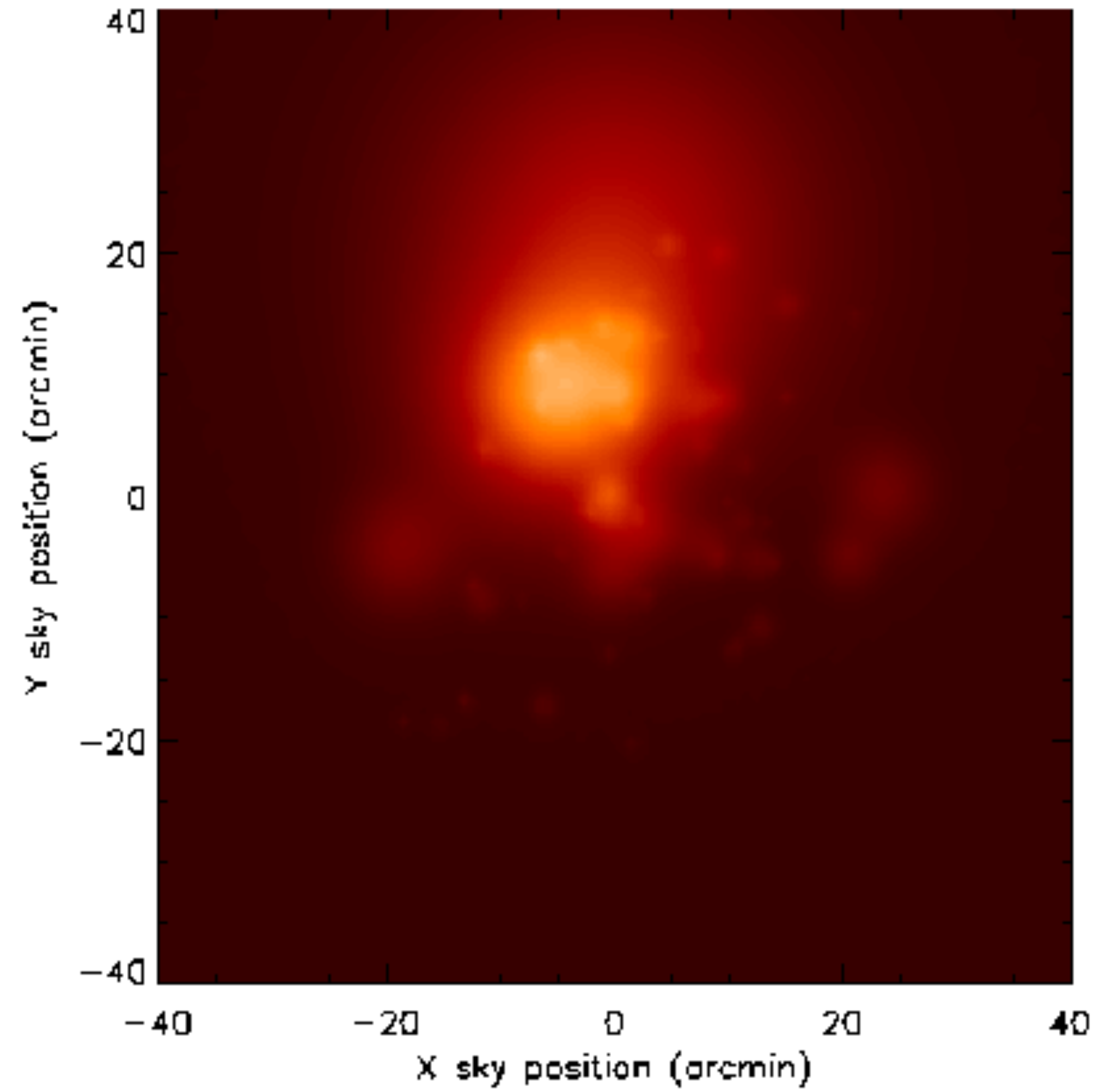

Building extended source models: implications for EoR science

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Building models for extended radio sources: implications for Epoch of Reionisation science

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Abstract

We test the hypothesis that limitations in the sky model used to calibrate an interferometric radio telescope, where the model contains extended radio sources, will generate bias in the Epoch of Reionisation (EoR) power spectrum. The information contained in a calibration model about the spatial and spectral structure of an extended source is incomplete because a radio telescope cannot sample all Fourier components. Application of an incomplete sky model to calibration of EoR data will imprint residual error in the data, which propagates forward to the EoR power spectrum. This limited information is studied in the context of current and future planned instruments and surveys at EoR frequencies, such as the Murchison Widefield Array (MWA), Giant Metrewave Radio Telescope (GMRT) and the Square Kilometre Array (SKA1-Low). For the MWA EoR experiment, we find that both the additional short baseline *uv*-coverage of the compact EoR array, and the additional long baselines provided by TGSS and planned MWA expansions, are required to obtain sufficient information on all relevant scales. For SKA1-Low, arrays with maximum baselines of 49 km and 65 km yield comparable performance at 50 MHz and 150 MHz, while 39 km, 14 km and 4 km arrays yield degraded performance.

Keywords: instrumentation: interferometers — methods: observational — telescopes — (cosmology:) dark ages, reionization, first stars

1 INTRODUCTION

A sky model for an interferometer telescope is used for calibration, source deconvolution, and source subtraction. The sky model can be obtained: (1) externally,

74 MHz Very Large Array Low Frequency Sky Survey redux (Lane et al., 2012), the MWA Commissioning Survey (MWACS, Hurley-Walker et al., 2014), MWA GLEAM (Wayth et al., 2015; Hurley-Walker et al., 2017), and GMRT TGSS (Intema et al., 2017). Cross-matching

Outline and methodology

How do limitations in our models of extended sources affect our ability to calibrate and clean data for EoR science?

