Point source modeling and removal

Outline:

- Background
- Point sources: some details
- Key imaging issues
  - gain calibration
  - imaging and deconvolution
  - primary beam response
- TGE: preliminary results
- Directions …

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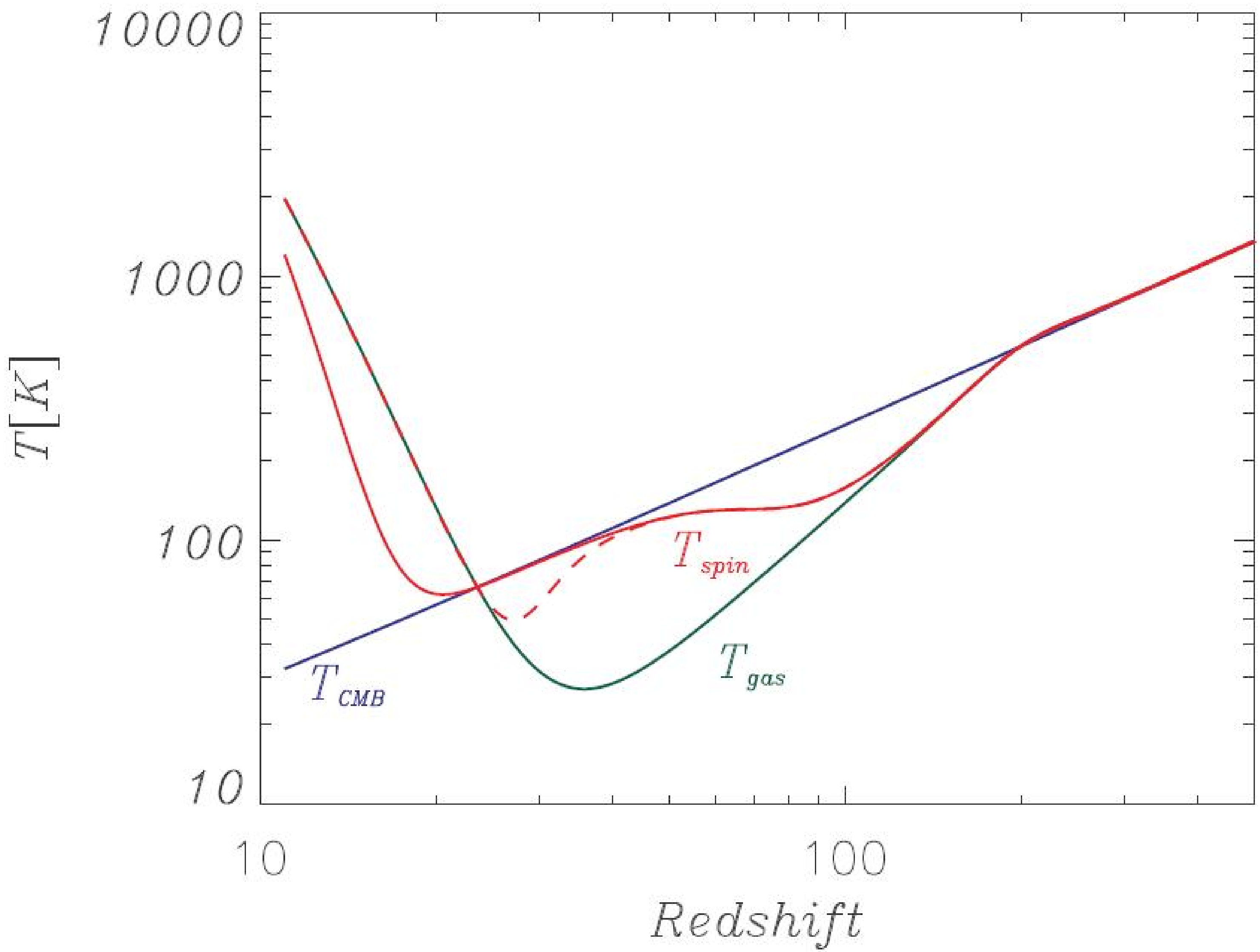
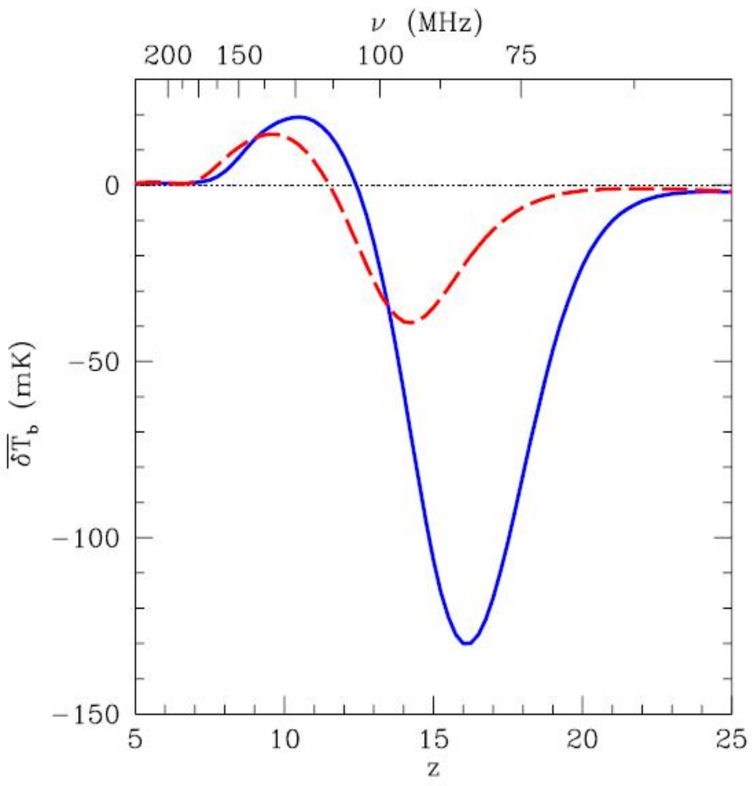
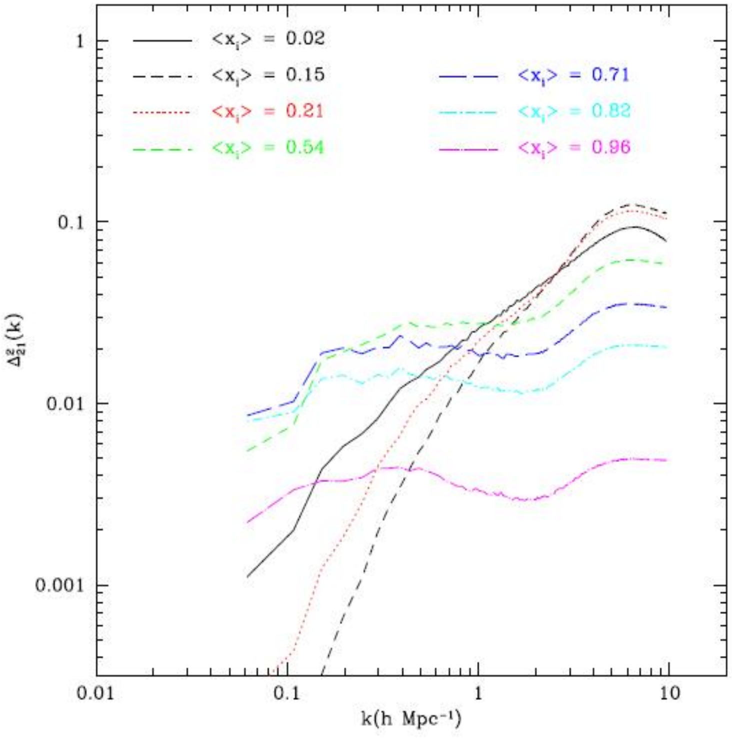
CMB, gas and spin temp.



Credit: Zaroubi (2012)

