Parity-Odd Modes in the 4PCF of BOSS DR12 CMASS and LOWZ

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The Renaissance was known for self-portraits

How did they do it?

Mirrors

"Art is the mirror of nature"

Borrow from Renaissance portraiture to *study* nature, and ask:

Is nature a mirror of itself?

Parity

CPT Theorem: Luders 1940—any Lorentz-invariant theory

Yet we have 1 billion baryons for every anti-baryon—fortunately

Requires breaking of CP symmetry

Perhaps just P symmetry

Inflation

Vanilla inflation predicts no parity-violation

But if there is a new force (or coupling, if you prefer), there could be

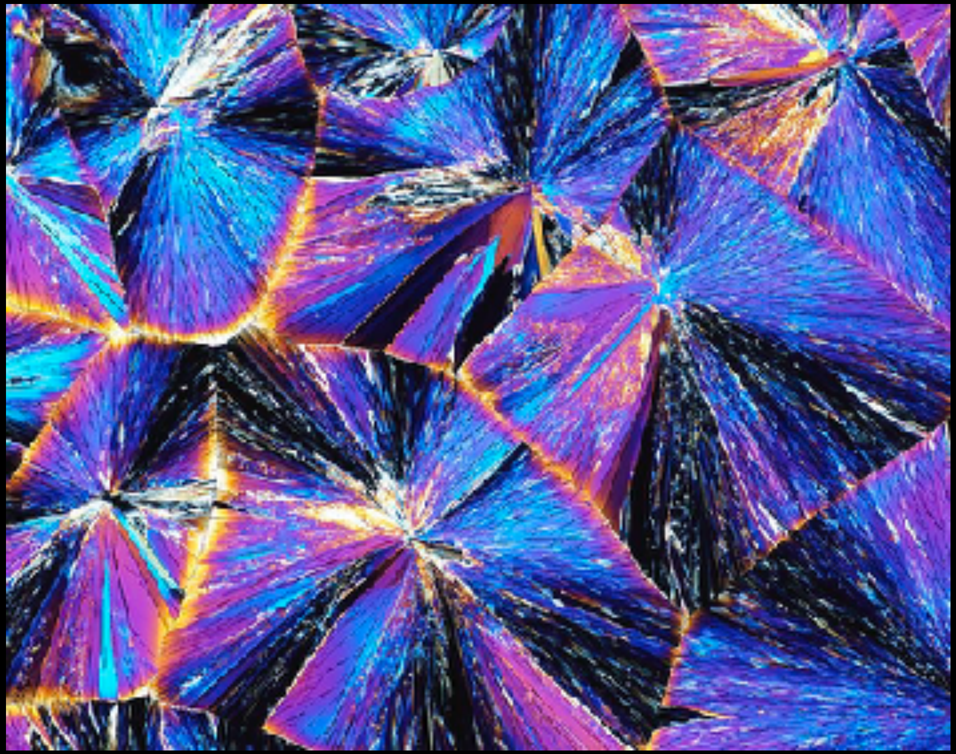
e.g. a term in the Lagrangian such as Maxwell tensor X Maxwell tensor dual

Or a term in the Riemann tensor and its dual

Back to history

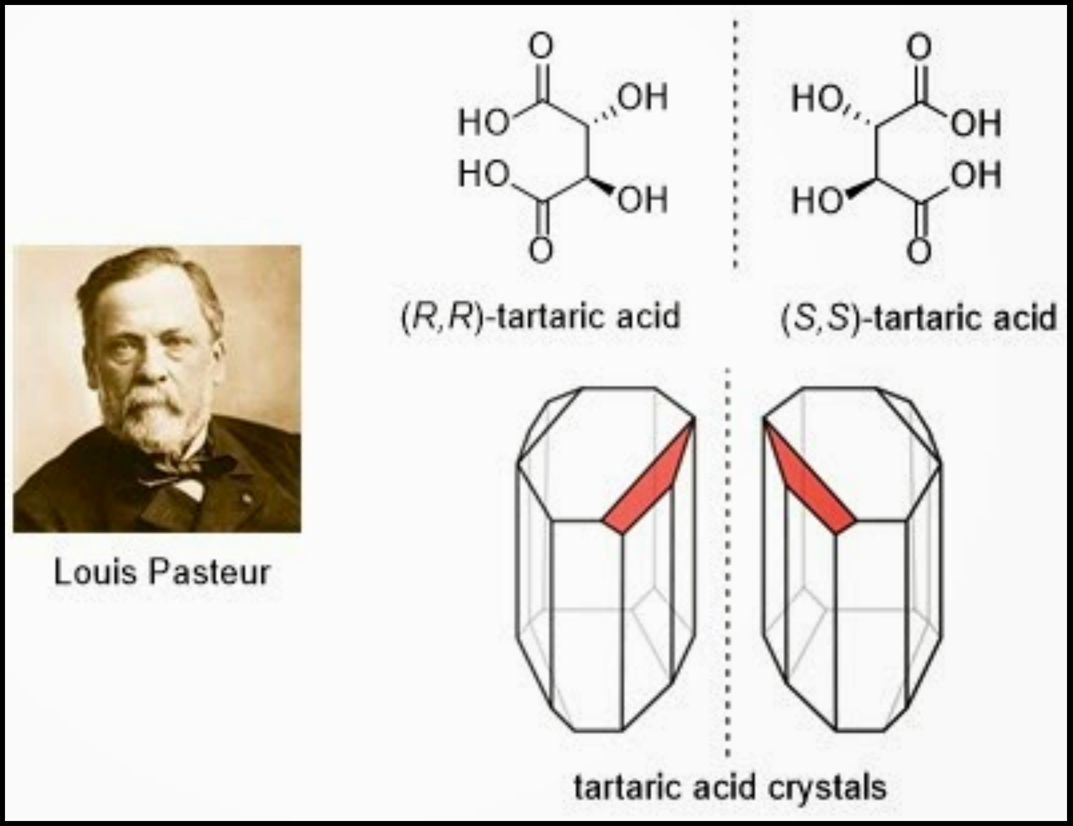
Pasteur: 1848—noticed that synthetically-produced tartaric acid produced no polarization of light when the light passed through it

But naturally-occurring tartaric acid did



Another history lesson

Also known as "stereoactive isomers" or "enantiomers"



So let us search for such “crystals”

Need to be 3D

Point = no

Line = no

Triangle = no (sadly for the 3PCF)

Tetrahedron = YES

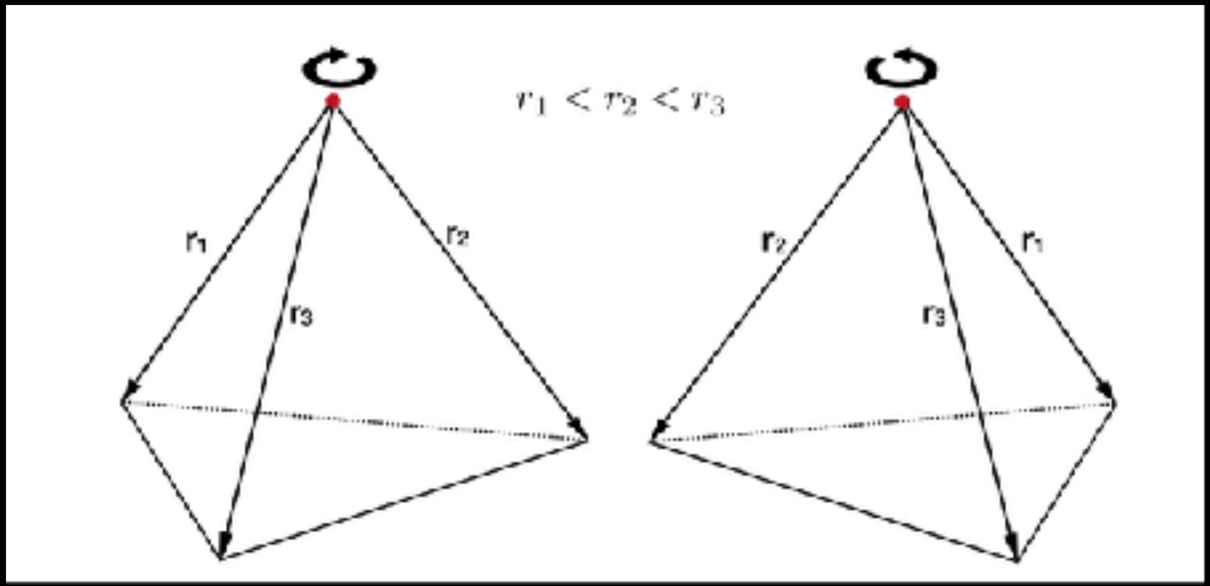
The Galaxy 4PCF

Fun part's over—or maybe just starting!
-> From human history, back to cosmology

4PCF = excess clustering of tetrahedra over and above what a spatially random distribution of points would have

4PCF Basis

Parametrize 4PCF by six variables:
3 side lengths from a given vertex,
3 angular momenta for dependence on angles around it



Angular basis functions = "isotropic functions" — total-angular-momentum-zero products of 3 spherical harmonics ("primary" galaxy is at the origin, so no harmonic needed for it)

The Galaxy 4PCF

Seek radial coefficients giving projection of 4PCF onto this angular basis:

$$\mathrm{4PCF} = \sum_{\ell_i} \boxed{\zeta_{\ell_1\ell_2\ell_3}(r_1, r_2, r_3)} \mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1, \hat{r}_2, \hat{r}_3)$$

$$\mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1, \hat{r}_2, \hat{r}_3) = \sum_{m_i} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} Y_{\ell_1 m_1}(\hat{r}_1) Y_{\ell_2 m_2}(\hat{r}_2) Y_{\ell_3 m_3}(\hat{r}_3)$$

Even/Odd Split

Both even and odd-parity basis functions

In standard picture, projection of 4PCF onto odd basis functions should be zero (up to fluctuations)

$$\begin{aligned}
\mathcal{P}_{111}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) &= -i\frac{3}{\sqrt{2}}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\,,\\
\mathcal{P}_{122}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) &= i\sqrt{\frac{45}{2}}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\,(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)\,,\\
\mathcal{P}_{133}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) &= -i\frac{15}{4}\sqrt{7}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\left[(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)^2-\frac{1}{5}\right],\\
\mathcal{P}_{144}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) &= +i\frac{21\sqrt{15}}{4}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\left[(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)^3-\frac{3}{7}(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)\right],\\
\mathcal{P}_{223}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) &= -i15\sqrt{\frac{5}{8}}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\left[(\hat{\mathbf{r}}_1\cdot\hat{\mathbf{r}}_3)\,(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)-\frac{1}{5}\hat{\mathbf{r}}_1\cdot\hat{\mathbf{r}}_2\right],
\end{aligned}$$

We have our basis

What about an *algorithm?*

How do you measure the 4PCF fast?

