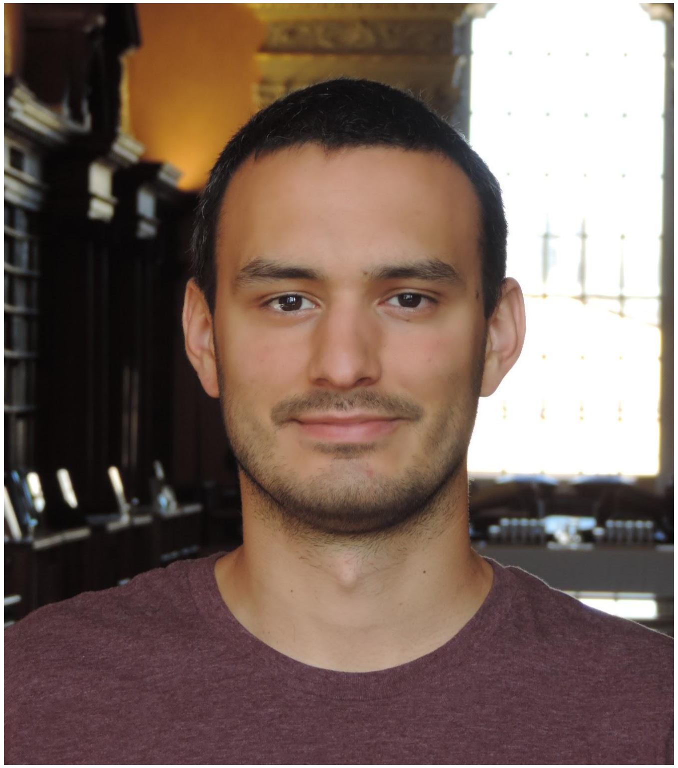
CORE COSMOLOGY LIBRARY

PRECISION COSMOLOGICAL PREDICTIONS FOR LSST

LSST DESC
Dark Energy Science Collaboration

Elisa



Not Elisa

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PRECISION COSMOLOGICAL PREDICTIONS FOR LSST

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Elisabeth Krause (U of Arizona)
30+ LSST DESC contributors

