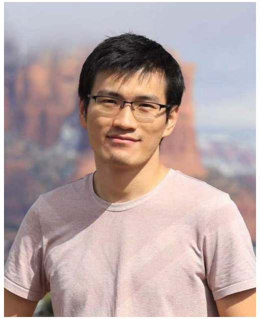
Kinematic Lensing

Developing a science case for the Roman Space Telescope

KL team - get involved!



Jiachuan Xu
Xu et al. (in prep)

Pranjal RS

Xiao Fang

Hung-Jin Huang

Maggie Smith

Eric Huff

Elisabeth Krause

Tim Eifler

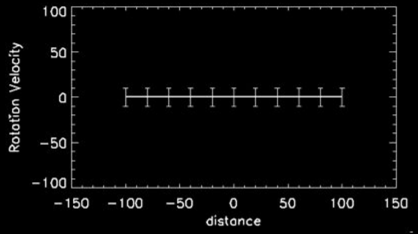
Spencer Everett

Yu-Hsiu Huang

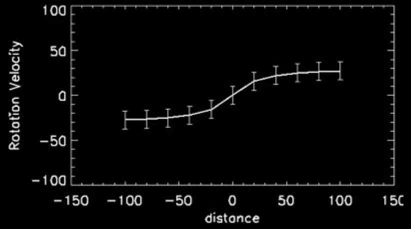
KL basics

image | **rotation curve**

face-on, but sheared

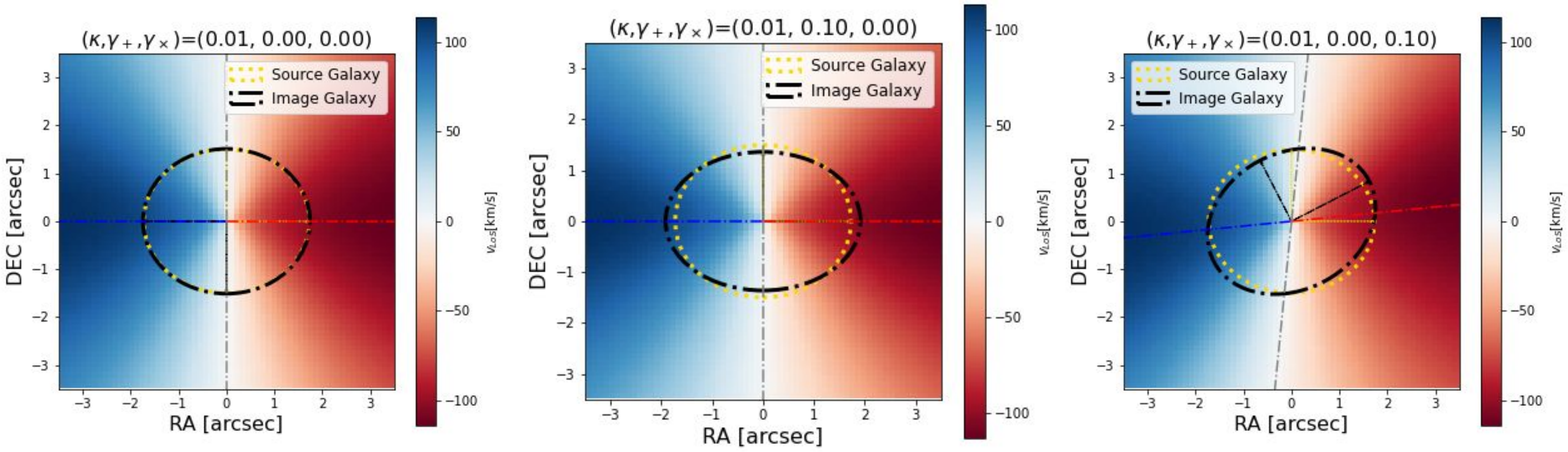


inclined, but not sheared



Kinematic Lensing breaks the degeneracy between inclination and ellipticity

Effect of shear on kinematic observables



original

γ_+ : degenerate with inclination

$\gamma_\times$: rotate shape and velocity

For technical details of the estimator please see [Huff et al (2013)] or [Xu et al. (in prep)]

KL effort - big picture projects overview

- Measurement and modeling pipeline - goal first measurement on Keck/HST/KMOS data
  - Keck slit spectroscopy (largest sample, limited signal in slit data)
  - HST Grism spectroscopy (higher spatial resolution, lower spectral resolution)
  - KMOS Integral field data (smaller sample, high spatial/spectral resolution)
- Roman Space Telescope feasibility study and science forecasts
  - Model KL Roman galaxy sample, redshift distribution and shape noise
  - Simulated analyses of Roman core science cases and integration of KL into multi-probe
- Accurate simulations accounting for complexity of real systems from Illustris TNG

Modeling Kinematic Lensing

- As a proof of concept we need to test KL on realistic data
- The best data we have is from long slit spectroscopy (Keck/HST)
- We have built a forward model that utilises KL to infer the shear
- We test our model on realistic mock data that include effects such as sky emission, atmospheric transmission, PSF convolution, etc
- The methodology can then be extended to other types of data eg., grism data from Roman

