Detection of the kinematic dipole with the large-scale structure of the Universe

Trabajo Fin de Grado

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24 septimbre 2020

Contents

1. Introduction: Standard Cosmological model

Cosmological observables: Cosmic microwave background (CMB) and large-scale structure (LSS)

Standard model of the universe (ΛCDM): Flat geometry and accelerated expansion

The expansion produces cosmological **redshift**

Composition: Dark energy (69%), CDM (26%), baryonic (5%)

Inflation: Initial perturbations leading to LSS

1. Introduction: Standard Cosmological model

Cosmological principle: Homogeneous and isotropic Universe at large scales

Kinematic dipole: Due to the motion of the Solar System with respect to the rest frame of the CMB

Our goals:

- Determine the capability of radio catalogues (SKA) to measure the kinematic dipole
- Provide a reasonable optimization approach and analyze its behaviour for different cases

1. Introduction: CMB dipole

CMB: *black body* radiation of mean T=(2.72548±0.00057) K
Fluctuations of order $\Delta T/T \approx 10^{-5}$

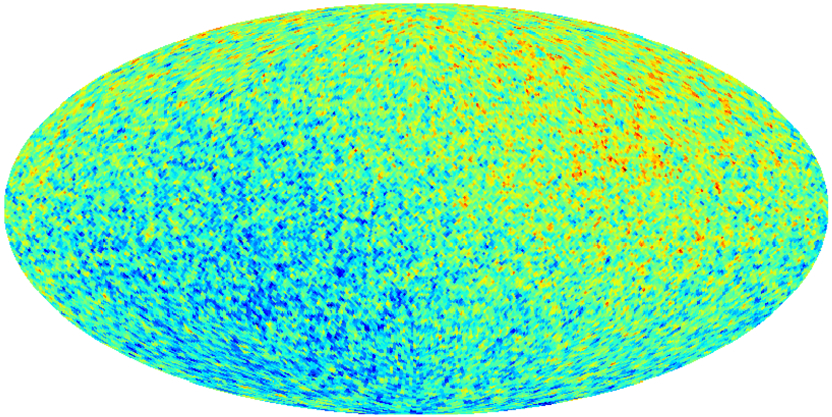
Dipole modulation of CMB monopole:

v=(369.82±0.11) km/s, (l,b)=(264.021±0.011 , 48.253±0.005)°

From modulation in fluctuations:

v=(384±78) km/s, (l,b)=(264 , 48)° , Δϕ~20°

Recent anomalies in the CMB at large angular scales, anisotropic Universe



1. Introduction: Dipole from LSS

$$\boldsymbol{d}_{radio} = \boldsymbol{d}_{motion} + \boldsymbol{d}_{structure} + \boldsymbol{d}_{foregrounds} + \boldsymbol{d}_{noise}$$

Structure dipole dominates at $z \ll 1$, radio surveys $z \gtrsim 1$

Foregrounds (Milky Way) and **noise** (shot noise) negligible

Motion, Doppler shift: $\nu_{\mathrm{obs}} = \nu_{\mathrm{rest}}\delta \quad ; \quad \delta \approx [1+(v/c)\cos\theta]$

$$\left(\frac{dN}{d\Omega}(S>,\boldsymbol{n})\right)_{obs} = \left(\frac{dN}{d\Omega}(S>,\boldsymbol{n})\right)_{rest}\left[1+[2+x(1+\alpha)]\left(\frac{v}{c}\right)\cos(\theta)\right]$$

With x=1, α=0.75, v = 369 km/s: amplitude A=0.00462

With NVSS and other surveys results not always consistent with those of the CMB, usually overestimation of A

1. Introduction: Square Kilometer Array

International project, 14 member countries (Spain in 2018)

Two phases: SKA1 (2028) and SKA2

Locations: South Africa (SKA-MID) and Australia (SKA-LOW)