Naive combinatorics is explosive!

Computing Summary

Lots of math: use GPUs

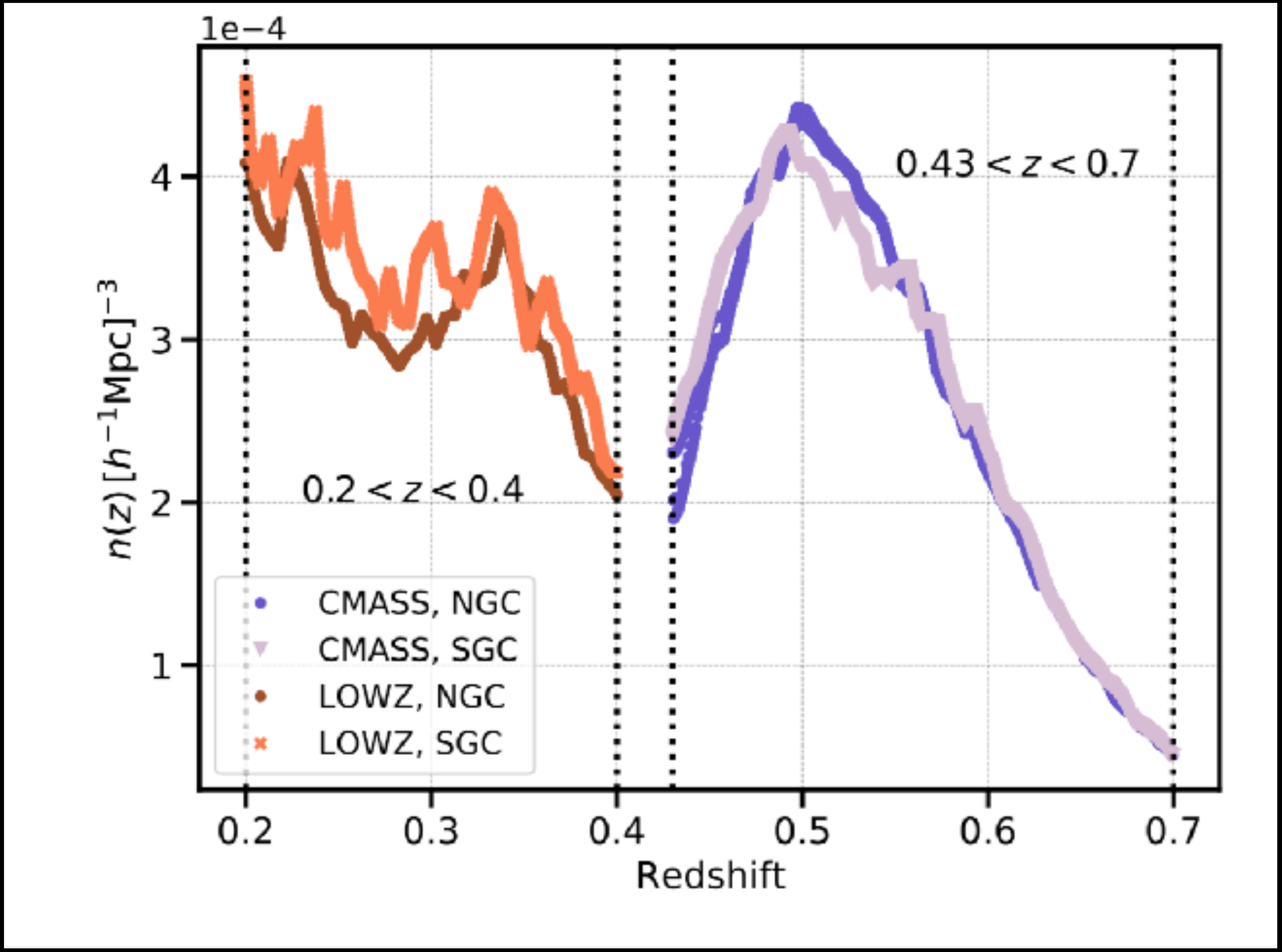
Code for 2-6PCF optimized for NVIDIA A100s

CADENZA

7.5M CPU hours = 20 months day and night on a 500-core cluster

1 month on 69 NVIDIA A100 GPUs

Data



SDSS DR12 BOSS CMASS and LOWZ samples

Covariance Matrix

Our fiducial analysis had ~9,000 degrees of freedom, >> number of mocks

Driven by fine radial binning needed to avoid incoherent co-adding of parity-odd signal if one sums over vertices of a tetrahedron

-> Cannot derive invertible covariance matrix from mocks

-> Other solutions

Covariance Matrix

3 Methods

1) Analytic: use GRF to compute analytic covariance matrix

2) Compressed: diagonalize analytic covariance, select a sub-space of "best" e-vectors, measure covariance directly from mocks in that smaller space

3) Direct: restrict angular momentum and/or side-length range to make d.o.f. small enough to determine C directly from mocks

The "Serious" Slide

$$\mathrm{Cov}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') = \mathrm{Cov}^{\mathrm{I}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') + \mathrm{Cov}^{\mathrm{II}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3').$$

$$\begin{aligned}\mathrm{Cov}^{\mathrm{I}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') &= (4\pi)^4 \sum_G (-1)^{\Sigma(\Lambda)(1-\mathcal{E}_G)/2} \sum_{L_1L_2L_3} \mathcal{D}^{\mathrm{P}}_{L_1L_2L_3}\, \mathcal{C}^{L_1L_2L_3}_{000} \begin{Bmatrix} \ell_{G1} & \ell_{G2} & \ell_{G3} \\ \ell_1' & \ell_2' & \ell_3' \\ L_1 & L_2 & L_3 \end{Bmatrix} \\ &\times \int \frac{s^2 ds}{V} \prod_{i=1}^{3} \left[(-1)^{(-\ell_{Gi}-\ell_i'+L_i)/2} \mathcal{D}^{\mathrm{P}}_{\ell_i\ell_i'L_i}\, \mathcal{C}^{\ell_{Gi}\ell_i'L_i}_{000}\, \xi(s) f_{\ell_{Gi}\ell_i'L_i}(r_{Gi}, r_i', s)\right],\end{aligned}$$

$$\begin{aligned}\mathrm{Cov}^{\mathrm{II}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') &= (4\pi)^4 \sum_{G,H} (-1)^{\Sigma(\Lambda')(1-\mathcal{E}_H)/2} \sum_{L_1L_2L_3} \mathcal{D}^{\mathrm{P}}_{L_1L_2L_3}\, \mathcal{C}^{L_1L_2L_3}_{000} \begin{Bmatrix} \ell_{G1} & \ell_{G2} & \ell_{G3} \\ \ell'_{H1} & \ell'_{H2} & \ell'_{H3} \\ L_1 & L_2 & L_3 \end{Bmatrix} \\ &\times \int \frac{s^2 ds}{V} \prod_{i=1}^{3} \left[(-1)^{(-\ell_{Gi}-\ell'_{Hi}+L_i)/2} \mathcal{D}^{\mathrm{P}}_{\ell_{Gi}\ell'_{Hi}L_i}\, \mathcal{C}^{\ell_{Gi}\ell'_{Hi}L_i}_{000}\right] \\ &\times f_{\ell_{G1}0\ell_{G1}}(r_{G1},0,s) f_{0\ell'_{H1}\ell'_{H1}}(0,r'_{H1},s) f_{\ell_{G2}\ell'_{H2}L_2}(r_{G2},r'_{H2},s) f_{\ell_{G3}\ell'_{H3}L_3}(r_{G3},r'_{H3},s).\end{aligned}$$

