Cosmology with LoTSS:
The angular two-point correlation function

Kosmologietag 2020

UNIVERSITÄT BIELEFELD

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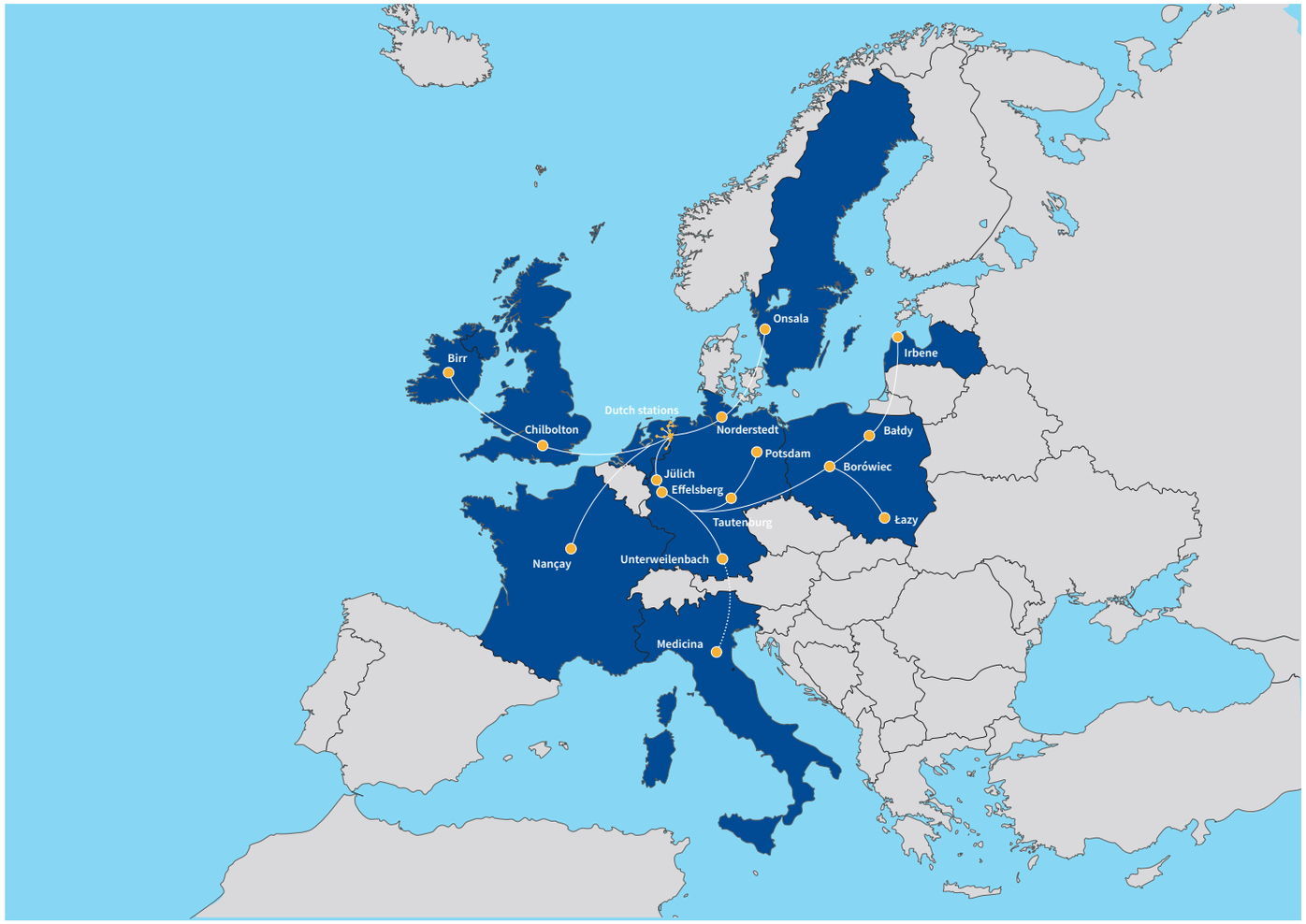
Collaborators

- Thilo Siewert, Catherine Hale (CSIRO Perth), Marian Biermann (Bielefeld), Dominik Schwarz
- Siewert et al 2019 (under revision..) arXiv:1908.10309v1
- LOFAR Key Science Project Surveys

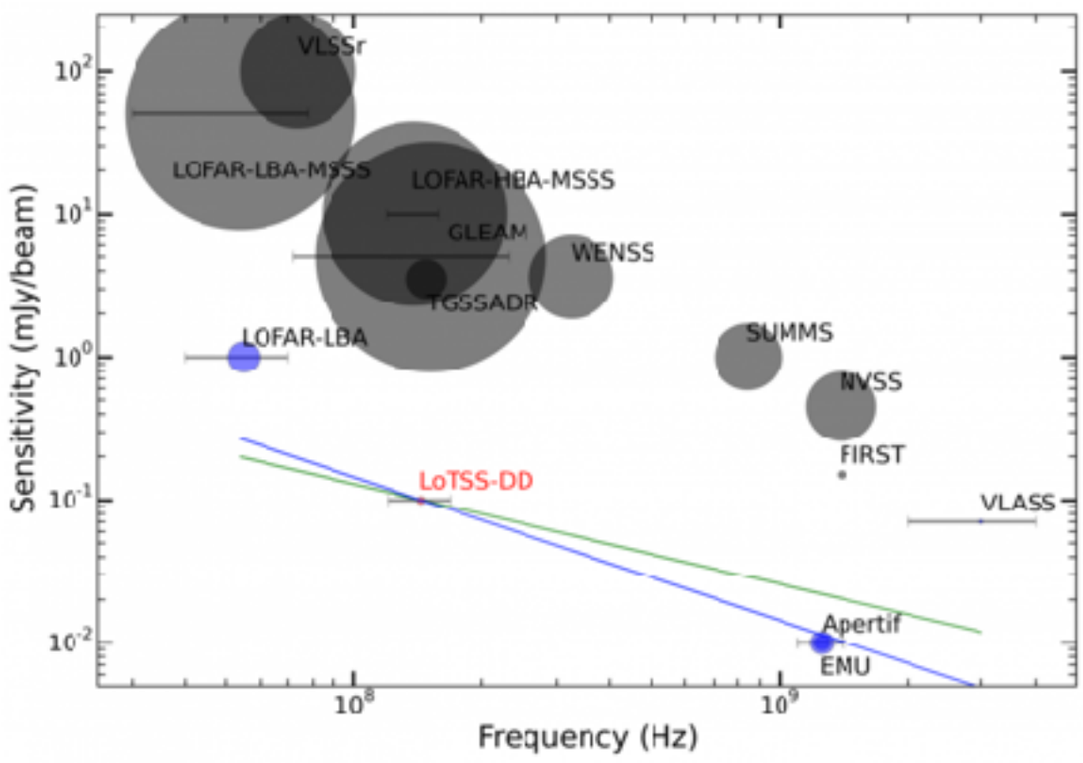
LOFAR..

- The Low Frequency Array, observing at low radio frequencies 10-240 MHz
- LOFAR consists of an array of dipole antenna fields
- van Harleem et al 2013, A&A 556, A2.
- 52 all across Europe. 2020.

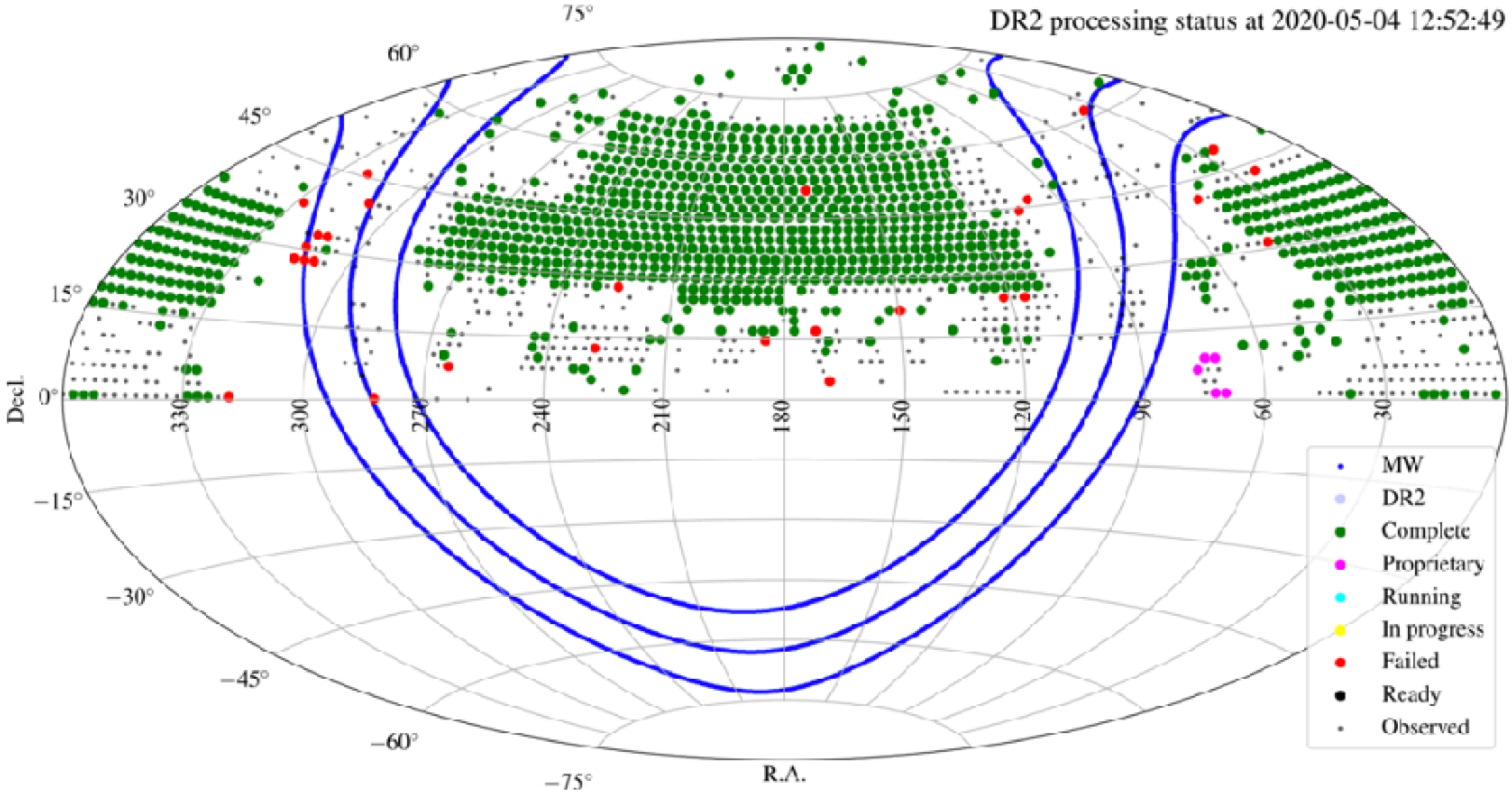


LoTSS..

