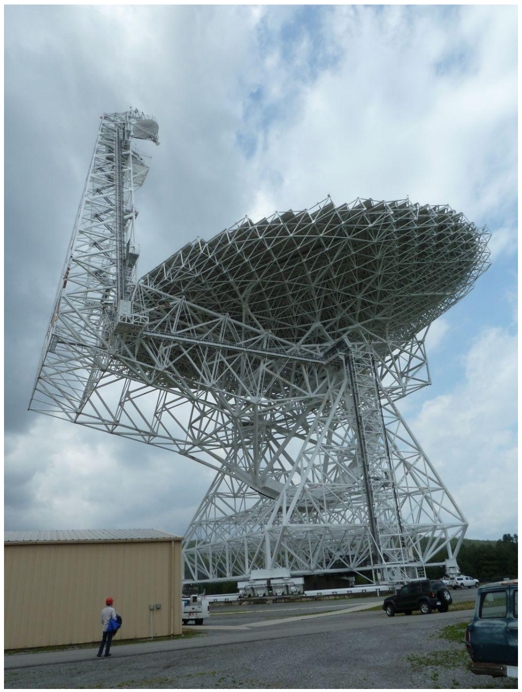
Results from the Green Bank Telescope 21 cm intensity survey



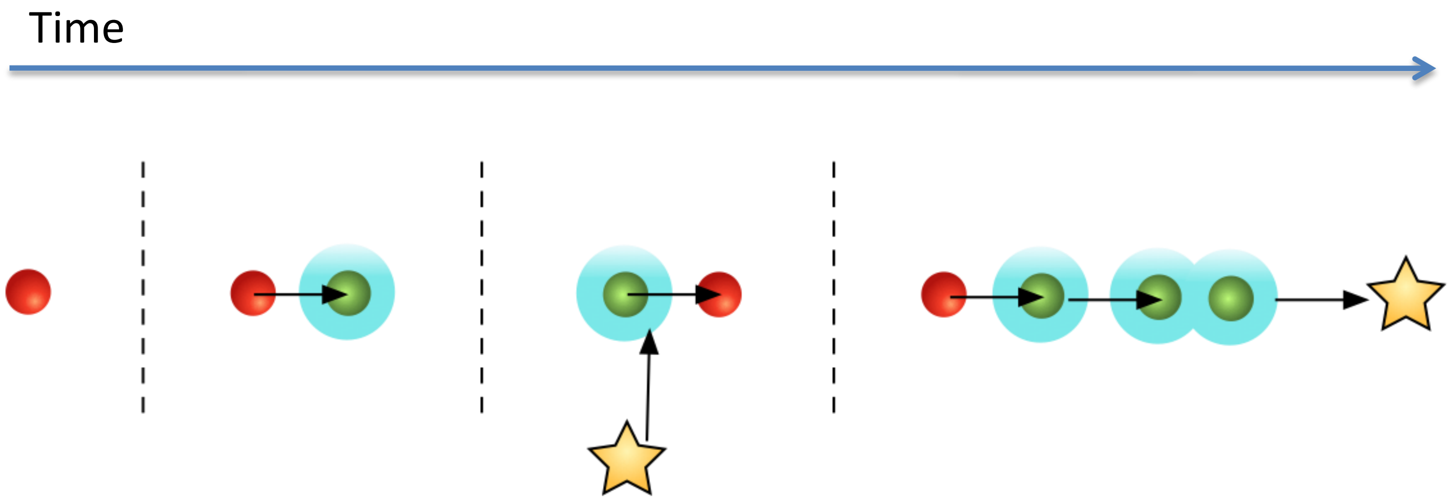
Eric Switzer

KITP, Apr. 26

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique theorique

Cross: 1208.0331 Masui, Switzer, et al.
Auto: 1304.3712 Switzer, Masui, et al.

Hydrogen

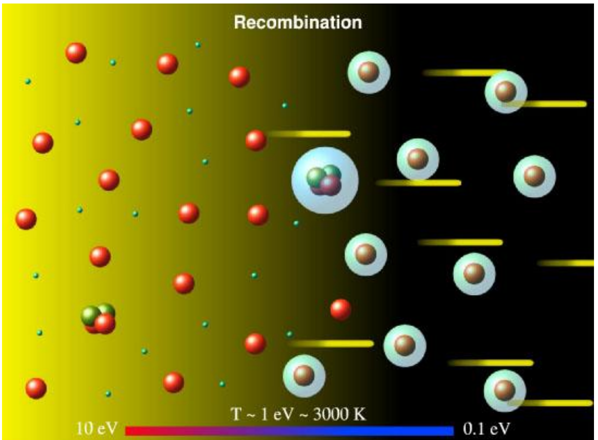


Recombination
380,000 yr
E_{bind}=13.6 eV

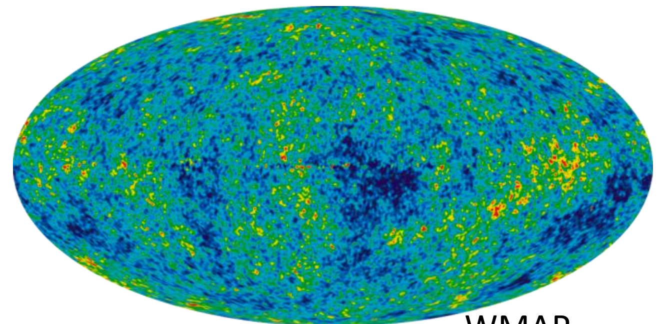
Reionization
~500 million yr

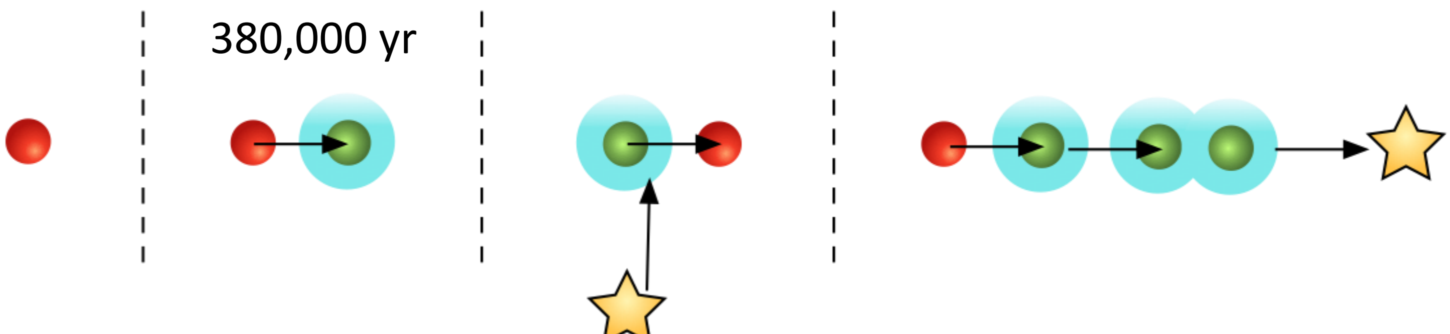
Star formation
Peaking ~4 Gyr

Hydrogen recombination



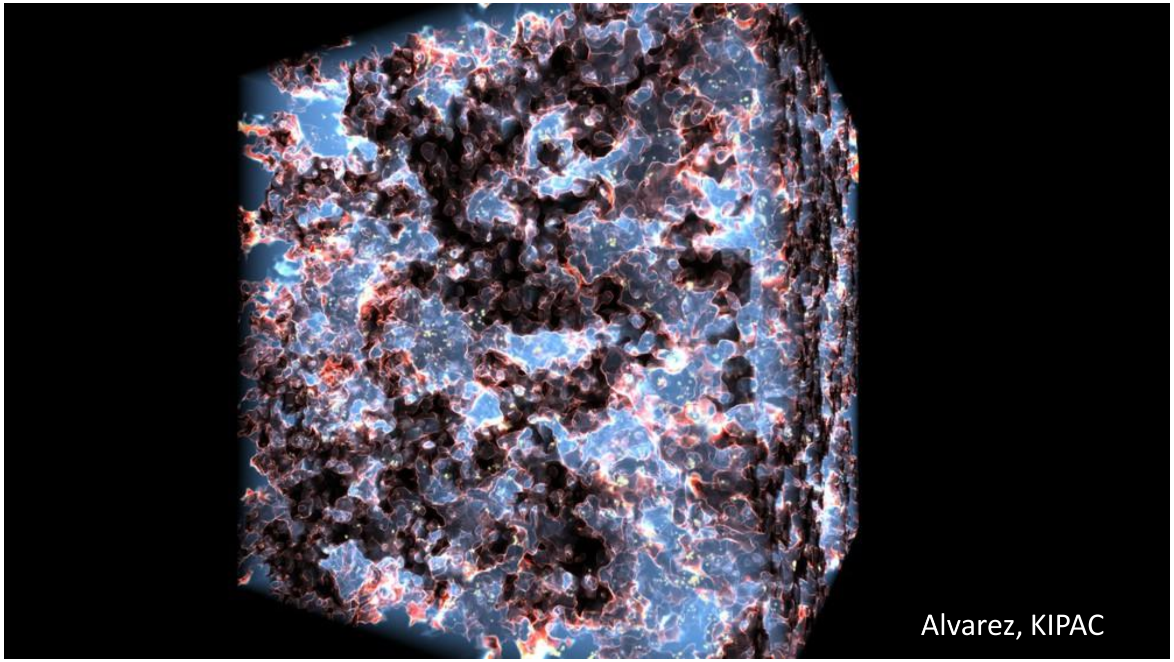
Kinney

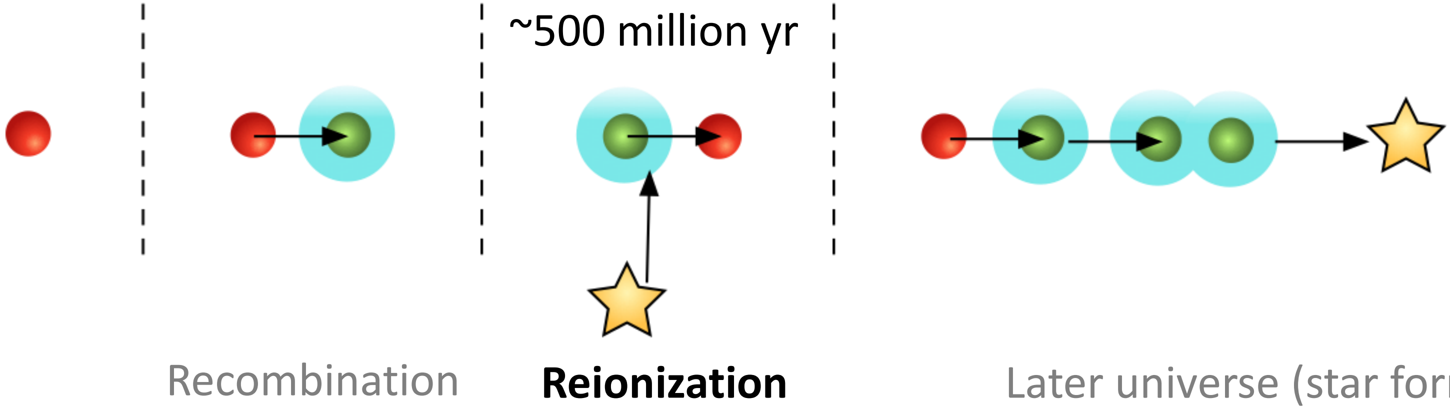

WMAP



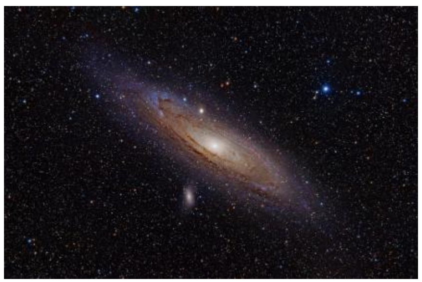
Recombination Reionization Later universe (star formation)

