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)

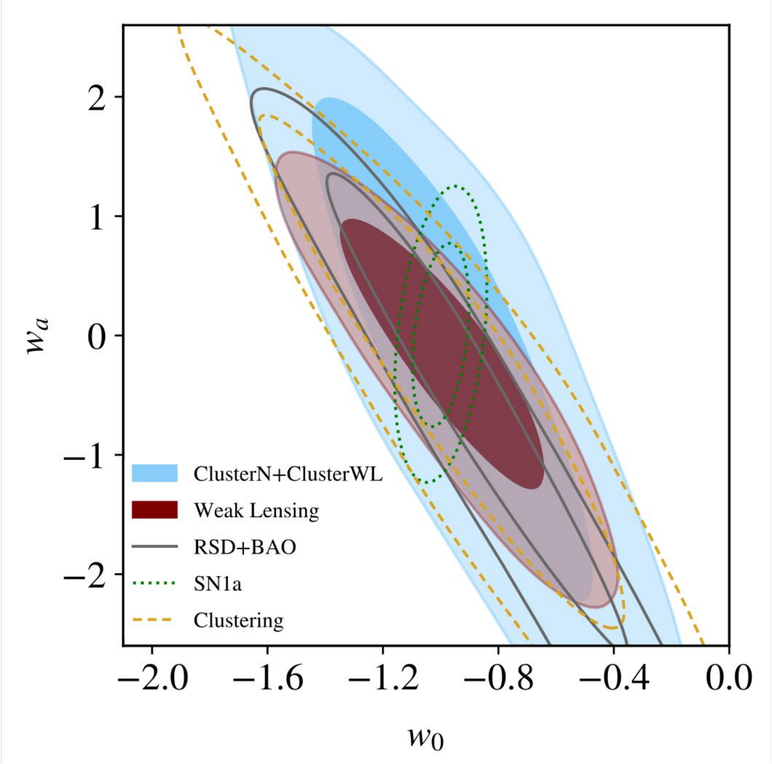
Topic 1: Multi-probe Inference (Forecasting results)

- 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

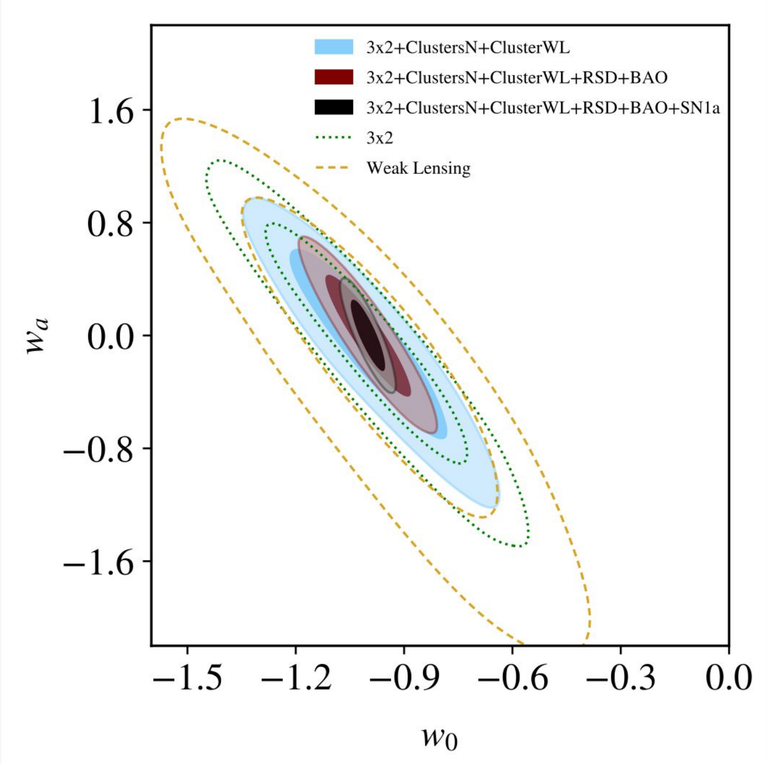
- Challenges:
  a. Speed: This pipeline needs to run very often, increasingly so, the closer we get to the data
  b. Precision/accuracy: The most relevant ingredients need to be modeled precisely/accurately, but avoid fine-tuning irrelevant aspects
  c. Constant iteration and updating as a function of 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

