Correcting galaxy overdensity field with imaging weights does not debias power spectrum (and higher-order statistics)

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New Strategies for Extracting Cosmology from Galaxy Surveys

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Scientific Interests

- Involved in DESI and DESC
- High redshift ($z > 1$) galaxy tracers (ELGs in DESI, LBGs in DESC and DESI-II) for cross-correlation analysis
- Bayesian and Joint Survey Inference and testing of fundamental physics models
    - Dark energy with LSS tracers
    - Dark matter with Milky Way tracers

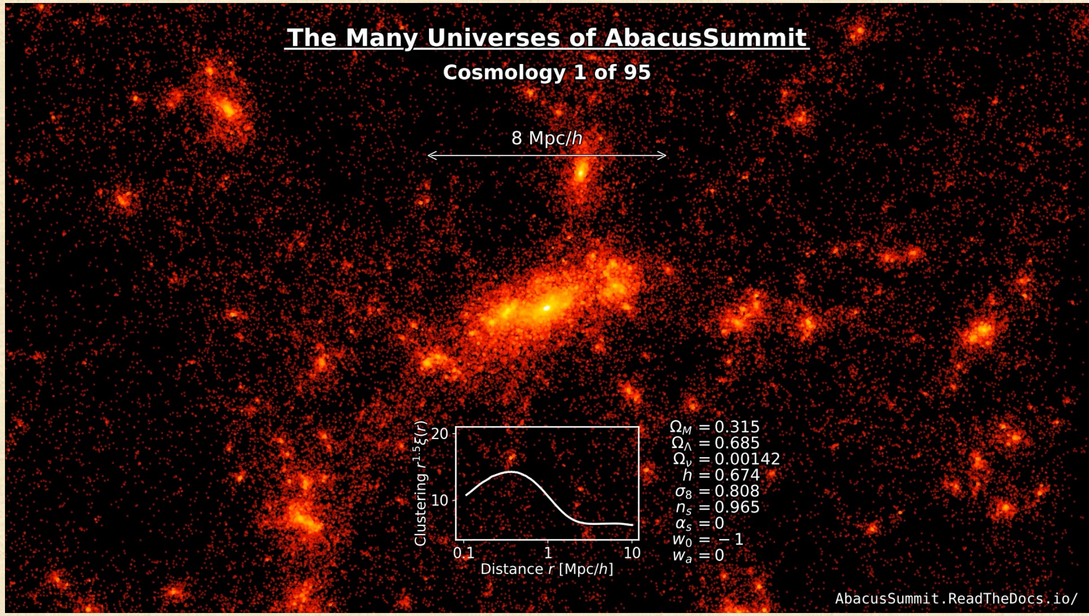
Structure of the Talk

- Cosmology from Surveys
- Definition of the Imaging Systematics problem
- Result 1: Bias of the Imaging Systematics Weights
  - Correction of the Bias
- Result 2: Marginalization of the Imaging Systematics Weights
- Result 3: Impact of Choice of Systematics (Dust) Maps
- Conclusion

Studying Cosmology from Data

Scientific Context

- Measuring the clustering (σ_8) of structure is a powerful way to constrain dark energy and dark matter



Measuring σ_8

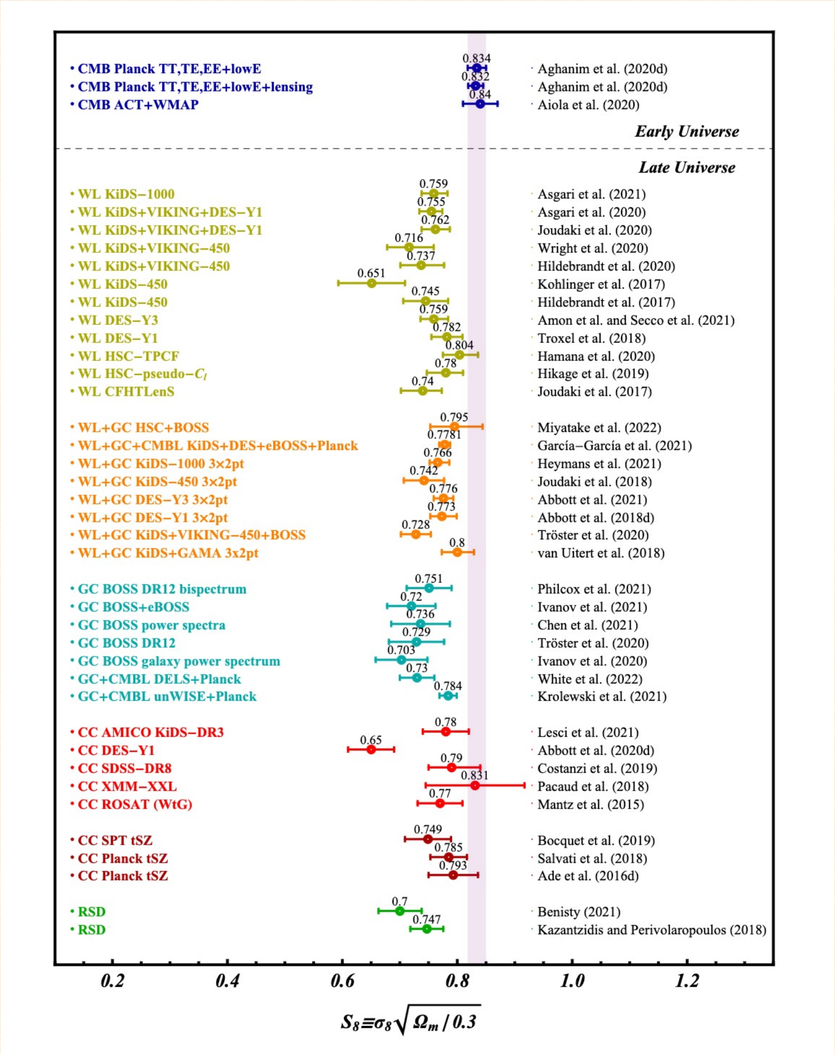
- Cross-correlating tracers of the matter density field
  - E.g., Galaxy number density and weak lensing of the CMB
- 2×2-pt function breaks galaxy-dark matter connection (galaxy bias) and σ_8 degeneracy
- Mathematically:

$$C_{gg} \sim b^2(z)\sigma_8^2$$
$$C_{\kappa g} \sim b(z)\sigma_8^2$$

Thus,

$$C_{gg}/C_{\kappa g} \sim b(z)$$

Tension in the σ_8 world



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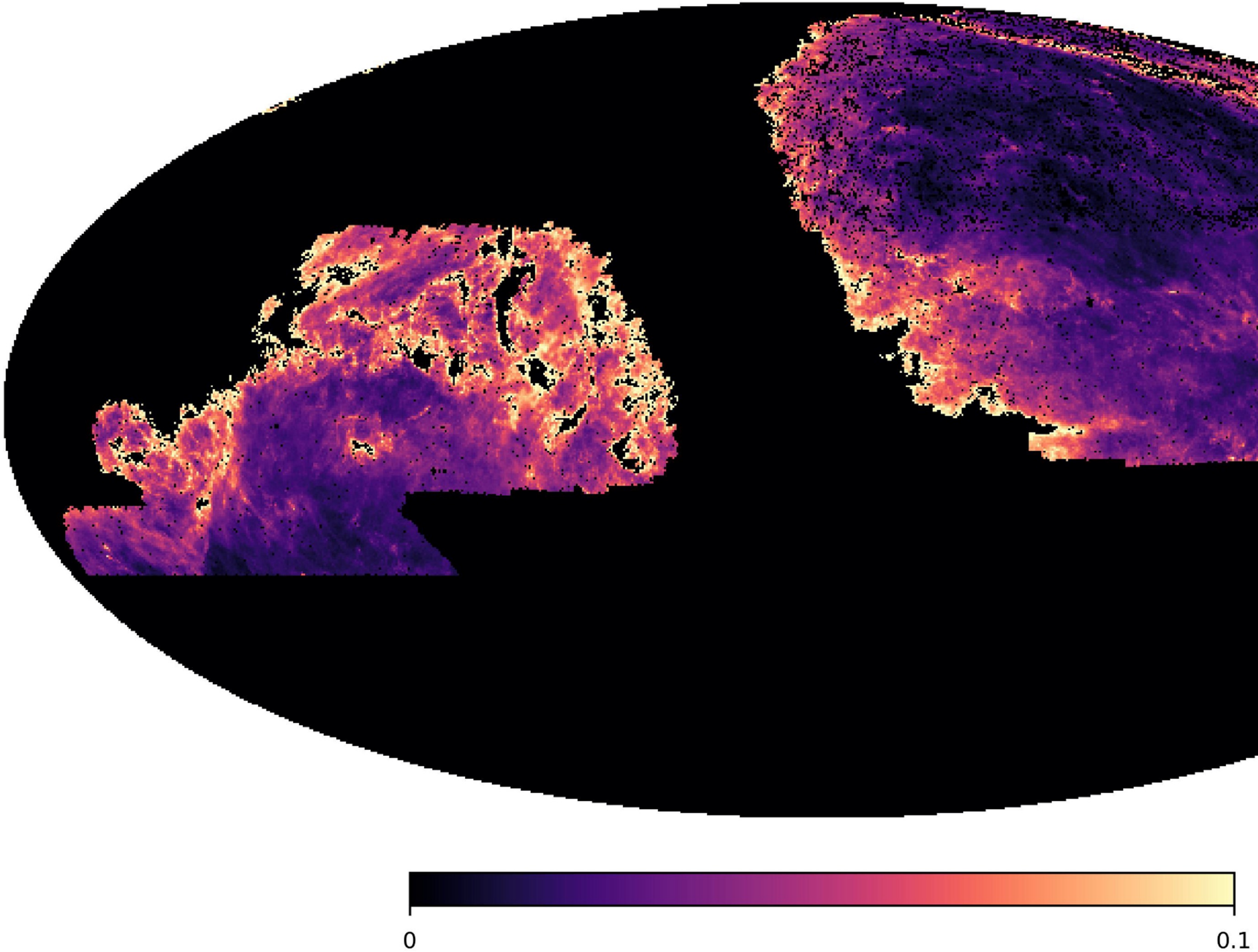
Defining the Problem of Imaging Systematics

Legacy Surveys Footprint



Schegel, Finkbeiner & Davis 1998

Defining Imaging Systematics Weights

Weights that characterize how foreground systematics fluctuate the true galaxy overdensity field

Relation to σ_8 Inference

Observed galaxy overdensity field at pixel x, $\delta_g^{obs}(x)$

True galaxy overdensity field at pixel x, $\delta_g^{t}(x)$

Residual systematics at pixel x, $\delta_{sys}(x)$

$$\delta_g^{obs}(x) = \delta_g^{t}(x) + \delta_{sys}(x)$$

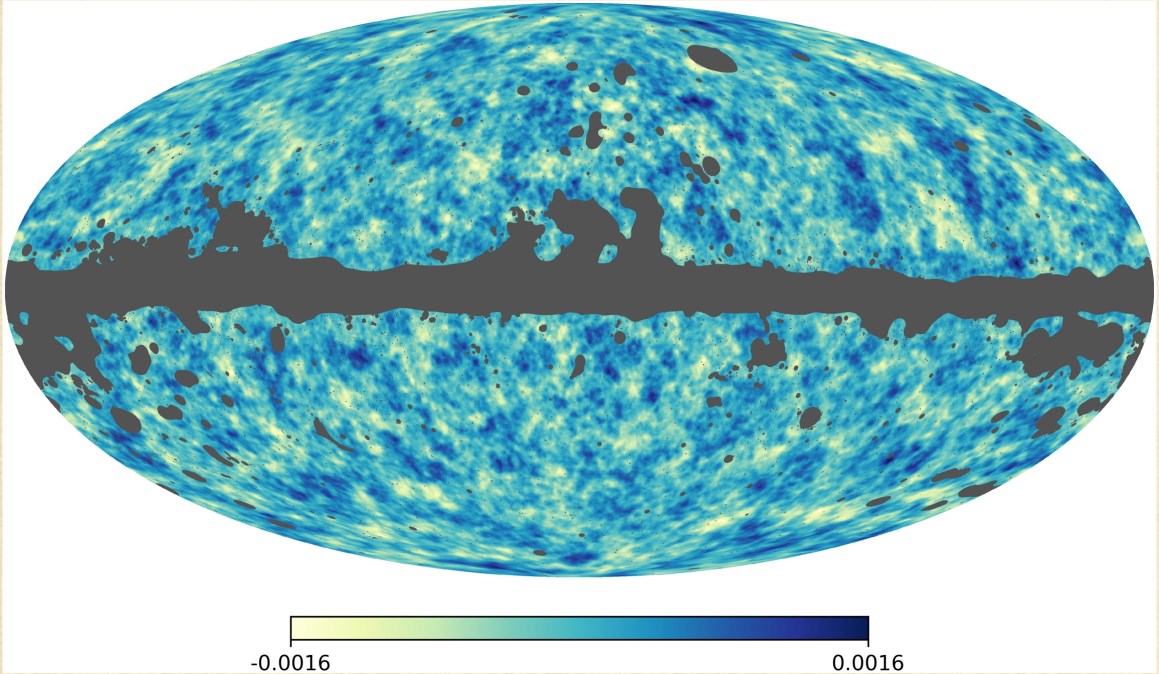
$$C_{gg}^{obs} = < \delta_g^{obs} \delta'^{obs}_g >$$
$$= < \delta_g^{t}(x) \delta'^{t}_g(x) > + < \delta_{sys}(x) \delta'_{sys}(x) >$$
$$= C_{gg}^{t} + C_{sys}$$

