NCRA • TIFR

UNIVERSITY OF TORONTO

DUNLAP INSTITUTE for ASTRONOMY & ASTROPHYSICS

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique

Forecasts for z=3.35 intensity mapping with the Ooty Wide Field Array

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CITA/Dunlap Institute, Toronto & NCRA-TIFR, Pune

14-Dec-2017, SALF-IV, Sydney

The OWFA group

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Ramu Yadav
Amit Mittal
and
Industry partners,
ORT engineers

HI in the Large Scale structure

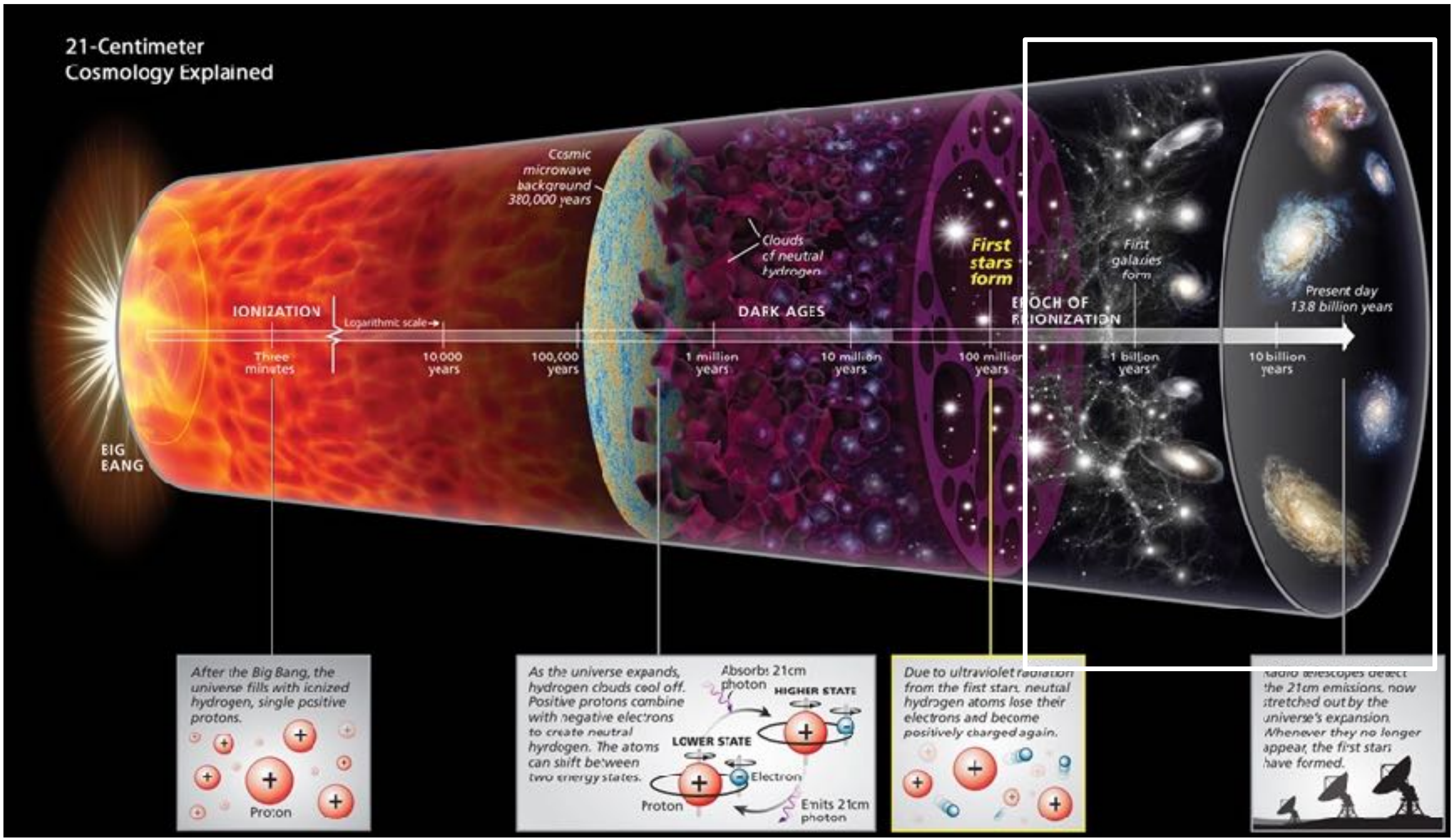
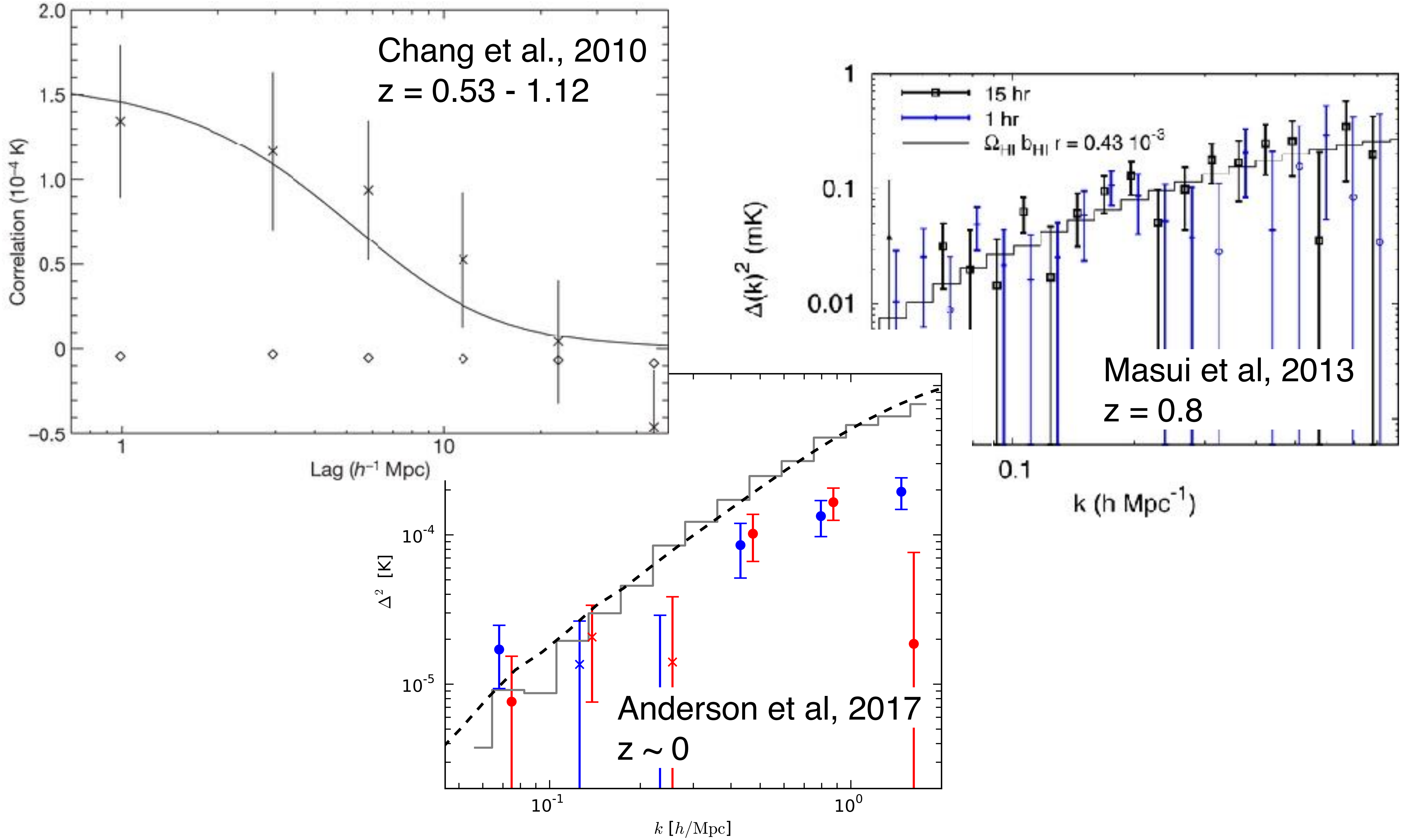


Image Credit : www.discovermagazine.com

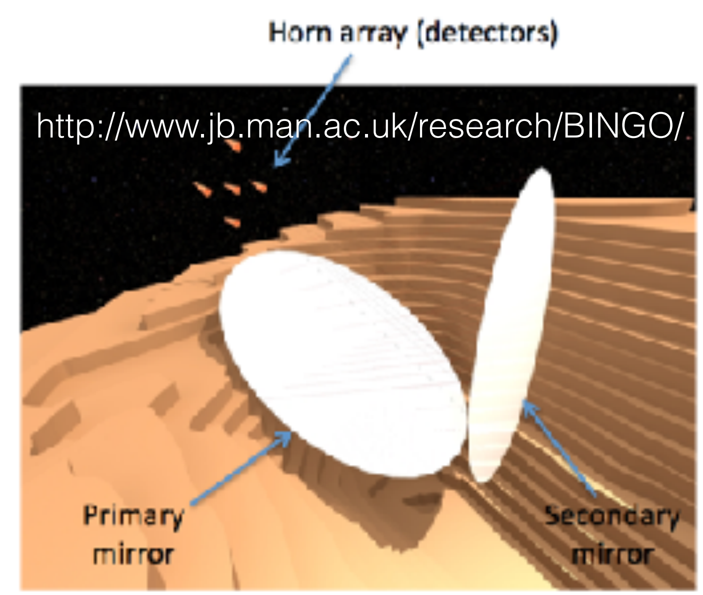
State-of-the-art



Upcoming 21-cm IM experiments

HIRAX

CHIME

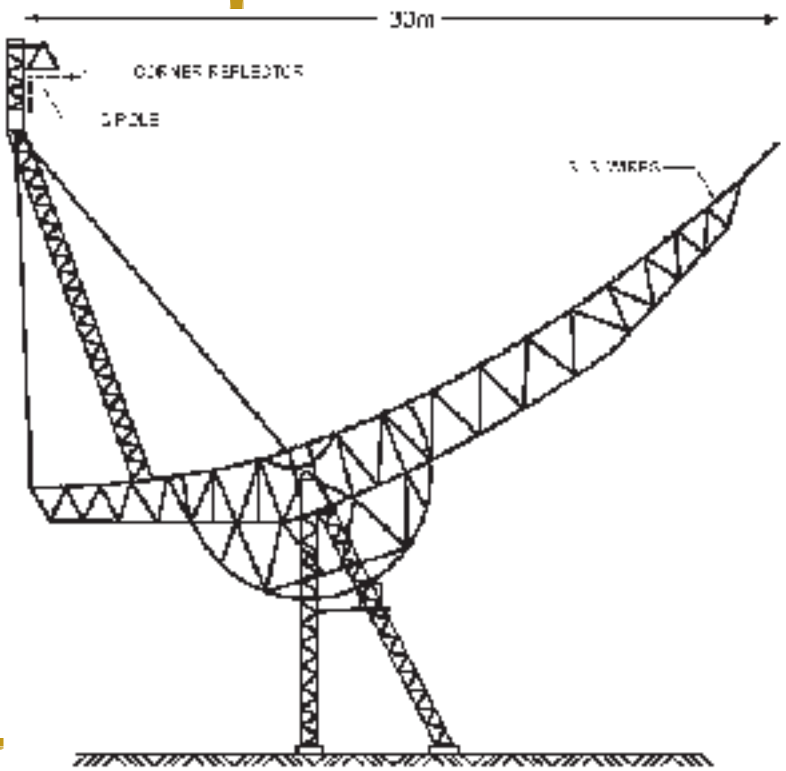


Tianlai CRT

BINGO

The Ooty Wide Field Array

- Upgrade to the Ooty Radio Telescope (ORT)
- 530m X 30m, 1056 dipoles
- Operates at 327 MHz, mostly IPS and pulsars
- Located on a hill, 11° slope
- Equatorial mount
- EW mechanical, NS electronic



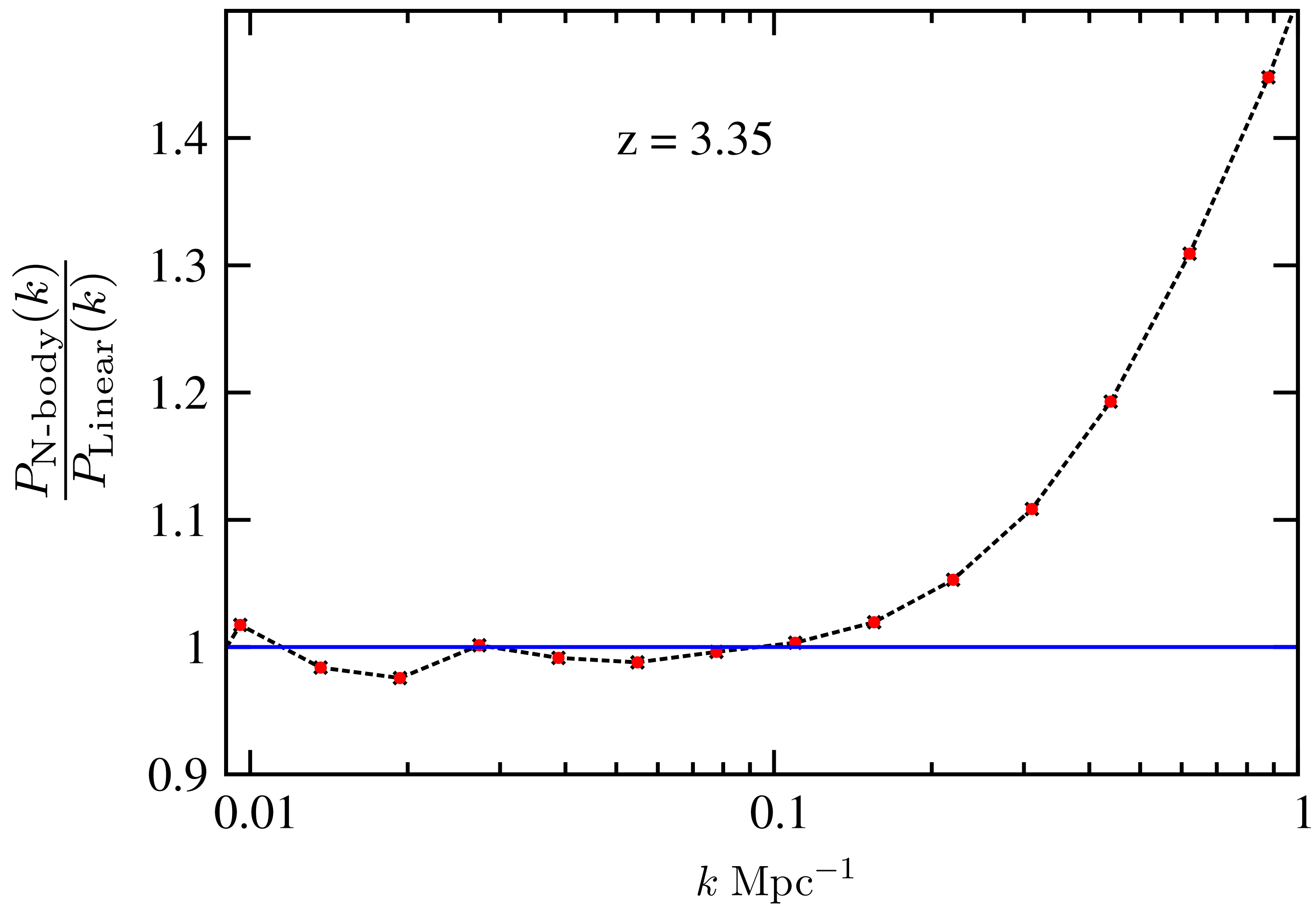
The Ooty Wide Field Array

- **Phase-II :** FoV = 28° X 2° 264 antennas
- **Phase-I :** FoV = 4.5° X 2° 40 antennas
- Bandwidth = ~35 MHz
- z = 3.35 for **HI**
- T_{sys} = 150 K

