Weak Lensing Without Shape Noise

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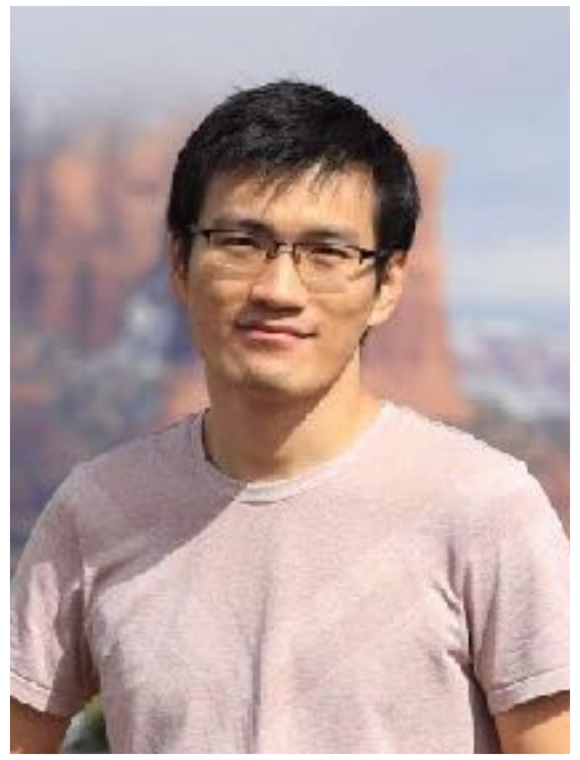
Xu et al. 2201.00739, RS et al. 2209.11811

Kinematic Lensing Team (UArizona, JPL)



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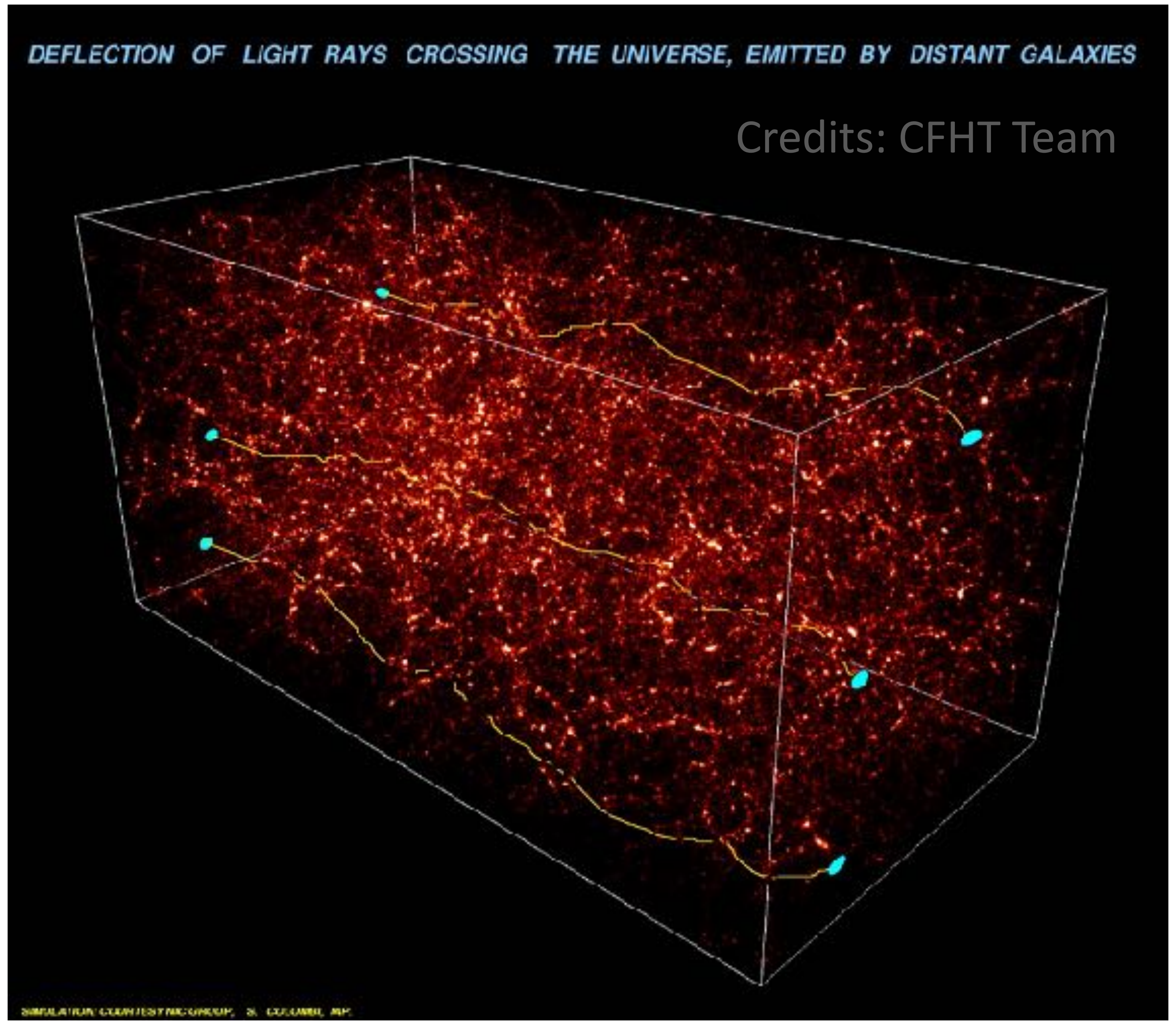
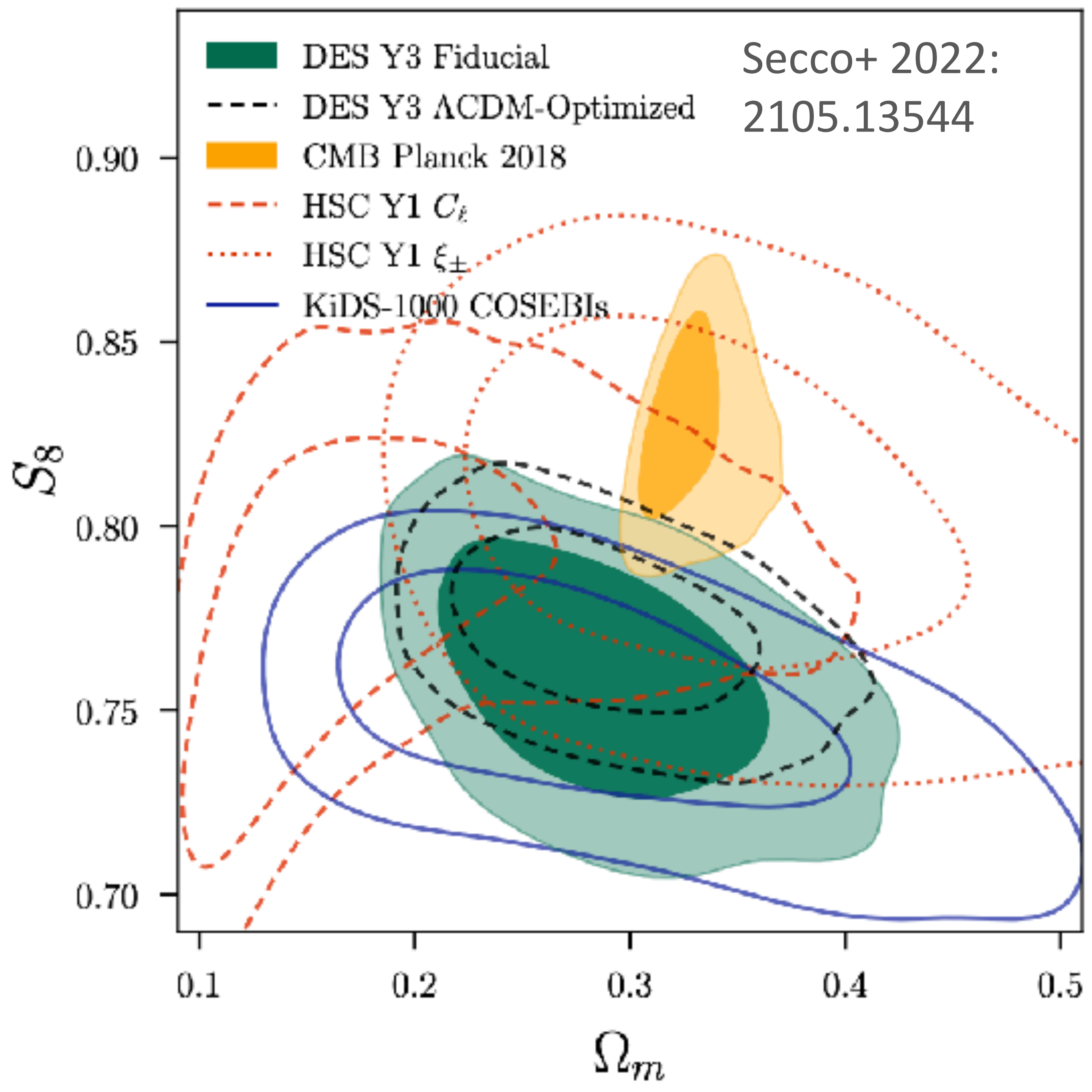
Weak Lensing

- Deflection of light by tidal field of large-scale structure causes coherent distortion, “shear”.
- Weak lensing is a unique cosmological probe measuring matter distribution.
- Essential tool for cosmology and galaxy evolution studies.
- Cosmology constraints from (galaxy) lensing intriguingly low in S8…



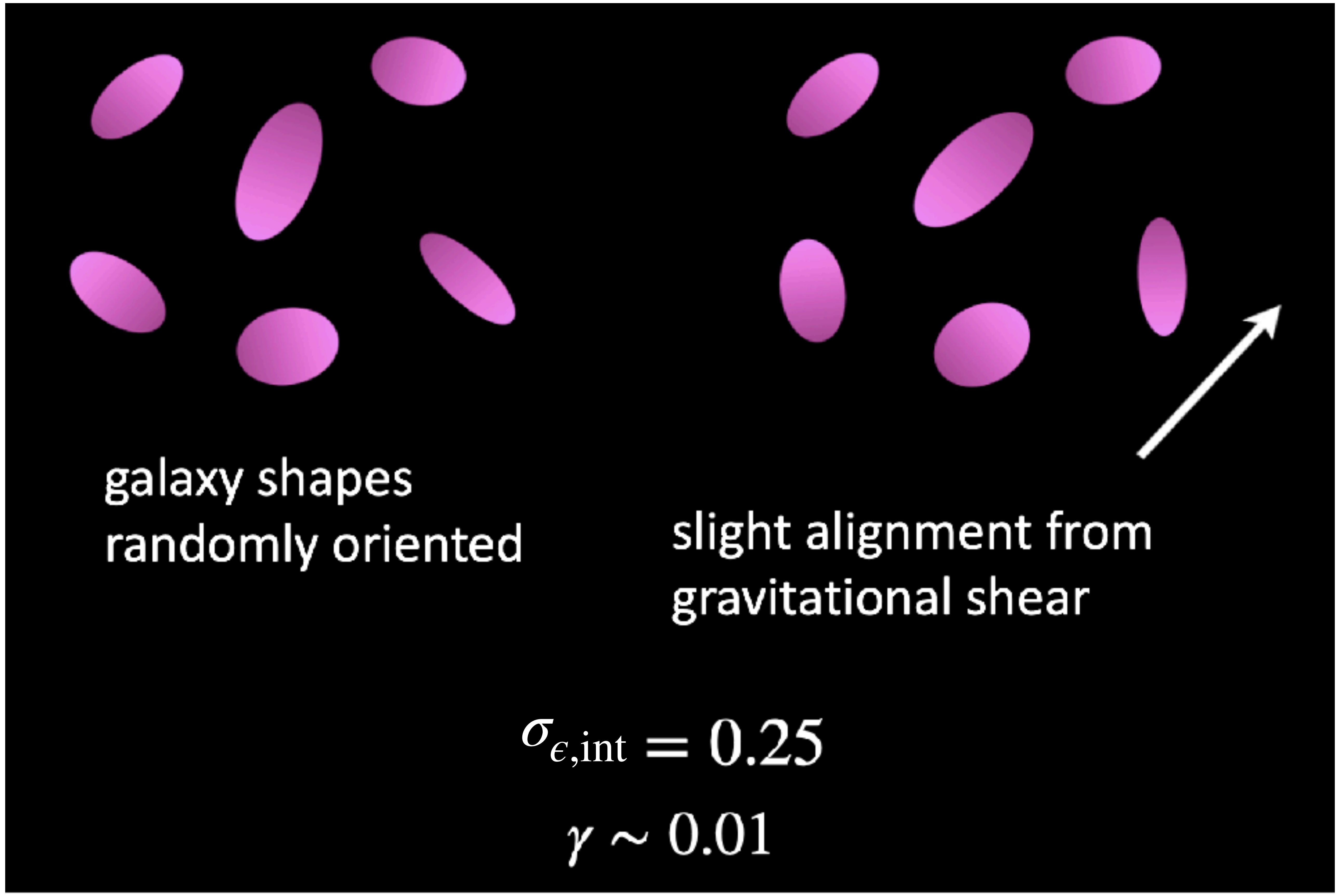


Galaxy Weak Lensing Measurements

- Weak lensing measurements are extremely challenging:
  - intrinsic galaxy shape is unobservable, degenerate with shear
  - ➡ **shape noise** $\sigma_\epsilon^2/n_{\rm gal}$, corresponds to SNR ~ 0.01 per galaxy
  - subject to multifarious systematics.

- Kinematic measurements can break the degeneracy between shapes and shear, and raise the SNR per galaxy to ~1.

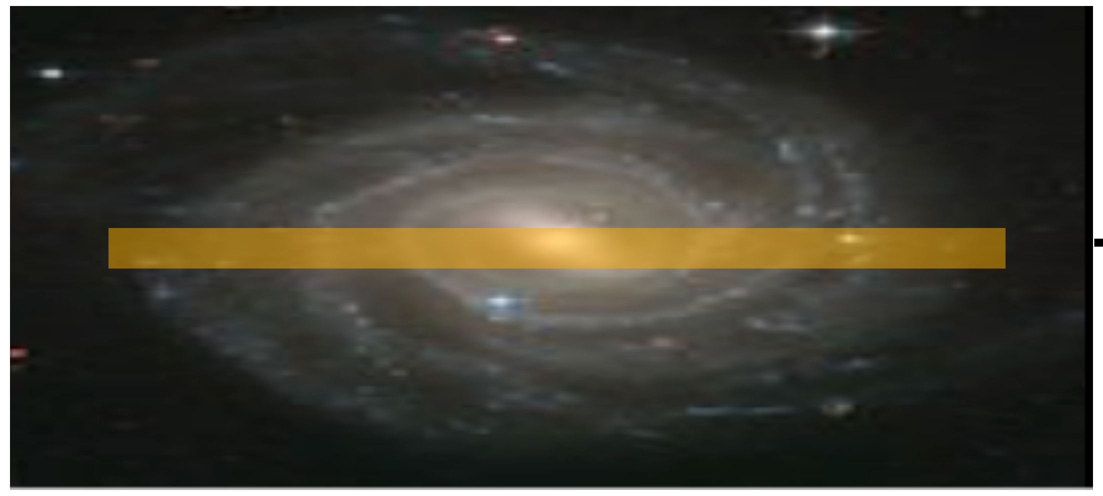
- This also eliminates the dominant lensing systematics (photo-z, intrinsic alignments).



