The Impact of Sky Model Defects on SKA EoR Experiments

A Source Blending Case Study

Chenxi Shan | Shanghai Jiao Tong University

Yongkai Zhu, Yuanyuan Zhao, Dongchao Zheng & **Haiguang Xu** @ SJTU
Sarah White @ Rhodes Sanjay Bhatnagar @ NRAO
Ben McKinley & Jack Line @ Curtin Zhenghao Zhu & Hekun Li @ SHAO

OUTLINE

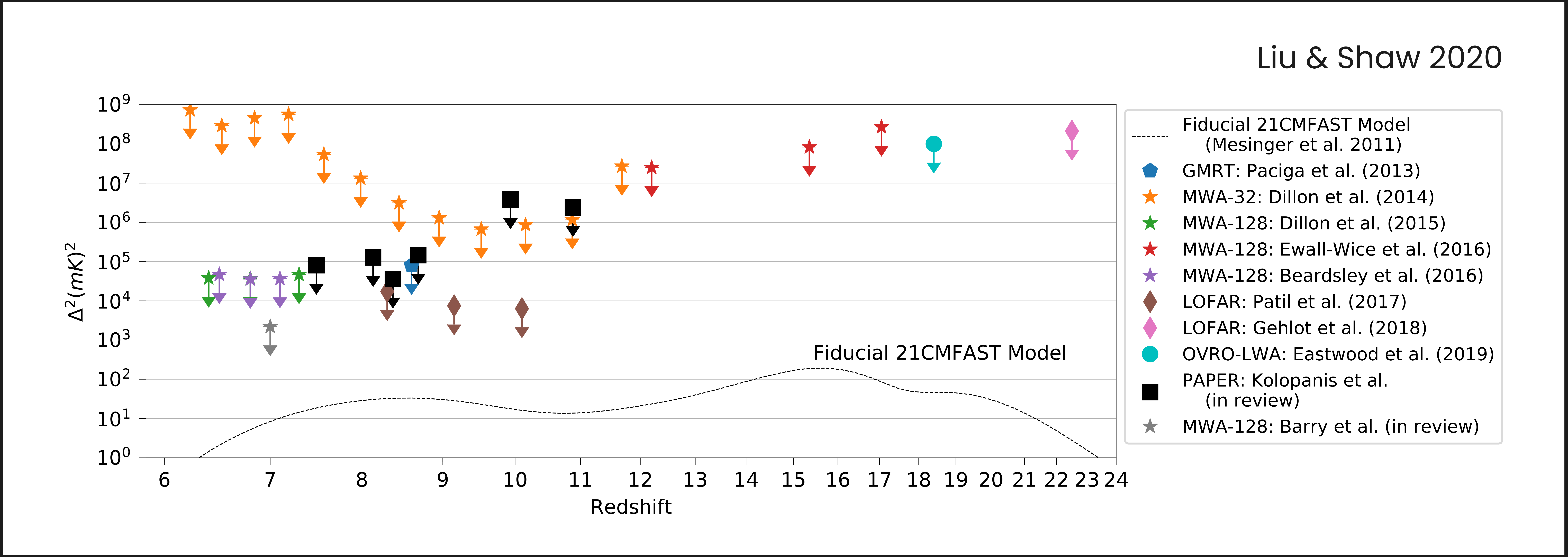
Background Systematics » Calibration-induced biases

Method Blending as a sky-model defect for the SKA1-Low
Hybrid Evaluation Pipeline (reconstructed sky)

Results Impact in the measurement (2D-PS) space

EoR Error Budget

Background



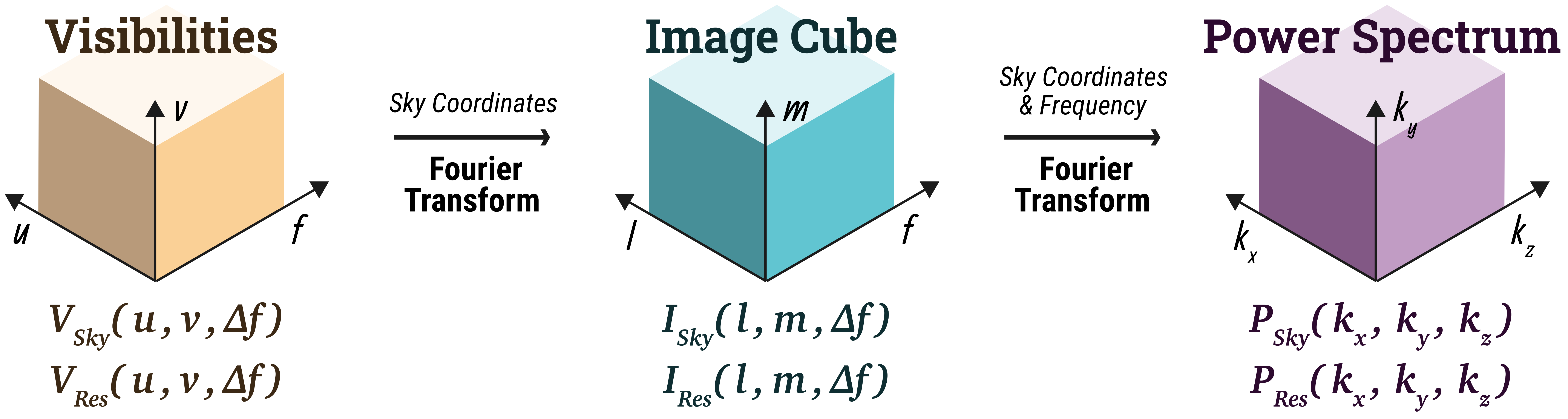
Calibration → Imaging → Analysis

Small Error Budget

How do we spend the error budget ?

EoR Error Budget

Background



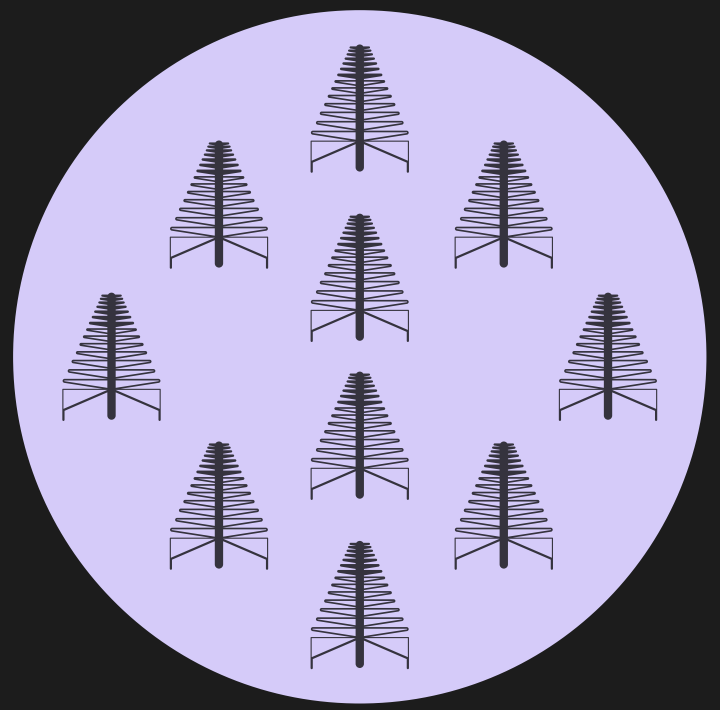
Callibration Error >> Propagation effect

Calibration

Background

Prior Knowledge

Raw Data → **Calibration** → Sci Data



Instrumental Effects

Telescope's Electronics
Bandpass Responses, etc.

LoS & External Effects

Radio Frequency Interference
Ionospheric Distortion, etc.

EoR Science: High precisin calibration Is required

Calibration

Background

$$V_{ij}^{sky-meas} = g_i^* g_j V_{ij}^{sky-true} + n_{ij}^{res}$$

V_{ij}^{meas} **Measured Visbility** → **Calibrate** → G_{ij} **Calibration Solutions** → **Apply** → V_{ij}^{cali} **Calibrated Visbility**

