The Dipole Problem in Cosmology

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Background

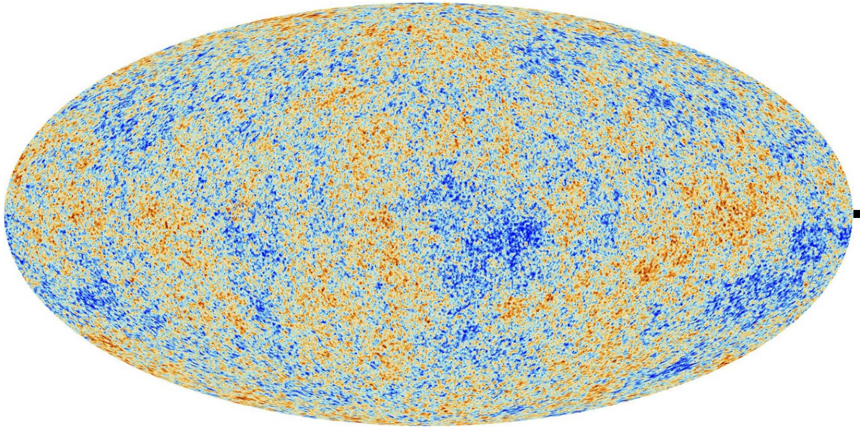
The “concordance” or “standard” cosmological model is ΛCDM:

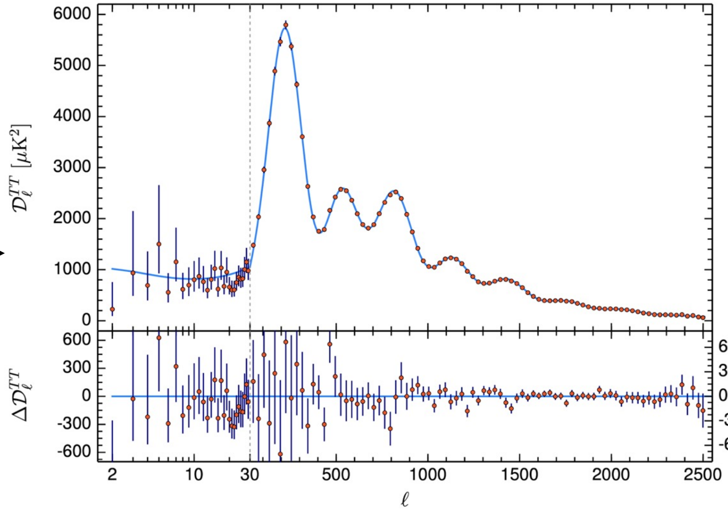
- Universe composed of radiation, “normal” matter, cold dark matter (CDM), and a cosmological constant Λ (i.e., dark energy).
- Universe is *statistically* homogeneous and isotropic on large ($\gtrsim$150 Mpc) scales. (the **Cosmological Principle**)
- *Assuming* the cosmological principle allows for use of the FLRW metric:

$$ds^2 = dt^2 - a(t)^2(dr^2 + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2)$$

The scale factor a(t) is governed by General Relativity, yielding the Friedmann equations. (c = 1, k = 0)

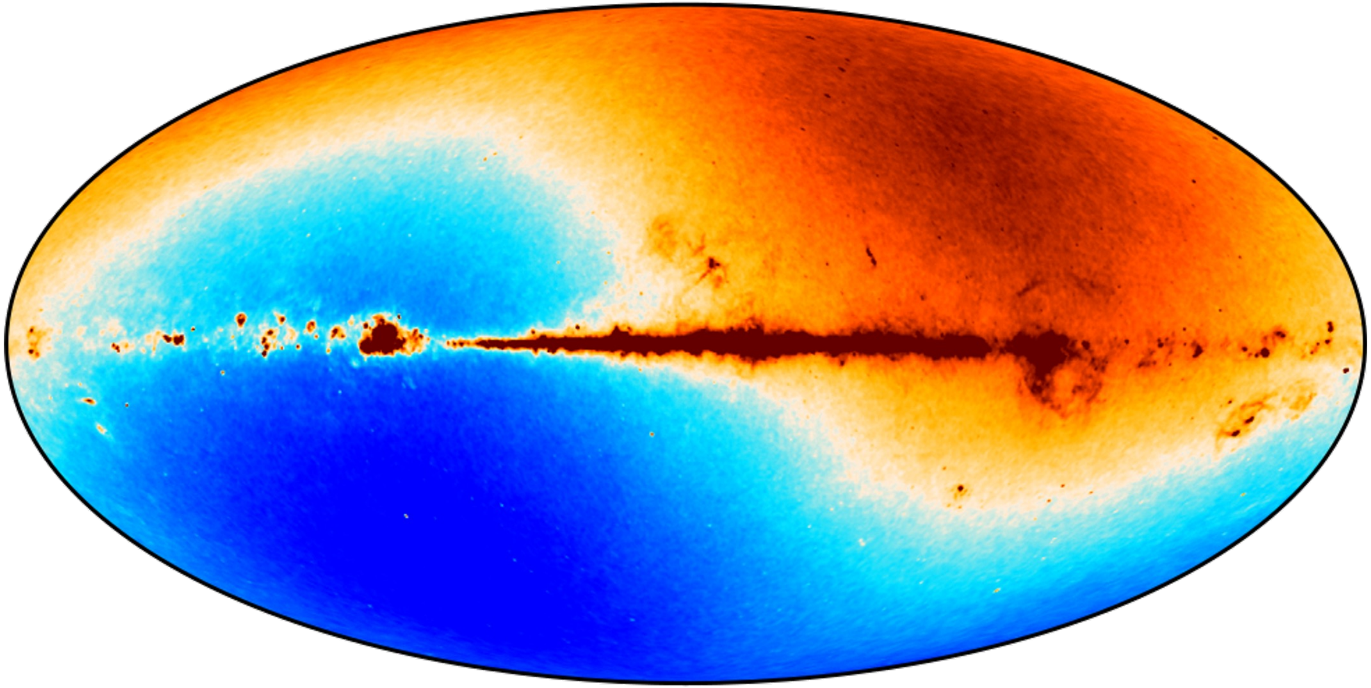
The common view





$$H_0,\ \Omega_\mathrm{m},\ \Omega_\mathrm{b},\ \Omega_\Lambda,\ \ldots$$

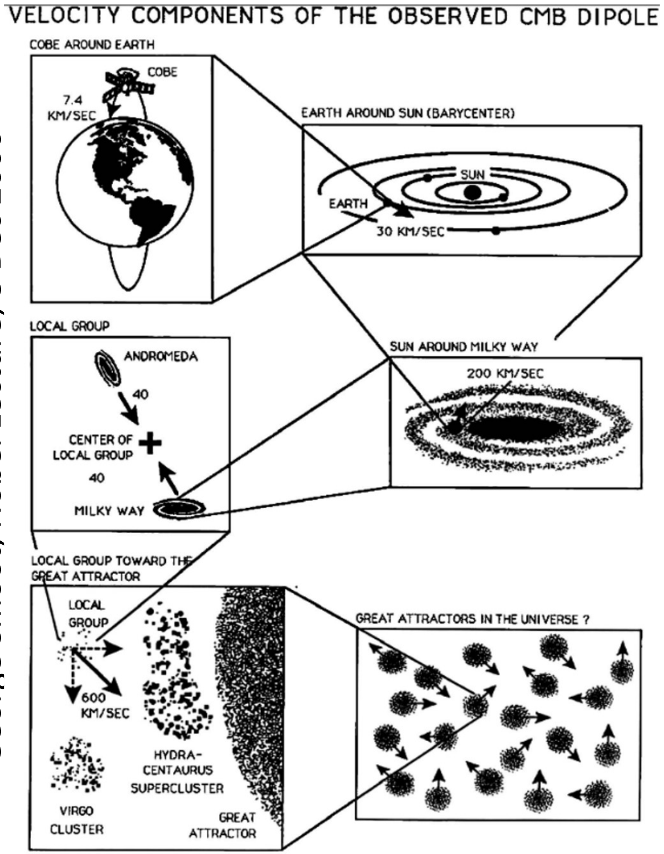
The microwave universe.



