# Cosmic Radio Dipole
# Multi-survey estimation

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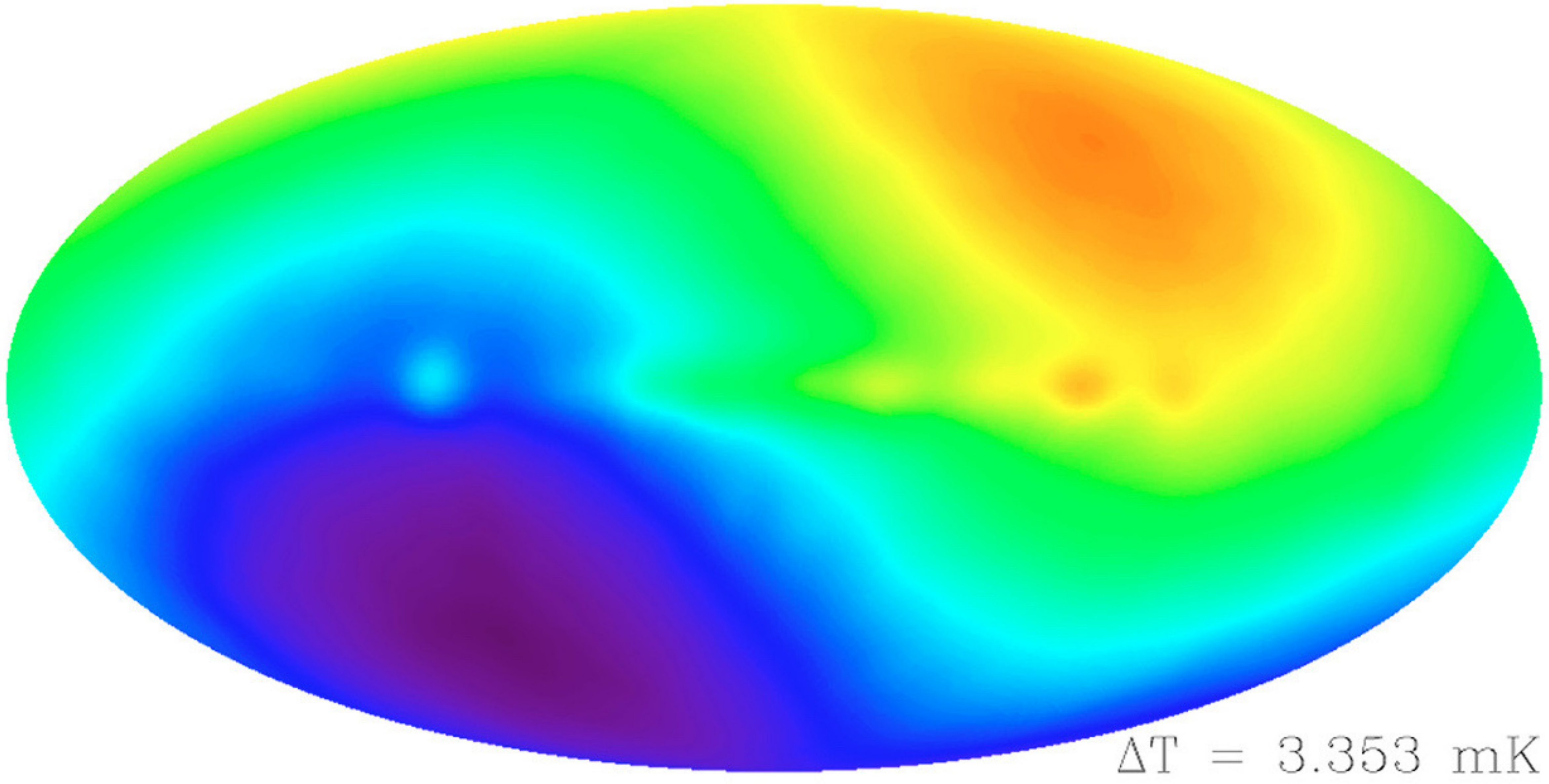
L. Böhme et al., in prep.

