Outline

- Dark Energy science with the LSST
  - Main dark energy probes
  - Systematics-limited analyses
- DESC projects and opportunities for engagement
  - The Core Cosmology Library
  - The LSS loop
  - LSS with HSC DR1
  - The 3x2pt pipeline
  - TJPCosmo
- Summary
● Dark Energy science with the LSST
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Dark Energy science with the LSST

Outstanding numbers:
- World's largest imager
  8.4 m, 9.6 sq-deg FOV
- Wide: 20K sq-deg
- Deep: r~27
- Fast: ~100 visits per year
- Big data: ~15 TB per day

Dark Energy Science Collaboration:
- Supernovae
- Cluster science
- Strong lensing
- Weak lensing
- Large-scale structure

LSST Coll. et al. 0912.0201
Main Dark Energy probes

Large-Scale Structure (DESC co-convener):
- DE affects cosmic density field
- Galaxy distribution $\leftrightarrow$ matter density
- Main systematic $\rightarrow$ galaxy-matter connection

In general:
$$\delta_g(x) = f[\delta_M(y)] + \epsilon(x)$$

On large scales:
$$\delta_g \sim b_g \delta_M$$
Main Dark Energy probes

Amplitude of fluctuations vs. Scale

- Growth
- Scale dependence
- Small scales

LSS $X$ and $✓$
Main Dark Energy probes

Weak gravitational lensing:

- Intervening matter modifies observed galaxy shapes.
- Tracer of the true matter distribution → no bias!
- Large radial projection kernel → no scale-dependence

Credit: NASA/ESA
Main Dark Energy probes

Amplitude of fluctuations

Scale

Growth

Scale dependence

Small scales

LSS
WL

LSS
WL
Main Dark Energy probes

LSS-WL complementarity

Amplitude of fluctuations

Scale dependence

Small scales

Growth

LSS ∨ WL

LSS ∨ WL

LSS ∨ WL

LSS ∨ WL

LSS + WL

DA et al. 1610.09290
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• **Summary**
Sky systematics:
- Galactic dust
- Star contamination
- Star obscuration
- Airmass, seeing, depth

Elvin-Poole et al. 2017
Sky systematics:
- Galactic dust
- Star contamination
- Star obscuration
- Airmass, seeing, depth

Photometric redshifts:
- Loss of small radial scales
- Complicated 3D analysis
  → tomography
- Uncertain redshift distributions

Hildebrandt et al. 2016
Sky systematics:
- Galactic dust
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- Airmass, seeing, depth

Photometric redshifts:
- Loss of small radial scales
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  → tomography
- Uncertain redshift distributions

Correlated systematics:
E.g. dust, blending etc.
Systematics-limited analyses: astrophysical systematics

**Galaxy clustering**
- Galaxy bias
- Magnification bias

**Weak lensing**
- Baryonic effects
- Intrinsic alignments

\[ \delta_g(x) = b_1 \delta_m(x) + b_2 \delta^2_m(x) + b_s s^2(x) + \cdots \]
\[ \gamma_{ij}^I = C_1 s_{ij} + C_2 (s_{ik} s_{kj}) + C_\delta (\delta s_{ij}) + C_t t_{ij} + \cdots \]

Credit: J. Blazek

Lorenz et al. 2017
Galaxy clustering
- Galaxy bias
- Magnification bias

Weak lensing
- Baryonic effects
- Intrinsic alignments

Systematics-limited analyses: astrophysical systematics

\[ \delta_g(x) = b_1 \delta_m(x) + b_2 \delta^2_m(x) + b_s s^2(x) + \cdots \]

\[ \gamma_{ij}^I = C_1 s_{ij} + C_2 (s_{ik} s_{kj}) + C_\delta (\delta s_{ij}) + C_t t_{ij} + \cdots \]

Credit: J. Blazek

Chisari et al. 2018

Lorenz et al. 2017

Credit: E. Chisari
Systematics-limited analyses: likelihood systematics

- Covariance matrices
- Correlated variables
- Non-Gaussian likelihoods

Krause et al. 2017
• Covariance matrices

• Correlated variables

• Non-Gaussian likelihoods

Systematics-limited analyses: likelihood systematics

Krause et al. 2017
Systematics-limited analyses: likelihood systematics

- Covariance matrices
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- Non-Gaussian likelihoods

Sellentin et al. 2017
Hamimeche and Lewis 2009
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The Dark Energy Science Collaboration (DESC)
The Dark Energy Science Collaboration (DESC)
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Concept:
“LSST DESC Core Cosmology Library (CCL) provides routines to compute general cosmological observables with validated numerical accuracy.”