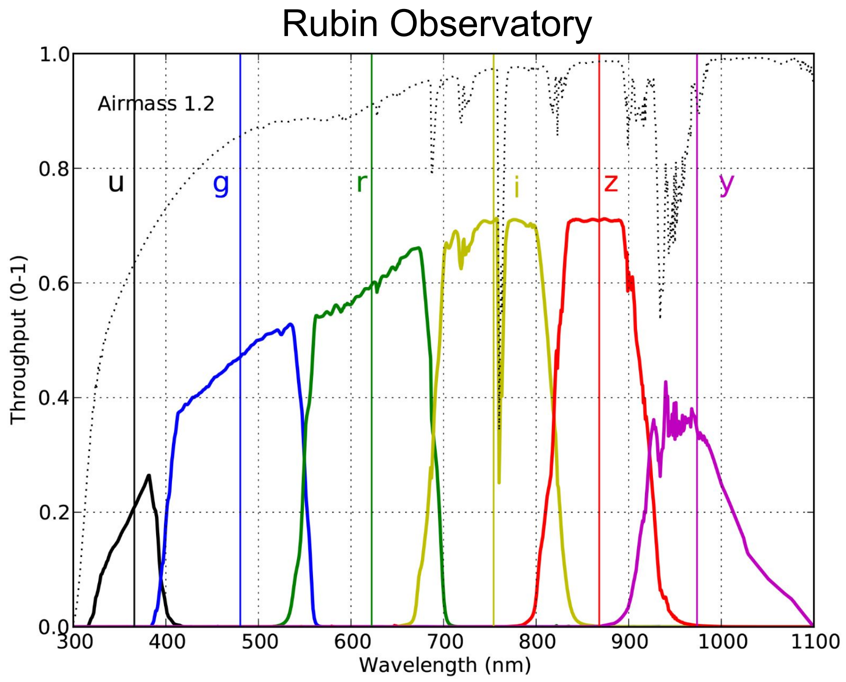


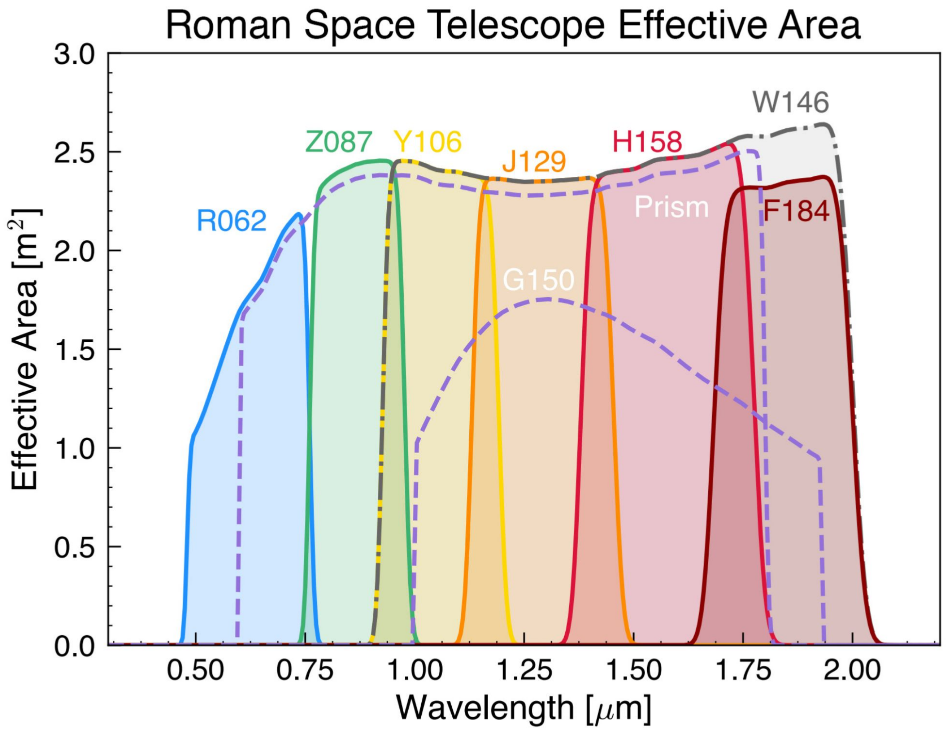
Single probe Analyses



Multi-probe analyses

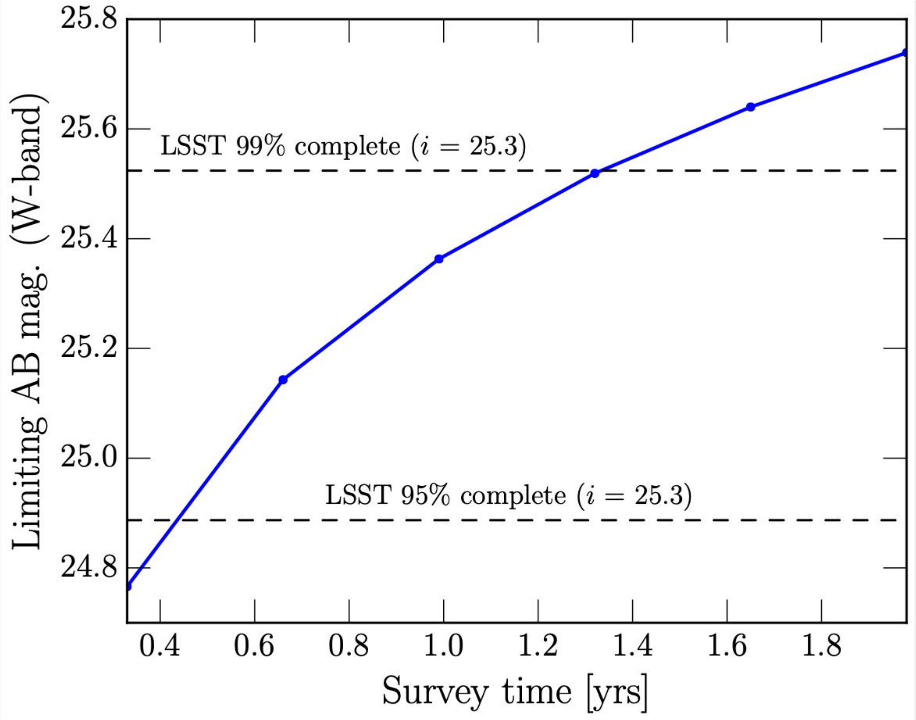
Roman "wide survey" idea - Synergies with Rubin





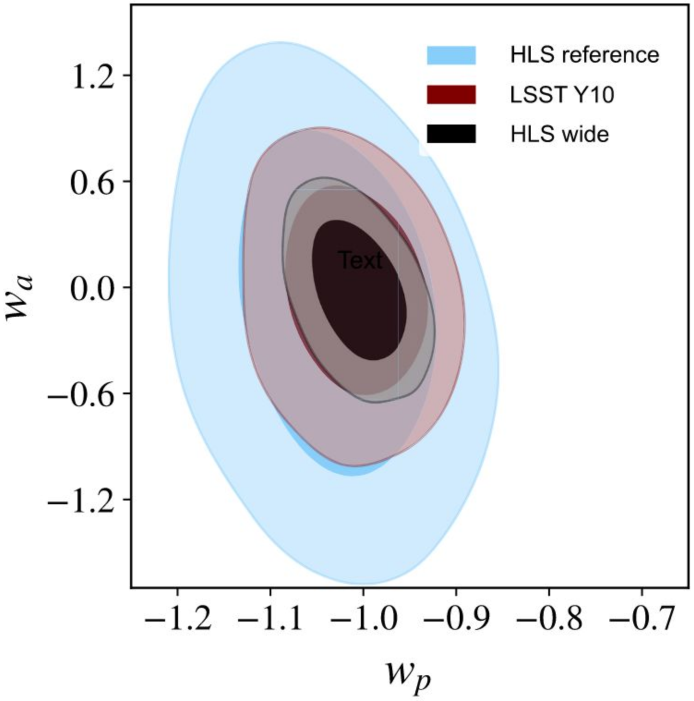
This concept combines the Roman W-band with the 6 LSST bands for photo-z

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
- 1year: 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)

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

Disclaimer: The usual caveats to the FoM metric apply

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Multi-probe Inference (Next Gen Pipeline)

Cocoa - **Co**baya-**Co**smoLike **A**rchitecture

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 - **Co**baya-**Co**smoLike **A**rchitecture

Fast evaluation + Easy to use

Hybrid MPI/OpenMP - walkers on steroids

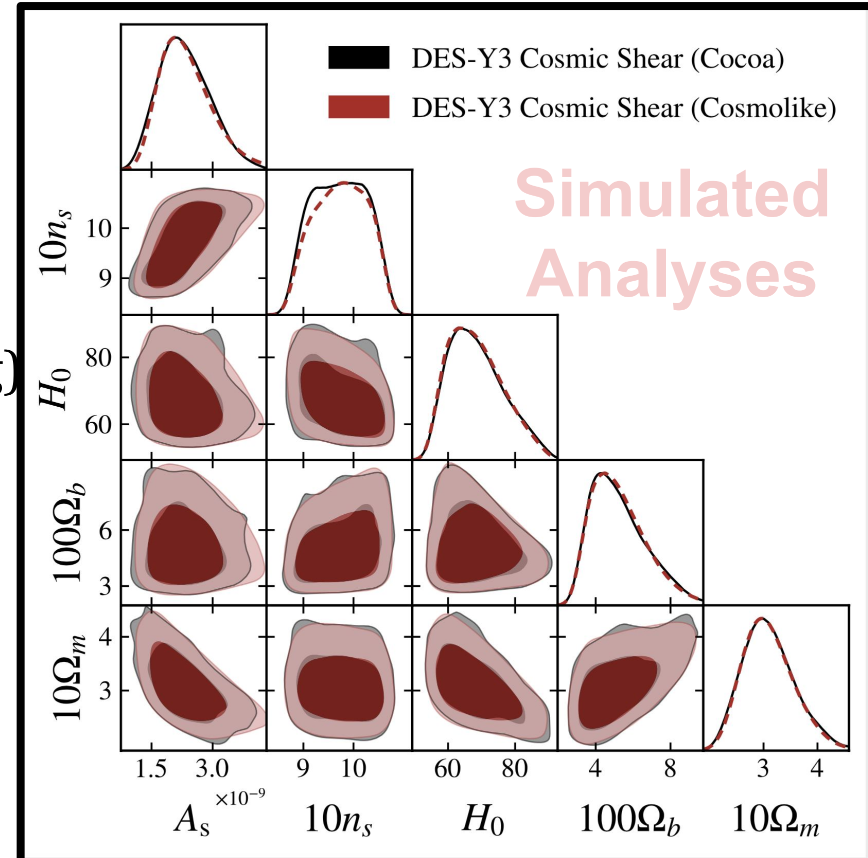
Total Evaluation - Boltzmann + Cosmolike

(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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Topic 1: Multi-probe Inference (2D+3D)

