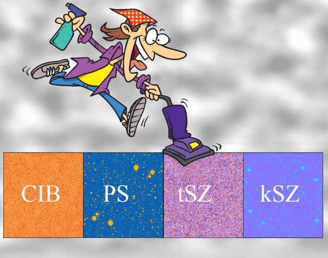
Accurate cosmology from CMB lensing and galaxy surveys

Noah Sailer

in collaboration with Martin White, Simone Ferraro, Emmanuel Schaan, ++

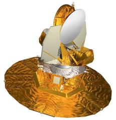


LSS surveys at a (very selective) glance

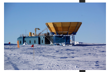
~2000s **~2010s** **~2020s** **~2030s**

CMB

WMAP



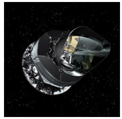
BICEP



O(10^3) detectors

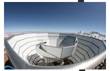
SPT

Planck



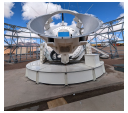
POLARBEAR

ACT



O(10^4) detectors

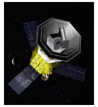
Simons Observatory



O(10^5) detectors

CMB-S4
Next Generation CMB Experiment

LiteBIRD



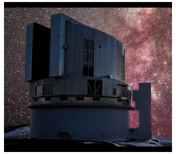
Galaxy images

O(10^8) galaxies

DES

KiDS

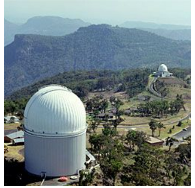
HSC



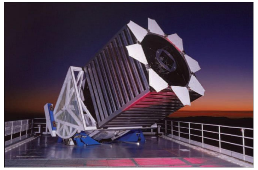
Rubin, O(10^{10}) galaxies

Galaxy redshifts

2dF, O(10^5) redshifts

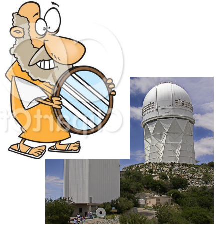


BOSS, O(10^6) redshifts



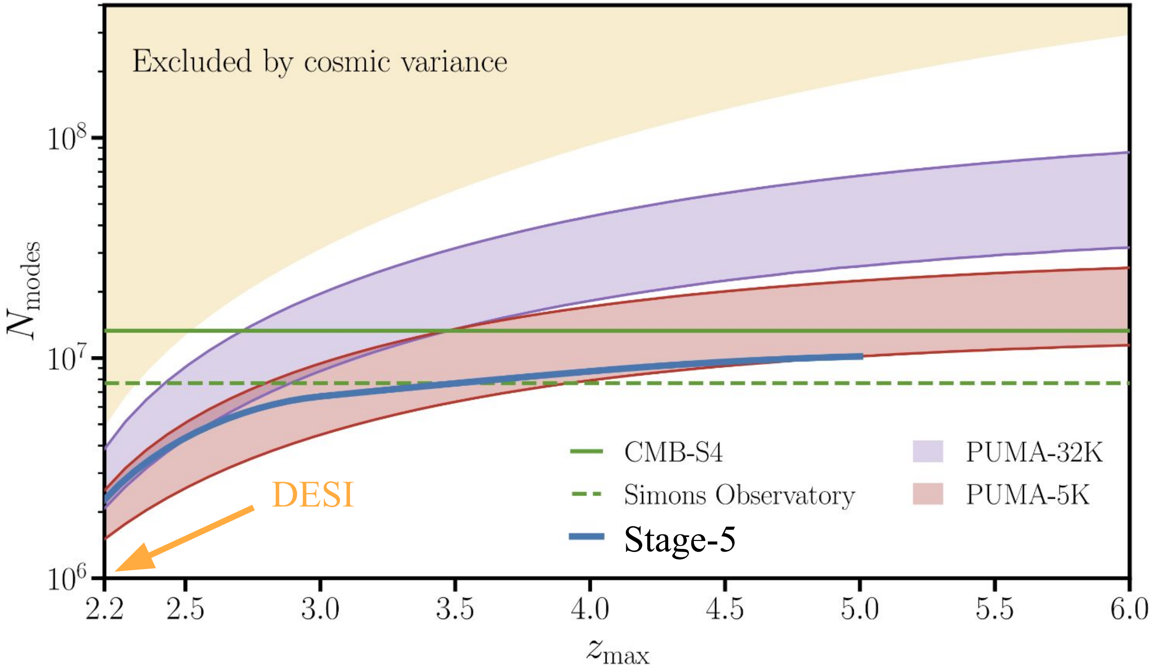
DESI, O(10^7) redshifts

Stage-5, O(10^8) redshifts



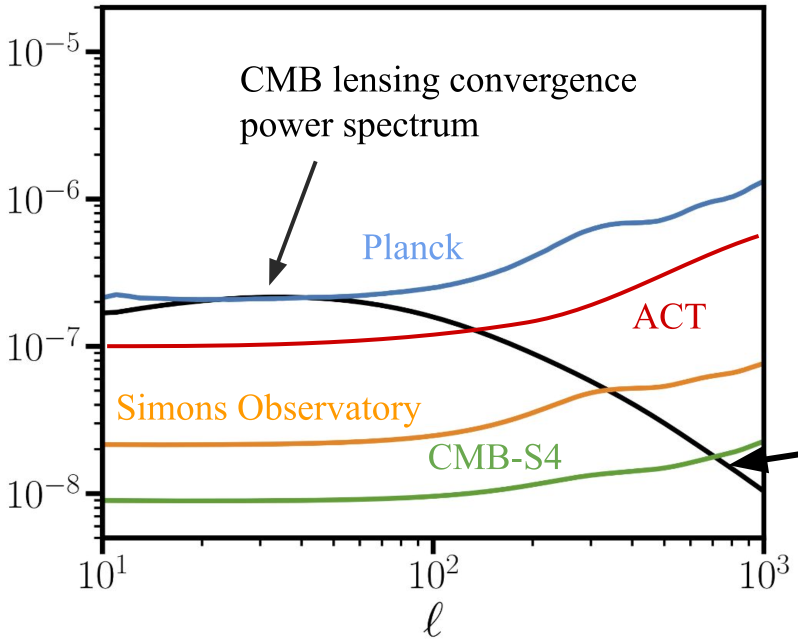
Significant improvements in precision

Effective number of linear modes



NS Castorina Ferraro White 2021

CMB lensing



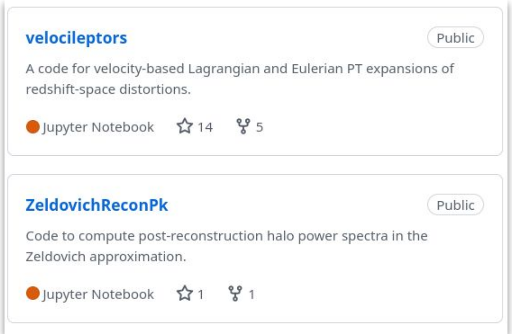
~ baryonic feedback non-negligible

Forecasts

- Full-shape $P_{gg}(k,\mu)$
- Projected C^{gg}, $C^{\kappa g}$

} linear theory from CLASS, non-linearities modeled with 1-loop LPT

- Only include quasi-linear k's
- $C^{\kappa\kappa}$ modeled with halofit ($L < 500$)
- Post-reconstruction $P_{gg}(k,\mu)$ within the Zel'dovich approximation



velocileptors Public

A code for velocity-based Lagrangian and Eulerian PT expansions of redshift-space distortions.

● Jupyter Notebook ☆ 14 5

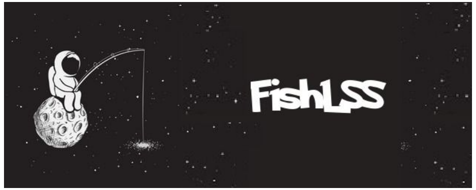
ZeldovichReconPk Public

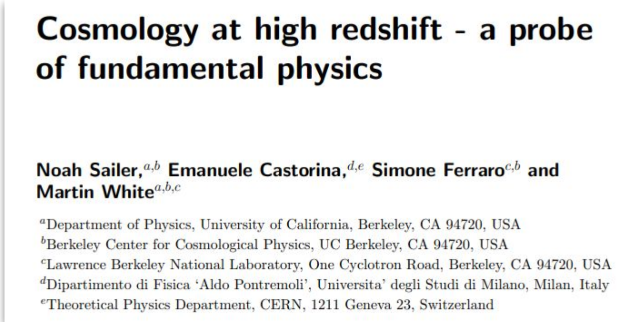
Code to compute post-reconstruction halo power spectra in the Zeldovich approximation.

● Jupyter Notebook ☆ 1 1

Code originally written for →

https://github.com/NoahSailer/FishLSS



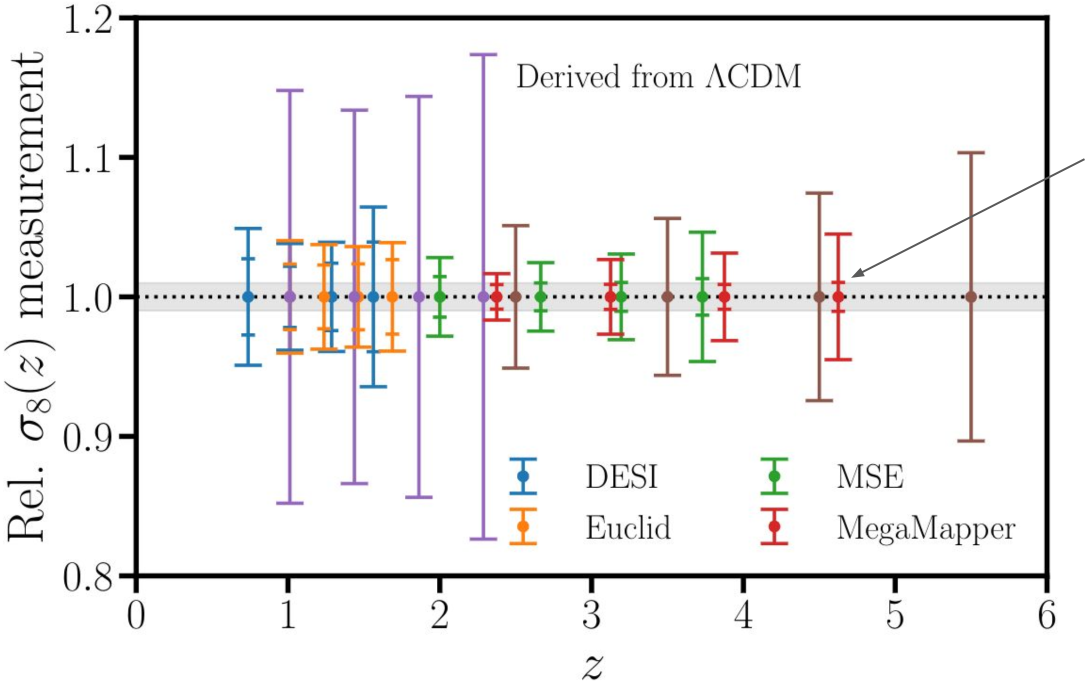


Cosmology at high redshift - a probe of fundamental physics

Noah Sailer,[a,b] **Emanuele Castorina,**[d,e] **Simone Ferraro**[c,b] **and Martin White**[a,b,c]

