



South-Western Institute for Astronomy Research
Yunnan University

Potential to constrain satellite intrinsic alignments with weak lensing peak statistics

Zuhui Fan
(SWIFAR, Yunnan University)

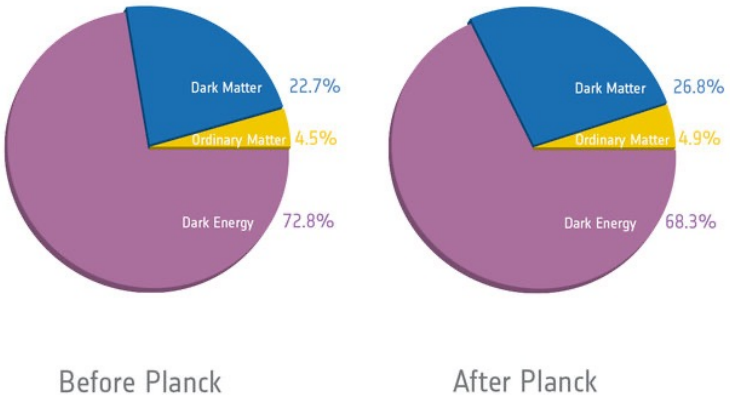
Oct-Nov. 2024 @ KIAS workshop

Outline

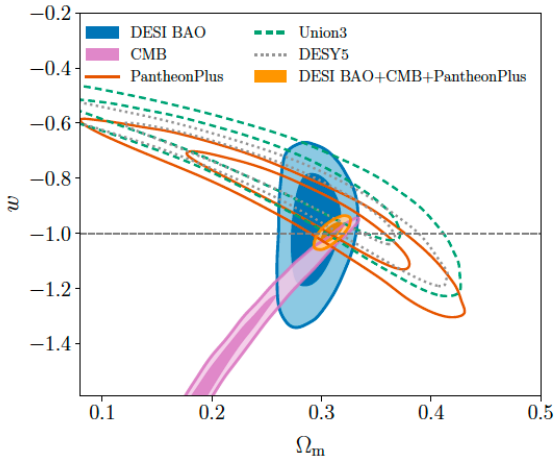
- Introduction
- Simulation studies of the impact of IA on WL peaks
- Modeling of IA impacts on WL peak statistics
- Summary

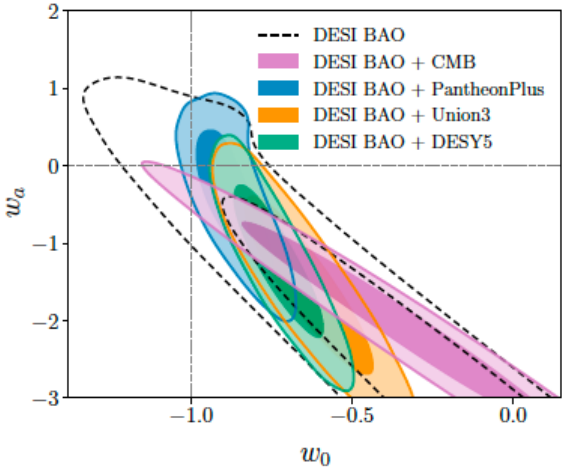
Introduction

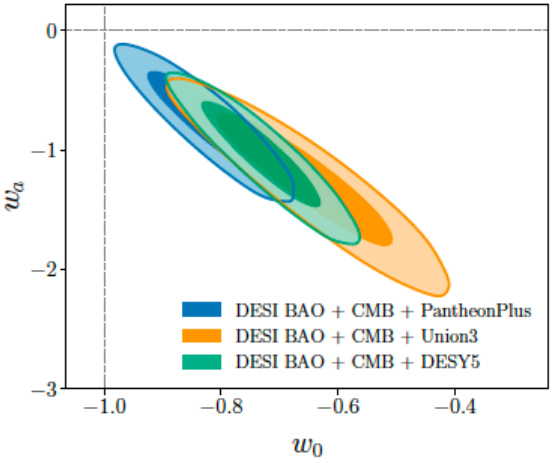
Cosmological observations play important roles in probing the Universe.



Understanding the nature of
the dark universe is a key driver
for current and upcoming large surveys.





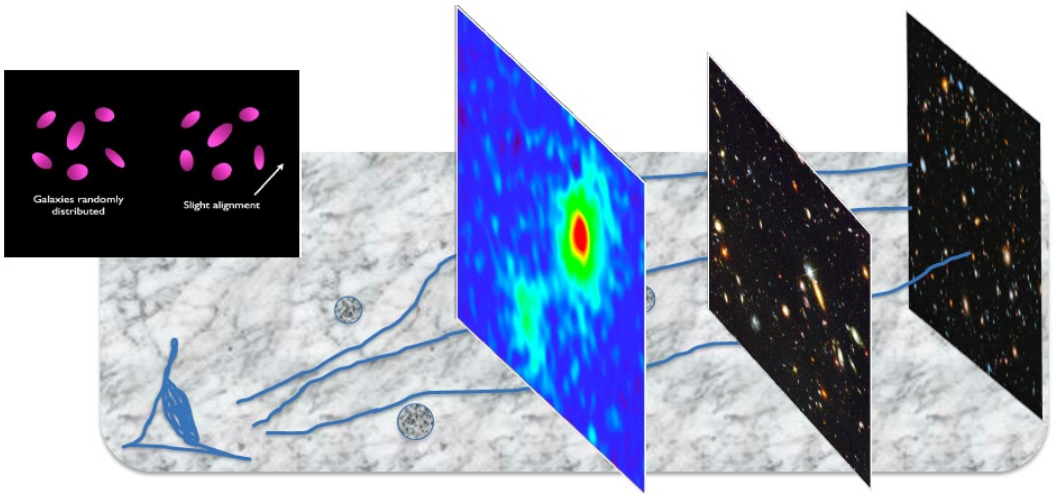


DESI Y1, arXiv: 2404.03002

Among different probes, the weak lensing effect is unique

Large-scale structures → bend the light rays gravitationally
Observables: tiny shape distortion and flux change → shear and magnification

