

Overdispersed Radio Source Counts and Excess Radio Dipole Detection

Lukas Böhme^{1,*}, Dominik J. Schwarz¹, Prabhakar Tiwari², Morteza Pashapour-Ahmadabadi¹,
Benedict Bahr-Kalus^{3,4,5}, Maciej Bilicki⁶, Catherine L. Hale⁷, Caroline S. Heneka⁸, and Thilo M. Siewert^{1,9}

¹*Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany*

²*Department of Physics, Guangdong Technion—Israel Institute of Technology, Shantou, Guangdong 515063, People's Republic of China*

³*INAF—Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese, Italy*

⁴*Dipartimento di Fisica, Università degli Studi di Torino, Via P. Giuria 1, 10125 Torino, Italy*

⁵*INFN—Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*

⁶*Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland*

⁷*Astrophysics, Department of Physics, Denys Wilkinson Building, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*

⁸*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*

⁹*Evangelisches Klinikum Bethel gGmbH, Kantensiek 11, 33615 Bielefeld, Germany*



(Received 3 March 2025; revised 2 July 2025; accepted 19 September 2025; published 10 November 2025)

The source count dipole from wide-area radio continuum surveys allows us to test the cosmological standard model. Many radio sources have multiple components, which can cause an overdispersion of the source counts distribution. We account for this effect via a new Bayesian estimator, based on the negative binomial distribution. Combining the two best understood wide-area surveys, NVSS and RACS-low, and the deepest wide-area survey, LoTSS-DR2, we find that the source count dipole exceeds its expected value as the kinematic dipole amplitude from standard cosmology by a factor of 3.67 ± 0.49 —a 5.4σ discrepancy.

DOI: [10.1103/6z32-3zf4](https://doi.org/10.1103/6z32-3zf4)

Introduction—The cosmological principle asserts that matter and radiation are isotropically and homogeneously distributed, assuming us to be typical observers. The dominant contribution to the photon number density in the Universe comes from the cosmic microwave background (CMB), a black body at $T_0 = 2.7$ K, which is observed to be highly isotropic. However, its primary deviation from isotropy is a temperature dipole with an amplitude of $T_1 = 3.4$ mK [1,2], attributed to the motion of the Solar System [3,4], with a speed of $v = (369.82 \pm 0.11)$ km/s [2].

The proper motion of an observer in an isotropic and homogeneous universe results in a dipole in the observed source counts [5]. For a flux-limited radio continuum survey, this anisotropy arises from (i) a Doppler shift in frequency ν , affecting the observed flux density S_ν , modeled as $S_\nu \propto \nu^\alpha$, with spectral index $\alpha = \alpha(\nu)$, and (ii) aberration, causing source displacement toward the direction of motion. The kinematic source count dipole is given by [5]

$$\mathbf{d} = (2 + x[1 - \alpha]) \frac{\mathbf{v}}{c}, \quad (1)$$

where $x = x(\nu)$ is the slope of the cumulative source count at the flux density limit, $dN/d\Omega(> S_\nu) \propto S_\nu^{-x}$, $\mathbf{v}$ is the velocity, and c the speed of light.

In addition, the observed source count dipole includes contributions from cosmic large-scale structures, known as the clustering dipole, and from shot noise due to the discrete nature of galaxy counts. Shot noise becomes less significant with a larger sample size. The clustering dipole depends on clustering strength, the growth factor, the redshift distribution of sources, and galaxy bias. In the flat lambda cold dark matter (Λ CDM) model, the clustering dipole is typically smaller than the kinematic dipole if the sources are predominantly at redshifts greater than 0.1 [6–11].

To measure the dipole anisotropy, a large-sky survey is required. Radio continuum surveys have been key due to their broad sky coverage and detection of radio sources, which are typically at higher redshifts. Recently, infrared quasar surveys have also contributed to such measurements. These surveys, using catalogs of radio sources and quasars, have detected a significant dipole [12–19], which is inconsistent with the size of the CMB-predicted kinematic dipole. A notable discrepancy of up to 5.7σ [10] has been observed between velocities inferred from the CMB

*Contact author: Lboehme@physik.uni-bielefeld.de

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

dipole and those from infrared sources, though the dipole directions align at $(\alpha_{RA}, \delta) = (168^\circ, -7^\circ)$ in equatorial coordinates [2].

In contrast, few studies [20,21] find no discrepancy with the size of the CMB-predicted kinematic dipole. In [20], the combination of two catalogs cancels their individual excess dipole amplitudes, as shown in [17]. The second study uses the sparsely sampled MeerKAT Absorption Line Survey Data Release 2 [21]. The pointings exhibit systematic variation in source density of up to 5%, as well as systematic trends with declination, both of which have been accounted for by an empirical fit.

Traditionally, studies have assumed that source counts follow a Poisson distribution, the standard model for shot noise, which works well for sparse data. However, high-resolution and high-sensitivity radio surveys challenge the independence of source assumptions due to overdispersion from multicomponent sources. This overdispersion is significantly better modeled using the negative binomial distribution [22], providing a more accurate representation of the counts and associated noise.

In this Letter, we present the first analysis of the radio source count dipole that accounts for overdispersion, including the deepest wide-area radio survey, the Low Frequency Array (LOFAR [23]) Two-metre Sky Survey Data Release 2 (LoTSS-DR2 [24]). Previous analyses of LoTSS-DR1 and LoTSS-DR2 excluded a Poissonian distribution with high statistical confidence, favoring a negative binomial distribution [25,26]. We extend this analysis to five other wide-area radio continuum surveys.

Data and theory—The following six surveys, sorted by increasing central frequency, are examined in this letter.

(1) The LoTSS-DR2 survey covers 5635 deg^2 of the northern sky at 144 MHz, detecting nearly 4.4×10^6 radio sources. It features a resolution of $6''$ and a median sensitivity of $83 \mu\text{Jy beam}^{-1}$, with an astrometric accuracy of $0.2''$. The point source completeness is estimated at 95% for 1.1 mJy. We use the inner masked regions as defined in [27].

(2) The TIFR GMRT Sky Survey, TGSS, alternative data release 1 [28], conducted by the Giant Meterwave Radio Telescope (GMRT [29]) covers the sky north of $\delta = -53^\circ$. It observes $\sim 0.62 \times 10^6$ sources at a central frequency of 147 MHz with a resolution of $25''$ for $\delta > 19^\circ$, and $25'' \times 25'' / \cos(\delta - 19^\circ)$ below. The median rms noise is $3.5 \text{ mJy beam}^{-1}$, while 50% point source completeness is expected to be reached at 25 mJy. We mask $\delta < -49^\circ$ and $\delta > 80^\circ$ and remove three under- or overdense regions, as seen in Fig. 2 in Appendix A in the End Matter.

(3) The Rapid ASKAP Continuum Survey, RACS, [30] is the first large-sky survey with the Australian Square Kilometre Array Pathfinder (ASKAP [31,32]). The first data release is RACS-low at 887.5 MHz [33]. The RACS-low survey covers the extragalactic sky ($|b| > 5^\circ$) for $\delta \leq +30^\circ$ at a resolution of $25''$ and finds $\sim 2.1 \times 10^6$ radio

sources. It is estimated to be 95% point source complete at an integrated flux density of $\sim 3 \text{ mJy}$.