$$C_{\kappa g}^{obs} = < \delta_g^{obs} \delta_\kappa > = C_{\kappa g}^{t}$$

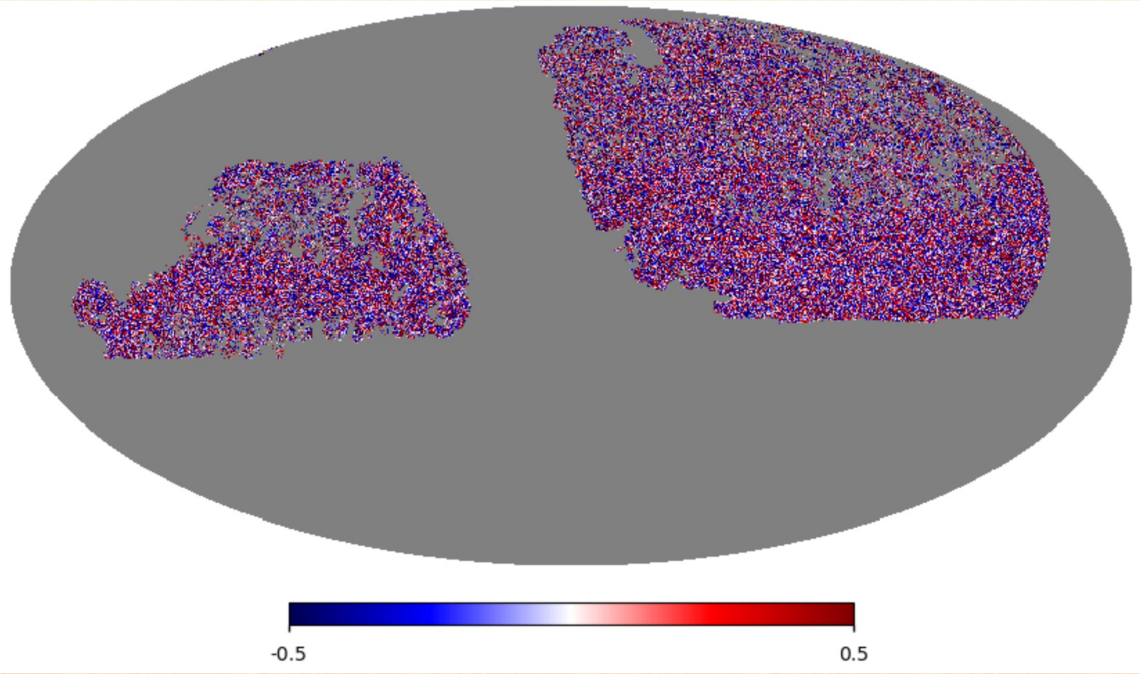
Misestimation of galaxy overdensity field leads to a higher inferred value of galaxy bias and **lower inferred value of σ_8**

Therefore, $C_{gg}^{obs} / C_{\kappa g}^{obs} \sim C_{gg}^{t} / C_{\kappa g}^{t} + C_{sys} / C_{\kappa g}^{t} = b(z) + C_{sys} / C_{\kappa g}^{t}$