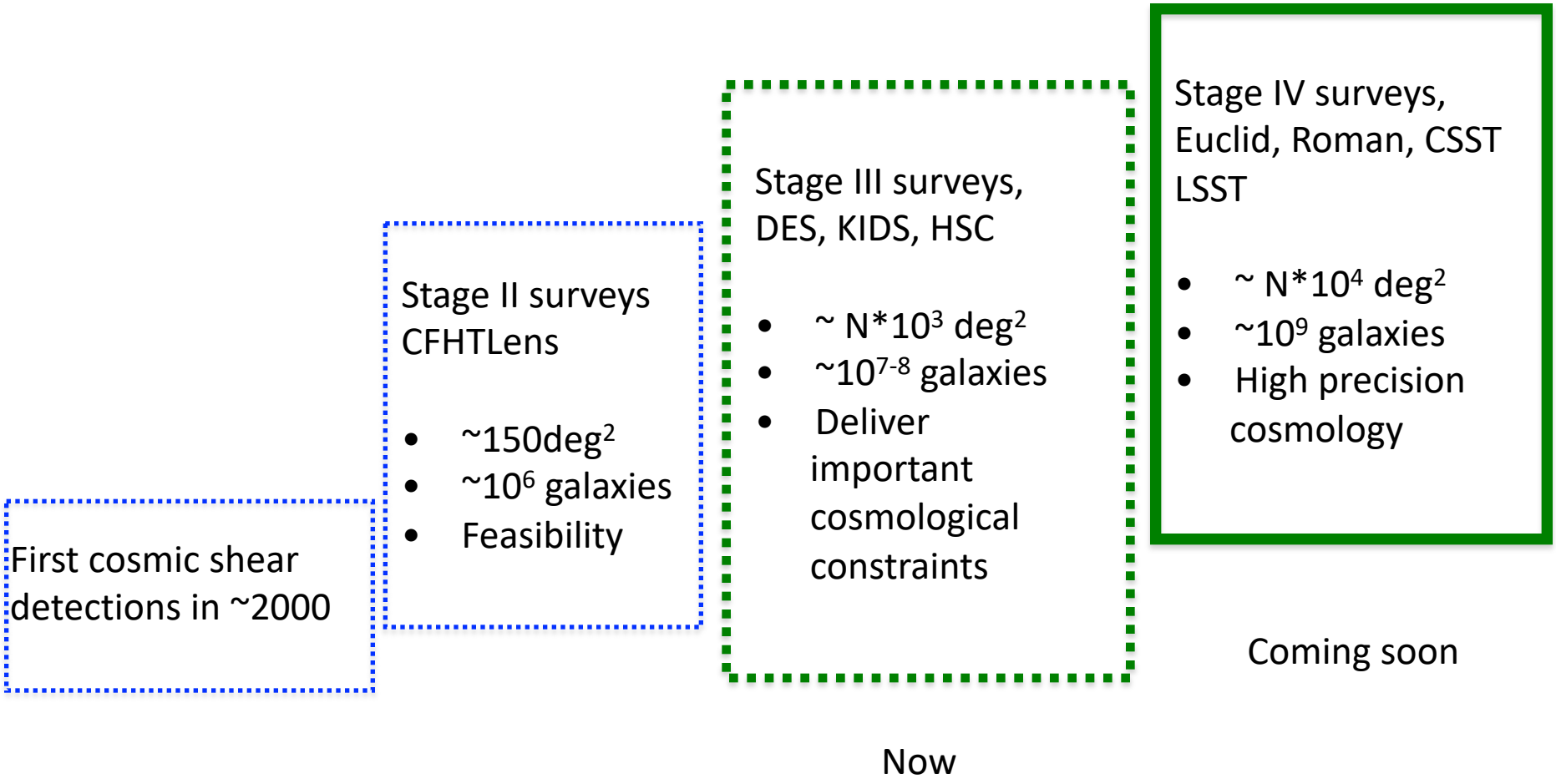
Gravitational in origin → unique probe to the dark side of the universe
dark matter and dark energy, law of gravity
Sensitive to both the cosmic expansion and the large scale structures
Cross correlation with galaxies and gas observables
-- probe the relation between dark matter and the luminouse parts
and constrain astrophysical process



Weak lensing signals are weak → large sample

The developments of observing facilities with large FoV and megapixel CCD detectors have revolutionized imaging surveys, allowing us to accurately measure the shapes of far-away galaxies

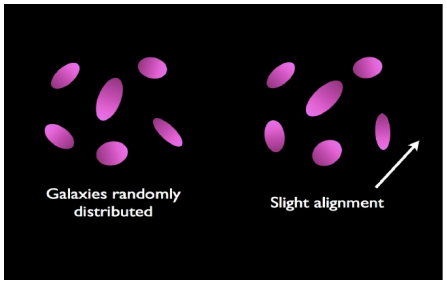
→ Weak lensing cosmology → statistical in nature

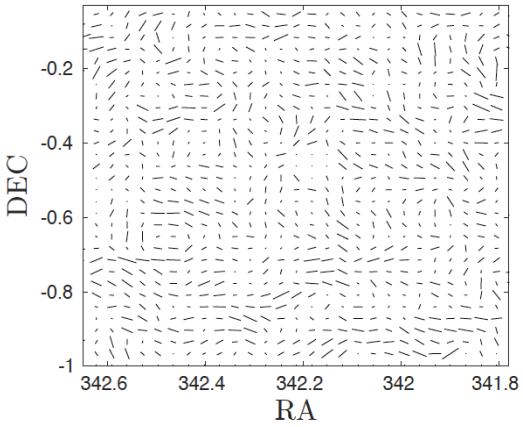


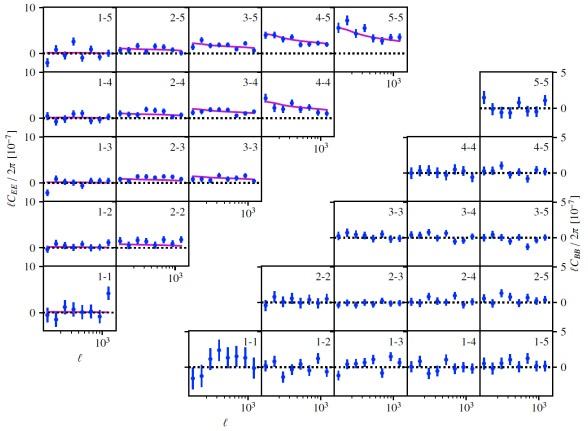
Statistical analyses – cosmic shear 2pt is the primary statistics

(3×2pt: cosmic shear+ galaxy clustering +galaxy-galaxy lensing)