# CMB Dipole

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

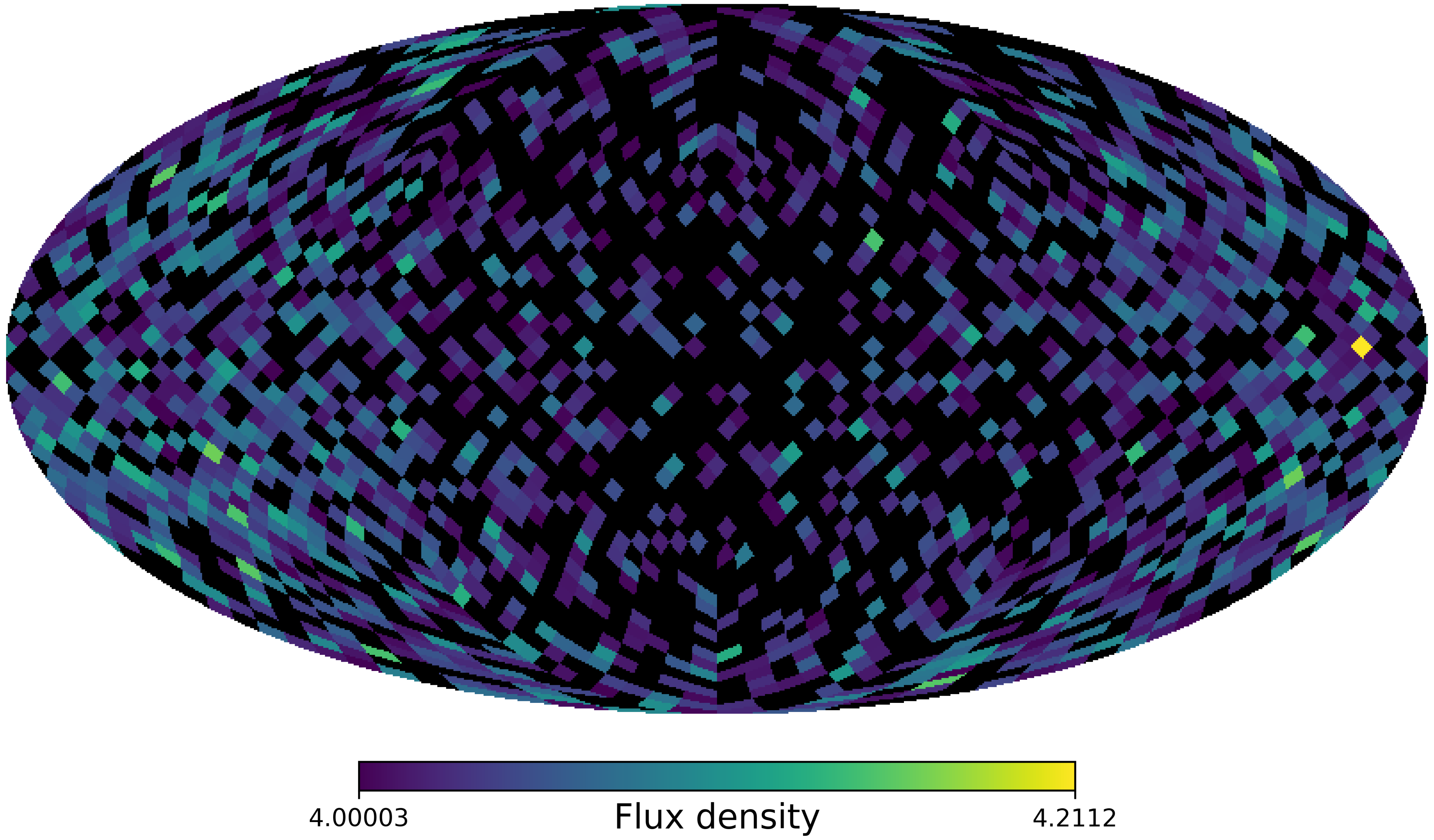
$$v_{\mathrm{CMB}} = 369.82 \pm 0.11\ \mathrm{km\,s^{-1}}$$ [3]




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

# Cosmic Radio Dipole

- $\bar{z} \approx 1$
- $d_{\text{radio}} = d_{\text{kin}} + d_{\text{matter}}$
- $d_{\text{matter}}$ expected to be small
- $d_{\text{kin}}$ 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“)

# Kinetic dipole in radio source counts

Counts-in-Cell

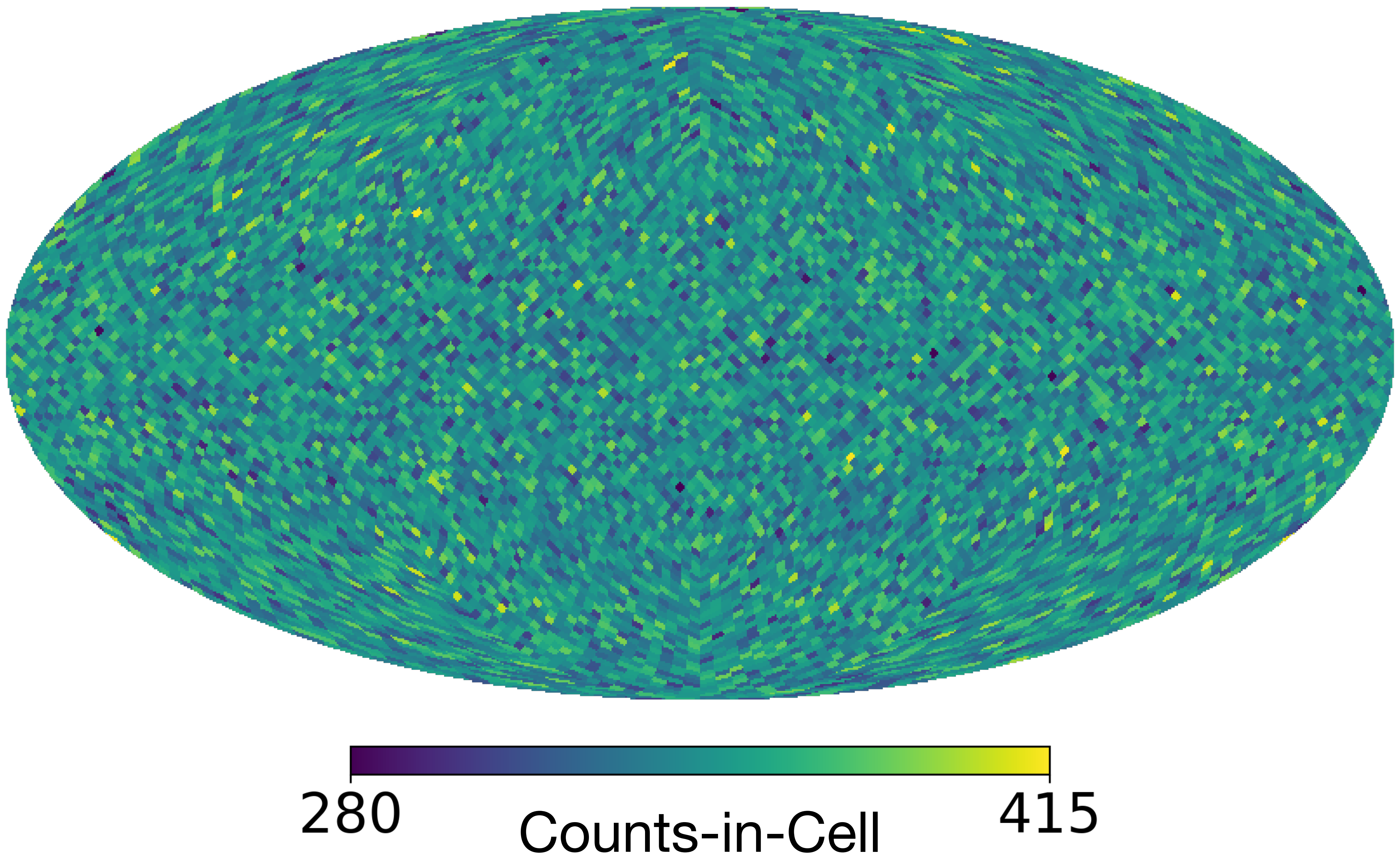
$$\frac{dN}{d\Omega}|_{\rm obs} = \frac{dN}{d\Omega}|_{\rm rest}(1 + d\cos\theta)$$