Will detect synchrotron emission and HI 21 cm line

Spiral interferometer arrays of dishes and antennas

Collecting area of 10^6 m

Wide Band 1 Survey: 22.8 μJy flux threshold at 10σ

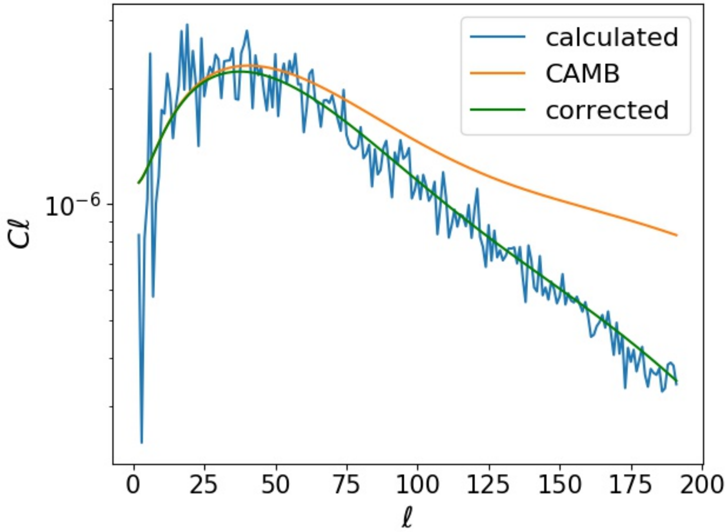
$0.35<\nu<1.05$ GHz , $0<z<6$

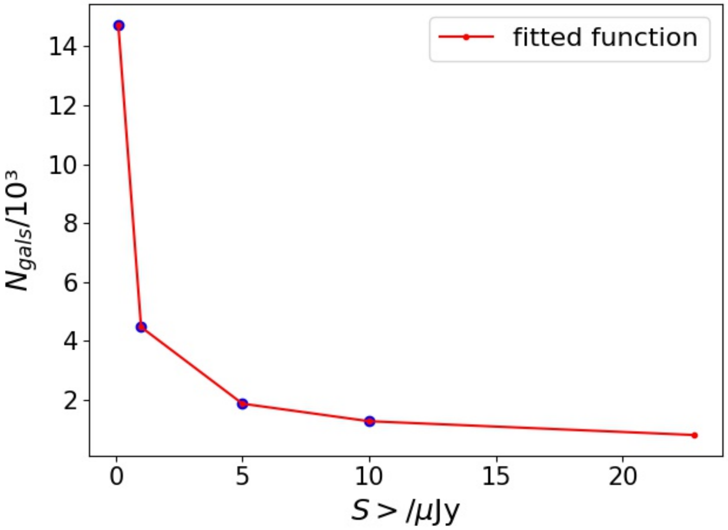
observable sky area $f_{\mathrm{sky}} \sim 0.63$

After removal of galactic plane $f_{\mathrm{sky}} \sim 0.50$

2. Simulations

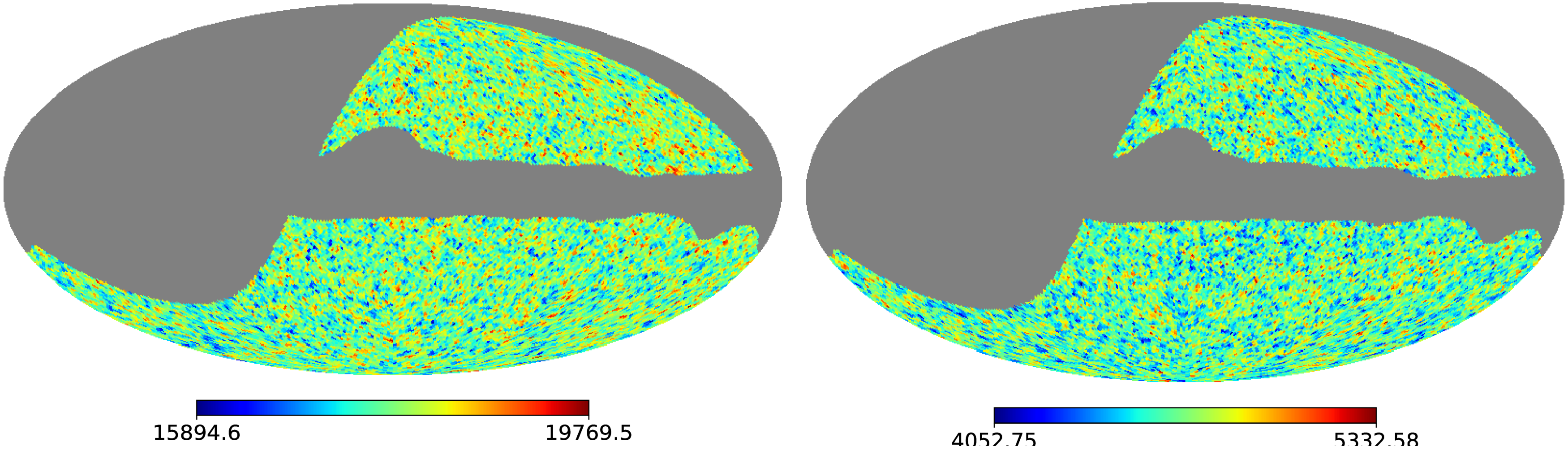
Angular power spectra from CAMB, **12 redshift bins**
Parameters from best-fit ΛCDM model by *Planck 2018*
Redshift distribution with polynomial fit (*Jarvis et al.* 2015)
Bias and **magnification bias** from *SKA Cosmology Group*





