21 cm Power Spectra & the MWA

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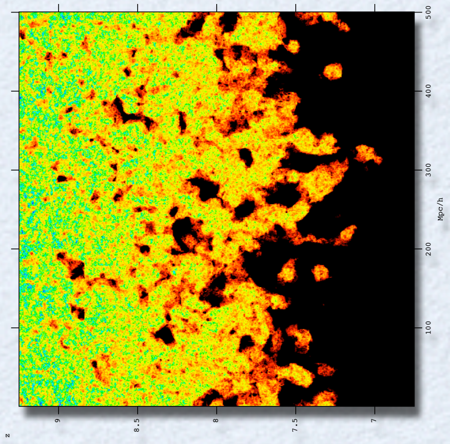
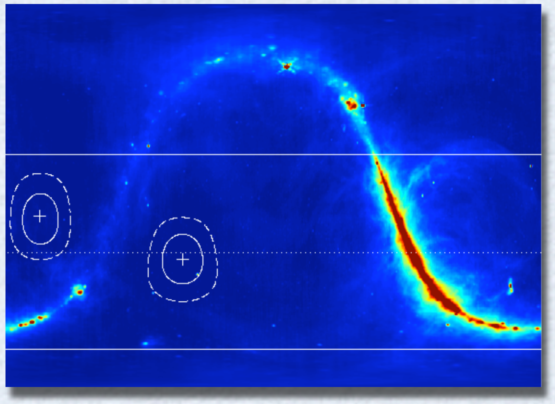
University of Washington
Stockholm, August 17, 2009

Overview

- EoR power spectrum

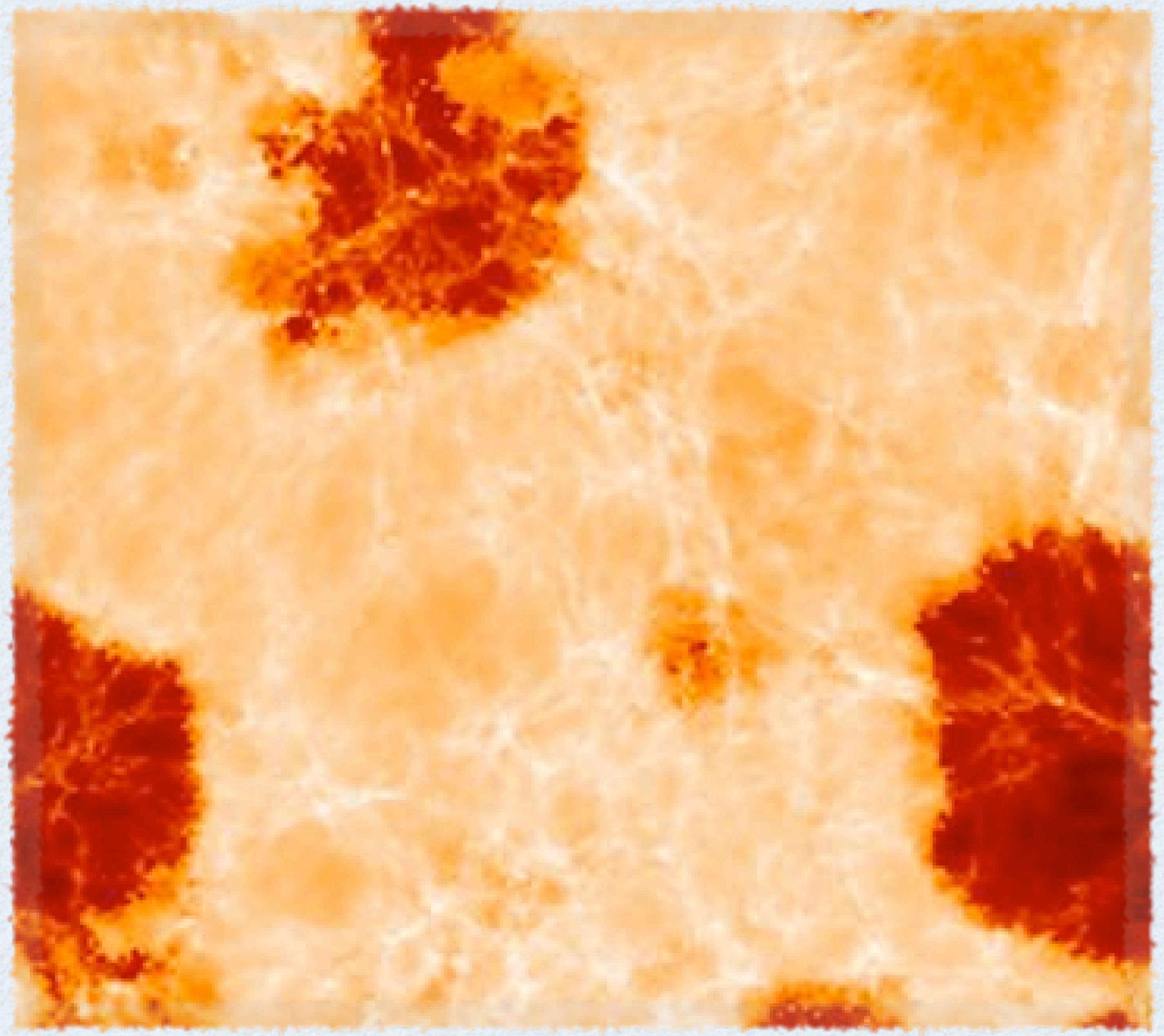


- Foregrounds & Calibration



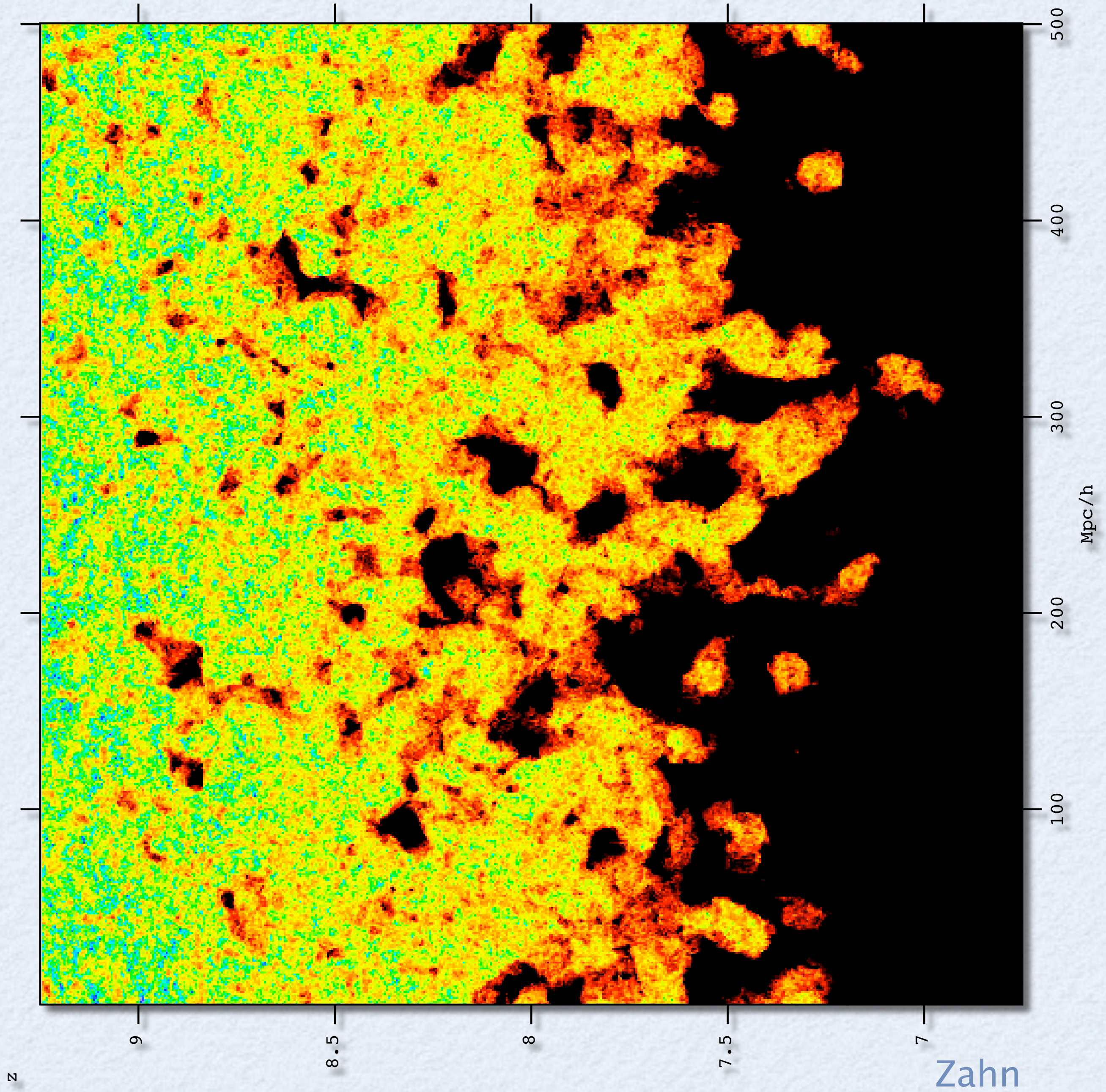
- Implications for cross-correlations

- MWA

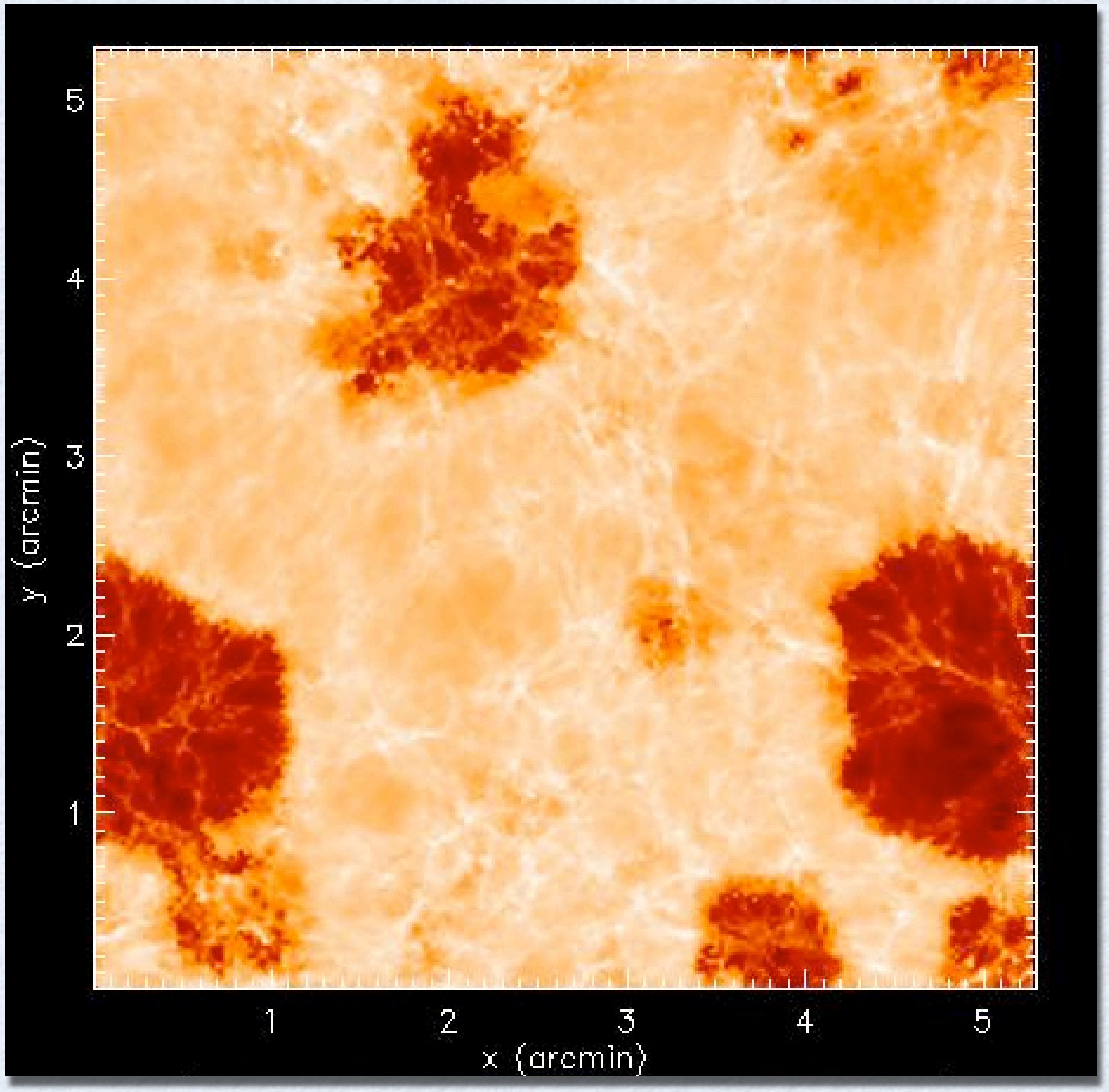


Epoch of Reionization

HI during EoR

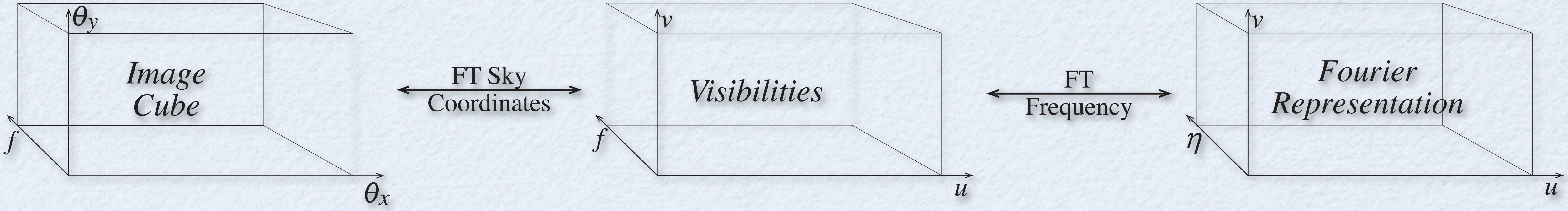


Zahn



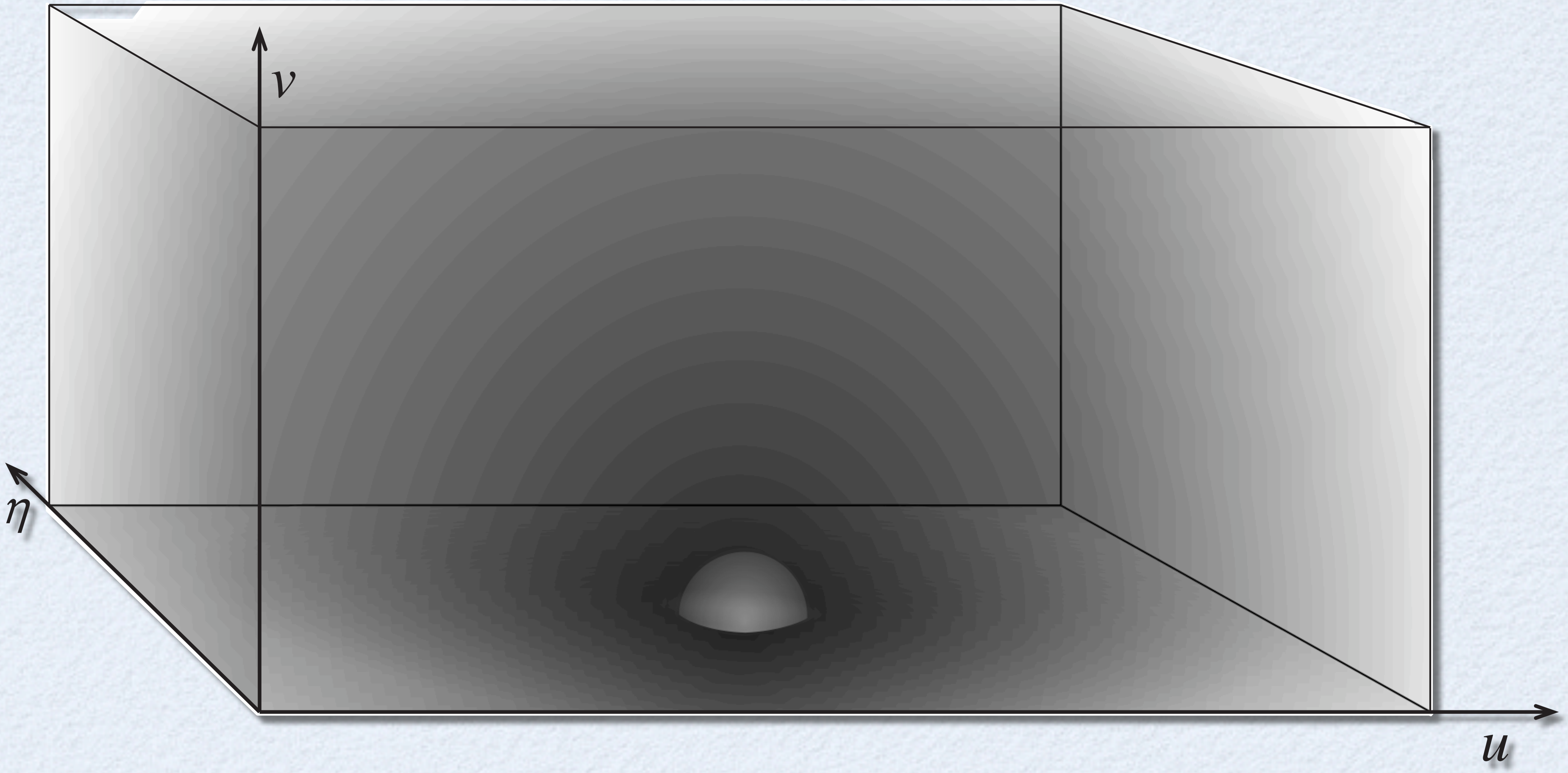
Furlanetto, Sokasian, Hernquist (2004)

EoR power spectrum



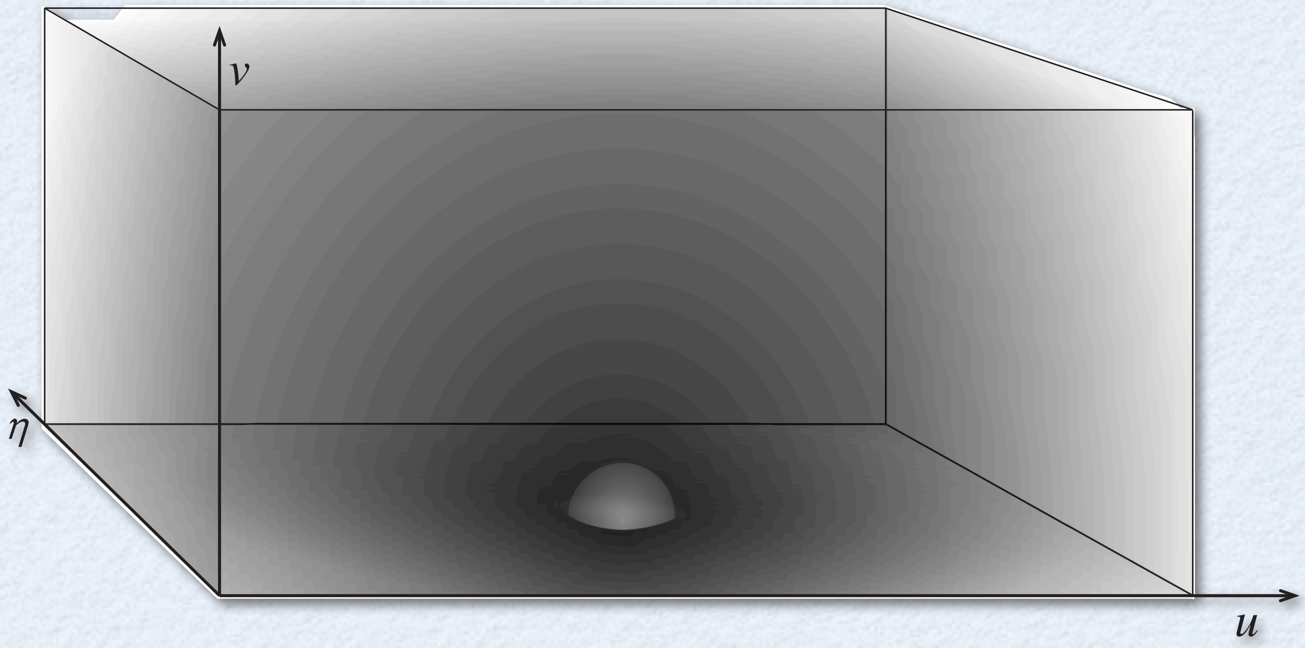
Morales & Hewitt (2004)

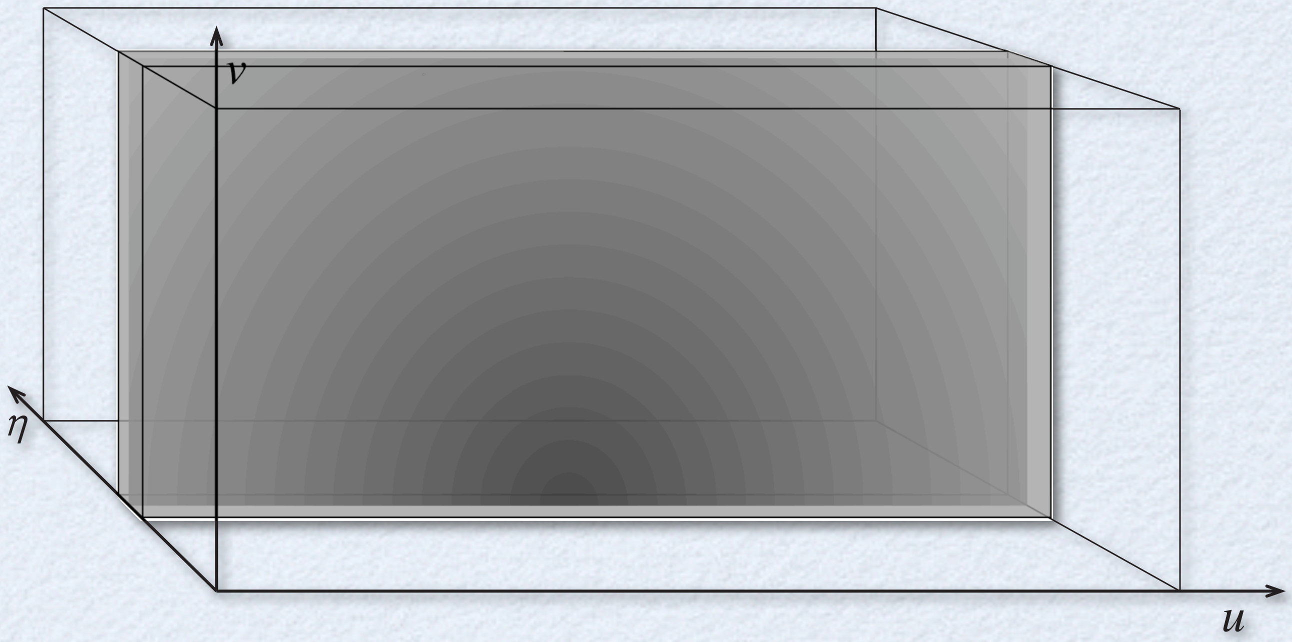
Spherical symmetry



Morales & Hewitt (2004)

