

Wising up to CatWISE

Using simulation-based inference to measure the cosmic dipole

Oliver Oayda

oliver.oayda@sydney.edu.au

PhD Candidate

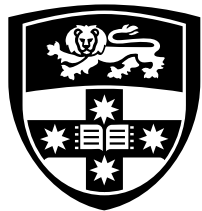
Sydney Institute for Astronomy

The University of Sydney

Supervised by

Geraint Lewis

Tara Murphy



THE UNIVERSITY OF
SYDNEY

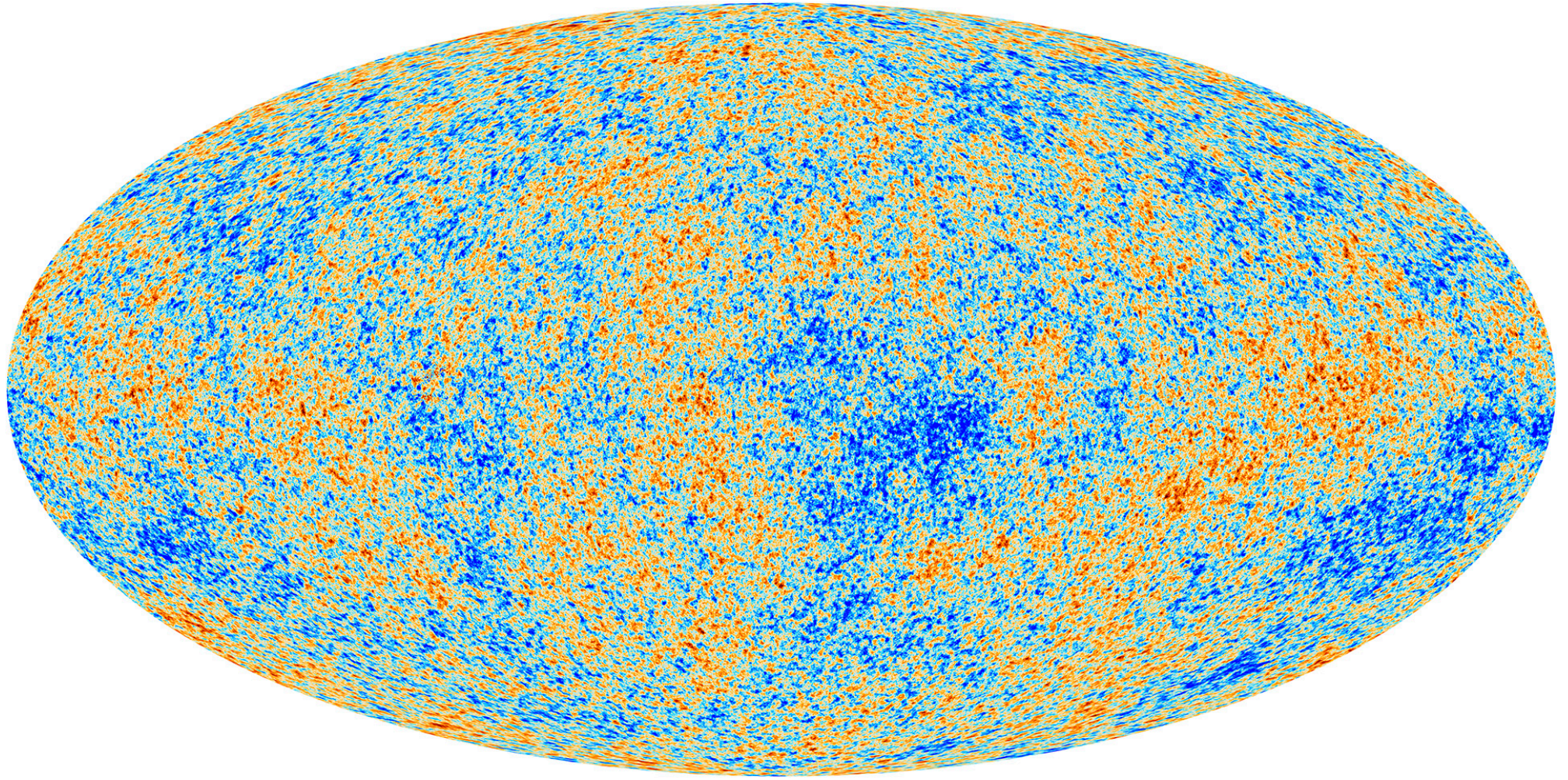
ML4ASTRO3

September 3, 2026



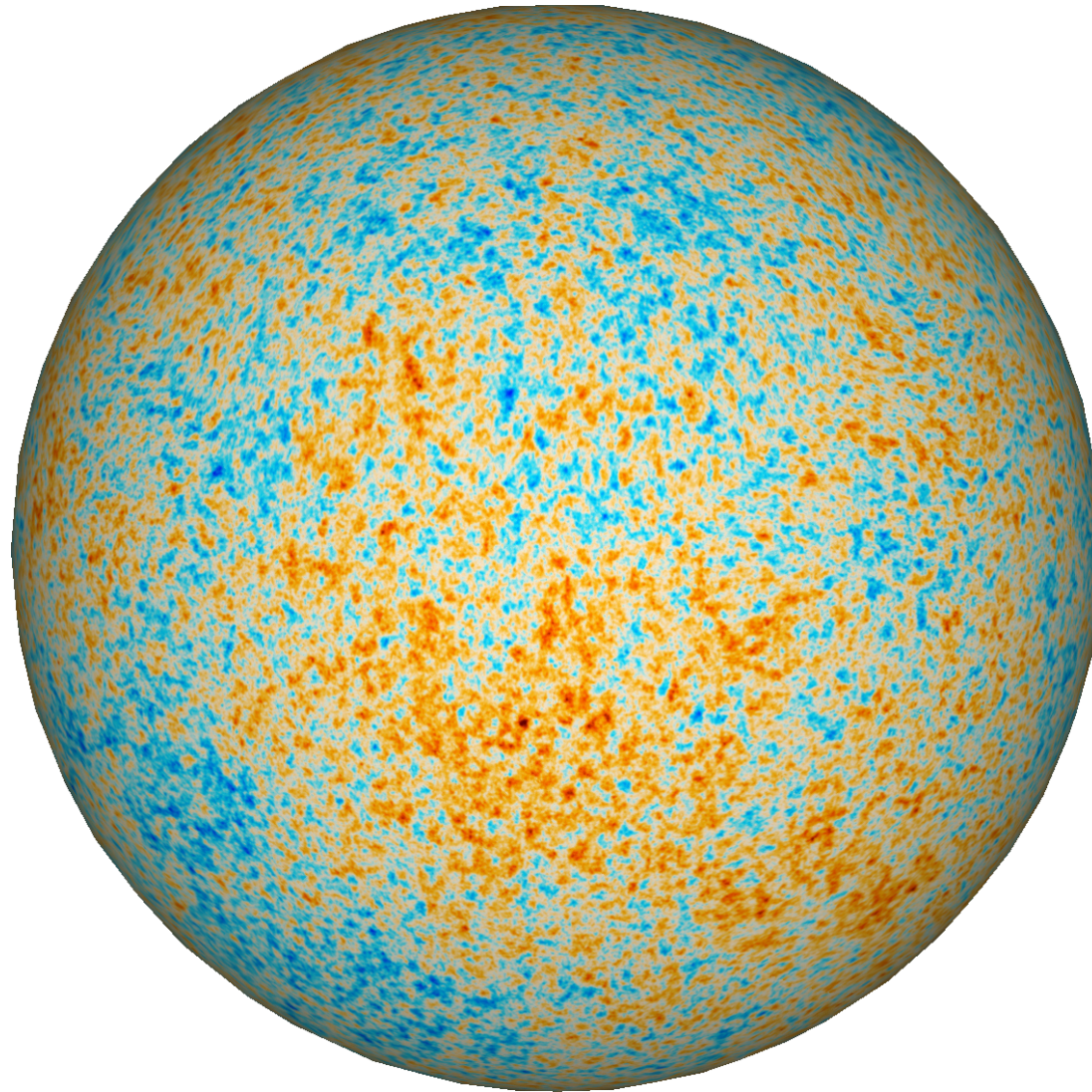
Simulation-based inference resolves
systematics.

The Kinematic Dipole



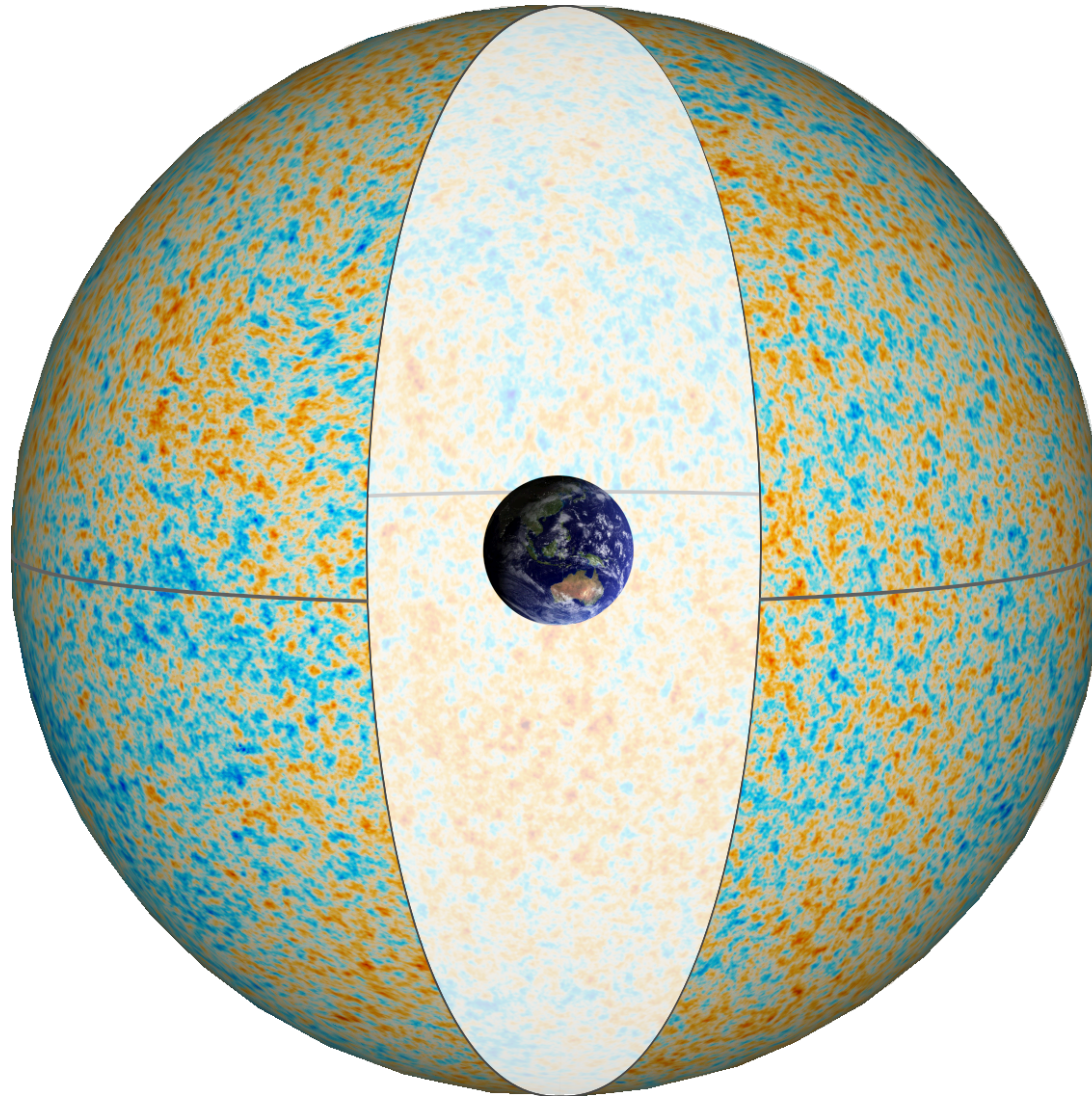
CMB temperature map (Planck satellite)

The Kinematic Dipole



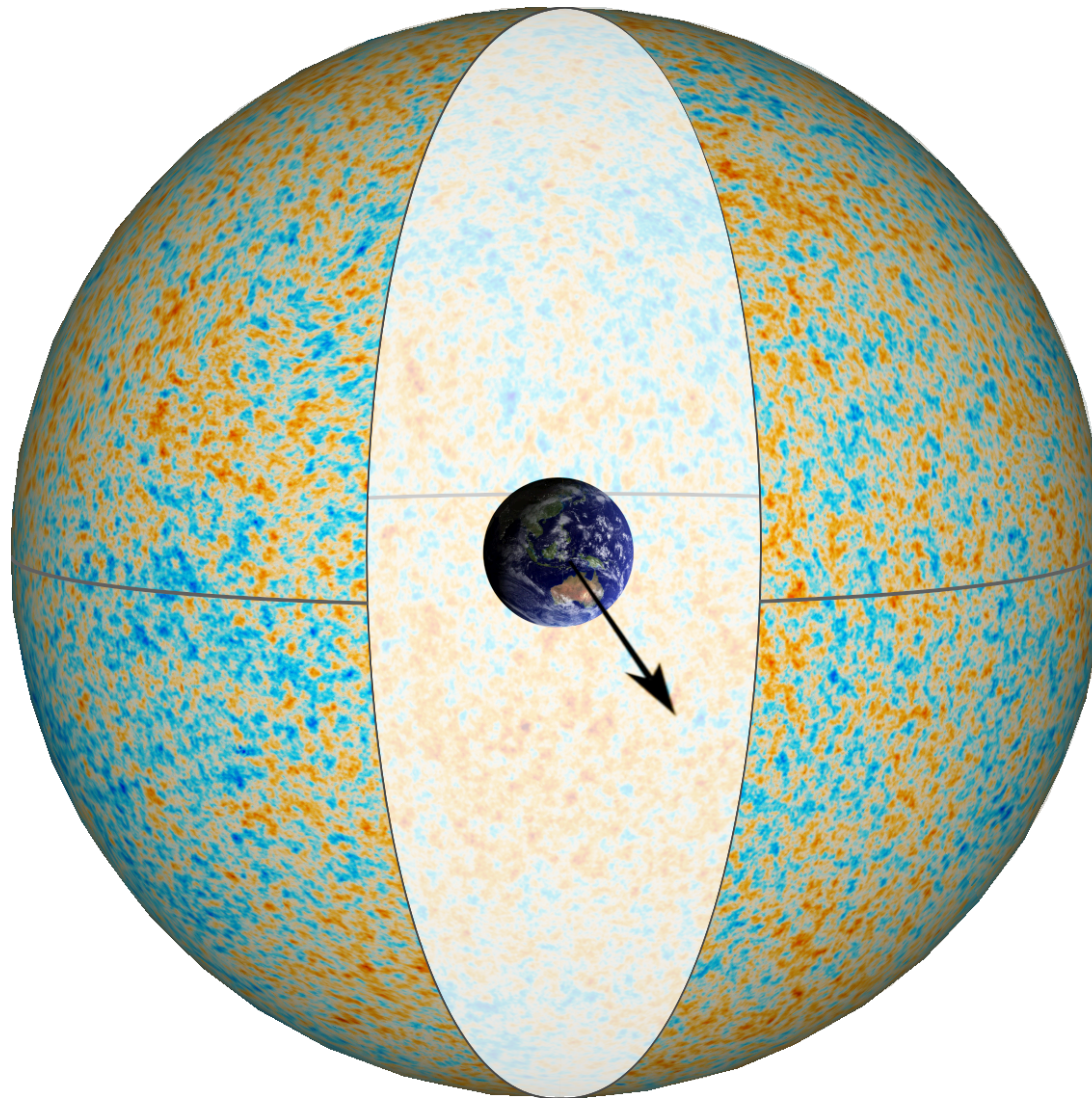
CMB as a sphere

The Kinematic Dipole



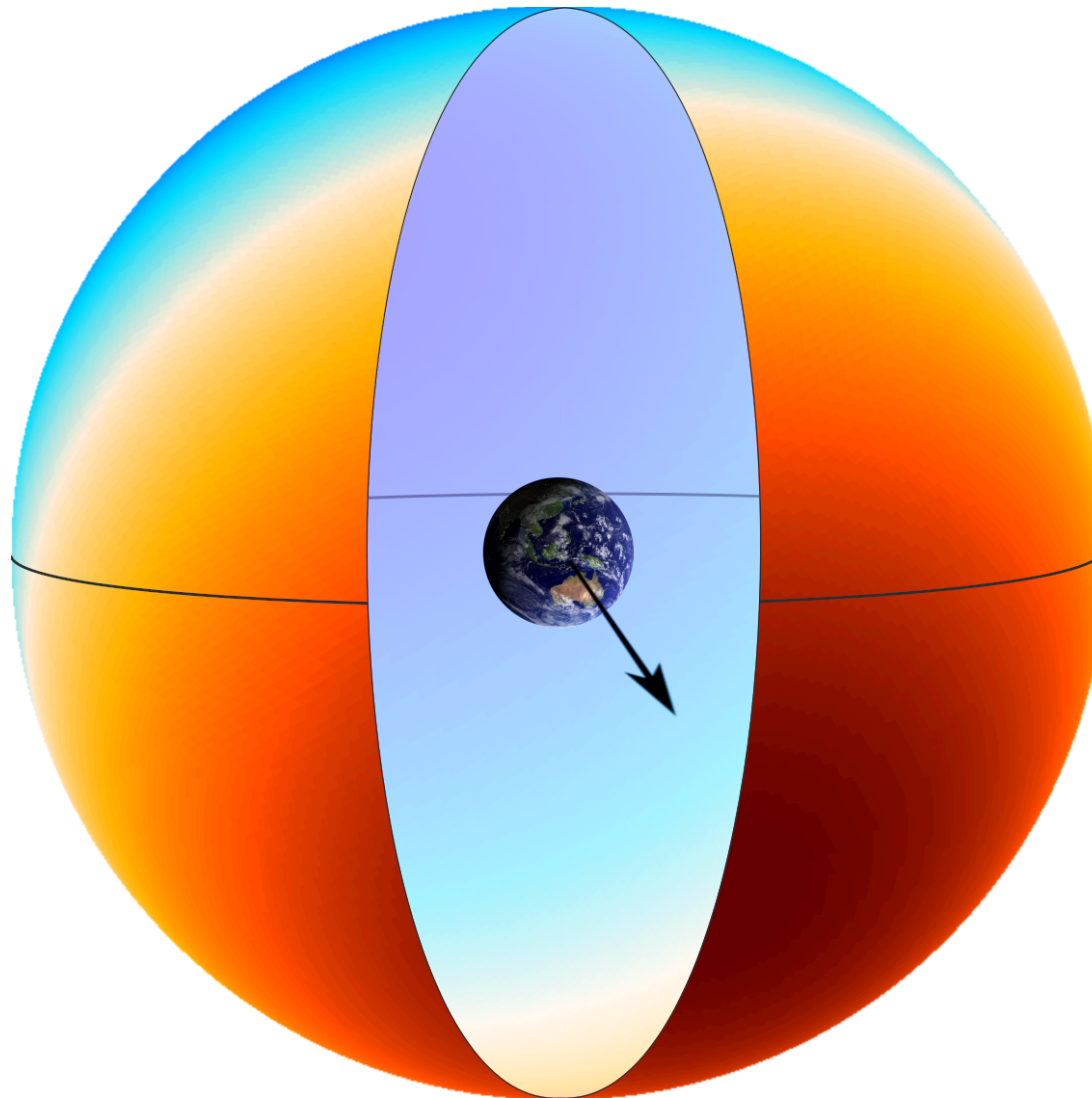
CMB as a sphere (Earth inside)

The Kinematic Dipole



We're moving through the Universe!

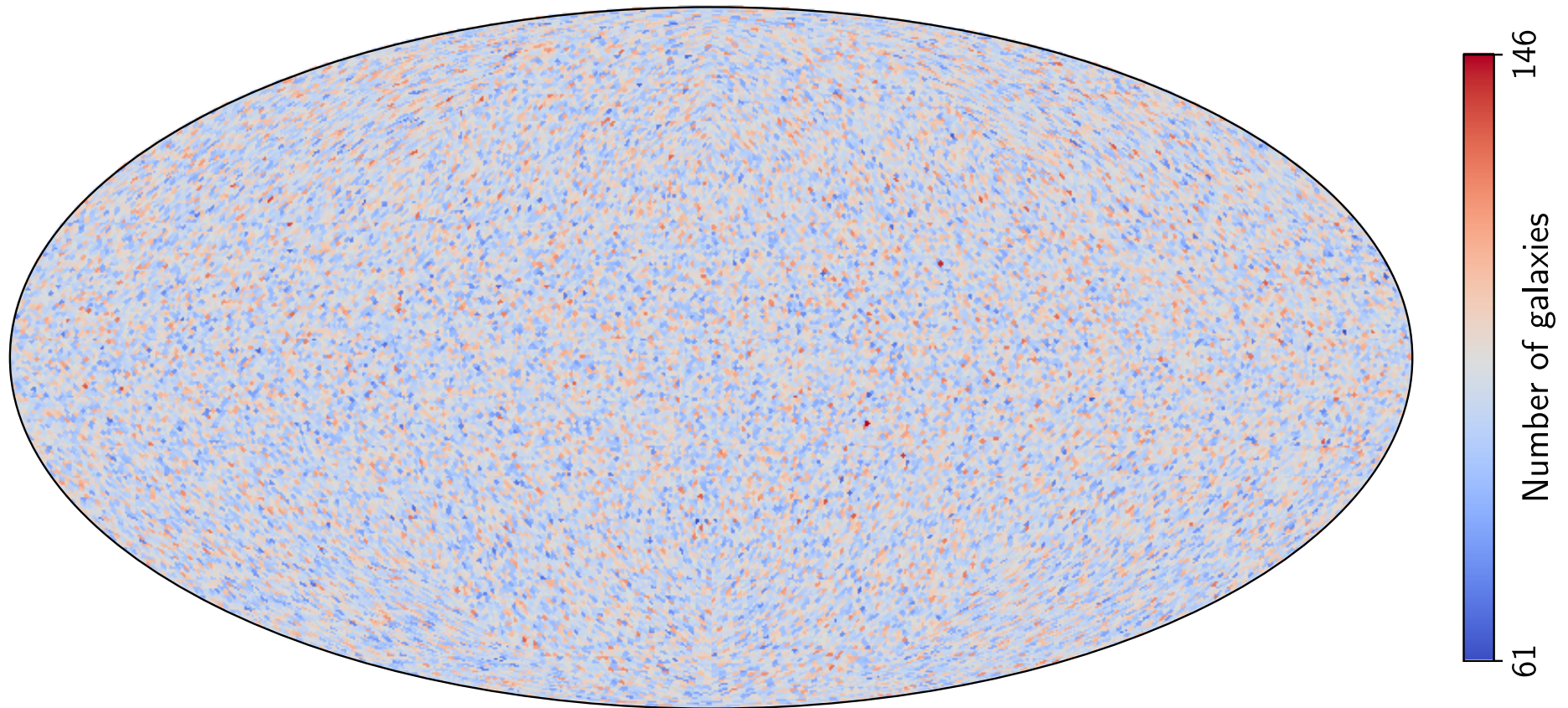
The Kinematic Dipole



Kinematic dipole as a sphere (Earth inside)

