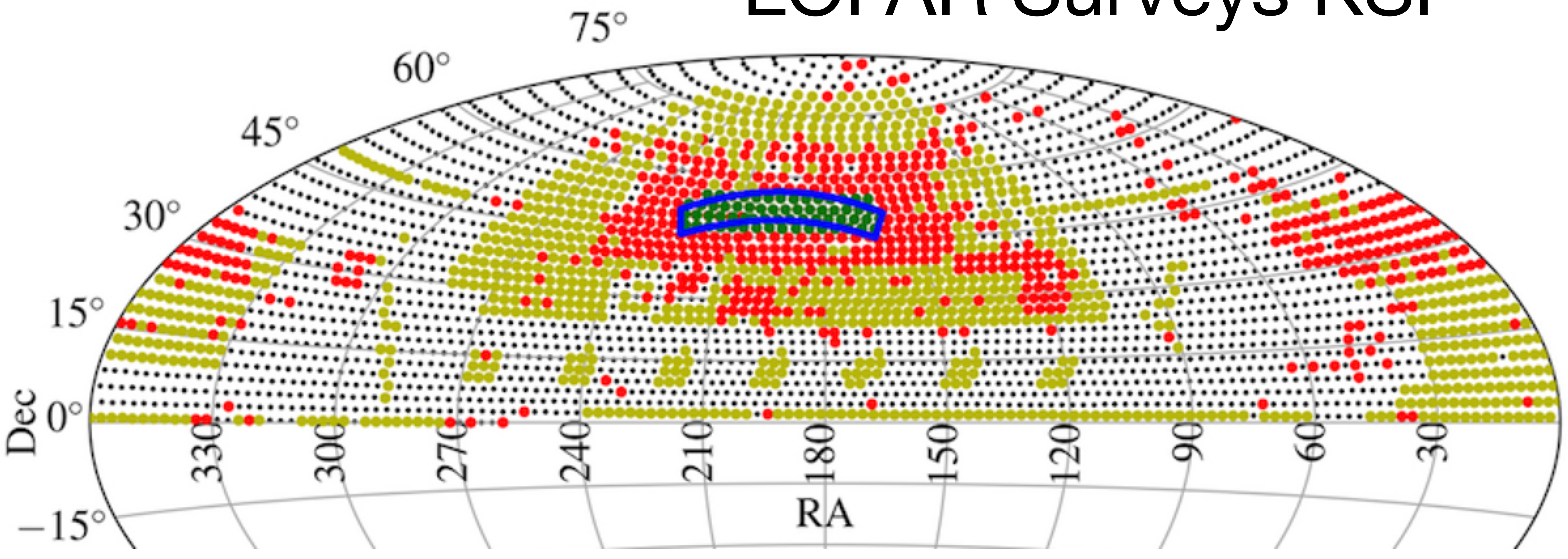
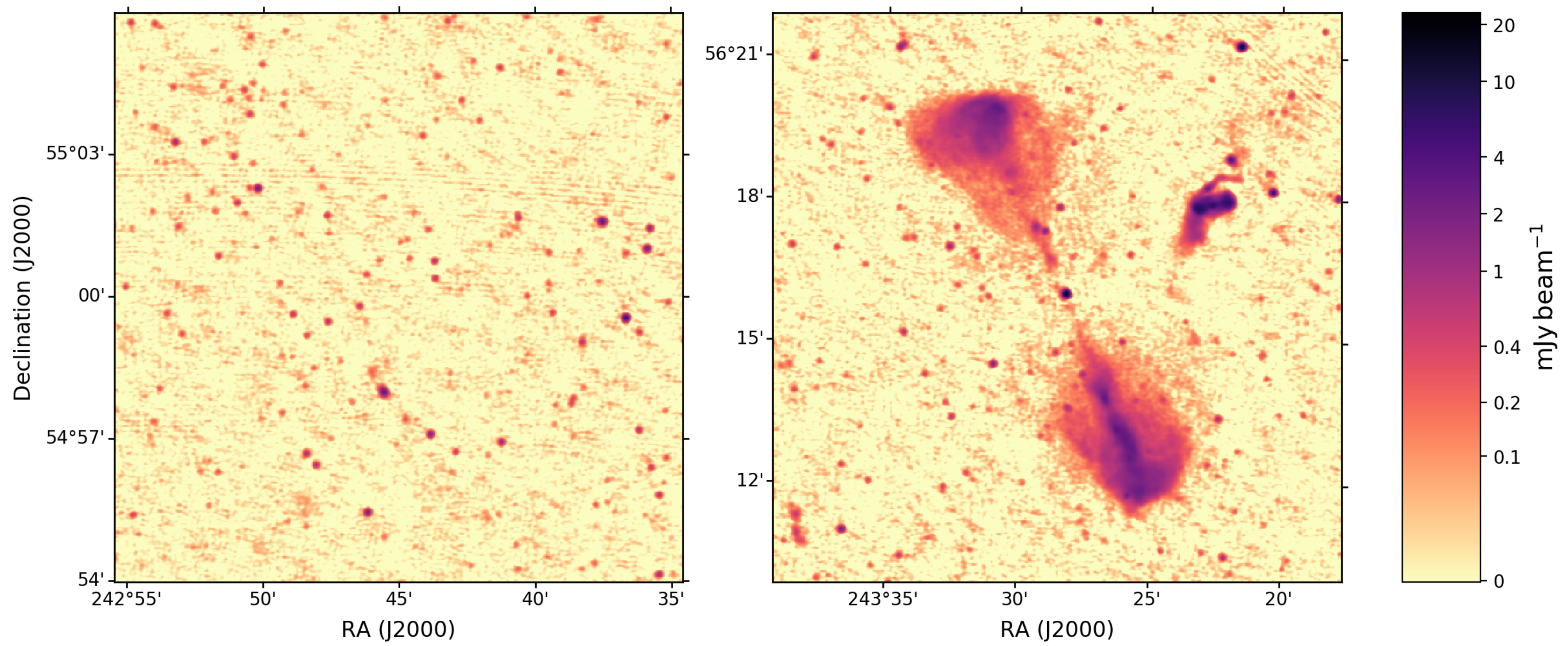
UNIVERSITÄT
BIELEFELD
Faculty of Physics

Cosmology from low frequency radio frequencies with LoTSS

Dominik J. Schwarz
LOFAR Surveys KSP — Cosmology Team



LoTSS-wide: DR1, Shimwell et al. 2019



Deep Fields: Elias-N1, Sabater et al. 2020

Low Frequency Array

LOFAR

International LOFAR Telescope:
9 Consortia (NL, DE, PL, F, IR, IT, LAT, S, UK)
51 Stations (37 NL)
6 Key Science Projects
3 Long Term Archives (NL, DE, PL)

LOFAR was designed and is operated by

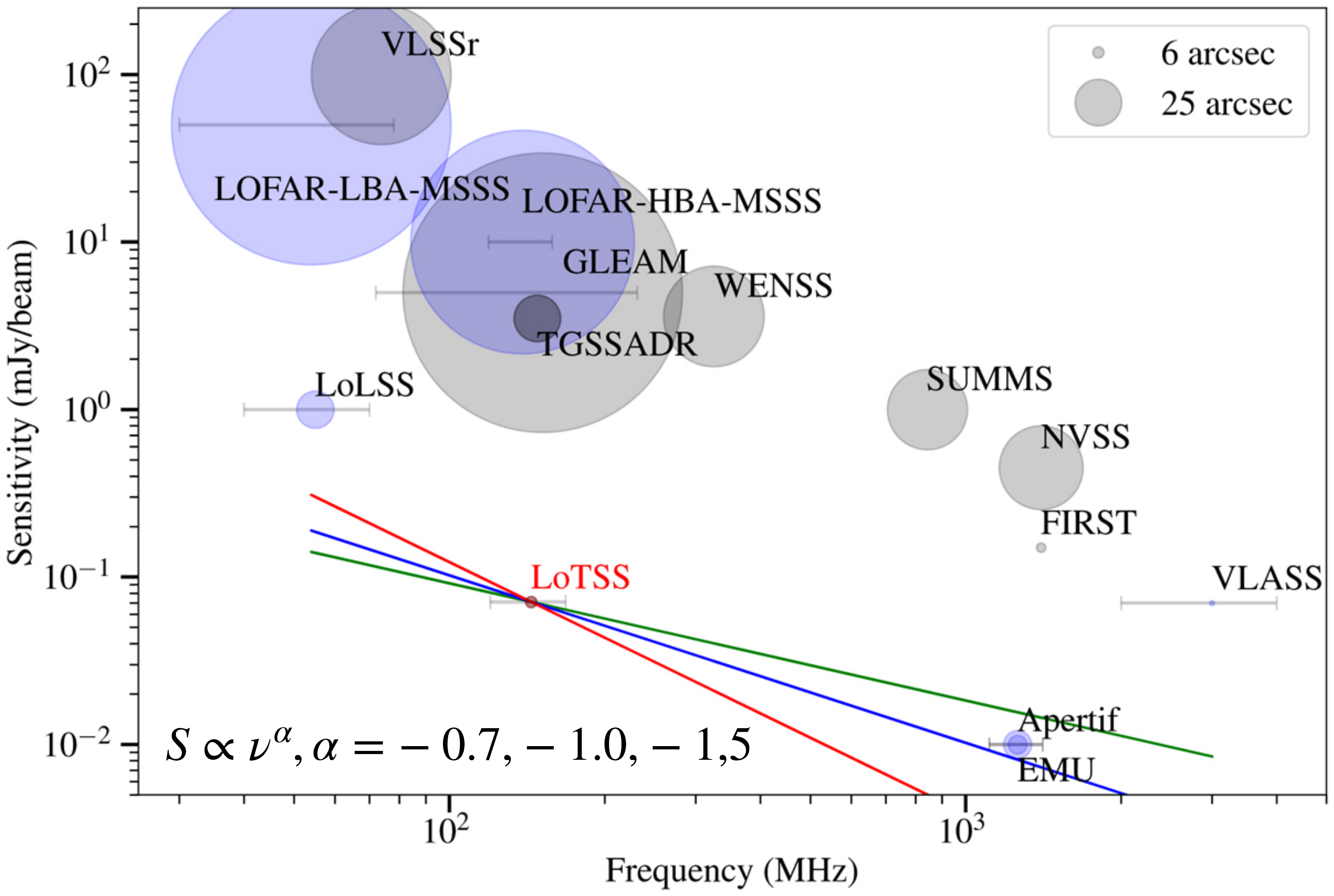
ASTRON

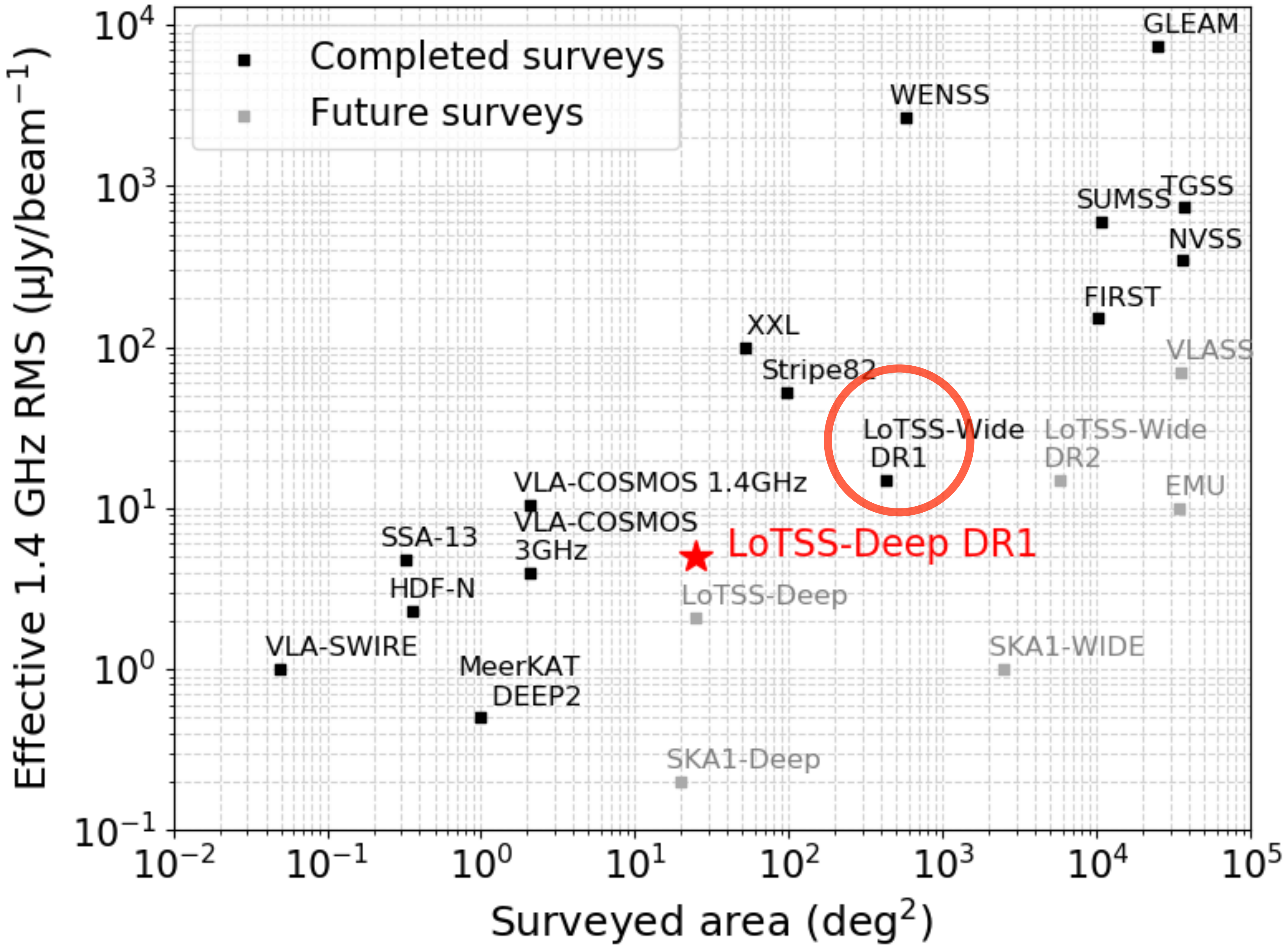

Station electronic
High band antennas
Low band antennas
LOFAR DE609 Norderstedt
Image Credit: Marcus Brüggen

