Epoch of Reionization

Miguel F. Morales

Santa Fe, March 7, 2011

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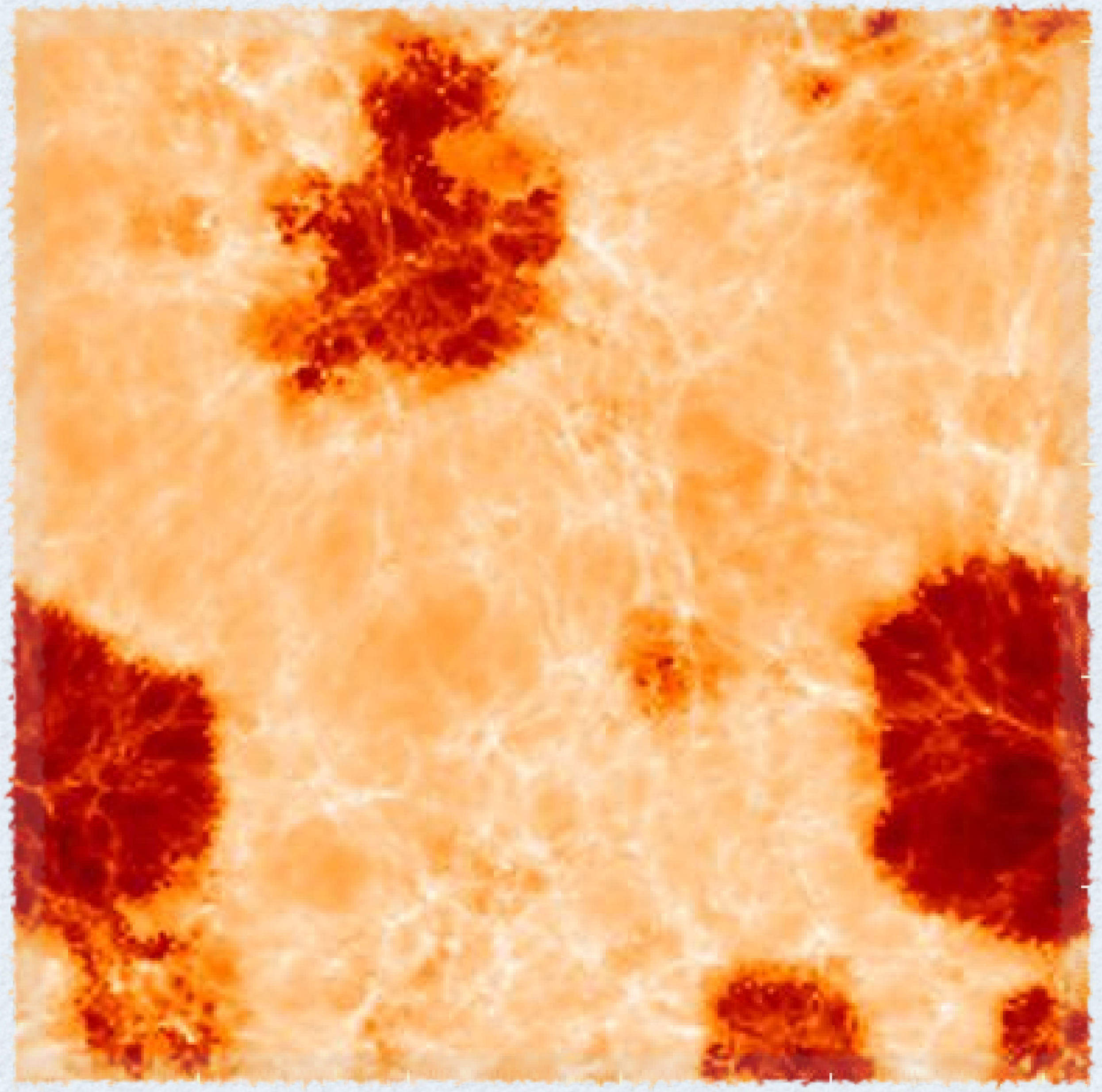
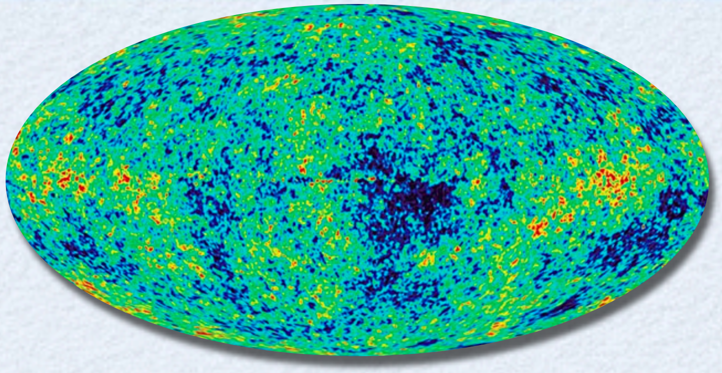
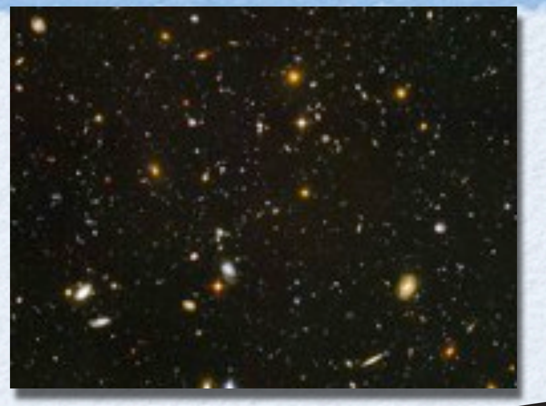
"Reionization and Cosmology with 21 cm Fluctuations,"
Morales & Wyithe, ARAA

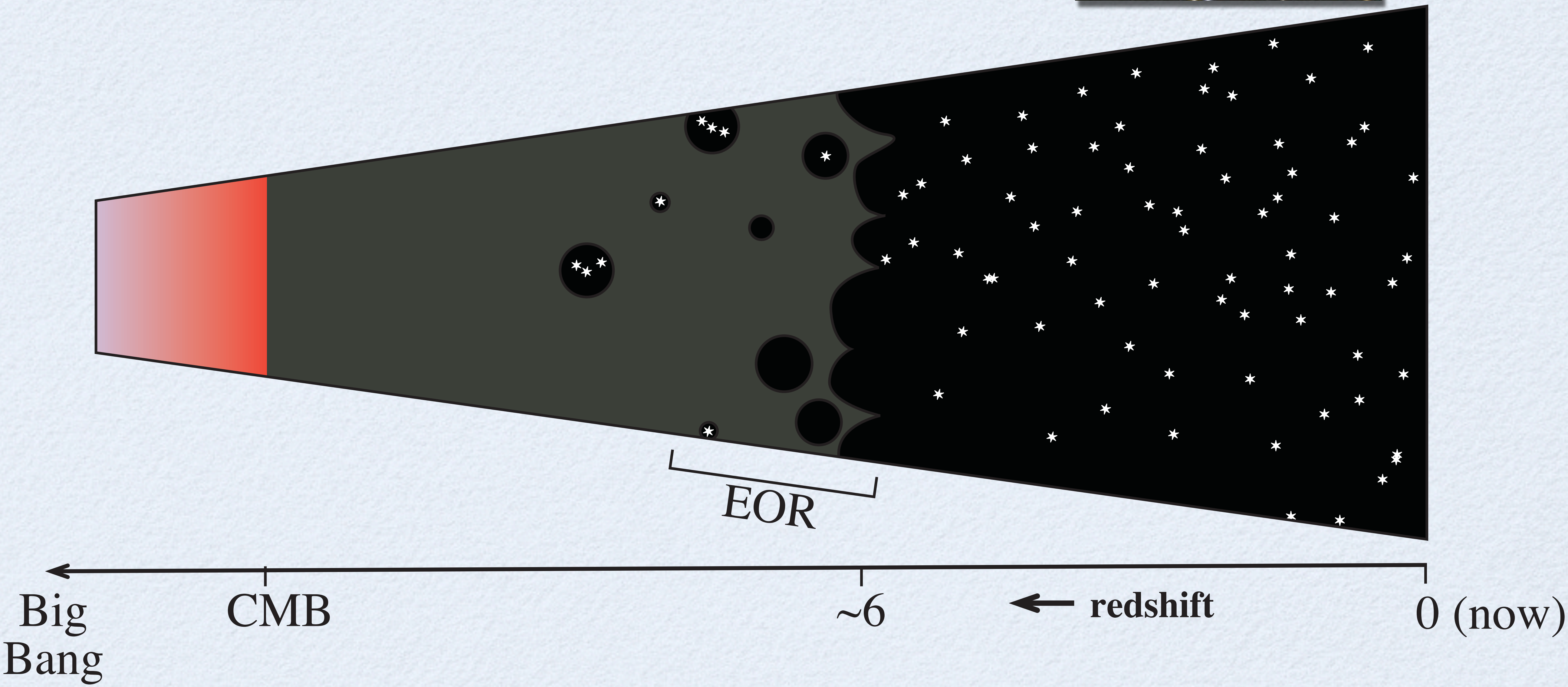


The cosmological HI signal

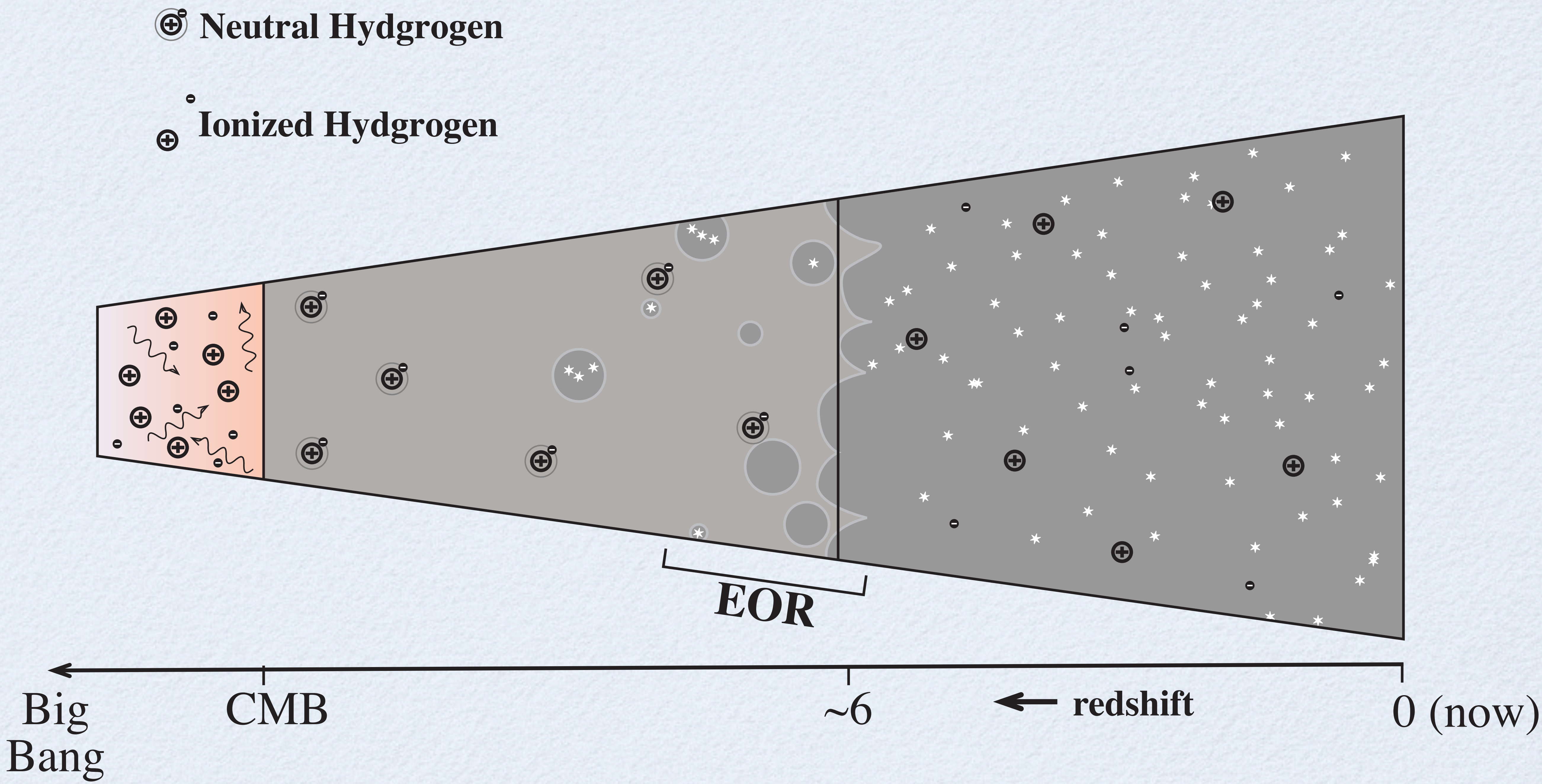
How did galaxies form?

