Universität Bielefeld

The angular two-point correlation function of LoTSS radio sources

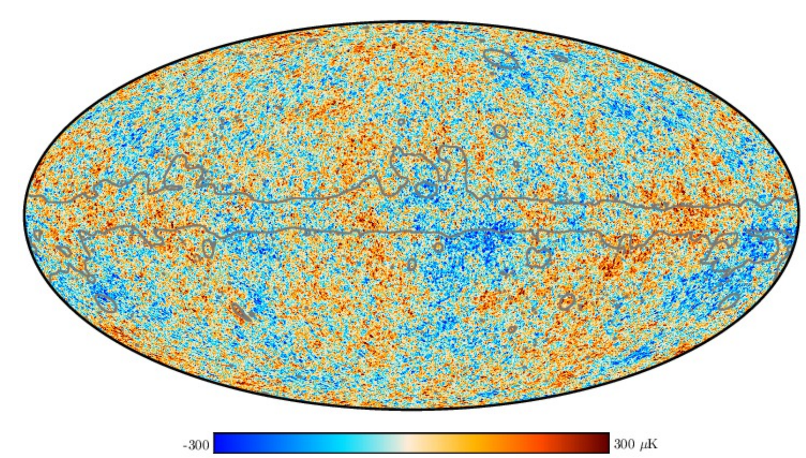
Dominik J Schwarz

and

Thilo Siewert, Catherine Hale, Nitesh Bhardwaj, Marian Biermann, David Bacon, Matt Jarvis, Huub Röttgering, Tim Shimwell and LOFAR Surveys KSP

Cosmology after Planck

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



Planck collaboration 2018

Consequences for radio sky

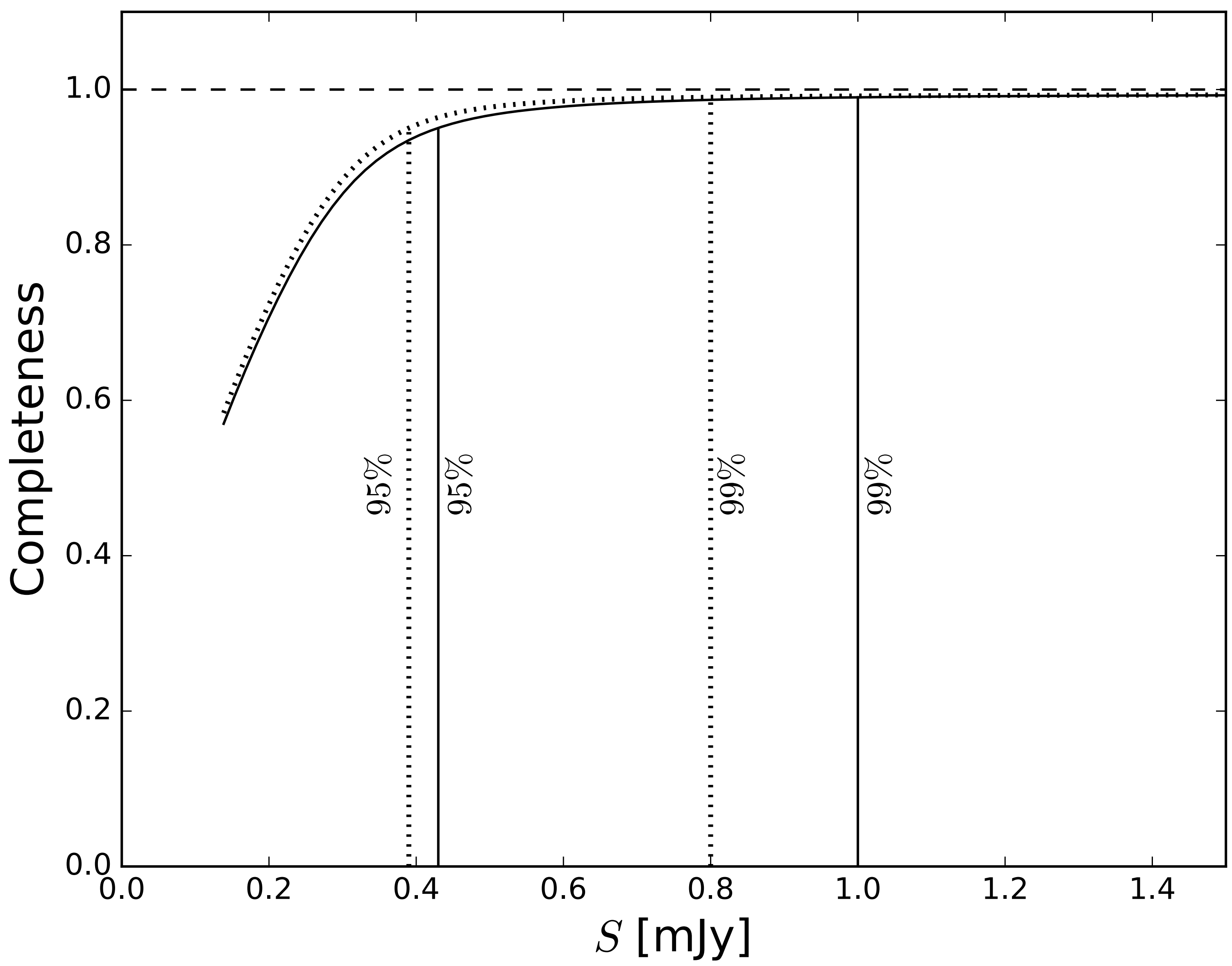
- Statistically isotropic distribution of radio sources
- For Gaussian fluctuations all information is contained in one- and two-point correlation functions

Focus on one- and two-point statistics of LoTSS-DR1

Draft written, to be submitted soon (Siewert et al.)

RESULTS PRESENTED HERE ARE PRELIMINARY

Point-source completeness

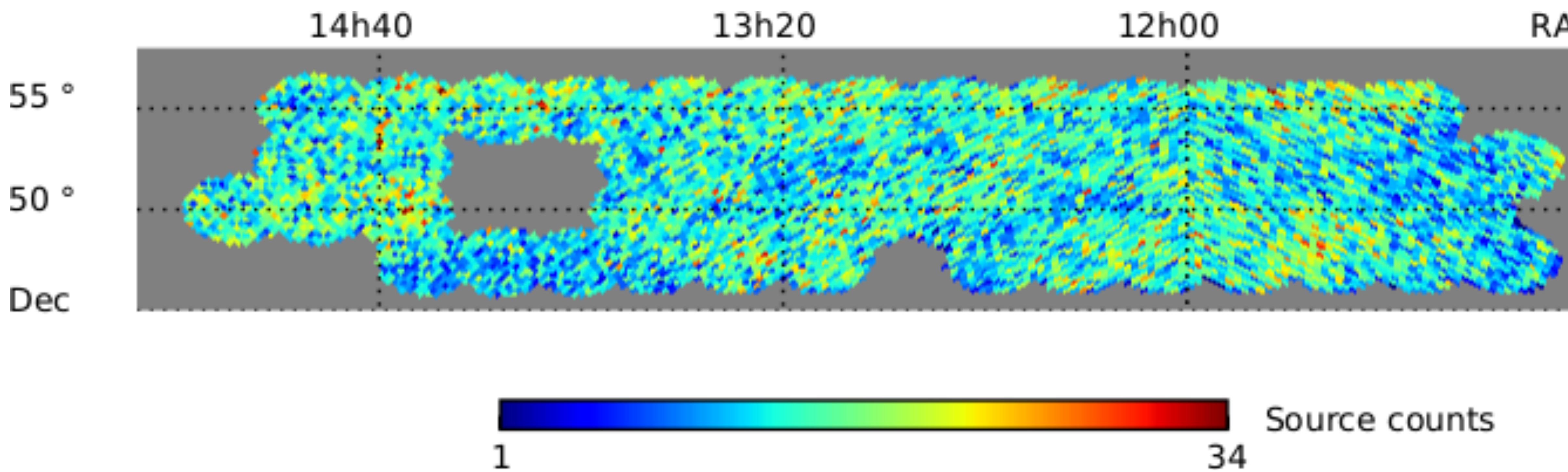


Full lines:
all 58 LoTSS-DR1 pointings,
325,694 sources

Dashed lines:
omit 5 most incomplete pointings,
306,670 sources

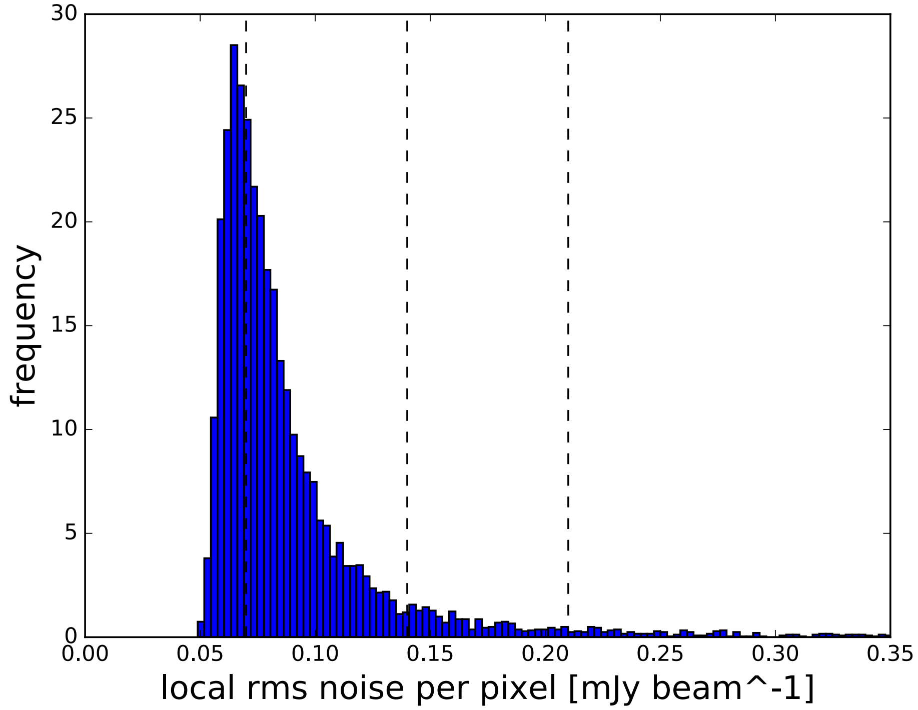
99% point-source complete at S > 1 (0.8) mJy for 58 (53) pointings

