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

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arxiv: 1909.07412

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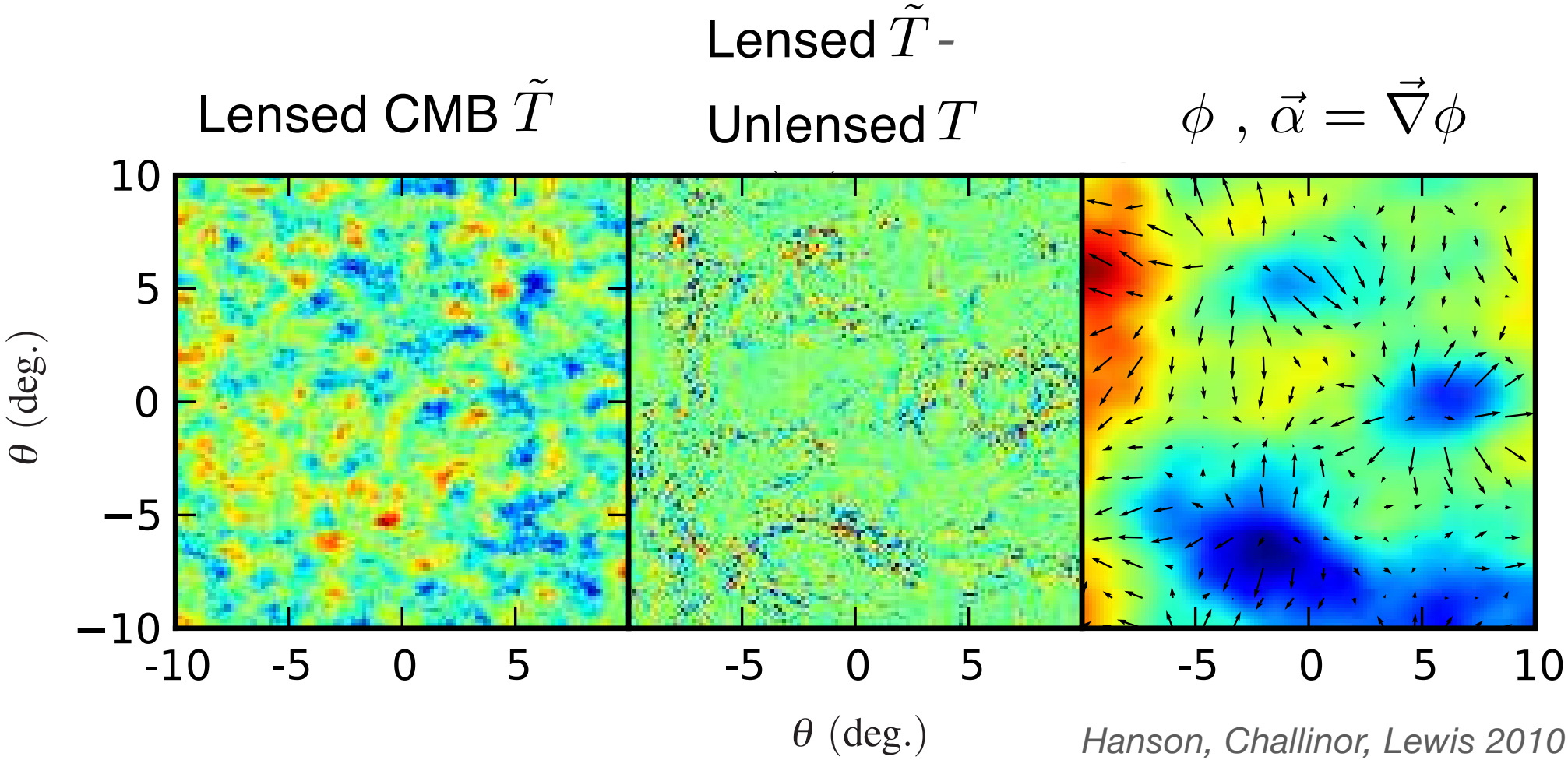
OVERVIEW

- Intro: cosmology from CMB lensing cross-correlations
- unWISE as ideal sample for a high-S/N measurement
  - highest CMB lensing cross-correlation S/N to date (S/N~80)
- Examples of systematics:
  - Measuring the unWISE redshift distribution
  - Leakage from low ℓ & mask deconvolution
- Nonlinearities & towards cosmological parameter constraints (preliminary): what is our take on the S8 tension?

CMB LENSING



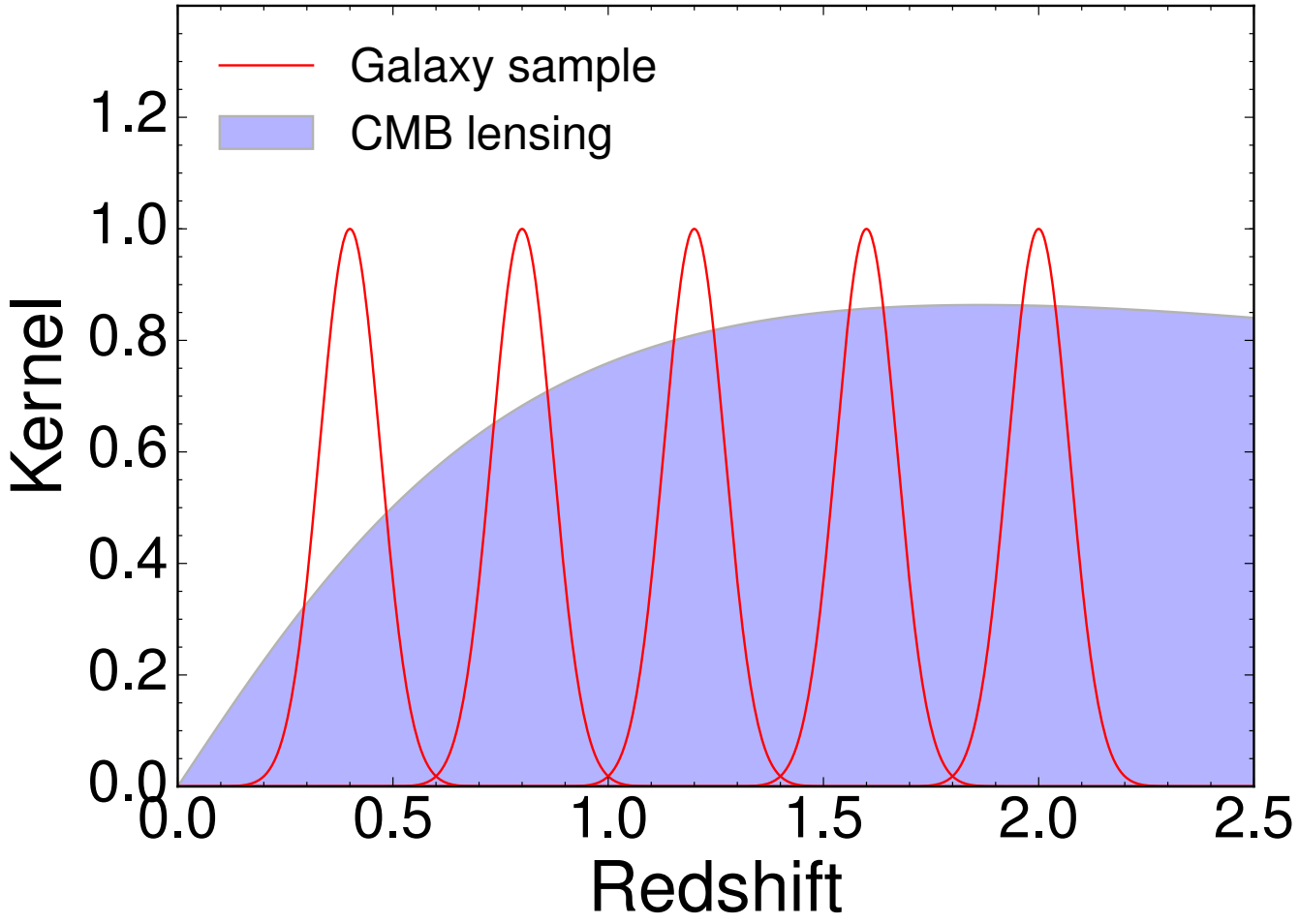
Hanson, Challinor, Lewis 2010
Hu & Okamoto 2002

- Alternative to galaxy lensing (no source z uncertainty, no shape measurement)

CMB LENSING TOMOGRAPHY

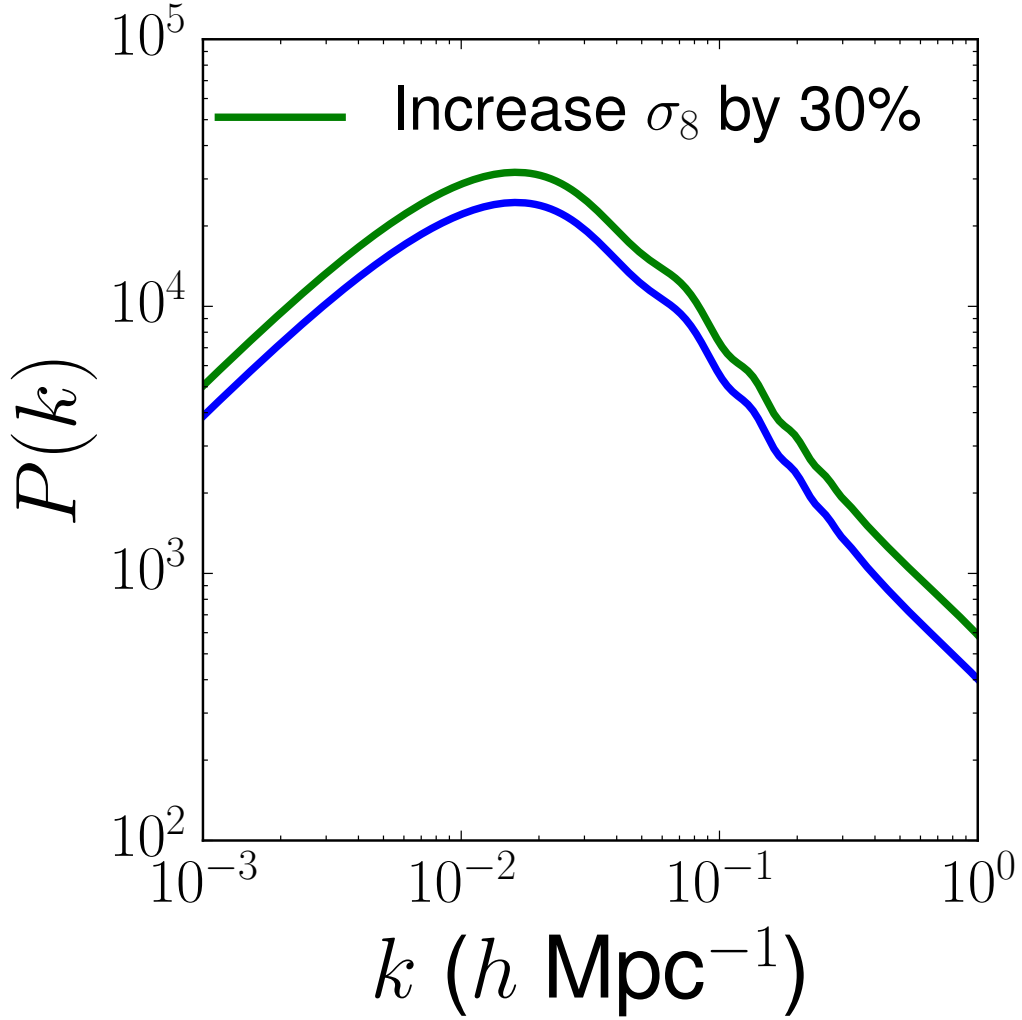
- CMB lensing cross-correlation + galaxy autocorrelation breaks b-σ_8 degeneracy

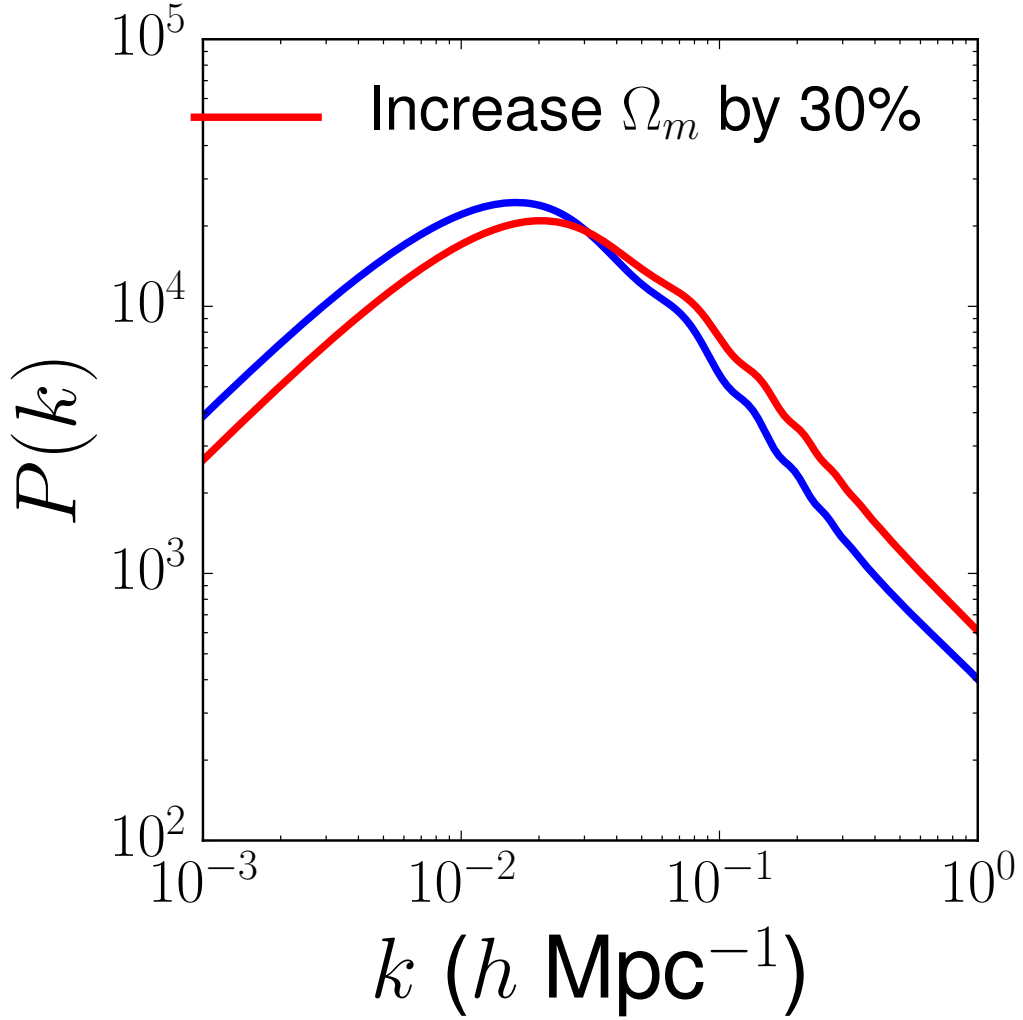
$$P_{gg} \propto b(k,z)^2 \sigma_8^2 P_m$$
$$P_{\kappa g} \propto b(k,z) \sigma_8^2 P_m$$



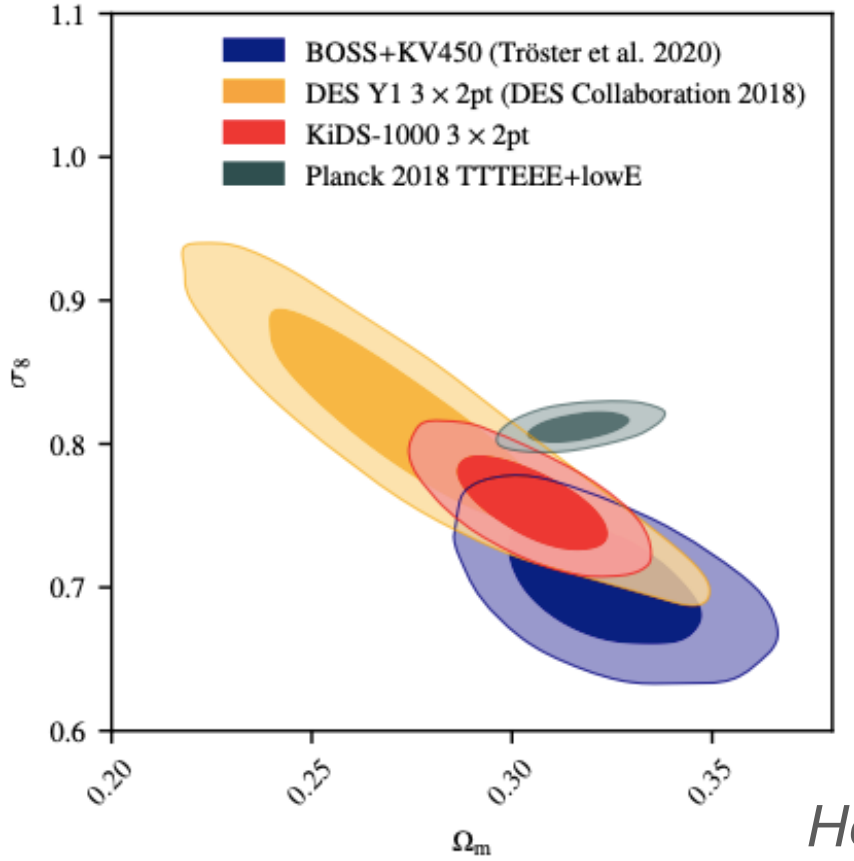
CONSTRAINING ΛCDM FROM CMB LENSING TOMOGRAPHY

- Lensing tomography probes power spectrum at different redshifts: primarily sensitive to σ_8 and Ω_m $S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$





S8 TENSION IN WEAK LENSING



$$P_{\kappa g} \propto b(z) S_8^2$$

$$P_{gg} \propto b(z)^2 S_8^2$$

$$S_8 \propto \frac{P_{\kappa g}}{\sqrt{P_{gg}}}$$

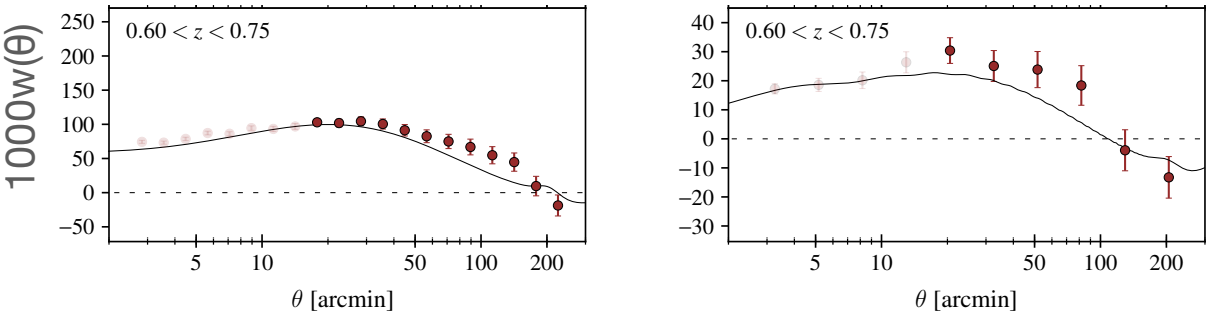
Heymans et al. 2020

- Can we use CMB lensing-LSS cross-correlations to address the S8 tension from KiDS and other weak lensing probes?
- KiDS: $S8 = 0.766$ vs 0.834 from Planck: requires 70σ detection to validate or disprove tension at 5σ