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

$$\begin{aligned}\mathrm{Cov}[P(\boldsymbol{k}), C^{(ij)}(\boldsymbol{l})] &= \frac{1}{V}\frac{1}{\Omega_s}\left[\langle\tilde{\delta}_{-\boldsymbol{k}}\tilde{\kappa}^{(i)}_{\boldsymbol{l}}\rangle\langle\tilde{\delta}_{\boldsymbol{k}}\tilde{\kappa}^{(j)}_{-\boldsymbol{l}}\rangle + \langle\tilde{\delta}_{\boldsymbol{k}}\tilde{\kappa}^{(i)}_{\boldsymbol{l}}\rangle\langle\tilde{\delta}_{-\boldsymbol{k}}\tilde{\kappa}^{(j)}_{-\boldsymbol{l}}\rangle\right] \\ &= \frac{\Omega_s}{V}P^2(\boldsymbol{k})\left[\int d\chi \int d\chi' g^{(i)}(\chi) g^{(j)}(\chi') e^{ik_\parallel(\chi-\chi')}\left[f_{\boldsymbol{k}_\perp,\boldsymbol{l}}(\chi) f_{\boldsymbol{k}_\perp,\boldsymbol{l}}(\chi') + f_{\boldsymbol{k}_\perp,-\boldsymbol{l}}(\chi) f_{\boldsymbol{k}_\perp,-\boldsymbol{l}}(\chi')\right]\right]\end{aligned}$$

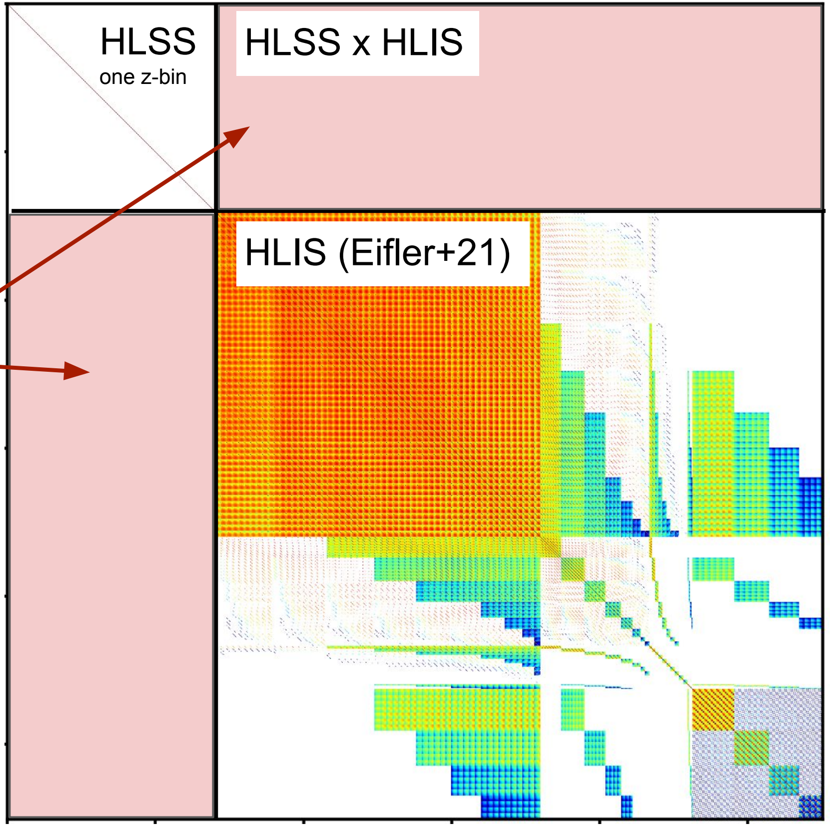
- Methodological advance that is of great interest beyond Roman, e.g., DESI x Rubin, Euclid

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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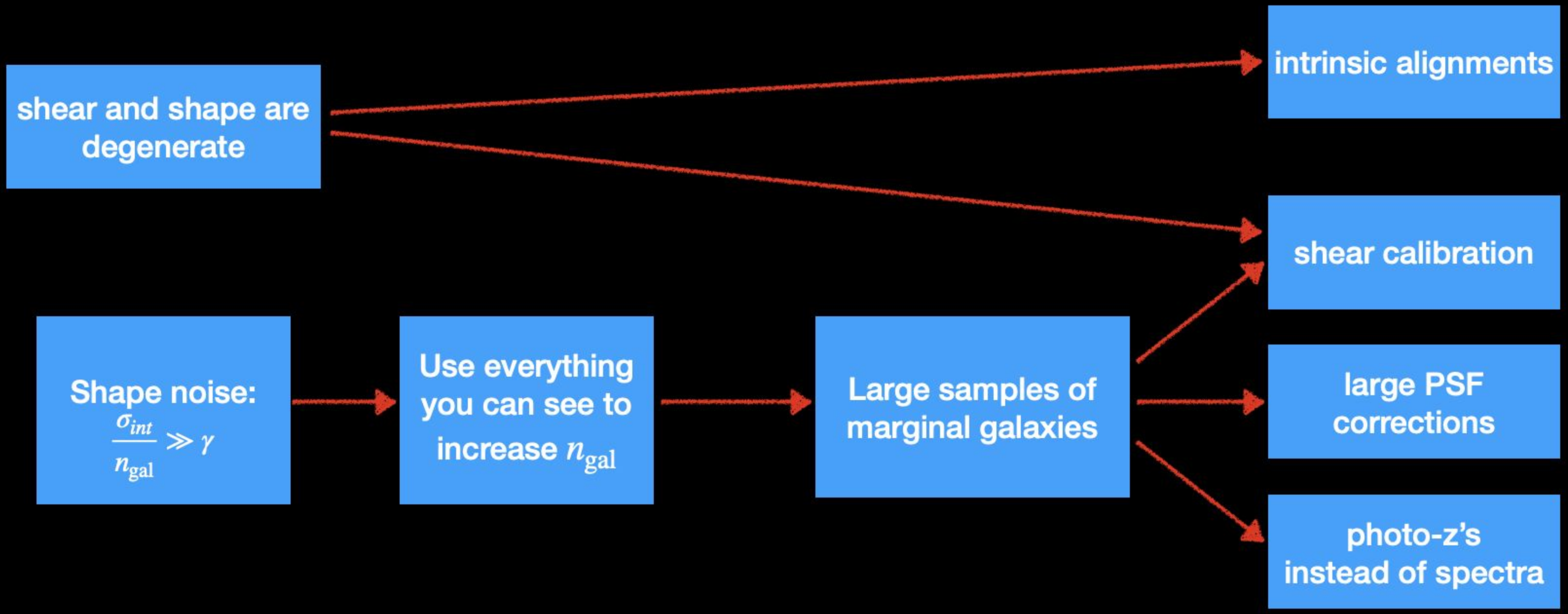
Wide variety of hard measurement problems in WL:
What are the root causes?



