UNIVERSITÄT BIELEFELD
Faculty of Physics

LOFAR ERIC

Cosmic Radio Dipole

Overdispersed radio source counts and excess radio dipole detection

LOFAR Family Meeting 2025

Lukas Böhme

Pashapour-Ahmadabadi, **Böhme**, et al.
A&A 698, A148 (2025)

Böhme+,
accepted for publication in PRL

UNIVERSITÄT BIELEFELD
Faculty of Physics

LOFAR ERIC

Cosmic Radio Dipole

ACCEPTED PAPER

Overdispersed radio source counts and excess radio dipole detection

Lukas Böhme, Dominik J. Schwarz, Prabhakar Tiwari, Morteza Pashapour-Ahmadabadi, Benedict Bahr-Kalus, Maciej Bilicki, Catherine L. Hale, Caroline S. Heneka, and Thilo M. Siewert

Phys. Rev. Lett. - **Accepted** 19 September, 2025

DOI: https://doi.org/10.1103/6z32-3zf4

Export Citation

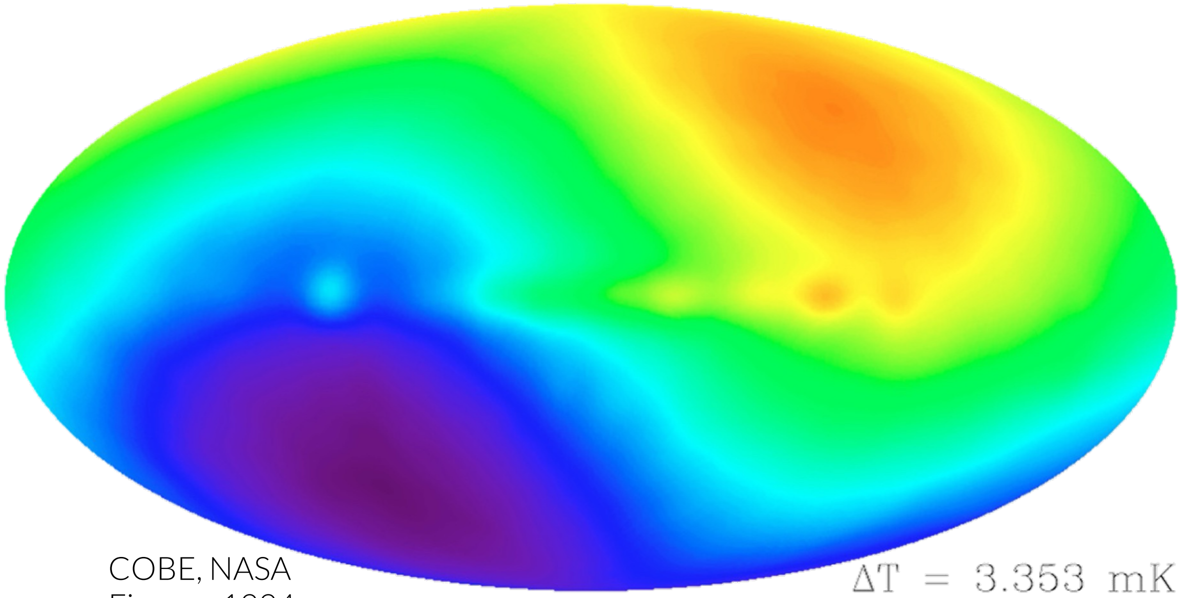
Pashapour-Ahmadabadi, Böhme, et al.
A&A 698, A148 (2025)

Böhme+,
accepted for publication in PRL

Cosmic Microwave Background

- First noted in 1967/69 [1]
- Clear result: 1994 COBE [2]
- Assumption: Only due to motion of the Solar System in relation to CMB rest-frame
- On the order of 10^{-3}

$$v_{\mathrm{CMB}} = 369.82 \pm 0.11 \ \mathrm{km\ s}^{-1} \quad [3]$$



COBE, NASA
Fixsen+ 1994

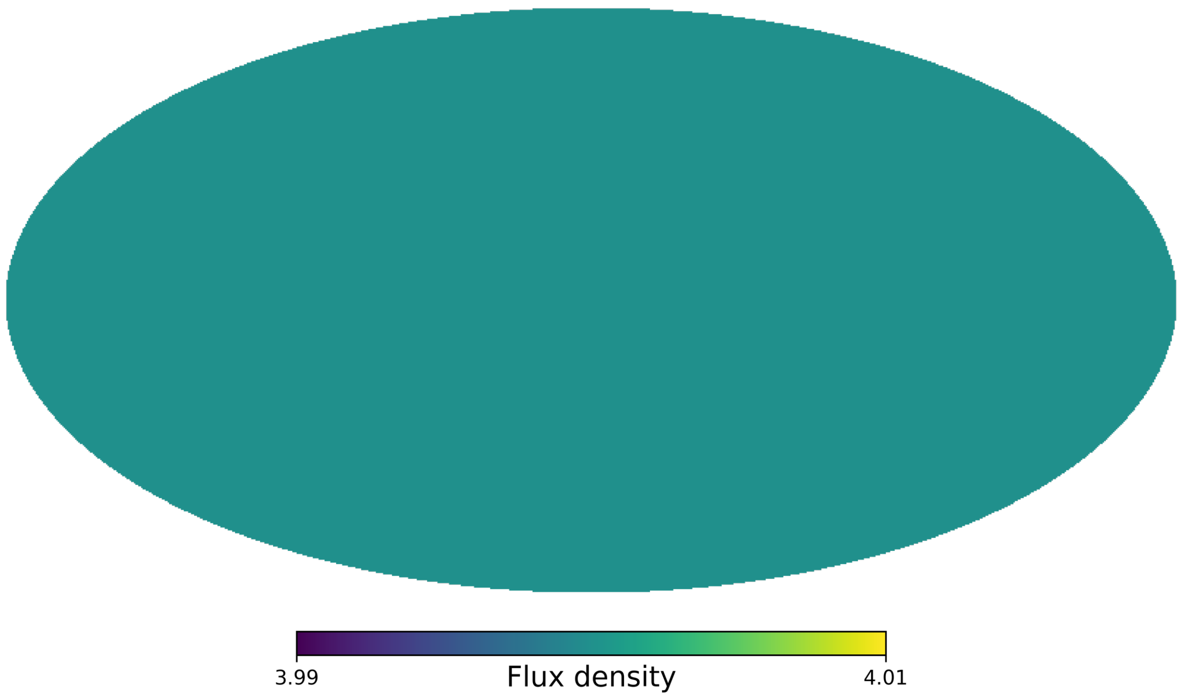
[1] Partridge and Wilkinson, 1967
[2] Fixsen et al. 1994
[3] Planck Collaboration 2020

Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\mathrm{radio}} = d_{\mathrm{kin}} + d_{\mathrm{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration