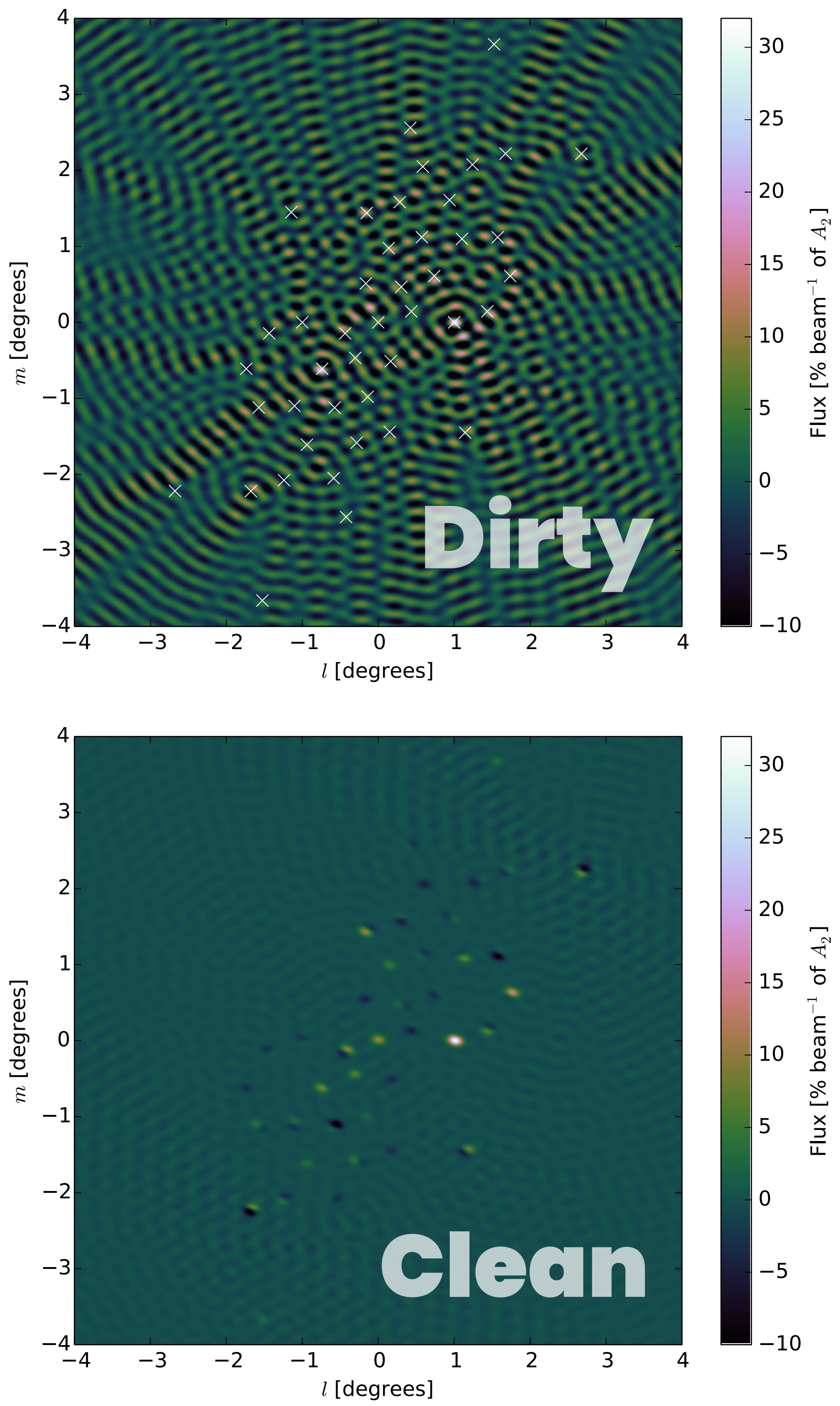
V_{ij}^{model} **Modelled Visbility** → **Calibrate**

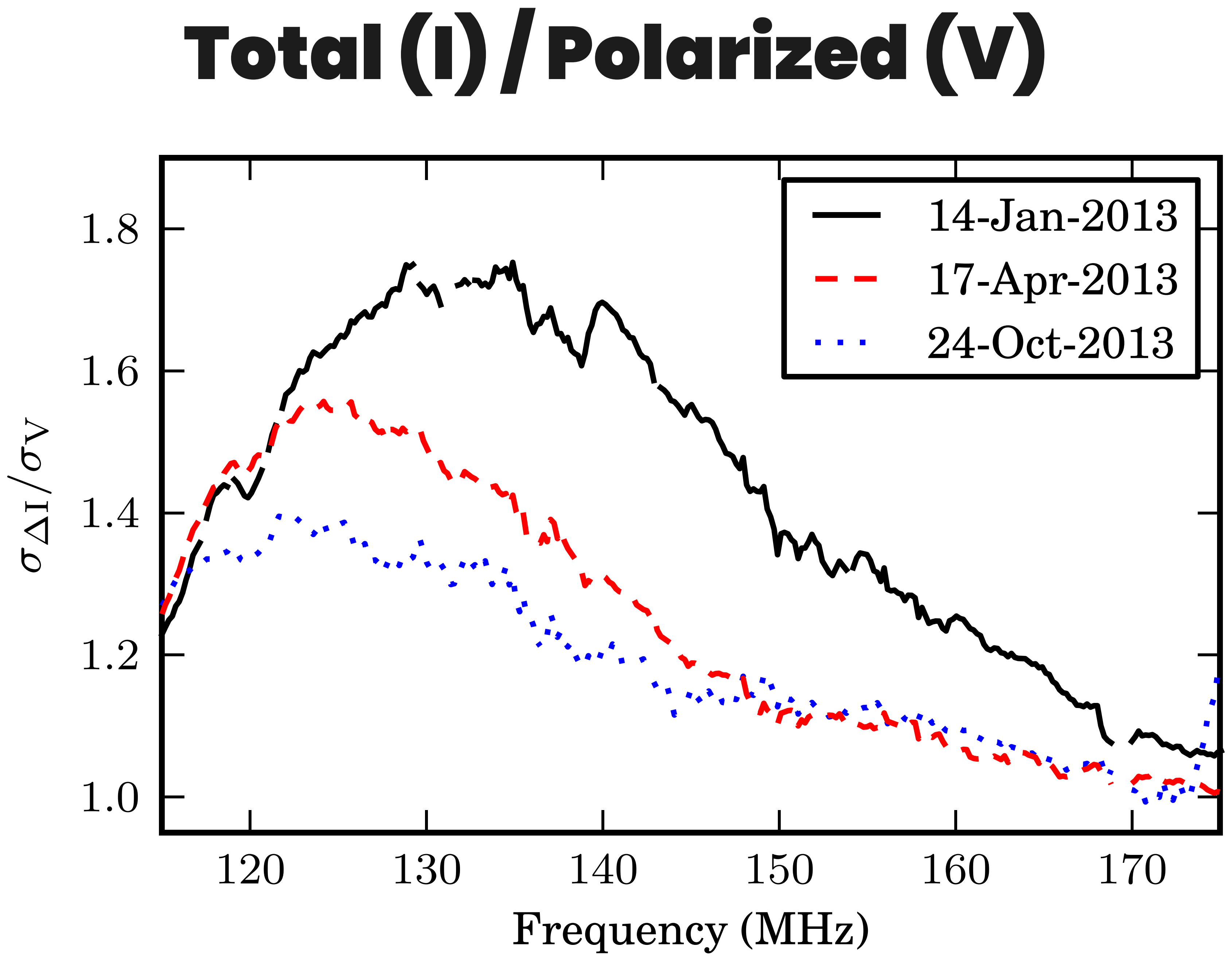
See detailed derivations in Wieringa 1992 & Liu et al. 2010

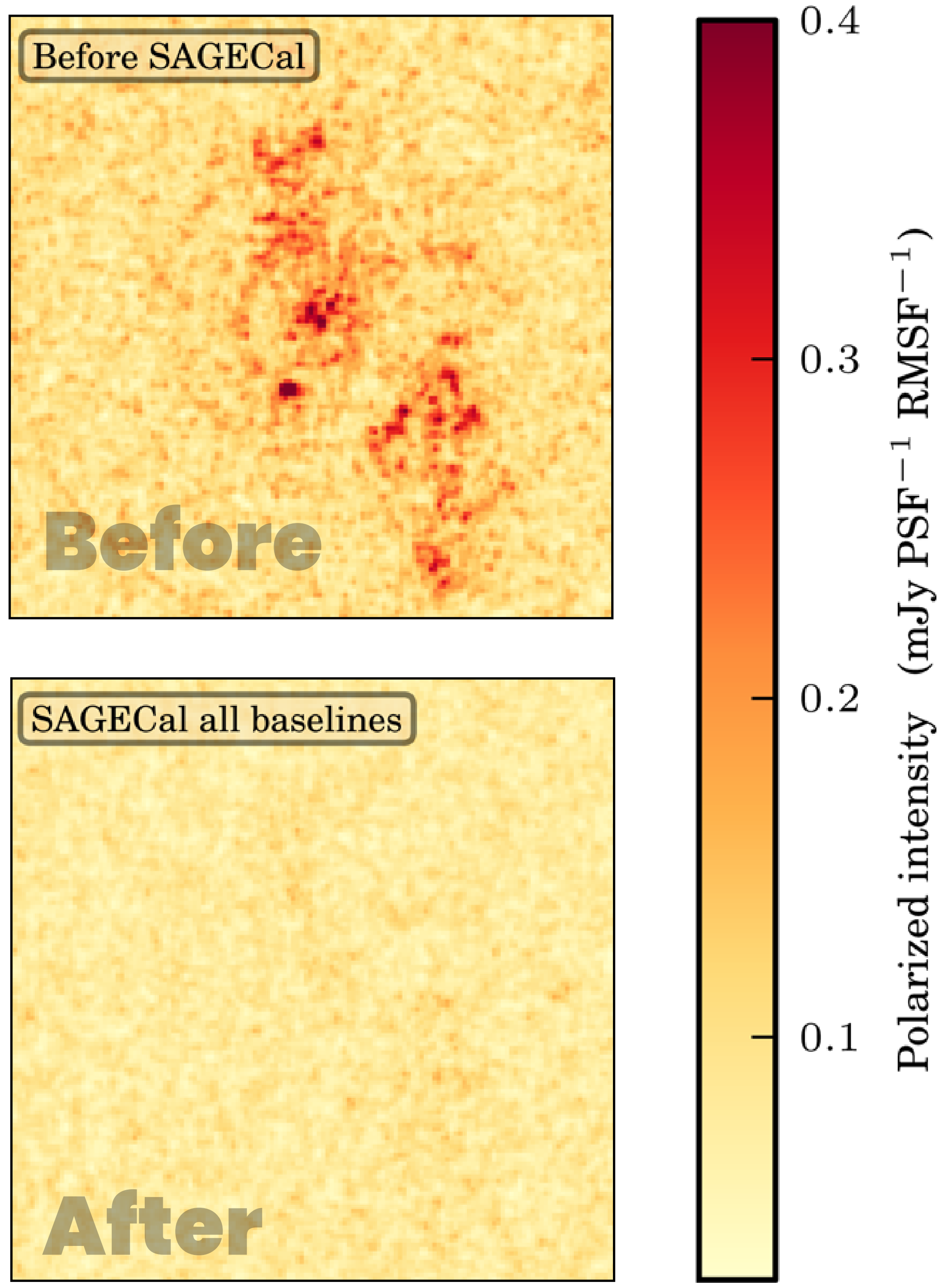
Calibration >> Infer the TRUE sky responses