KL basics

image

face-on, but
sheared

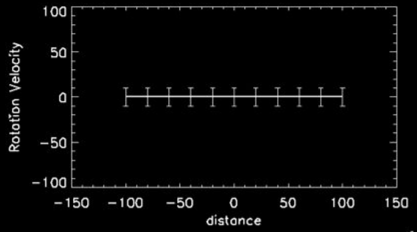
inclined, but
not sheared

KL basics

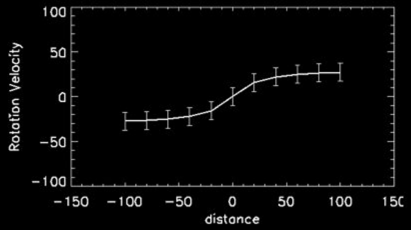
image

rotation curve

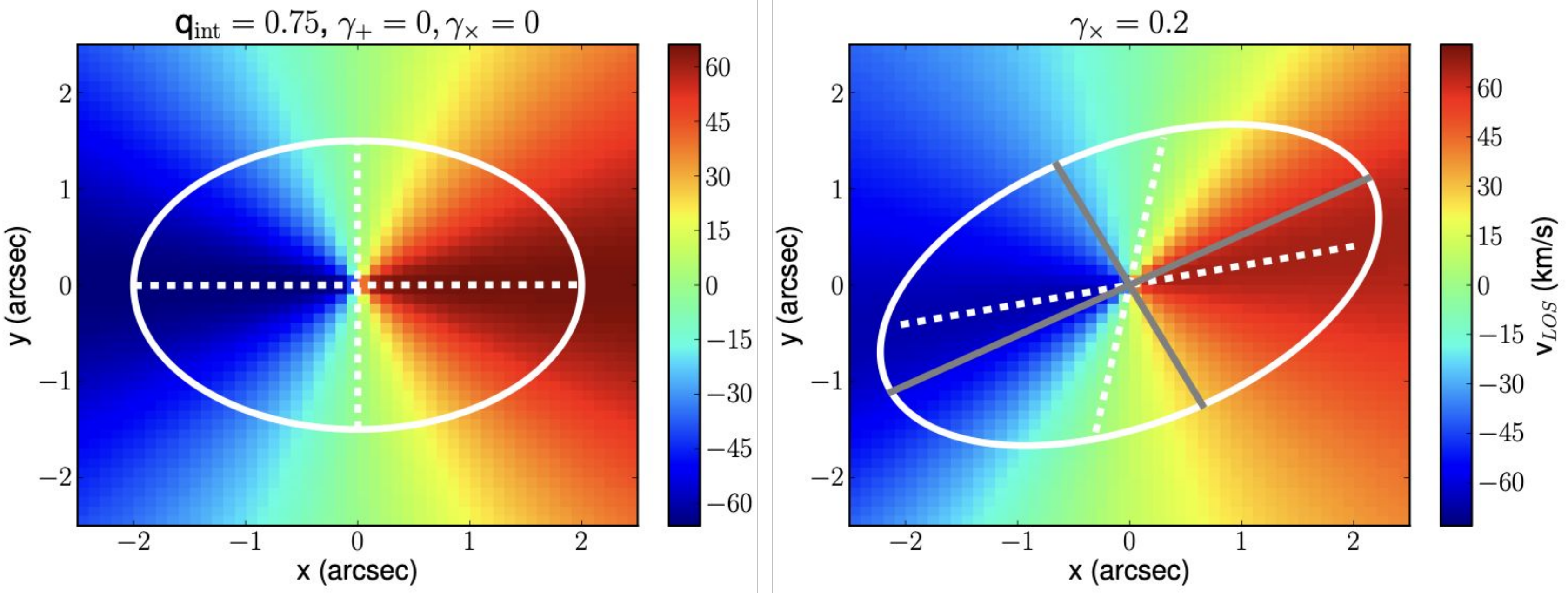
face-on, but sheared



inclined, but not sheared



Effect of shear on kinematic observables:



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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

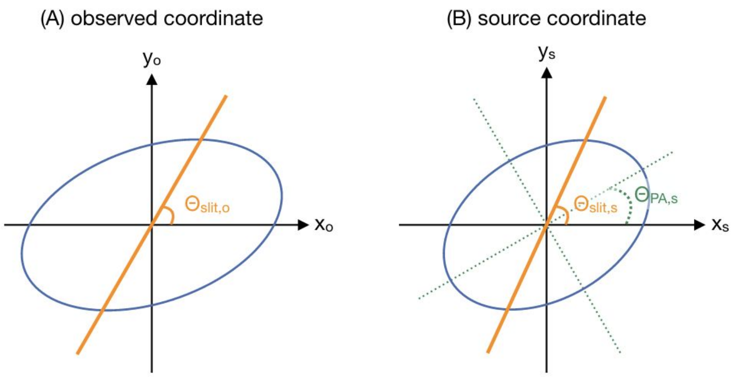
- Below I describe the modeling pipeline and early results based on simulations

KL Measurement pipeline

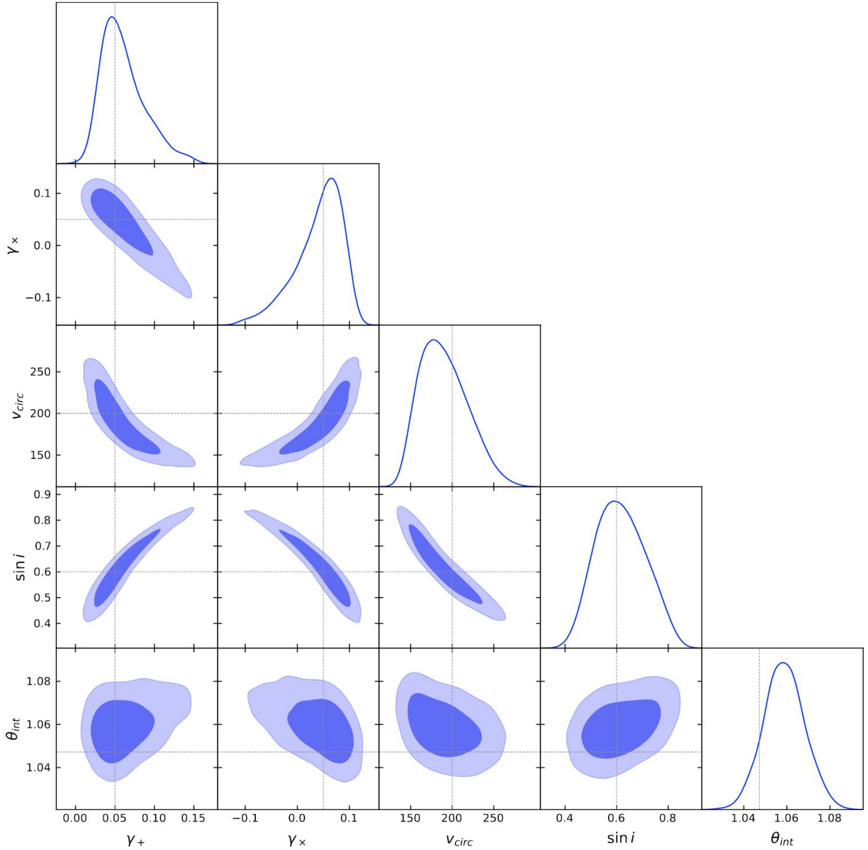
- Image model
  - Use Galsim to model image
  - n=1 inclined Sersić profile (r_{hl} , q_z , sin*i*)
- Spectrum model
  - Model the slit as a 2D grid
  - Apply coordinate transformations to the grid accounting for the effects of shear, intrinsic galaxy position angle and inclination
  - Assume arc tan velocity field
  - Tully-Fisher prior on maximum circular velocity

