UNIVERSITÄT BIELEFELD
Faculty of Physics

LOFAR

Cosmology with the LOFAR Two-metre Sky Survey

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for the LOFAR Key Science Project Surveys — Cosmology Team

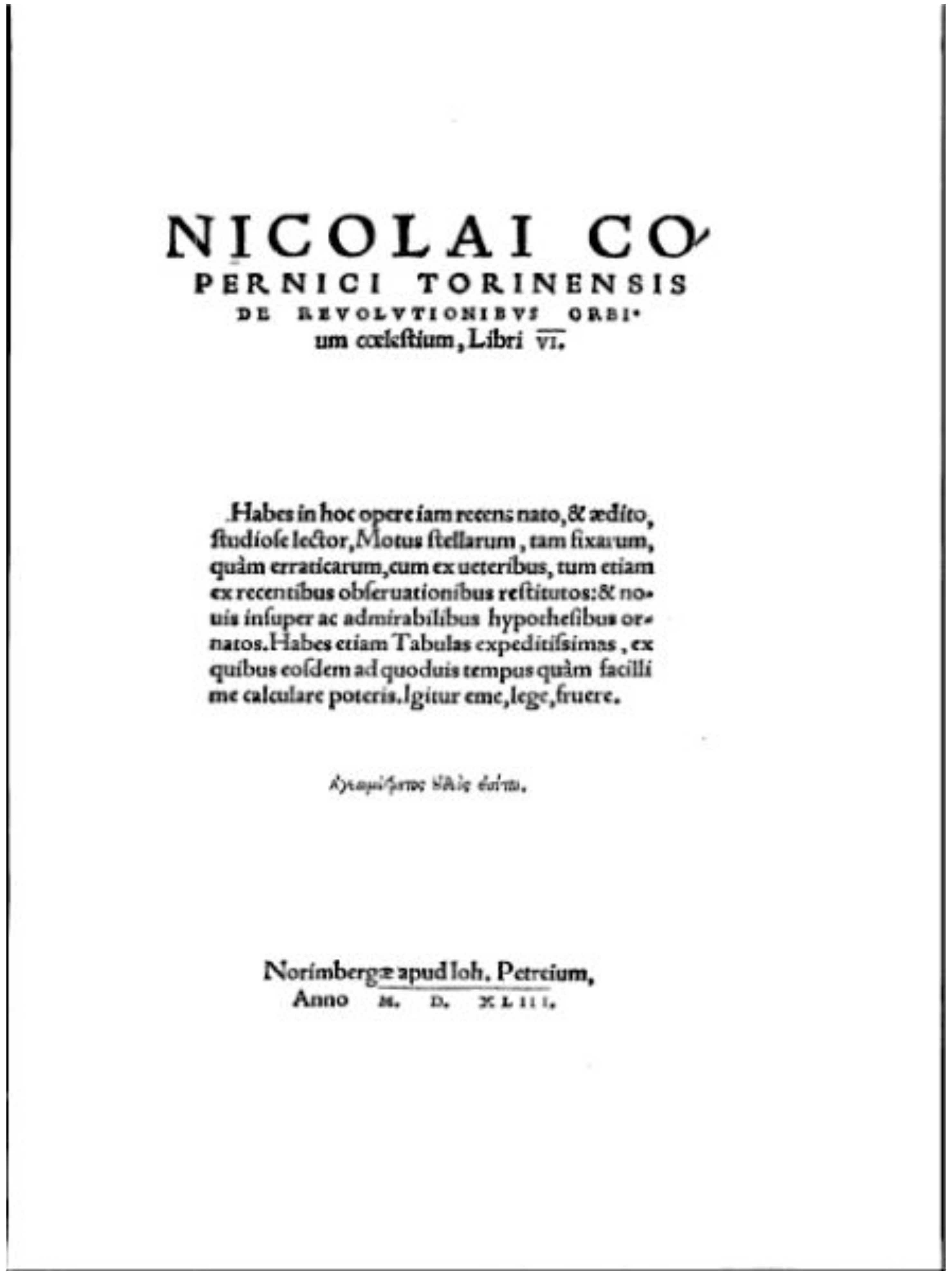
lofar-surveys.org

LFM 2023, Olsztyn

Copernican Principle,

the cosmological principle, and the fair sampling hypothesis

- „The centre of Earth is not the centre of the world, but only of gravity and of the lunar orbit.“ Copernicus
- **Cosmological principle:** Einstein, inspired by Mach
  spatially isotropic and homogeneous ⇒ ∃ cosmic time & rest frame
- **Copernican principle:** We are **typical observers** Bondi
- **LSS** as **stationary stochastic process — fair sampling** Neyman & Scott
- The **CMB is isotropic** (at 1 per cent level) Penzias & Wilson
  Dipole O(10^{-3}) from proper motion Stewart & Sciama, Peebles & Wilkinson
- Isotropy and Copernican principle ⇒ Cosmological principle
- LOFAR radio continuum surveys allow us to
  1. test nature of stochastic process underlying LSS and
  2. measure source count dipole to test cosmological principle



NICOLAI CO-
PERNICI TORINENSIS
DE REVOLVTIONIBVS ORBI-
um cœlestium, Libri VI.

Habes in hoc opere iam recens nato, & ædito, studiose lector, Motus stellarum, tam fixarum, quàm erraticarum, cum ex ueteribus, tum etiam ex recentibus obseruationibus restitutos: & nouis insuper ac admirabilibus hypothesibus ornatos. Habes etiam Tabulas expeditissimas, ex quibus eosdem ad quoduis tempus quàm facillime calculare poteris. Igitur eme, lege, fruere.

Ἀγεωμέτρητος οὐδεὶς εἰσίτω.

Norimbergæ apud Ioh. Petreium,
Anno M. D. XLIII.

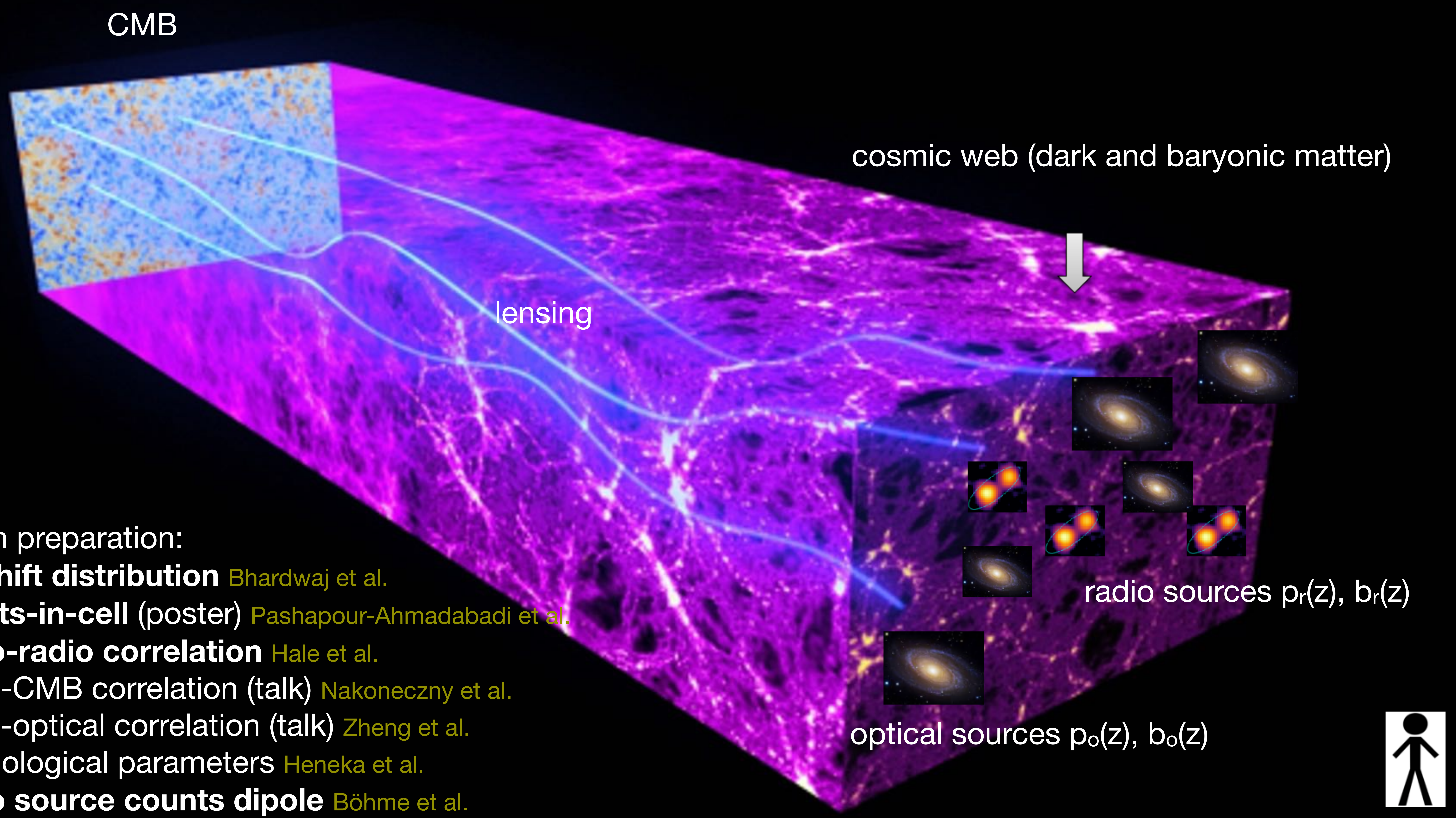
Radio Cosmology

Questions

- Characterise stochastic process of **cosmic large scale structure**
  Motivation: Is the sample fair (complete, etc.)? Are radio sources drawn from a Poisson process?
  Probe: **Counts-in-cells** (LoTSS-DR1: Siewert et al. 2020)

- Constrain **cosmological parameters**
  Motivation: Several tensions in cosmology: H_0, S_8/σ_8, curvature, …
  No evidence for non-Gaussianity so far: two-point statistics
  Probe: **Auto- and cross-correlations at small angles**
  (LoTSS-DR1: Siewert et al. 2020, Alonso et al. 2021, Tiwari et al. 2022)

- Does the **rest-frame of matter** agree with the CMB frame?
  Motivation: Excess of radio source and quasar count dipoles (Secreste et al. 2022, Wagenveld et al. 2023)
  Frequency dependence of radio source count dipole? (Siewert et al. 2021)
  Challenge to the Cosmological Principle (for recent summary see e.g. Peebles 2022)
  Probe: **Dipole in radio source counts**



Works in preparation:

- **Redshift distribution** Bhardwaj et al.
- **Counts-in-cell** (poster) Pashapour-Ahmadabadi et al.
- **Radio-radio correlation** Hale et al.
- Radio-CMB correlation (talk) Nakoneczny et al.
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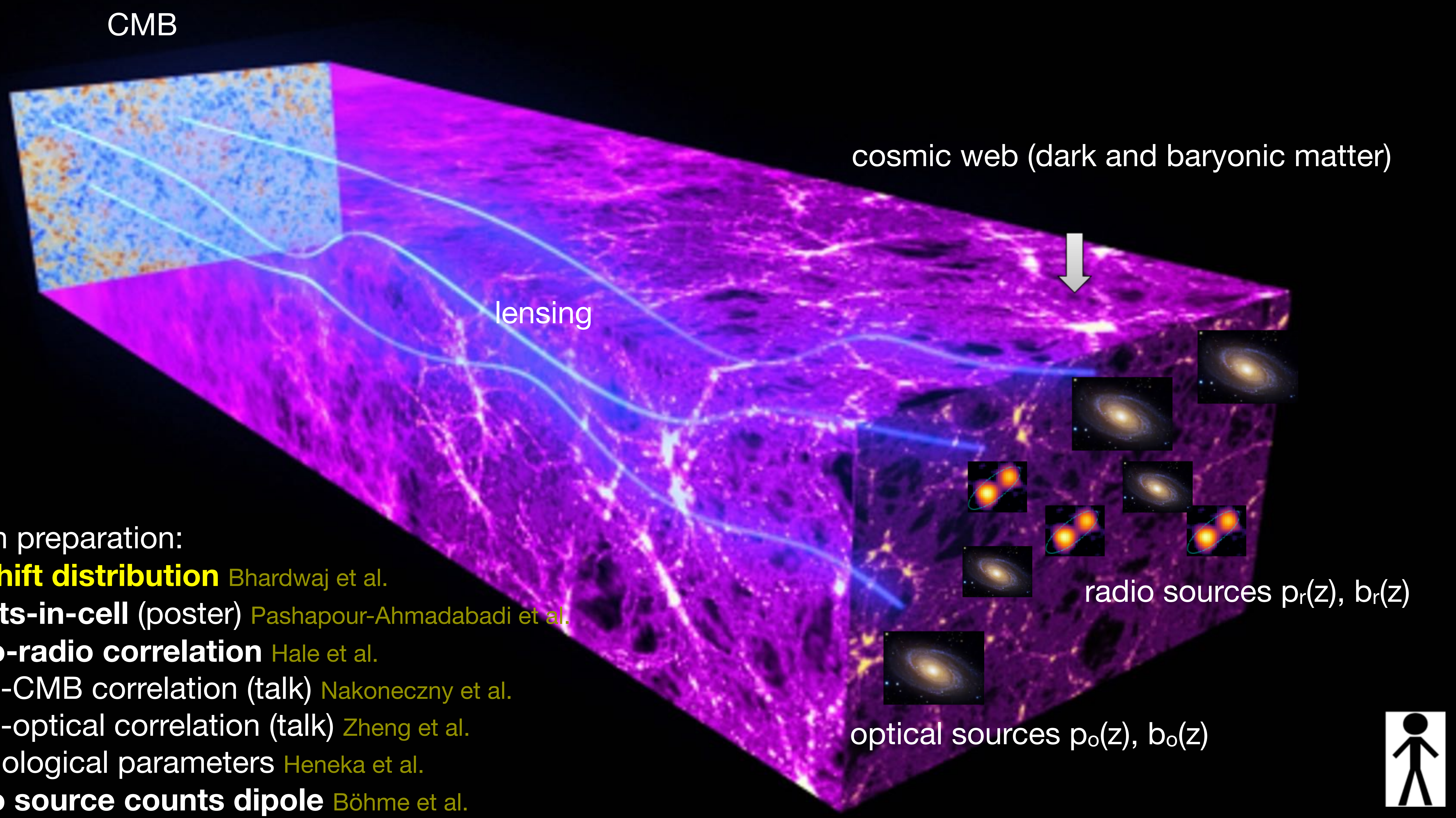
- **Radio source counts dipole** Böhme et al.