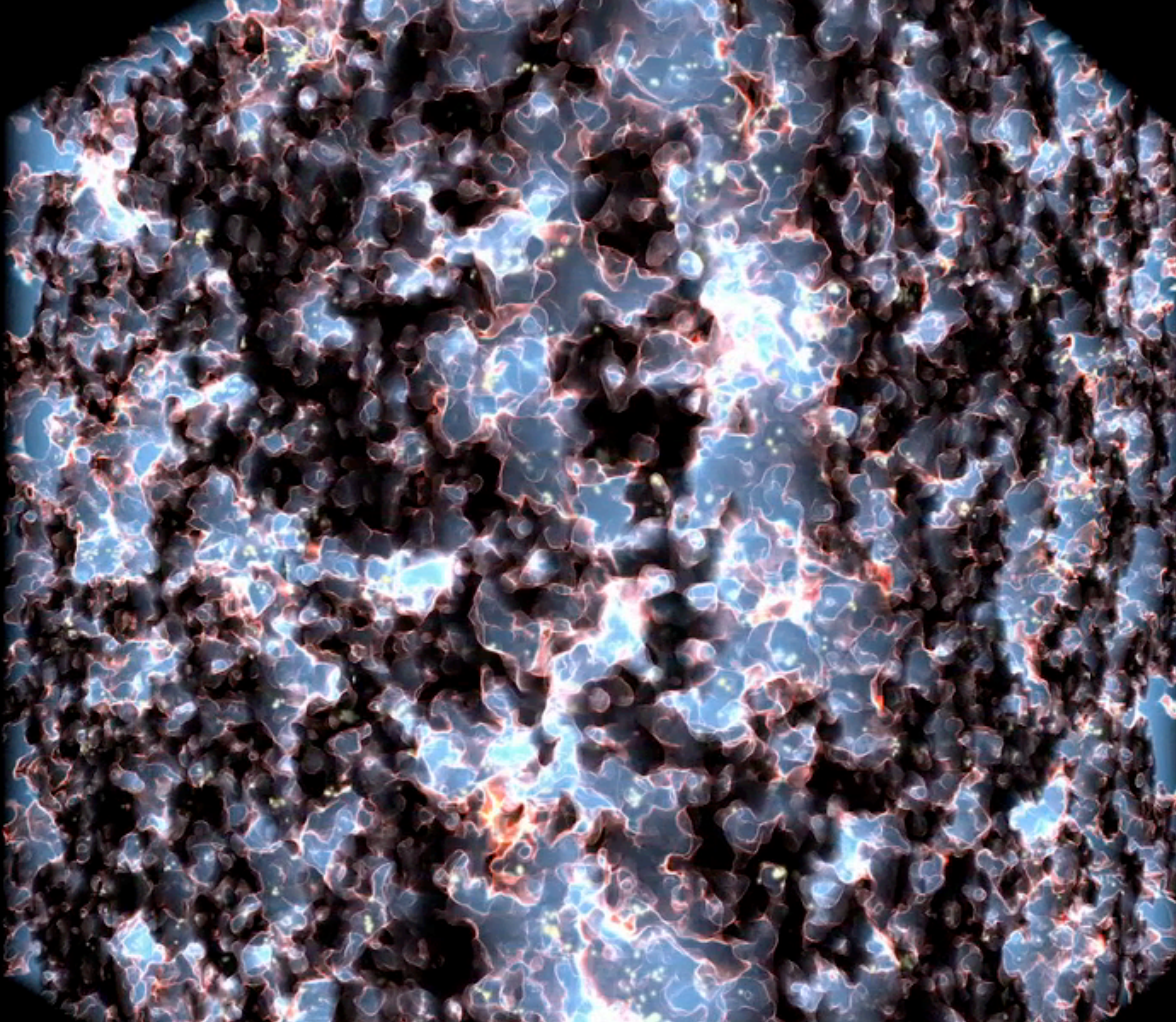




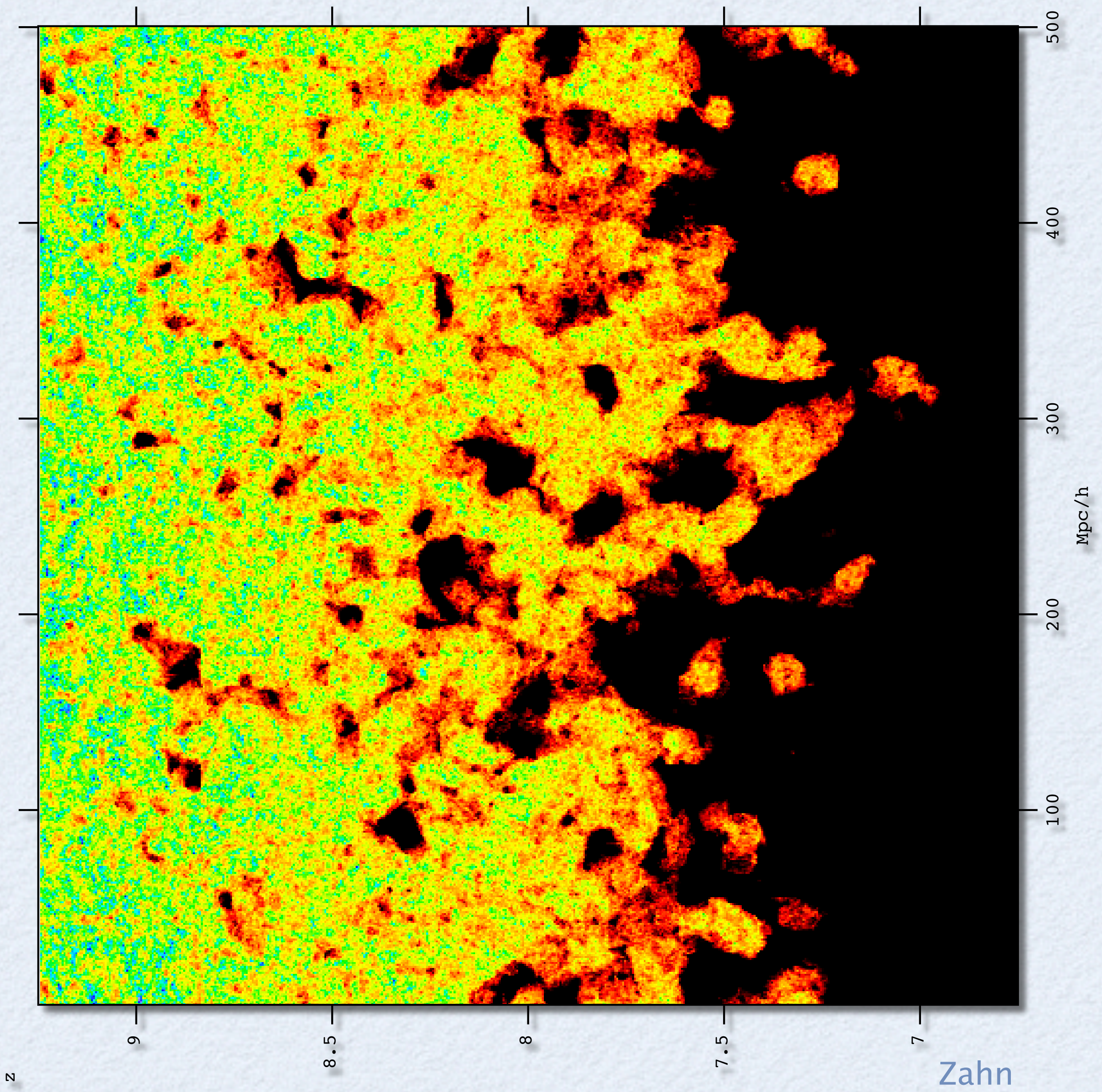


Short history of hydrogen

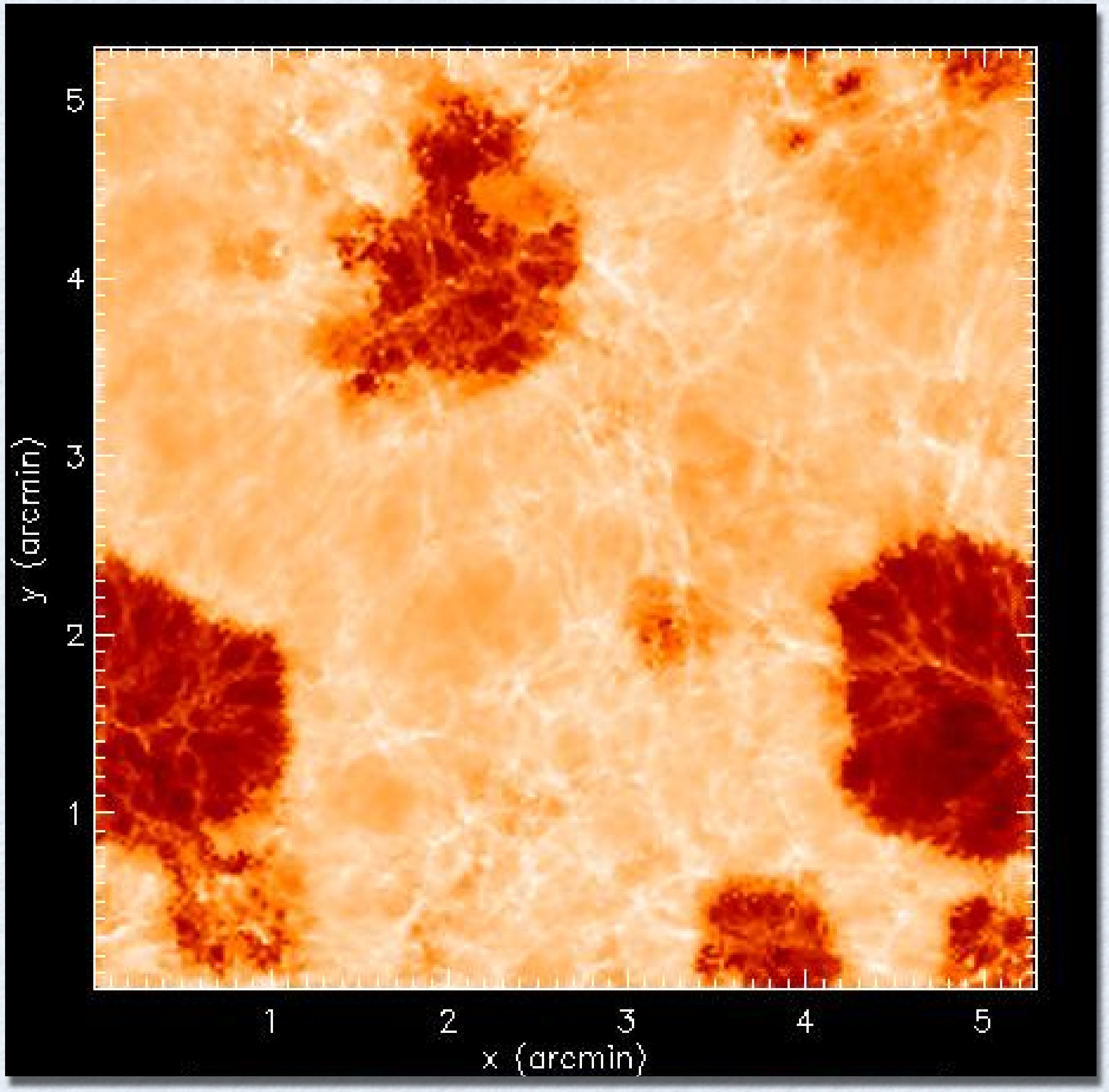




HI during EoR

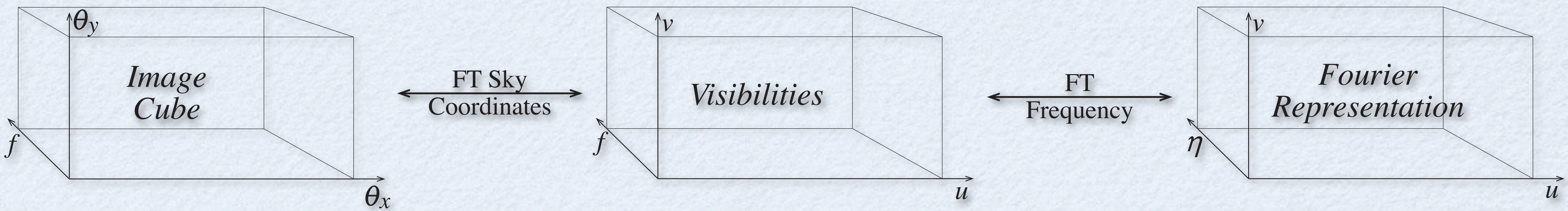


Zahn



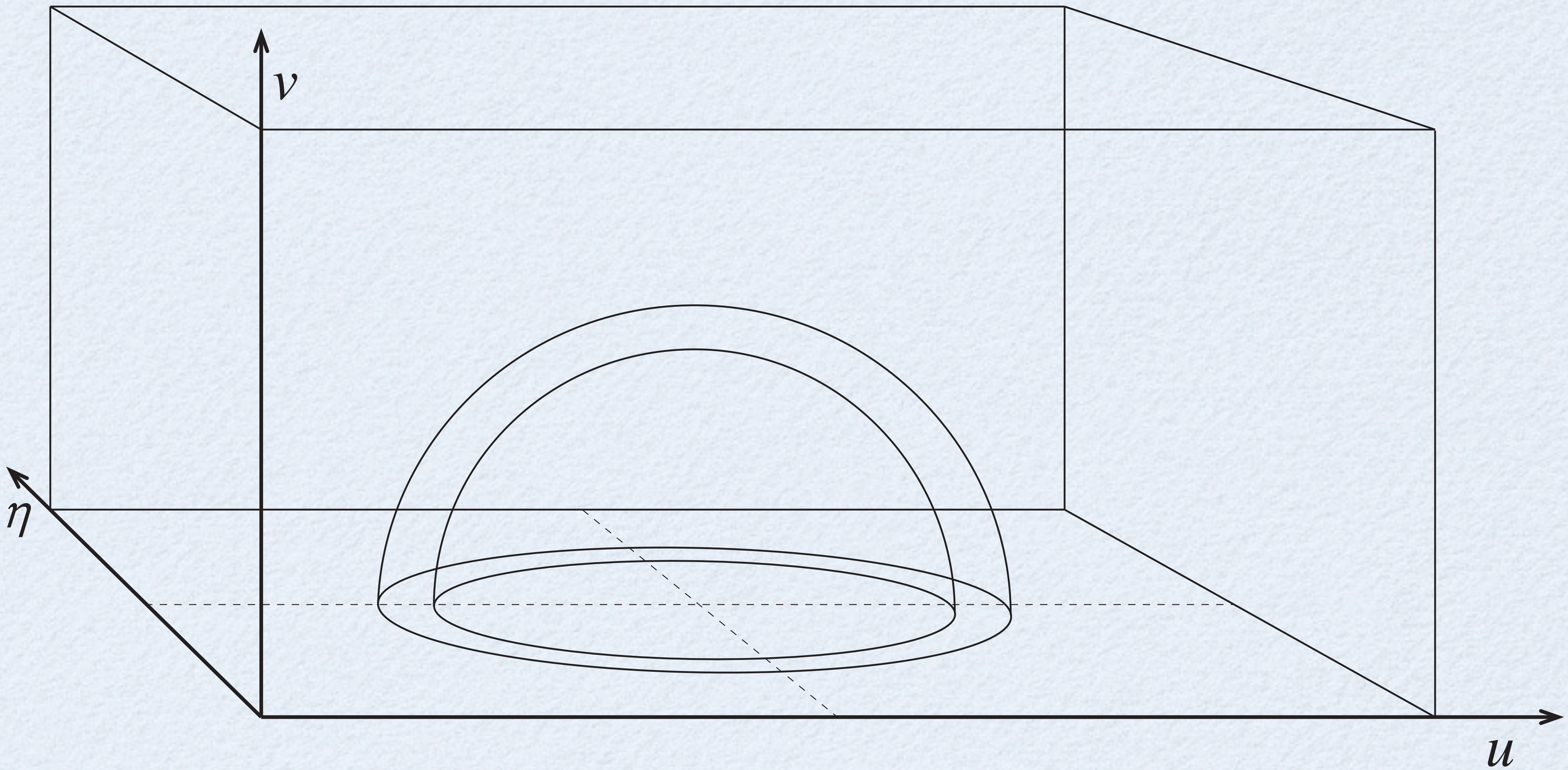
Furlanetto, Sokasian, Hernquist (2004)

Statistical EoR detection



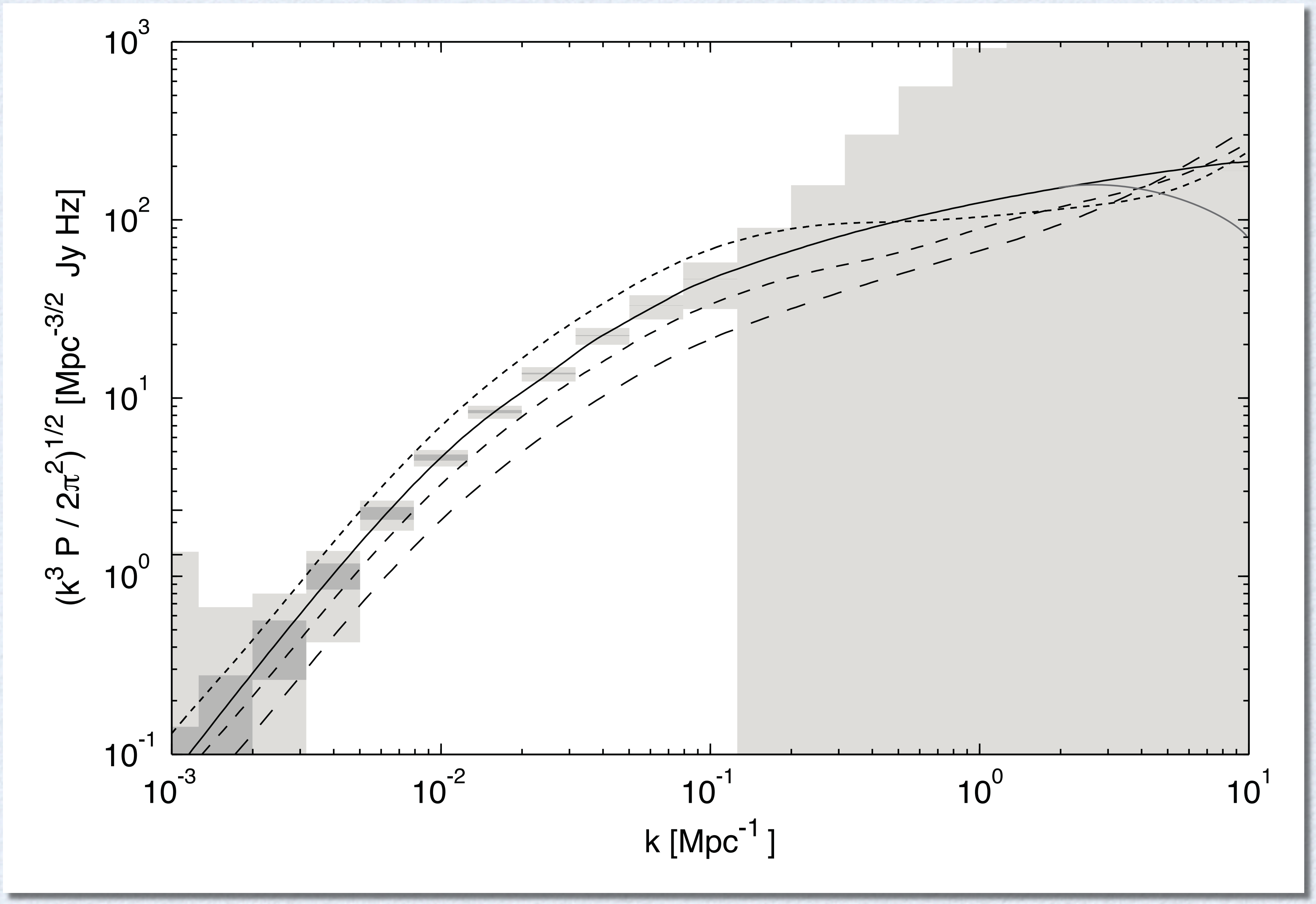
Morales & Hewitt (2004)

Spherical symmetry



Morales & Hewitt (2004)

EoR power spectrum

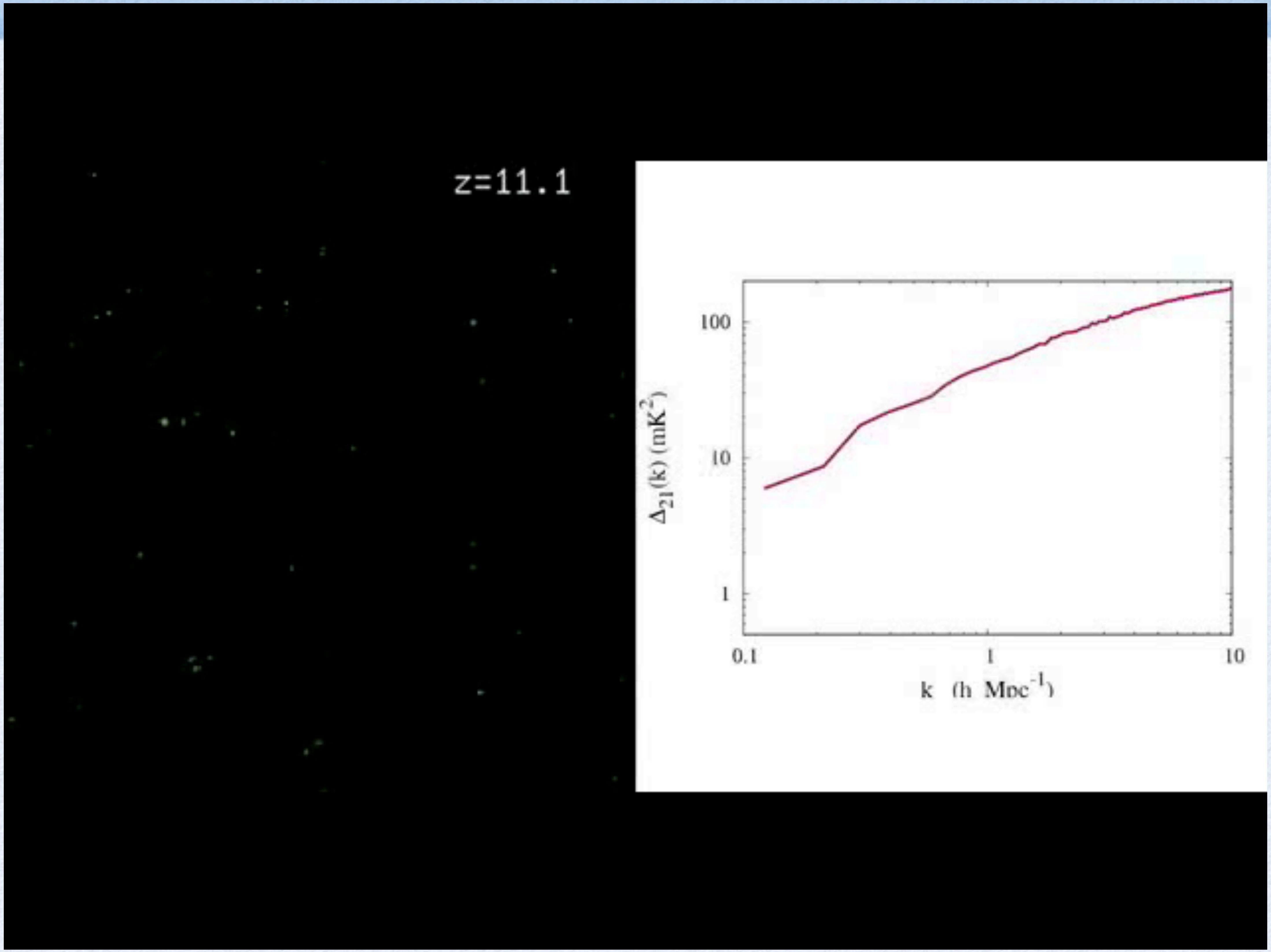


Furlanetto, Zaldarriaga, Hernquist (2004a,b)
Bowman, Morales & Hewitt (2005)

$z = 8$, 360 hours of integration

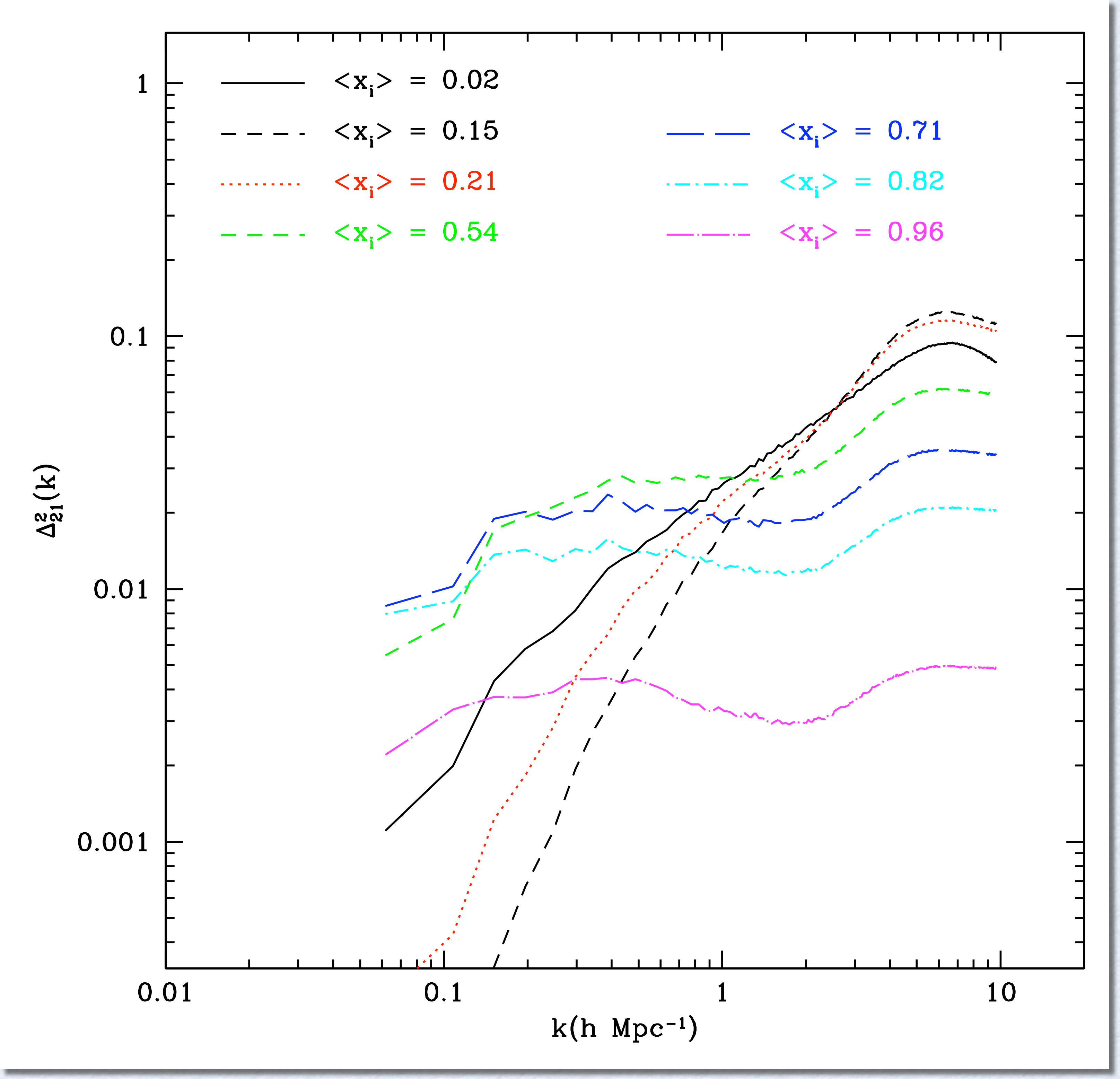
Kaplinghat (2005)