Symmetry separation





Morales, Bowman & Hewitt (2006)

EoR *k*-space coverage

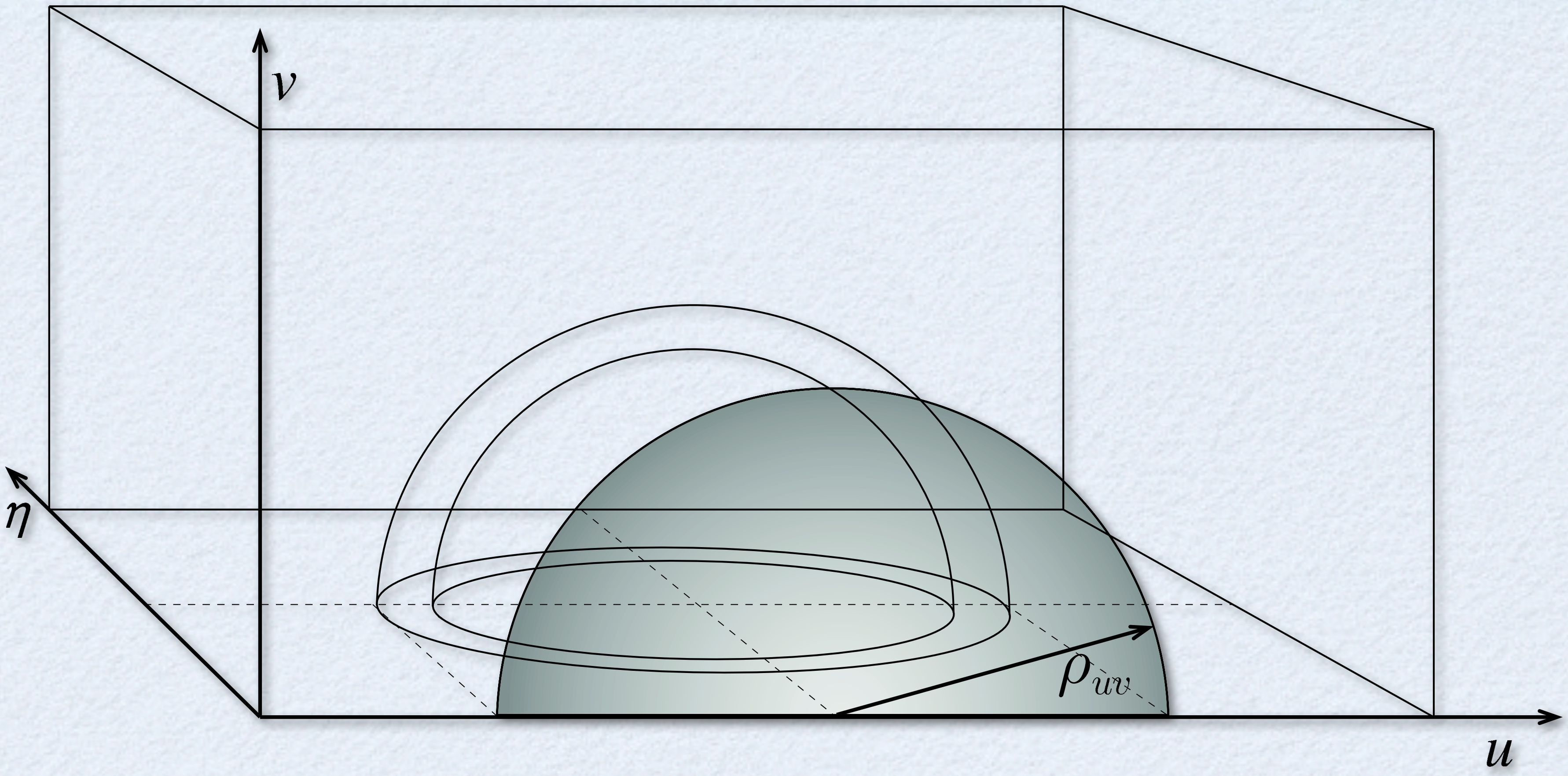


TABLE 1.

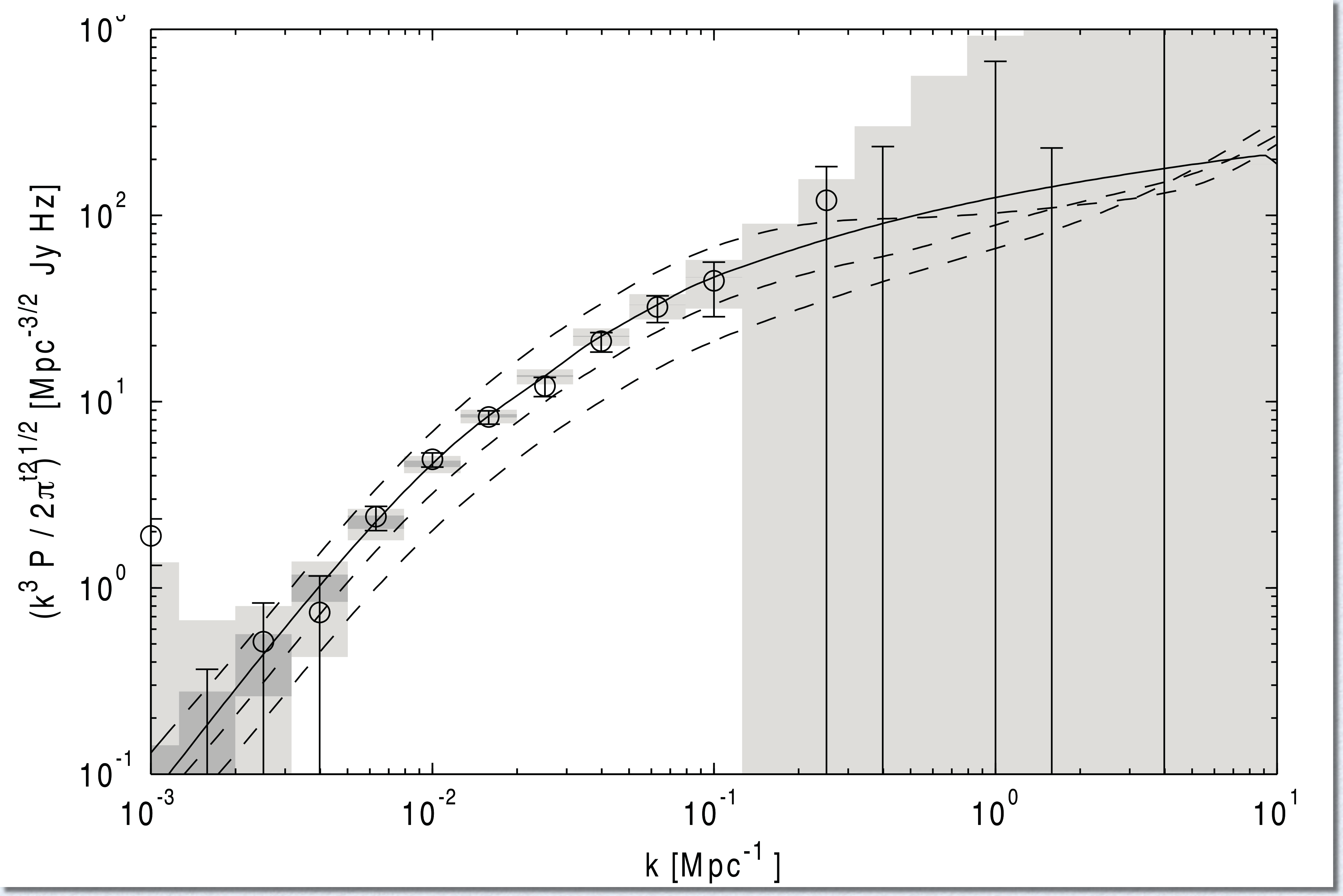
	$A_t\rvert_{dA}$	$A_t\rvert_{N_A}$	$dA\rvert_{A_t}$	B	$\lvert\mathbf{u}\rvert$	t
Power Spectrum S/N	A_t^2	$A_t^{3/2}$	$(dA)^{-1/2} \propto$ FOV	$B^{1/2}$	$\lvert\mathbf{u}\rvert\,\bar{n}(\lvert\mathbf{u}\rvert)$	t

NOTE. — This table lists the scaling relationships of the key equations. In order, the variables in each column are: total array area holding the size of each antenna constant $A_t|_{dA}$ (adding antennas), total array area holding the number of antennas and distribution constant $A_t|_{N_A}$ (increasing antenna size), the size of each antenna with the total array area held constant $dA|_{A_t}$ (dividing area into more small antennas), the total bandwidth B, the sensitivity as a function of wavenumber length $|\mathbf{u}|$, and the total observing time t.

Morales (2005)

Survey speed with compact antenna distribution

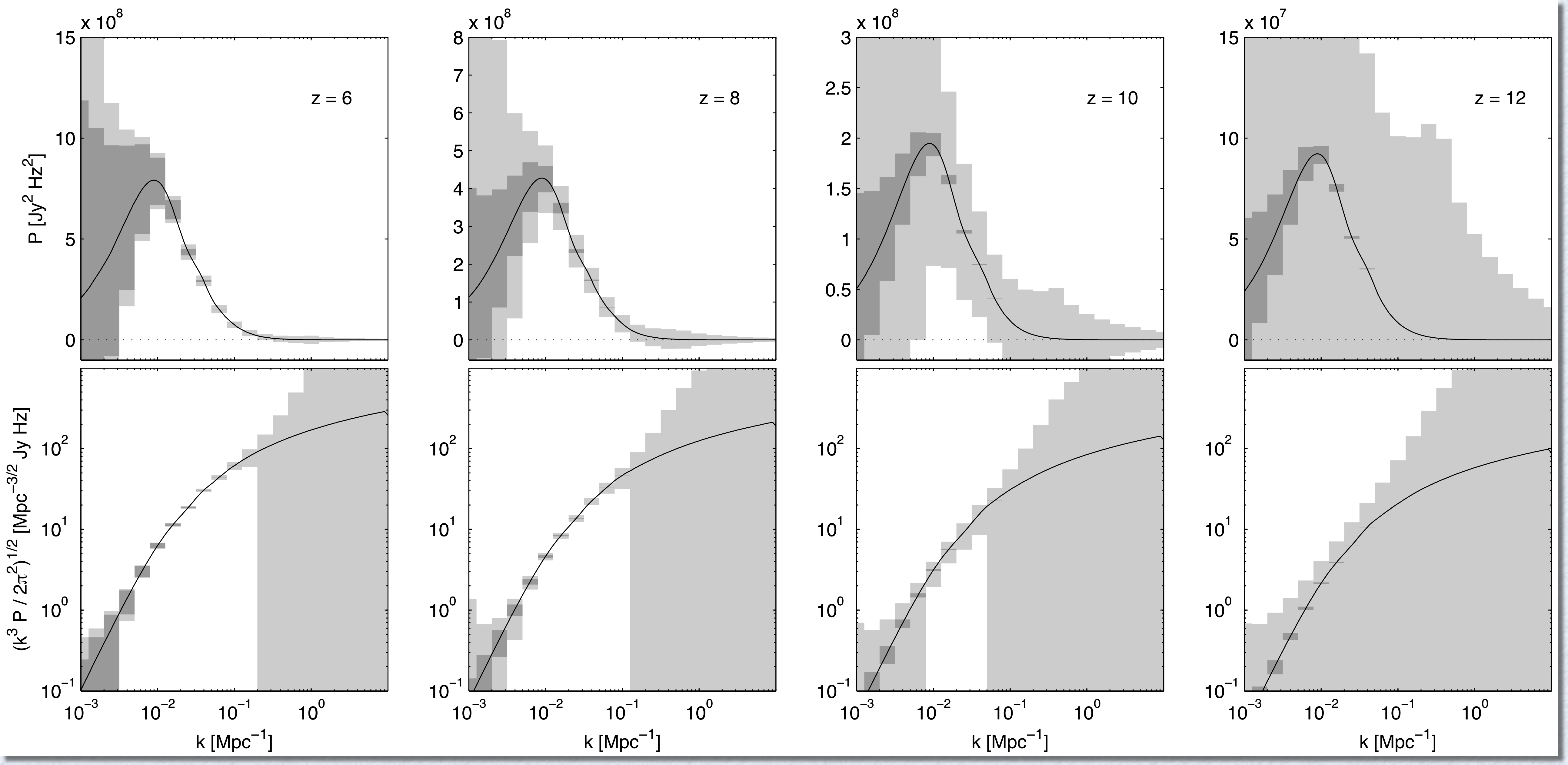
Power spectrum



z = 8, 360 hours of integration

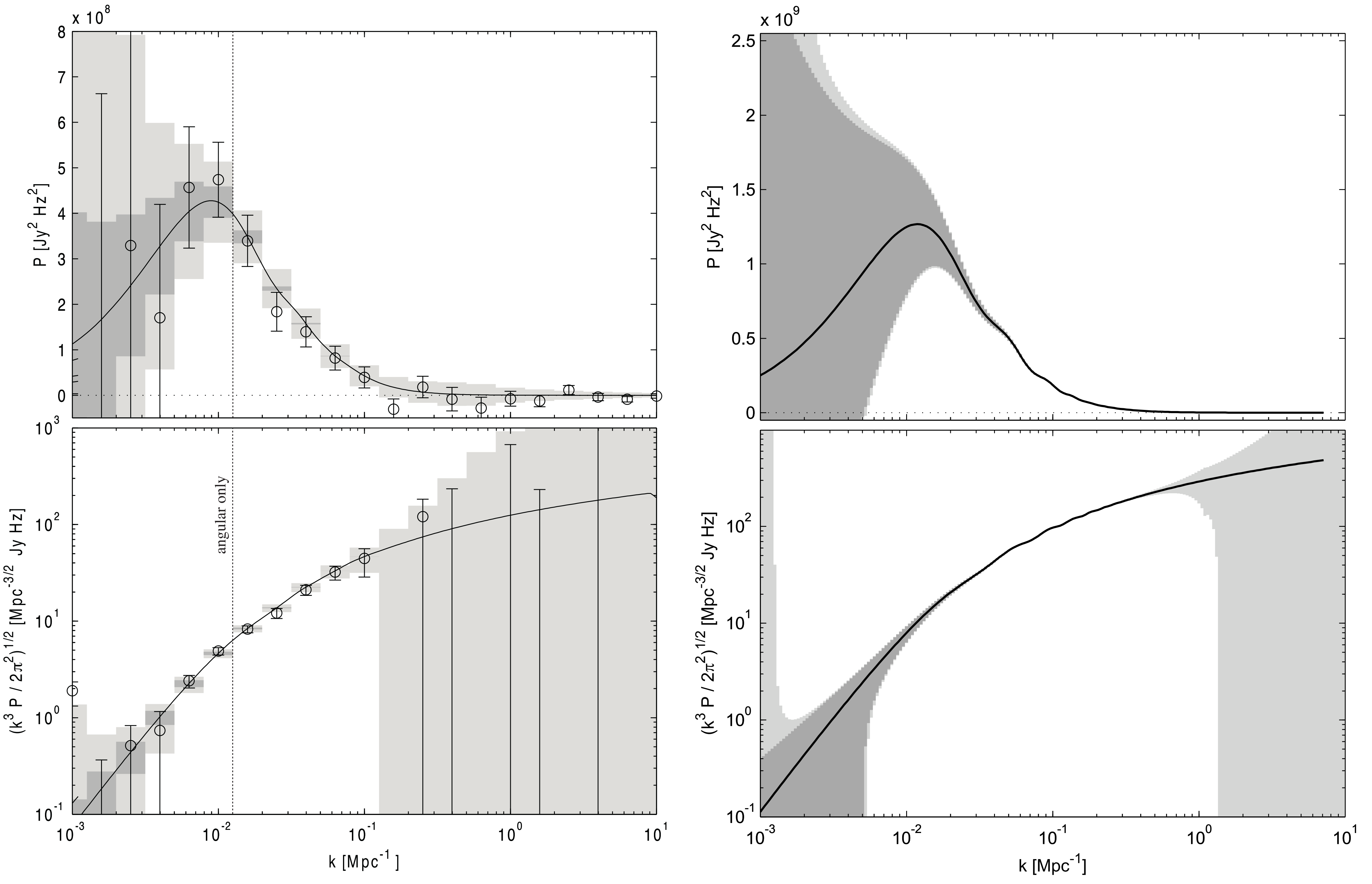
Bowman, Morales & Hewitt (2005)

MWA sensitivity vs. redshift

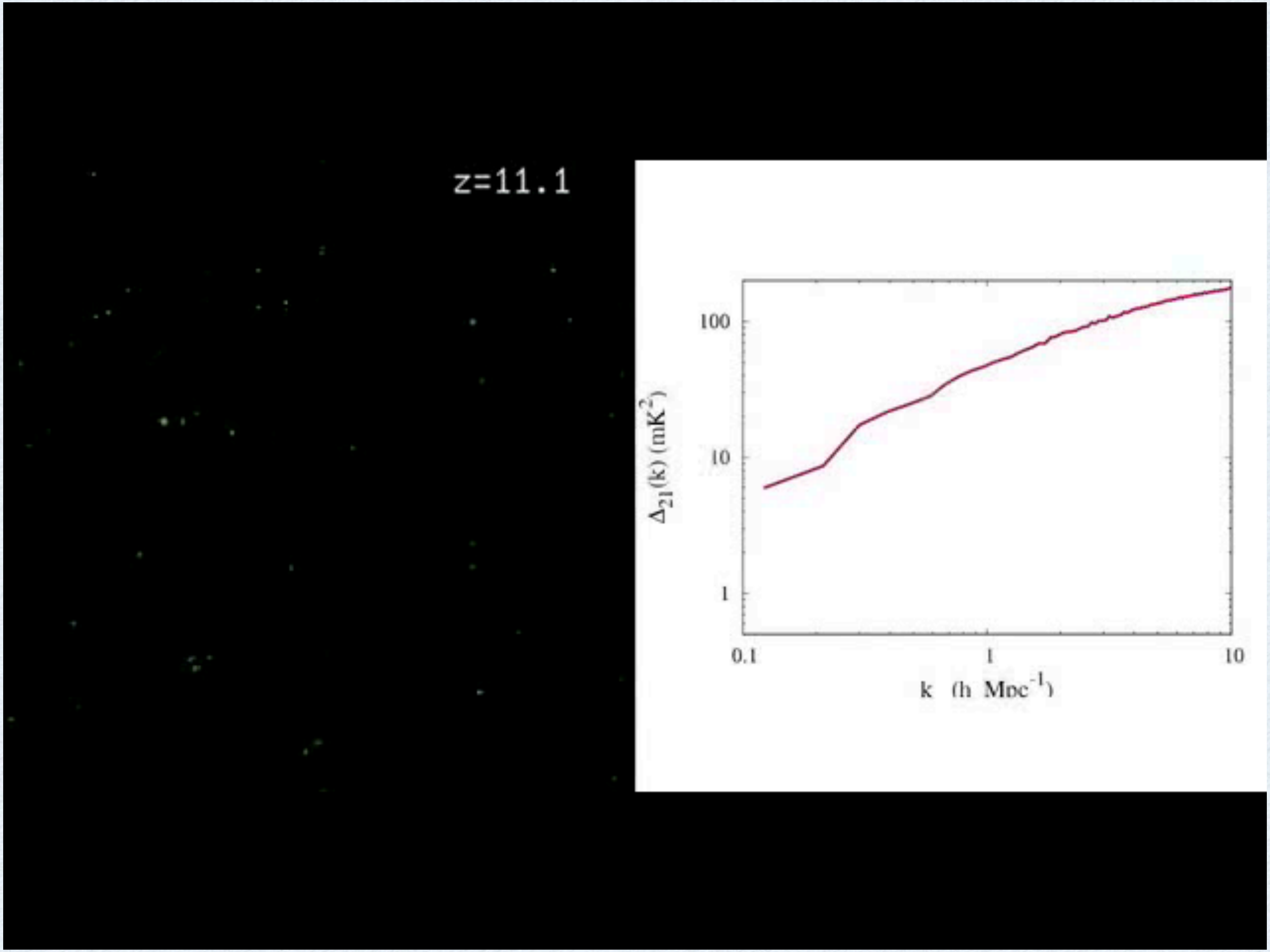


Bowman, Morales & Hewitt (2005)

