Uncovering the origin of the cosmic radio dipole

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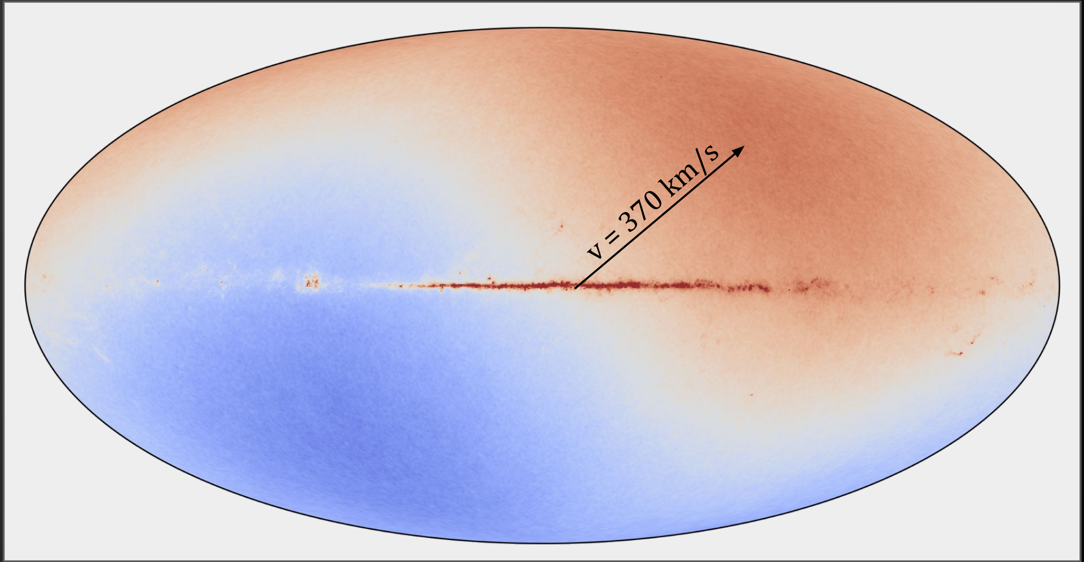
The cosmic dipole

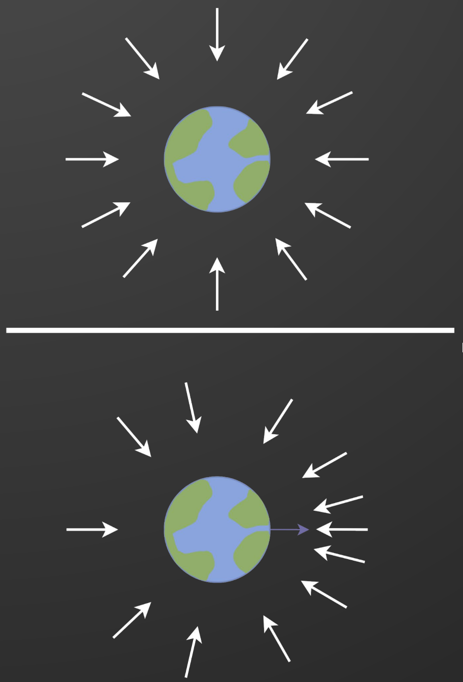
The cosmic dipole is the largest **anisotropy** seen in the CMB.

It is assumed to be caused by our velocity, which through the **Doppler effect** causes a dipole in the observed sky temperature of the CMB.

From the CMB dipole we can derive that the Solar system moves with 369.82 ± 0.11 km/s..



The kinematic dipole in galaxy surveys



Relativistic aberration

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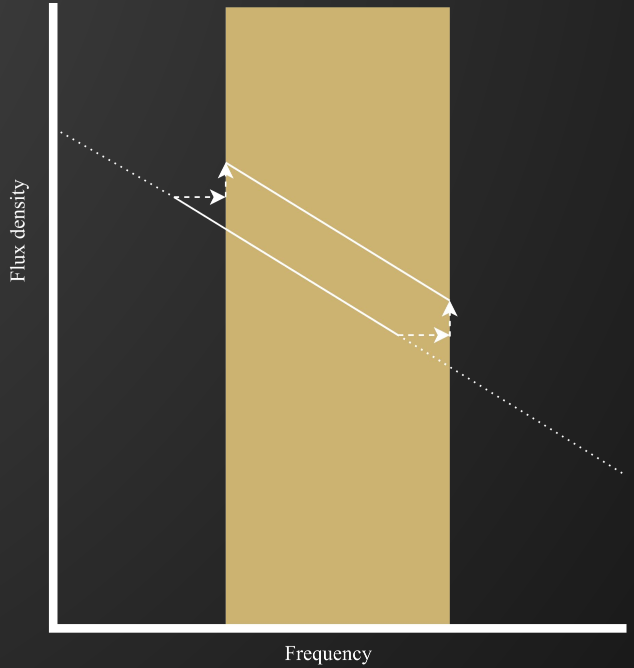

Doppler boost and Doppler shift

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A dipole in the number of distant sources, with **amplitude**