Counting Galaxies

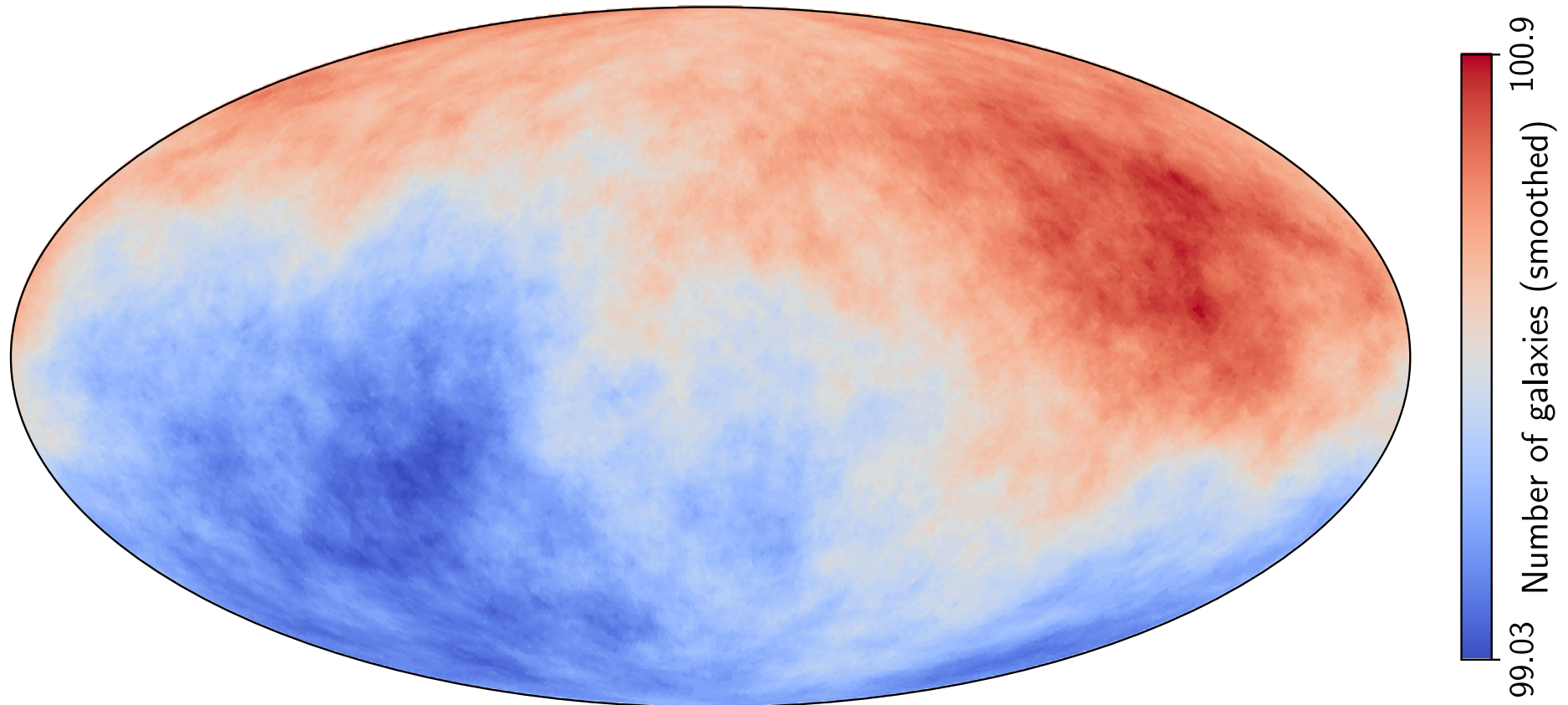
$$N_i = \overline{N} (1 + \mathcal{D} \cos \theta_i)$$



Simulated isotropic galaxy map (+ dipole)

Counting Galaxies

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



Simulated isotropic galaxy map (+ dipole)