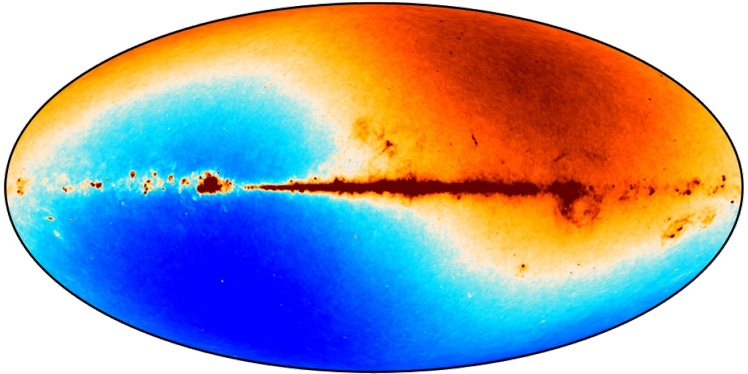
Credit: Beyond Planck

The null hypothesis: motion w.r.t. CMB → relativistic aberration + Doppler

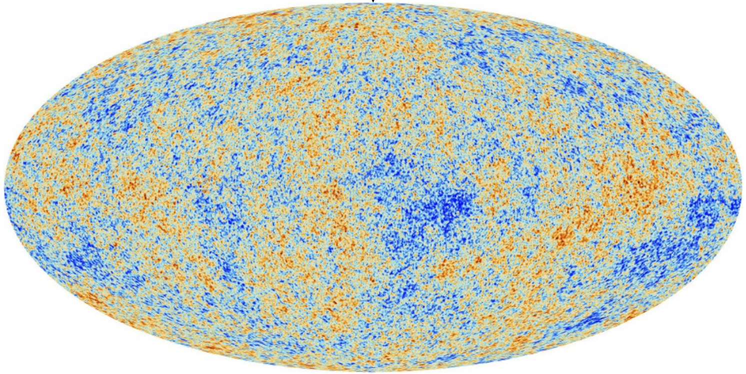
George Smoot, Nobel Lecture, 8 Dec 2006



$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$



minus 370 km s^{-1}
plus inpainting



The null hypothesis: motion w.r.t. CMB → relativistic aberration + Doppler

Ellis & Baldwin (1984):

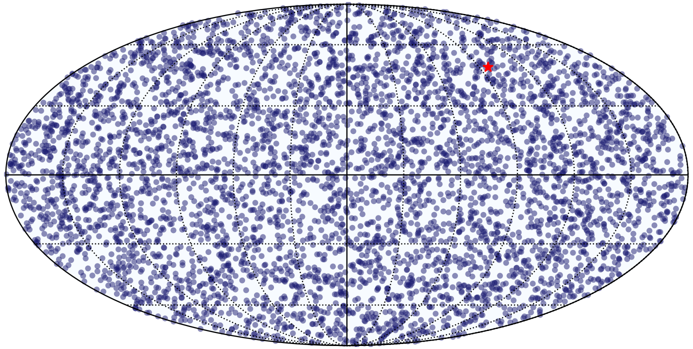
Modulation of source <u>counts:</u>

$$\frac{dN}{d\Omega}(> S_{\rm cut}) = 1 + \boxed{[2 + x(1+\alpha)]\boldsymbol{\beta}\cdot\hat{\boldsymbol{n}}} + \mathcal{O}(\beta^2)$$

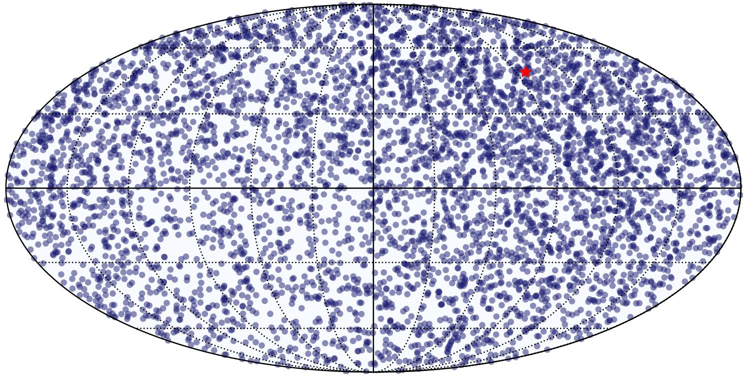
Modulation is dipole for β ~ 0.001

The null hypothesis: motion w.r.t. CMB → relativistic aberration + Doppler

Galaxies / quasars in CMB "rest frame"



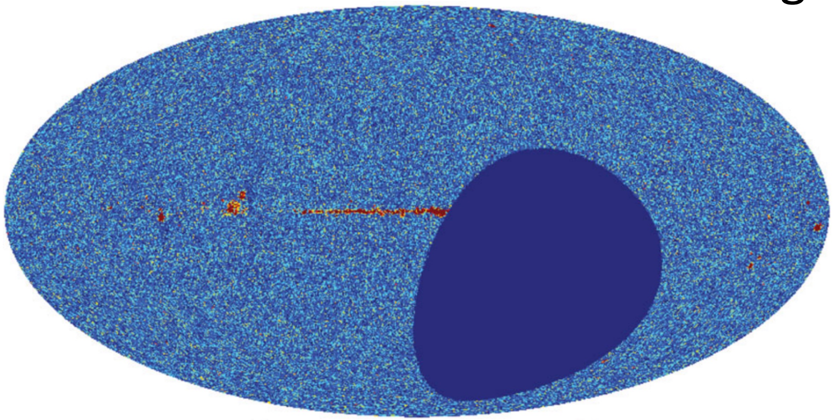
…and this dipole should be the same for all cosmological "test particles" (galaxies, quasars) that "move" in the Hubble flow.



Kinematic dipole (greatly exaggerated)

Provided that the Cosmological Principle is accurate.