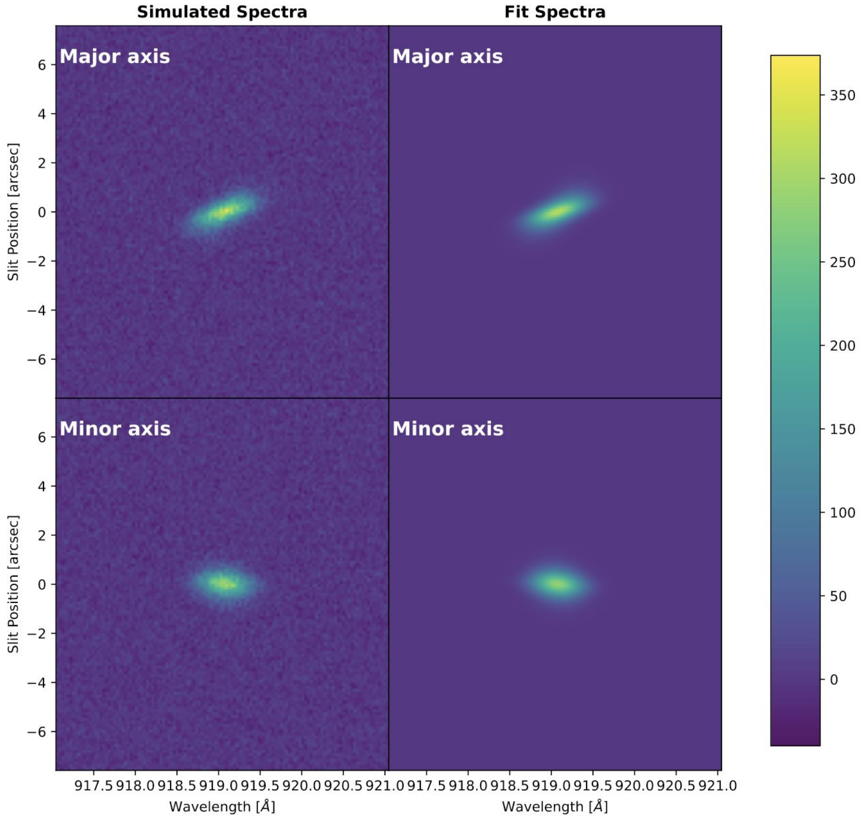
Table 1. Fit parameters

Parameter	Description	Prior
γ_+	Shear component	$\mathcal{U}$(-0.7, 0.7)
$\gamma_\times$	Shear component	$\mathcal{U}$(-0.7, 0.7)
$r_{\rm hl}^{\rm image}$	Image half-light radius	$\mathcal{U}$(0.15, 5)
$r_{\rm hl}^{\rm spec}$	Spectrum half-light radius	$\mathcal{U}$(0.15, 5)
I_0	Central brightness	$\mathcal{U}(1, 10^4)$
$V_{\rm circ}$	Maximum circular velocity	$\mathcal{N}(\log V_{\rm TF}, \sigma_{\rm TF})$
r_0	Galaxy dynamic center	$\mathcal{U}$(-2, 2)
$r_{\rm vscale}$	Velocity scale radius	$\mathcal{U}$(0.1, 10)
$\sin i$	Galaxy inclination angle	$\mathcal{U}$(-1, 1)
$\theta_{\rm int}$	Intrinsic galaxy position angle	$\mathcal{U}(-\pi/2, \pi/2)$



Results from Simulations





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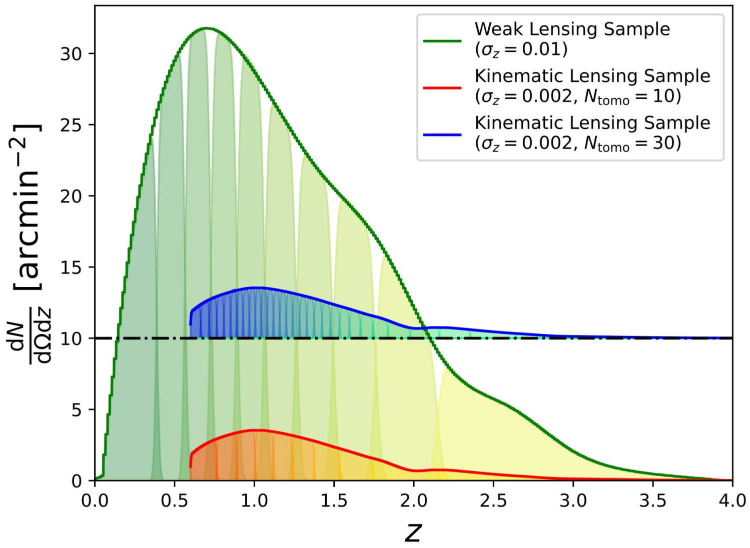
Defining the KL sample



Obtained from COSMOS and CANDELS

- Scenarios Definition:

Reference HLS Imaging

- J+H band combined $S/N > 18$
- Ellipticity error $\sigma_e < 0.2$
- Resolution factor $R > 0.4$

$$n_{\rm gal}^{\rm WL} = \frac{51}{\rm arcmin^2}$$
$$\sigma_\epsilon^{\rm WL} = 0.37$$

Reference HLS Spectroscopy

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

50% success rate

$$n_{\rm gal}^{\rm KL} = \frac{4}{\rm arcmin^2}$$
$$\sigma_\epsilon^{\rm KL} = 0.035$$

CosmoLike Likelihood/Cov Settings

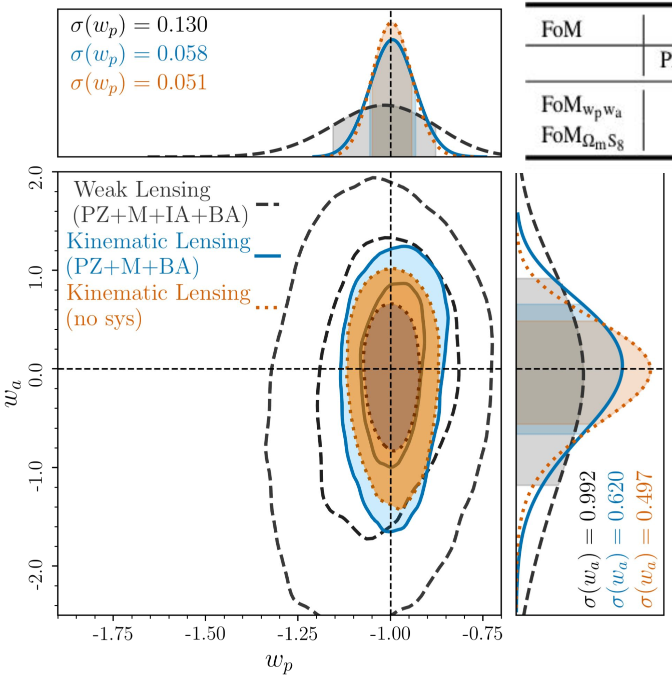
- Observable: shear-shear power spectrum $C^{ij}_{\kappa\kappa}(\ell)$ (20 log bins from $30 \leq \ell \leq 4000$)
- Covariance matrix: Gaussian + non-Gaussian + super-sample covariance, $\Omega_{\rm s} = 2000\,\mathrm{deg}^2$
- Cosmological parameters sampled: $\{\Omega_{\rm m},\ \sigma_8,\ n_s,\ w_0,\ w_a,\ \Omega_b,\ h\}$
- Systematics modeling

	Systematic Parameters	WL		KL	
		Fiducial	Prior	Fiducial	Prior
Photo-z uncertainty (PZ)	$\Delta^i_{\rm z,src}$	0.0	$\mathcal{N}(0, 2\mathrm{e}{-3})$	0.0	$\mathcal{N}(0, 4\mathrm{e}{-4})$
	$\sigma^i_{\rm z,src}$	0.01	$\mathcal{N}(0.01, 2\mathrm{e}{-3})$	0.002	$\mathcal{N}(0.002, 4\mathrm{e}{-4})$
Shear calibration bias (M)	m^i	0.0	$\mathcal{N}(0, 2\mathrm{e}{-3})$	0.0	$\mathcal{N}(0, 4\mathrm{e}{-4})$
Intrinsic alignment (IA)	$A_{\rm IA}$	5.92	$\mathcal{N}$(5.92,3.0)	-	-
	$\beta_{\rm IA}$	1.1	$\mathcal{N}$(1.1,1.2)	-	-
	$\eta_{\rm IA}$	-0.47	$\mathcal{N}$(-0.47,3.8)	-	-
	$\eta_{\rm IA}^{\rm high-z}$	0.0	$\mathcal{N}$(0.0,2.0)	-	-
Baryon effects (BA)	Q_1	0.0	$\mathcal{N}$(0.0,16.0)	0.0	$\mathcal{N}$(0.0,16.0)
	Q_2	0.0	$\mathcal{N}$(0.0,2.0)	0.0	$\mathcal{N}$(0.0,2.0)
	Q_3	0.0	$\mathcal{N}$(0.0,0.8)	0.0	$\mathcal{N}$(0.0,0.8)

