensity mapping can be used as mass tracer, probing distortions in redshift space

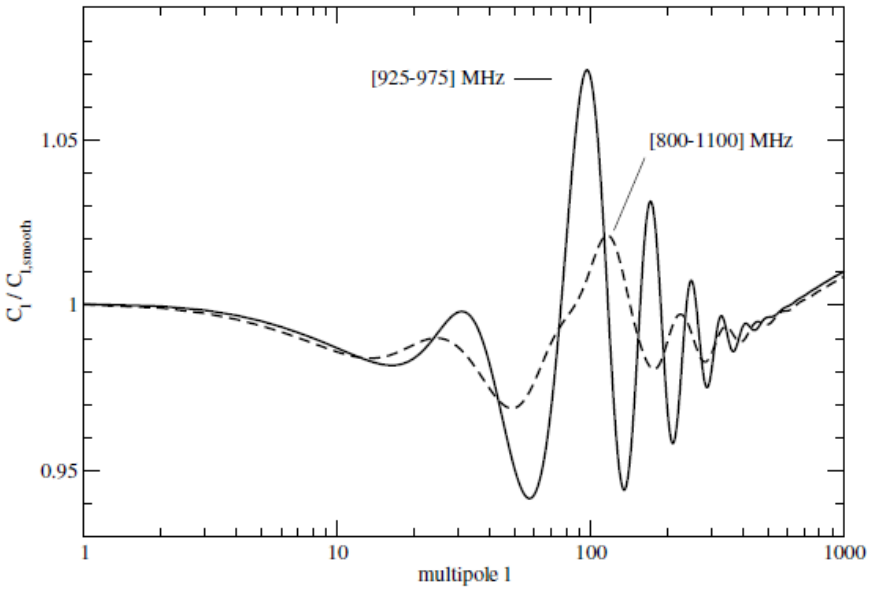
- ☐ No competition in the radio
- ☐ Complementary to large optical surveys



- Large beam on the sky (≈1 deg) contains many galaxies.
- HI signal is measured through its overall intensity

BAOs in Intensity mapping.

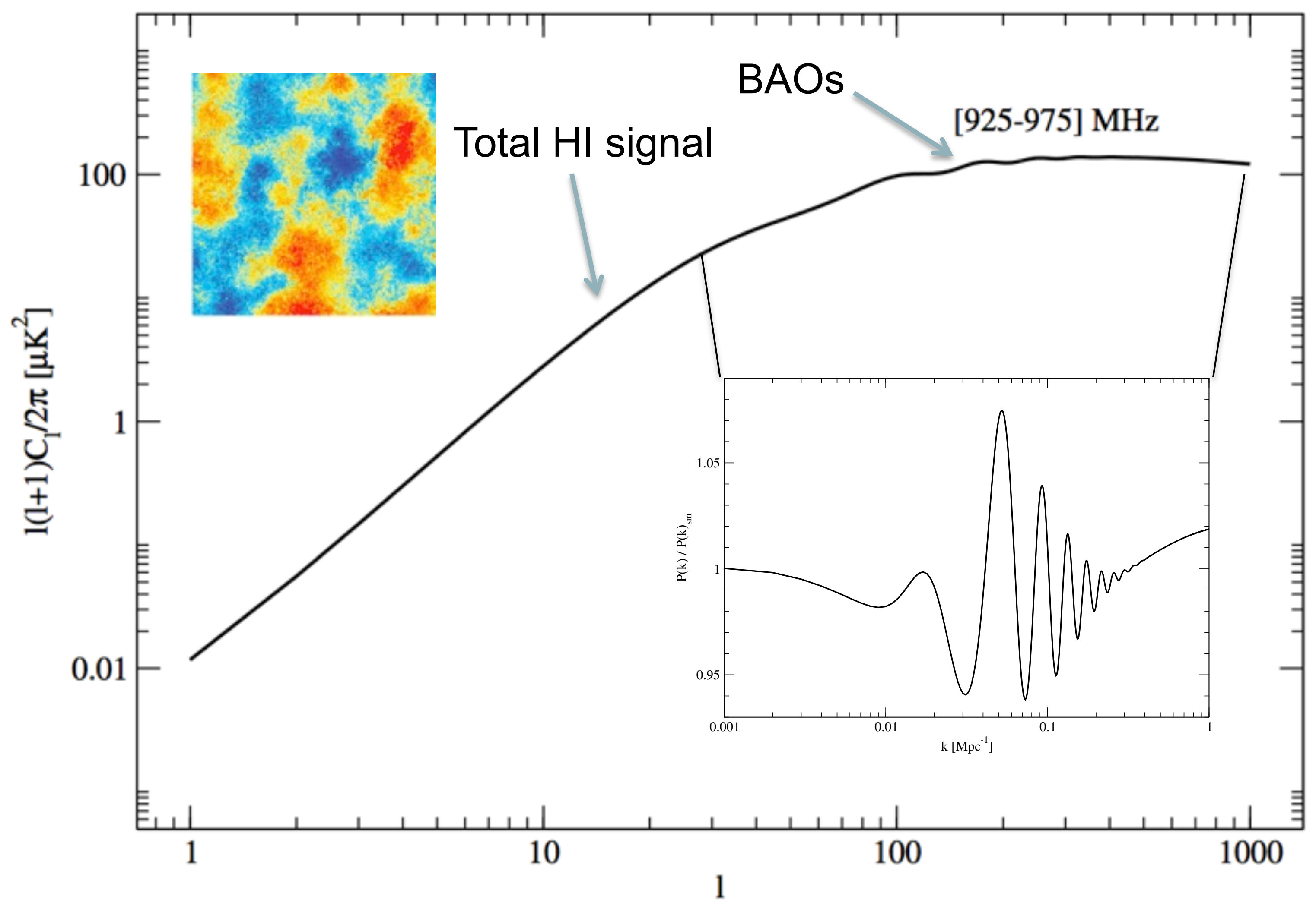
2-D angular power spectrum



- BAOs on scales few deg to ~30 arcmin at z=0.3
- Average in frequency to reduce noise (larger bandwidth)
- Averaging over ~50 MHz (equivalent to delta z ~ 0.05) is optimal
- Average more than this smoothes out the BAO wiggles

