Wising up to CatWISE

Using simulation-based inference to measure the cosmic dipole

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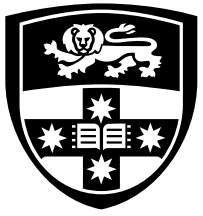
The University of Sydney

Supervised by
Geraint Lewis
Tara Murphy



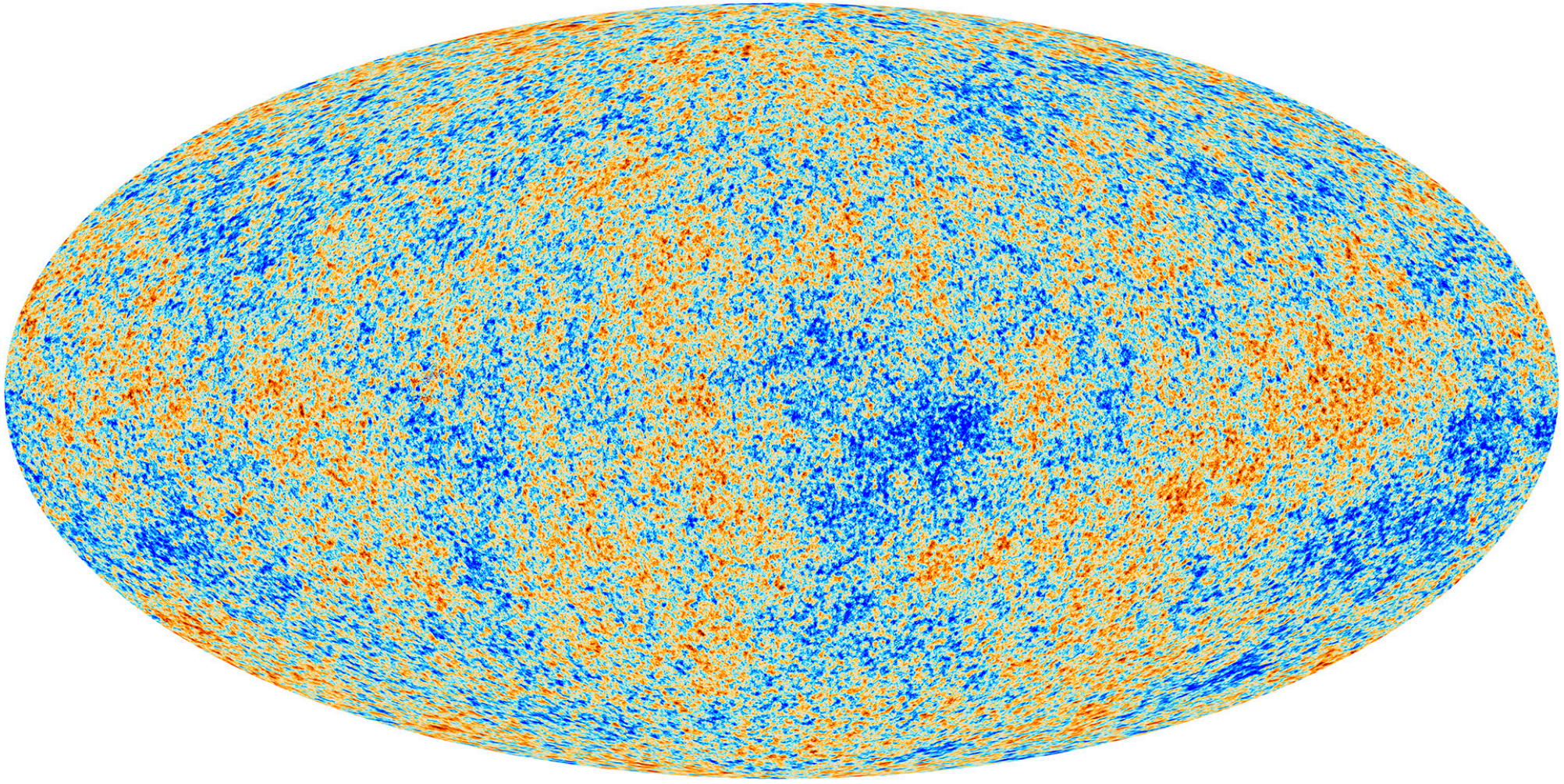
THE UNIVERSITY OF SYDNEY

ASA ASM

July 7, 2026

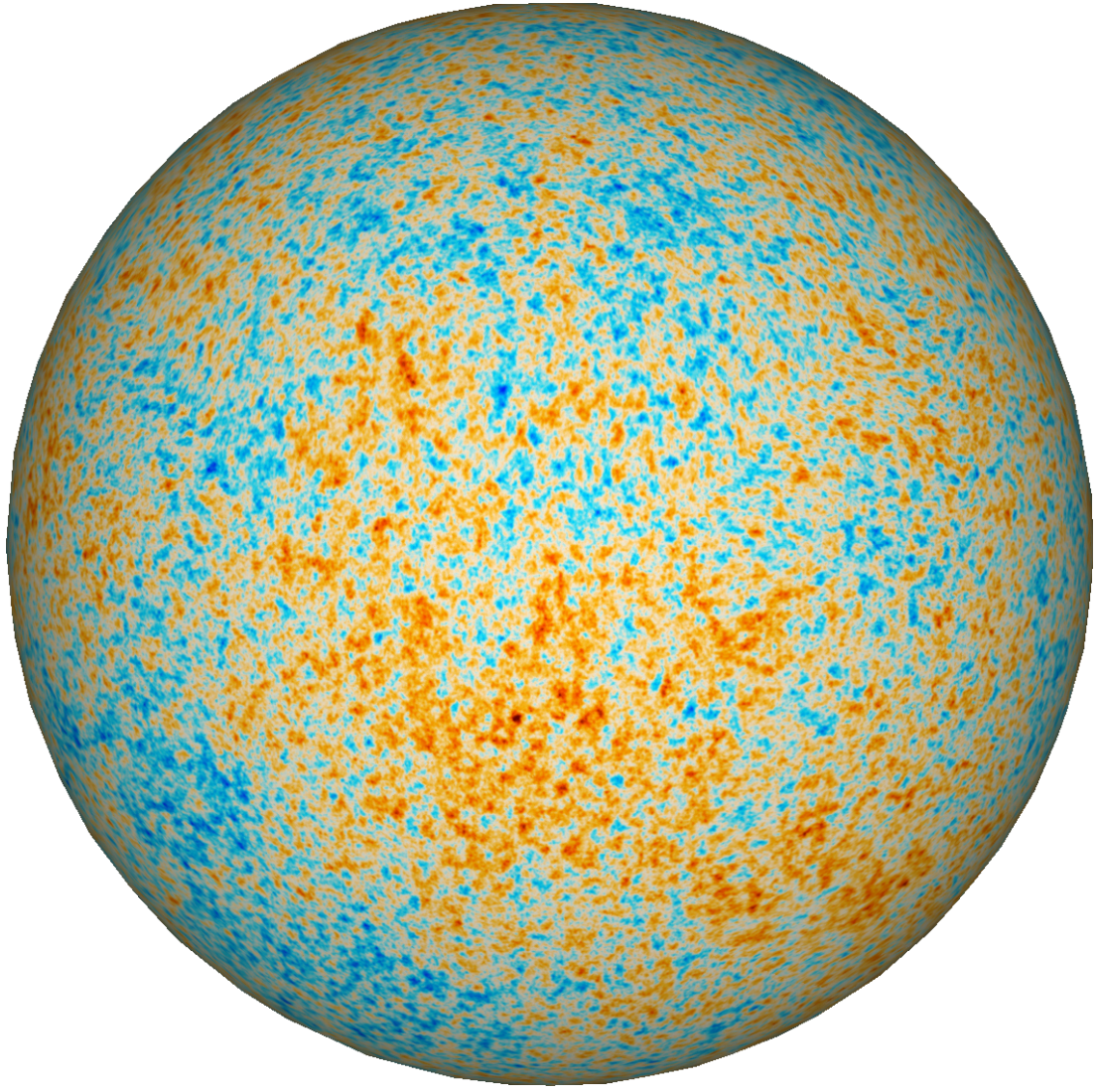
Simulation-based inference resolves systematics.

The Kinematic Dipole



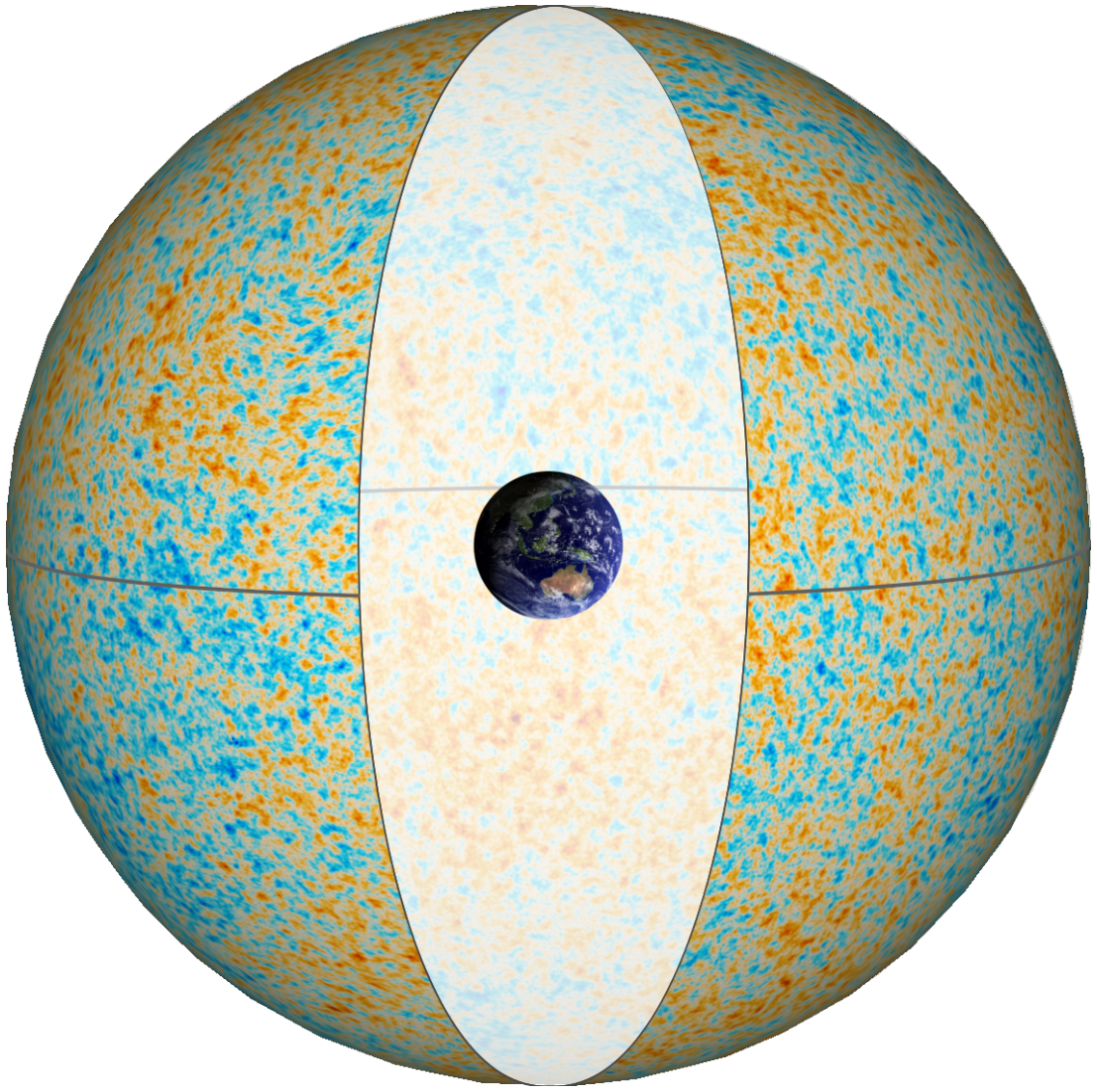
CMB temperature map (Planck satellite)

The Kinematic Dipole



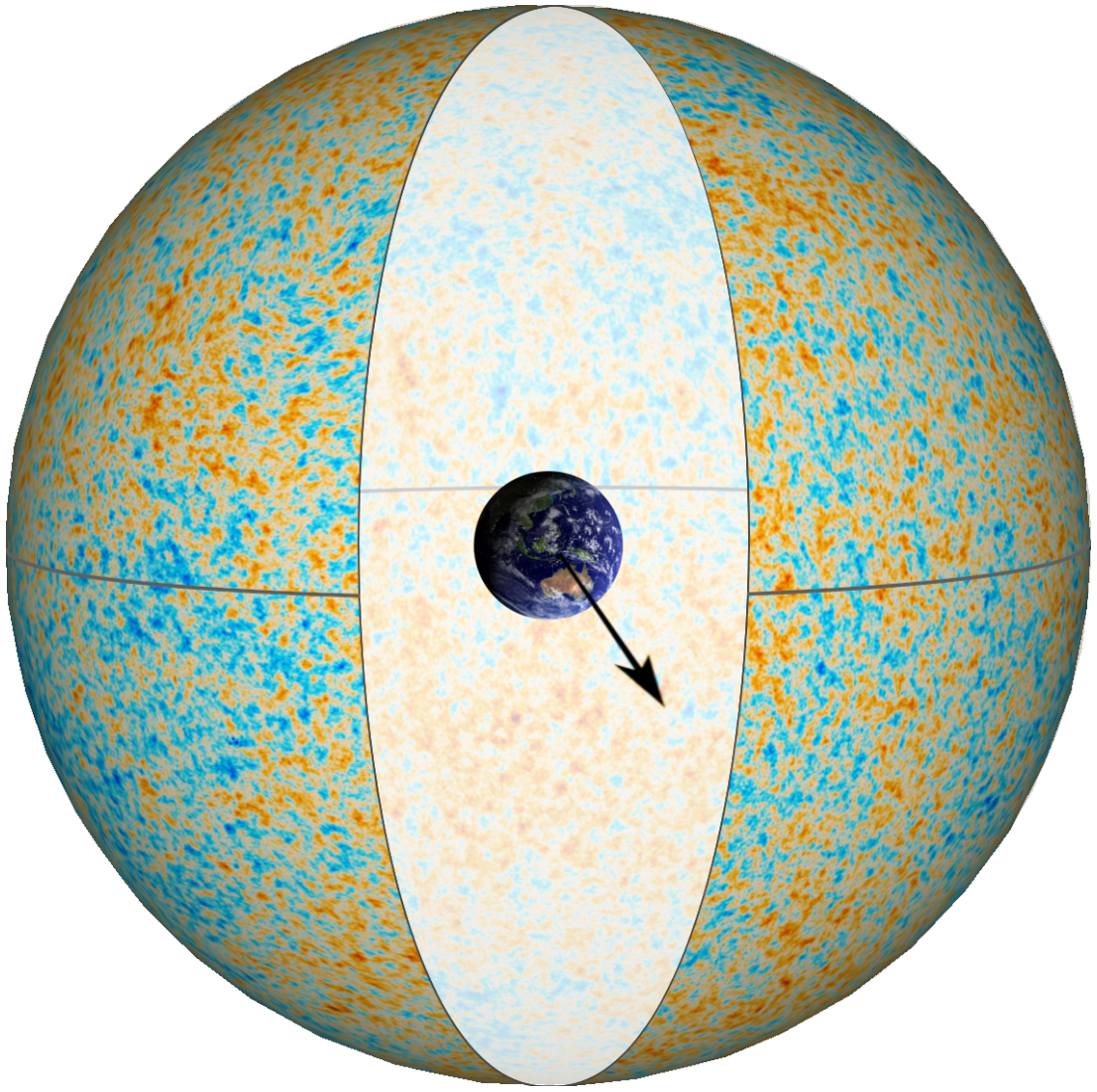
CMB as a sphere

The Kinematic Dipole



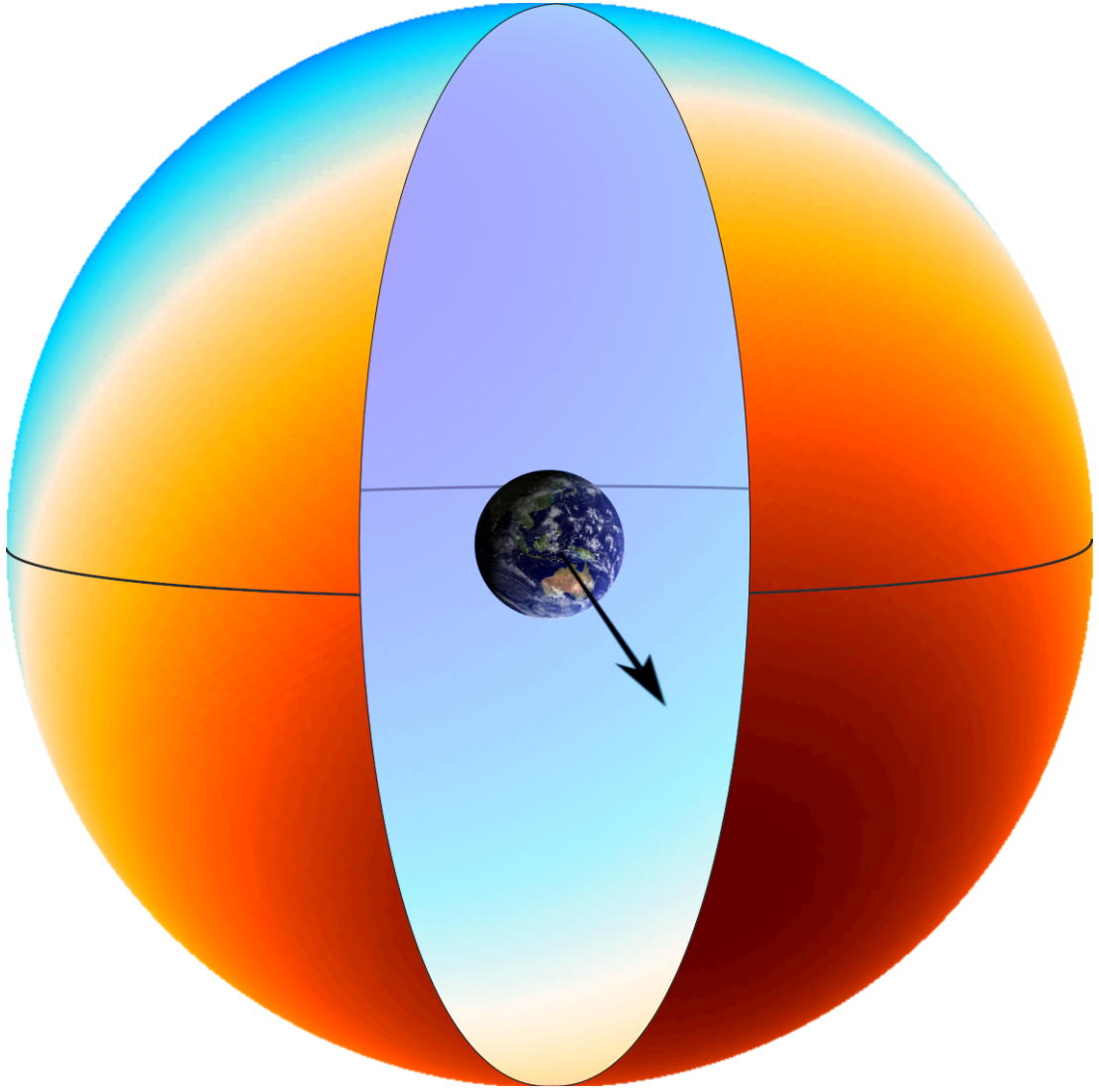
CMB as a sphere (Earth inside)

The Kinematic Dipole



We’re moving through the Universe!