(4) The RACS-mid survey is the second data release of RACS at 1367.5 MHz [34] and covers the sky at $\delta \leq +49^\circ$. We use here the catalog where images are convolved to a fixed $25''$ resolution, which consists of 3×10^6 radio sources. The estimated point source completeness is 95% at 1.6 mJy. For both RACS releases (low and mid) we mask $\delta < -78^\circ$ and $\delta > +28^\circ$ as well as three and one small fields, respectively.

(5) The NRAO VLA Sky Survey, NVSS, [35] covers the sky for $\delta \geq -40^\circ$ at 1400 MHz and a resolution of $45''$. The completeness is given as 99% at 3.4 mJy. We mask $\delta < -39^\circ$ to prevent edge effects due to binning.

(6) The Very Large Array Sky Survey, VLASS, [36,37] observes the sky north of $\delta = -40^\circ$ in S band (2–4 GHz) at a resolution of $2''.5$. The point source completeness of 99.8% is reached at 3 mJy. A flux density correction of 10% is applied to the cataloged flux densities from the first epoch [36]. For masking we remove $\delta < -40^\circ$.

Additionally, for all surveys we mask the Galactic plane at latitudes $|b| < 10^\circ$. Measurements are additionally affected by systematics, even above the completeness limit. To achieve a homogeneous sky coverage, flux density cuts up to an order of magnitude above the completeness limit are necessary [19,38].

The counts-in-cells distribution of continuum radio sources above a certain flux density is expected to follow a homogeneous Poisson point process [39,40]. The probability of finding N sources with an expected mean λ is given by the Poisson distribution

$$P_P(N) = \frac{\lambda^N}{N!} e^{-\lambda}, \quad (2)$$

where the variance is $\sigma_P^2 = \lambda$.

However, the Poisson model cannot describe the observed overdispersion in source counts, as the high-resolution radio sky includes not only independent point sources but also multiple components from extended sources. Source-finding algorithms struggle to associate multicomponent sources, and may count components as individual sources [24,41]. This results in overdispersion, where the observed variance of source counts exceeds the mean. To address this, we adopt a compound Poisson (Cox) process [42]. A brief overview of the model is provided below; for details, see Refs. [25,26].

In any cell i , the number of independent radio objects is O_i , with each object having C_{ji} components, where $j \in [1, \dots, O_i]$. The total count of observed radio sources in cell i is

$$N_i = \sum_{j=1}^{O_i} C_{ji}. \quad (3)$$

If O_i follows a Poisson distribution with mean λ , and C_{ji} follows a logarithmic distribution $\text{Log}(p)$ with $p \in (0, 1)$ [43], this results in a negative binomial distribution. The probability of detecting N_i radio sources in cell i is [26]

$$P_{\text{NB}}(N_i) = \binom{N_i + r - 1}{N_i} p^{N_i} (1 - p)^r, \quad (4)$$

where p encodes clustering, and r relates to the Poisson mean λ by $r = \lambda(1 - p)/p$. The average number of components per object are given by the logarithmic distribution expectation

$$\mu_{\text{Log}} = \frac{-1}{\ln(1 - p)} \frac{p}{1 - p}. \quad (5)$$

The mean and variance of the negative binomial distribution are

$$\mu_{\text{NB}} = \frac{pr}{1 - p}, \quad \sigma_{\text{NB}}^2 = \frac{pr}{(1 - p)^2}.$$

So far, this model describes a uniform Universe with random fluctuations due to shot noise. To include the radio source count dipole, we adopt the Bayesian approach that was proposed for the Poisson distribution [19]. The source count dipole $\mathbf{d}$ is a variation of the expected source counts λ_i for cell i ,

$$\lambda_i = \lambda(1 + d \cos \theta_i), \quad (6)$$

with θ_i the angle between the observed cell i and the dipole direction. For the negative binomial distribution the parameter r is directly linked to the direction-dependent quantity

$$r_i = r(1 + d \cos \theta_i). \quad (7)$$

To estimate the source count dipole, we maximize the log-likelihood of the negative binomial dipole distribution

$$\begin{aligned} \log \mathcal{L} = & \sum_i [\log(\Gamma[N_i + r_i]) - \log(\Gamma[r_i]) \\ & + r_i \log(1 - p) + C_i], \end{aligned} \quad (8)$$

where $C_i = N_i \log p - \log(\Gamma[N_i + 1])$, and $\Gamma[\cdot]$ denotes the gamma function. We use a Markov chain Monte Carlo method to estimate r , d , and the direction $\theta(\alpha_{\text{RA}}, \delta)$, while p is inferred from the empirical mean and variance via $p = 1 - \hat{\mu}/\hat{\sigma}^2$.

Table I lists the number of cells, reduced χ_r^2 values of the best-fit Poisson and negative binomial distributions, and the inferred mean number of components μ_{Log} for each radio continuum surveys. Figure 2 in Appendix A in the End Matter displays the corresponding masked survey maps, counts-in-cells histograms, and comparisons between the

TABLE I. Comparison of counts in cells between best-fit Poisson and negative binomial distributions as seen in Fig. 2 in Appendix A in the End Matter. Cells cover a sky area of $\sim 3.4 \text{ deg}^2$.

Survey	No. of cells	$S_{\text{min}}(\text{mJy})$	$\chi_{r,P}^2$	$\chi_{r,NB}^2$	μ_{Log}
LoTSS-DR2	1267	5	2.25	0.76	1.70 ± 1.28
TGSS	8395	100	23.79	0.87	1.22 ± 0.55
RACS-low	7347	20	4.51	1.18	1.10 ± 0.33
RACS-mid	7365	20	2.80	0.70	1.07 ± 0.27
NVSS	8364	20	4.14	1.09	1.09 ± 0.32
VLA	8369	10	40.9	0.90	1.32 ± 0.71

two best-fit distributions. The negative binomial distribution provides a significant better fit to the overdispersed data across all surveys.

Results—We use the HEALPix [44] binning scheme with $N_{\text{side}} = 32$, yielding 12 288 equal-area sky cells. Log-likelihoods are maximized using Bilby [45,46] with the EMCEE sampler [47]. Estimator accuracy was verified through numerical simulations with 3×10^5 sources over the extragalactic sky ($-20^\circ < \delta < 90^\circ$), matching the source count and sky coverage of the surveys used.

To find the expected dipole amplitude d_{exp} from the inferred CMB dipole velocity, we measure x and α for each survey and flux density cut. x is measured over a narrow flux range [$\mathcal{O}(1 \text{ mJy})$] around the flux density cut to ensure a good fit. For α , a simple positional cross-matching method is applied between surveys, with a search radius equal to half the resolution of NVSS, $45''/2$; a flux density cut is applied to the survey for which α is calculated. The expected dipole amplitude is calculated using Eq. (1) and the results are summarized in Table II. More details can be found in Table IV in the End Matter.