MWA vs. MWA5000

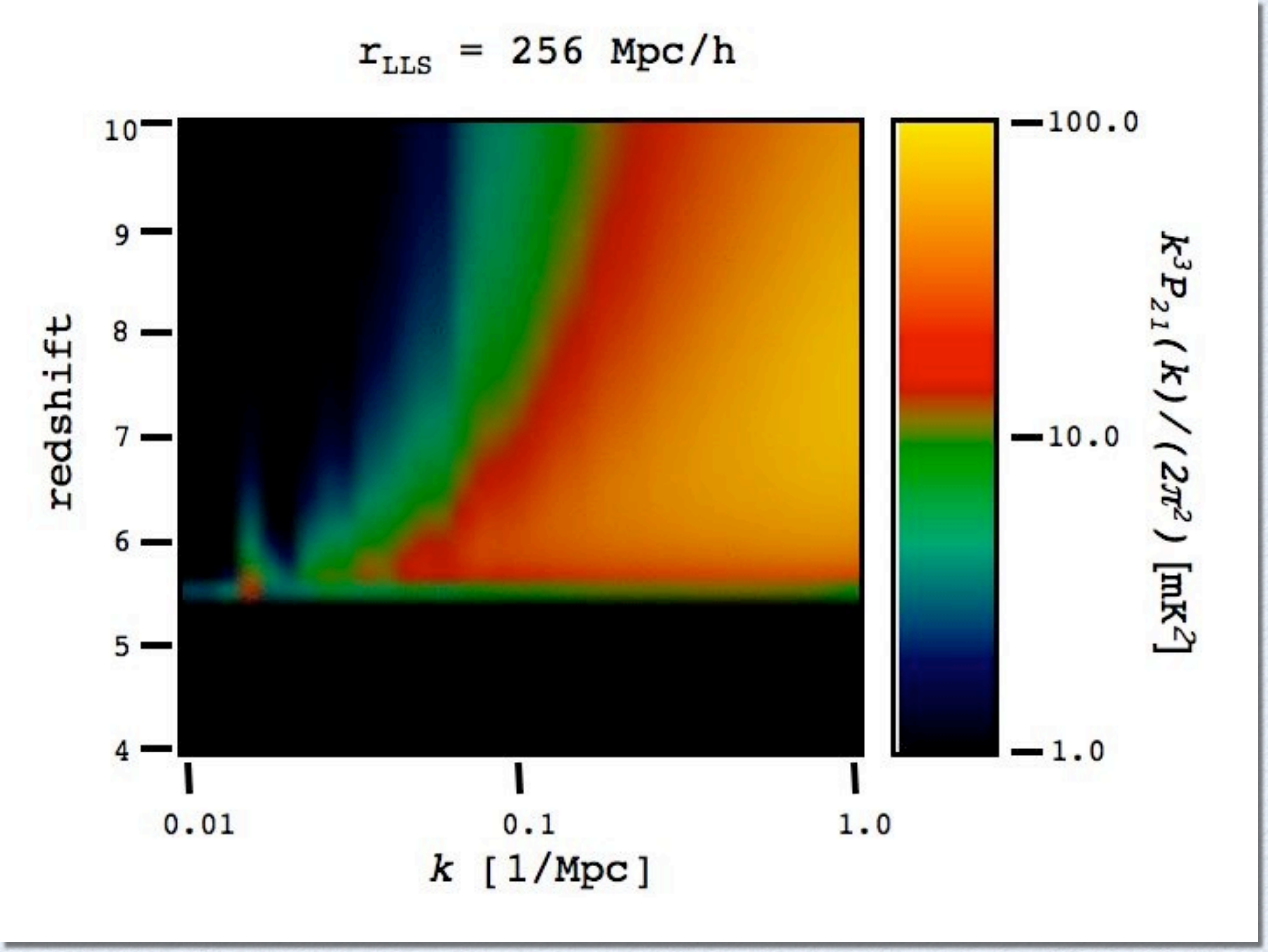


Power spectrum dynamics



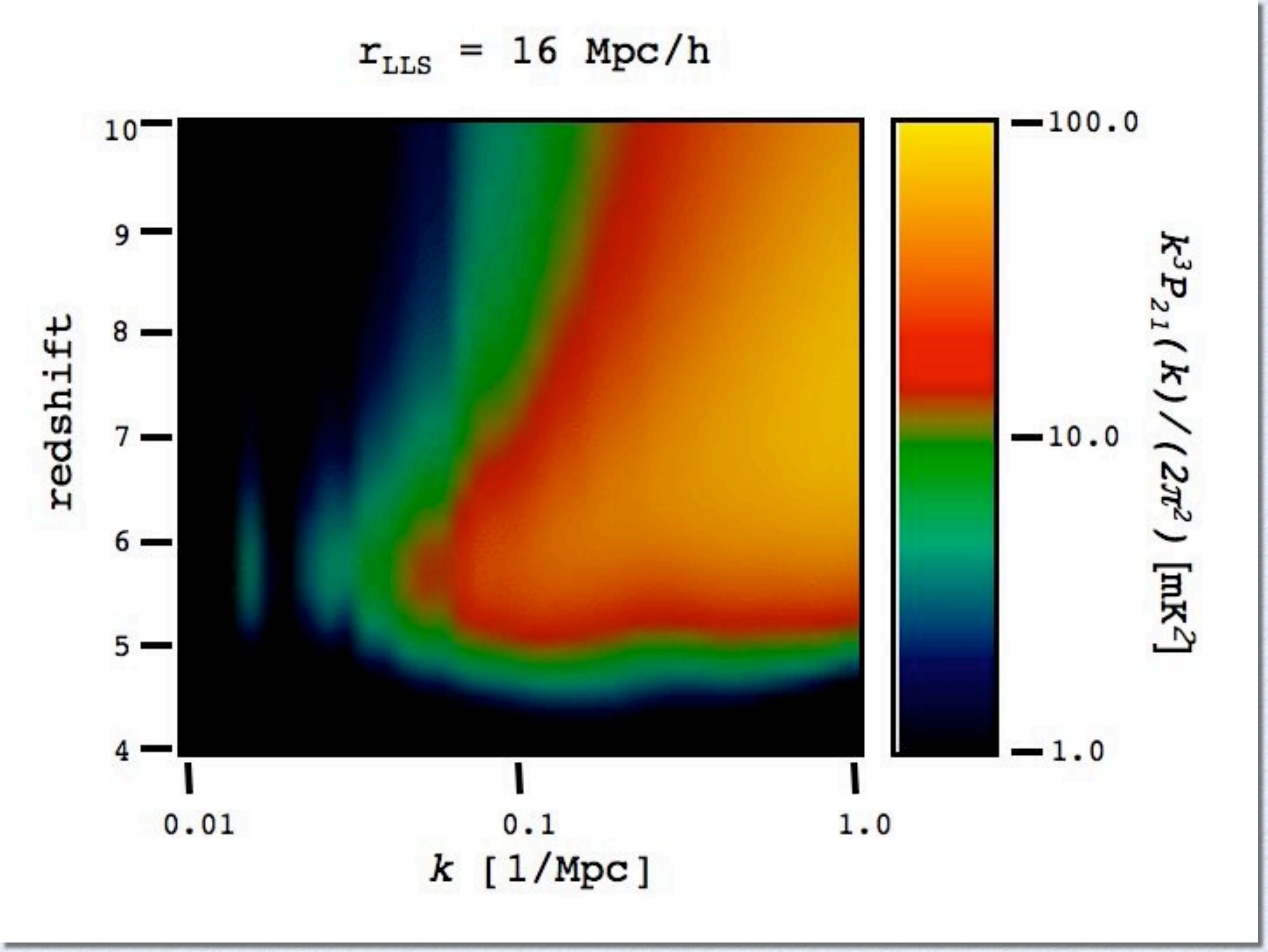
McQuinn

PS dynamics



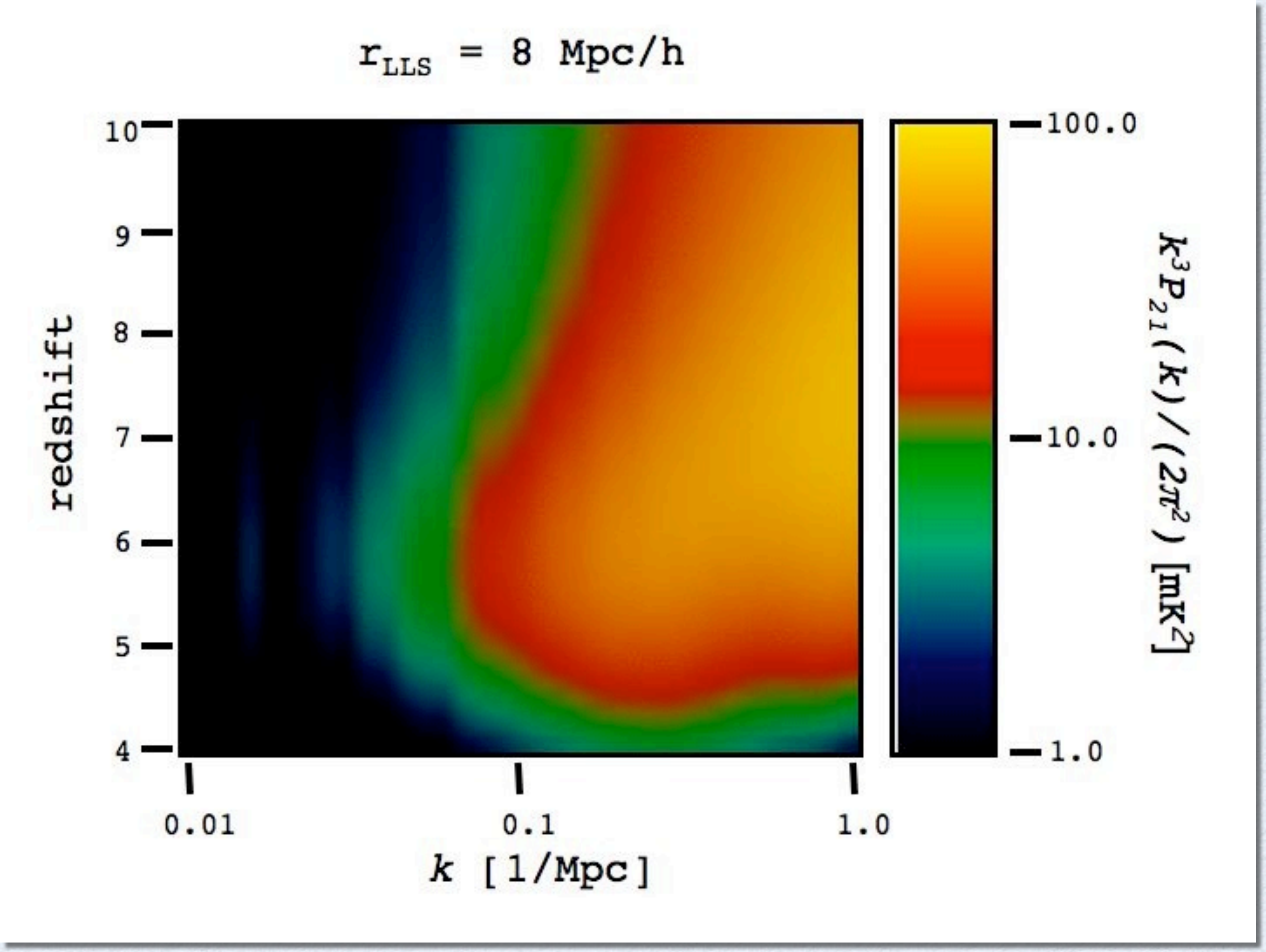
Alvarez

PS dynamics



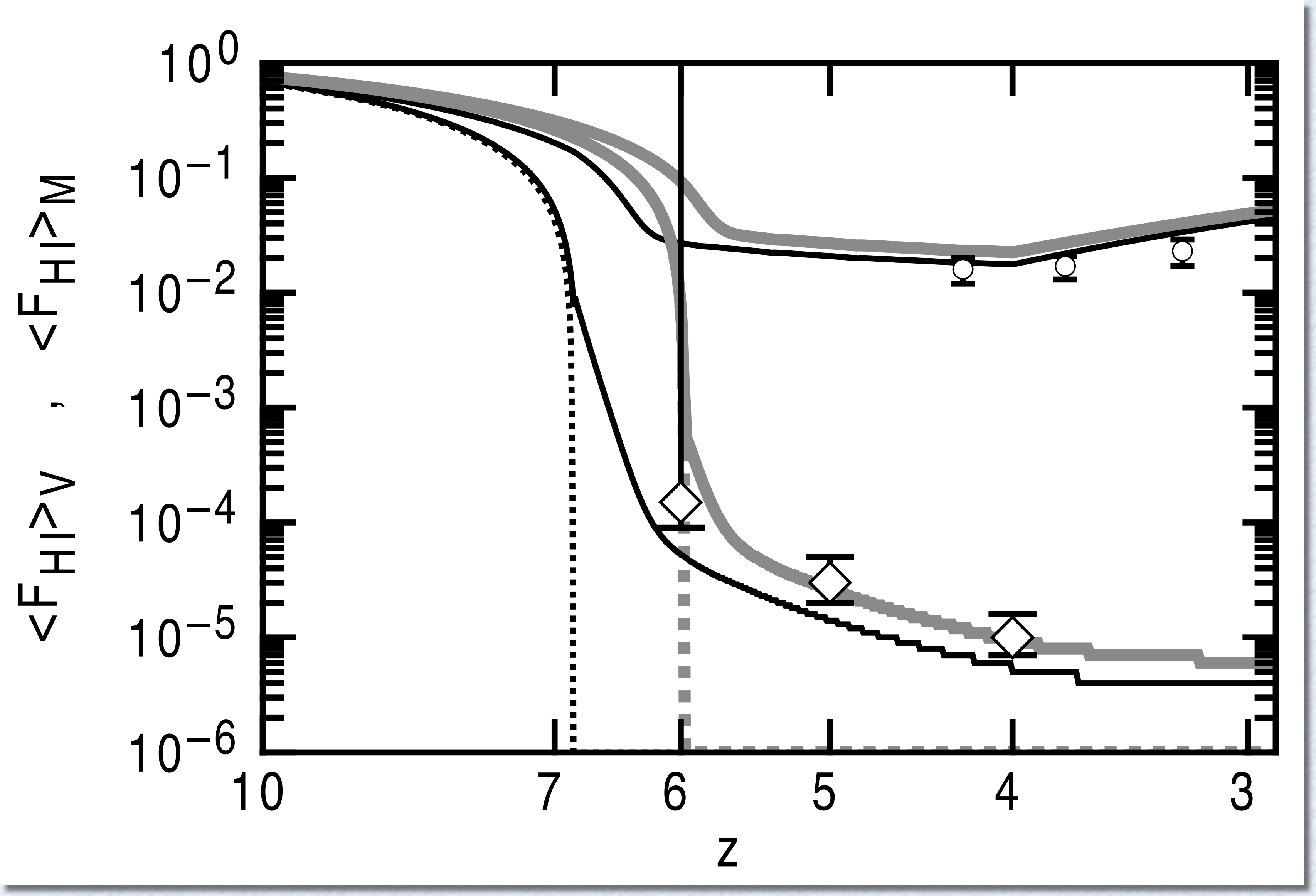
Alvarez

PS dynamics



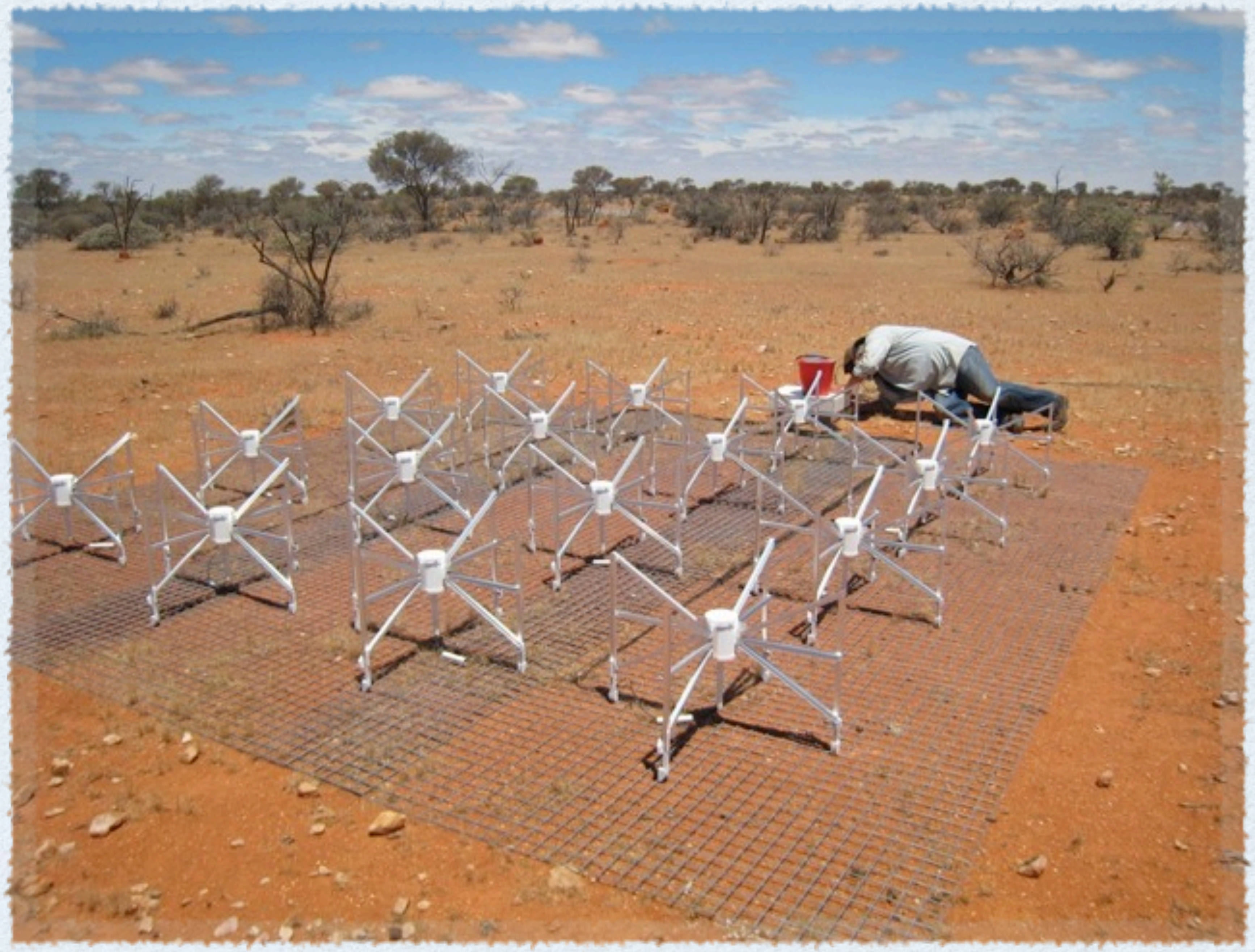
Alvarez

Dark energy with HI



Wyithe & Loeb (2007)

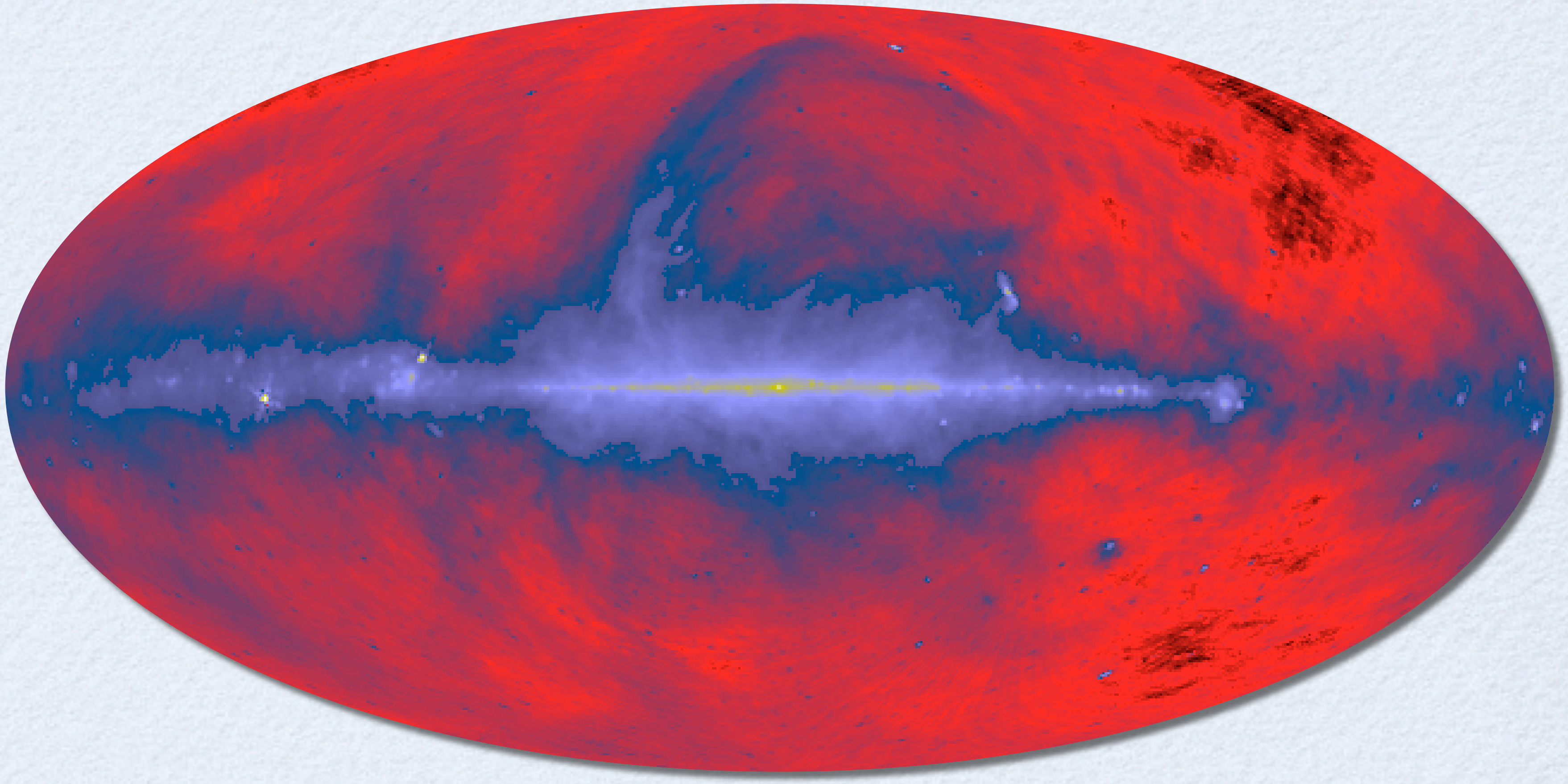
!