- Models are built from observations with interferometers
- Interferometers have limited spatial and spectral sampling

—> Extended source models are necessarily incomplete

—> Treating an incomplete source model as the “truth” for calibration and source peeling introduces biases and residual signal

Outline and methodology

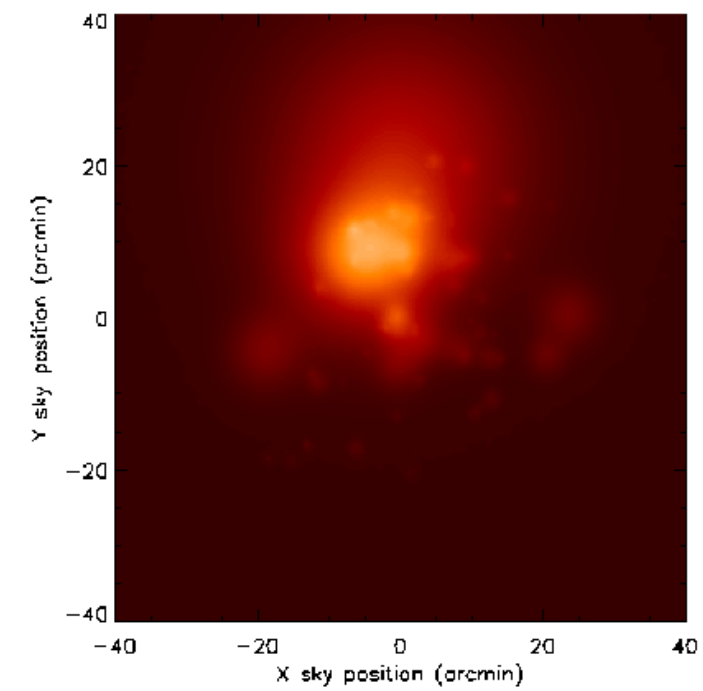
How do limitations in our models of extended sources affect our ability to calibrate and clean data for EoR science?

- Form generic parametric model for an extended low-frequency source
- Compute precision with which model parameters can be measured with a given instrument
- Propagate parameter uncertainties to EoR power spectrum
- Assess residual/biased power from uncertainties

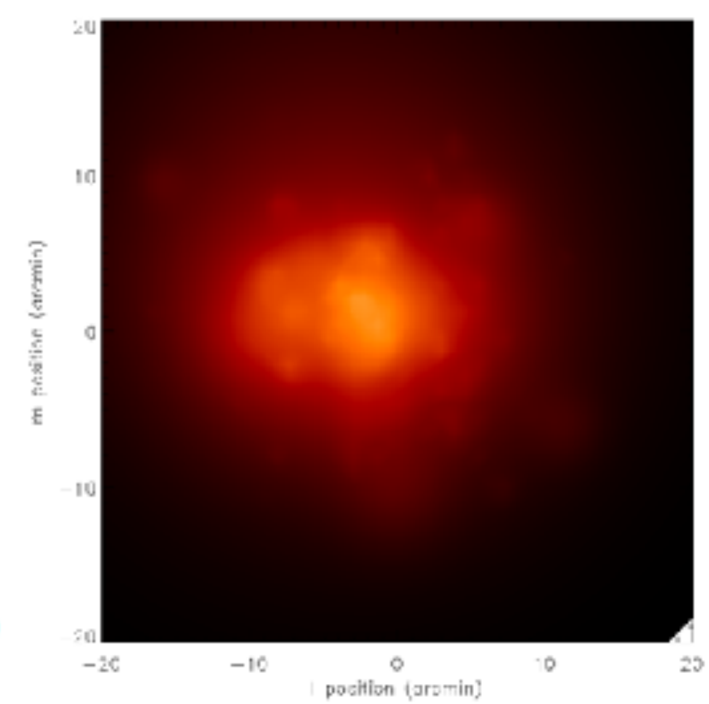
MWA128T (Wayth+ 2016, Hurley-Walker+ 2017, Line+ 2016)
MWA 256T
MWA128 + GMRT TGSS (Intema+ 2017)
SKA-Low (39km, 49km, 65km maximum baselines)

Gaussian-based source model

- Summation over multi-scale Gaussians
- 5 parameters: amplitude, sky position, scale, spectral index
- Spatial modes encompass SKA-Low baselines
- Scales are spaced linearly to form complete sampling



Parameter	Value (scale i)
a_i (Jy/bm)	$1/\sqrt{1+i}$
l_i (arcmin)	$\mathcal{N}(0, \Delta l^2 = 10^2)$
m_i (arcmin)	$\mathcal{N}(0, \Delta m^2 = 10^2)$
σ_i (rad)	$1/k_i$
γ_i	$\mathcal{N}(-0.8, \Delta\gamma^2 = 0.02^2)$

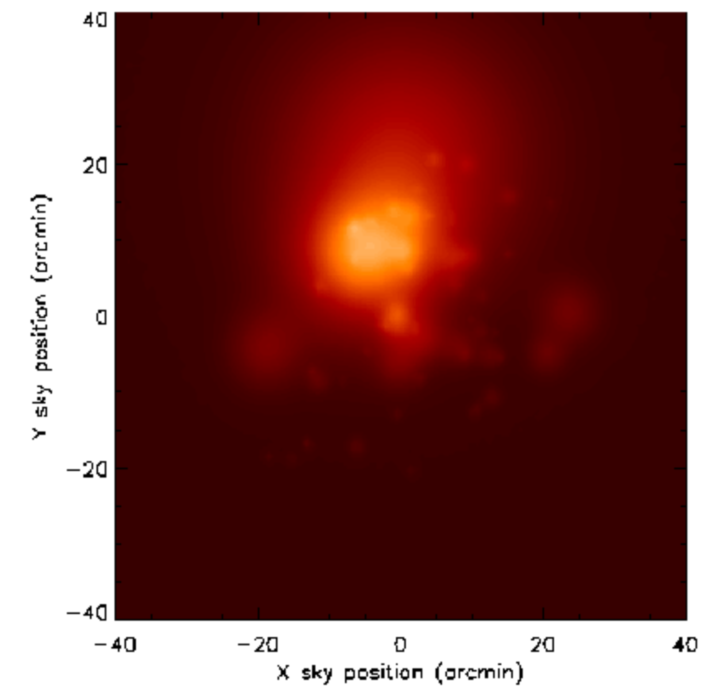


$$\mu(\vec{u}, \nu; \vec{\theta}) = \sqrt{2\pi} \sum_{i=1}^{57} a_i \sigma_i^2 \left(\frac{\nu}{\nu_0}\right)^{\gamma_i} \times \exp\left(-2\pi i \vec{u} \cdot \vec{l}_i\right) \exp\left(-2|u|^2 \pi^2 \sigma_i^2\right)$$