The novel estimator introduced in Eq. (8) is applied to each survey at different flux density cut. A uniform prior is used for both dipole direction and amplitude d , labeled as “Free” in Table III. Restricting the direction to the CMB dipole direction is labeled as “CMB.” The “Free” results

TABLE II. Expected dipole amplitude d_{exp} using (1), the flux density cut, the measured spectral index α , and the corresponding differential source count slope x . Errors for x are smaller than 10^{-3} and therefore not listed, but used in the error calculation of d_{exp} .

Survey	$S_{\text{min}}(\text{mJy})$	x	α	$d_{\text{exp}} (\times 10^{-2})$
LoTSS-DR2	5	0.74	-0.73 ± 0.23	0.405 ± 0.021
TGSS	100	0.79	-0.76 ± 0.18	0.418 ± 0.018
RACS-low	20	0.85	-0.98 ± 0.24	0.454 ± 0.025
RACS-mid	20	0.88	-0.81 ± 0.30	0.443 ± 0.025
NVSS	20	0.88	-0.73 ± 0.23	0.435 ± 0.025
VLA	10	0.99	-0.71^a	0.456 ± 0.037

^aTaken from [36], which used the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST [48]) to calculate α .

TABLE III. Measurement results of amplitude d and direction (α_{RA} , δ) of the radio source count dipole and comparison between Poisson (P) and negative binomial distribution (NB). $S_{\min}$ is the applied minimum flux density cut at the survey’s frequency, while this value scaled to 144 MHz is given as S_{144} and calculated with a general spectral index of -0.75 . The direction “Free” refers to an unconstrained estimator, with the preferred direction given in the columns (α_{RA} , δ). “CMB” refers to the constrained estimator, where the direction is fixed to the CMB dipole direction. Values without error bars were fixed during parameter estimation.

Survey	ν (MHz)	$S_{\min}$ (mJy)	S_{144} (mJy)	N	Direction	$d(P)$ ($\times 10^{-2}$)	$d(NB)$ ($\times 10^{-2}$)	$\alpha_{RA}(P)$ (deg)	$\alpha_{RA}(NB)$ (deg)	$\delta(P)$ (deg)	$\delta(NB)$ (deg)
LoTSS-DR2	144	5	5	376 658	CMB	$1.36^{+0.24}_{-0.30}$	$1.39^{+0.45}_{-0.42}$	167.94	167.94	-6.94	-6.94
TGSS	147	100	102	234 619	Free	$5.33^{+0.34}_{-0.36}$	$5.33^{+0.40}_{-0.42}$	$140.7^{+3.5}_{-3.7}$	$140.7^{+4.4}_{-4.4}$	$1.5^{+4.6}_{-4.4}$	$1.6^{+5.6}_{-5.2}$
		100			CMB	$4.51^{+0.30}_{-0.34}$	$4.51^{+0.36}_{-0.40}$	167.94	167.94	-6.94	-6.94
RACS-low	888	20	78	330 540	Free	$1.78^{+0.26}_{-0.26}$	$1.80^{+0.28}_{-0.30}$	$191.1^{+9.7}_{-9.8}$	$191.1^{+10.8}_{-10.8}$	$5.8^{+13.8}_{-12.5}$	$6.0^{+14.2}_{-14.1}$
		20			CMB	$1.70^{+0.24}_{-0.24}$	$1.73^{+0.27}_{-0.30}$	167.94	167.94	-6.94	-6.94
RACS-mid	1367	20	108	237 069	CMB	$1.15^{+0.30}_{-0.30}$	$1.15^{+0.33}_{-0.33}$	167.94	167.94	-6.94	-6.94
NVSS	1400	20	110	263 125	Free	$1.54^{+0.30}_{-0.34}$	$1.54^{+0.36}_{-0.36}$	$148.4^{+12.6}_{-12.5}$	$148.1^{+13.9}_{-13.1}$	$-10.3^{+14.7}_{-14.4}$	$-9.5^{+16.0}_{-15.6}$
		20			CMB	$1.36^{+0.27}_{-0.30}$	$1.36^{+0.30}_{-0.30}$	167.94	167.94	-6.94	-6.94
VLAAS	3000	10	97.5	275 516	CMB	$0.55^{+0.27}_{-0.30}$	$0.55^{+0.36}_{-0.30}$	167.94	167.94	-6.94	-6.94
Survey combination					Direction	$d/d_{\exp}(P)$	$d/d_{\exp}(NB)$	$\alpha_{RA}(P)$	$\alpha_{RA}(NB)$	$\delta(P)$	$\delta(NB)$
RACS-low + NVSS					Free	$3.55^{+0.46}_{-0.46}$	$3.57^{+0.50}_{-0.50}$	$175.4^{+8.3}_{-8.1}$	$175.0^{+9.0}_{-8.9}$	$-3.0^{+10.5}_{-10.5}$	$-2.8^{+11.8}_{-11.3}$
LoTSS-DR2 + RACS-low + NVSS					Free	$3.92^{+0.46}_{-0.45}$	$3.67^{+0.49}_{-0.49}$	$156.1^{+6.8}_{-6.7}$	$164.9^{+8.3}_{-8.0}$	$-20.1^{+9.6}_{-8.7}$	$-10.8^{+11.4}_{-10.8}$

fall into two categories: (i) “Problematic,” in which LoTSS-DR2, RACS-mid, and VLAAS show unreliable δ retrievals, with TGSS yielding an unusually high amplitude; and (ii) “Robust,” in which RACS-low and NVSS provide stable and robust measurements, as listed in Table III under “Free.”

Figure 3 in the End Matter illustrates δ behavior across flux density cuts. LoTSS-DR2 and VLAAS tend toward the celestial poles, while RACS-mid shows strong flux-dependent variations in δ . For LoTSS-DR2, this is expected due to limited sky coverage and is confirmed via simulations with the survey mask. Using random mocks [27] and injecting a dipole as in Table III, we find a pronounced variance of δ . VLAAS consistently favors $\delta \geq 60^\circ$, regardless of flux cut, indicating systematic issues, likely from declination-dependent effects. As VLAAS is based on *Quick Look* images, it lacks the precision of fully calibrated surveys. Dipoles near the poles can result from declination-dependent systematics in telescope sensitivity or calibration. For RACS-low and NVSS, we confirm previous results [19] showing that the excess dipole is about 3.5 times the expected CMB dipole amplitude.

We confirm the increased dipole in TGSS, which is roughly 10 times larger than the CMB expectation [16]. This excess likely stems, at least partly, from large-scale systematic deviations in flux density calibration [49]. However, an improved catalog [50] does not yield a lower amplitude.

Next, we constrain the estimator’s direction to the CMB dipole to measure the amplitude projected along that axis,

applying robust flux density cuts for each survey, well above the 95% completeness limits and in line with prior works. For LoTSS-DR2 and RACS-mid, the constrained estimator yields results consistent with the reported dipole excess of $\approx 3 \times d_{\exp}$. However, these values should be considered lower bounds, since the true dipole may deviate by several tens of degrees from the CMB dipole direction. This is evident in VLAAS, where the constrained amplitude matches expectations, but the actual orientation differ by 60° – 80° (see Fig. 3 in the End Matter.)

