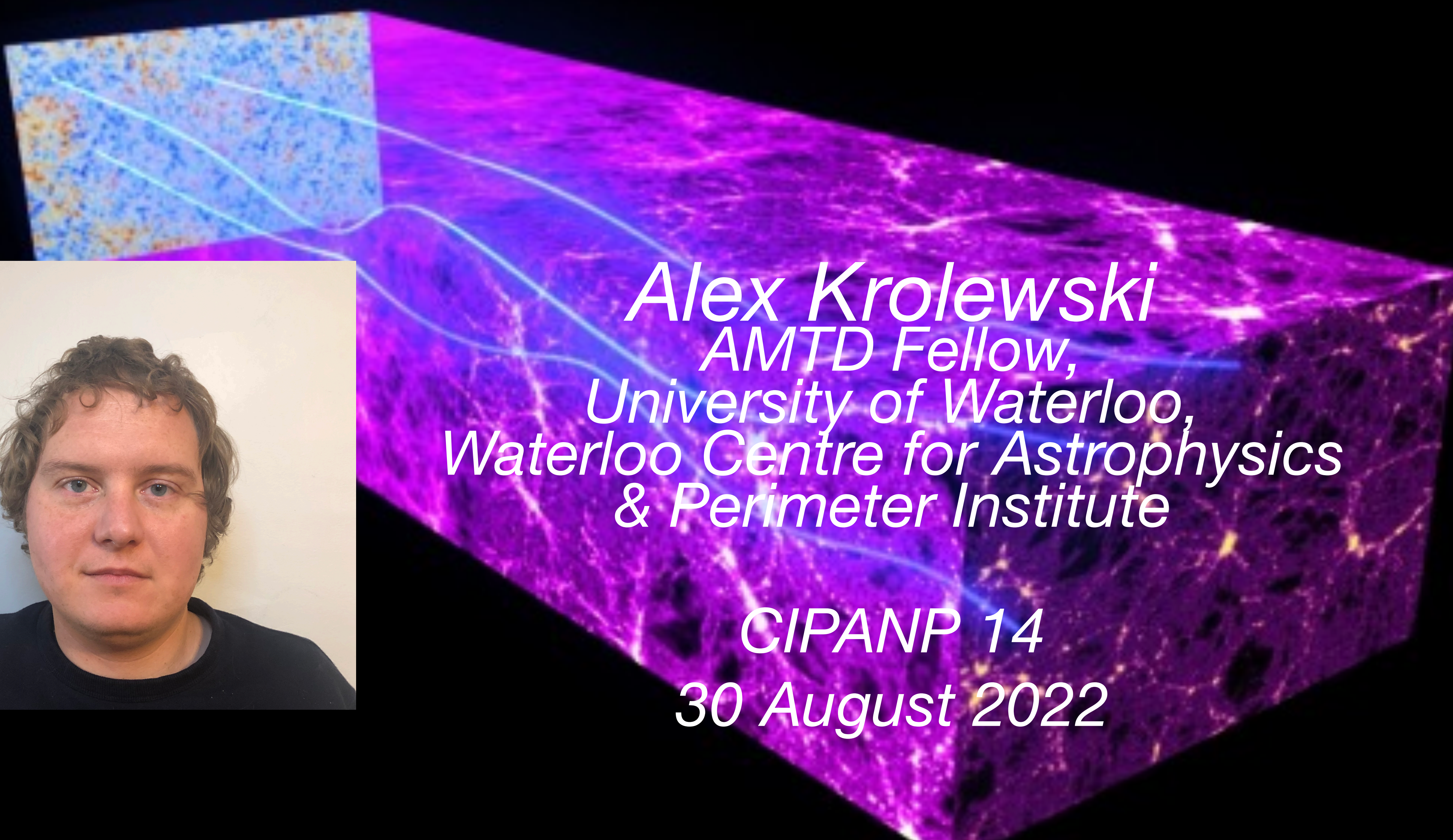
Cosmology from CMB lensing cross-correlations: matter power spectrum and primordial non-Gaussianity



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& Perimeter Institute

CIPANP 14
30 August 2022

OUTLINE

- Testing the S_8 tension with unWISE galaxies x Planck CMB lensing
- Local primordial non-Gaussianity from CMB lensing cross-correlations with DESI quasars x Planck CMB lensing
- Co-authors:

Simone Ferraro

Martin White

Eddie Schlafly

Will Percival

DESI collaboration

Cosmology from unWISE x Planck CMB lensing:

arXiv:2105.03421 [JCAP 12 (2021) 028] and
arXiv:1909.07412 [JCAP 05 (2020) 047]

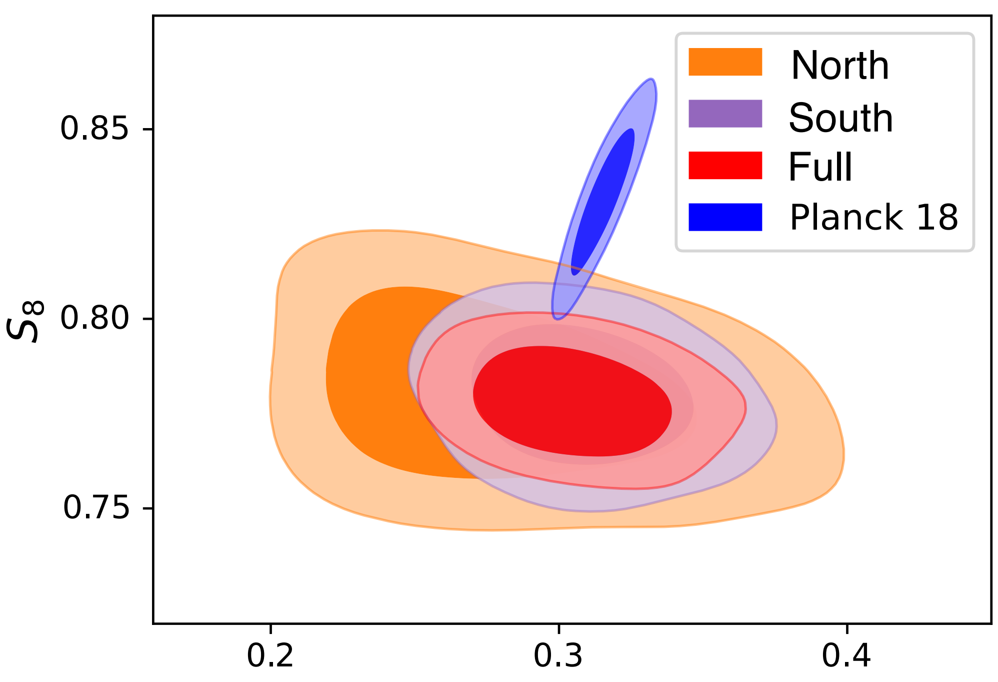
Primordial non-Gaussianity from CMB lensing cross-correlations

(paper in prep)

LENSING TENSION: CRACKS IN ΛCDM?

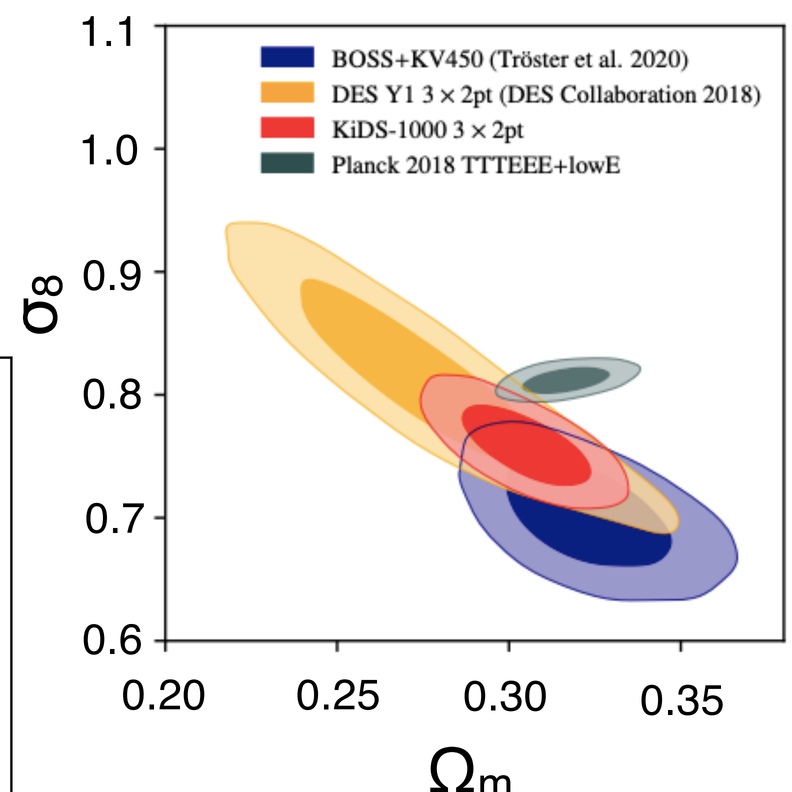
- Some weak lensing surveys (and also some galaxy clustering analyses) find $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$ ~ 10% lower than Planck
- ~2-3σ lensing tension: new physics or systematics?

DES-Y1 + KiDS-1000 public reanalysis



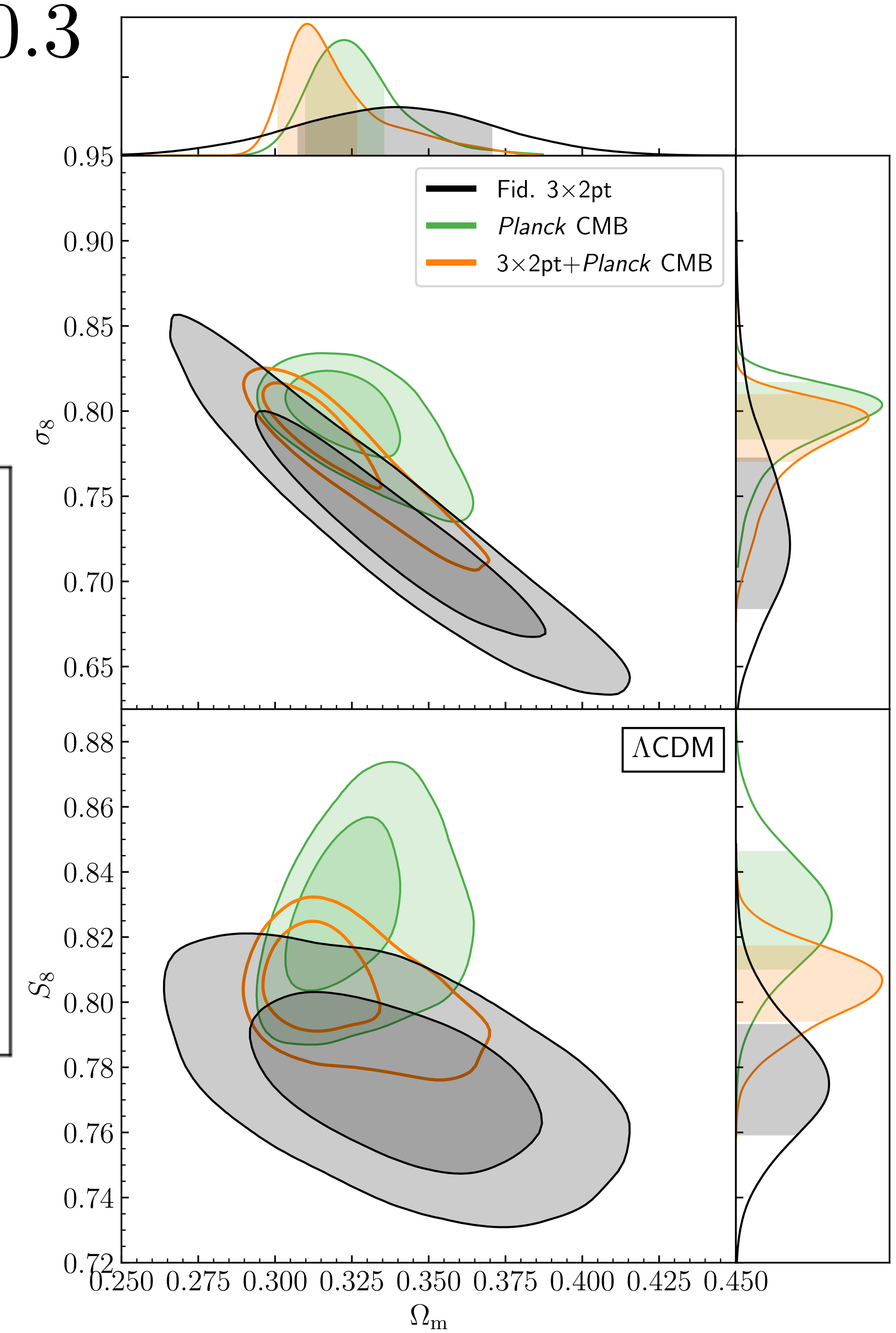
Garcia-Garcia et al. 2021

KiDS-1000



Heymans et al. 2021

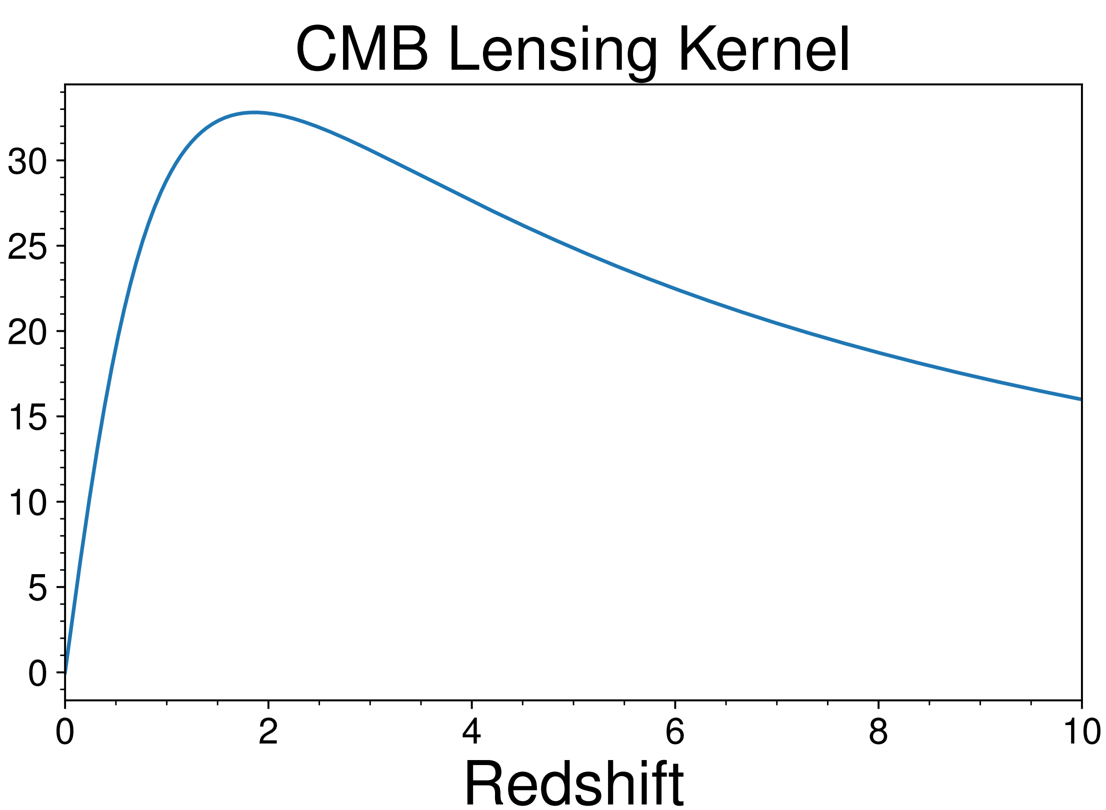
DES-Y3

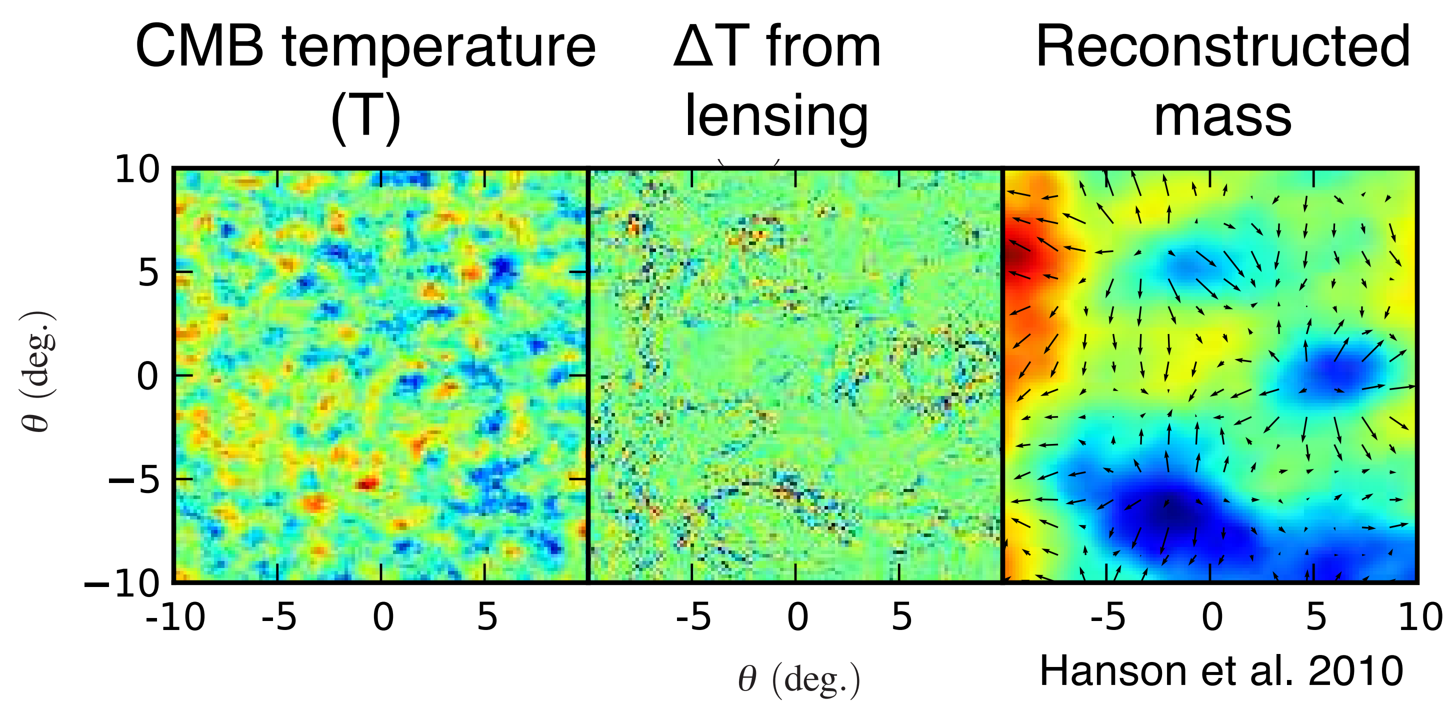


DES Collaboration, 2021

WEAK LENSING OF THE CMB

- Test lensing tension with a similar measurement with different systematics
- Lensing of the CMB: lens is (almost) all the matter in the universe!
- Best measurements from Planck: CMB lensing across (nearly) full sky
- Imprint of lensing is tiny, but very distinctive (non-Gaussian) compared to the Gaussian fluctuations from primary CMB

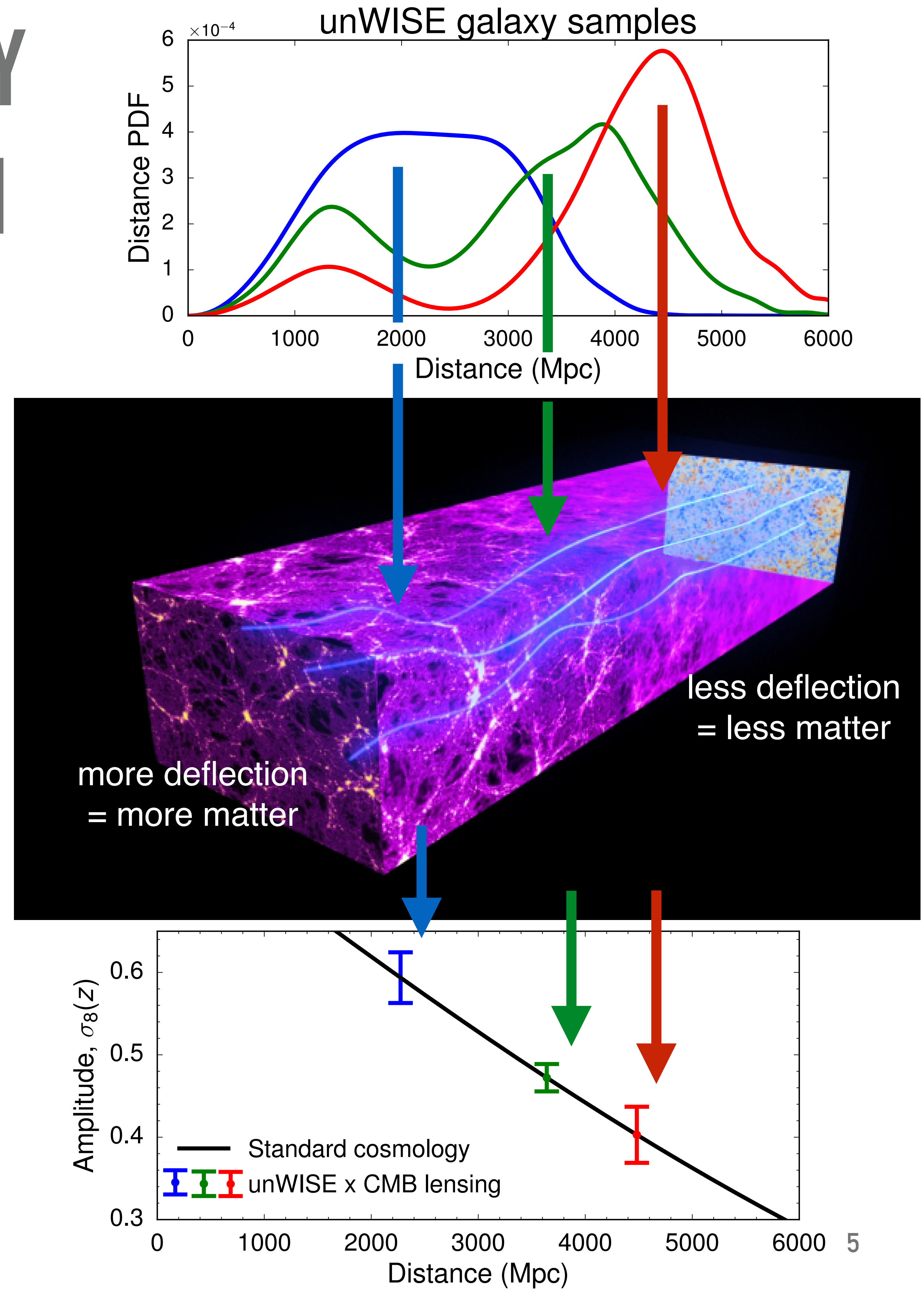




Hanson et al. 2010

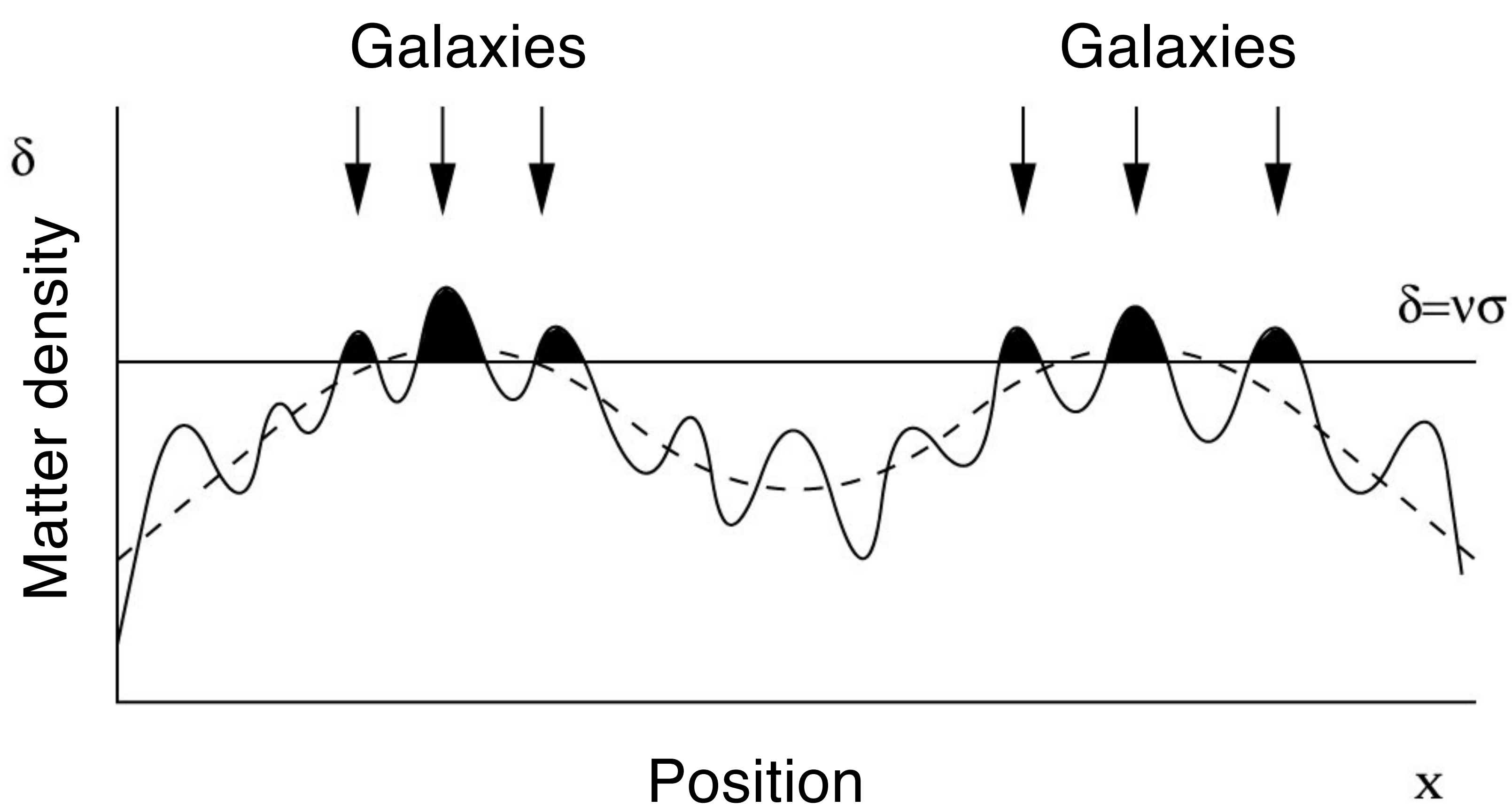
CMB LENSING GALAXY CROSS-CORRELATION

- By cross-correlating CMB lensing with galaxies at different redshifts, you can probe matter distribution *tomographically* (rather than a single integral to z=1100)
- More information from cross-correlation than auto-correlation alone