Parameter Estimation: Fisher Information

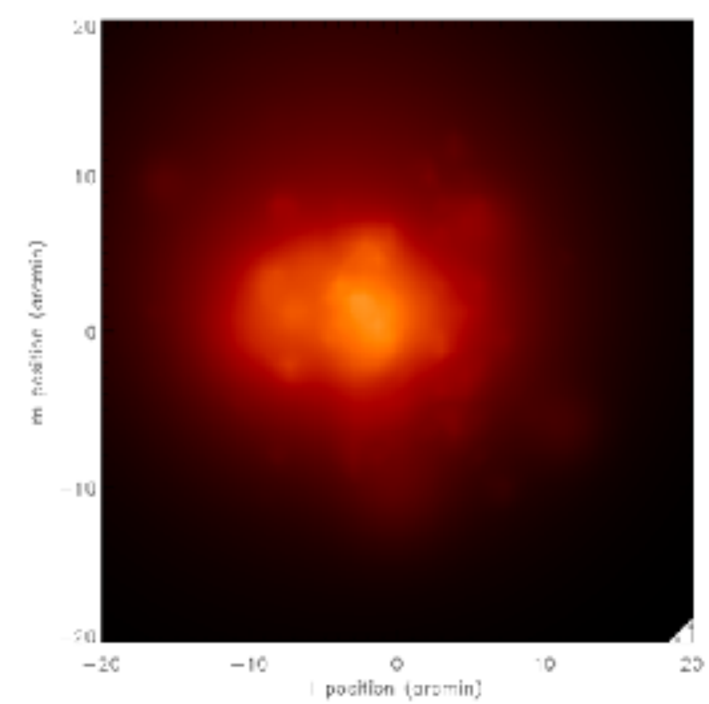
- Fisher Information, I: information available in data to estimate a parameter value
- “Noise” covariance matrix includes thermal and point source (confusion)

$$[I]_{ab} = \left(\frac{\partial\vec{\mu}}{\partial\theta_a}\right)^{\dagger} C^{-1} \left(\frac{\partial\vec{\mu}}{\partial\theta_b}\right)$$



$${}_{th}\mathbf{C}(u,v;\nu,\nu') = \left(\frac{2k\mathrm{T}_{\mathrm{sys}}}{\mathrm{A}_{\mathrm{eff}}}\right)^2 \frac{1}{\Delta\nu\Delta t}\delta(\nu-\nu')\ \mathrm{Jy}^2$$

$$\begin{aligned} {}_{fg}\mathbf{C}(\vec{u};\nu,\nu') &= \frac{\alpha}{3-\beta}\frac{S_{\mathrm{max}}^{3-\beta}}{S_0^{-\beta}}\frac{\pi c^2\epsilon^2}{D^2}\frac{1}{\nu^2+\nu'^2} \\ &\times \exp\left(\frac{-|\vec{u}|^2c^2f(\nu)^2\epsilon^2}{4(\nu^2+\nu'^2)D^2}\right)\mathrm{Jy}^2 \end{aligned}$$

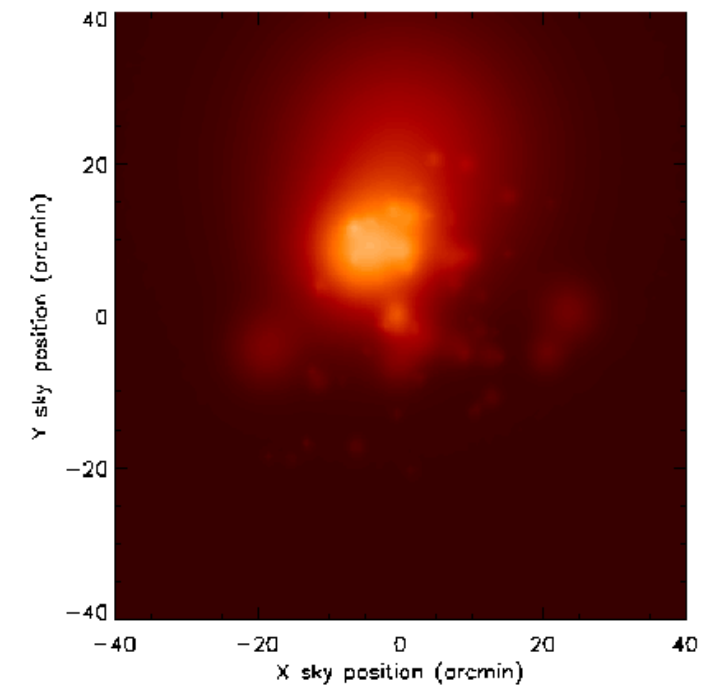


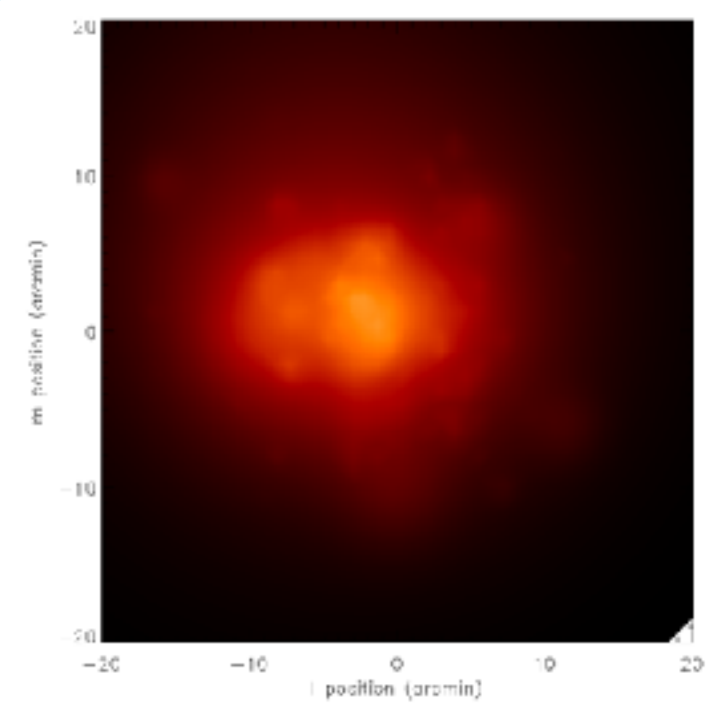
Error propagation: parameters to visibilities to power

- Fisher Information, I: information available in data to estimate a parameter value
- “Noise” covariance matrix includes thermal and point source (confusion)