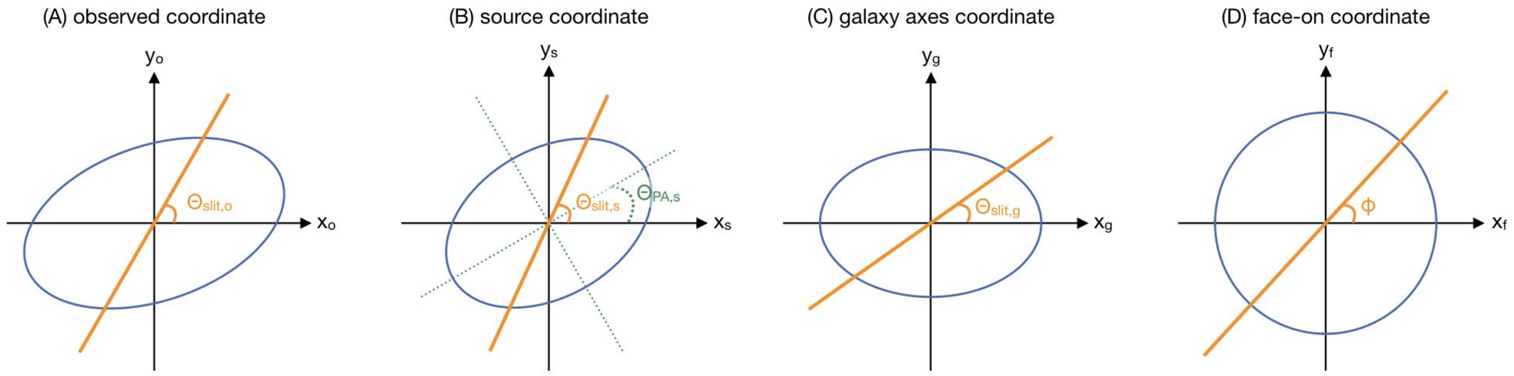
2D Forward Model

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

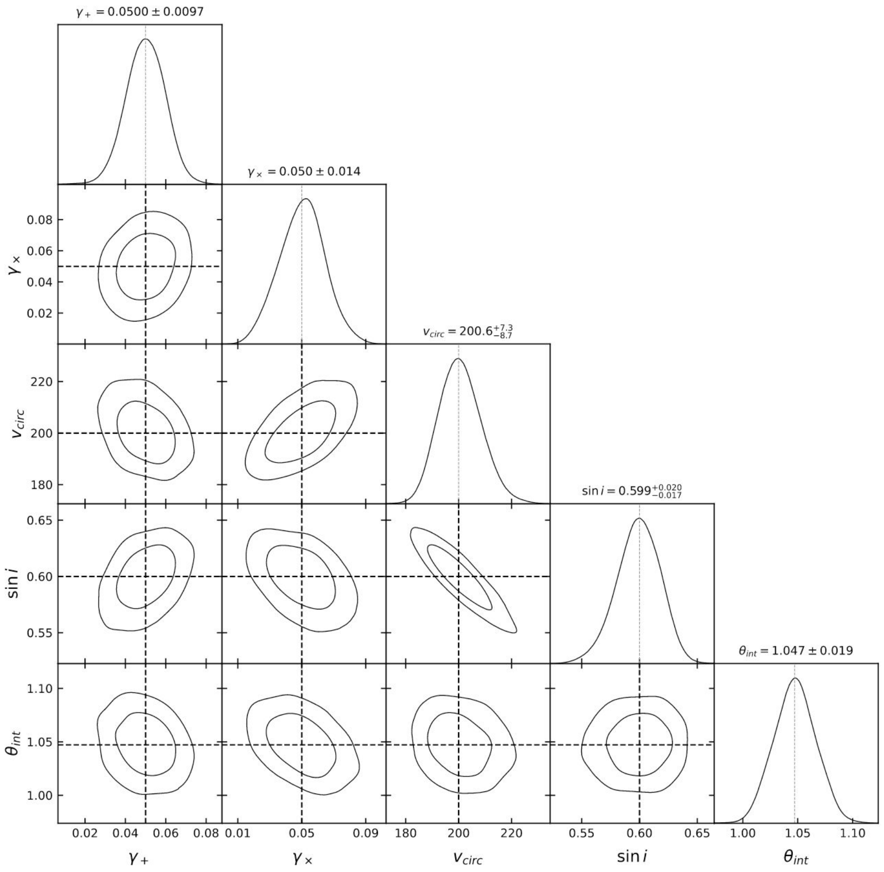
- Spectrum model
  - Model the slit as a 2D grid
  - Apply coordinate transformations to account for the effects of shear, intrinsic galaxy position angle and inclination
  - arc tan velocity field
  - Tully-Fisher prior on maximum circular velcoity

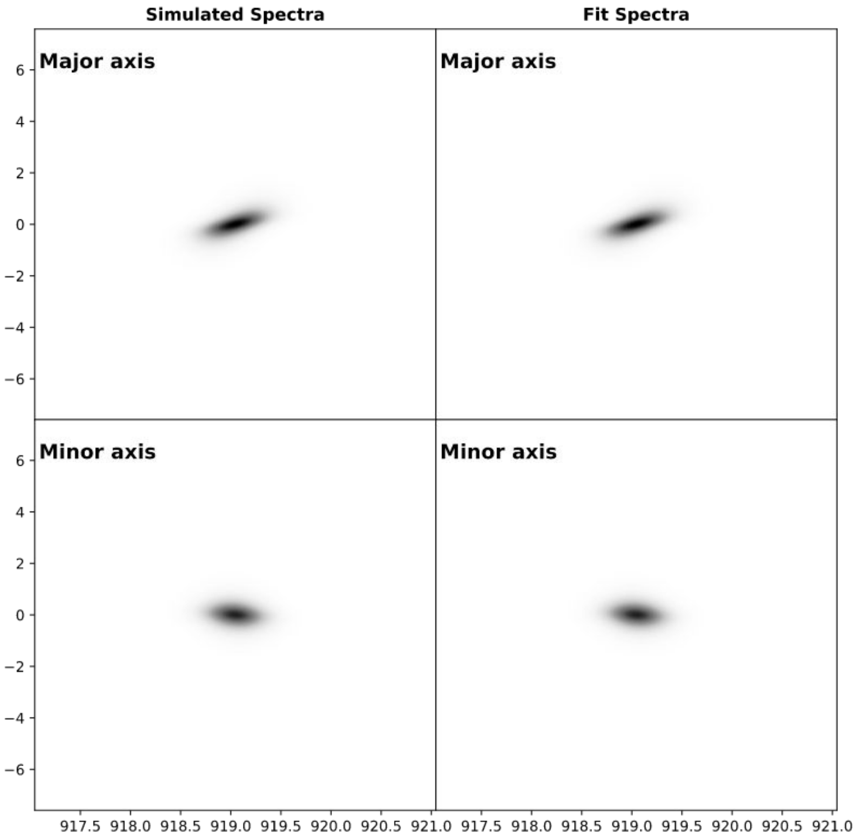
Table 1. Fit parameters

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	$\mathcal{U}(-\pi/2, \pi/2)$

