Confronting the Cosmological Principle:

Surveys, Statistics & Systematics

Geraint F. Lewis

The University of Sydney

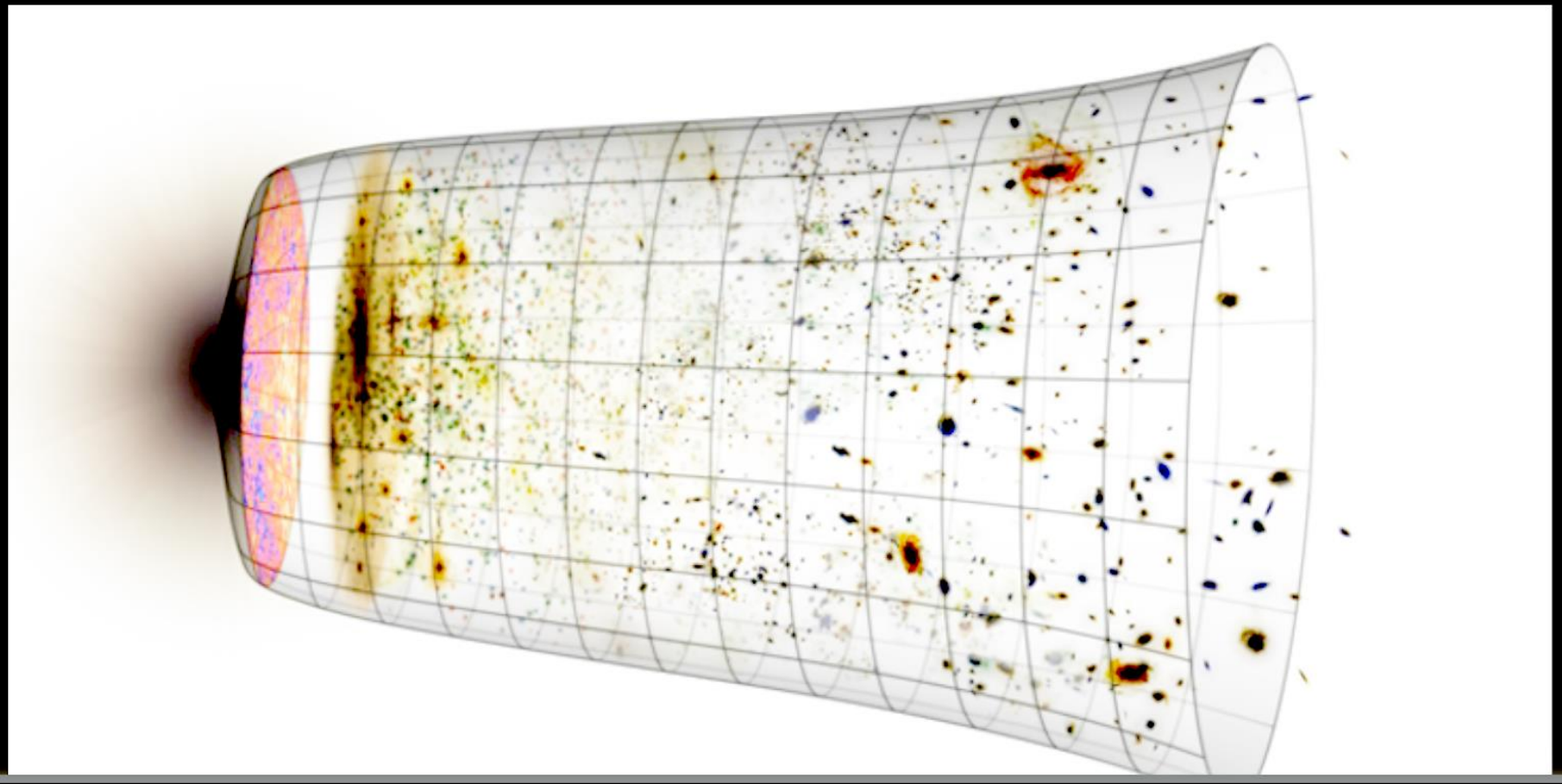
Everything's In Tension These Days

/ Events

Challenging the standard cosmological model

15 - 16 April 2024 09:00 - 17:00 The Royal Society Watch online

Register now

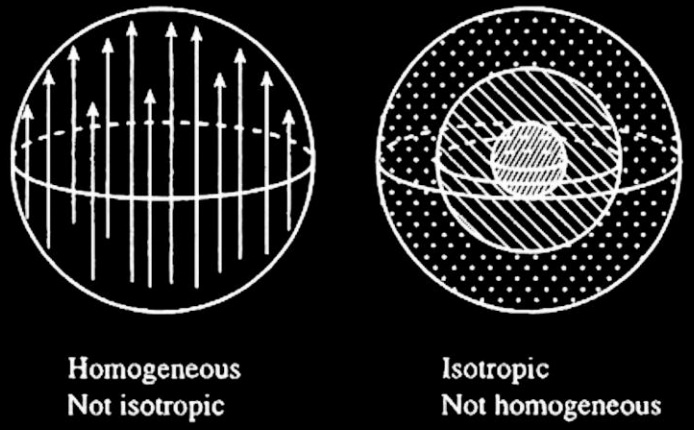


H_0 Tension
S_8 Tension
Bulk Flows
Giant Arcs

The largest in magnitude is the Dipole Tension.

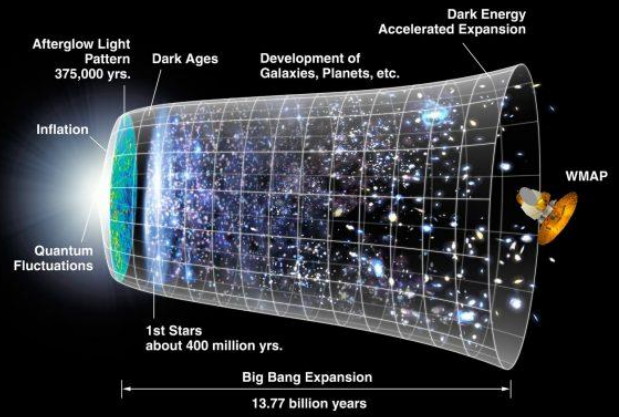
The Cosmological Principle

Isotropy & Homogeneity → Maximal Symmetries → FLRW Spacetime → Modern Cosmology

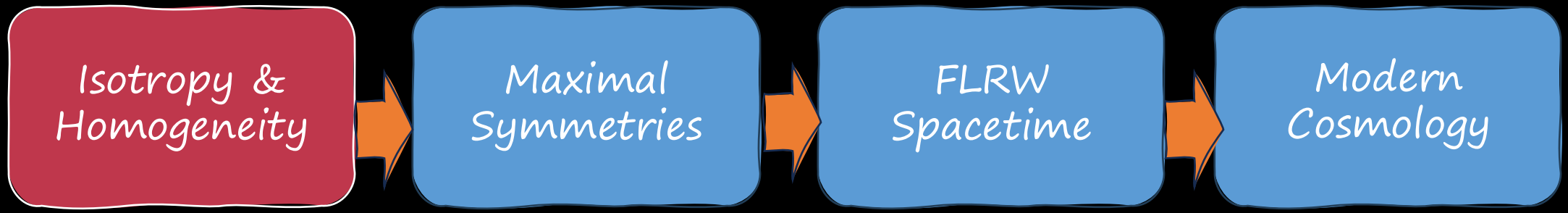


Homogeneous
Not isotropic

Isotropic
Not homogeneous



The Cosmological Principle

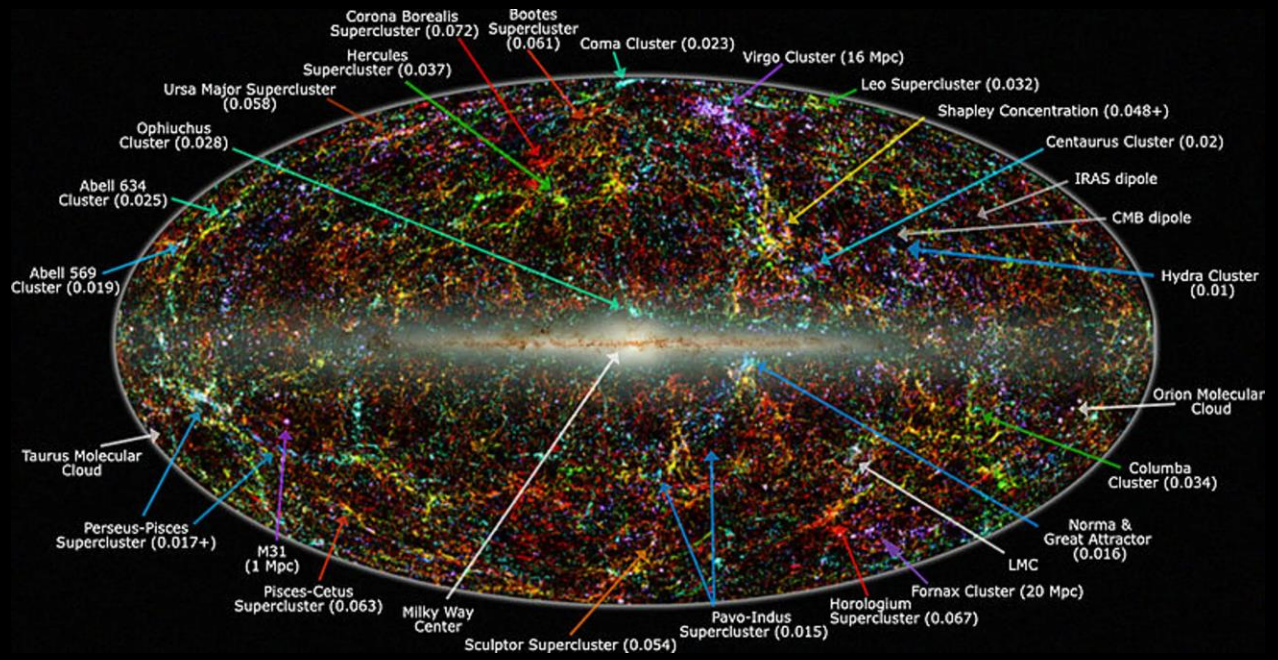


Is this bit correct?

The Cosmological Principle

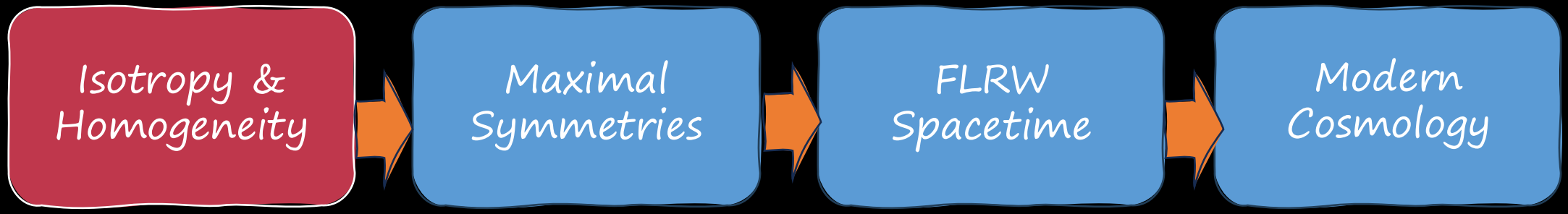
Isotropy & Homogeneity → Maximal Symmetries → FLRW Spacetime → Modern Cosmology

Is this bit correct?



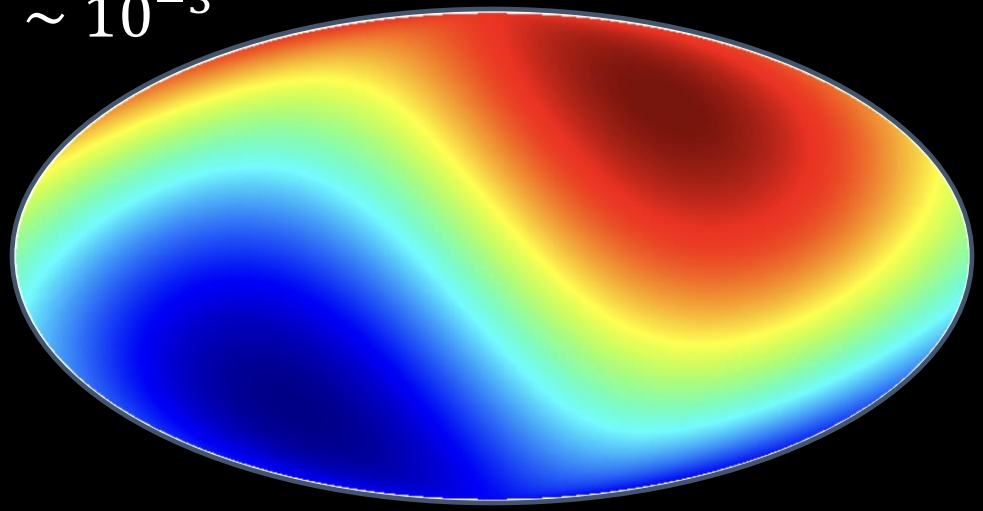
If we smooth the universe on scales of ~70-100 Mpc then (fingers crossed) the Cosmological Principle holds.

The Cosmological Principle



Is this bit correct?

$$\frac{\Delta T}{T} \sim 10^{-3}$$



CMB possesses a prominent dipole, 100x structure perturbations

Interpreted as a kinematic departure from the Hubble flow of ~370 km/s

We are not Comoving Observers!

