Confronting the Cosmic Dipole Tension

Systematics, Surveys and Statistics

Oliver Oayda

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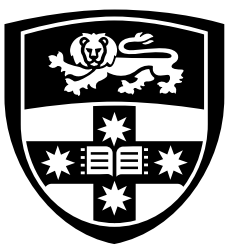
Sydney Institute for Astronomy
The University of Sydney

Supervised by
Geraint Lewis
Tara Murphy

June 26, 2025



THE UNIVERSITY OF
SYDNEY

CosmoVerse@Istanbul

June 2025

The cosmological principle might be in trouble. Future surveys will be decisive. How can we prepare?

The Kinematic Dipole

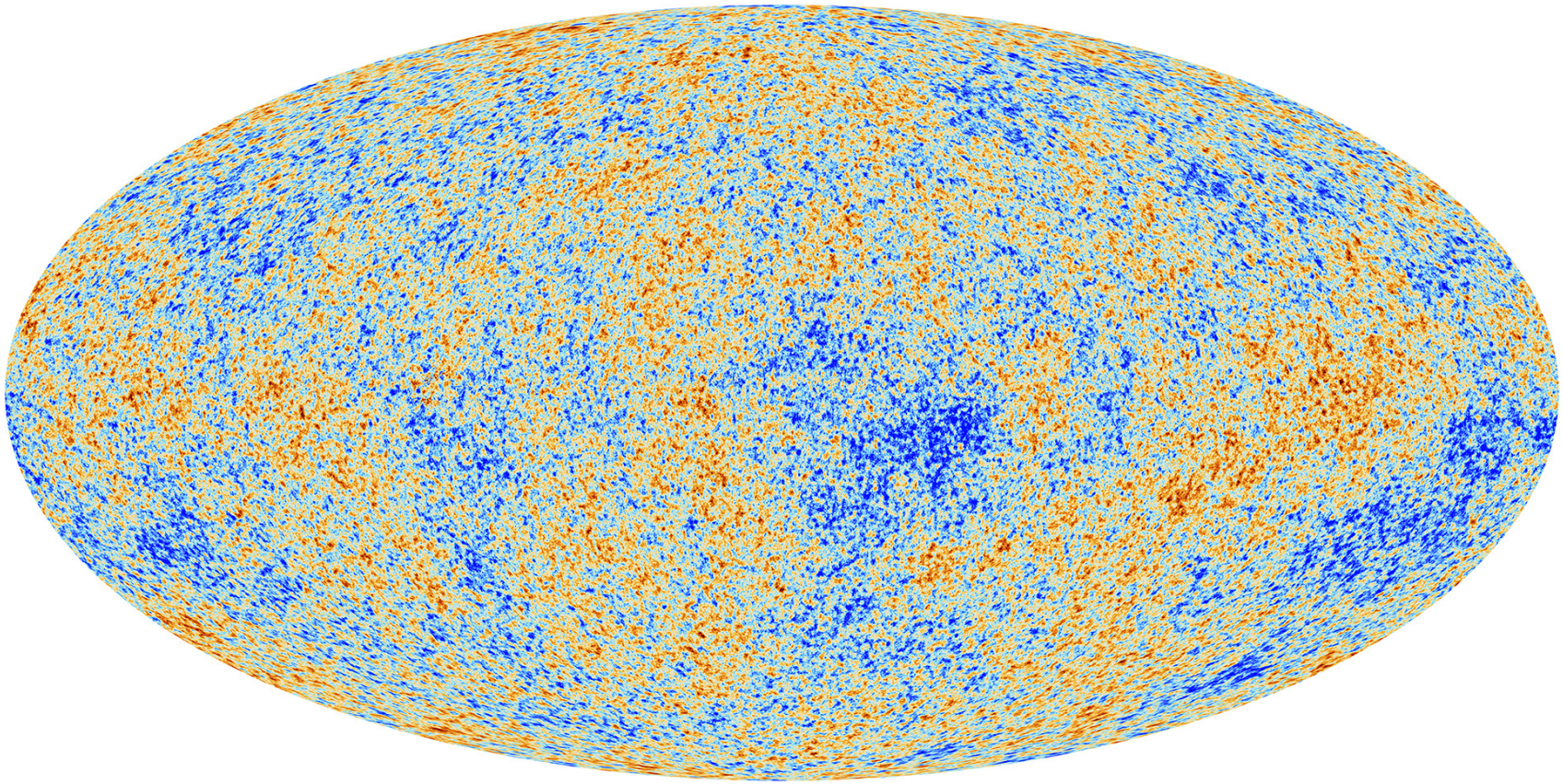


Figure 1: CMB temperature map (dipole excluded; Planck).

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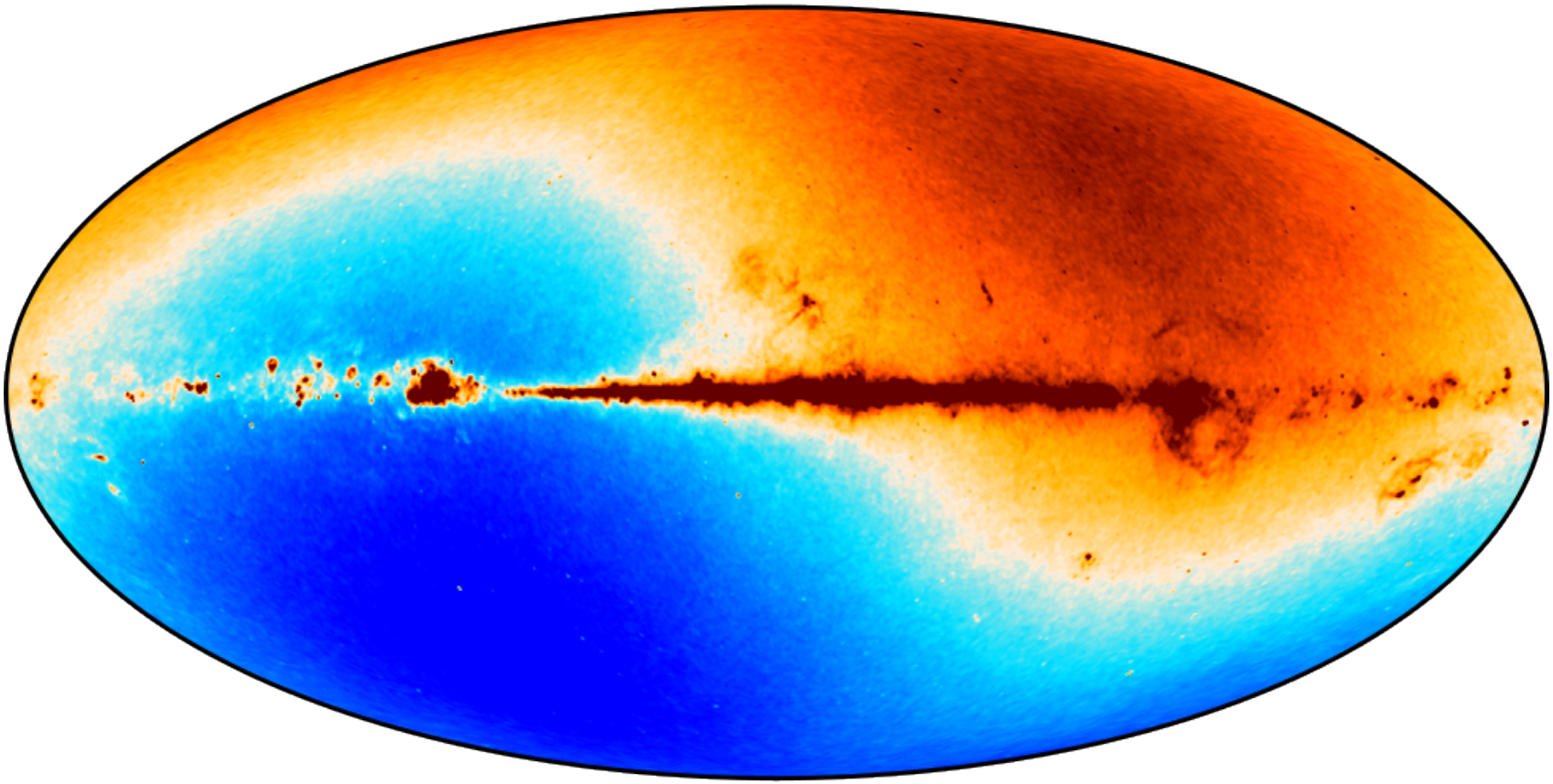

Figure 1: CMB temperature map (dipole included; BeyondPlanck).
★: dipole direction.

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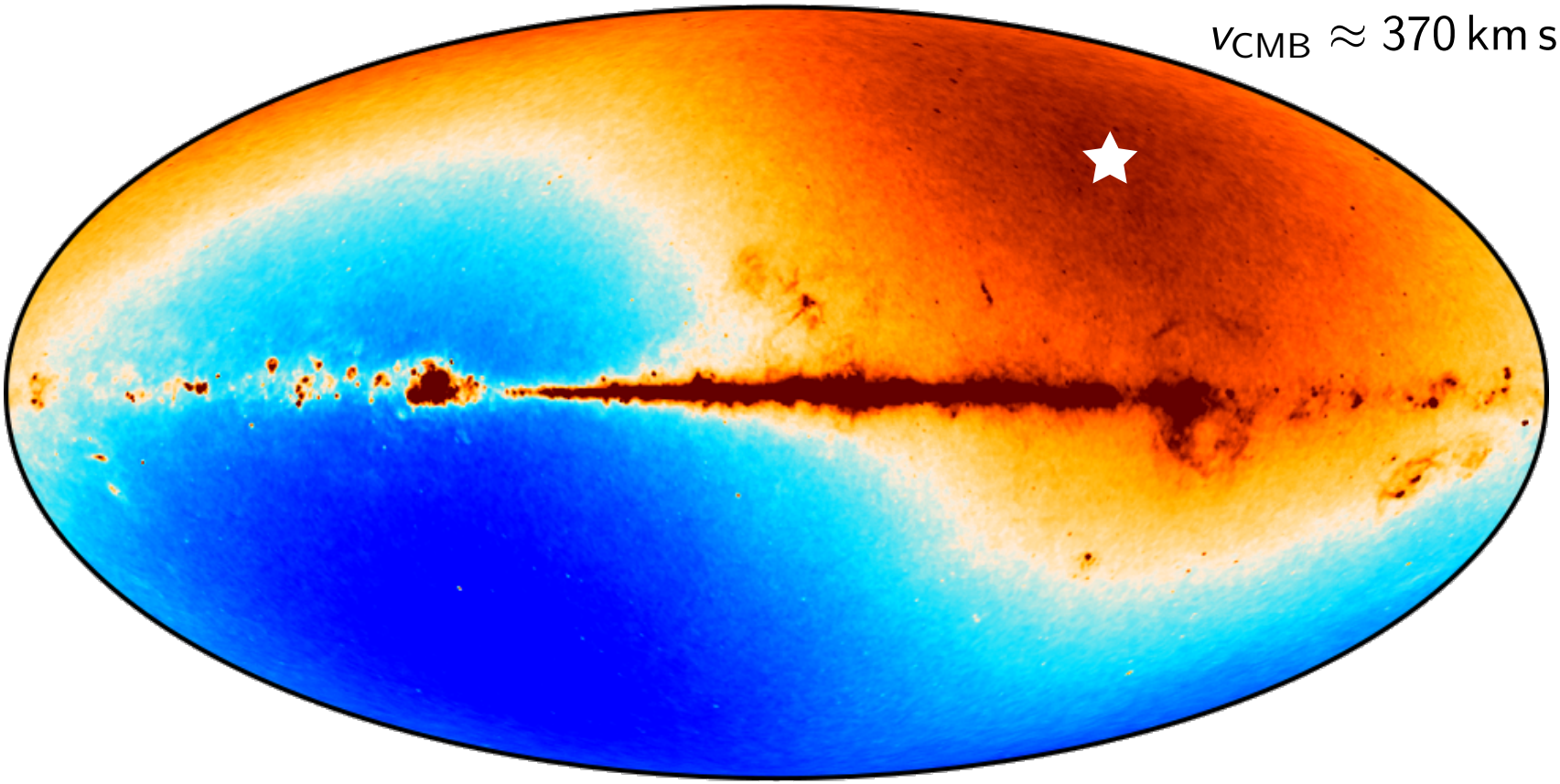

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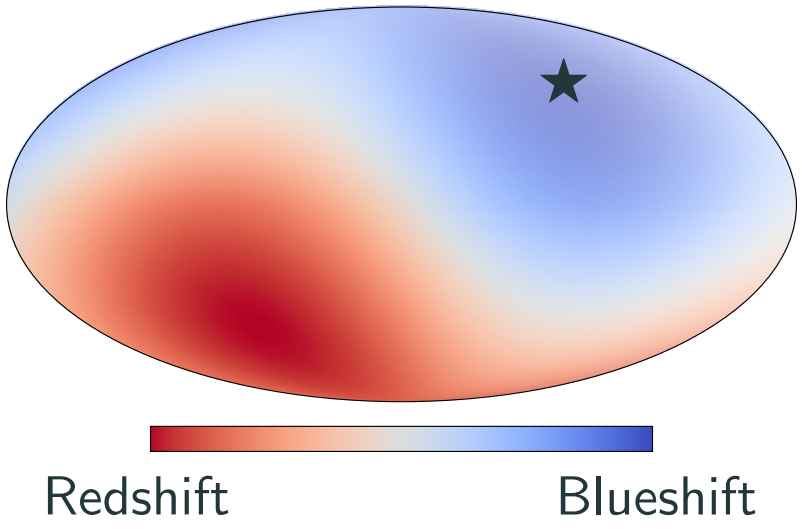
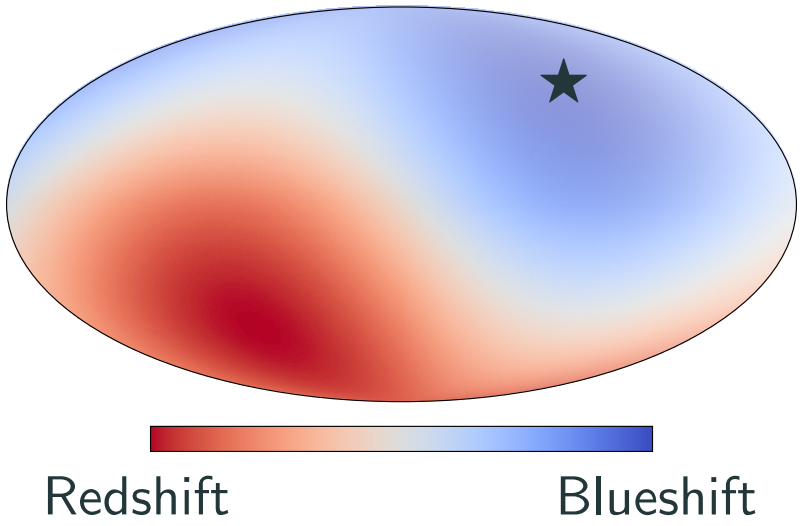
The Ellis & Baldwin Dipole



Our motion $\Longrightarrow$ a dipole in source density.

The Ellis & Baldwin Dipole



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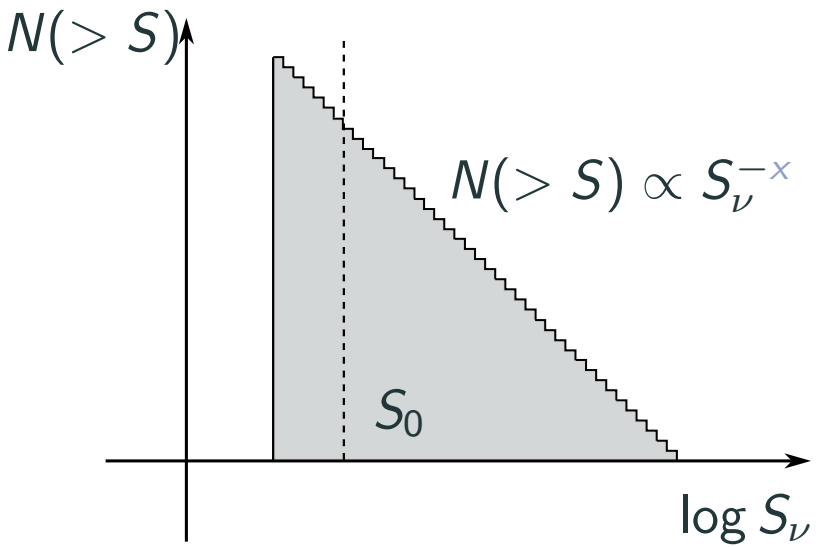

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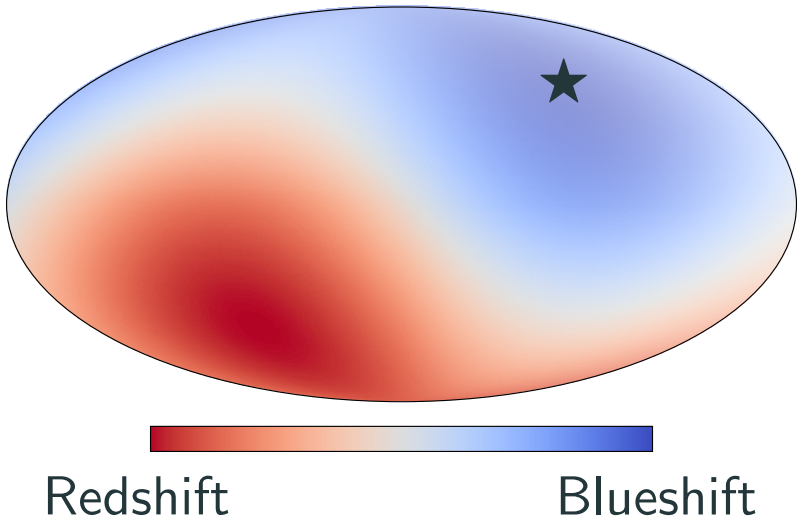

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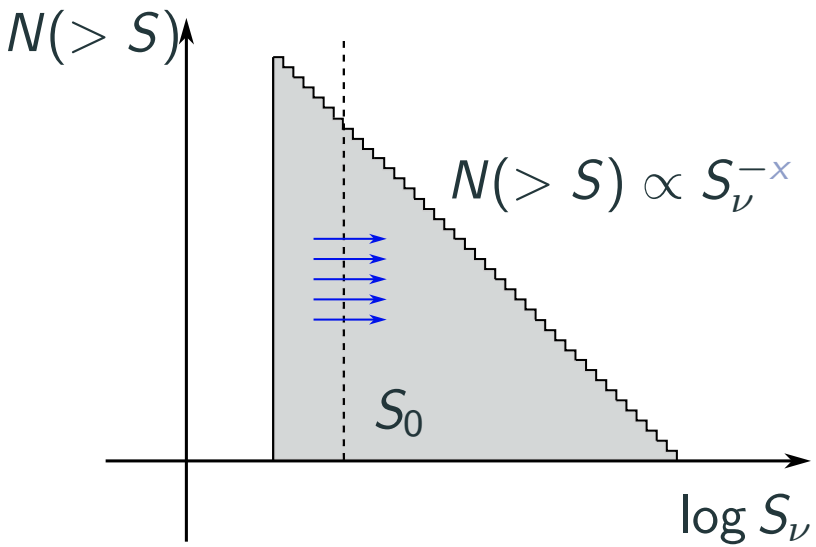

