Cosmology from CMB lensing tomography to z=2 with galaxies from the unWISE catalog

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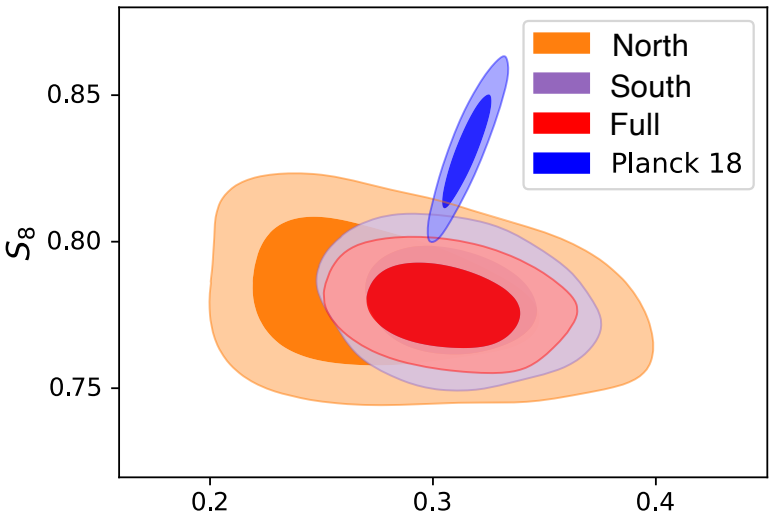
from arXiv:2105.03421 [JCAP 12 (2021) 028]
and arXiv:1909.07412 [JCAP 05 (2020) 047]

LENSING TENSION: CRACKS IN ΛCDM?

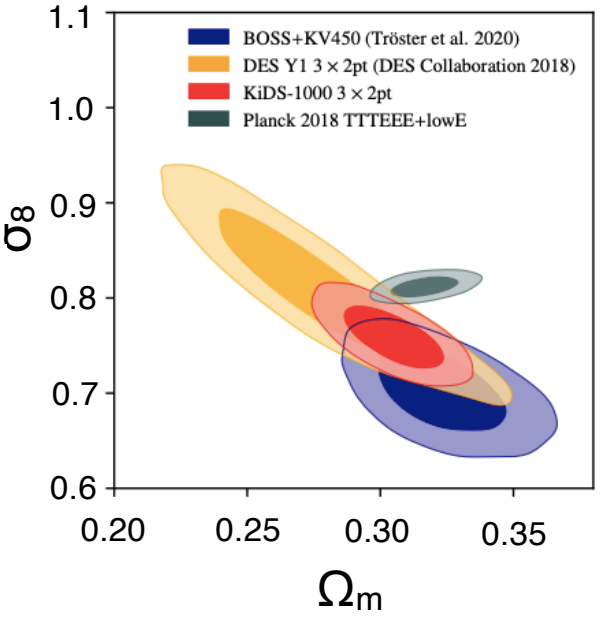
- Some weak lensing surveys (and also some galaxy clustering analyses) find $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$ ~ 10% lower than Planck
- ~2-3σ lensing tension: new physics or systematics?

