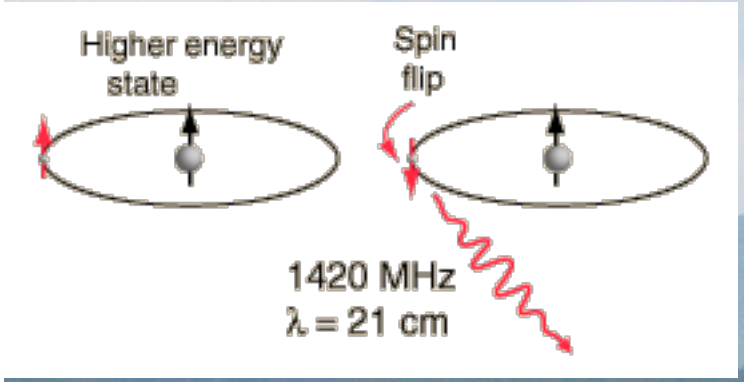
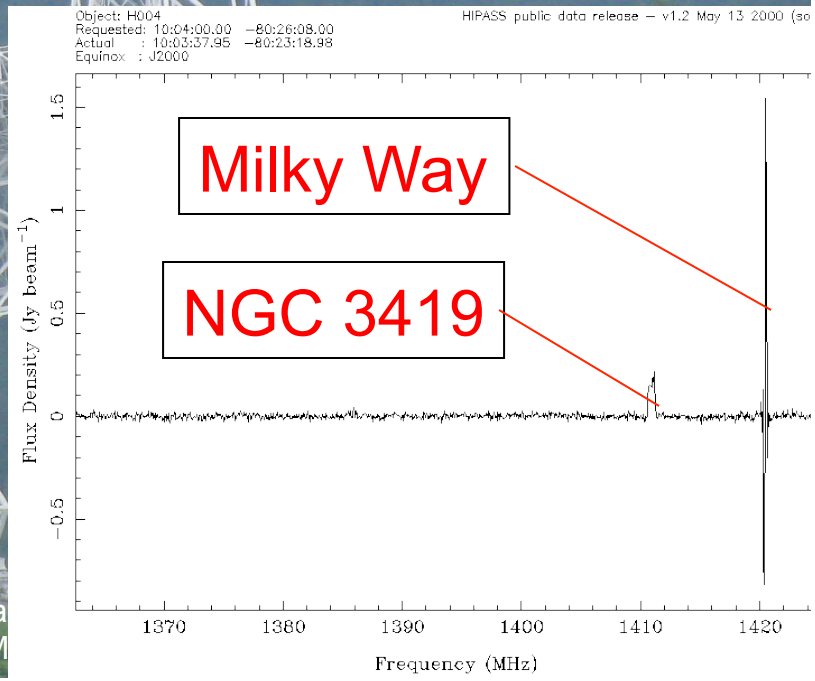
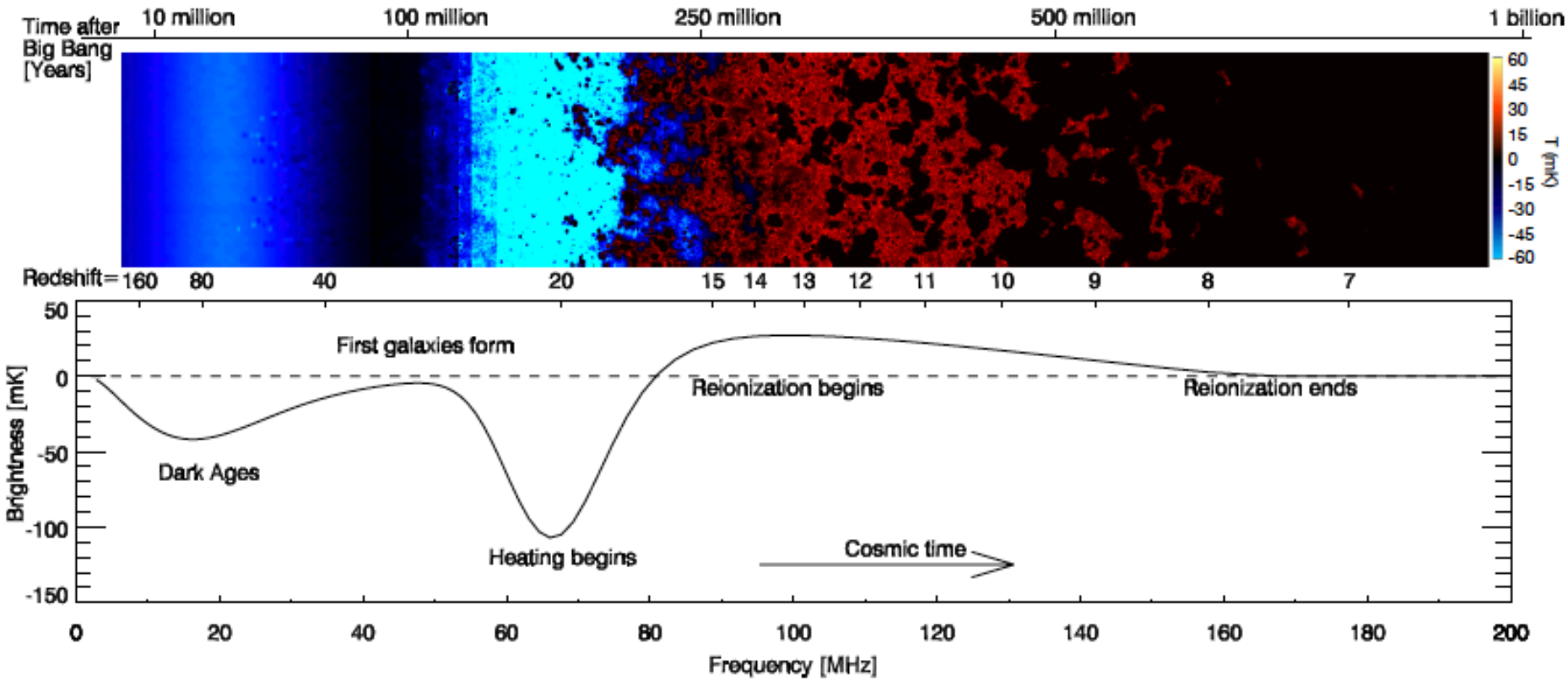
Overview of 21 cm Experiments





Peter Timbie
Department of Physics
UW-Madison

21 cm cosmology timeline



Pritchard & Loeb Rep. Prog. Phys. 75 (2012)

21 cm Cosmology Goals

- **Observe global 21-cm spectrum**
  EDGES, SCI-HI, DARE

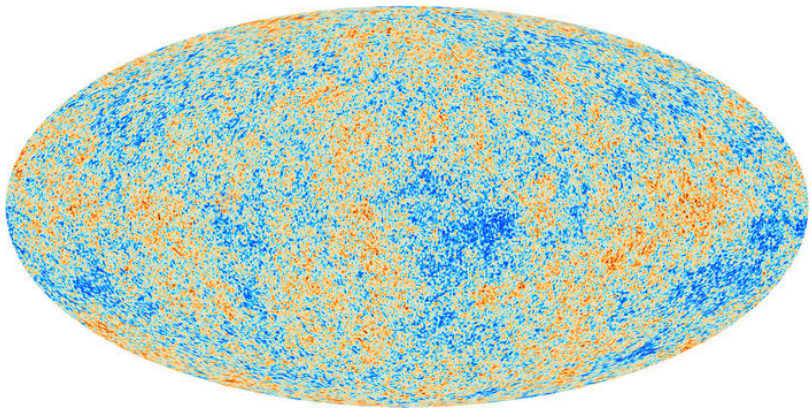
- **Observe the Cosmic Dark Ages (z > 10)**
  LWA

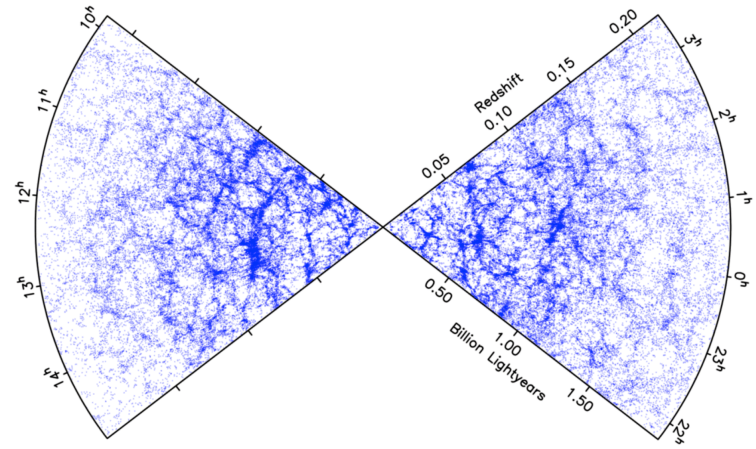
- **Observe Epoch of Reionization (z ~ 10)**
  CMA21, PAPER, MWA, LOFAR

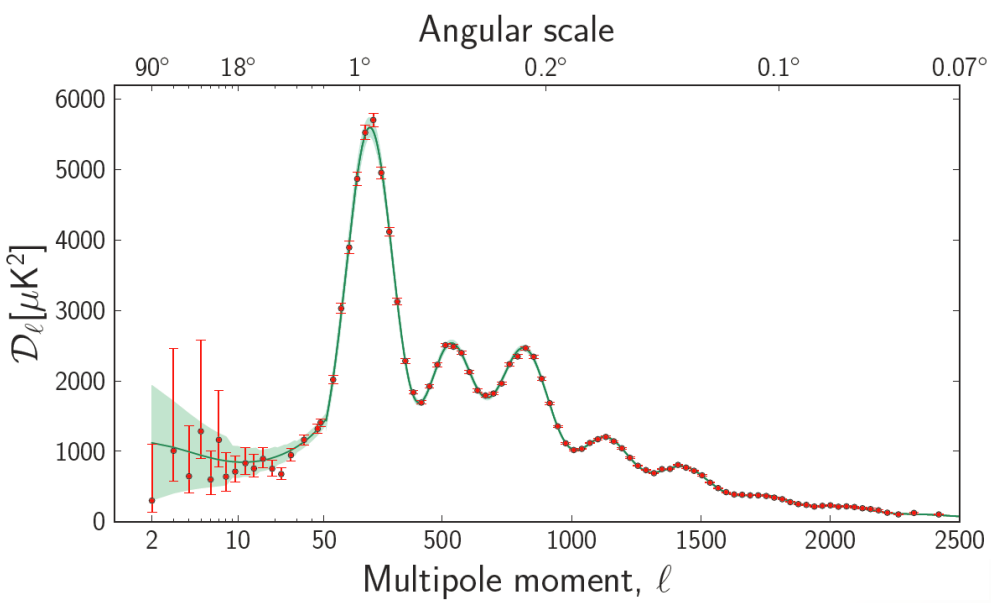
- **Observe Large-Scale Structure at 'Late-times' (z < 3)**
  dark energy
  non-Gaussianity (probe of inflation)
  neutrino mass, etc.
  BINGO, FAST, **GBT, Parkes, CHIME, HIRAX**, **PAON**, **TIANLAI**, SKA