[a]Department of Physics, University of California, Berkeley, CA 94720, USA
[b]Berkeley Center for Cosmological Physics, UC Berkeley, CA 94720, USA
[c]Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
[d]Dipartimento di Fisica 'Aldo Pontremoli', Universita' degli Studi di Milano, Milan, Italy
[e]Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland

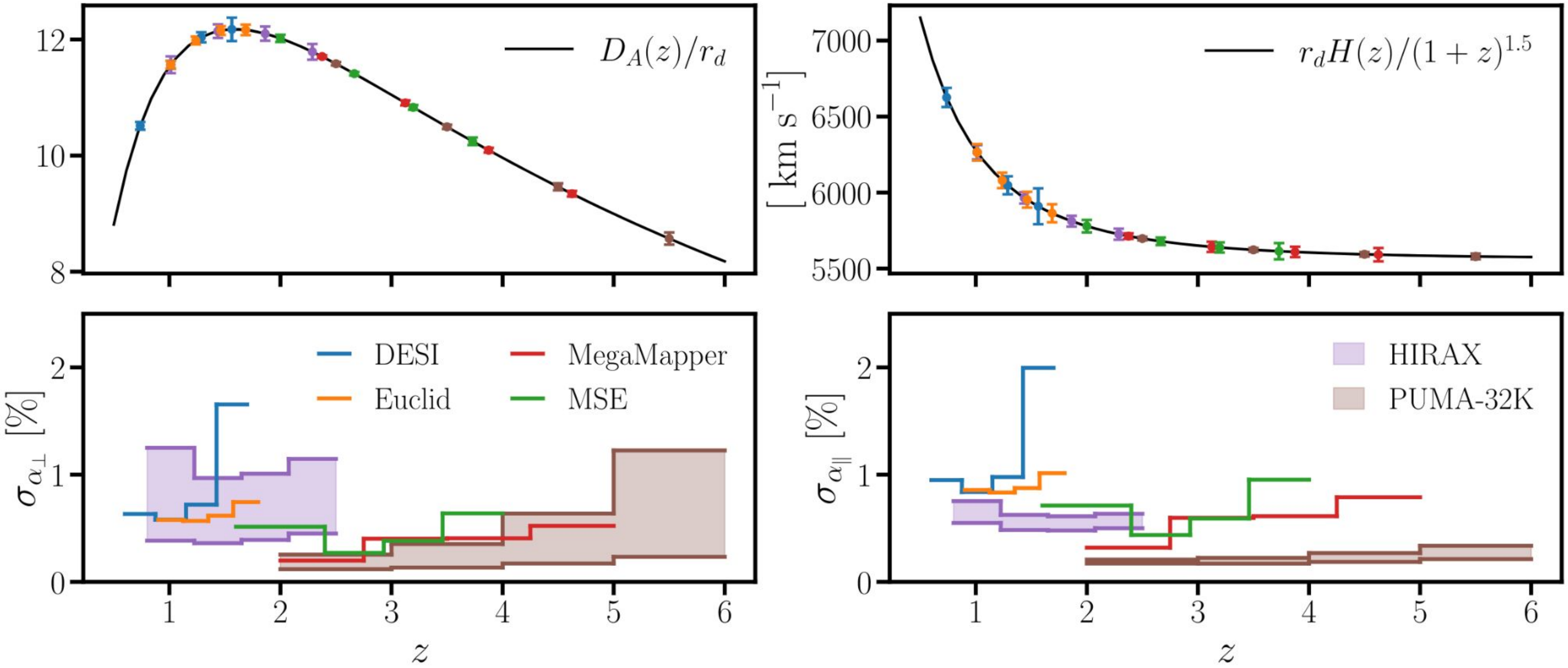
Structure growth



Significant improvements from cross-correlations with CMB lensing (SO)

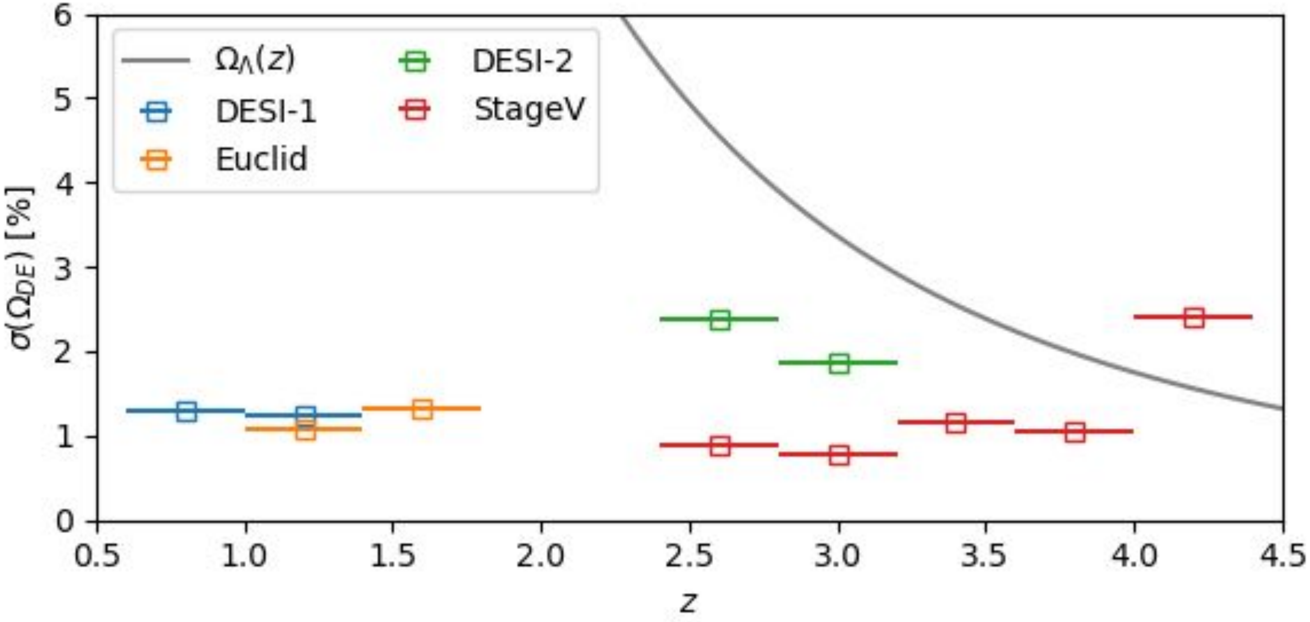
NS Castorina Ferraro White 2021

BAO measurements (distances)



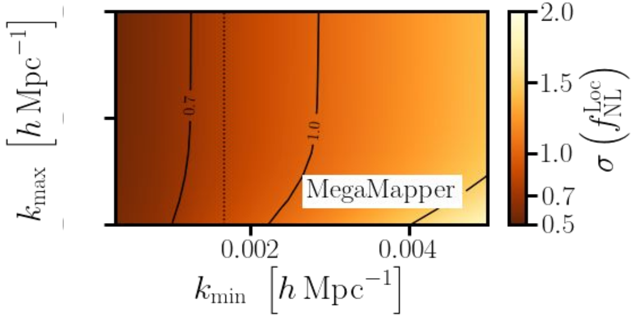
NS Castorina Ferraro White 2021

Detection of DE vs. redshift



Inflation: Primordial Non-Gaussianity

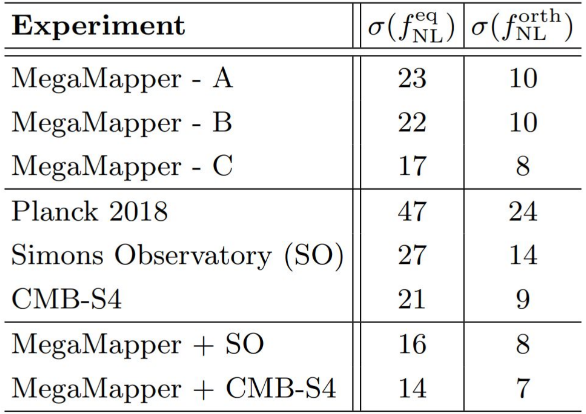
Local PNG



NS, Castorina, Ferraro, White 2021

Potential 10x improvement from multi-tracer (Sullivan, Prijon, Seljak 2023)

