Cosmological Inference
Pipelines and Projects

HLS Team
Overview

1. Multi-probe inference
   a. Forecasting results - overview (Tim Eifler)
   b. Next Gen Pipeline - Cocoa (Vivian Miranda)
   c. 2D+3D (Elisabeth Krause)

2. Kinematic Lensing
   a. Concepts+Overview (Eric Huff)
   b. Measurement with Keck and HST (Pranjal Singh)
   c. KL with Roman Space Telescope (Jiachuan Xu)

3. Roman voids for cosmology (Alice Pisani)
Topic 1: Multi-probe Inference (Forecasting results)

- **Goals of the forecasting pipeline:** Study science return, aka quantify error budget as a function of
  a. science cases/parameterizations (dark energy, modified gravity, etc)
  b. multiple probes (weak lensing, clustering, clusters, cross-correlations)
  c. galaxy samples, redshift distributions, scales
  d. survey strategy
  e. systematics models and mitigation strategy
  f. statistical uncertainties and probe-correlations
  g. synergies with external datasets

- **Challenges:**
  a. Speed: This pipeline needs to run very often, increasingly so, the closer we get to the data
  b. Precision/accuracy: The most relevant ingredients need to be modeled precisely/accurately, but avoid fine-tuning irrelevant aspects
  c. Constant iteration and updating as a function of better understanding the error budget from upstream pipeline/mock development and from community wide knowledge
  d. User-friendliness, documentation
Some Results - Reference Survey

see Eifler, Miyatake, Krause, Heinrich, Miranda, Hirata, Xu, many others, MNRAS 2021

Single probe Analyses

Multi-probe analyses
Roman “wide survey” idea - Synergies with Rubin

This concept combines the Roman W-band with the 6 LSST bands for photo-z
Explore Roman W-band Wide Survey, 18000 deg^2

- 5 months: Roman can cover all of LSST’s area and obtain space quality shape measurements for 95% of the LSST Y10 gold sample
- 1 year: Same as above for all sky
- Interesting for many science cases beyond DE
- Disclaimer: W-band only survey is more easily affected by systematics
- Idea: Combine W-band survey with Roman multi-band photometry as in the reference survey
3x2 simulated analysis Roman+Rubin

Weak lensing and Galaxy Clustering (photo-z) only, no clusters, spec-z, SN, CMB

Includes 56 dims of systematics modeling:
- Shear calibration
- Galaxy bias
- photo-z
- IA
- Baryons

FoM (Roman wide + Rubin) = 2.4 x FoM (LSST only)
FoM (Roman wide + Rubin) = 5.5 x FoM (Roman Reference survey)

Disclaimer: The usual caveats to the FoM metric apply
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Multi-probe Inference (Next Gen Pipeline)

Cocoa - Cobaya-CosmoLike Architecture

Address the previous challenges w/ conservative well-tested solutions

- Challenges:
  a. Speed:
     i. Cosmolike in C language (for speed).
     ii. Multithreading w/ MPI+OpenMP + Smart Caching of intermediate results.
     iii. Adopt Cobaya (based on state-of-the-art CosmoMC) for low overhead integration w/ other datasets + MCMC samplers that are well understood by the community.
  b. Precision/accuracy:
     i. Based on Cosmolike, well tested state-of-the-art framework (in C language) for weak lensing 2pt functions with many options for science modeling (continuous improvements based on ground-based collaborations)
  c. Userfriendliness, documentation
     i. Integration between C and Python for better user interface
     ii. Continuously building documentation on github
Multi-probe Inference (Next Gen Pipeline)

**Cocoa - Cobaya-CosmoLike Architecture**

Fast evaluation + Easy to use

Hybrid MPI/OpenMP - walkers on steroids

Total Evaluation - Boltzmann + Cosmolike

(DES-Y3 like analysis w/ complex syst modeling)

- 1 OpenMP ~7 seconds
- 4 OpenMP threads ~2.2 seconds
- 8 OpenMP threads ~1.25 seconds

Total cores for a single chain: ~12-32 cores

Reasonably easy to adapt to LCDM extensions
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Historically, imaging and spectroscopic cosmology analyses carried out as independent analyses (mostly even by separate survey collaborations)

- However, if surveys overlap, redshift-space power spectra and angular clustering statistics are inherently correlated
- UA group derived first rigorous cross-covariance between 3D and 2D measurements from mode counting arguments

\[
\text{Cov}[P(k), C^{(i)j}(l)] = \frac{1}{V} \frac{1}{\Omega_s} \left[ \langle \tilde{\delta}_{-k} \tilde{\kappa}_l^{(i)} \rangle \langle \tilde{\delta}_k \tilde{\kappa}_l^{(j)} \rangle + \langle \tilde{\delta}_k \tilde{\kappa}_l^{(i)} \rangle \langle \tilde{\delta}_{-k} \tilde{\kappa}_l^{(j)} \rangle \right] \\
= \frac{\Omega_s}{V} p_2(k) \left[ \int d\chi \int d\chi' g^{(i)}(\chi) g^{(j)}(\chi') e^{ik \parallel (\chi - \chi')} \left[ f_{k_1, l}(\chi) f_{k_1, l}(\chi') + f_{k_1, -l}(\chi) f_{k_1, -l}(\chi') \right] \right]
\]