$$d_{exp} = (2 + x(1 + \alpha))\frac{v_{\rm CMB}}{c} \approx 0.5\times10^{-2}$$ [1]

Radio survey dependent

➢ 0.5% effect at max. and minimum

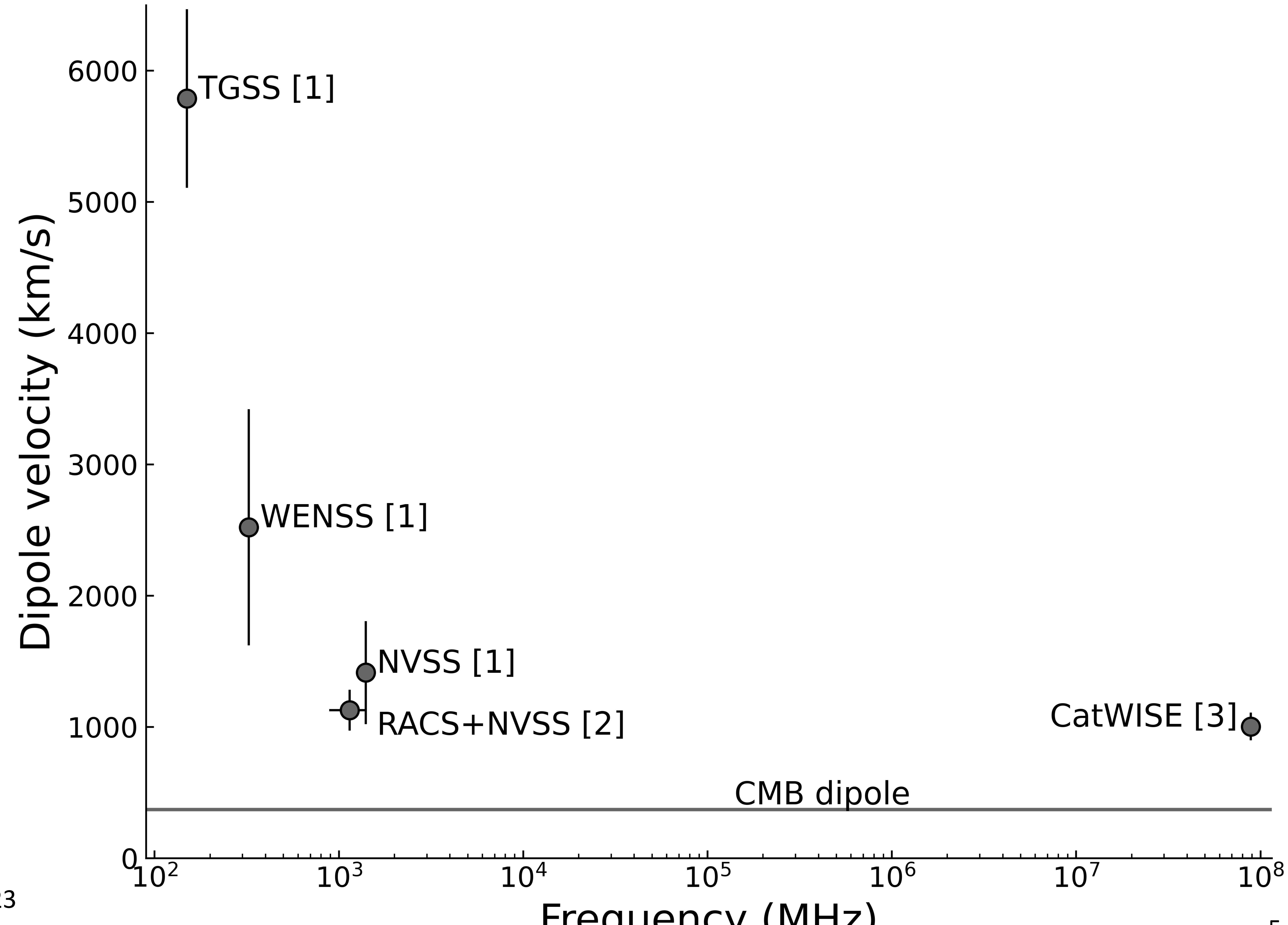
Simulated randoms with dipole signal




[1] Ellis and Baldwin, 1984

# Current measurements

- Open questions:
  - Frequency dependence?
  - Excess compared to CMB?





