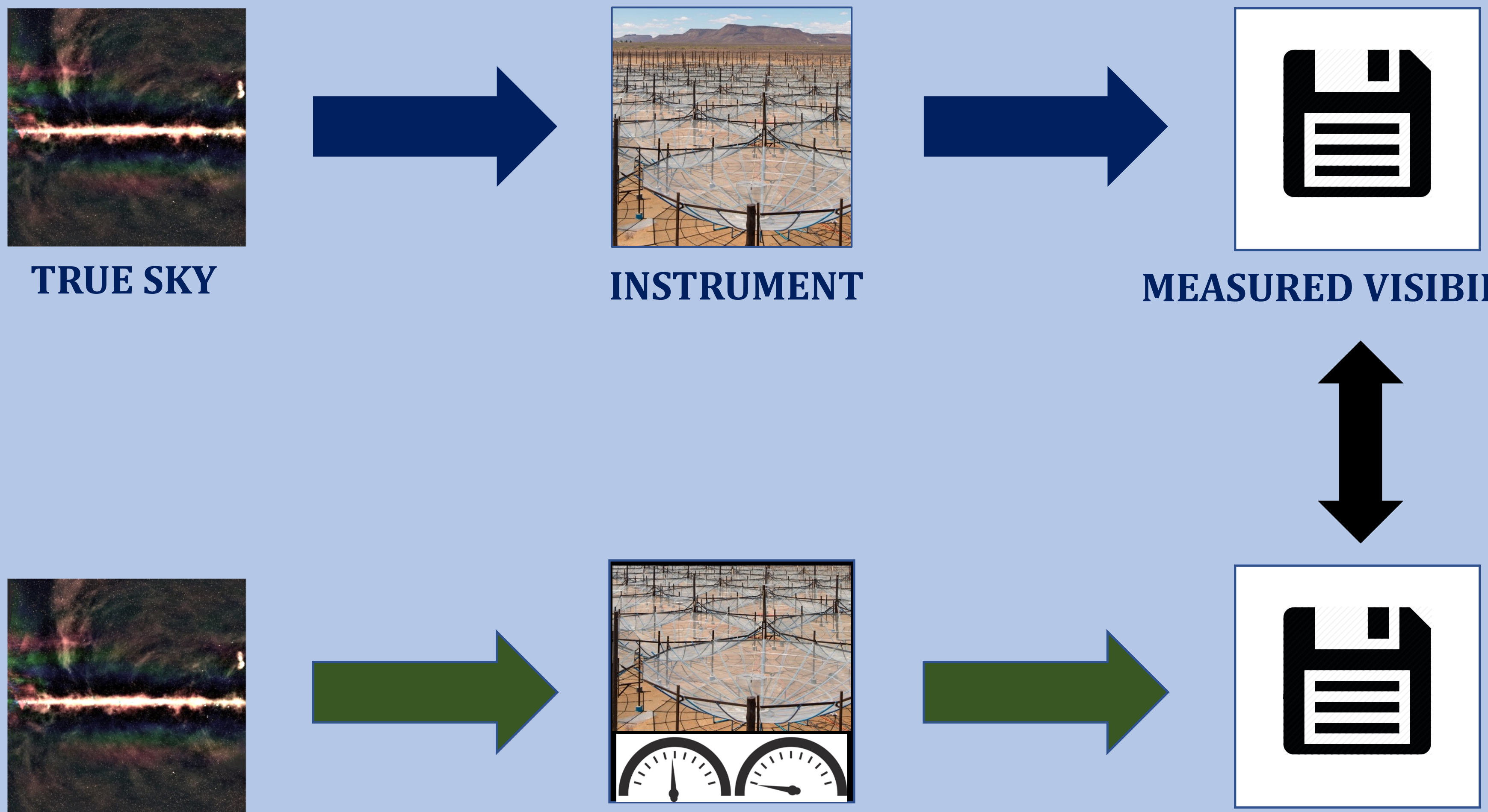
Achieving Precision Calibration for 21 cm Cosmology with DWCal

Ruby Byrne

21 cm Cosmology Workshop

Aug. 31, 2022

Calibration



Data Pipeline:

TRUE SKY

INSTRUMENT

MEASURED VISIBILITIES

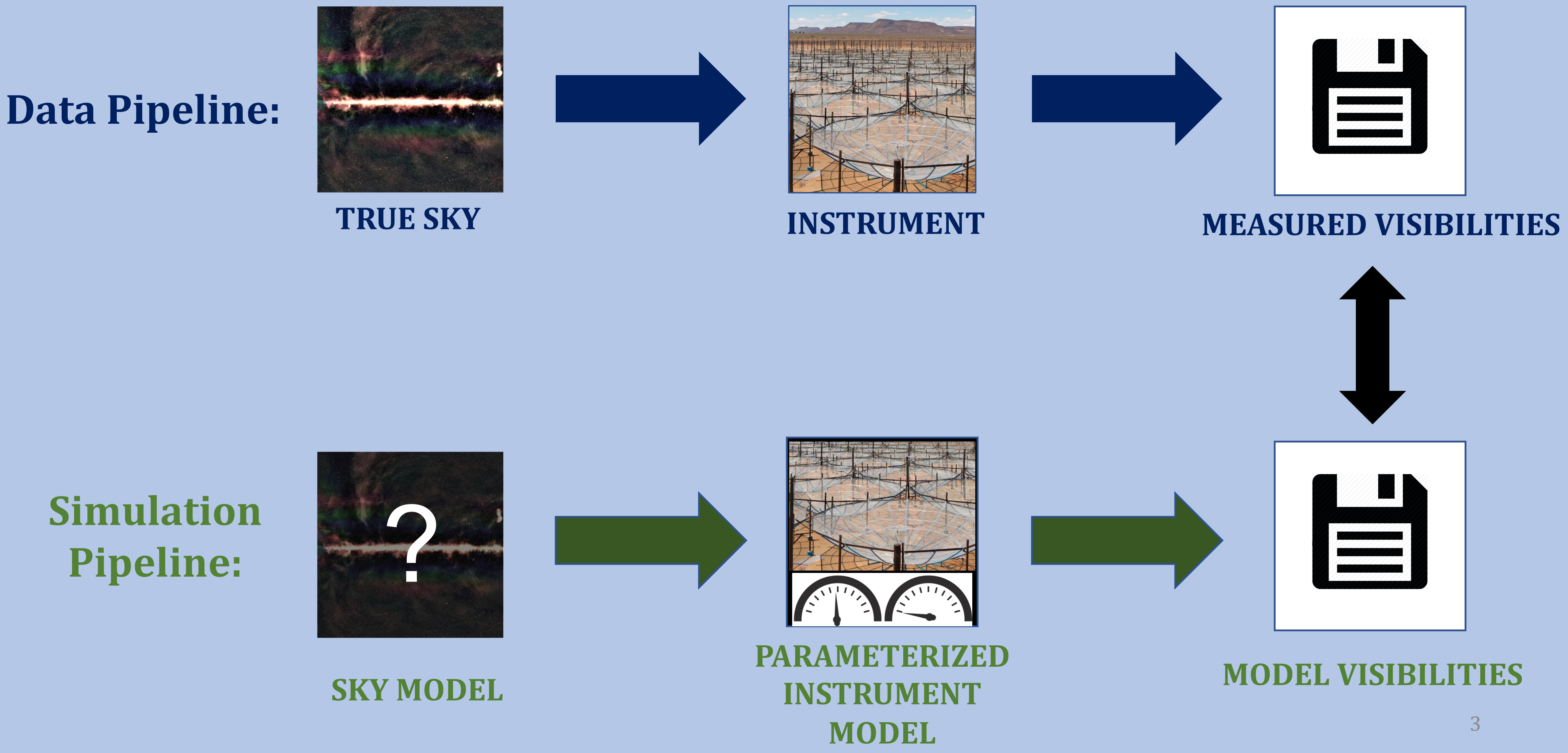
Simulation Pipeline:

SKY MODEL

PARAMETERIZED INSTRUMENT MODEL

MODEL VISIBILITIES

Calibration



Data Pipeline:

TRUE SKY

INSTRUMENT

MEASURED VISIBILITIES

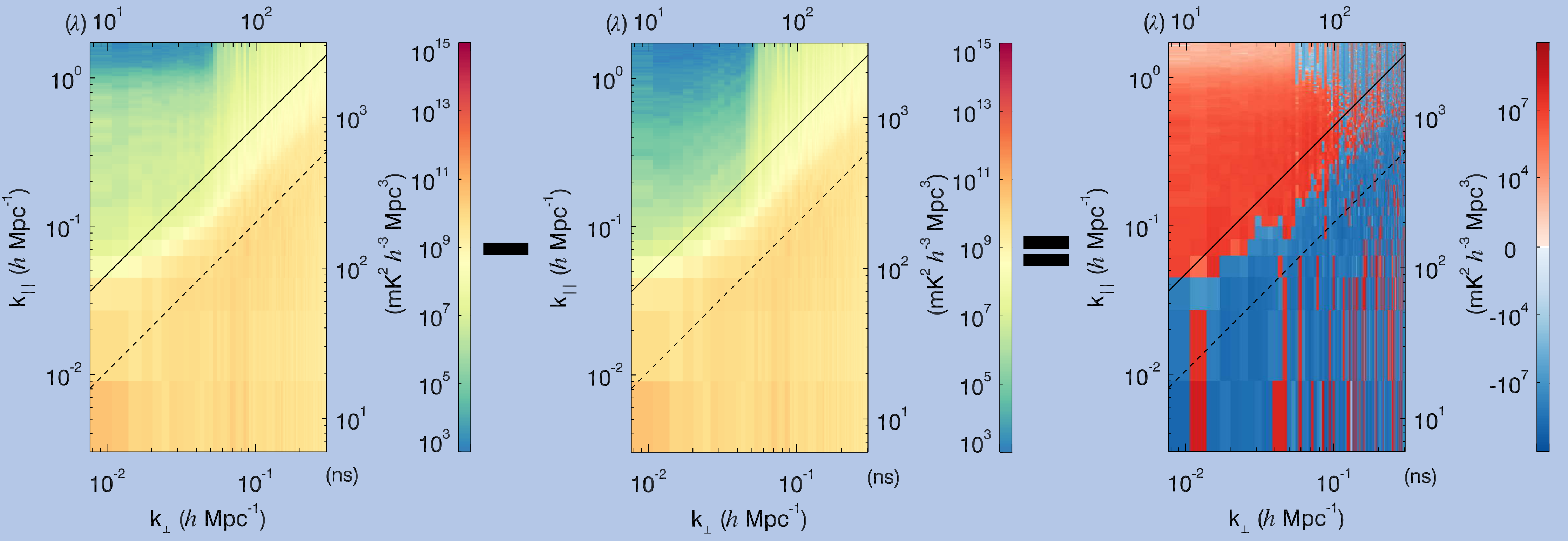
Simulation Pipeline:

SKY MODEL

PARAMETERIZED INSTRUMENT MODEL

MODEL VISIBILITIES

Calibration in the Presence of Sky Model Error


Calibrated to an incomplete sky model

Perfect calibration

Difference

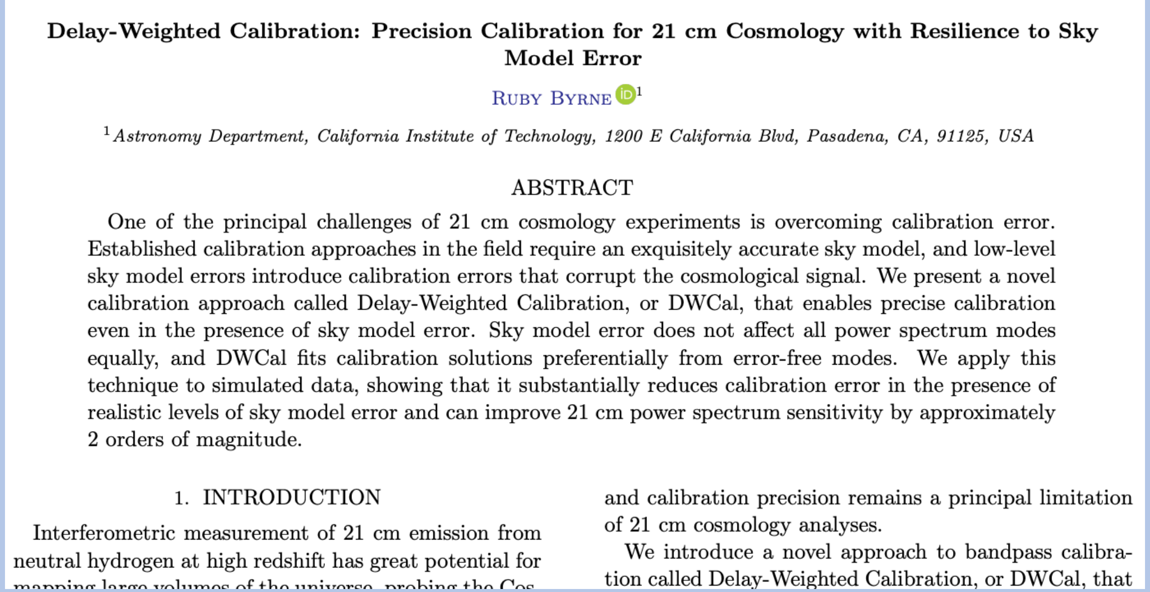
Source: Barry et al. 2016

Precision Calibration with Sky Model Error: A Few Approaches

- Frequency-, antenna-, and time-averaging: Assumes smooth bandpasses and stable and uniform arrays
- Short baseline calibration/autocorrelation calibration: Calibrates from measurements less affected by sky model error
- Redundant calibration: Fits sky signal from baseline redundancy, but is still susceptible to sky model error in constraining the bulk array response in absolute calibration (see Byrne et al. 2019)
- Unified calibration (Byrne et al. 2021): Middle ground between sky-based and redundant calibration, does not improve absolute calibration performance
- CALAMITY (Ewall-Wice et al. in review): Directly fits sky signal assuming spectral smoothness
- BayesCal (Sims et al. in review): Imposes Bayesian priors on the gain solutions
- CorrCal (Sievers 2017): Models the sky as a Gaussian random field

Delay-Weighted Calibration (DWCal)

- Mitigates the impact of sky model error in calibration by downweighting modes affected by sky model error
- Constrains calibration preferentially from error-free modes
- Same number of calibration parameters and degeneracies as sky-based calibration
- Makes no assumptions about the gains’ spectral smoothness or uniformity



Delay-Weighted Calibration: Precision Calibration for 21 cm Cosmology with Resilience to Sky Model Error

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ABSTRACT

One of the principal challenges of 21 cm cosmology experiments is overcoming calibration error. Established calibration approaches in the field require an exquisitely accurate sky model, and low-level sky model errors introduce calibration errors that corrupt the cosmological signal. We present a novel calibration approach called Delay-Weighted Calibration, or DWCal, that enables precise calibration even in the presence of sky model error. Sky model error does not affect all power spectrum modes equally, and DWCal fits calibration solutions preferentially from error-free modes. We apply this technique to simulated data, showing that it substantially reduces calibration error in the presence of realistic levels of sky model error and can improve 21 cm power spectrum sensitivity by approximately 2 orders of magnitude.

1. INTRODUCTION

Interferometric measurement of 21 cm emission from neutral hydrogen at high redshift has great potential for

and calibration precision remains a principal limitation of 21 cm cosmology analyses.

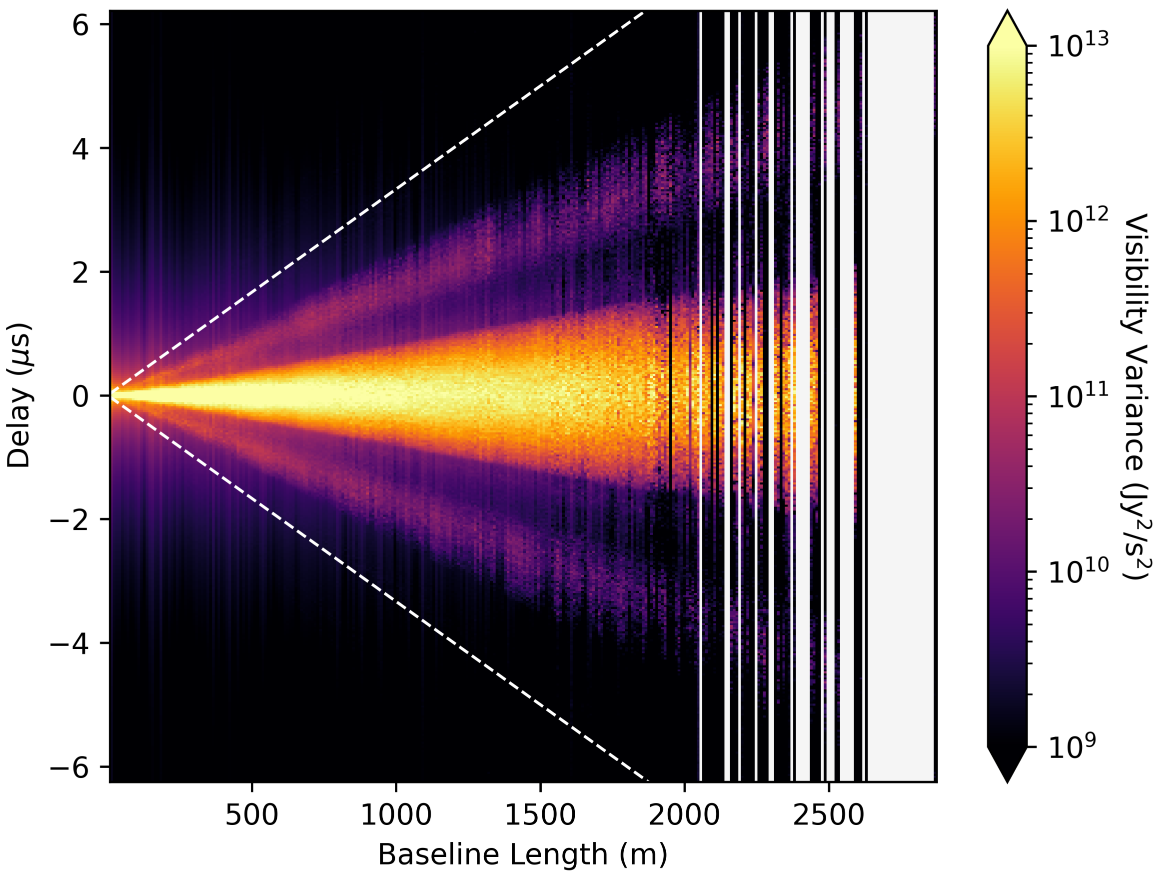
We introduce a novel approach to bandpass calibration called Delay-Weighted Calibration, or DWCal, that