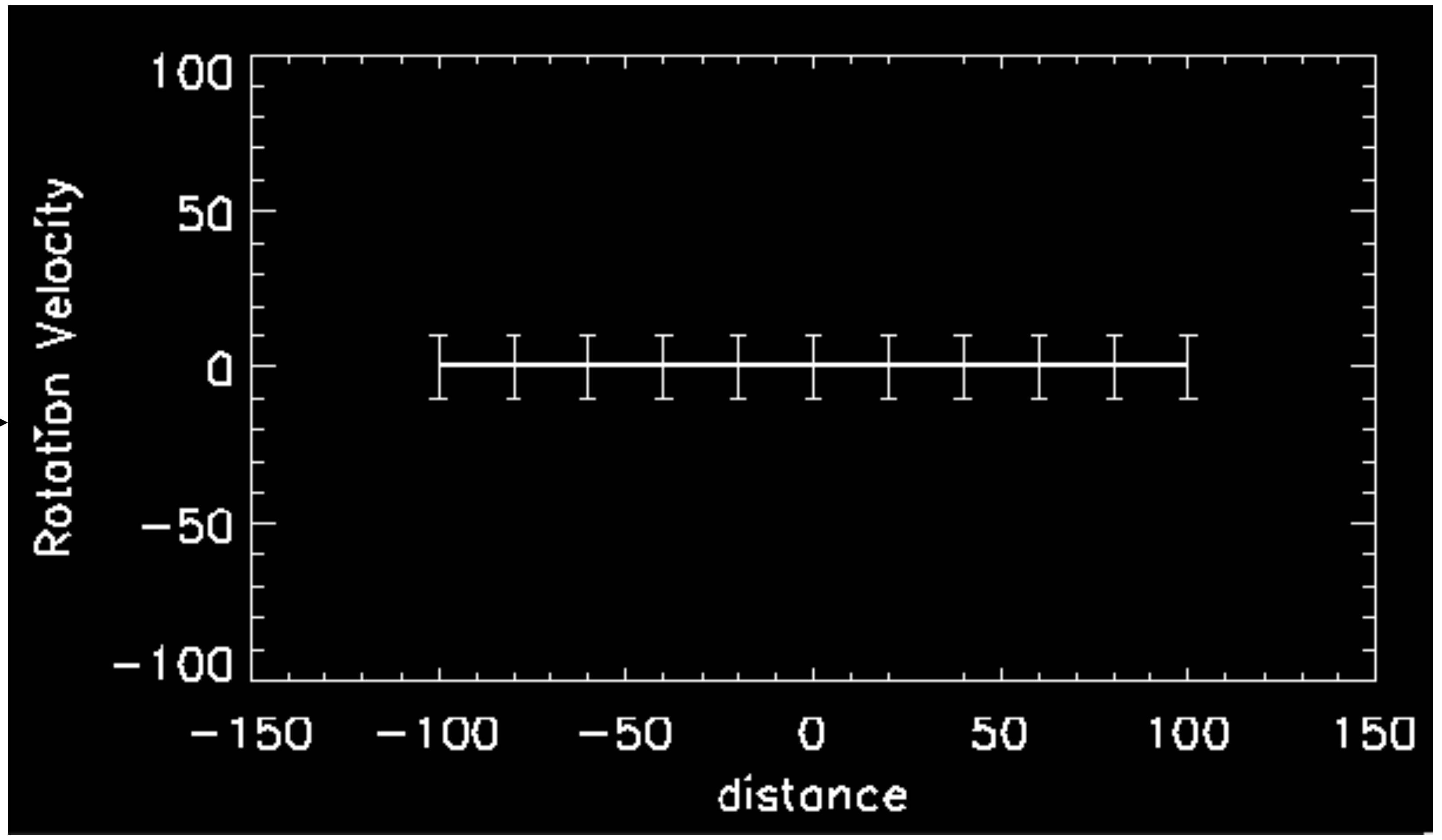
goal: measure shear to %-level precision on individual galaxies.

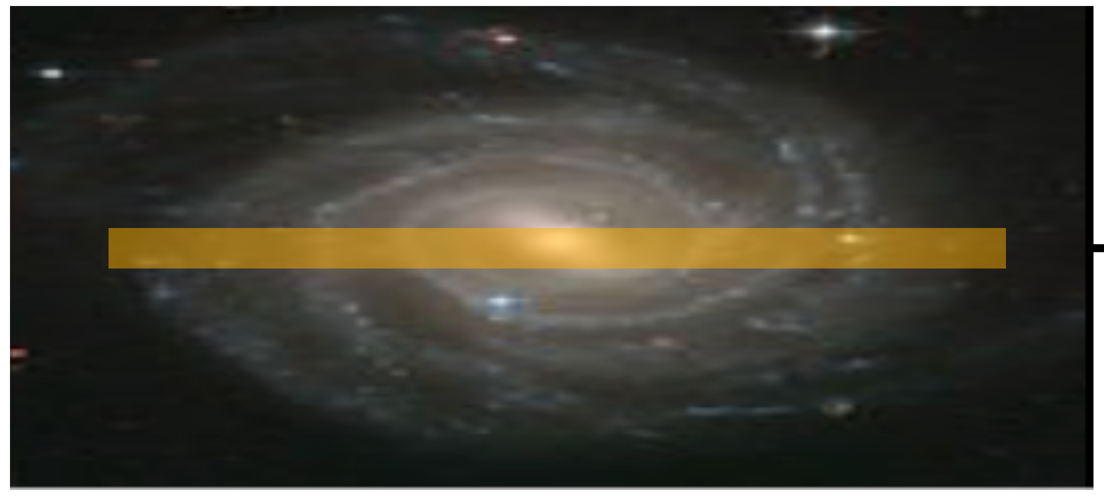
Weak Lensing & Galaxy Kinematics

How does kinematic information break the shape-shear degeneracy?

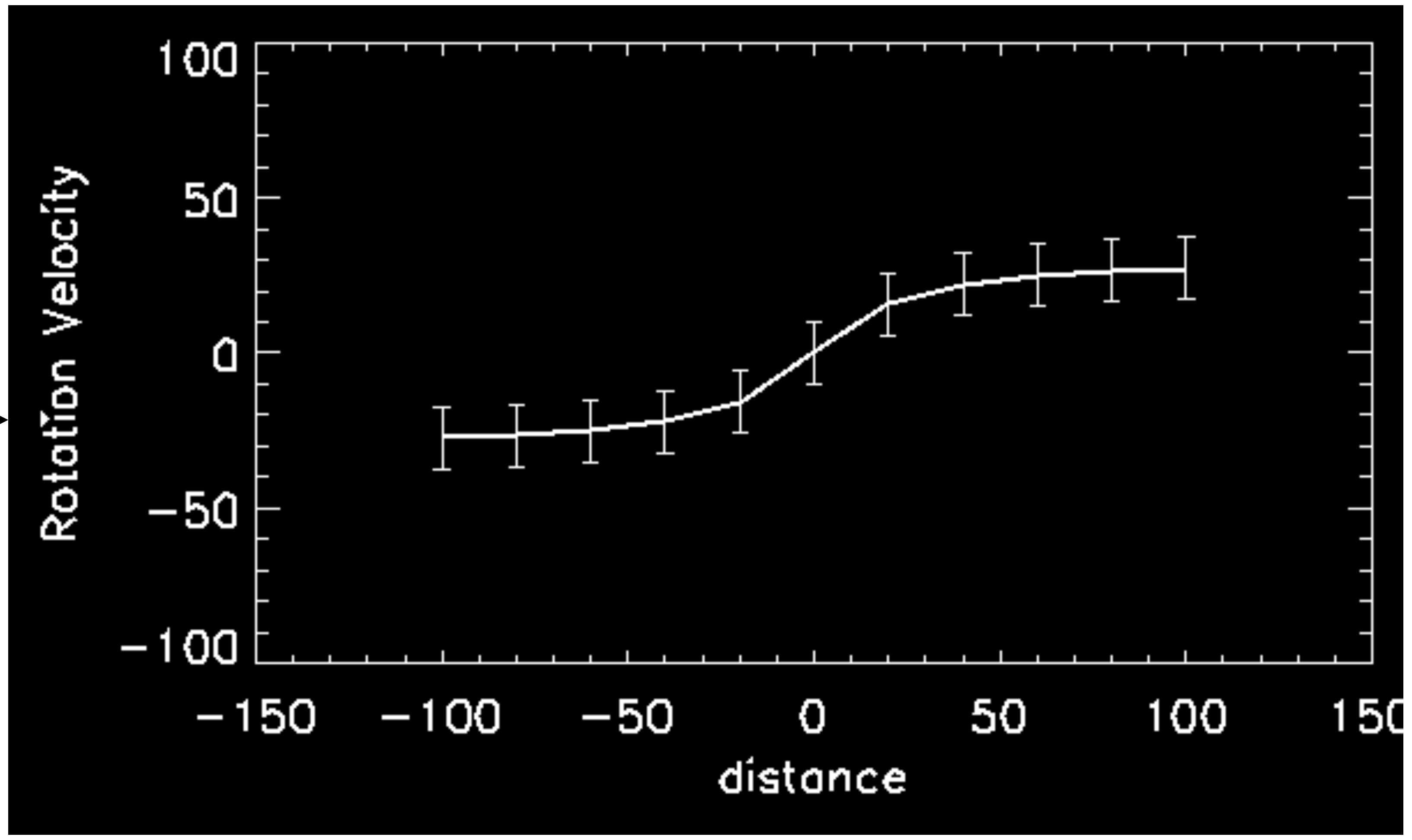


Sheared but face-on





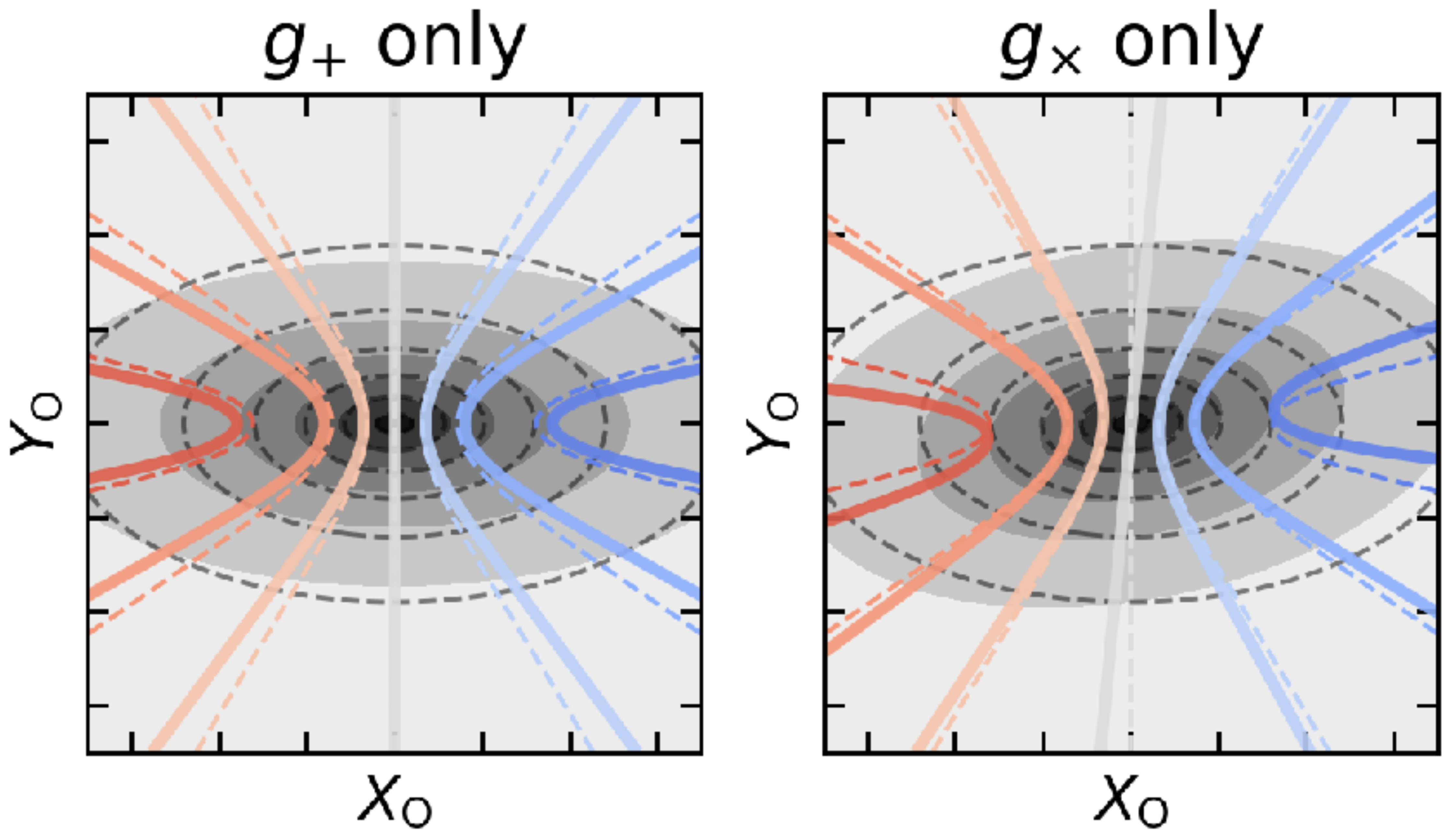
Inclined but not sheared



Weak Lensing & Galaxy Kinematics

Impacts of different shear components

- Define shear components in galaxy major axis frame, g_+ and $g_\times$
- The impact of g_+ on galaxy morphology and kinematic is similar to the one of a different inclination angle
- $g_\times$ creates non-axisymmetric velocity distribution and offset between morphology/kinematic axes (Blain 2002)
- Need more information to constraint g_+ and inclination angle i!



Xu et al. (2022)

Weak Lensing & Galaxy Kinematics

How to break the $i - g_+$ degeneracy?

- **<u>Method 1</u>**: cluster lensing / galaxy-galaxy lensing: get tangential direction from the closest cluster/galaxy (Morales 2006, de Burgh-Day et al. 2015a,b, Gurri et al. 2020, DiGiorgio et al. 2021)