Special Relativity

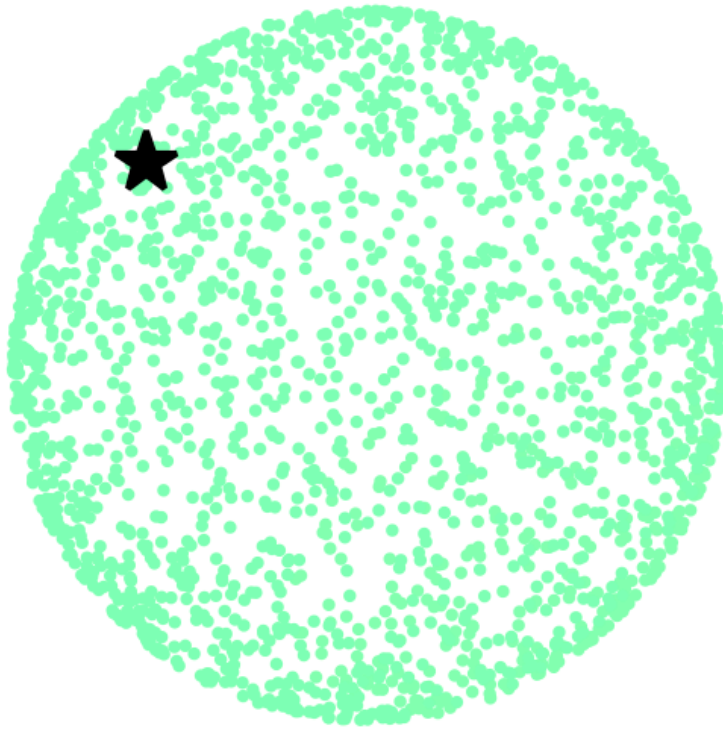
Aberration

Doppler boosting

Special Relativity

Aberration

Doppler boosting

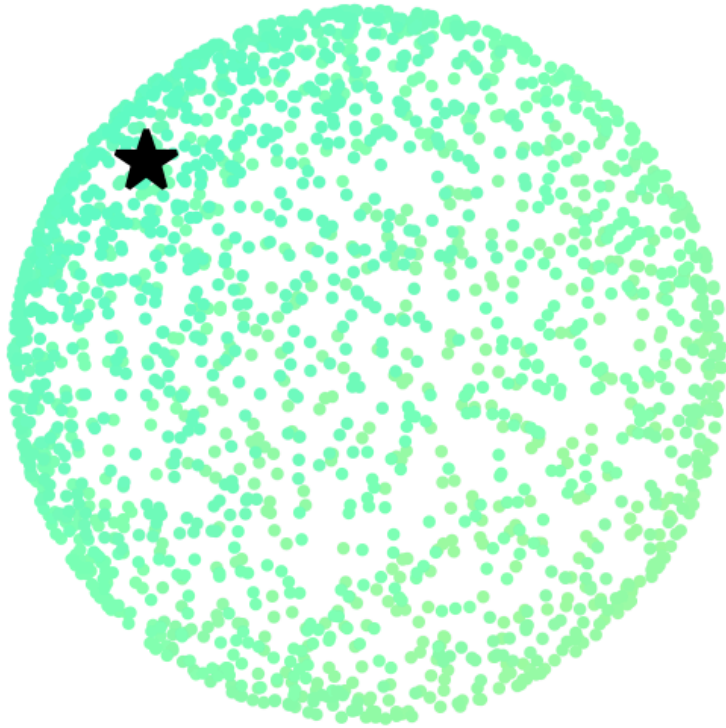


Speed (c) 0.025

Special Relativity

Aberration

Doppler boosting

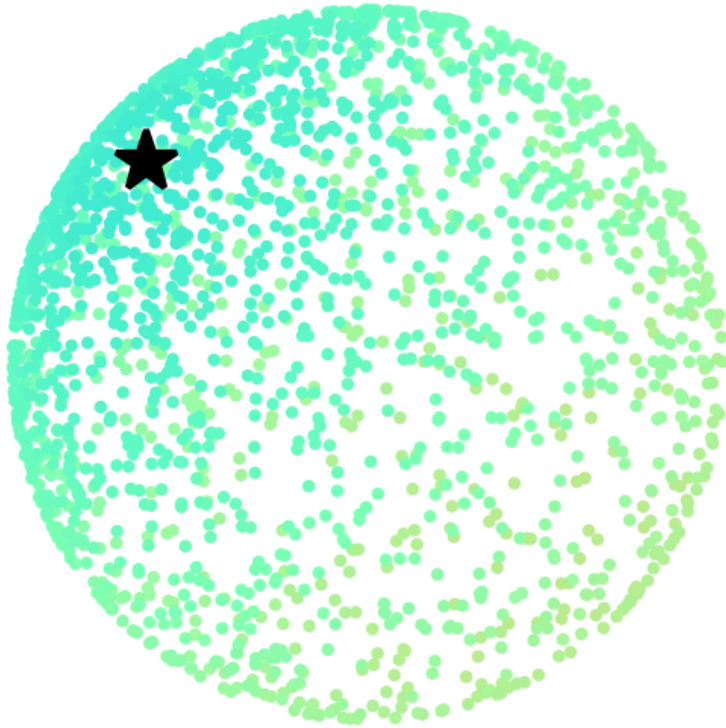


Speed (c)  0.244

Special Relativity

Aberration

Doppler boosting

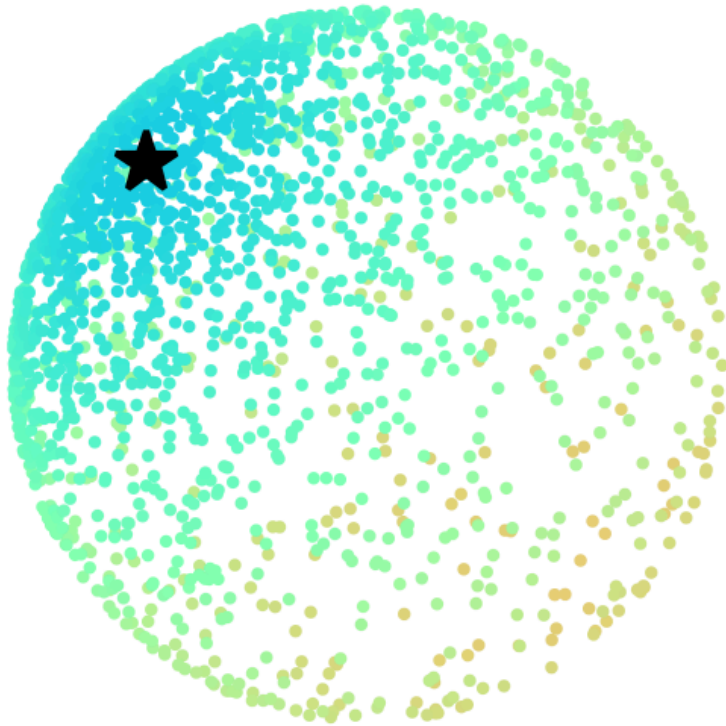


Speed (c)  0.462

Special Relativity

Aberration

Doppler boosting

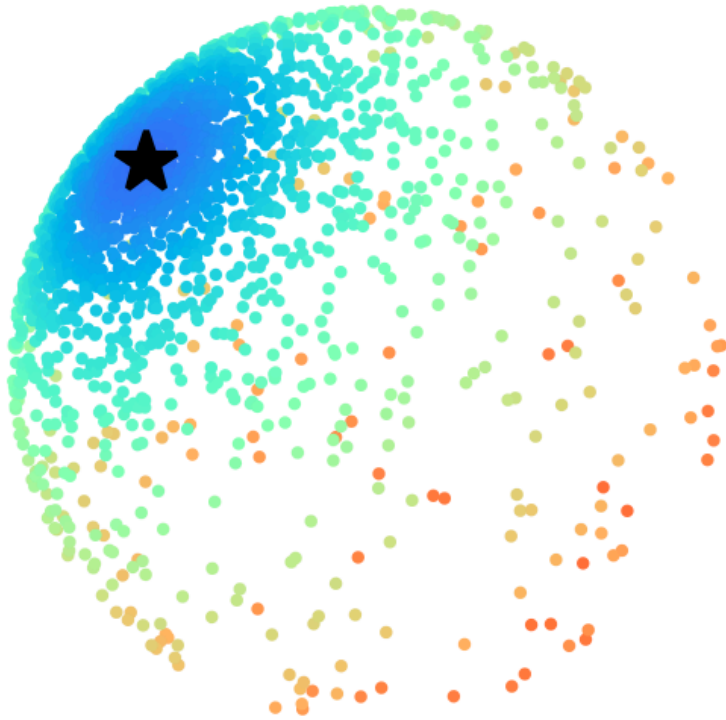


Speed (c)  0.681

Special Relativity

Aberration

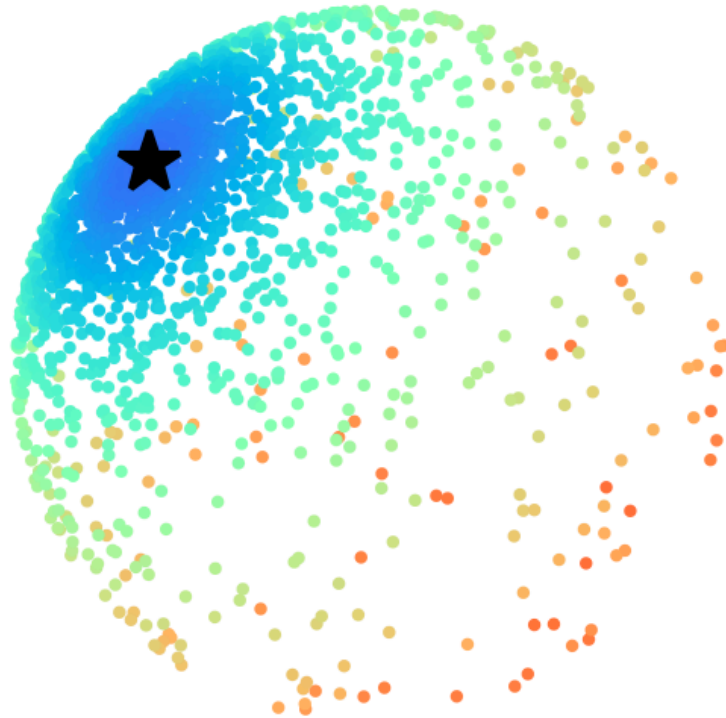
Doppler boosting



Speed (c) 0.9

Special Relativity

Aberration

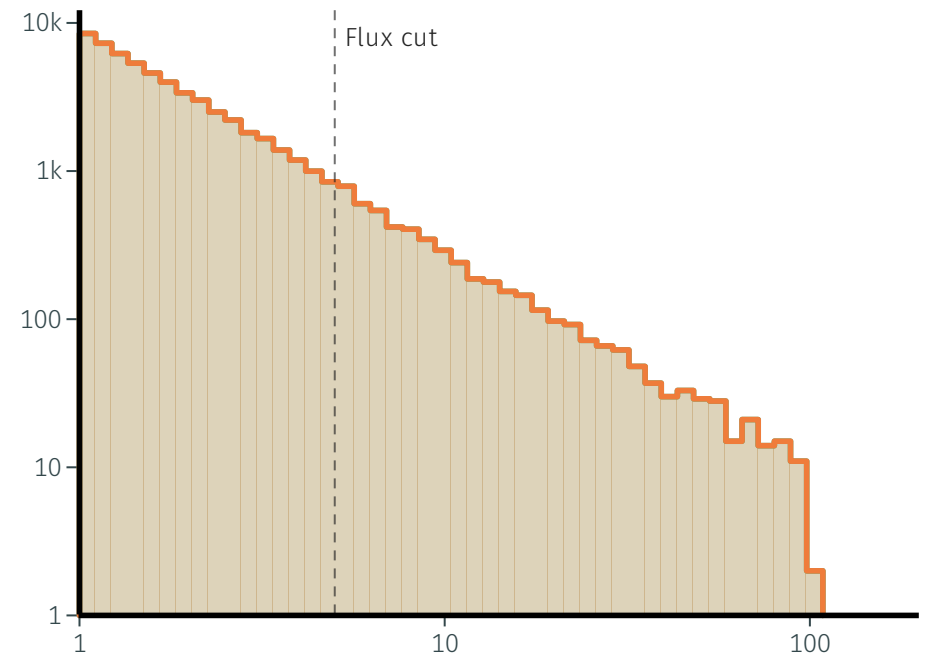


Speed (c) 0.9

Doppler boosting

Rest frame Observer frame

↑ Count in each flux bin

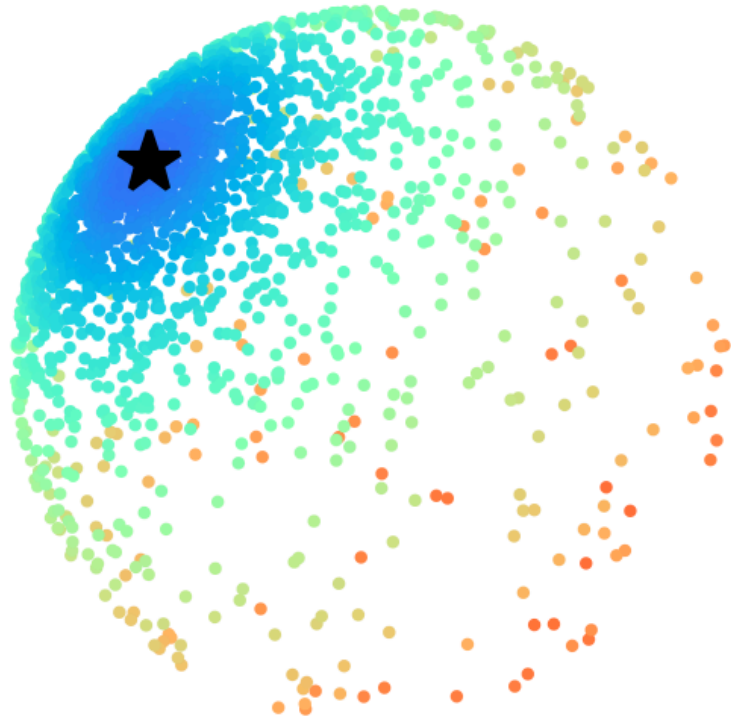


Speed (c) 0.000

Flux density →

Special Relativity

Aberration

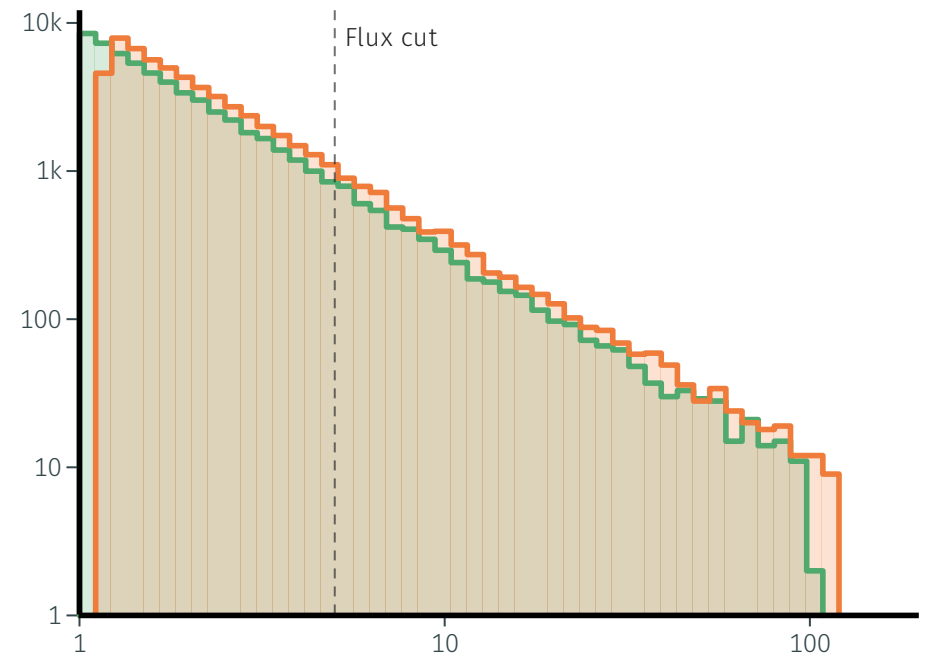


Speed (c) 0.9

Doppler boosting

Rest frame Observer frame

↑ Count in each flux bin

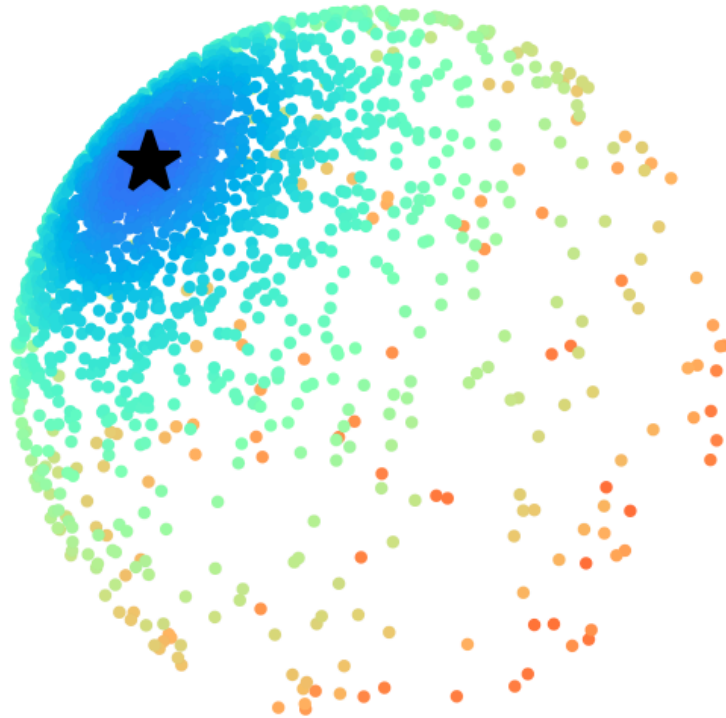


Speed (c) 0.075

Flux density →

Special Relativity

Aberration

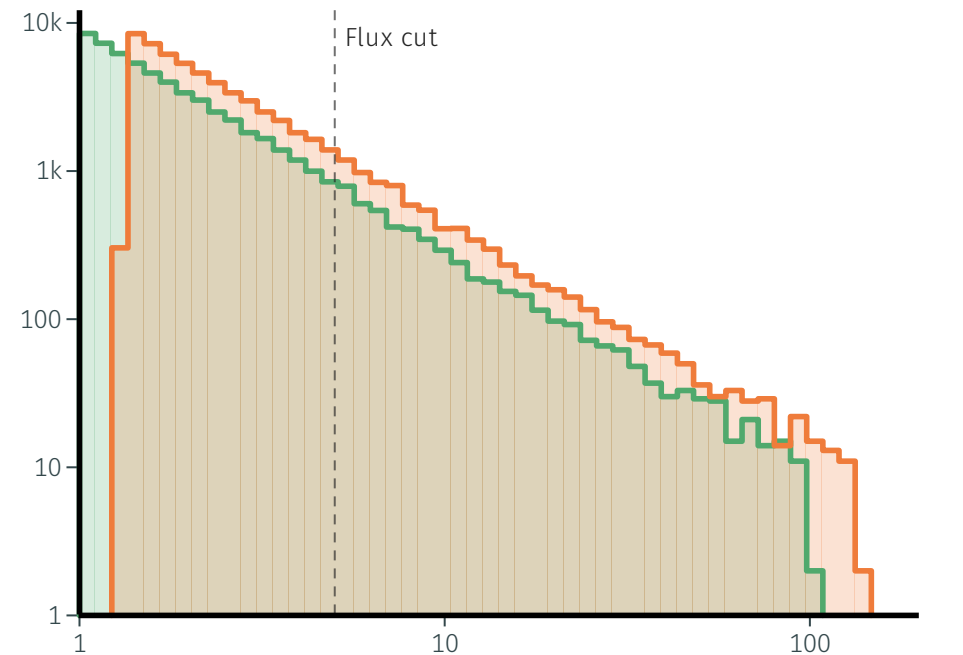


Speed (c) 0.9

Doppler boosting

Rest frame Observer frame

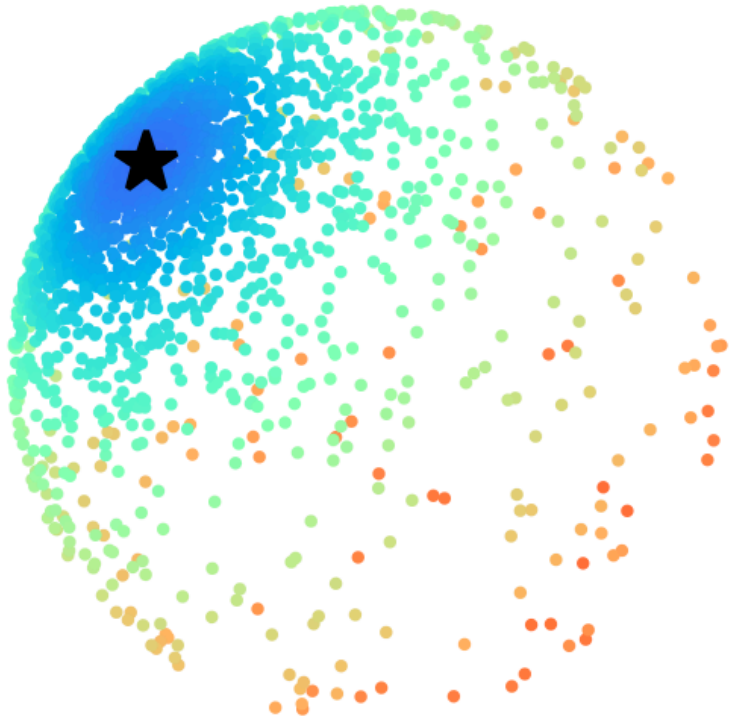
↑ Count in each flux bin



Speed (c) 0.150

Special Relativity

Aberration

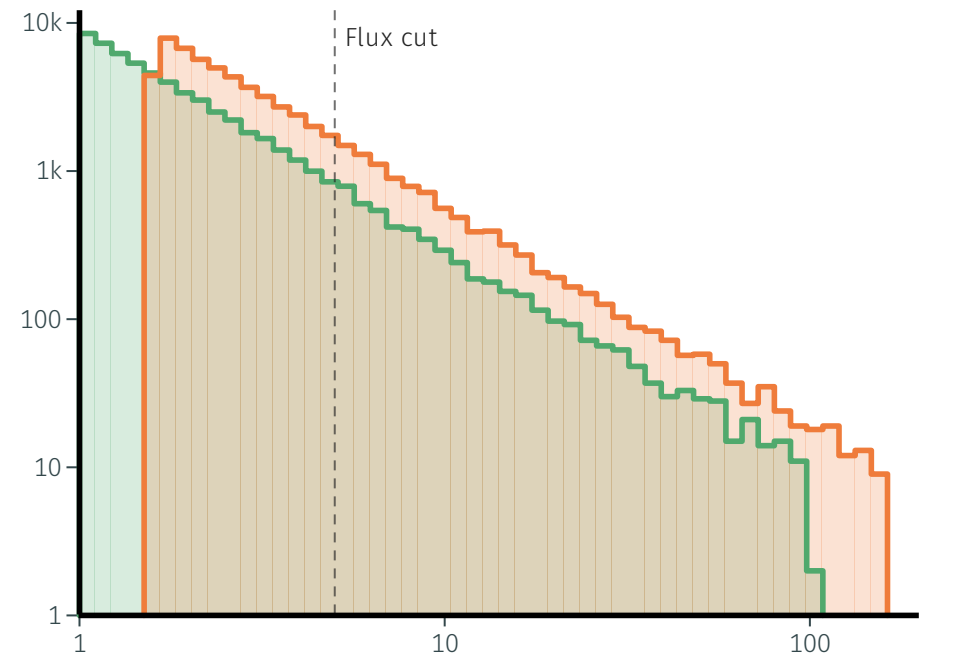


Speed (c) 0.9

Doppler boosting

Rest frame Observer frame

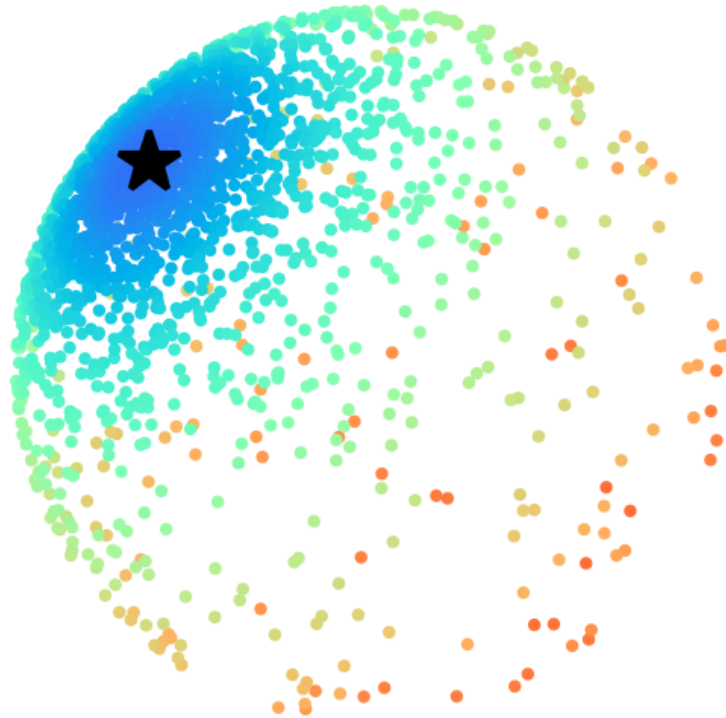
↑ Count in each flux bin



Speed (c) 0.225

Special Relativity

Aberration

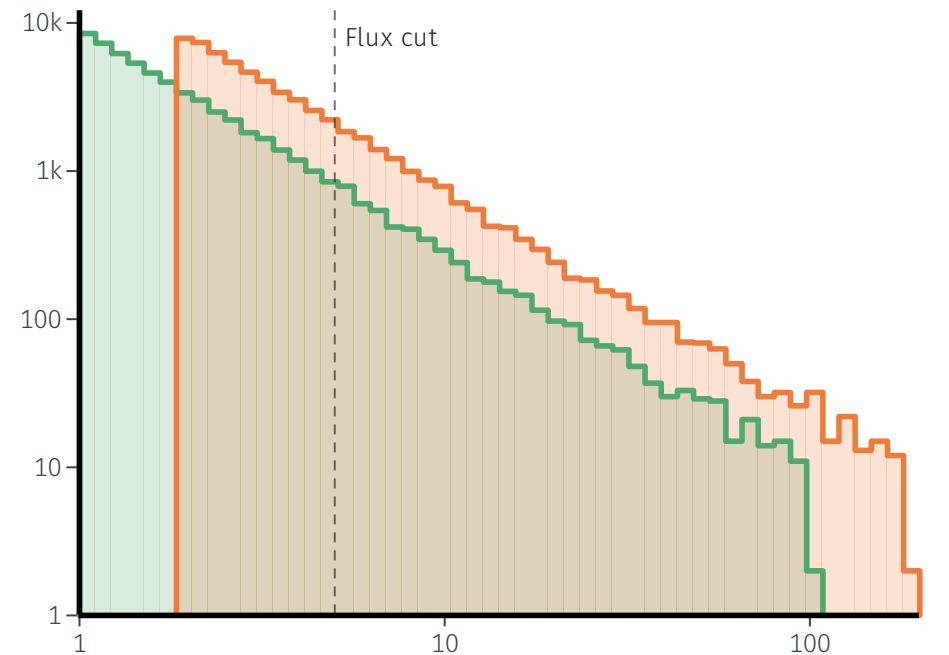


Speed (c) 0.9

Doppler boosting

Rest frame Observer frame

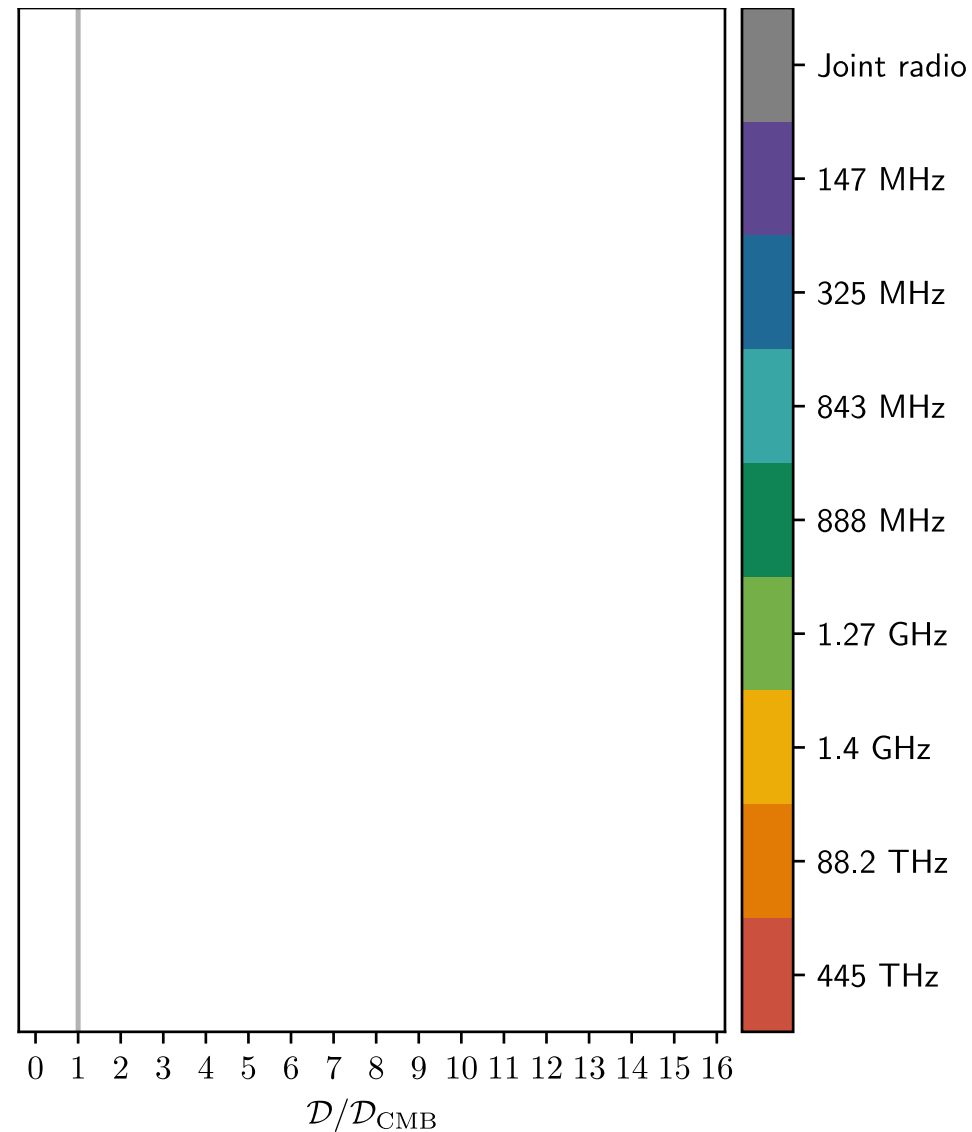
↑ Count in each flux bin



Speed (c) 0.300

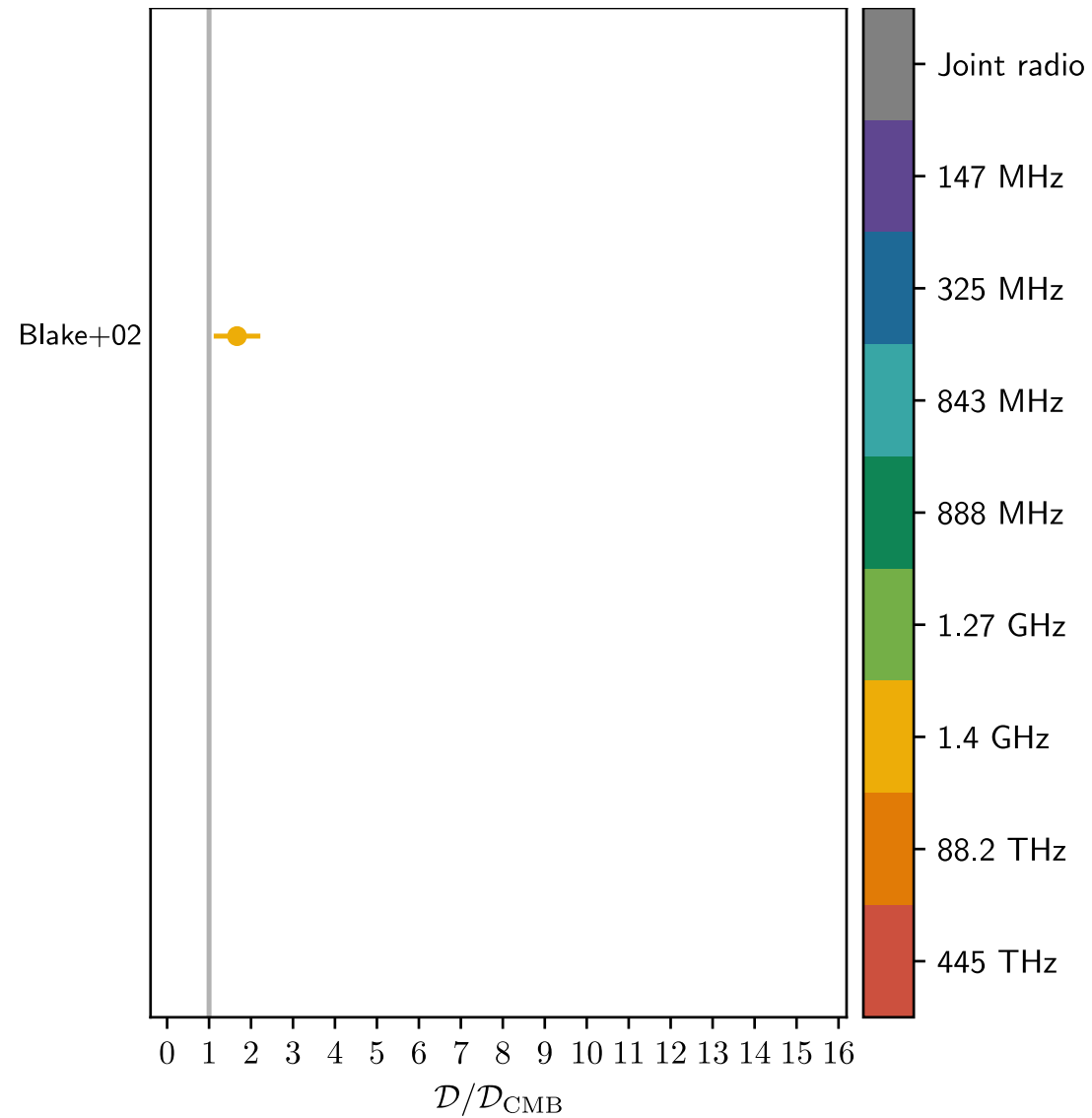
Flux density →

The Amplitude Excess



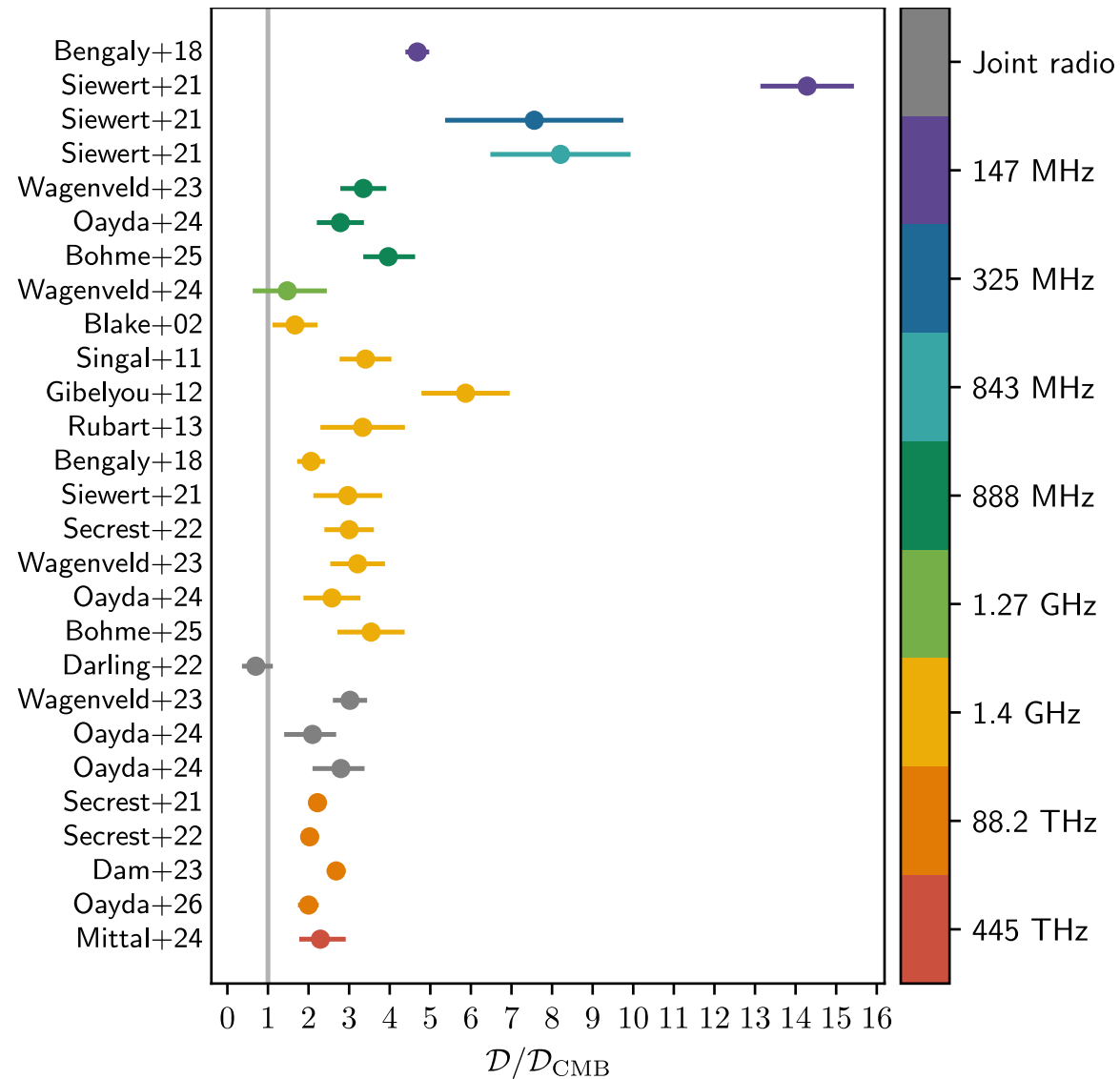
The cosmic dipole should be **consistent** with the CMB dipole.

The Amplitude Excess



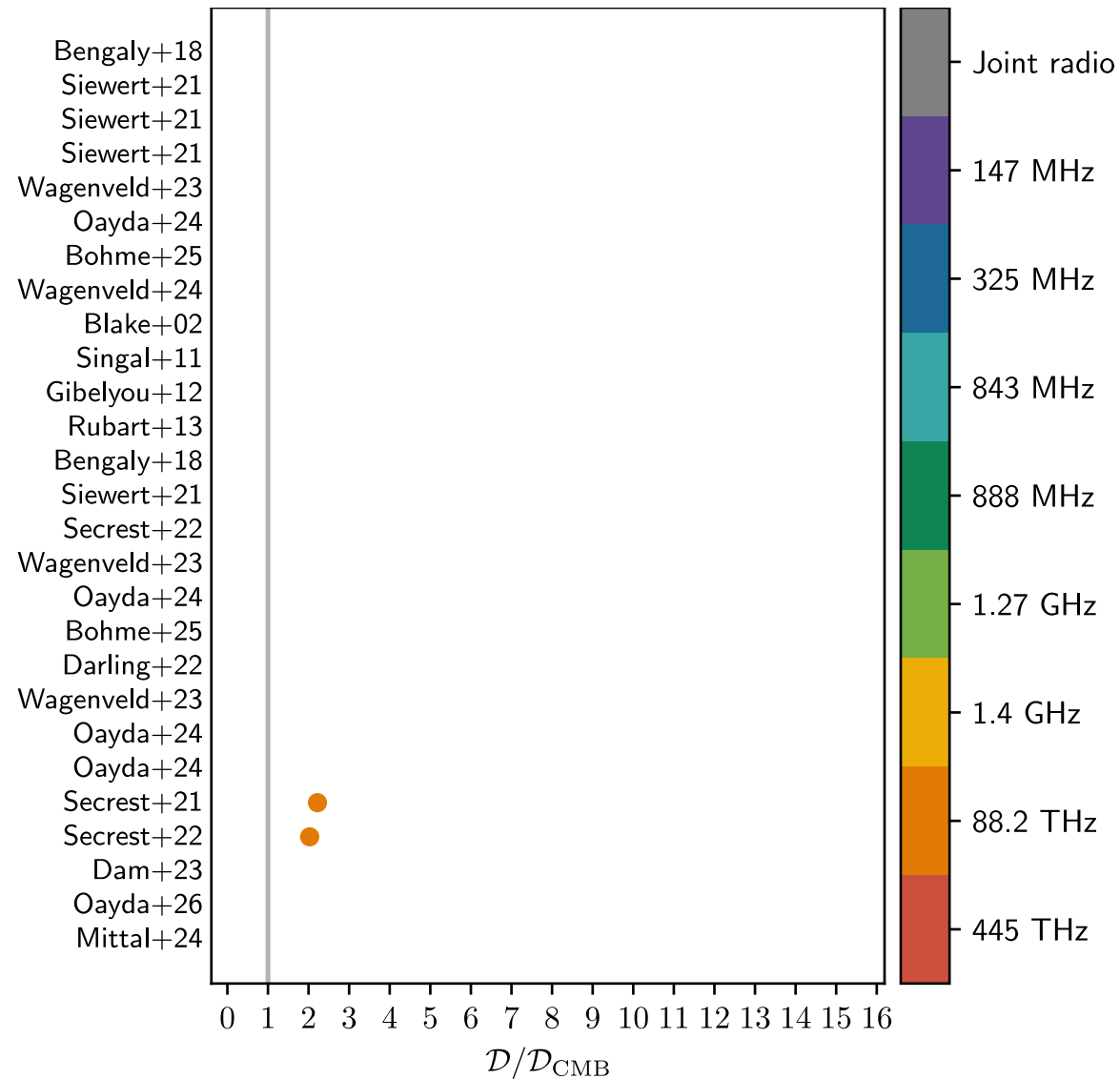
All is well!