Subrahmanya, Manoharan & Chengalur, 2017
Prasad & Subrahmanya, 2010

The Ooty Wide Field Array

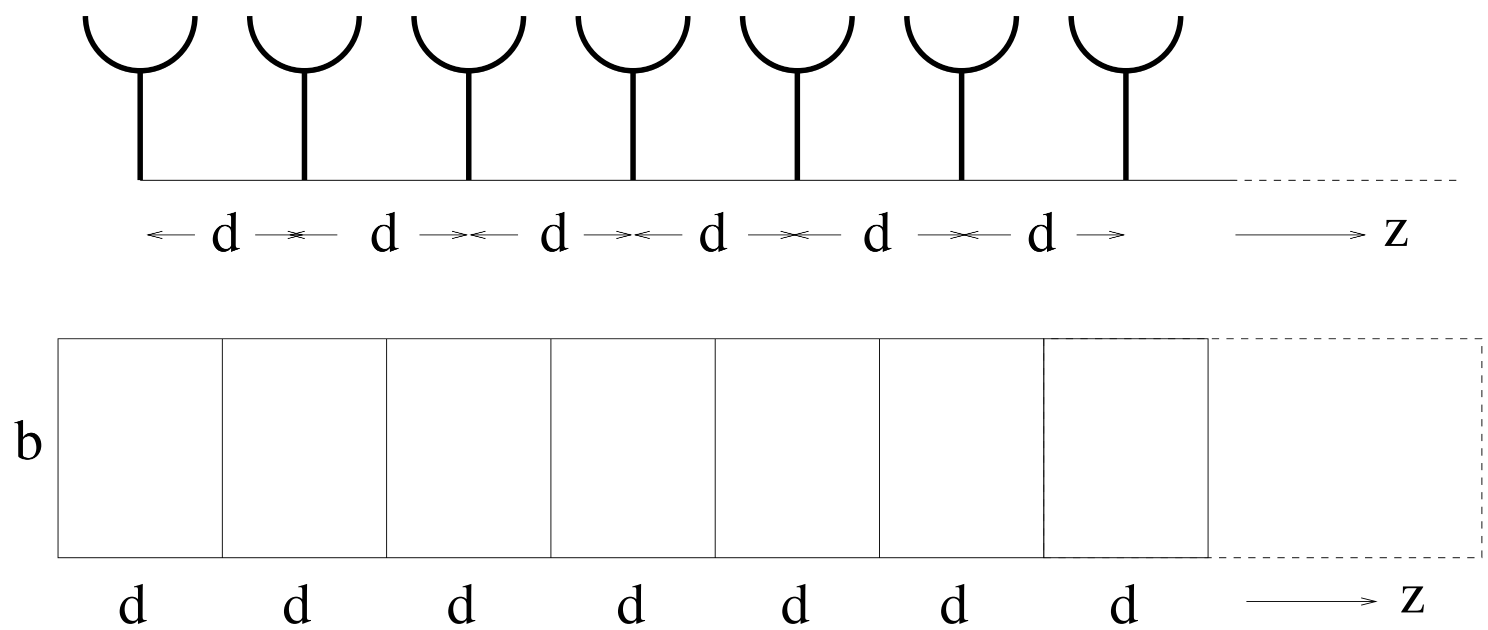
Structure in transition from linear to non-linear

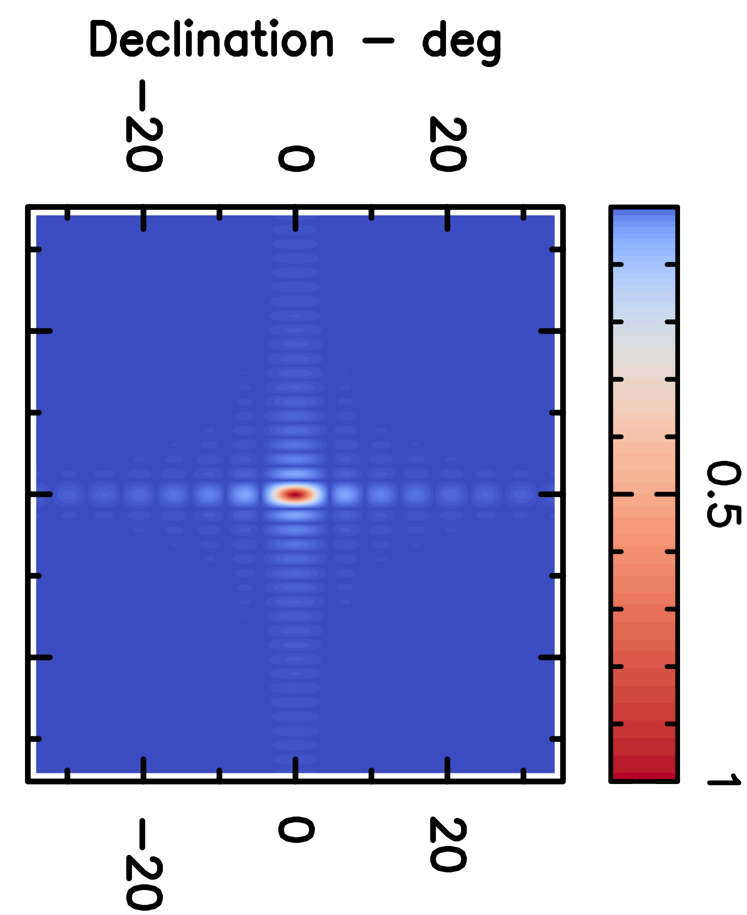


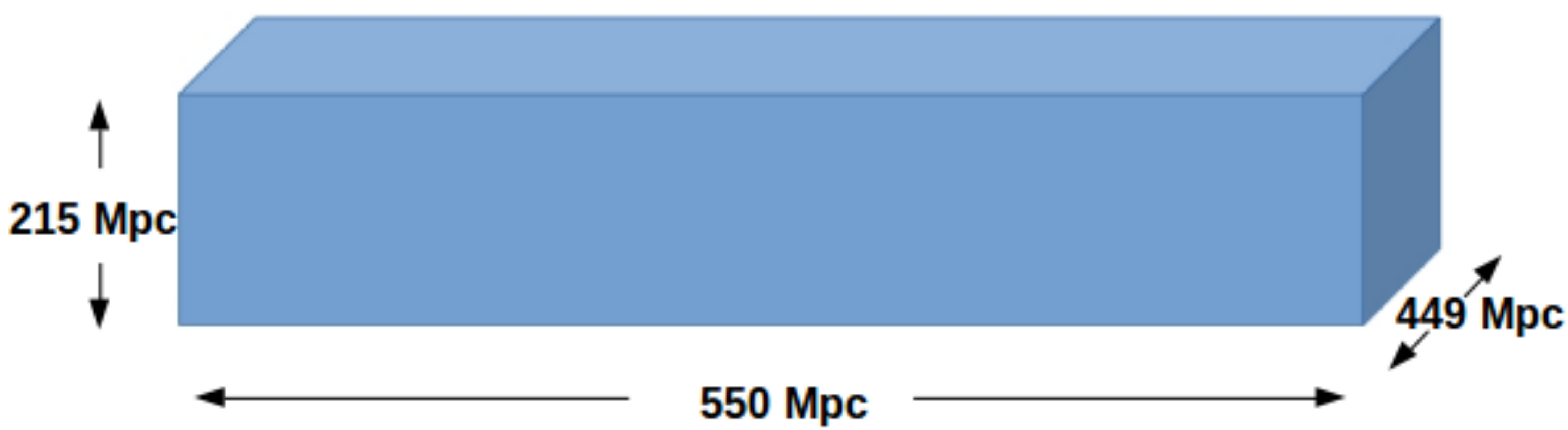
Chatterjee, Bharadwaj & Marthi 2017, JApA special issue

The Ooty Wide Field Array

Phase-I

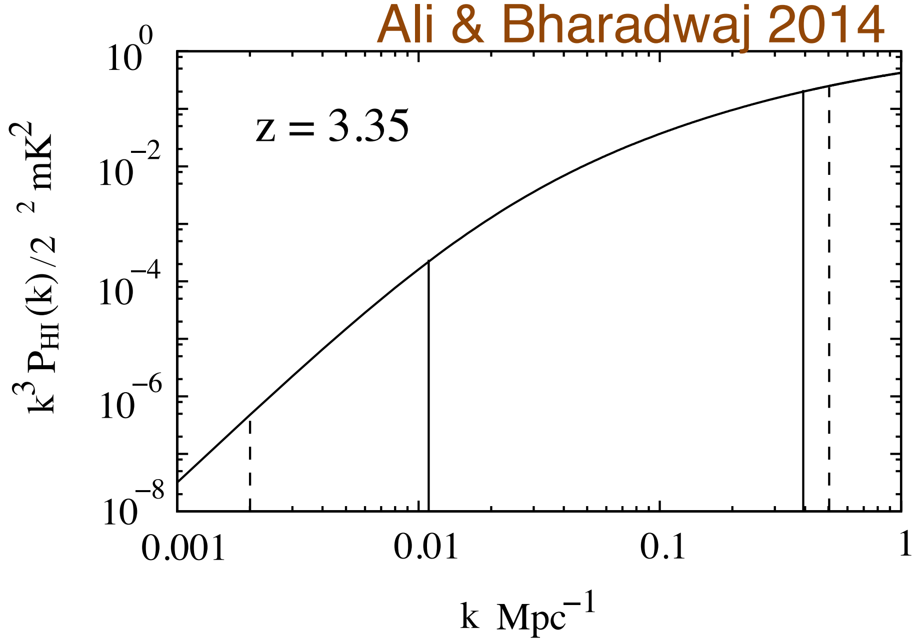






HI power spectrum forecasts

Ali & Bharadwaj 2014



$$P_{\rm HI}(\mathbf{k},\mu) = b^2\ \bar{x}_{\rm HI}^2\ \bar{T}^2\ [1+\beta\mu^2]^2\ P(\mathbf{k})$$

$$\bar{T}(z) = 4.0\ (1+z)^2 \left(\frac{\Omega_b h^2}{0.024}\right)\left(\frac{0.7}{h}\right)\left(\frac{H_0}{H(z)}\right)\ \mathrm{mK}$$

$$A_{\rm HI} = \bar{x}_{\rm HI}\, b_{\rm HI} \qquad \beta = f(\Omega)/b_{\rm HI} \qquad \mu = k_\parallel / k$$