The HI signal power spectrum

Cosmological HI signal is weak! (≈100 μK rms) and on degree scales

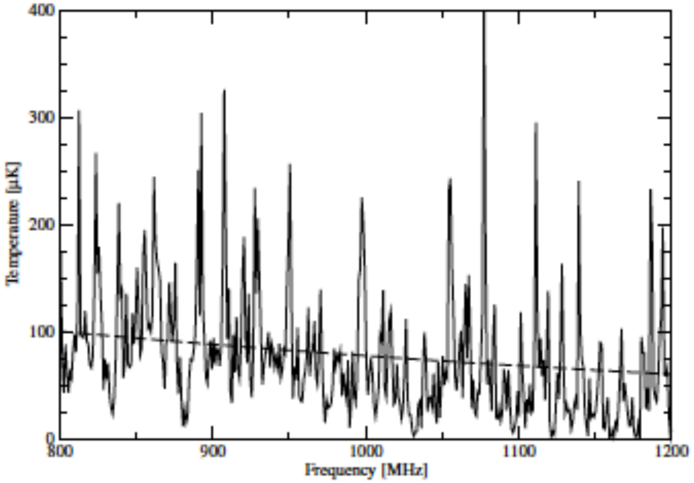


BAOs

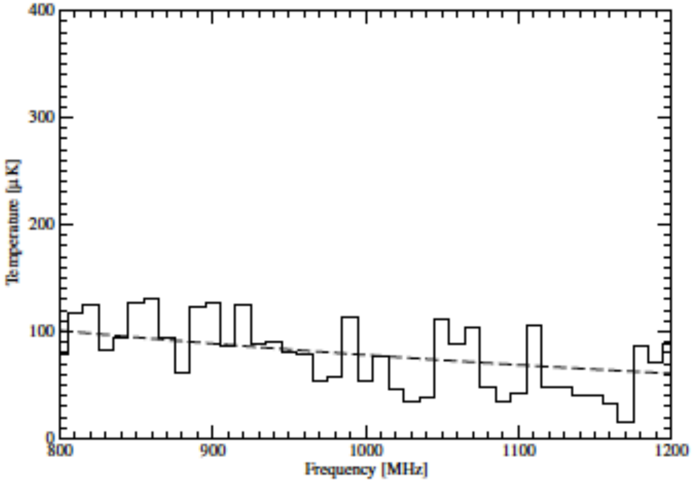
Total HI signal

$l \approx (200/\theta)$ degrees

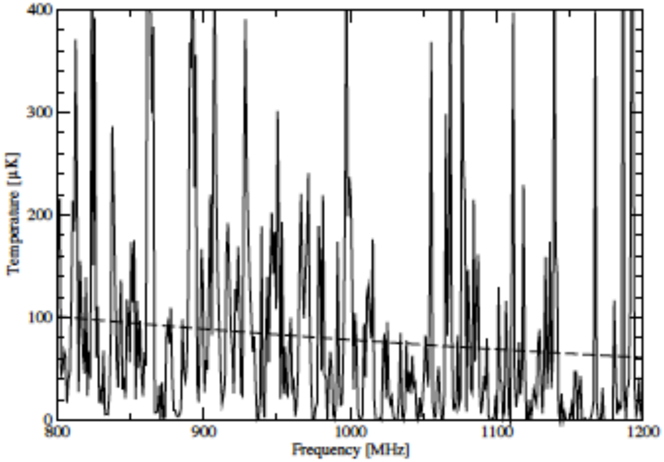
Frequency windows and FWHM



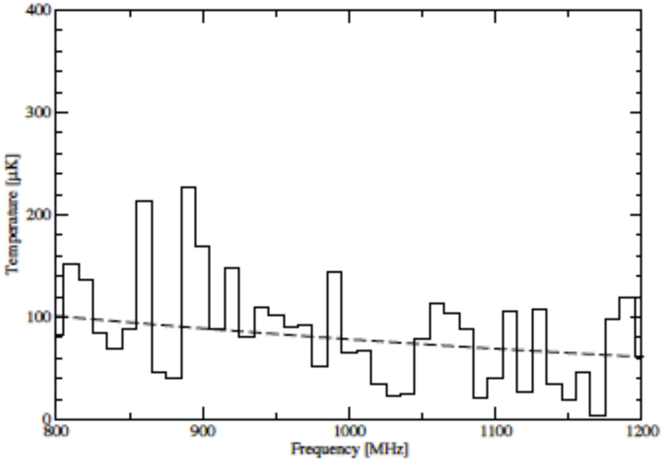
(a) $\Delta f = 1\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 60\,\mathrm{arcmin}$



(b) $\Delta f = 10\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 60\,\mathrm{arcmin}$



(c) $\Delta f = 1\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 20\,\mathrm{arcmin}$



(d) $\Delta f = 10\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 20\,\mathrm{arcmin}$

graphs from Battye et al., 2013

Why BAO in radio and maybe in total intensity?

- Complementary to optical data, different systematics
- Decay time of HI hyperfine transition is ~ 10^15 seconds, but, 75% of visible matter in the Universe is made of H…
- Efficient alternative for measuring a large number of galaxies individually (plus integrating the signal “alla” CMB allows for the reuse of a vast experiment in instrumentation and data analysis)
- Interferometers are excellent instruments for these measurements, can be… expensive and hard to operate/maintain
- Single-dish instruments have been used for a first detection of the 21m line in cross correlation, (although for interferometers one should wait for CHIME and FAST)
- Approach: single-dish, many horns X single horn per dish

Battye, R.A. et al. MNRAS (2013) and arXiv:1610.06826
Wuensche, C. A. et al. arXiv:1803.01644

Importance of confirmation!

Baryon Acoustic Oscillations in the Lyα forest of BOSS DR11 quasars.
T. Delubac et al. [BOSS Collaboration] – A&A 574, A59 (2015), arXiv: 1404.1801

- From adjusting the BAO peaks and combining with the ΛCDM fiducial values from Planck+ WMAP:

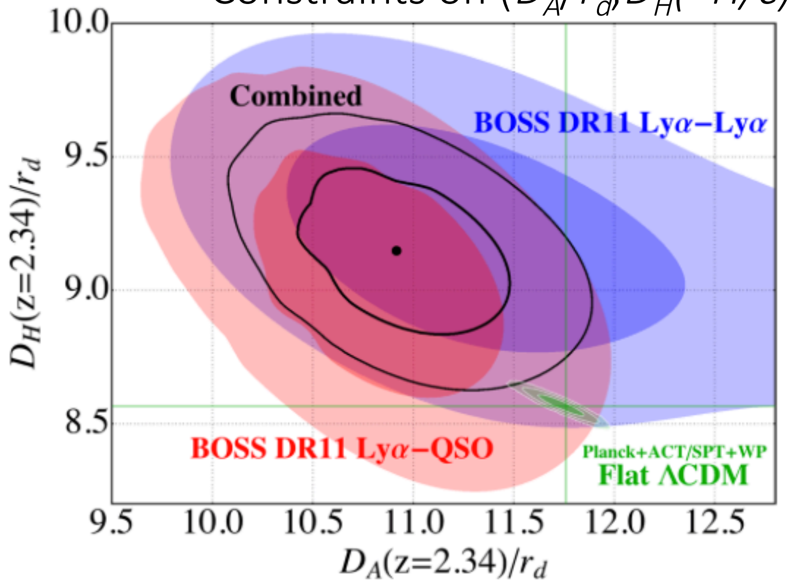
$$
\begin{aligned}
H(z=2.34) &= (222 \pm 7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}) \times \frac{147.4\,\mathrm{Mpc}}{r_d}\\
D_A(z=2.34) &= (1662 \pm 96\,\mathrm{Mpc}) \times \frac{r_d}{147.4\,\mathrm{Mpc}},
\end{aligned}
$$

$$r_d = 147.4\ \mathrm{Mpc}$$

- Values differ: 1.8σ from Planck+WP;

1.6σ from WMAP9+ACT+SPT

Constraints on (D_A/r_d,D_H(=H/c)/r_d)



Conclusion:

Approximately 2σ below the value of D_H

And 2σ above the value of D_A

compared to the ΛCDM prediction.