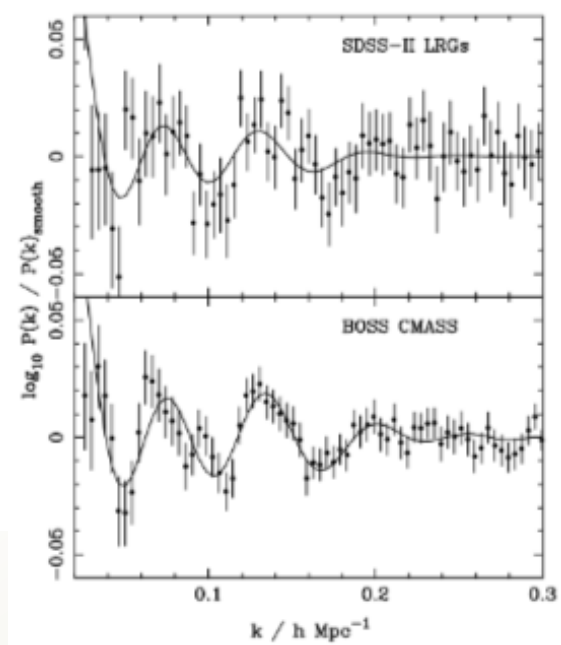
- **Monitor time-dependent sky**
  Pulsars, FRB's

BAO: Baryon Acoustic Oscillations in pre-recombination era → CMB acoustic peaks & a standard ruler in the galaxy density field

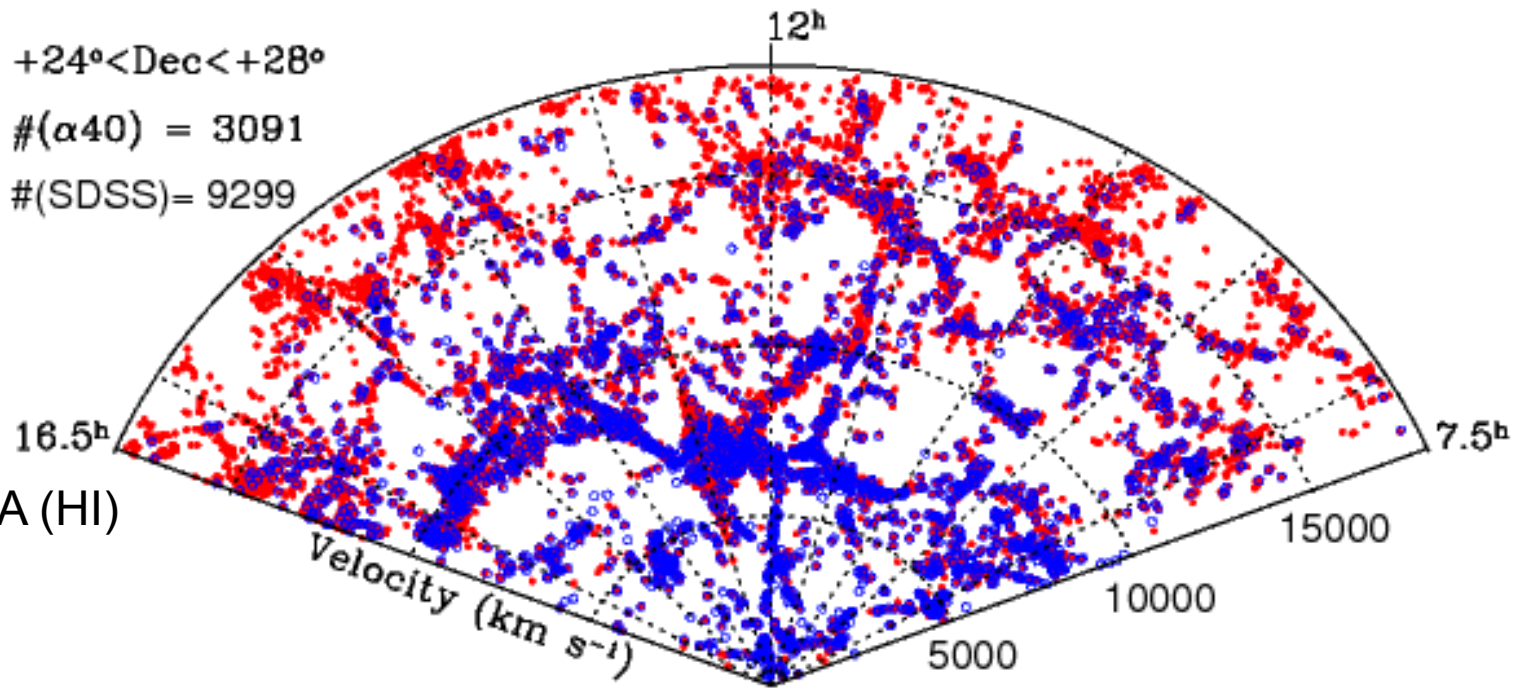








HI and Optical Surveys Detect Similar Structure to z ~ 0.07



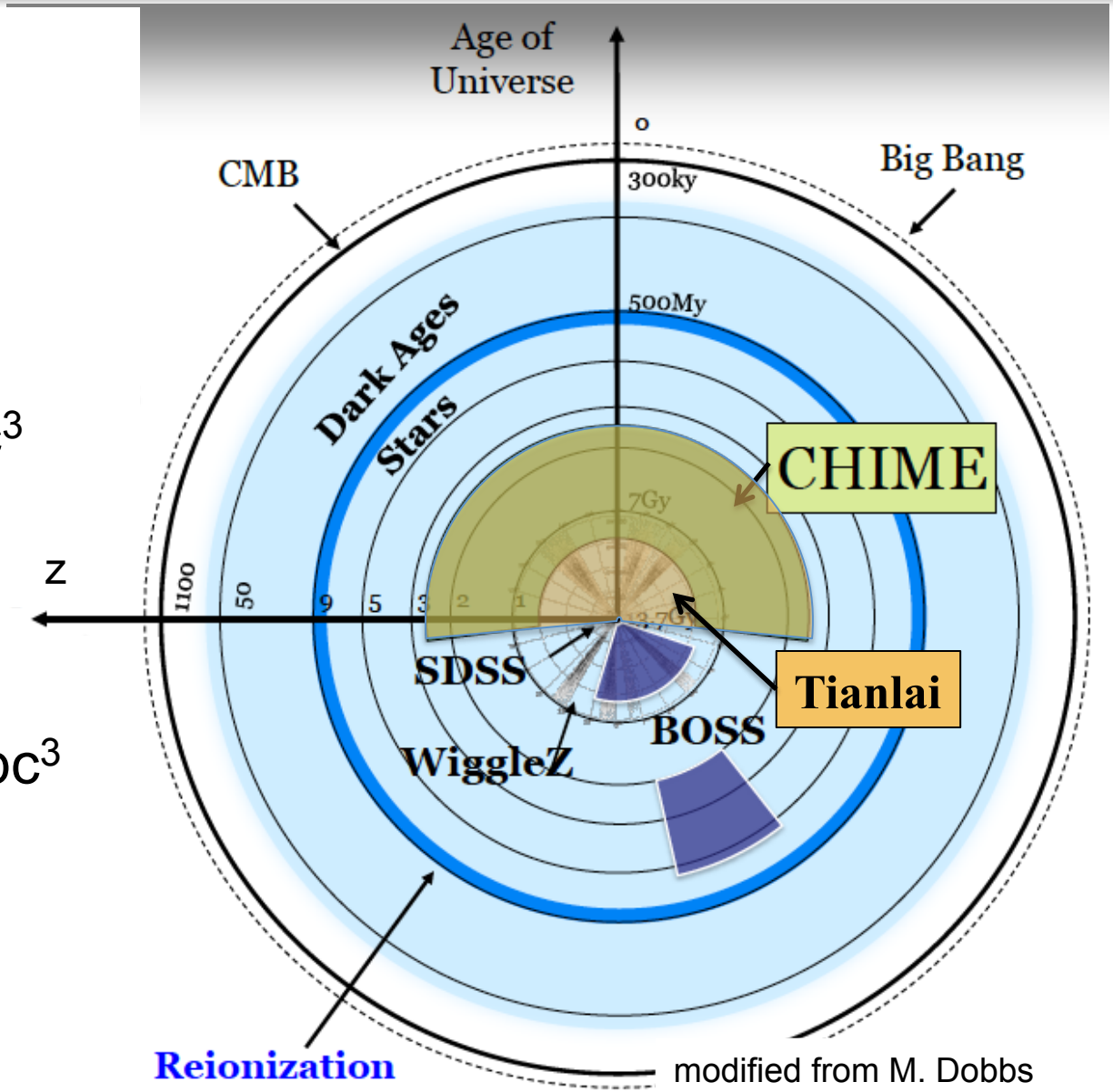
- ALFALFA (HI)
- SDSS

Haynes et al. (2011)