PREVIOUS CMB-LSS CROSS CORRELATIONS

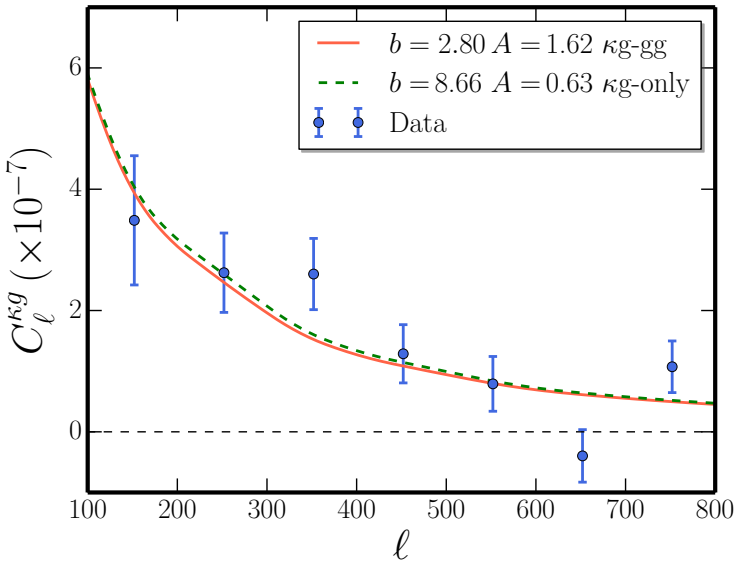
DES x SPT-Planck, 20σ

galaxy-galaxy *galaxy-CMB lens*



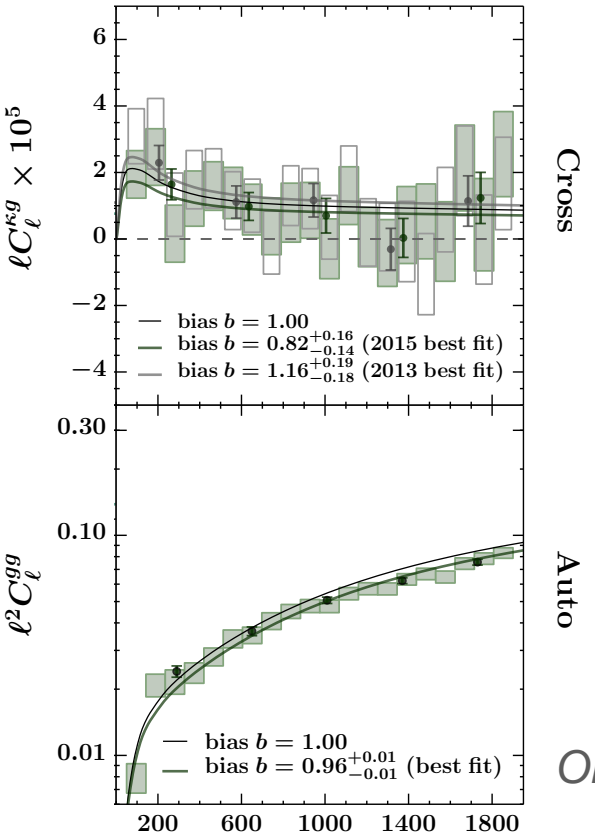
Omori et al. 2019

Herschel x Planck, 10σ



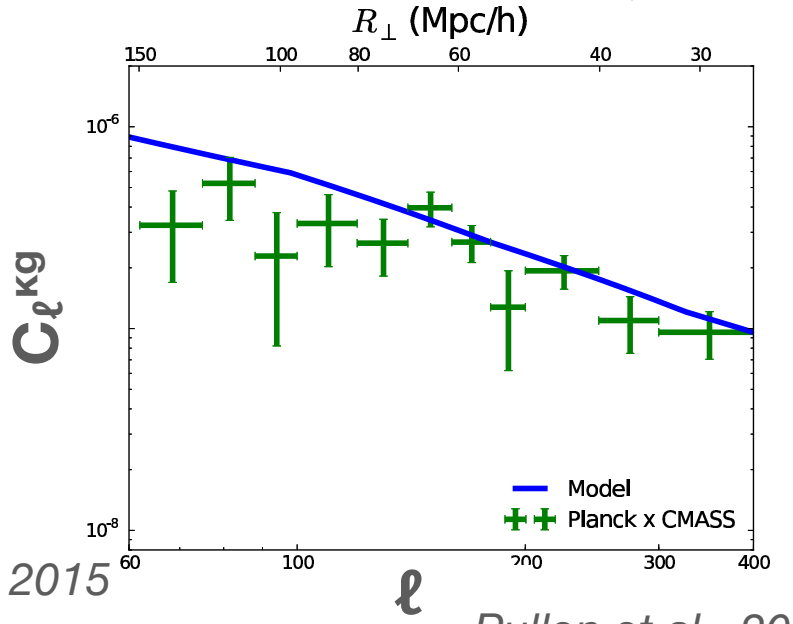
Bianchini et al., 2015

CFHT x Planck, ~6σ



Omori & Holder 2015

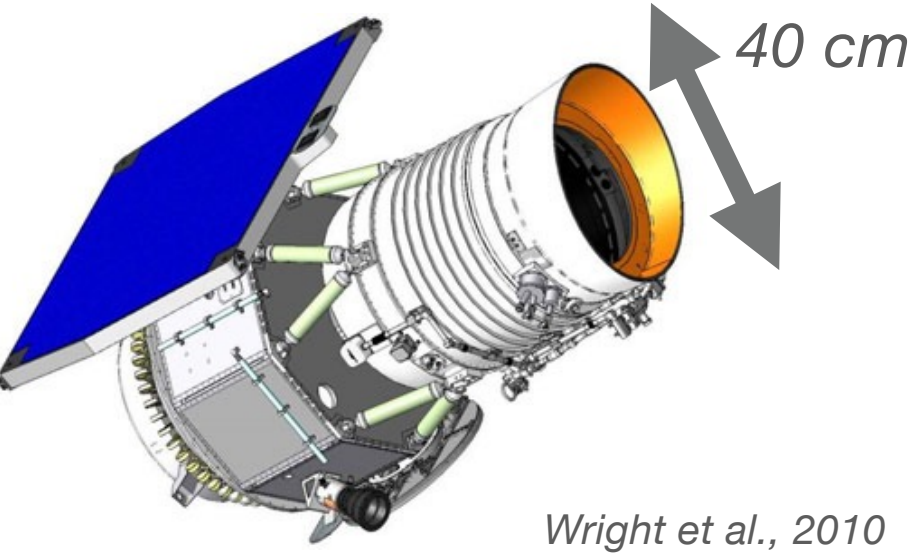
CMASS x Planck, ~8σ



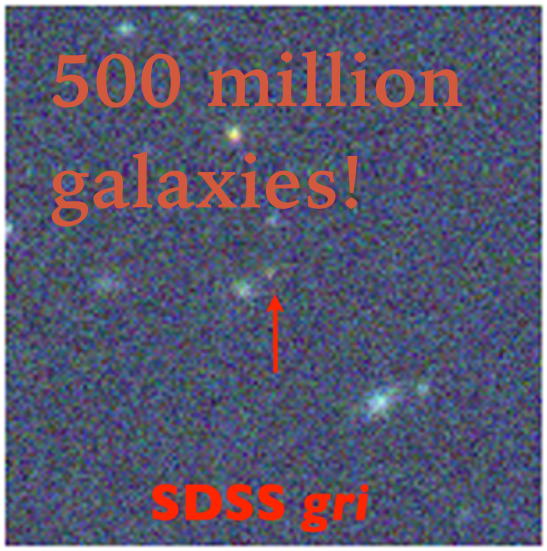
Pullen et al., 2016

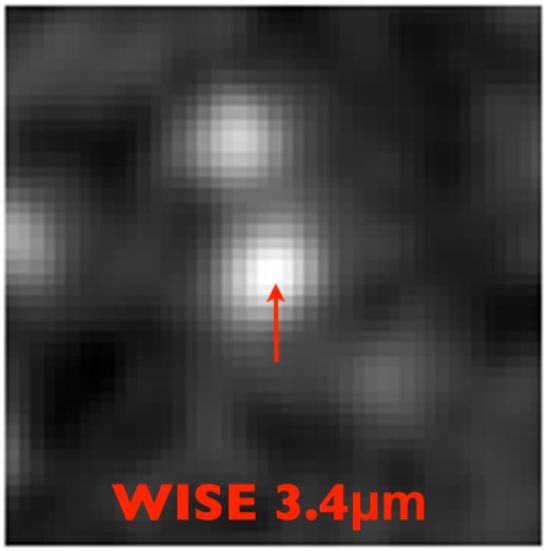
BUILDING THE BEST CMB–LSS CORRELATION

- 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



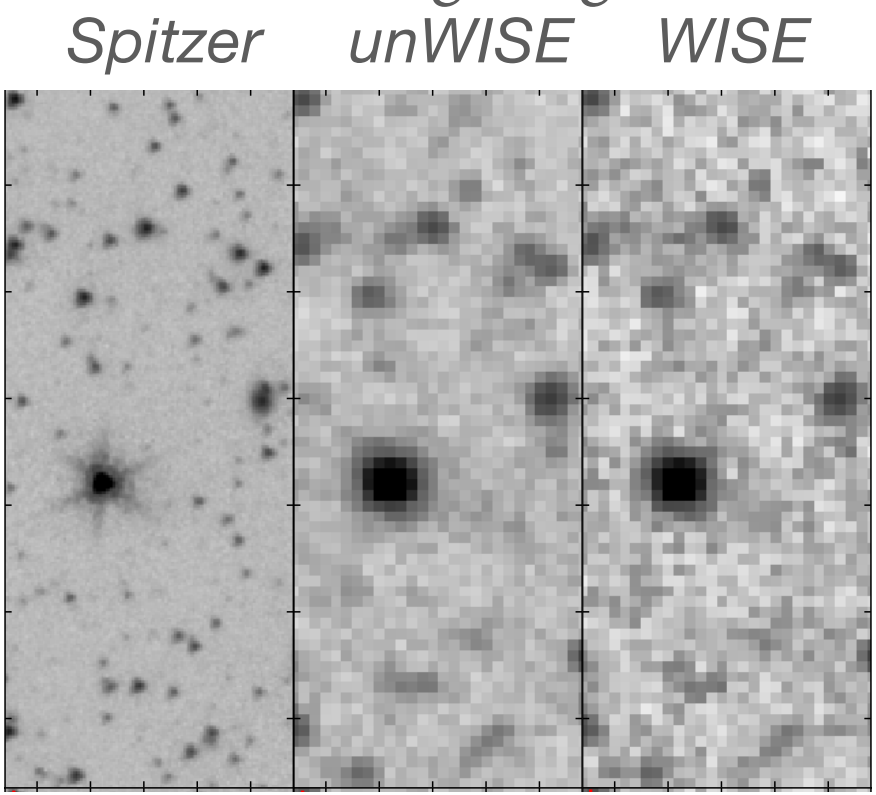
Wright et al., 2010

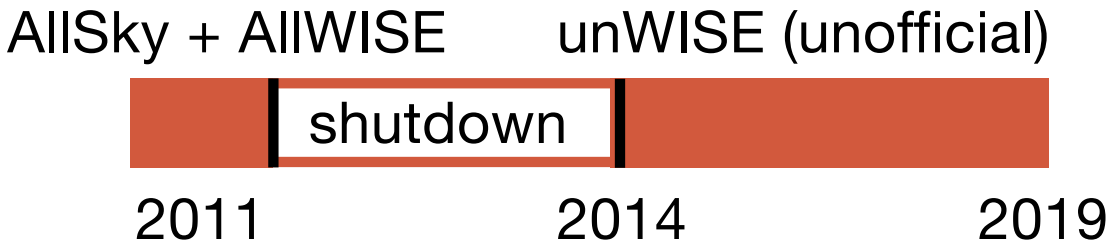




unWISE CATALOG

- Original 13 month mission (2010) + NeoWISE re-activation 2014-present (3.4, 4.6 μm only)
  - No official WISE catalog after 2012 (despite 5x more data)
- unWISE: unofficial catalog, outgrowth of forced photometry for DESI targeting

