Title: What is S_8(z_low) actually?

Speakers: Noah Sailer

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

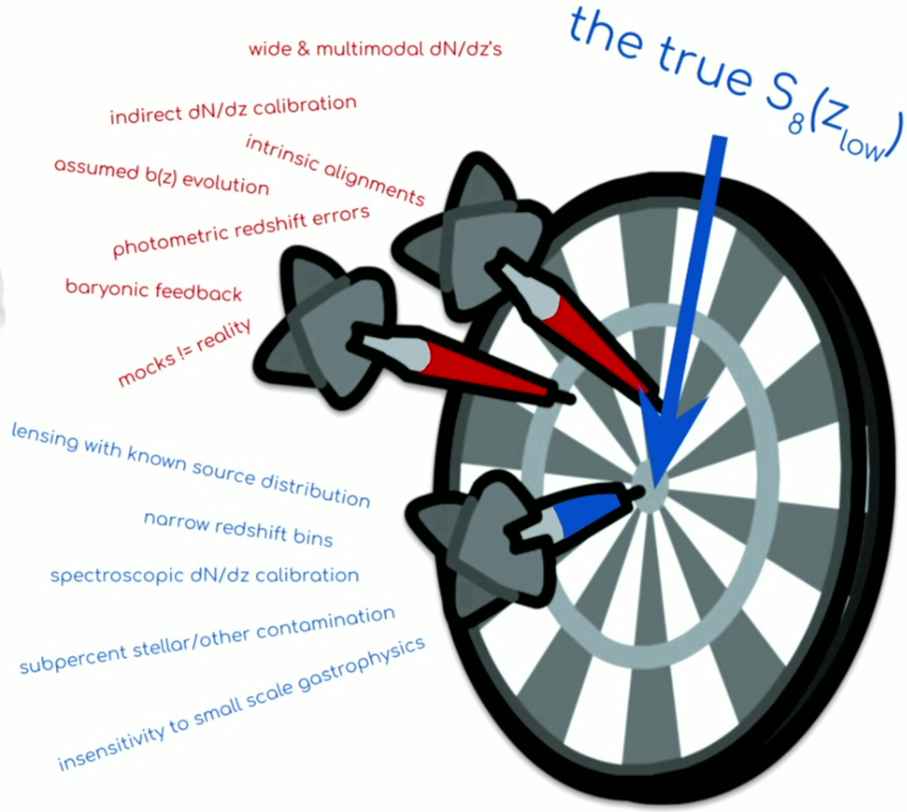
Date: October 15, 2024 - 11:00 AM

URL: https://pirsa.org/24100110

Abstract:

Claims of a low clustering amplitude (S_8) at low redshifts from weak galaxy lensing measurements trace back nearly a decade, however, recent work suggests these results may be driven by large baryonic feedback or mischaracterization of linear alignments. I will present a complimentary approach to measure the evolution of S_8(z) using spectroscopically calibrated DESI galaxies and the latest CMB lensing measurements from Planck and ACT. These data are insensitive to many of the systematic complications present in galaxy lensing measurements, while our fiducial Hybrid Effective Field Theory model robustly regulates the information obtainable from smaller scales, such that our cosmological constraints are reliably derived from the (predominantly) linear regime. Our tomographic analysis of DESI Luminous Red Galaxies (LRG) prefers a slightly lower (5 − 7%) value of S_8 than primary CMB measurements with a statistical significance ranging from 1.8 − 2.3σ. Intriguingly, our lowest redshift LRG bin is most discrepant with a Planck cosmology, leaving open the possibility that structure growth is slowing down for redshifts z < 0.5. To address this possibility, I will conclude my talk with preliminary results from the DESI Bright Galaxy Survey, which enable tomographic S_8(z) measurements over the redshift range 0.1 \lesssim z \lesssim 0.4.

What is $S_8(z_{low})$ ...actually?



Noah Sailer

in collaboration with Simone Ferraro, Martin White, Joshua Kim, Mathew Madhavacheril ++

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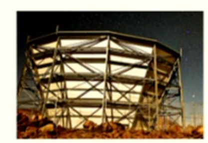
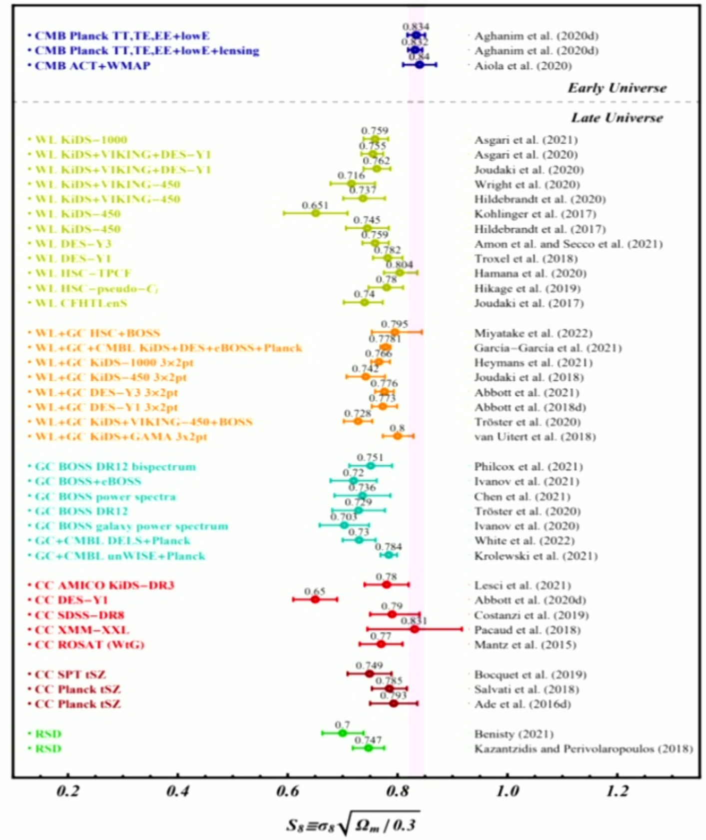


S_8 "tension"

≃ 5-10% discrepancy between **some** low- and high-redshift measurements of the linear power spectrum amplitude



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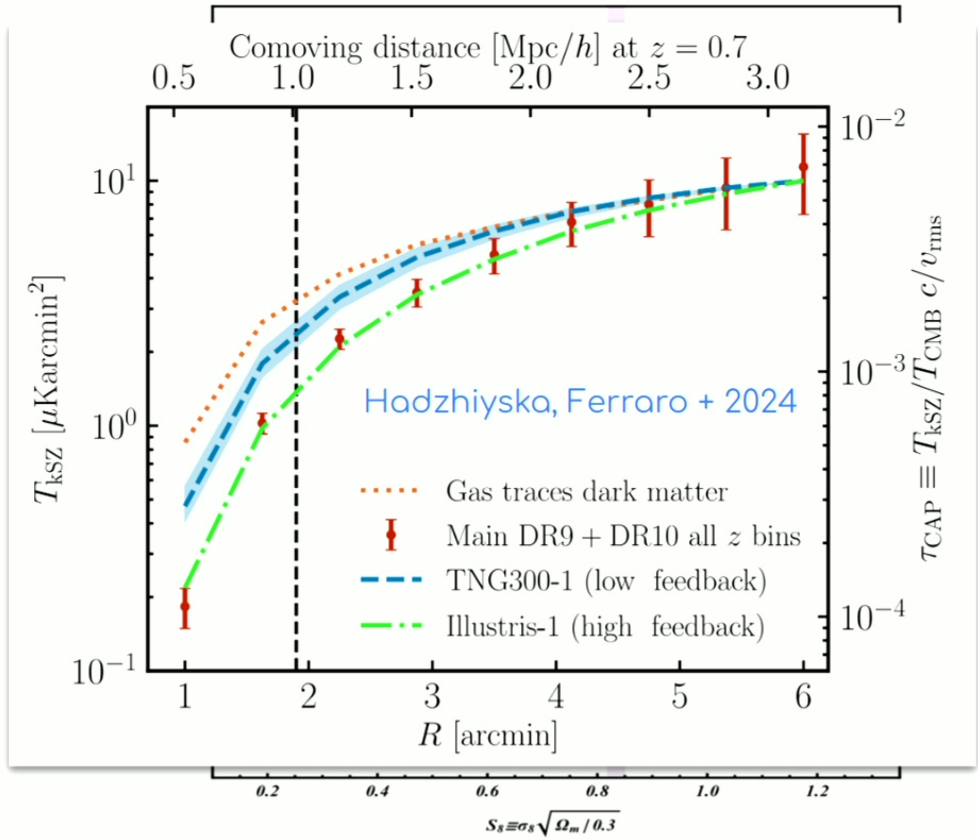
may indicate systematics, e.g. small-scale **baryonic feedback**



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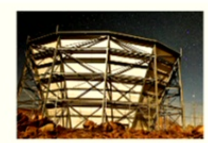
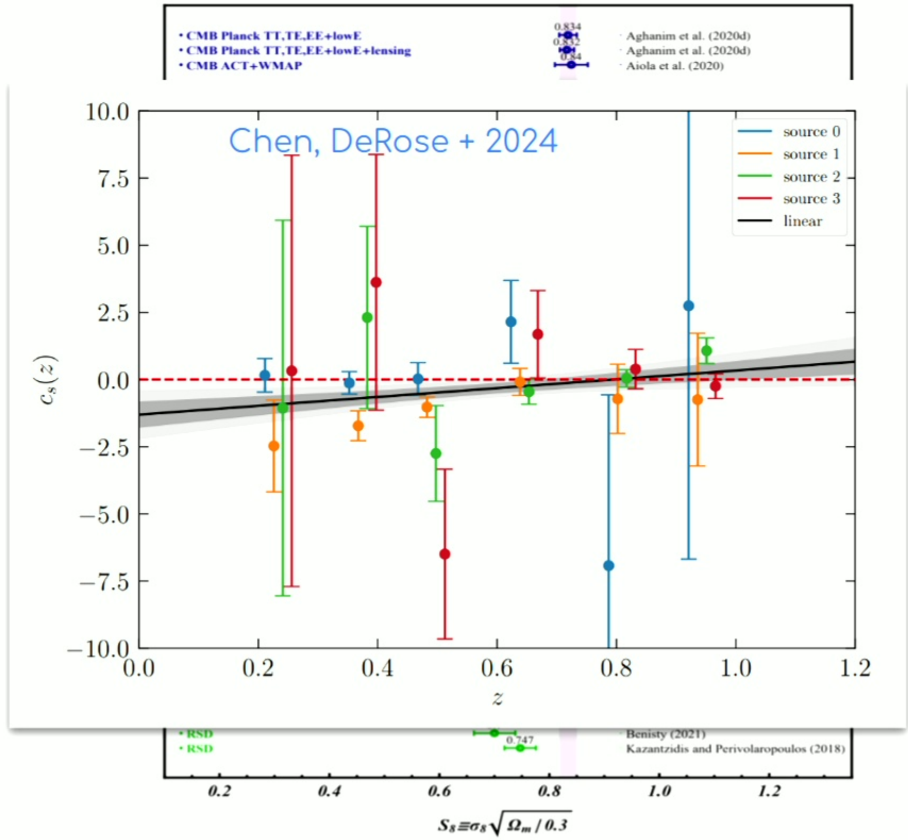


S_8 “tension”

≈ 5-10% discrepancy between **some** low- and high-redshift measurements of the linear power spectrum amplitude

may indicate systematics, e.g. small-scale **baryonic feedback** or **intrinsic alignments**



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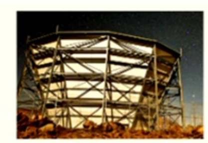
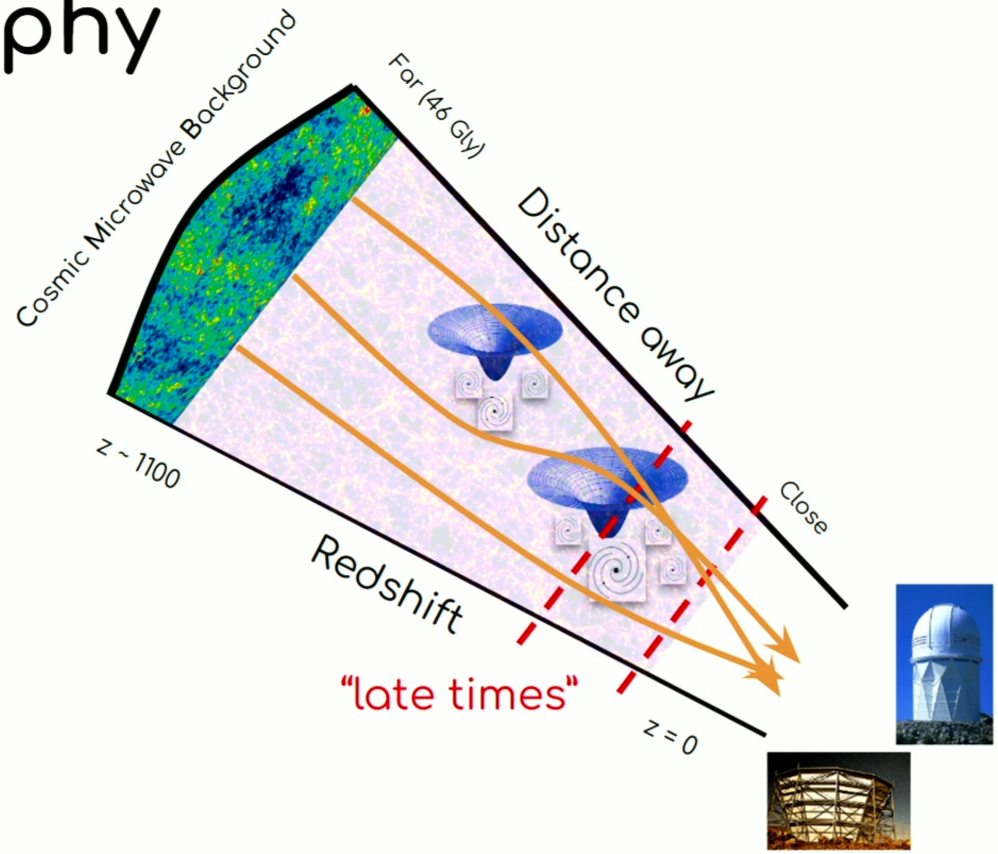


CMB lensing tomography

CMB lensing

Clean probe of the integrated late-time (z ≃ 0.5 – 5) structure

$$\kappa = \int dz \, W^{\kappa}(z) \, \delta_m$$



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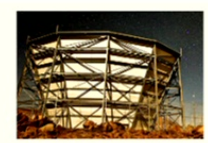