21 cm surveys can explore huge comoving volumes

1 h^{-3} Gpc^3

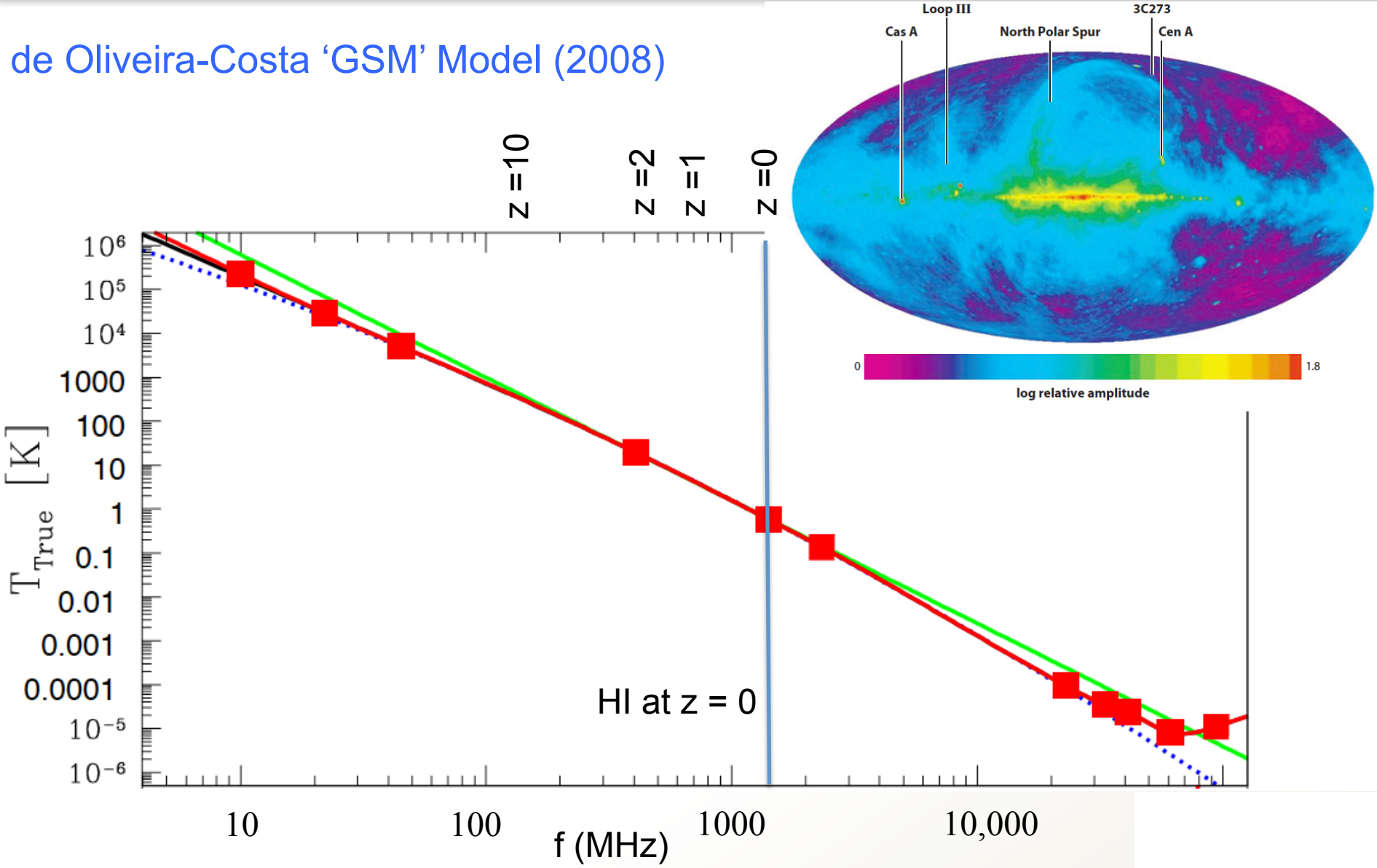
200 h^{-3} Gpc^3



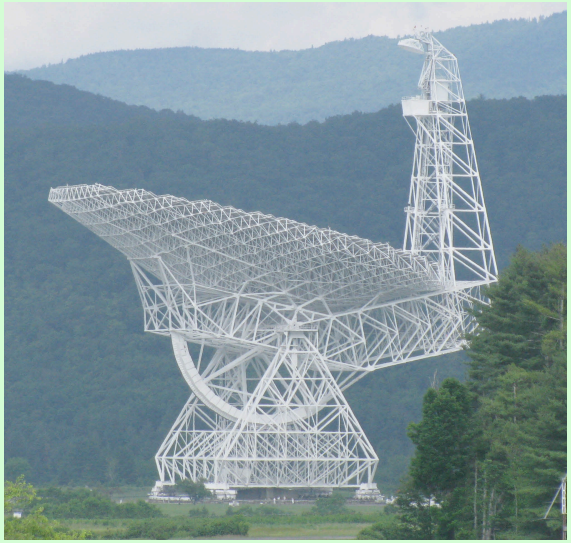
modified from M. Dobbs

Galactic Foregrounds are ~ 10^4 X Brighter than HI at z ~ 1!

de Oliveira-Costa 'GSM' Model (2008)



First Steps with Intensity Mapping at GBT



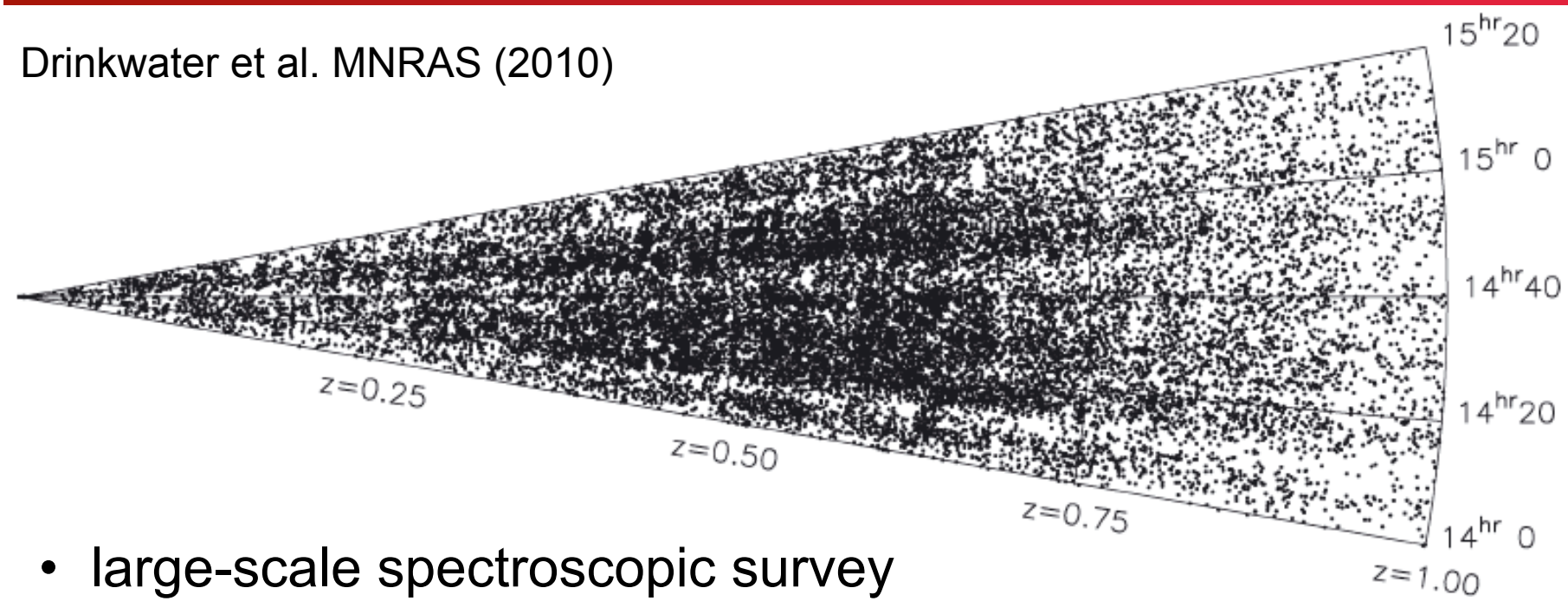
- clean beam, unblocked aperture (100 m)
- quiet cooled receiver (T_{sys} ~ 25 K)
- for 700–900 MHz band (z ~ 0.59 – 1.0)
- angular resolution good for intensity mapping ~0.25° ➔10 h^{-1} Mpc at z ~ 0.8
- available for ~ 100's of hours
- ASIAA, CMU, CITA (+ NAOC, UW-Madison)

Tests of:

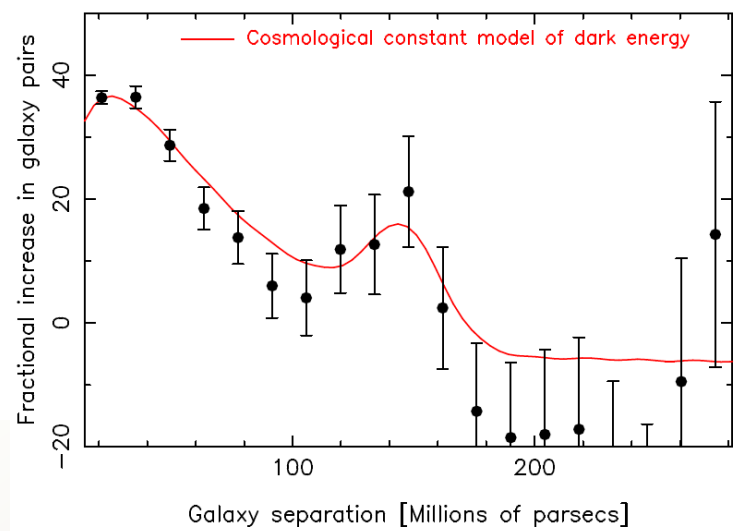
- foreground removal
- RFI removal
- HI intensity mapping
  - cross-correlation with optical surveys
  - autocorrelation
- HI abundance (Ω_{HI})