All measurements are repeated with the Poisson estimator [19] for which the results are also provided in Table III. Differences between the Poisson and negative binomial estimators mainly appear in the error bars, which vary significantly depending on survey properties such as resolution and sensitivity. For instance, in LoTSS-DR2, the standard deviation under the negative binomial model is 0.44×10^{-2} , compared to 0.27×10^{-2} for the Poisson case, an increase of around 60%.

As the final step of our analysis, we combine the two wide-area surveys, RACS-low and NVSS, which are the only ones yielding stable results with the unconstrained estimator, both alone and together with the deeper LoTSS-DR2 survey (without fixing the dipole direction).

As shown in Fig. 1 and detailed in Table III, the combined measurement from all three surveys yields a direction closely aligned with the CMB dipole (α_{RA}, δ) = $(165^\circ \pm 8^\circ, -11^\circ \pm 11^\circ)$, with an angular separation $\Delta\theta = (5 \pm 10)^\circ$, and amplitude $(3.67 \pm 0.49) \times d_{\exp}$. Adding LoTSS-DR2 increases the discrepancy in

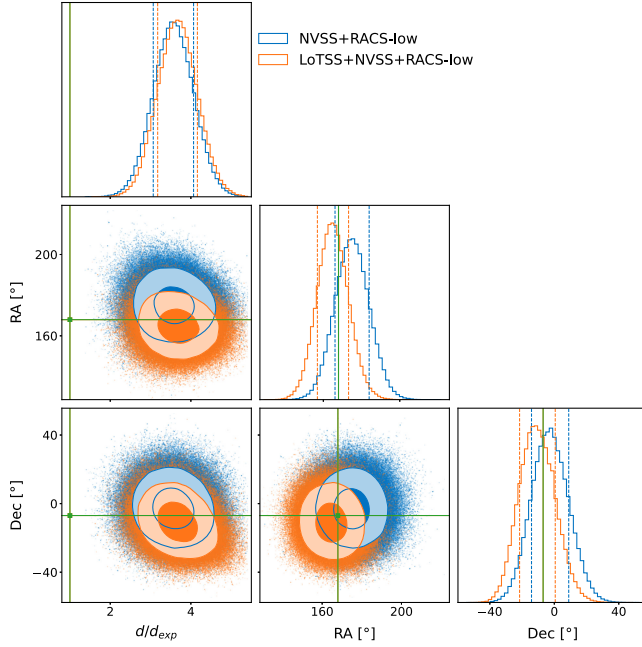


FIG. 1. Corner plot for the combined dipole estimate from LoTSS-DR2, NVSS, and RACS-low. The amplitude is presented in multiples of the expected dipole amplitude, with the green lines and dot representing the expected values based on the CMB dipole.

amplitude from 4.8σ (using the Poisson estimator on RACS-low and NVSS [19]) to over 5.4σ with our negative binomial estimator. Applying the negative binomial estimator to RACS-low and NVSS alone (with the same parameters as [19]) reduces the tension to 4.5σ , with $\Delta\theta = (8 \pm 10)^\circ$, as expected due to the larger error bars.

Conclusion—In this Letter, we develop a new radio dipole estimator based on the negative binomial distribution, motivated by the observed source count distribution. It is applied to six different radio surveys spanning 120 MHz to 4 GHz, covering most of the northern or southern sky.

Combining two wide-area surveys (RACS-low, NVSS) with the deeper LoTSS-DR2, our estimator robustly constrains the dipole amplitude to $(3.67 \pm 0.49) \times d_{\text{exp}}$, revealing a 5.4σ excess over the CMB-inferred kinematic dipole. The direction remains consistent with the CMB dipole within 1σ . This marks the first significant detection of the radio dipole excess using radio surveys alone.

We find that the multicomponent nature of radio sources, captured by our estimator, is a key factor in measuring the cosmic radio dipole and can increase the amplitude uncertainty by up to 60%.

Possible explanations for the excess radio source count dipole include greater-than-expected contamination from local sources, potentially producing a clustering dipole not predicted by Λ CDM [6,7]. A local bulk flow extending beyond Λ CDM expectations may also contribute [51–53].

Another possible explanation is systematics, extensively studied across many surveys (see Appendix B in the End Matter for references and details). Achieving precise flux density calibration over wide fields is challenging and may introduce bias. An alternative strategy is sparse sky sampling via independent pointings, which yields a dipole consistent with the CMB expectation [21]; however, unlike the active galactic nuclei-dominated surveys in this Letter, that sample is dominated by star-forming galaxies.

Survey geometry, whether sparse or wide, can itself bias dipole measurements and must be tested via simulations. Galactic synchrotron emission may affect sensitivity if not properly addressed during calibration. However, it is unlikely that these systematics would be consistent across all radio frequencies or mimic results seen in infrared quasars studies [54].

A genuine discrepancy between the dipole amplitudes measured in the CMB and large-scale structure frames would have profound cosmological implications. Depending on whether the cause is local or large-scale, it could challenge the cosmological principle itself.

Upcoming large-area sky surveys such as LoTSS-DR3, LoLSS-DR2 (northern sky at 54 MHz), RACS-high [55], RACS-low-DR2, EMU [56,57], and eventually the SKA surveys, along with wide-field spectroscopic follow-ups like the WEAVE-LOFAR project [58], will significantly improve our understanding of the origin of the radio dipole.

We used a range of Python software packages during the production of this Letter, including Astropy [59–61], Matplotlib [62], NumPy [63], SciPy [64], HEALPY [65], and HEALPix [66].

Acknowledgments—We acknowledge discussions with Nathan Secrest, Sebastian von Hausegger, and Jonah Wagnveld, who helped us to sharpen and develop our arguments. L. B. acknowledges support by the Studienstiftung des deutschen Volkes. M. P.-A. acknowledges support from the German Federal Ministry of Research, Technology and Space (BMFTR) grant ErUM-IFT 05D23PB1. B. B.-K. acknowledges support from INAF for the project “Paving the way to radio cosmology in the SKA Observatory era: synergies between SKA pathfinders/precursors and the new generation of optical/near-infrared cosmological surveys” (CUP C54I19001050001). M. B. is supported by the Polish National Science Center through Grants No. 2020/38/E/ST9/00395 and No. 2020/39/B/ST9/03494. C. L. H. acknowledges support from the Oxford Hintze Centre for Astrophysical Surveys, which is funded through generous support from the Hintze Family Charitable Foundation. C. S. H.’s work is funded by the Volkswagen Foundation. C. S. H. acknowledges additional support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy EXC 2181/1–390900948 (the