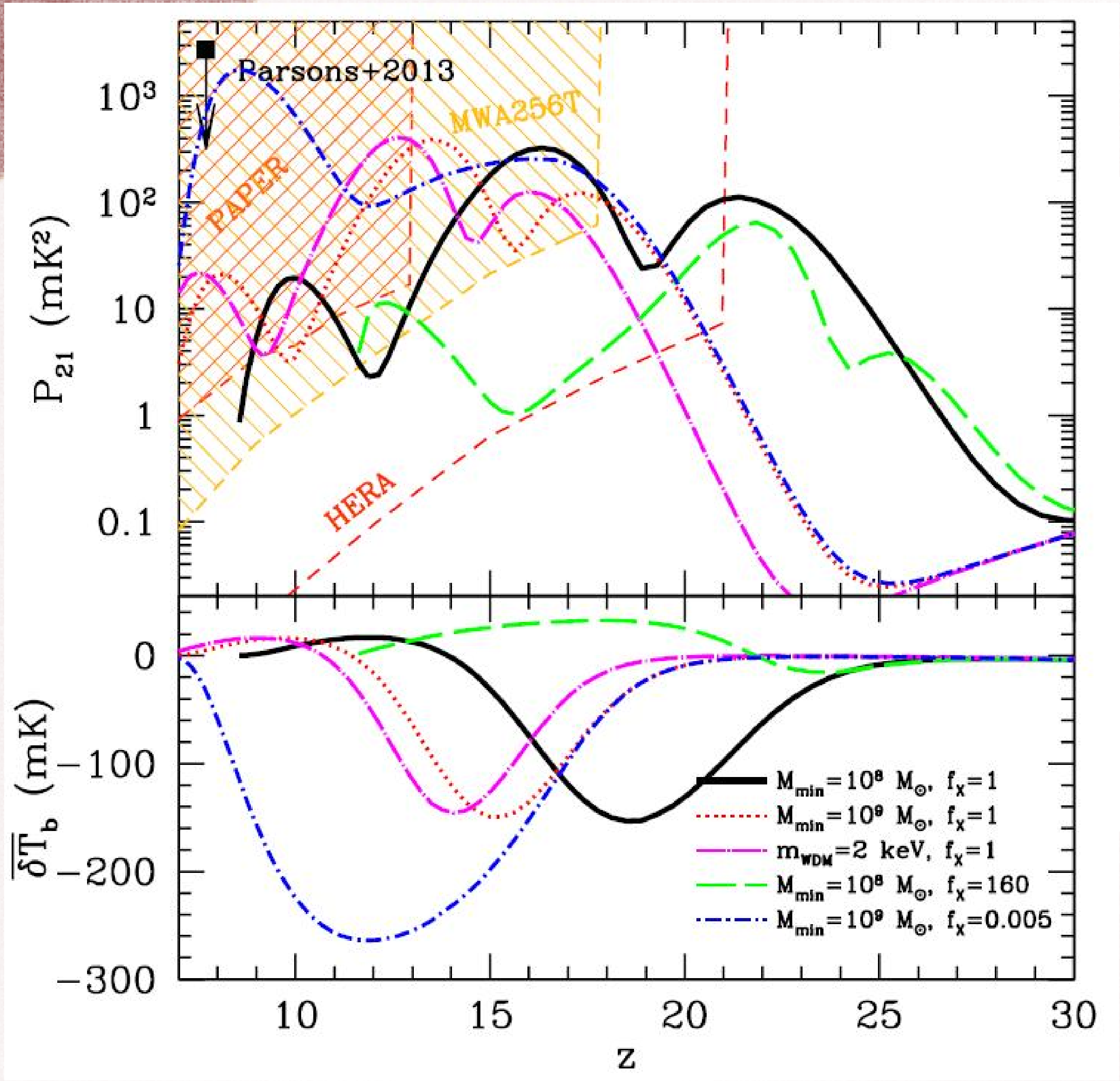
Global signal and power spectrum





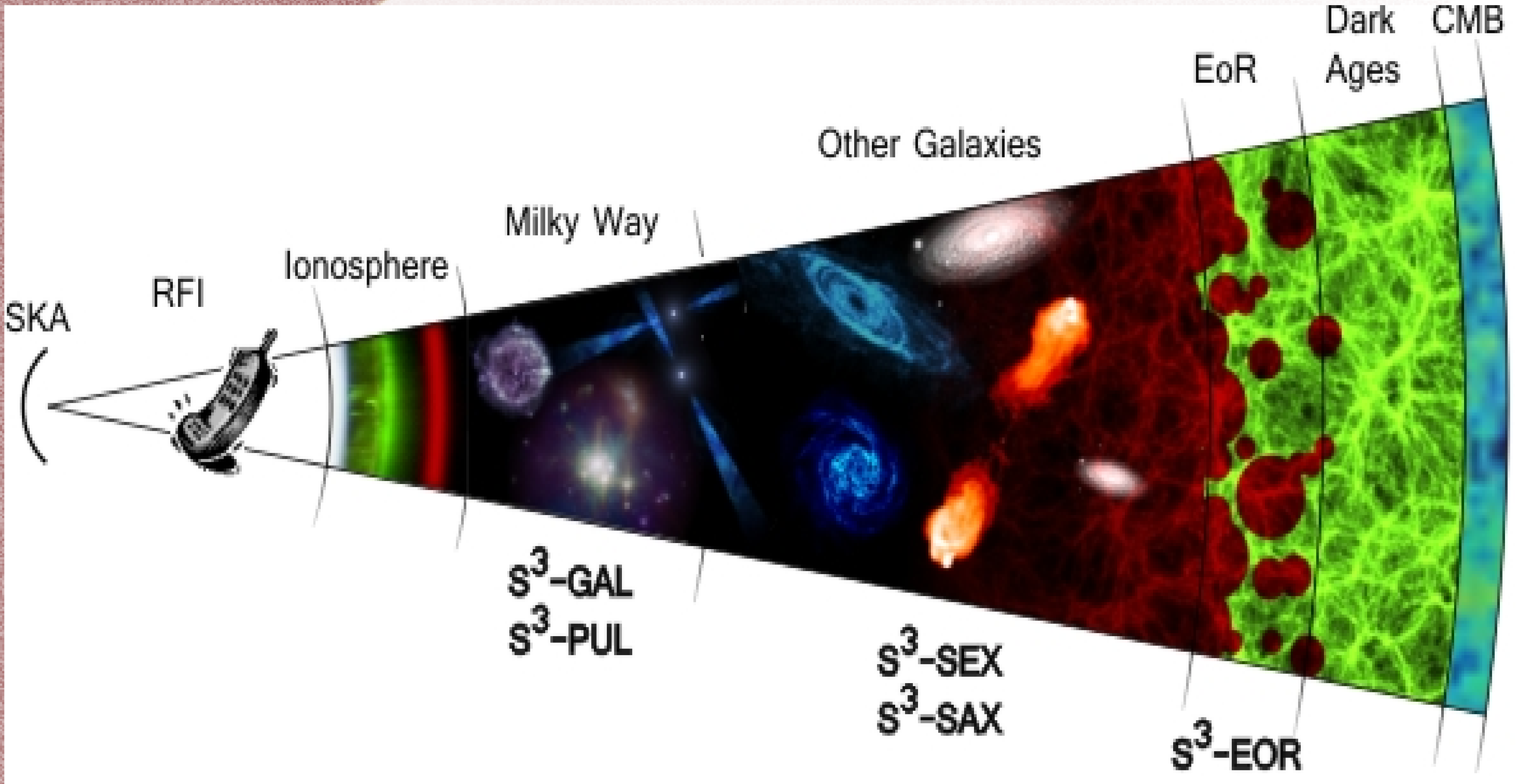
Credit: Backer et al.; HERA Astro2010 paper

Global signal and power spectrum



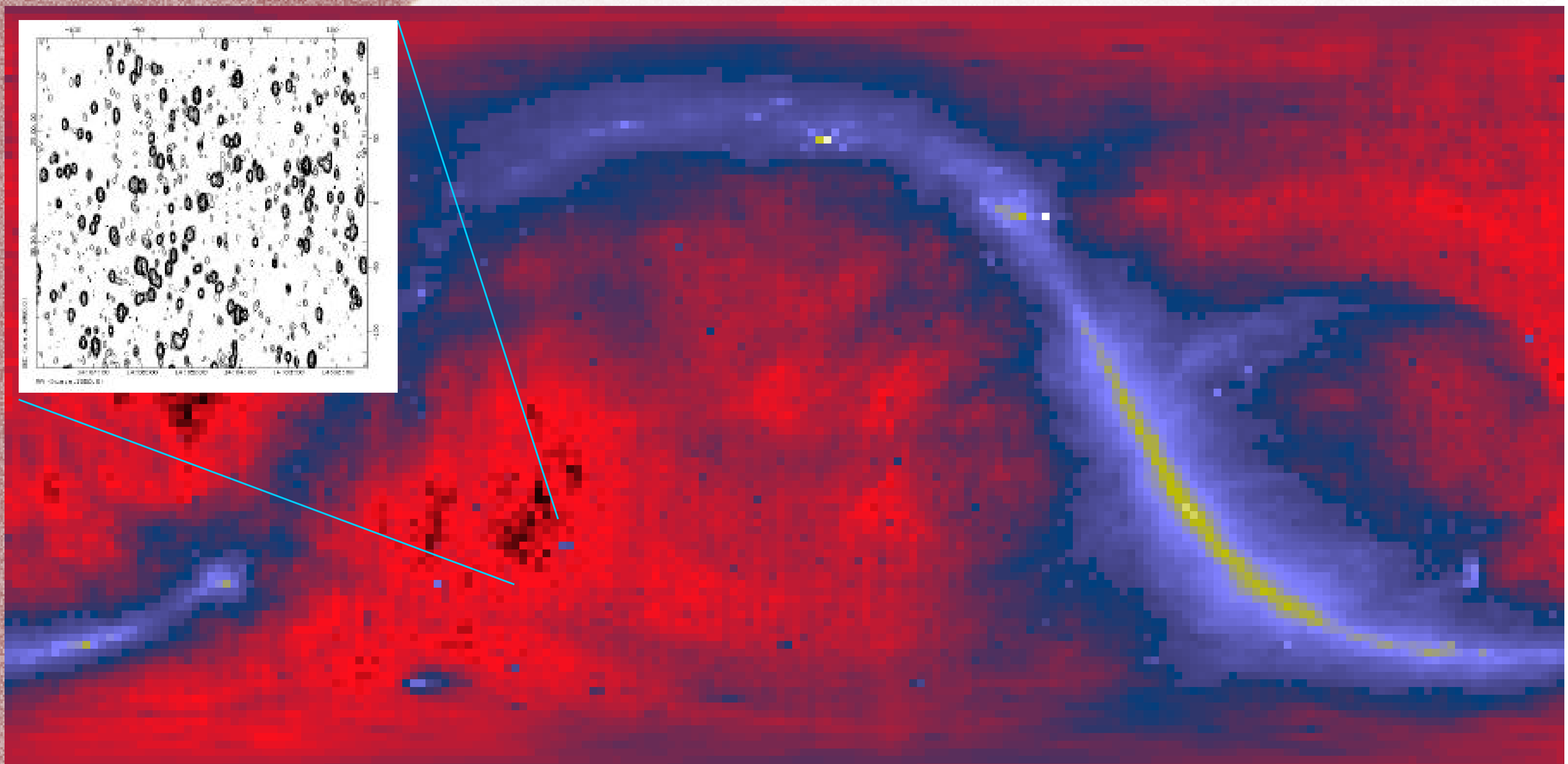
Credit: Furlanetto (2015)

Signal, foregrounds …



Credit: SKA Simulated Skies, Univ. of Oxford

Low frequency foreground – hot, confused sky



Credit: Haslam et al. 1982; 408 MHz

Coldest regions: $T \sim 100\ (\nu\ /200\ \mathrm{MHz})^{-2.6}$ K

Galactic (90%); Extragalactic (10%) ~ 1 source/deg^2 with $S_{140} > 1$ Jy

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Point sources …

$$\frac{\mathrm{d}N}{\mathrm{d}S} = \frac{4000}{\mathrm{Jy} \times \mathrm{Sr}} \left(\frac{S}{1\,\mathrm{Jy}} \right)^{-1.75}$$

Credit: di Matteo+ (2002); Ali+ (2008)

Point sources …

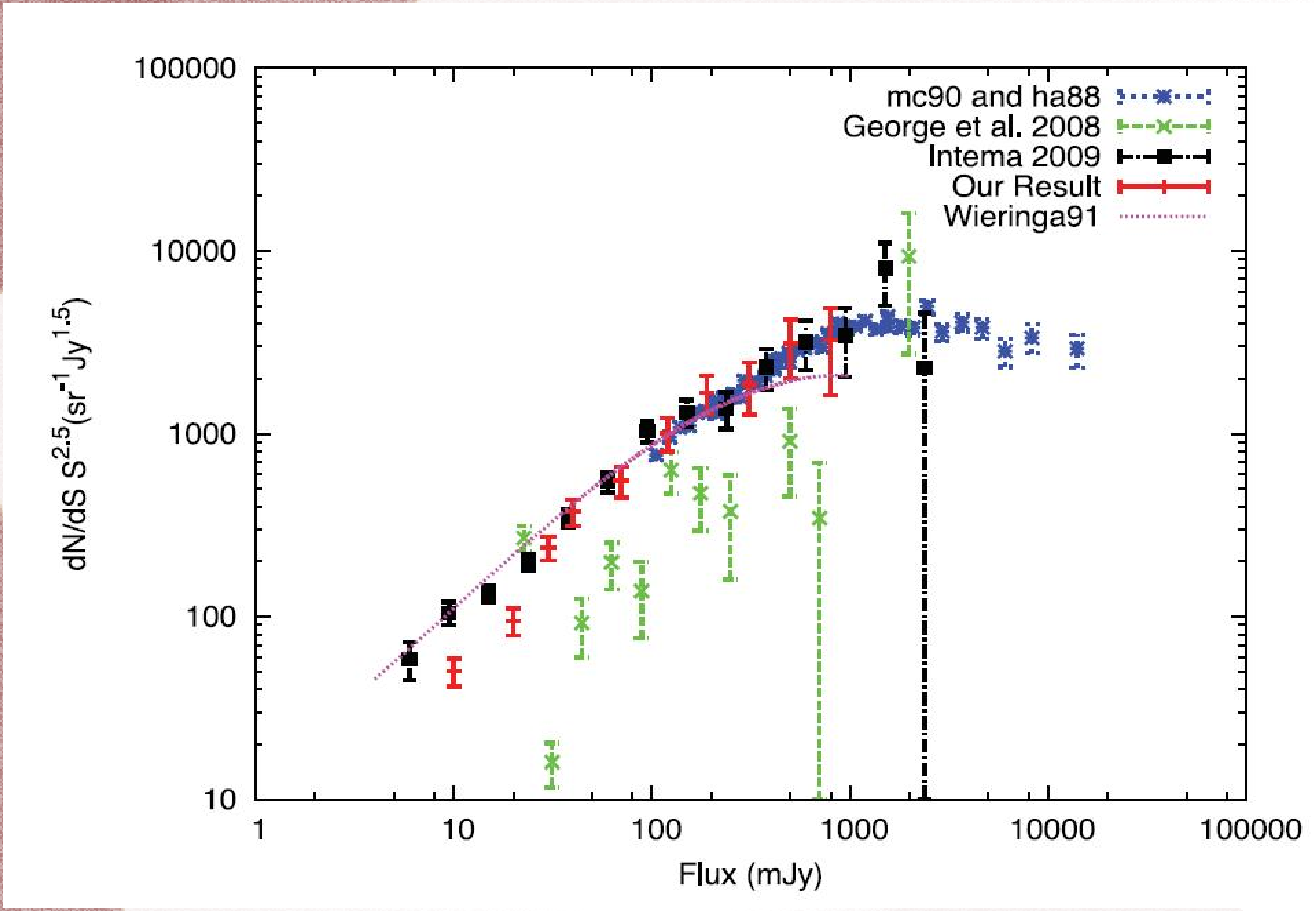
$$\frac{\mathrm{d}N}{\mathrm{d}S} = \frac{4000}{\mathrm{Jy} \times \mathrm{Sr}} \left(\frac{S}{1\,\mathrm{Jy}} \right)^{-1.75}$$

$$\log_{10}\left(\frac{\mathrm{d}N}{\mathrm{d}S} S^{2.5}\right) = 0.976 + 0.6136x + 0.3028x^2 - 0.083x^3$$

where $x = \log_{10}(S)$ and S is given in mJy.