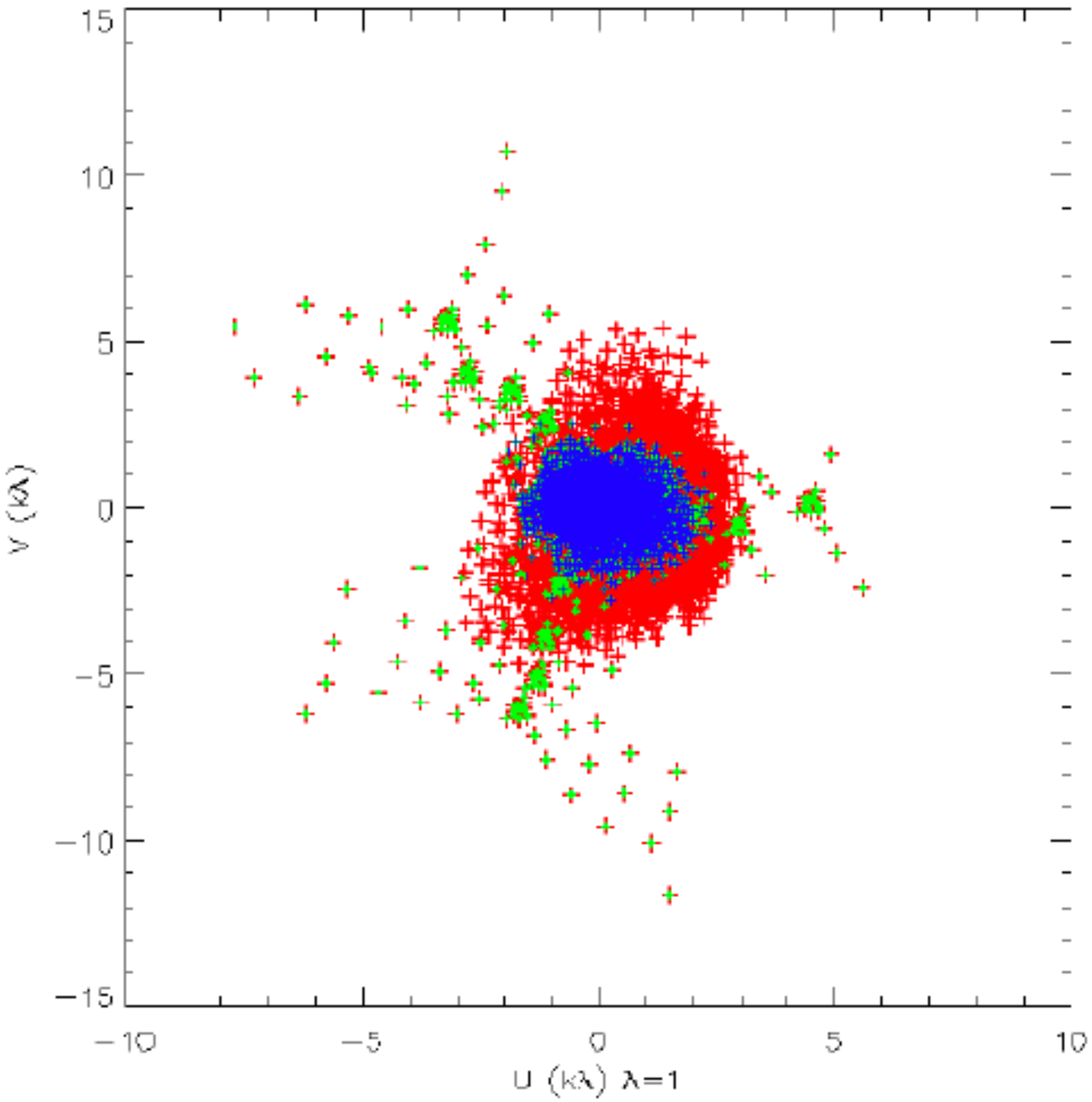
$$\mathbf{C}_V(u,v;\nu) = \boldsymbol{J}^\dagger \boldsymbol{I}^{-1} \boldsymbol{J}$$

$$\Delta P(k_\perp, k_{||}) = (\mathcal{F}_\nu^\dagger \mathcal{W}^\dagger \mathbf{C}_V \mathcal{W} \mathcal{F}_\nu)\ \delta(k_{||} - k'_{||}, k_\perp^2 - u^2 - v^2)$$