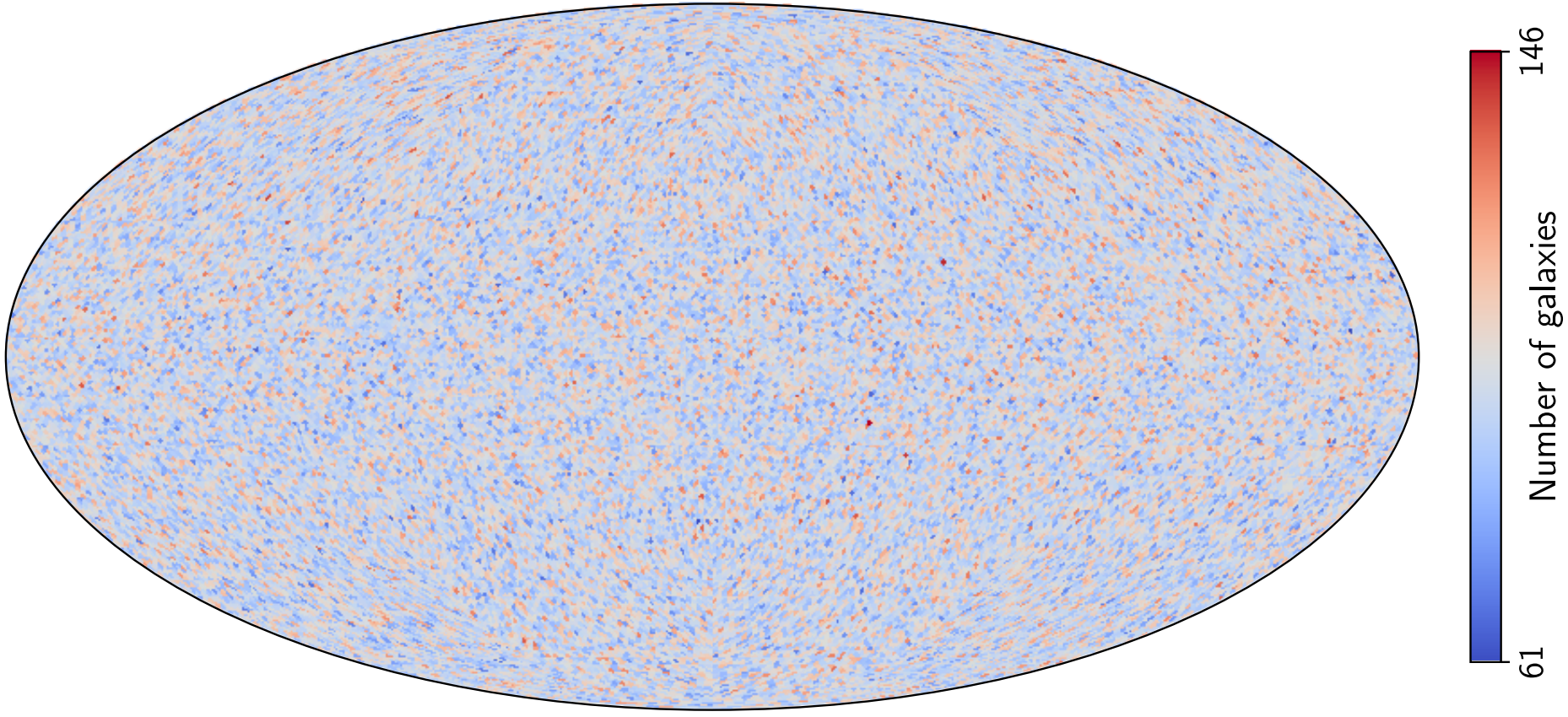
The Kinematic Dipole



Kinematic dipole as a sphere (Earth inside)

Counting Galaxies

$$N_i = \overline{N}(1 + \mathcal{D}\cos\theta_i)$$



Simulated isotropic galaxy map (+ dipole)

Counting Galaxies

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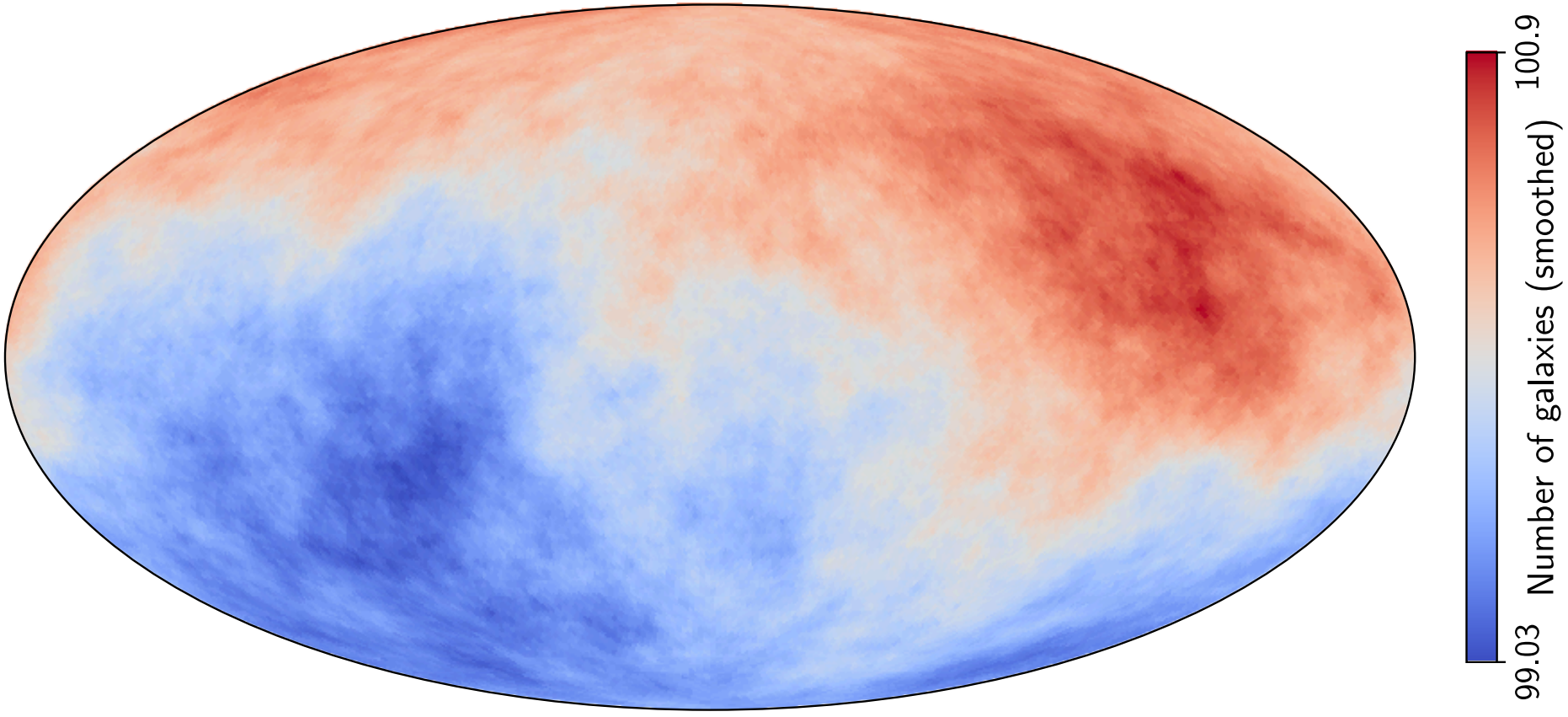
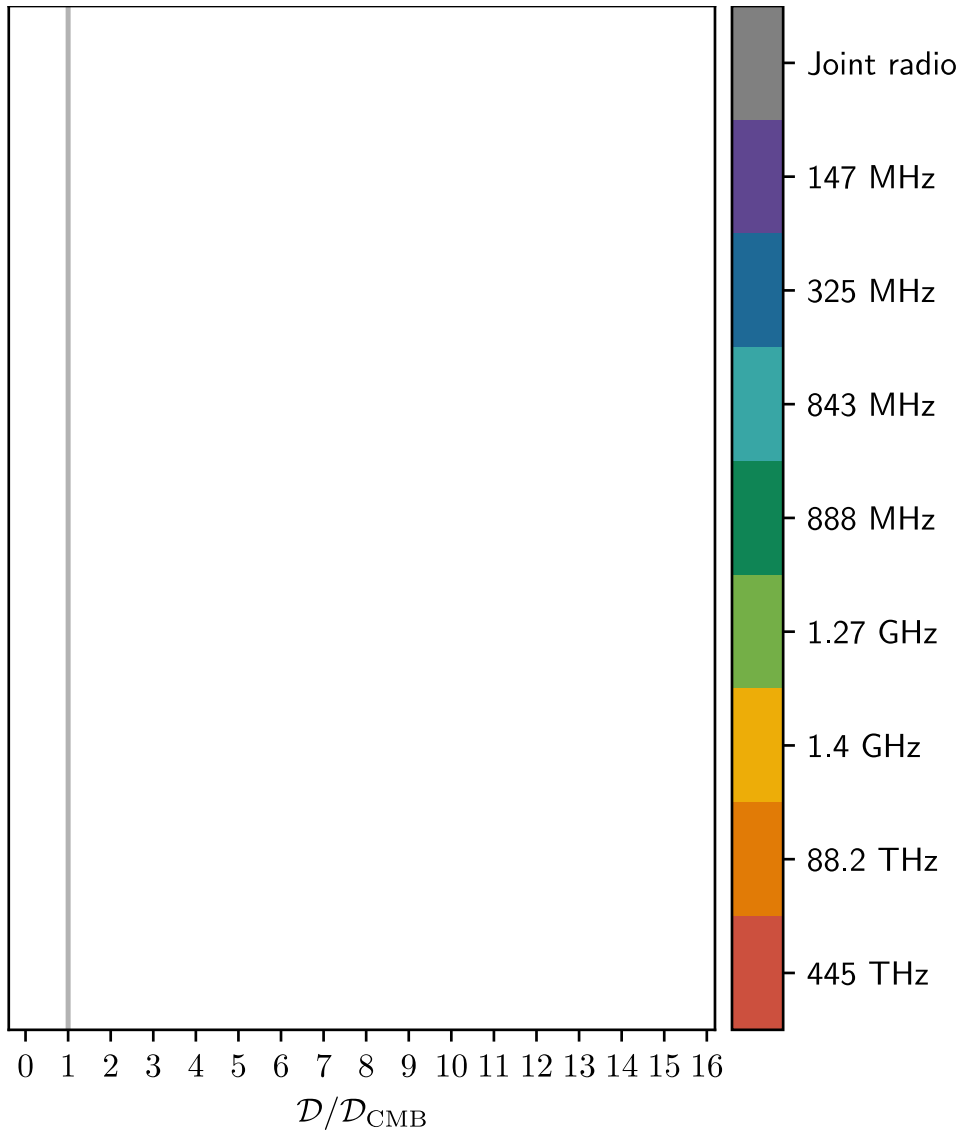


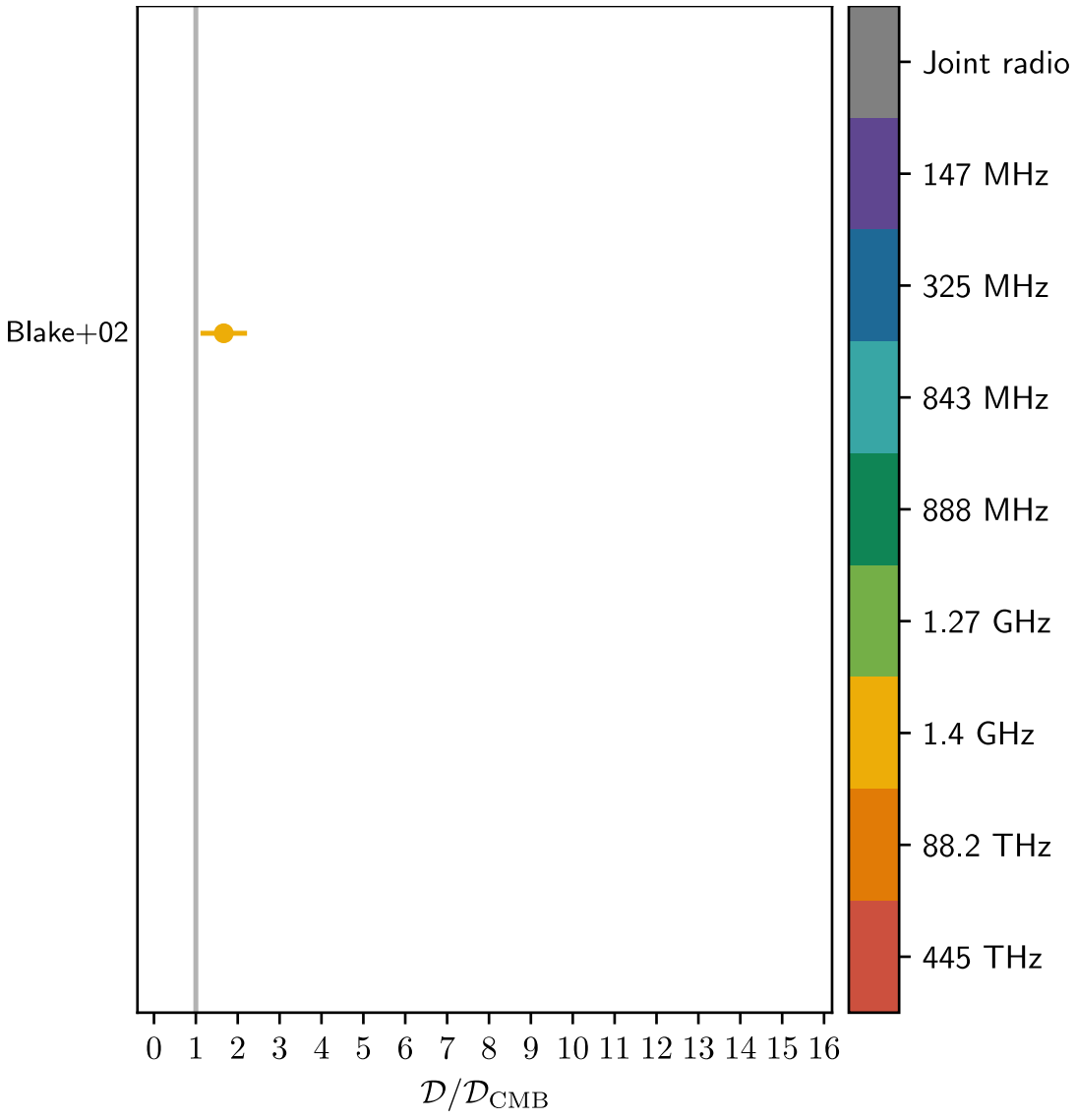
Simulated isotropic galaxy map (+ dipole)

The Amplitude Excess



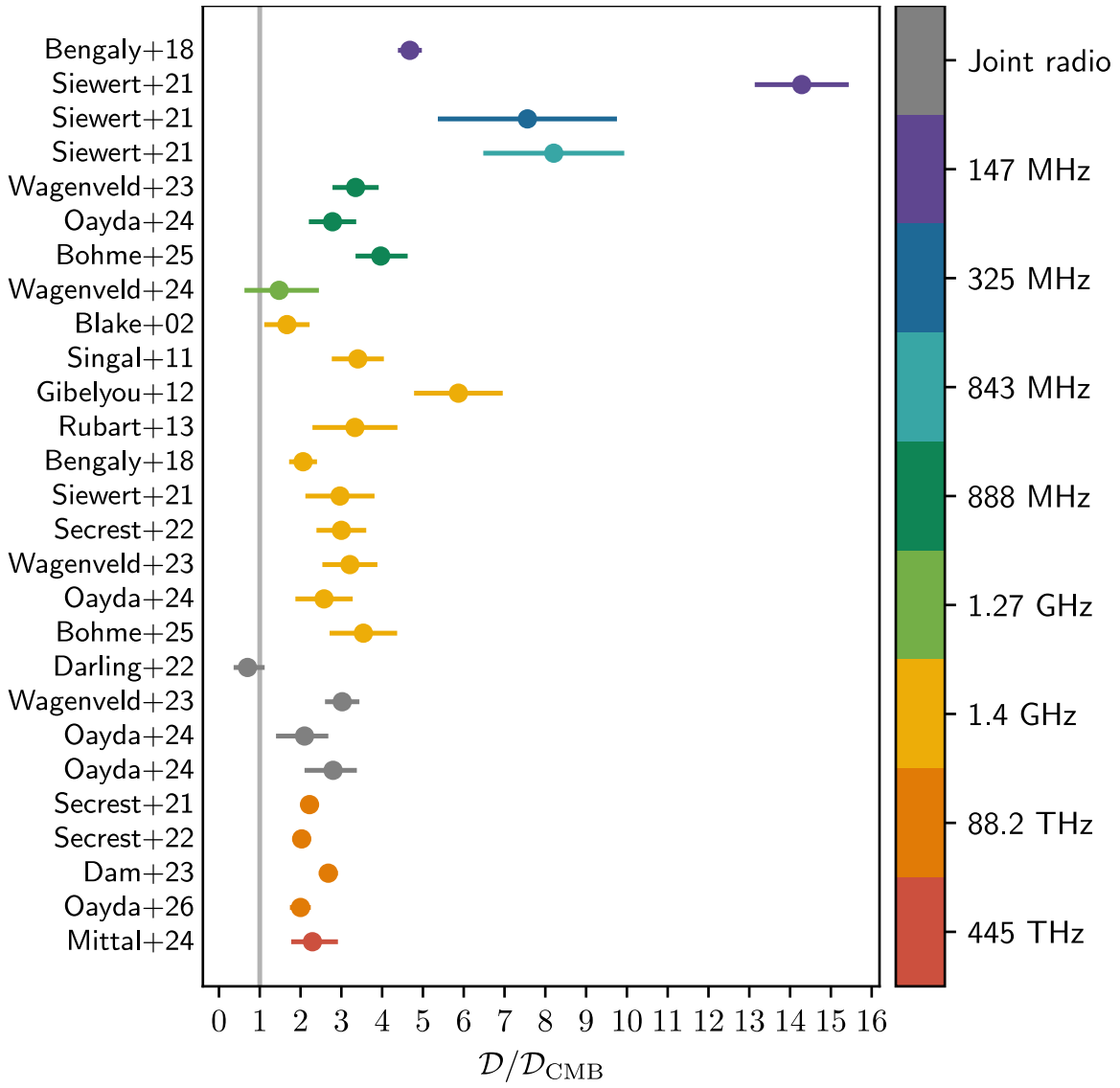
The cosmic dipole should be consistent with the CMB dipole.

The Amplitude Excess



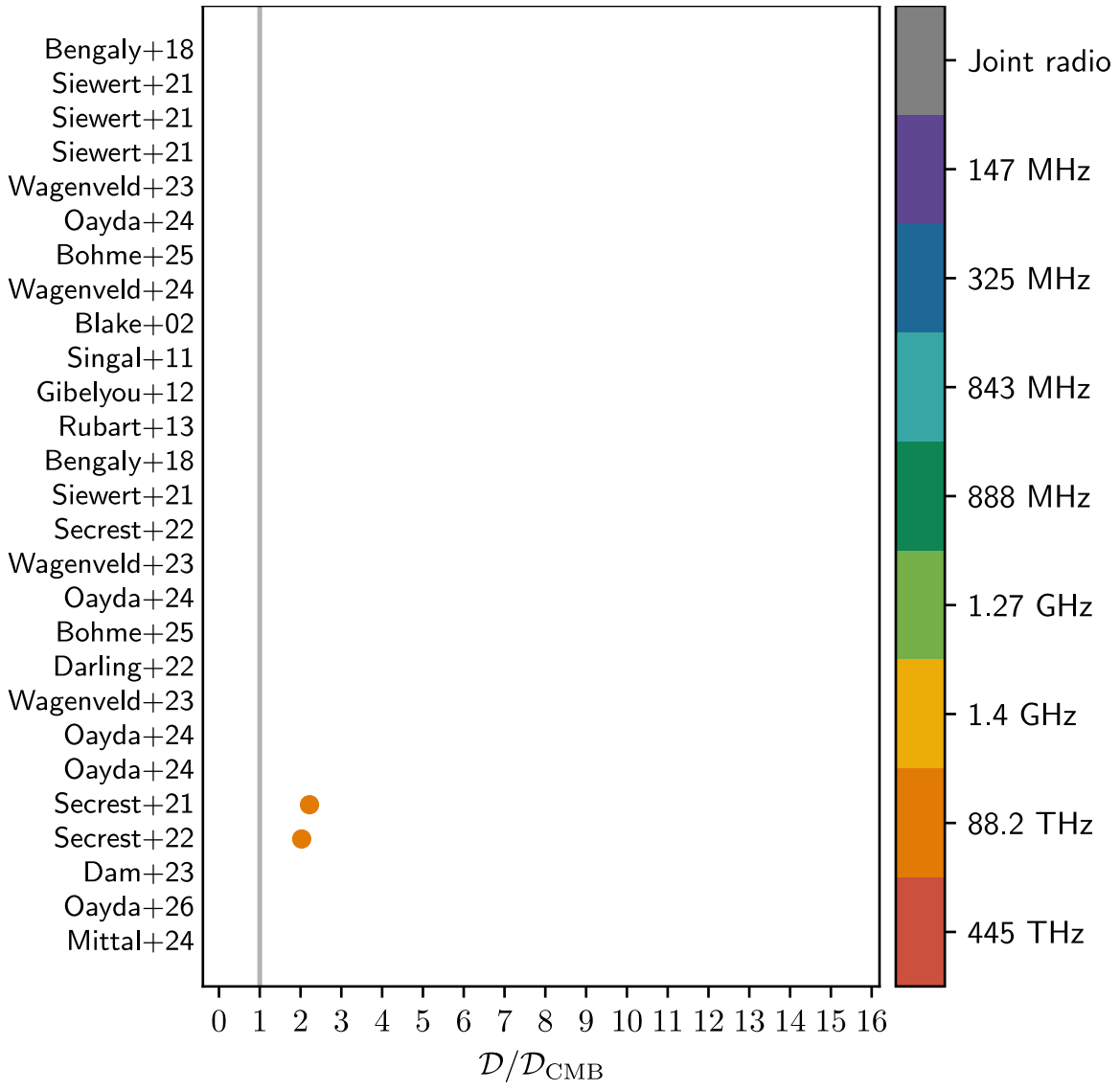
All is well!