Heidelberg STRUCTURES Excellence Cluster). LOFAR is the Low Frequency Array designed and constructed by ASTRON. It has observing, data processing, and data storage facilities in several countries, which are owned by various parties (each with their own funding sources), and which are collectively operated by the ILT foundation under a joint scientific policy. The ILT resources have benefited from the following recent major funding sources: CNRS-INSU, Observatoire de Paris and Université d'Orléans, France; BMFT, MIWF-NRW, MPG, Germany; Science Foundation Ireland (SFI), Department of Business, Enterprise and Innovation (DBEI), Ireland; NWO, The Netherlands; The Science and Technology Facilities Council, UK; Ministry of Science and Higher Education, Poland; The Istituto Nazionale di Astrofisica (INAF), Italy. This scientific work uses data obtained from Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. We acknowledge the Wajarri Yamaji People as the Traditional Owners and native title holders of the Observatory site. CSIRO's ASKAP radio telescope is part of the Australia Telescope National Facility ([67]). Operation of ASKAP is funded by the Australian Government with support from the National Collaborative Research Infrastructure Strategy. ASKAP uses the resources of the Pawsey Supercomputing Research Centre. Establishment of ASKAP, Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, and the Pawsey Supercomputing Research Centre are initiatives of the Australian Government, with support from the Government of Western Australia and the Science and Industry Endowment Fund. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. The VLA is run by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Data availability—The data that support the findings of this article are openly available [24,28,33–36,50,68].

-
- [1] A. A. Penzias and R. W. Wilson, A measurement of excess antenna temperature at 4080 Mc/s, *Astrophys. J.* **142**, 419 (1965).
 - [2] N. Aghanim, Y. Akrami, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro *et al.* (Planck Collaboration), Planck 2018 results. I. Overview and the cosmological legacy of Planck, *Astron. Astrophys.* **641** (2020).
 - [3] J. M. Stewart and D. W. Sciama, Peculiar velocity of the Sun and its relation to the cosmic microwave background, *Nature (London)* **216**, 748 (1967).
 - [4] P. J. E. Peebles and D. T. Wilkinson, Comment on the anisotropy of the primeval fireball, *Phys. Rev.* **174**, 2168 (1968).
 - [5] G. F. R. Ellis and J. E. Baldwin, On the expected anisotropy of radio source counts, *Mon. Not. R. Astron. Soc.* **206**, 377 (1984).
 - [6] P. Tiwari and A. Nusser, Revisiting the NVSS number count dipole, *J. Cosmol. Astropart. Phys.* **03** (2016) 062.
 - [7] C. A. P. Bengaly, T. M. Siewert, D. J. Schwarz, and R. Maartens, Testing the standard model of cosmology with the SKA: The cosmic radio dipole, *Mon. Not. R. Astron. Soc.* **486**, 1350 (2019).
 - [8] Y.-T. Cheng, T.-C. Chang, and A. Lidz, Is the radio source dipole from NVSS consistent with the cosmic microwave background and Λ CDM?, *Astrophys. J.* **965**, 32 (2024).
 - [9] O. T. Oyda and G. F. Lewis, Testing the cosmological principle: On the time dilation of distant sources, *Mon. Not. R. Astron. Soc.* **523**, 667 (2023).
 - [10] L. Dam, G. F. Lewis, and B. J. Brewer, Testing the cosmological principle with CatWISE quasars: A Bayesian analysis of the number-count dipole, *Mon. Not. R. Astron. Soc.* **525**, 231 (2023).
 - [11] P. Tiwari, D. J. Schwarz, G.-B. Zhao, R. Durrer, M. Kunz, and H. Padmanabhan, An independent measure of the kinematic dipole from SDSS, *Astrophys. J.* **975**, 279 (2024).
 - [12] C. Blake and J. Wall, A velocity dipole in the distribution of radio galaxies, *Nature (London)* **416**, 150 (2002).
 - [13] A. K. Singal, Large peculiar motion of the solar system from the dipole anisotropy in sky brightness due to distant radio sources, *Astrophys. J.* **742**, L23 (2011).
 - [14] C. Gibelyou and D. Huterer, Dipoles in the sky, *Mon. Not. R. Astron. Soc.* **427**, 1994 (2012).
 - [15] M. Rubart and D. J. Schwarz, Cosmic radio dipole from NVSS and WENSS, *Astron. Astrophys.* **555**, A117 (2013).
 - [16] T. M. Siewert, M. Schmidt-Rubart, and D. J. Schwarz, Cosmic radio dipole: Estimators and frequency dependence, *Astron. Astrophys.* **653**, A9 (2021).
 - [17] N. J. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee, and S. Sarkar, A challenge to the standard cosmological model, *Astrophys. J.* **937**, L31 (2022).
 - [18] V. Mittal, O. T. Oyda, and G. F. Lewis, The cosmic dipole in the Quia sample of quasars: A Bayesian analysis, *Mon. Not. R. Astron. Soc.* **527**, 8497 (2024).
 - [19] J. D. Wagnveld, H. R. Klöckner, and D. J. Schwarz, The cosmic radio dipole: Bayesian estimators on new and old radio surveys, *Astron. Astrophys.* **675**, A72 (2023).
 - [20] J. Darling, The universe is brighter in the direction of our motion: Galaxy counts and fluxes are consistent with the CMB dipole, *Astrophys. J. Lett.* **931**, L14 (2022).
 - [21] J. D. Wagnveld, H. R. Klöckner, N. Gupta, S. Sekhar, P. Jagannathan, P. P. Deka, J. Jose, S. A. Balashev, D. Borgaonkar, A. Chatterjee *et al.*, The MeerKAT absorption line survey data release 2: Wideband continuum catalogues and a measurement of the cosmic radio dipole, *Astron. Astrophys.* **690**, A163 (2024).
 - [22] N. L. Johnson, A. W. Kemp, and S. Kotz, *Univariate Discrete Distributions*, 3rd ed. (Wiley, Hoboken, NJ, 2005).
 - [23] M. P. van Haarlem, M. W. Wise, A. W. Gunst, G. Heald, J. P. McKean, J. W. T. Hessels, A. G. de Bruyn, R. Nijboer, J. Swinbank, R. Fallows *et al.*, LOFAR: The LOW-Frequency ARray, *Astron. Astrophys.* **556**, A2 (2013).
 - [24] T. W. Shimwell, M. J. Hardcastle, C. Tasse, P. N. Best, H. J. A. Röttgering, W. L. Williams, A. Botteon, A. Drabent,