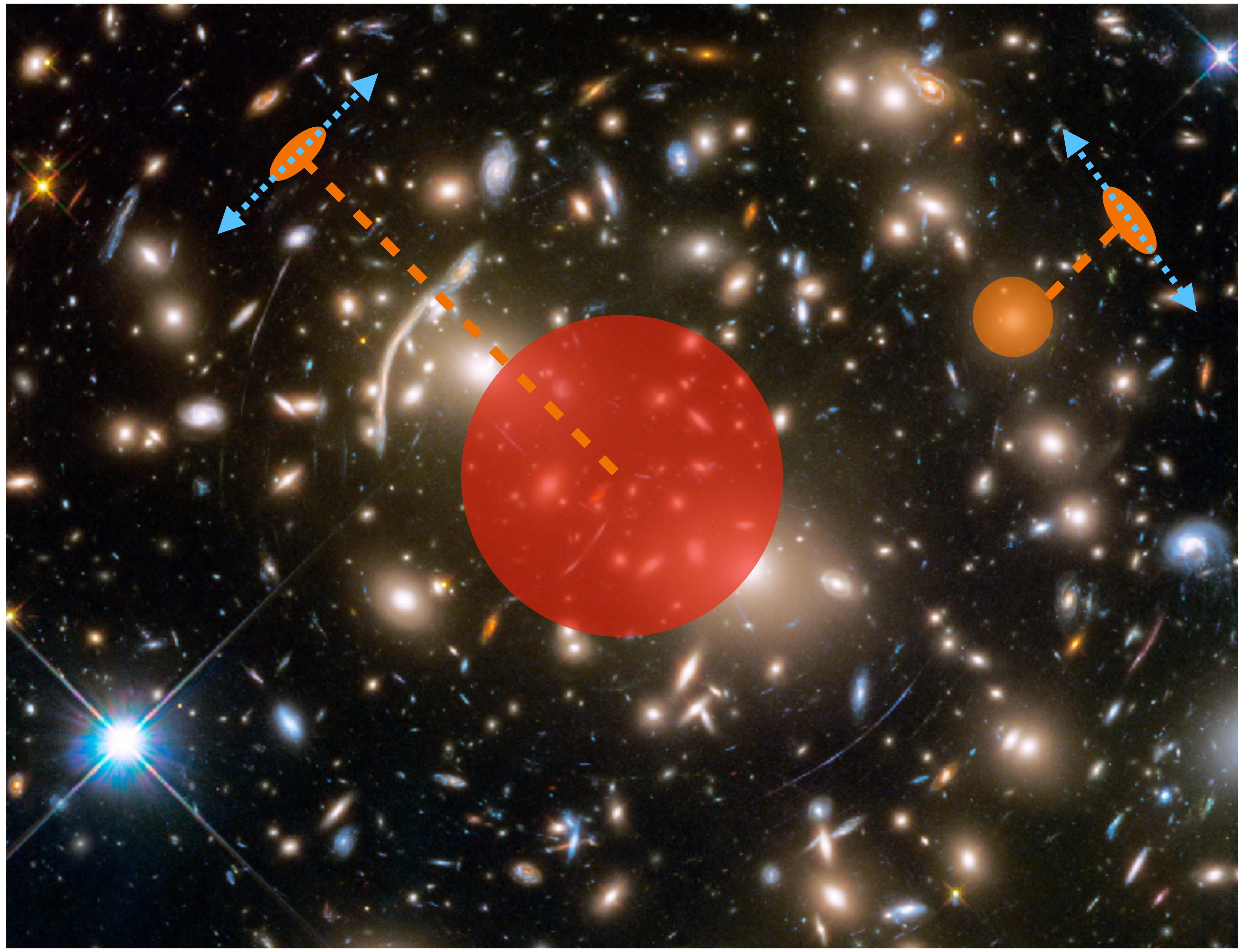


Image Credit: NASA/HST

Weak Lensing & Galaxy Kinematics

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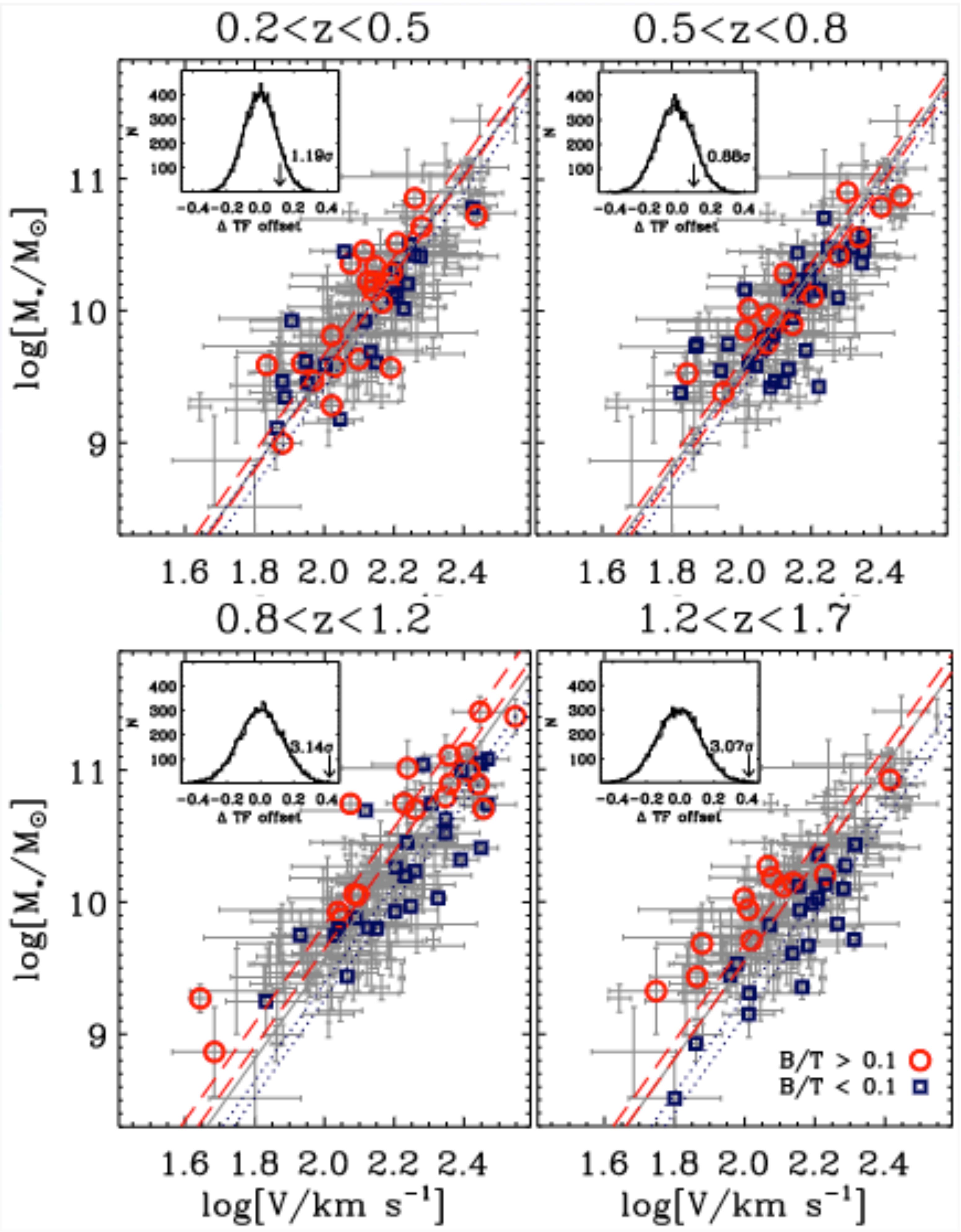
- **Method 1**: cluster lensing / galaxy-galaxy lensing: get tangential direction from the closest cluster/galaxy (Morales 2006, de Burgh-Day et al. 2015a,b, Gurri et al. 2020, DiGiorgio et al. 2021)

- **Method 2**: Tully-Fisher relation (Huff, EK et al. 2013)

$$\log_{10}(v_{\rm circ}) = a + b(M_B - M_p) + \tilde{\epsilon}$$

$\tilde{\epsilon}$ is the intrinsic Gaussian scatter of TF relation, which is around $0.05\ dex$ (Reyes et al. 2011)

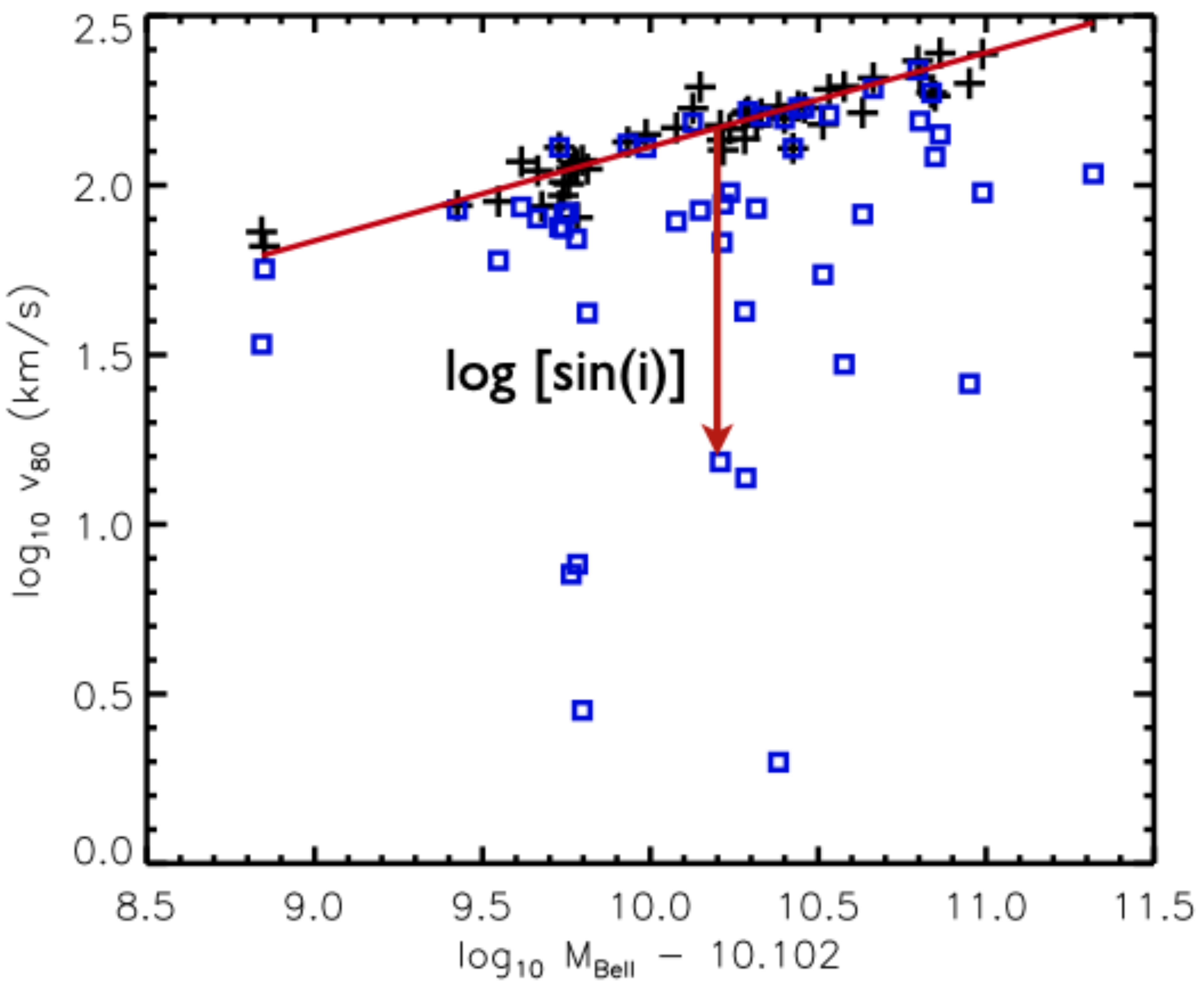


Miller et al. 2013

Weak Lensing & Galaxy Kinematics

Breaking the $i - g_+$ degeneracy with the TFR

blue points: uncorrected for inclination

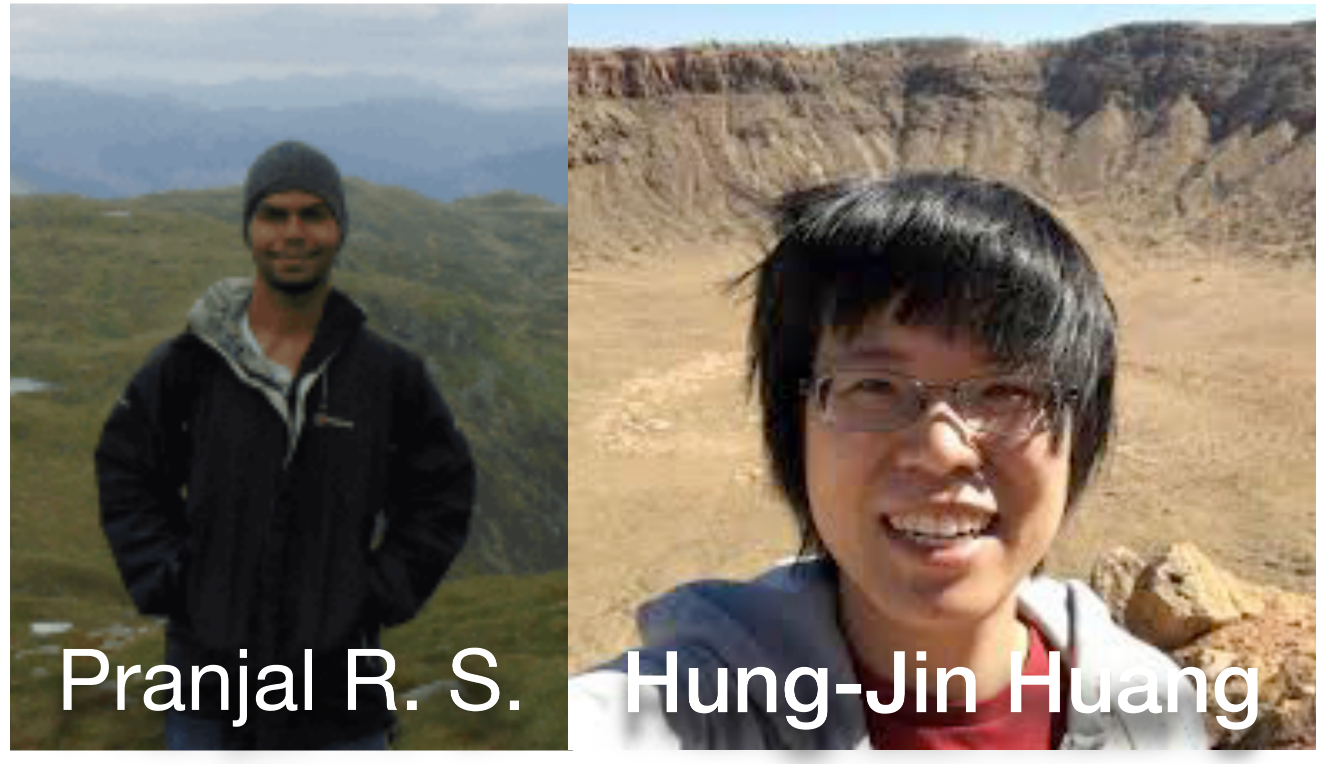


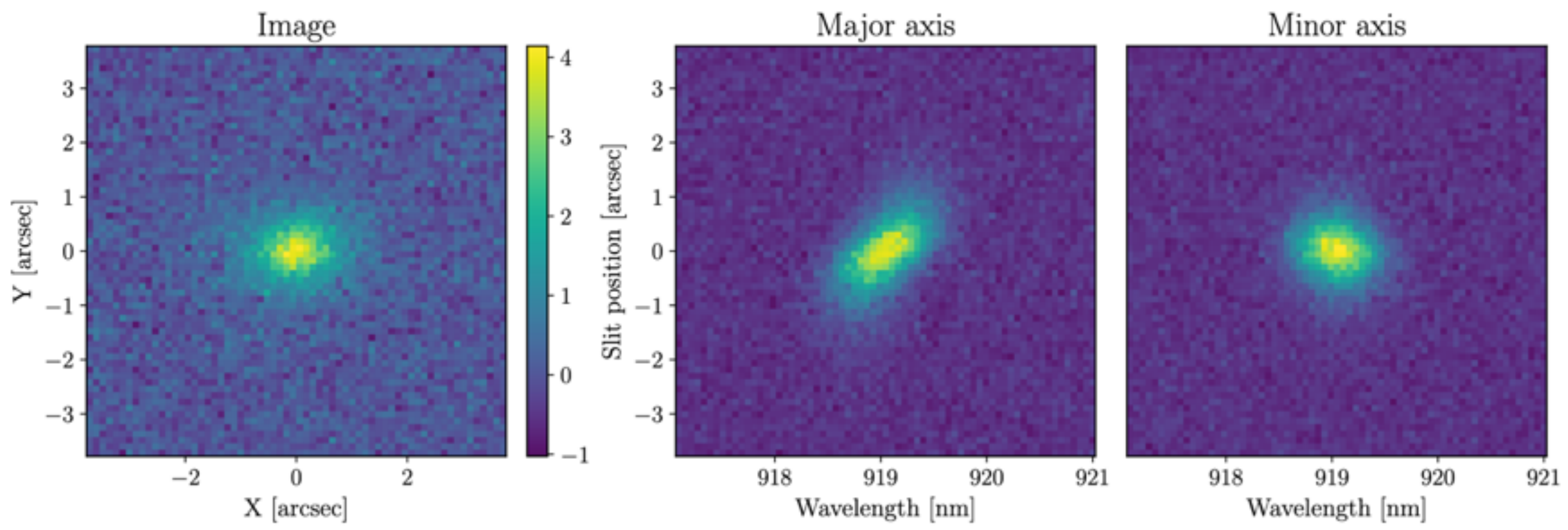
red trendline: Tully-Fisher Relation

For disk galaxies, *sin(i)* determines the unlensed galaxy ellipticity.
Comparing unlensed and observed shape determines the *second* shear component.