Power spectrum dynamics



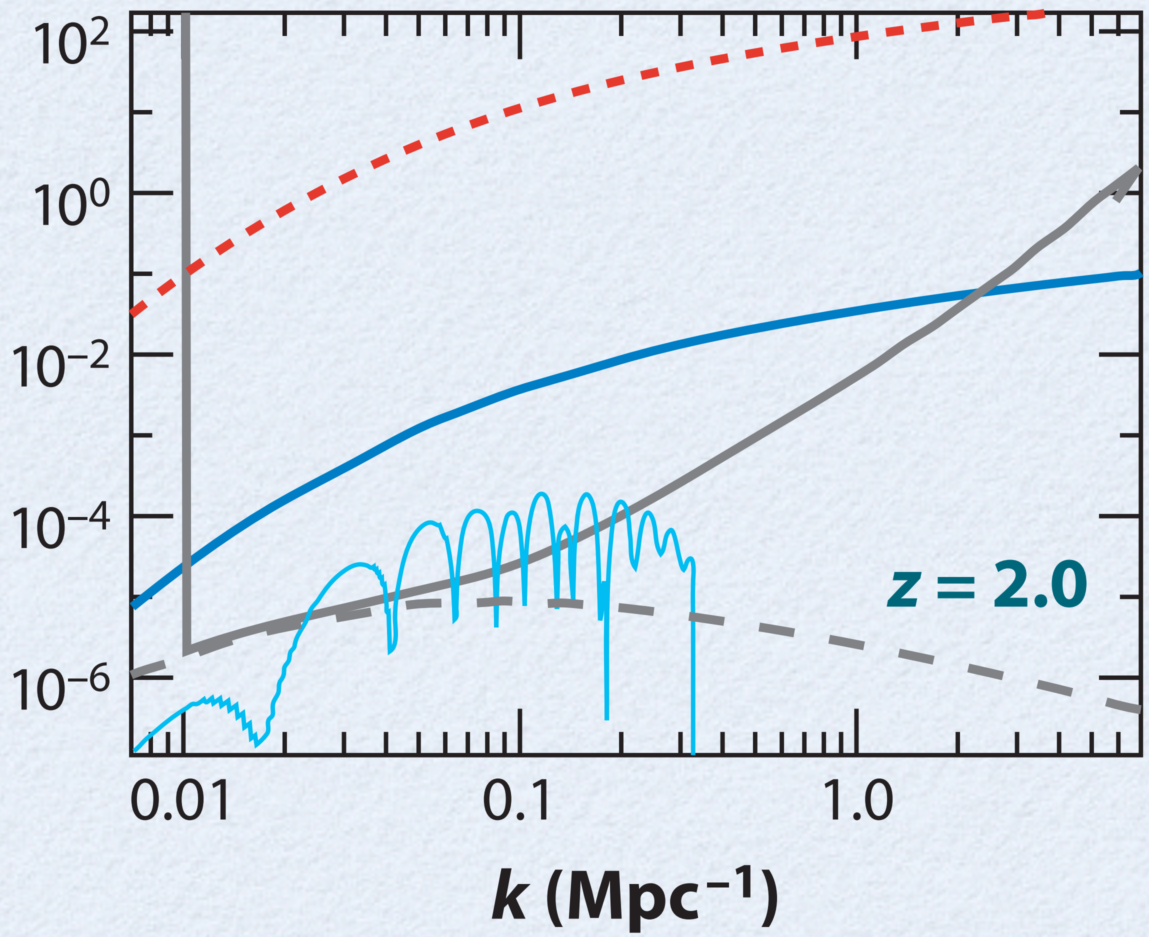
McQuinn

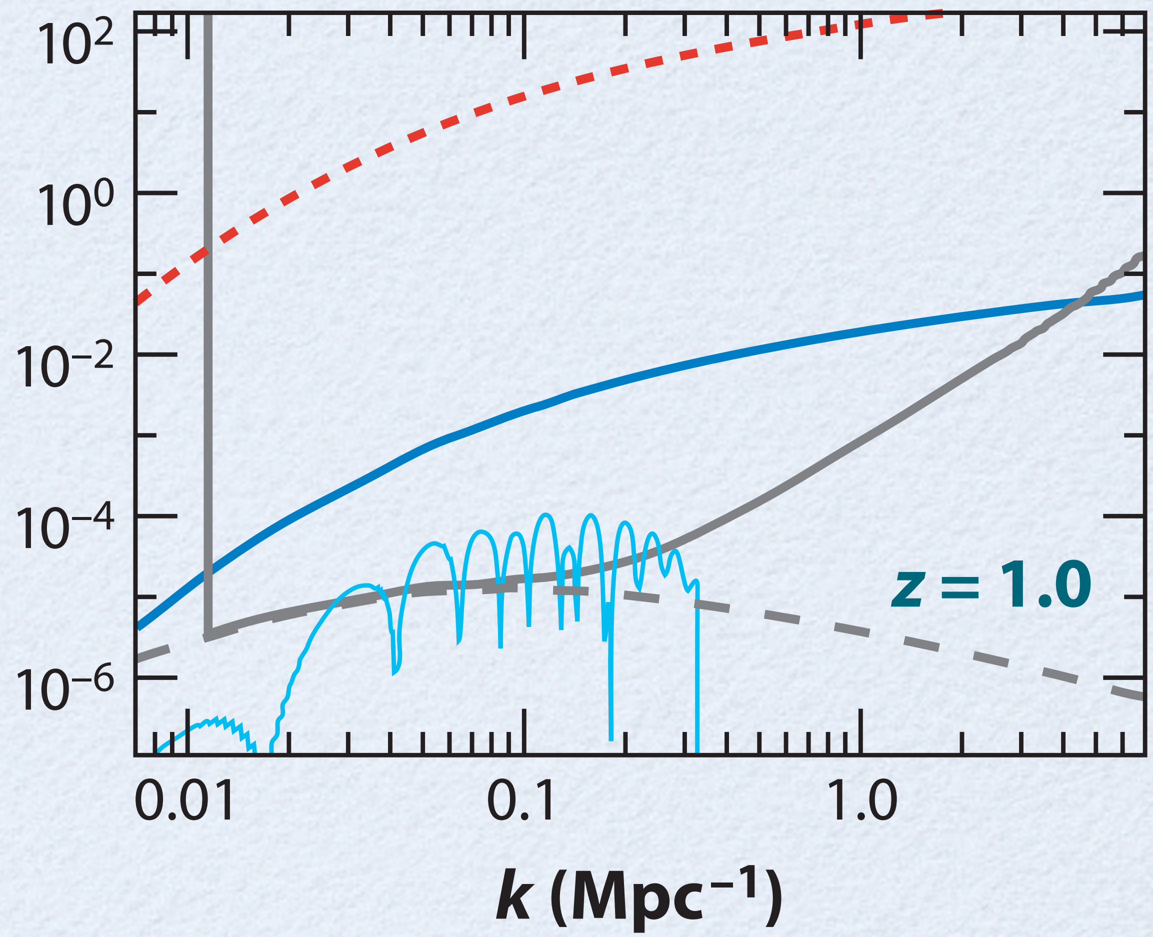
HI power spectra evolution



Lidz

Dark energy with HI

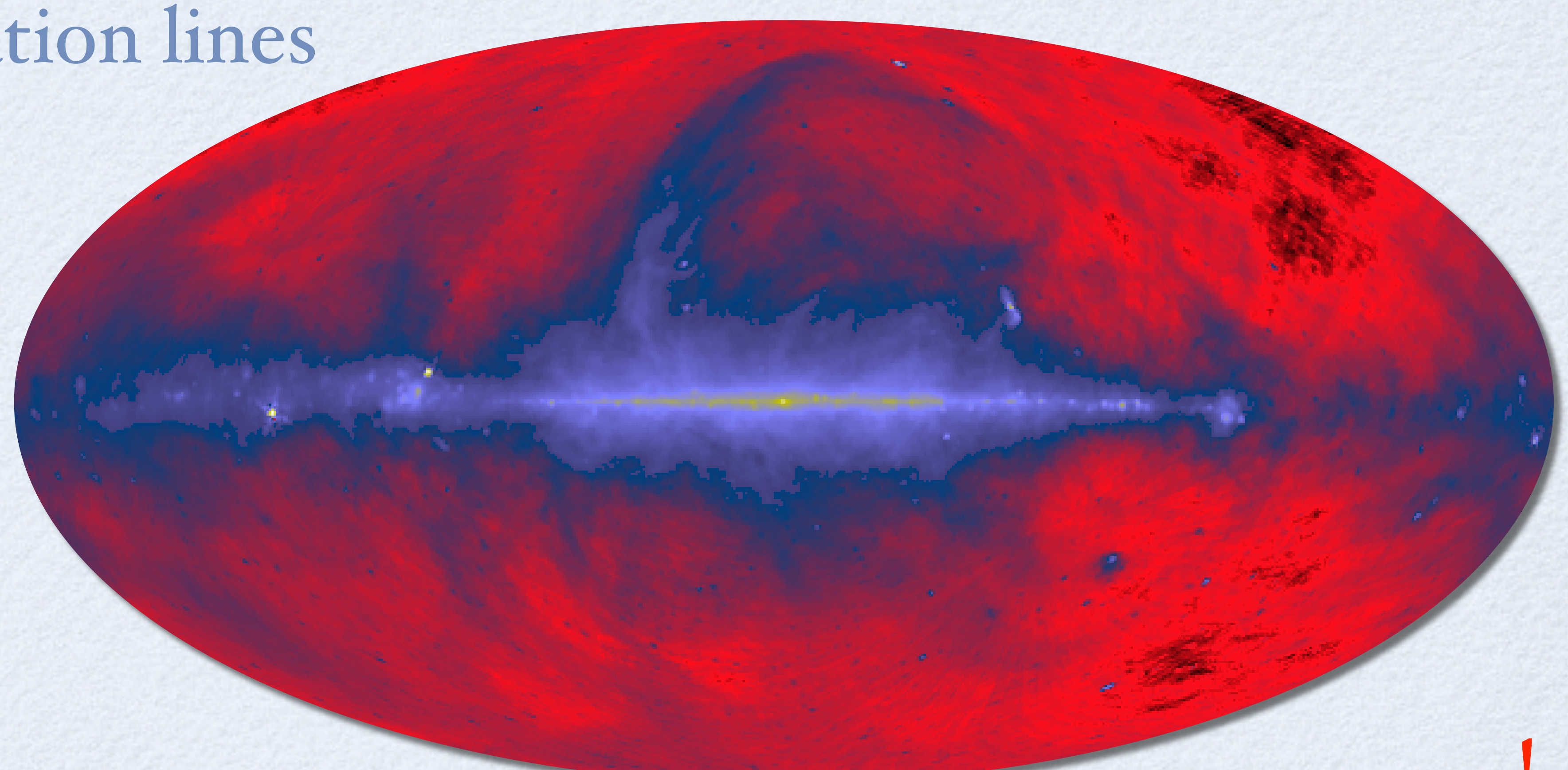




Morales & Wyithe (2010)

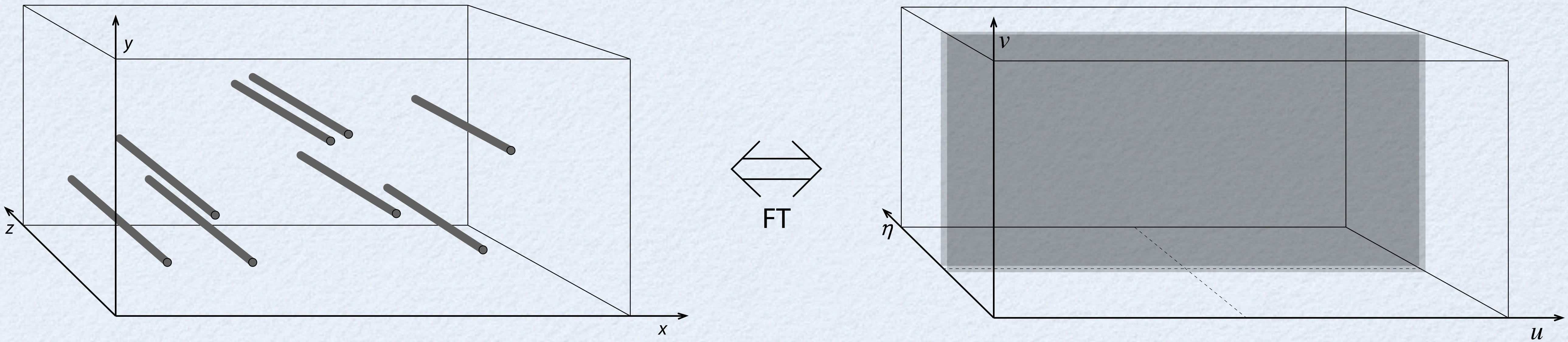
Why is this hard? Foregrounds

- Galactic emission (polarized and Faraday rotated)
- Bright point sources
- Faint point sources
- Instrumental contamination
- Radio recombination lines
- RFI
- Mode mixing
- ...

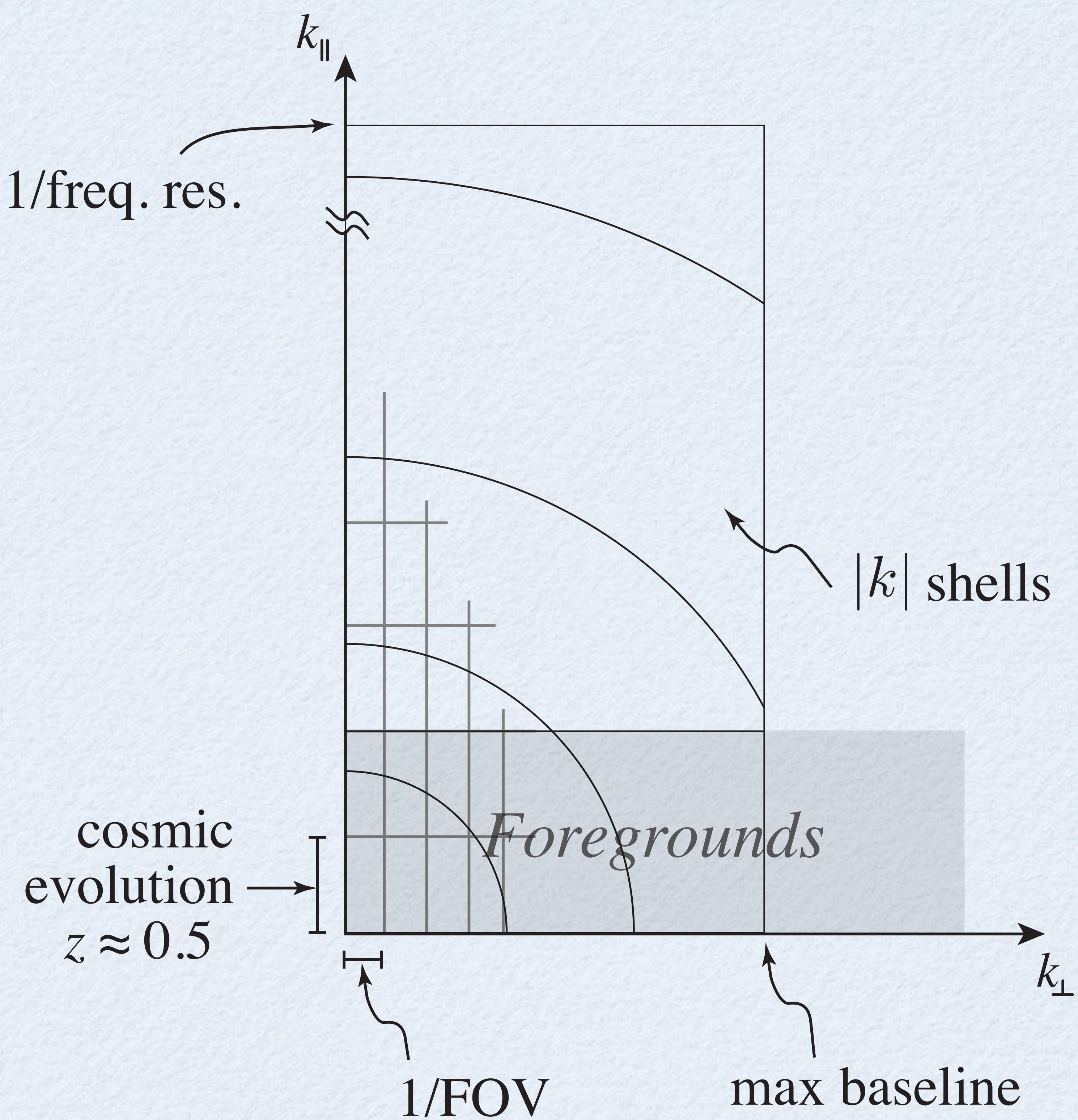


!