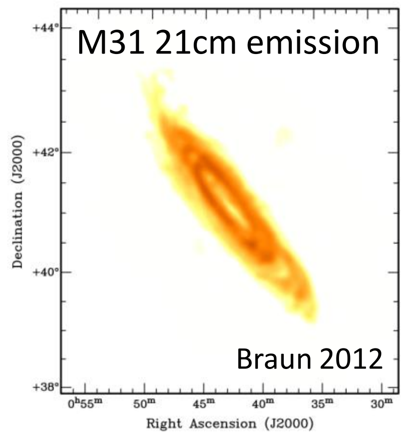
Hydrogen reionization

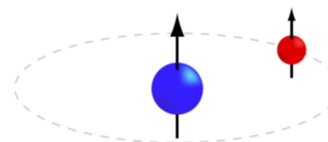




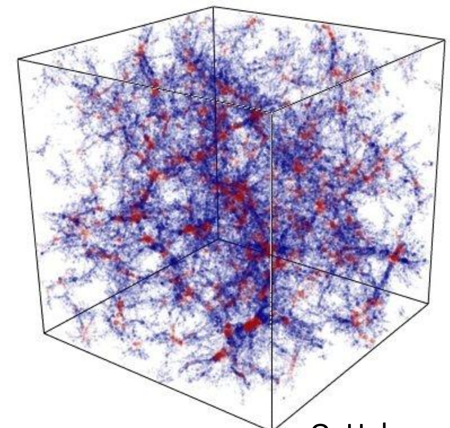
Hydrogen: recent universe



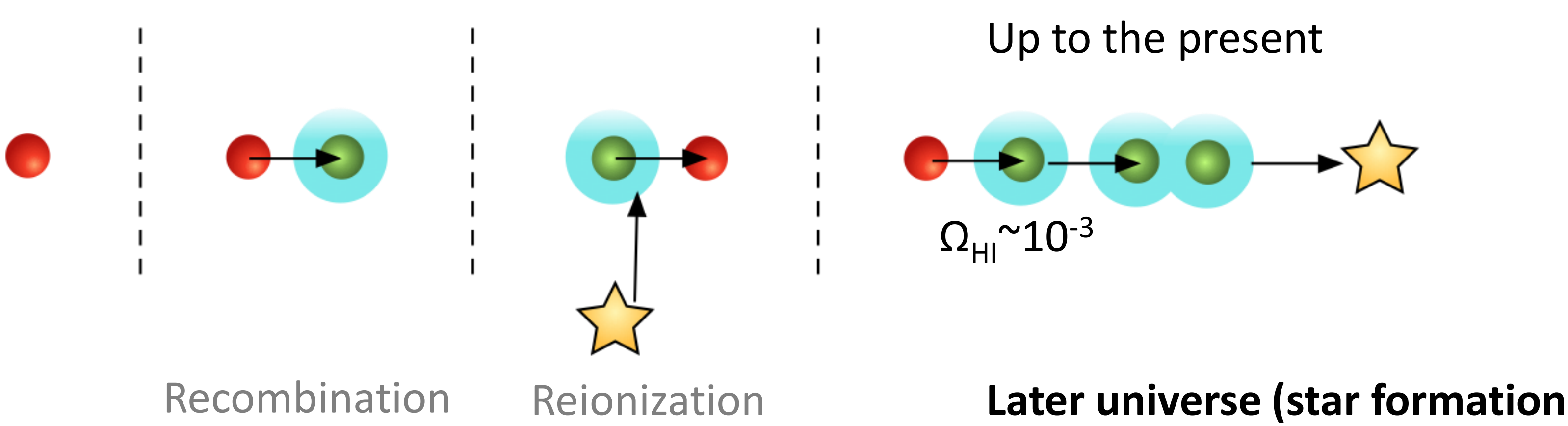




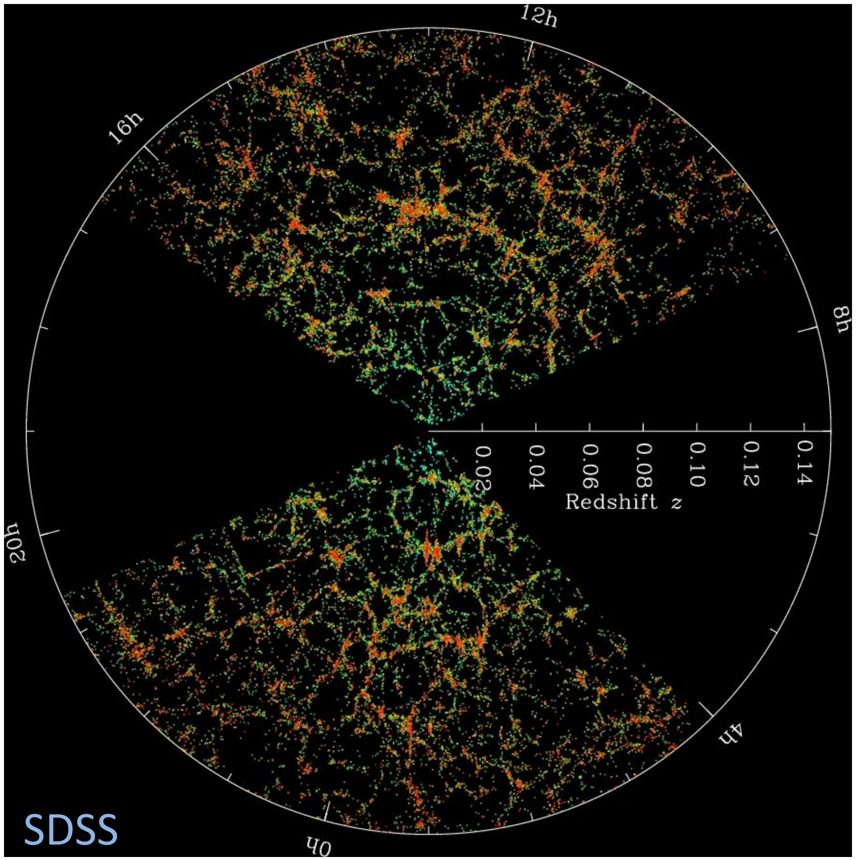
21cm spin-flip

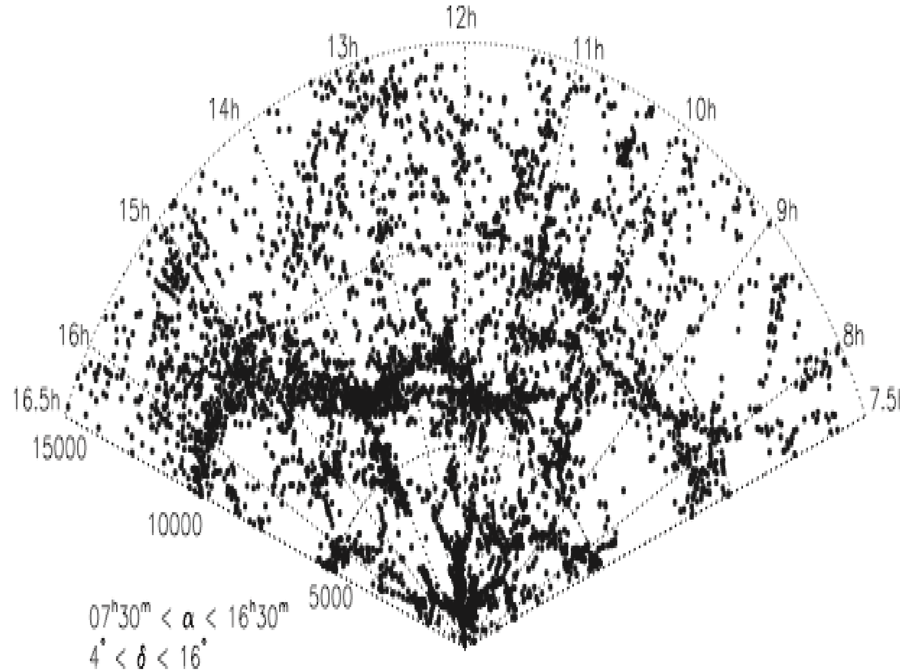


O. Hahn



Galaxy surveys

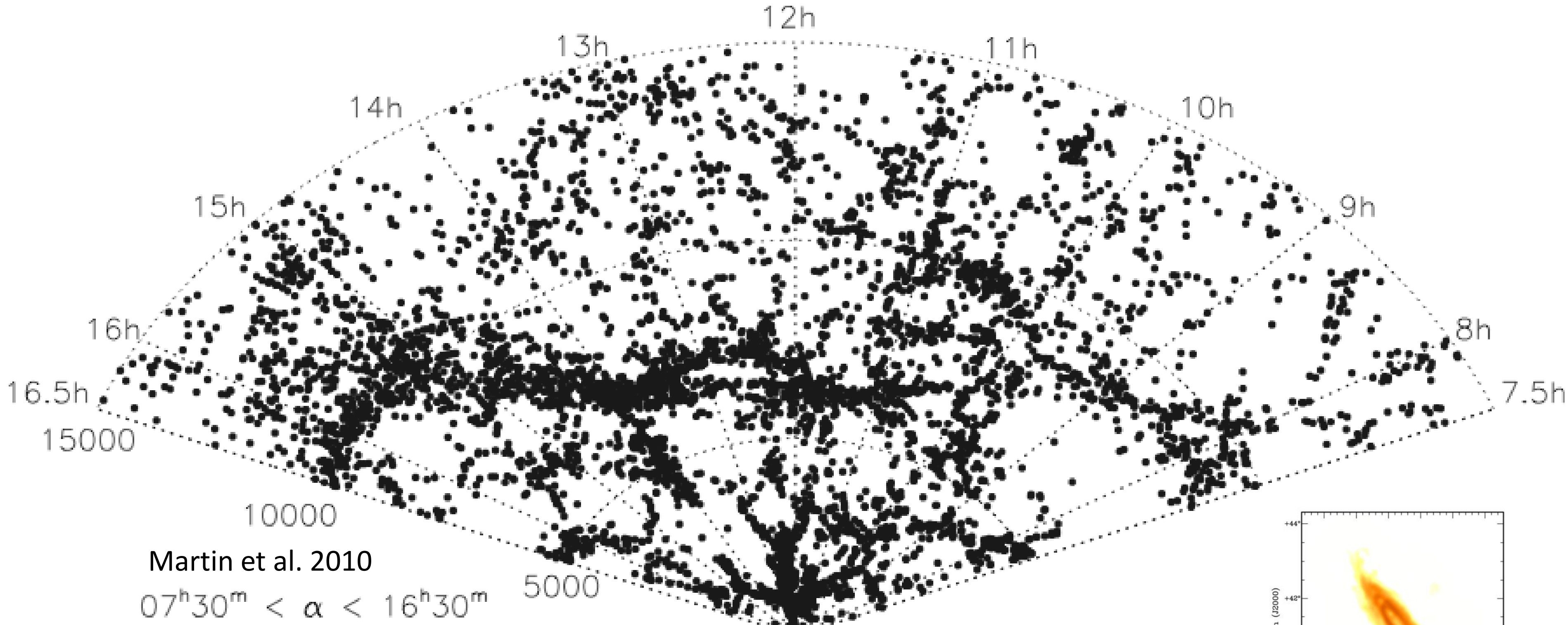




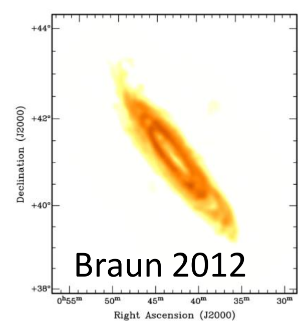
Martin et al. 2010

Arecibo ALFALFA galaxy survey, z<0.1

Detection vs. Intensity



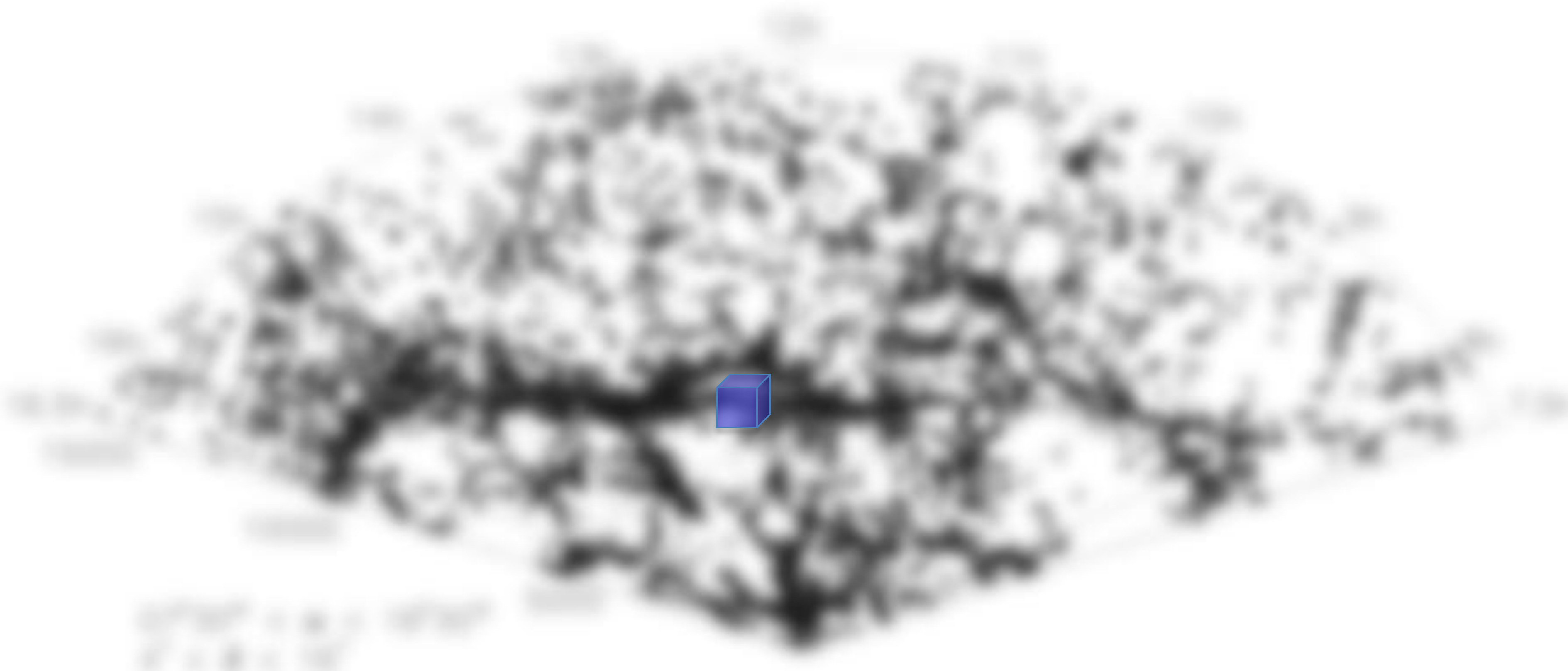
Martin et al. 2010



Braun 2012

Detection of HI in individual systems
Gives LSS and HI mass function (tail)
Needs high significance per galaxy: low-z, large sensitive telescope

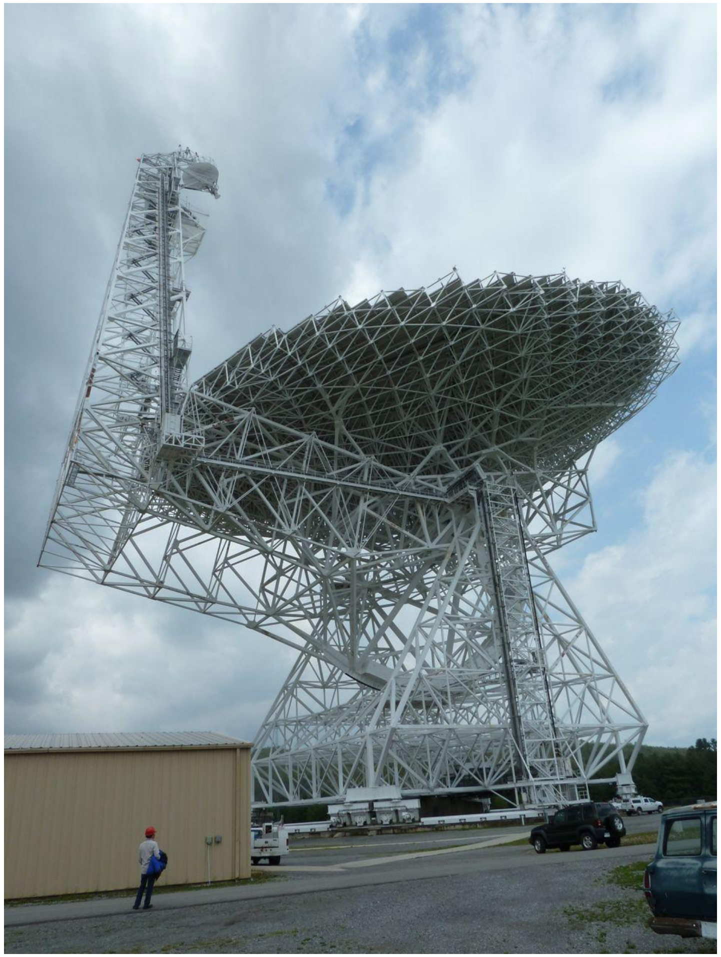
Detection vs. Intensity



Gives LSS and total HI in cubes: integral of mass function, Ω_{HI}
Resolution: smallest cosmologically relevant scale (> nonlinear)
SNR of entire oscillation mode, not individual galaxy