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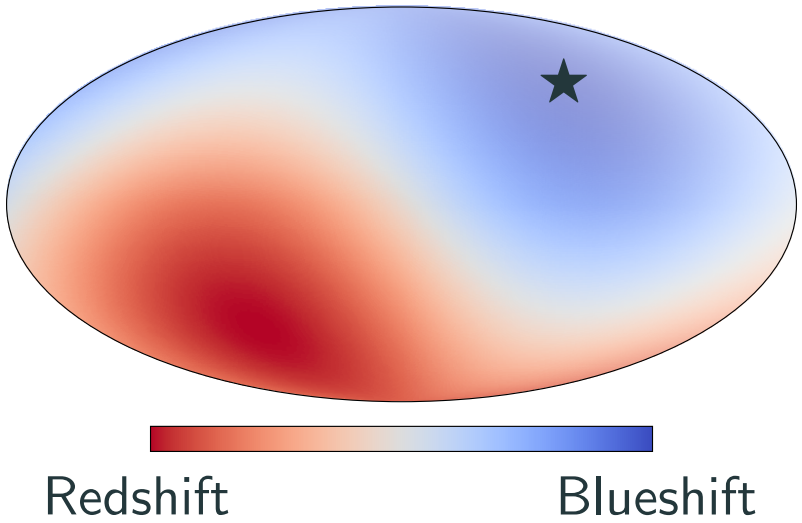

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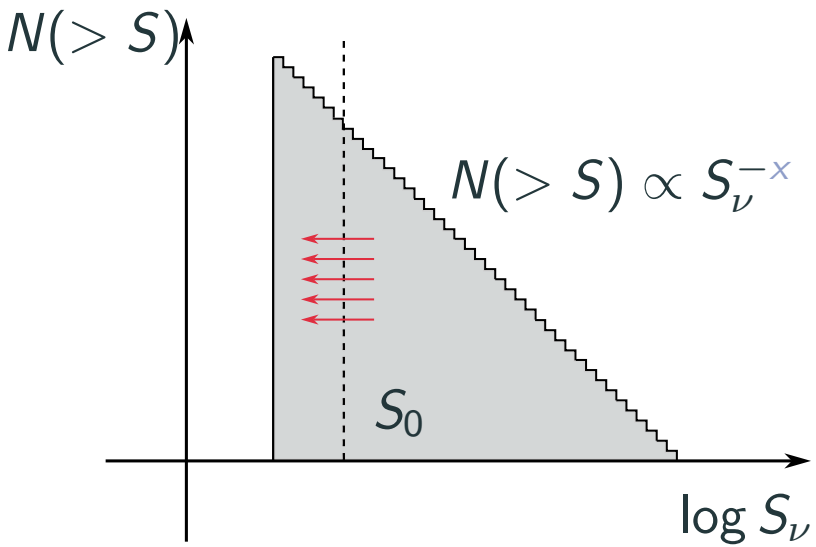

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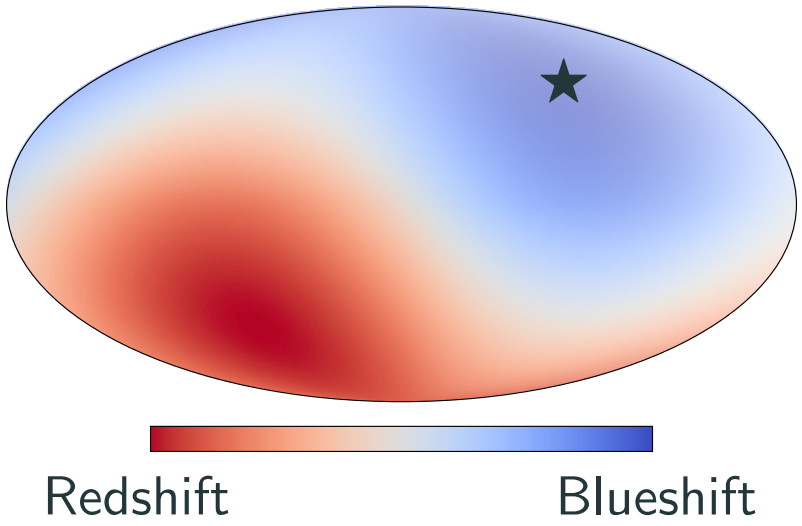

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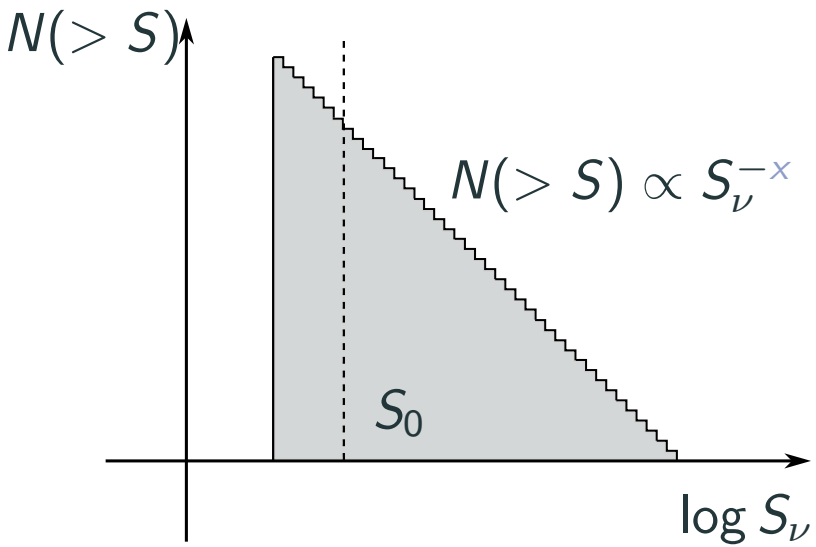

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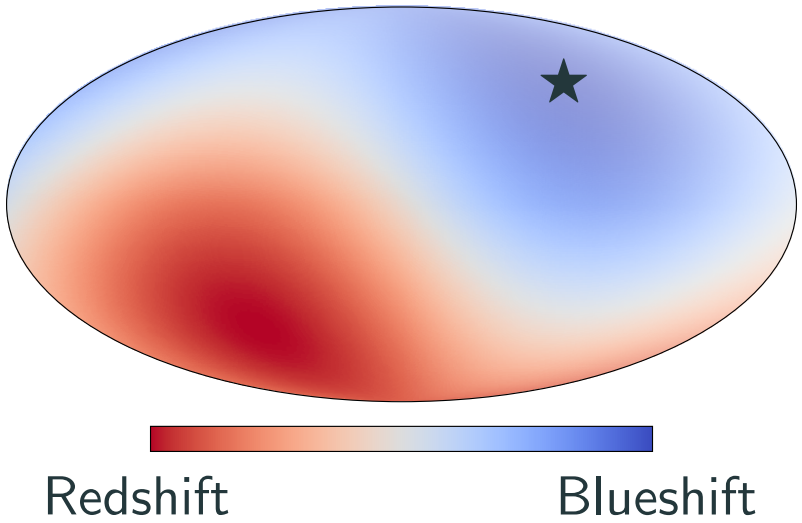

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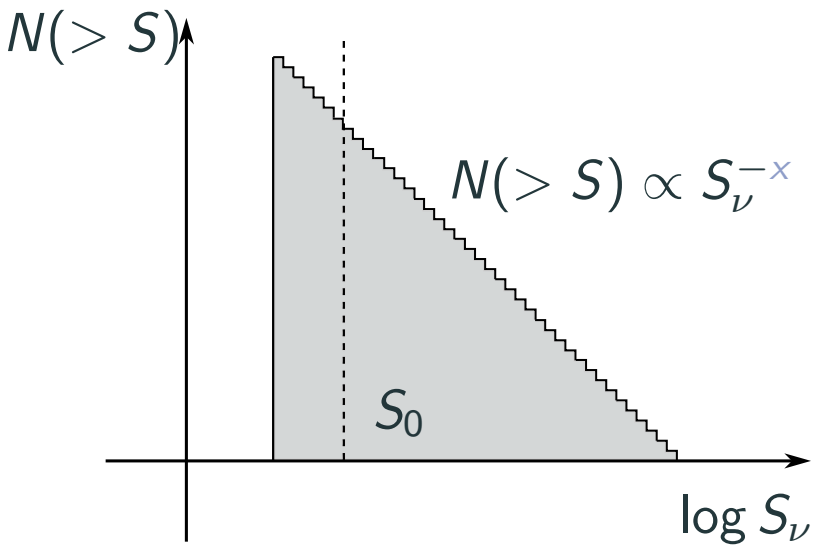

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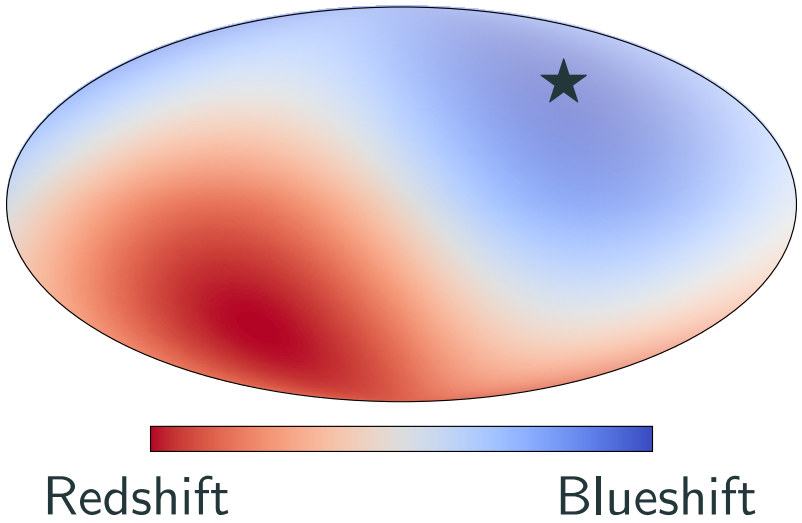

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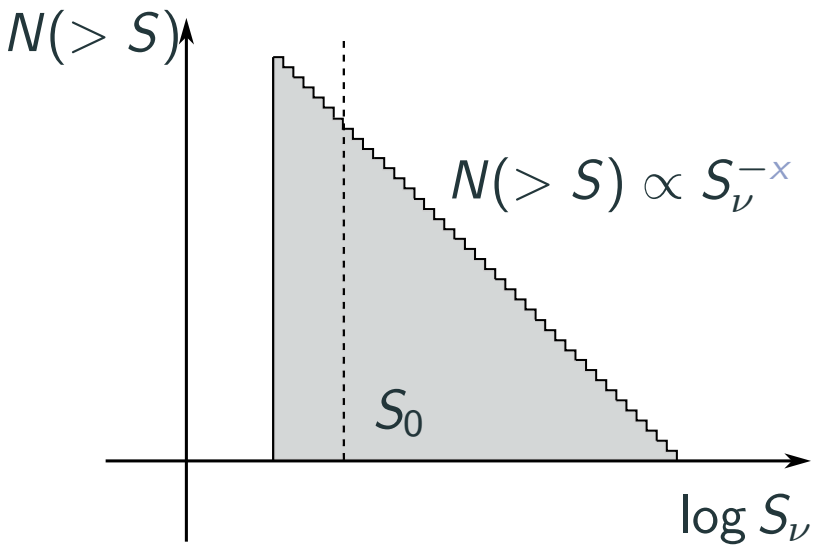
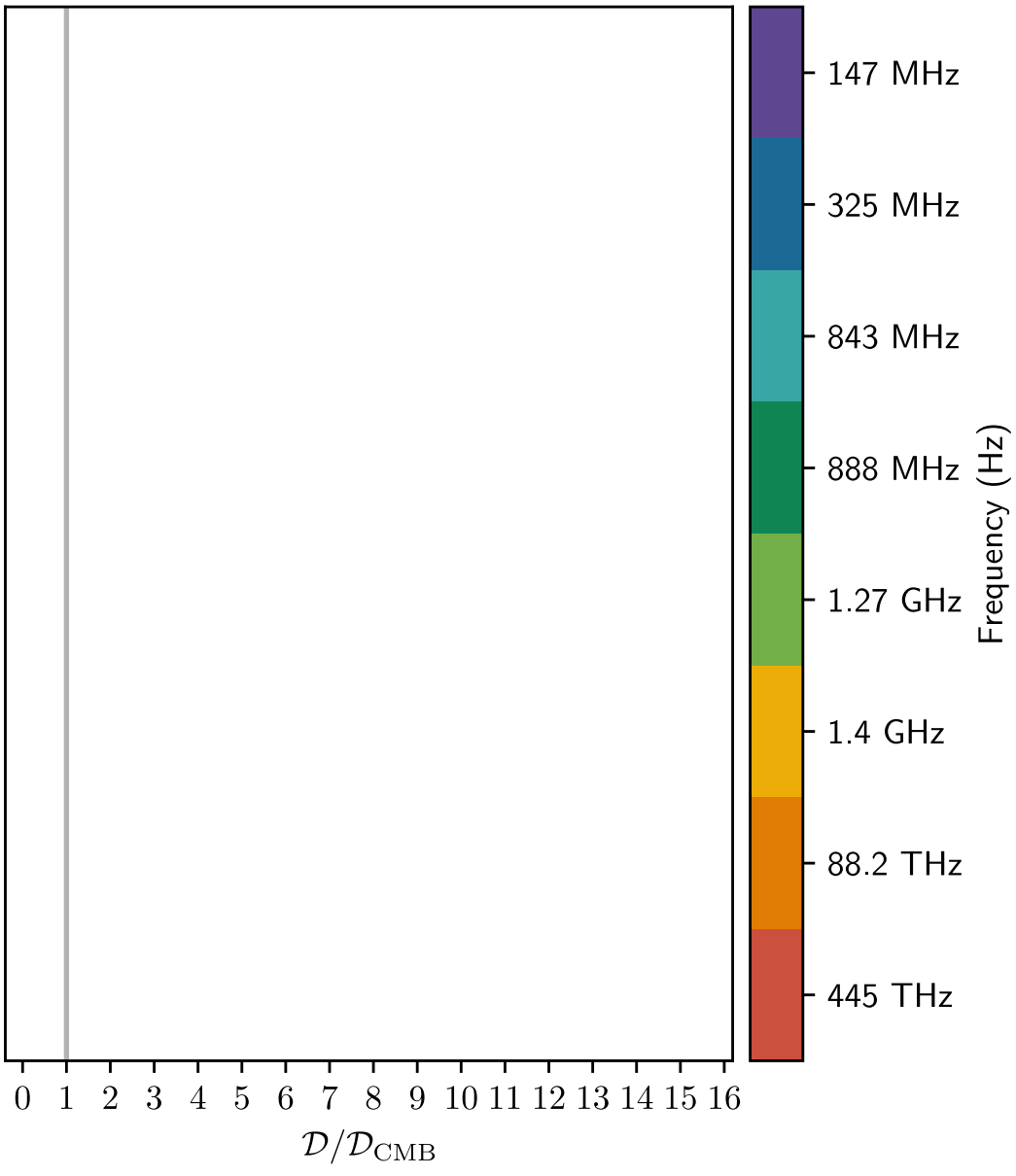


Typical values: 0.004 – 0.007.

A *0.5% effect!*

The Amplitude Excess



Cosmic dipole should be consistent with CMB dipole...

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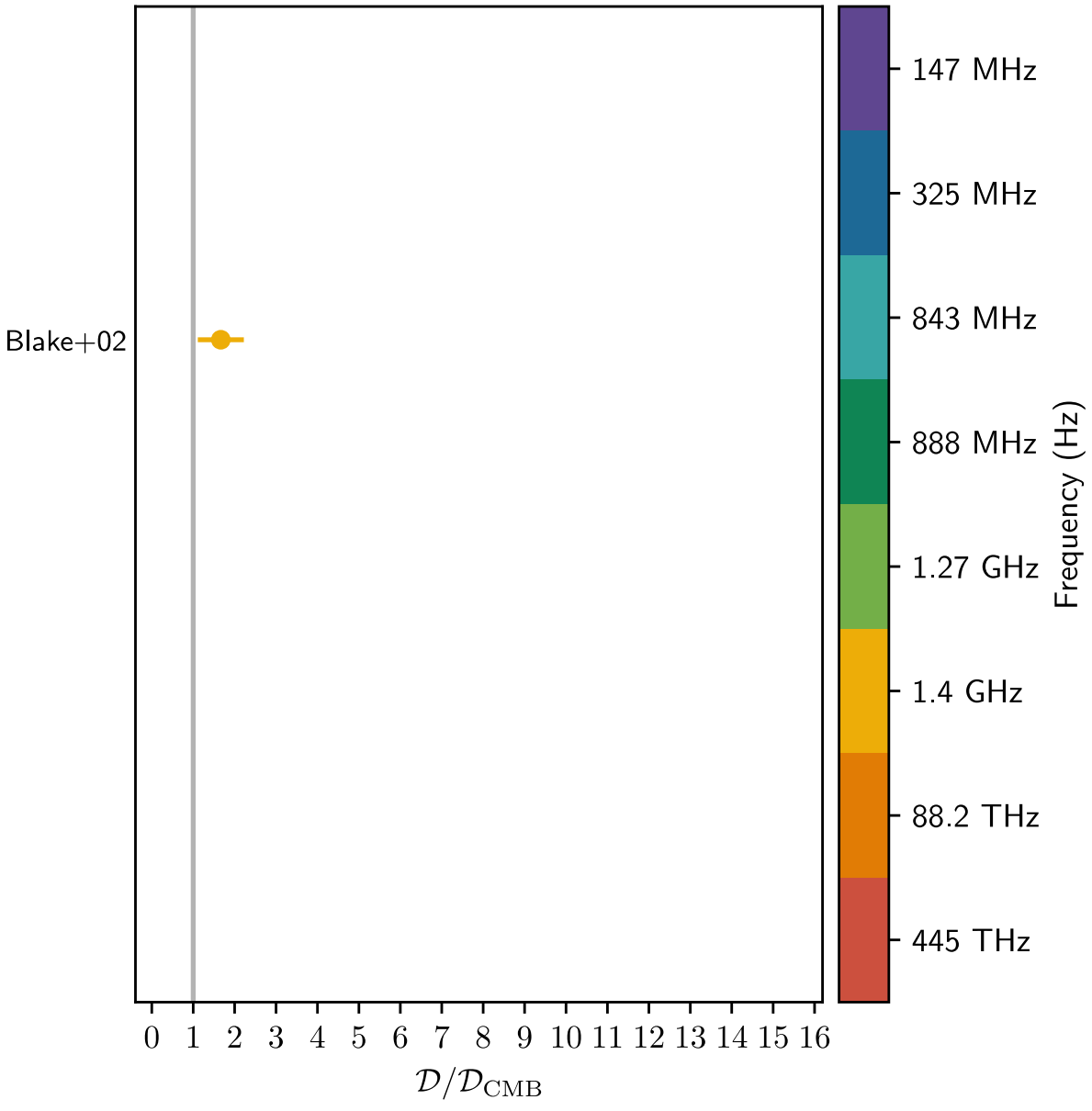

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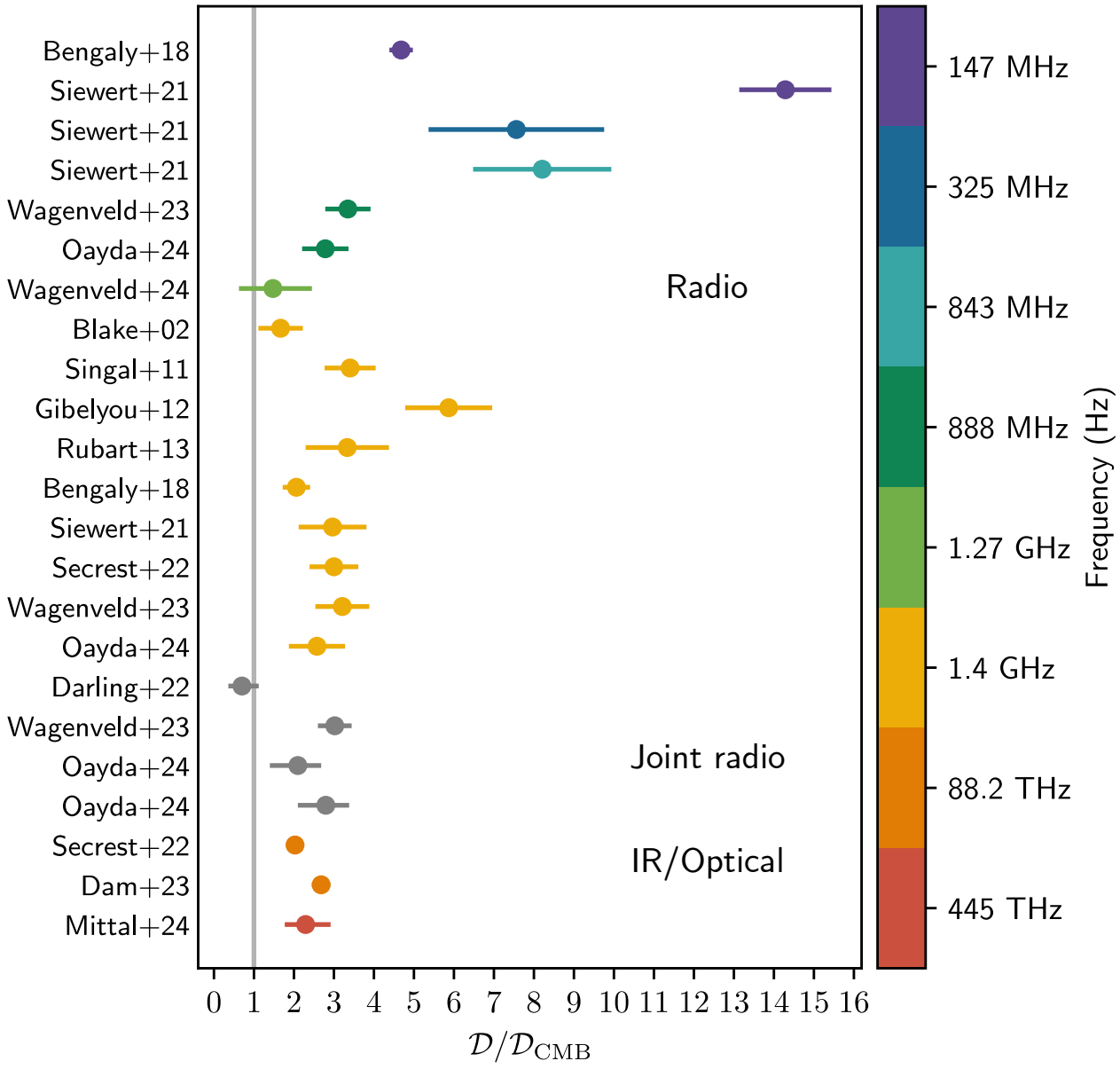

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All is well!