Measurement Pipeline

Slit spectrum





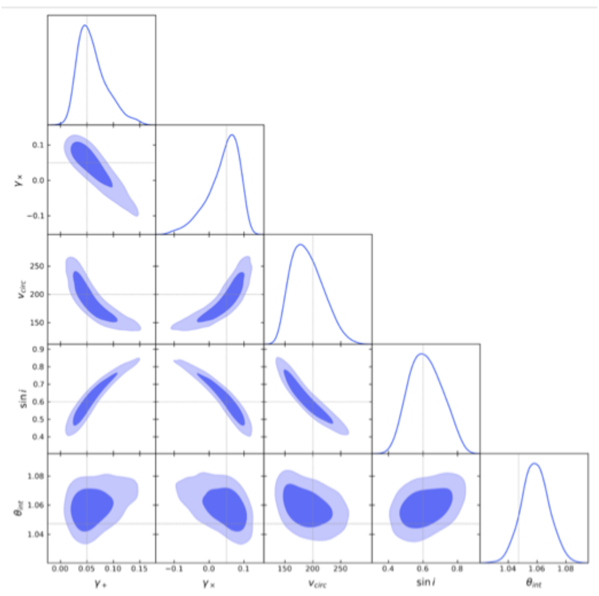
Simulations → Mock Data Vector

Tully-Fisher Prior

2D Forward Model → Image Model

2D Forward Model → Spectrum Model

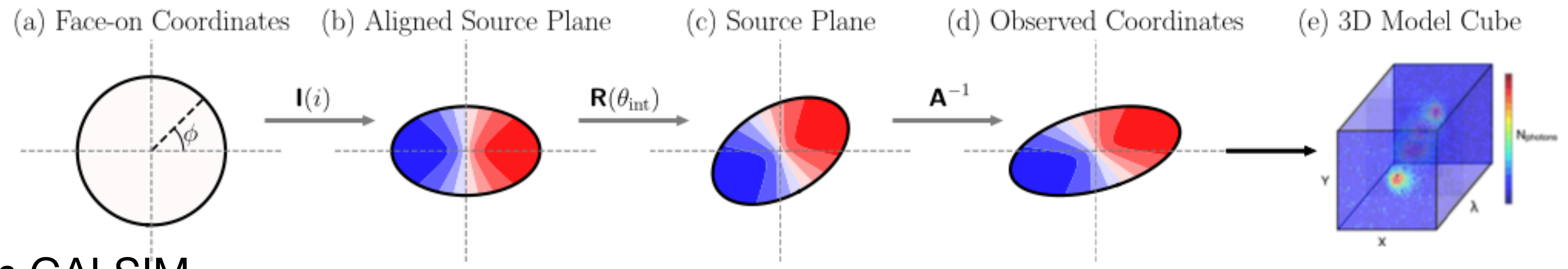
MCMC → Shear Constraints



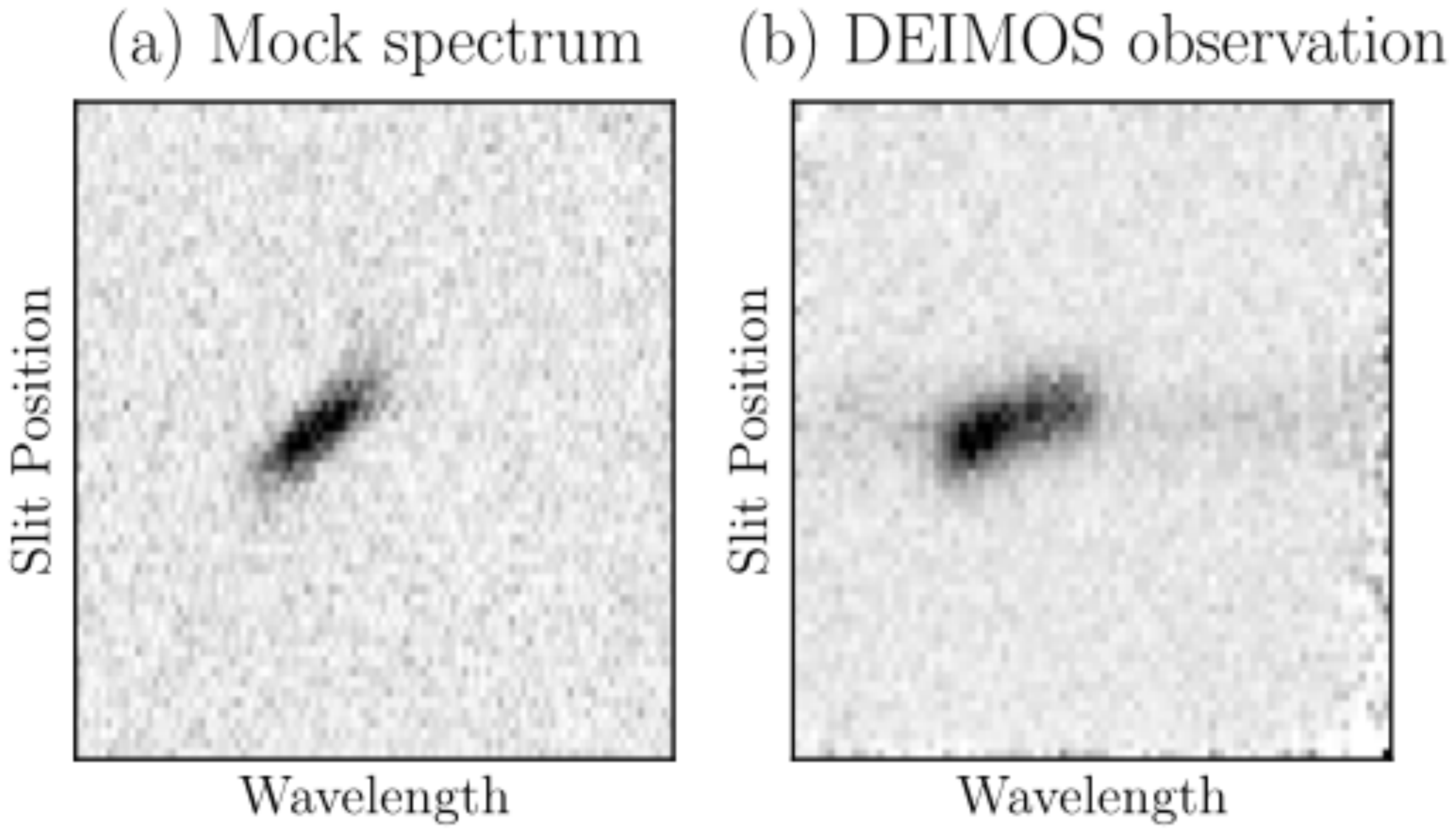
RS et al. 2209.11811

Measurement Pipeline

Slit spectrum



- **Simulations**
  - Image and spectrum modeling based on GALSIM
  - Account for sky emission, atmosphere, instrument & CCD, PSF
- **Fast 2D Forward Model**
  - Image model
    - Model the image using $n = 1$ Sersic profile with edge-on aspect ratio q_z
    - Apply rotation $(\theta_{\rm int})$ and shear $(\gamma_+, \gamma_\times)$
  - Spectrum model
    - $v(r) = v_0 + \dfrac{2}{\pi} v_{\rm circ} \tan^{-1}(r/r_{\rm vscale})$
    - Transform the velocity field to account for galaxy inclination, intrinsic P.A., and shear
    - Flexible 2D slit mask configuration



Shape Noise Estimates

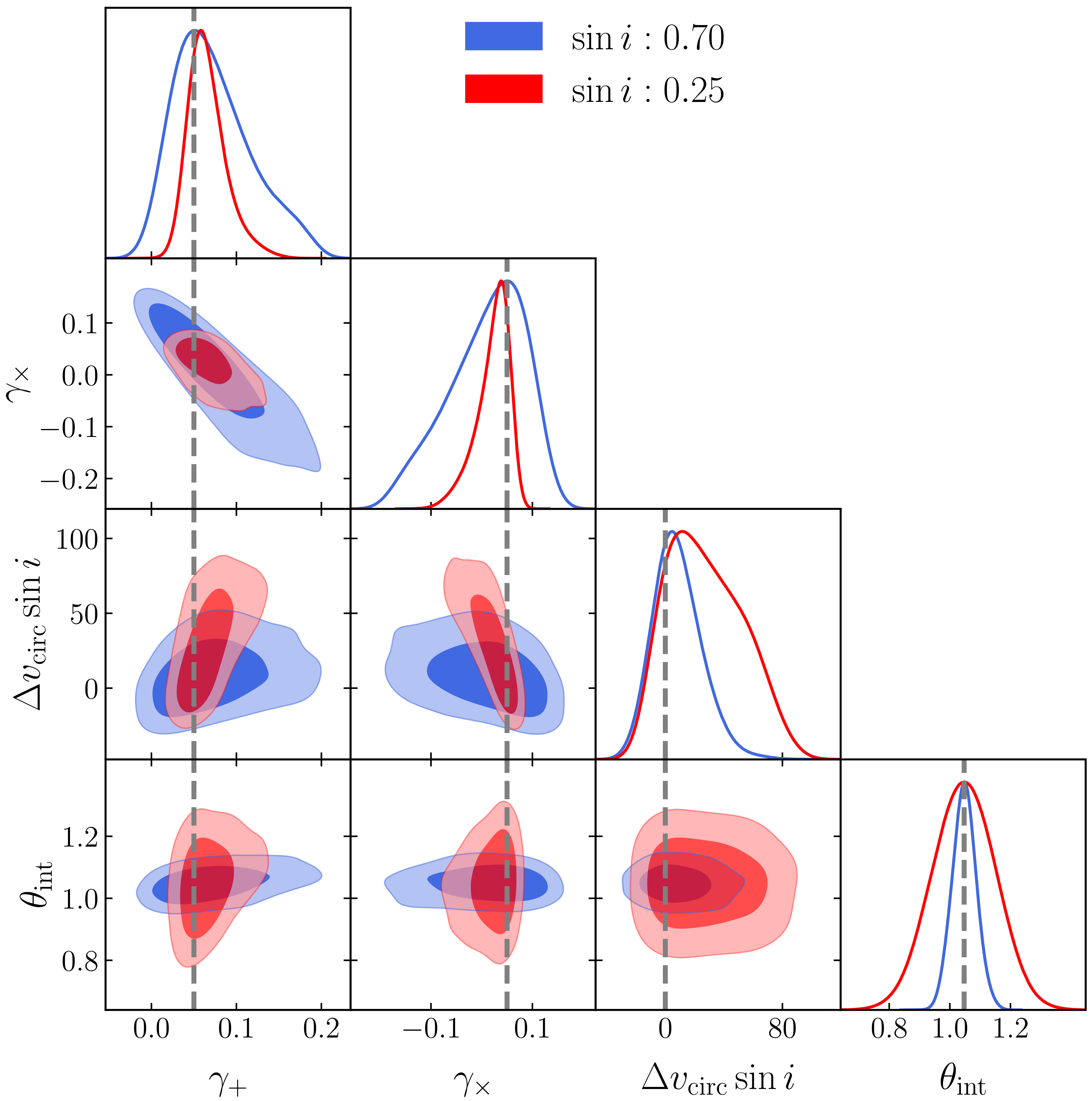
Slit spectrum

- Analyze synthetic DEEP2-like spectra (noiseless realization, SNR~30) with fast forward model

- Unbiased shear posteriors on noiseless data

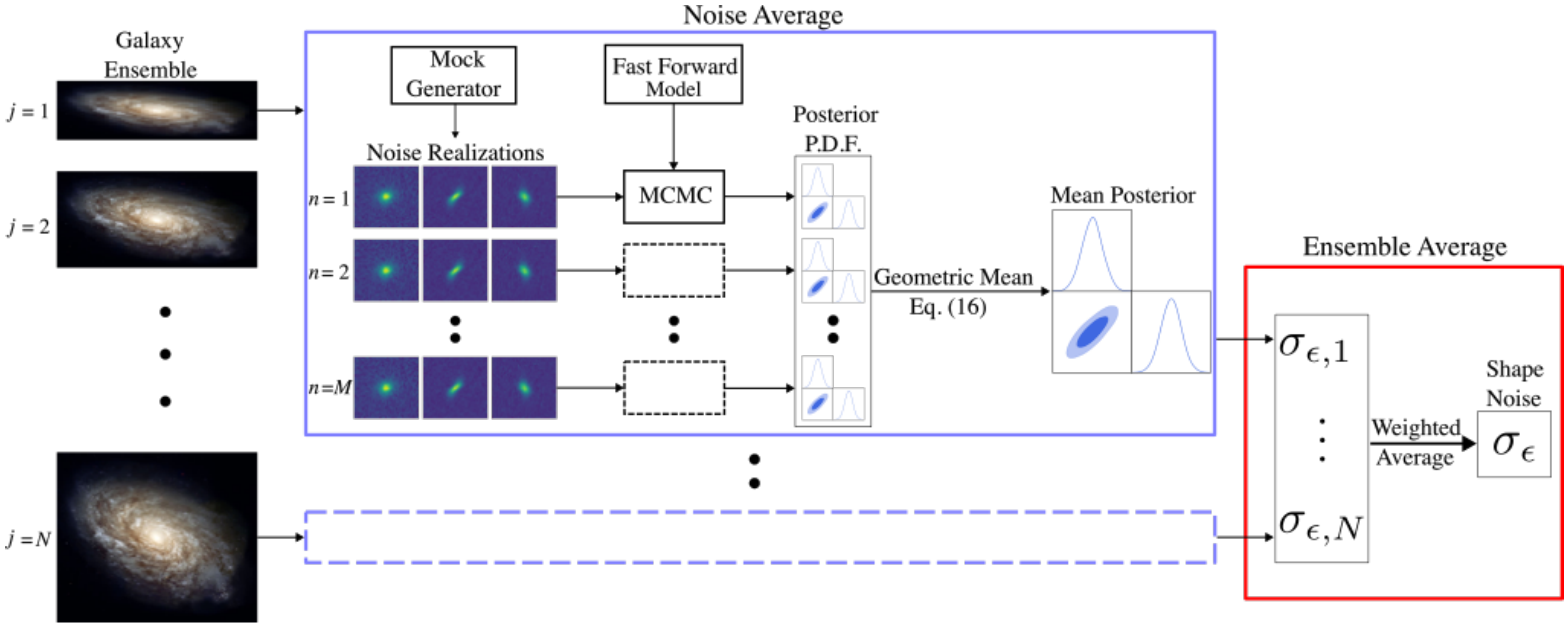
  - fitting 11 parameters to each galaxy is not hopeless

Next: check that noise causes only scatter, not biases.