The Amplitude Excess

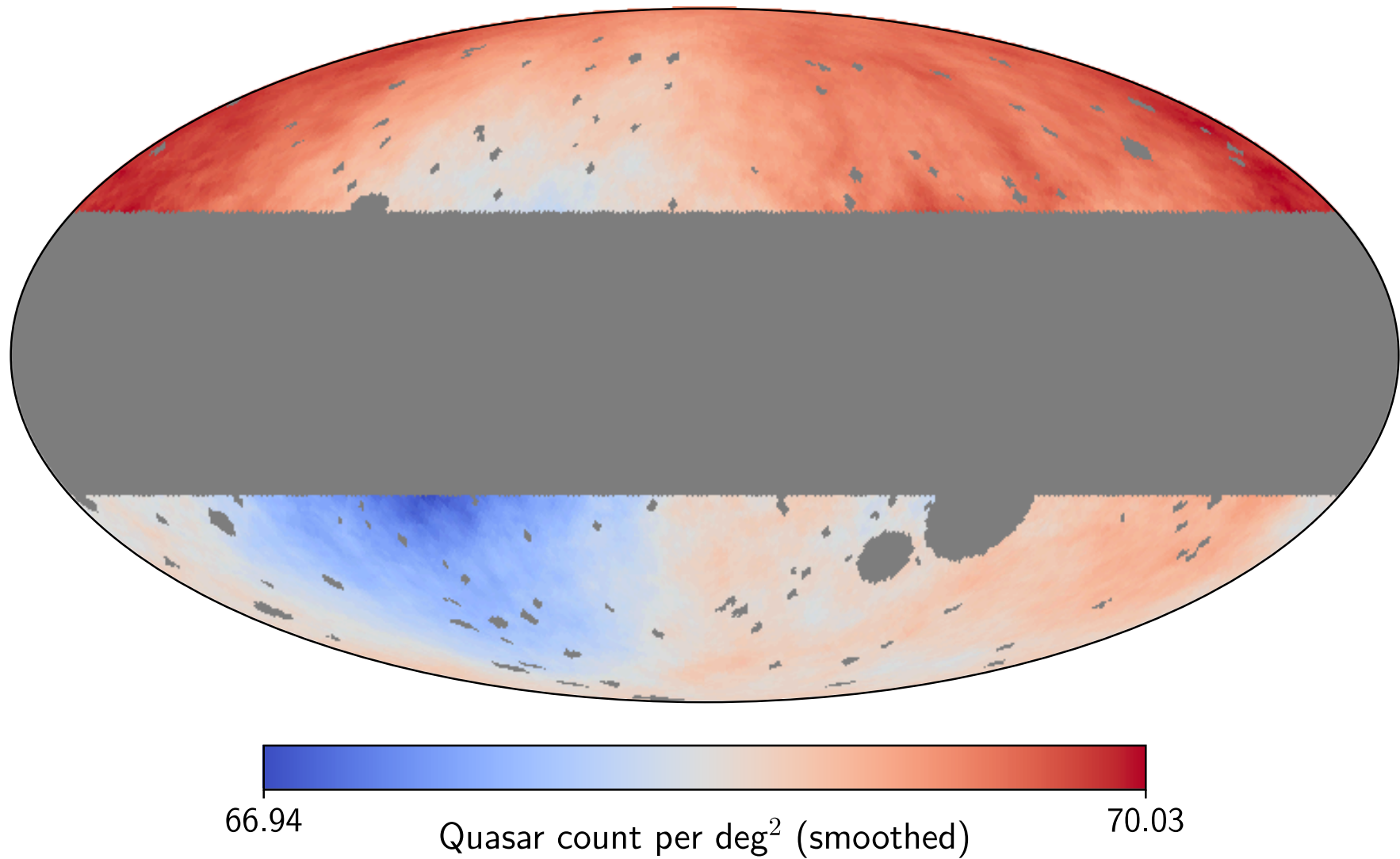


Wait...

The Amplitude Excess

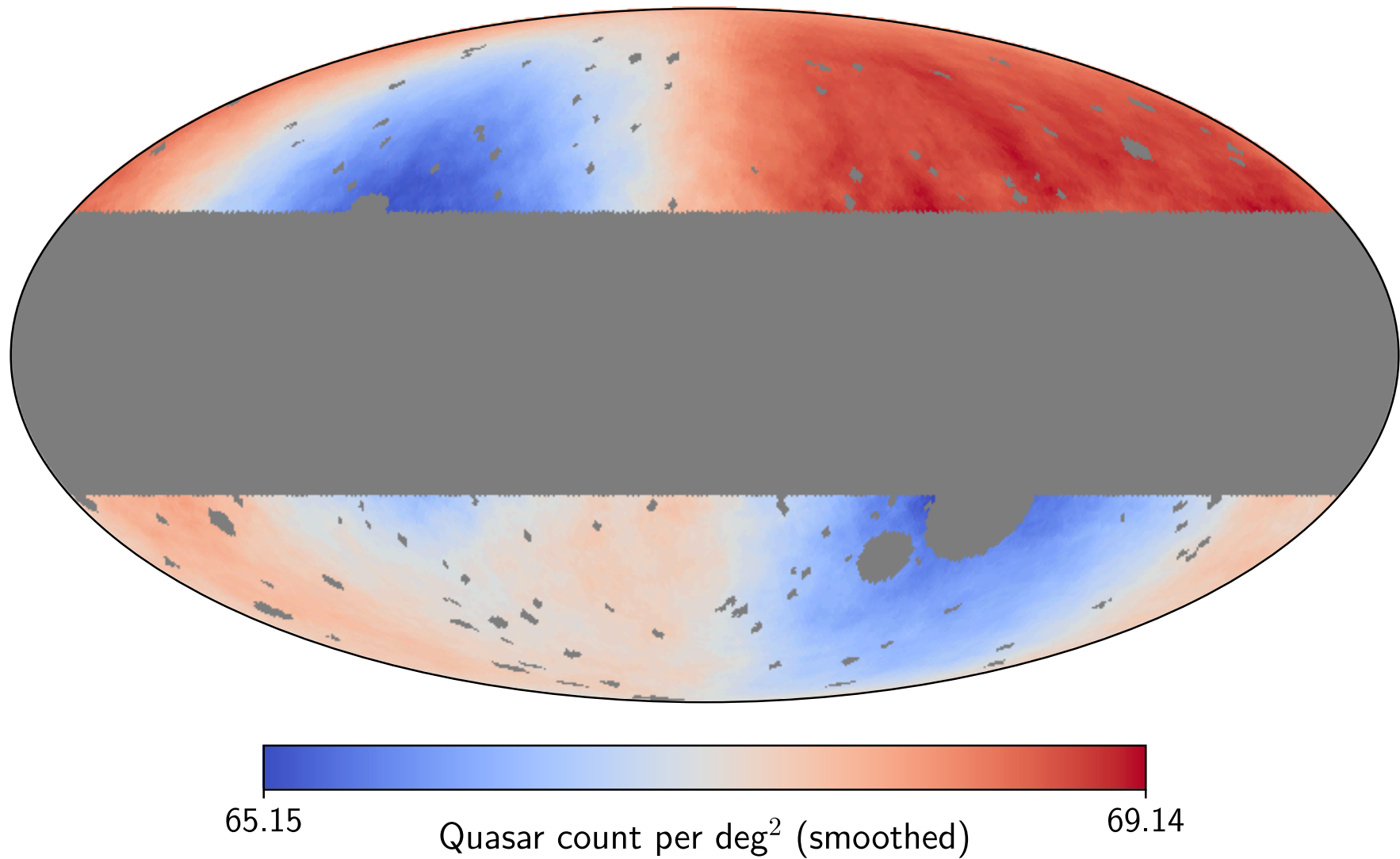


The CatWISE Sample



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

© 2021. The Author(s). Published by the American Astronomical Society.

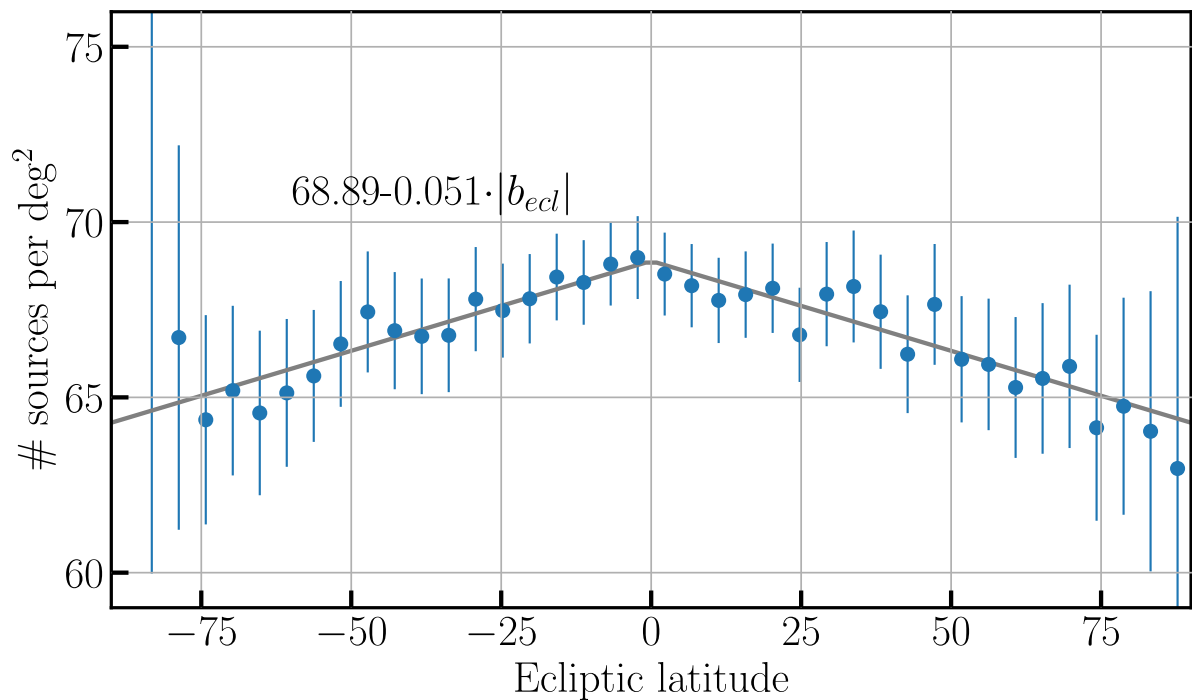
OPEN ACCESS

<https://doi.org/10.3847/2041-8213/abdd40>



A Test of the Cosmological Principle with Quasars

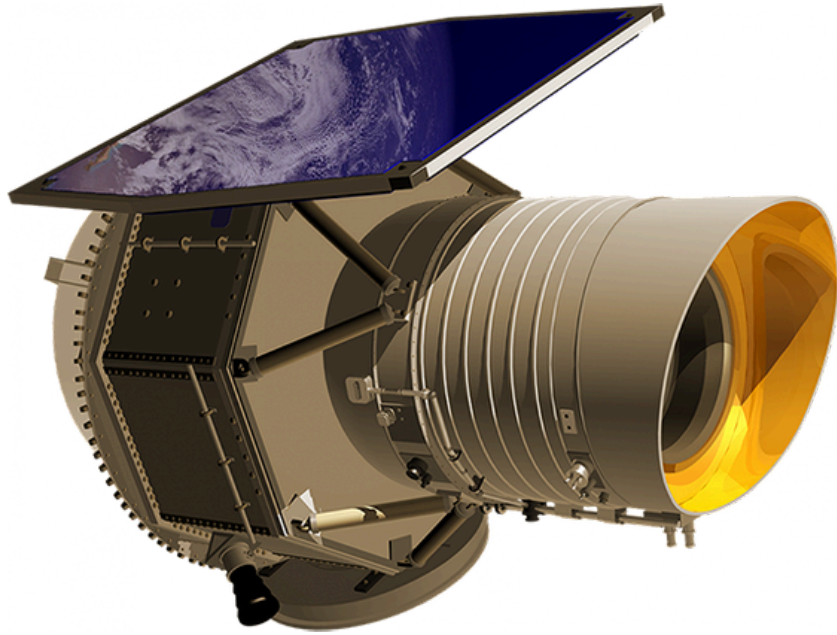
Nathan J. Secrest¹ , Sebastian von Hausegger^{2,3,4} , Mohamed Rameez⁵ , Roya Mohayaee³ , Subir Sarkar⁴ , and Jacques Colin³



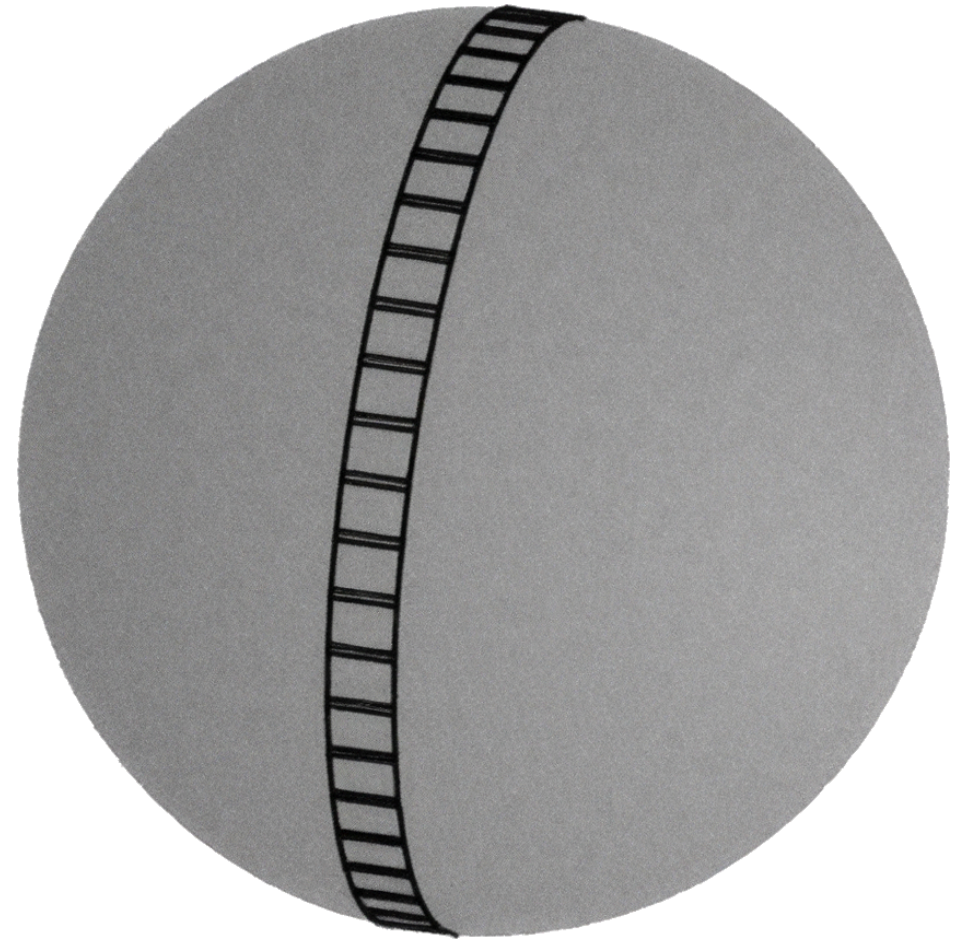
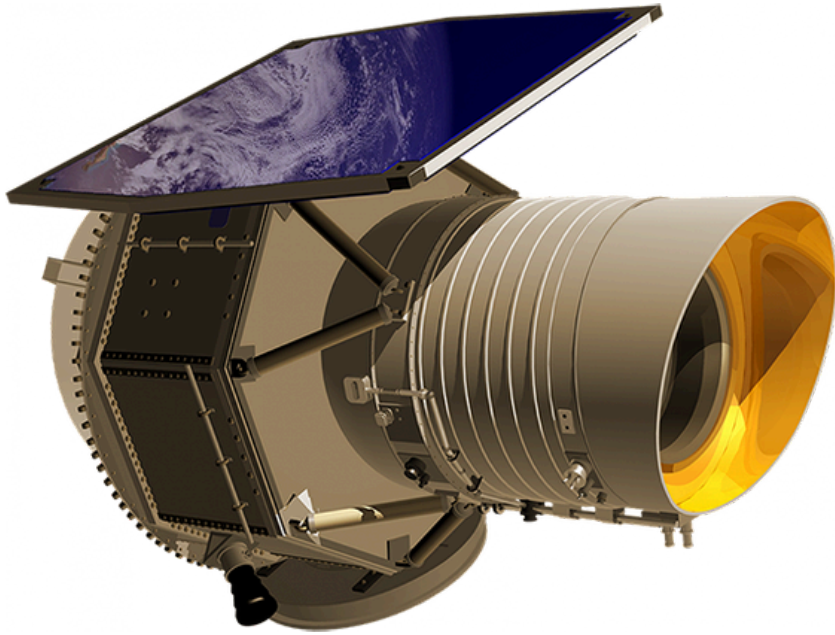
Linear fit to density vs. declination (Secrest+21)

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

WISE's Scanning Law

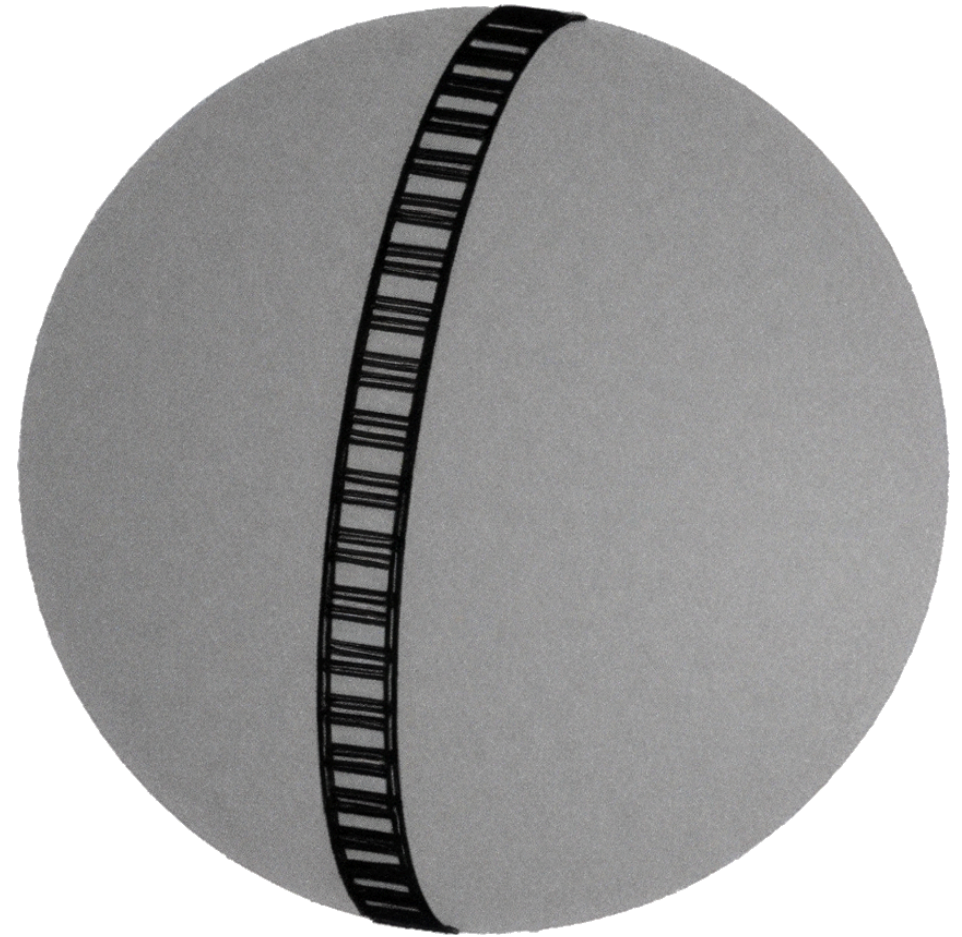
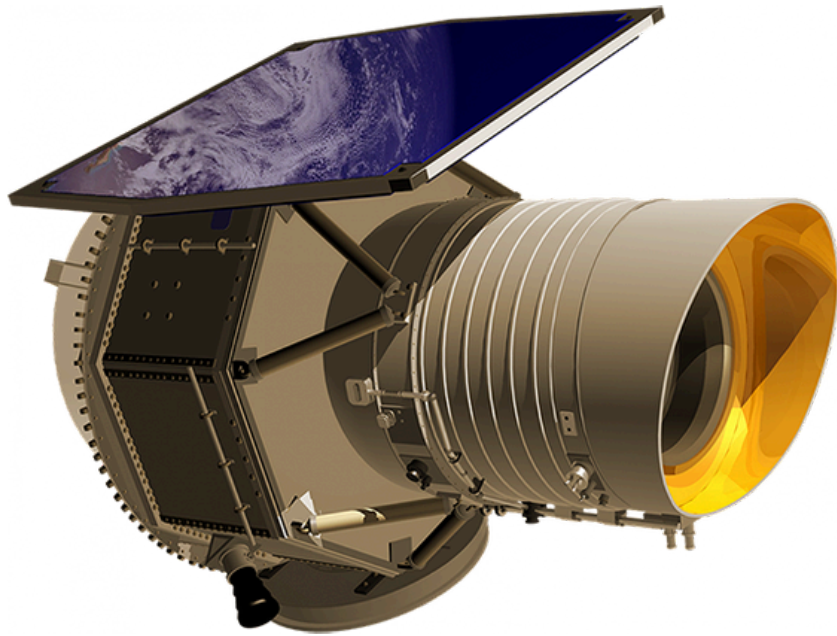


WISE's Scanning Law



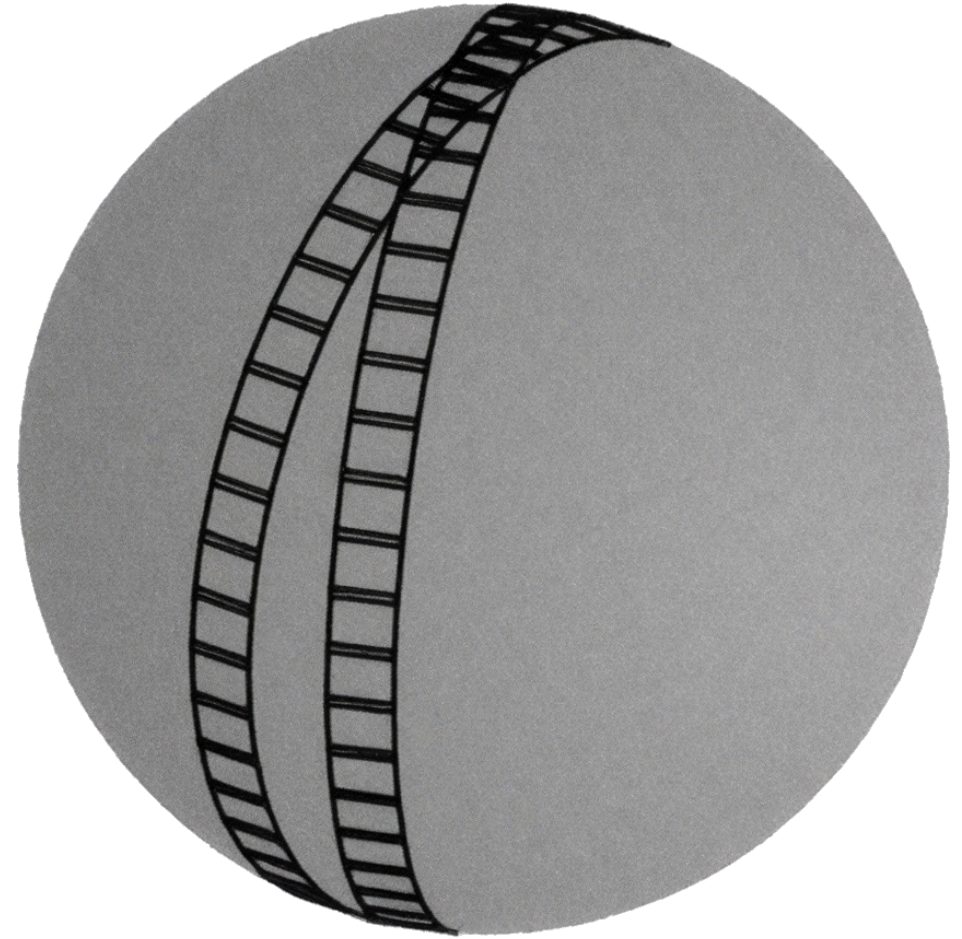
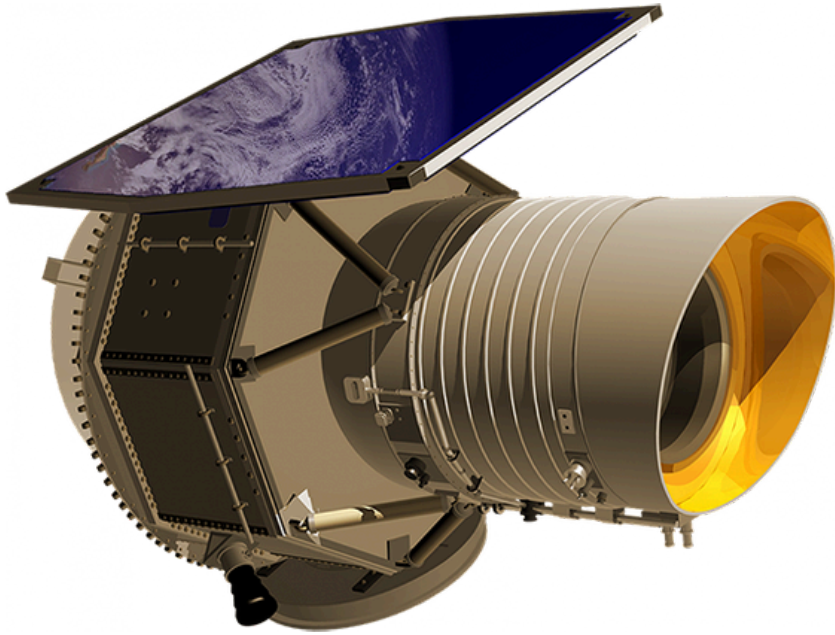
Frames over 1 orbit