Wait...

The dipole tension, like the Hubble tension, challenges the fiducial ΛCDM paradigm.

The Three S's

1. **S**ystematics
   - Are we measuring what we think we're measuring?
2. **S**urvey design or **S**trategy
   - How do we optimise information?
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The cosmic dipole in the Quaia sample of quasars: a Bayesian analysis

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[1]*Department of Physical Sciences, IISER Mohali, Knowledge City, Sector 81, SAS Nagar, Manauli PO 140306, Punjab, India*
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- Quaia sample, *Gaia* DR3 quasars
- Storey-Fisher et al. (2024)

(2024) MNRAS 527(3) 8497

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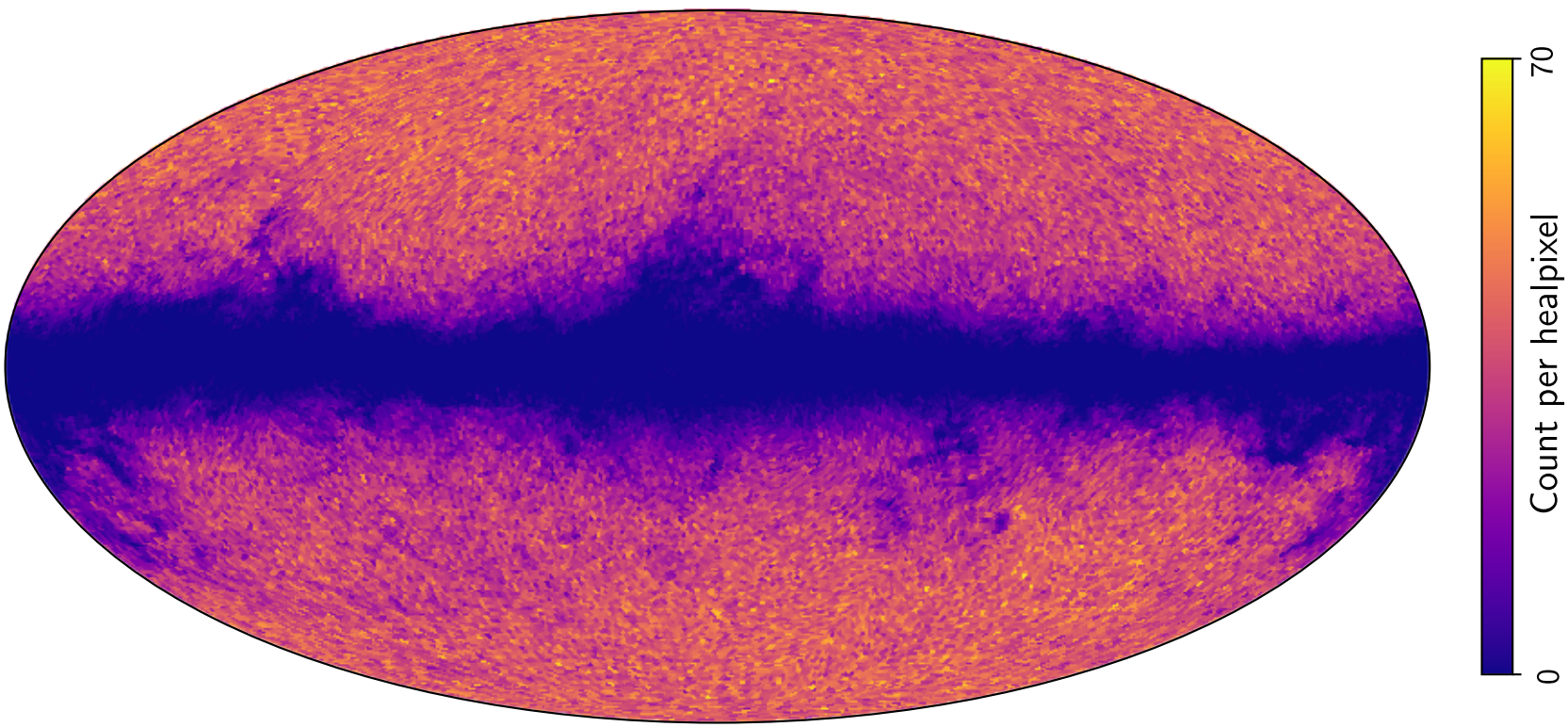

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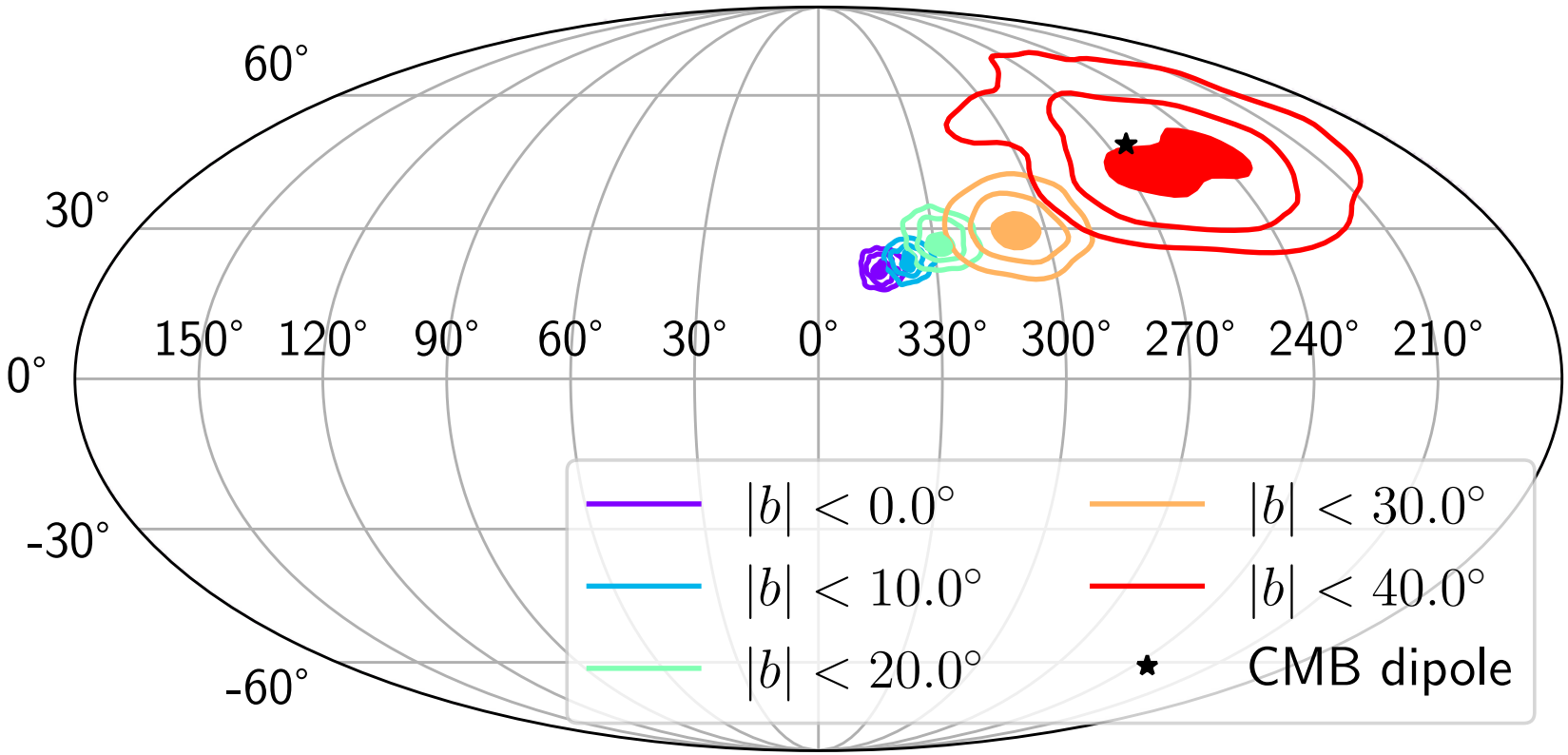

Amplitude $\mathcal{D}$ (10^{-3})	37^{+4}_{-4}	34^{+4}_{-4}	25^{+5}_{-5}	17^{+6}_{-6}	11^{+6}_{-5}	5★

NVSS & RACS — Local Sources Matter!

A Bayesian approach to the cosmic dipole in radio galaxy surveys: joint analysis of NVSS & RACS

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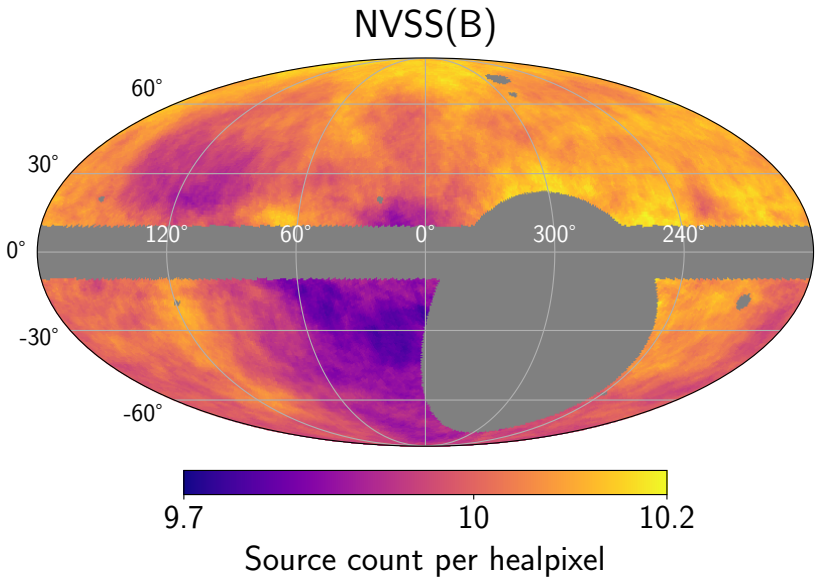

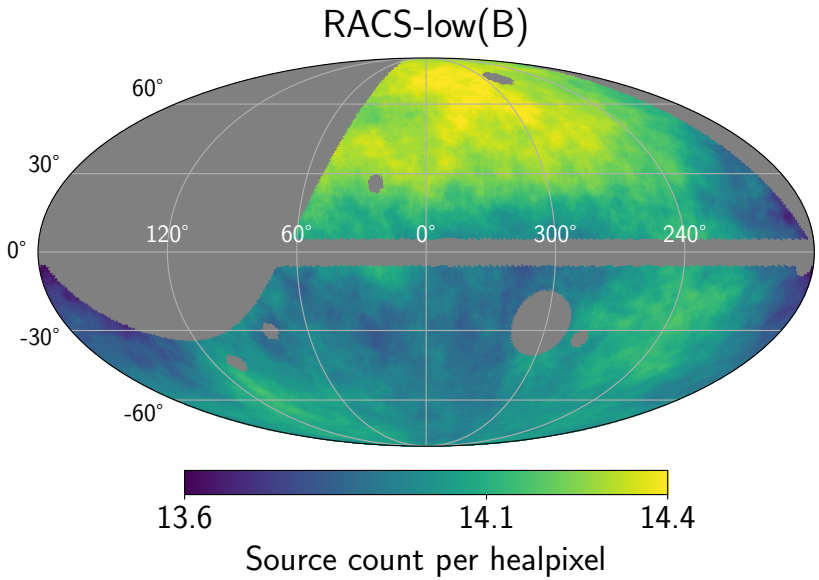

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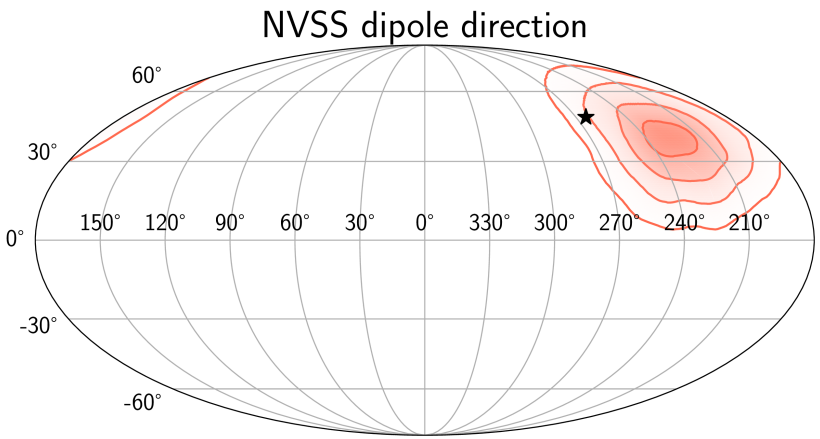

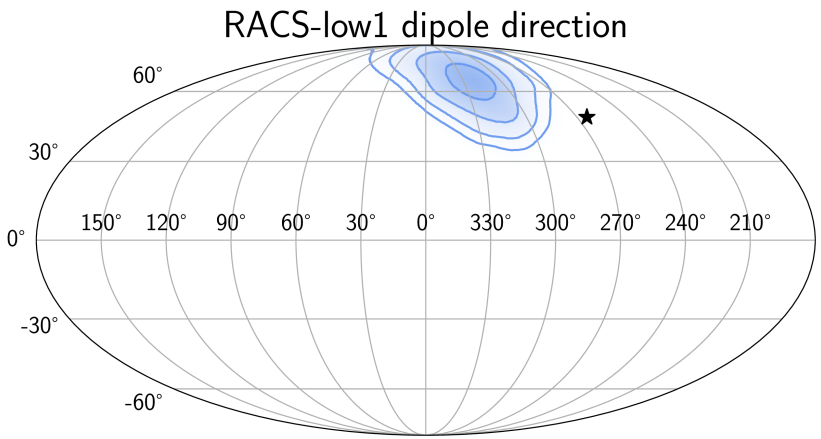

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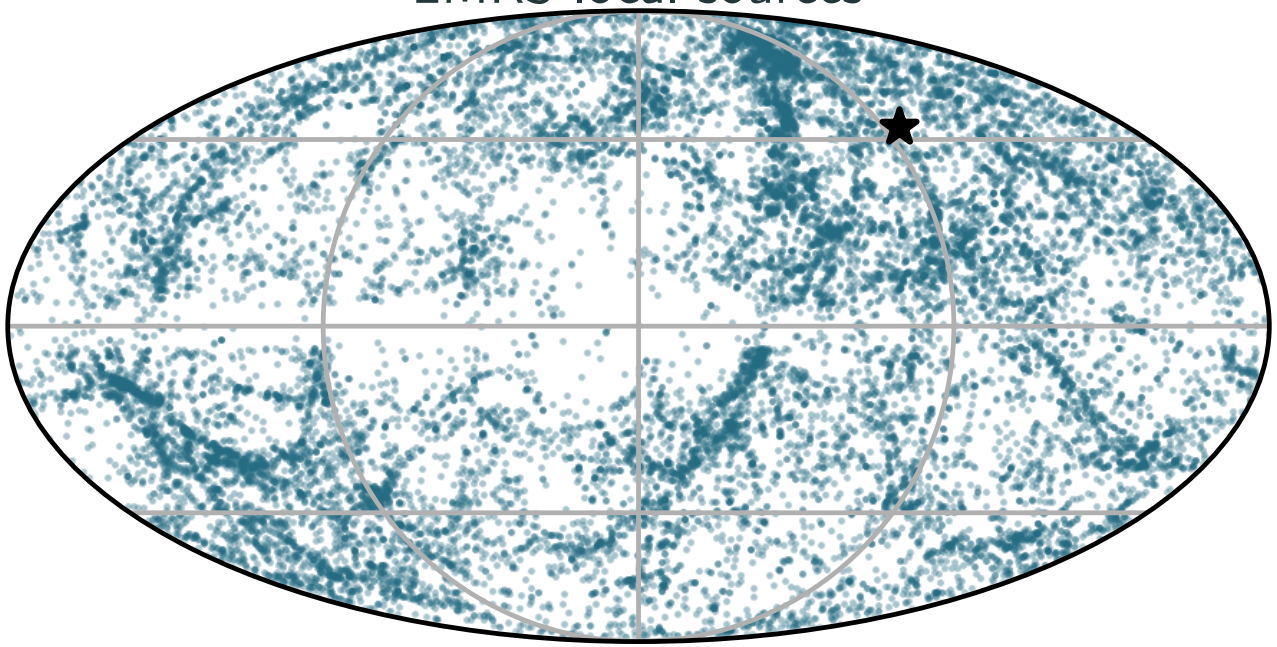
2MRS local sources