Paper: on ApJS, arXiv:1812.05995.
GitHub repo: https://github.com/LSSTDESC/CCL

LSST DESC Dark Energy Science Collaboration

Introduction to CCL

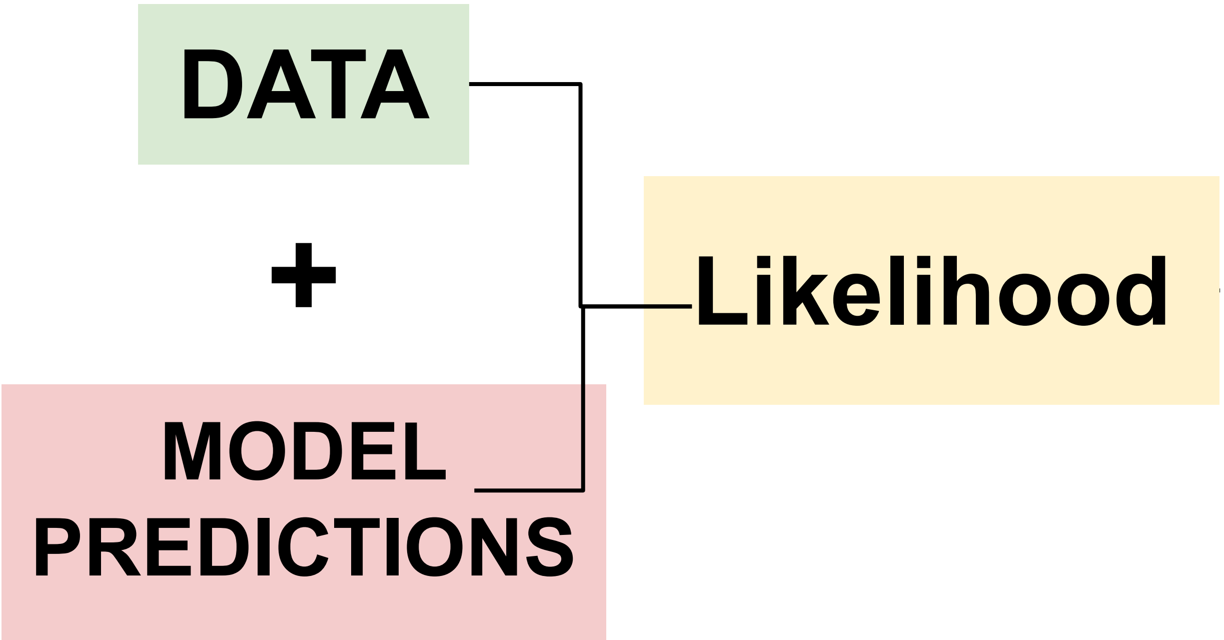
Dark Energy Science Collaboration

DATA

+

MODEL PREDICTIONS

Introduction to CCL



Introduction to CCL

LSST DESC
Dark Energy Science Collaboration

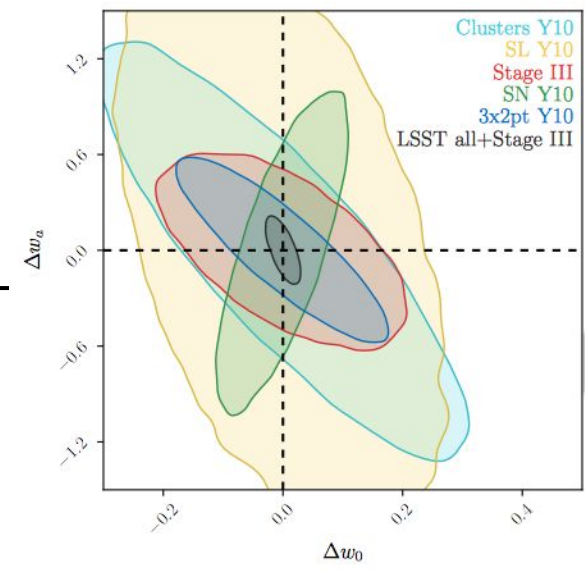