LoTSS-DR1 value added source catalogue counts-in-cell map

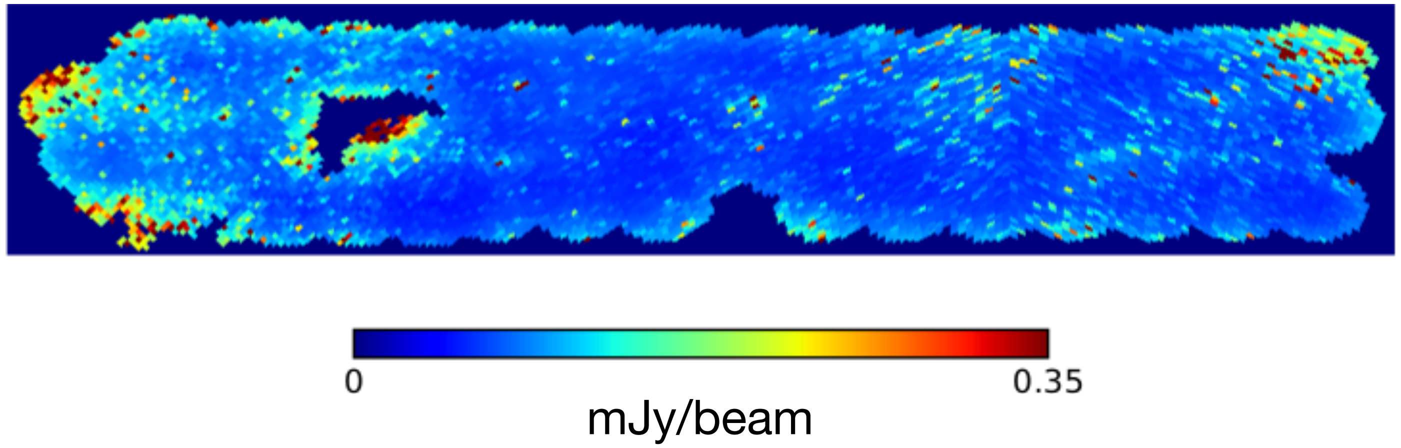


**Healpix Nside = 256, counts in cell all sources after masking and for S > 1 mJy ,
Map contains 102 940 radio sources**

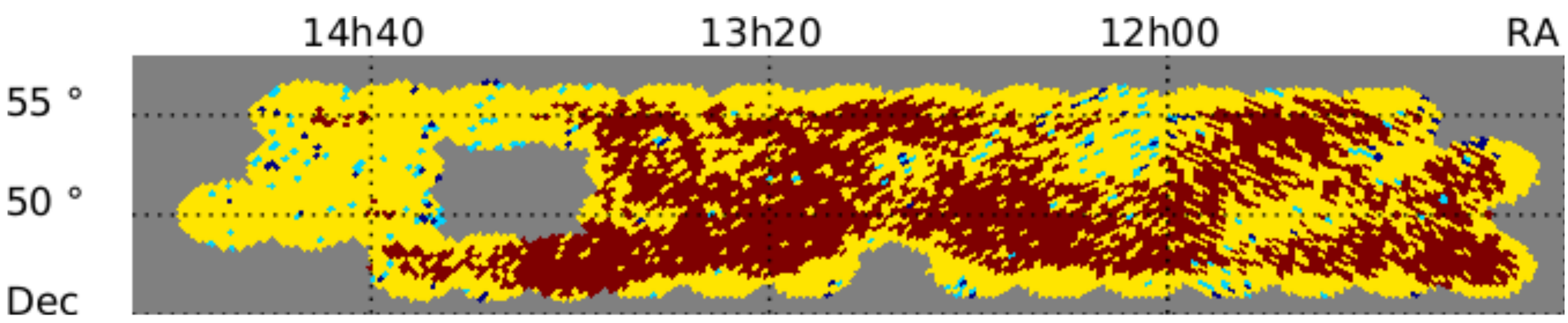
Set of masks



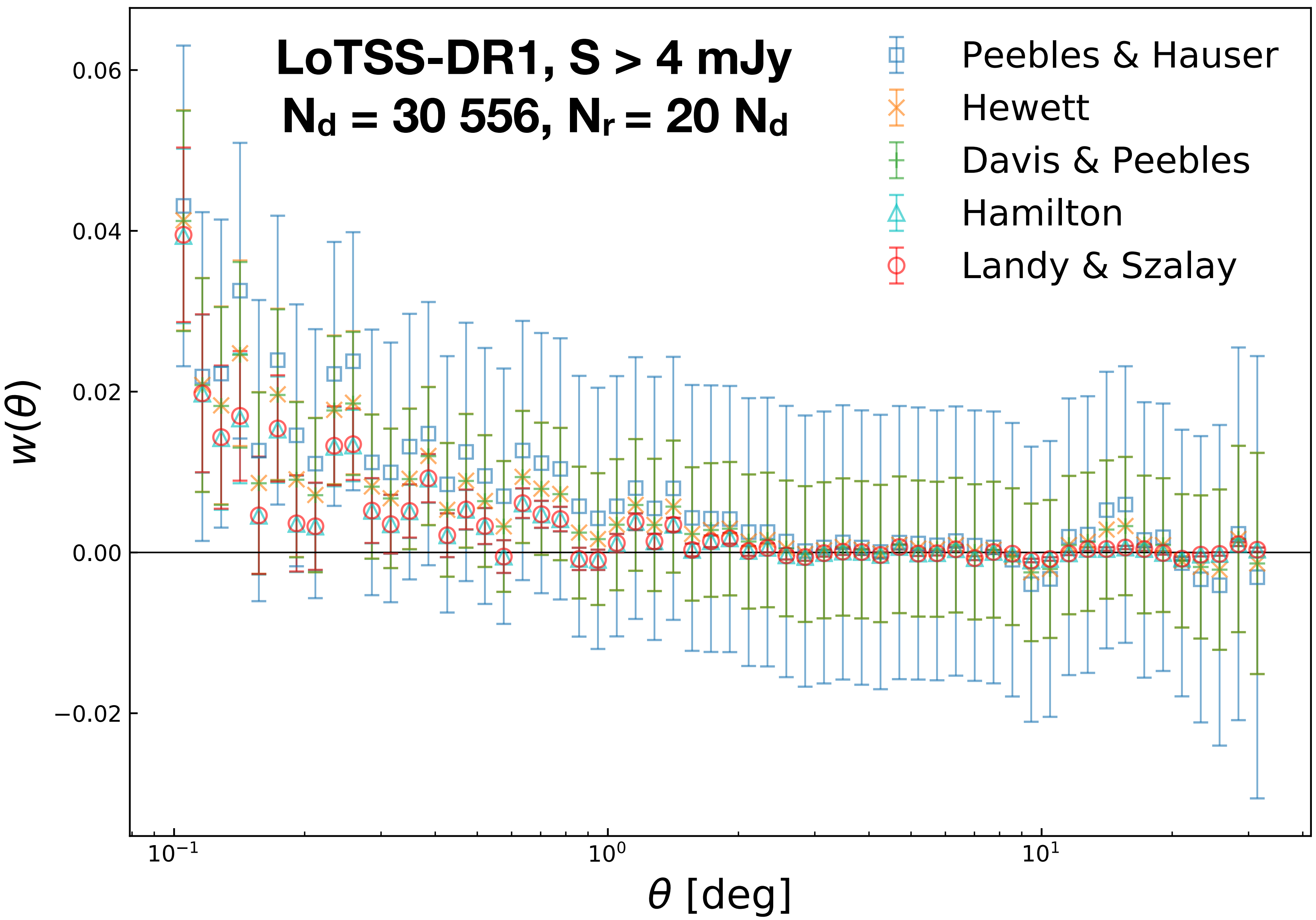
map of rms noise per Healpix cell



mask 1 2 3 **d** (remove incomplete pointings and incompletely sampled cells)



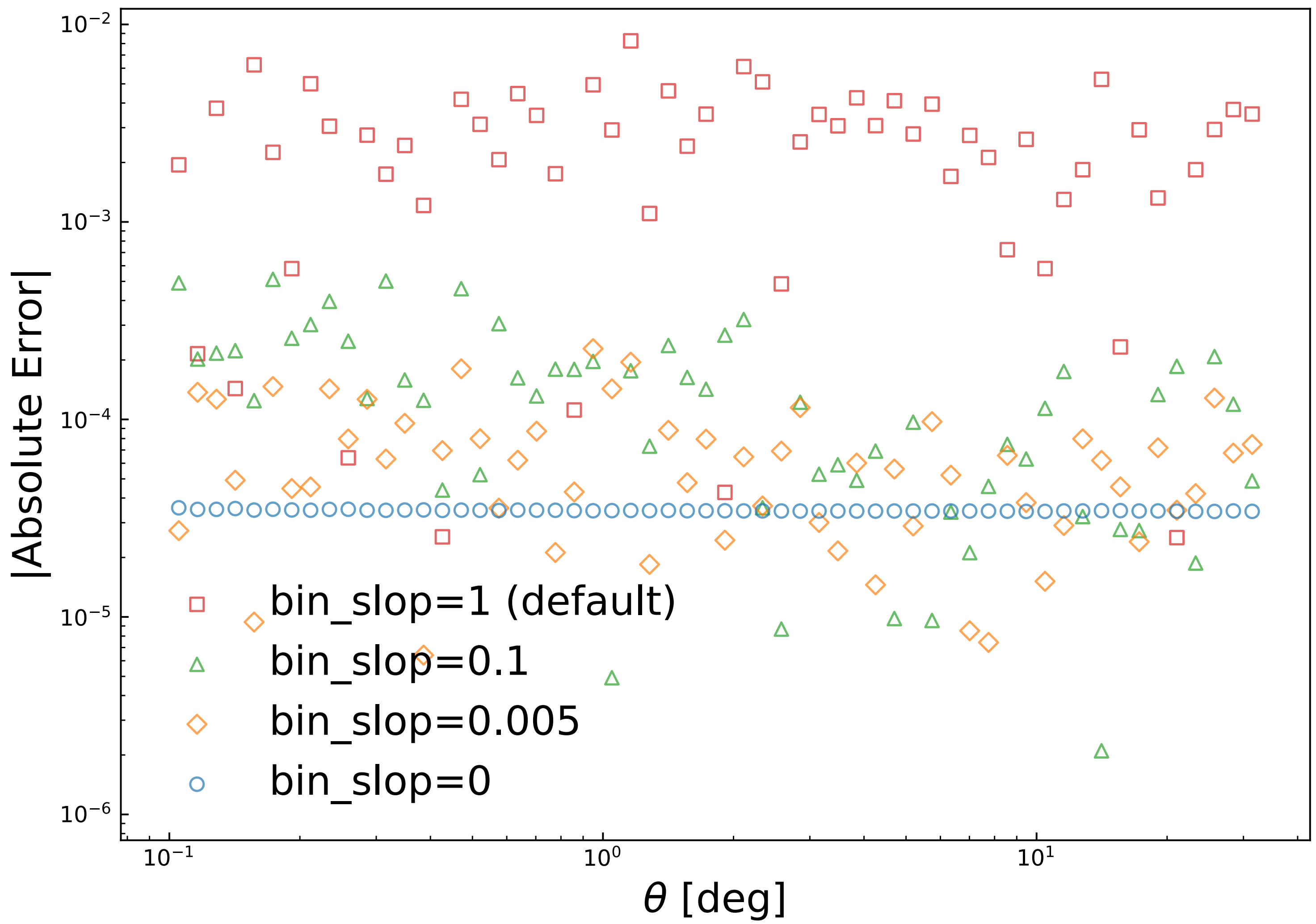
Estimator



Landy-Szalay (1993) **estimator: minimal bias and minimal variance**
w = (DD - 2 DR + RR)/RR

Landy & Szalay and Hamilton estimators are superior

Accuracy of algorithm

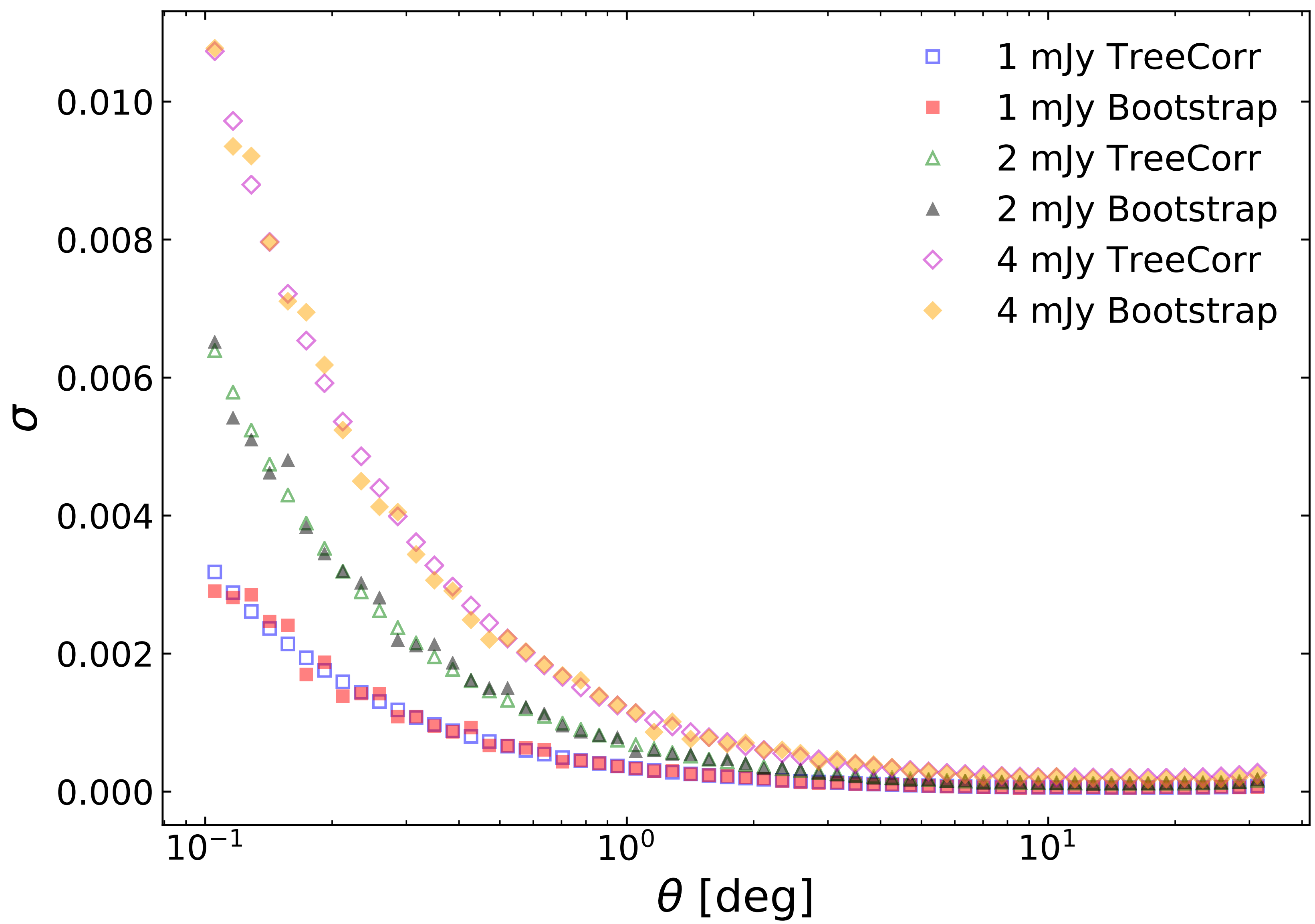


Calculation of 2pt correlation is numerically compute intense:
N(random) >> N(data),
problem scales with N(random)2**