WiggleZ Dark Energy Survey: correlate with GBT survey

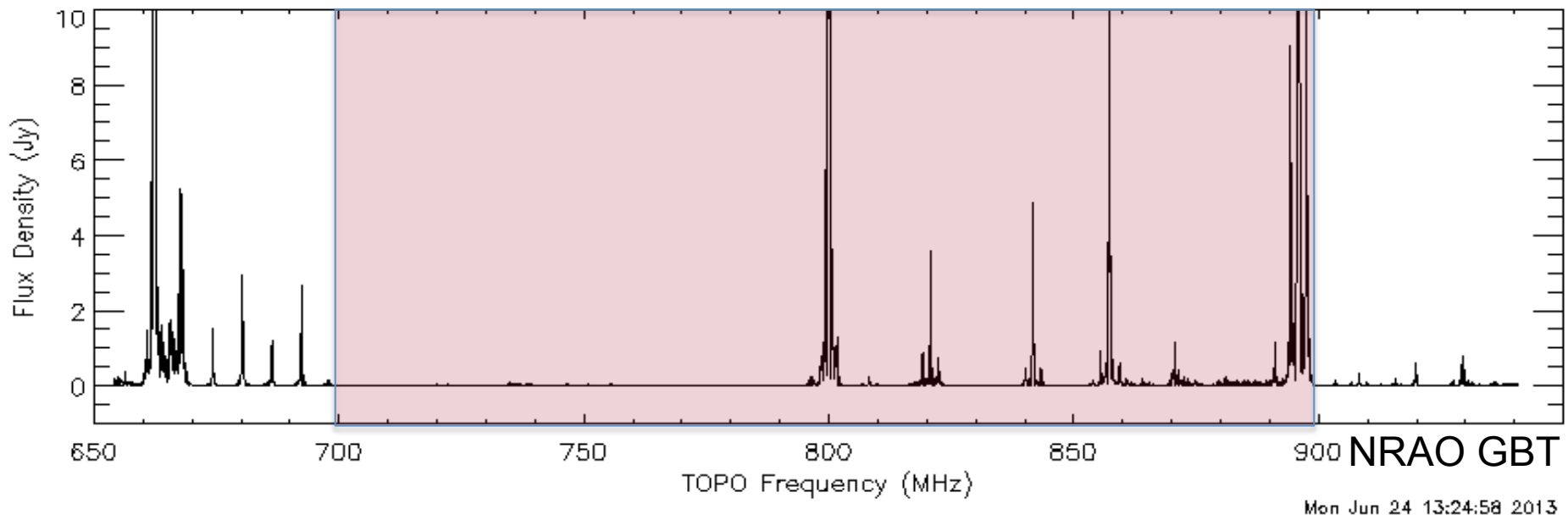
Drinkwater et al. MNRAS (2010)



- large-scale spectroscopic survey
- emission-line galaxies
- selected from UV and optical imaging
- ~ 350 galaxies deg^{-2}
- 1000 deg^2
- Anglo-Australian telescope



RFI Jungle



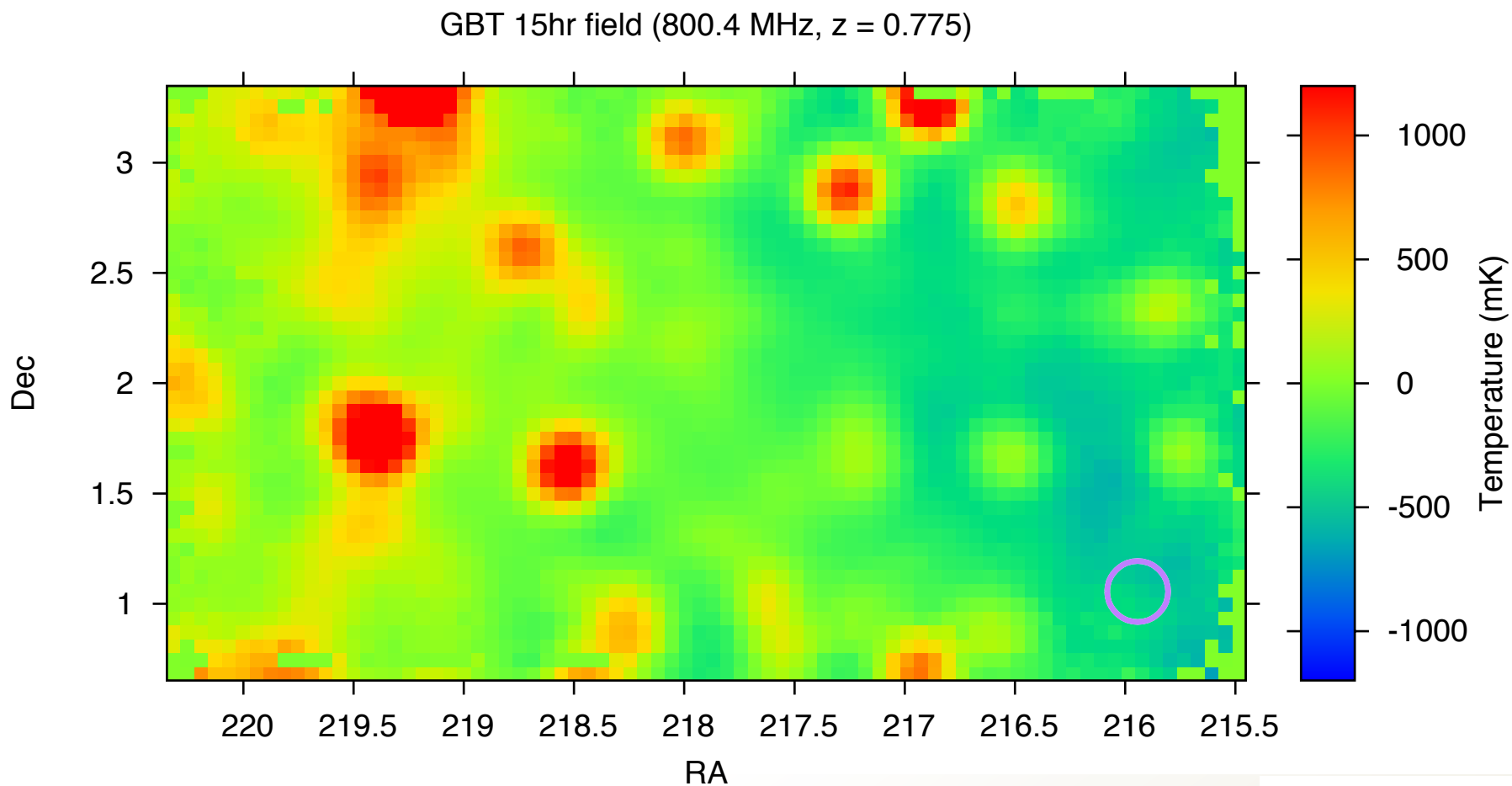
Removal techniques

- High resolution spectra (200 MHz/ 4096 ~ 50 kHz bins)
- Variance
- Linear polarization

E. Switzer

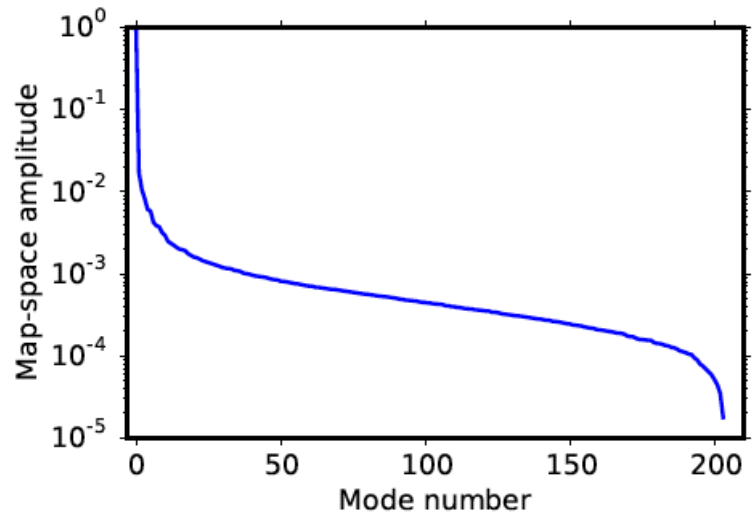
GBT map before foreground removal WiggleZ field

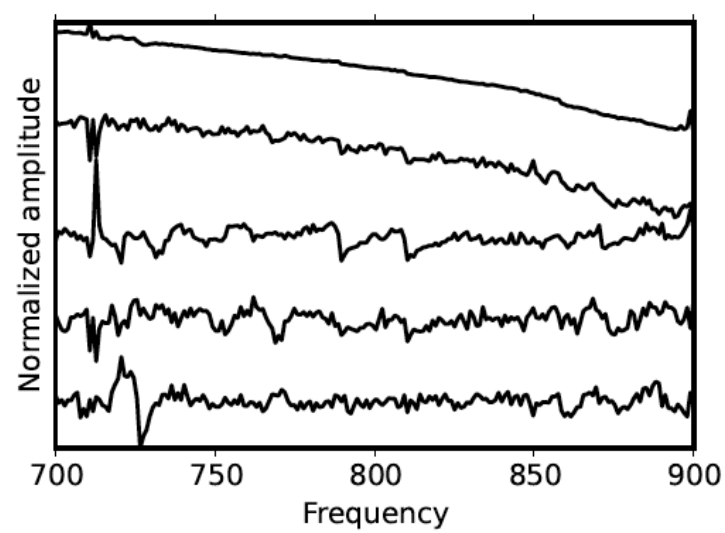
Masui et al. ApJ 763:L20 (2013)



Foreground removal

- *Instrumental effects* (polarization leakage from P→I) and Faraday rotation produce structure in spectra of bright foregrounds.
- In each angular pixel, use **singular value decomposition (SVD)** to find largest modes in frequency (redshift) direction.
- Simulate/ correct for signal subtracted by this method.
- In *cross-correlation* with galaxy survey, unremoved foregrounds increase noise, but don't bias the power spectrum. Optimum number of cut modes ~ 15.
- In *auto-correlation*, unremoved foregrounds bias the power spectrum.