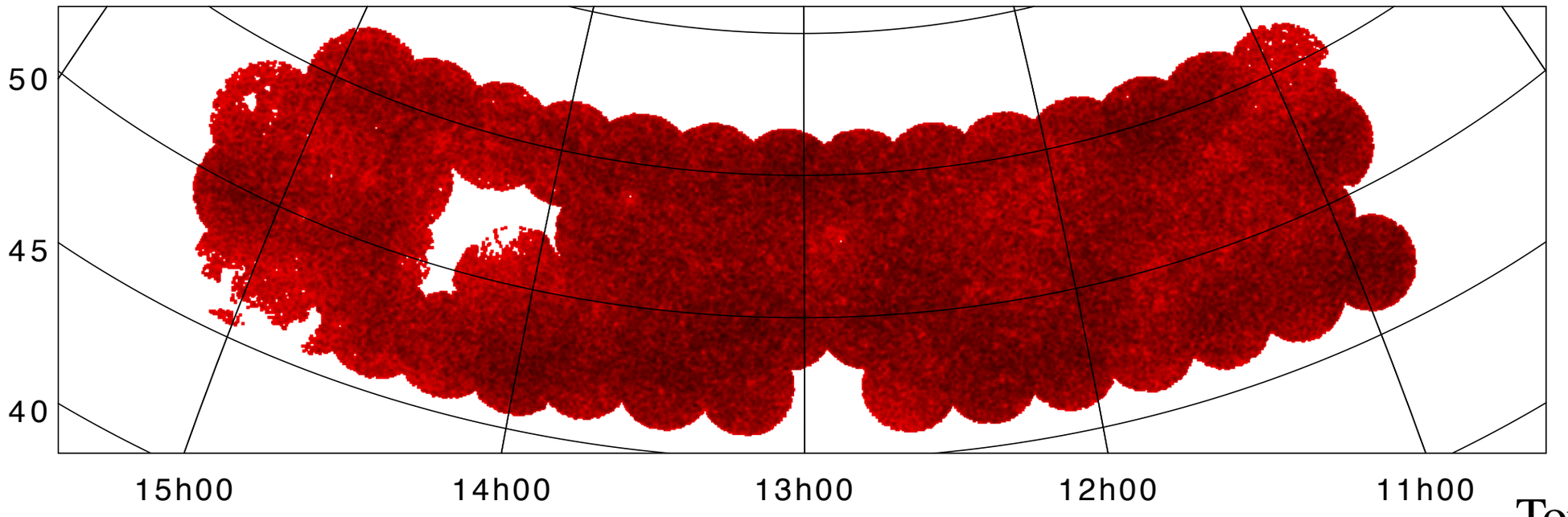
- LOFAR HBA 144 MHz, Two-metre Sky Survey, Shimwell et al. (2017, 2019).
- The aim is to survey the whole northern sky at the full resolution 6 ″, sensitivity ~ 70 μJy/beam, over 15 million radio sources.
- Optical identifications (Williams et al. 2019) and photometric redshifts (Duncan et al. 2019).
- Future: International baselines LOFAR Telescope improves resolution to 0.5 ″, HST, Euclid.



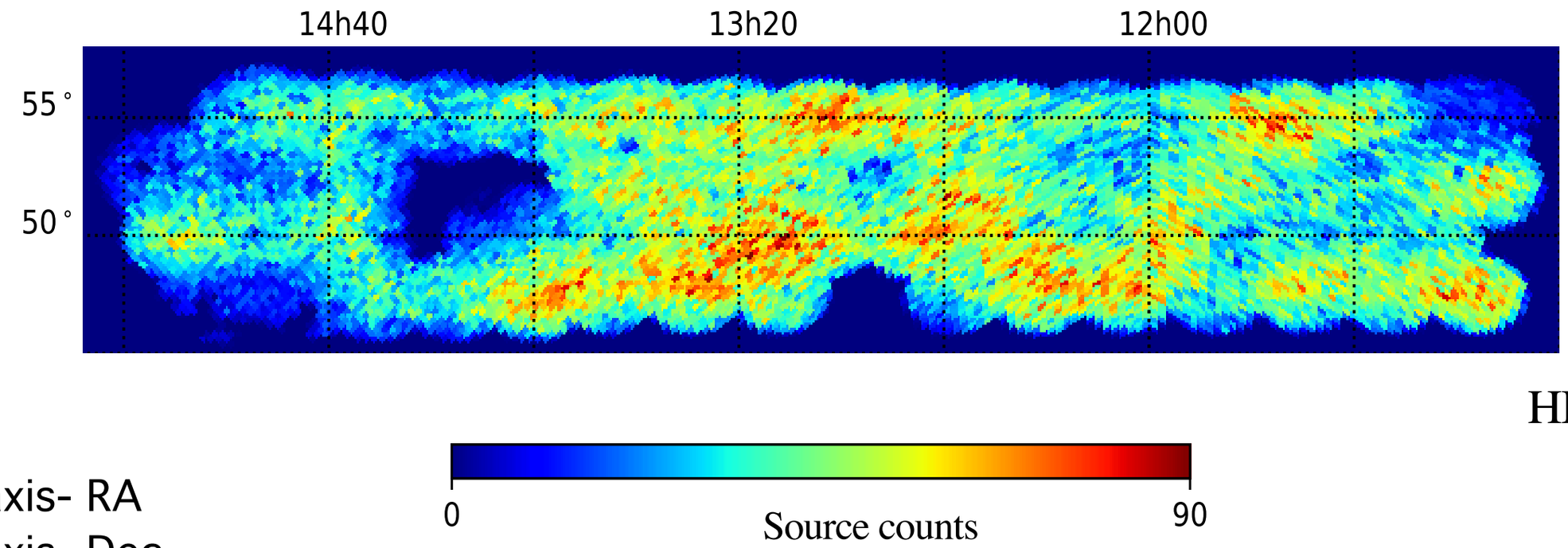
Current status…



LoTSS-DR1 value added catalogue, contains 318,520 sources of which 231,716 have optical/near-IR identifications in Pan-STARRS/WISE



Topcat Image



HEALPix Image

X axis- RA
Y axis- Dec

Cosmology

- Large scale structure
- Statistically isotropic distribution of radio sources
- measure and compare to existing studies- TGSS, NVSS, simulations.
- Angular two-point correlation
- Bias parameters, $b(z)$, relationship between source count fluctuations and underlying total density fluctuations as a function of scale and time…
- Parameters describing the total density of matter, Ωm…
- Primordial non-Gaussianity of density modes, which affects the measured Two- point statistics, shows as an increase in amplitude of the correlation function.

The angular two-point correlation function (2pacf)

- A measure of ‘clustering’ of galaxies
- For a distribution of galaxies, it quantifies the excess probability or the likelihood of finding a galaxy within certain separation angle from a given galaxy in contrast to a homogenous, isotropic and Poisson distribution
- In practice, it is estimated by counting galaxy-galaxy pairs and comparing it to pair counts for a Poisson distribution, random.

2pacf..

- Angular case, Spatial Poisson Process, Homogeneous, Isotropic

  Peebles(1980)

$$dP = Nd\Omega$$
$$dP_{12} = N_1 N_2 d\Omega_1 d\Omega_2 (1 + w(\theta))$$

- Theoretically, as a function on a sphere

$$w(\theta, S) = \frac{1}{4\pi} \sum_{\ell=0}^{\infty} (2\ell + 1) C_\ell(S) P_\ell(\cos\theta).$$

The coefficients C_ℓ are called the angular power spectrum.

- C_l can be computed from CAMB code or equivalent packages, distribution of matter to power spectrum in late time cosmology, given the best fit cosmological parameters from PLANCK and $b(z)$, $N(z)$.

2pacf..