TreeCorr code by Jarvis et al. (1993) **approximates and speeds up calculation based on a tree algorithm**

We tested TreeCorr by comparing it to a self-written brute force code: default setting of TreeCorr is not good enough for our purpose

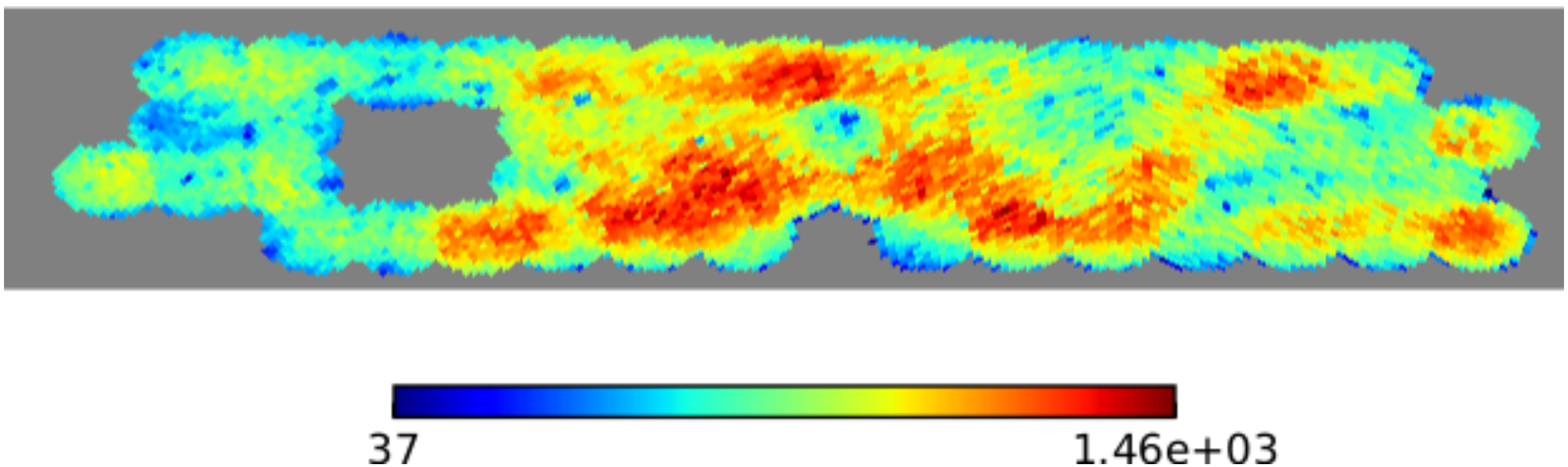
Error estimation



TreeCorr: standard deviation estimated from variance of LS estimator
Bootstrap: standard deviation estimated from 100 bootstrap samples

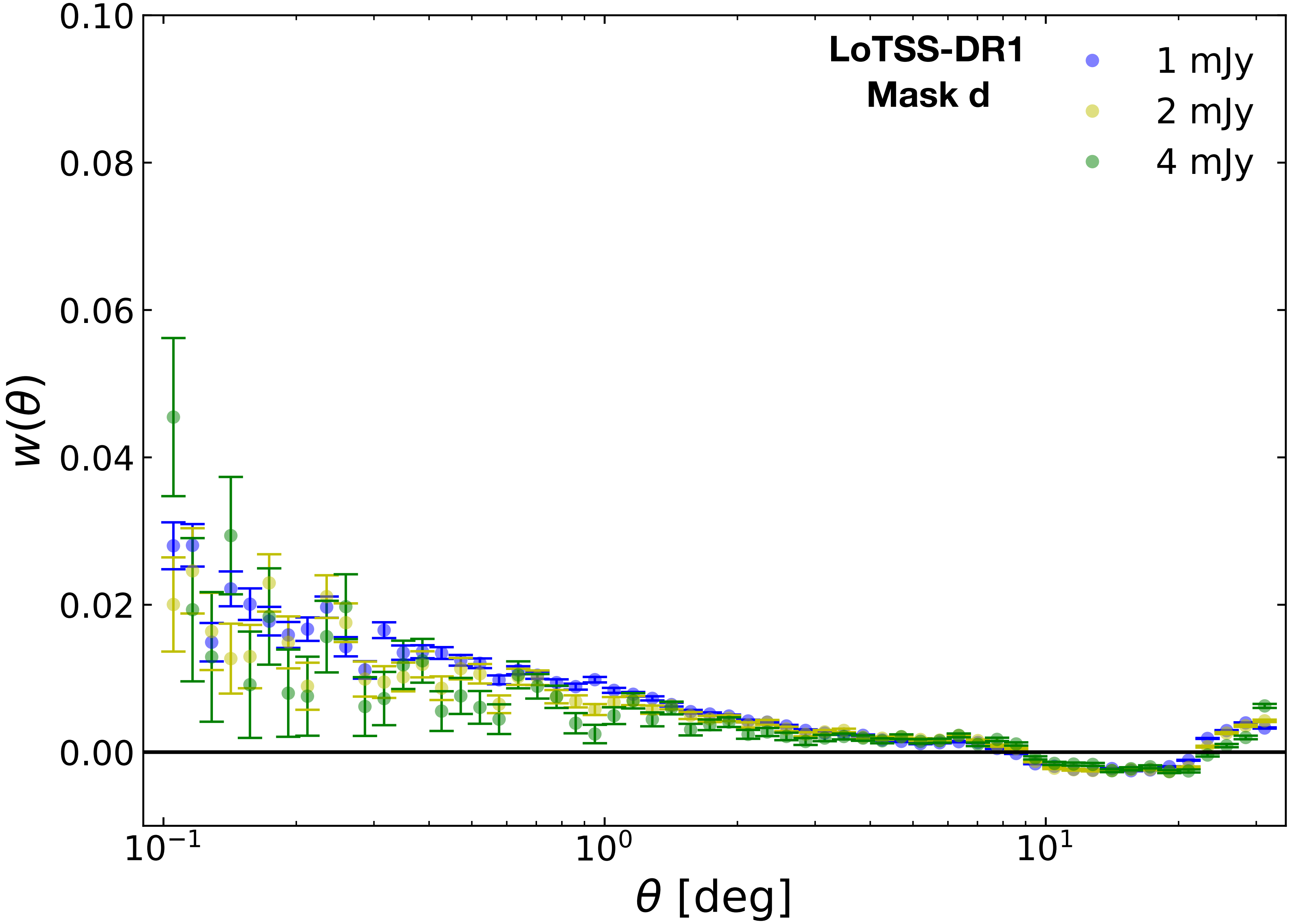
Excellent agreement of expectation and bootstrap result

Mock catalogues



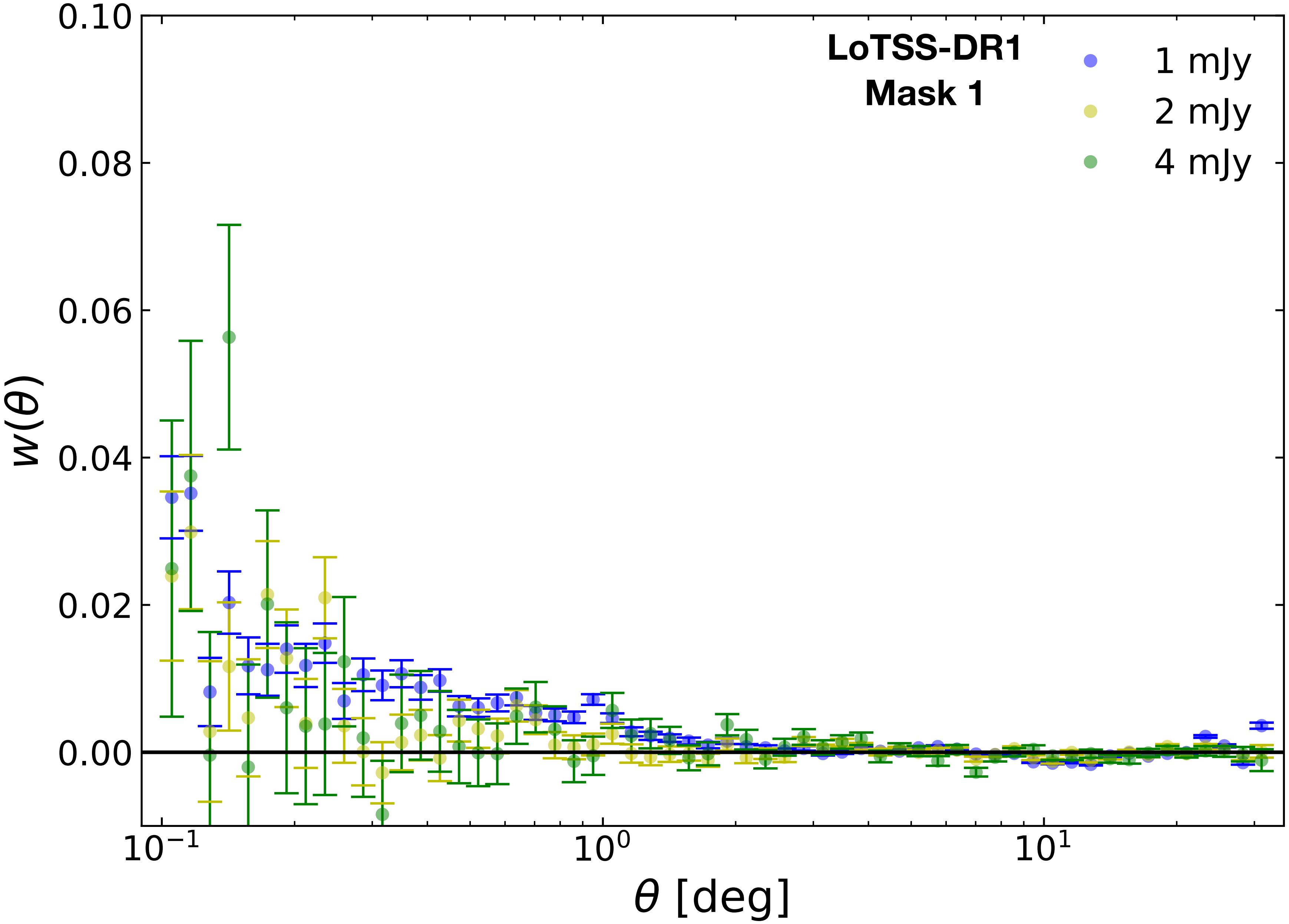
Masked mock catalogue, based on measured local rms noise, 5 sigma threshold, number of mock sources is 20 x radio sources in each pointing