Extensive studies about different systematics

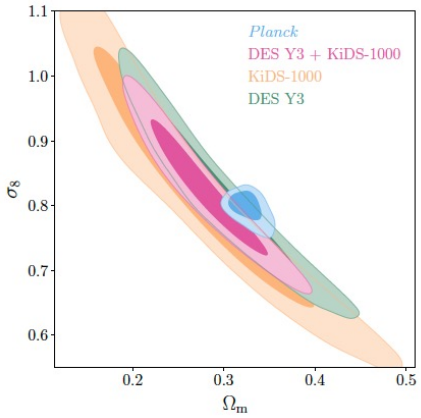


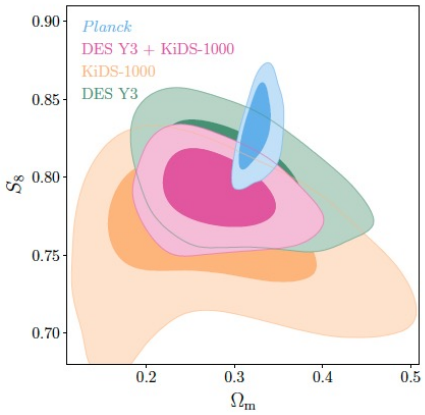


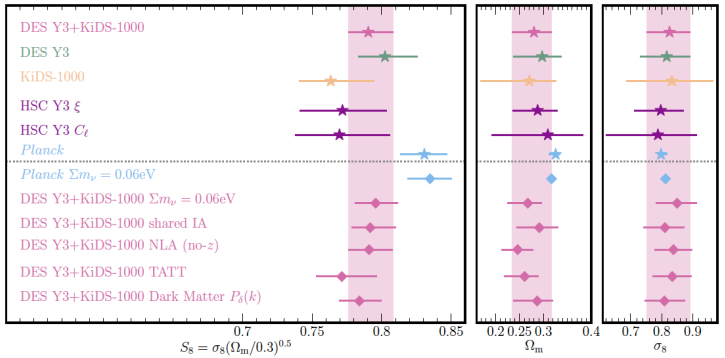


Revealed potential S8 tension

Heymans et al. 2021 (KiDS 1000)

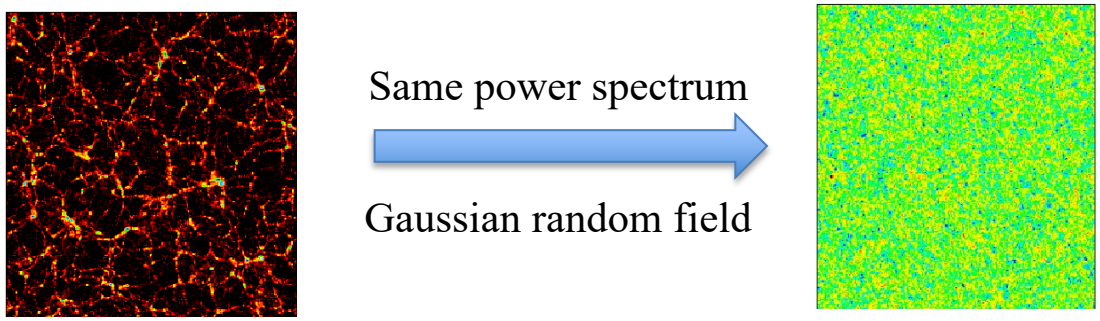






Abbott et al. 2023, DES Y3+KiDS-1000

Because of the non-Gaussian nature of the cosmic structures, statistics beyond the two-point analyses are needed to fully explore the cosmological Information embedded in the WL data



3pt correlation. (e.g., Fu et al. 2014, Burger et al. 2023)
Higher order CDF (e.g., Anbajagane et al. 2023)
Minkowski functionals (e.g., Grewal et al. 2022, Armijo et al. 2024)
Machine learning (e.g., Ribli et al. 2019, Fluri et al. 2022, Lu et al. 2023)
Scattering transformation (e.g., Cheng & Menard 2021, Cheng et al. 2024)
……

Peak statistics (e.g., Liu,X. et al. 2015, Liu,J. et al. 2015, Liu, X. et al. 2016, Kacprzak et al. 2016, Martinet et al. 2018, Shan et al. 2018, Zurcher et al. 2022, Liu,X. et al. 2023, Harnois-Deraps et al. 2024, …)

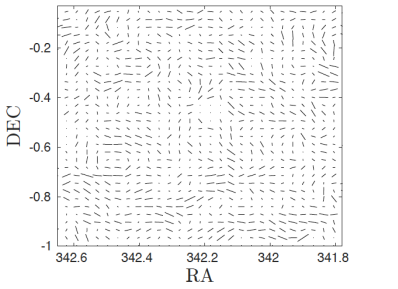
Weak lensing peak statistics

LOS matter concentrations (× lensing efficiency) → high WL signals → peaks in the WL mass maps → nonlinear and non-Gaussian features → cosmological inferences

To predict the cosmological dependences

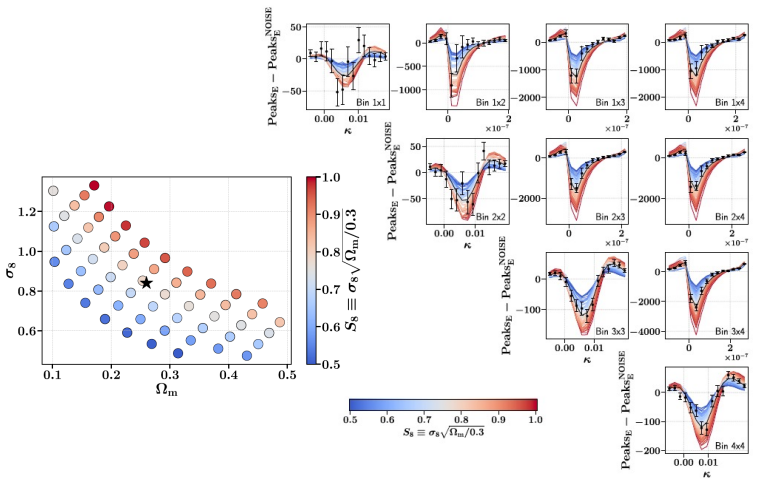
Run large sets of simulations to build numerical templates

