International Centre for Radio Astronomy Research

Curtin University

The University of Western Australia

Between Wedge and Window:

An improved point-source foreground model for the EoR.

STEVEN MURRAY, ICRAR/CURTIN + CAASTRO, PERTH, AUSTRALIA.

…WITH CATH TROTT AND CHRIS JORDAN.

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Basis of this talk

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AN IMPROVED STATISTICAL POINT-SOURCE FOREGROUND MODEL FOR THE EPOCH OF REIONIZATION

S. G. Murray[1,2], C. M. Trott[1,2] and C. H. Jordan[1,2]

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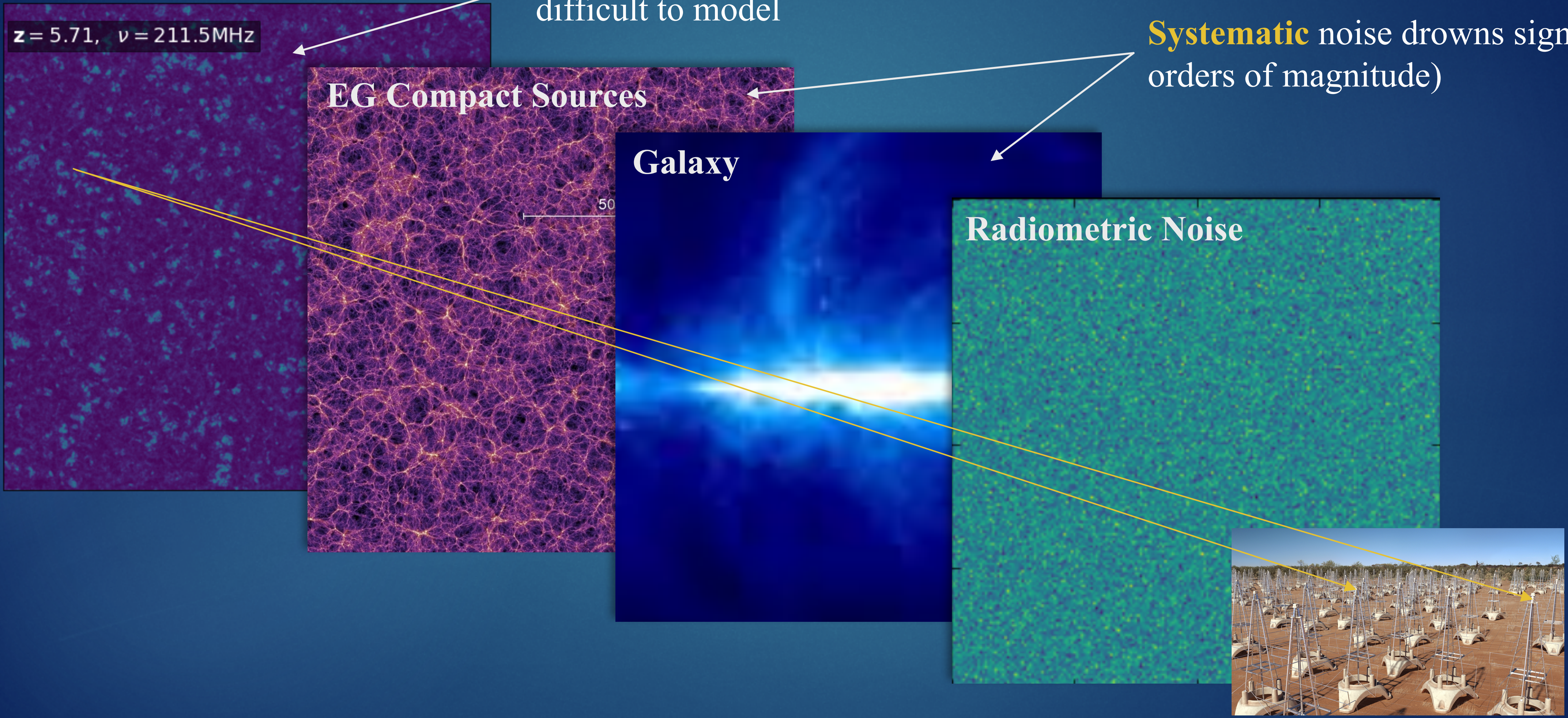
ABSTRACT

We present a sophisticated statistical point-source foreground model for low-frequency radio Epoch of Reionization (EoR) experiments using the 21 cm neutral hydrogen emission line. Motivated by

The Challenge of the EoR

Complex astrophysics makes signal difficult to model

Systematic noise drowns signal (~4 orders of magnitude)