Cross-matching up to $z \approx 0.04 \implies$ 10–15% drop in $\mathcal{D}$

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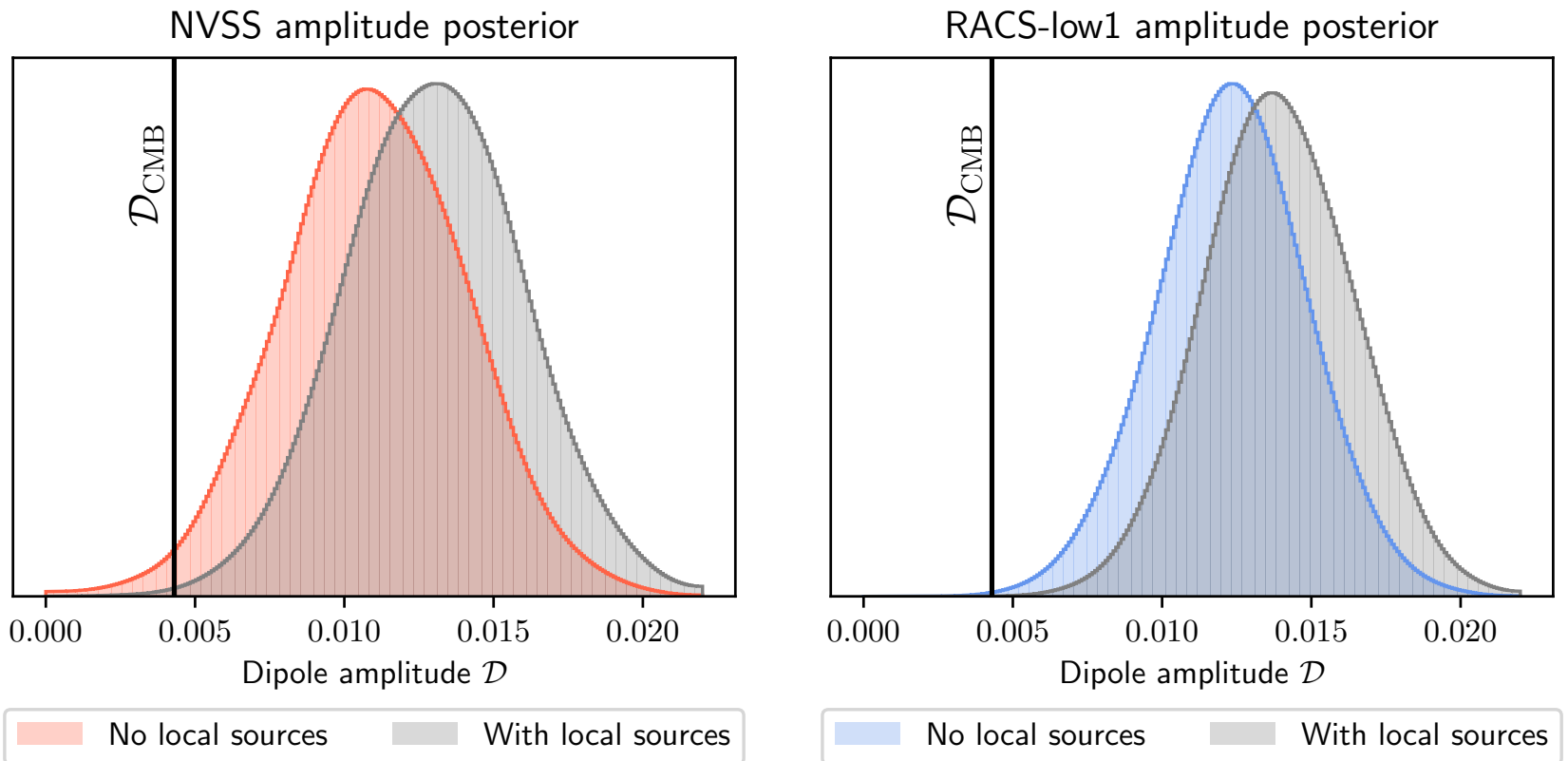

Pure kinematic interpretation an approximation...

Anticipating the Square Kilometre Array

- Generate mock SKA source catalogues/maps based on observing config (Hale, Tiwari and von Hausegger).
- Input: ΛCDM matter power spectrum.
- $\ell = 1$ moment — not kinematic!

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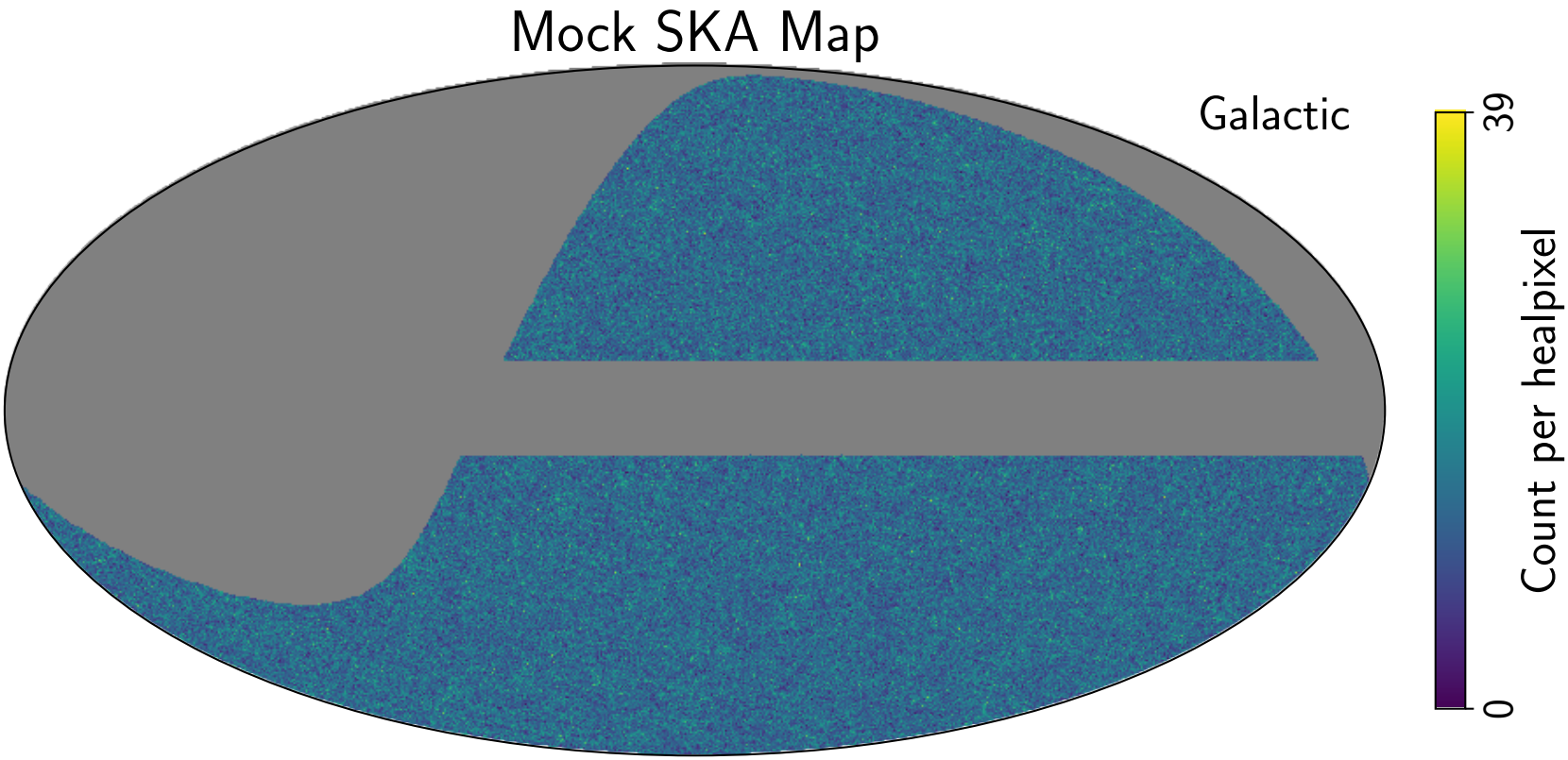

with M. Land-Strykowski and V. Mittal

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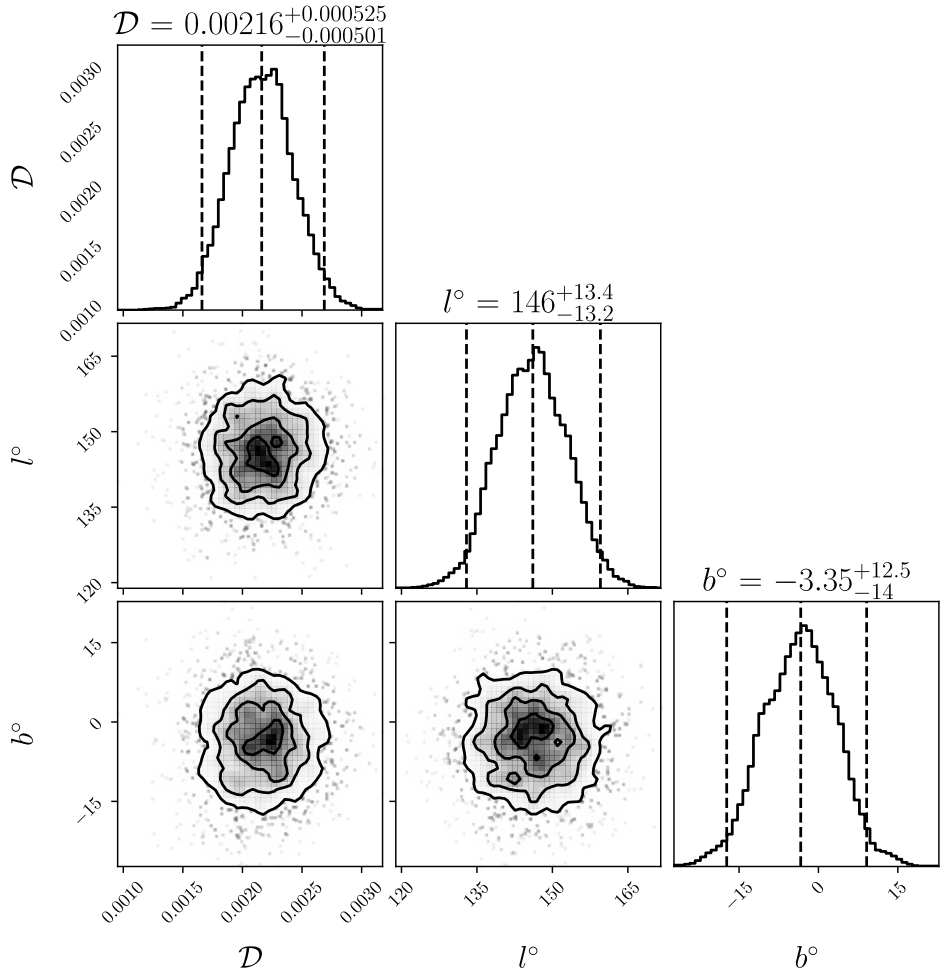

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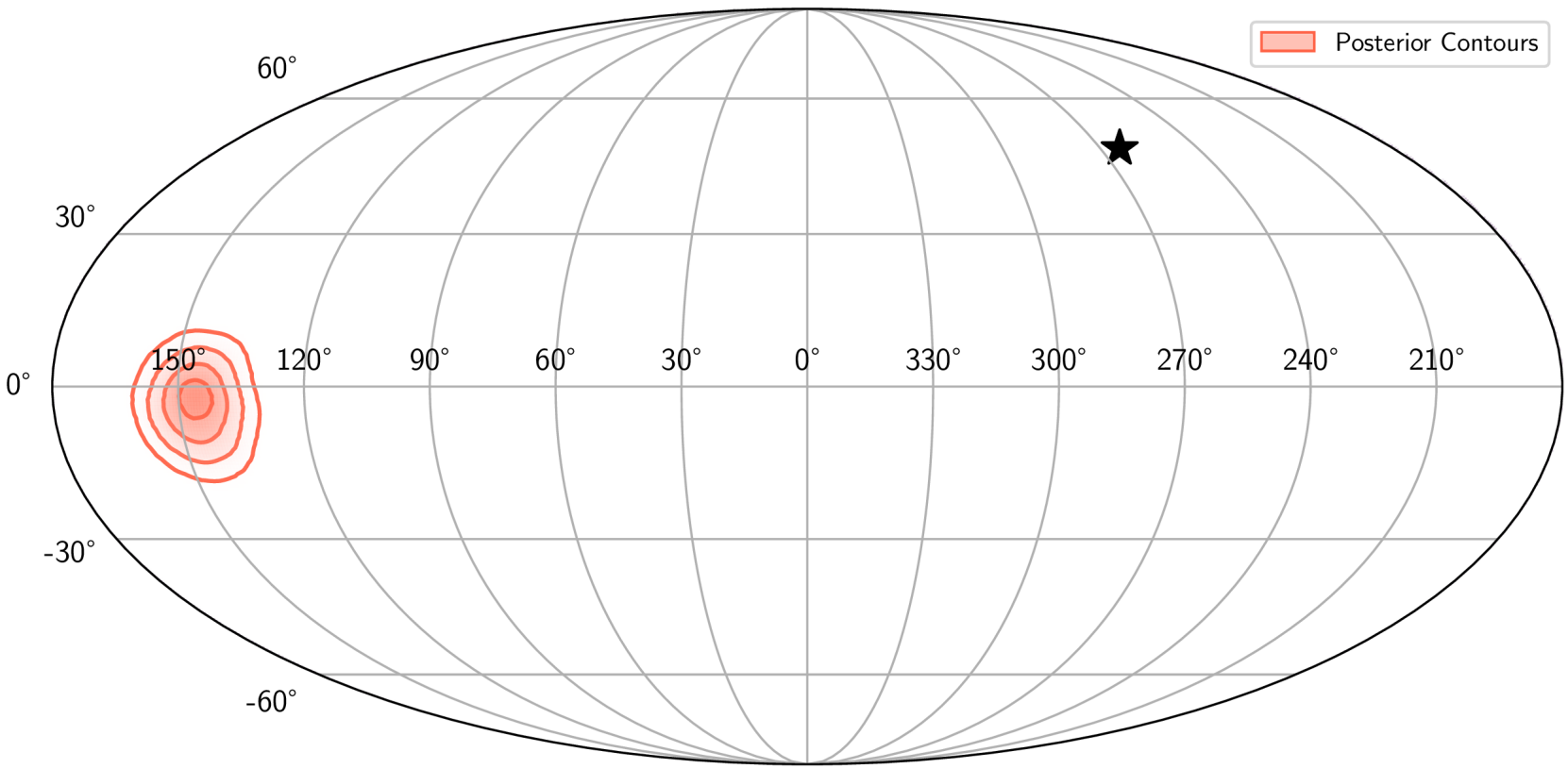

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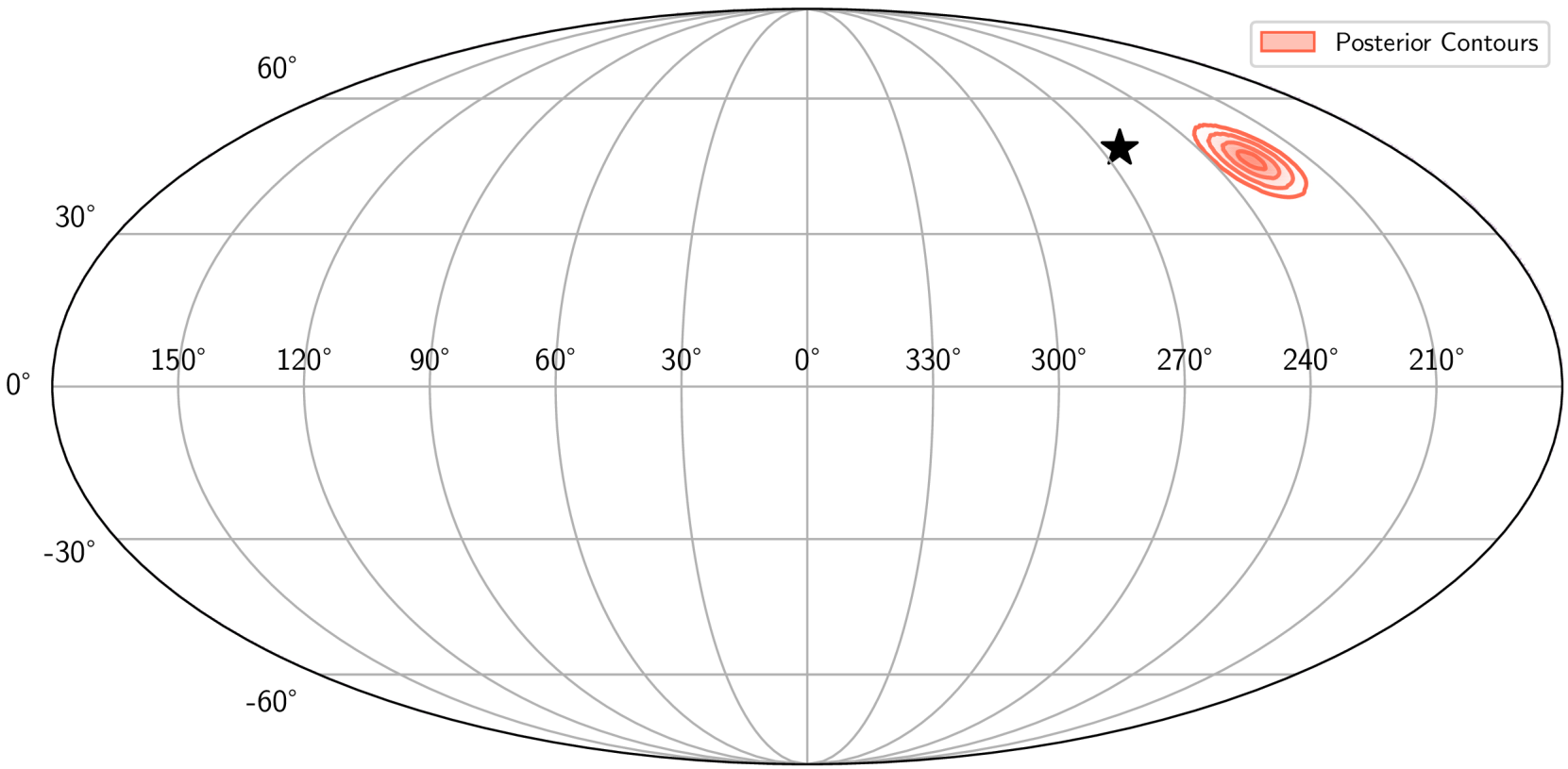

Clustering 'drags' inferred dipole. $D_{\text{clust.}} \approx 0.002$, $D_{\text{kin.}} \approx 0.005$

with M. Land-Strykowski and V. Mittal

Source Counts & Sky Coverage

Cosmic multipoles in galaxy surveys – I. How inferences depend on source counts and masks

Oliver T. Oayda ,★ Vasudev Mittal and Geraint F. Lewis
Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia

(2025) MNRAS 537(1) 1

- Synthesis of source count, sky coverage and position of visible sky.
- Optimising these yields the highest information (D_{KL}).

