SO Likelihood Codes for CMB Combined Probes

Ian Harrison with SO LT.1 Group

From Planck to the Future of CMB
Ferrara
26 May 2022

- Slides are at:

bit.ly/ianh_ferrara22

Slides available at http://bit.ly/ianh_ferrara22

- SO codes for Likelihoods and Theory vectors: “SOLikeT”
- Talk about plans and work in progress
- Focus on two aspects:
  - Code development workflow
  - LSS cross-correlation likelihoods (including two examples)

Introduction

The Simons Observatory Collaboration

Slides available at http://bit.ly/ianh_ferrara22

- 10 Countries, 40+ Institutions, 306 Researchers
- Design, build, test, calibrate, deploy:
  - Hardware: SAT and LAT
  - Reduction methods & software to create data vectors with uncertainties
  - Inference methods & software to interpret what this tells us about the Universe
- Time schedule:
  - 2022: Validation, integration, test
  - Mid 2023: First science observations
  - Mid 2024 – Mid 2029: Full science observations

Human/Sociological Challenge
cf Matsumara, Staggs talks; BeyondPlanck on Open Science

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Many important interfaces between models and experts

Human/Sociological Challenge
cf Matsumara, Staggs talks; BeyondPlanck on Open Science

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SOLikeT

Introduction

Slides available at http://bit.ly/ianh_ferrara22

- SO Likelihoods & Theories -> SOLikeT
  Leads: Martina Gerbino, IH, Tim Morton
  Many contributors!
- Collect, test and cohere theory vector and likelihood codes developed across SO
- Aim for holistic / joint inference
  - Instrument, astrophysics, cosmology are all together in the data
  - Many-part data vector (SO and non-SO)
  - Consistent parameterisation, modelling calculations across all parts of the theory vectors

$$\vec{d}_{\rm tot} - F(\vec{\theta})$$

Data vector — Theory vector

$$\vec{d}_{\rm tot} = \{\vec{d}_{C_\ell^{TT}}, \vec{d}_{C_\ell^{TE}}, \vec{d}_{C_\ell^{EE}}, \vec{d}_{C_\ell^{\kappa\kappa}}, \vec{d}_{C_\ell^{g\kappa}}$$

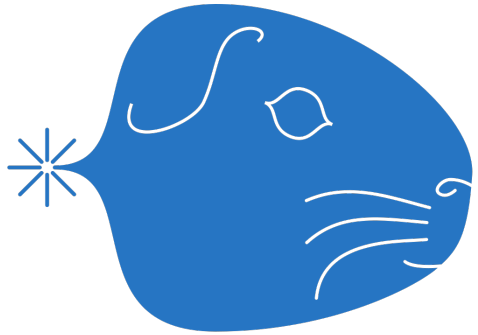
$$\vec{\theta} = \{\Omega_{\rm m}, \tau, \Delta^{93}_{\rm band}, a_{\rm tSZ}, \ldots\}$$