Foreground symmetry



k-space measurement

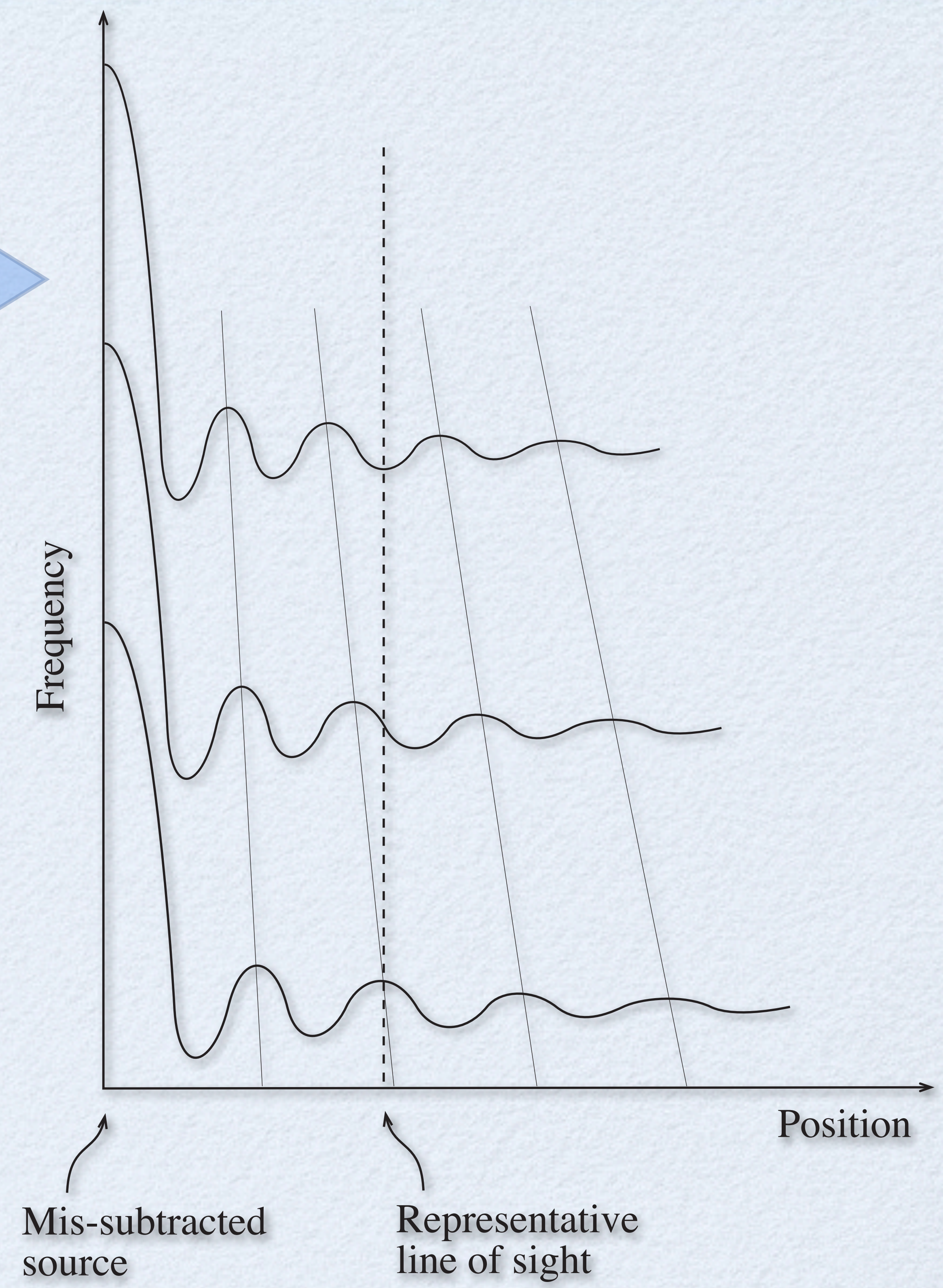


Mode mixing

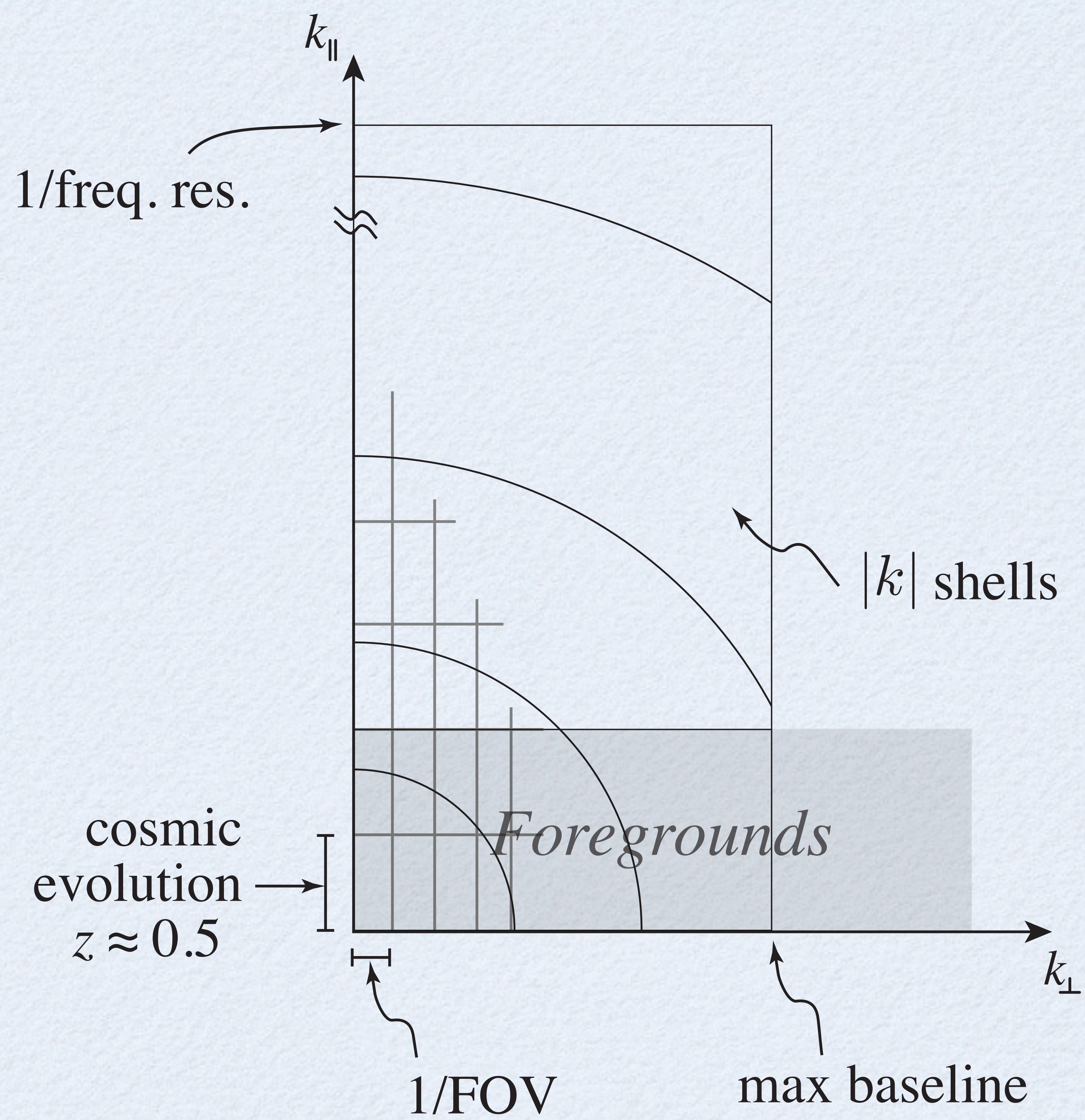
- Frontier of foreground subtraction is interactions between calibration and foregrounds
- Need measurement fidelity of 10^{-4} – 10^{-6}
- Effectively a product of the calibration errors and foreground uncertainty

Examples

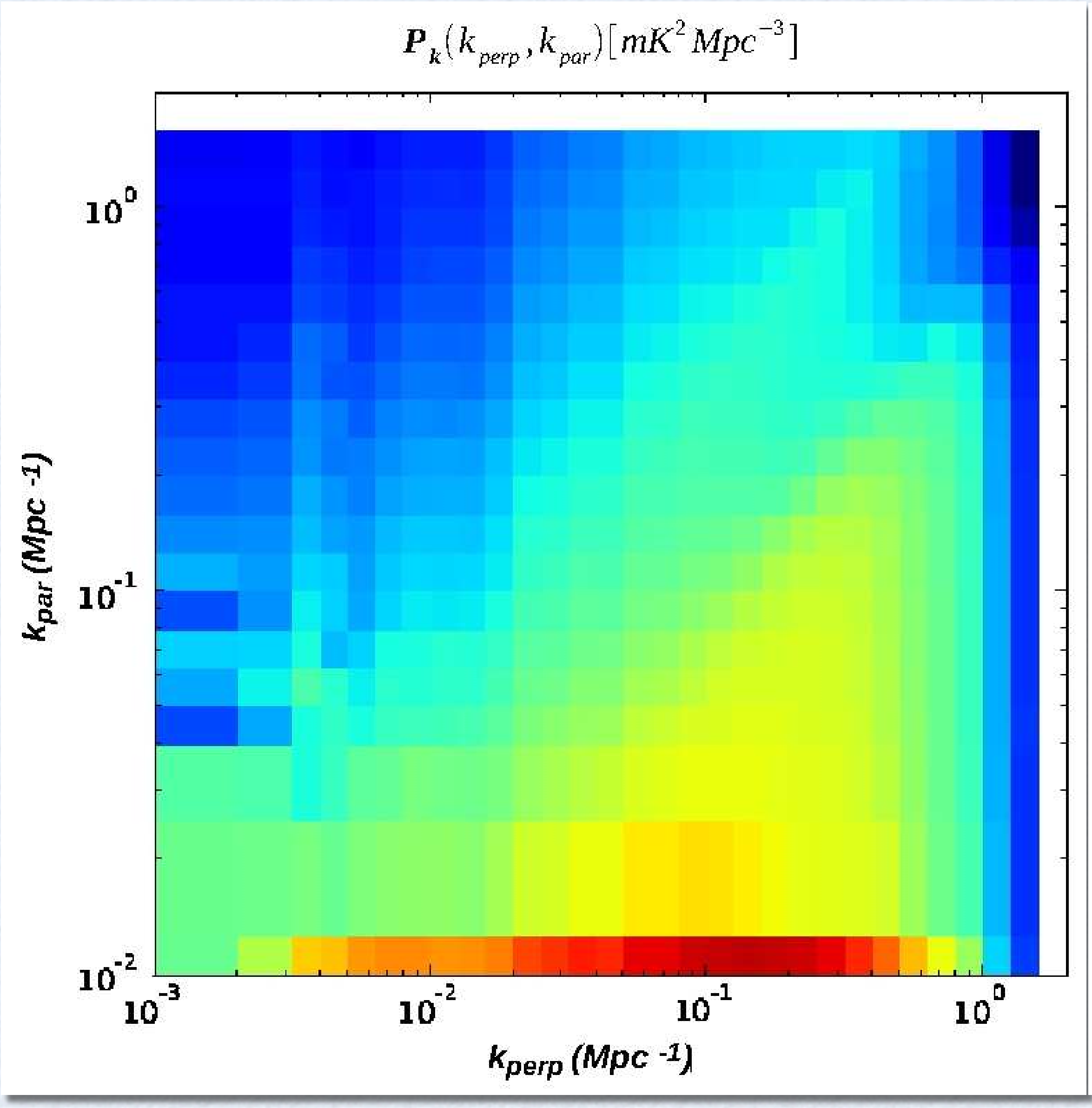
- Chromatic array beam (PSF) & residual source flux, residual frequency ripple
- Polarized foreground & polarization mis-calibration, flux leakage from Q & U → I
- Antenna beam dependence & point sources, decorrelation of visibilities at different frequencies

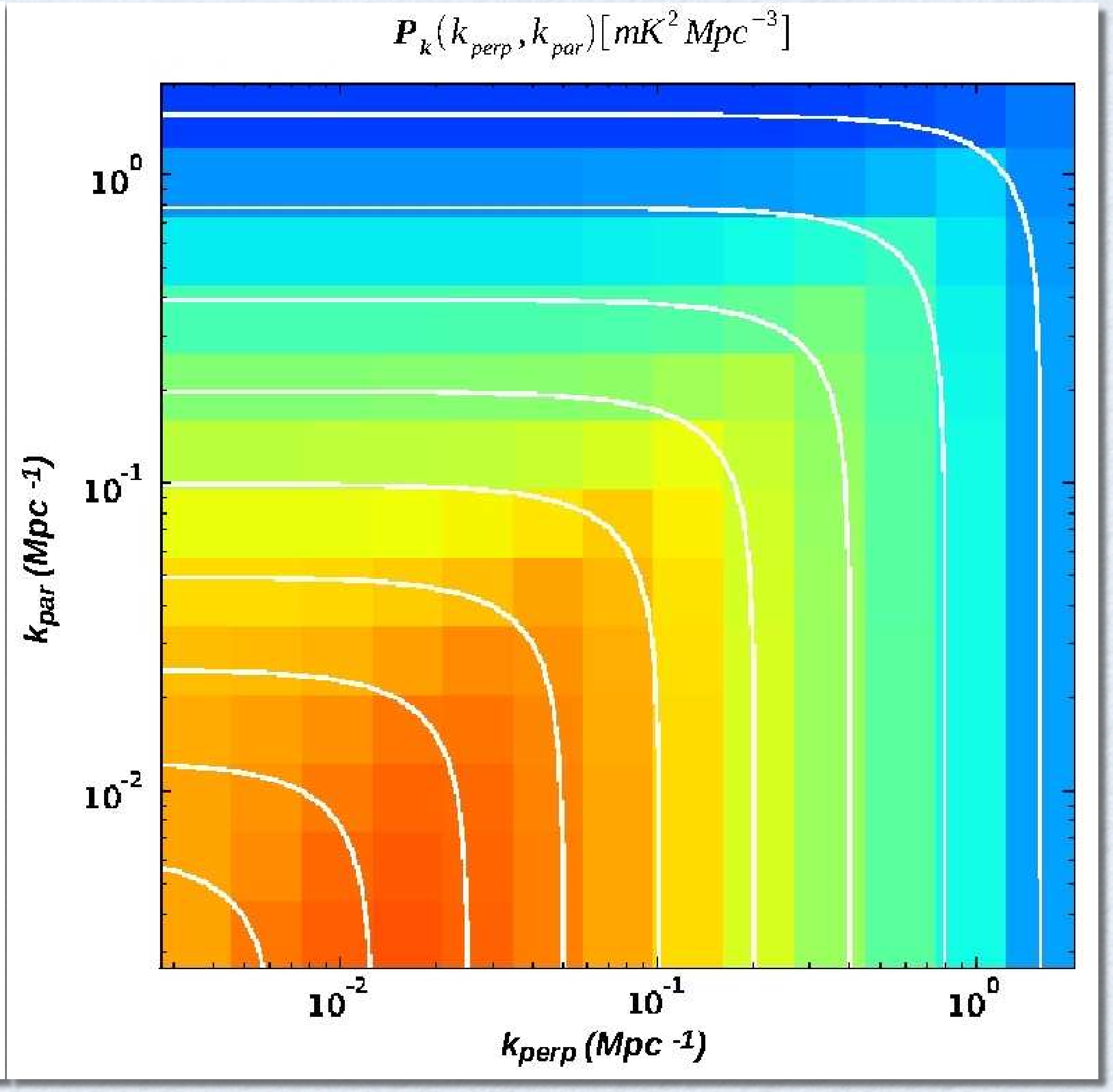


k-space measurement



Bright source location error





Datta et al. (2010)

HERA

A roadmap for learning how to perform precision low redshift observations and build second generation EoR observatories (HERA II).


MWA

MWA Collaboration

MWA Collaboration

MIT

CfA

THE UNIVERSITY OF MELBOURNE

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

ASU

CSIRO

Curtin University

ICRAR
International Centre for Radio Astronomy Research

PERTH OBSERVATORY

THE UNIVERSITY OF SYDNEY

W

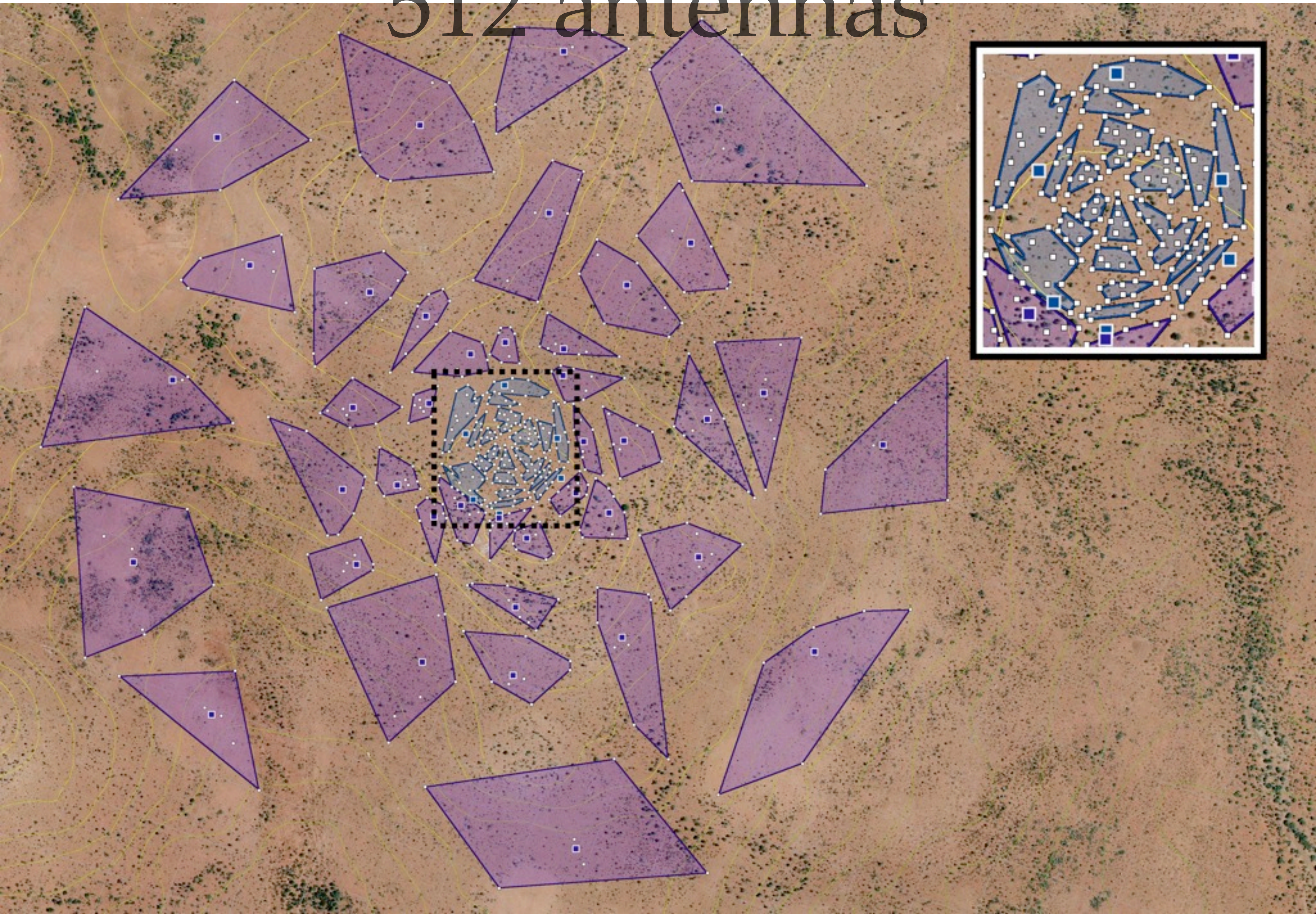
THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