Angular 2-point correlation



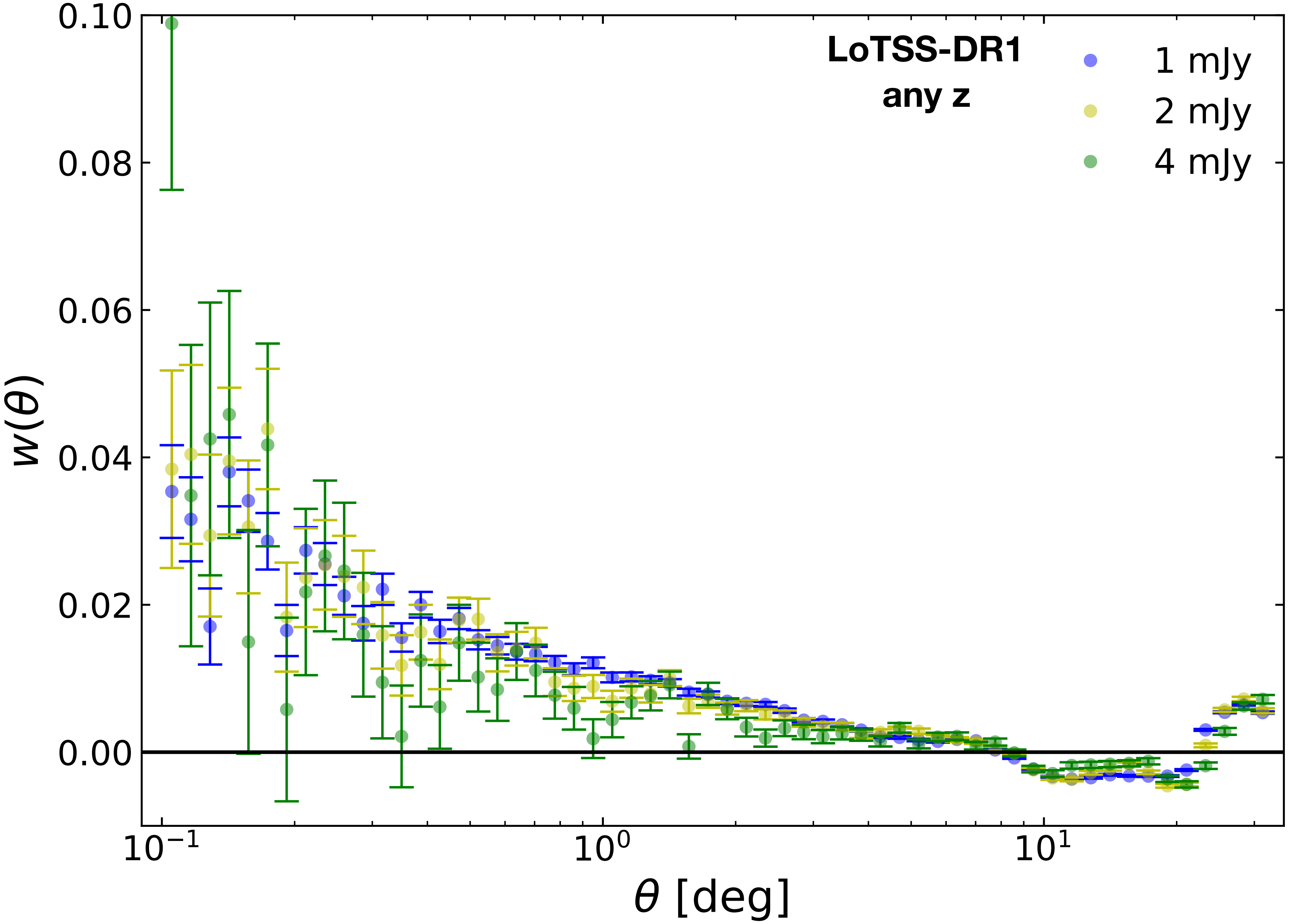
Correlations consistent for different flux thresholds, w < 10^{-2} above 1 deg,
weaker correlations than from TGSS-ADR (Intema et al. 2017)
stronger correlations than from NVSS (Blake & Wall 2002, 2004; Overzier et al. 2003)

Angular 2-point correlation



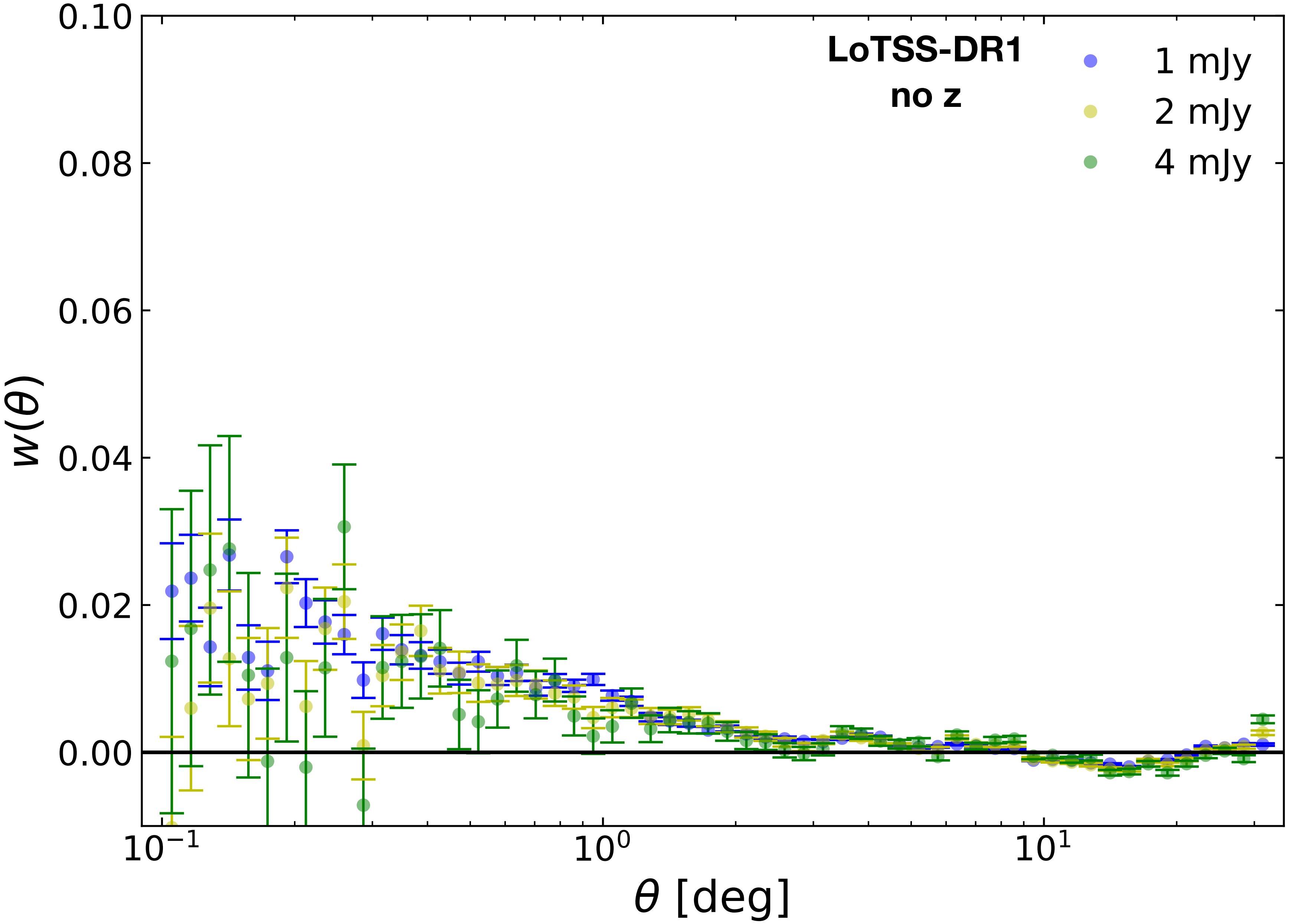
Using only the lowest rms noise regions of survey reduces correlation

Angular 2-point correlation



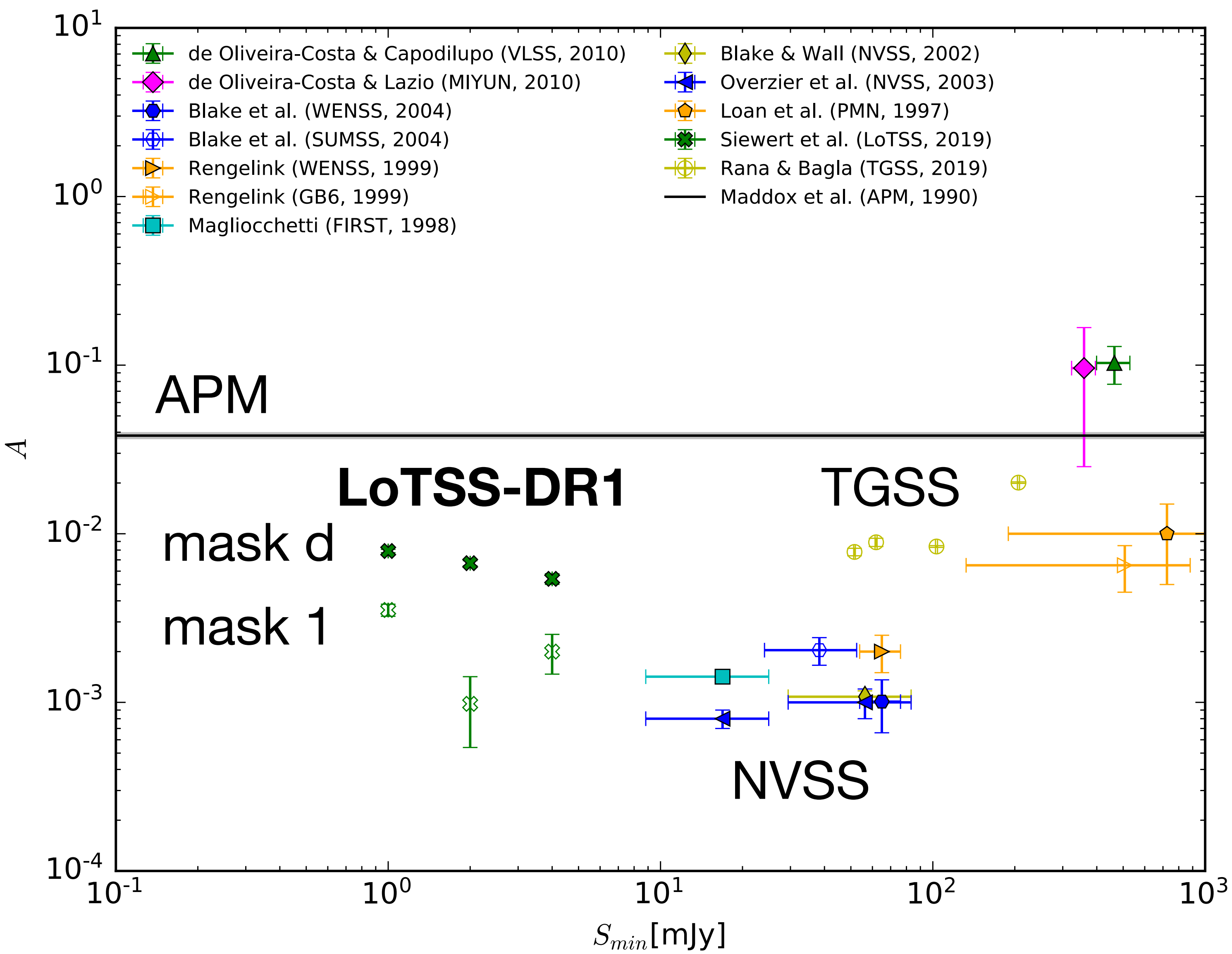
Sources that have a photo-z estimate show a stronger correlation

Angular 2-point correlation



Sources not detected in PanSTARRS show weaker correlation, indicates that those are indeed at higher redshifts

Compare to other surveys



Flux density scaled to 144 MHz
with spectral index α = - 0.8

Fit: $w(\theta) = A\,(\theta/1\text{deg})^{-\gamma}$

Motivated by Limbers equation and well established in optical, infrared and radio in 1990s

For 0.2 deg < θ < 2 deg:

S > 1 mJy (mask 1)

$A = (3.5 \pm 0.3) \times 10^{-3}$, $\gamma = 0.9 \pm 0.1$

S > 2 mJy (mask 1)