WISE's Scanning Law



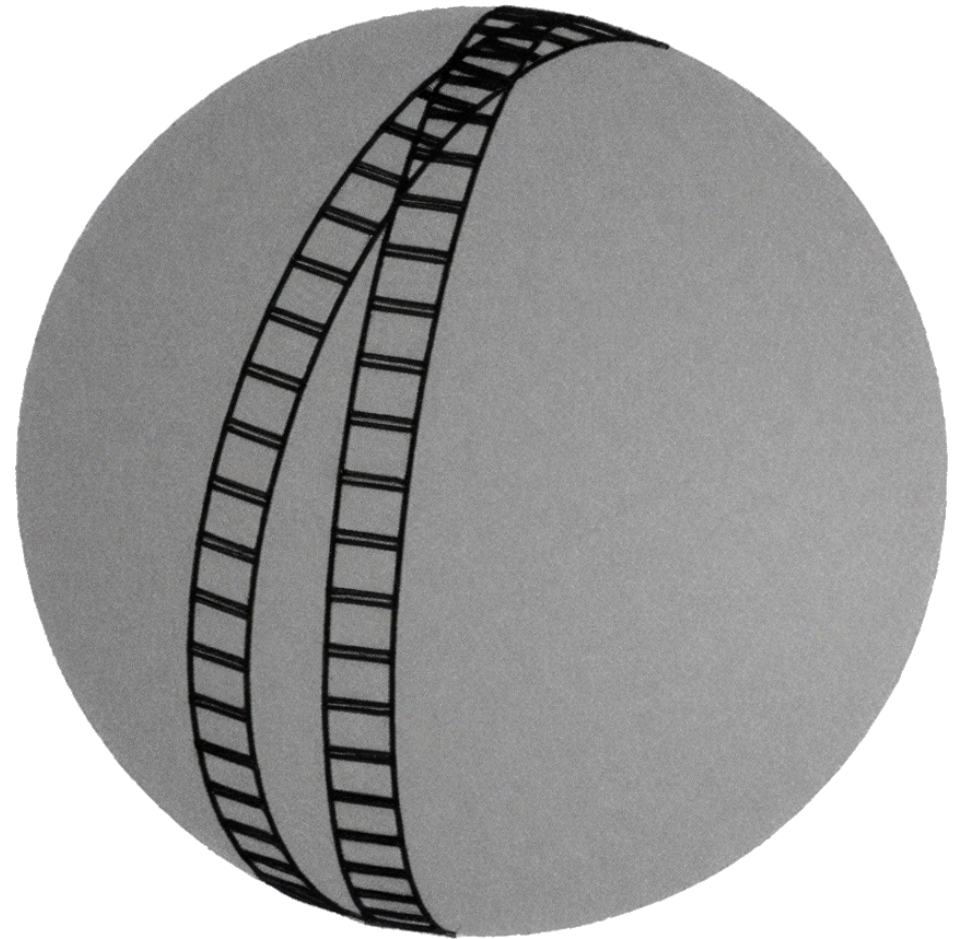
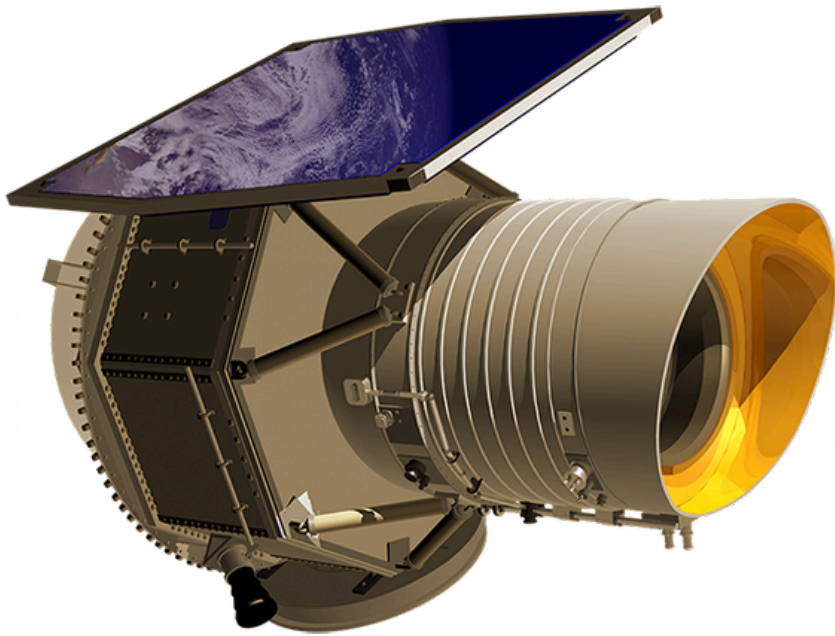
Frames over 2 orbits

WISE's Scanning Law



Frames over 2 orbits 20 days apart

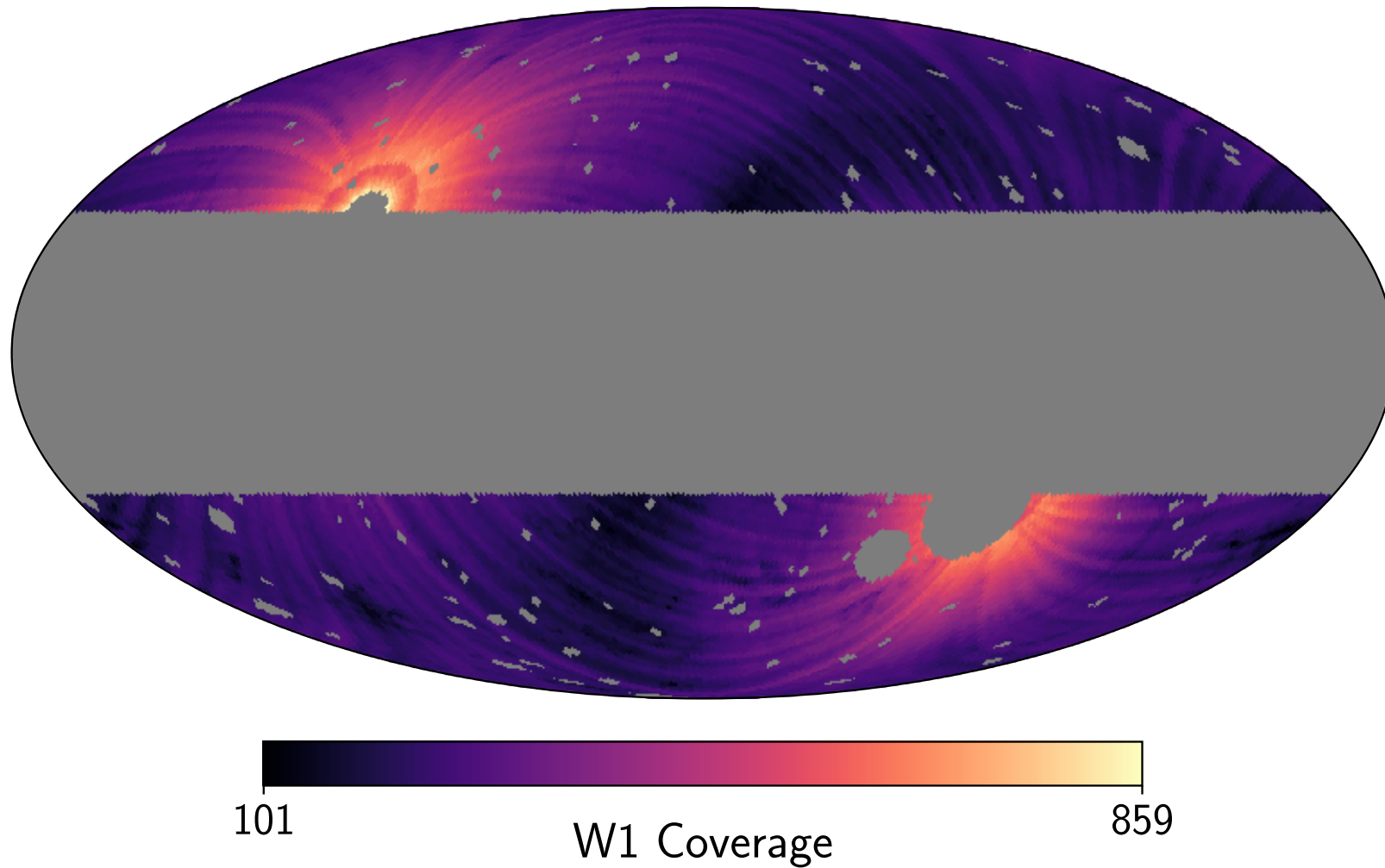
WISE's Scanning Law



Frames over 2 orbits 20 days apart

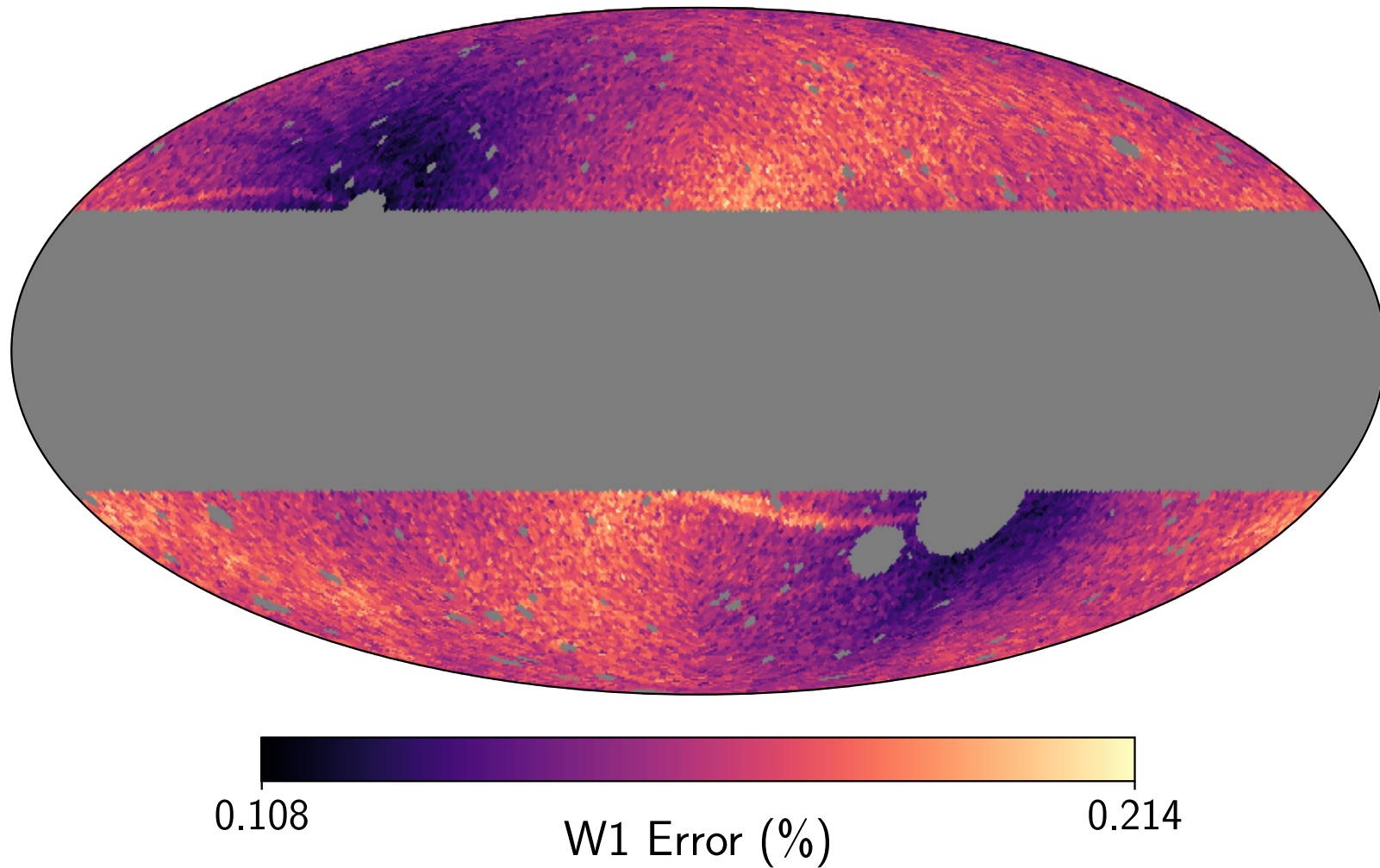
Obeys a **scanning law** over the survey's lifetime

Photometric Errors



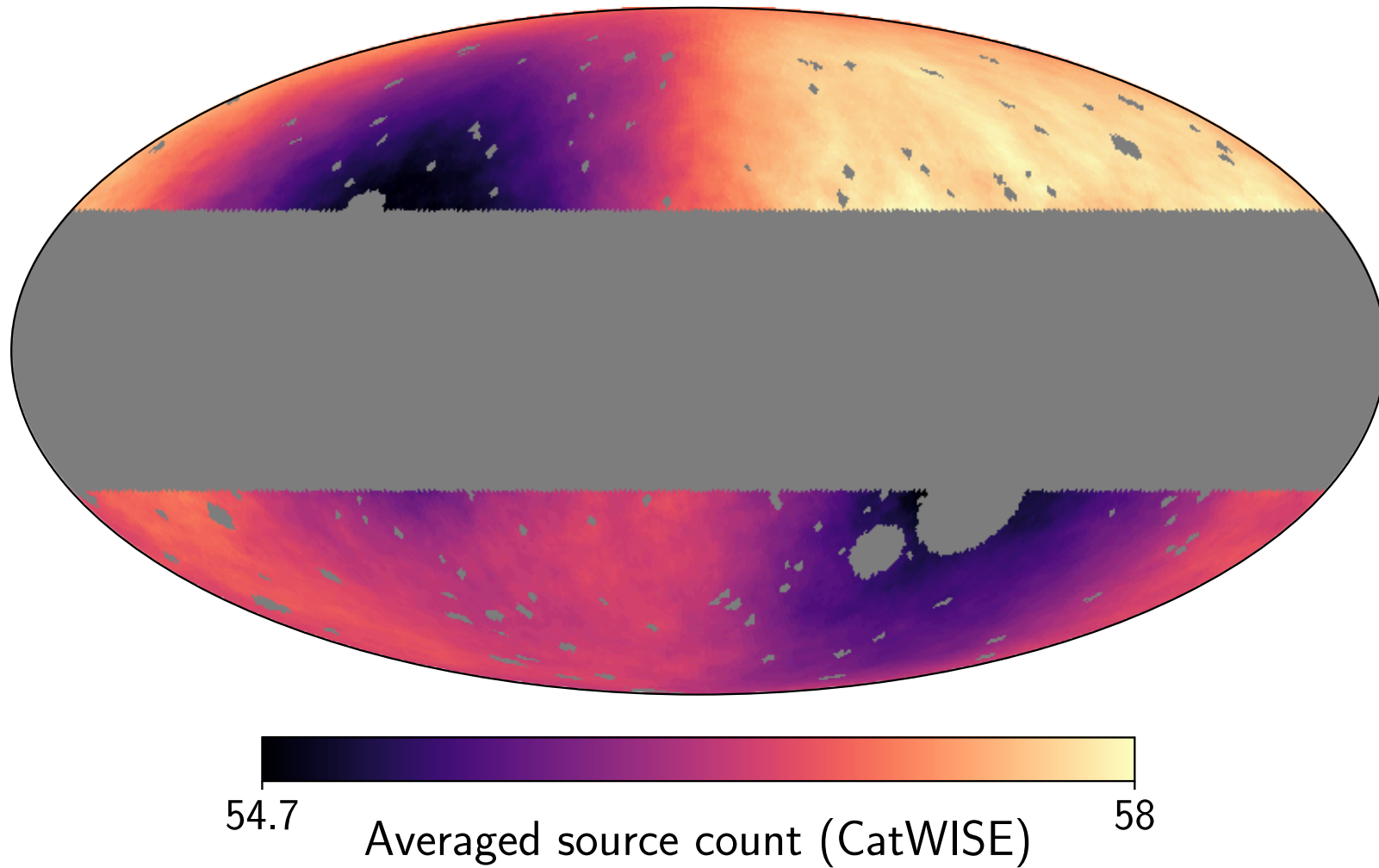
WISE coverage in W1 band for the Secret+21 sample

Photometric Errors



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

Photometric Errors



CatWISE quasar map, no linear weighting

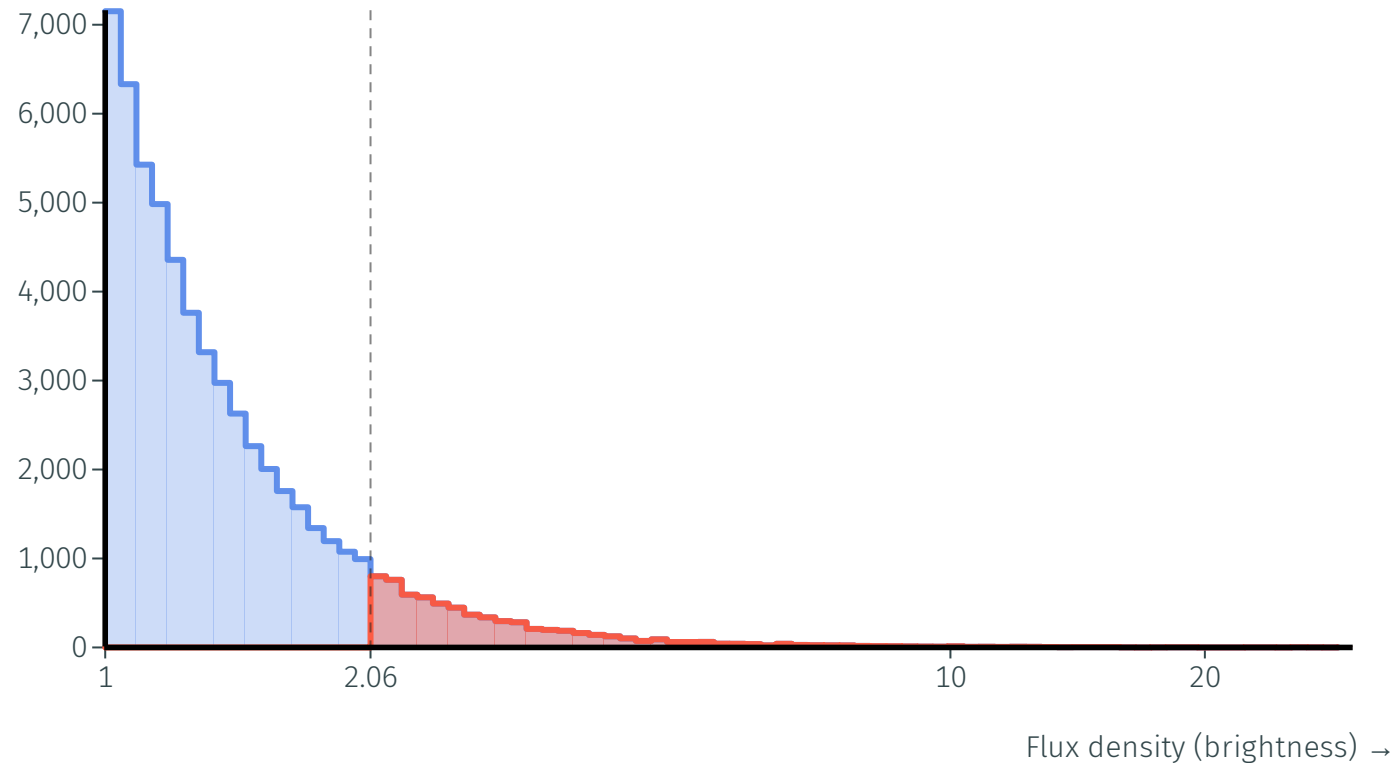
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 0.00

↑ Count in each flux bin



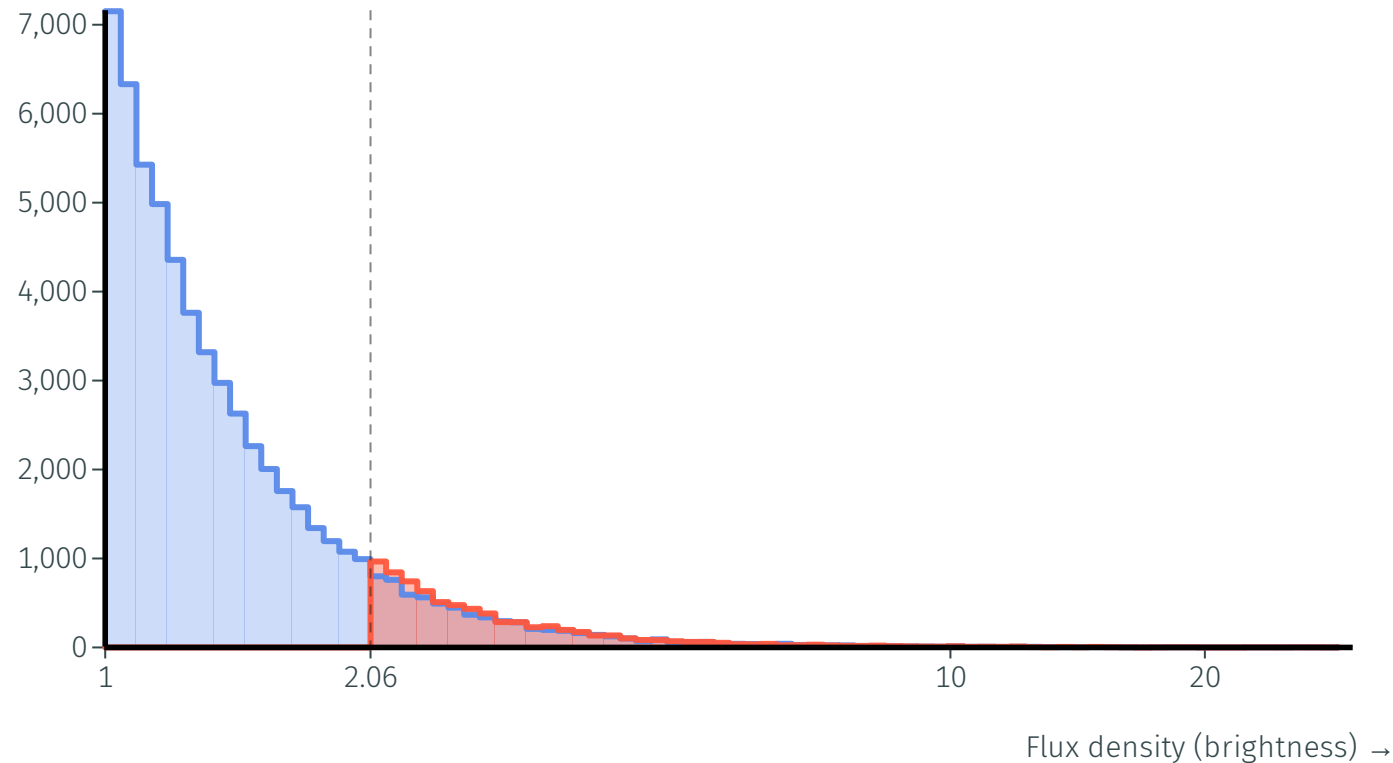
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 0.25