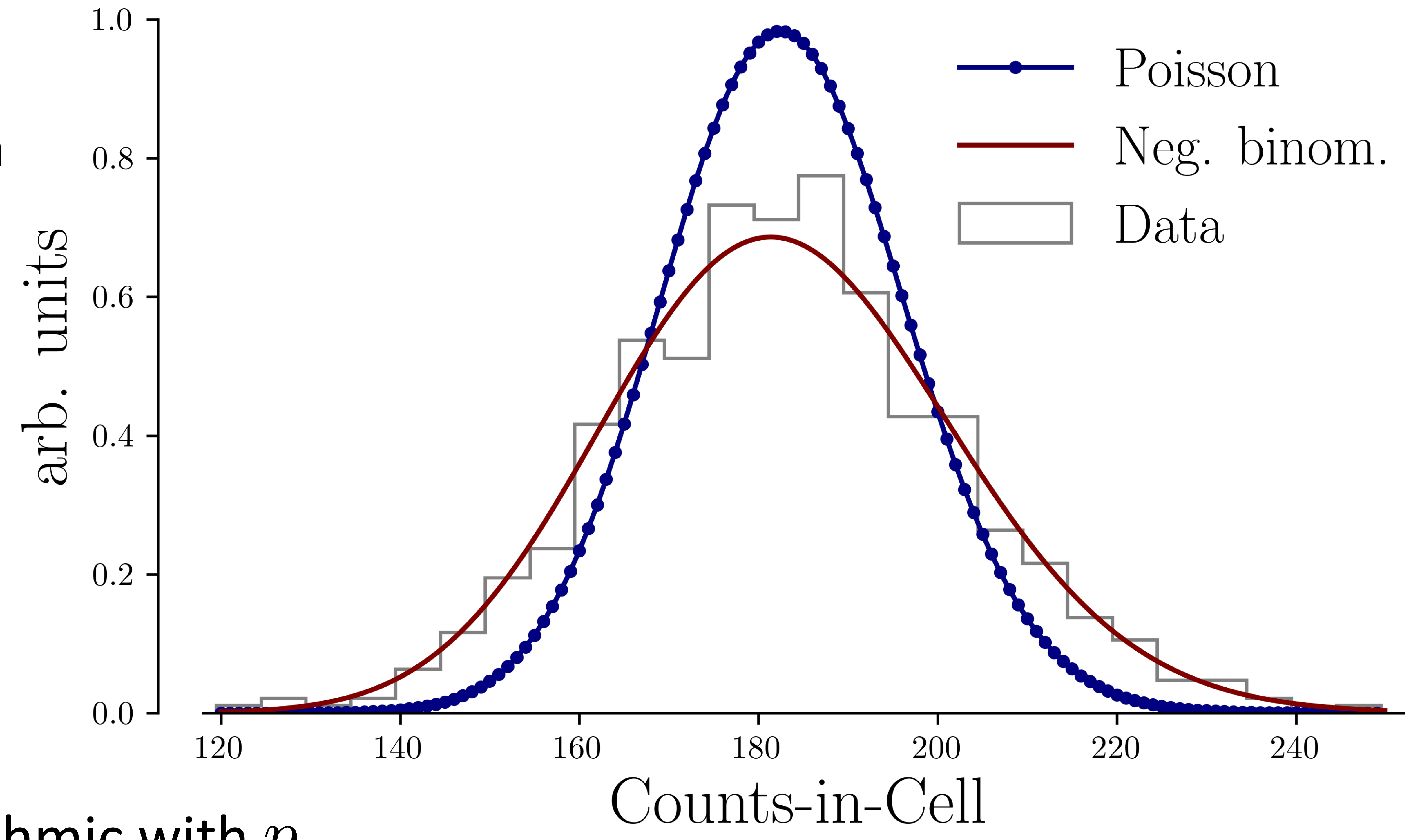
[1] Siewert et al. 2021
[2] Wagenveld et al. 2023
[3] Dam et al. 2023

# Negative binomial distr.

- Negative binomial distr. gives best description of data (prev. talk by Morteza)
- $N = \sum_{j=1}^{S} C_j$
  - $N$ – Count of radio sources in any cell
  - $S$ – Poisson distr. number of physical objects
  - $C_j$ – #of components of object $j$ in $S$, distr. logarithmic with $p$