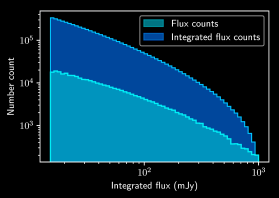
Influence on Cosmological Source Counts

On the expected anisotropy of radio source counts

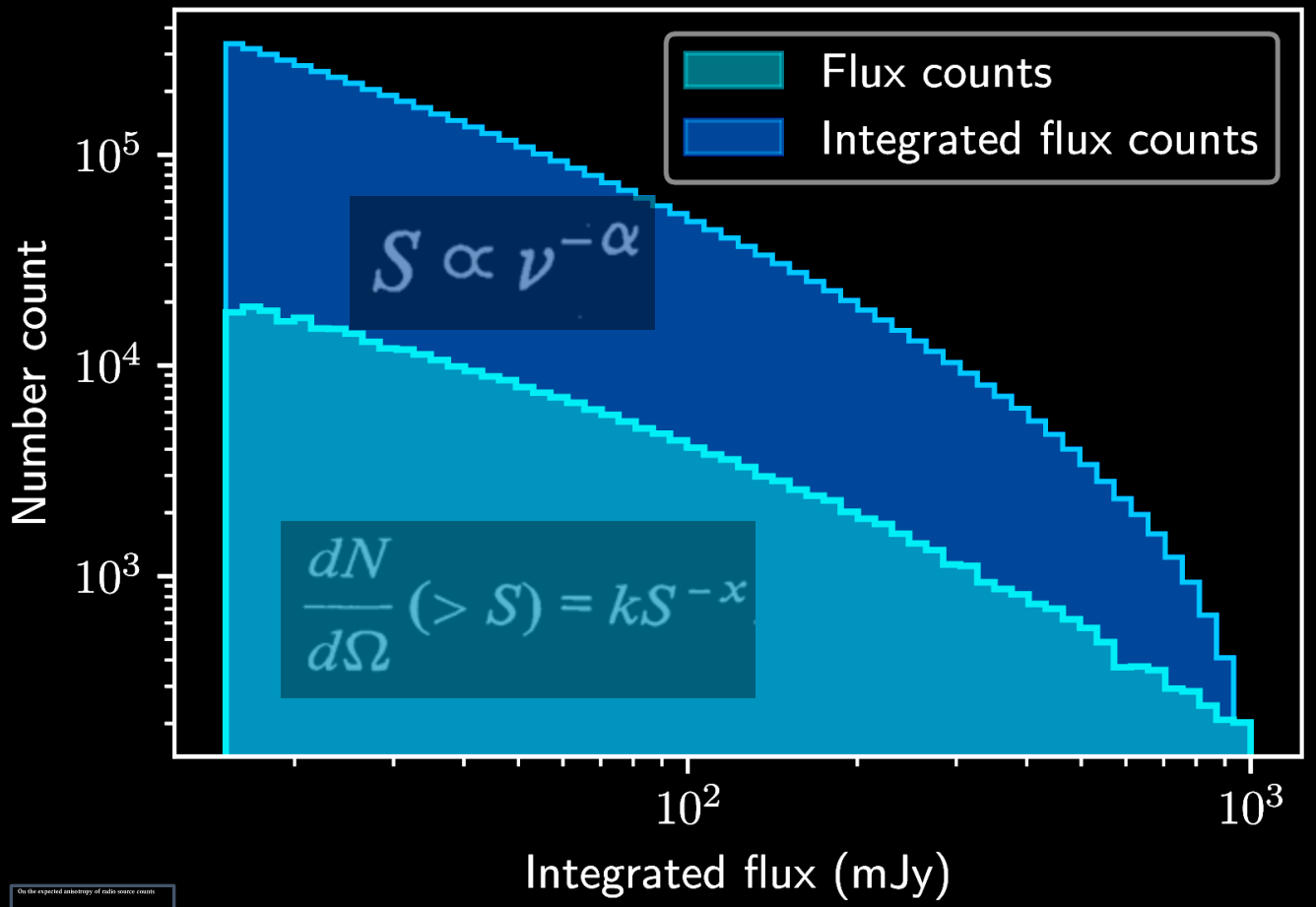
G. F. R. Ellis★ and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Received 1983 May 31; in original form 1983 March 31

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity in a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to their rest frame; this velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement between these velocities.



Influence on Cosmological Source Counts

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G. F. R. Ellis* and J. E. Baldwin† Oxford Academy of Oxon, Excelsior, Oxon

Received 1983 May 11; in original form 1983 March 31

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity is a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to (but not those) the velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement between these indications.

$$(dN/d\Omega)_{\text{obs}} = (dN/d\Omega)_{\text{rest}}\,\delta^{2+x(1+\alpha)}$$

$$\delta \approx [1+(v/c)\cos\theta]$$

Dipole modulation over sky
The modulation is small (<1%)
It's a numbers game!

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]

[1] U.S. Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392-5420, USA; nathan.j.secrest.civ@mail.mil
[2] INRIA, 615 Rue du Jardin-Botanique, F-54600 Nancy Grand-Est, France
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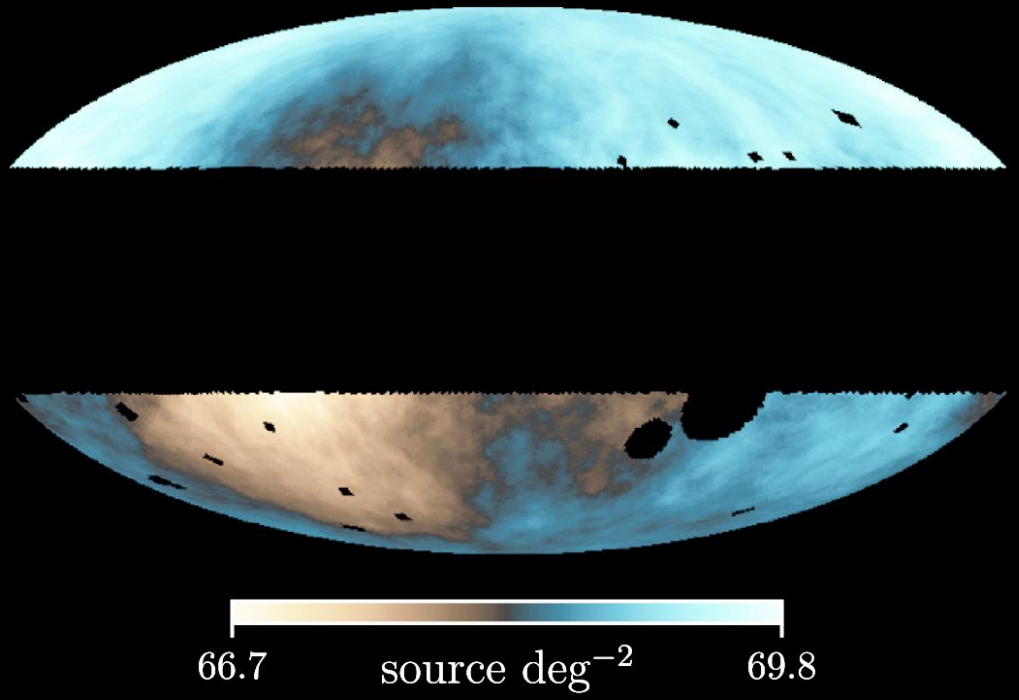
[5] Dept. of High Energy Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
Received 2020 September 29; revised 2021 January 18; accepted 2021 January 19; published 2021 February 25

1.36 million quasars

Selected from Widefield Infrared Survey Explorer (WISE)

Colour-cuts to separate quasars from stars



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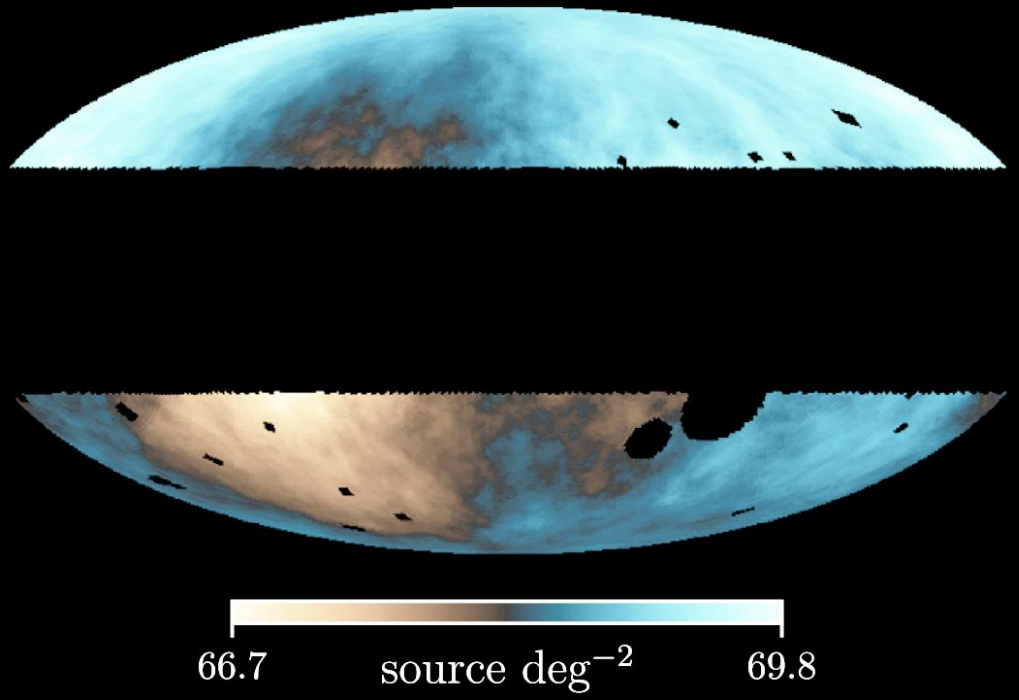
Frequentist approach:

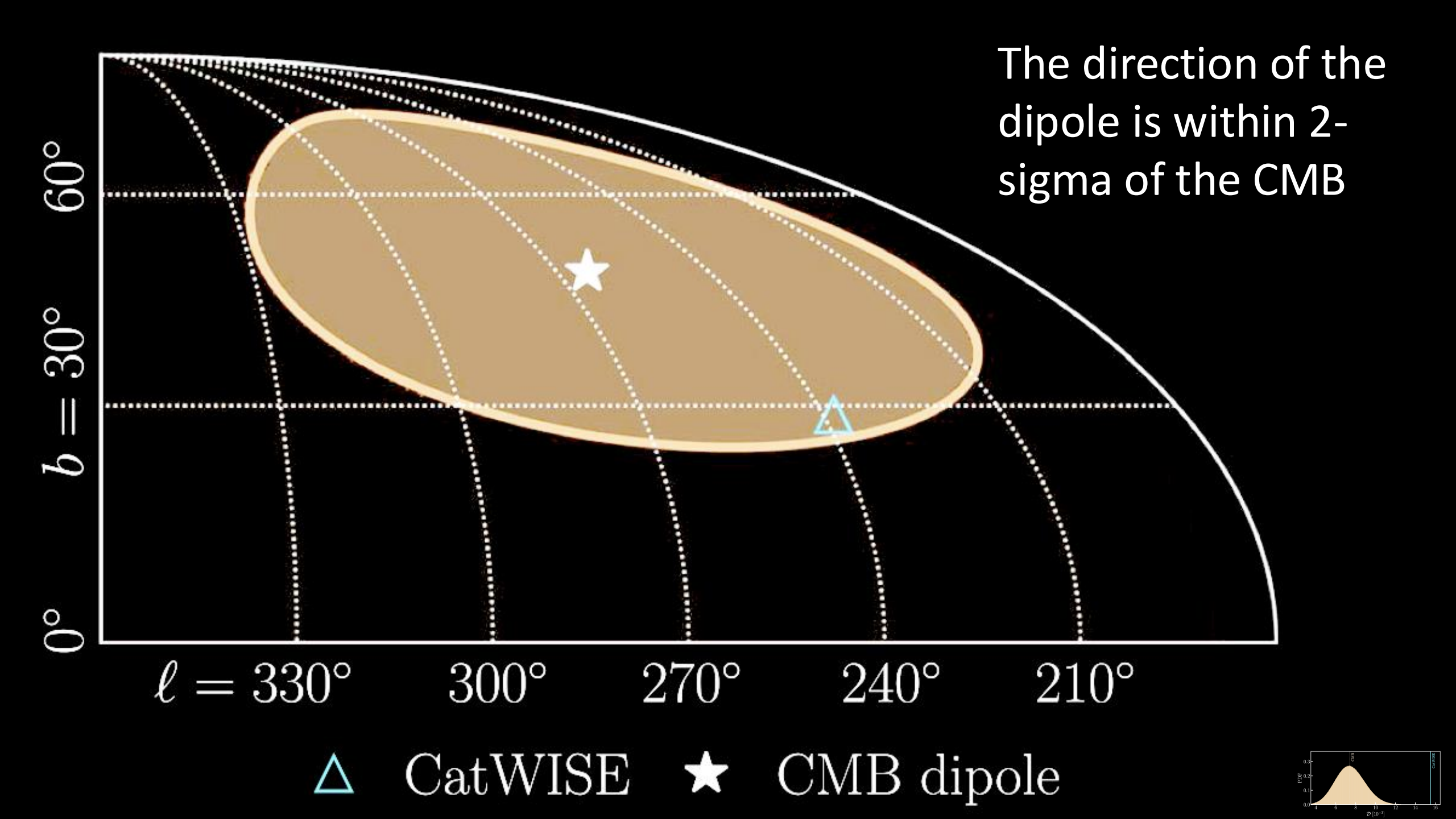
Use an estimator

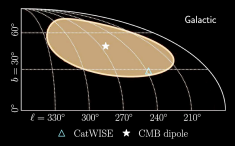
Assume the CMB velocity as a null

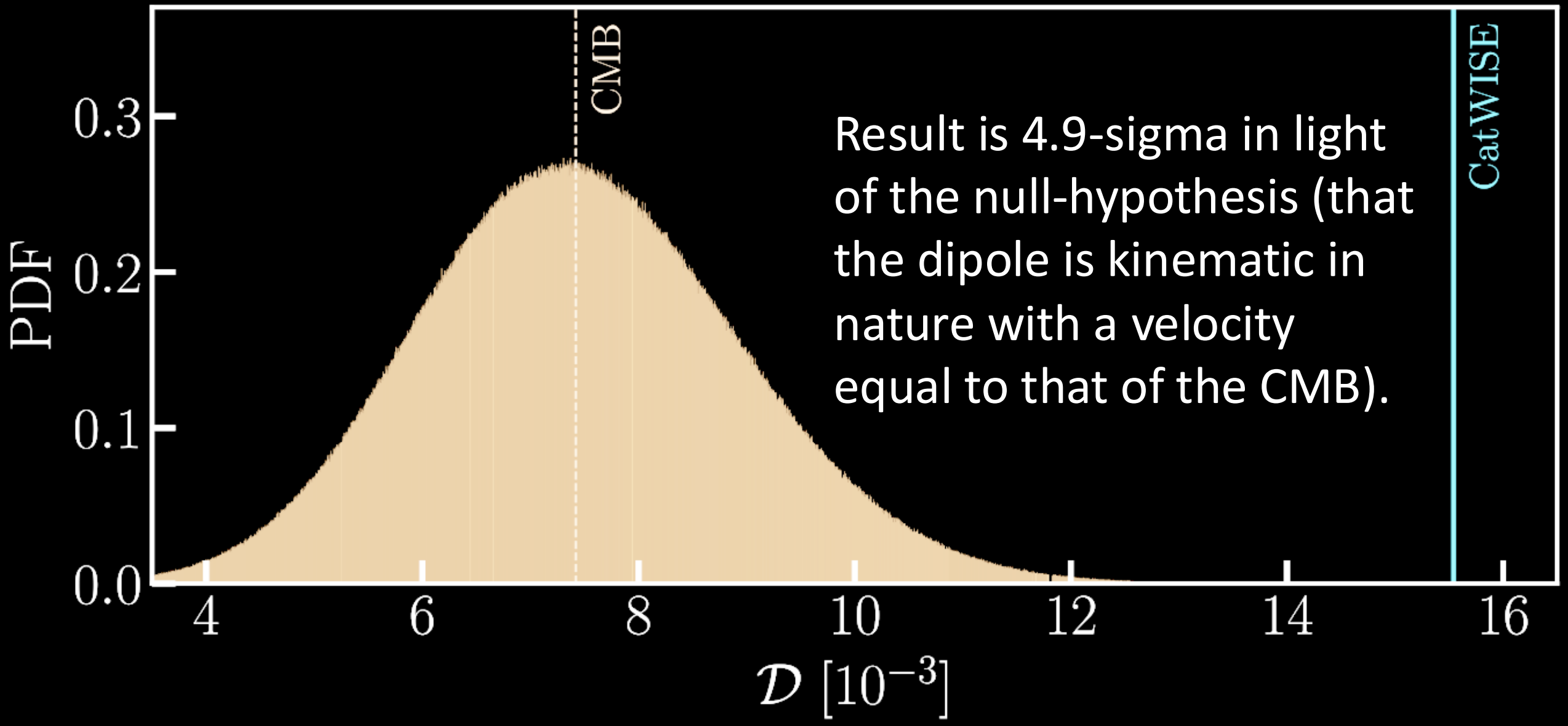
"Fix" an ecliptic bias (WISE scanning)