The Amplitude Excess



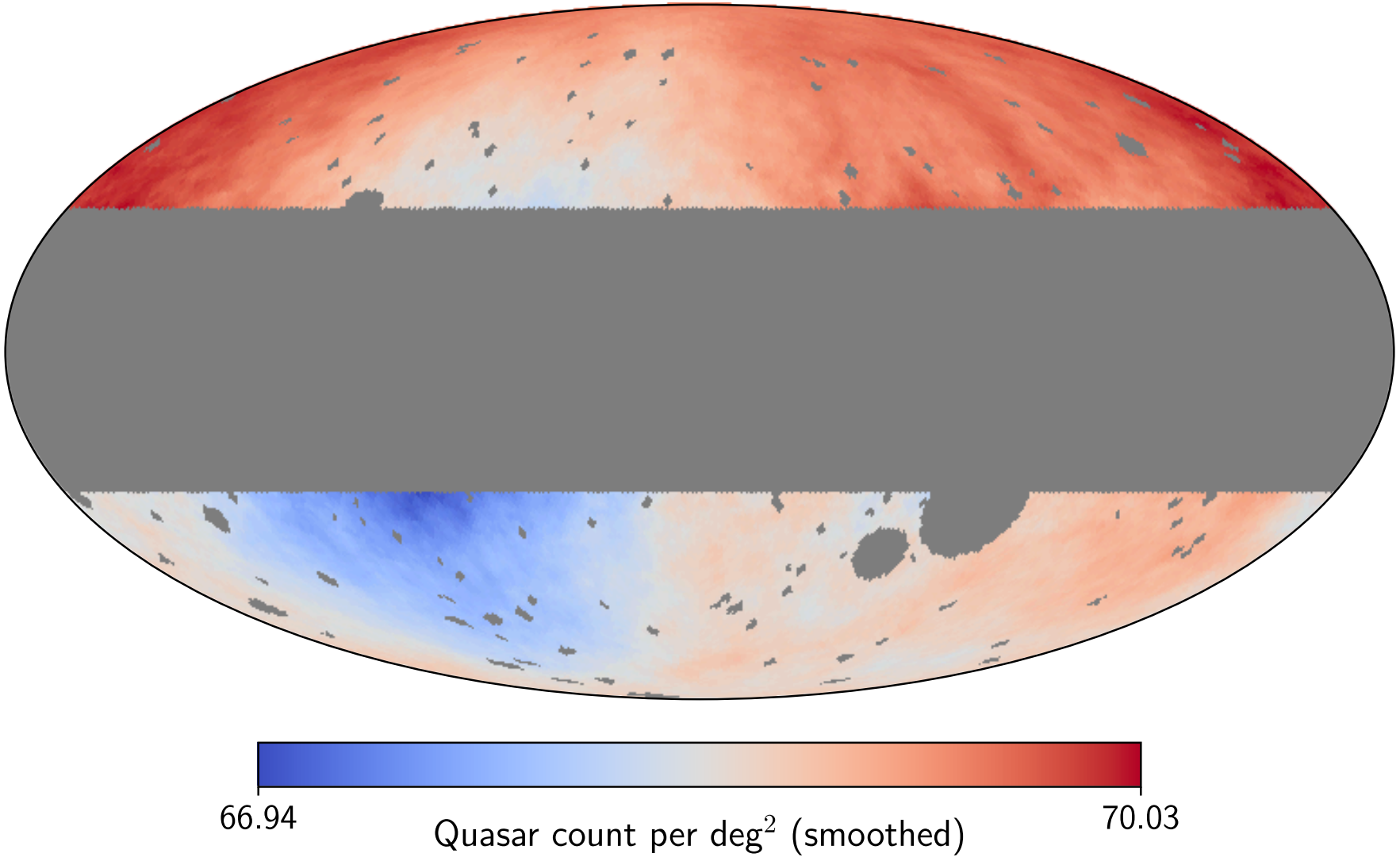
Wait...

The Amplitude Excess



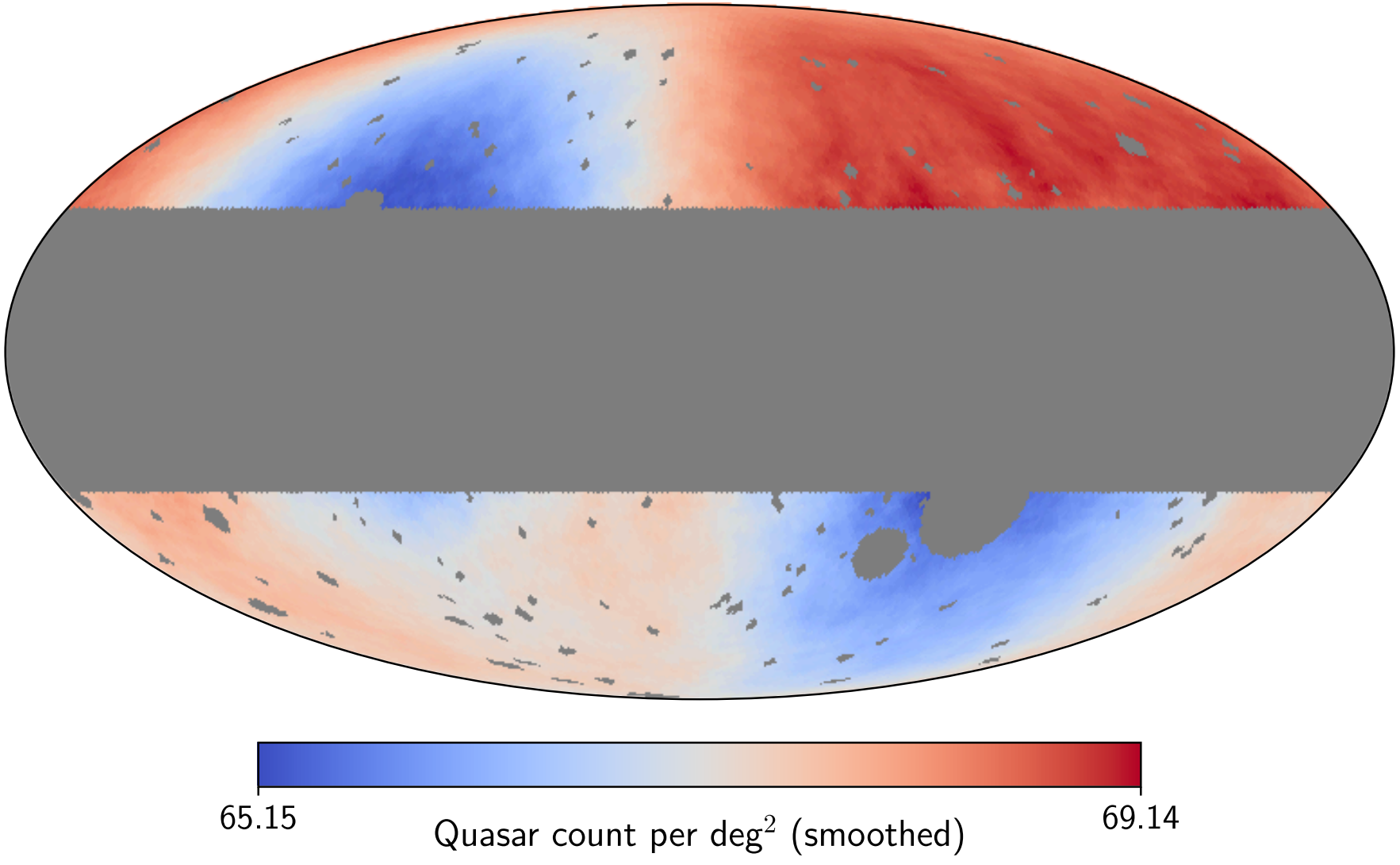
Focus: Secrest+21/22, CatWISE2020

The CatWISE Sample



CatWISE quasar map from Secrest+21

The CatWISE Sample



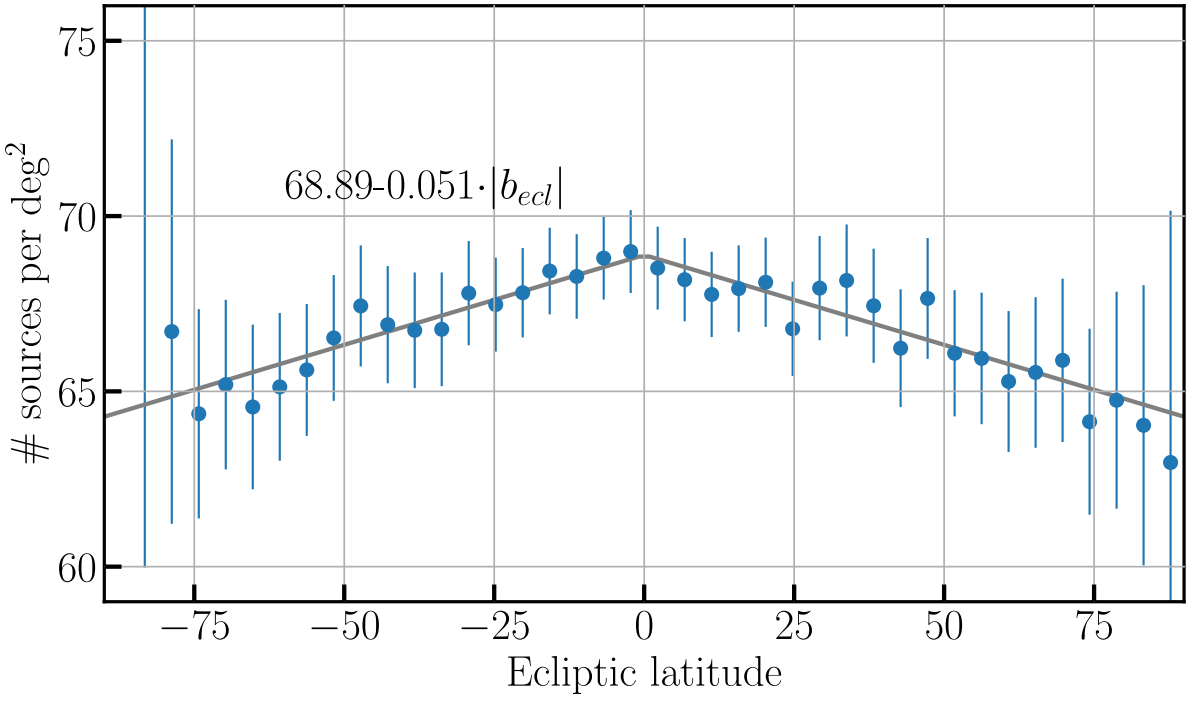
CatWISE quasar map, no linear weighting

Correcting for the Bias

The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.org/10.3847/2041-8213/abdd40

A Test of the Cosmological Principle with Quasars

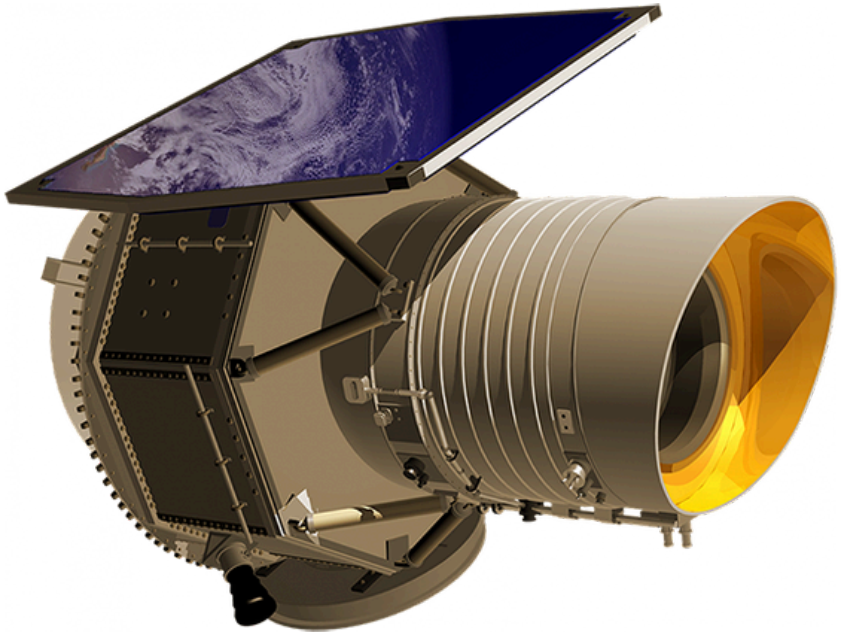
Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]



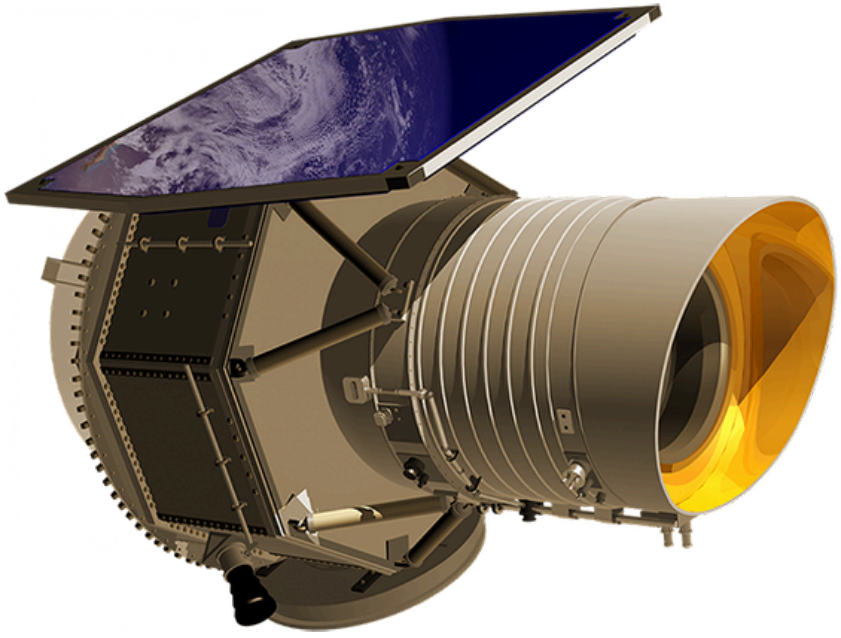
Linear fit to density vs. declination (Secrest+21)

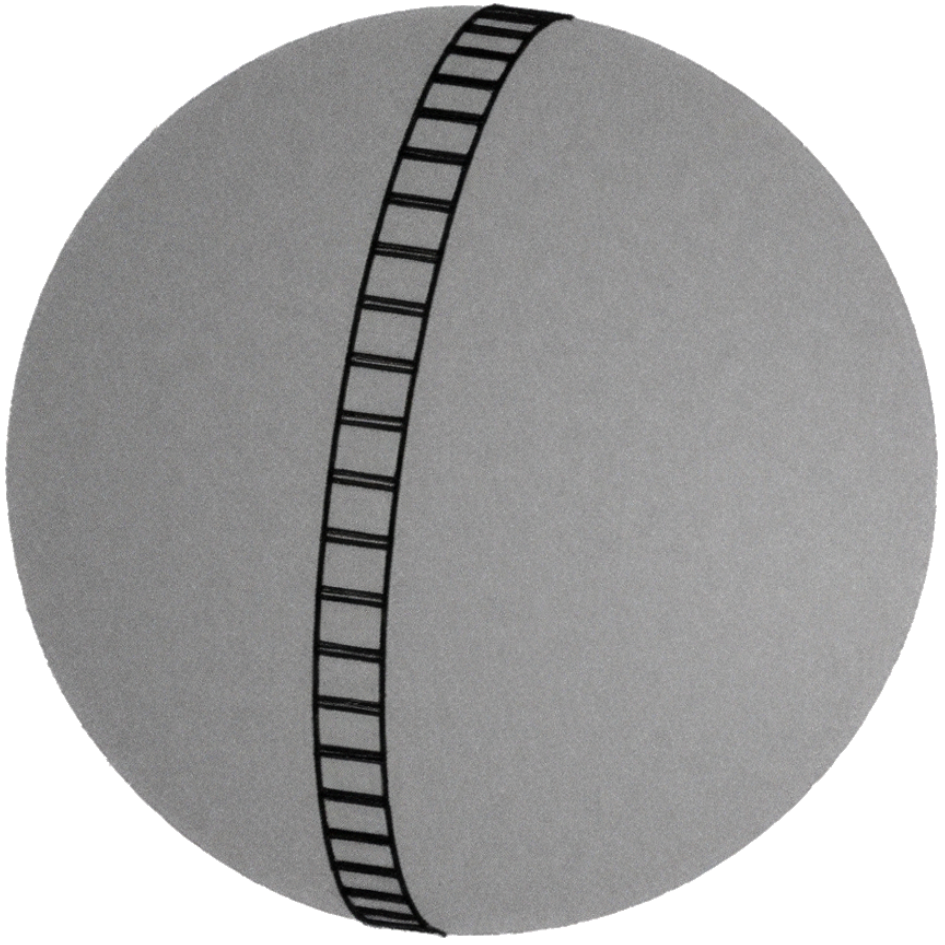
Is it good enough to make an ad hoc correction after the fact?