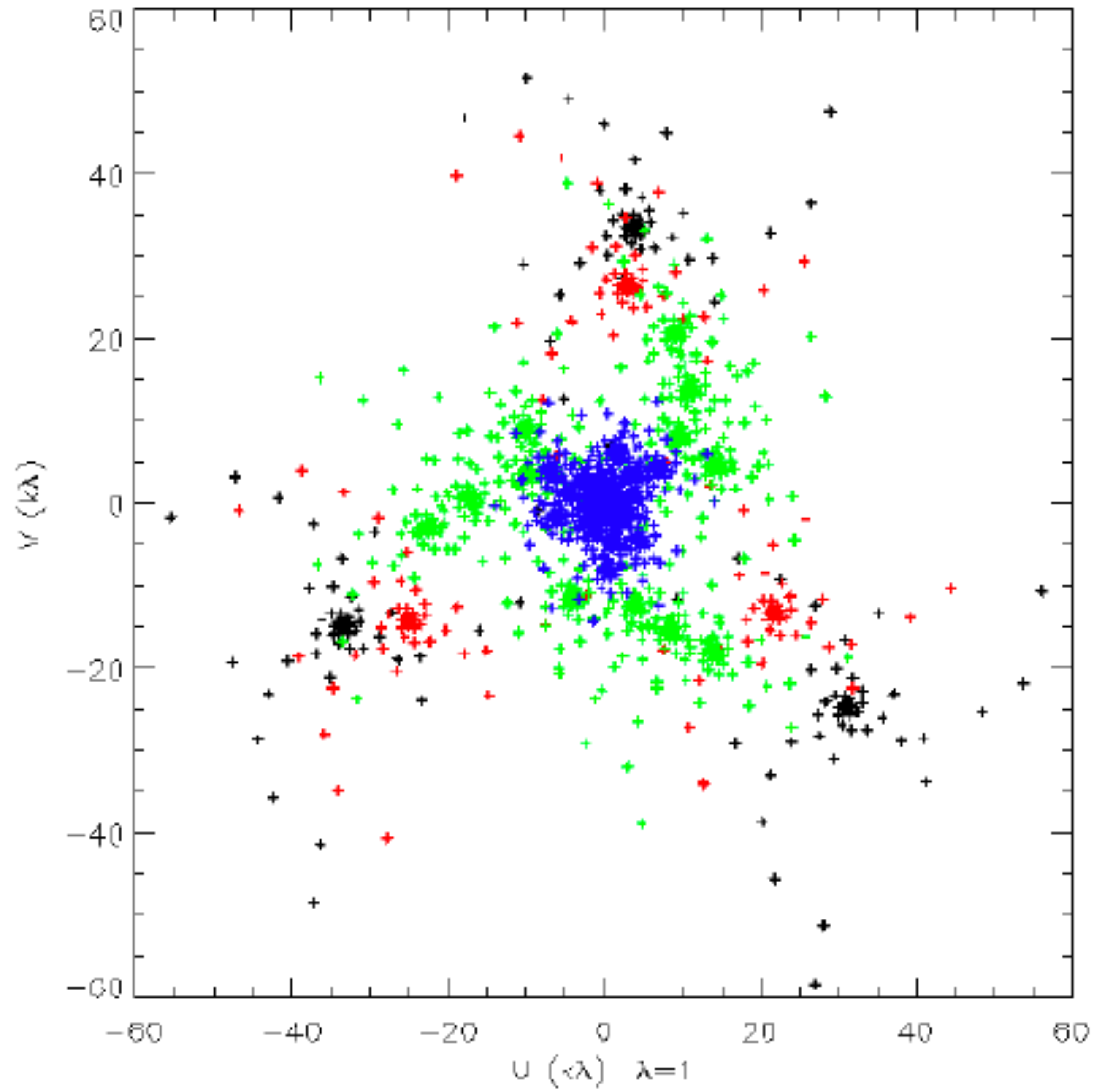




Instrument models: snapshot uv coverage



MWA128
MWA128 + GMRT TGSS
MWA256 + GMRT TGSS



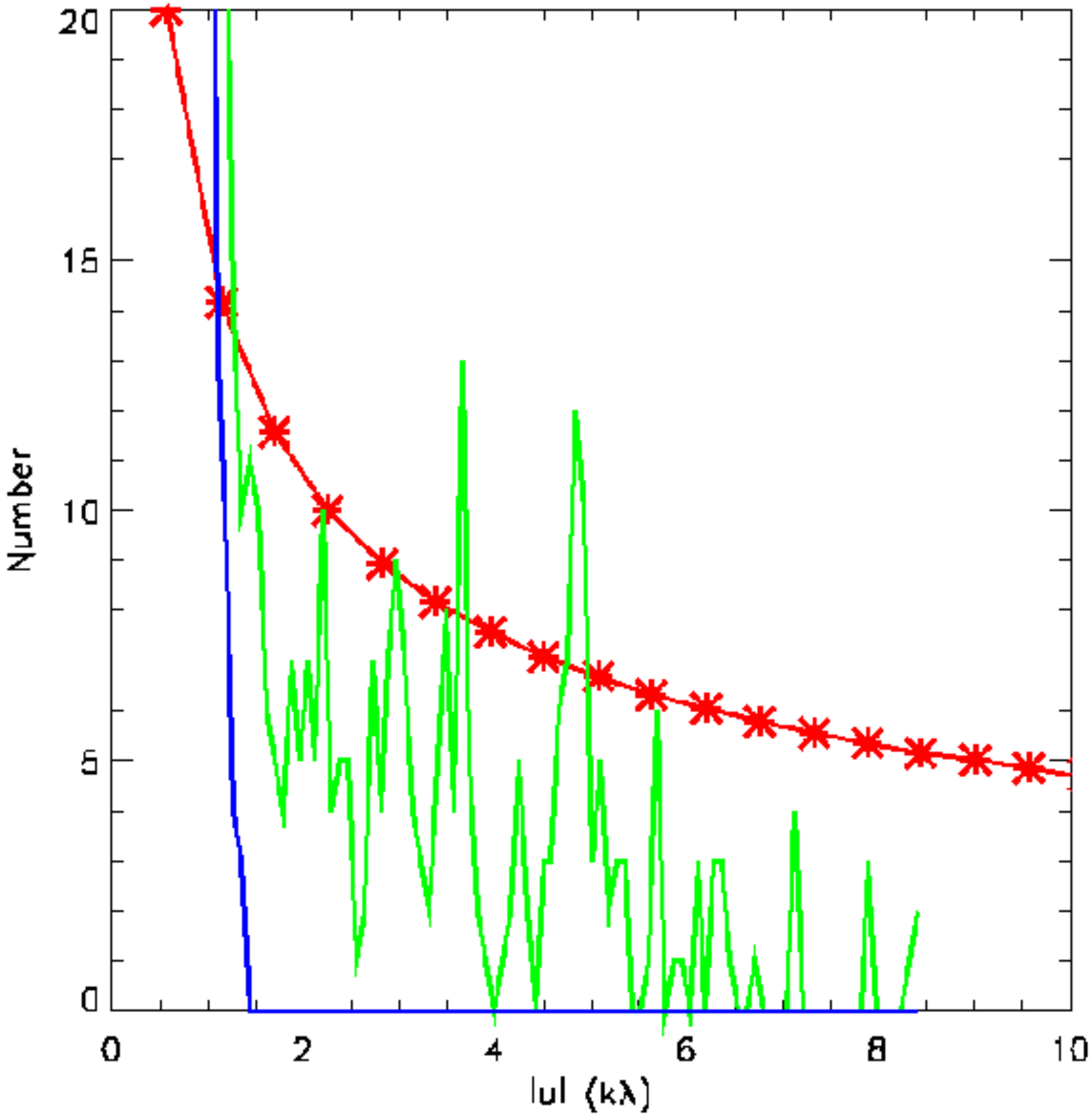
SKA 14km
SKA 39km SKA 49km
SKA 65km