The 2D Power Spectrum and Foreground Suppression

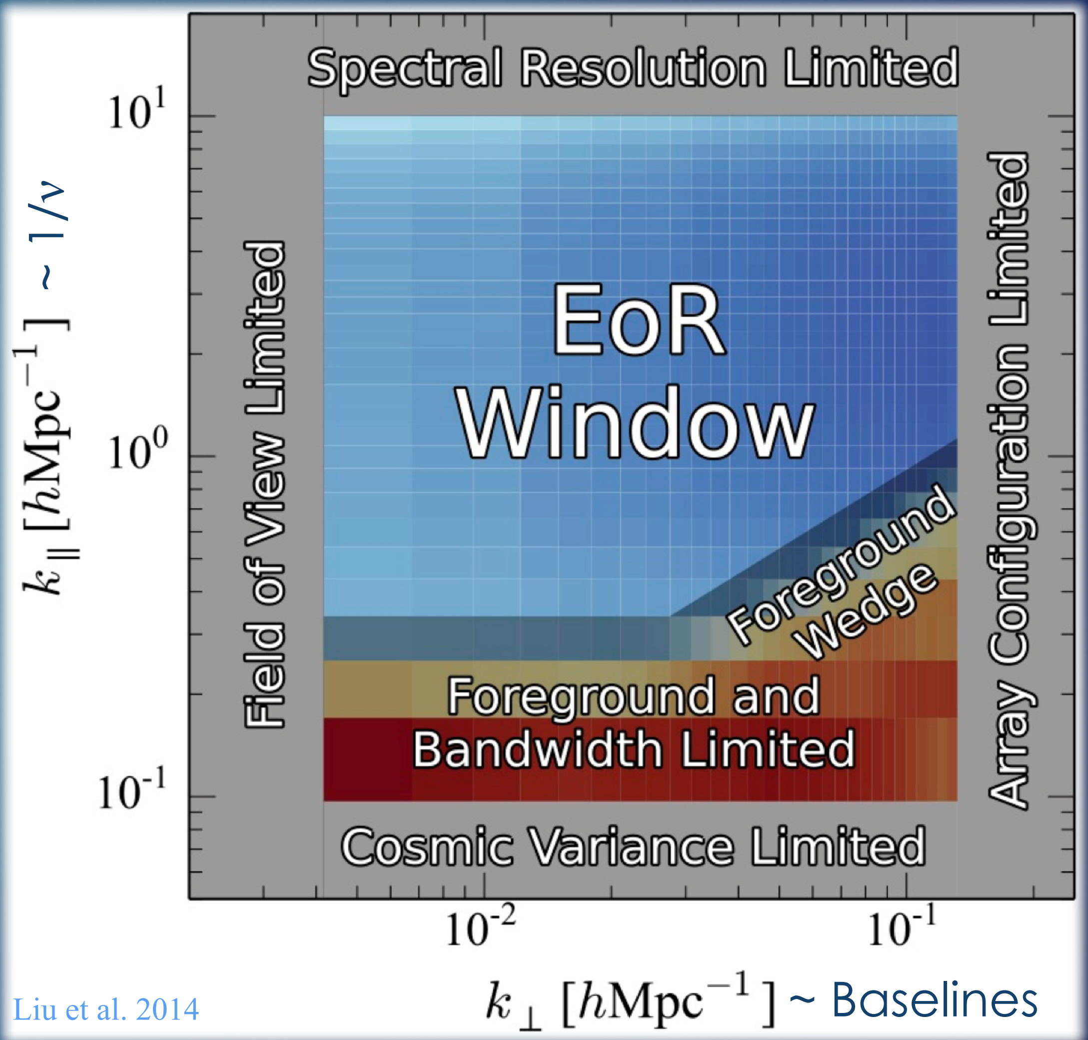
Most experiments try to detect the 1D PS.

2D PS useful diagnostic – separates frequency- and baseline-dependent effects.

Foreground removal attempts to remove foregrounds and see inside the wedge.

Foreground avoidance ignores modes in the wedge.

Foreground suppression optimally down-weights noisy modes to use *all data*, given a *model covariance* from *residual* foregrounds.
(Liu+Tegmark 2011, Liu+2014a,b)



Liu et al. 2014

A Framework for Statistical Point-Source Foregrounds (CHIPS)