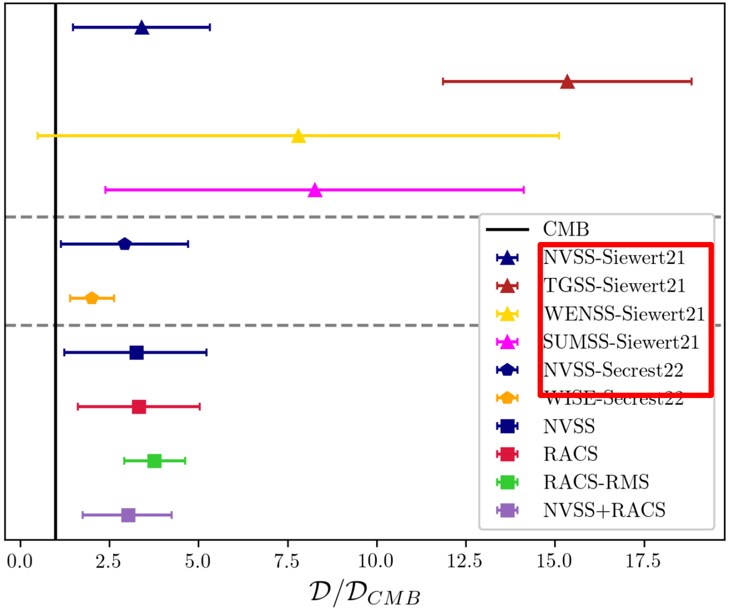
The NRAO VLA Sky Survey (NVSS; 1998): first constraints with ~0.5 million radio galaxies



Gibelyou & Huterer (2012)

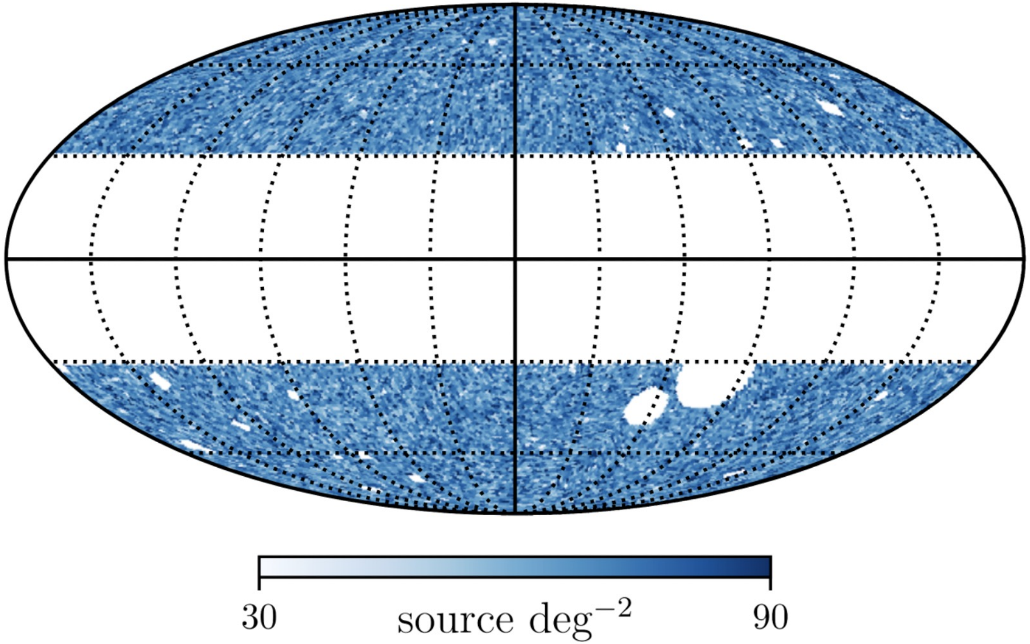
(Except Blake & Wall 2002), Singal (2011), Gibelyou & Huterer (2012), Rubart & Schwarz (2013), Tiwari et al. (2015), Tiwari & Nusser (2016), Colin et al. (2017), Bengaly et al. (2018), Siewert et al. (2021):

→ ~3σ tension with kinematic expectation!



Radio results with 3σ error bars from Wagenveld et al. (2023) with some earlier radio results highlighted

Secrest+21: 1.4 million quasars selected with WISE



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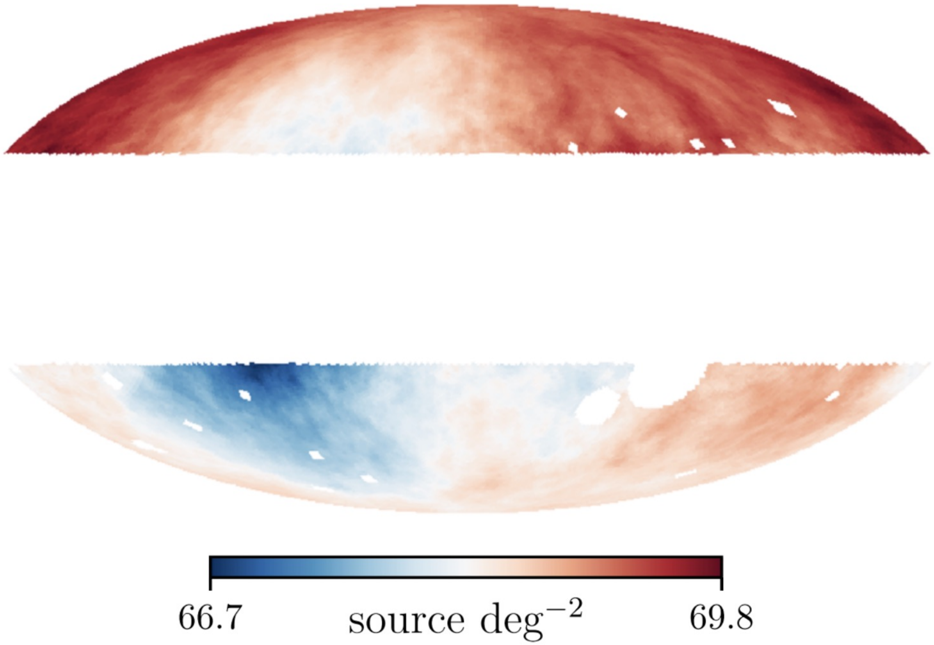
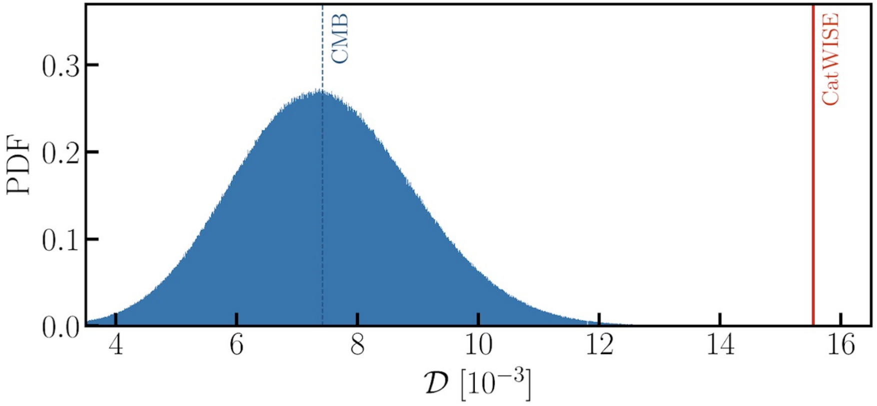
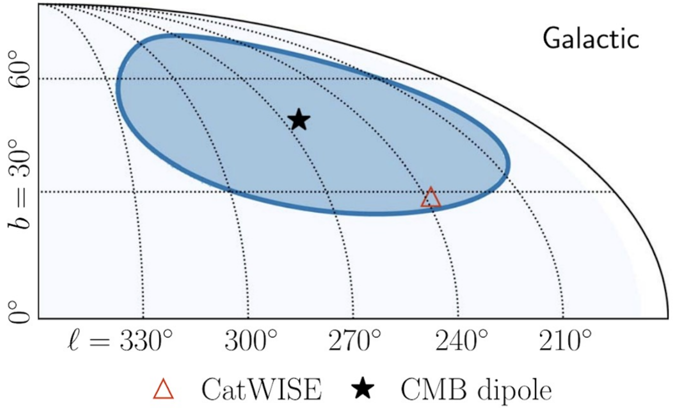


Smoothed map reveals clear dipole signal!