Credit: ESA and Planck Collaboration



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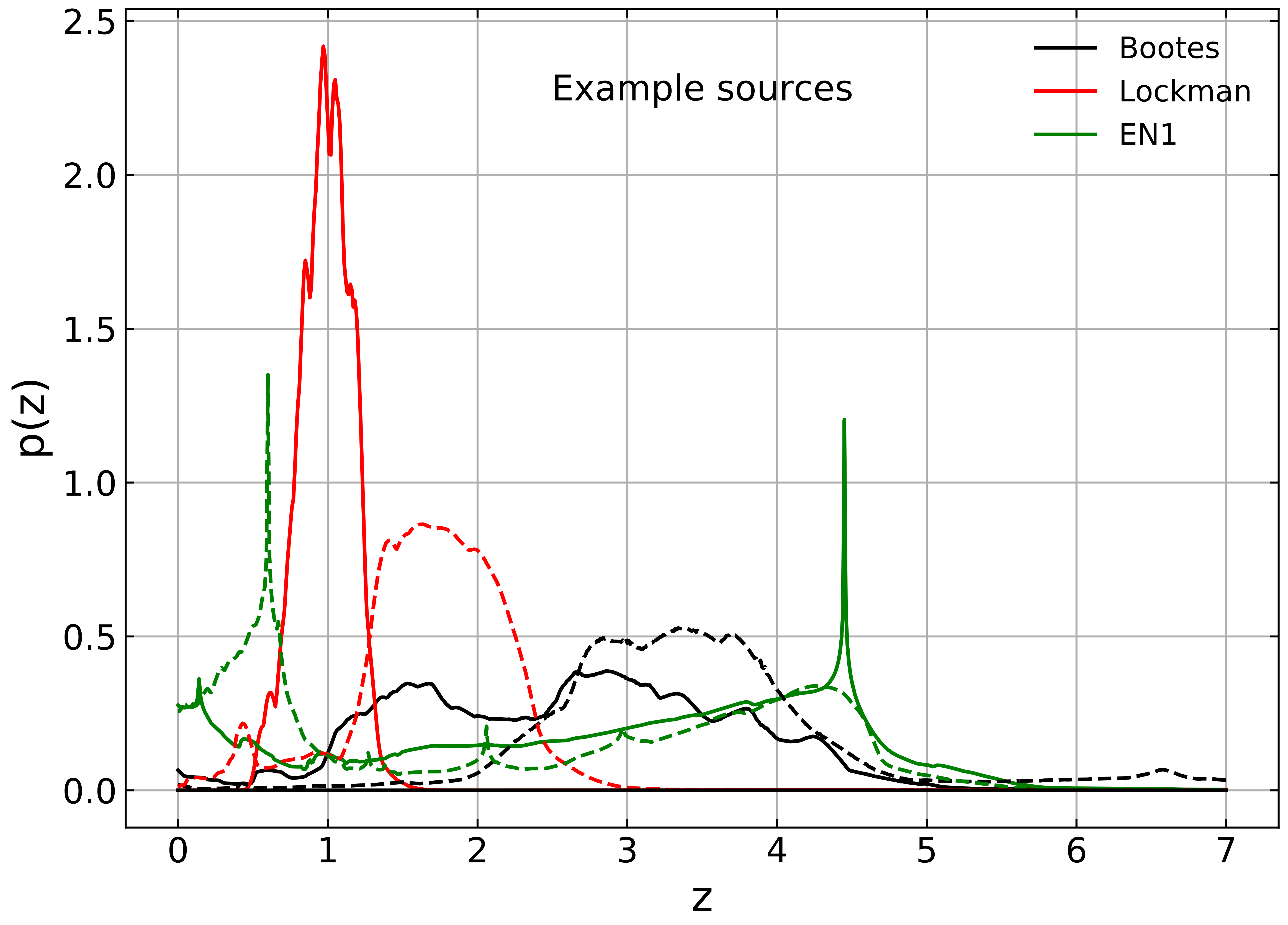
Credit: ESA and Planck Collaboration

Photometric redshifts from LoTSS Deep Fields

Some examples for posteriors of photometric redshifts

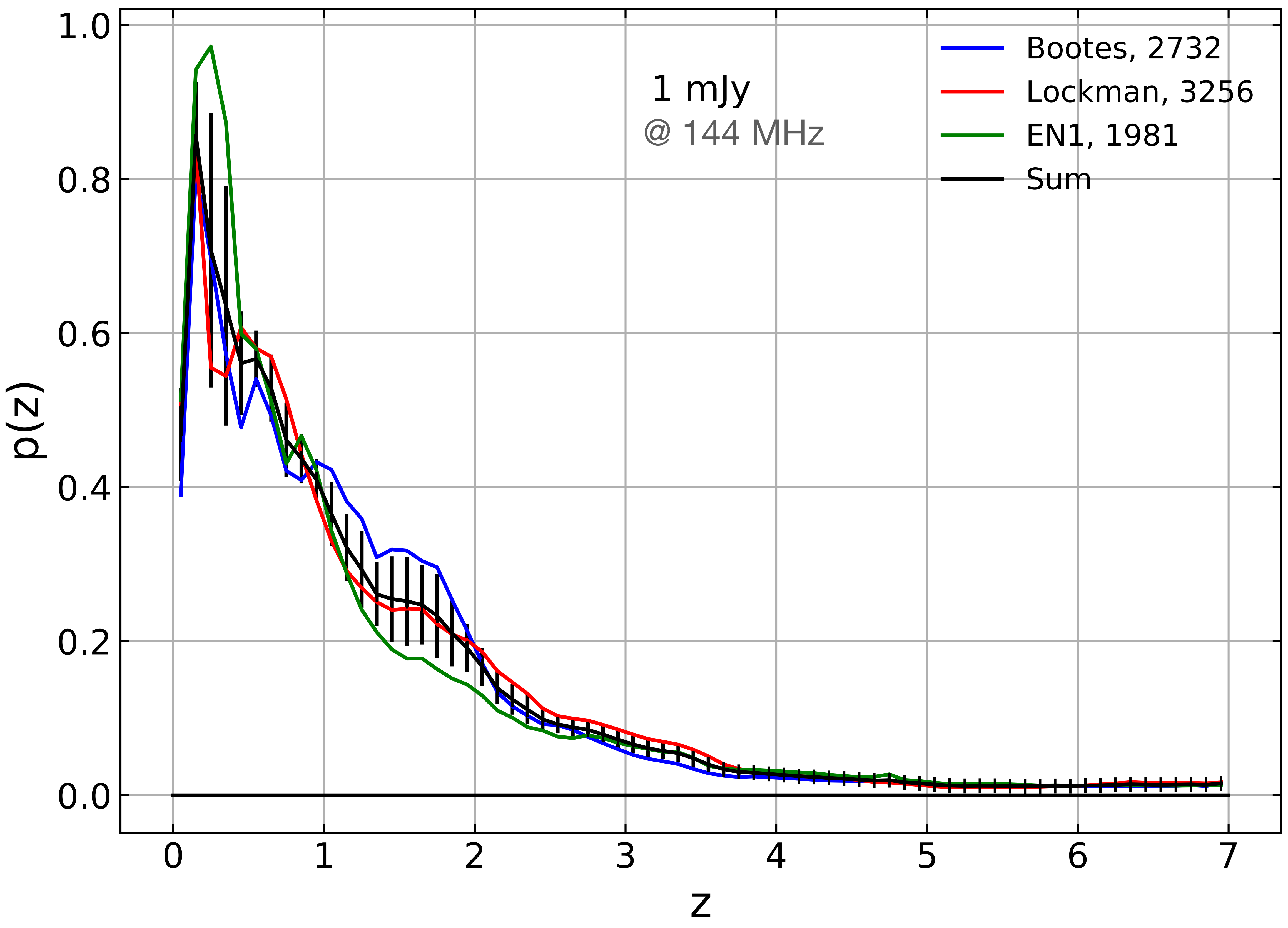
- Value added catalogue provides z_{best}, estimates for the 80% credibility intervals of the first and second mode of the posterior photo-z estimate
  Duncan et al 2021
- z_{best} histogram does not properly reflect information contained in posterior
- Our approach: stack all *posterior* p(z) for LoTSS Deep Field DR1 sources per field and combine them as a weighted sum. Use properly weighted bootstrap resampling to obtain error estimates

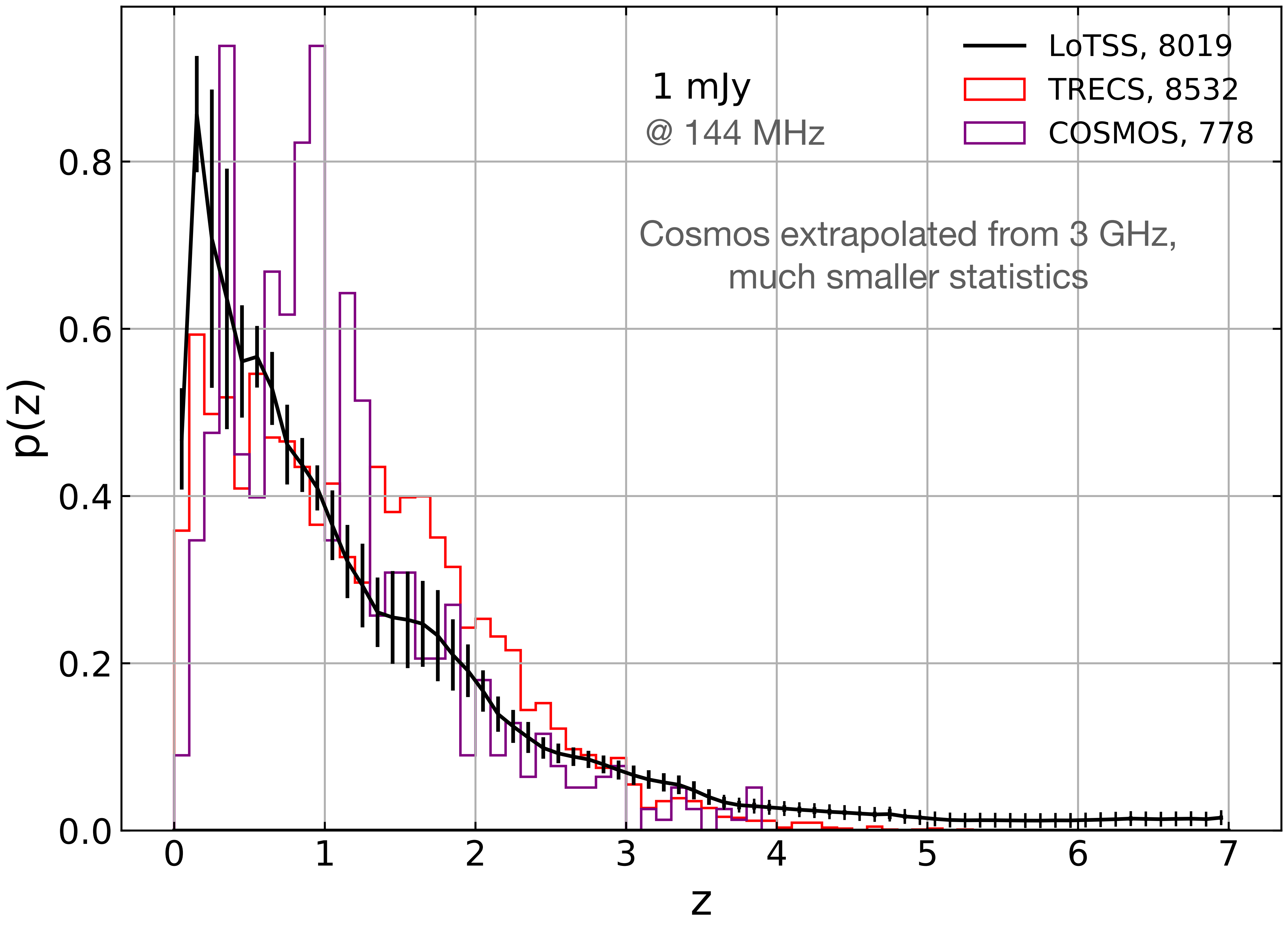


Bhardwaj et al. in preparation

Photometric redshifts from LoTSS Deep Fields

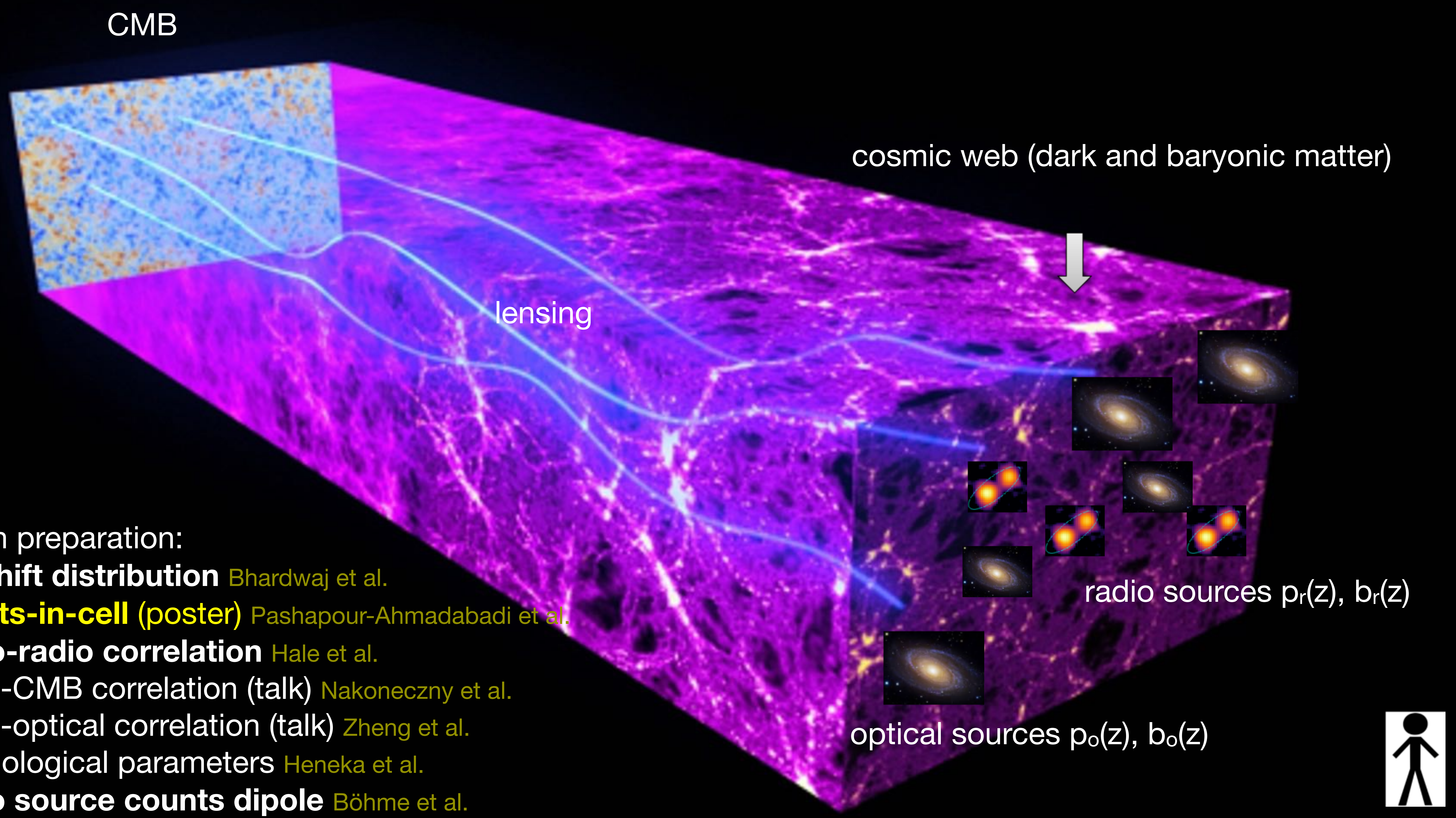
Crucial to estimate the distributions of redshifts





Bootstrap from posterior p(z) from Duncan et al. 2021
for all LoTSS Deep DR1 radio sources (misses 5% of redshifts)
Variation between fields due to **systematics in photometric redshifts** and **cosmic variance**