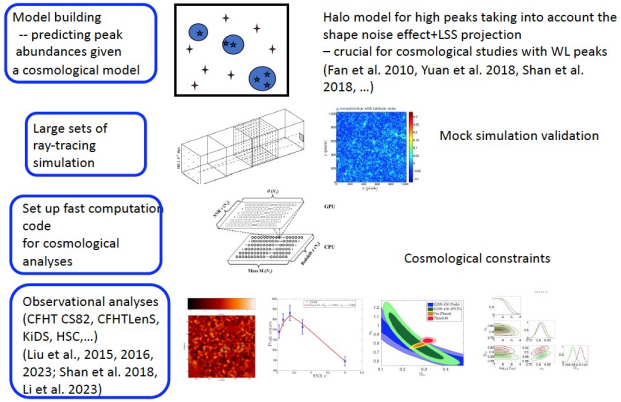
Incorporate theoretical modeling – our approach -- valid for high peaks



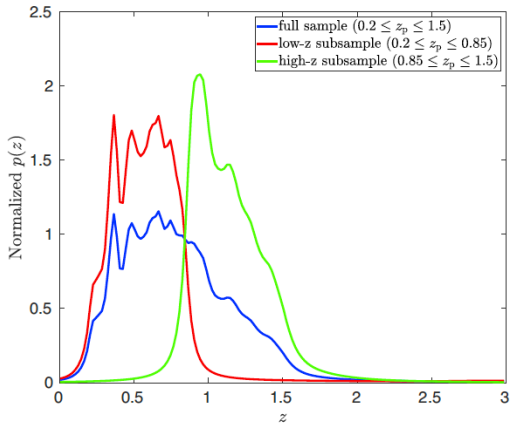
Liu,X. et al. 2015

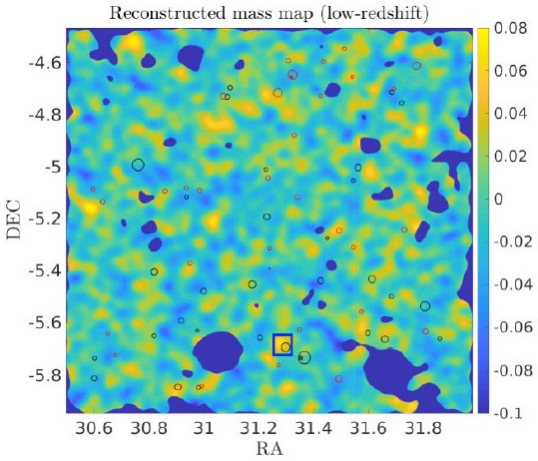
e.g., Zurcher et al. 2022, DES Y3

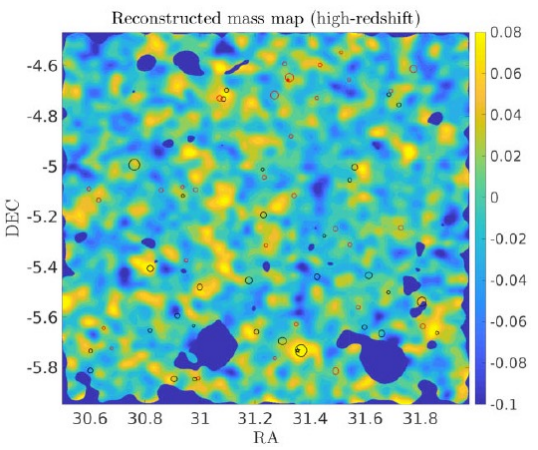


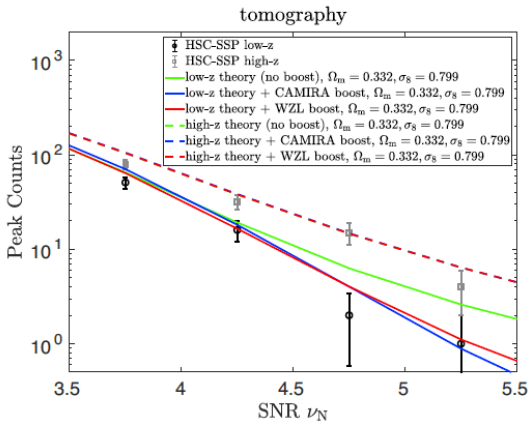


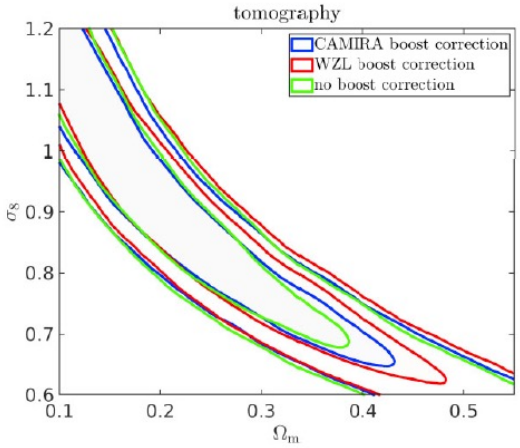
Cosmological constraints from HSC-SSP tomographic WL peak abundances (Liu et al. 2023) – high peaks with the model approach