WISE's Scanning Law



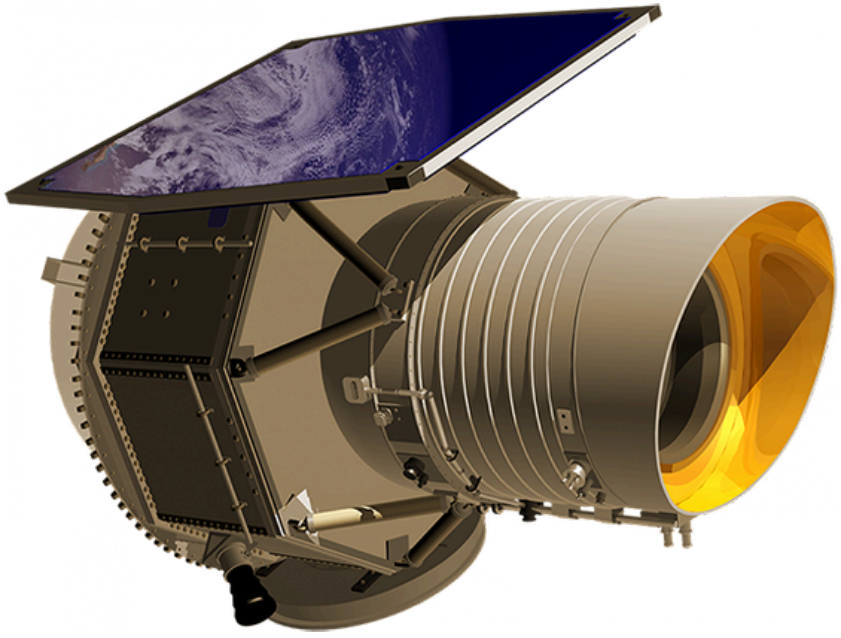
WISE's Scanning Law

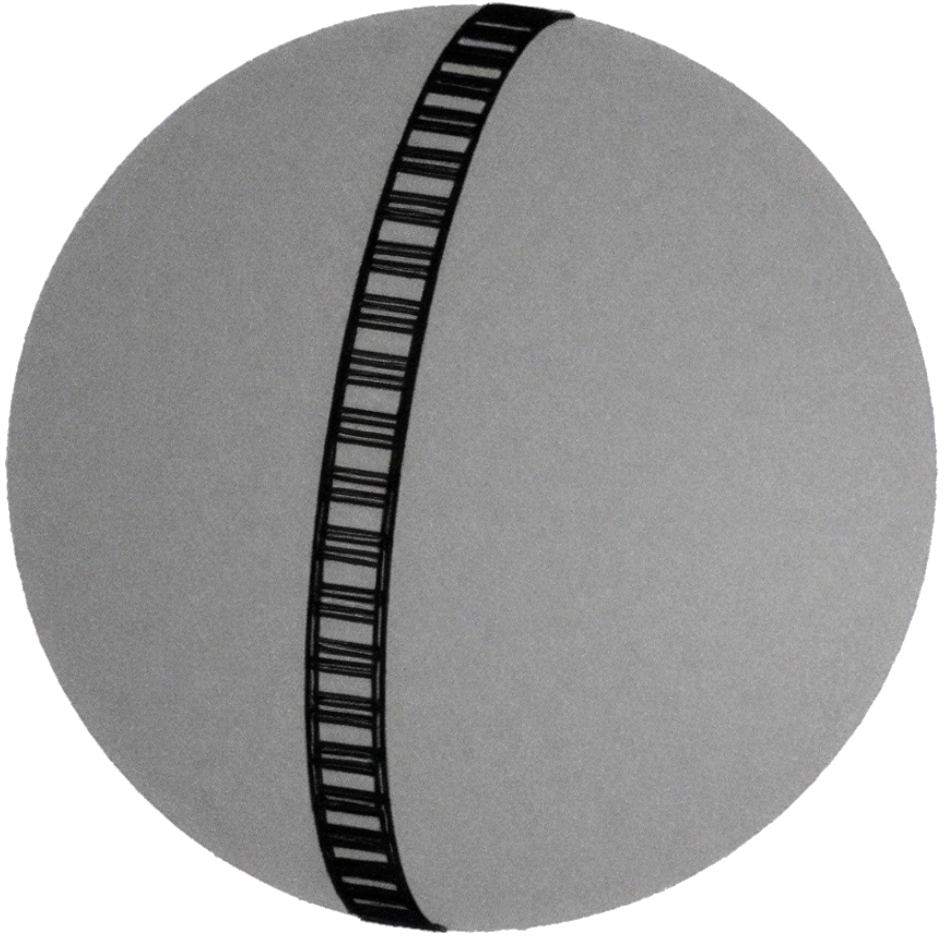




Frames over 1 orbit

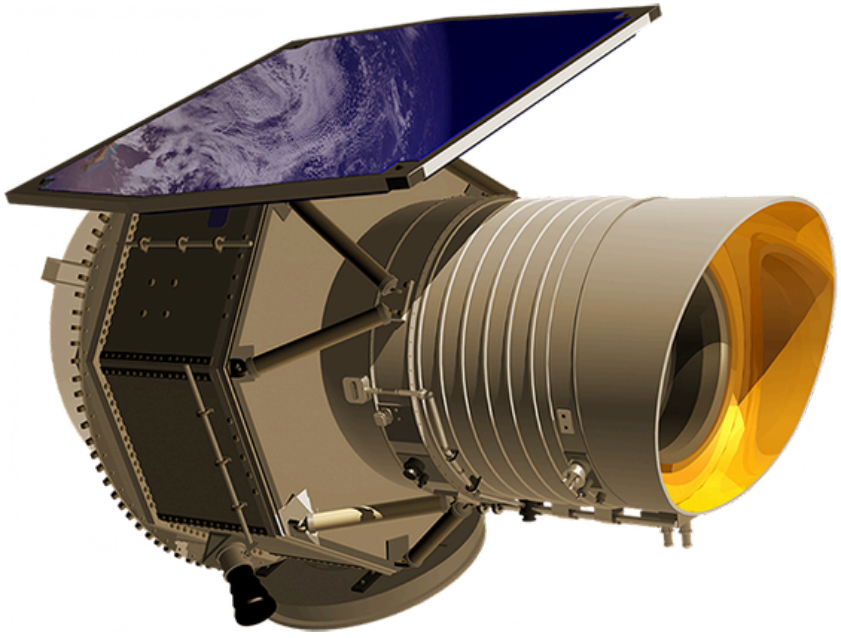
WISE's Scanning Law

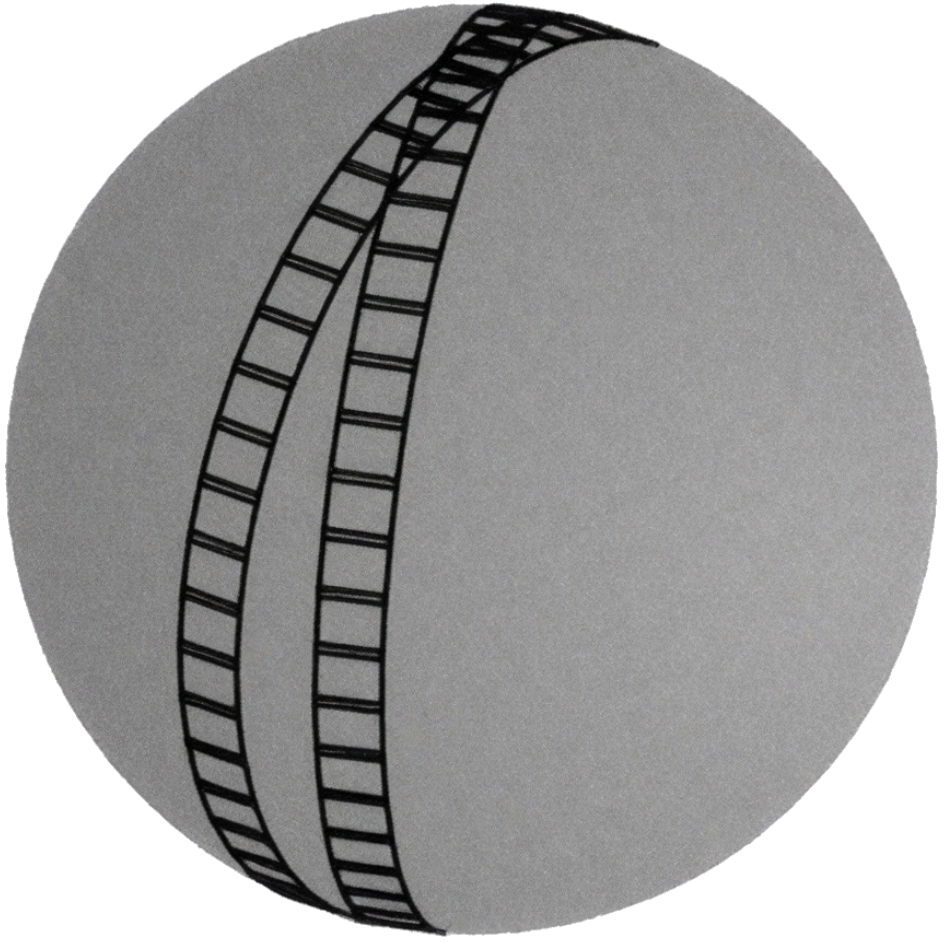




Frames over 2 orbits

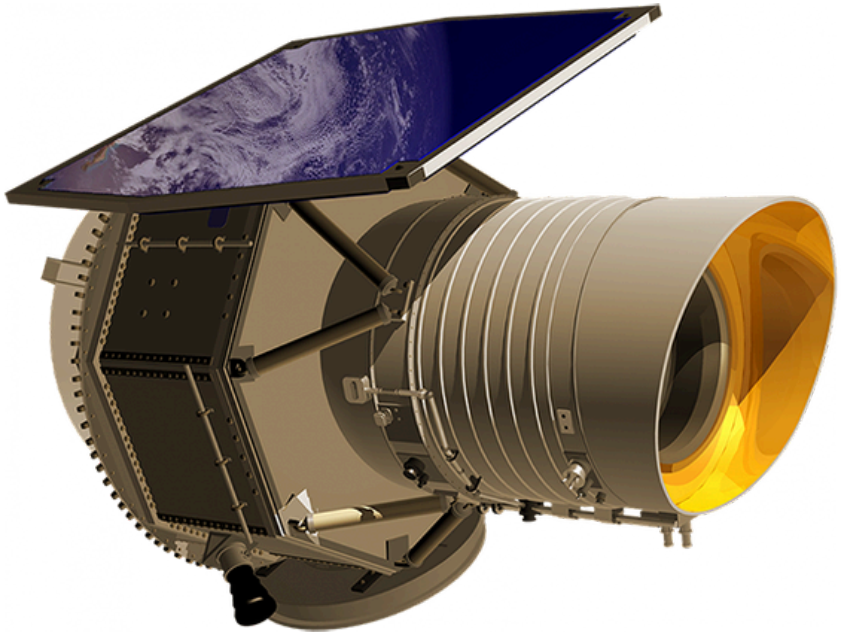
WISE's Scanning Law

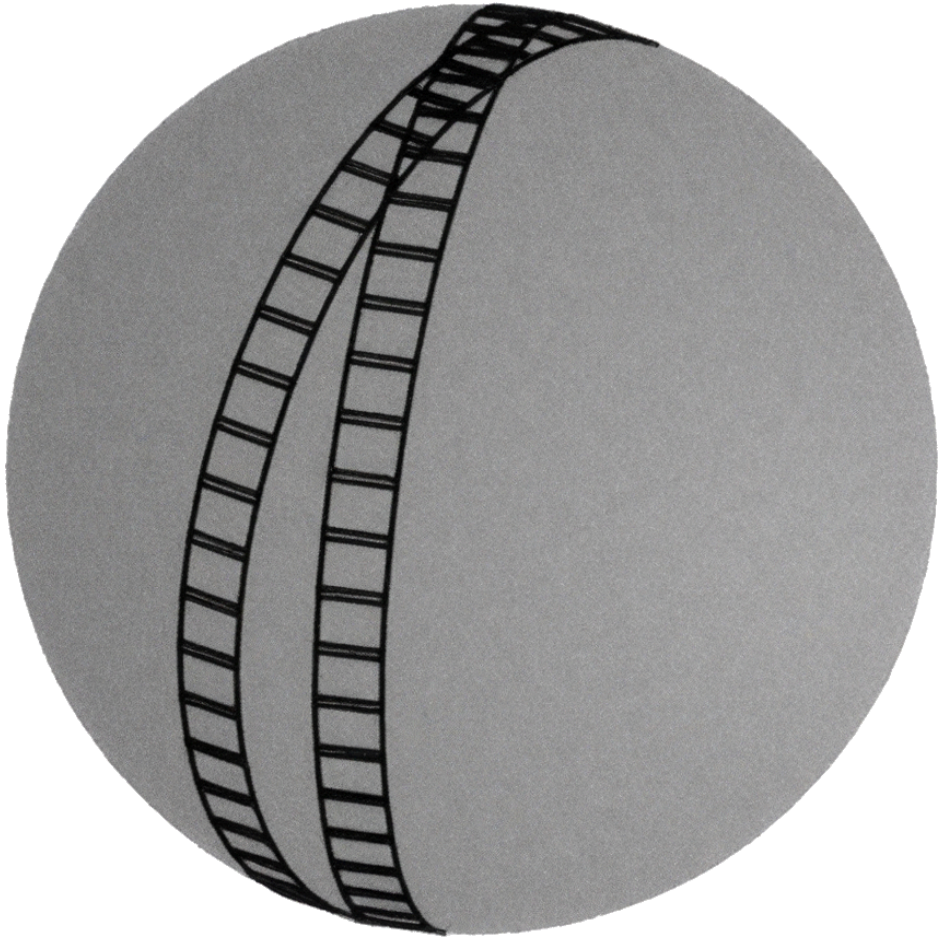




Frames over 2 orbits 20 days apart

WISE's Scanning Law

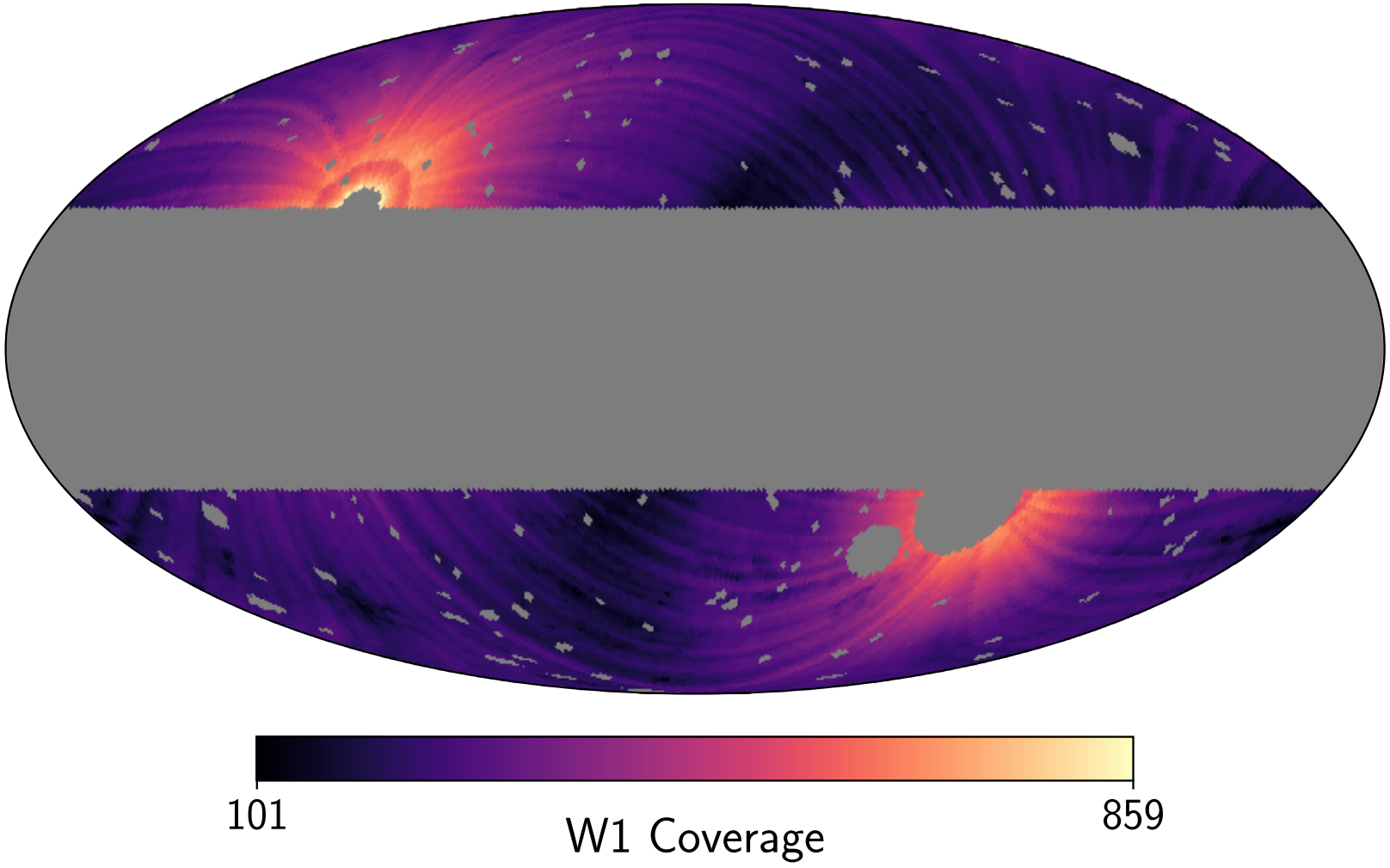




Frames over 2 orbits 20 days apart

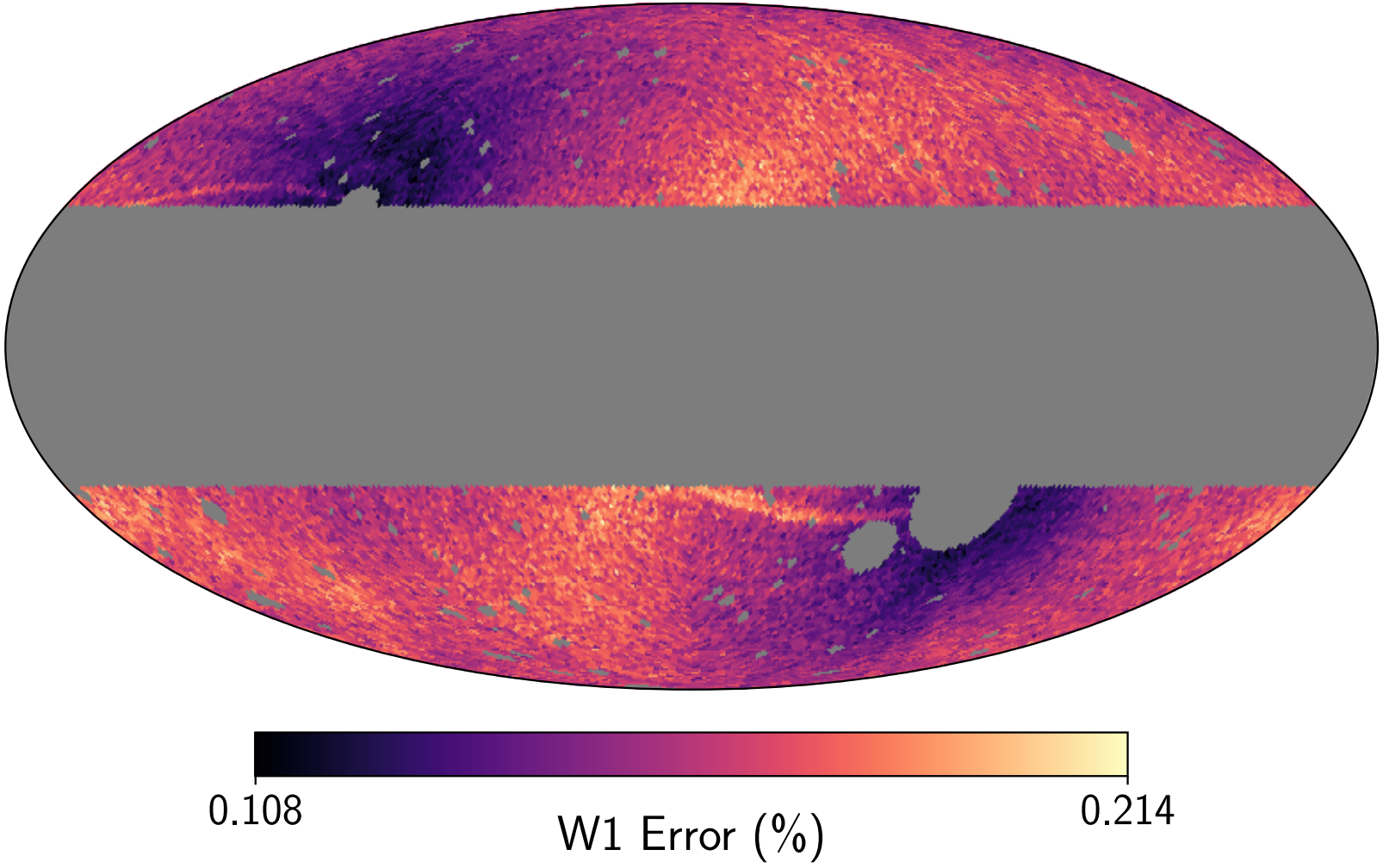
Obeys a scanning law over the survey's lifetime

Photometric Errors



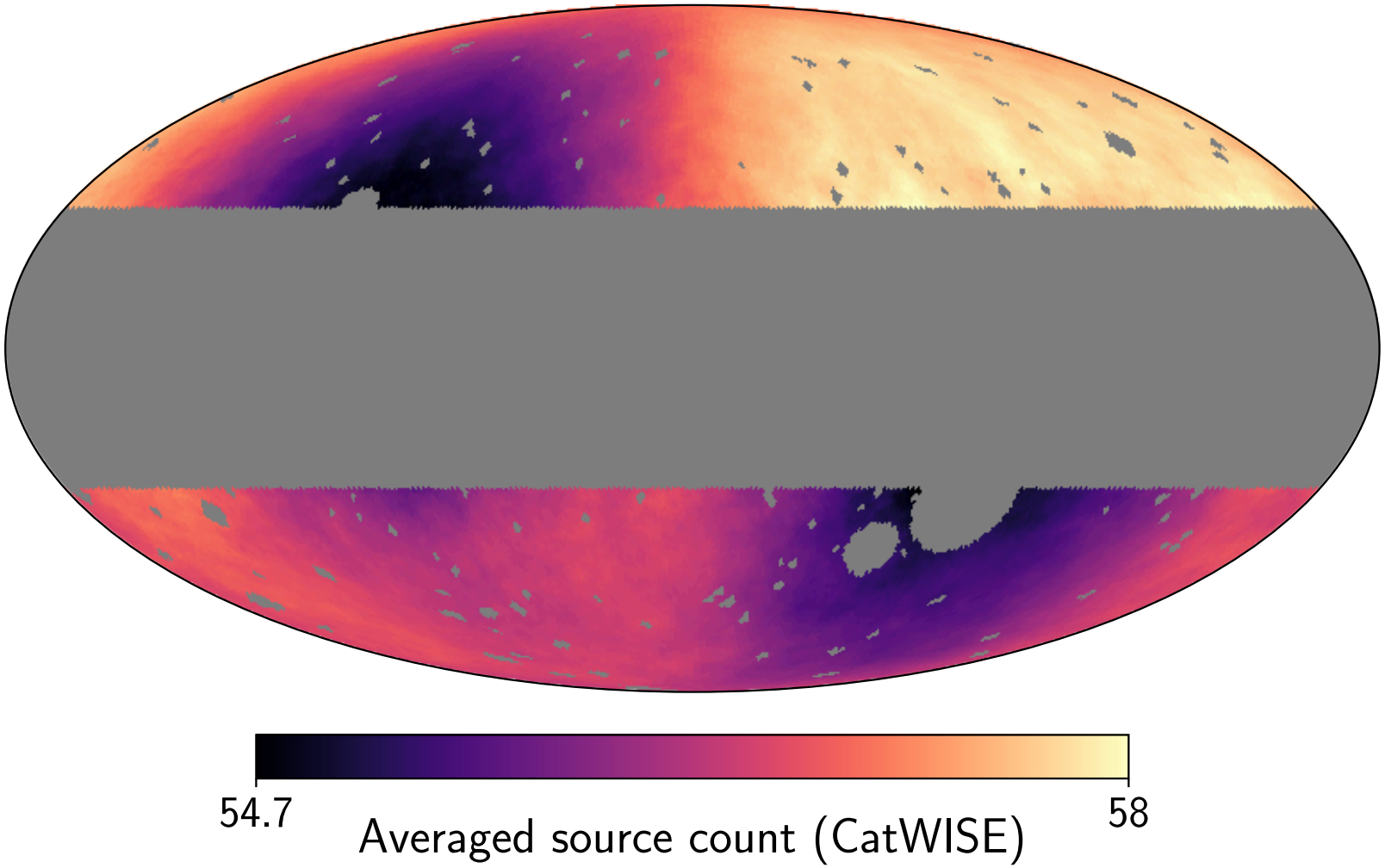
WISE coverage in W1 band for the Secrest+21 sample