- Landy-Szalay estimator,

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

- For large enough random catalogue, theoretical expectation,

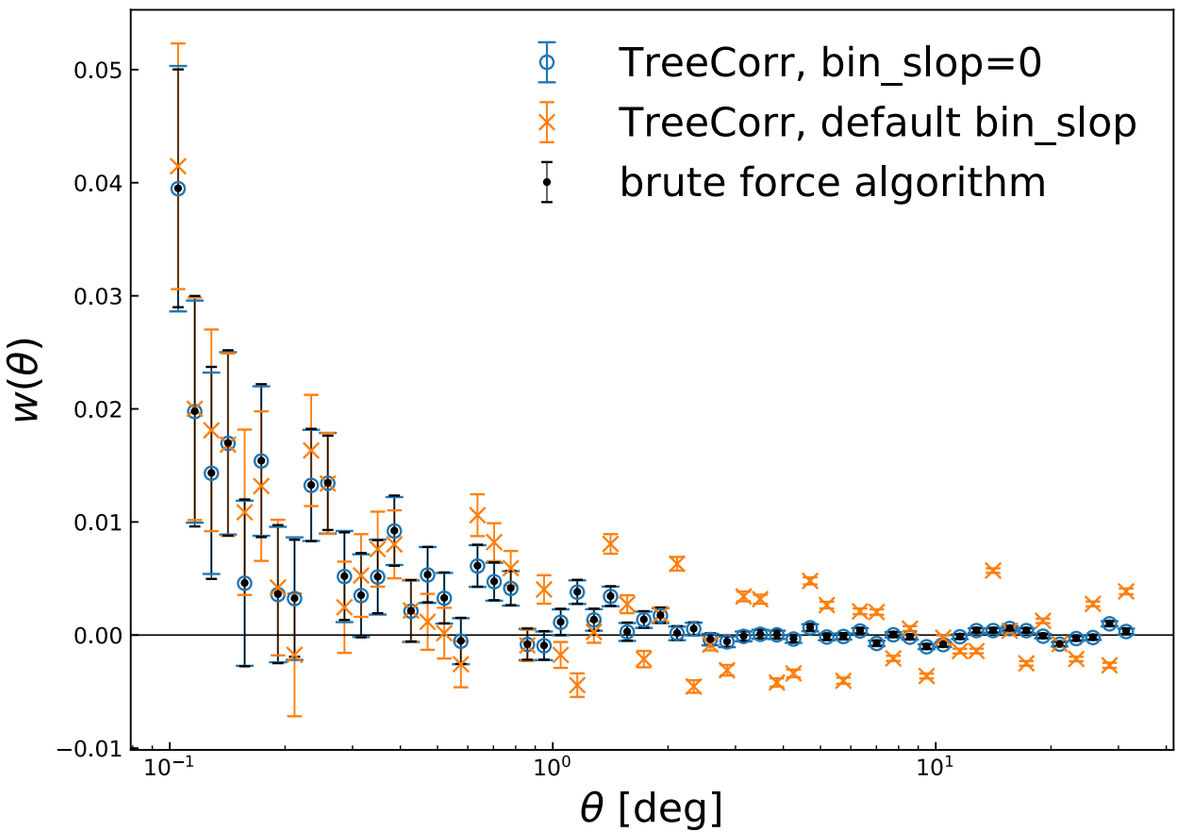
$$E(\hat{w}(\theta)) = (1 + w(\theta))/(1 - w_\Omega)$$
$$\approx w(\theta) - w_\Omega$$

- w_Ω, is known as the 'integral constraint', given a model for $w(\theta)$,

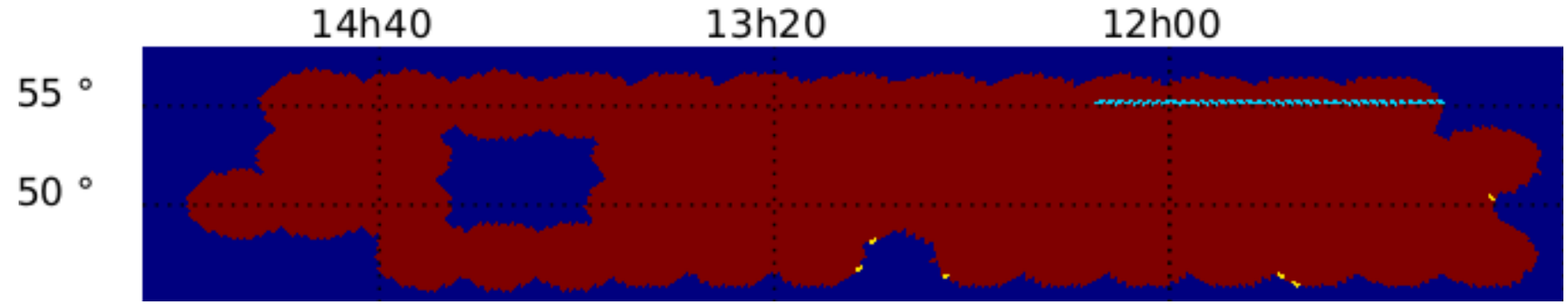
$$w_\Omega = (\sum_\theta RR(\theta)w(\theta))/\sum_\theta RR(\theta)$$

Estimating code

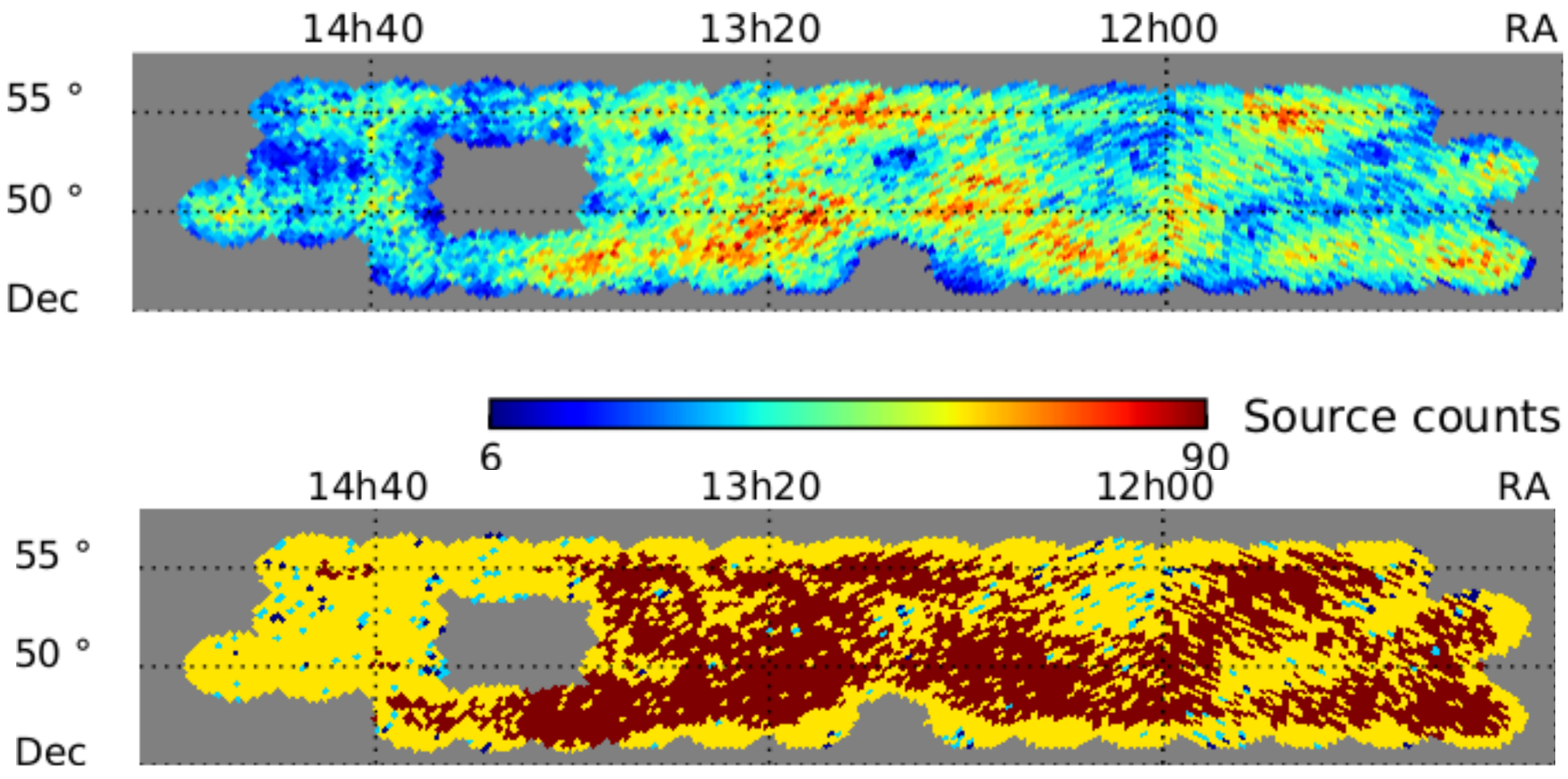
- TreeCorr (Jarvis et al.)
- Logarithmic binning
- $O(N_1 N_2)$, $O(N_1 + N_2)$
- Range [.1 , 32] deg, b_slop = 0, metric = ‘Arc’



Masking..