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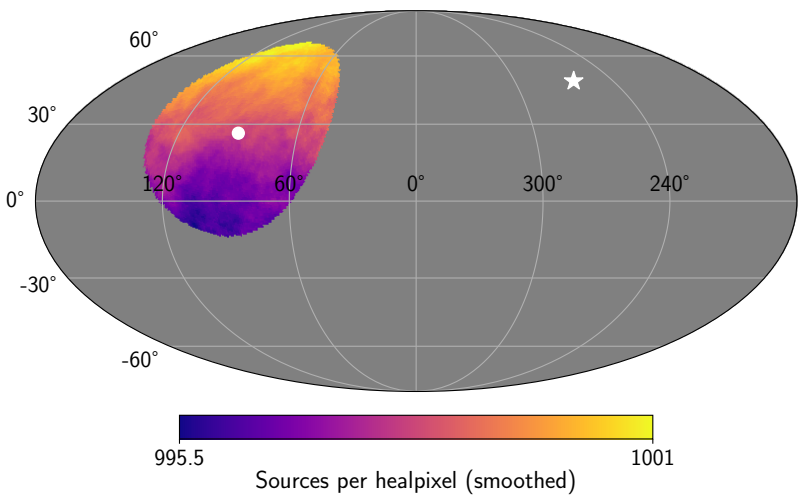

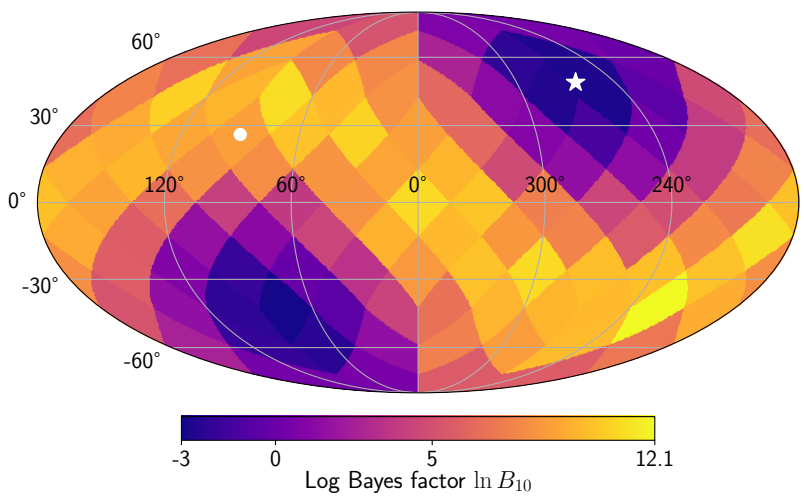

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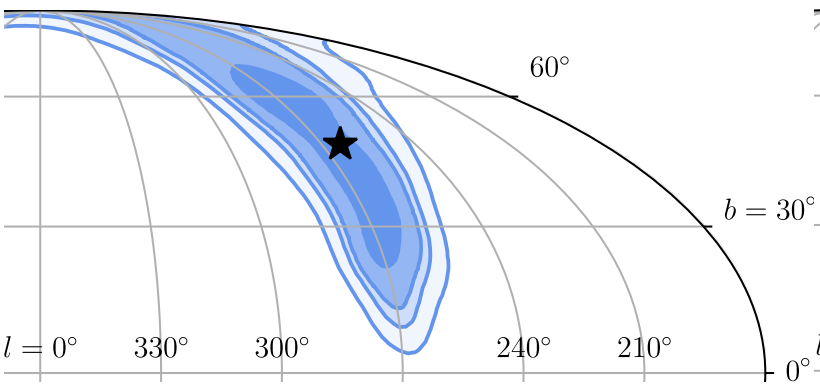
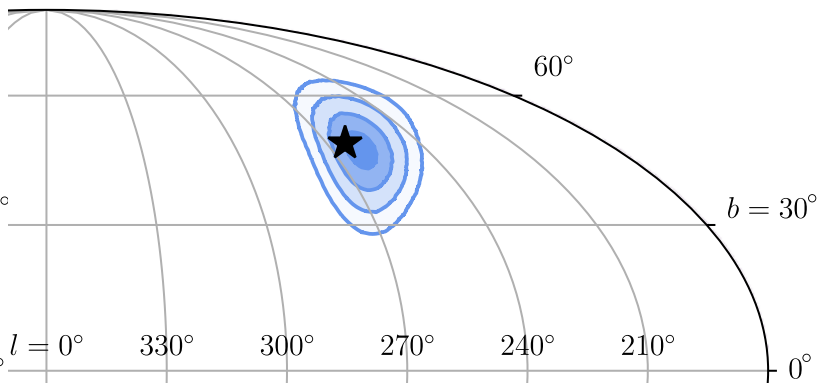


40° slice, 5.75 million sources



40° slice, 150 million sources

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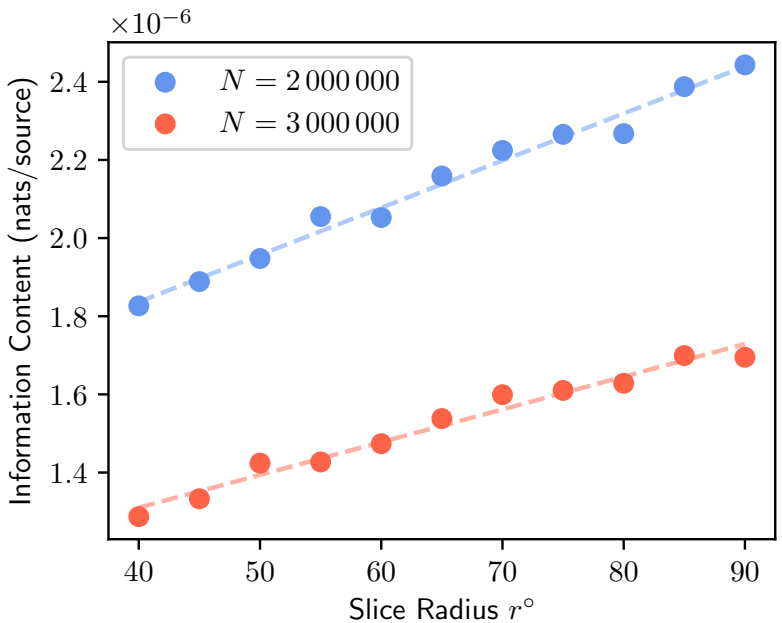

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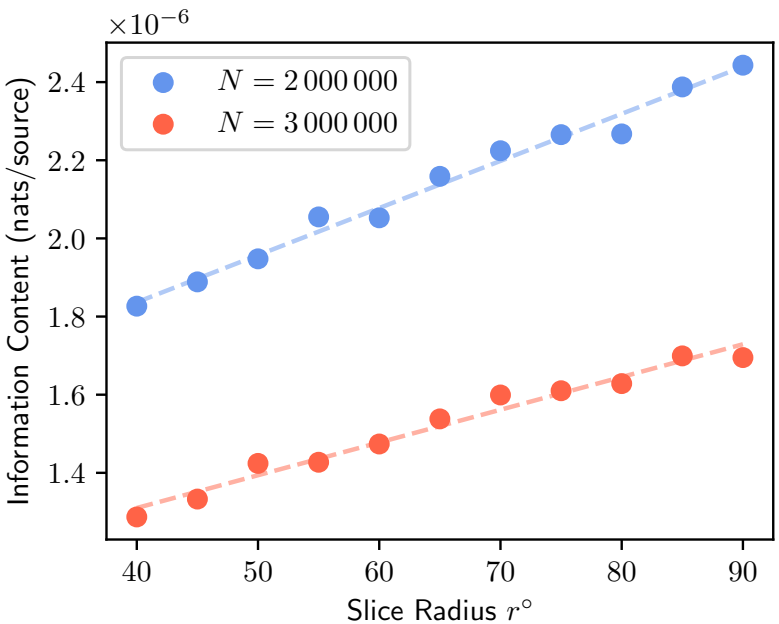

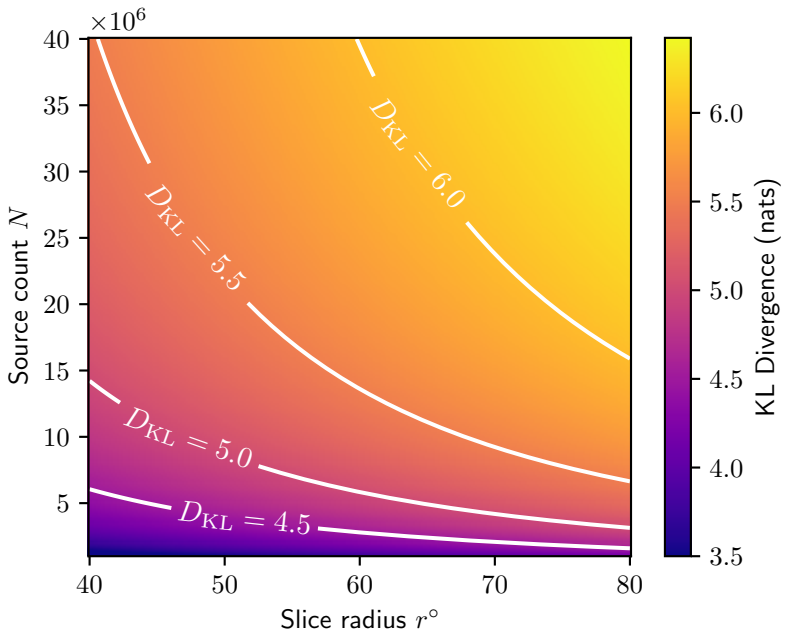

Cosmic multipoles in galaxy surveys – I. How inferences depend on source counts and masks

Oliver T. Oayda ,★ Vasudev Mittal and Geraint F. Lewis
Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia

(2025) MNRAS 537(1) 1

- Synthesis of source count, sky coverage and position of visible sky.
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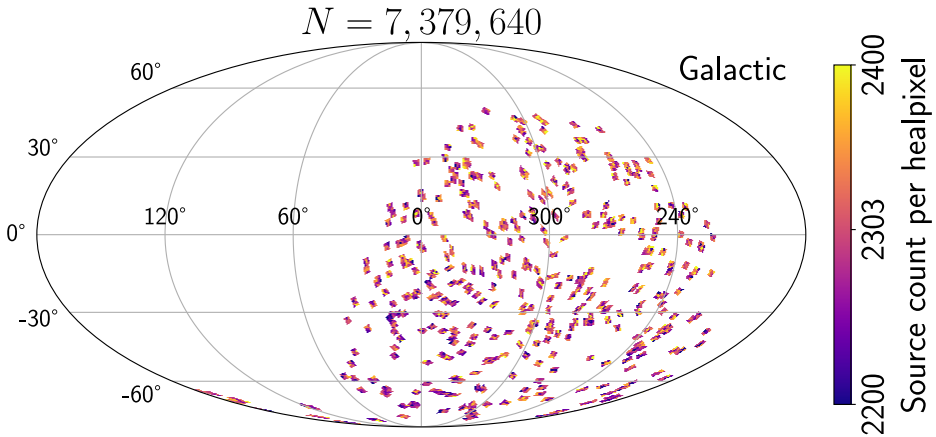

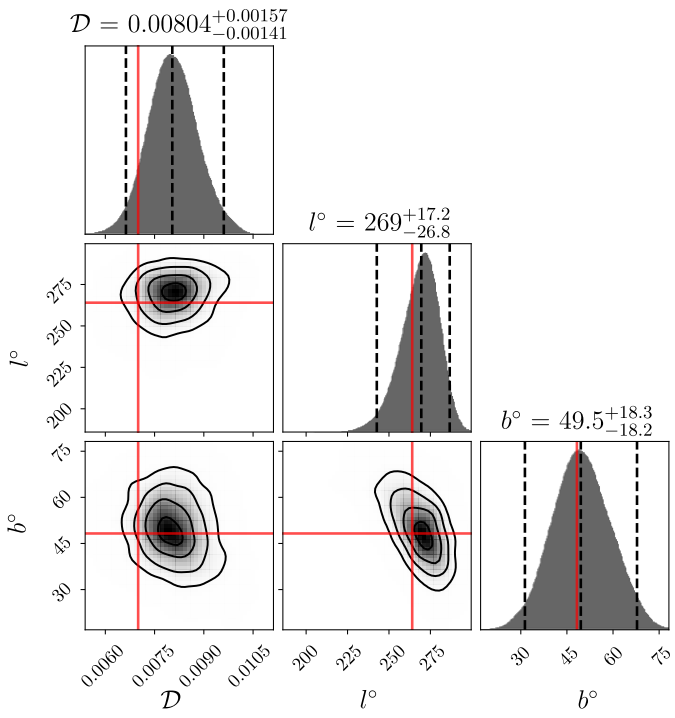

Journeying Towards Higher Orders

Why do we want to account for higher ℓ's?

- Incomplete sky coverage $\implies$ power leakage (Abghari et al. 2024).

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- Higher order multipoles?
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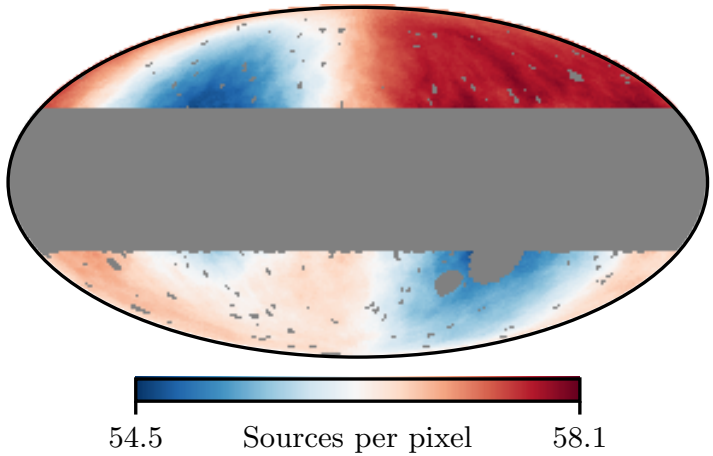

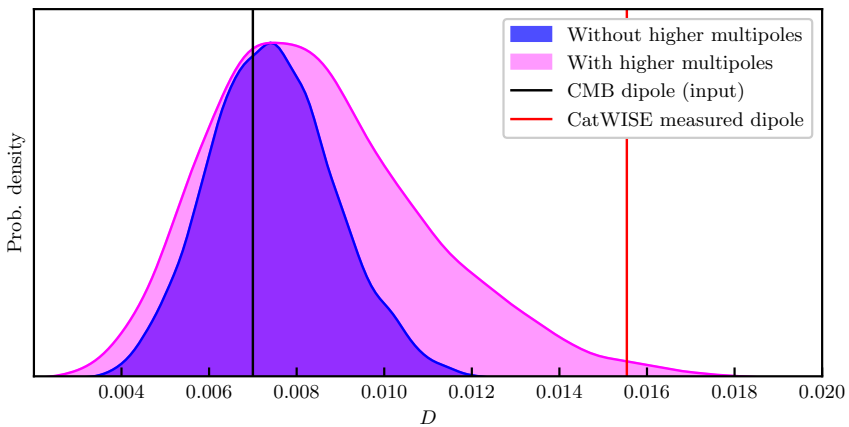

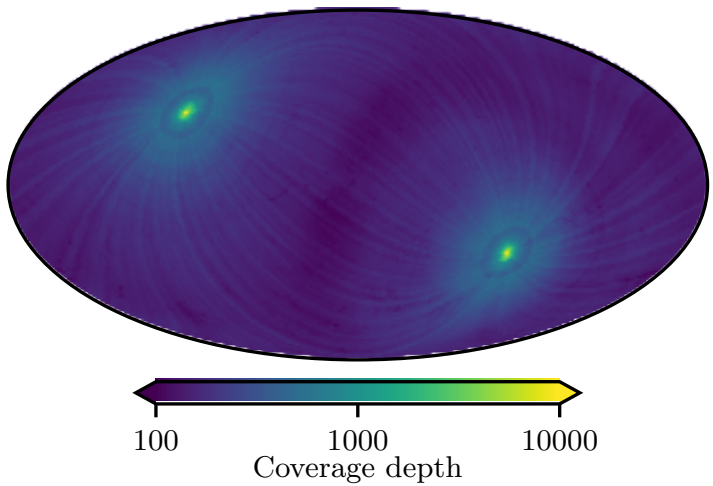

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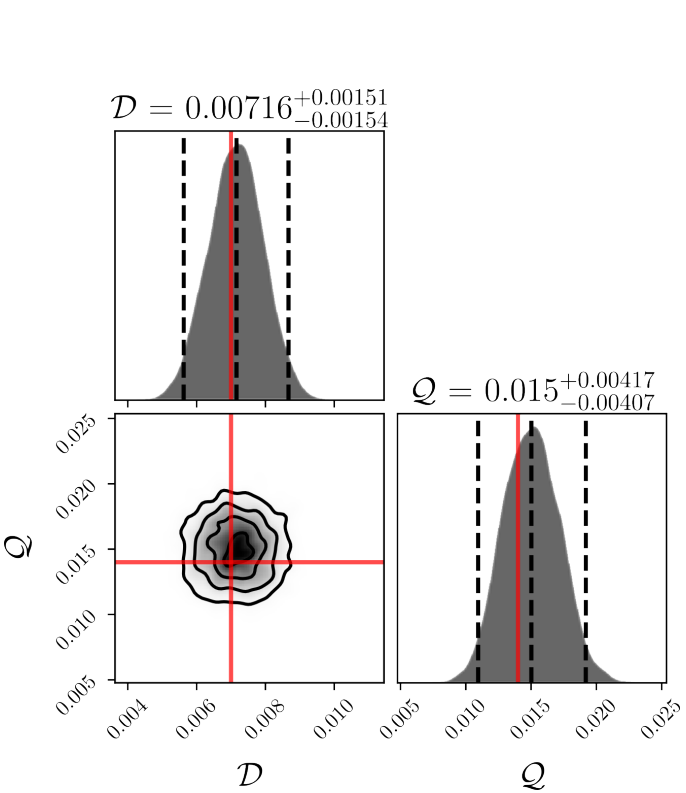

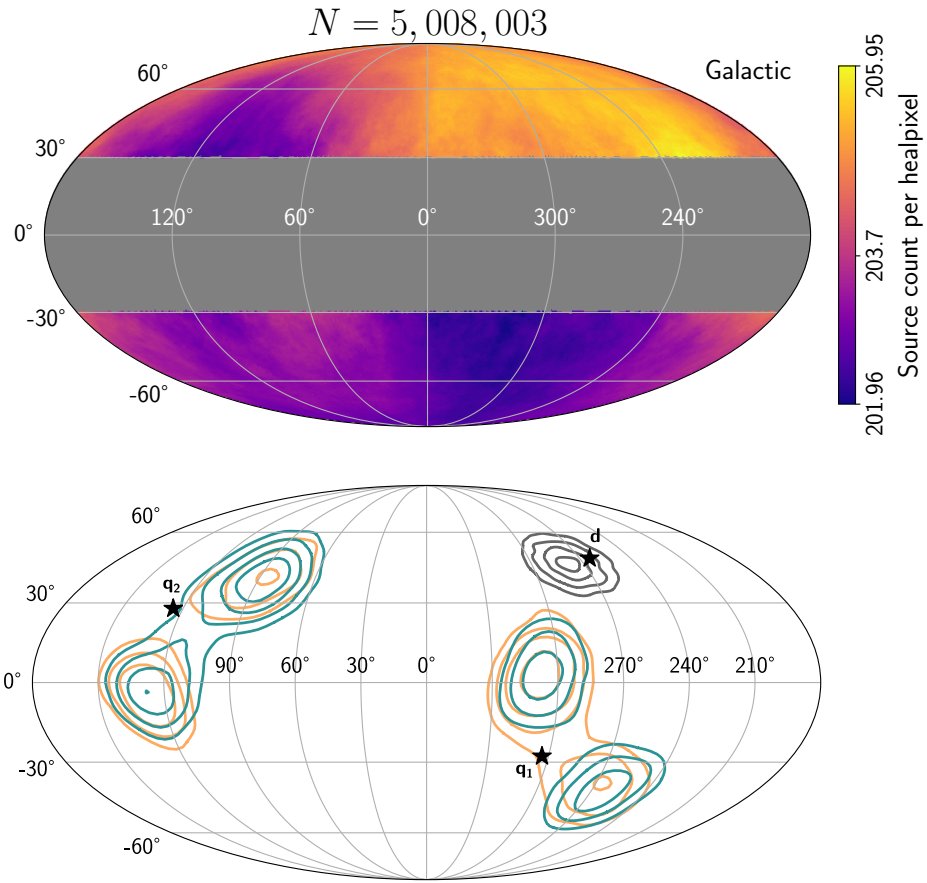

The dipole & quadrupole are disentangled from each other!