Statistical Model Components

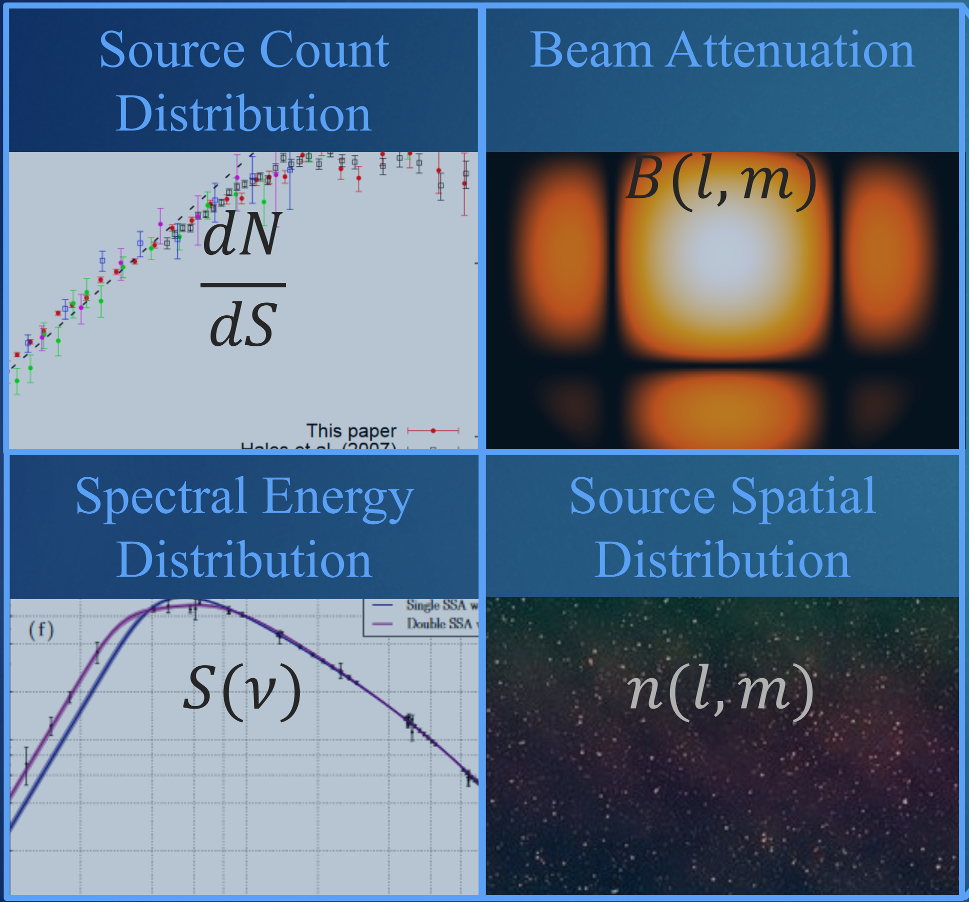


Image Credits: Franzen et al (2016), Tingay et al. (2013), Callingham et al. (2015), ICRAR/Hurley-Walker et. Al (2016)

$C_{FG}(u,\nu)$ ~FT → $C_{FG}(P)$

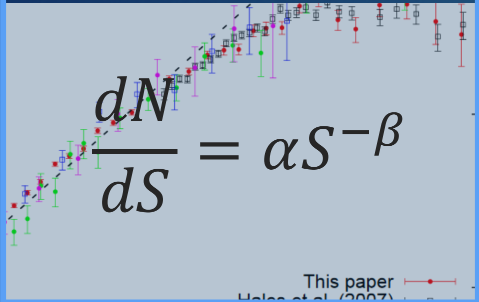
Covariance of 2D power spectrum

Covariance between visibilities on the same baseline at different frequencies.