Cosmic Radio Dipole

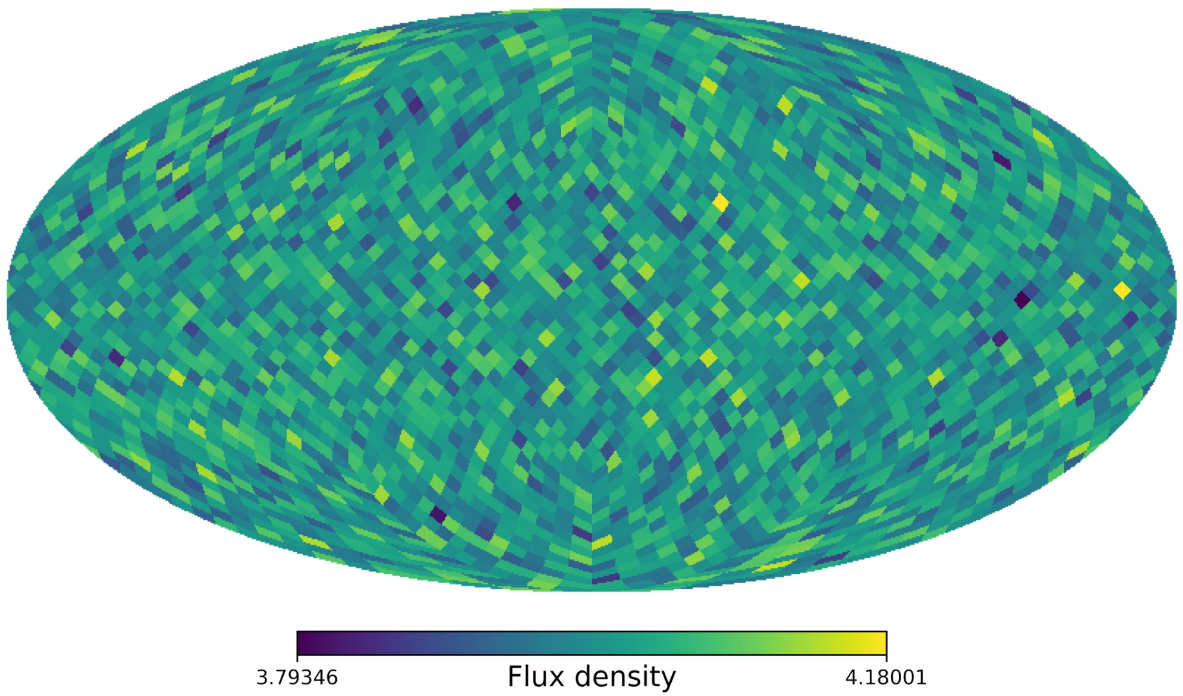
- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration



Each pixel ≙ 1 source at 4mJy

Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration



Each pixel ≙ 1 source at 4mJy + Noise

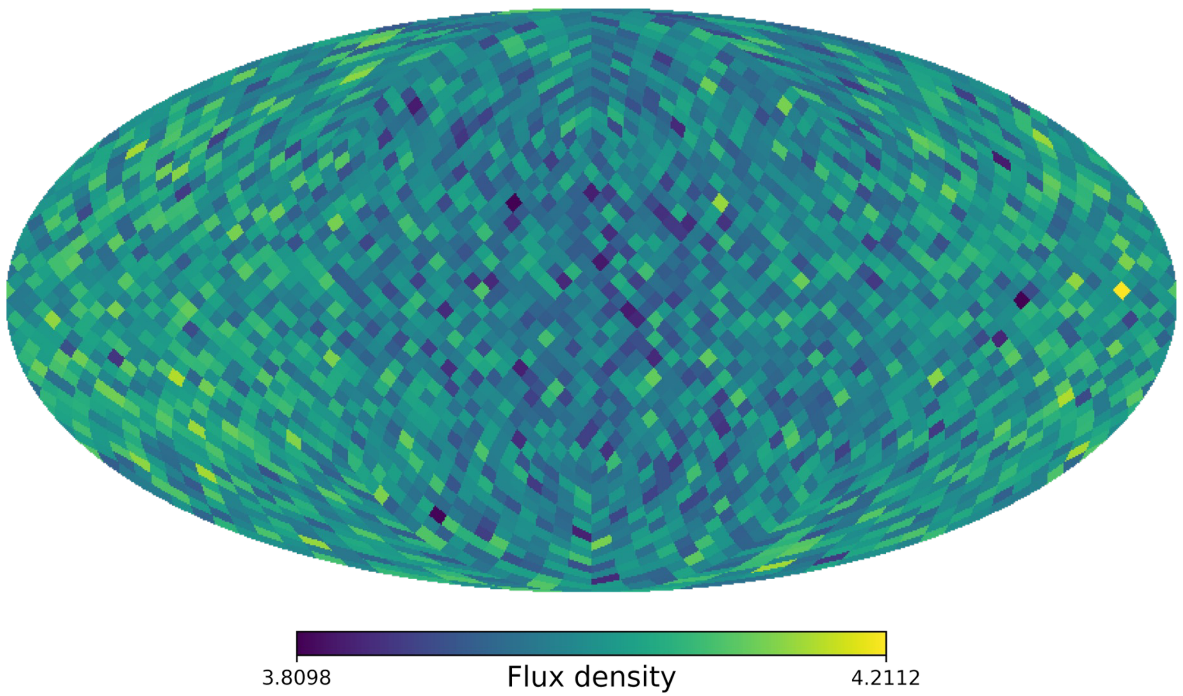
UNIVERSITÄT BIELEFELD
Faculty of Physics

Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration

Doppler shift

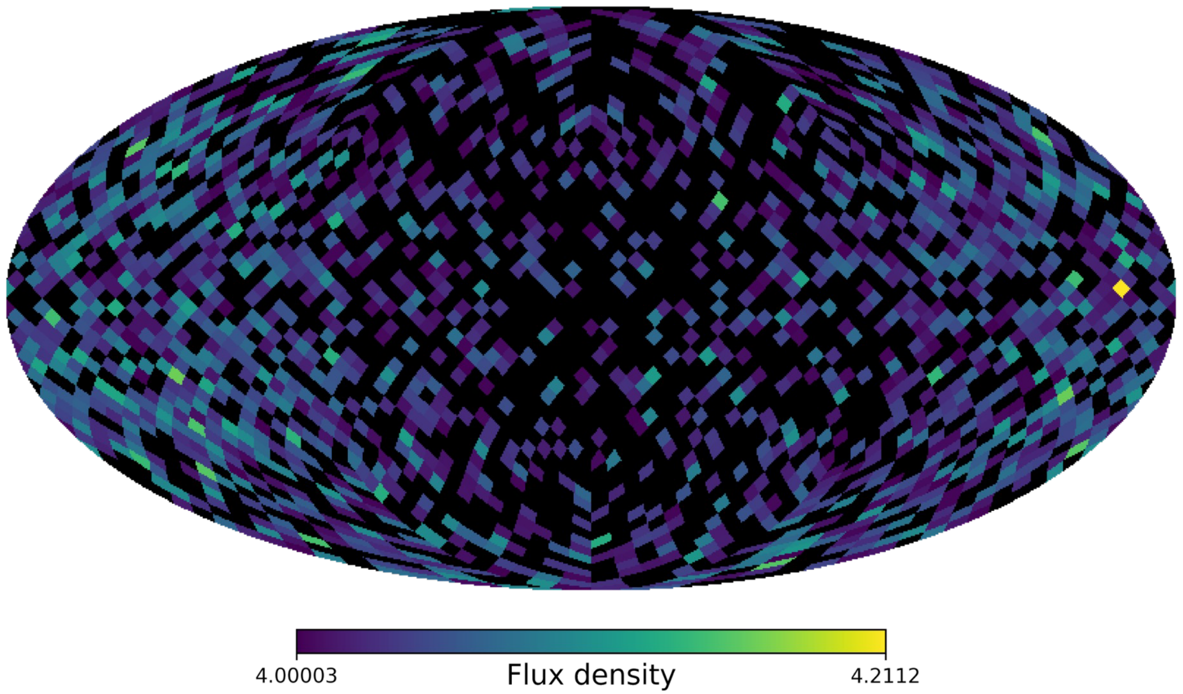
- Change in frequency
  - Change in flux density ($S \propto \nu^{-\alpha}$)