Only 5 in 10 million instances exceed found dipole.

(p-value = 5 x 10^{-7}, or 4.9σ)





Independently confirms previous radio findings.

Independent radio results confirmed, but how comparable are these results?

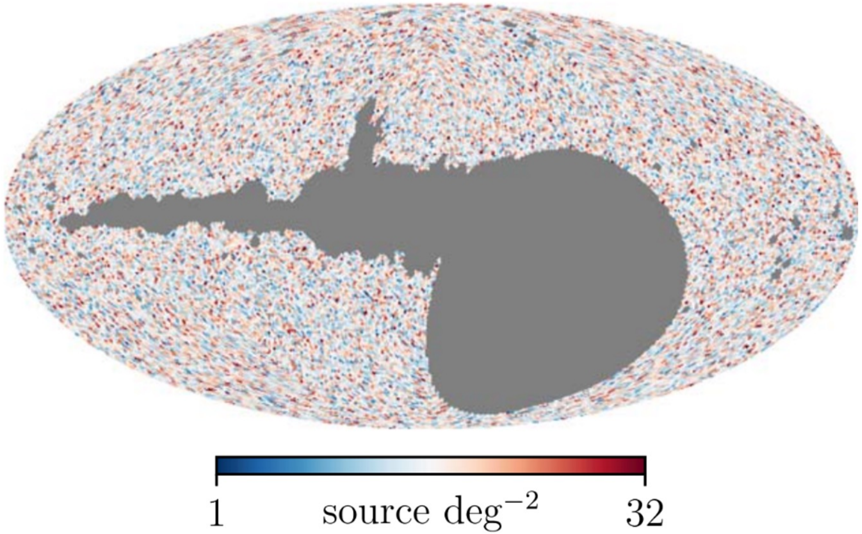
- Different masking strategies
- Different dipole estimators (e.g., quadratic vs. linear)
- Systematics may have been missed
- Effect of shared sources (that are radio galaxies AND quasars)?

Repeated systematics checks on NVSS catalog.

Main systematics:

- declination (VLA D/DnC configuration change)
- Galactic synchrotron

→ 508,144 sources



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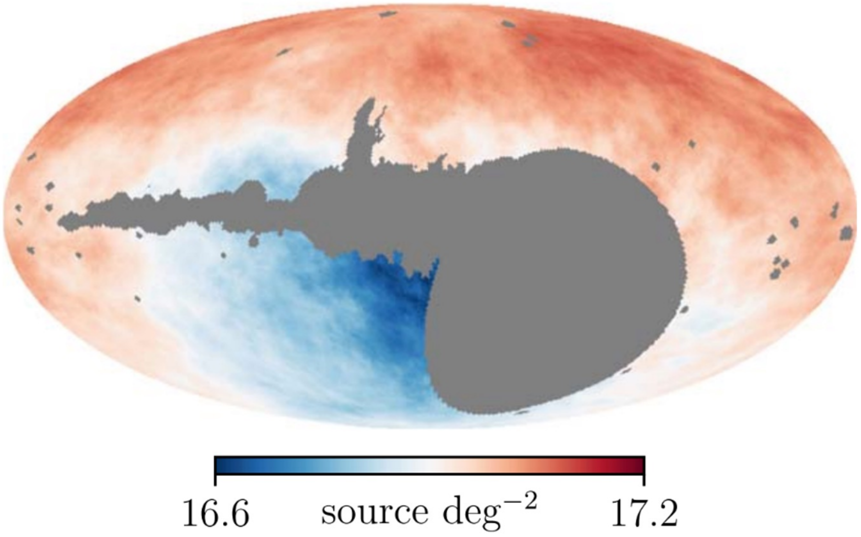


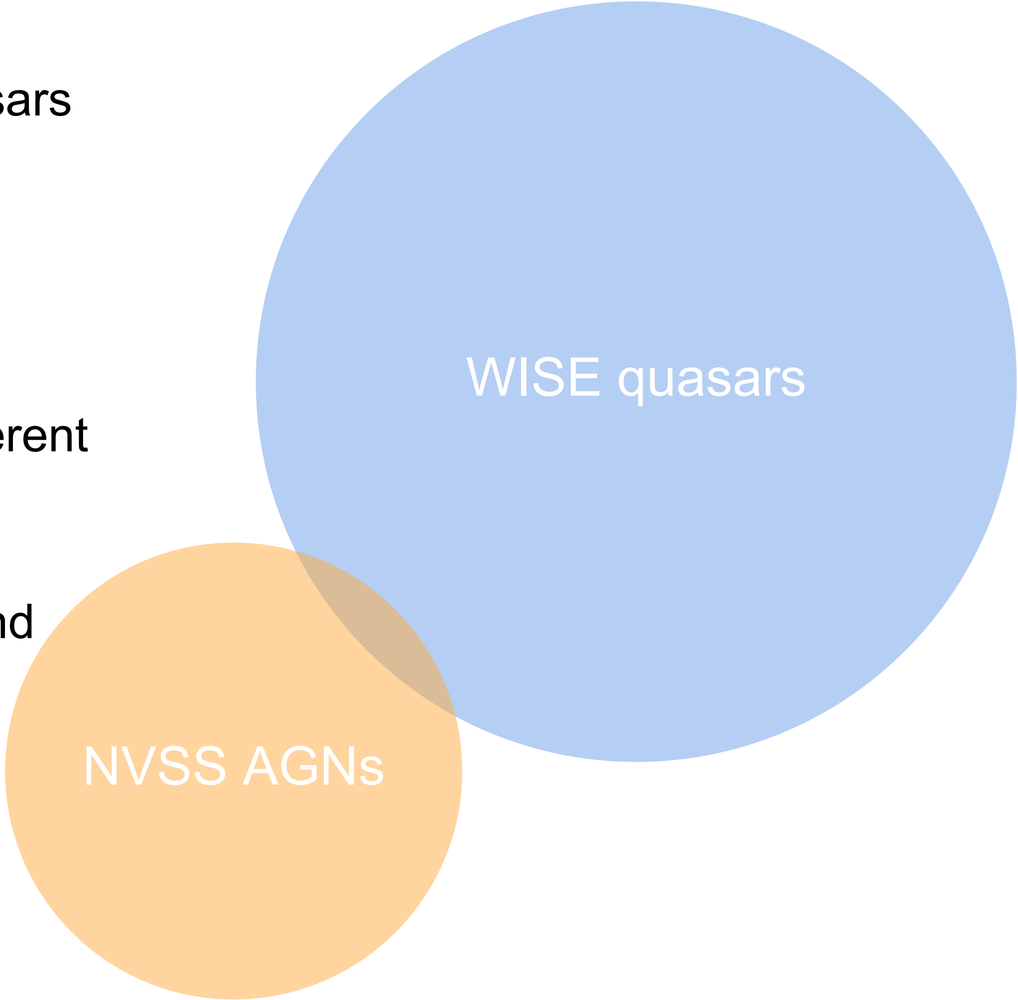
dipole signal in smoothed map

Shared sources: **1.4%** of WISE quasars

Why?