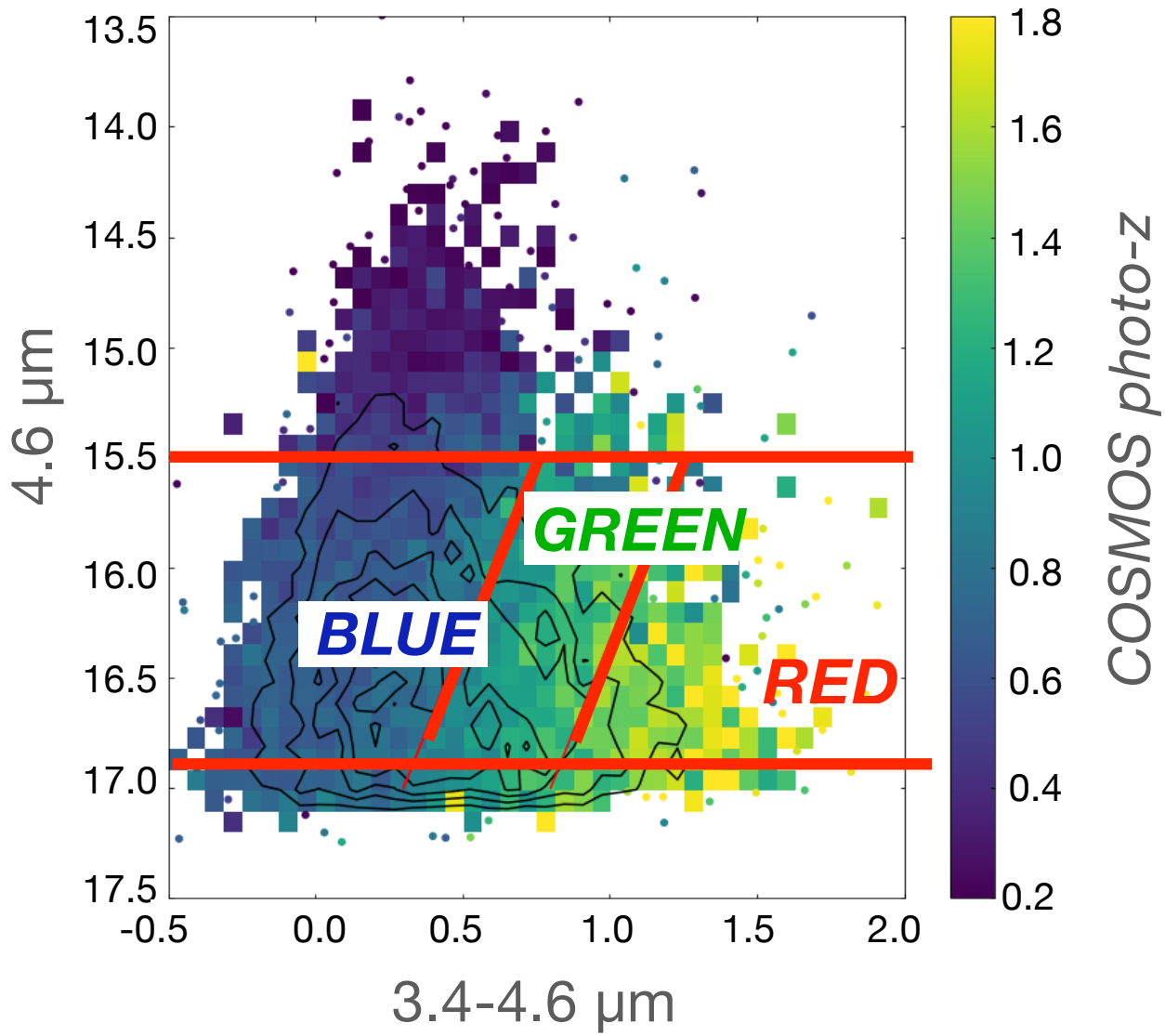




Schlafly et al. 2019

catalog.unwise.me

unWISE GALAXY SAMPLES

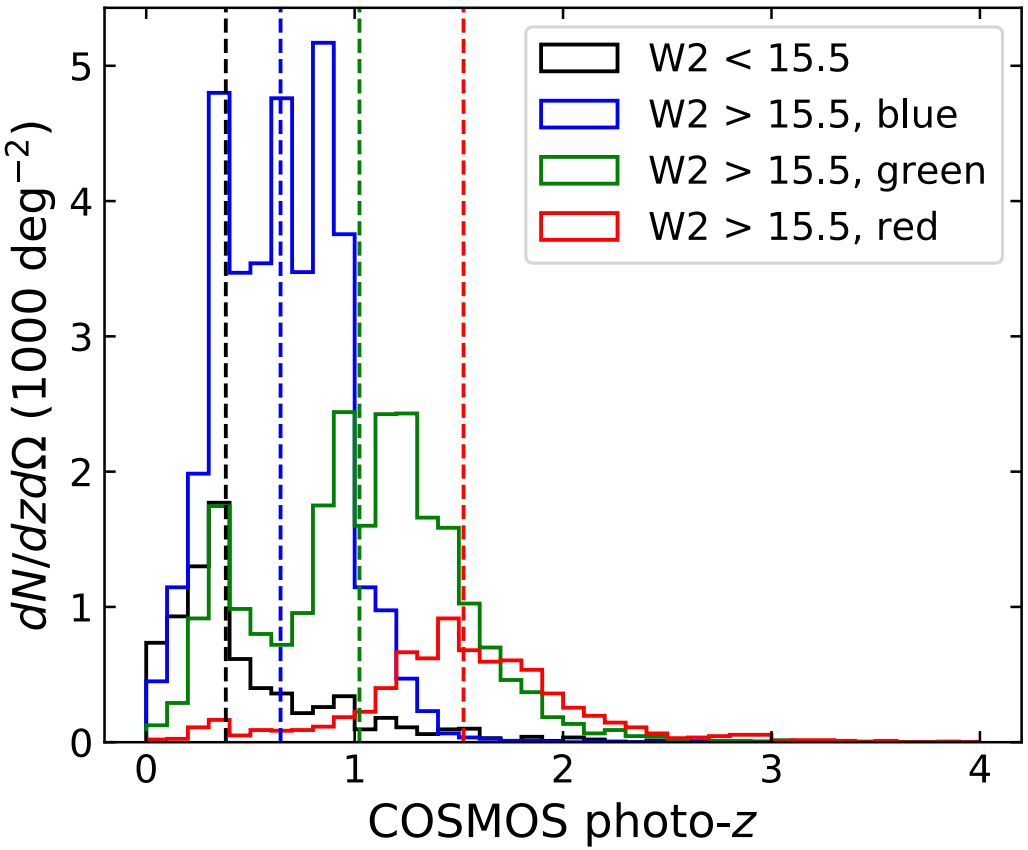


Schlafly et al. 2019

- Remove stars using GAIA: 1% stellar contamination

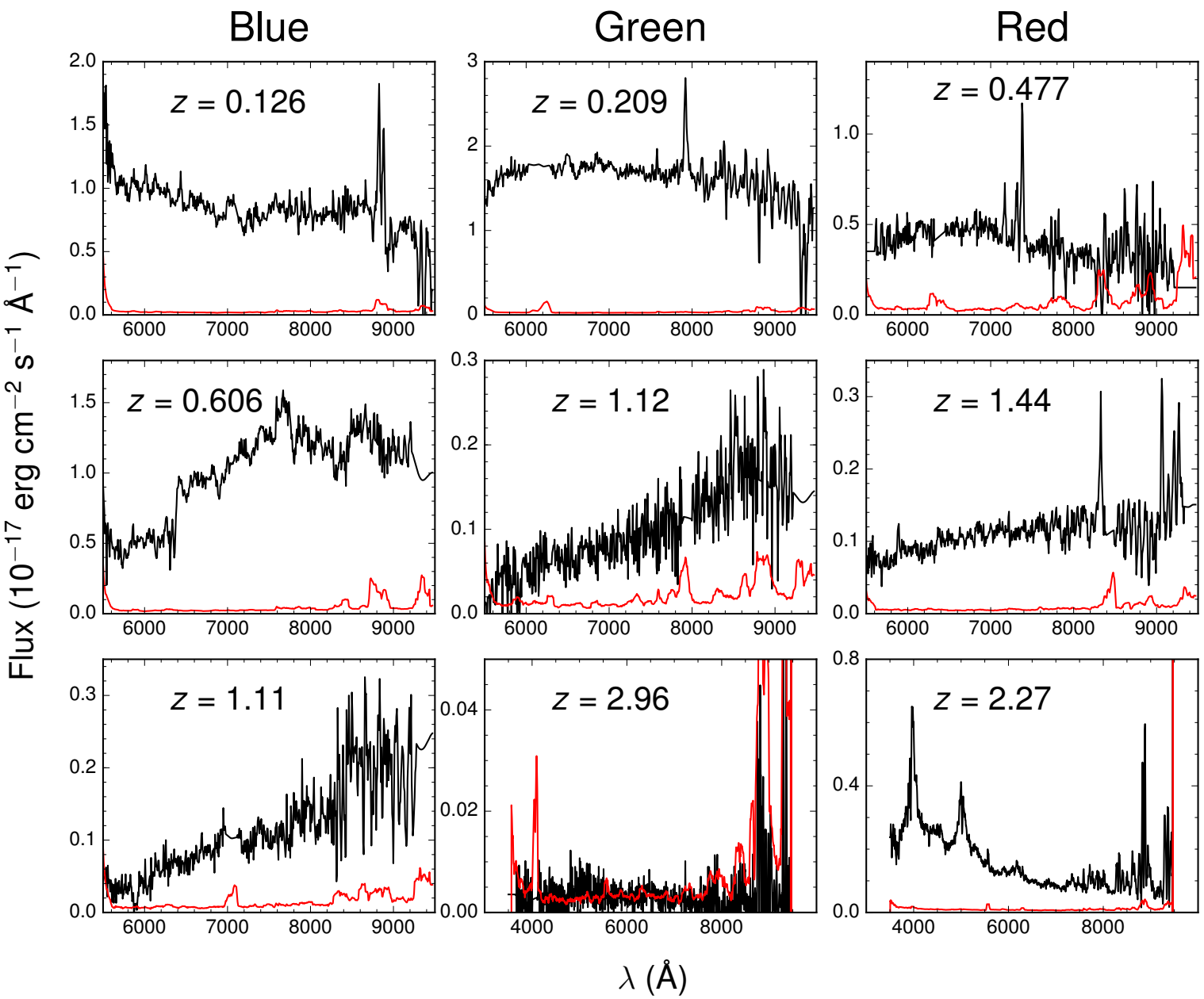
unWISE GALAXY SAMPLES

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

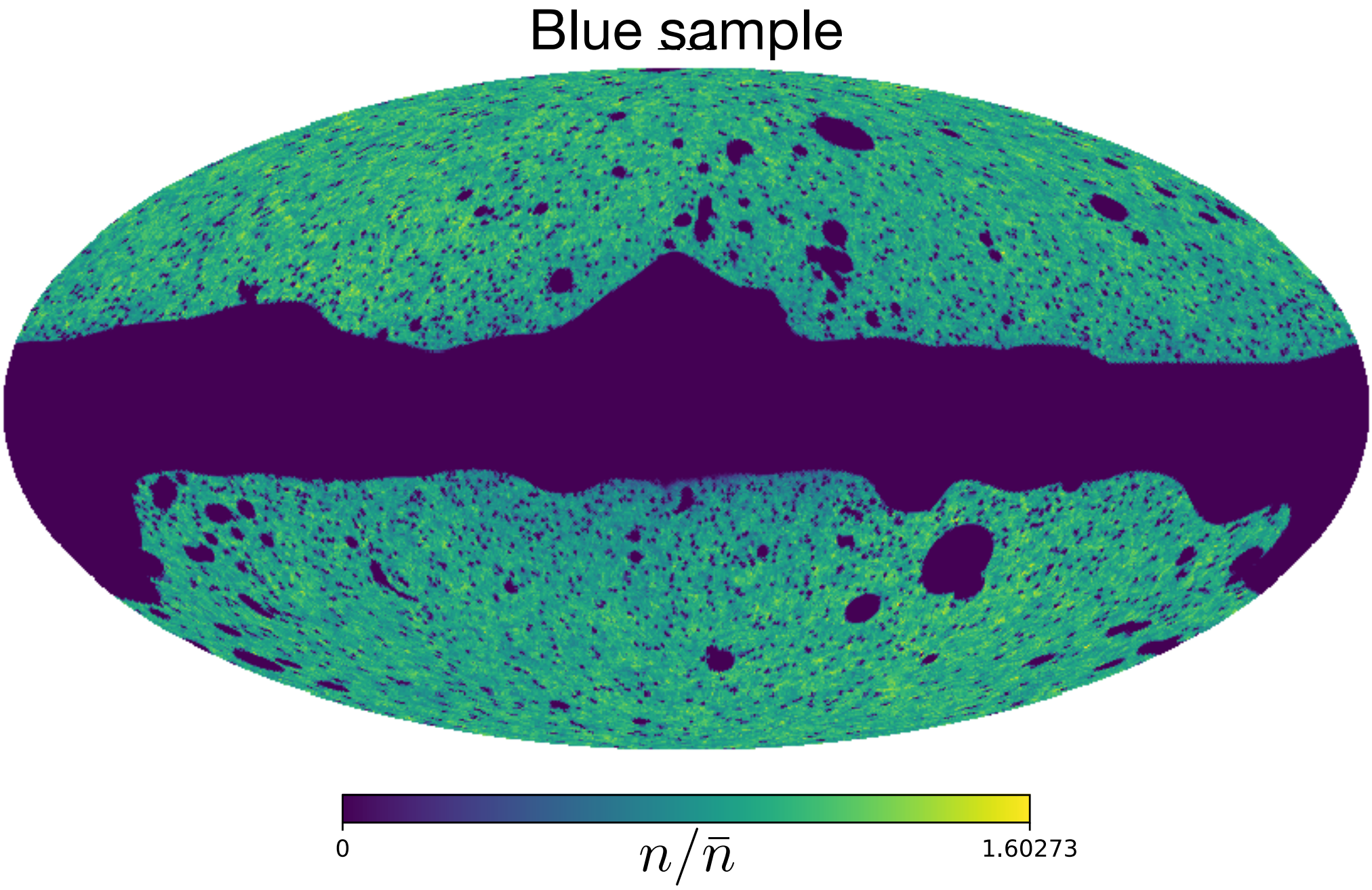


Schlafly et al. 2019

OPTICAL SPECTRA OF unWISE GALAXIES

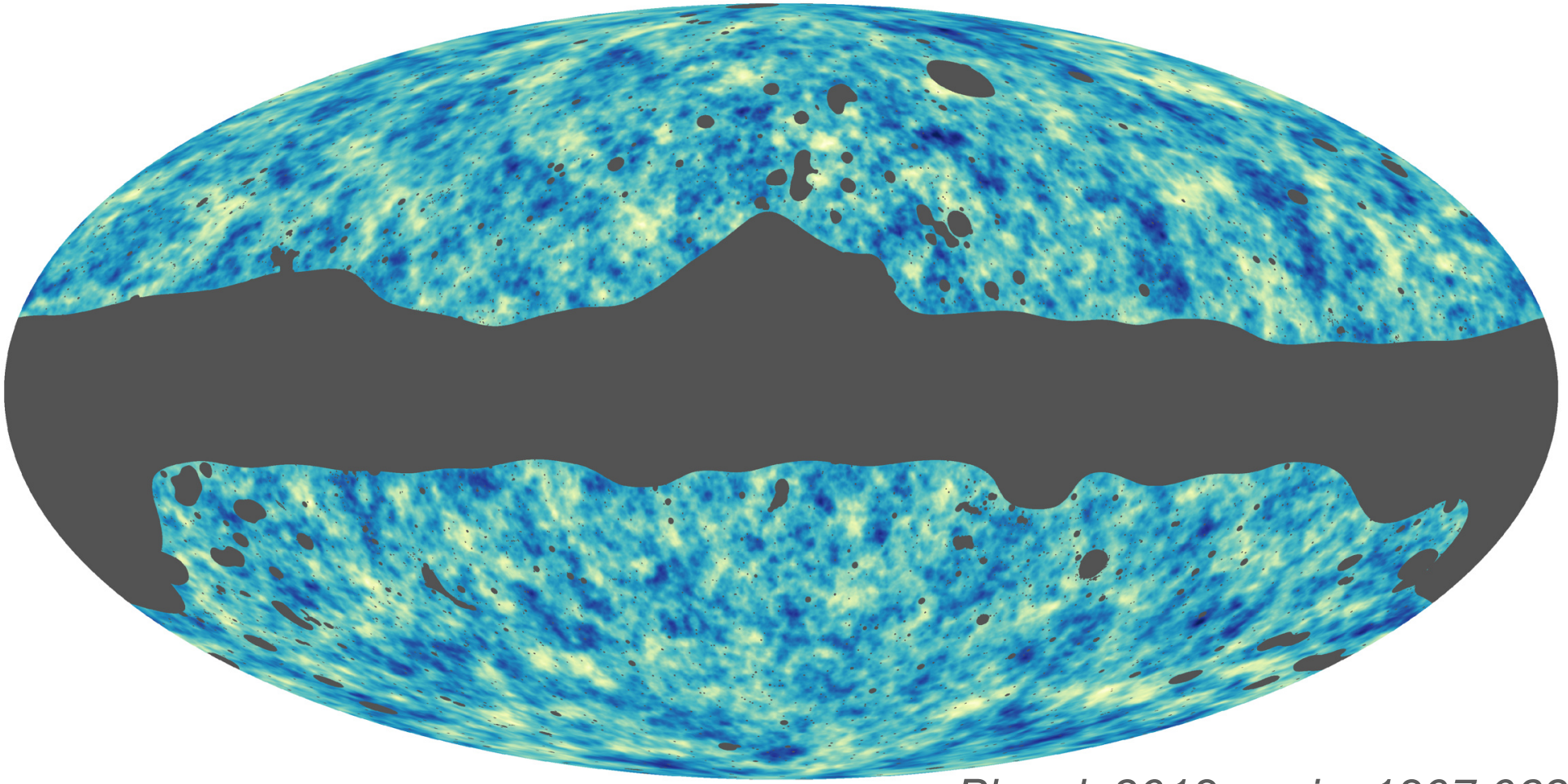


SKY DISTRIBUTION



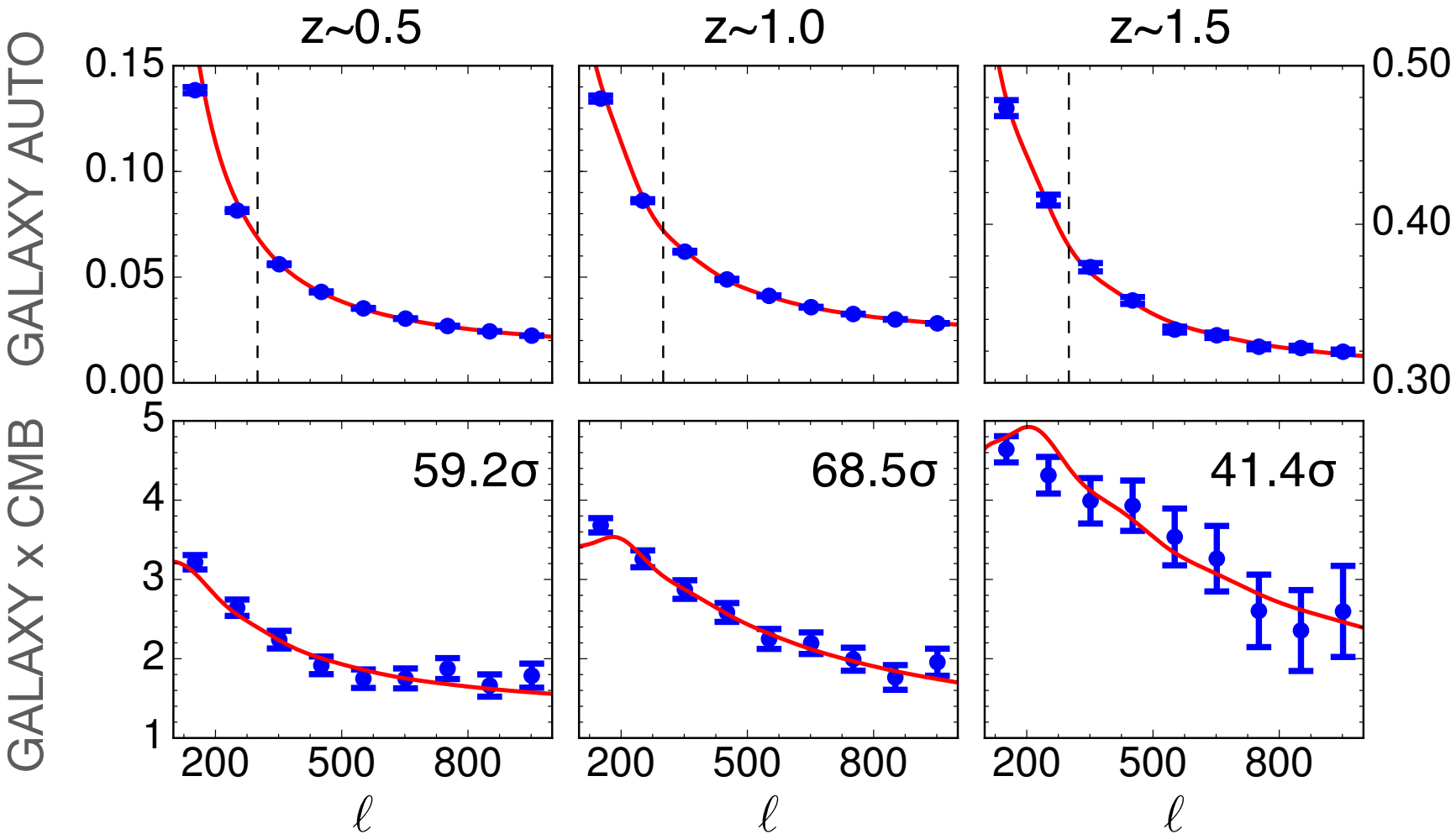
PLANCK CMB LENSING

- Planck 2018 minimum-variance lensing maps + masks



Planck 2018, arxiv: 1807.06210

AUTO & CROSS SPECTRA



- Model with Halofit x linear bias (+magnification bias)

$$P_{\rm mg}(k,z) = b_{\rm lin}(z) P_{\rm mm}(k,z) \quad P_{\rm gg}(k,z) = b^2_{\rm lin}(z) P_{\rm mm}(k,z) + \text{Shot Noise}$$

- Total S/N = 79.3

INTERPRETATION CHALLENGES

- (few) Percent-level precision demands tight systematic control!
- Major systematics in this work:
  - unWISE redshift distribution
  - extra systematic power at large scales in auto-correlation (and its coupling to the mask)
  - modeling nonlinearities

MEASURING THE REDSHIFT DISTRIBUTION

- Photometric redshifts impossible with 2 bands
- Matching to COSMOS photo-z yields approximate dN/dz but suffers from small area, photo-z errors, blending issues
- Alternative: dN/dz from cross-correlations with SDSS spectroscopic surveys (e.g. Menard et al. 2013)

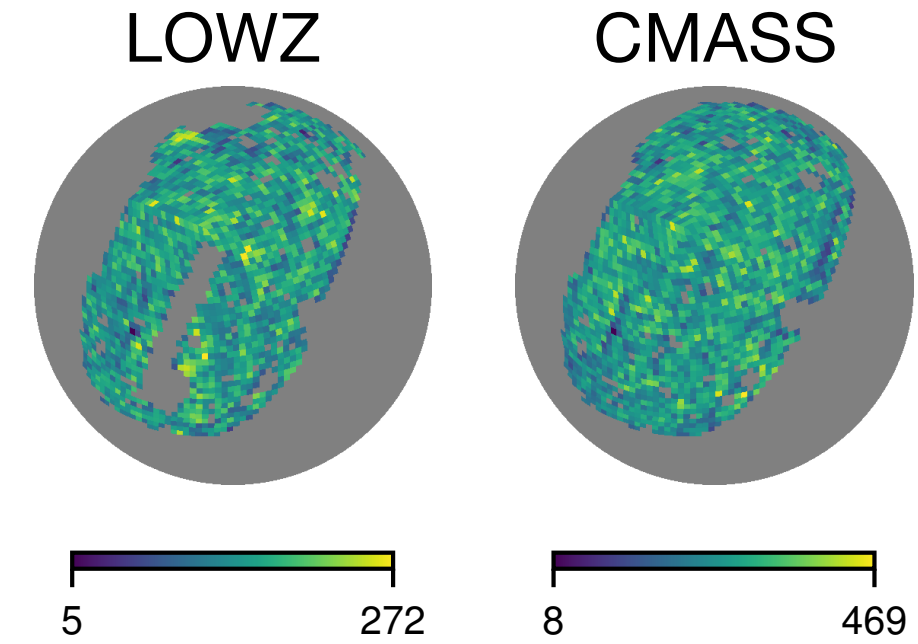
$$\bar{w}_{\rm sp}(z) = b_{\rm sml,s}(z)\, b_{\rm sml,p}(z)\, H(z)\, \frac{dN_{\rm p}}{dz}\, I(z)$$

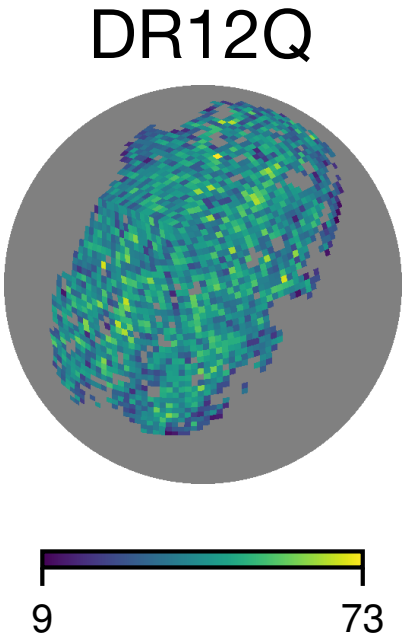
- Constrains b(z) dN/dz: you need b(z) as well as dN/dz for galaxy kernel!

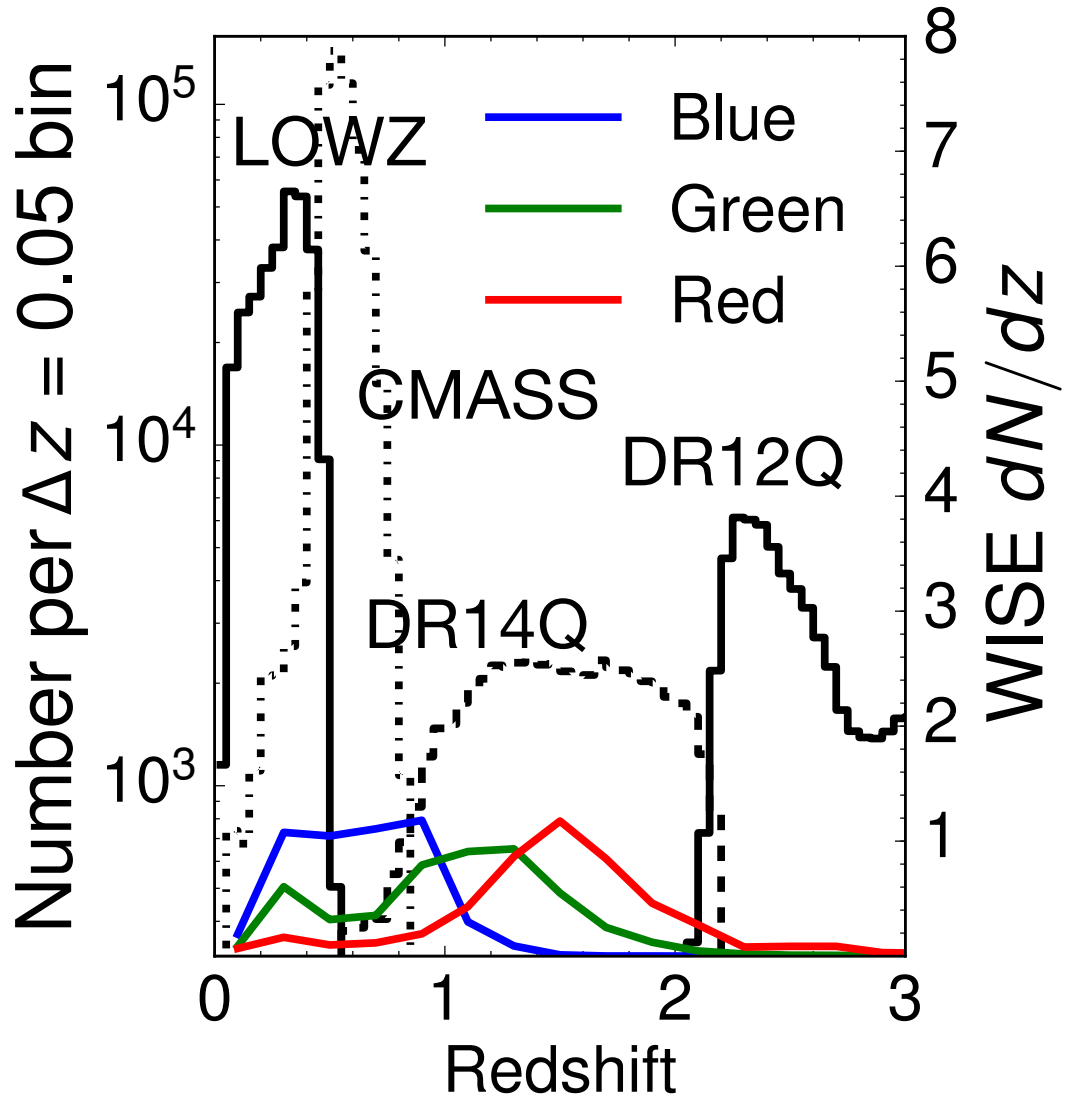
$$C_\ell^{\kappa g} = \int d\chi \frac{b(z)\, dN/d\chi\, W^\kappa(\chi)}{\chi^2} P(k\chi = \ell + 1/2)$$

$$C_\ell^{gg} = \int d\chi \frac{[b(z)\, dN/d\chi]^2}{\chi^2} P(k\chi = \ell + 1/2)$$