Data

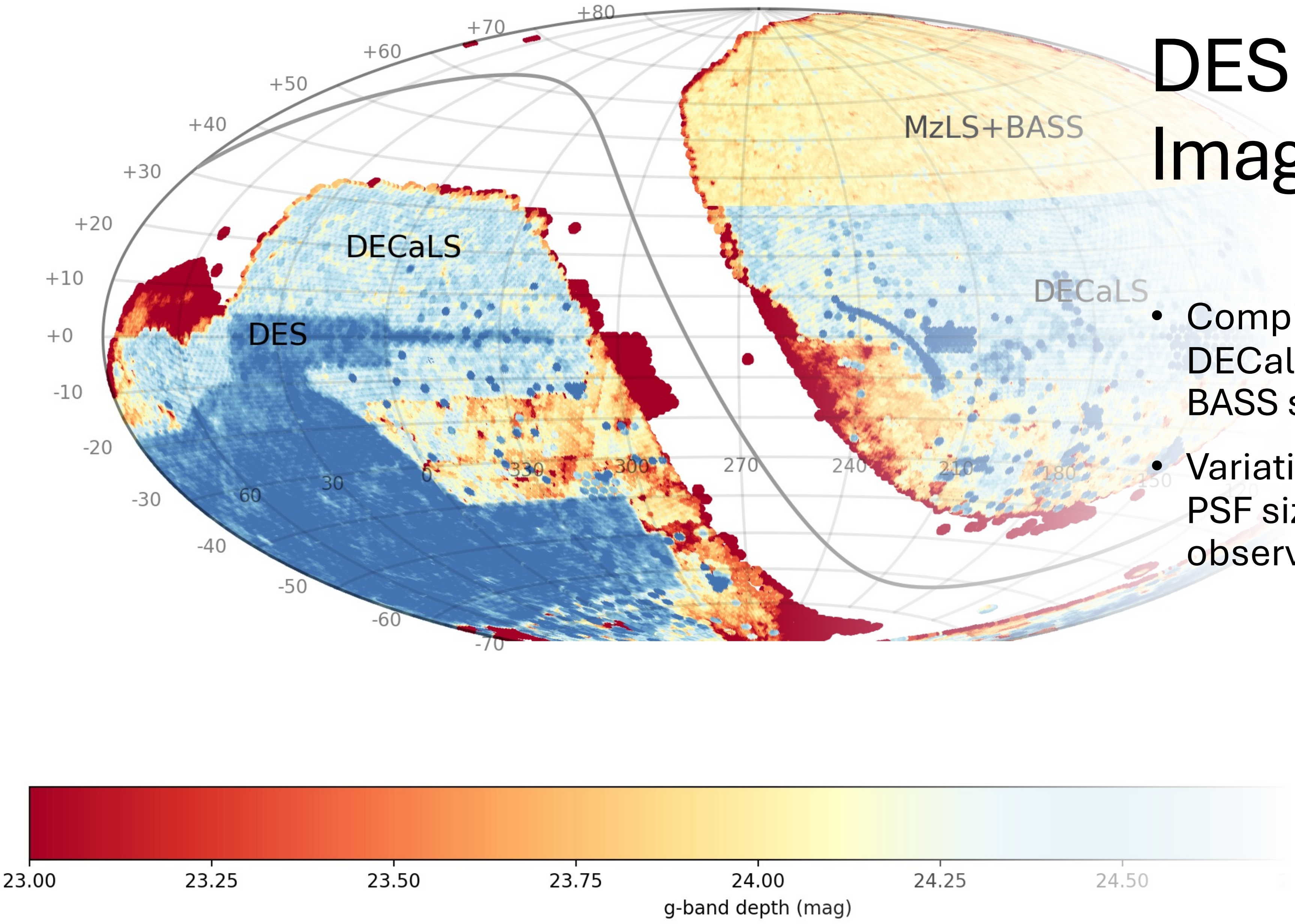


Planck CMB Lensing 2018 Release



DESI Legacy Surveys Emission-Line Galaxies

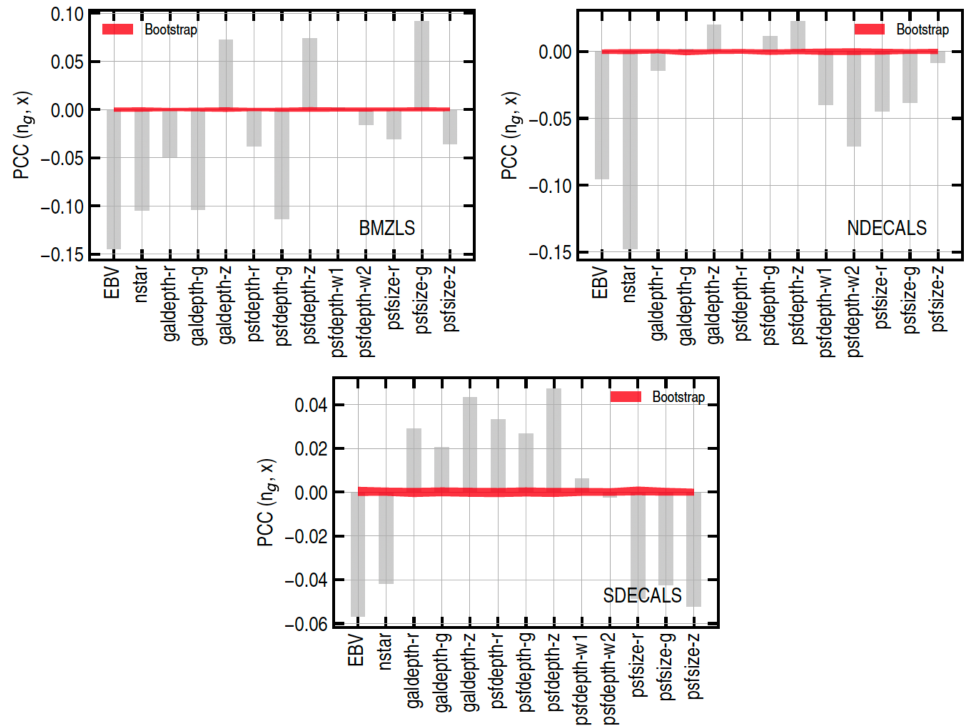
DESI Legacy Imaging Surveys

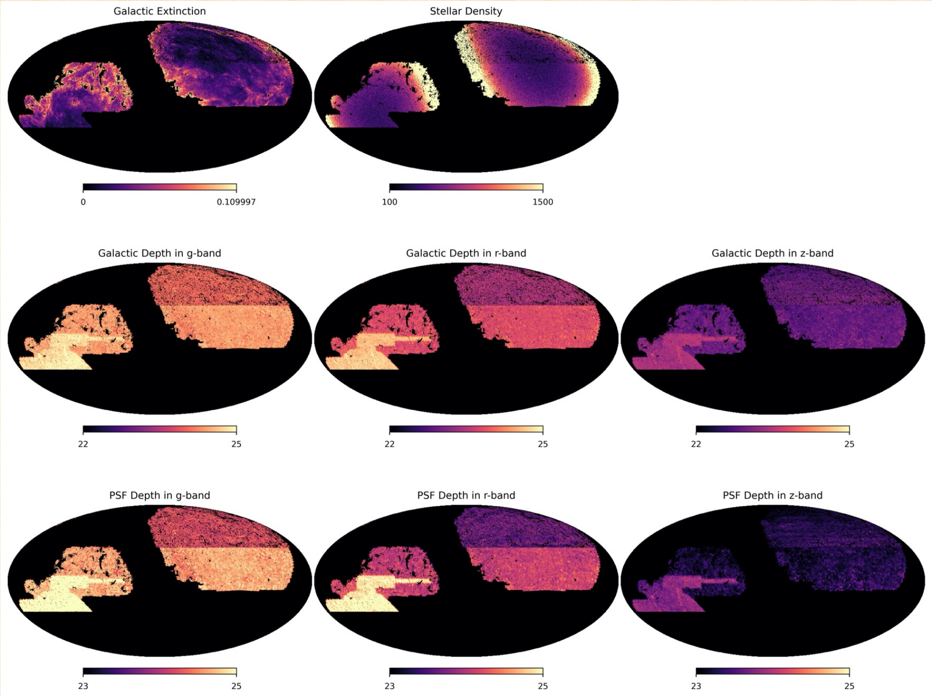


- Compilation of DECaLS North, DECals South, DES, MzLS and BASS surveys
- Variation is Galactic extinction, PSF size, depth, etc. affects observed galaxy density

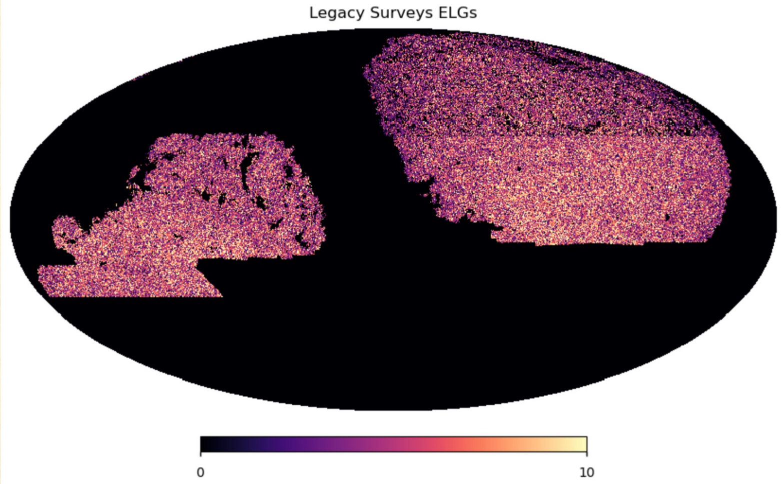
Estimating Imaging Systematics Weights

- Foreground systematics are uncorrelated with Large-Scale Structures
- If correlated:
  - Solve for weights per pixel that minimize observed correlation