Motivation:
• Precision cosmology → controlled accuracy
• Multiple probes → consistency
• Synergies → generality
CCL: science capabilities

Cosmology
$\Omega_M, w_0, \sigma_8 \ldots$

CLASS
HaloFit
Emulators
E&H, BBKS

Matter power Spectrum $P(k)$

Background quantities
$d_A(z), \chi(z), D(z), f(z)\ldots$

Density tracers:
(GC, WL, CMBL \ldots)
(incl. astrophysical syst.)

Angular correlation Functions $\xi(\theta)$

Halo model quantities
$n(M), b(M), \sigma(M)$

Angular power spectra $C_\ell$
LSST DESC Core Cosmology Library (ccl) provides routines to compute basic cosmological observables with validated numerical accuracy.

The library is written in C99 and all functionality is directly callable from C and C++ code. We also provide Python bindings for higher-level functions.
In [1]:

```python
import numpy as np
import pylab as plt
import pyccl as ccl

%matplotlib inline

Omega_c = 0.27, Omega_b = 0.045,
h = 0.7, A_s = 2.1e-9, n_s = 0.96

z = np.linspace(0., 1., 200)
dNdz = np.exp(-(z - 0.5)**2)
lens = ccl.ClTracerLensing(cosmo, False, z=z, n=dNdz)
ell = np.arange(2, 100)
cls = ccl.angular_cl(cosmo, lens, lens, ell)

plt.loglog(l, Cl)
```
CCL: software implementation

DESC Core Cosmology Library: cosmology routines with validated numerical accuracy

In [1]:
```python
import numpy as np
import matplotlib.pyplot as plt
import pyccl as ccl

%matplotlib inline

cosmo = ccl.Cosmology(Omega_c=0.27, Omega_b=0.045,
                      h=0.67, A_s=2.1e-9, n_s=0.96)

z = np.linspace(0., 1., 200)
dNdz = np.exp(-(z - 0.5)**2)
lens = ccl.ClTracerLensing(cosmo, False, z=z, n=dNdz)

ell = np.arange(2, 100)
cls = ccl.angular_cl(cosmo, lens, lens, ell)
```
CCL: coding with a bunch of physicists

+23 others!

- Work through github
- Contributions through pull requests
- Strict code review
- New science subject to external benchmarks
- Unit tests!
- More unit tests!
- Bi-weekly telecons
- Crucial project management
- Paper out soon!
CCL: coding with a bunch of physicists

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E. Chisari
• Generic non-linear formalisms for 2-point functions
• Halo models
• Beyond wCDM
• Beyond 2-point functions
• Consistent LSS-CMB correlations
• Primordial non-Gaussianity

https://github.com/DarkEnergyScienceCollaboration/CCL
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**The LSS loop**

**Idea:**
Fast round-trip loop that allows us to validate our pipeline with good statistics.

**Motivation:**
- Make sure we have all the necessary pieces.
- Incremental improvement by gradually adding more realism.
- Science! Quantitative analysis of the impact of different systematics.

https://github.com/LSSTDESC/2pt_validation/
**The LSS loop: CoLoRe**

**Idea:**
Run **FAST** simulations of multiple correlated cosmological observables.

**Currently implemented:**
- Galaxy clustering
- Weak lensing
- Intensity mapping
- CMB lensing
- ISW

---

3D Gaussian fields at $z=0$. Cartesian box

- Physical $\delta (>1)$ (LN, 1LPT, 2LPT...)
- Interpolation to spherical shells
- Rotation to observer coordinates
- Light-cone evolution
- Biasing

$
\mathbf{K} \quad \mathbf{\phi} \quad \mathbf{\delta_a} \quad \mathbf{V_r} \quad \mathbf{\nabla^2\phi}
$

---

https://github.com/damonge/CoLoRe
The LSS loop: fastcat

**Idea:**
Software to post-process clean galaxy catalogs and add “dirt” (sky systematics, photo-z uncertainties, stars etc.)

**Currently implemented**
- Different photo-z models
- Depth variations through input window function

**Wishlist**
- Scale to LSST-like sample sizes
- Realistic dust models (e.g. correlation with PZ).
- Realistic star contamination.