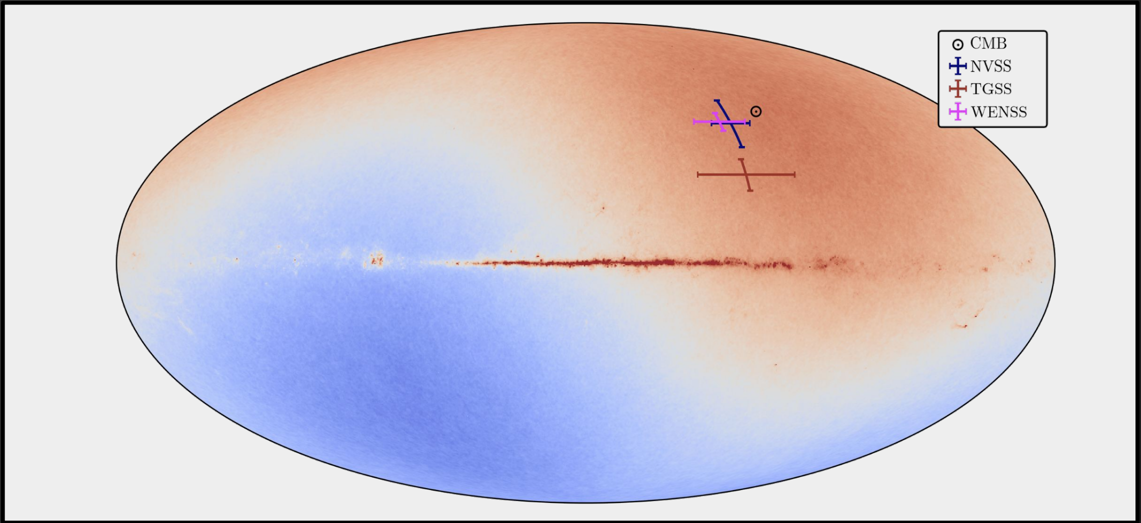
$$\mathcal{D}_{kin} = [1+x(1+\alpha)]\beta$$

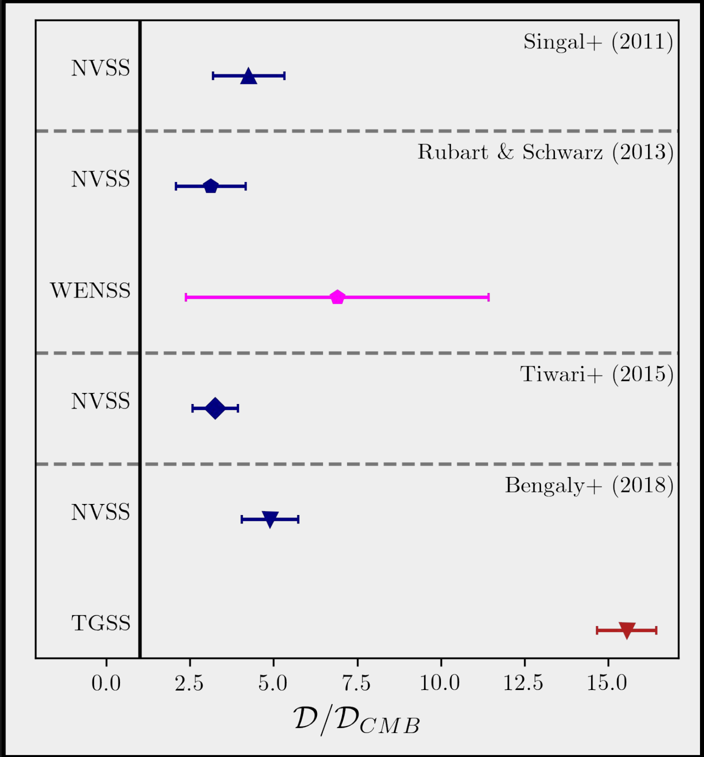
For a typical galaxy survey, the dipole has an amplitude of

$$\mathcal{D}_{kin} \sim 5 \times 10^{-3}$$

For a statistically significant measurement, need hundreds of thousands of sources!

An unexpectedly strong dipole





Even though the radio dipole is consistent with the direction of the CMB dipole, it has a **significantly higher amplitude**

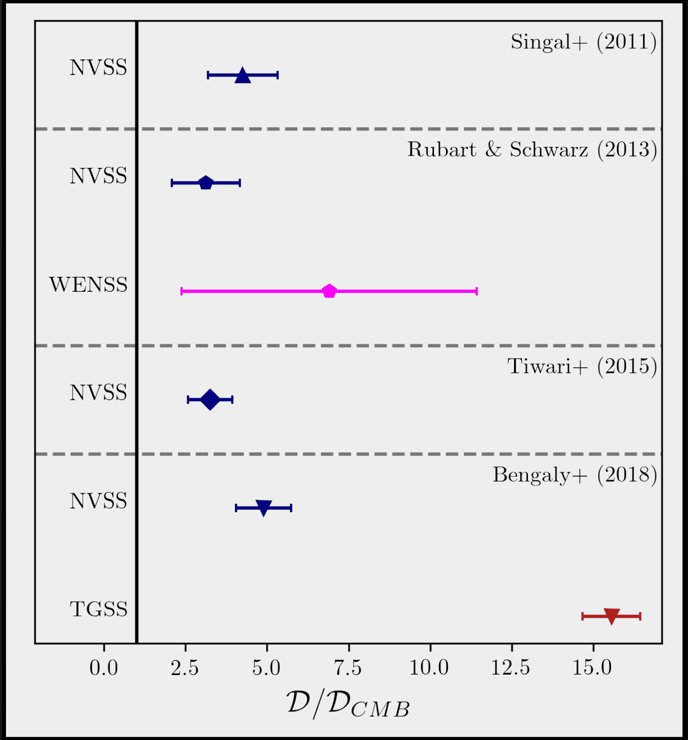
Interpretations of the anomalous radio dipole