Photometric Errors



Source photometric error (%) in W1 band for the Secrest+21 sample

Photometric Errors

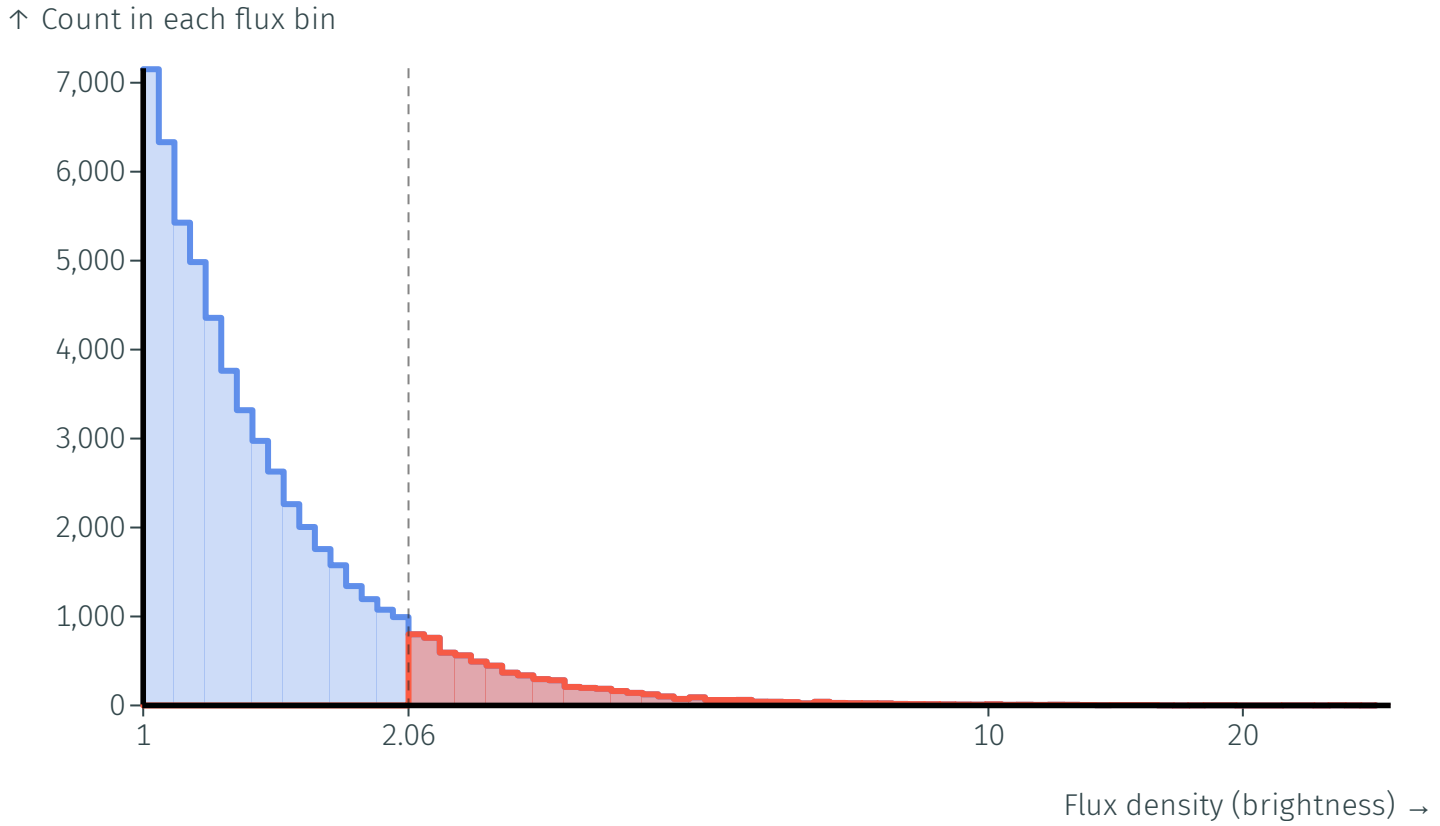


CatWISE quasar map, no linear weighting

Eddington Bias

Sampled flux = True flux + Noise

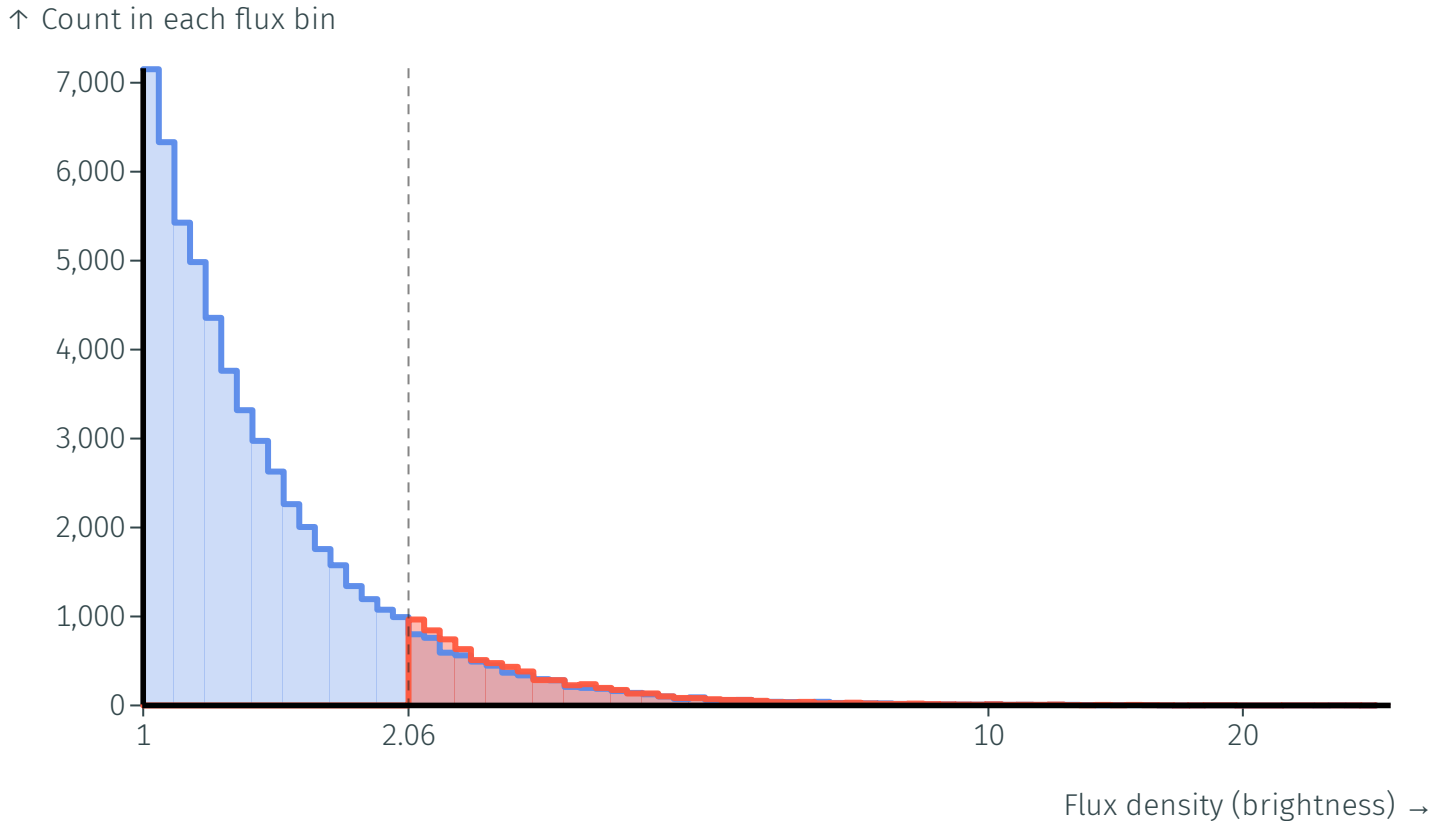
Flux cut 2.06 Noise 0.00



Eddington Bias

Sampled flux = True flux + Noise

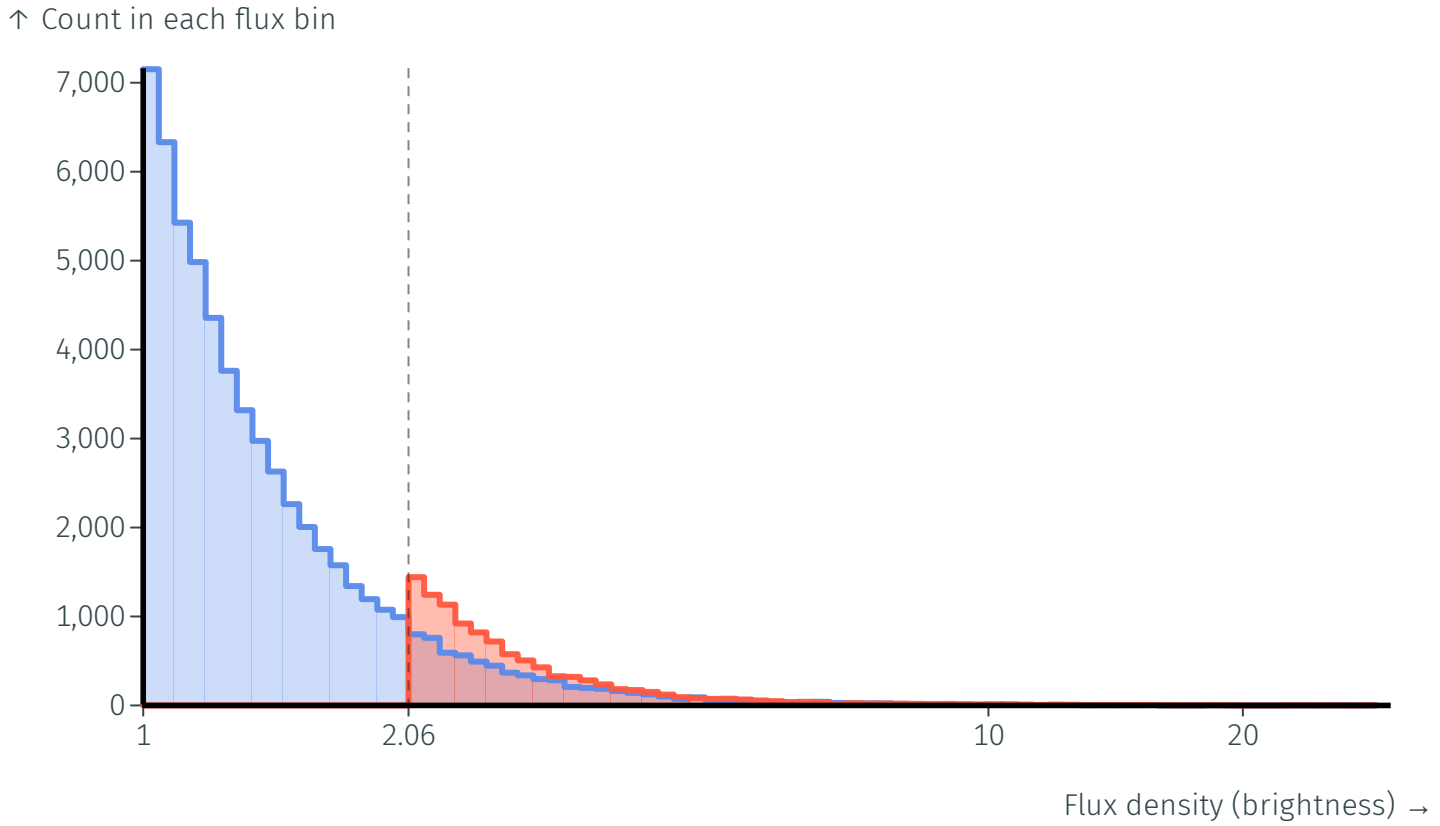
Flux cut 2.06 Noise 0.25



Eddington Bias

Sampled flux = True flux + Noise

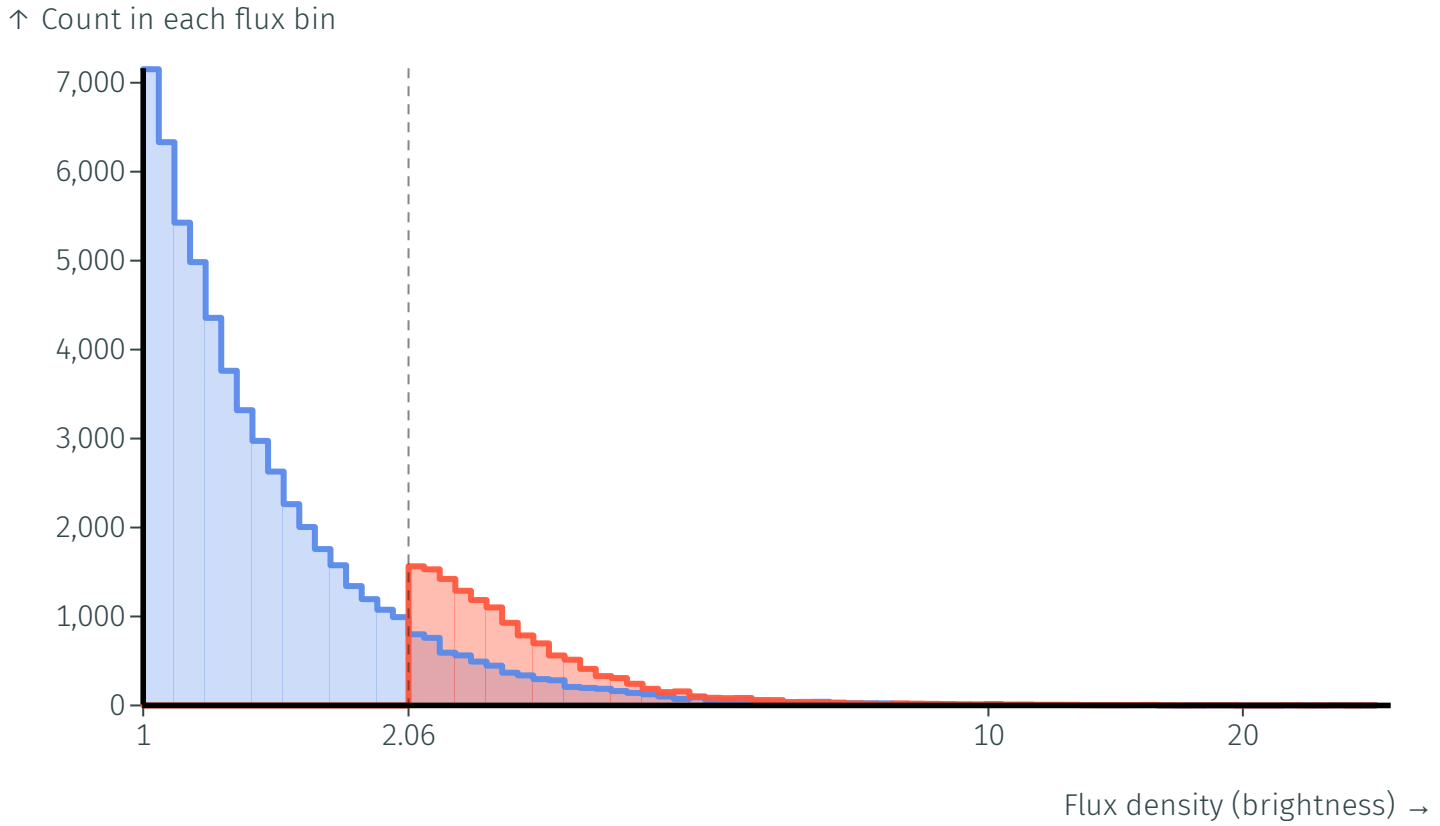
Flux cut 2.06 Noise 0.50



Eddington Bias

Sampled flux = True flux + Noise

Flux cut 2.06 Noise 0.75



Eddington Bias

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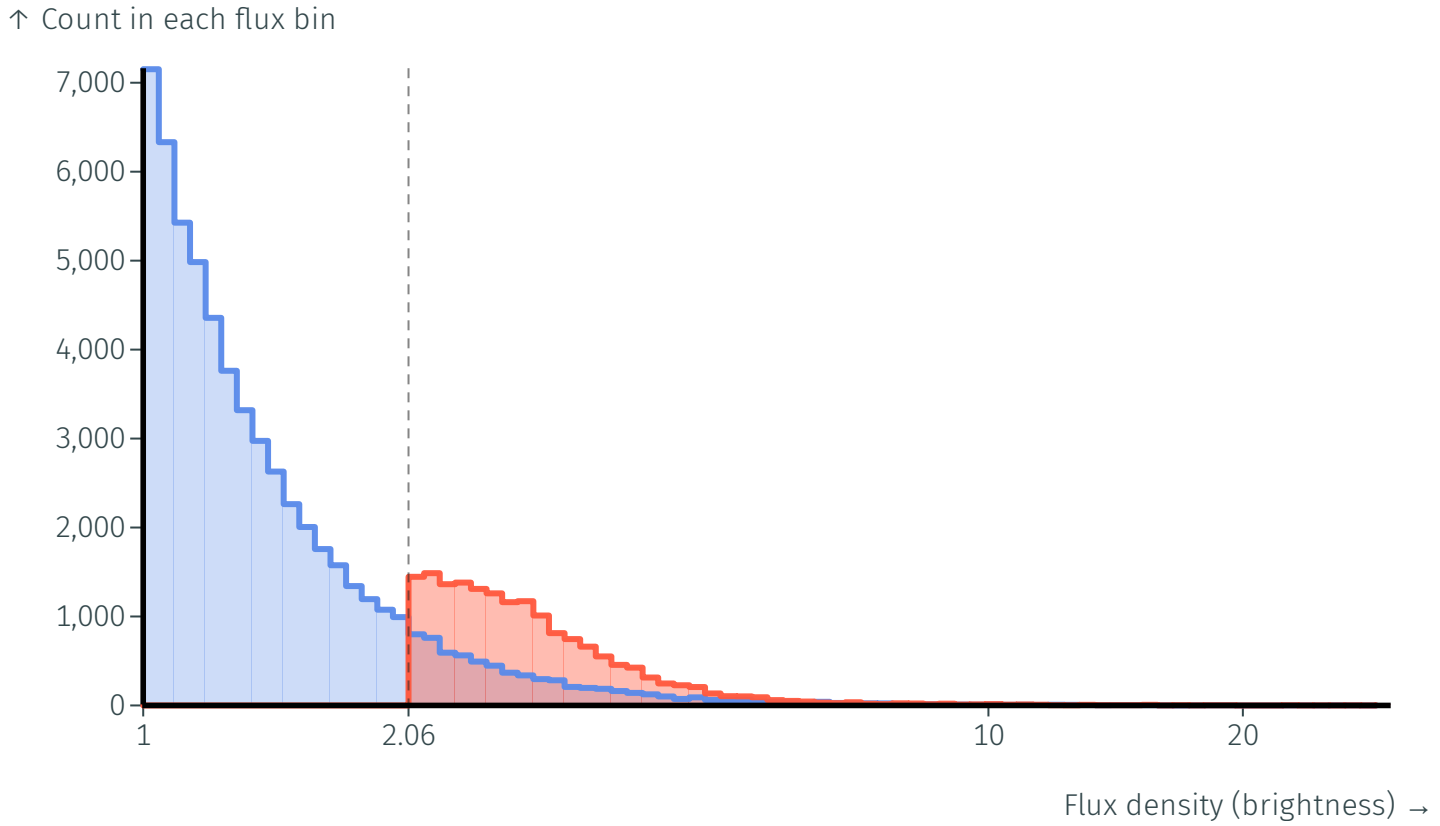
Flux cut 2.06 Noise 1.00