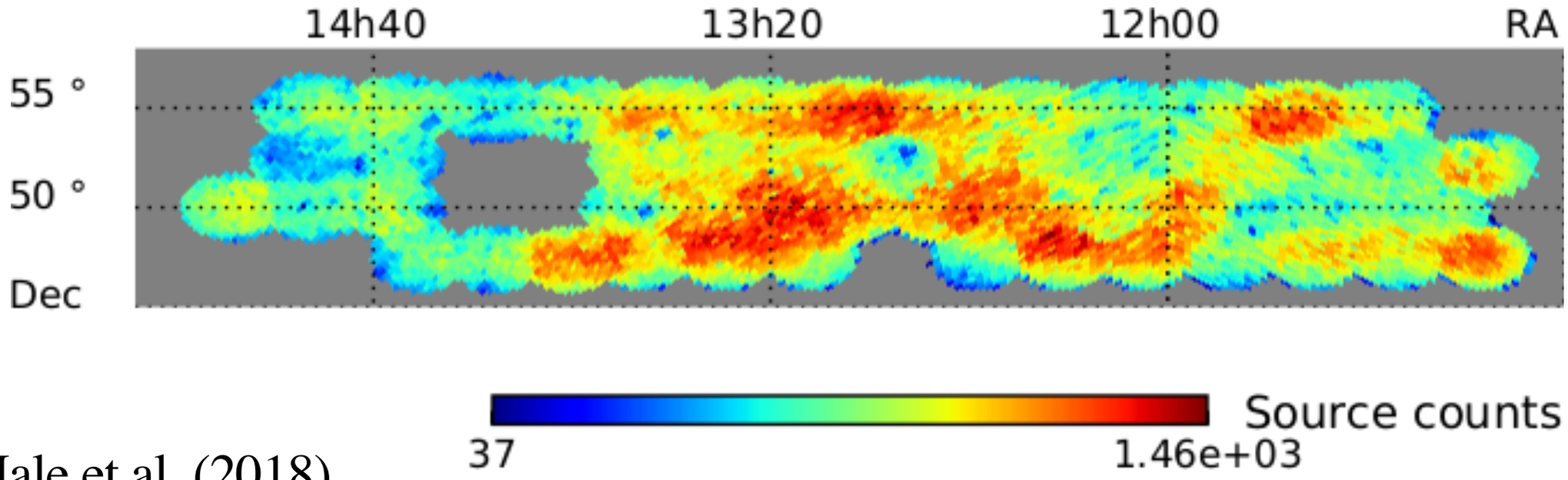


Default ‘mask d’: 53 pointings, at least 5 sources, 1.7 deg



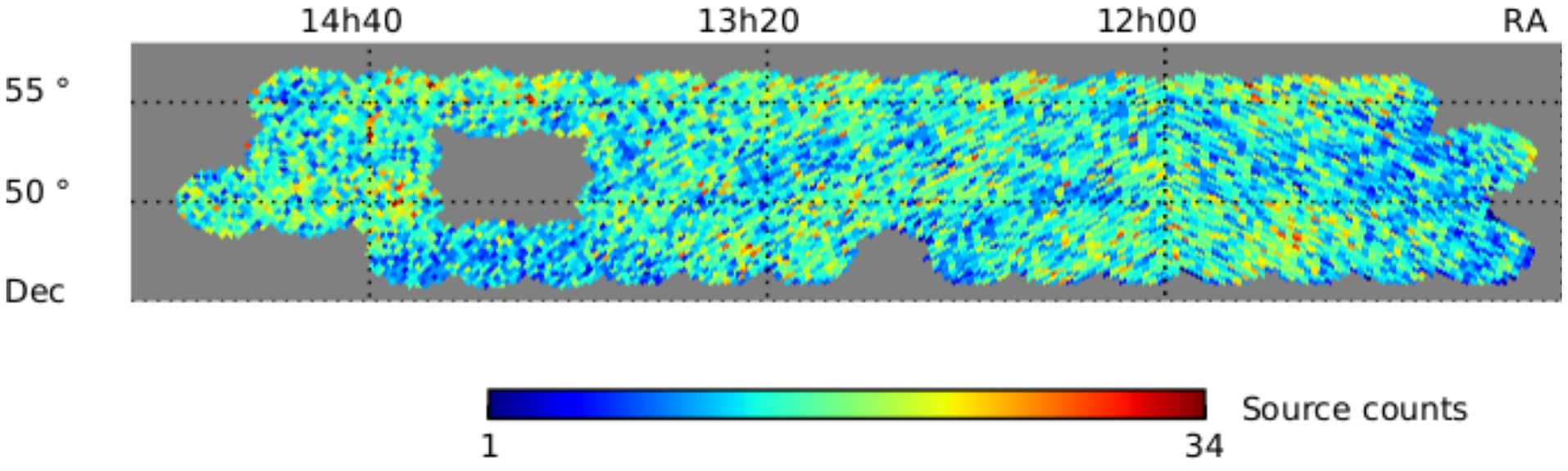
The red cells are included for an average noise < 0.07 mJy/beam in the HEALPix cells (‘mask 1’), red and yellow pixels are included for an average noise of < 0.14 mJy/beam (‘mask 2’) and red, yellow and light blue cells are included for an average noise of < 0.21 mJy/beam (‘mask 3’).

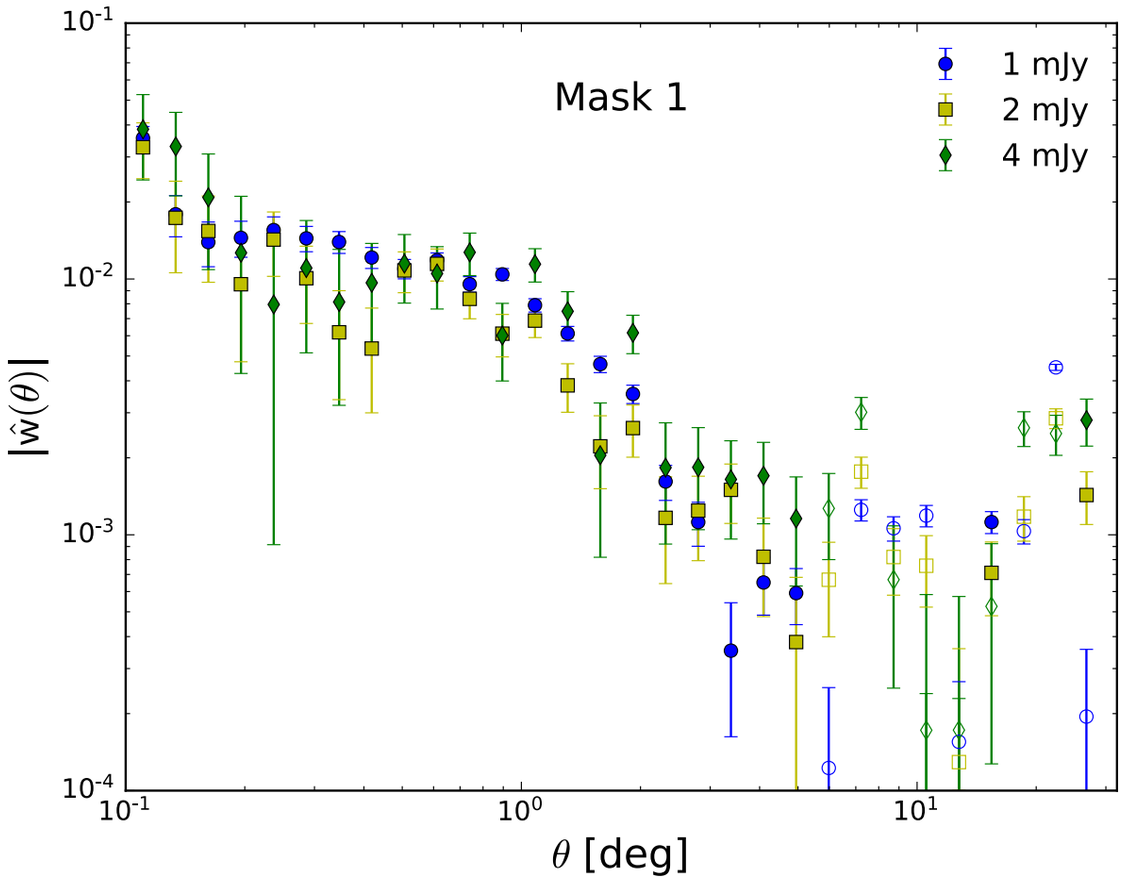
Mocks..