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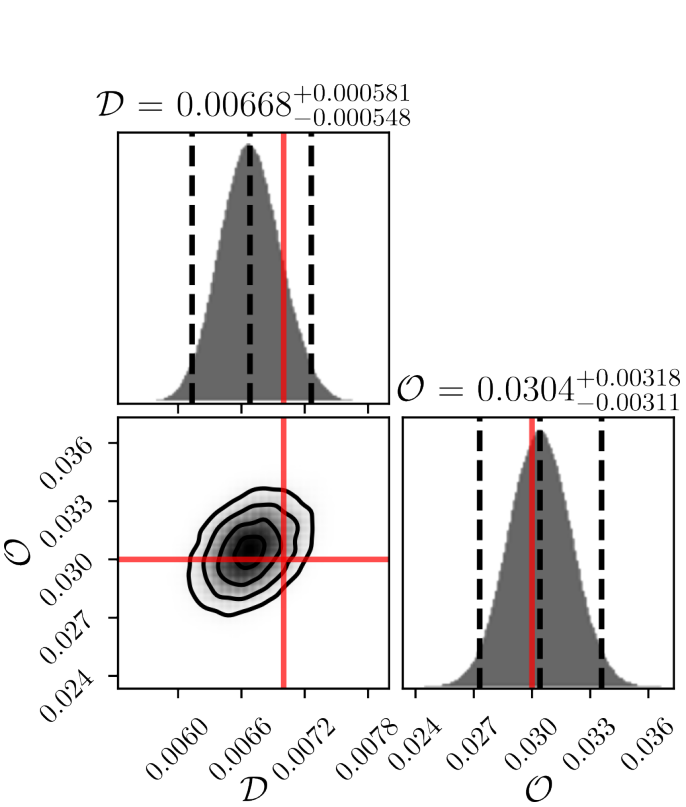

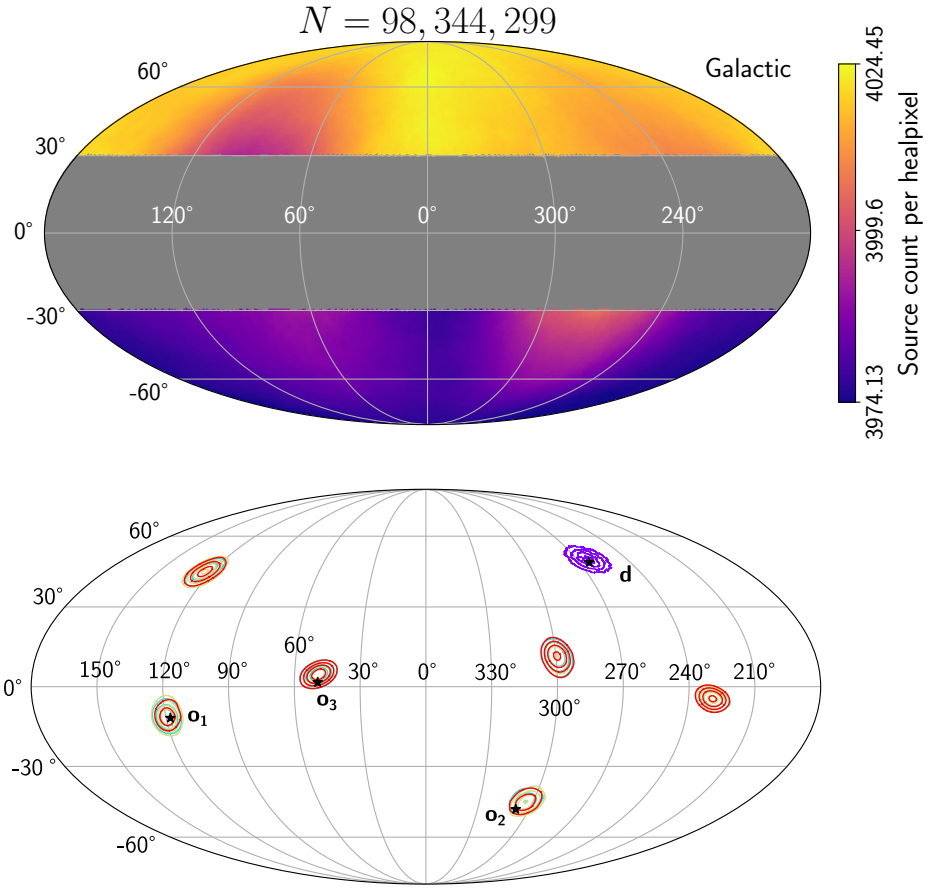

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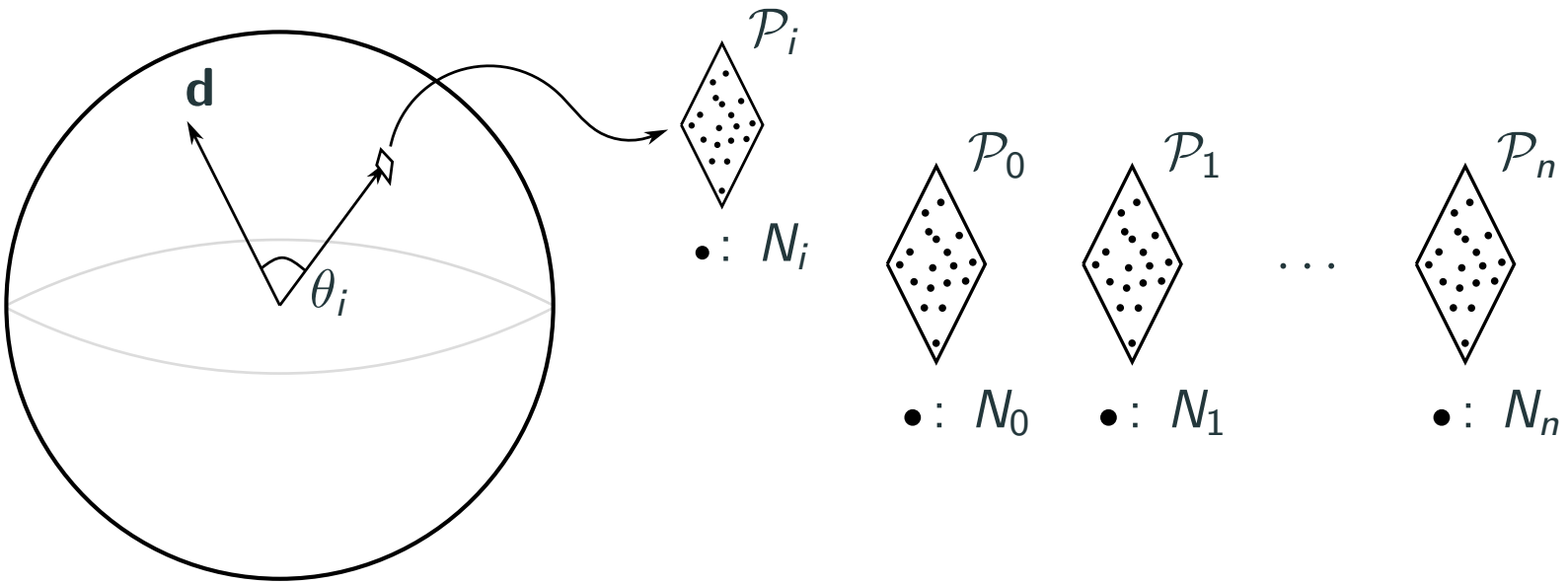
There's No Power Greater Than S...



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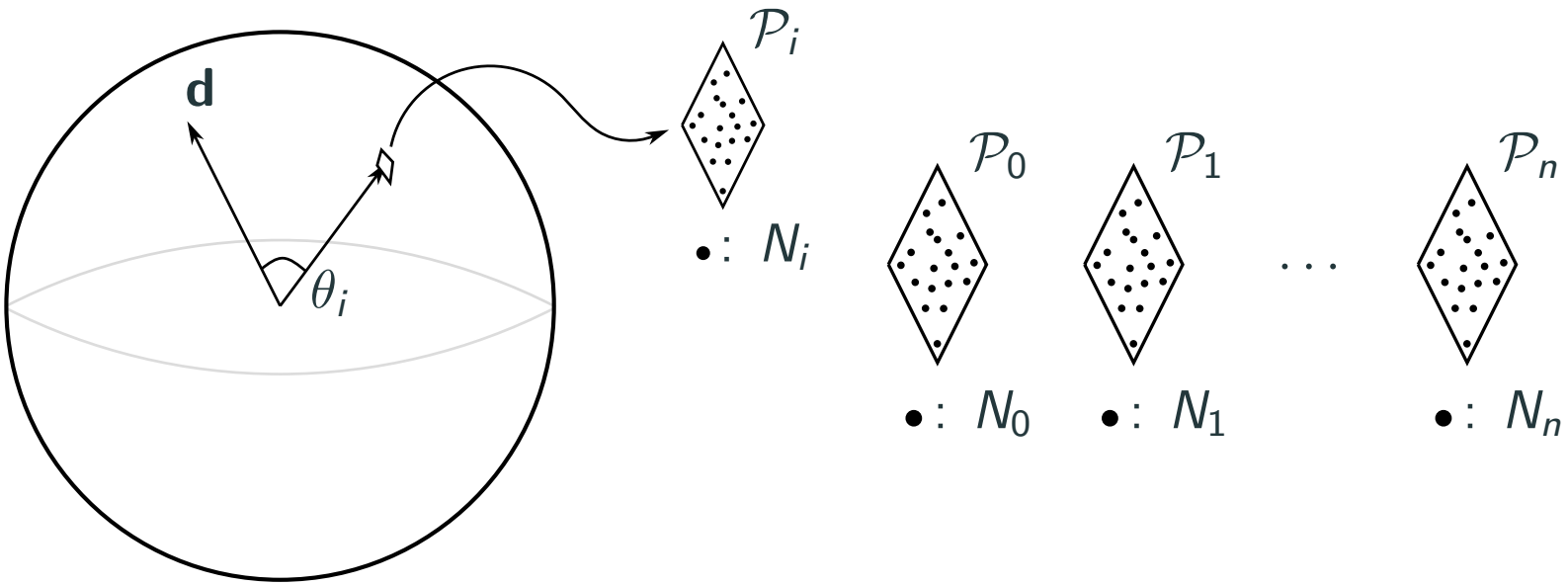

The classic likelihood-based approach:

$$P(\Theta|\mathbf{D}, M) = \frac{\mathcal{L}(\mathbf{D}|\Theta, M)\,\pi(\Theta|M)}{\mathcal{Z}(\mathbf{D}|M)}.$$

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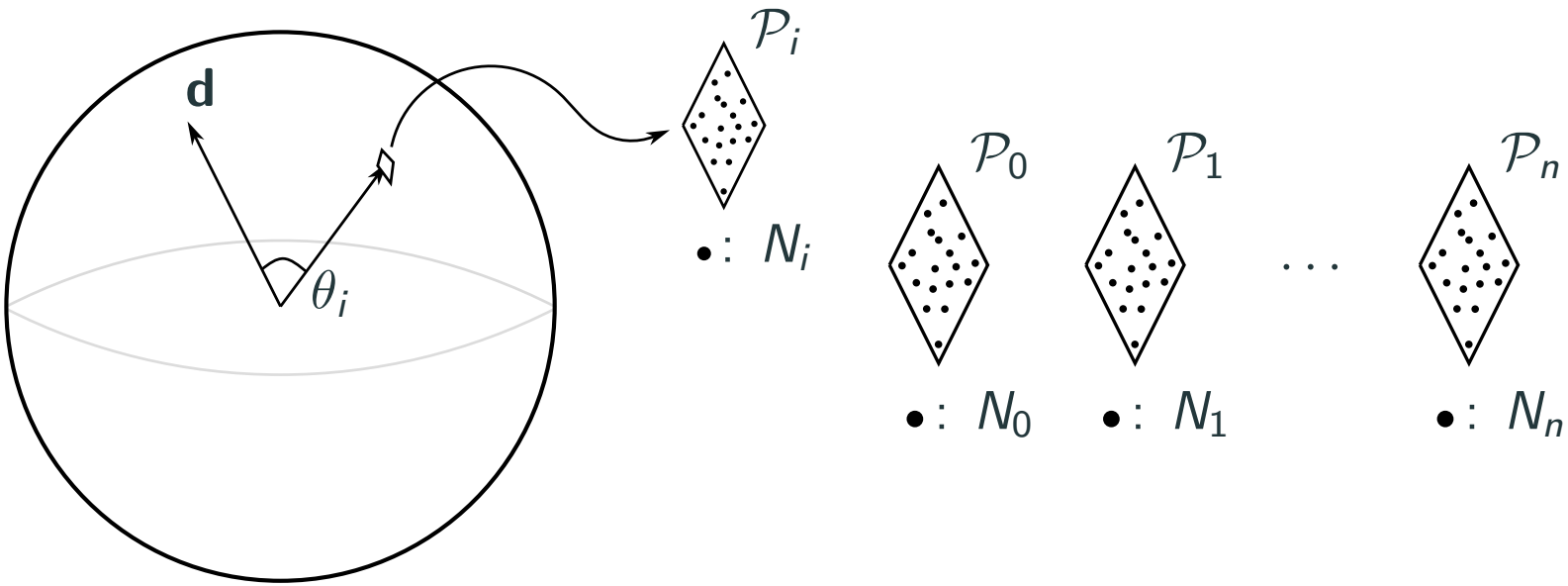

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We suppose $P(N_i|M_{\text{dipole}}) = \text{Pois}(\lambda_i)$ where

$$\lambda_i = \bar{N}(1 + \mathcal{D}\cos\theta).$$

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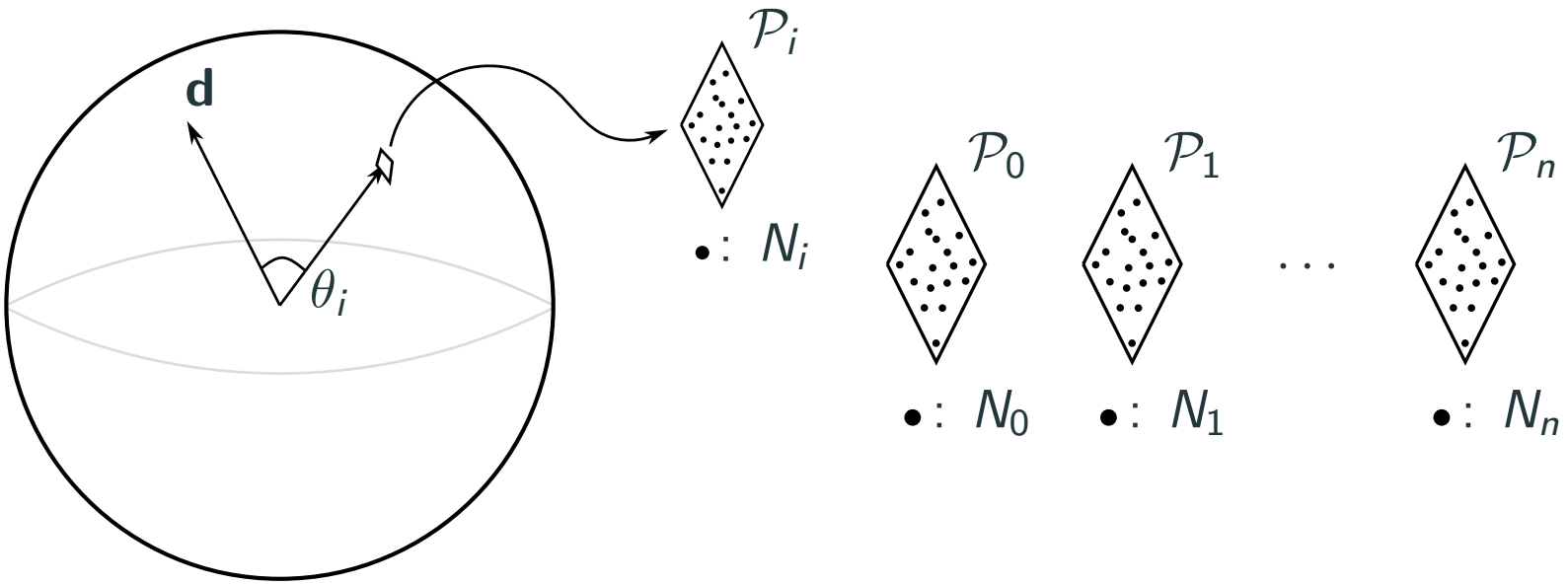

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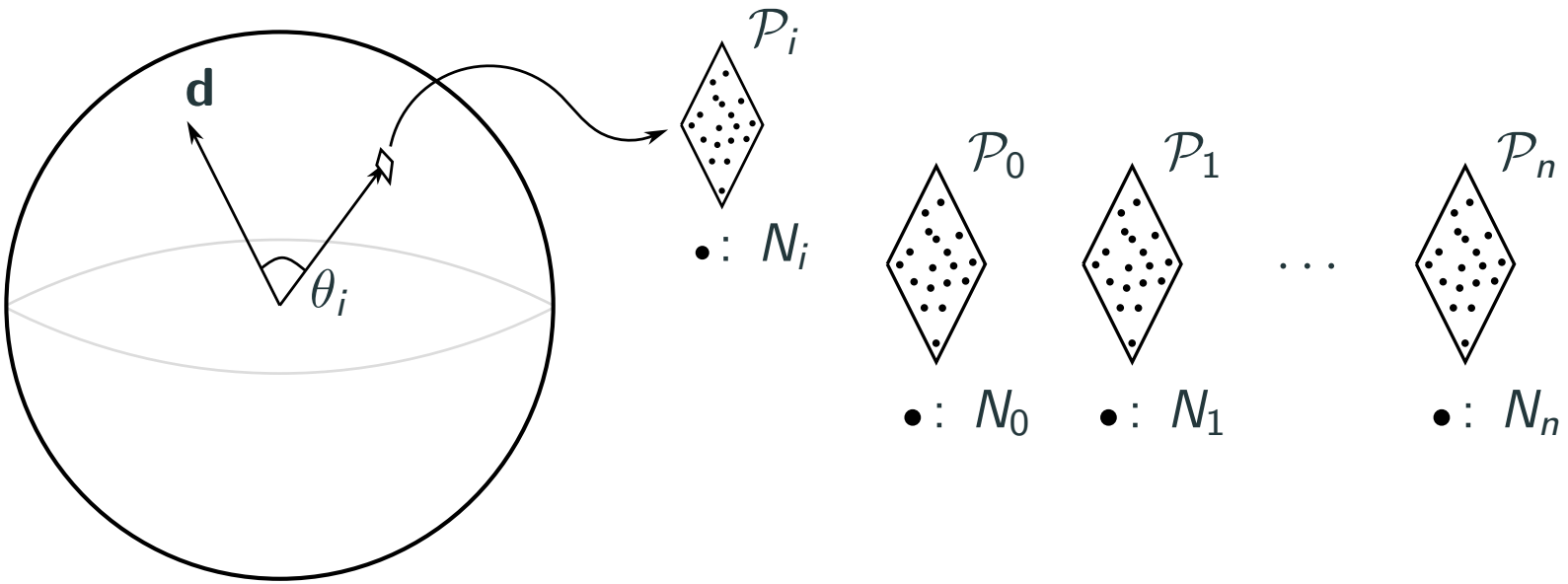

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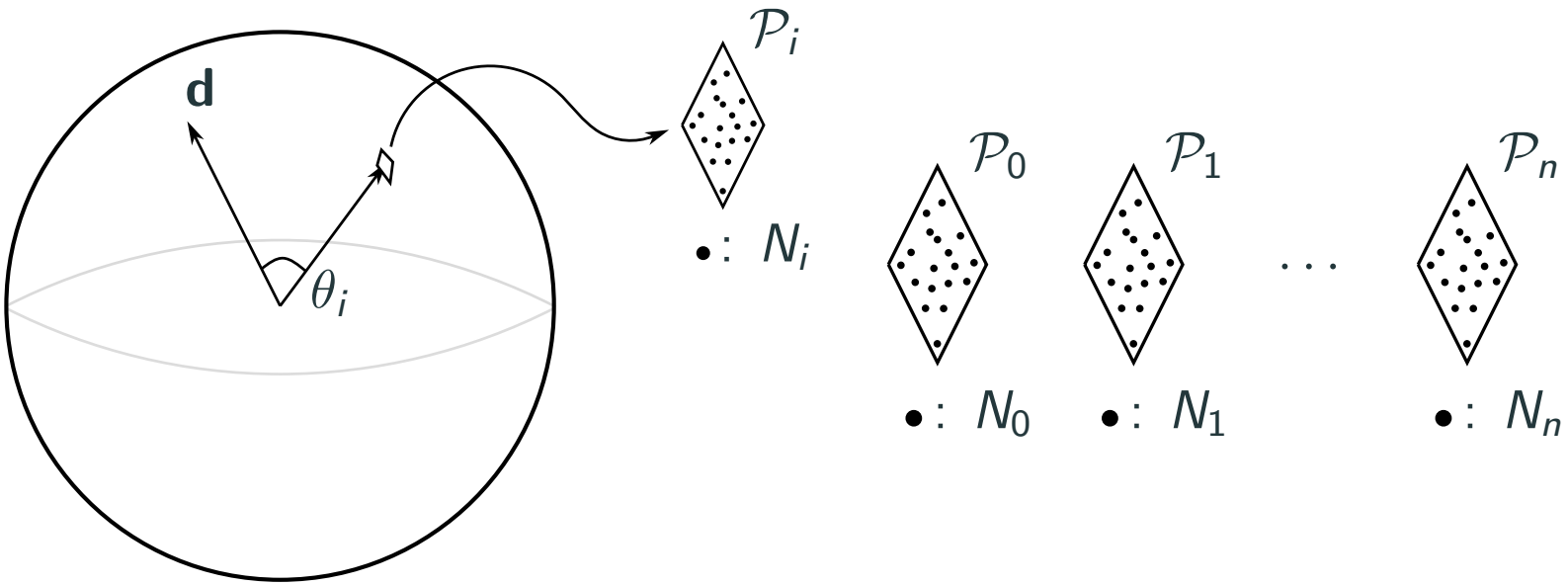

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Take data-generating process $f_M : \Theta \to \mathbf{D}$.