Byrne 2022 (in review), arXiv:2208.04406

Model visibility error is *compact* in delay space

- Visibilities simulated with FHD based on the MWA Phase I
- “True” visibilities simulated from the GLEAM catalog (Hurley-Walker et al. 2017)
- Model visibilities simulated from an incomplete catalog missing the faintest sources
- Calibration sky model includes 90% of the full catalog’s power
- Assume a frequency-invariant beam

Simulated Model Visibility Error



DWCal Formalism

- Typical (sky-based) calibration minimizes

$$\chi^2(\vec{g}) = \sum_{f} \sum_{jk} \left| g_j(f) g_k^*(f) v_{jk}(f) - m_{jk}(f) \right|^2$$

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model visibilities

per-antenna,
per-frequency
complex gains

data visibilities

DWCal Formalism

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$$\chi^2(\vec{g}) = \sum_{f} \sum_{jk} \left| g_j(f) g_k^*(f) v_{jk}(f) - m_{jk}(f) \right|^2$$

model visibilities

sum over
frequencies

per-antenna,
per-frequency
complex gains

data visibilities

sums over baselines
j, k index antennas

DWCal Formalism

- Typical (sky-based) calibration minimizes

$$\chi^2(\vec{g}) = \sum_{f} \sum_{jk} \left| g_j(f) g_k^*(f) v_{jk}(f) - m_{jk}(f) \right|^2$$

- From the Plancherel theorem we can rewrite as

$$\chi^2(\vec{g}) = \sum_{\eta} \sum_{jk} \left| FT\left[g_j(f) g_k^*(f) v_{jk}(f) - m_{jk}(f) \right] \right|^2$$

- η is “delay”, the Fourier dual of frequency

DWCal Formalism

- Introduce a delay- and baseline-dependent weighting function

$$\chi^2(\vec{g}) = \sum_{\eta}\sum_{jk}\left|FT\left[g_j(f)g_k^*(f)v_{jk}(f) - m_{jk}(f)\right]\right|^2$$

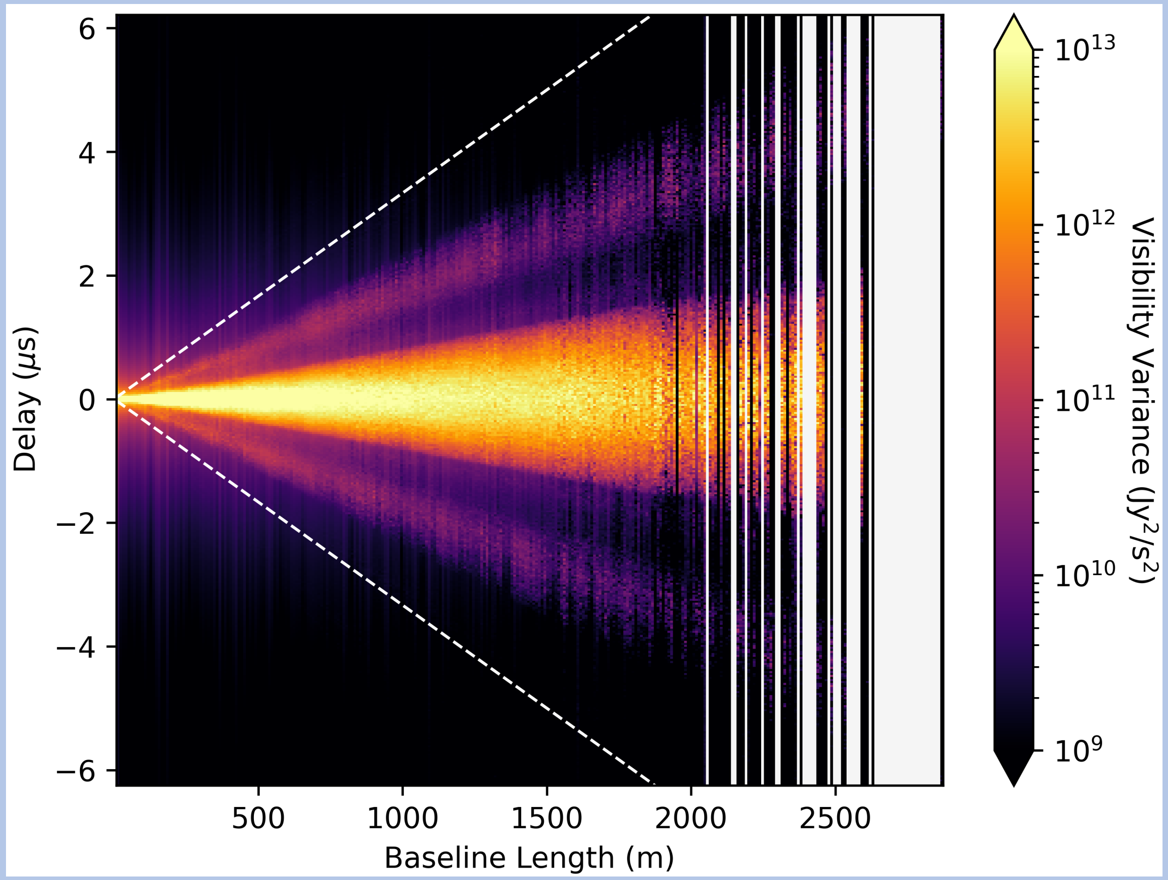
$$\Downarrow$$

$$\chi^2(\vec{g}) = \sum_{\eta}\sum_{jk}\widetilde{W_{jk}}(\eta)\left|FT[g_j(f)g_k^*(f)v_{jk}(f) - m_{jk}(f)]\right|^2$$