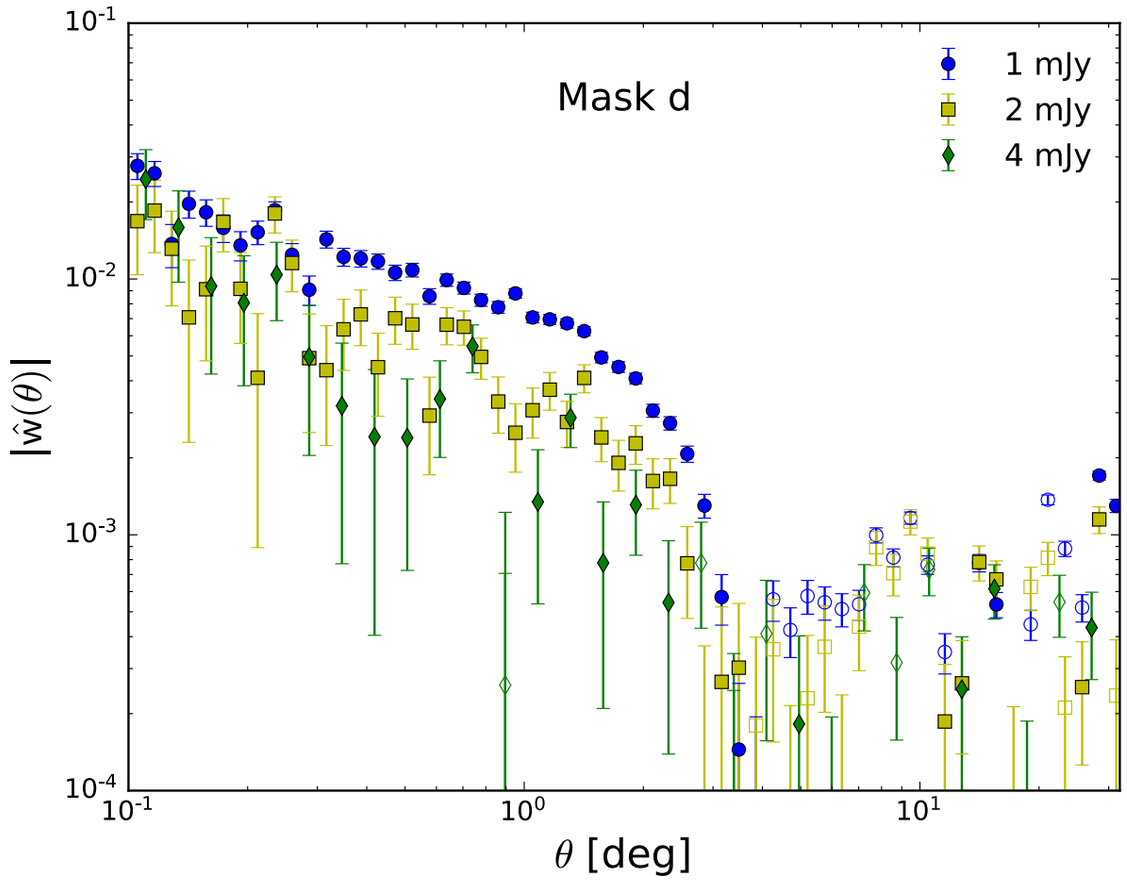


- Hale et al. (2018)
- SKA Design Study and Simulated Skies (SKADS, Wilman et al 2010)
- Pointing wise, random source position in pointing and flux+ from SKADS.
- flux+ > 5 times local rms noise
- Quality of mocks vs random (spatial poisson), size of mocks…

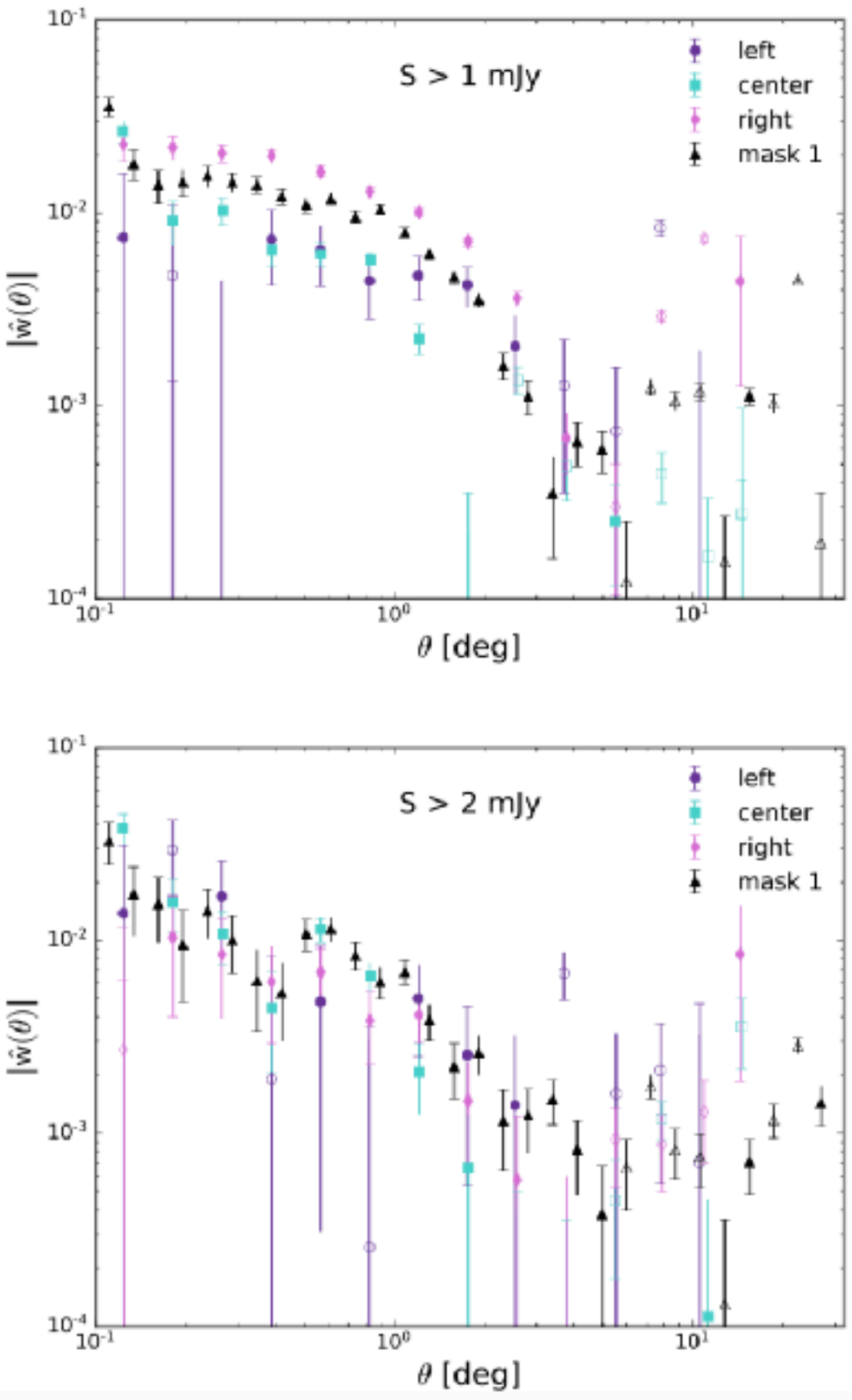
Results…

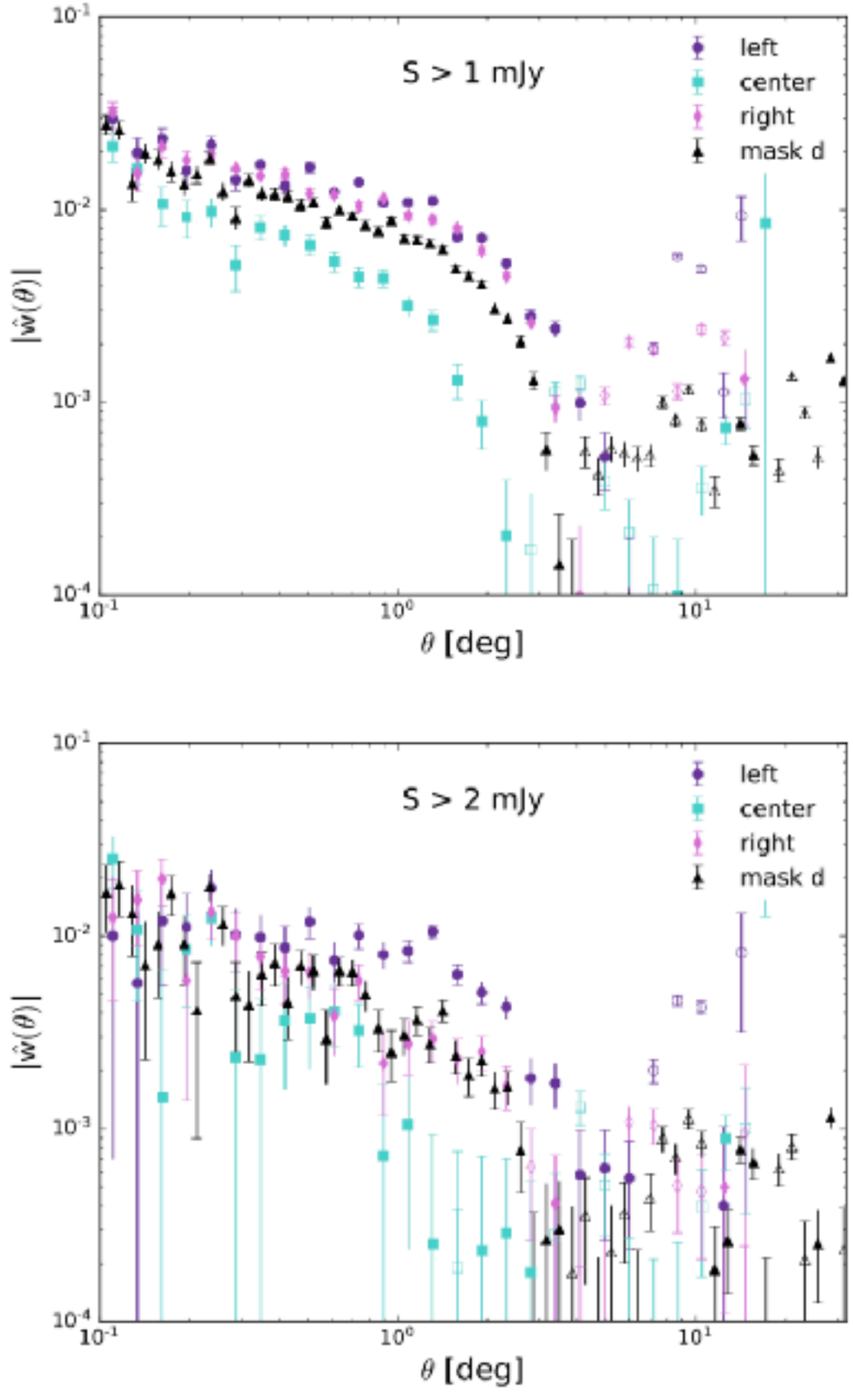

14h40
13h20
12h00
RA
55 °
50 °
Dec
Source counts
1
34


Mask 1
1 mJy
2 mJy
4 mJy
$|\hat{w}(\theta)|$
θ [deg]


Mask d
1 mJy
2 mJy
4 mJy
$|\hat{w}(\theta)|$
θ [deg]

Results..