Much easier to achieve ➔ jump to high redshift
Conceptually: 3D CMB experiment with large foregrounds

GBT 21 cm intensity mapping collaboration

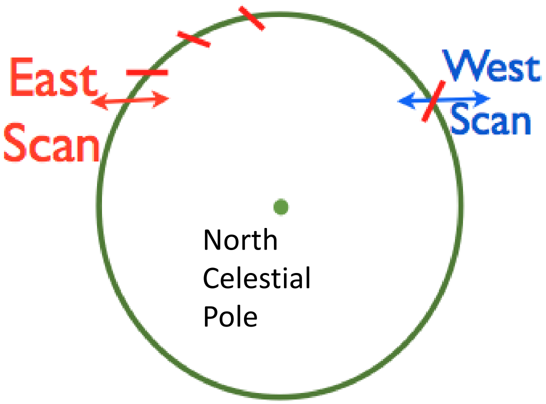
- **Academia Sinica** (Tzu-Ching Chang, Victor Yu-wei Liao)
- **Beijing** (Xuelei Chen, Yi-Chao Li)
- **Carnegie Mellon University** (Aravind Natarajan, Jeff Peterson, Tabitha Voytek)
- **CITA/UToronto** (Nidhi Banavar, Liviu Calin, Marat Mufteev, Kiyo Masui, Ue-Li Pen, Richard Shaw, Eric Switzer)
- **McGill** (Kevin Bandura)
- **Wisconsin** (Chris Anderson, Peter Timbie)



The Green Bank Telescope

100 m diameter, largest steerable dish
FWHM~0.3 deg

700-900 MHz or z=0.58 to 1
System temperature ~30 K
Out of the galactic plane
Insensitive to weather
Scripted remote observing

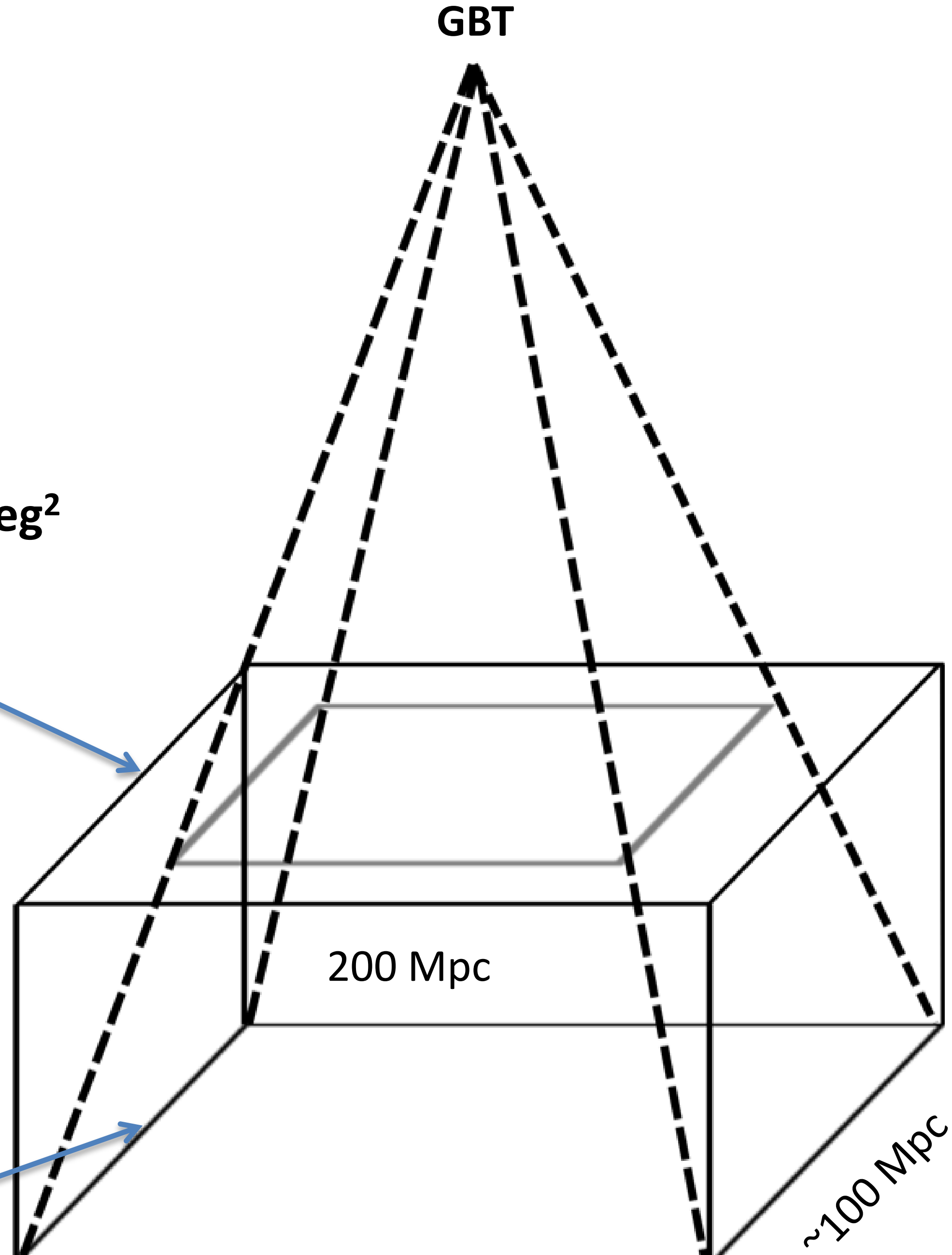


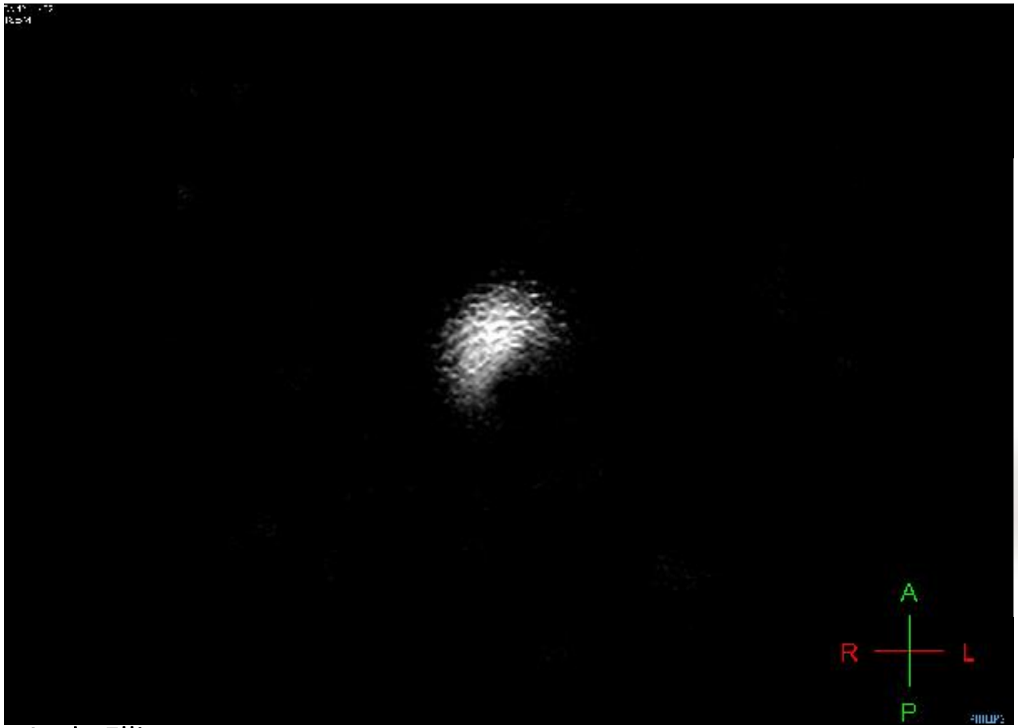
224 hr integration on ~75 deg^2

900 MHz, z=0.6, 2.1 Gpc

256 spectral slices.
~ 3-4 Mpc/slice.
Each is a map of
diffuse emission.
(like the CMB)