$A = (1.0 \pm 0.4) \times 10^{-3}$, $\gamma = 1.4 \pm 0.5$

NVSS at S > 10 mJy

Blake & Wall 2002, Overzier et al. 2003

$A = (1.08 \pm 0.09) \times 10^{-3}$, $\gamma = 0.83 \pm 0.05$

TGSS at S > 100 mJy

Rana & Bagla 2018

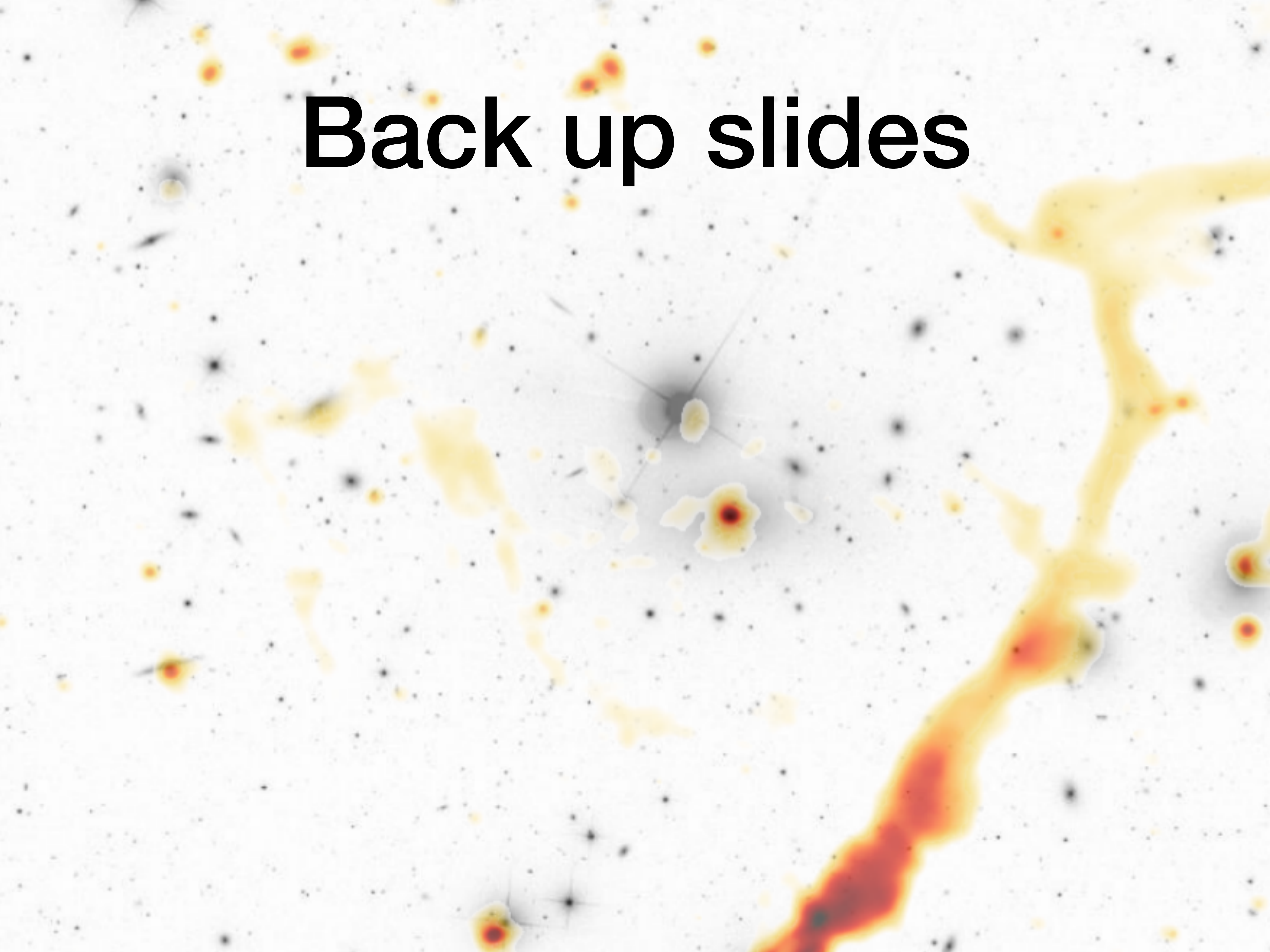
$A = (8.4 \pm 0.1) \times 10^{-3}$, $\gamma = 0.72 \pm 0.11$

see also Dolfi et al. 2019

Conclusions

- LoTSS-DR1 is point source complete at 99% at > 1 mJy
- **Statistical isotropy at 1 deg < θ < 30 deg ($w(\theta) < 10^{-2}$)**
- Conservative cut (mask 1)
  LoTSS-DR1 S > 1 mJy: γ = 0.9 ± 0.1; A = (3.5 ± 0.3) x10^{-3},
  LoTSS-DR1 S > 2 mJy: γ = 1.4 ± 0.5; A = (1.0 ± 0.4) x10^{-3}, c.f.
  NVSS S > 10 mJy: γ = 0.83 ± 0.05; A = (1.08 ± 0.09) x10^{-3}
  NB: ~ 500 000 NVSS sources vs. ~ 40 000 LoTSS sources
- need to measure and understand redshift distribution, selection and bias functions before we can link to cosmological parameter estimation

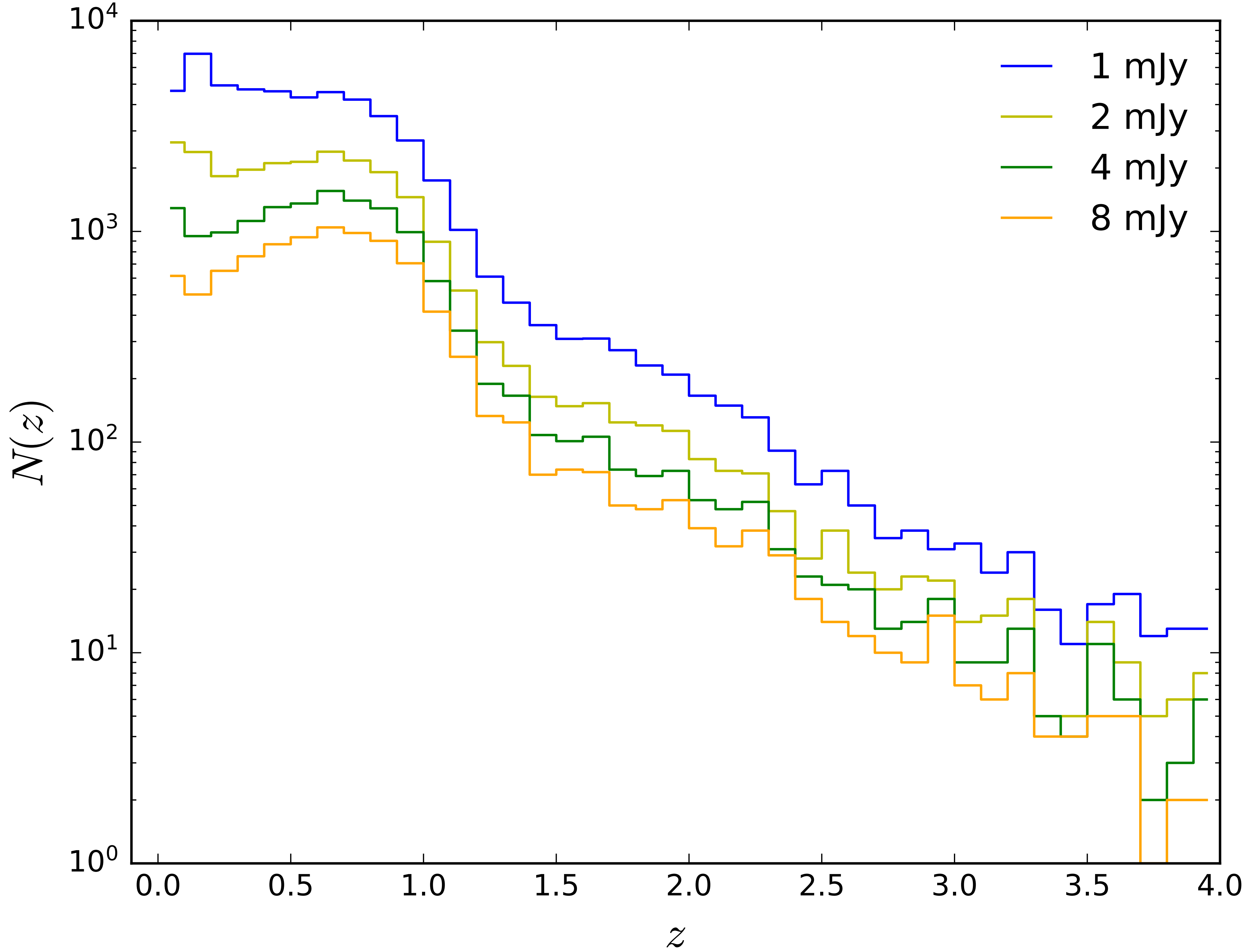
Back up slides



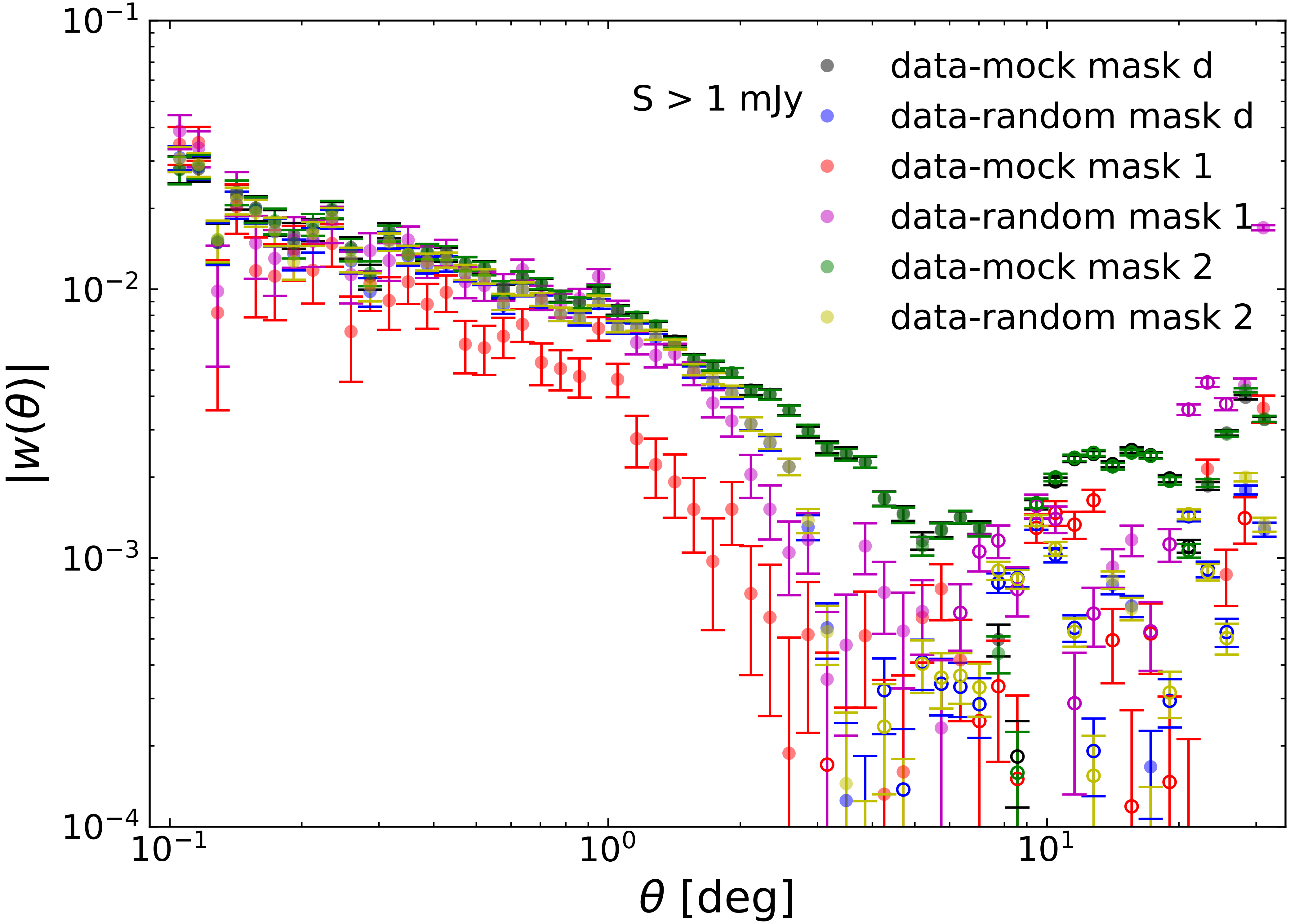
Cosmology with LoTSS

- DR1 (420 sqdeg): ~ 320,000 sources, ~ 50% with photo-z
  Shimwell et al. 2017, 2019, Williams et al. 2019, Duncan et al. 2019,
  develop methods and recover established cosmology in order to test methods
- DR2 (2000 sqdeg): apply and improve methods established in DR1 and test cosmological model (cross- and auto-correlations), more sources than NVSS
- DR3+: probe largest angular scales (Gaussianity, kinematic dipole)

LoTSS-DR1 photo-z distribution



Angular 2-point correlation



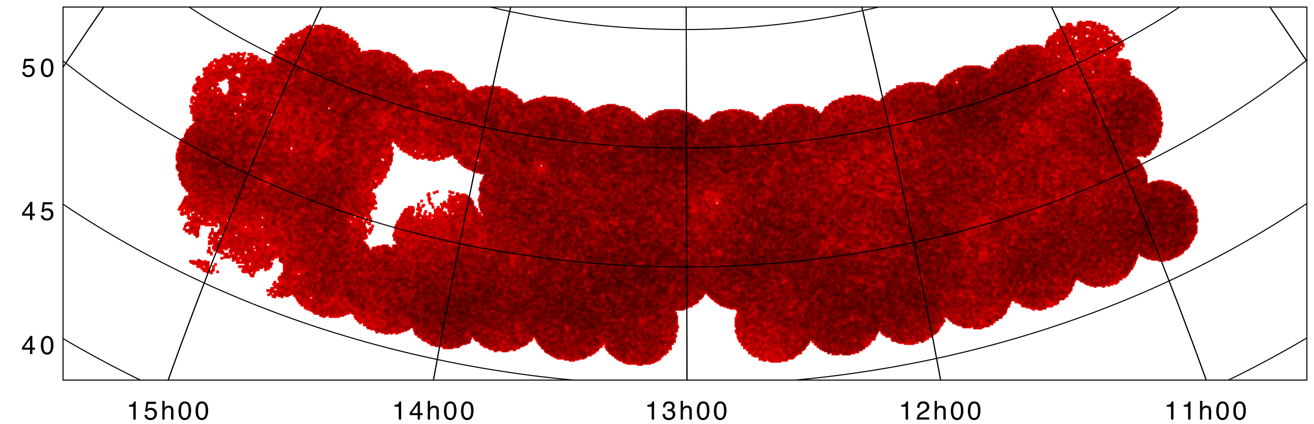
Radio Cosmology

Current best cosmological tests of spatial source distribution on radio sky are still based on NVSS (~ 1.7 million sources)