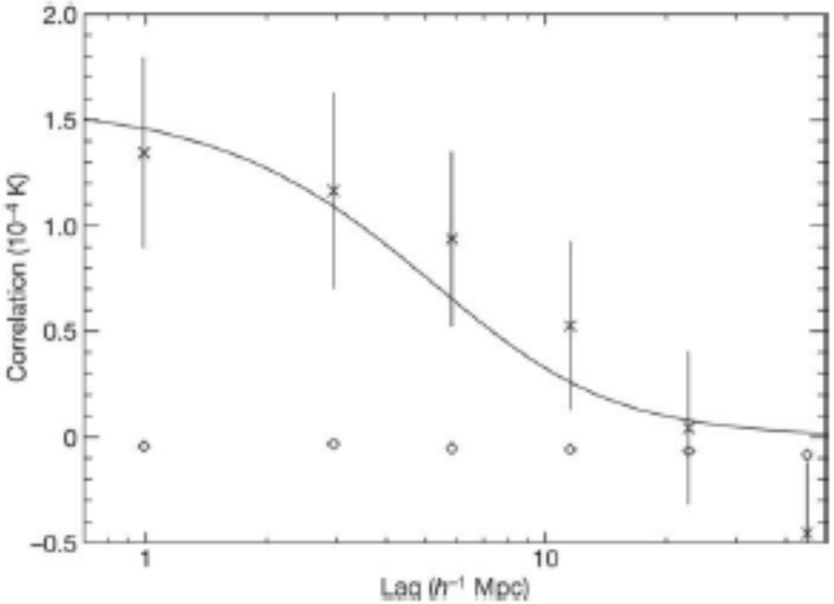
NOT THE ONLY TENSION IN THE MODEL!

Outline:

- Background of the 21cm: EoR and IM
- Current status on IM.
- One of the main problems: Foreground subtraction.
- Looking forward

Detection in cross correlation!

- Have ~10^5 L_* galaxies/BAO volume - individual galaxies not that important. Use aggregate signal from many galaxies with low resolution survey.
- Signal is O(0.1 mK), while galactic foreground is O(10^5 K)
- Sample variance limits => map sensitivity of 1-2μJy necessary

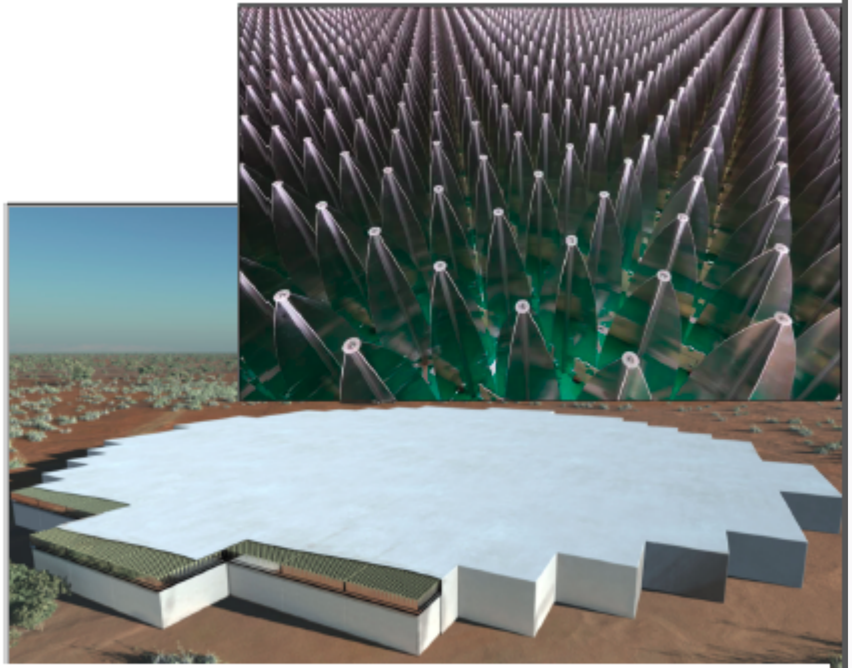


- First HI intensity mapping detection, DEEP2 density field x GBT HI brightness temperature cross correlation at z=0.8

T-C Chang *et al.* *Nature* **466**, 463-465 (2010) doi:10.1038/nature09187

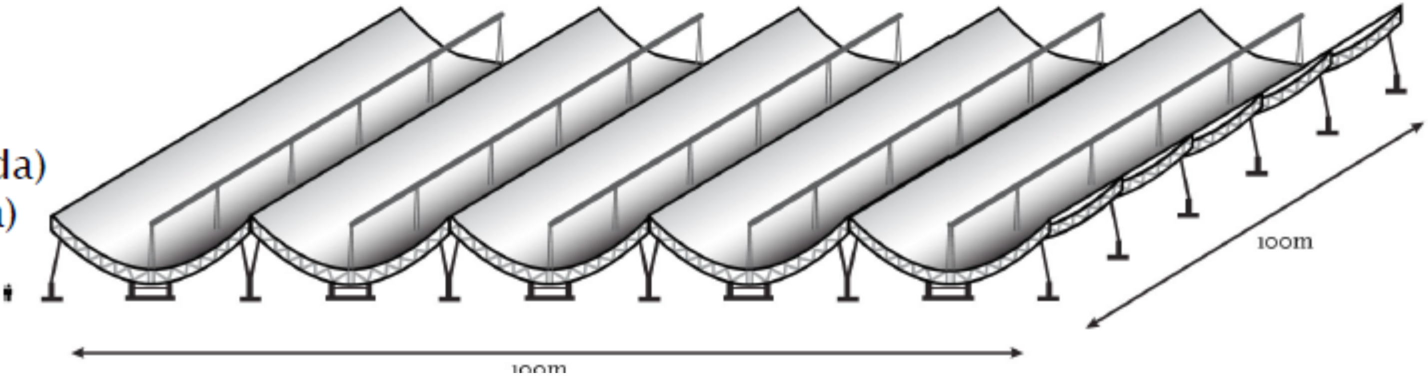
Experiments…

- <u>Interferometers</u>
  - Provide higher resolution
  - Ideally minimum baseline ~ 10 m for large scales…