Systematic, such as:

- ➢ There are unknown systematic effects in the data that have not been dealt with
- ➢ Some assumptions that we are making about how sources should behave is wrong

Cosmological, such as:

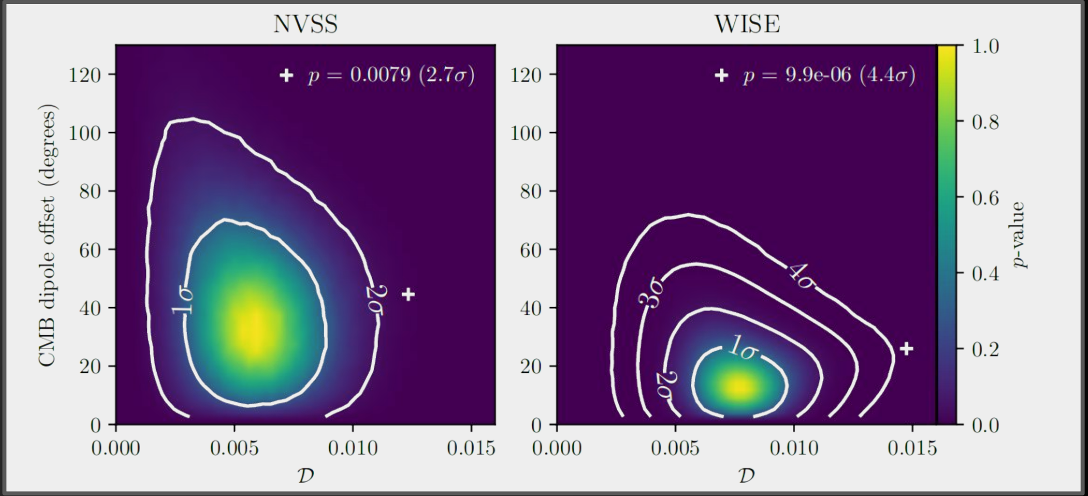
- ➢ There is an anisotropy in the distribution of distant sources
- ➢ Distant sources do not share a rest frame with the cosmic microwave background



No longer just a radio dipole

AGN in the infrared CatWISE2020 catalogue also showed an anomalously high **number count dipole amplitude** (Secrest et al. 2021; Secrest et al. 2022)

With $>10^6$ sources used for the dipole estimate, its significance was nearly **5σ,** the **most significant** measurement of the number count dipole thus far!

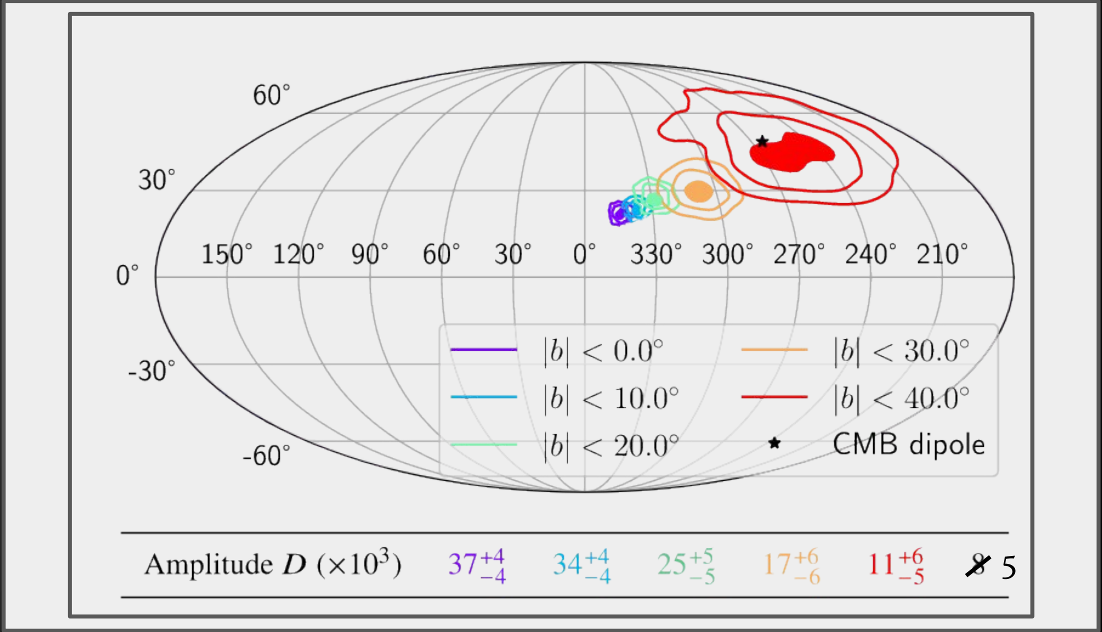


Secrest et al. (2022)

No longer just a radio dipole

The **Quaia catalogue** , with AGN selected from Gaia, once again showed a **higher dipole amplitude than expected** (Mittal et al. 2024).