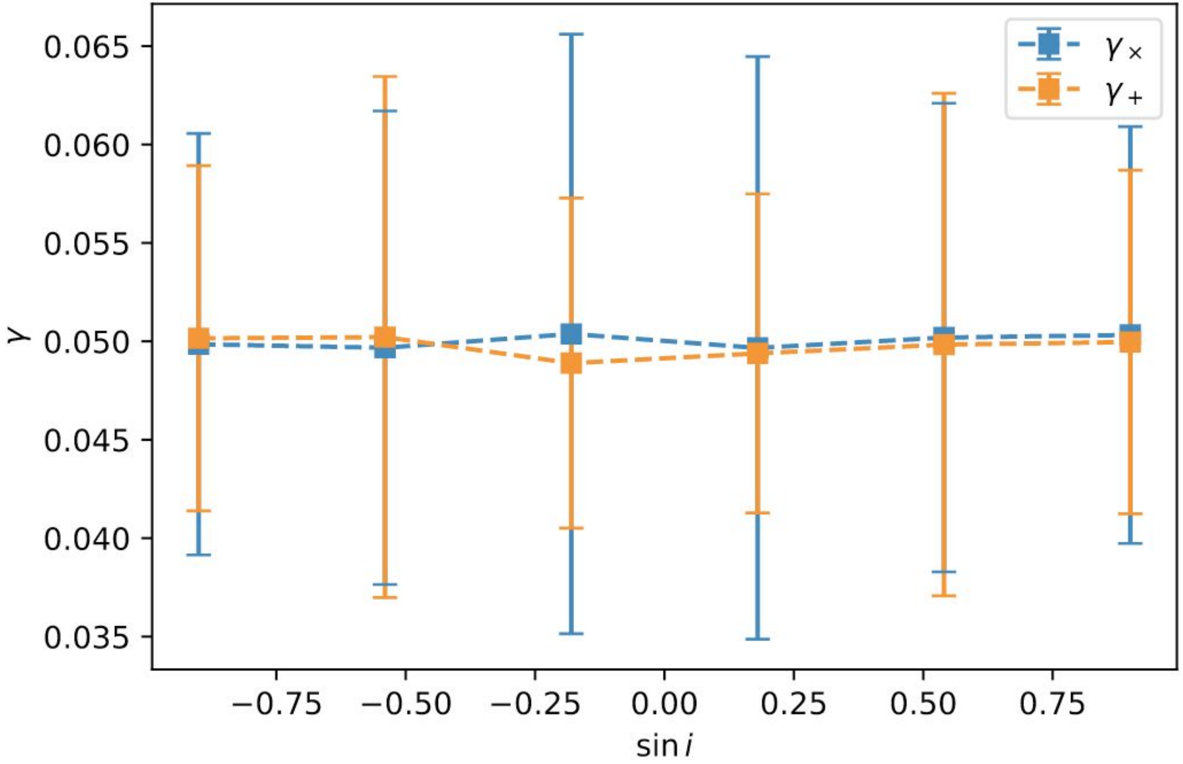


Results: 2D Forward Model





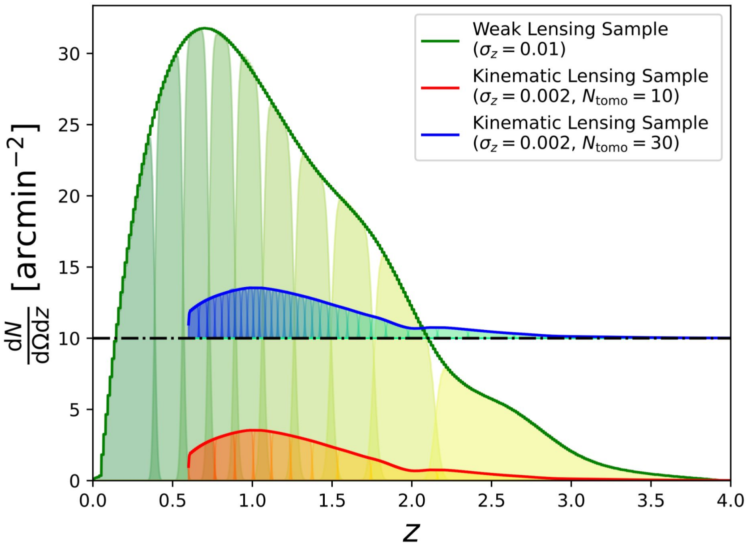
Shear Constraints vs. Galaxy Properties



Forecasting KL performance with *Roman*

- Defining the KL sample
  - Key sample parameters: number density and shape noise
- Likelihood modeling
- Forecast results:
  - Kinematic lensing v.s. standard weak lensing
  - Impact of systematics
  - Impact of narrow tomography

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 $\rm H_\alpha$, $\rm H_\beta$ 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

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

Defining the KL sample: number density

- We also validate source galaxy number density via multiple methods:
  - EL-COSMOS Catalog (Saito et al. 2020):
    - Based on COSMOS2015 catalog
    - More physical emission line modeling
    - w/o grism spectra failure rate
  - Galacticus + CLOUDY (Zhai et al. 2019):
    - Based on semi-analytic models
    - w/o grism spectra failure rate
  - *Roman* AFTA 2015 (Spergel et al. 2015):
    - Based on luminosity function
    - Outdated grism response
    - w/ observation inefficiencies

EL-COSMOS: $n_{\mathrm{gal}} = \frac{12}{\mathrm{arcmin}^2}$

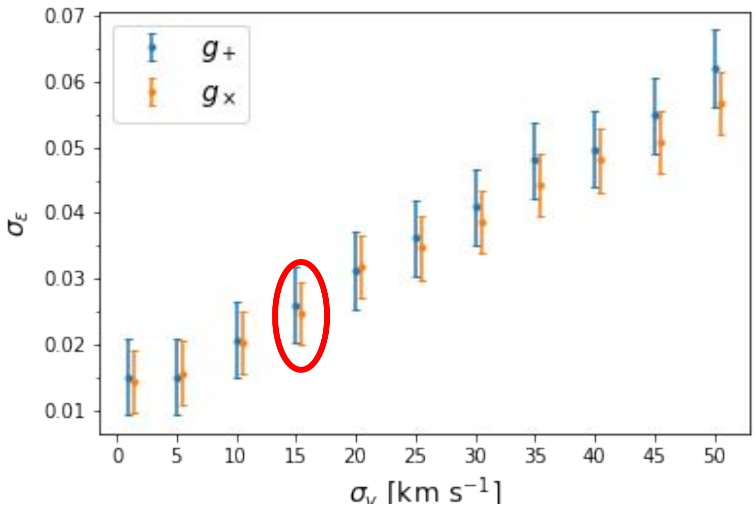
Galacticus + CLOUDY: $n_{\mathrm{gal}} = \frac{4.14}{\mathrm{arcmin}^2}$

average $\longrightarrow$ $\langle n_{\mathrm{gal}} \rangle \approx \frac{8}{\mathrm{arcmin}^2}$

Roman AFTA 2015: $n_{\mathrm{gal}} = \frac{2.25}{\mathrm{arcmin}^2}$ new grism response $\longrightarrow$ $\langle n_{\mathrm{gal}} \rangle \approx \frac{3.63}{\mathrm{arcmin}^2}$

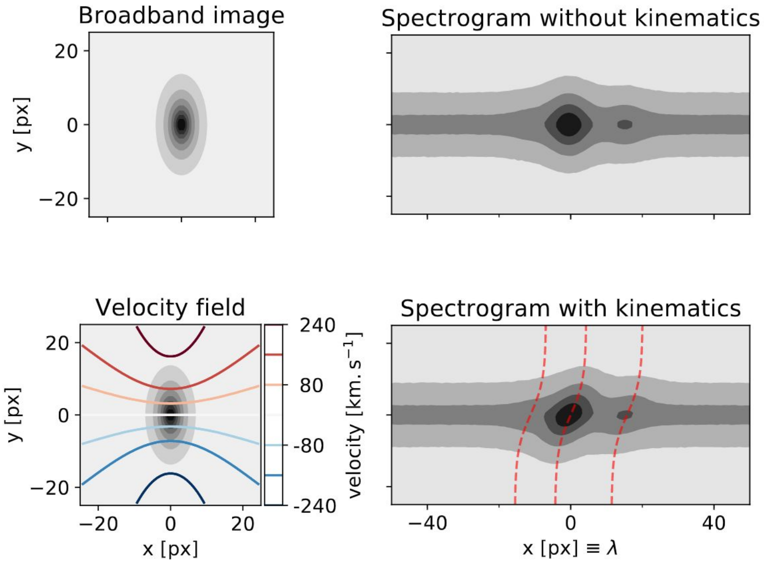
Defining the KL sample: shape noise

- Toy model validation:
  - Data vector: $(\epsilon_1, \epsilon_2, v_{\rm major}, v_{\rm minor}, M_{\rm B})$
  - For every item in a random ensemble, derive maximum-likelihood shear estimate, and its variance σ_g^2 from Fisher matrix
  - Derive shape noise as ensemble std of MLE shear estimates, weighted by σ_g^{-2}
  - $\sigma_\epsilon \approx 0.035$ when $\sigma_v \approx 15\,{\rm km\,s^{-1}}$
- Can *Roman* grism measure disk kinematics with $\sigma_v \approx 15\,{\rm km\,s^{-1}}$?



Can *Roman* grism measure disk kinematics?

- HST/WFC3-Grism (3x worse than the *Roman Space Telescope* Grism) recovers rotation velocities with a precision of $\sigma_v = 15 - 30\,\mathrm{km\,s^{-1}}$



Galaxy	GLASS #1134	GLASS #399
Cluster / field	MACS1423	MACS0717
M_{F140W}	20.8	20.8
Grism	G102	G141
Emission lines	Hα	[O III] ×2 rolls
R_{kin} (km s^{-1} px^{-1})	700	1000
PA (1)	4.6 ± 0.4	52.2 ± 0.4
z_{HST} (2)	0.55000 ± 0.00465	1.68700 ± 0.00806
$z_{\mathrm{no-kin}}$ (3)	0.55237 ± 0.00016	1.69088 ± 0.00025
z_{kin} (4)	0.55201 ± 0.00002	1.69175 ± 0.00006
$v_0 \sin i$ (5)	205 ± 28	287 ± 15
$w_0 \sin i$ (6)	242 ± 28	605 ± 32
$A_{\mathrm{H}\alpha}$ (7)	55.7 ± 2.9	–
$A_{\mathrm{O\,III}}$ (7)	–	96.9 ± 1.5
σ (8)	2.96 ± 0.15	6.38 ± 0.09
η (9)	1.014 ± 0.012	1.048 ± 0.005
z-score (10)	12.7	25.5

Outini & Copin (2020)