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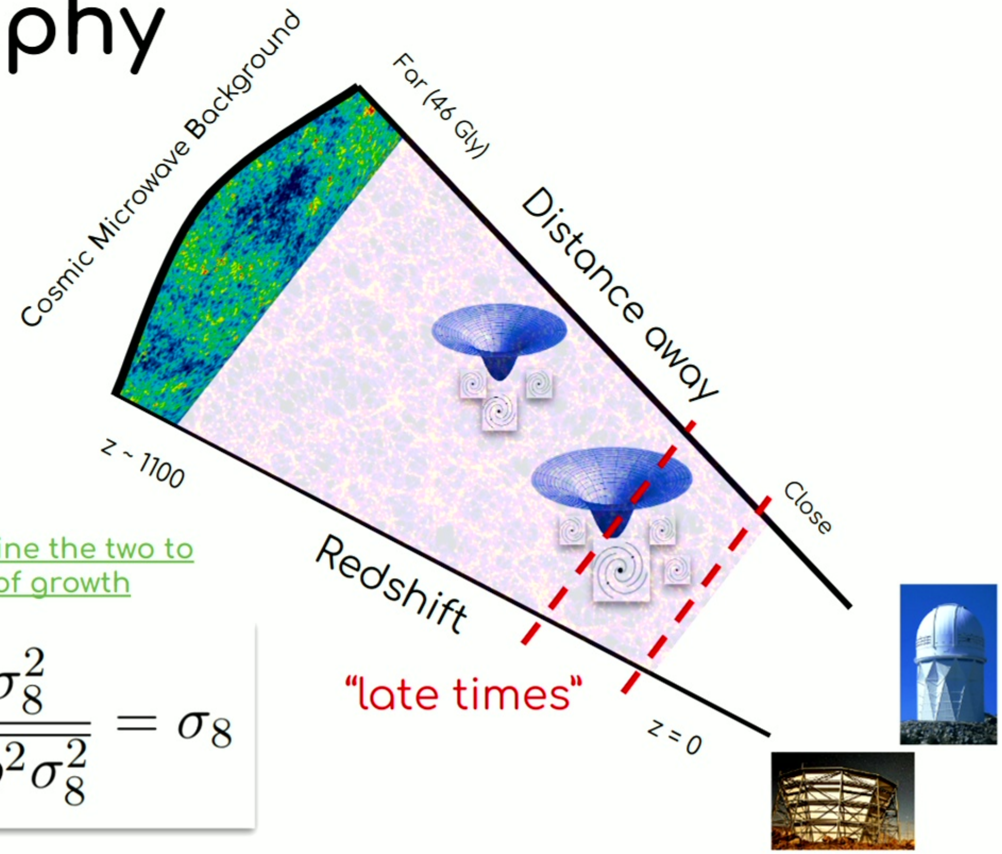
Galaxy clustering

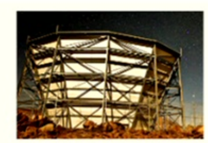
Biased probe of integrand

$$\delta_g = b\, \delta_m$$

Tomography = combine the two to constrain evolution of growth

$$\frac{C^{\kappa g}}{\sqrt{C^{gg}}} \sim \frac{b\sigma_8^2}{\sqrt{b^2\sigma_8^2}} = \sigma_8$$





Sales pitch slide – CMB lensing tomography with DESI LRGs

$S_8 \sim C^{kg} / \sqrt{C^{gg}}$ from cross-correlating the legacy survey DESI Luminous Red Galaxy (**LRG**) sample with Planck PR4 + ACT DR6 CMB lensing maps

Noah Sailer | Joshua Kim | Simone Ferraro | Mathew Madhavacheril | Martin White

Data & analysis choices tailored for systematics mitigation

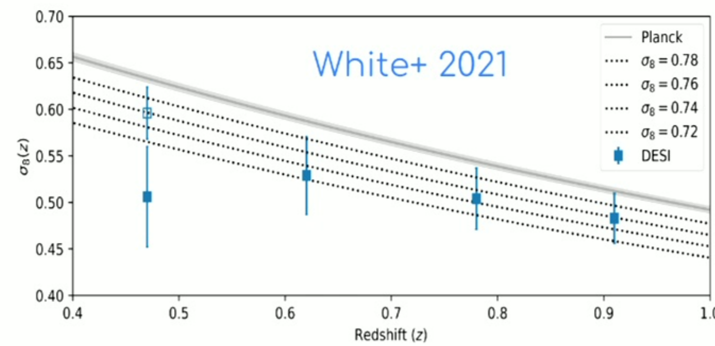
Redshift distributions: 4 photo-z bins, **dN/dz directly calibrated using 2.3 million DESI redshifts**

Narrow bins: **neglecting redshift evolution leads to sub-% errors**

Observational systematics: **99% redshift success rate, subpercent stellar contamination systematics weights impact clustering by < 1%**

Modelling of galaxies: HEFT model makes our **analysis largely agnostic towards the complicated physics of galaxy formation**

Previous analysis with Planck PR3 found $S_8 = 0.73 \pm 0.03$



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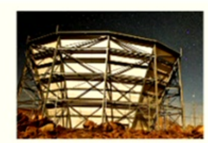
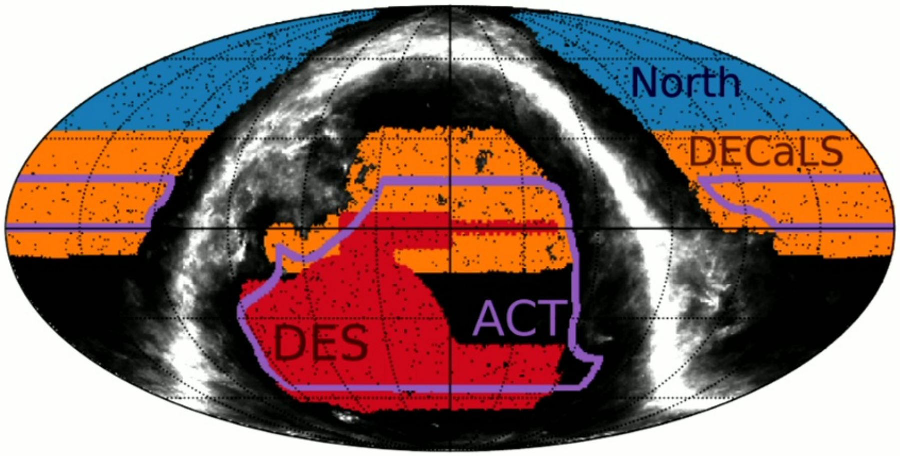


DESI Luminous Red Galaxies (LRGs)

Legacy imaging survey (DR9) currently being used by DESI for targeting

- DES
- DECaLS
- North (BASS + MzLS)

Covers 18,200 deg^2 with a surface density of 500 deg^{-2}



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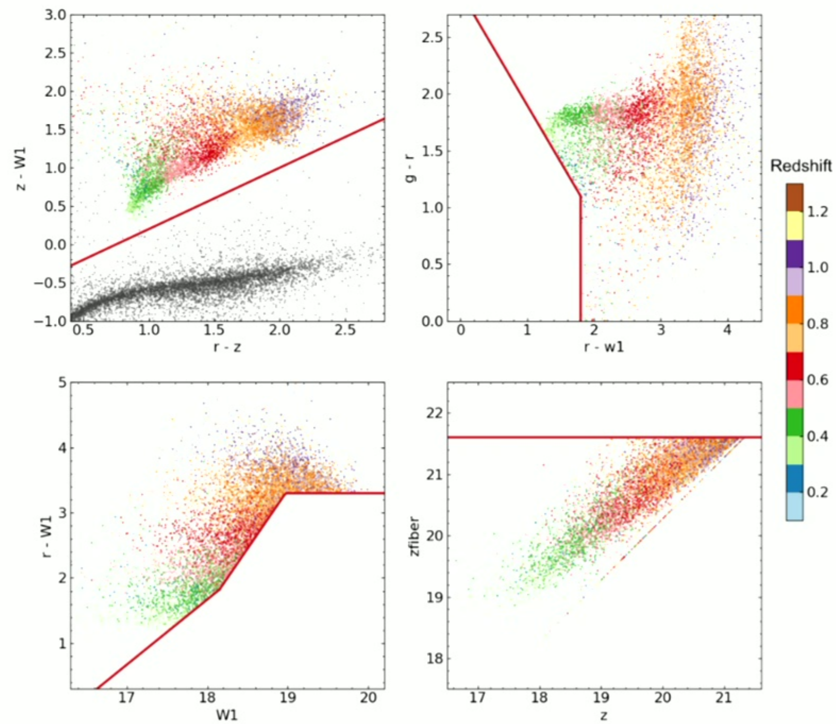
DESI Luminous Red Galaxies (LRGs)

Selection includes three color cuts in (g, r, z, Wise W1) to

- mitigate stellar contamination (0.3%)
- remove galaxies below z < 0.4
- constant number density to z = 0.8

additional cut in z-band fiber mag to produce a tail in the dN/dz extending just beyond z = 1

99% redshift success rate!



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DESI LRG photo-z's

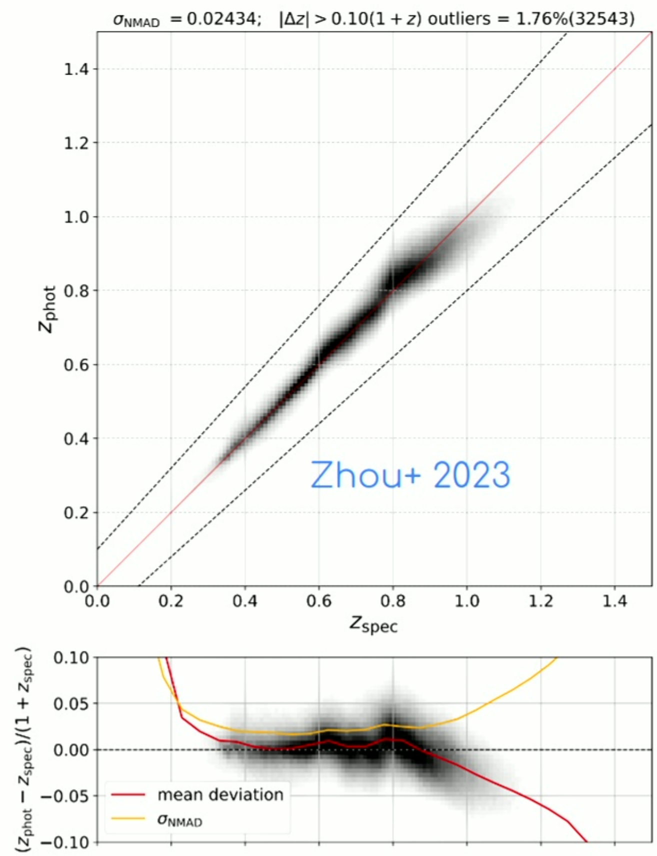
Photo-z's from random forest trained on (~1.9 million) spectra from many previous surveys

B Photometric redshifts Zhou+ 2023

Data from the following surveys were used for photo-z training in [23] and is reused for the new photo-z's presented here: 2dFLenS [46], AGES [47], COSMOS2015 photo-z's [48], DEEP2 [49] and DEEP3 [50], GAMA[51], OzDES [52] (updated to DR2), SDSS Main Galaxy Sample [53] and LRG sample [54], BOSS [55, 56] (updated to SDSS DR16 [57]), VIPERS [58], VVDS [59] and WiggleZ [60]. Quality cuts on these datasets are described in [23].

in addition to early DESI data.

Photo-z accuracy: $\sigma_z/(1+z)$ ~ 0.02



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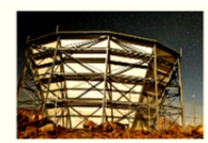
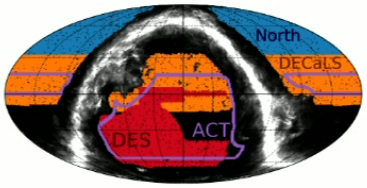


DESI LRG photo-z bins



LRGs divided into four photo-z bins

- accurate photo-z's → narrow photo-z bins
- insensitive to assumed evolution within each photo-z bin

dN/dz calibrated for each bin using 2.3 million DESI redshifts

- 99% redshift success rate → high-fidelity dN/dz
- weight by spec-z success probability

measured dN/dz variations on different imaging footprints

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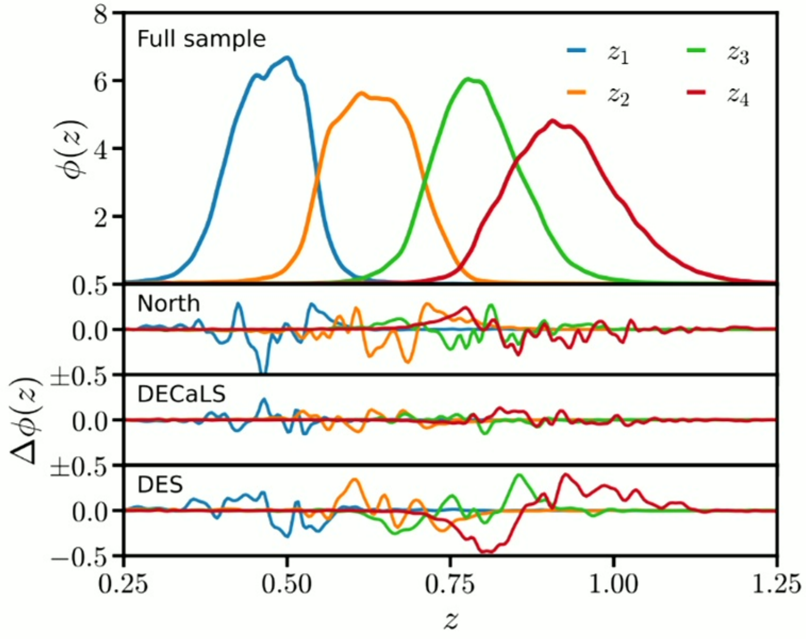
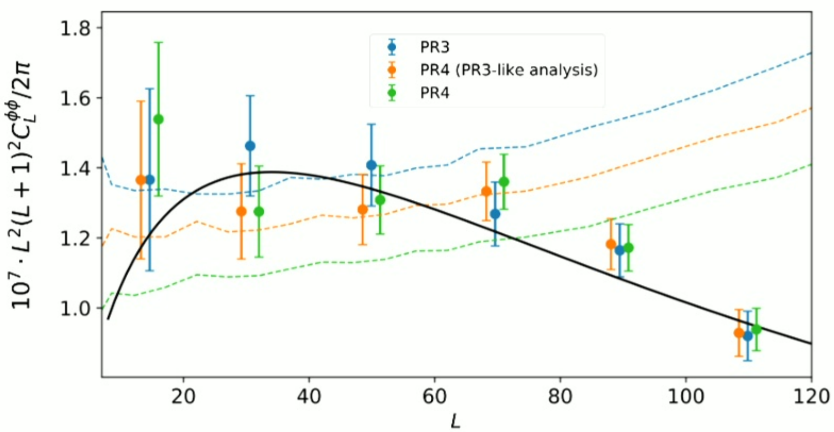