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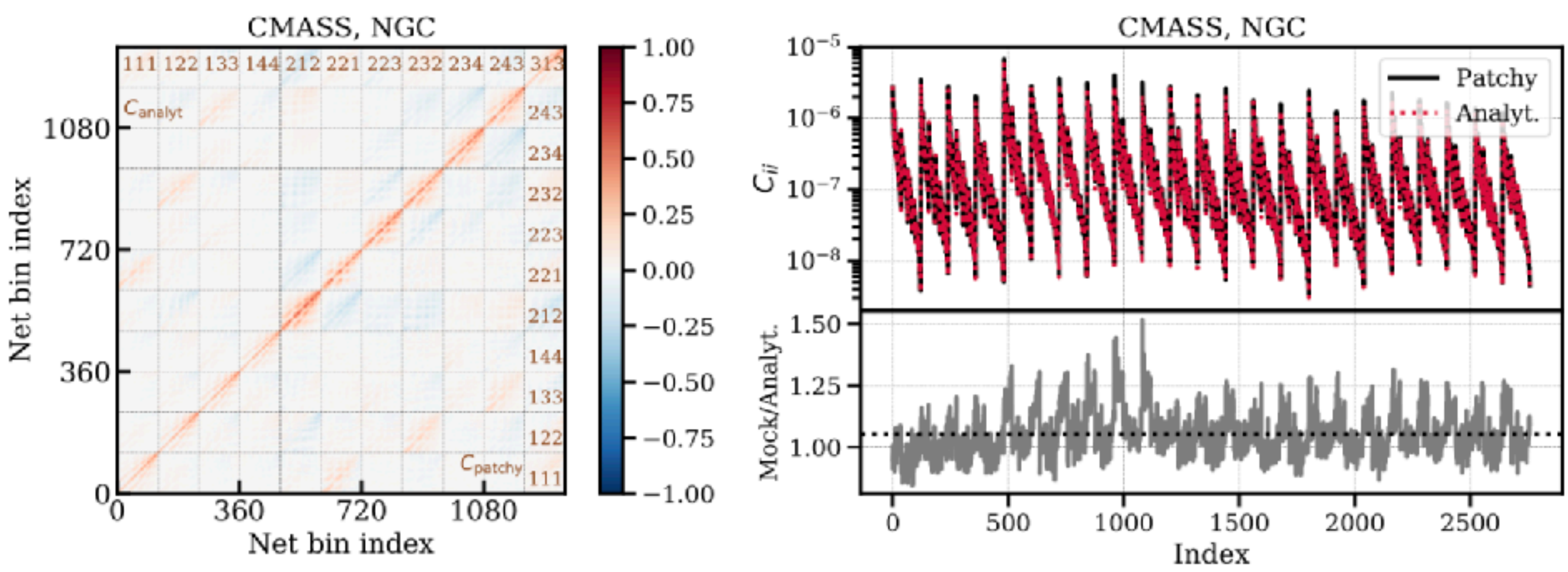
Comparison of Mock and Analytic Covariance



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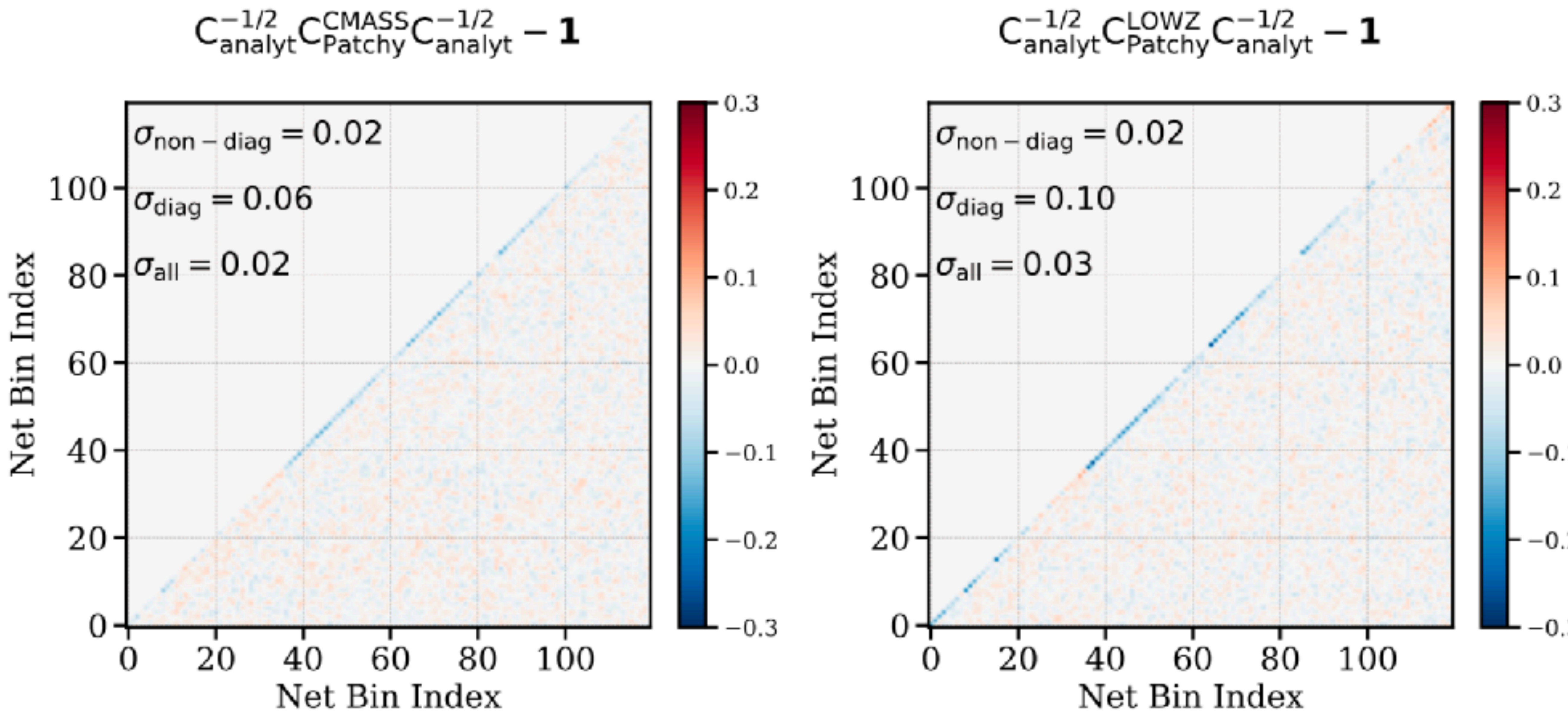
Half-Inverse Test



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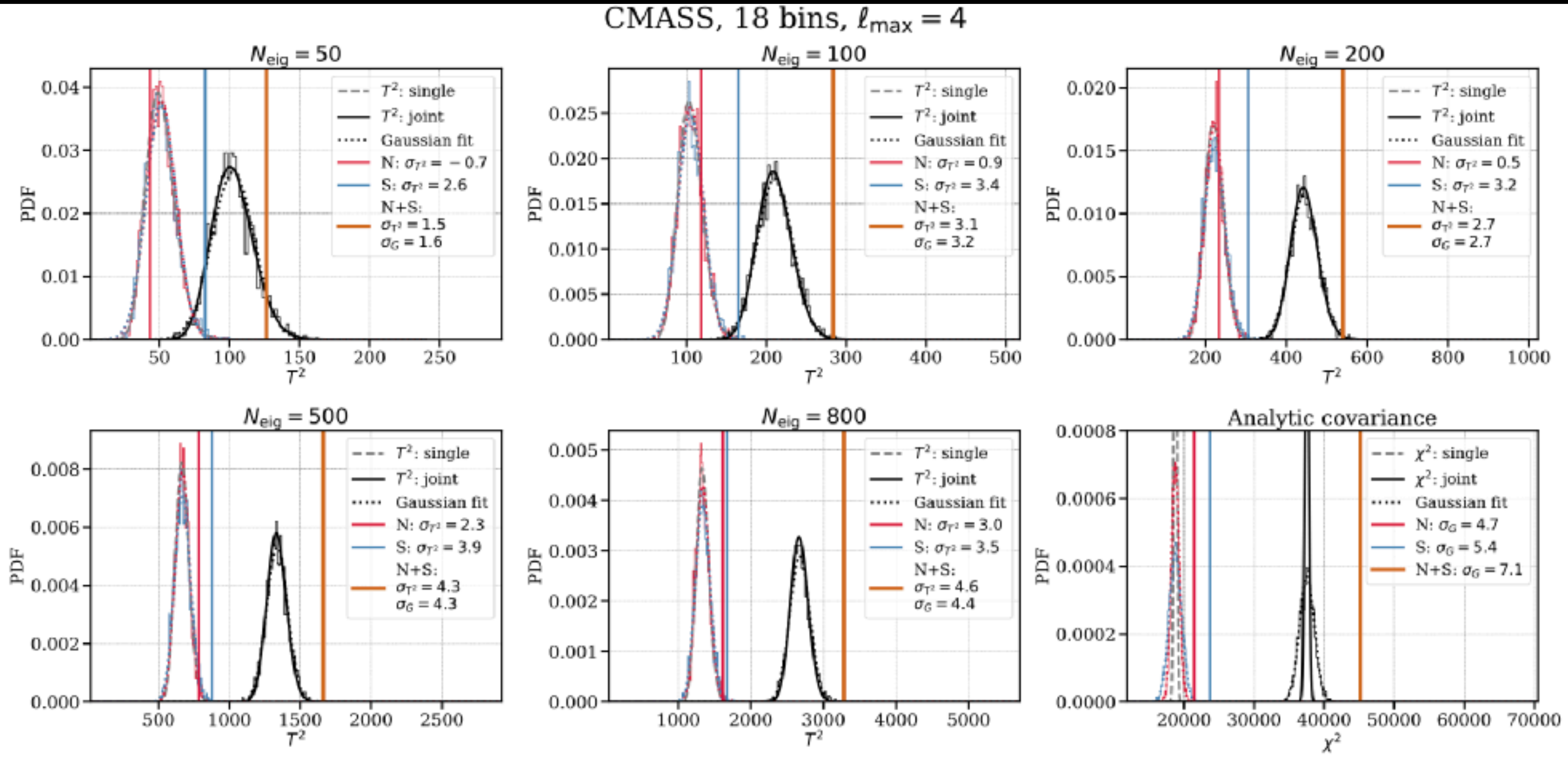
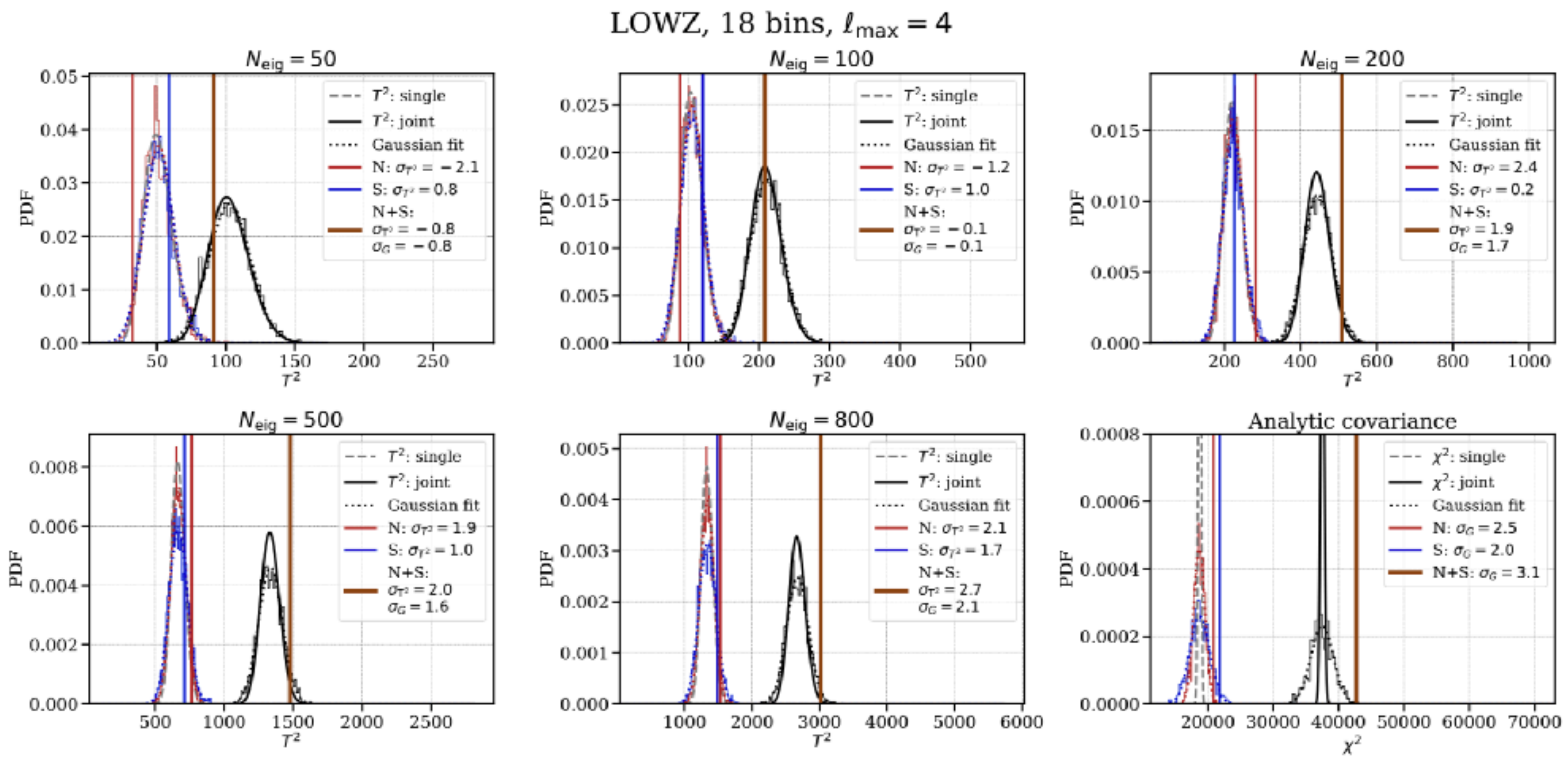
BOSS Results