Eddington Bias

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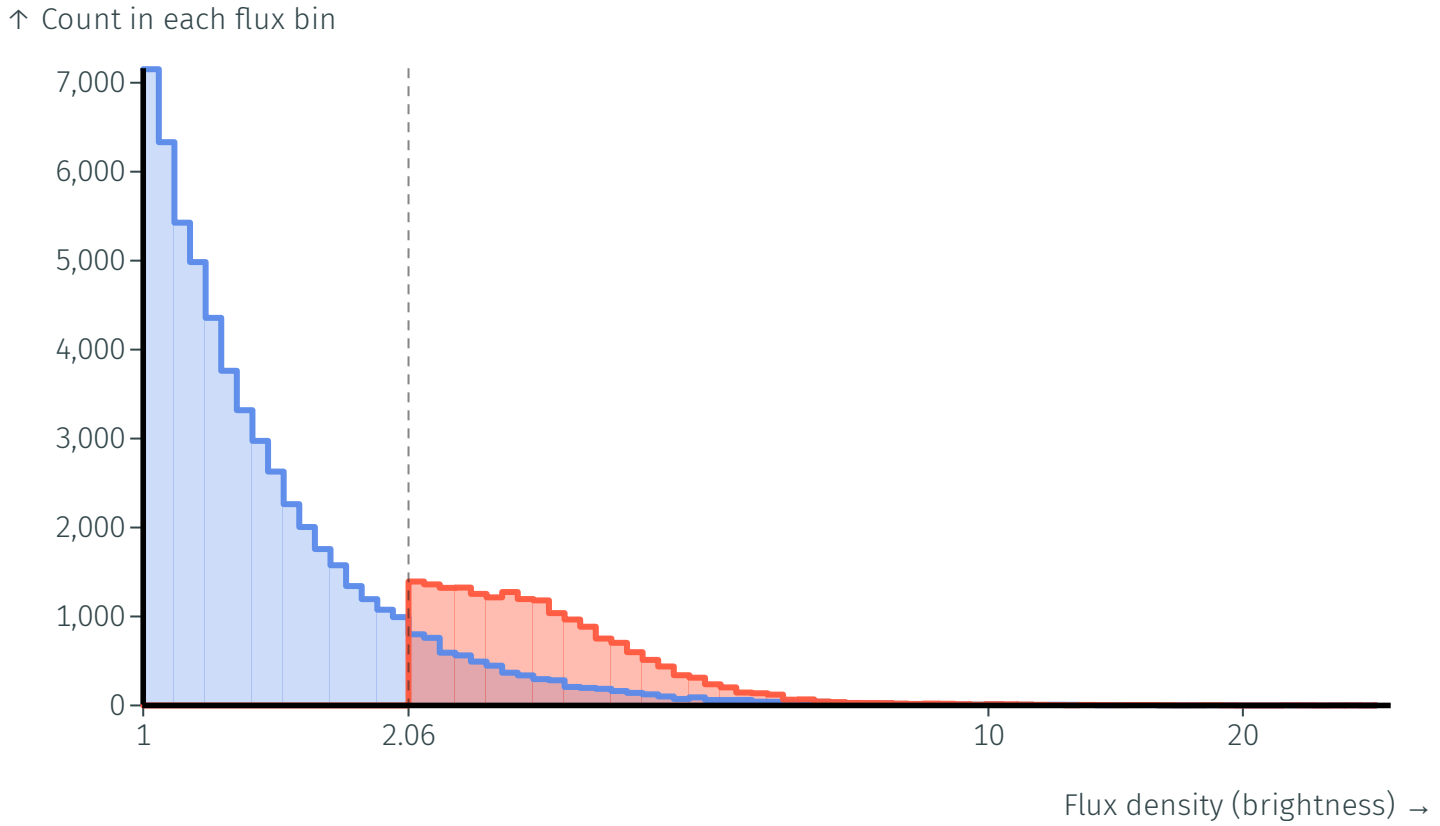

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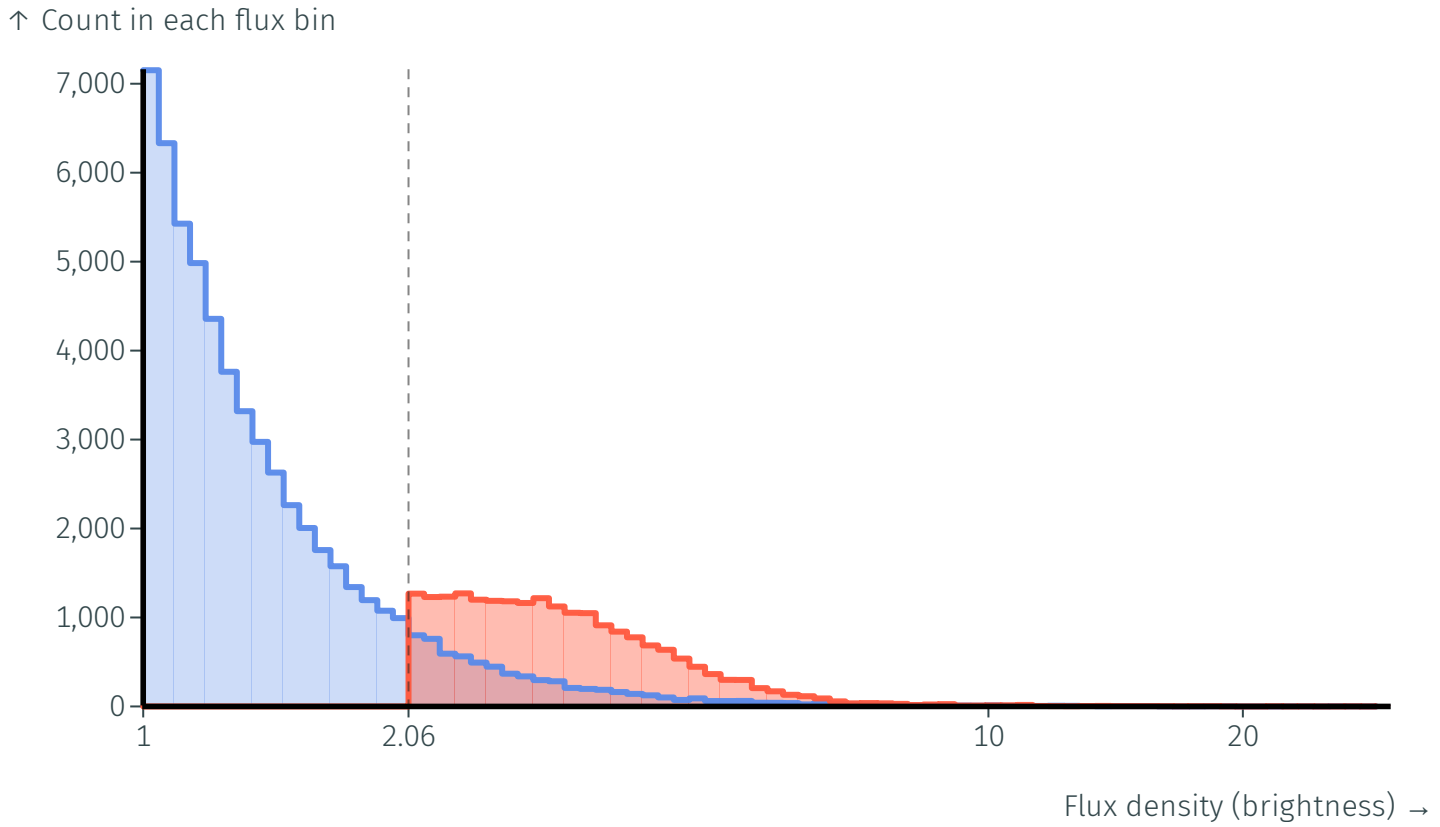

Eddington Bias

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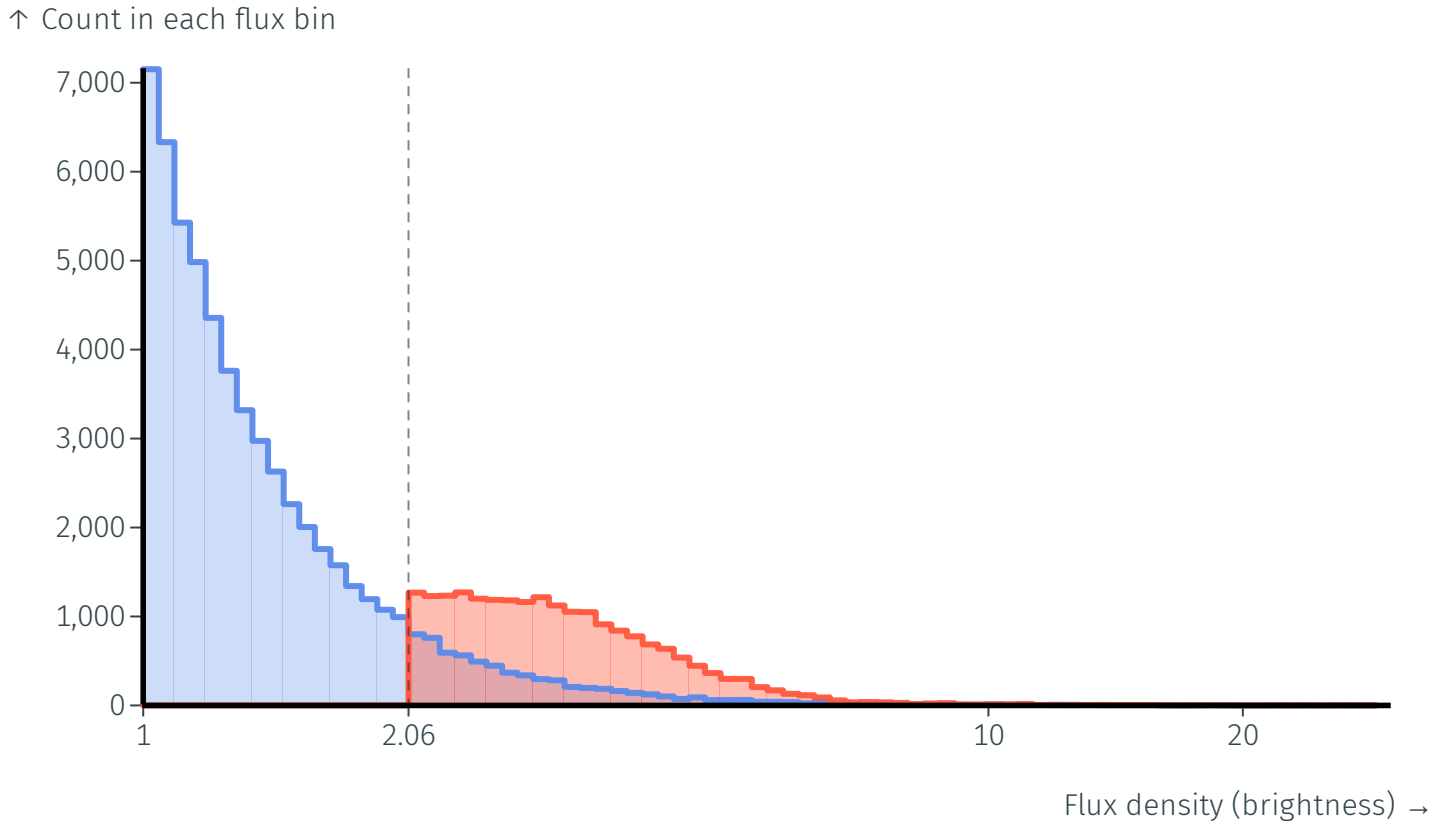


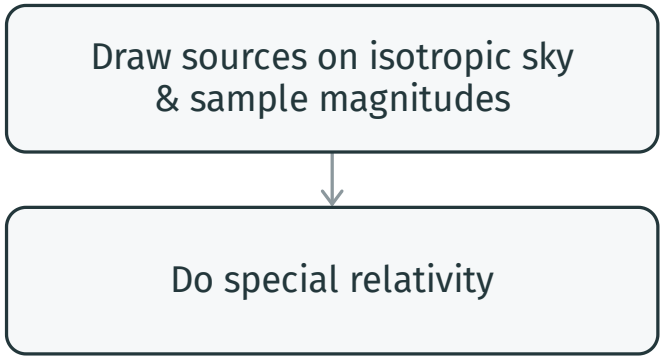
What if the noise varies over the sky? 🤔

This is just something we can simulate!

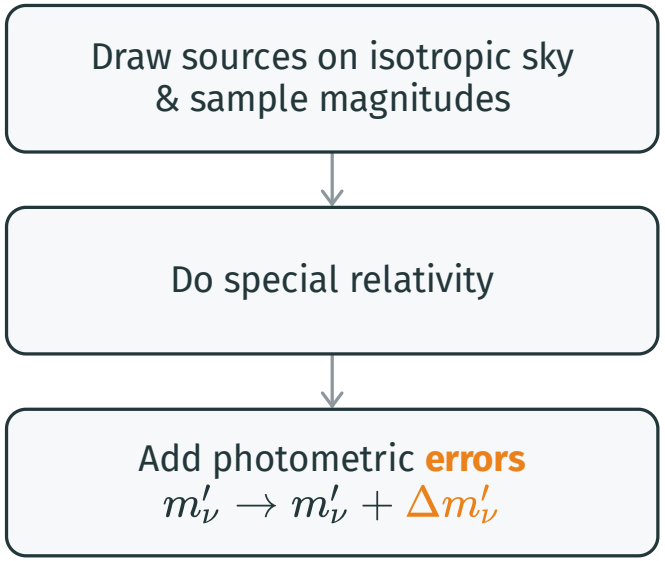
Simulations

Draw sources on isotropic sky
& sample magnitudes

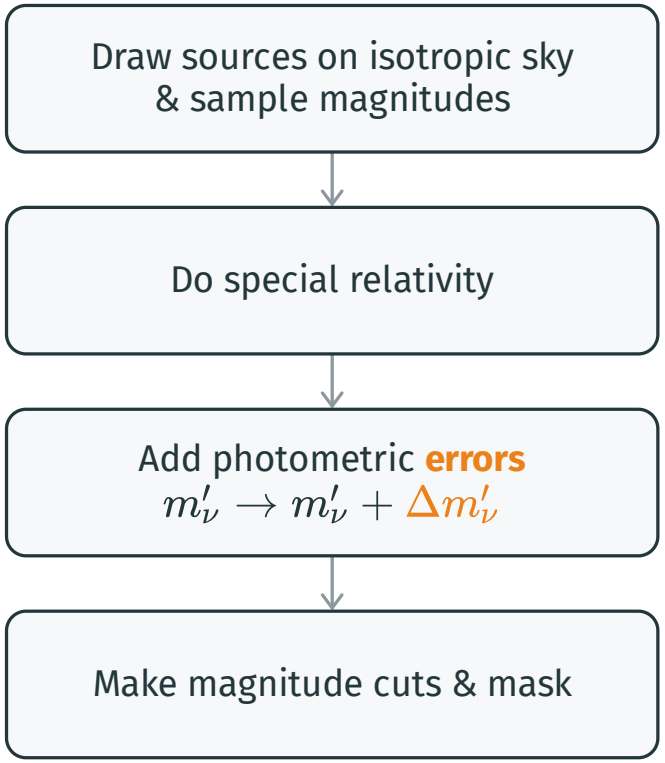
Simulations



Simulations



Simulations



Simulations

Draw sources on isotropic sky & sample magnitudes

↓

Do special relativity

↓

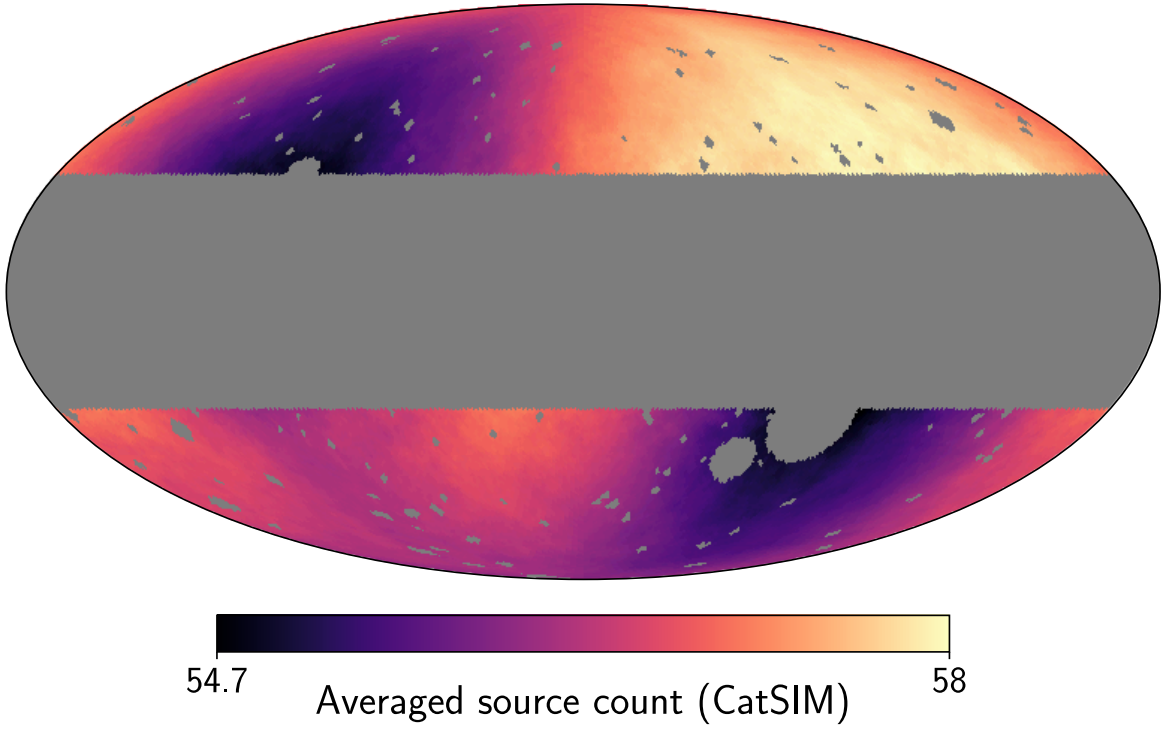
Add photometric **errors**
$m'_\nu \to m'_\nu + \Delta m'_\nu$

↓

Make magnitude cuts & mask

↓

Output: CatSIM density map



Simulated quasar map

Simulations

Draw sources on isotropic sky & sample magnitudes

↓

Do special relativity

↓

Add photometric **errors**
$m'_\nu \to m'_\nu + \Delta m'_\nu$

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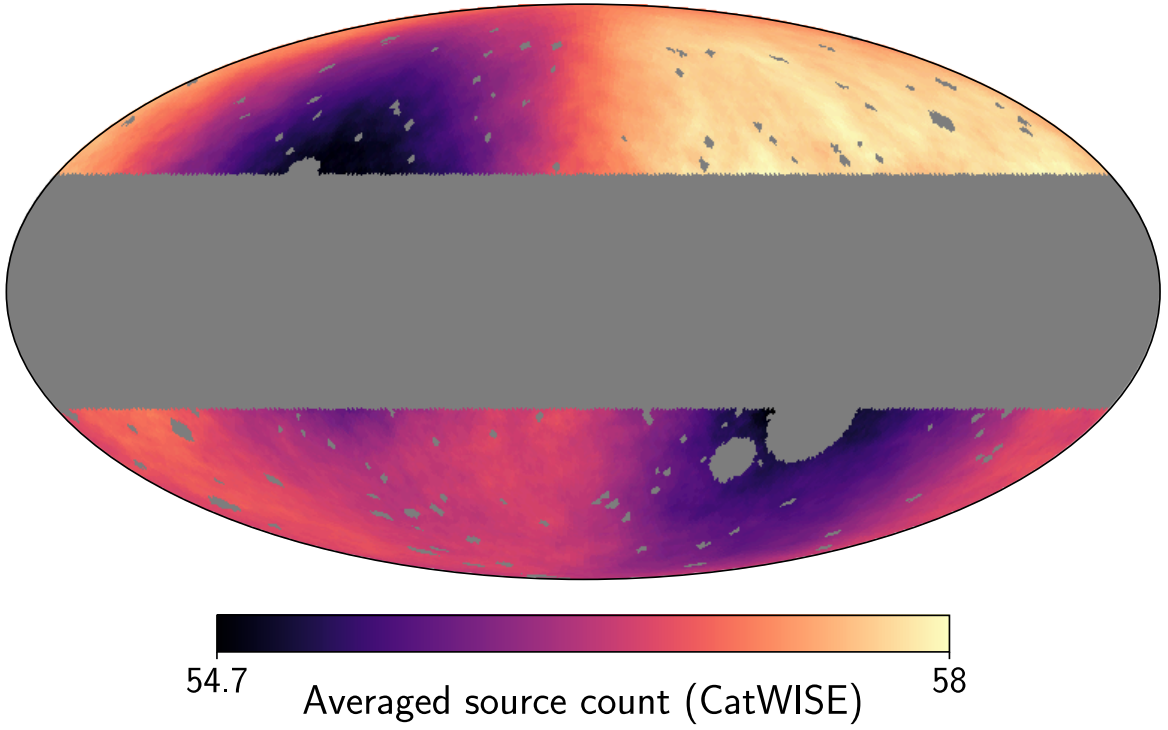


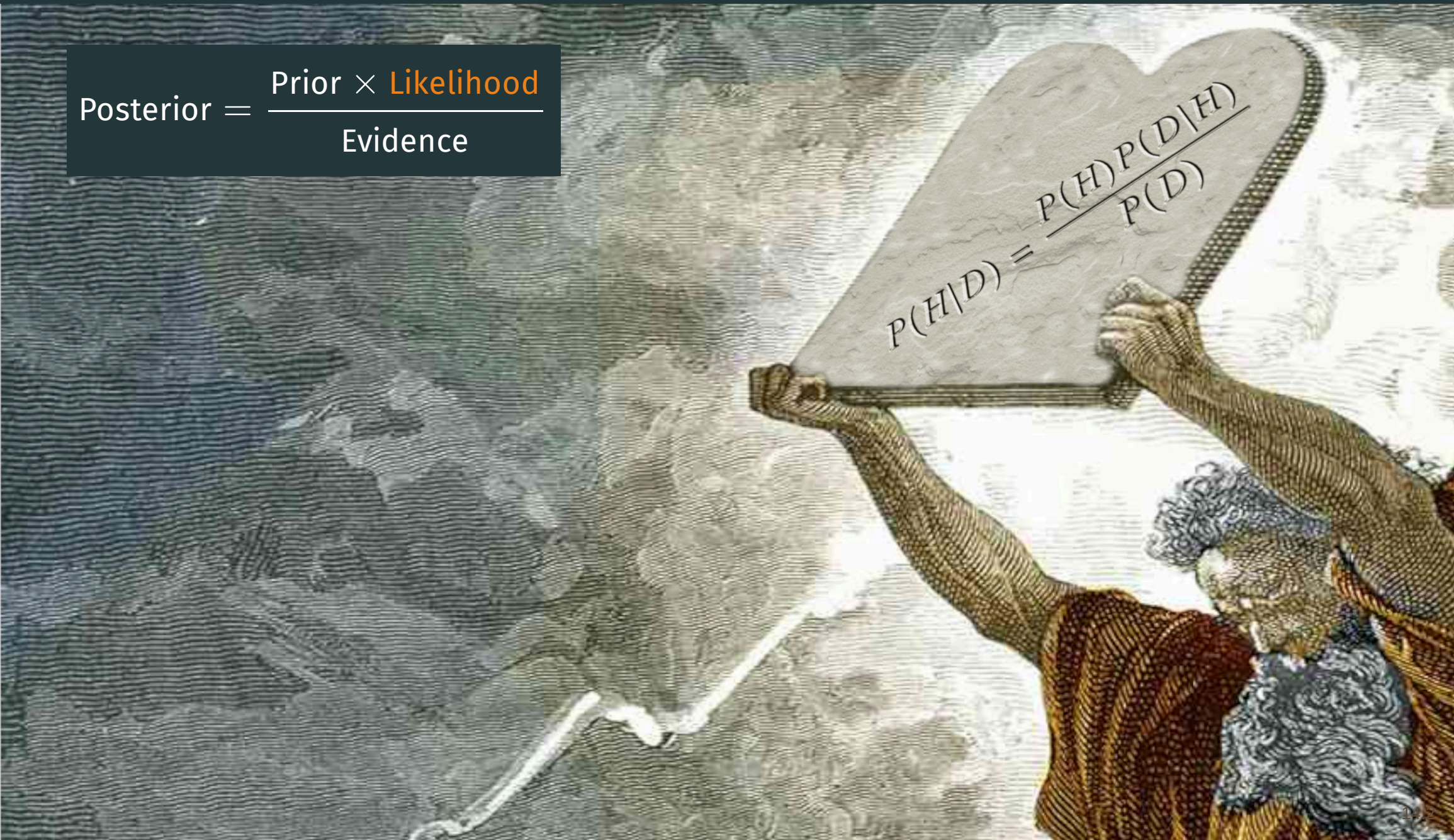
Actual quasar map

One Thing Left To Do...