LOFAR Two-metre Sky Survey

lofar-surveys.org

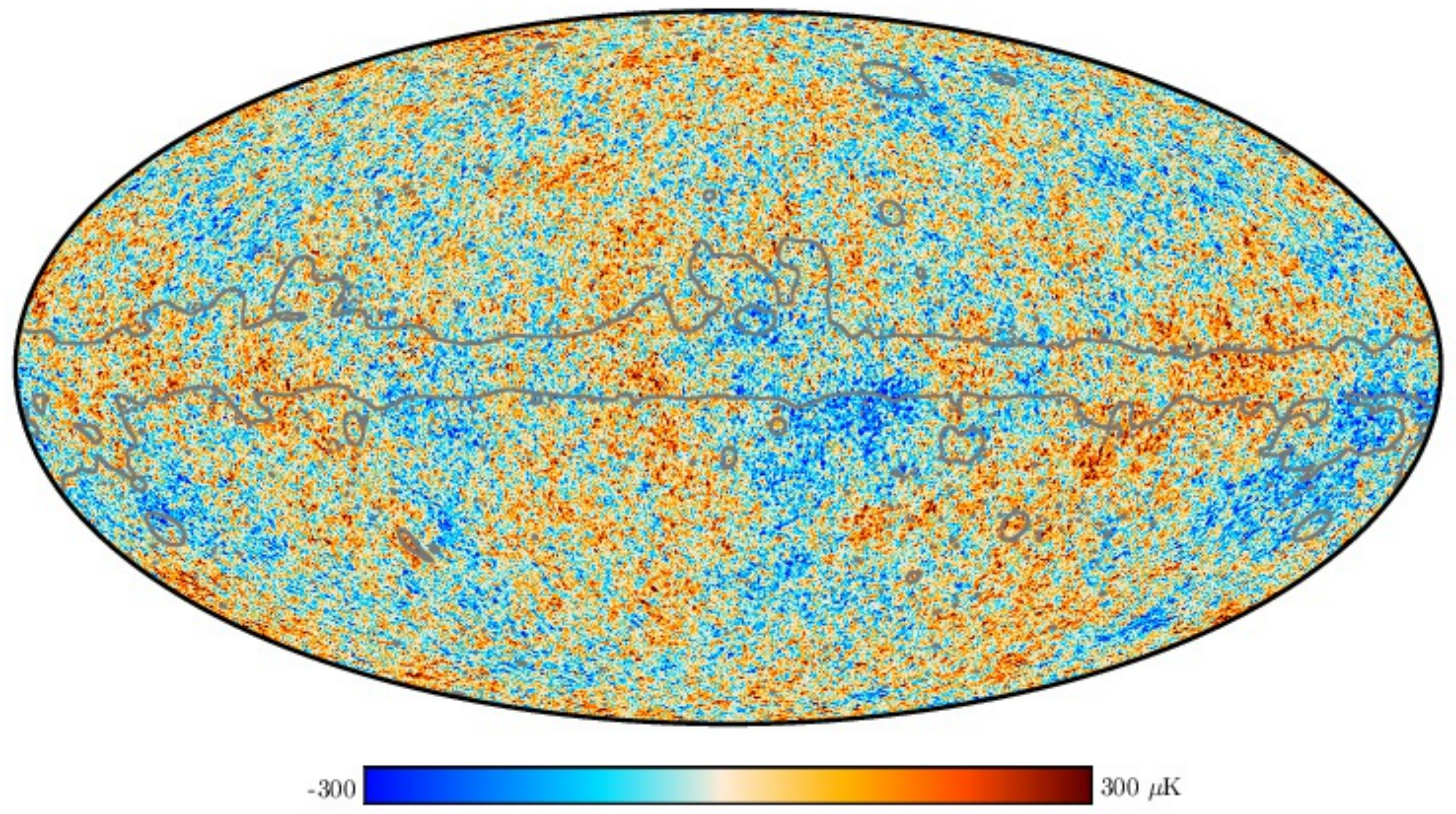
Tiered survey of Northern radio sky at 144 MHz (120 - 168 MHz), angular resolution of 6”
Value added source catalogue: matched radio components, identified optical and infrared counterparts, and photo-z’s





LoTSS-Wide DR1: Shimwell et al. 2019 **LoTSS-Deep DR1: Tasse et al. 2020**

Fundamental assumptions of cosmology



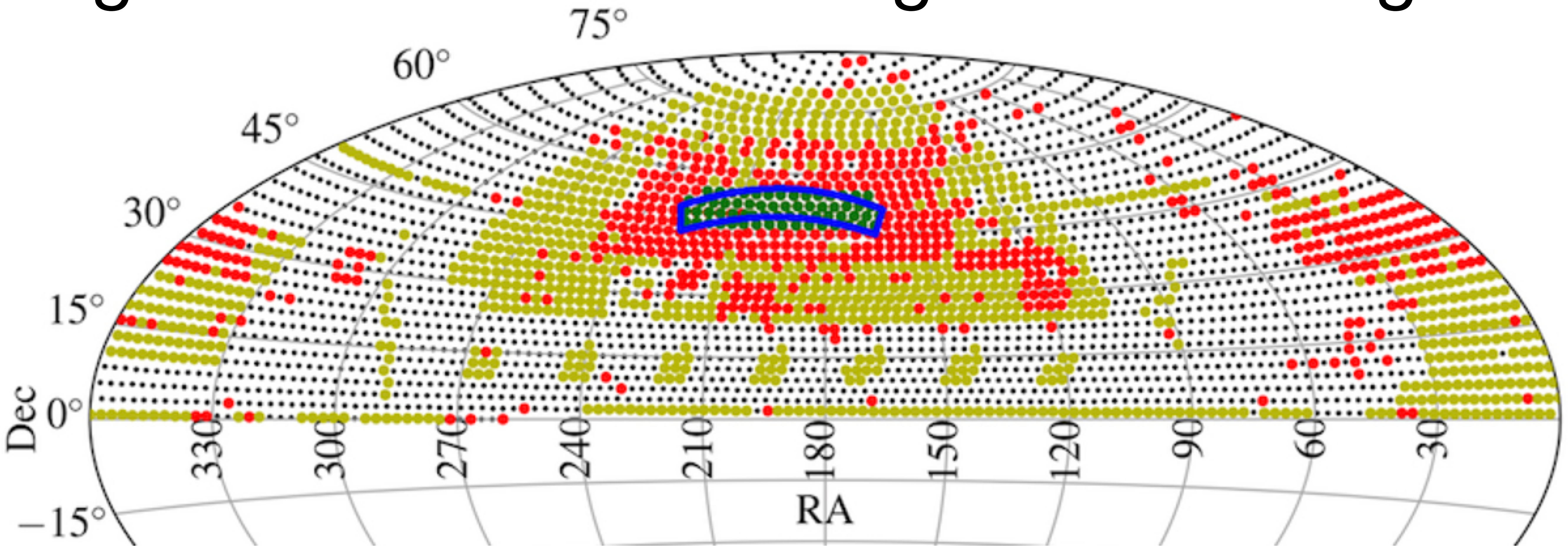
Planck collaboration 2018

- Statistically isotropic and homogeneous Universe
- Gaussian matter and curvature fluctuations
- Scale-invariant power spectrum
- Structure grows via gravitational instability, described by general relativity
- Dark matter and cosmological constant

Consequences for radio sky

- Statistically isotropic distribution of radio sources
- Gaussian fluctuations, thus all information is contained in the one- and two-point distribution functions
- Use radio sources as test particles to probe the large scale structure of the Universe at large and ultra-large scales and over a huge redshift range

We used LoTSS-DR1 (green pointings) to develop pipelines and tested them; established that low frequency radio sources allow us to recover known cosmology