CosmoLike Likelihood/Cov Settings

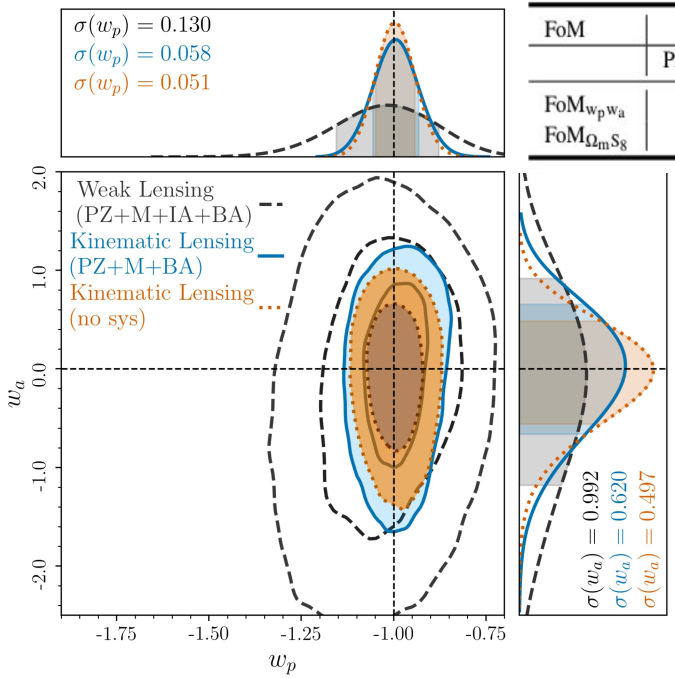
- Observable: shear-shear power spectrum $C^{ij}_{\kappa\kappa}(\ell)$ (20 log bins from $30 \leq \ell \leq 4000$)
- Covariance matrix: Gaussian + non-Gaussian + super-sample covariance, $\Omega_\mathrm{s} = 2000\,\mathrm{deg}^2$
- Cosmological parameters sampled: $\{\Omega_\mathrm{m},\ \sigma_8,\ n_s,\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

	Systematic Parameters	WL		KL	
		Fiducial	Prior	Fiducial	Prior
Photo-z uncertainty (PZ)	$\Delta^i_{\mathrm{z,src}}$	0.0	$\mathcal{N}(0, 2\mathrm{e}{-3})$	0.0	$\mathcal{N}(0, 4\mathrm{e}{-4})$
	$\sigma^i_{\mathrm{z,src}}$	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_{IA}	5.92	$\mathcal{N}(5.92,3.0)$	-	-
	β_{IA}	1.1	$\mathcal{N}(1.1,1.2)$	-	-
	η_{IA}	-0.47	$\mathcal{N}(-0.47,3.8)$	-	-
	$\eta^{\mathrm{high-z}}_{\mathrm{IA}}$	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	$\mathcal{N}(0.0,0.8)$

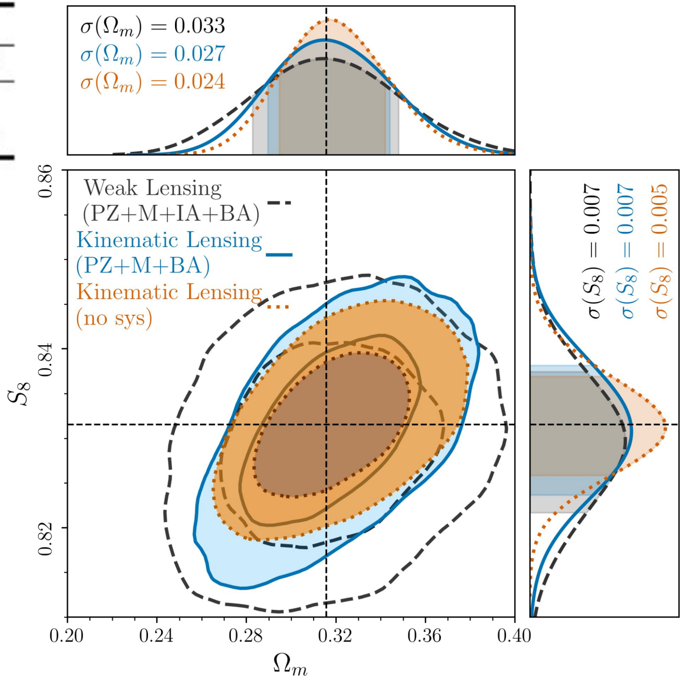
Similar to the *Roman Space Telescope* x Rubin Observatory (Eifler et al. 2021)

Forecast results: WL v.s. KL

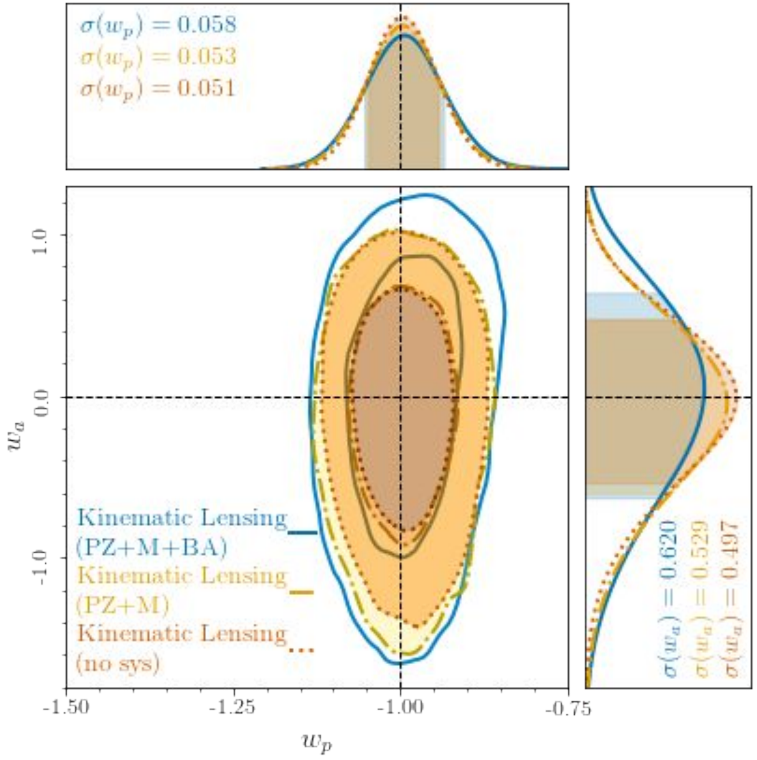
- Figure-of-Merit: 3.65x enhancement in $w_\mathrm{p} - w_a$ 1.70x enhancement in $\Omega_\mathrm{m} - S_8$



FoM	WL	KL(N_tomo = 10)		
	PZ+M+IA+BA	PZ+M+BA	PZ+M	no sys
$\mathrm{FoM}_{w_\mathrm{p}w_\mathrm{a}}$	10.55	38.51	47.85	59.58
$\mathrm{FoM}_{\Omega_\mathrm{m}S_8}$	5307	9017	11533	13543



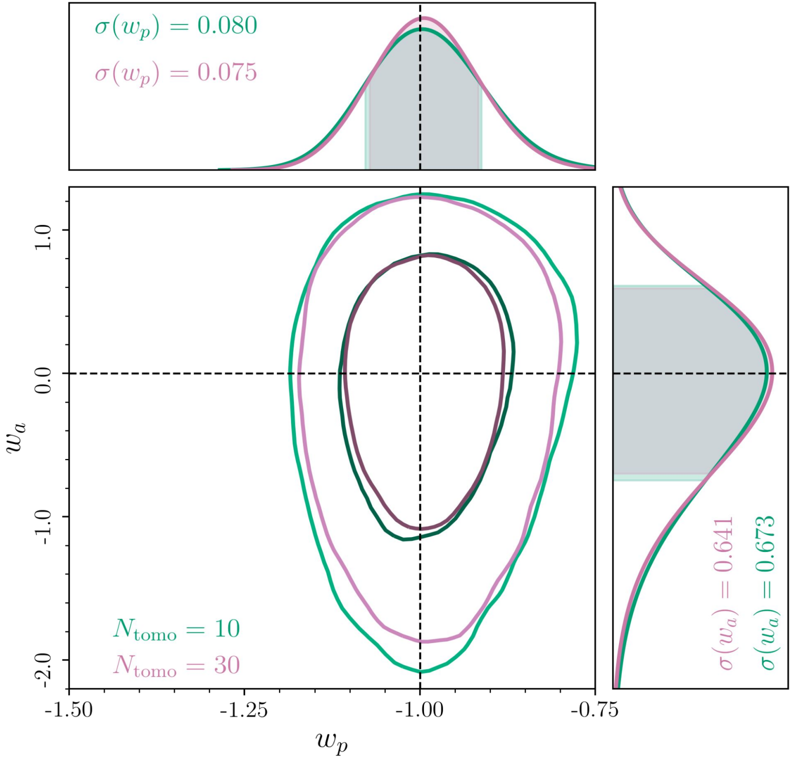
Forecast results: impact of systematics



- 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
$\mathrm{FoM}_{w_p w_a}$	10.55	38.51	47.85	59.58
$\mathrm{FoM}_{\Omega_m S_8}$	5307	9017	11533	13543