README.md

**fastcat**

Fast and dirty creation of fast and dirty mock galaxy catalogs

https://github.com/slosar/fastcat
The LSS loop: NaMaster

Galaxy positions

Mask $w(\theta)$

Overdensity map
$\delta(\theta) = n(\theta)/[\bar{n} w(\theta)] - 1$

Systematics maps

Power spectrum
$C_\ell^{12}$

Mode-coupling Matrix
$M_{\ell\ell'}(w_1, w_2)$

Deprojection bias
$B_{\ell}^{12}$

Contaminant deprojection

NaMaster

Idea:
Fast and general code to compute $C_l$ between any two fields defined on $S^2$. Include systematics marg. at the map level.

https://github.com/damonge/NaMaster
The LSS loop: Current status

Validated:
- CoLoRe
- NaMaster
- CCL
- fastcat

First chains run during hack day (Feb. SLAC meeting).
The LSS loop: open projects. Contribute!

• Finish validation at the likelihood level
• Implement more complex systematics in fastcat
• Scale fastcat up
• Start using it for science!
  • Dust-photo-z correlation
  • Photo-z – Clustering strength correlation
  • Dust resolution needs for LSST galaxy clustering

https://github.com/LSSTDESC/2pt_validation/
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Idea:
Use public HSC data to perform galaxy clustering analysis.

Motivation:
- Same DM pipeline and data format as LSST.
- Learn from these data and use them to improve LSST DM.
- Unused state-of-the-art data!
- New regime of depth and systematics
- Prove that $C_\ell$ pipelines can deal with this.
LSS with HSC: work done

Characterized global sky systematics:
- Dust extinction
- Star contamination
- Depth variations
- Bright-object mask
LSS with HSC: work done

Measured un-binned power spectra:
LSS with HSC: work done

Compared against simplest theory!

Photo-z characterization + linear bias + CCL
LSS with HSC: work to be done. Contribute!

- Characterize per-exposure systematics (airmass, PSF etc.)
- Study photo-z binning and per-bin systematics
- ...
- Full cosmological analysis!

https://github.com/LSSTDESC/HyperSupremeStructure-HSC-LSS
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**3x2pt** stands for the three most relevant 2-point correlation functions for cosmology:

- Galaxy - Galaxy
- Galaxy - Lensing
- Lensing - Lensing

**Idea:** develop a joint analysis pipeline between LSS and WL with 3x2pt as data vector.

**Motivation:**
- WL and LSS will only constrain DE if combined
- Similar observables: two-point functions of different fields
- Shared systematics (photo-z, sky, astrophysics)
The 3x2pt pipeline

Tonnes of things to be done!
- Data formats (maps, catalogs, 2-points)
- Systematics mapper
- Masks and random catalog
- Sample selectors
- ...

Tonnes of applications!
- Consistent analysis of existing data
- Analysis of LSST DC2-3 and commissioning data
- Extensions to Nx2pt (Clusters, CMB lensing, tSZ) or even NxMpt

https://github.com/LSSTDESC/TXPipe
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Idea:
Likelihood module that can combine multiple cosmological probes with theory predictions to obtain joint constraints on cosmological parameters.

Motivation:
- Non-trivial endeavour: multiple probes (>5!) with correlated signal, noise and systematics.
- Generic analysis models for different probe combinations.
- Generic implementation of systematic models that can easily grow in complexity.
- Avoid inconsistencies between probes in terms of theory or systematics.

Note: TJPCosmo != CCL
TJPCosmo: status and plans

First hack at Oxford
~3 weeks ago
TJPCosmo: status and plans

Implementation of first 3x2pt likelihood!
• Dark Energy from LSST from 5 different probes
• Huge potential for LSS+WL (3x2pt)
• Lots of work going on:
  • **CCL**: theory calculator
  • **LSS loop**: fast simulations for LSS pipeline tests (and science!)
  • **LSS with HSC**: new data, new challenges
  • **3x2pt pipeline**: flagship analysis for LSST
  • **TJPCosmo**: robust parameter inference for multi-probe experiments
• Open and friendly work environment. **Contribute!**
Summary

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- Huge potential for LSS+WL (3x2pt)
- Lots of work going on:
  - **CCL**: theory calculator
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Obrigado!