DES-Y1 + KiDS-1000 public reanalysis



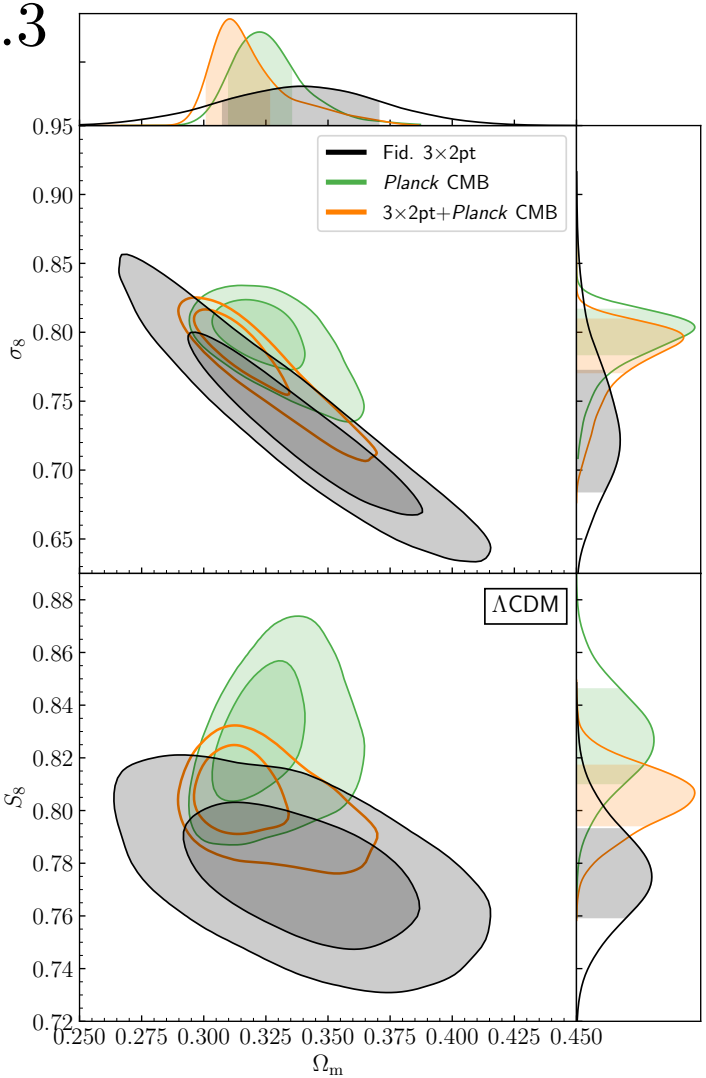
Garcia-Garcia et al. 2021

KiDS-1000



Heymans et al. 2021

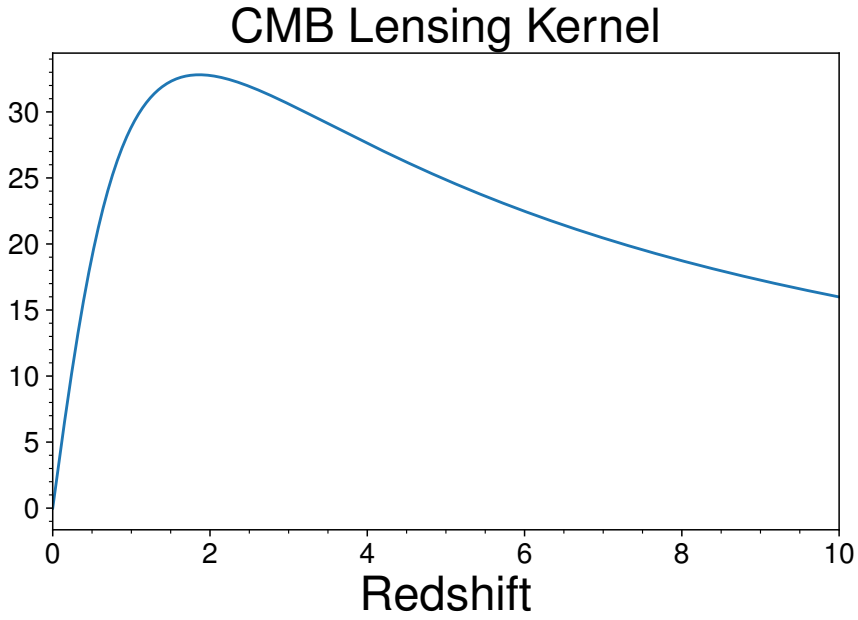
DES-Y3

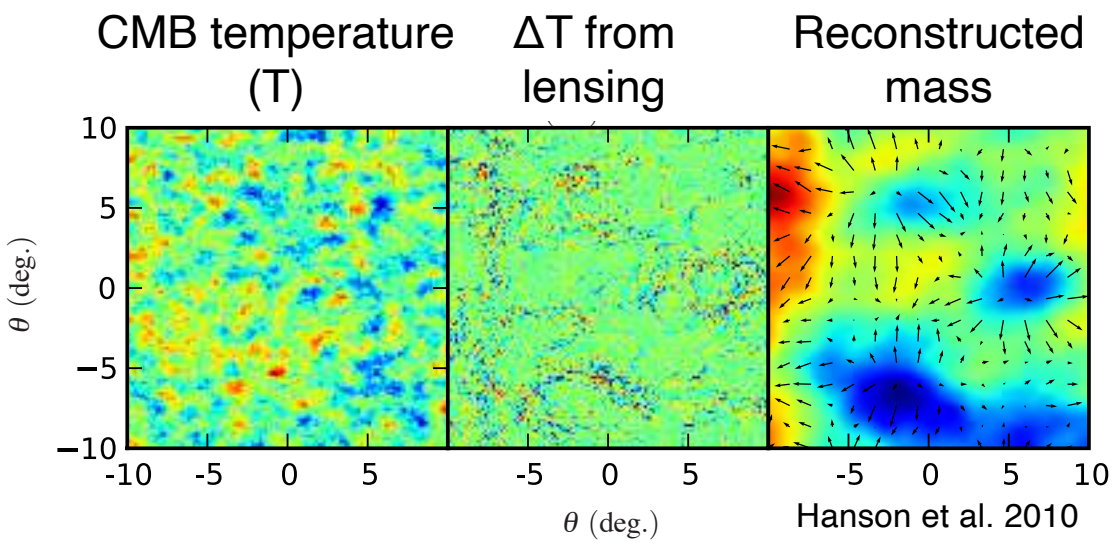


DES Collaboration, 2021

WEAK LENSING OF THE CMB

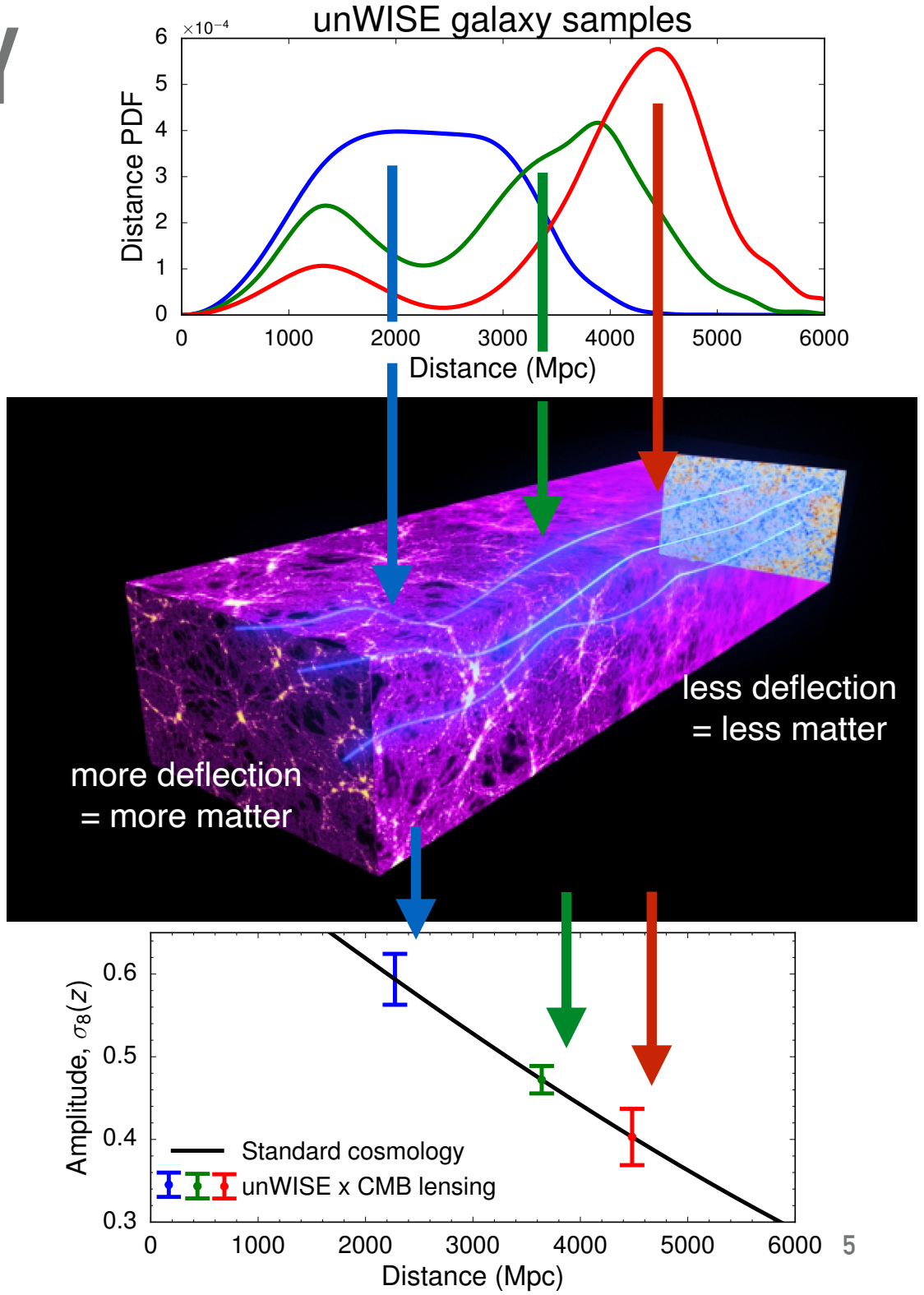
- Test lensing tension with a similar measurement with different systematics
- Lensing of the CMB: lens is (almost) all the matter in the universe!
- Imprint of lensing is tiny, but very distinctive (non-Gaussian) compared to the Gaussian fluctuations from primary CMB





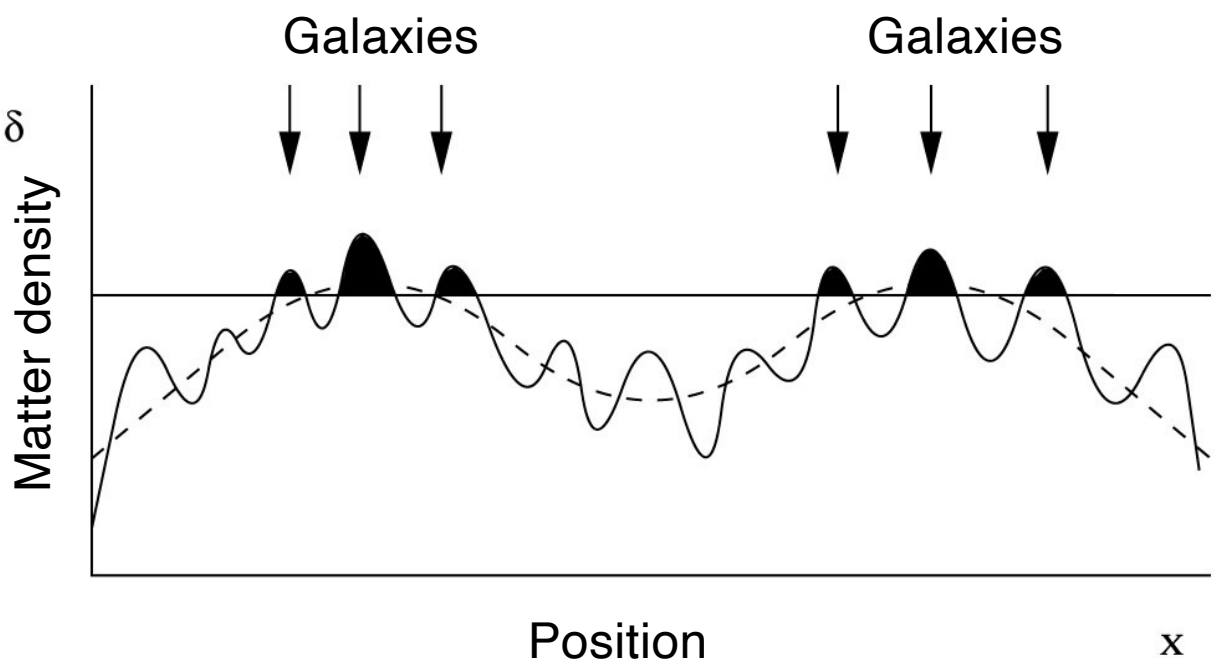
CMB LENSING GALAXY CROSS-CORRELATION

- 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



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

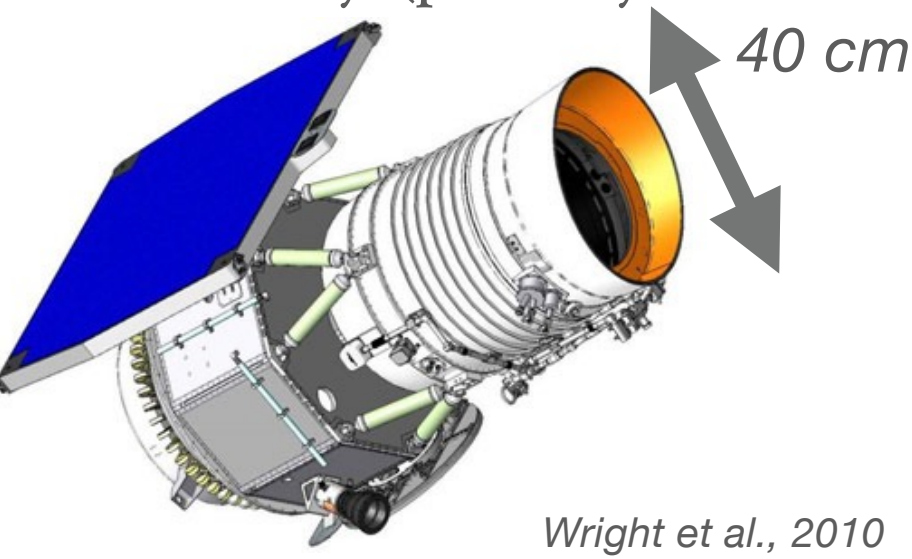
$$C_\ell^{\kappa g} \propto b(k,z) \sigma_8^2 P_m$$

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

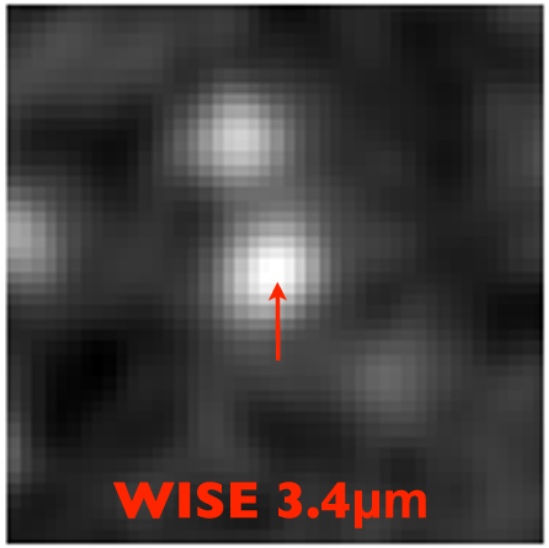
$$\rightarrow \mathrm{S/N}(\sigma_8) = \mathrm{S/N}(C_\ell^{\kappa g})$$

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)