2. Simulations

Simulations following multivariate **log-normal distribution**
FLASK gives source count HEALPix maps (N_{side}=64)
$12N_{\text{side}}$ pixels of same area
100 simulations for four flux thresholds (1, 5, 10, 22.8 μJy)
Each simulation divided in **12 bins**, from there **4 samples**



3. Optimization

Quadratic estimator (*Bengaly et al. 2018*)**:**

Variate parameters to obtain minimum of function

$$\min \sum_p \left(\frac{\left[N_{\boldsymbol{p}} - \overline{N}\left(1 + A\cos\theta_{\boldsymbol{p}}\right)\right]^2}{\overline{N}\left(1 + A\cos\theta_{\boldsymbol{p}}\right)} \right)$$

Three methods:

- **Nelder-Mead**, variations of a simplex
- **Newton's conjugate gradient** (NCG), exact Hessian
- **L-BFGS-B**, updated approximation of Hessian

Estimation of amplitude and direction coordinates:

Pixel, cartesian (x,y,z) or galactic (l,b)

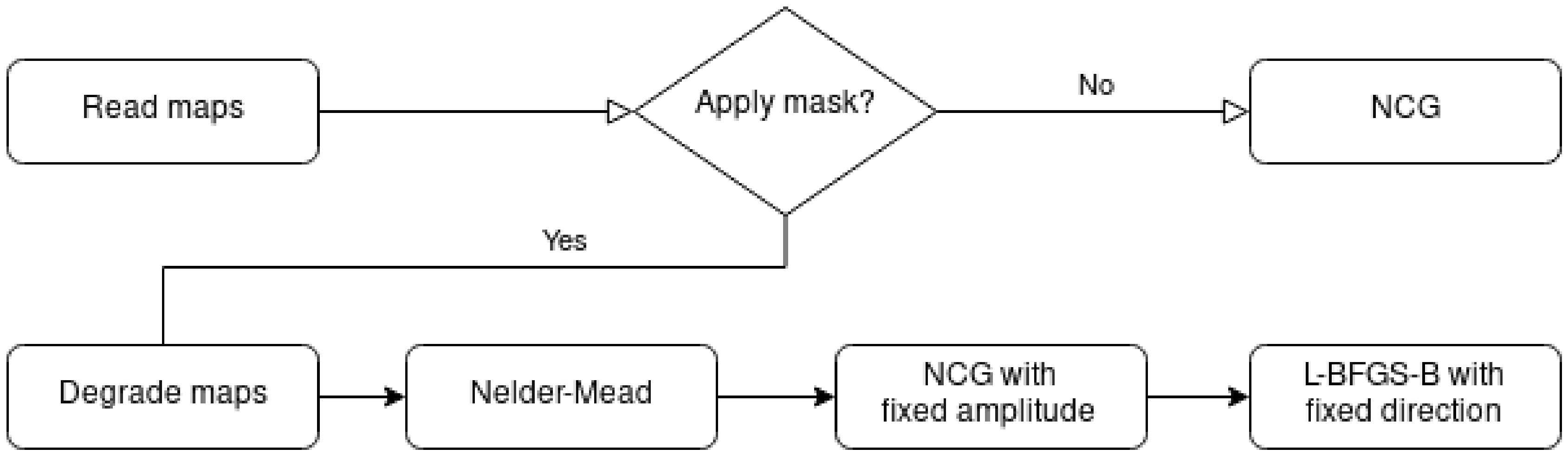
3. Optimization: Our approach

Only **pixel number** estimation works for masked-sky

Only method with pixel number is Nelder-Mead

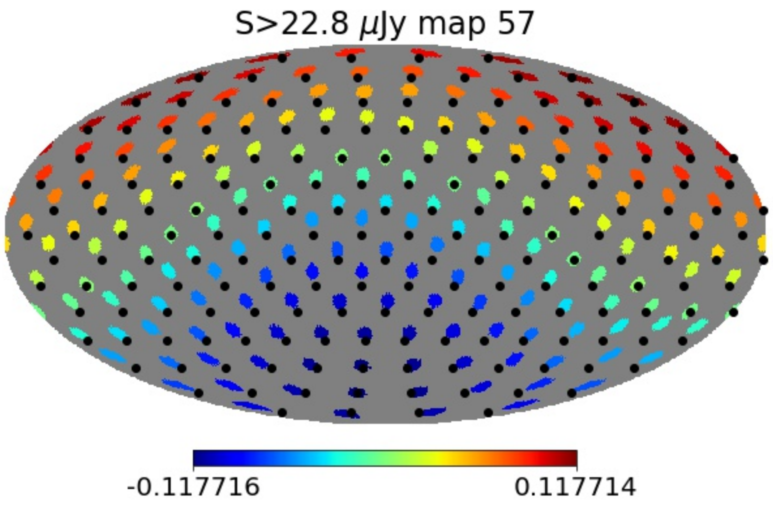
Degrade maps to N_{side}=32, less calculation time