CMASS



CMASS, 18 bins, $\ell_{max} = 4$
$N_{eig} = 50$
$N_{eig} = 100$
$N_{eig} = 200$
$N_{eig} = 500$
$N_{eig} = 800$
Analytic covariance
T^2: single
T^2: joint
Gaussian fit
N: $\sigma_{T^2} = -0.7$
S: $\sigma_{T^2} = 2.6$
N+S: $\sigma_{T^2} = 1.5$ $\sigma_G = 1.6$
N: $\sigma_{T^2} = 0.9$
S: $\sigma_{T^2} = 3.4$
N+S: $\sigma_{T^2} = 3.1$ $\sigma_G = 3.2$
N: $\sigma_{T^2} = 0.5$
S: $\sigma_{T^2} = 3.2$
N+S: $\sigma_{T^2} = 2.7$ $\sigma_G = 2.7$
N: $\sigma_{T^2} = 2.3$
S: $\sigma_{T^2} = 3.9$
N+S: $\sigma_{T^2} = 4.3$ $\sigma_G = 4.3$
N: $\sigma_{T^2} = 3.0$
S: $\sigma_{T^2} = 3.5$
N+S: $\sigma_{T^2} = 4.6$ $\sigma_G = 4.4$
χ^2: single
χ^2: joint
N: $\sigma_G = 4.7$
S: $\sigma_G = 5.4$
N+S: $\sigma_G = 7.1$
PDF
T^2
χ^2

LOWZ



LOWZ, 18 bins, $\ell_{max} = 4$
$N_{eig} = 50$
$N_{eig} = 100$
$N_{eig} = 200$
$N_{eig} = 500$
$N_{eig} = 800$
Analytic covariance
PDF
T^2
χ^2
T^2: single
T^2: joint
Gaussian fit
N: $\sigma_{T^2} = -2.1$
S: $\sigma_{T^2} = 0.8$
N+S: $\sigma_{T^2} = -0.8$ $\sigma_G = -0.8$
N: $\sigma_{T^2} = -1.2$
S: $\sigma_{T^2} = 1.0$
N+S: $\sigma_{T^2} = -0.1$ $\sigma_G = -0.1$
N: $\sigma_{T^2} = 2.4$
S: $\sigma_{T^2} = 0.2$
N+S: $\sigma_{T^2} = 1.9$ $\sigma_G = 1.7$
N: $\sigma_{T^2} = 1.9$
S: $\sigma_{T^2} = 1.0$
N+S: $\sigma_{T^2} = 2.0$ $\sigma_G = 1.6$
N: $\sigma_{T^2} = 2.1$
S: $\sigma_{T^2} = 1.7$
N+S: $\sigma_{T^2} = 2.7$ $\sigma_G = 2.1$
χ^2: single
χ^2: joint
N: $\sigma_G = 2.5$
S: $\sigma_G = 2.0$
N+S: $\sigma_G = 3.1$

Summary Table

		CMASS		LOWZ	
Bins	σ_{eff}, Detection Significance	NGC	SGC	NGC	SGC
18	split	4.7	5.4	2.5	2.0
	joint	7.1		3.1	
10	split	3.3	2.6	1.8	1.9
	joint	4.0		2.7	
6	split	-0.7	1.2	-	-
	joint	0.4		-	

Self-Calibration Using Even- Parity Sector

Demand consistency in even-parity modes -> control covariance to prevent mismatch in true **C** of data vs. **C** of mocks

Consistency in Even-Parity Sector	CMASS 18 bins	Rescaling Factor	Rescaled Odd Detection Significance
1 standard deviation	Analytic Covariance	0.88	2.0σ
	$N_{\rm eig} = 800$	0.98	4.0σ
3 standard deviation	Analytic Covariance	0.94	4.6σ
	$N_{\rm eig} = 800$	-	4.4σ