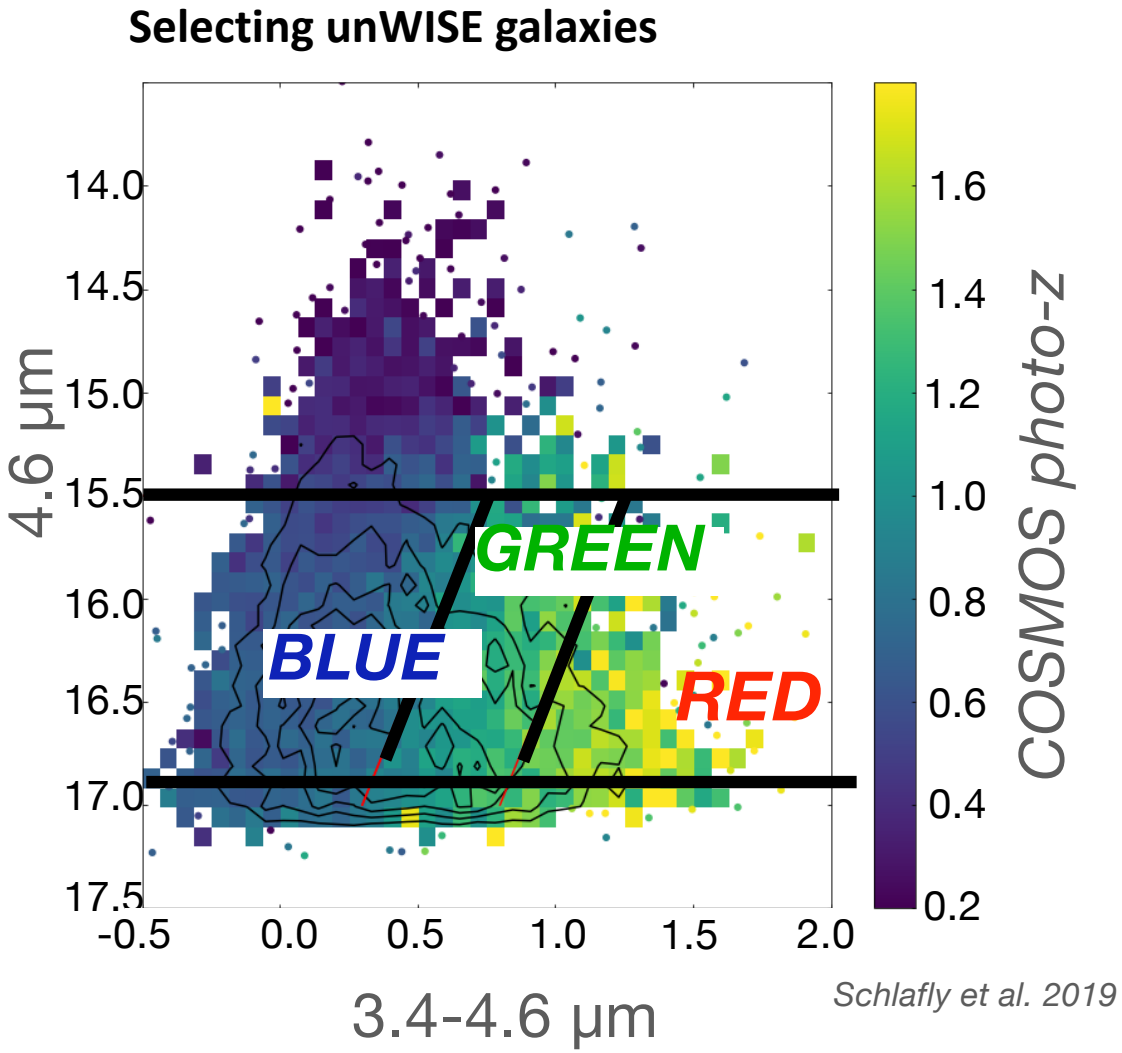


Wright et al., 2010



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

unWISE GALAXY SAMPLES



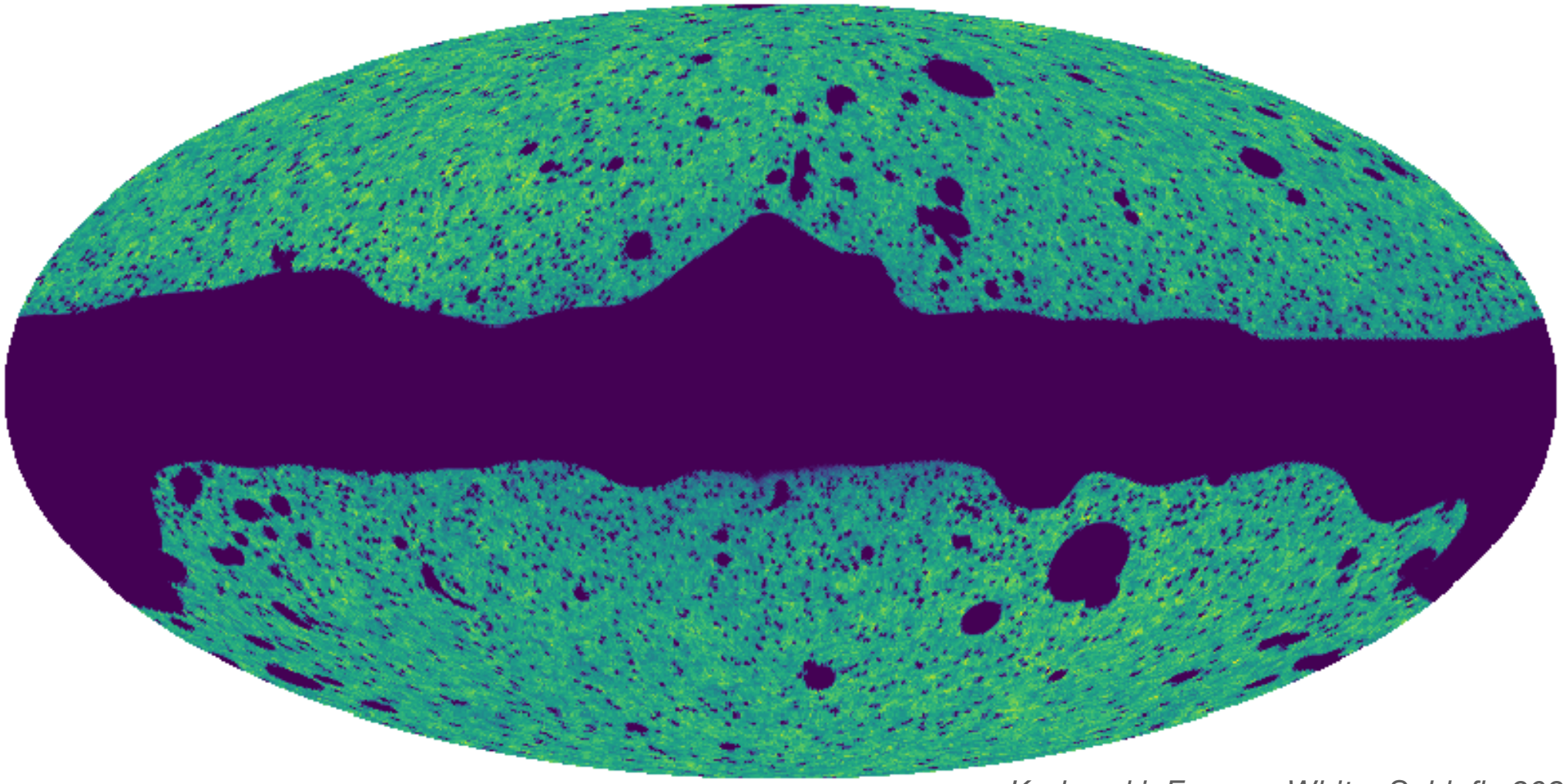
Schlafly et al. 2019

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

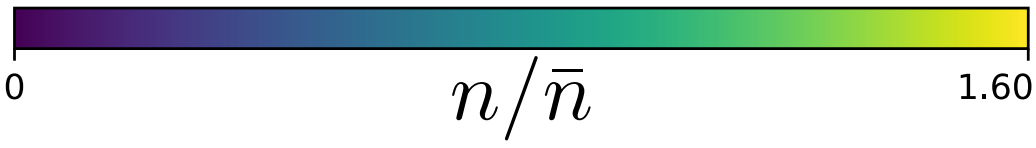
Sample	Mean z	Number density (deg^{-2})
Blue	0.6	3409
Green	1.1	1868
Red	1.5	144