SPECTROSCOPIC SAMPLES



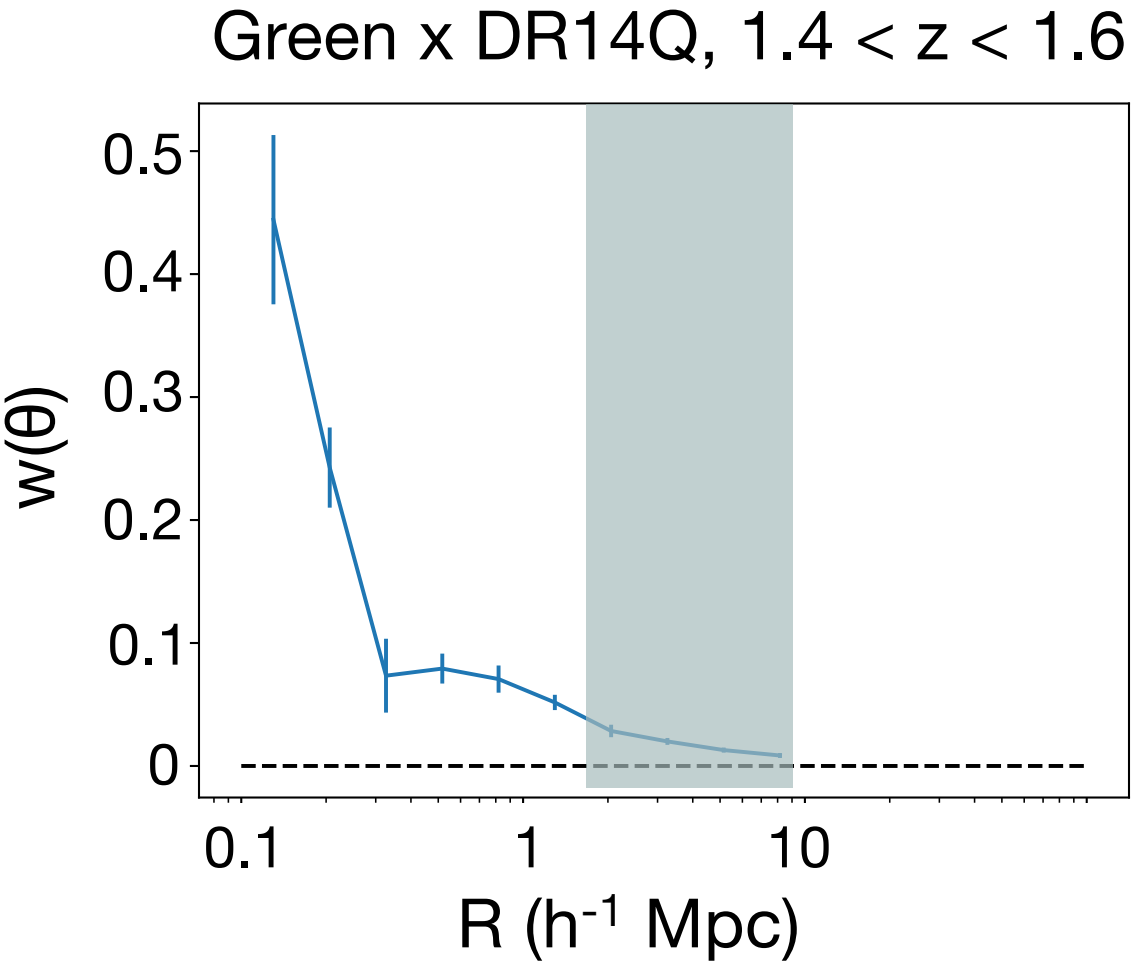




CLUSTERING REDSHIFT METHOD

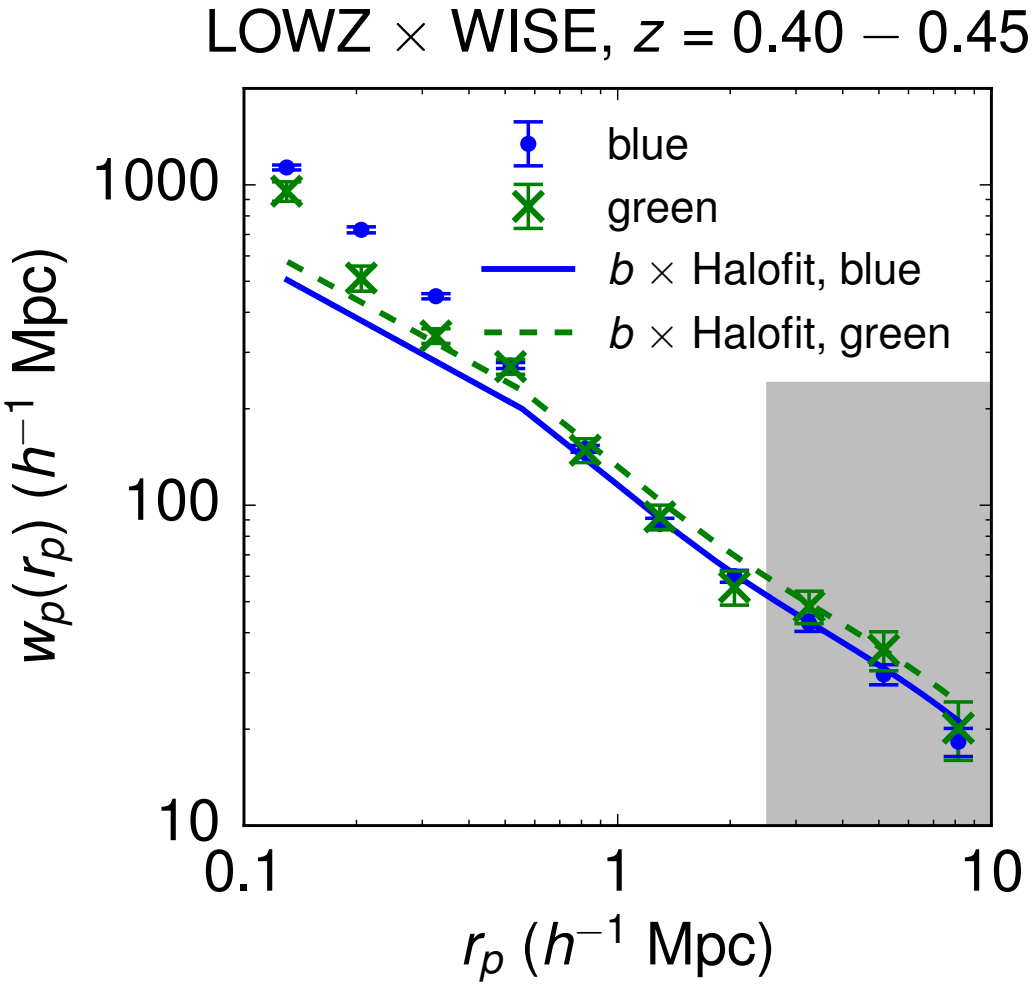
- Real-space method as in Menard et al., 2013

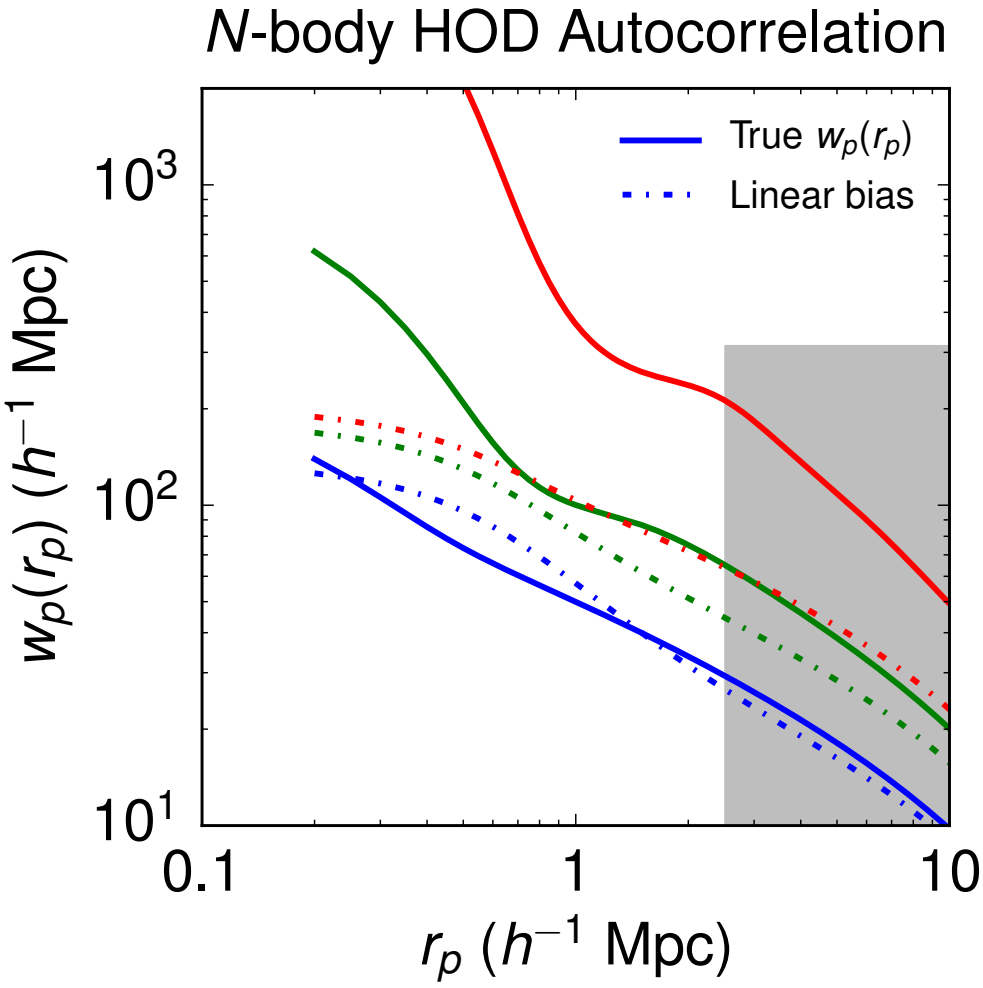
$$\hat{w}(\theta) = \frac{D_{\rm s}D_{\rm p}}{D_{\rm s}R_{\rm p}}\frac{N_{\rm R}}{N_{\rm D}} - 1$$



HOW TO DETERMINE SCALE CUT?

- Scales used in clustering redshifts should match scales used in C_ℓ^{gg}, C_ℓ^{kg} as well as possible

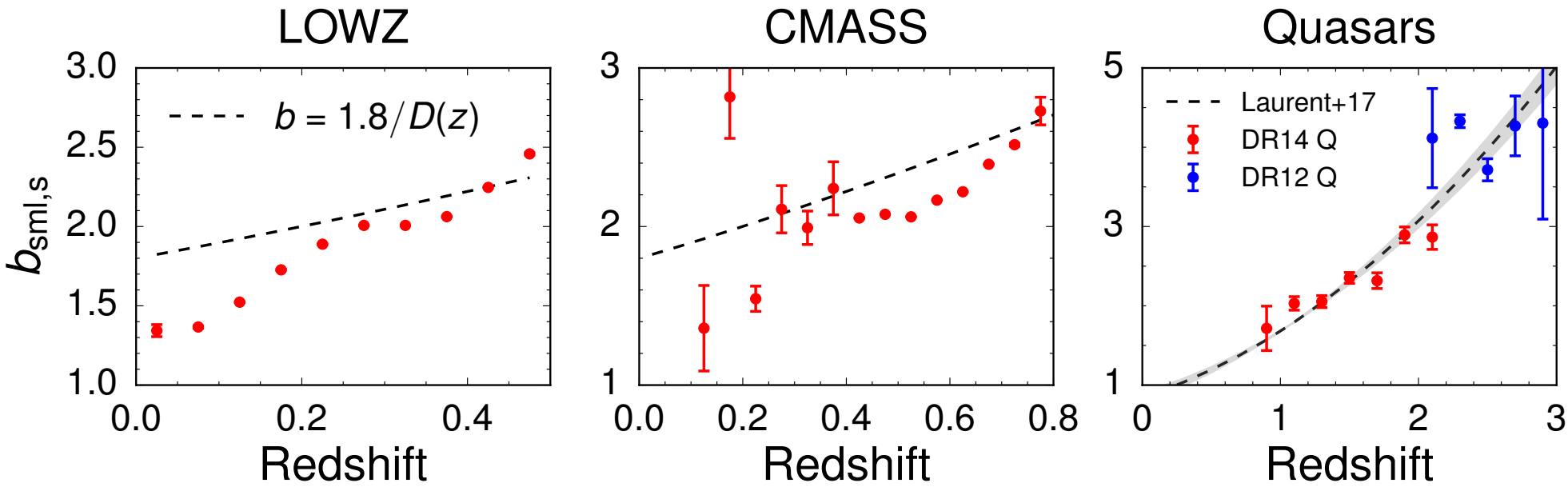




SPECTROSCOPIC BIAS EVOLUTION

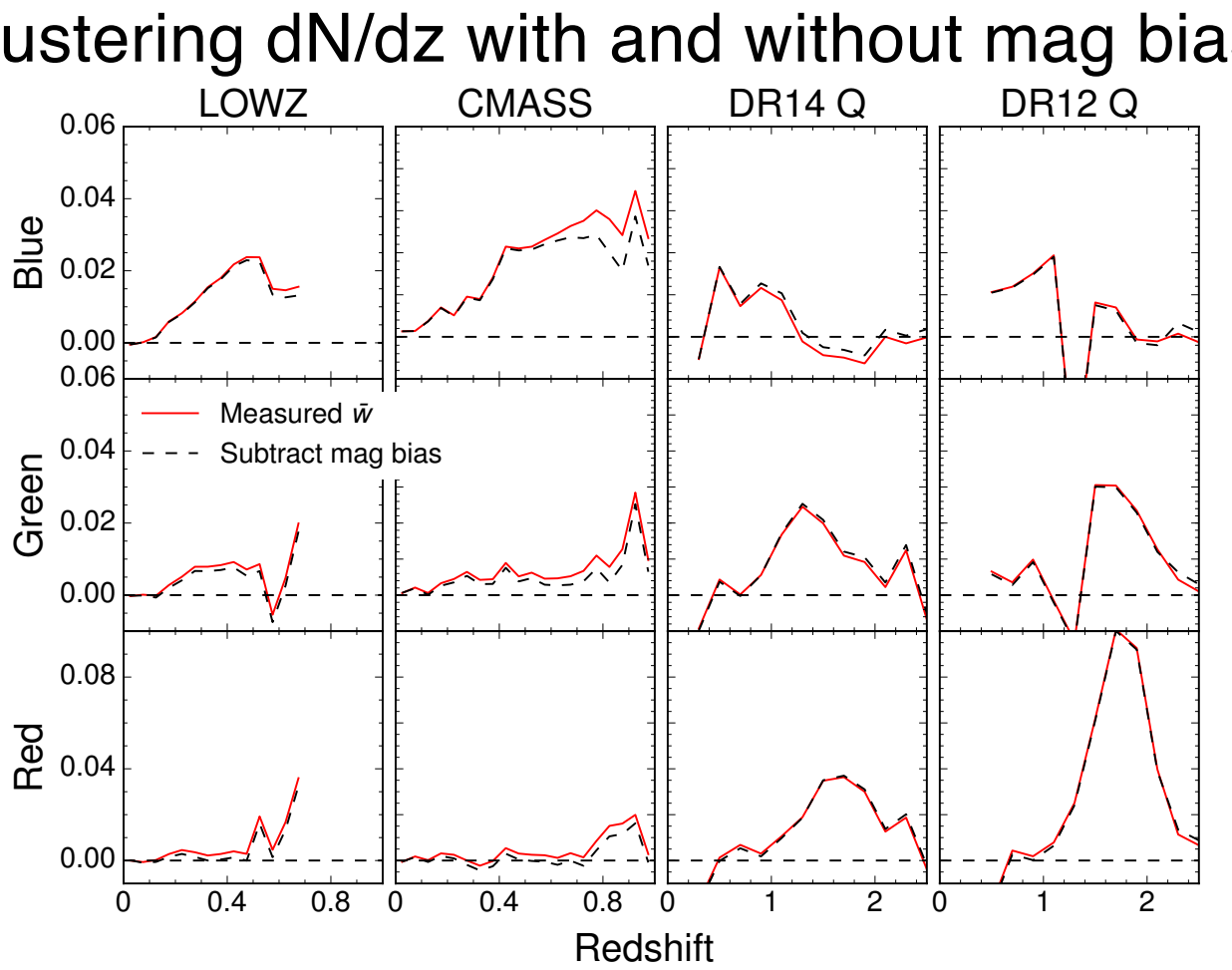
$$\bar{w}_{\rm sp}(z) = b_{\rm sml,s}(z)\, b_{\rm sml,p}(z)\, H(z)\, \frac{dN_{\rm p}}{dz}\, I(z)$$

- Passive evolution models are not correct in detail for the spectroscopic samples