Each pixel ≙ 1 source at 4mJy + Noise + Doppler shift

Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration



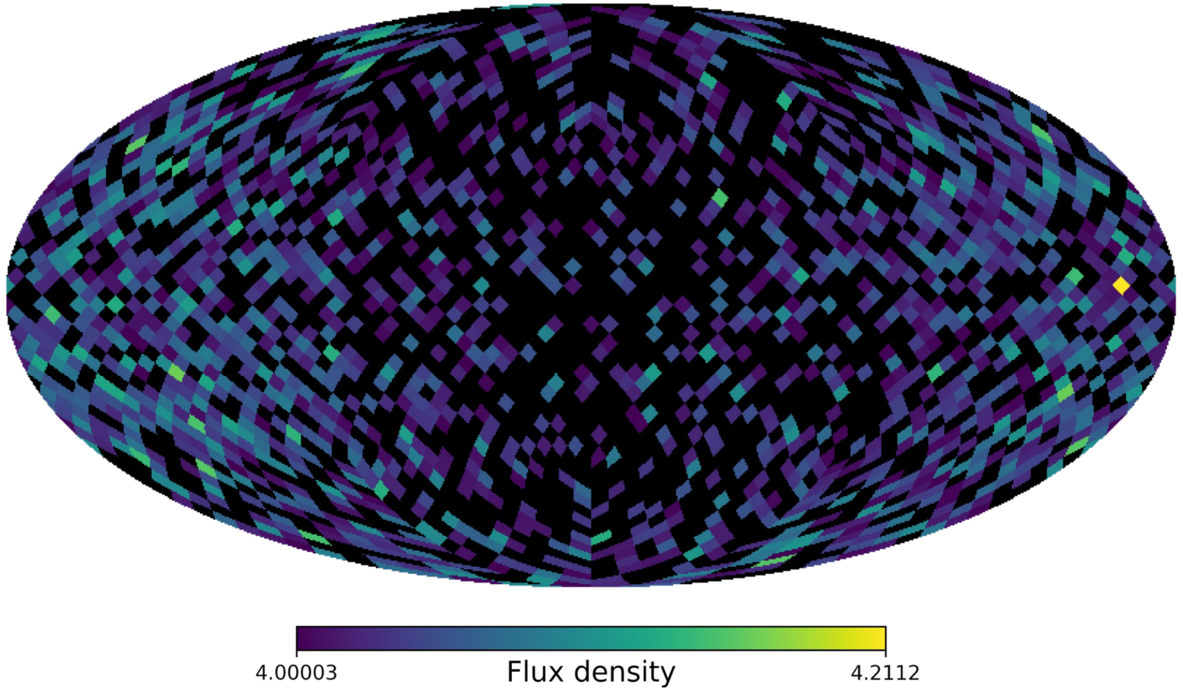
Doppler shift

- Change in frequency
  - ➢ Change in flux density ($S \propto \nu^{-\alpha}$)

Each pixel ≙ 1 source at 4mJy + Noise
+ Doppler shift
+ 4mJy flux cut

Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{cluster}}$
- d_{cluster} expected to be small (local)
- d_{kin} due to Doppler shift & Aberration



Doppler shift

- Change in frequency
  - ➢ Change in flux density ($S \propto \nu^{-\alpha}$)

Aberration

- Change of observed angle towards direction of motion („Clustering“)

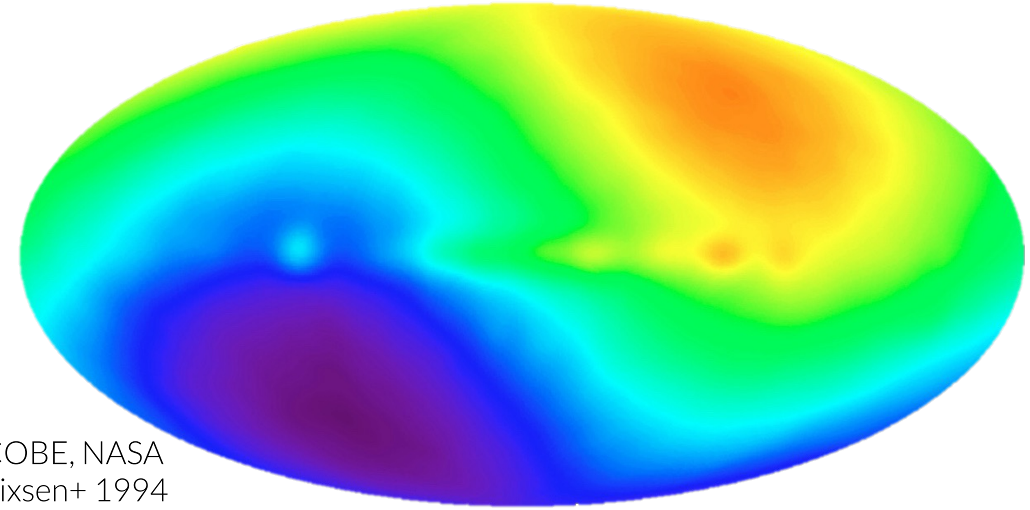
Each pixel ≙ 1 source at 4mJy + Noise
+ Doppler shift
+ 4mJy flux cut

UNIVERSITÄT BIELEFELD
Faculty of Physics

Source Count Dipole

Counts-in-cell

$$\left.\frac{dN}{d\Omega}\right|_{\mathrm{obs}} = \left.\frac{dN}{d\Omega}\right|_{\mathrm{rest}} (1 + d\cos\theta)$$



COBE, NASA
Fixsen+ 1994

Source Count Dipole

Counts-in-cell

$$\left.\frac{dN}{d\Omega}\right|_{\mathrm{obs}} = \left.\frac{dN}{d\Omega}\right|_{\mathrm{rest}} (1 + d\cos\theta)$$