CMB lensing

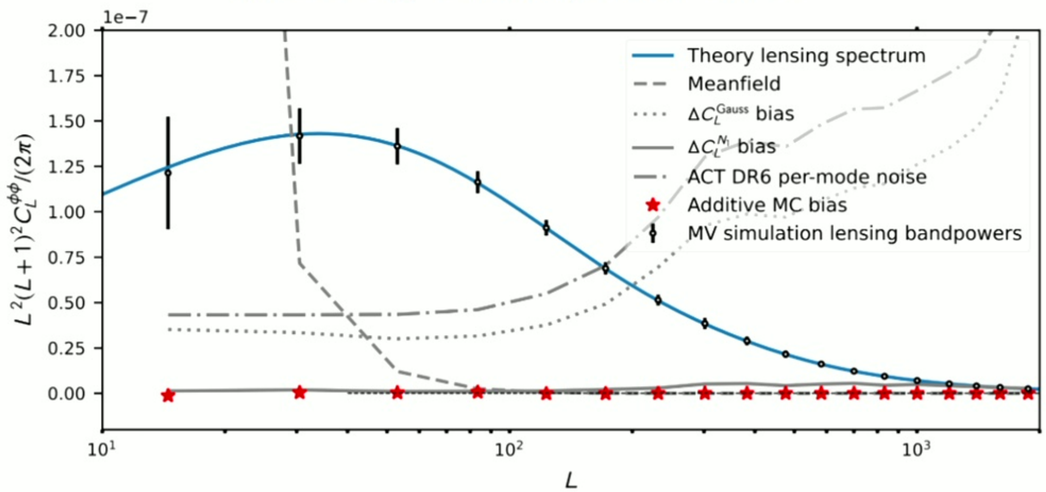
Planck PR4 Carron+ 2022

- Some additional data, more optimal lensing estimator and filtering
- **“Full sky”**
- Signal dominated to L~80
- 16,600 deg^2 overlap with LRGs



ACT DR6 Qu+ 2023

- 90, 150, 220 GHz data (through 2021)
- **Lowest noise wide-field map available**
    - signal dominated to L~200
- Passed ~200 systematics checks!
- 7,900 deg^2 overlap with LRGs



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Some challenges

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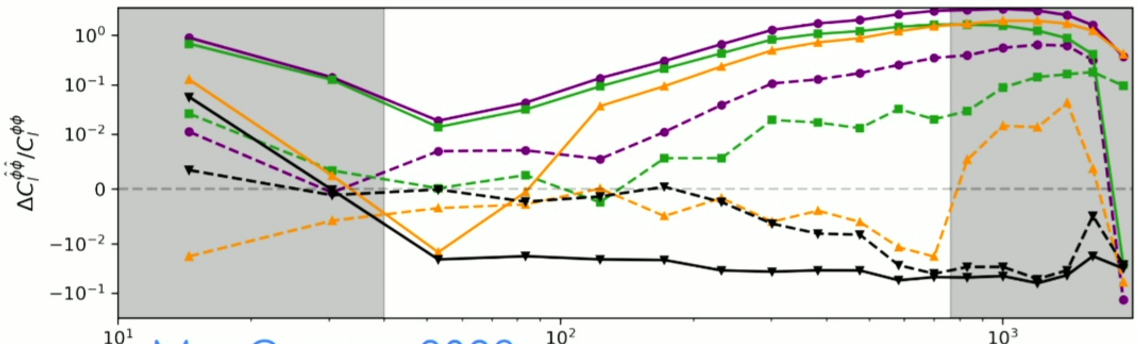
Challenge 1: Extragalactic foregrounds

Higher resolution from ACT → push to smaller scales in lensing reconstruction

Extragalactic foregrounds have significant small-scale power

Result in significant biases for ACT if not properly taken into account!



MacCrann+ 2023

Biases from WebSky foreground sims without migiation (solid purple)

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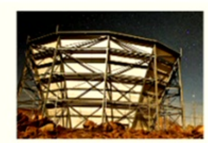


Foreground biases to $C^{\kappa g}$

ACT reconstructs the CMB lensing convergence (κ) with a **Quadratic Estimator**

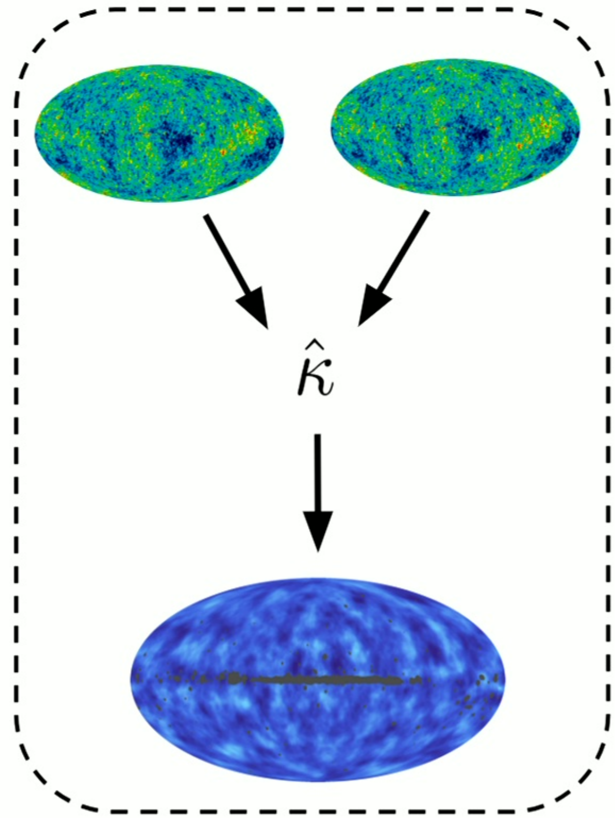
$$\hat{\kappa} \sim \sum_{ij} W_{ij}\, T_i T_j$$

$C^{\kappa g} \sim \langle \hat{\kappa} g \rangle$ is actually a *bispectrum* $\langle T T g \rangle$.

If T^{obs} contains a foreground f, picks up bias

$$\langle f f g \rangle$$

Nonzero if foregrounds are **correlated with lensing** and **non-Gaussian**



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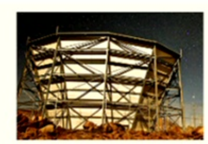

Foreground Mitigation

Two choices

$$\hat{\kappa} \sim \sum_{ij} W_{ij}\, T_i T_j$$

"Multifrequency"

In addition to "standard" deprojection	e.g. Darwish ++ 2020
Gradient cleaning	Madhavacheril, Hill 2018
Partial deprojection	**NS**, Schaan, Ferraro, Darwish, Sherwin 2021 Darwish, Sherwin, **NS**, Schaan, Ferraro 2021

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Foreground Mitigation

Two choices

$$\hat{\kappa} \sim \sum_{ij} W_{ij} \, T_i \, T_j$$

"Geometric" choose weights to null template ffg bispectrum $\sum_{ij} W_{ij} \hat{B}_{ij}^{ffg} = 0$

Shear estimator (large lens limit) extension to full sky	Schaan, Ferraro 2018 Qu, Challinor, Sherwin 2022
Point source hardening	Namikawa, Hanson, Takahashi 2013 Osborne, Hanson, Dore 2014
(tSZ) Profile hardening extension to polarization	NS, Schaan, Ferraro 2020 NS, Ferraro, Schaan 2022

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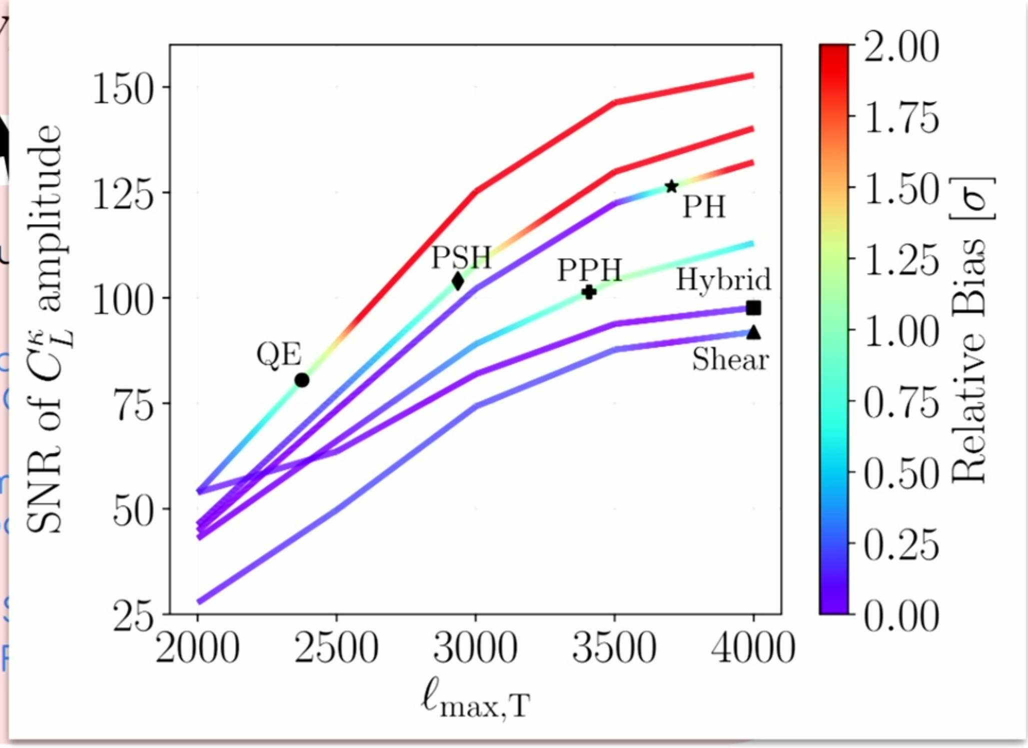
Foreground Mitigation

Profile hardening (PH) adopted as baseline T estimator in ACT DR6 analysis

Two choices

$$\hat{\kappa} \sim \sum_{ij} W$$



"Geometric" choose weights to nu

Shear estimator (large lens limit)
extension to full sky
Scho
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Point source hardening
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extension to polarization
NS, S
NS, F

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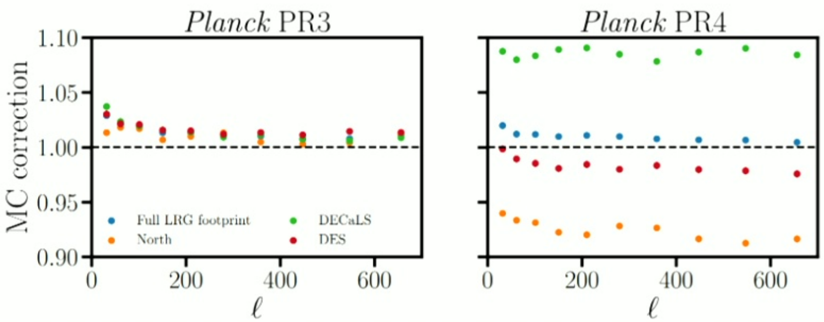
“Challenge” 2: normalization correction

Gerrit realized that previous cross-correlation measurements had not been corrected for a normalization correction, some confusion ensued…

Need for correction arises from mode-couplings (e.g. from masking or filtering) which are not properly forward modeled in MASTER algorithm

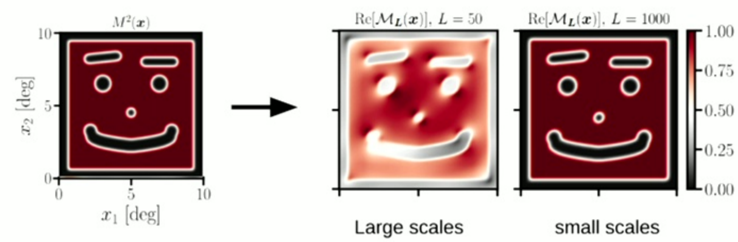
Aside 1 NS, Kim, Ferraro+ 2024

Norm correction varies significantly across footprints for PR4!



Aside 2 NS, Farren, Ferraro, White (in prep)

Mode-induced couplings can be computed with FFTs in the flat-sky limit “effective mask” approximation



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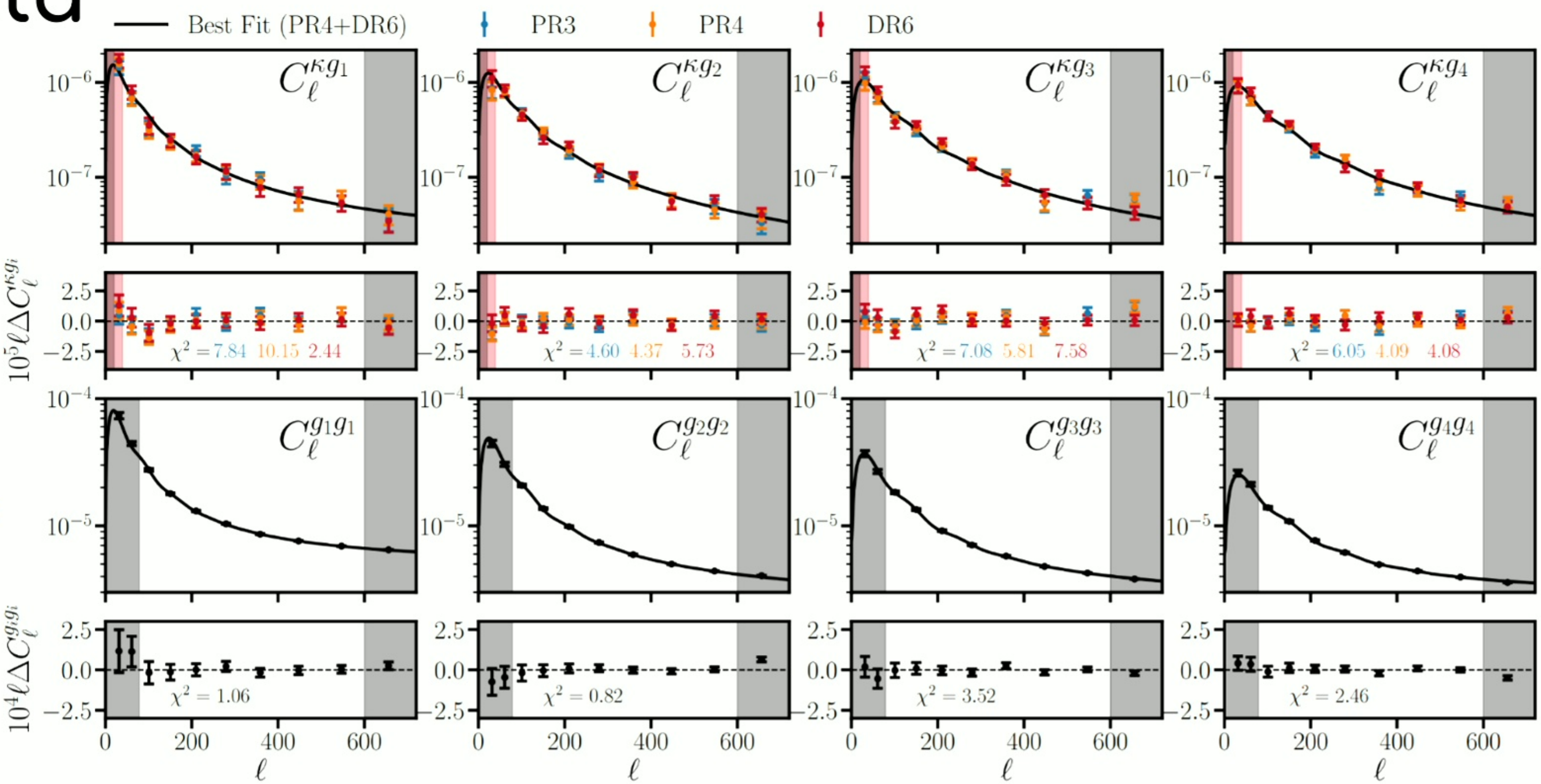
The data