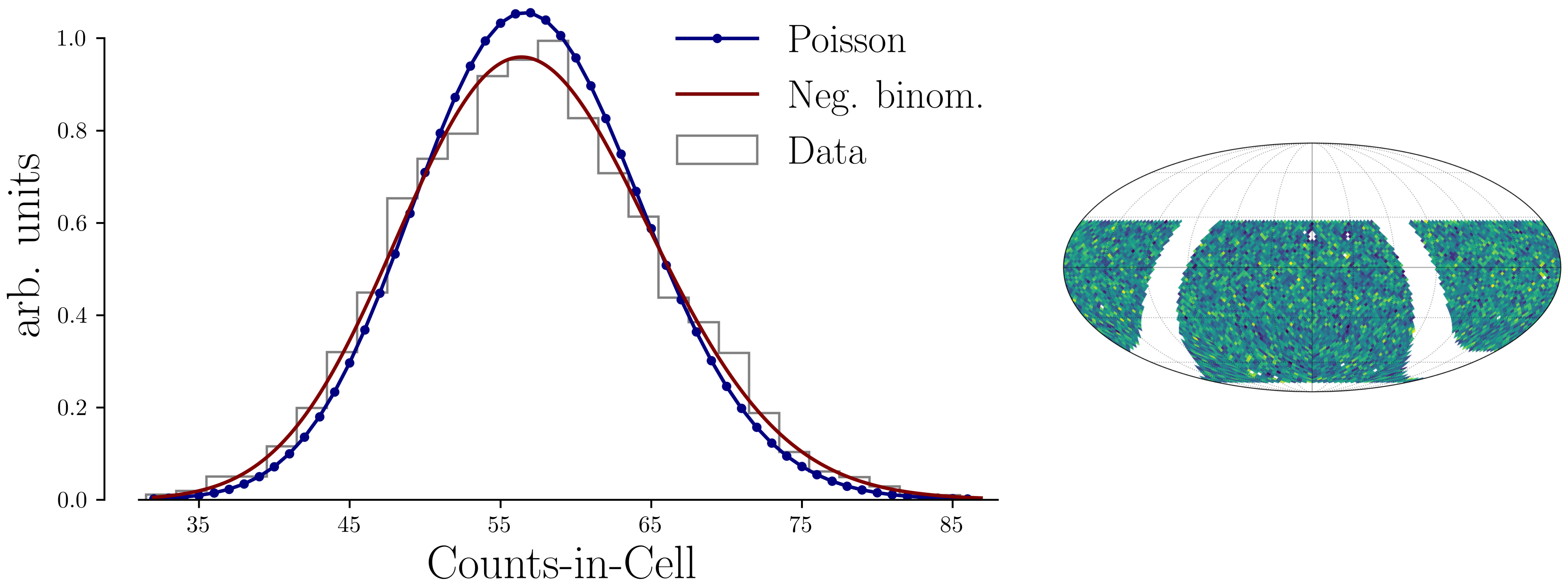
➡ $P_{\mathrm{NB}}(k) = \binom{k+r-1}{k} p^k (1-p)^r \qquad p = \frac{\lambda}{\sigma^2}, \;\; r = \frac{p\lambda}{1-p}$

LoTSS-DR2 ($S_{\mathrm{min}} = 10\mathrm{mJy}$, 144MHz)