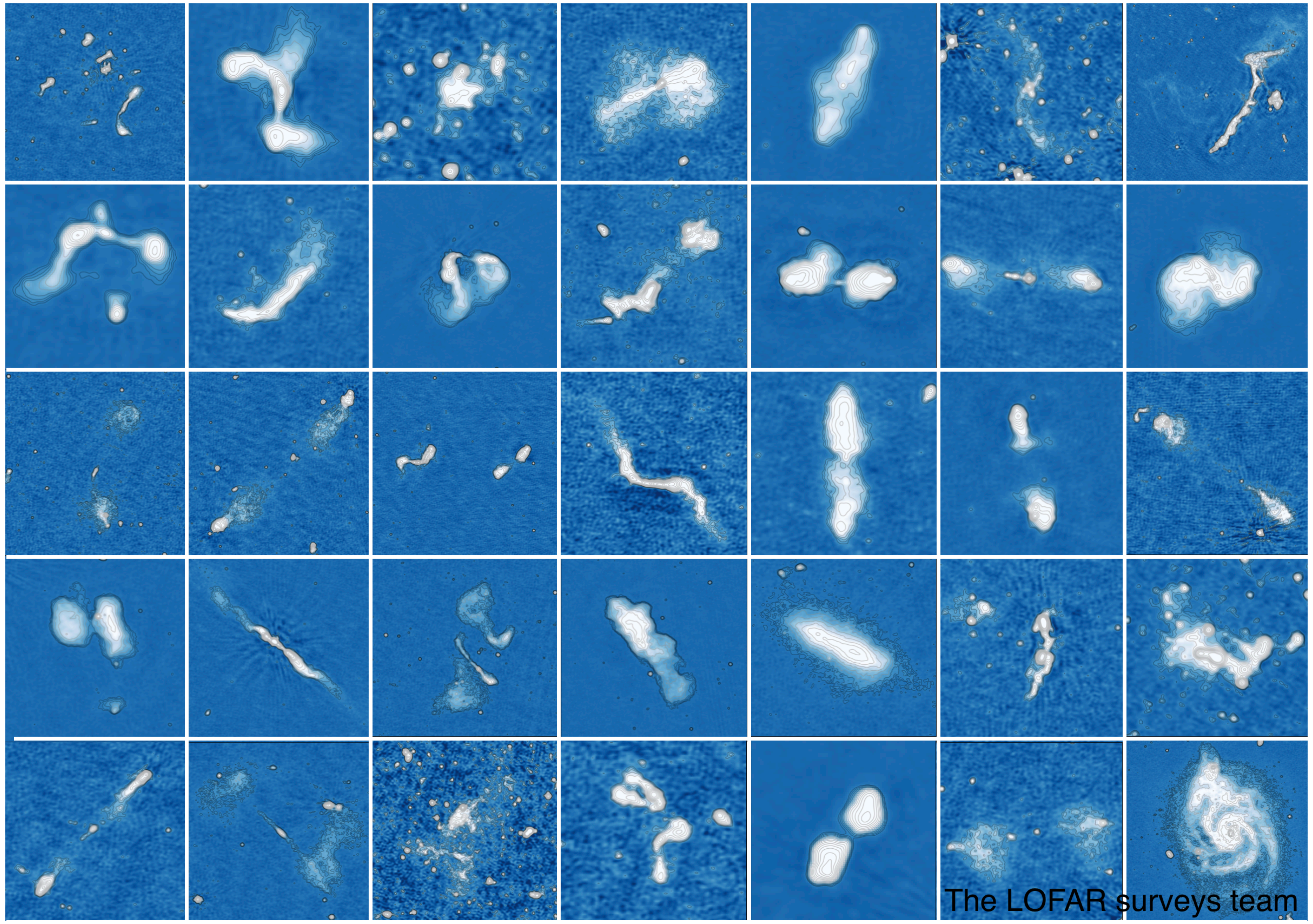


Siewert et al. 2020

LoTSS-wide: DR1, Shimwell et al. 2019

LoTSS-wide DR1

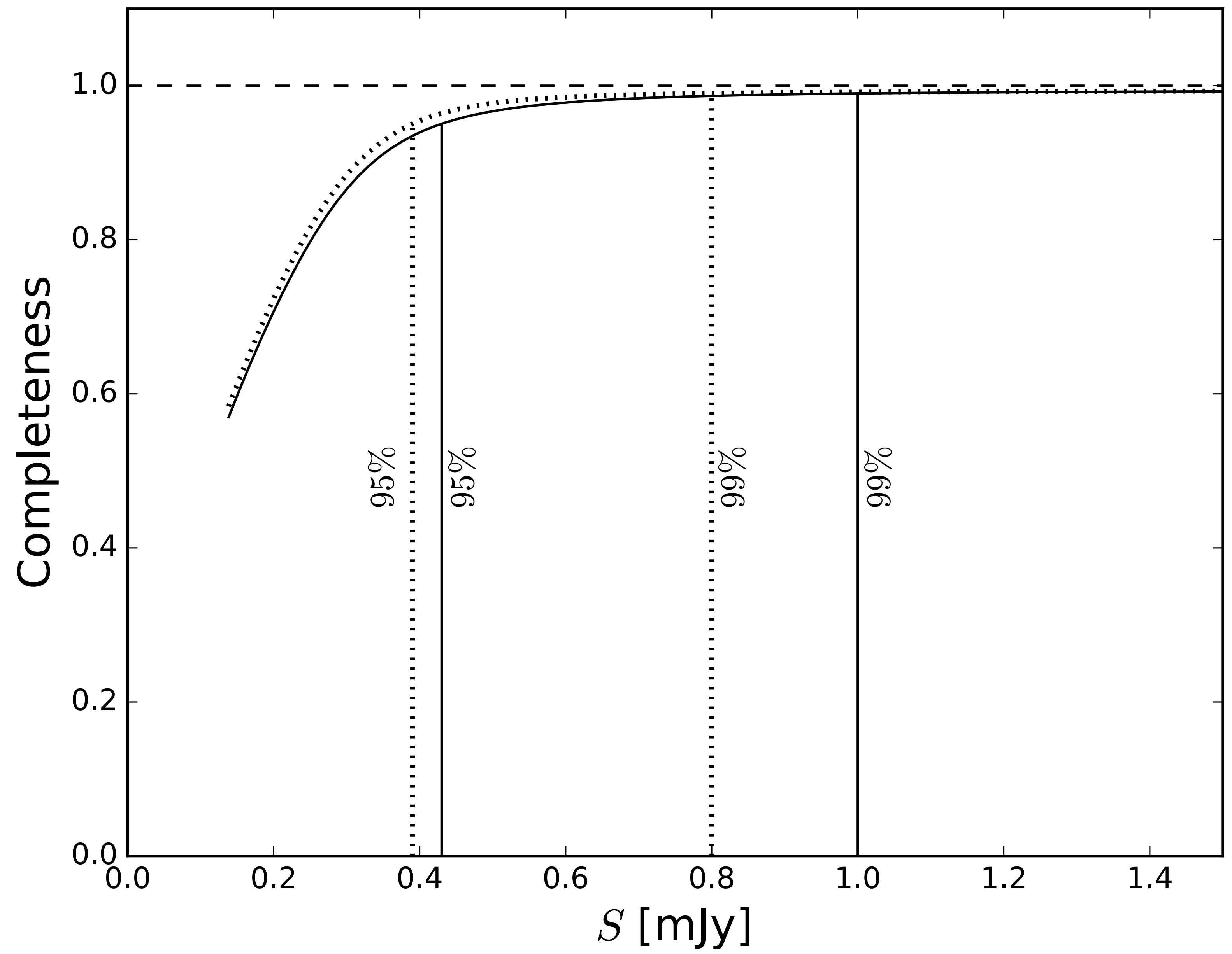
- 424 square degrees (Hetdex region)
- 325,694 radio sources
- AGNs, SFGs, clusters, etc.
- Median rms noise: 71μJy/beam
- angular resolution: 6”
- Value added catalogue:
  318,520 sources of which
  231,716 sources are matched to
  Pan-STARRS and/or WISE
- Photo-z’s for ~ 50% of all radio sources



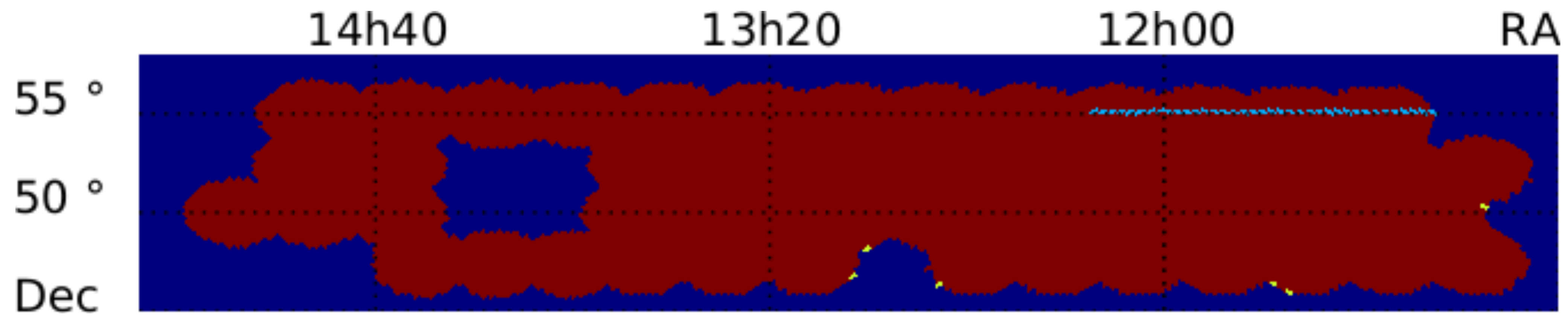
LoTSS-wide: DR1, Shimwell et al. 2019, Williams et al. 2019, Duncan et al. 2019

Completeness and masking

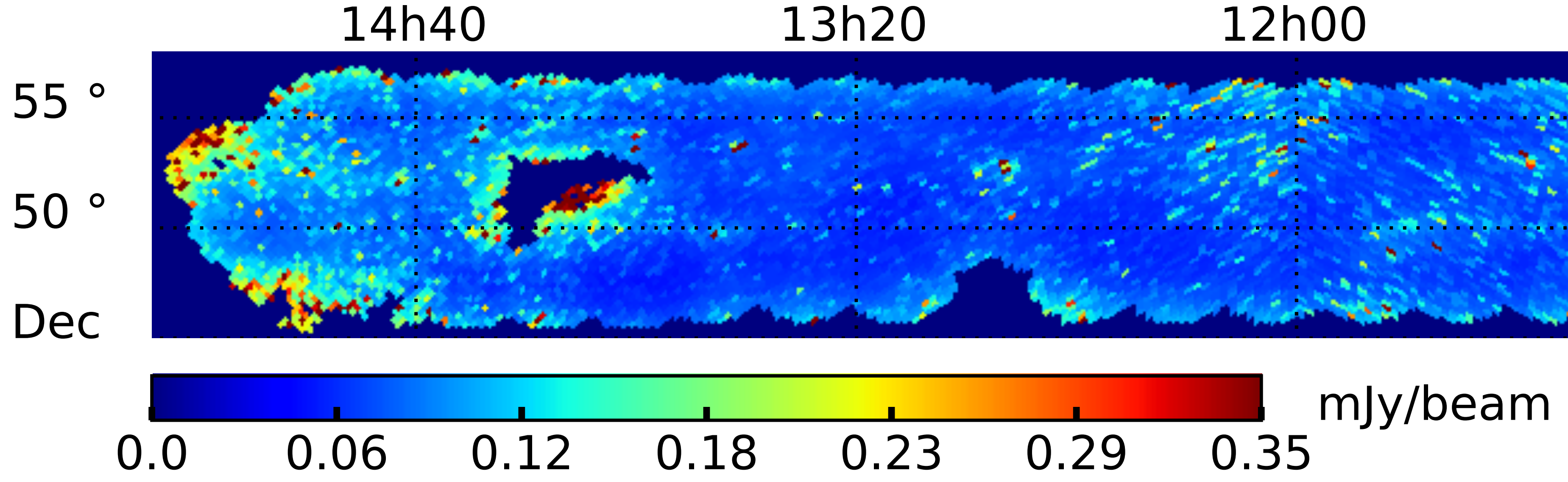
Point source completeness vs flux density