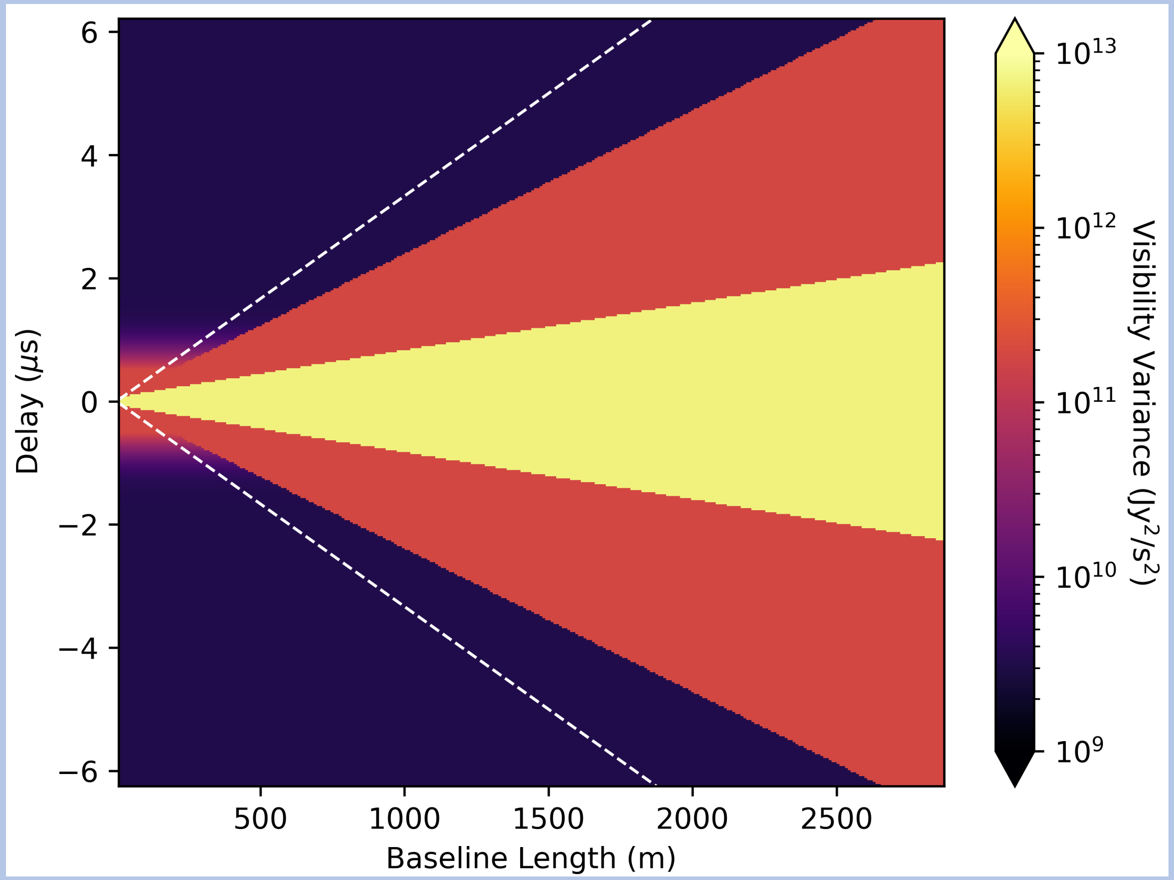
- Convert back to frequency domain

$$\chi^2(\vec{g}) = \sum_{f}\sum_{f'}\sum_{jk} W_{jk}\,(f - f')\left[g_j(f)g_k^*(f)v_{jk}(f) - m_{jk}(f)\right]\left[g_j(f')g_k^*(f')v_{jk}(f') - m_{jk}(f')\right]^*$$