THE UNIVERSITY of WISCONSIN MADISON

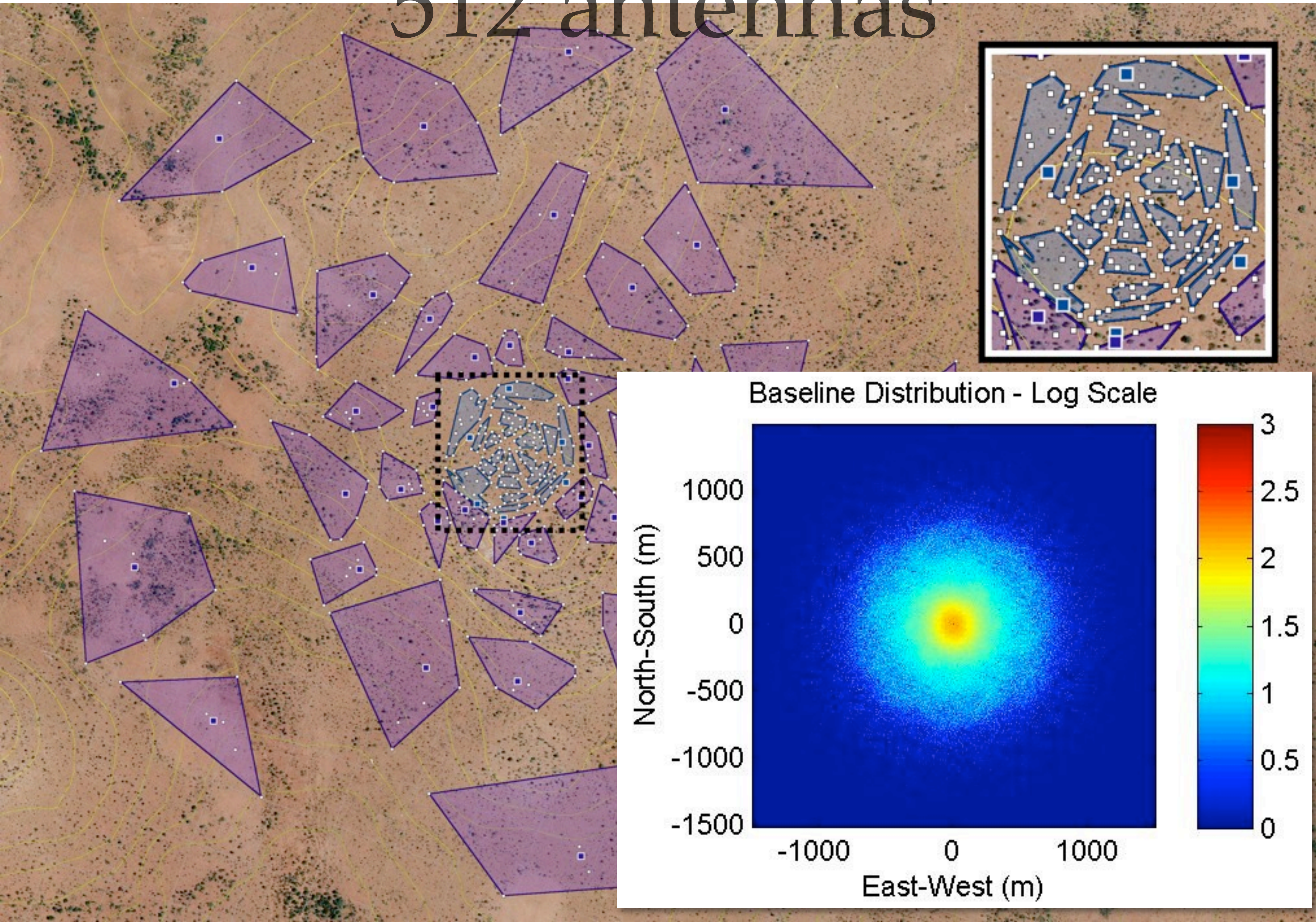
MWA Collaboration

G. Allen, W. Arcus, D. G. Barnes, A. Bastidas-Fry, A. P. Beardsley, L. Benkevitch, G. Bernardi, C. R. Boutan, J. D. Bowman, F. H. Briggs, R. J. V. Brissenden, J. D. Bunton, S. Burns, I. H. Cairns, D. Campbell-Wilson, R. J. Cappallo, P. A. Carroll, S. Chatterjee, M. A. Clark, B. E. Corey, A. J. Coster, M. Dawson, A. De Gans, A. de Oliveira-Costa, D. DeBoer, M. Derome, A. Deshpande, L. deSouza, R. G. Edgar, T. Elton, D. Emrich, P. J. Erickson, S. R. Furlanetto, B. M. Gaensler, S. Gleadow, M. G. Glossop, R. Goeke, M. R. Gopalakrishna, A. J. Green, L. J. Greenhill, L. Harvey-Smith, M. Haverkorn, B. J. Hazelton, D. E. Herne, L. Hernquist, J. N. Hewitt, R. Jackson, P. A. Kamini, D. L. Kaplan, J. C. Kasper, B. Kincaid, J. Kocz, R. Koenig, E. Kowald, E. Kratzenberg, A. Liu, A. Loeb, C. J. Lonsdale, M. J. Lynch, S. Madhavi, L. D. Matthews, S. R. Mc Whirter, N. M. McClure-Griffiths, D. A. Mitchell, M. F. Morales, J. M. Moran, E. Morgan, T. Murphy, A. Ng, D. Oberoi, S. M. Ord, J. Pathikulangara, B. Pindor, T. Prabu, P. Quinn, R. A. Remillard, T. Robishaw, A. E. E. Rogers, A. Roshi, J. E. Salah, R. J. Sault, A. Schinckel, B. P. Schmidt, S. S. Sethi, N. U. Shankar, K. S. Srivani, L. Staveley-Smith, J. Stevens, R. S. Subrahmanyan, I. S. Sullivan, M. Tegmark, D. S. Thakkar, S. J. Tingay, J. Tuthill, A. Vaccarella, H. V. Vedantham, M. Waterson, R. Wayth, R. L. Webster, A. R. Whitney, A. J. Williams, C. Williams, J. S. B. Wyithe, M. Zaldarriaga

512 antennas



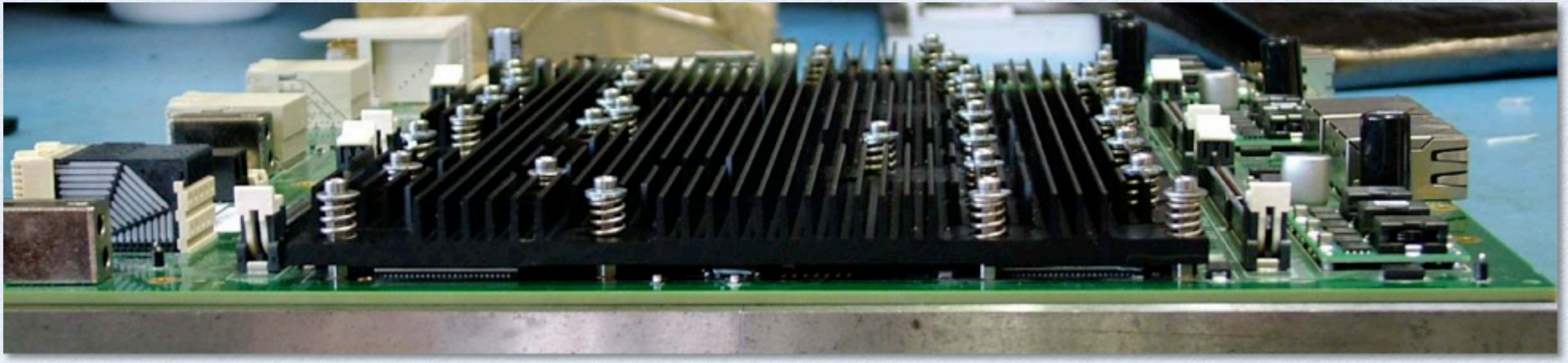
512 antennas



Tracking antennas

80–300 MHz

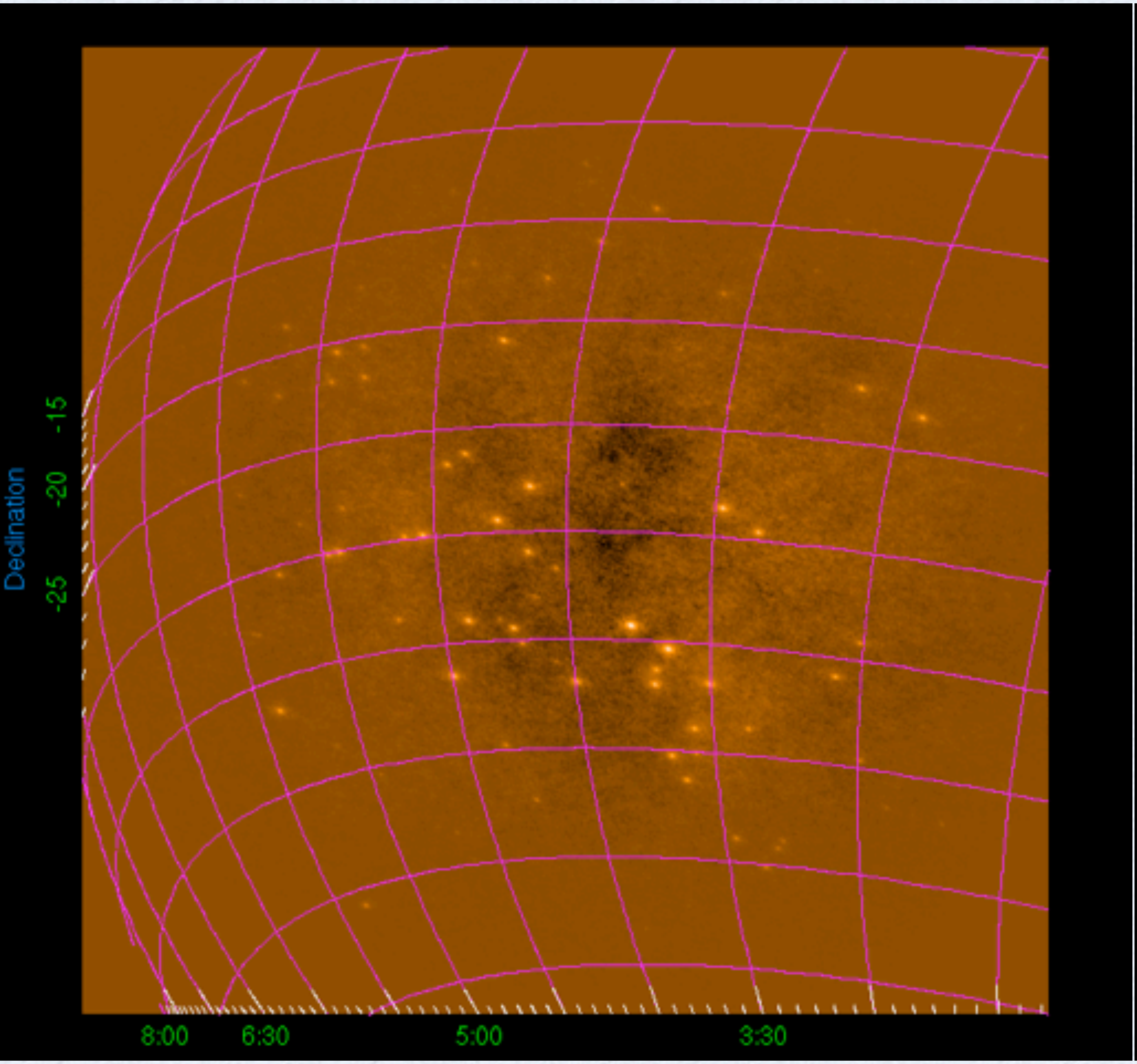
Large N correlator

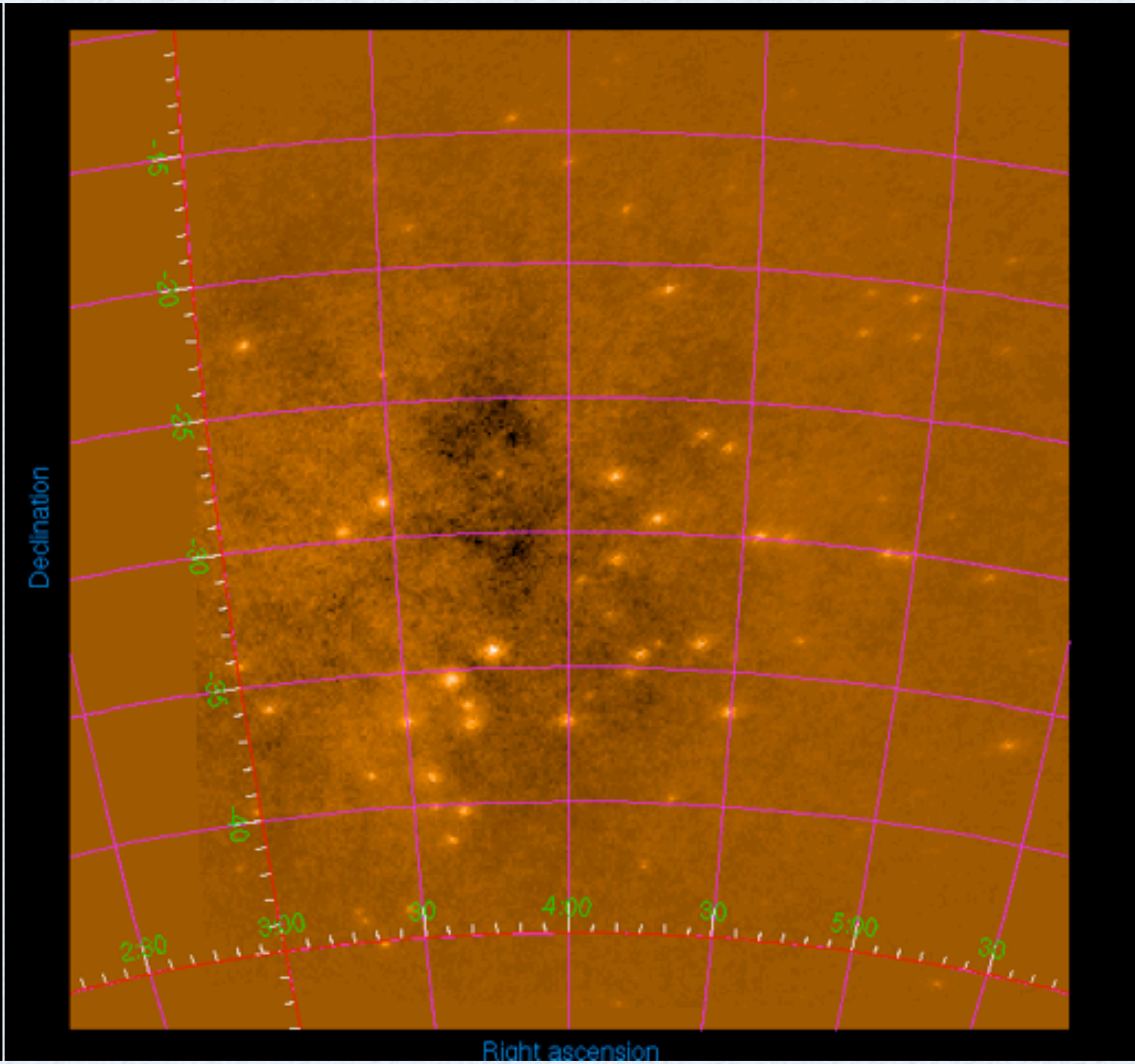


- 31 MHz bandwidth
- 10 kHz frequency resolution
- 131,072 baselines x 4 polarizations
- 1.6 Gvis. every 1/2 second

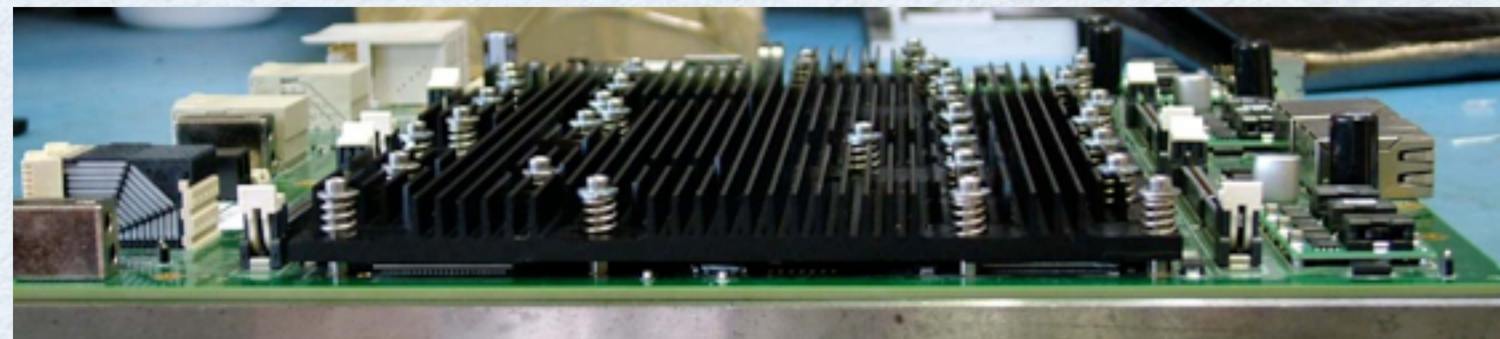
Holographic realtime calibration

Holographic realtime calibration





Antenna, receiver, & correlator designs verified



EoR foreground subtraction

Geil, P. M., B. M. Gaensler, and J. S. B. Wyithe "Polarised foreground removal at low radio frequencies using rotation measure synthesis: Uncovering the signature of hydrogen reionisation," ApJ in press

Datta, A., J. D. Bowman, and C. L. Carilli "Bright Source Subtraction Requirements for Redshifted 21 cm Measurements," 2010, ApJ

Morales, M. F. and J. S. B. Wyithe "Reionization and Cosmology with 21-cm Fluctuations," 2010, ARA&A

Liu, A., M. Tegmark, J. Bowman, J. Hewitt, and M. Zaldarriaga "An improved method for 21-cm foreground removal," 2009, MNRAS

Liu, A., M. Tegmark, and M. Zaldarriaga "Will point sources spoil 21-cm tomography?," 2009, MNRAS

Bowman, J. D., M. F. Morales, and J. N. Hewitt "Foreground Contamination in Interferometric Measurements of the Redshifted 21 cm Power Spectrum," 2009, ApJ

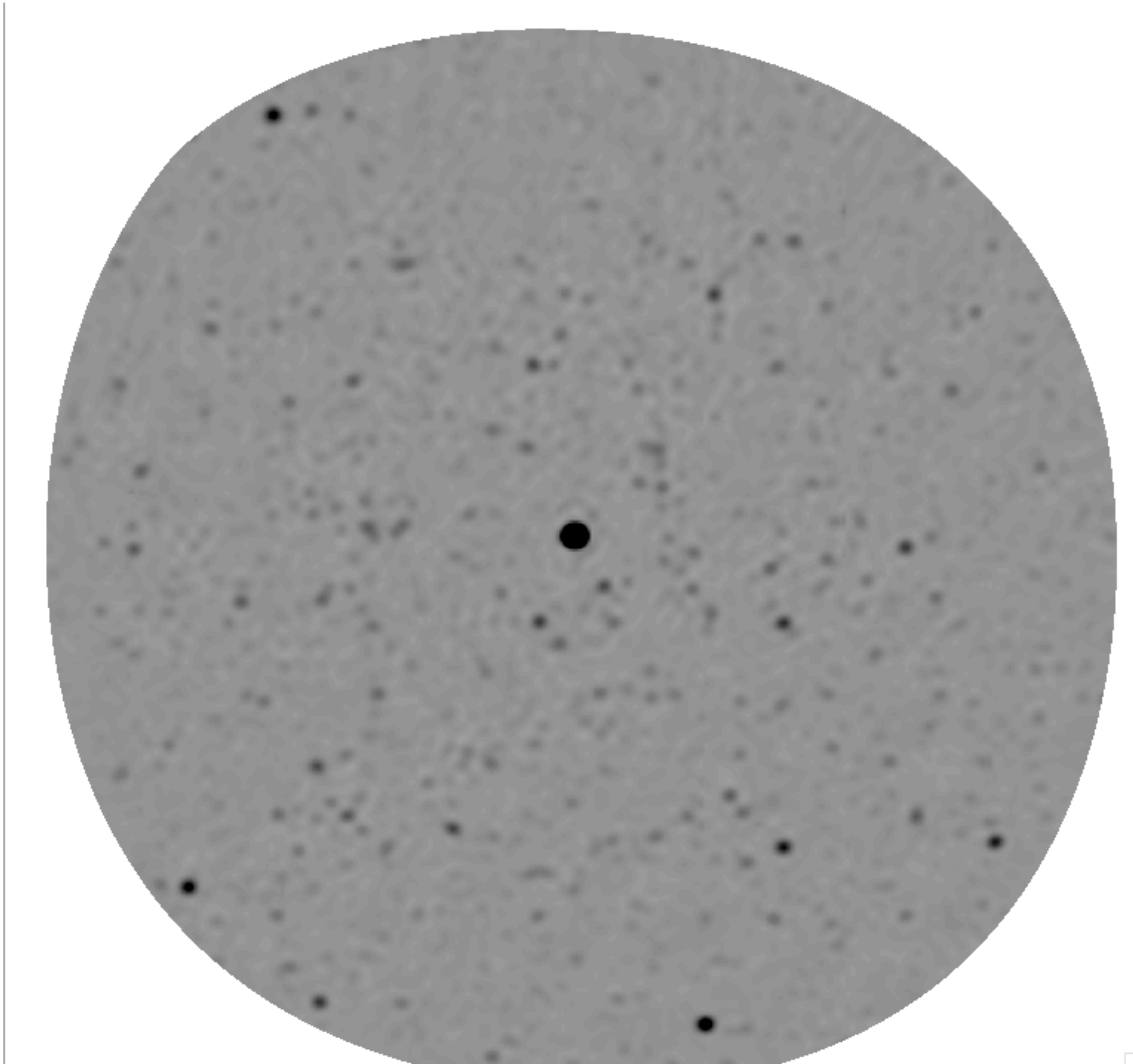
Geil, P. M., J. S. B. Wyithe, N. Petrovic, and S. P. Oh "The effect of Galactic foreground subtraction on redshifted 21-cm observations of quasar HII regions," 2008, MNRAS