One Thing Left To Do...

One Thing Left To Do...

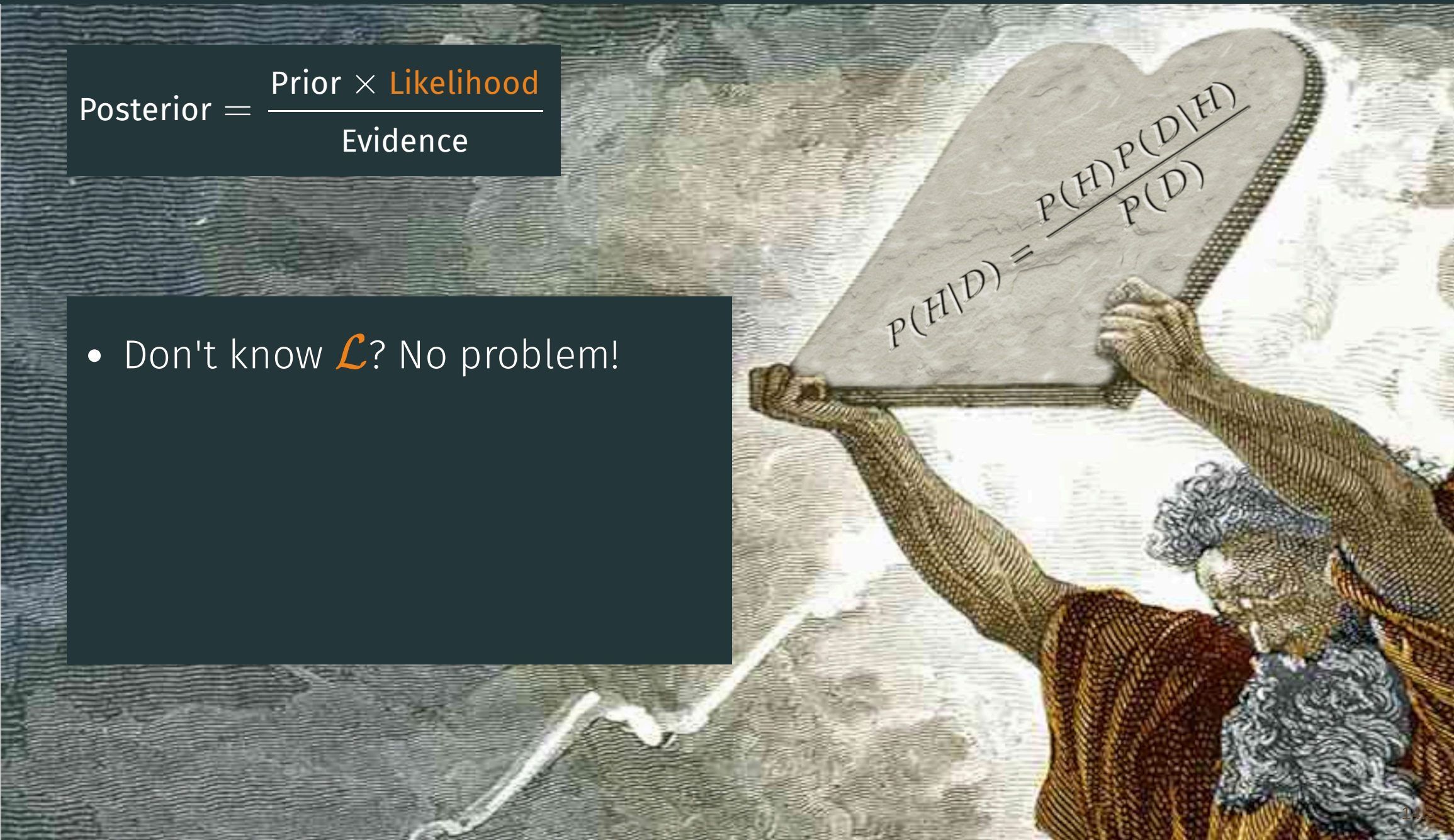
$$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$



One Thing Left To Do...

$$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$

- Don't know $\mathcal{L}$? No problem!



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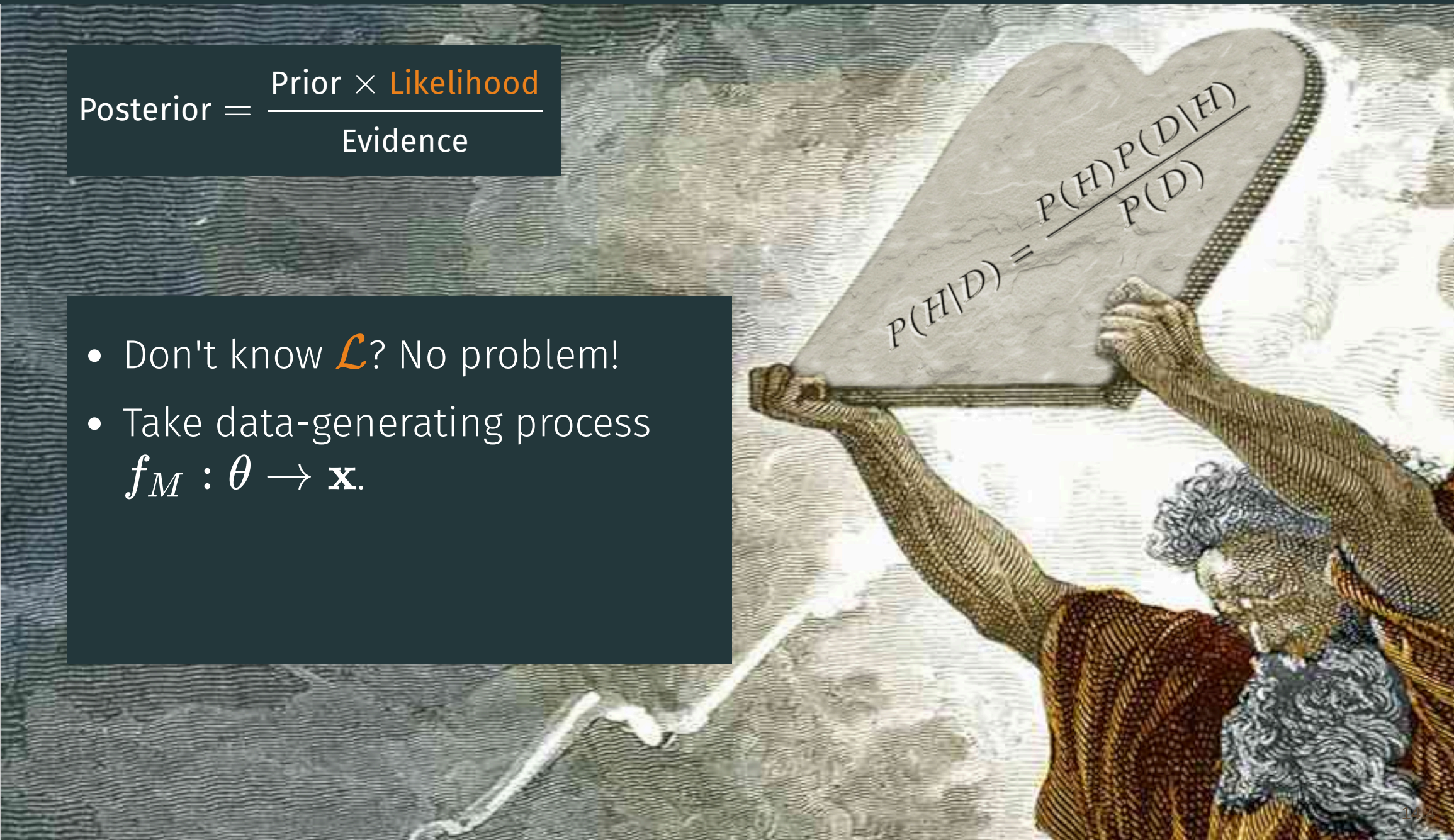
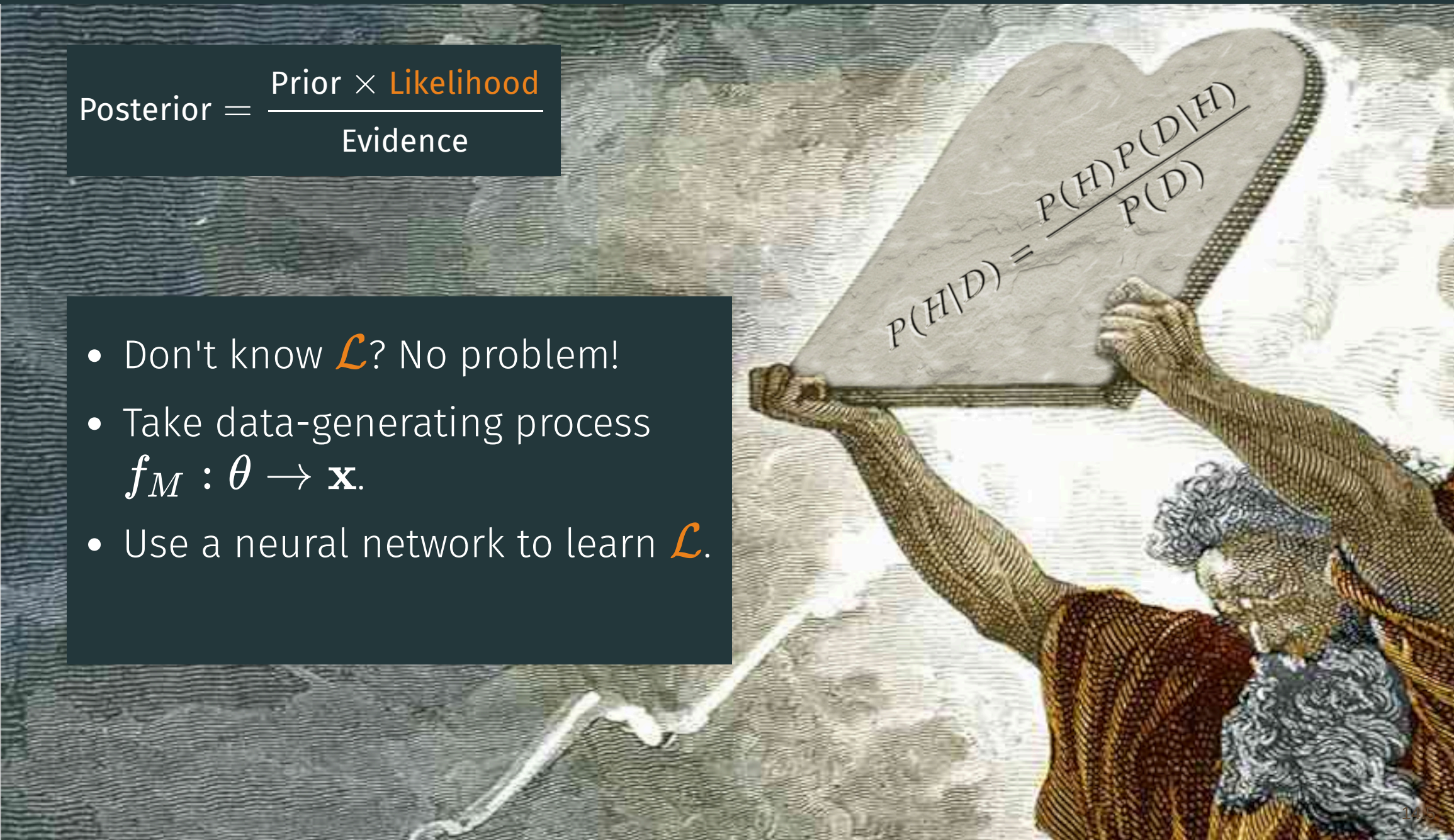


- Don't know $\mathcal{L}$? No problem!
- Take data-generating process $f_M : \theta \to \mathbf{x}$.

One Thing Left To Do...

$$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$



- Don't know $\mathcal{L}$? No problem!
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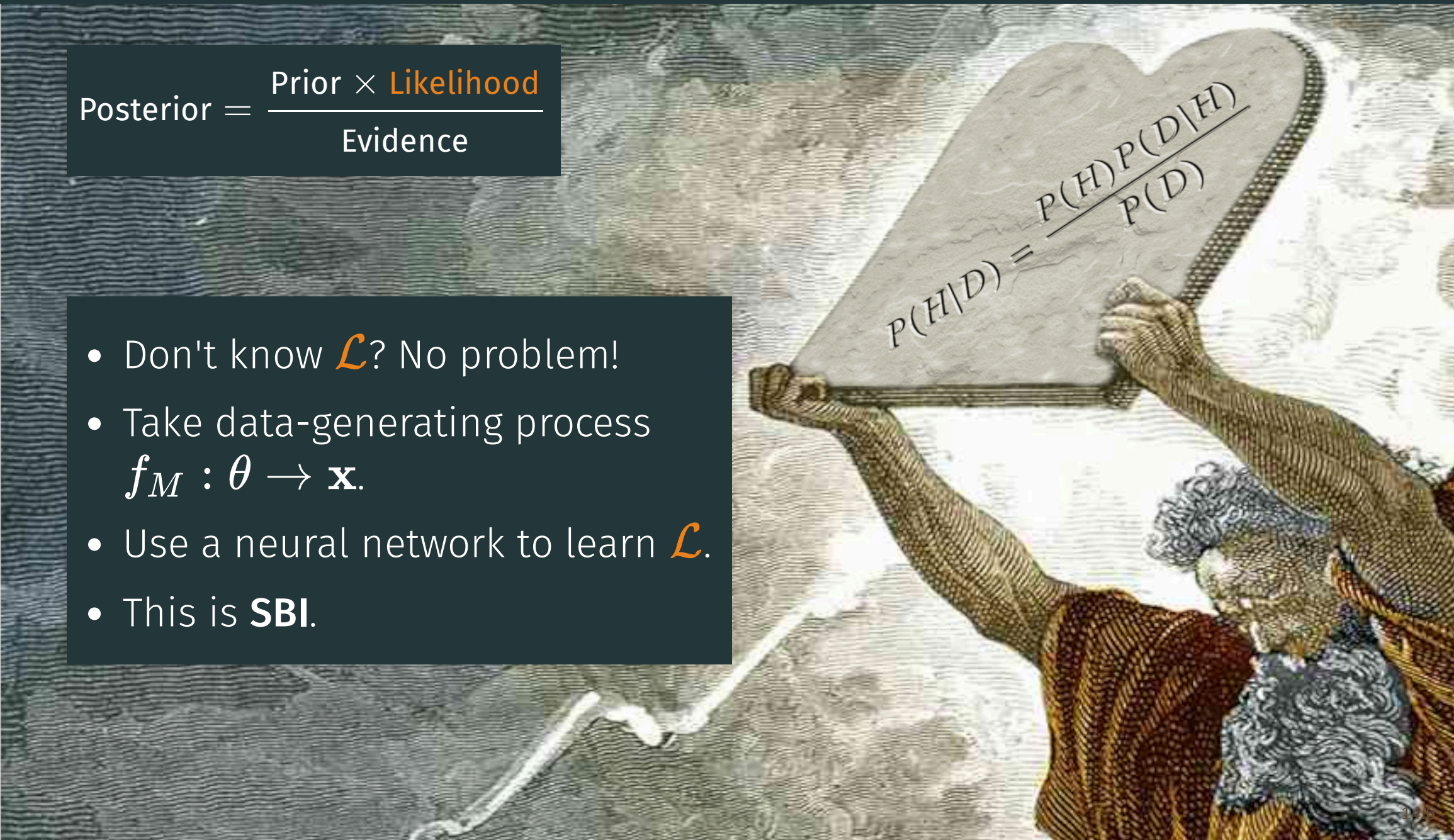
- Use a neural network to learn $\mathcal{L}$.

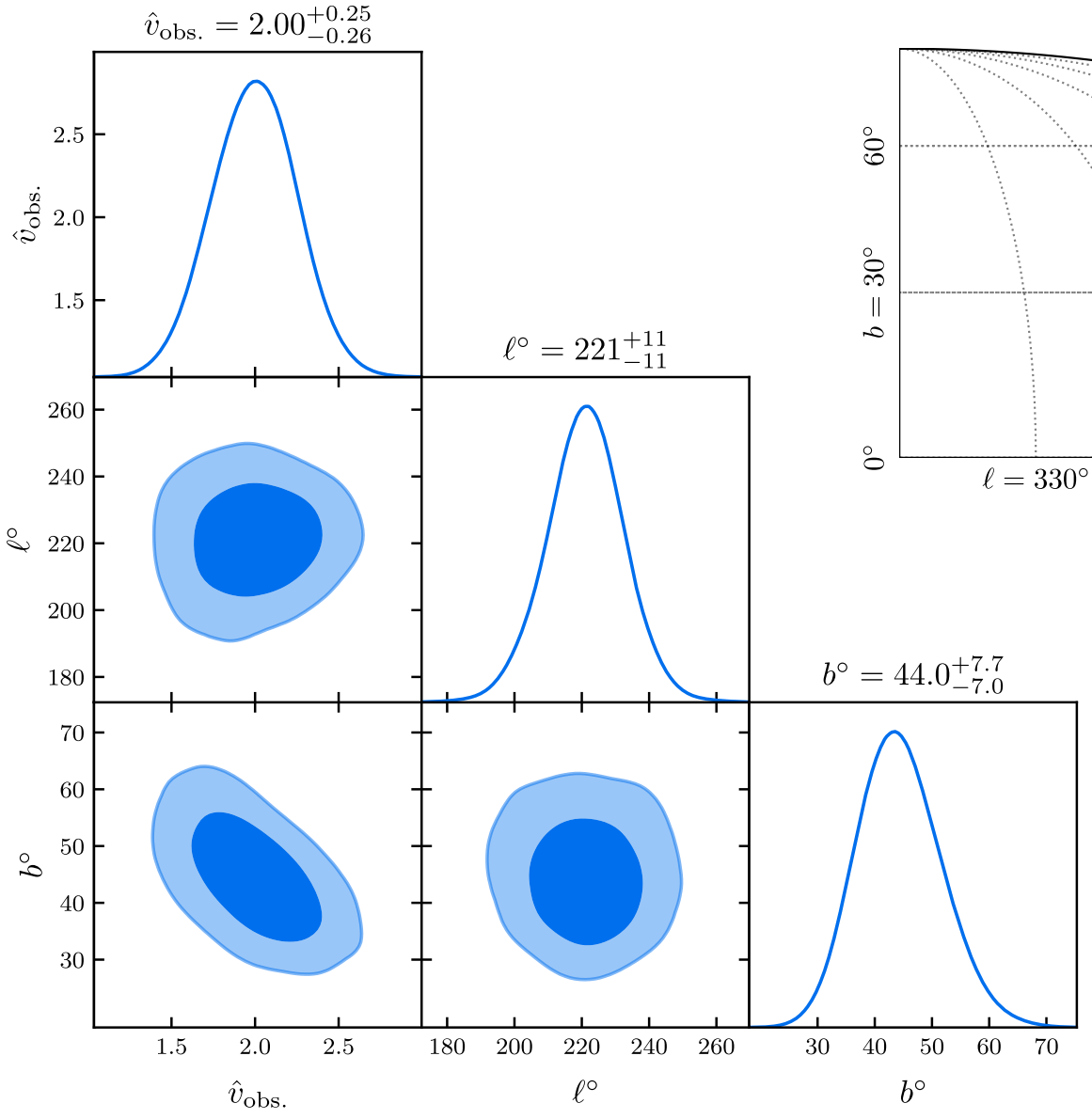
One Thing Left To Do...