Radio galaxies and quasars are different kinds of object!

- Radio galaxies: evolved, “red and dead” massive ellipticals
- Quasars: bluer, gas-rich disk galaxies



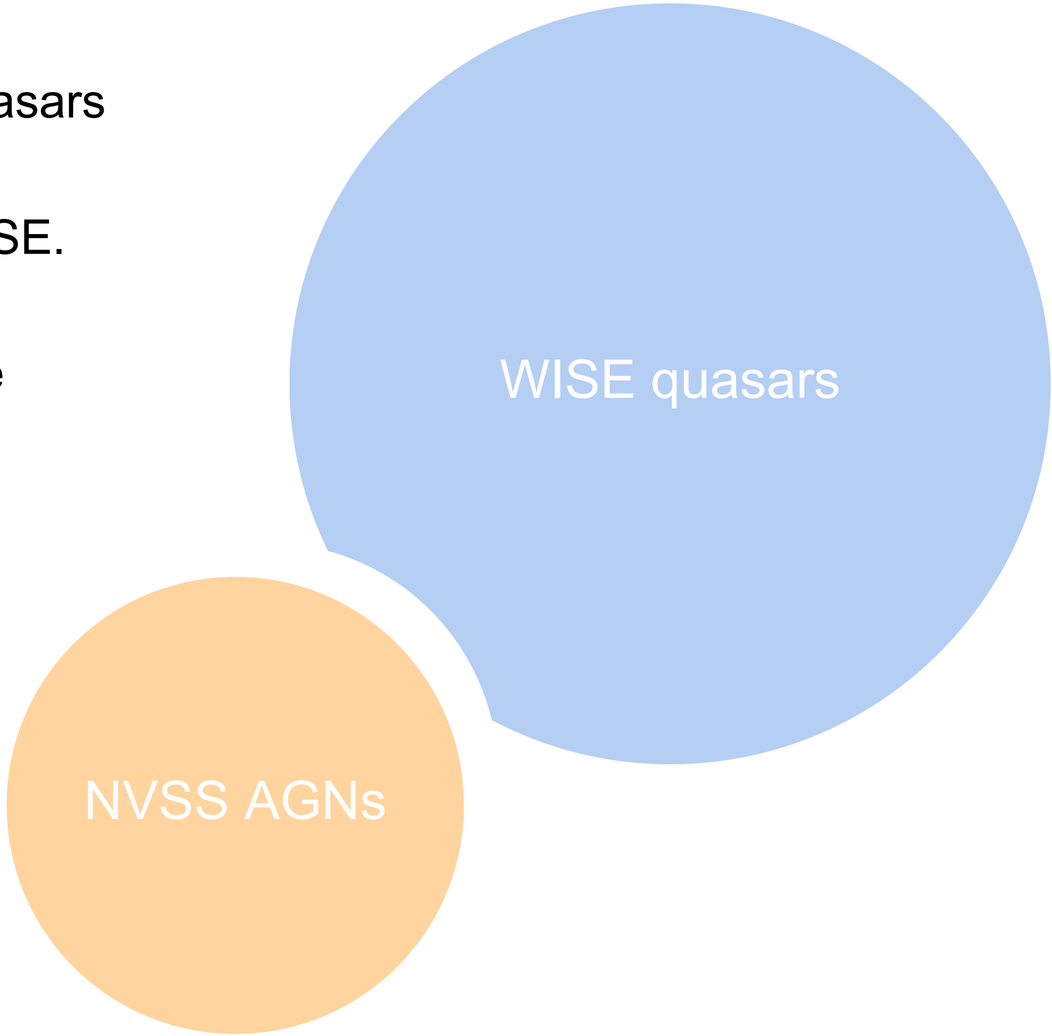
Shared sources: 1.4% of WISE quasars

Removed shared sources from WISE.

Kept sources in NVSS to maximize sources in smaller catalog.

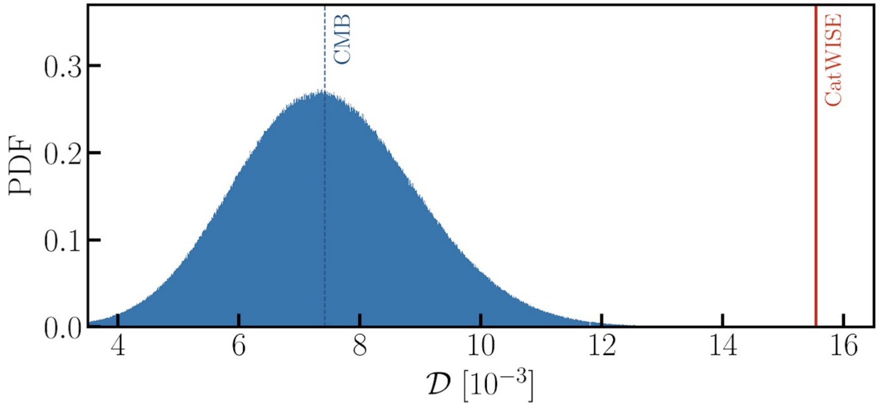
WISE quasars in unshared regions removed randomly to preserve uniformity.

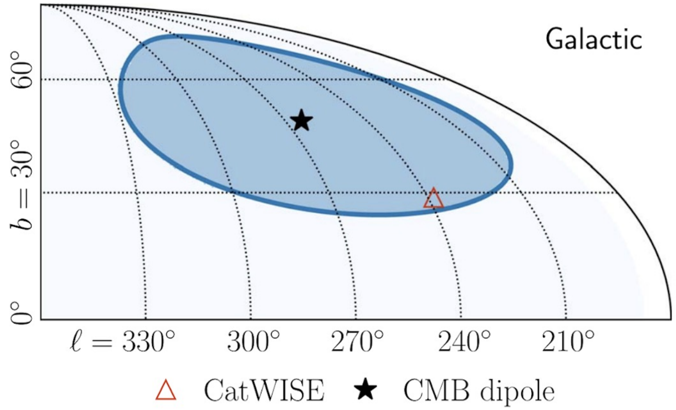
→ **Totally orthogonal catalogs.**



Rejecting the null hypothesis

Secrest+21 defined the *p*-value as the fraction of null skies *within* found CMB offset with *D* exceeding the kinematic prediction.