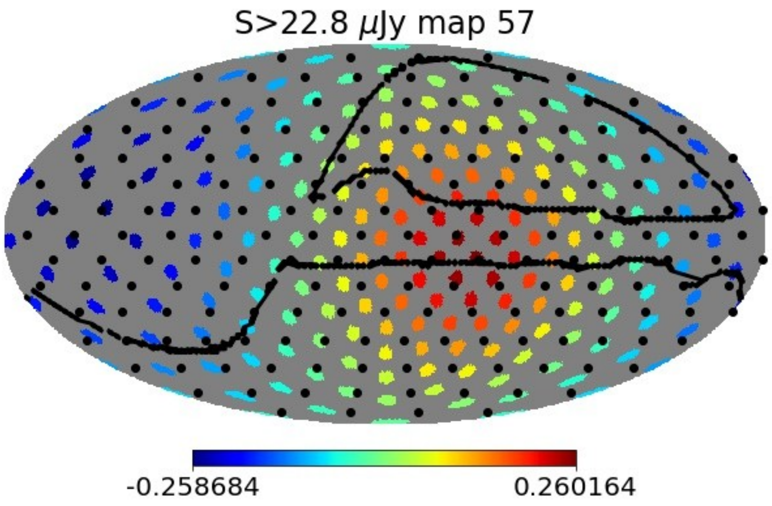
Cartesian {x,y,z} estimation more accurate



3. Optimization: Validation

Full-sky (left): highest errors in **random** position
Masked-sky (right): highest error **shifted** to center
Deviations from true direction, bigger with mask
There is a **systematic effect** in the method for masked-sky





4. Results

Masked maps						
$S>/\mu$Jy	Sample	$A/10^3$	l/deg	b/deg	θ/deg	$N_{gal}/10^7$
1	full	4.68±0.51	266.41±9.81	43.53±6.34	9.35±11.54	135.35
	z>0.5	4.67±0.18	267.11±3.97	44.19±2.20	5.37±6.21	123.98
	no Mod	4.29±0.50	266.62±10.56	43.23±6.41	10.01±12.72	135.35
	structure	0.86±0.41	–	–	–	135.35
5	full	4.83±0.67	267.75±13.49	43.54±9.67	12.97±15.17	44.13
	z>0.5	4.76±0.24	266.86±4.35	43.17±2.96	6.43±7.56	38.62
	no Mod	4.26±0.67	268.17±15.23	42.84±10.9	14.64±17.46	44.13
	structure	1.25±0.56	–	–	–	44.13
10	full	4.94±0.92	267.46±15.95	39.11±10.74	16.51±20.02	24.62
	z>0.5	4.82±0.23	268.47±5.84	40.93±3.41	9.0±10.81	21.08
	no Mod	4.28±0.91	267.72±17.92	37.55±12.46	18.96±22.92	24.62
	structure	1.61±0.65	–	–	–	24.62
22.8	full	4.91±0.99	270.6±18.16	39.73±11.97	17.74±21.22	11.53
	z>0.5	4.87±0.34	269.73±5.19	38.84±3.49	11.0±12.44	9.67
	no Mod	4.17±1.00	271.59±21.18	38.2±13.69	20.64±25.58	11.52
	structure	1.78±0.77	–	–	–	11.53
CMB		4.62	264.02	48.25	–	–

4. Results

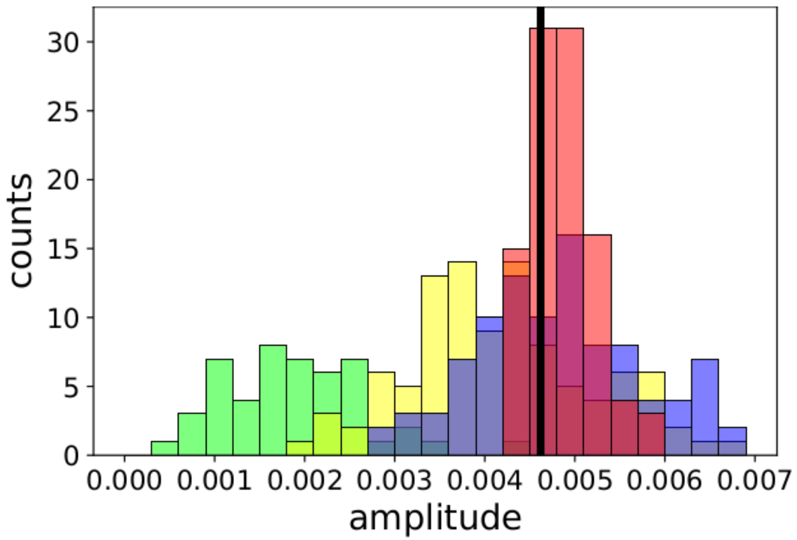
The amplitude estimations have a **symmetric distribution**, shifted from the CMB