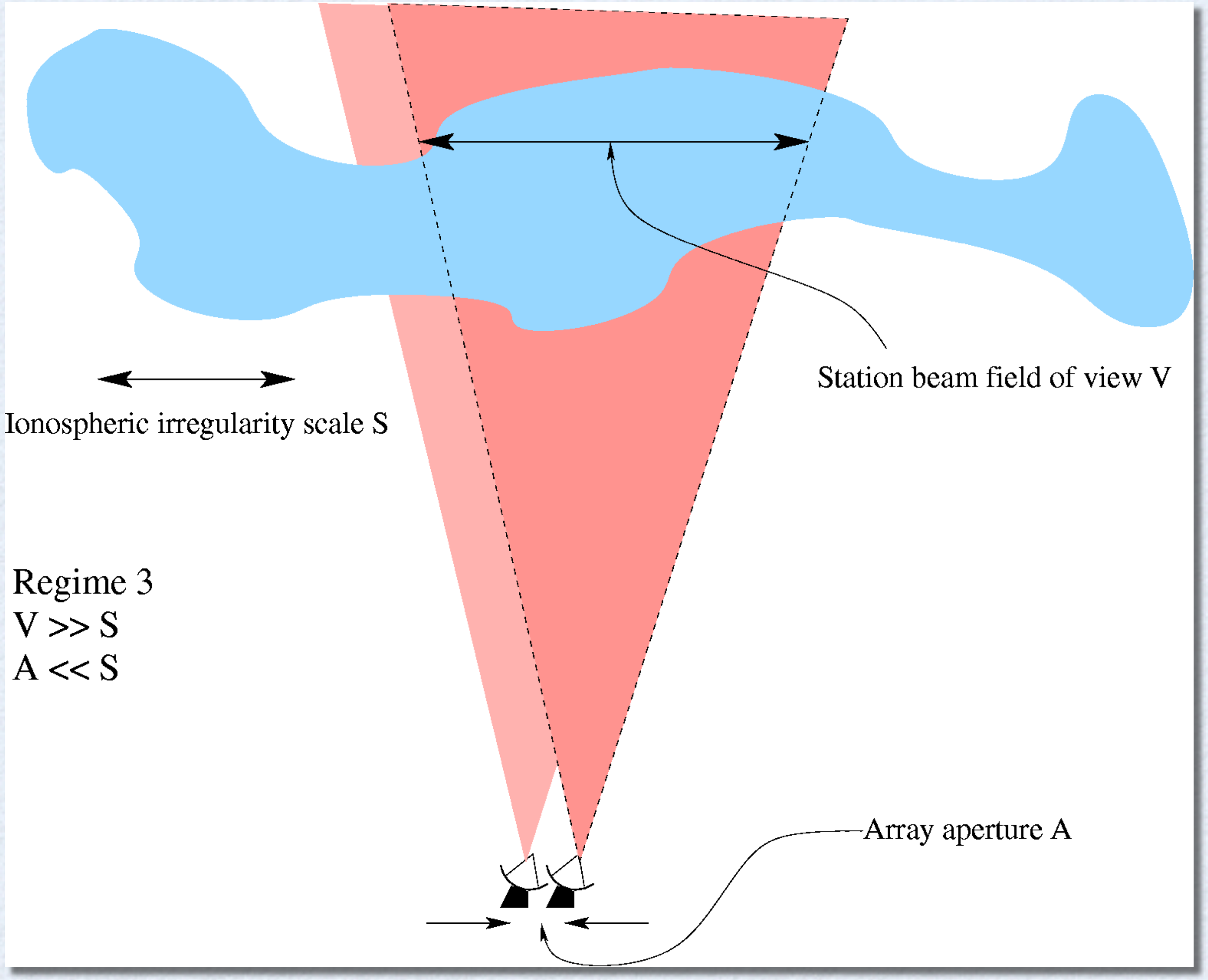
Part 2: making it work

Foregrounds

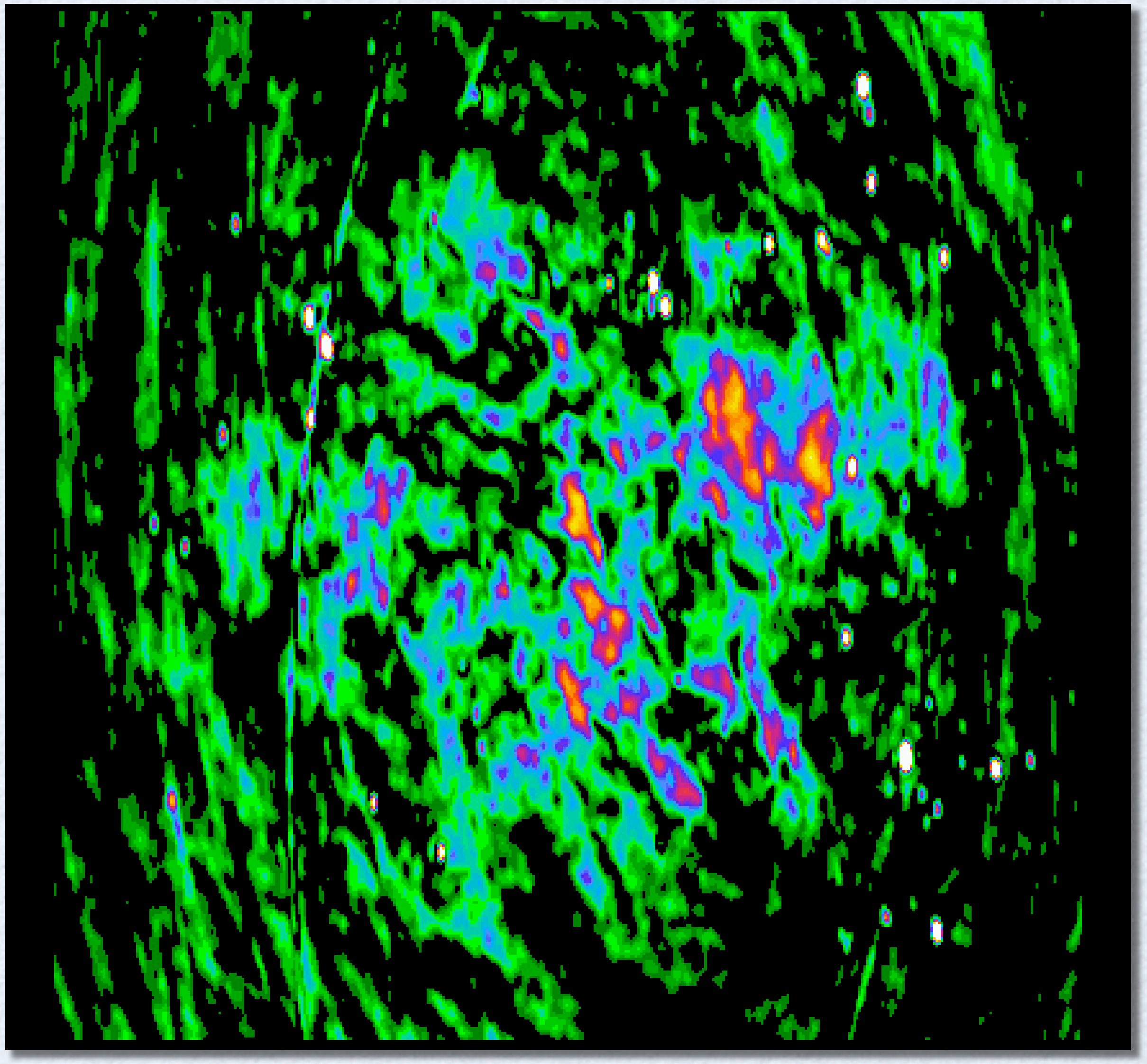
- Faint point sources
- Galactic emission
- Radio recombination lines
- RFI
- Others!



Ionosphere & Polarization

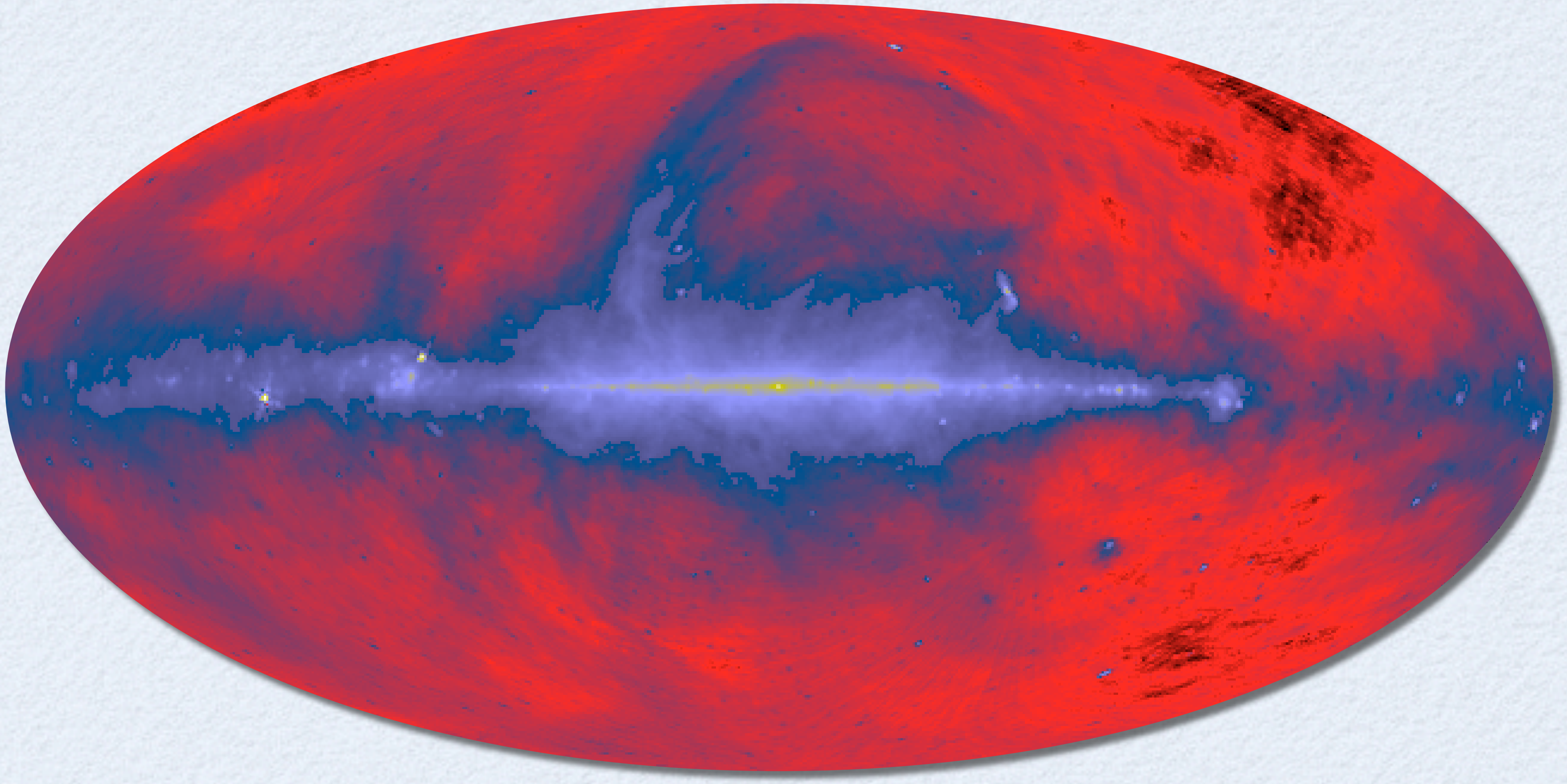


Lonsdale (2004)

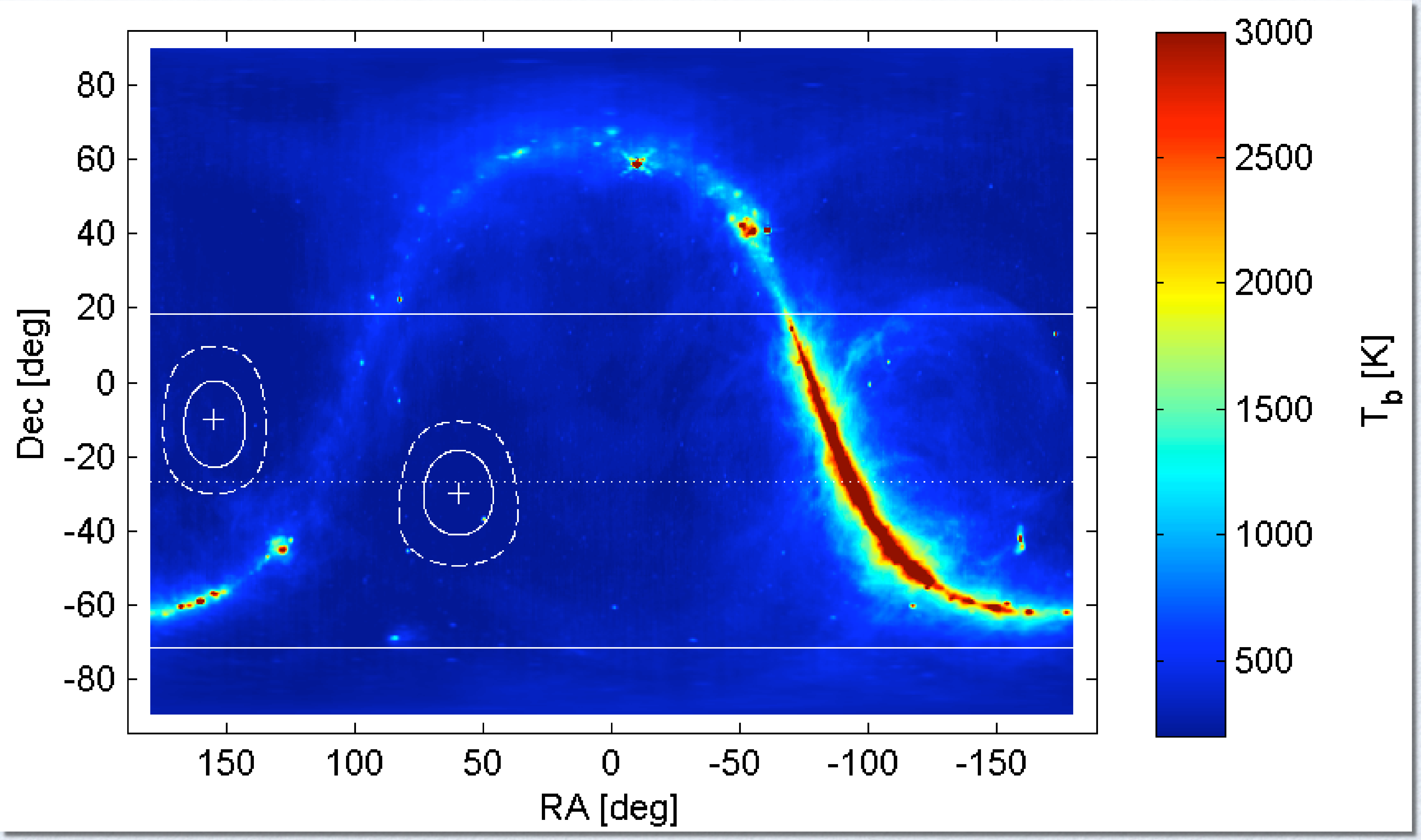


325 MHz polarized flux, 6° x 6°,
4’ beam, 5 K peaks (de Bruyn)

Astrophysical foregrounds

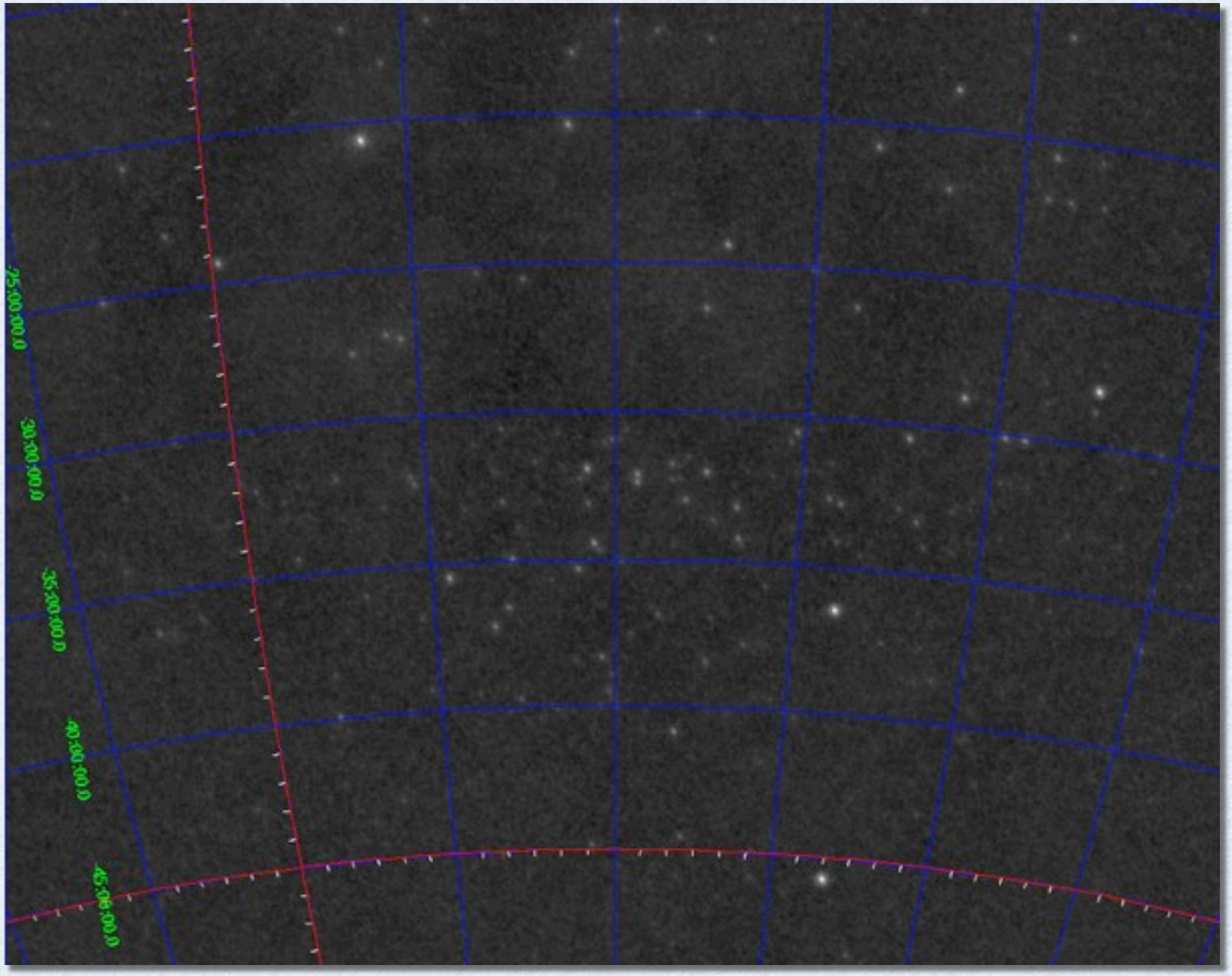


Galactic emission



Bright sources

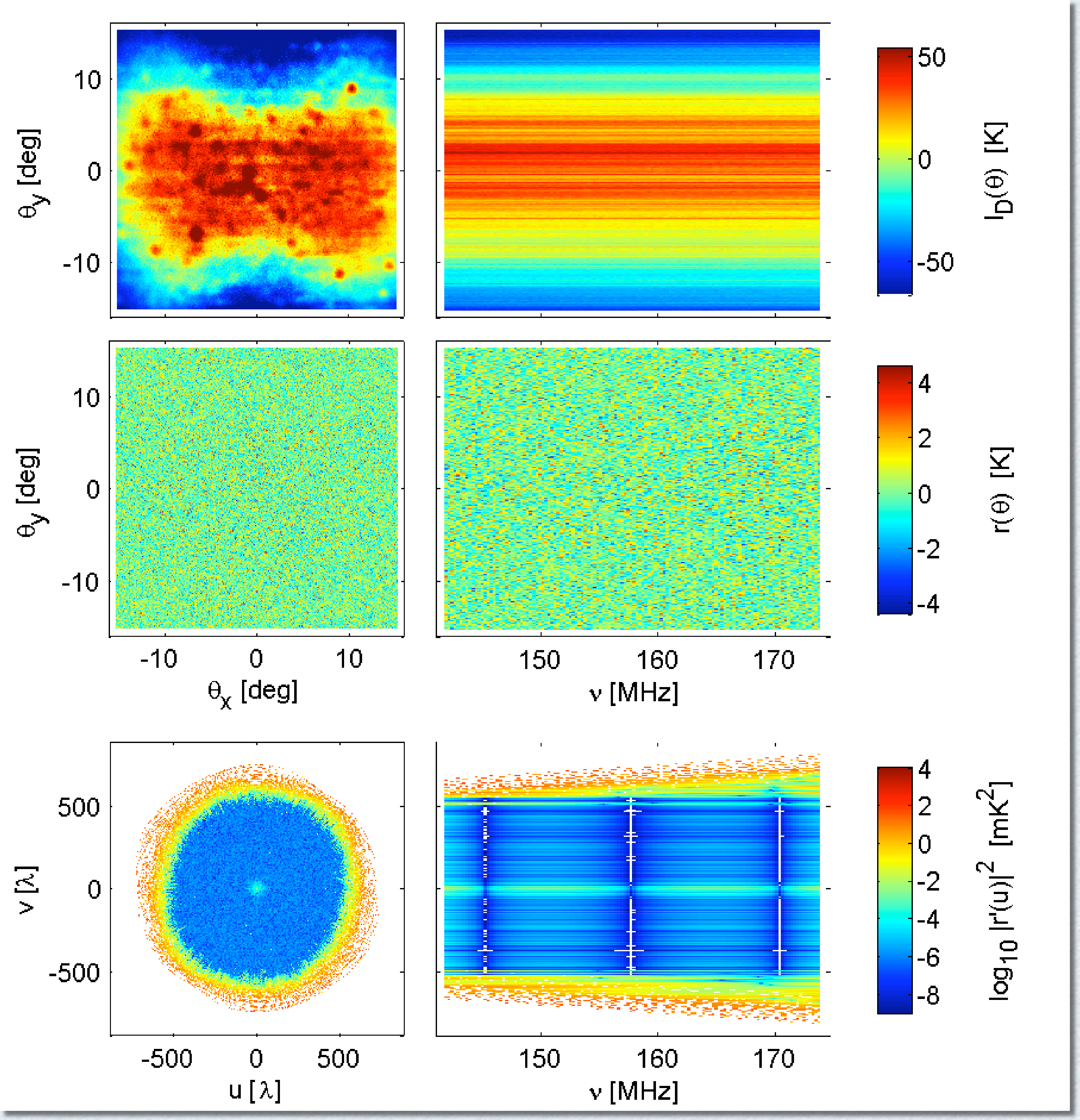
- Subtract bright sources– deconvolution