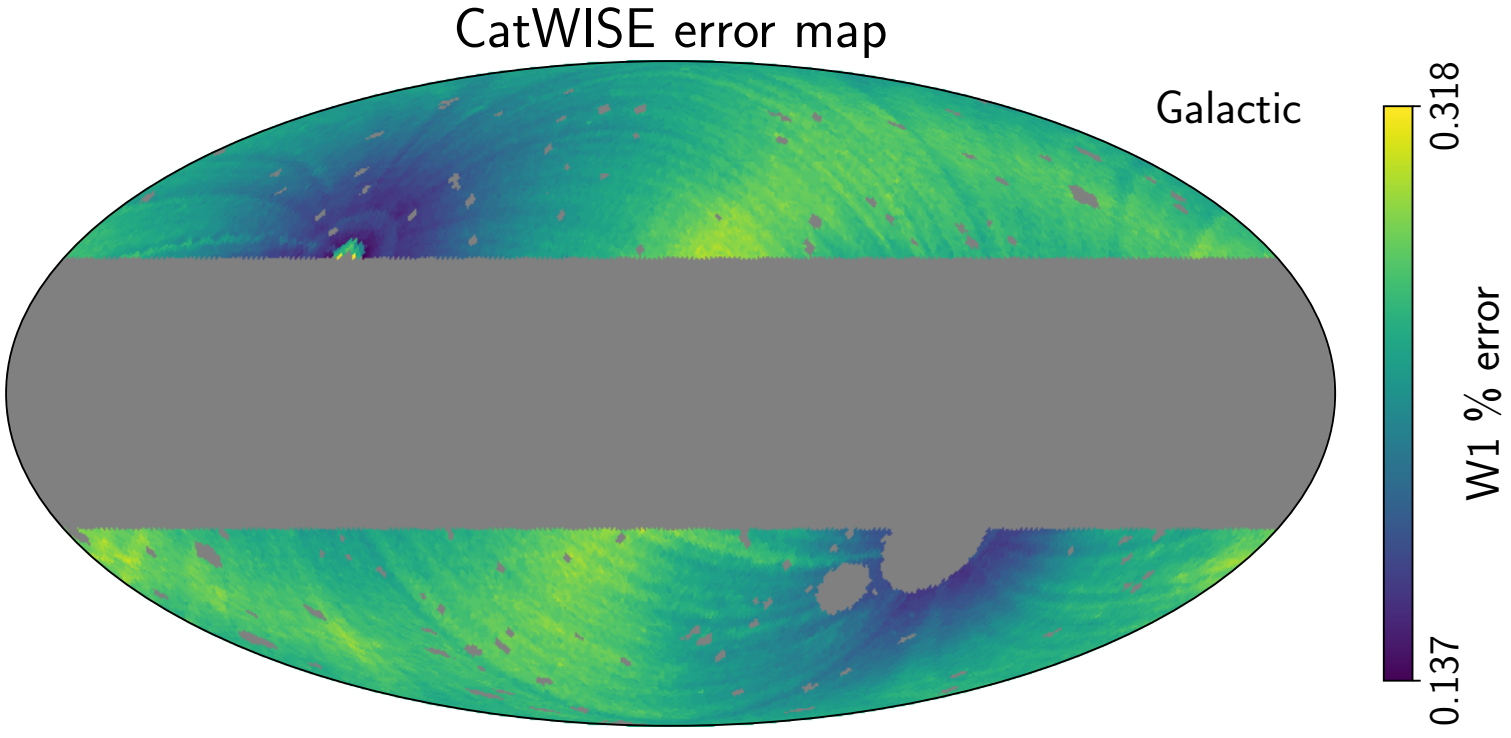
Use neural network to learn $P(\Theta|\mathbf{D}, M)$.

This is **S**imulation-**b**ased **I**nference.

Simulating CatWISE

- Photometric noise varies with sky position.
- Mimics CatWISE coverage variation.
- Eddington-bias-like effect: can simulate!

Oayda et al. (in preparation)



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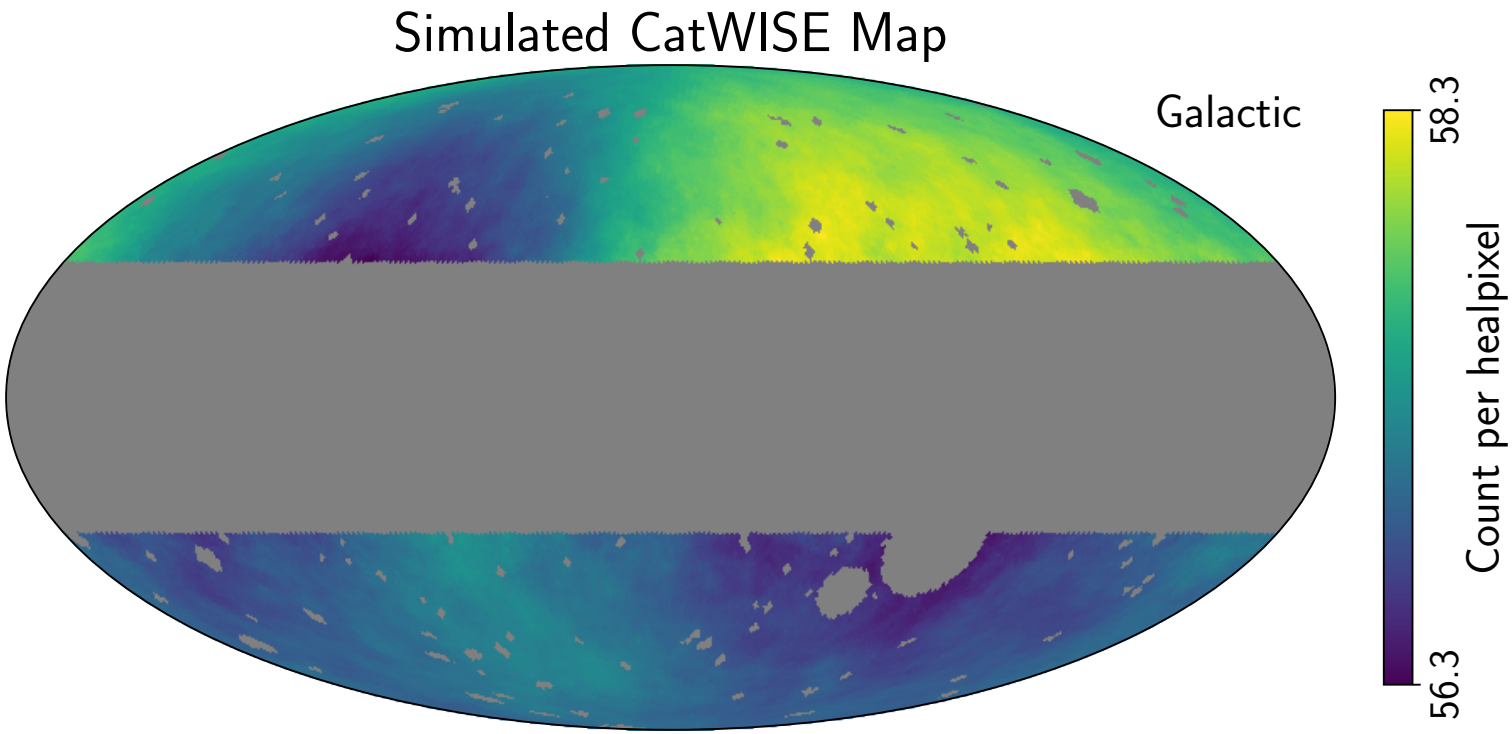

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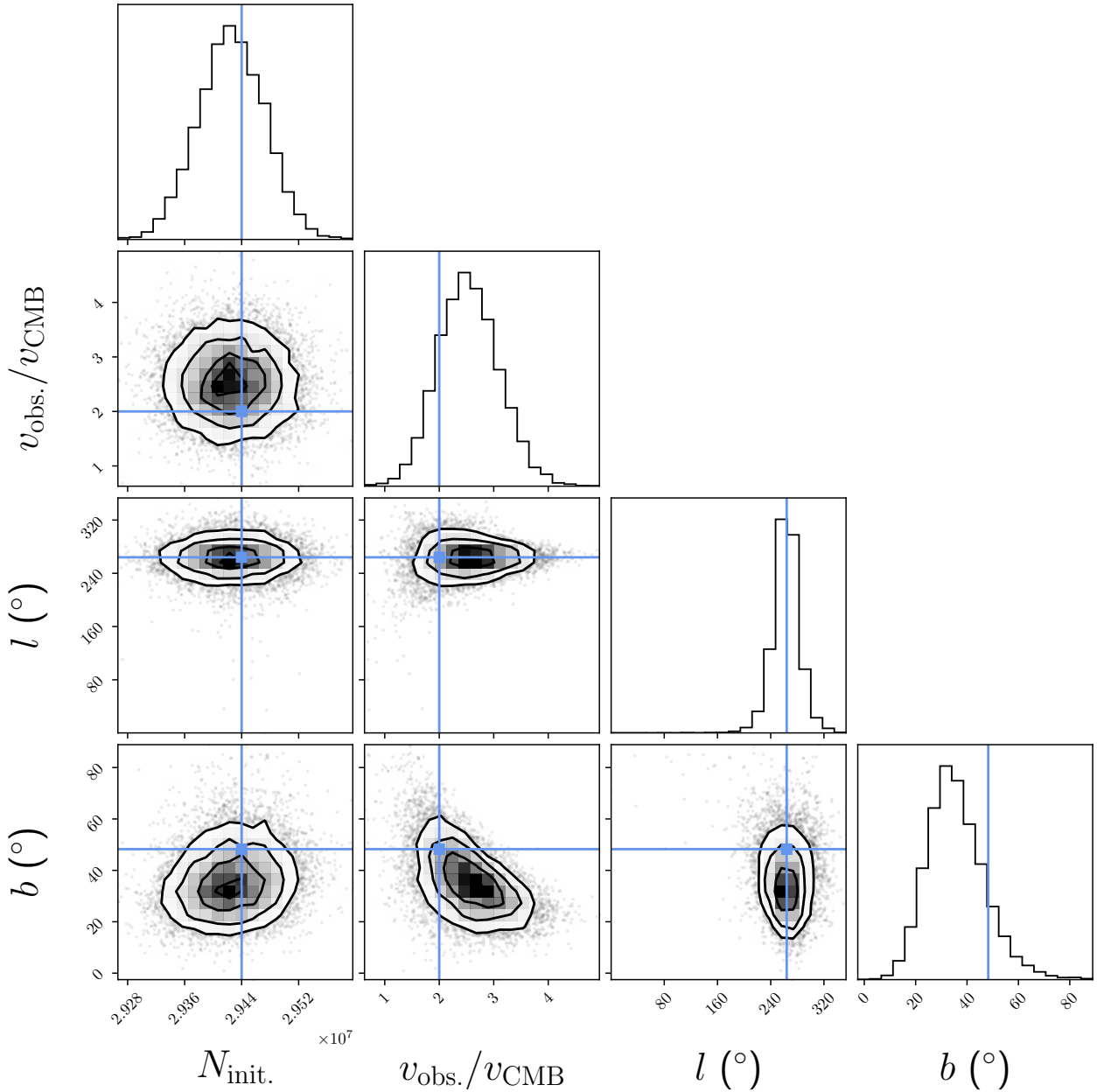

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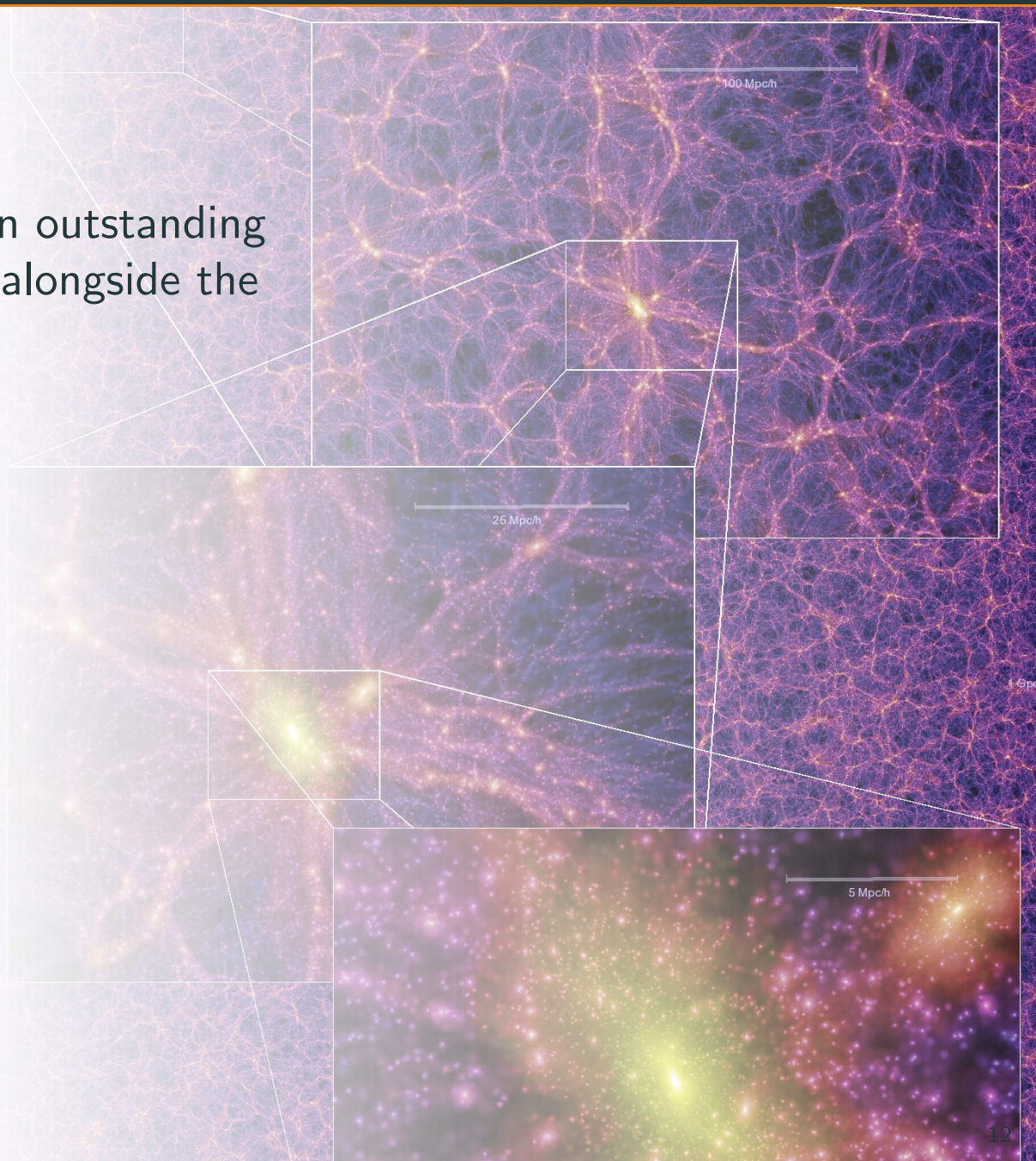

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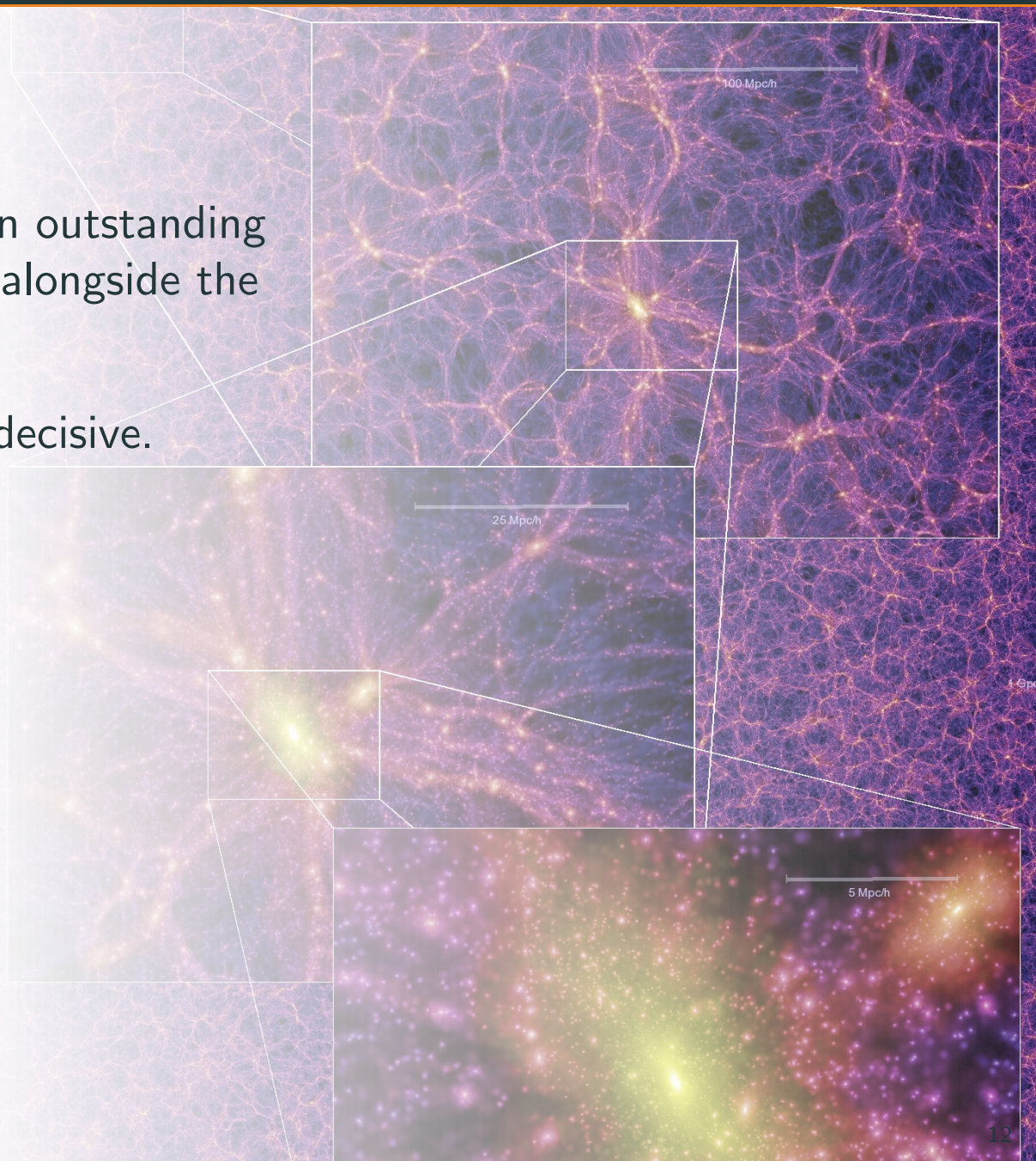