The direction of the dipole is within 2-sigma of the CMB

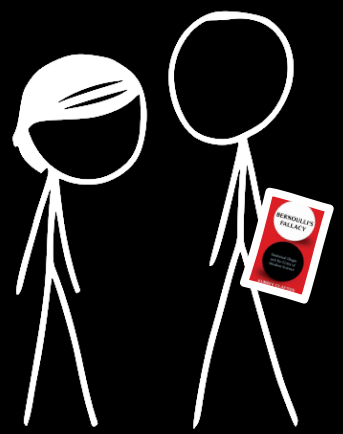






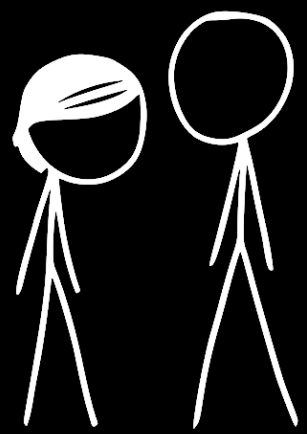
Result is 4.9-sigma in light of the null-hypothesis (that the dipole is kinematic in nature with a velocity equal to that of the CMB).

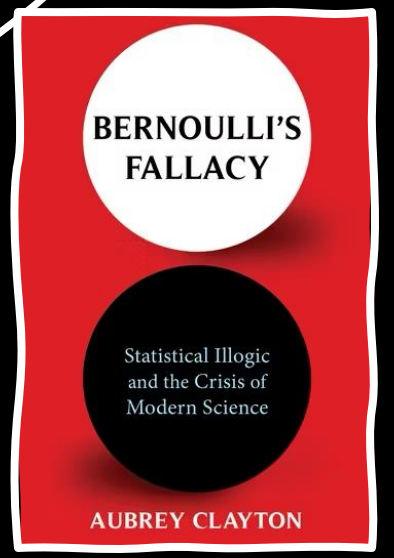
Is there really a dipole in this data?
How sure this isn't just a fluctuation around the monopole?
Is the dipole present in other data?
If it is, how much do we believe this is different to the CMB?



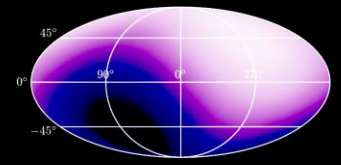
What we need is a robust approach to hypothesis testing.

We need to take a look at this within the framework of Bayesian probability.





Defining the Hypotheses: Monopole, dipole, quadrupole. What parameters are fixed vs free



Defining the Model and Likelihood (including survey properties).

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(\hat{\mathbf{n}}) = \bar{N}(1 + \mathbf{d}\cdot\hat{\mathbf{n}}), \qquad p(N_i \,|\, \theta) = \frac{\lambda_i^{N_i}\, \mathrm{e}^{-\lambda_i}}{N_i!}.$$

Insert data

$$\underbrace{p(\theta \,|\, y, M)}_{\text{posterior}} = \frac{\overbrace{p(y \,|\, \theta, M)}^{\text{likelihood}}\ \overbrace{p(\theta \,|\, M)}^{\text{prior}}}{\underbrace{p(y \,|\, M)}_{\text{evidence}}} = \frac{\overbrace{\mathcal{L}(\theta)}^{\text{likelihood}}\ \overbrace{\pi(\theta)}^{\text{prior}}}{\underbrace{z}_{\text{evidence}}},$$

$$\underbrace{\frac{p(M_1 \,|\, y)}{p(M_2 \,|\, y)}}_{\text{posterior odds}} = \underbrace{\frac{p(y \,|\, M_1)}{p(y \,|\, M_2)}}_{\text{Bayes factor}} \times \underbrace{\frac{p(M_1)}{p(M_2)}}_{\text{prior odds}}.$$

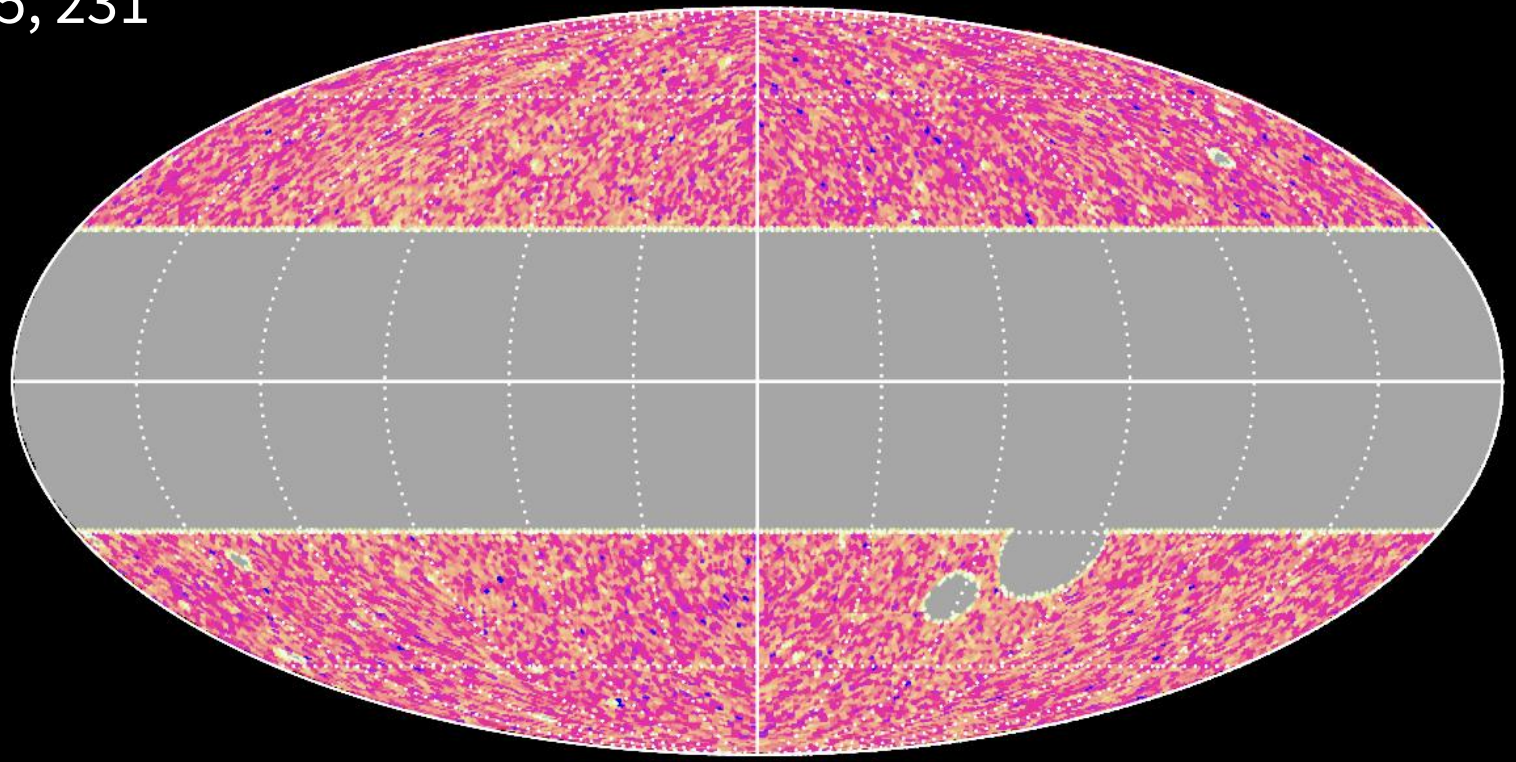
Assess hypotheses

Model	Description	$\ln(Z)$
M_0	Null (no dipole)	-87707.67
M_1	Amplitude and direction fixed to CMB, no bias	-87652.04
M_2	Direction fixed to CMB, no bias	-87625.43
M_3	All parameters free, except no bias	-87624.18
M_4	Amplitude and direction fixed to CMB	-87472.77
M_5	Direction fixed to CMB	-87445.27
M_6	All parameters free	-87444.17

Testing the Cosmological Principle with CatWISE Quasars: A Bayesian Analysis of the Number-Count Dipole

Lawrence Dam[1,2],* Geraint F. Lewis[1]† & Brendon J. Brewer[3]
[1]*Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia*
[2]*Département de Physique Théorique and Center for Astroparticle Physics, Université de Genève, 24 quai Ernest-Ansermet, 1211 Genève 4, Switzerland*
[3]*Department of Statistics, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*

MNRAS (2023), 525, 231



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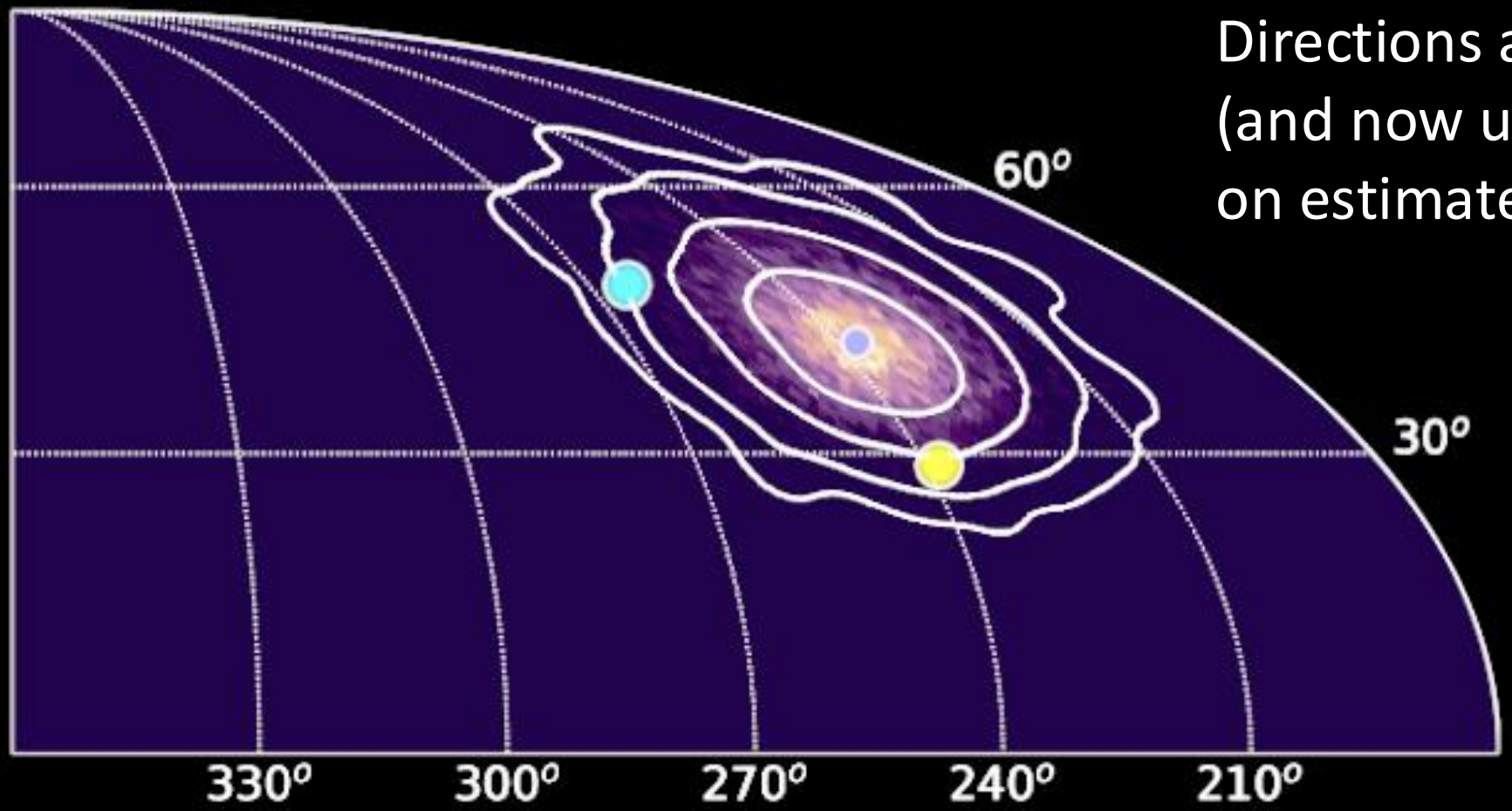
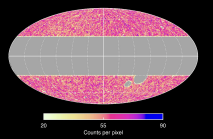
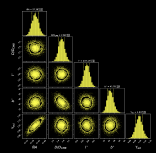


Directions are consistent (and now uncertainties are on estimated parameters).