CMB lensing x Galaxies

Galaxies x Galaxies

$C^{\kappa g}$ SNR = 50



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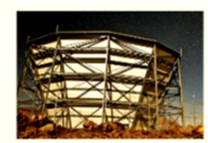


The model(s)

- Hybrid Effective Field Theory Modi, Chen, White 2019 ++

  Galaxies form biased tracer of initial CDM+baryons, and advected with displacements from simulations

$$1 + \delta_g(x) = \int d^3q \, F(q) \, \delta^D(x - q - \Psi(q))$$

Expand to 2[nd] order in perturbations and 1[st] order in derivatives

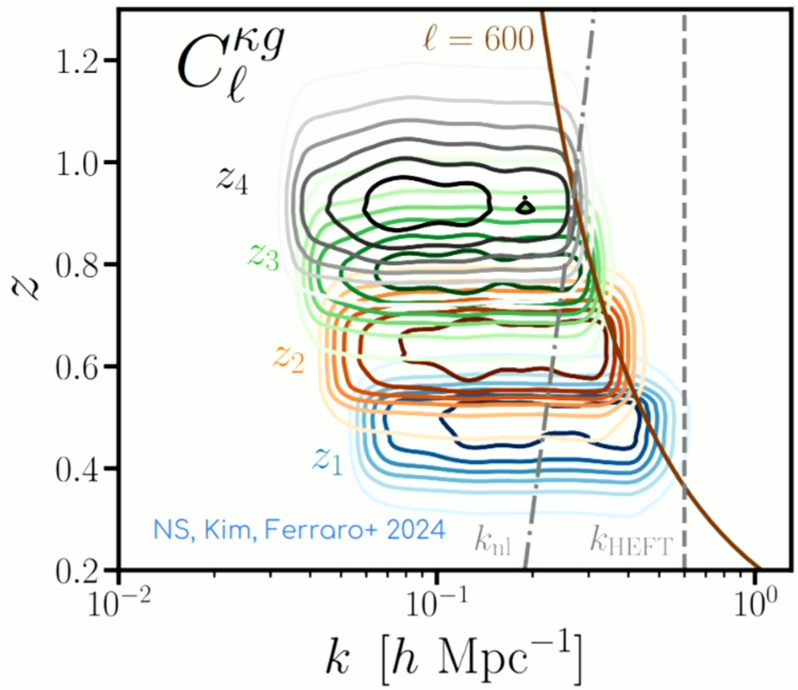
Aemulus ν
Two-fluid (cb and ν) N-body
DeRose+2023, Kokron

Percent-level accuracy out to k = 0.6 h/Mpc Kokron

- Linear theory (on linear scales)

- Model "independent" (fixed shape) approach

SNR per dlnk dz



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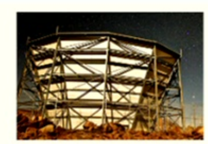
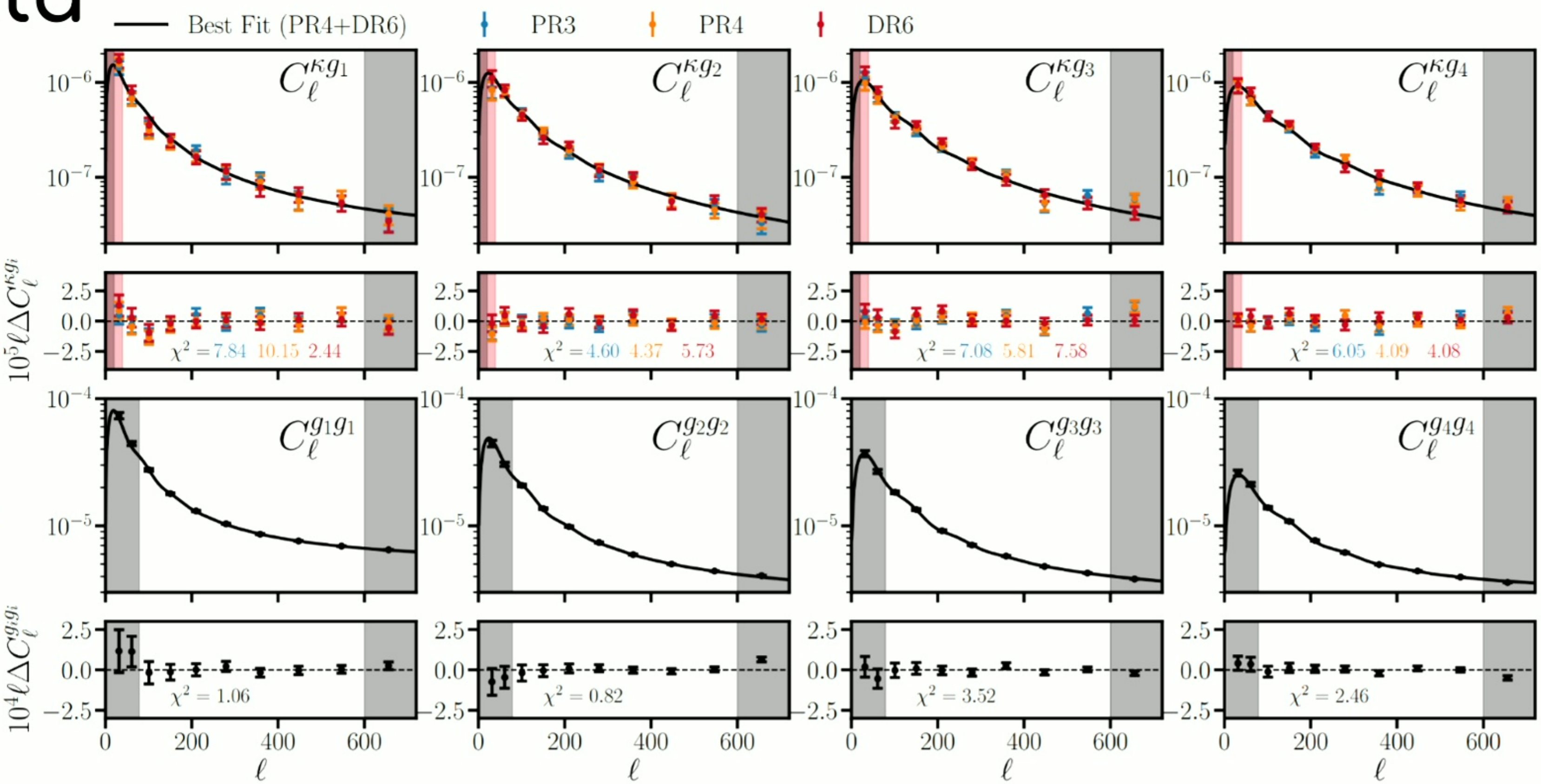


The data

CMB lensing x Galaxies

Galaxies x Galaxies

$C^{\kappa g}$ SNR = 50



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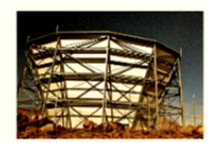

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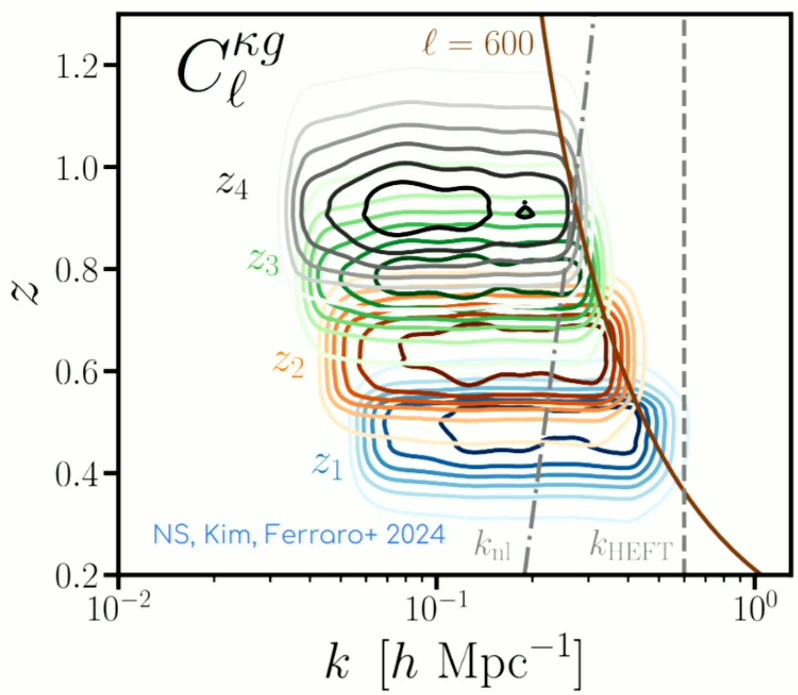

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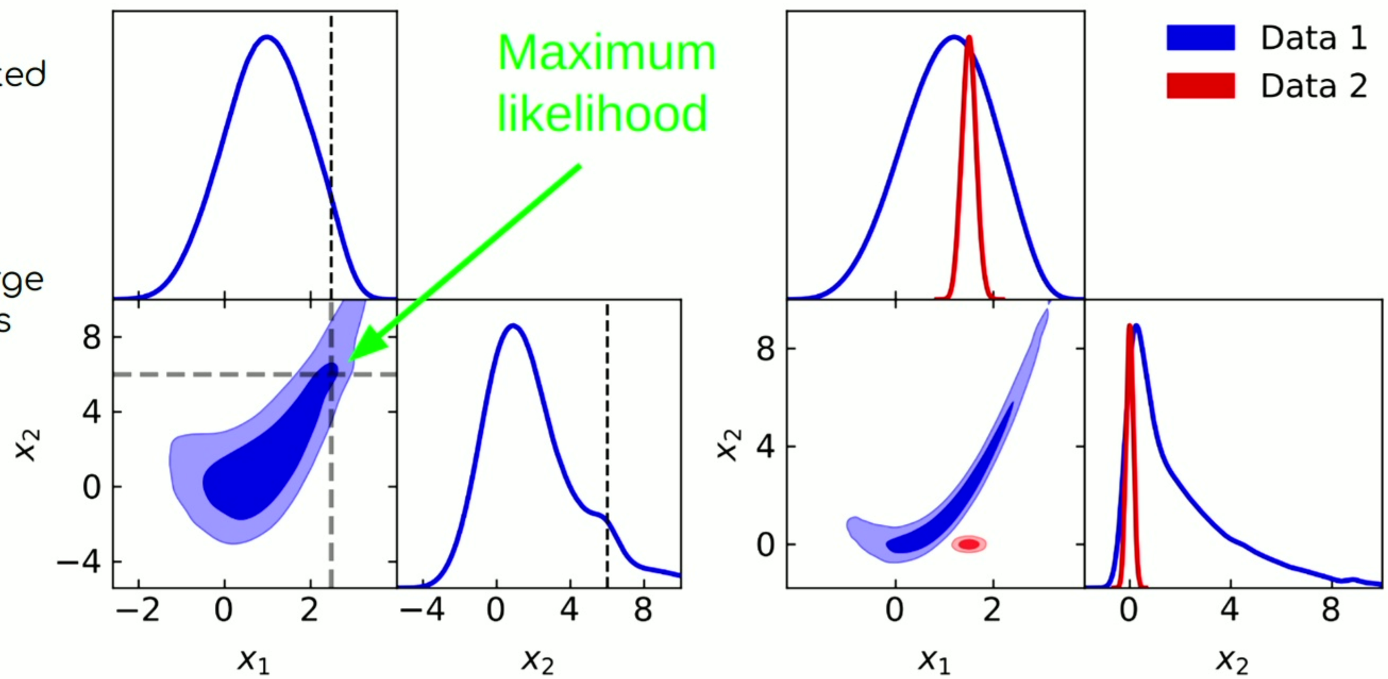
Volume effects

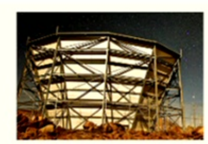
Interpretation of marginal posteriors is more complicated than the naive