Credit: di Matteo+ (2002); Wieringa (1991)

Point sources …



Credit: Ghosh+ (2012)

Point sources …

$$\frac{\mathrm{d}N}{\mathrm{d}S} = \frac{4000}{\mathrm{Jy} \times \mathrm{Sr}} \left(\frac{S}{1\,\mathrm{Jy}} \right)^{-1.75}$$

$$C_l(\nu_1, \nu_2) = A \left(\frac{\nu_f}{\nu_1} \right)^{\bar{\alpha}} \left(\frac{\nu_f}{\nu_2} \right)^{\bar{\alpha}} \left(\frac{1000}{l} \right)^{\beta} I_l(\nu_1, \nu_2),$$

$$I_l(\nu_1, \nu_2) = \exp\left[-\log_{10}^2 \left(\frac{\nu_2}{\nu_1} \right) / 2\xi^2 \right]$$

Credit: di Matteo+ (2002); Ali+ (2008)

Point sources …

$$C_l(\nu_1, \nu_2) = A \left(\frac{\nu_f}{\nu_1}\right)^{\bar{\alpha}} \left(\frac{\nu_f}{\nu_2}\right)^{\bar{\alpha}} \left(\frac{1000}{l}\right)^{\beta} I_l(\nu_1\,, \nu_2).$$

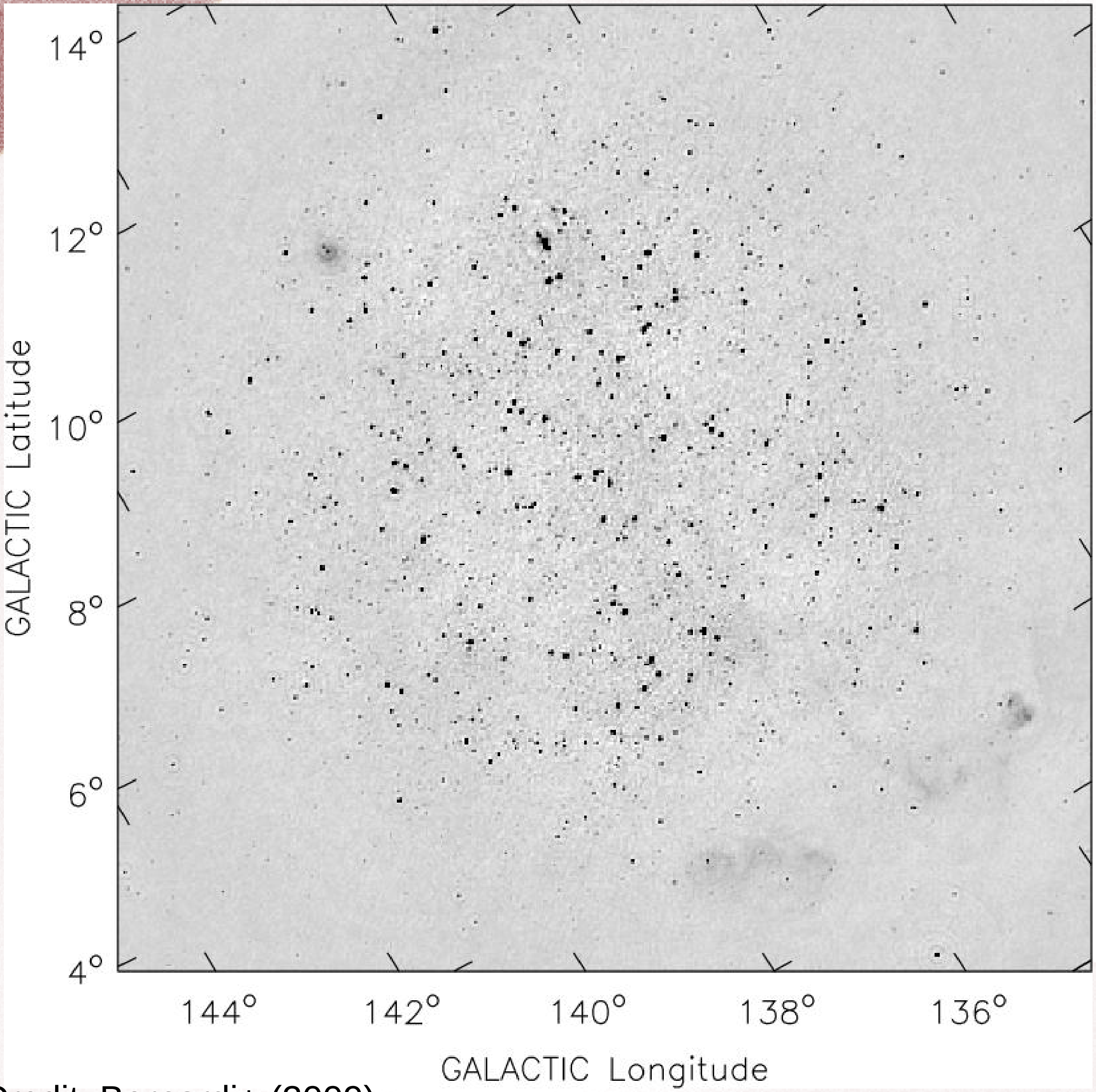
$$I_l(\nu_1\,, \nu_2) = \exp\left[-\log_{10}^2\left(\frac{\nu_2}{\nu_1}\right)/2\xi^2\right]$$

Table 1. Fiducial values of the parameters used for characterizing different foreground contributions.

Foregrounds	$A(\mathrm{mK}^2)$	$\bar{\alpha}$	β	ξ
Point source (Poisson part)	$1.2 \times 10^4\,(\frac{S_{\mathrm{cut}}}{\mathrm{Jy}})^{1.25}$	2.07	0	1
Point source (clustered part)	$6.1 \times 10^3\,(\frac{S_{\mathrm{cut}}}{\mathrm{Jy}})^{0.5}$	2.07	1.1	2
Galactic synchrotron	700	2.80	2.4	4

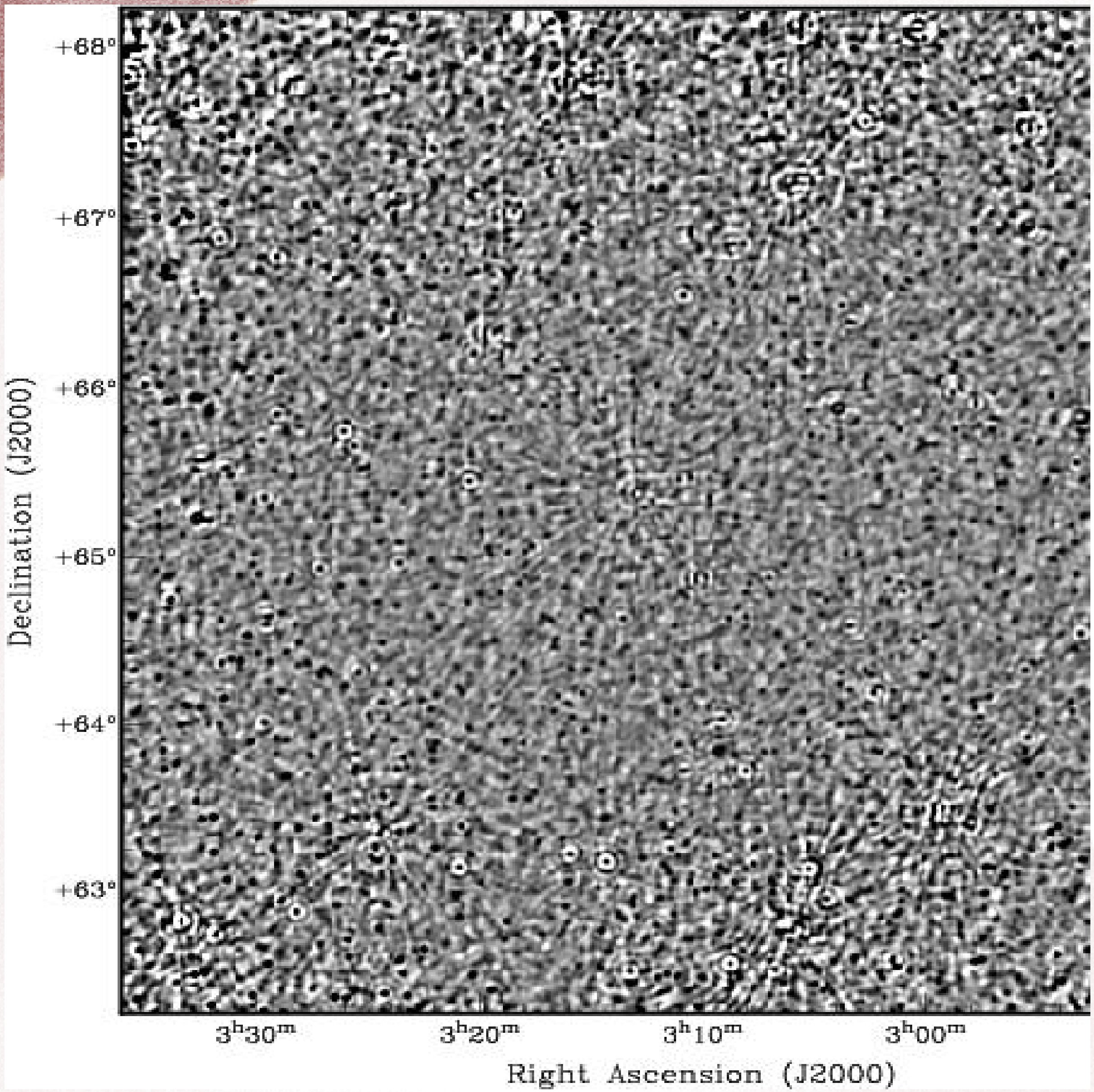
Credit: di Matteo+ (2002); Ali+ (2008)