Shape Noise Estimates

Slit spectrum

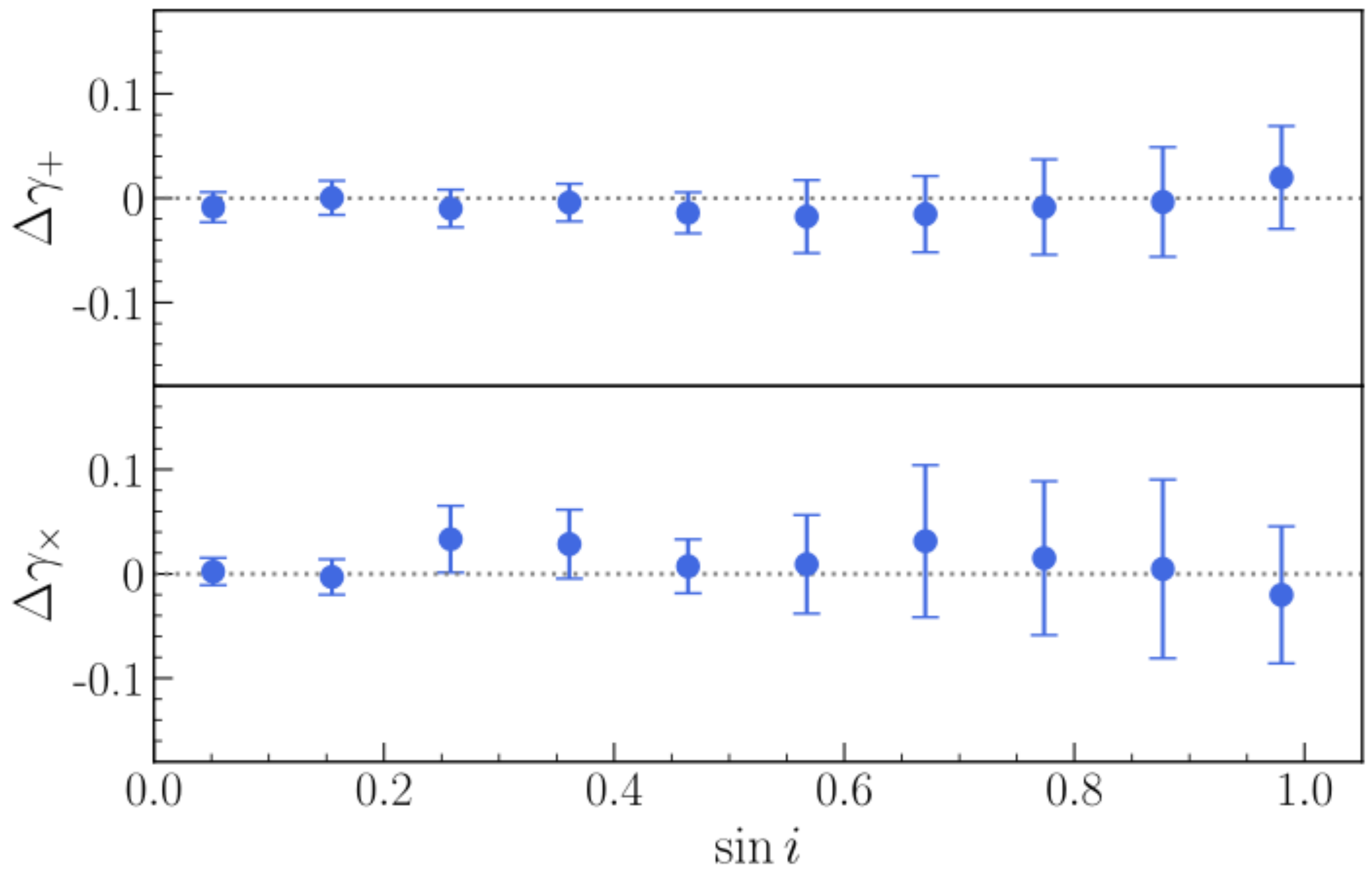


Goal: check that pixel noise causes only scatter, not biases.

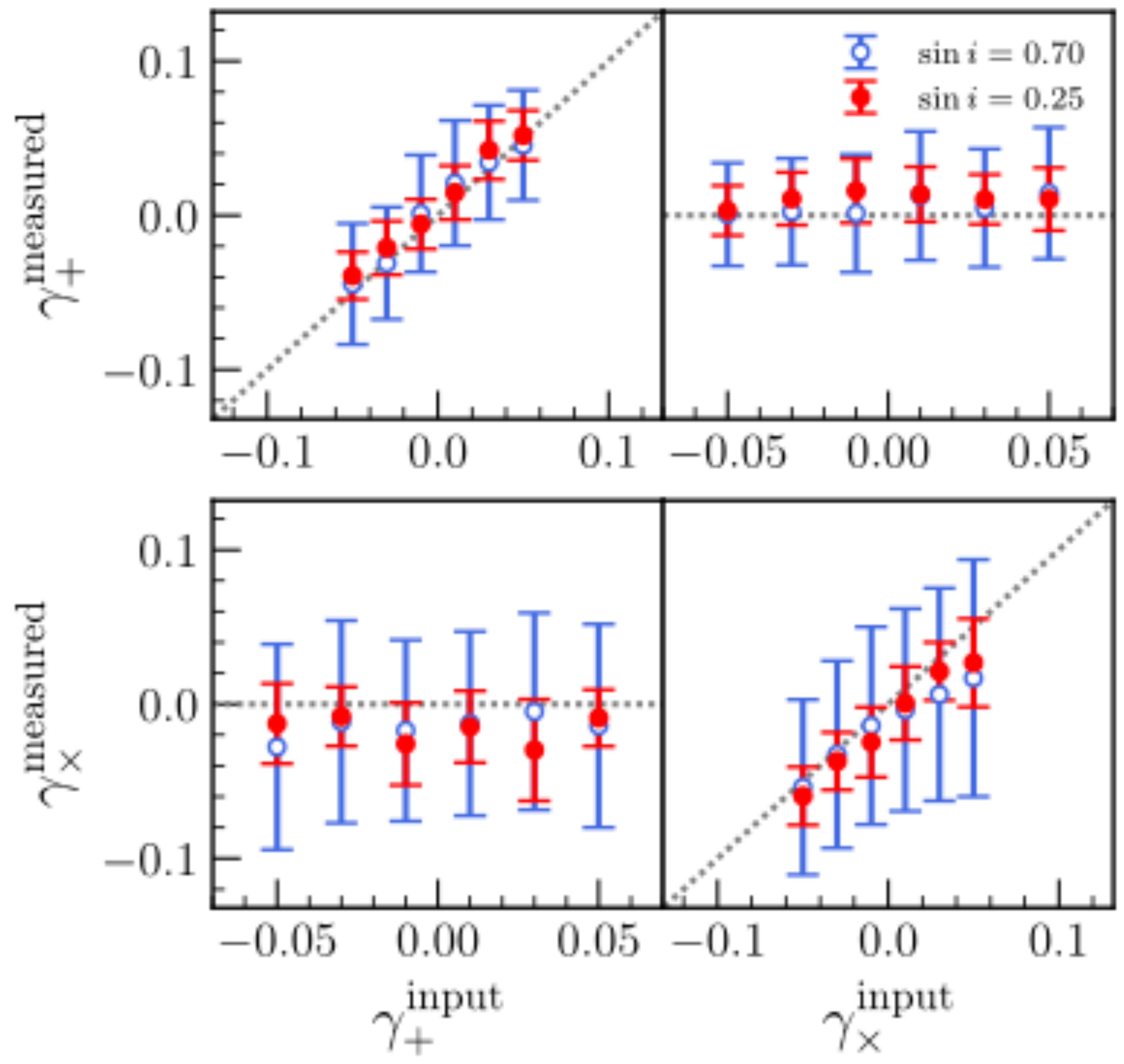
Shape Noise Estimates

Slit spectrum

Each data point averages over 20 noise realizations.



Bias of measured shear as a function of inclination



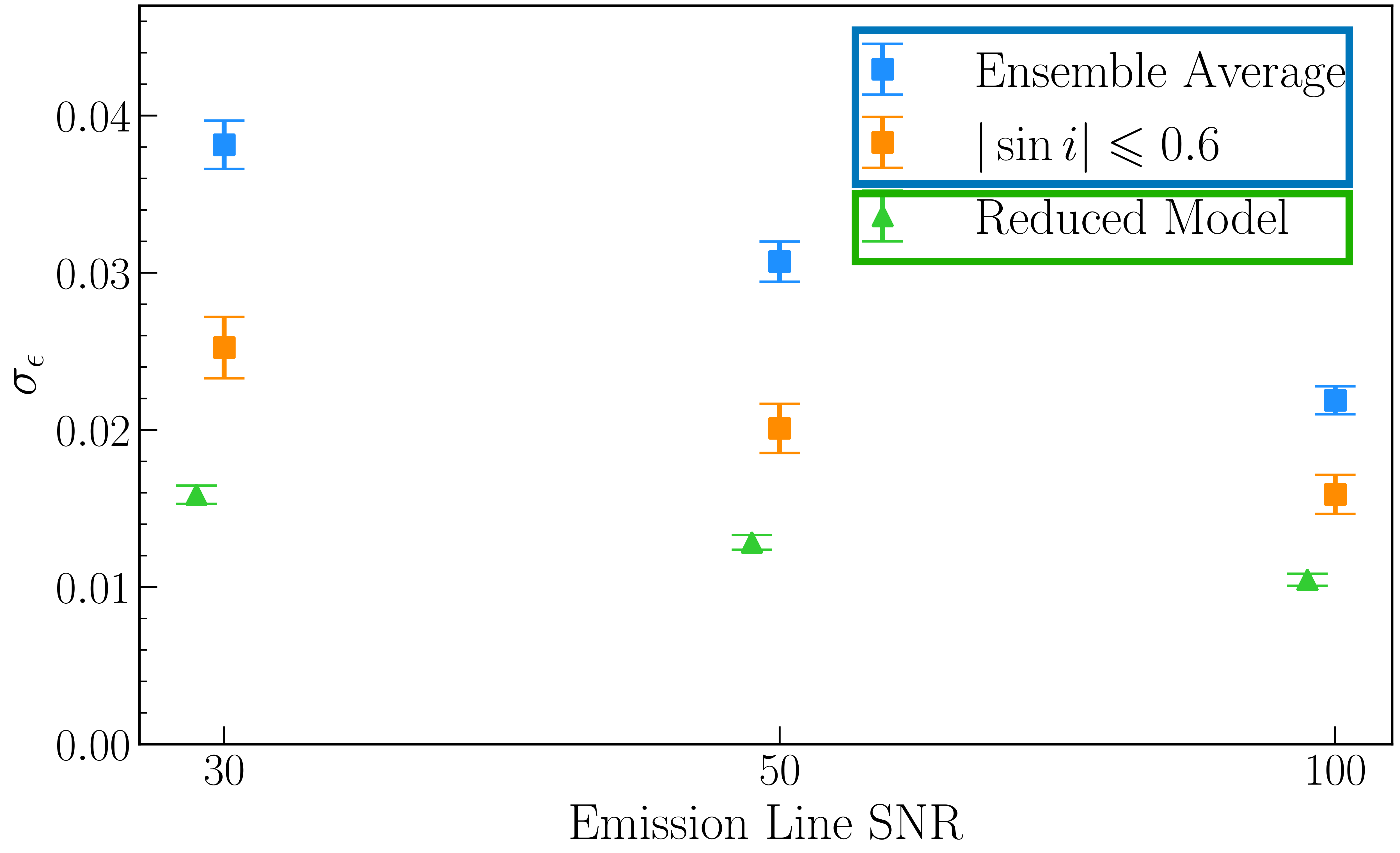
$$\gamma_{+,\times}^{\text{measured}} = (1 + m_1)\gamma_{+,\times}^{\text{input}}$$

$$\gamma_{+,\times}^{\text{measured}} = m_2\gamma_{\times,+}^{\text{input}}$$

Measured vs. input shear for two galaxy inclinations
$\langle m1 \rangle = -0.05 \pm 0.06$ and $\langle m2 \rangle = 0.02 \pm 0.08$

Shape Noise Estimates

Slit spectrum



11 fit parameters:
['g1','g2','vcirc','sini','theta_int','r_hl_image'
,'r_hl_spec','vscale','v_0','I0', 'bkg_level']

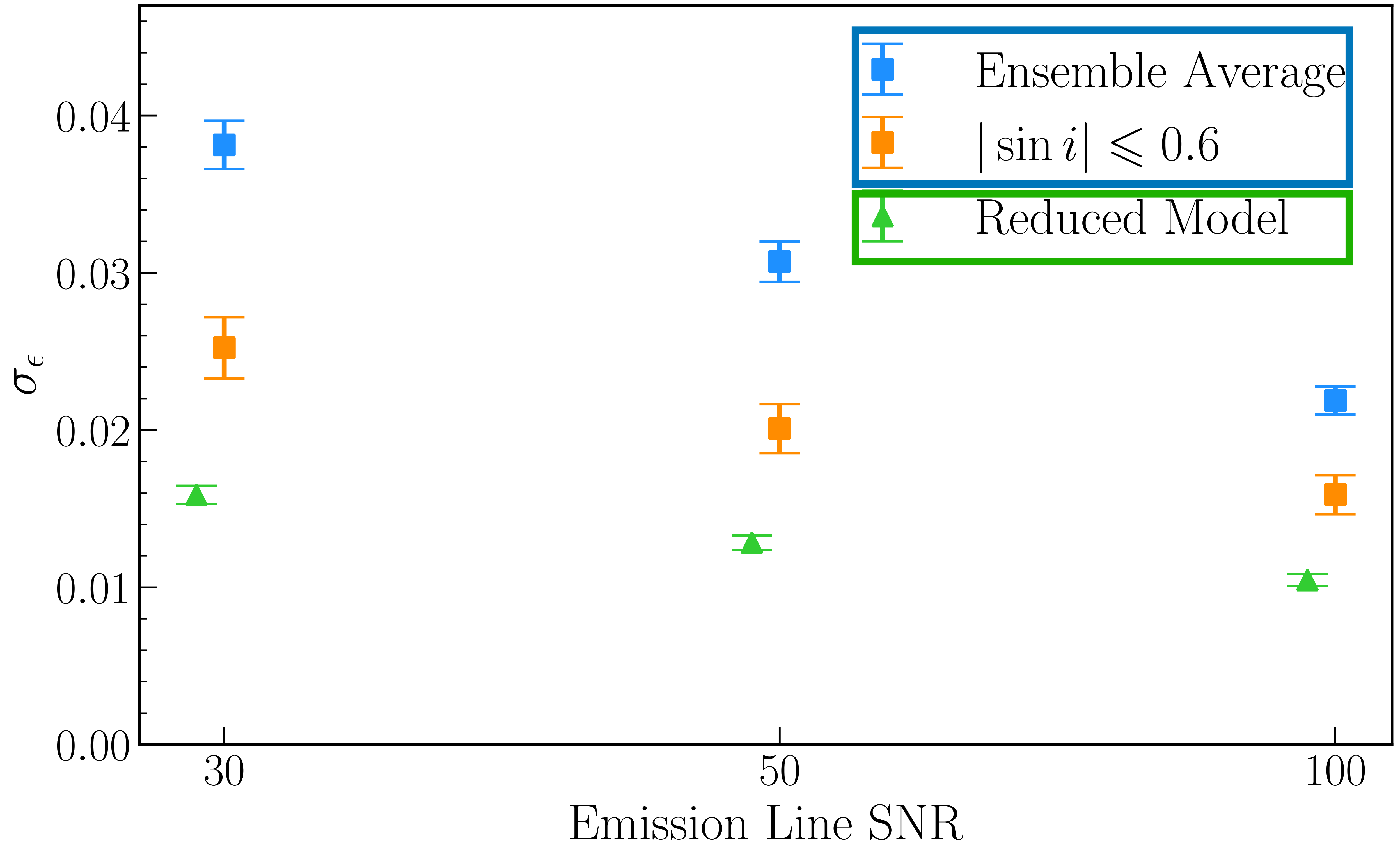
6 fit parameters:
['g1','g2','vcirc','sini','theta_int','I0']

σ_ϵ ~10 smaller than for traditional lensing!