Ill-calibration Effects

Background







Imaging Artefacts
Wijnholds et al. 2016

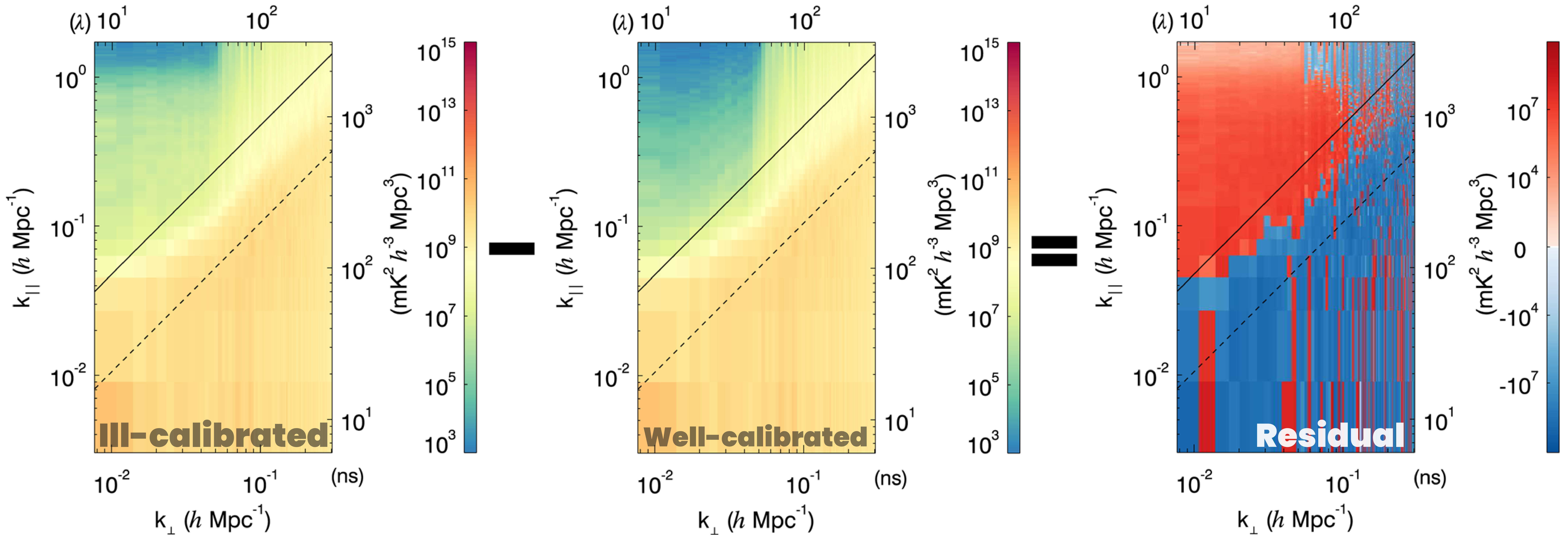
Access Noises
Patil et al. 2016

Emission Suppression
Patil et al. 2016

Ill-calibration Effects

Access power within EoR window

Barry et al. 2016



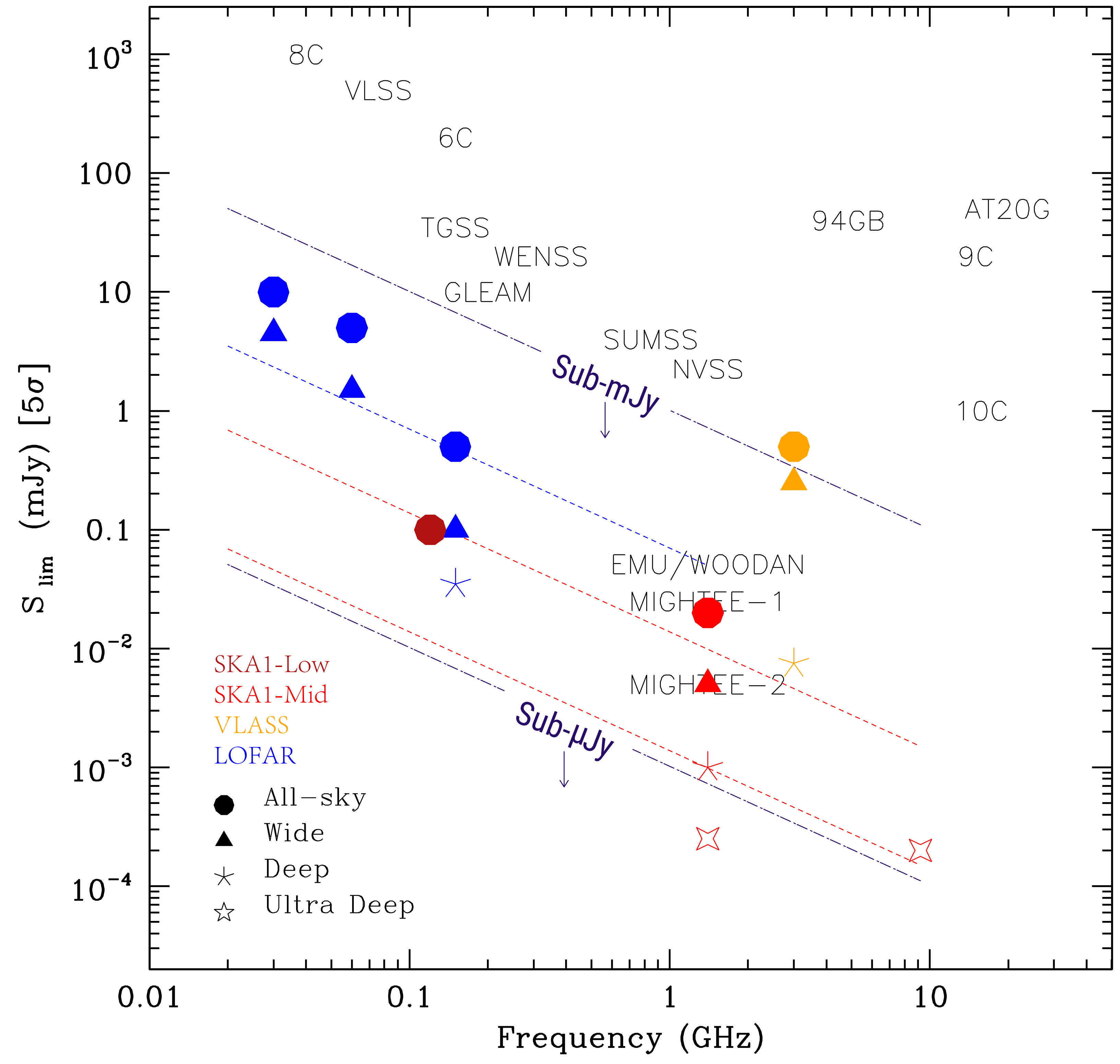
Propagated biases in the PS space hinder the EoR detection

How to idenitify sources of error ?