unWISE SKY DISTRIBUTION

Blue: z~0.5 sample

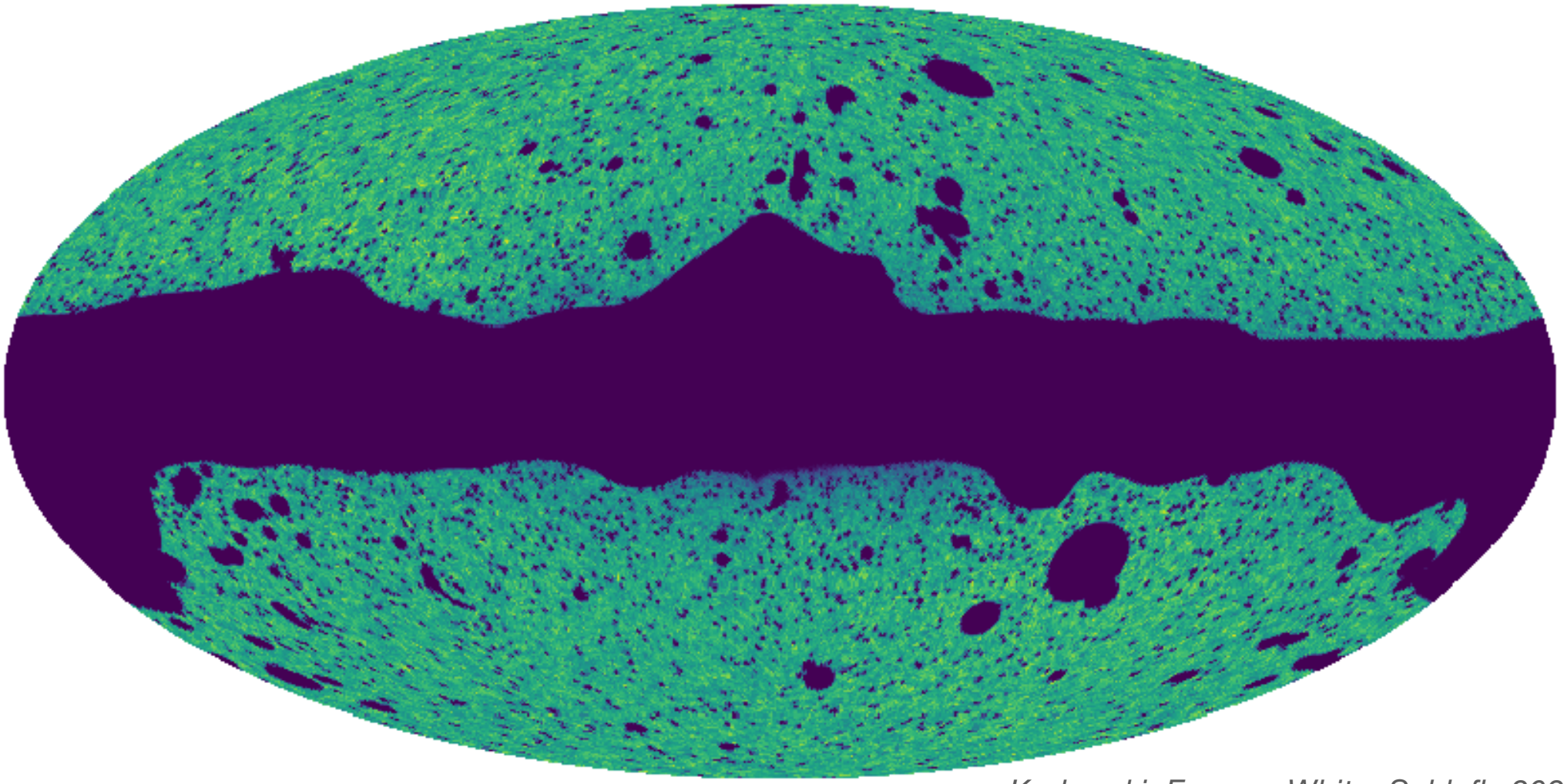


Krolewski, Ferraro, White, Schlafly 2020

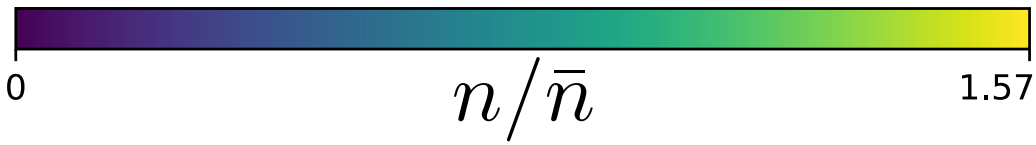


unWISE SKY DISTRIBUTION

Green: z~1.0 sample

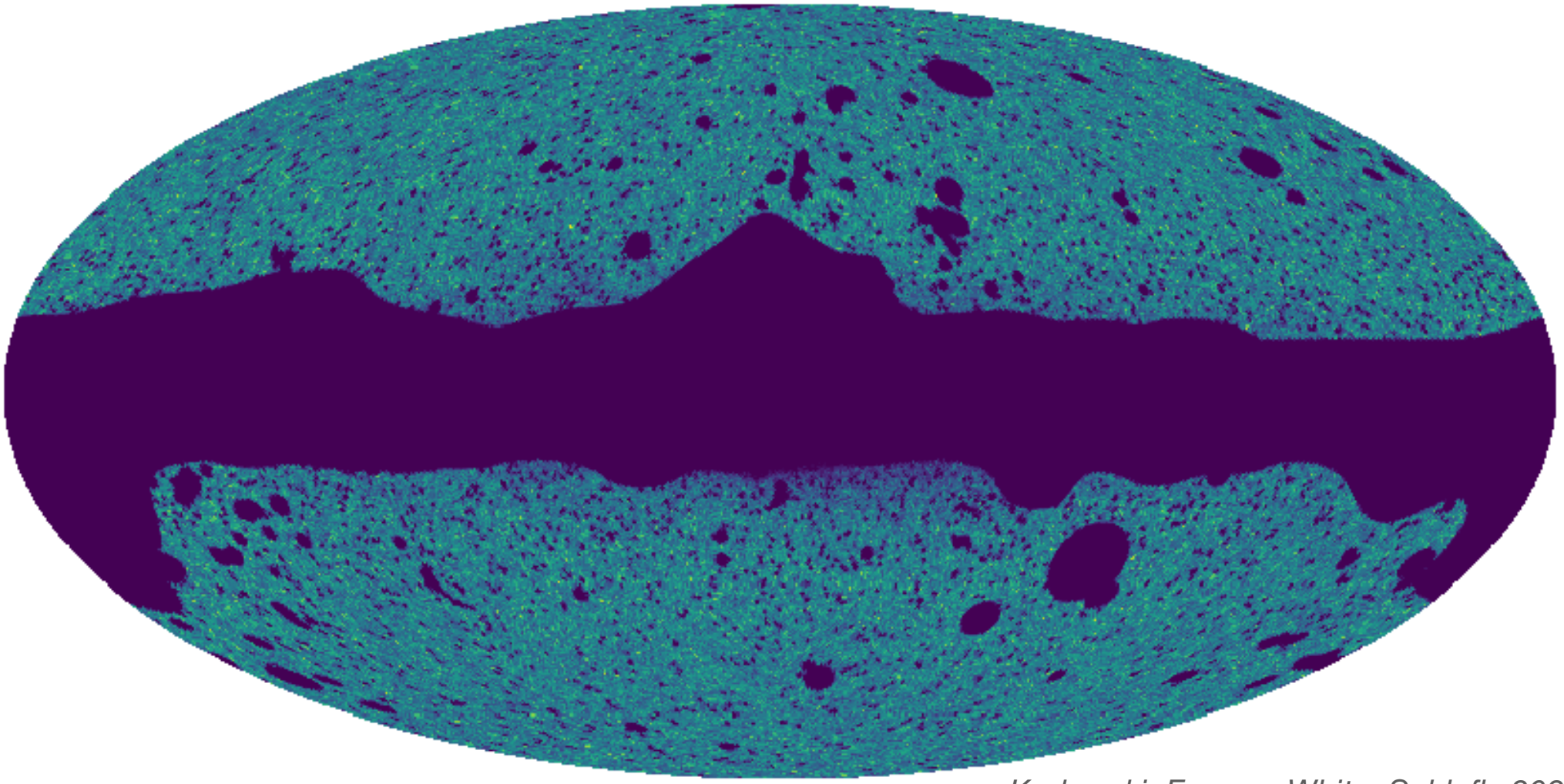


Krolewski, Ferraro, White, Schlafly 2020

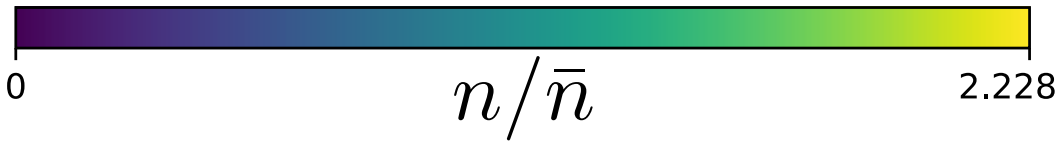


unWISE SKY DISTRIBUTION

Red: z~1.5 sample

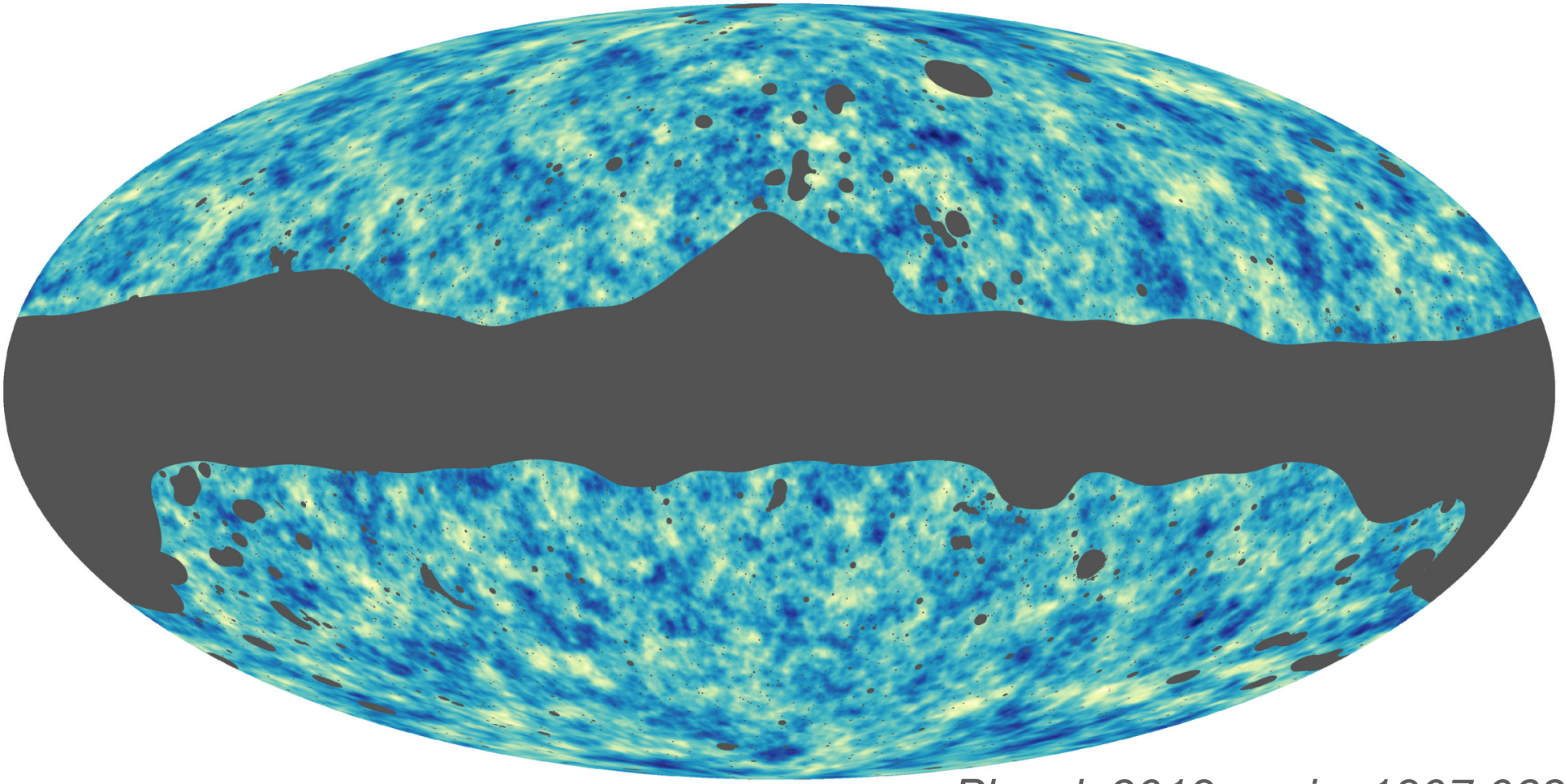


Krolewski, Ferraro, White, Schlafly 2020



CMB LENSING FROM PLANCK