Bhardwaj et al. in preparation



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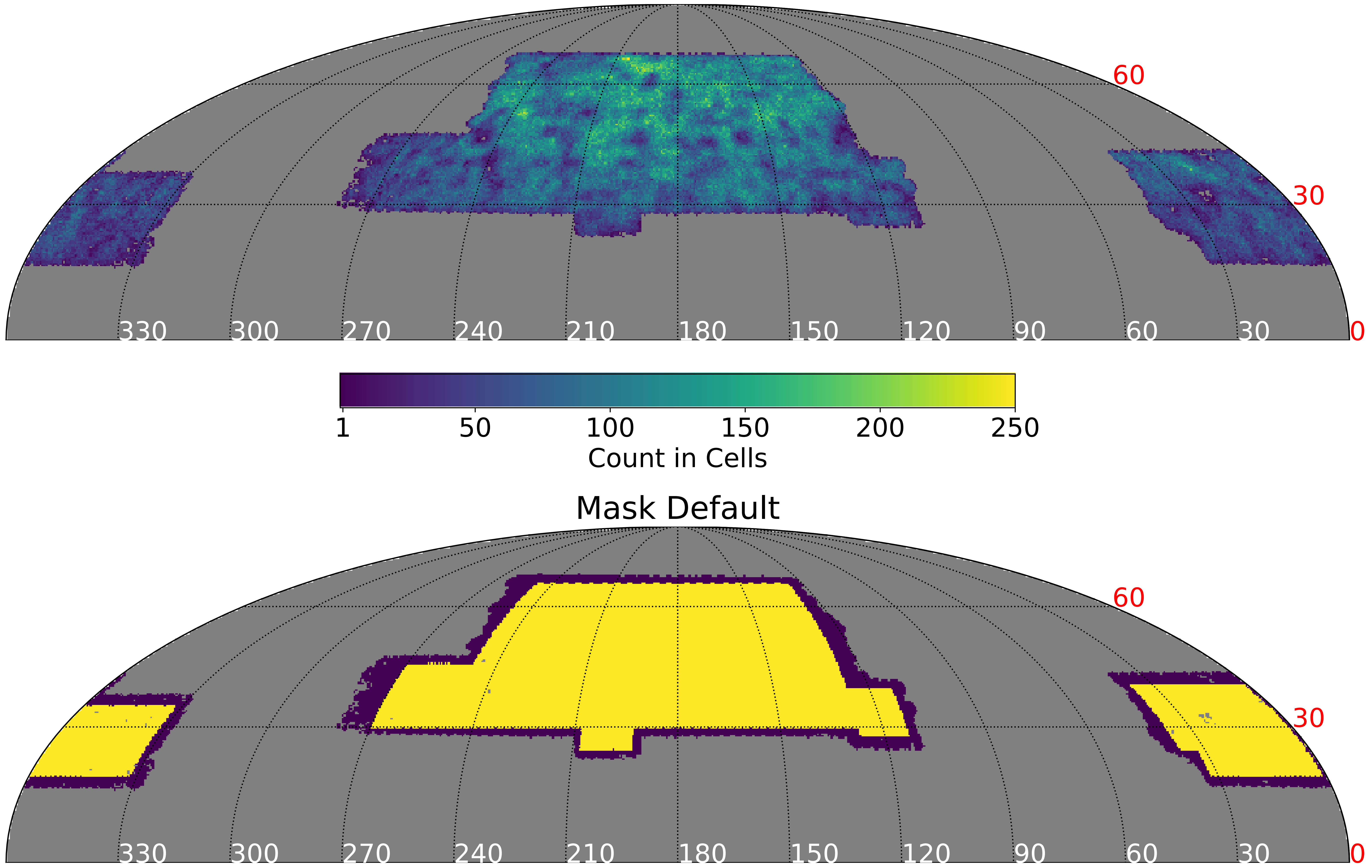
Counts-in-Cell

Sampling of radio sources is not homogeneous



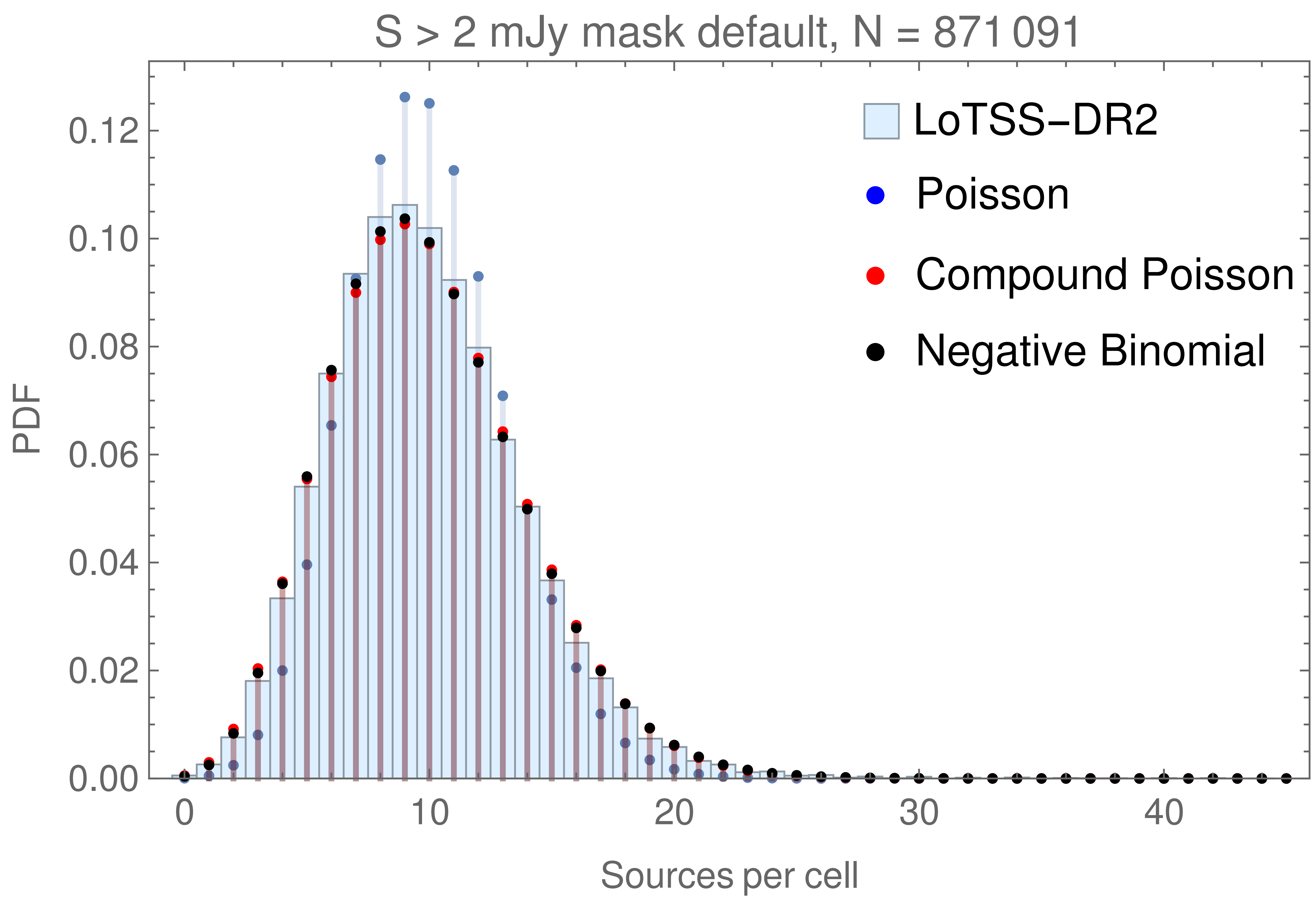
Sampling depends on
1. local rms noise,
2. distance from pointing centre,
3. number of pointings used in mosaic,
4. elevation of pointing

use spatial masks and flux density thresholds to ensure sample homogeneity

Pashapour-Ahmadabadi et al. in prep.

Counts-in-Cell

Radio sources follow a Cox process rather than a Poisson process



Pashapour-Ahmadabadi et al. in preparation;
See poster for more

Deviation from Poissonian distribution due to:

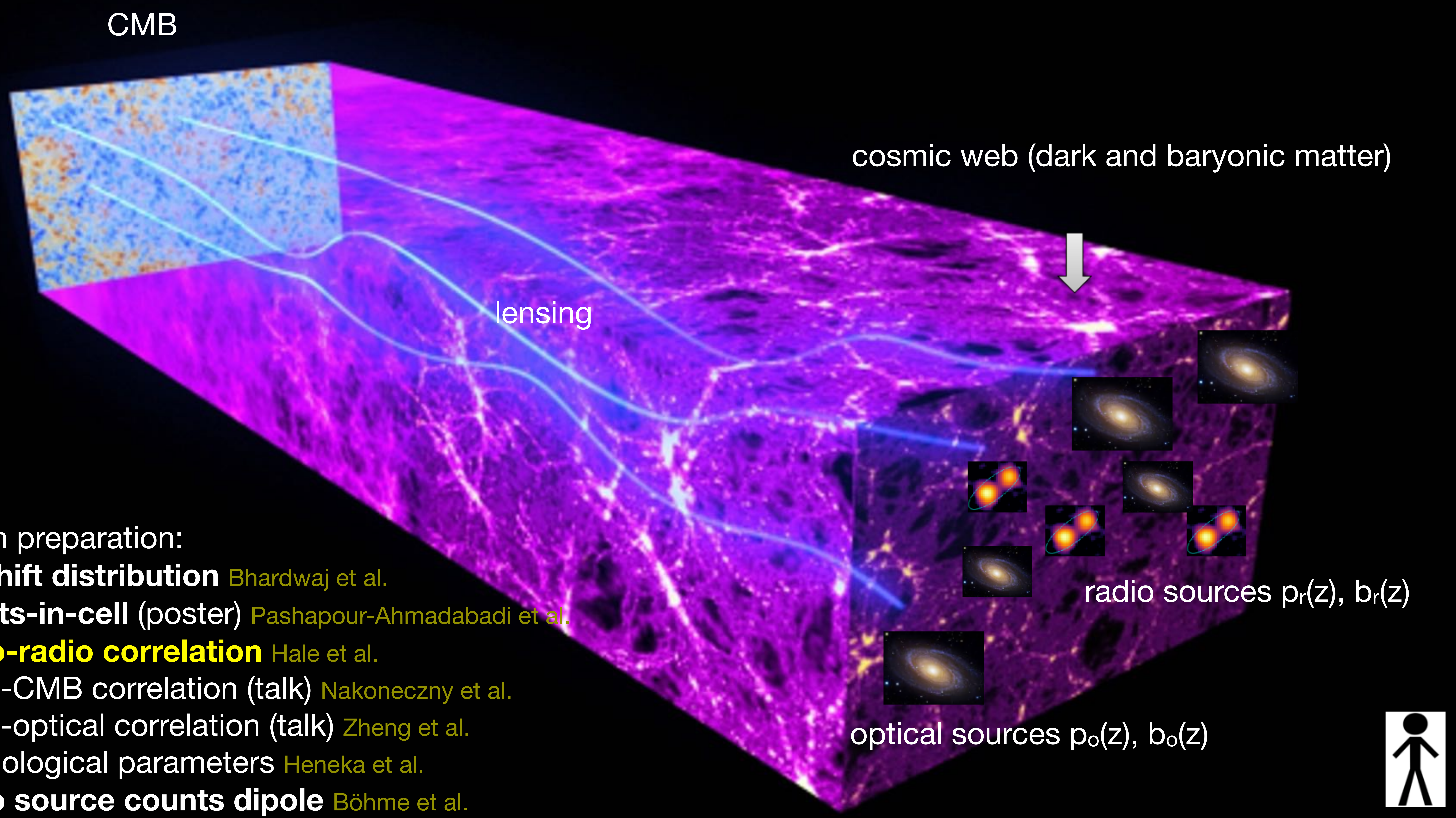
1. **Multicomponent sources** (e.g. FR II) and **artefacts** (violate statistical independence)

2. **Resolved sources** (violate point-like assumption of Poisson process)

3. Cosmic large scale structure

Negative binomial distribution describes counts of individuals across various species of plants and animals (Fisher, Corbet & Wilson 1943; Bliss & Fisher 1954).

Radio components = individuals
Radio sources (FRI, FRII, SFG, …) = species



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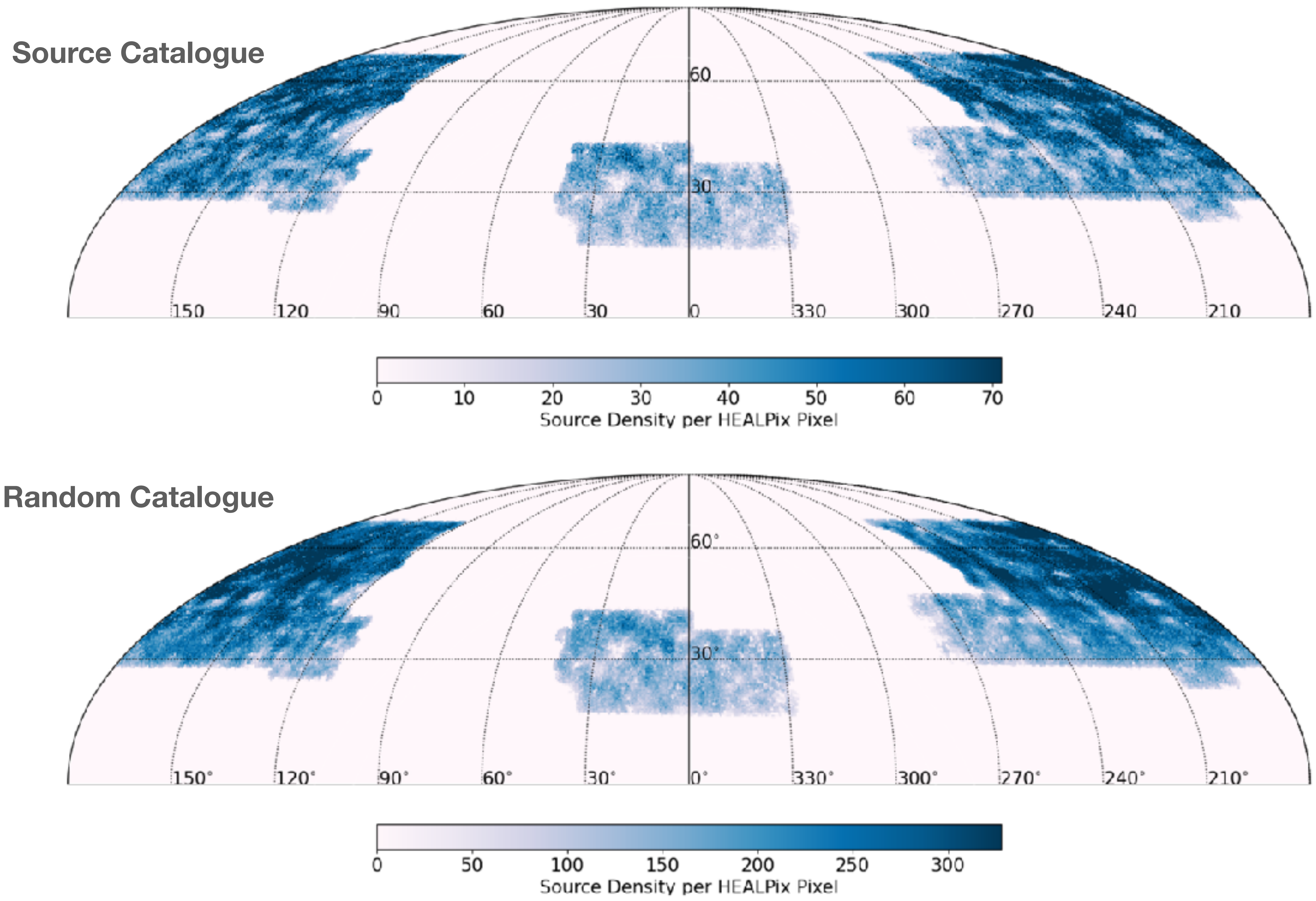
Credit: ESA and Planck Collaboration

Angular two-point correlation

Random Catalogue and estimator



Account for local rms noise, smearing dependent on distance from pointing centre, and elevation dependence of observations:

Apply spatial mask and use data and randoms at S > 1.5 mJy and SNR > 7.5

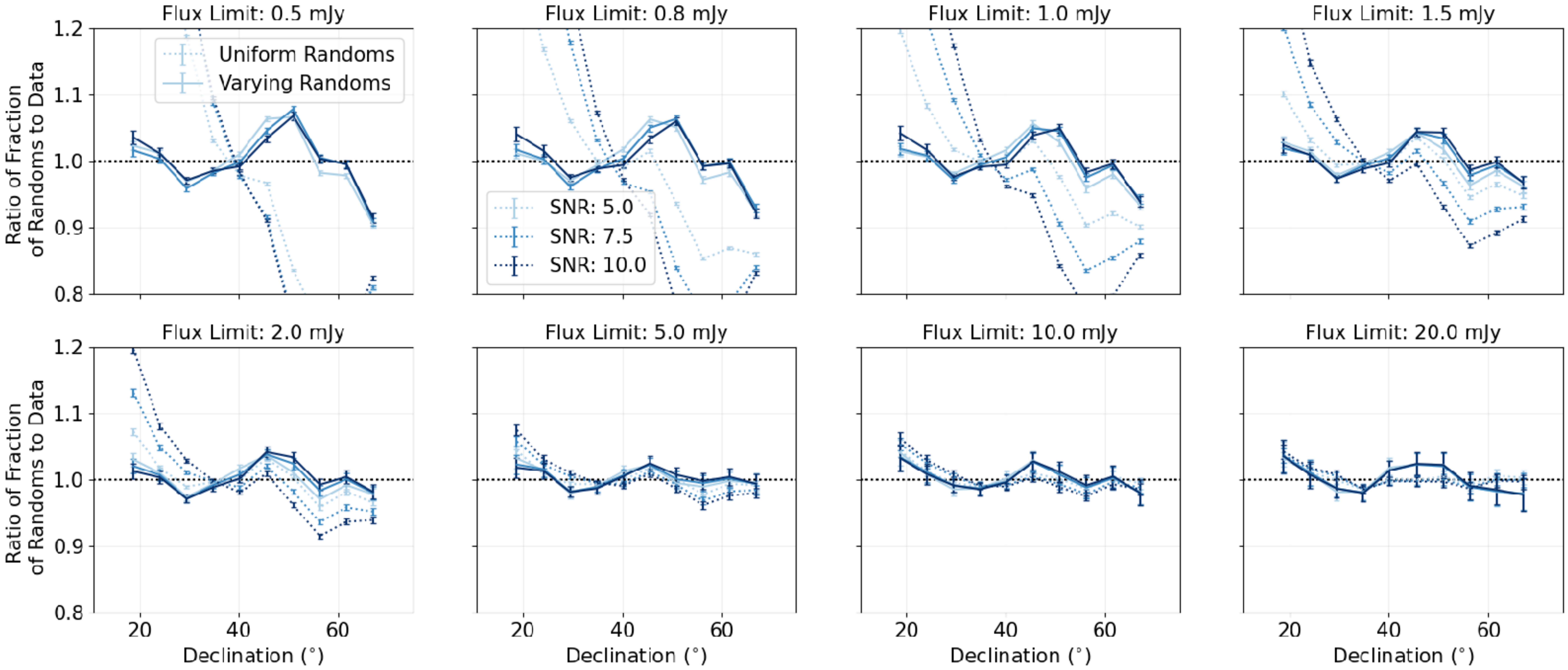
Use Landy-Szalay (optimal) estimator

$$\hat{\omega}(\theta) = \frac{DD - 2DR + RR}{RR}$$

Hale et al. in preparation

Preparation of Randoms Catalogue

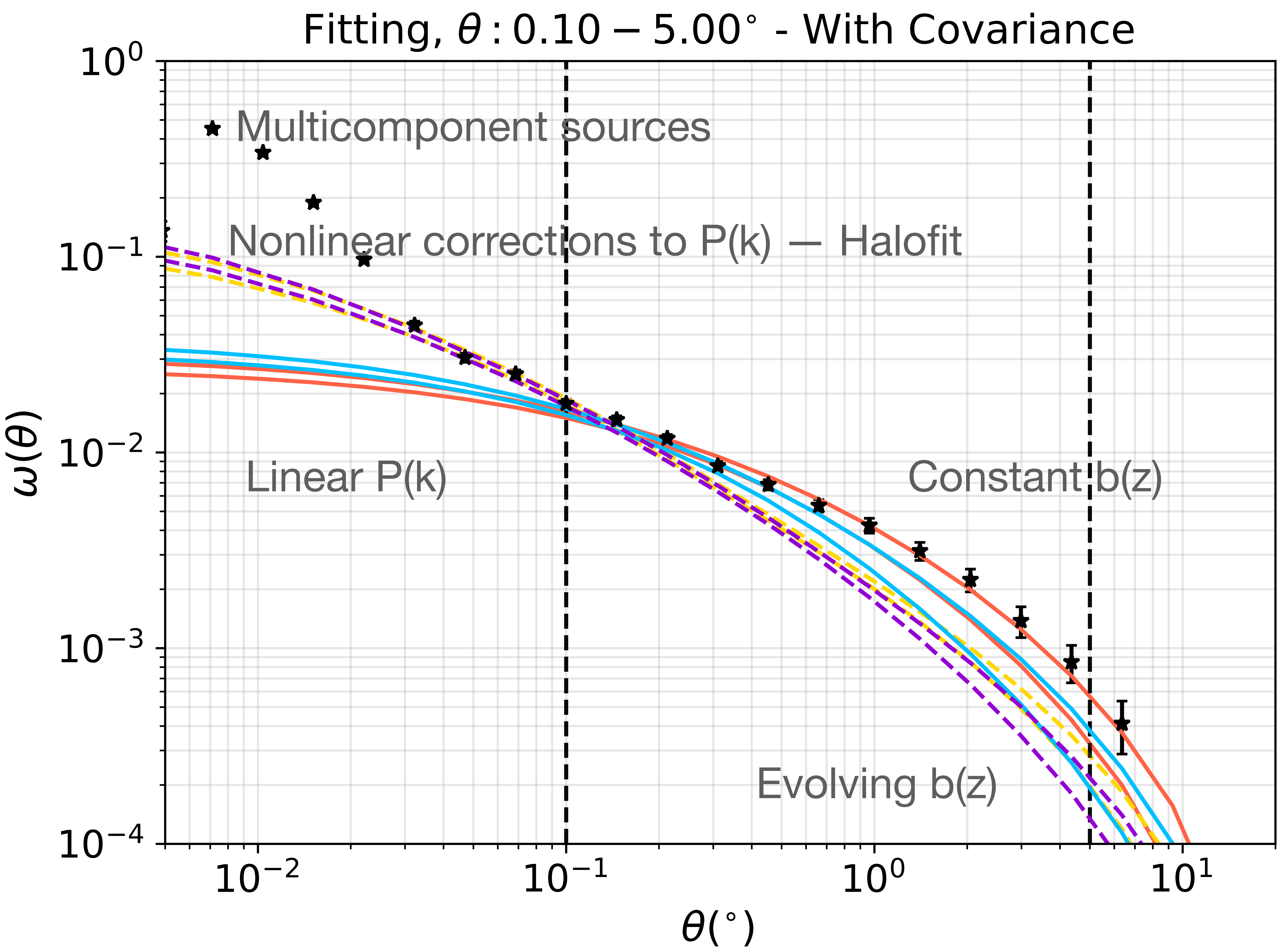
Account for instrumental and pipeline imperfections



Hale et al. in preparation

Angular two-point correlation

Evolving bias $b(z) = b_0/D(z)$ on top of linear/non-linear matter fluctuations



- Fit Planck best-fit LCDM model (fixed cosmology)
- Use LoTSS deep fields photo-z's
- **High-fidelity measurement of $\omega(\theta)$**
- Evolving bias (linear)

  $b(z=0) = 1.81^{+0.16}_{-0.13}$

  $b(z=0.9) = 2.86^{+0.25}_{-0.21}$
- **Sensitive to non-linear large-scale structure and multi-component sources at $\theta < 0.1\,\mathrm{deg}$**

Hale et al. in preparation

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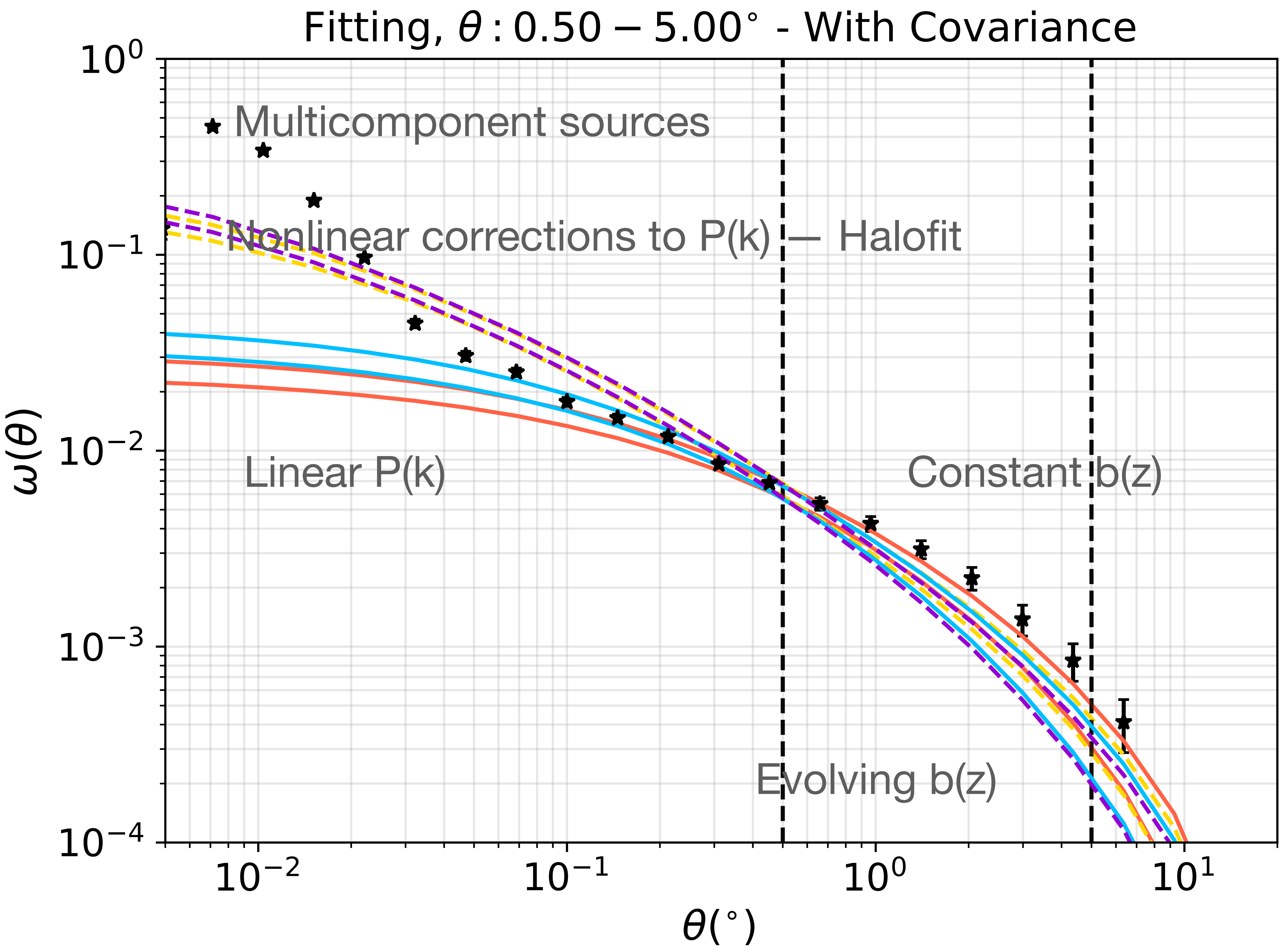

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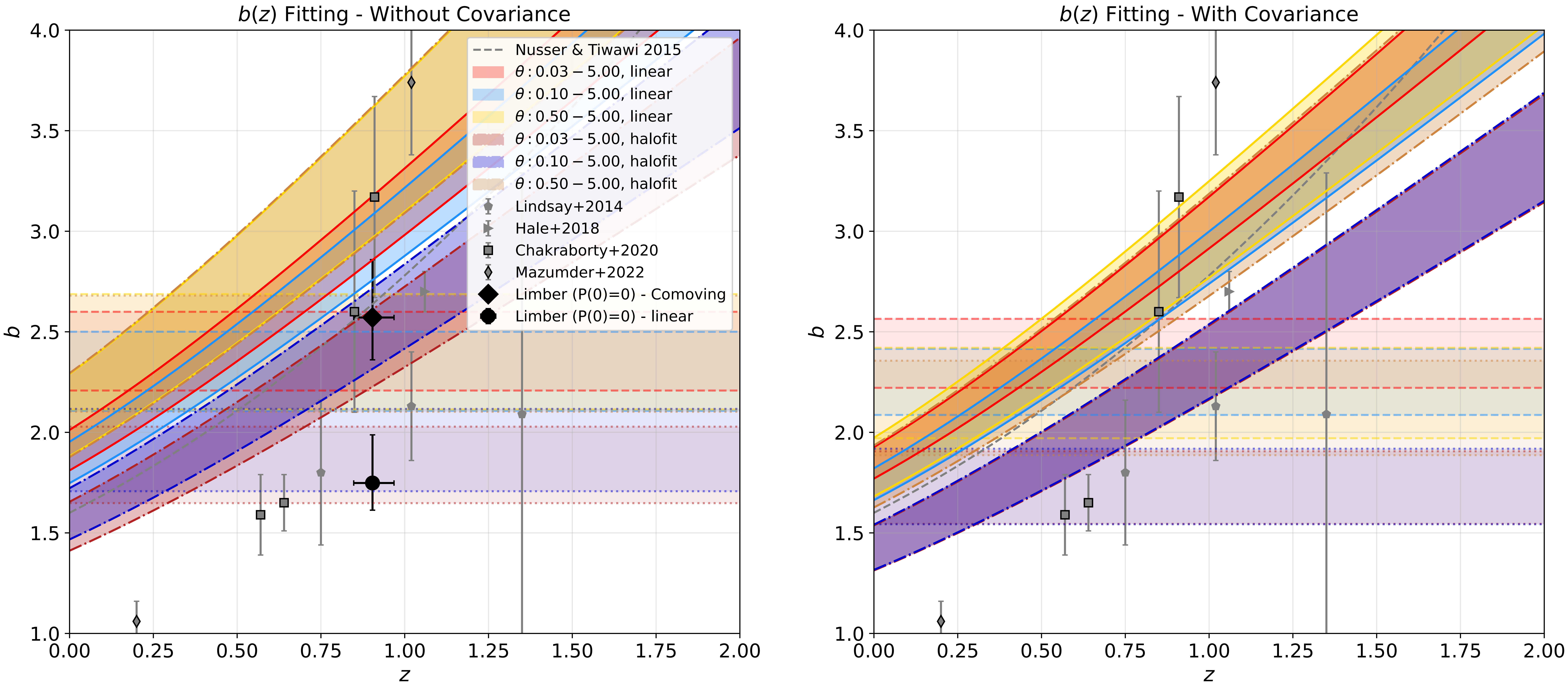
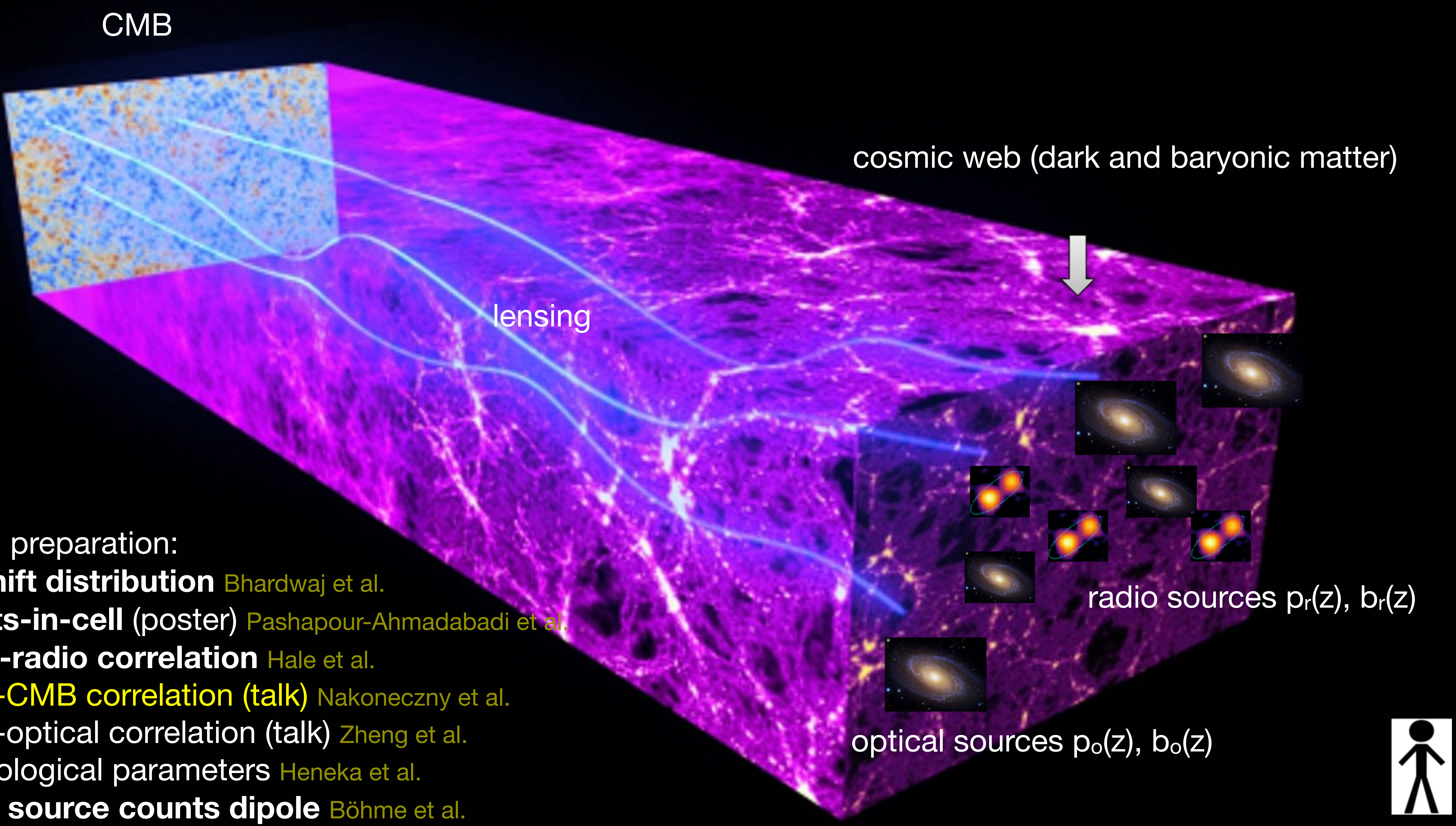
Hale et al. in preparation