CMB LENSING TOMOGRAPHY

- Galaxies are *biased*: their clustering is enhanced relative to matter
- Must add the galaxy autocorrelation to the CMB lensing cross-correlation to break bias-σ_8 degeneracy



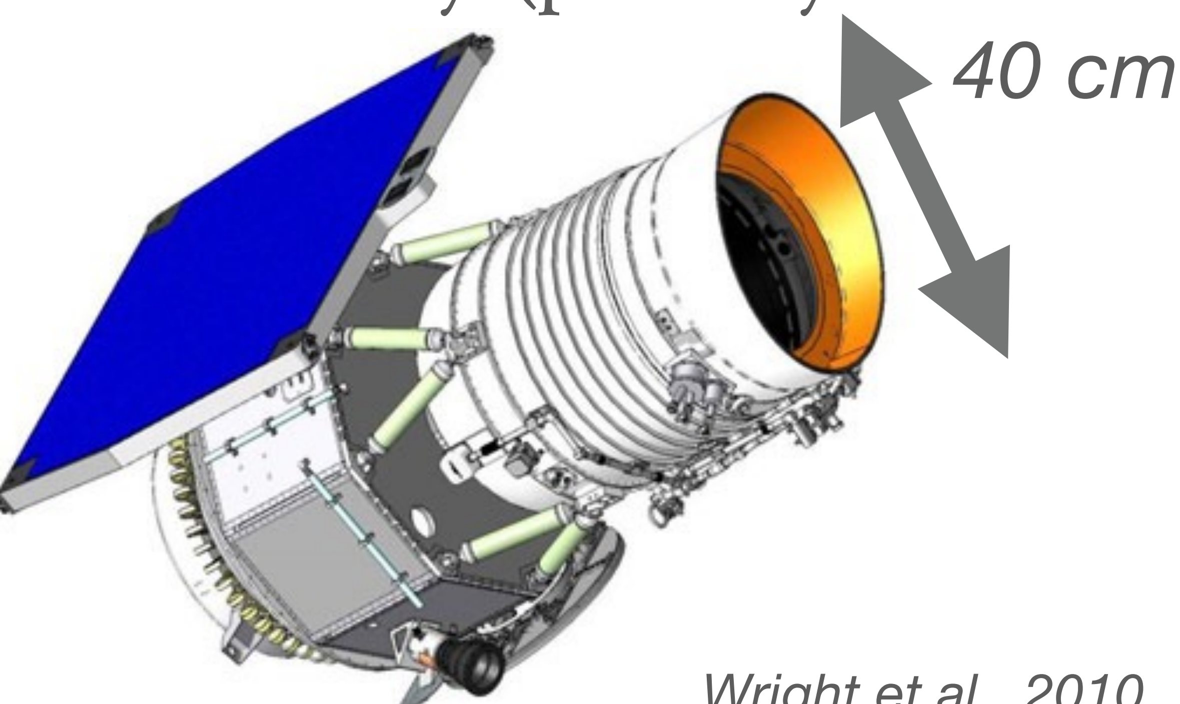
$$C_\ell^{gg} \propto b(k,z)^2 \sigma_8^2 P_m$$

$$C_\ell^{\kappa g} \propto b(k,z) \sigma_8^2 P_m$$

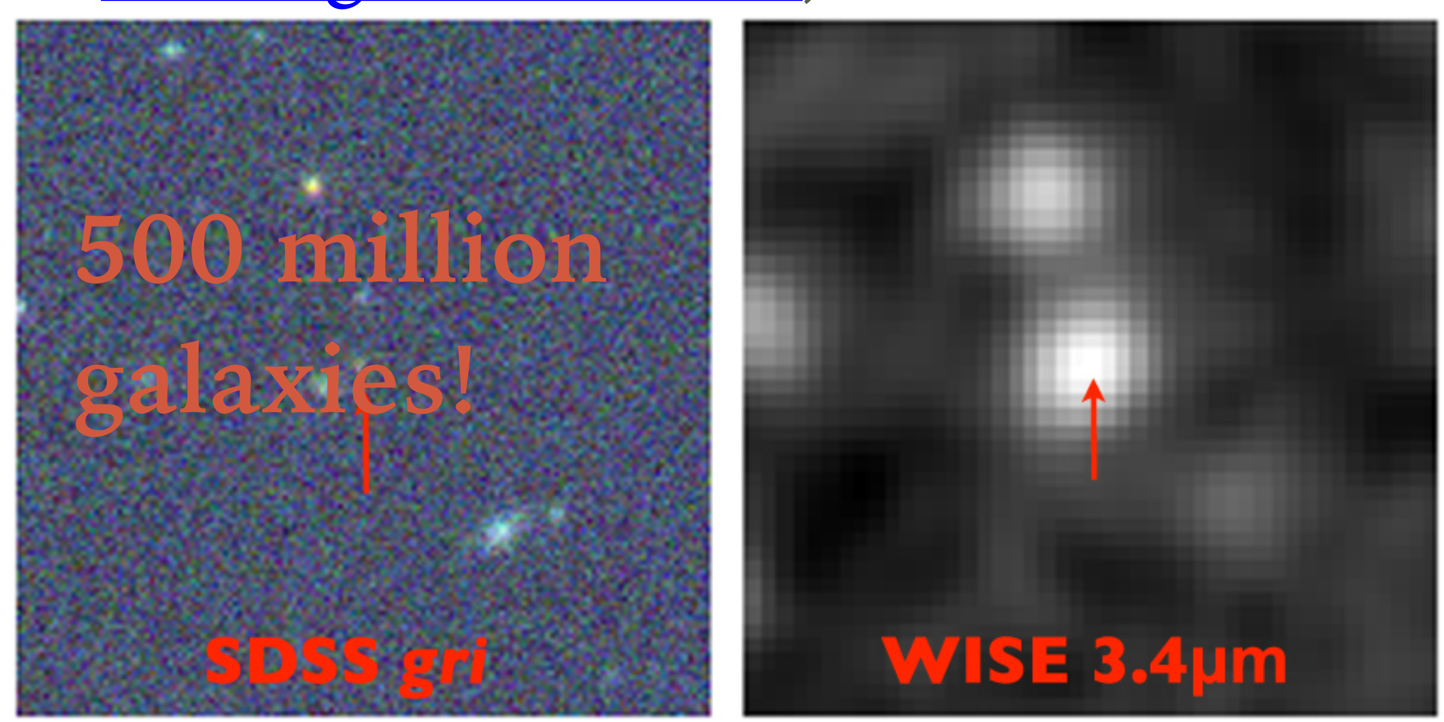
$$\longrightarrow \sigma_8 \propto \frac{C_\ell^{\kappa g}}{\sqrt{C_\ell^{gg}}}$$

BUILDING THE HIGHEST S/N CMB-LSS CORRELATION

- Advantages of WISE:
  - All-sky satellite mission
  - Infrared survey (3.4, 4.6 μm): negative K-correction for old stellar populations—measure galaxies out to z~2
- unWISE catalog: additional 5 years beyond original WISE survey (publicly available at catalog.unwise.me)



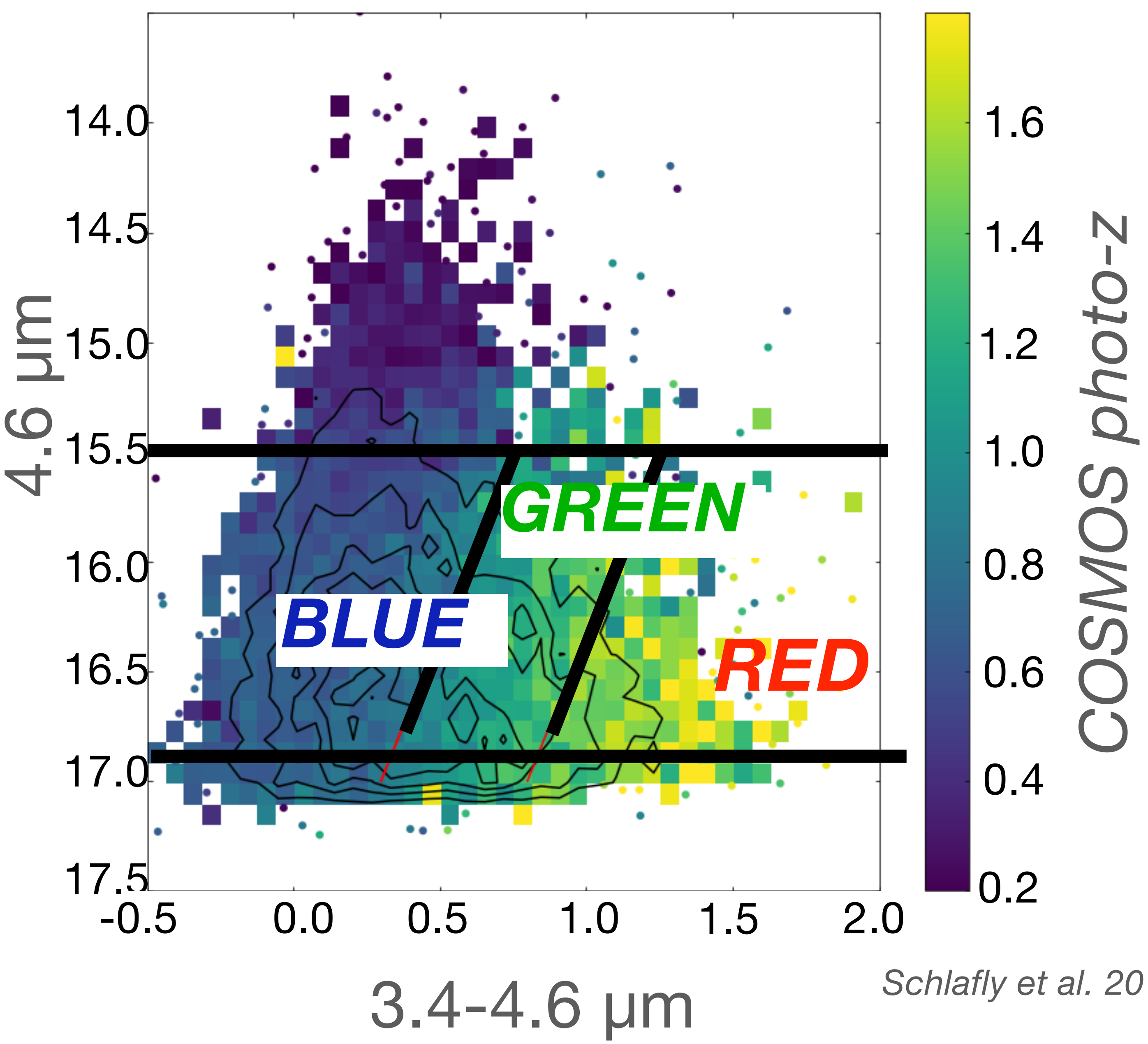
Wright et al., 2010



unWISE: Meisner et al. (2020)
Schlafly et al. (2020)

unWISE GALAXY SAMPLES

Selecting unWISE galaxies



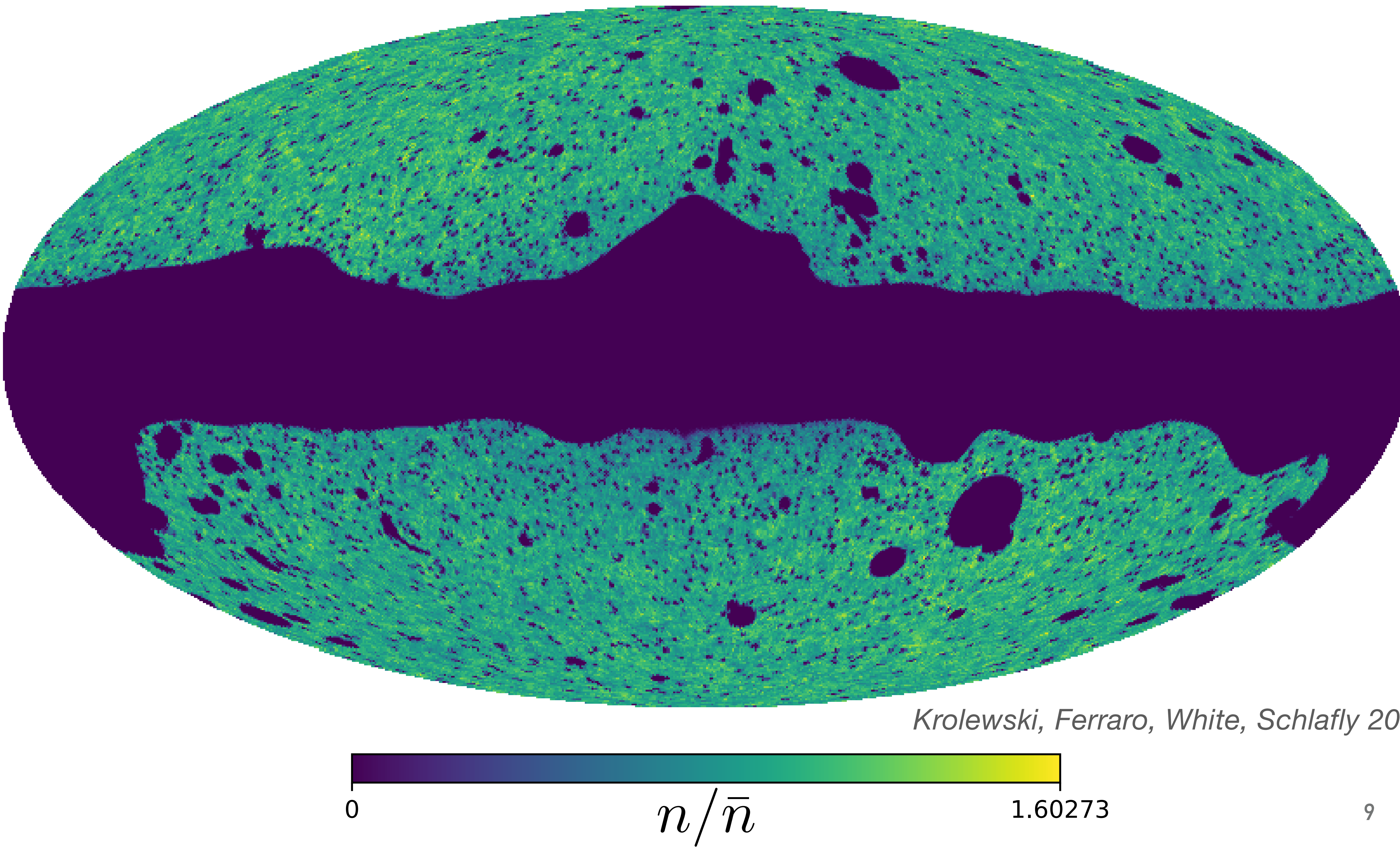
Schlafly et al. 2019

- Define 3 samples using unWISE colors and remove stars using GAIA photometry (1% residual stellar contamination)