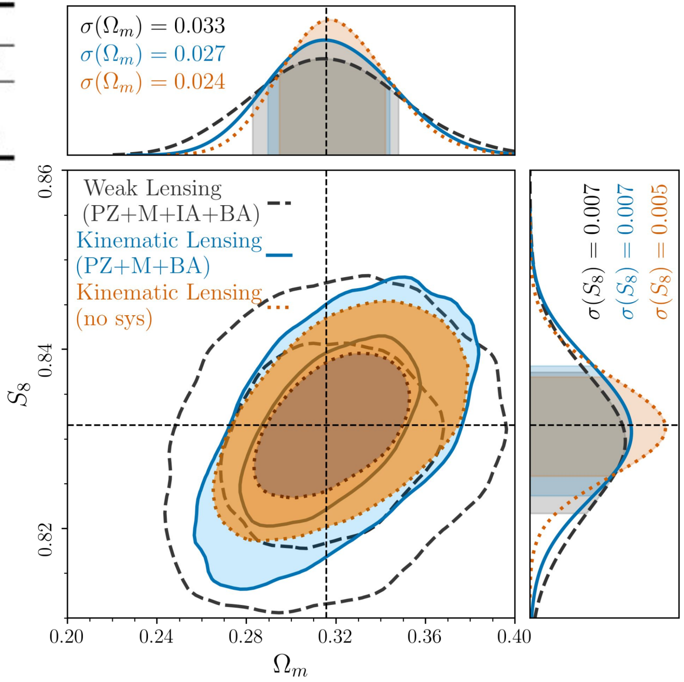
Similar to the *Roman Space Telescope* x Rubin Observatory (Eifler et al. 2021)

Forecast results: WL v.s. KL

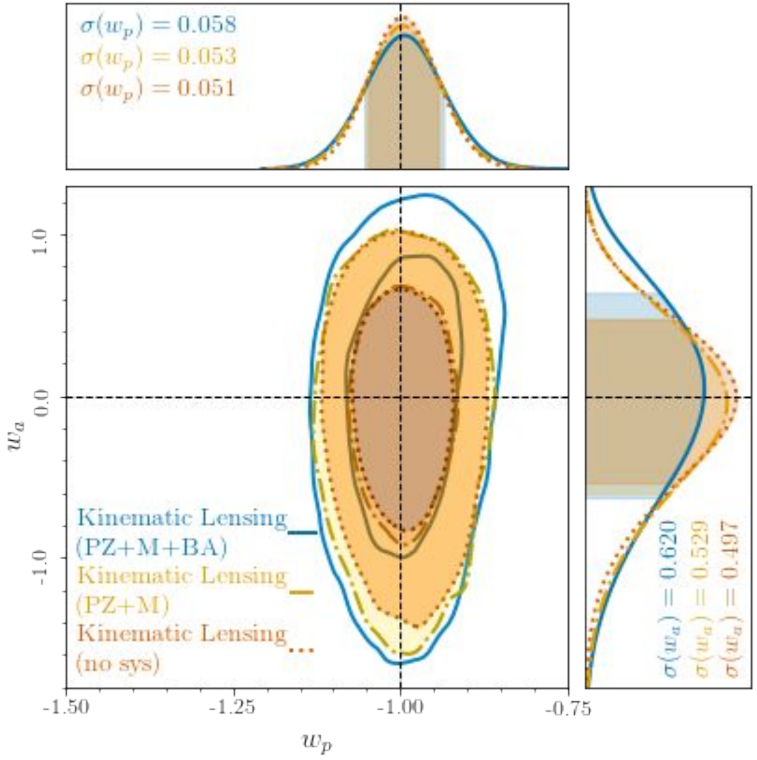
- Figure-of-Merit: 3.65x enhancement in $w_\mathrm{p} - w_a$ 1.70x enhancement in $\Omega_\mathrm{m} - S_8$



FoM	WL	KL(N_{tomo} = 10)		
	PZ+M+IA+BA	PZ+M+BA	PZ+M	no sys
$\mathrm{FoM}_{\mathrm{w_p w_a}}$	10.55	38.51	47.85	59.58
$\mathrm{FoM}_{\Omega_\mathrm{m} \mathrm{S_8}}$	5307	9017	11533	13543



Forecast results: impact of systematics



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

FoM	WL	KL($N_{\rm tomo}$ = 10)		
	PZ+M+IA+BA	PZ+M+BA	PZ+M	no sys
$\mathrm{FoM}_{\mathrm{w_p w_a}}$	10.55	38.51	47.85	59.58
$\mathrm{FoM}_{\Omega_m S_8}$	5307	9017	11533	13543

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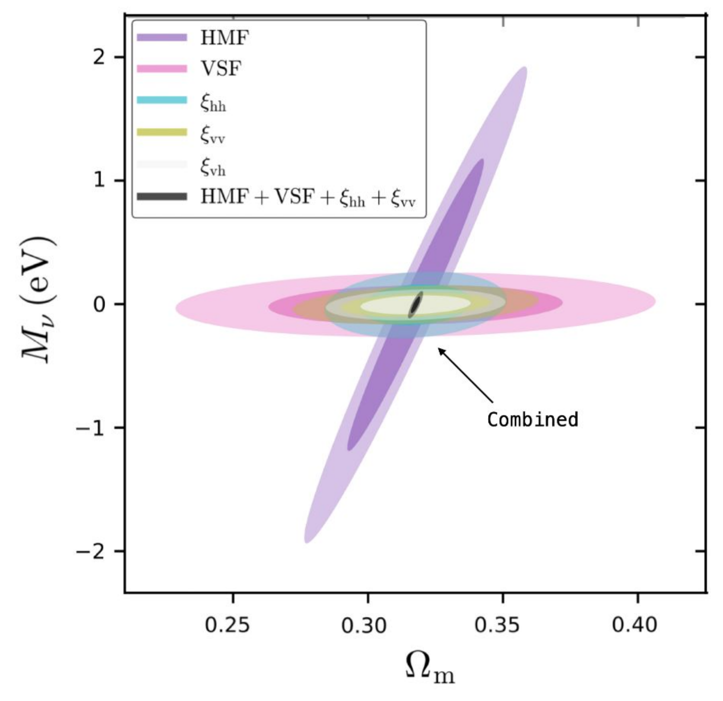
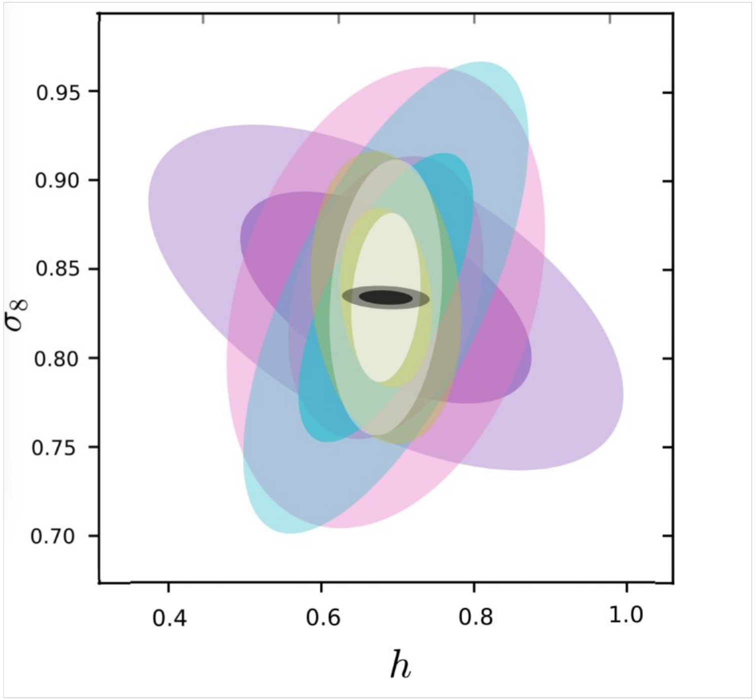
Topic 3: Roman voids for cosmology