$\theta = \angle$ (Pixel, direction of motion)

$dN/d\Omega(>S) \propto S^{-x}$ Slope in source counts

$S \propto \nu^{-\alpha}$ Spectral index

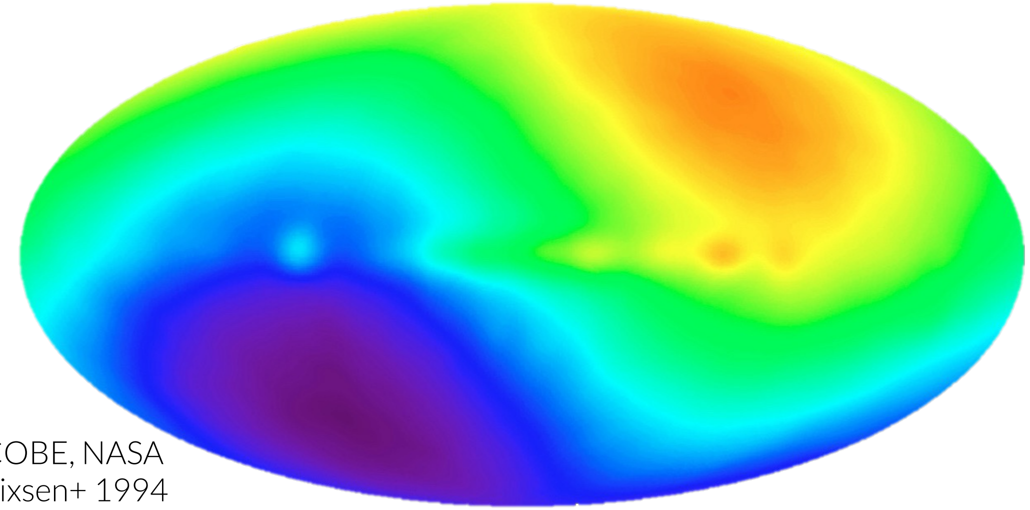
$@S_{\mathrm{min}}$

Radio survey dependent

$$d_{exp} = (2 + x(1+\alpha))\frac{v_{\mathrm{CMB}}}{c} \approx 0.5 \times 10^{-2}$$

⇒ 0.5% effect at max and min

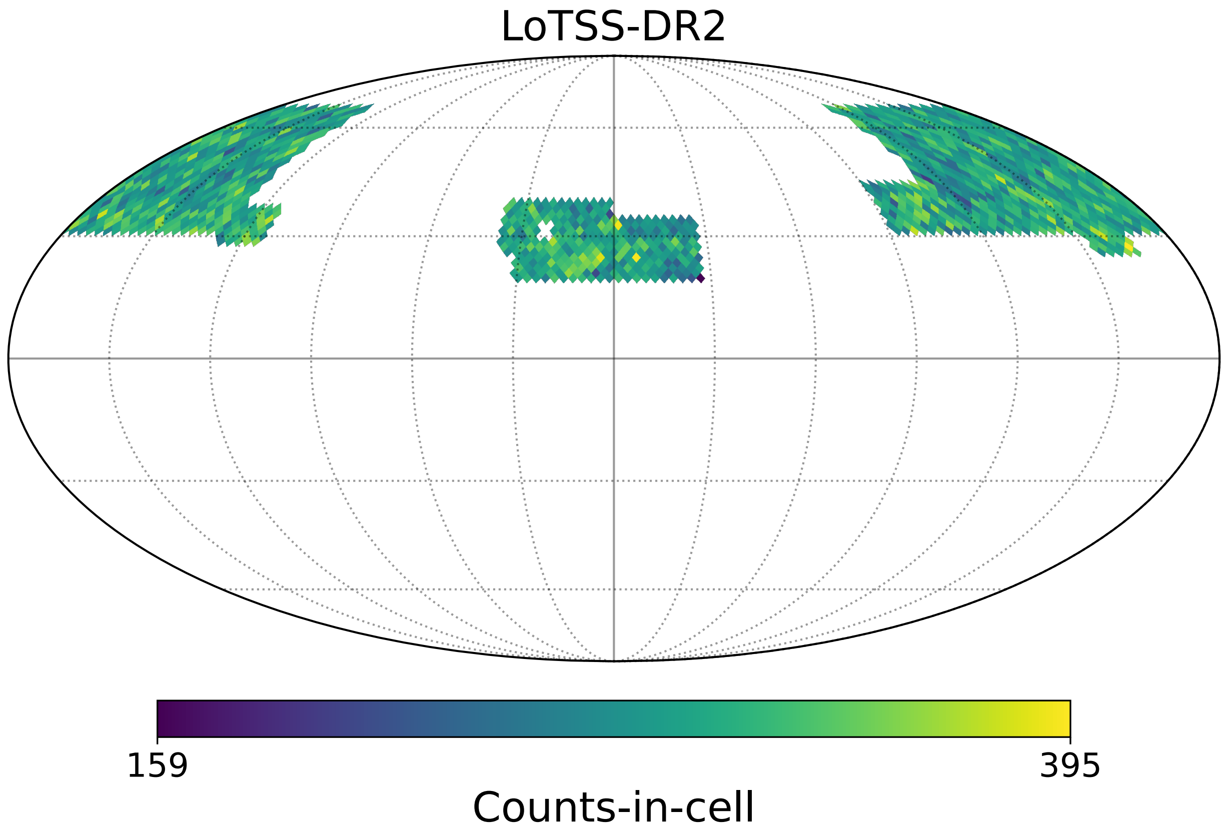
$v_{\mathrm{CMB}} = 369.82\,\mathrm{km\,s^{-1}}$

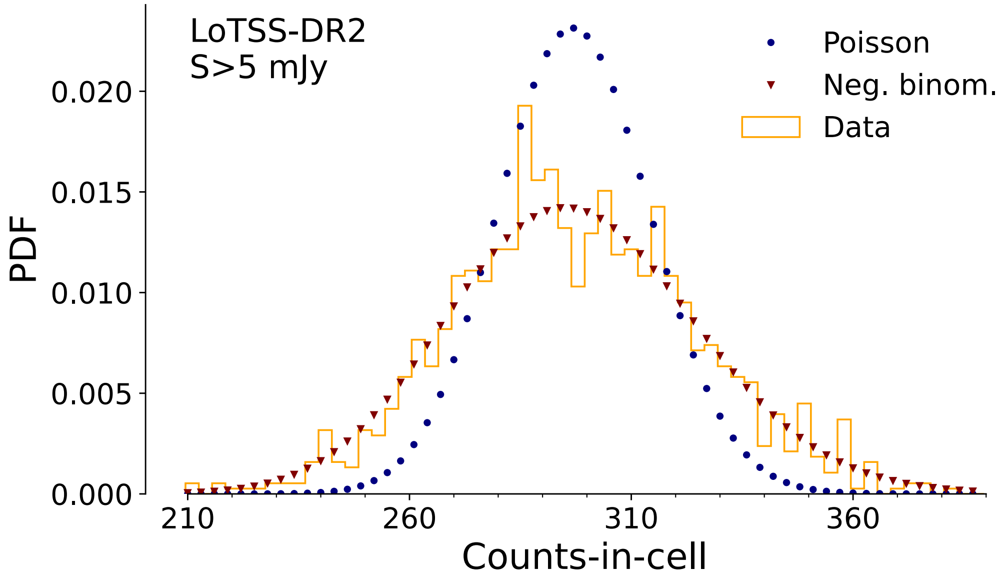


COBE, NASA
Fixsen+ 1994

(Ellis and Baldwin, 1984)