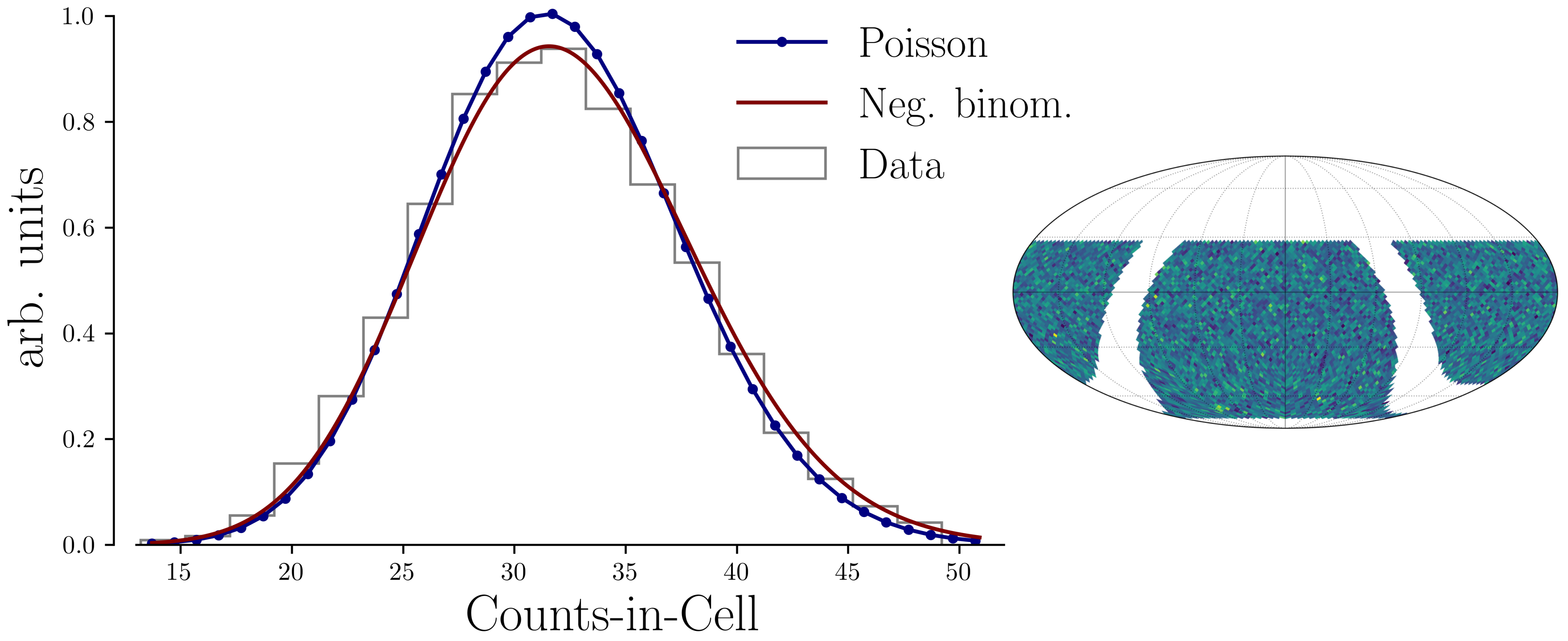


# Data used

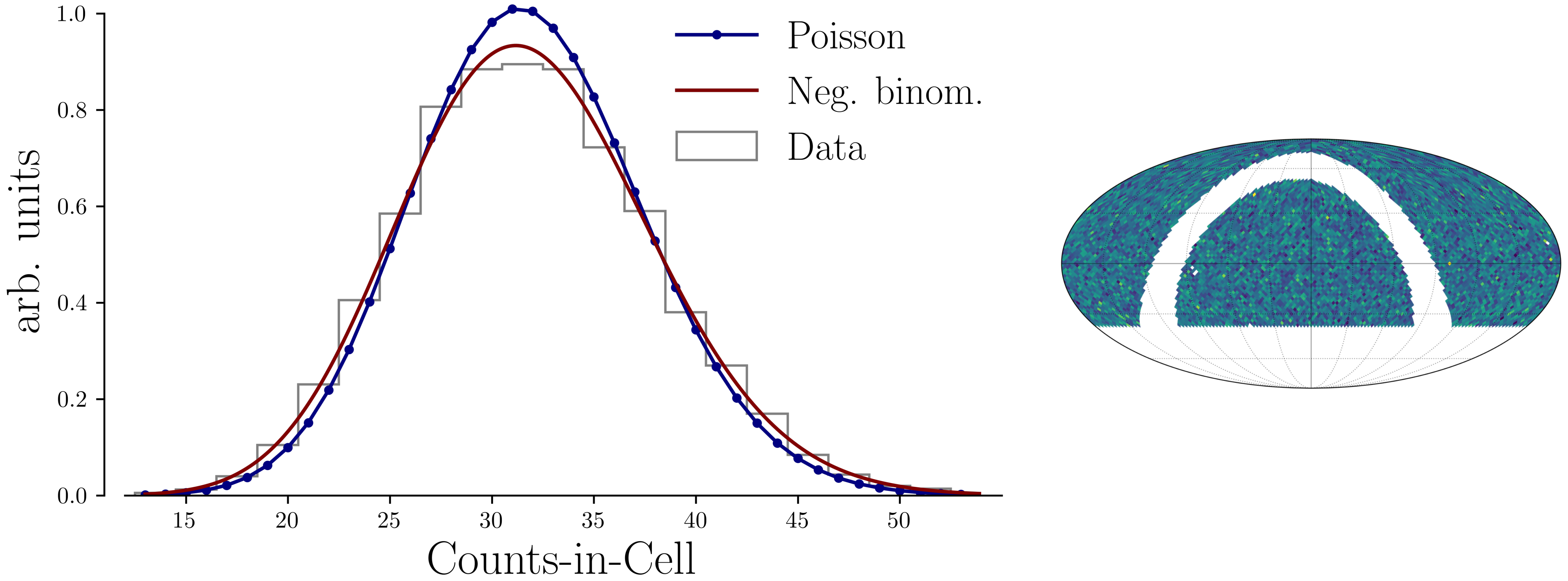
RACS-low ($S_{\rm min} = 15 {\rm mJy},\ 888 {\rm MHz}$)