$(\mu_a - \mu_b) / (\sigma^2_a + \sigma^2_b)^{1/2}$

when the likelihood has a large number of dimensions and is non-Gaussian

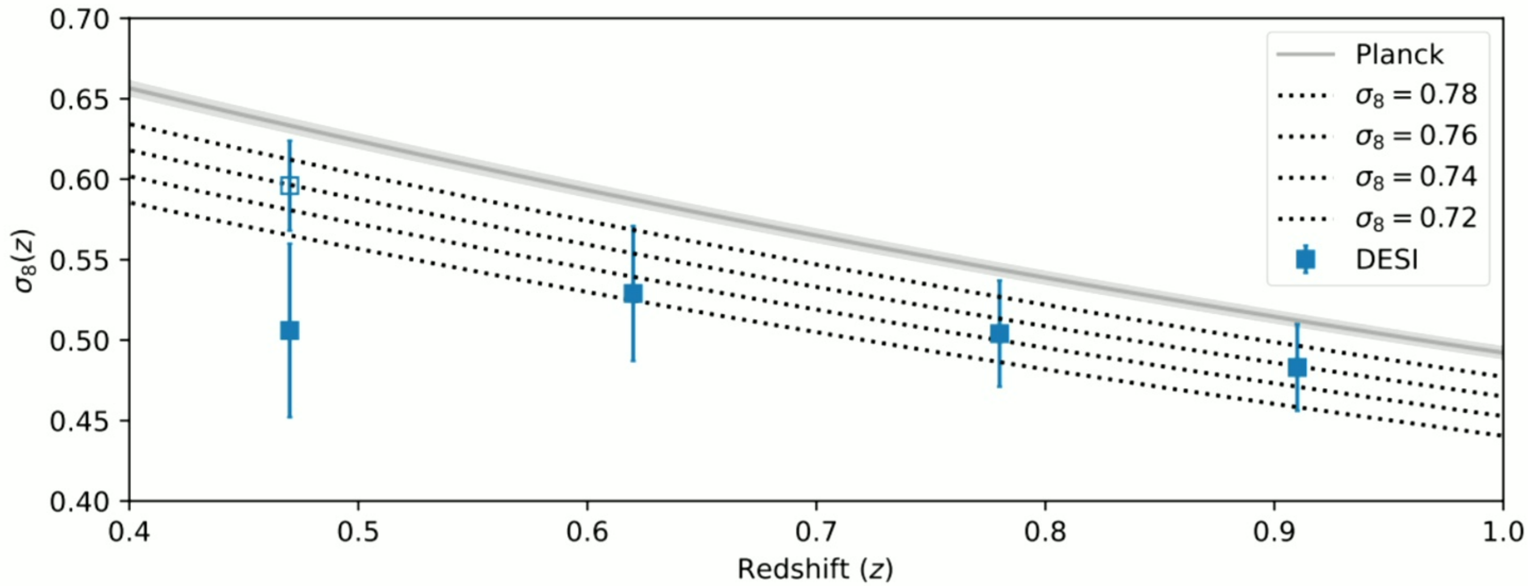


Maus+ 2024



Volume effects

Present in White+ 2021 analysis



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Mitigating volume effects

Only way I know of – add informative priors

In White+ 21 the "counterterms" ($\propto$ k^2 P) for the auto and cross were varied independently

"Counterterm" contribution arises primarily from derivative bias

$$F = 1 + b_1\delta + \cdots + b_\nabla \nabla^2 \delta$$

allowing us to relate the two $\alpha_x = \dfrac{\alpha_a}{2b_1^E} + \epsilon$ up to small corrections

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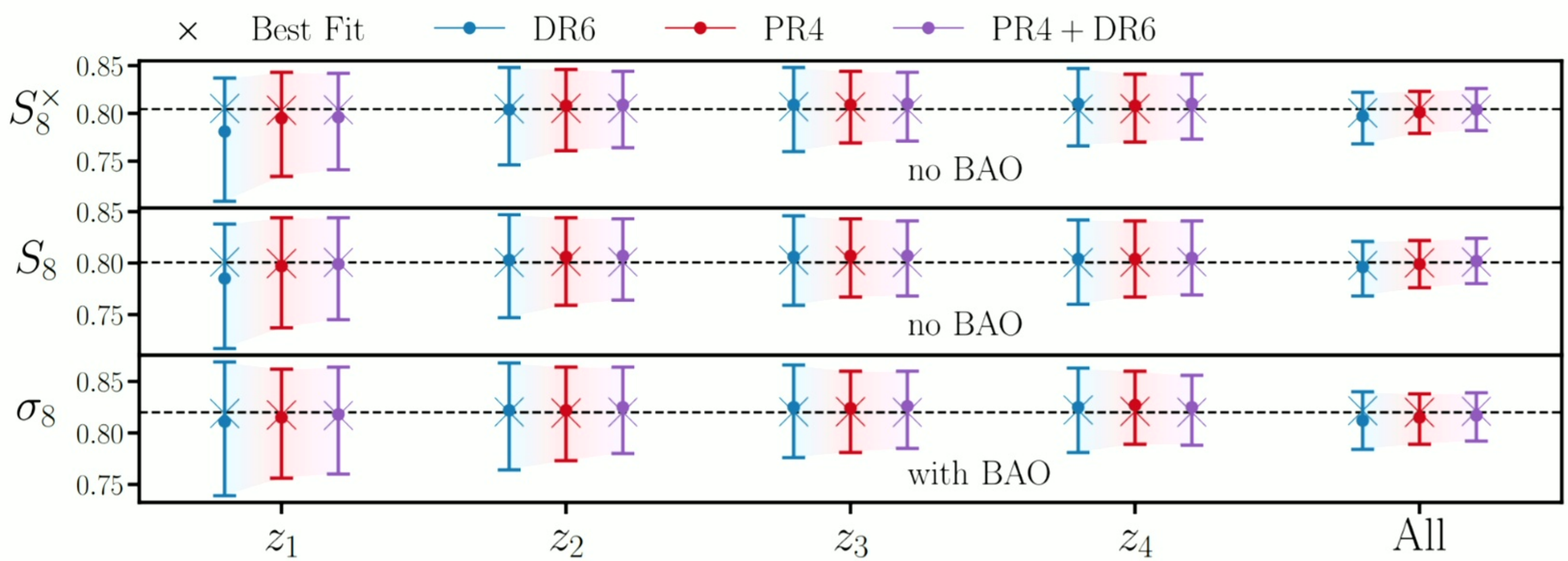
Volume effects negligible for us

Fit to noiseless model prediction with a DR6, PR4 or PR4 + DR6 like covariance



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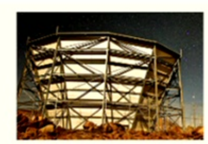
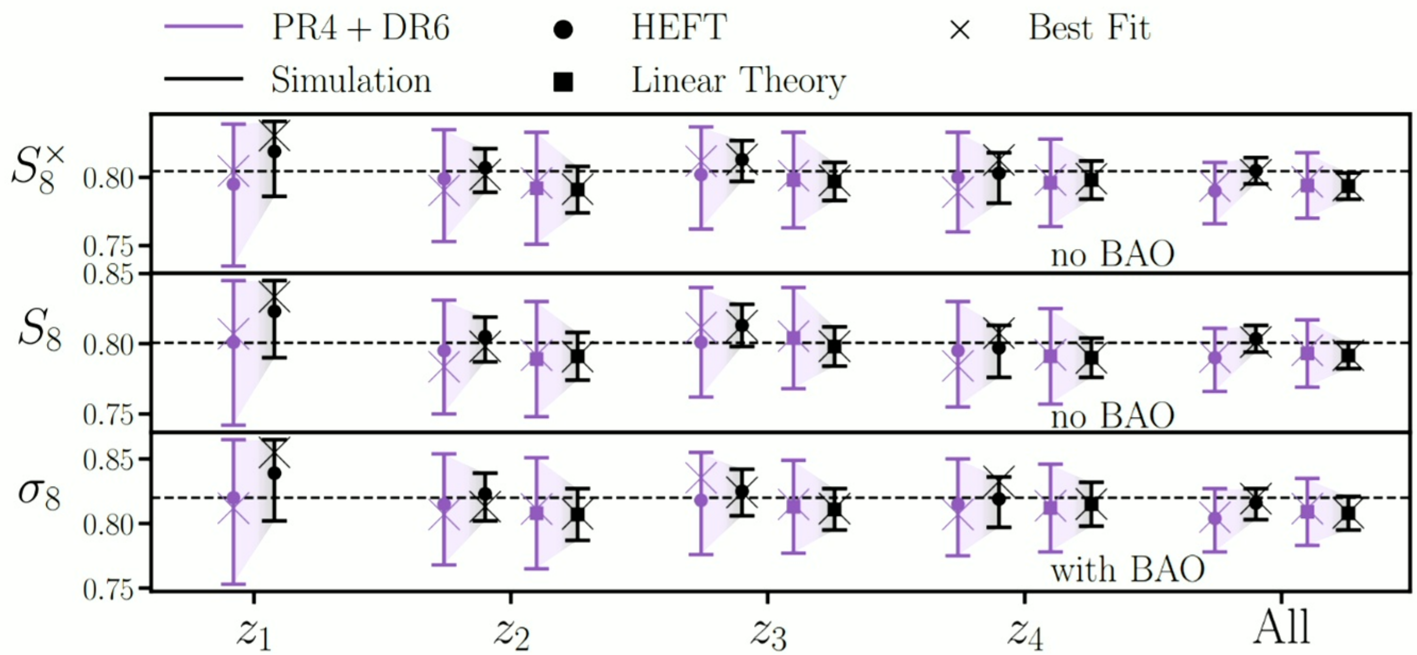


We tried it on mocks and it works

Fits to Buzzard mocks when adopting a data- or simulation-like covariance



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We did some checks ✓

Data level

- null correlation with curl estimator
- null correlation with CMB deprojected reconstruction
- consistent $C^{\kappa g}$ when using CIB deprojected ILC
- consistency when adopting more conservative galactic, extinction and stellar density masks
- negligible correlations between galaxies and their systematic weights
- consistency in both galactic hemispheres

Data level and Inference level

- variations in $C^{\kappa g}$ and C^{gg} across imaging footprints
- variations in $C^{\kappa g}$ and C^{gg} on footprints with/without direct spectroscopic calibration
- consistent $C^{\kappa g}$ when measured with different frequencies or temperature vs polarization
- consistency of galaxy-galaxy cross-spectra with that predicted from fits to $C^{\kappa g}$ and C^{gg} alone
- consistency between ACT and Planck

Inference level

- robustness to different scale cuts
- robustness to different priors
- consistent results from all three fiducial models
- consistent cosmology from all four redshift bins
- consistent results when galaxy mask restricted to only overlap with CMB lensing mask

Simulation level

- expect negligible contamination from extragalactic foregrounds from Websky sims

No evidence for statistically significant systematic contamination at the parameter level

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Some thorns

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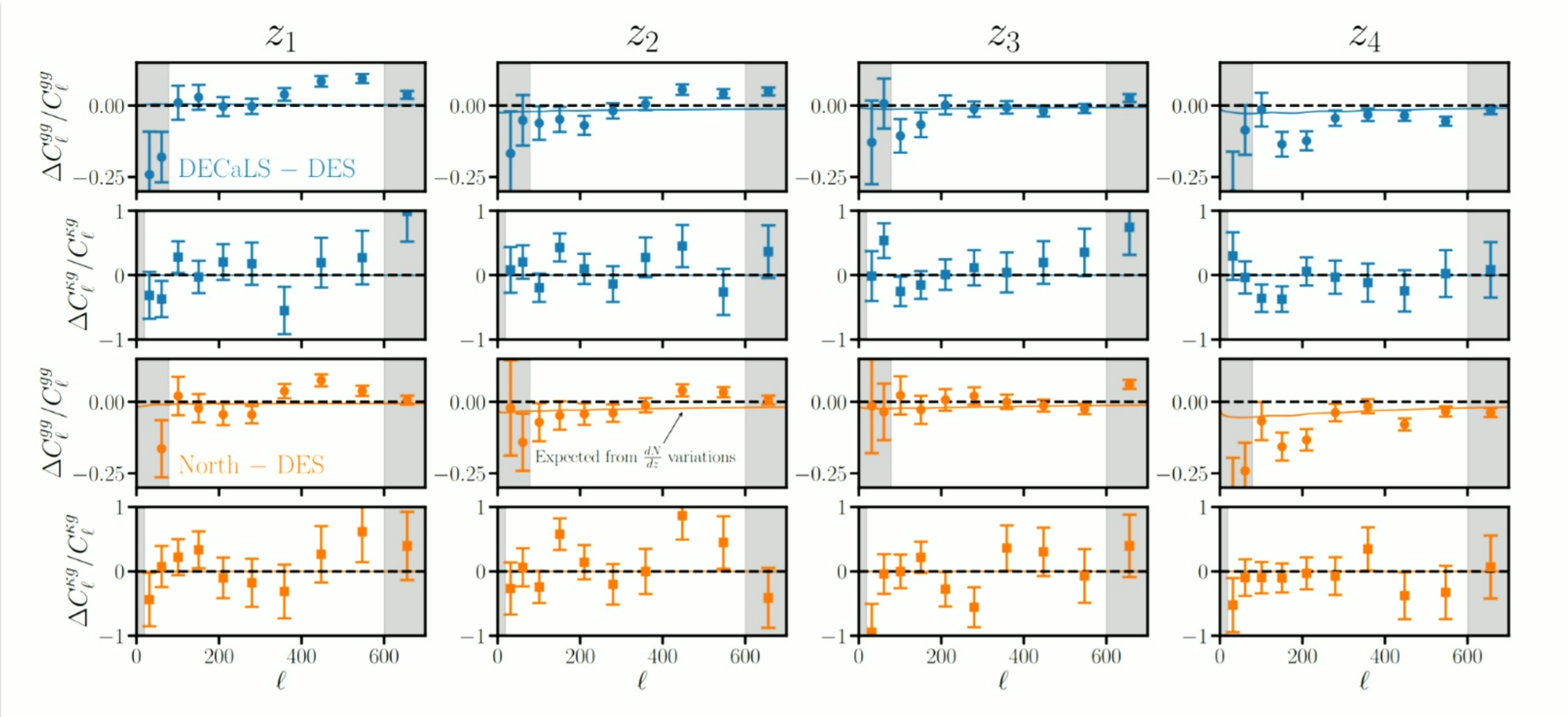
Thorn 1 – clustering variations on the sky



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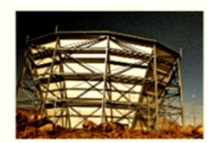