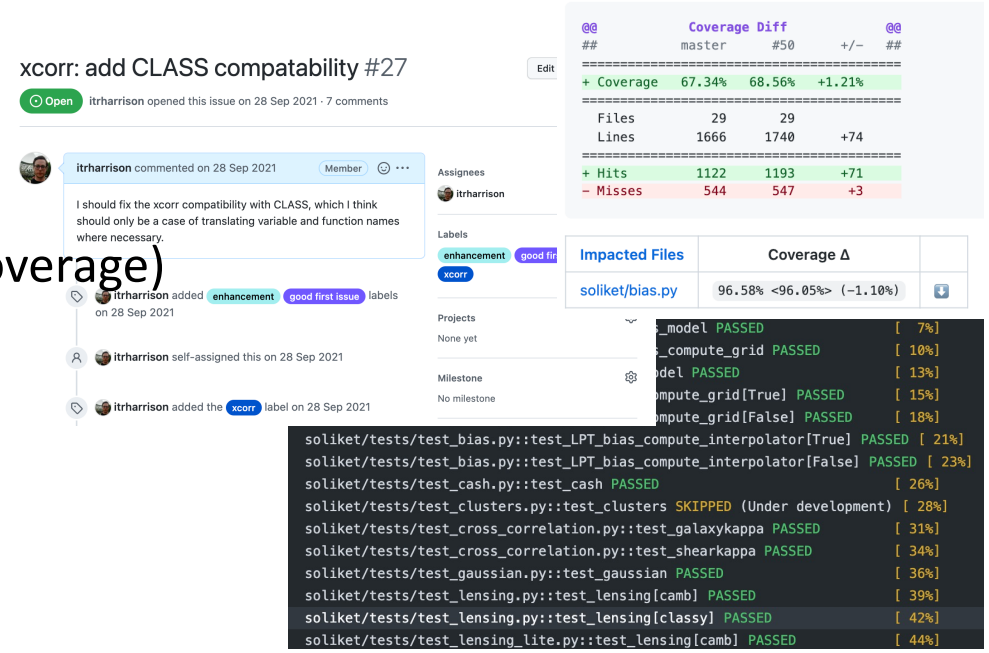
SOLikeT

Development Workflow

Slides available at http://bit.ly/ianh_ferrara22

- Implemented within cobaya sampling framework
- Development in public github repo: github.com/simonsobs/SOLikeT
- Open, flexible, understandable, reliable, fast (enough)
- Better practices for code development
  - Issues to describe and discuss new features, implementations, bug fixes
  - Work on well-managed branches
  - Write Unit Tests (which are automatically checked for coverage)
  - Require code review for merging into main branch
  - Written guidelines on how to contribute





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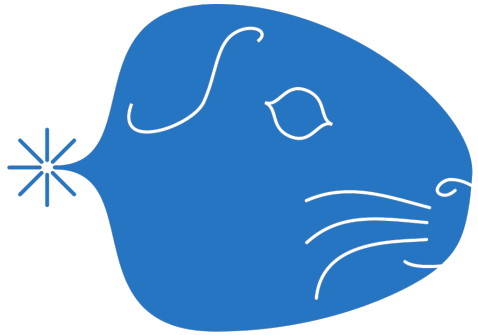

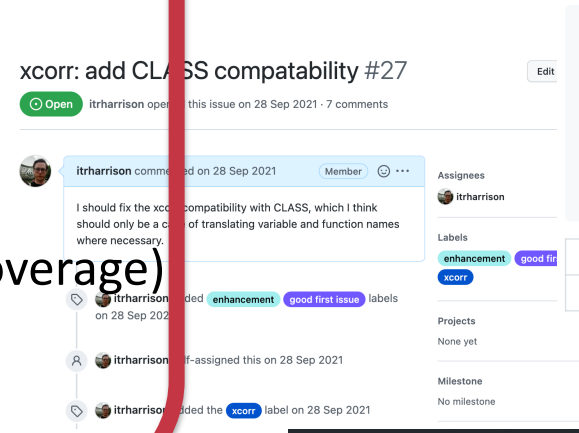

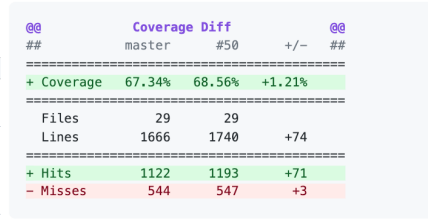

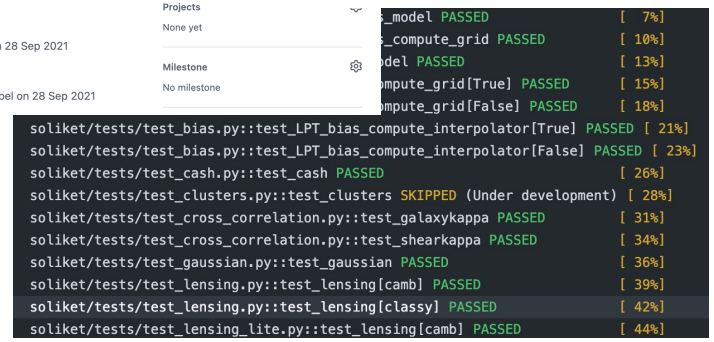

Enables holistic / joint inference

SOLikeT

Implemented Likelihoods

- Current / in development likelihoods:
  - MFLike (CMB multi-frequency *TTTEEE*) Gerbino, Pagano et al
  - Cluster (unbinned SZ cluster counts) Battaglia et al
  - BinnedCluster ({1D, 2D} binned SZ cluster counts) Lee, Bollet et al
  - Lensing (CMB lensing power spectrum)
  - {Galaxy, Shear}Kappa (CCL-calculator galaxy {density, shear} x CMB lensing) Harrison, Lemos
  - Xcorr (galaxy {density, shear} x CMB lensing) Harrison from Krolewski et al
  - SZ ({k, T}SZ Temperature, pressure and density profiles) Moser, Battaglia et al