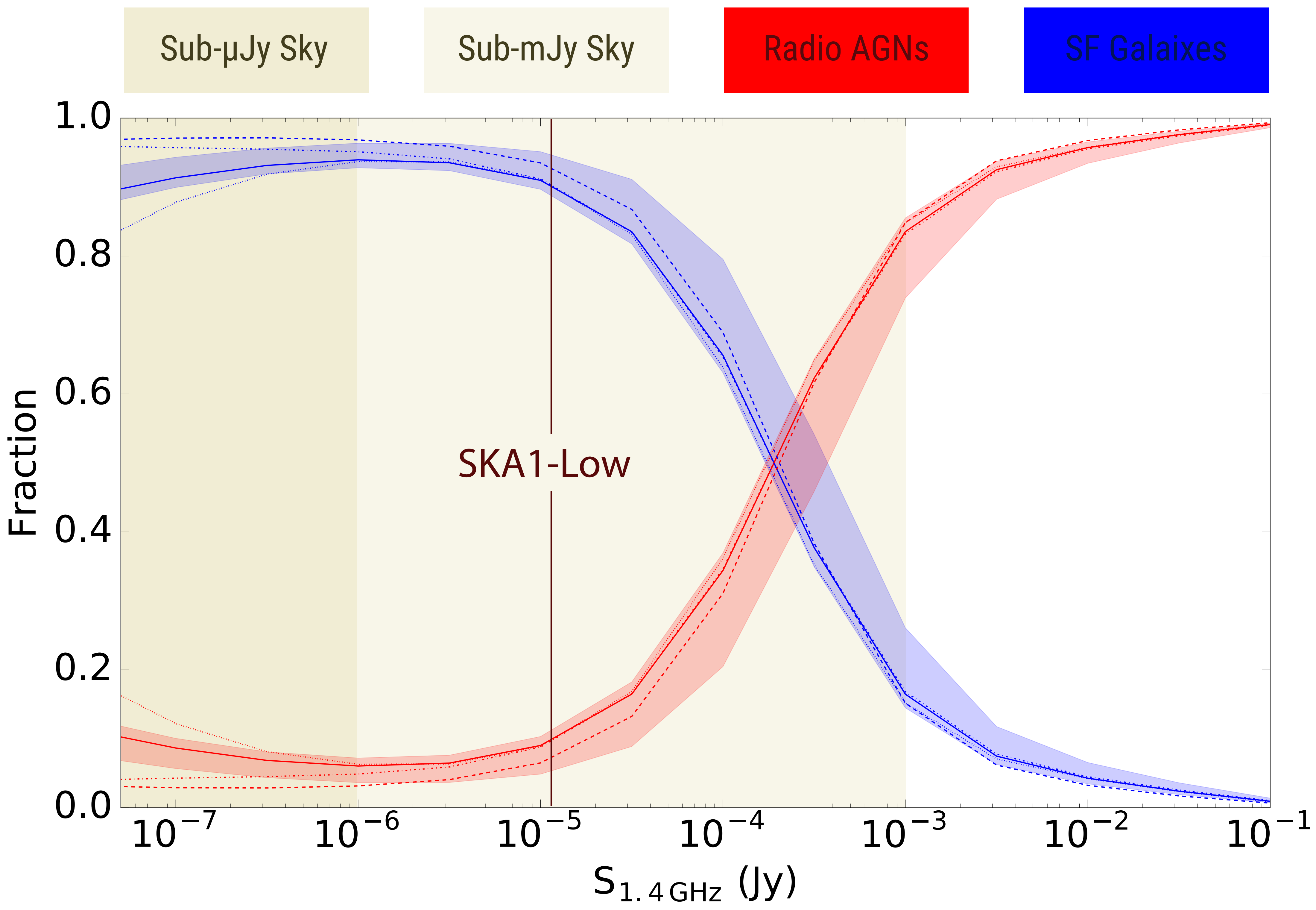
SKA Sky Model Populations

Method

Modified from Prandoni et al. 2015



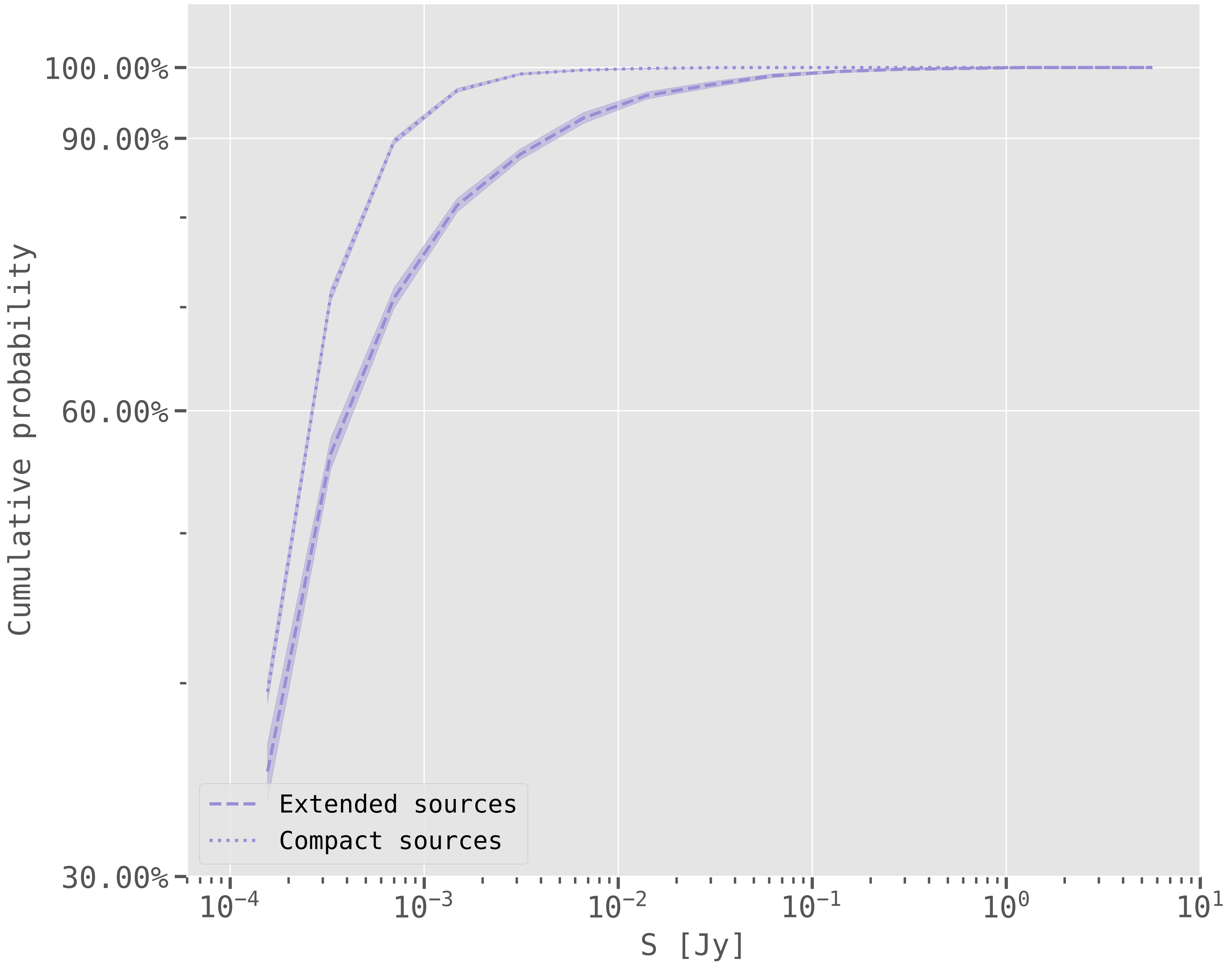
Modified from Novak et al. 2018



Discrete >> Crowded Sky (the same populations as optical)