- Methodological advance that is of great interest beyond Roman, e.g., DESI x Rubin, Euclid

Ongoing work by Supranta Sarma Boruah, Elisabeth Krause, Tim Eifler
Topic 1: Multi-probe Inference (2D+3D)

HLSS and HLIS probe cosmic structure in overlapping volume

- Accurate joint analyses require accounting for covariance between different observables
- Cross-covariance between projected statistics and redshift space power spectrum ignored in previous forecasts
- Updated forecasts using cross-covariance between HLSS and HLIS measurements ongoing
- Cross-covariance will enable cross-correlation science, e.g., galaxy-galaxy lensing with HLSS galaxies as lenses

Ongoing work by Supranta Sarma Boruah, Elisabeth Krause, Tim Eifler
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3. **Roman voids for cosmology** (Alice Pisani)
Wide variety of hard measurement problems in WL:
What are the root causes?

shear and shape are degenerate

Shape noise:
\[
\frac{\sigma_{int}}{n_{\text{gal}}} \gg \gamma
\]

Use everything you can see to increase \( n_{\text{gal}} \)

Large samples of marginal galaxies

- intrinsic alignments
- shear calibration
- large PSF corrections
- photo-z's instead of spectra
KL basics

face-on, but sheared

inclined, but not sheared
Effect of shear on kinematic observables:

$q_{\text{int}} = 0.75, \gamma_+ = 0, \gamma_\times = 0$

$q_{\text{int}} = 0.2$
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Topic 2: Kinematic Lensing (Measurement)

- Kinematic Lensing is a promising technique and possibly really powerful for Roman

- Given KL is new, we want to test if it works in practice and so I am working on a measurement using Keck data

- Below I describe the modeling pipeline and early results based on simulations
KL Measurement pipeline

- **Image model**
  - Use Galsim to model image
  - $n=1$ inclined Sersić profile ($r_{hl}$, $q_z$, sin$i$)

- **Spectrum model**
  - Model the slit as a 2D grid
  - Apply coordinate transformations to the grid accounting for the effects of shear, intrinsic galaxy position angle and inclination
  - Assume arc tan velocity field
  - Tully-Fisher prior on maximum circular velocity

### Table 1. Fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_+$</td>
<td>Shear component</td>
<td>$\mathcal{U}(-0.7, 0.7)$</td>
</tr>
<tr>
<td>$\gamma_x$</td>
<td>Shear component</td>
<td>$\mathcal{U}(-0.7, 0.7)$</td>
</tr>
<tr>
<td>$r_{hl,\text{image}}$</td>
<td>Image half-light radius</td>
<td>$\mathcal{U}(0.15, 5)$</td>
</tr>
<tr>
<td>$r_{hl,\text{spec}}$</td>
<td>Spectrum half-light radius</td>
<td>$\mathcal{U}(0.15, 5)$</td>
</tr>
<tr>
<td>$I_0$</td>
<td>Central brightness</td>
<td>$\mathcal{U}(1, 10^4)$</td>
</tr>
<tr>
<td>$V_{\text{circ}}$</td>
<td>Maximum circular velocity</td>
<td>$\mathcal{N}(%logV_{TF}, \sigma_{TF})$</td>
</tr>
<tr>
<td>$r_0$</td>
<td>Galaxy dynamic center</td>
<td>$\mathcal{U}(-2, 2)$</td>
</tr>
<tr>
<td>$r_{\text{vscale}}$</td>
<td>Velocity scale radius</td>
<td>$\mathcal{U}(0.1, 10)$</td>
</tr>
<tr>
<td>sin$i$</td>
<td>Galaxy inclination angle</td>
<td>$\mathcal{U}(-1, 1)$</td>
</tr>
<tr>
<td>$\theta_{\text{int}}$</td>
<td>Intrinsic galaxy position angle</td>
<td>$\mathcal{U}(-\pi/2, \pi/2)$</td>
</tr>
</tbody>
</table>
Results from Simulations
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Defining the KL sample

- Scenarios Definition:
  
  **Reference HLS Imaging**
  - J+H band combined $S/N > 18$
  - Ellipticity error $\sigma_e < 0.2$
  - Resolution factor $R > 0.4$