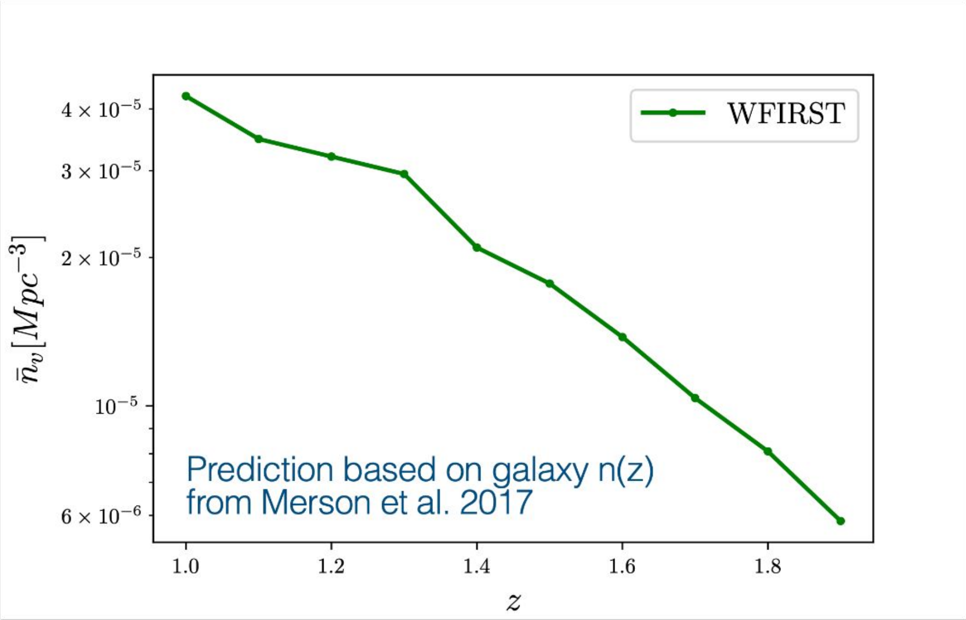
Voids have a strong sensitivity to cosmology
(Dark energy, massive neutrinos, growth of structure)

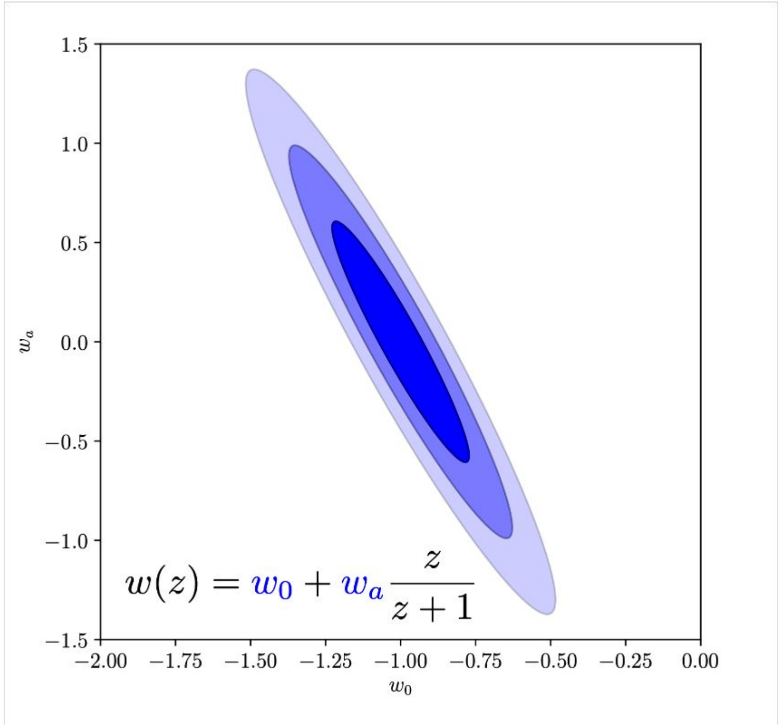




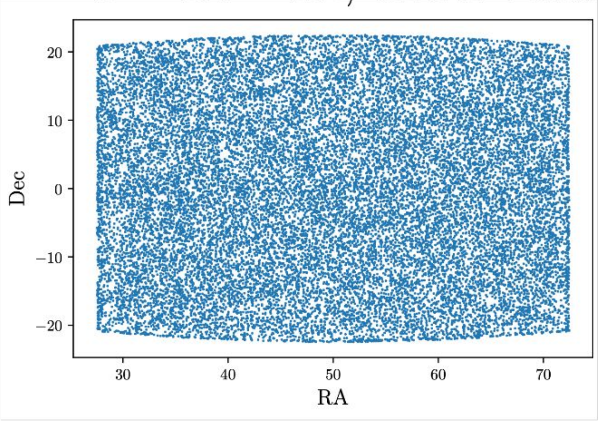
Kreisch, Pisani, Villaescusa-Navarro, Spergel, Wandelt, Hamaus and Bayer ArXiv: 2107.02304

Roman will provide access to a unique set of cosmic voids.

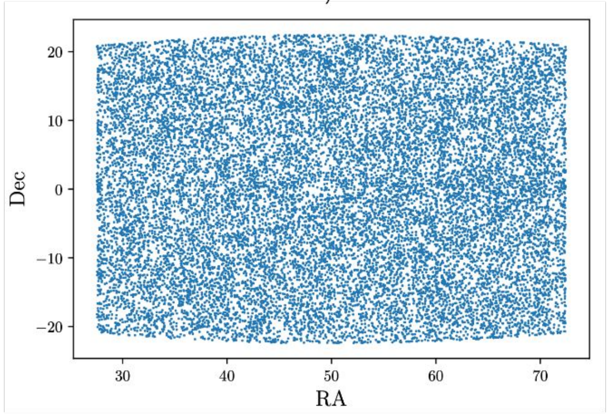




$z = 1.0 - 1.2;\ 31421$ voids



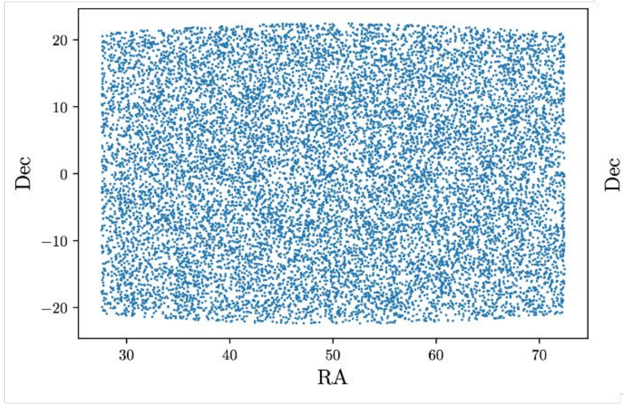
$z = 1.2 - 1.4;\ 24907$ voids



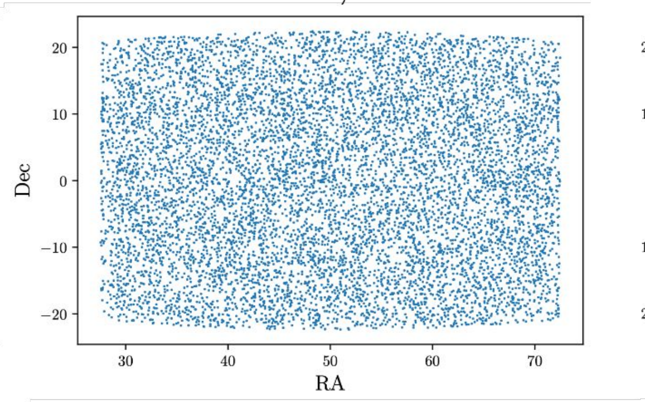
Roman voids

~ 100000 voids!