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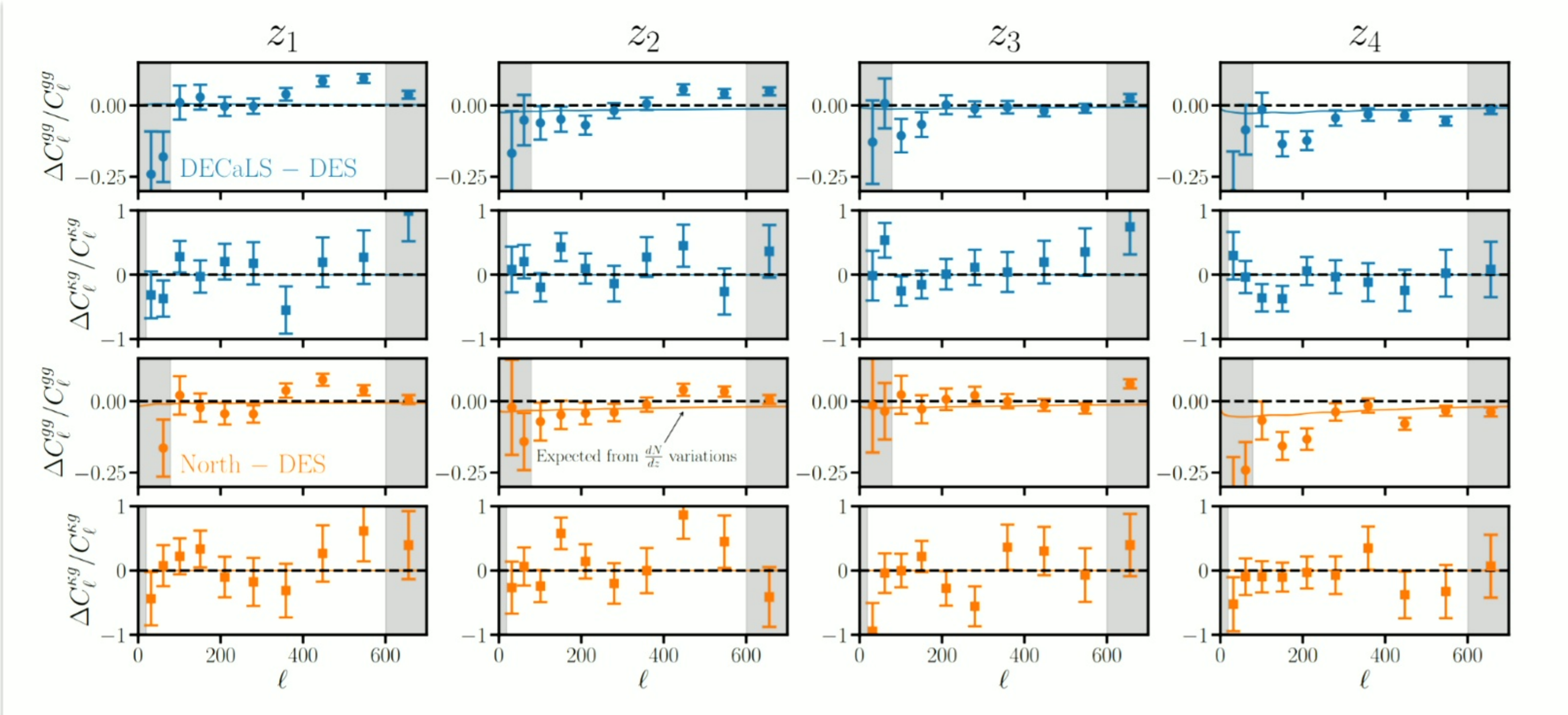

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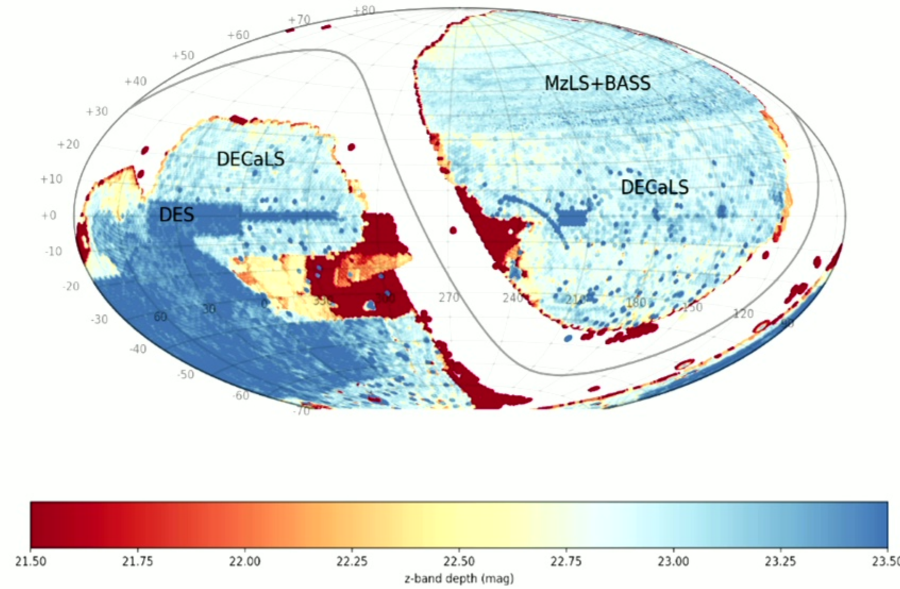
Hypothesis – depth variations

- regions with lower photometric noise have fewer low-mass objects scattering into the sample -> leads to a larger linear bias



- **Relevant question for us:** are variations large enough to warrant treating each imaging region as a different sample?

https://www.legacysurvey.org/status/

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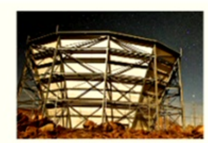
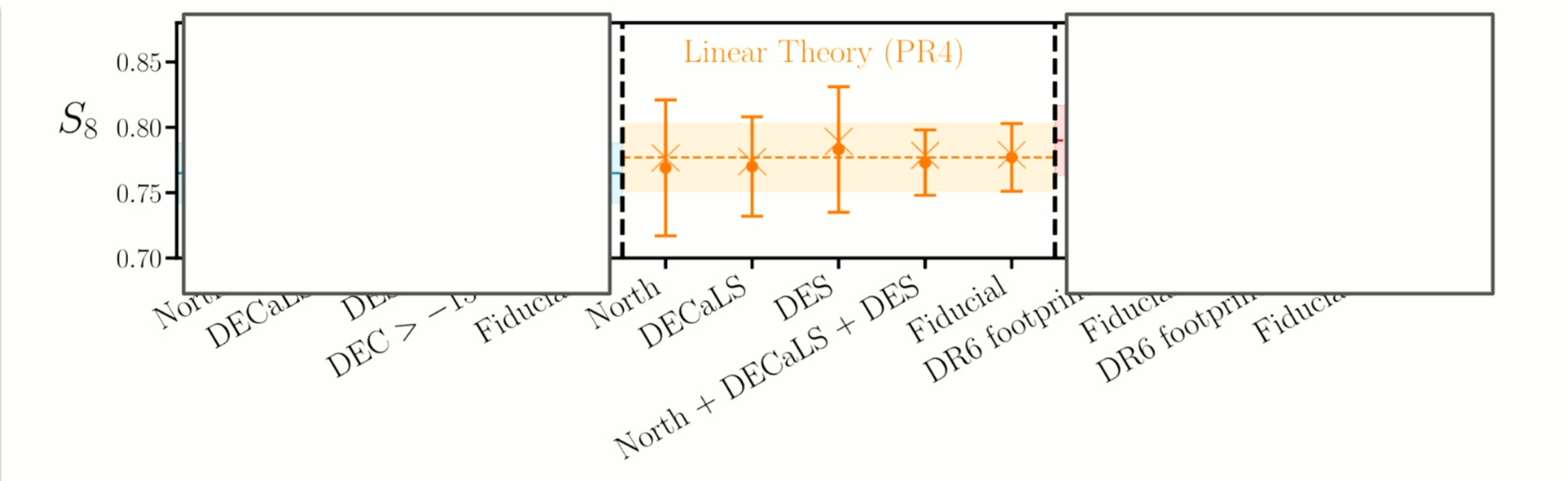


Thorn 1 – clustering variations on the sky

Back of the envelope: provided that $C^{\kappa g}$ and C^{gg} are measured on the same footprint, bias to S_8 goes like $(\Delta b/b)$^2 ~ 0.25%, not bad!



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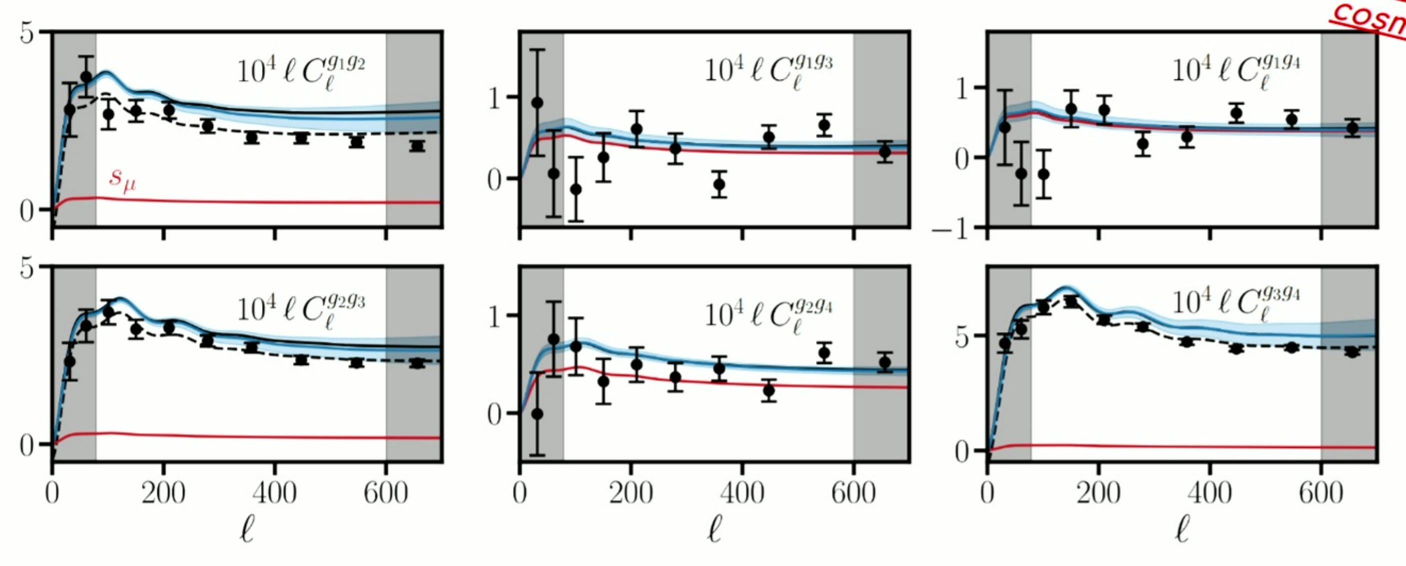
Thorn 2 – galaxy cross-spectra

Measured cross-spectra for neighboring bins (1-2, 2-3, 3-4) are smaller than predicted from fits to galaxy auto's and cross with CMB lensing (by up to 20%)

We do not fit to these data in our cosmological analysis



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Potential explanations

Modelling

To predict the galaxy cross-spectra we made several **additional assumptions**

- bias parameters only depend on redshift, not on the redshift bin (e.g. hi-z tail of z1 could differ from the low-z tail of z2)

- linear interpolation of bias parameters

- neglect correlated shot noise

Systematic modulation

- galaxy cross-spectra are significantly more sensitive to dN/dz variations (up to 15% variations)

- the probability that a galaxy is assigned to e.g. bin 1 or bin 2 at a fixed redshift may be modulated by an observational effect (e.g. extinction) that could lead to negative correlations between neighboring redshift bin

- systematic contamination (not captured by weights) which is negatively correlated for neighboring bins

- **Maximally pessimistic scenario:** a systematic contaminant is present in the galaxy auto-spectra (increasing Cgg), which leads to an overprediction of the cross-spectra

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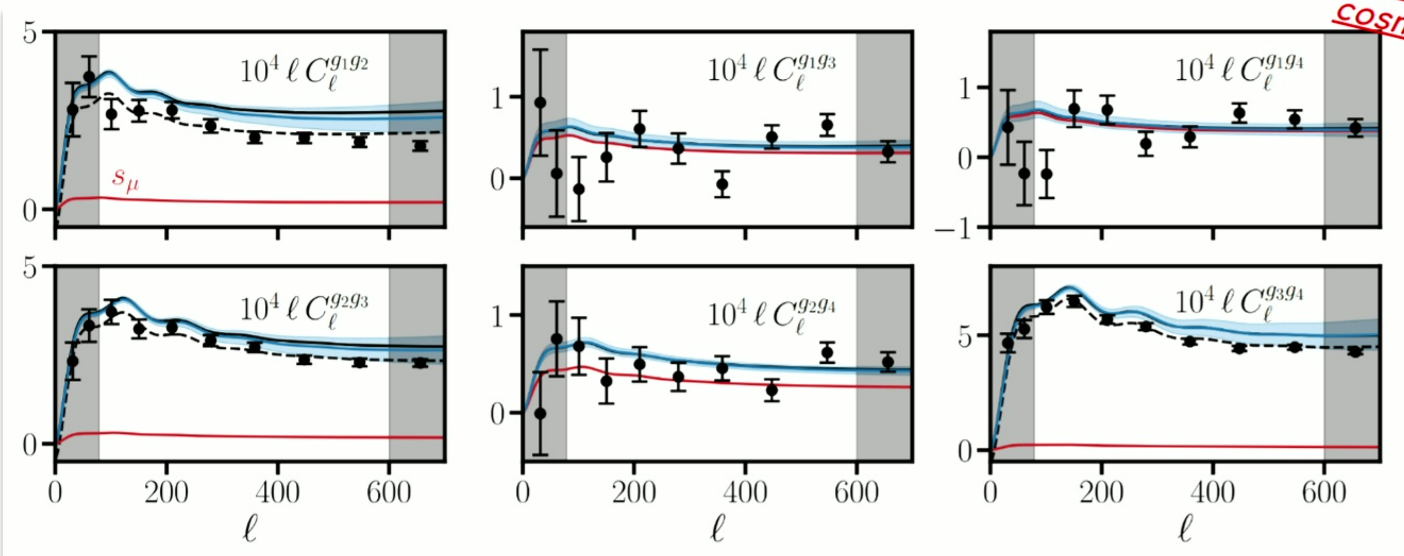

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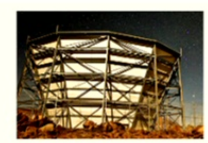

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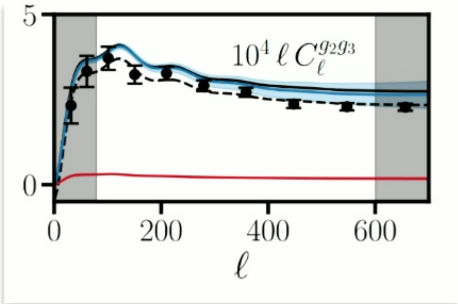
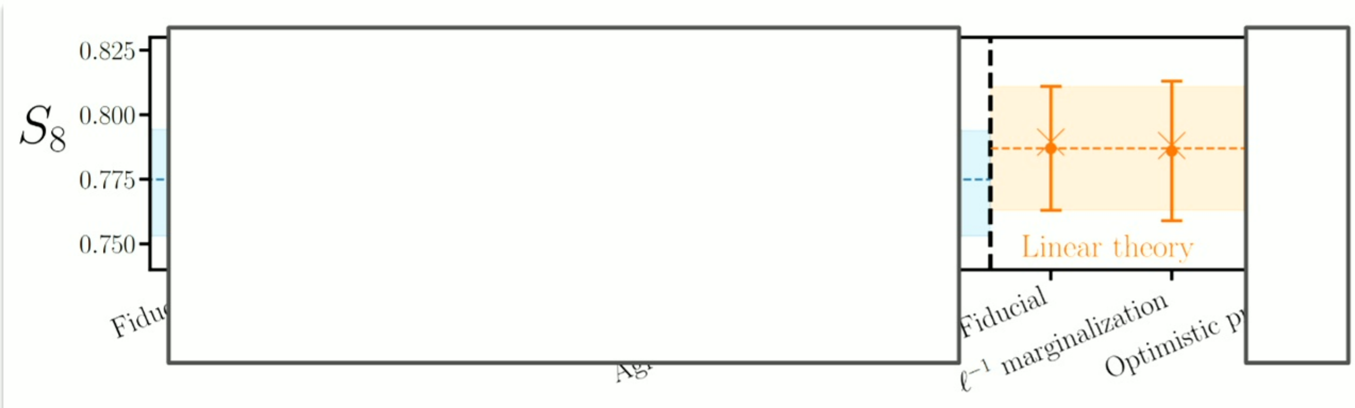
Worst case scenario isn't scary