↑ Count in each flux bin



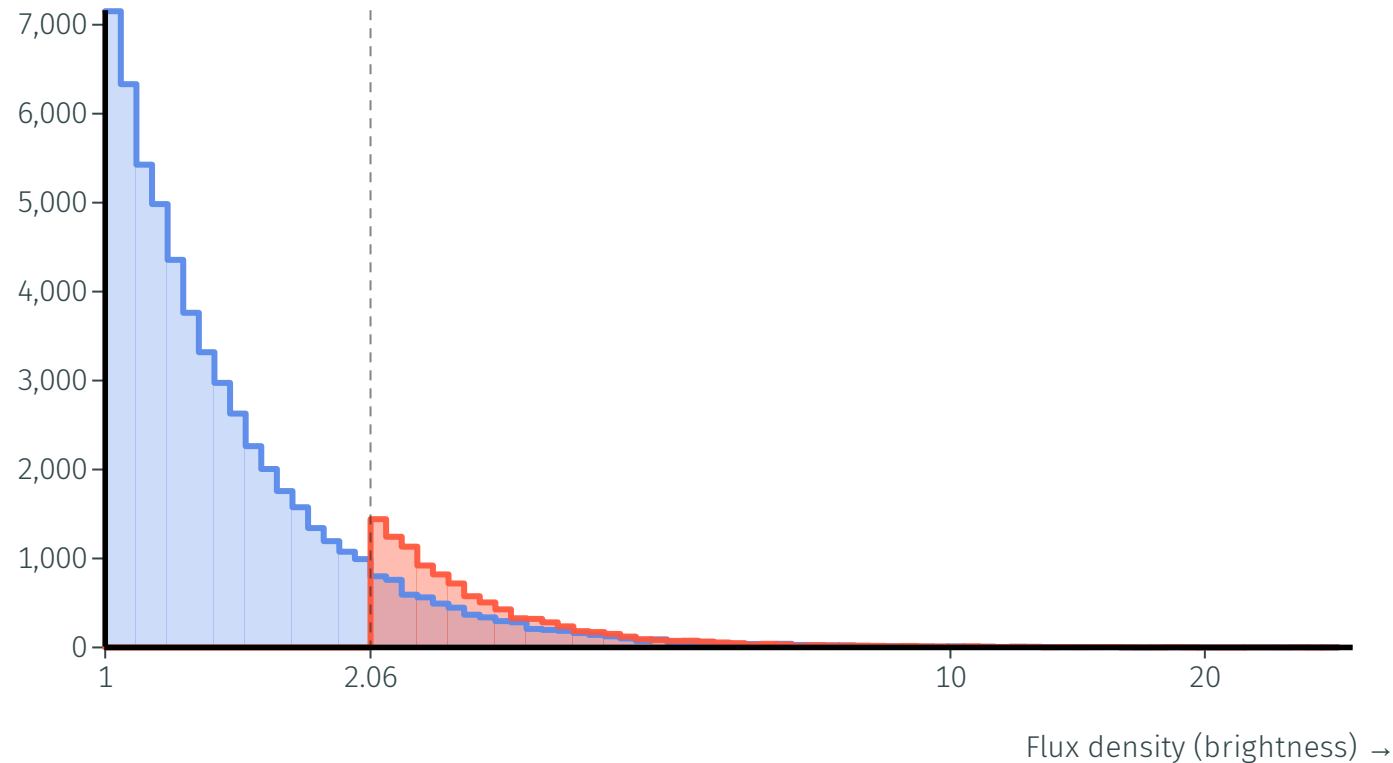
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 0.50

↑ Count in each flux bin



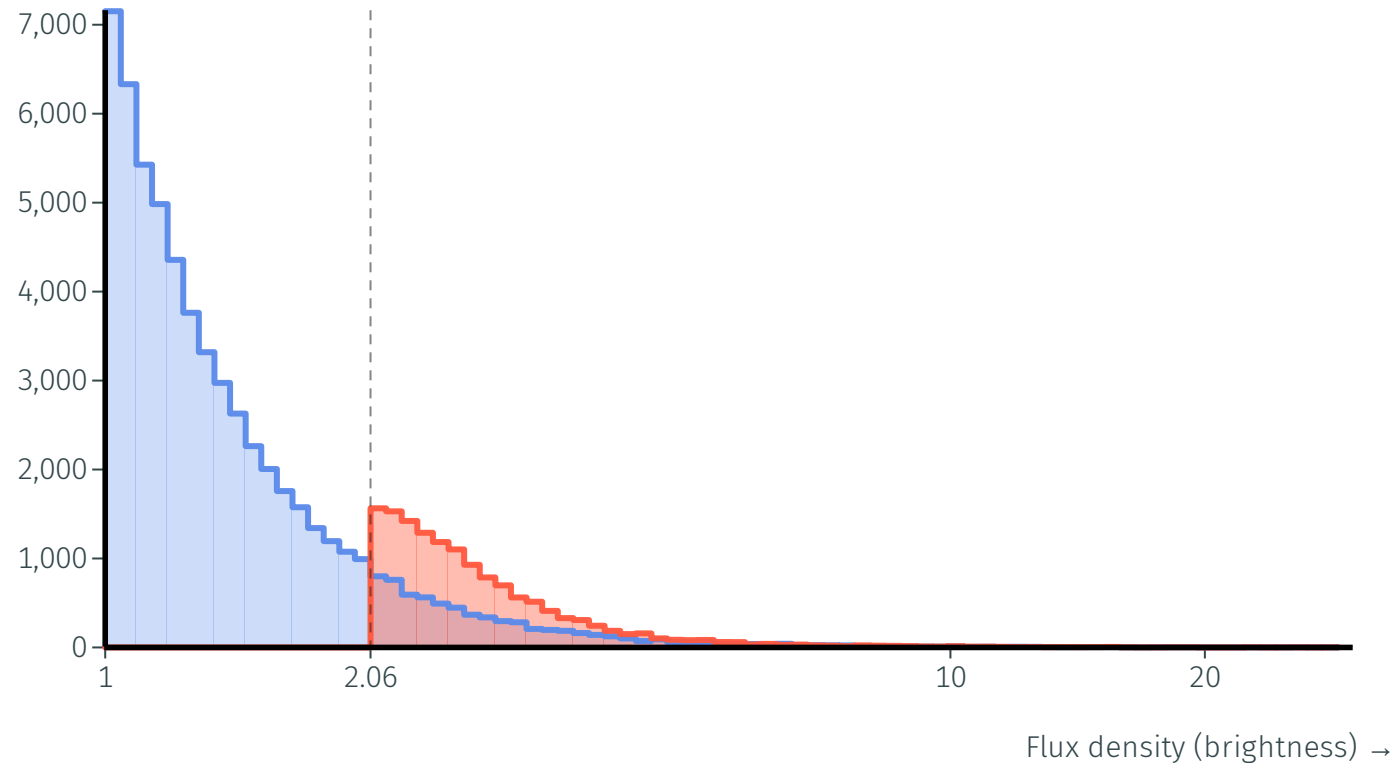
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 0.75

↑ Count in each flux bin



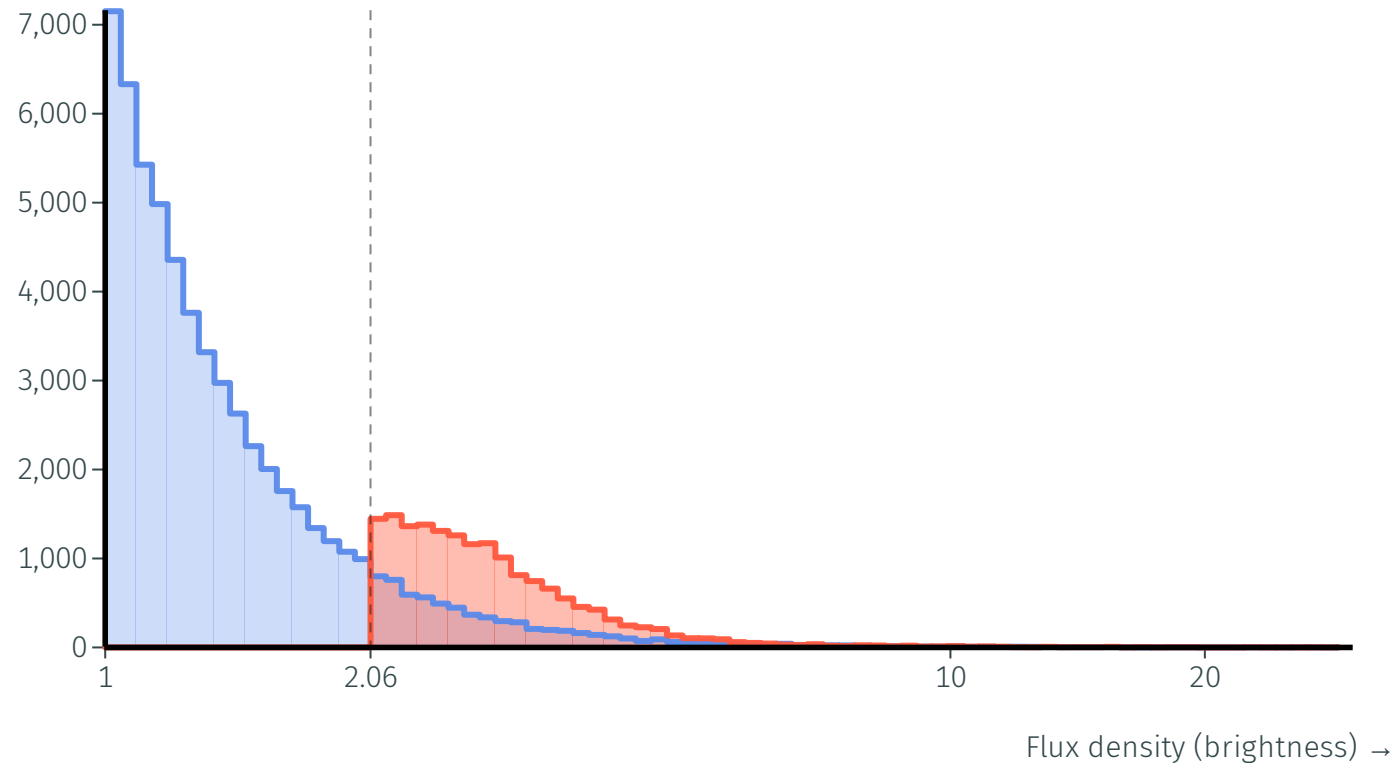
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 1.00

↑ Count in each flux bin



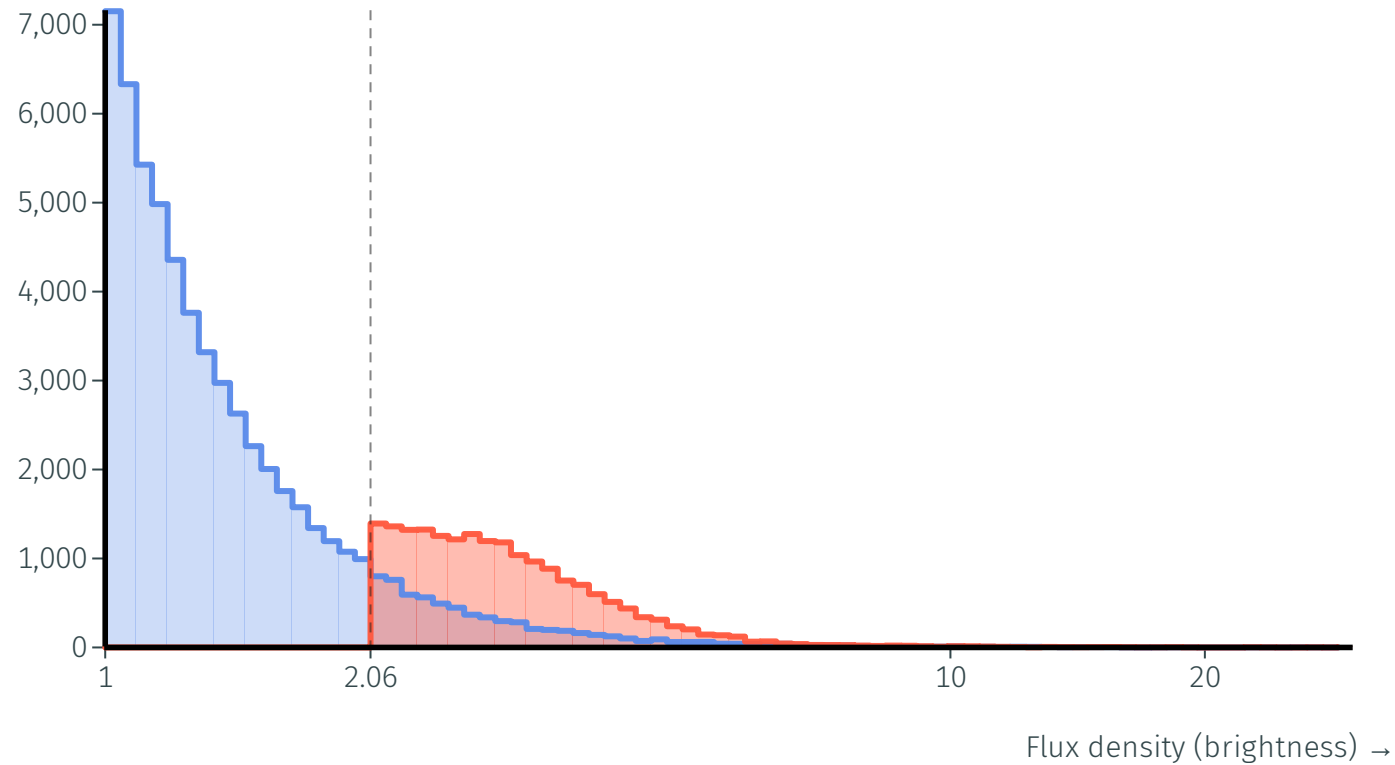
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 1.25

↑ Count in each flux bin



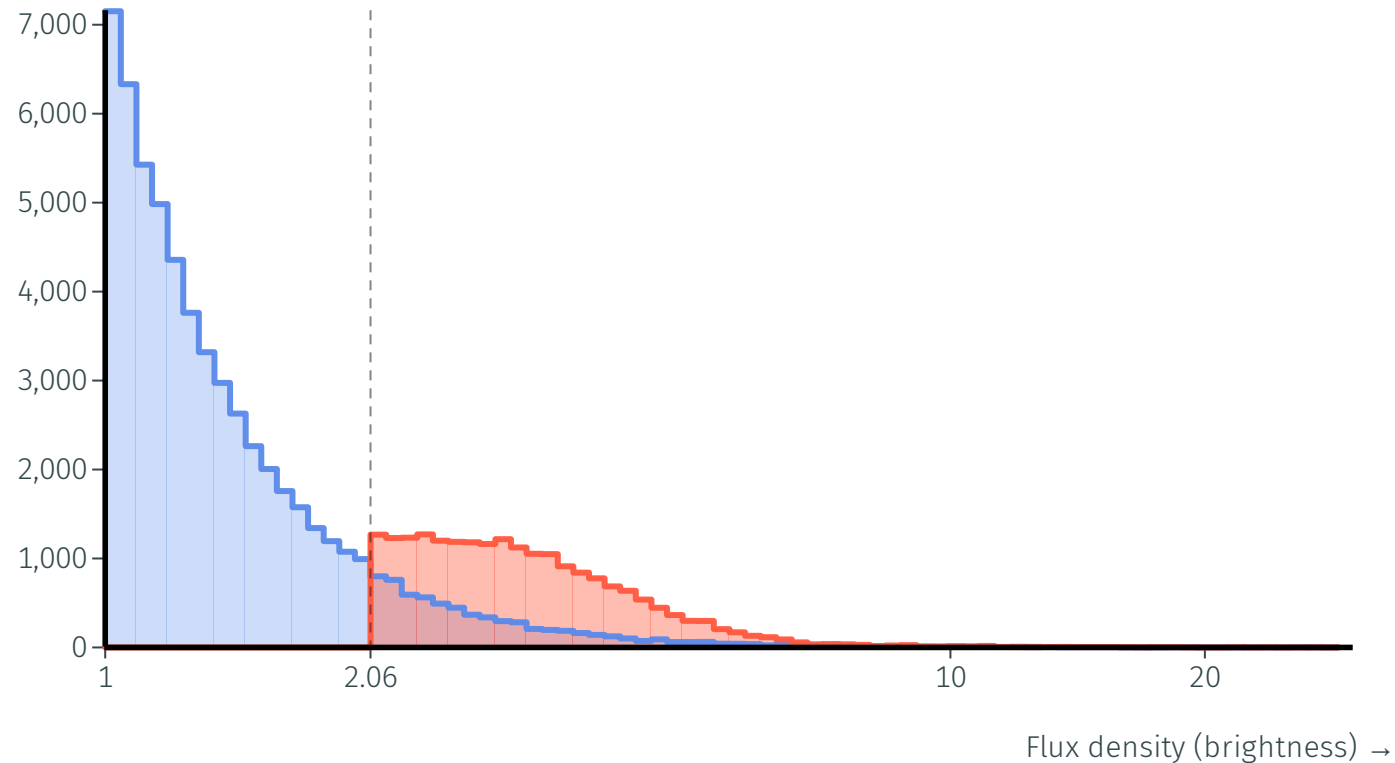
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 1.50

↑ Count in each flux bin



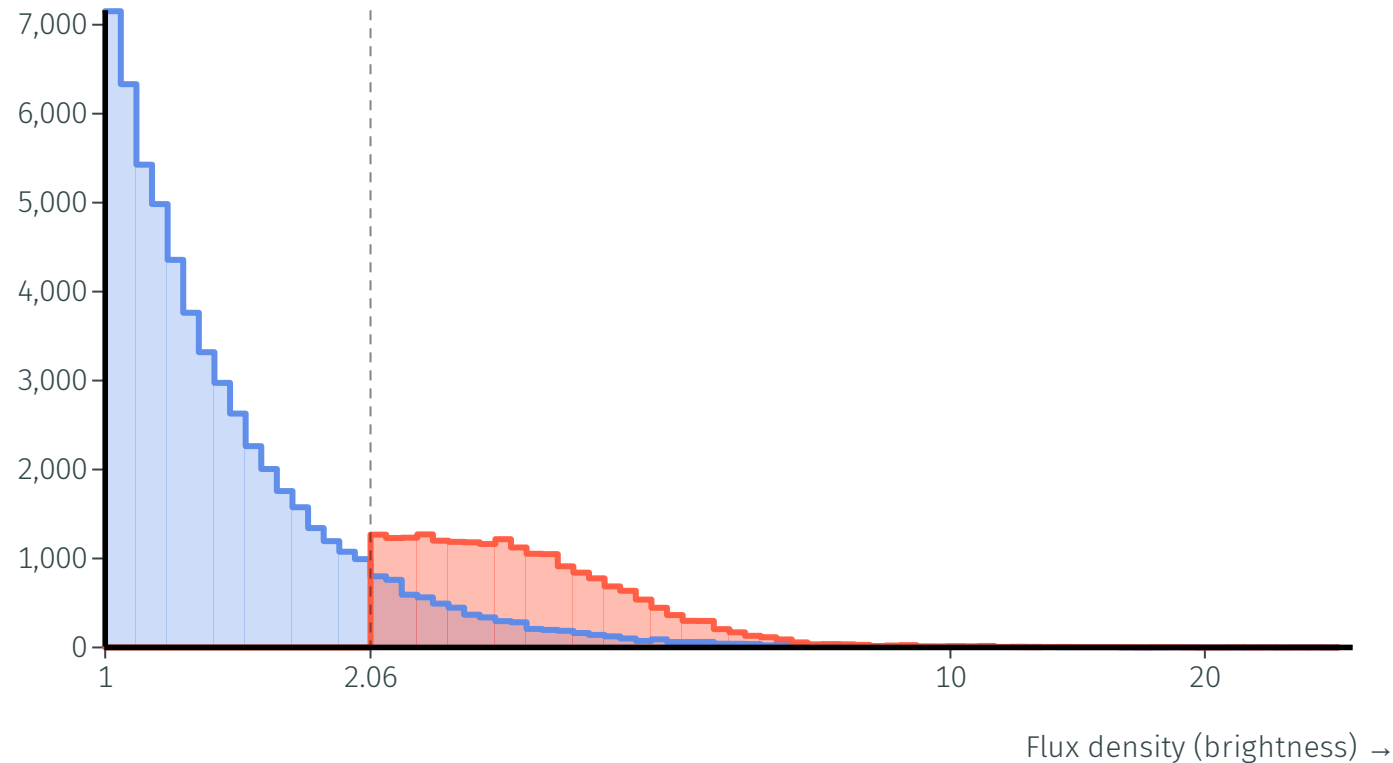
Eddington Bias

$$\text{Sampled flux} = \text{True flux} + \text{Noise}$$

Flux cut 2.06

Noise 1.50

↑ Count in each flux bin



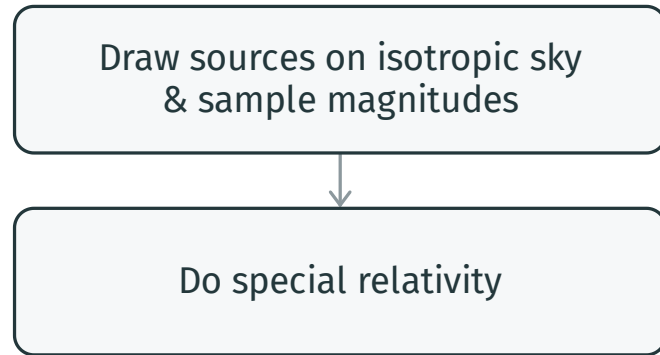
What if the noise varies over the sky? 🤔

This is just something we can simulate!