Morales, M. F. "A Technique for Weak Lensing with Velocity Maps: Eliminating Ellipticity Noise in H I Radio Observations," 2006, ApJ

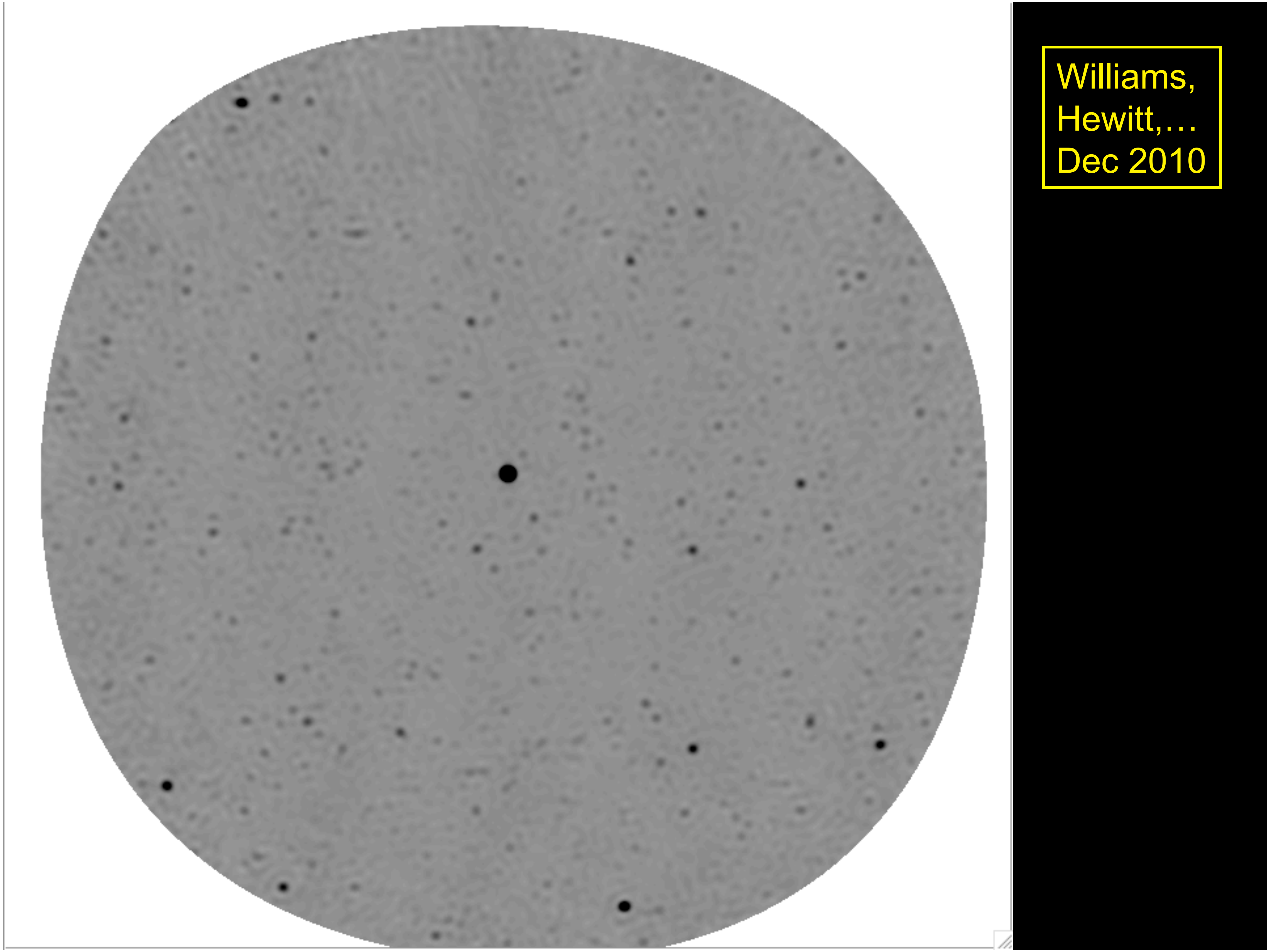
Morales, M. F., J. D. Bowman, and J. N. Hewitt "Improving Foreground Subtraction in Statistical Observations of 21 cm Emission from the Epoch of Reionization," 2006, ApJ

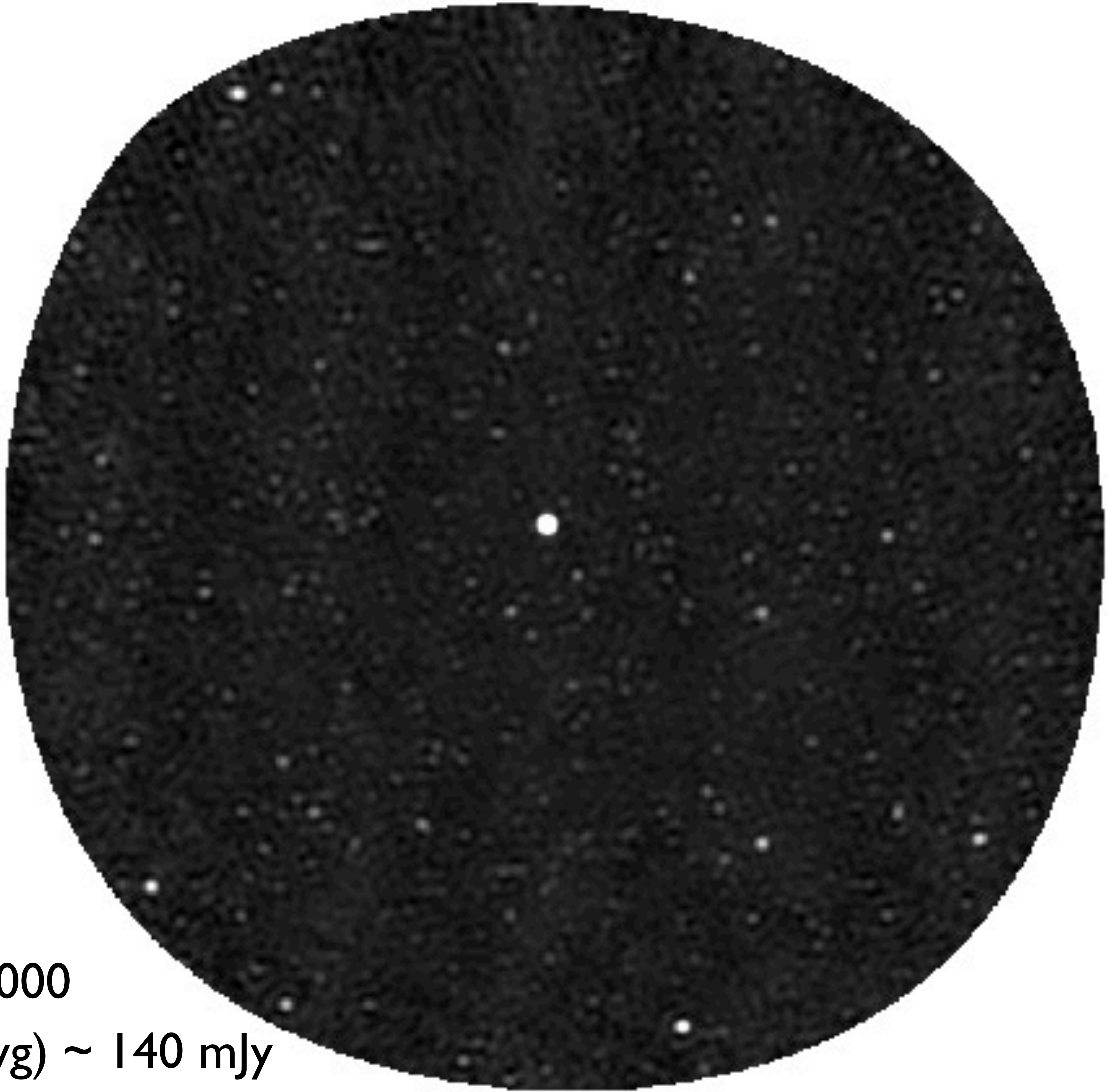
Morales, M. F. and J. Hewitt "Toward Epoch of Reionization Measurements with Wide-Field Radio Observations," 2004, ApJ