DATA

+

MODEL PREDICTIONS

Likelihood

Cosmological constraints



From the LSST DESC Science Requirements Document

Introduction to CCL

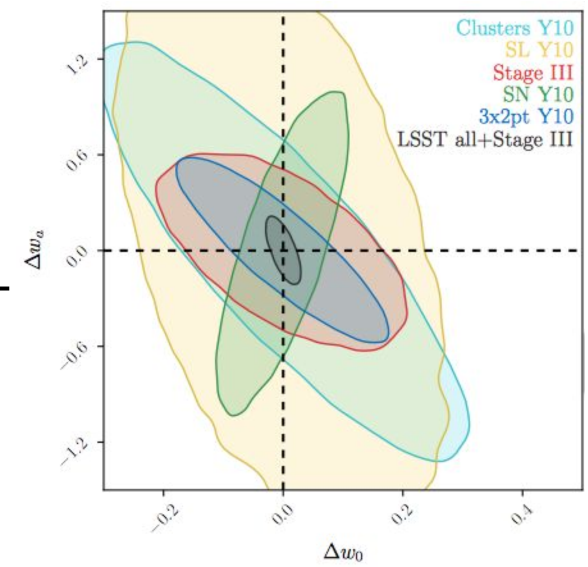
DATA

+

CCL

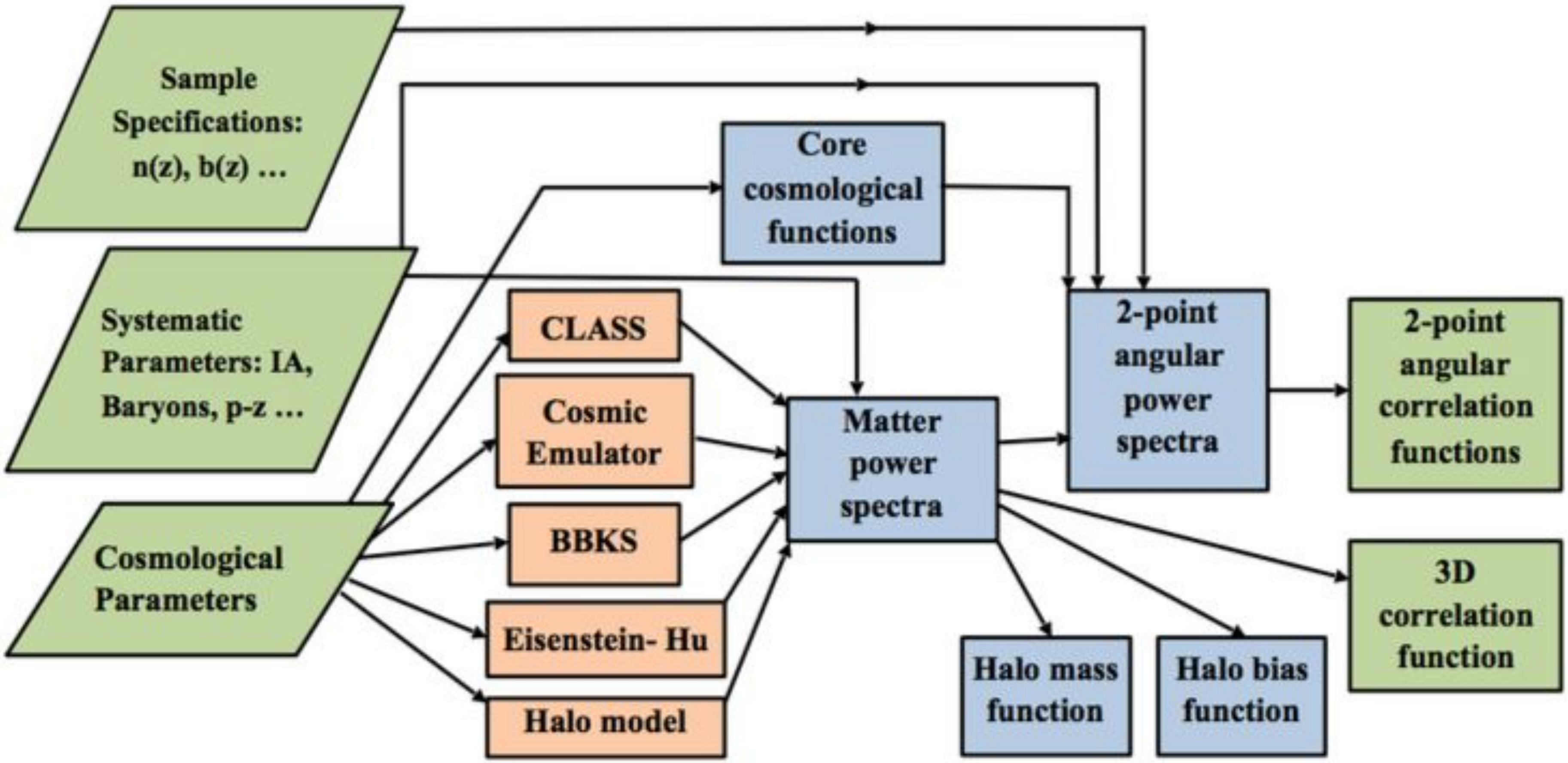
Likelihood

Cosmological constraints



From the LSST DESC Science Requirements Document

Current CCL capabilities



From the CCL paper.