700 MHz, z=1, 3.3 Gpc

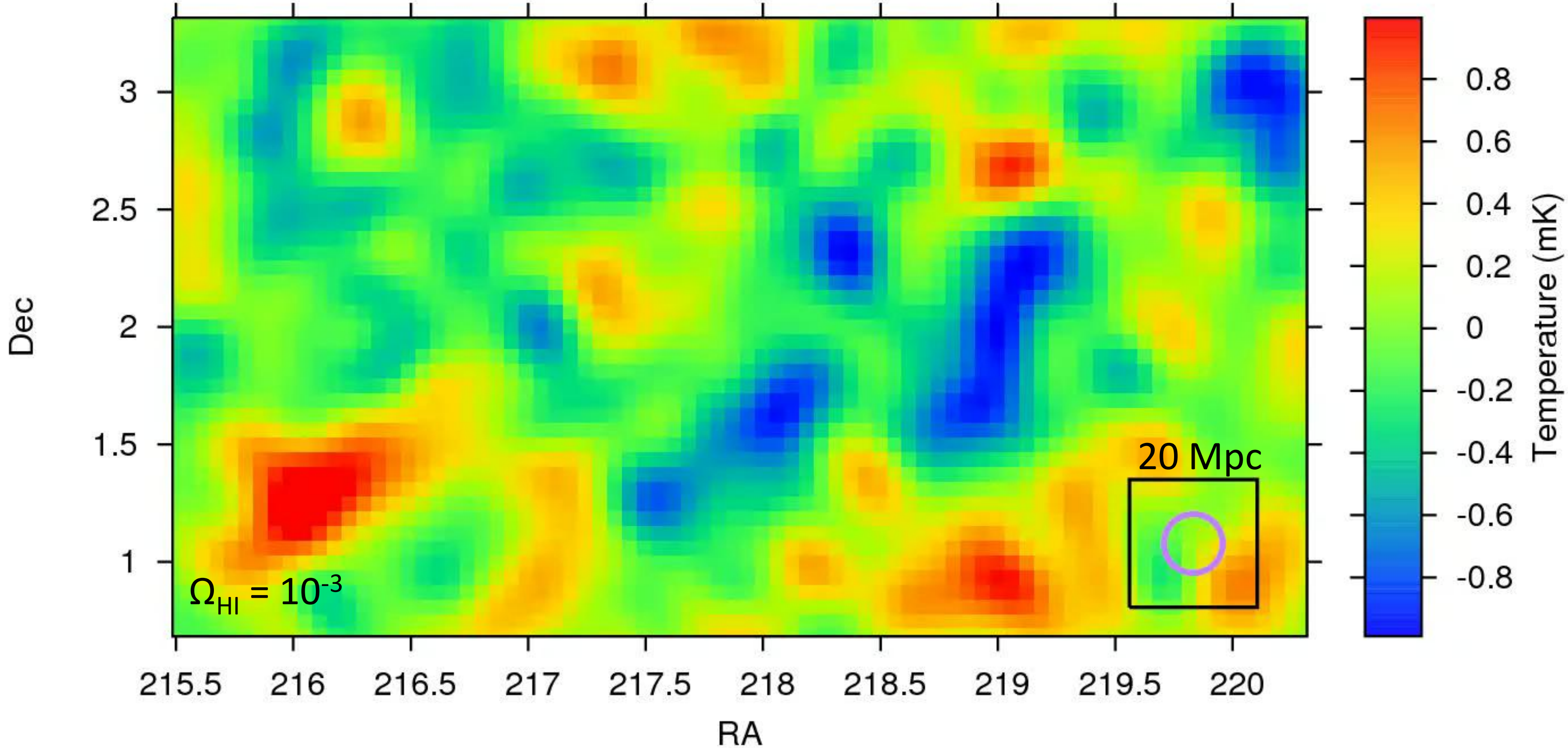




Andy Ellison

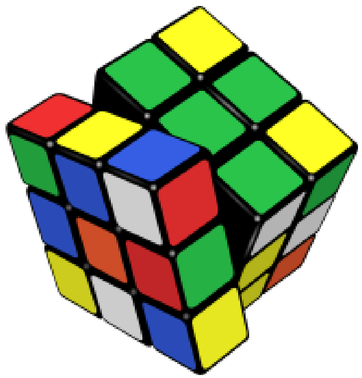
Signal-only simulations

$$T_b = 0.29 \frac{\Omega_{\rm HI}}{10^{-3}} \left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.37} \right)^{-\frac{1}{2}} \left(\frac{1+z}{1.8} \right)^{\frac{1}{2}} \ {\rm mK}$$

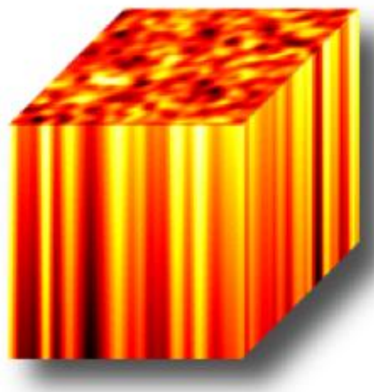


Box: 78x43x256, FWHM~0.3 deg, pixel = 0.25 FWHM

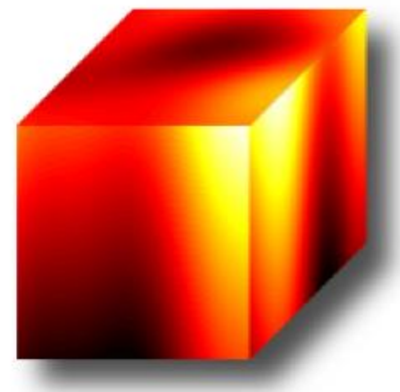
Radio-frequency Interference



Extragalactic



Galactic



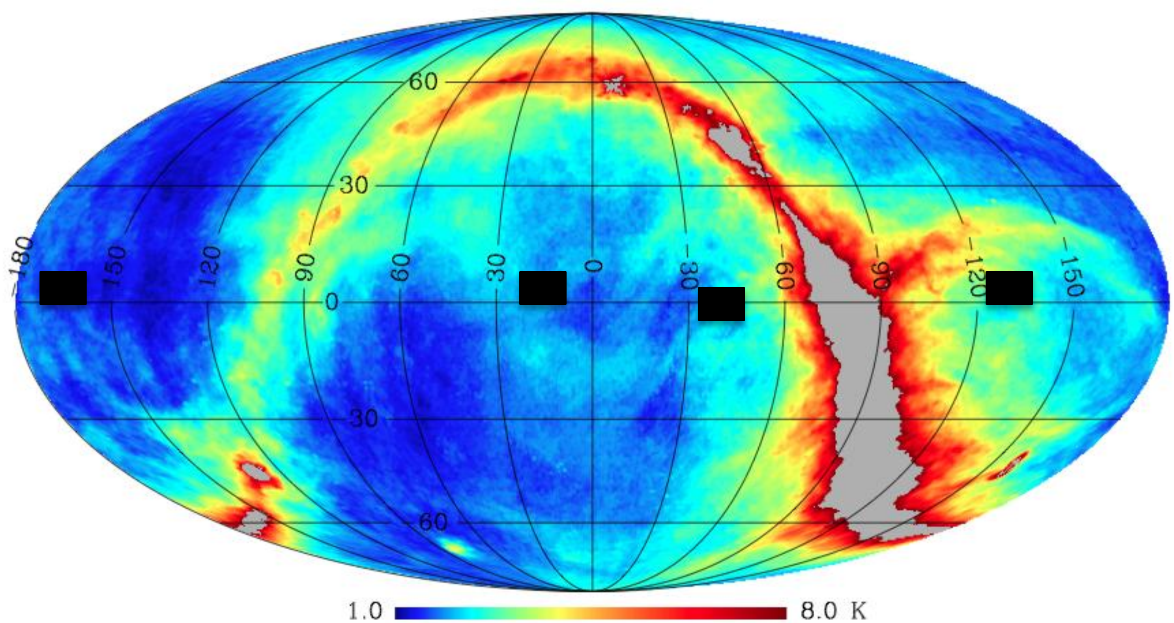
Detector noise

Dillon 2012

15hr field: 105 hours obs., ~5°x3° "deep field"

1hr field: 84 hours obs. 9°x5° "wide field"

k>0.1 h Mpc^{-1}



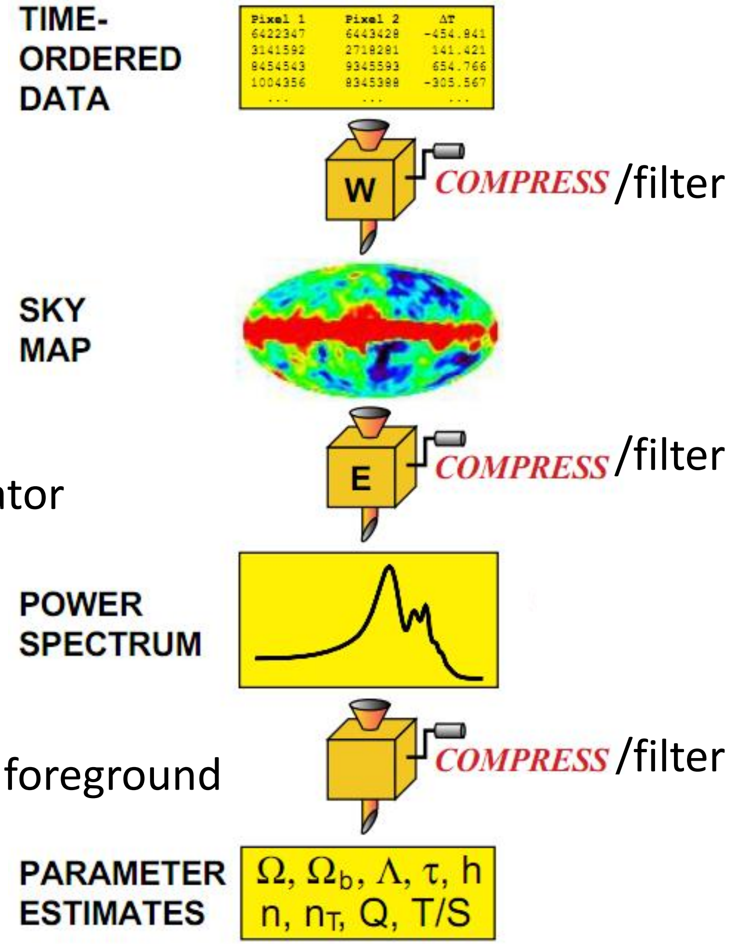
Battye et al. 2012, from Haslam 408 MHz map