-> can afford smaller sample size/more expensive measurements

Shape Noise Estimates

Slit spectrum



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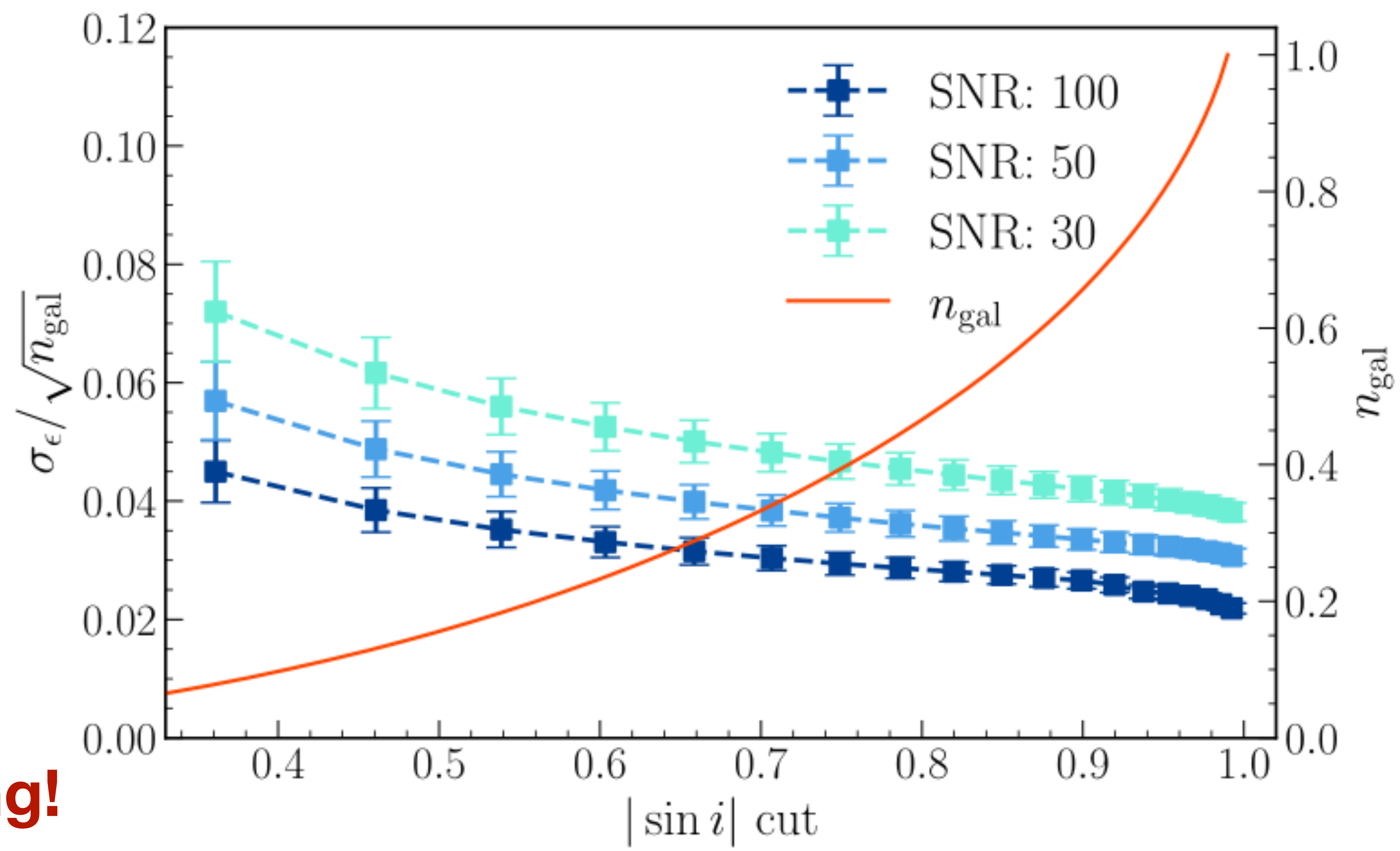


σ_ϵ **~10 smaller than for traditional lensing!**

-> can afford smaller sample size/more expensive measurements

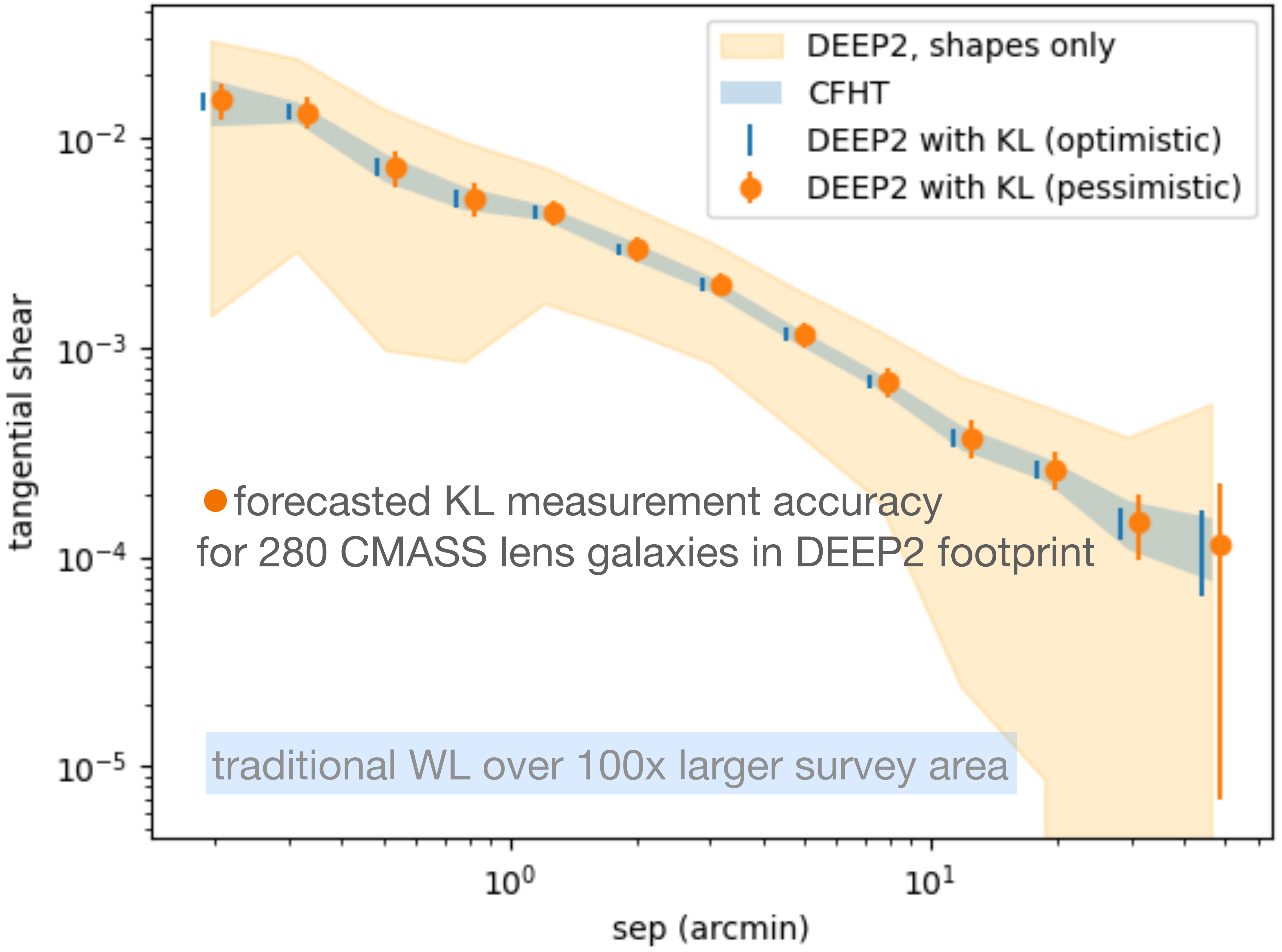
Galaxy-Galaxy Lensing Pilot Measurement

DEEP2 Slit Spectra

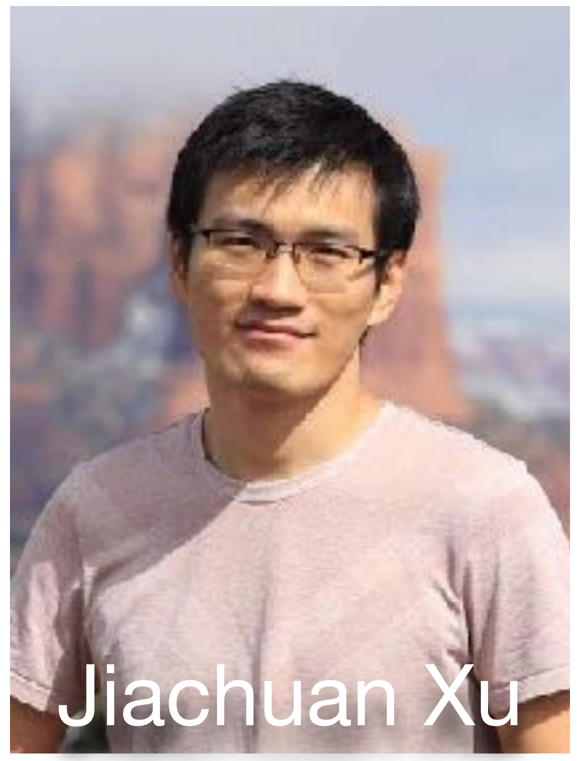
KL galaxy-galaxy lensing measurements for order-of-magnitude smaller lens samples than traditional WL lensing

-> precision measurements of halo masses for small lens samples, characterize environment dependence + assembly bias.

DEEP2 provides only one slit orientation per galaxy. For g-g lensing, use lens+source positions to project expected tangential shear onto slit position.



KL with *Roman Space Telescope*



- Why *Roman Space Telescope*?
  - Wide FoV: $0.281\,\mathrm{deg}^2$
  - Space-quality imaging and grism data ($\mathrm{PSF} \approx 0.13''$)
  - Moderate grism resolution ($R = 461\lambda/[1\mathrm{um}]$)
  - $2{,}000\,\mathrm{deg}^2$ overlapping imaging and grism survey in the reference design

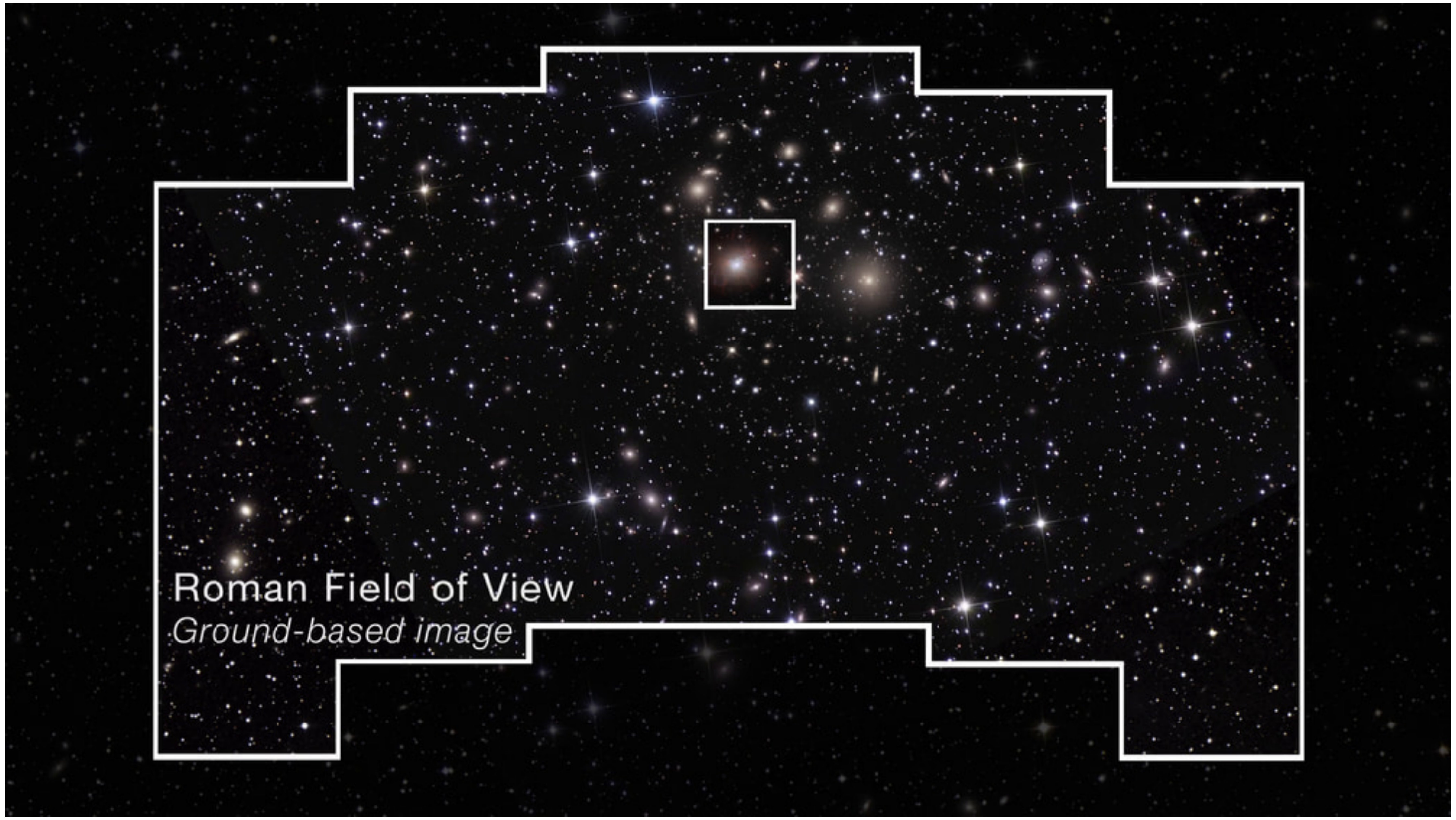


Image Credit: NASA

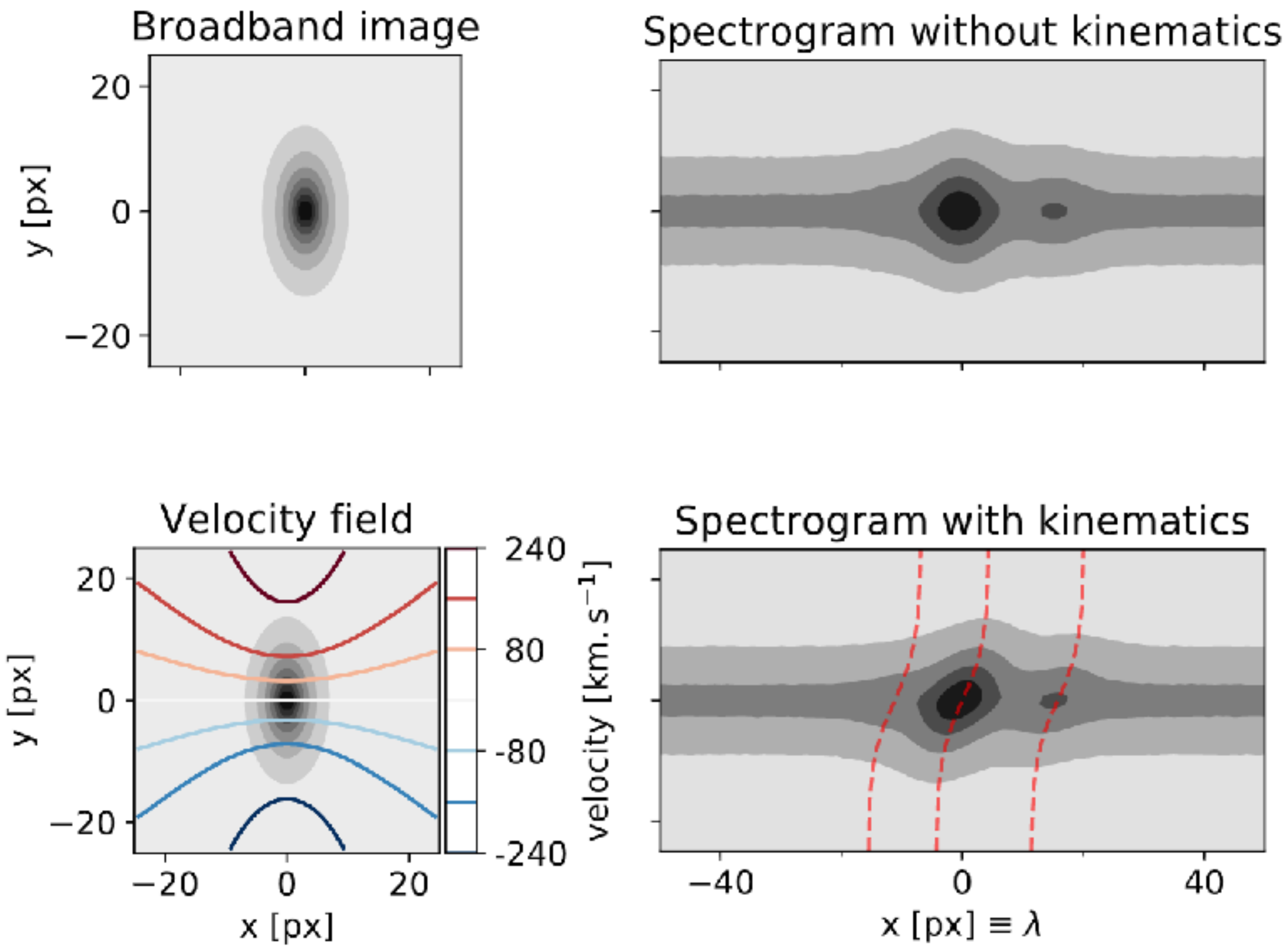
Xu et al. 2201.00739

KL *Roman Space Telescope*

Can *Roman* grism measure disk kinematics?