Confusion level sources

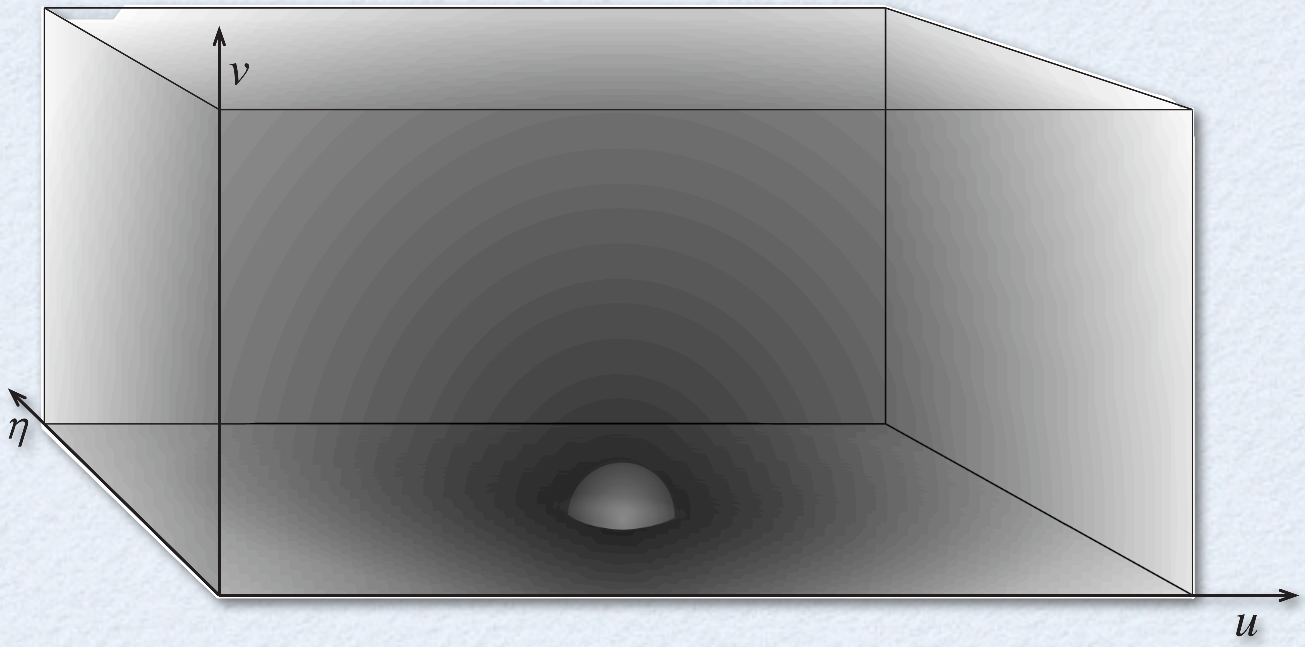
Bowman (2007) &
Bowman et al. (2008)

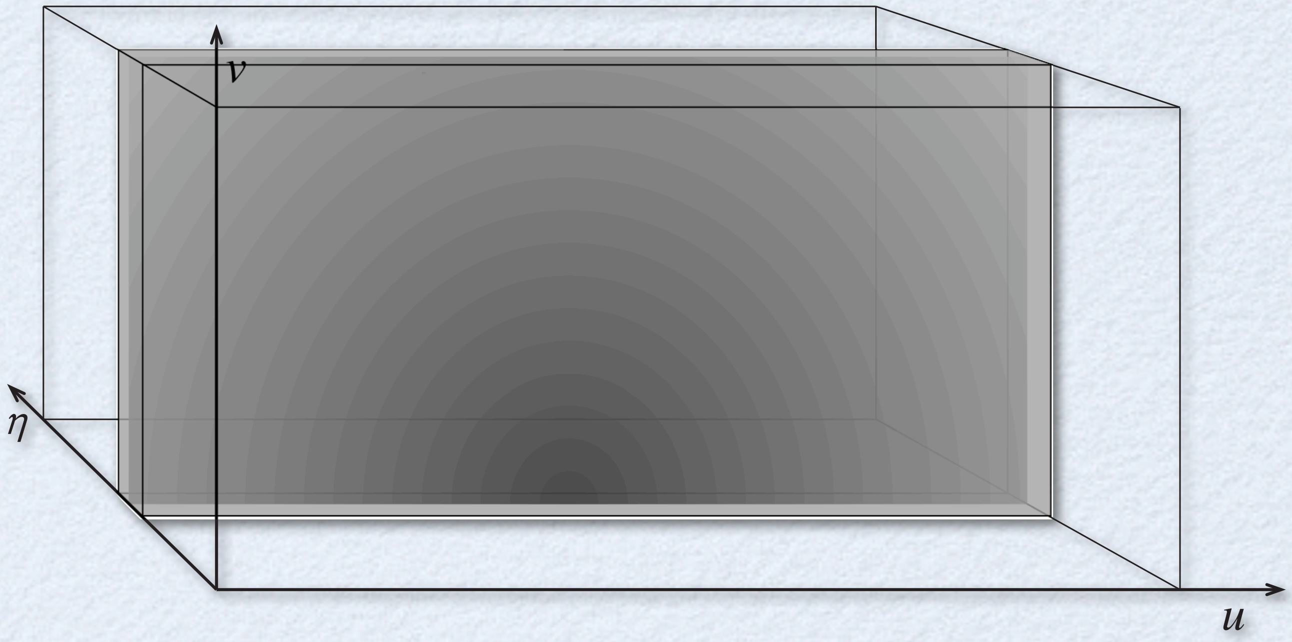
Subtraction of confusion level sources with freq. dependent effects for MWA.



Bowman et al. (2008)

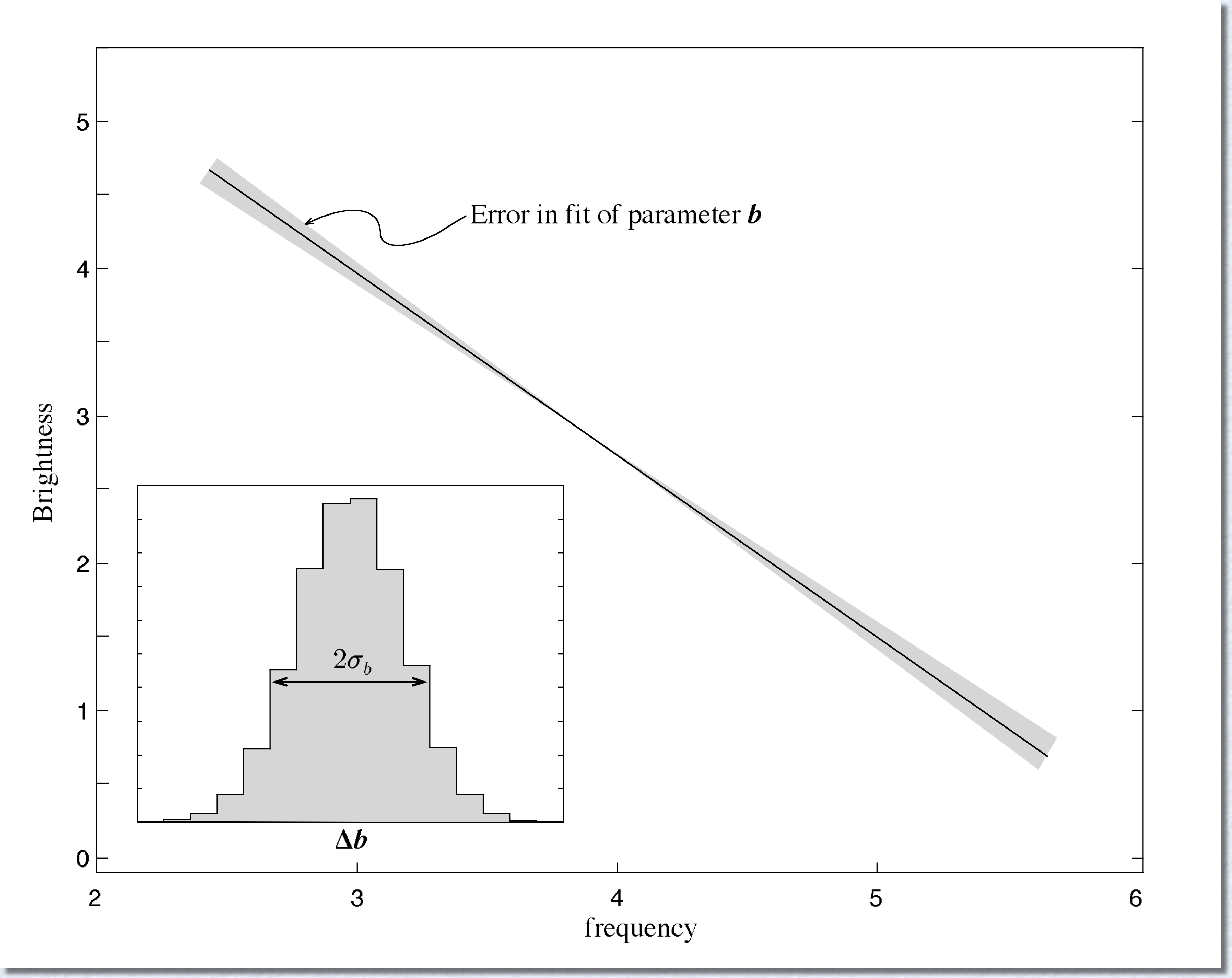
Symmetry separation





Morales, Bowman & Hewitt (2006)

Signal extraction



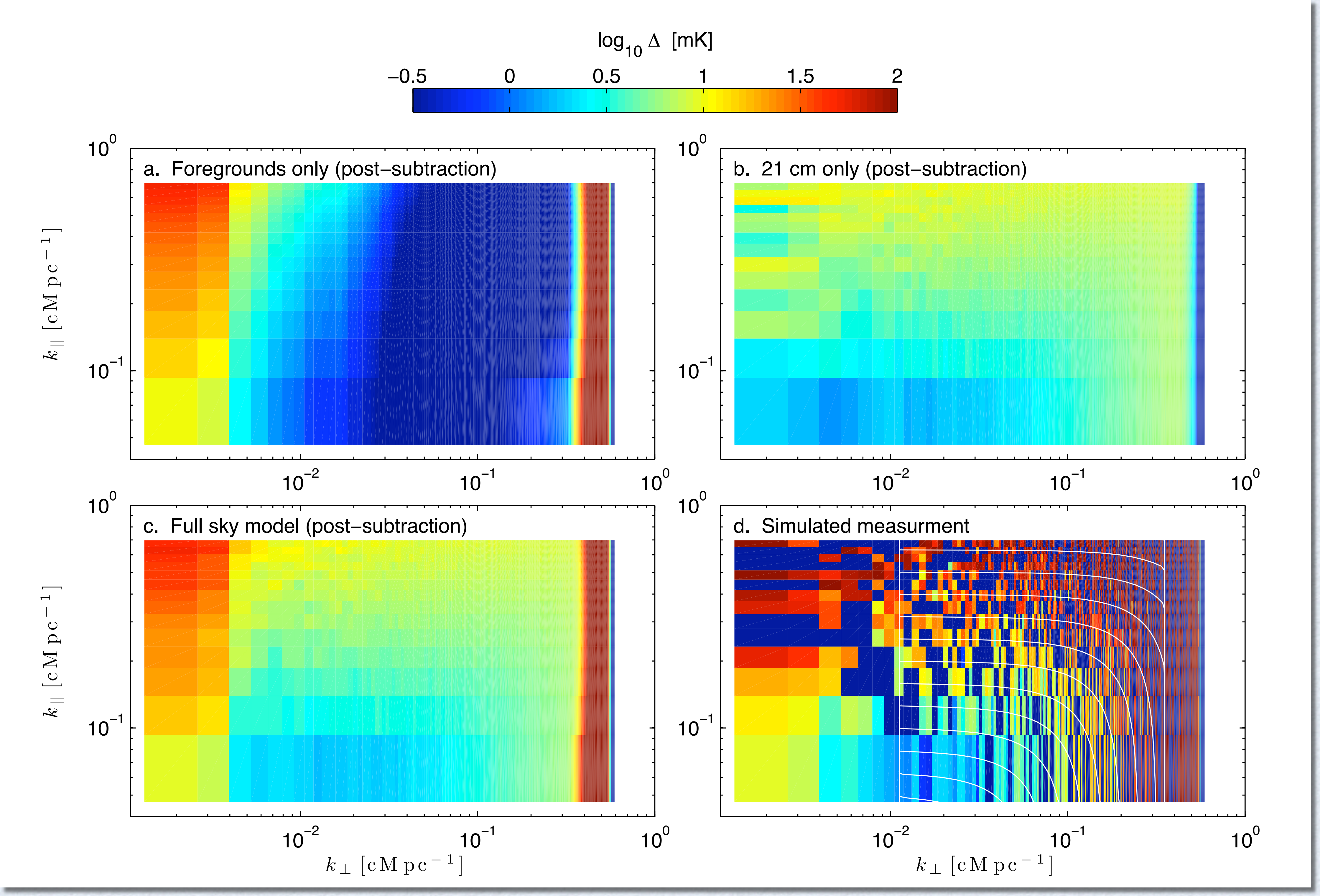
Morales, Bowman & Hewitt (2006)

Signal extraction

$$\Delta S(f) = \Delta a\, df^2 + \Delta b\, df + \Delta c$$

$$\langle P_s(\eta) \rangle = 2\Theta d\Omega B^2 \left[\frac{\sigma_a^2}{\pi^2 \eta^4} + \frac{\sigma_b^2}{\pi^2 \eta^2} + \sigma_{c'}^2 \delta^k(\eta) \right]$$

Signal extraction



Bowman et al. (2008)

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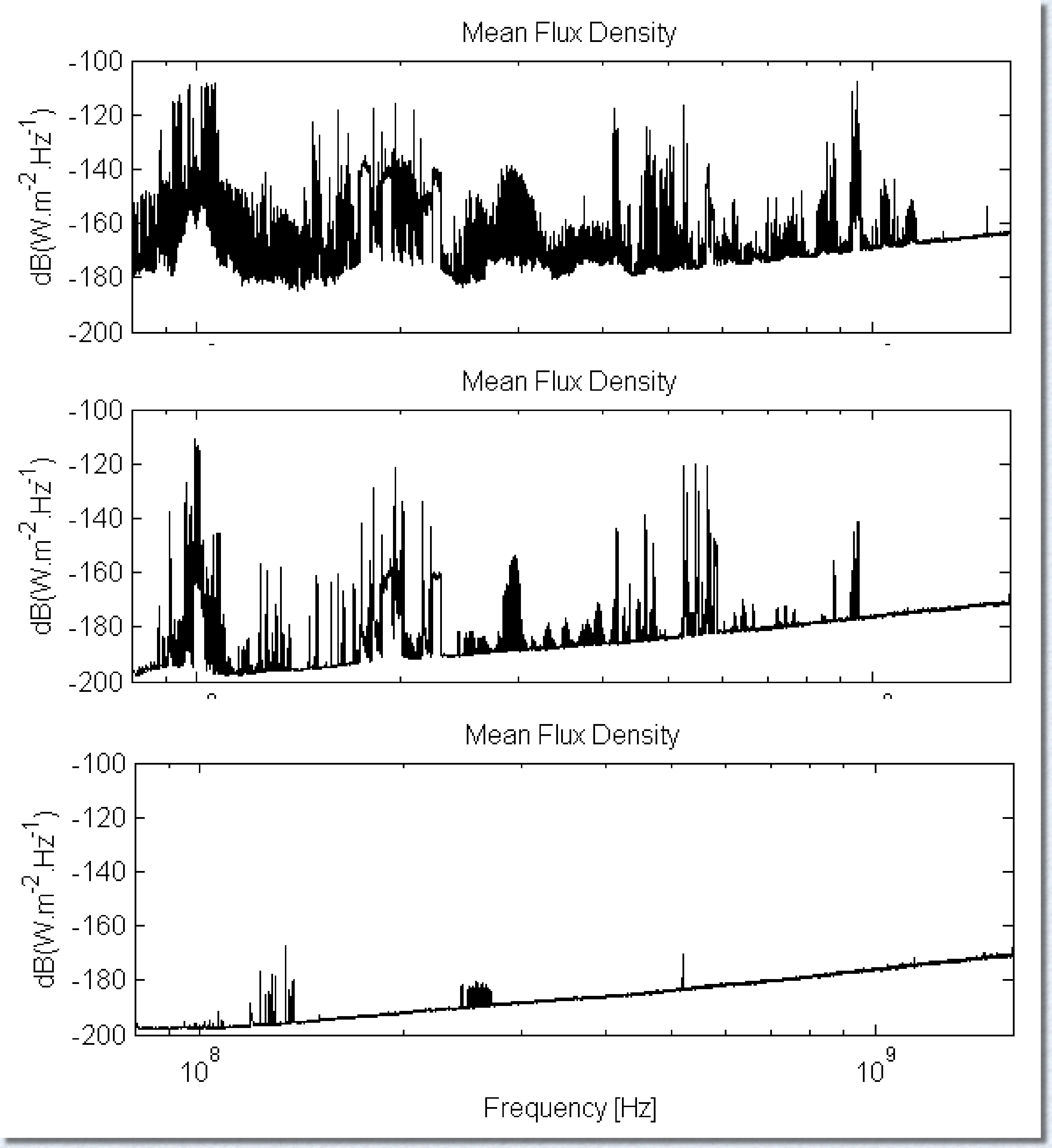
Observational foregrounds



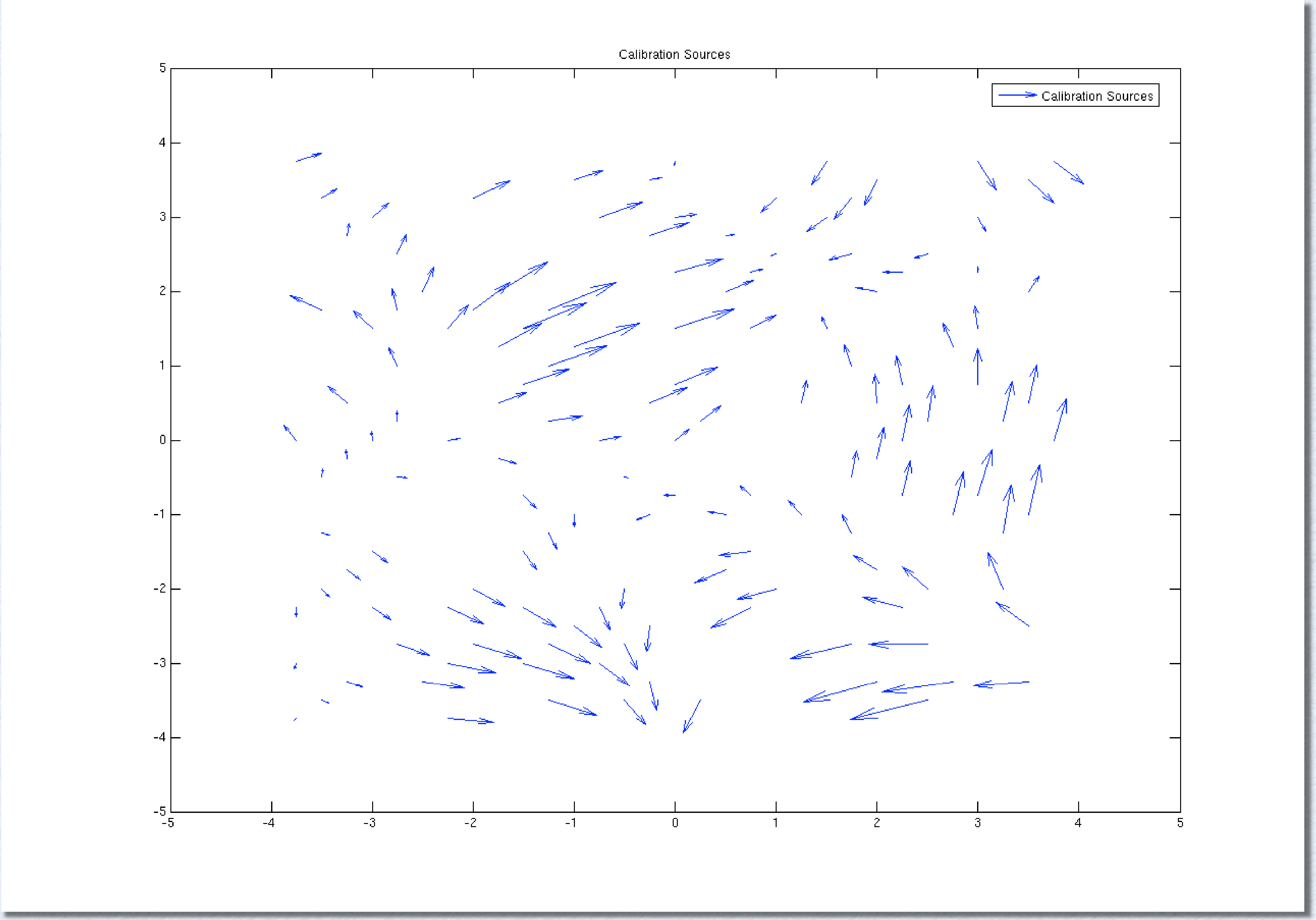
Western Australia

Very radio quiet

Western Australia

Very radio quiet

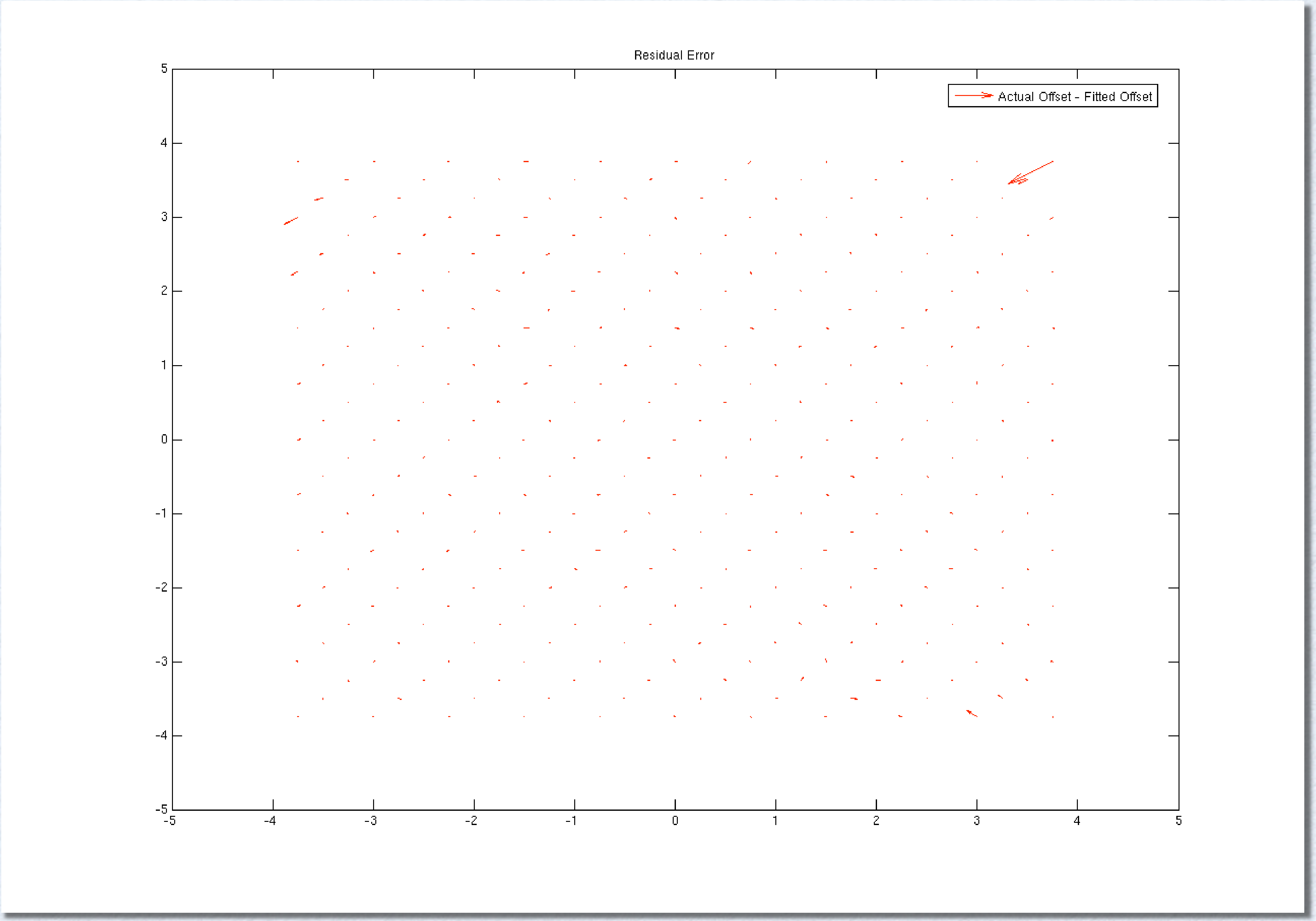
Ionospheric calibration



(Doeleman, Ting)