Introduction to CCL

Core Cosmology Library for LSST-DESC

Cosmological quantities to validated numerical accuracy

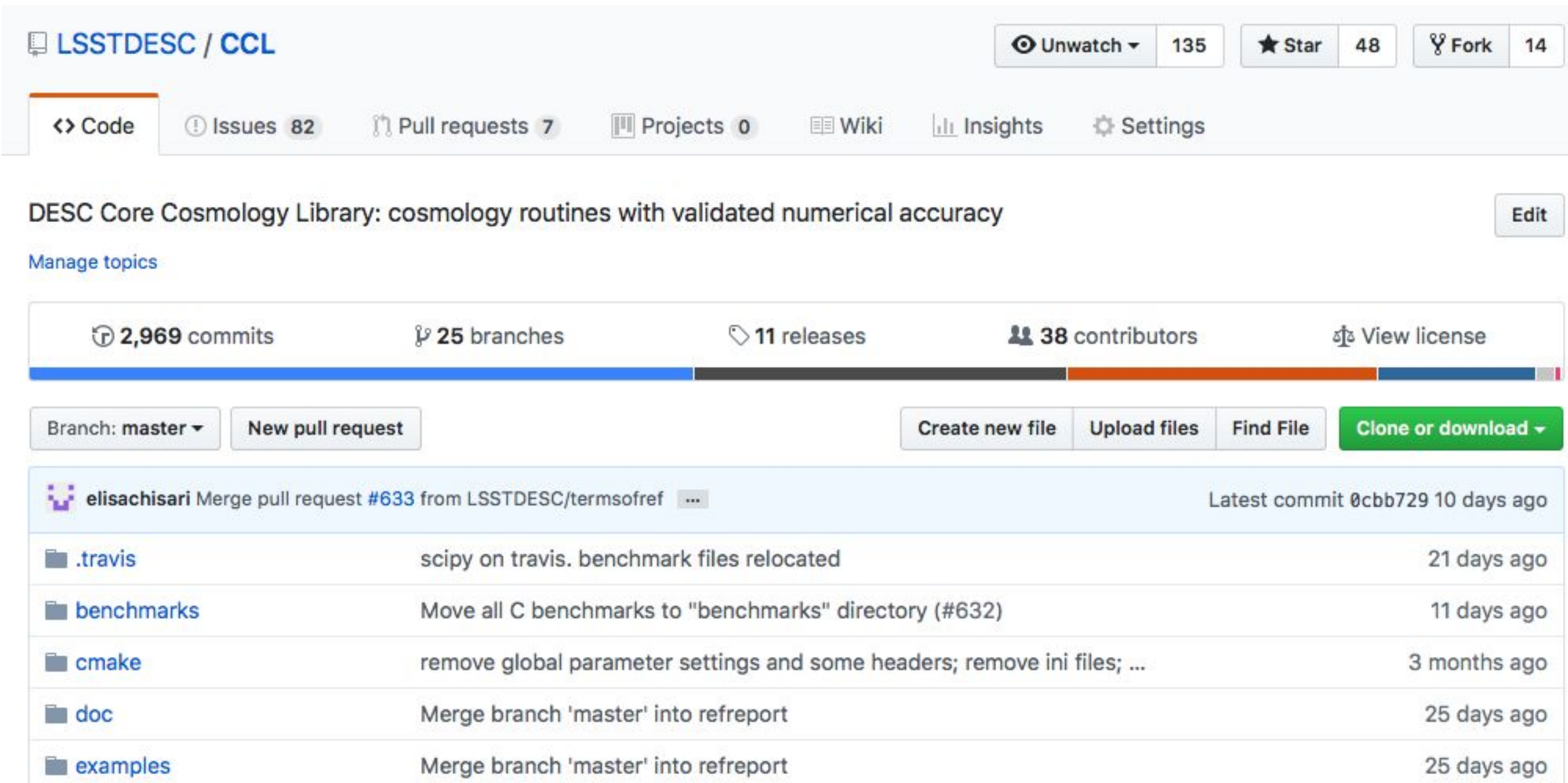
CCL features

- **A wide range of models**
  (e.g., including massive neutrinos)
- **A wide range of observables**
  (e.g., angular power spectra)
- **State-of-the-art tools**
  (e.g., emulators)
- **Accurate numerical validation**

The CCL repository

CCL sits within the LSST DESC GitHub repository.

Publicly available with **multiple releases.** Paper **documents v1.**



The CCL paper

arXiv:1812.05995

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CORE COSMOLOGY LIBRARY: PRECISION COSMOLOGICAL PREDICTIONS FOR LSST

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ABSTRACT

The Core Cosmology Library (CCL) provides routines to compute basic cosmological observables to a high degree of accuracy, which have been verified with an extensive suite of validation tests. Predictions are provided for many cosmological quantities, including distances, angular power spectra, correlation functions, halo bias and the halo mass function through state-of-the-art modeling prescriptions available in the literature. Fiducial specifications for the expected galaxy distributions for the Large Synoptic Survey Telescope (LSST) are also included, together with the capability of computing redshift distributions for a user-defined photometric redshift model. A rigorous validation procedure, based on comparisons between CCL and independent software packages, allows us to establish a well-defined numerical accuracy for each predicted quantity. As a result, predictions for correlation functions of galaxy clustering, galaxy-galaxy lensing and cosmic shear are demonstrated to be within a fraction of the expected statistical uncertainty of the observables for the models and in the range of scales of interest to LSST. CCL is an open source software package written in C, with a python interface and publicly available at https://github.com/LSSTDESC/CCL.

1. INTRODUCTION

Starting in the next decade, large-scale galaxy surveys will drive a new era of high precision cosmology (LSST Dark Energy Science Collaboration 2012; Green et al. 2011; Laureijs et al. 2011). One of their main goals is to answer the question of the origin of cosmic acceleration, in other words, to elucidate the nature of "dark energy", broadly understood as a family of potential models: from a cosmological constant to a dynamical field and modifications of gravity (see for example Carroll 2001; Peebles & Ratra 2003; Padmanabhan 2003; Copeland et al. 2006; Ishak 2007; Weinberg et al. 2013 and references therein). These data will also allow us to shed light on a number of open questions in fundamental physics, such as the nature of dark matter (Feng

- ➔ **Describes models** available for each observable
- ➔ Discusses **implementation details**
- ➔ **Documents the validation procedure** and results for each observable
- ➔ Provides **minimal usage guidelines**
- ➔ Lists **future steps.**