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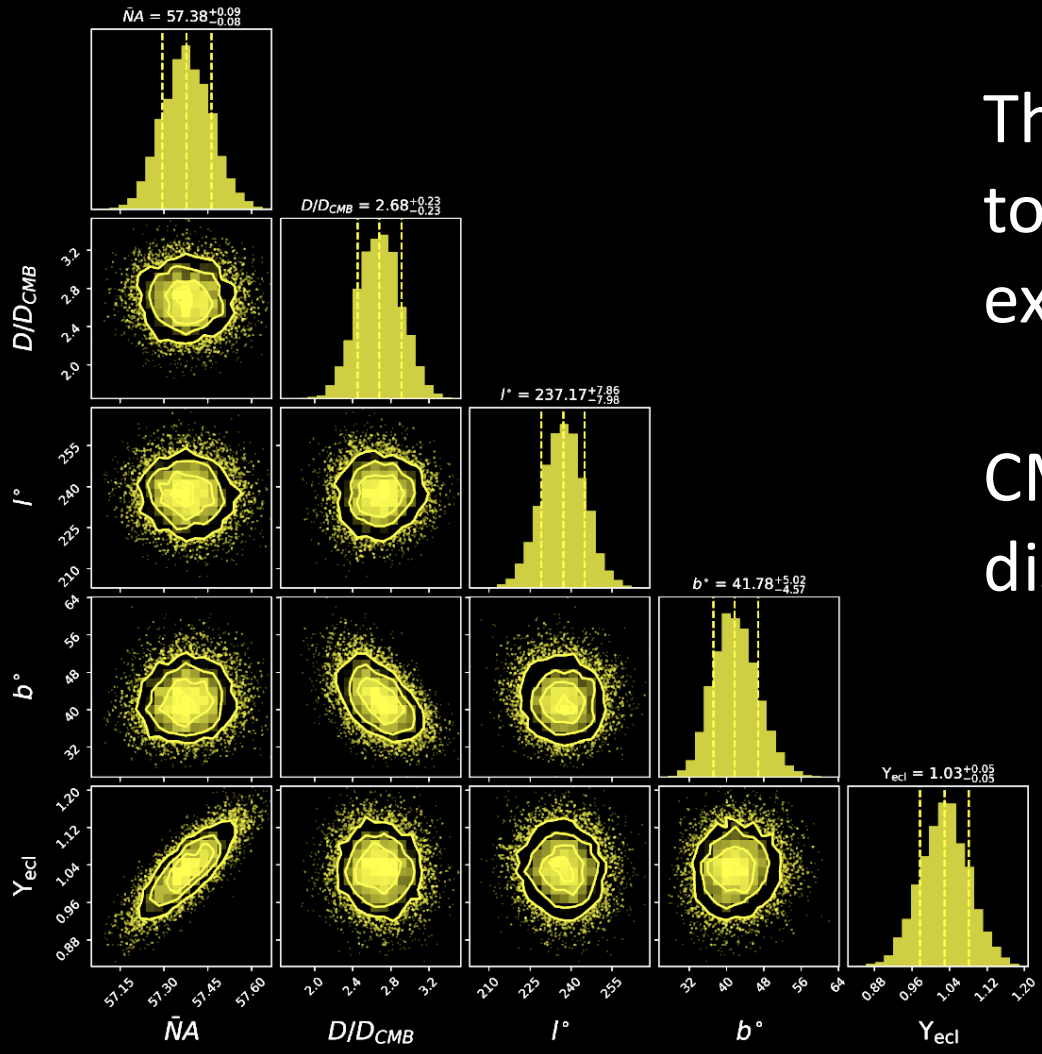
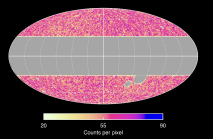
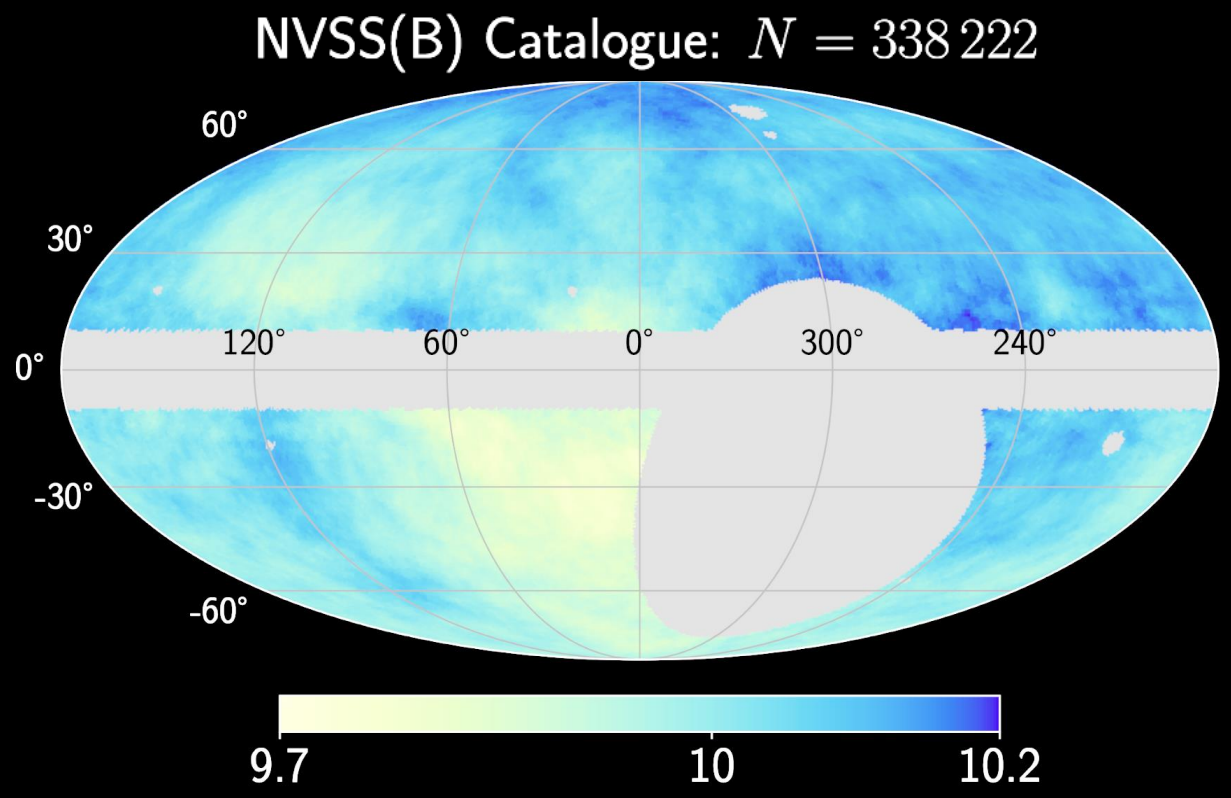


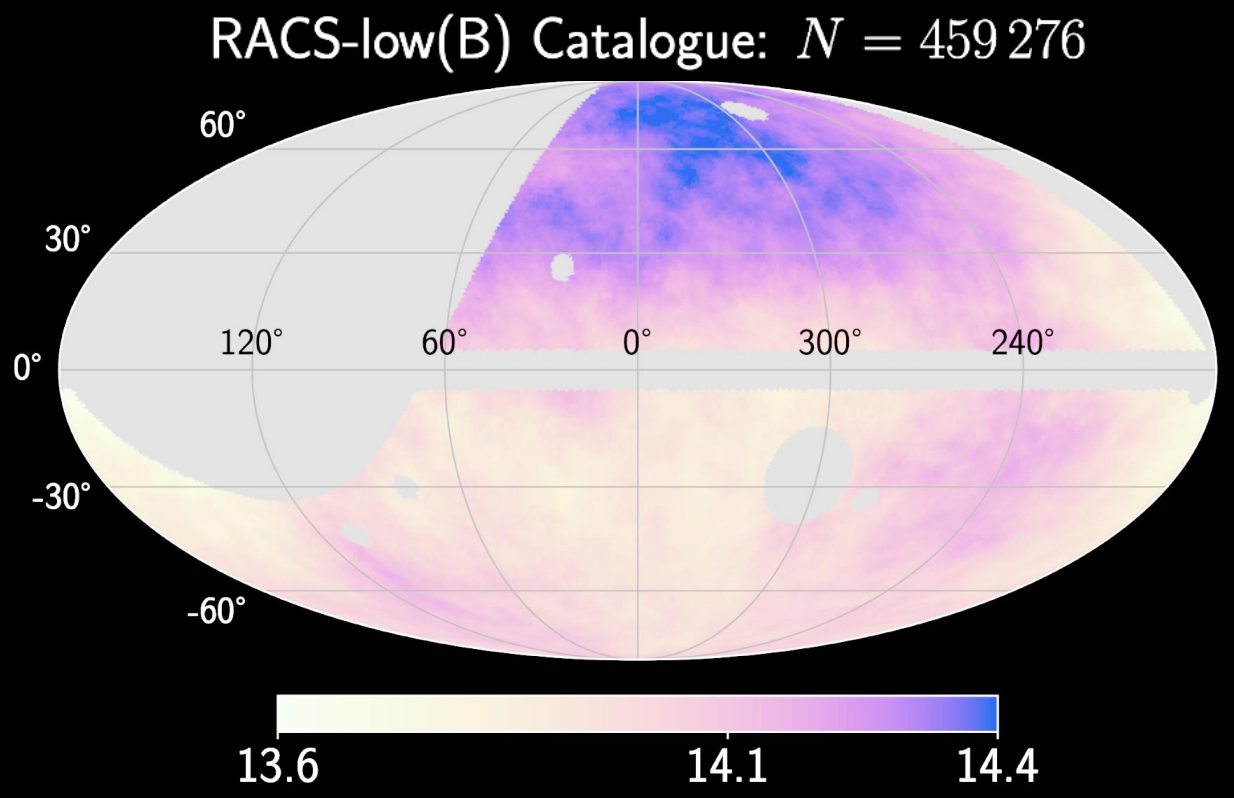
The dipole amplitude is still too large (compared to CMB expectation) by ~2.5x

CMB dipole is strongly disfavoured by the evidence



Combining Data Sets





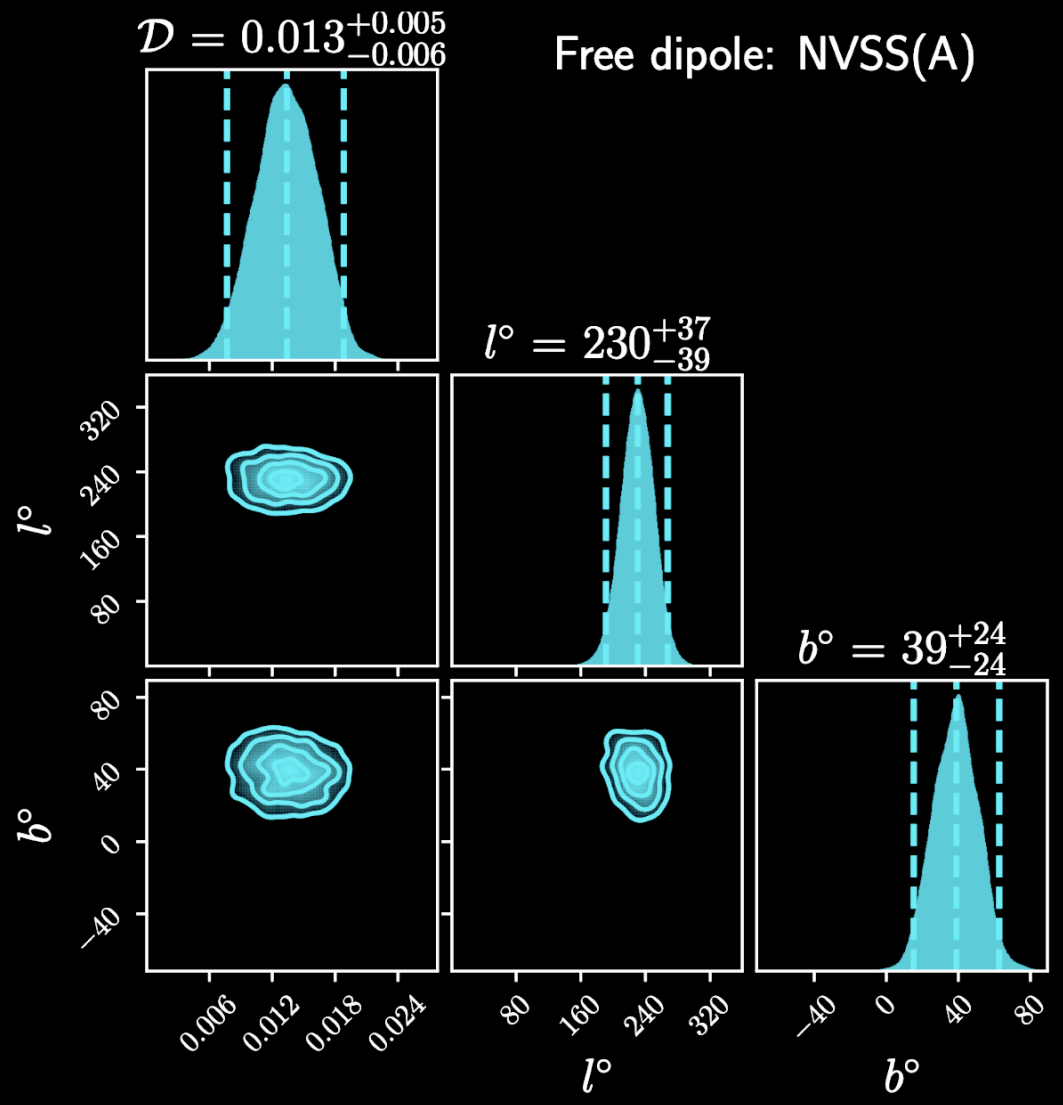
A Bayesian approach to the cosmic dipole in radio galaxy surveys: Joint analysis of NVSS & RACS