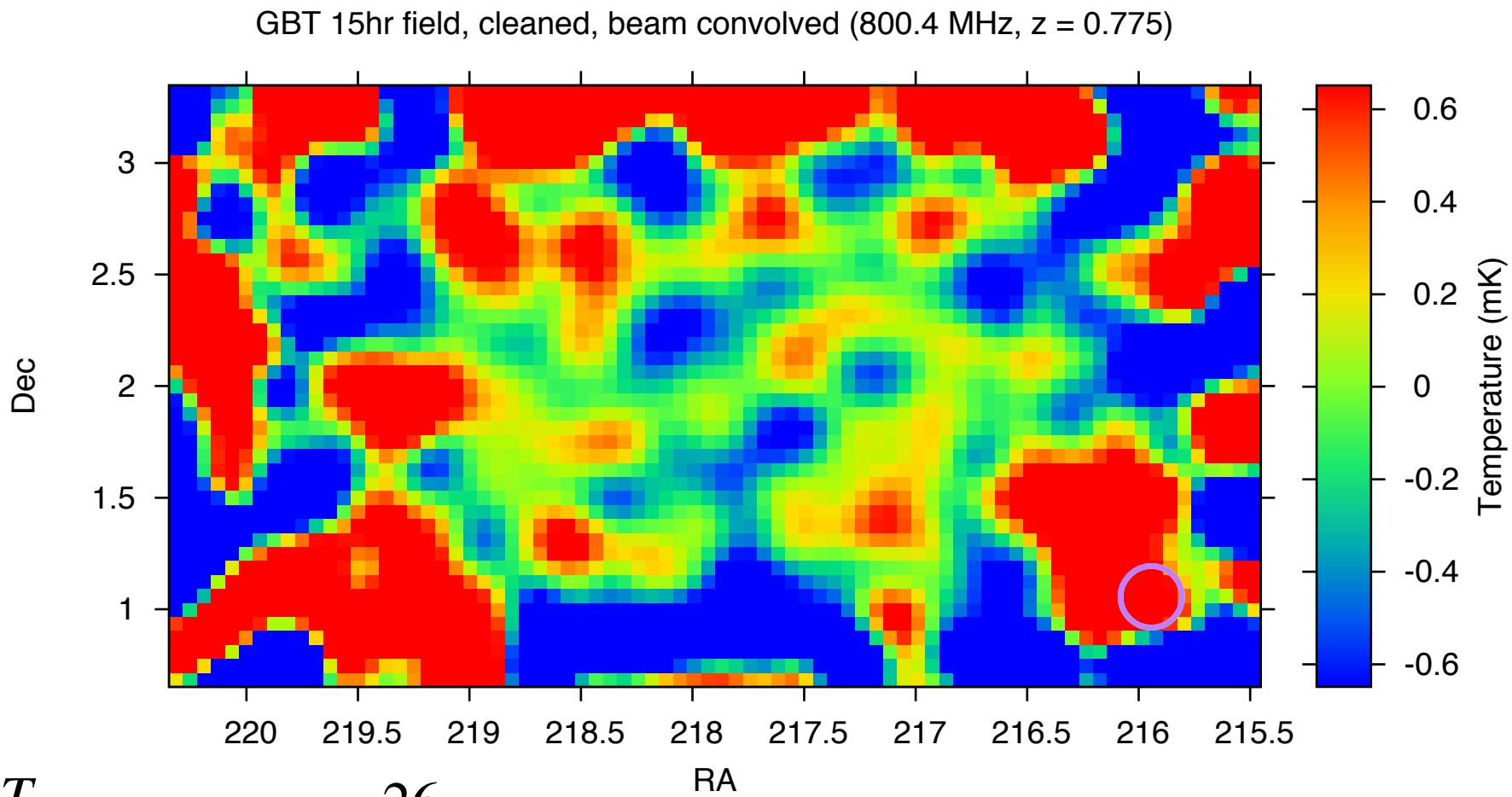




Switzer et al. 1504.07527v1

Cleaned 21-cm GBT map

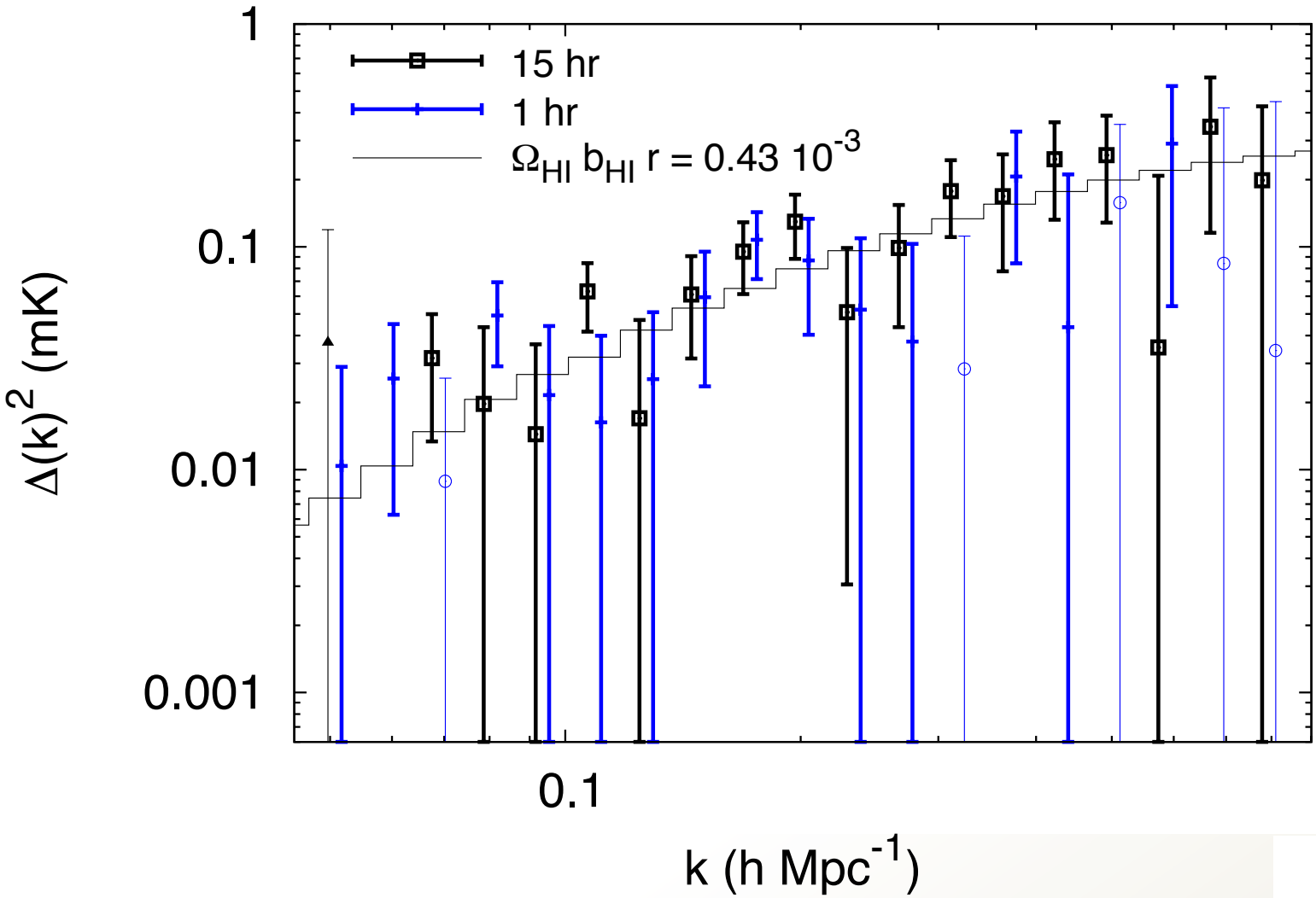
Masui et al. ApJ 763:L20 (2013)



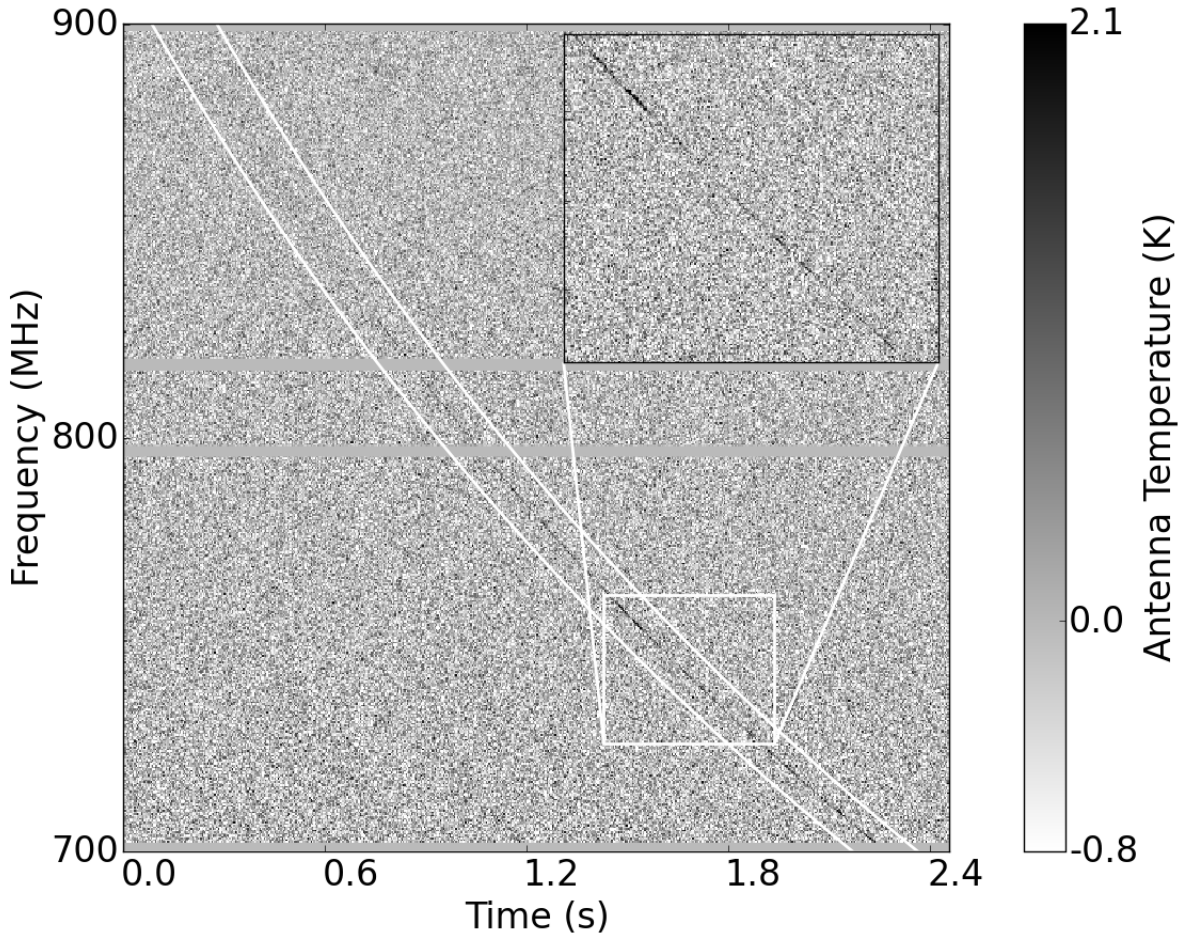
$$\frac{T_{Sys}}{\sqrt{\Delta\nu\tau}} = \frac{26}{\sqrt{0.78\ \mathrm{MHz} \times 2200\ \mathrm{s}}} = 0.63\ \mathrm{mK/beam}$$