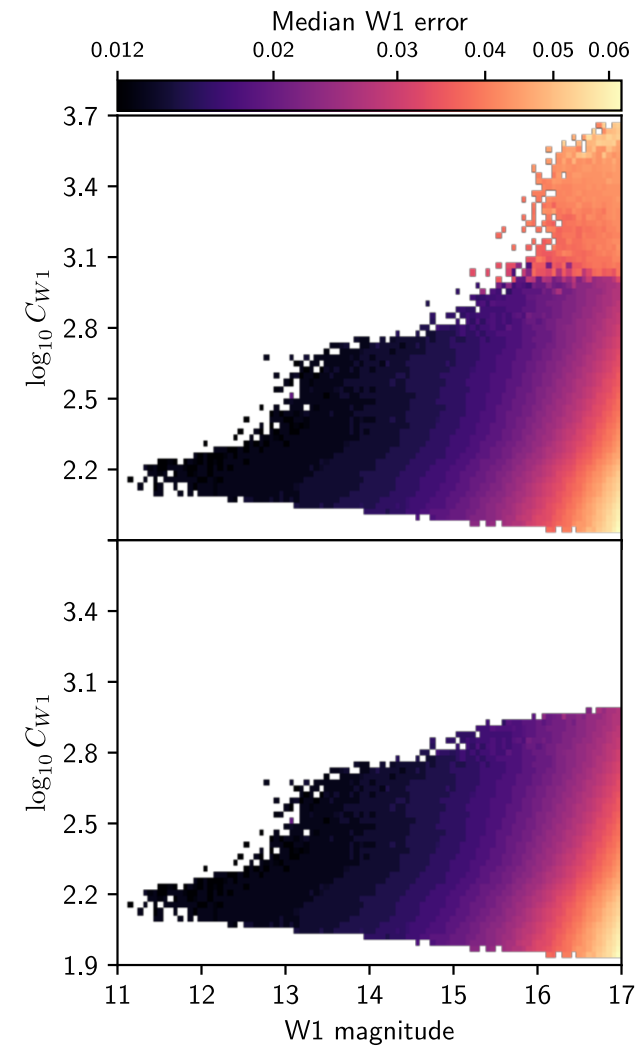
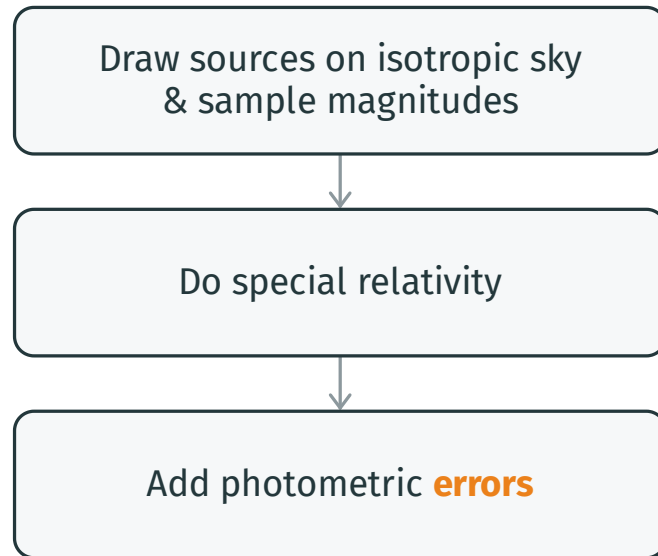
Simulations

Draw sources on isotropic sky
& sample magnitudes

Simulations

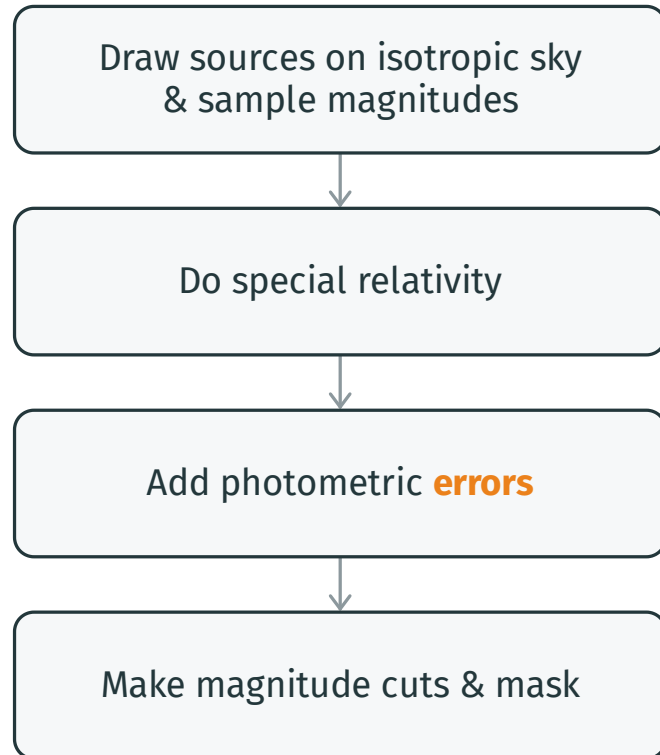


Simulations

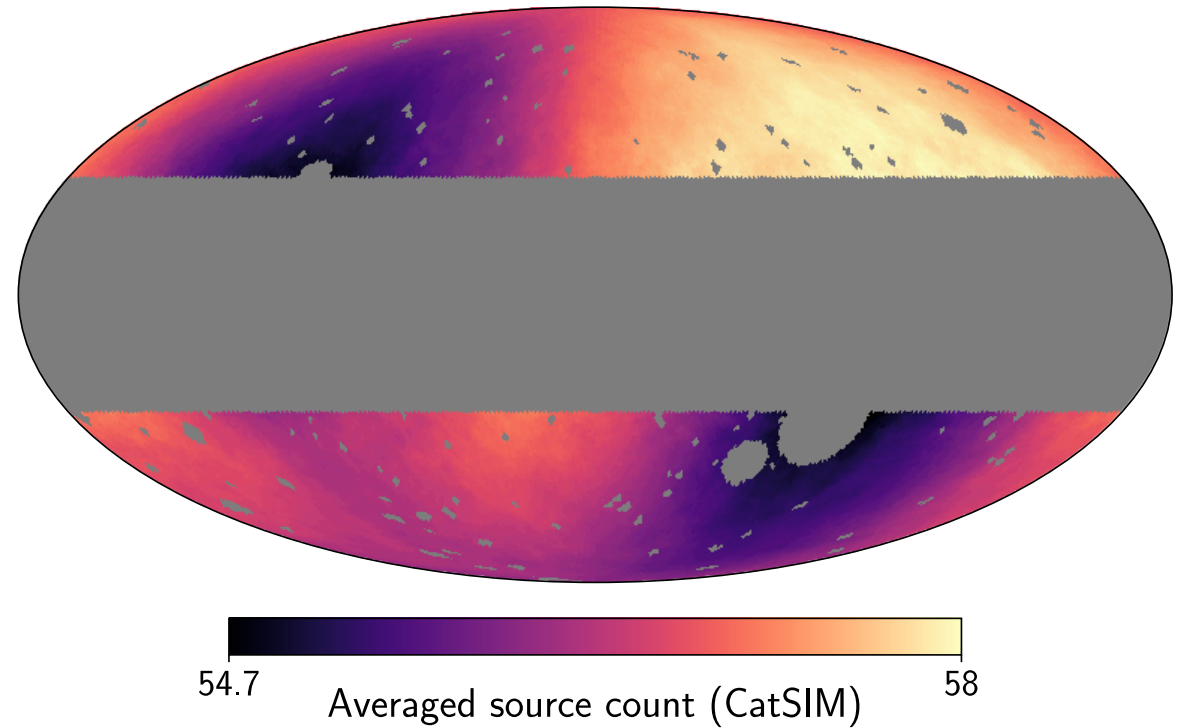
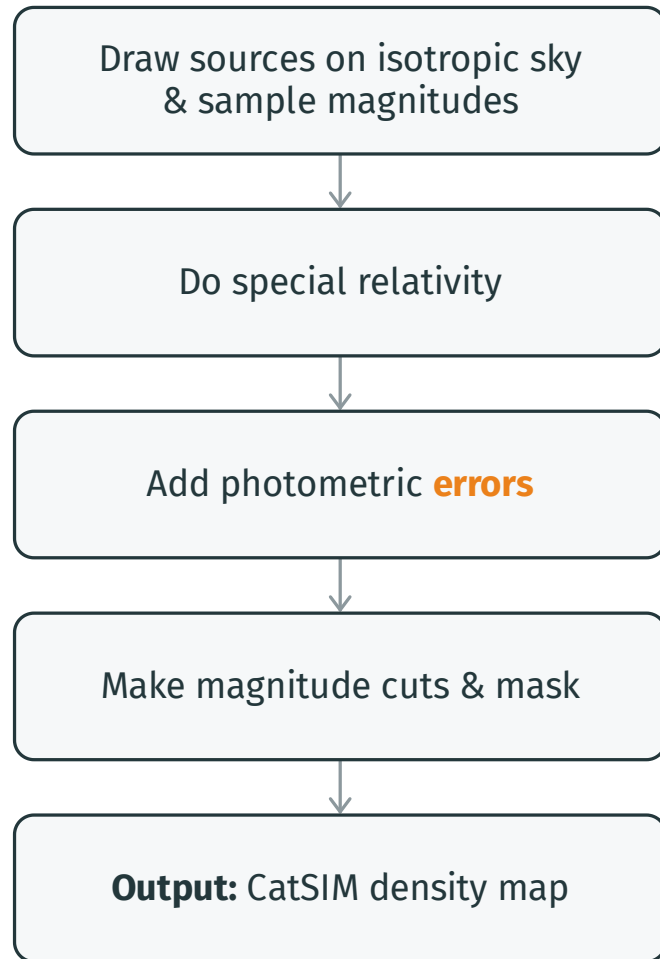


$$m'_{\nu} \rightarrow m'_{\nu} + \Delta m'_{\nu}$$

Simulations

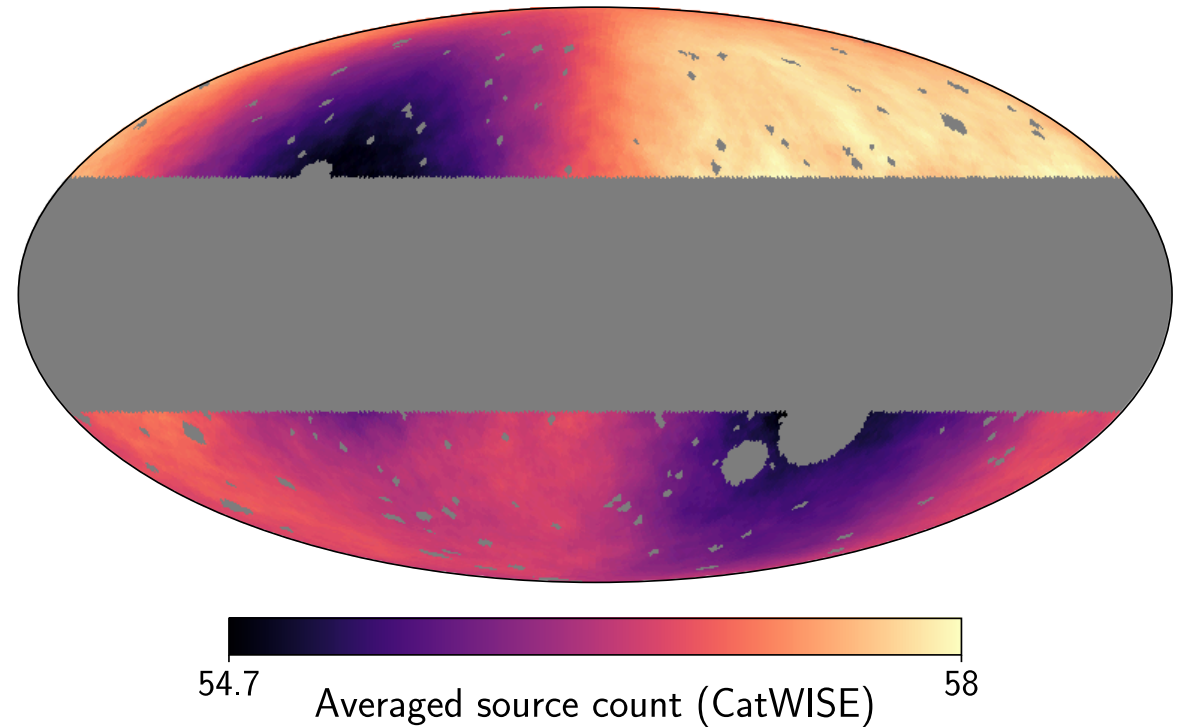
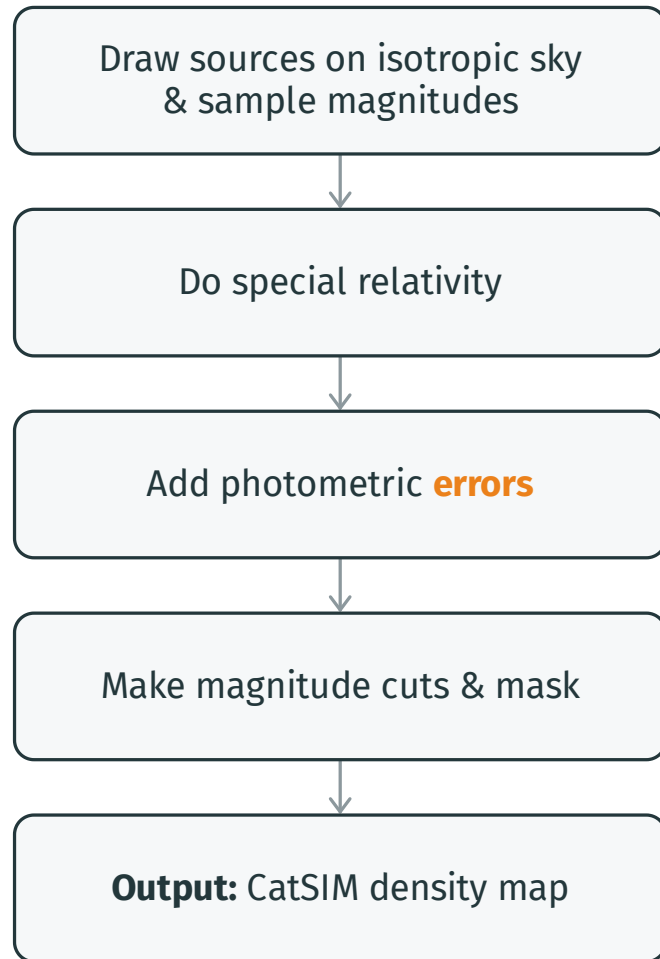


Simulations



Simulated quasar map

Simulations



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!



One Thing Left To Do...

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

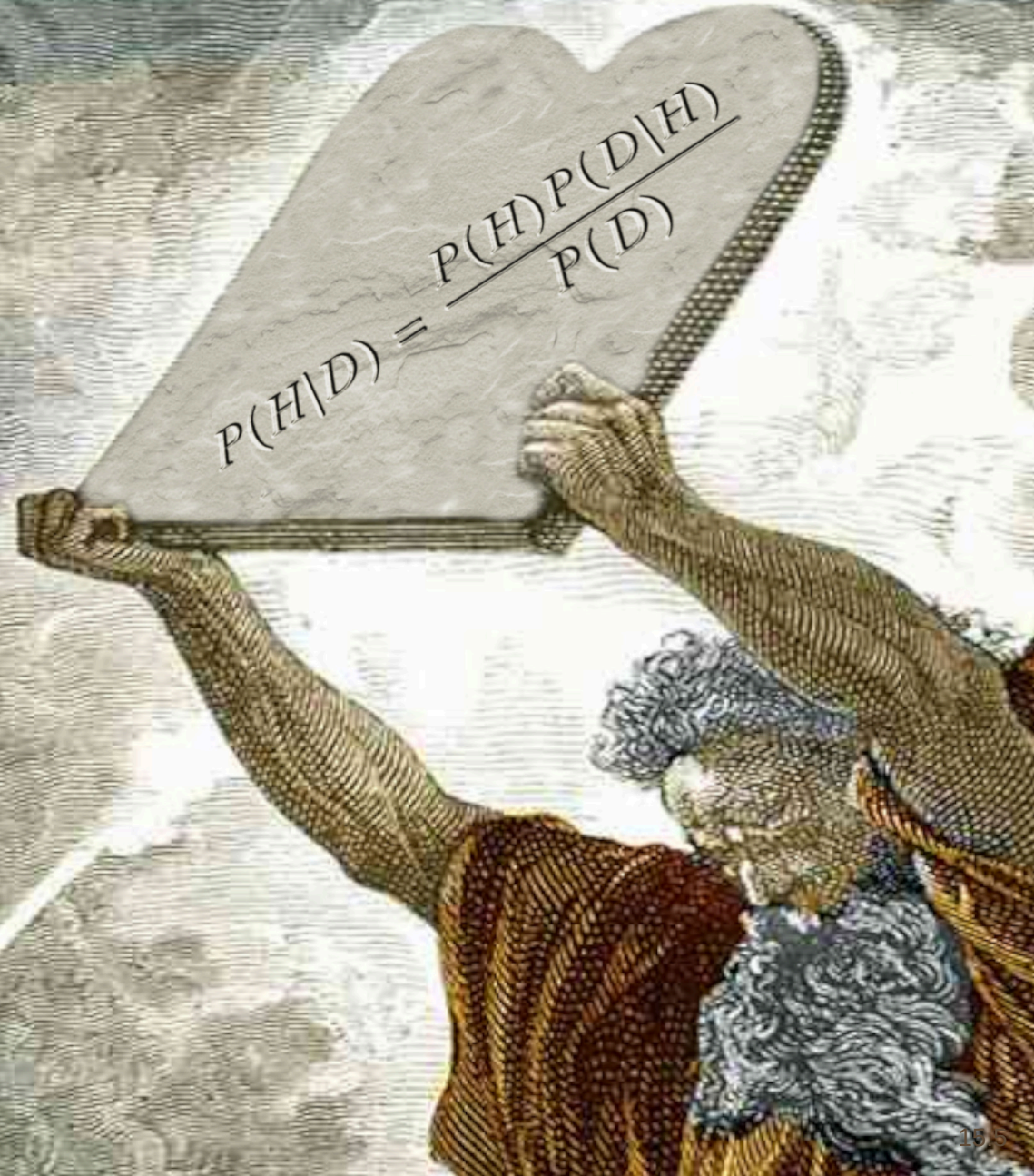
- Don't know $\mathcal{L}$? No problem!
- Take data-generating process $f_M : \theta \rightarrow \mathbf{x}$.



One Thing Left To Do...

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

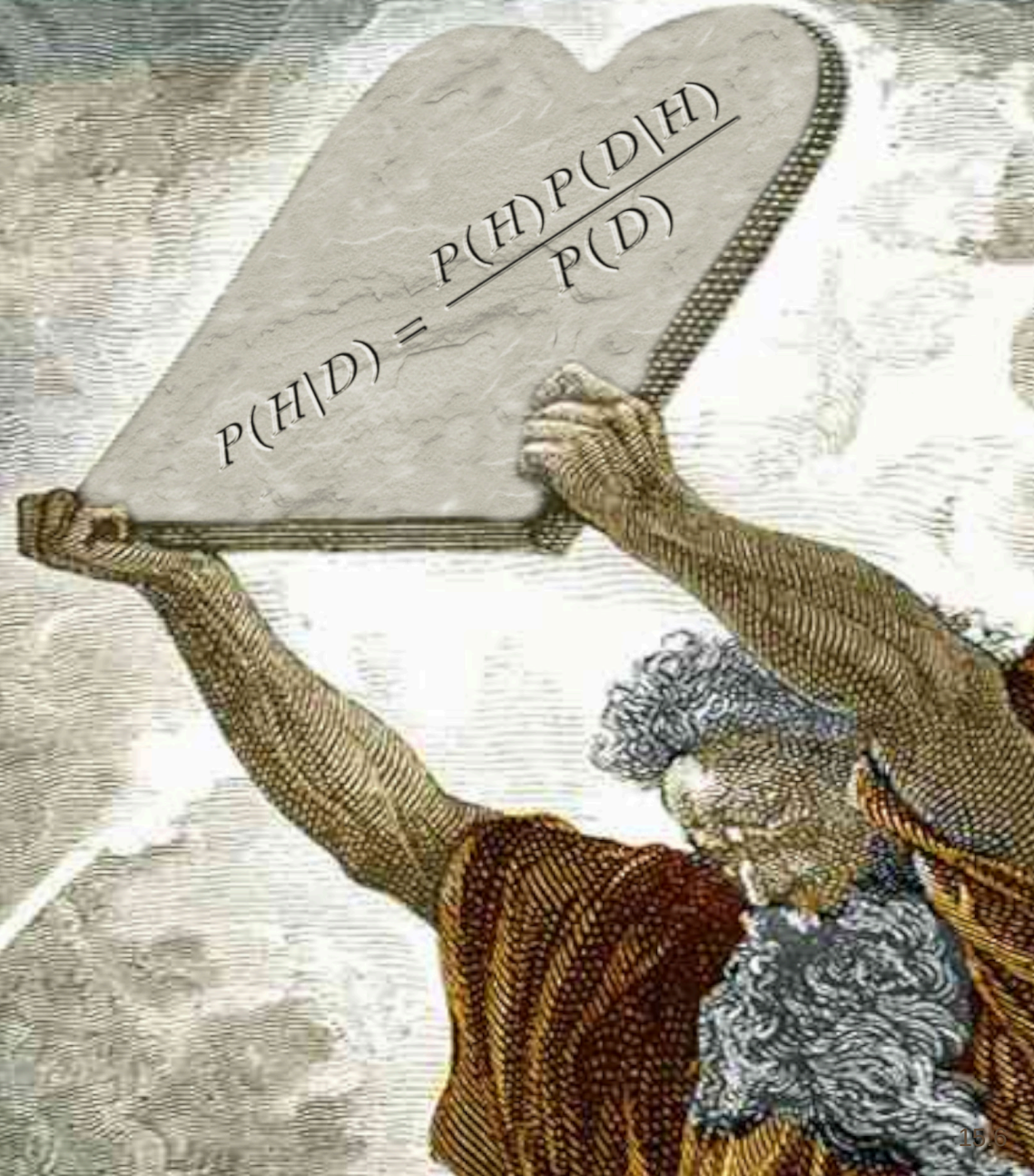
- Don't know $\mathcal{L}$? No problem!
- Take data-generating process $f_M : \theta \rightarrow \mathbf{x}$.
- Use a neural network to learn $\mathcal{L}$.



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 $f_M : \theta \rightarrow \mathbf{x}$.
- Use a neural network to learn $\mathcal{L}$.
- This is **SBI**.



Normalising Flows

Normalising Flows

- **Goal:** describe the d -dimensional base distribution $\mathcal{L}(\mathbf{x} \mid \theta)$.

Normalising Flows

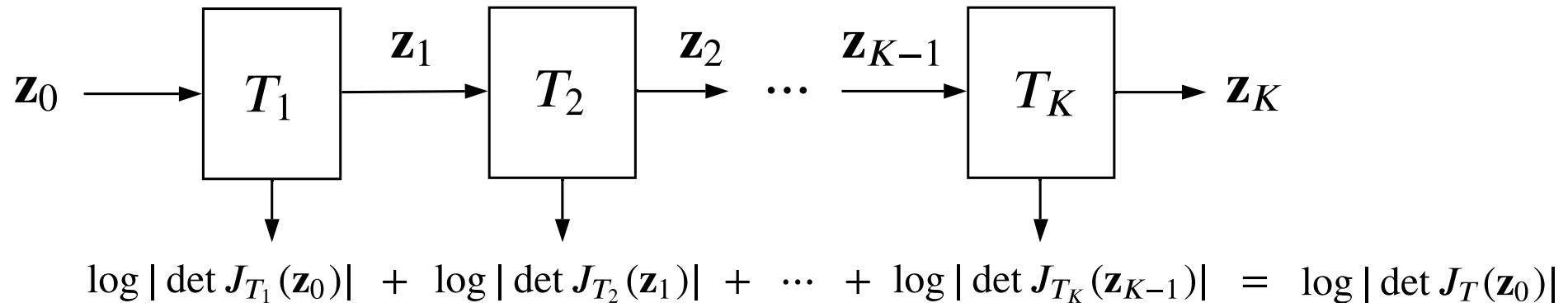
- **Goal:** describe the d -dimensional base distribution $\mathcal{L}(\mathbf{x} \mid \theta)$.
- We use a series of **Masked Autoregressive Flows** (MAFs).

Normalising Flows

- **Goal:** describe the d -dimensional base distribution $\mathcal{L}(\mathbf{x} \mid \theta)$.
- We use a series of **Masked Autoregressive Flows** (MAFs).
- A *flow* transforms a simple distribution into a complex one.

Normalising Flows

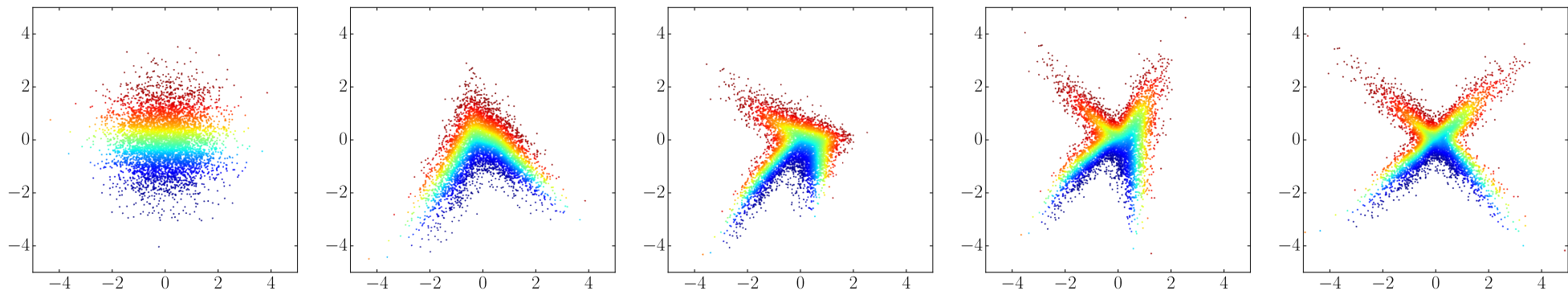
- **Goal:** describe the d -dimensional base distribution $\mathcal{L}(\mathbf{x} \mid \boldsymbol{\theta})$.
- We use a series of **Masked Autoregressive Flows** (MAFs).
- A *flow* transforms a simple distribution into a complex one.