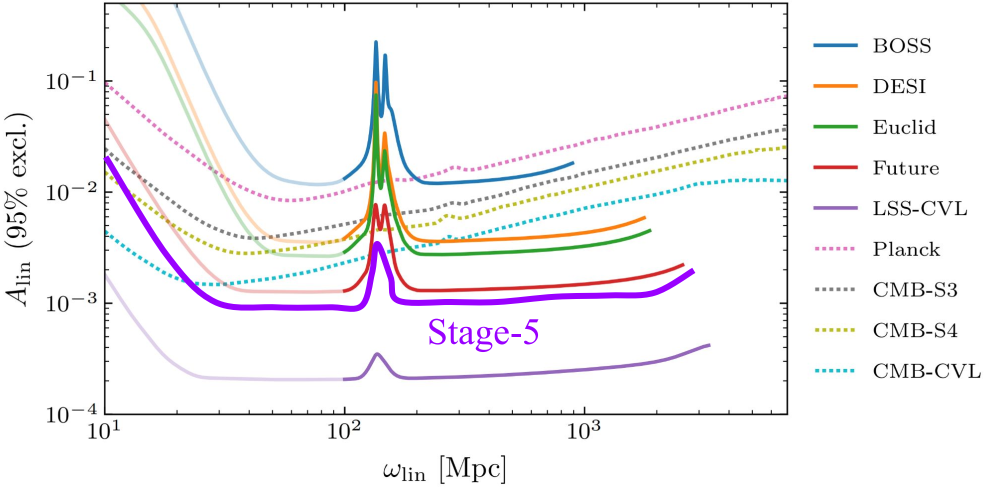
Non-local PNG



Experiment	$\sigma(f_{\rm NL}^{\rm eq})$	$\sigma(f_{\rm NL}^{\rm orth})$
MegaMapper - A	23	10
MegaMapper - B	22	10
MegaMapper - C	17	8
Planck 2018	47	24
Simons Observatory (SO)	27	14
CMB-S4	21	9
MegaMapper + SO	16	8
MegaMapper + CMB-S4	14	7

Cabass, Ivanov, Philcox, Simonovic, Zaldarriaga 2022

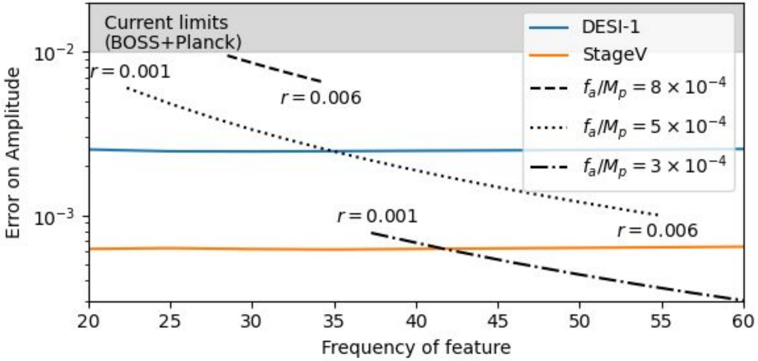
Inflation: Primordial Features



Stage-5

Beutler et al. 2020

Axion monodromy



White, Silverstein, Green

Light relics

$$\rho_r = \frac{\pi^2}{15}\left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] T_\gamma^4$$

$$N_{\text{eff}} = 2.99 \pm 0.34$$

from Planck + BAO

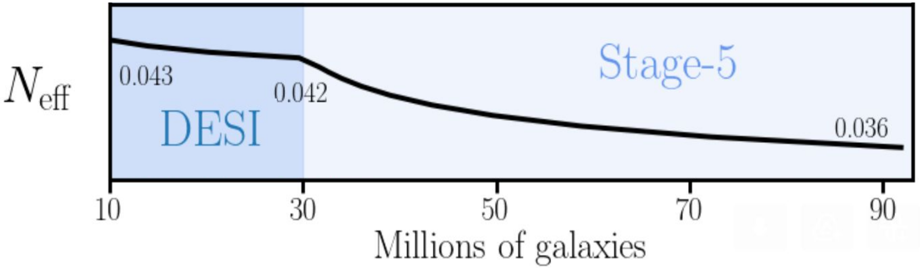
$\Delta N_{\text{eff}} > 0.027$ (scalar), 0.047 (Weyl fermion), 0.054 (vector boson)

CMB

- SO goal: $\sigma(N_{\text{eff}}) = 0.050$
- CMB-S4: $\sigma(N_{\text{eff}}) = 0.025$

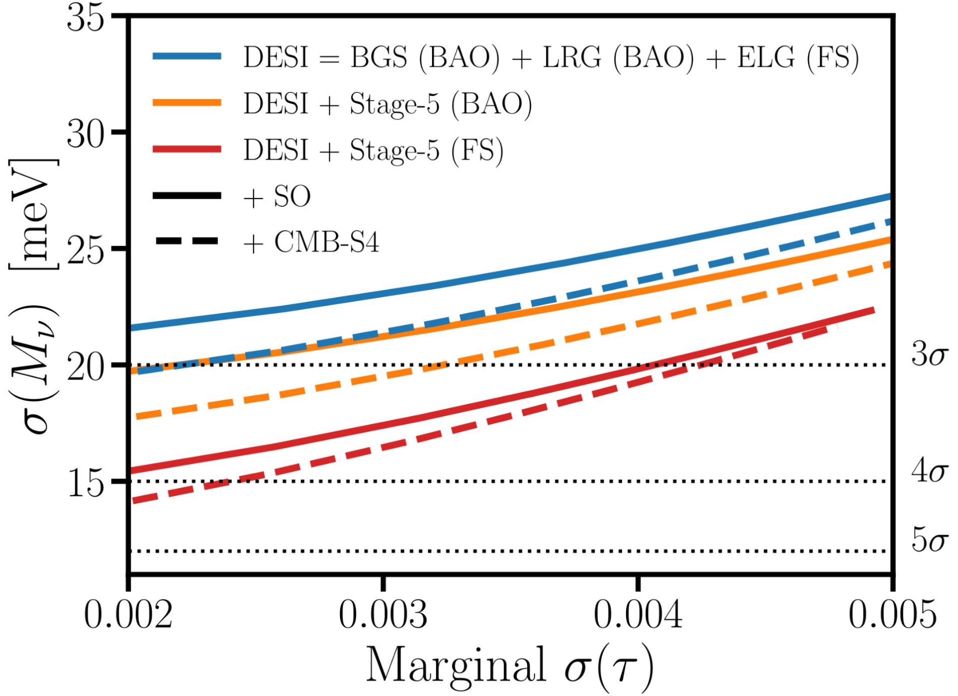
CMB-S4 + Stage-V: $\sigma(N_{\text{eff}})$ = **0.022**

SO + LSS



LSS largely immune to Y_p!

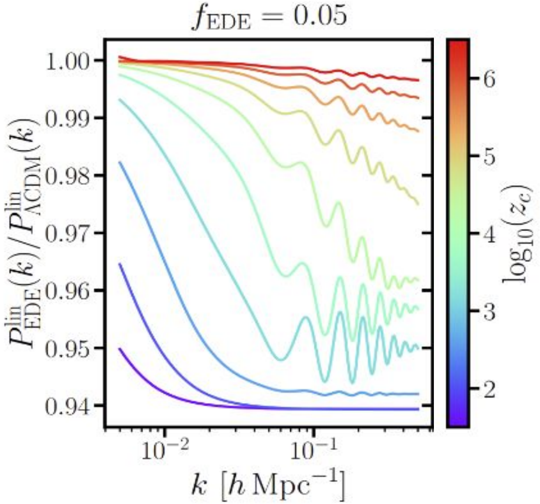
Neutrino mass



NS, Ferraro, White (in prep.)

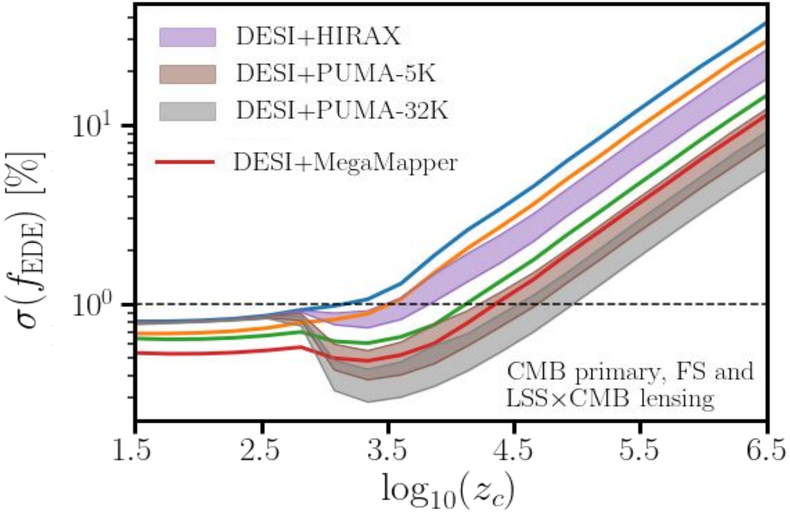
High-z expansion history

- Sudden changes to the expansion history (e.g. EDE at z_c) induce features in the power spectrum k_{hor}



Hill, McDonough, Toomey, Alexander 20

- Can constrain %-level deviations out to redshift 10^4



NS, Castorina, Ferraro, White 2021

From forecasts to measurements

What could possibly go wrong?

S_8 “tension”

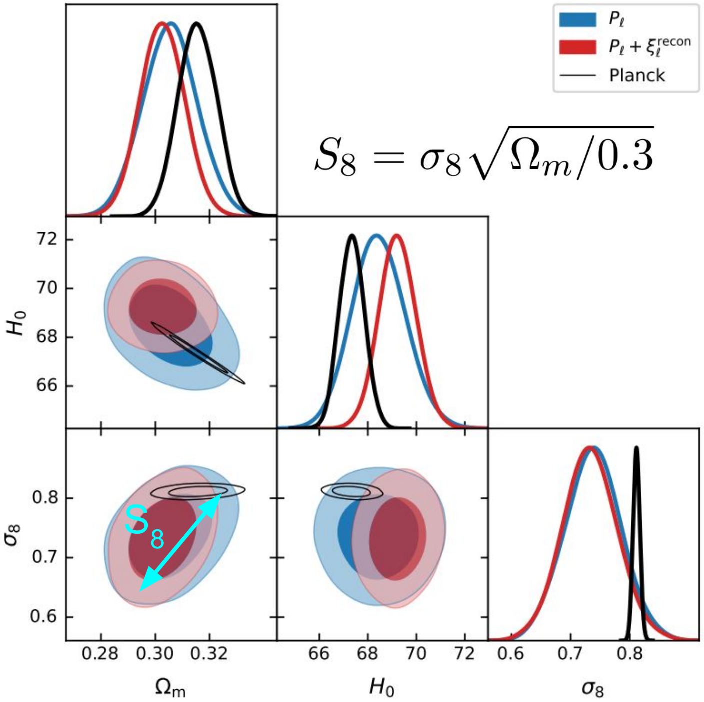
~5 - 10% difference in “early” and “late” time measurements of P(k) amplitude

a.k.a. “lensing is low” problem in cosmic shear & galaxy-galaxy lensing

Systematics?