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- Aim to start moving from “collection phase” to consolidation/coherence phase over summer SO meeting

SO-LSS Cross-Correlations

Introduction

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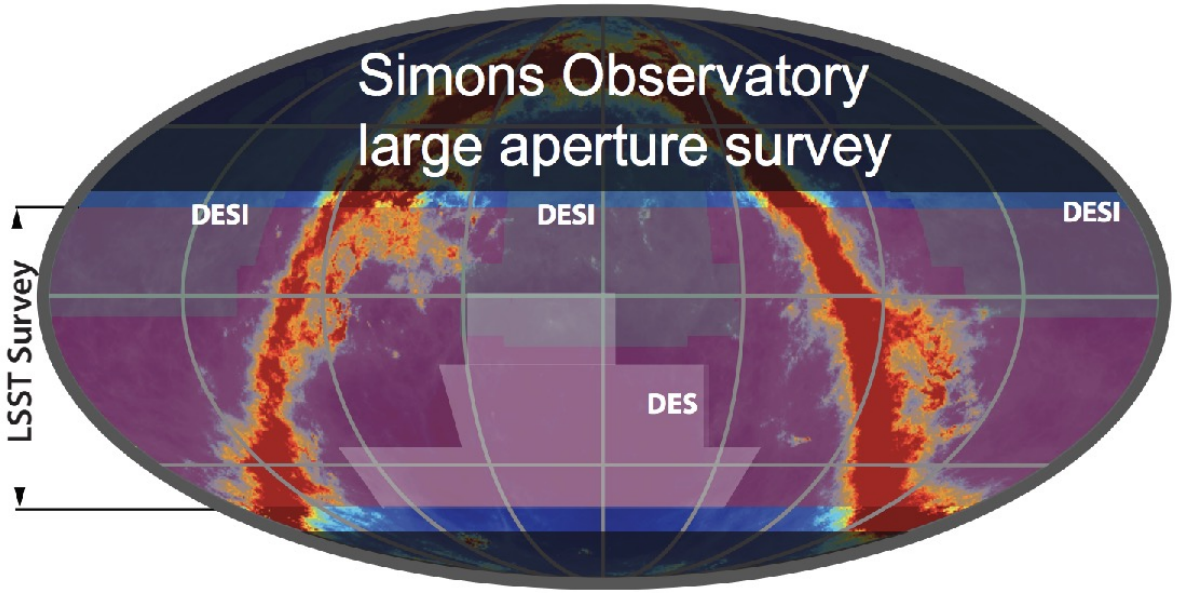
- SO's 2023-28 observing timeline overlaps with Rubin Observatory, DESI, Euclid
- CMB and optical surveys both measure large-scale matter and baryon distribution.
- Better together! Growth of cosmic structure, constraints on baryonic feedback, calibrating systematic effects…



	Parameter	SO-Baseline[a] (no syst)	**SO-Baseline**[b]	SO-Goal[c]	Current[d]	Method	Sec.
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\rm NL}^{\rm local}$	1.8	**3**	1	5	$\kappa\kappa\times$ LSST-LSS+3-pt	5.3
		1	**2**	1		kSZ + LSST-LSS	7.5
Relativistic species	$N_{\rm eff}$	0.055	**0.07**	0.05	0.2	$TT/TE/EE+\kappa\kappa$	4.1
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2
		0.035	**0.04**	0.03		tSZ-N × LSST-WL	7.1
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO	7.2
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS	5.3
		1.2%	**2%**	1%		tSZ-N × LSST-WL	7.1
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE+\kappa\kappa$	4.3
Galaxy evolution	$\eta_{\rm feedback}$	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI	7.3
	$p_{\rm nt}$	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6

[a] This column reports forecasts from earlier sections (in some cases using 2 s.f.) and applies no additional systematic error.
[b] This is the nominal forecast, increases the column (a) uncertainties by 25% as a proxy for instrument systematics, and rounds up to 1 s.f.
[c] This is the goal forecast, has negligible additional systematic uncertainties, and rounds to 1 s.f.
[d] Primarily from [44] and [287].

Table 9. Summary of SO key science goals. All of our SO forecasts assume that SO is combined with *Planck* data.