Bharadwaj, Sarkar & Ali 2015
Sarkar, Bharadwaj & Ali 2017

$A_{\rm HI} = 4.0 \times 10^{-2}$

$\beta = 4.93 \times 10^{-1}$

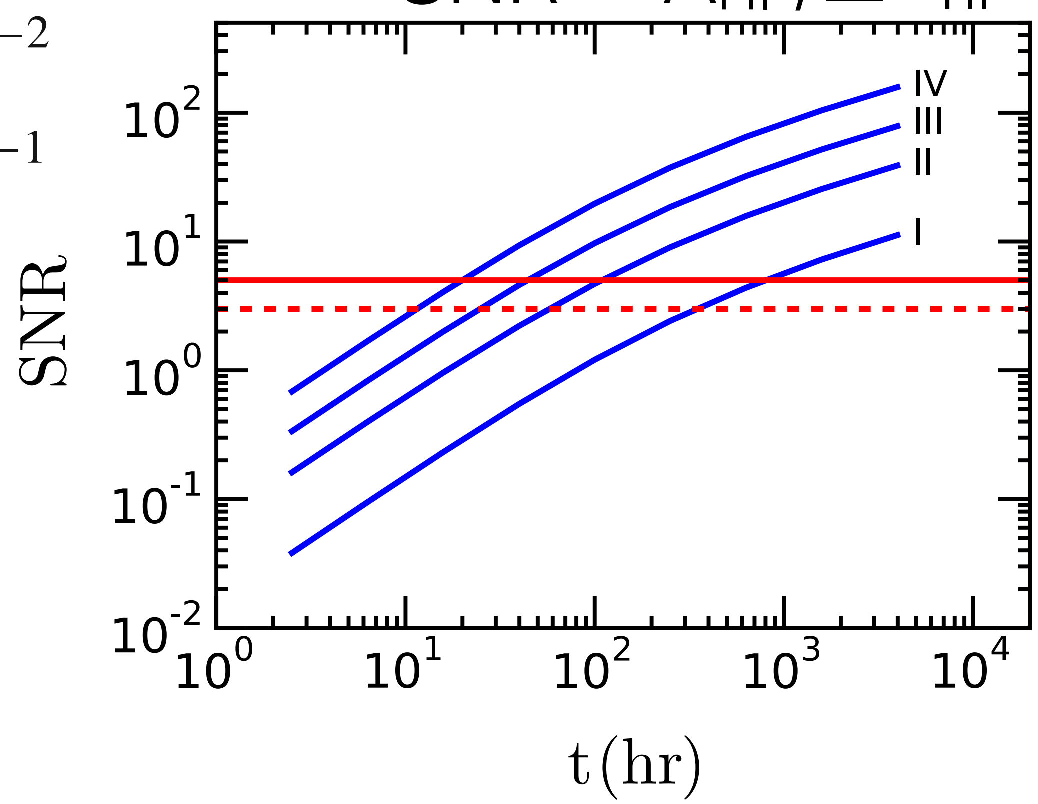
$\bar{x}_{\rm HI} = 0.02$

Zafar et al., 2013

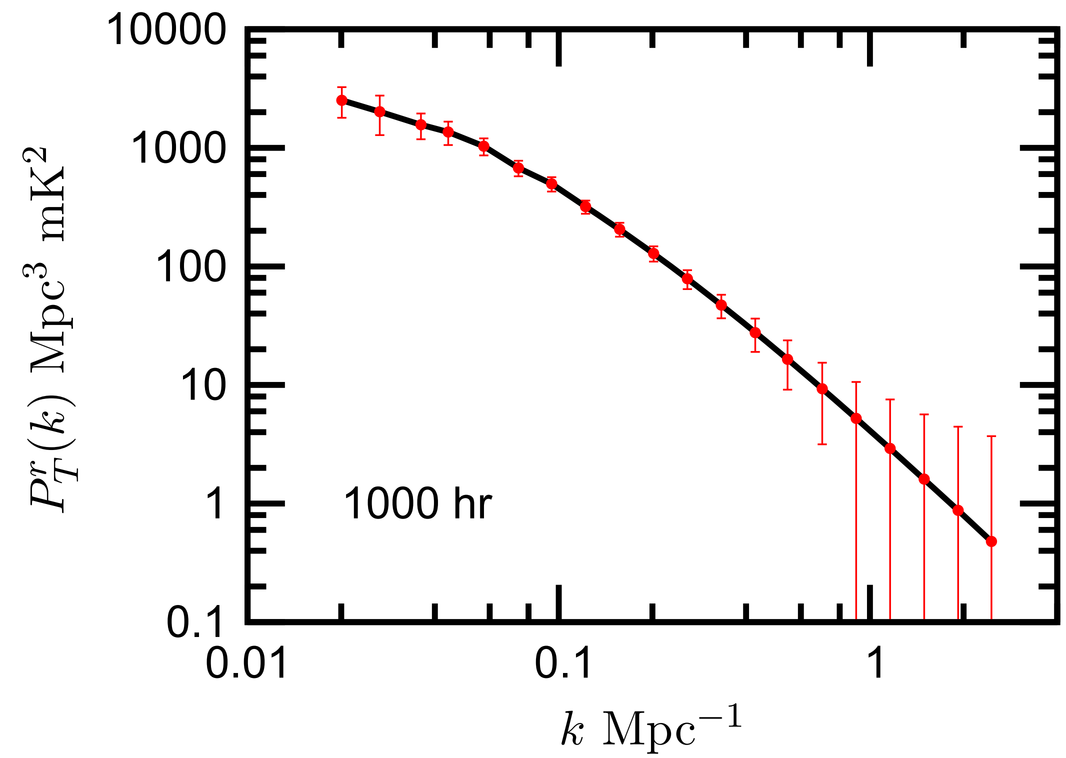
$b_{\rm HI} = 2$

Bagla et al., 2010

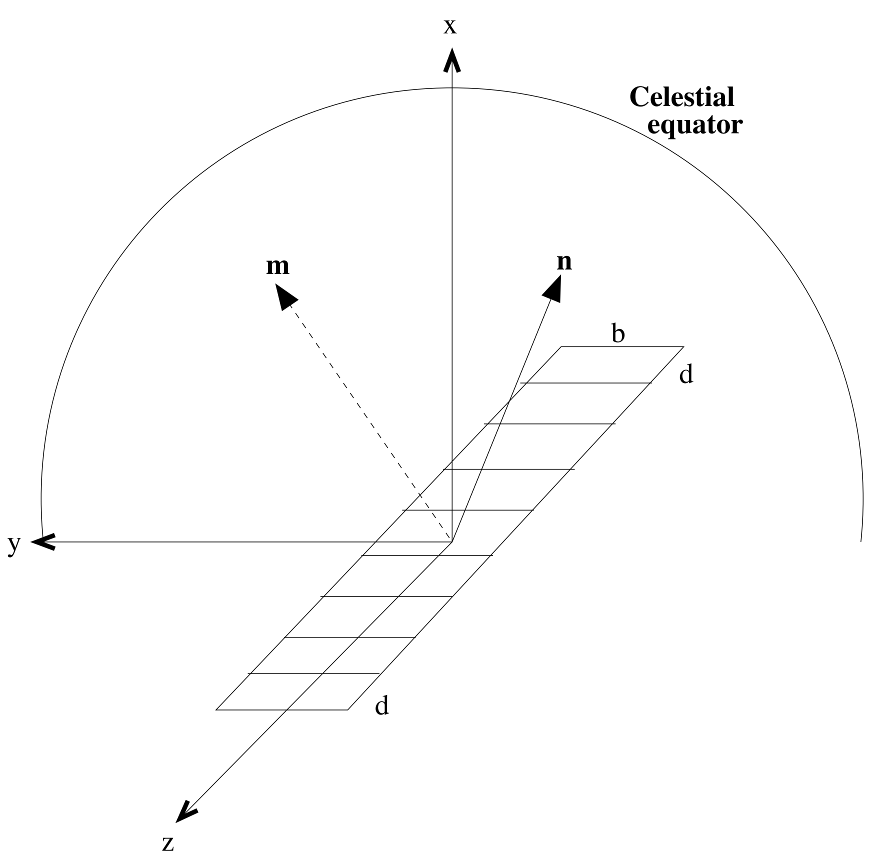
SNR = $A_{\rm HI} / \Delta A_{\rm HI}$

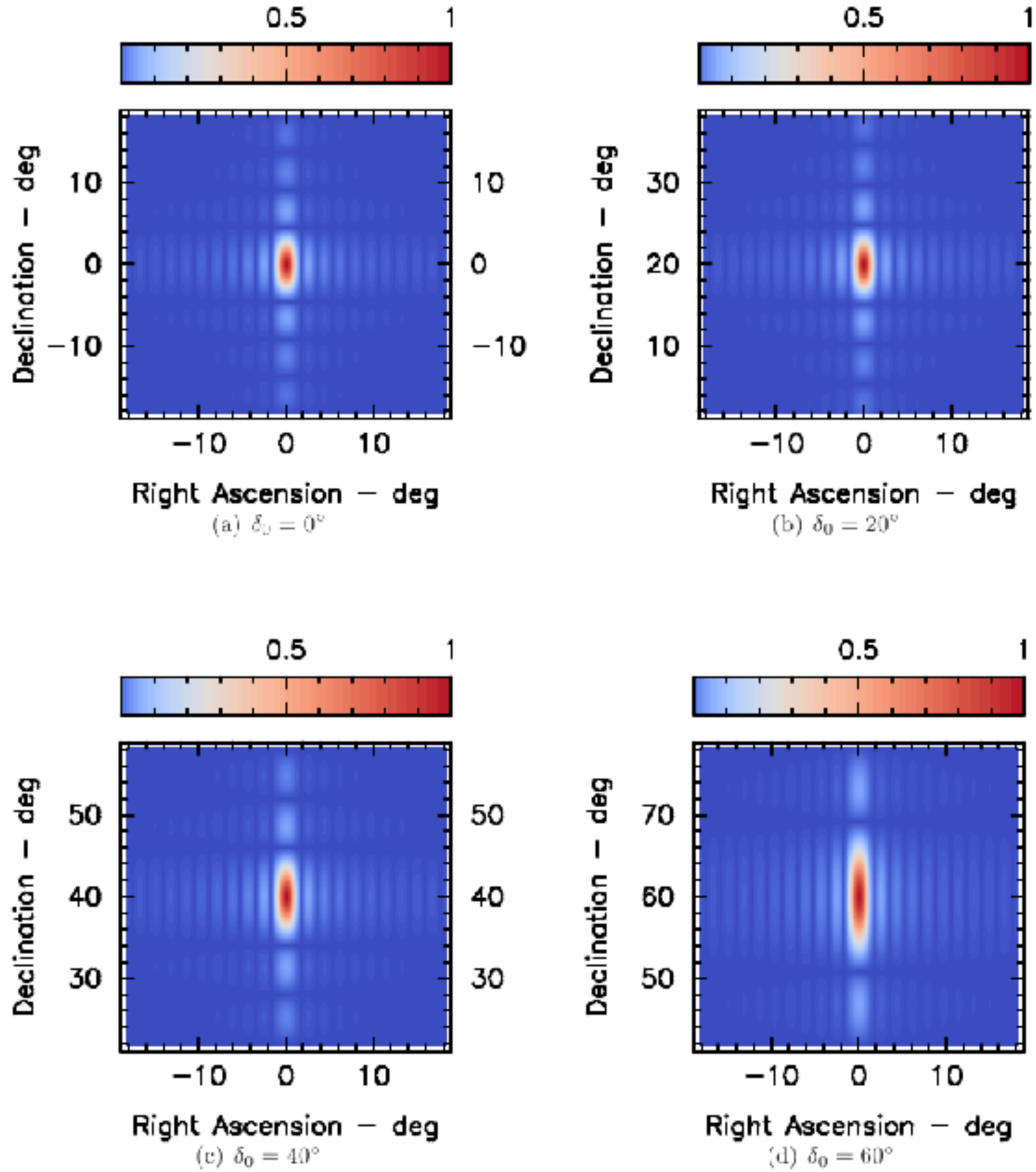


Binned power spectrum



Instrument and foreground simulations



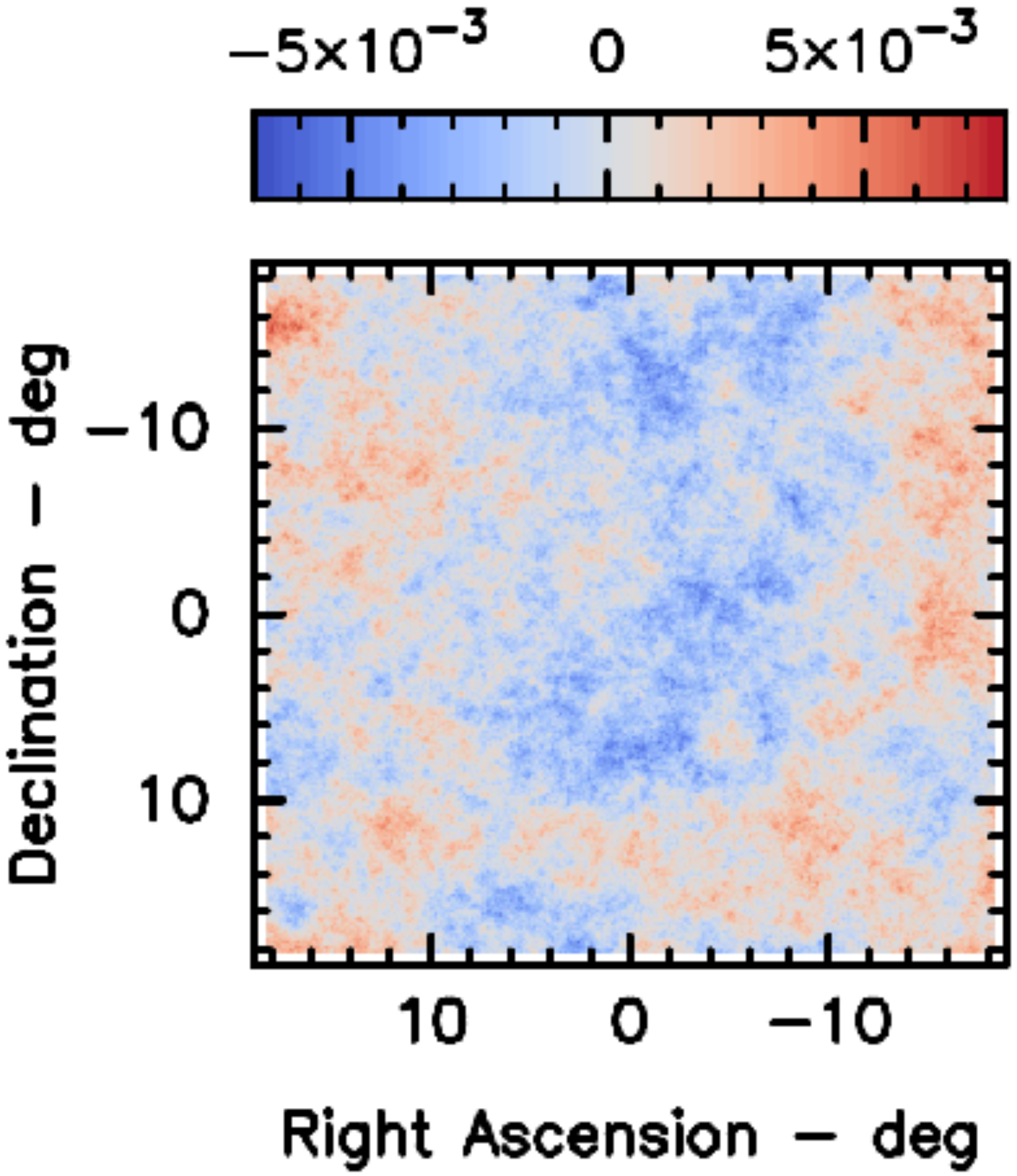


(a) $\delta_0 = 0°$ (b) $\delta_0 = 20°$ (c) $\delta_0 = 40°$ (d) $\delta_0 = 60°$