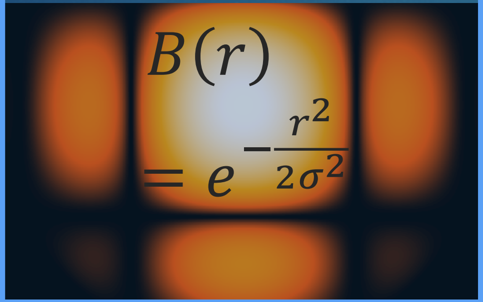
Current Simple Component Models

Statistical Model Components

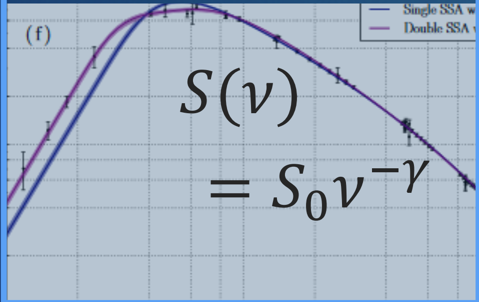
Source Count Distribution



Beam Attenuation



Spectral Energy Distribution



Source Spatial Distribution

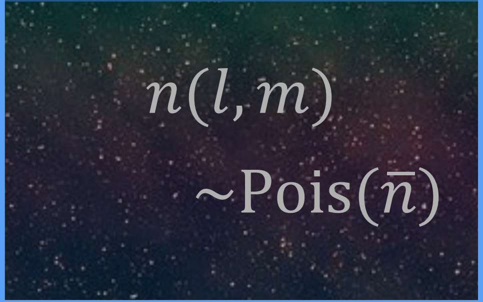


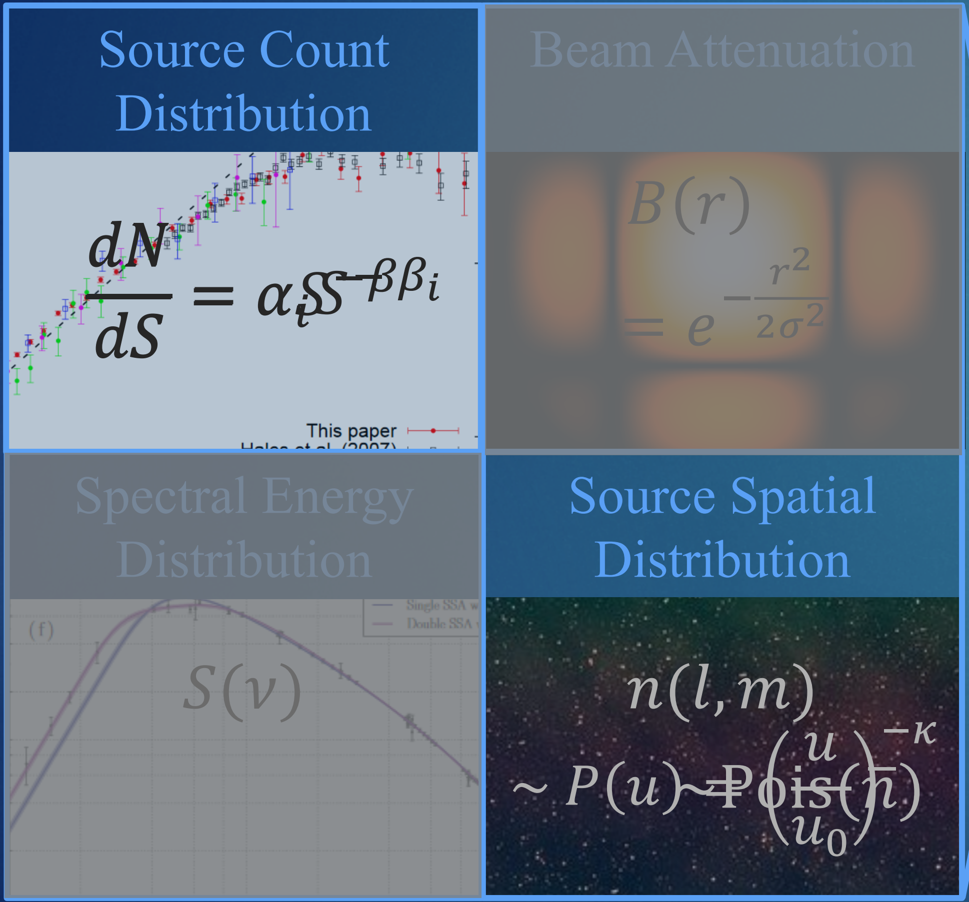
Image Credits: Franzen et al (2016), Tingay et al. (2013), Callingham et al. (2015), ICRAR/Hurley-Walker et. Al (2016)

$$2\pi(f_0' f_0'')^{-\gamma}\mu_2\Sigma_\nu^2 \exp(-2\pi^2 u^2 f_\nu^2 \Sigma_\nu^2)$$

- Smooth frequency dependence
- Exponential decay with on-sky scale
- Second moment of source-count distribution
- Dependence on beam-width
- Exponential decay with frequency difference

A Revised Model

Statistical Model Components



Dependence on source spatial distribution

Beam-width dependence

Exponential decay with on-sky scale

$$2\pi\sigma^2\mu_1^2\left(\frac{2\pi u}{u_0}\right)^{-\kappa}\frac{q^{-\kappa/2}(1+p^2)^{\kappa/2-1}}{f'^{\kappa+\gamma}_0\, f''^{2+\gamma}_0}e^{2\pi^2\sigma^2u^2(q-2)}$$

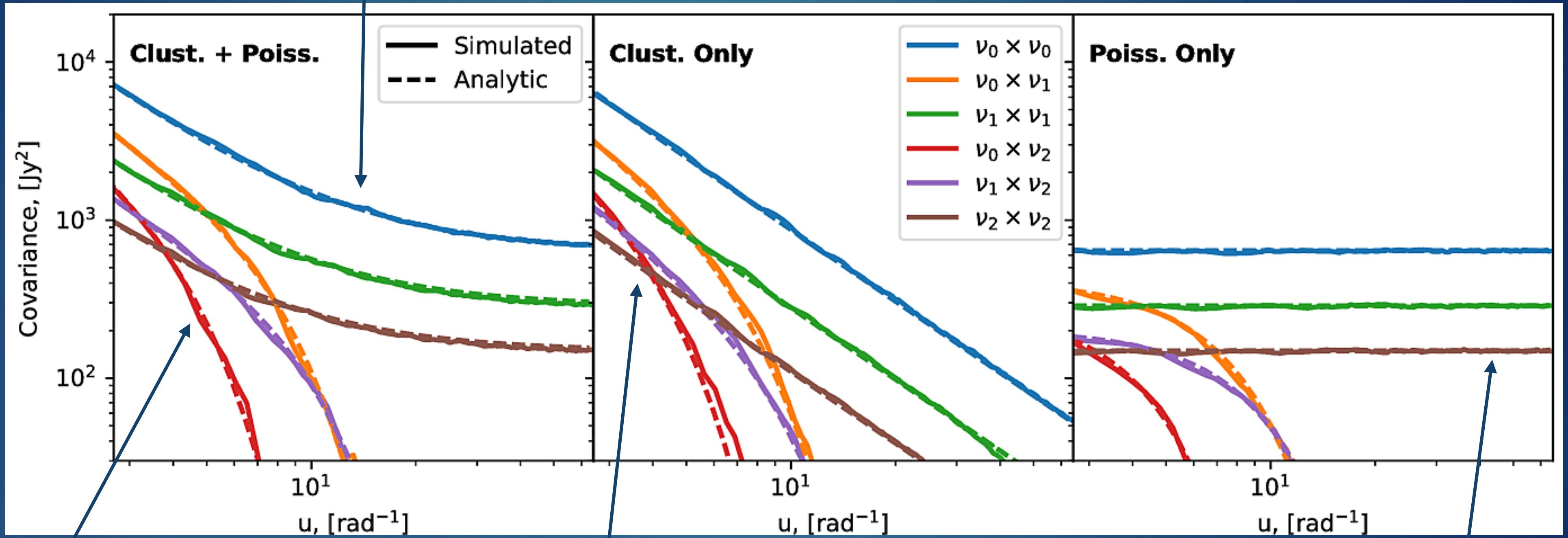
First moment of source count distribution