- HST/WFC3 G141 (3x worse than Roman) recovers rotation velocities with a precision of
  $\sigma_v = 15 - 30\,\mathrm{km/s}$

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

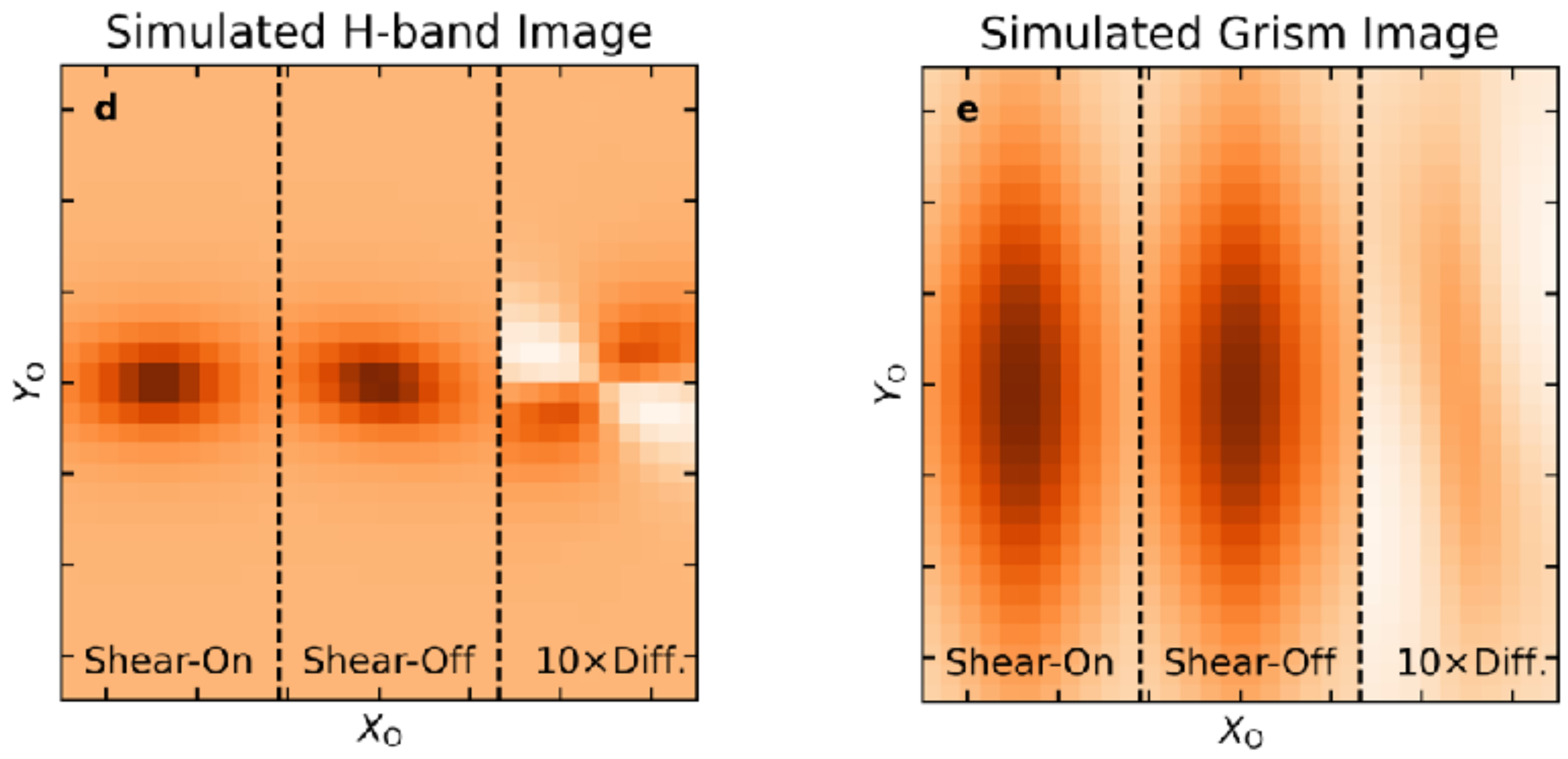


Outini & Copin (2020)

KL with *Roman Space Telescope*

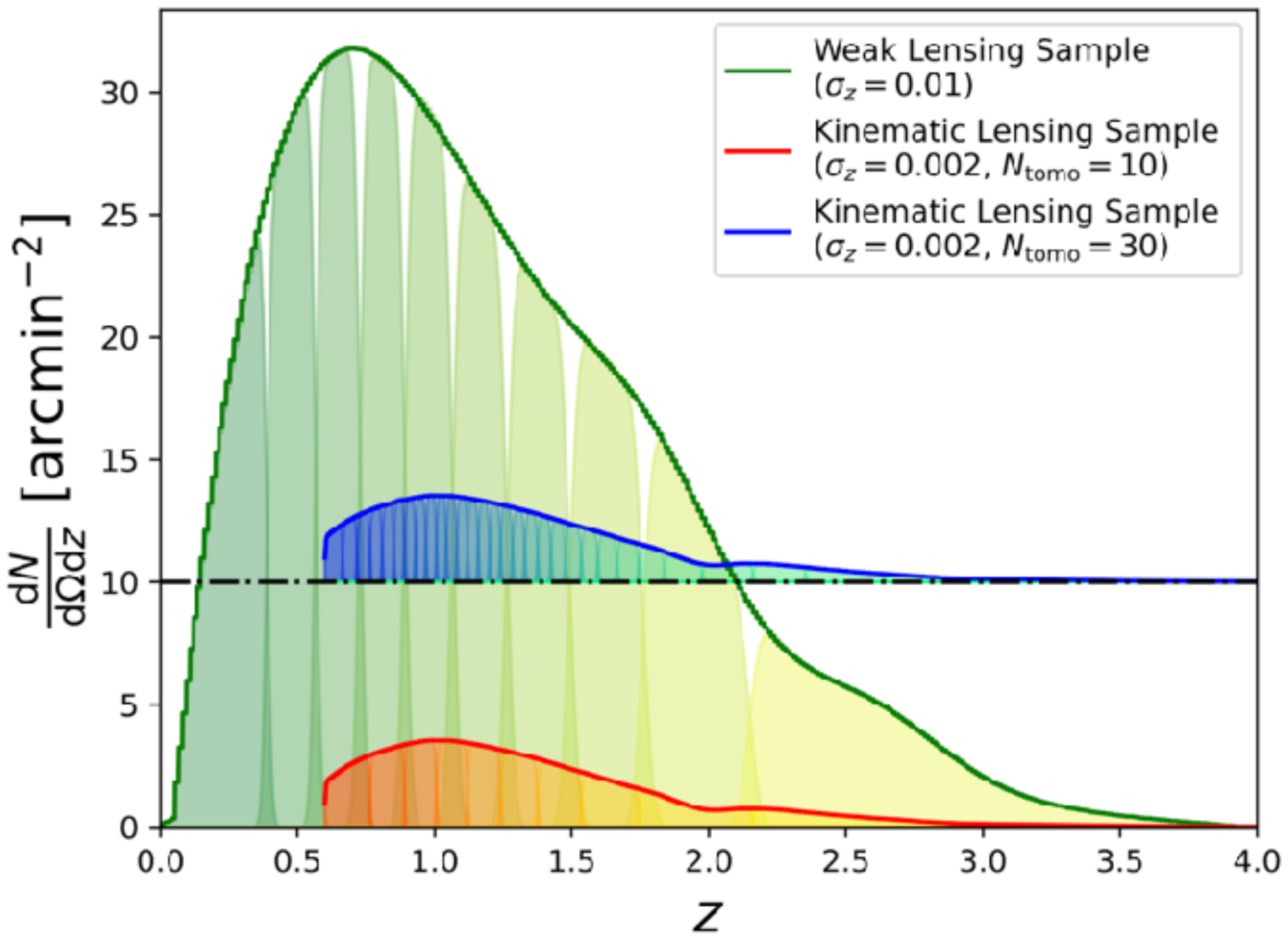
Can *Roman* grism measure disk kinematics?

- HST/WFC3 G141 (3x worse than Roman) recovers rotation velocities with a precision of $\sigma_v = 15 - 30\,\mathrm{km/s}$
- With the spectral resolution of Roman grism, we expect to see smaller velocity uncertainty and solid shear measurements