- nonlinear scales (k > 0.6 h/Mpc), modeling baryons, redshift distribution, intrinsic alignments …

Presence in (quasi-linear) LSS:	S_8
Planck CMB + CMB Lensing	0.832 ± 0.013
BOSS BAO + Full Shape	0.736 ± 0.051



$$S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$$

Chen, Vlah, White 2021

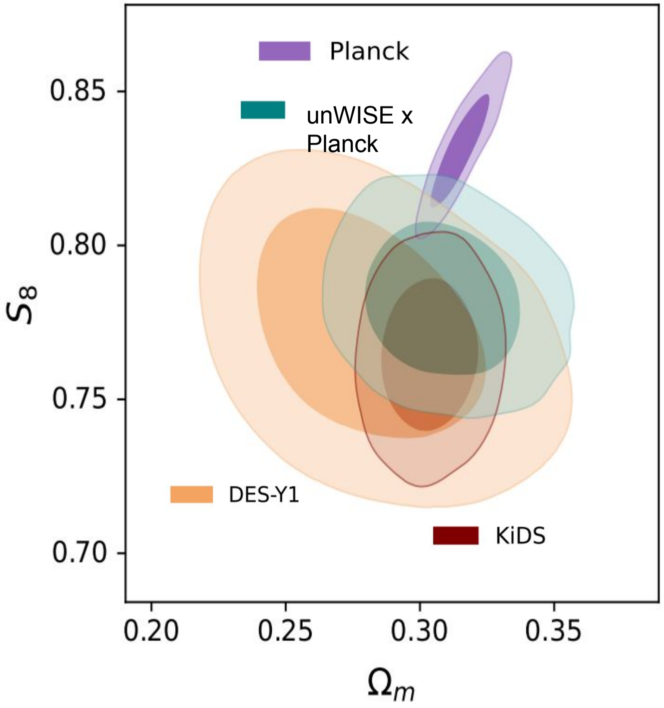
S_8 “tension”

Additional systematics?

Cross-correlations typically cleaner

- e.g. immune to uncorrelated biases

Presence in x-corr	S_8
Planck CMB + CMB Lensing	0.832 ± 0.013
unWISE x Planck	0.776 ± 0.017

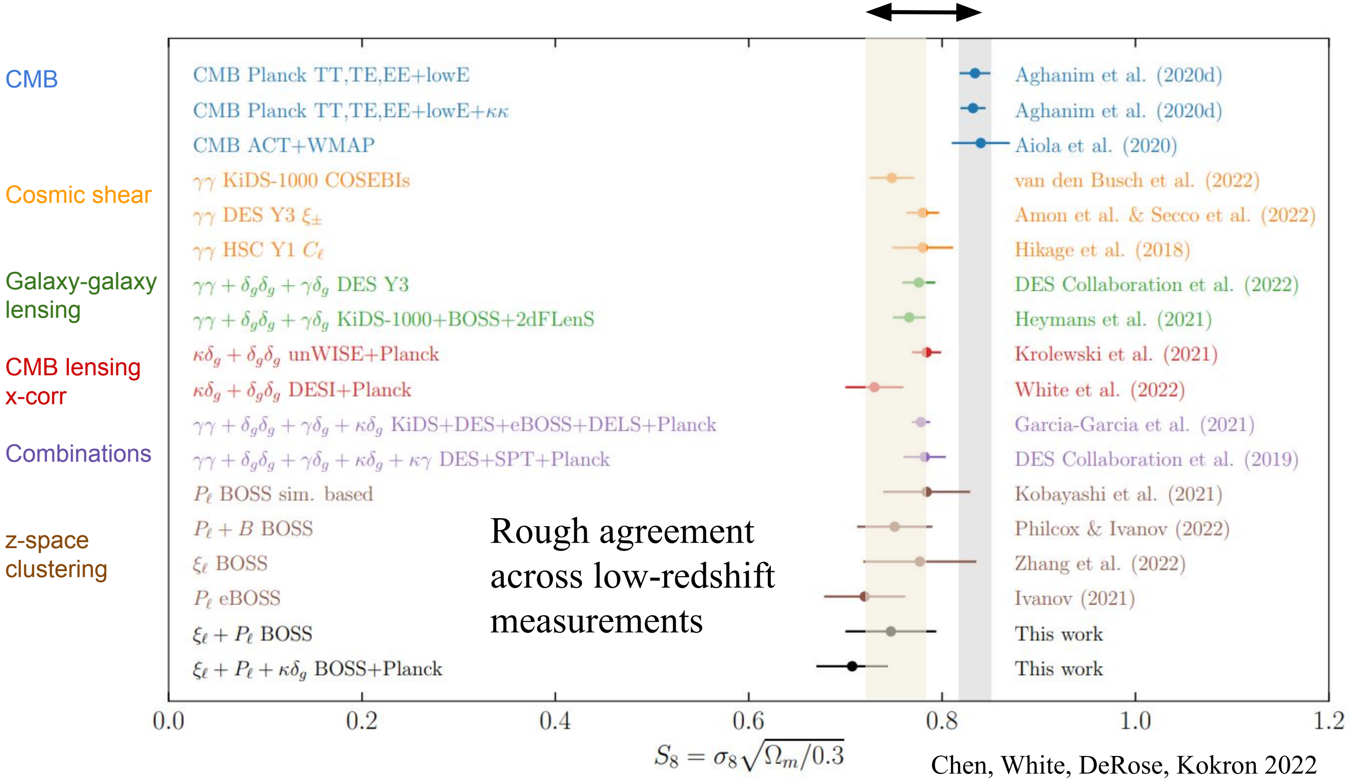


Krolewski, Ferraro, White 2021

*re-analysis in progress

S_8 “tension”

Disagreement with CMB at ~3σ level



Rough agreement across low-redshift measurements

Chen, White, DeRose, Kokron 2022

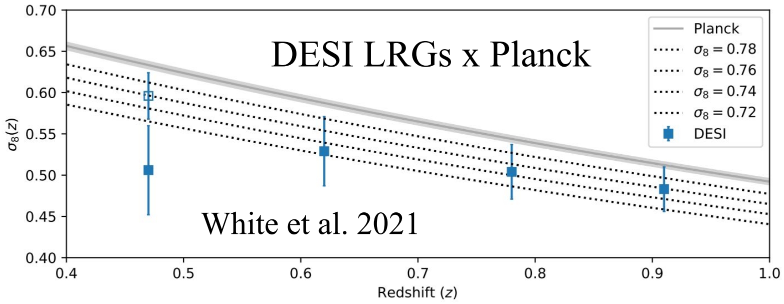
S_8 "tension"

What we know:

- Low S_8 measurements from **low-redshifts ($z < 1$)**

CMB:	0.832 ± 0.013
CMB lensing:	0.83 ± 0.03

- **~3σ** tension with CMB
- Rough agreement across a **broad range of scales**
  - e.g. shear vs. redshift-space galaxy clustering



DESI LRGs x Planck

White et al. 2021

What's going on?

Systematics?

$$S_8 \sim \frac{C^{\kappa g}}{\sqrt{C^{gg}}}$$

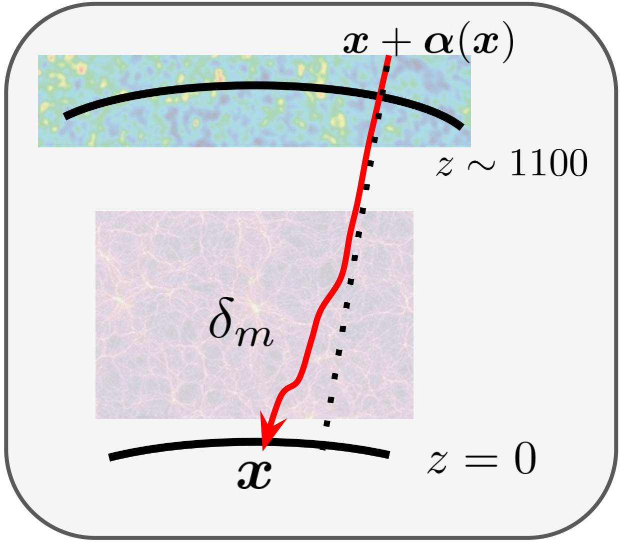
Biases from contaminated lensing maps

Systematics in galaxy maps (e.g. incorrect systematic weights)

If real, departure from ΛCDM!?

Foreground-immune CMB lensing reconstruction

CMB lensing

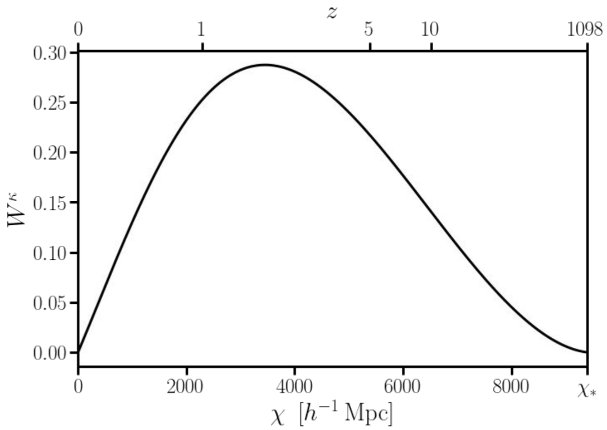


~arcmin deflections coherent on ~degree scales

$$T^{\rm lensed}(\boldsymbol{x}) = T^{\rm unlensed}(\boldsymbol{x}+\boldsymbol{\alpha}(\boldsymbol{x}))$$

Conventionally measure lensing convergence

$$\boxed{\kappa = -\frac{1}{2}\boldsymbol{\nabla}\cdot\boldsymbol{\alpha}} \sim \int dz\, W^\kappa(z)\,\delta_m$$



Clean probe of late-time structure evolution: $\sigma_8(z)$, neutrino masses, etc. Crucial for r-searches!