Systematics

Explored a large number

Few of the most interesting/salient ones

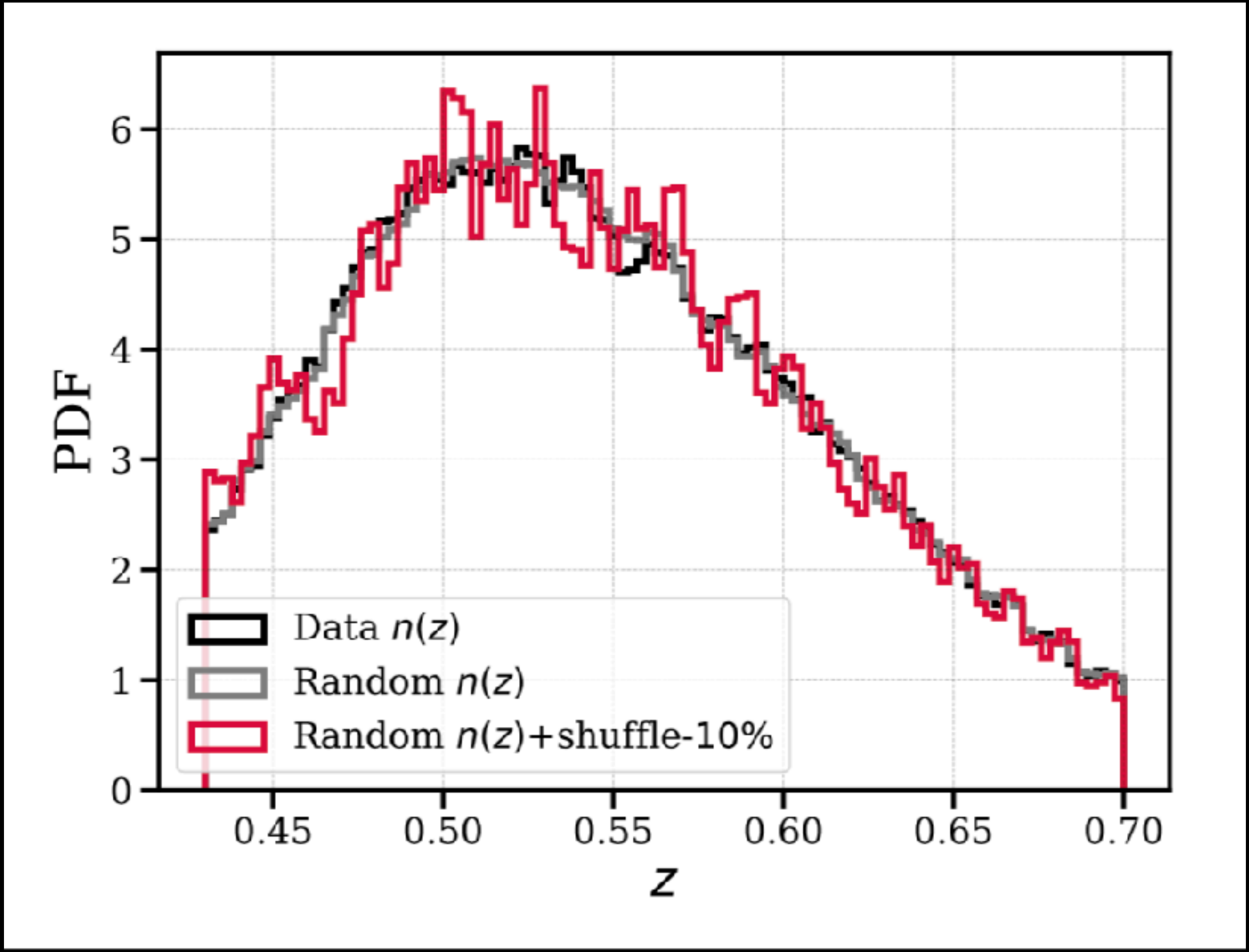
Redshift Errors

Other Weights Being Wrong

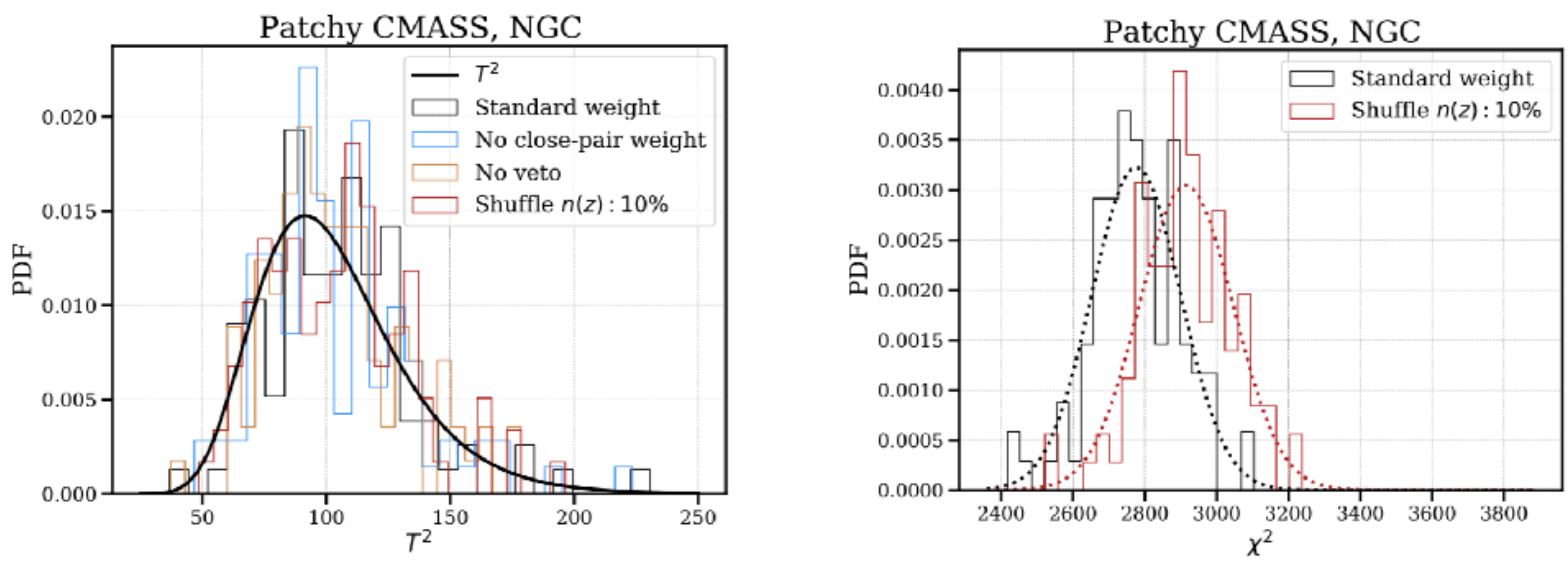
Split Sky

Fiber-magnitude and plate-location dependent redshift failures

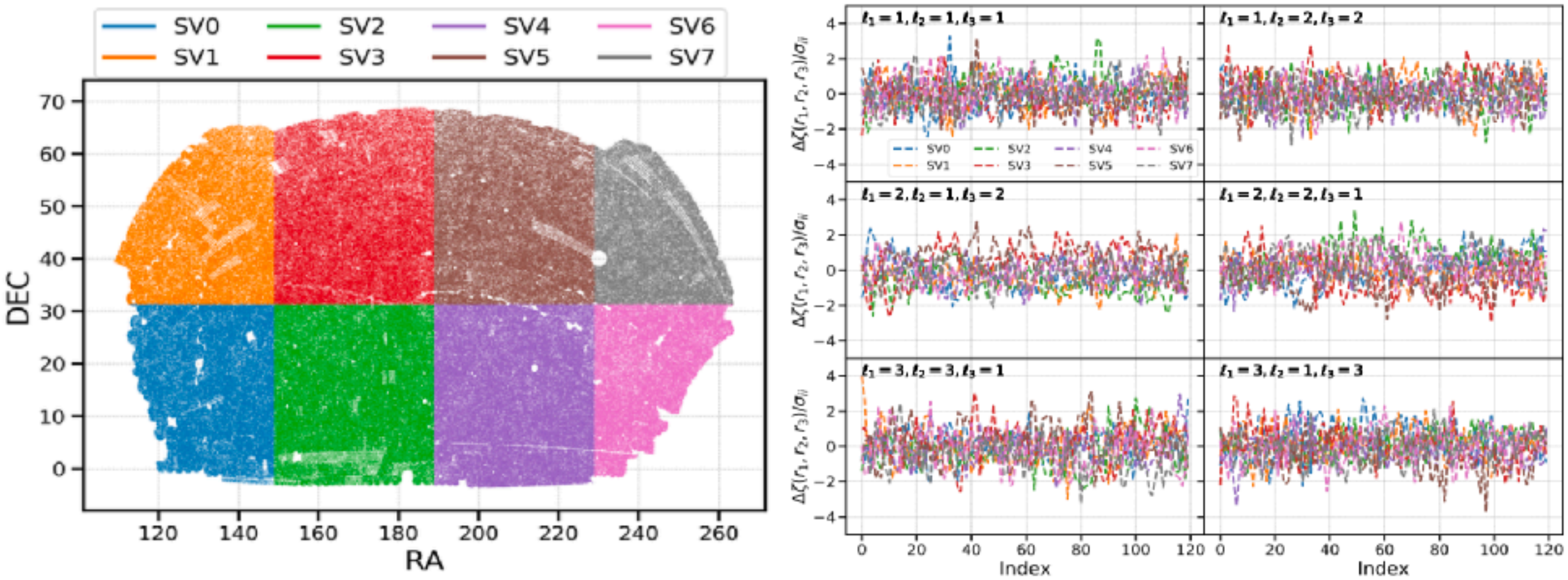
Redshift Errors



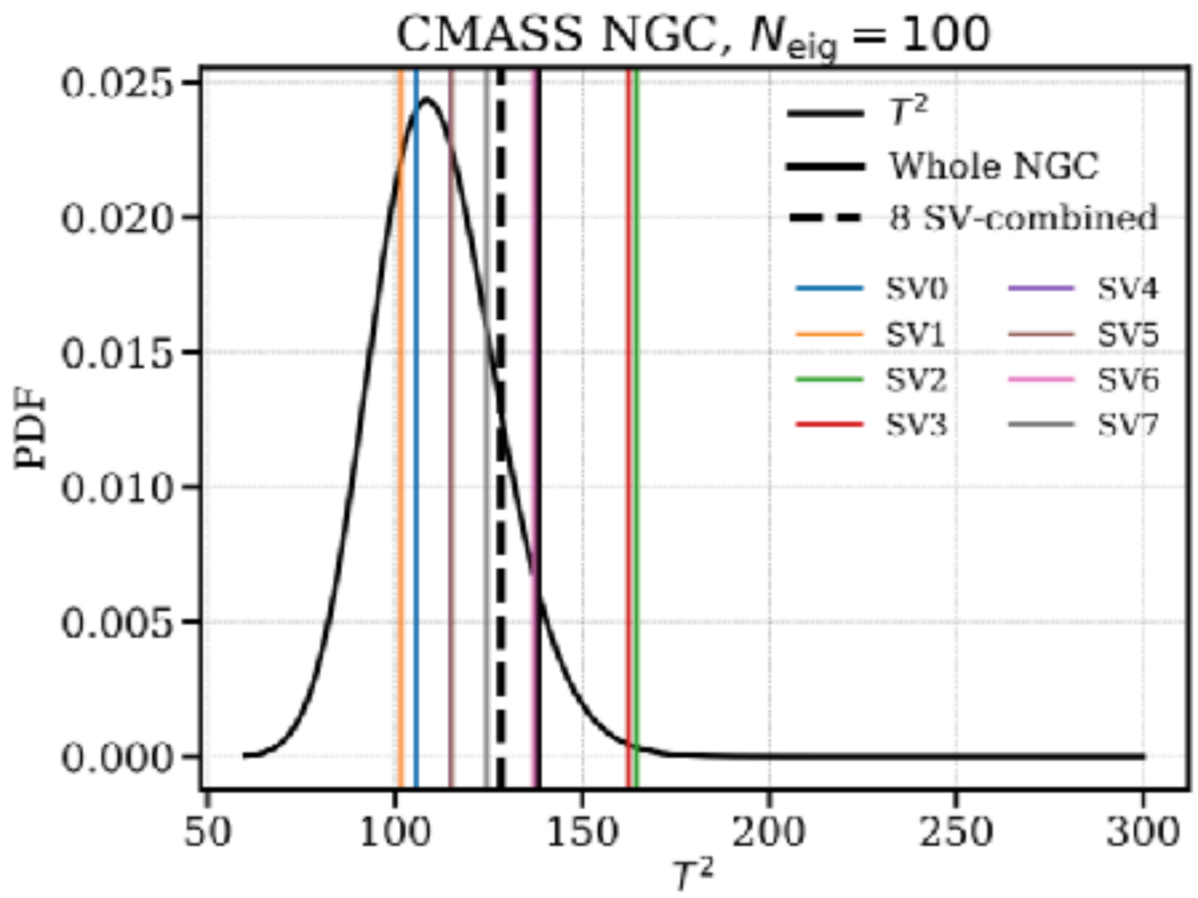
Redshift Errors & Other Weights



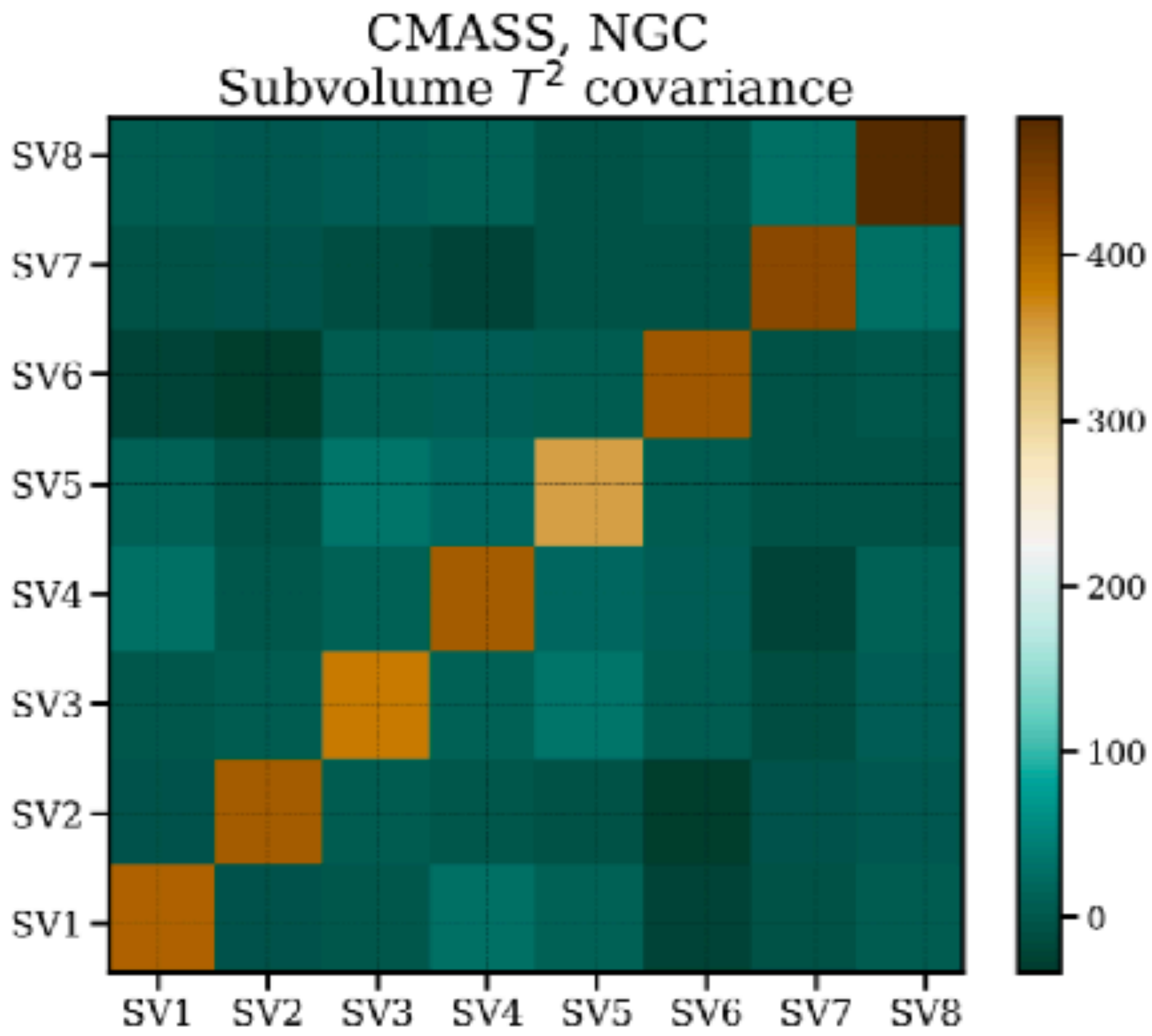
Split Sky