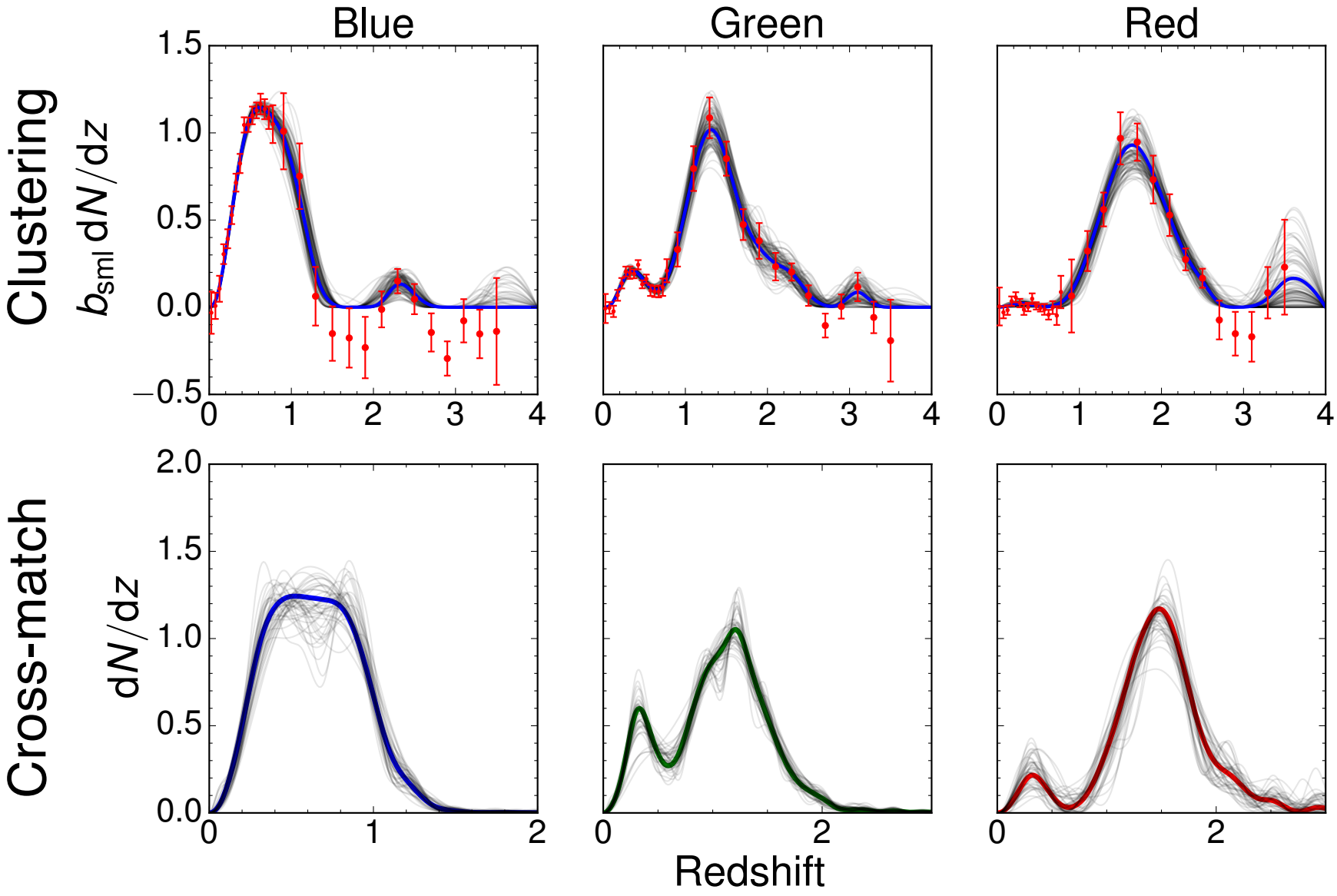


IMPACT OF MAGNIFICATION BIAS

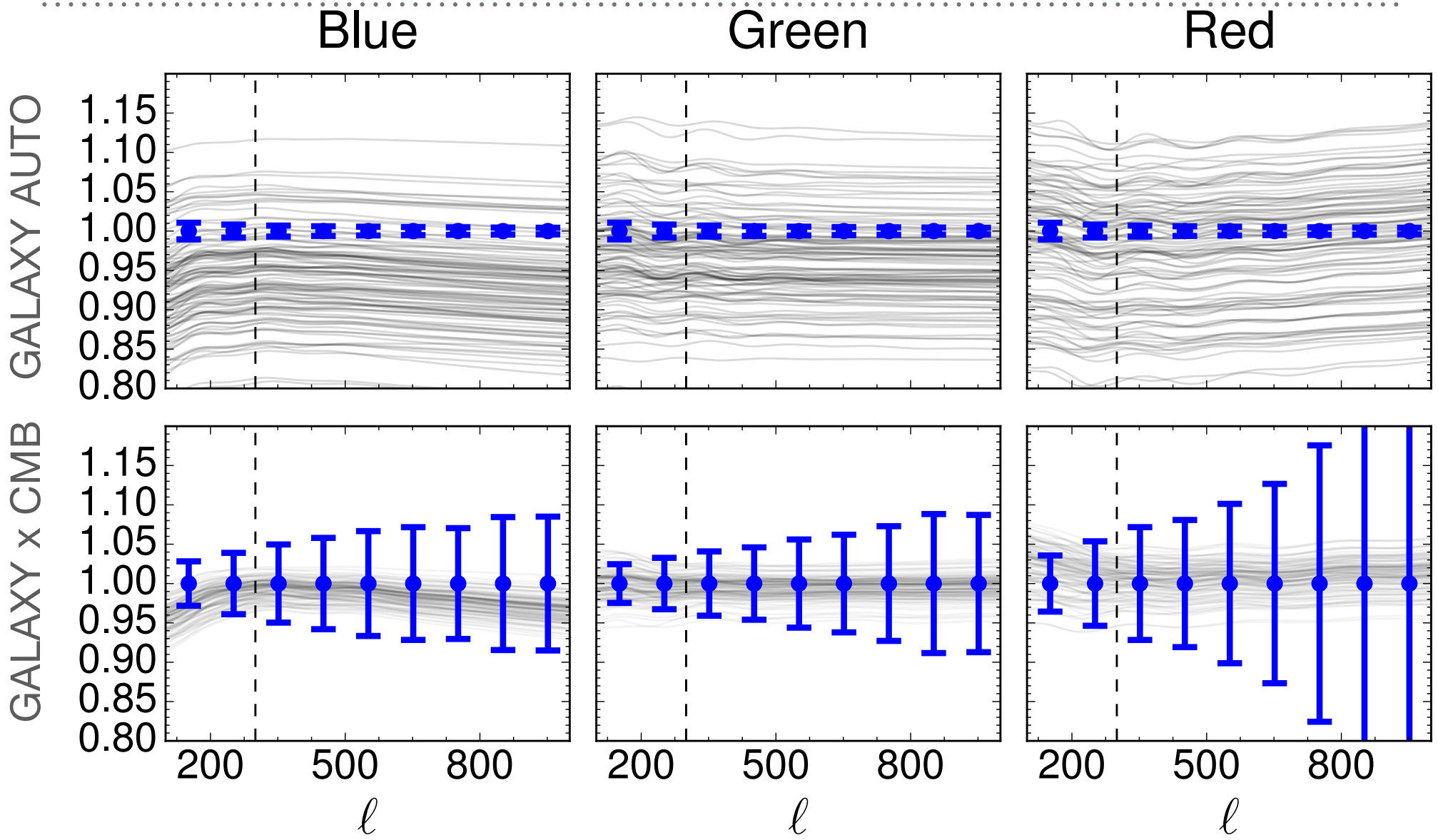
- Photo-spectro cross-correlations may also be due to lensing magnification bias (particularly in tails)
- Neglecting magnification bias shifts results by ~1 sigma



COMBINED dN/dz



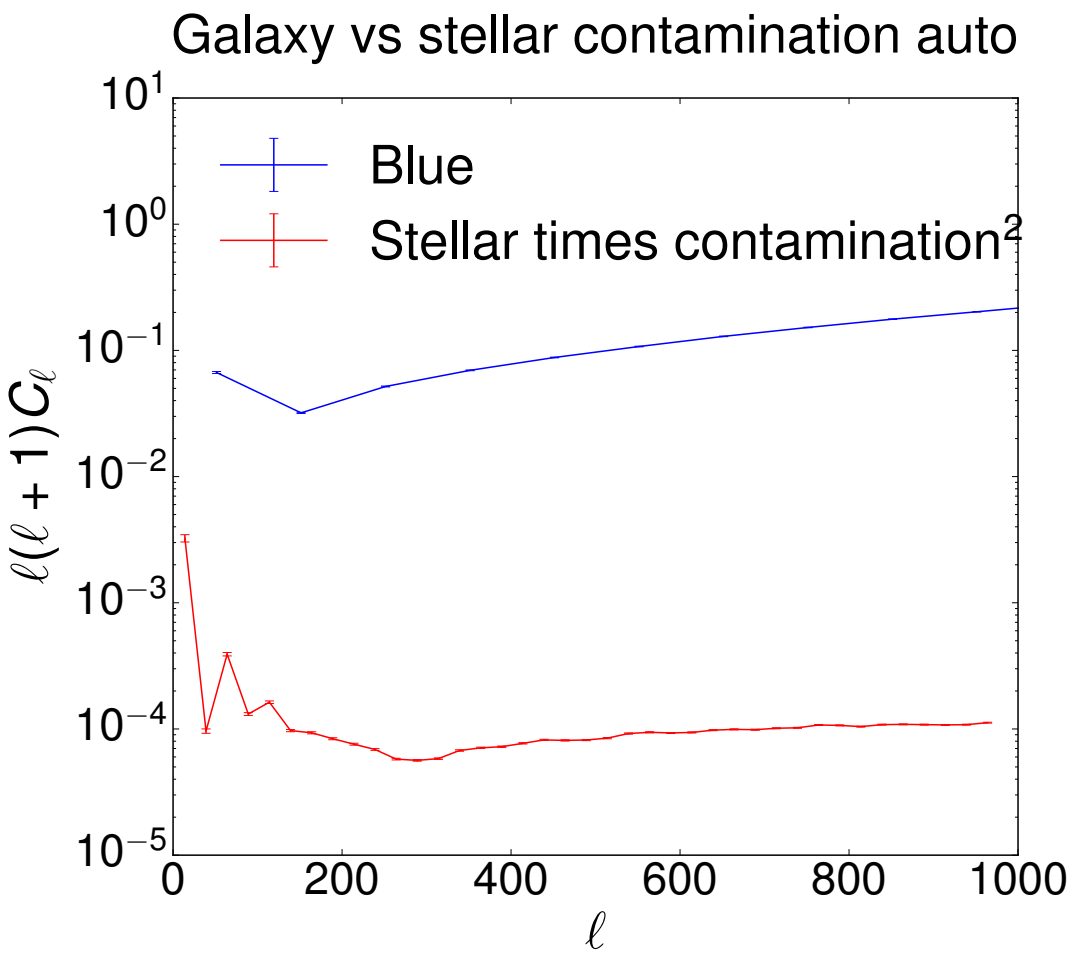
IMPACT OF UNCERTAIN dN/dz ON POWER SPECTRA



STELLAR CONTAMINATION

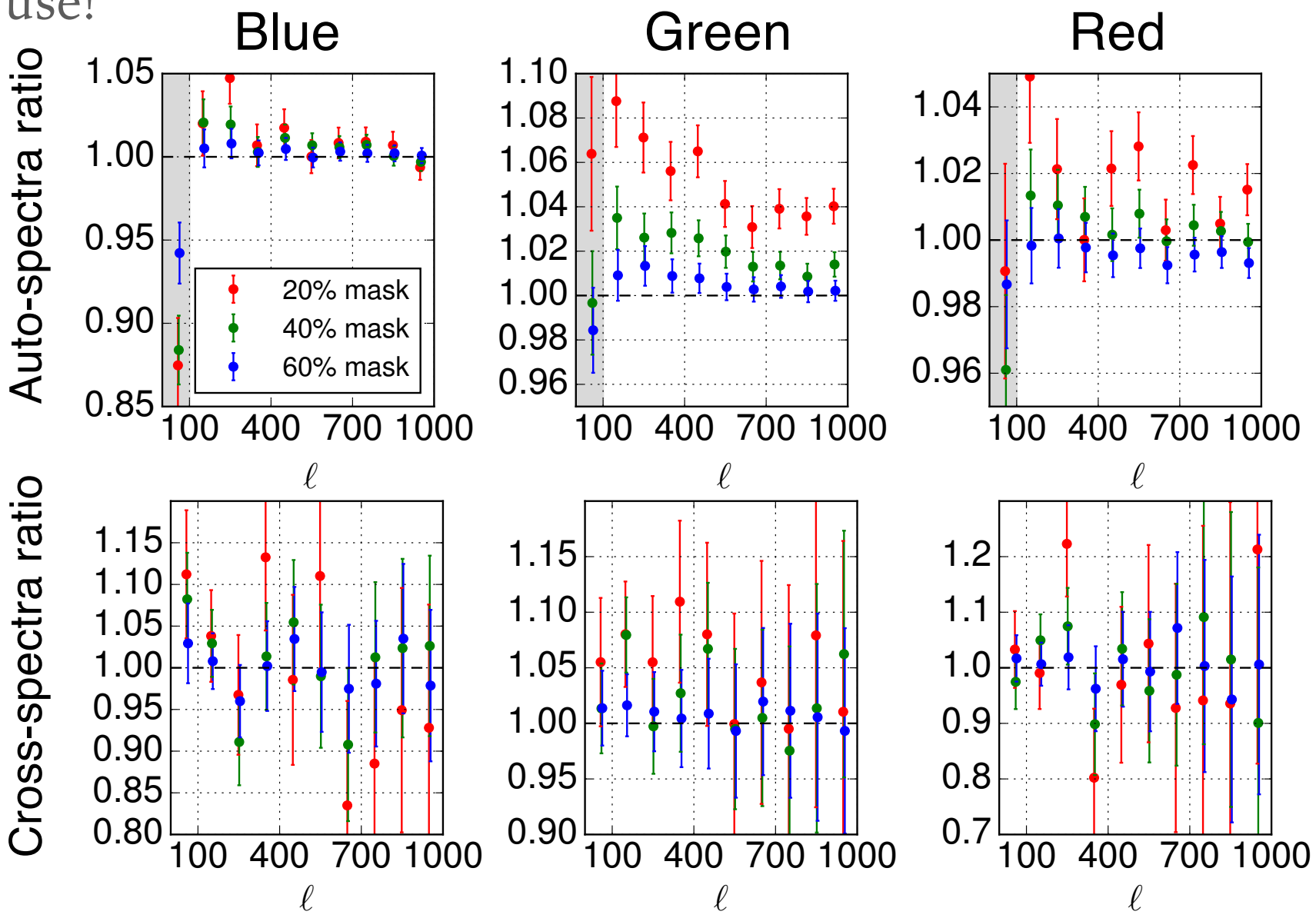
- If stars are unclustered, the effect of stellar contamination on number density is degenerate with bias
- ϵ_s : stellar contamination fraction

$$b^{\rm eff} = b^{\rm true} \frac{1}{1+\epsilon_s}$$



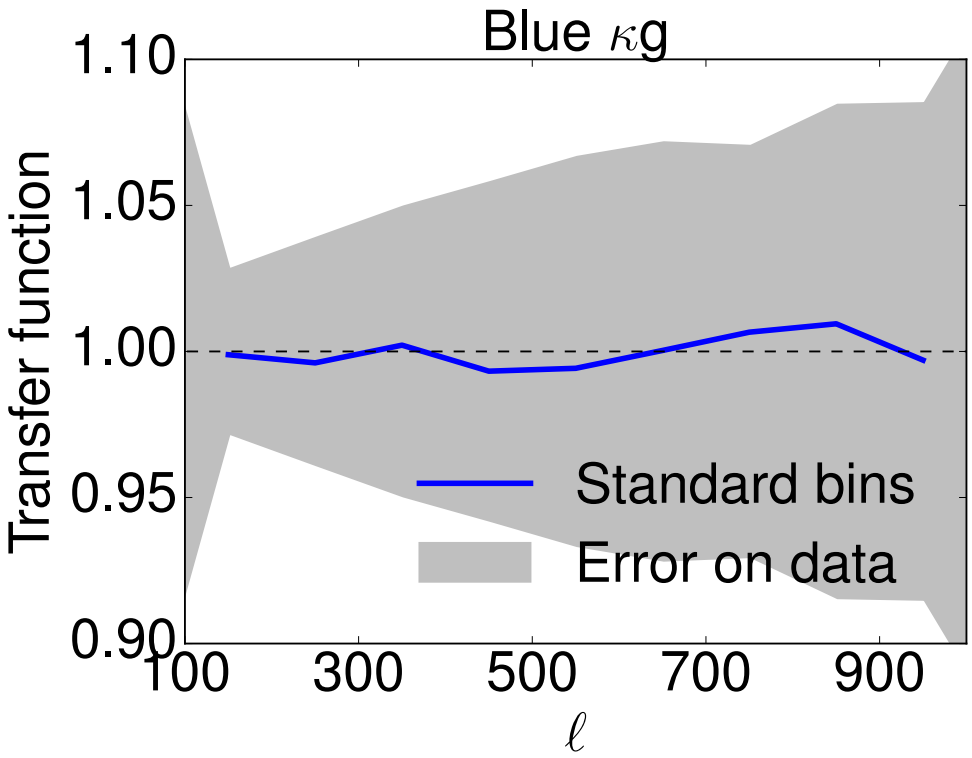
CHANGING THE GALACTIC MASK

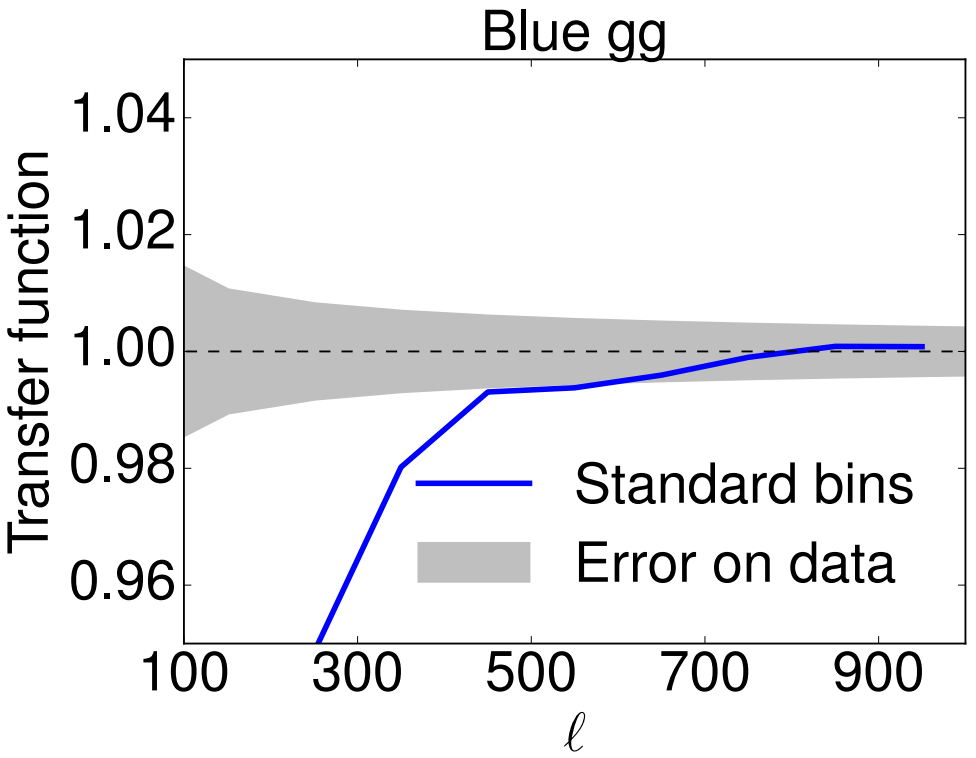
- $\ell < 100$ in auto shows trends with masking choice: do not use!



TESTING THE MASK DECONVOLUTION

- One danger from stellar contamination: coupling between the galaxy mask and the signal
- Test mask deconvolution by creating mock Gaussian realizations of galaxy & CMB lensing fields
- Mask, measure pseudo-C_ℓ, deconvolve mask → compare to input C_ℓ





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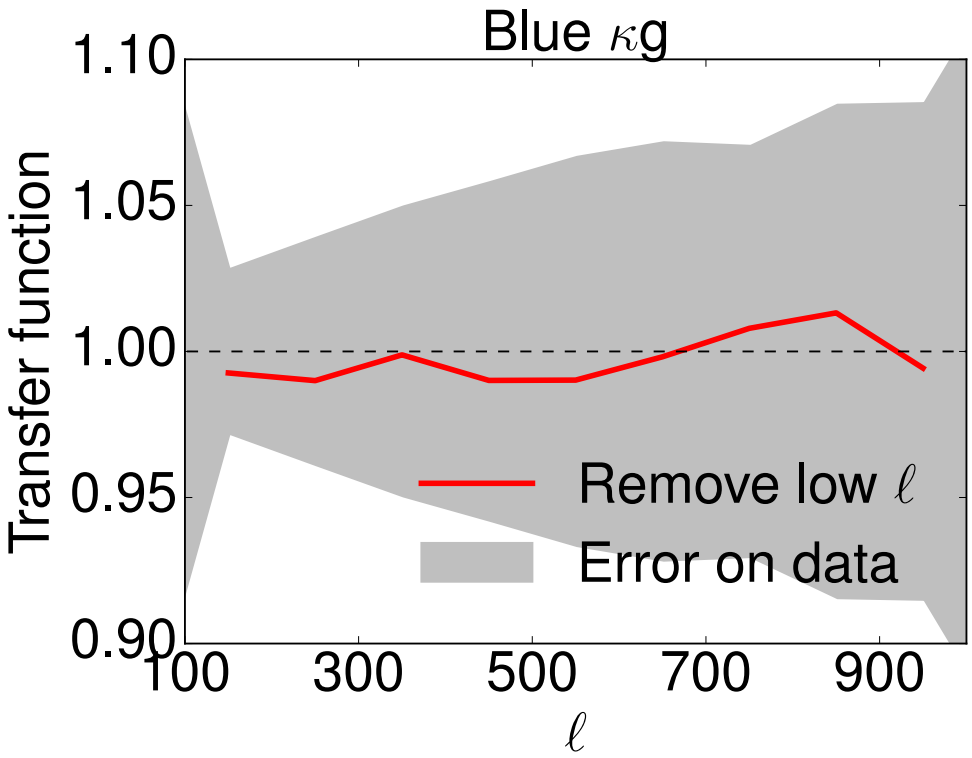
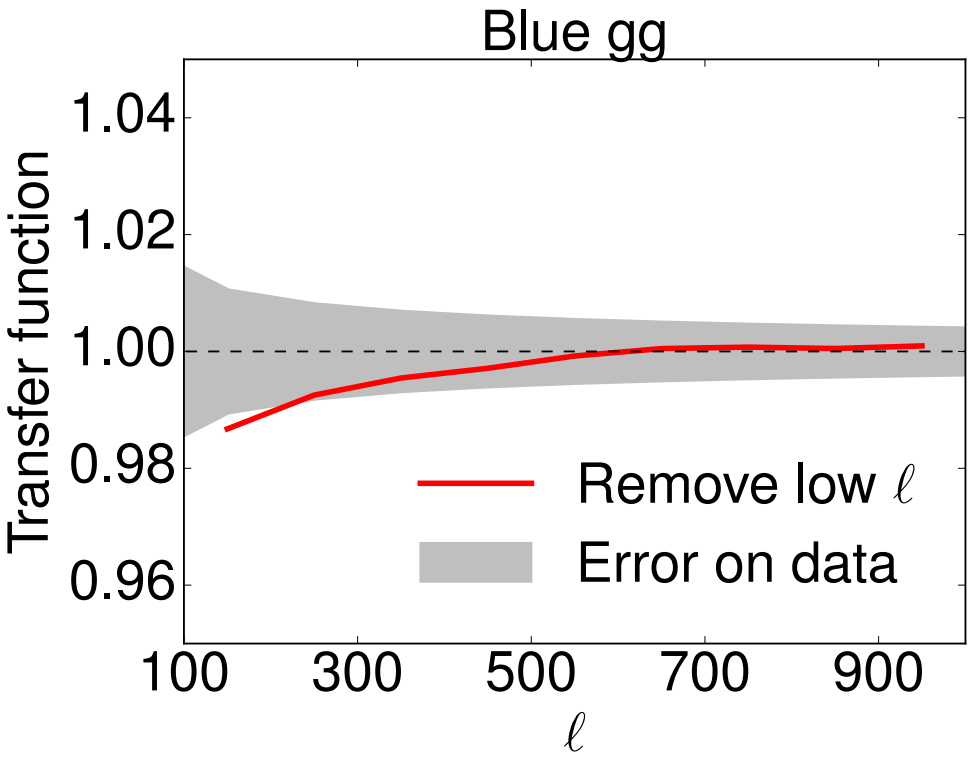
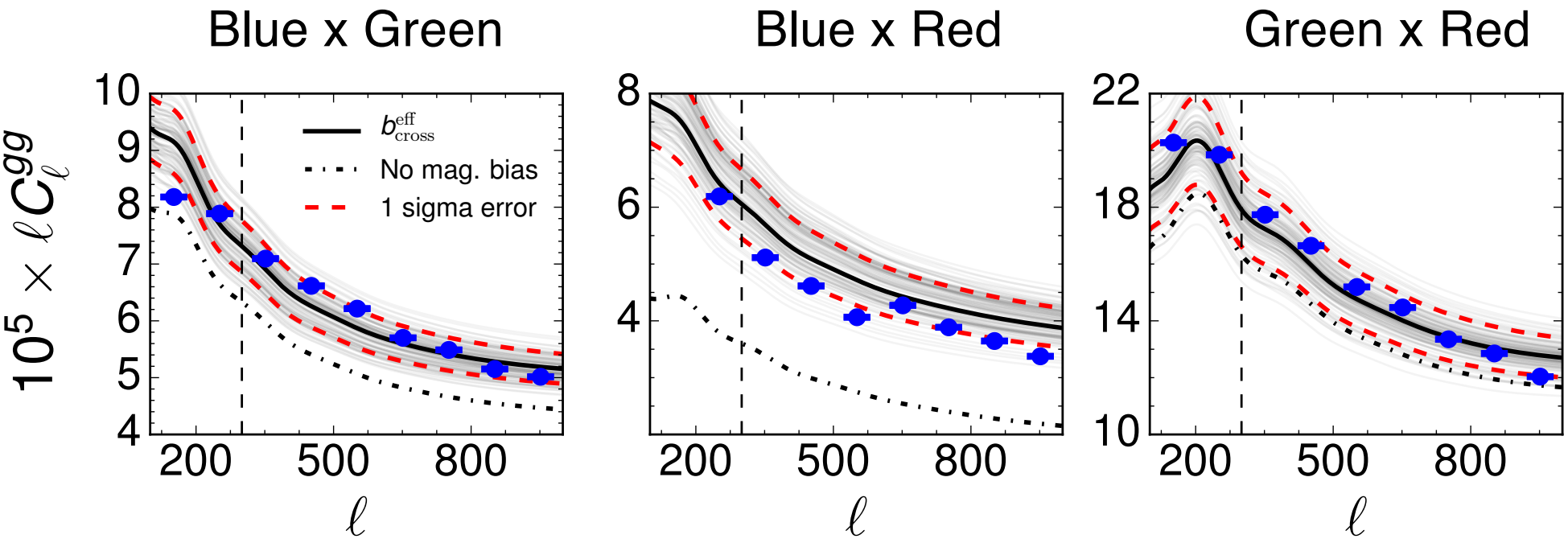