From: The Simons Observatory: science goals and forecasts

Peter Ade, et al., JCAP02 (2019) 056

SO-LSS Cross-Correlations

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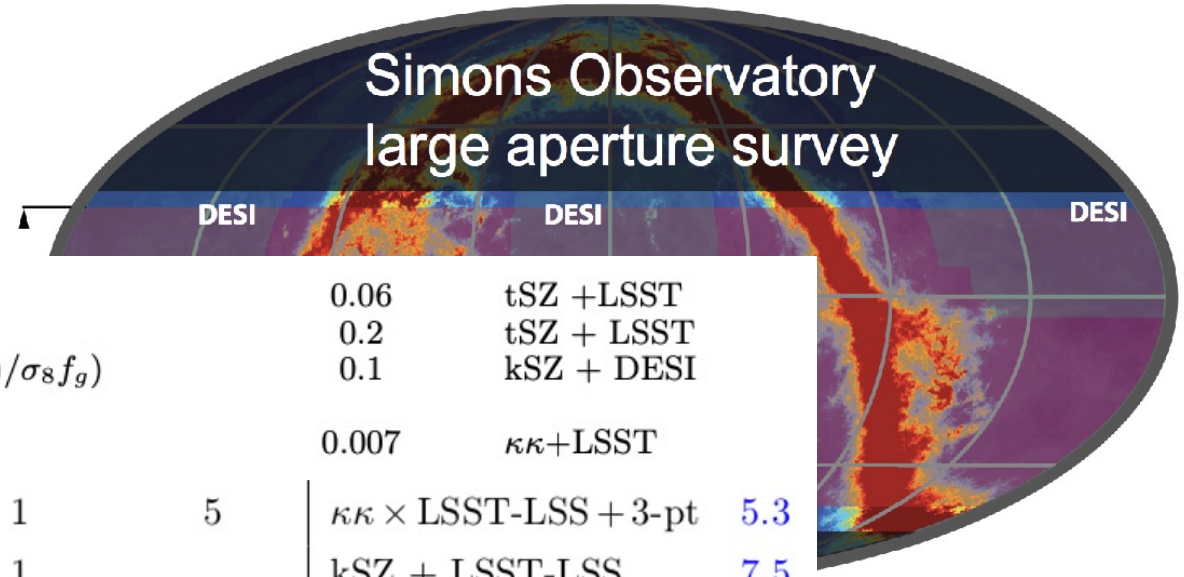
- CMB a
  meas
  baryo
- Bette
  cosm
  baryc
  syste



Dark energy or modified gravity	w_0				0.06	tSZ +LSST	
	w_a				0.2	tSZ + LSST	
	Growth rate $(\Delta(\sigma_8 f_g)/\sigma_8 f_g)$				0.1	kSZ + DESI	
Shear bias calibration		$m_{z=1}$			0.007	$\kappa\kappa$+LSST	
	$f_{\rm NL}^{\rm local}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt	5.3
		1	**2**	1		kSZ + LSST-LSS	7.5
	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2
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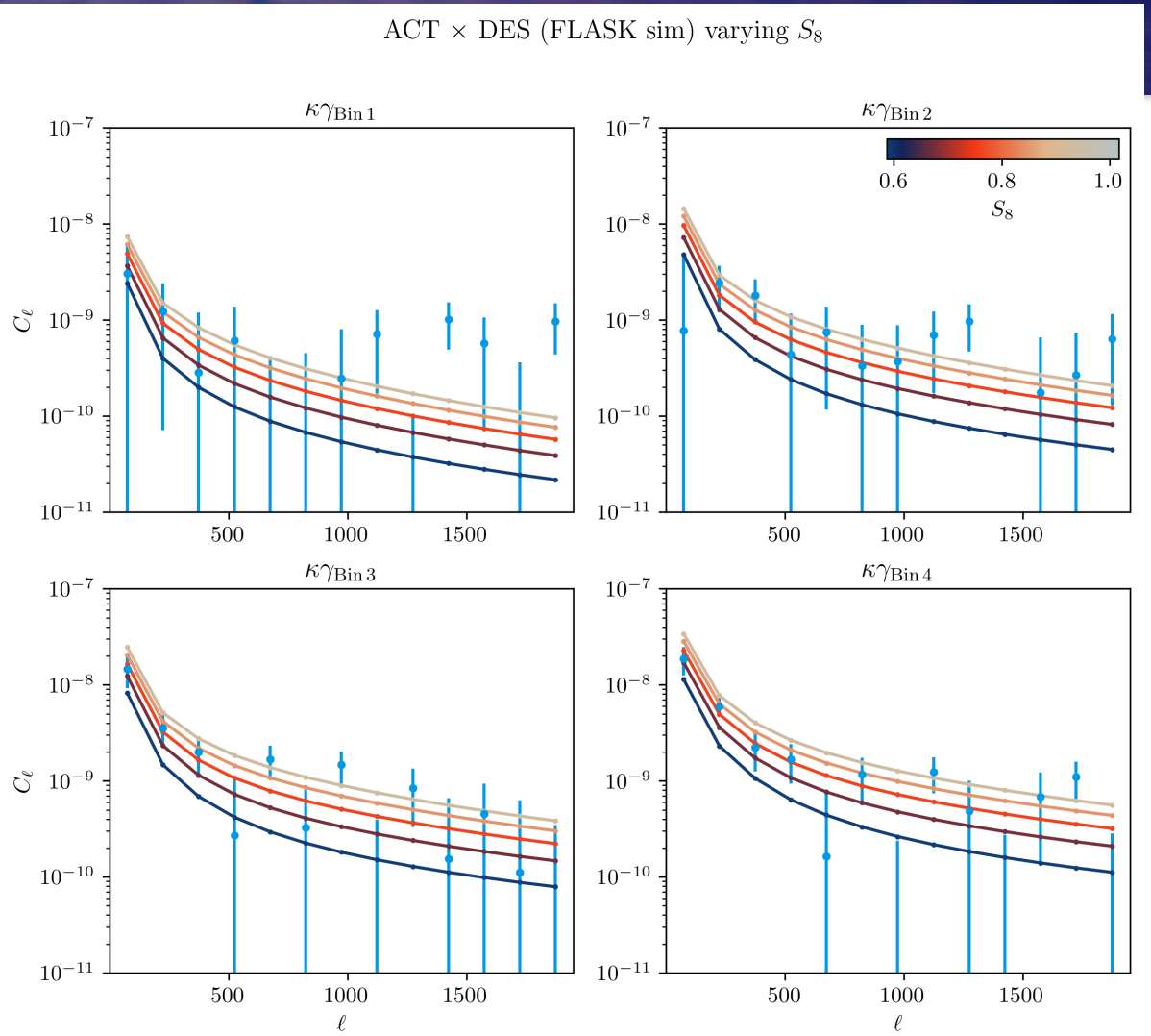
SOLikeT Testbeds