HI – WiggleZ cross-power spectrum

Masui et al. ApJ 763:L20 (2013)

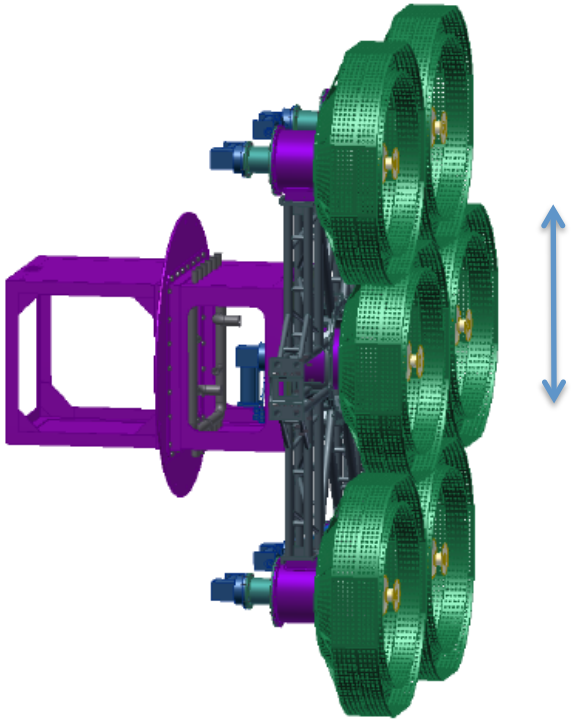


Fast Radio Burst Discovered!
Pulse arrival time vs frequency for FRB 110523

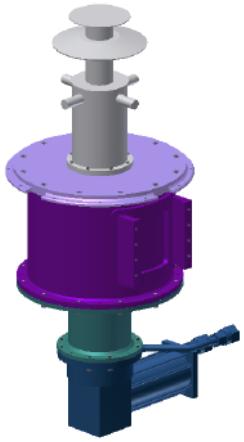


Masui et al. 2015

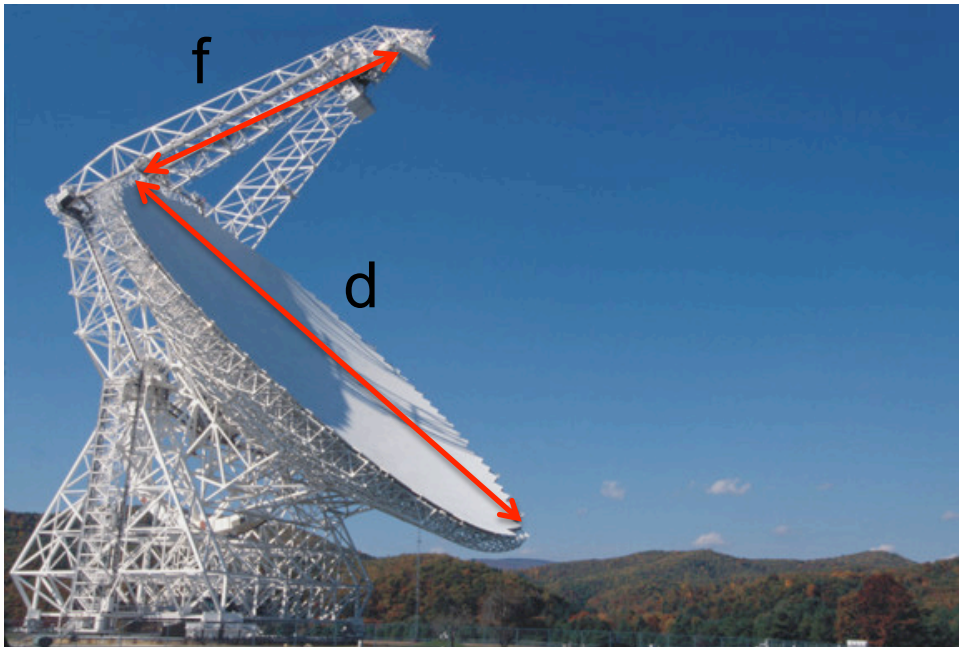
GBT 800 MHz 7-element array



1.0 m

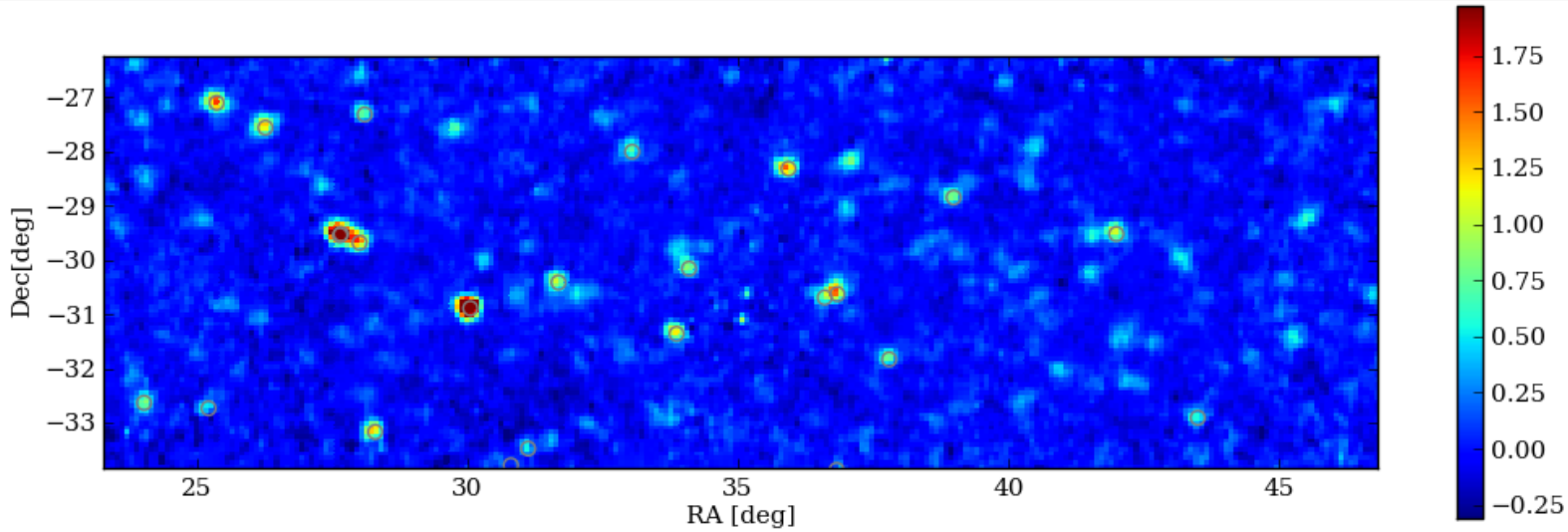


Each feed antenna has an independent cryostat & cooler



ASIAA, NRAO, UW-Madison

Parkes 21 cm Survey



Stacking Analysis

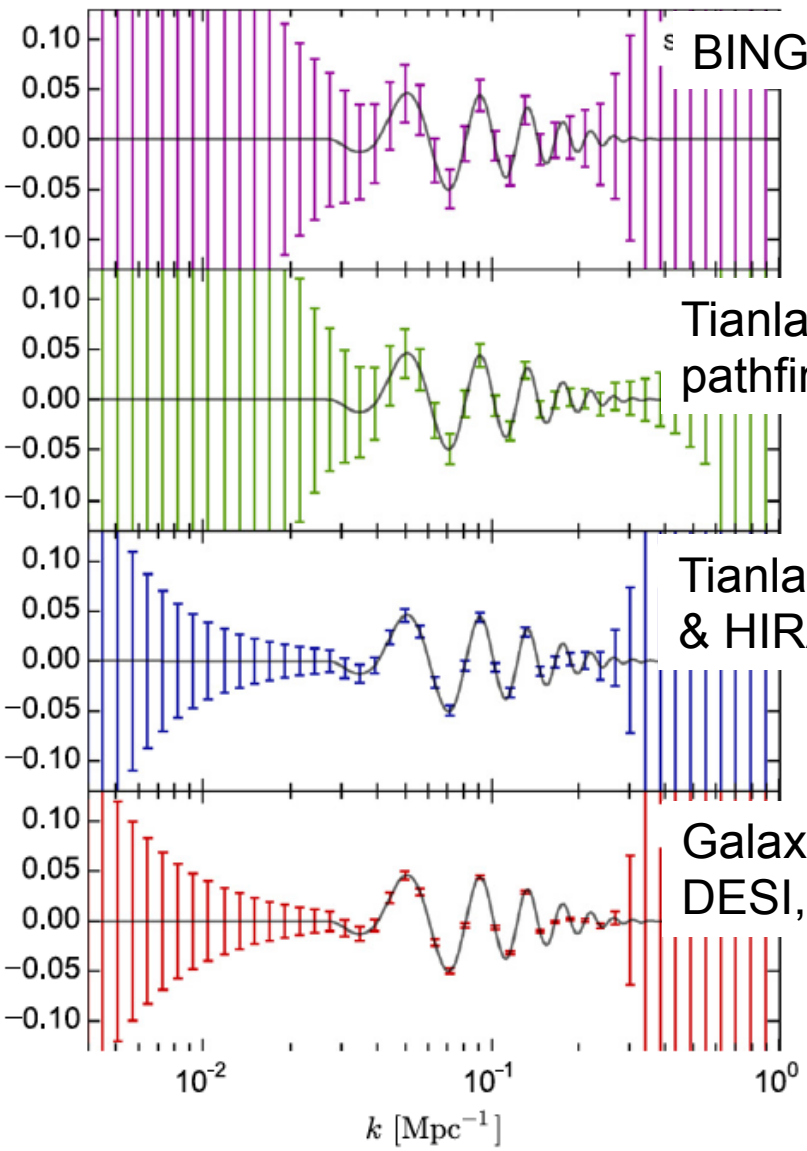
- ASIAA, CITA, CMU, NAOC, UW-Madison
- 0.25^{o} beam ~ 1.5 h^{-1} Mpc
- cross-correlate with 2dF galaxy redshift survey
  - 220,000 galaxies, z ~ 0.11
- 300 hrs being analyzed now
  - 1500 deg^2 ~ most of 2dF volume
  - 10^7 h^{-3} Mpc^3
- parallel mapmaker for multibeam receiver