Regression



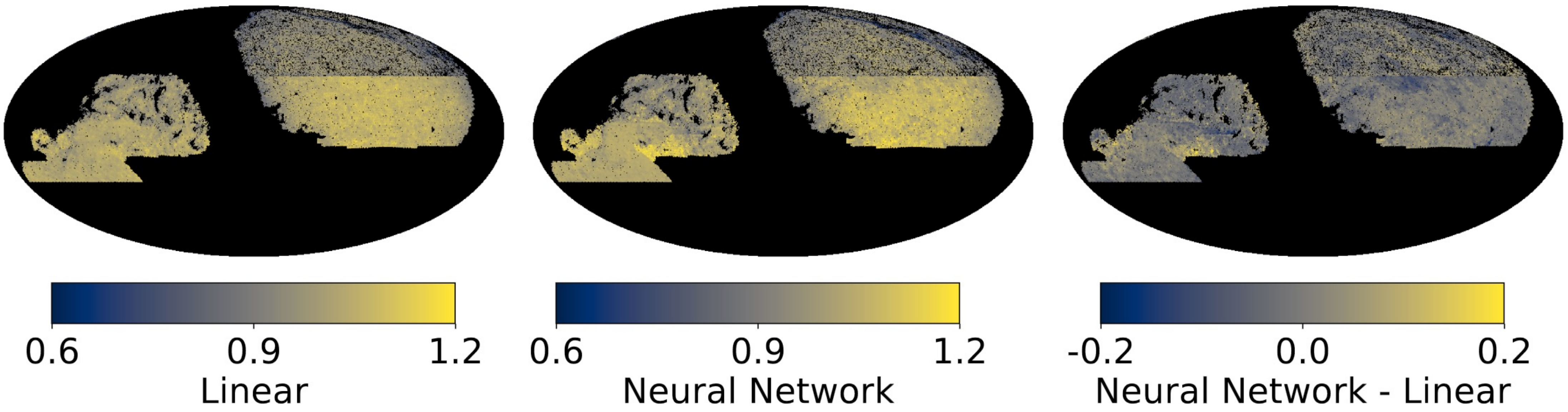
Features, x_i

Observed Number Density, y

Result 1: Bias in Imaging Systematics Weights

Estimator of the imaging systematics weights is biased in power spectrum and needs to be corrected for

Neural Network Regressor learns complex foreground better than Linear Regressor



Correcting for Bias in Power Spectrum

- Sample posterior of imaging systematics maps
- Use (Gaussian) simulation to model contribution of additive and multiplicative bias in power spectrum
  - Assume,

$$\delta_g^{obs,t}(x) = W_g^t \delta_g^t(x)$$

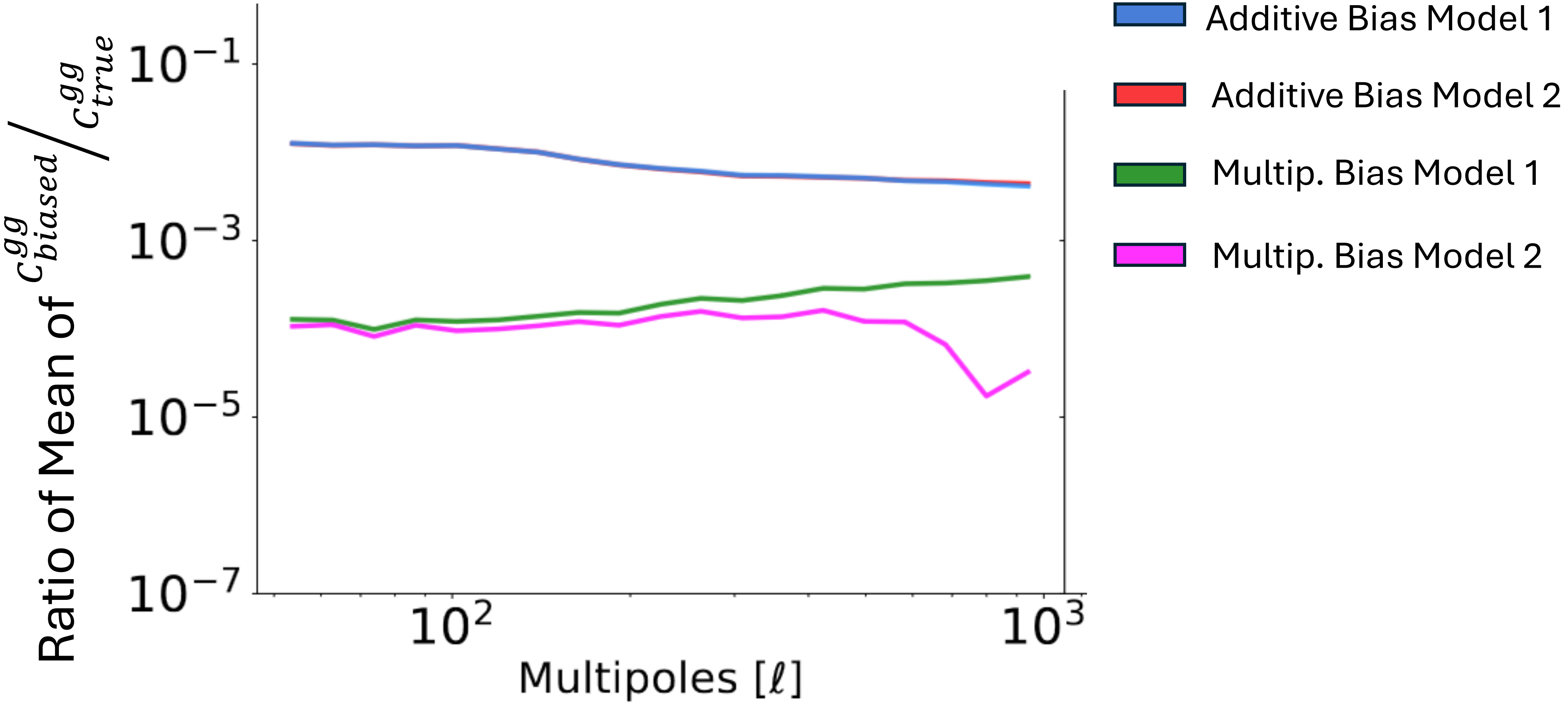
  - Simulate,

$$\delta_g^{obs,i}(x) = W_{g,i}(x)[1 + \delta_g^t(x)] - W_g^t(x)$$
$$= \left[W_{g,i}(x) - W_g^t(x)\right] + W_{g,i}(x)\delta_g^t(x)$$