ACT kappa x DES shear

- ACT lensing map
- DES Y3 shear catalogue
  - 4 tomographic bins
- Measures S_8 structure clustering parameter
- Calibration of galaxy shear systematics
  - Δz mean redshift of source galaxy $n(z)$
  - m galaxy shear multiplicative bias
  - Intrinsic Alignment model parameters



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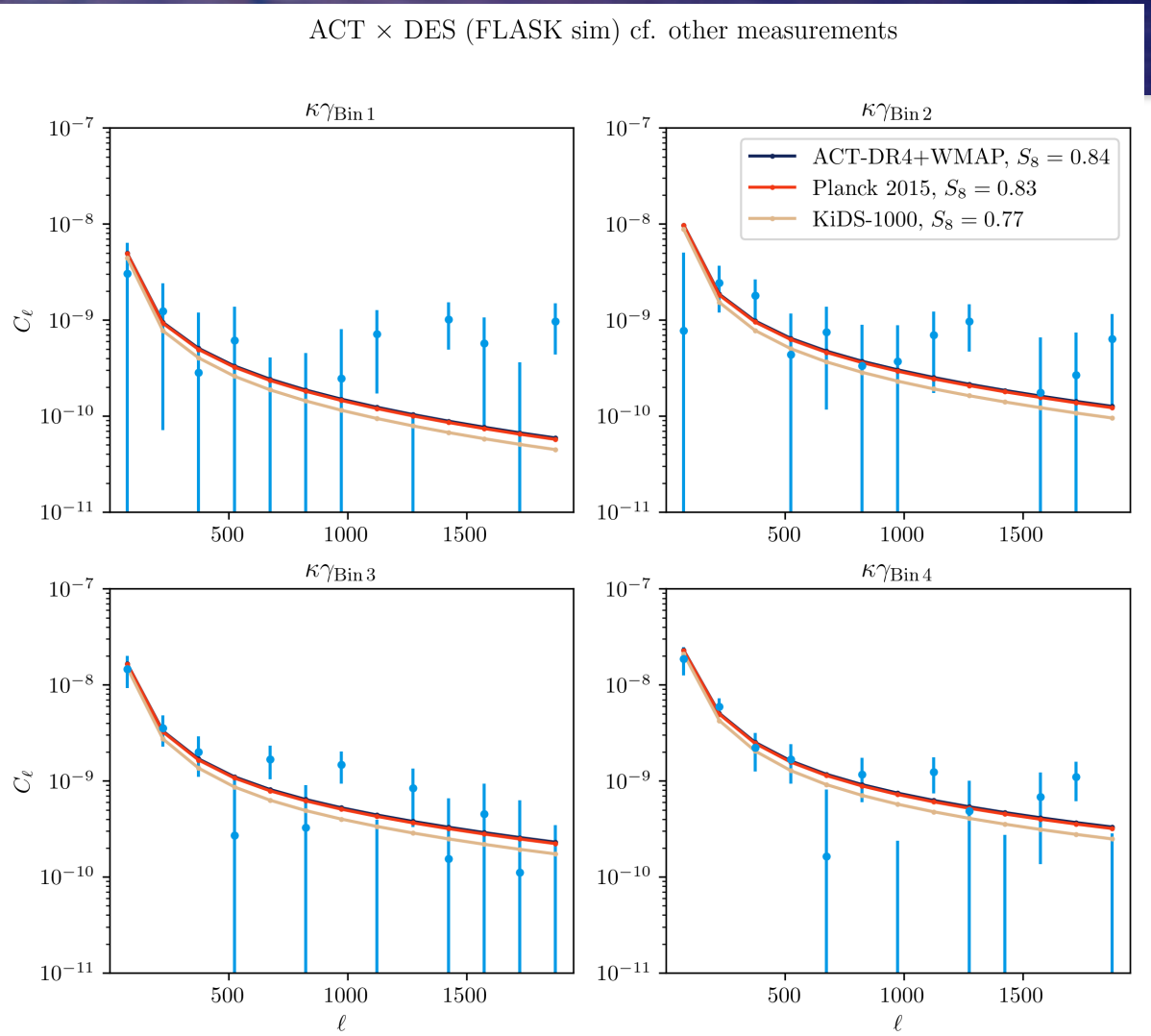