Sample	Mean z	Number density (deg^{-2})
Blue	0.6	3409
Green	1.1	1868
Red	1.5	144

unWISE SKY DISTRIBUTION

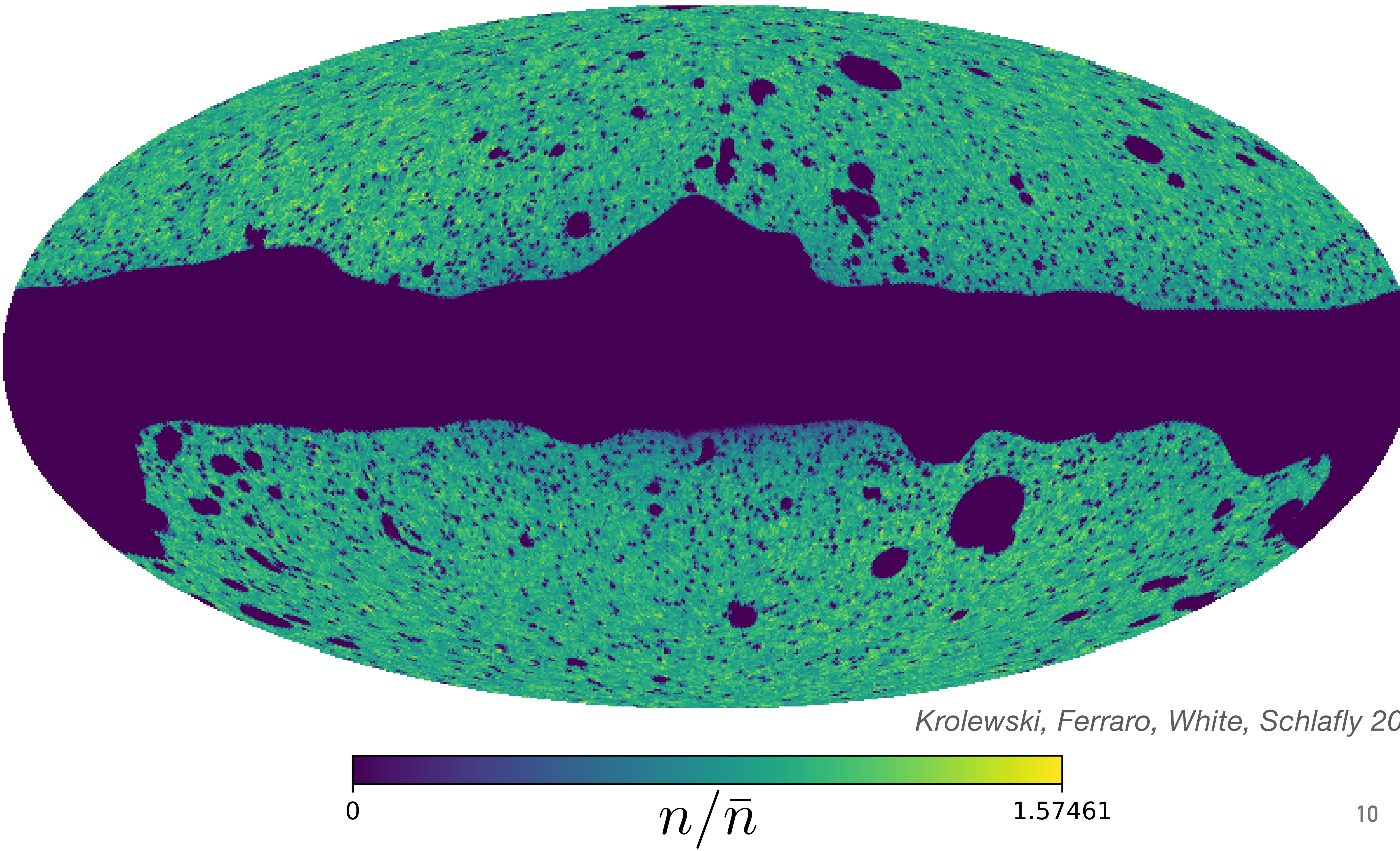
Blue: z~0.5 sample



Krolewski, Ferraro, White, Schlafly 2020

unWISE SKY DISTRIBUTION

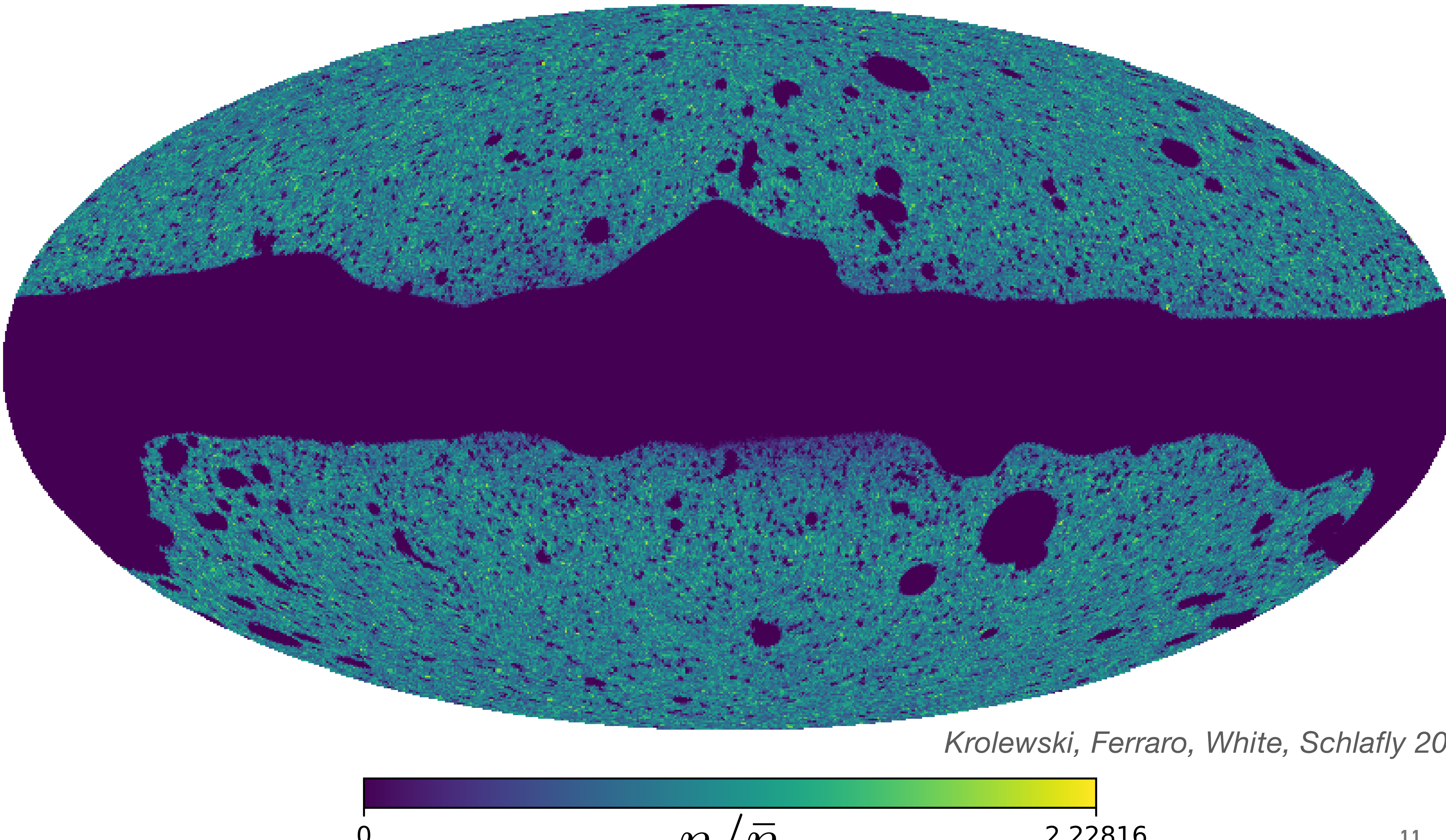
Green: z~1.0 sample



Krolewski, Ferraro, White, Schlafly 2020

unWISE SKY DISTRIBUTION

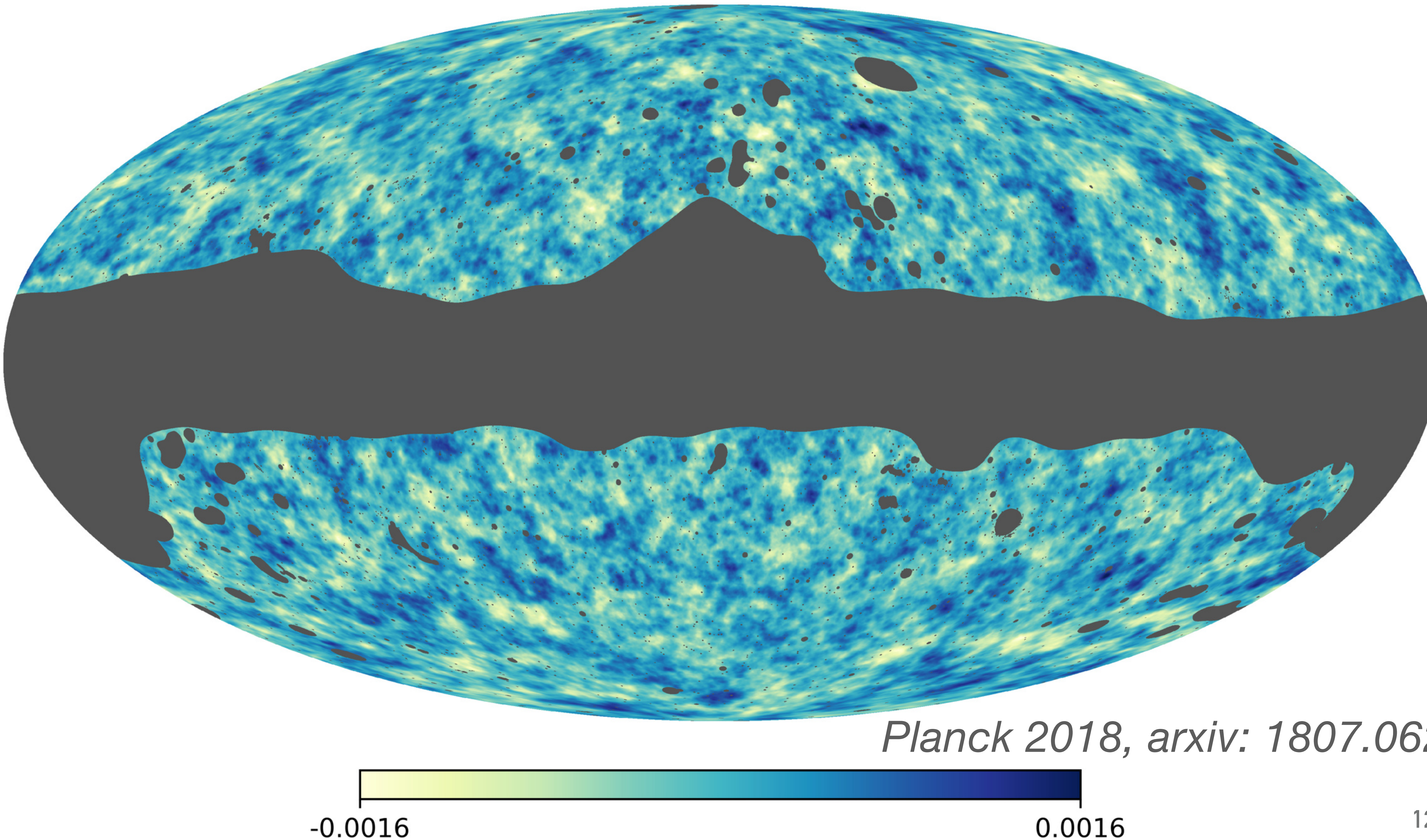
Red: z~1.5 sample



Krolewski, Ferraro, White, Schlafly 2020

CMB LENSING FROM PLANCK

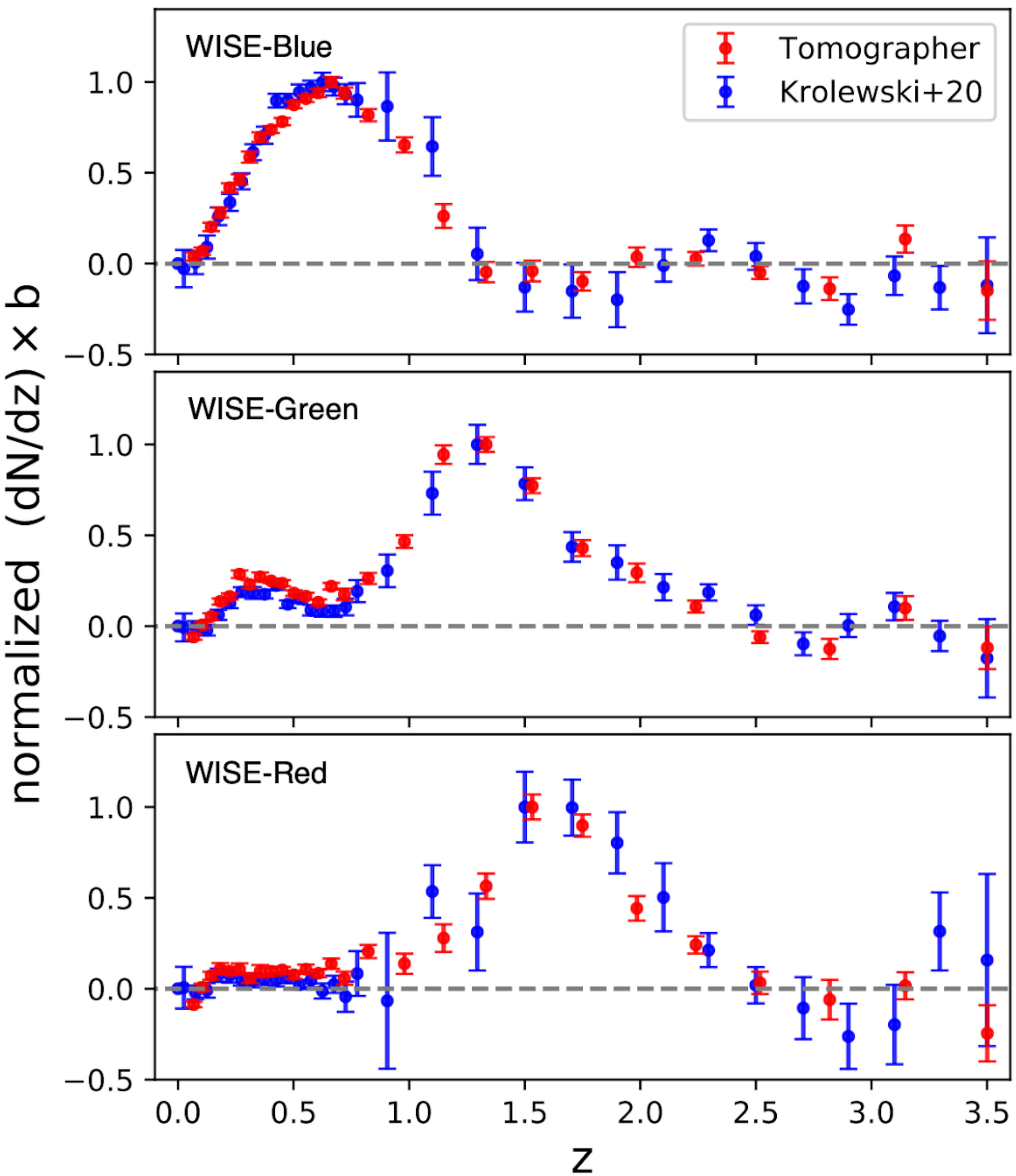
- Planck 2018 minimum-variance lensing maps + masks



Planck 2018, arxiv: 1807.06210

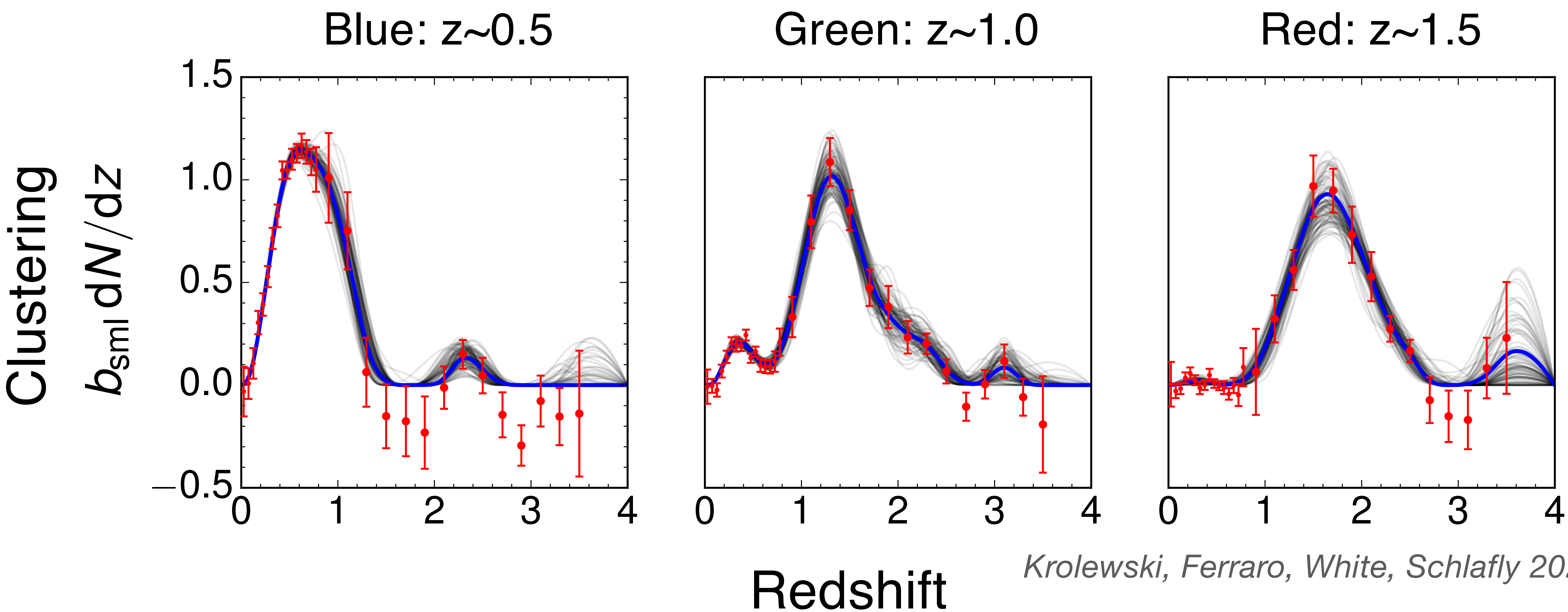
REDSHIFT DISTRIBUTION: CLUSTERING REDSHIFTS

Validation with Yi-Kuang Chiang's "Tomographer"



- WISE photo-z impossible (only 2 bands) & cross-matched photo & spec z only available in very small areas
- We use clustering redshifts instead! (e.g. Menard et al. 2013)

BIAS-WEIGHTED REDSHIFT DISTRIBUTION



Krolewski, Ferraro, White, Schlafly 2020

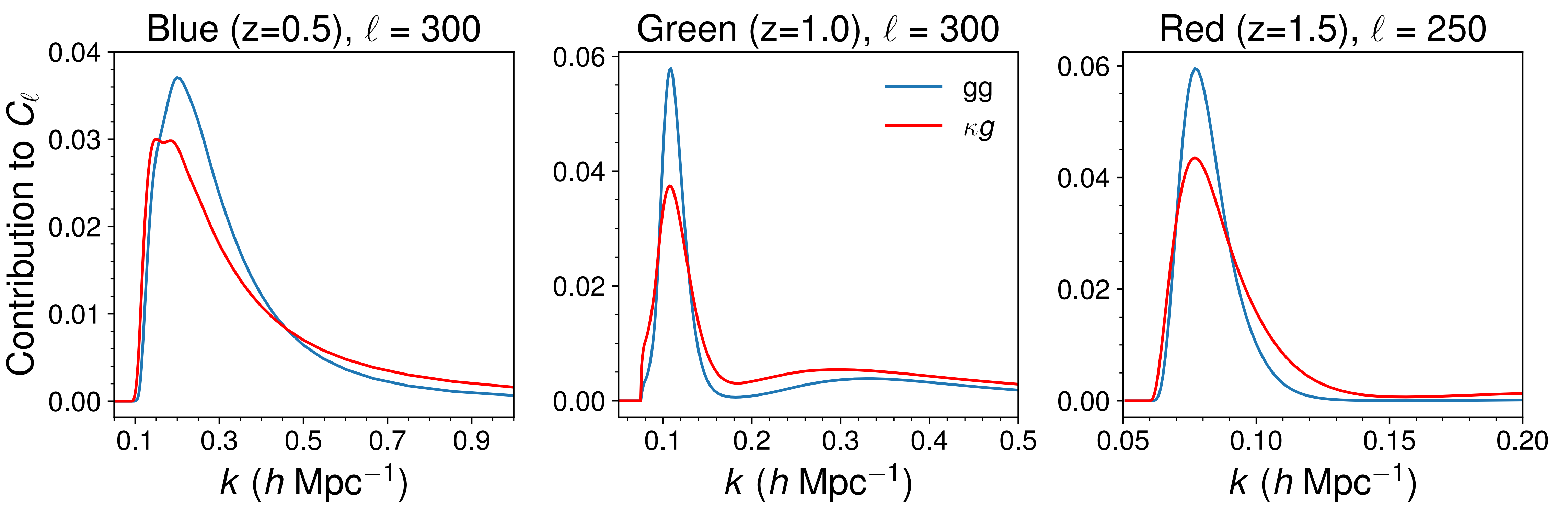
- Clustering measurement is noisy: we correctly propagate the error into our cosmological constraints
- High-z bumps likely noise (not seen in cross-matched COSMOS photo-z's)

MODELLING

- Hybrid PT/empirical model: linear bias times Halofit, plus higher bias terms

$$P_{gg} = b_1^2 P_{mm,\mathrm{Halofit}} + \mathrm{higher\ bias} + \mathrm{Shot\ Noise}$$
$$P_{gm} = b_1 P_{mm,\mathrm{Halofit}} + \mathrm{higher\ bias}$$

- Fix cosmology & $b_2(z)/b_s(z)$ in higher bias terms
- $\ell_{\mathrm{max}} = 250$ (300), but nonzero contribution from low z/high k: must be tested on mocks!



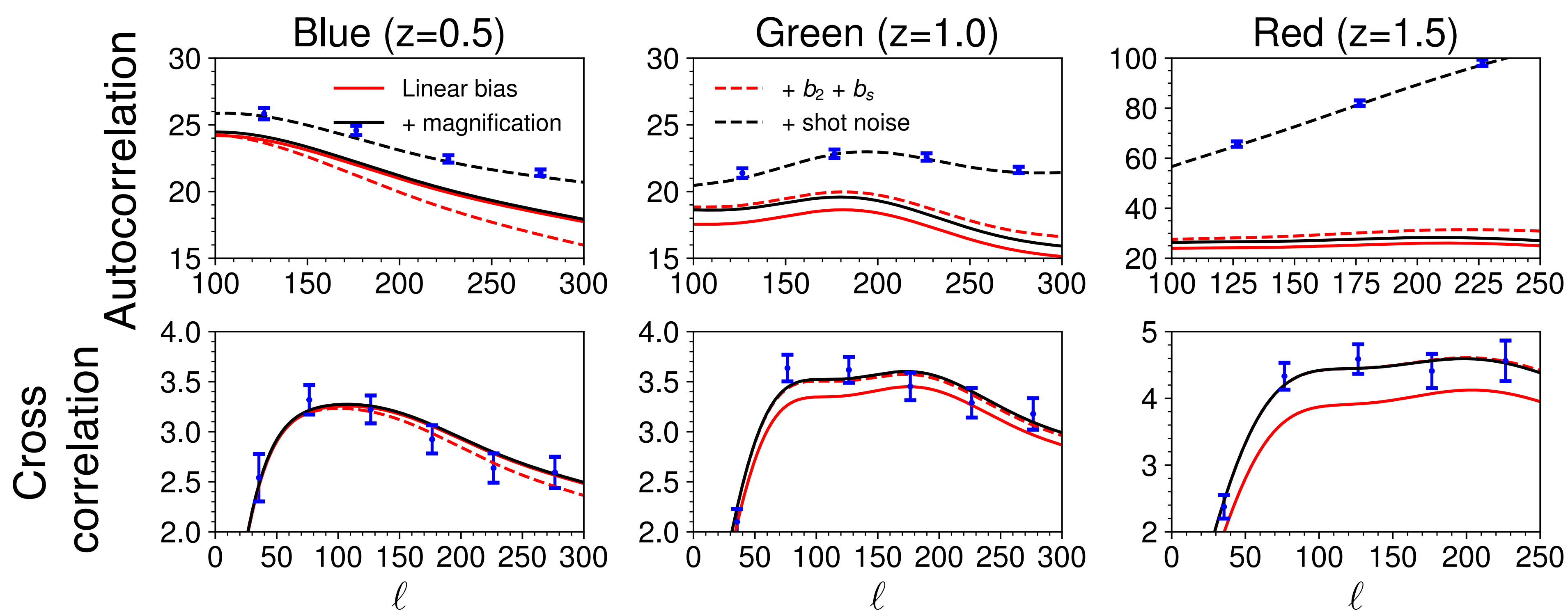
- Recall Limber projection: $k\chi = \ell + 1/2$

MODELLING

- Hybrid PT/empirical model: linear bias times Halofit, plus higher bias terms

$$P_{gg} = b_1^2 P_{mm,\mathrm{Halofit}} + \mathrm{higher\ bias} + \mathrm{Shot\ Noise}$$
$$P_{gm} = b_1 P_{mm,\mathrm{Halofit}} + \mathrm{higher\ bias}$$

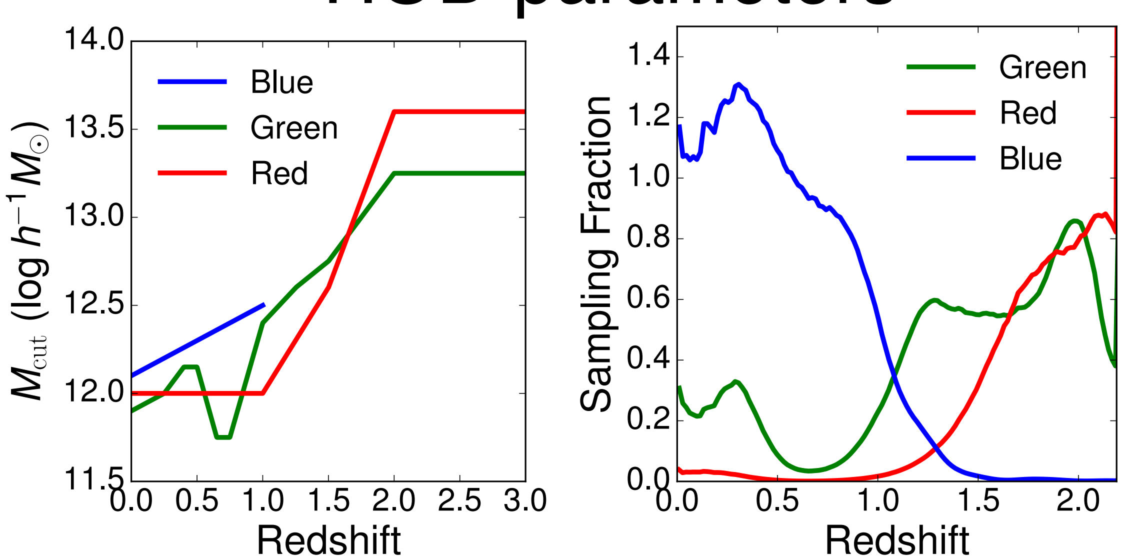
- Magnification bias also included, with 10% prior on the slope (s)
- 6 parameter model: h, Ω_m, log$A$, b_1, s, shot noise
    - Fix n_s and Ω_b to Planck values; fix $\Omega_\mathrm{m}h^3$ to Planck value (from angular size of sound horizon)
    - dN/dz is uncertain: average over chains from many dN/dz samples



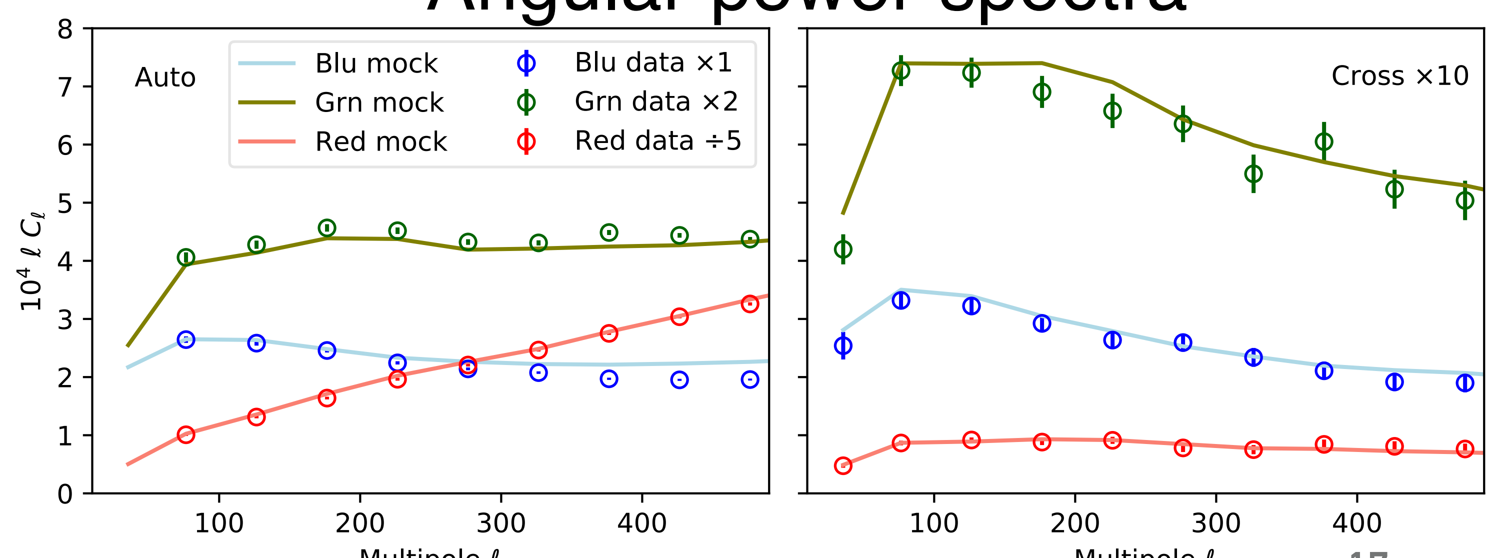
MOCK TESTS: SETUP

- Goal: plausible mocks to test analysis pipeline, *not* to calibrate model or covariances (don't take too seriously!)
- FastPM lightcone (CrowCanyon2 simulation), L = 4 h^{-1} Gpc and 1e10 h^{-1} $M_\odot$ resolution
  - Galaxies follow basic Zheng07 HOD, parameters adjusted to match bias evolution & power spectra
- Match the number density, bias evolution, and b(z) * dN/dz (i.e. clustering redshifts)