Source Blending

Method



Discerte Source Model

+

(65-km) SKA Array Config

+

(Confusion-limited) Noise Level

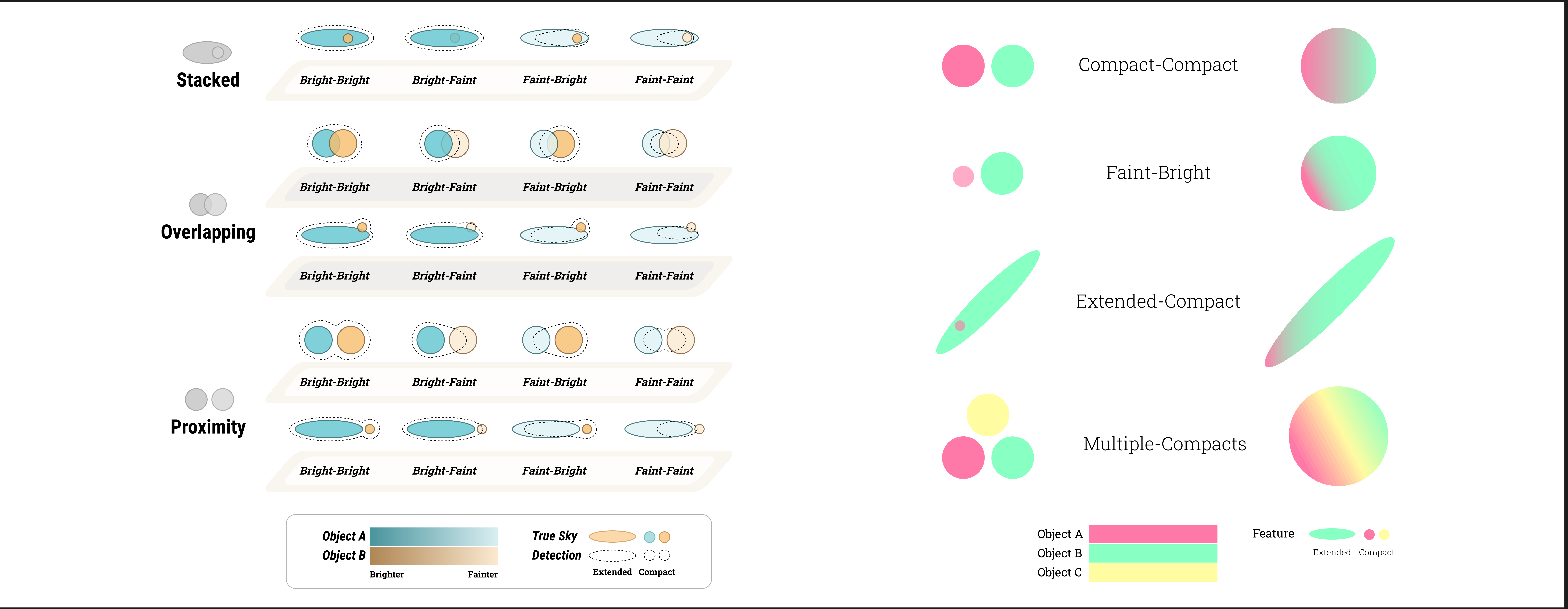
=

Blending Ratio: 5 - 20%

Confusion limited SKA1-Low >> Moderate blending levels

Blending Effects

Method



Spatial domain

Flux + Position Error

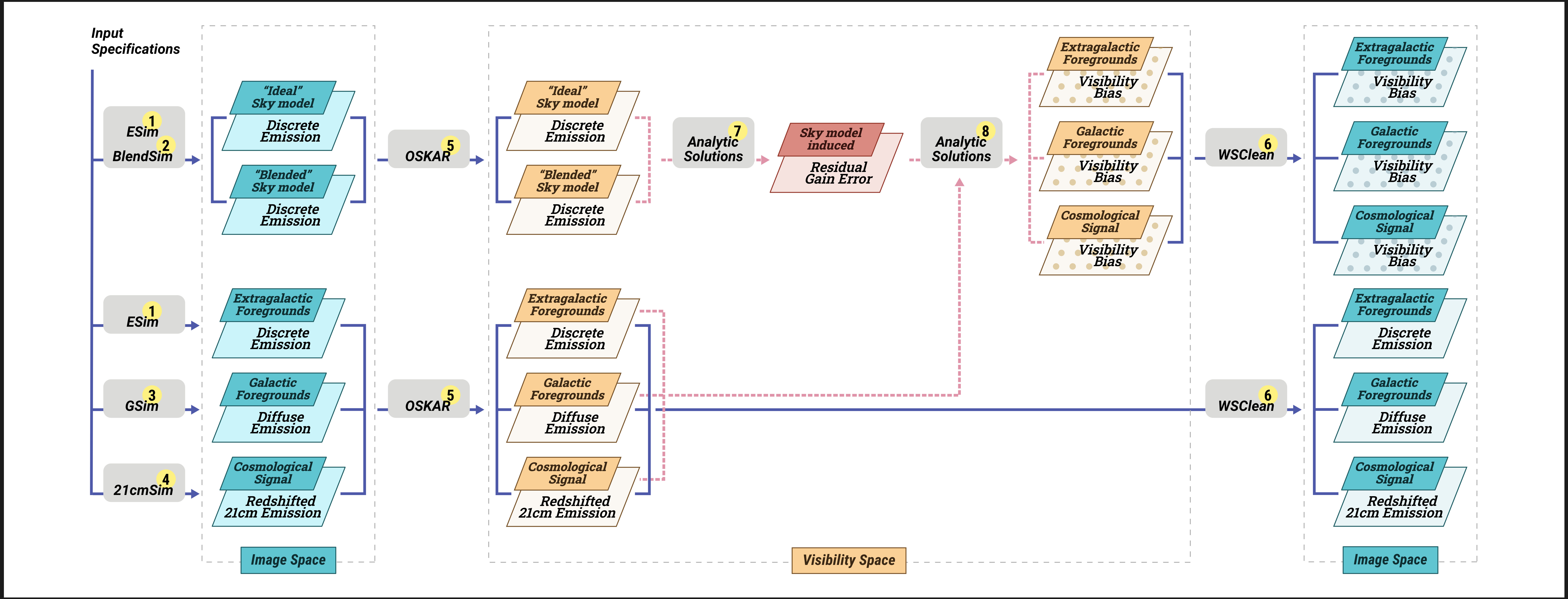
Spectral domain

Spectral index deviation

How to evaluate the impact ?

Evaluation Pipeline

Method



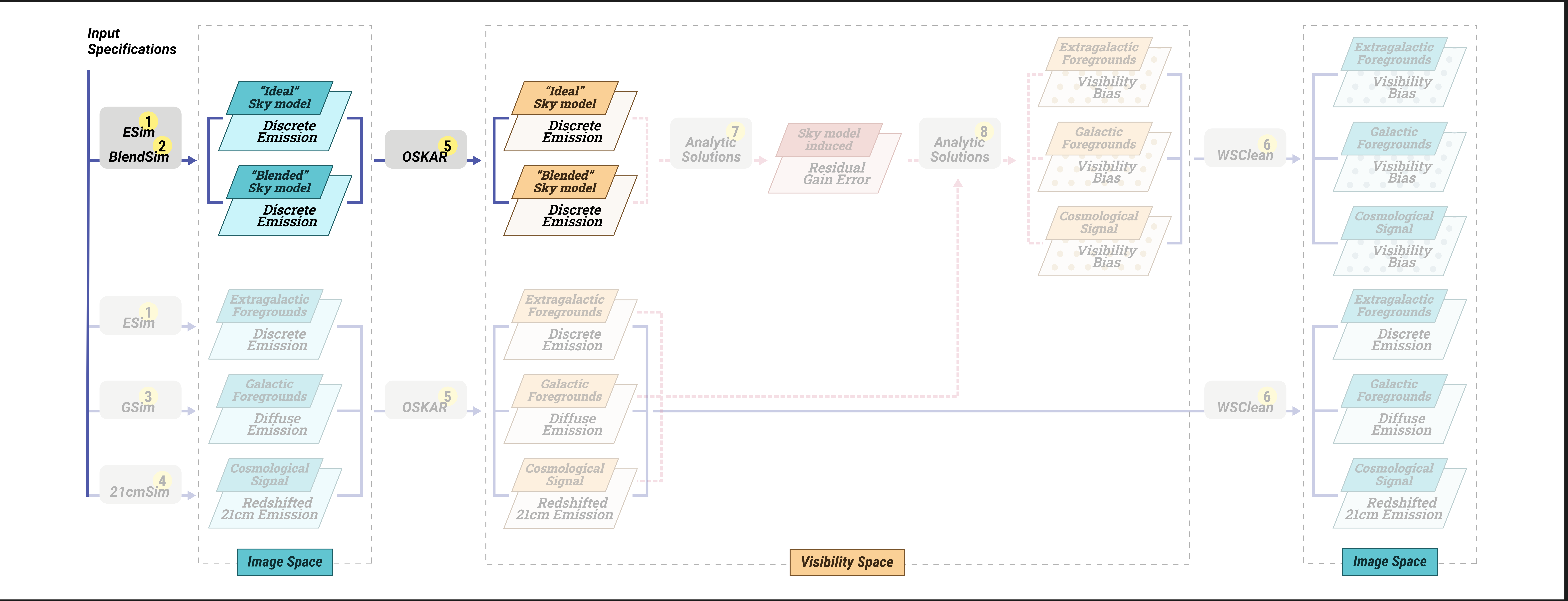
Block Digaram of the Simulation & Analytic Pipeline

- Analytic Pipeline
- Simulation Pipeline
- Name 0 Software modules
- 0 Software lables
- Sky maps: Sky emission & sky model
- Dirty & Clean maps: Sky emission
- Dirty & Clean maps: Propogation visibility bias
- Data: Blending induced residual error
- 'Observed' visibilities: Sky emission & sky model
- 'Observed' visibilities: Propogation viaibility bias