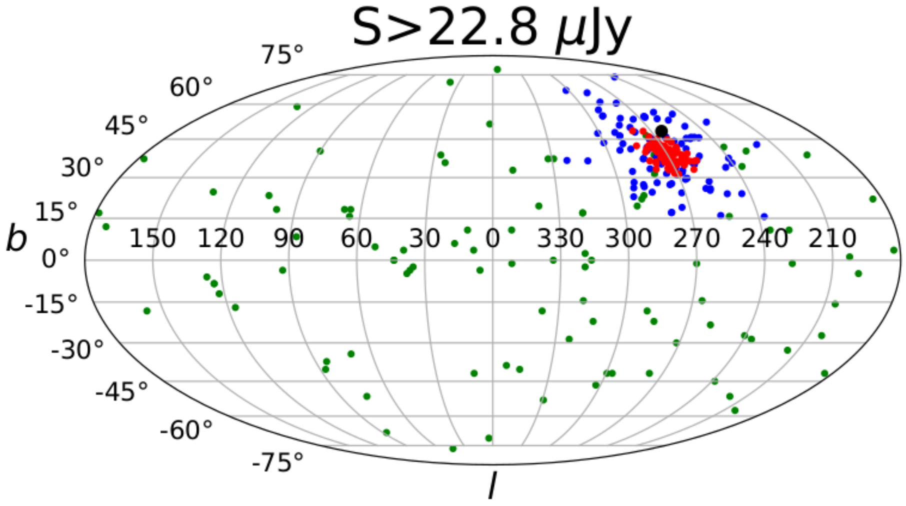
Full (red) narrow, *structure* (green) very wide

Directions scattered near CMB, small shift

Structure dipole in random directions

no Mod
z>0.5
full
structure





5. Conclusions

Results in general show **good agreement** with CMB

Systematic errors due to reduced observable sky (mask)

SKA data is expected to produce **better** or similar results than other galaxy surveys

Better than from CMB dipole modulation

After removing the **local structure** they are very accurate

Lower flux threshold improves results to a certain point

SKA is a **promising tool** to corroborate the standard cosmological model and to provide further insight into the CMB anomalies

5. Conclusions

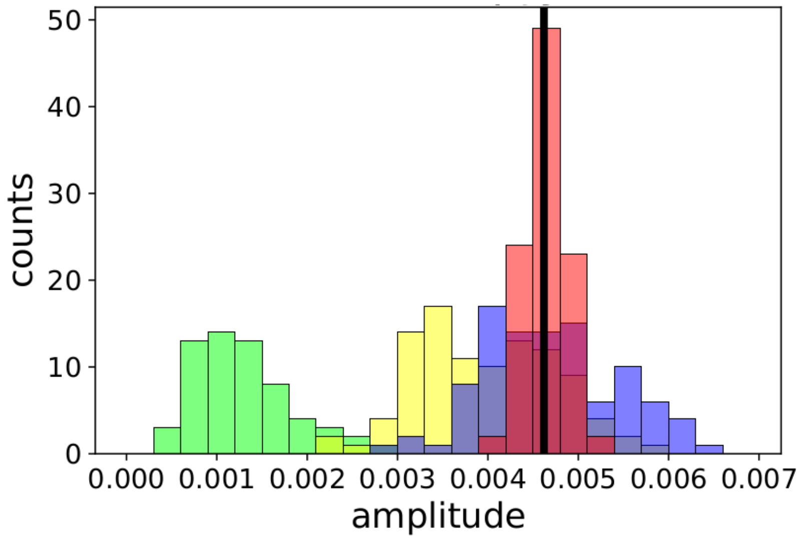
We have identified several points that could be extended in a **future work:**

- Correct systematics from the mask
- Deeper analysis of structure dipole
- Estimator based on likelihood and explore with MCMC