Estimation regimes and residuals

RFI, data quality
calibration

Empirical cleaning
Crossed quadratic estimator

Foregrounds

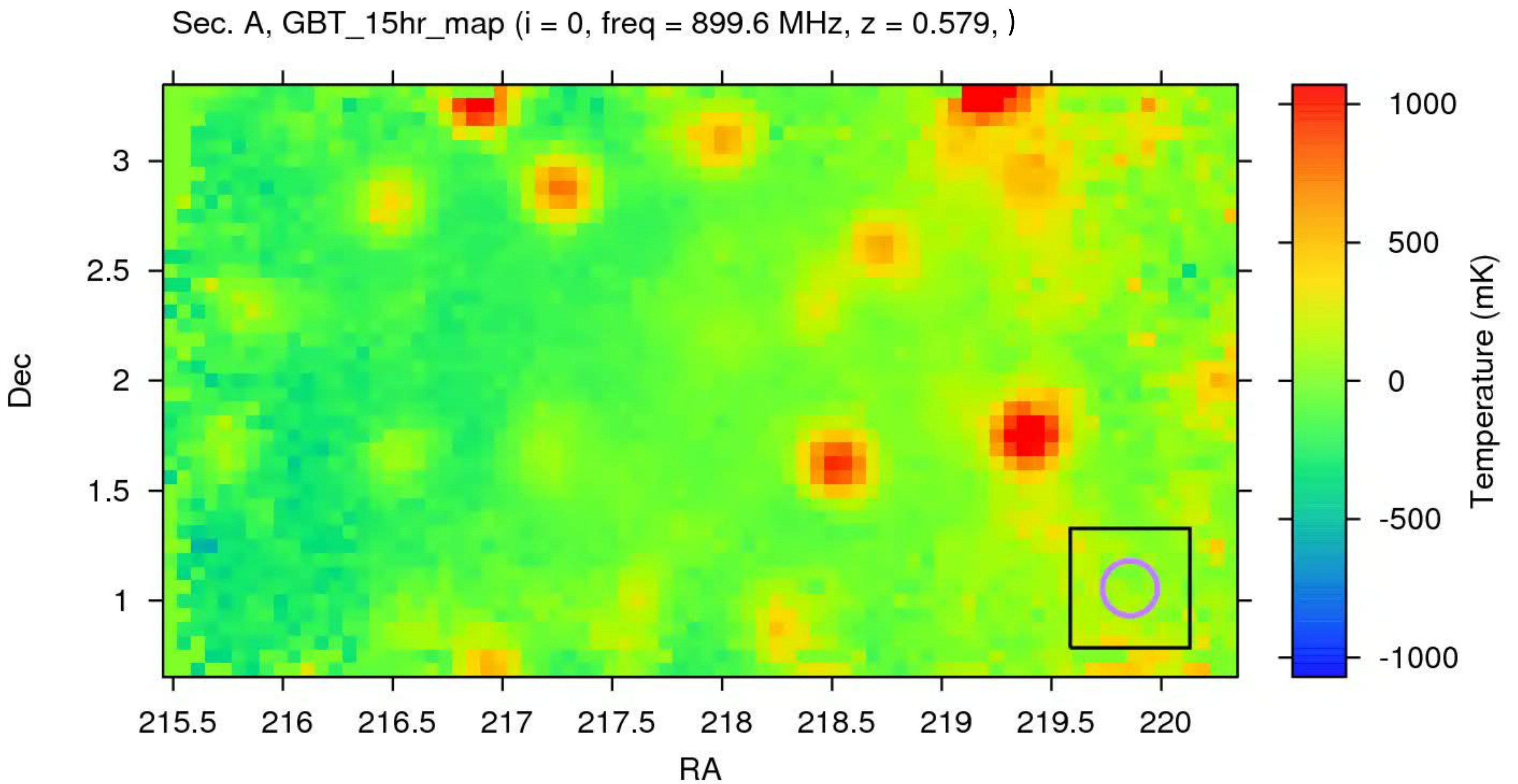


Residual
foregrounds

Marginalize over additive foreground

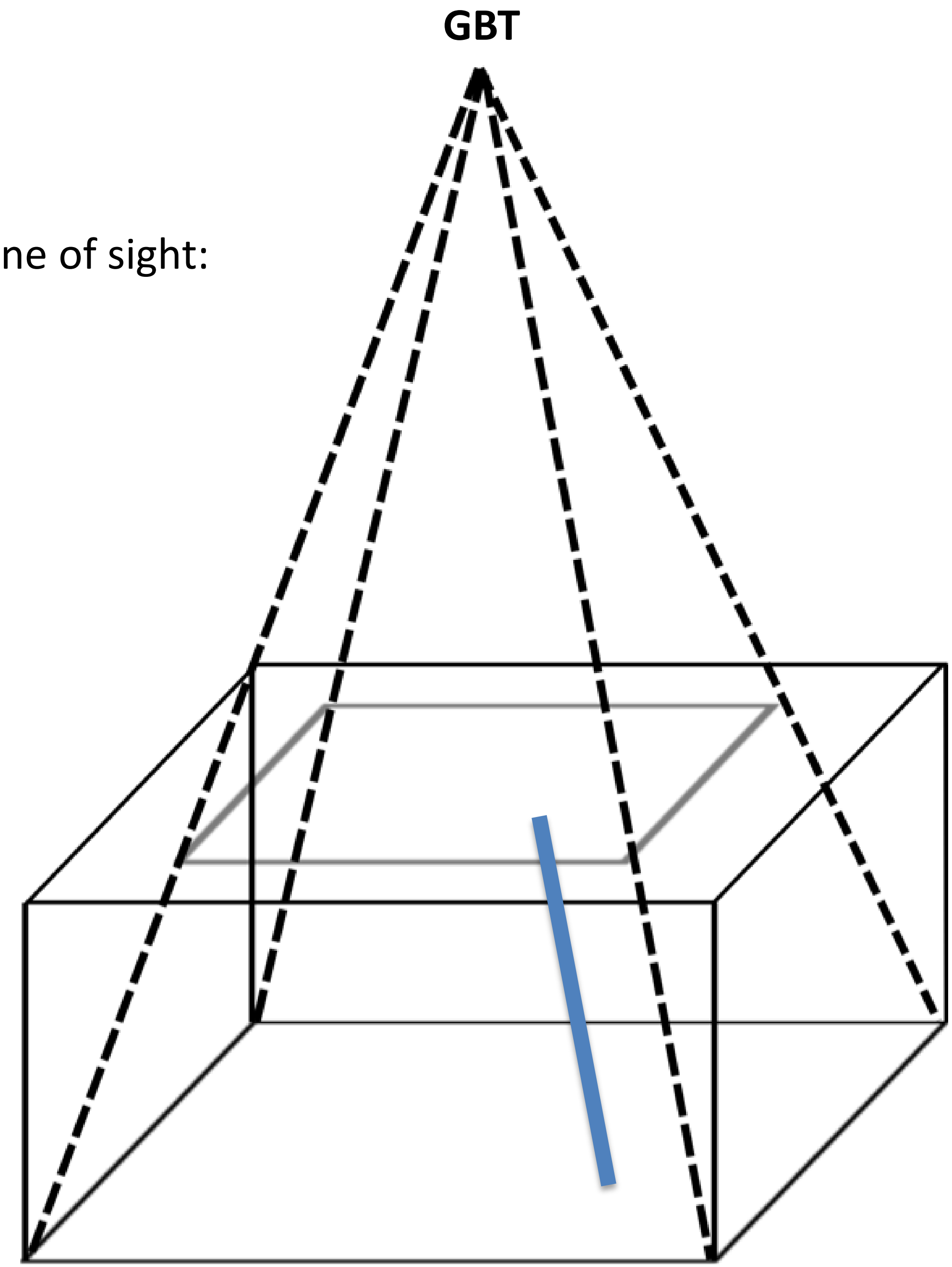
M. Tegmark's data purifier

The real data



Foreground cleaning along the line of sight:

1. Orthogonal polynomials
2. Modes from a foreground covariance **model**
3. Empirically-determined



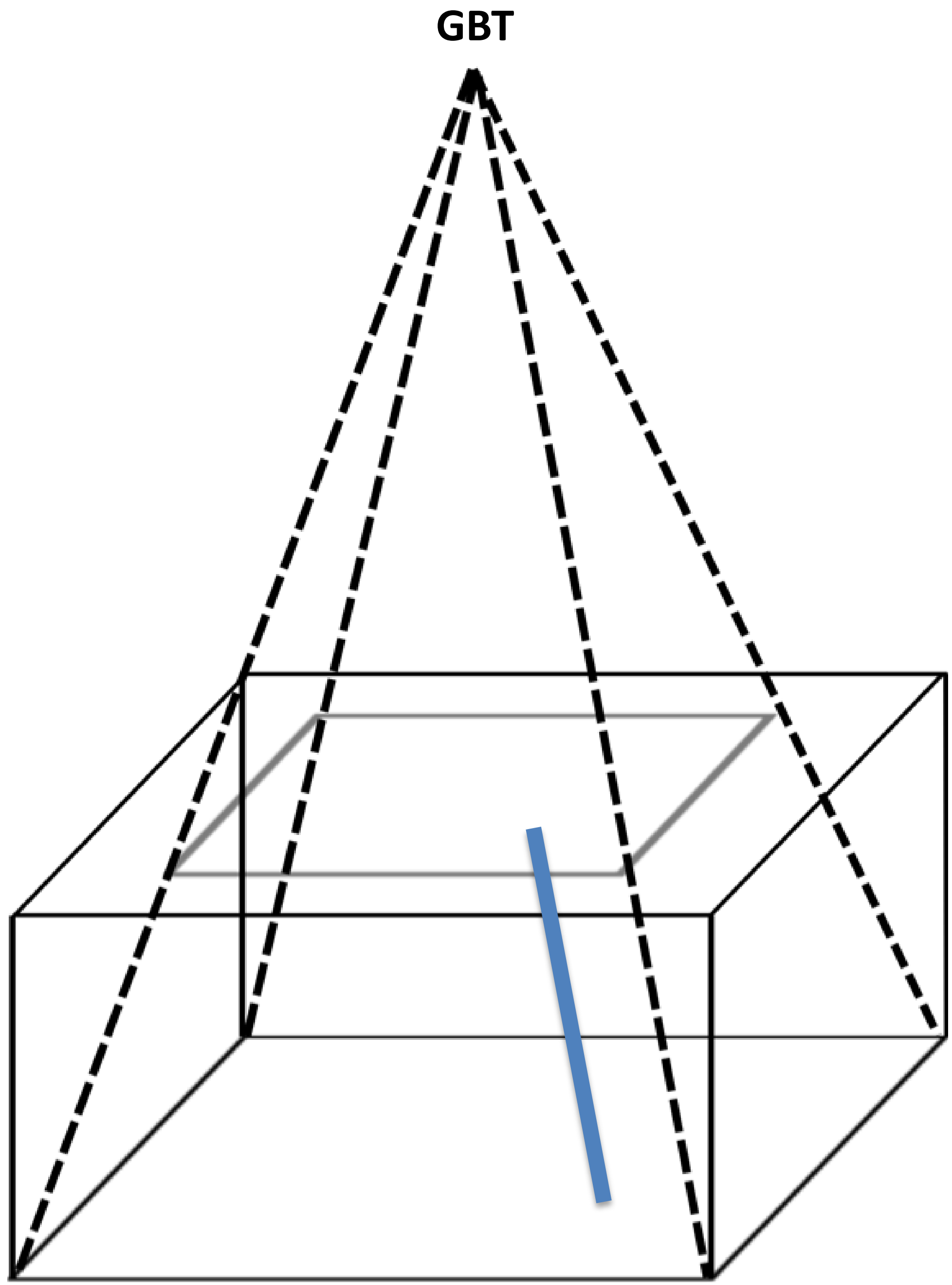
Foregrounds: “smooth” spectra with **few degrees of freedom**.

Signal: rich spectra with **many degrees of freedom**.

Technically: make low-rank approximation to covariance and remove contaminated modes along each line of sight.

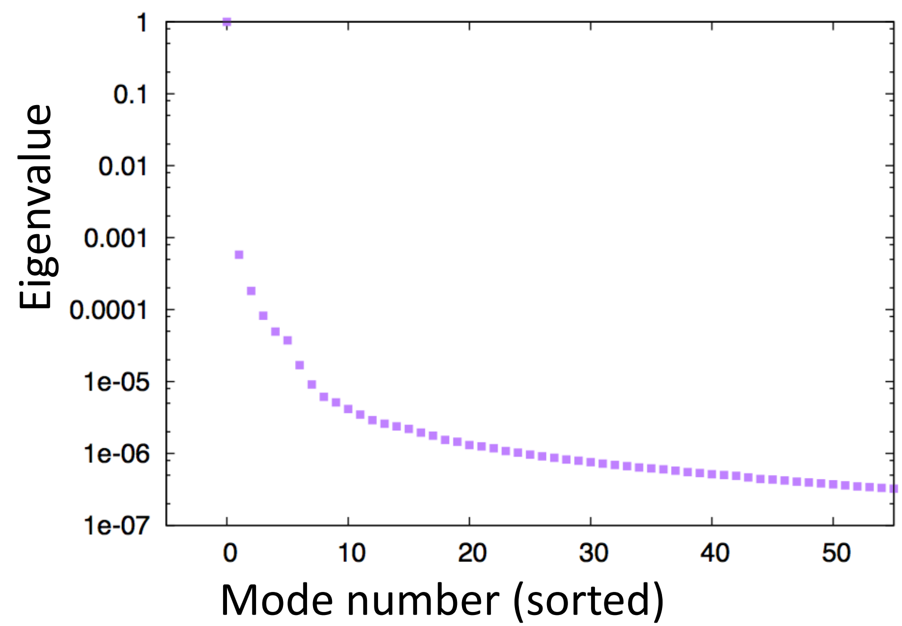
These modes are NOT smooth polynomials. Calibration, real foregrounds, etc.

Account for any signal lost. Subtle -- I can address this in questions.