Additive bias   Multiplicative bias

  - Compare, true observed power spectrum with realizations

Simulation-based Approach corrects for bias in power spectrum



Result 2: Marginalization of Imaging Systematics Weights Estimator Uncertainty

Marginalizing the estimator leads to a lower SNR of power spectrum

Imaging Weights Uncertainty

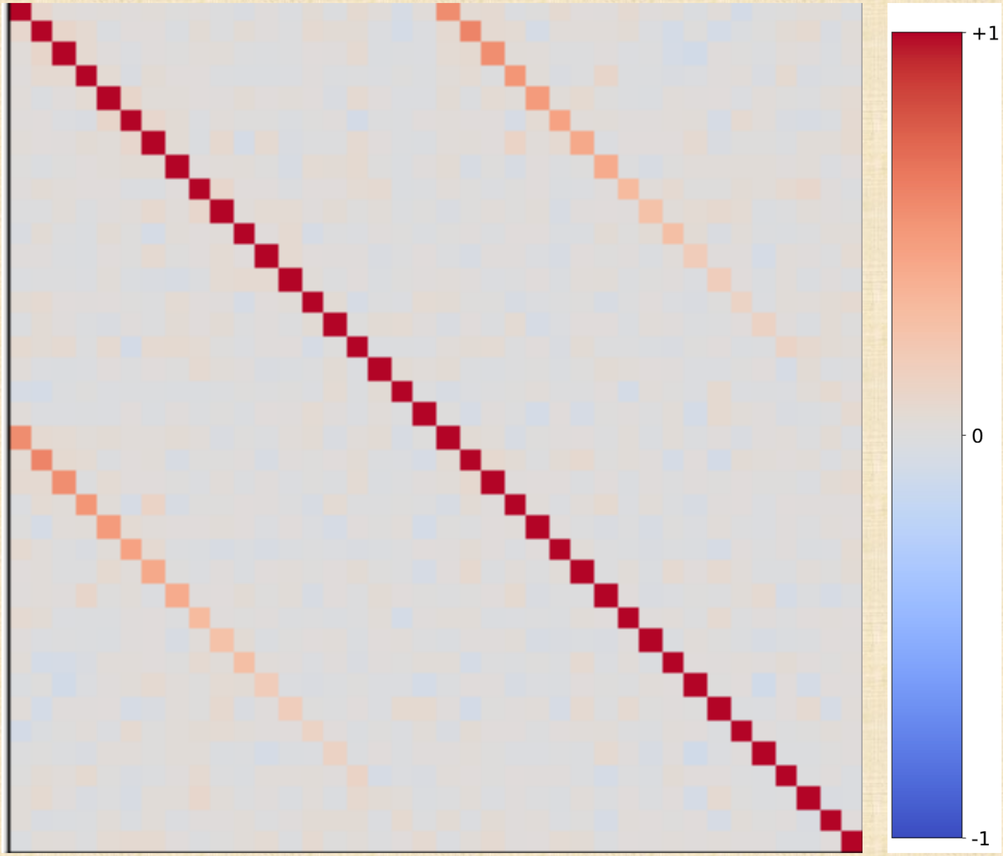
Regression gives us best fit values, not uncertainties

0.82	0.91	1
1.2	0.67	0.98
1.33	0.25	0.78

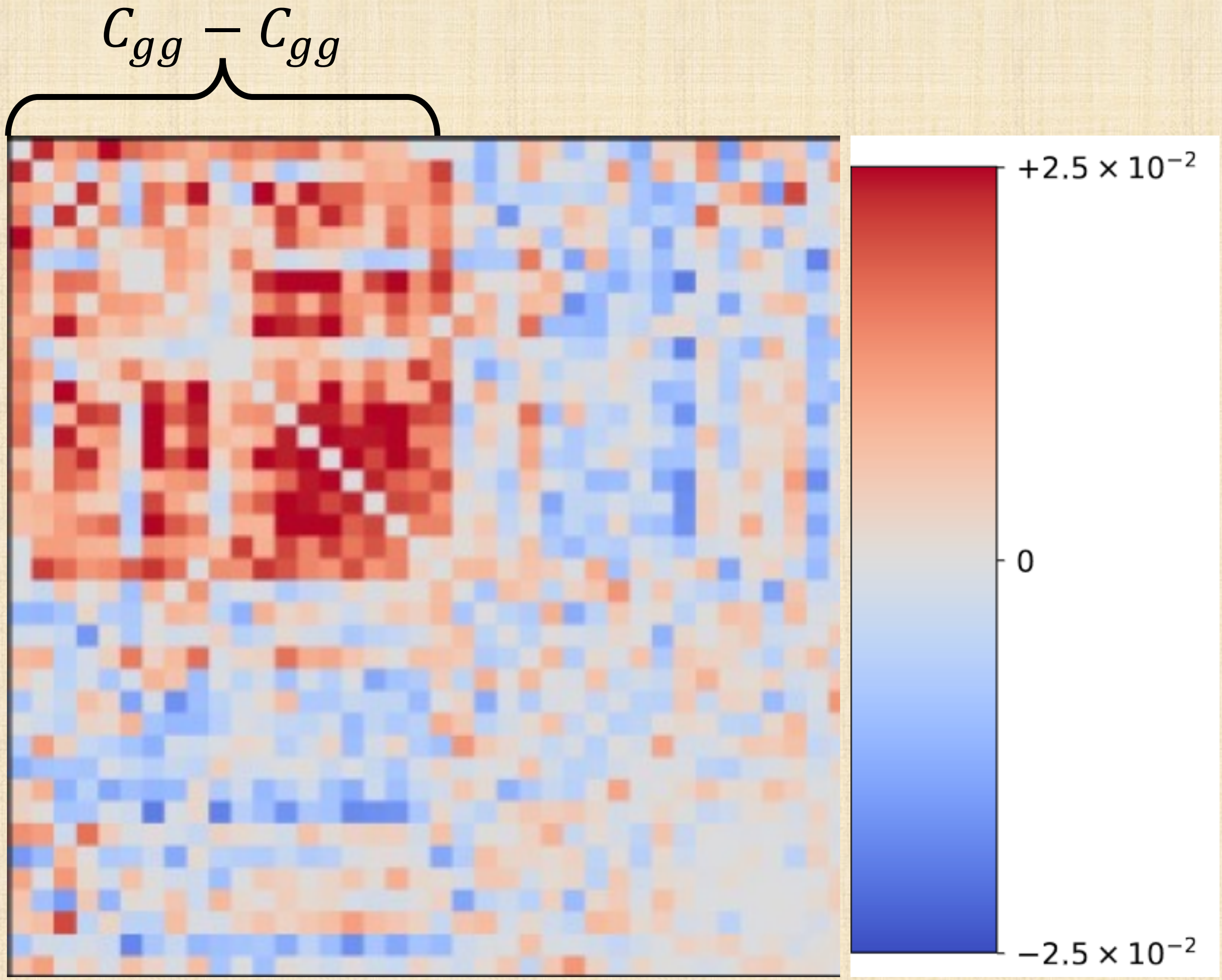
0.82 ± 0.02	0.91 ± 0.1	1 ± 0.04
1.2 ± 0.7	0.67 ± 0.05	0.98 ± 0.2
1.33 ± 0.12	0.25 ± 0.09	0.78 ± 0.01

But should we care about the uncertainties?