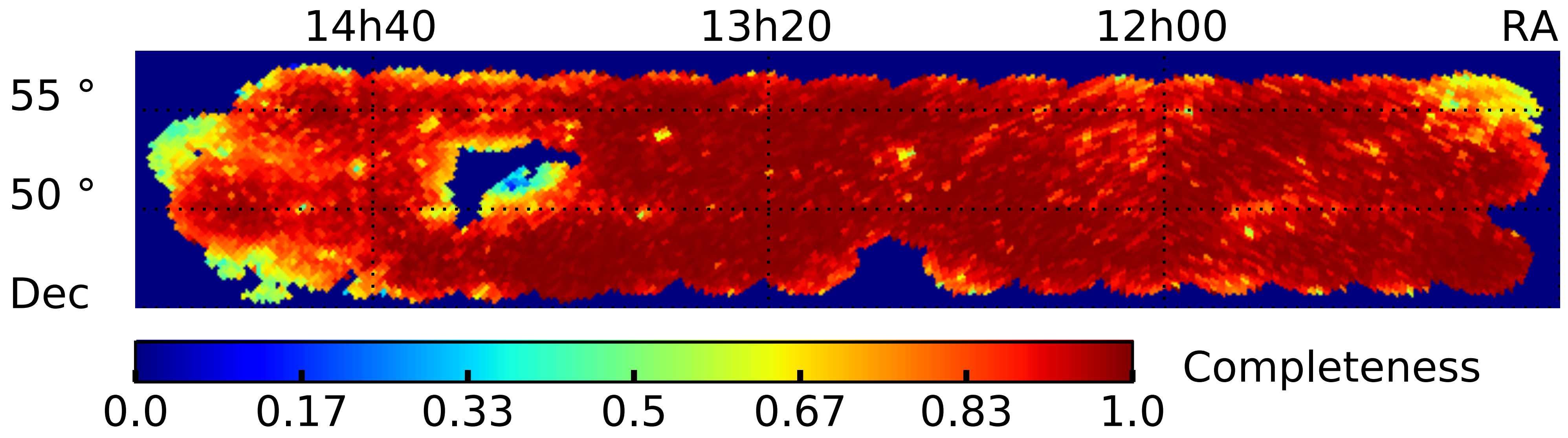
Default mask based on completeness



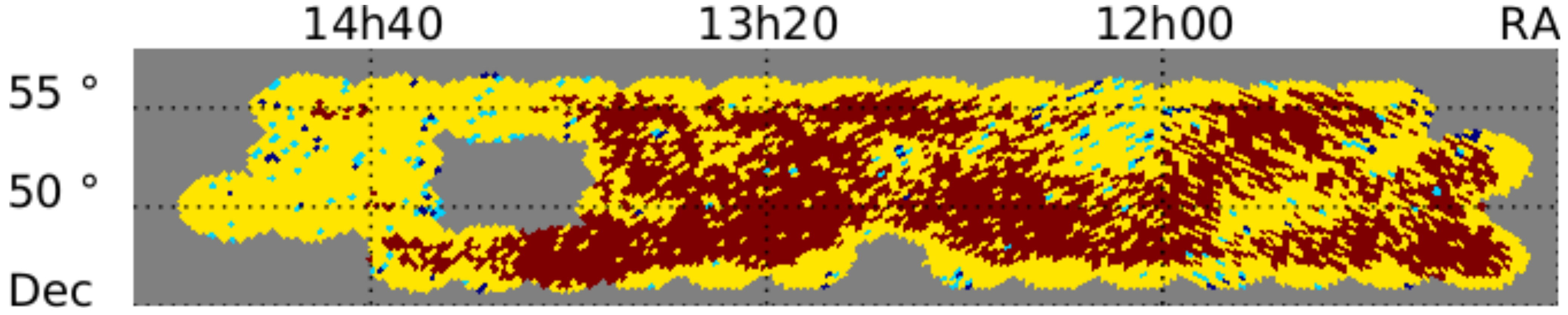
Rms noise per pixel



Pixel completeness for S > 0.39 mJy



Masks based on rms noise per pixel

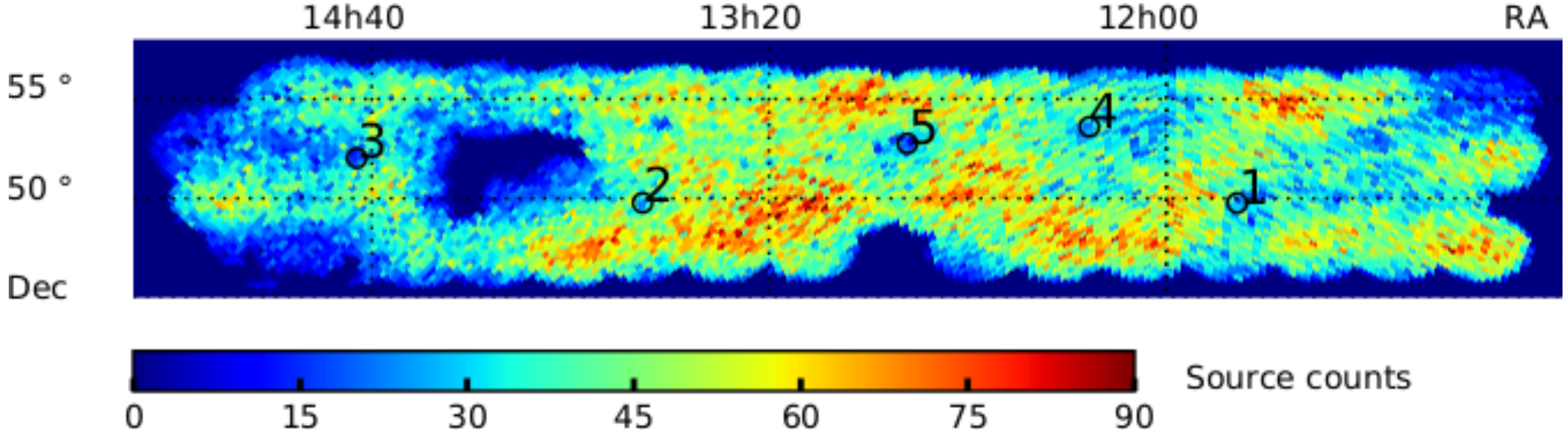


Siewert et al. 2020

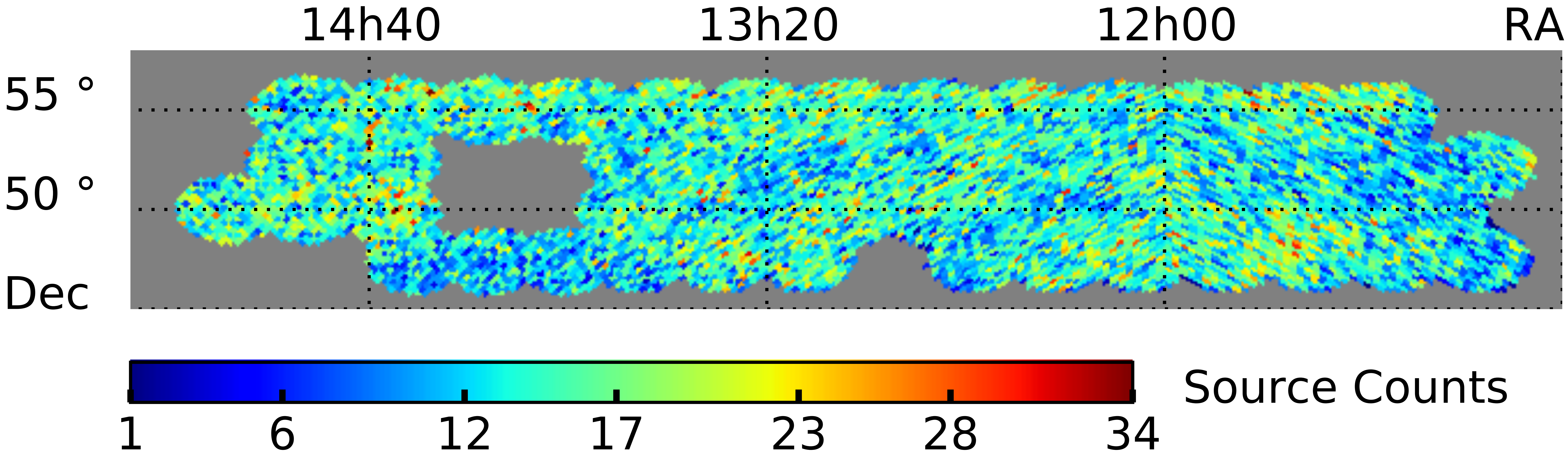
Spatial distribution of radio sources

Radio source distribution from value added source catalogue

Variation mainly due to varying rms noise (ionosphere, calibration)



Apply completeness mask and flux density threshold of S = 1 mJy



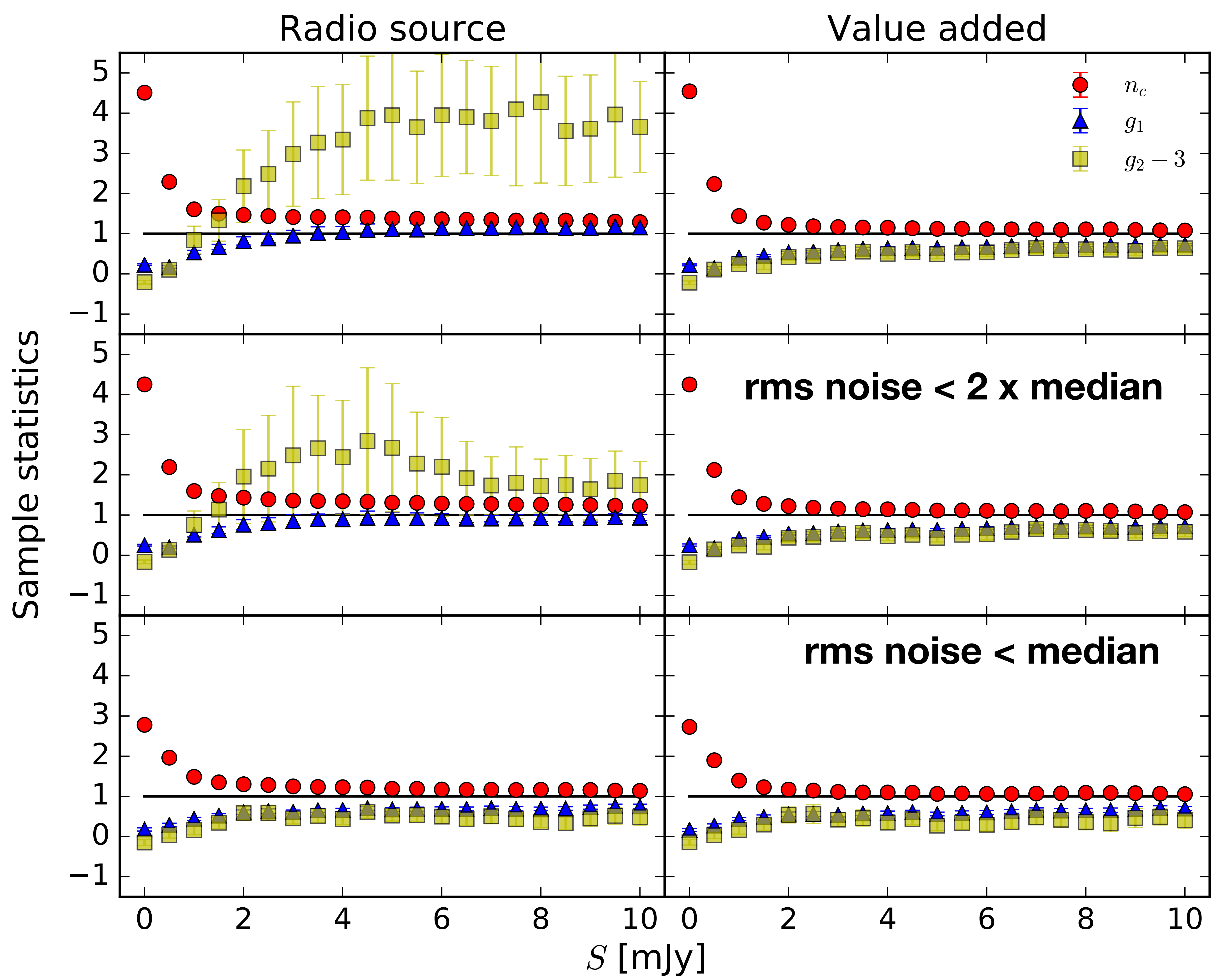
Siewert et al. 2020

Distribution of counts in cell

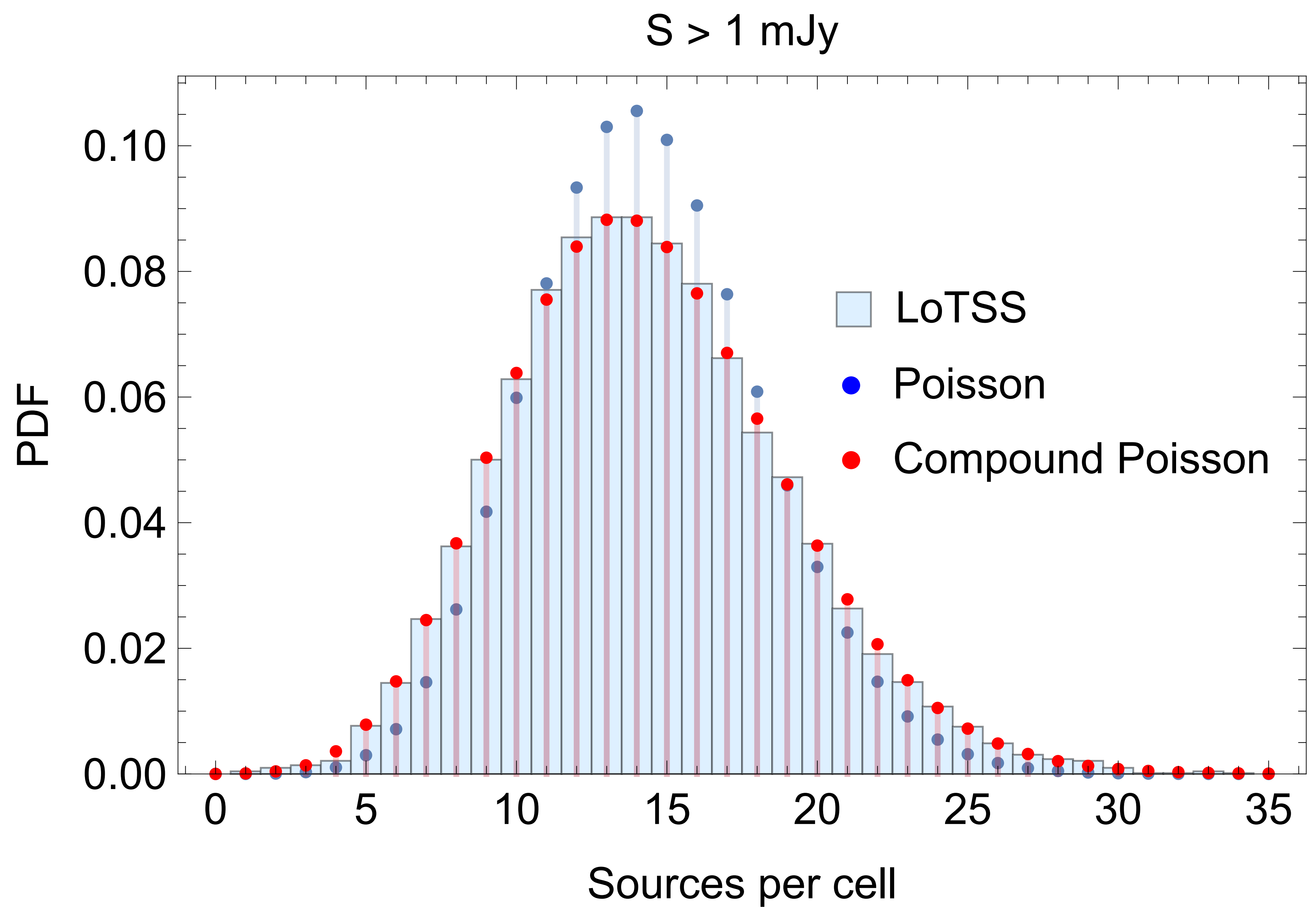
- Counting radio sources per solid angle (cell or pixel) might be expected to be a Poisson process
- Deviations from a Poisson process might be expected due to
(i) resolved sources (blending), (ii) clustering, (iii) multicomponent sources
- (i) is not be an issue as long as flux density is well above confusion limit
(ii) is expected to be a small effect for large pixels, depends on pixel size
(iii) obvious issue: radio source catalogue → value added catalogue
- Cox or compound Poisson process (count components and objects):

$$p_k^{\mathrm{CP}} = \sum_{n=0}^{\infty} \left[\frac{(n\gamma)^k e^{-n\gamma}}{k!} \frac{\beta^n e^{-\beta}}{n!} \right] \qquad \bar{N} \equiv \mathrm{E}[k] = \beta\gamma, \qquad \mathrm{Var}[k] = \beta\gamma(1+\gamma) = \bar{N}(1+\gamma).$$