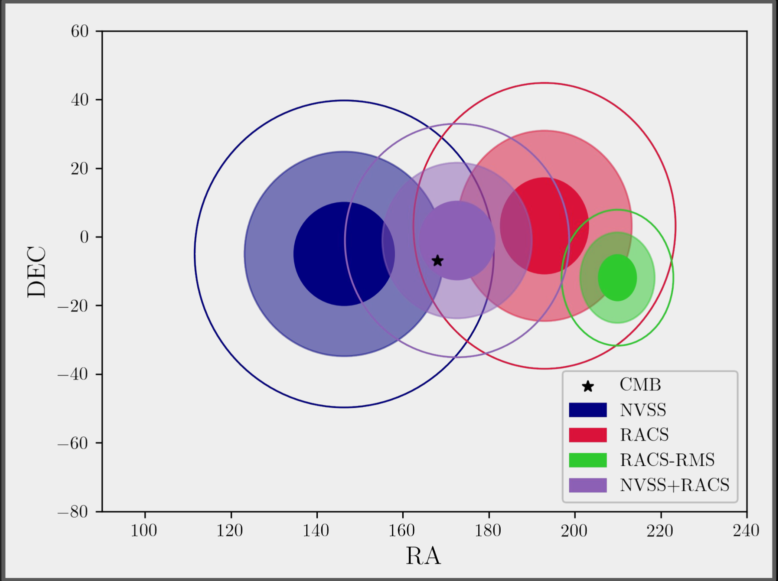
Caveat: cross-matching WISE, and accounting for dust extinction, scanning patterns etc. creates a **complicated selection function.** Small errors can have big impacts!



Mittal et al. (2024)

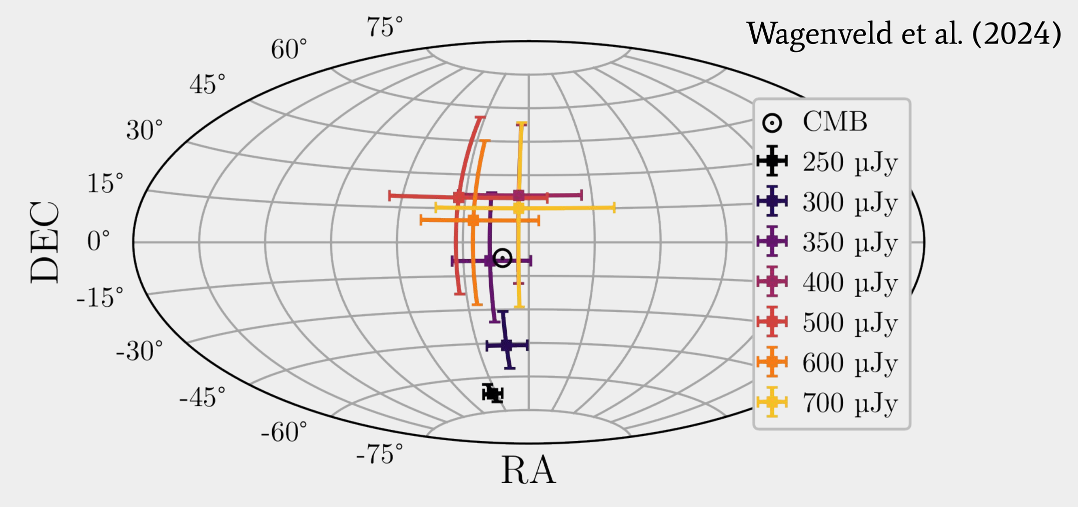
Joint dipole estimation

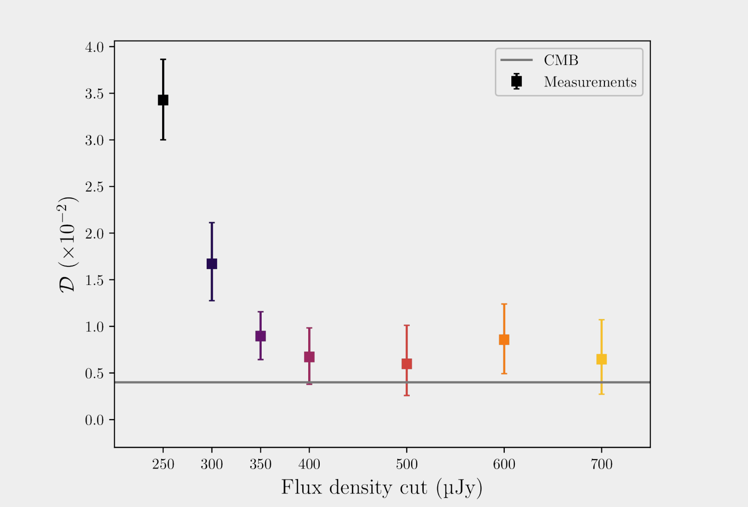
- Taking the product of likelihoods of different catalogues yields a joint dipole estimate
- Massive increase in sensitivity to the dipole
- Combining NVSS & RACS gives:
  - 800,000 sources
  - A dipole direction **perfectly matching with CMB**
  - Amplitude **three times** higher than CMB expectation, with **4.8 σ significance**