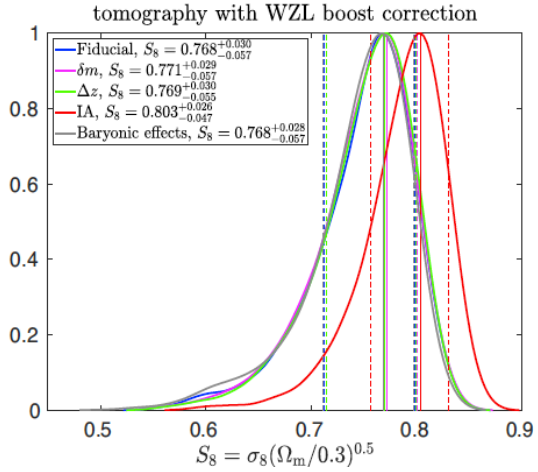










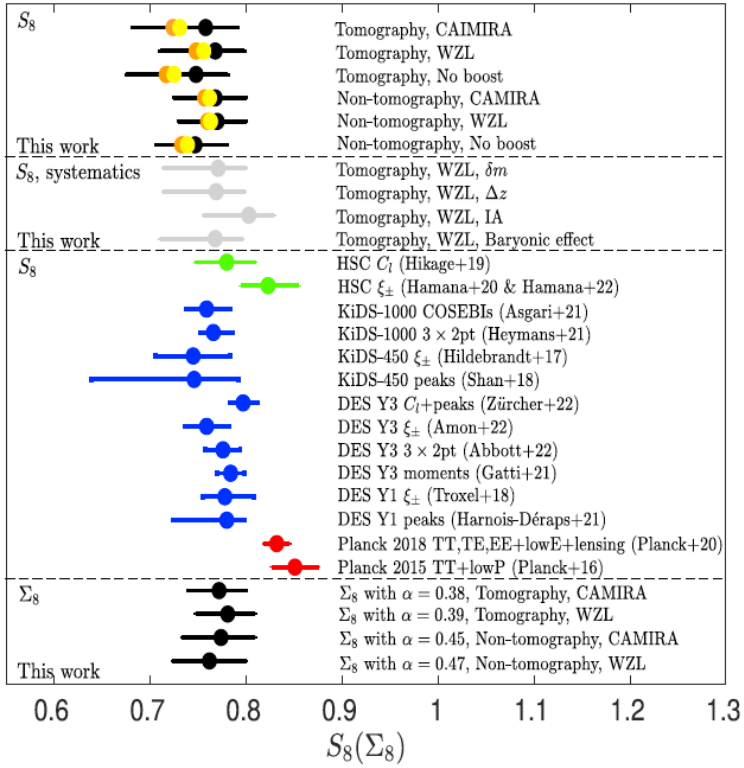


We also analyze other systematics: photo-z, m, baryonic effect – insignificant

IA effect is less than but close to 1σ depending on the strength of IA

Table 2. Summary for S_8 and Σ_8 constraints of mock simulation analyses and real observations.

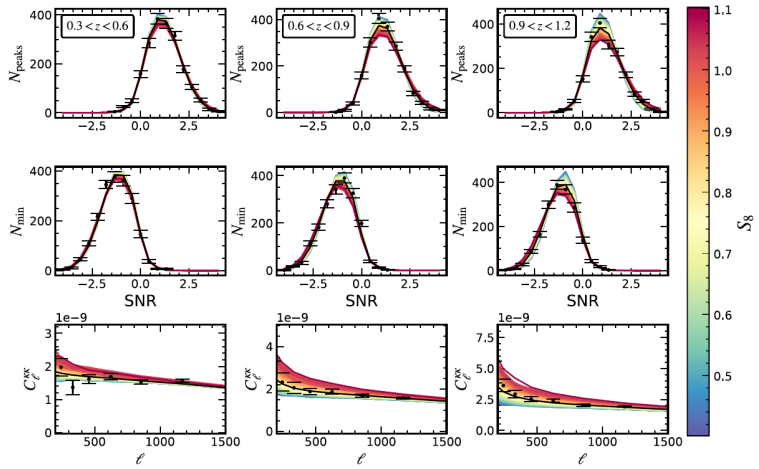
		S_8	Σ_8	α
Mock	Non-tomography	$0.778^{+0.027}_{-0.035}$	$0.781^{+0.032}_{-0.033}$	0.457 ± 0.014
	Tomography	$0.791^{+0.022}_{-0.036}$	$0.778^{+0.025}_{-0.028}$	0.433 ± 0.013
	Four-bin tomography	$0.792^{+0.025}_{-0.042}$	$0.776^{+0.028}_{-0.028}$	0.401 ± 0.014
Obs.	Non-tomography (CAMIRA)	$0.768^{+0.032}_{-0.043}$	$0.774^{+0.035}_{-0.040}$	0.462 ± 0.013
	Tomography (CAMIRA)	$0.758^{+0.033}_{-0.076}$	$0.772^{+0.028}_{-0.032}$	0.382 ± 0.013
	Non-tomography (WZL)	$0.770^{+0.030}_{-0.040}$	$0.762^{+0.038}_{-0.038}$	0.469 ± 0.015
	Tomography (WZL)	$0.768^{+0.030}_{-0.057}$	$0.781^{+0.028}_{-0.033}$	0.381 ± 0.012

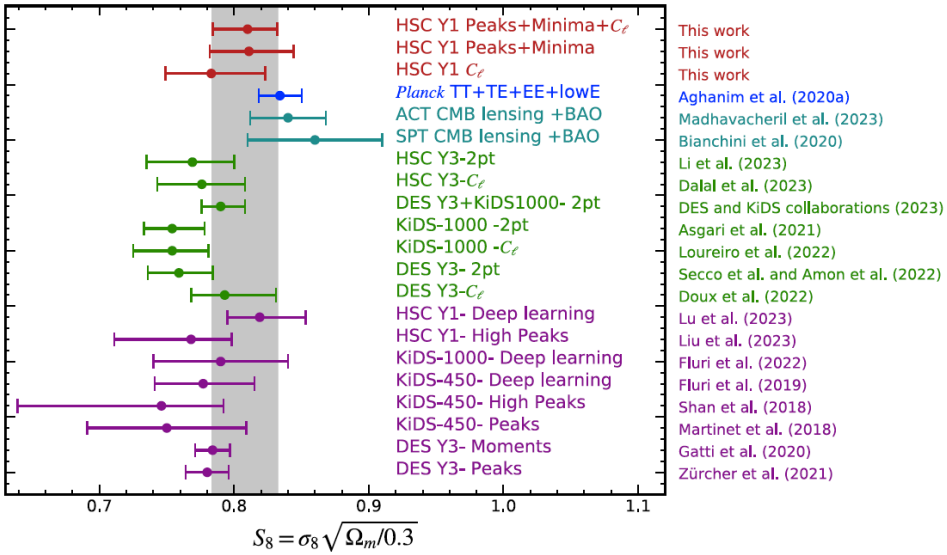


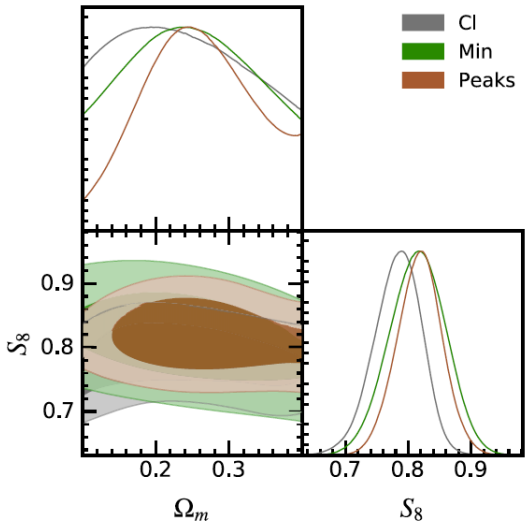
* Consistent with HSC correlation studies
* 2-bin tomography → reduce the uncertainty of $\Sigma_8 = \sigma_8(\Omega_m/0.3)^\alpha$ ($\alpha \approx 0.38$) by a factor of ~1.3
* Dilution and IA are becoming important