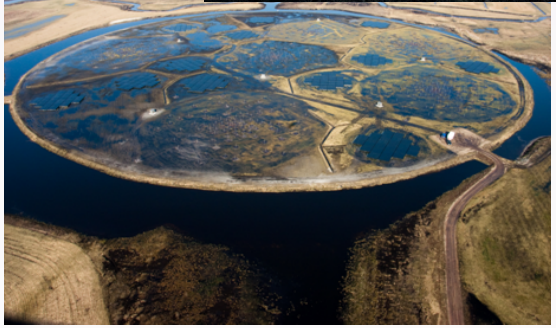


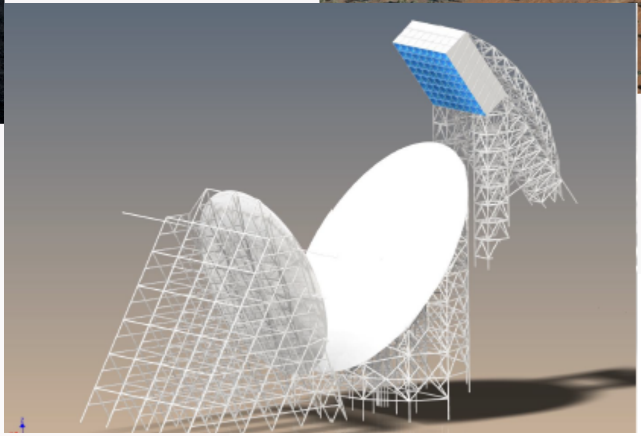
Dense aperture array systems

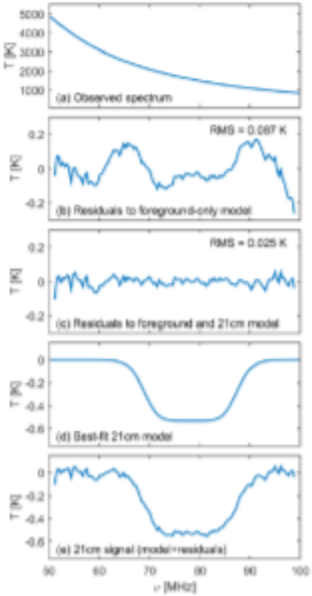
- CHIME (Canada)
- Tianlai (China)
- HIREX(SA)

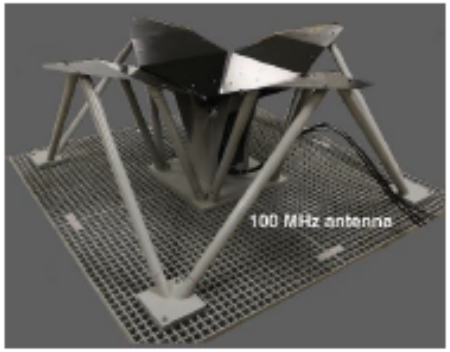


Experiments

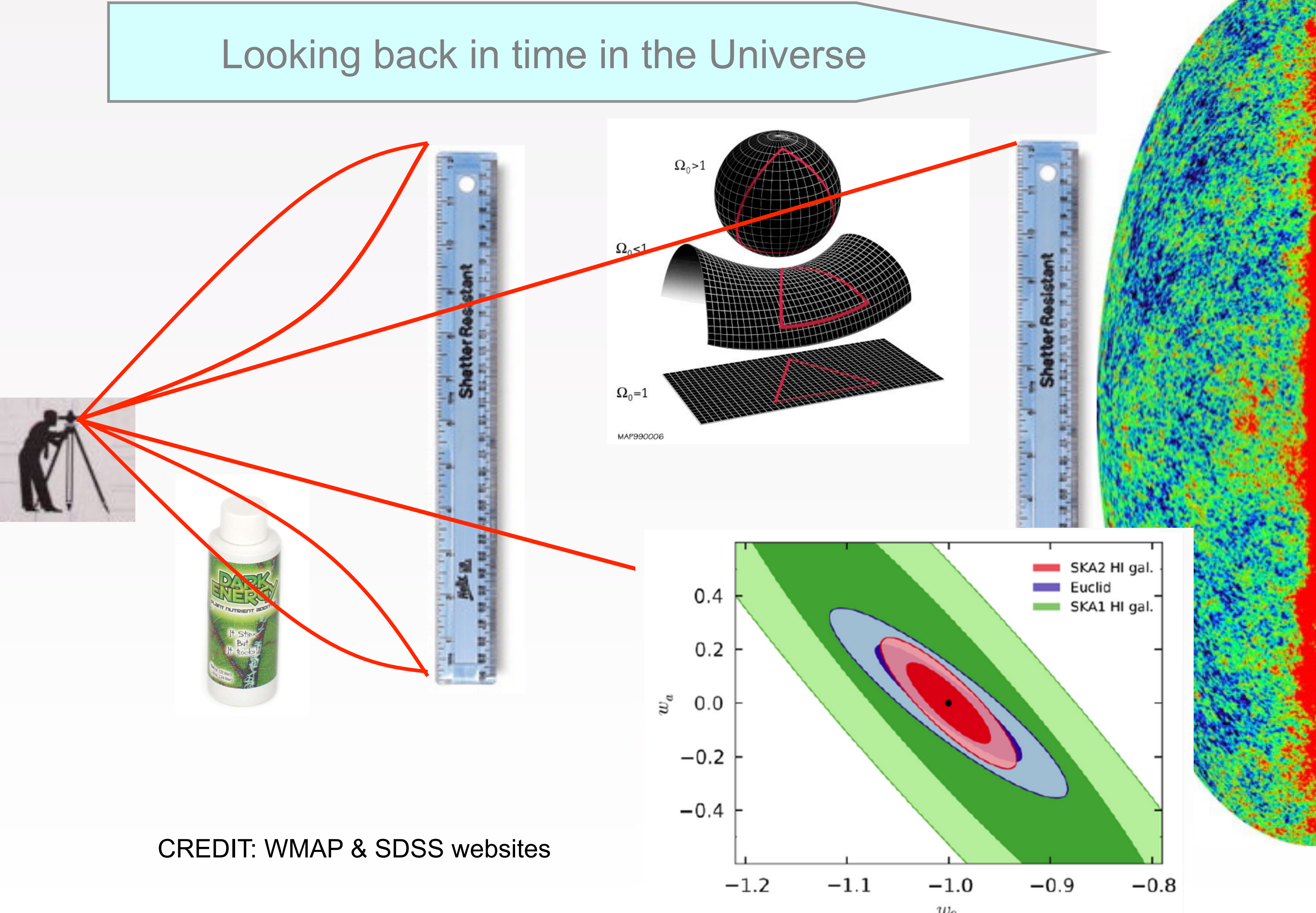








There are many forecasts in the literature… EoR and BAO



Looking back in time in the Universe

CREDIT: WMAP & SDSS websites

There are many forecasts in the literature… EoR and BAO

Returning to reionisation:
Redshift space disortions:

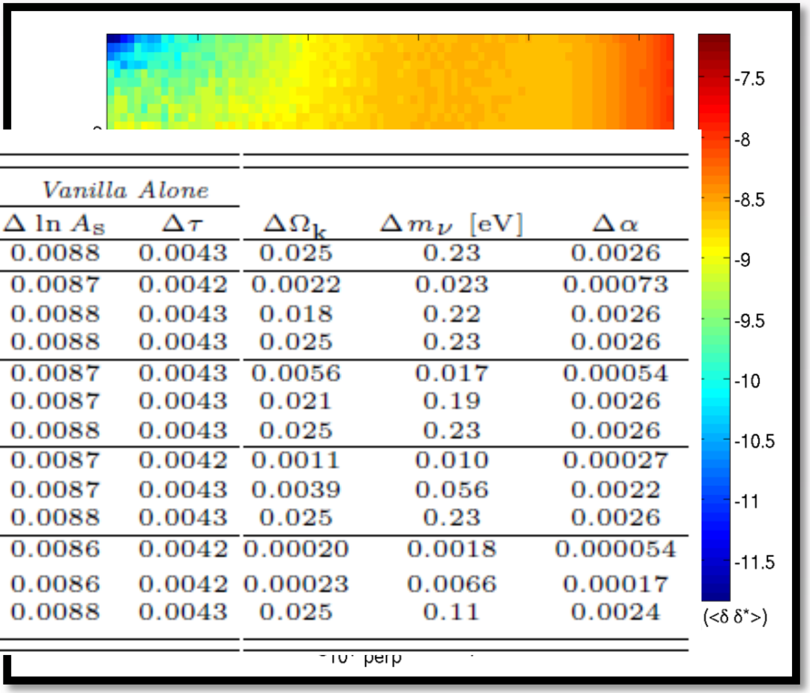
$$P^{s,\mathrm{qlin,3D}}_{\Delta T}(\mathbf{k}) = \widehat{\delta T}_b^2(z_{\cos})\left[P_{\delta^r_{\rho\mathrm{HI}},\delta^r_{\rho\mathrm{HI}}}(k) + 2P_{\delta^r_{\rho\mathrm{H}},\delta^r_{\rho\mathrm{HI}}}(k)\,\mu_{\mathbf{k}}^2 + P_{\delta^r_{\rho\mathrm{H}},\delta^r_{\rho\mathrm{H}}}(k)\,\mu_{\mathbf{k}}^4\right]$$

$$\begin{aligned} P_{\mu^0}(k) &= \widehat{\delta T}_b^2 P^r_{\delta_{\rho\mathrm{HI}},\delta_{\rho\mathrm{HI}}}(k) \\ &= \widehat{\delta T}_b^2\left[P^r_{\delta_{x\mathrm{HI}},\delta_{x\mathrm{HI}}}(k) + 2P^r_{\delta_{x\mathrm{HI}},\delta_{\rho\mathrm{H}}}(k)\right.\end{aligned}$$

		Vanilla Alone								
		$\Delta\Omega_\Lambda$	$\Delta\ln(\Omega_m h^2)$	$\Delta\ln(\Omega_b h^2)$	Δn_s	$\Delta\ln A_s$	$\Delta\tau$	$\Delta\Omega_k$	Δm_ν [eV]	$\Delta\alpha$
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+LOFAR	All OPT	0.0044	0.0052	0.0051	0.0018	0.0087	0.0042	0.0022	0.023	0.00073
	All MID	0.0070	0.0081	0.0059	0.0032	0.0088	0.0043	0.018	0.22	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+MWA	All OPT	0.0063	0.0074	0.0055	0.0024	0.0087	0.0043	0.0056	0.017	0.00054
	All MID	0.0061	0.0070	0.0056	0.0030	0.0087	0.0043	0.021	0.19	0.0026
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+SKA	All OPT	0.00052	0.0018	0.0040	0.00039	0.0087	0.0042	0.0011	0.010	0.00027
	All MID	0.0036	0.0040	0.0044	0.0025	0.0087	0.0043	0.0039	0.056	0.0022
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23	0.0026
+FFTT^b	All OPT	0.00010	0.0010	0.0029	0.000088	0.0086	0.0042	0.00020	0.0018	0.000054
	All MID	0.00038	0.00034	0.00059	0.00033	0.0086	0.0042	0.00023	0.0066	0.00017
	All PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.11	0.0024

$$P_{\mu^4}(k) = \widehat{\delta T}_b^2 P^r_{\delta_{\rho\mathrm{H}},\delta_{\rho\mathrm{H}}}(k)\,.$$

$$\delta^r_{\rho\mathrm{HI}} = \delta^r_{\rho\mathrm{H}} + \delta^r_{x\mathrm{HI}} + \delta^r_{\rho\mathrm{H}}\,\delta^r_{x\mathrm{HI}}$$



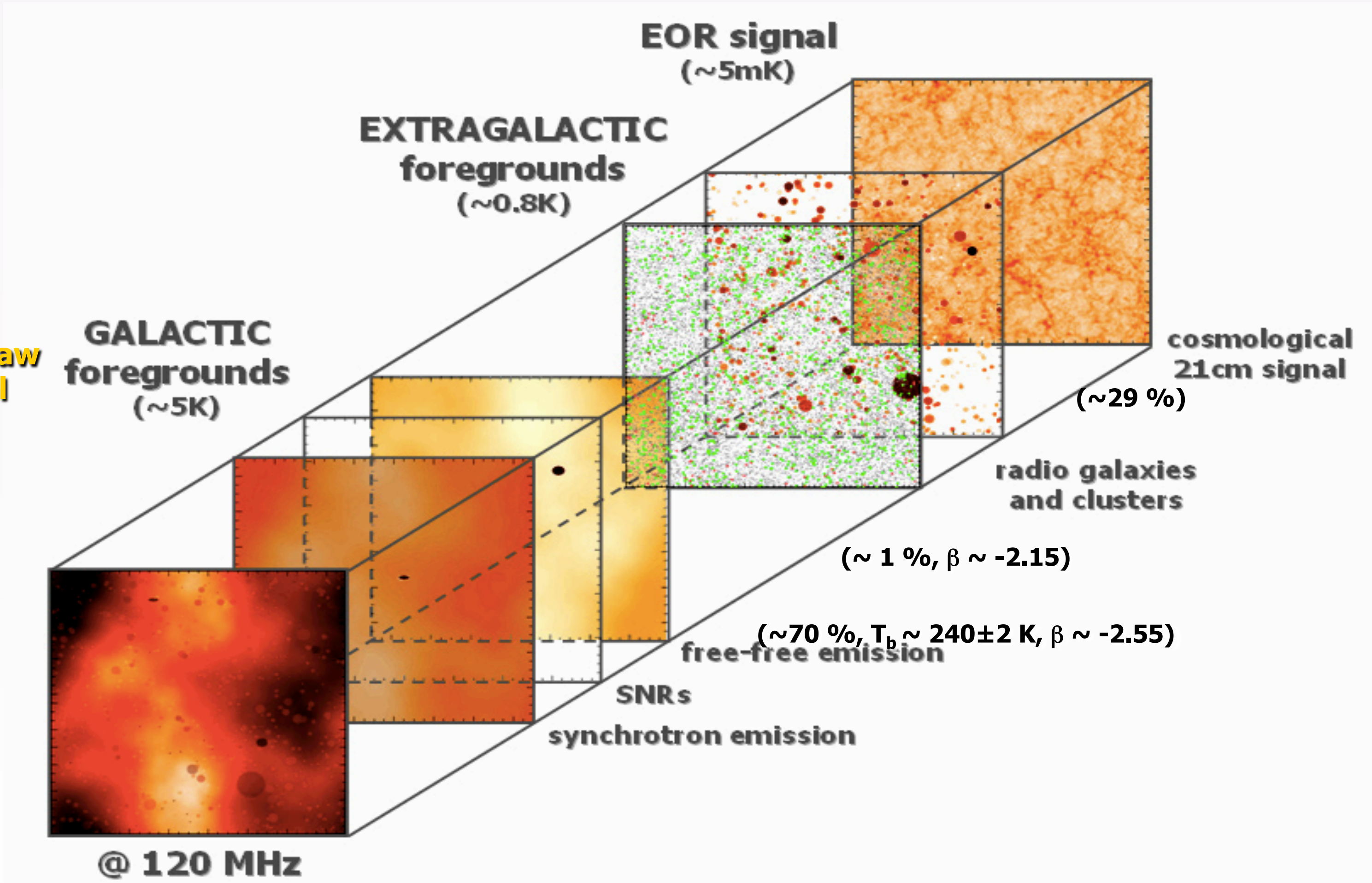
Barkana & Leob 10
Mao et al 08.11.