CMB lensing reconstruction (temperature)

Weak lensing (~arcmin deflections)

$$T^{\text{lensed}}(x) = T^{\text{unlensed}}(x) + \underbrace{\boldsymbol{\alpha}(x)\cdot\boldsymbol{\nabla}T^{\text{unlensed}}(x)}_{\text{convolution in L-space}} + \cdots$$

“Off-diagonal” Fourier modes are coupled

$$\langle T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}}\rangle_{\text{at fixed }\kappa_{\boldsymbol{L}}} = f^{\kappa}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}}\ \kappa_{\boldsymbol{L}} + \cdots$$

linear response to lensing

$$f^{\kappa}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} \equiv \frac{2\boldsymbol{L}}{L^2}\cdot\left[\boldsymbol{\ell}C^0_\ell + (\boldsymbol{L}-\boldsymbol{\ell})C^0_{|\boldsymbol{L}-\boldsymbol{\ell}|}\right]$$

Solve for κ!

$$\hat{\kappa}_{\boldsymbol{L}} = \frac{T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}}}{f^{\kappa}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}}} \xrightarrow{\text{generalize}} \boxed{\hat{\kappa}_{\boldsymbol{L}} = N_{\boldsymbol{L}} \int_{\boldsymbol{\ell}} F^{\kappa}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}}\ T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}}}$$

Weights *arbitrary*, typically chosen to minimize variance (standard QE: Hu, Okamoto 2002)

Quadratic Estimators

Most general QE

$$\hat{\kappa}_{\boldsymbol{L}} = N^{\kappa}_{\boldsymbol{L}} \sum_{ij} \int_{\boldsymbol{\ell}} F^{ij}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} \tilde{M}^i_{\boldsymbol{\ell}} \tilde{M}^j_{\boldsymbol{L}-\boldsymbol{\ell}}$$

Collection of lensed maps

Arbitrary weights

Normalized so that $\langle \hat{\kappa}_L \rangle_{\text{fixed } \kappa_L} = \kappa_L$, making use of

$$\langle \tilde{M}^i_{\boldsymbol{\ell}} \tilde{M}^j_{\boldsymbol{L}-\boldsymbol{\ell}} \rangle_{\text{fixed } \kappa_L} = f^{ij}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} \, \kappa_{\boldsymbol{L}} + \cdots$$

Straightforward to derive optimal weights.

Foreground biases (CMB lensing)

CMB lensing convergence measured with **Quadratic Estimator**

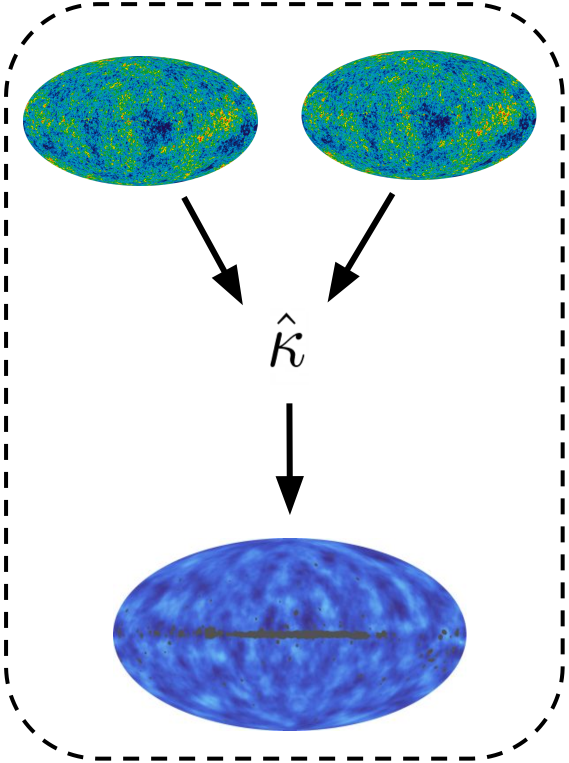
$$\hat{\kappa} \sim \sum_{ij} F_{ij} \, T_i \, T_j$$

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

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

$$\langle s s g \rangle$$

Nonzero if foregrounds are **correlated with galaxy sample** and **non-Gaussian**



CMB foregrounds

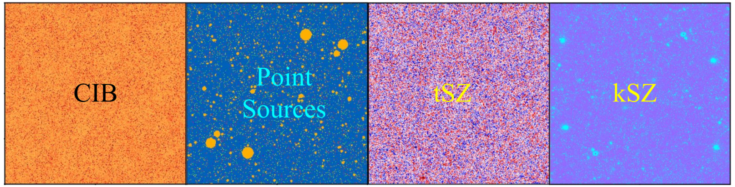
- Extragalactic foregrounds:
  - Cosmic Infrared Background (CIB)
  - Radio point sources
  - thermal- and kinetic- Sunyaev-Zel'dovich effects

- Galactic foregrounds:
  - Extinction → galaxy selection
  - Dust emission → CMB κ

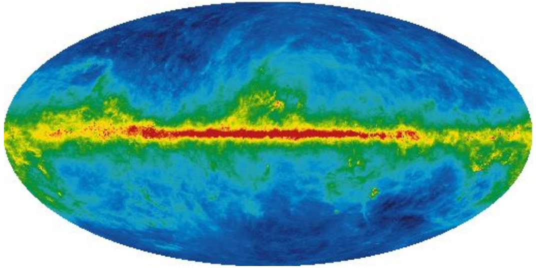
Also show up in polarization

- Radio point sources polarized at few % level
- Polarization from patchy reionization

Sehgal et al. 2009

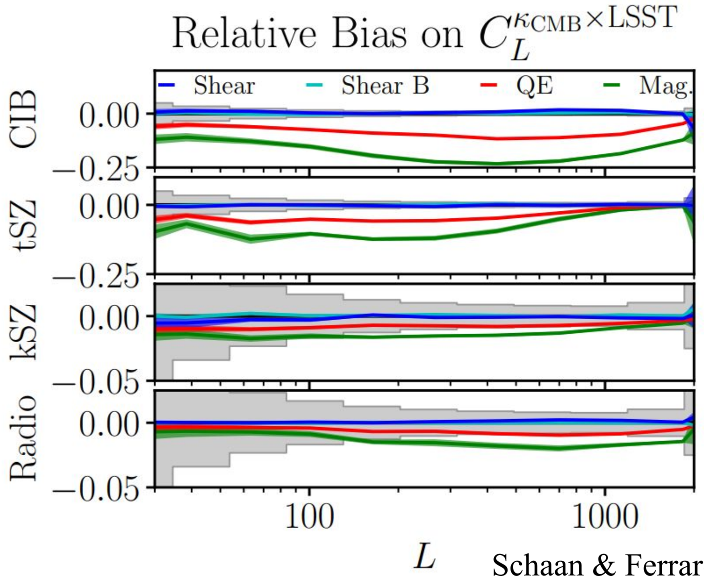


Schlegel, Finkbeiner, Davis 1998



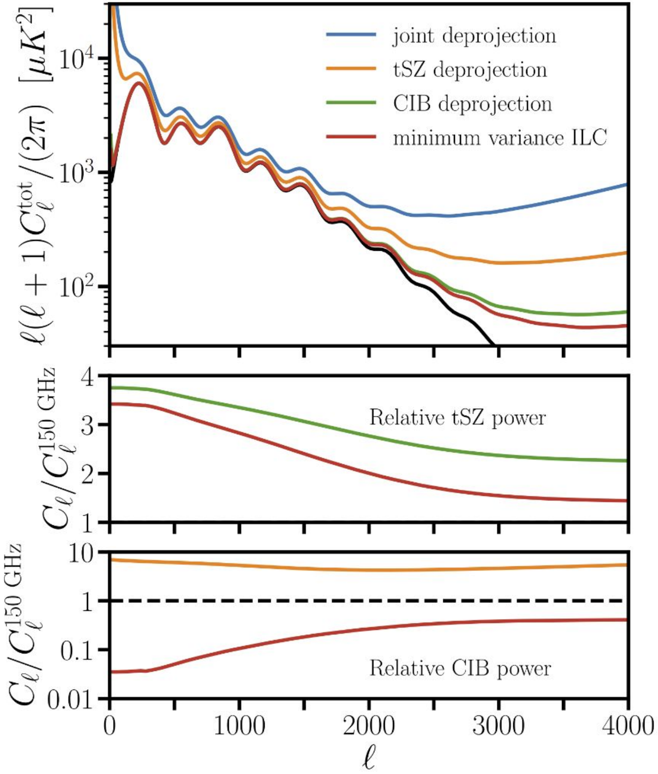
Extragalactic foreground biases

Extragalactic biases to cross-correlations are highly significant (in temp.) if unaccounted for