Validation scheme

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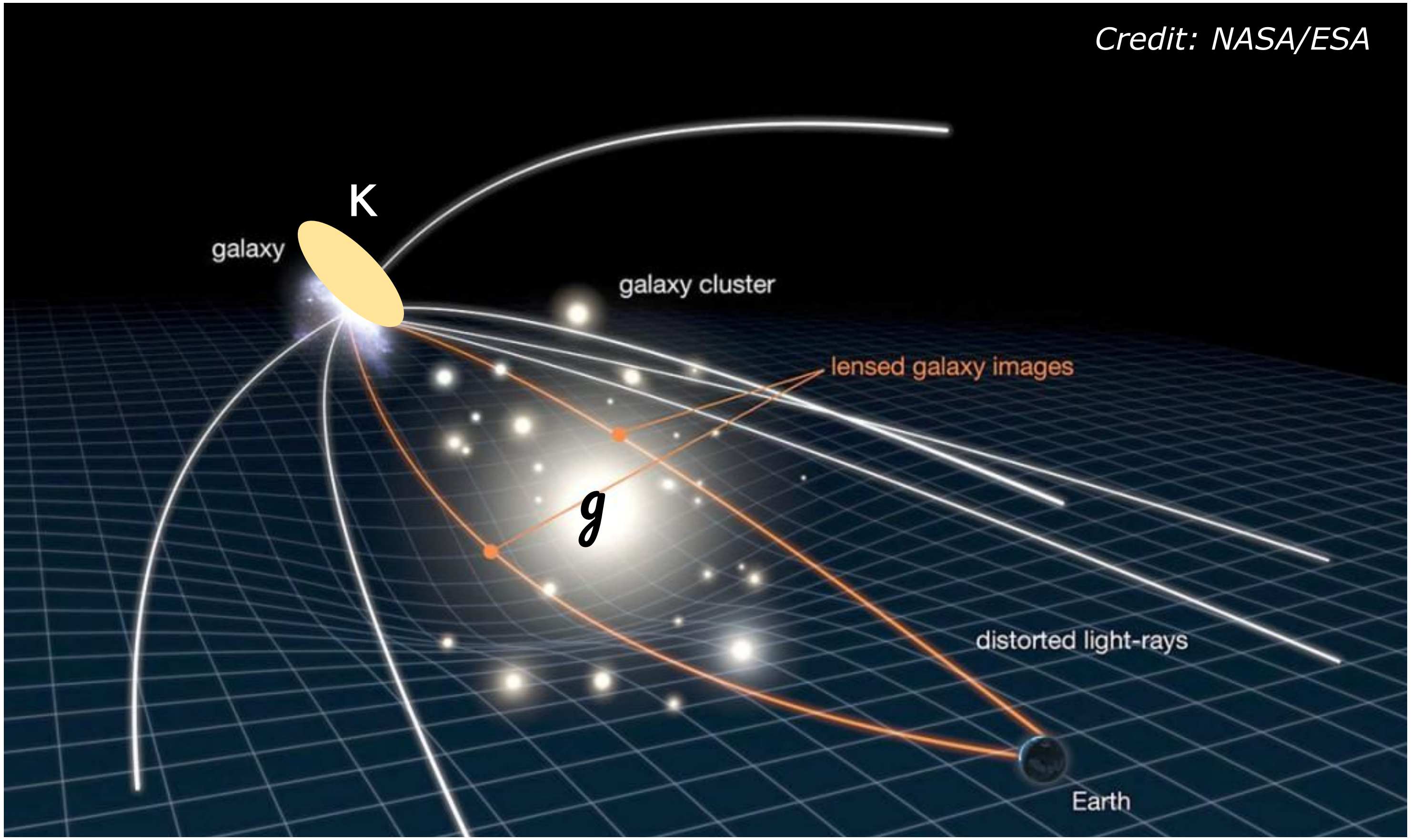
- ➔ **Independent predictions** available for each observable
- ➔ Independent codes made **publicly available** within repository
- ➔ **Automated** accuracy checks run upon commits to the repository and at will by the user
- ➔ **Paper documents level of accuracy achieved**
- ➔ **Angular power spectra and correlation functions accuracy guaranteed within a fraction of LSST statistical uncertainties**

Validation example: angular power spectra for 3x2pt



$\langle \kappa\kappa \rangle$, $\langle g\kappa \rangle$, $\langle gg \rangle$

Validation example: angular power spectra for 3x2pt

Cosmic shear

$$C_{\kappa\kappa}^{ij}(l) = \int d\chi \frac{q_\kappa^i(\chi) q_\kappa^j(\chi)}{\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