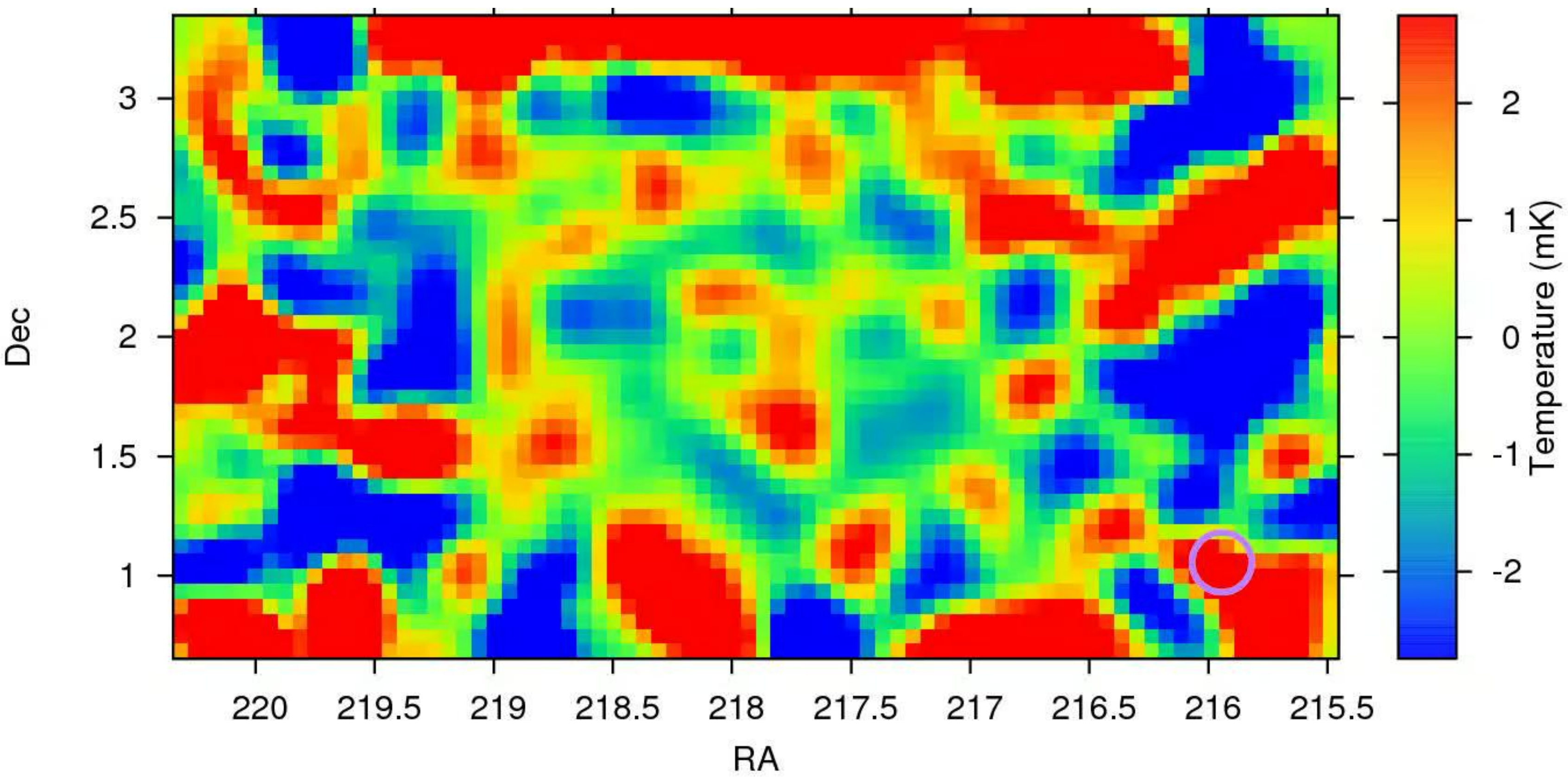
Considerations for instrumentation

- Instrument response: proliferation of bright foregrounds into new DOF
- Polarized beam response
- Wideband gain stability
- Estimating foreground modes with sufficient fidelity to remove them



Modes falling off rapidly: **few DOF to describe most of the foregrounds.**

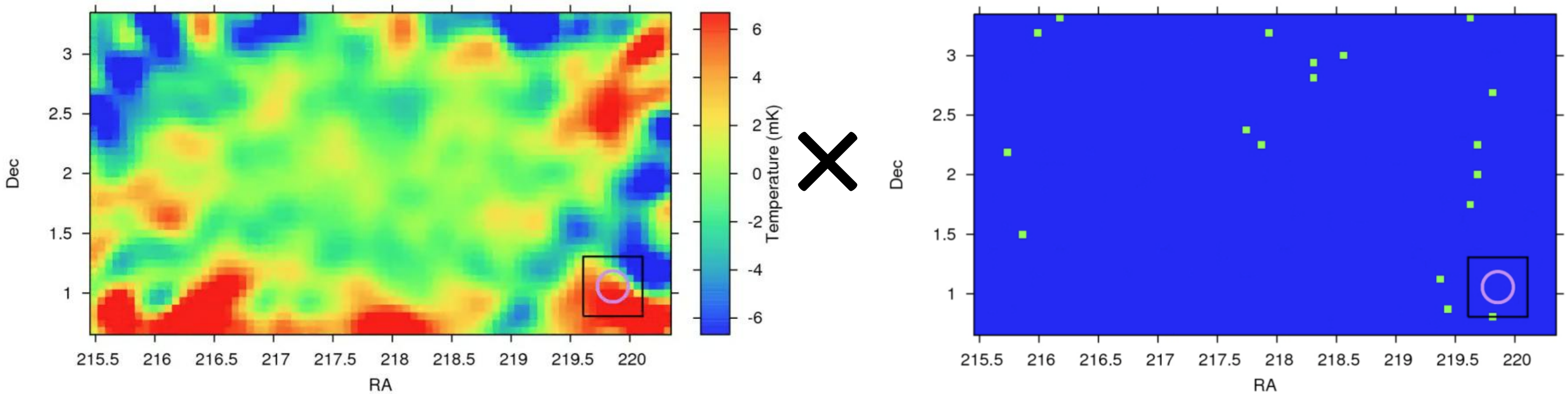
Real data, cleaned, beam convolved



S/N insufficient for an image of HI per slice; pursue statistical detection
Signal loss from foreground subtraction at this level is modest.

The 21 cm cross-power

Crosspower:



WiggleZ galaxy survey

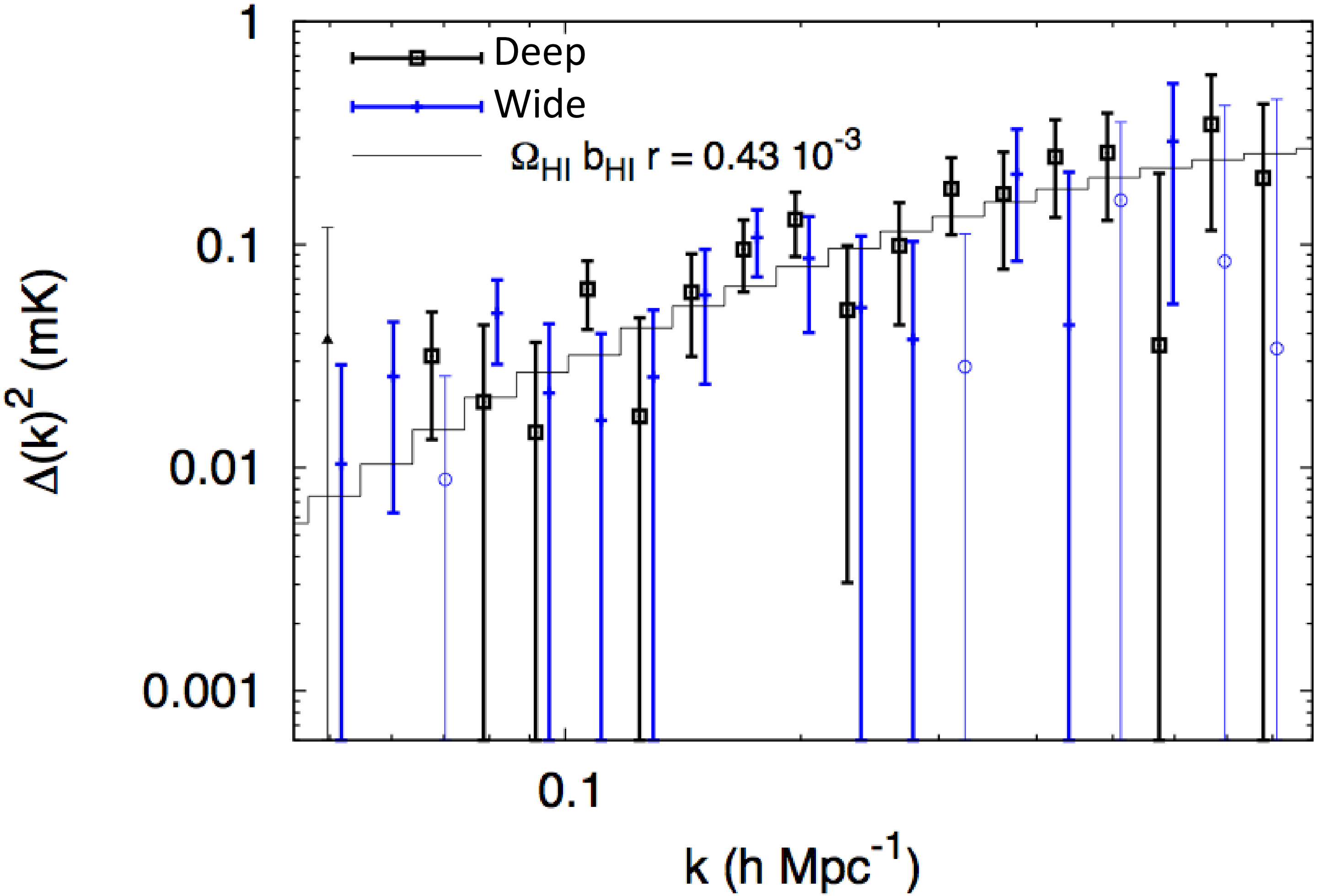
Residual foregrounds will increase errors
Unambiguous indication of cosmological structure

Fields may not correlate perfectly: **lower limit** on the 21 cm fluctuation power

MEASUREMENT OF 21 CM BRIGHTNESS FLUCTUATIONS AT $z \sim 0.8$ IN CROSS-CORRELATION

K. W. Masui[1,2], E. R. Switzer[1,3], N. Banavar[4], K. Bandura[5], C. Blake[6], L.-M. Calin[1], T.-C. Chang[7], X. Chen[8,9], Y.-C. Li[8], Y.-W. Liao[7], A. Natarajan[10], U.-L. Pen[1], J. B. Peterson[10], J. R. Shaw[1], T. C. Voytek[10]