Forecast results: narrow tomography KL measurement

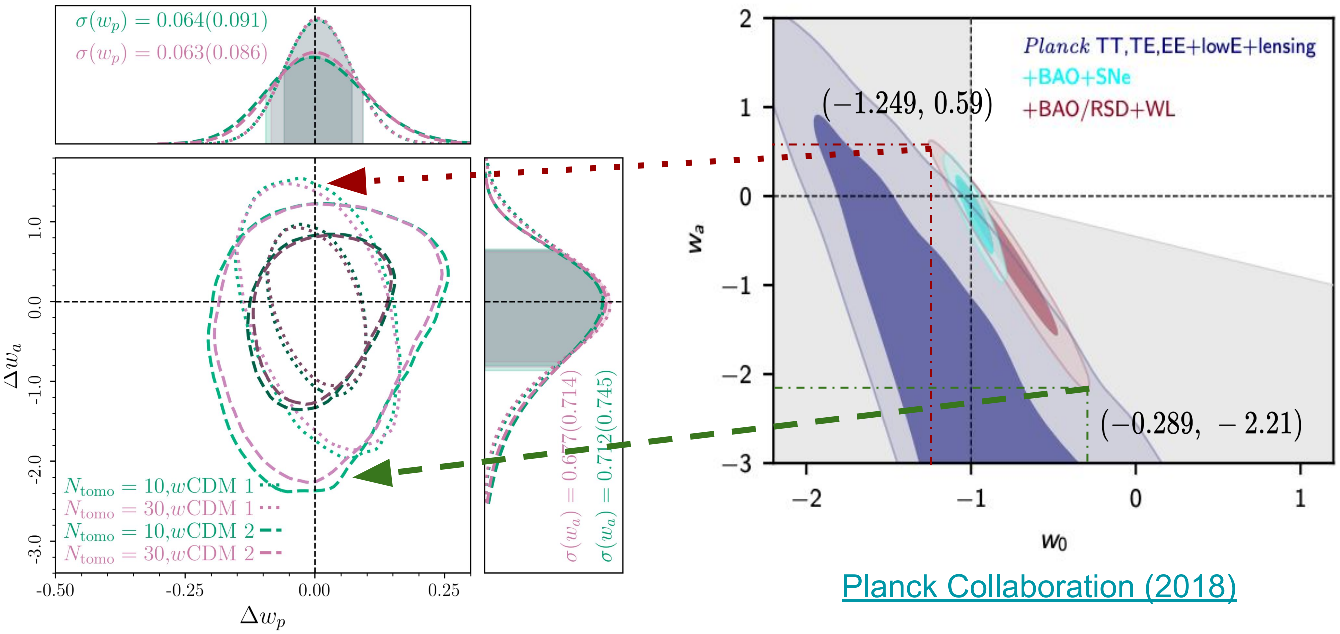


- Question: Is there more information when we have more narrow tomography bins?

  Almost no...

Forecast results: narrow tomography KL measurement

- Question: Is there more information when we have more narrow tomography bins? No…
- Question: If dark energy evolves with time, does more information come from more bins?



Planck Collaboration (2018)

Summary of forecasting KL performance with *Roman*

- The *Roman Space Telescope* is likely to measure disk kinematic of emission line galaxies with $\sigma_v \approx 15\,\mathrm{km\,s^{-1}}$, which translates to a shape noise of $\sigma_\epsilon \approx 0.035$Assuming overlapping HLIS and HLSS sample, the KL sample has $n_{\rm gal} = 4\,\mathrm{arcmin}^{-2}$with observational inefficiencies accounted.
- Considering shear-shear power spectrum only, KL can enhance the FoM on $w_0 - w_a$ by more than 2x, and the FoM on $\Omega_{\rm m} - S_8$by $\sim 70\%$
- We find more narrow tomography bins will not increase the FoM on $w_0 - w_a$even when assuming upper limits of currently allowed time-dependent dark energy as the true model
- We also derive shear estimator of KL in a pedagogical way in our paper.

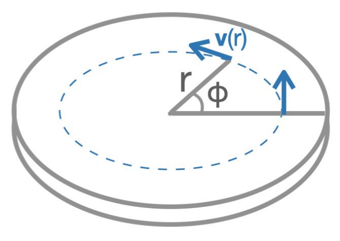
Future works:

- Extensions to 3x2pt and 6x2pt
- Interface with grism simulation pipeline to improve realism
- Explore wide *Roman* HLS scenarios: wide single-band imaging + wide grism

Exploring astrophysical uncertainties in **IllustrisTNG**

current pipeline assumptions

- Intrinsically round disk
- Smooth sersic light profile
- Cylindrical symmetric rotation curve



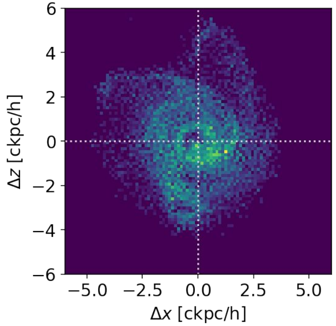
$$v(r) = v_0 + \frac{2}{\pi} v_{\rm circ} \tan^{-1}\left(\frac{r - r_0}{v_{\rm scale}}\right)$$

on-going works

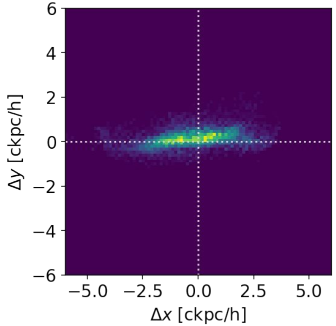
- **TNG-mock pipeline**
  Creating realistic galaxy mock images and spectra from hydro-sims
  -- Hung-Jin Huang, Maggie Smith
- **Improving data analysis pipeline**
  Increasing model complexity to account for hydro simulation-based kinematics
  -- Maggie Smith
- **New project**
  Exploring environmental dependence of TF-relation in TNG
  -- Yu-Hsiu Huang

TNG mocks -- mock spectra data from TNG galaxy kinematics

face-on view

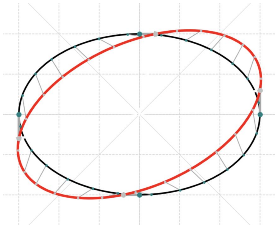


edge-on view



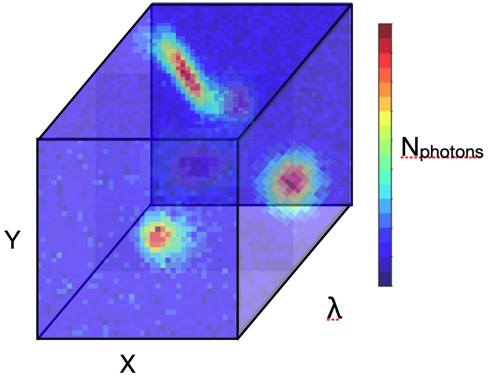
redshift : 0.3
snapshot ID: 78
subhaloID : 35