SV0
SV1
SV2
SV3
SV4
SV5
SV6
SV7
DEC
RA
$\ell_1=1,\ell_2=1,\ell_3=1$
$\ell_1=1,\ell_2=2,\ell_3=2$
$\ell_1=2,\ell_2=1,\ell_3=2$
$\ell_1=2,\ell_2=2,\ell_3=1$
$\ell_1=3,\ell_2=3,\ell_3=1$
$\ell_1=3,\ell_2=1,\ell_3=3$
$\Delta\zeta(r_1,r_2,r_3)/\sigma_{ii}$
Index

Split Sky

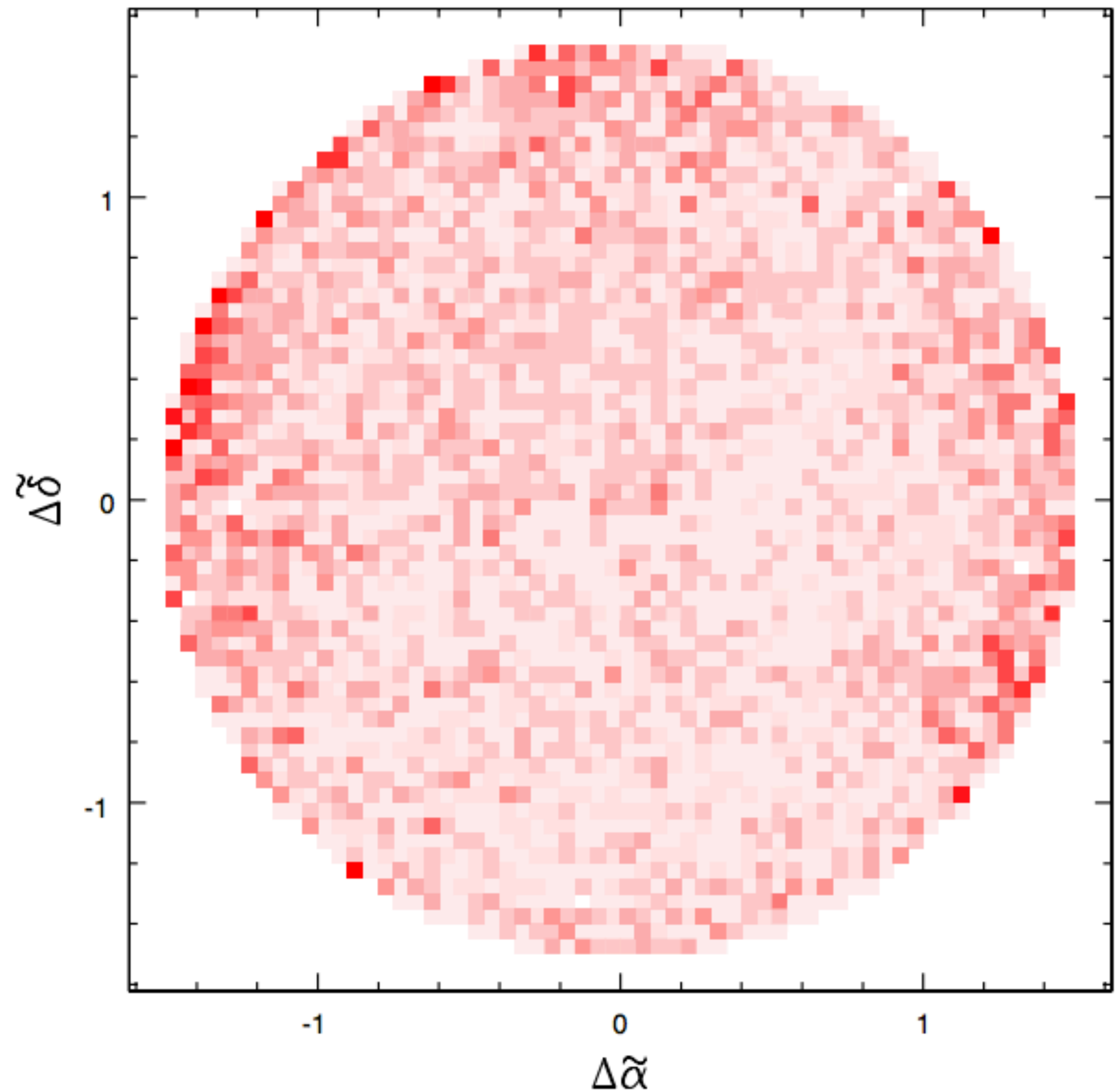


CMASS NGC, $N_{\rm eig} = 100$
PDF
T^2
Whole NGC
8 SV-combined
SV0
SV1
SV2
SV3
SV4
SV5
SV6
SV7
0.000
0.005
0.010
0.015
0.020
0.025
50
100
150
200
250
300
T^2