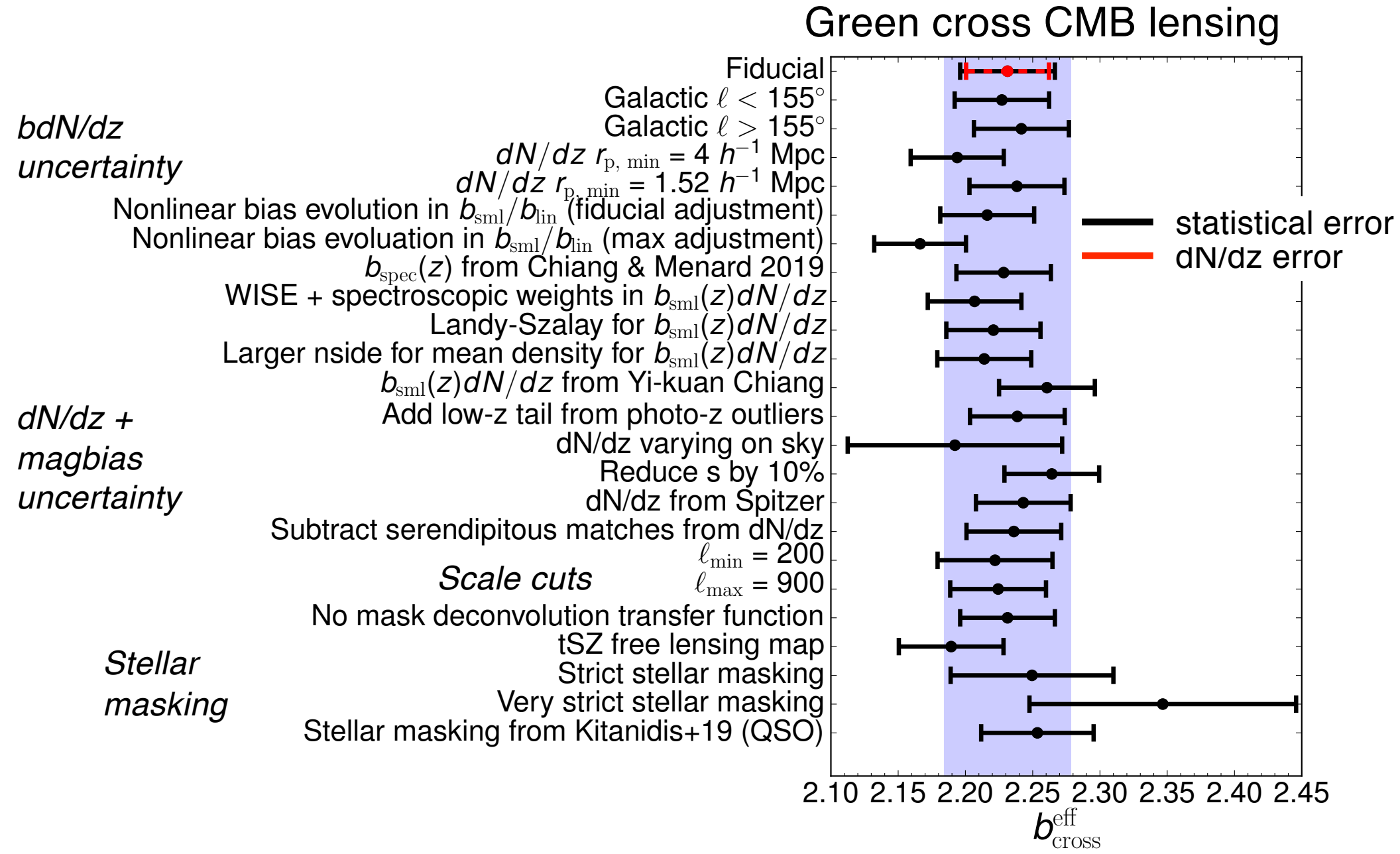


GALAXY CROSS SPECTRA

- Use best-fit biases from CMB lensing cross-correlations to predict theory curves for cross spectra
- Reasonably consistent; requires some fraction of green and red galaxies to inhabit the same halos (cross shot-noise)



SYSTEMATICS SUMMARY



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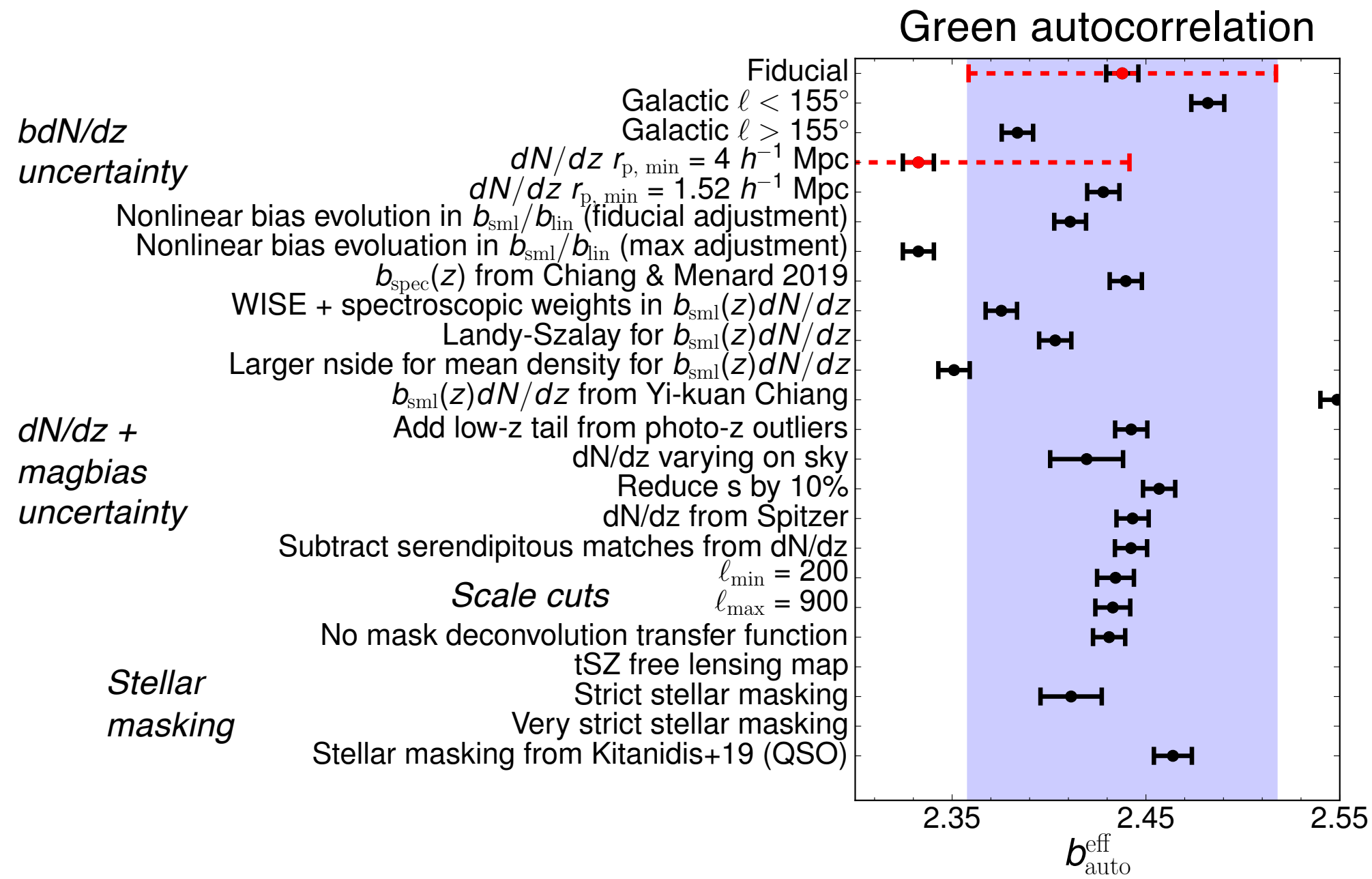
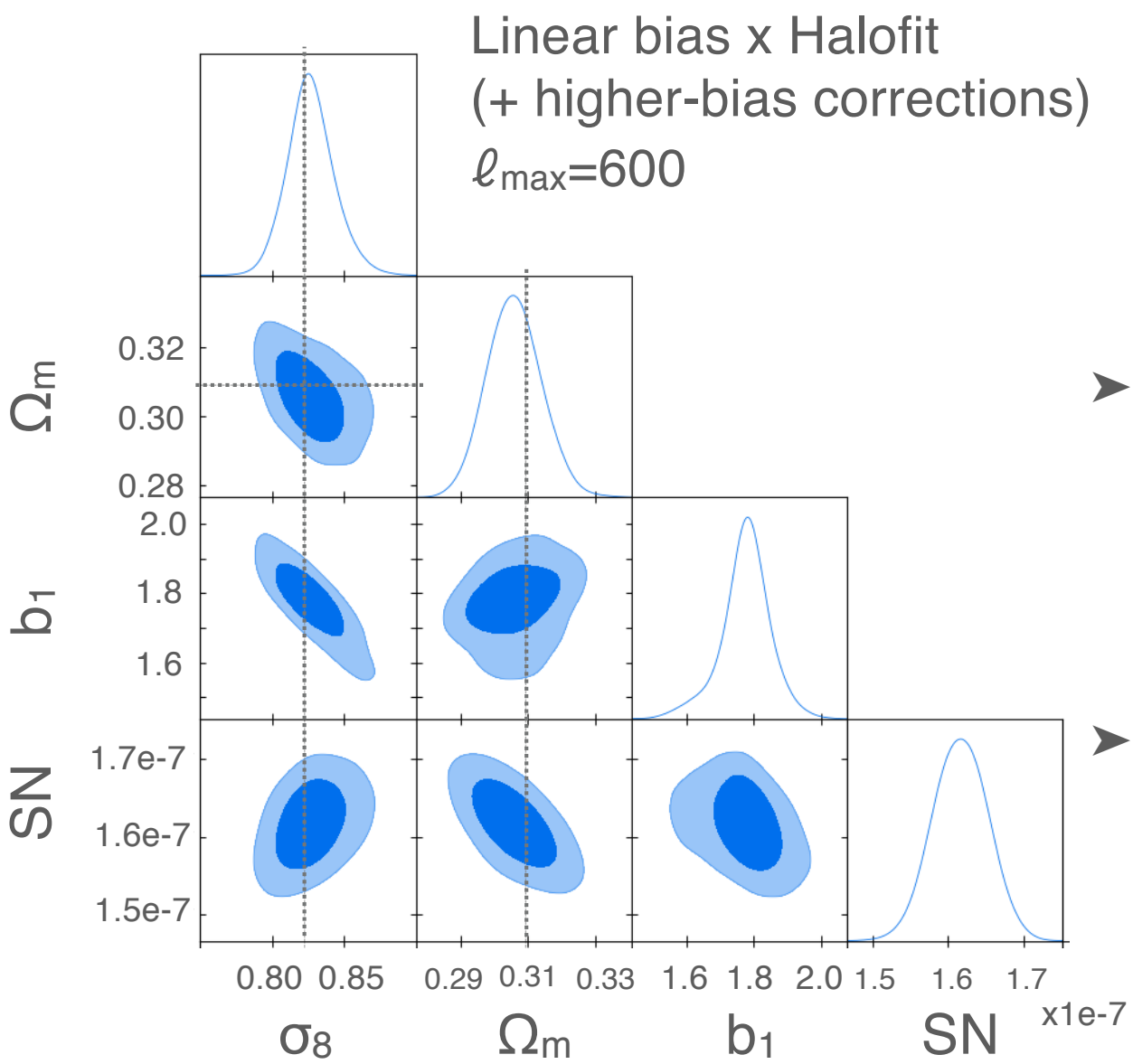


CONSTRAINING COSMOLOGY

PRELIMINARY MOCKS

z~1 sample, mock data



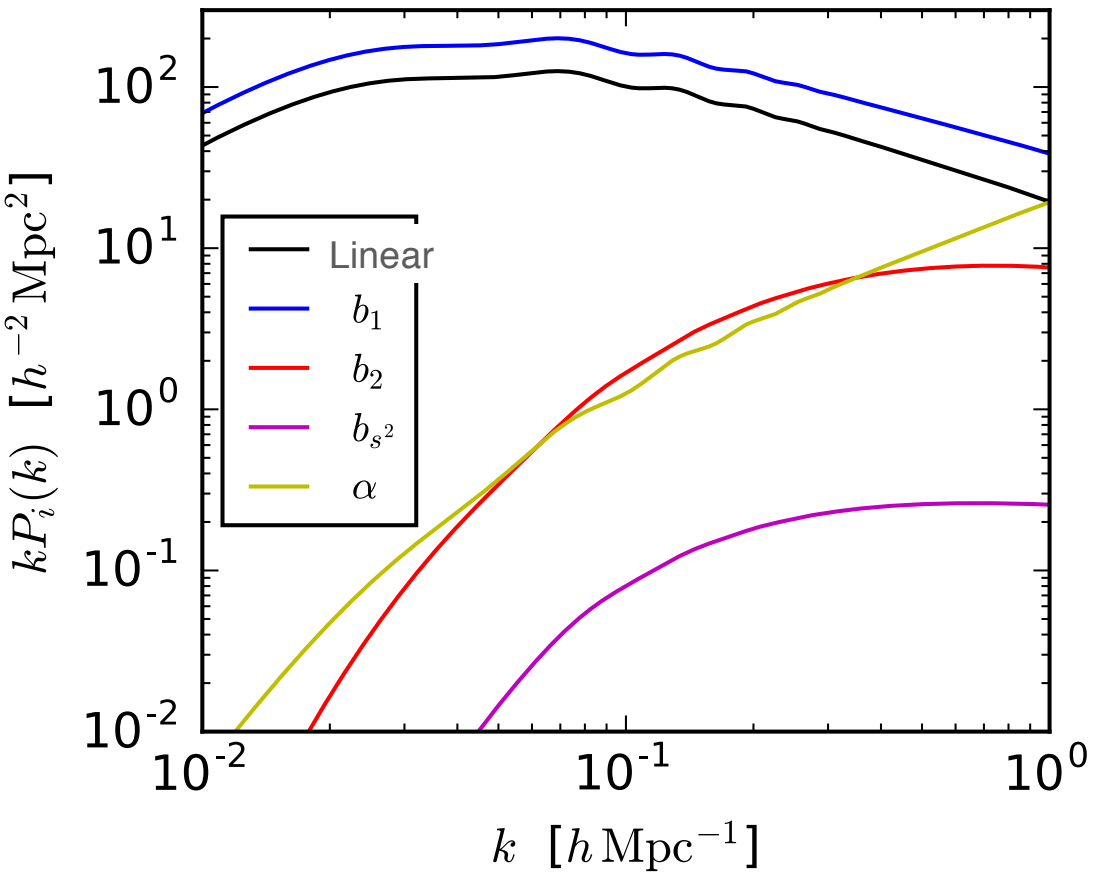
- Create mock dataset to test cosmology pipeline and impact of nonlinearities and uncertain dN/dz
- Model also marginalizes over uncertain magnification bias and redshift distribution
- Currently: testing on different HODs, redshift distributions

NONLINEAR BIAS MODEL

- Lagrangian PT + bias + EFT: CLEFT (Modi, White & Vlah 2017)

$$P_{mg}(k) = \left(1 - \frac{\alpha_\times k^2}{2}\right) P_{\rm Zel'dovich} + P_{\rm 1-loop} + \frac{b_1}{2} P_{b_1} + \frac{b_2}{2} P_{b_2}$$

$$+ \frac{b_{s^2}}{2} P_{b_{s^2}} + \frac{b_{\nabla^2}}{2} P_{b_{\nabla^2}} + s_\times$$