DWCal Implementation: Defining the weighting function



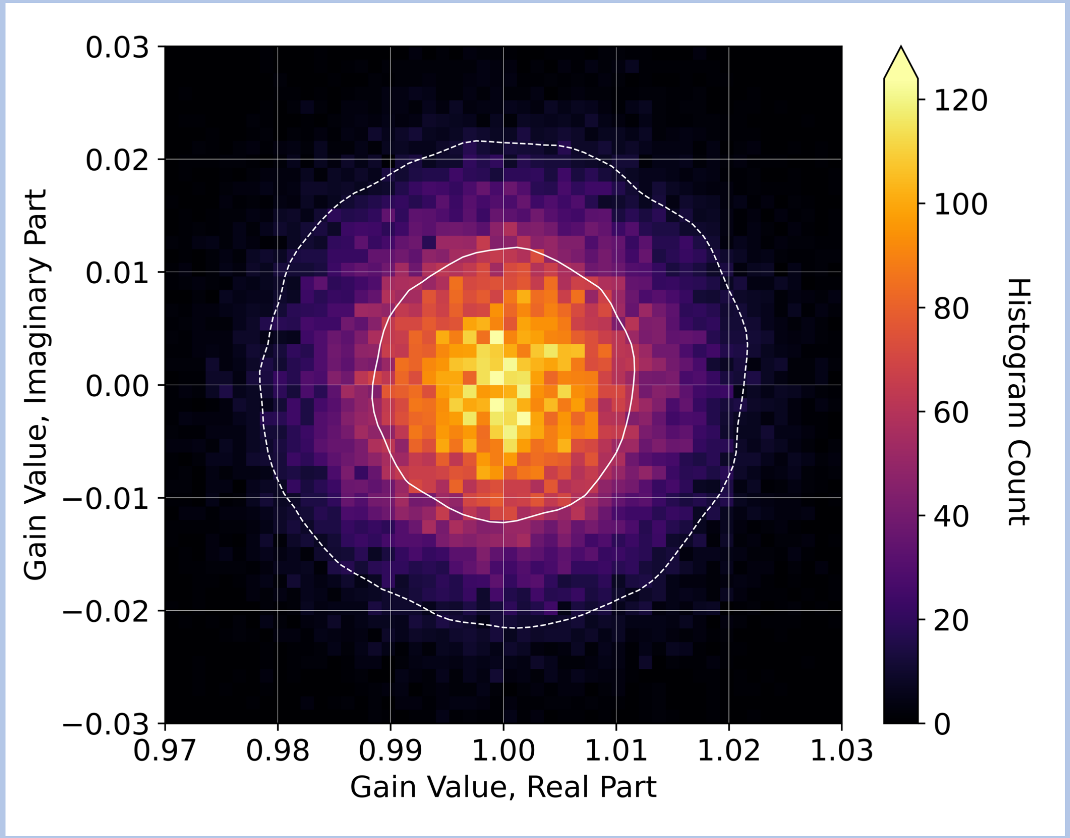
Model Visibility Error



Estimated Model Visibility Error Variance

Calibration Simulation

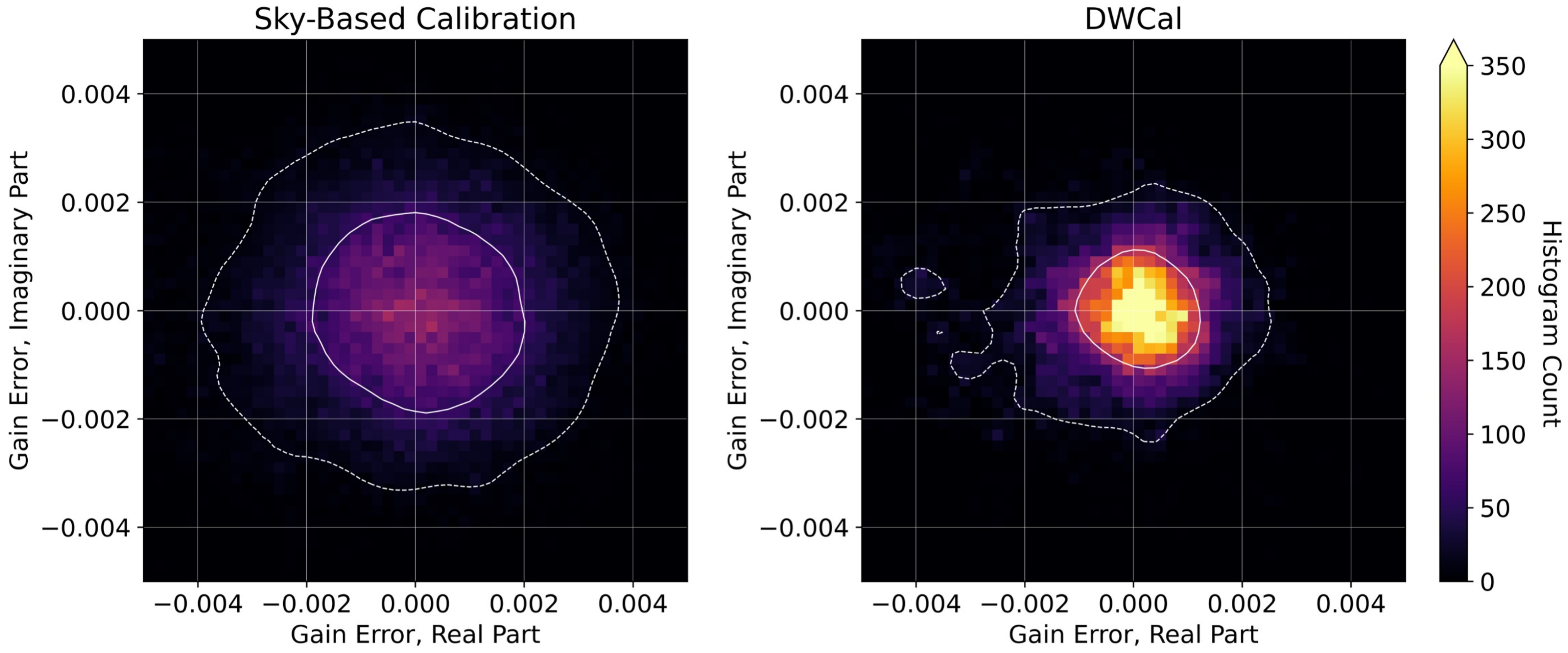
True Gain Values



- Noise-free simulation
- Calibration error arises from missing sources in the sky model only
- True gains are randomized