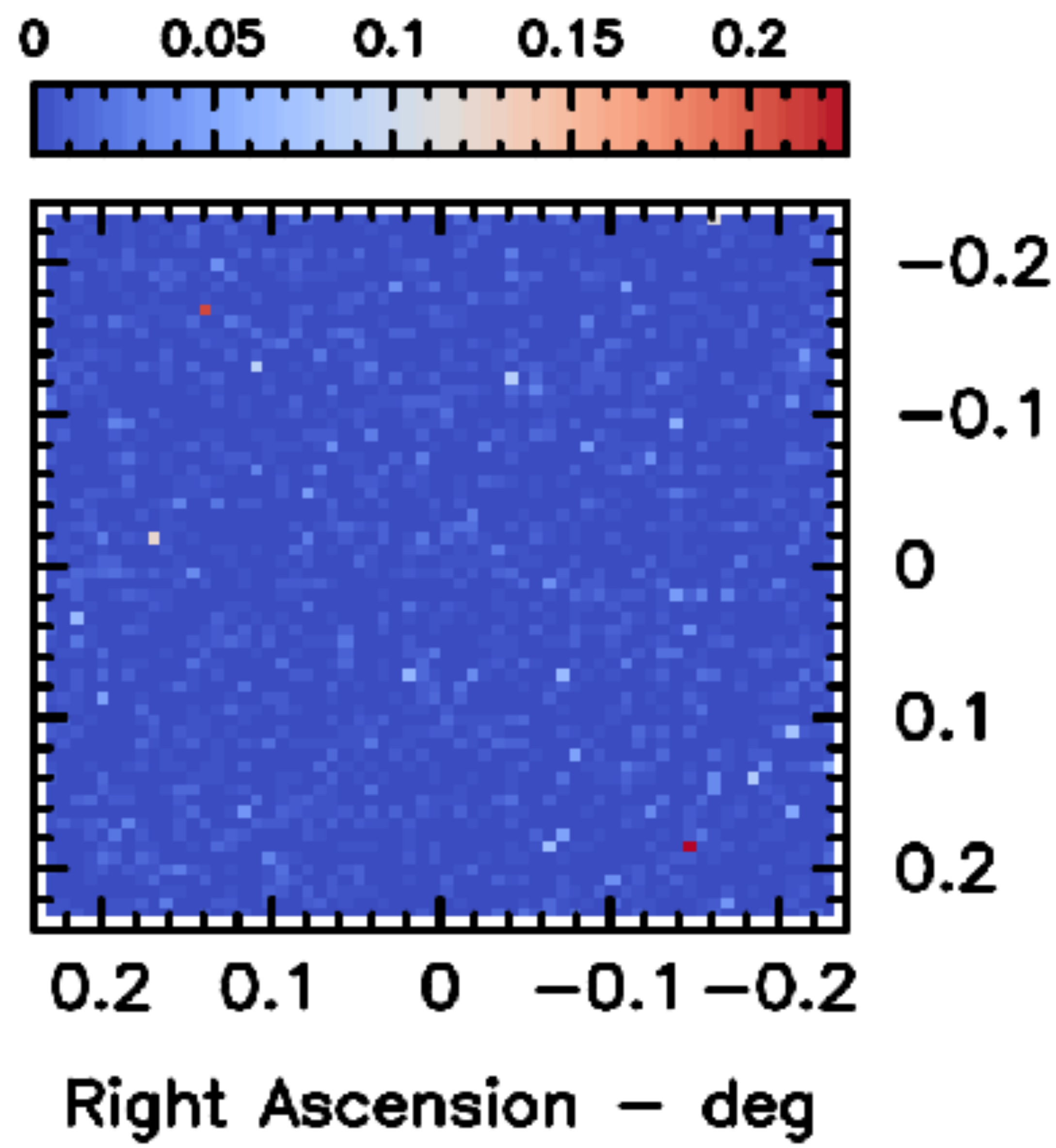
Marthi, 2017
Marthi et al., 2017

Instrument and foreground simulations

$$C_\ell(\nu) = A_0 \left(\frac{\nu_0}{\nu}\right)^{2\alpha} \left(\frac{\ell_0}{\ell}\right)^{\gamma}$$

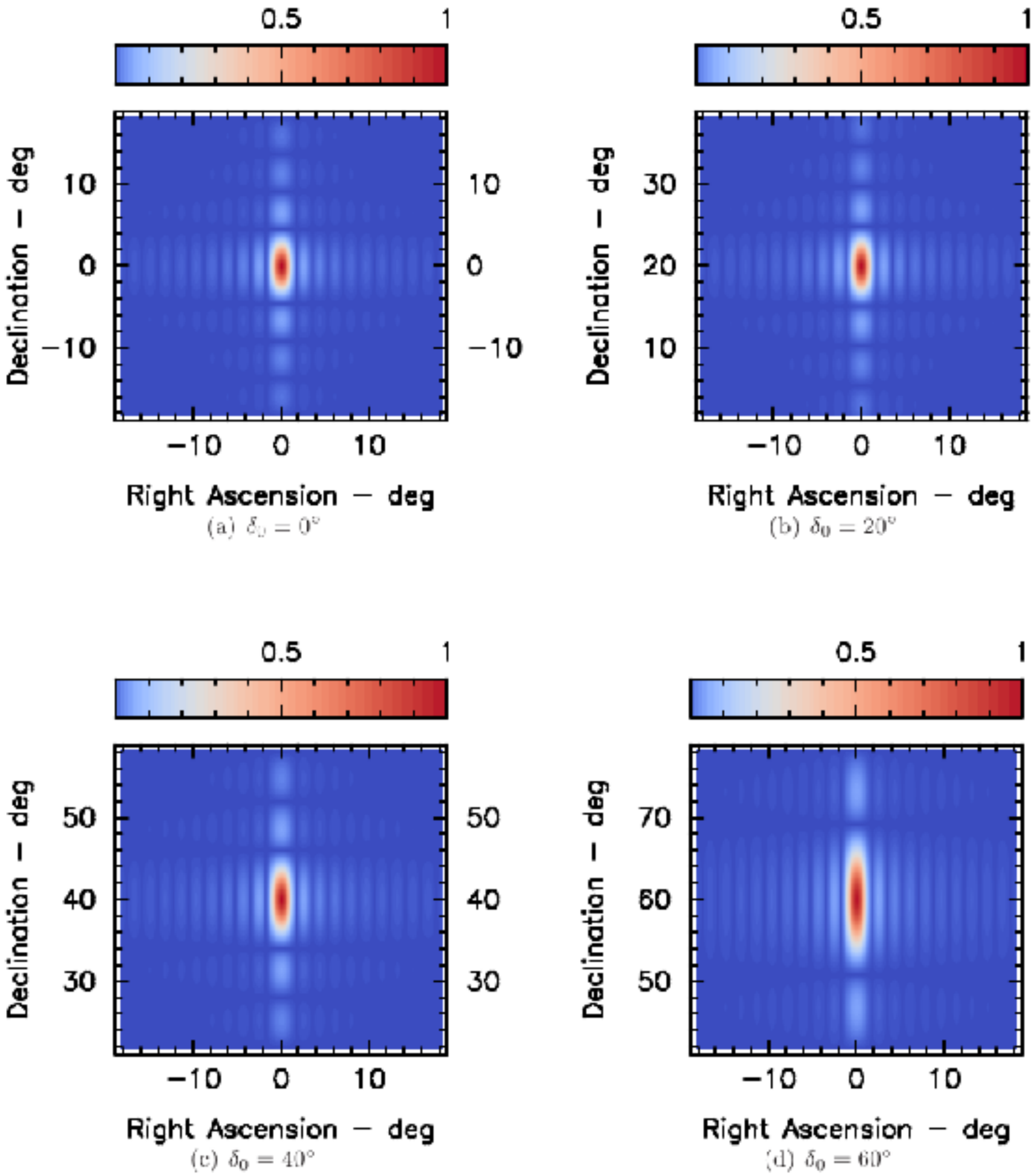


$$C_\ell = C_\ell^{\mathrm{P}} + C_\ell^{\mathrm{cl}}$$

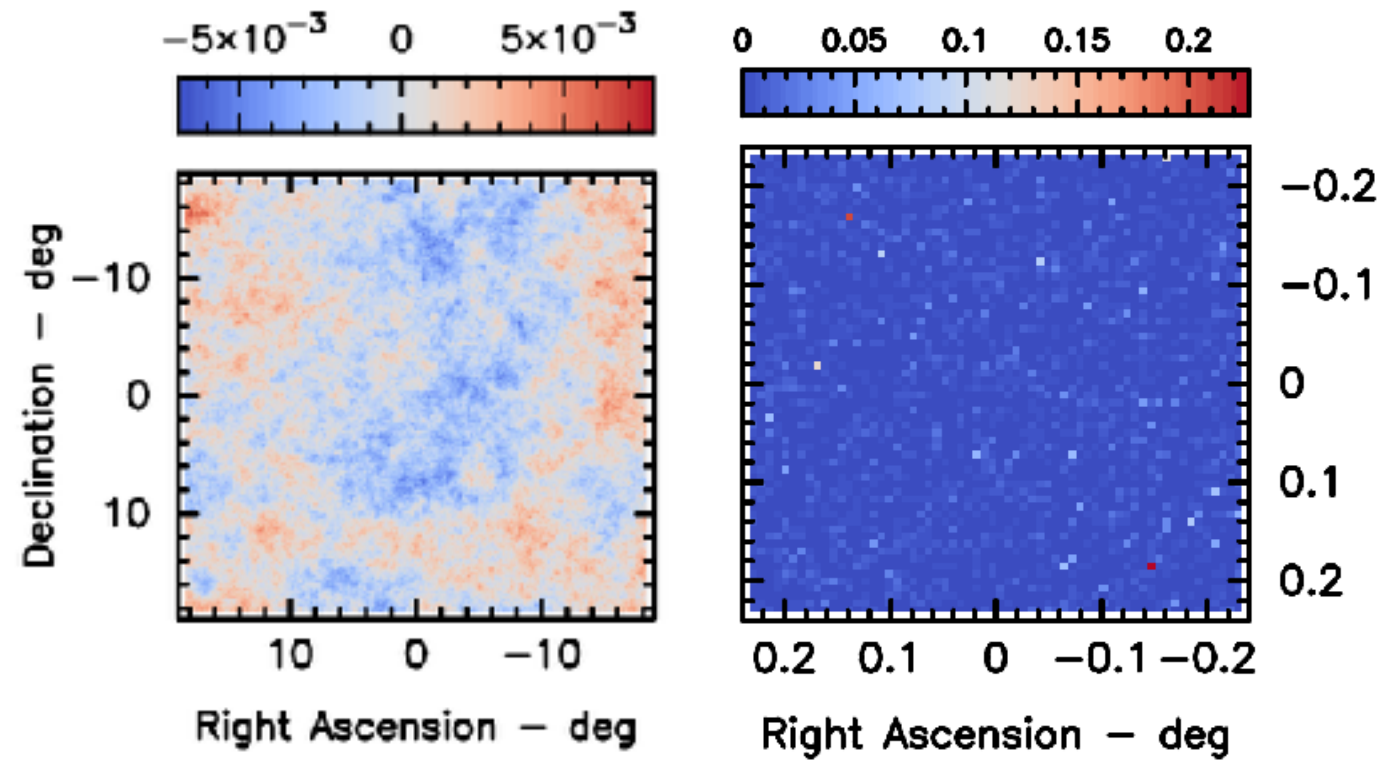


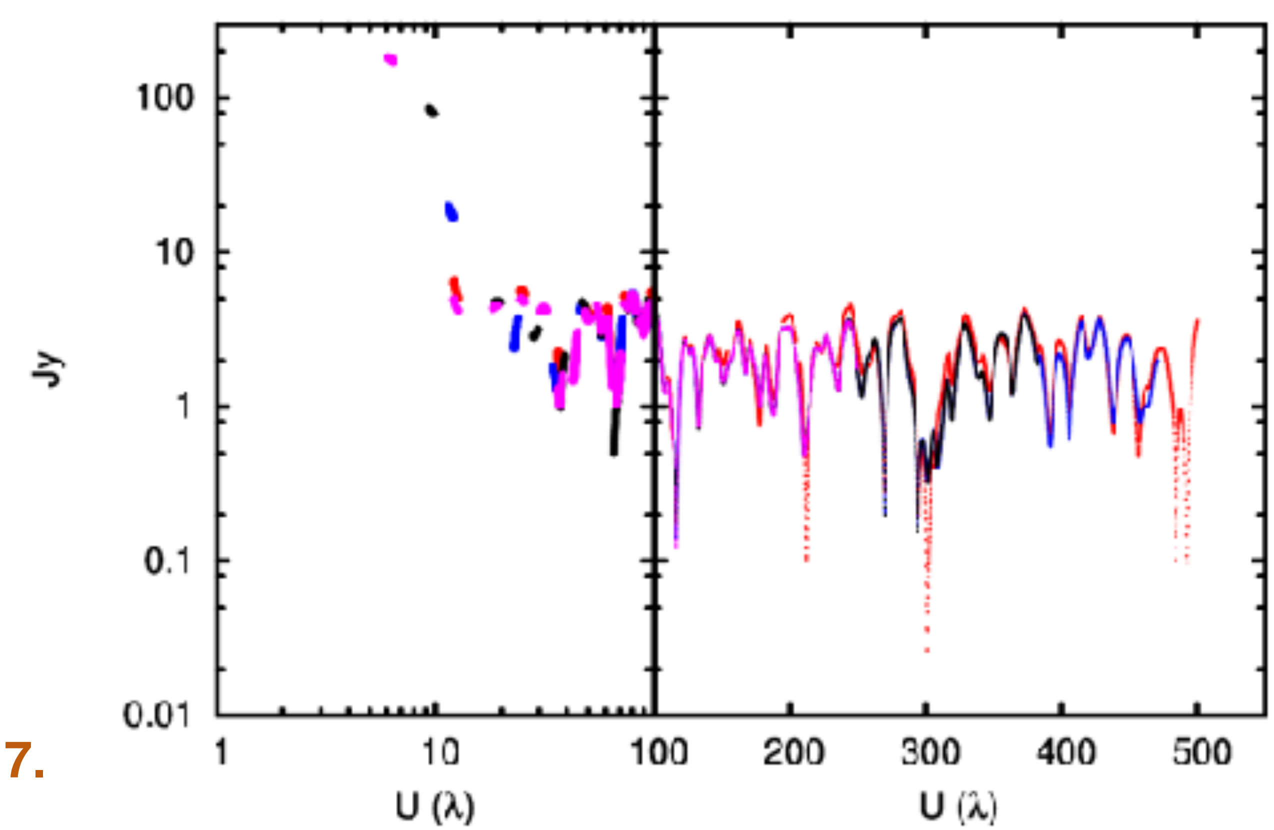
Marthi, Chatterjee, Chengalur & Bharadwaj, 2017, MNRAS.