Residuals are very well fit by 1/ell term, with a coefficient of 5e-5 (dashed line)

Test: allow for a 1/ell contribution to the galaxy auto-spectra and marginalize over the coefficient with a N(0,1e-4) prior



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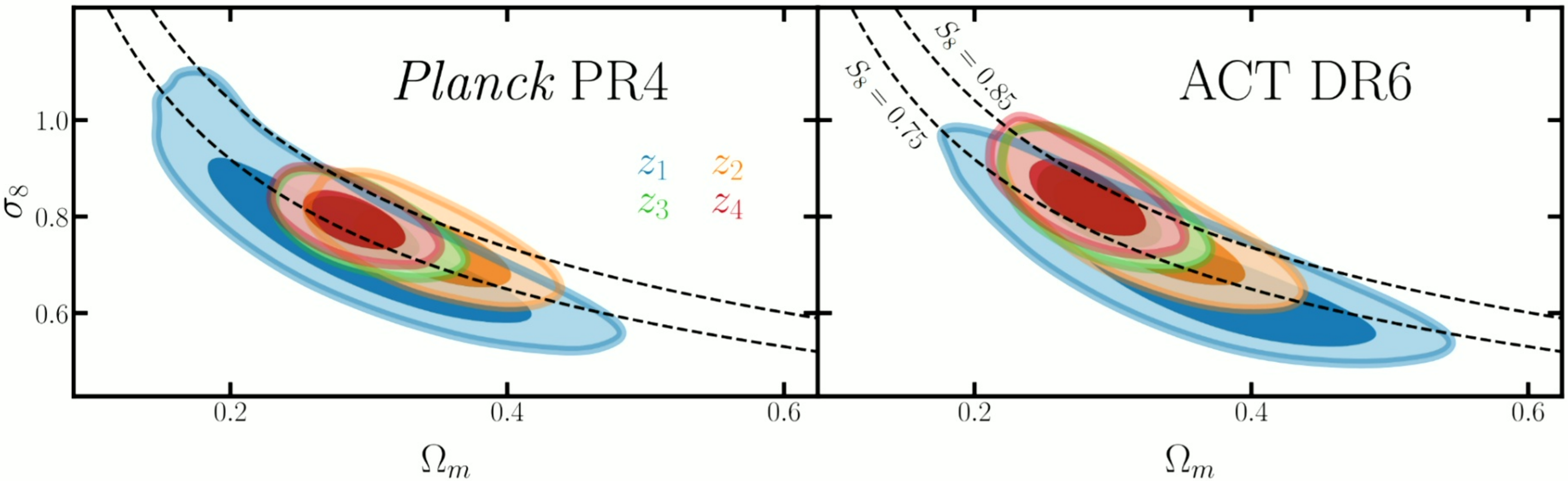
Individual constraints



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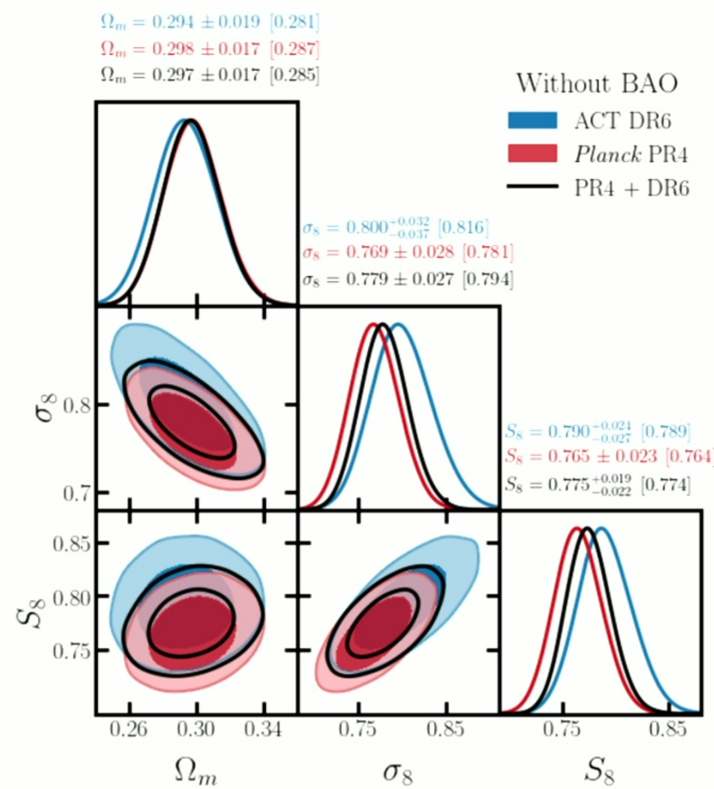
Combined constraints

$$\textit{Planck}\ \text{PR4:}\ \ S_8 = 0.765 \pm 0.023$$

$$\text{ACT DR6:}\ \ S_8 = 0.790^{+0.024}_{-0.027}$$

$$\text{Combined:}\ \ S_8 = 0.775^{+0.019}_{-0.022}$$



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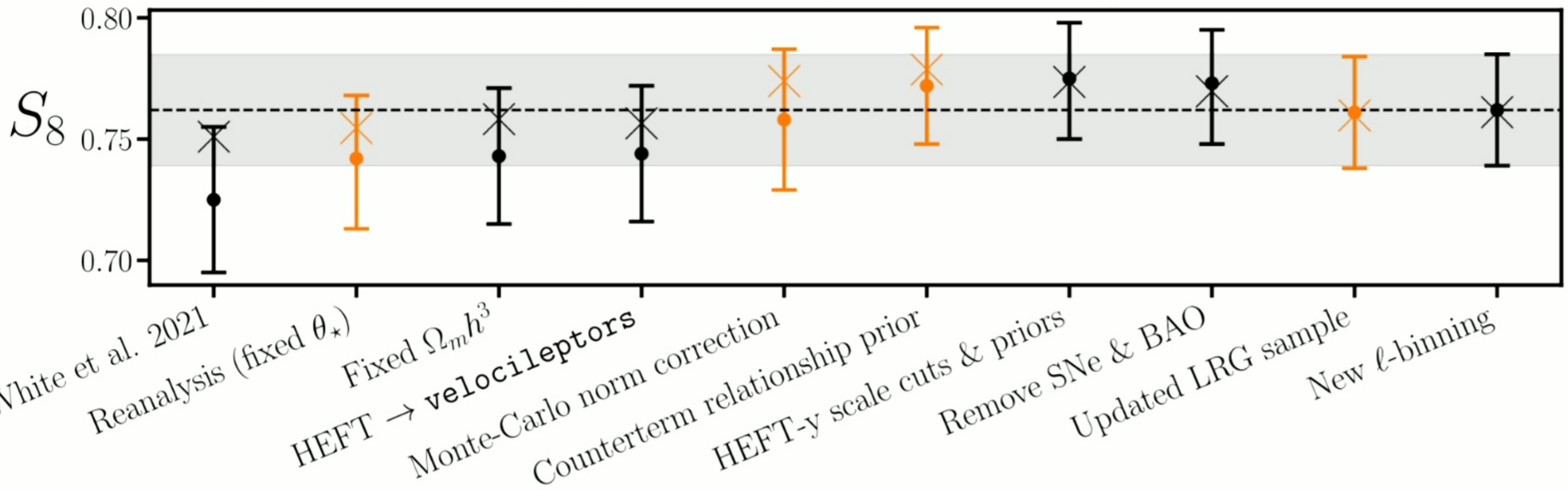
Connecting the dots to White+ 2021

updates with significant impact in orange



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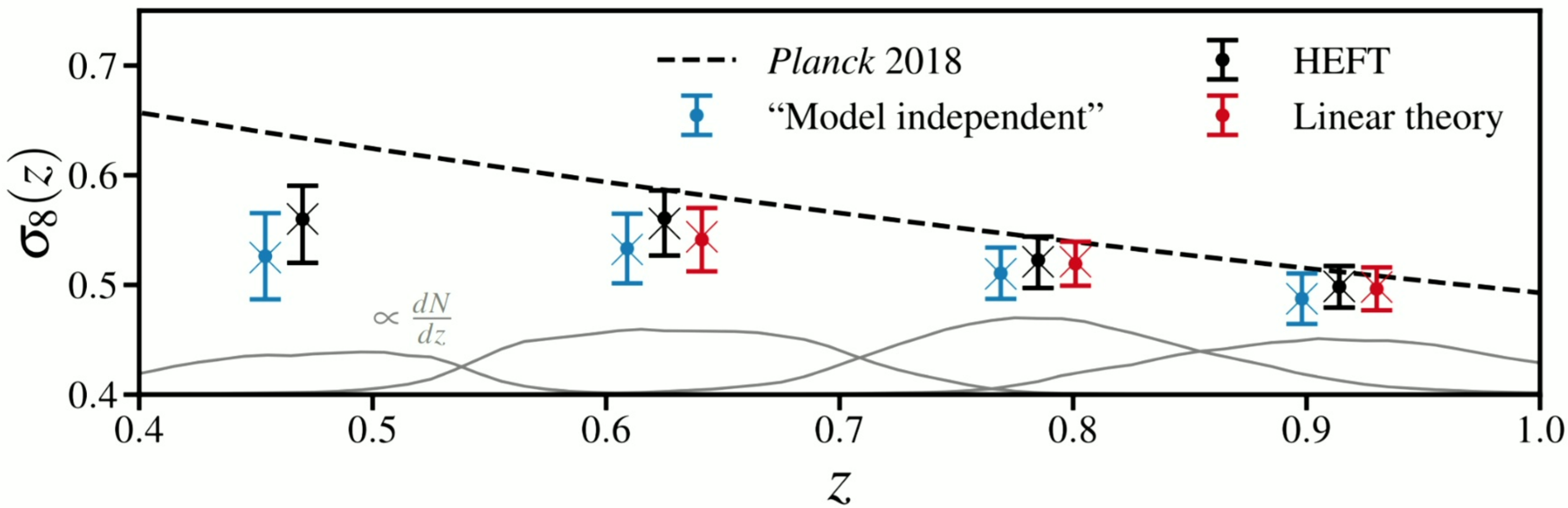
Model comparison



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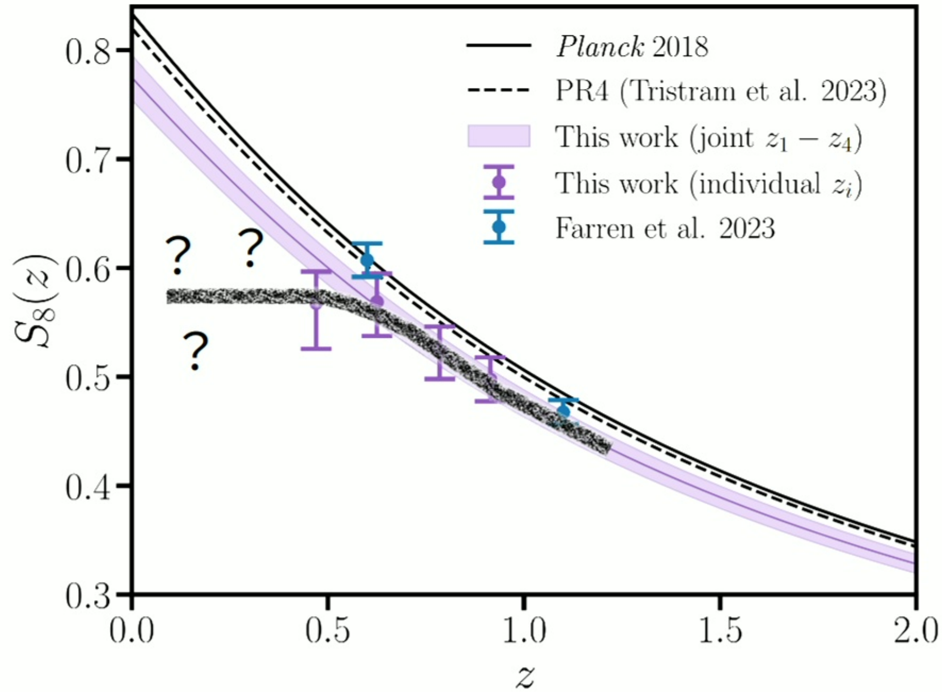
Comparison with *Planck*

Amplitude ≈ 5% lower than predicted by primary CMB at ≈ 2σ significance

Lowest z-bin most discrepant

IS STRUCTURE GROWTH SLOWING DOWN?