Point sources …



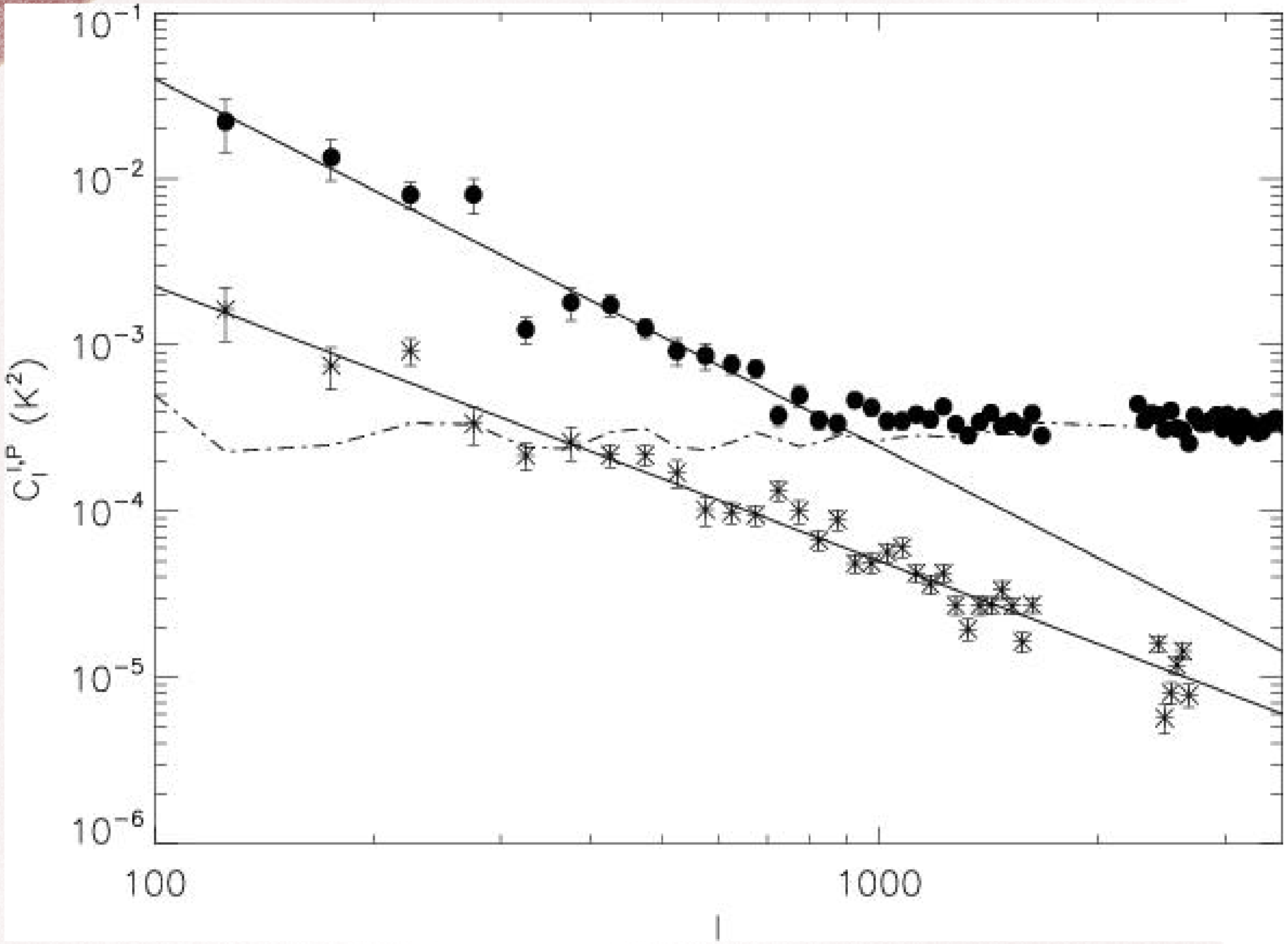
Credit: Bernardi+ (2009)

Point sources …



Credit: Bernardi+ (2009)

Point sources …

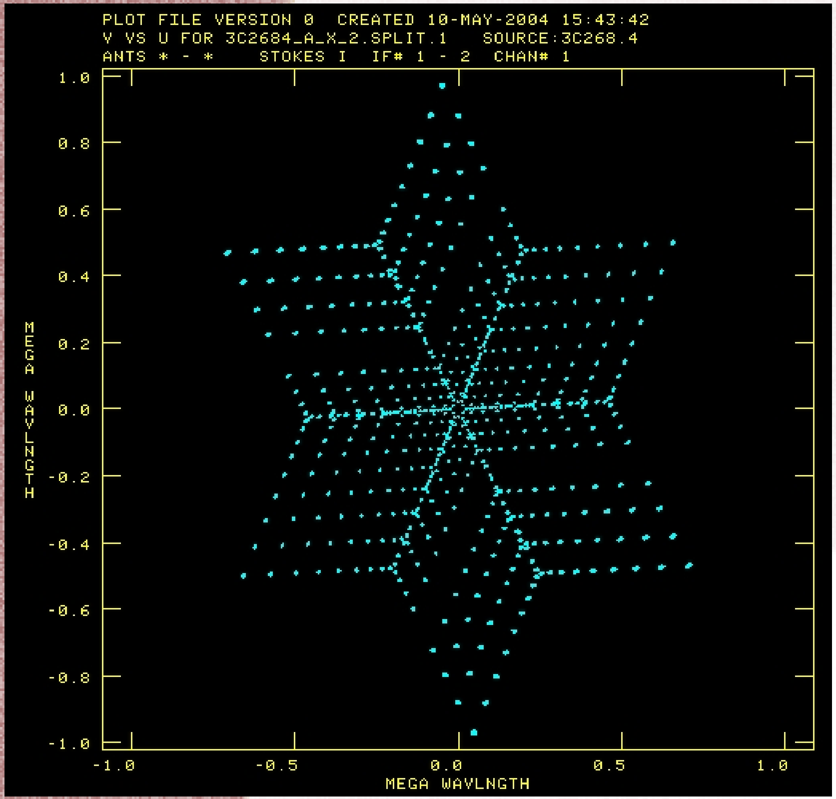


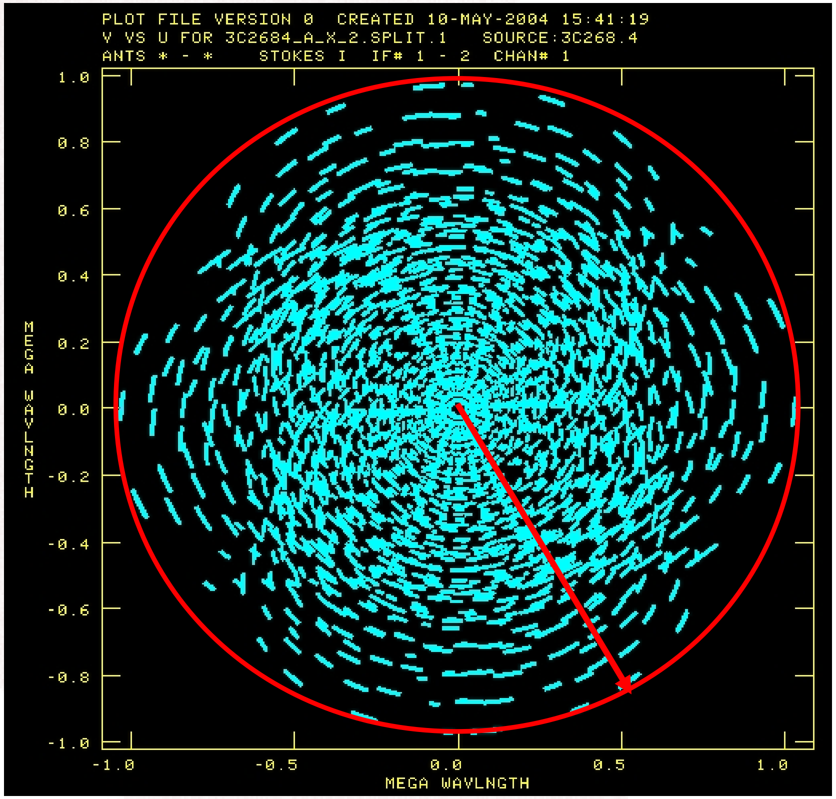
Credit: Bernardi+ (2009)

Accurate modeling and removal

- Pindor et al. (2010): Removal from “dirty” snapshot image using match filtering

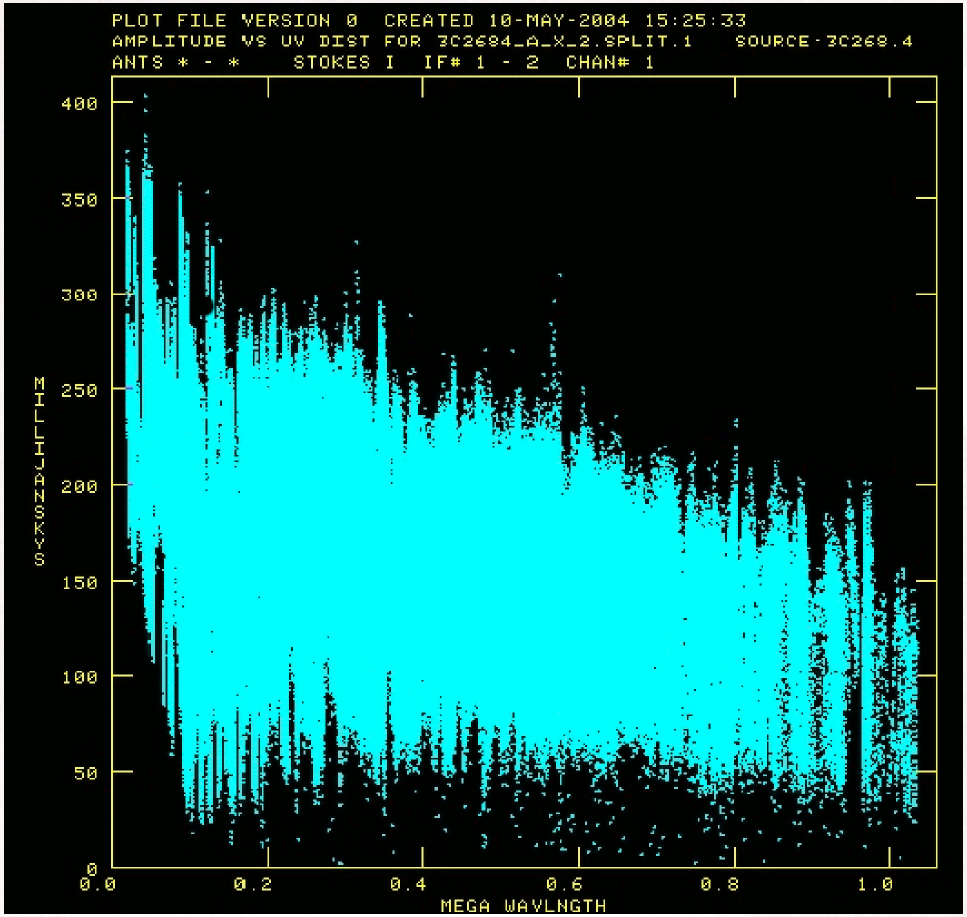
“uv coverage”