  
  **Reference HLS Spectroscopy**
  - At least one of $H_\alpha$, $H_\beta$ and $[O_\text{III}]$ is resolved within $1 - 2 \mu m$
  - Emission flux $> 10^{-16}$ erg/s/cm$^2$
  - Half-light radius $> 0.1''$
  - $z$-band magnitude $\leq 24.5$

Obtained from COSMOS and CANDELS
CosmoLike Likelihood/Cov Settings

- Observable: shear-shear power spectrum $C_{kk}^{ij}(\ell)$ (20 log bins from $30 \leq \ell \leq 4000$)
- Covariance matrix: Gaussian + non-Gaussian + super-sample covariance, $\Omega_s = 2000 \text{ deg}^2$
- Cosmological parameters sampled: $\{\Omega_m, \sigma_8, n_s, w_0, w_a, \Omega_b, h\}$
- Systematics modeling

<table>
<thead>
<tr>
<th>Systematic Parameters</th>
<th>WL</th>
<th>KL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fiducial</td>
<td>Prior</td>
</tr>
<tr>
<td>$\Lambda_{\text{z,src}}$</td>
<td>0.0</td>
<td>$\mathcal{N}(0, 2e^{-3})$</td>
</tr>
<tr>
<td>$\sigma_{\gamma,\text{src}}^2$</td>
<td>0.01</td>
<td>$\mathcal{N}(0.01, 2e^{-3})$</td>
</tr>
<tr>
<td>$m^i$</td>
<td>0.0</td>
<td>$\mathcal{N}(0, 2e^{-3})$</td>
</tr>
<tr>
<td>$A_{1A}$</td>
<td>5.92</td>
<td>$\mathcal{N}(5.92,3.0)$</td>
</tr>
<tr>
<td>$\beta_{1A}$</td>
<td>1.1</td>
<td>$\mathcal{N}(1.1,1.2)$</td>
</tr>
<tr>
<td>$\eta_{1A}$</td>
<td>-0.47</td>
<td>$\mathcal{N}(-0.47,3.8)$</td>
</tr>
<tr>
<td>$\eta_{\text{high-z}}$</td>
<td>0.0</td>
<td>$\mathcal{N}(0.0,2.0)$</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>0.0</td>
<td>$\mathcal{N}(0,0.16,0)$</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>0.0</td>
<td>$\mathcal{N}(0,0.2,0)$</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>0.0</td>
<td>$\mathcal{N}(0,0.08)$</td>
</tr>
</tbody>
</table>

Similar to the *Roman Space Telescope* x Rubin Observatory (*Eifler et al. 2021*)
Forecast results: WL v.s. KL

- Figure-of-Merit: 3.65x enhancement in $w_p - w_a$ 1.70x enhancement in $\Omega_m - S_8$
Forecast results: impact of systematics

- Photo-z and shear calibration uncertainties are comparable with baryon effects uncertainty

<table>
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<tr>
<th>FoM</th>
<th>WL</th>
<th>KL ($N_{\text{bins}} = 10$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PZ+M+BA</td>
<td>PZ+M+BA</td>
</tr>
<tr>
<td>FoM$_{wp\Lambda}$</td>
<td>10.55</td>
<td>38.51</td>
</tr>
<tr>
<td>FoM$<em>{\Omega</em>{\Lambda}}$</td>
<td>5307</td>
<td>9017</td>
</tr>
</tbody>
</table>
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Topic 3: Roman voids for cosmology

Voids have a strong sensitivity to cosmology (Dark energy, massive neutrinos, growth of structure)

Kreisch, Pisani, Villaescusa-Navarro, Spergel, Wandelt, Hamaus and Bayer ArXiv: 2107.02304
Roman will provide access to a unique set of cosmic voids.

Prediction based on galaxy $n(z)$ from Merson et al. 2017

$$w(z) = w_0 + w_a \frac{z}{z + 1}$$
Roman voids
\[ \sim 100000 \text{ voids!} \]

Roman void size function

$dN/dn(R_v)$ vs. $R_v$ for $z = 1.2 - 1.4$

$dN/dn(R_v)$ vs. $R_v$ for $z = 1.4 - 1.6$

$dN/dn(R_v)$ vs. $R_v$ for $z = 1.6 - 1.8$

$dN/dn(R_v)$ vs. $R_v$ for $z = 1.8 - 2.0$
Monopole and quadrupole of the void-galaxy cross-correlation function

\[
\xi^s(s) = \xi(r) + \frac{f}{3b} \bar{\xi}(r) + \frac{f}{b} \mu^2 [\xi(r) - \bar{\xi}(r)]
\]
Further work needed

- Void-galaxy cross-correlation function theoretical prediction fit to voids from the HLSS galaxy mock for up-to-date forecasts.
- Void size function
- Void-void autocorrelation
- Complete the pipeline to prepare data analysis