weights — matter power spectrum

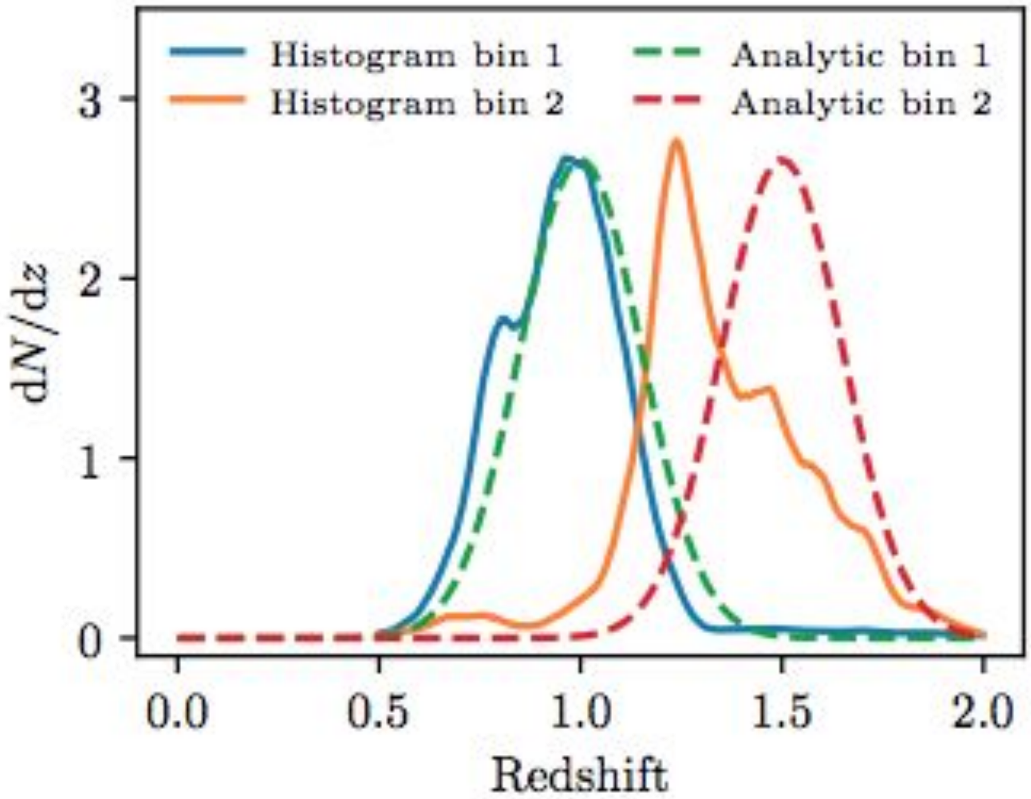
Redshift distribution

$$q_\kappa^i(\chi) = \frac{3H_0^2\Omega_m}{2c^2} \frac{\chi}{a(\chi)} \int_\chi^{\chi_h} d\chi' \frac{n_\kappa^i(z(\chi'))dz/d\chi'}{\bar{n}_\kappa^i} \frac{\chi' - \chi}{\chi'}$$

Average surface density of galaxies per bin

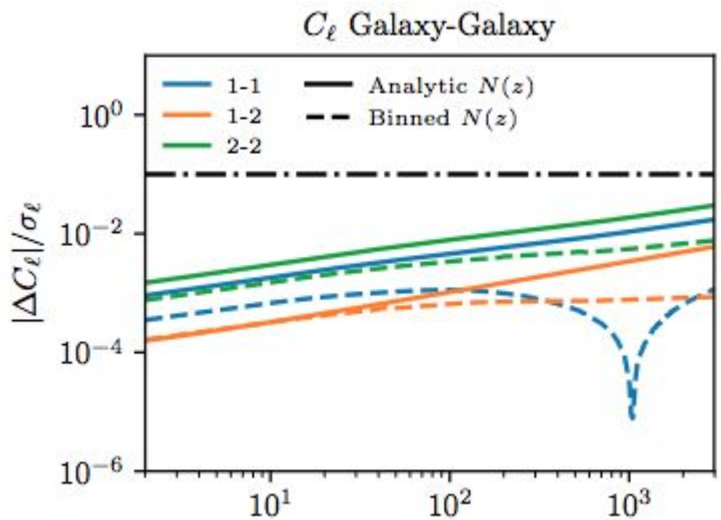
$$\bar{n}_{g/\kappa}^i = \int dz \, n_{g/\kappa}^i(z)$$

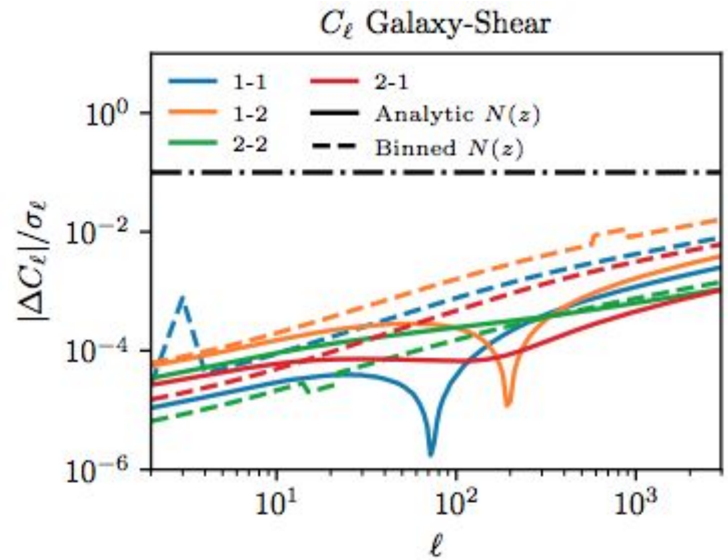
Validation example: angular power spectra for 3x2pt