Inclination
P.A. rotation
+
sheared
(x-y plane)

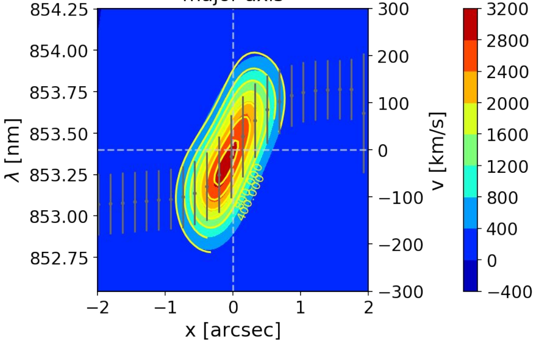


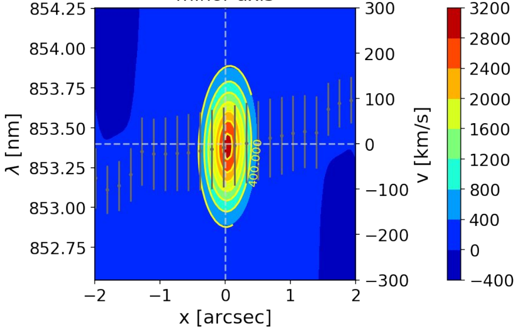
particle LOS velocity
+
weighted by
particle SFR∝ $L_{H\alpha}$
+
sky template (noise)

3D model cube

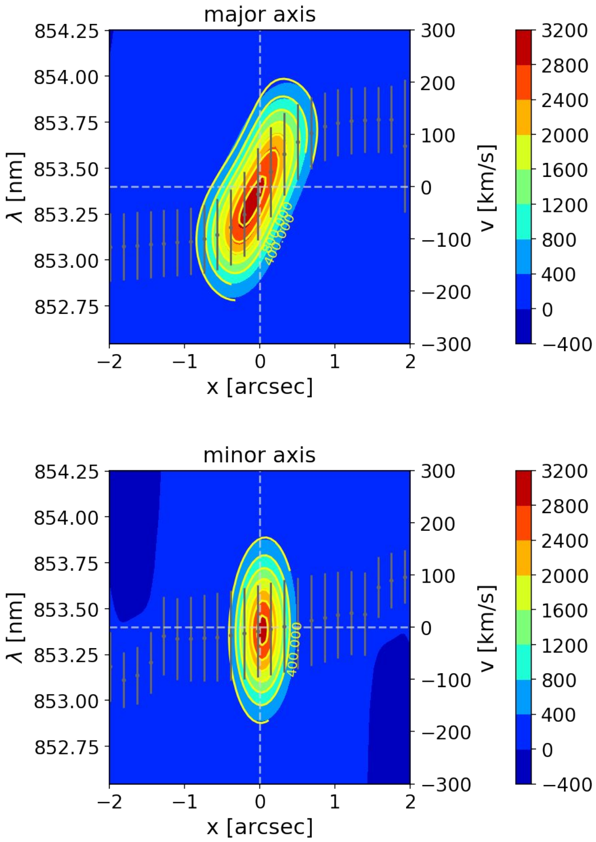


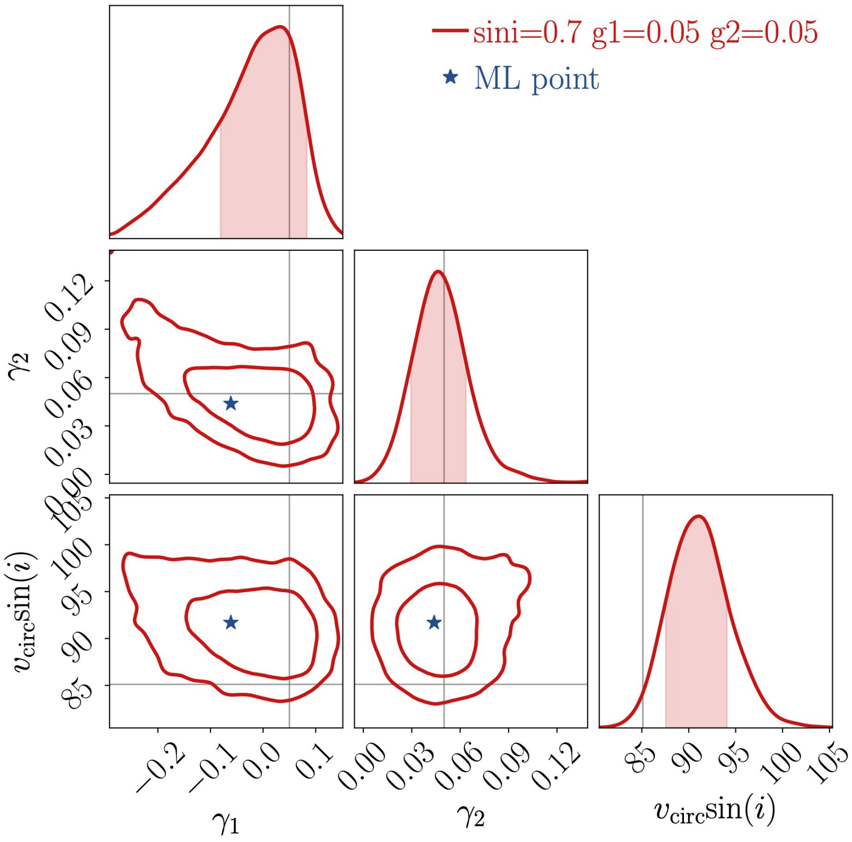
long slit spectra





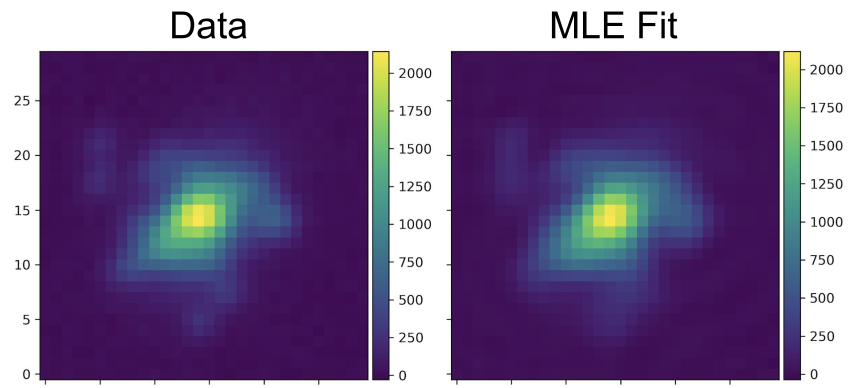
TNG mocks -- mock spectra data from TNG galaxy kinematics





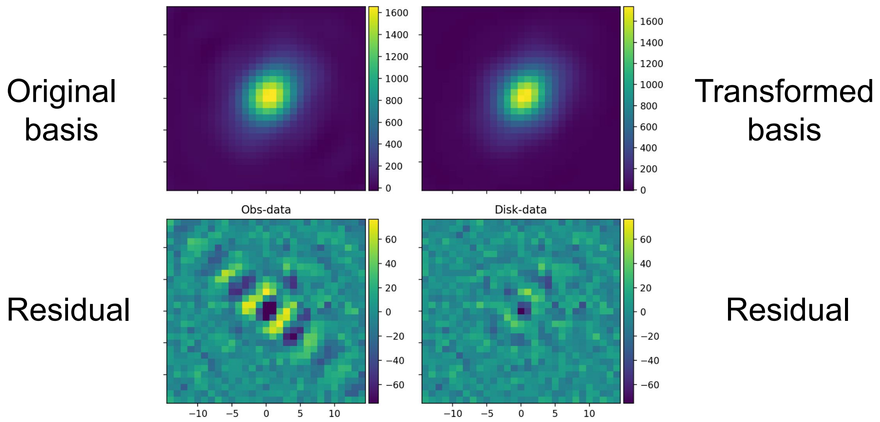
Realistic Intensity Profile Modeling - Spencer Everett