Distribution of counts in cell



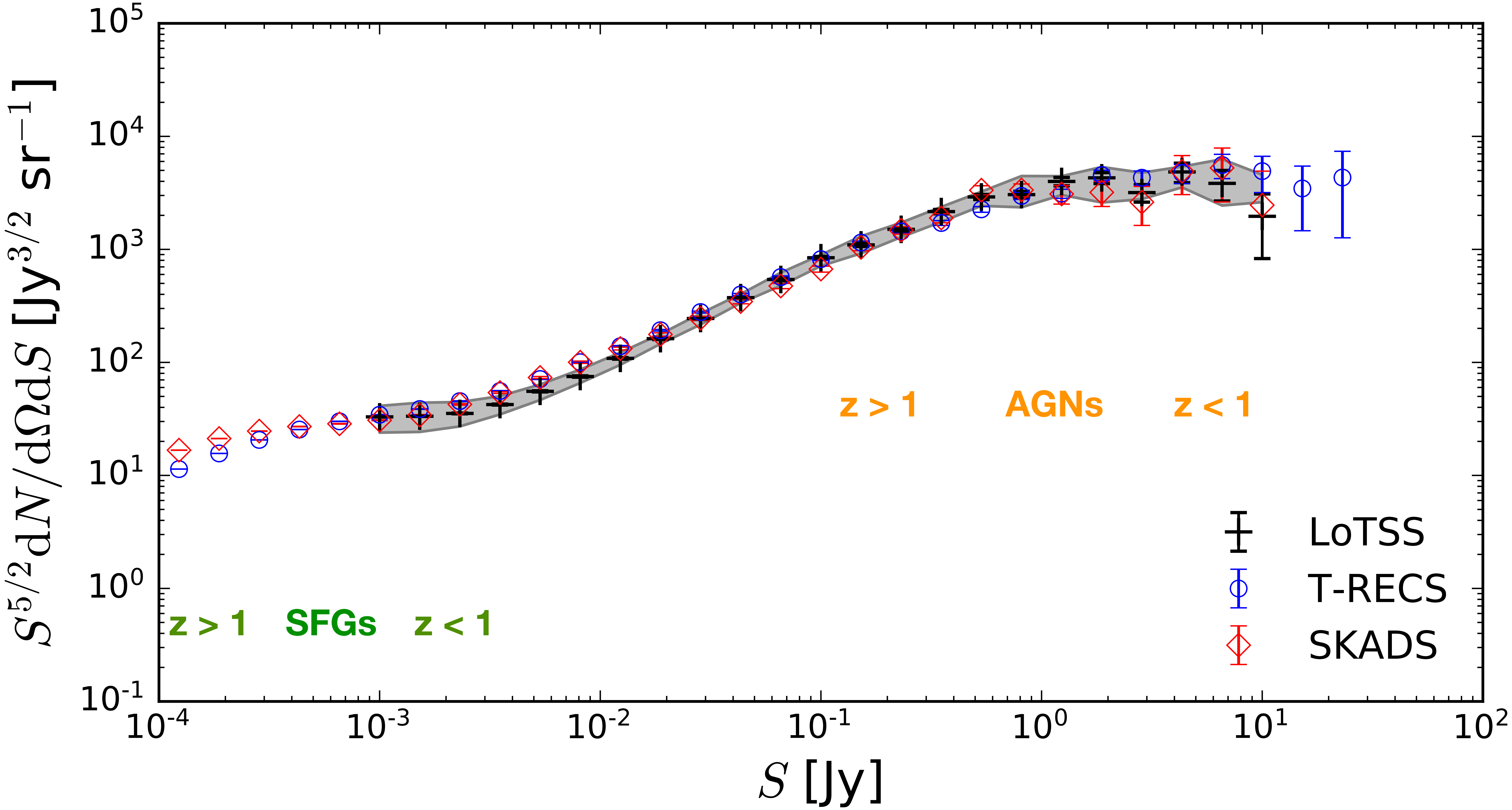
Red: variance/mean Blue: skewness Yellow: excess kurtosis



Sources follow compound Poisson distribution
Must be taken into account when estimating cosmological parameters

Siewert et al. 2020

Differential source counts



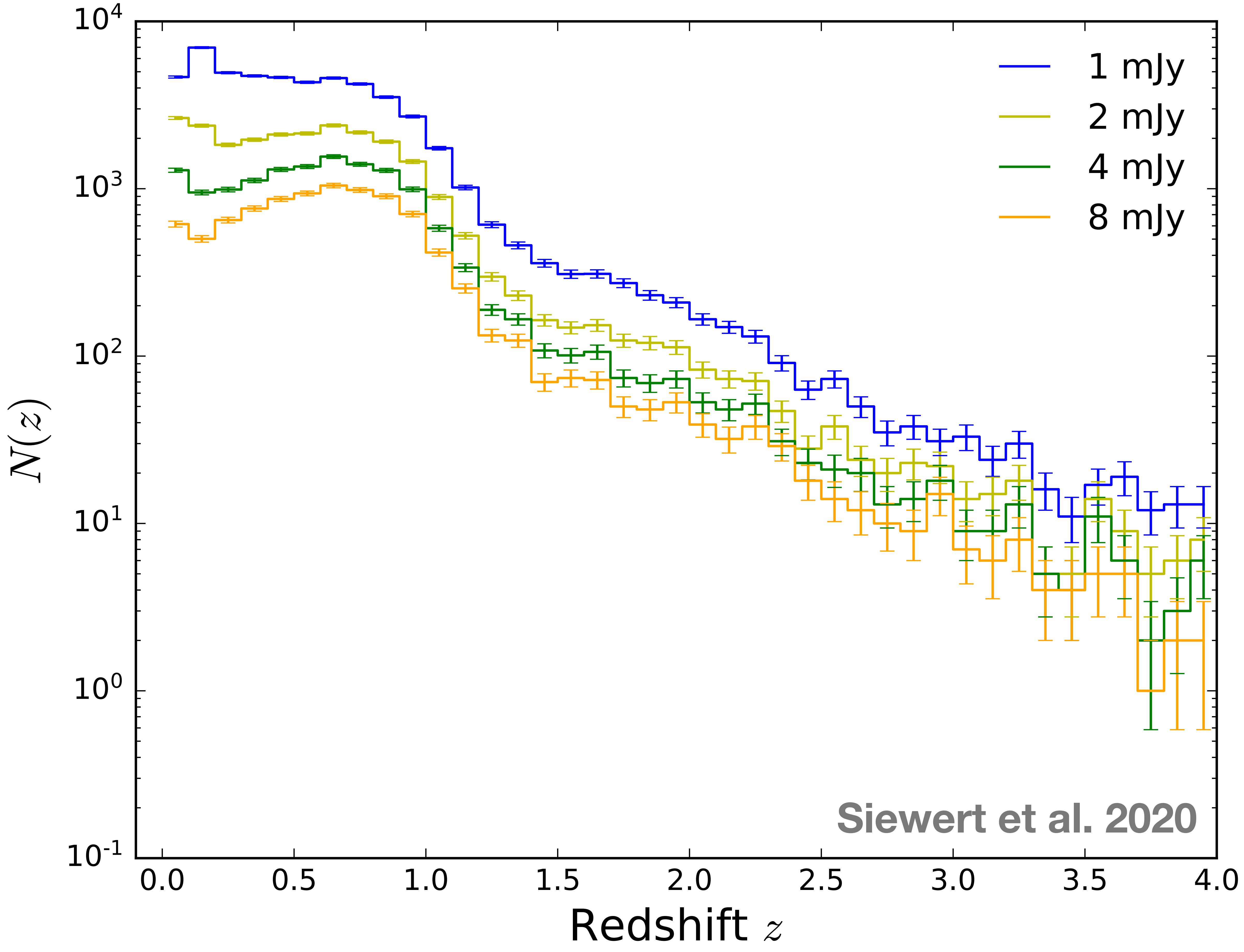
Differential source counts from value added catalogue, normalised to static Euclidean universe; matches other surveys and simulations

Confirms that we see at least two different populations of radio sources: AGNs and SFGs

Use them as independent tracers of the large scale structure

Siewert et al. 2020

Distribution of photo-z’s



Histogram of best redshift estimate (spectroscopic or median of photo-z) for flux limited sample after applying completeness mask

- We have photo-z’s for about 50% of all radio sources of value added catalogue
  Duncan et al. 2019
- photo-z’s based on cross-id’s with Pan-STARRS and WISE
  Williams et al. 2019
- This distribution is not a measurement of the complete radio sample, as there are additional selection effects

Angular two-point correlation

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

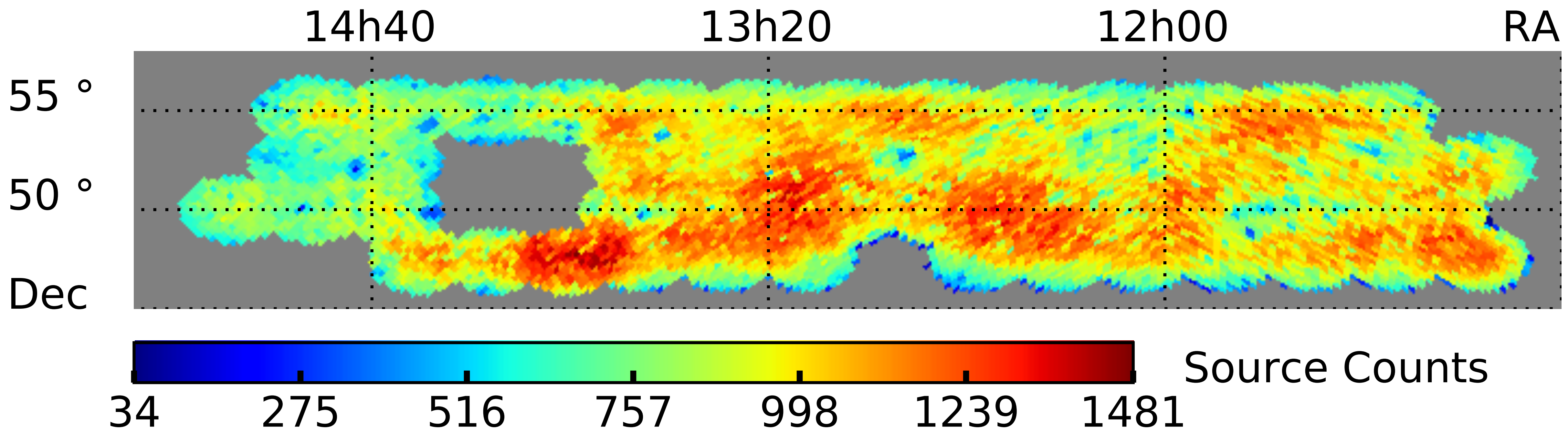
Landy-Szalay estimator (1993): minimal bias and variance

$$\langle \hat{w}(\theta) \rangle = \frac{1 + w(\theta)}{1 + w_\Omega} - 1 \approx w(\theta) - w_\Omega,$$

$$w_\Omega = \frac{\sum_{\mathrm{bins}} RR(\theta) w(\theta)}{\sum_{\mathrm{bins}} RR(\theta)}.$$