Counts-in-cell



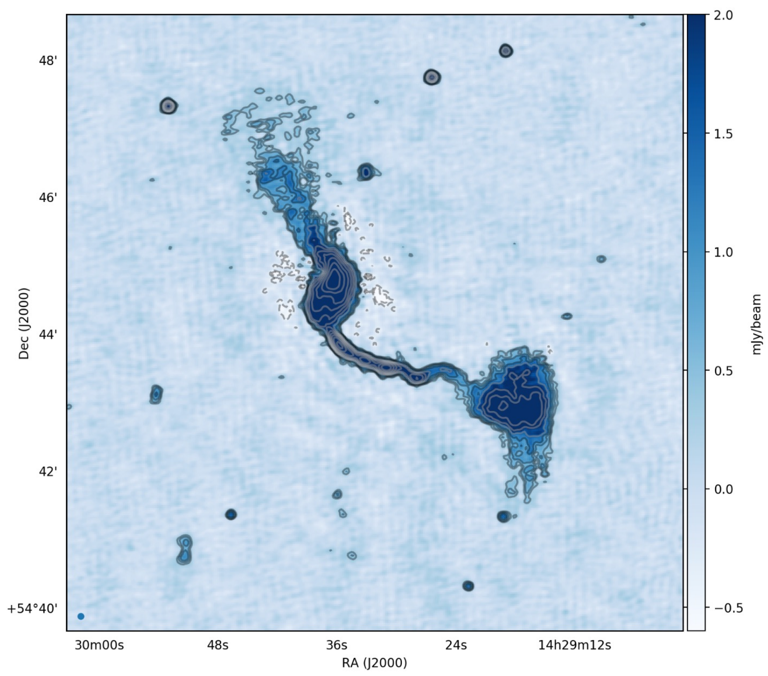


Both: Böhme+, PRL

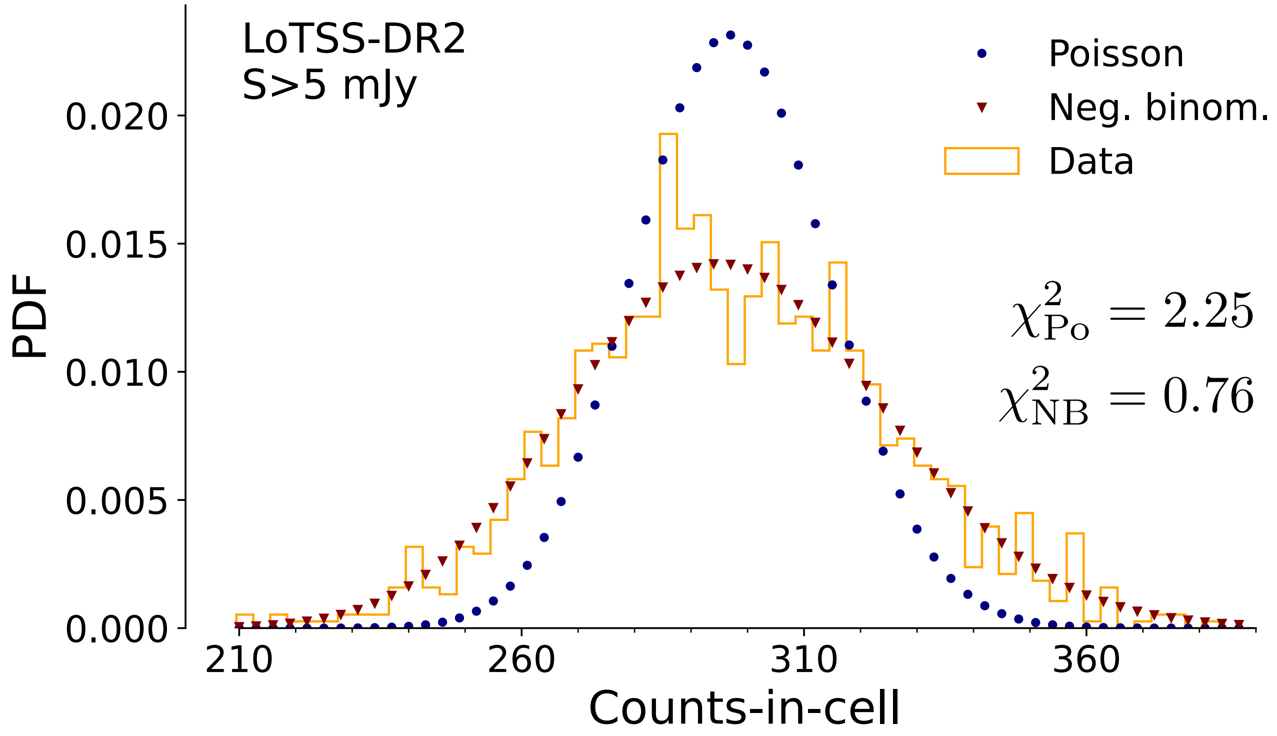
UNIVERSITÄT
BIELEFELD
Faculty of Physics