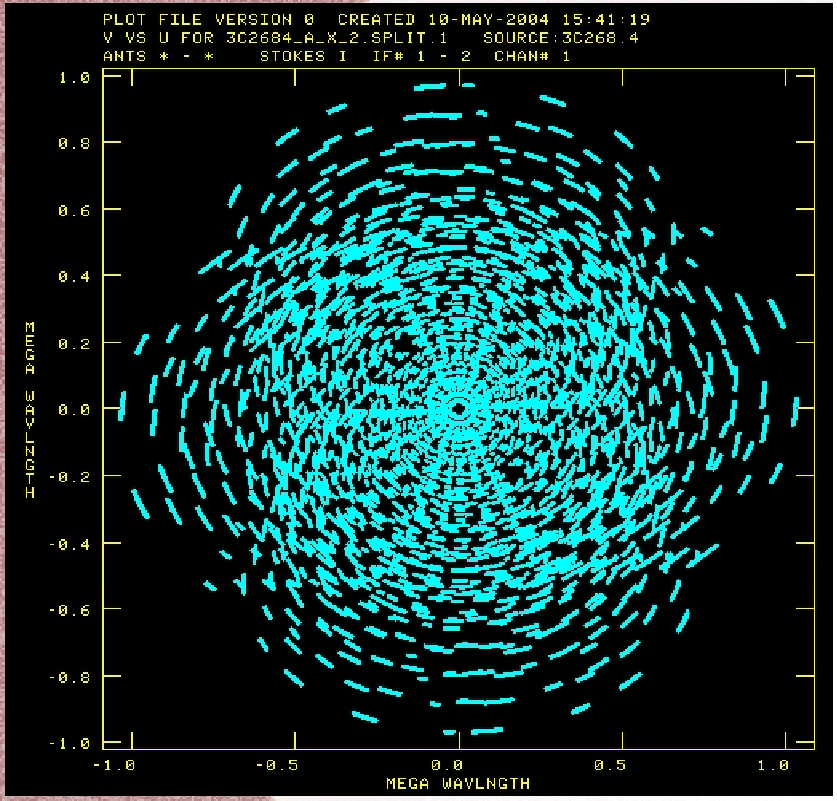


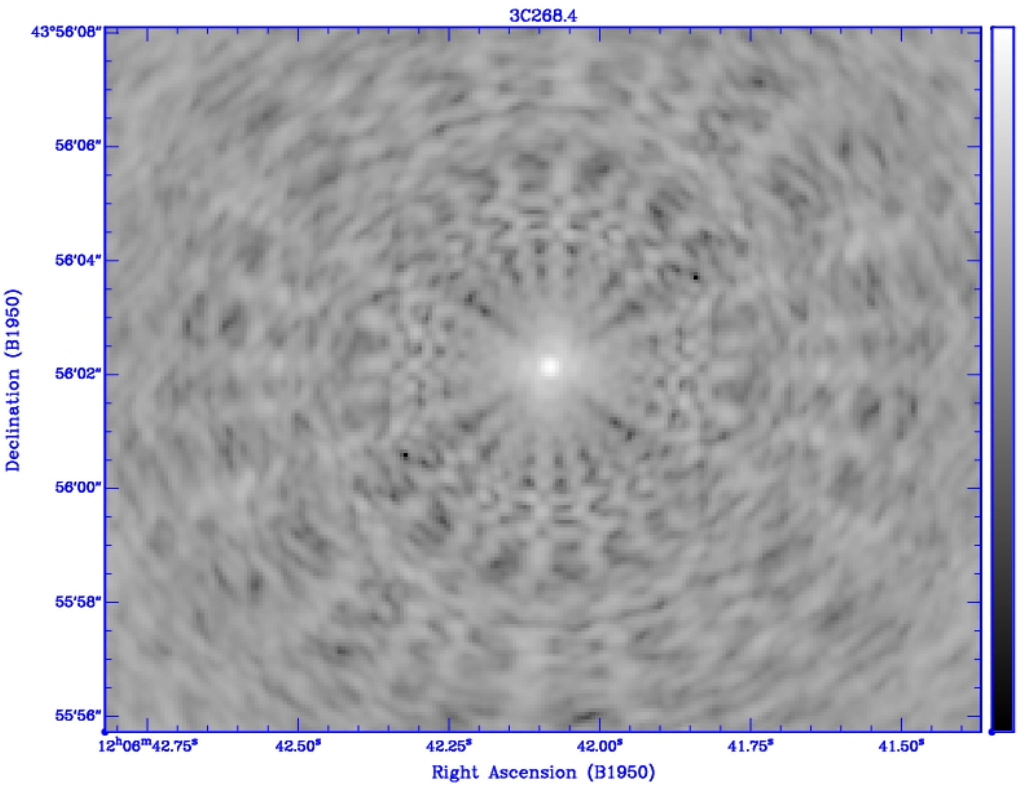
35.6 km

Visibility amplitudes



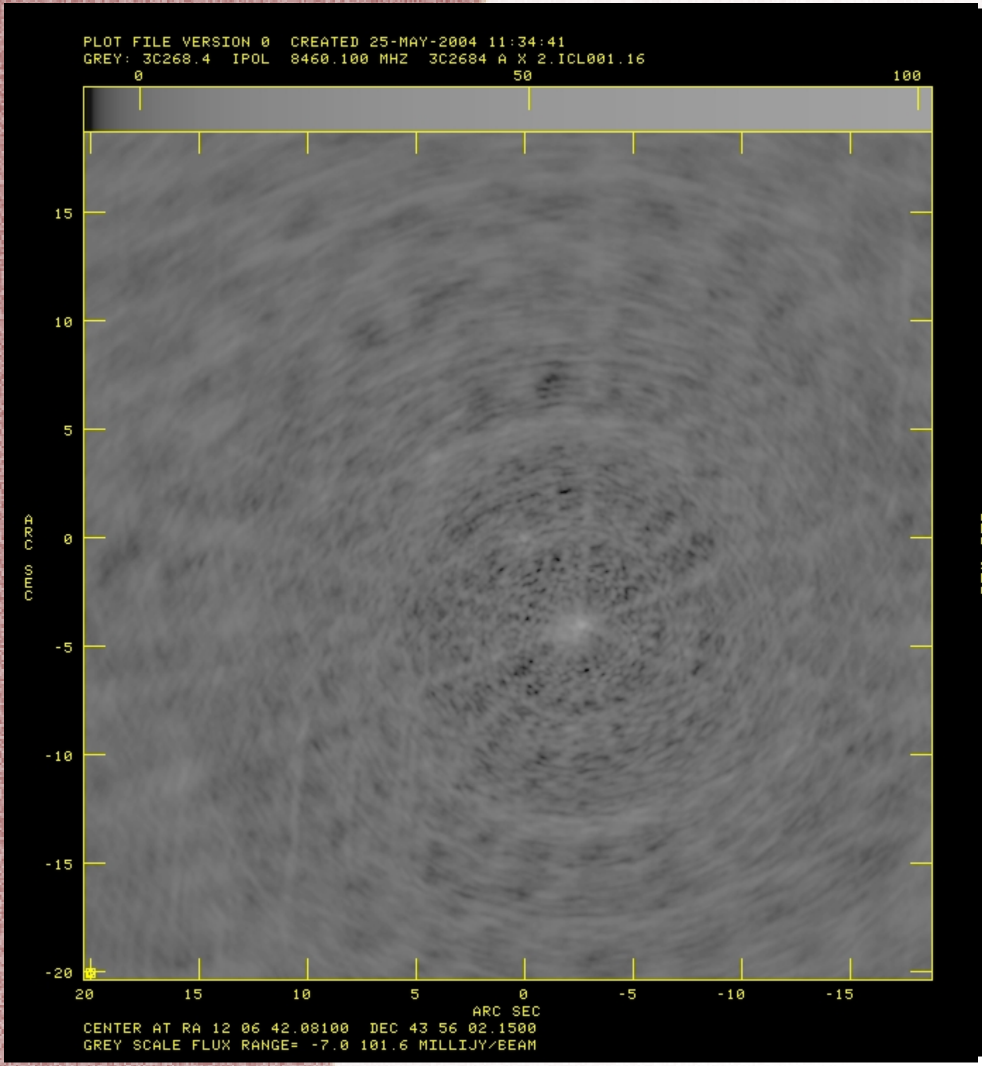
The "dirty" beam/map



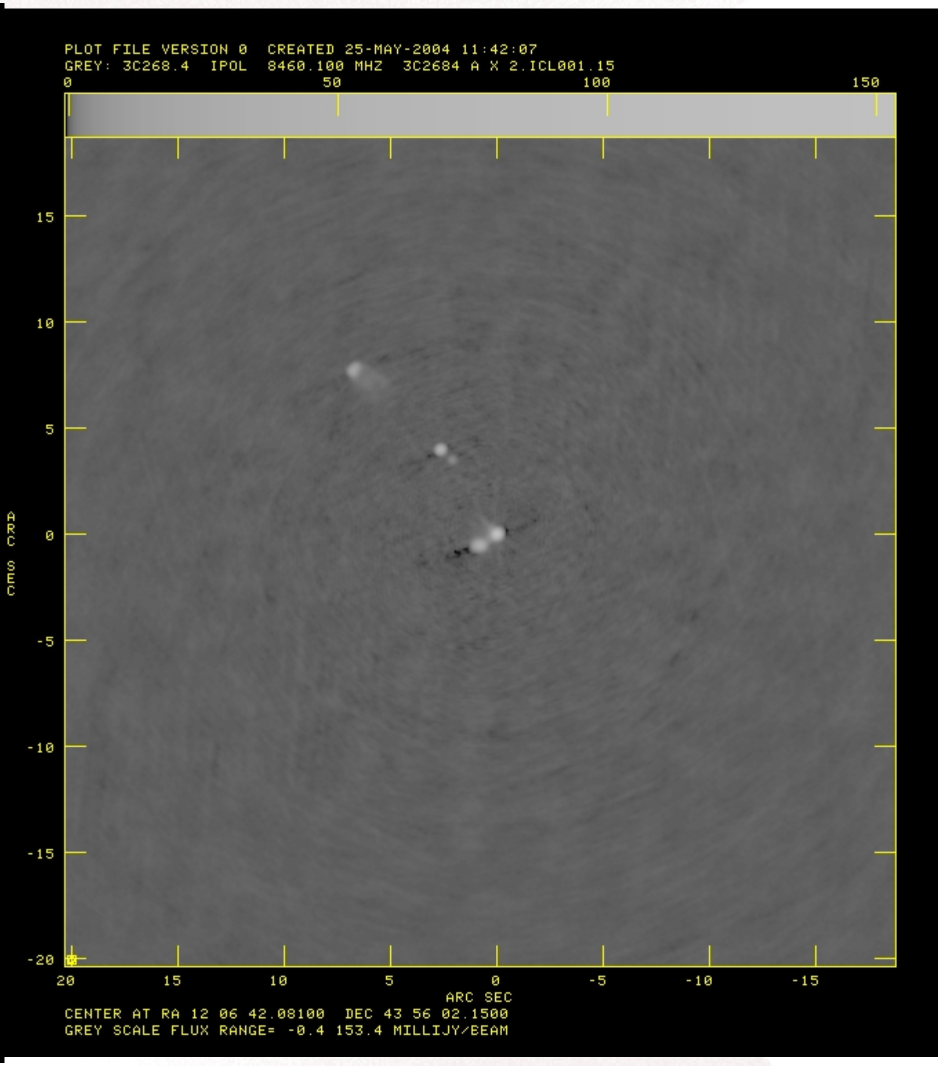


Deconvolution: The CLEAN map

“Dirty” map before CLEAN



After CLEAN



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  - very accurate position will be helpful

- Datta et al. (2010): 0.1 arcsec position accuracy, 0.05% accuracy in gain amplitude

Accurate modeling and removal

- Pindor et al. (2010): Removal from “dirty” snapshot image using match filtering
  - very accurate position will be helpful