Up to 1500 sources with known location, fit every 8 seconds → rubber sheet

Ionospheric calibration

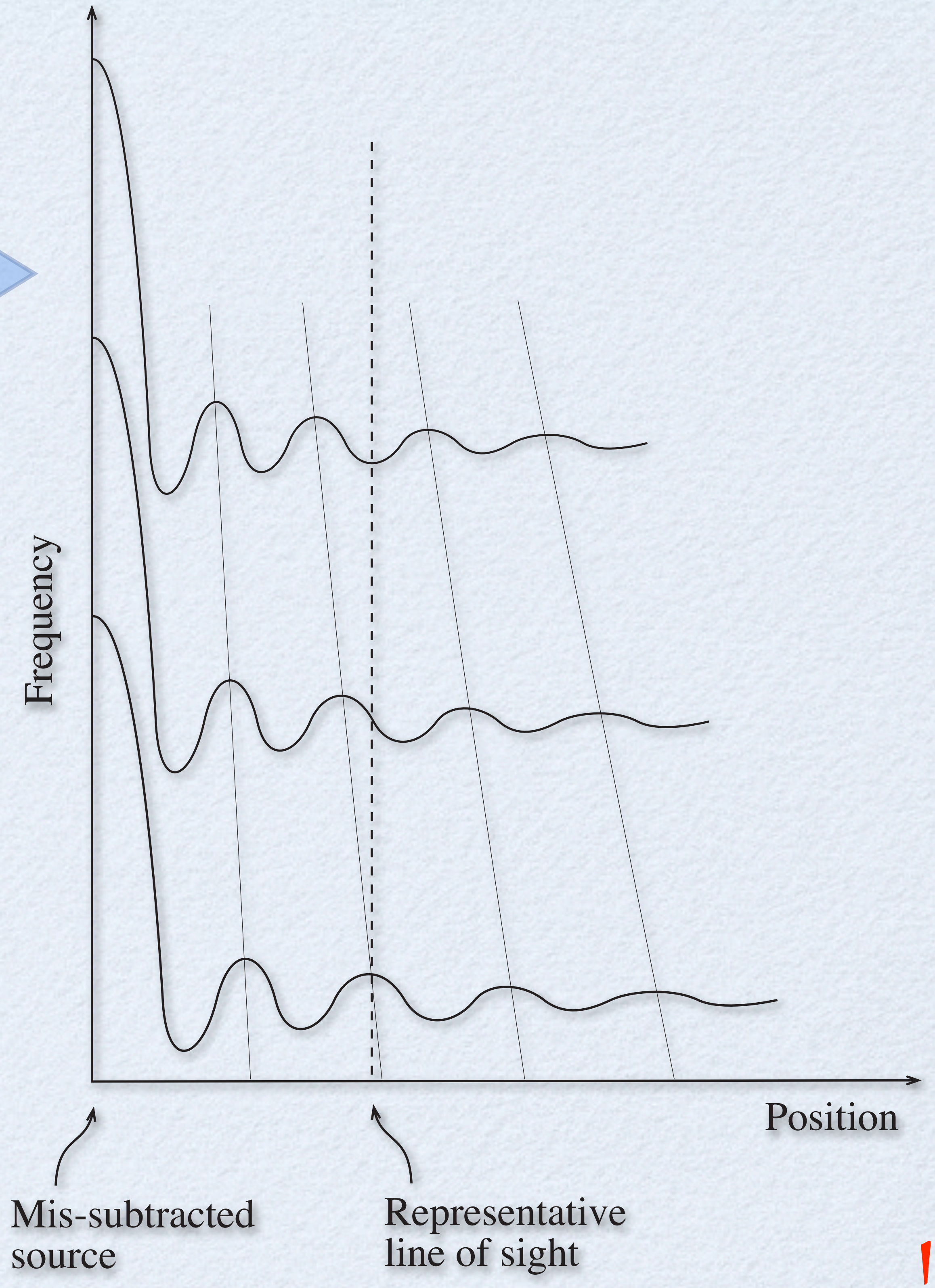


(Doeleman, Ting)

Up to 1500 sources with known location, fit every 8 seconds → rubber sheet

Mode mixing

- 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

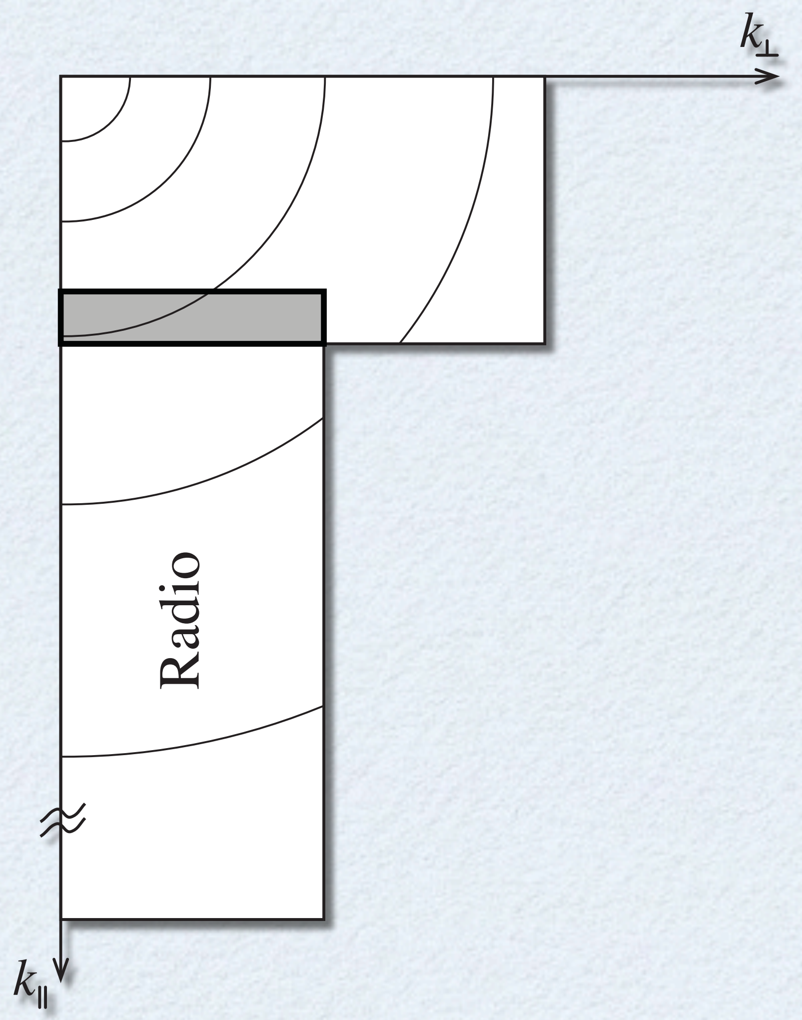


!

Mode mixing

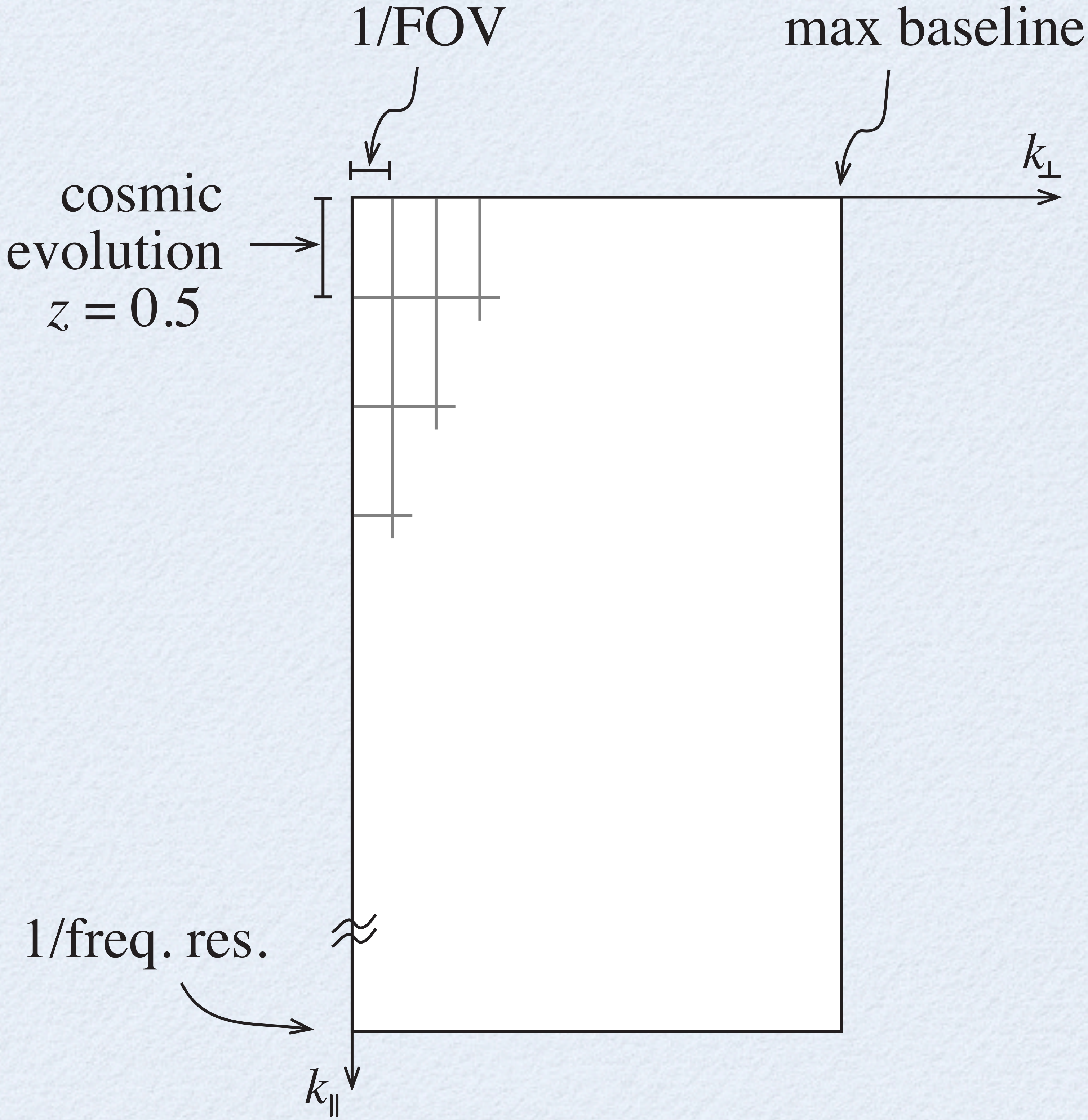
- If both instrumental response and foregrounds were spectrally smooth, subtraction would be straight-forward
- Frequency dependent instrumental effects mix the position-dependent foreground into a frequency ripple
- Measurement fidelity of $10^{-4} - 10^{-6}$, via combination of:
  - Calibration
  - Determination of foreground

Can be either calibration and/or measurement of foreground, it is the product that is important