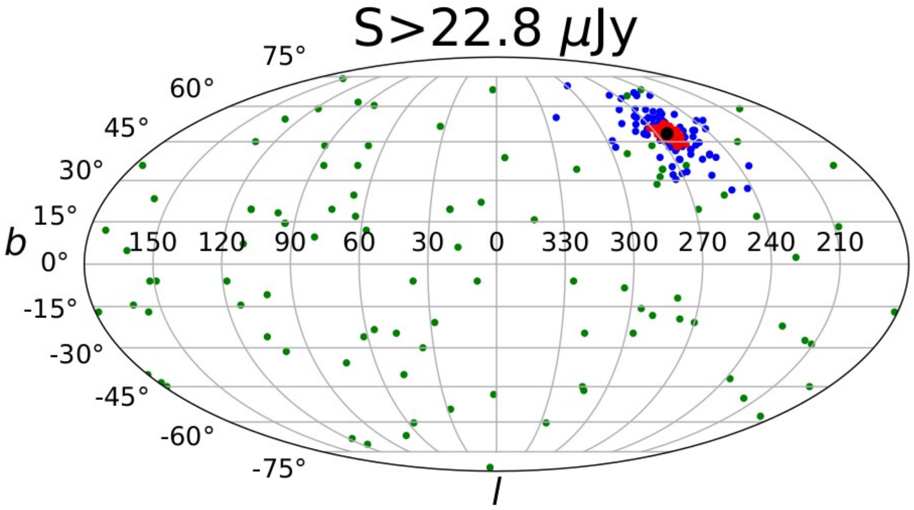
The code I wrote to obtain the galaxy maps and to obtain the results presented in this work can be found in the GitHub repository **Radio-Dipole**:

BACK-UP SLIDES

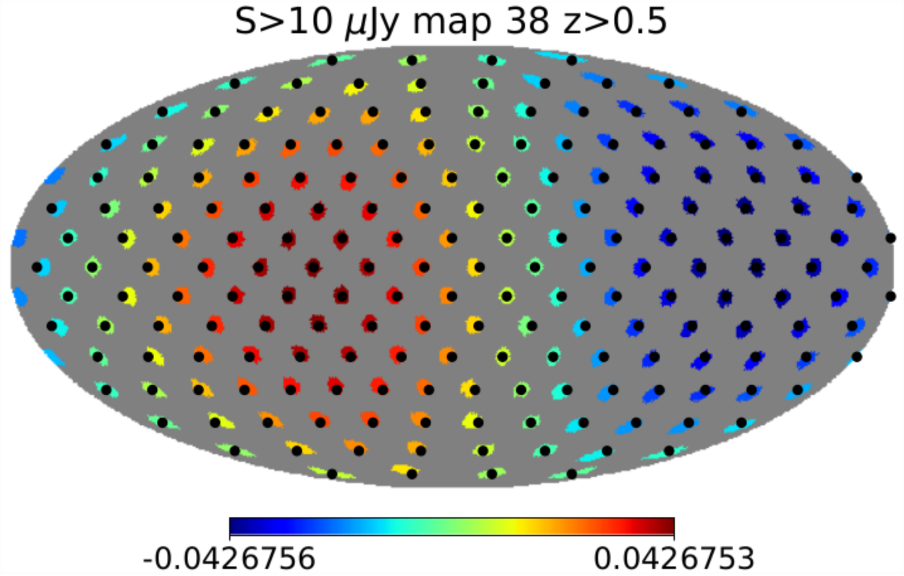
Full-sky maps						
$S>/\mu$Jy	Sample	$A/10^3$	l/deg	b/deg	θ/deg	$N_{gal}/10^7$
1	full	4.60±0.42	263.59±4.89	48.01±3.94	3.93±4.57	268.67
	z>0.5	4.60±0.12	264.11±1.15	48.16±0.87	0.83±1.22	246.10
	no Mod	4.23±0.42	262.8±6.03	47.83±4.41	4.87±6.23	268.67
	structure	0.66±0.28	–	–	–	268.67
5	full	4.68±0.60	263.86±9.54	48.08±5.44	6.54±7.23	87.60
	z>0.5	4.64±0.16	264.16±2.16	48.62±1.51	1.71±2.18	76.66
	no Mod	4.09±0.59	264.5±10.05	48.23±7.48	8.13±10.32	87.60
	structure	0.99±0.37	–	–	–	87.60
10	full	4.74±0.76	263.03±10.86	47.08±6.24	8.22±10.57	48.88
	z>0.5	4.63±0.18	264.03±2.82	48.14±1.75	2.12±2.86	41.84
	no Mod	4.10±0.80	262.49±14.66	46.52±8.57	11.41±15.13	48.88
	structure	1.17±0.49	–	–	–	48.88
22.8	full	4.73±0.80	263.7±13.18	48.0±8.65	10.04±11.47	22.86
	z>0.5	4.65±0.22	263.53±3.01	48.24±1.83	2.24±2.97	19.19
	no Mod	3.97±0.77	262.92±15.39	48.52±10.40	12.28±14.29	22.86
	structure	1.30±0.58	–	–	–	22.86
CMB		4.62	264.02	48.25	–	–