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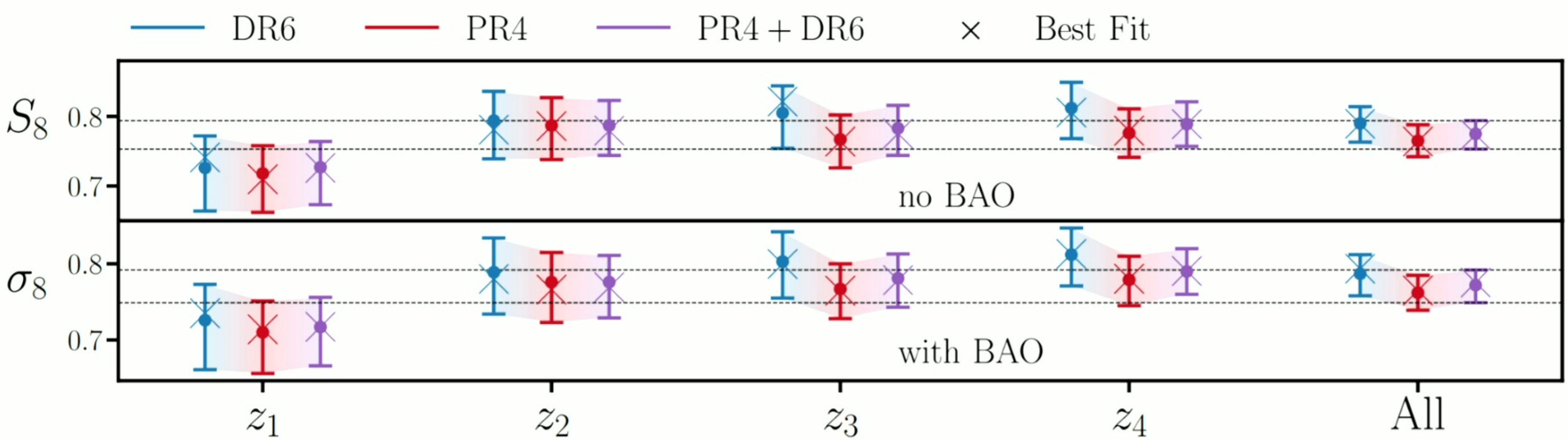
Self consistency



No significant evidence for structure growth slowing down

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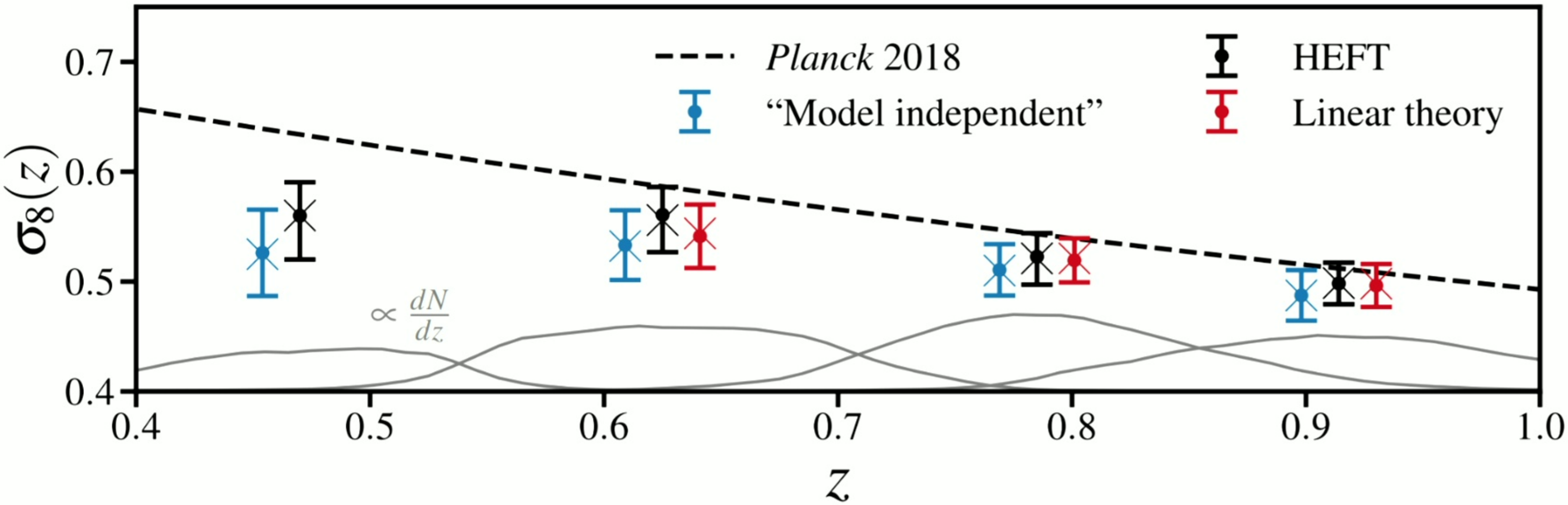
Model comparison



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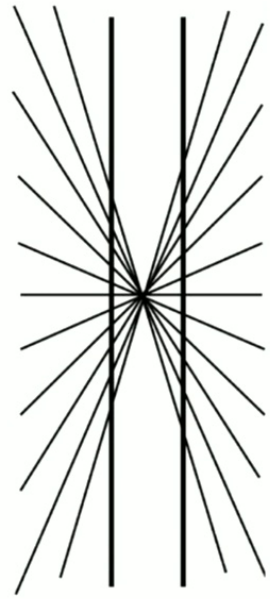
Hering illusion (1861)



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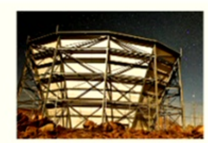

If you're still not convinced...

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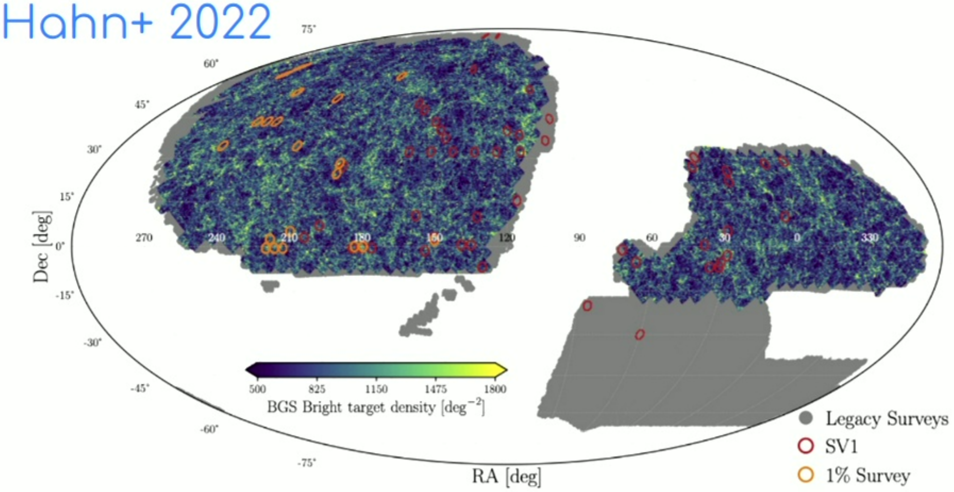
DESI BGS tomography

Analogous recipe to LRG sample but with a different selection to isolate low-z galaxies

Chen, DeRose+ 2022 splits the BGS legacy sample into two photo-z bins, calibrates dN/dz with DESI spectroscopy and estimates magnification biases using finite differences

Hahn+ 2022



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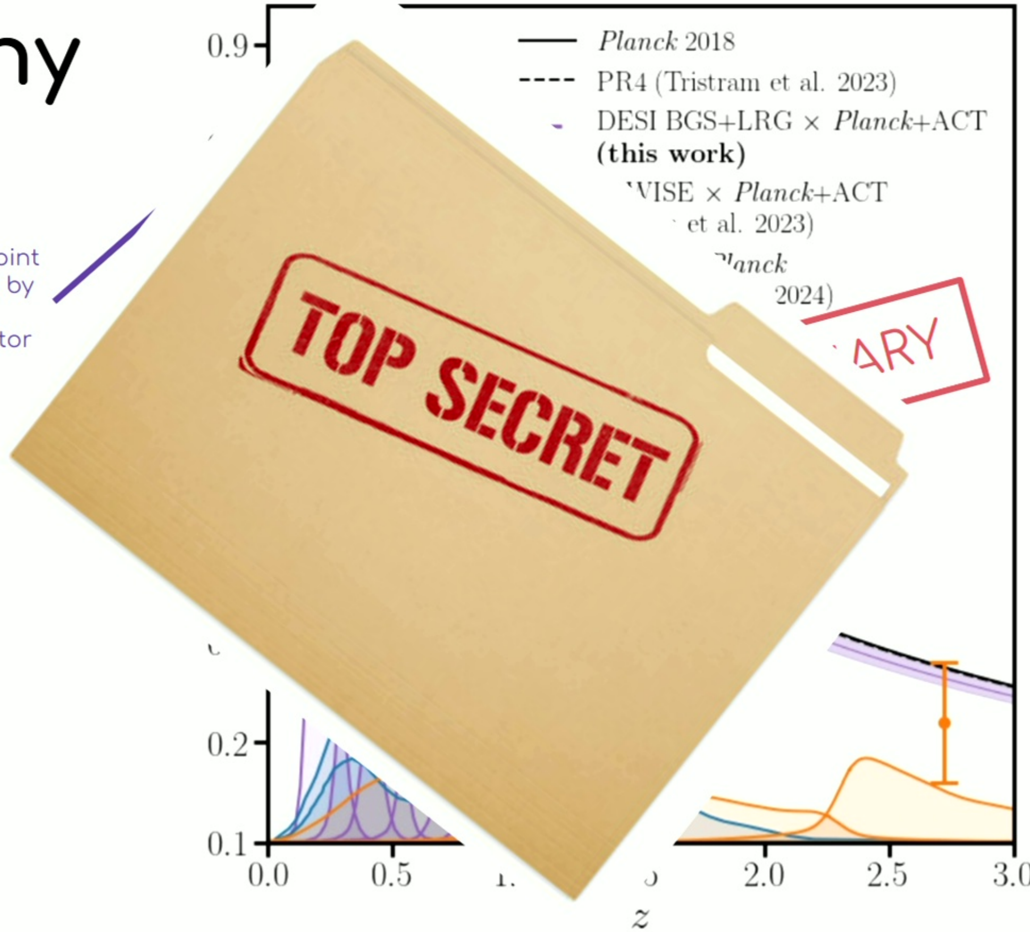
DESI BGS tomography

Each BGS point is multiplied by a random blinding factor drawn from N(1 , 0.05)



Turn the crank!

https://github.com/NoahSailer/MaPar/

same HEFT model & kmax, but with tighter priors
(higher order biases less important for BGS)

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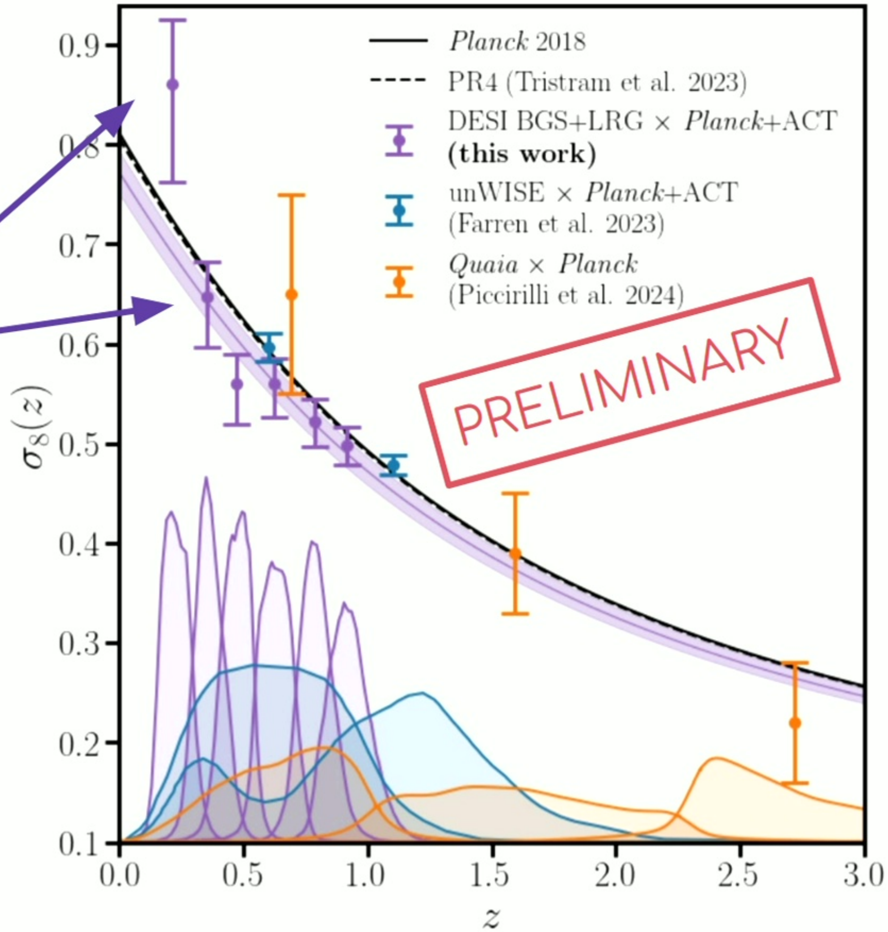

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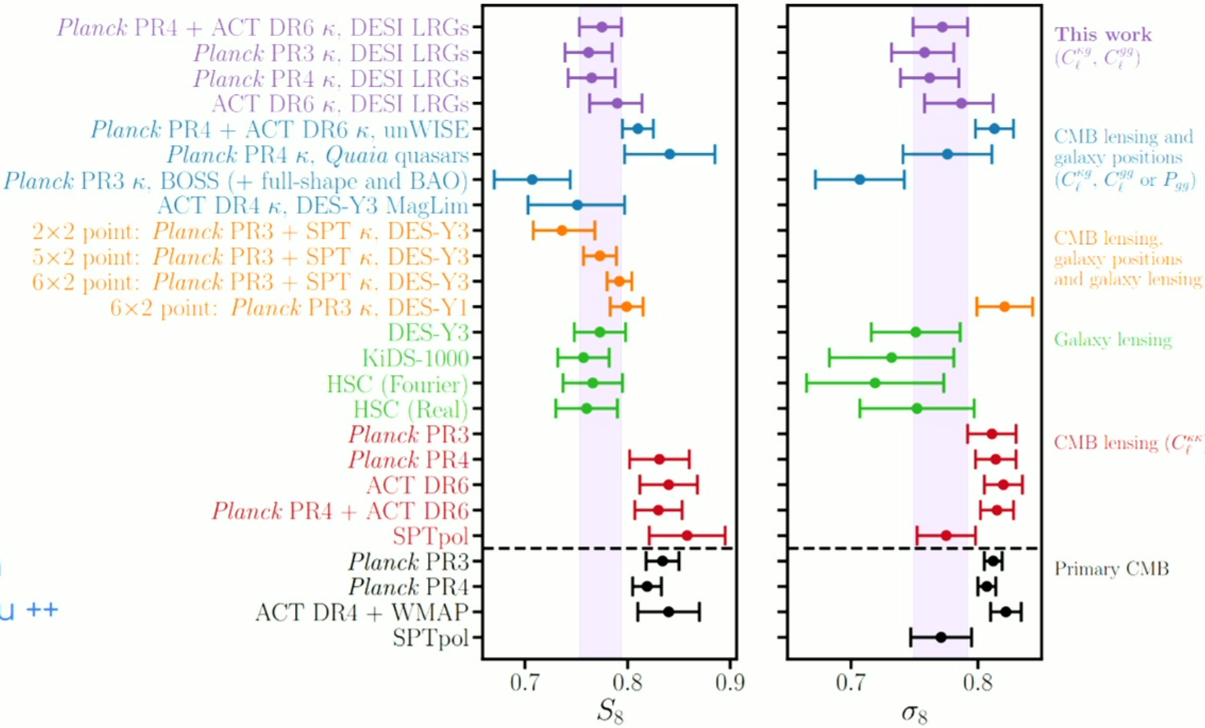
Conclusions

Is the S_8 tension "real"? **I think no, consistent with ~2σ fluctuation**

With DESI BAO σ_8 consistent to within 1σ, is Planck's Ω_m too high?

...on the off chance that it isn't a fluctuation, **can't blame baryons**

The (near) future:
- joint analysis with 3D power spectrum
  Maus, Sailer, Ferraro, White, DeRose, Zhou ++



The End

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