HOD parameters



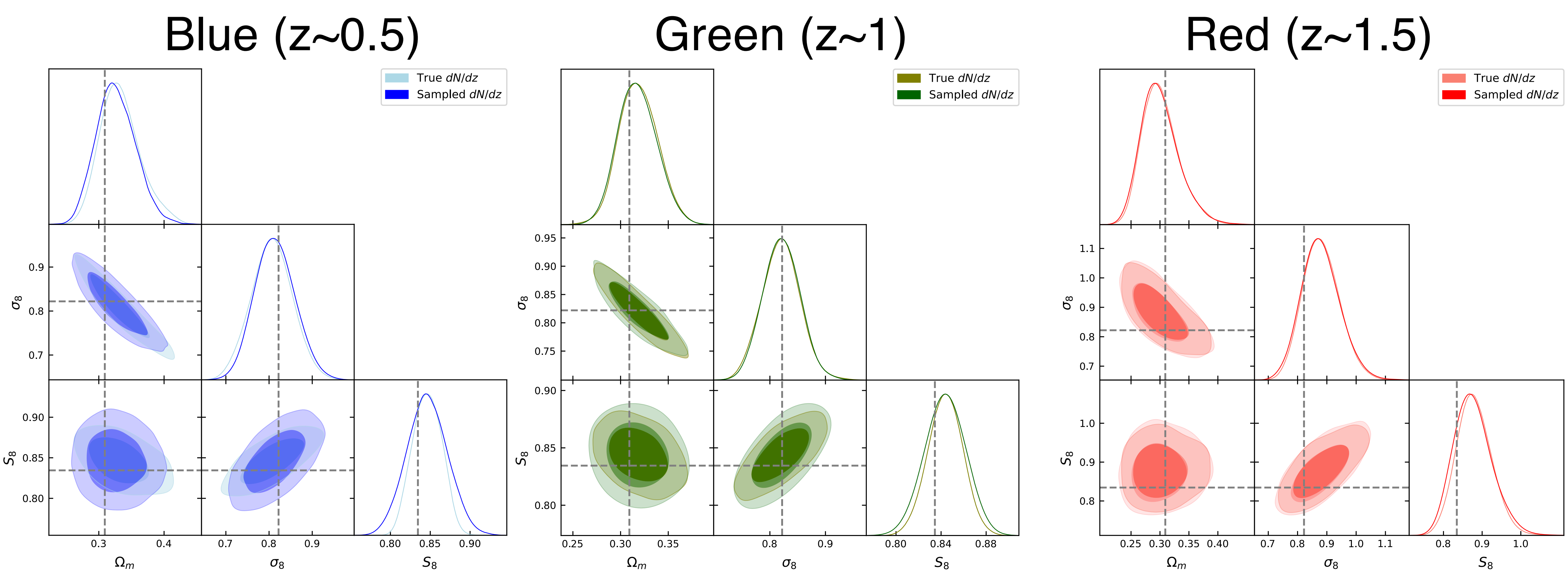
Angular power spectra



MOCK TESTS: VALIDATION

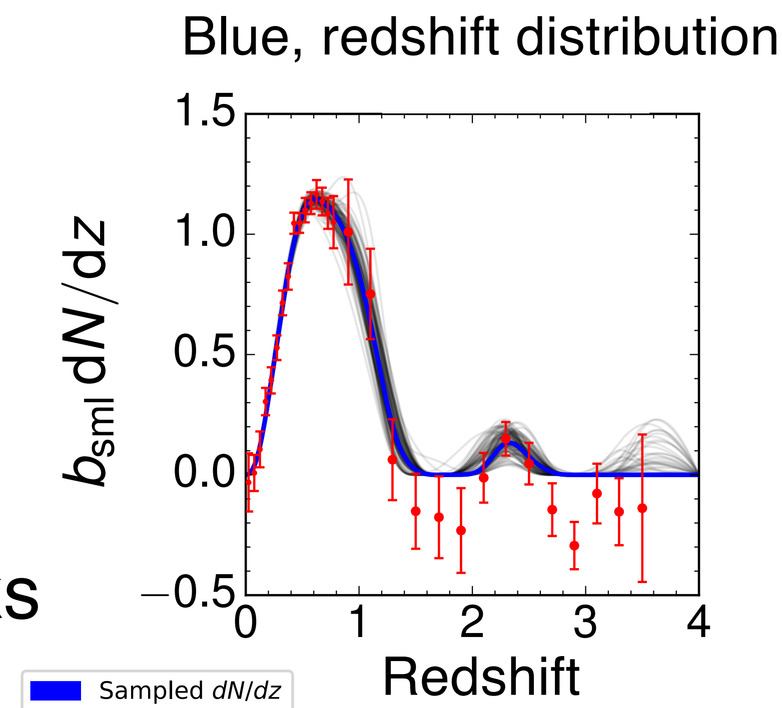
- We recover unbiased (<0.5σ) constraints from blue and green, validating model and scale cuts
  - Red has little statistical power and negligible impact on results

Test	Ω_m	Bias/σ	σ_8	Bias/σ	S_8	Bias/σ
True value	0.3092	–	0.822	–	0.835	–
Blue	0.3244 ± 0.030	0.51	0.812 ± 0.046	-0.22	0.844 ± 0.026	0.37
Green	0.3167 ± 0.020	0.37	0.820 ± 0.033	-0.07	0.843 ± 0.017	0.47
Red	0.2983 ± 0.033	-0.33	0.875 ± 0.064	0.83	0.874 ± 0.047	0.83

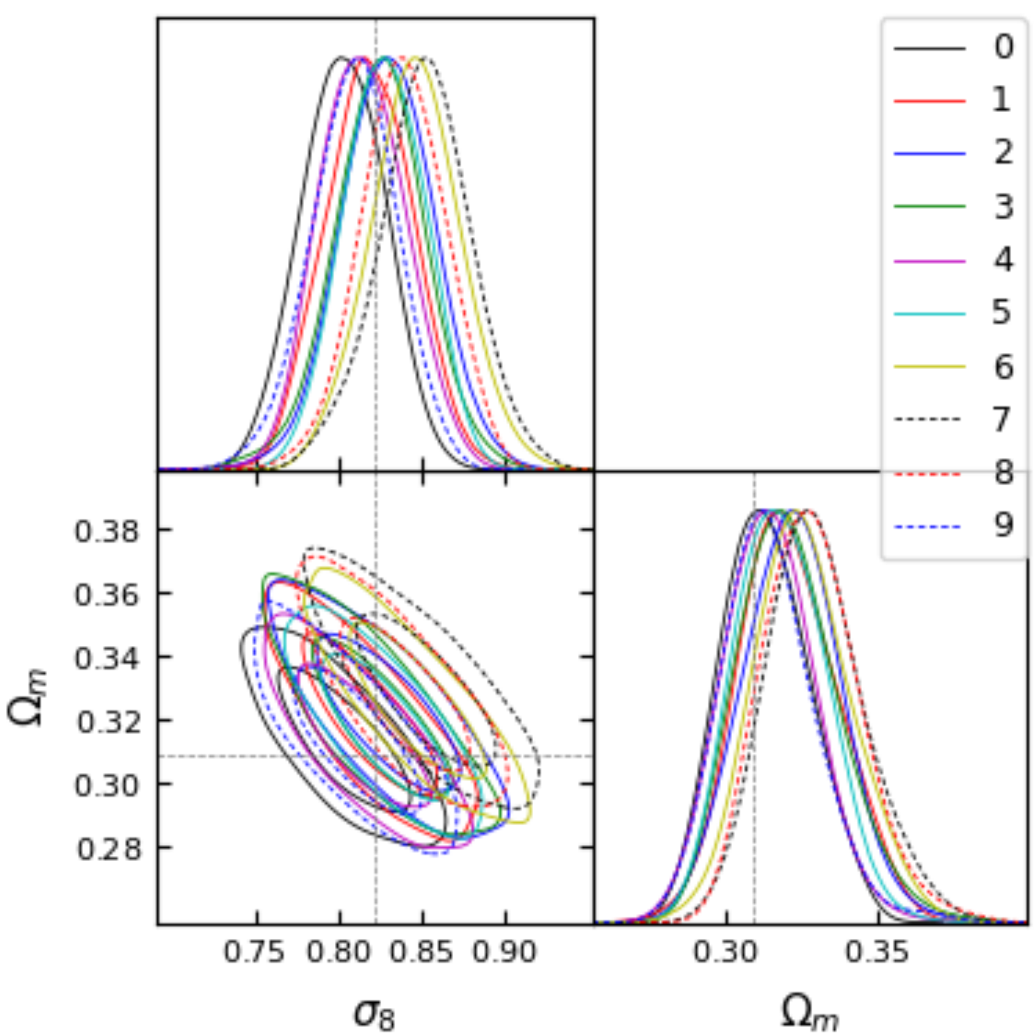


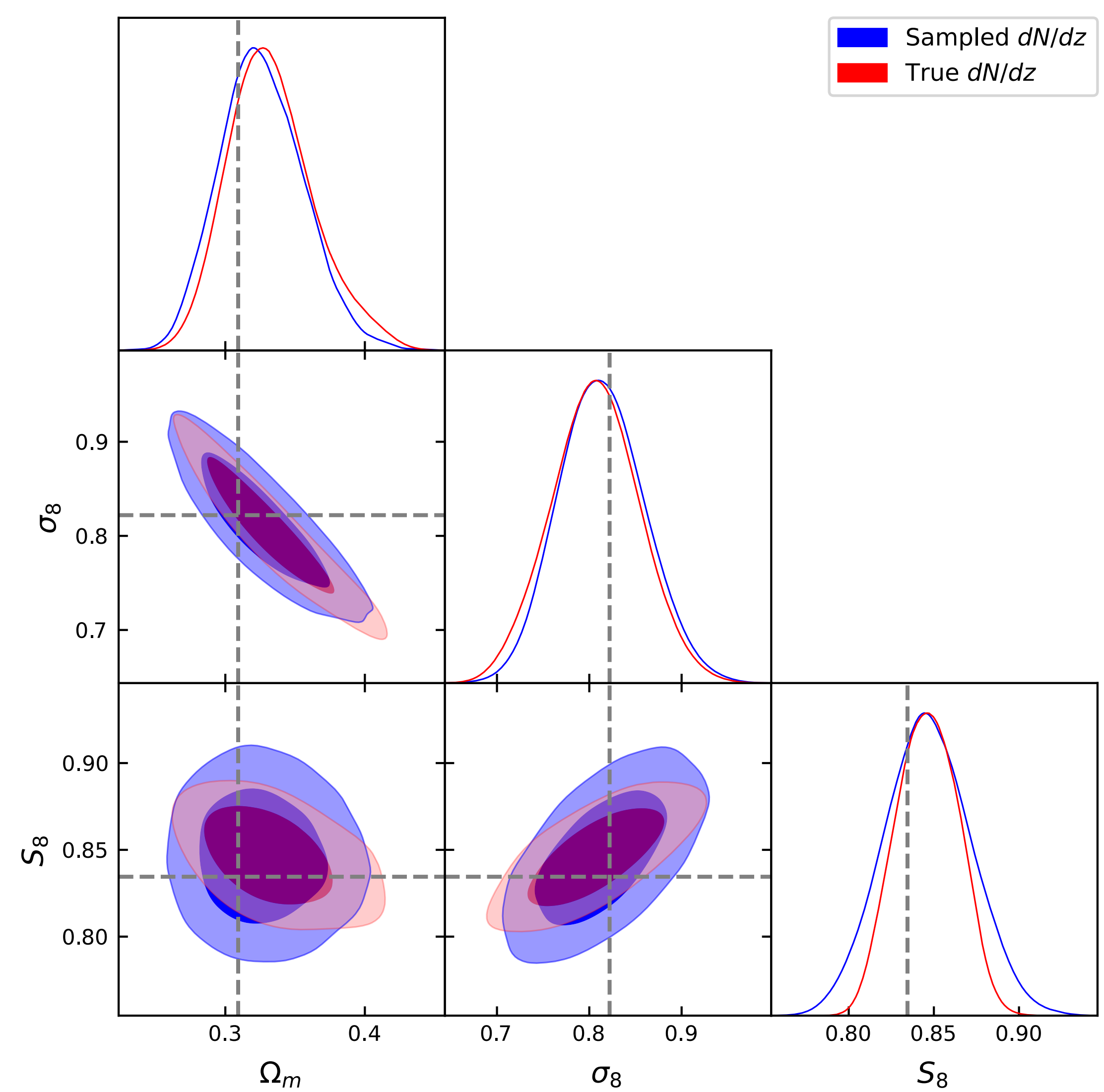
MOCK TESTS: MARGINALIZING dN/dz

- Marginalize over redshift distribution uncertainty by sampling noise-realizations of b(z) * dN/dz
  - <15% impact on marginalized Ω_m and σ_8
  - 20-50% impact on S_8 (largest for blue)

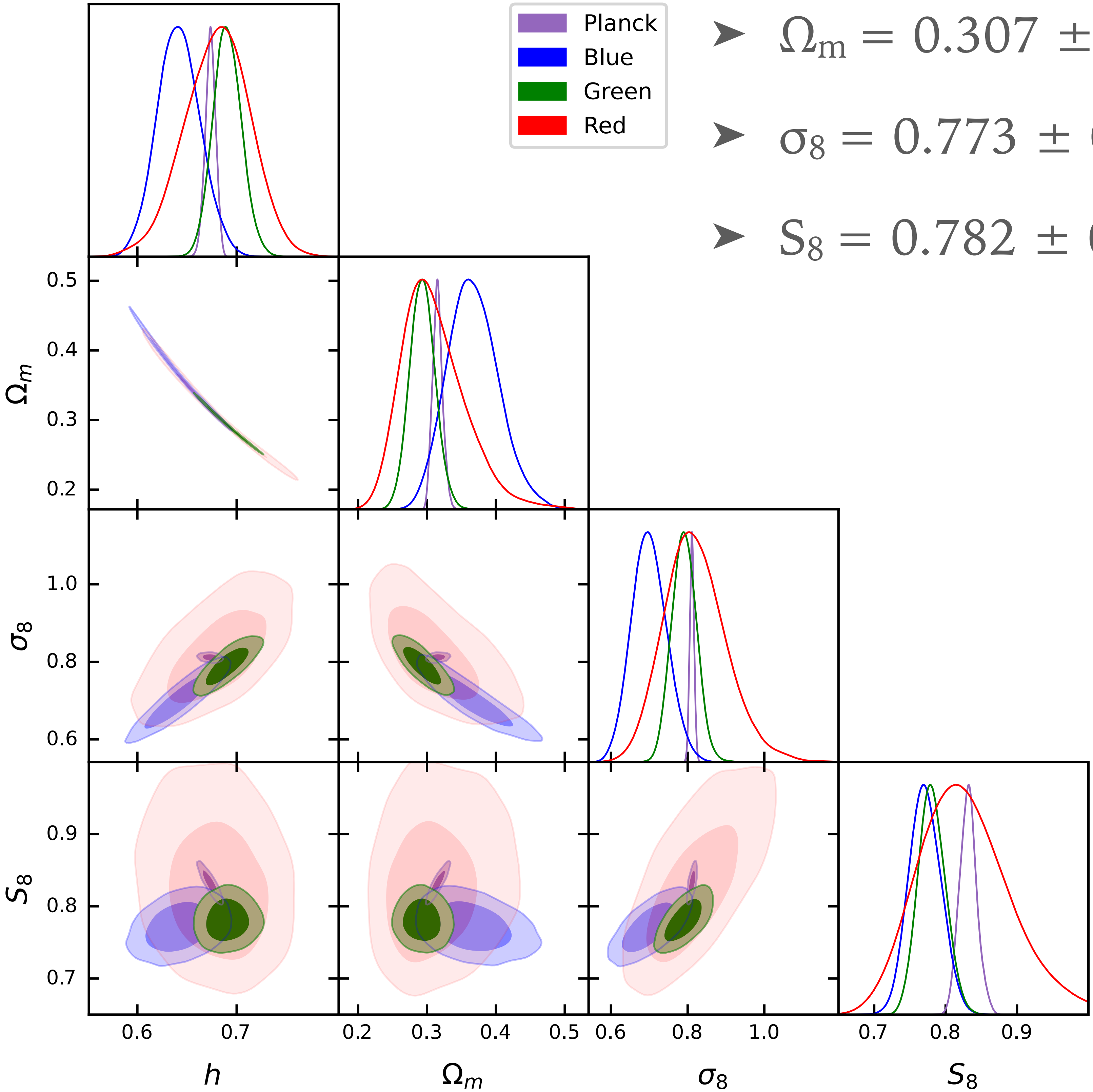


Blue, CrowCanyon2 mocks





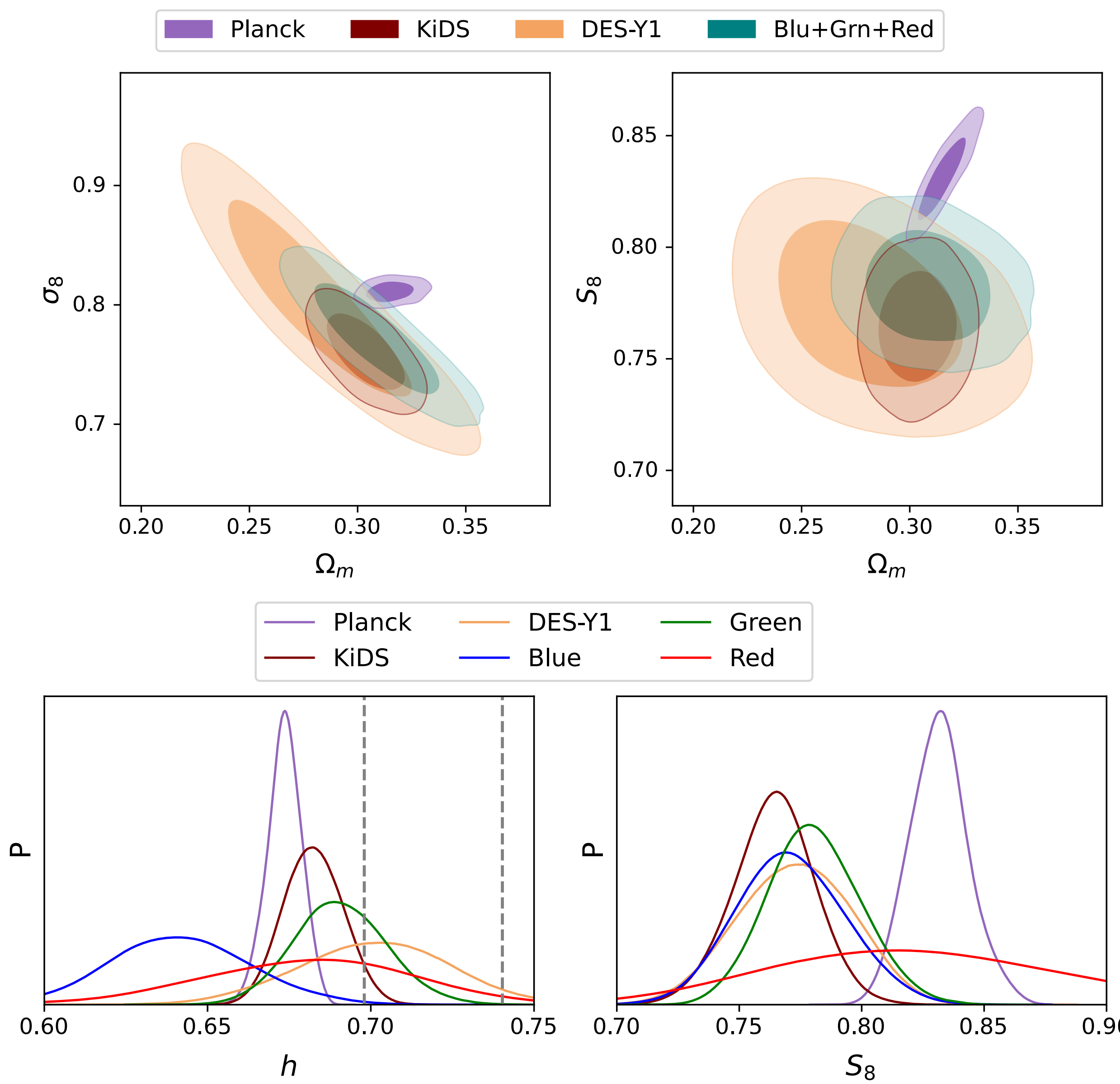
COSMOLOGY CONSTRAINTS



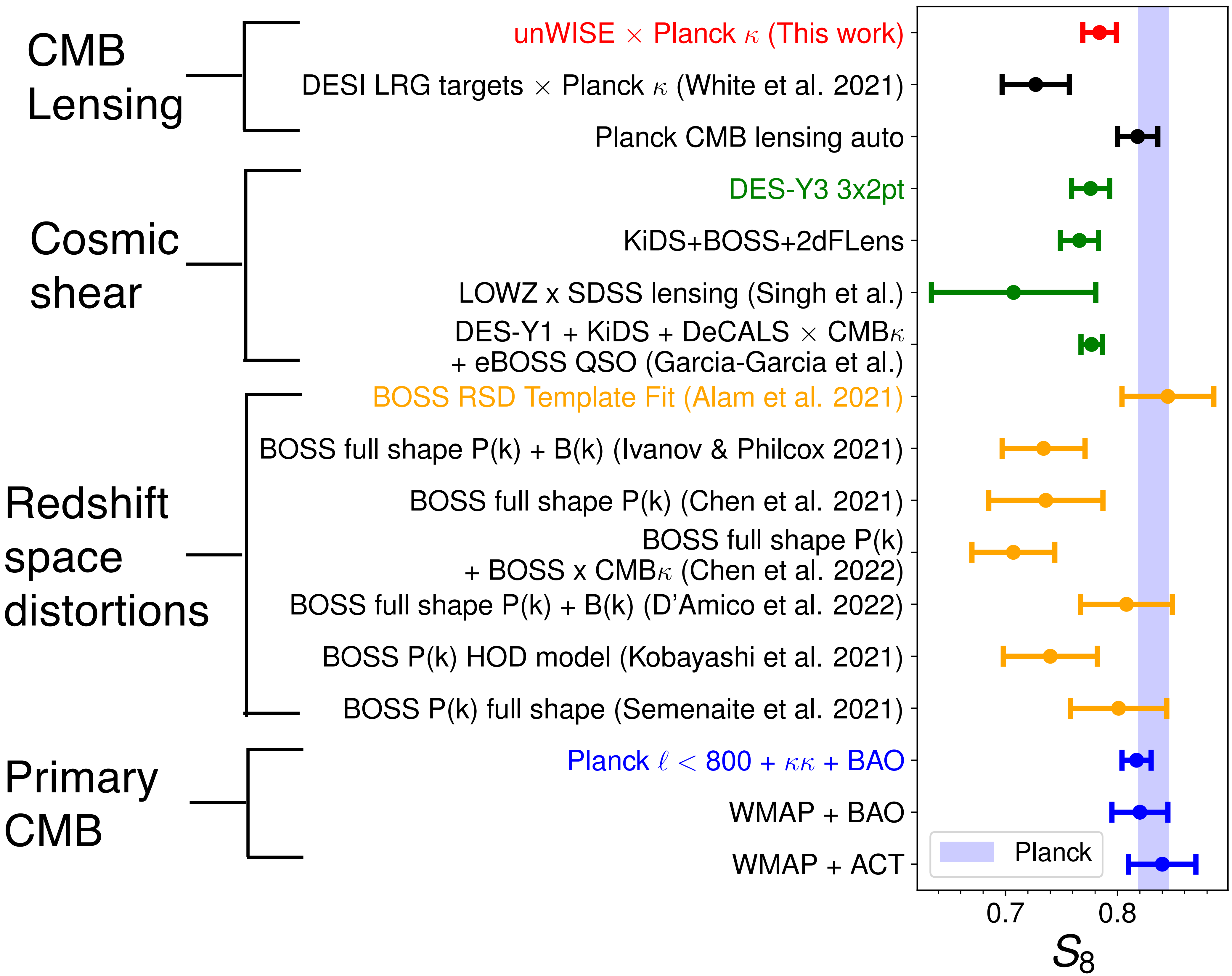
- $\Omega_m = 0.307 \pm 0.018$ (P18: 0.315 ± 0.017)
- $\sigma_8 = 0.773 \pm 0.029$ (P18: 0.811 ± 0.006)
- $S_8 = 0.782 \pm 0.015$ (P18: 0.832 ± 0.013)

LENSING TENSION?