SOLikeT Testbeds

ACT kappa x DES shear

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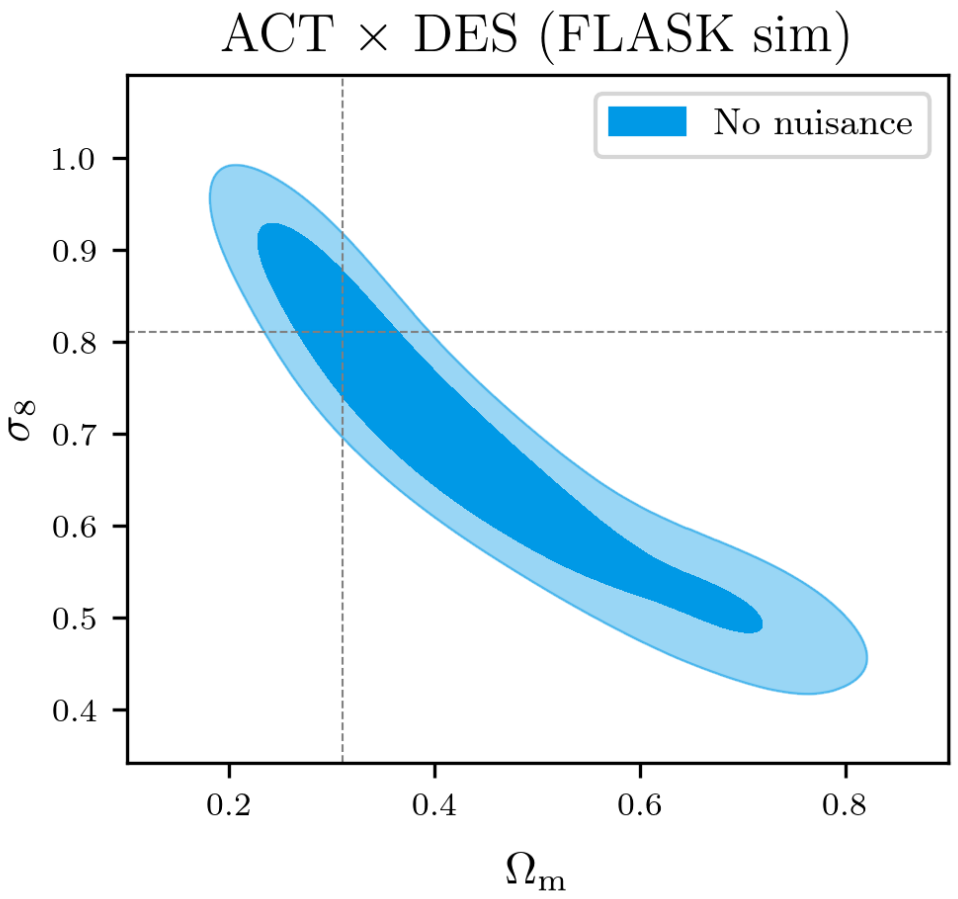
- FLASK simulation, covariance matrix, data validation thanks to Shabbir Shaikh (ASU)
- Total forecast SNR ~9
  - Robertson et al 2021 SNR 7.7
  - Marques et al 2020 SNR 3.1
- Have run initial chains without nuisance parameters