S > 1 mJy
left
center
right
mask 1
$|\hat{w}(\theta)|$
θ [deg]


S > 1 mJy
left
center
right
mask d
$|\hat{w}(\theta)|$
θ [deg]

S > 2 mJy
left
center
right
mask 1
$|\hat{w}(\theta)|$
θ [deg]

S > 2 mJy
left
center
right
mask d
$|\hat{w}(\theta)|$
θ [deg]

Survey	S_{min} [mJy]	z	$A(\times10^{-3})$	γ	$w_\Omega(\times10^{-3})$	χ^2/dof	N
LoTSS-DR1	1	n.a.	$7.00^{+0.18}_{-0.18}$	$0.58^{+0.04}_{-0.04}$	1.9	4.47	102 940
mask d	2	n.a.	$3.57^{+0.25}_{-0.26}$	$0.67^{+0.10}_{-0.10}$	0.8	2.06	51 288
	4	n.a.	$2.45^{+0.45}_{-0.46}$	$0.87^{+0.24}_{-0.23}$	0.4	1.97	30 556
LoTSS-DR1	1	n.a.	$7.29^{+0.32}_{-0.32}$	$0.65^{+0.06}_{-0.06}$	2.0	3.44	40 599
mask 1	2	n.a.	$5.16^{+0.52}_{-0.52}$	$0.68^{+0.14}_{-0.14}$	1.3	2.12	19 719
	4	n.a.	$7.51^{+0.69}_{-0.69}$	$0.57^{+0.14}_{-0.13}$	2.3	1.22	11 269
LoTSS-DR1	1	Any z	$9.62^{+0.23}_{-0.23}$	$0.65^{+0.03}_{-0.03}$	2.4	1.75	52 012
mask z	2	Any z	$6.58^{+0.42}_{-0.43}$	$0.84^{+0.08}_{-0.08}$	1.1	1.25	24 420
	4	Any z	$4.65^{+0.78}_{-0.80}$	$0.84^{+0.25}_{-0.24}$	1.2	1.45	14 506
LoTSS-DR1	1	$z < 0.376$	$19.82^{+0.64}_{-0.64}$	$0.74^{+0.04}_{-0.04}$	4.1	2.05	20 377
mask z	1	$0.376 \leq z < 0.705$	$9.99^{+0.60}_{-0.61}$	$0.94^{+0.07}_{-0.07}$	1.4	0.88	14 727
	1	$0.705 \leq z$	$9.73^{+0.04}_{-0.04}$	$0.68^{+0.06}_{-0.06}$	2.2	0.69	16 908
	2	$z < 0.376$	$23.02^{+1.59}_{-1.59}$	$0.82^{+0.09}_{-0.09}$	4.1	2.13	8 430
	2	$0.376 \leq z < 0.705$	$6.50^{+0.10}_{-0.10}$	$0.99^{+0.18}_{-0.19}$	0.9	0.60	7 189
	2	$0.705 \leq z$	$7.30^{+0.90}_{-0.90}$	$0.74^{+0.18}_{-0.17}$	1.5	0.77	8 801
TGSS-ADR1	100	n.a.	$10.16^{+0.44}_{-0.44}$	$0.59^{+0.07}_{-0.07}$	1.9	1.83	219 303
This work App. A	200	n.a.	$11.65^{+0.70}_{-0.70}$	$0.51^{+0.11}_{-0.11}$	2.7	1.35	119 021
TGSS RB19	100	n.a.	8.4 ± 0.1	0.72 ± 0.11		-	163 654

NVSS, WENSS, TGSS..A=10e-3, Gamma ~ 0.7- 1.1

Z, CAMB code predictions…

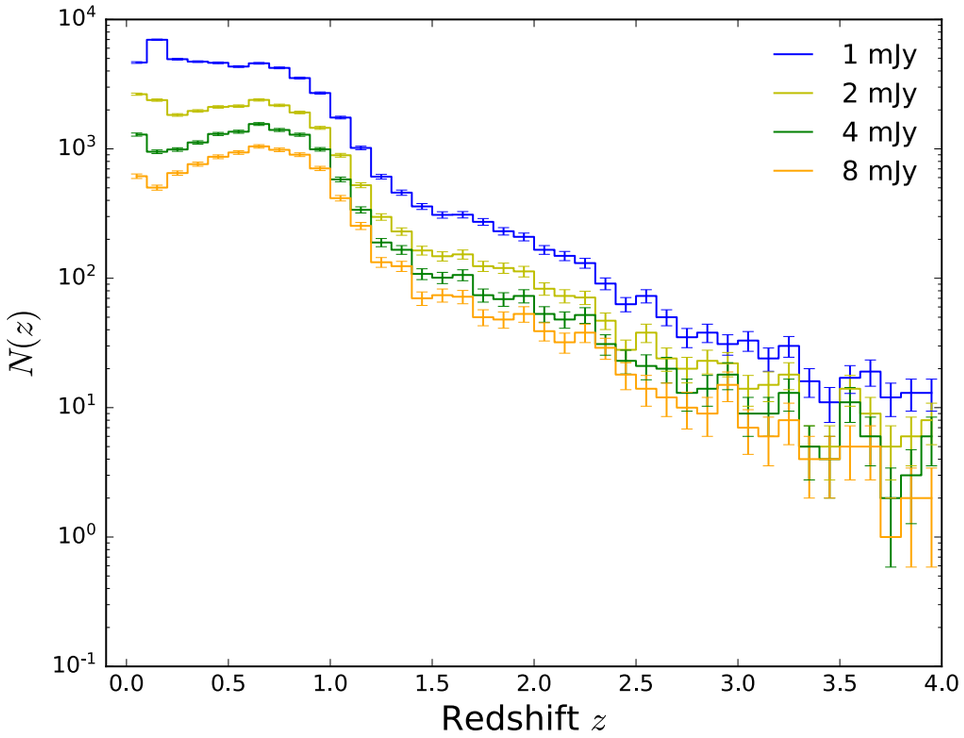
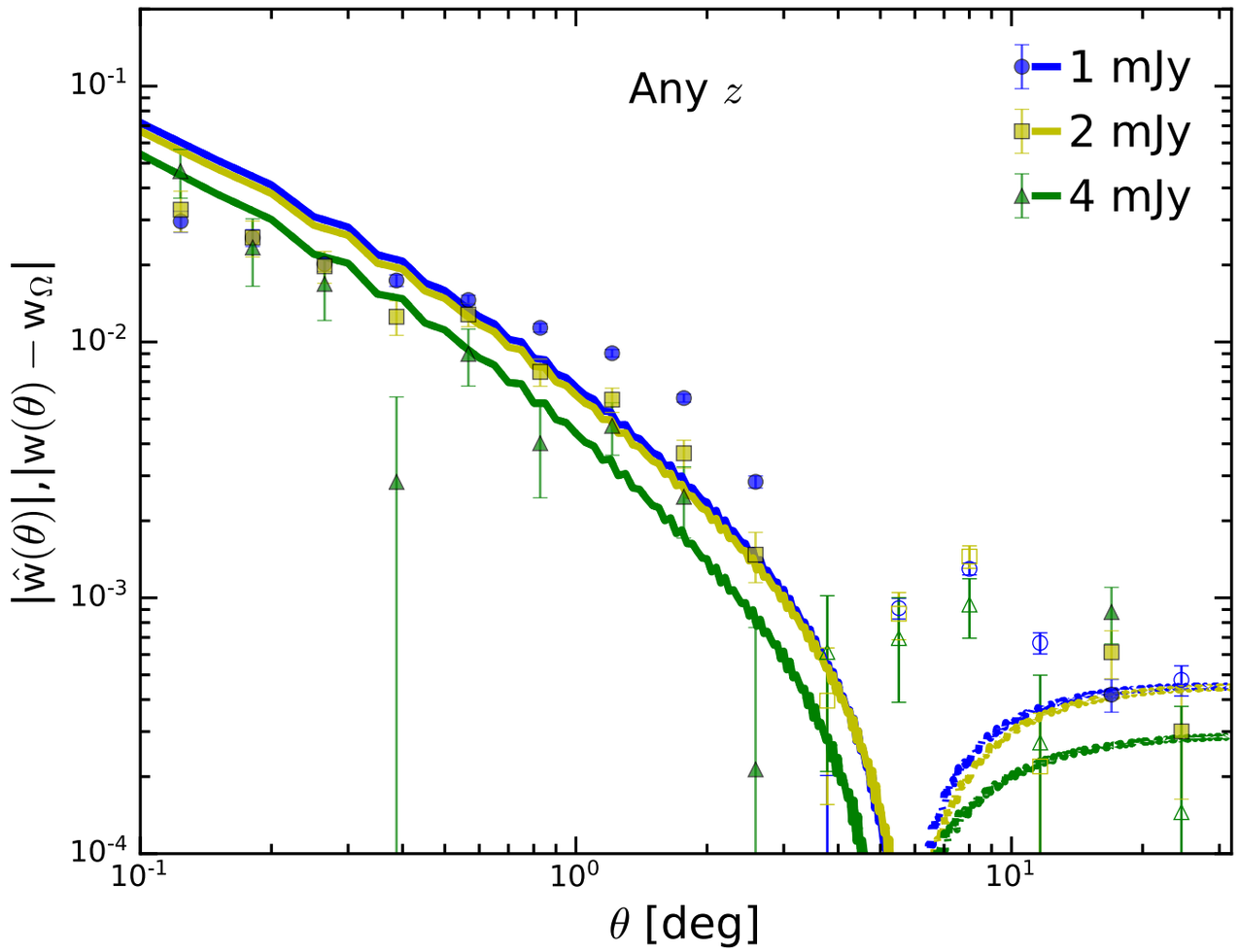