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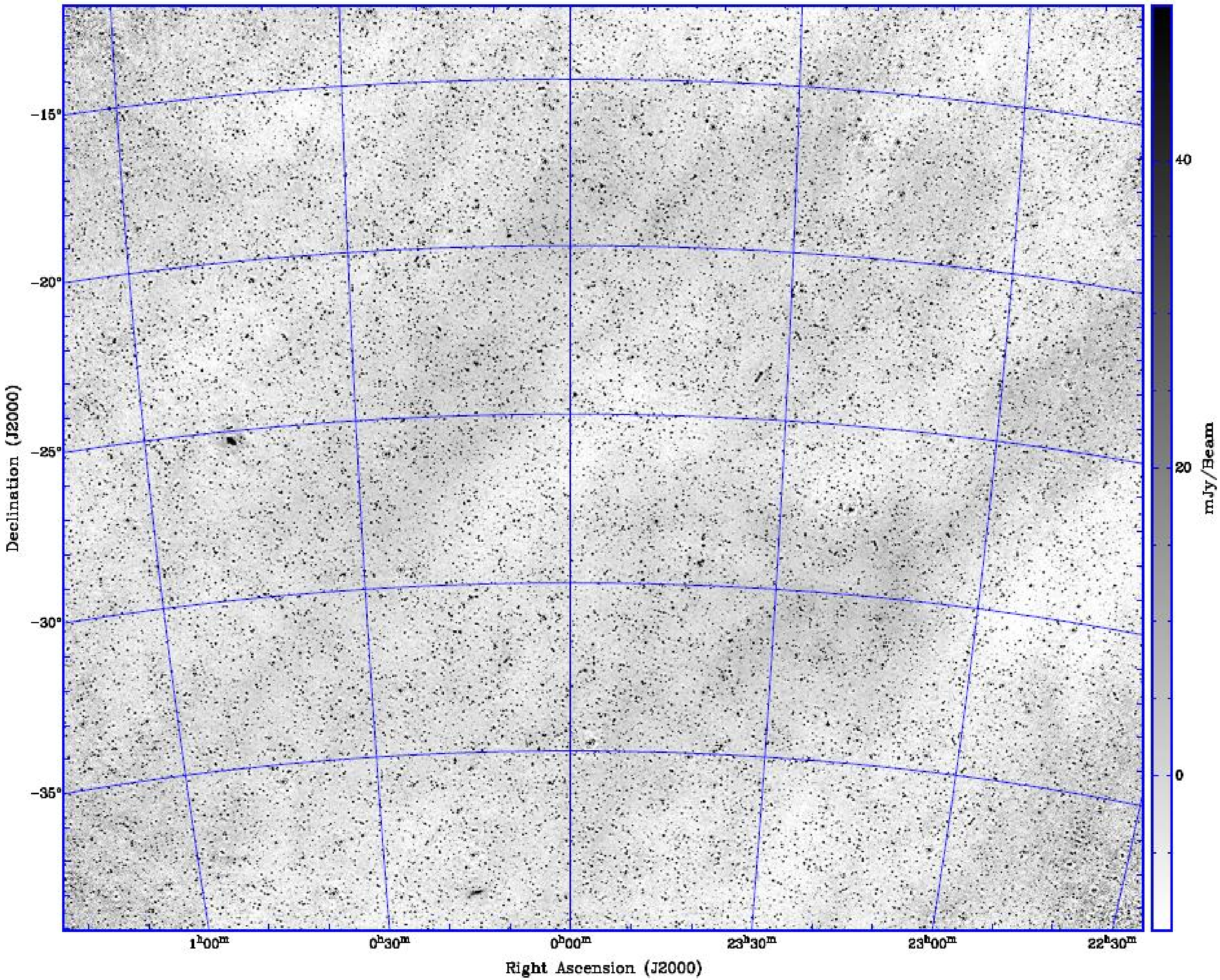
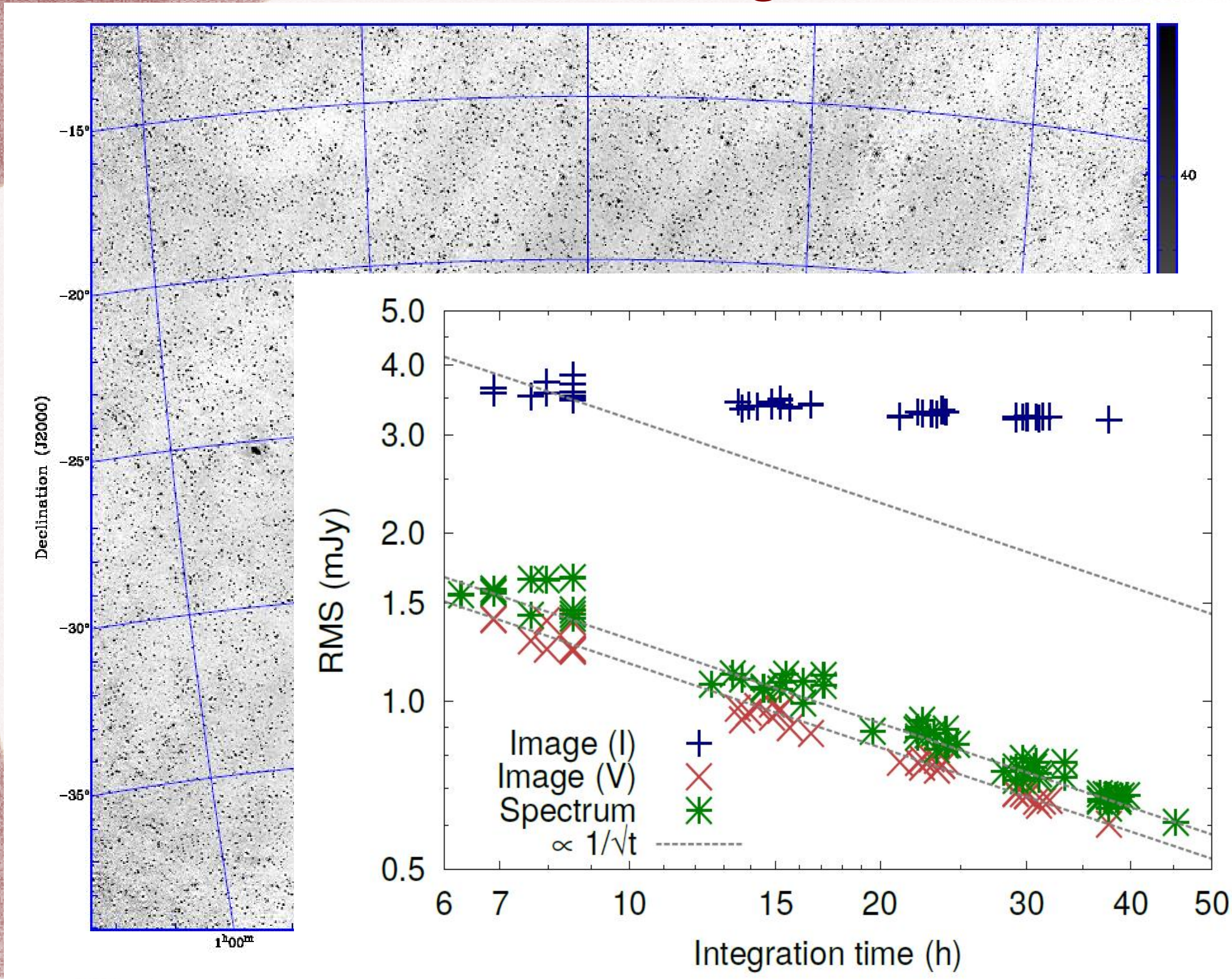
- WSCLEAN + IONPEEL (Offringa+ 2014): 45 deg x 30 deg EoR-0 field with MWA … one of the deepest field with 45 hr time (Offringa+ '15)

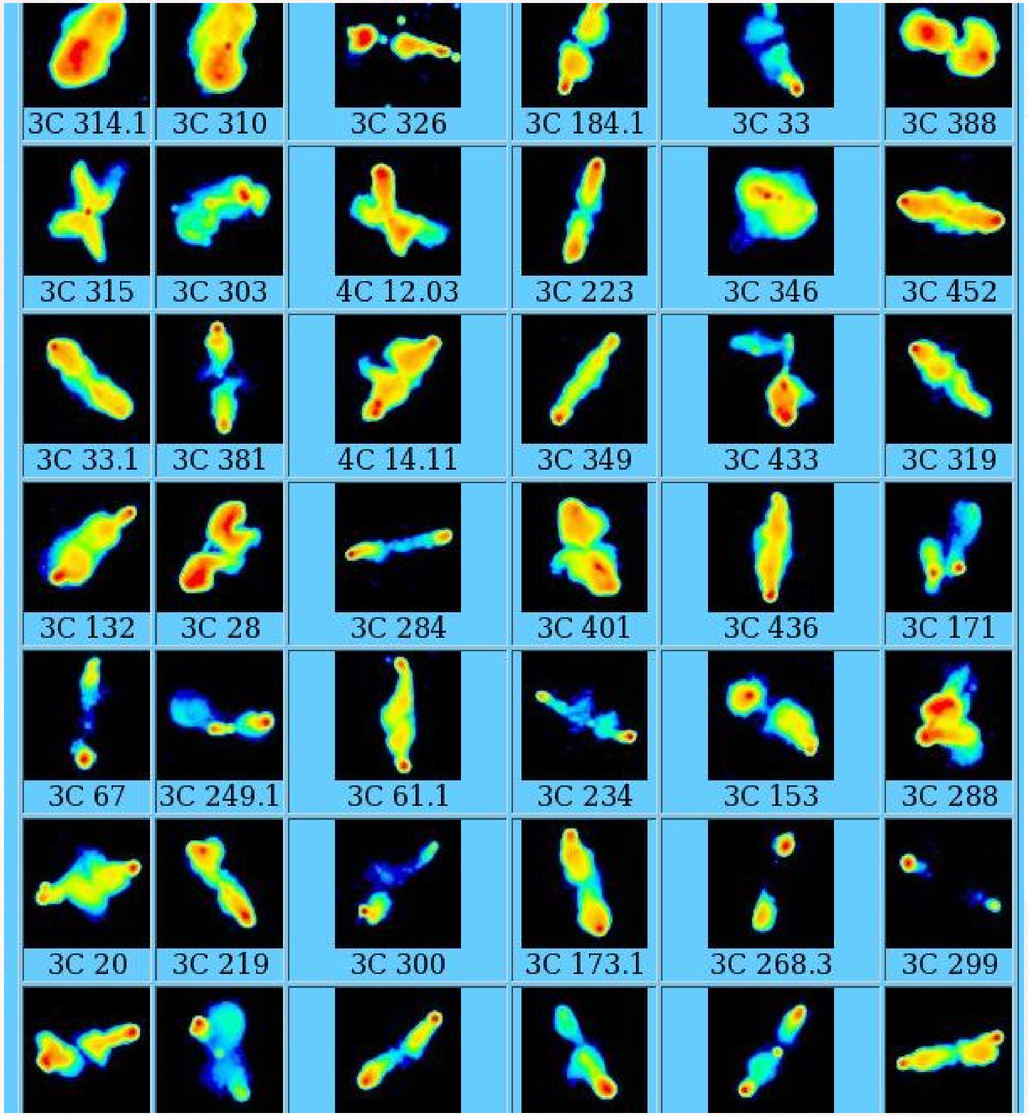
Accurate modeling and removal



Accurate modeling and removal



What about marginally resolved sources?