"Smooth" dependence on frequency

Image Credits: Franzen et al (2016), Tingay et al. (2013), Callingham et al. (2015), ICRAR/Hurley-Walker et. Al (2016)

Model Features I: *Test vs Simulation*

Transition point

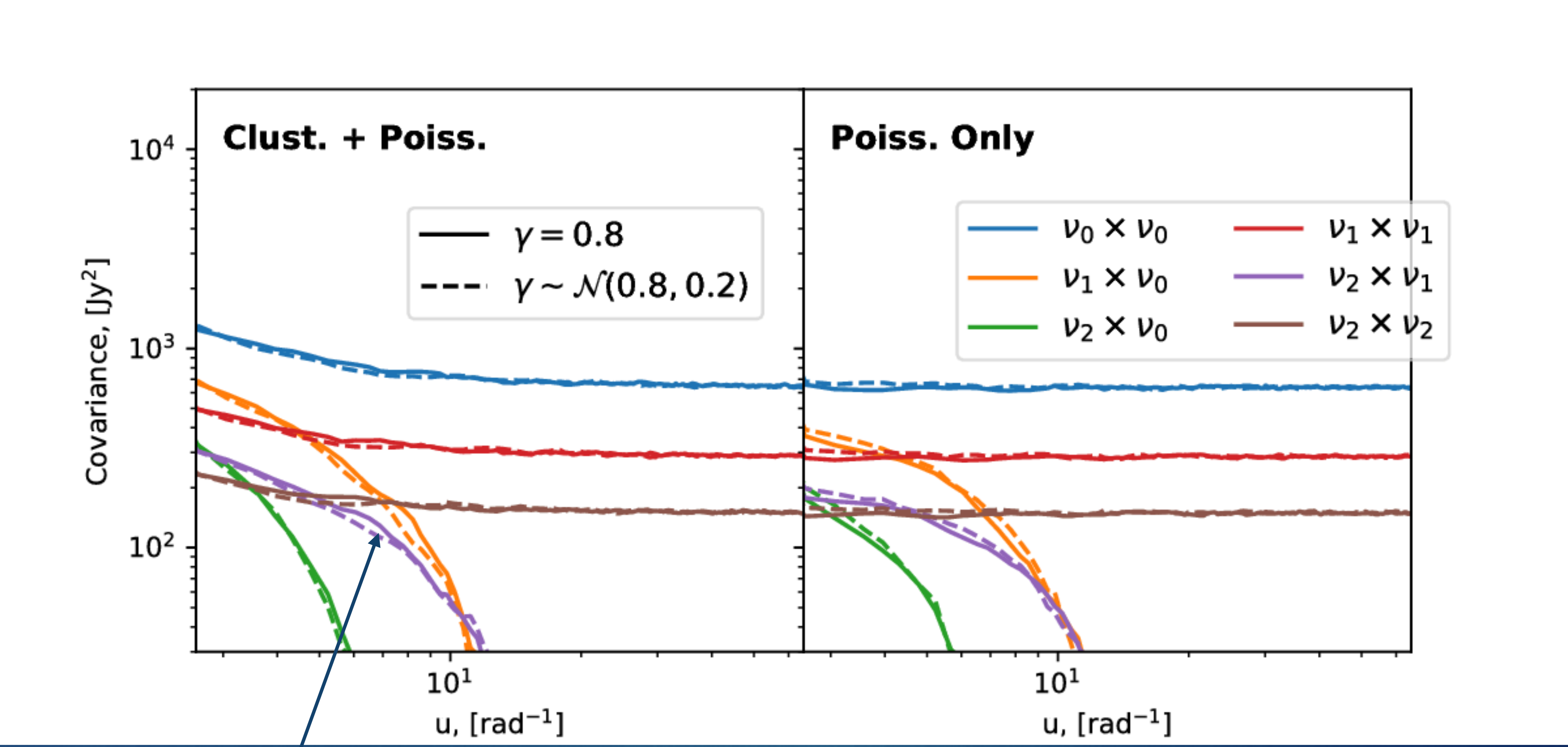


Analytic solution agrees with simulation

Clustering dominates on large scales

Poisson noise dominates on small scales

Model Features I: *Testing Spectral Index Distribution*