Instrument and foreground simulations



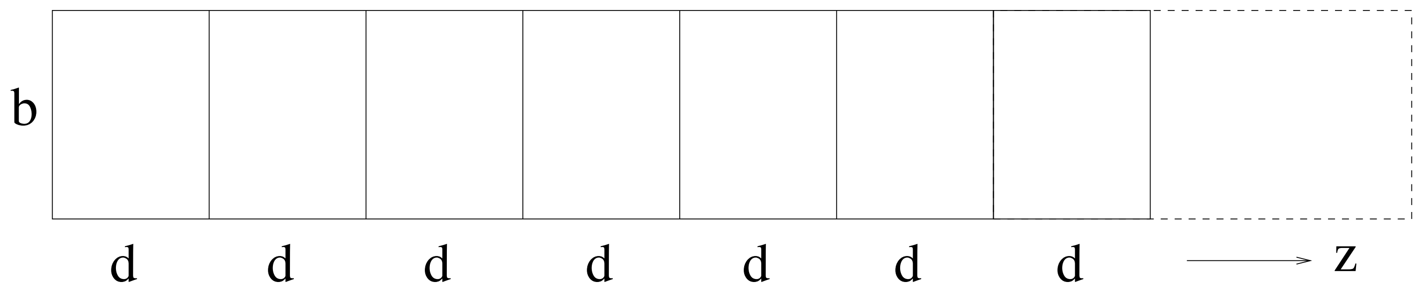
(a) $\delta_0 = 0°$
(b) $\delta_0 = 20°$
(c) $\delta_0 = 40°$
(d) $\delta_0 = 60°$

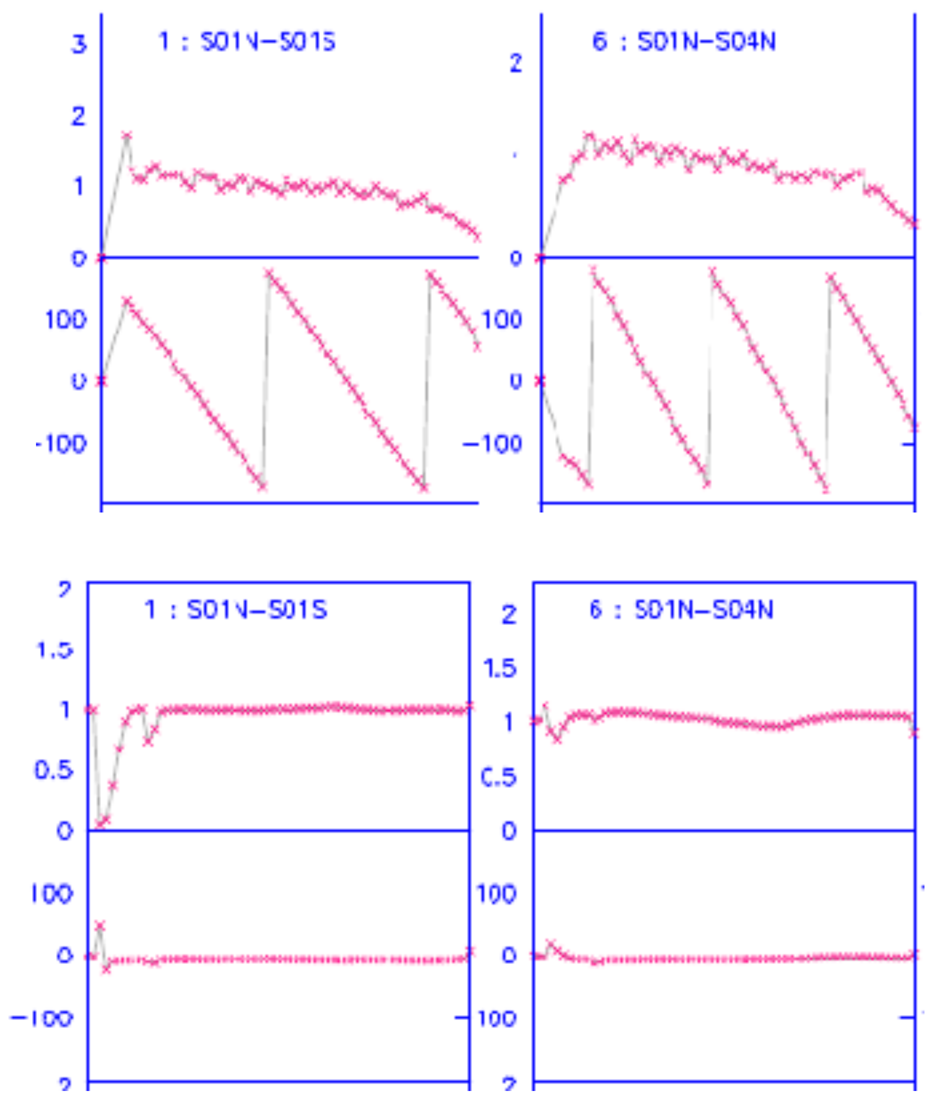




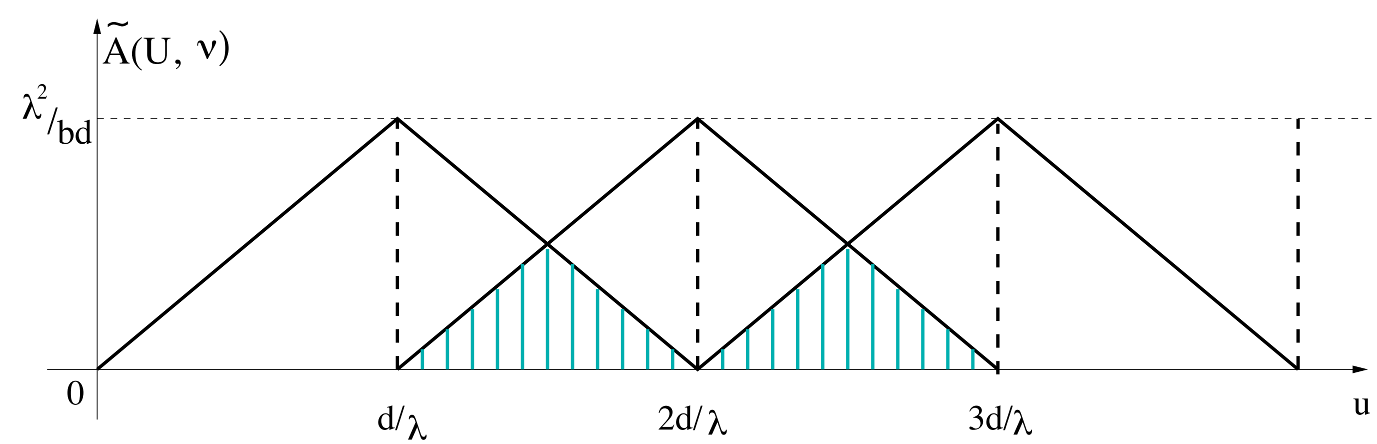
Marthi, 2017
Marthi, Chatterjee, Chengalur & Bharadwaj 2017.

Redundancy and redundancy calibration





Fast N^2 non-linear solver, can run in real time



Marthi & Chengalur, 2014, MNRAS.

Visibility covariance power spectrum estimator

$$\mathbf{S}_2(\mathbf{U}_n, \mathbf{U}_m, \nu_i, \nu_j) \equiv \langle \mathcal{V}(\mathbf{U}_n, \nu_i)\mathcal{V}^*(\mathbf{U}_m, \nu_j)\rangle$$

Datta & Choudhury 2007

$$\mathbf{S}_2(\mathbf{U}_n, \Delta\nu) = \left(\frac{\partial B}{\partial T}\right)^2 C_\ell(\Delta\nu)\left[\int d^2\mathbf{U}' |\tilde{A}(\mathbf{U}_n - \mathbf{U}')|^2\right]$$

$$\mathcal{V}(\mathbf{U}_n, \nu) = \sum_{i=0}^{N_n} \mathcal{V}^{(i)}(\mathbf{U}_n, \nu) \quad \Big| \quad \mathcal{V}'(\mathbf{U}_n, \nu) = \sum_{i=0}^{N_n} |\mathcal{V}^{(i)}(\mathbf{U}_n, \nu)|^2$$

$$\mathbf{S}_2(\mathbf{U}_n, \nu_i, \nu_j) = \frac{\mathcal{V}(\mathbf{U}_n, \nu_i)\mathcal{V}^*(\mathbf{U}_n, \nu_j) - \delta_{ij}\mathcal{V}'(\mathbf{U}_n, \nu_i)}{N_n^2 - \delta_{ij}N_n}$$

Marthi, Chatterjee, Chengalur & Bharadwaj 2017.

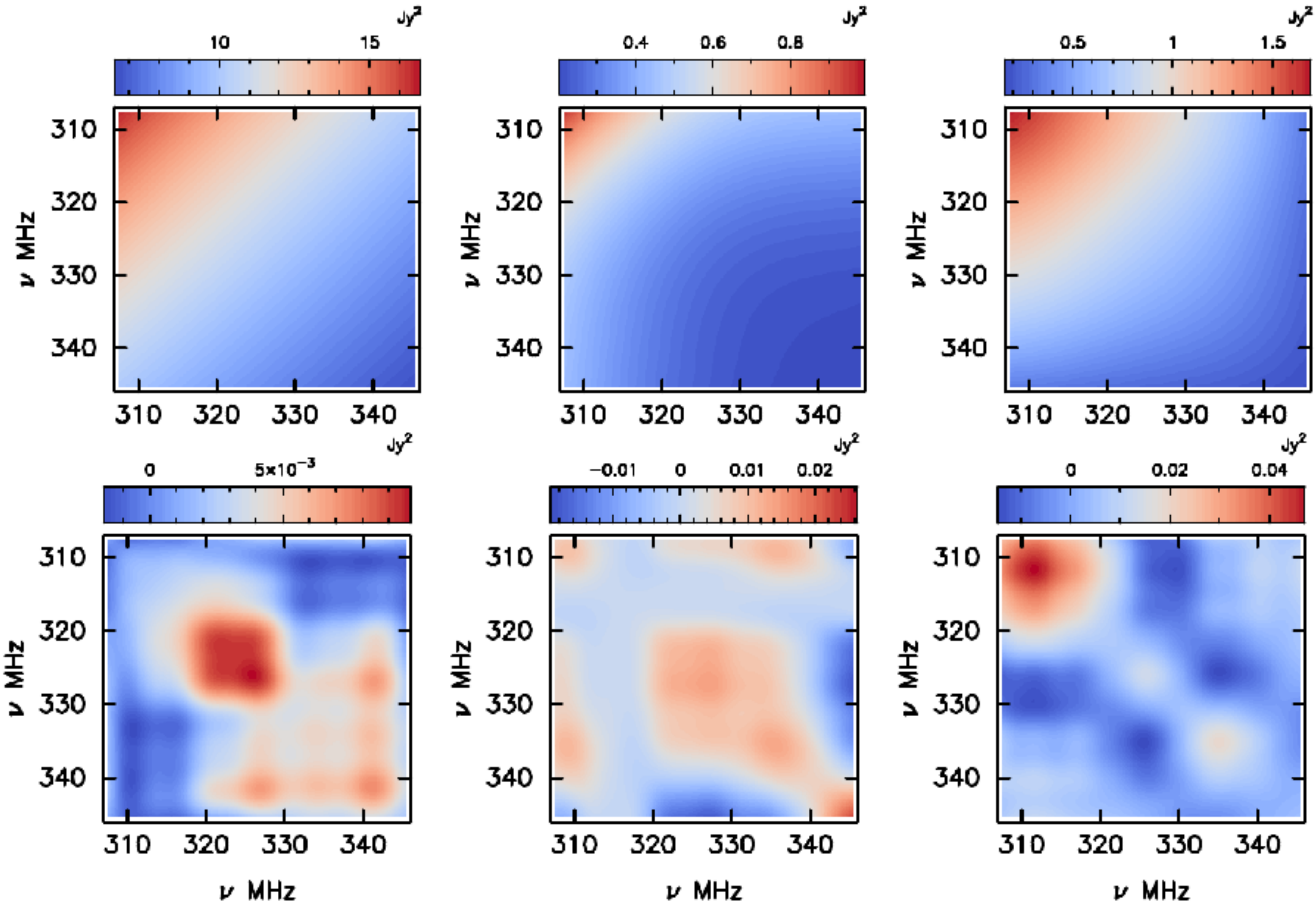
<u>Phase-I</u>

Antennas : 40	Unique baselines : 39
Baselines : 780	Channels : 312

One Hermitian product per baseline, each 312 X 312.

Visibility covariance power spectrum estimator

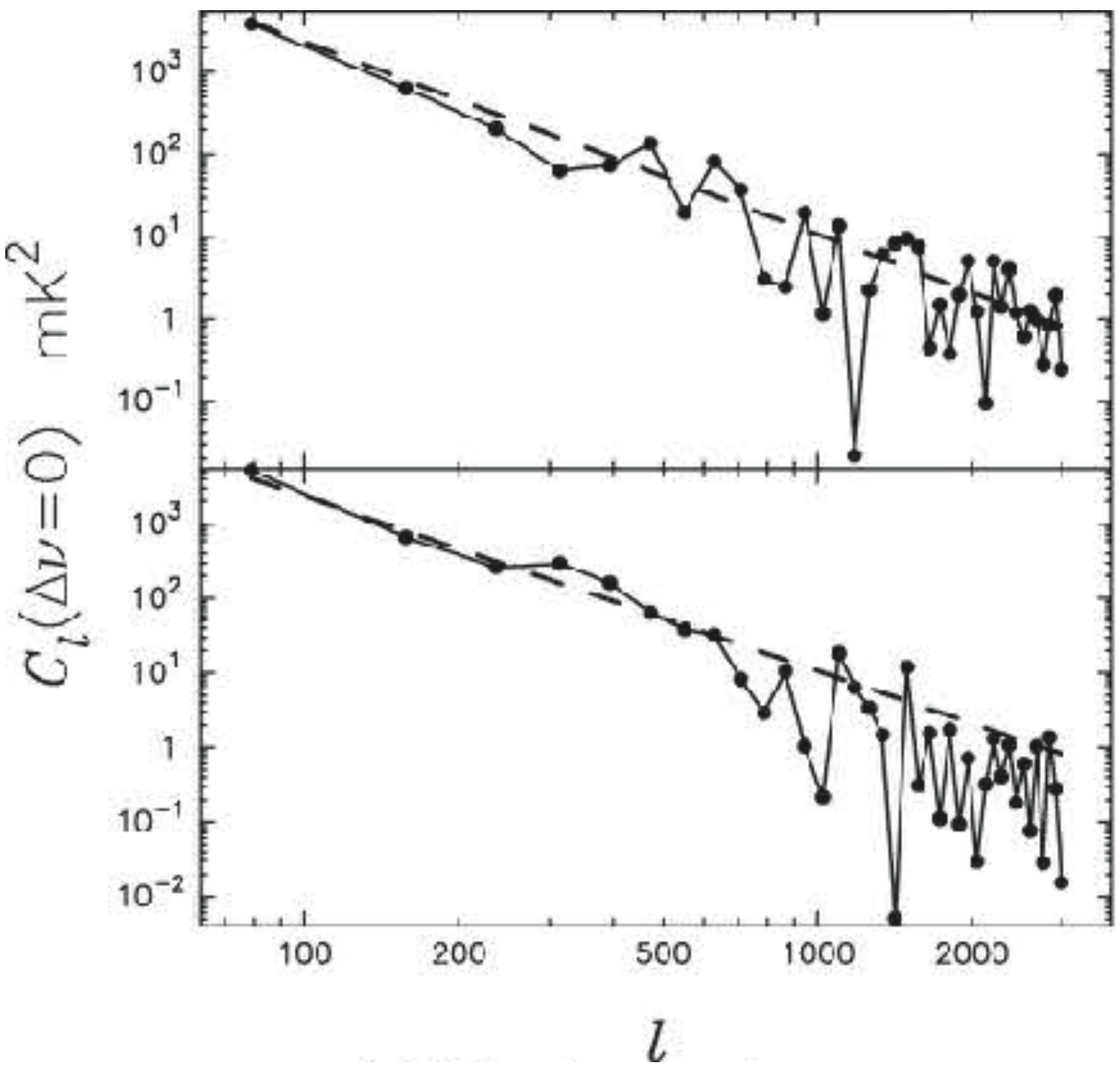
Marthi, Chatterjee, Chengalur & Bharadwaj, 2017