Draft version September 3, 2012

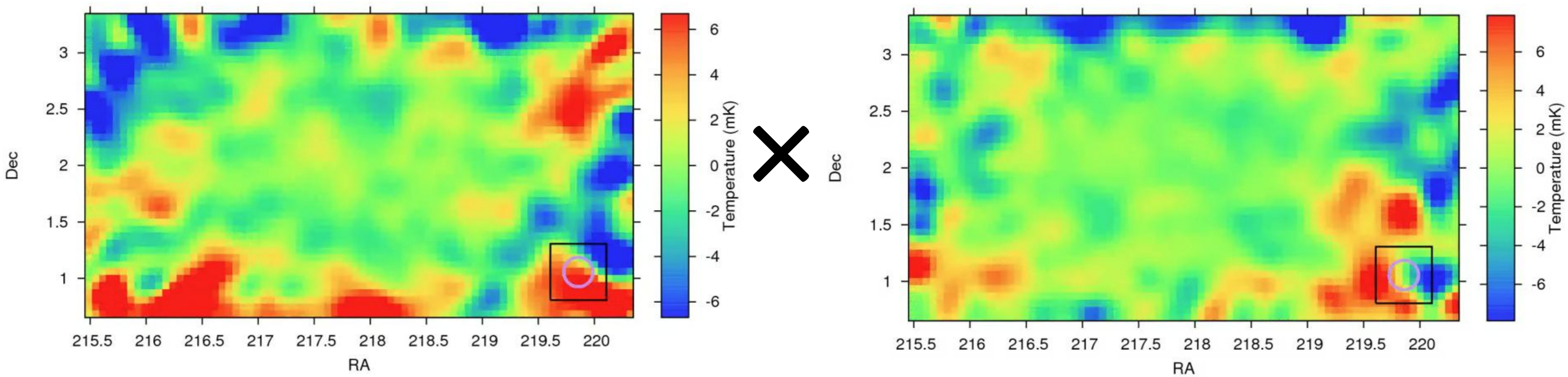


$$\Omega_{\rm HI} b_{\rm HI} r = [0.43 \pm 0.07({\rm stat.}) \pm 0.04({\rm sys.})] \times 10^{-3}$$

previous DEEP2 xcorr, Ω_{HI} rb = (5.5±1.5) 10^{-4}

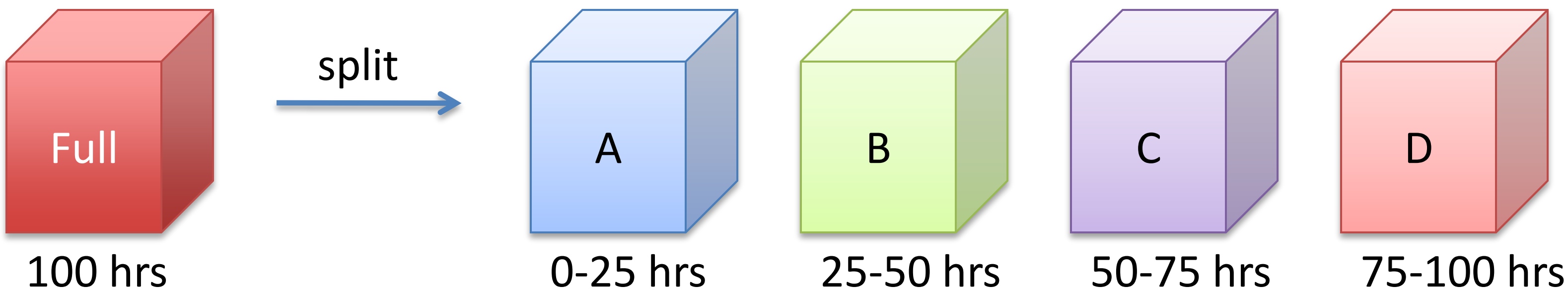
The 21 cm auto-power

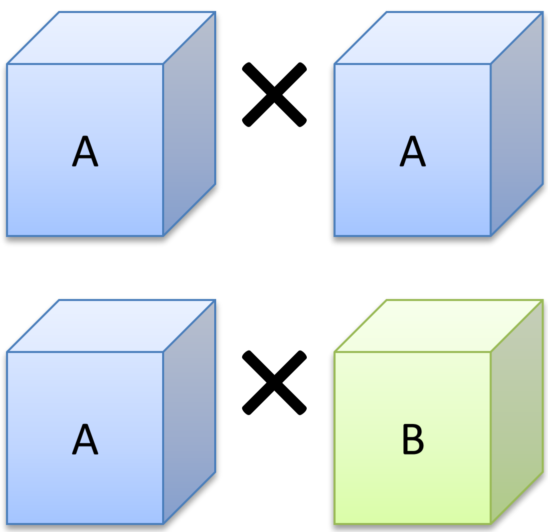
Autopower:



Residual foregrounds will bias the power spectrum (**upper bound**)

Splitting the season



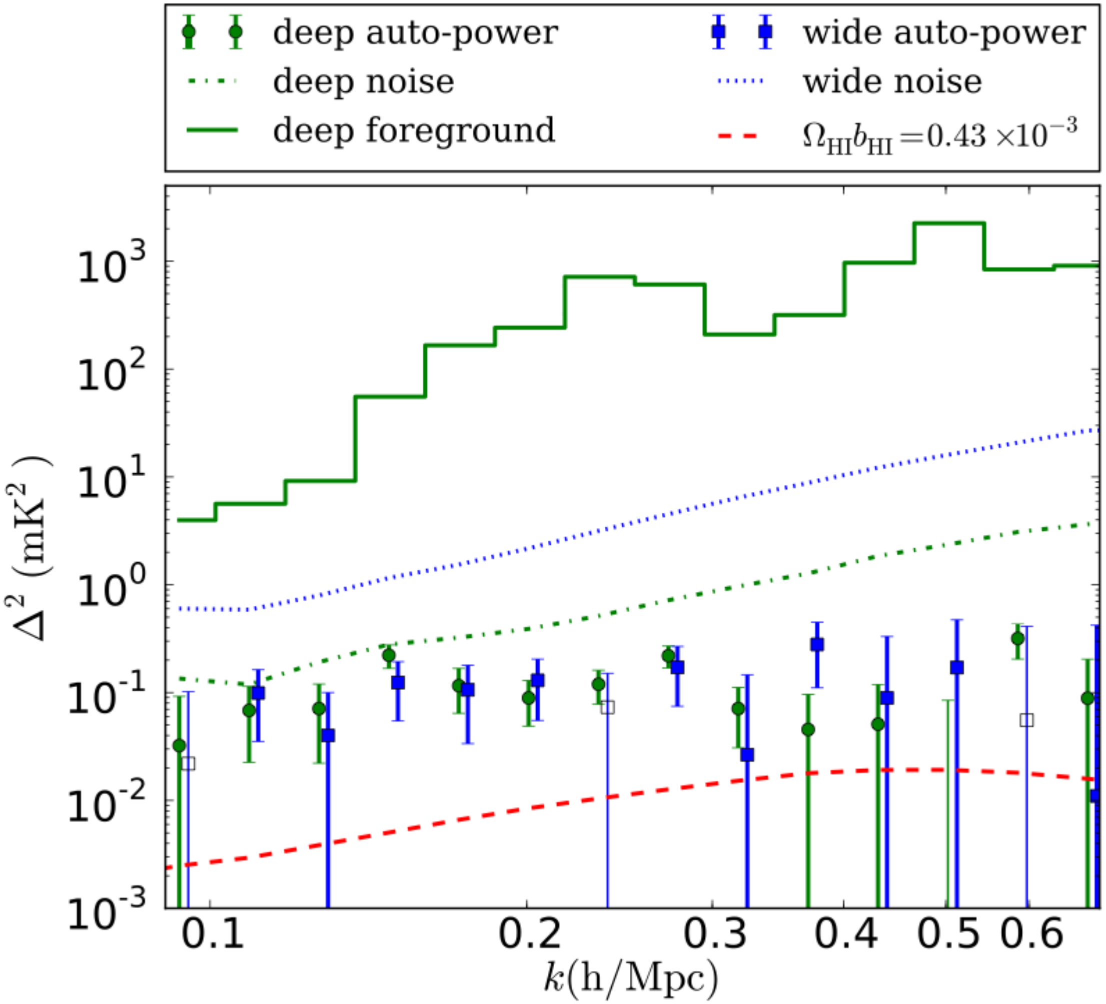


Signal power plus noise power.

Thermal noise and some RFI
is uncorrelated across time.

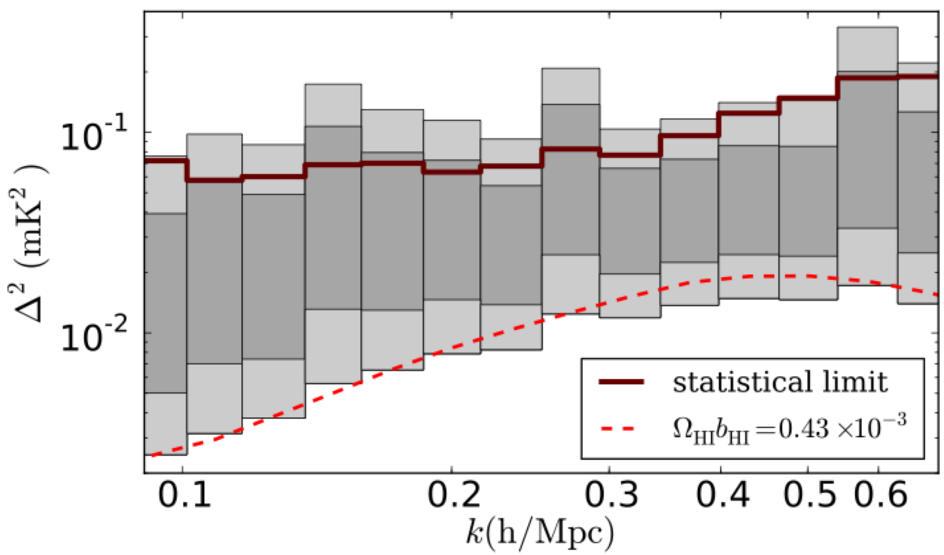
Form 6 unique pairs; rudimentary errors (agrees with Gaussian error)

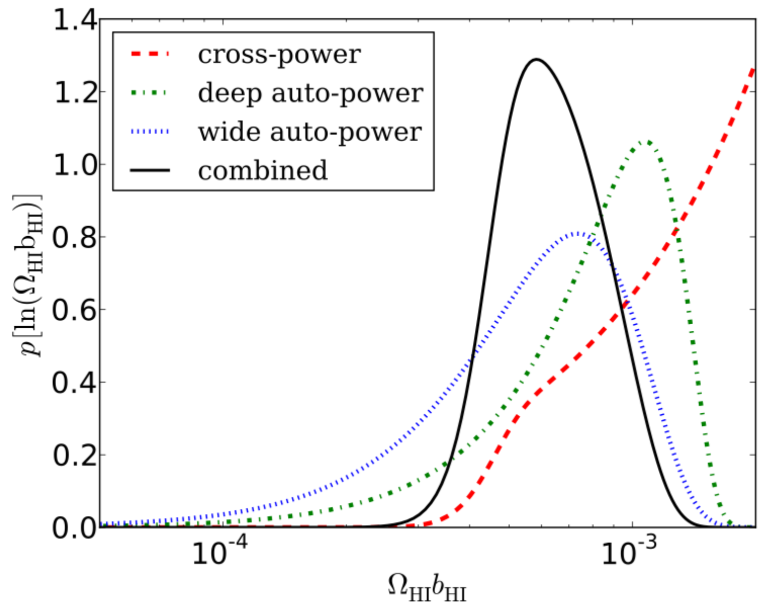
Temperature scales



1304.3712 Switzer, Masui, et al.

Auto-power constraints

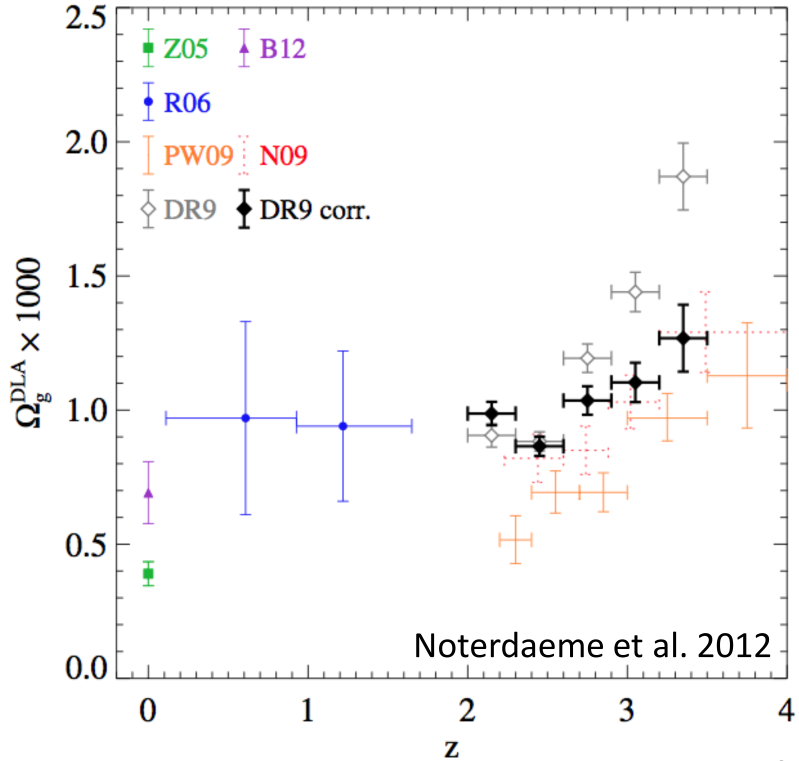




$$p(s_k|\mathbf{d}_k) = \int p(s_k, r, f_k^{\rm deep}, f_k^{\rm wide}|\mathbf{d}_k)\, {\rm d}r\, {\rm d}f_k^{\rm deep}\, {\rm d}f_k^{\rm wide}$$

Determine abundance times bias independently of stochasticity
Determination, not “measurement”.