Outline:

- Background of the 21cm: EoR and IM
- Current status on IM.
- One of the main problems: Foreground subtraction.
- Looking forward

EoR-IM: the FG problem

- featureless power law
- variation in spectral index with position on the sky and with frequency



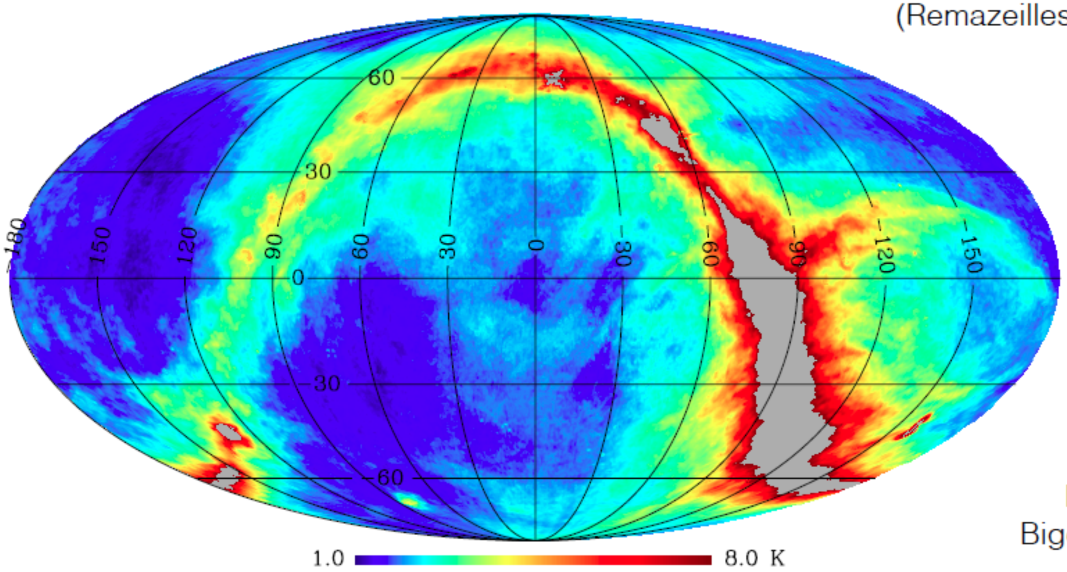
SIMULATIONS: 5° x 5° filed of view, ~ 0.6 arcmin resolution and freq. range: 115-180 MHz

Jelic et al., 2008, MNRAS

Foreground contamination

- Diffuse Galactic continuum radiation - synchrotron and free-free radiation
- Spectrum expected to be smooth (should allow for it to be subtracted)
- Mean ~5K at 1 GHz
- Fluctuations on degree scales **~70mK**
- Note: HI signal ~ 0.1 mK !

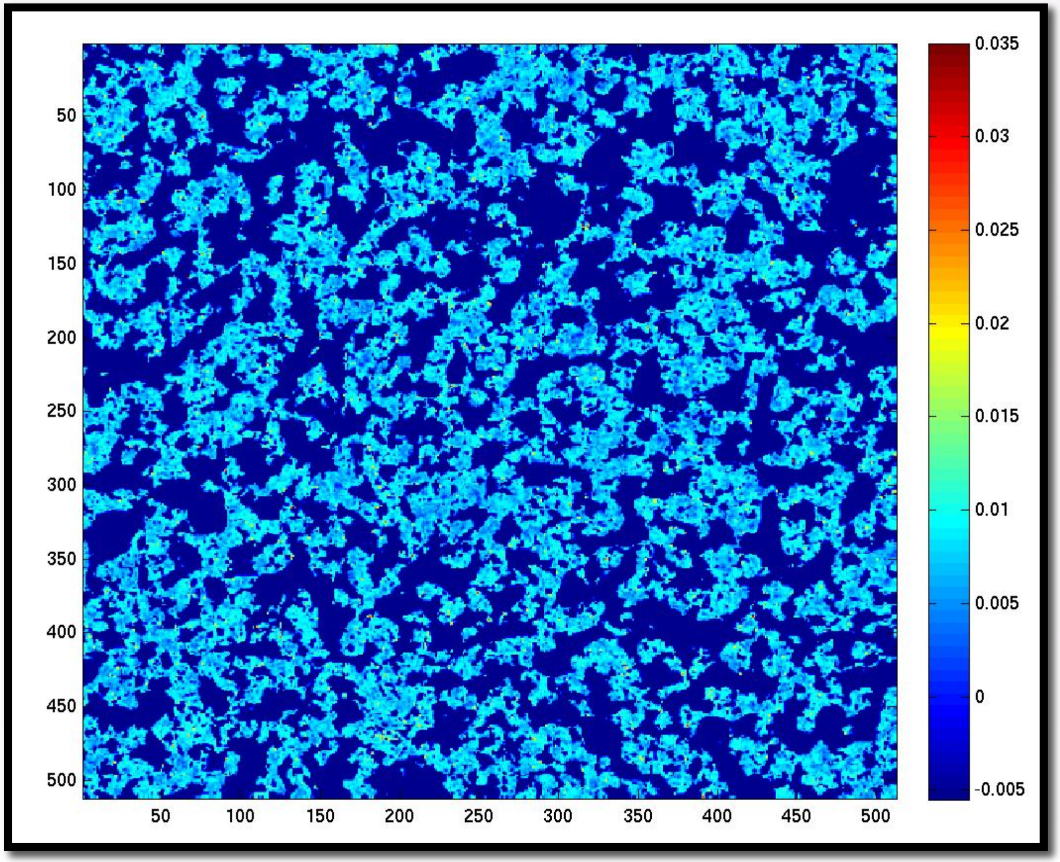
Improved 408 MHz Haslam map now available
(Remazeilles et al. 2015)



Battye et al. (2013);
Bigot-Sazy et al. (in prep.)