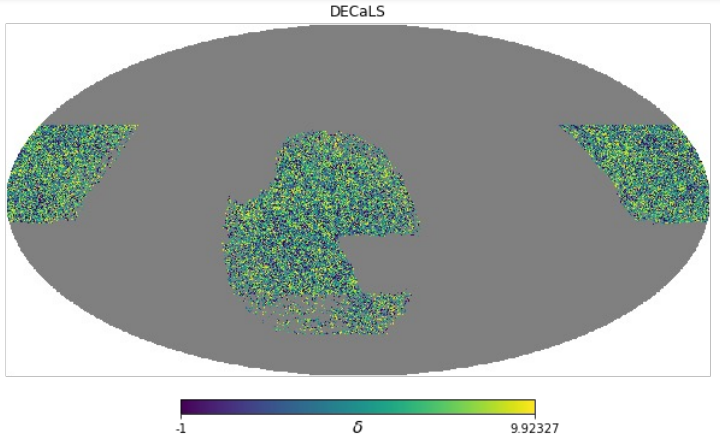
SOLikeT Testbeds

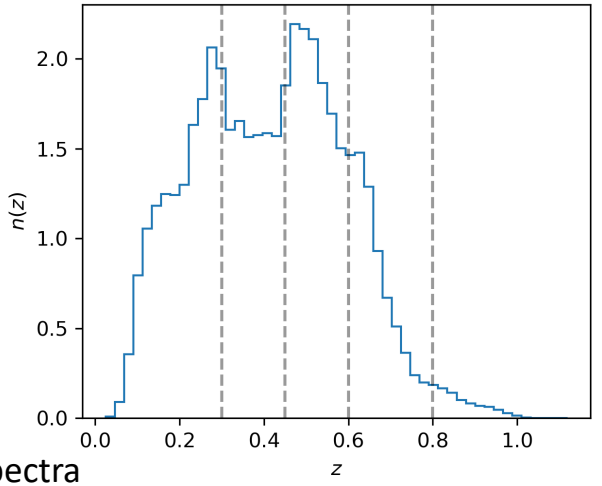
ACT kappa x DELS galaxies

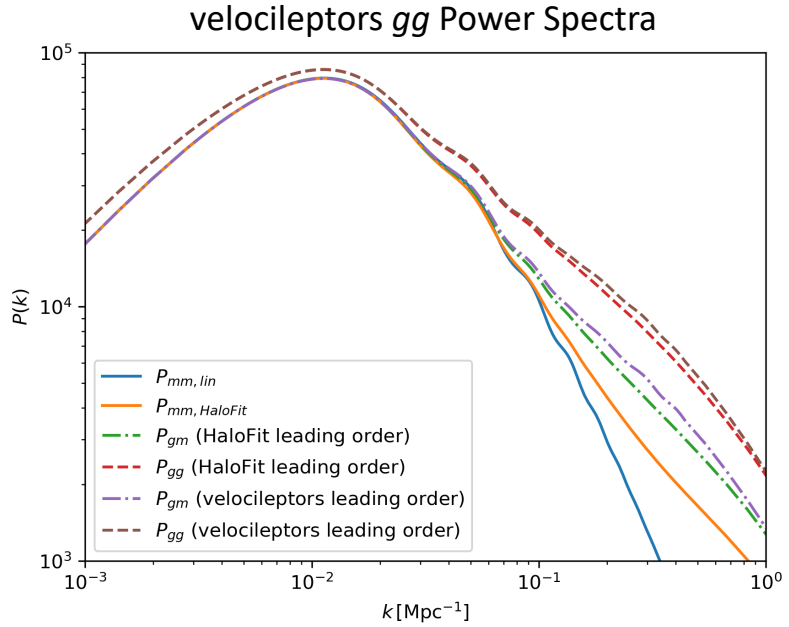
Slides available at http://bit.ly/ianh_ferrara22