Multifrequency Angular Power Spectrum

Marthi, Chatterjee, Chengalur & Bharadwaj, 2017

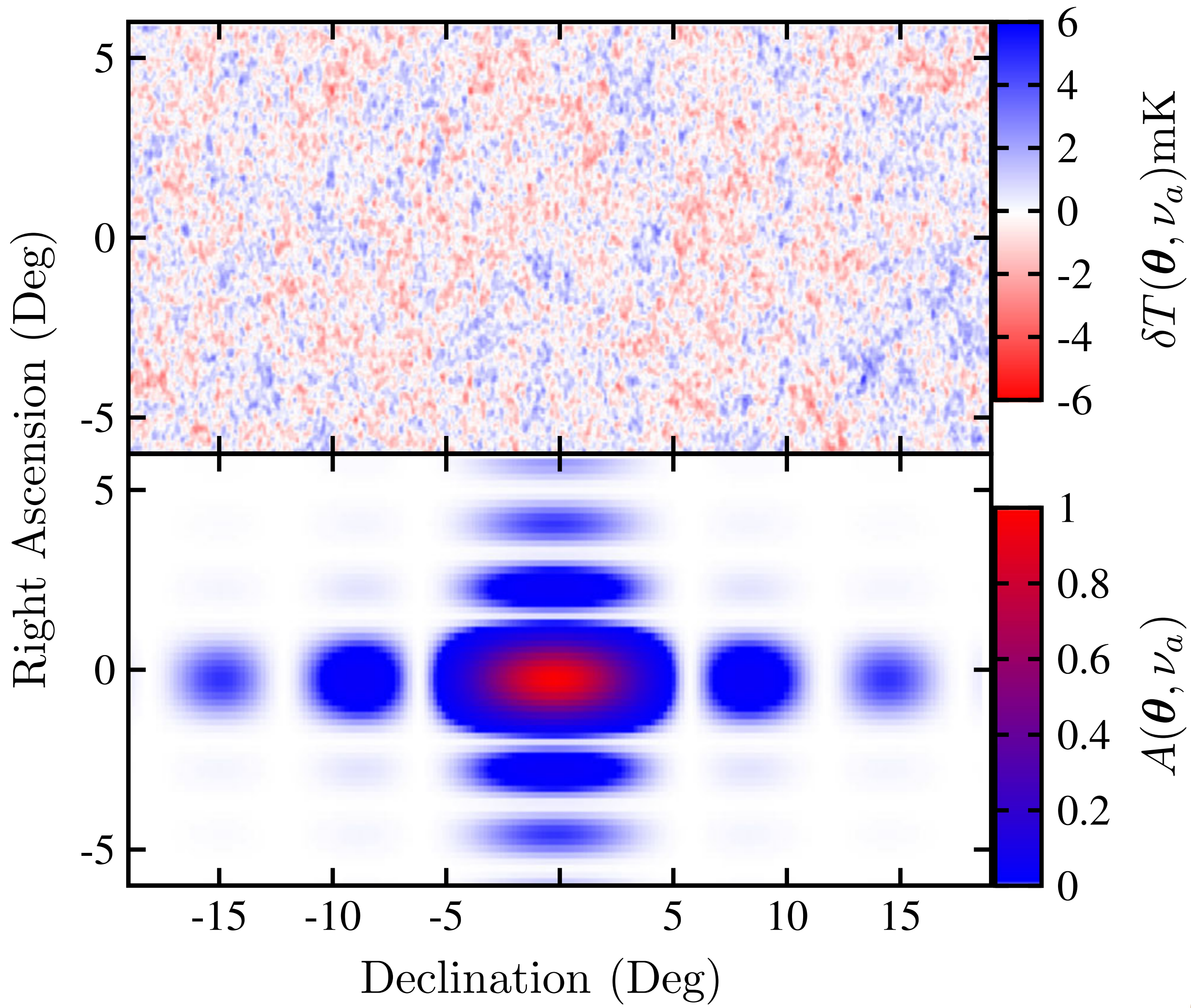
$$\mathbf{S}_2(\mathbf{U}_n, \Delta\nu) = \left(\frac{\partial B}{\partial T}\right)^2 C_\ell(\Delta\nu) \left[\int d^2\mathbf{U}' |\tilde{A}(\mathbf{U}_n - \mathbf{U}')|^2\right]$$

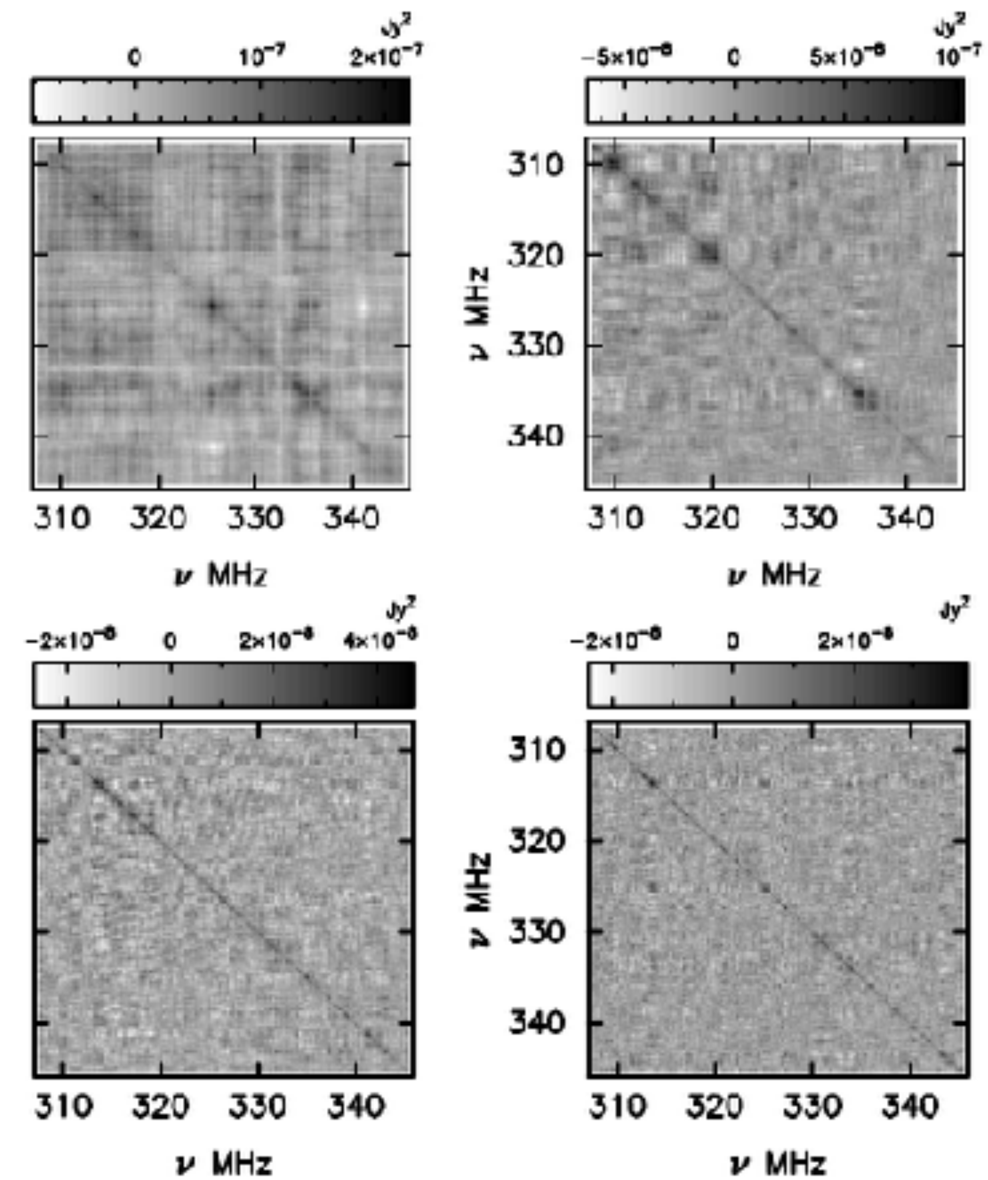


The HI signal

$$\bar{T}(z) = 4.0\ (1+z)^2\ \left(\frac{\Omega_b h^2}{0.024}\right)\left(\frac{0.7}{h}\right)\left(\frac{H_0}{H(z)}\right)\ \mathrm{mK}$$

LCDM $P(\mathbf{k})$ $\longrightarrow$ $P_{\rm HI}(\mathbf{k},\mu) = b^2\ \bar{x}_{\rm HI}^2\ \bar{T}^2\ [1+\beta\mu^2]^2\ P(\mathbf{k})$