Instrument models: sampling scales

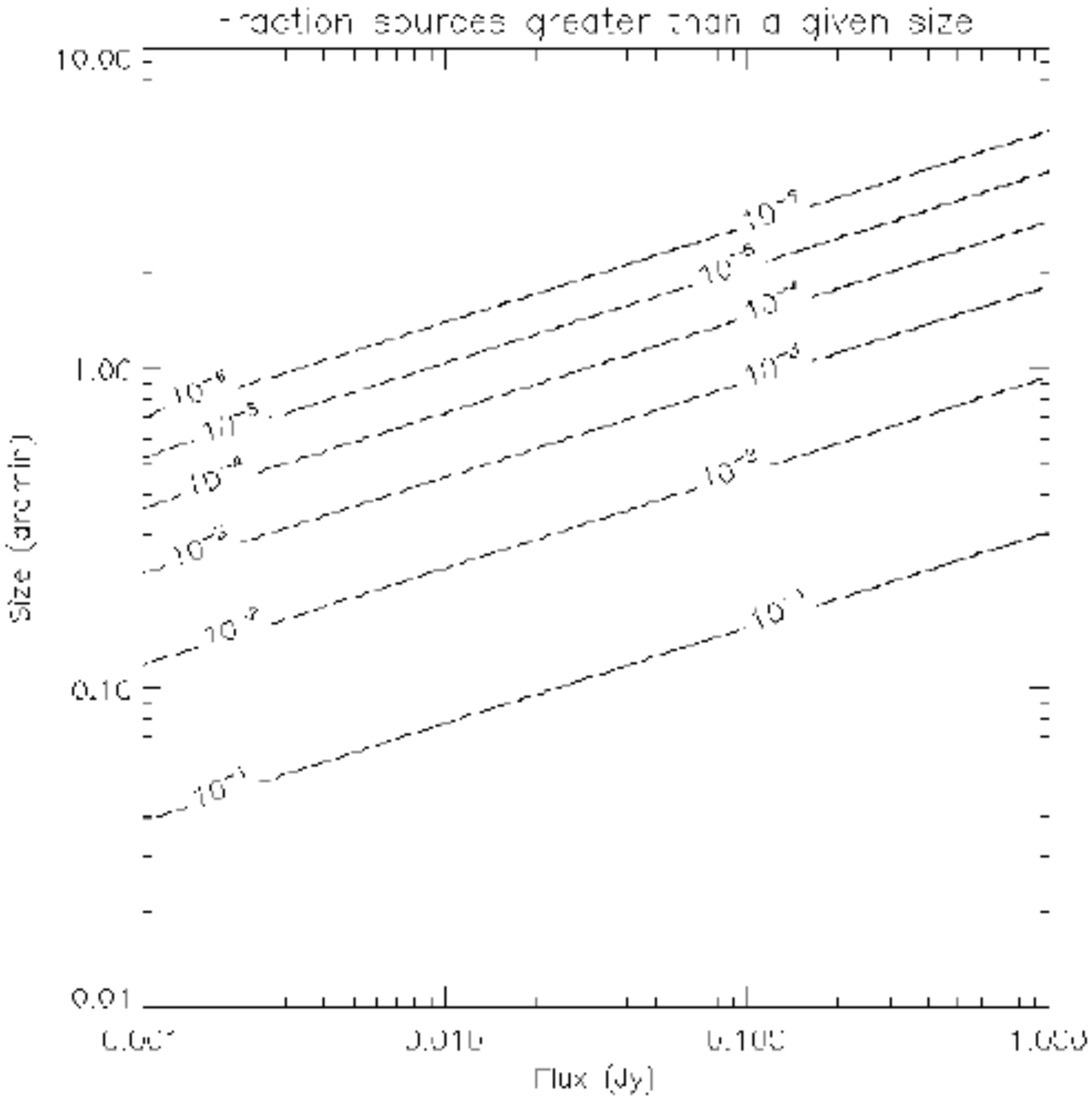
MWA128

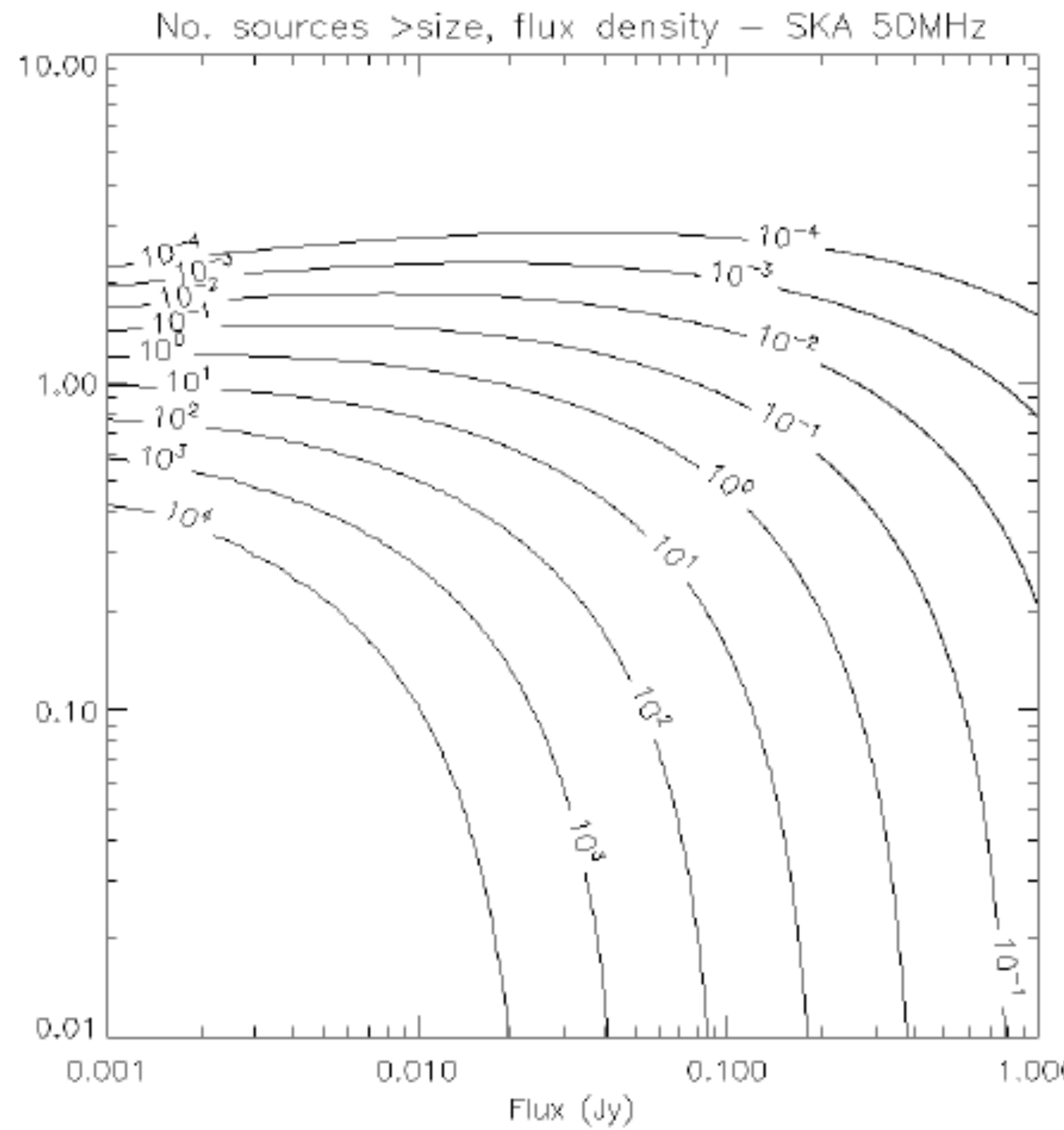
MWA256 + GMRT TGSS

Source scales and signal



Number of extended sources in FOV?