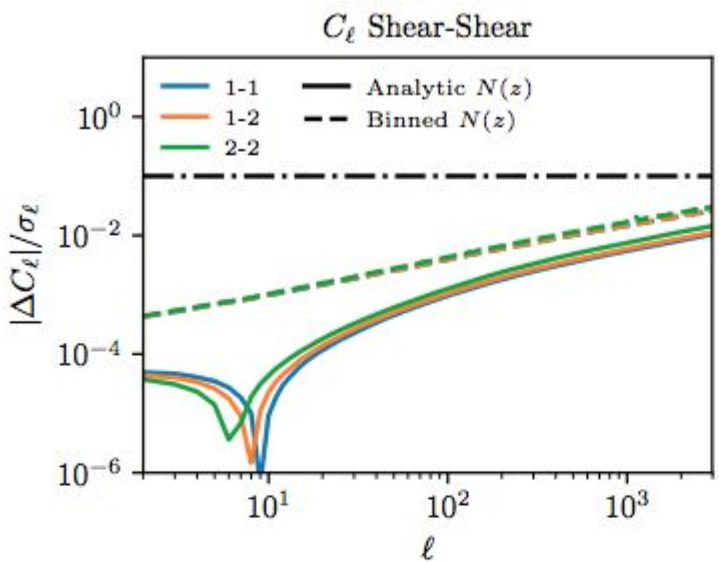


Redshift distributions for validation

Validation example: angular power spectra for 3x2pt







Angular power spectra numerical accuracy within a fraction of LSST statistical uncertainties

$$\mathcal{A} = \left| \frac{C_\ell^{\rm CCL} - C_\ell^{(i)}}{\sigma_\ell} \right|$$