- 2.3 sigma detection of ISW in NVSS x WMAP
  Bough & Crittenden 2002, 2004, …. updates with Planck: Stölzner et al. 2018, …
- claims of detection of f_NL from NVSS turned out to be systematic, weak limits: $-36 < f_{NL} < 45$ at 95%
  Xia et al. 2010, Giannantonio et al. 2014, Chen & Schwarz 2016, …
- radio dipole (~15 deg directional uncertainty, ~ 40% error on amplitude, good agreement with direction of CMB dipole, excess in amplitude for unknown reason)
  Blake & Wall 2002, Singal 2012, Rubart & Schwarz 2013, Tiwari & Nusser 2016, …

Analysis pipeline

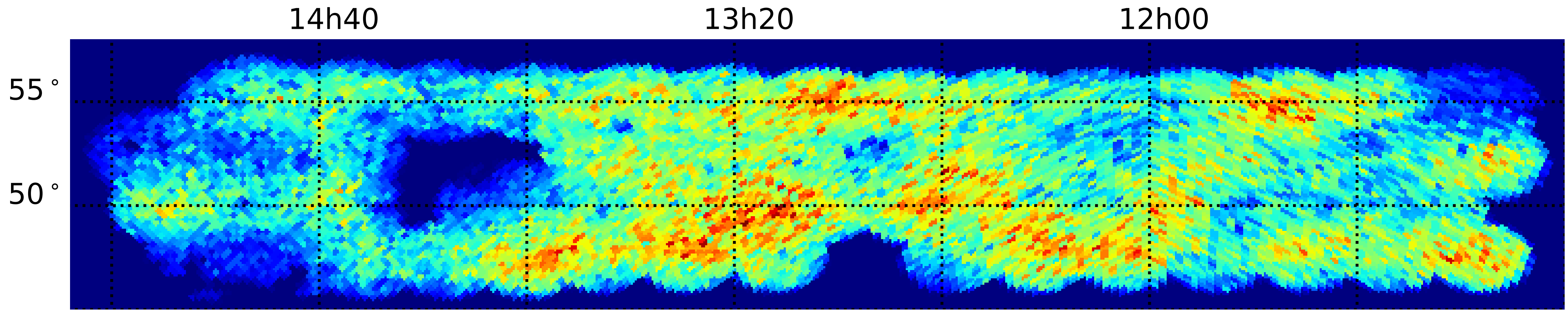
1. Identify incomplete pointings
2. Map value added catalogue to counts-in-cell
3. Apply masks
4. Apply flux thresholds
5. Generate mock catalogues



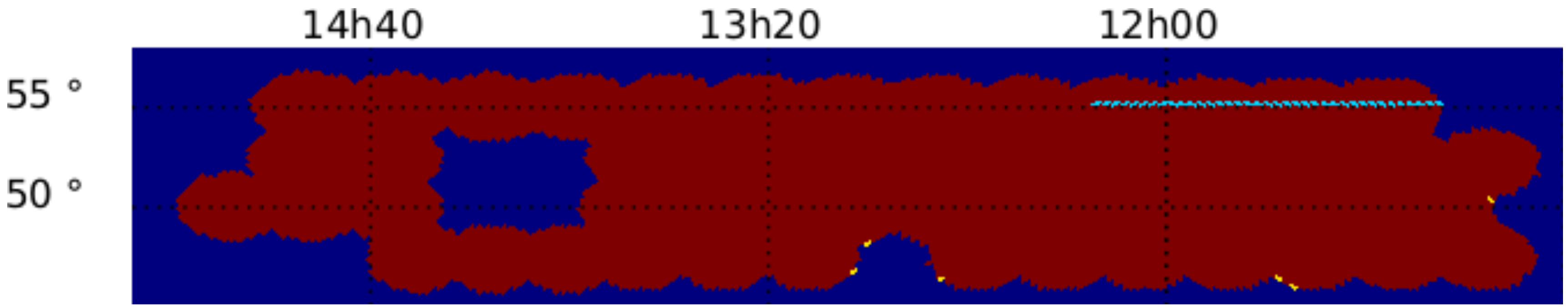
LoTSS-DR1 radio sources

6. One-point statistics: distribution of counts-in-cell and differential number counts
7. **Two-point statistics:** angular 2pt correlation between 0.1 deg and 30 deg
8. Test for self-consistency, **compare to previous works** and simulations

Masking

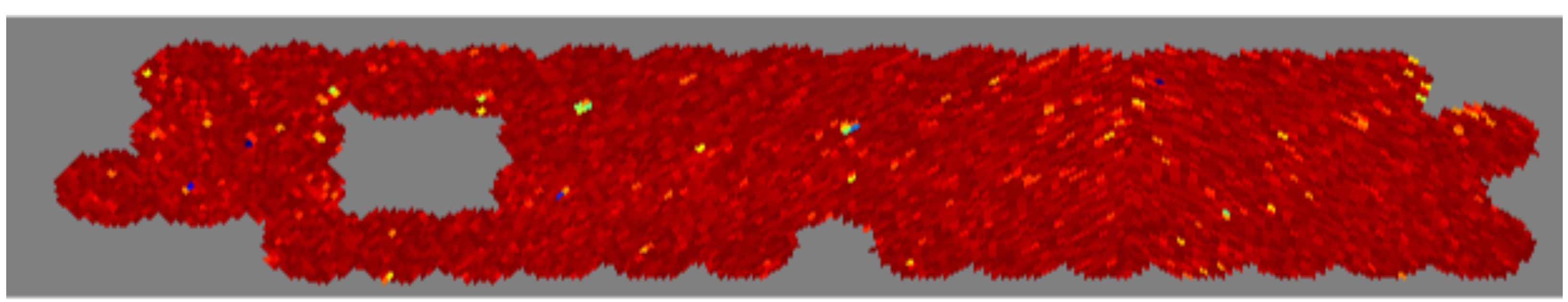


Healpix (equal area pixels) Nside = 256, counts-in-cells, all sources

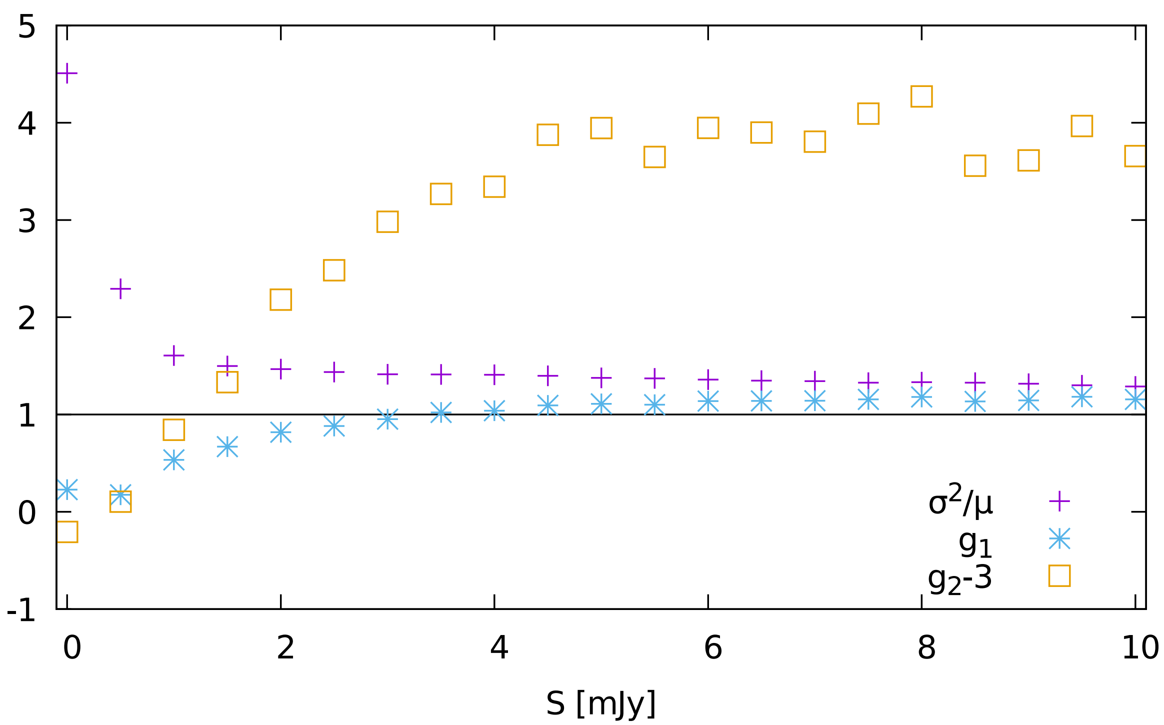


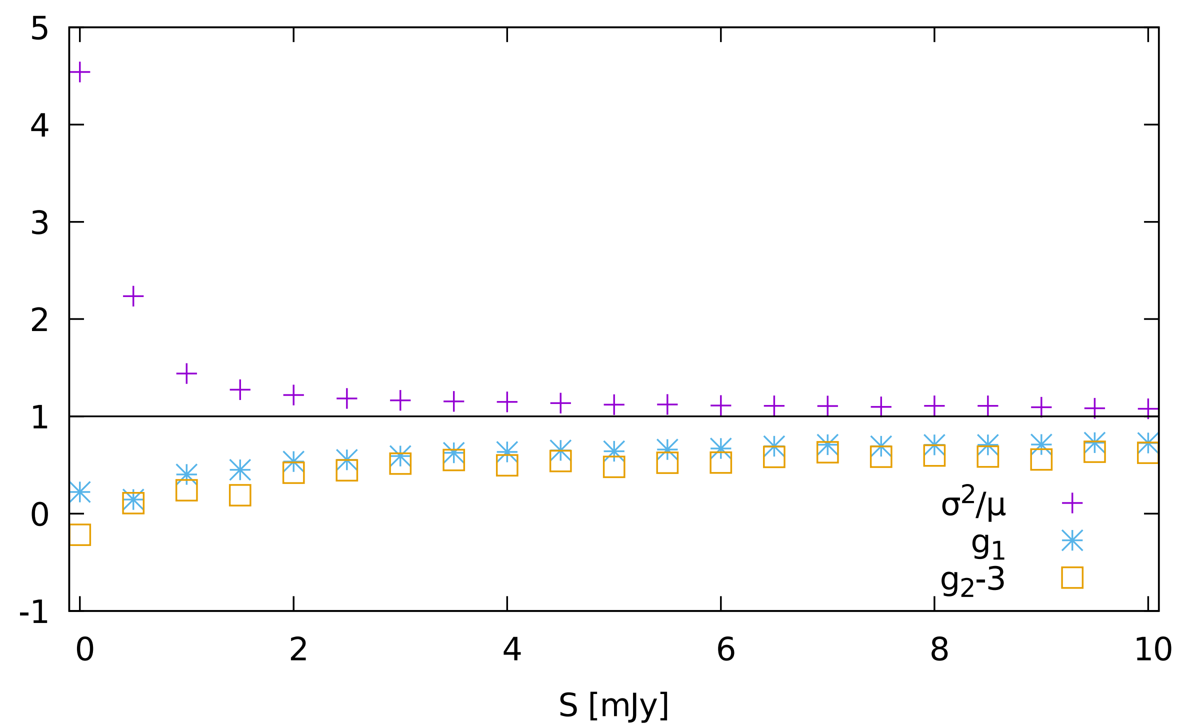
Masks:
red (included pointings)
yellow (edge effects)
light blue (missing photo-z)