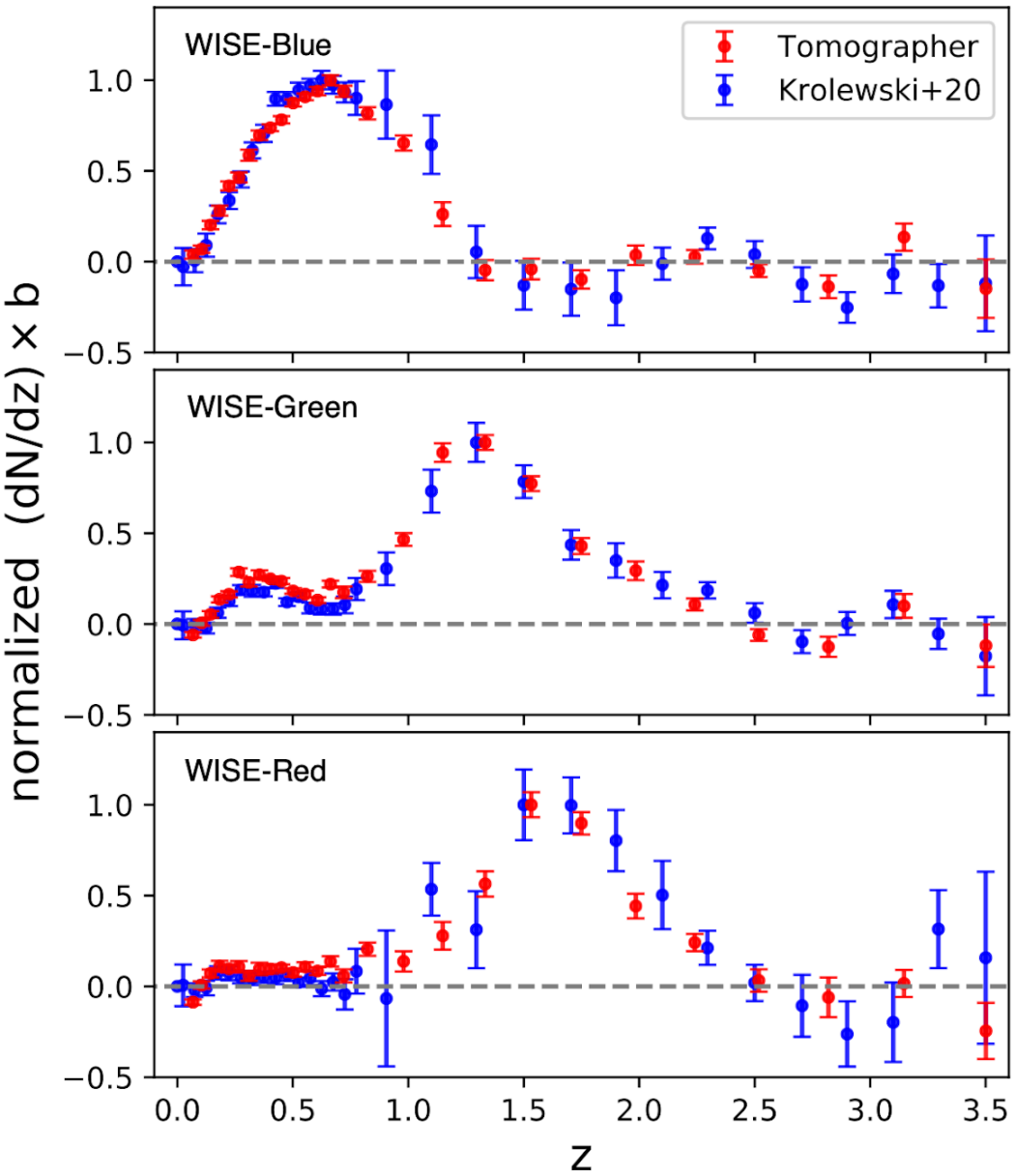
- Planck 2018 minimum-variance lensing maps + masks



Planck 2018, arxiv: 1807.06210

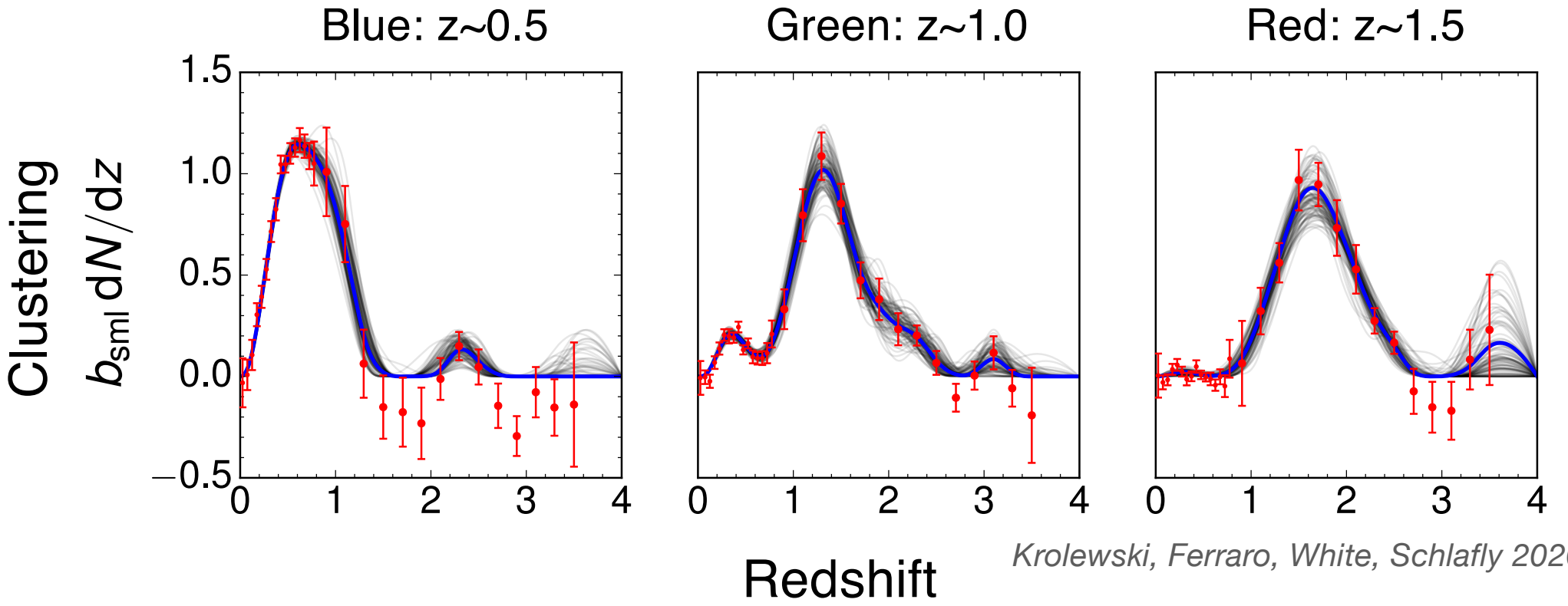
REDSHIFT DISTRIBUTION: CLUSTERING REDSHIFTS

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

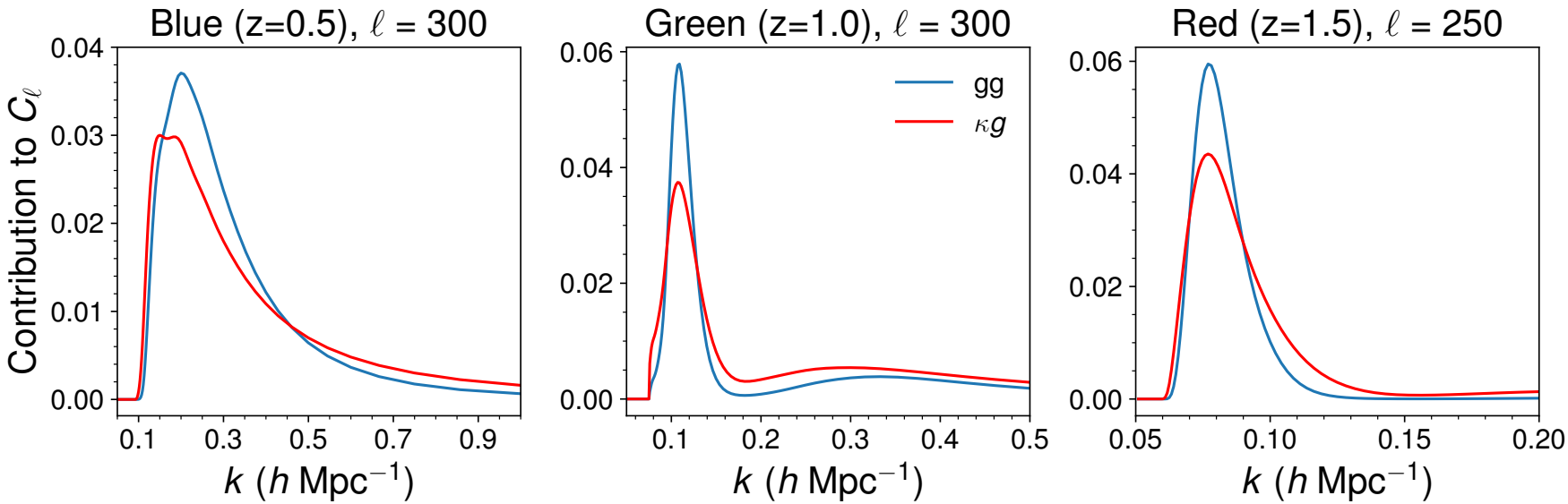
- Clustering measurement is noisy: we correctly propagate the error into our cosmological constraints
- High-z bumps likely noise (not seen in cross-matched COSMOS photo-z's)