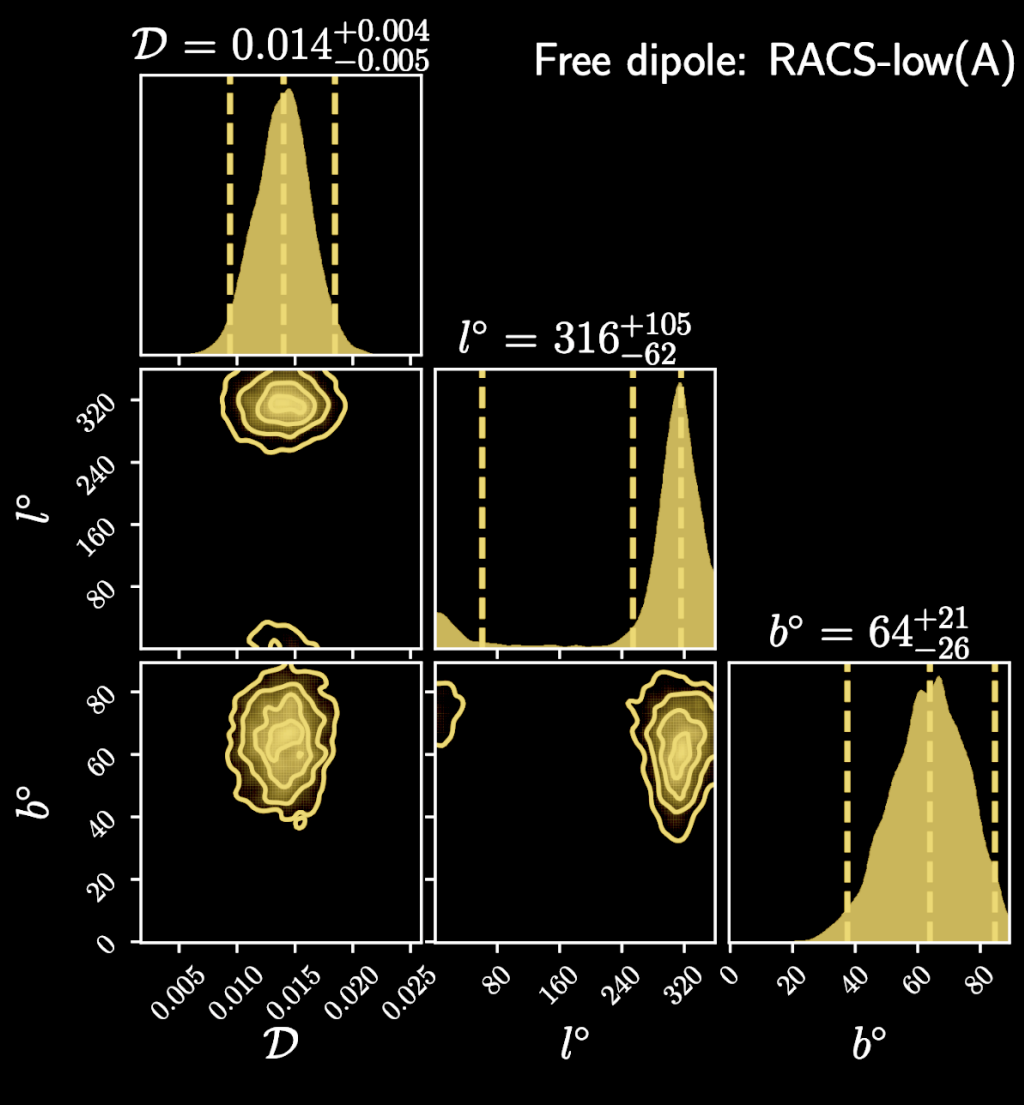
Oliver T. Oayda,[1]★ Vasudev Mittal[1,2], Geraint F. Lewis[1], and Tara Murphy[1]

[1]*Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia*

[2]*Department of Physical Sciences, IISER Mohali, Knowledge City, Sector 81, SAS Nagar, Manauli PO 140306, Punjab, India*

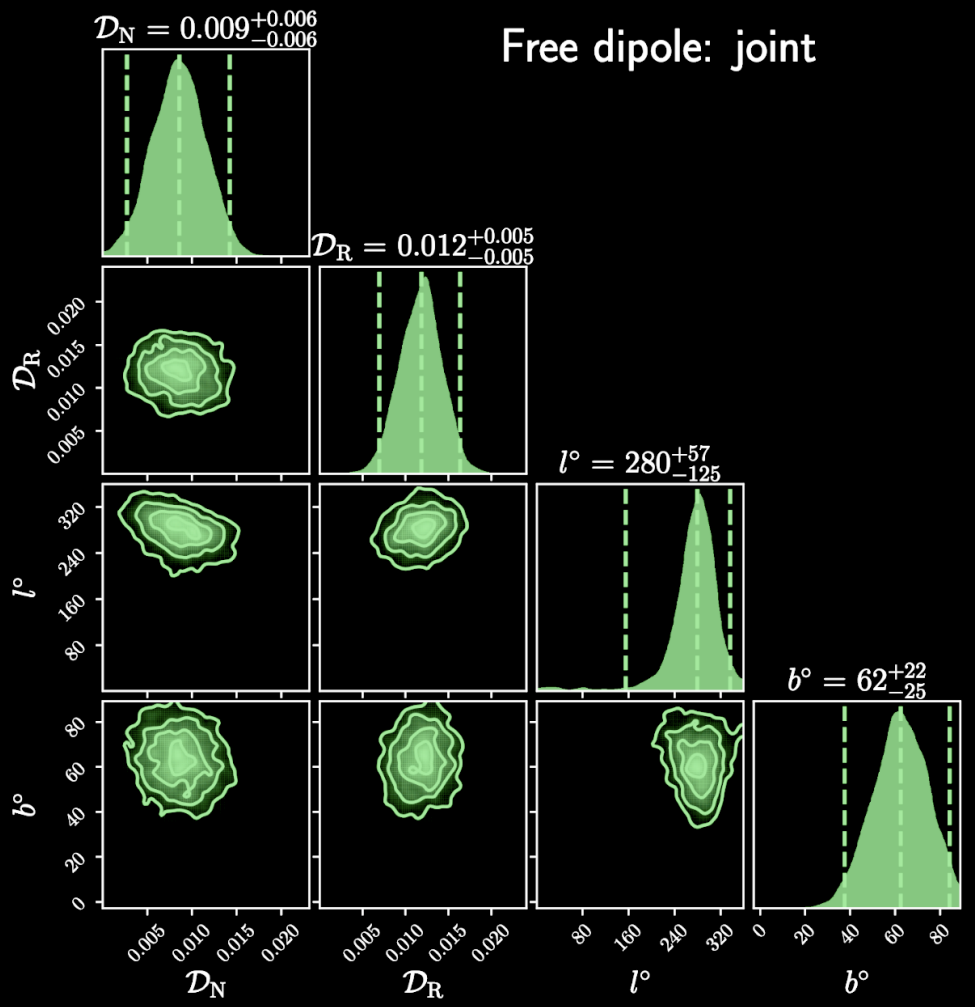
MNRAS (2024) 531, 4545

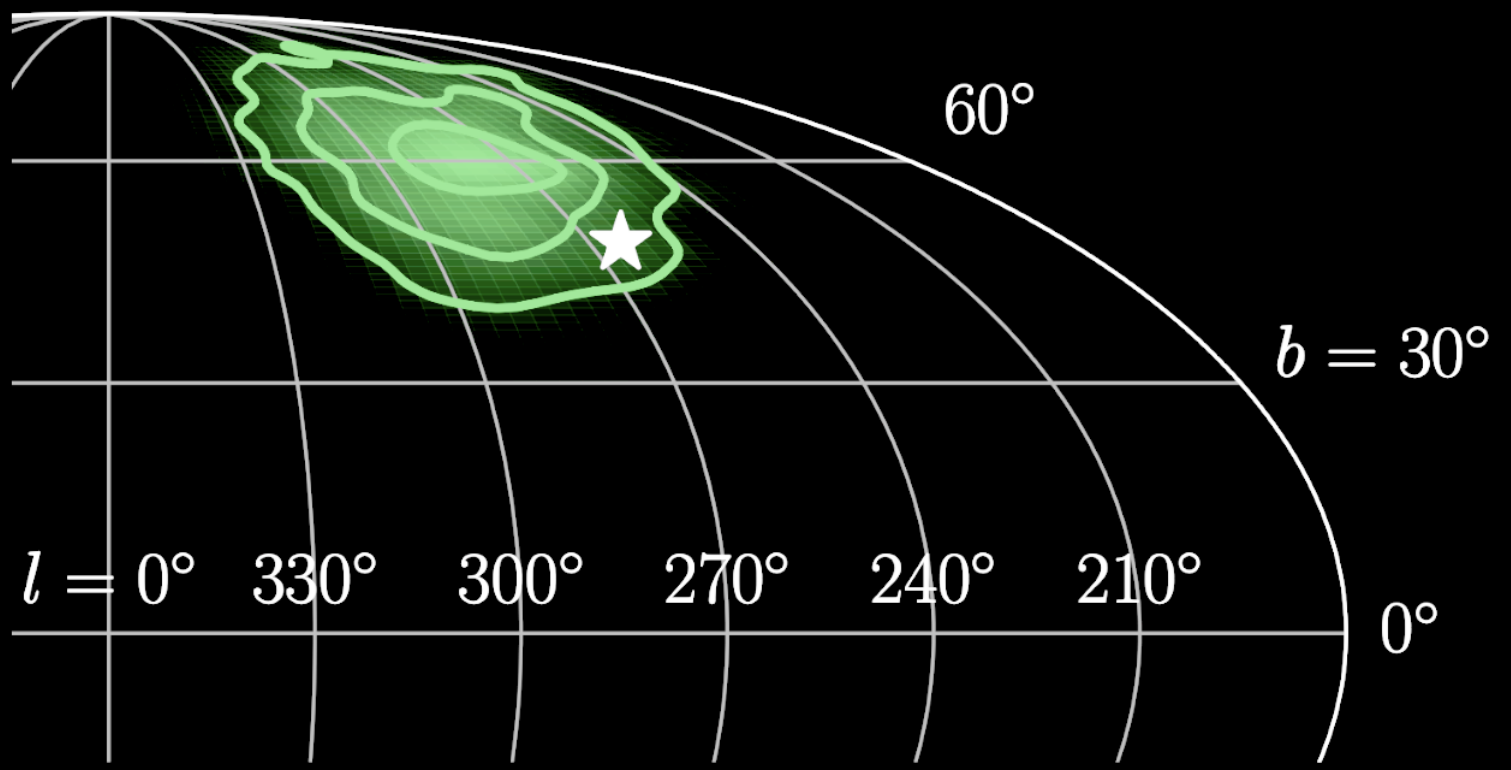




$\ln \mathcal{L}_{\mathrm{NVSS}}$ $\ln \mathcal{L}_{\mathrm{RACS}}$

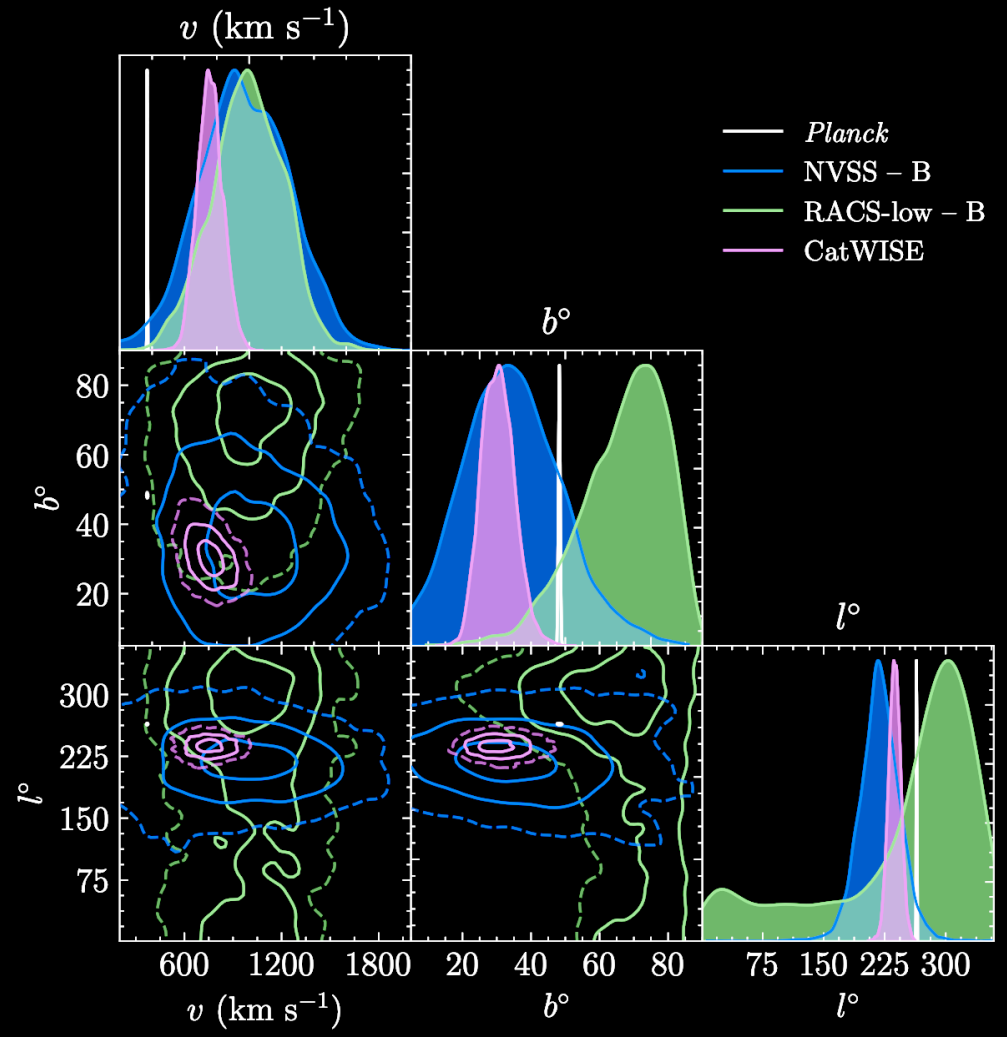
Free dipole: joint

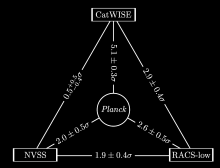




$$\ln \mathcal{L} = \ln \mathcal{L}_\mathrm{NVSS} + \ln \mathcal{L}_\mathrm{RACS}$$

Evidence & Suspicion (see Will Handley)





Land-Strykowski et al. (submitted)

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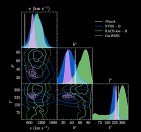