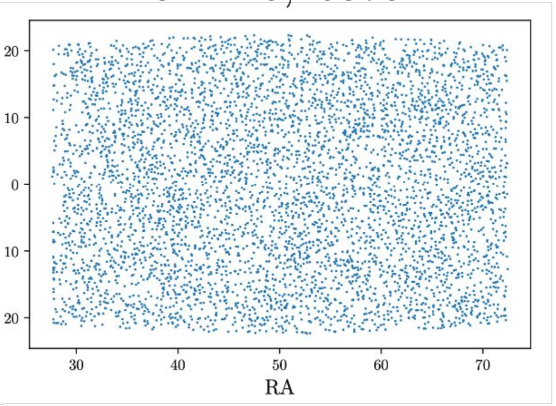
$z = 1.4 - 1.6;\ 18258$ voids



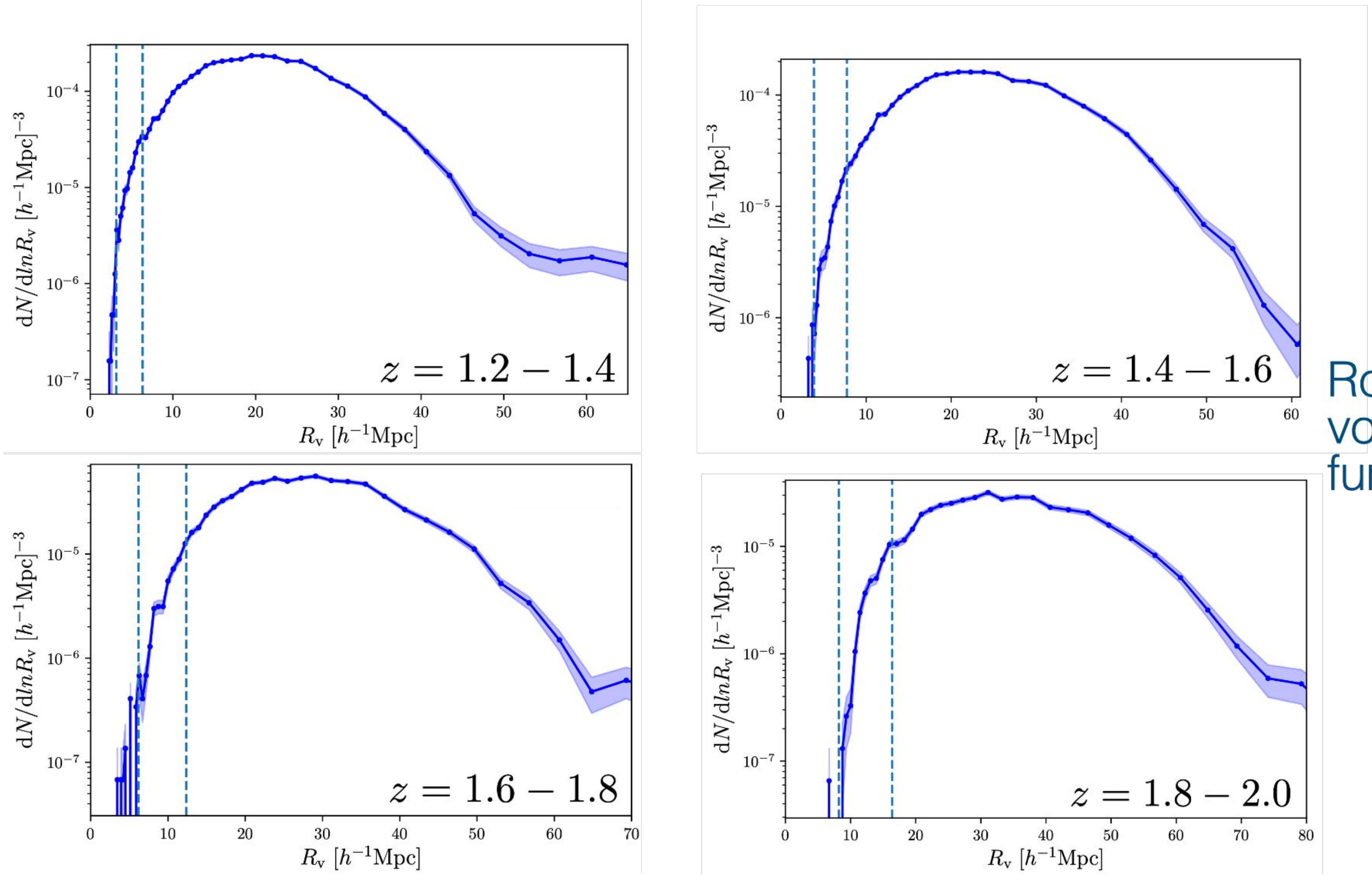
$z = 1.6 - 1.8;\ 12187$ voids



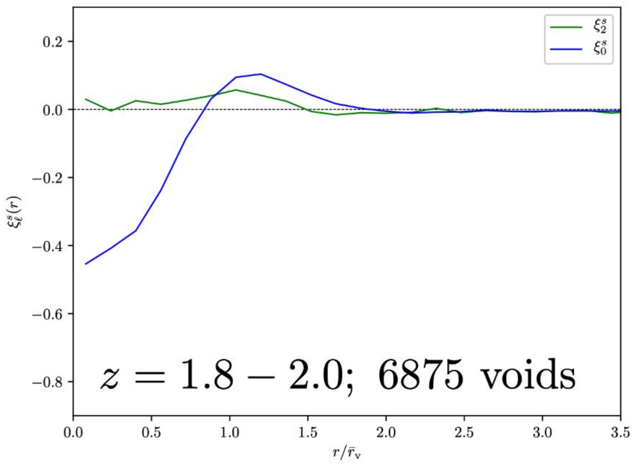
$z = 1.8 - 2.0;\ 6875$ voids



Based on HLSS galaxy mock (Zhai, Chuang, Wang, Benson and Yepes 2021, MNRAS, ArXiv: 2008.09746)

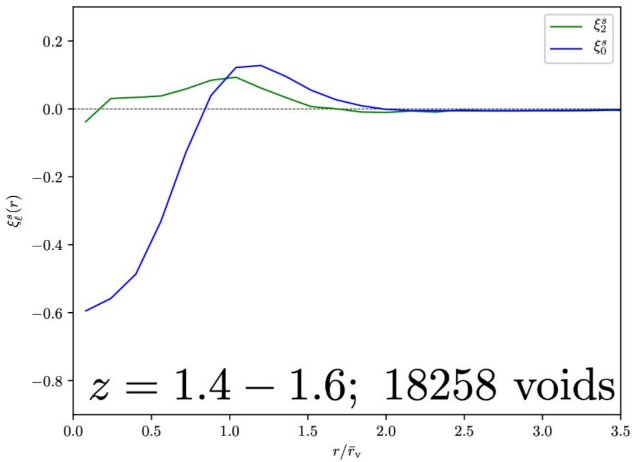


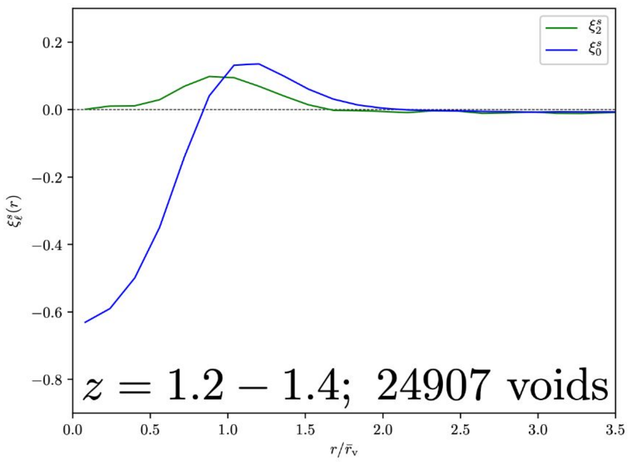
Roman void size function



Monopole and quadrupole of the void-galaxy cross-correlation function

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





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