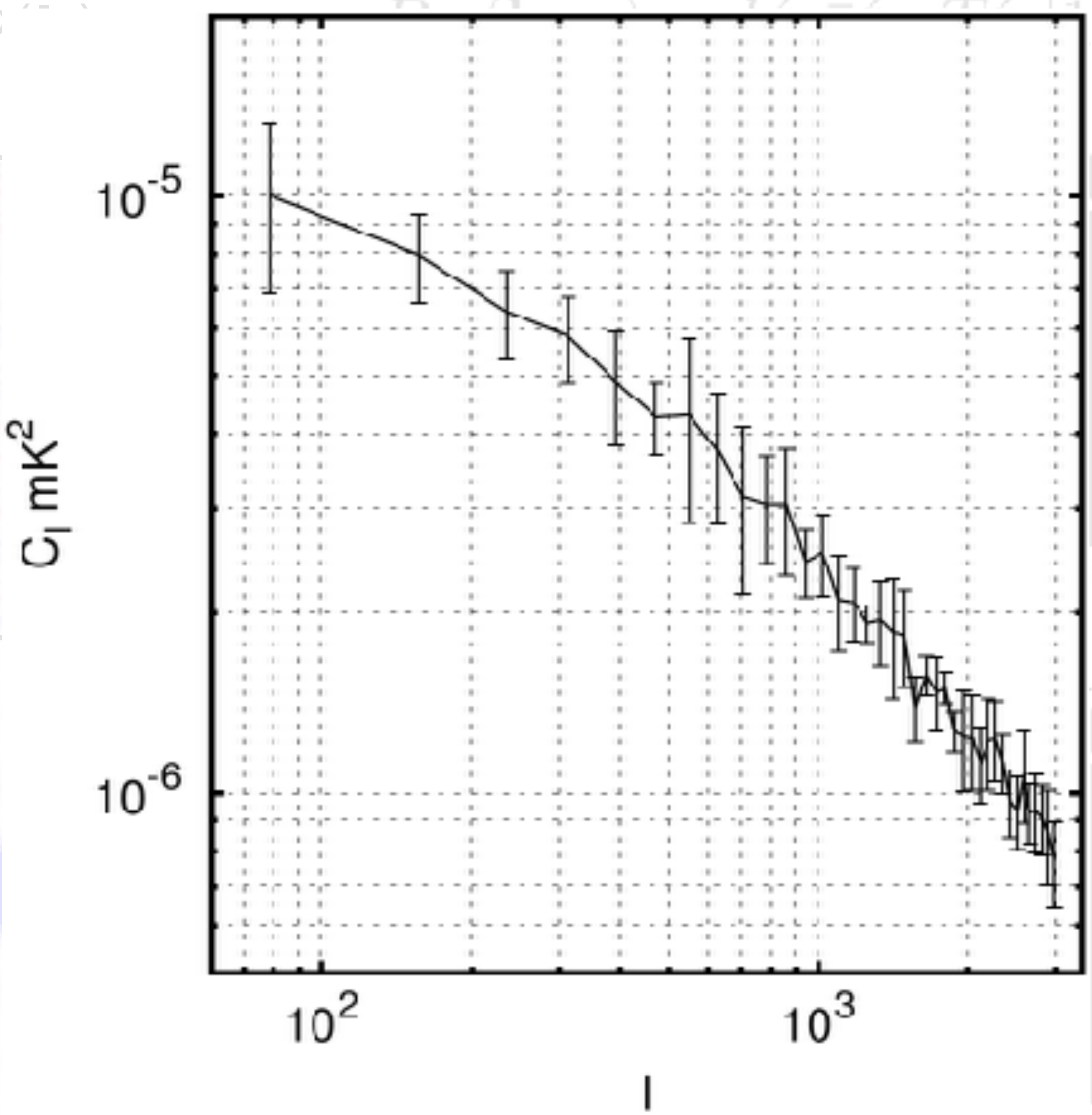




Chatterjee, Bharadwaj & Marthi, 2017

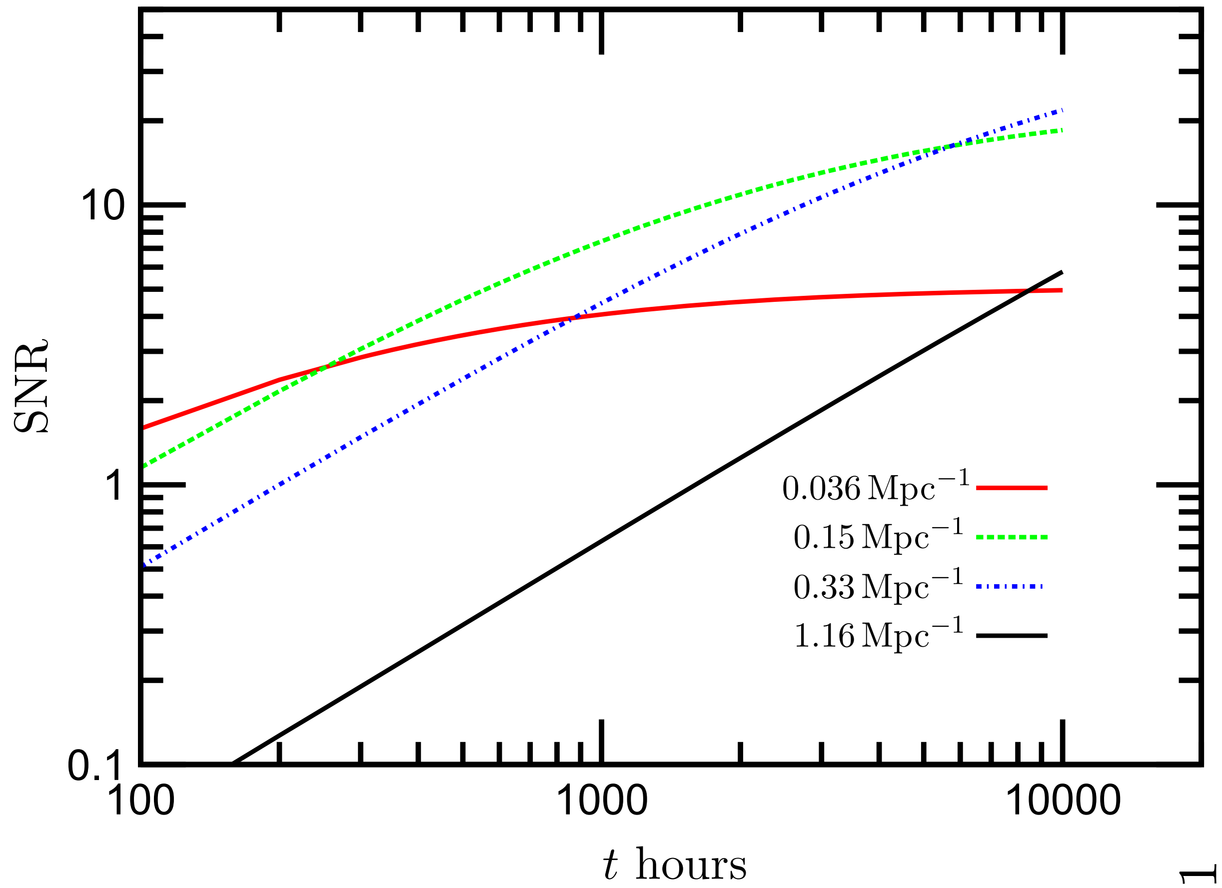
The HI signal

Prediction for $C_\ell(\triangle\nu{=}0)$ considering the instrument response

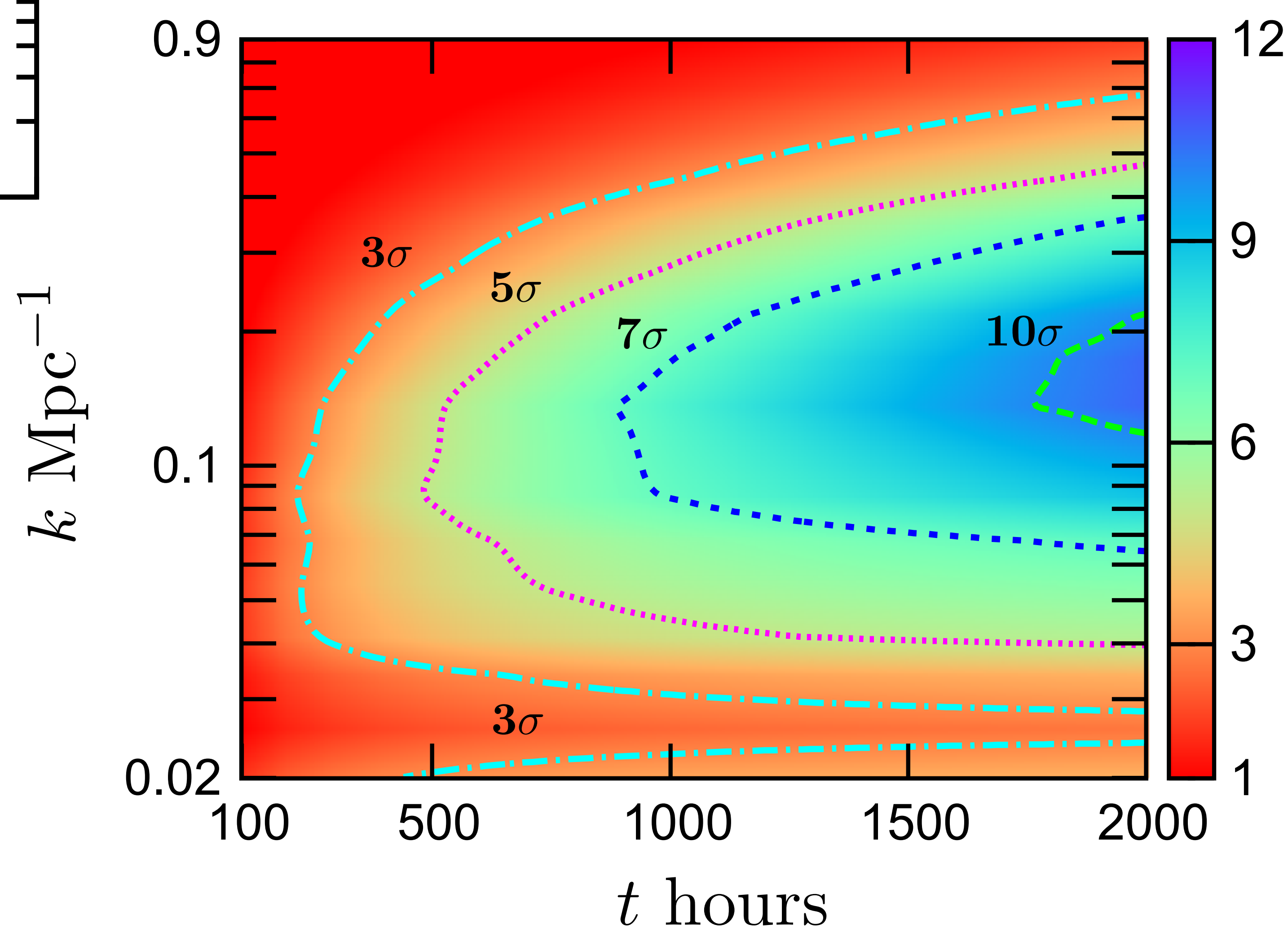


Marthi, Chatterjee, Bharadwaj & Chengalur, 2018, *in prep.*

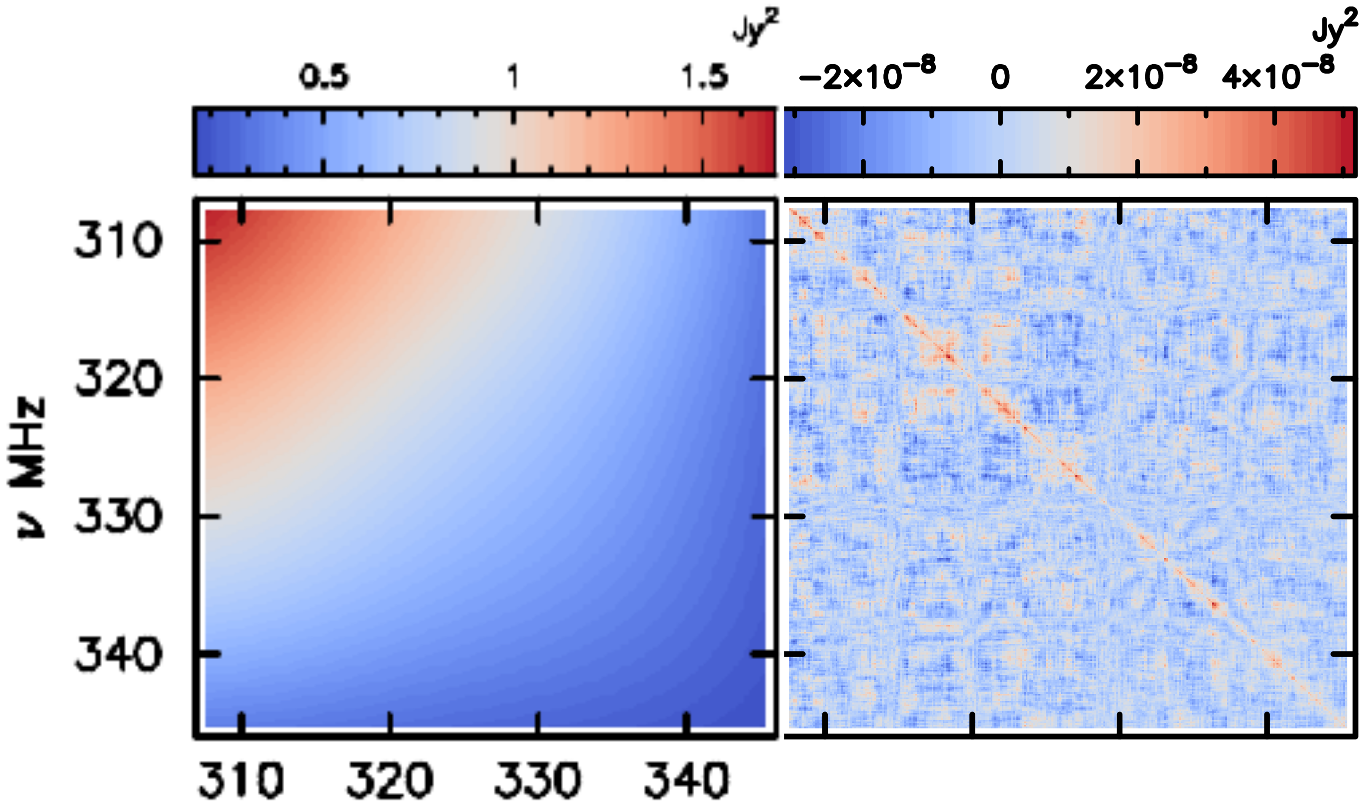
Forecast for HI detectability

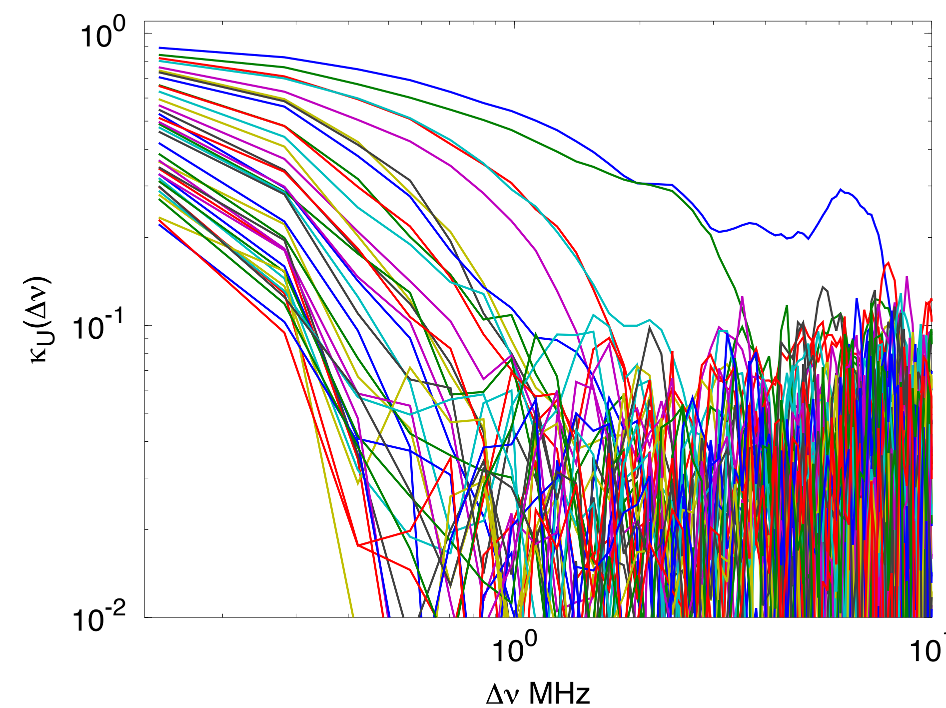


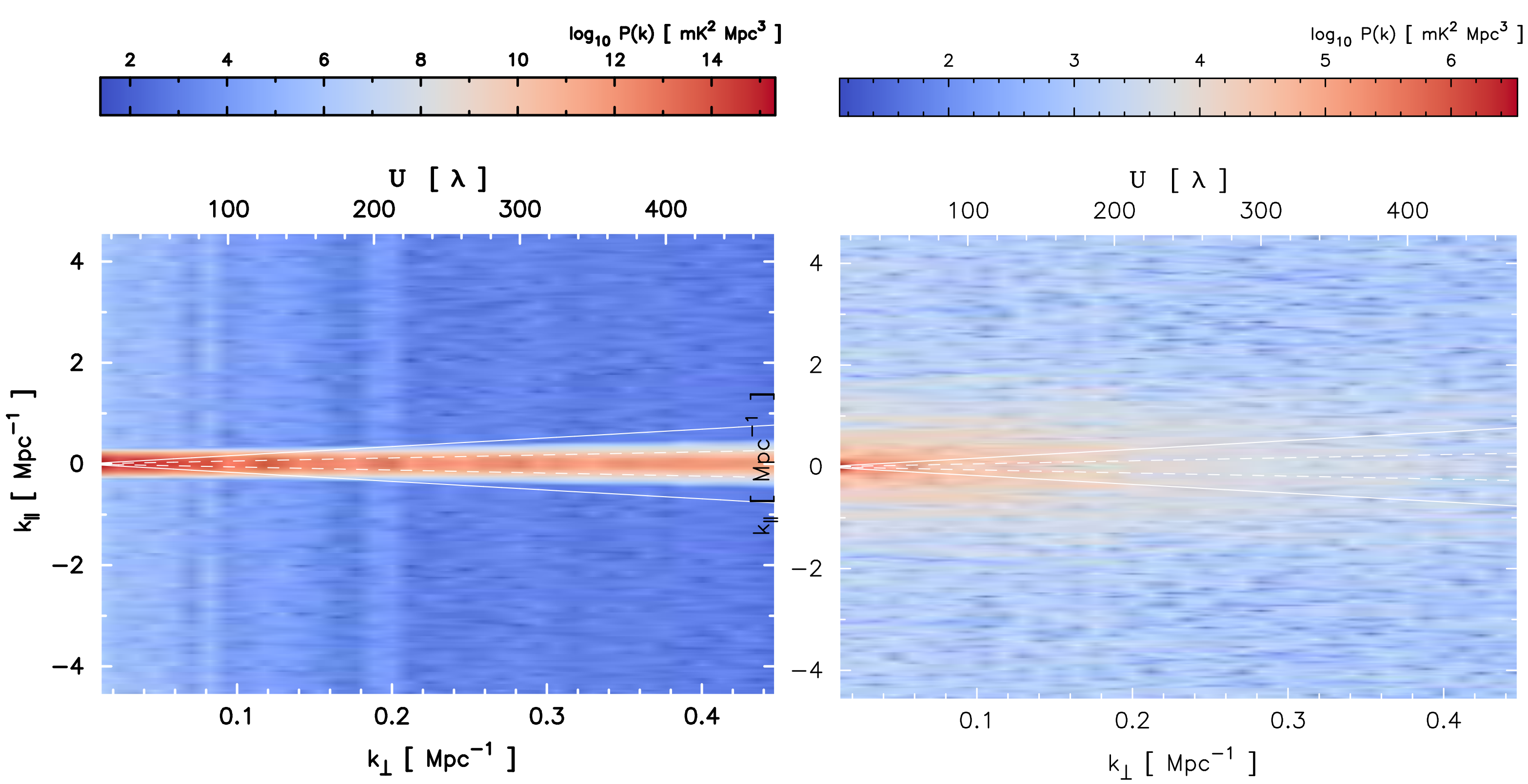
Sarkar, Bharadwaj & Ali 2017



Signal-foreground separation







Summary

- OWFA is upgraded ORT - new flexible backend
- Transients and FRB searches - large FoV
- z=3.3 is interesting, accessible to OWFA
- Visibility-based power spectrum estimation
- Polarization is unknown territory
- Transit / tracking observations
- Full-spec correlator ready, to be deployed, testing in progress