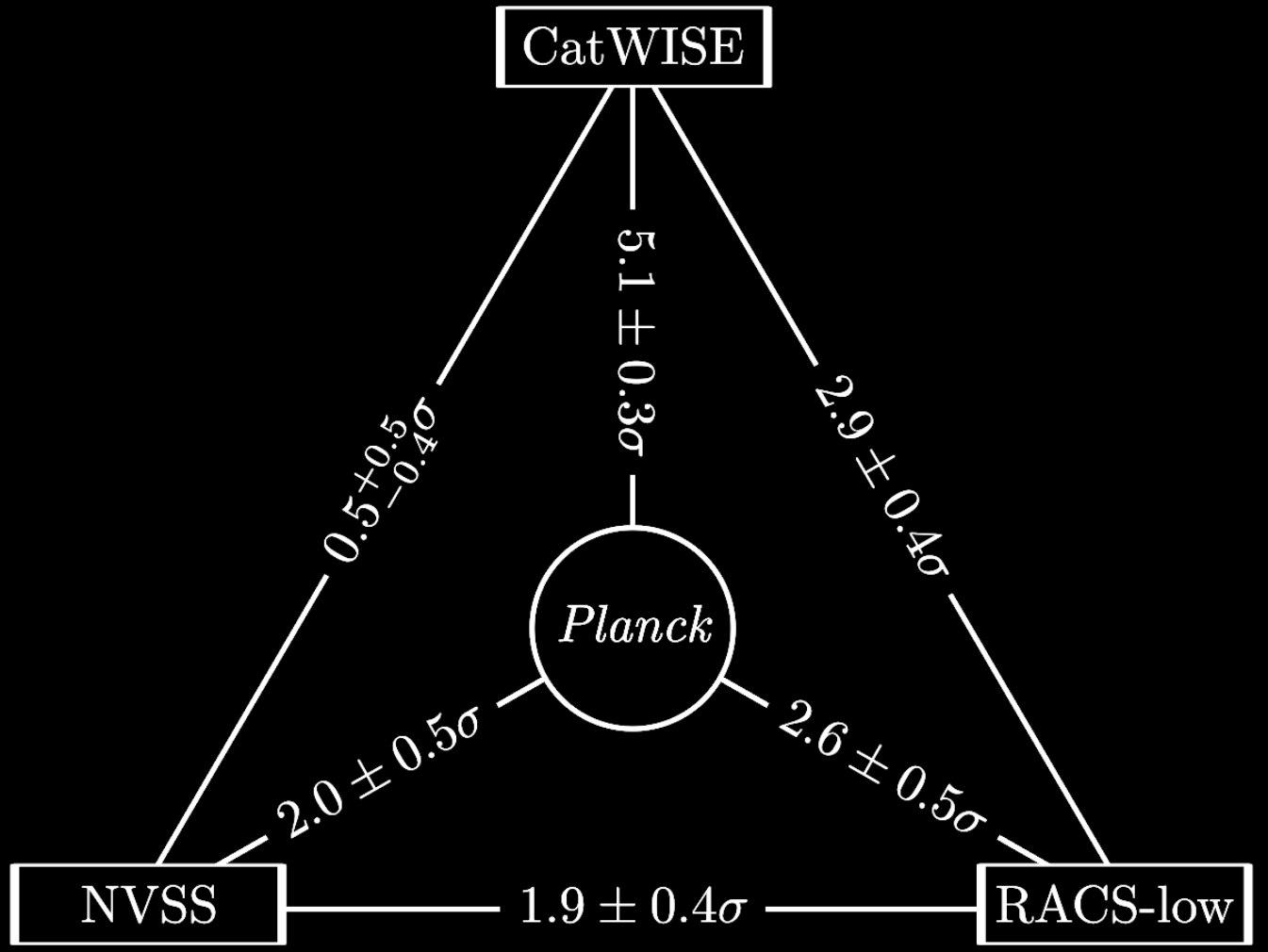

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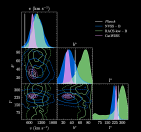
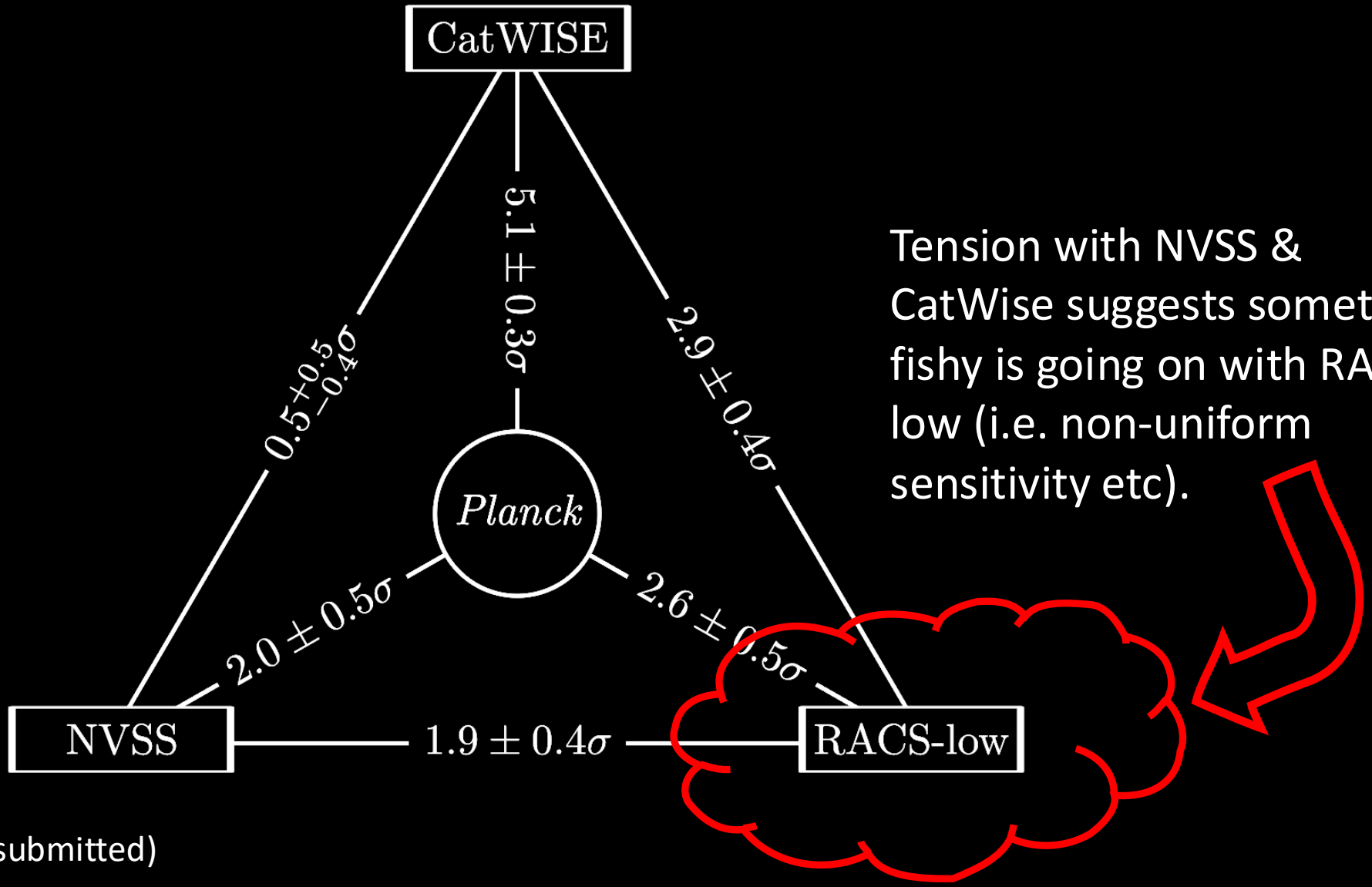
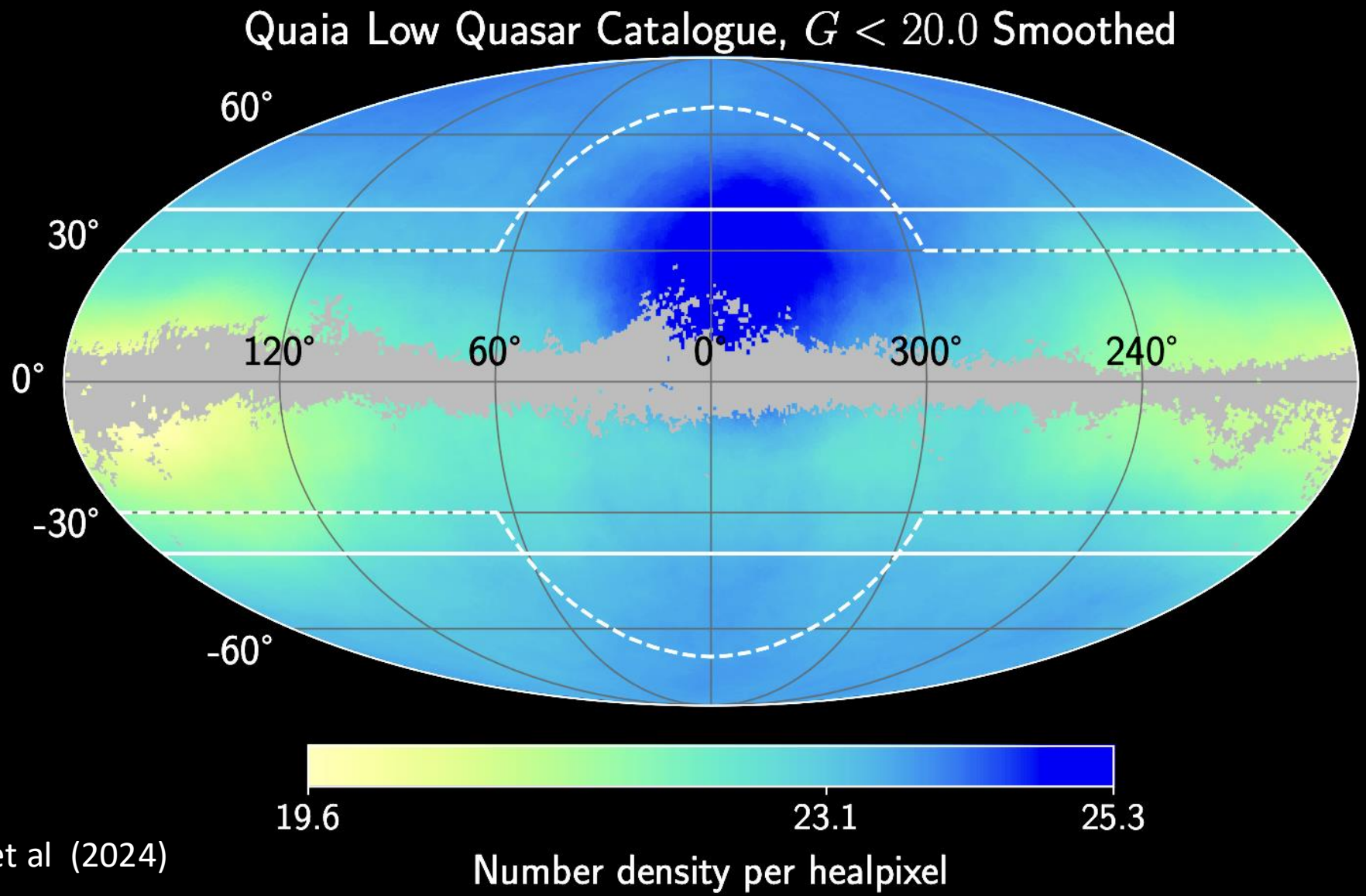




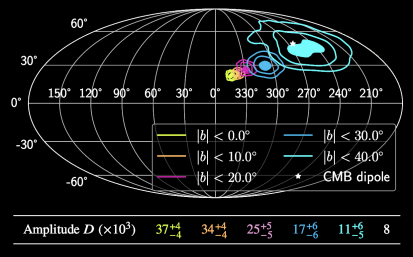
Tension with NVSS & CatWise suggests something fishy is going on with RACS-low (i.e. non-uniform sensitivity etc).

Land-Strykowski et al. (submitted)

Dealing with Systematics and Selections



Storey-Fisher et al (2024)