The Key Modules

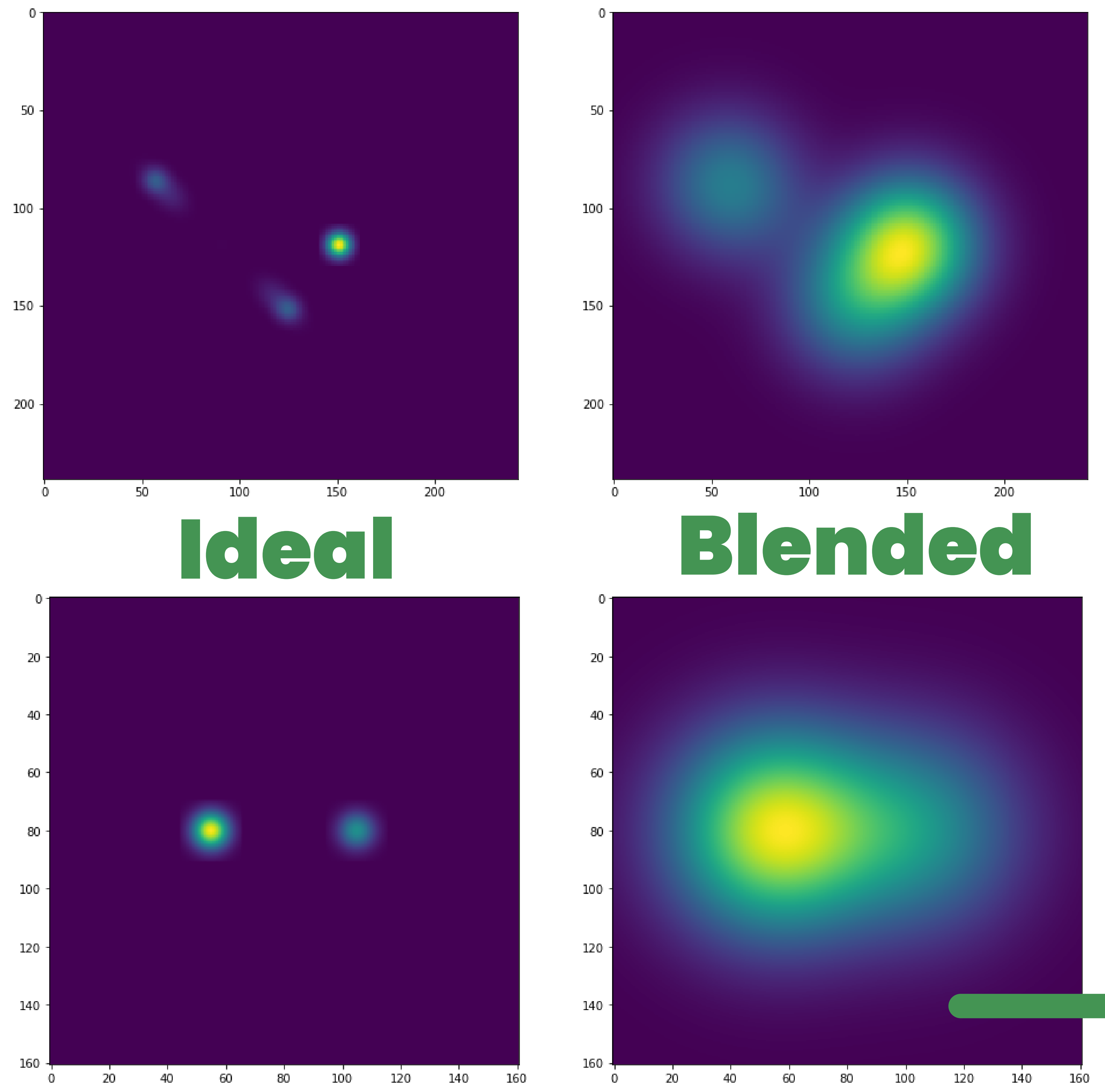
Pipeline: Blending Effects

Method



ESim + BlendSim >> Sky model pairs

Blending Effects



FG21Sim+ Simulation Suite

ESim (Simple/Gaussian/Fedility) + BlendSim

Spatial domain:

Source pairs * clean beam

>> distorted flux density distribution

Spectral domain:

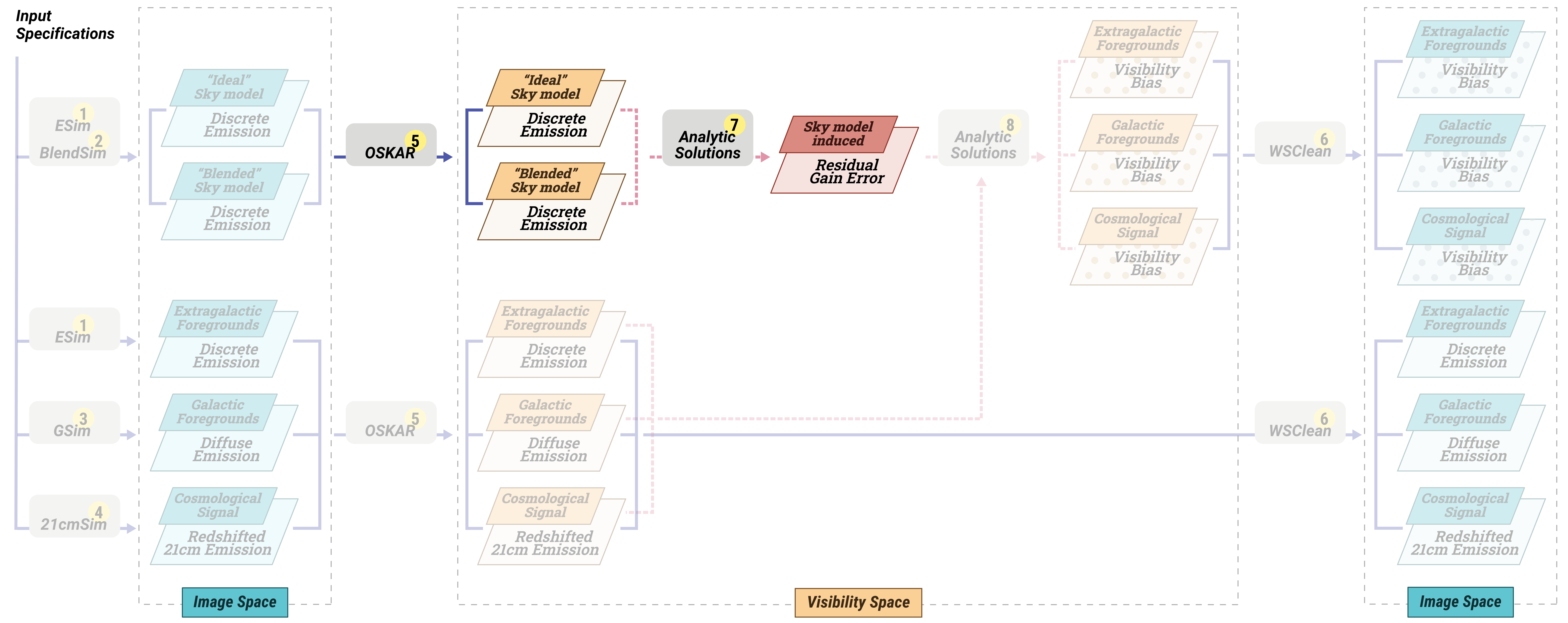
Source pairs fits new spectral index

>> deviated integrated spectral index

Looks like a Jetted-FR1 (One of the most common RGs)

Next-gen E2E simulation suite >> Simulate defects

Pipeline: Defects Evaluation Method



SVD-based Bias Estimator >> Gain errors

Defects Evaluation

Method

$$V_{ij}^{sky-meas} = g_i^* g_j V_{ij}^{sky-model}{}_{\text{'ideal'}} + n_{ij}^{res}$$

+

$$V_{ij}^{sky-meas} = g_i^* g_j V_{ij}^{sky-model}{}_{\text{'defected'}} + n_{ij}^{res}$$

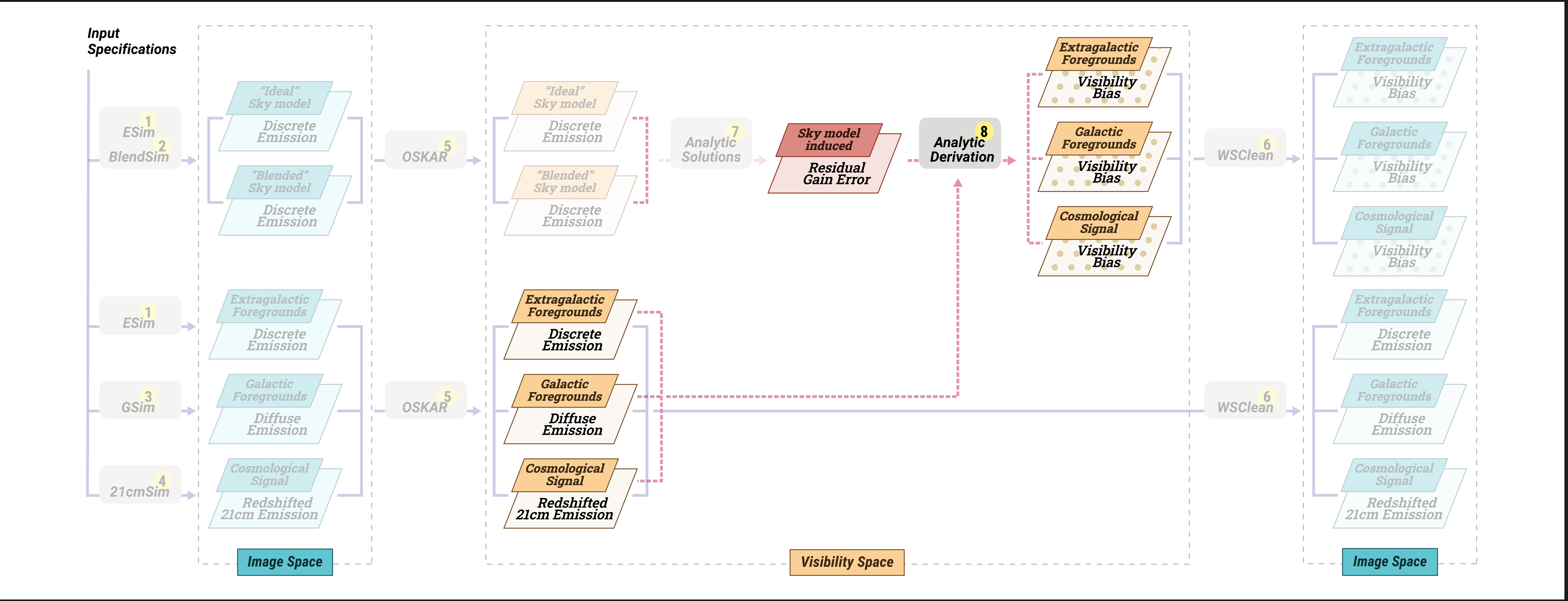
↓

$$n_{ij}^{res} + g_i^* g_j V_{ij}^{sky-model}{}_{\text{'ideal'}} = g_i^* g_j V_{ij}^{sky-model}{}_{\text{'defected'}} + n_{ij}^{res}$$