MODELLING

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

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

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

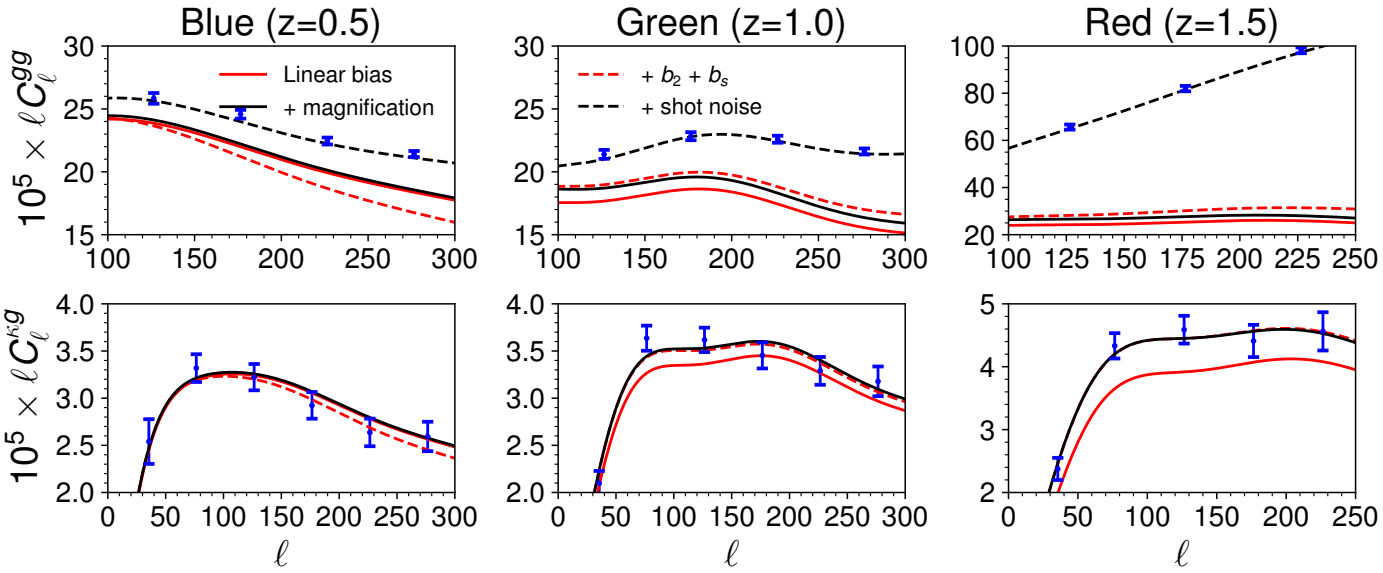
MODELLING

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

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

$$P_{gm} = b_1 P_{mm,\mathrm{Halofit}} + \text{higher bias}$$

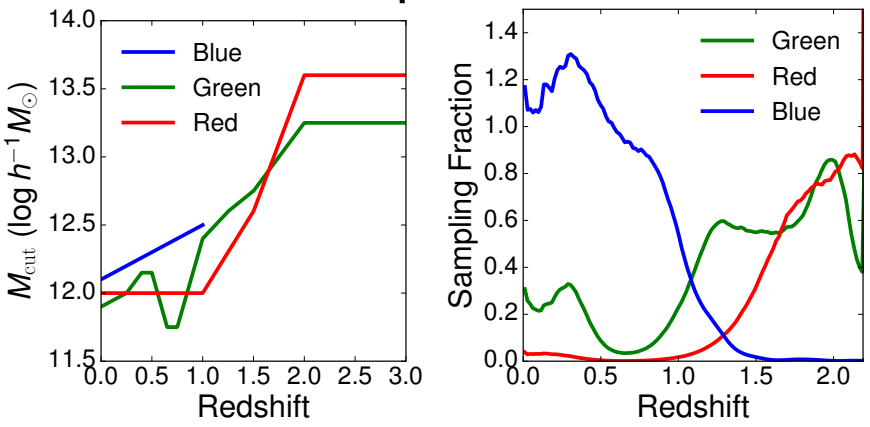
- Magnification bias also included, with 10% prior on the slope (s)
- 5 parameter model: Ω_m, log$A$, b_1, s, shot noise
  - Fix n_s and Ω_b to Planck values; fix $\Omega_\mathrm{m}h^3$ to Planck value (from angular size of sound horizon)
  - dN/dz is uncertain: average over chains from many dN/dz samples



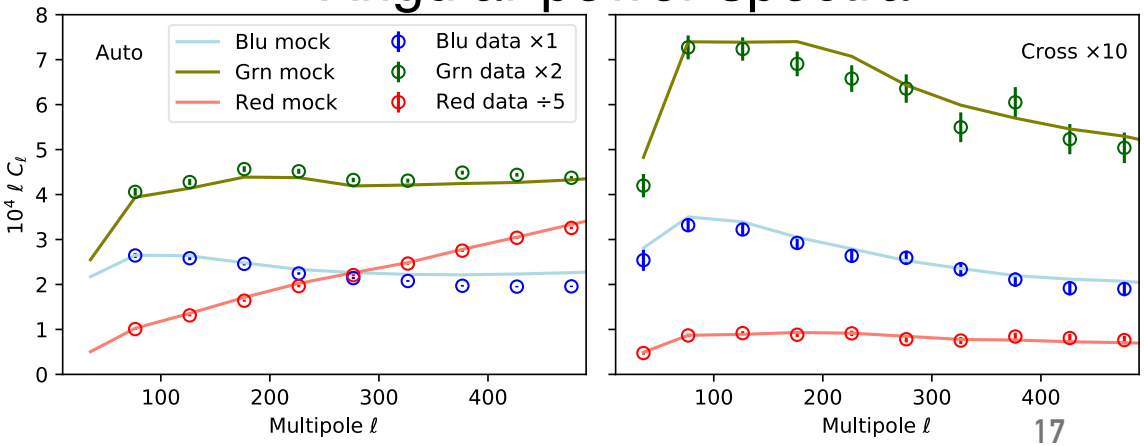
MOCK TESTS: SETUP

- 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

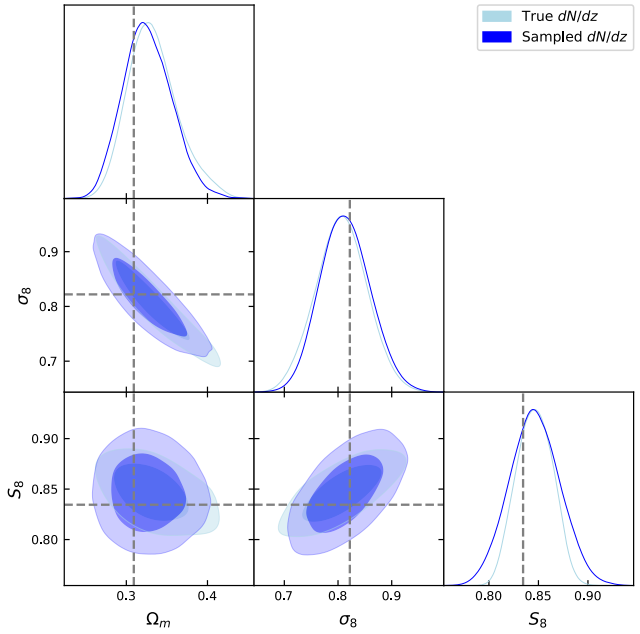


MOCK TESTS: VALIDATION

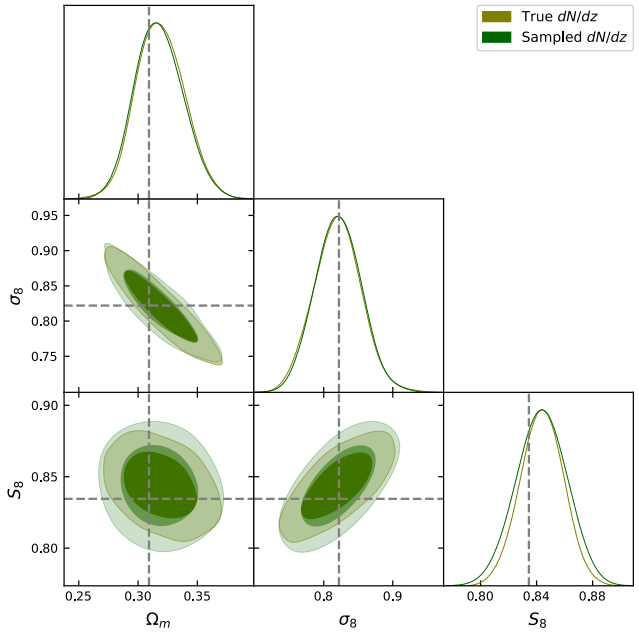
- We recover unbiased (<0.5σ) constraints from blue and green, validating model and scale cuts
  - Red has little statistical power and negligible impact on results