Composing individual bijections, adapted from Papamakarios et al. (2019).

Normalising Flows

- **Goal:** describe the d -dimensional base distribution $\mathcal{L}(\mathbf{x} \mid \theta)$.
- We use a series of **Masked Autoregressive Flows** (MAFs).
- A *flow* transforms a simple distribution into a complex one.



Results

Bayes Factors

Model	$\ln \mathcal{B}$
-------	-------------------

Bayes factors with respect to the **fiducial model**.

Bayes Factors

Model	$\ln \mathcal{B}$
Free dipole, extra error, Gaussian	0.0 $\pm$ 0.0

Bayes factors with respect to the **fiducial model**.

Bayes Factors

Model	$\ln \mathcal{B}$
Dipole from Secrest+21	2.8 ± 0.9
Dipole from Dam+23	1.9 ± 0.8
Free dipole, extra error, Gaussian	0.0 ± 0.0

Bayes factors with respect to the **fiducial model**.

Bayes Factors

Model	$\ln \mathcal{B}$
Dipole from Secrest+21	2.8 ± 0.9
Dipole from Dam+23	1.9 ± 0.8
Free dipole, extra error, Gaussian	0.0 ± 0.0
CMB velocity & direction	-8.3 ± 0.9

Bayes factors with respect to the **fiducial model**.

Bayes Factors

Model	$\ln \mathcal{B}$
Dipole from Secrest+21	2.8 ± 0.9
Dipole from Dam+23	1.9 ± 0.8
Free dipole, extra error, Gaussian	0.0 ± 0.0
CMB direction, free velocity	-2.4 ± 0.9
CMB velocity & direction	-8.3 ± 0.9

Bayes factors with respect to the **fiducial model**.

Bayes Factors

Model	$\ln \mathcal{B}$
Dipole from Secrest+21	2.8 ± 0.9
Dipole from Dam+23	1.9 ± 0.8
Free dipole, extra error, Gaussian	0.0 ± 0.0
CMB direction, free velocity	-2.4 ± 0.9
CMB velocity & direction	-8.3 ± 0.9
Free dipole, no extra error	-113.6 ± 6.4

Bayes factors with respect to the **fiducial model**.

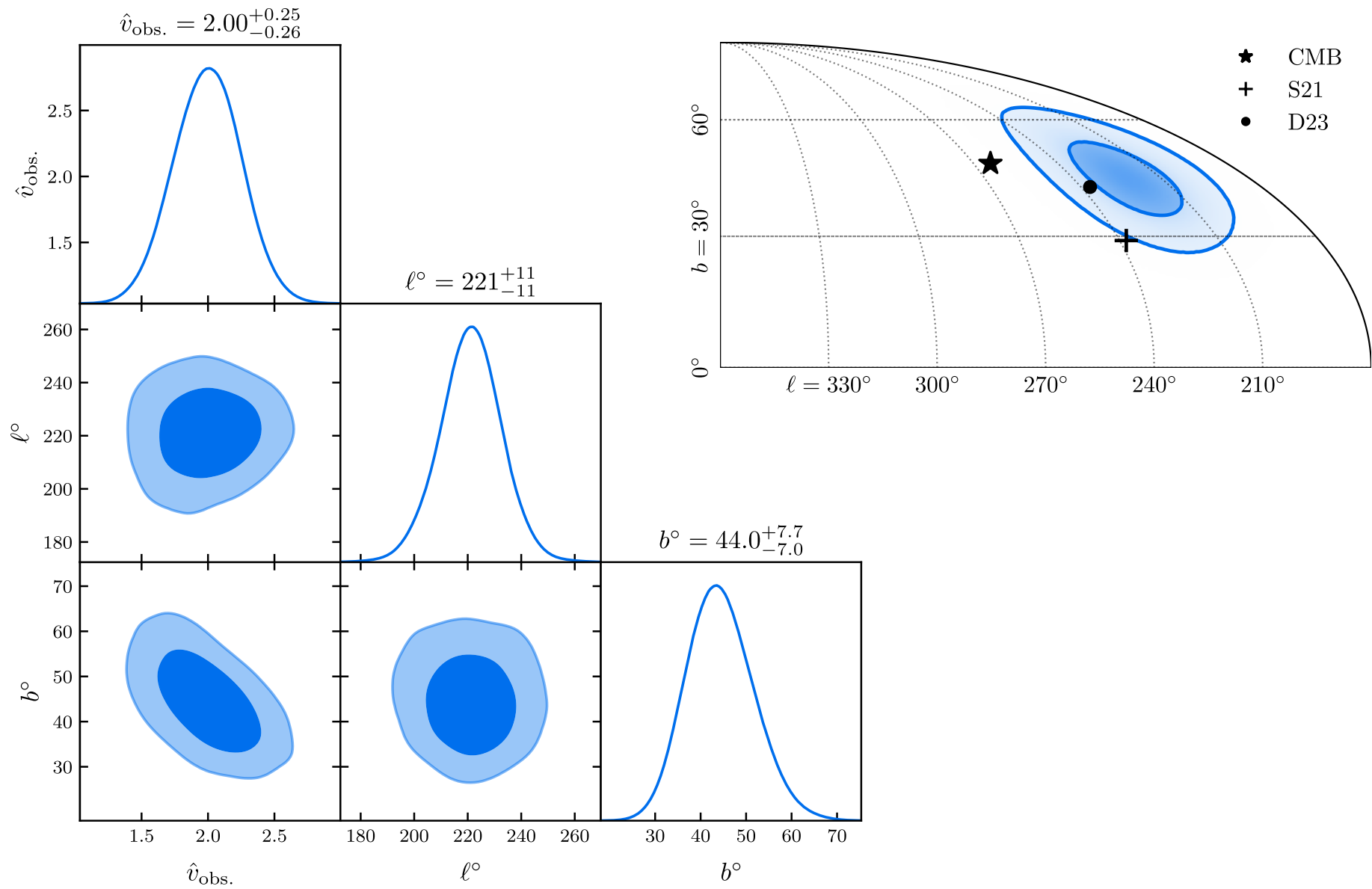
Bayes Factors

Model	$\ln \mathcal{B}$
Dipole from Secrest+21	2.8 ± 0.9
Dipole from Dam+23	1.9 ± 0.8
Free dipole, extra error, Gaussian	0.0 ± 0.0
CMB direction, free velocity	-2.4 ± 0.9
CMB velocity & direction	-8.3 ± 0.9
Free dipole, no extra error	-113.6 ± 6.4

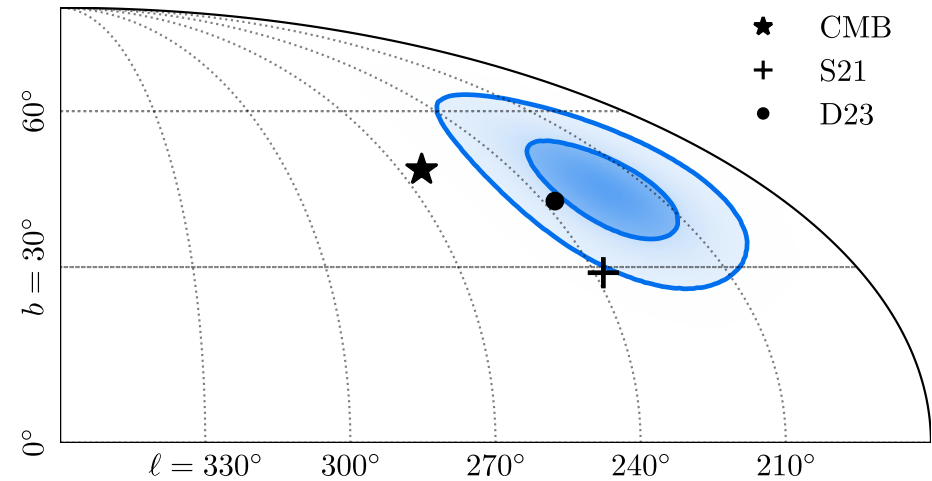
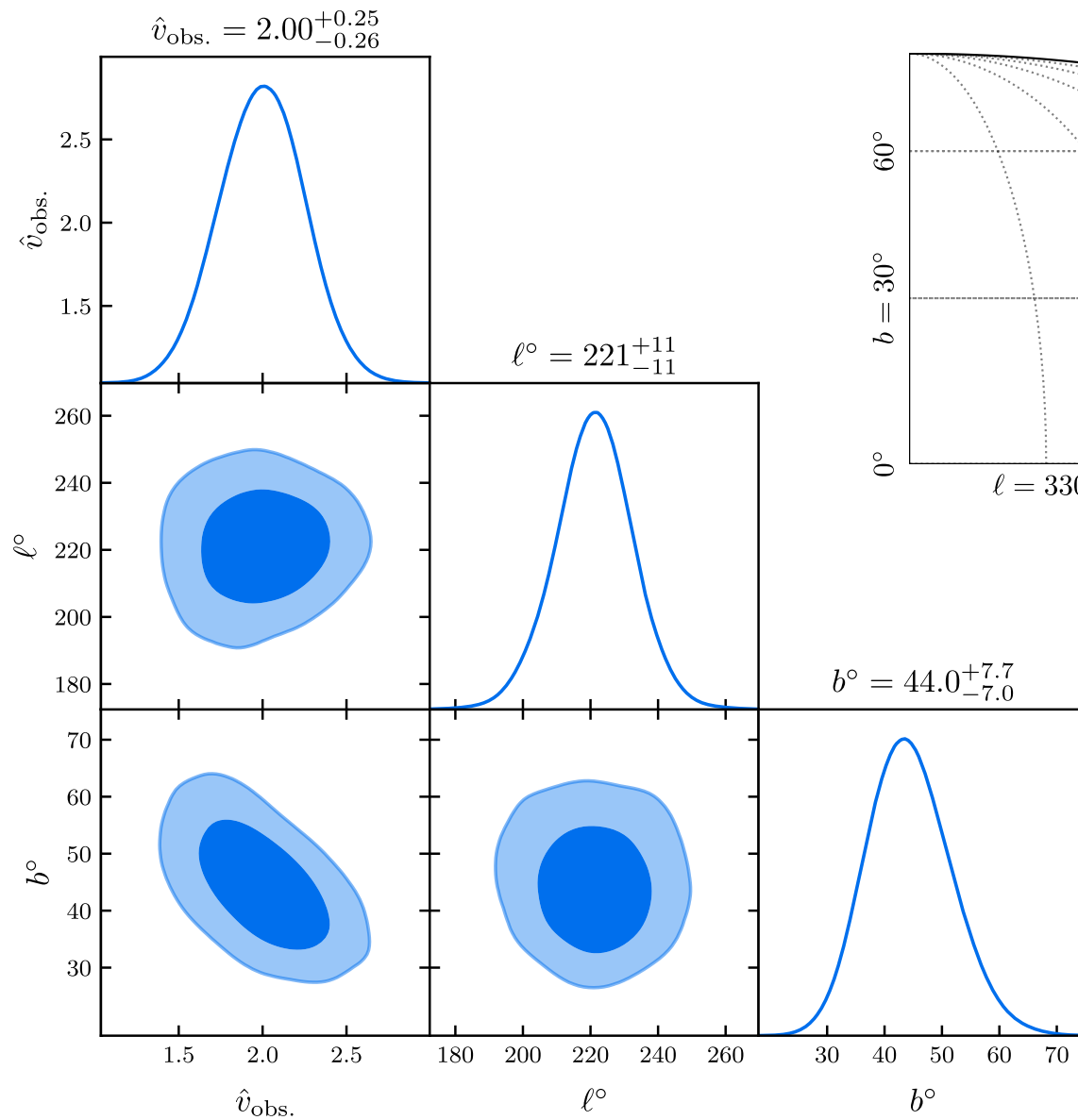
Bayes factors with respect to the **fiducial model**.

- We need an **extra error** term to explain the data.
- CMB dipole is ruled out convincingly.

CatSIM Results



CatSIM Results

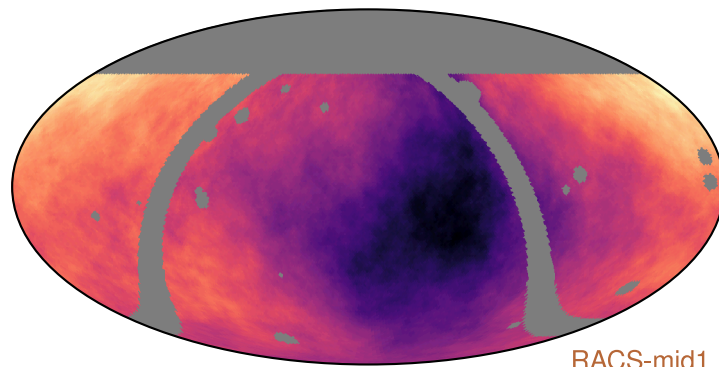
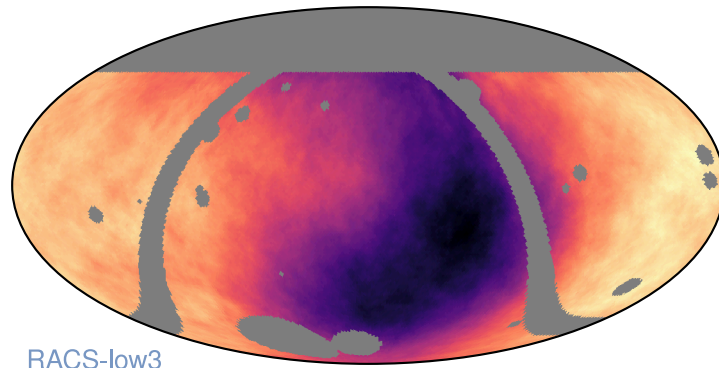


Confirms cosmic dipole tension.

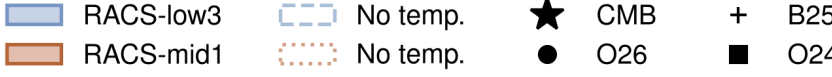
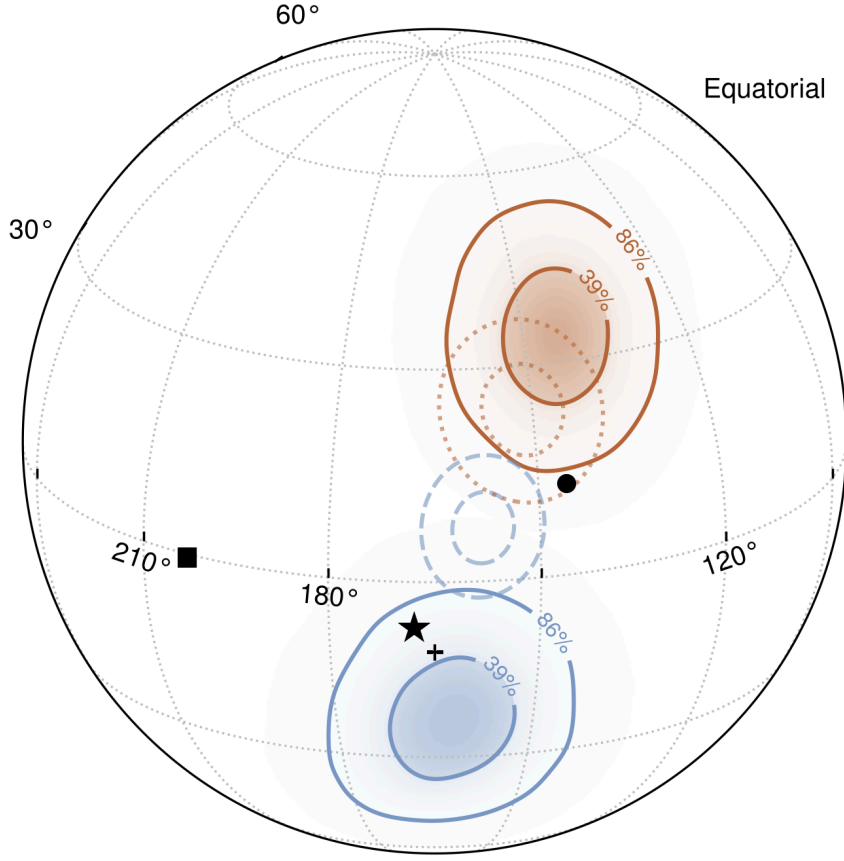
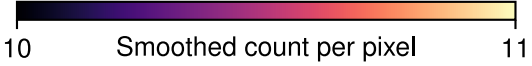
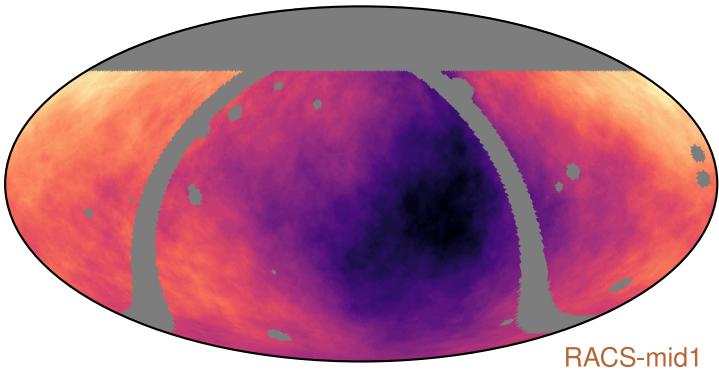
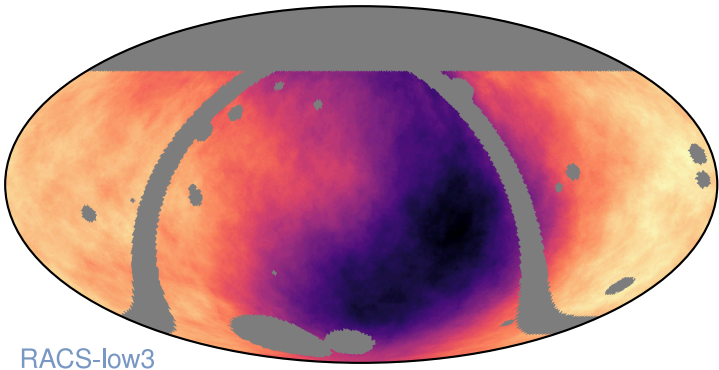
We've got to be careful of our instruments!

Cracking into RACS?

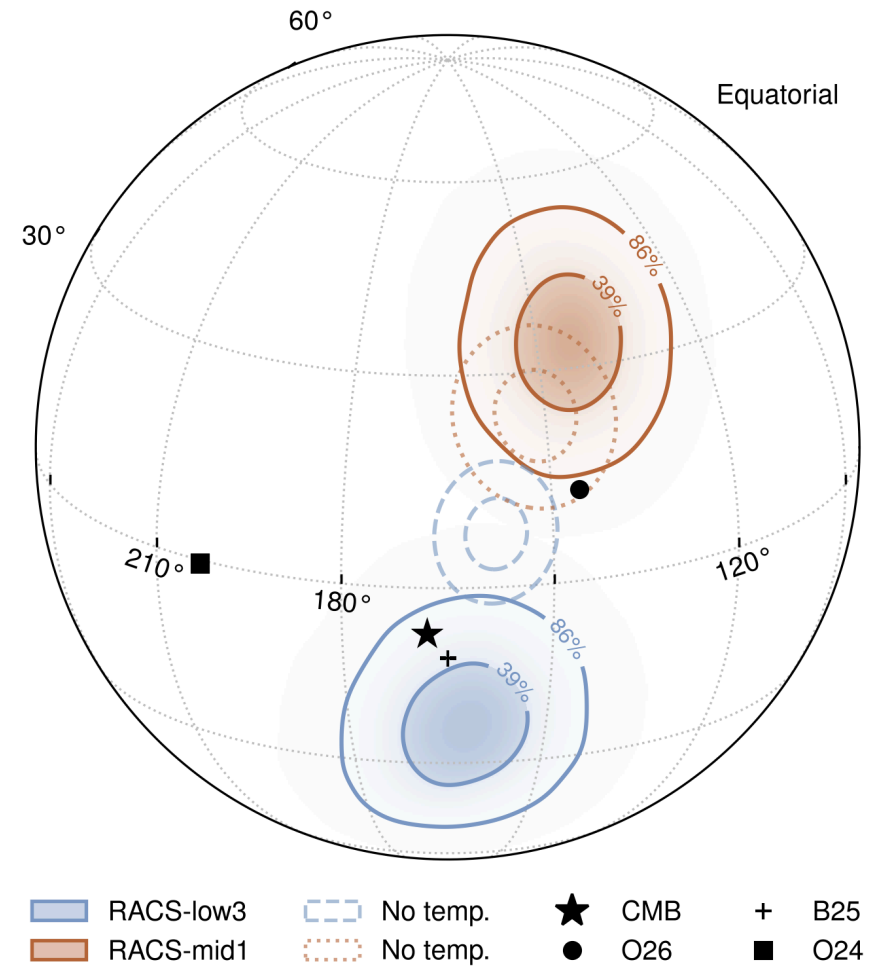
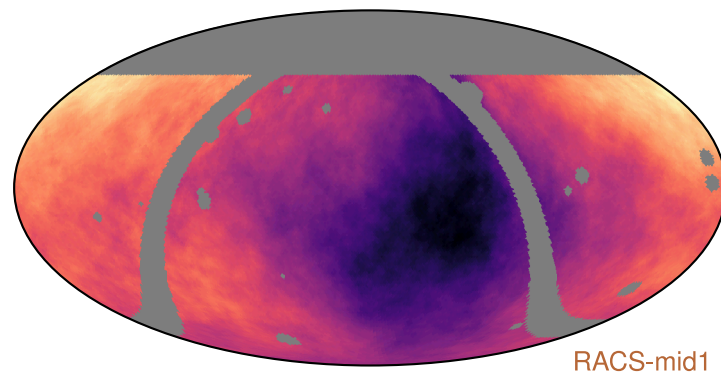
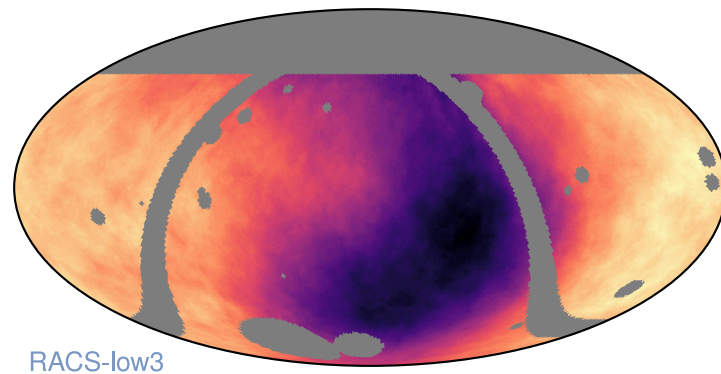
Cracking into RACS?



Cracking into RACS?



Cracking into RACS?



Oayda et al. in preparation, coming very soon...

Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oayda   and Geraint F. Lewis 

Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oayda ★ and Geraint F. Lewis 

- Describe and account for ecliptic bias



Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oayda ★ and Geraint F. Lewis 

- Describe and account for ecliptic bias
- Measure cosmic dipole



Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oayda   and Geraint F. Lewis 

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

Wising up to CatWISE: using simulation-based inference to interpret the ecliptic bias and confirm the cosmic dipole excess

Oliver T. Oayda ★ and Geraint F. Lewis 

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



oayda.net



o-oayda

Validation