Linear bias

Comparison of different measurements



Hale et al. in preparation



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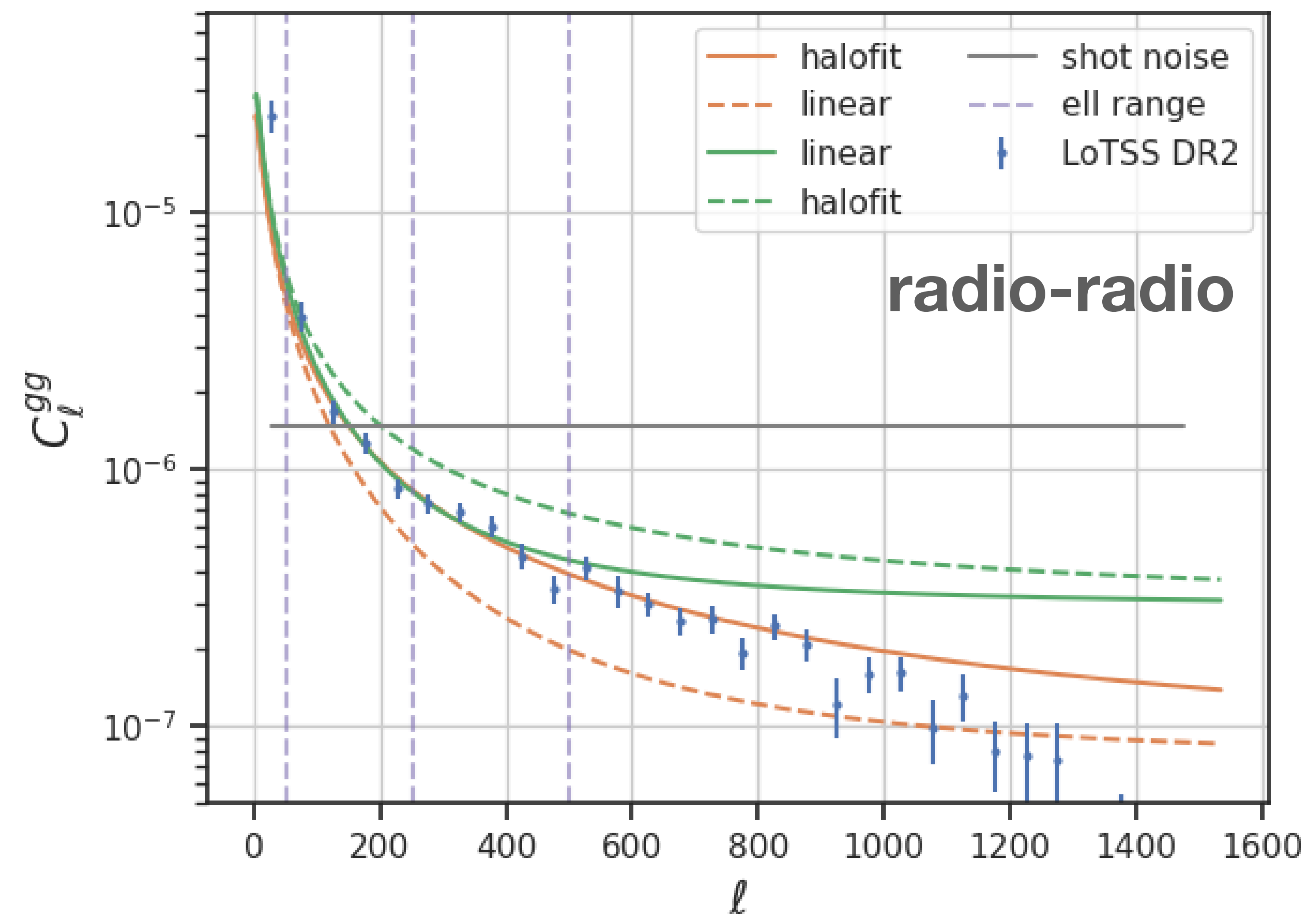
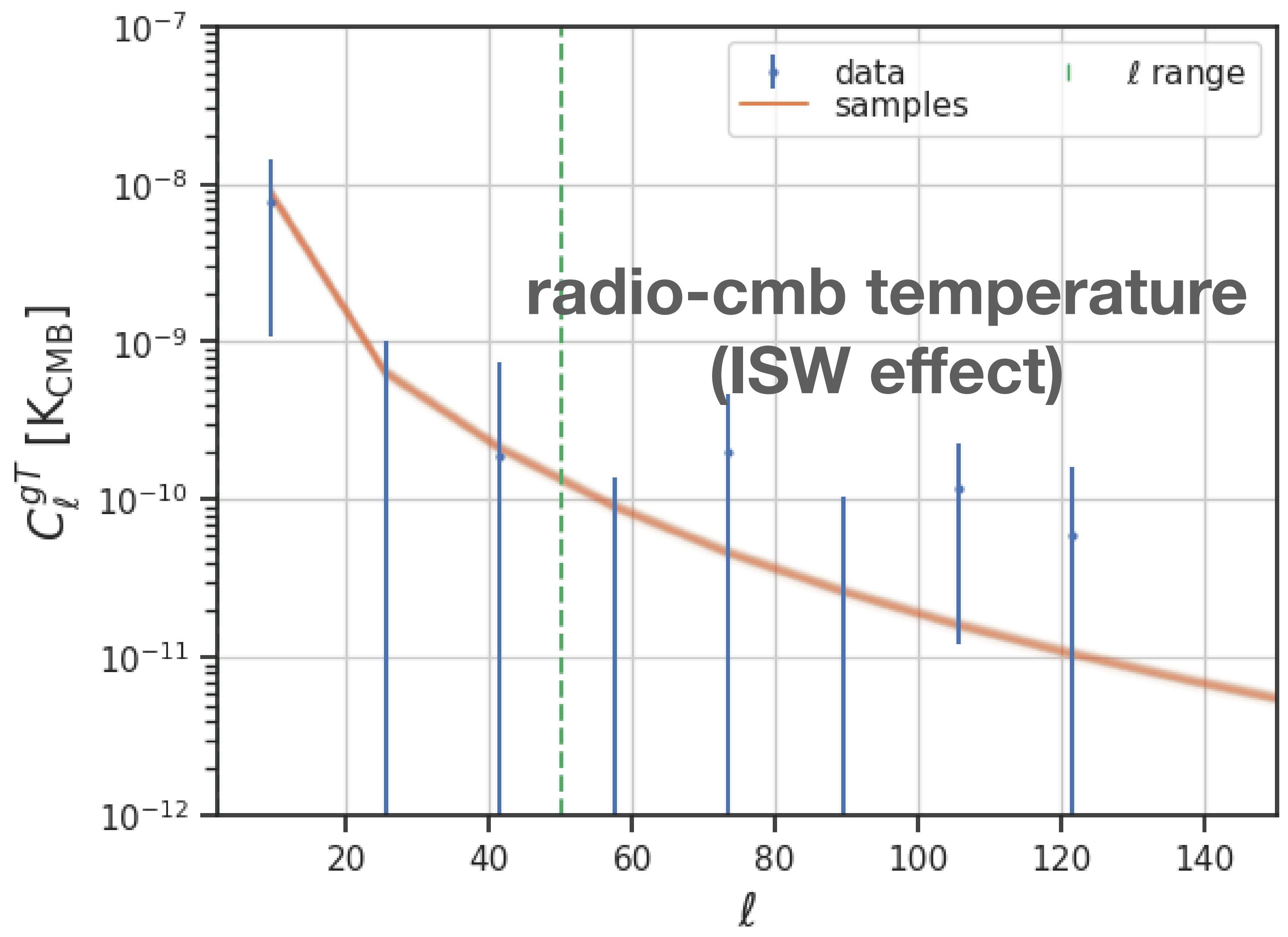
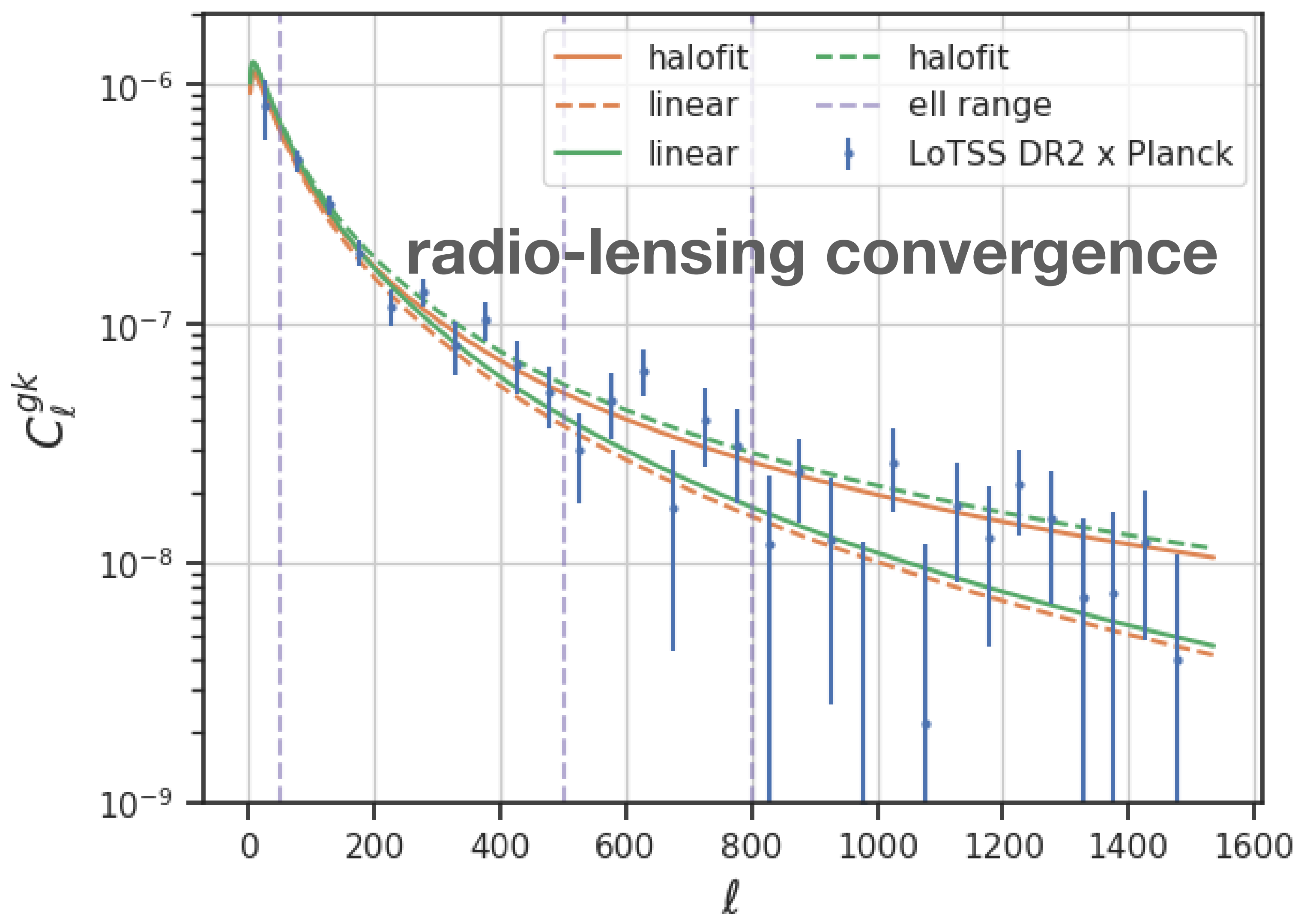
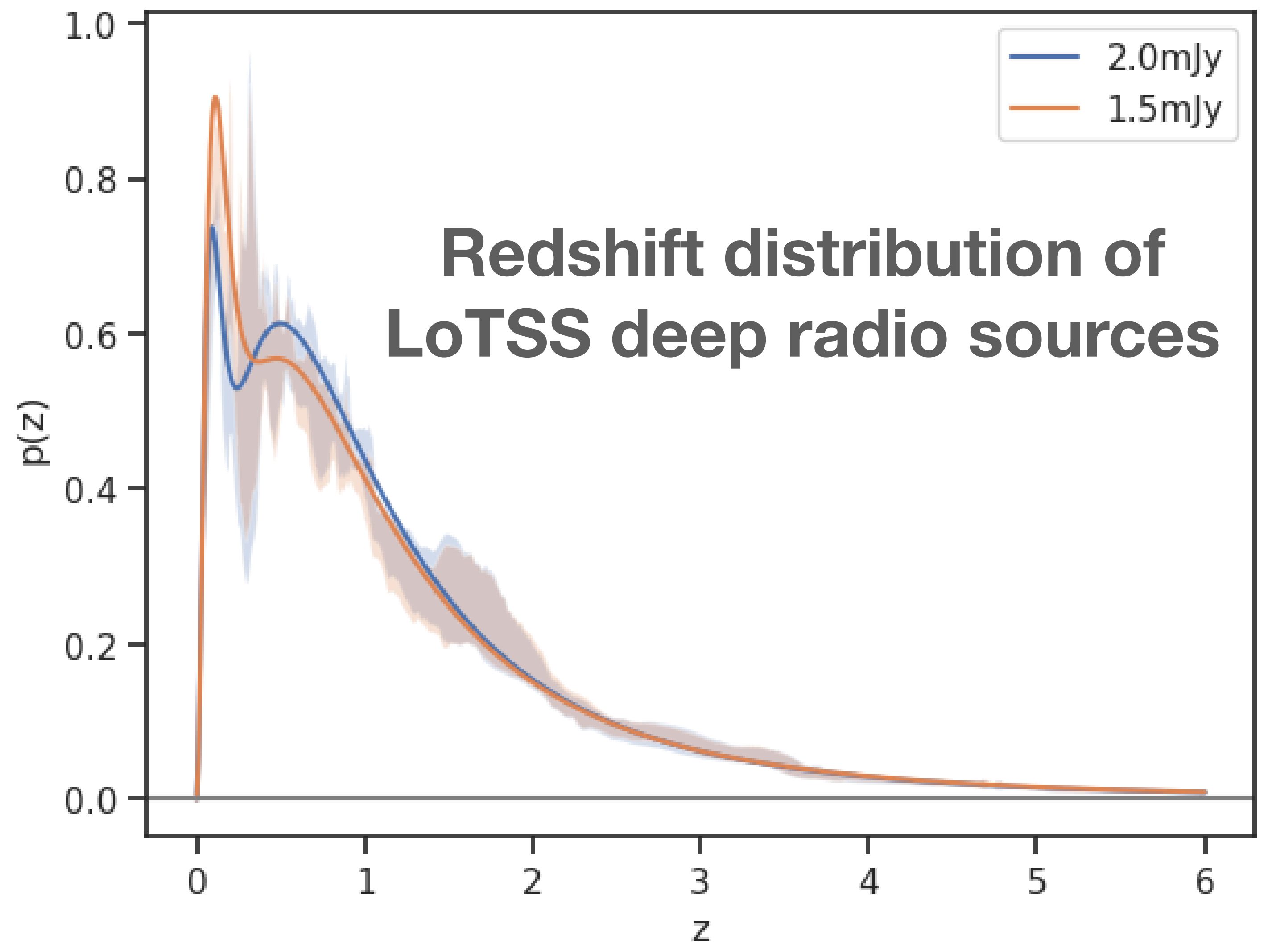
Angular Power Spectra