Full set of validation tests

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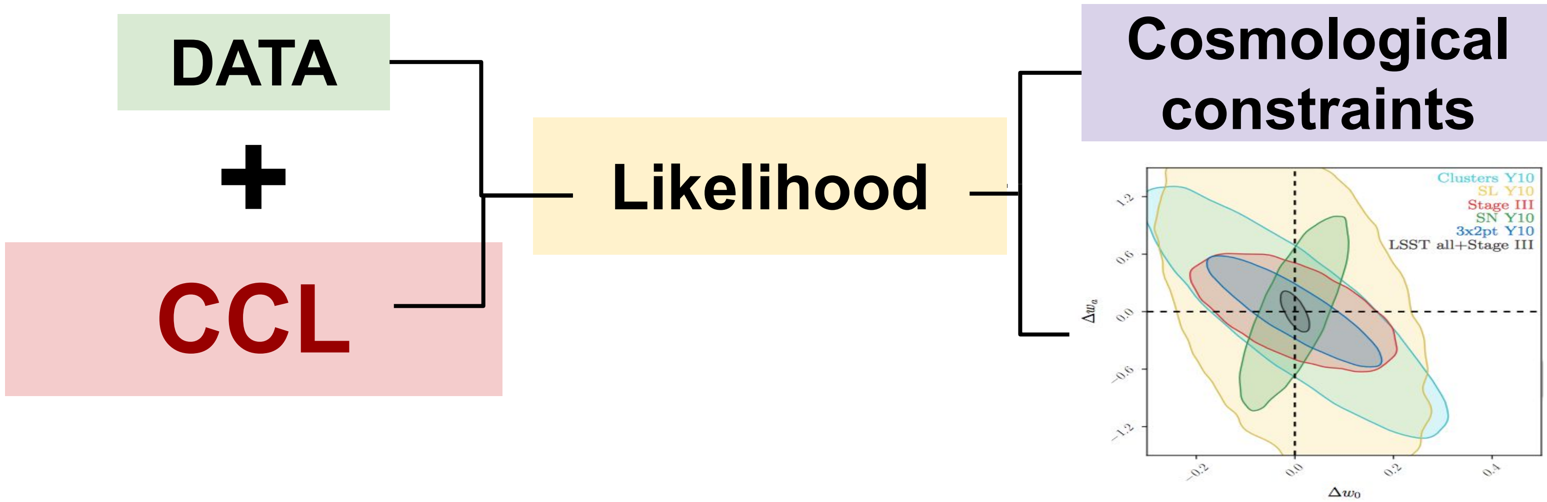
Quantity	Equation/ Reference	Cosmologies	Range	Agreement with benchmarks, $\mathcal{A}$	Figure
Comoving radial distance, χ	(7)	CCL1-5,7-11	$0.01 \leq z \leq 1000$	5×10^{-7}	Fig. 2
Growth factor, D	(10)	CCL1-5	$0.01 \leq z \leq 1000$	6×10^{-6}	Fig. 2
$\sigma(M)$ (BBKS)	(48)	CCL1-3	$10^{10} \leq M/\mathrm{M}_\odot \leq 10^{16}$	3×10^{-5}	Fig. 8
$\log[\sigma^{-1}(M)]$ (BBKS)	(91)	CCL1	$10^{10} \leq M/\mathrm{M}_\odot \leq 10^{16}$	10^{-3}	Fig. 8
$\mathcal{H} \equiv \log[(M^2/\bar{\rho}_m)dn/dM]$	(92), Tinker et al. (2010)	CCL1	$10^{10} \leq M/\mathrm{M}_\odot \leq 10^{16}$ & $z=0$	5×10^{-5}	Fig. 8
$P(k)$ (BBKS)	(15)	CCL1-3	$10^{-3} \leq k/(h/\mathrm{Mpc}) \leq 10$ & $0 \leq z \leq 5$	10^{-5}	-
$P(k)$ (Eisenstein & Hu)	Eisenstein & Hu (1998)	CCL1	$10^{-3} \leq k/(h/\mathrm{Mpc}) \leq 10$ & $z=0$	10^{-5}	-
$P(k)$ (CLASS linear & HaloFit)	Takahashi et al. (2012)	see Table 5	$10^{-3} \leq k/\mathrm{Mpc} \leq 20$ & $z=\{0,2\}$	$\sim 10^{-3}$	Figs. 3 , 4, 5 & 6
$P(k)$ (CosmicEmu wCDM)	Lawrence et al. (2017)	M1,M3,M M6,M8,M10	$10^{-3} \leq k/\mathrm{Mpc}^{-1} \leq 5$ & $z=0$	10^{-2}	Fig. 7 (left panel)
$P(k)$ (CosmicEmu νCDM)	Lawrence et al. (2017)	M38,M39,M40 M42	$10^{-3} \leq k/\mathrm{Mpc}^{-1} \leq 5$ & $z=0$	3×10^{-2}	Fig. 7 (right panel)
$P(k)$ (Halo model)	Cooray & Sheth (2002)	CCL1, *WMAP7* *Planck* 2013	$10^{-4} \leq k/h\mathrm{Mpc}^{-1} \leq 10^2$ & $z=0,1$	10^{-3}	Fig. 10
$P(k)$ (baryonic)	(18), Schneider & Teyssier (2015)	-	$10^{-5} \leq k/h\mathrm{Mpc}^{-1} \leq 10$ & $z=0$	10^{-12}	-
C_ℓ clustering	(21),(22)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_\ell$	Fig. 12
C_ℓ weak lensing	(21),(28)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_\ell$	Fig. 12
C_ℓ gxy-gxy lensing	(21),(22),(28)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_\ell$	Fig. 12
C_ℓ intrinsic alignments	(21),(30)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_\ell$	-
C_ℓ CMB lensing auto	(21),(31)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_l$	Fig. 13
C_ℓ CMB lensing cross	(21),(22),(28),(31)	CCL6	$2 \leq \ell \leq 3000$	$0.1\sigma_\ell$	Fig. 13
$\xi_\pm, \xi_{gg}, \xi_{ggl}$	(43),(41),(39)	CCL6	$0.01 < \theta/\mathrm{deg} < 5$	$0.5\sigma_{\mathrm{LSST}}$	Figs. 14 and 15
3D correlation, ξ	(44)	CCL1-3	$0.1 < r/\mathrm{Mpc} < 250$ & $0 \leq z \leq 5$	4×10^{-2}	Figs. 16 and 17
C_ℓ clustering non-Limber	(21),(22),(25)	CCL1	$500 \leq \ell < 1000$	2×10^{-2}	-
C_ℓ clustering Angpow	(21),(22),(25)	CCL1	$2 \leq \ell < 1000$	3×10^{-3}	Fig. 18 (right panel)

From the CCL paper.

Summary



Cosmological predictions to a validated numerical accuracy:

- **For a wide range of models** (e.g., including massive neutrinos)
- **For a wide range of observables** (e.g., angular power spectra)
- **Using state-of-the-art tools** (e.g., emulators)
- A DESC-wide effort with DESC tools and **significant engagement of LSST:UK**

The future of CCL

- **Extending the range of models**
  (e.g., modified gravity, perturbation theory).

- **Extending the range of observables**
  (e.g., cluster lensing, cluster mass functions)

- **Seamless integration with the joint-probes likelihood pipeline.**

- **Exploring accuracy vs speed**.

Thank you