Normal Dist. of Spec. Index does not change results

Callingham+2017

Model Features II: *Source-Counts*

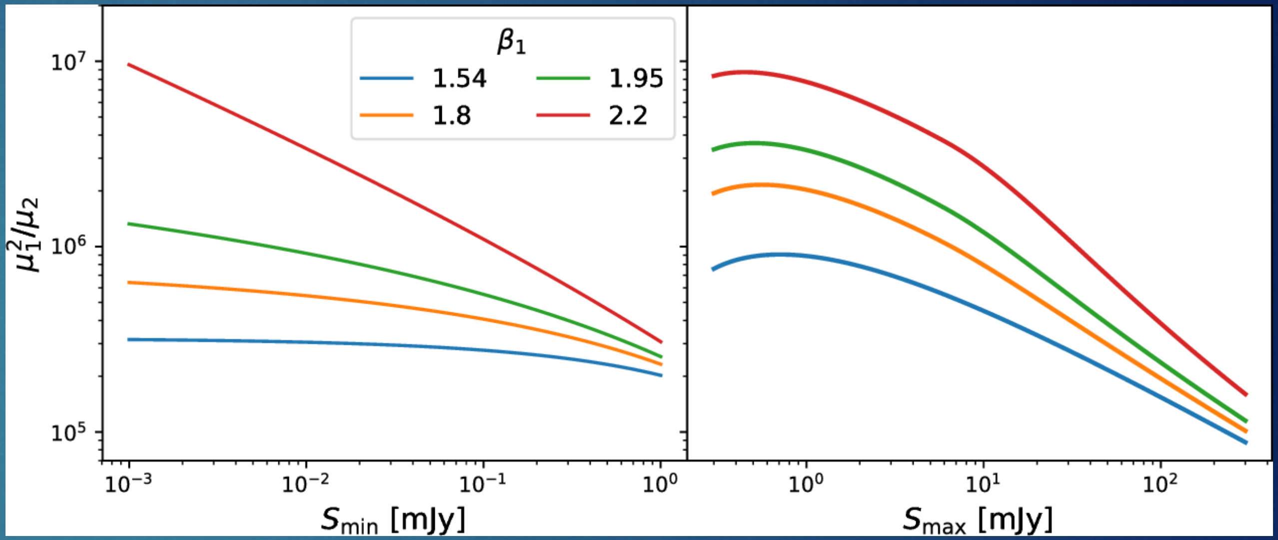
The scale above which clustering dominates is important:

$$u_{\star} = \left(\frac{\mu_1^2}{\mu_2}\right)^{1/\kappa} \frac{u_0}{2\pi}$$

Clustering more important if:

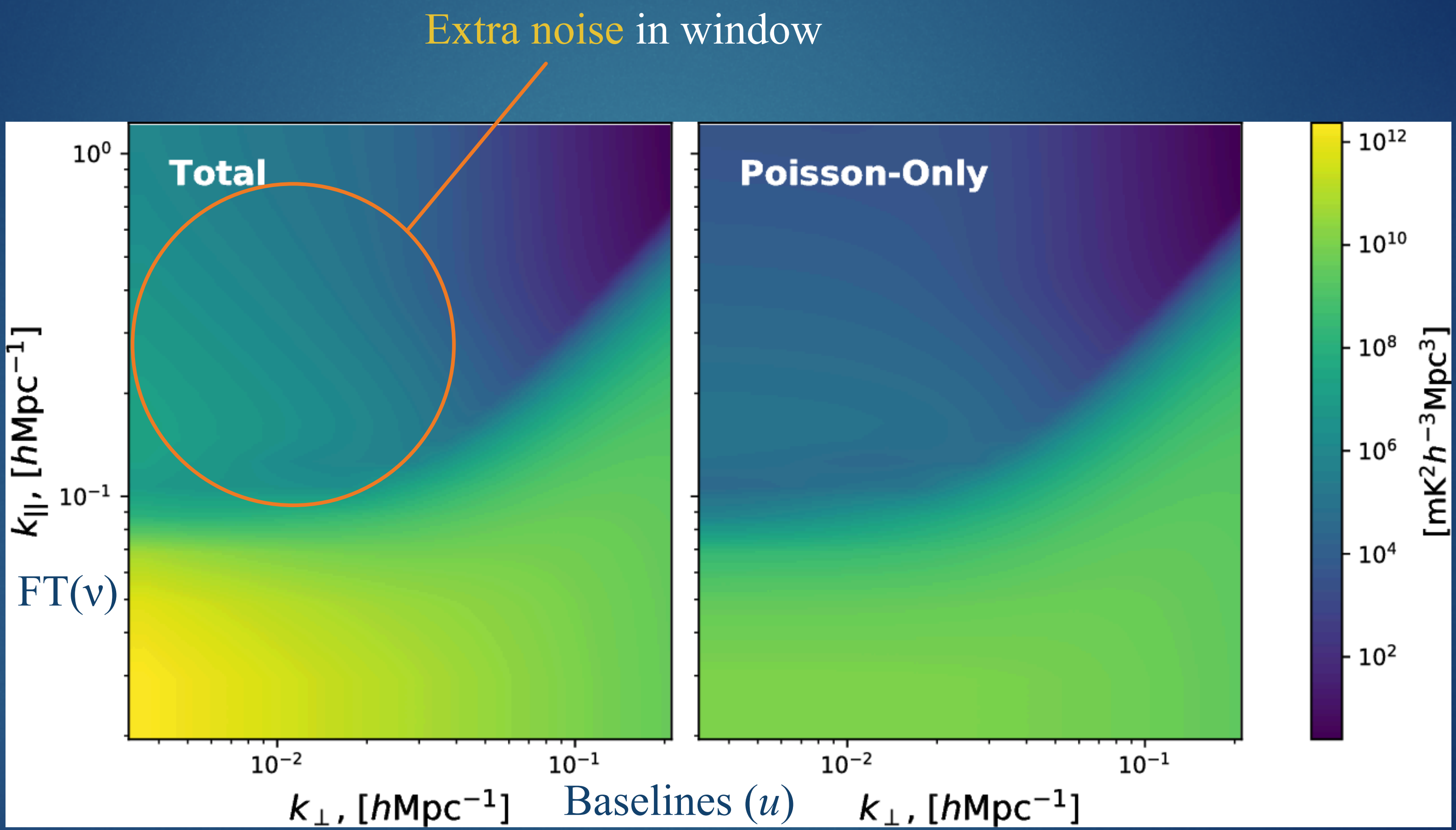
- Fainter sources exist
- More sources peeled (SKA!)
- Fainter sources more abundant