Simulations: Foregrounds, Noise, Signal

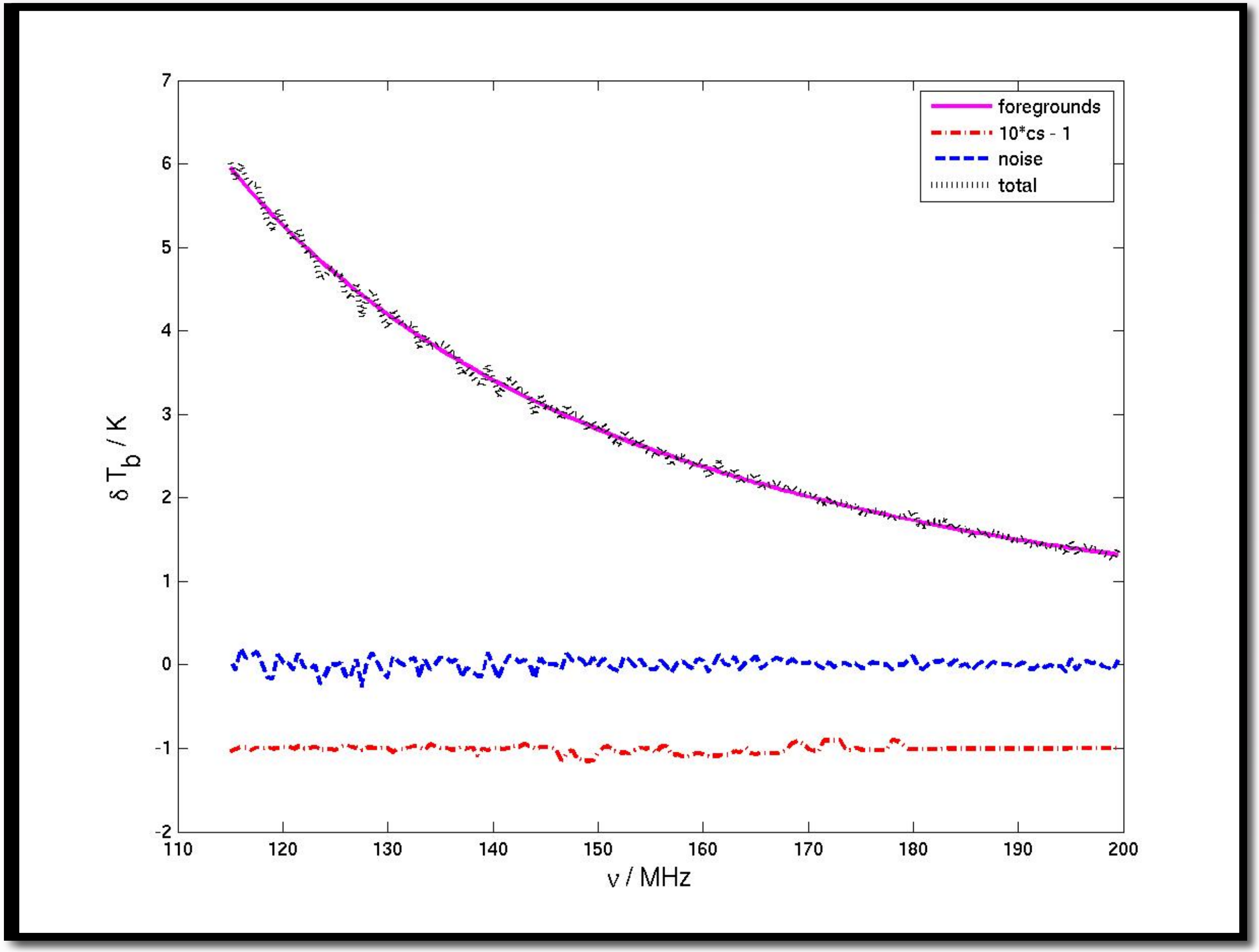
- Foregrounds: Simulations from *Jelic V., Zaroubi S., Labropoulos P. et al. 2008, MNRAS, 389, 1319:*
  - Galactic synchrotron radiation, galactic free-free emission
  - Extragalactic radiation from radio galaxies and clusters
- 21cmFAST *(Mesinger A., Furlanetto S., Cen R., 2011, MNRAS, 411,955)*
  - 10°x10° x170 slice in frequency, d \nu=0.5 Mhz. Frequency 115 to 200 MHz (z ~ 11.3 – 6.1)
  - Box size of 1.8 Gpc over 512 pixels ~3MPc/pixel.
- Noise: an MS of our simulation was filled with a Gaussian distribution
  - e.g. 52mK at 150MHz for 600 hours of LOFAR observing time.



Foreground map at 150MHz for a 10°x10° observing window. Temperature scale in K.

Problem Outline

- 21cm signal dominated both by foregrounds and by noise.
- Currently most foreground cleaning methods are parametric, e.g. polynomial.
- Non-parametric methods have emerged - Wp smoothing (Harker 09).
- Other, powerful techniques have been used on the CMB...



Problem Outline techniques used:

Spectral smoothness allows separation of 21cm. Options:

1 Fit power law to maps
2 Remove low order polynomials or some constraint fit
3 Measure components and model components
4 Measure modes of the foregrounds from a given FG model
5 Use sparse or indepenent components of the FG model.
6 .....

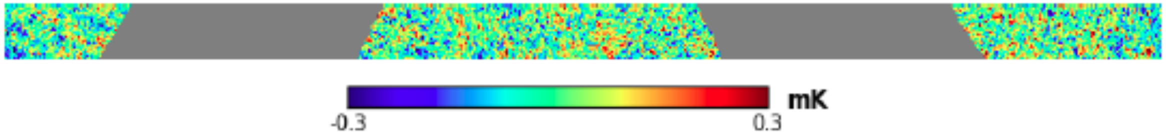
Issues:

- Mode mixing of angular and frequency fluctuations by frequency-dependent beams (esp. interferometers.
- Robustness Biasing introduced if foreground model poorly understood (esp. non-gaussianities).
- Statistical Optimality Need to keep track of transformations on statistics, for optimal PS estimation
- Model Dependent [4] although in simulatons there are excellent results.