- We find ~2.4σ tension in S_8 for our fiducial blue+green combined constraint (similar to KiDS, DES-Y1 results)
  - Caveat: errorbars increase when we free b_2 (although consistency with Planck requires somewhat implausible b_2 values)
  - Work in progress to better constrain b_2 by extending the scales that are modelled

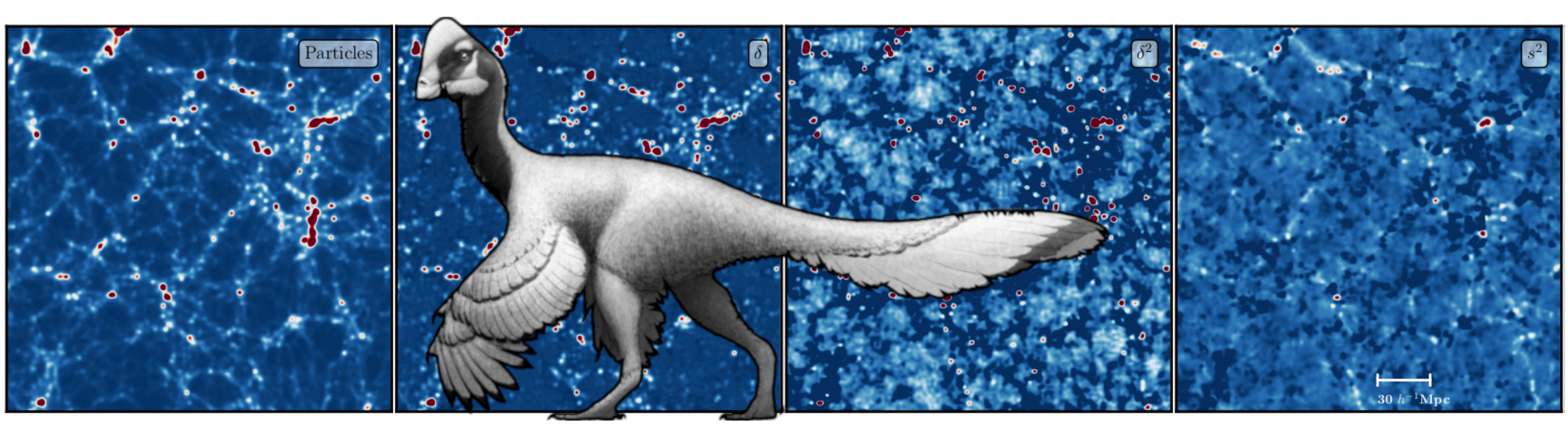


STATUS OF THE S8 TENSION

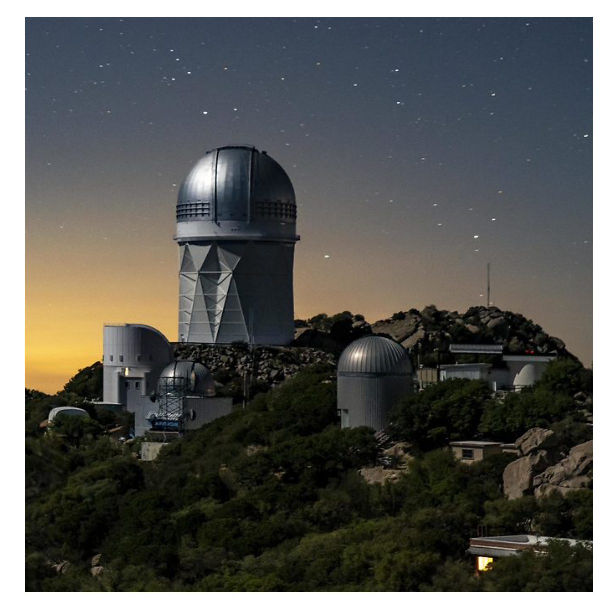


NEXT STEPS

- Further robustness checks and combined analysis with other probes (e.g. CMB lensing auto-correlation)
- unWISE x ACT CMB lensing analysis currently in prep (led by G. Farren & B. Sherwin)
- Biggest area of improvement: better modeling
  - Full PT models?
  - Emulator + PT approach (Anzu, Kokron+21; HEFTY, Hadzhyiska+21)
- We also have spectroscopic N(z) from designated observations with DESI and GTC: will reduce uncertainty due to uncertain dN/dz



https://github.com/kokron/anzu



DESI, Mayall Telescope

TESTING INFLATION WITH PRIMORDIAL NON-GAUSSIANITY

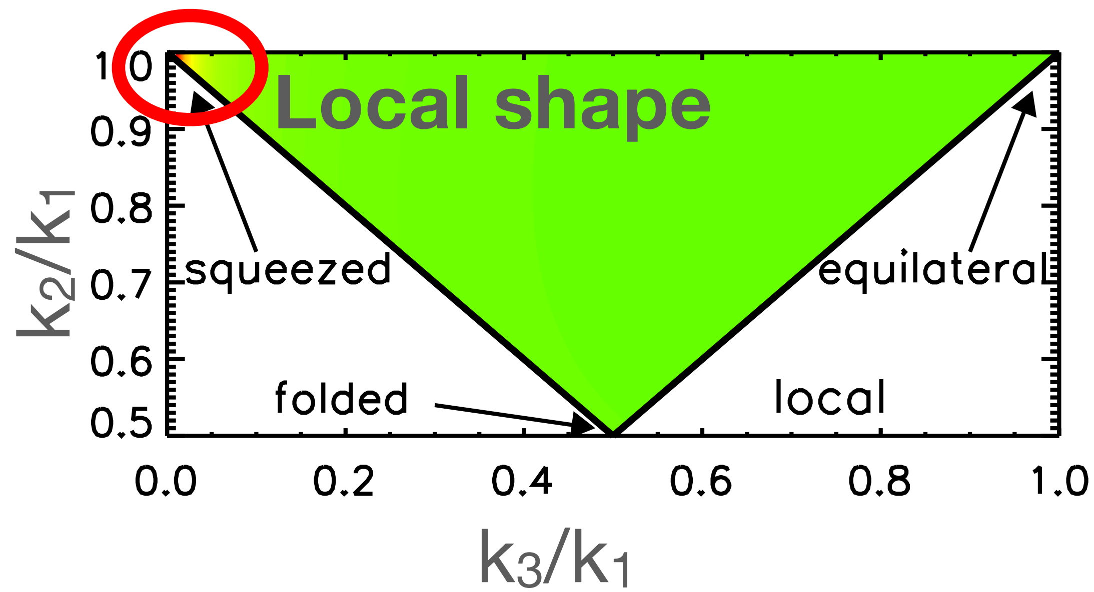
- Inflation produces initial conditions that are *nearly* Gaussian and scale-invariant
- In single-field slow-roll inflation, non-Gaussianity produces "local" bispectrum

$$\Phi = \phi_G + f_{\rm NL}^{\rm loc}\phi_G^2$$

$$B_{\rm local}(k_3 << k_1 \sim k_2) = 4 f_{\rm NL}^{\rm loc} P_\Phi(k_1) P_\Phi(k_3)$$

$$= \frac{5}{3}(1-n_s) P_\Phi(k_1) P_\Phi(k_3)$$

$$\Rightarrow \boxed{f_{\rm NL} = 0.017}$$



Komatsu 2010, arXiv 1003.6097

- $f_{\rm NL} \sim O(1)$ is a natural target
  - Detecting $f_{\rm NL} \sim 1$ rules out single-field slow-roll
  - Likewise, multi-field inflation generally predicts $f_{\rm NL} \sim 1$
- Complementary to B-modes in the CMB as unique probe of 10^{15} GeV inflationary physics

NON-GAUSSIANITY IN LARGE-SCALE STRUCTURE

- Best existing constraints on f_{NL} from Planck CMB bispectrum:
  - $f_{NL} = -0.9 \pm 5.1$
- Primary CMB is already cosmic variance limited: no further improvement expected!
- Non-Gaussianity also has detectable imprint on large-scale structure of biased tracers (i.e. galaxies)

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$$\nabla^2 \Phi = \nabla^2 \phi_G + 2 f_{\rm NL}^{\rm loc} [\phi_G \nabla^2 \phi_G + |\nabla \phi_G|^2]$$

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$$\delta = \delta_G \left[1 + 2 f_{\rm NL}^{\rm loc} \frac{\phi_G}{g(a)}\right]$$

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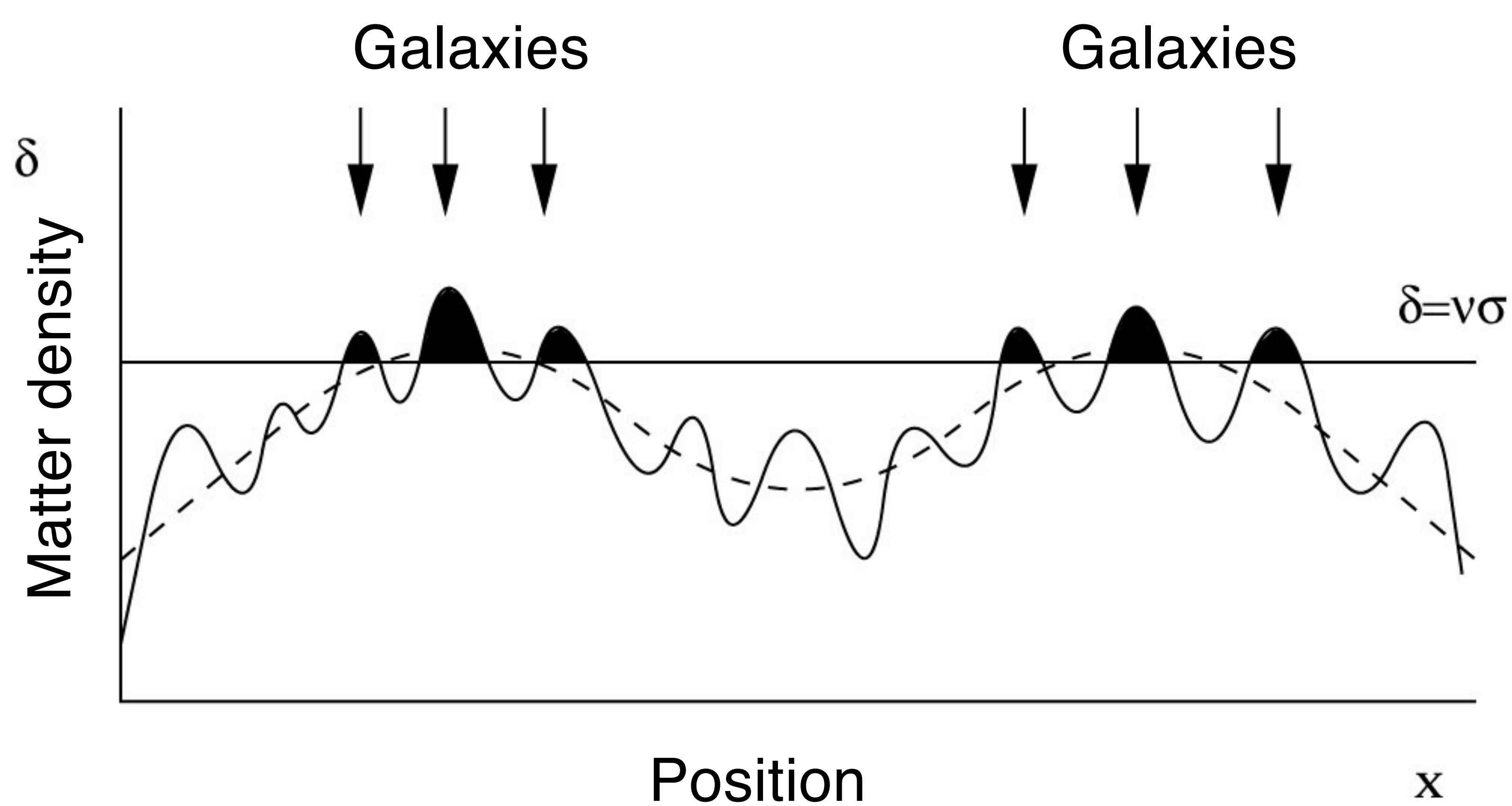
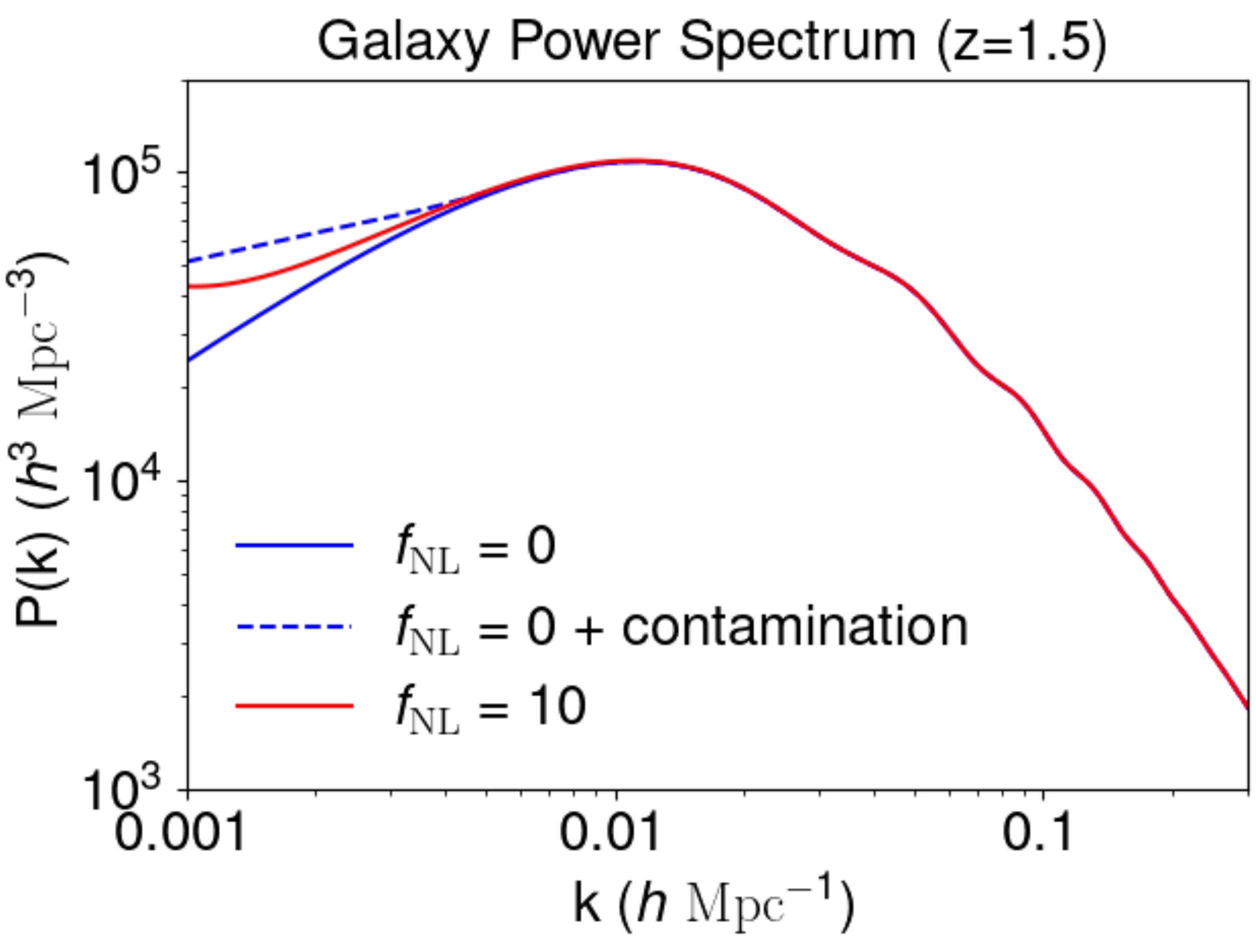
- Creates **scale-dependent bias** $\propto 1/k^2$



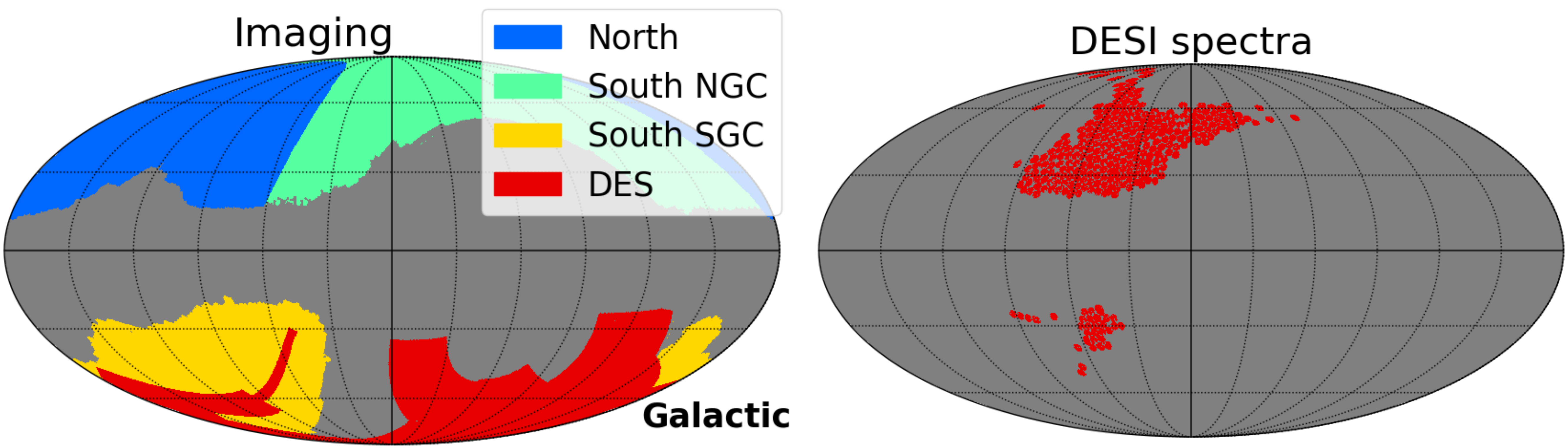
CMB LENSING AND PRIMORDIAL NON-GAUSSIANITY



- Galaxy/quasar autocorrelation most commonly used to constrain f_{NL}
  - Large angular scale systematics can be degenerate with f_{NL} and degrade/bias constraint
- Advantages of CMB lensing cross-correlation
  - Higher redshift = stronger signal
  - Full sky = good coverage of large scales
  - Systematics typically not correlated between galaxies and CMB lensing

DESI QUASAR TARGETS

- CMB lensing is an *angular* observable: only requires the sample's statistical redshift distribution rather than 3D positions
    - Redshifts from first 2 months of 5-yr DESI survey are more than adequate!
- Select a "cleaner" sample of DESI quasar targets to ensure high redshift completeness and purity
- Cross-correlate with Planck 2018 CMB lensing
- Preliminary results!



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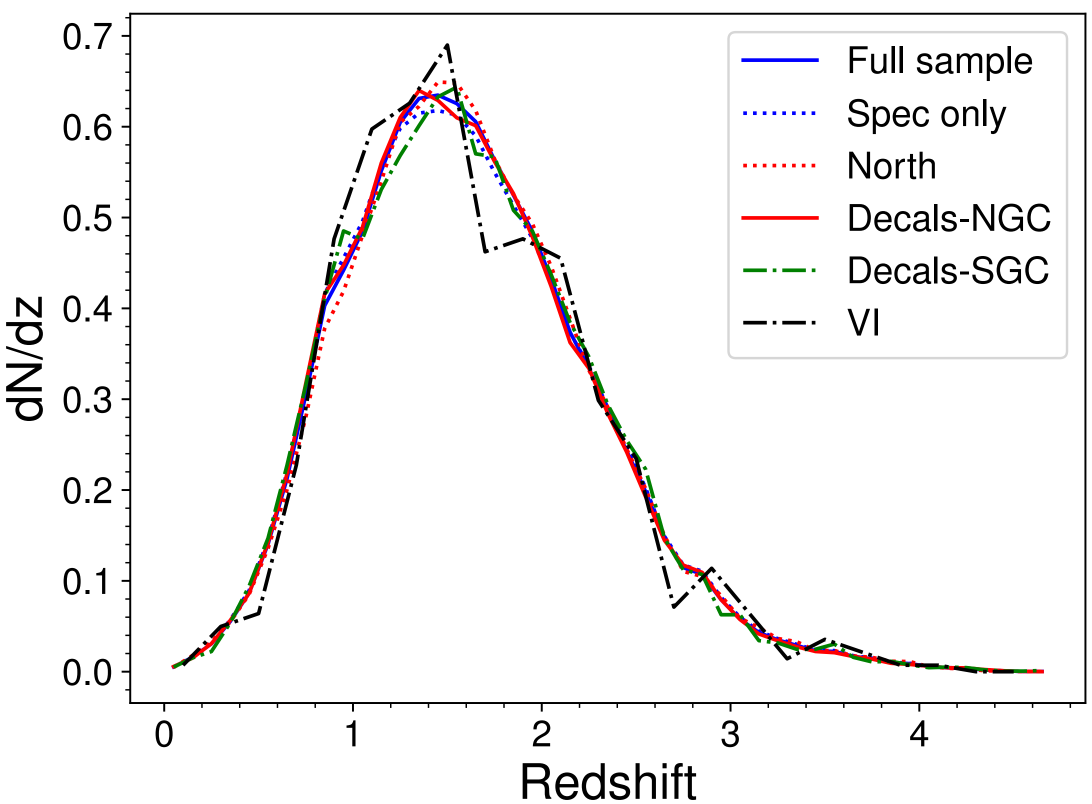
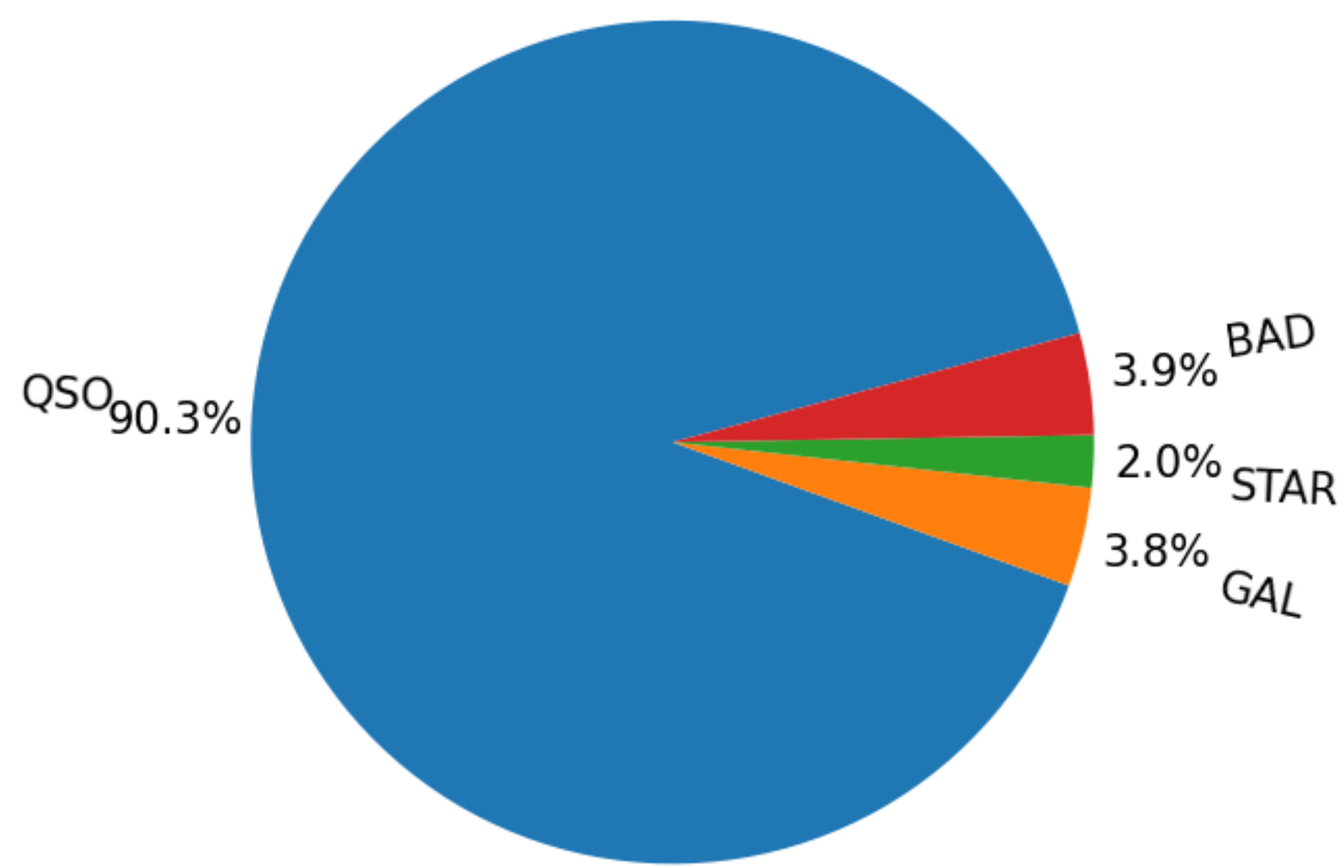


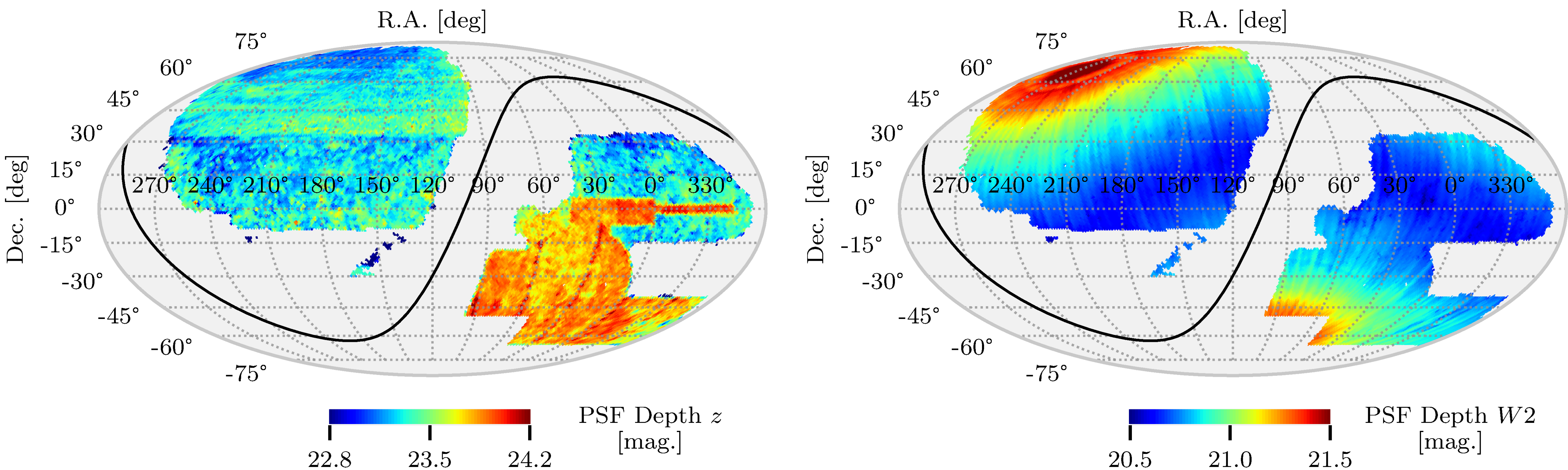


REMOVING IMAGING SYSTEMATICS

- Imaging systematics add *signal* to the auto-correlation and *increase noise* in the cross-correlation (even without biasing signal)
- Covariance for a Gaussian random field:

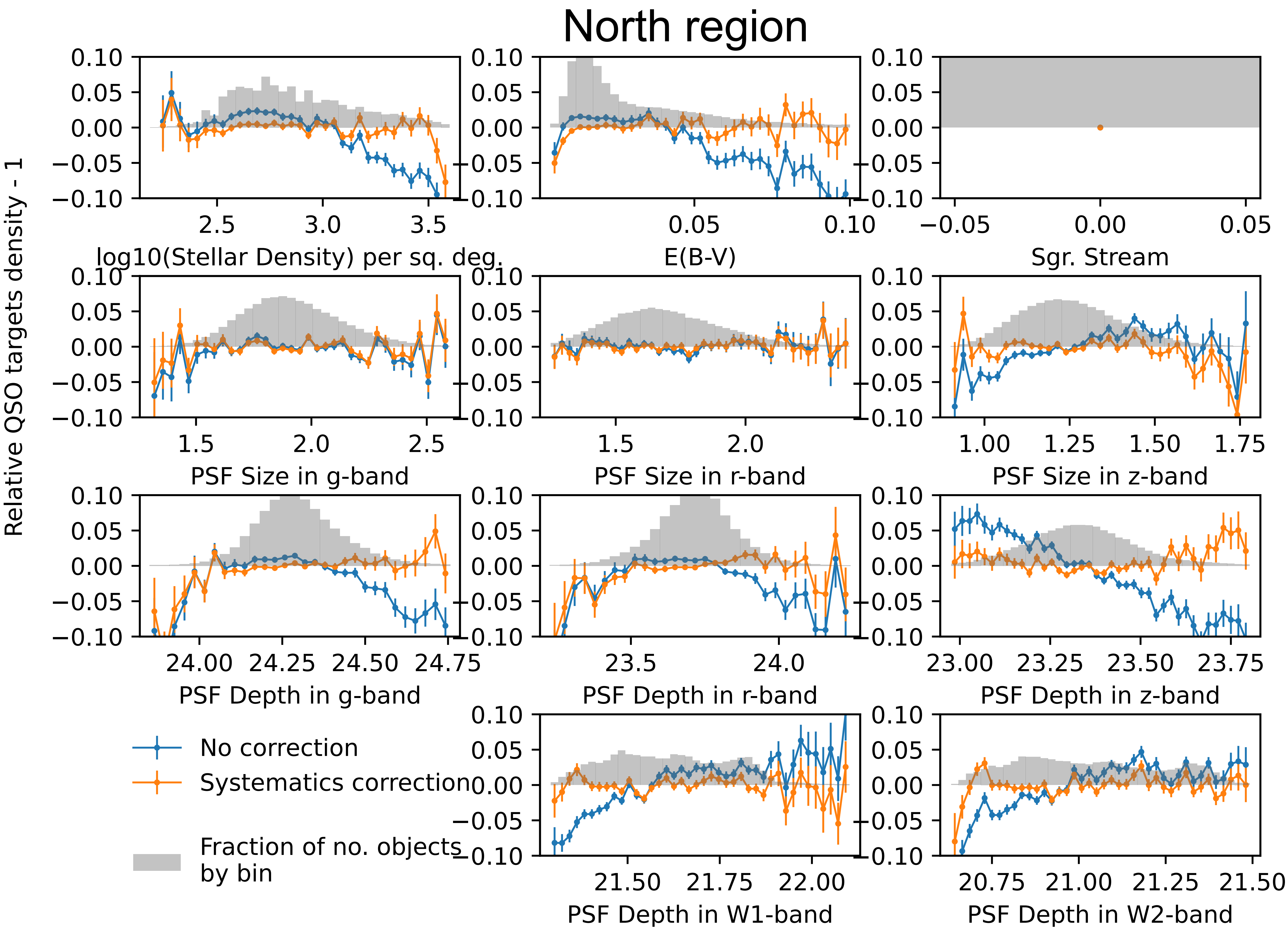
$$\mathrm{Cov}(C_\ell^{\kappa g}) \propto [(C_\ell^{\kappa g})^2 + (C_\ell^{gg} + N_\ell^{gg})(C_\ell^{\kappa\kappa} + N_\ell^{\kappa\kappa})]$$

- Reduce noise on the cross-correlation by regressing out trends with stellar density, imaging depth, extinction, etc.



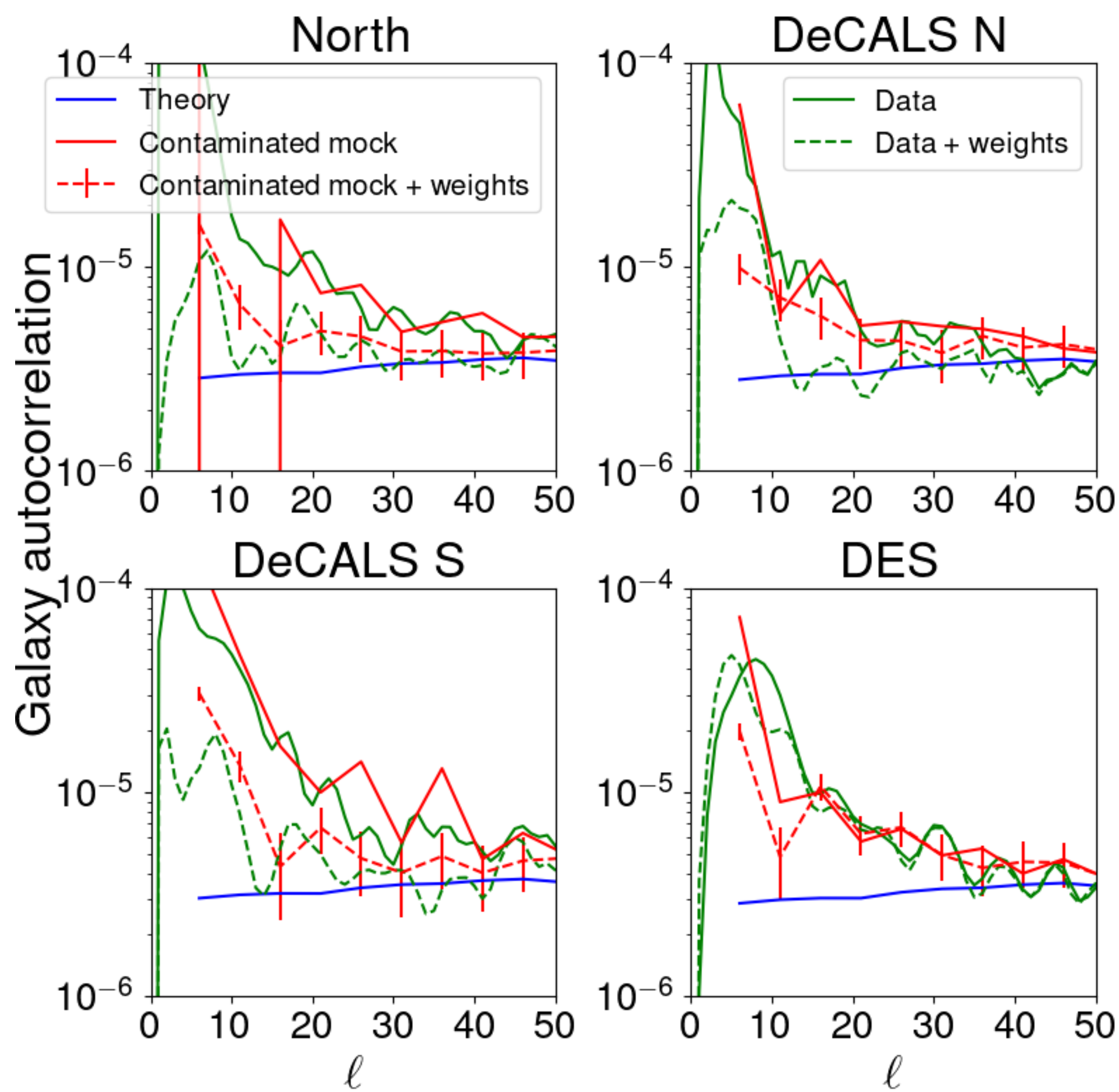
Chaussidon et al. 2022, 2108.03640

REMOVING IMAGING SYSTEMATICS

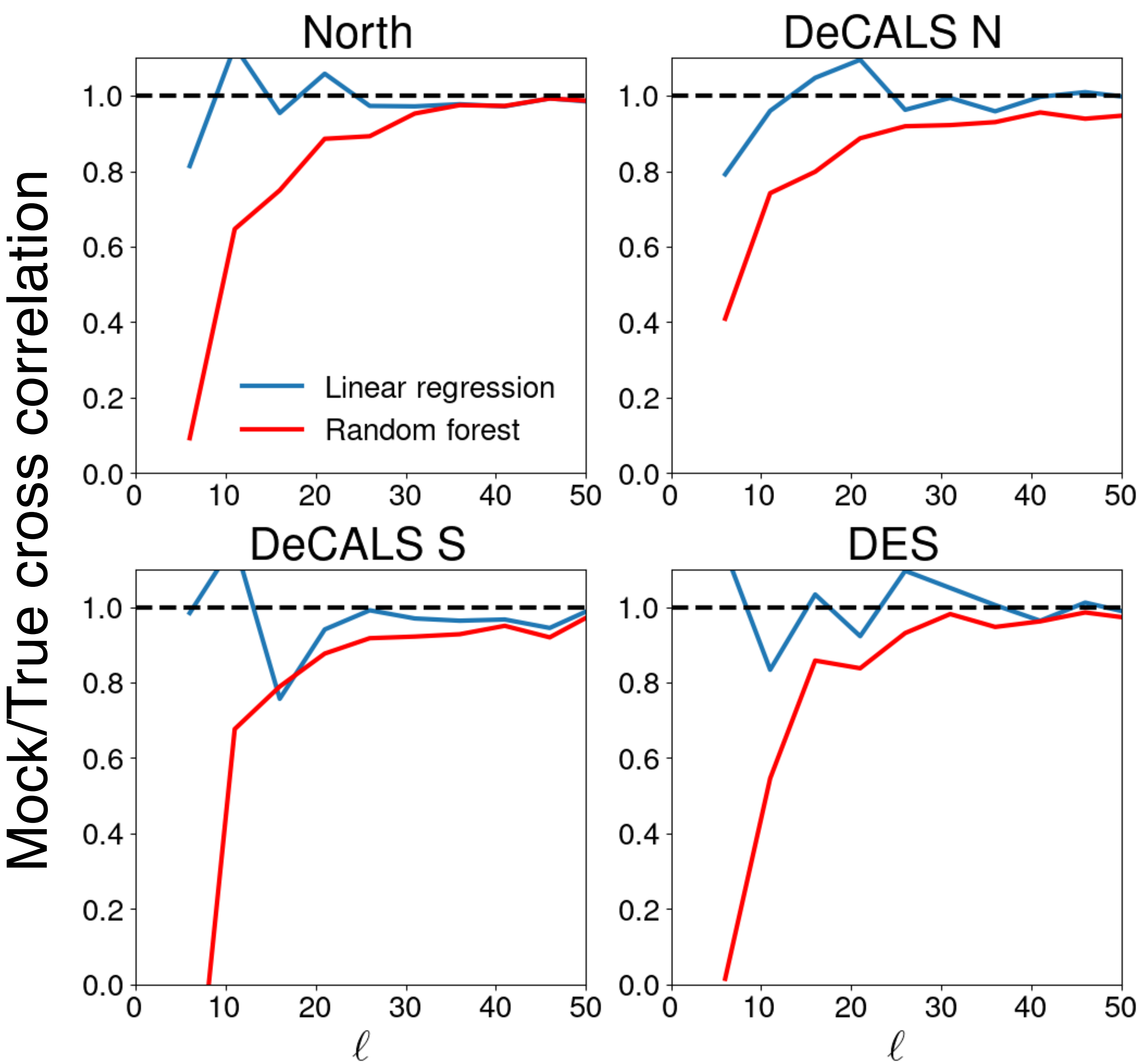


CONTAMINATED MOCKS

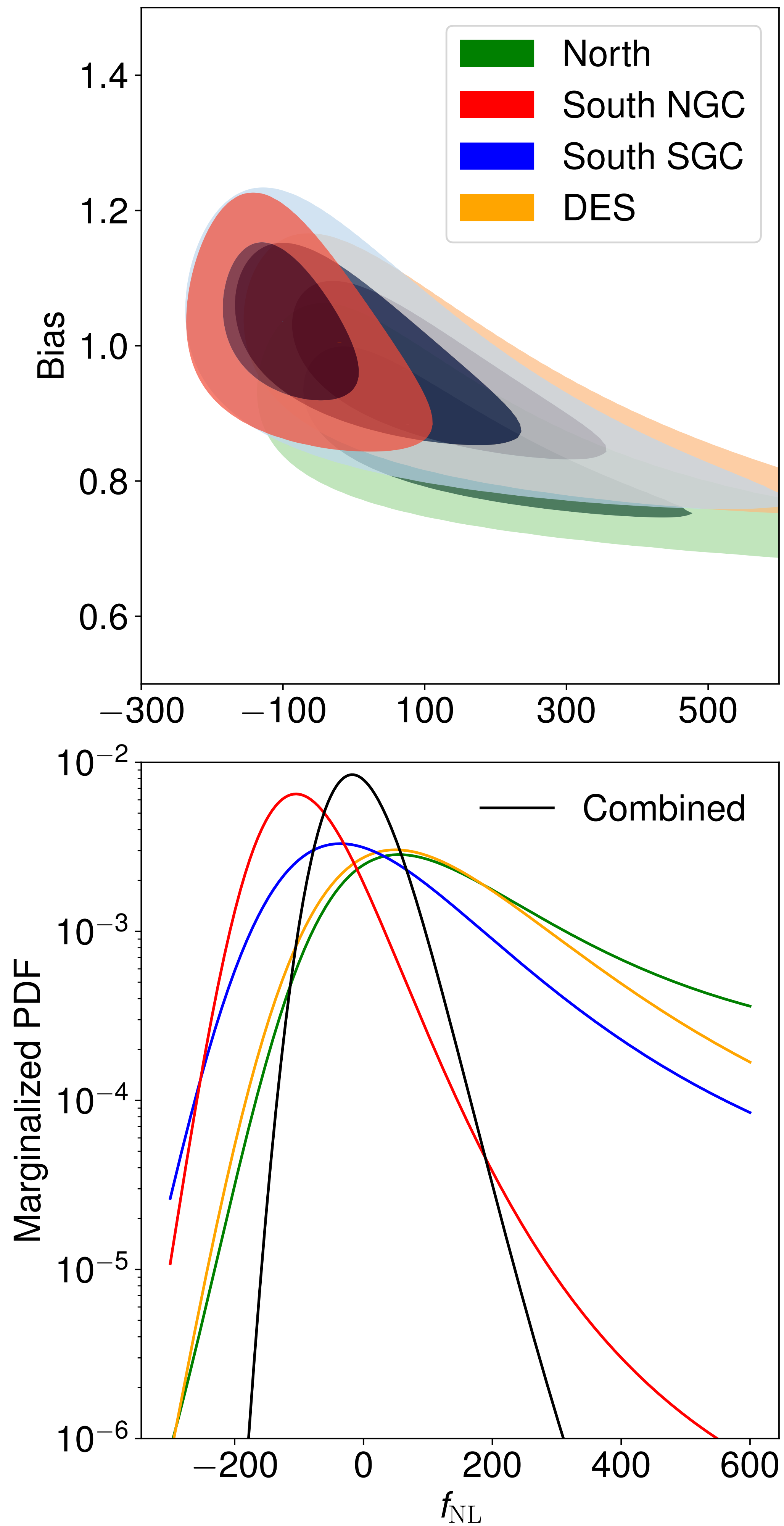
- Overfitting is a big problem: regression may remove real cosmological signal!
- Validate the regression with mocks
  - Create “contaminated mocks” with identical systematics trends to the data
  - Re-run regression on “contaminated mocks”
  - Validate against input power spectrum



CONTAMINATED MOCKS



- Random Forest method is too flexible and has *severe* overfitting
  - Despite recovering autocorrelation accurately, cross-correlation is >50% attenuated at $\ell < 10$
- We instead use simpler linear regression
- Number of imaging templates restricted (<7) to ensure accurate recovery down to $\ell = 5$



RESULTS

- Preliminary results: $f_{\rm NL} = -11^{+51}_{-44}$
- Robust to various systematics tests (no galaxy weights; tSZ-free lensing; changing covariance); consistent between regions; and well-fit by data
- Errorbar consistent with Fisher forecast given extra noise from un-mitigated systematics
- Slightly weaker constraints than BOSS/eBOSS galaxy correlations ($\sigma_{f_{\rm NL}}$~20-30)
  - But better cross-correlation results on horizon using full DESI spectroscopic quasar sample

QUESTIONS?

NEXT STEPS & RELATED WORK

IMPROVING THE REDSHIFT DISTRIBUTION WITH DESI

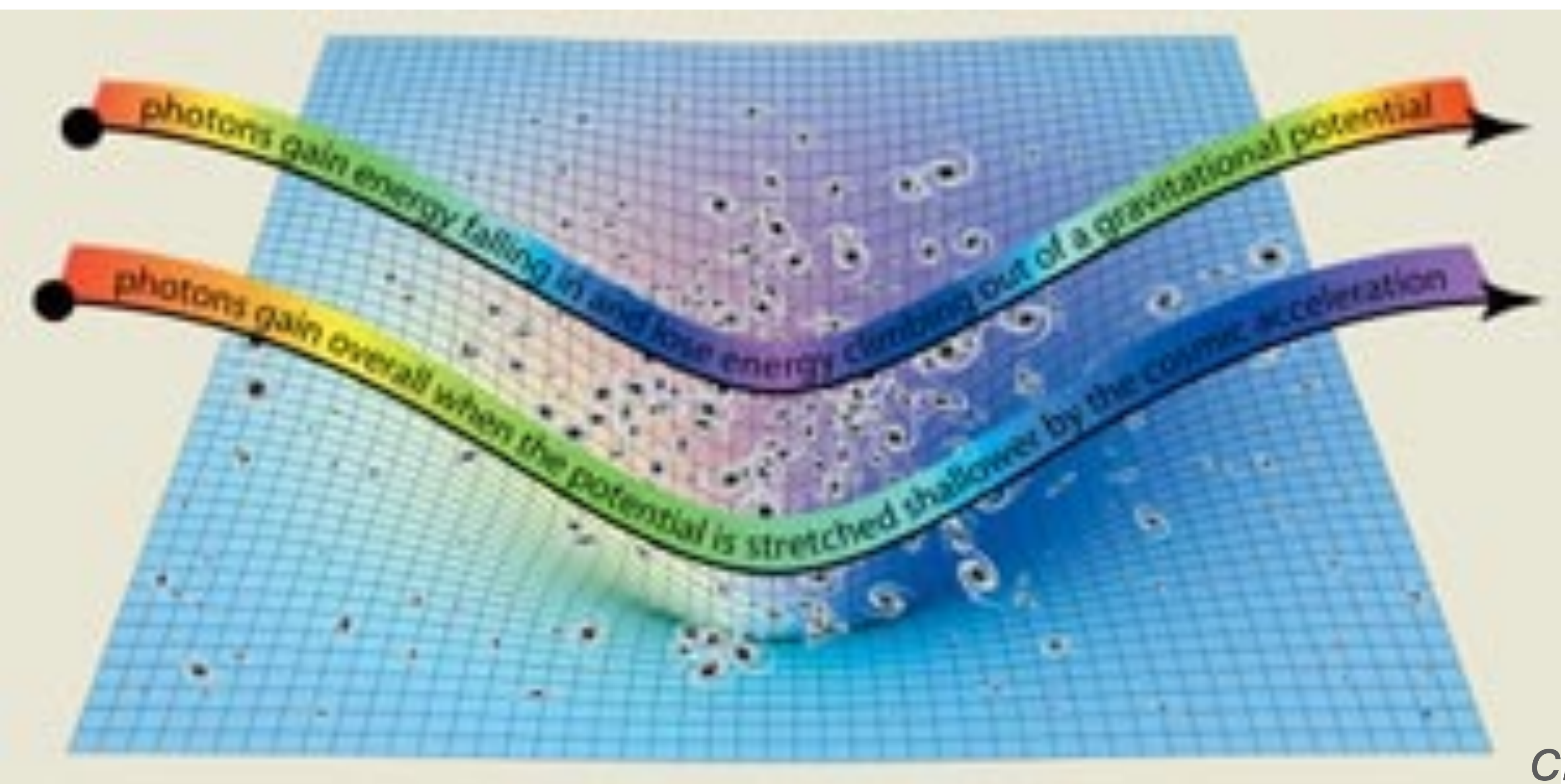
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

- Redshift distribution is largest source of systematic error
- With 3 DESI pointings (4.5 hours) as part of SV in April 2021, we will obtain 15,000 redshifts (enough to reduce the uncertainty from dN/dz)
- Additional observations on GTC (10m telescope) for faintest sources

INTEGRATED SACHS-WOLFE EFFECT

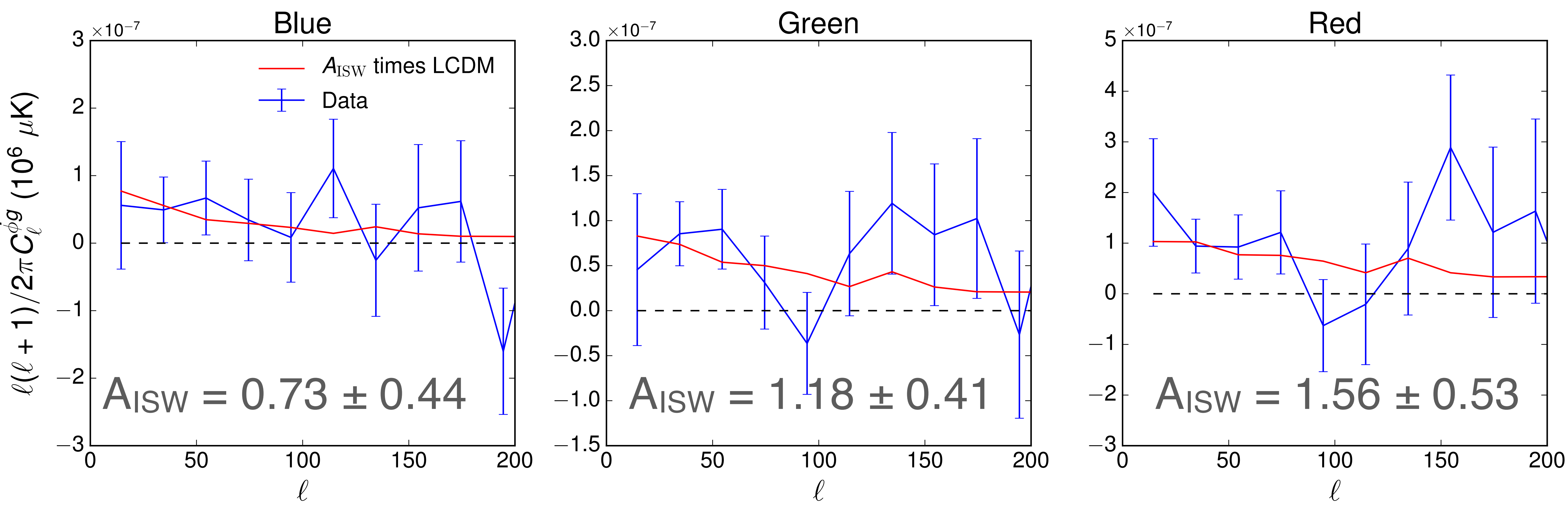
- Photons gravitationally redshift and blueshift as they pass in and out of potential wells
- If potential is decaying (e.g. from Dark Energy), there is a net blueshift, inducing a correlation between CMB Temperature and galaxies: direct evidence for Dark Energy



cmbcorrelations.com

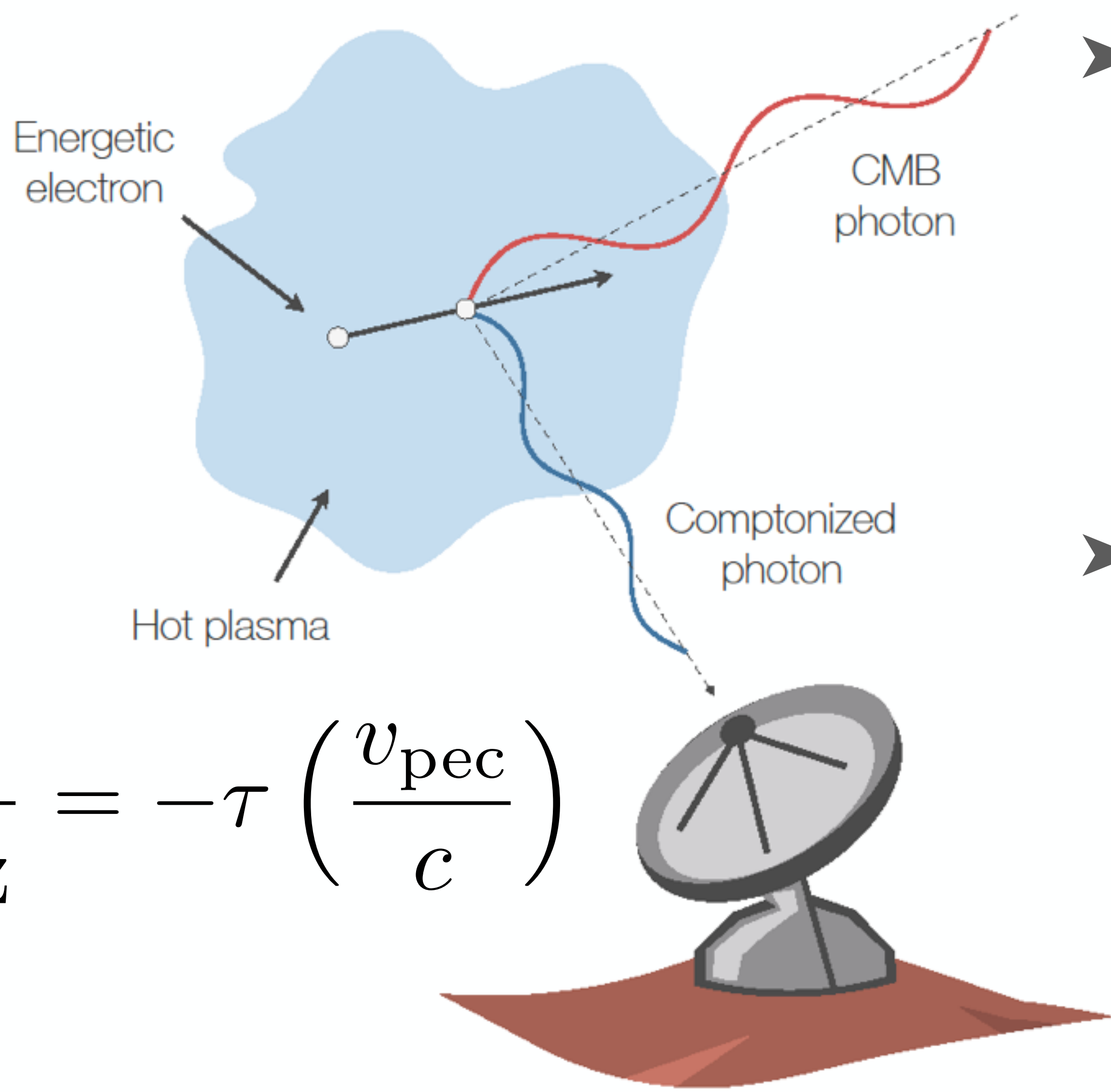
INTEGRATED SACHS-WOLFE EFFECT

➤ 4σ detection of ISW from unWISE:



PROJECTED-FIELD KINETIC SUNYAEV-ZEL'DOVICH MEASUREMENT

- Photons inverse-Compton scatter off free electrons in hot cluster/group gas (Sunyaev-Zel'dovich effect)

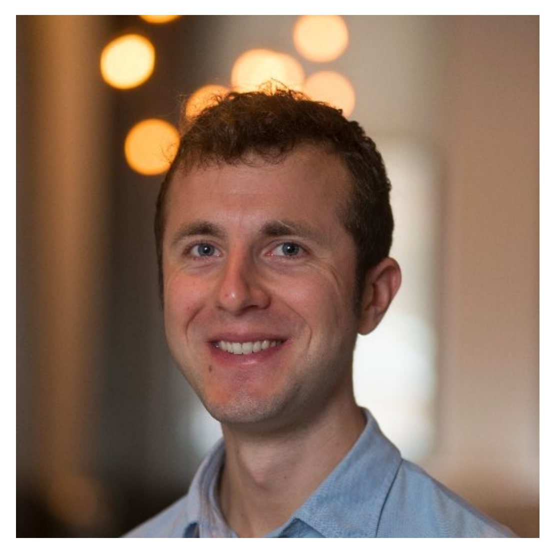


$$\frac{\Delta T}{T_{\mathrm{kSZ}}} = -\tau \left(\frac{v_{\mathrm{pec}}}{c} \right)$$

- Thermal effect: electron velocity from temperature, characteristic distortion in CMB spectrum
- Kinetic effect: electron velocity from bulk velocity, no temperature distortion but correlations between temperature and velocity

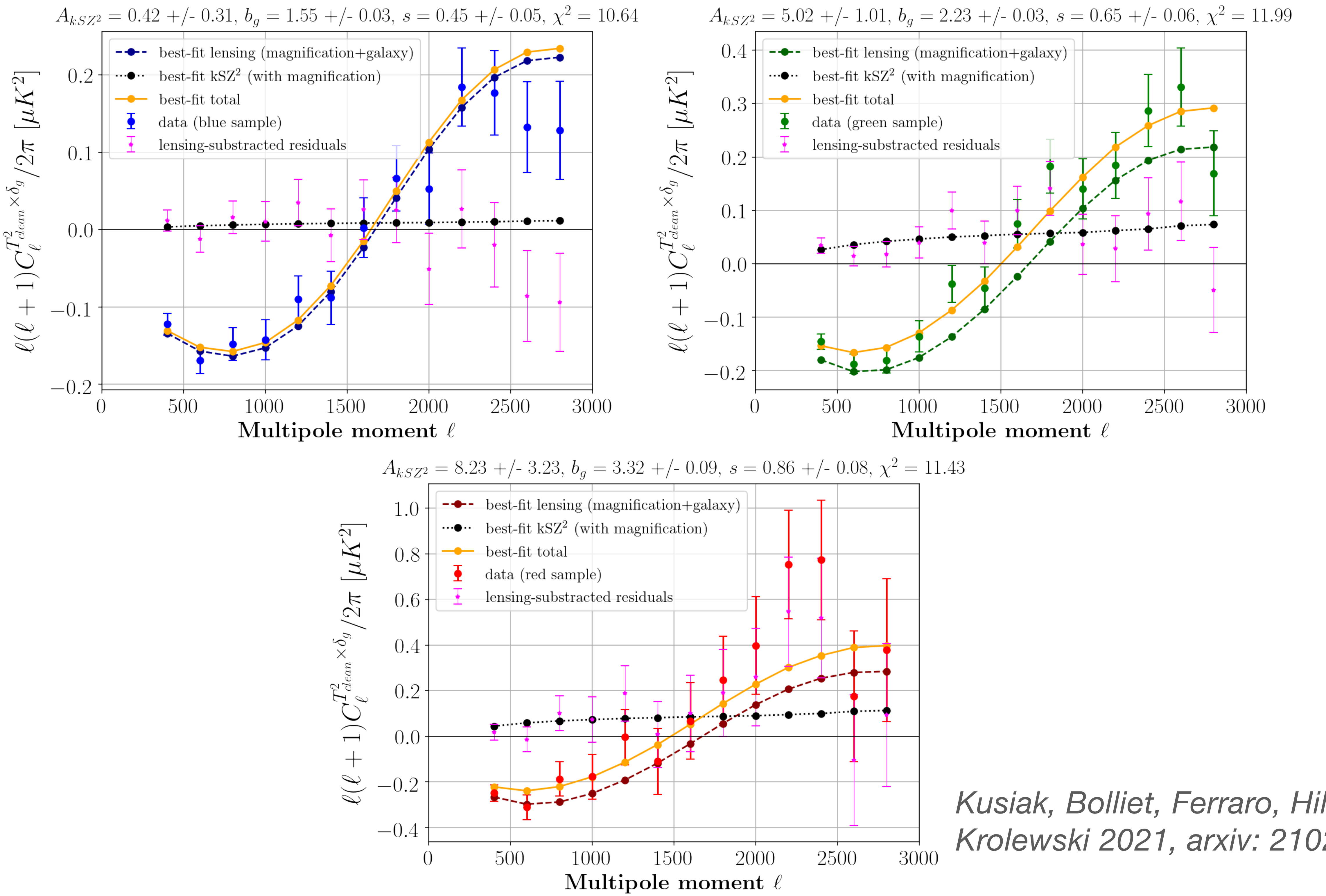
PROJECTED-FIELD KINETIC SUNYAEV-ZEL'DOVICH MEASUREMENT

- Can detect kSZ effect using projected fields only, measuring the bispectrum <TTδ>
- Use T-map cleaned of foregrounds (LGMCA) and asymmetric estimator to increase S/N
- >5σ detection of kSZ cross-correlation with unWISE; anomalously high (4σ and 3σ) for green and red samples



Kusiak, Bolliet, Ferraro, Hill, Krolewski 2021, arxiv: 2102.01068

PROJECTED-FIELD KINETIC SUNYAEV-ZEL'DOVICH MEASUREMENT



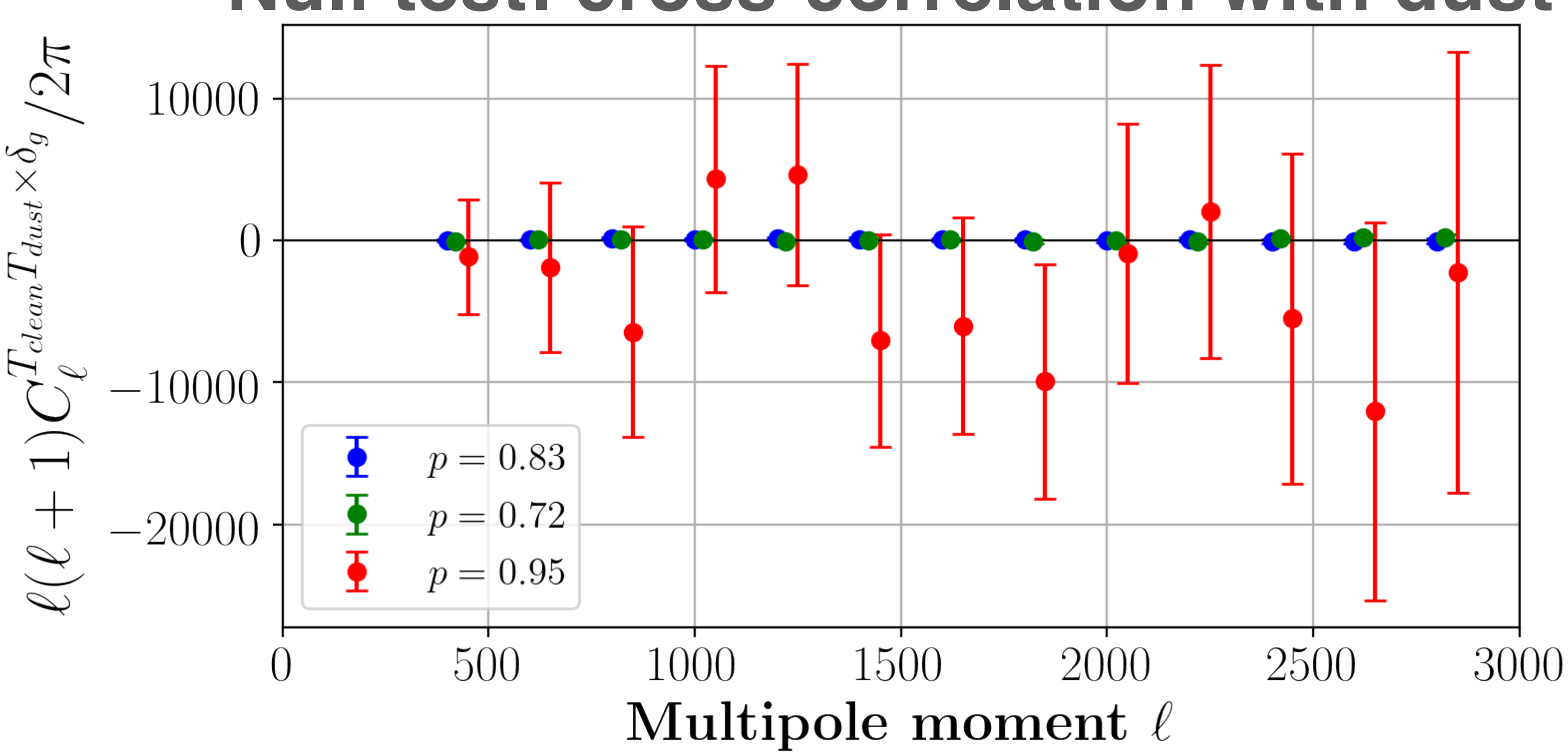
Kusiak, Bolliet, Ferraro, Hill, Krolewski 2021, arxiv: 2102.01068

PROJECTED-FIELD KINETIC SUNYAEV-ZEL'DOVICH MEASUREMENT

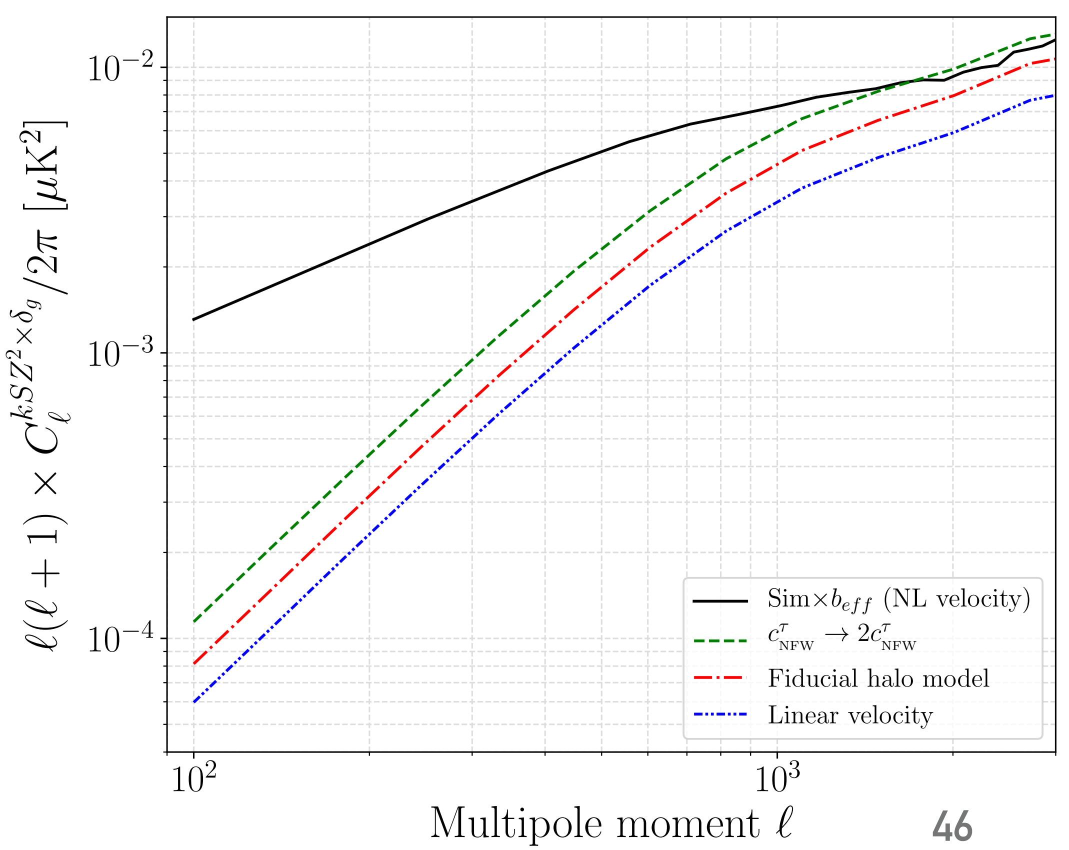
Kusiak, Bolliet, Ferraro, Hill, Krolewski 2021, arxiv: 2102.01068

- What is behind the anomalously high detection?
- Not dust: extensive validation, dust nulling, checking with different maps
- Maybe our theory model breaks down at small scales: HOD effects important?

Null test: cross-correlation with dust



1-halo contribution



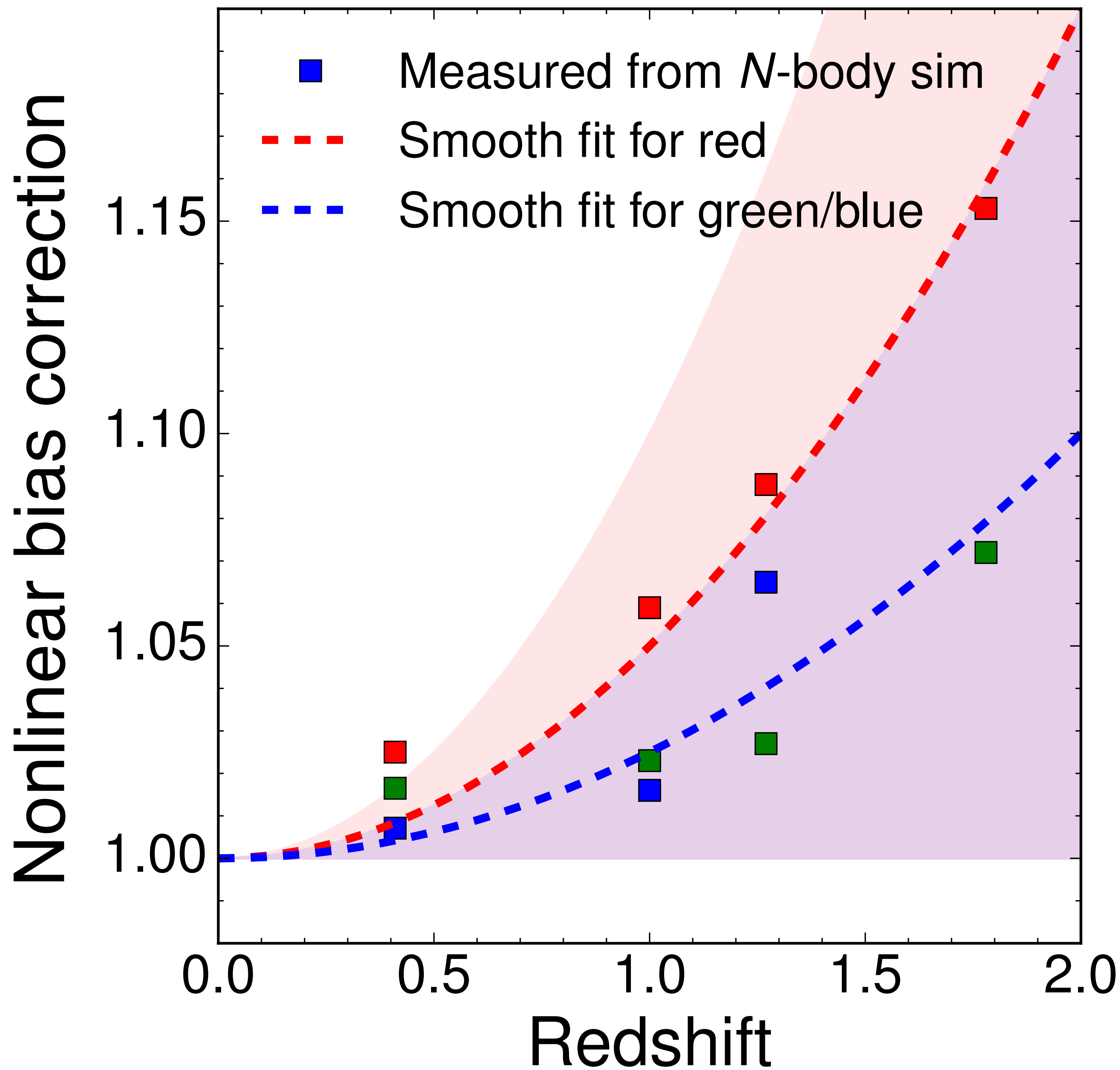
SUMMARY

- unWISE is a powerful sample for cosmology: CMB lensing cross-correlation with S/N ~80 from 150 million galaxies at $z<2$
  - Cosmological constraints ongoing: 2% constraints in s8 and om
- Presented methods, measurement & systematics checks
- Challenges and promise for cosmology at the few-percent precision
- Next steps:
  - sample over cosmological parameters: measure Ω_m and σ_8, marginalizing over dN/dz
  - say something interesting about lensing tension?

BACKUP SLIDES

NONLINEAR BIAS EVOLUTION

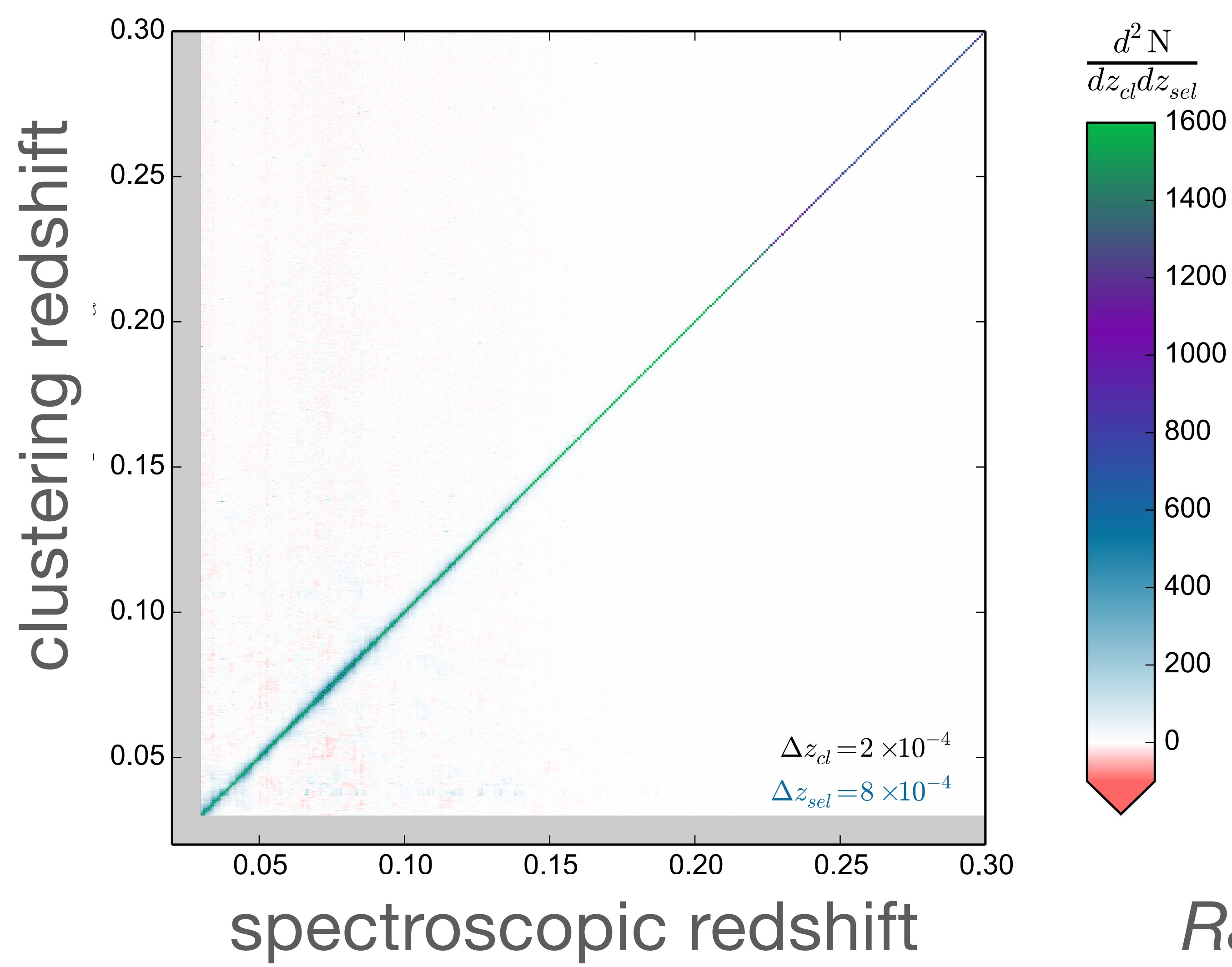
- Residual impact of nonlinear bias on $2.5 < r < 10\ h^{-1}$ Mpc is small



unWISE REDSHIFT DISTRIBUTION

➤ Measure dN/dz from cross-correlations with SDSS

$$\bar{w}_{\mathrm{sp}}(z) = b_{\mathrm{sml,s}}(z)\, b_{\mathrm{sml,p}}(z)\, H(z)\, \frac{dN_{\mathrm{p}}}{dz}\, I(z)$$