Wagenveld et al. (2023)

The radio dipole with MeerKAT

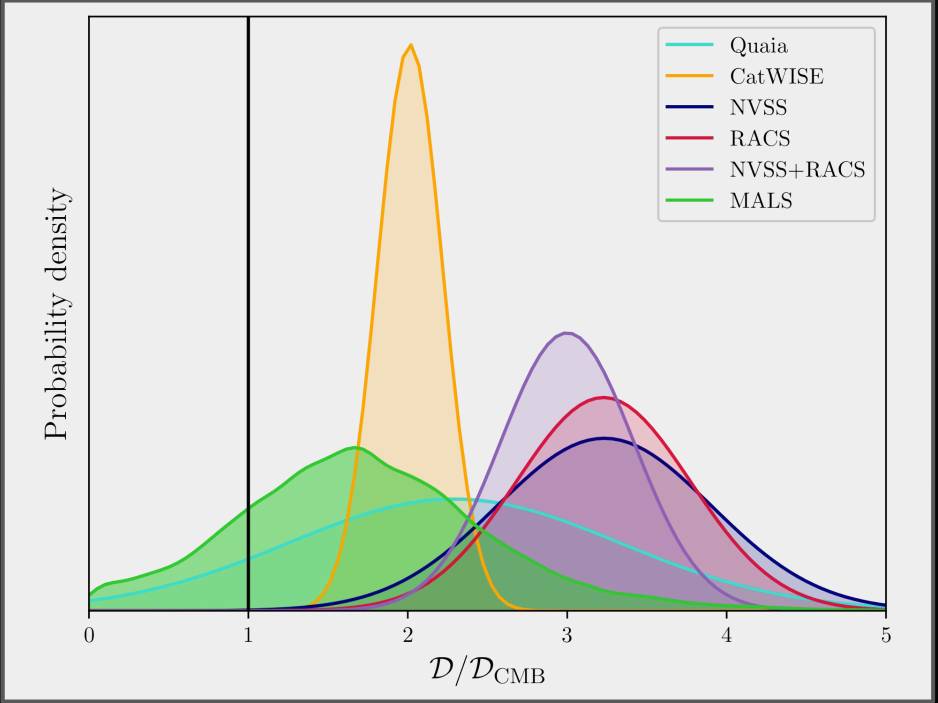




- The dipole signal was obscured by a strong systematic effect as a function of elevation. Including a model in the dipole estimator to to fit for this relation accounted for this problem
- Both the **direction** and **amplitude** are close to CMB expectation
- May be due to the dominant source population at flux limit: **star-forming galaxies**

The state of dipole measurements

- The dipole has now been measured with many galaxy catalogues
  - At different wavelengths and different instruments
    - Radio
    - Infrared
    - Optical
  - With different populations
    - AGN
    - SFGs
- What more information can we get from these different probes?



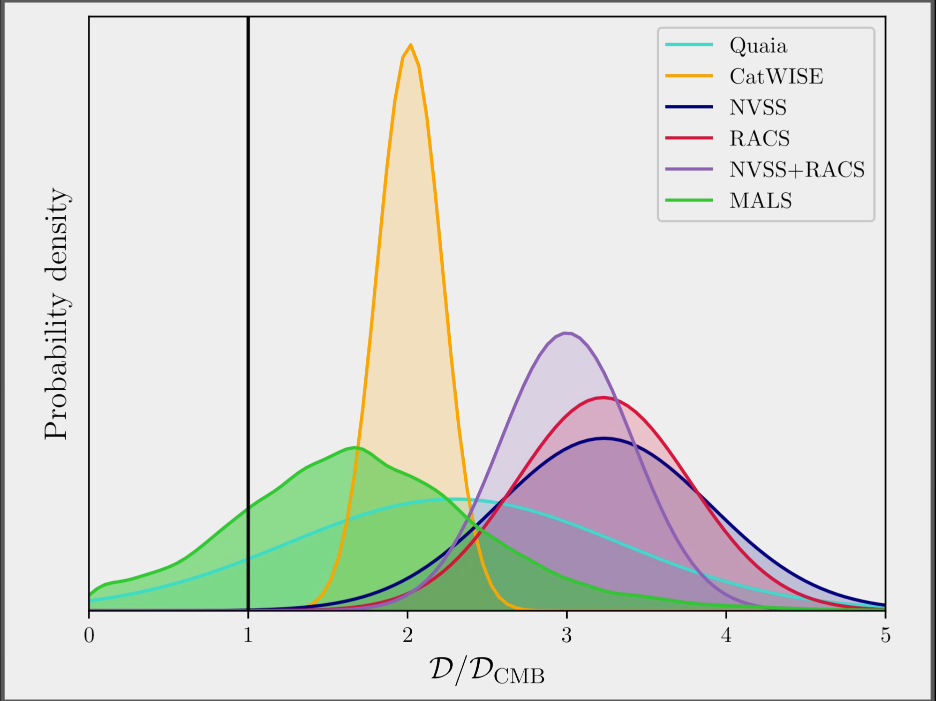
Wagenveld et al. (2024)

Isolating the kinematic component

Given the **excess** dipole we are measuring, can we be sure that it is fully kinematic?