- A. Mechev, A. Shulevski *et al.*, The LOFAR two-metre sky survey. V. Second data release, *Astron. Astrophys.* **659**, A1 (2022).
- [25] T. M. Siewert, C. Hale, N. Bhardwaj, M. Biermann, D. J. Bacon, M. Jarvis, H. J. A. Röttgering, D. J. Schwarz, T. Shimwell, P. N. Best *et al.*, One- and two-point source statistics from the LOFAR two-metre sky survey first data release, *Astron. Astrophys.* **643**, A100 (2020).
- [26] M. Pashapour-Ahmadabadi, L. Böhme, T. M. Siewert, D. J. Schwarz, C. L. Hale, C. Heneka, P. Tiwari, and J. Zheng, Cosmology from LOFAR two-metre sky survey data release 2: Counts-in-cells statistics, *Astron. Astrophys.* **698**, A148 (2025).
- [27] C. L. Hale, D. J. Schwarz, P. N. Best, S. J. Nakoneczny, D. Alonso, D. Bacon, L. Böhme, N. Bhardwaj, M. Bilicki, S. Camera *et al.*, Cosmology from LOFAR two-metre sky survey data release 2: Angular clustering of radio sources, *Mon. Not. R. Astron. Soc.* **527**, 6540 (2023).
- [28] H. T. Intema, P. Jagannathan, K. P. Mooley, and D. A. Frail, The GMRT 150 MHz all-sky radio survey. First alternative data release TGSS ADR1, *Astron. Astrophys.* **598**, A78 (2017).
- [29] G. Swarup, Giant metrewave radio telescope (GMRT), in *IAU Colloquium 131: Radio Interferometry. Theory, Techniques, and Applications*, Astronomical Society of the Pacific Conference Series Vol. 19, edited by T. J. Cornwell and R. A. Perley (Astronomical Society of the Pacific, San Francisco, 1991), pp. 376–380.
- [30] D. McConnell, C. L. Hale, E. Lenc, J. K. Banfield, G. Heald, A. W. Hotan, J. K. Leung, V. A. Moss, T. Murphy, A. O’Brien *et al.*, The rapid ASKAP continuum survey I: Design and first results, *Publ. Astron. Soc. Aust.* **37**, e048 (2020).
- [31] S. Johnston, R. Taylor, M. Bailes, N. Bartel, C. Baugh, M. Bietenholz, C. Blake, R. Braun, J. Brown, S. Chatterjee *et al.*, Science with ASKAP, *Exp. Astron.* **22**, 151 (2008).
- [32] A. W. Hotan, J. D. Bunton, A. P. Chippendale, M. Whiting, J. Tuthill, V. A. Moss, D. McConnell, S. W. Amy, M. T. Huynh, J. R. Allison *et al.*, Australian square kilometre array pathfinder. I. System description, *Publ. Astron. Soc. Aust.* **38**, e009 (2021).
- [33] C. L. Hale, D. McConnell, A. J. M. Thomson, E. Lenc, G. H. Heald, A. W. Hotan, J. K. Leung, V. A. Moss, T. Murphy, J. Pritchard *et al.*, The rapid ASKAP continuum survey paper II: First stokes I source catalogue data release, *Publ. Astron. Soc. Aust.* **38**, e058 (2021).
- [34] S. W. Duchesne, J. A. Grundy, G. H. Heald, E. Lenc, J. K. Leung, D. McConnell, T. Murphy, J. Pritchard, K. Rose, A. J. M. Thomson *et al.*, The rapid ASKAP continuum survey V: Cataloguing the sky at 1 367.5 MHz and the second data release of RACS-mid, *Publ. Astron. Soc. Aust.* **41**, e003 (2024).
- [35] J. J. Condon, W. D. Cotton, E. W. Greisen, Q. F. Yin, R. A. Perley, G. B. Taylor, and J. J. Broderick, The NRAO VLA sky survey, *Astron. J.* **115**, 1693 (1998).
- [36] Y. A. Gordon, M. M. Boyce, C. P. O’Dea, L. Rudnick, H. Andernach, A. N. Vantyghem, S. A. Baum, J.-P. Bui, M. Dionyssiou, S. Safi-Harb *et al.*, A quick look at the 3 GHz radio sky. I. Source statistics from the very large array sky survey, *Astrophys. J. Suppl. Ser.* **255**, 30 (2021).
- [37] M. Lacy, S. A. Baum, C. J. Chandler, S. Chatterjee, T. E. Clarke, S. Deustua, J. English, J. Farnes, B. M. Gaensler, N. Gugliucci *et al.*, The Karl G. Jansky very large array sky survey (VLASS). Science case and survey design, *Publ. Astron. Soc. Pac.* **132**, 035001 (2020).
- [38] O. T. Oayda, V. Mittal, G. F. Lewis, and T. Murphy, A Bayesian approach to the cosmic dipole in radio galaxy surveys: Joint analysis of NVSS & RACS, *Mon. Not. R. Astron. Soc.* **531**, 4545 (2024).
- [39] J. Neyman, E. L. Scott, and C. D. Shane, The index of clumpiness of the distribution of images of galaxies, *Astrophys. J. Suppl. Ser.* **1**, 269 (1954).
- [40] P. J. E. Peebles, *The Large-Scale Structure of the Universe*, Princeton Series in Physics (Princeton University Press, Princeton, NJ, 1980).
- [41] M. J. Hardcastle, M. A. Horton, W. L. Williams, K. J. Duncan, L. Alegre, B. Barkus, J. H. Croston, H. Dickinson, E. Oasing, H. J. A. Röttgering *et al.*, The LOFAR two-metre sky survey. VI. Optical identifications for the second data release, *Astron. Astrophys.* **678**, A151 (2023).
- [42] D. R. Cox, Some statistical methods connected with series of events, *J. R. Stat. Soc. Ser. B* **17**, 129 (1955).
- [43] R. A. Fisher, A. S. Corbet, and C. B. Williams, The relation between the number of species and the number of individuals in a random sample of an animal population, *J. Anim. Ecol.* **12**, 42 (1943).
- [44] <http://healpix.sourceforge.net>
- [45] G. Ashton, M. Hübner, P. D. Lasky, C. Talbot, K. Ackley, S. Biscoveanu, Q. Chu, A. Divakarla, P. J. Easter, B. Goncharov *et al.*, Bilby: A user-friendly Bayesian inference library for gravitational-wave astronomy, *Astrophys. J. Suppl. Ser.* **241**, 27 (2019).
- [46] I. M. Romero-Shaw, C. Talbot, S. Biscoveanu, V. D’Emilio, G. Ashton, C. P. L. Berry, S. Coughlin, S. Galadage, C. Hoy, M. Hübner *et al.*, Bayesian inference for compact binary coalescences with bilby: Validation and application to the first LIGO-Virgo gravitational-wave transient catalogue, *Mon. Not. R. Astron. Soc.* **499**, 3295 (2020).
- [47] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman, EMCEE: The MCMC Hammer, *Publ. Astron. Soc. Pac.* **125**, 306 (2013).
- [48] R. H. Becker, R. L. White, and D. J. Helfand, The FIRST survey: Faint images of the radio sky at twenty centimeters, *Astrophys. J.* **450**, 559 (1995).
- [49] P. Tiwari, S. Ghosh, and P. Jain, The galaxy power spectrum from TGSS ADR1 and the effect of flux calibration systematics, *Astrophys. J.* **887**, 175 (2019).
- [50] N. Hurley-Walker, A rescaled subset of the alternative data release 1 of the TIFR GMRT sky survey, [arXiv:1703.06635](https://arxiv.org/abs/1703.06635).
- [51] Y. Hoffman, D. Pomarède, R. B. Tully, and H. M. Courtois, The dipole repeller, *Nat. Astron.* **1**, 0036 (2017).
- [52] R. Watkins, T. Allen, C. J. Bradford, A. Ramon, A. Walker, H. A. Feldman, R. Cionitti, Y. Al-Shorman, E. Kourkchi, and R. B. Tully, Analysing the large-scale bulk flow using cosmicflows4: Increasing tension with the standard cosmological model, *Mon. Not. R. Astron. Soc.* **524**, 1885 (2023).
- [53] Courtois, H. M., Dupuy, A., Guinet, D., Baulieu, G., Ruppén, F., and Brenas, P., Gravity in the local universe: Density and velocity fields using cosmicflows-4, *Astron. Astrophys.* **670**, L15 (2023).