Modi Vlah & White 2017

CONSTRAINING COSMOLOGY

PRELIMINARY MOCKS

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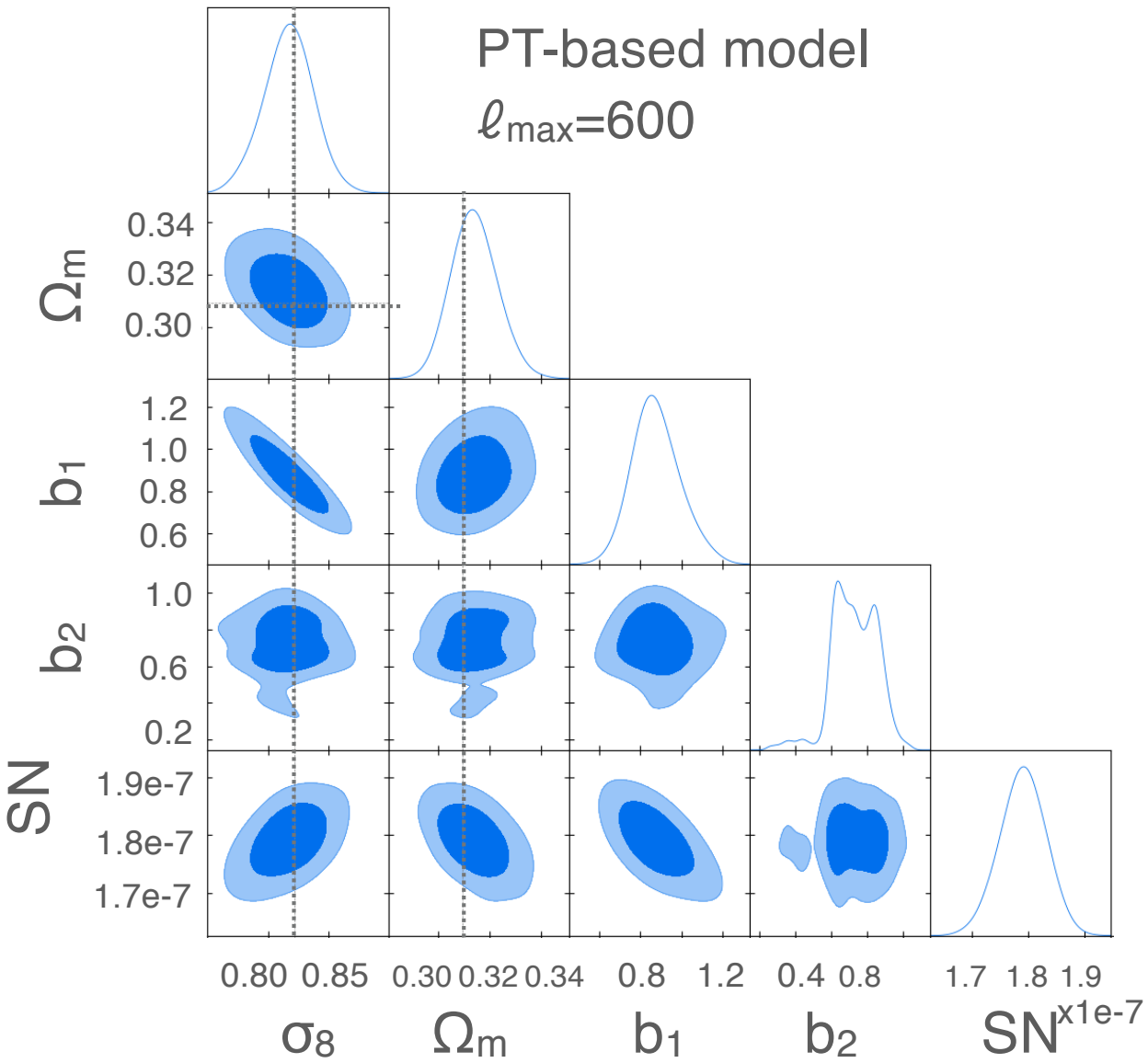


- Still working out kinks with PT model: volume effects, counter-term, slightly worse χ^2 than Halofit

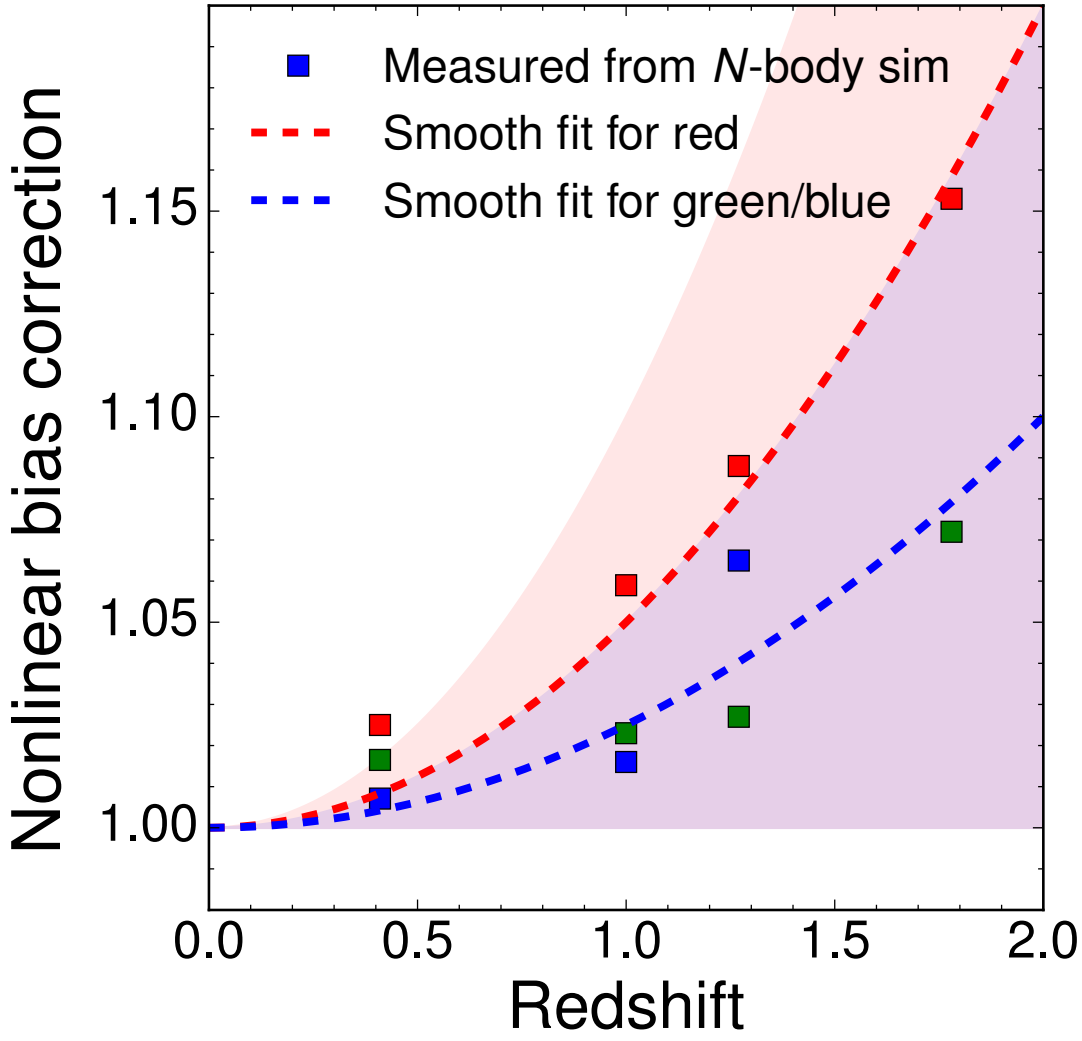
CONCLUSIONS & NEXT STEPS

- CMB lensing cross-correlation with S/N ~80 from 500 million galaxies at $0 < z < 2$
- 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

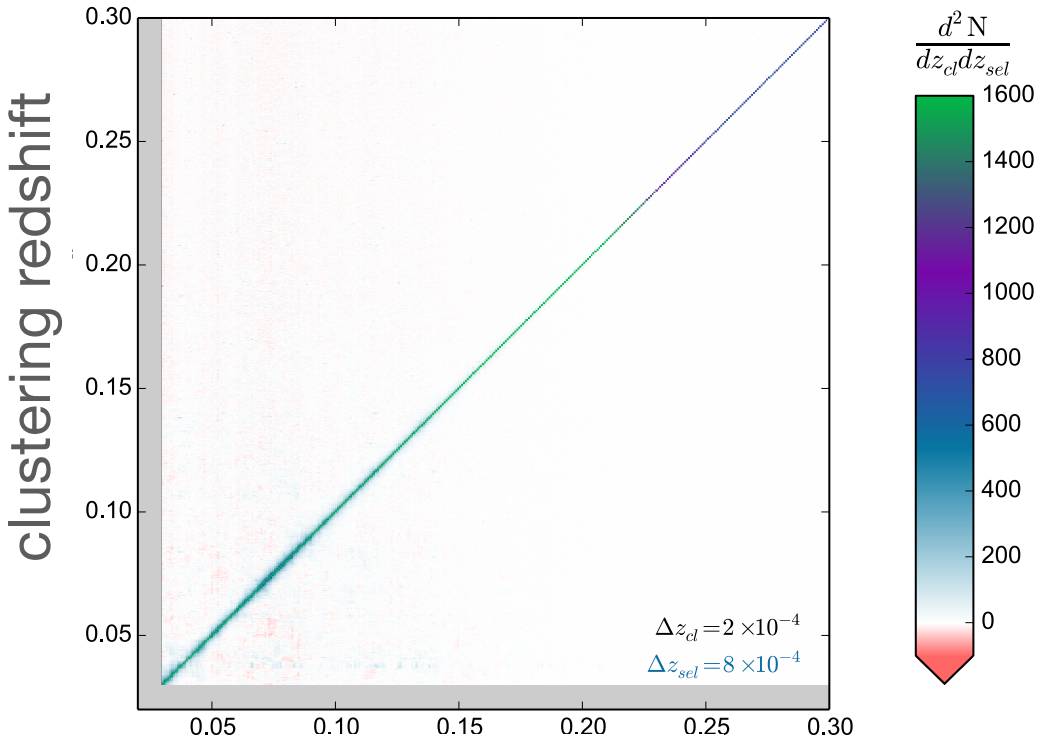
- Residual impact of nonlinear bias on $2.5 < r < 10\ h^{-1}$ Mpc is small



unWISE REDSHIFT DISTRIBUTION

- Measure dN/dz from cross-correlations with SDSS

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



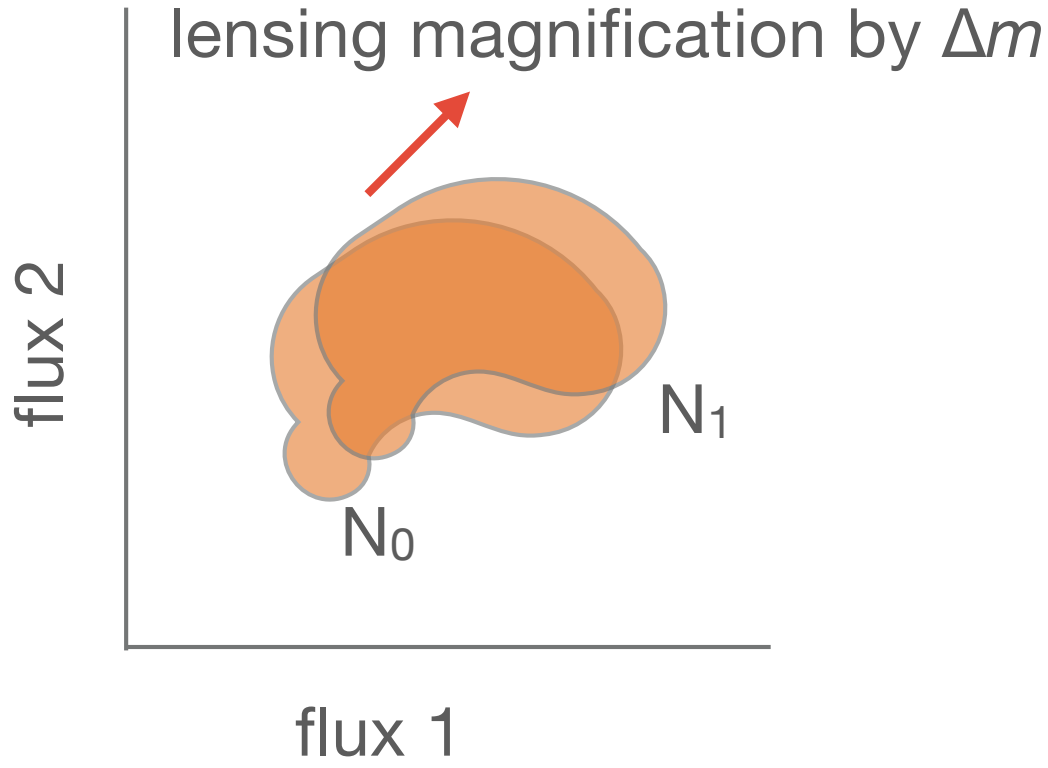
Rahman et al. 2015

- cross-check with cros MOS photo-z

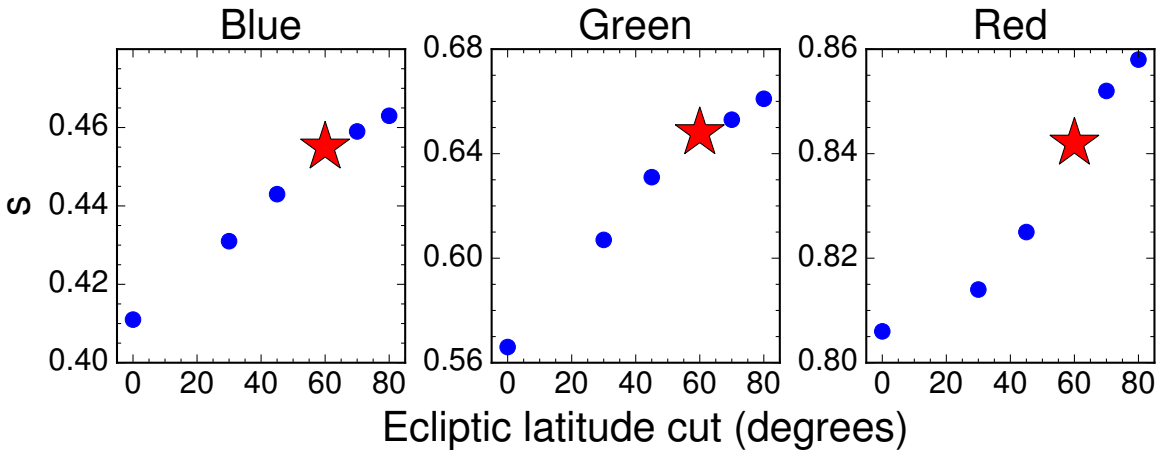
MEASURING s

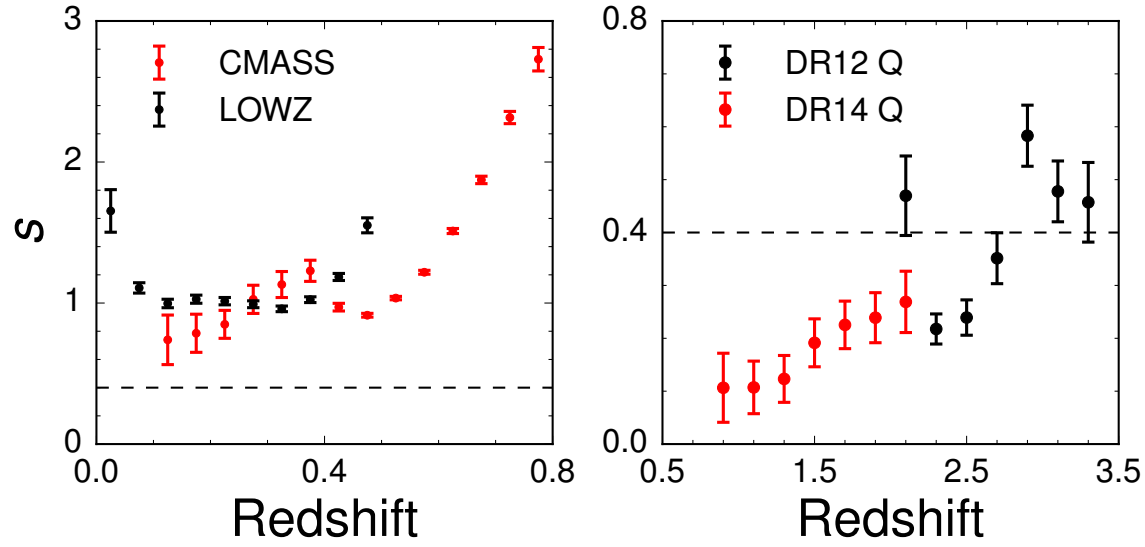
- s is response of number density to lensing magnification

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

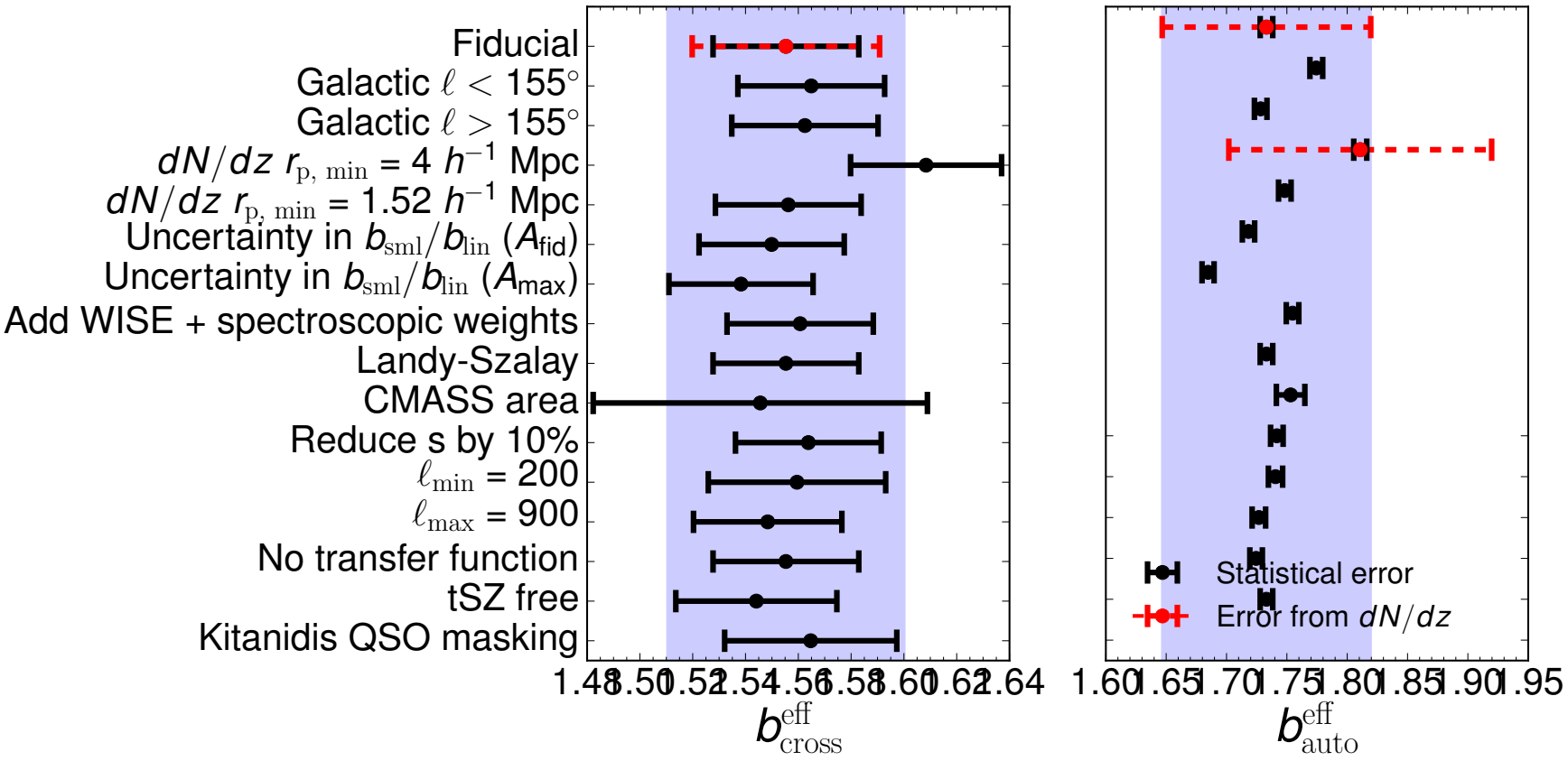


MEASURING MAGNIFICATION BIAS

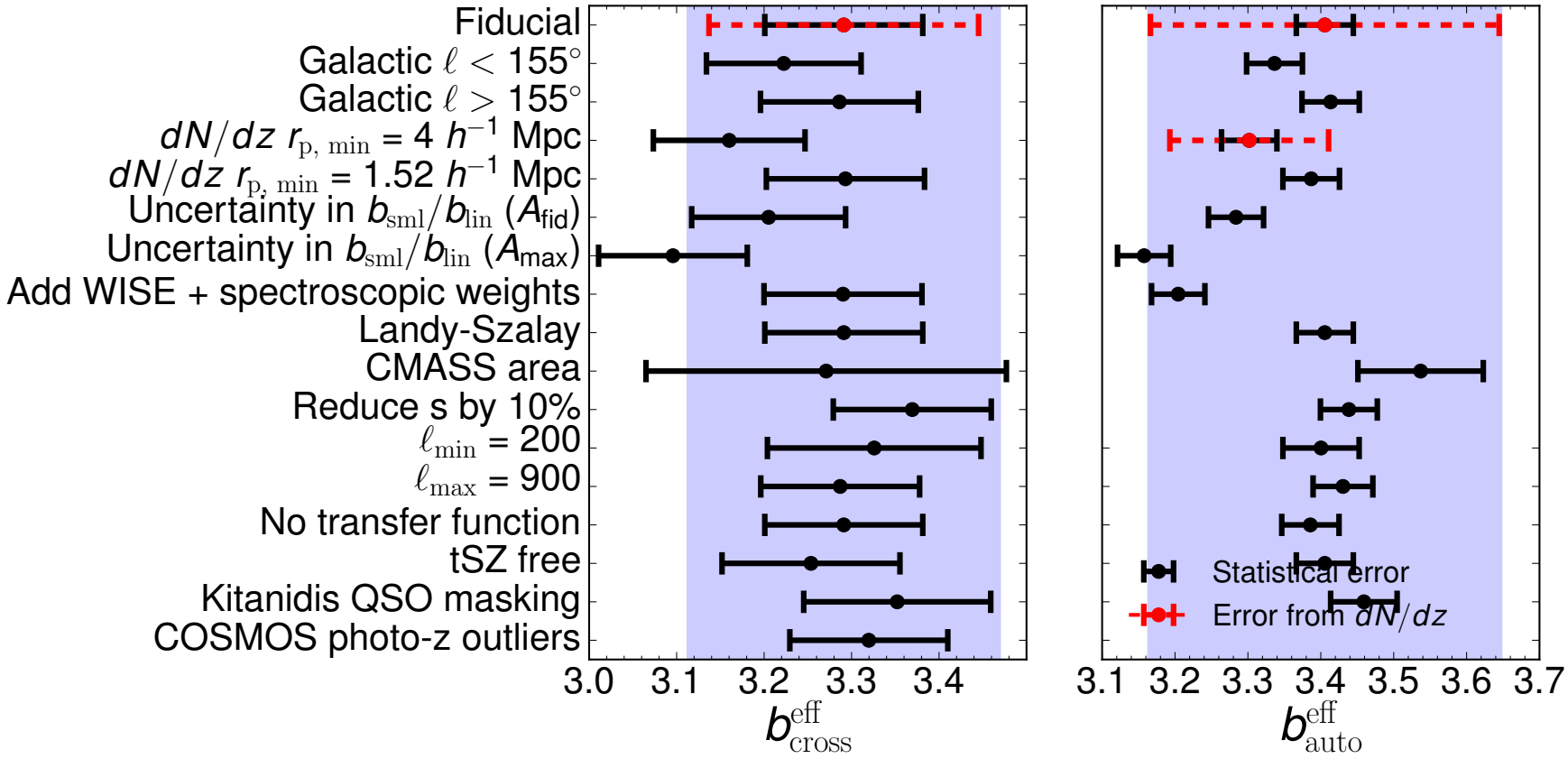




SYSTEMATICS SUMMARY (BLUE SAMPLE)