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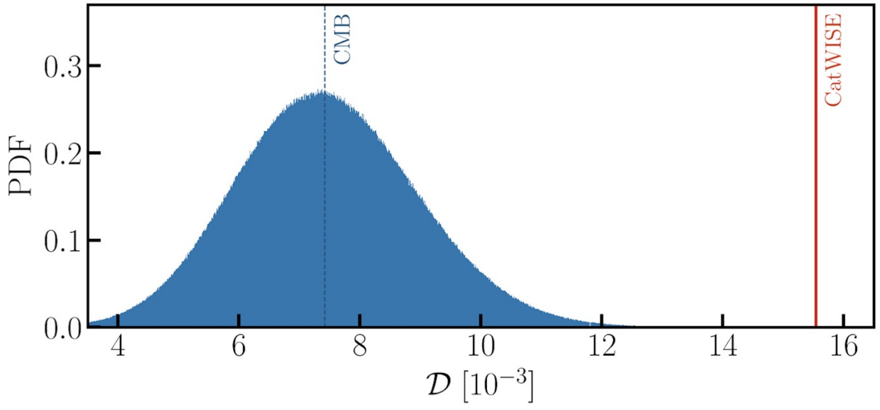
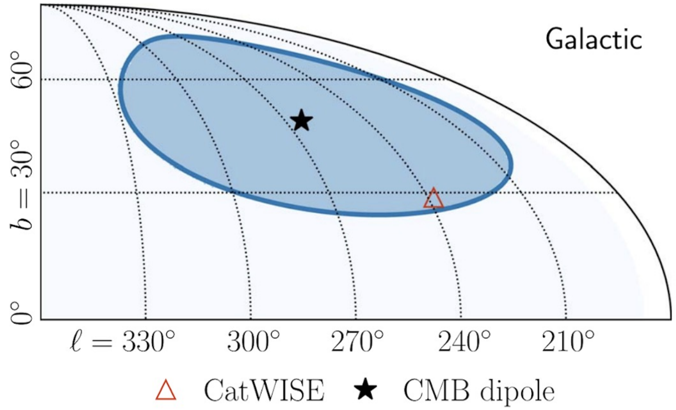




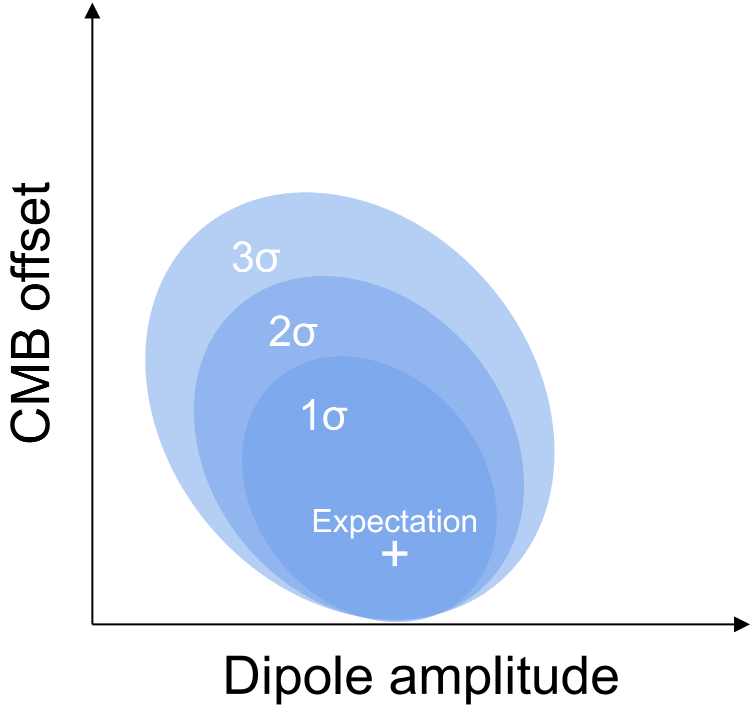
In a way, this places a preference on dipoles aligned near to the CMB.

It is not the most general test of the null hypothesis. (Why should we expect an anomalous dipole to align with that of the CMB?)

Rejecting the null hypothesis

- Dipole amplitude and CMB offset are *correlated*: larger dipole amplitude = smaller CMB offset under the null hypothesis.

Smaller found dipole with larger CMB offset could be just as significant as larger dipole with smaller offset: 2D *p*-value does not bias interpretation of found dipole!

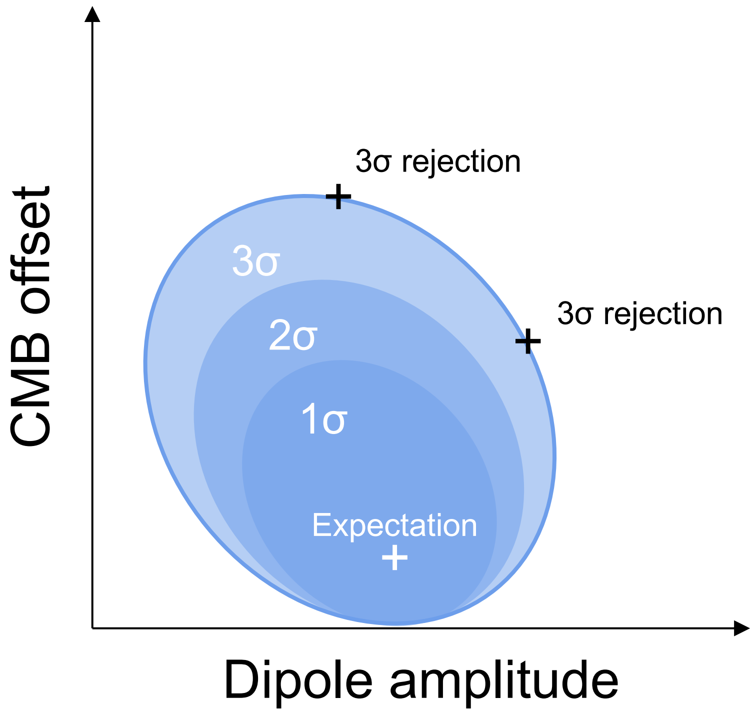


Rejecting the null hypothesis

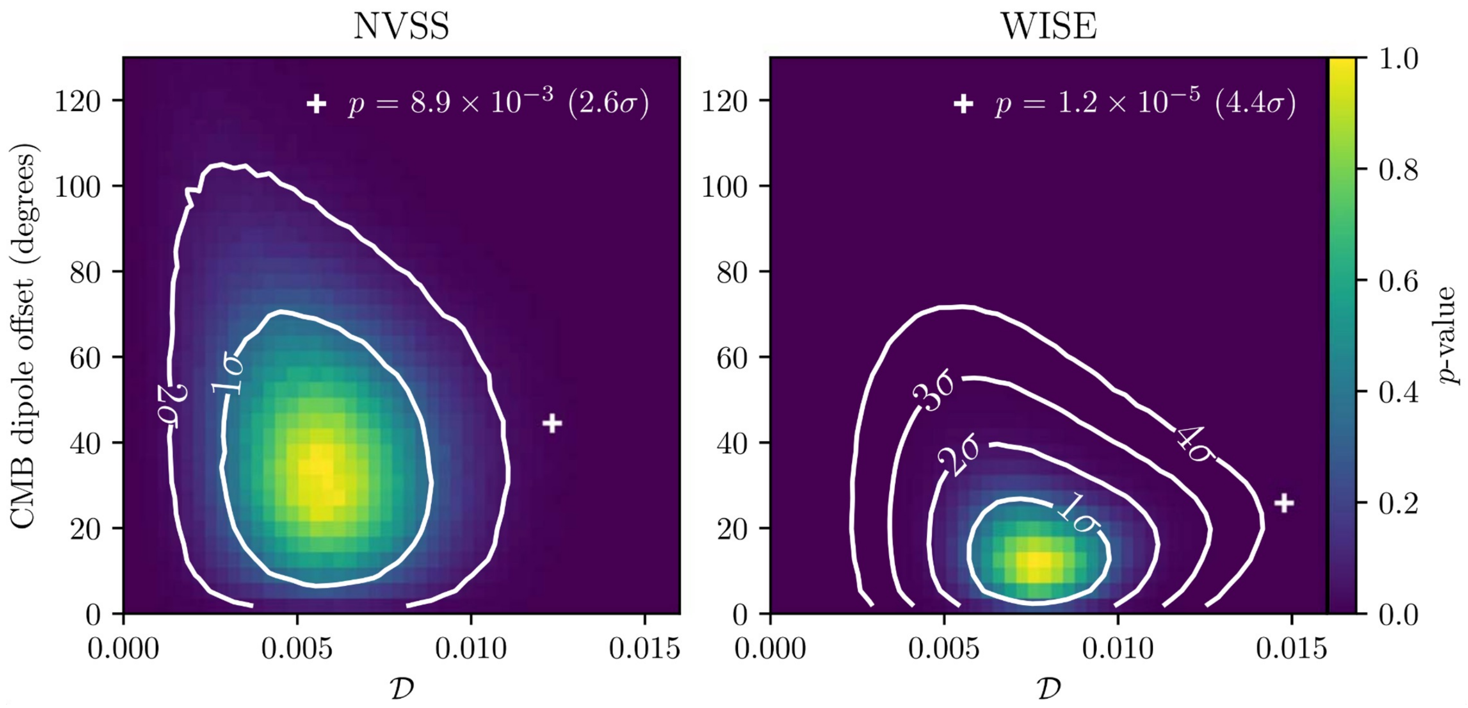
Define *p* as location of found dipole along contour of equal probability.