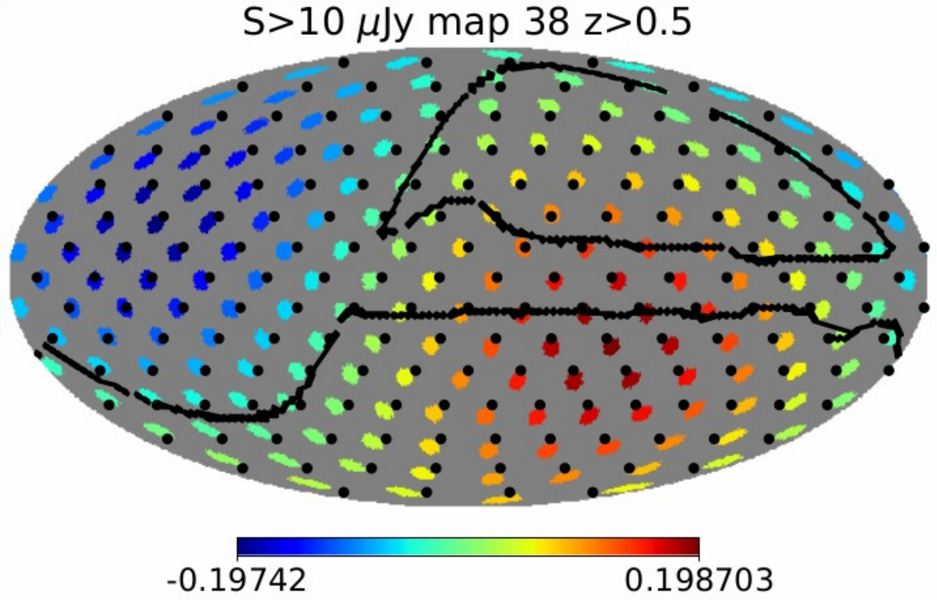
counts
amplitude
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0
10
20
30
40
50



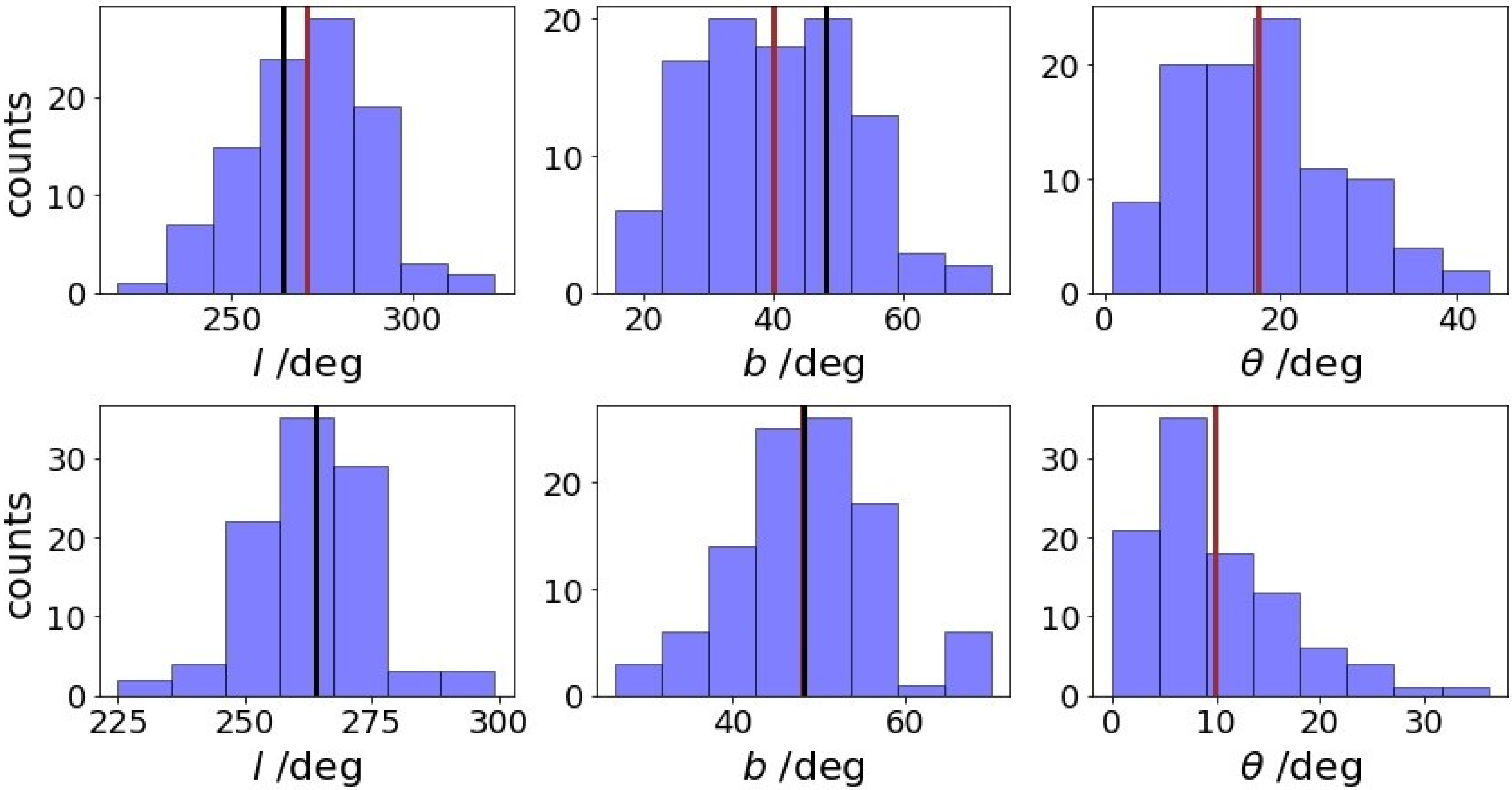
S>22.8 μJy
b
l
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150
120
90
60
30
0
330
300
270
240
210