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

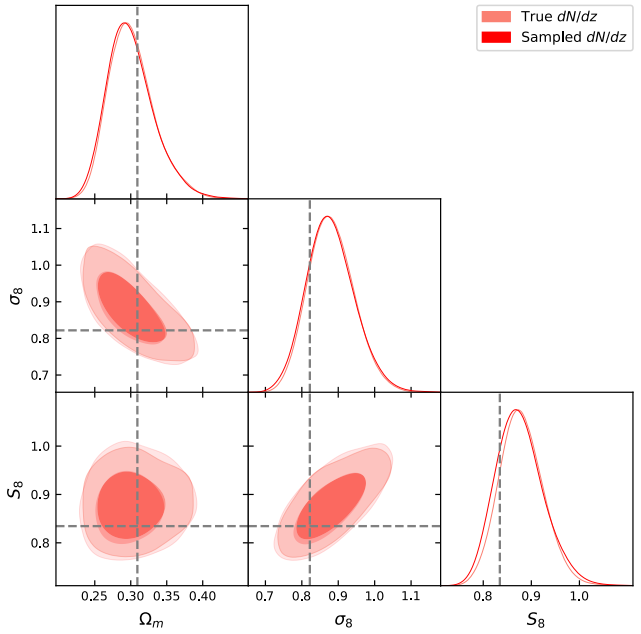
Blue (z~0.5)



Green (z~1)



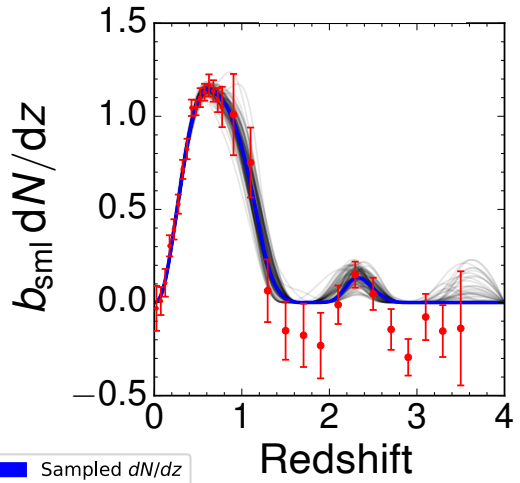
Red (z~1.5)



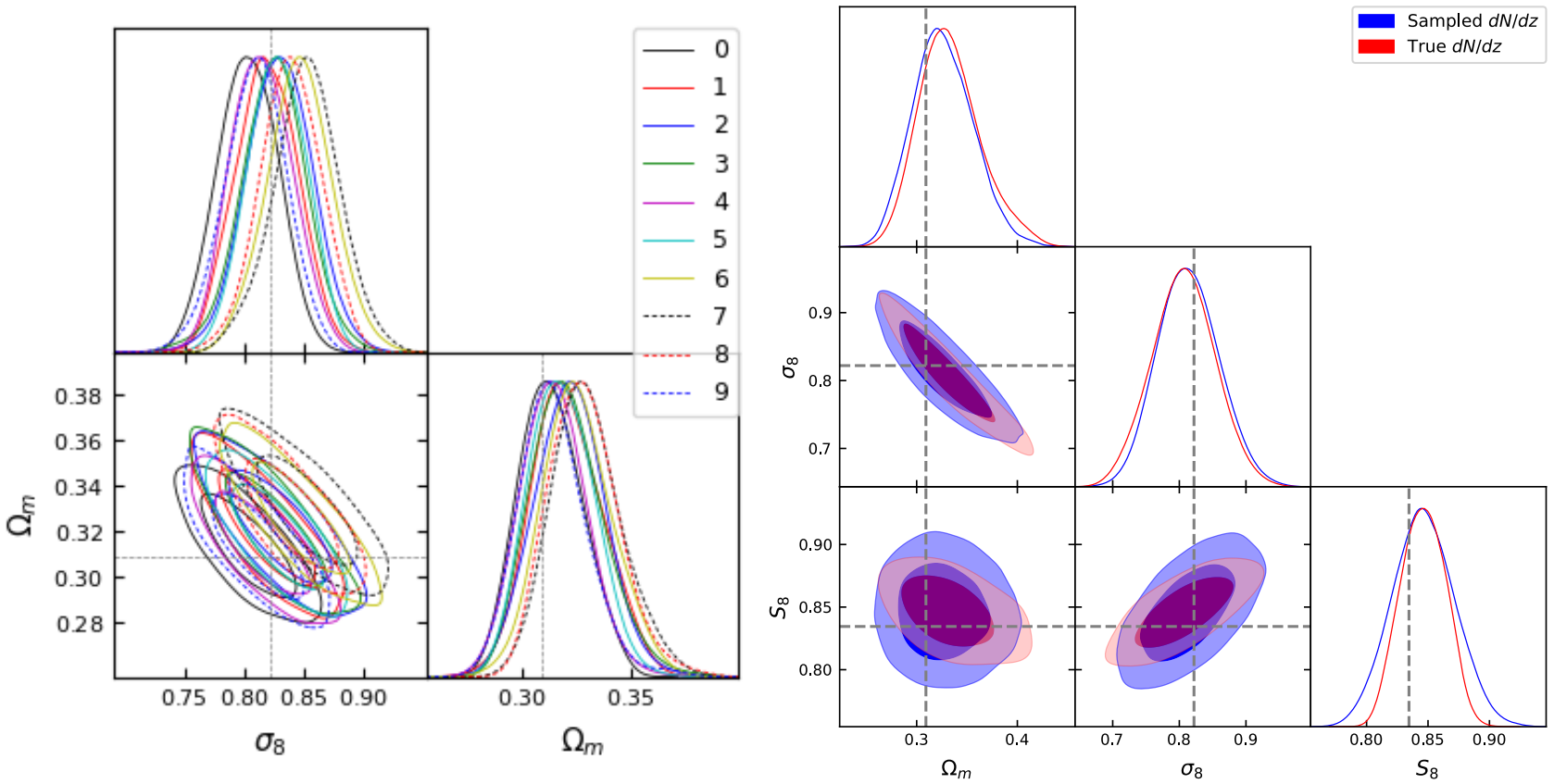
MOCK TESTS: MARGINALIZING dN/dz

- 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)