Auto- and cross-correlation with CMB temperature and lensing (Planck 2018)









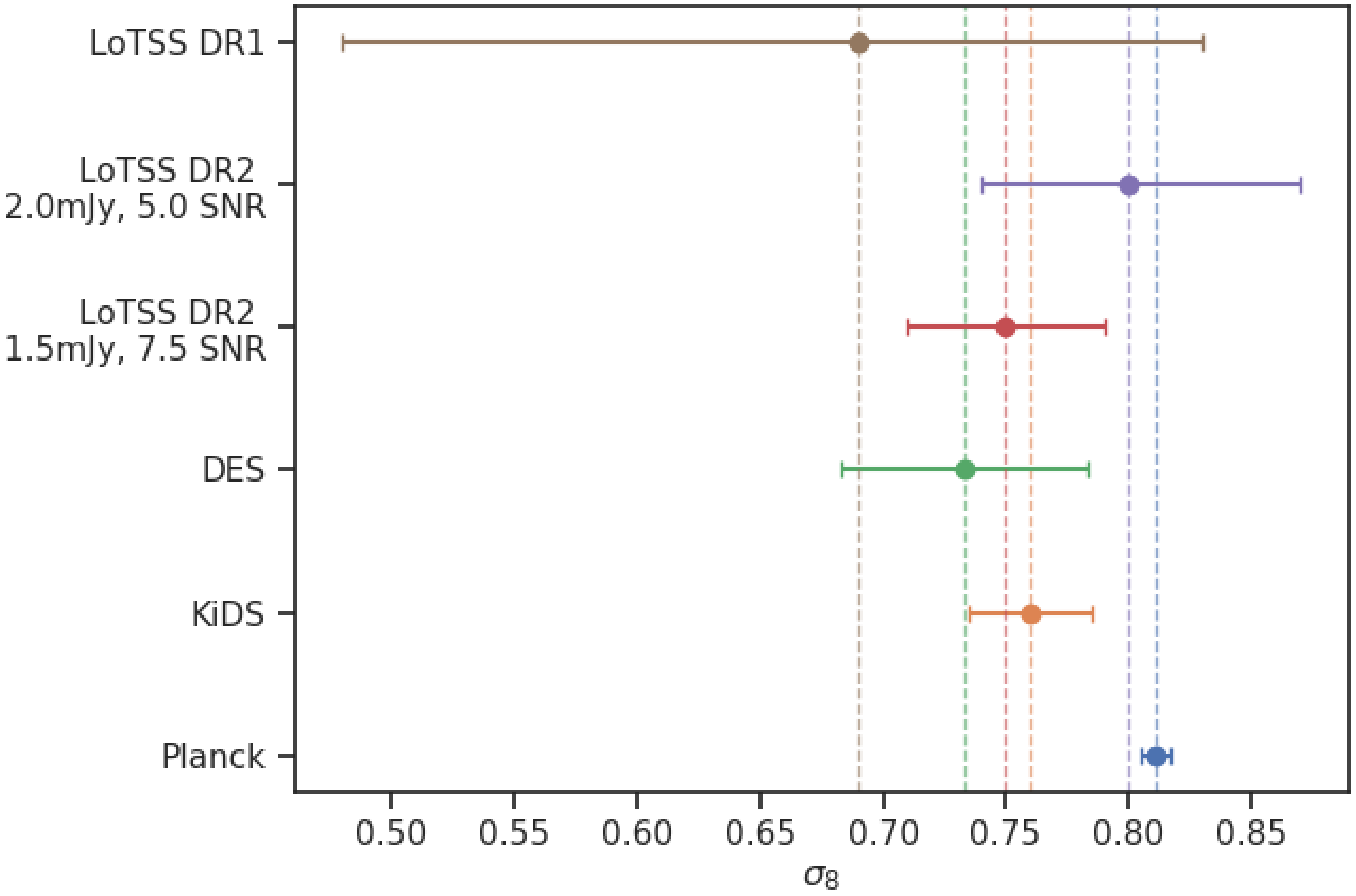
- **Radio-CMB lensing detection at 22 sigma**
- **Consistent with expected ISW effect**
- **Allows to fit p(z), b(z) and σ_8 in linear regime**
- Here: LCDM background parameters fixed to Planck 2018 best-fit values

Nakoneczny et al. in preparation
See talk by Maciej Bilicki

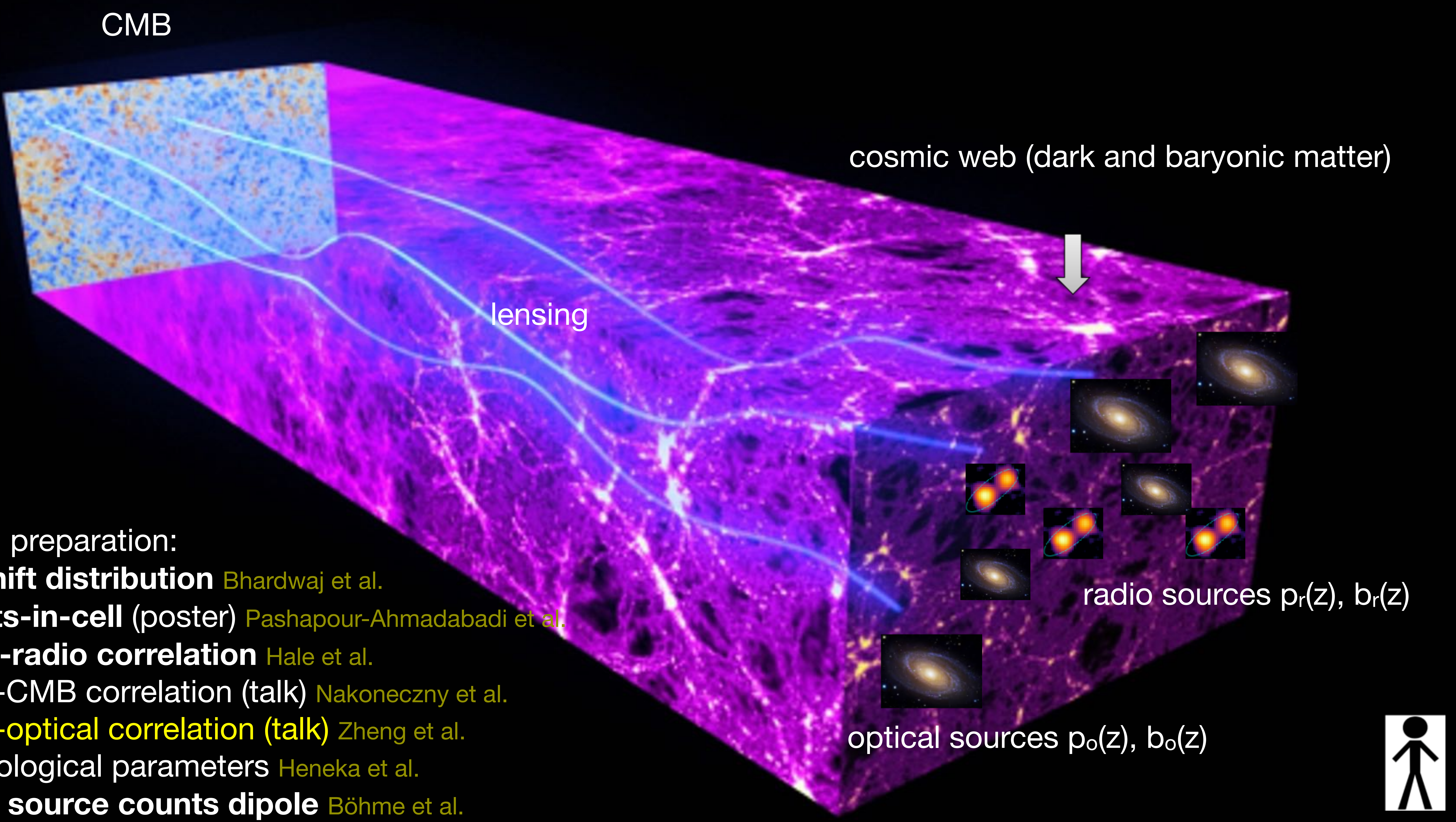
Clustering strength

Can LOFAR help to resolve the σ_8 tension ?

- σ_8 measures rms matter density fluctuation in a ball of radius 8 h^{-1} Mpc
- **Major improvement** from DR1 Alonso et al. 2021 to DR2 Nakoneczny et al. in prep.
- Results depend on signal-to-noise ratio (SNR) and flux density cut and change within 1σ
- **LOFAR starts to be competitive with dedicated surveys like DES and KiDS**



Nakoneczny et al. in preparation



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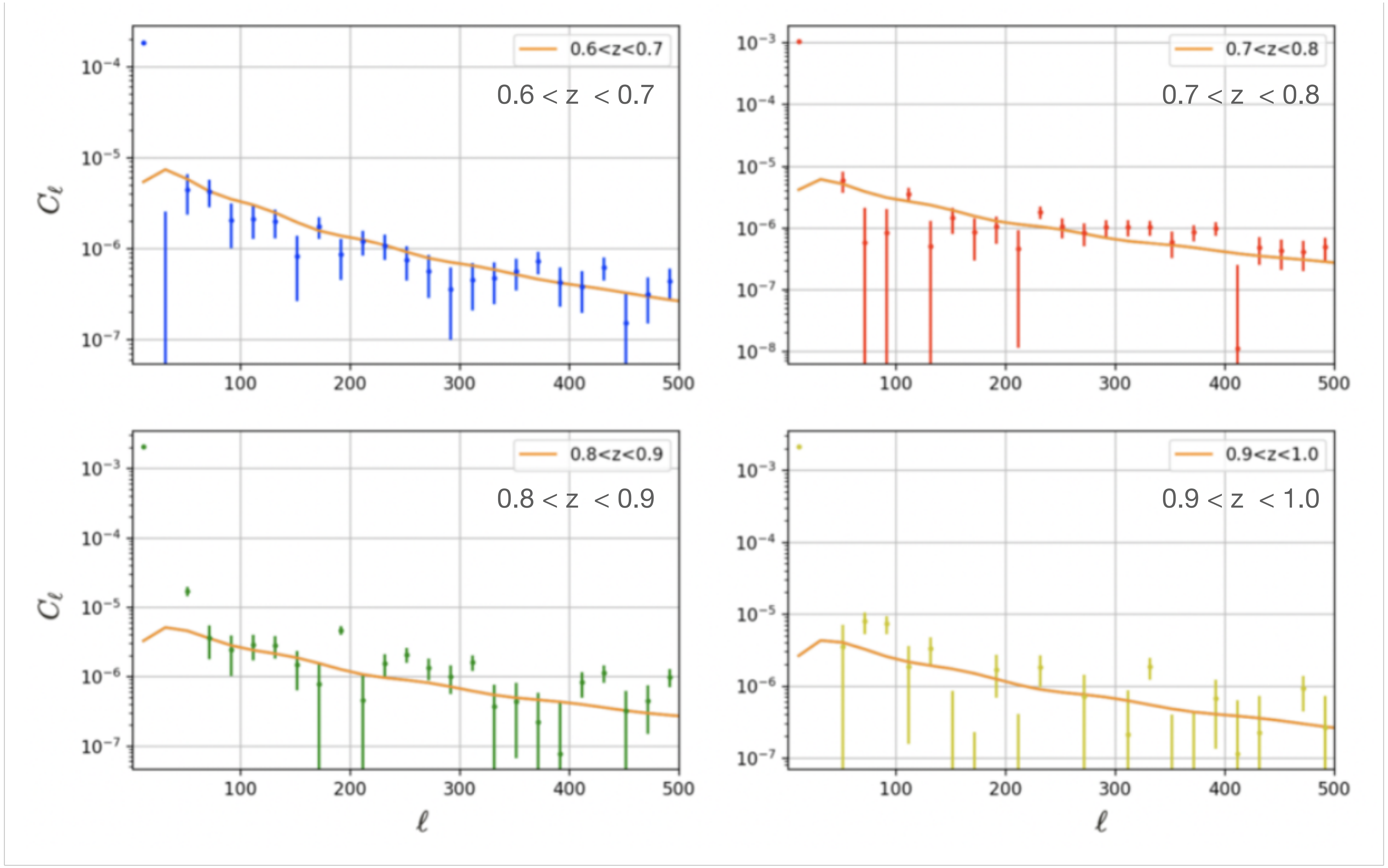
Credit: ESA and Planck Collaboration

Angular Power Spectra

Cross-correlation with eBOSS LRG sample (Dawson et al. 2016)



$b_o(z)$ eBOSS: EZmock
$p_o(z)$ eBOSS: catalogue

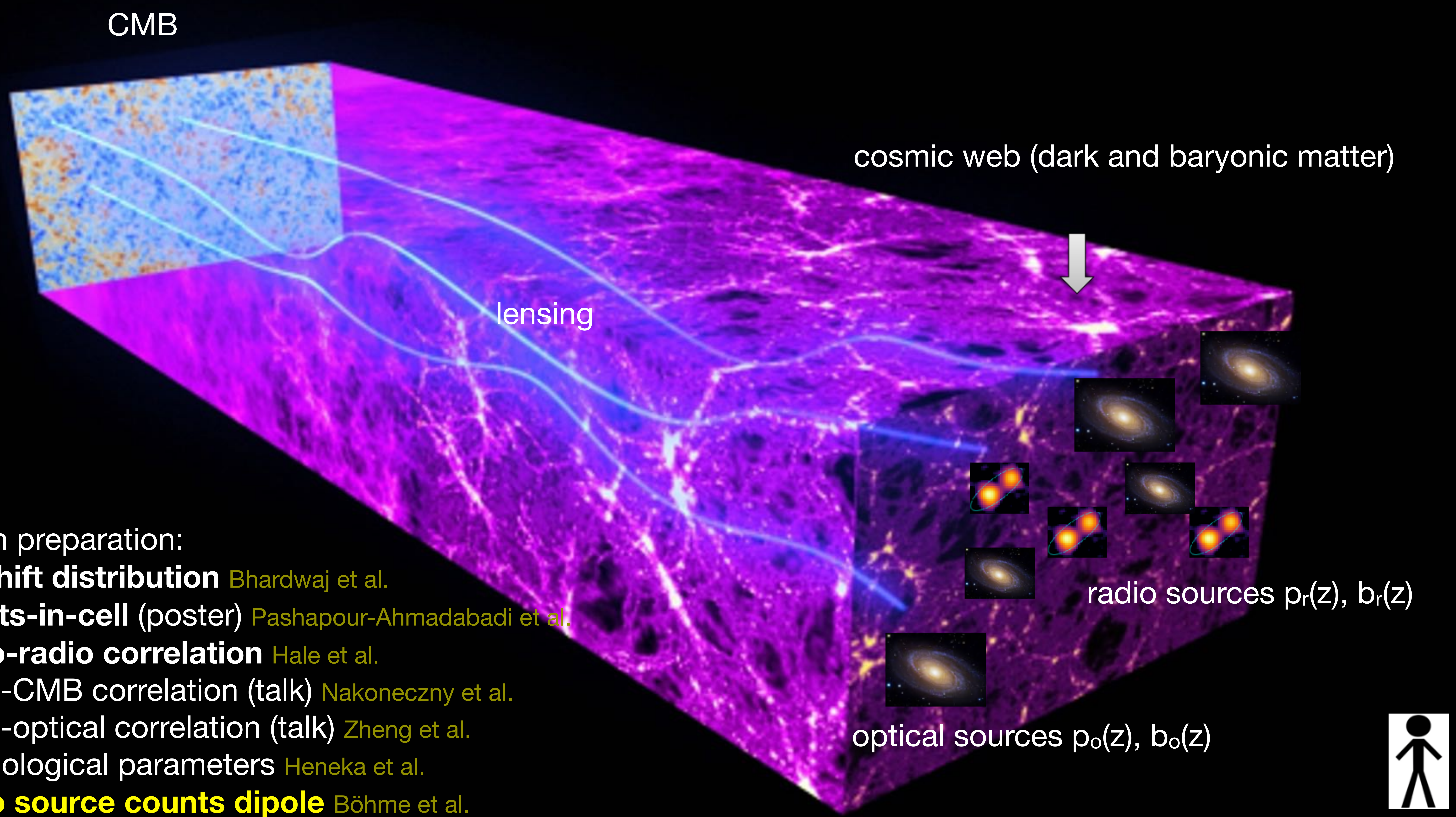
$b_r(z)$ LoTSS-DR1: Tiwari et al. 2022
$p_r(z)$ LoTSS: T-RECS Bonaldi et al. 2019