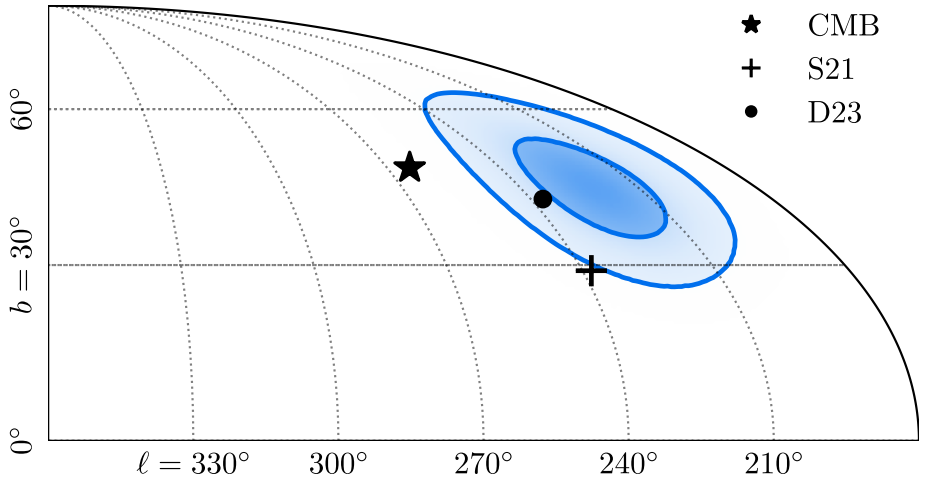
$$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$



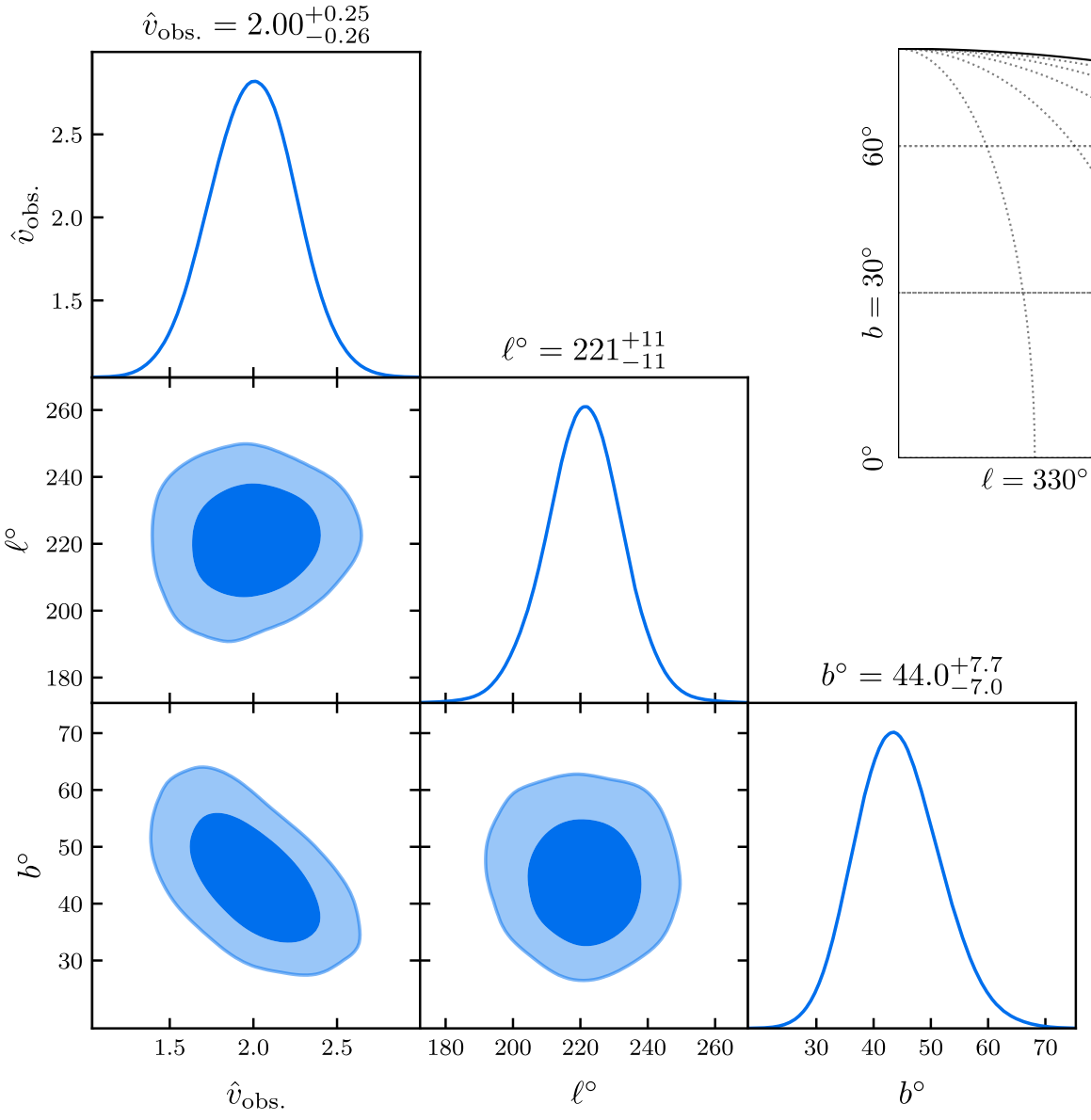
- Don't know $\mathcal{L}$? No problem!
- Take data-generating process $f_M : \theta \to \mathbf{x}$.
- Use a neural network to learn $\mathcal{L}$.
- This is **SBI**.

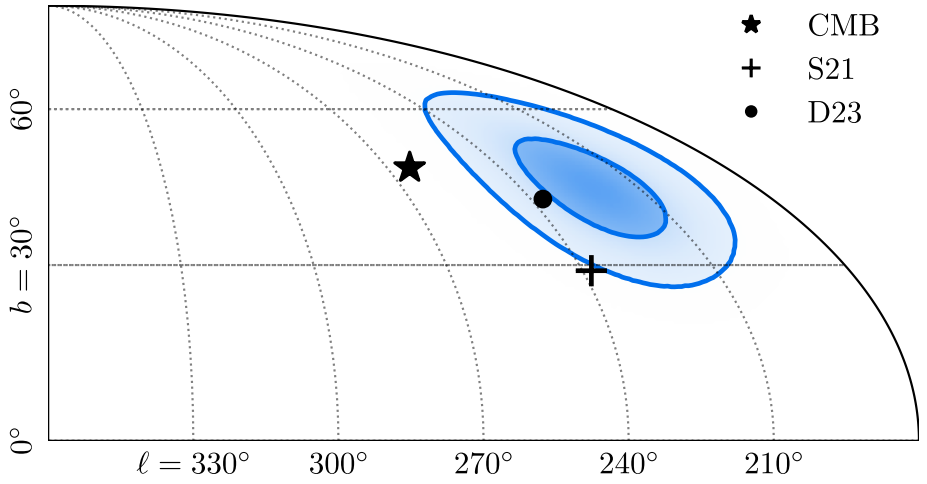
CatSIM Results





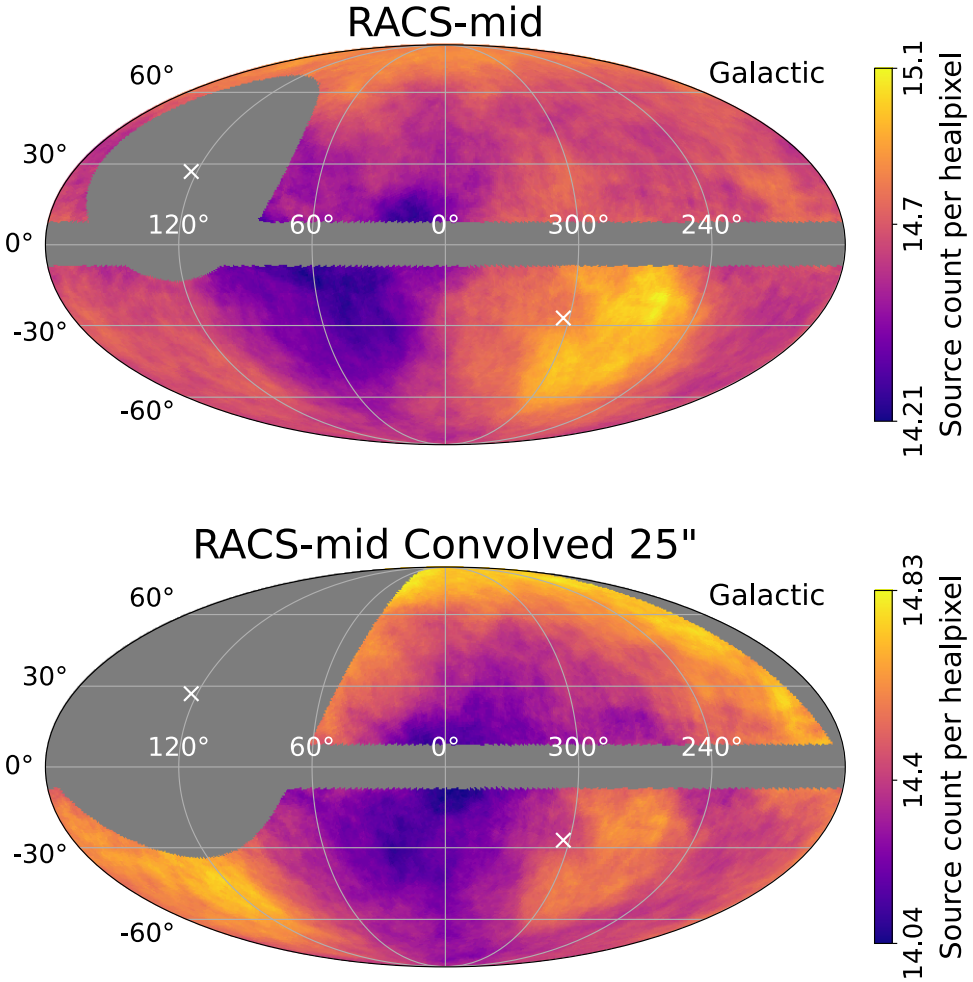
CatSIM Results



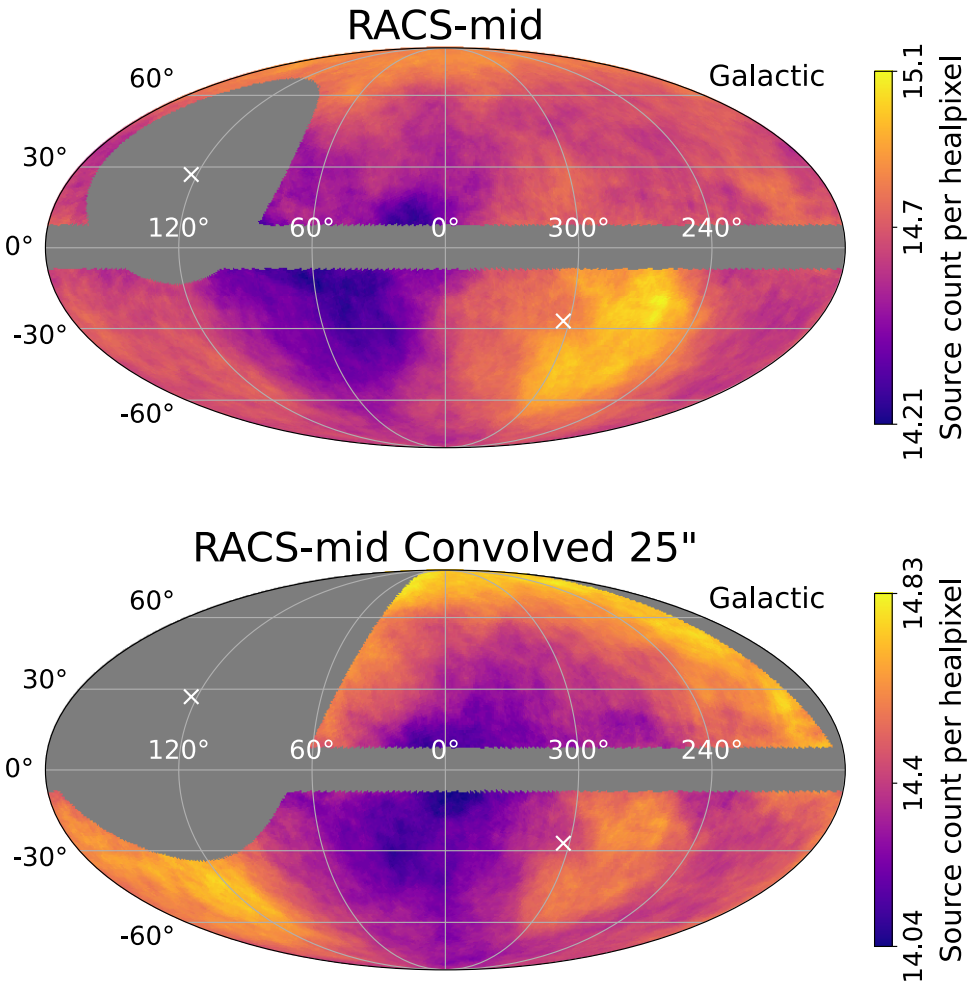


Confirms cosmic dipole tension.

Where To Next?

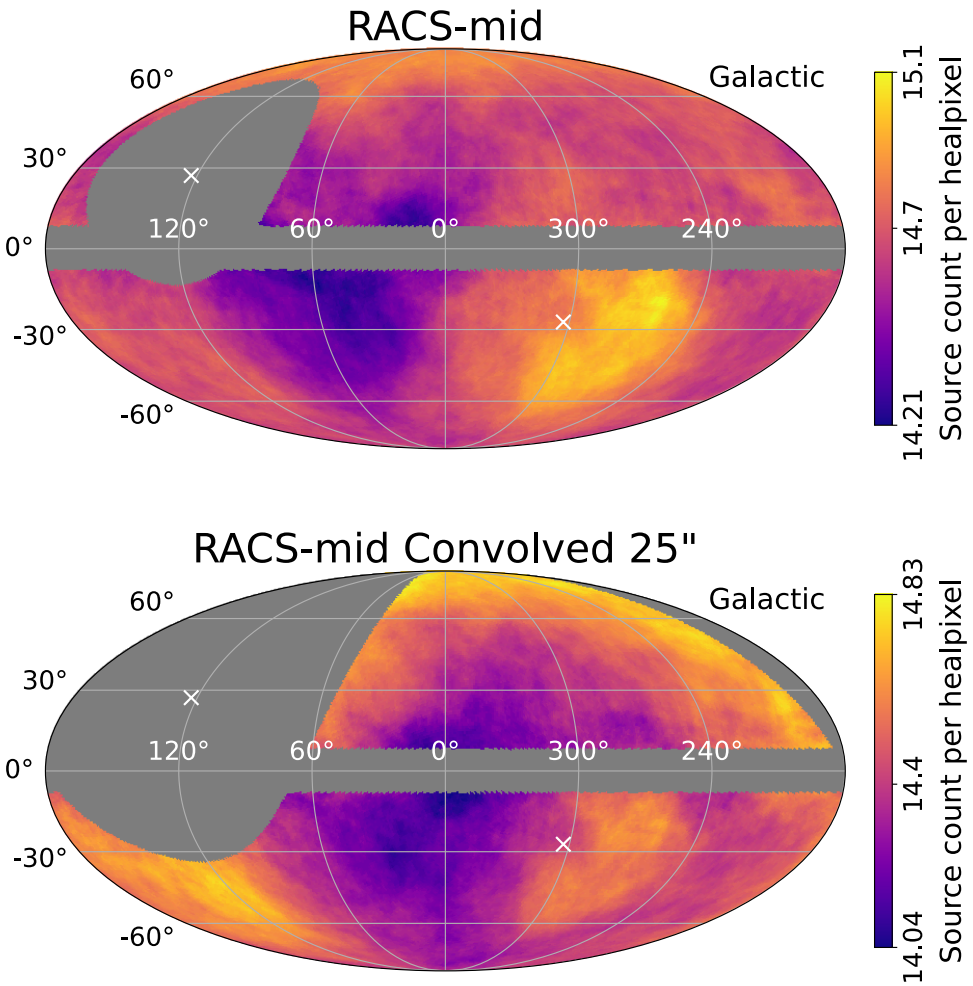


Where To Next?



- Can we extend to other surveys?

Where To Next?



- Can we extend to other surveys?
- Let's forward model! Account for resolution, flux calibration, etc.

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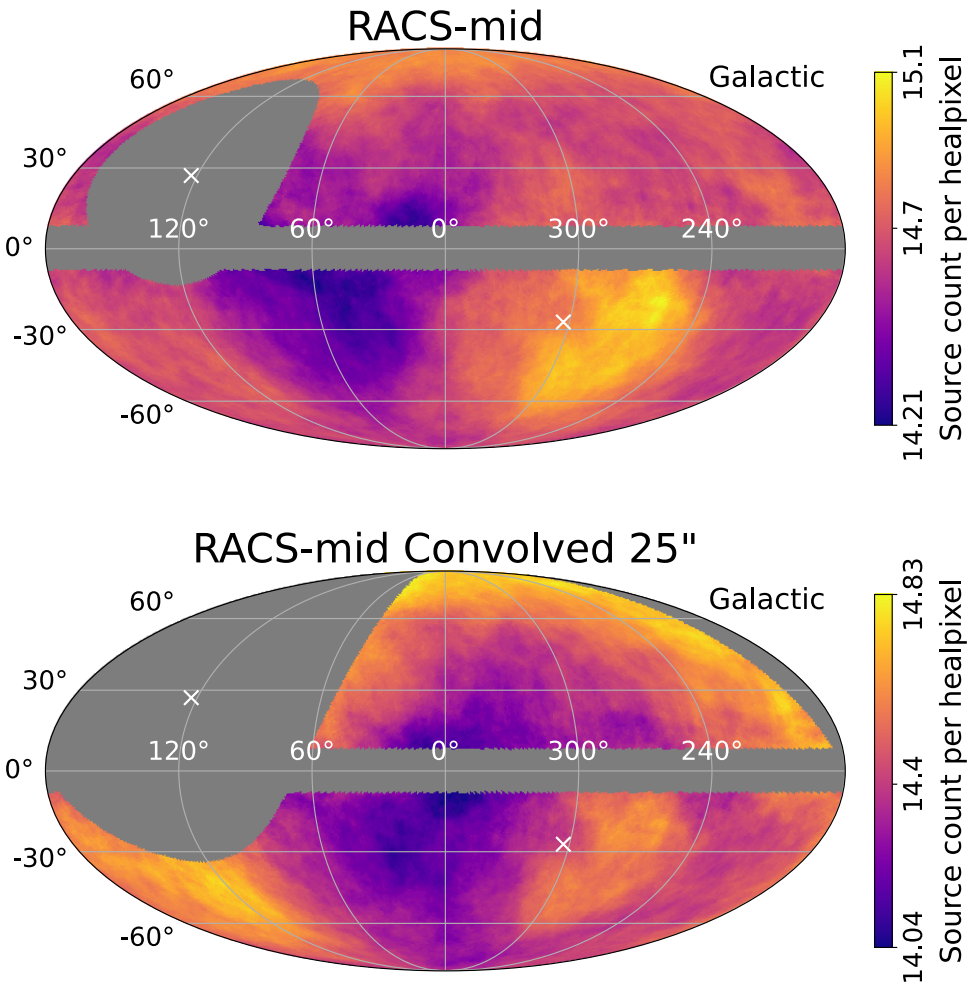

- Can we extend to other surveys?
- Let's forward model! Account for resolution, flux calibration, etc.
- Infer cosmology and systematics together.

- Describe and account for ecliptic bias ✓

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- Measure cosmic dipole ✓

- Describe and account for ecliptic bias ✓
- Measure cosmic dipole ✓
- Leverage power of simulations and SBI ✓