Leahy, Bridle, Strom; DRAGN Atlas

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Wish-list

- Well-characterized calibrators for flux, phase, bandpass and polarization calibrations
- Accurate gain calibration
- Direction dependent gain calibration
- Imaging with
  - wide band, wide field, high resolution
  - primary beam correction
  - spectral index++ correction
  - (multi-scale deconvolution)
- Fast and accurate subtraction of components

Wish-list

- Well-characterized calibrators for flux, phase, bandpass and polarization calibrations
  - a lot of progress over the last few years

Wish-list

- Well-characterized calibrators for flux, phase, bandpass and polarization calibrations
- Accurate gain calibration
  - (instrument + ionosphere) challenging

Wish-list

- Well-characterized calibrators for flux, phase, bandpass and polarization calibrations
- Accurate gain calibration
- Direction dependent gain calibration
  - computation intensive + many issues

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  - wide band, wide field, high resolution
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Many recent algorithm developments (e.g. Rao+ CASA CLEAN with MS-MFS, AW-proj)

Wish-list

- Well-characterized calibrators for flux, phase, bandpass and polarization calibrations
- Accurate gain calibration
- Direction dependent gain calibration
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  - wide band, wide field, high resolution
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  - spectral index++ correction
  - (multi-scale deconvolution)
- Fast and accurate subtraction of components

“TGE”

- Less computation due to gridding, yet remove noise bias self-consistently

- Taper the sky response, wide-field imaging, primary beam corrections, direction dependent gains will have less effect

- Reduce the contribution of residual point sources far away from the field centre

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TGE: Tapered Gridded Estimator

$$\mathcal{V}_{cg} = \sum_i \tilde{w}(\mathrm{U}_g - \mathrm{U}_i)\, \mathcal{V}_i$$

Choudhuri et al. (2014, 2016) + Work in progress

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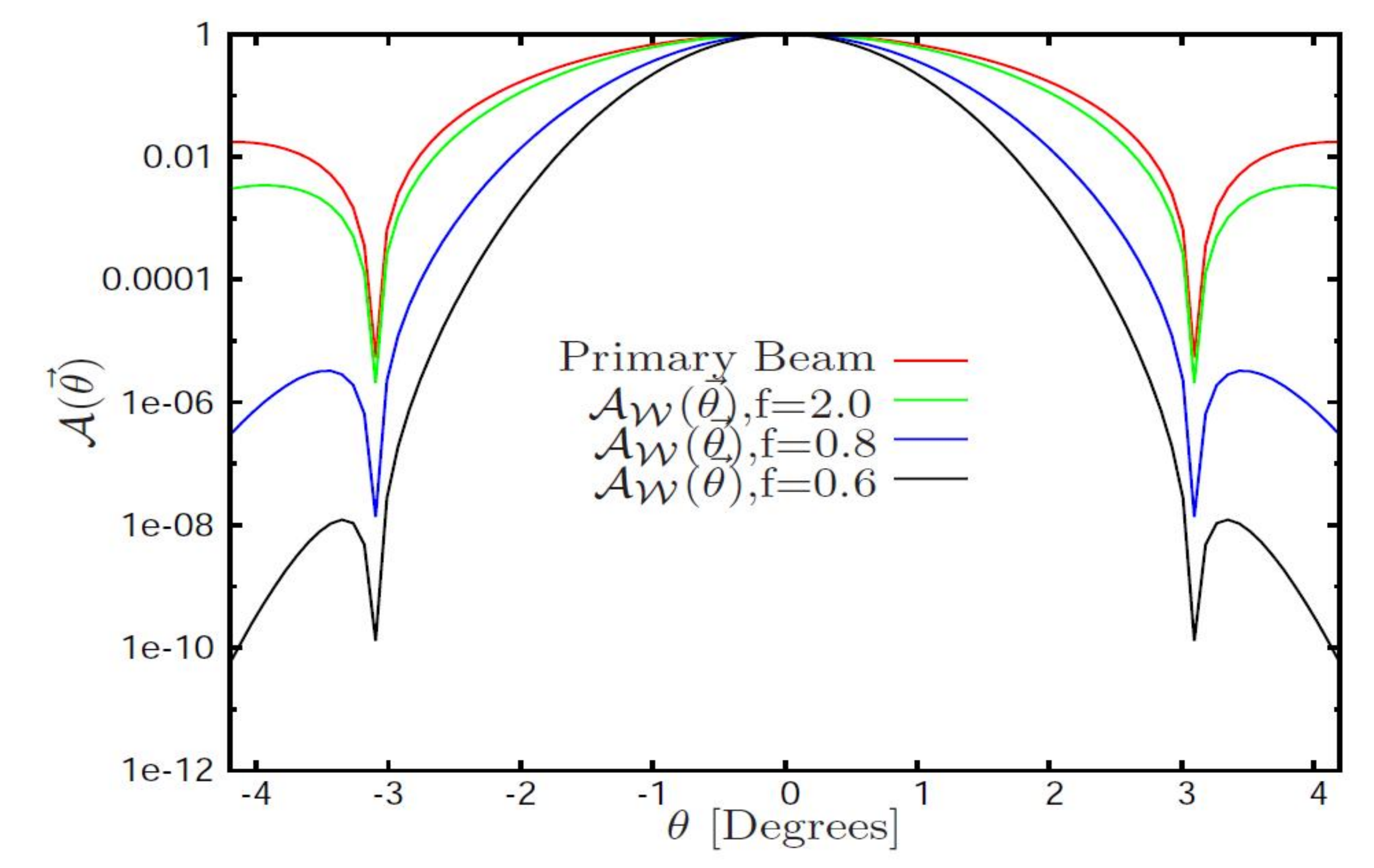


Choudhuri et al. (2014, 2016) + Work in progress

TGE: Tapered Gridded Estimator

$$\mathcal{V}_{cg} = \sum_i \tilde{w}(\mathbf{U}_g - \mathbf{U}_i)\, \mathcal{V}_i$$

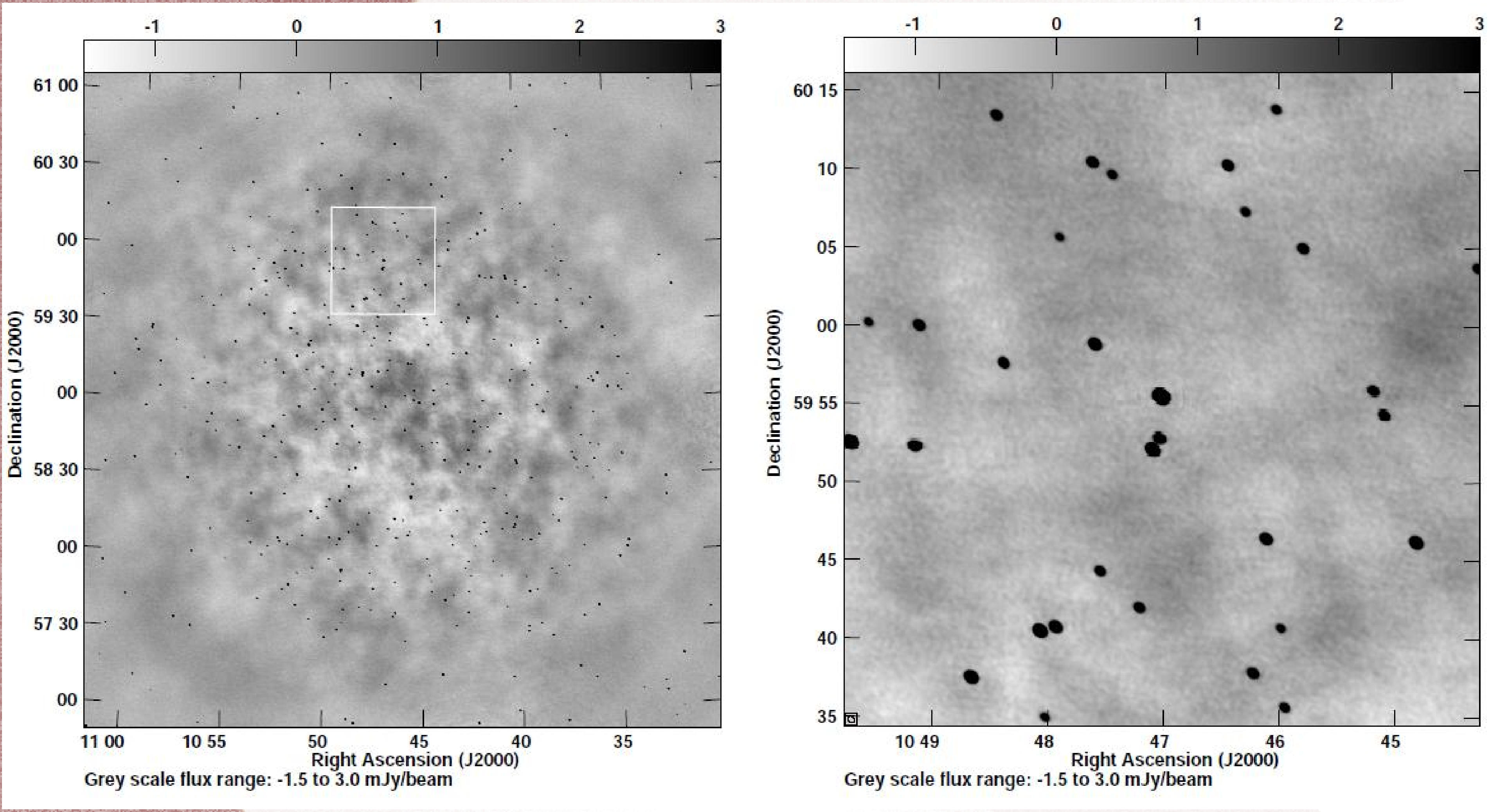
$$\langle \mid \mathcal{V}_{cg} \mid^2 \rangle = V_{1g} C_{2\pi U_g} + \sum_i \mid \tilde{w}(\mathbf{U}_g - \mathbf{U}_i) \mid^2 \langle \mid \mathcal{N}_i \mid^2 \rangle$$

$$\hat{E}_g = M_g^{-1} \left(\mid \mathcal{V}_{cg} \mid^2 - \sum_i \mid \tilde{w}(\mathbf{U}_g - \mathbf{U}_i) \mid^2 \mid \mathcal{V}_i \mid^2 \right)$$