Neutral hydrogen evolution

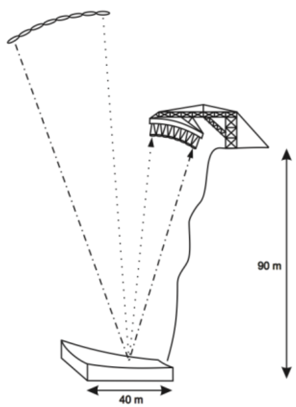


Our measurements suggest $\Omega_{HI}(z=0.8)$ between 0.5×10^{-3} and 1.3×10^{-3} (**Integral HI**)

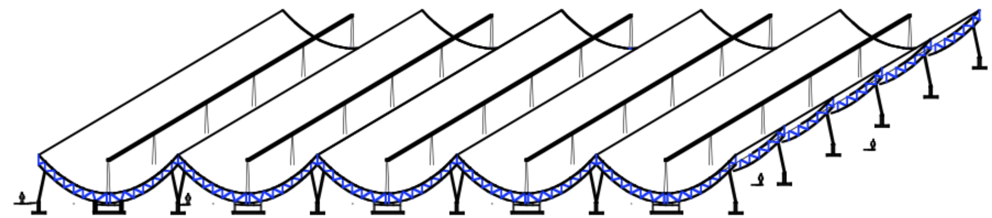
- HI is an intermediate phase of ionized gas from the IGM that supplies star formation (H_2), not part of a closed reservoir within galaxies. (Bauermeister 2010)
- Separate bias and abundance using redshift-space distortions.
- With 1 year on a dedicated interferometer (CHIME), ~% level constraint of HI abundance.

Proposed experiments

GBT-Multibeam (PI: T.-C. Chang)

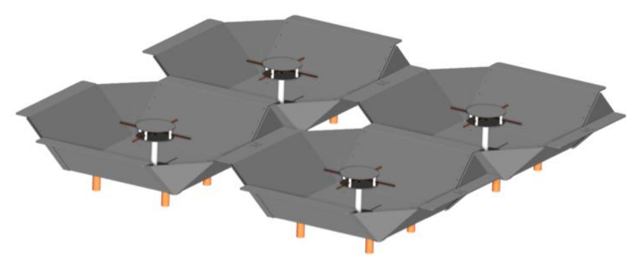


BINGO Battye et al. 2012



CHIME

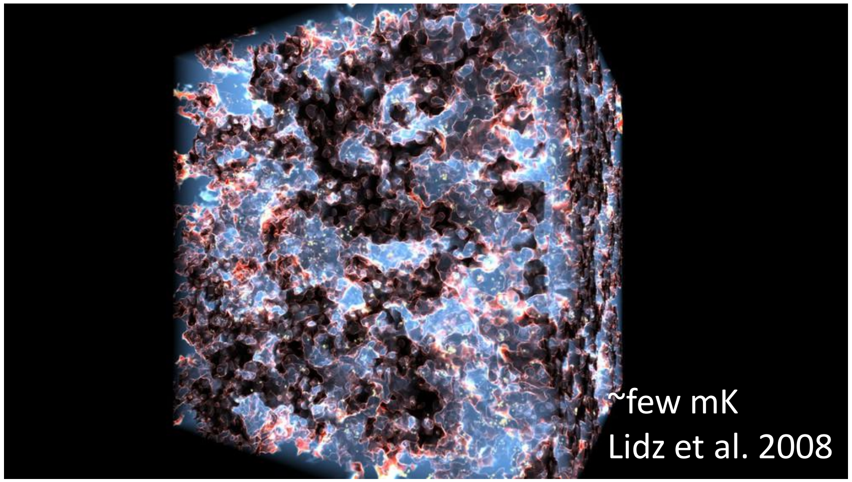
100x100m from 400 MHz to 800 MHz; noise ~50 K.
z=0.7-2.5: map the Dark Energy-driven transition,
20 Glyr/side ~0.2 Gpix. (design similar to CRT)

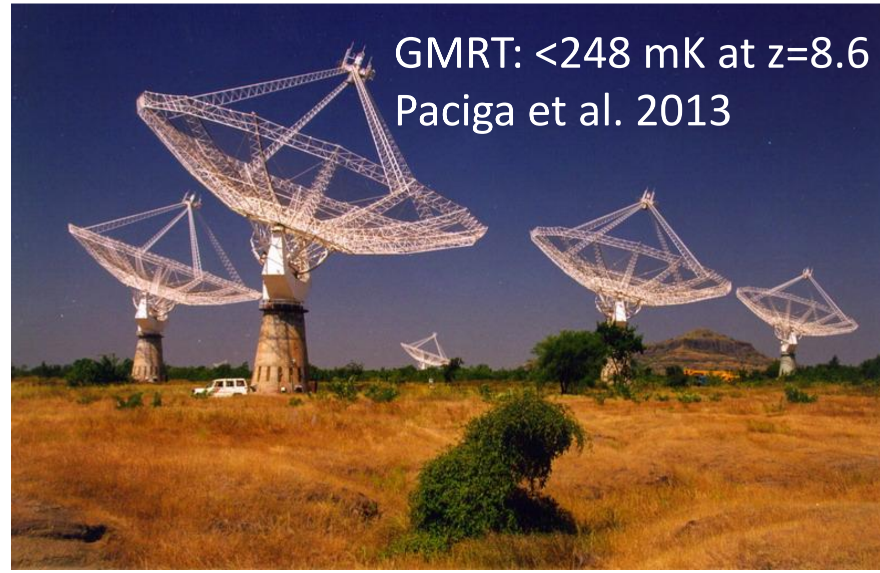


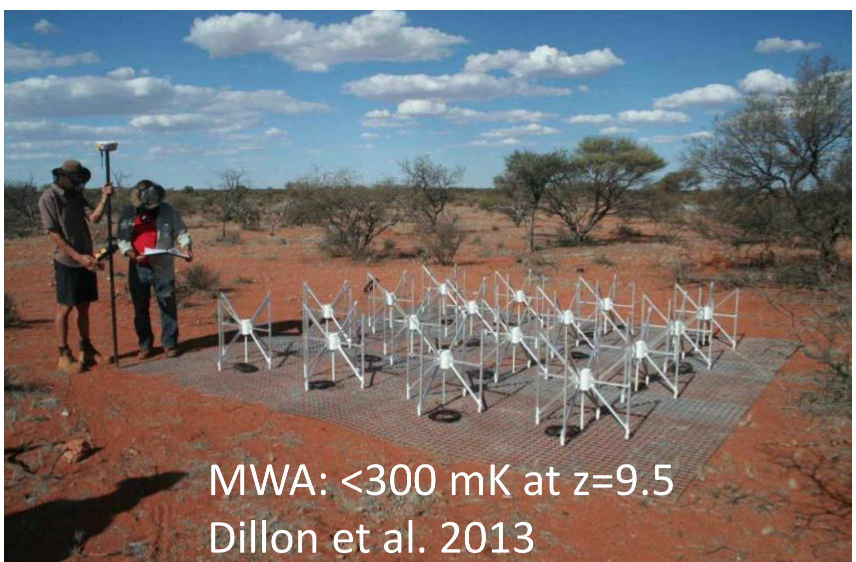
BAOBAB, Pober et al. 2012

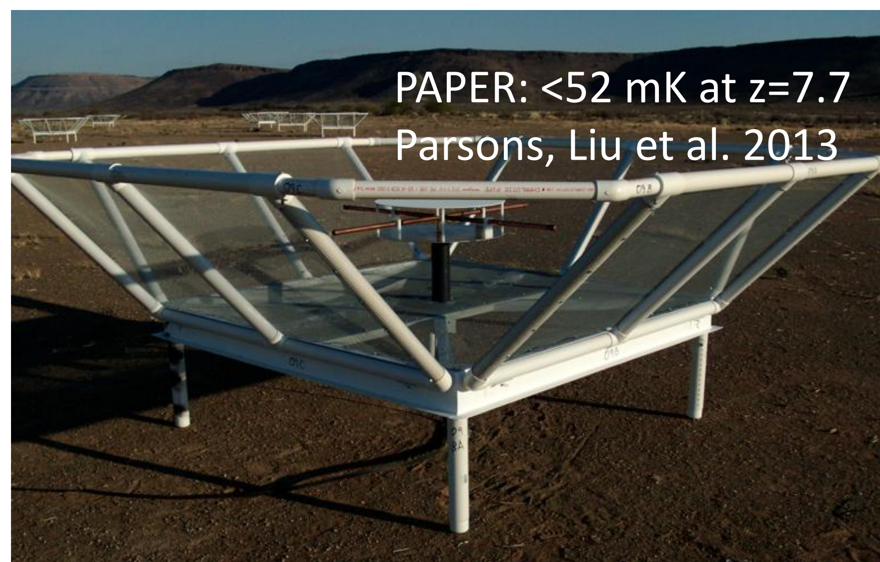
BAOradio, Ansari et al. 2012

Recent 21cm reionization results

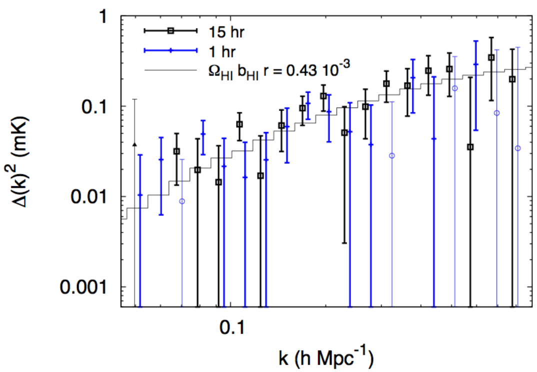








Opening a new window on the cosmos



Integrated abundance of neutral hydrogen at z~0.8. With more data: break abundance/bias degeneracy.

Our group: first detection of cosmological structure in 21 cm. Foregrounds cleaned from 1 K to < 1 mK.

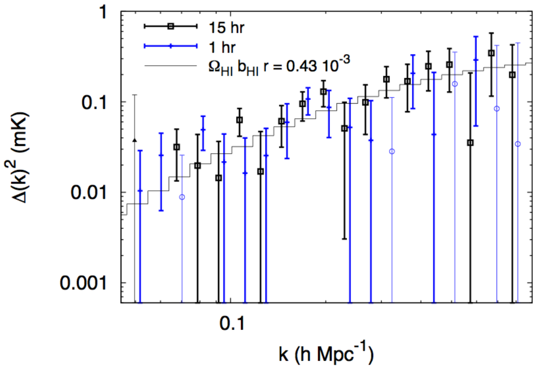
Present

Challenges:

- Like kSZ detection (foreground removal)
- Like B-modes (inst. systematic control)
- Multiplicative and additive bias

Cross: 1208.0331 Masui, Switzer et al. 5 pages
Auto: 1304.3712 Switzer, Masui, et al. 5 pages

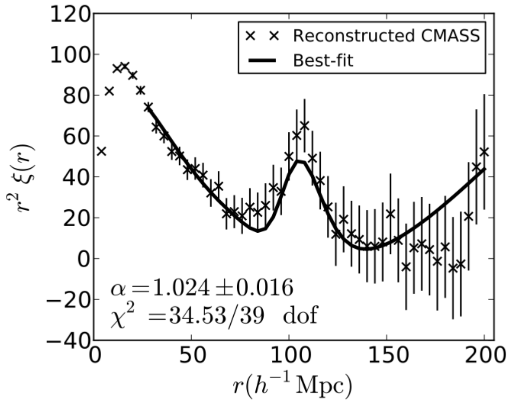
Opening a new window on the cosmos



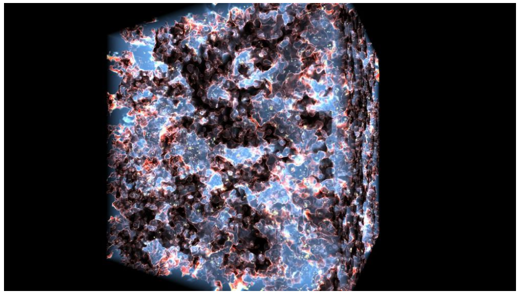
Integrated abundance of neutral hydrogen at z~0.8. With more data: break abundance/bias degeneracy.

Our group: first detection of cosmological structure in 21 cm. Foregrounds cleaned from 1 K to < 1 mK.

Present



Baryon acoustic oscillations: A clean tracer of the early universe from very complex structure.



Transfer/scale methods we learn in this concrete setting to 21cm measurements of reionization.

Future