We can account for more realistic galaxy intensity profiles by using an arbitrary 2D basis, such as shapelets:



- Can quickly solve for MLE of basis coefficients given sampled g, theta_int, etc.
- Flexible intensity profile modeling without cost of marginalizing directly in sampler

Nmax=12; 91 shapelets:



Using a basis that has been ***transformed*** in an identical way as the data:

- Use sampled projection + rotation + shear
- Efficiently represents profile with less functions and up-weights profiles generated from inclined, disk-like galaxies

Discussion - Extensions to multi-probe

- 6x2 is relatively straightfwd since we can switch out the corresponding modules for the LSSTxSO with the WFIRST KL lensing routines.
- Clusters is same as above but switching WL -> KL routines in the WFIRST multi-probe paper
- Covariances for low shape noise values are likely hard
- kSZ needs to be implemented more cleanly in CosmoLike; this will require several hack days
- Very interesting to push KL to smaller scales, more narrow tomography bins, and optimizing this for non-std science cases (PCA dark energy, modified gravity, DM-DE interaction, etc)

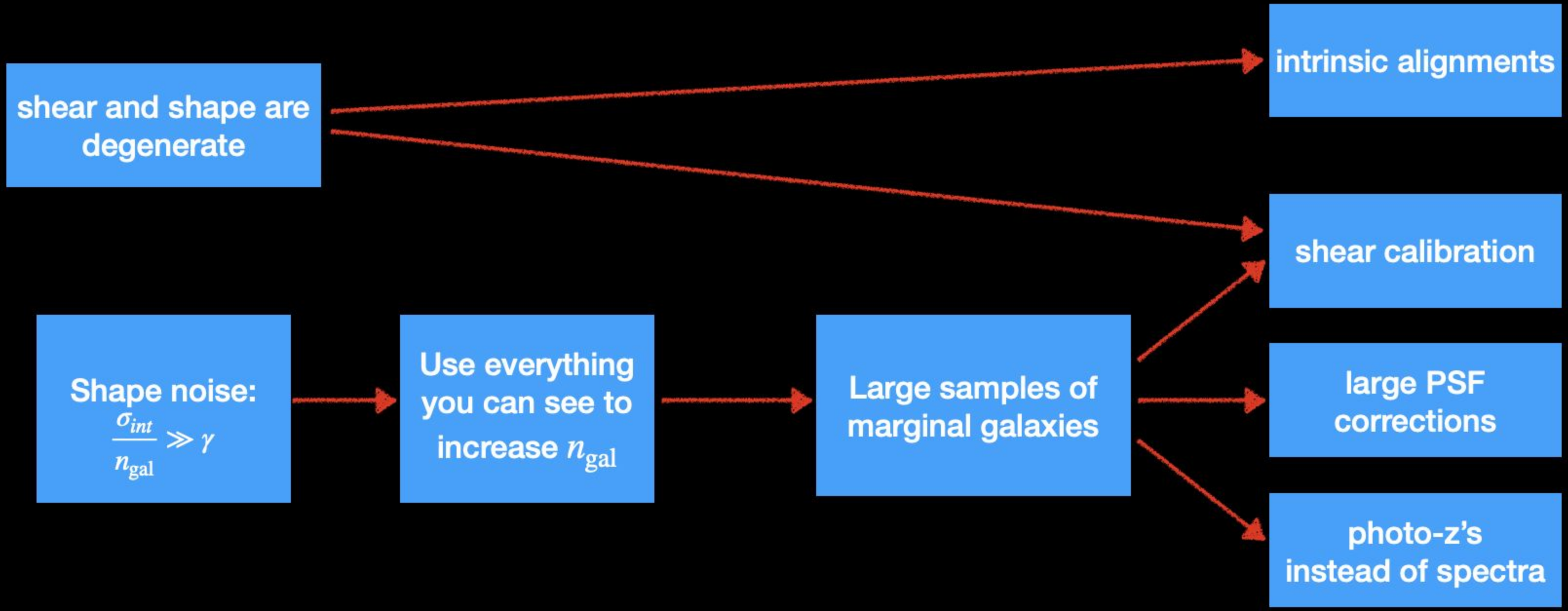
Discussion - Measurement Considerations

- Environment dependence of the TF relation
- Complex Emission line morphology, especially as compared to stellar disk
- Shear-like modes arising from tidal fields (e.g., not strictly spin-2)
- Not clear that we’ve a full accounting of observational systematics for spectroscopic lensing: sampling, spectral response, etc.
- Are there other scaling relations accessible with the same data that could improve constraints?
- Can we use lensing as our cluster mass proxy, without an additional calibrator? (Rozo)