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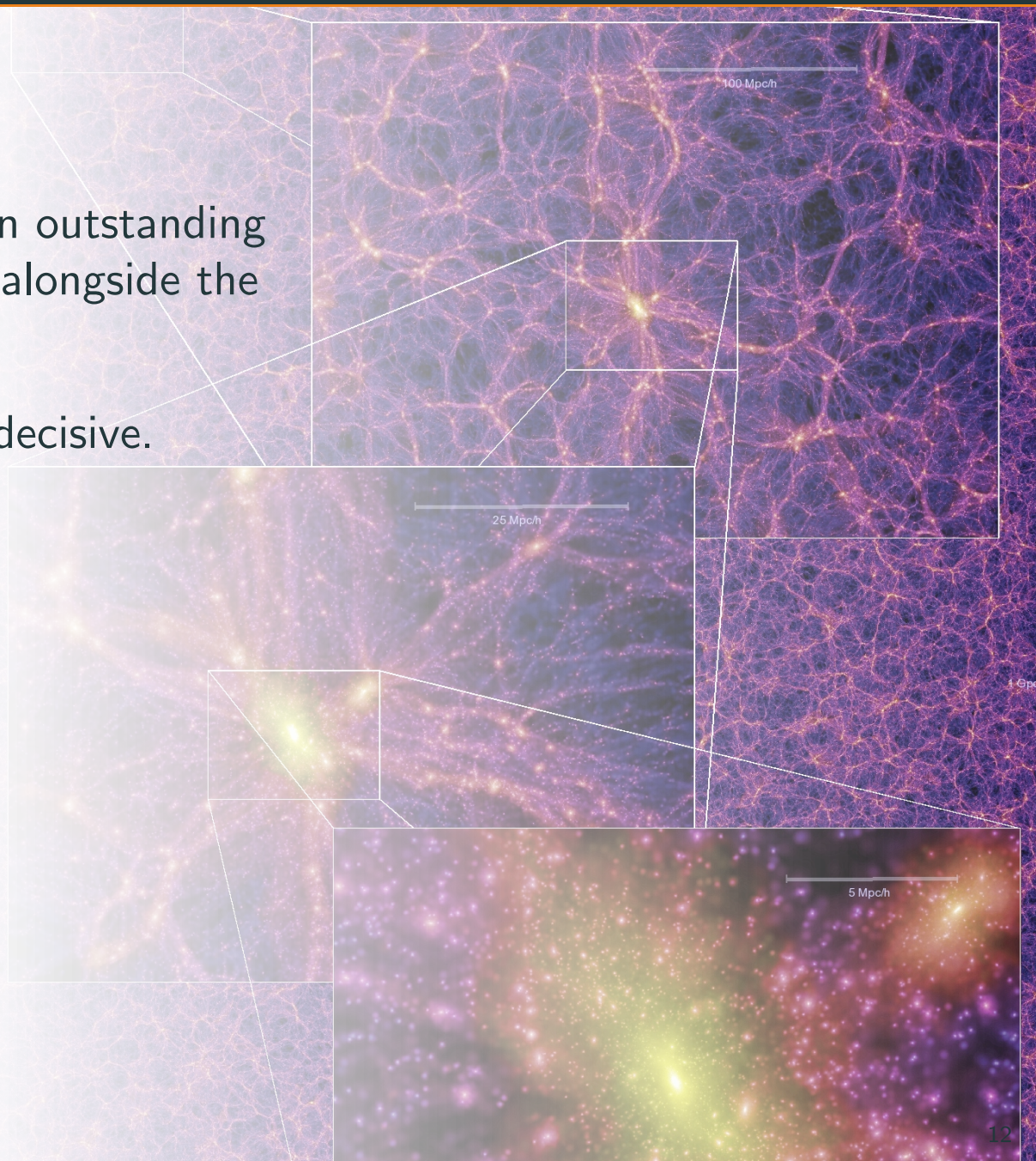

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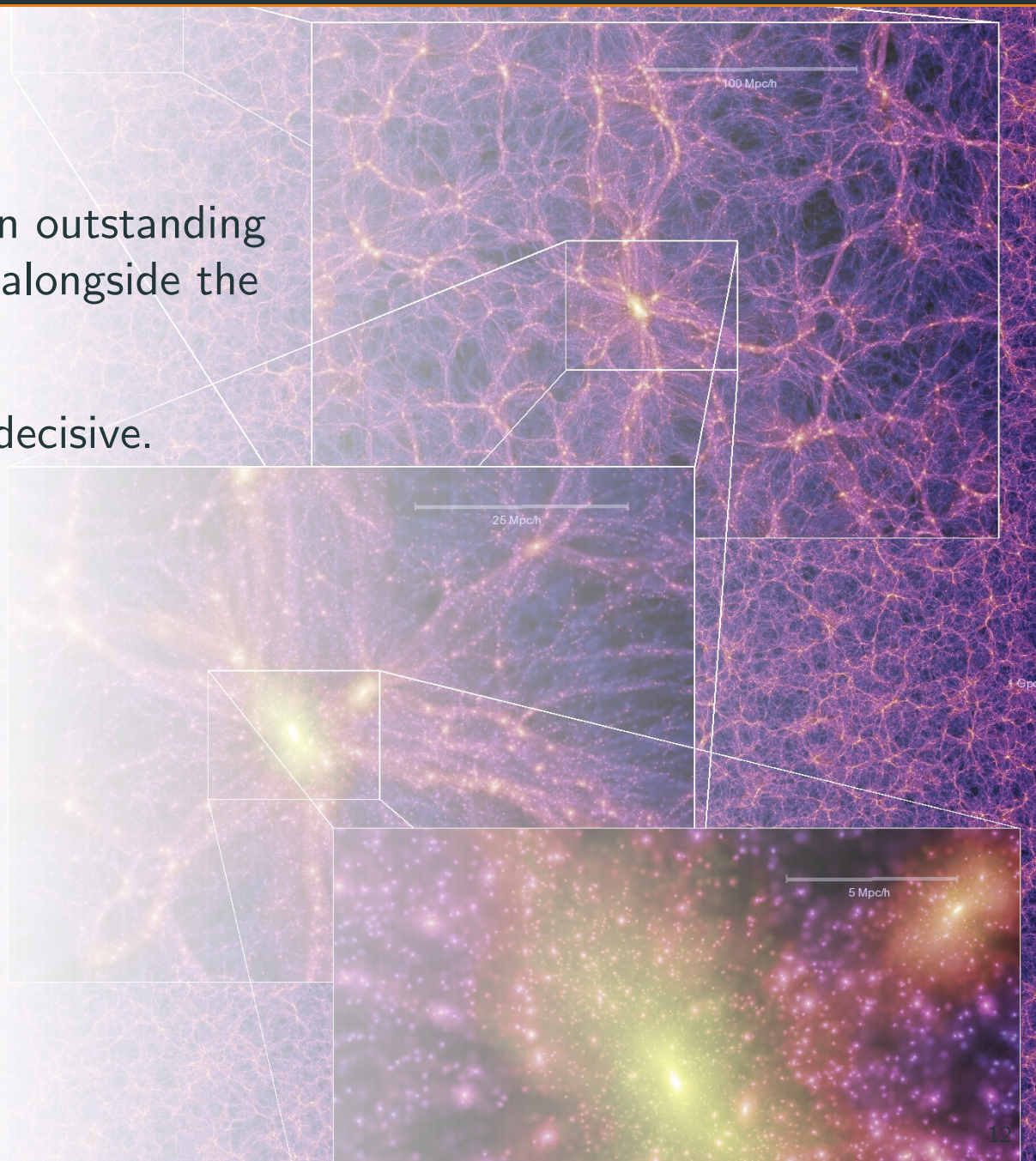

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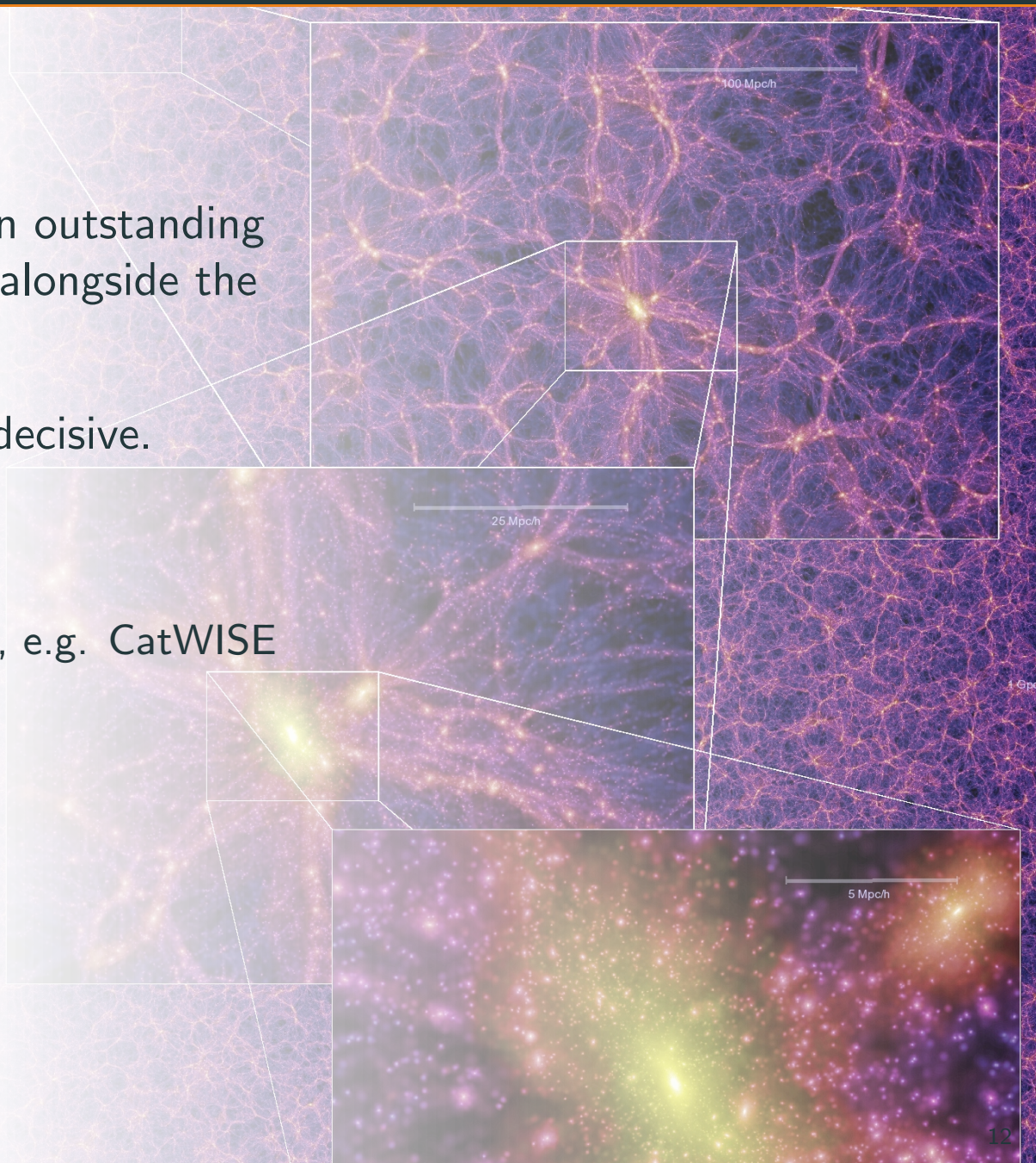

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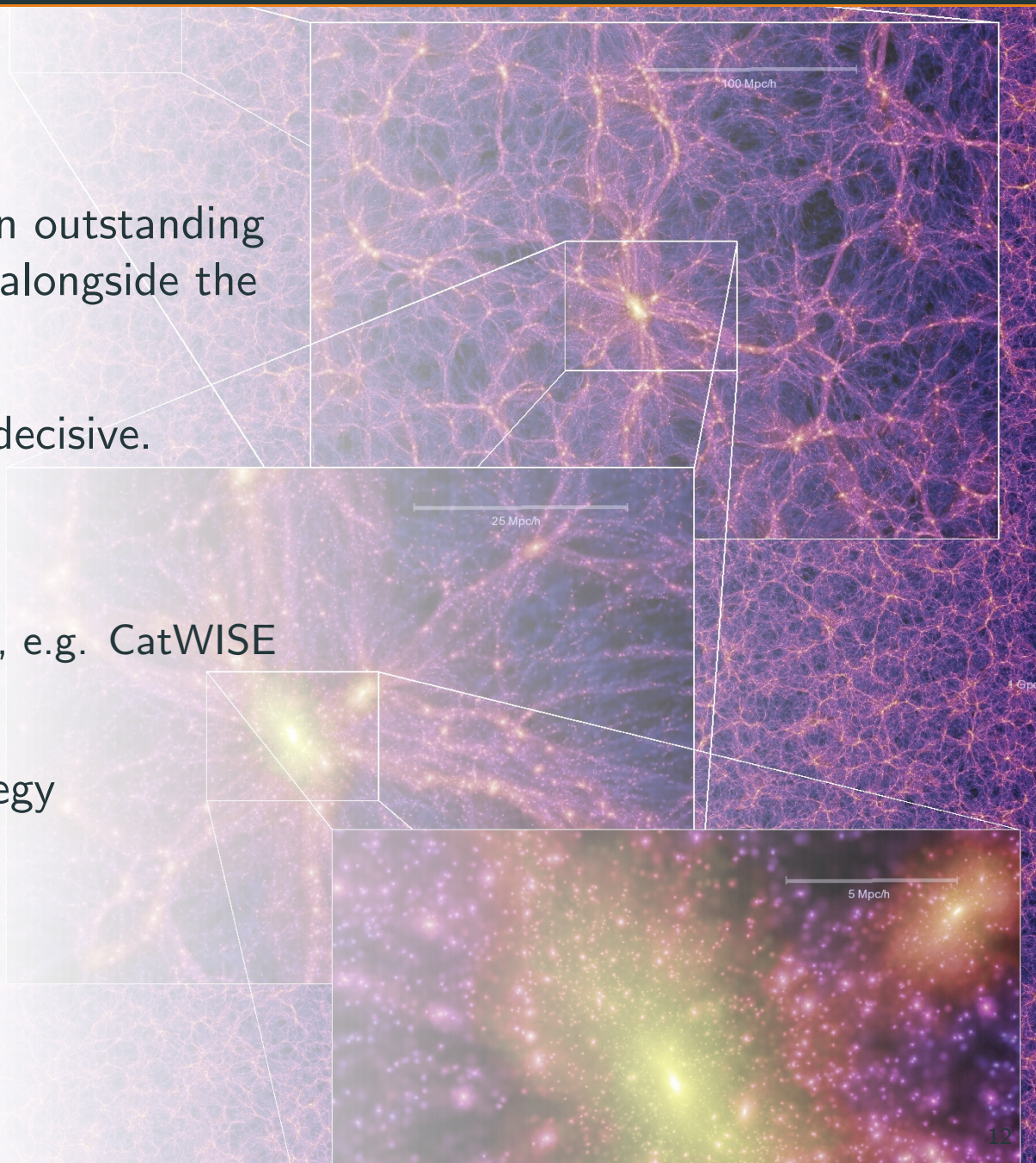

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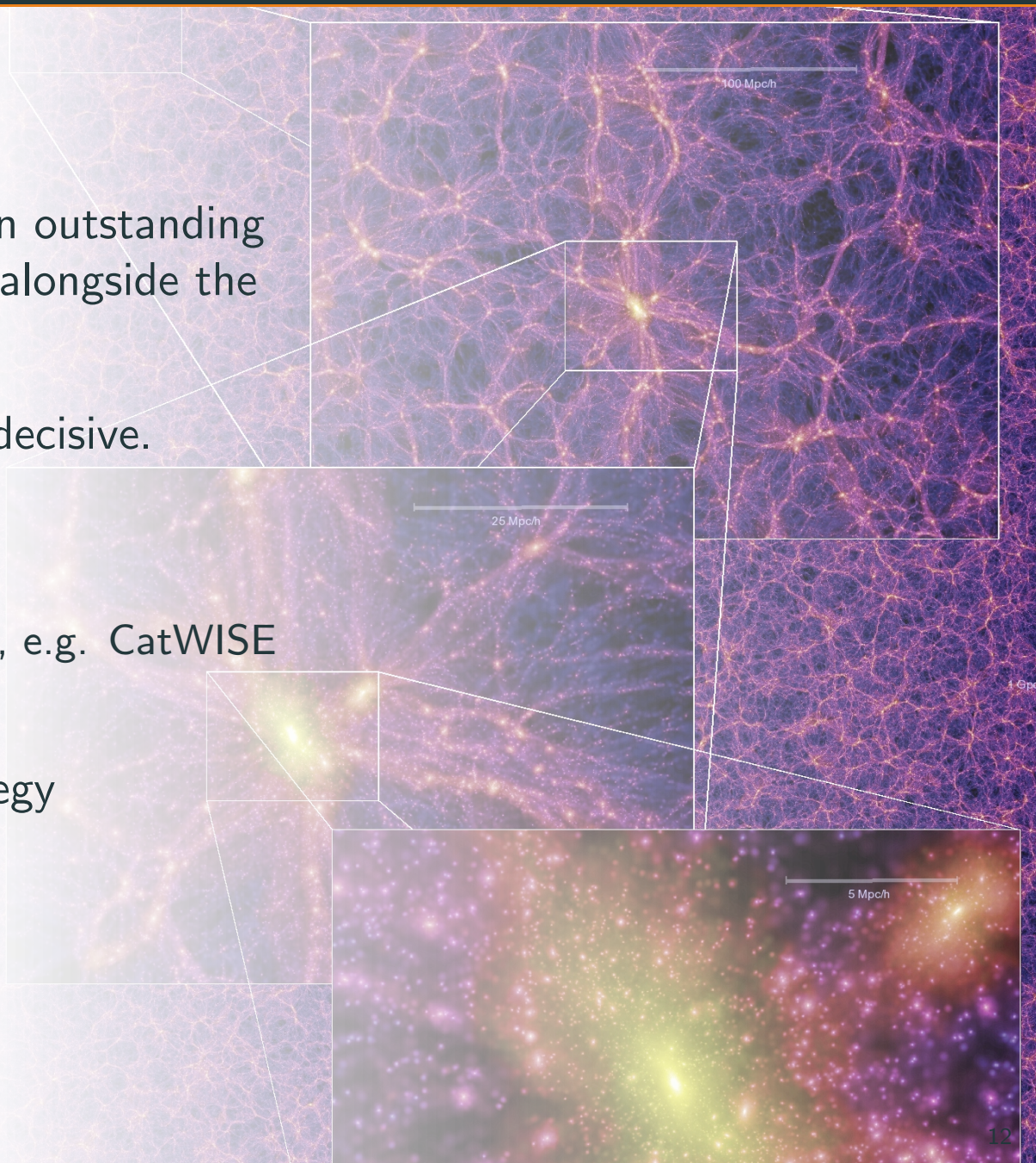

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