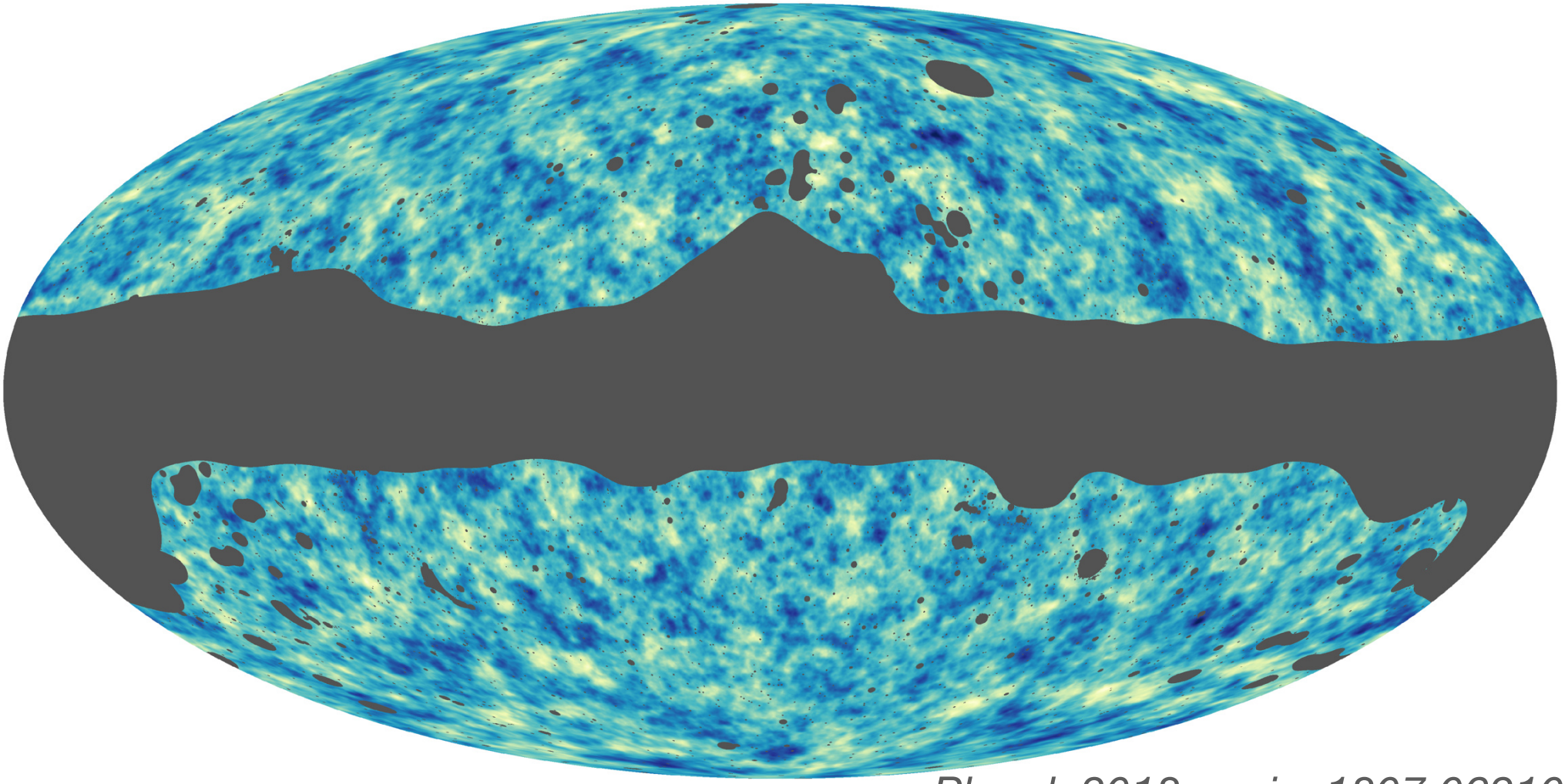


SYSTEMATICS SUMMARY (RED SAMPLE)



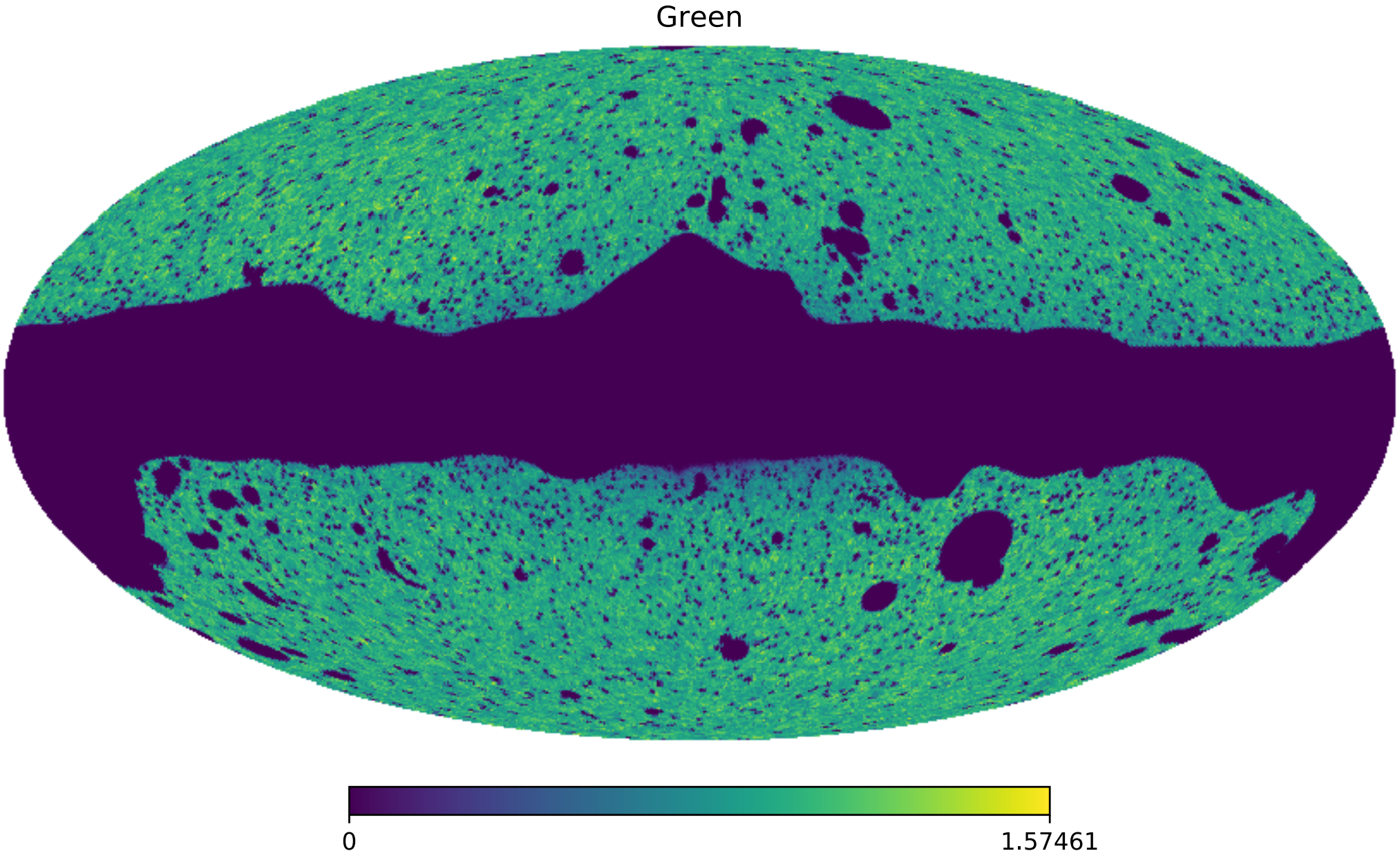
PLANCK LENSING MAP

- Auto-spectrum detected at 40σ

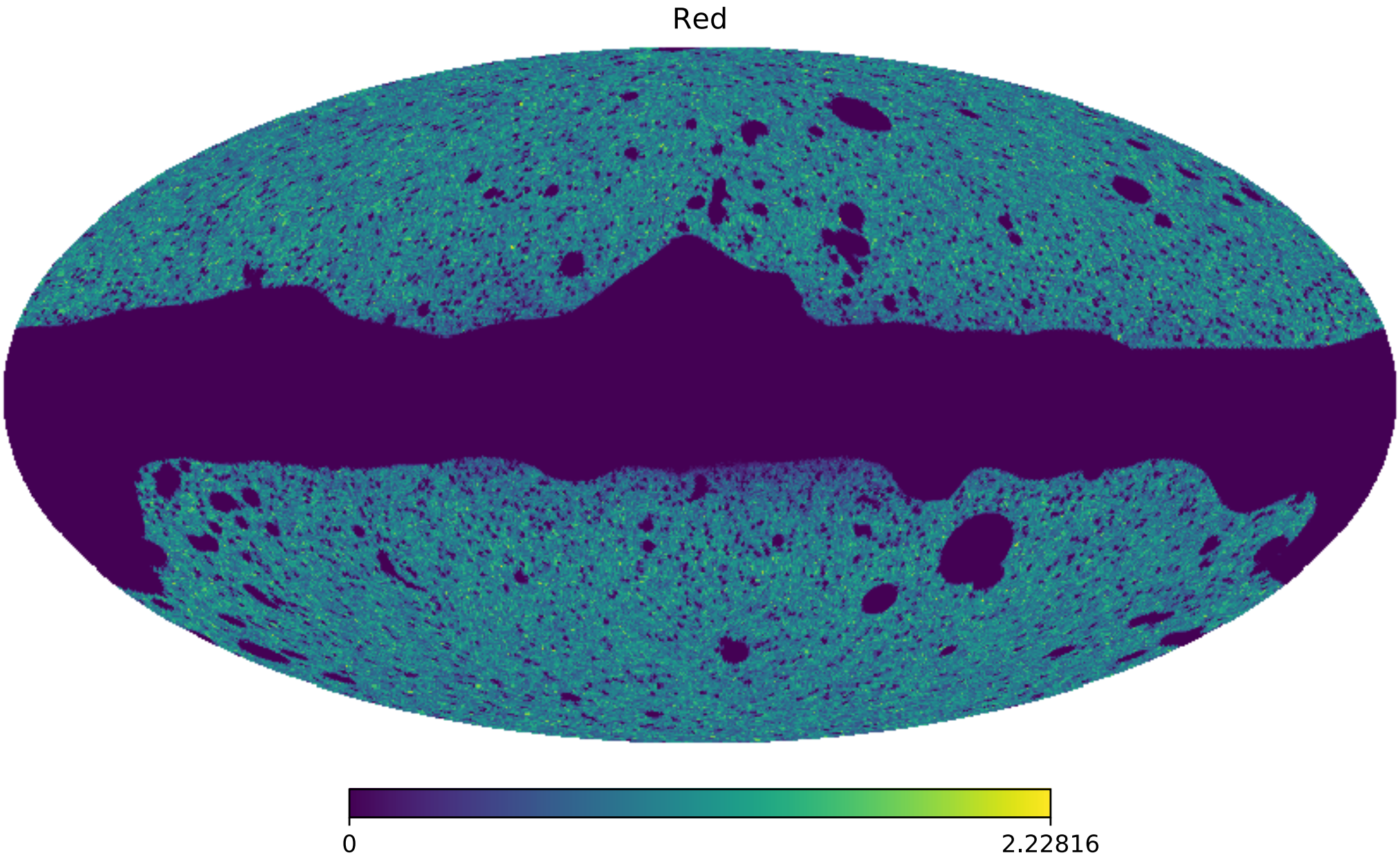


Planck 2018, arxiv: 1807.06210

SKY DISTRIBUTION

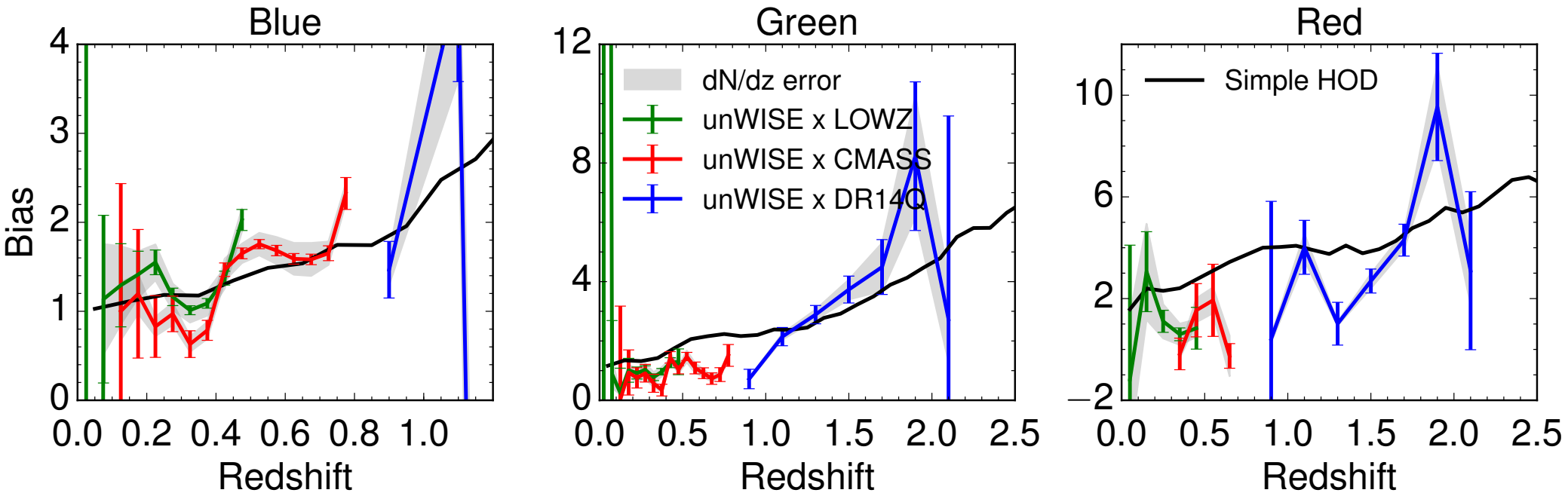


SKY DISTRIBUTION

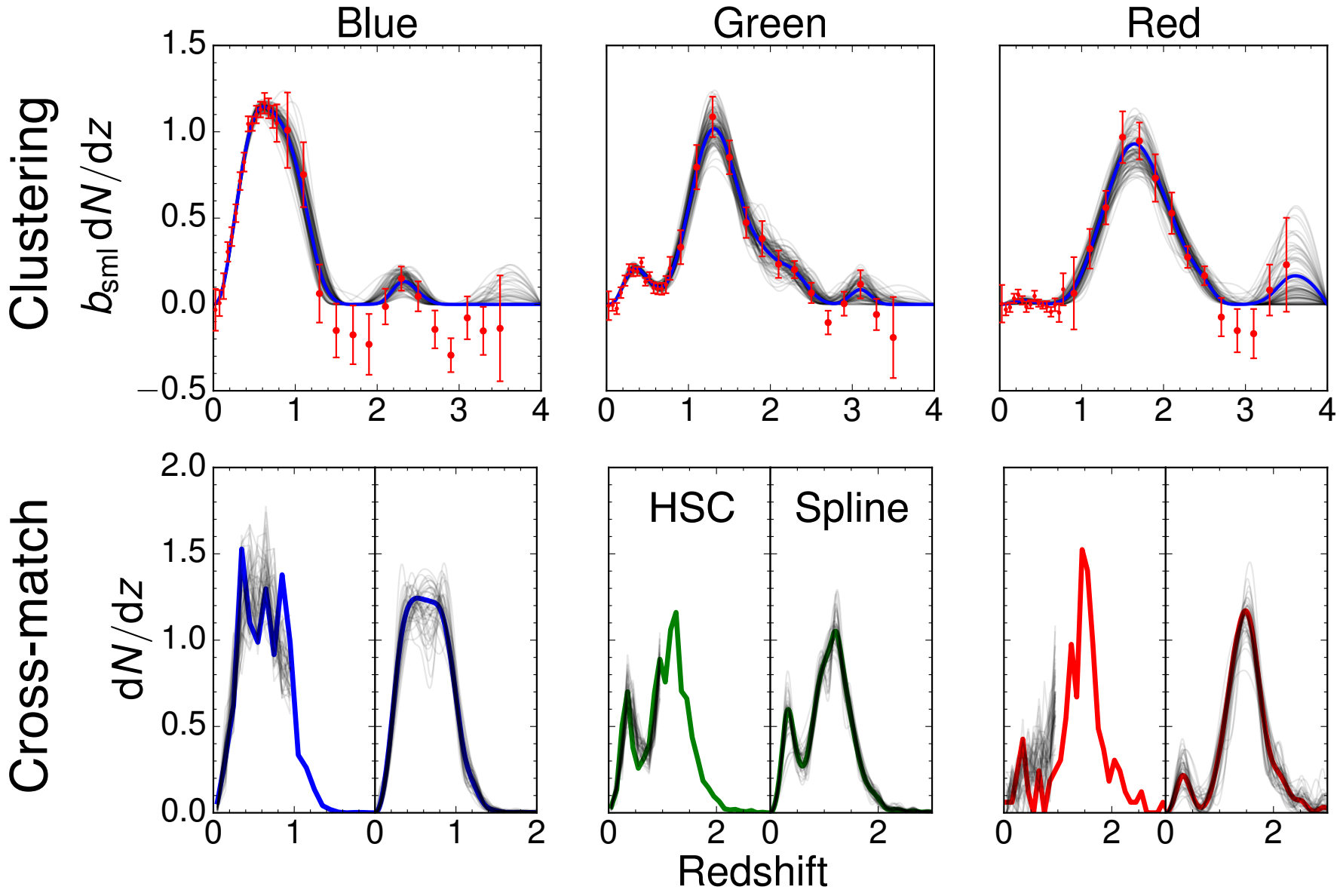


dN/dz CONSISTENCY

- 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