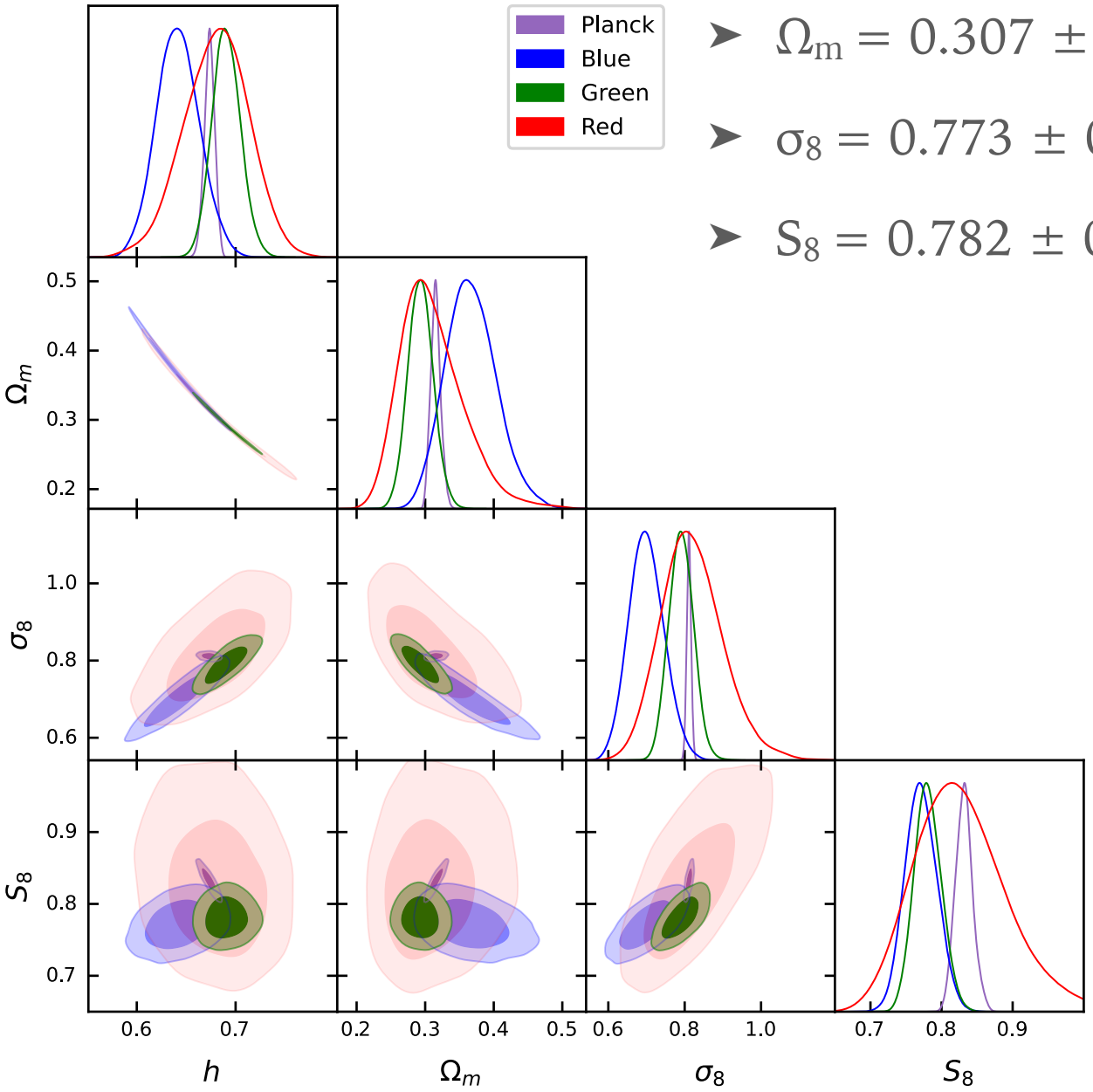
Blue, redshift distribution



Blue, CrowCanyon2 mocks



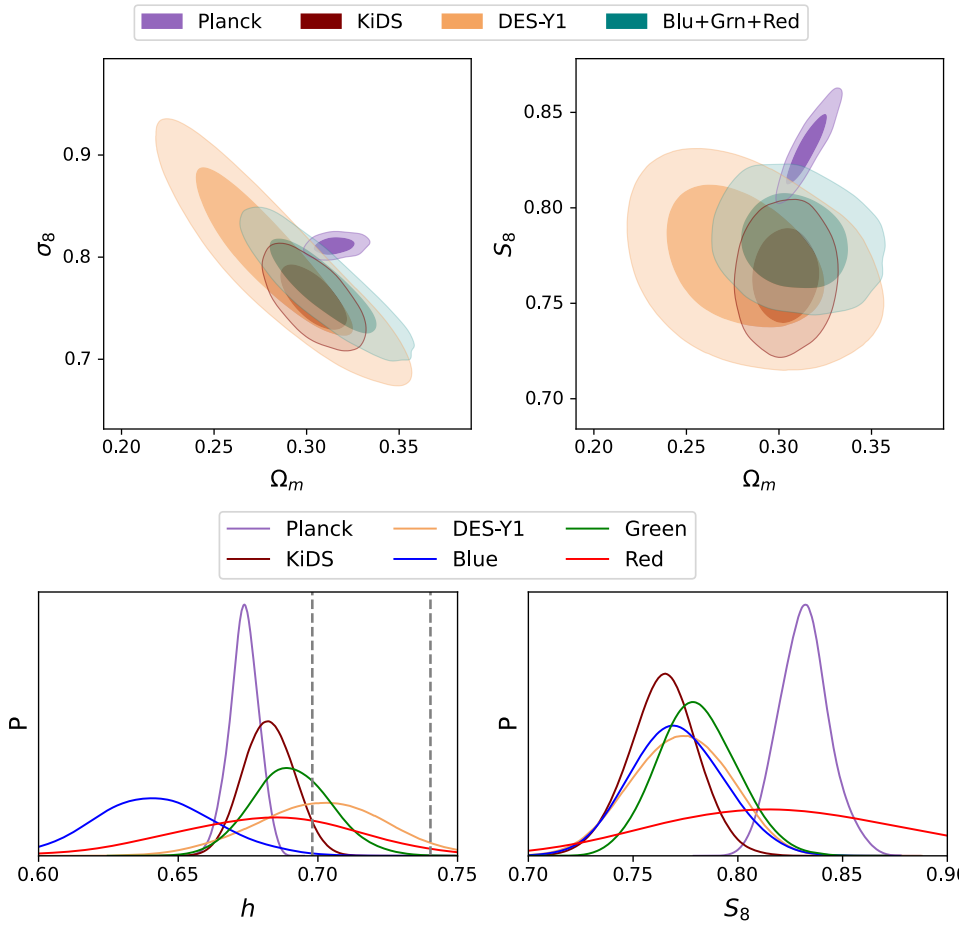
COSMOLOGY CONSTRAINTS



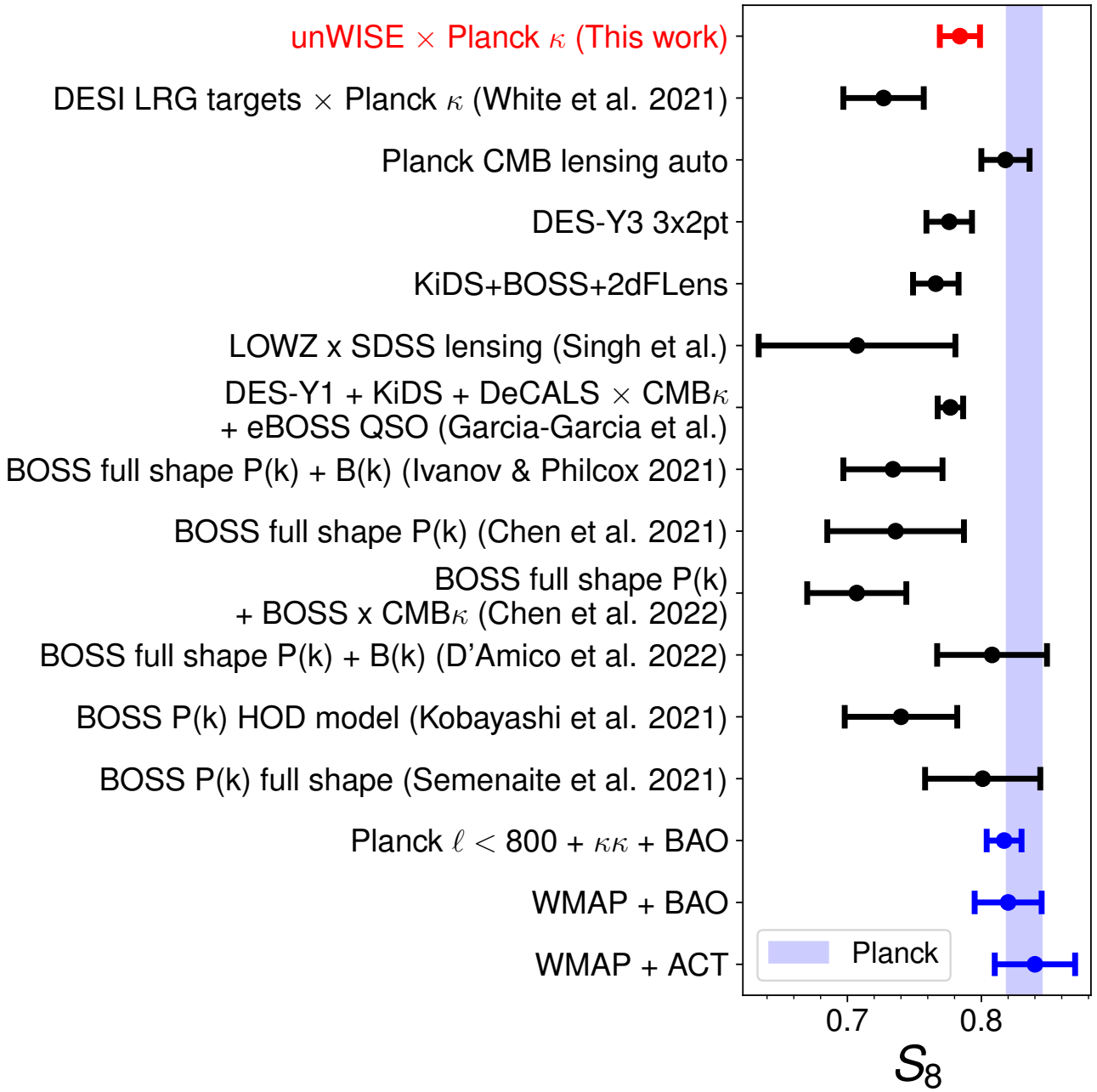
- $\Omega_m = 0.307 \pm 0.018$ (P18: 0.315 ± 0.017)
- $\sigma_8 = 0.773 \pm 0.029$ (P18: 0.811 ± 0.006)
- $S_8 = 0.782 \pm 0.015$ (P18: 0.832 ± 0.013)

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

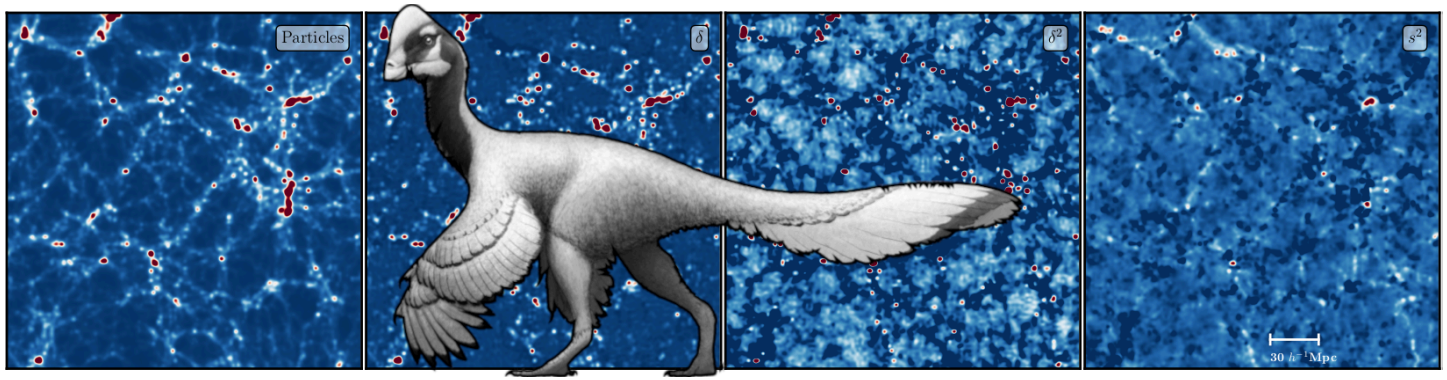


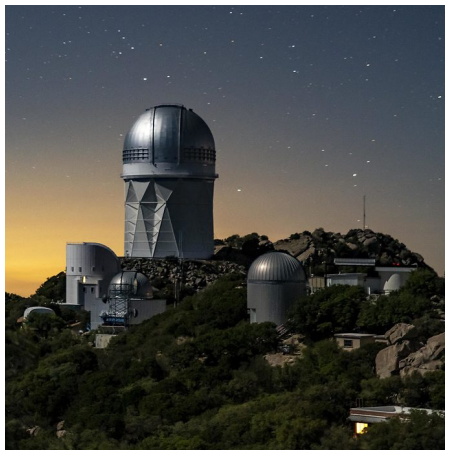
STATUS OF THE S8 TENSION



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: will reduce uncertainty due to uncertain dN/dz





https://github.com/kokron/anzu

DESI, Mayall Telescope