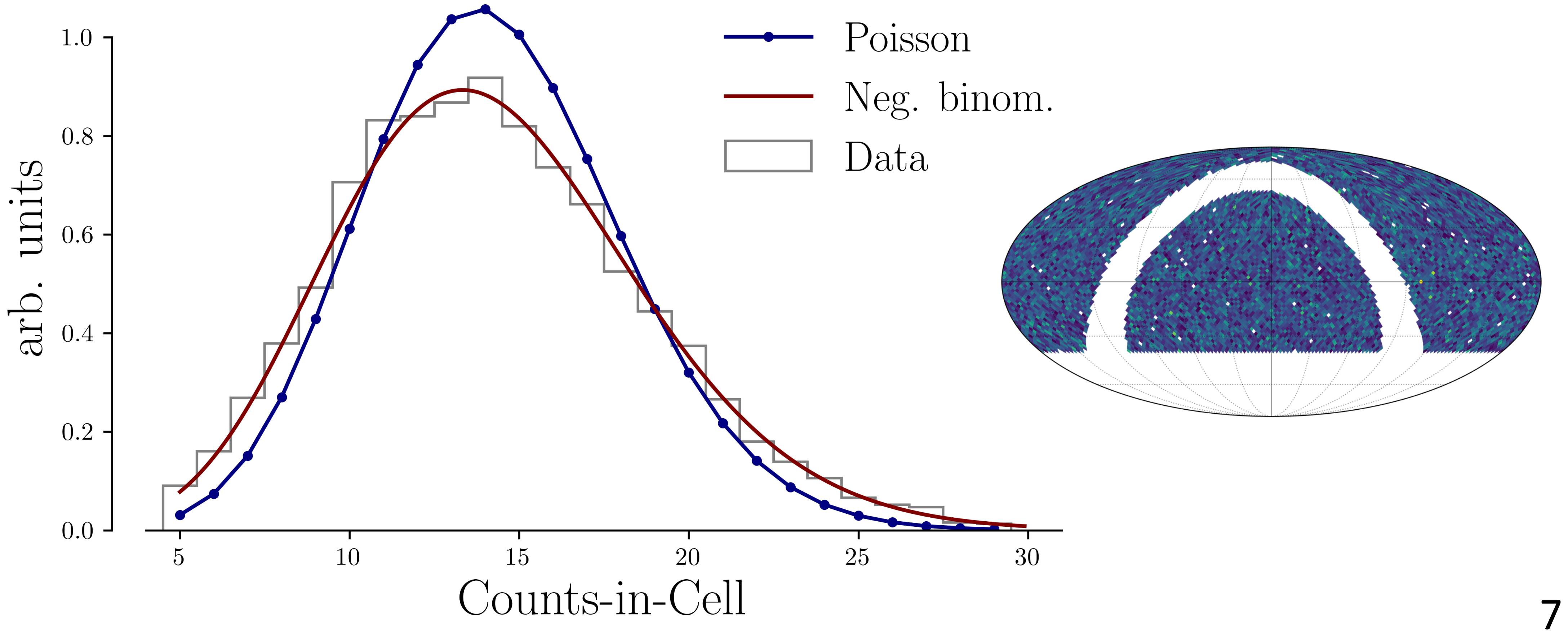

RACS-mid ($S_{\rm min} = 20 {\rm mJy},\ 1368 {\rm MHz}$)




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




VLASS ($S_{\rm min} = 20 {\rm mJy},\ 3000 {\rm MHz}$)



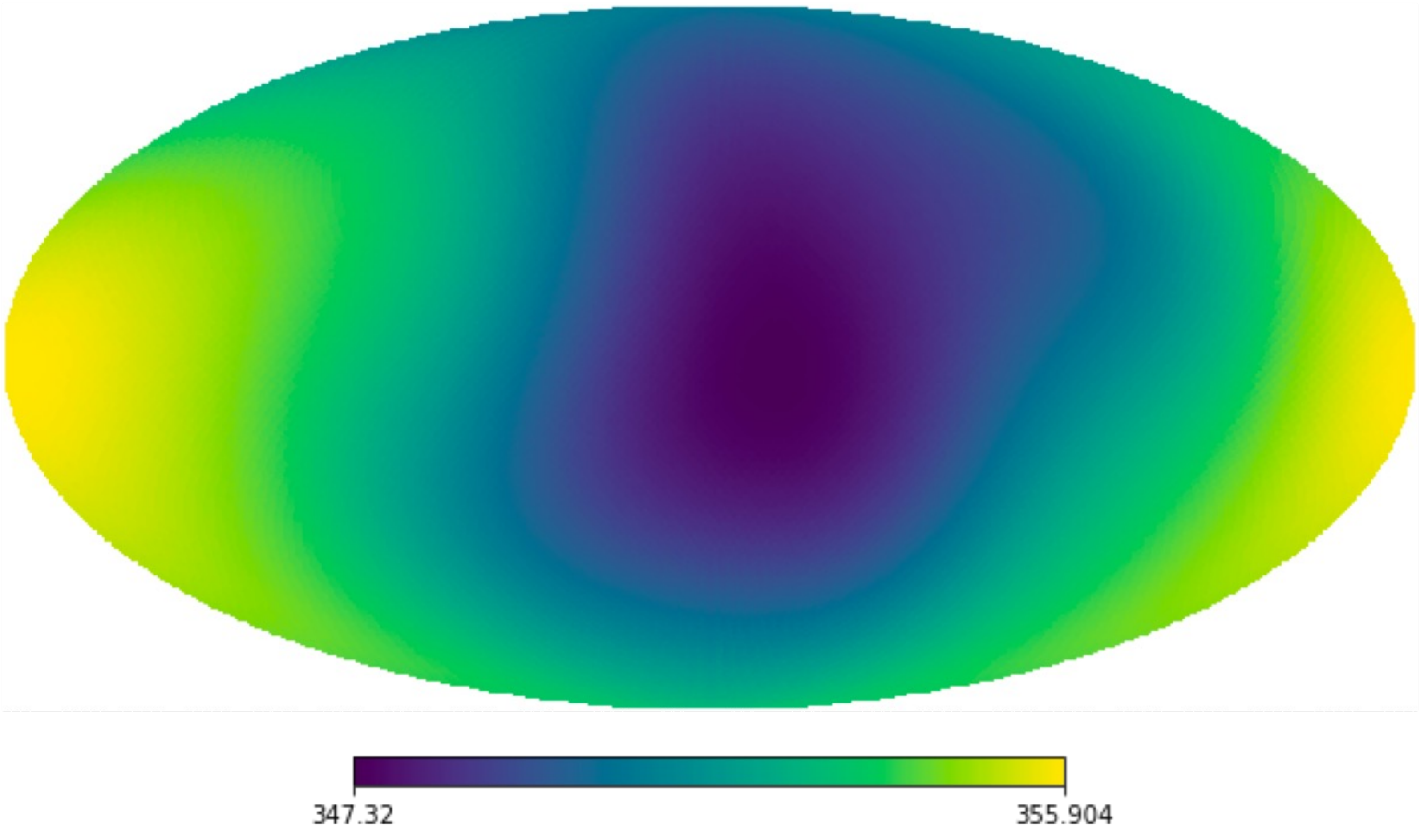
# Estimator for radio source counts

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

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

Dipole affects mean count

$$r(\mathbf{d}) = r(1 + d\cos\theta)$$




- Minimise the negative log-likelihood with Bilby [1,2]
  - Assume: CMB dipole direction (most studies confirm this)
- Multi-survey estimation:
  - Simply 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