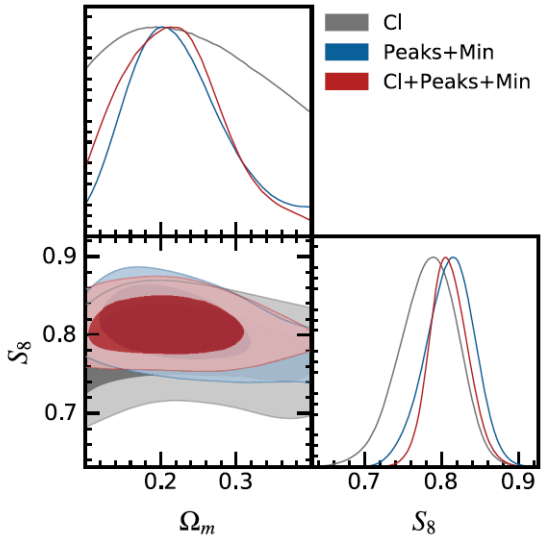
Cosmology from WL peaks+minima with HSC first year data (Marques et al. 2024)

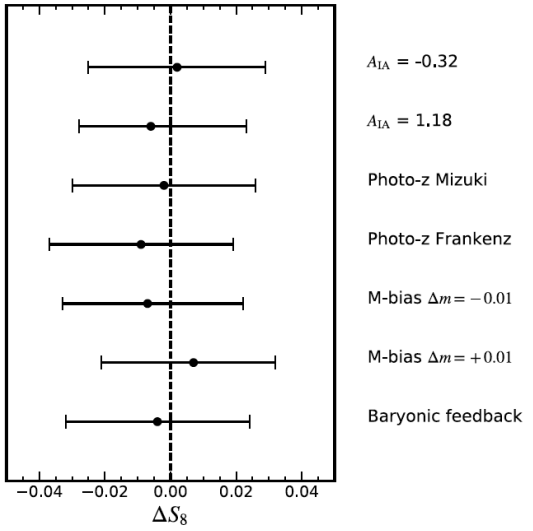
-- emulator-based approach









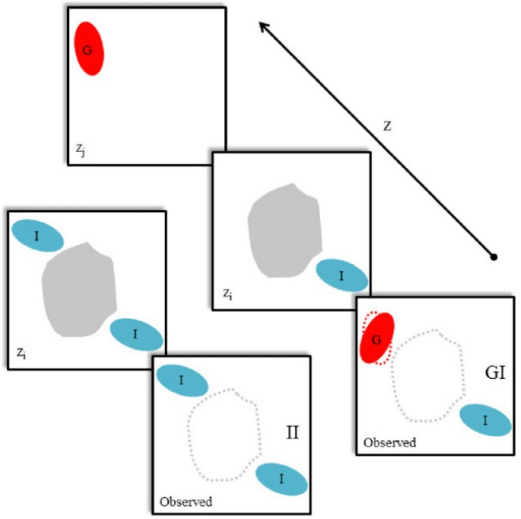


With the increase of WL statistics, systematic effects will be the dominant factors limiting the constraining power of WL cosmological studies. Galaxy intrinsic alignments (IA) is one of main systematics.

$$\gamma^{obs} = \gamma + \gamma^{I} \Rightarrow \underset{GG}{<\gamma_i^{obs}\gamma_j^{obs}>} = \underset{GG}{<\gamma_i\gamma_j>} + \underset{GI}{<\gamma_i^{I}\gamma_j>} + \underset{GI}{<\gamma_i\gamma_j^{I}>} + \underset{II}{<\gamma_i^{I}\gamma_j^{I}>}$$

lensing signal

Intrinsic ellipticity



The IA effects on WL 2pt analyses have been studied systematically and extensively.

Their impacts on WL peak statistics are much less investigated

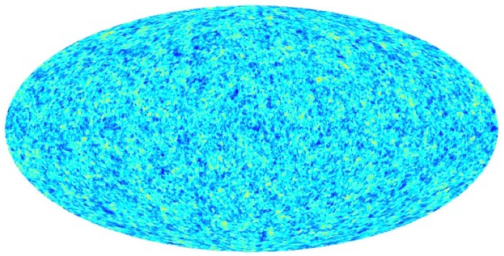
-- only show some effects from specific simulations

-- lack of systematic analyses and modeling

Troxel & Ishak 2015, Phys. Rep. 558, 1

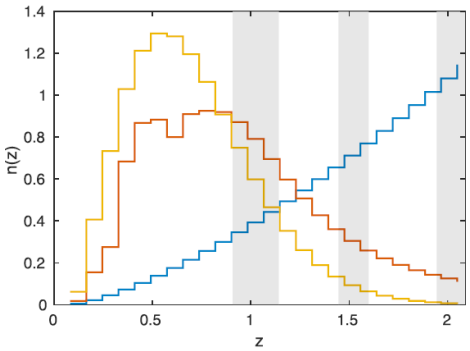
- **Simulation studies of IA impacts on WL peak statistics** (Zhang et al. 2022, ApJ)

Using cosmological simulations with semi-analytical galaxy formation (Wei et al. 2018)



Central and satellite galaxies (Guo et al. 2013, Luo et al. 2016)
Bulge to total flux ratio B/T>/<0.6 → early/late type galaxies

Early type: follow their host dark matter halos
Late type: disks are perpendicular to the angular momentum of their host halos