- [54] N. J. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee, S. Sarkar, and J. Colin, A test of the cosmological principle with quasars, *Astrophys. J.* **908**, L51 (2021).
- [55] S. W. Duchesne, K. Ross, A. J. M. Thomson, E. Lenc, T. Murphy, T. J. Galvin, A. W. Hotan, V. Moss, and M. T. Whiting, The rapid ASKAP continuum survey (RACS) VI: The RACS-high 1655.5 MHz images and catalogue, *Publ. Astron. Soc. Aust.* **42**, e038 (2025).
- [56] R. P. Norris, A. M. Hopkins, J. Afonso, S. Brown, J. J. Condon, L. Dunne, I. Feain, R. Hollow, M. Jarvis, M. Johnston-Hollitt *et al.*, EMU: Evolutionary map of the universe, *Publ. Astron. Soc. Aust.* **28**, 215 (2011).
- [57] A. M. Hopkins, A. Kapinska, J. Marvil, T. Vernstrom, J. D. Collier, R. P. Norris, Y. A. Gordon, S. W. Duchesne, L. Rudnick, N. Gupta *et al.*, The evolutionary map of the universe: A new radio atlas for the southern hemisphere sky, *Publ. Astron. Soc. Aust.* **42**, e071 (2025).
- [58] D. J. B. Smith, P. N. Best, K. J. Duncan, N. A. Hatch, M. J. Jarvis, H. J. A. Röttgering, C. J. Simpson, J. P. Stott, R. K. Cochrane, K. E. Coppin *et al.*, The WEAVE-LOFAR survey, in *SF2A-2016: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, edited by C. Reyl  , J. Richard, L. Cambr  sy, M. Deleuil, E. P  contal, L. Tresse, and I. Vauglin (2016), pp. 271–280.
- [59] T. P. Robitaille, E. J. Tollerud, P. Greenfield, M. Droettboom, E. Bray, T. Aldcroft, M. Davis, A. Ginsburg, A. M. Price-Whelan *et al.* (Astropy Collaboration), Astropy: A community Python package for astronomy, *Astron. Astrophys.* **558**, A33 (2013).
- [60] A. M. Price-Whelan, B. M. Sip  cz, H. M. G  nther, P. L. Lim, S. M. Crawford, S. Conseil, D. L. Shupe, M. W. Craig, N. Dencheva *et al.* (Astropy Collaboration), The Astropy project: Building an open-science project and status of the v2.0 core package, *Astron. J.* **156**, 123 (2018).
- [61] A. M. Price-Whelan, P. L. Lim, N. Earl, N. Starkman, L. Bradley, D. L. Shupe, A. A. Patil, L. Corrales, C. E. Brasseur *et al.* (Astropy Collaboration), The Astropy project: Sustaining and growing a community-oriented open-source project and the latest major release (v5.0) of the core package, *Astrophys. J.* **935**, 167 (2022).
- [62] J. D. Hunter, Matplotlib: A 2D graphics environment, *Comput. Sci. Eng.* **9**, 90 (2007).
- [63] S. van der Walt, S. C. Colbert, and G. Varoquaux, The NumPy array: A structure for efficient numerical computation, *Comput. Sci. Eng.* **13**, 22 (2011).
- [64] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright *et al.*, SciPy 1.0: Fundamental algorithms for scientific computing in Python, *Nat. Methods* **17**, 261 (2020).
- [65] A. Zonca, L. Singer, D. Lenz, M. Reinecke, C. Rosset, E. Hivon, and K. Gorski, HEALPY: Equal area pixelization and spherical harmonics transforms for data on the sphere in Python, *J. Open Source Software* **4**, 1298 (2019).
- [66] K. M. G  rski, E. Hivon, A. J. Banday, B. D. Wandelt, F. K. Hansen, M. Reinecke, and M. Bartelmann, HEALPix: A framework for high-resolution discretization and fast analysis of data distributed on the sphere, *Astrophys. J.* **622**, 759 (2005).
- [67] <https://ror.org/05qajvd42>
- [68] L. B  hme, D. Schwarz, P. Tiwari, M. Pashapour-Ahmadabadi, B. Bahr-Kalus, M. Bilicki, C. Hale, C. Heneka, and T. M. Siewert, Code for “Overdispersed radio source counts and excess radio dipole detection”, Zenodo (2025), [10.5281/zenodo.17166250](https://zenodo.org/record/17166250).
- [69] C. G. T. Haslam, C. J. Salter, H. Stoffel, and W. E. Wilson, A 408-MHz all-sky continuum survey. II. The atlas of contour maps, *Astron. Astrophys. Suppl. Ser.* **47**, 1 (1982).
- [70] M. Remazeilles, C. Dickinson, A. J. Banday, M.-A. Bigot-Sazy, and T. Ghosh, An improved source-subtracted and destriped 408-MHz all-sky map, *Mon. Not. R. Astron. Soc.* **451**, 4311 (2015).

End Matter

Appendix A: Additional figures and tables—This section includes additional figures and tables that provide detailed information on the improvement of the negative binomial distribution for radio surveys, the fitting of the spectral index, and the flux density dependence of the radio dipole direction. Figure 2 displays maps and histograms, along with the best-fit Poisson and negative binomial distributions for all six radio surveys. The maps show the applied masks and counts in cells for the corresponding flux density cut. The chosen flux density cuts guarantee a high degree of completeness and that all six surveys are dominated by radio emission associated with active Galactic nuclei. The histogram highlights the enhancement achieved by the negative binomial distribution in comparison to the Poisson distribution in describing the observed counts-in-cells distribution. Fitting parameters are provided in the main text, Table I. Table IV details the cross-matching results for survey pairs. To determine the spectral index of a given radio

survey, the chosen mask and flux density cut are applied, and it is matched to another survey without a flux density cut. If multiple matches occur, the flux densities are summed, especially when cross-matching between low- and high-resolution surveys. The table also shows the percentage of matches in the overlap of the two surveys. For example, matching LoTSS-DR2 with a 5 mJy flux density cut to NVSS results in 51% of LoTSS-DR2 sources matching 83% of NVSS sources in the overlap. The resulting spectral index is $\alpha = -0.73 \pm 0.23$. Figure 3 illustrates (α_{RA}, δ) as a function of the flux density cut for all six radio surveys. As discussed in the main text, this helps determine which flux density cuts and surveys are considered robust and which are analyzed with the constrained estimator.