Idea: Leverage the fact that different catalogues have different **expected kinematic dipoles** to separate it from a potential residual, **non-kinematic** dipole component.

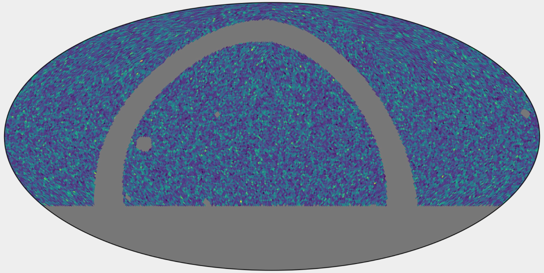
$$\mathcal{D}_i = [2 + x_i(1 + \alpha_i)]\beta + \mathcal{D}_{resid}$$



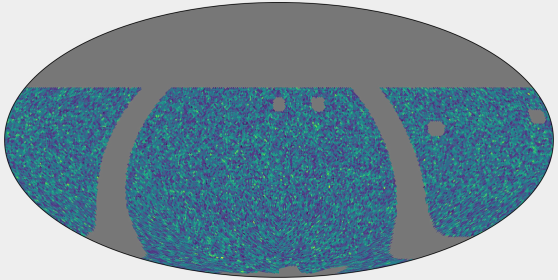
Wagenveld et al. (2024)

Joint dipole estimation with even more catalogues

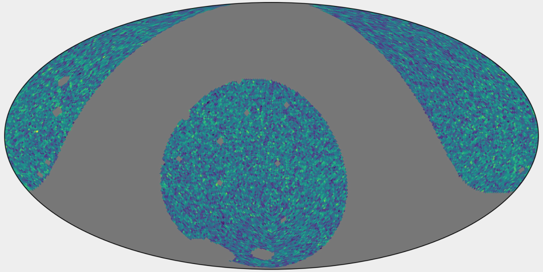
NVSS
350,000 sources
Measured amplitude 3σ from CMB dipole
Kinematic expectation:
$\mathcal{D}_{kin} = 0.41 \times 10^{-2}$



RACS-low
450,000 sources
Measured amplitude 4σ from CMB dipole
Kinematic expectation:
$\mathcal{D}_{kin} = 0.41 \times 10^{-2}$



CatWISE
1,600,000 sources
Measured amplitude 5σ from CMB dipole
Kinematic expectation:
$\mathcal{D}_{kin} = 0.73 \times 10^{-2}$



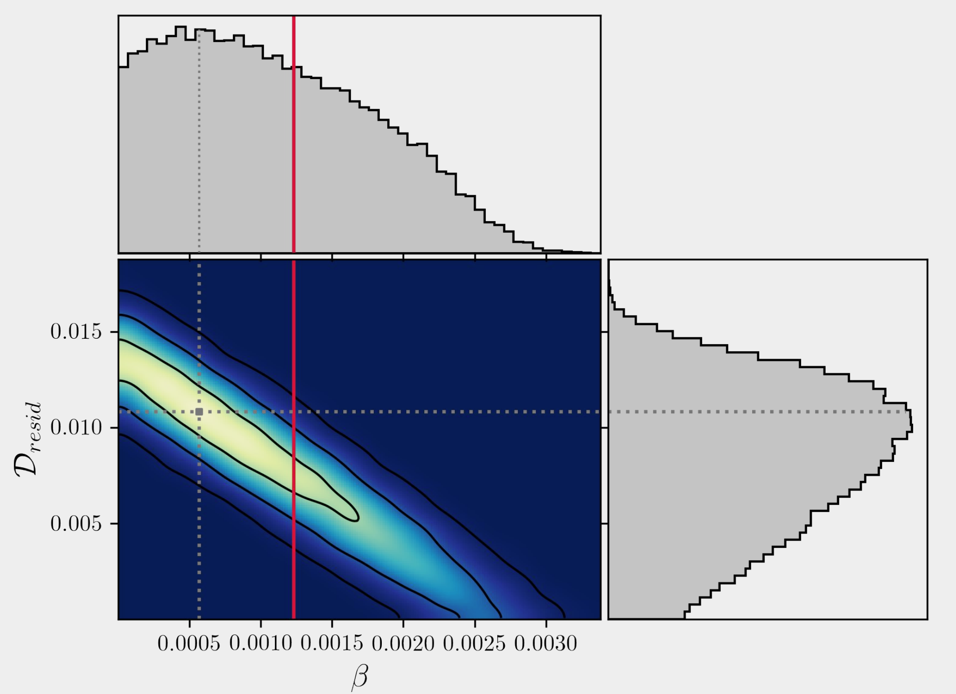
Disentangling kinematic and residual components

Kinematic and residual components are mostly **degenerate** , but due to CatWISE having a relatively **low measured dipole** amplitude, low velocities are preferred