Counts-in-cell

- ✖ Poisson distr. Point sources
- ✔ Negative binomial distribution



Shimwell+ 2019



Böhme+, PRL

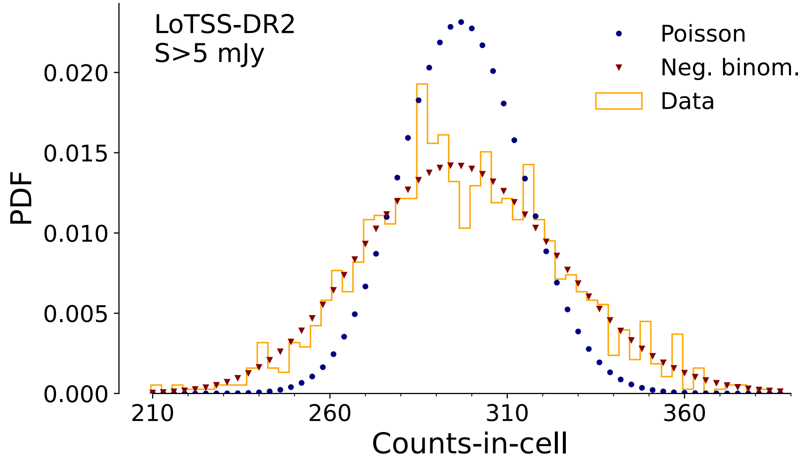
Negative binomial distribution

Poisson distributed physical objects

Model: $$N = \sum_{j=1}^{O} C_j$$

Number components of object j, distributed logarithmic with p

Count of radio sources in cell



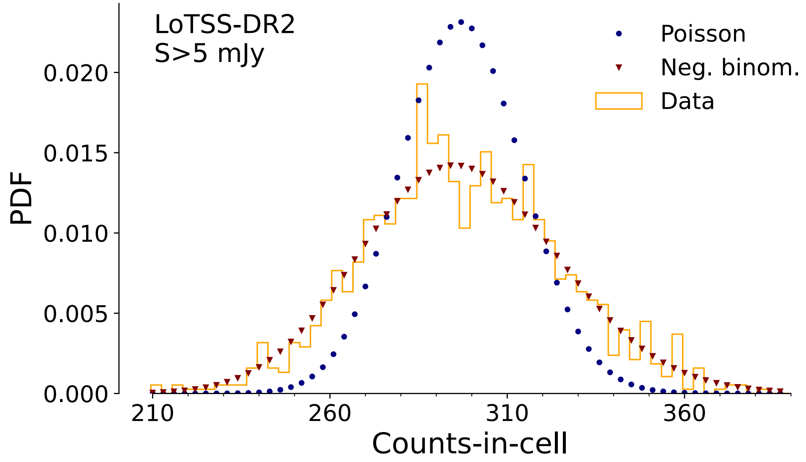
Negative binomial distribution

Poisson distributed physical objects

Model: $$N = \sum_{j=1}^{O} C_j$$

Number components of object j, distributed logarithmic with p

Count of radio sources in cell



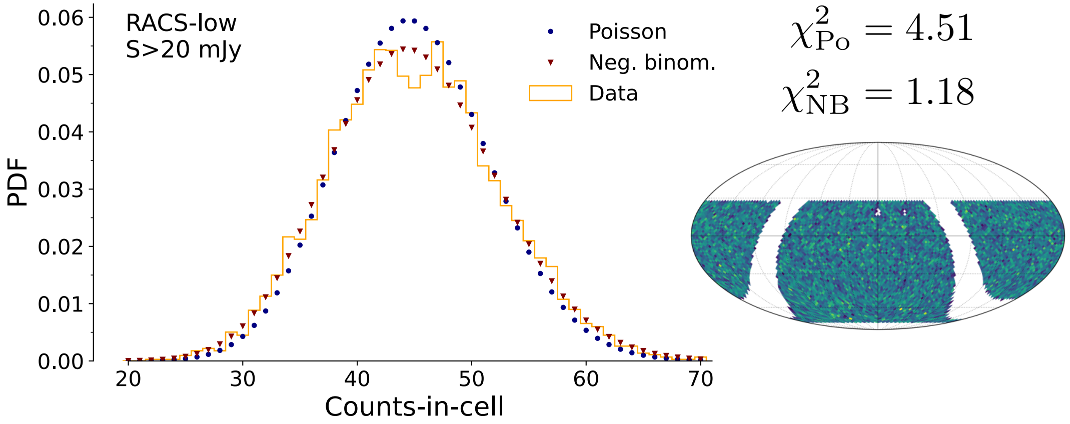
$$P_{\mathrm{NB}}(N) = \binom{N+r-1}{N} p^N (1-p)^r$$

$$p = 1 - \frac{\mathbb{E}[\mathrm{Data}]}{\mathbb{V}ar[\mathrm{Data}]}, \quad r = \frac{\mathbb{E}[\mathrm{Data}]^2}{\mathbb{V}ar[\mathrm{Data}] - \mathbb{E}[\mathrm{Data}]}$$

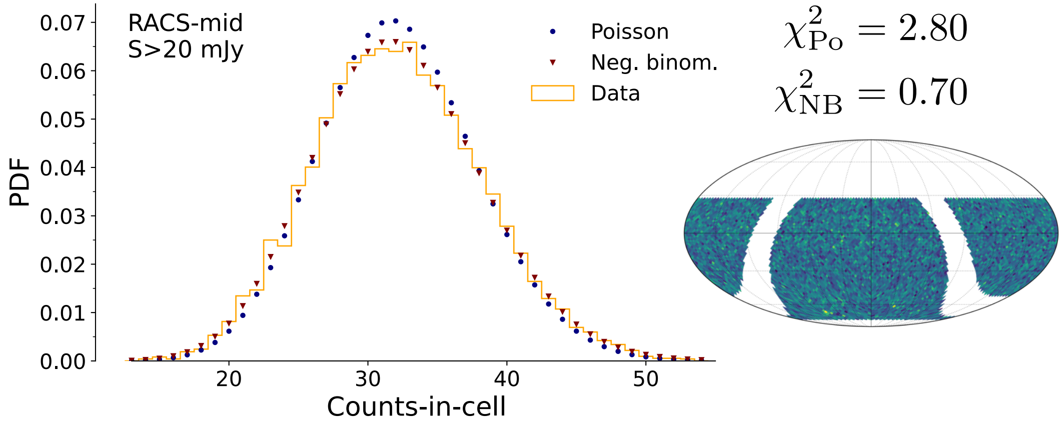
$p \to 0$, $r \to \infty$ Poissonian limit, $0 < p < 1$: Clustering

Data distribution

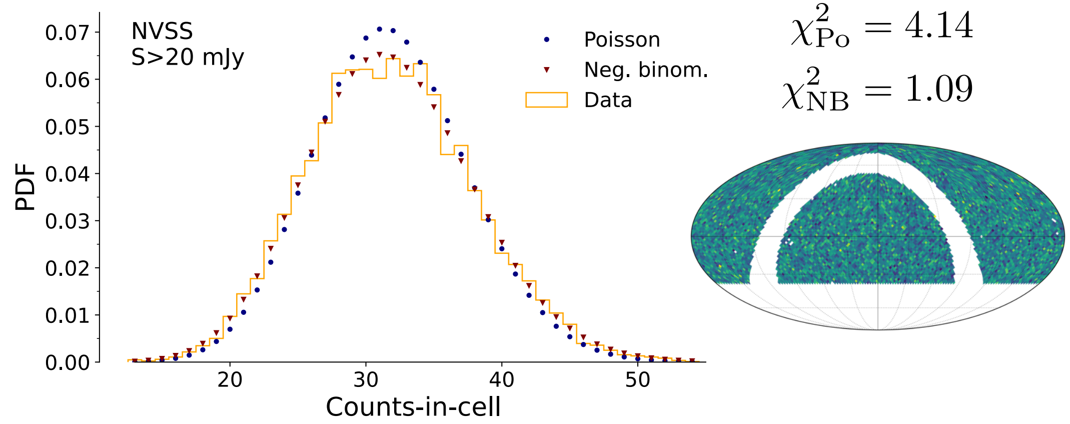
RACS-low $(S_{\rm min} = 20\,{\rm mJy}, 888\,{\rm MHz})$