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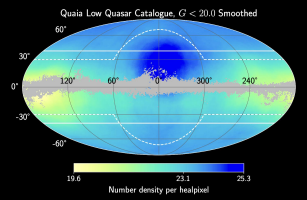
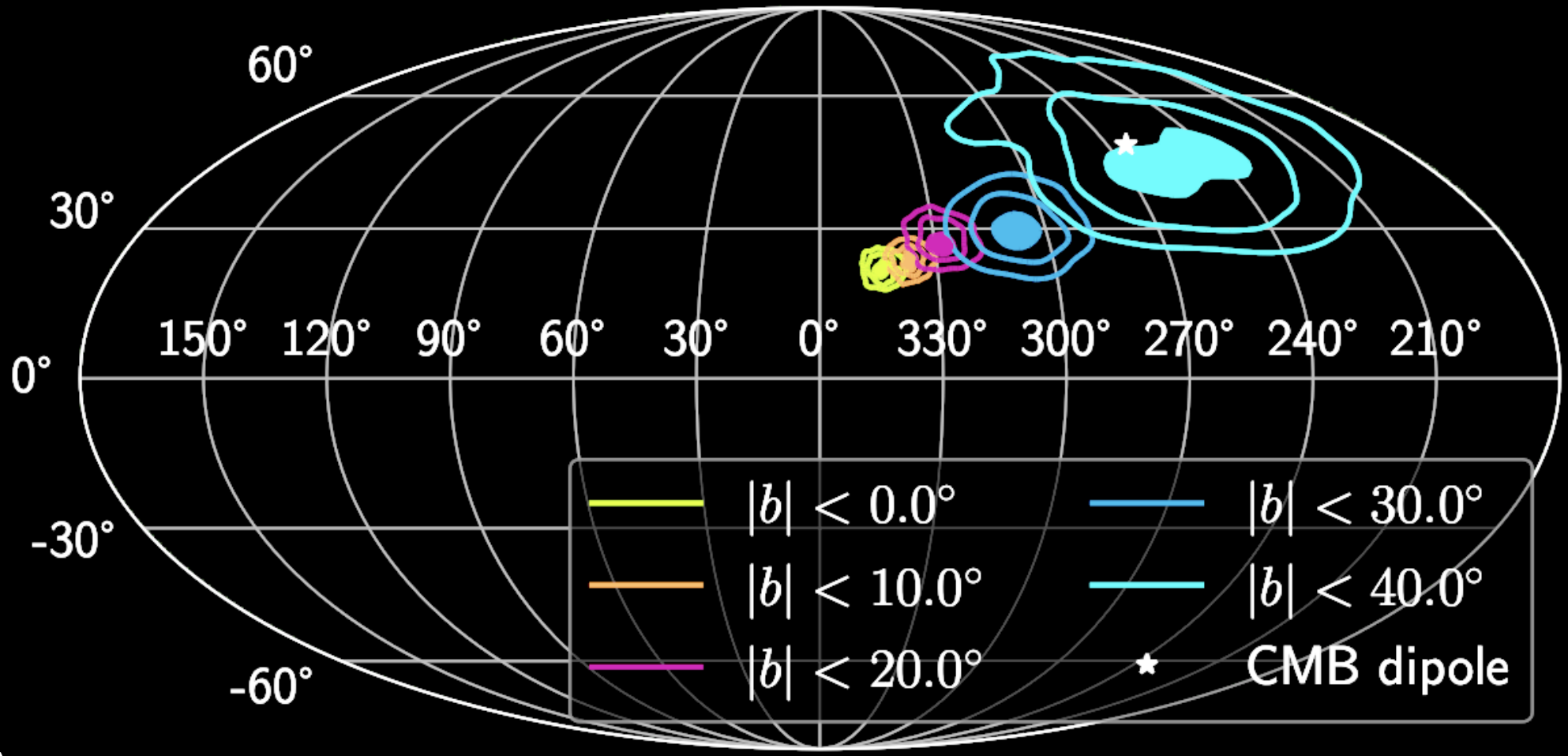
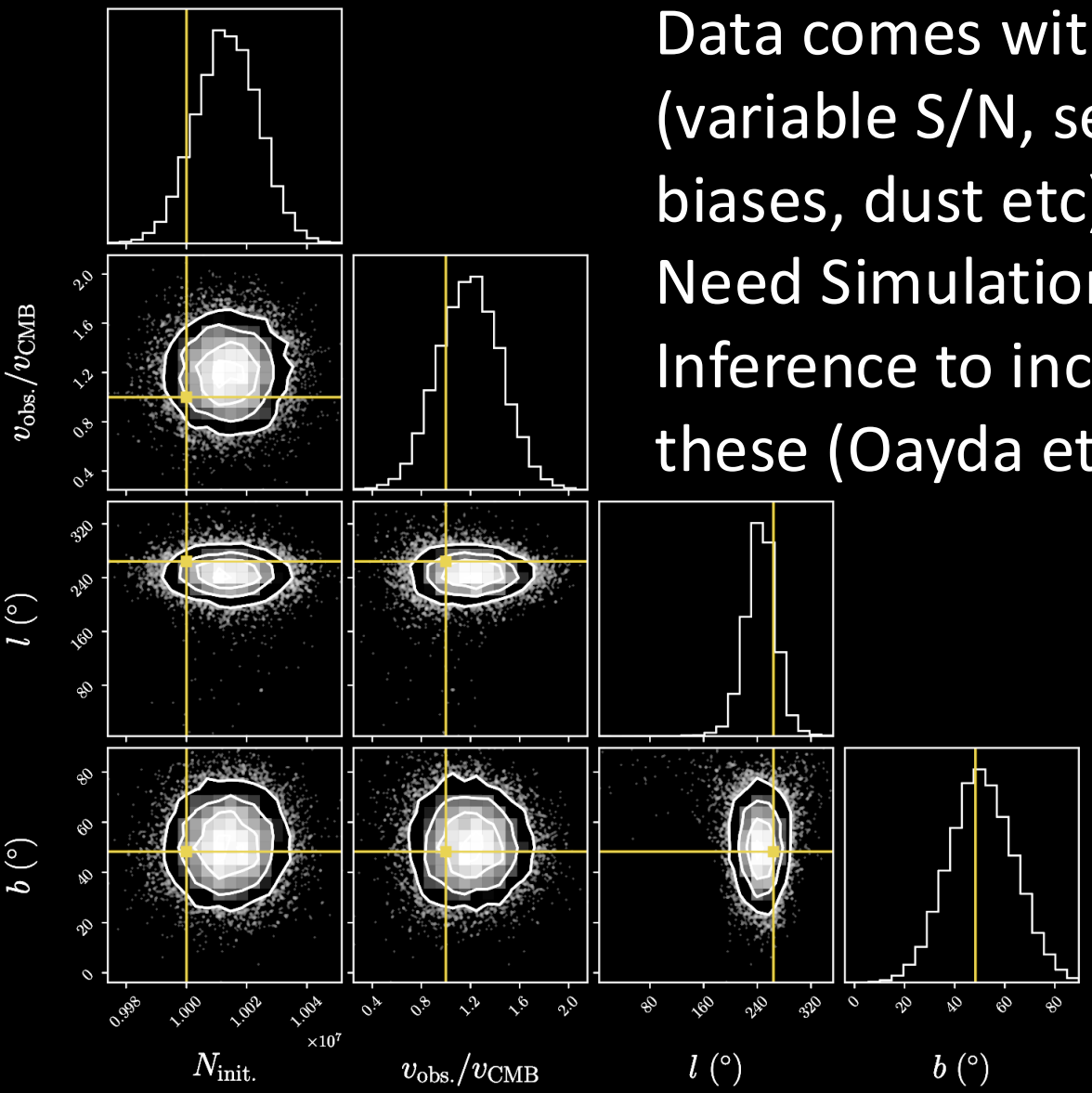




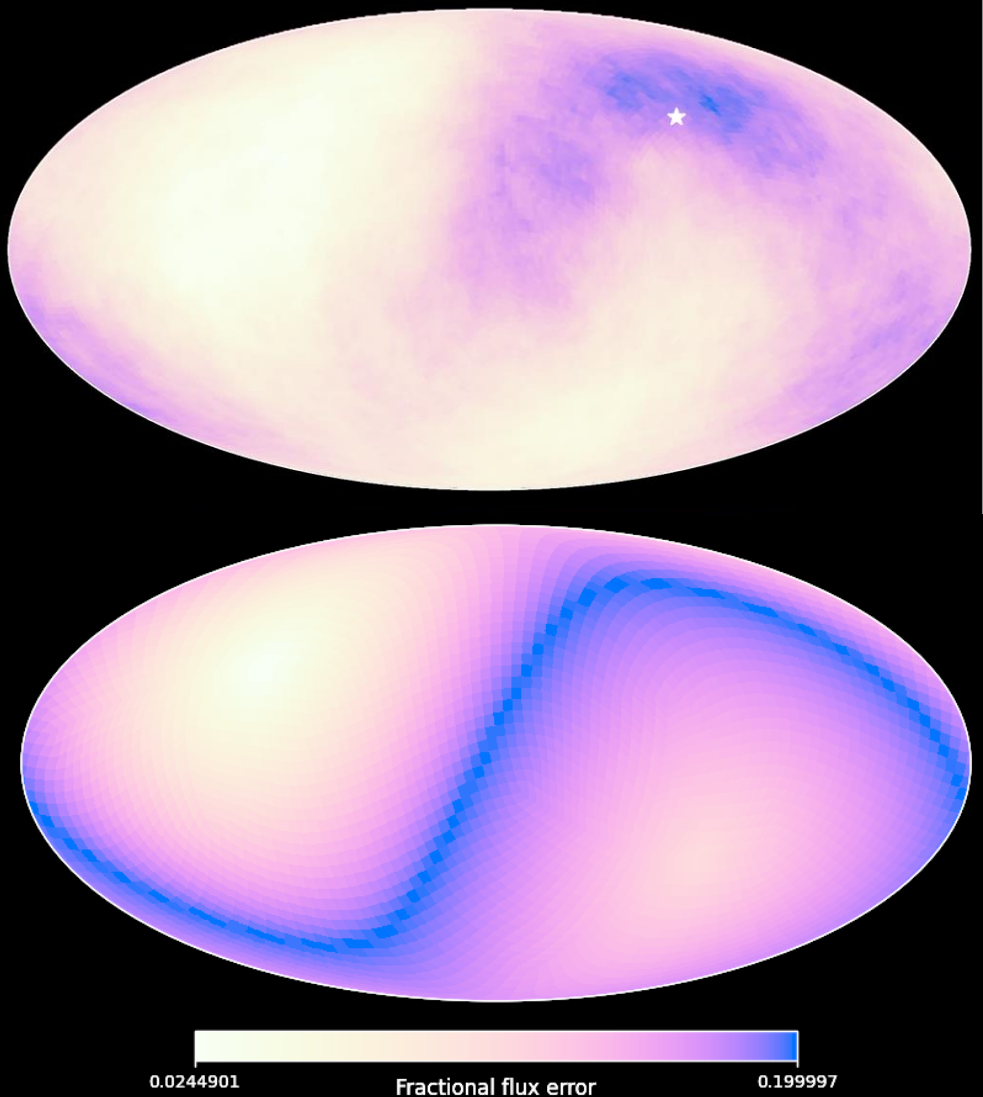
Mittal et al (2024)

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

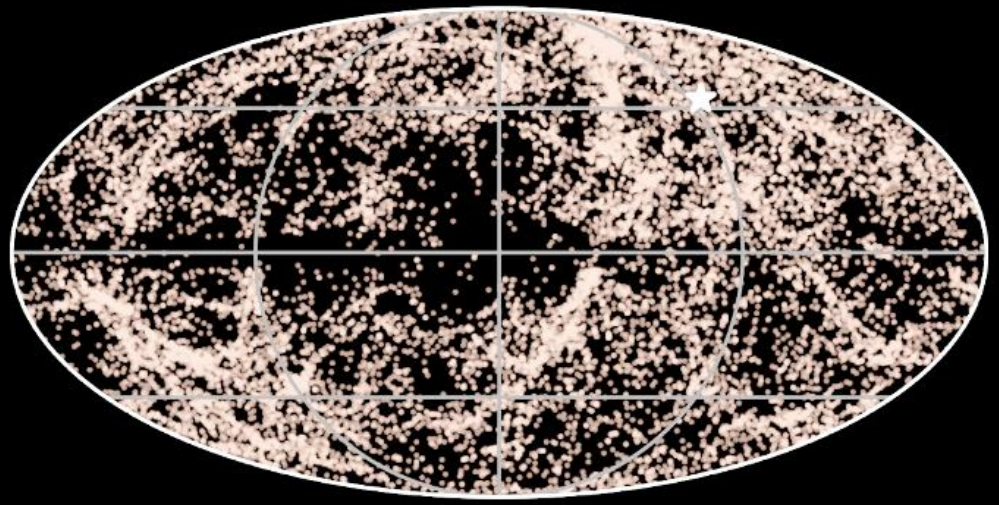
Dealing with Systematics and Selections



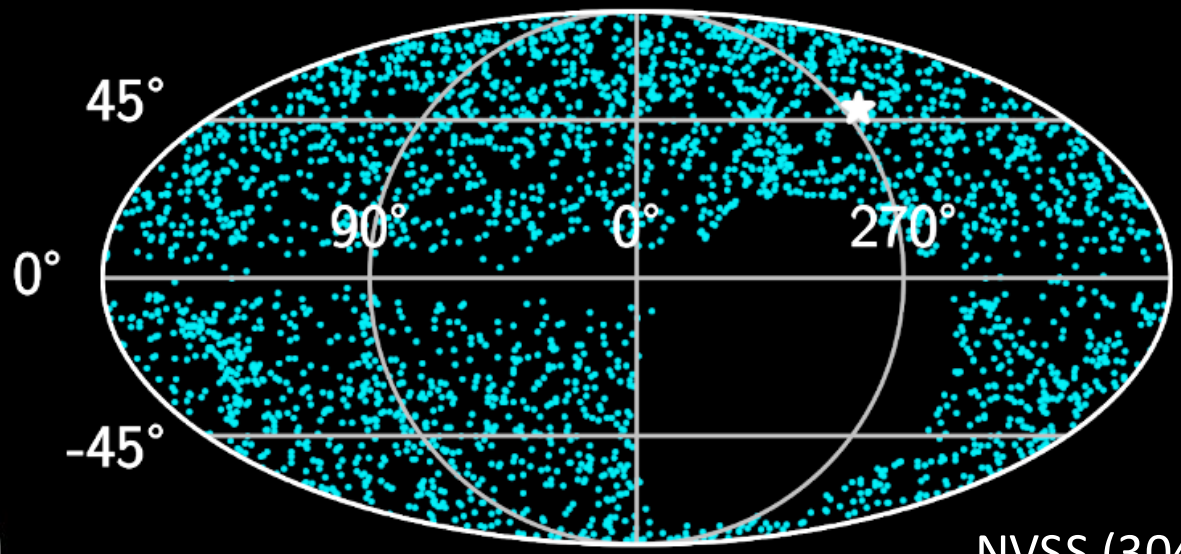
Data comes with peculiarities (variable S/N, selection biases, dust etc).
Need Simulation-Based Inference to incorporate these (Oayda et al. in prep).



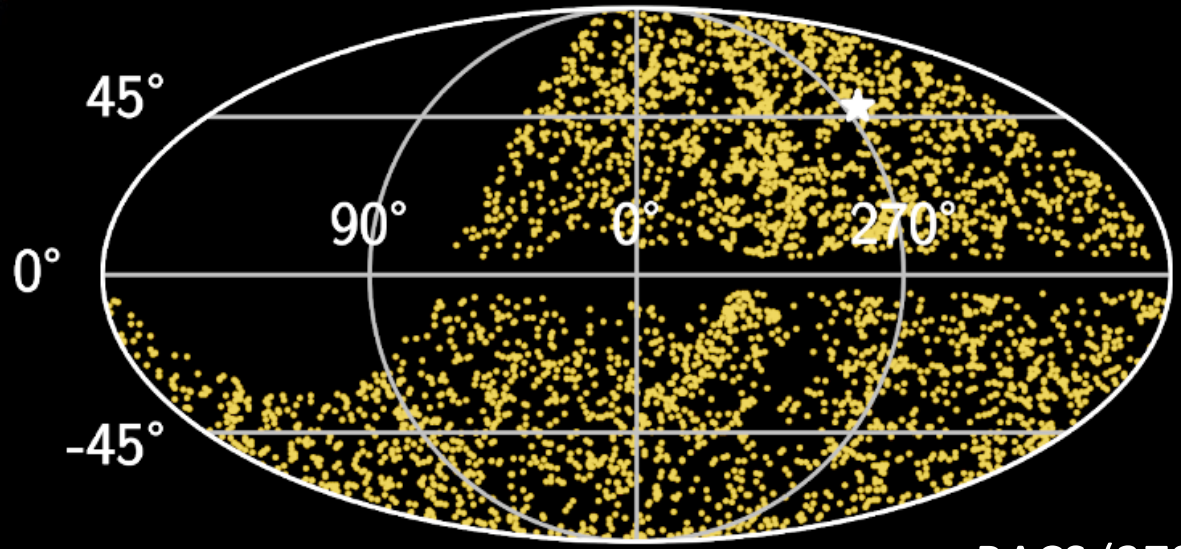
The Effect of Local Structure



NED and 2MRS sources
($z < 0.02$)