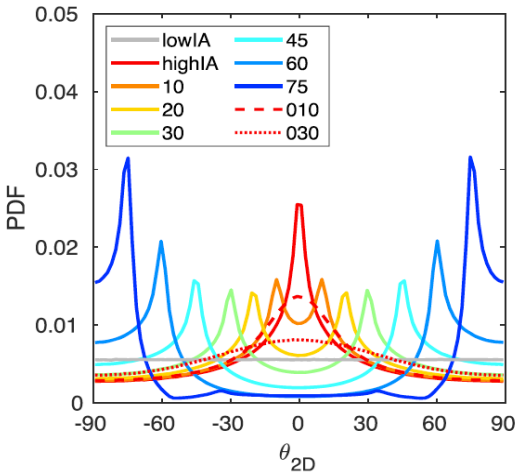


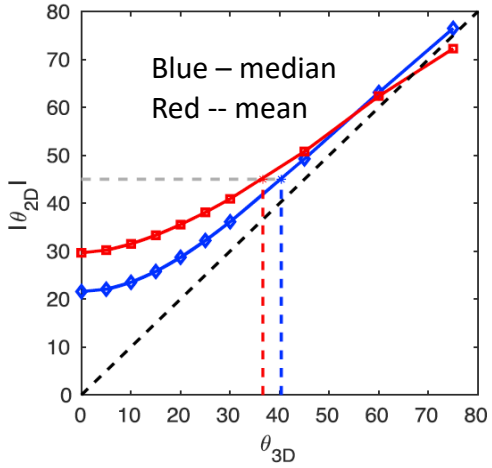
red: Euclid-like
yellow: KiDS-like).

We change satellite IA to study their impacts on WL peaks
High-IA : radially aligned satellites
Low-IA: randomly orientated satellites

$$f(\theta_{3D})d\theta_{3D}\,d\phi = A\exp\left[-\frac{1}{2}\left(\frac{\theta_{3D}-\theta_0}{\sigma_\theta}\right)^2\right]d\theta_{3D}\times\sin(\theta_{3D})d\phi$$

Redshift distribution	ng (arcmin^{-2})		satellite alignment angle (°)	satellite alignment with dispersion (°)
KiDS	8		HighIA, 5,10, 25,20, 25, 30, 45, 60, 75, LowIA	Mean=0, σ=10,20,30 Mean=30, σ=10, 20, 30, 45, 60, 75
Euclid/CSST	30	20	HighIA, 5,10, 25,20, 25, 30, 45, 60, 75, LowIA	Mean=0, σ=10,20,30 Mean=30, σ=10, 20, 30, 45, 60, 75
z=[0.91,1.14]	20		HighIA, 5,10, 25,20, 25, 30, 45, 60, 75, LowIA	
z=[1.45,1.60]	20		HighIA, 5,10, 25,20, 25, 30, 45, 60, 75, LowIA	
z=[1.94,2.09]	20		HighIA, 5,10, 25,20, 25, 30, 45, 60, 75, LowIA	





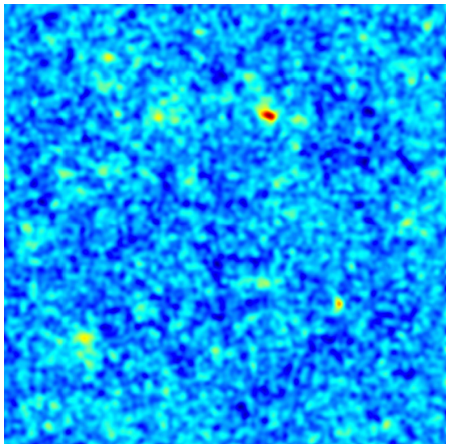
We change satellites' alignments to generate different IA samples.

Centrals' IA as Wei et al.

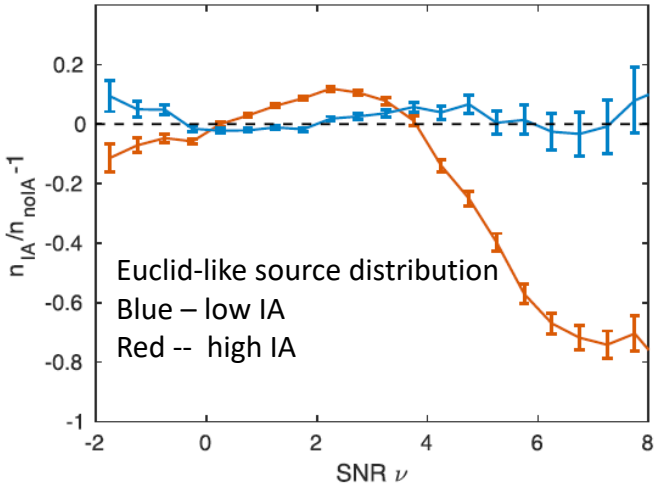
From “observed” galaxy ellipticities → convergence maps → peaks

156 * (3*3 deg^2)~1400 deg^2

For comparison, we also generate no-IA samples by first randomly rotating all the galaxies to eliminate IA and then adding lensing signals

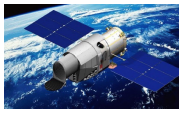


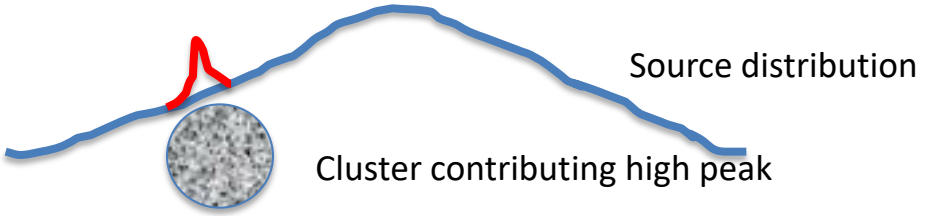


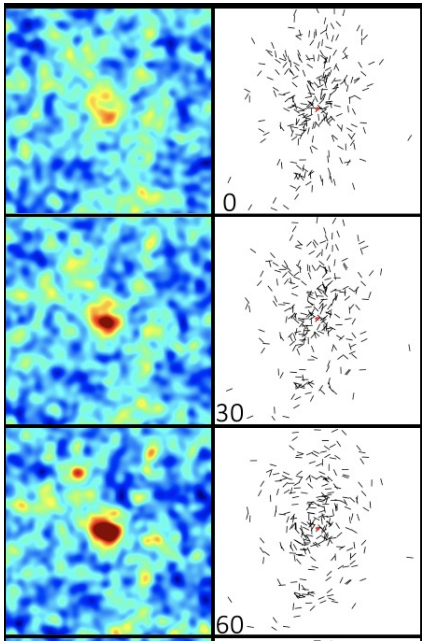


Satellite IA plays the dominant role affecting peak statistics

How do the IA effects arise?