More null skies outside of contour

→ **Most conservative estimate of *p***



Result

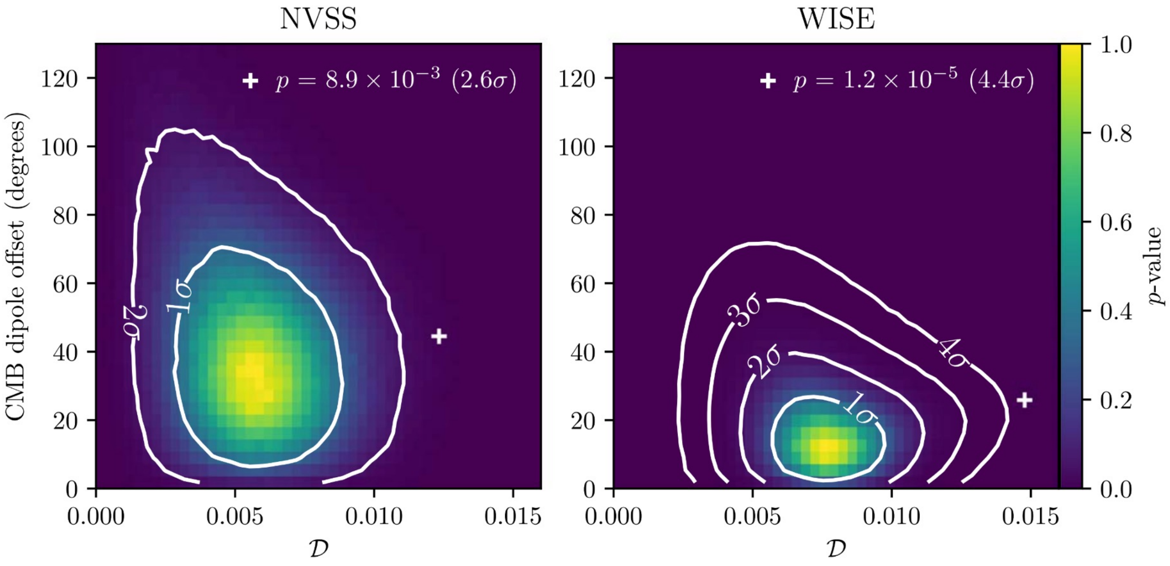


NVSS
WISE
+ $p = 8.9 \times 10^{-3}$ (2.6σ)
+ $p = 1.2 \times 10^{-5}$ (4.4σ)
CMB dipole offset (degrees)
120
100
80
60
40
20
0
1σ
2σ
3σ
4σ
0.000
0.005
0.010
0.015
$\mathcal{D}$
1.0
0.8
0.6
0.4
0.2
0.0
p-value

Result

Independent results may be combined using the weighted Z-score:

$$Z_{\text{joint}} = \frac{\sum_i w_i Z_i}{\sqrt{\sum_i w_i^2}}$$



NVSS (2.6σ, 0.5 million objects)

WISE (4.4σ, 1.6 million objects)