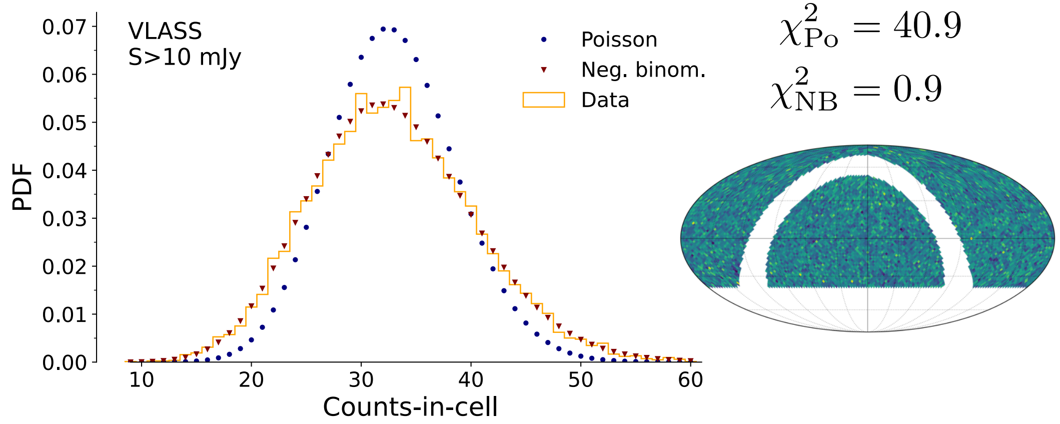
RACS-mid $(S_{\rm min} = 20\,{\rm mJy}, 1368\,{\rm MHz})$



NVSS $(S_{\rm min} = 20\,{\rm mJy}, 1400\,{\rm MHz})$



VLASS $(S_{\rm min} = 10\,{\rm mJy}, 3000\,{\rm MHz})$



UNIVERSITÄT BIELEFELD
Faculty of Physics

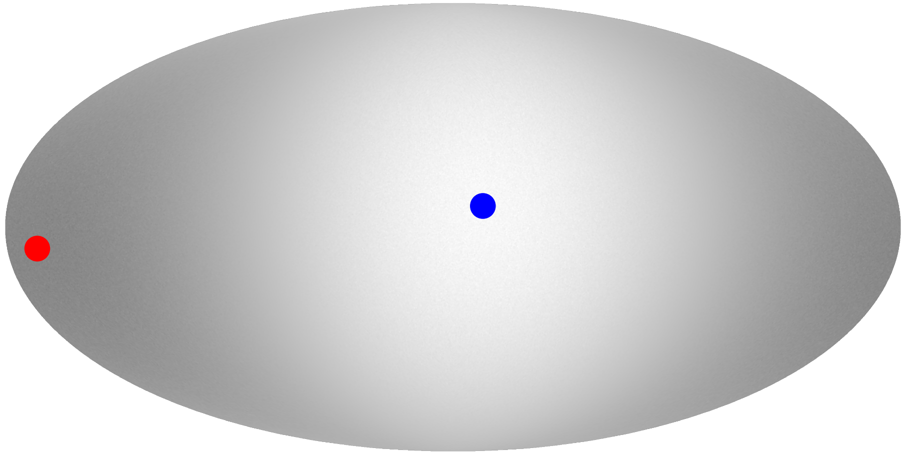
Estimator for radio source counts

- Likelihood for the negative binomial distr. with dipole given by:

$$L(n|\mathbf{d}) = \sum_i \binom{n_i + r_i - 1}{n_i} (1-p)^{n_i} p^{r_i}$$

Dipole affects mean count as a function of direction

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



[1] Ashton et al. 2019
[2] Romero-Shaw et al. 2020

Estimator for radio source counts

- Likelihood for the negative binomial distr. with dipole given by:

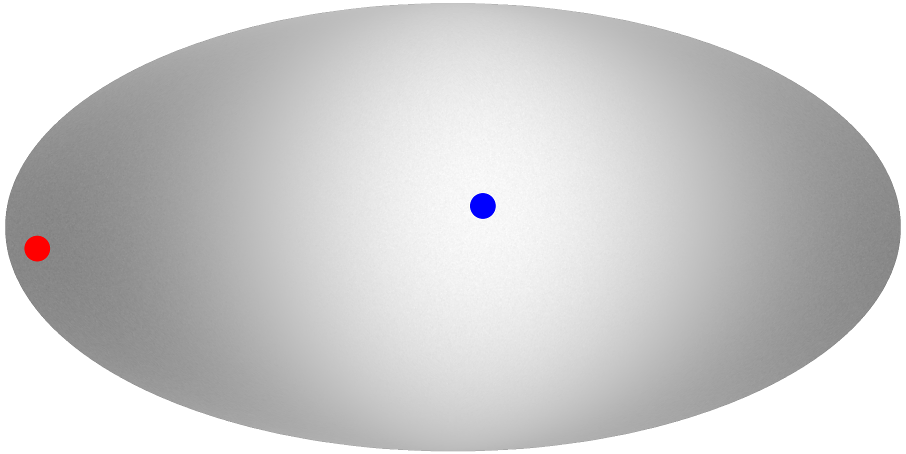
$$L(n|\mathbf{d}) = \sum_i \binom{n_i + r_i - 1}{n_i} (1-p)^{n_i} p^{r_i}$$

Dipole affects mean count as a function of direction

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

- Minimise the negative log-likelihood with Bilby [1,2]