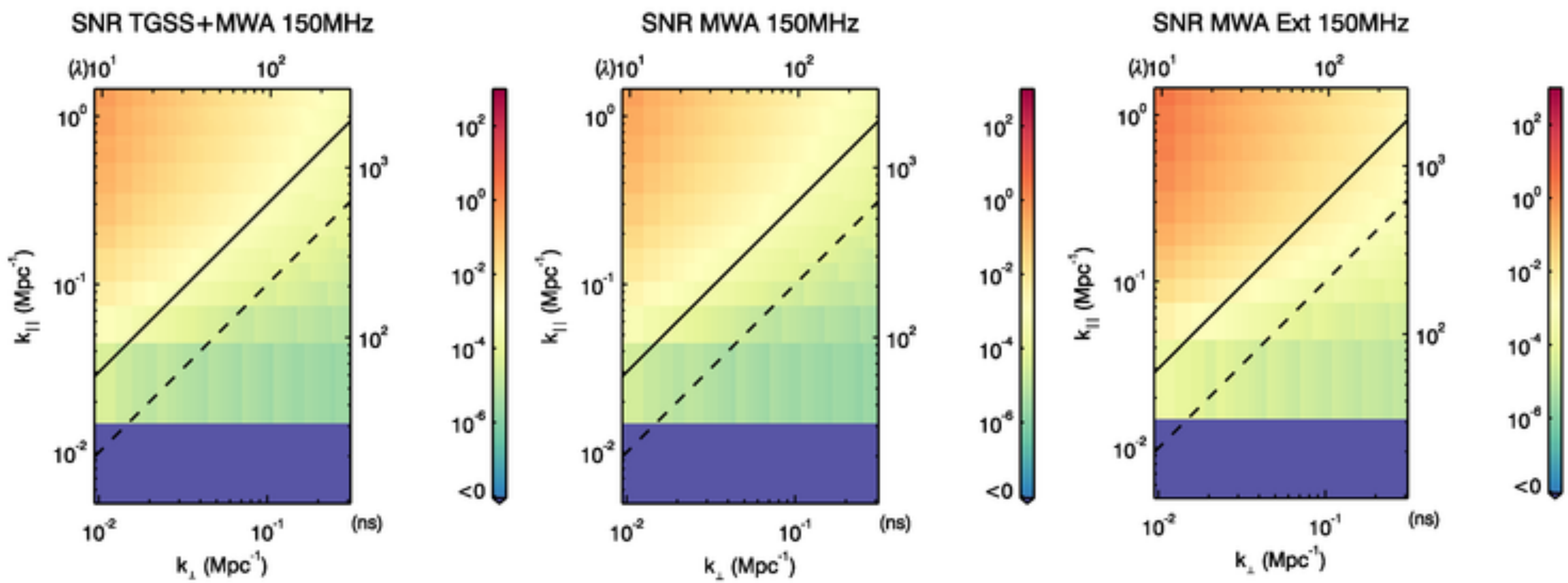


Estimate fraction of sources > size, flux density

Integrate over source count density for number of sources in FOV > size

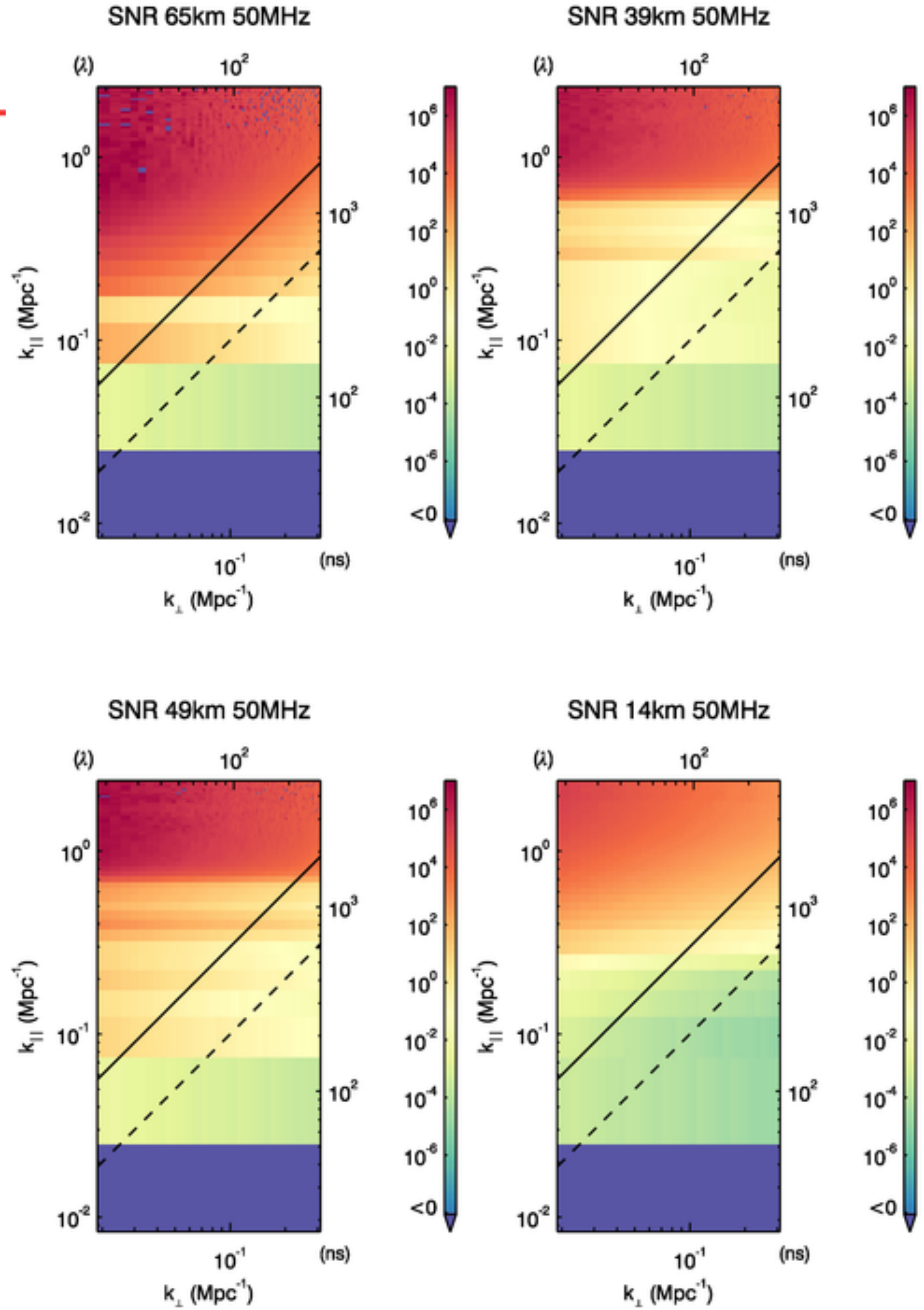
Results I: MWA

Signal-to-“noise” ratio (mock 21cm signal)



TGSS + Long MWA baselines (good uv-coverage) yield adequate coverage of spatial scales

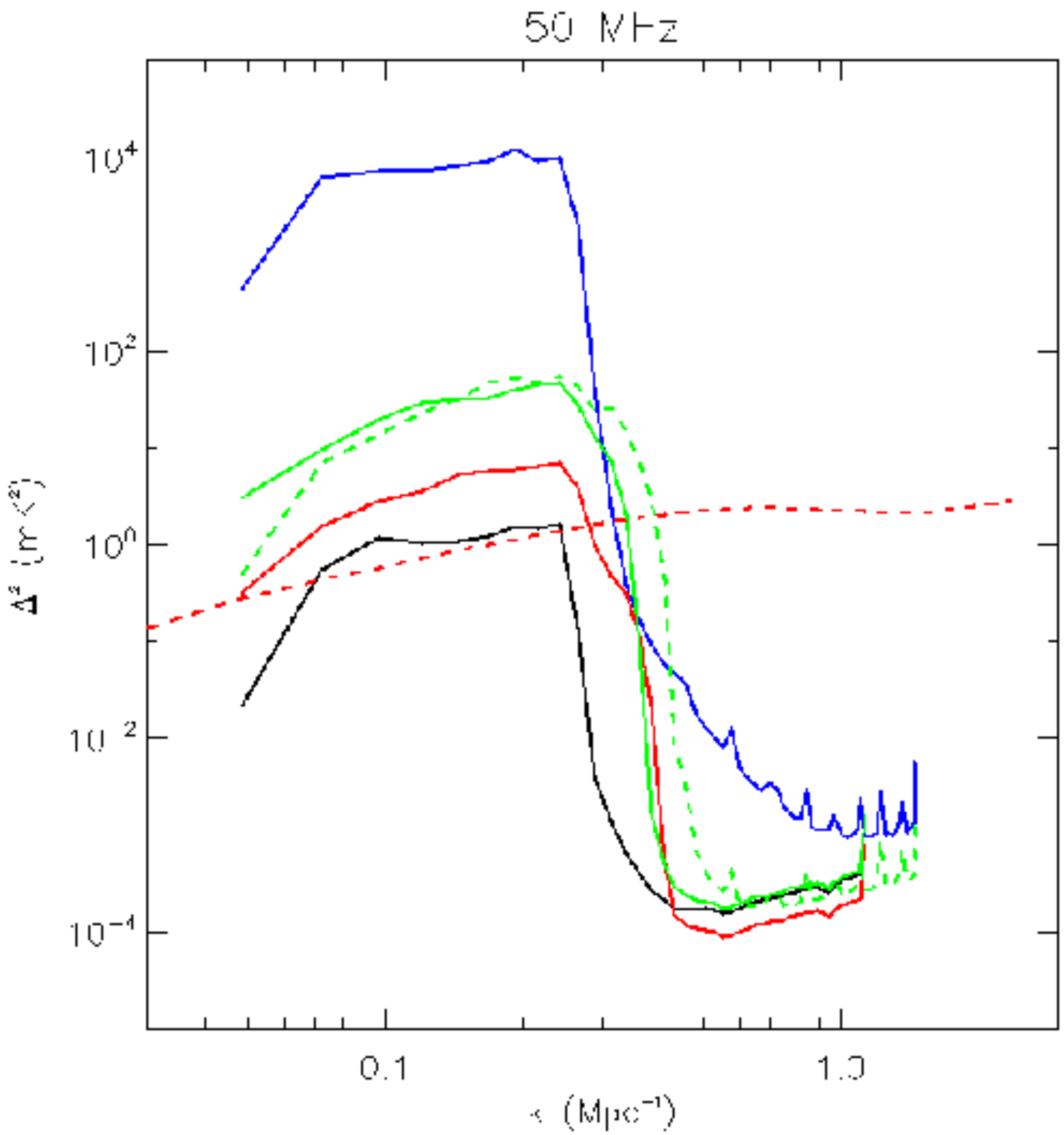
Results II: SKA (50 MHz)



50 MHz: sources are brighter and signal is weaker

Clear poor behaviour for 14km baselines

Results I: SKA



SKA 14km
SKA 39km
SKA 49km
SKA 65km

TGSS + Long MWA baselines (good uv-coverage) yield adequate coverage of spatial scales

Summary

- Observational EoR is limited primarily by residual and mis-modelled foregrounds
- Brighter foregrounds have a larger impact than weaker (despite there being more weaker sources)
- Bright extended sources have power on all spatial scales
- Treating an incomplete sky model as the "truth" for calibration and source peeling leaves residuals

—> MWA+TGSS has sufficient scales to build a sky model. MWA upgrade has many advantages

—> Limiting SKA-Low longest baseline to 39km risks high-redshift measurements.