Schaan & Ferraro 2018

"Standard" ILC approaches lead to huge noise costs



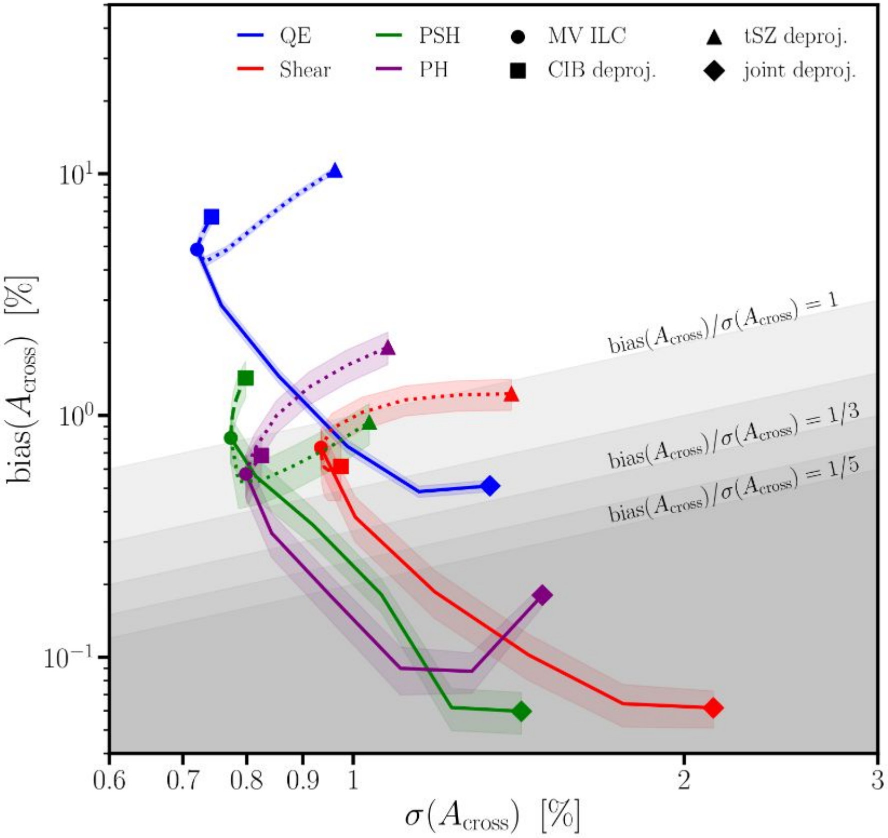
NS, Schaan, Ferraro, Darwish, Sherwin 2021

“Tailored” ILC weights

Very simple compromise – draw a line:

$$\boldsymbol{w}_\ell(t) = t\boldsymbol{X}_\ell + (1-t)\boldsymbol{w}_\ell^{\mathrm{ILC}}$$

Only need to pay a 30-40% noise cost, instead of a factor of 2



NS, Schaan, Ferraro, Darwish, Sherwin (2021)

Geometric approaches

Can phrase foreground bias at the map level

$$\langle TT\rangle_{\text{fixed }\kappa_L, s_L} \sim f^{\kappa}\,\kappa_L + g\, s_L$$

Linear response to lensing

Linear response to foreground

$\hat{\kappa} \sim \sum_{ij} F_{ij}\, T_i\, T_j$, choose weights to mitigate sensitivity to foregrounds

- "Shear-only" reconstruction $\sum_{ij} F_{ij}\, g_{ij} \ll 1$
- Bias-hardening $\sum_{ij} F_{ij}\, g_{ij} = 0$

What does the foreground linear response g_{ij} look like?

Foreground response

$$\langle TT\rangle = f^{\kappa}\,\kappa$$

$$\big\downarrow$$

Recast linear response in terms of bi-/power- spectra

$$f^{\kappa} = \langle TT\kappa\rangle/\langle\kappa\kappa\rangle$$

$$\big\downarrow$$

Generalize to foreground linear response (temperature)

$$g = \langle sss\rangle/\langle ss\rangle$$

$$\big\downarrow$$

More generally for polarization

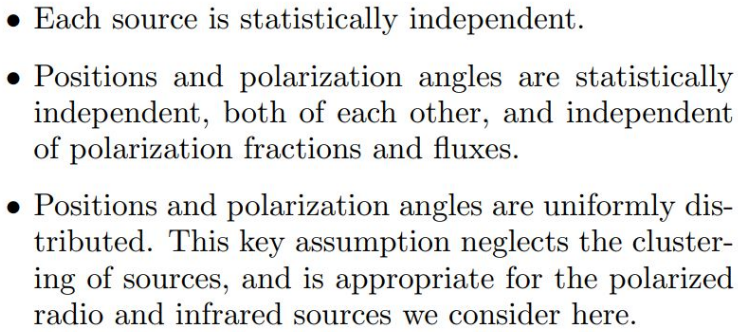
$$\langle s^X_{\boldsymbol{\ell}}\, s^Y_{\boldsymbol{L}-\boldsymbol{\ell}}\rangle' = \textstyle\sum_Z g^{XY,Z}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}}\ s^Z_{\boldsymbol{L}}$$

$$g^{XY,Z}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} = \frac{\langle s^X_{\boldsymbol{\ell}}\, s^Y_{\boldsymbol{L}-\boldsymbol{\ell}} s^Z_{-\boldsymbol{L}}\rangle}{\langle s^Z_{\boldsymbol{L}} s^Z_{-\boldsymbol{L}}\rangle}.$$

"Model":

Foreground is a collection of sources with identical profiles

E.g. for temperature $s^T_{\boldsymbol{\ell}} = \sum_i s_i e^{-i\boldsymbol{\ell}\cdot\boldsymbol{x}_i} u_{\boldsymbol{\ell}}$



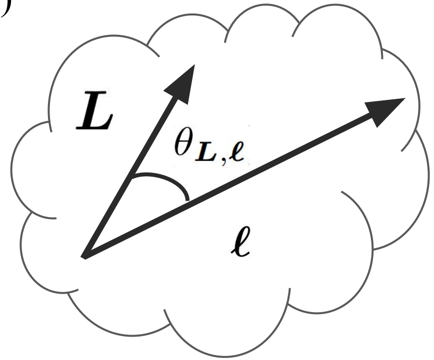
- Each source is statistically independent.
- Positions and polarization angles are statistically independent, both of each other, and independent of polarization fractions and fluxes.
- Positions and polarization angles are uniformly distributed. This key assumption neglects the clustering of sources, and is appropriate for the polarized radio and infrared sources we consider here.

Plug and chug!

E.g. for temperature $g_{\ell,L-\ell} \propto u_{\ell}\, u_{|L-\ell|}/u_L$

“Shear-only” reconstruction (temp.)

Reconstructing lensing on large scales (~degrees) from small scales (~arcmin)
Small parameter: **L/l** (Large-lens limit)



Lensing

$$f^{TT}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} = C^{TT}_{\ell}\left[\frac{d\ln \ell^2 C^{TT}_{\ell}}{d\ln \ell} + \cos(2\theta_{\boldsymbol{L},\boldsymbol{\ell}})\frac{d\ln C^{TT}_{\ell}}{d\ln \ell}\right] + \cdots$$

Foregrounds

$$g^{TT,T}_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} = \mathcal{A}\frac{u_\ell}{u_L}\left\{u_\ell - L u'_\ell \cos(\theta_{\boldsymbol{L},\boldsymbol{\ell}})\right\} + \cdots$$

Only keep clean quadrupole: $F_{\boldsymbol{\ell},\boldsymbol{L}-\boldsymbol{\ell}} \propto \cos(2\theta_{\boldsymbol{L},\boldsymbol{\ell}})$ (field-level) bias suppressed by $(L/l)^2$

Schaan & Ferraro 2018

Bias-hardening

$$\mathcal{L} = (\text{variance}) + \lambda_1 \, R^{\kappa,s}$$

Choose weights to minimize (Gaussian) noise of estimator

Subject to having no response to foreground

$$\sum_{ij} F_{ij} \, g_{ij} = 0$$

Easy to generalize to N foregrounds (or polarization) – add more Lagrange multipliers!

Osborne, Hanson, Dore 2013
Namikawa Hanson Takahashi 2013
NS Schaan Ferraro 2020

Robustness to assumed profile

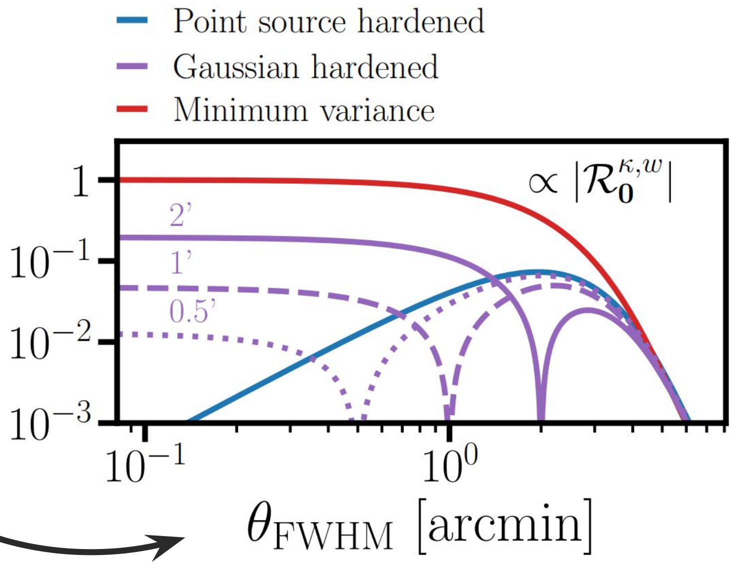
Assumed some profile for the sources

$$s_{\boldsymbol{\ell}}^T = \sum_i s_i e^{-i\boldsymbol{\ell}\cdot\boldsymbol{x}_i} u_{\boldsymbol{\ell}}$$