Selected HI Large-Scale Structure Instruments

		T_{inst}	$N_d x N_b$	D_{dish} (m)	z_{min}	z_{max}	S (deg^2)
single dish	GBT	29	1x1(7)	100	0.54	1.09	100
	Parkes	23	1x13	64	0.00	0.23	5,000
	BINGO	*50*	*1x50*	*25*	*0.13*	*0.48*	*5,000*
	FAST	*20*	*1x20*	*500*	*0.42*	*2.55*	*2,000*
interferometer	CHIME 4, 100 m cyl.	50	1280x1	20	0.77	2.55	25,000
	Tianlai 8, 120 m cyl.	50	2048x1	15	0.00	2.55	25,000
	HIRAX	50	1024x1	5	0.77	2.55	15,000
interf. + autocor.	*SKA1-MID*	*20*	*190x1*	*15*	*0.00*	*3.06*	*25,000*
	SKA1-SUR	*30*	*96x36*	*15*	*0.23*	*1.38*	*25,000*

from Bull *et al.* ApJ 803 (2015)

BAO forecasts

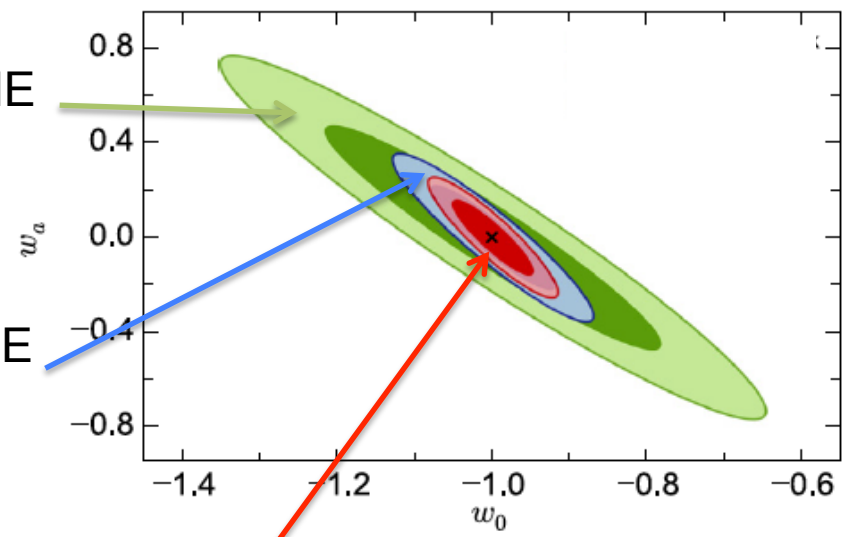


BINGO, Parkes, GBT-7

Tianlai & CHIME pathfinders

Tianlai & CHIME & HIRAX full

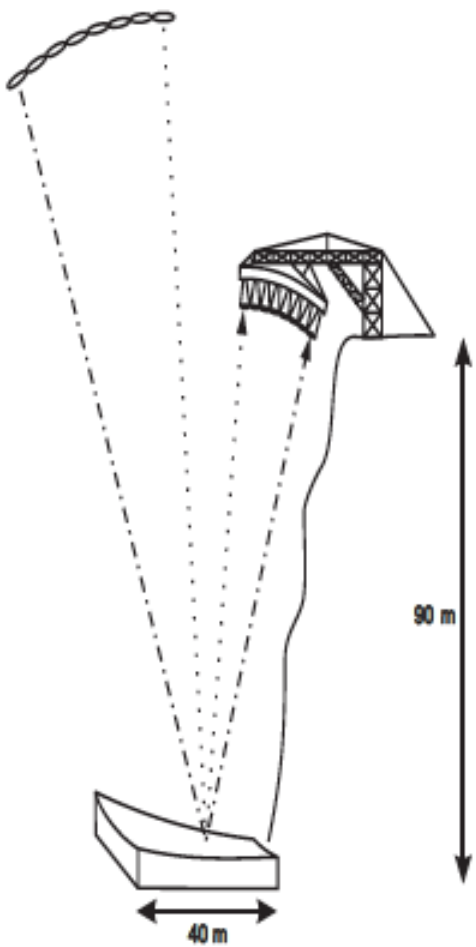
Galaxy redshift surveys DESI, Euclid, WFIRST



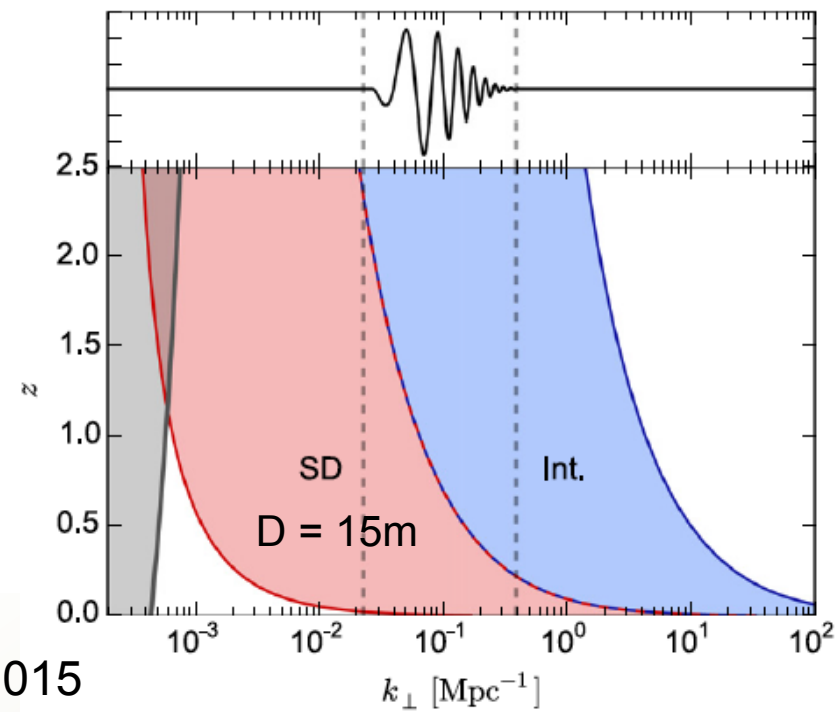
$$\frac{p}{\rho} = w(a) \sim w_0 + \frac{z}{1+z} w_a$$

Bull et al. (2015)

BINGO
BAO from Integrated Neutral Gas Observations

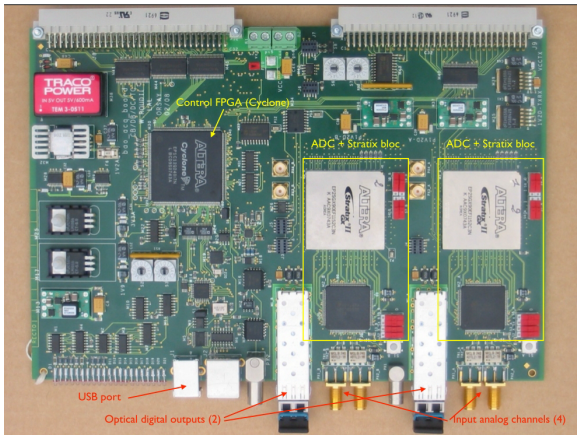


- University of Manchester
- Battye et al. MNRAS 434 (2013)
- single-dish using natural landscape
- drift scans
- map-making on large scales uses reference beams to iew NCP or SCP



Bull et al. 2015

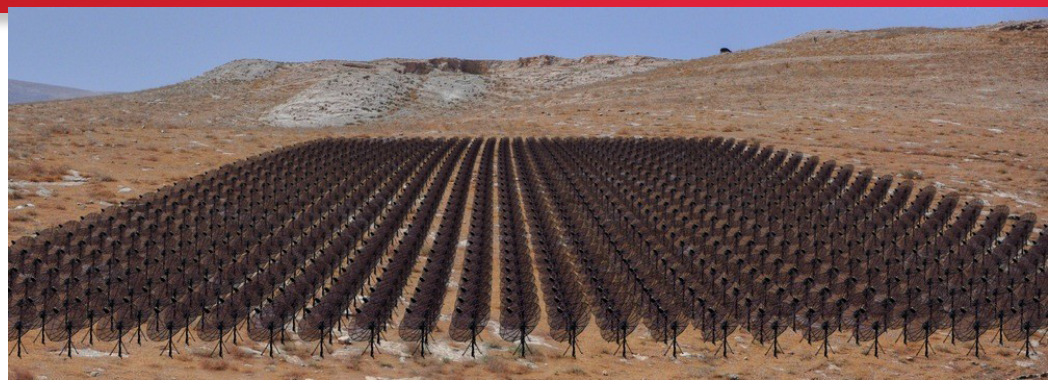
PAON-4
Paraboles A l'Observatory de Nancay