Photo z's for 50% of radio sources



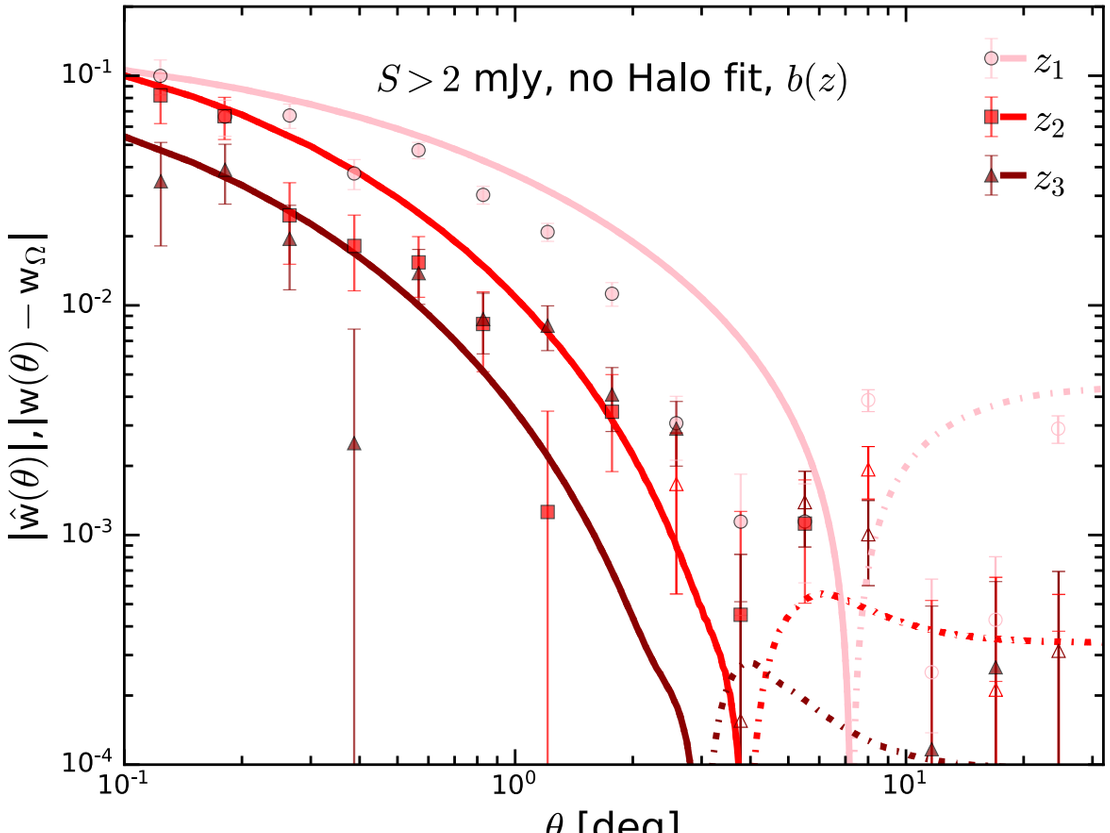
Best fit PLANCK cosmological parameters and bias from NVSS sources Tiwari & Nusser 2015

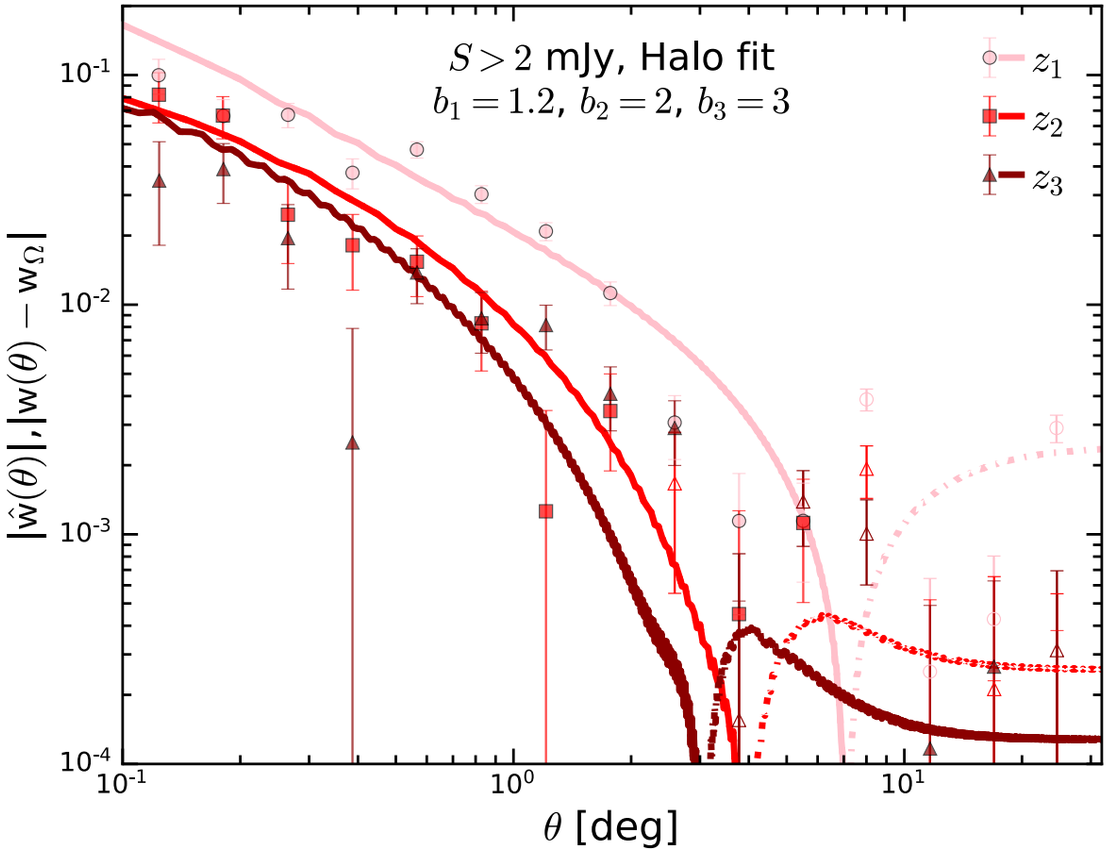
$$H_0 = 67.32 \text{ km s}^{-1} \text{ Mpc}^{-1},$$

$$\Omega_b h^2 = 0.022383, \ \Omega_c h^2 = 0.12011,$$

$$\ln(10^{10} A_s) = 3.0448, \ n_s = 0.96605.$$

$$z_1 < z_2 < z_3$$





$$b(z) = 1.6 + 0.85z + 0.33z^2$$

Tiwari and Nusser 2015

Conclusions

- From Jack knife tests, 2pacf, flux calibration issues

- Resolved with DR2, larger survey area, cosmological parameters

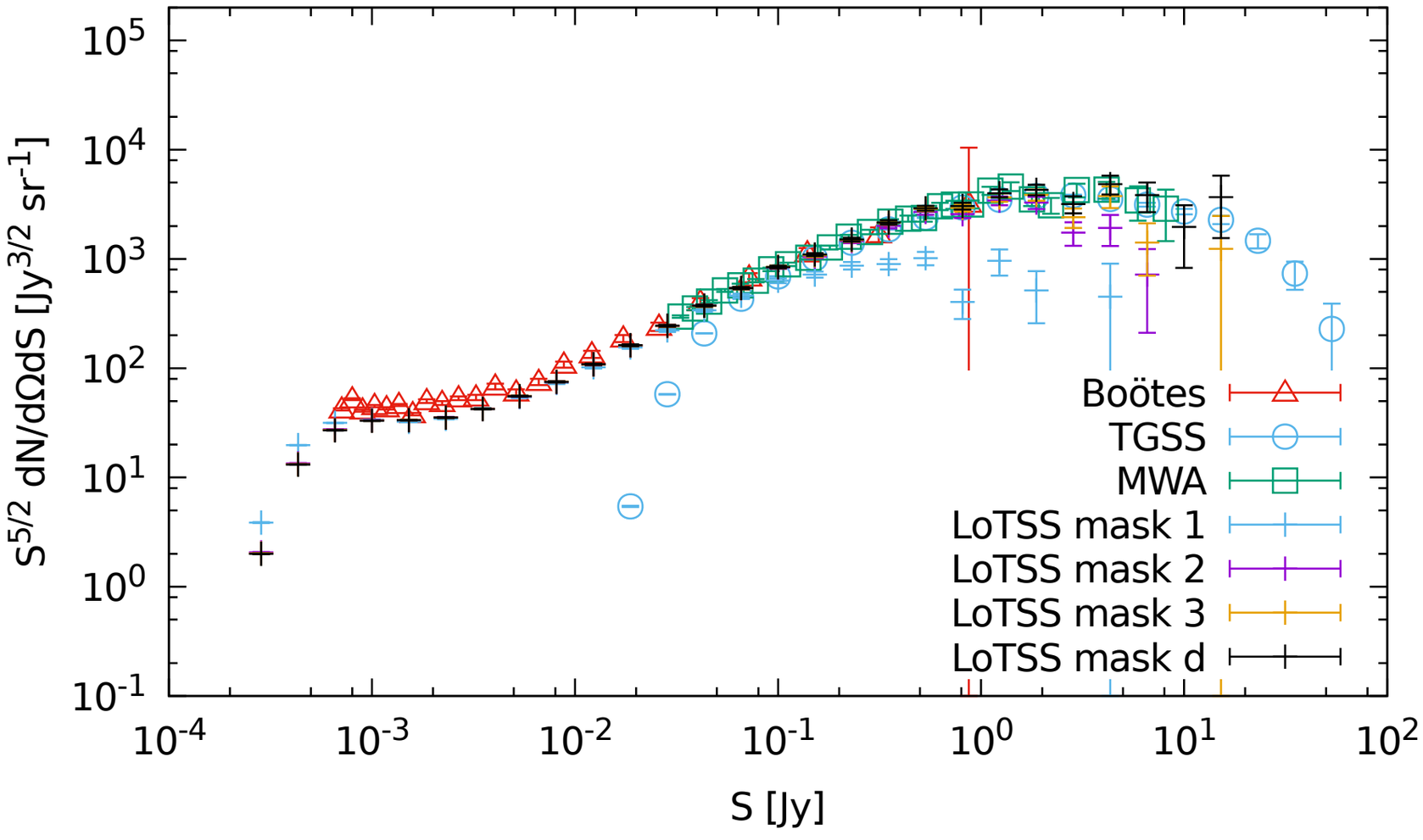
- For higher flux cuts, good results for now, 2mJy
- DR1 is just 4% of the total sky to be covered by LoTSS