CMASS, NGC
Subvolume T^2 covariance
SV1
SV2
SV3
SV4
SV5
SV6
SV7
SV8
0
100
200
300
400

Redshift Failures



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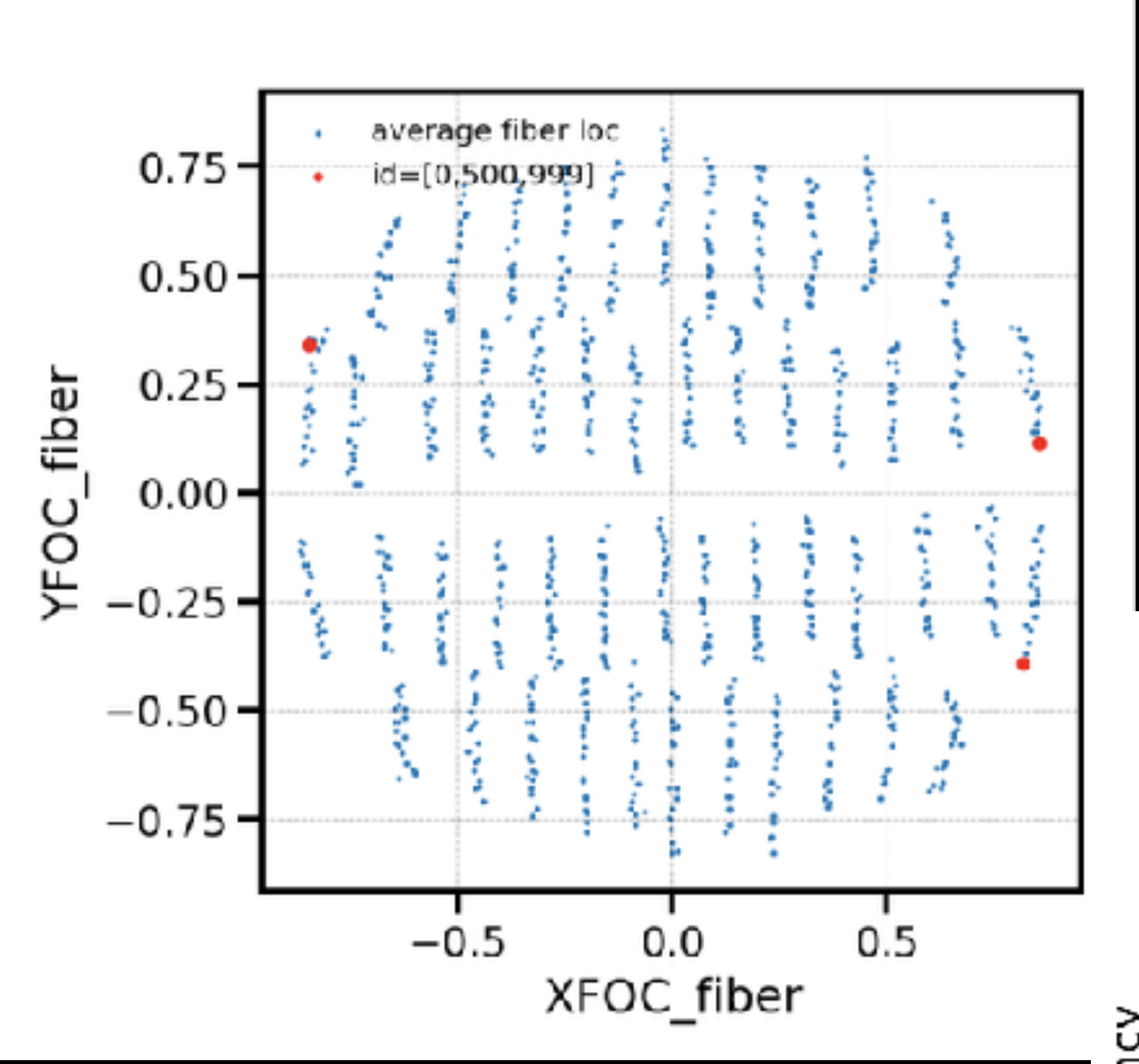
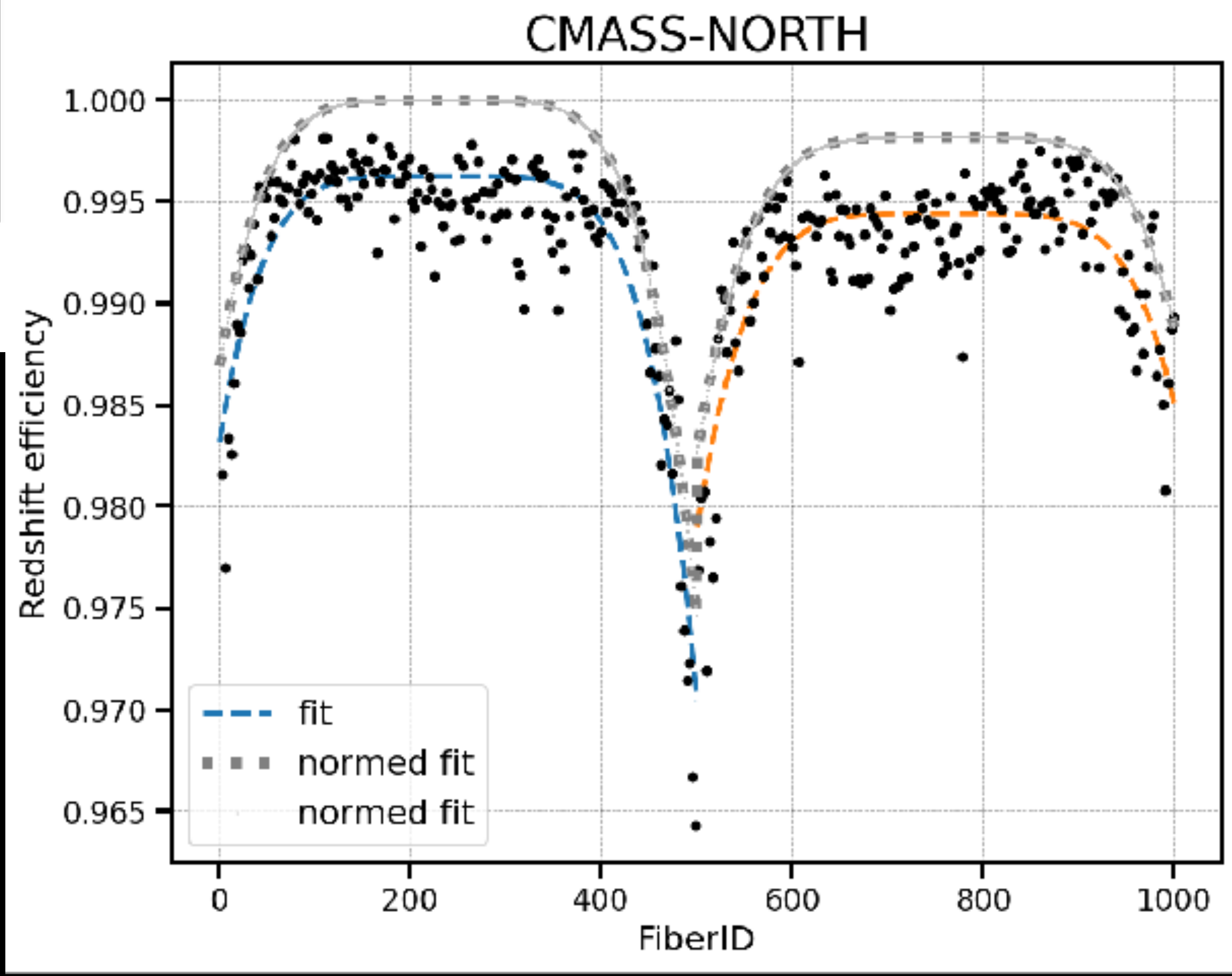
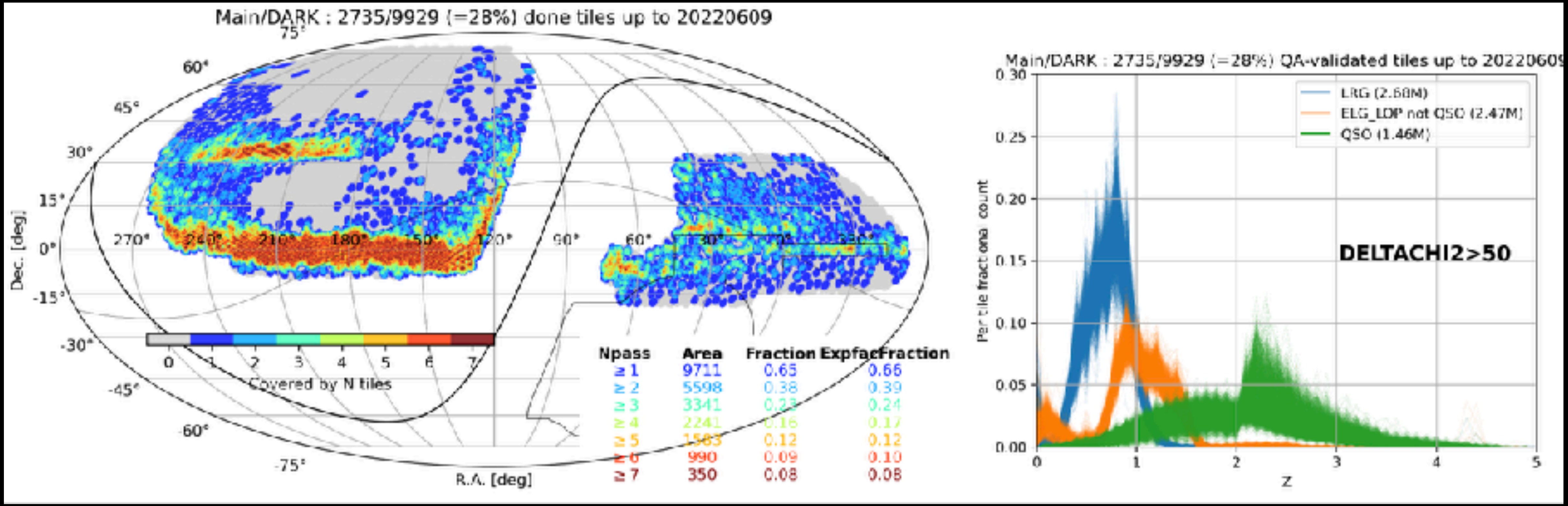