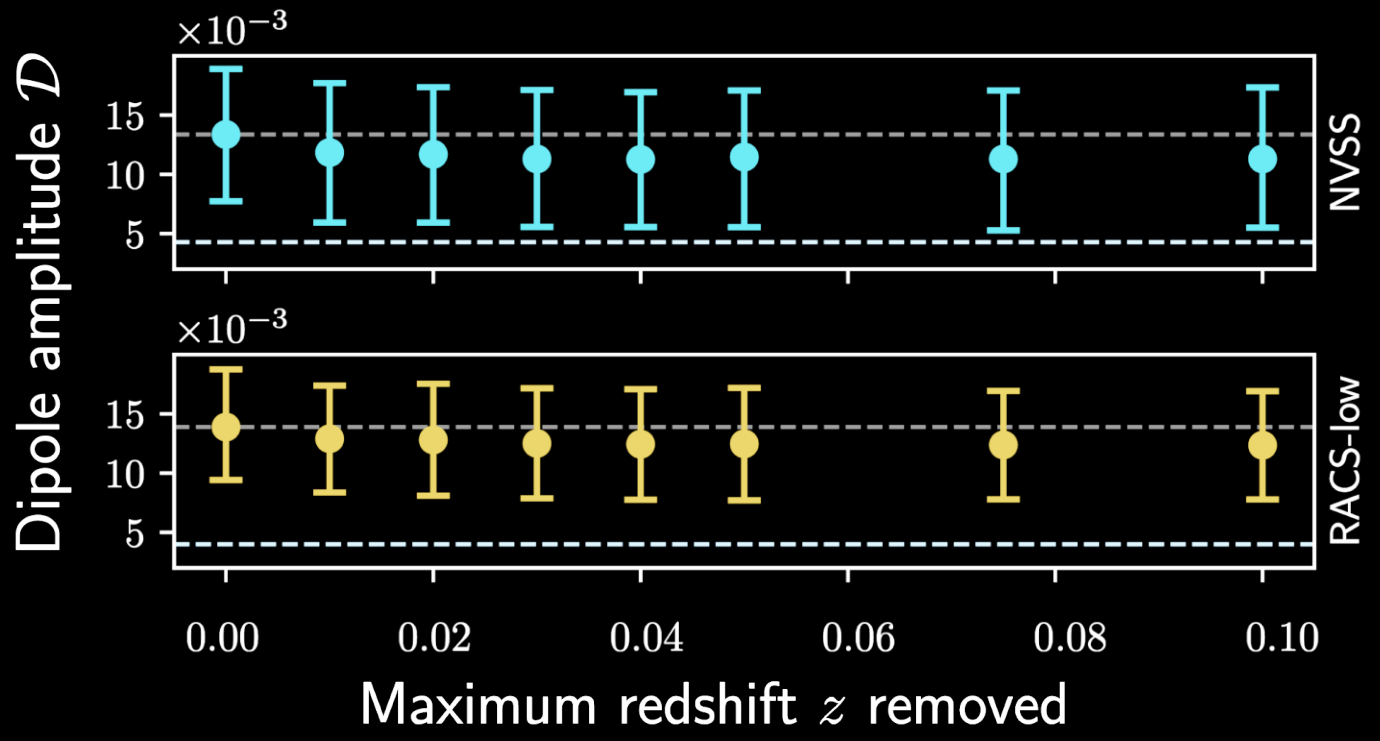


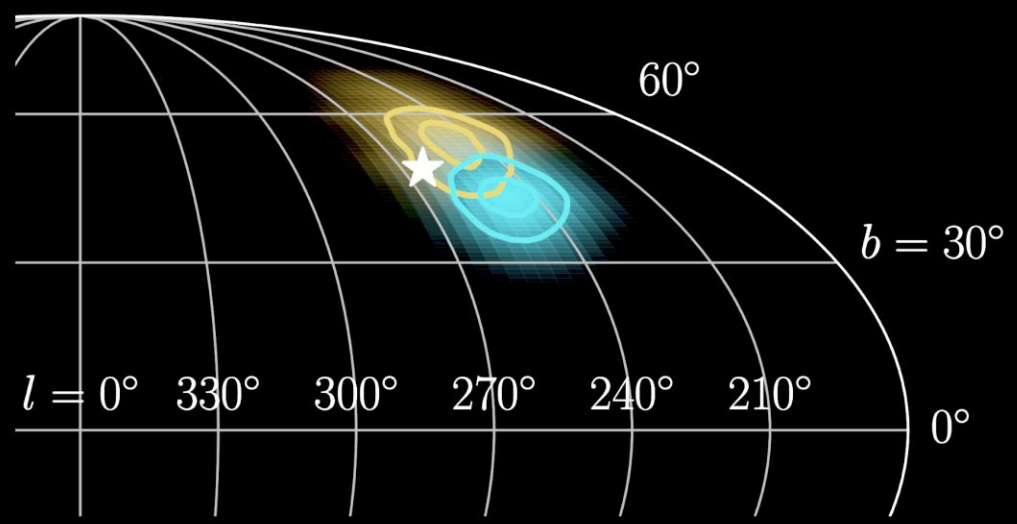
NVSS (3049 sources)



RACS (3700 sources)

The Effect of Local Structure

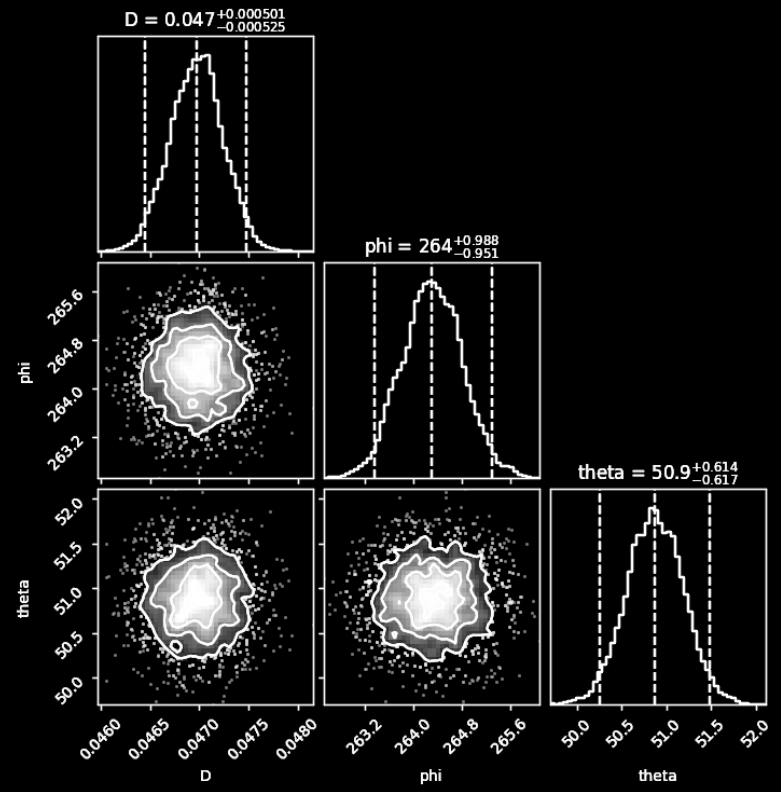


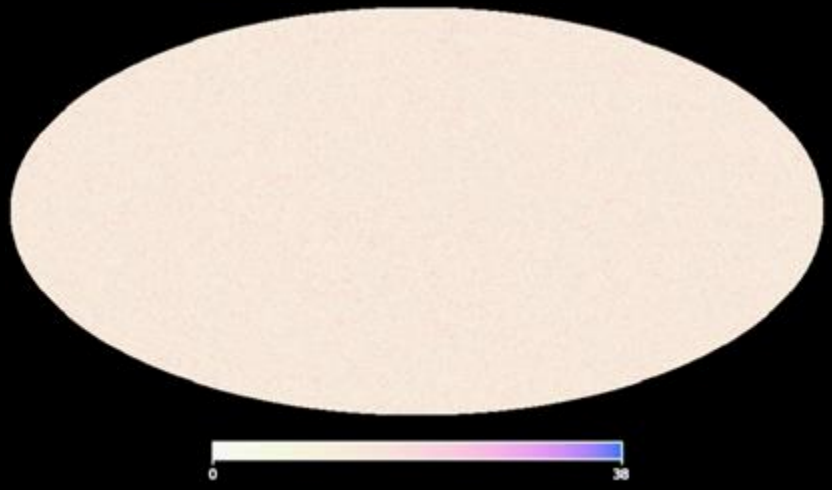


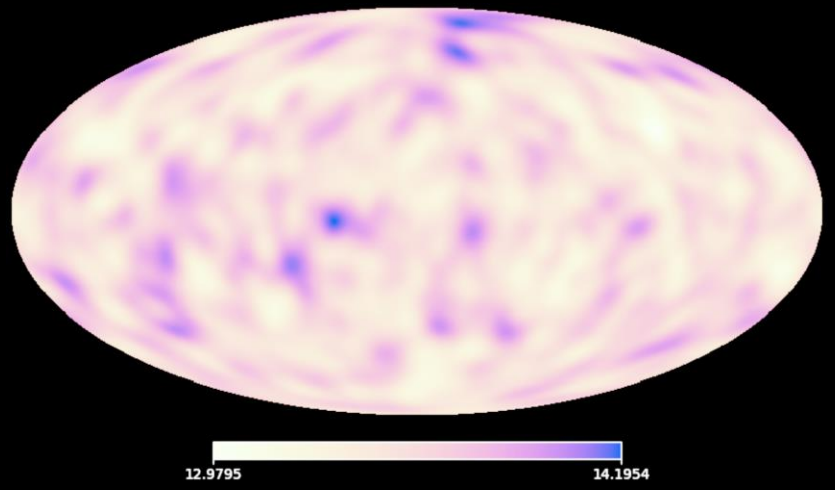
We will need to consider higher-order multipoles to account for local clustering, requiring careful consideration of how to explore the posterior space (Oayda et al. 2025).

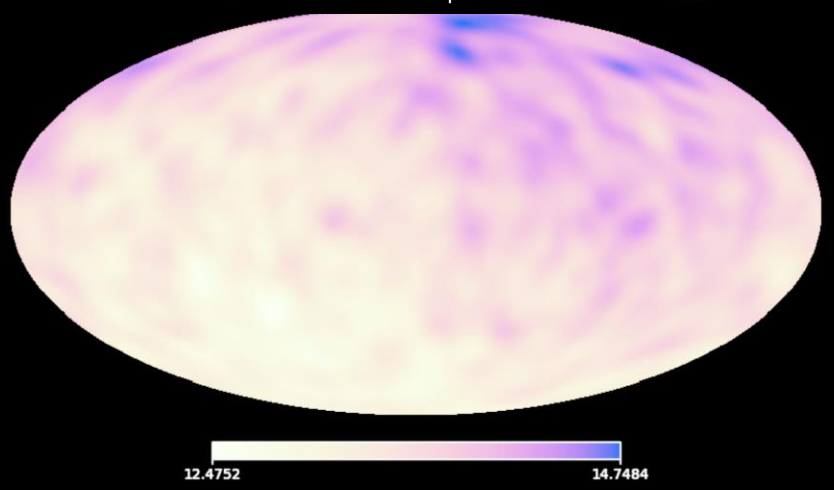
Future Forecasting: Square Kilometre Array

Exploring forecasting for future facilities (current focus on SKA). Need to go beyond number counts to include sensitivity, masking, large-scale structure etc to obtain a realistic measure of the dipole.





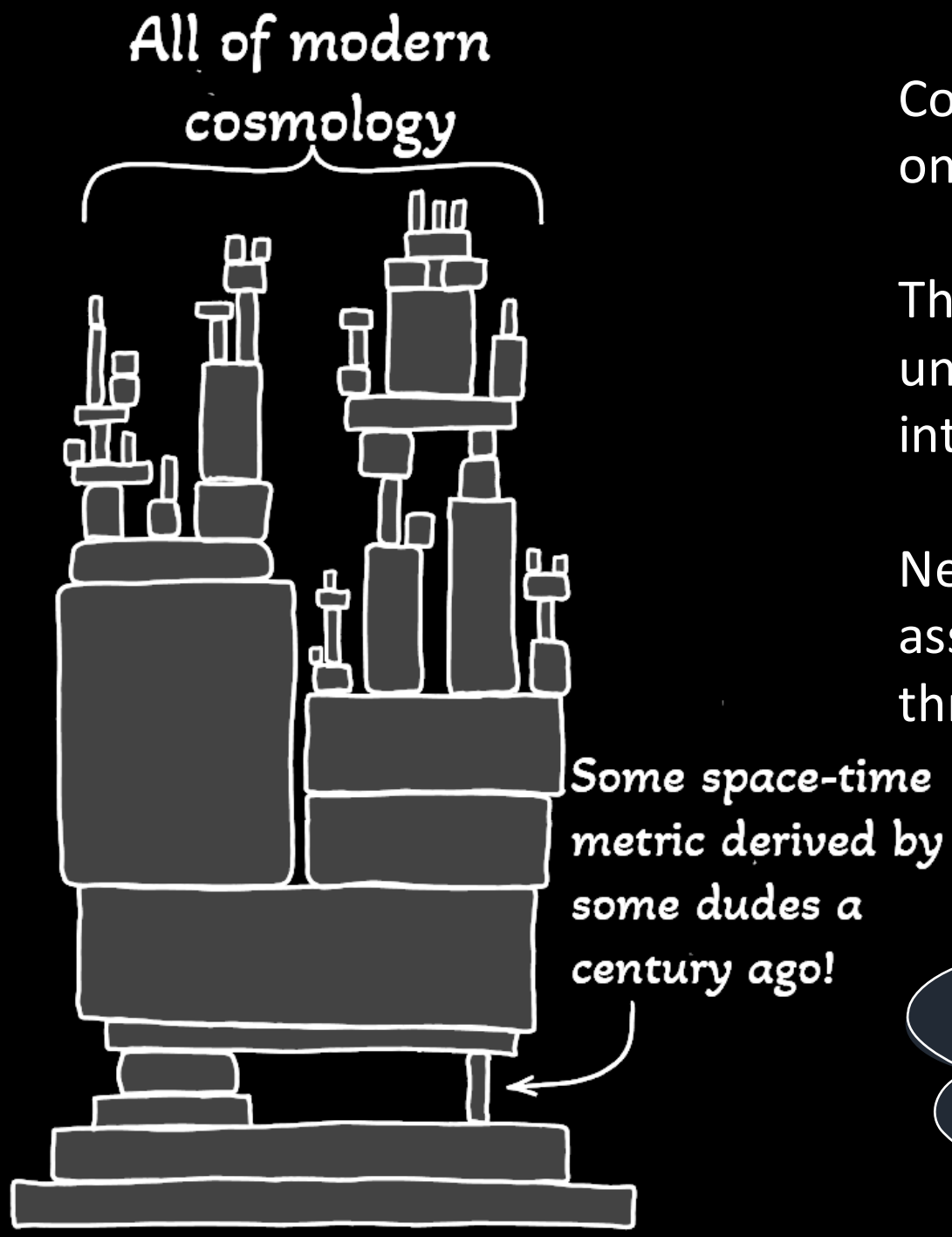




Conclusions: The Cosmic Dipole tension appears to be one of the most significant tensions.

The measurement of the dipole properties depends on understanding various factors and incorporating them into the analysis.

Need a robust framework (Bayesian) framework to assess whether the Cosmological Principle is under threat.



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Questions?