Sky model pairs » Relative gain errors

Pipeline: Visibility-bias

Method



Visibility Bias Estimation >> Propagated biases

Simulation Specs

Method

Smallest physical scale > SKA1-Low resolution > 6" @ 200 MHz

Quantify the impact of source blending at 3 levels

High	Blending Ratio: 5%
Mid	Blending Ratio: 0.5%
Low	Blending Ratio: 0.05%

Component	Usage	Sky Coverage	Pixel Size	Exposure	Preprocessing	Post-processing
'Ideal' sky model	Calibration	$5^\circ \times 5^\circ$	1 arcsec	2 min	None	None
'Blended' sky model	Calibration	$5^\circ \times 5^\circ$	1 arcsec	2 min	None	None
Extragalactic foregrounds	Evaluation	$2^\circ \times 2^\circ$	2 arcsec	6 h	Bright sources are masked	Clean images are cropped as $1^\circ \times 1^\circ$
Galactic foregrounds	Evaluation	$2^\circ \times 2^\circ$	2 arcsec	6 h	Tapered at 1.5°	Clean images are cropped as $1^\circ \times 1^\circ$
EoR signal	Evaluation	$2^\circ \times 2^\circ$	2 arcsec	6 h	None	Dirty images are cropped as $1^\circ \times 1^\circ$

CPU, GPU, Memory expensive: Resolution over FoV

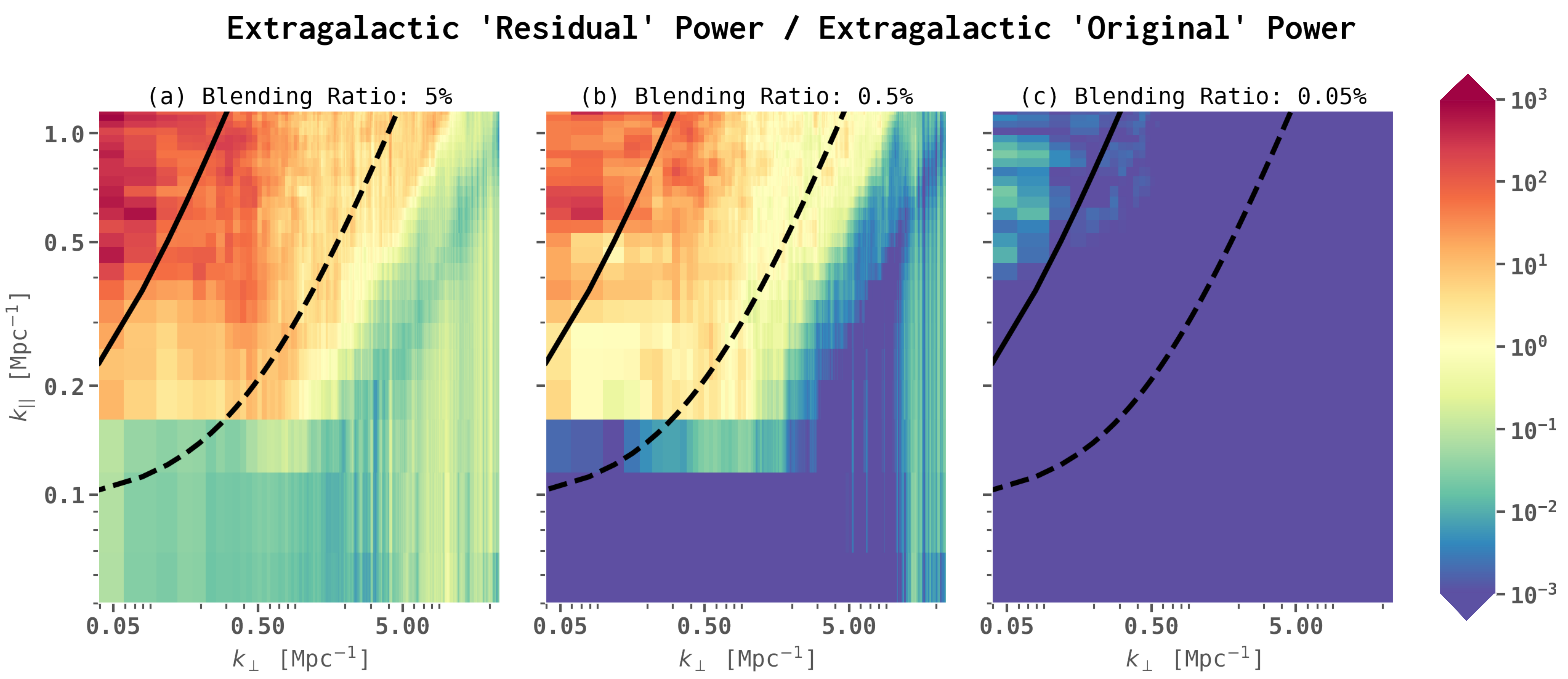
The Impact in the 2D-PS space.