Systematics Summary

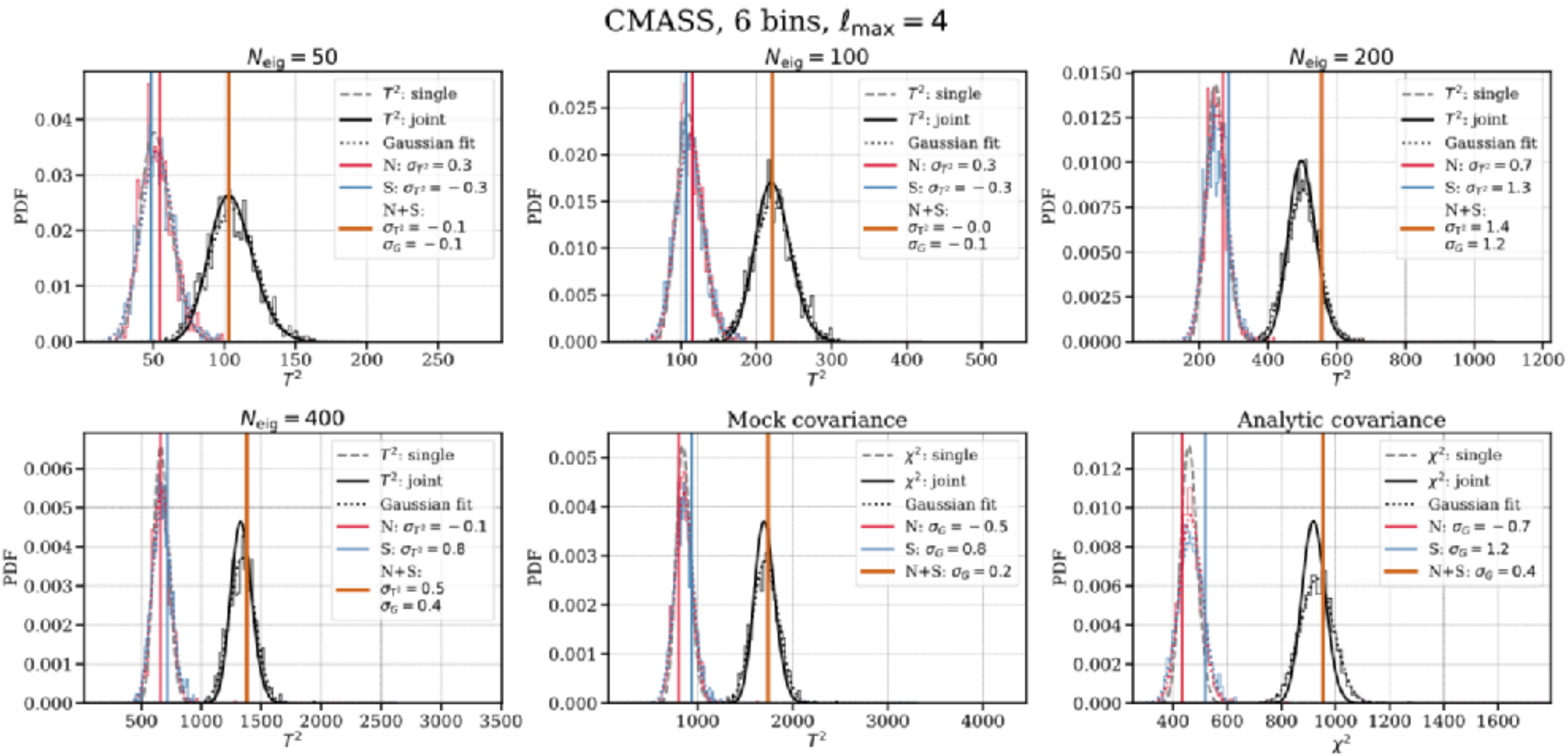
Parity	Number of Bins	Redshift Failure	Fiducial Cosmology	Distortion in Selection Function
Odd	10	1.5	$\sim$1.5	$\sim$1.0
	18	2.5	$\sim$2.5	$\sim$1.7
Even	10	0.9	$\sim$0.7	$\sim$0.6
	18	1.8	$\sim$1.9	$\sim$2.4

Outlook



Main/DARK : 2735/9929 (=28%) done tiles up to 20220609
Dec. [deg]
R.A. [deg]
Covered by N tiles
Npass Area Fraction ExpfacFraction
≥1 9711 0.65 0.66
≥2 5598 0.38 0.39
≥4 2241 0.16 0.17
≥5 1583 0.12 0.12
≥7 350 0.08 0.08
Main/DARK : 2735/9929 (=28%) QA-validated tiles up to 20220609
LRG (2.68M)
ELG_LOP not QSO (2.47M)
QSO (1.46M)
DELTACHI2>50
Per tile fractional count
z

Thanks!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$\sigma_{T^2} = -0.1$
$\sigma_G = -0.1$
N: $\sigma_{T^2} = 0.3$
S: $\sigma_{T^2} = -0.3$
N+S:
$\sigma_{T^2} = -0.0$
$\sigma_G = -0.1$
N: $\sigma_{T^2} = 0.7$
S: $\sigma_{T^2} = 1.3$
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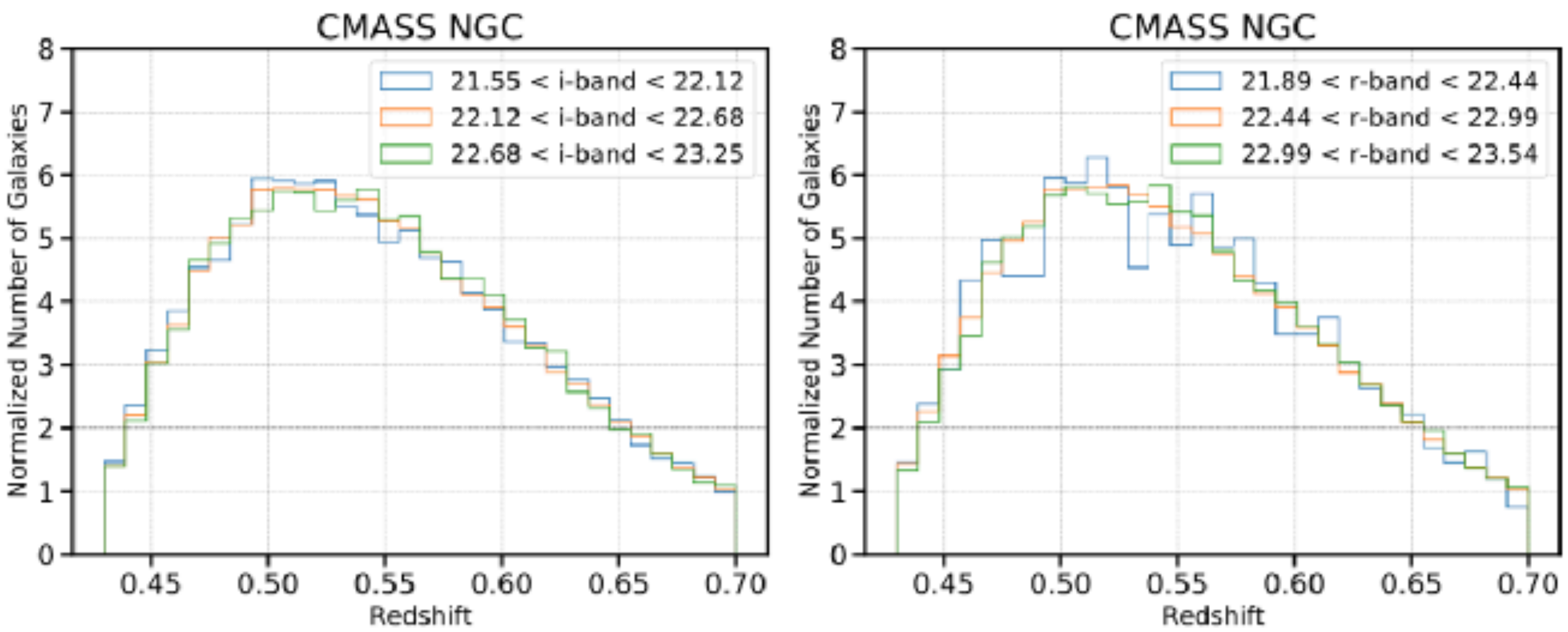

Figure D1. Redshift dependence on imaging depth for CMASS NGC. *Left*: The normalized galaxy number counts as a function of redshi for the i-band, where we split the sample into three bins in imaging depth. *Right*: Same as the left but for the r-band. Here we can se that the the three bins in i- and r-band have very similar $n(z)$, which implies that the imaging depth is unlikely to impact our analysis