Cosmology with the Roman Space Telescope: Weak Lensing and Beyond

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On behalf of the SIT on Cosmology with the High Latitude Survey

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Image credit: NASA
Science Goals

- Exploring the nature of cosmic acceleration:
  - Dark energy or modified gravity?
  - If dark energy, how does it evolve?
- Cosmological Phenomenology of DE/MG
  - Expansion history/geometry: e.g. wCDM v.s. LCDM
  - Growth history/clustering: e.g. f(R) gravity v.s. GR
- HLS survey has two components:
  - HLSS spectroscopic galaxy redshift survey
  - HLIS multi-probe analysis from imaging data (WL, GGL, 2D clustering, galaxy clusters), which is the focus of this talk

Spergel et al. (2015)
Reference High Latitude Imaging Survey

**Instrument Capabilities**

- **Survey area:** 2,000 sq deg
- **Bandpasses:** Y, J, H and F184
- **Survey depth:** 26.7 (5σ point source in J-band)
Cosmological Probes

- What can be measured from imaging
  - Galaxy shapes -> WL
  - Galaxy position -> 2D clustering
  - Galaxy clusters
  - Cross-correlations thereof (GGL, cluster WL)

- Observables that enter into forecasted imaging based multi-probe analysis (Eifler et al. 2021b)
  - Shear-shear auto-correlation
  - Shear-galaxy cross-correlation
  - Galaxy-galaxy auto-correlation
  - Cluster number counts
  - Cluster-shear cross-correlation

- Other probes that can be included are, e.g. peak statistics, magnification, cluster clustering, voids, higher order stats, etc
Galaxy Sample Definition (based on CANDELS catalog)

Source galaxy (used for WL)
- J+H band combined $S/N > 18$
- Ellipticity error $\sigma_e < 0.2$
- Resolution factor $R > 0.4$

\[
\frac{dN}{d\Omega} = \frac{51}{\text{arcmin}^2}
\]
\[
\sigma_e = 0.37
\]

Lens galaxy (used for 2D clustering)
- $S/N > 10$ in Y, J, H, F184
- $S/N > 5$ in each LSST band
- expect $u$

\[
\frac{dN}{d\Omega} = \frac{66}{\text{arcmin}^2}
\]

Galaxy clusters
- Optical-selected clusters (e.g. Rykoff et al. 2014)
- Falls in redshift range [0.4, 1.2] and optical richness range [40, 220]

Eifler et al. (2021b)
Systematics considered

- Photo-z uncertainties: percent-level precision can be reached with self-organizing map (Hemmati et al. 2019)
- Shear calibration bias: recent detector and image simulations (Troxel et al. 2021, Givans et al. 2021, Lin et al. 2021) show the shear calibration bias generally falls between the optimistic and pessimistic cases
- Cluster mass-observable relation: From Murata et al. (2018), the mass-observable relation has a scatter around 0.46 dex
- For intrinsic alignment, baryonic physics and linear galaxy bias, we choose non-informative flat priors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\Lambda_{z,\text{lens}}$</td>
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</tr>
<tr>
<td>$\sigma_{z,\text{lens}}$</td>
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<tr>
<td>$\Lambda_{z,\text{source}}$</td>
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</tr>
<tr>
<td>$\sigma_{z,\text{source}}$</td>
<td>0.01</td>
</tr>
<tr>
<td>Source photo-z (opt)</td>
<td>Gauss (0.0, 0.002)</td>
</tr>
<tr>
<td>Source photo-z (pess)</td>
<td>Gauss (0.05, 0.02)</td>
</tr>
<tr>
<td>$m_i$</td>
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<tr>
<td>Shear calibration (opt)</td>
<td>Gauss (0.0, 0.002)</td>
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<tr>
<td>Shear calibration (pess)</td>
<td>Gauss (0.05, 0.02)</td>
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Intrinsic alignment

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<tr>
<td>$\beta_{1A}$</td>
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</tr>
<tr>
<td>$\eta_{1A}$</td>
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<td>$\eta_{1A,\text{high-z}}$</td>
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Baryonic physics

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<td>$Q_1$</td>
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<tr>
<td>$Q_2$</td>
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</tr>
<tr>
<td>$Q_3$</td>
<td>0.0</td>
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</table>

Galaxy bias (tomographic bins)

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{1z}^i$</td>
<td>1.3 + i × 0.1</td>
</tr>
</tbody>
</table>