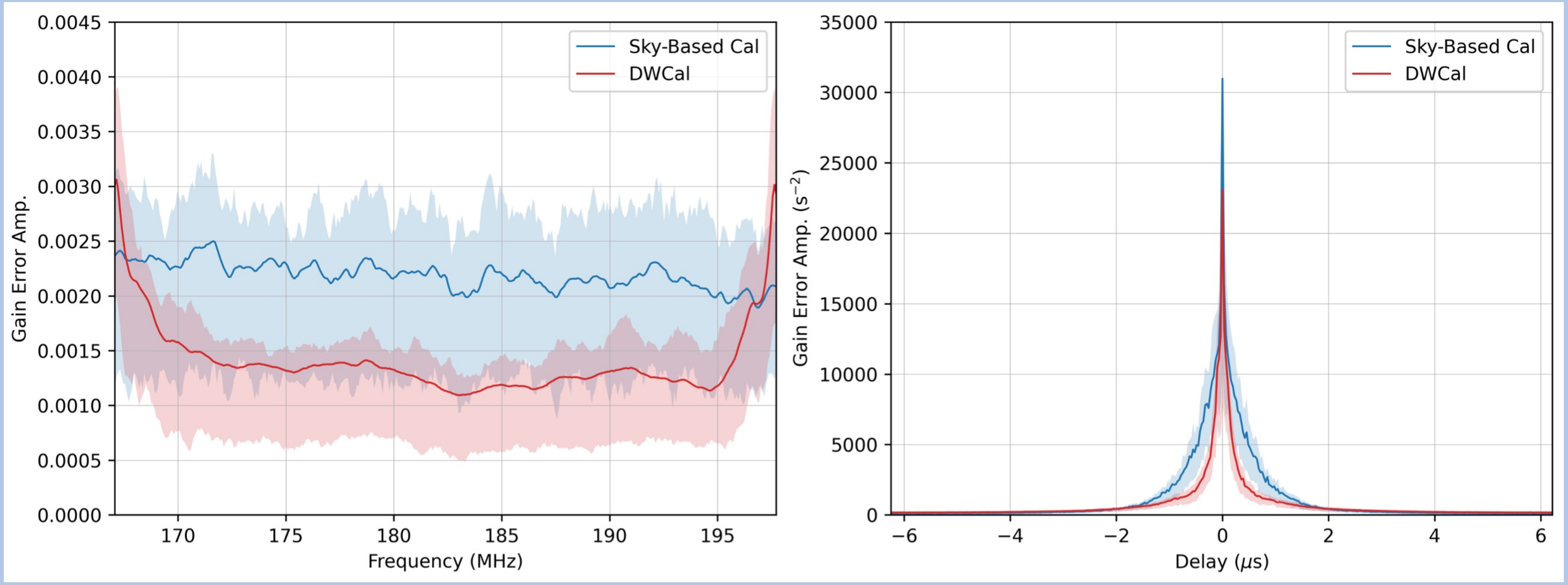
Calibration Results

Calibrated Gain Error



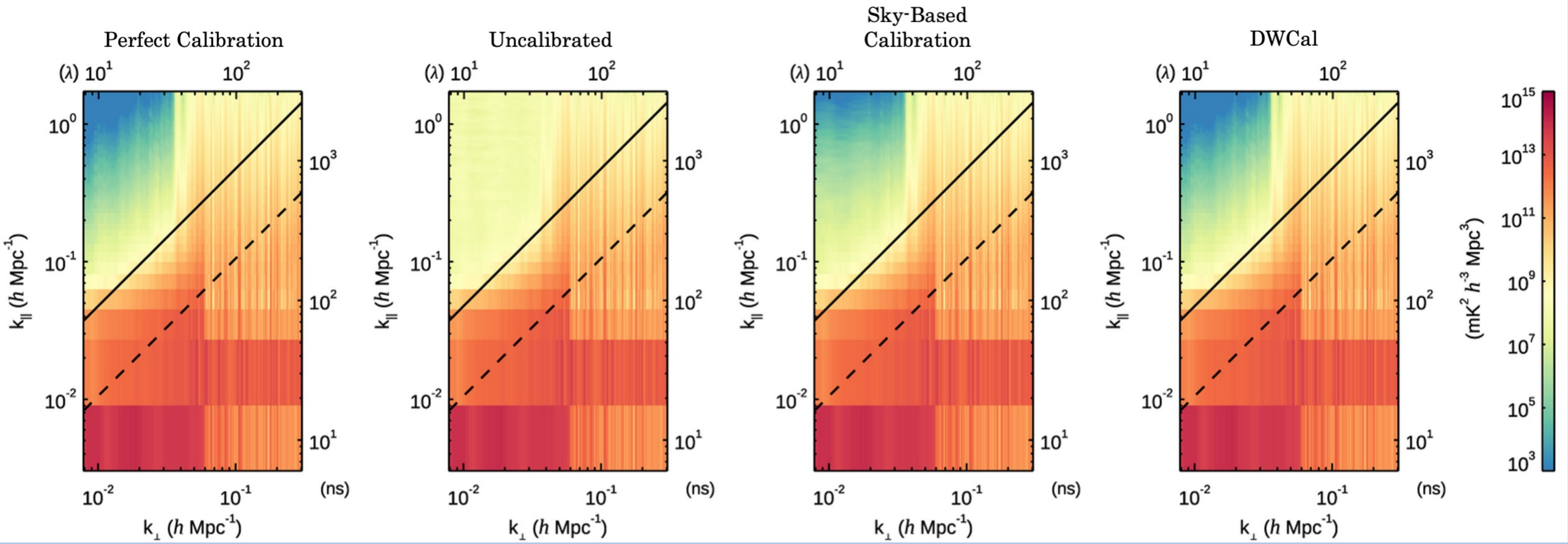
Calibration Results

Calibrated Gain Error



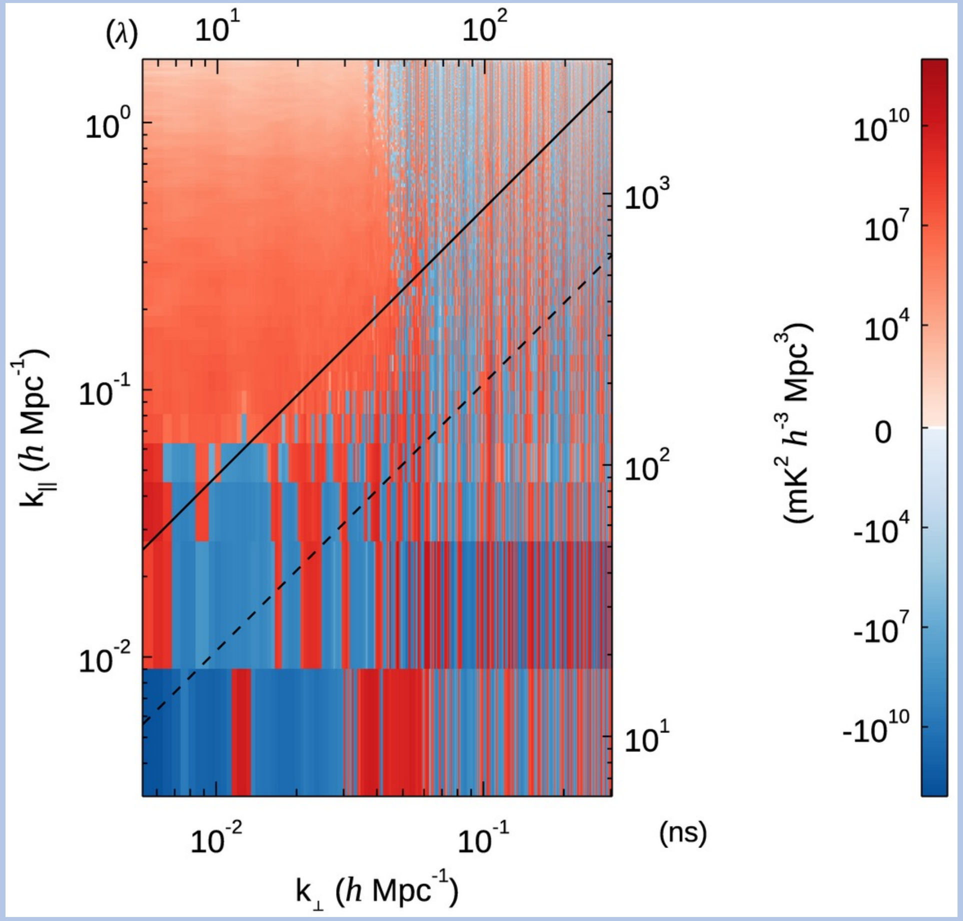
Calibration Results: 2D Power Spectra

calculated with the FHD/eppsilon power spectrum pipeline

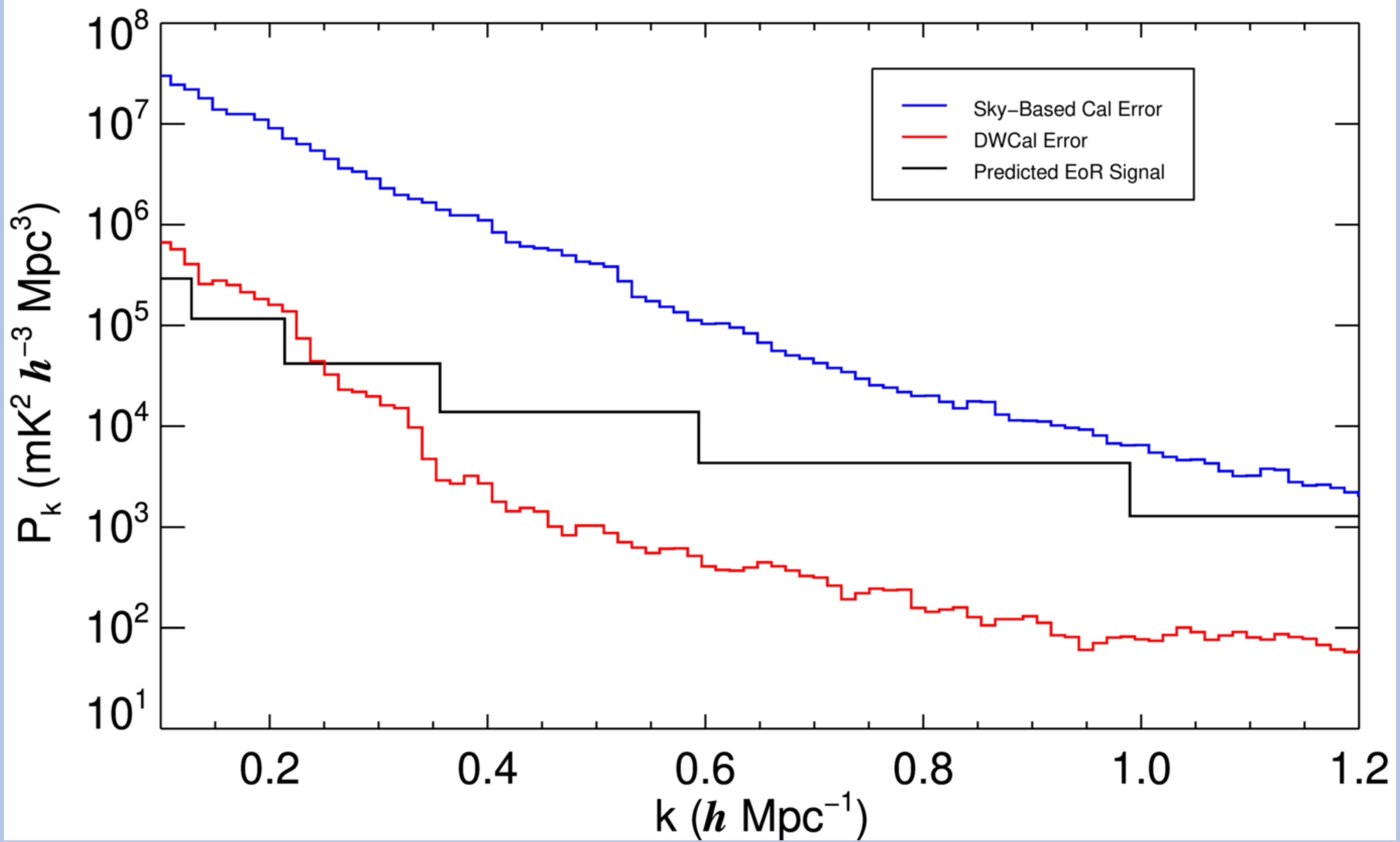


Calibration Results:
2D Power Spectrum Difference

Sky-Based Calibration – DWCal



Calibration Results: 1D Power Spectrum



DWCal is highly flexible and broadly applicable

- Redundant calibration: Delay weighting can be applied in the absolute calibration step
- Unified calibration with delay weighting
- DWCal with autocorrelations
- Fully-polarized DWCal
- Alternative gain parameterization, e.g., low-order polynomial across frequency

So you want to try DWCal?

- Check out the paper (currently in review): https://arxiv.org/abs/2208.04406
- Code is available on GitHub: https://github.com/rlbyrne/dwcal
- Tutorial Jupyter notebook available on Github
- Let me know if you have questions!

Conclusion

- DWCal performs better than typical sky-based calibration in the presence of sky model error
- Does not require fitting additional calibration parameters
- No assumptions about the gains (e.g., spectral smoothness, temporal stability, uniformity)
- No new degeneracies
- Highly flexible and applicable to many calibration approaches