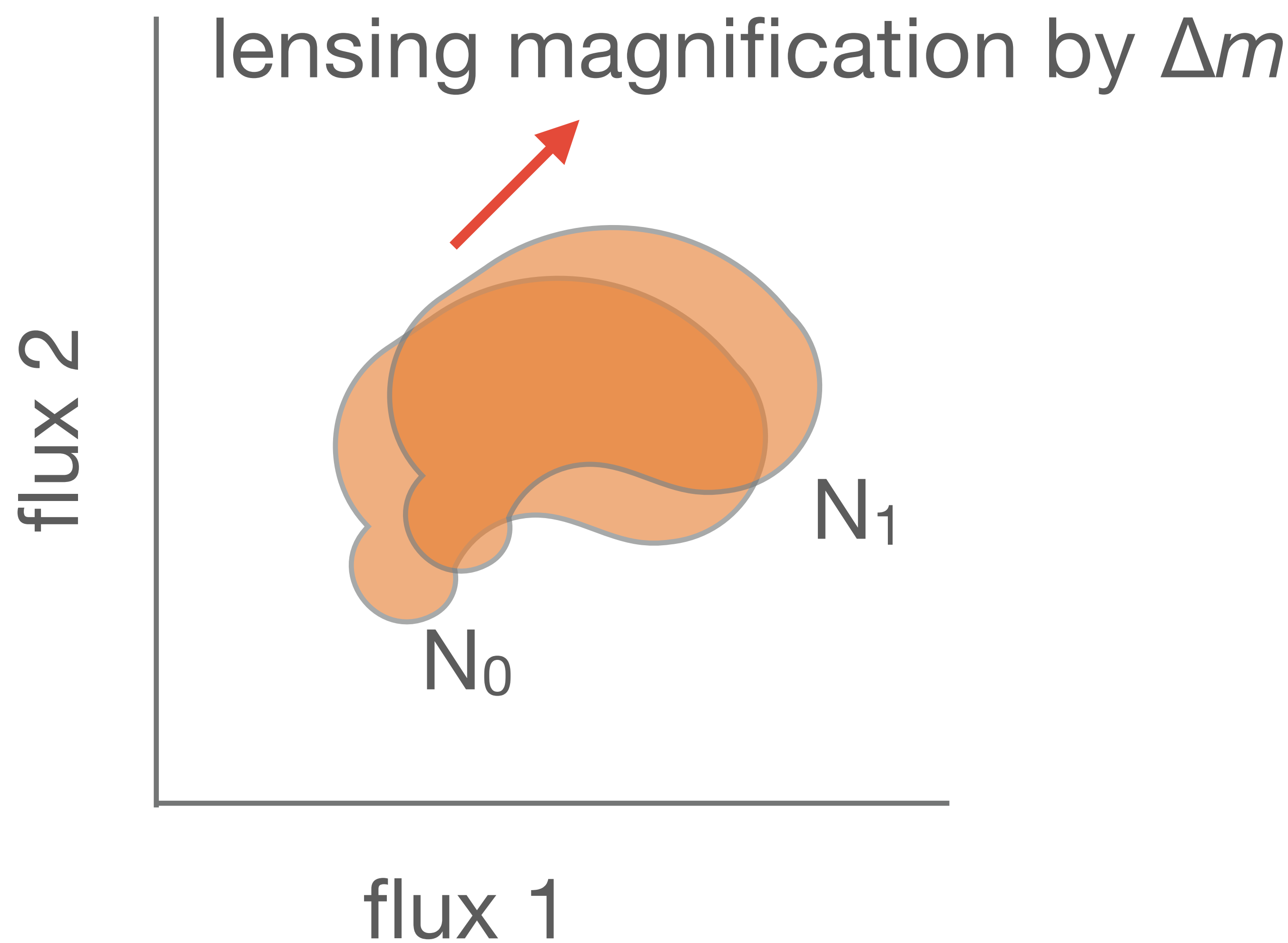
Rahman et al. 2015

➤ cross-check with cros MOS photo-z

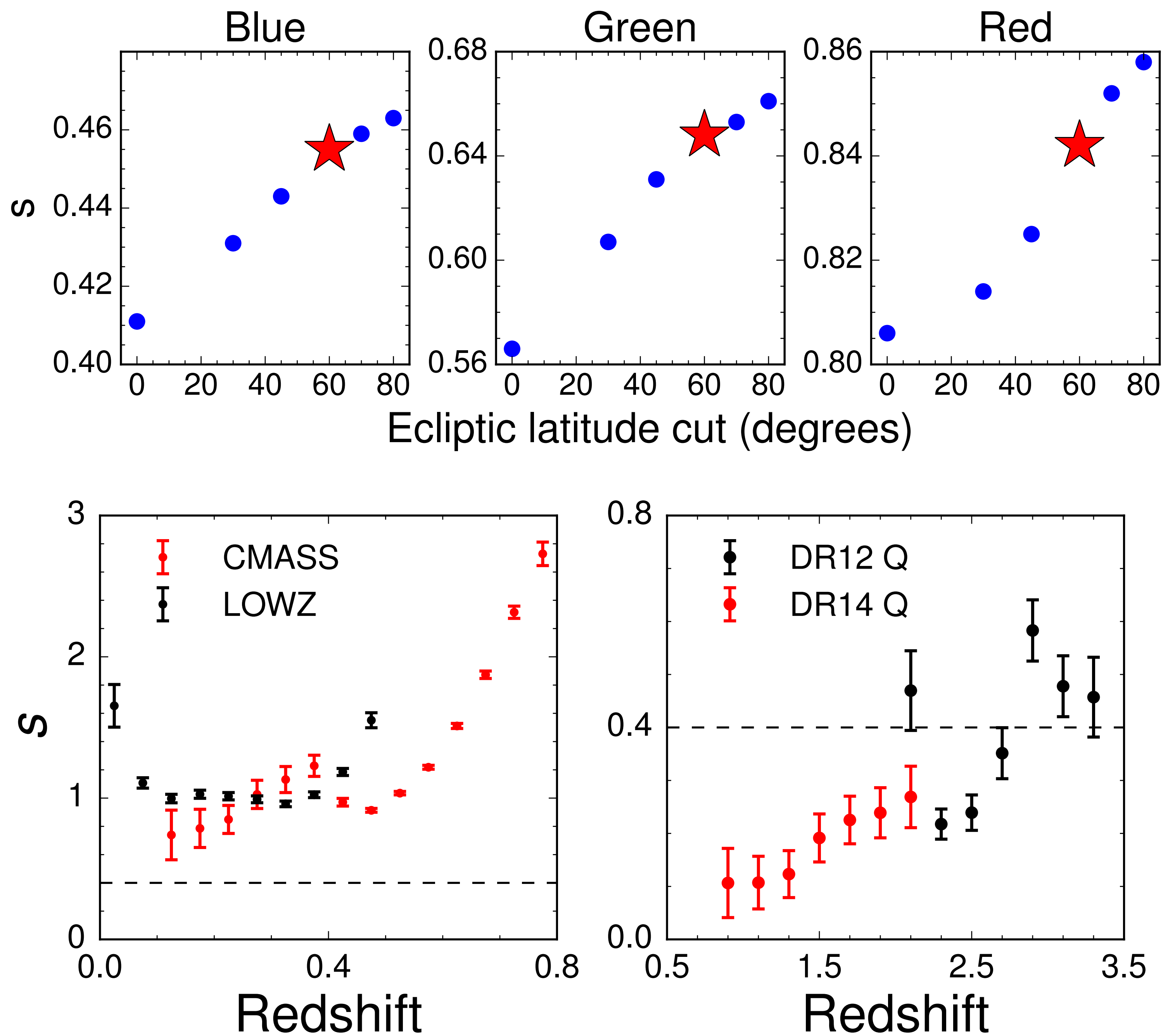
MEASURING s

- s is response of number density to lensing magnification

$$s \equiv \frac{\log_{10} N_1 - \log_{10} N_0}{\Delta m}$$

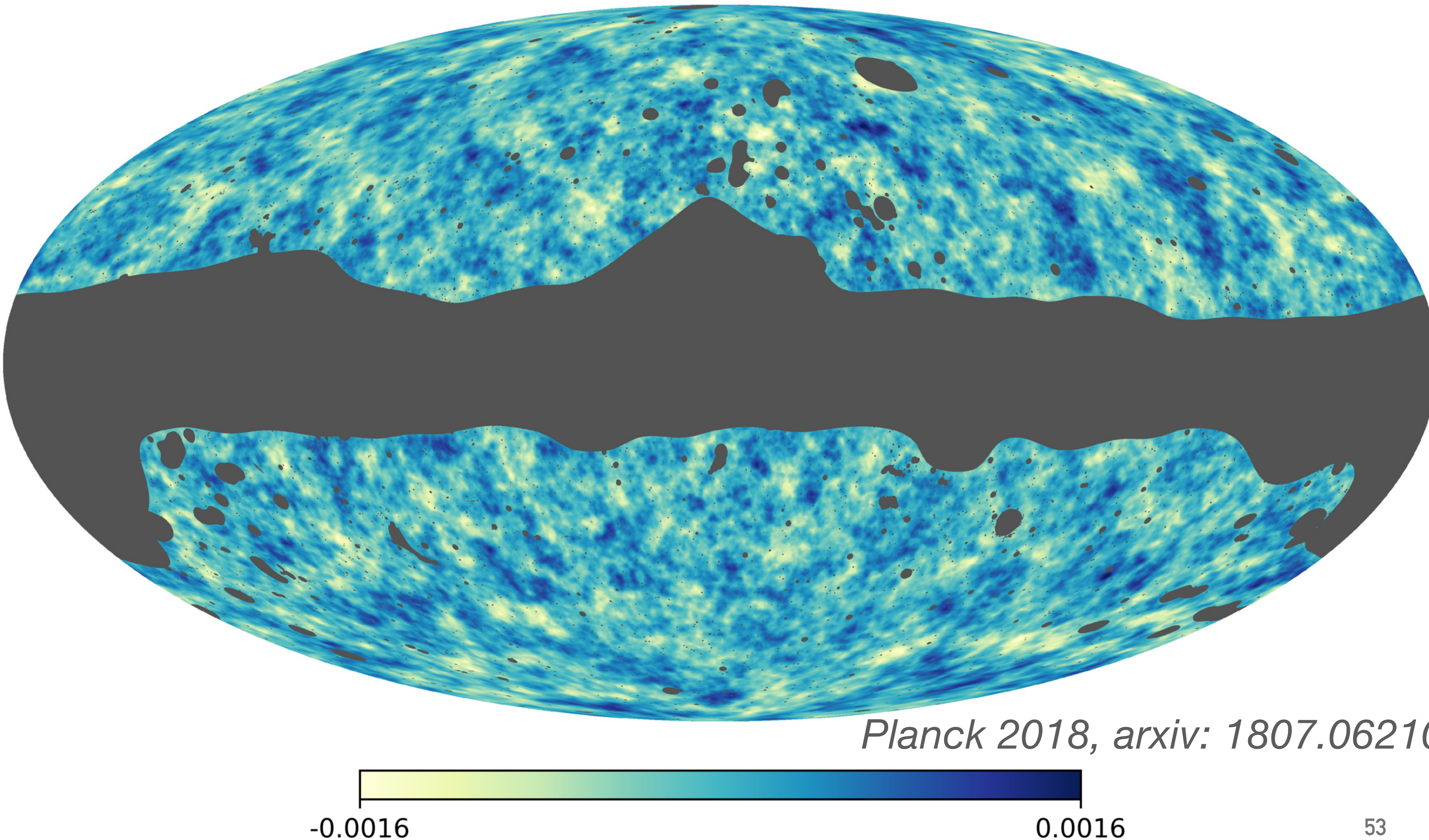


MEASURING MAGNIFICATION BIAS



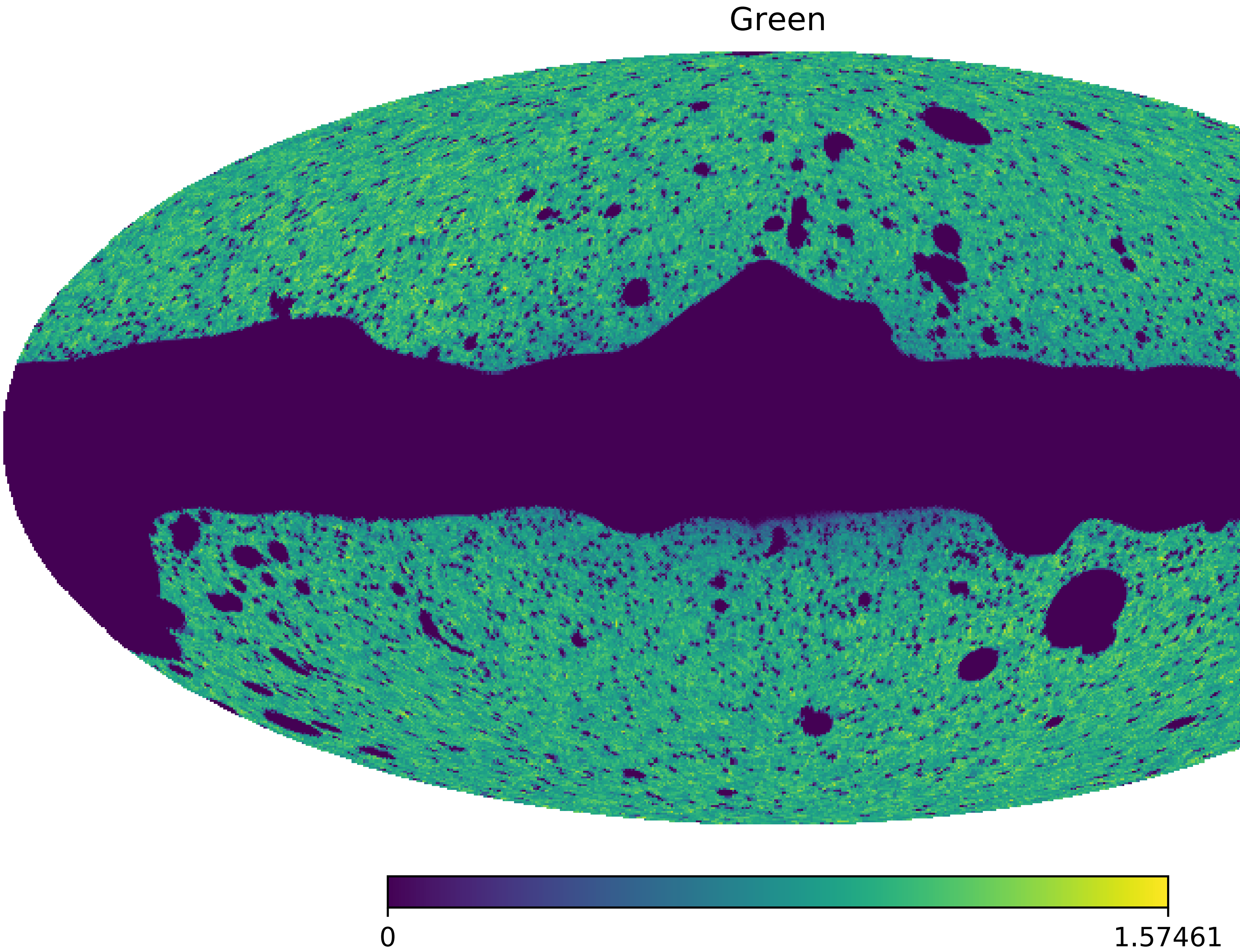
PLANCK LENSING MAP

- Auto-spectrum detected at 40σ

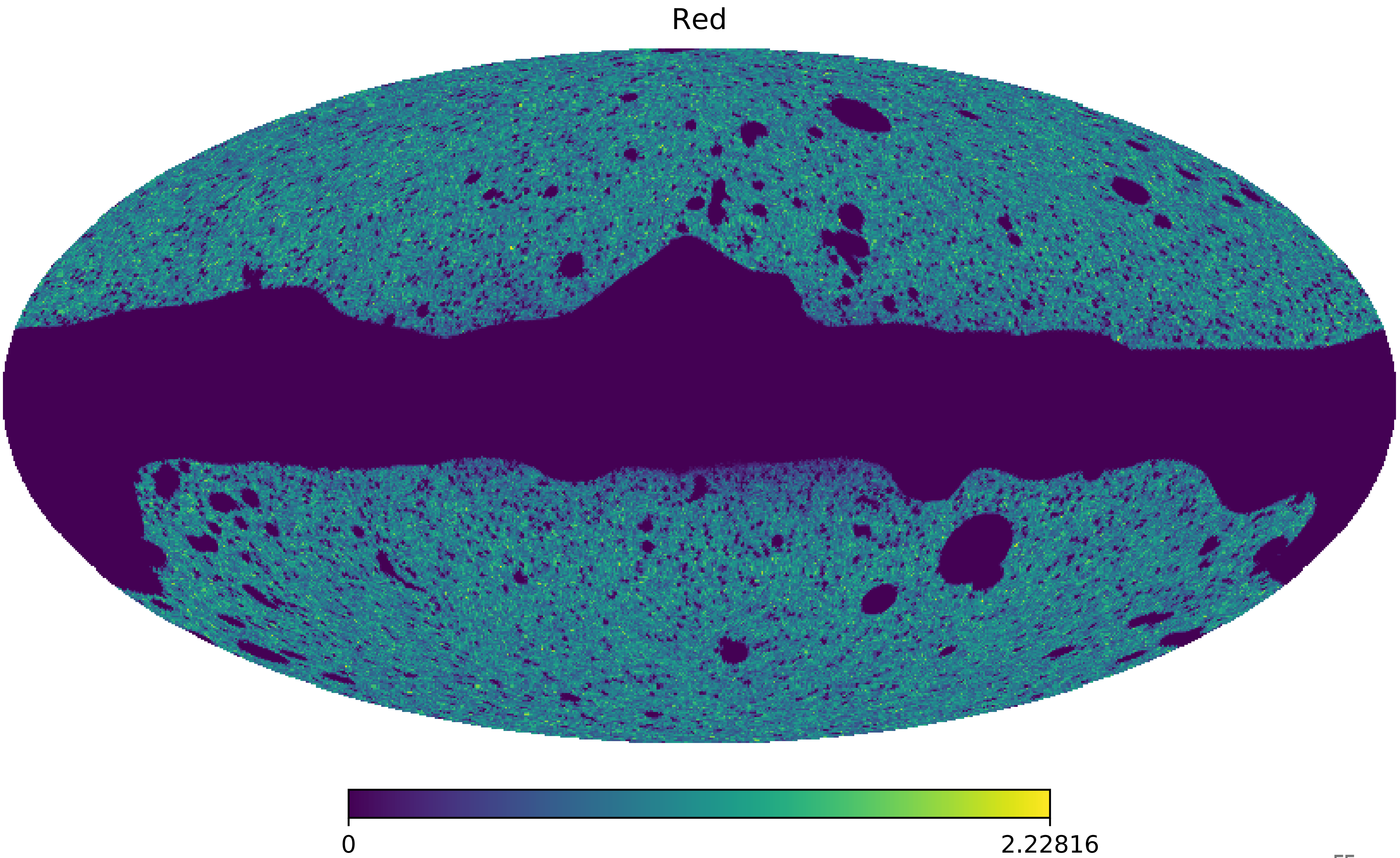


Planck 2018, arxiv: 1807.06210

SKY DISTRIBUTION

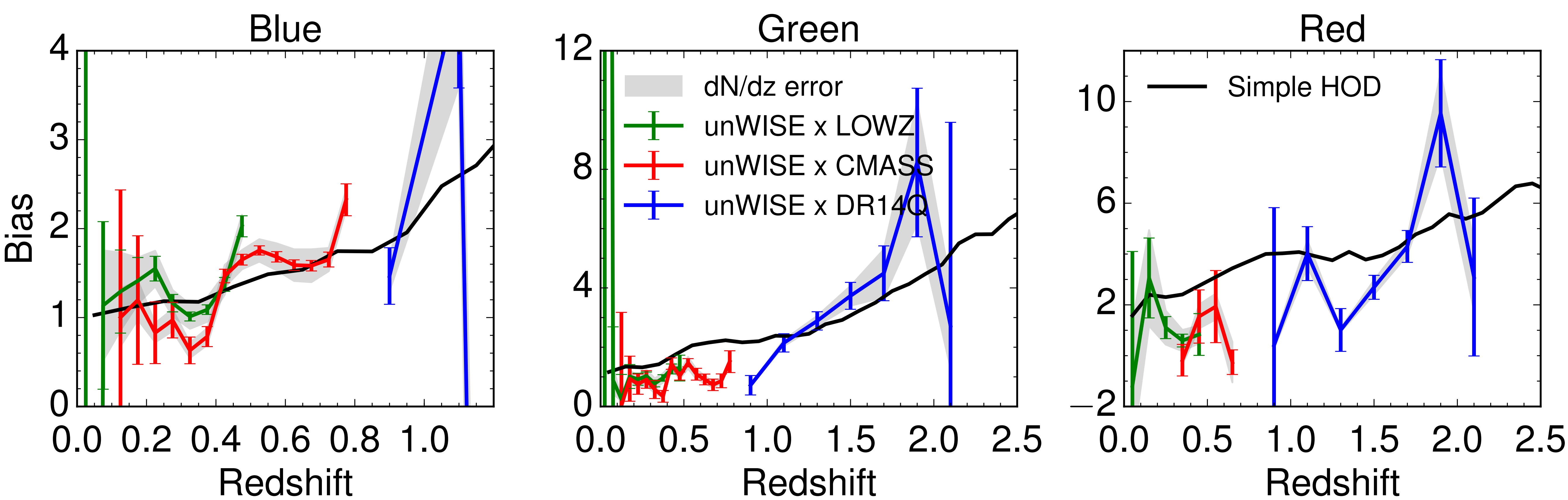


SKY DISTRIBUTION

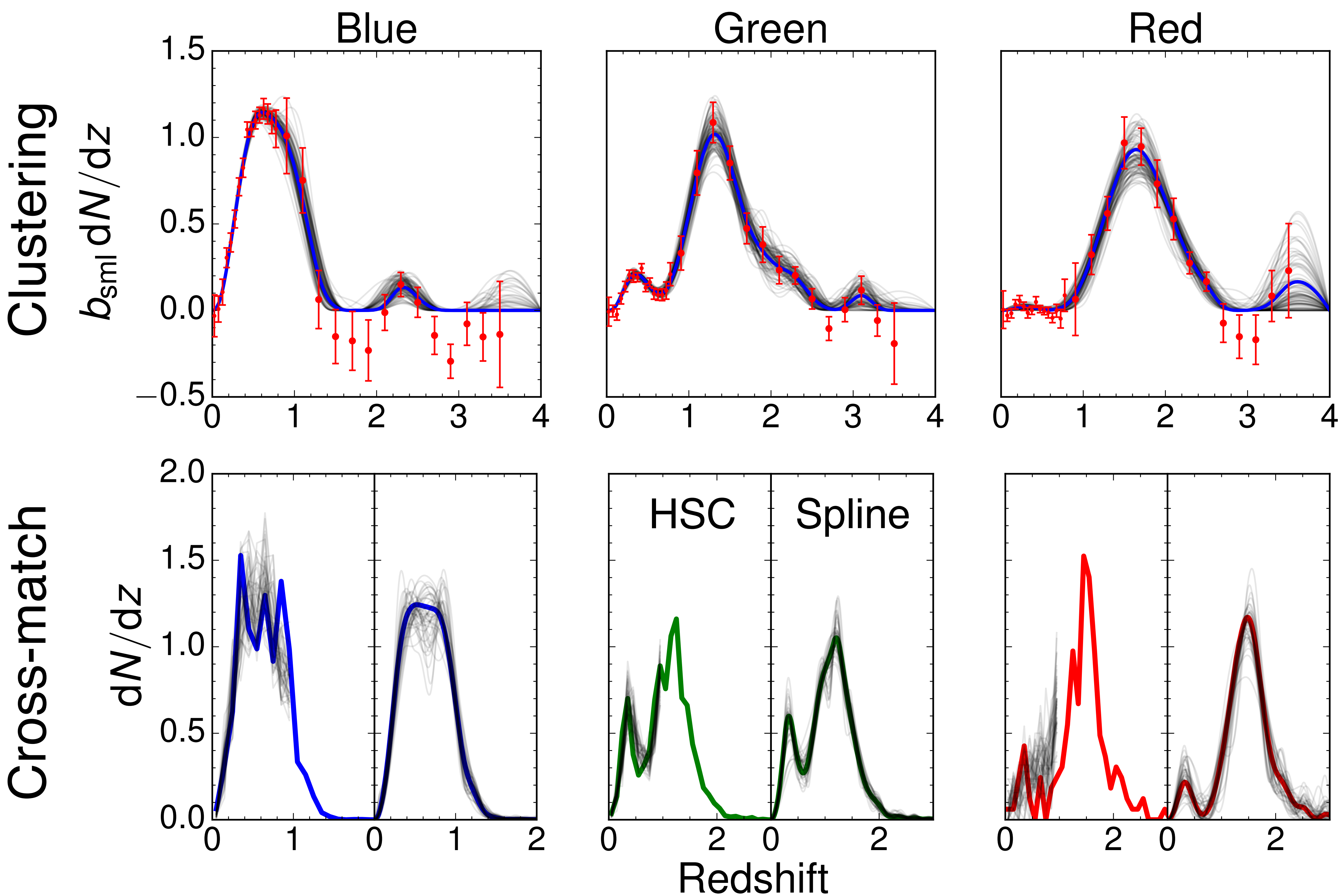


dN/dz CONSISTENCY

➤ Photo-spectro clustering is roughly consistent with COSMOS dN/dz and a simple HOD for unWISE galaxies



COMBINED dN/dz



IMPACT ON POWER SPECTRA

- CMB lensing cross-correlation

Sample	Bias	Error from dn/dz	χ^2/dof
Blue	1.56 ± 0.039	0.0329	6.04/5
Green	2.25 ± 0.052	0.0271	2.44/5
Red	3.49 ± 0.161	0.1371	1.66/5

- Auto-correlation

Sample	Bias	Error from dn/dz	χ^2/dof
Blue	1.71 ± 0.0072	0.0842	16.7/4
Green	2.46 ± 0.0121	0.0788	4.16/4
Red	3.29 ± 0.0787	0.267	9.82/4

CHANGING THE ECLIPTIC MASK