Eifler et al. (2021a, b)
Roman Reference Survey: Multi-probe from Imaging
Eifler, Miyatake, Krause, Heinrich, Miranda, Hirata, Xu, many others 2021

Individual probes - constraining power on dark energy

Multi-Probe Analysis
Roman wide survey idea: Synergies with the Rubin Observatory

see Eifler, Simet, Krause, Heinrich, Hirata, Huang, Fang, Miranda, Mandelbaum, Doux, many others 2021

- Idea 1: Use W-band of Roman to cover LSST area (or more? … one can dream…)
  5 months: Roman W-band can cover all of LSST’s area and obtain space quality shape measurements for 95% of the LSST Y10 gold sample.
  Interesting for many science cases beyond DE
  Disclaimer: W-band only survey is more easily affected by systematics

- Idea 2: Combine wide W-band survey with smaller multi-band photometry as in the reference survey to calibrate W-band data
Roman wide survey idea: Synergies with the Rubin Observatory

- 3x2pt analysis: 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
Synergies between Roman HLS and CMB Lensing from Simons Observatory

- 6x2pt analysis: auto- and cross-correlation among \( \{\delta_g, \gamma, \kappa_{\text{CMB}}\} \)
- Realistic systematics: galaxy bias, IA, baryonic effects, shear calibration bias, photo-z
- Adding CMB lensing improves \( \text{FoM}_{w_0 w_a} \) by a factor of 2.4 and \( \text{FoM}_{\mu_0 \Sigma_0} \) by 64%
- Adding CMB lensing also helps in galaxy bias self-calibration and constraining modified gravity significantly. A wide HLS idea is also compelling in the context of 6x2pt strategy

Wenzl et al. (2021) arXiv: 2112.07681
Kinematic lensing (Huff et al., 2013) is a novel weak lensing technique combining imaging and spectrum to estimate shear distortion.

- Shear distorts the photometry image and the spectrum of galaxies differently. Combining both helps breaking the degeneracy between intrinsic shape and shear, suppress shape noise by an order of magnitude.

- KL is a fantastic science case that combines the capabilities of the spectroscopic and imaging component of Roman HLS.

**Xu et al. (2021)
arXiv: 2201.00739**
Kinematic Lensing with Roman HLS

- Shear-shear autocorrelation only
- KL sample defined by overlap of HLS Imaging and Spectroscopy samples, has a shape noise of 0.035 and a number density of 4 per sq arcmin. Other systematics, like photo-z uncertainties, shear calibration bias and intrinsic alignment are also better controlled.
- Compared to traditional WL, KL improves $\text{FoM}_{w_0w_p}$ by a factor of 2.65, and $\text{FoM}_{\Omega_m\sigma_8}$ by 70%.
- Future works include multiprobe extensions and exploring the wide survey strategy.

Xu et al. (2021)
arXiv: 2201.00739
Summary

- A multi-probe analysis combining cosmic shear, photometric clustering, photometric galaxy-galaxy lensing, galaxy cluster number counts, galaxy cluster lensing and 3D BAO/RSD has shown that Roman HLS along can reach a standard DE FoM > 300, although more works are needed to increase the realism.
- A wide Roman HLS survey, e.g. use 5-months to cover LSST footprint in W-band, can generate space quality shape measurements for 95% of the LSST Y10 gold sample and has 4.5 times higher standard DE FoM than the reference HLS design, at the cost of systematic controls gain from multiband imaging.
- Synergy between Roman HLS and Simon Observatory CMB lensing can improve the constraining power on DE/MG models significantly. Meanwhile, systematics like galaxy bias and shear calibration bias can also get self-calibrated.
- The capabilities of Roman HLS enable a self-contained kinematic lensing survey, which is a novel weak lensing technique integrating image and spectrum dataset to estimate shear with high S/N. The reference HLS can gain huge constraining power on DE equation of state for free with the new KL technique applied.
- Note that the survey strategy of Roman is open for modification to maximize the science output given any new analysis technique/datasets are available.
Roman Multiprobe

<table>
<thead>
<tr>
<th>Probe</th>
<th>Multiprobe FoM summary</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Individual</td>
</tr>
<tr>
<td>Cosmic shear</td>
<td>9.8</td>
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<tr>
<td>3×2</td>
<td>23.46</td>
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<tr>
<td>Clusters</td>
<td>3.86</td>
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<tr>
<td>RSD + BAO</td>
<td>8.19</td>
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<tr>
<td>SN Ia</td>
<td>24.62</td>
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*Notes.* Note that 3×2 includes cosmic shear. All FoMs assume a flat universe.