→ **5.1σ**

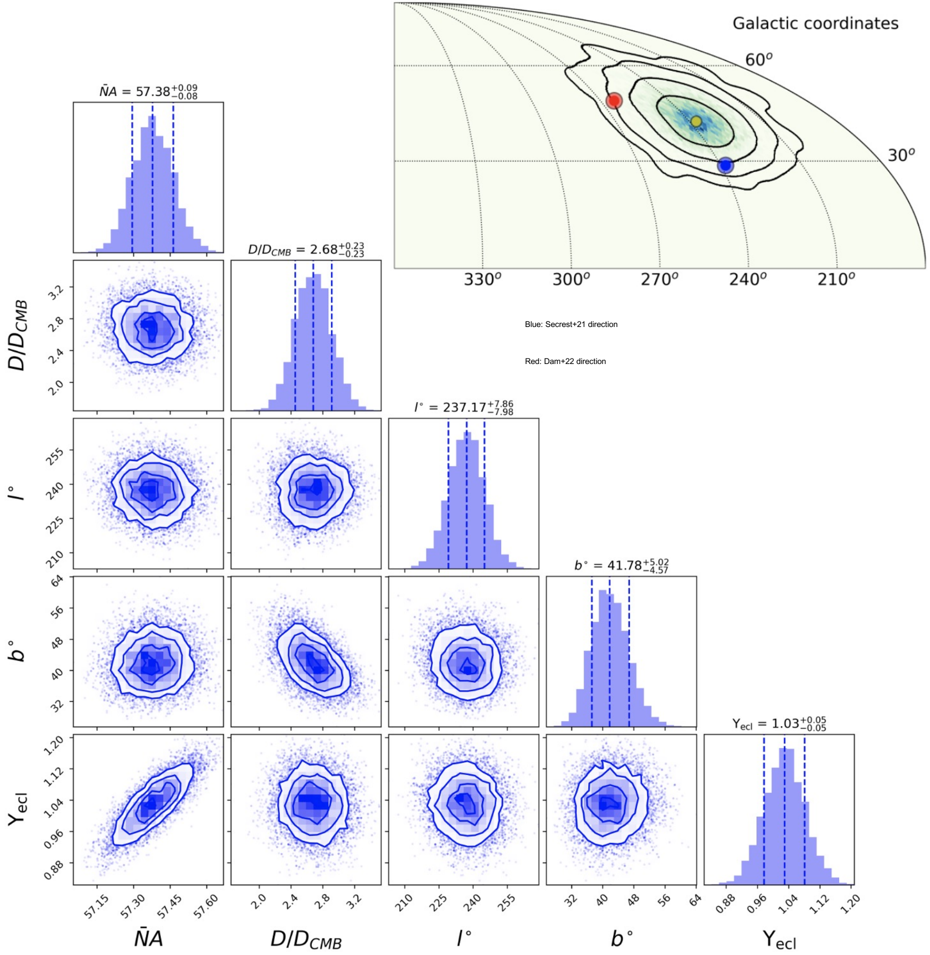
Okay, Bayesian…

Dam+23 performed a Bayesian analysis of the WISE quasar catalog from Secrest+21

- Poissonian likelihood
- Uniform priors

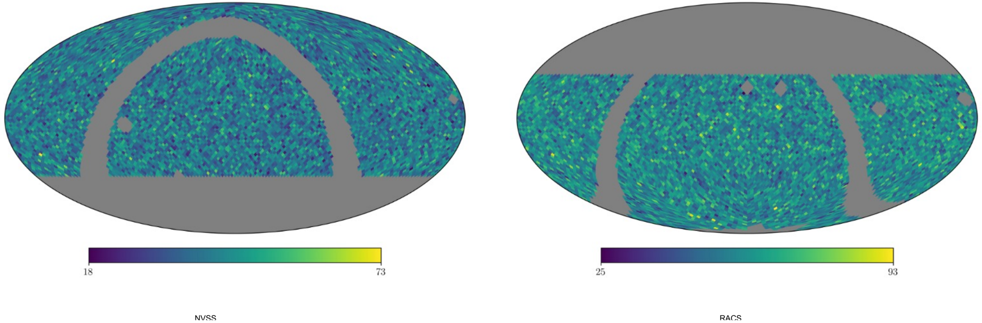
→ Found D/D_{CMB} = 2.7

Marginalizing over all other parameters, CMB dipole amplitude rejected at **5.7σ** level



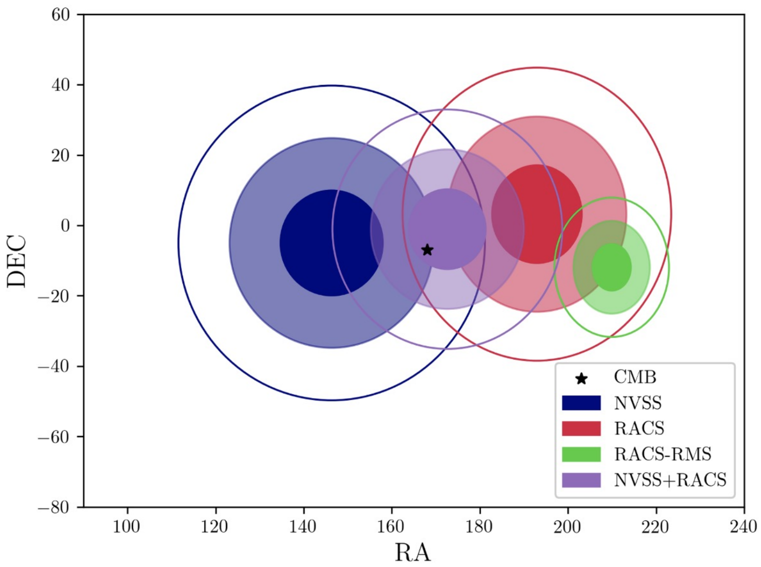
NA = mean count per sky pixel; Y_{ecl} = fractional offset of ecliptic latitude bias from value found by Secrest+21

Okay, Bayesian…



Wagenveld+23

- Used multi-Poisson MLE with novel term to account for survey non-uniformity to maximize source counts in estimator.

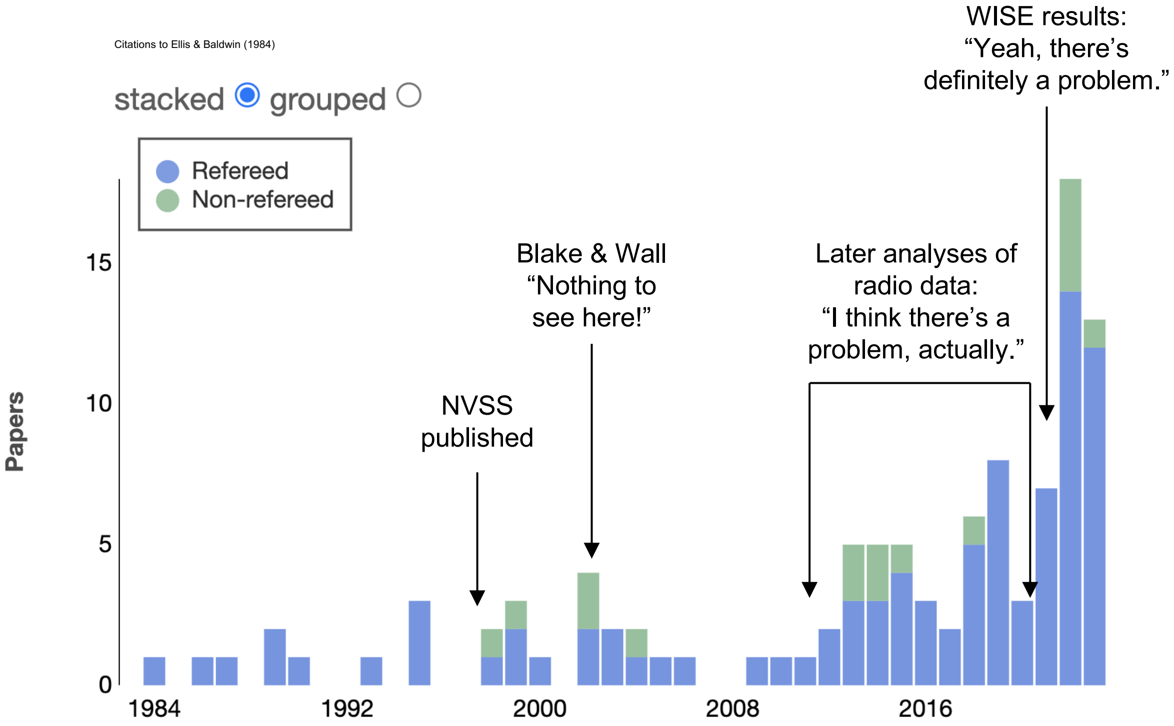


Reject CMB dipole at **4.8σ** level, ***the highest using <u>only</u> radio data.***

<u>My view:</u> Orthogonality of radio galaxies and quasars suggests joint significance of cosmic dipole problem exceeding 6σ!

New interest in an old test.

- No catalog existed suitable for EB84 test until 1998.
- Earliest test claimed consistency with CMB dipole
- Later tests found moderate tension.
- *Independent tests with quasars, joint tests reject kinematic expectation at high significance.*



(ADS)

The bottom line: statistical significance of the cosmic dipole problem is no longer in question.

- Quasars alone: ~ 5σ (Secrest+21, Dam+23)
- Radio galaxies alone: ~ 5σ (Wagenveld+23)
- For comparison, Hubble tension: ~ 5σ (Riess+22)

Orthogonality of radio galaxies and quasars imply joint significance of cosmic dipole problem *exceeding 6σ.*

Orthogonality of surveys (radio arrays on Earth, WISE satellite) suggest observational systematics cannot be responsible.

Concluding remarks

1. FLRW-based cosmologies like ΛCDM now have a critical, foundational problem, because the cosmological principle appears strongly violated.

2. The dipole problem in cosmology is only getting *worse* with new analyses and data. (Potential relief from redshift evolution, lensing, remaining systematics does not appear to be helping significantly.)

3. Need to understand the physical nature of the problem better:

   - Only radio galaxies and quasars? Or all matter? (Euclid?)

   - Kinematic mismatch? Or fundamental anisotropy?

   - Redshift tomography? What about high-z universe?

Thank you, Subir!

And *thank you* to my collaborators for inviting me to join this work!

- Sebastian von Hausegger
- Mohamed Rameez
- Roya Mohayaee
- Subir Sarkar
- Jacques Colin