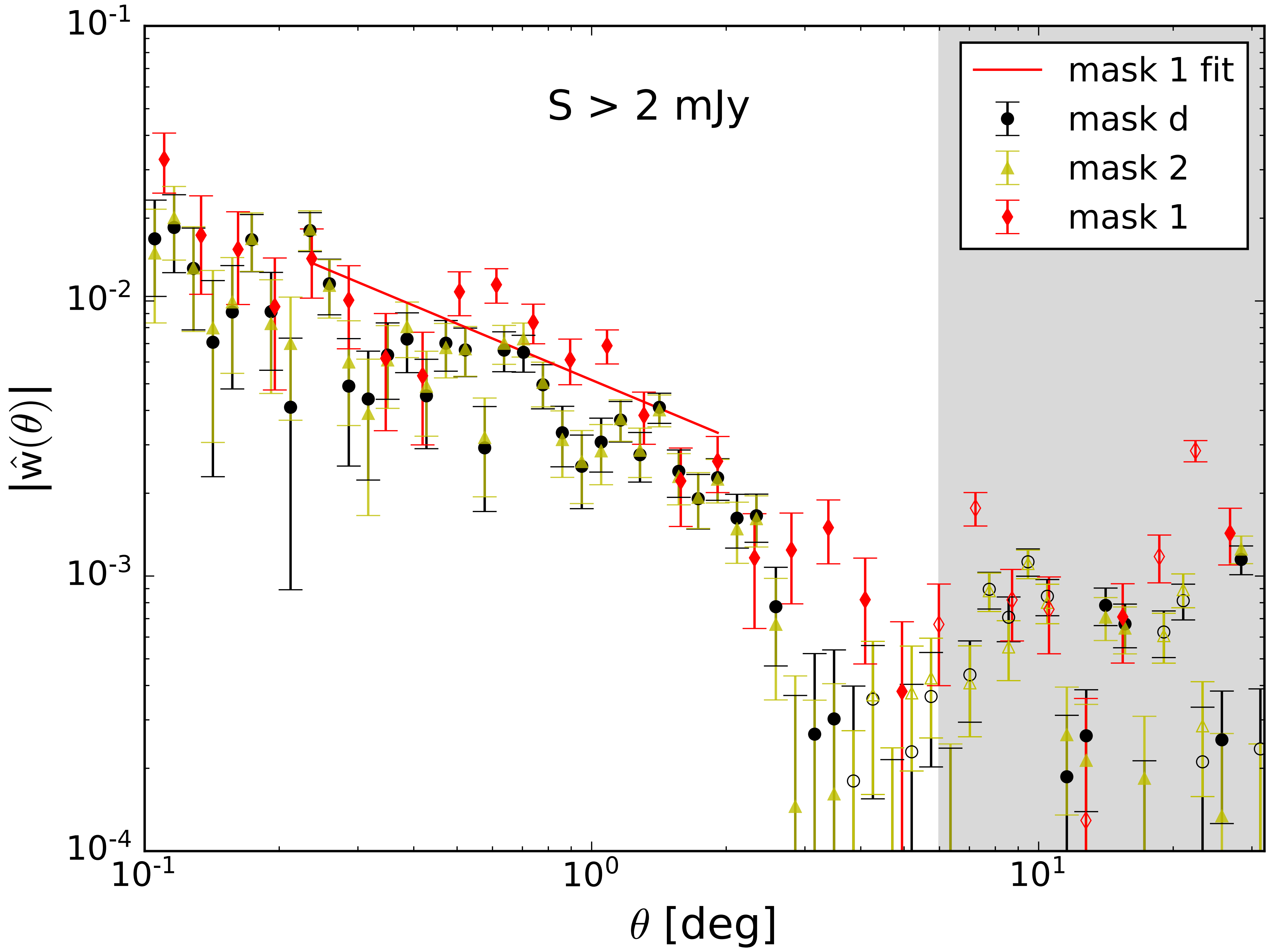
$$\mathrm{Var}[\hat{w}(\theta)] = \left(\frac{1 + w(\theta)}{1 + w_\Omega} \right)^2 \frac{2}{N_\mathrm{d}(N_\mathrm{d} - 1) G_\mathrm{p}(\theta)} \approx \frac{2}{N_\mathrm{d}(N_\mathrm{d} - 1) G_\mathrm{p}(\theta)},$$

Random point source catalogue, based on rms noise map



Siewert et al. 2020

Angular two-point correlation



Siewert et al. 2020

Flux limited angular 2pt correlation from value added catalogue:

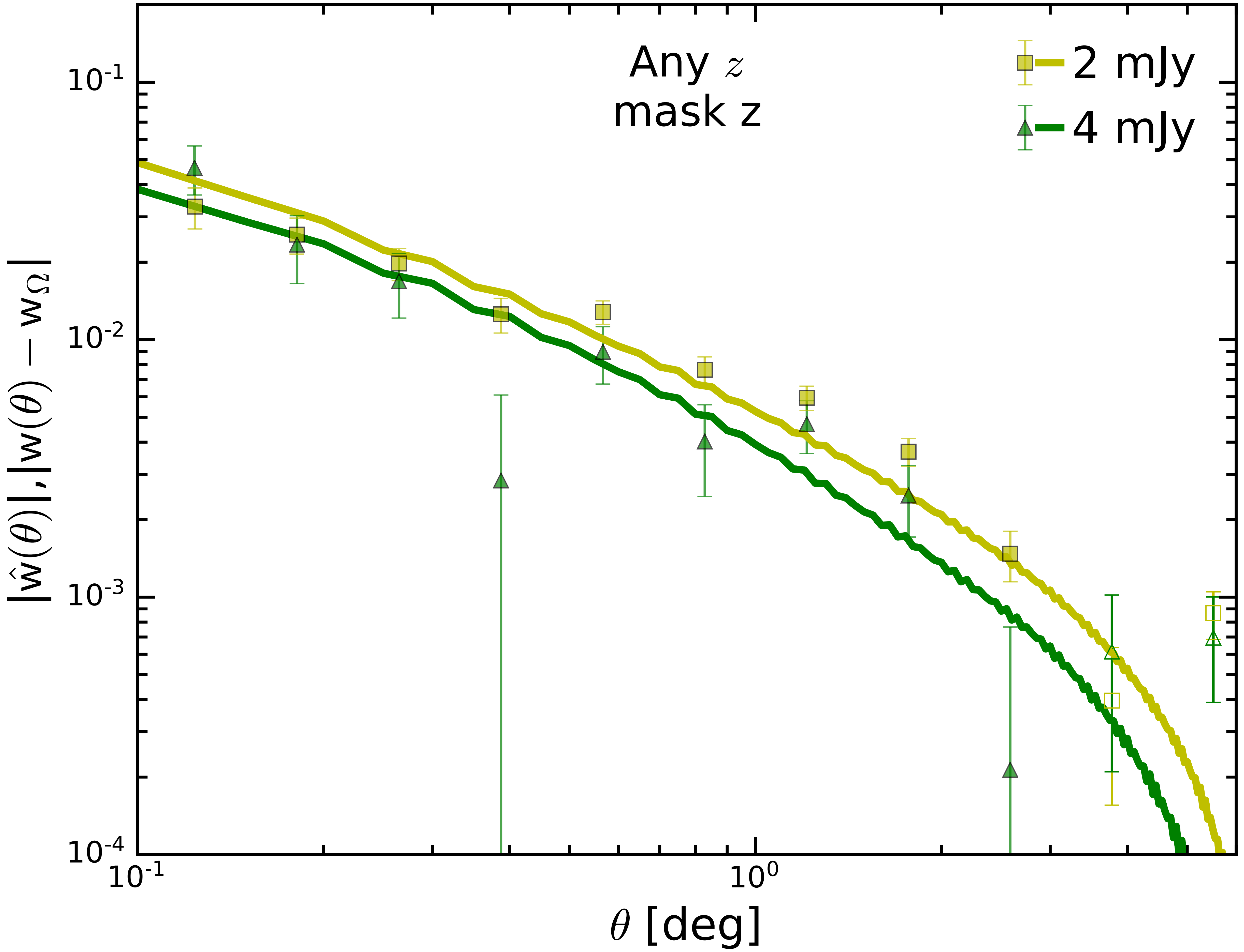
fits a power law at $\theta < 6$ deg

drop at > 2 deg is due to bias, i.e. integral constraint

we identified systematic issues with the flux density calibration between different pointings

(to be addressed in upcoming DR2)

Angular two-point correlation



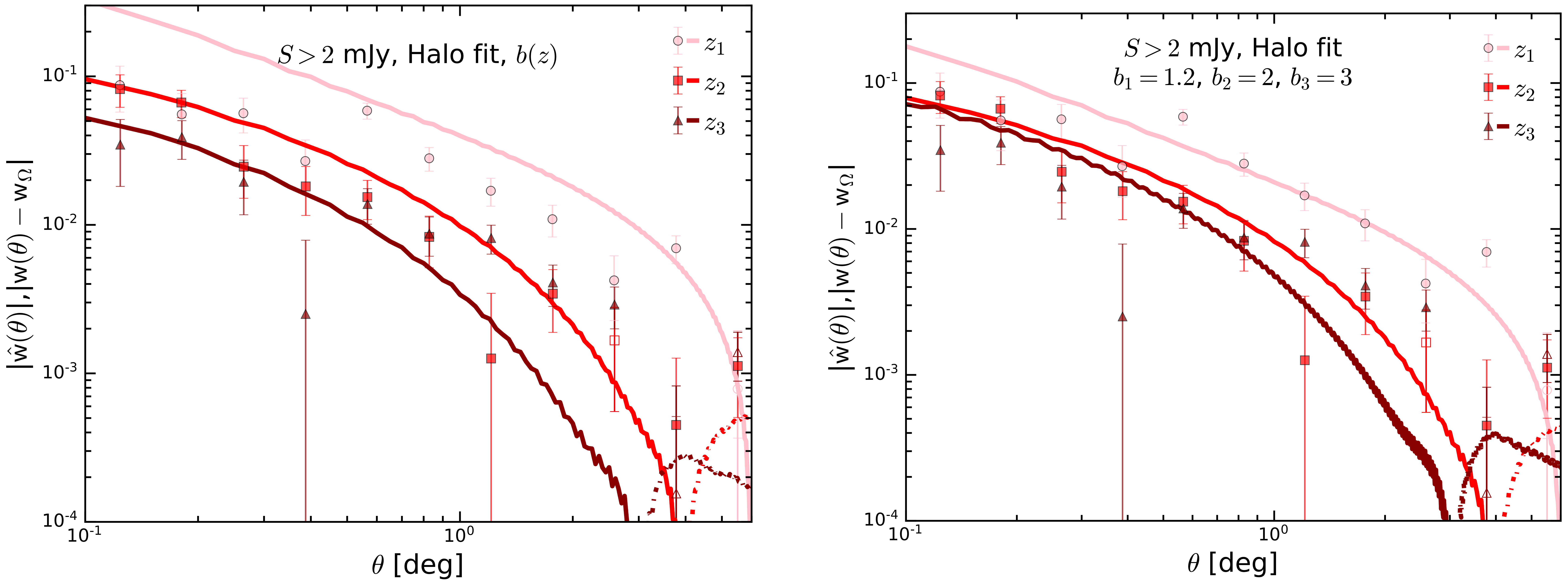
Siewert et al. 2020

Restrict to flux limited photo-z samples and $\theta < 6$ deg:

Compare LoTSS data to a prediction based on **Planck 2018 best-fit cosmology**, **LoTSS photo-z distribution**, a **bias function** based on NVSS sources, $b(z) = 1.6 + 0.85z + 0.33z^2$ **(Tiwari & Nusser 2016)**, with **halo fit** and **lensing** options obtained by **CAMBsources**

Good agreement, no free fit parameter

Angular two-point function for three redshift bins



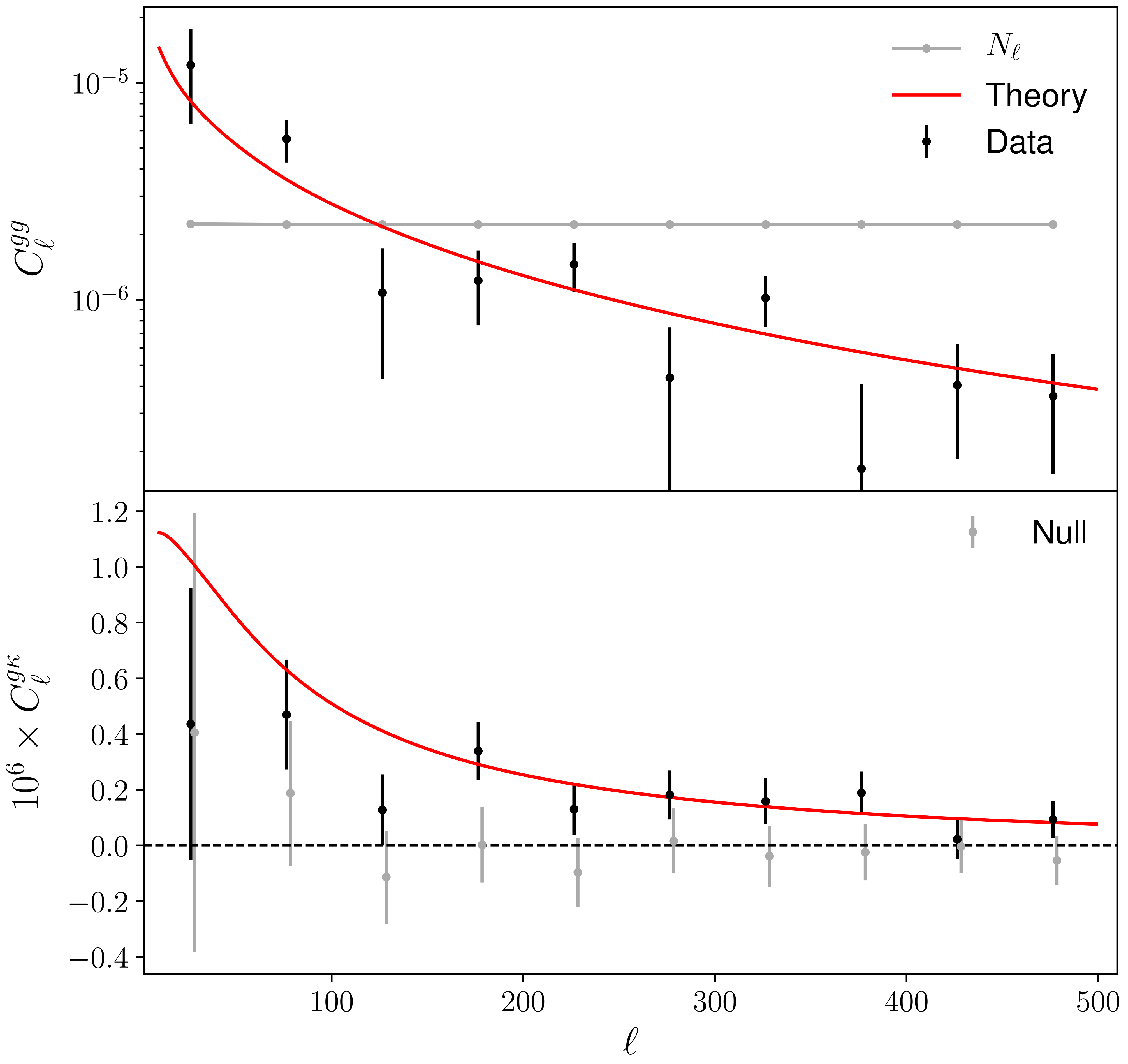
Compare different bias functions for three redshift bins ($z_1 :\ 0 < z < 0.38;\ z_2 :\ 0.38 < z < 0.71;\ z_3 :\ 0.71 < z$ **)**