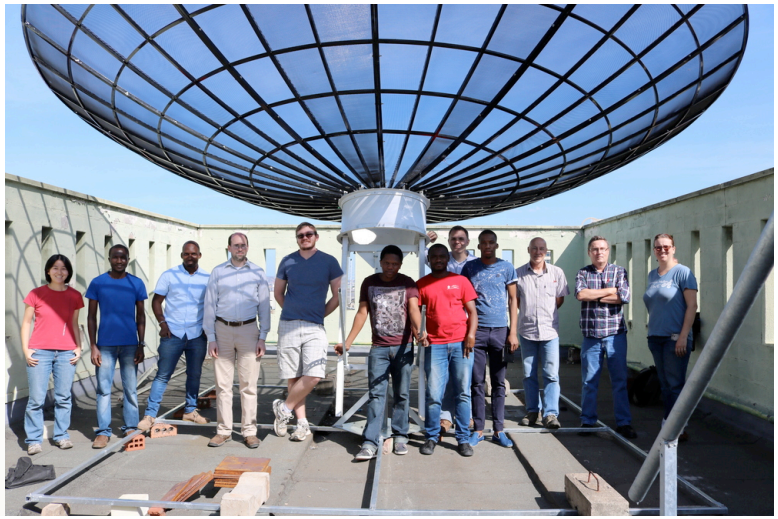
Université Paris-Sud
Observatoire de Paris
Laboratoire Lagrange
Centre d'Etudes de Saclay

- 5-m diameter dishes in transit array
- FPGA – based BAORadio backend
- tests of 21-cm intensity mapping

HIRAX
Hydrogen Intensity and Real-time Analysis eXperiment



UKZN, DUT South Africa
SKA site Karoo desert
1024, 6 meter dishes (1st from Beifang)
close-packed regular array
observations start 2018
CHIME correlator
other science:
    FRB, pulsars, HI absorbers



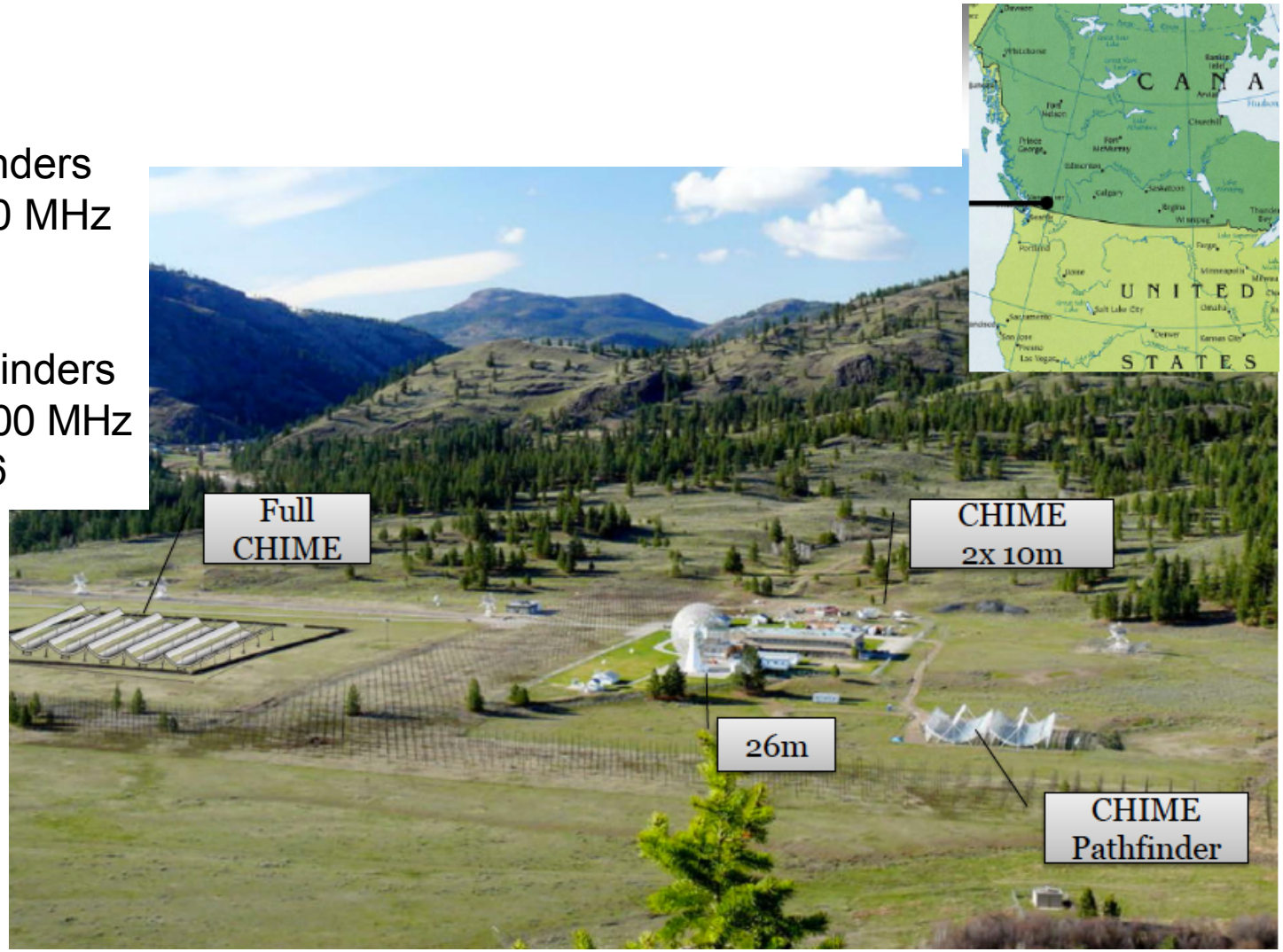
CHIME
(Canadian Hydrogen Intensity Mapping Experiment)

Prototype
- 2, 8m dishes
- 4 channels

Pathfinder
- 2, 20mx40m cylinders
- 256 channels, 400 MHz

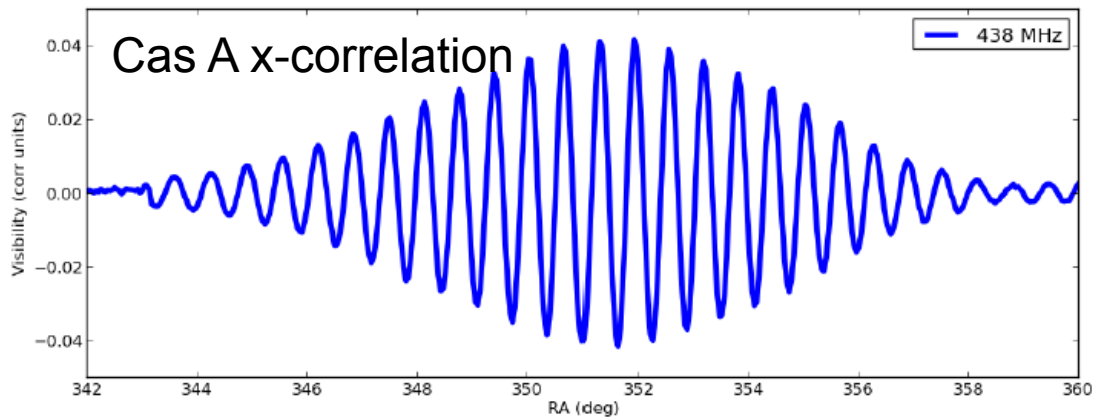
Full CHIME - funded
- 4, 20mx100m cylinders
- 1280 channels, 400 MHz
- operating in 2016

UBC
DRAO
McGill
NRC-CNRC
Toronto

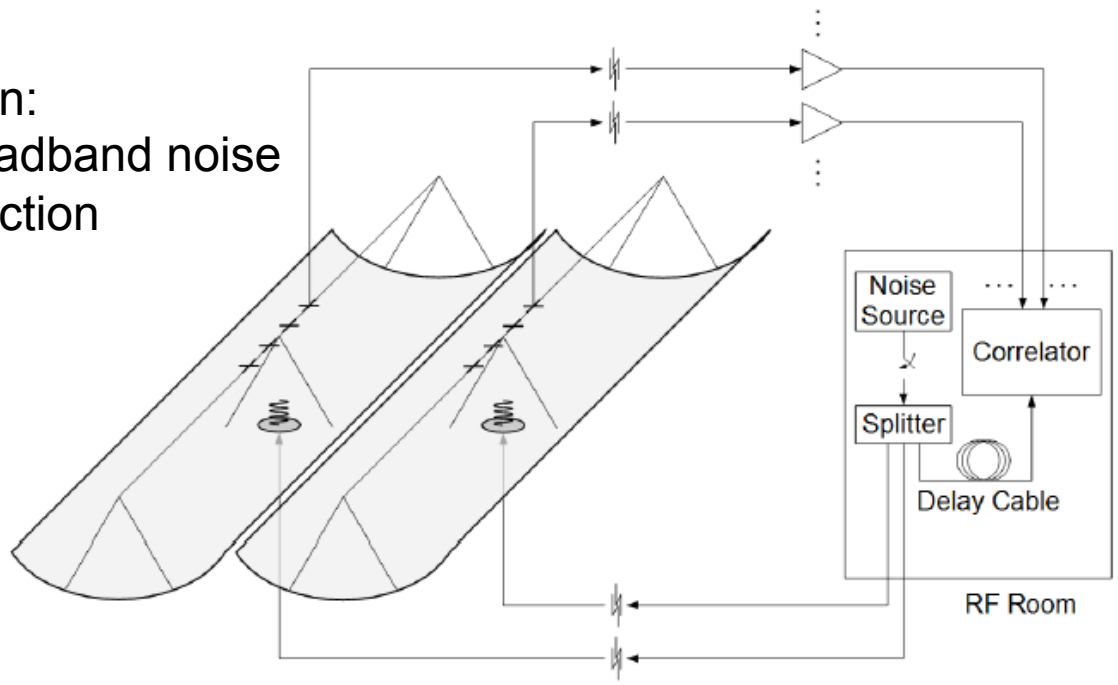


CHIME calibration

Beam:
pulsar 'holography':
correlate cylinder feeds
with 26 m dish



Gain:
broadband noise
injection



Laura Newburgh 1406.2267

Summary: big steps soon for HI 'tomography'

In the next 12 months Tianlai and other 21-cm intensity-mapping experiments will have interferometer sky data:

- first light for Tianlai
- tests of correlators
- calibration
- maps
- foreground removal from large arrays