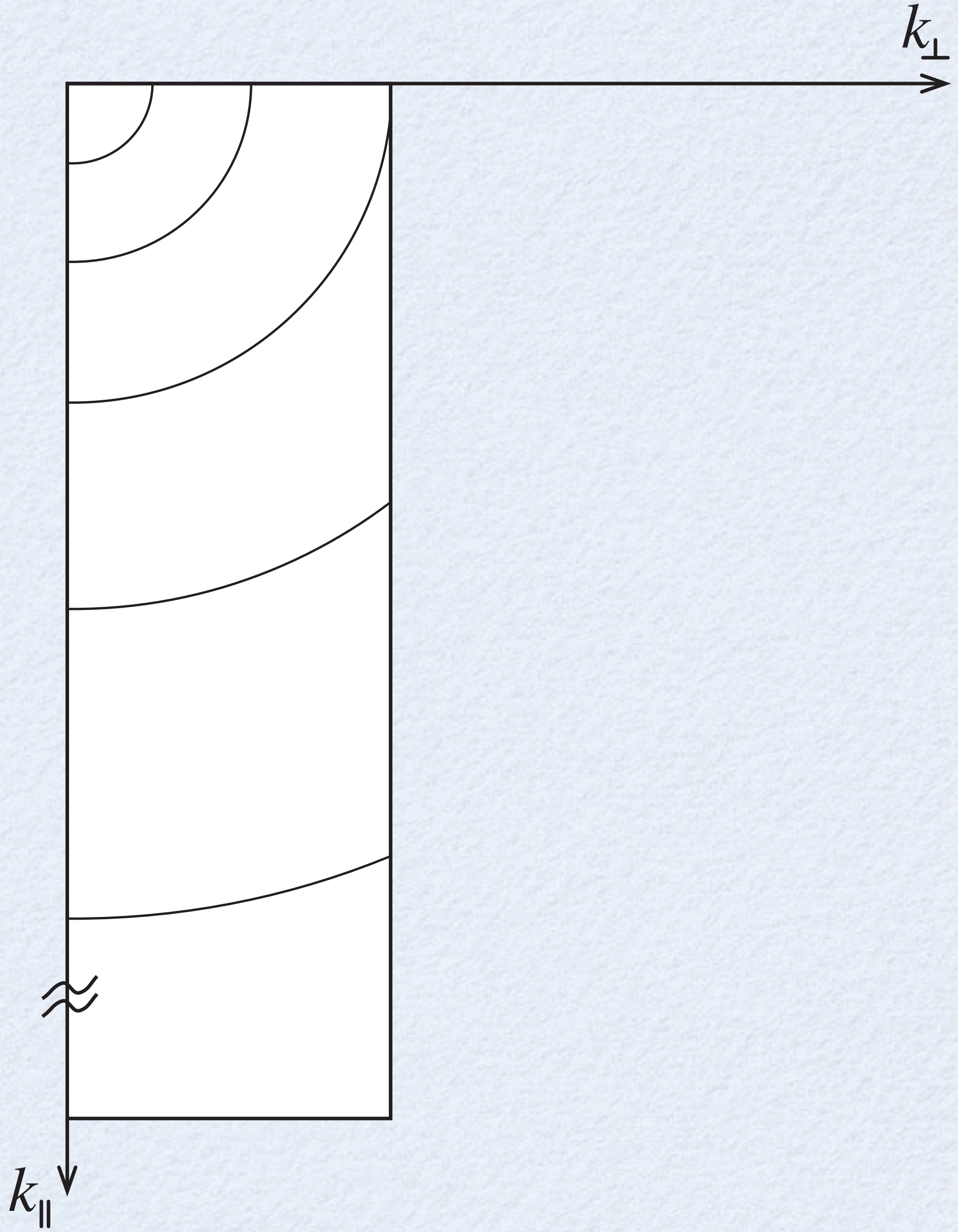
Cross-correlations & *k*-space overlap

Radio *k*-space sensitivity



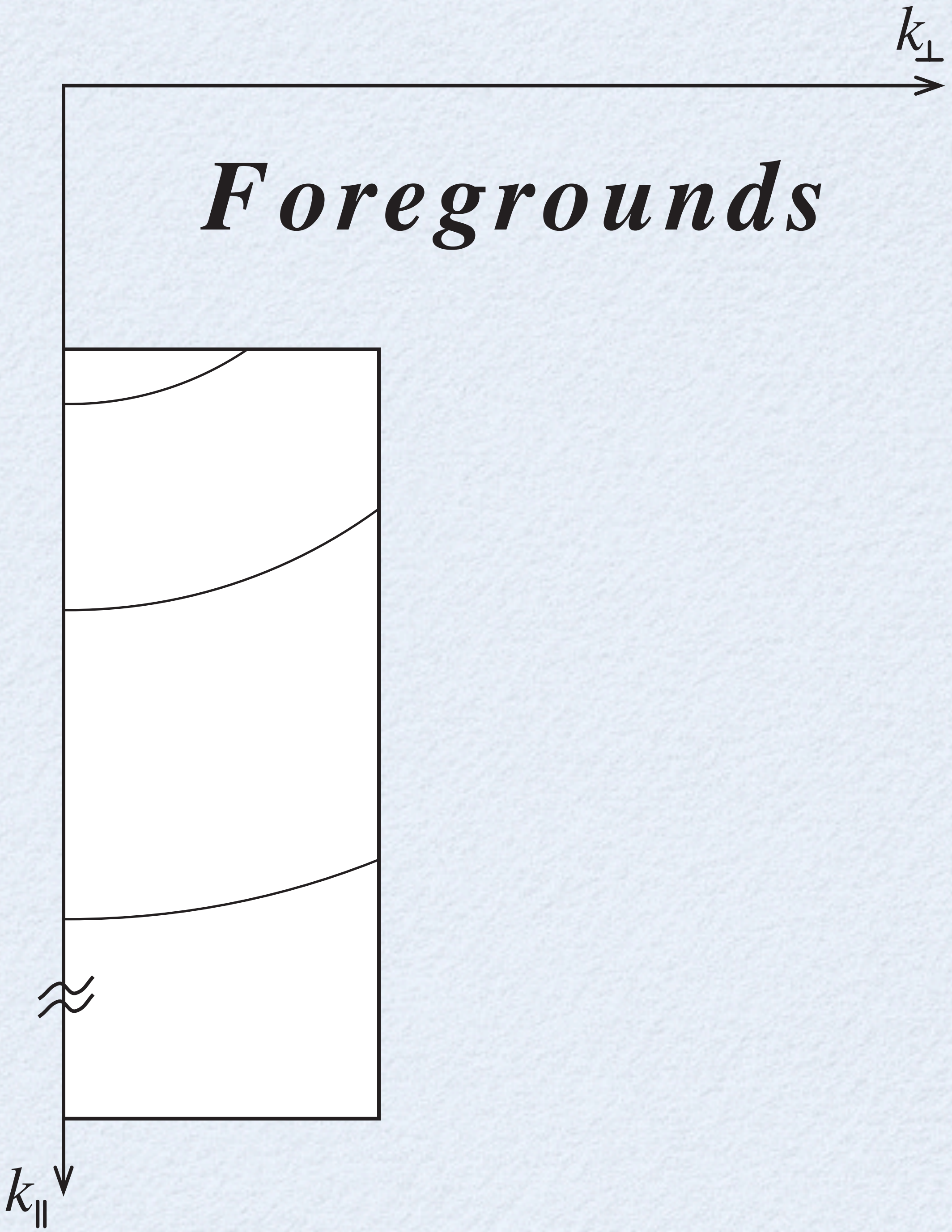
1^{st} gen. radio noise sensitivity

Short baselines

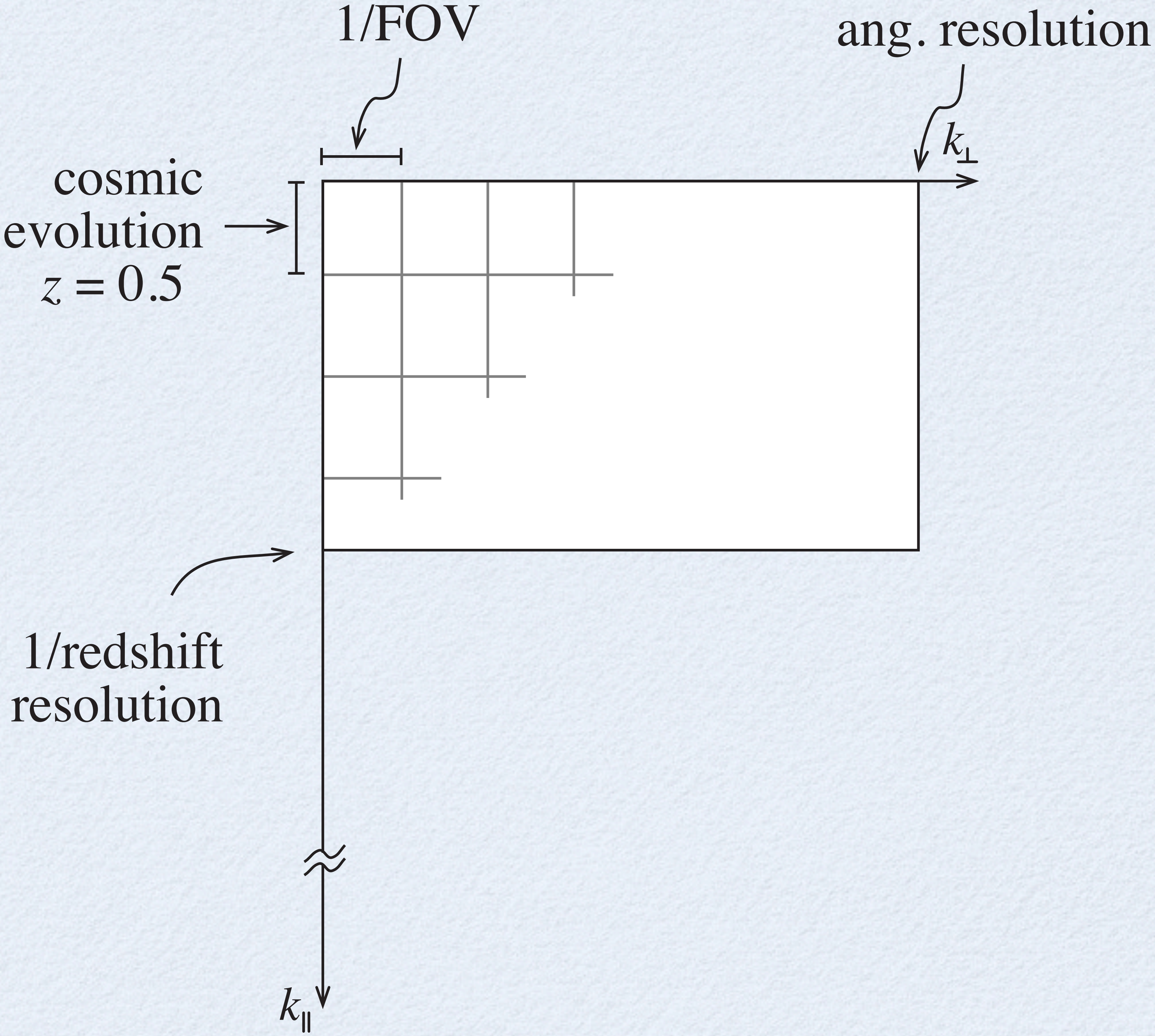


Radio foreground limitations

Foregrounds at low *k* parallel

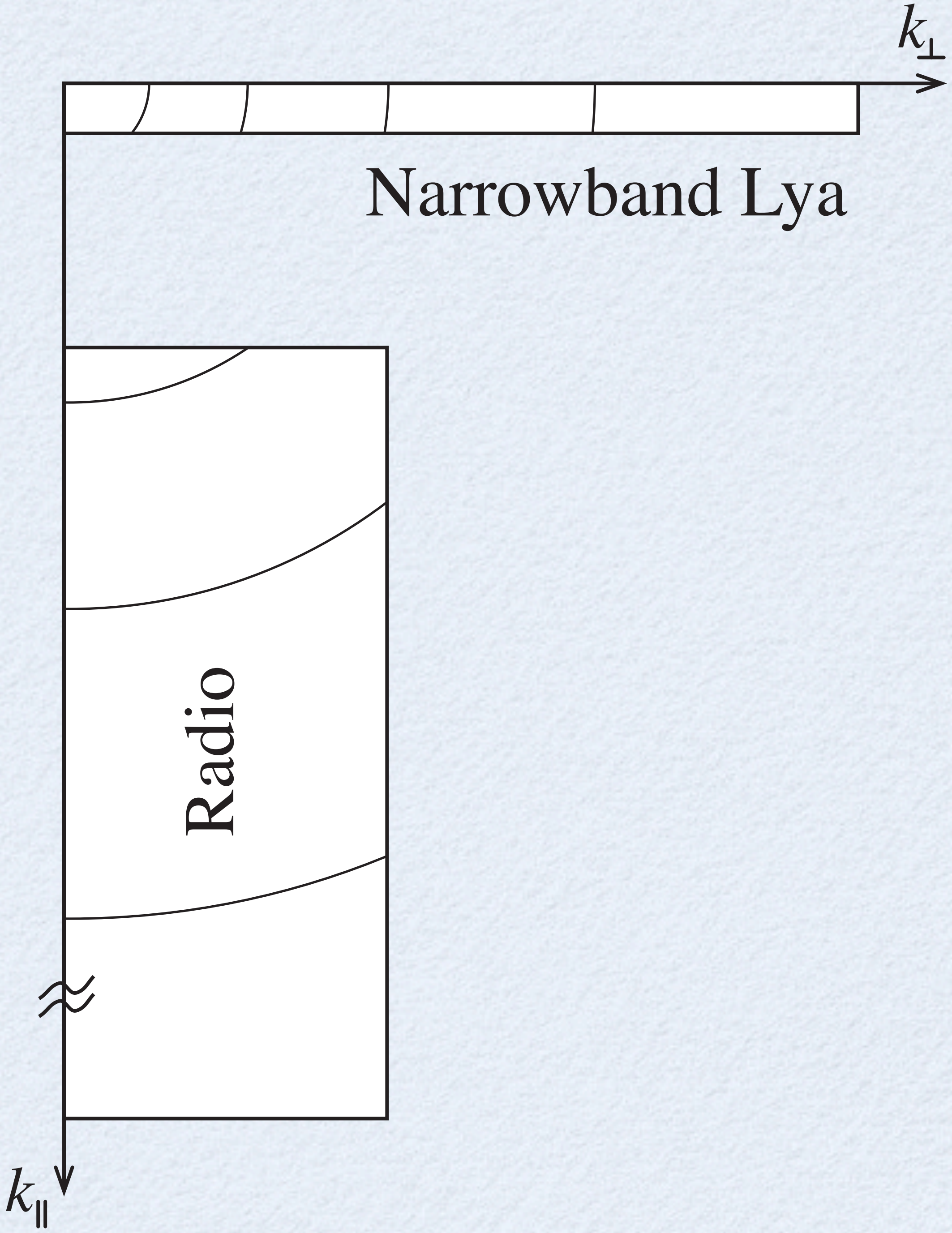


OIR *k*-space sensitivity



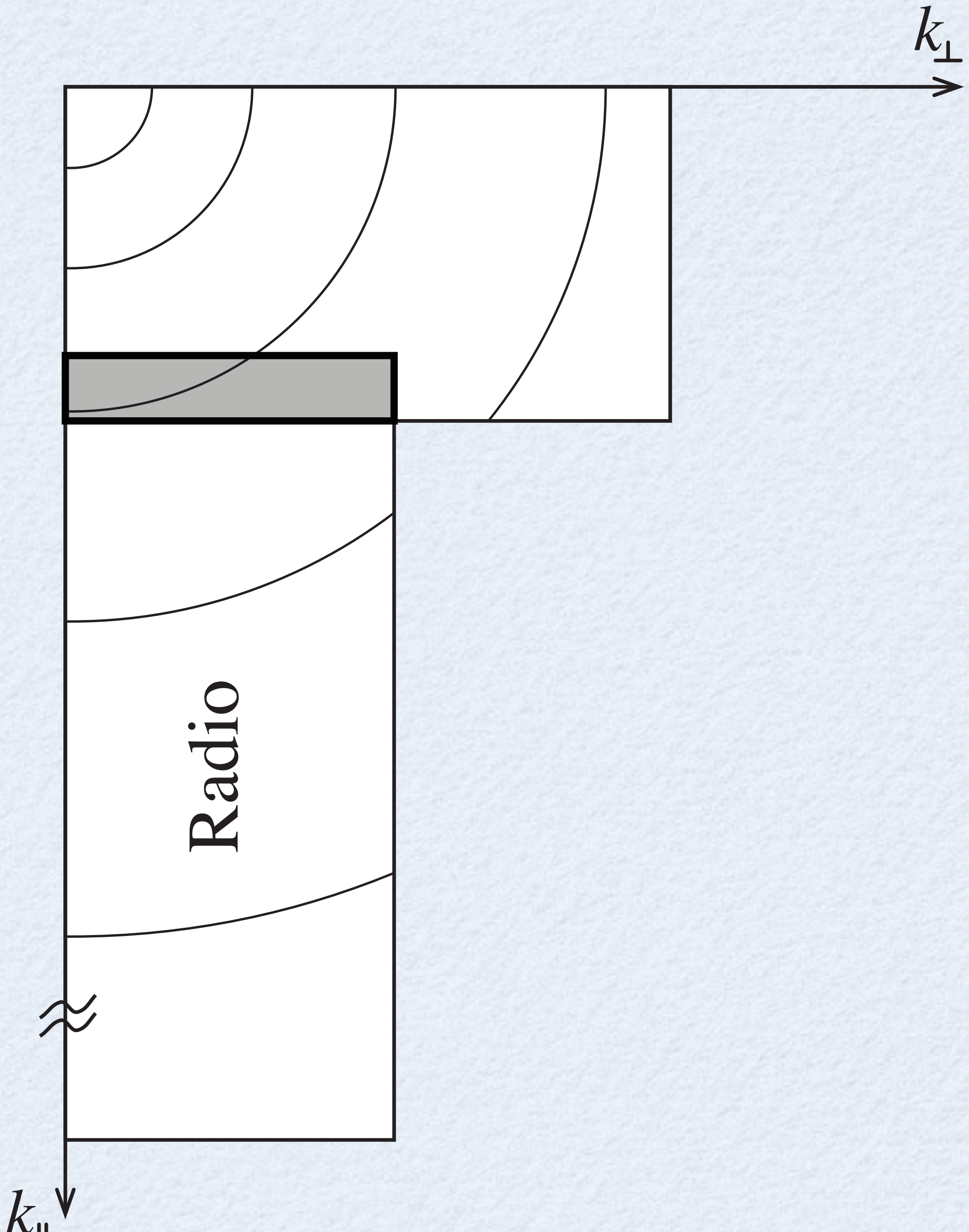
Narrowband Lyα

No overlap!

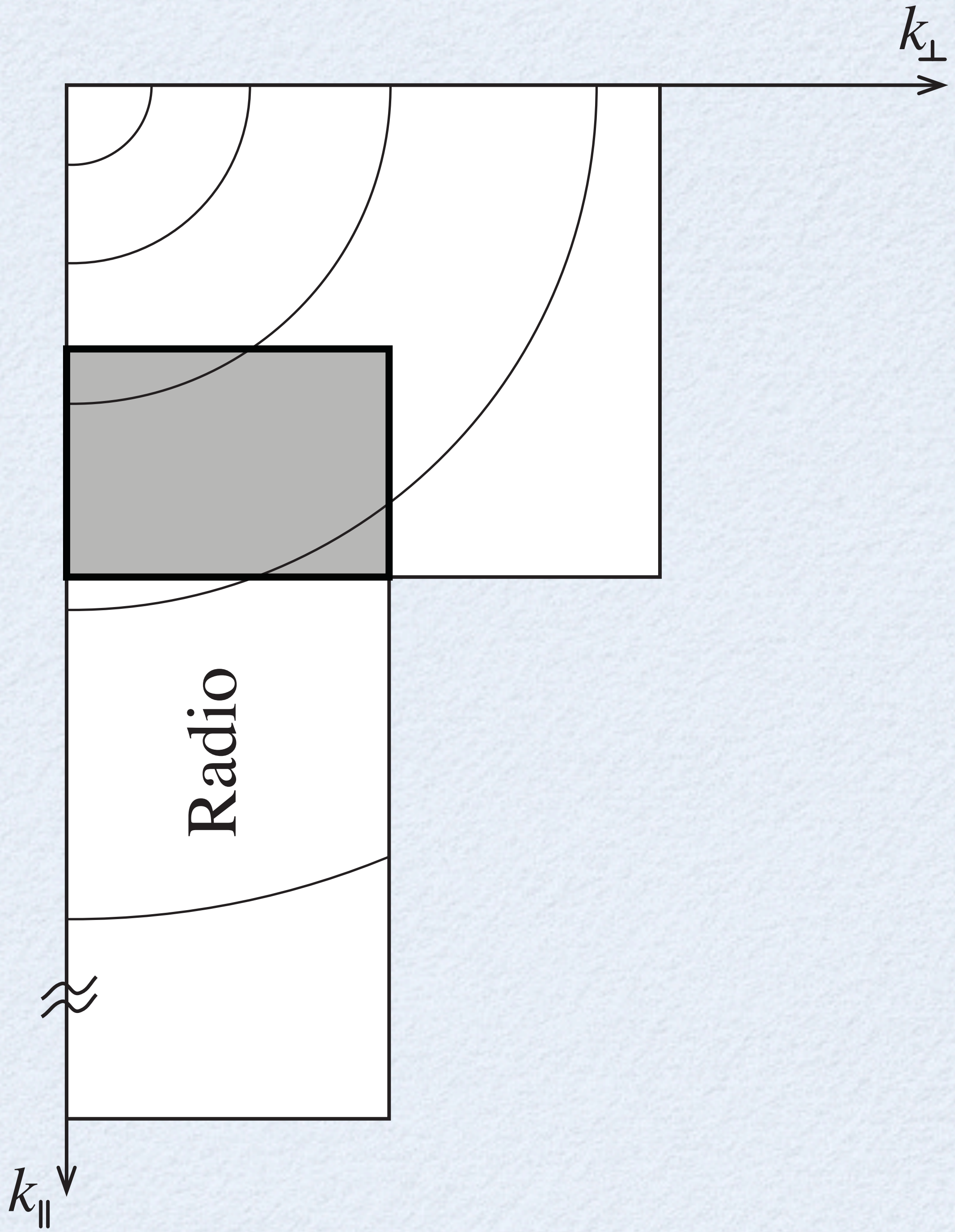


‘Photo-z’ OIR

$\Delta z \approx 0.1$ gives only 2 modes overlap in k parallel



‘Spectroscopic’ OIR



Lessons

- Similar length scales is not sufficient, need *k*-space overlap for cross-correlations
- Requires good OIR spectral resolution
- Need good survey volume overlap (advantage LOFAR)

Murchison Widefield Array

MWA Collaboration

MIT Haystack Observatory

MIT Kavli Institute

Harvard CfA

University of Washington

U. Melbourne

ANU/Stromlo

Curtin U.

Sydney U.

U. of Western Australia

CSIRO

Raman Research Institute

MWA Collaboration

Murchison Widefield Array

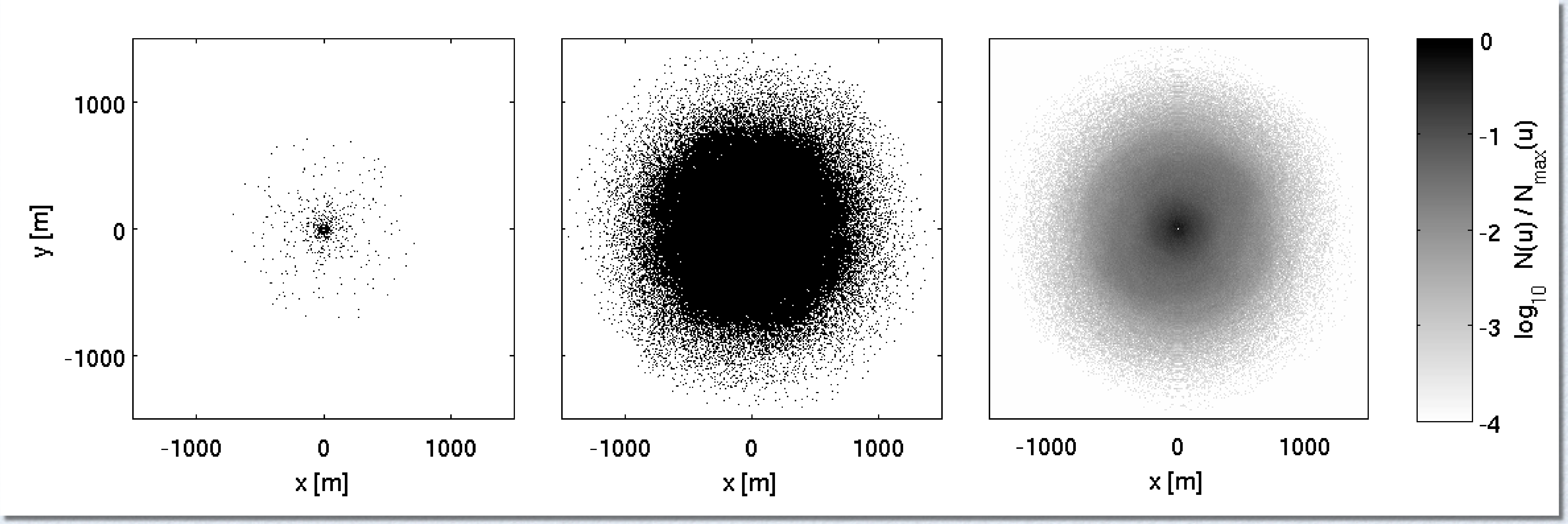
- 512 16 dipole antennas
- 80–300 MHz
- Radio quiet Murchison site
- Very wide 20°– 40° field of view
- Full cross-correlation of all 512 antennas
- Strict attention to systematics

Goals of MWA

- Key science drivers:
    - Epoch of Reionization
    - Heliospheric science — FR & IPS
    - Radio transients

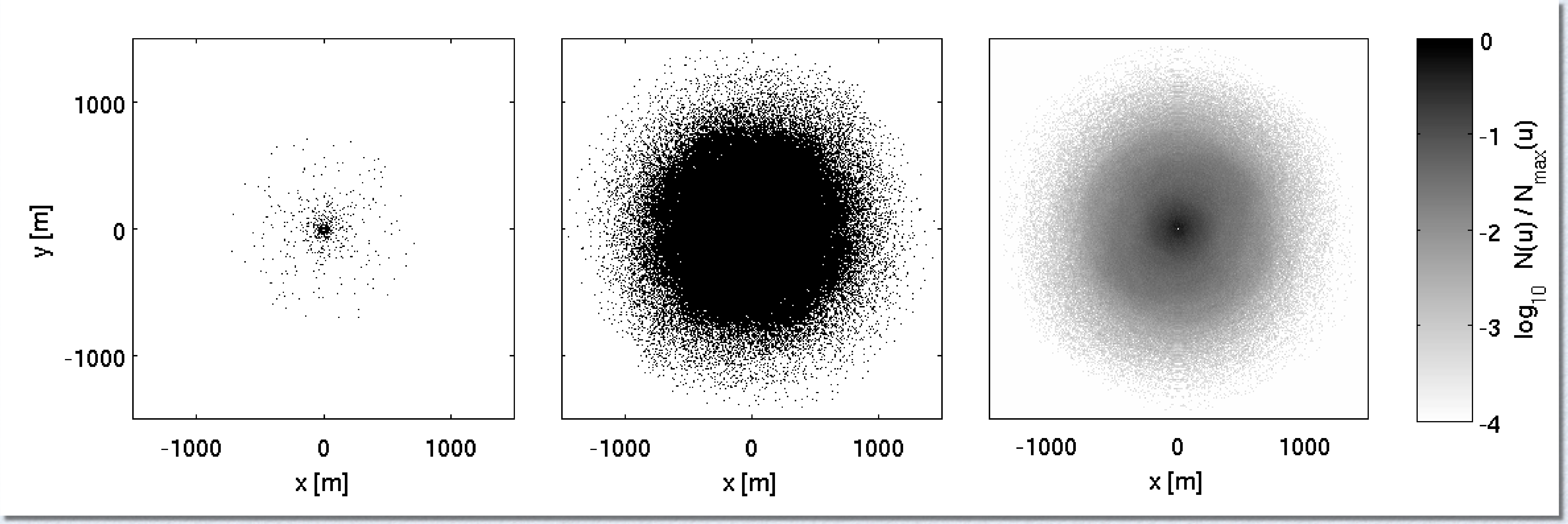
!