Experience with site



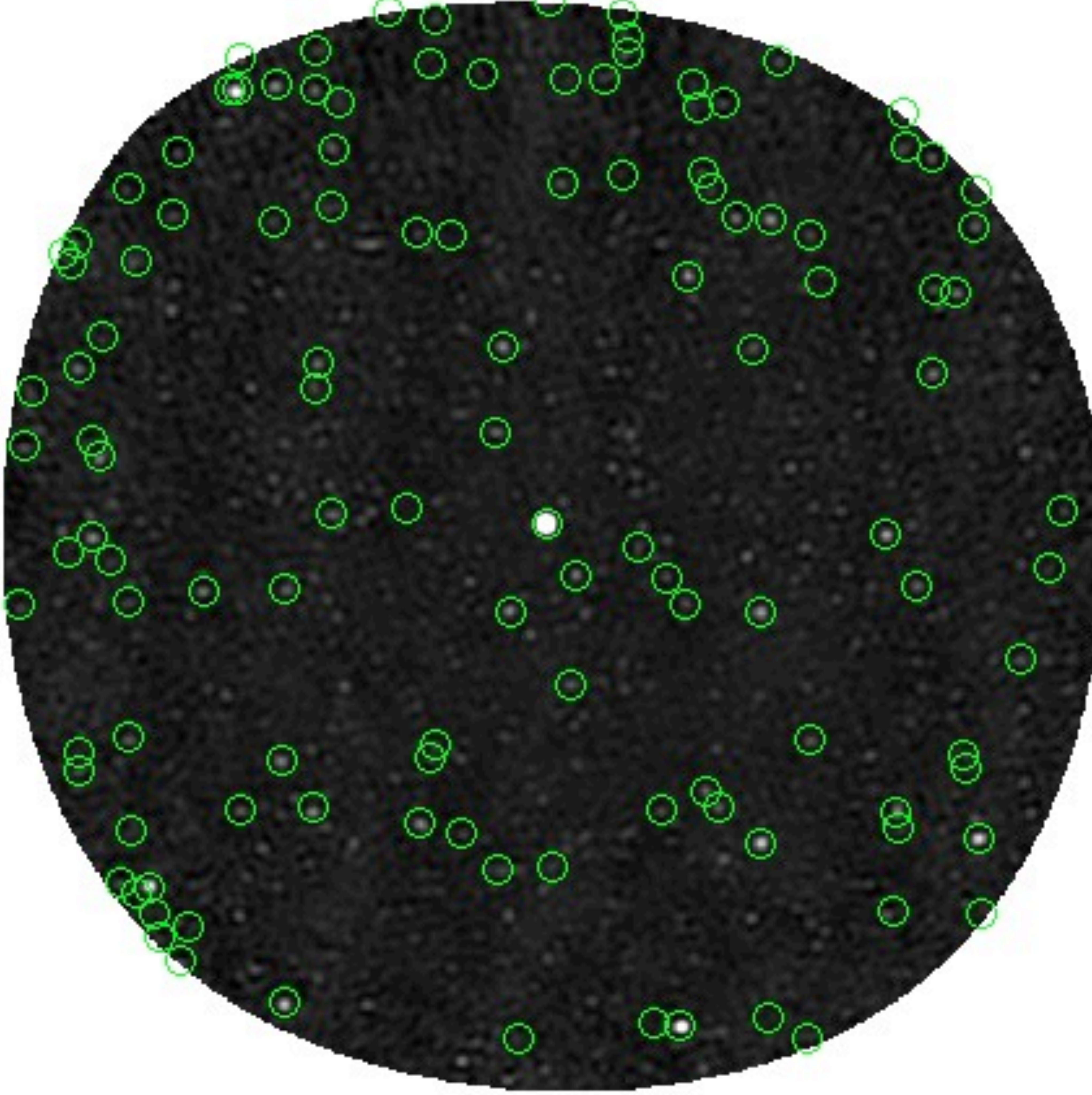
Briggs,…
X11 data
2010


Williams,
Hewitt,…
Dec 2010

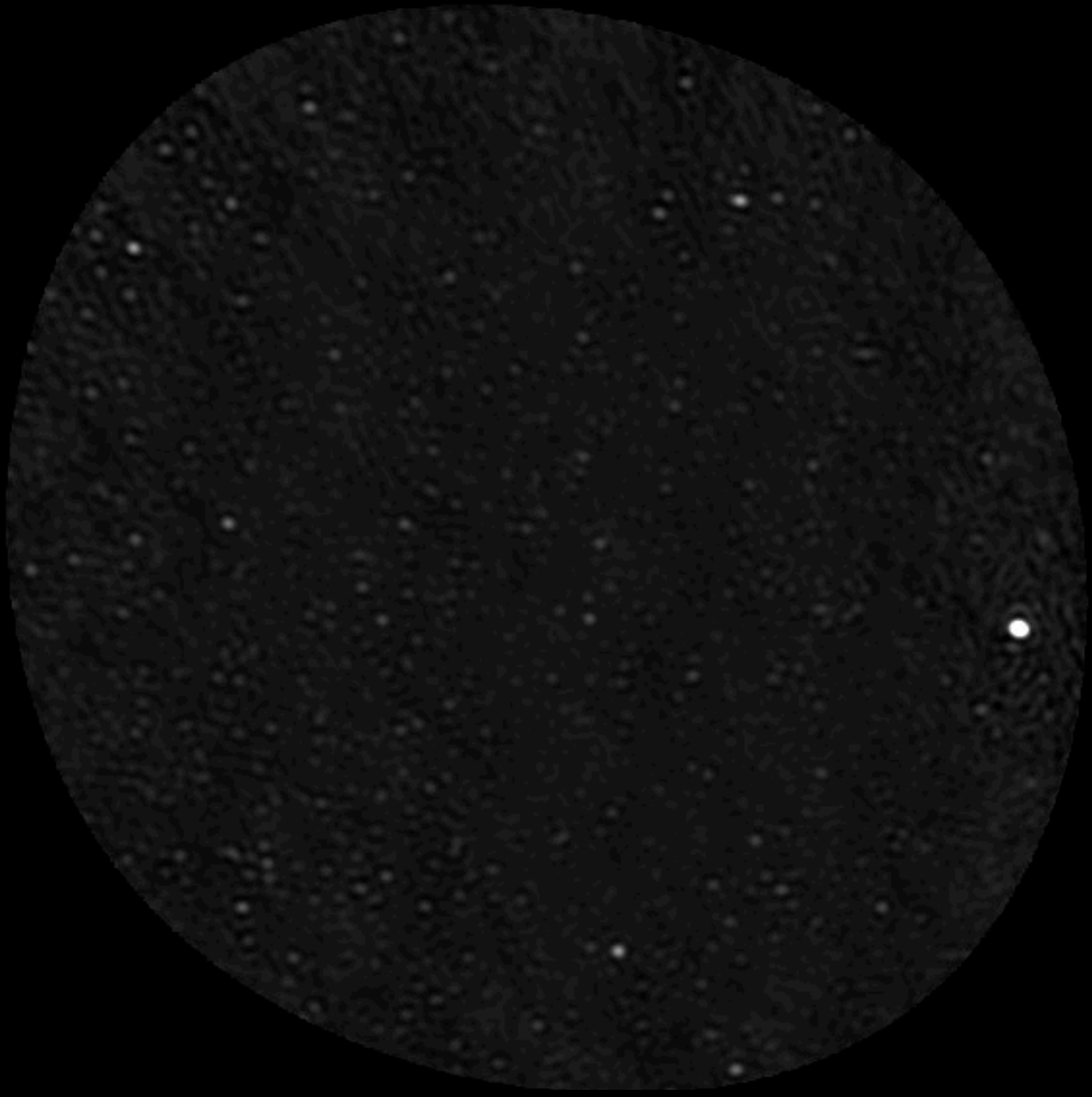


DR ~ 7000

RMS (avg) ~ 140 mJy



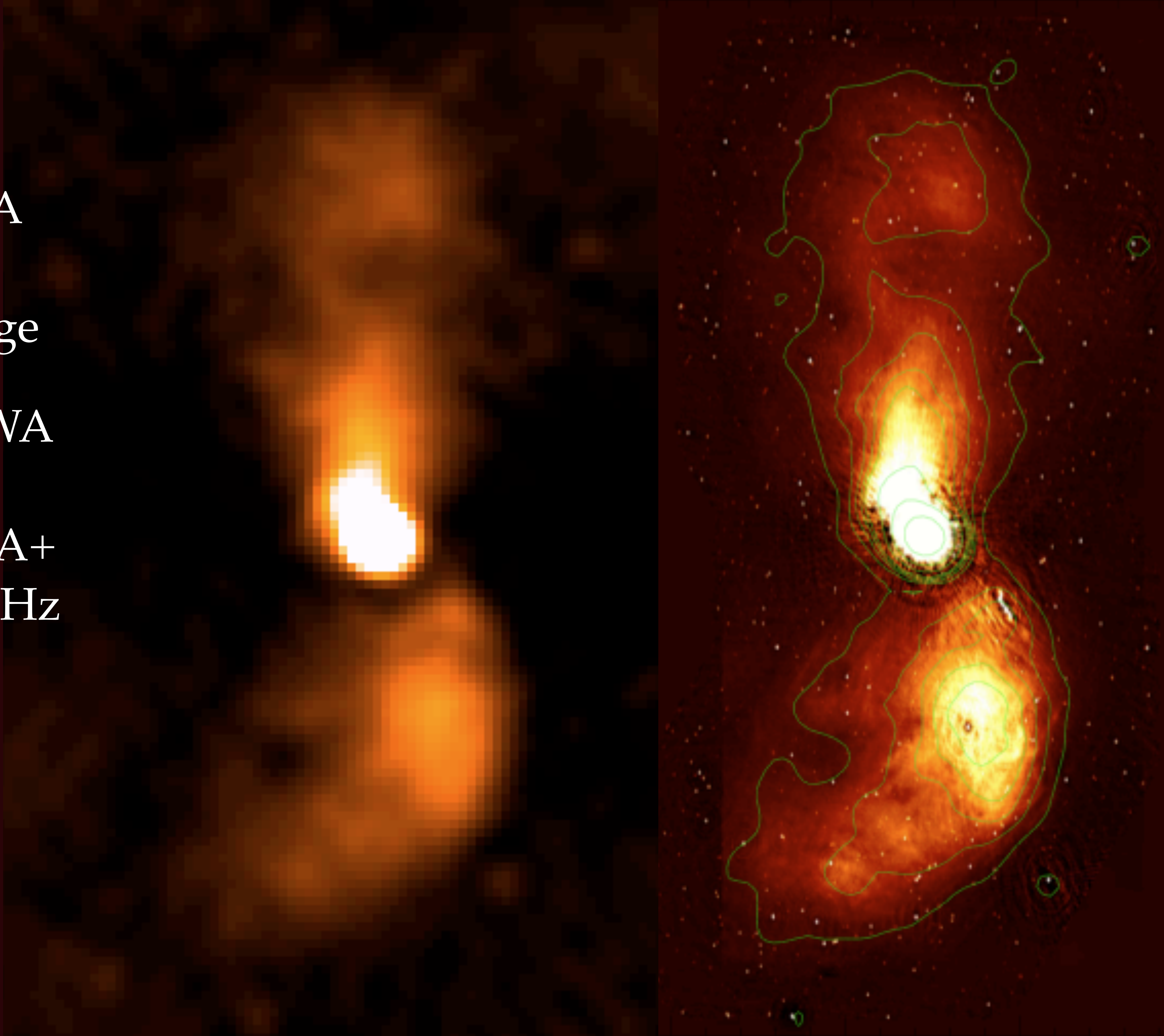
EOR2



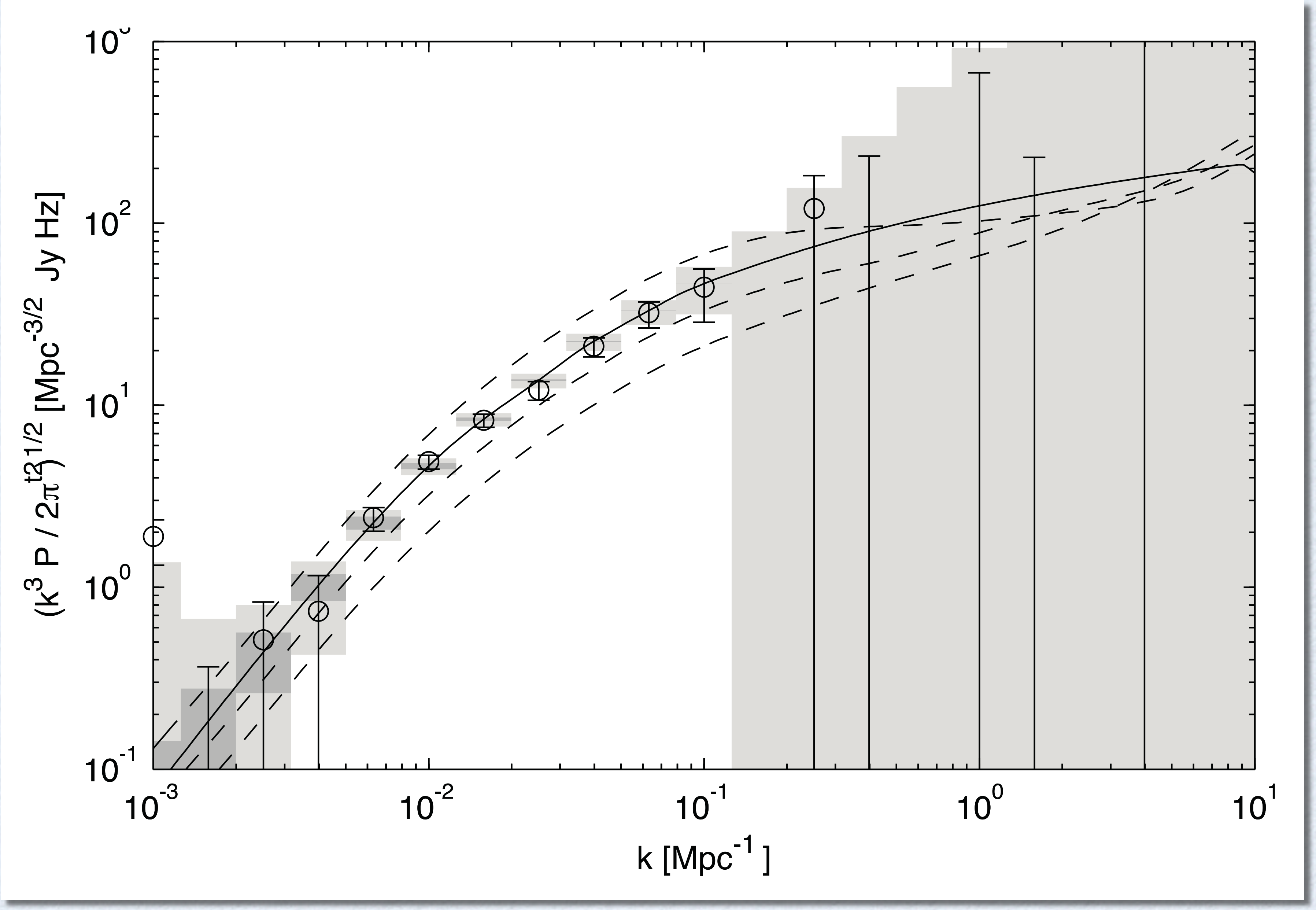
Cen A

Left: MWA 32T 115 MHz image

Right: MWA contours over ACTA+ PKS 1.4 GHz image



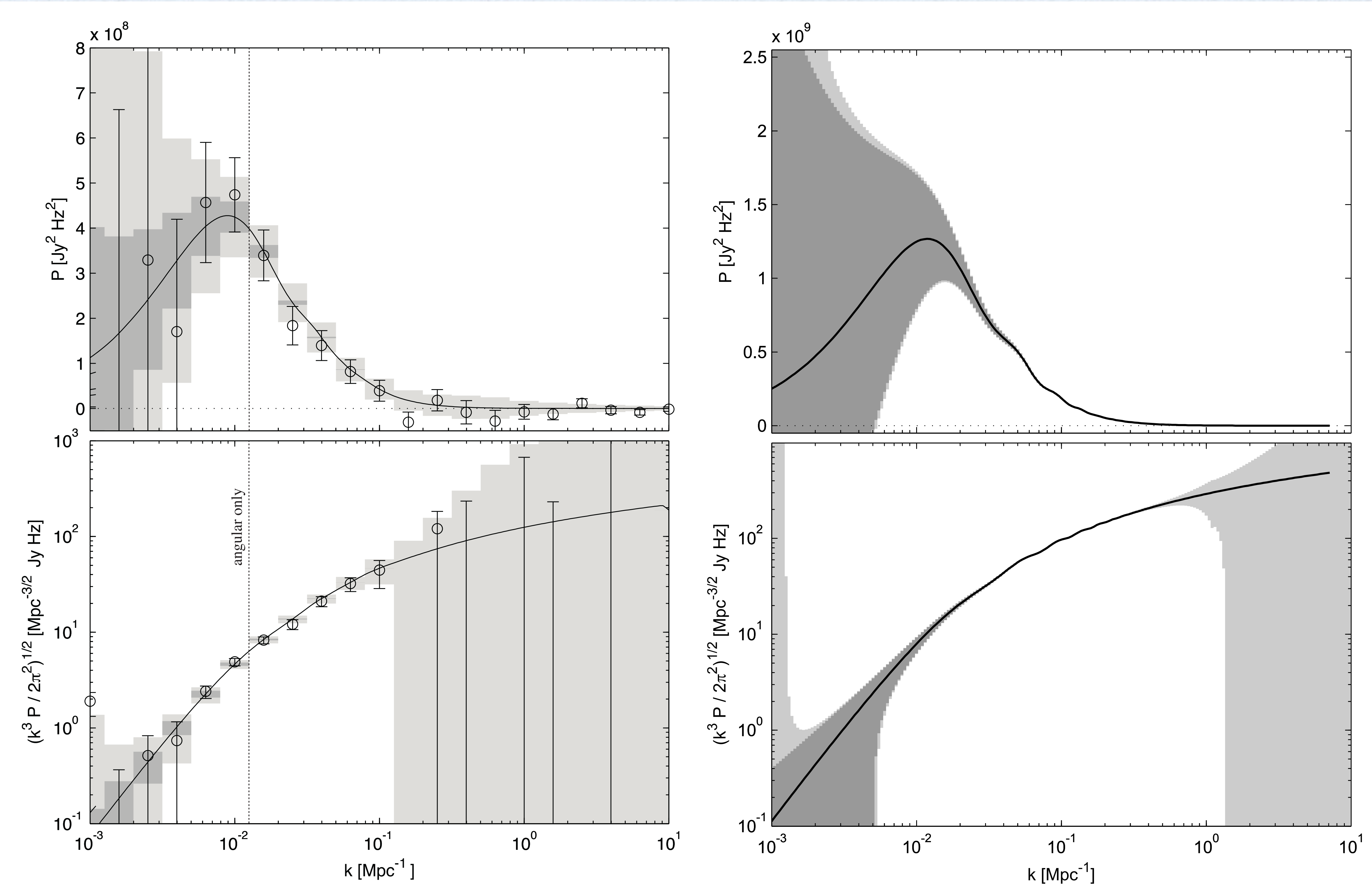
MWA power spectrum sensitivity



z = 8, 360 hours of integration

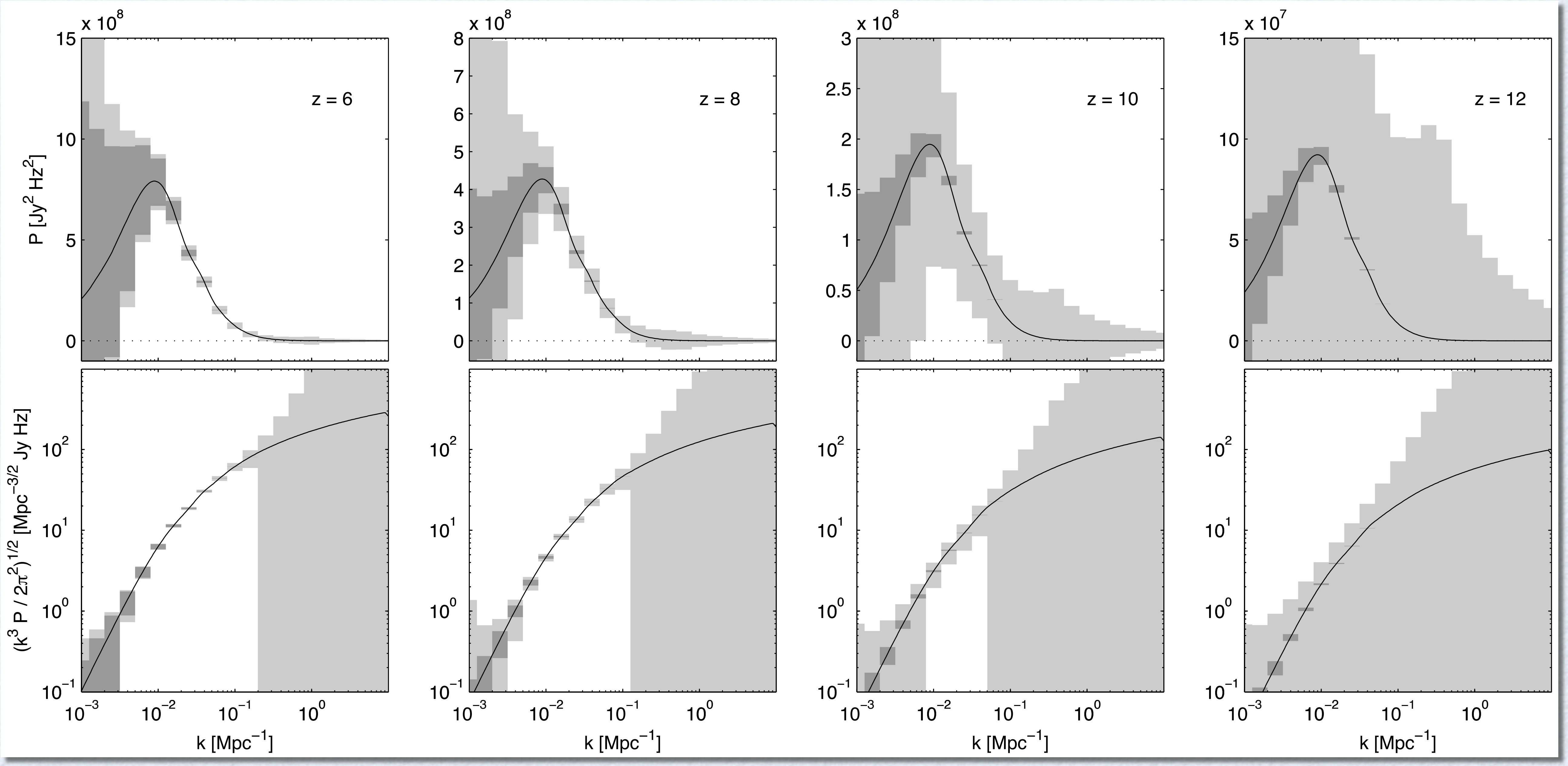
Furlanetto, Zaldarriaga, Hernquist (2004a,b)
Bowman, Morales & Hewitt (2005)
Kaplinghat (2005)

MWA vs. HERA



x 10^8
P [Jy^2 Hz^2]
angular only
(k^3 P / 2π^2)^1/2 [Mpc^-3/2 Jy Hz]
k [Mpc^-1]
x 10^9
P [Jy^2 Hz^2]
(k^3 P / 2π^2)^1/2 [Mpc^-3/2 Jy Hz]
k [Mpc^-1]

MWA sensitivity vs. redshift



Bowman, Morales & Hewitt (2005)

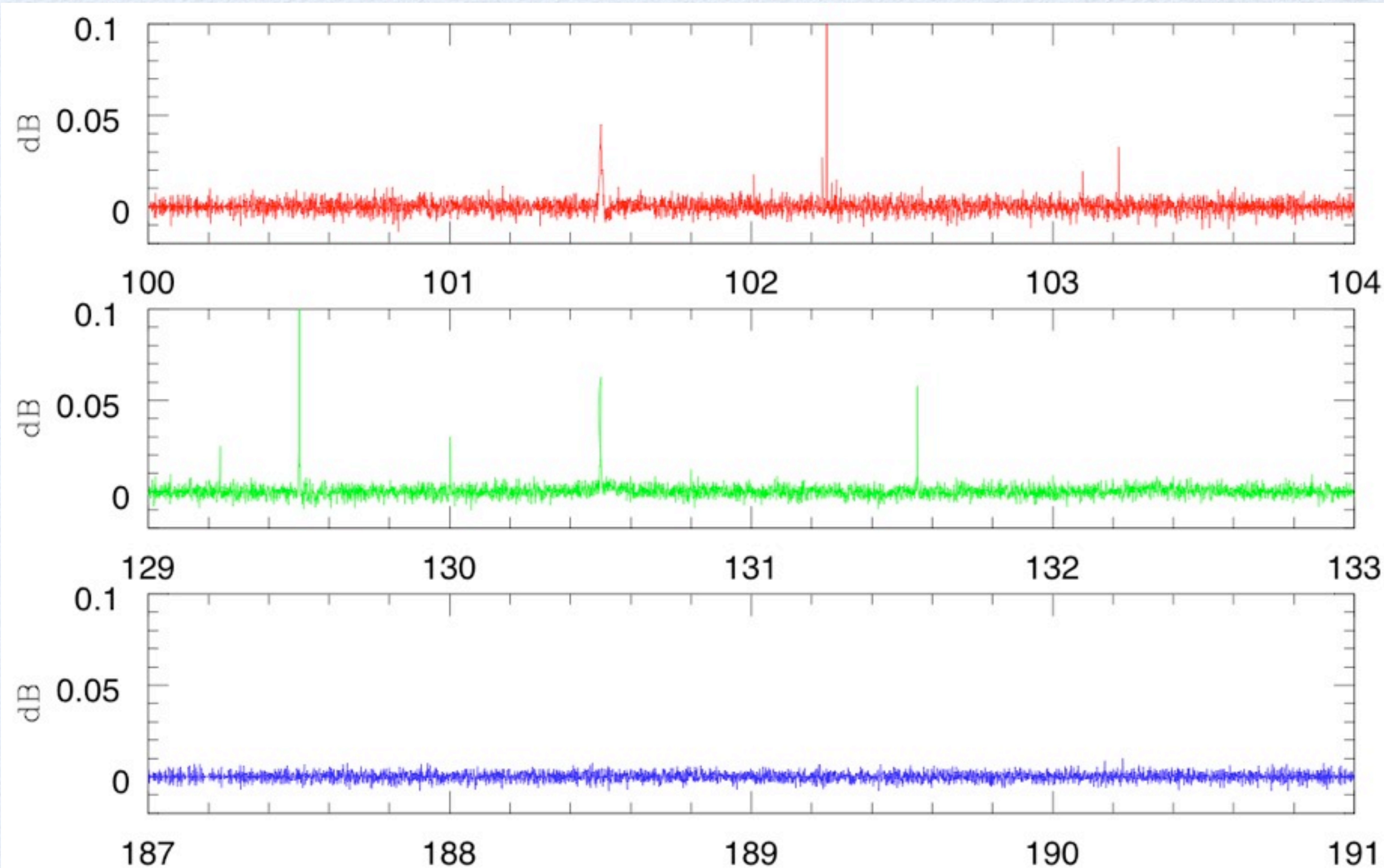
Western Australia

Very radio quiet

Western Australia

Very radio quiet

RFI



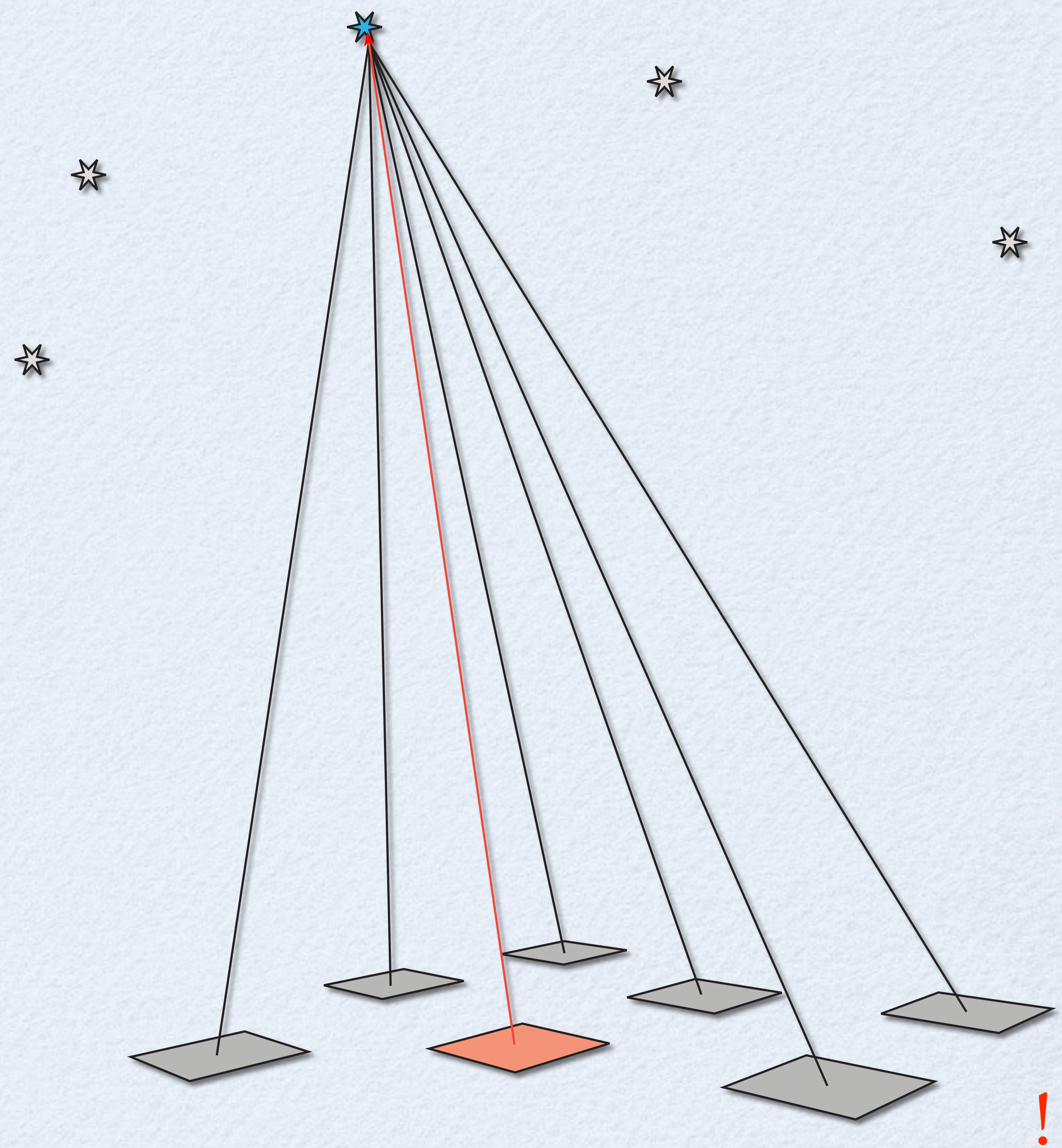
0.1
dB 0.05
0
100
101
102
103
104
0.1
dB 0.05
0
129
130
131
132
133
0.1
dB 0.05
0
187
188
189
190
191