2D Power Spectrum

Results

Access Power

Additive powers are leaked into the EoR-windows



Bounderies: Solid - Horizon & Dashed -- FoV | Shared Colorbar

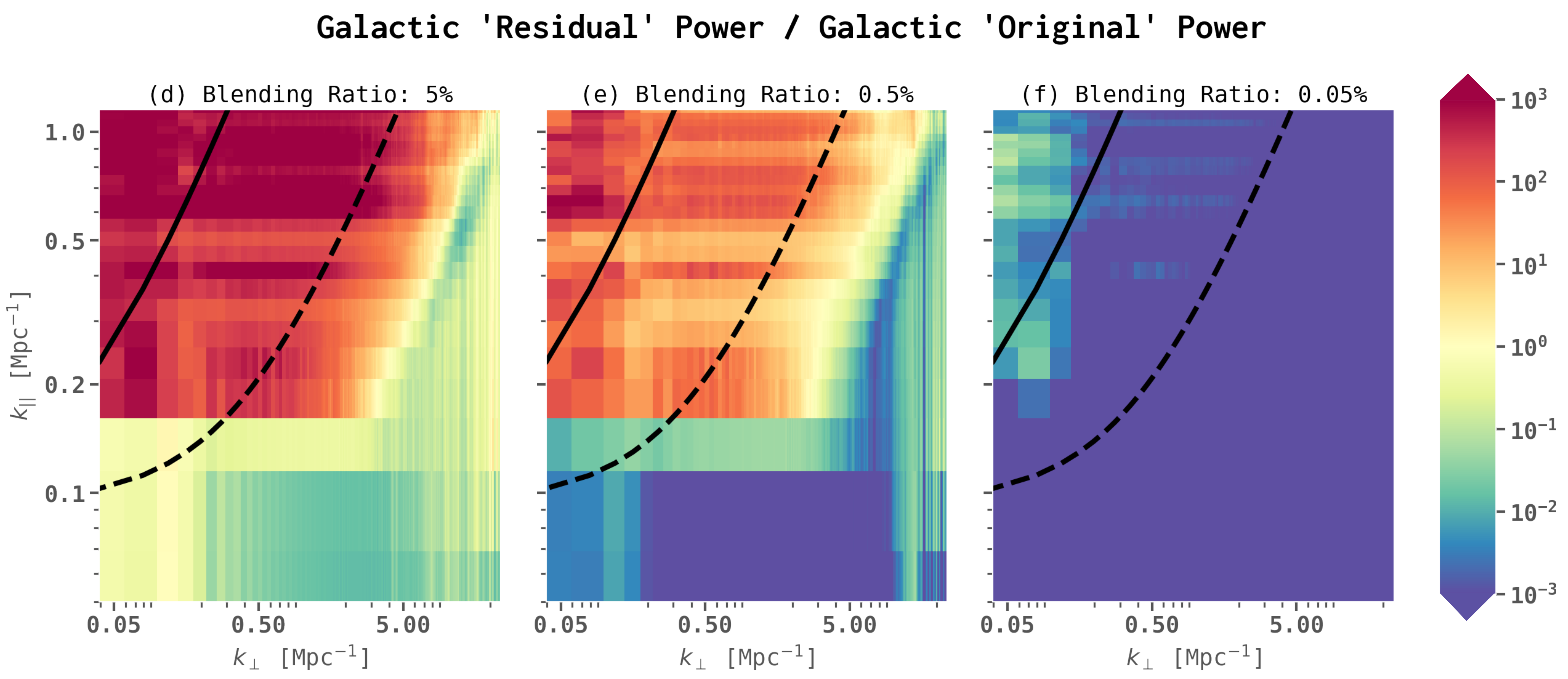
‘Residual’ powers vs ‘Original’ powers

2D Power Spectrum

Results

Access Power

Additive powers are leaked into the EoR-windows



Bounderies: Solid - Horizon & Dashed -- FoV | Shared Colorbar

'Residual' powers vs 'Original' powers

2D Power Spectrum

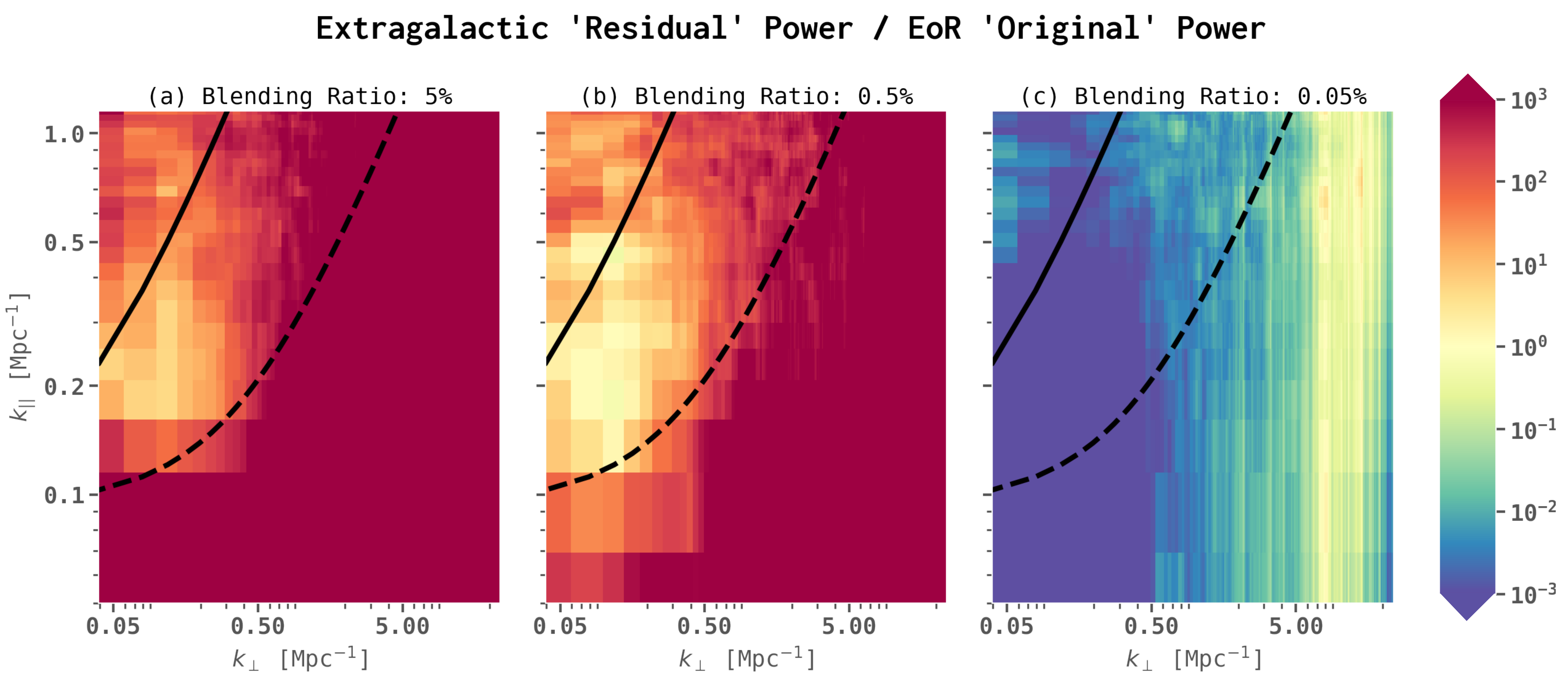
Results

PS impact

High Blending Ratio: 5%
Strong within both boundries

Mid Blending Ratio: 0.5%
Strong within Horizon

Low Blending Ratio: 0.05%
Interference within both



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'Residual' powers vs 'Original' EoR powers

2D Power Spectrum

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PS impact

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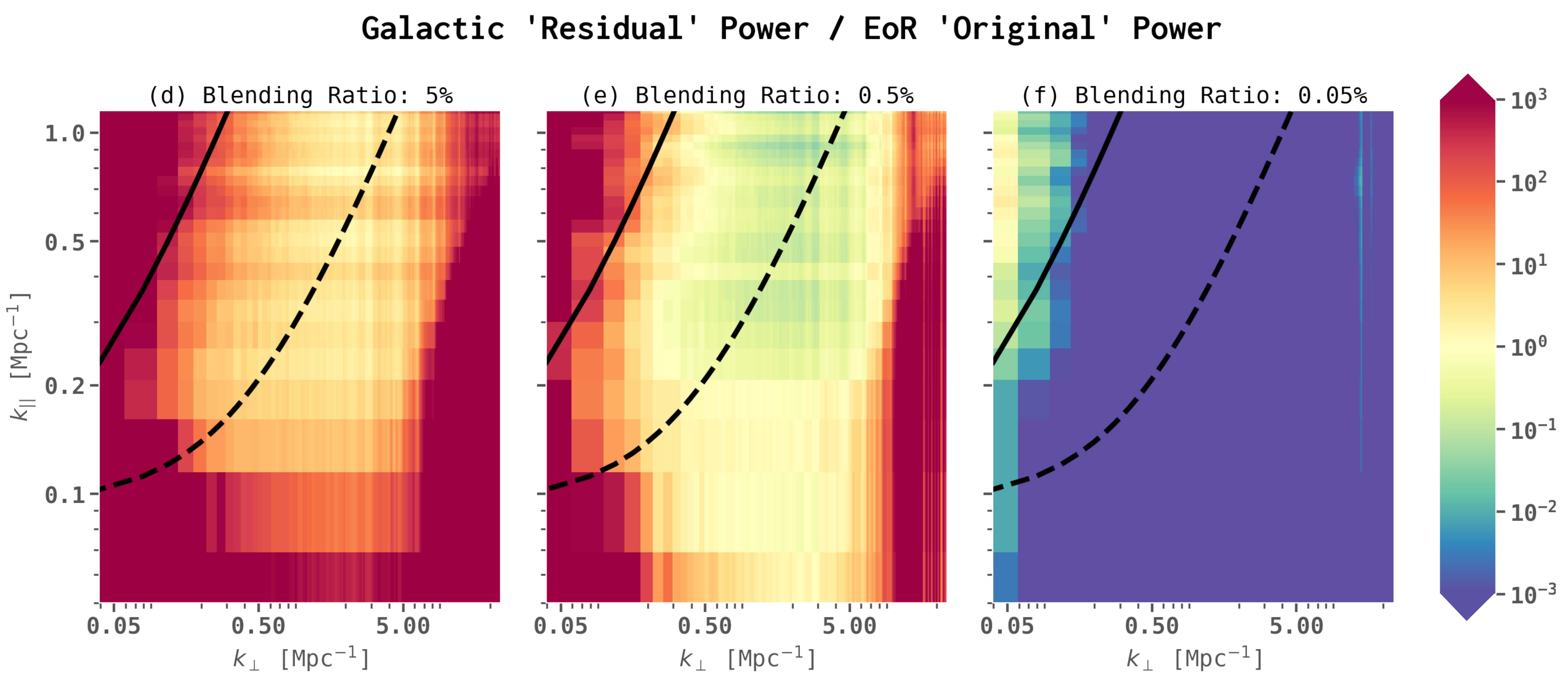
Strong within both boundries

Mid Blending Ratio: 0.5%
Strong within Horizon

Low Blending Ratio: 0.05%
Interference within Horizon



Bounderies: Solid - Horizon & Dashed -- FoV | Shared Colorbar

'Residual' powers vs 'Original' EoR powers

Summary

- EoR Experiments operate under precesion analysis pipeline
- Sky model defects ›› residual gain errors ›› visibility, imaging, PS biases
- Source blending will be a key defect to combat for SKA1-Low
- Blending-induced Ill-calibration + strong foregrounds ›› hinders EoR detection
- De-blending is required for the sky-model construnction for the SKA1-Low

Fg21Sim+ is an open-source project, it acknowledges

- Fg21Sim Core Liberary developed by Weitian Li
- 21cmFAST*, OSAKR, WSClean, DUCC0, & HEALPix from the open-source community
  Special thanks to Pro. Andrei Mesinger for the help with the 21-cm simulation
- Computation ›› GRAVITY & SGI cluster @ SJTU

Thank you.