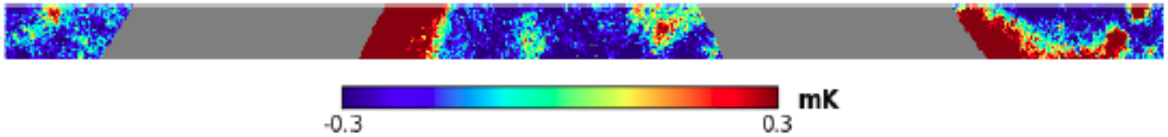
Effects on the power spectrum

Bigot-Sazy, Dickinson, Battye, Browne et al, MNRAS 2015

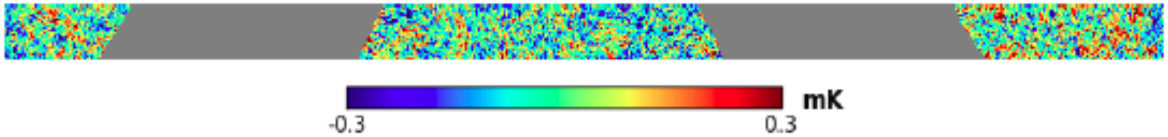
Foreground separation using PCA



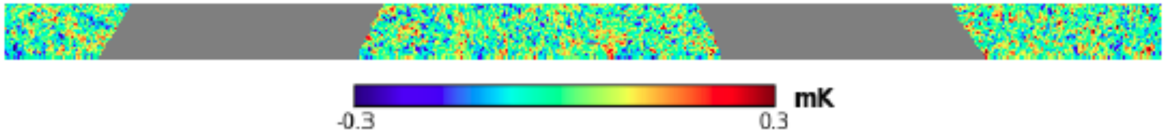
(a) Input HI signal



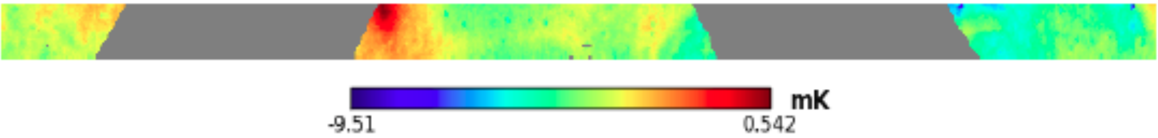
(b) PCA 1 mode removed



(c) PCA 3 modes removed



(d) PCA 7 modes removed

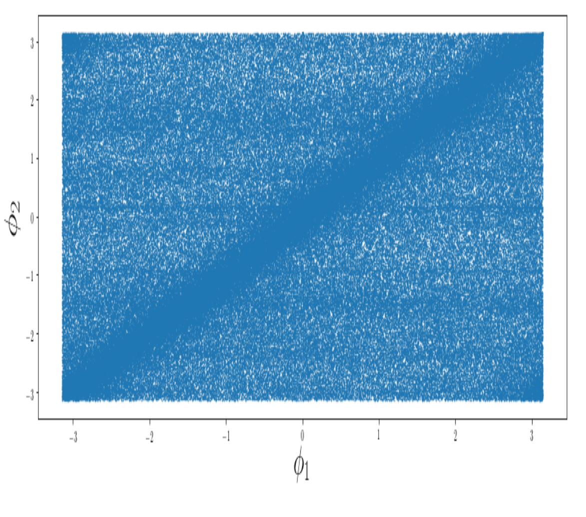


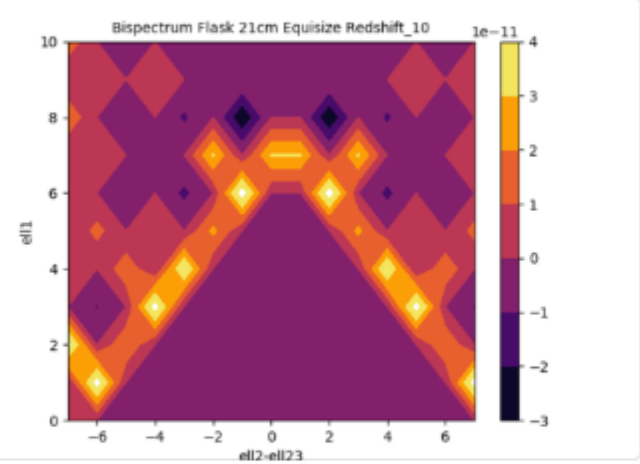
(e) Parametric fitting

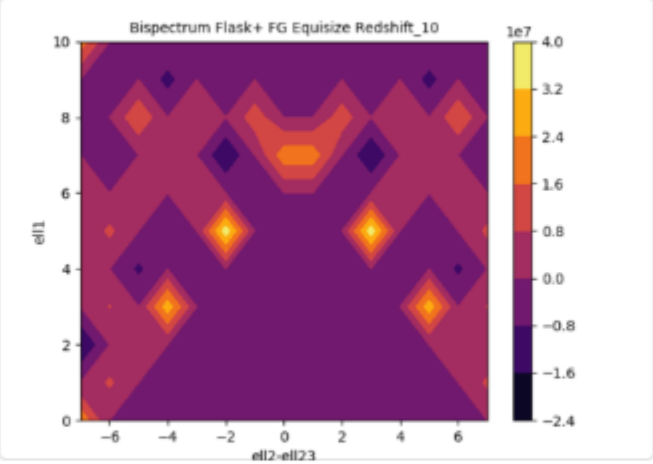
Good !

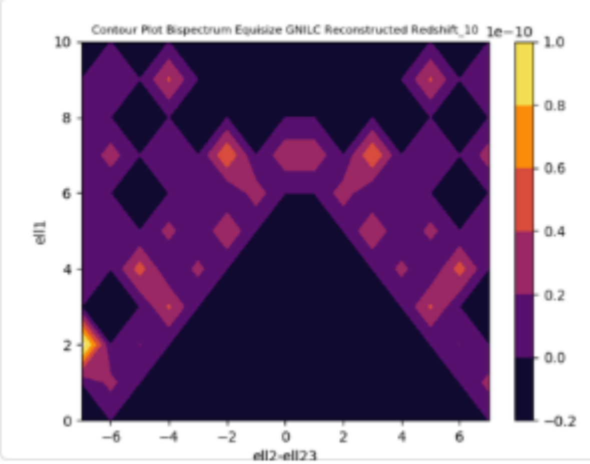
Investigating using Bispectrum and phase analysis to test the foreground subtraction method.

- Method of choice here was GNILC used by the Bingo collaboration.
- Maps foregrounds were subtracted as discussed and analysis tools were created to benchmark phase correlations and bispectrum of residuals.









Residual Projection

- We can project different signal elements onto the source space using the mixing matrix (A) calculated by GMCA in order to understand the amount of leakage.

- $R_{fg} = fg - (A (A^T A)^{-1} A^T) fg$

Amount of foreground leakage into reconstructed nocs

- $C_{nocs} = (A (A^T A)^{-1} A^T) (no+cs)$
  Amount of simulated no+cs leakage into the reconstructed foregrounds.
- $N_{nocs} = (A (A^T A)^{-1} A^T) (no)$ ->
  could try to correct for that!

Conclusions… Looking forward.

- 21cm is a very rich area of research
- Lots to be done, relating to astrophysics, cosmology, statistical methods (component separation), etc...
- We have to firm up a detection of IM in order to hopefully bring all the promises which we theoretically know exist in this area of science.
- The reconstructed maps will have a huge wealth of not only comsological but also astrophysical data.

Future Questions:

- What are the future hurdles that the projects we will heard about this week will have… Possibly calibration and foreground subtraction, but we should hear from the different projects themselves.