Appendix B: Systematic effects of radio surveys—The systematic effects regarding the large-scale structure of LoTSS-DR2 were discussed and studied in [24,26,27].

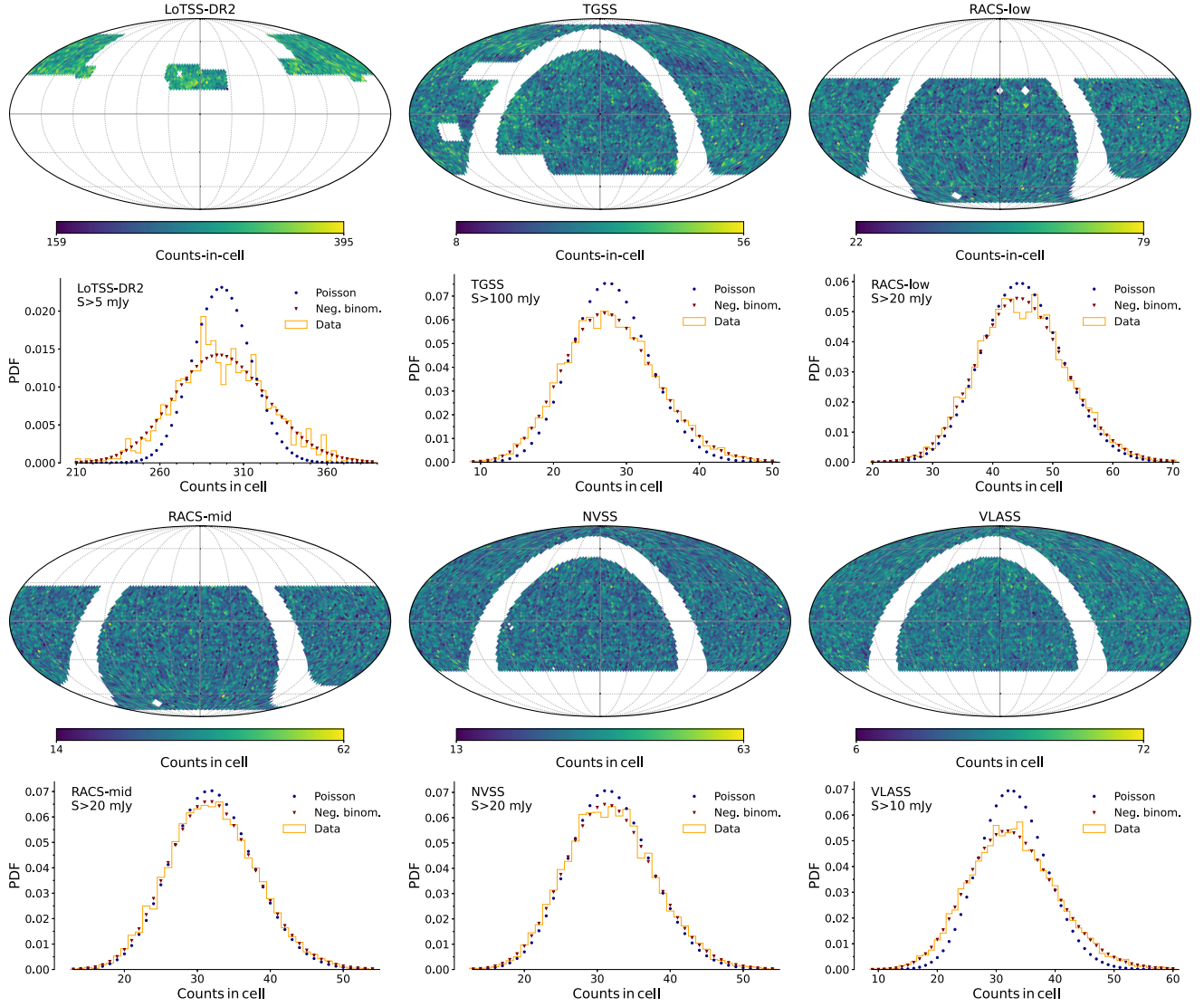


FIG. 2. Maps (first and third row) and histograms (second and fourth row) of source counts from six radio continuum surveys and their best-fit Poisson and negative binomial distributions.

TABLE IV. Percentage of matched radio sources for pairs of surveys and derived mean spectral index, both calculated in their overlap. The third column gives the percentage of matched sources for the first and second surveys, respectively. The given flux density cut is applied to the first survey only, and none applied to the second.

Surveys	$S_{\min}$ (mJy)	Percent matched	α
LoTSS-DR2–NVSS	5	51%/83%	-0.73 ± 0.23
TGSS–NVSS	100	97%/16%	-0.76 ± 0.18
RACS-low–NVSS	20	97%/25%	-0.98 ± 0.24
RACS-low–RACS-mid	20	99%/19%	-0.95 ± 0.23
RACS-mid–VLASS	20	81%/23%	-0.81 ± 0.30
FIRST–VLASS ^a	...	...	-0.71

^aTaken from [36], which used the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST [48]) to calculate α .

Simulations of the LoTSS-DR2 sky coverage and number density show that the dipole retrieval in declination has a small bias but is mainly dominated by a large variance. Simulations using the understood and modeled LoTSS-DR2 systematics, as described by random mocks [27], show that a retrieval of the dipole direction is not possible, due to limited sky coverage. Additionally, we find no cross-correlation between the LoTSS-DR2 map and Galactic synchrotron emission as described by the 408 MHz all-sky Haslam map [69] from [70]. Reference [19] showed that there also is no cross-correlation between the RACS-low number count maps and Galactic synchrotron emission. For NVSS, [35] provides an extensive discussion of observational systematic effects. Systematic effects of NVSS with respect to estimators, survey geometry, flux density cuts, shot noise, and more have been studied in [6,15–17].

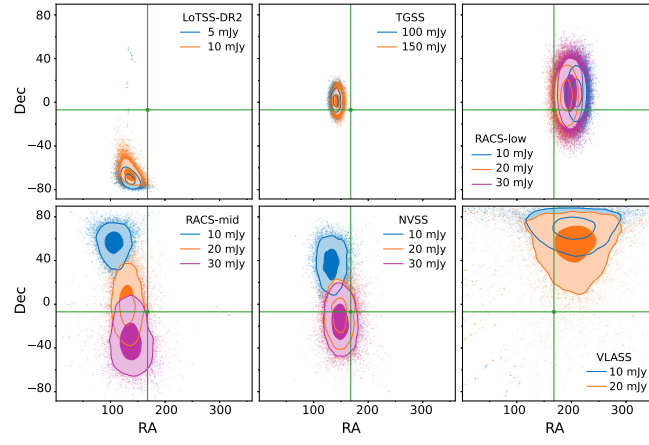


FIG. 3. Declination and right ascension of source count dipole for all six radio surveys for different flux density cuts using the unconstrained estimator. The green lines and dot represent the expected value based on the CMB dipole.