Best fit kinematic dipole **equal or lower than CMB expectation**

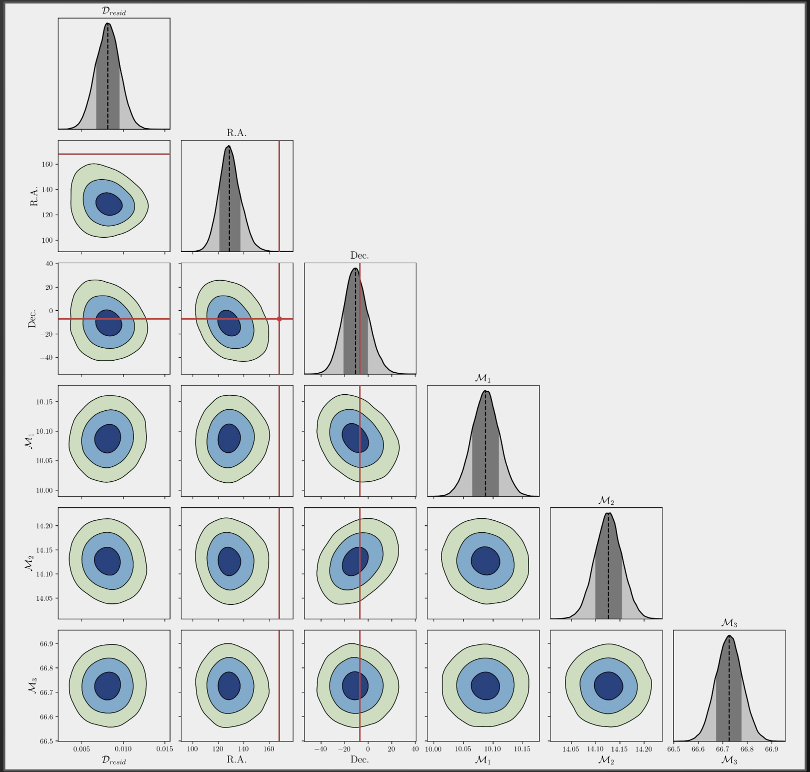
Strong evidence for a **residual, non-kinematic, dipole component**

$$\mathcal{D}_i = [2 + x_i(1 + \alpha_i)]\beta + \mathcal{D}_{resid}$$



Wagenveld et al. (in prep)