Theory

Detection of radio-LRG cross-correlation in each redshift bin

Towards detection of baryon acoustic oscillations in radio surveys

Zheng et al. in preparation
See talk by Jinglang Zheng



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Credit: ESA and Planck Collaboration

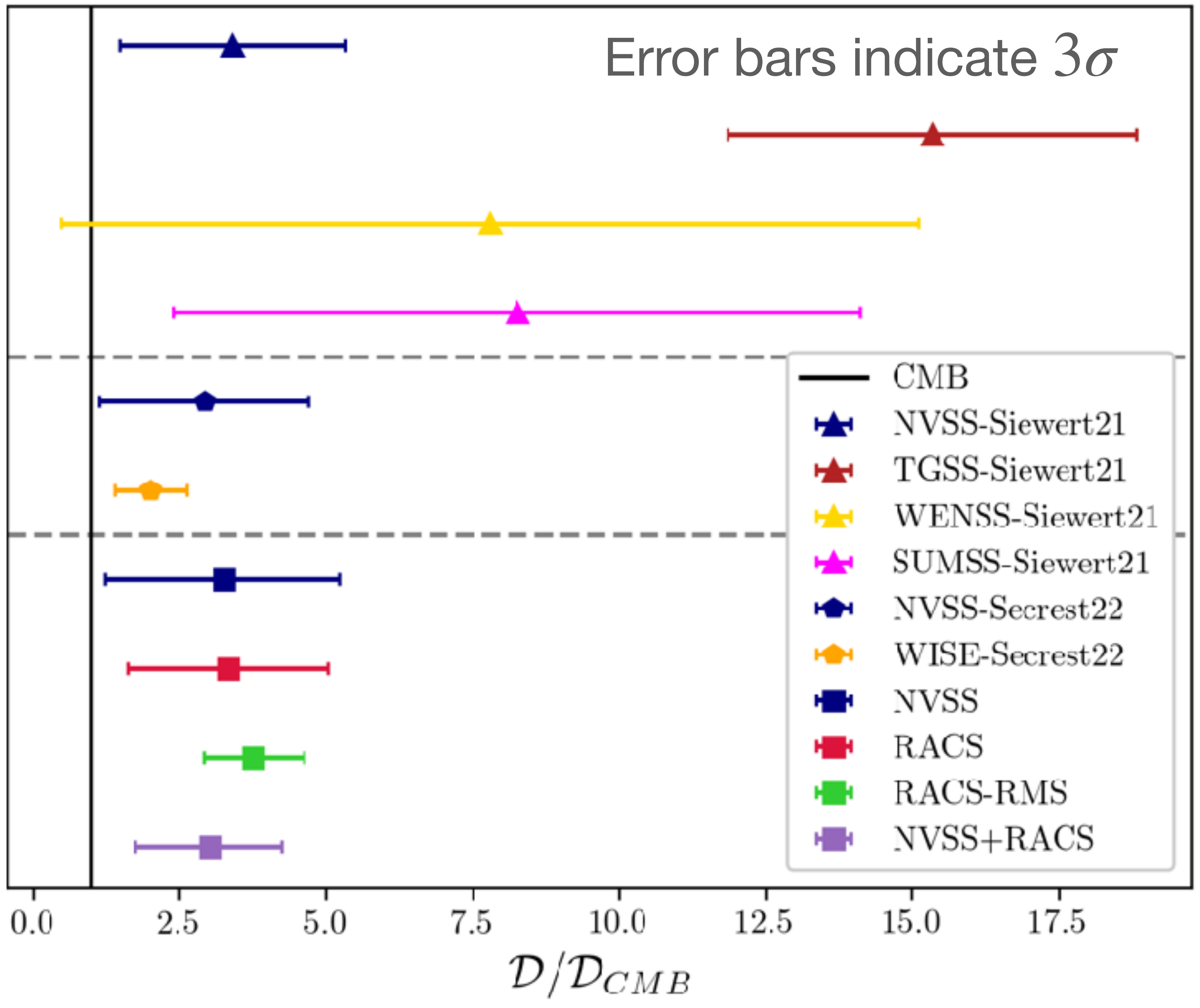
Cosmic structure dipole

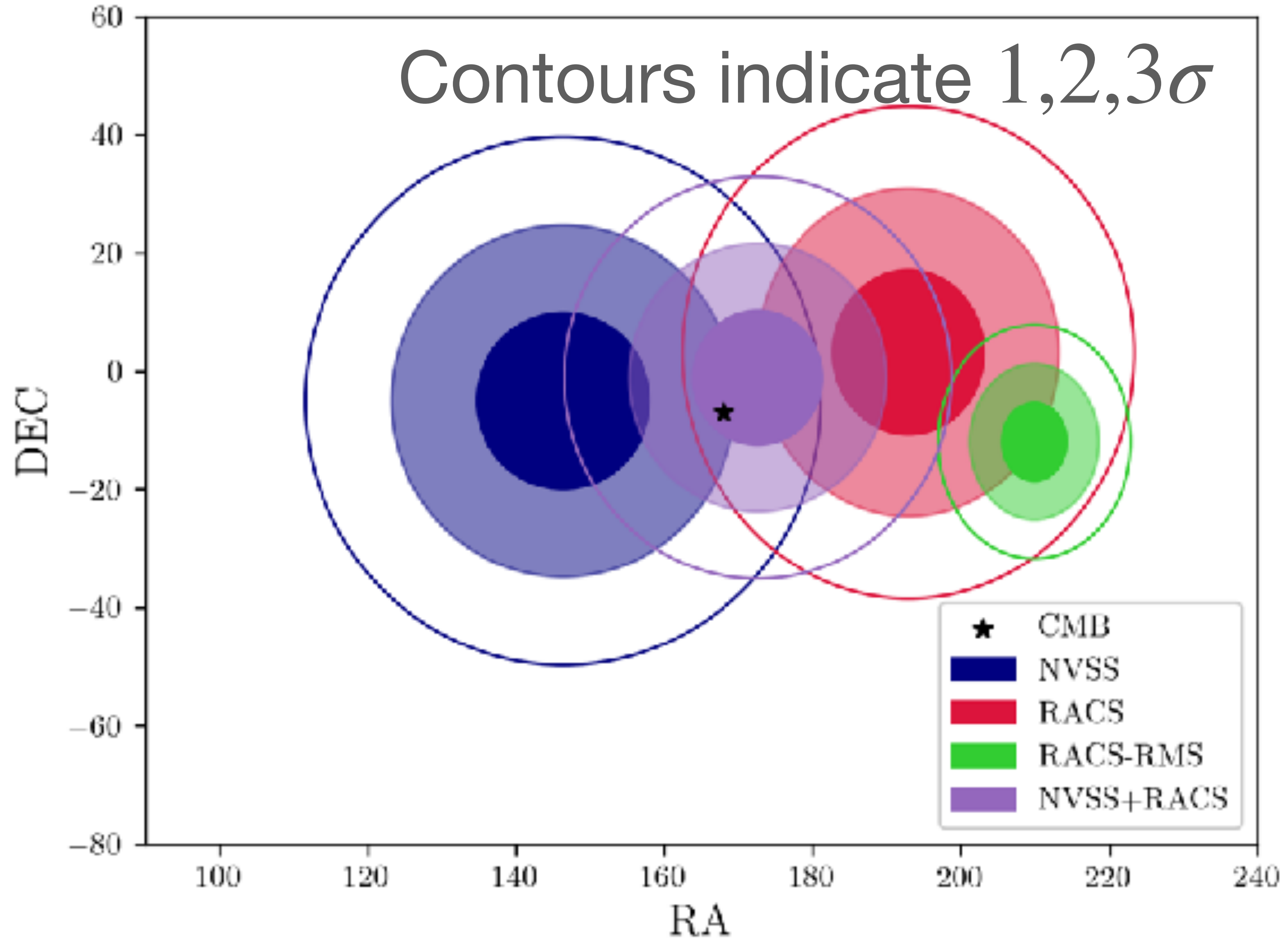
A new cosmological puzzle ?

- Hubble and S_8 tensions are well established
- Disagreement between **CMB dipole** and **cosmic structure dipole** reached significance of $\sim 5\sigma$

WISE quasars: Secrest et al. 2022

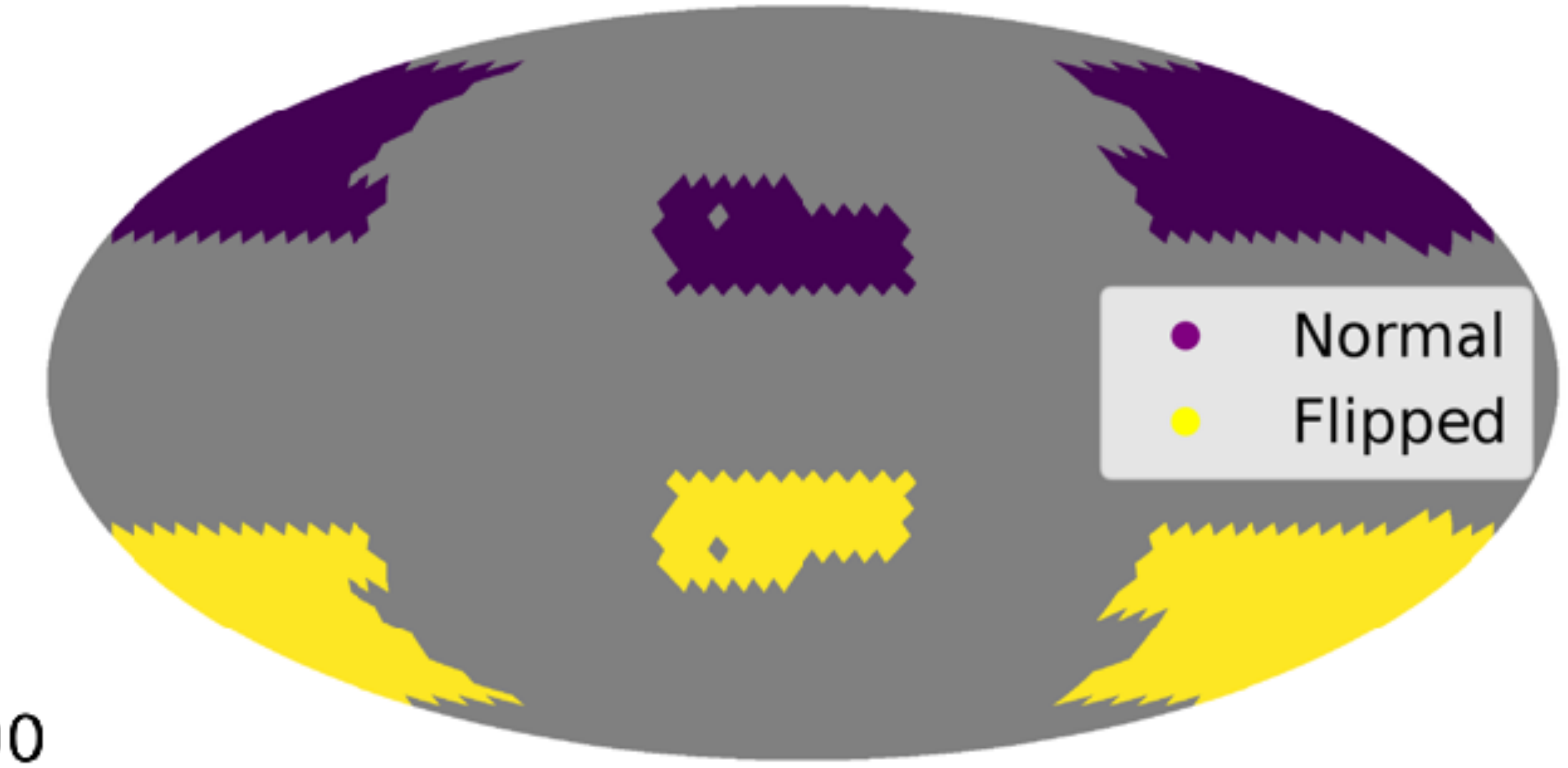
NVSS & RACS:
Wagenveld, Klöckner, Schwarz 2023



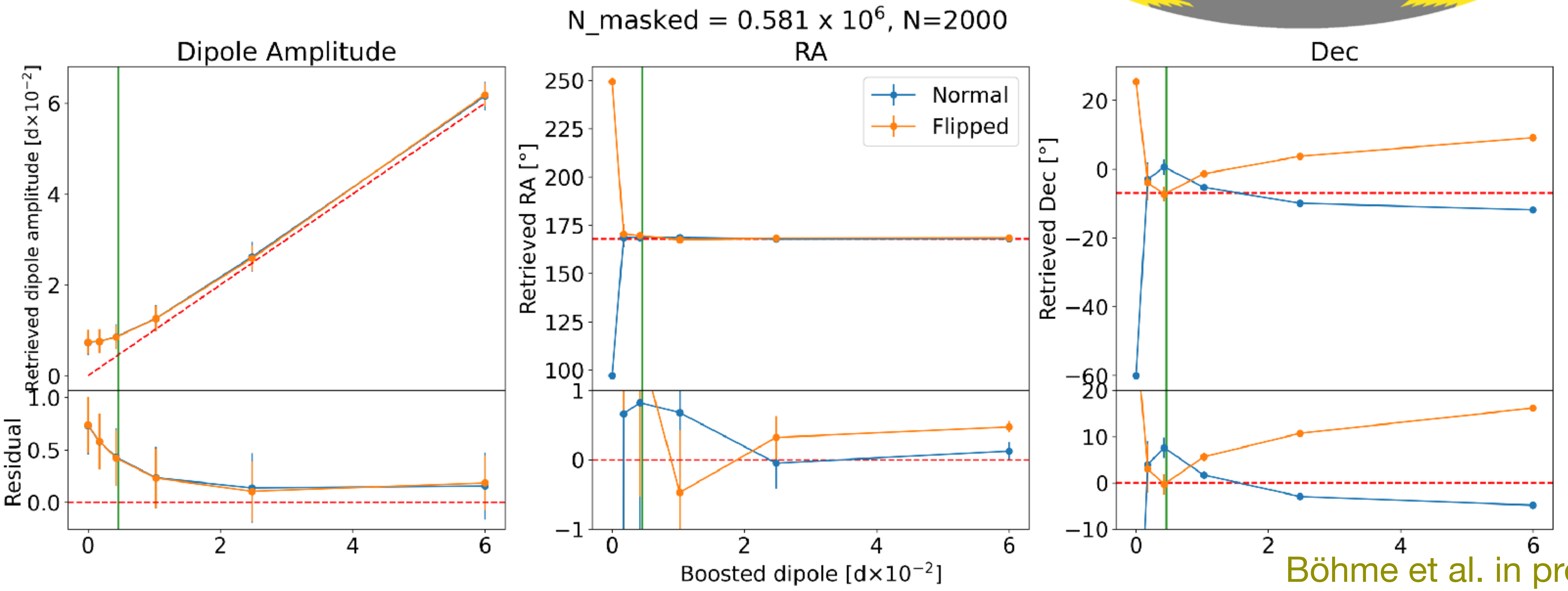


Cosmic Radio Dipole from LOFAR surveys

Can we expect to be able to measure it?