MWA antenna distribution



Bowman (2007)

MWA antenna distribution



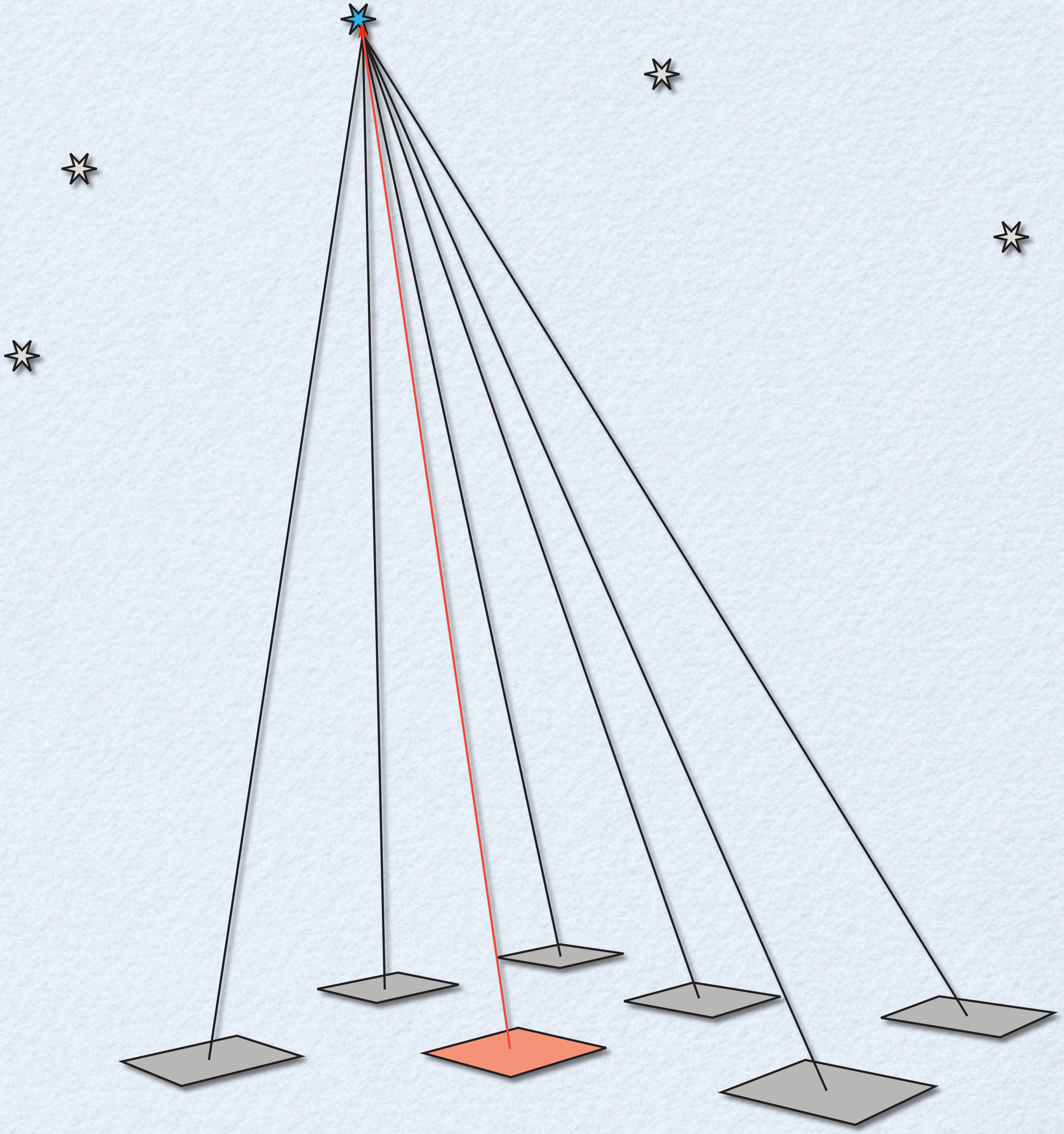
Bowman (2007)

1.5 G visibilities every 1/2 second; 19 GB/s

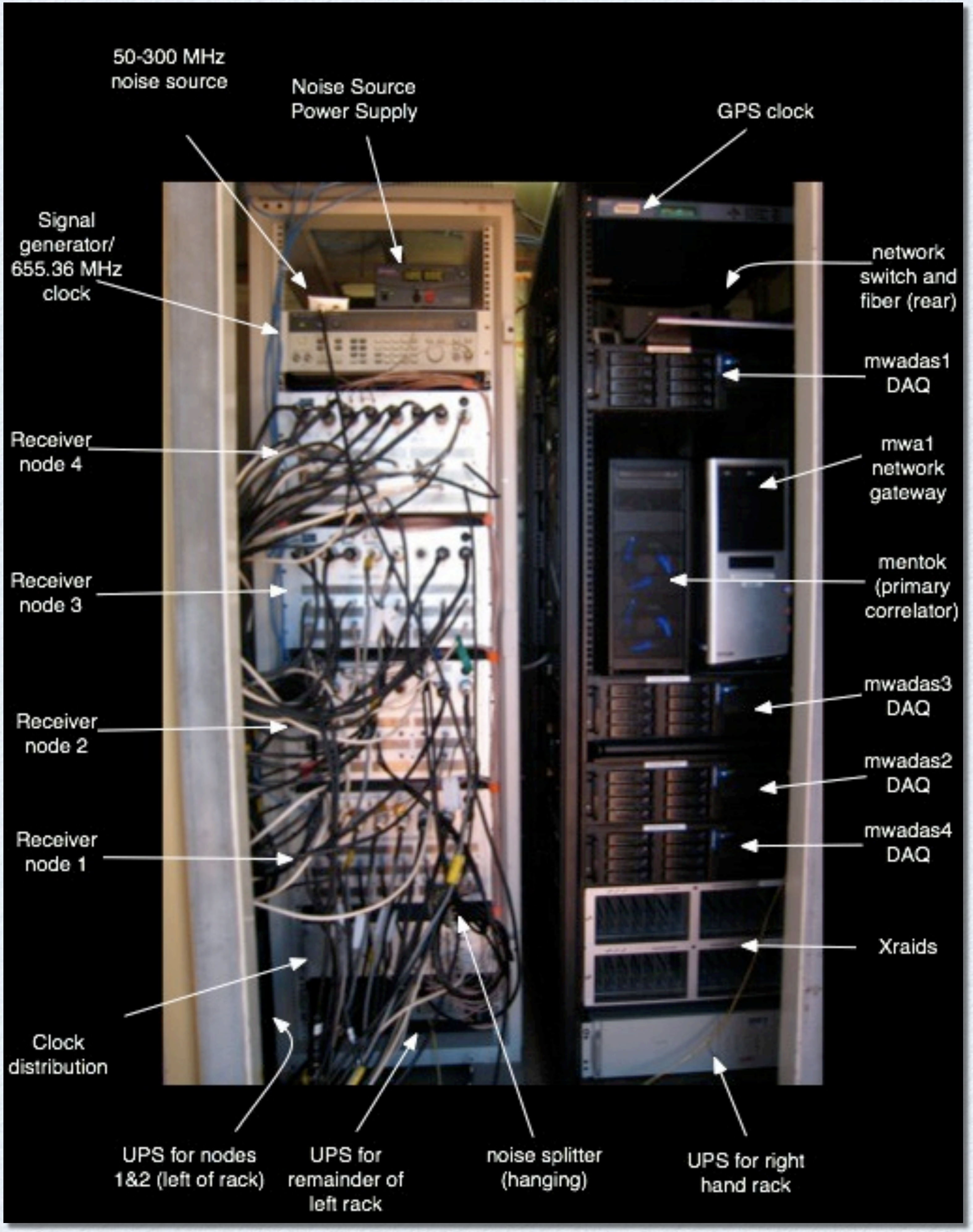
!!

Instrumental calibration

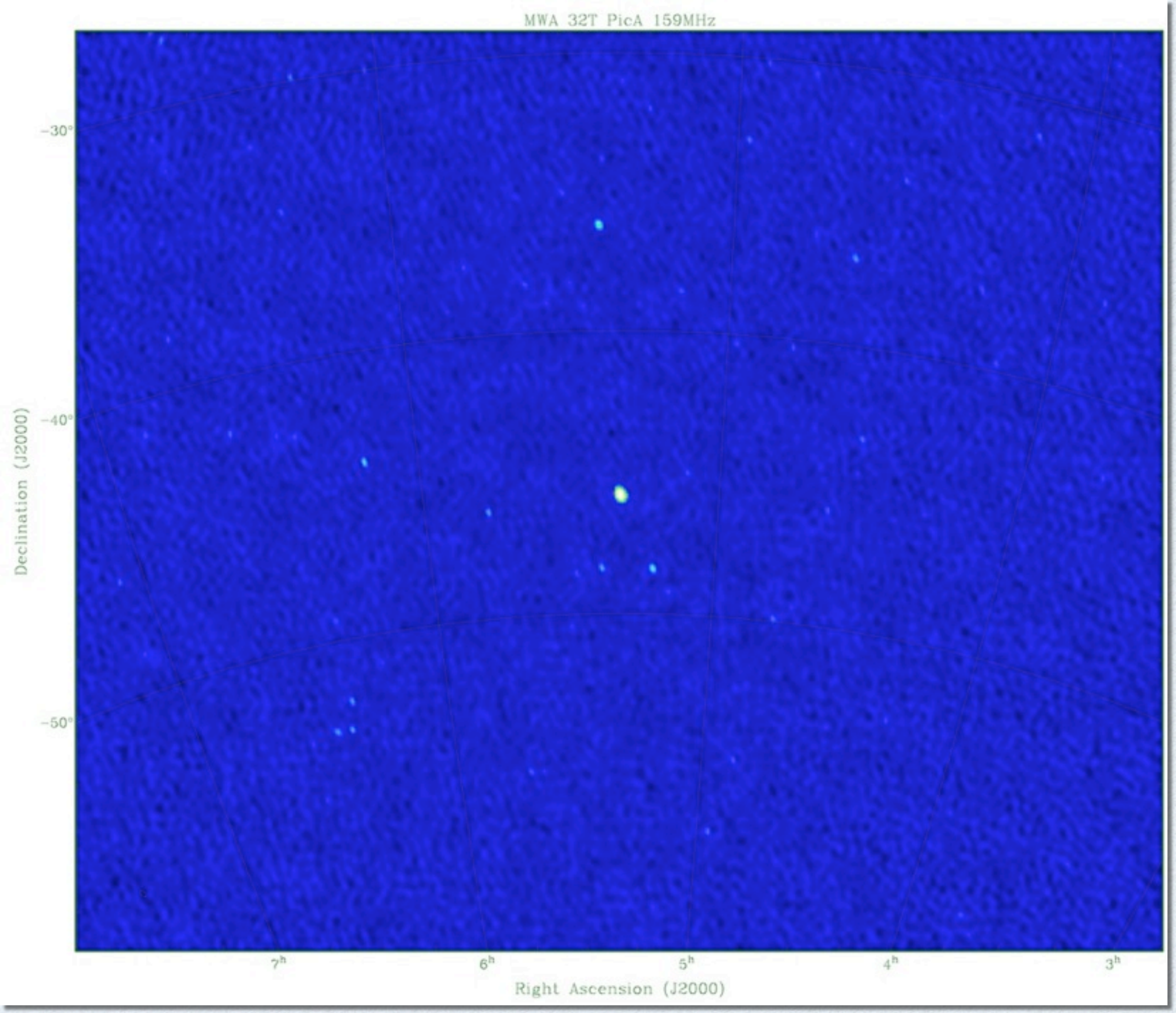
- Gain from one antenna to rest of array, simultaneously for all antennas & 100 sources



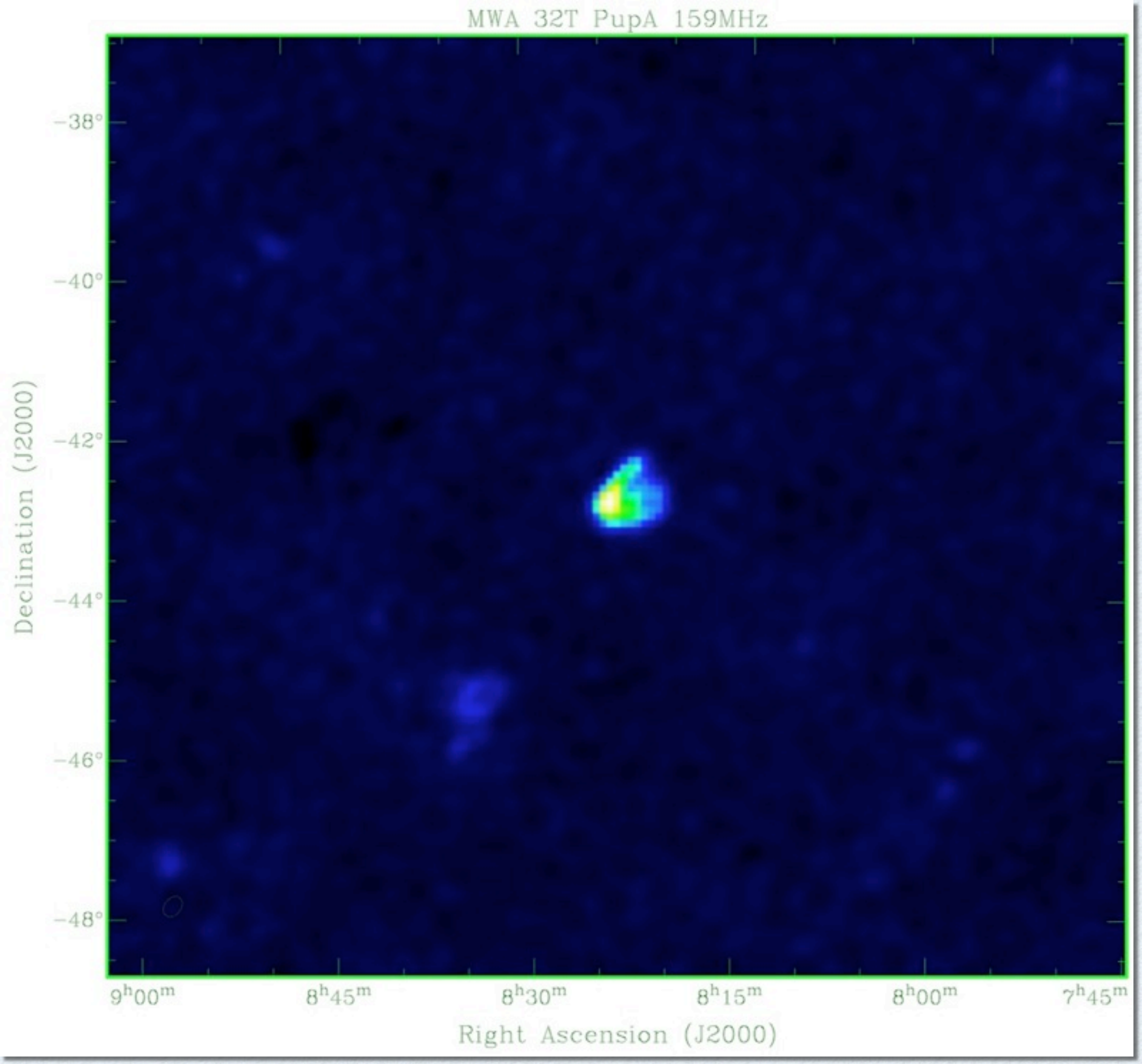
32T prototype


50-300 MHz noise source
Noise Source Power Supply
GPS clock
Signal generator/ 655.36 MHz clock
network switch and fiber (rear)
mwadas1 DAQ
Receiver node 4
mwa1 network gateway
Receiver node 3
mentok (primary correlator)
mwadas3 DAQ
Receiver node 2
mwadas2 DAQ
Receiver node 1
mwadas4 DAQ
Xraids
Clock distribution
UPS for nodes 1&2 (left of rack)
UPS for remainder of left rack
noise splitter (hanging)
UPS for right hand rack

!

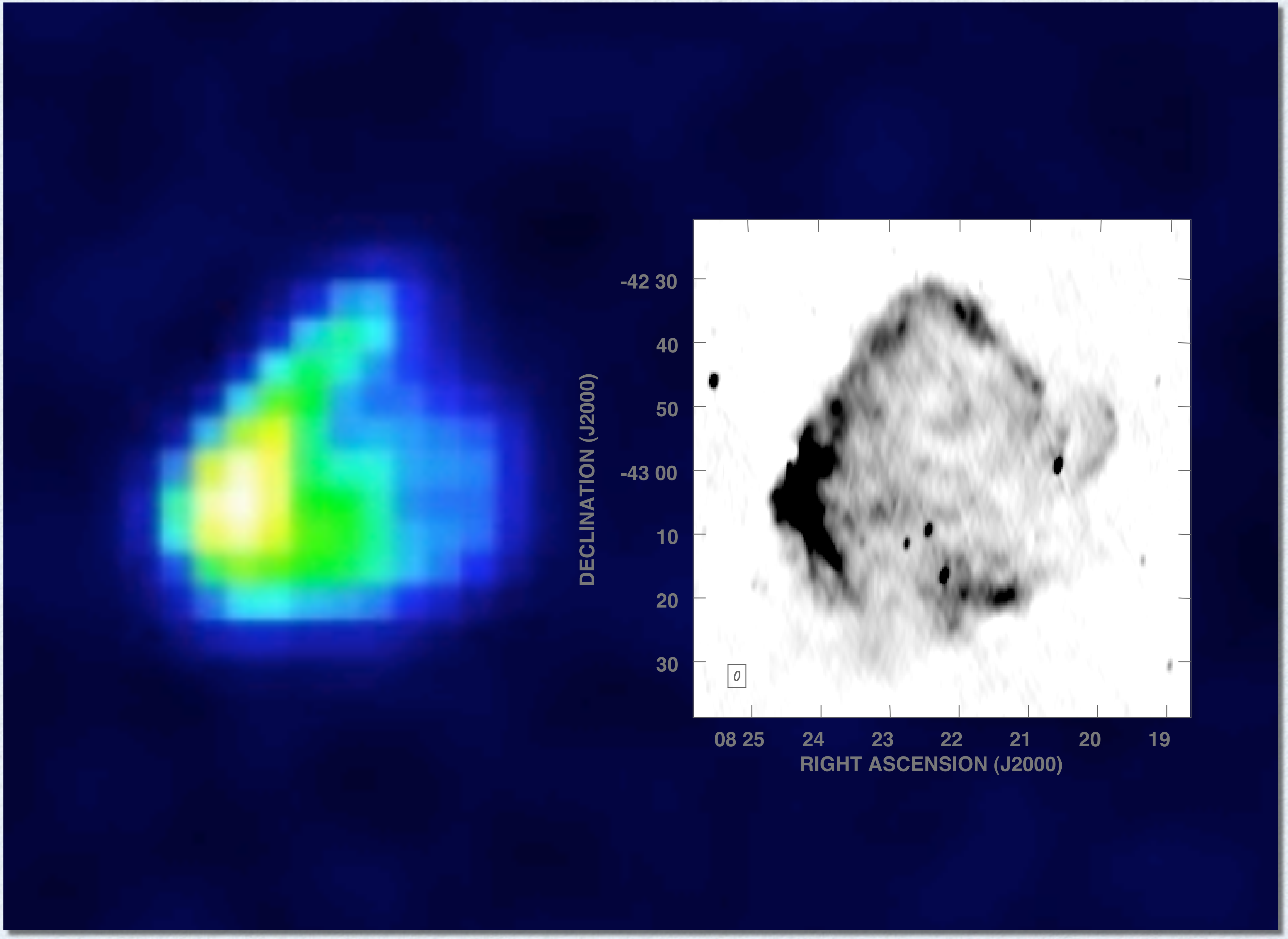

MWA 32T PicA 159MHz
-30°
-40°
-50°
Declination (J2000)
7h
6h
5h
4h
3h
Right Ascension (J2000)

Wayth


MWA 32T PupA 159MHz
−38°
−40°
−42°
−44°
−46°
−48°
Declination (J2000)
9h00m
8h45m
8h30m
8h15m
8h00m
7h45m
Right Ascension (J2000)

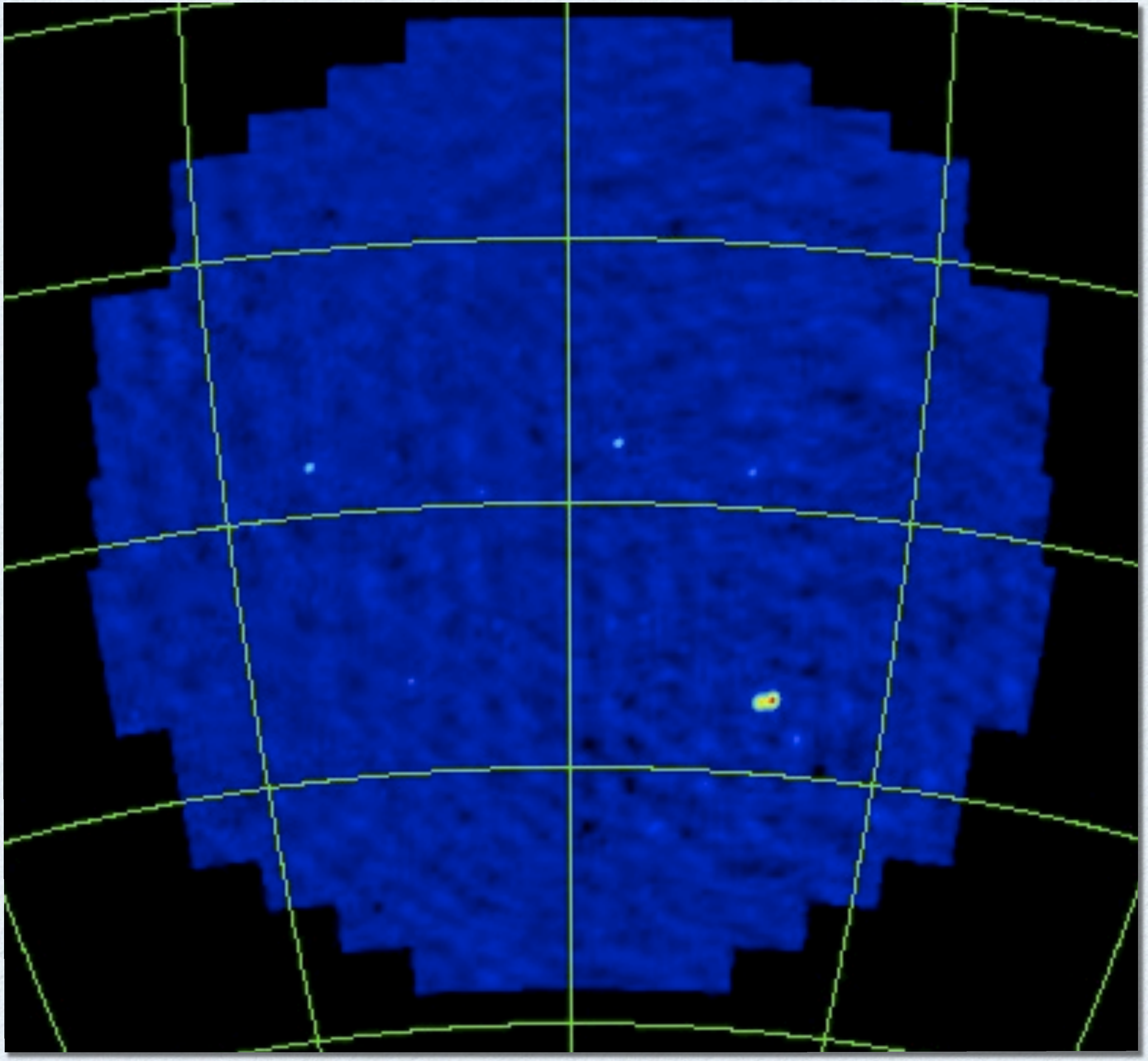
Wayth

vs. VLA & Bonn image (327 & 408)



Wayth; Castelletti et al. (2006)

Primary EoR field



Williams