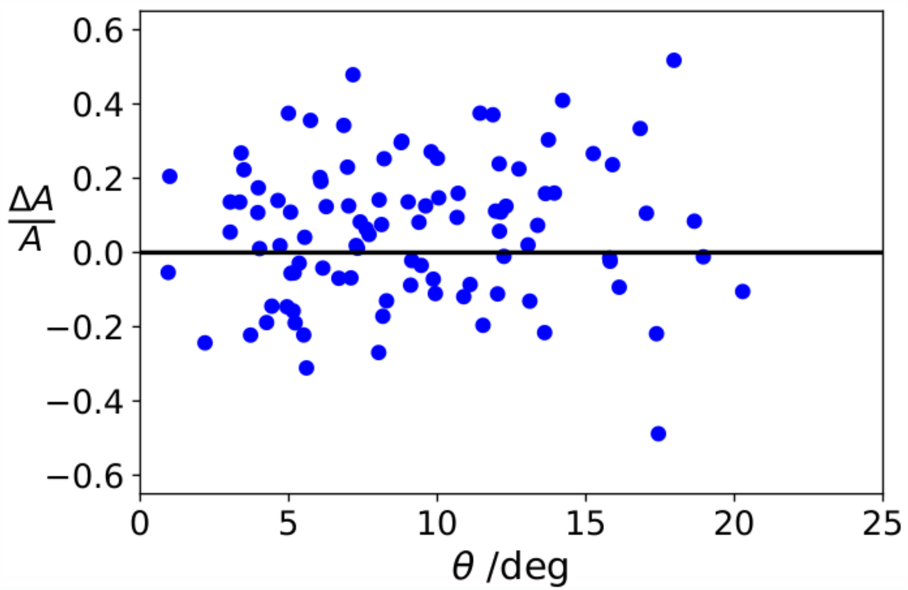


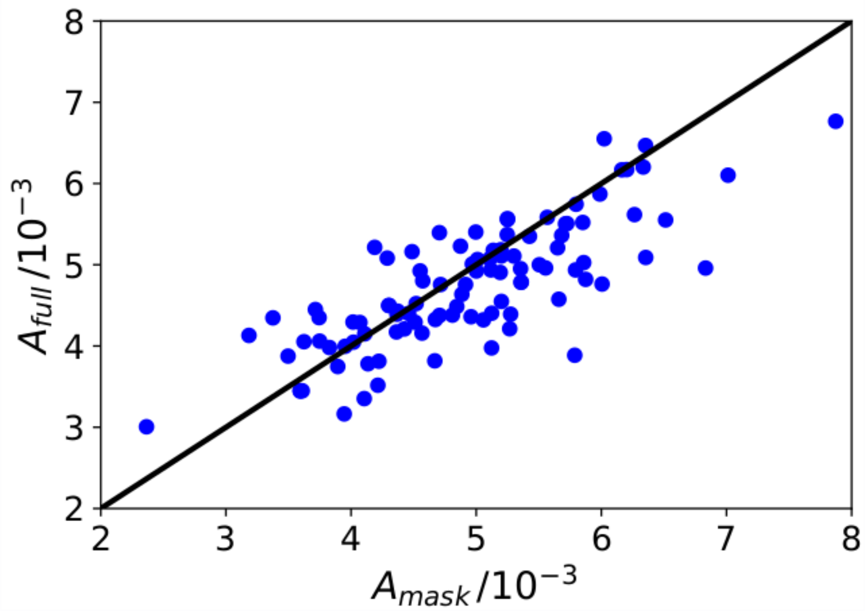
S>10 μJy map 38 z>0.5
-0.0426756
0.0426753



S>10 μJy map 38 z>0.5
-0.19742
0.198703


counts
l /deg
b /deg
θ /deg
counts
l /deg
b /deg
θ /deg


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
$\frac{\Delta A}{A}$
0
5
10
15
20
25
θ /deg


8
7
6
5
4
3
2
$A_{full}/10^{-3}$
2
3
4
5
6
7
8
$A_{mask}/10^{-3}$