Data are consistent with the growth of structure as the universe expands, BUT

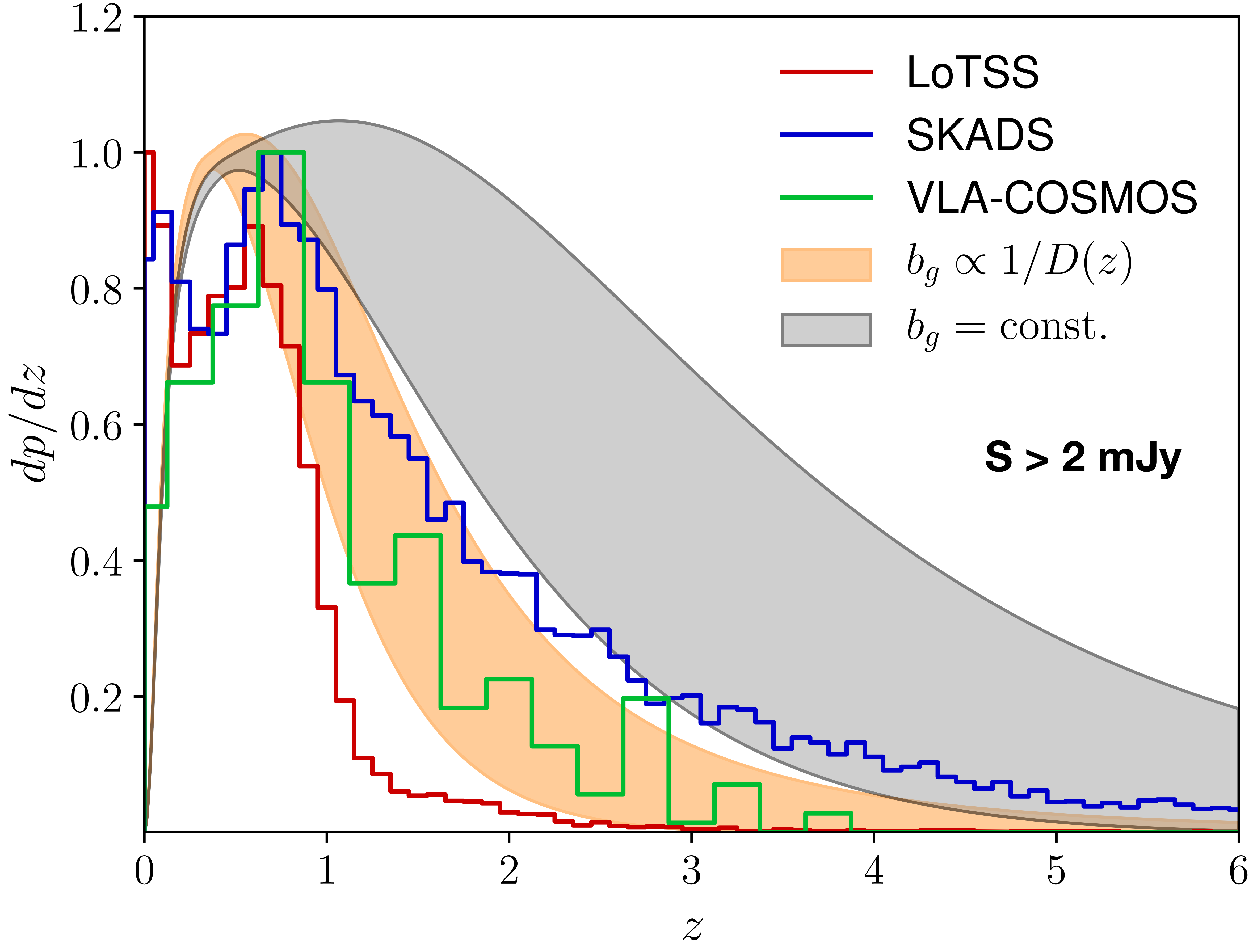
require better understanding/measurement of bias before we can start to extract cosmological parameters

Siewert et al. 2020

Cross-correlation with CMB lensing



Galaxy-galaxy and galaxy-lensing convergence correlation (LoTSS-DR1— Planck)
Theory is based on SKADS and Planck 2018 best-fit cosmology with bias ~ 1/D(z)

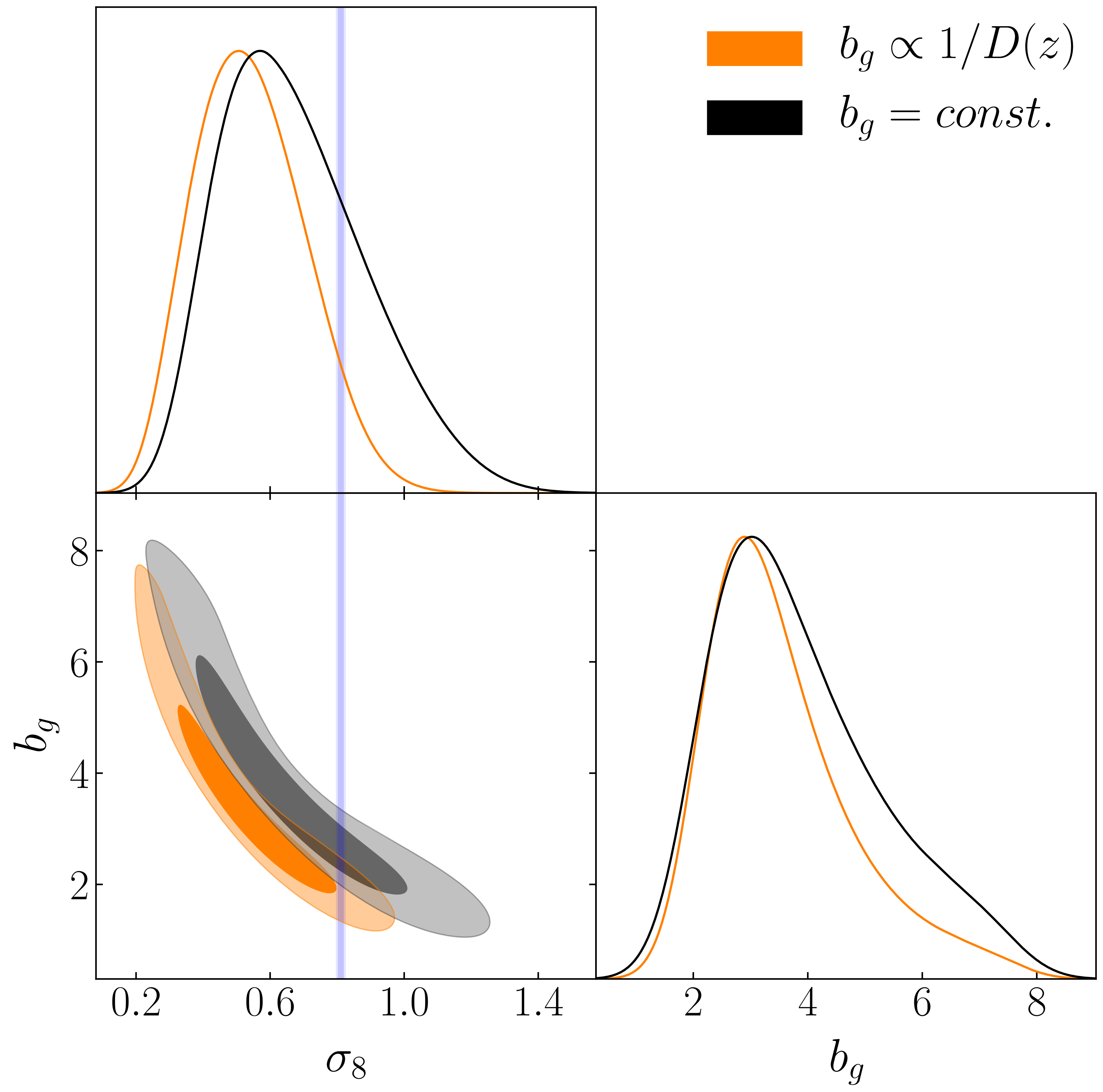


Reconstruction of redshift distribution for all LoTSS soucres depends on bias

Alonso et al. 2020

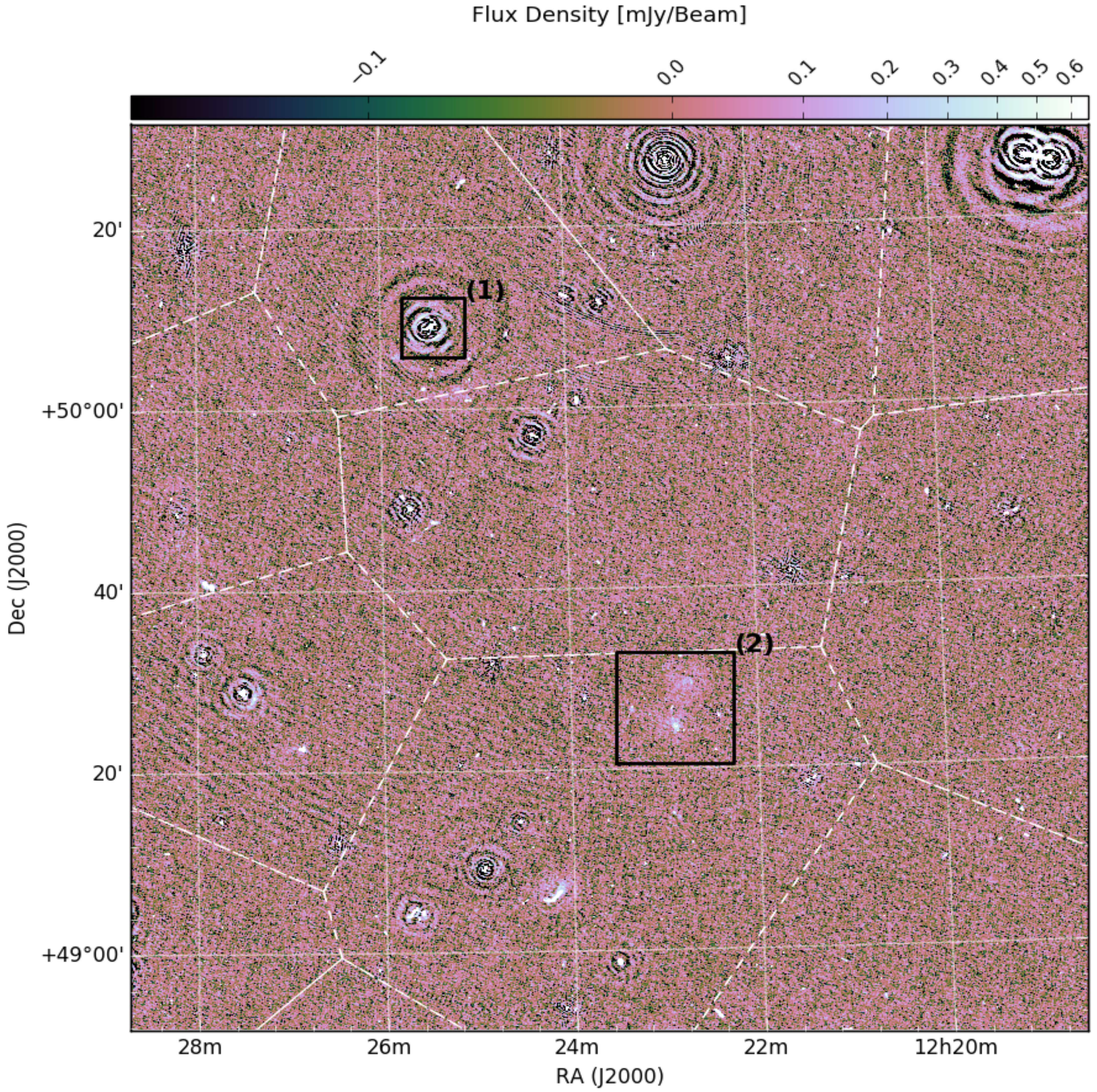
Cosmic tensions

- Can LoTSS contribute to the discussion of the H_0 and S_8 tensions?
- Not with LoTSS-DR1, but a first test is promising
- LoTSS-DR1 data disfavour constant bias, evolving bias prefers lower value of S_8
- Need to break degeneracies between redshift distribution and bias function (is the same for H_0)