KL with *Roman Space Telescope*

Galaxy sample definition



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

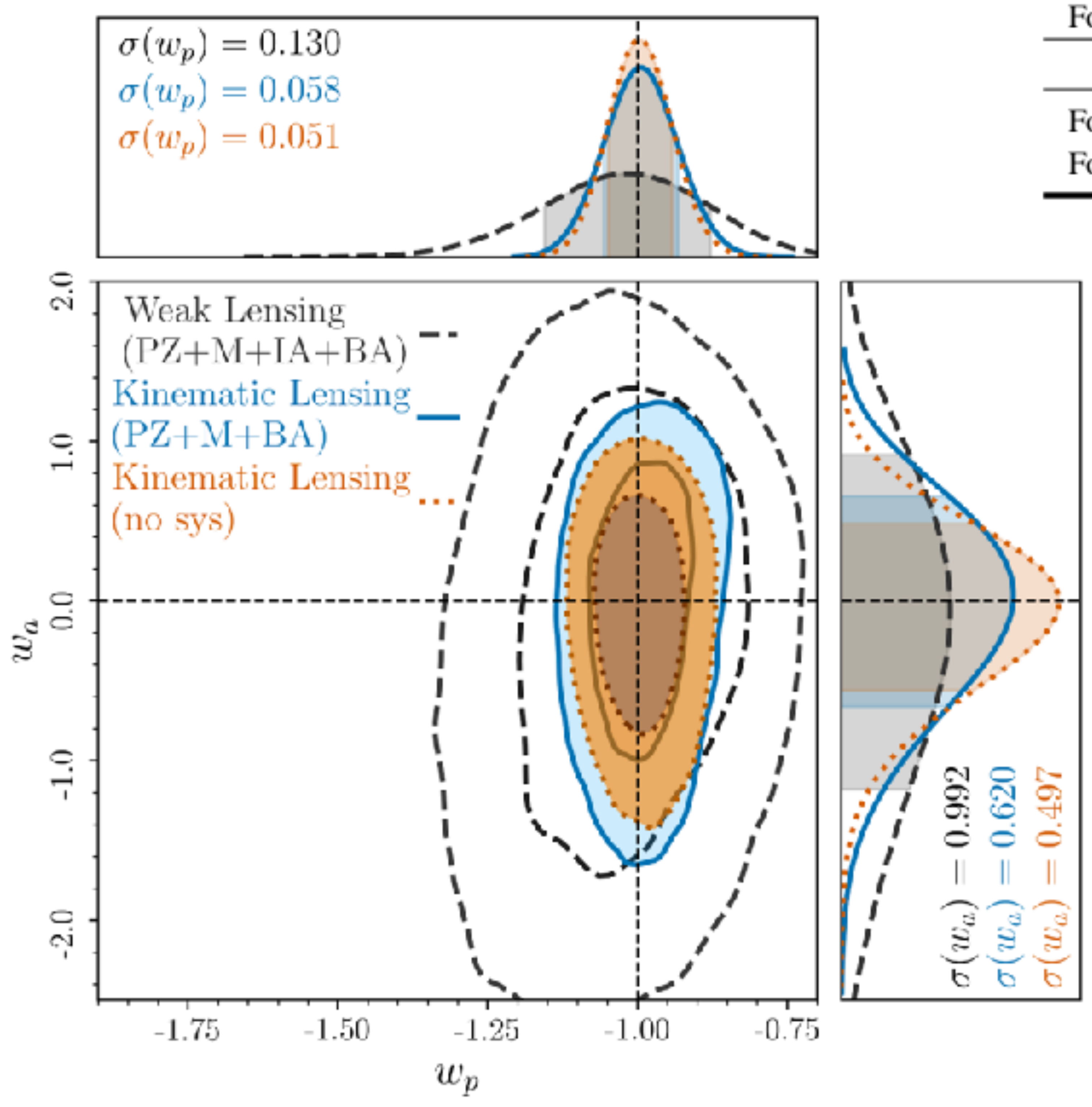
50% success rate

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

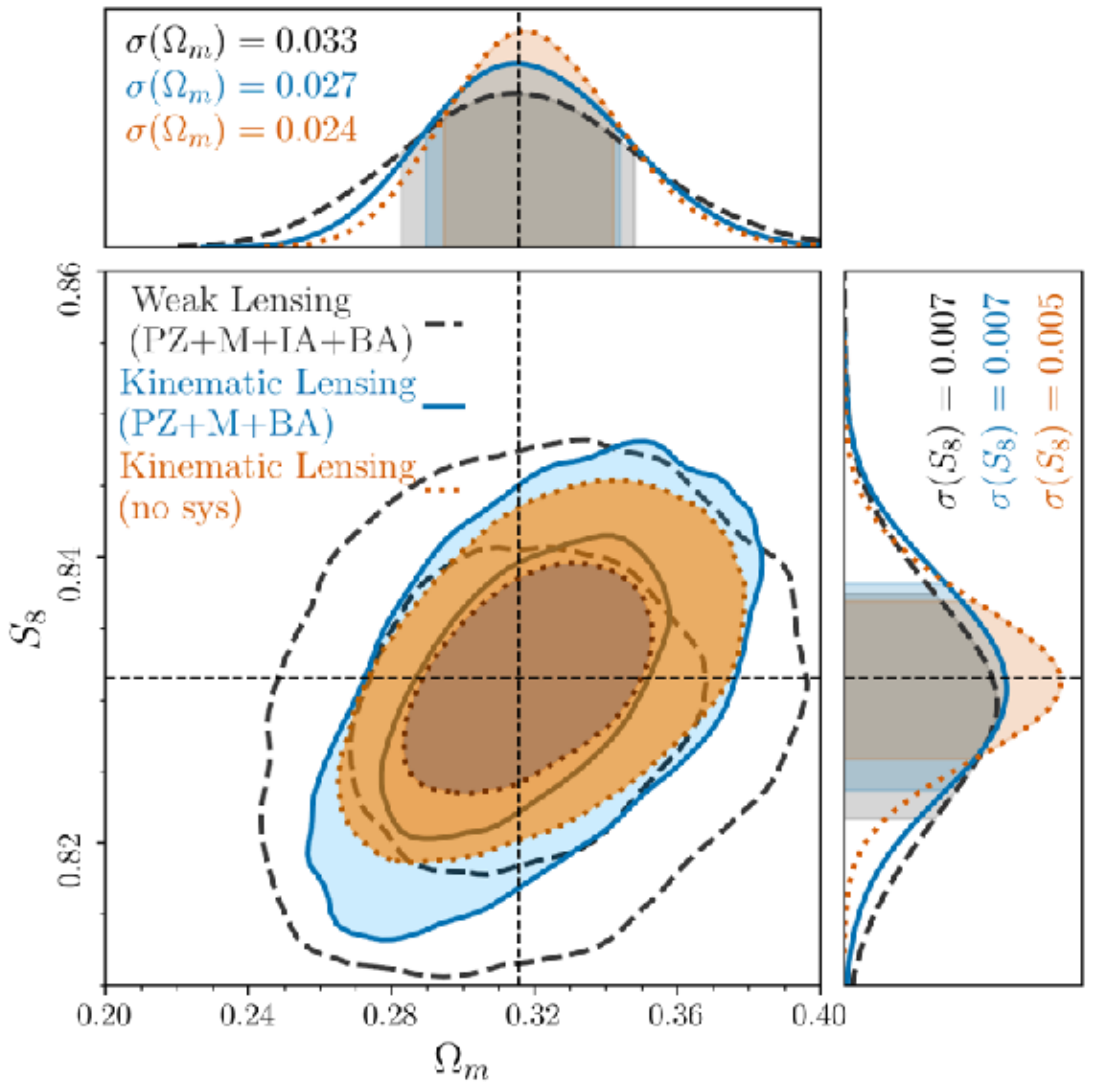
KL with *Roman Space Telescope*

Forecast result: WL v.s. KL

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

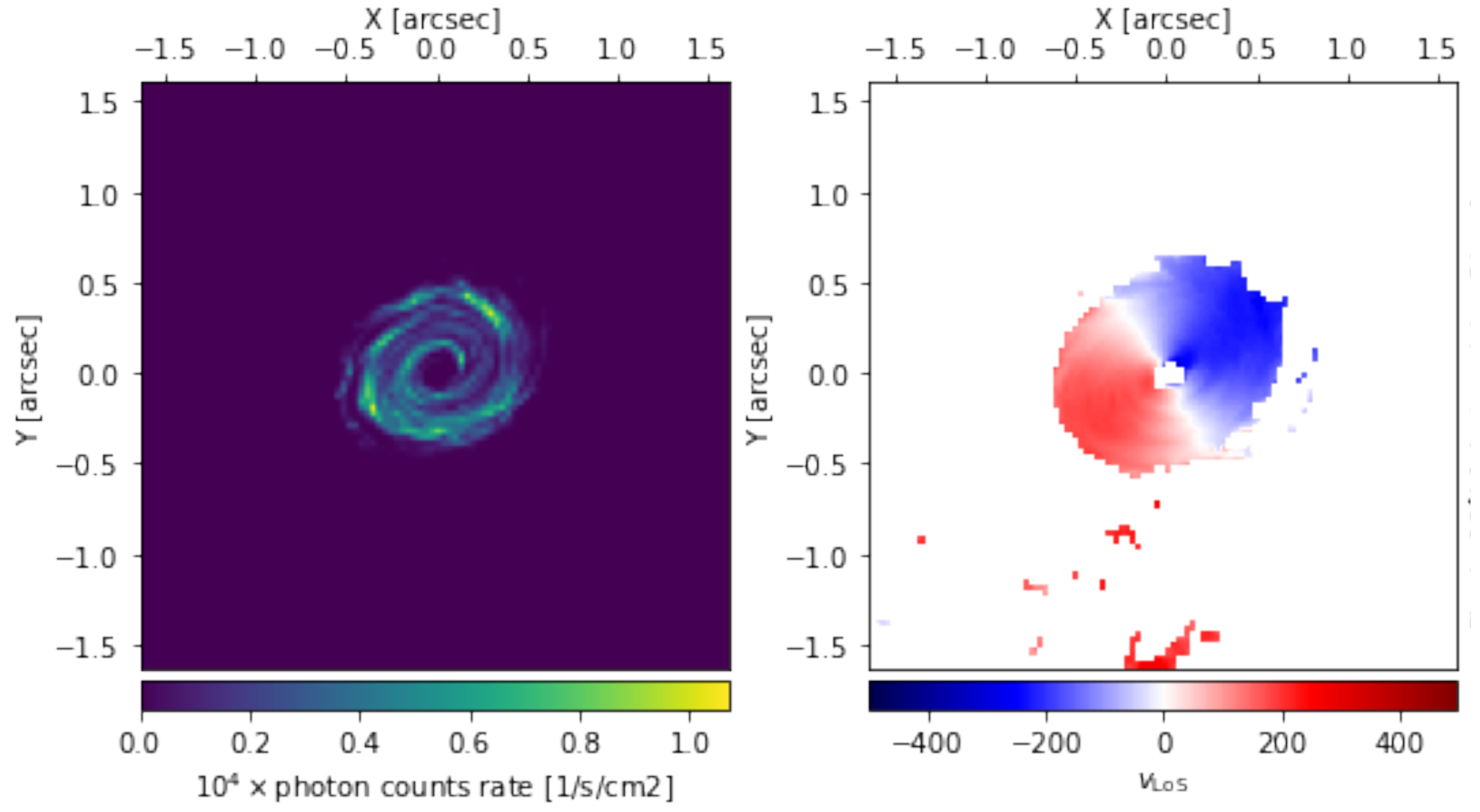


FoM	WL	KL(N_tomo = 10)		
	PZ+M+IA+BA	PZ+M+BA	PZ+M	no sys
$\mathrm{FoM}_{w_p w_a}$	10.55	38.51	47.85	59.58
$\mathrm{FoM}_{\Omega_m S_8}$	5307	9017	11533	13543



Shear Systematics

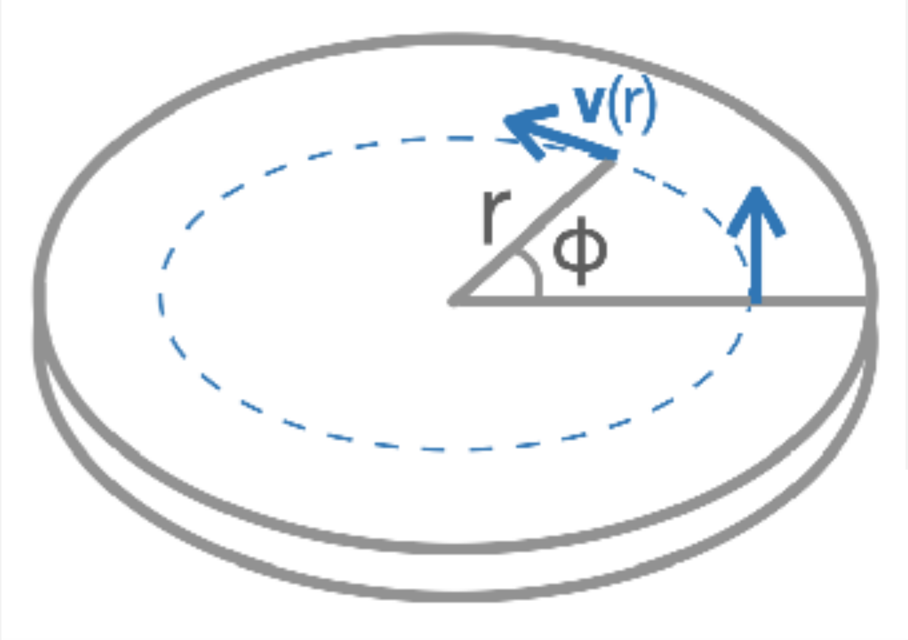
	Redshifts	Shape Measurements	Intrinsic Alignments (IA)
Traditional WL	photometric	low SN images	mitigated at modeling level
KL	spectroscopic	high SN images	measure unlensed (but aligned) shape



Exploring astrophysical uncertainties

current pipeline assumptions

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



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

Ongoing work

- **Astrophysical scatter** Shear estimates for MANGA galaxies

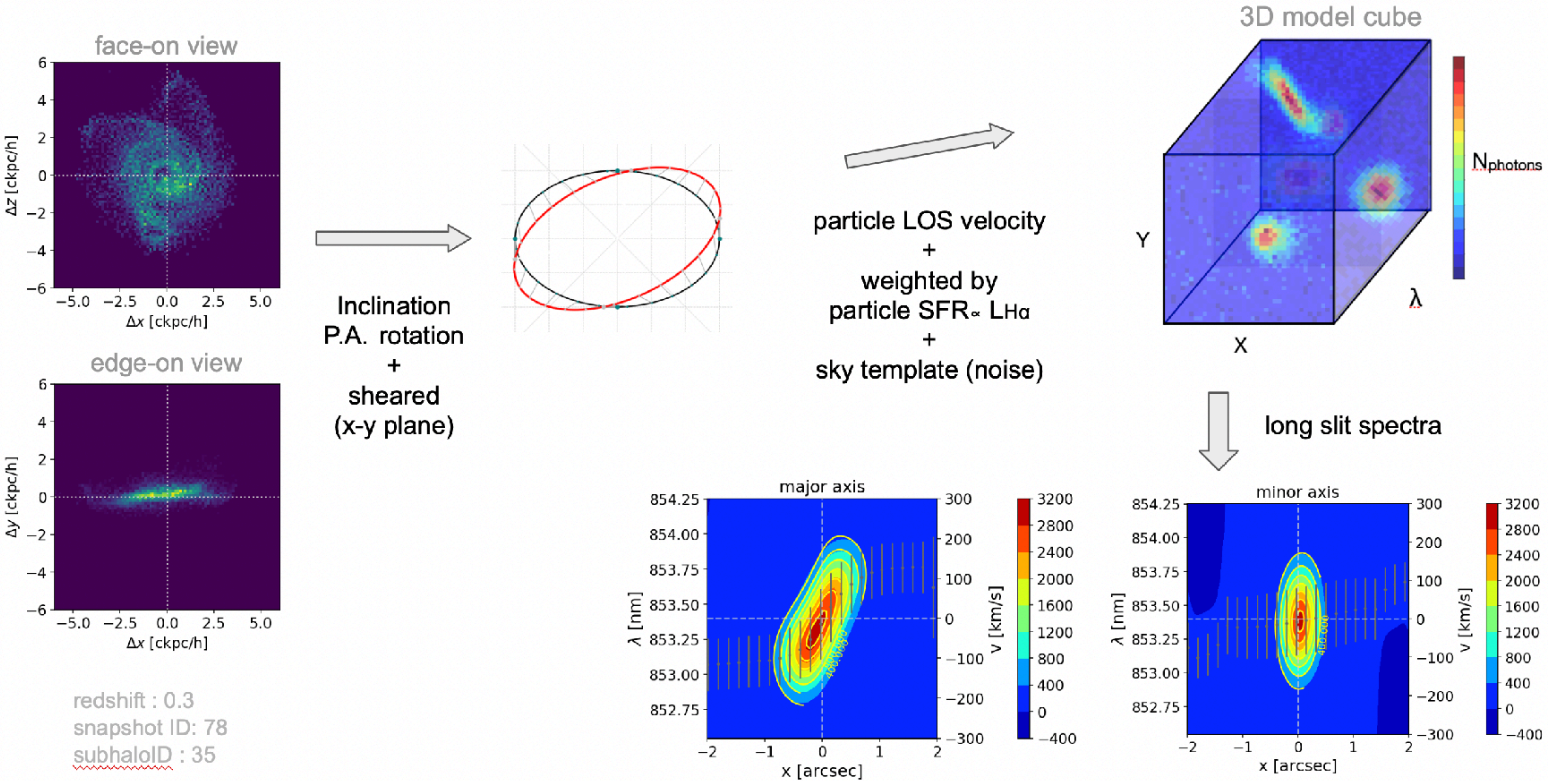
  -- Pranjal RS
- **TNG-mock pipeline** Develop realistic galaxy mock images and spectra from hydro-sims

  -- Hung-Jin Huang, Maggie Smith
- **Astrophysical scatter mitigation** Increase model complexity to account for hydro simulation-based kinematics

  -- Maggie Smith
- **Population-level systematics** Test for environmental dependence of TF-relation in TNG

  -- Yu-Hsiu Huang

TNG mocks -- mock spectra data from TNG galaxy kinematics

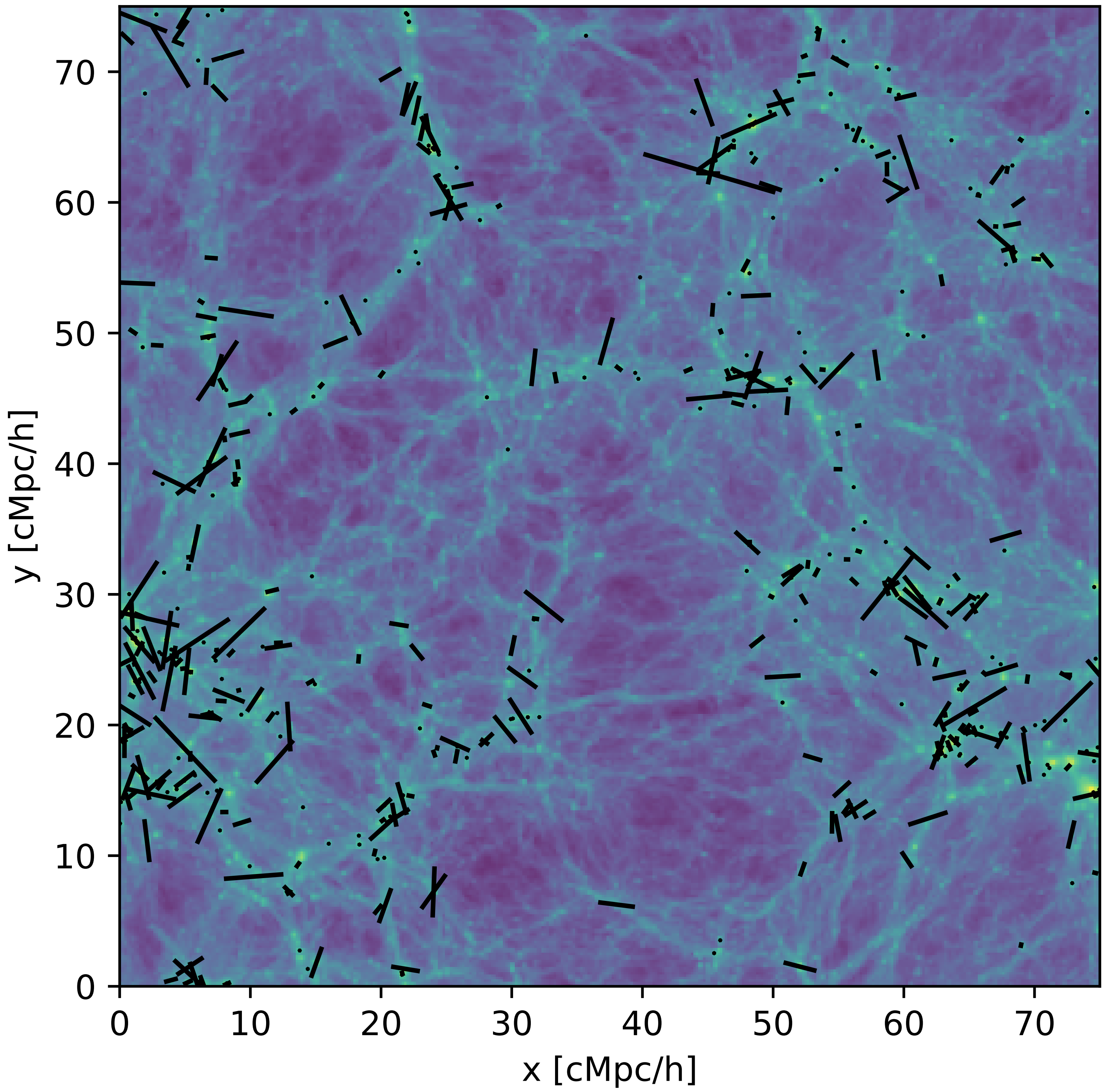


Astrophysical Biases?
TFR environmental dependence

- Used TNG-100-1 to investigate the dependency of the TF relation and its scatter on the galaxy environment

$$\hat{\varepsilon}_{\rm int} = \frac{1 - \sqrt{1 - (1 - q_z^2)\sin^2\hat{i}}}{1 + \sqrt{1 - (1 - q_z^2)\sin^2\hat{i}}} \qquad \sin\hat{i} = \frac{v_{\rm major}}{v_{\rm TF}}$$

- **Find no correlation of TFR scatter with with tidal field,** not an intrinsic alignment analog
  - still need to check disk thickness variations, may cause shear biases if correlated with disk orientation w.r.t. tidal field
  - other galaxy properties?



Shear Systematics

	Redshifts	**Shape Measurements**	**Intrinsic Alignments (IA)**	**IA analogues**	**Kinematic Substructure**
Traditional WL	photometric	low SN images	mitigated at modeling level	N/A	N/A
KL	spectroscopic	high SN images	measure unlensed (but aligned) shape	at most weak correlation of astrophysical scatter and tidal field(?)	accounted for by TFR scatter?

Summary

- Imaging + galaxy kinematics breaks degeneracy of intrinsic galaxy shape and shear
- 10x reduction in shape noise can compensate for reduced source density
    - Competitive cosmic shear constraints feasible even with Roman grism
- Developed and validated kinematic lensing analysis pipeline
- First galaxy-galaxy lensing measurement with DEEP2 in progress
- Ongoing work: characterize astrophysical systematics in simulations
    - find no environmental dependence of the Tully Fisher relation
    - optimize sample selection

- Design of optimal kinematic lensing surveys ongoing
    - Determine resolution requirements with targeted LBT, MMT, Palomar observations
    - Feasibility of KL multiple fiber pointings?