(u=1 for PS) **How sensitive are we to the choice in u?**

$$\langle\hat{\kappa}\rangle = \kappa + R^{\kappa,s}\, s$$

Suppose true profile is some Gaussian with width



NS Ferraro Schaan 2022

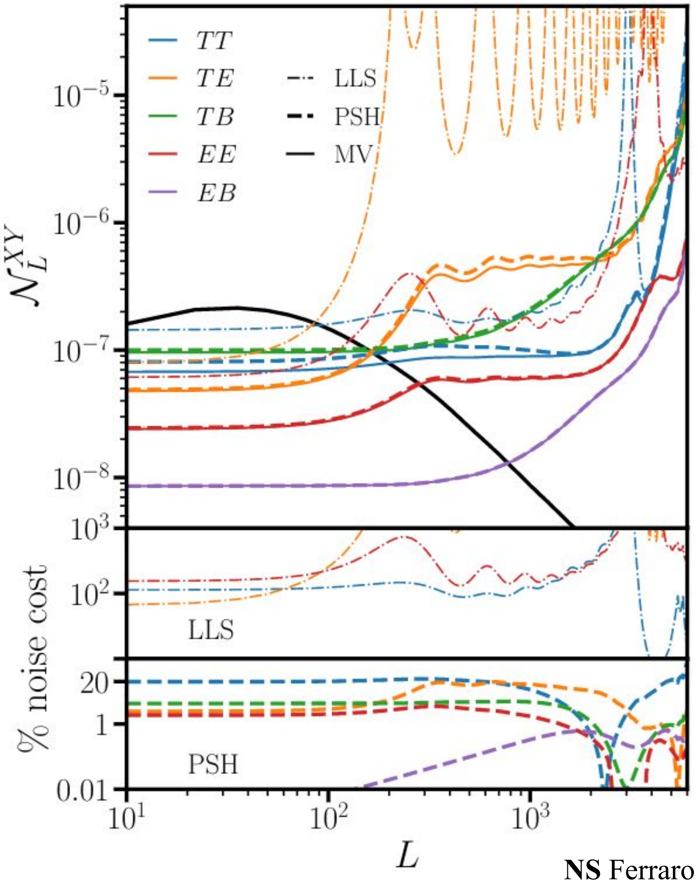
Noise cost

- “Shear-only” reconstruction: ~ **factor of 2**
- Bias hardening: < **20%**

Details

Single frequency (150 GHz)
1.4 arcmin FWHM

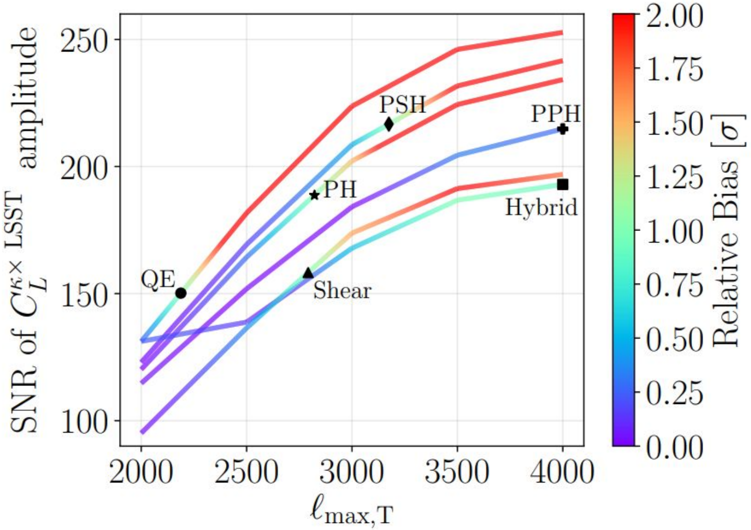
$$\Delta_T = 1\ \mu\text{K-arcmin}$$
$$\ell_{\max,T} = 3500$$
$$\ell_{\max,P} = 5000$$



NS Ferraro Schaan 2022

Bias reduction (temp)

- For fixed l_{max}, hardening against a tSZ-profile reduces bias by order-of-magnitude at 10% noise cost
- In principle can push to higher l_{max} while remaining unbiased
- Lower bias, lower noise ☺



NS Schaan Ferraro 2019

Bias reduction (polarization)

Details

WebSky sims (Li+22)

5 mJy mask threshold

p = 3%

Single frequency (150 GHz)

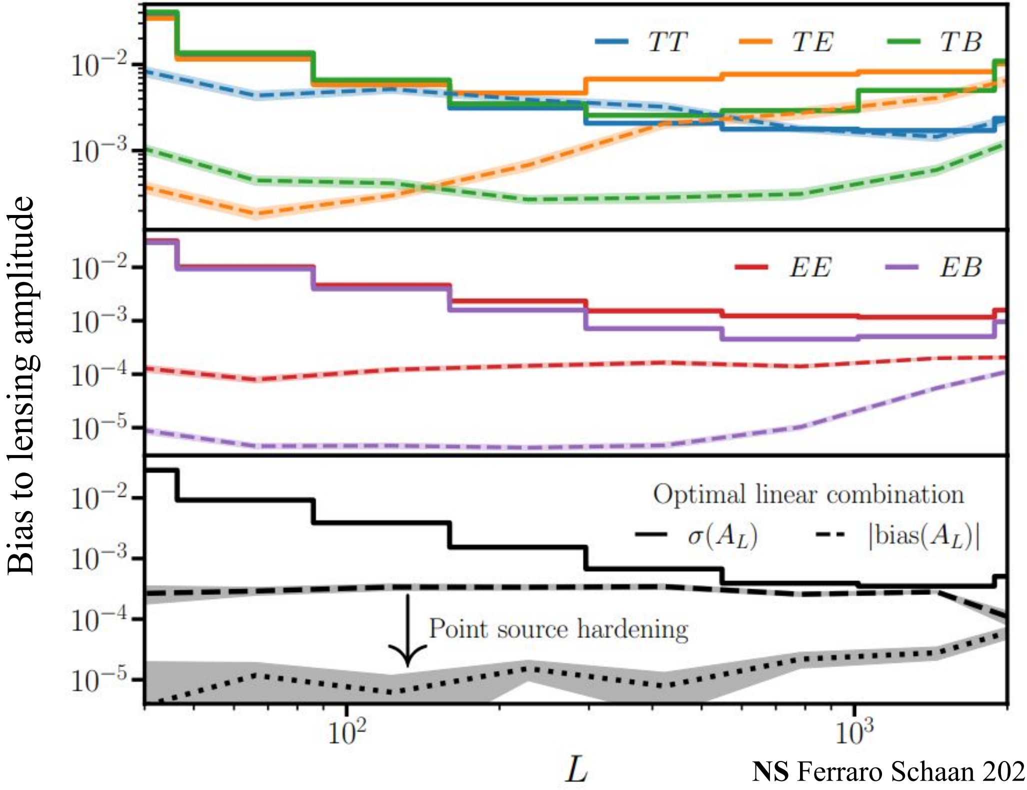
1.4 arcmin FWHM

$\Delta_T = 1\ \mu$K-arcmin

$\ell_{\max,T} = 3500$

$\ell_{\max,P} = 5000$

Radio PS only



NS Ferraro Schaan 2022

Foreground-immune reconstruction: summary

In addition to "standard" multi-frequency approaches, we now have

- "Tailored" multi-frequency weights

- Shear-only estimators
  - Weights suppress response to foregrounds in "large-lens limit"

- Profile-hardened estimators
  - Weights have zero-response to a collection of unclustered sources with identical tSZ-like profiles
  - Can in theory achieve a higher SNR (while staying unbiased) than the traditional QE by pushing the reconstruction to smaller scales

- Optimally combine geometric and multi-frequency methods (Darwish Sherwin **NS** Schaan Ferraro 2021)
  - Temperature-only: reduce bias by **order of magnitude** at **few% noise cost**

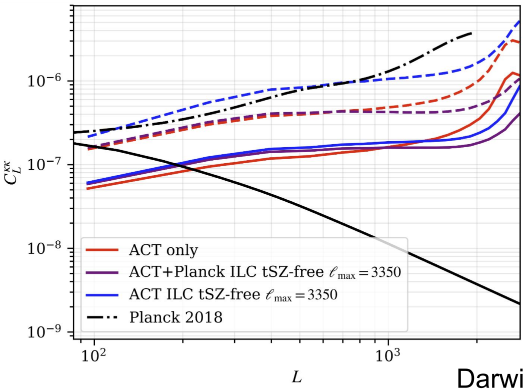
- Polarization: Bias-reduced by ~10x (in cross, ~2x in auto) at sub-percent noise cost

$\sigma_8(z)$ from DESI x ACT

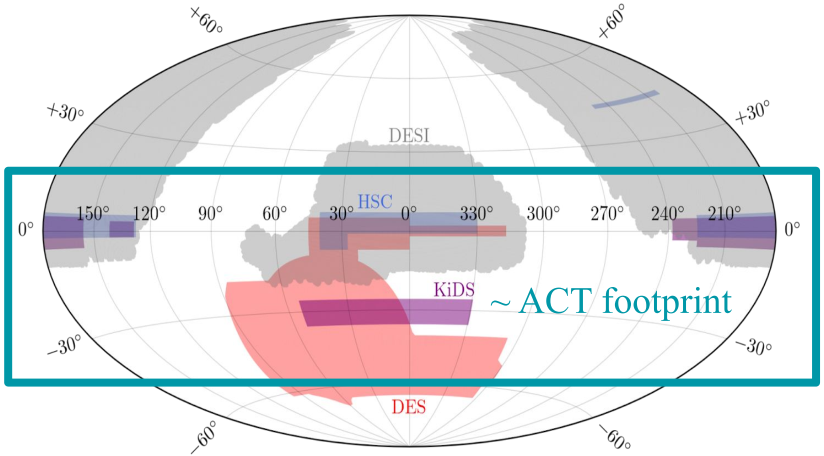
ACT CMB lensing

DESI-ACT MoU – latest ACT CMB lensing map (Qu et. al. in prep.)

- 90, 150, 220 GHz data (through 2021) co-added with Planck (**results on Tuesday!**)
- **Lowest noise wide-field map available**
    - signal dominated to L~200
    - ~13k sq. deg. overlap with LRGs
- Passed ~200 systematics checks!