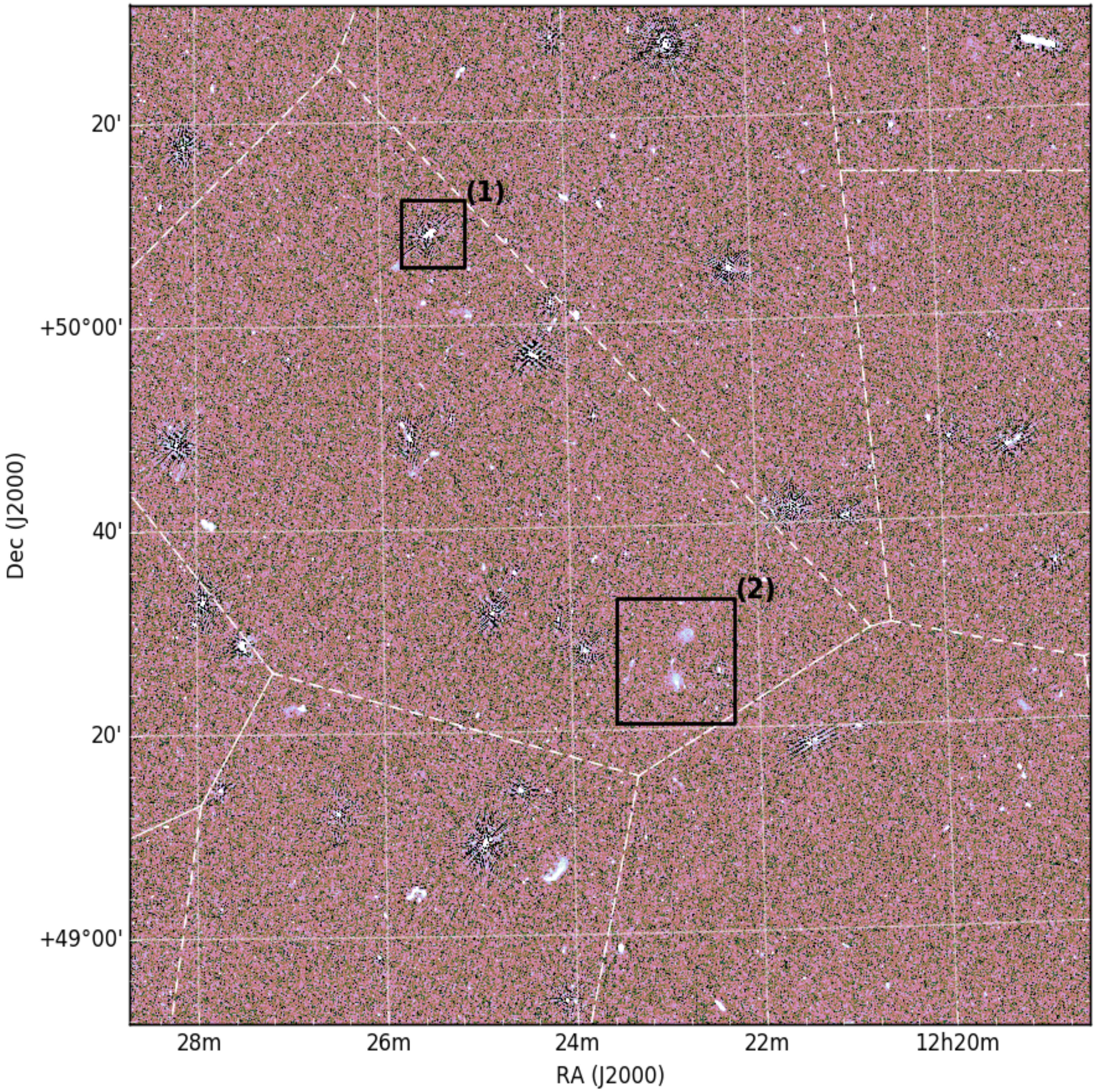


Alonso et al. 2020

Improved imaging algorithm



LoTSS-Wide DR1



LoTSS-Deep DR1 & LoTSS-DR2

Tasse et al. 2020

Sky temperature at 144 MHz

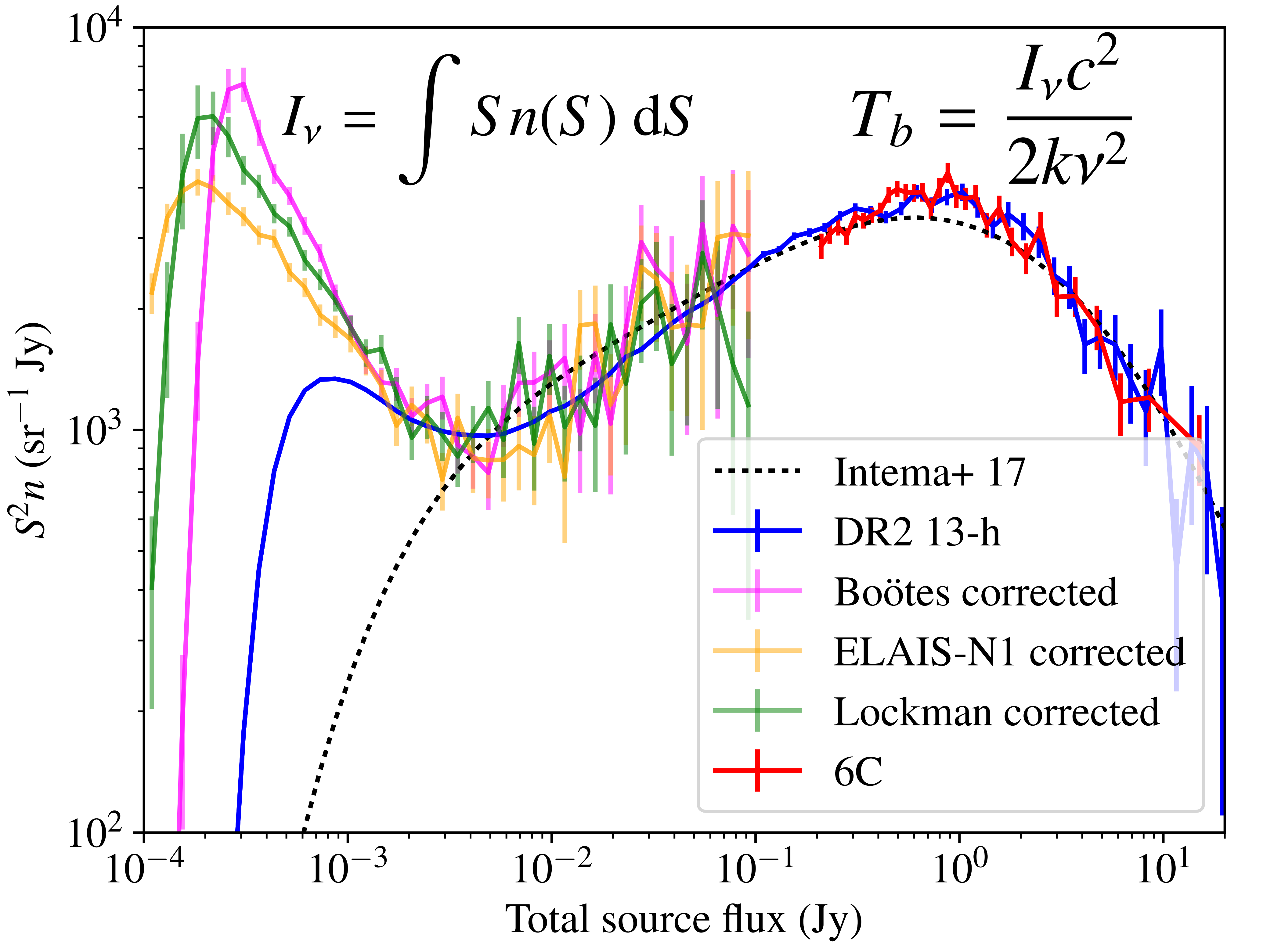
- ARCADE 2: excess radiation over CMB plus Milky Way at high radio frequencies
  Fixsen et al 2011

- Can the extragalactic radio background explain the excess?

- LoTSS Deep Fields: $T_{\mathrm{sky}\ (144\ \mathrm{MHz})} = 44 \pm 2$ K, does not explain $T_{\mathrm{ARCADE2}\ (\mathrm{extrapolated\ to\ 144\ MHz})}$ ~190 K

- Unlikely that ARCADE 2 excess is due to extragalactic radio sources, unless they are huge (> 1 deg)

- Also relevant to EDGES result, extrapolation to 78 MHz: $T_{\mathrm{sky}\ (78\ \mathrm{MHz})} = 235 \pm 18$ K
  (assuming spectral index - 2.7 ± 0.1)



Hardcastle et al. 2020

Conclusions

- At 144 MHz, radio sources above 2 mJy are dominantly AGNs, which are distributed over a huge range in redshift.
- Allow us to study the evolution of structure formation from high z utill today.
- At flux densities below 2 mJy, SFGs dominate and will allow us to investigate the largest scales on the sky at $z < 1$, as radio sources do not suffer from dust extinction and we can therefore observe wider area than optical surveys.
- **The distribution of large scale structure as inferred from LoTSS-DR1 is compatible with statistical isotropy and the Planck 2018 best-fit model.** With LoTSS-DR2 will allow us to measure several cosmological parameters.
- The **counts-in-cell statistics deviates from a Poissonian distribution**, a compound Poisson distribution provides a good fit.
- **Faint extragalactic radio sources can make up 1/4 of the ARCADE-2 excess radiation.**

Outlook

- LoTSS Deep Fields DR1 (Böotes, Lockman hole, Elias-N1: measure **redshift distribution** (95% of all sources have photo-z's), **AGN/SFG separation,** corresponding **luminosity functions,** and their **evolution** (in press A&A, 2021)

- Use **LoTSS-DR2** (5700 square degrees, 4.5 million radio sources, improved flux density calibration, **second half of 2021**) to gain an order of magnitude in sky coverage and statistics, will allow us to constrain cosmological models

- **LOFAR-WEAVE** (to start in 2021) will provide spectroscopic follow up of 1 million LoTSS selected radio sources

- **LoLSS:** Corresponding survey at 42 — 66 MHz, will cover 25 - 30% of sky

Acknowledgements
LOFAR Surveys Key Science Project

ASTRON
Universiteit Leiden
SURF
Science and Technology Facilities Council
University of Hertfordshire
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
The Open University
THE UNIVERSITY of EDINBURGH
UCD DUBLIN
SPONSORED BY THE
Federal Ministry of Education and Research
INAF ISTITUTO NAZIONALE DI ASTROFISICA
l'Observatoire de Paris
UNIVERSITÄT BIELEFELD

Thank you for your attention

Support us in the cross id effort by visiting lofargalaxyzoo.nl

References

- T.W. Shimwell et al., *The LOFAR Two-metre Sky Survey II: First Data Release*, A&A 622 (2019) A1, arXiv:1811.07926
- W.L. Williams et al., *The LOFAR Two-metre Sky Survey (LoTSS) III. First Data Release: optical/IR identifications and value-added catalogue*, A&A 622 (2019) A2, arXiv:1811.07927
- K.J. Duncan et al., *The LOFAR Two-metre Sky Survey IV. First Data Release: Photometric redshifts and rest-frame magnitudes*, A&A 622 (2019) A3, arXiv:1811.07928
- T.M. Siewert et al., *One- and Two-point Source Statistics from the LOFAR Two-metre Sky Survey First Data Release*, A&A 643 (2020) A100, arXiv:1908.10309
- D. Alonso et al., *Cross-correlating radio continuum surveys and CMB lensing: constraining redshift distributions, galaxy bias and cosmology*, arXiv:2009.01817
- C. Tasse et al., *The LOFAR Two Meter Sky Survey: Deep Fields, I -- Direction-dependent calibration and imaging,* arXiv:2011.08328
- M.J. Hardcastle et al., *The contribution of discrete sources to the sky temperature at 144 MHz*, arXiv:2011.08294