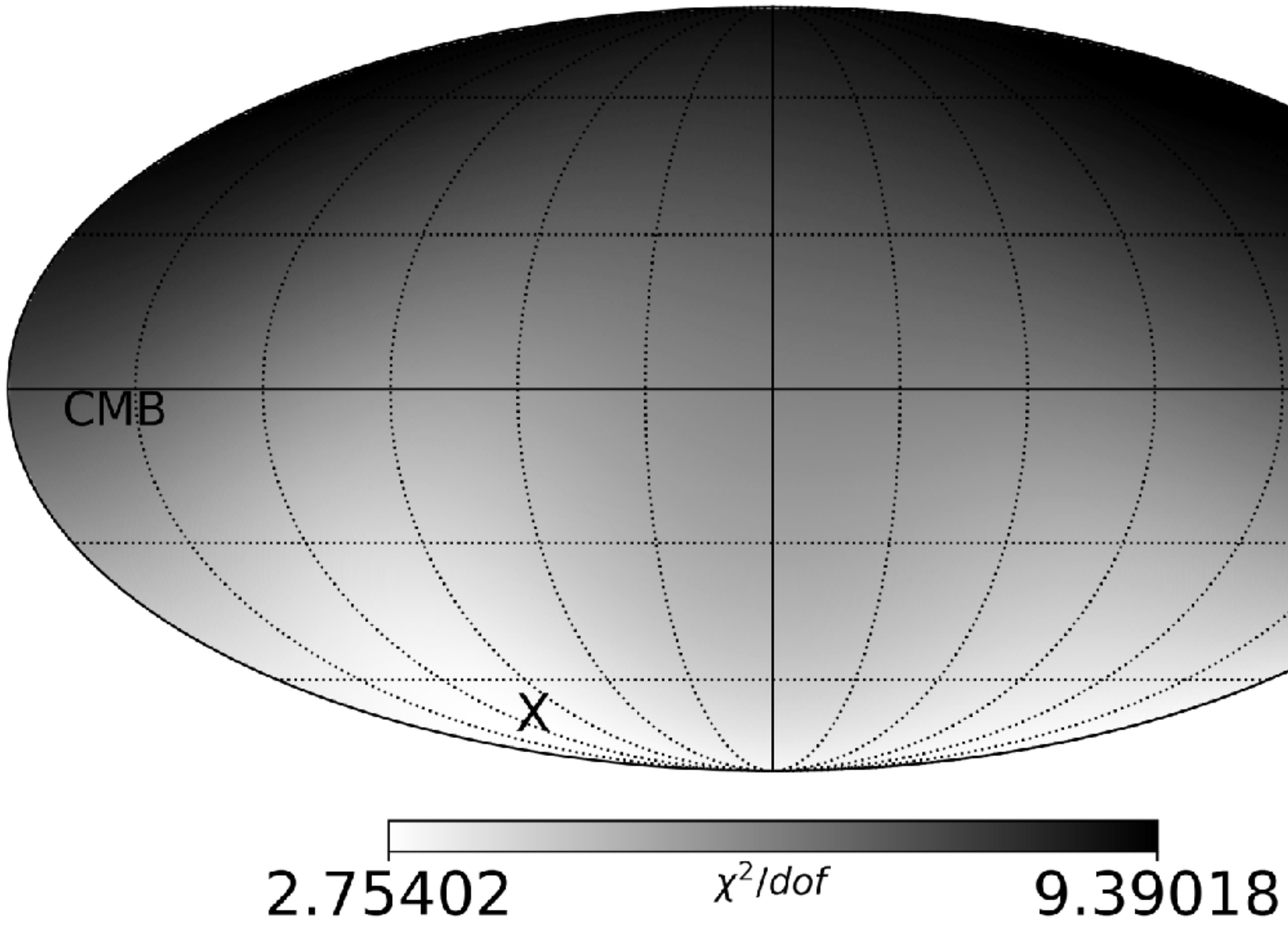
- Simulations for LoTSS-DR2 sky coverage
  → **insufficient sky coverage** to fix declination



Böhme et al. in preparation

Source Count Dipole Estimate from LoTSS-DR2

Dipole almost aligned with equatorial coordinates: Systematics !



- Source count dipole to low resolution maps is highly significant and **dominated by systematics**
- $S > 4$ mJy, $N_{side} = 32$
- (RA,dec) = (137,-73)
- D = 0.1 !!
- Estimator picks up declination/elevation dependence of source counts

Böhme et al. in preparation

Constraint estimates

Preliminary results from LoTSS-DR2

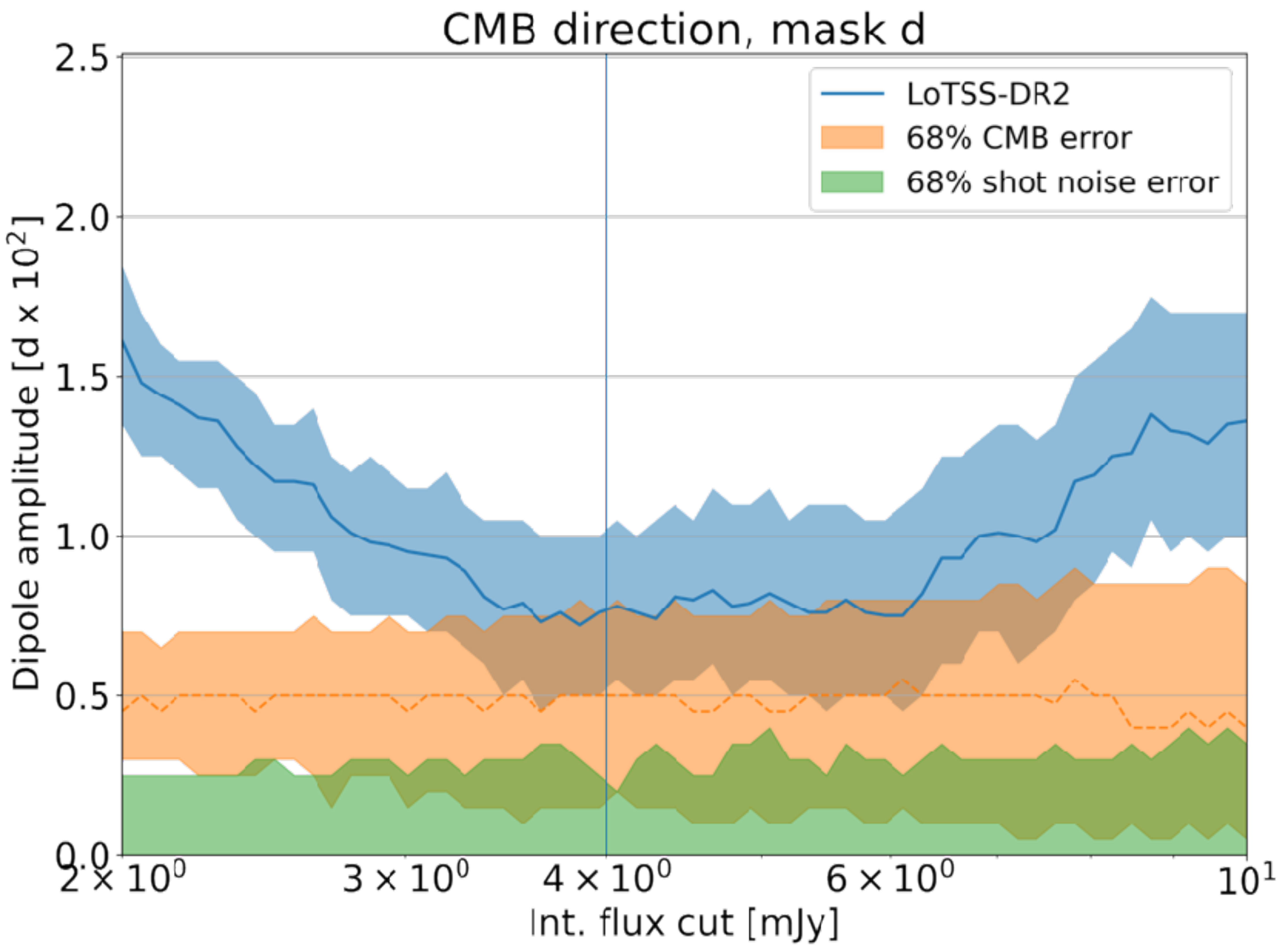
- **Fix dipole direction,**
  fit monopole and
  dipole amplitude,
  use quadratic estimator

- For S > 4 mJy:

$$D = 0.0078^{+0.0027}_{-0.0023}$$

- **Consistent with dipole excess and with CMB dipole**

- Need more data!



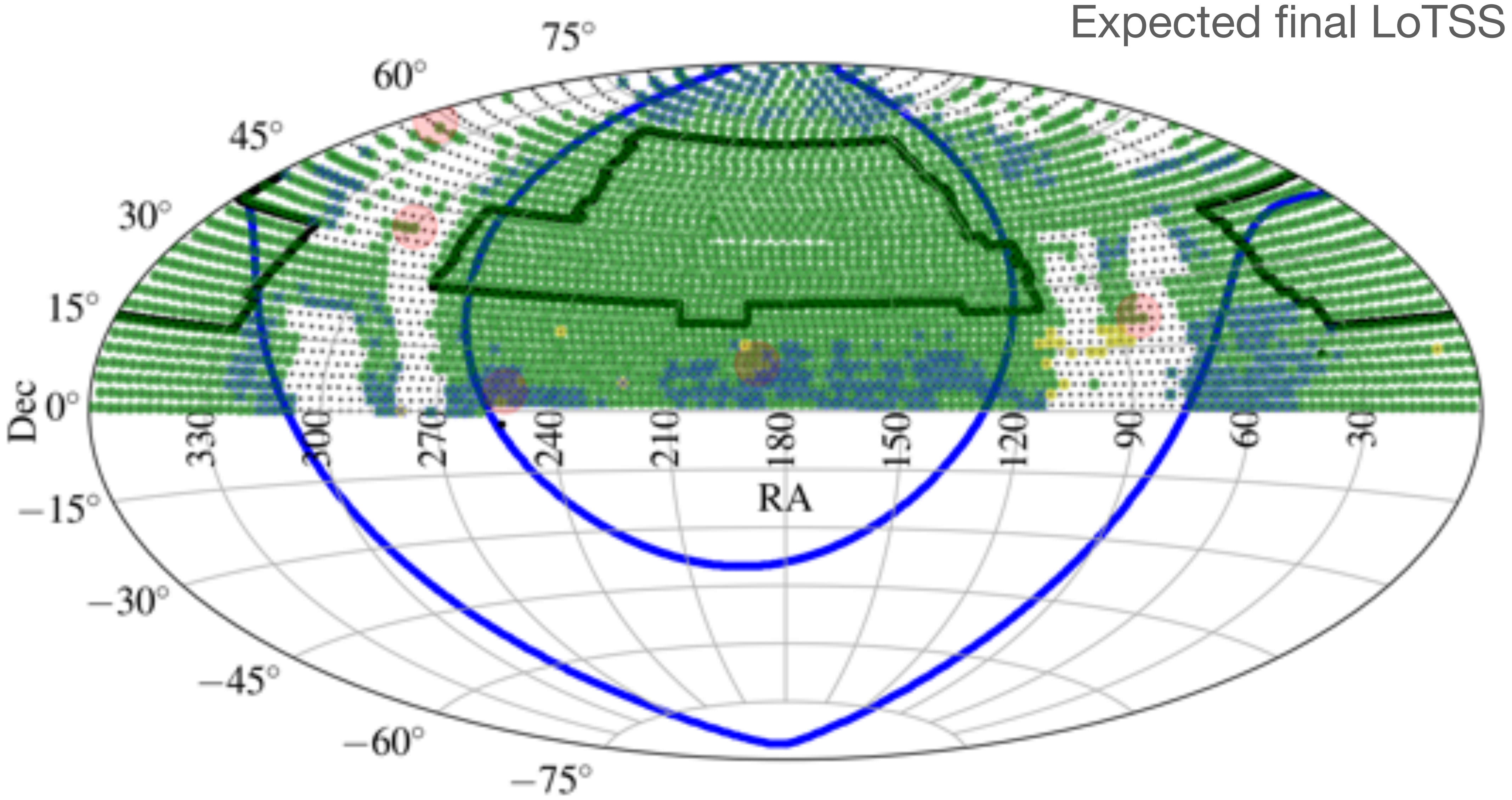
Böhme et al. in preparation

How to obtain best possible results

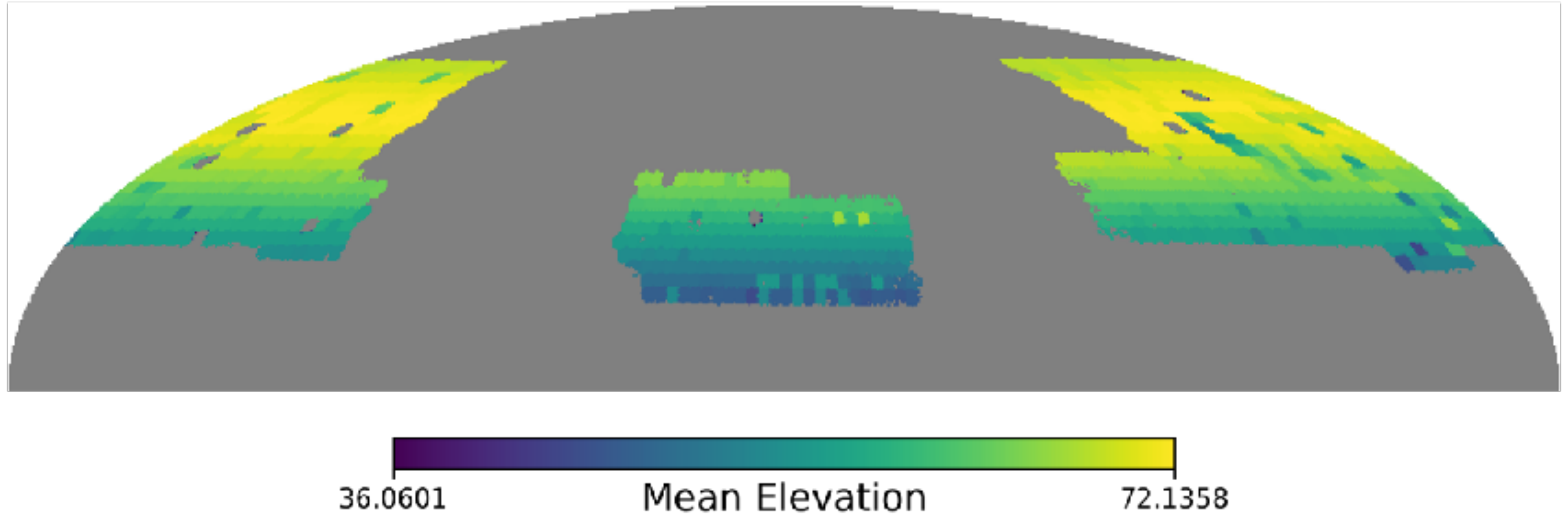
Importance of availability of data at various processing levels and metadata

- Complete LoTSS wide and deep fields, complete LoLSS, cross match both, identify artefacts, identify multicomponent sources
- Obtain spectroscopic z from WEAVE-LOFAR (restricted to S > 8 mJy on wide area), plan for synergies with Euclid and UNIFORM for smaller flux densities
- Try to break degeneracy between declination and mean elevation
- Improve access to instrumental, environmental and pipeline data and metadata to simplify identification and mitigation of systematics

Expected final LoTSS



Mean elevations of LoTSS-DR2 pointings



Cosmological Conclusions
LoTSS-DR2 preliminary results

- Radio sources with **multiple components** impact the analysis — **Cox process**
- Precise and **consistent estimates on linear bias b(z)** from three different methods: auto-correlation and p(z), cross-correlation with CMB lensing, cross-correlation with optical galaxies
- Constant bias is disfavoured, $b(z) = b_0/D(z)$ is consistent with model independent approach
- **Measure** σ_8 with precision comparable to that of current weak lensing studies
- First study of **BAO**s with a radio continuum survey
- Joint analysis of all probes will allow us to constrain more cosmological parameters, e.g. w_{de}
- **For fixed dipole direction, consistent with CMB prediction**, but also with excess at higher frequencies, but in disagreement with the extremely large value of the source count dipole form TGSS

Conclusion and Outlook

Competitive constraints and independent checks of cosmology from radio surveys

- LoTSS-DR1 (424 sq deg): radio sources can probe cosmology (Siewert et al. 2021)
- LoTSS-DR2 (5600 sq deg): high significance of radio-lensing correlation and radio-optical BAO and competitive constraints — **cross identification and photo-zs are essential**
- **Better than forecasted** (Raccanelli et al. 2012), missed out cross identifications and photo-zs
- **Ongoing:** LoTSS-DR2 **Value Added Source catalogue** Hartcastle et al. in preparation
- Complete LoTSS in 2024 (before LOFAR2.0 upgrade): **all extragalactic northern sky** — ~ 2 x LoTSS-DR2, essential for cosmic radio dipole, ISW and primordial non-Gaussianity
- **WEAVE-LOFAR** (starts later this year): spectroscopic redshifts for 1 million radio sources