$$\langle \hat{E}_g \rangle = C_{\ell_g}$$

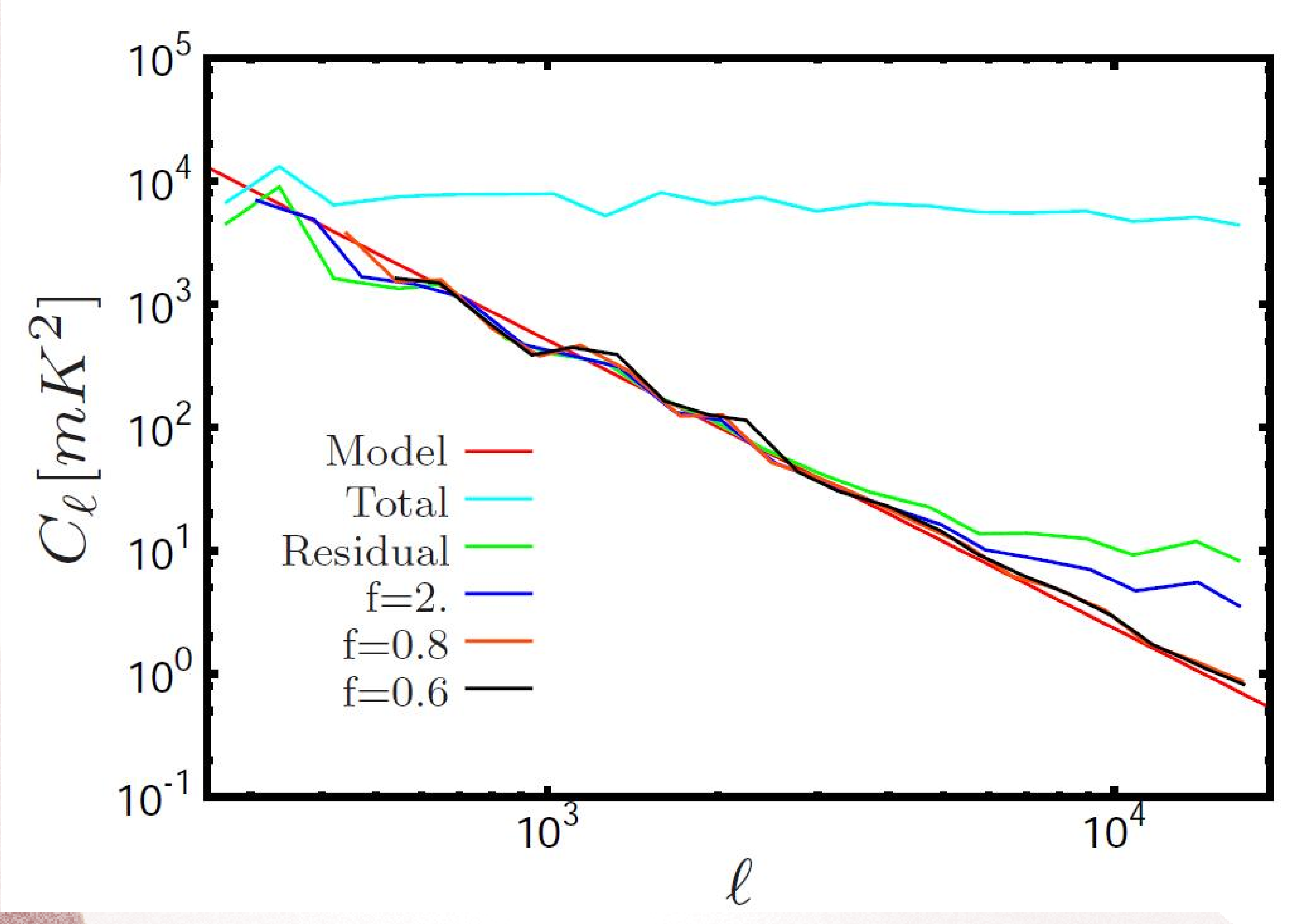
Choudhuri et al. (2014, 2016) + Work in progress

TGE: easier foreground removal



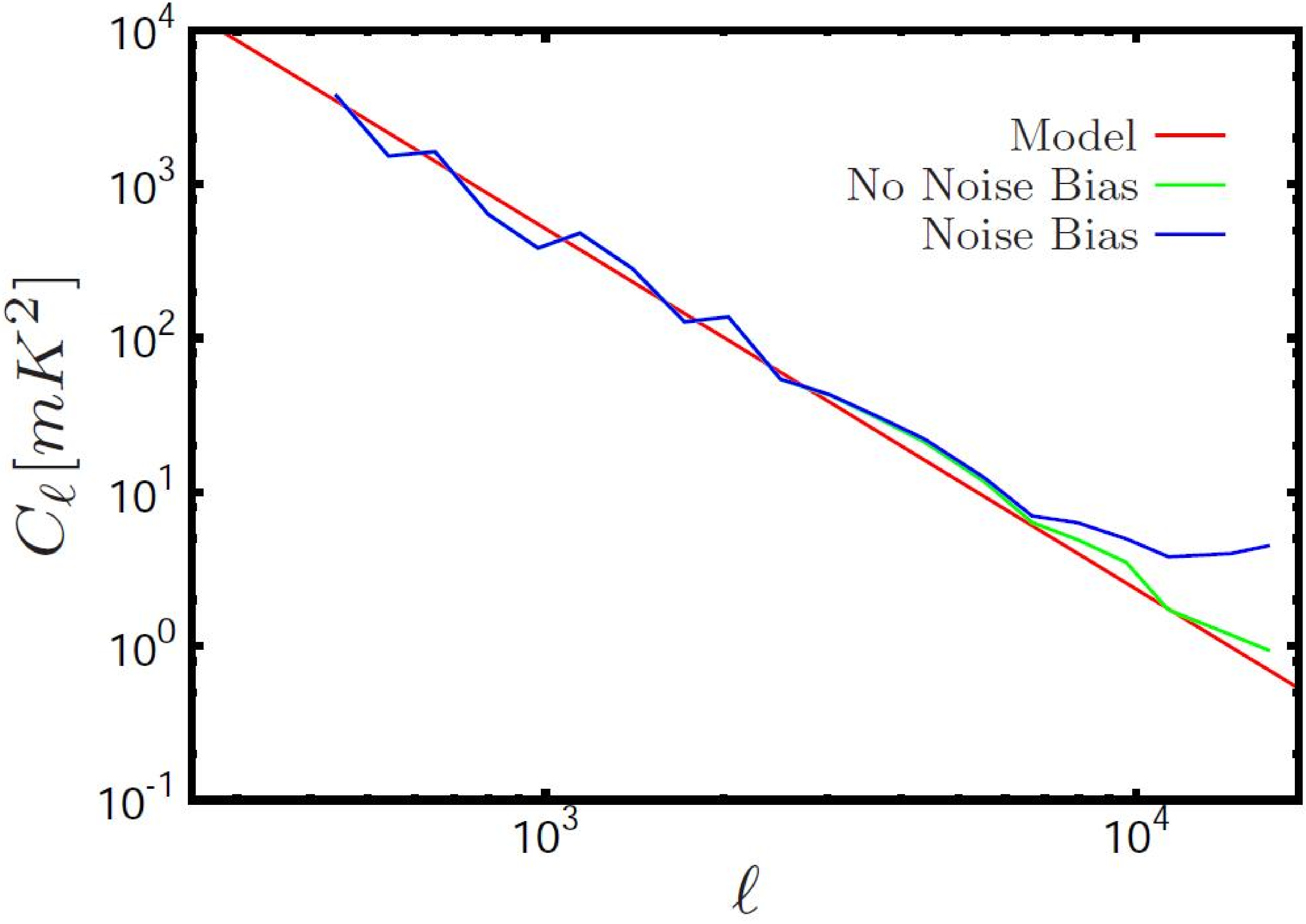
Choudhuri et al. (2014, 2016) + Work in progress

Results: Effect of tapering



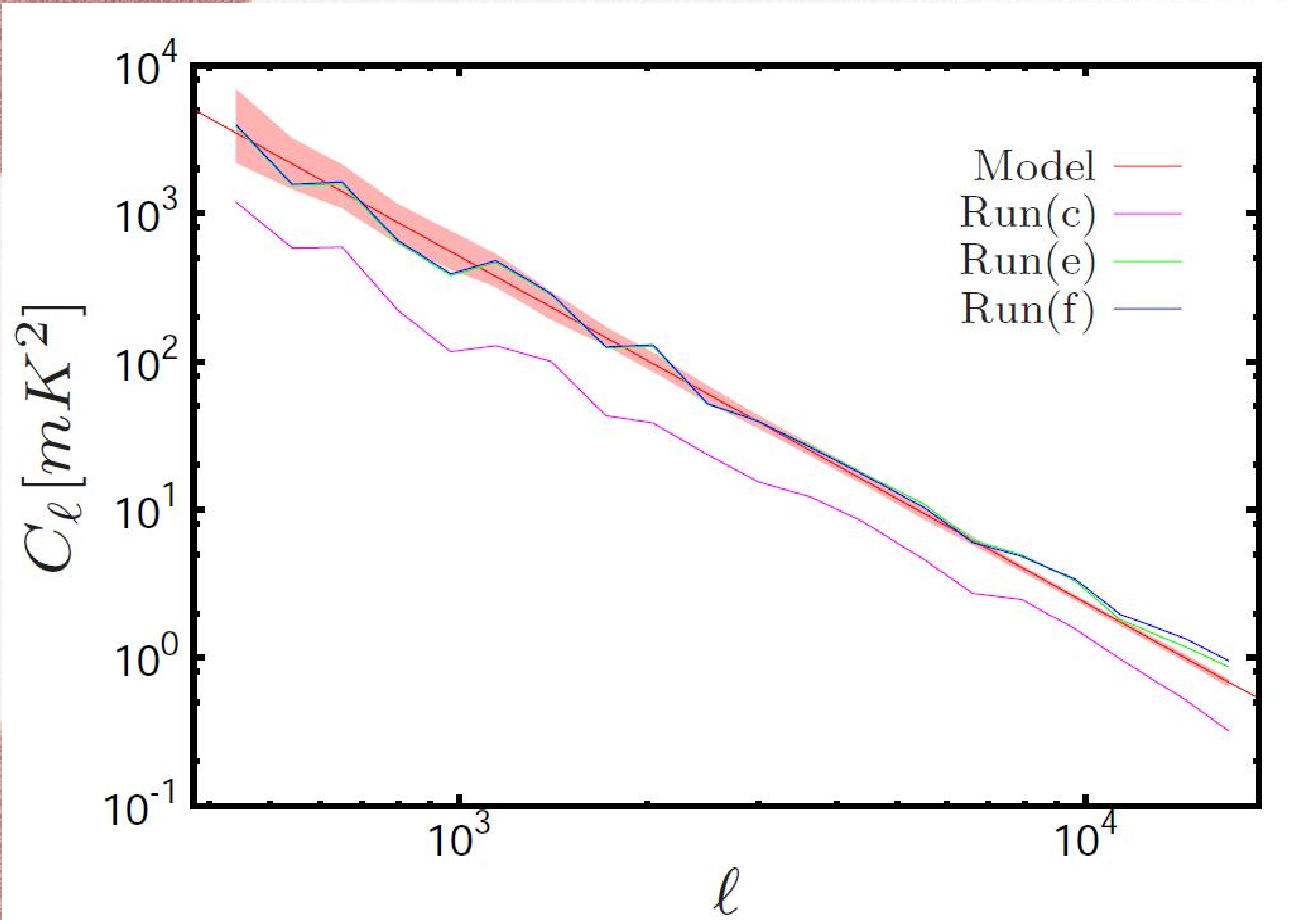
Choudhuri et al. (2014, 2016) + Work in progress

Results: Noise bias subtraction



Choudhuri et al. (2014, 2016) + Work in progress

Results: Different CLEANing options



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Directions …

- How accurately can we calibrate uGMRT low-freq.
  - including polarization calibration

- How accurately we can recover (point) source position, flux density, spectral index?
  - Effectiveness of wide band, wide field imaging
  - CASA MS-MFS, AW-proj. with uGMRT
  - How well we can model the primary beam (+ its polarization properties)
  - Marginally resolved source? multi-scale cleaning?

- Optimum source identification, cataloguing …

Conclusions …

- Point source foreground removal is one of the major challenges for EoR 21 cm experiments
- There are significant progress in some of the aspects (e.g. imaging and deconvolution algorithms), but wide field imaging with desired level of accuracy is still challenging for multiple reasons.
- The Tapered Gridded Estimator can potentially takes care of a few of the issues at least to some extent. It seems to be a promising tools to handle both the foreground and the noise bias.