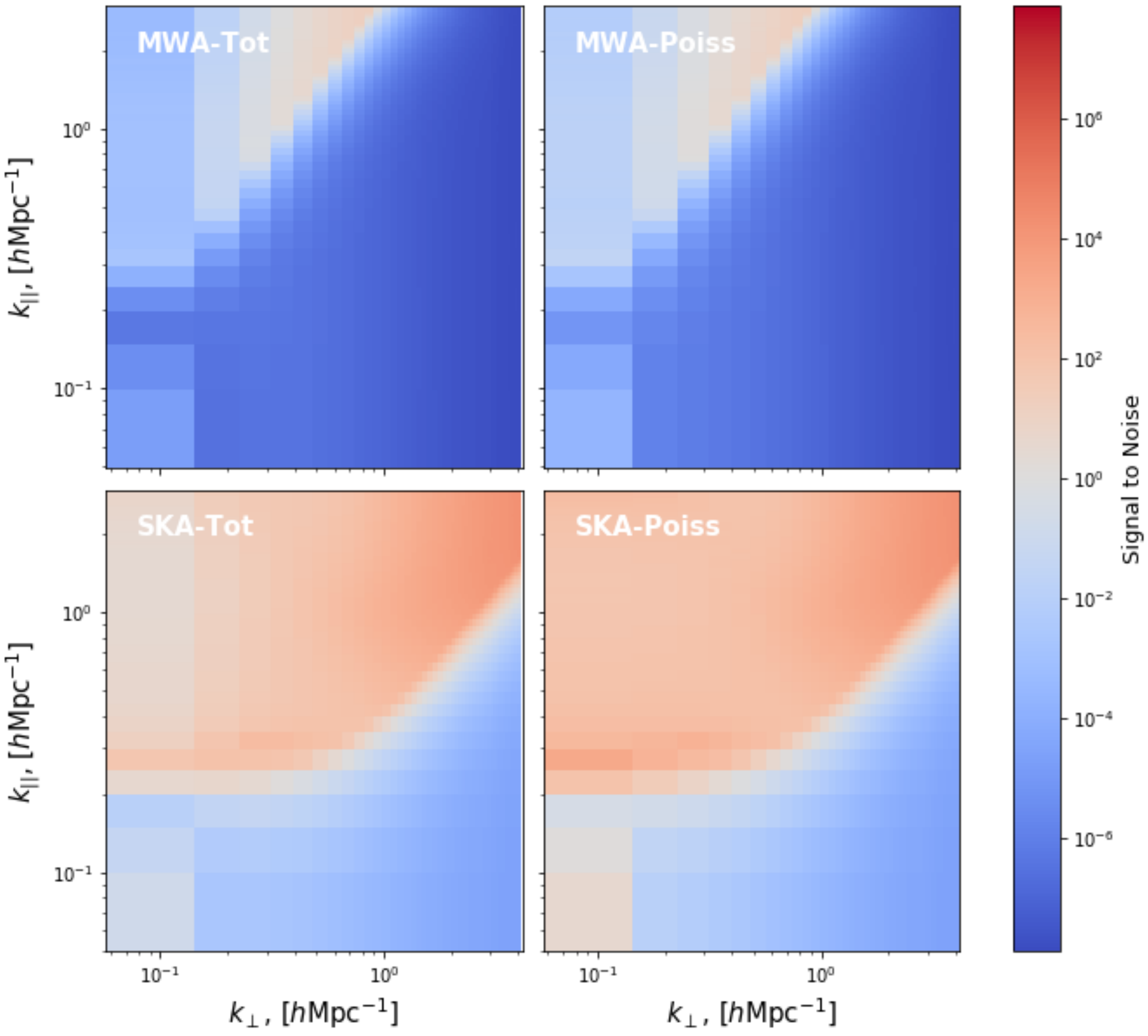
Very large-scale-heavy source distribution may push clustering into unobserved scales.



Current knowledge of the faint source population lets $u_{\star}$ range from 13 to 5000 – from unobservable to dominant over the entire range.