Murchison Widefield Array

- 512 16 dipole antennas
- 80–300 MHz
- Radio quiet Murchison site
- Very wide 20°–40° field of view
- Full cross-correlation of all 512 antennas

Instrumental calibration

- Gain from one antenna to rest of array, simultaneously for all antennas & 100 sources



Galaxy surveys vs. intensity mapping

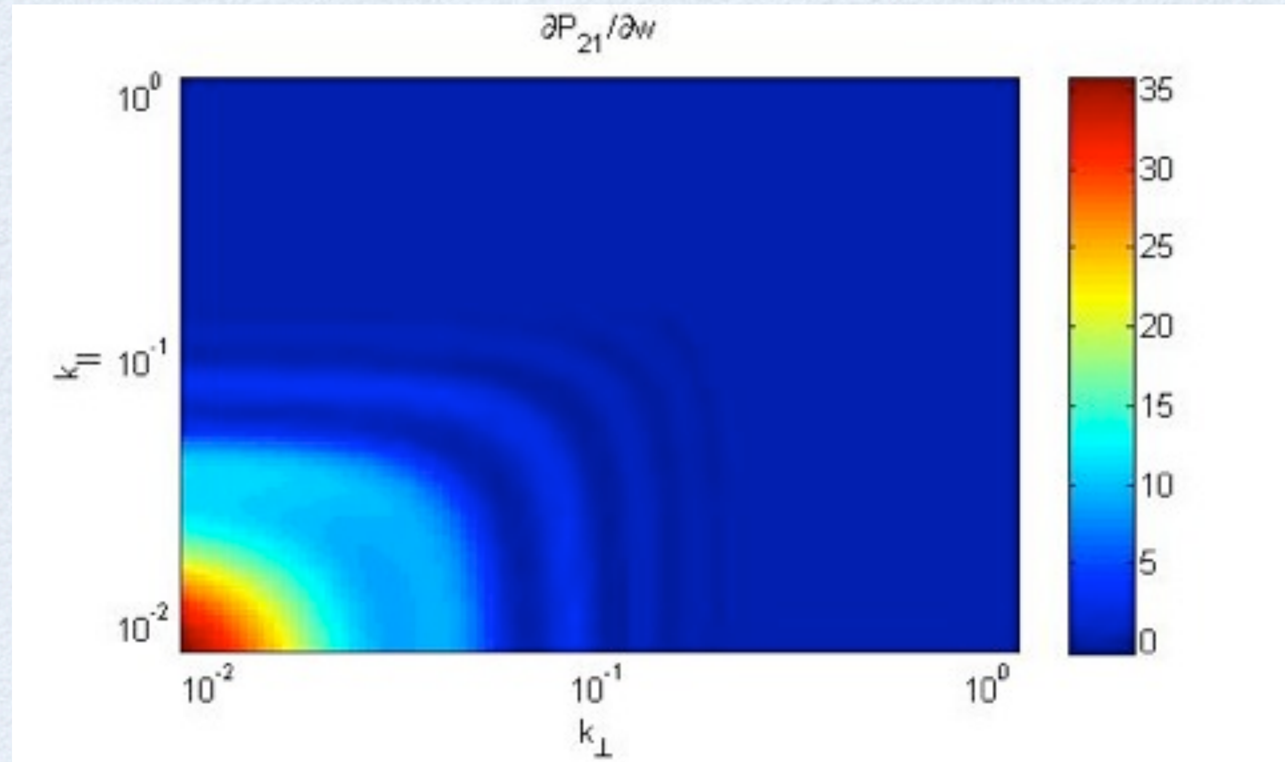
Galaxy survey: select galaxies above noise threshold, cross-correlate positions

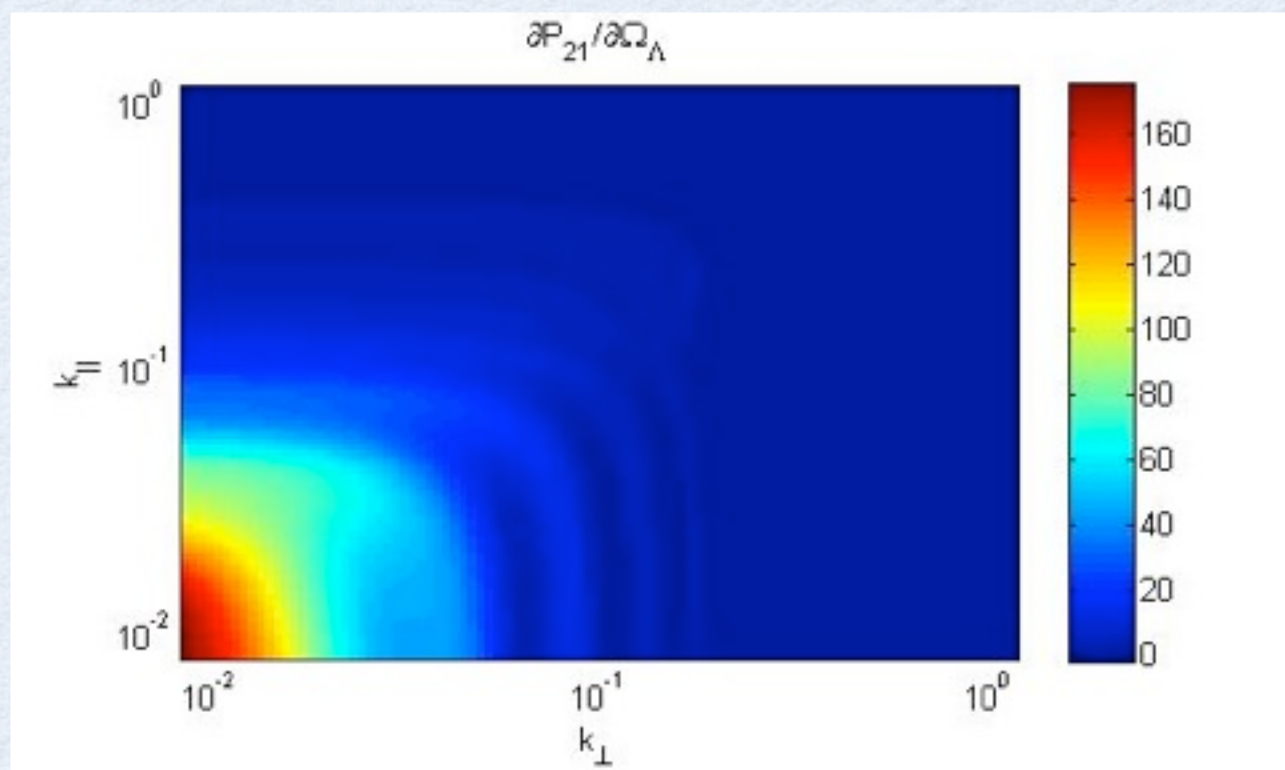
Intensity mapping: correlate density of HI emission in low resolution measurements

- Include emission from all galaxies (most below detection threshold)
- All baselines on BAO scales

k-space Fisher matrixes

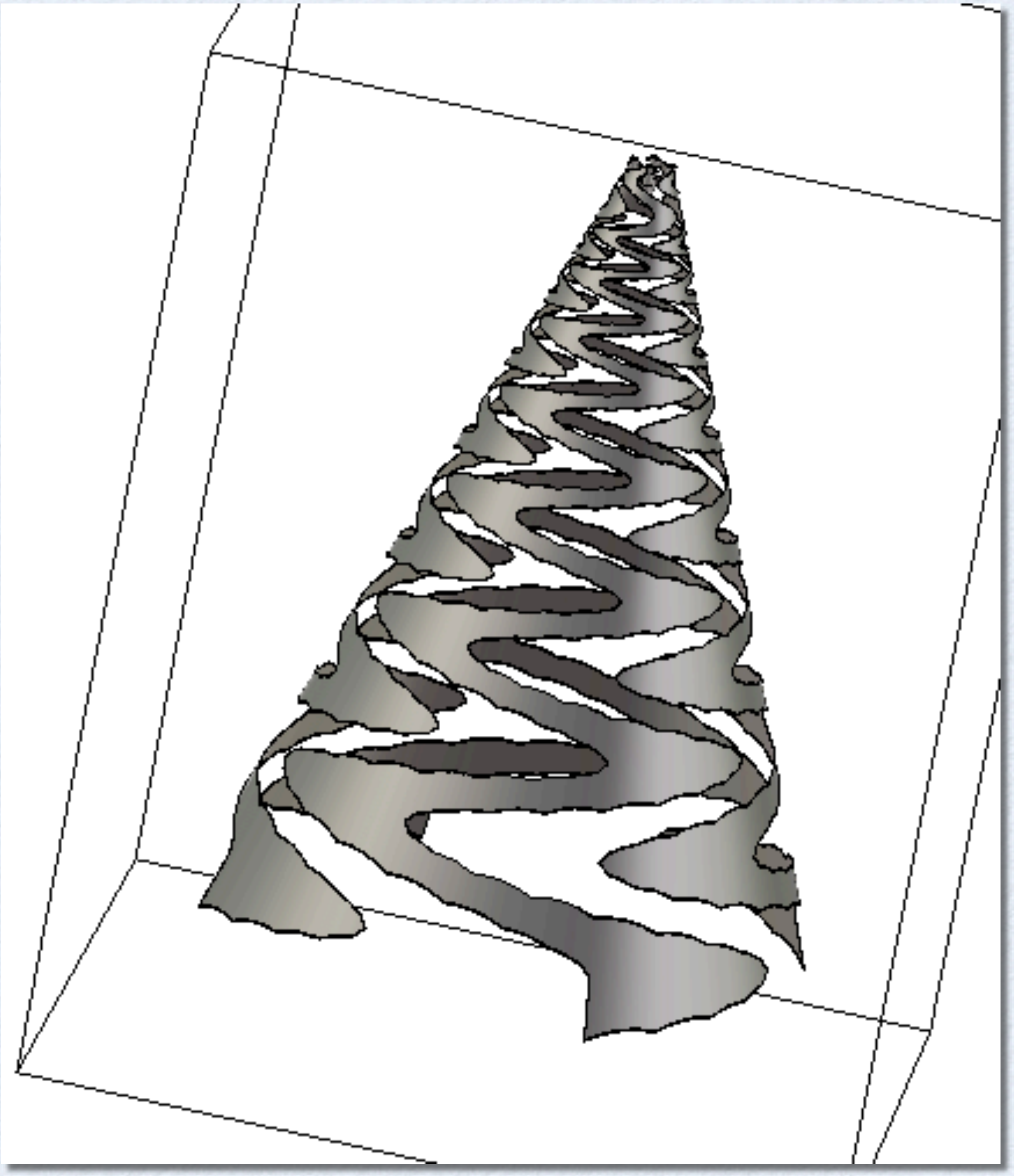
Tuning parameter sensitivity

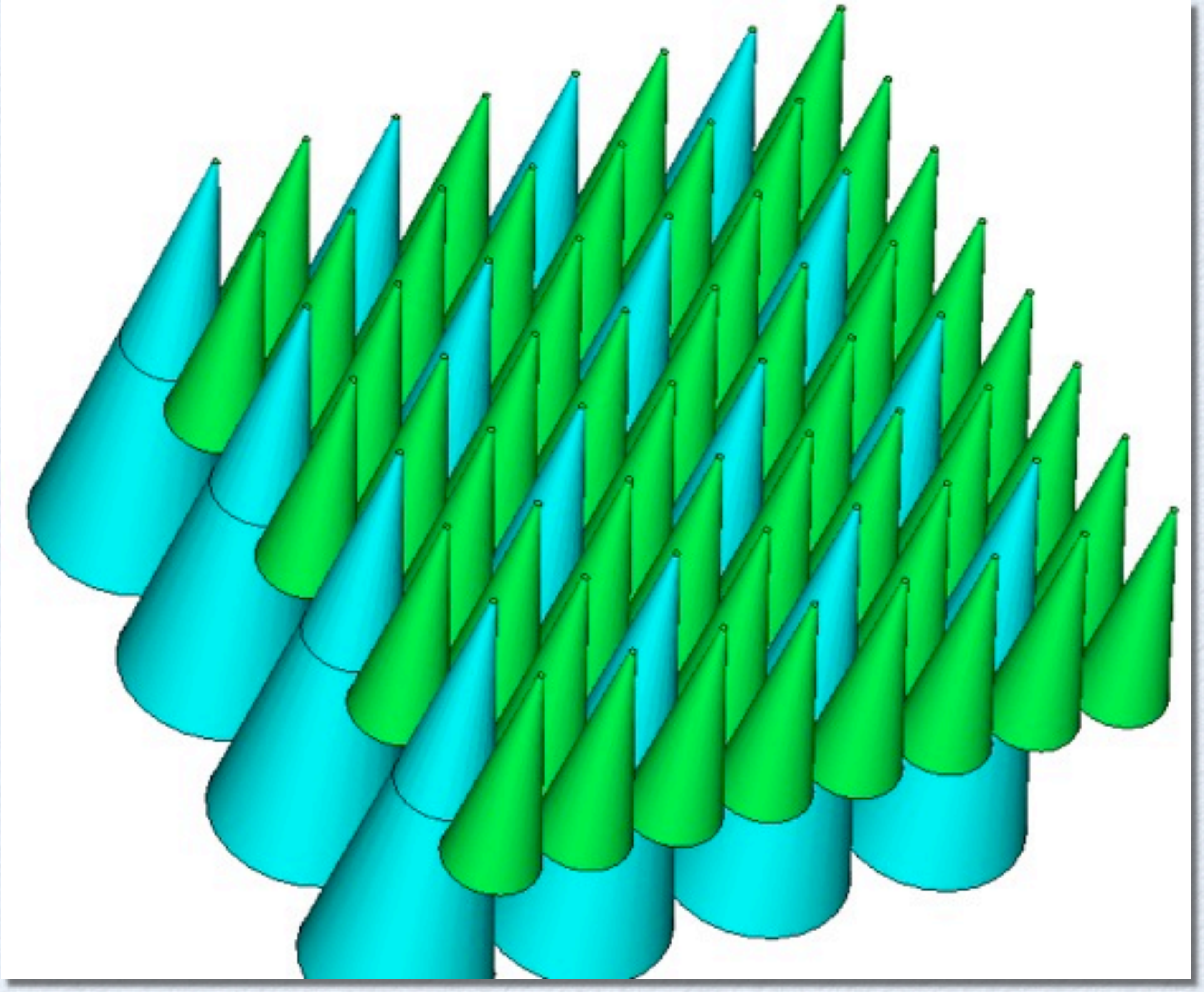




Visbal, in prep.

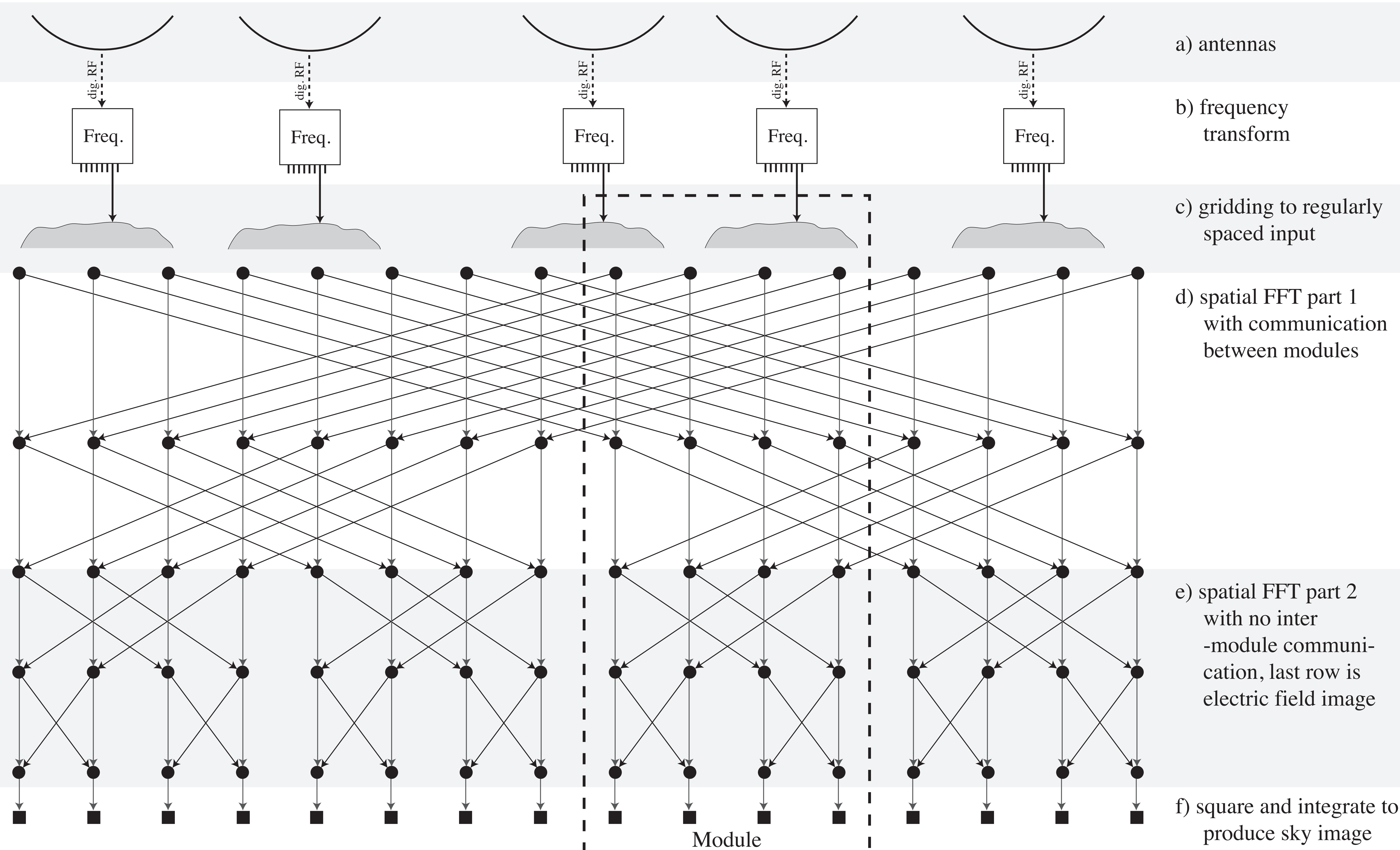
Sierpinski carpet





350–1500 MHz; z = 0–4

MOFF correlator



(Morales) !

Science

- BAO and cosmology parameters, z of 1–3.5
- Gravitational waves via millisecond pulsar timing
- Ephemerides of most southern pulsars every week
- Full-sky pulsar survey

CARPE

Number of antennas	2500 (steerable)
Antenna element size	1.1 m^2
Total collecting area	$\sim$2750 m^2 (freq. dependent)
Field of view	400 sq. deg ($\sim 20^\circ_{\rm FWHM}$)
Instantaneous bandwidth	300 MHz
Maximum baseline	250 m
Angular resolution at z=1 (710 MHz)	6 arcmin
System temperature at z=1, T_{sys}	35 K

http://www.phys.washington.edu/users/mmorales/carpe/

Performance

Cosmology parameters

	Ω_Λ	$\Omega_\mathrm{m}h^2$	$\Omega_\mathrm{b}h^2$	n_s	$A_\mathrm{s}^2 \times 10^{10}$	α	$\Omega_\nu h^2$	w	τ	Y_He	x_HI1	x_HI2
Fiducial Values	0.7	0.147	0.023	0.95	25.0	0.0	0.00054	-1	0.10	0.24	0.02	0.0
RCT	0.015	0.013	0.0032	0.027	–	0.012	0.0024	0.087	–	–	0.003	0.000520
Planck	0.096	0.0061	0.00024	0.0094	0.27	0.0071	0.0059	0.16	0.0051	0.015	–	–
RCT+Planck	0.01	0.00079	0.00018	0.0055	0.22	0.0042	0.00089	0.048	0.0041	0.008	0.00066	0.000310

Pulsar search