# Dipole measurements from LoTSS-DR2 In CMB direction

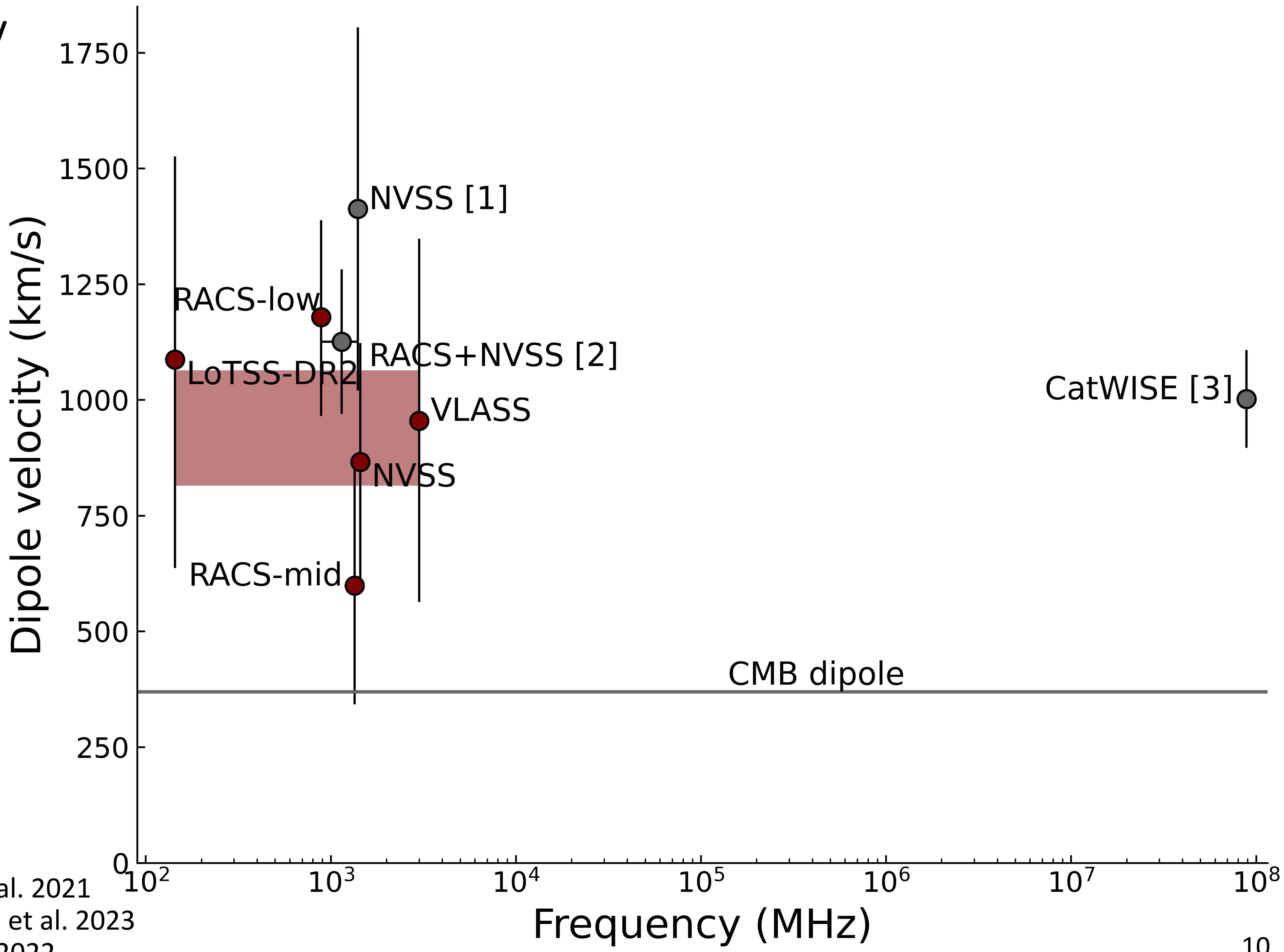
PRELIMINARY


| Survey | $v$ (km/s) |
|---|---|
| LoTSS-DR2 | $1087^{+439}_{-450}$ |
| RACS-low | $1179^{+209}_{-214}$ |
| RACS-mid | $599^{+267}_{-257}$ |
| NVSS | $866 \pm 257$ |
| VLASS | $955^{+393}_{-392}$ |
| Combined | $941^{+123}_{-126}$ |

# Conclusion, future prospects

- Individual surveys: weakly reject CMB, strongly reject TGSS, no frequency dependence
- Joint estimate raises significant tension with CMB
- Consistent with previous measurements

- Future large area sky surveys: LoTSS-DR3, LoLSS-DR2, RACS-high, RACS-low2, **SKA**
- Wide-field spectroscopic follow ups: WEAVE-LOFAR
- More thorough analysis of systematics





[1] Siewert et al. 2021
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[3] Dam et al. 2022