Darwish et al. 2020



~ ACT footprint

Figure: Johannes Lang

DESI Luminous Red Galaxies (LRGs)

DESI LRG (legacy) imaging

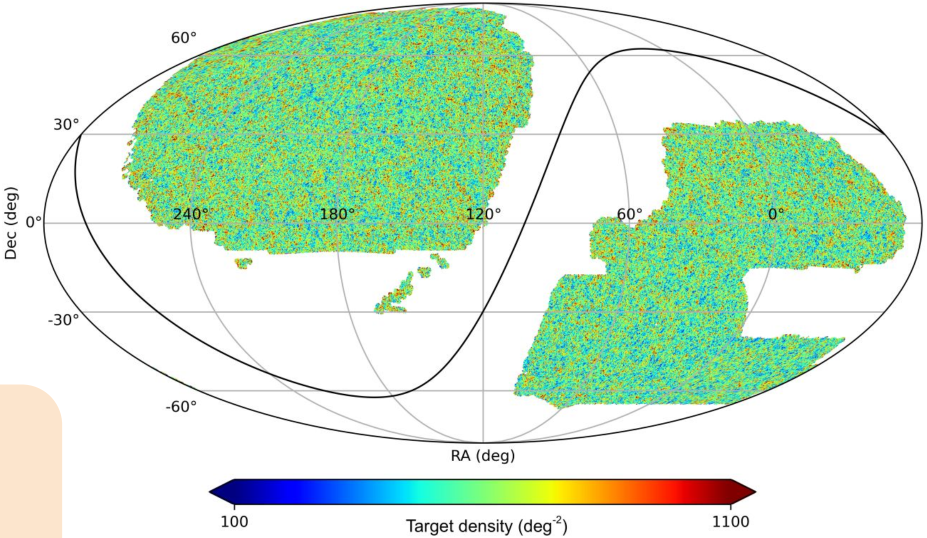
Ideal sample for robust S_8 measurement

Precision: dense sample over large area

- 8 million galaxies
- 18k sq. deg.
- $0.4 < z < 1$

Accuracy: robust against common systematics

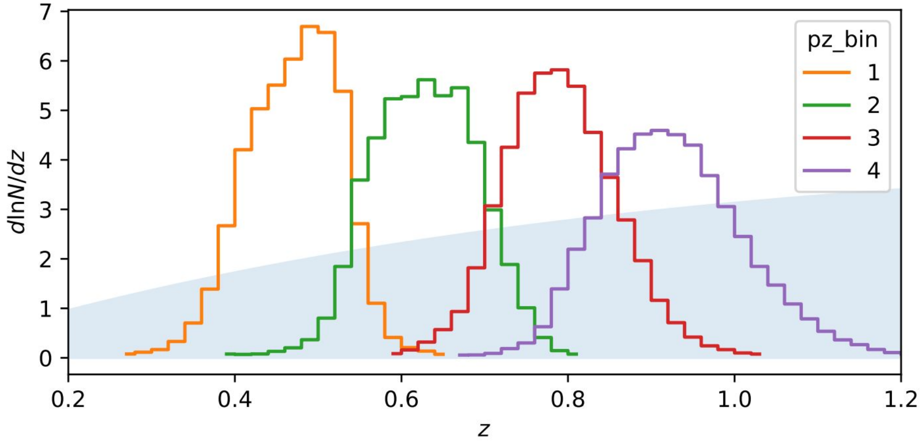
- 99% redshift completeness
- Negligible stellar contamination (~0.5%)
- Systematics weights impact C^{gg} by < 2%



Zhou et al. 2022

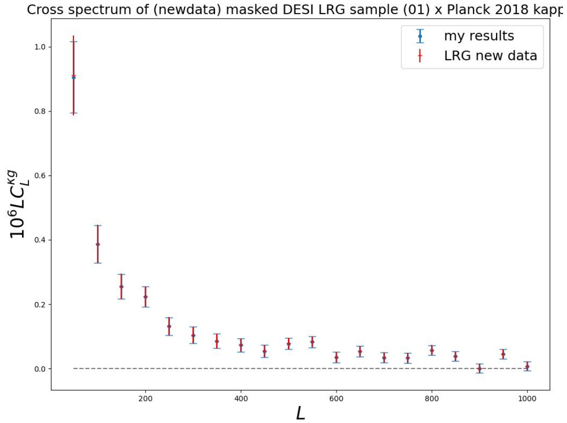
DESI Luminous Red Galaxies (LRGs)

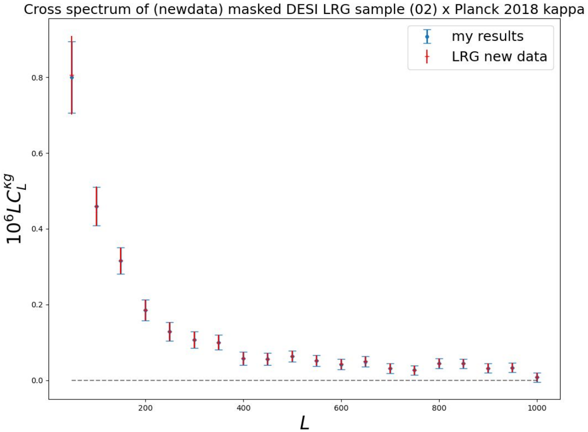
- Spectroscopically-calibrated photo-z’s
    - negligible redshift-distribution errors
    - 9k sq. deg. of full spectroscopy, can check for variations in dn/dz
- Narrow redshift bins
    - evolution within each bin is negligible
    - simplifies modeling
- Track evolution of $S_8(z)$

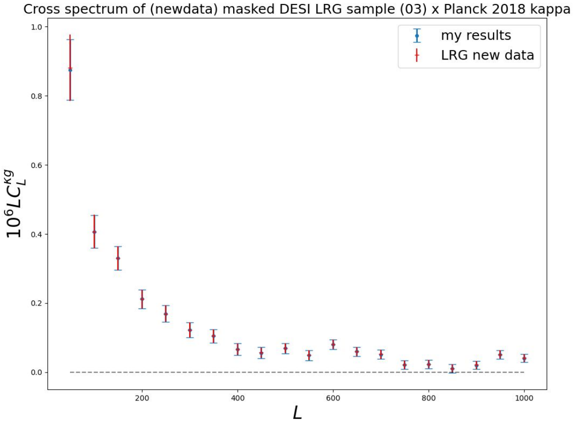


White et al. 2021

Very preliminary (and blinded) data


Cross spectrum of (newdata) masked DESI LRG sample (01) x Planck 2018 kapp


Cross spectrum of (newdata) masked DESI LRG sample (02) x Planck 2018 kappa


Cross spectrum of (newdata) masked DESI LRG sample (03) x Planck 2018 kappa

Figures from Joshua Kim

DESI x ACT robustness

Many more knobs and buttons to play with!

“Standard” checks

- Agreement across scale cuts
- Agreement in different hemispheres
- Agreement across redshift bins
- Swap out (binary) multifrequency combinations
- Correlate CMB-free reconstruction with LRGs, compare with simulations
- Null-test: curl estimator x LRGs
- Correlate CMB lensing with LRG systematic weights
- …

Novel checks

- Agreement between minimum variance, shear-only, and profile-hardened lensing estimators
- Null test: Correlate CMB-free (profile-hardened) reconstruction with LRGs
- Bias-harden curl estimator to isolate secondary bias, compare with sims
- …

DESI x ACT robustness

Unanswered question: importance of galactic foregrounds?

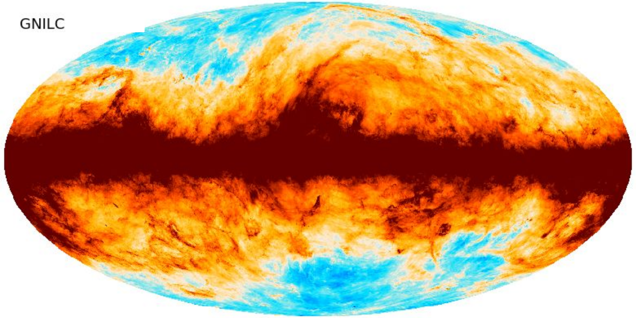
- < 5% correlation between LRGs and Planck extinction maps
  - hopefully small effect

- Traditional extinction templates correlate with LLS
  - HI emission-based templates (Lenz, Hensley, Doré 2017)
  - New stellar reddening-based templates (Mudur, Park, Finkbeiner 2022)
  - Even newer stellar reddening templates w/ DESI data (Zhou in prep.)

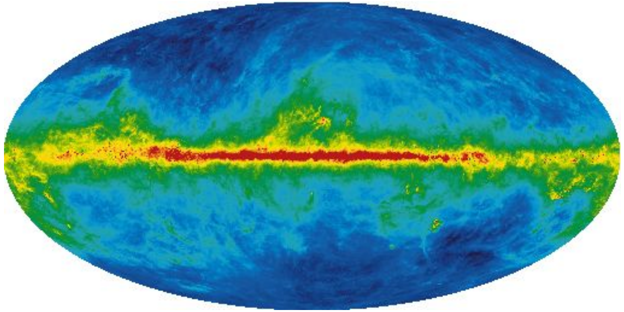
How strongly correlated are **emission** and **extinction**?

How does this propagate to $C^{\kappa g}$?

Work in progress! (w/ Anton Lizancos & Simone Ferraro)



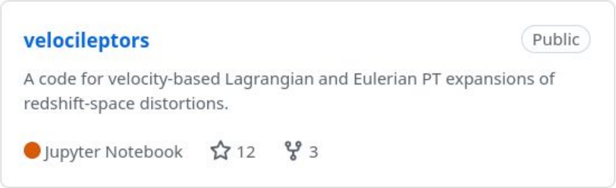
emission, Planck 13



extinction, SFD 98

$S_8(z)$ from DESI x ACT

Analysis will be **blinded** until robustness tests passed



velocileptors Public

A code for velocity-based Lagrangian and Eulerian PT expansions of redshift-space distortions.

Model for $C^{\kappa g}$ and C^{gg}

- 1-loop Lagrangian perturbation theory (velocileptors)
- Galaxies treated as an effective fluid
    - exhaustive set of EFT biases and counterterms

$$P_{\rm gg} = \left(1 - \frac{\alpha_a k^2}{2}\right) P_{\rm Z} + P_{1-\rm loop} + b_1 P_{\rm b_1} + b_2 P_{\rm b_2} + b_1 b_2 P_{\rm b_1 b_2} + b_1^2 P_{\rm b_1^2} + b_2^2 P_{\rm b_2^2}$$

$$P_{\rm gm} = \left(1 - \frac{\alpha_\times k^2}{2}\right) P_{\rm Z} + P_{1-\rm loop} + \frac{b_1}{2} P_{\rm b_1} + \frac{b_2}{2} P_{\rm b_2}$$

Covariance

- Compare both analytic (Gaussian) and numerical methods
- MoU access to mock κ realizations, brute force covariance

Entire pipeline will be made **public**

- map making, covariance estimation, theory, …

Looking forward

Later this year:

- Jointly analyze cross-correlation & DESI year 1 BAO
- 9k sq. deg. of spectroscopic LRG data

If tension alleviated

- Joint DESI + CMB neutrino mass measurement

Otherwise

- Constrain ΛCDM alternatives!
- For "early-time" solutions, plug and chug…

Stay tuned!