Fixing the kinematic dipole

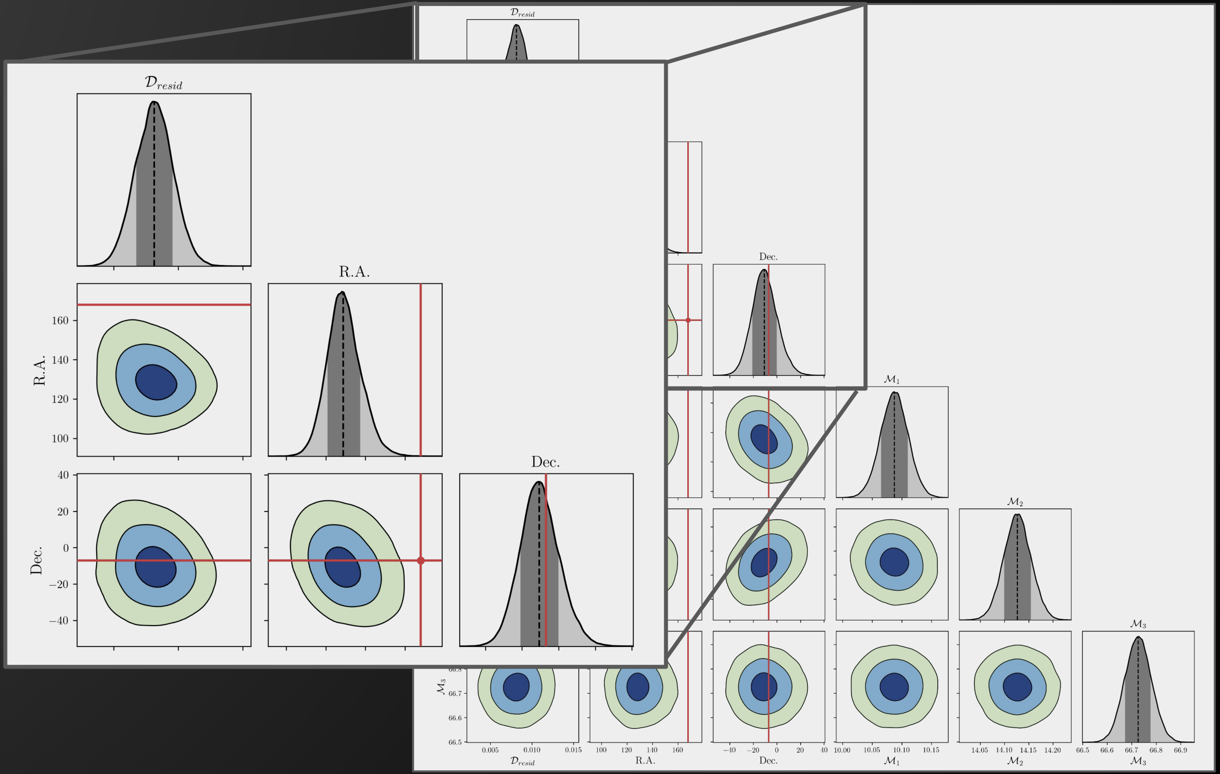


Fixing the kinematic dipole

Assume kinematic dipole is equal to **CMB expectation**

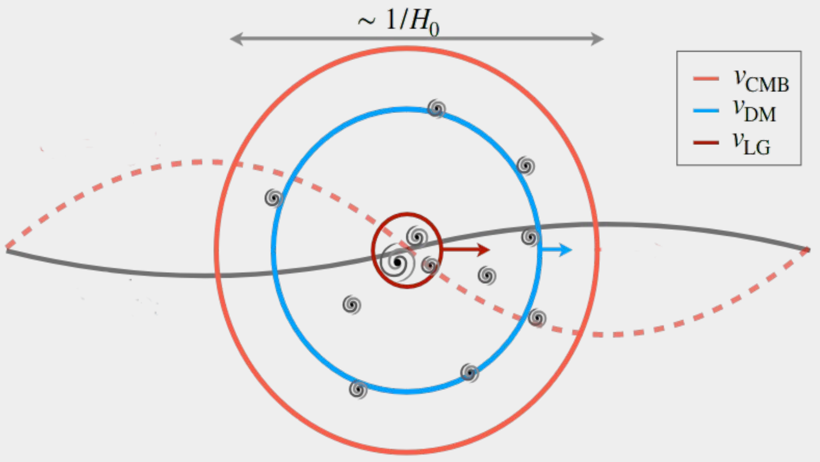
Residual dipole is 38 degrees offset, **4.4 σ**, from CMB dipole

Residual dipole is detected with **5.5 σ**, with amplitude of **$\mathcal{D}$ = (0.81 ± 0.14) x 10 $^{-2}$**



Dipole cosmology

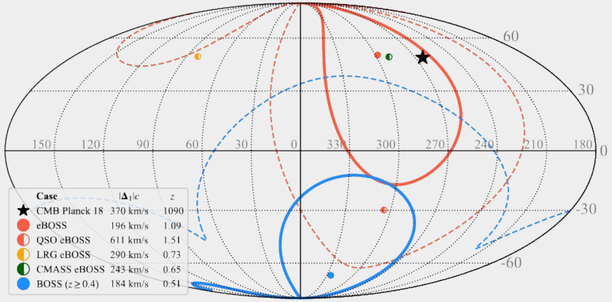
- ➢ Three components that can be moving
  - Local volume
  - Matter (represented by number count dipole)
  - Cosmic microwave background
- ➢ If $\beta < \beta_{CMB}$:
  - The CMB dipole can still be partially intrinsic
  - The matter kinematic dipole is reduced because it is also moving w.r.t. the CMB
- ➢ If $\beta = \beta_{CMB}$:
  - Matter and CMB rest frame are in agreement
- ➢ In either case, a large residual anisotropy is present, which is tough to interpret in a homogeneous and isotropic Universe



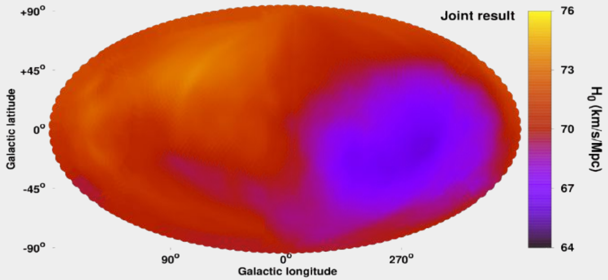
Domenech et al. (2022)

What about other probes?

- **CMB aberration measurements**
  - Consistency with CMB Doppler boost (Saha et al. 2021; Ferreira & Quartin 2021)
- **Tomographic redshift dipole**
  - Only sensitive to kinematic component
  - Tentative evidence of consistency with velocity from CMB dipole (Ferreira & Marra 2024; Tiwari et al. 2024)
- **Solar system motion from SNIa**
  - Close to velocity from CMB dipole (Horstmann et al. 2022; Sorrenti et al. 2023)
- **Bulk flows**
  - Might not converge to CMB rest frame (Watkins et al. 2023)
  - Could account for the dipole in cluster scaling relations (Migkas et al. 2021)



Ferreira & Marra (2024)



Migkas et al. (2021)

Conclusion

- The cosmic radio dipole is no longer just a radio dipole, it has been seen at **other wavelengths** , making it more relevant than ever
- With the current suite of dipole measurements, it is difficult to say where the excess dipole amplitude is coming from, although there is evidence that it is **not kinematic**
- Some **other cosmological probes** see dipoles as well, although it is not clear how (if they even are) they are related to this one
- Future radio observatories (**SKA, DSA-2000**) will provide invaluable deep radio data to further our understanding of the dipole, especially considering a tentative hint at the dipole being **different for SFGs and AGN**

Dipole estimators

Linear estimator

Sum source positions to retrieve largest anisotropy

> No model assumptions
> Incomplete sky coverage introduces bias, accounting for it is complicated

$$\vec{d} = \frac{3}{N} \sum \vec{r}_i$$

Quadratic estimator

Minimise χ^2 to obtain best fit dipole model

> Assumes dipole model
> Implicitly assumes Gaussian distribution of counts in cells

$$\chi^2 = \sum_i \frac{(n_i - n_{i,m})^2}{n_{i,m}}$$

Bayesian estimator

Maximise likelihood to obtain best fit dipole

> Assume Poisson dist. of counts in cells
> Extensions to likelihood are straightforward

$$\mathcal{L}(n) = \prod_i \frac{\lambda^{n_i} e^{-\lambda}}{n_i!}$$