Comparison of Covariance Matrices

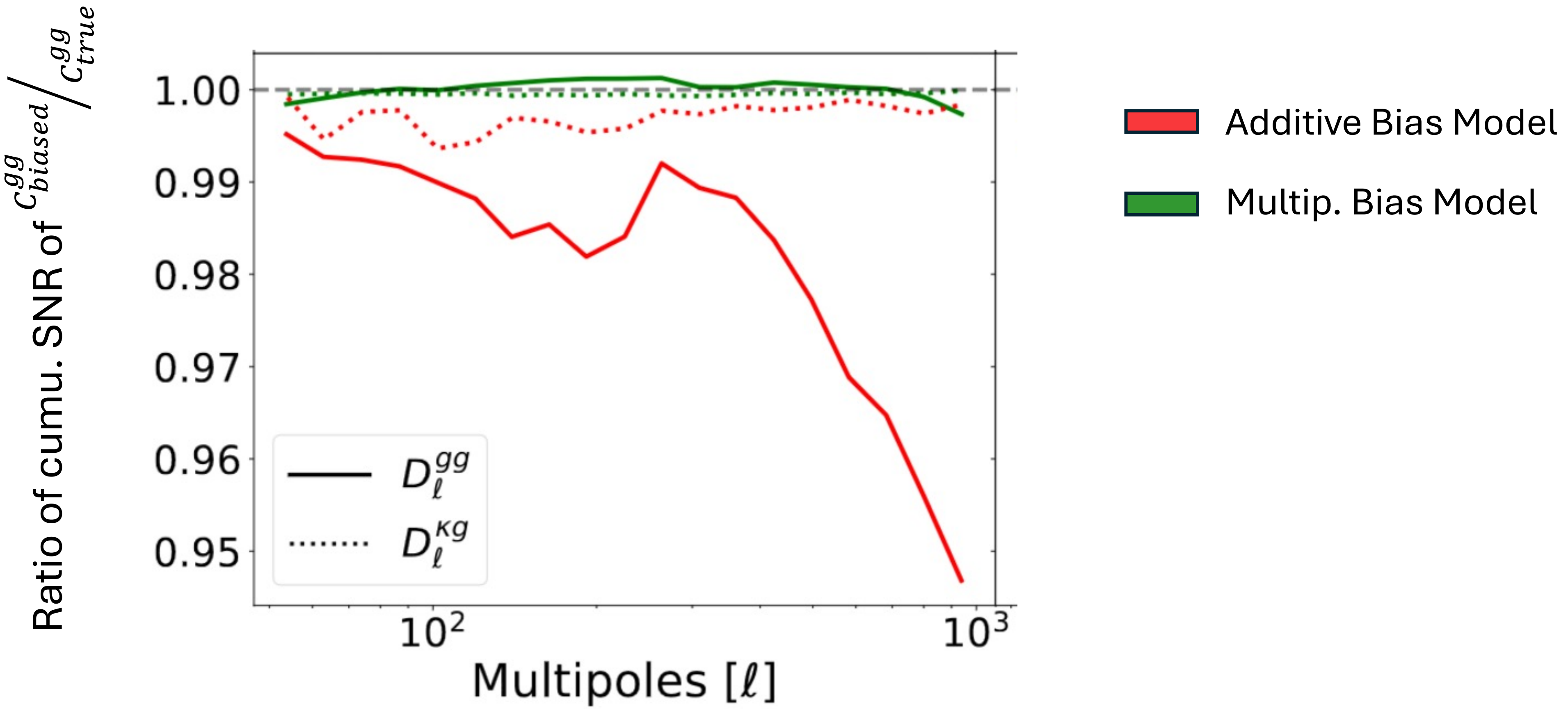


No Bias



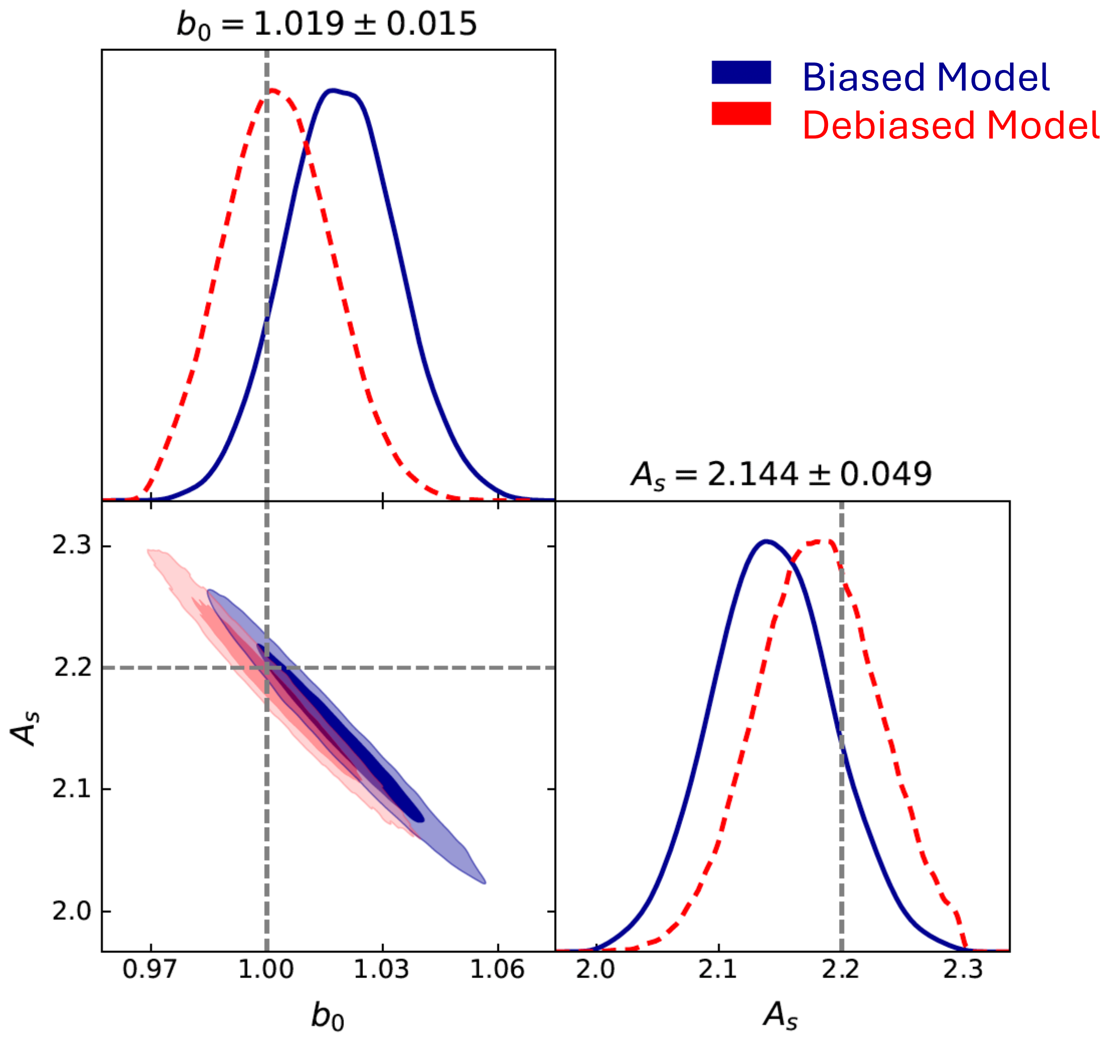
Additive Bias – No Bias

Marginalizing the Estimator leads to a loss in SNR



Combined Result: Impact on Cosmological Parameter Inference

Additive bias reduces inferred σ_8 and increases volume of error ellipsoid

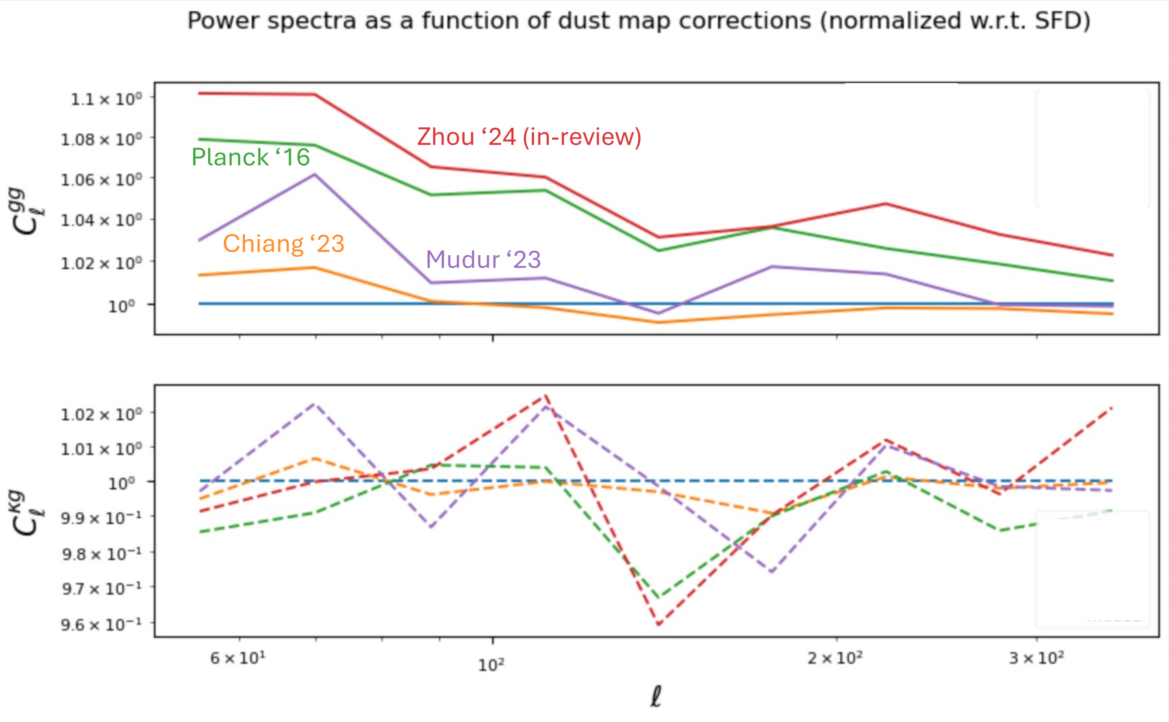


Result 3: Impact of Dust Map (New Result)

Choice of baseline systematics maps needs to be marginalized over

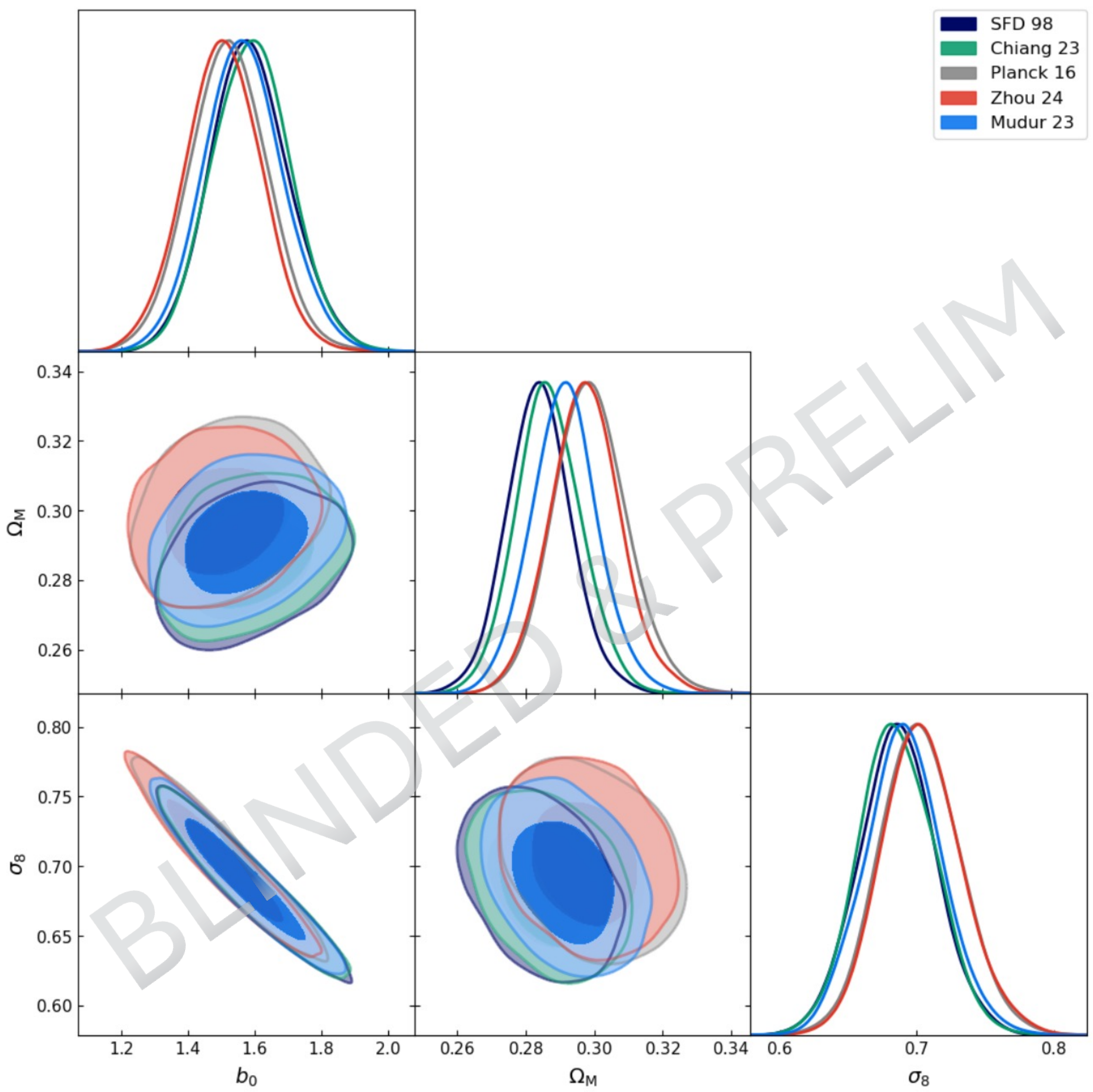
Choice of Systematics Maps

- Systematics template map itself can be treated as random variable
- If tracer of systematics template, e.g., dust, is biased:
  - Affects observed galaxy-galaxy clustering



Karim+ 24 (in collaboration-wide review

Choice of dust map template introduces systematic bias



Karim+ 24 (in collaboration-wide review

Key Takeaways:

- Unbiased galaxy overdensity estimator DOES NOT imply unbiased higher-order (including power spectrum) estimators
- Neural-network based estimators have higher variance but lower bias when it comes to complicated systematics
- Imaging weights uncertainty needs to be marginalized over for proper SNR
- For Legacy Surveys ELGs X Planck CMB Lensing:
    - A_S is $\sim$ 2% lower in the biased model
    - Relative error of A_S increased by $\sim$ 5% when properly marginalizing over the imaging systematics estimator
- Choice of systematics maps has a noticeable impact on cosmological parameters
    - SFD versus Zhou ’24 (or Planck ’16) show a noticeable shift in the $\sigma_8 - \Omega_M$ plane

Extra Slides