Completeness map at S > 1 mJy

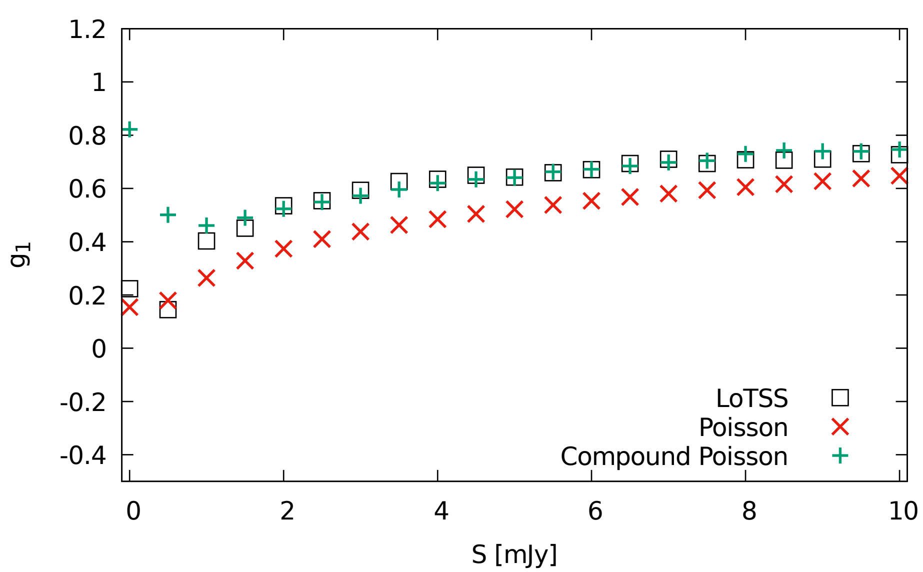


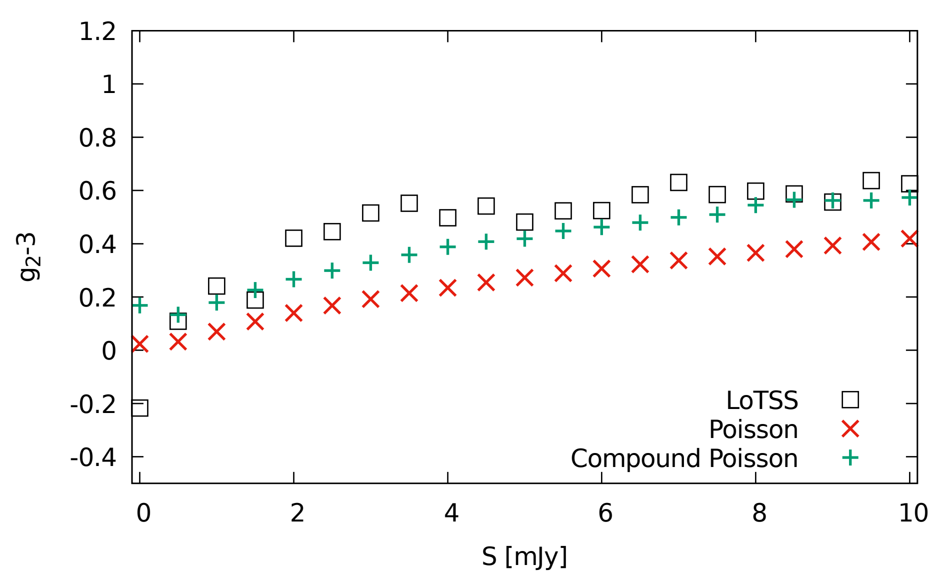
Statistical moments





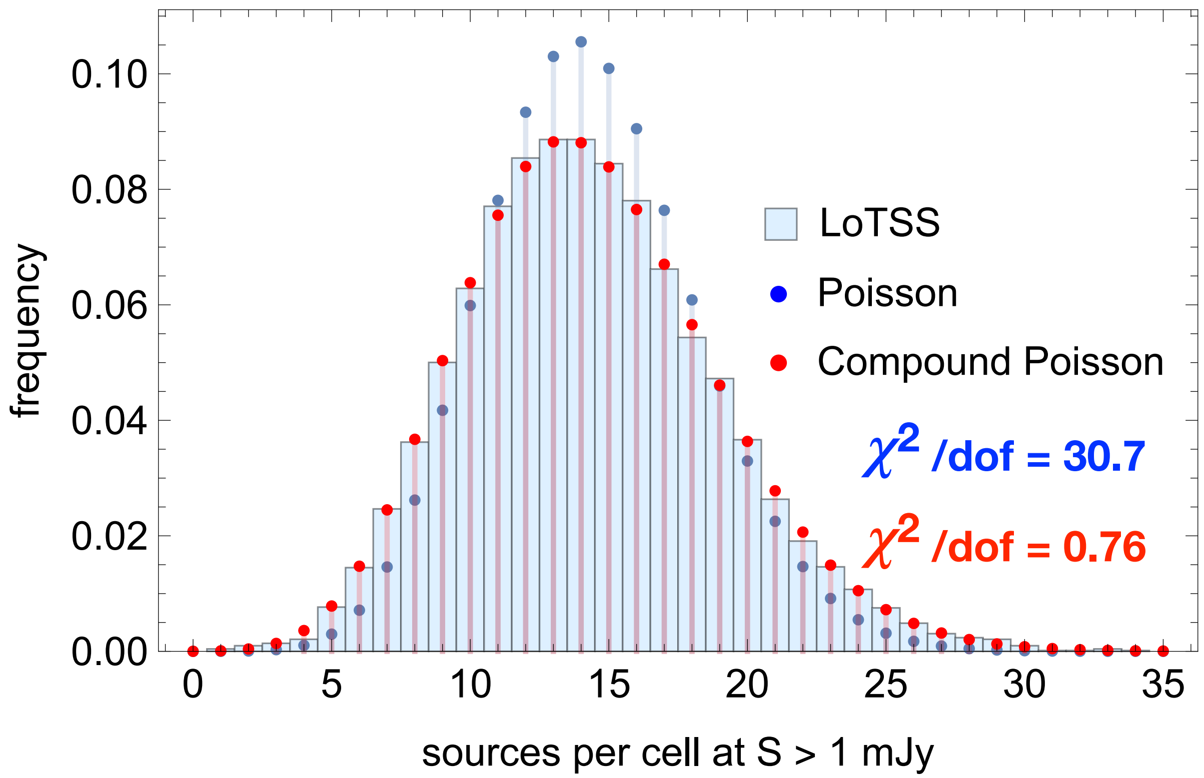
Counts-in-cell variance/mean (= clustering parameter), coefficients of skewness and excess curtosis for radio source (left) and value added source (right) catalogues

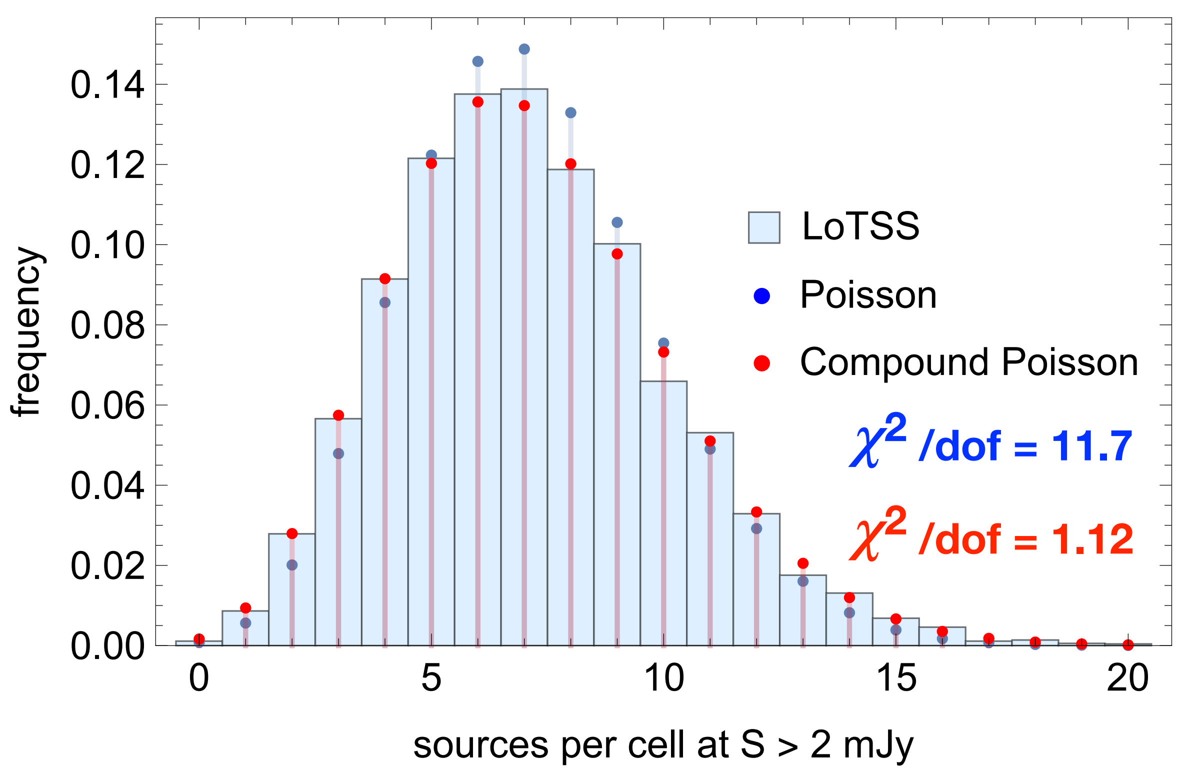




Comparison to Poisson and compound Poisson distributions

Counts-in-cell: distribution





histograms of counts in cell do not fit to a Poisson distribution, but are a perfect match to compound Poisson distribution

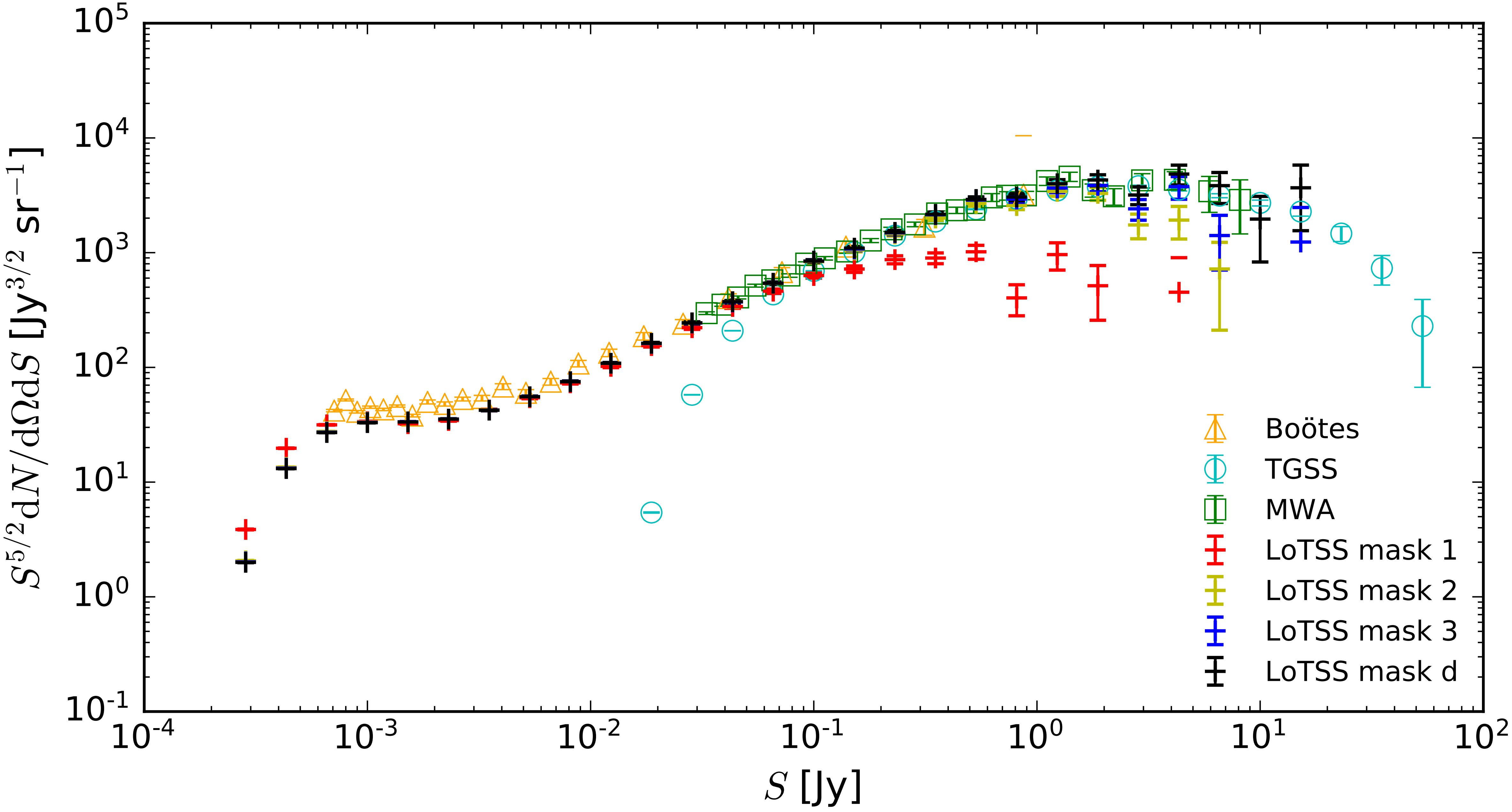
for statistically independent, homogeneously distributed, and arbitrarily small sources we expect a spatial Poisson process (see e.g. Peebles 1980)