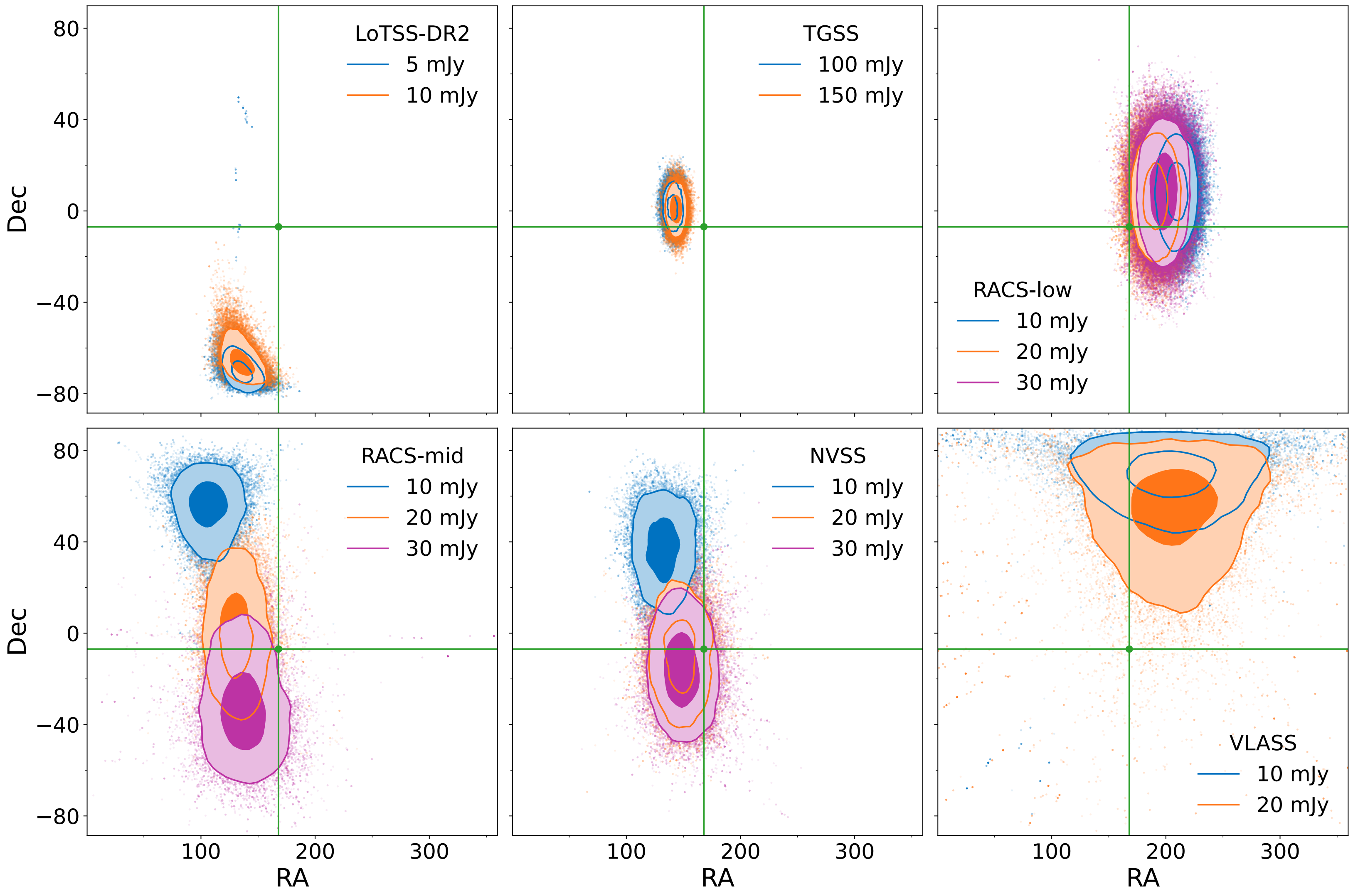
- Multi-survey estimation:
  - Add log-likelihoods to obtain a combined estimate
  - +Assume: Same underlying dipole in all surveys



[1] Ashton et al. 2019
[2] Romero-Shaw et al. 2020

Radio Dipole

- LoTSS-DR2 alone:
  too small sky coverage
- TGSS:
  abnormal amplitude
- RACS-mid:
  inconsistent
- VLASS:
  problematic issues



Böhme+, PRL

UNIVERSITÄT BIELEFELD
Faculty of Physics

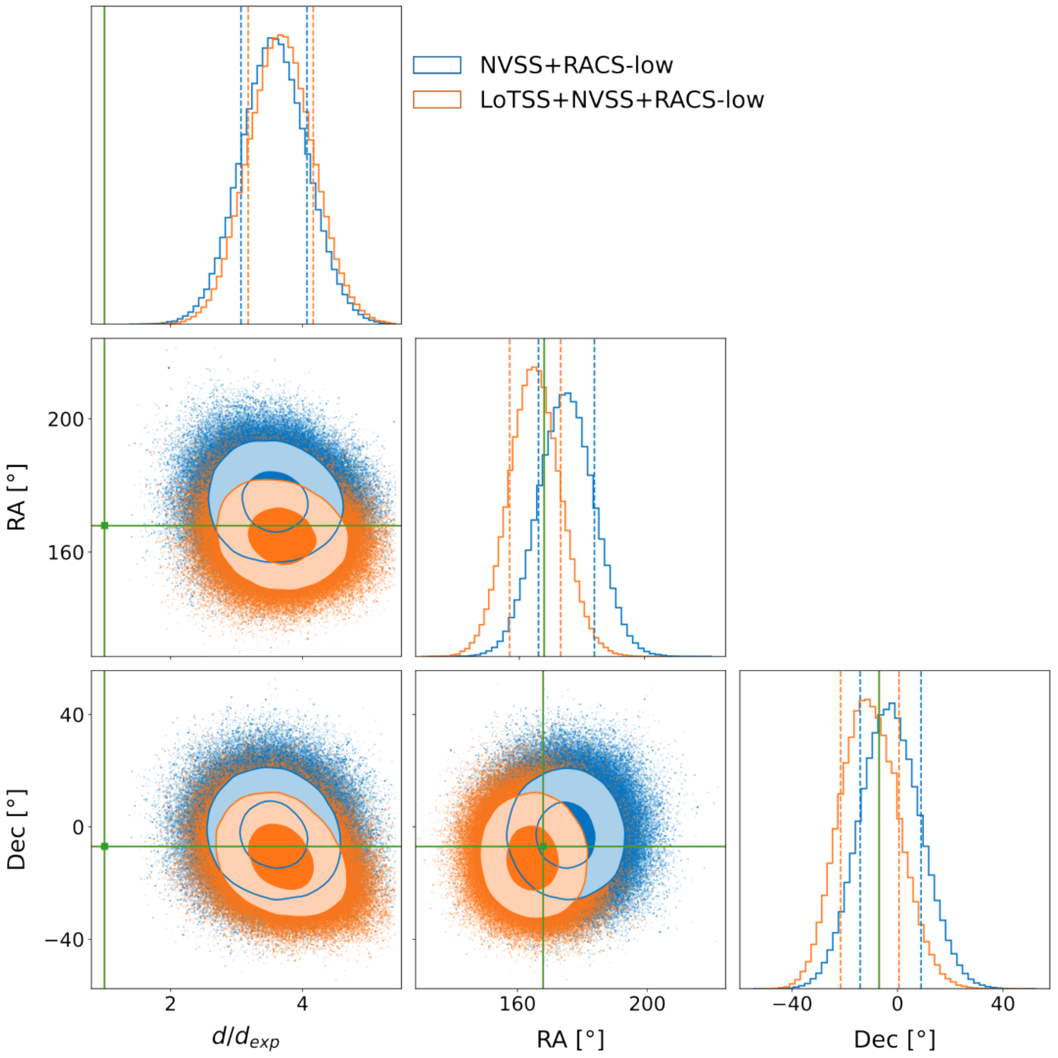
Joint estimate

- Combine
  - LoTSS-DR2
  - RACS-low
  - NVSS

  to get coverage + sensitivity

- A factor 3.67±0.49 higher than CMB, direction well aligned

- Through the addition of LoTSS-DR2: 5.4σ discrepancy in amplitude to CMB



Böhme+, PRL

Conclusion, future prospects

- Joint estimate raises significant tension with CMB, consistent with previous measurements
- Future large area sky surveys will help
- Wide-field spectroscopic follow ups:
  WEAVE-LOFAR -> Removing low-z/local sources