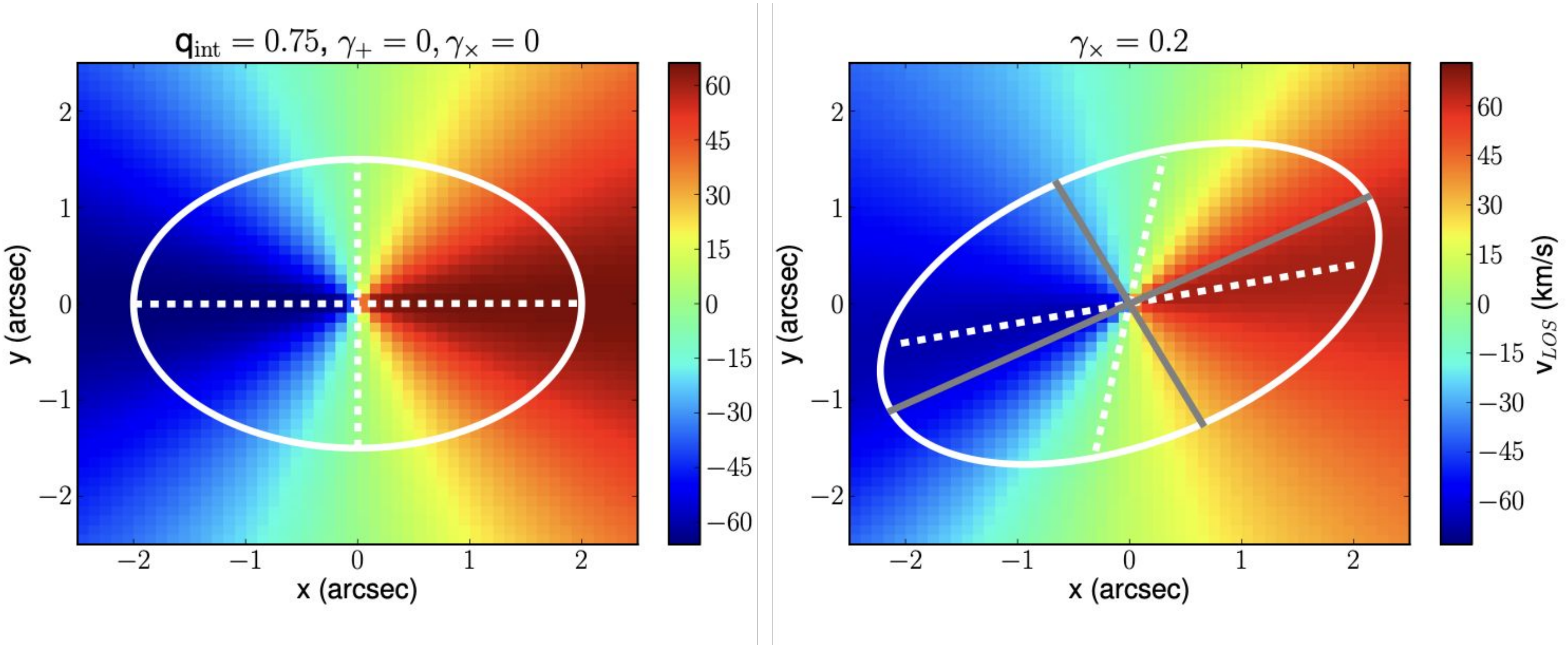
Discussion - Survey Strategy Study

- Question: What is the optimal survey strategy and implementation for WFIRST
- Some considerations:
  - Does KL benefit from 4 different bands or is a W-band survey preferable?
  - Given that we need overlapping spectroscopic info, we need to explore imaging+spectroscopy over the same area
  - How can we ensure that we get sufficiently high S/N spectra (deep survey, dither pattern, rotation of telescope) - can this be implemented in the ETC? Hard, easy?
  - Deep vs wide… what is better?
  - How could this be implemented within a WFIRST survey - HLS, GO?
  - Which strategies are useful to explore to make use of ground-space synergies? Which instruments from the ground can be used to get higher S/N spectra, e.g. for calibration (PFS, DESI+, dedicated Keck program,...) ?

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



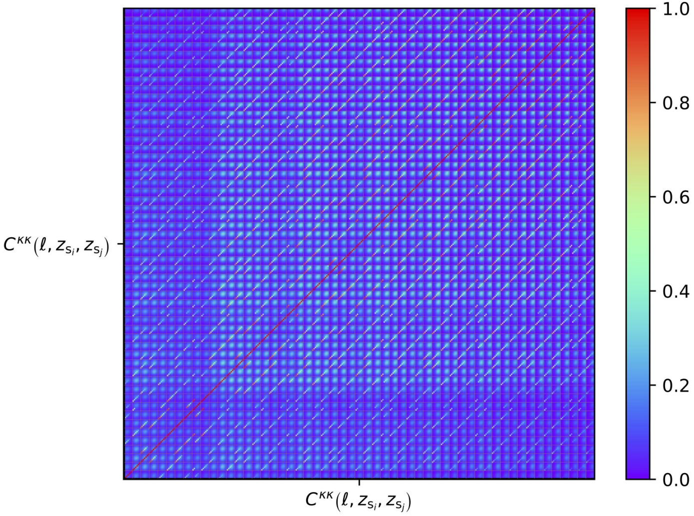
Effect of shear on kinematic observables



For technical details of the estimator please see [Huff et al (2013)] or [Xu et al. (in prep)]

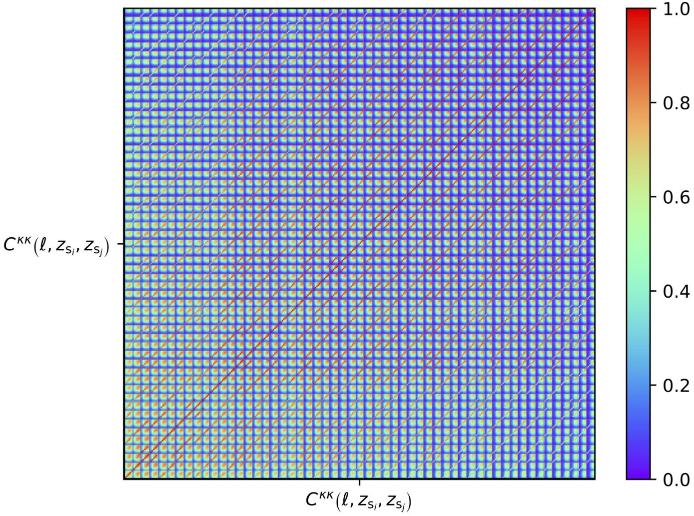
Covariance Matrix

Standard Covariance as in WFIRST WL multi-probe paper



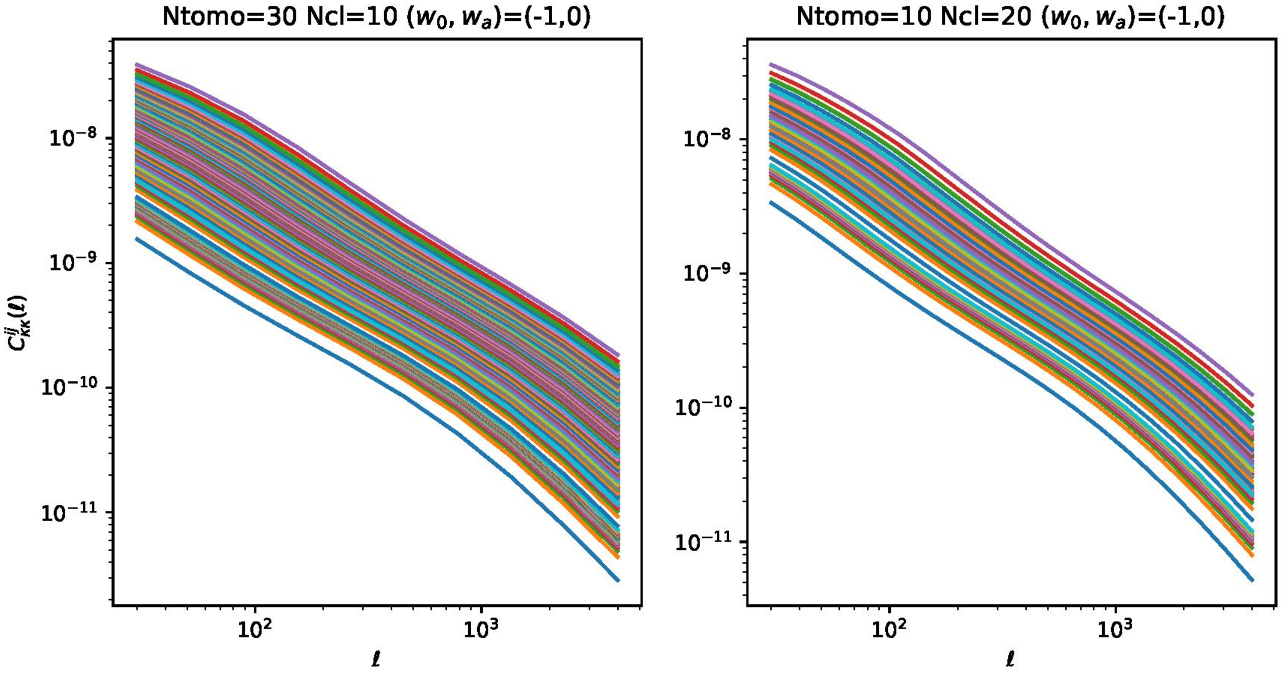
Weak Lensing
(1100 data points)

Lower shape noise on the diagonal causes off-diagonal elements to be more important



Kinematic Lensing
(1100 data points)

Smooth Angular Power Spectra



Summary

- The Roman Space Telescope is likely to measure disk kinematic of emission line galaxies with an accuracy of ~ tens of km/s, which translates to a shape noise of $\sigma_\epsilon \leq 0.05$
- Assuming overlapping HLIS and HLSS, the KL sample has $n_{\rm gal} = 8\,{\rm arcmin}^{-2}$
- Considering shear-shear power spectrum only, KL can enhance the FoM on $w_0 - w_a$ by more than 2x, and the FoM on $\Omega_{\rm m} - S_8$ by $\sim 70\%$
- We find more narrow tomography bins will not increase the FoM on $w_0 - w_a$, even when assuming upper limits of currently allowed time-dependent dark energy as the true model
- Future work:
  - Extension to 3x2pt and 6x2pt
  - Explore wide Roman HLS survey scenarios: wide single-band imaging + wide Grism?
  - Interface with the KL measurement simulation pipeline to further improve the accuracy of Roman Space Telescope KL forecasts