multi-component sources violate the first condition, but can be modelled as a compound Poisson process (also called Cox process)

resolved sources violate the third condition, but the total area of all resolved sources is just a tiny fraction of the survey area

fluctuations in local rms noise violate homogeneity

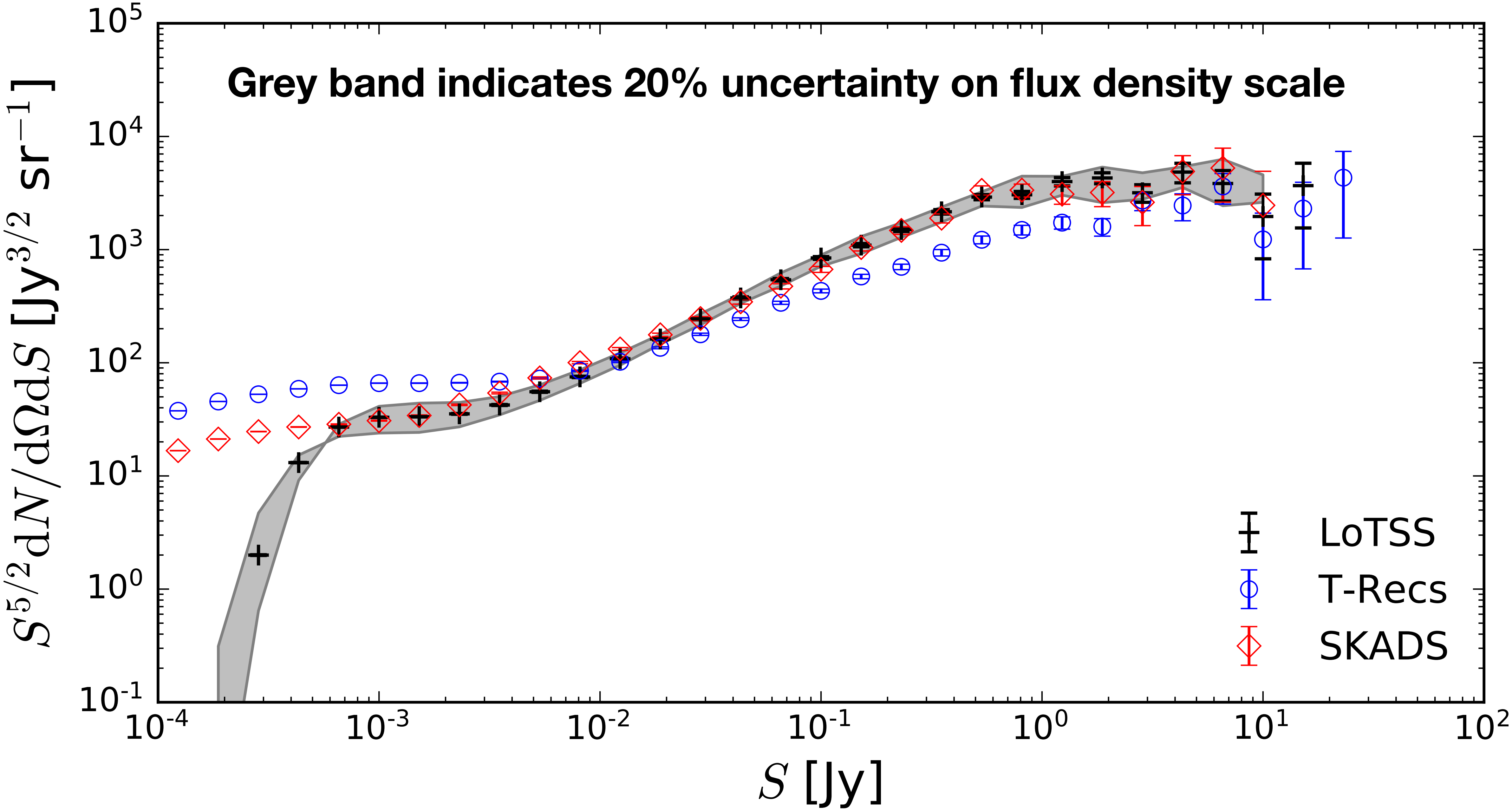
Differential source counts



No completeness correction applied,
errors are just counting error, identical to bootstrap errors

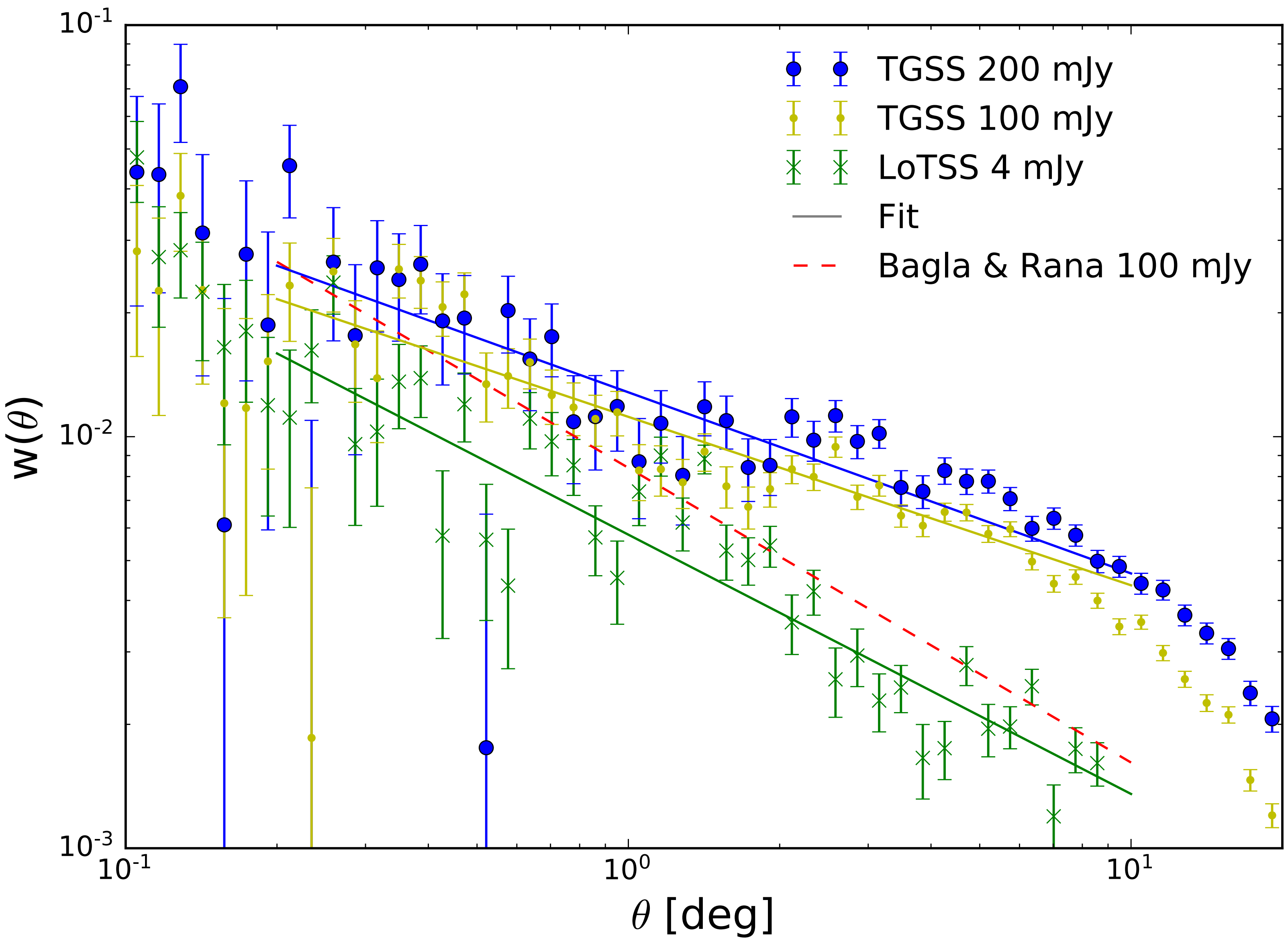
Compare to Boötes (LOFAR, Williams et al. 2016), TGSS (Intema et al. 2017), MWA (Franzen et al. 2016)

Differential source counts



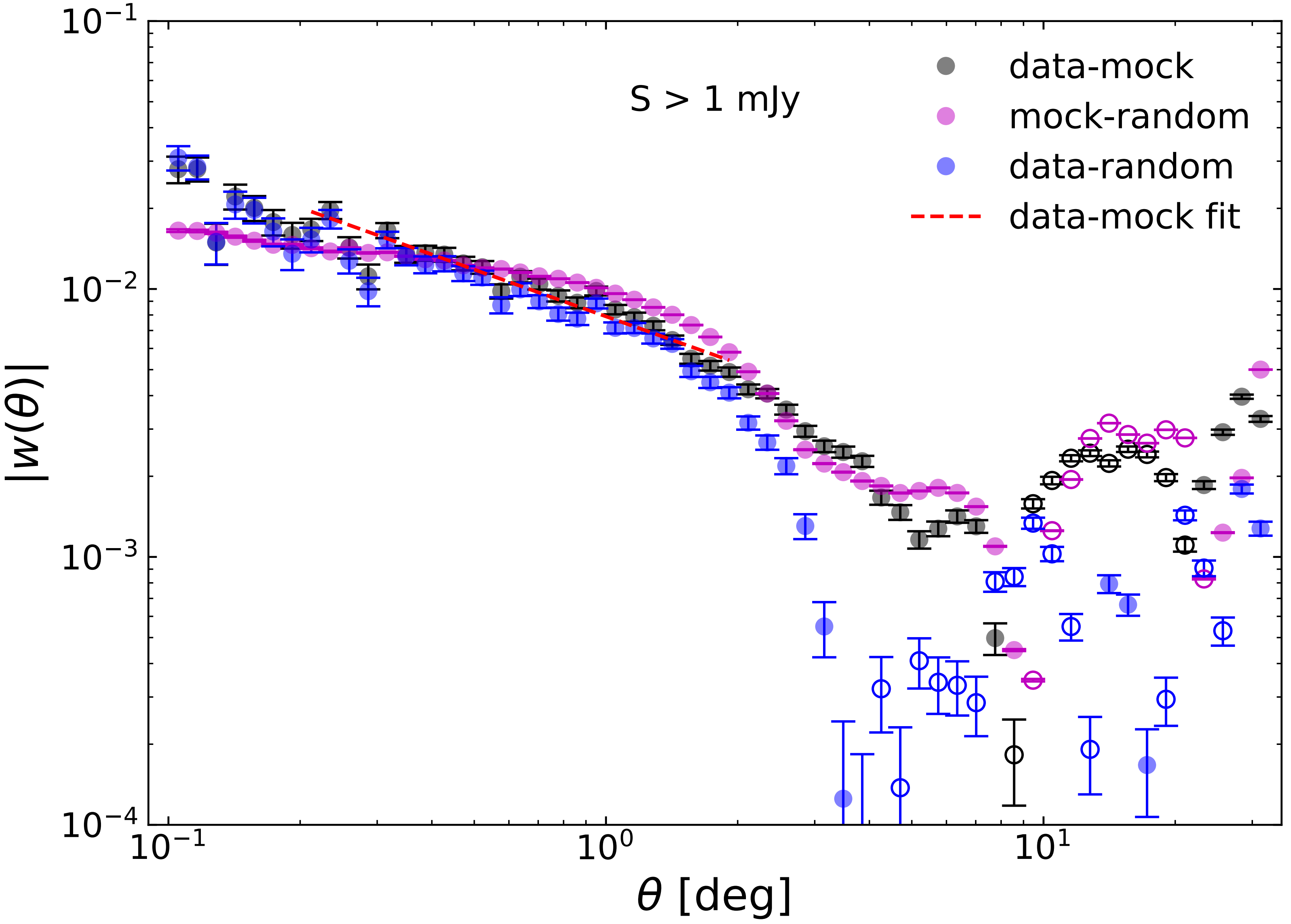
Comparison to simulations: SKADS (Wilman et al. 2008) **and T-Recs** (Bonaldi et al. 2018)
T-Recs underestimates AGNs and overestimates SFGs

Angular 2-point correlation



Use TreeCorr (Jarvis et al. 2004) and LS estimator, errors from bootstrap resampling
Correlations consistent for different flux thresholds, w < 10^{-2} above 1 deg,
weaker correlations than from TGSS-ADR (Intema et al. 2017)

Angular 2-point correlation



Angular 2-point correlation