Instrument and foreground simulations

$$C_\ell(\nu) = A_0 \left(\frac{\nu_0}{\nu}\right)^{2\alpha} \left(\frac{\ell_0}{\ell}\right)^{\gamma}$$

$$C_\ell = 513\ \mathrm{mK}^2 \times \left(\frac{150}{326.5}\right)^{2\times 2.54} \left(\frac{1000}{\ell}\right)^{2.34}$$

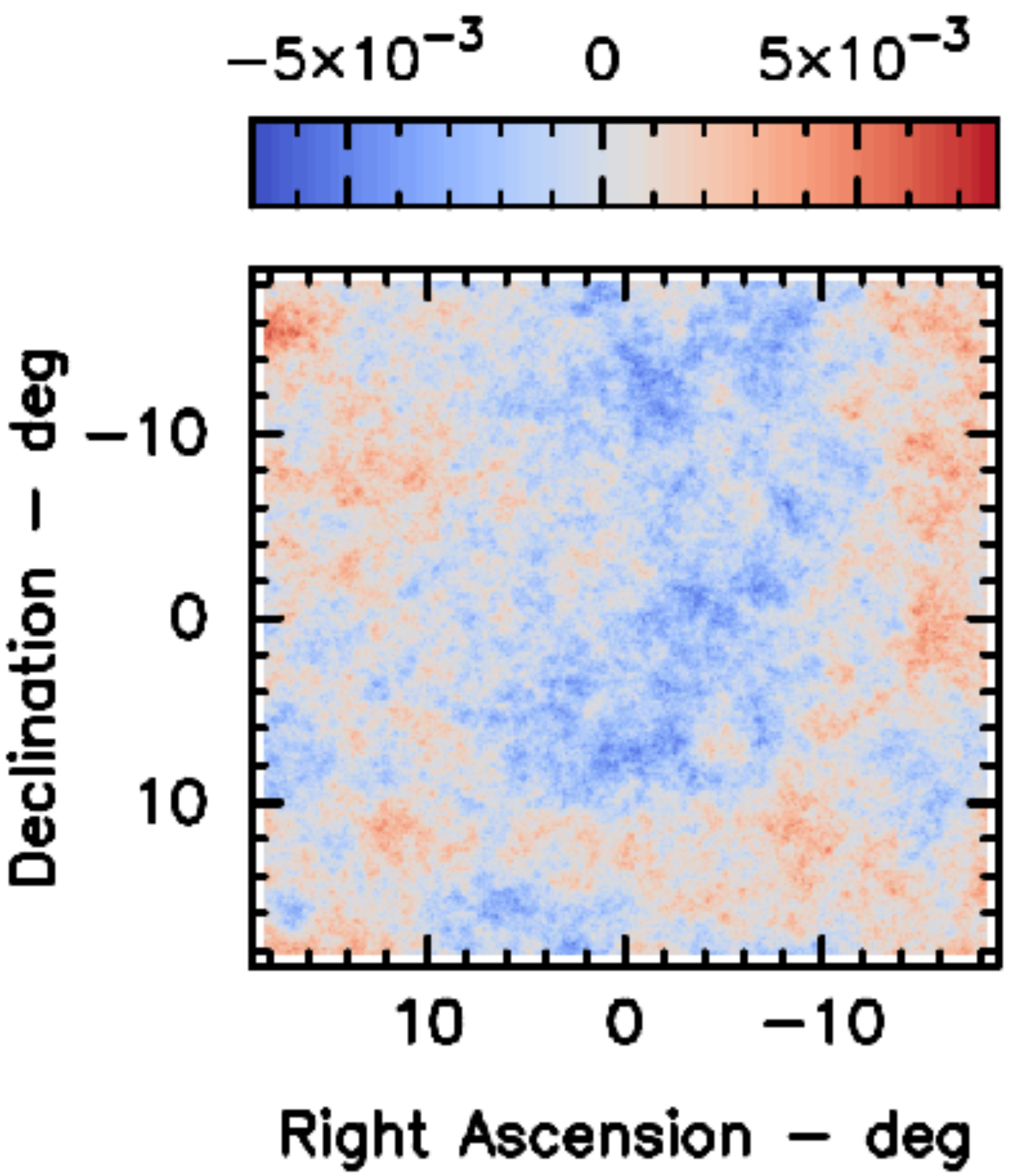
Ghosh et al., 2012, Rogers & Bowman., 2008

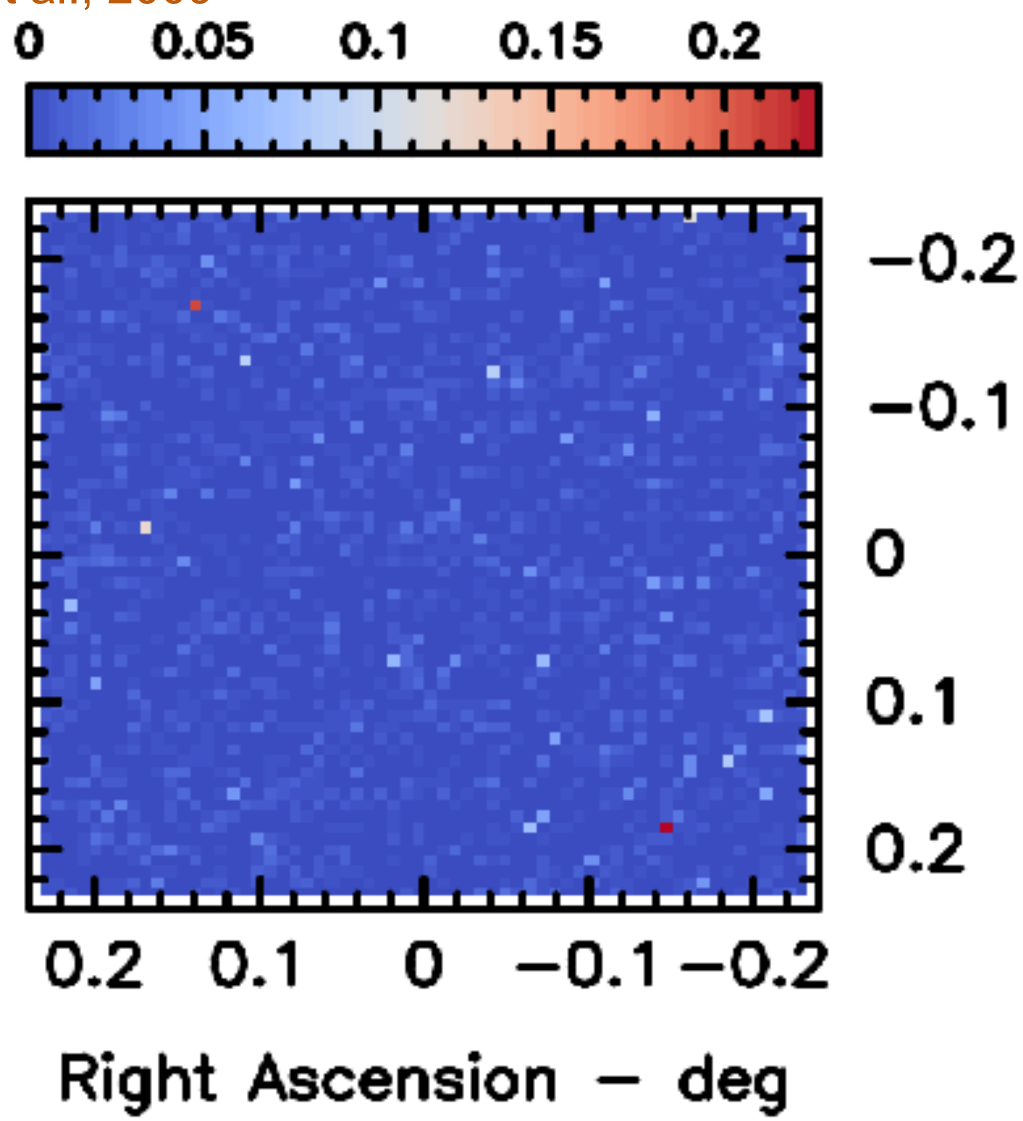
$$C_\ell = C_\ell^{\mathrm{P}} + C_\ell^{\mathrm{cl}}$$

$$C_\ell^{\mathrm{cl}} = 0.88 \times \frac{2\pi}{\theta_0^{-\beta}} \left(\frac{\partial B}{\partial T}\right)^{-2} \left[\int_0^{S_c} S \frac{dN}{dS} dS\right]^2 \ell^{\beta-2}$$

$$C_\ell^{\mathrm{P}} = \left(\frac{\partial B}{\partial T}\right)^{-2} \left[\int_0^{S_c} S^2 \frac{dN}{dS} dS\right]$$

Ali & Bharadwaj 2014, Owen & Morrison 2008, Sirothia et al., 2009

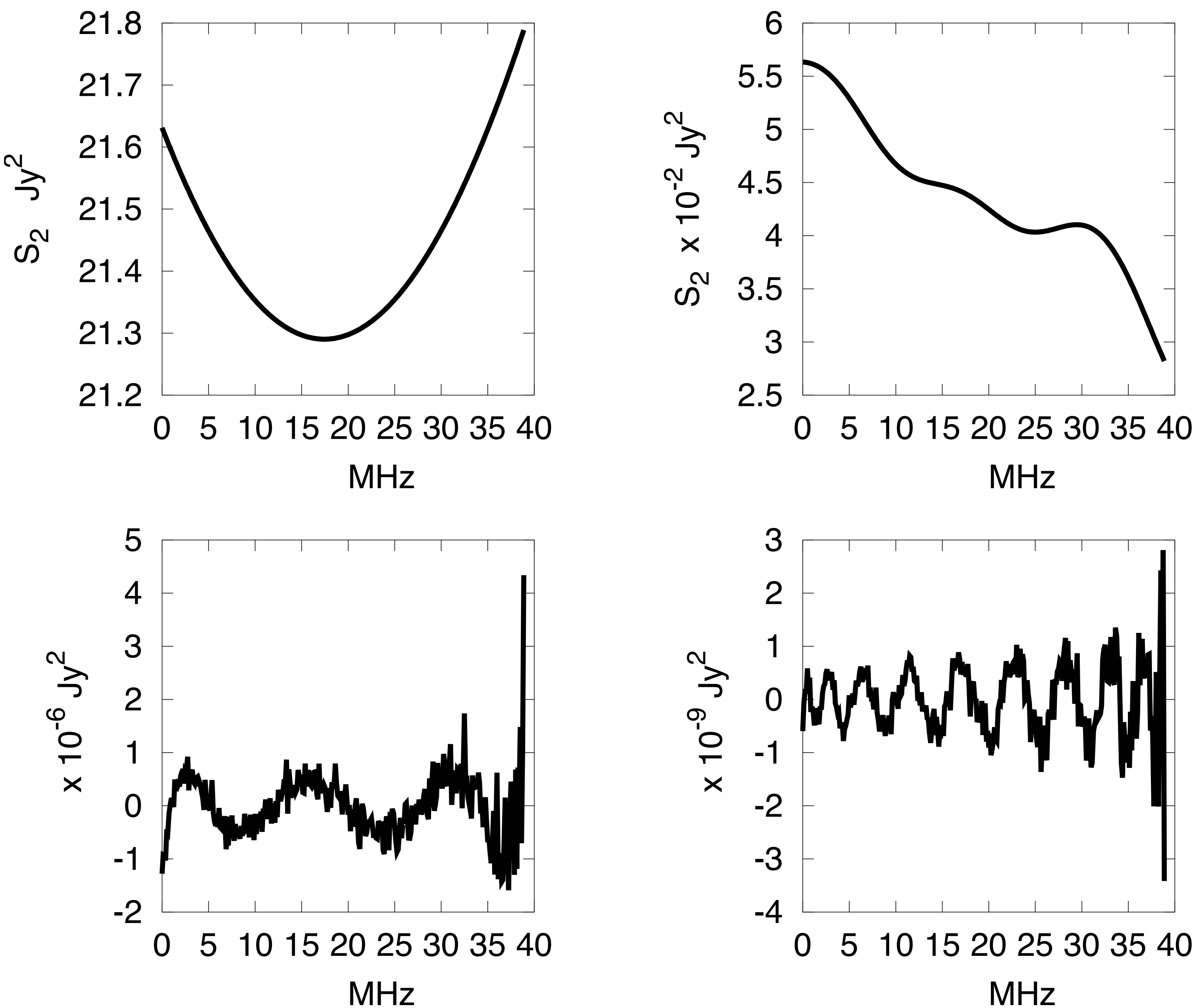




Marthi, Chatterjee, Chengalur & Bharadwaj, 2017, MNRAS.

Chromatic systematics

$$\mathbf{S}_2(\mathbf{U}_n, \nu_i, \nu_j) \sim |\mathbf{I}(\boldsymbol{\theta}, \nu_0)|^2 \, |\mathbf{A}(\boldsymbol{\theta}, \nu_0)|^2 \, e^{-i2\pi m\left(\frac{nd}{\lambda_0}\right)\left(\frac{\nu_i - \nu_j}{\nu_0}\right)}$$



$$|\mathbf{I}(\boldsymbol{\theta}, \nu_0)|^2 = \mathbf{I}(\boldsymbol{\theta}, \nu_i)\mathbf{I}^*(\boldsymbol{\theta}, \nu_j)$$

$$|\mathbf{A}(\boldsymbol{\theta}, \nu_0)|^2 = \mathbf{A}(\boldsymbol{\theta}, \nu_i)\mathbf{A}^*(\boldsymbol{\theta}, \nu_j)$$

Chromatic systematics