Model Features III: *Power-Spectrum Covariance*





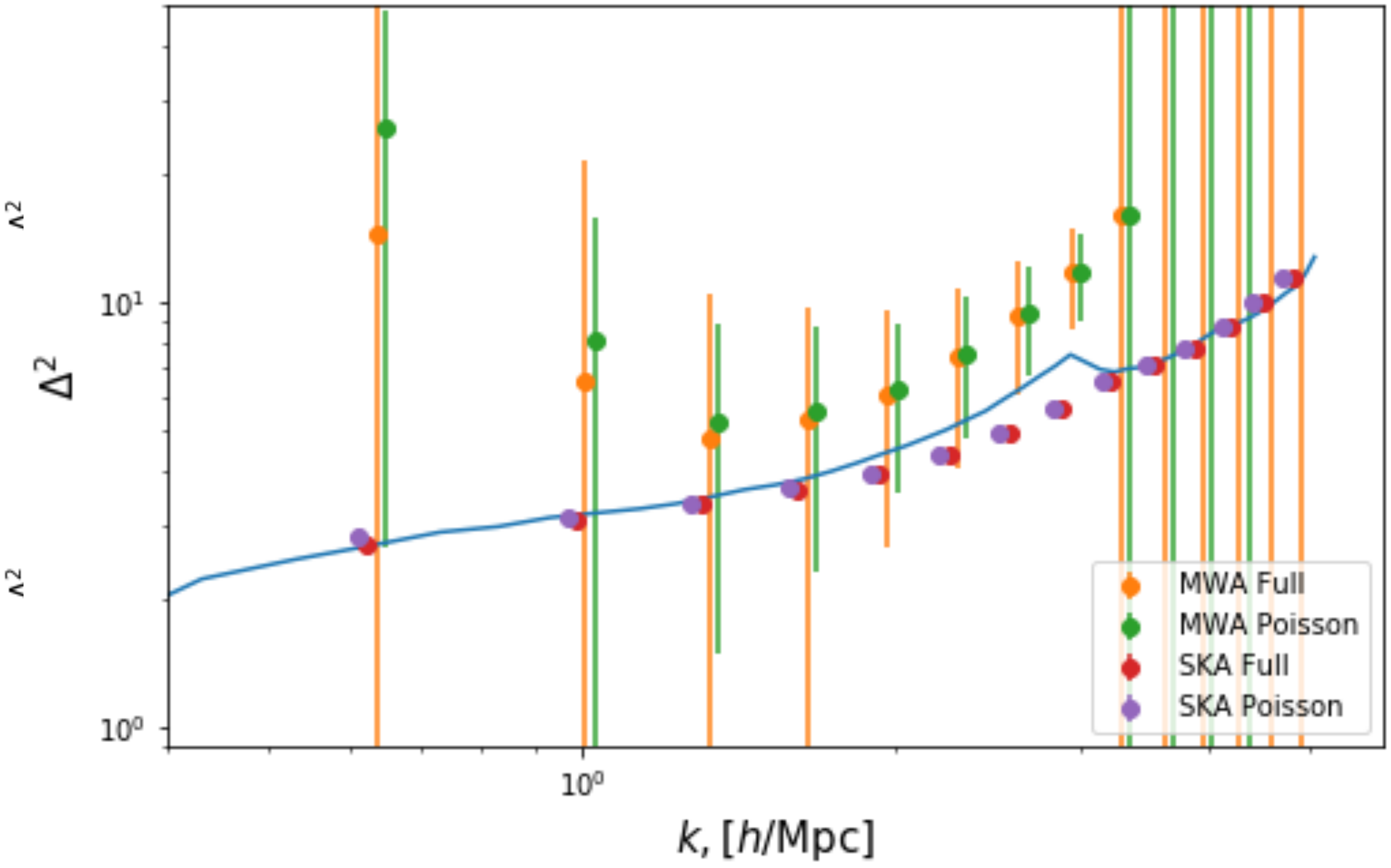
A Signal-to-Noise Estimate

Fiducial Model:

κ: 1.5 | u_0: 0.5
S_{max}: 30/1 mJy (MWA/SKA)
S_{min}: 0.1 mJy | β_1: 1.95

Caveats!

1. Spectral/Spatial limits from simulation, not instrument.
2. Only point-source foregrounds present.



Bias from Ignorance

Fiducial Model:

κ: 1.5 | u_0: 0.5
S_{max}: 30/1 mJy (MWA/SKA)
S_{min}: 0.1 mJy | β_1: 1.95

Caveats!

1. Same caveats apply
2. Highly uncertain κ
3. Observations more biased by large LOS scales.

Limitations and Assumptions

- True only for delay-spectrum (covariance for single baseline).
- Does not yield covariance between u bins.
- Assumes all residual compact sources are point sources.
- Assumes flat-sky approximation.
- Power spectrum model not physically motivated – investigate HOD/CLF models to jointly specify source counts and clustering.
- Final results ignore galactic foregrounds, which outshine point sources on largest scales.

Summary and Conclusions

- Biggest challenge for EoR detection is systematic foregrounds (more time + bigger telescope doesn't help!)
- A promising approach is to use inverse covariance weighting to suppress foreground contamination.
  - Requires realistic model of foreground covariances.
- We derived a new foreground covariance model using realistic source count and spatial distributions.
  - Realism could be enhanced by next-generation surveys on SKA1.
- Our model predicts:
  - Extra covariance on largest scales.
  - This effect grows (relatively) stronger for deeper surveys (i.e. SKA!)
  - SKA1 (and SKA2) will require high-fidelity models of source clustering to accurately predict large-scale EoR PS.