- ACT DR4 lensing map
- DELS: DECALS + BASS-MZLS galaxies
  - 4 tomographic bins
  - As in Hang et al 2021

- Galaxy power spectrum non-linear models (implemented as cobaya Theory classes)
  - velocileptors
  - FastPT thanks to Pablo Lemos







SOLikeT Testbeds

ACT kappa x DELS galaxies

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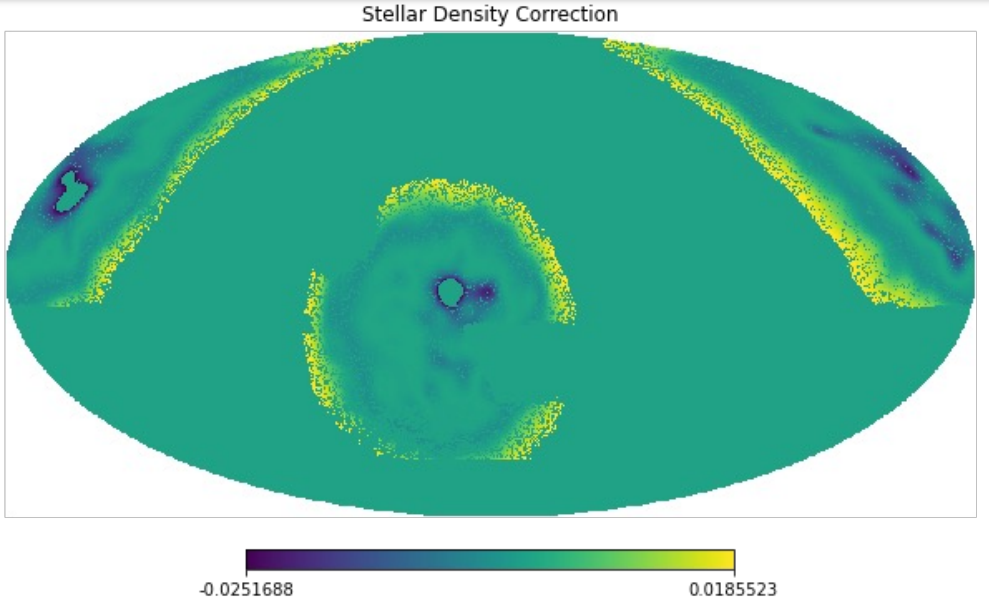
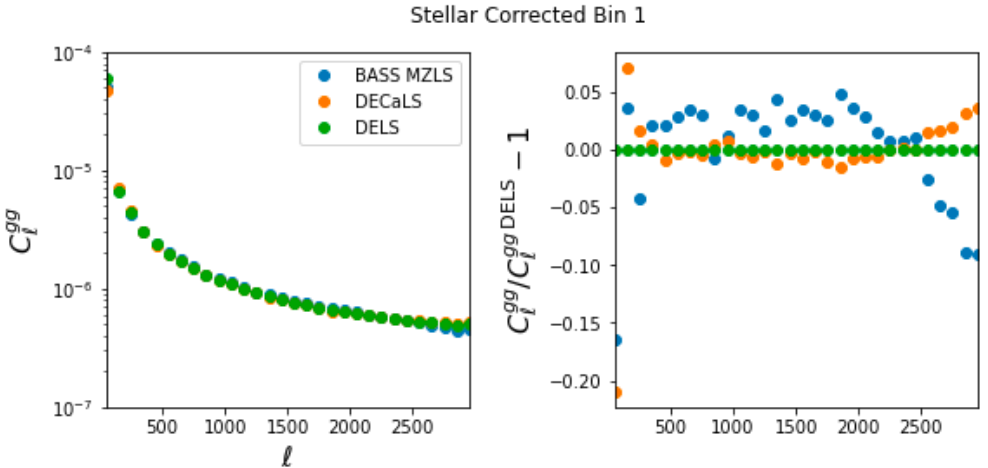
- Work in progress…
- Performing systematics tests on *gg* data
- Forecast SNR ~25
  - Krolewski et al 2021 SNR 80
  - Kitanidis and White 2021 SNR 27





Conclusions

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- Simons Observatory developing theory prediction and likelihood codes within cobaya

- "SOLikeT"
  - Open, reliable, well-tested
  - Coherently model multiple data vector types in CMB and cross-correlations

- Starting to deploy and test on current data
  - ACT CMB lensing x DES galaxy shear
  - ACT CMB lensing x DELS galaxy density