- Agreement between 0.3 - 4 deg with CAMB code predictions, PLANCK Best fit cosmological parameters

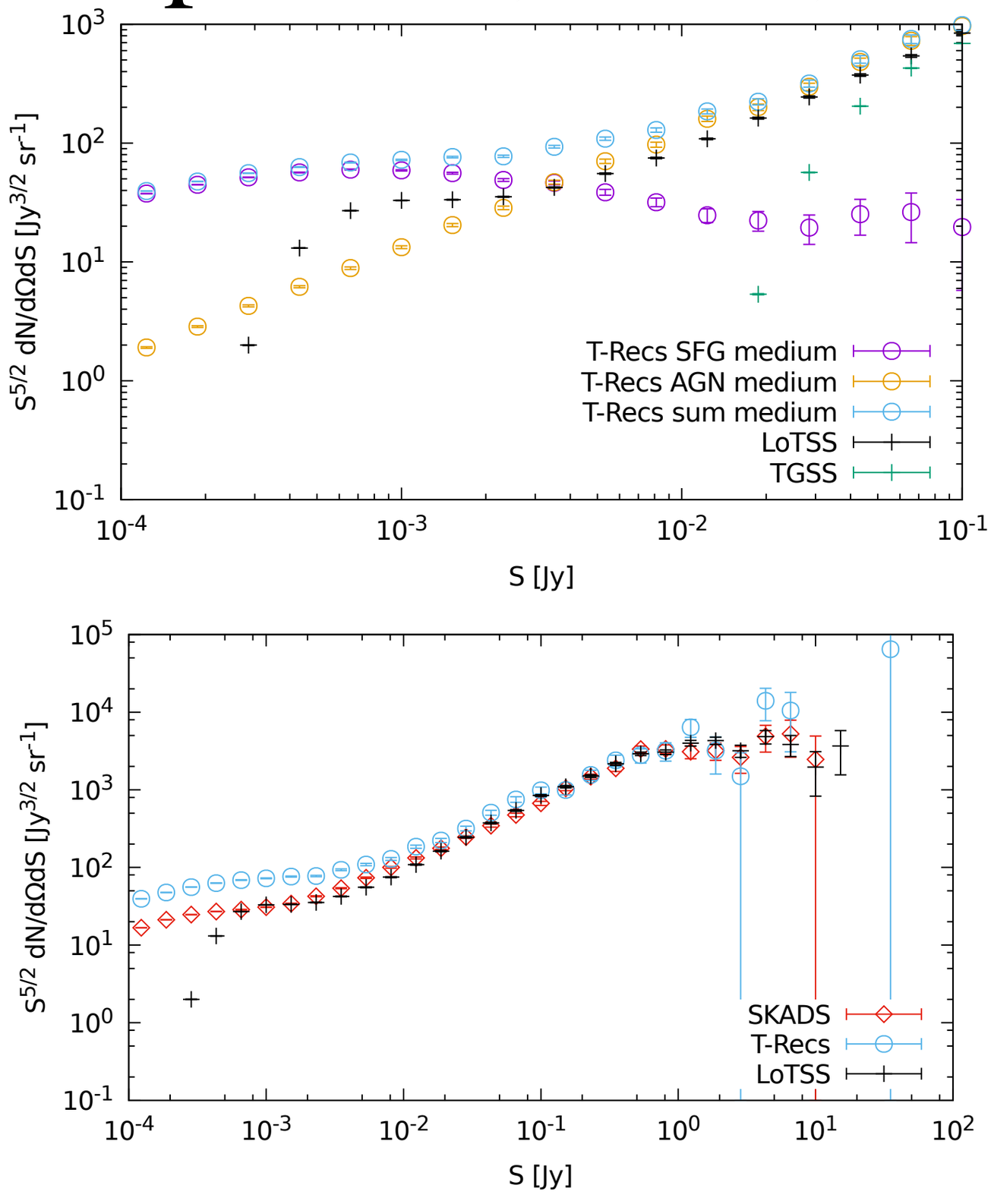
LOFAR Galaxy zoo: https://www.zooniverse.org/projects/chrismrp/radio-galaxy-zoo-lofar/about/research

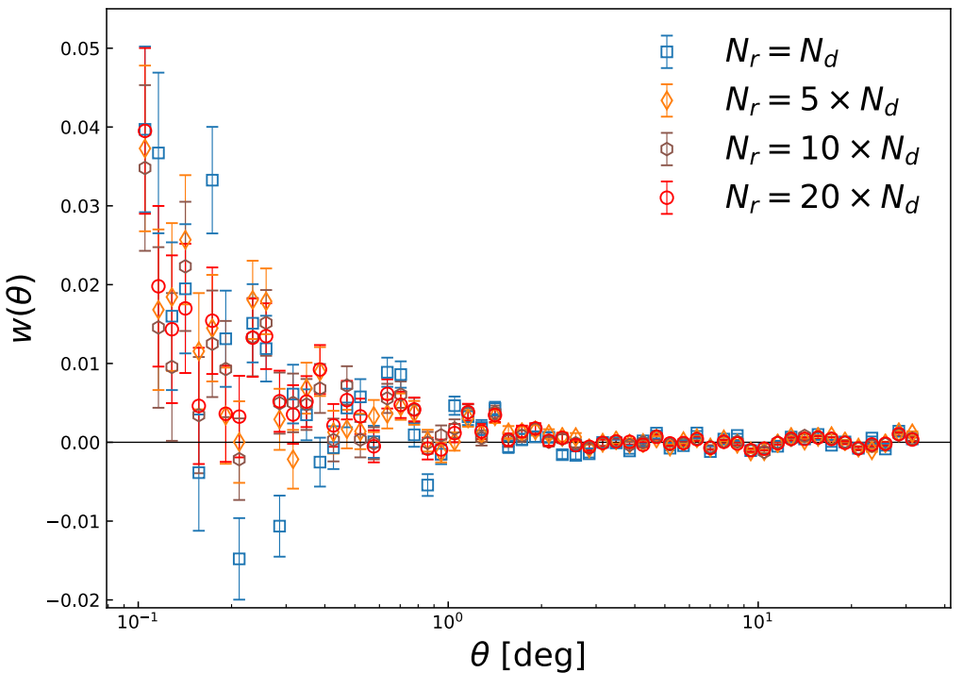
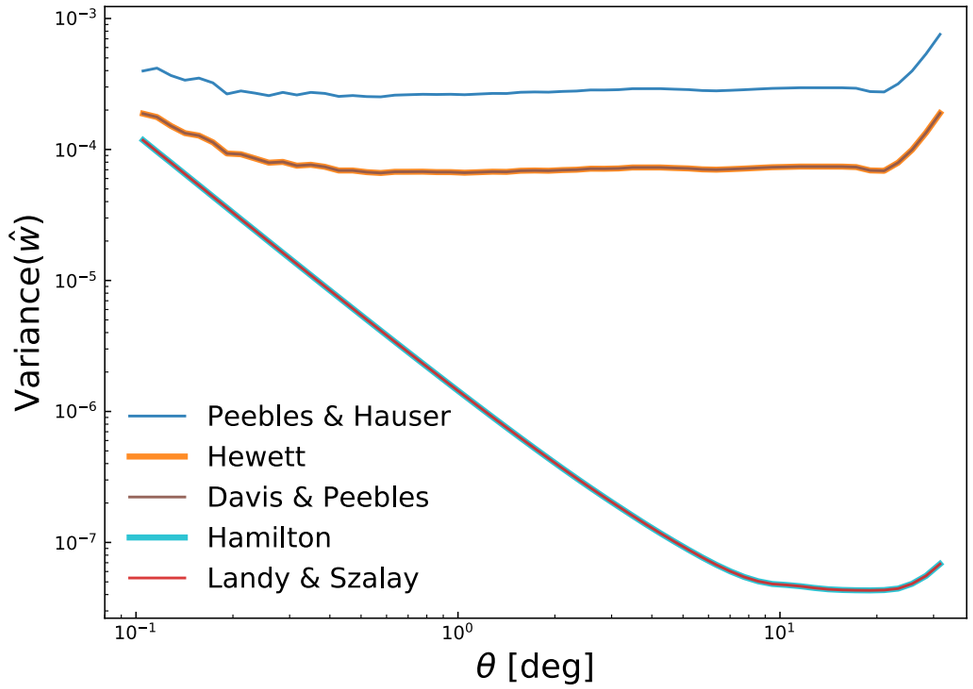
Thank you!

Differential source counts



Comparison, AGN, SFG



Estimators

- Peebles & Hauser $(DD - RR)/RR$
- Hewett $(DD - DR)/RR$
- Davis & Peebles $(DD - DR)/DR$
- Hamilton $(DD * RR - DR^2)/DR^2$
- Landay & Szalay $(DD - 2DR + RR)/RR$