Matched peak comparison

Source sample contains cluster member galaxies

→ Affect their host cluster peak signals

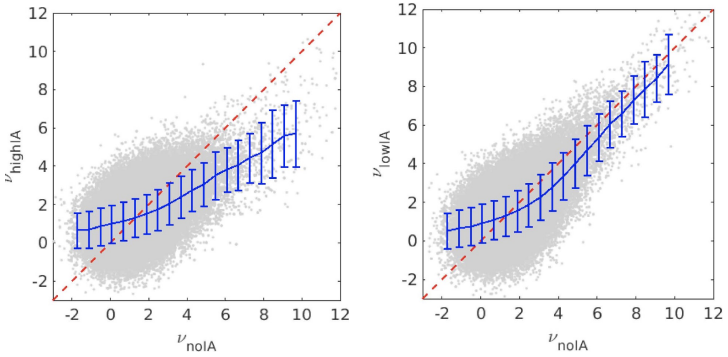
→ Closely related to the dilution effect

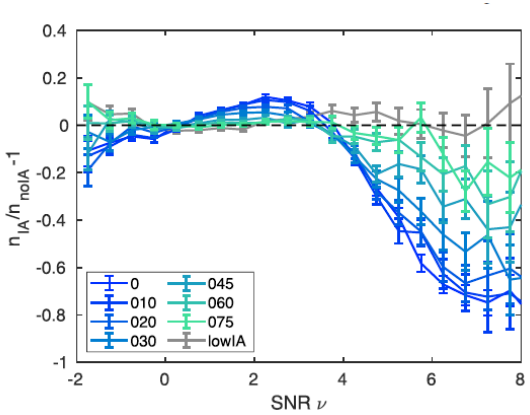
$$\frac{\sum_{N_b}\gamma+\sum_{N_c}e}{N_b+N_c}\Big/\left(\frac{\sum_{N_b}\gamma}{N_b}\right)=\frac{N_b}{N_b+N_c}\left(1+\frac{\sum_{N_c}e}{\sum_{N_b}\gamma}\right)$$

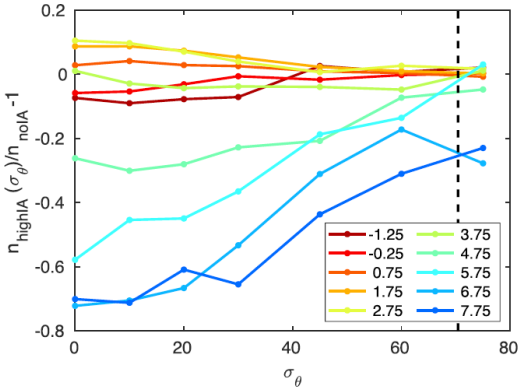
dilution IA

High peaks are affected more significantly

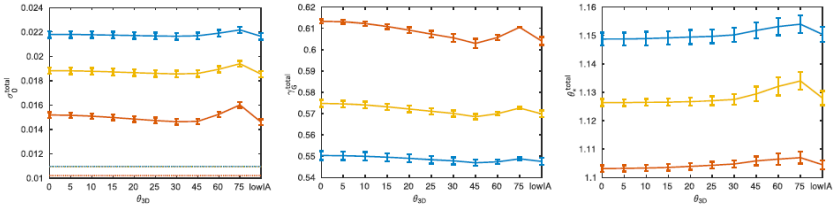
For Euclid-like, ~40-20% decrease of peaks with S/N>~4 for σ_θ ~40°-80°

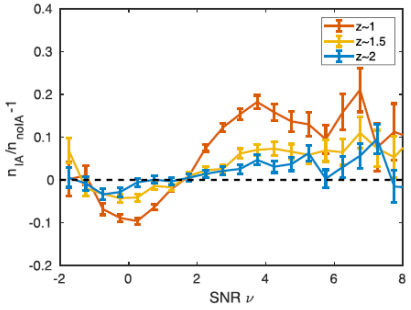


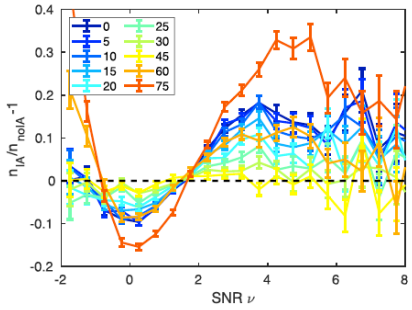


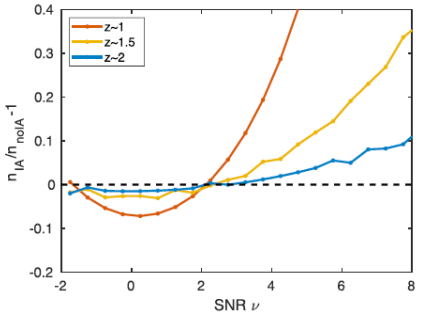


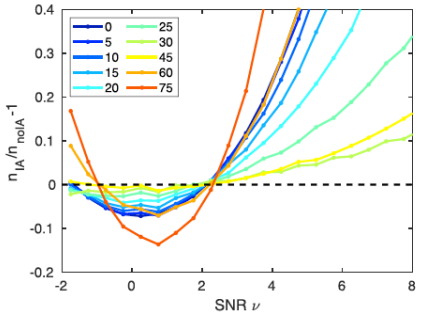
For source galaxies in narrow redshift bins











Pure Gaussian model comparisons

-- The behaviors are different: satellite IA affects cluster WL signals insignificantly because no foreground cluster members are in the source sample

-- IA contributes (both central and satellite) **additional noise** → affects peak statistics

Summary of IA effects on WL peaks

-- Decrease cluster WL signals because of their members in the shear sample

-- Change the noise properties

Incorporate IA into our model

-- reduce the cosmological bias

-- constrain IA simultaneously, particularly satellite IA

- **Modeling the impact of IA on WL peaks** (Zhang et al. 2024, in preparation)

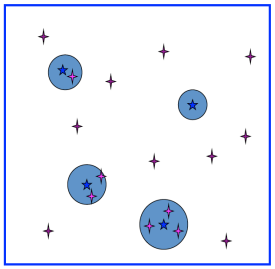
Theoretical model – Halo based (Fan et al. 2010, Yuan et al. 2018)

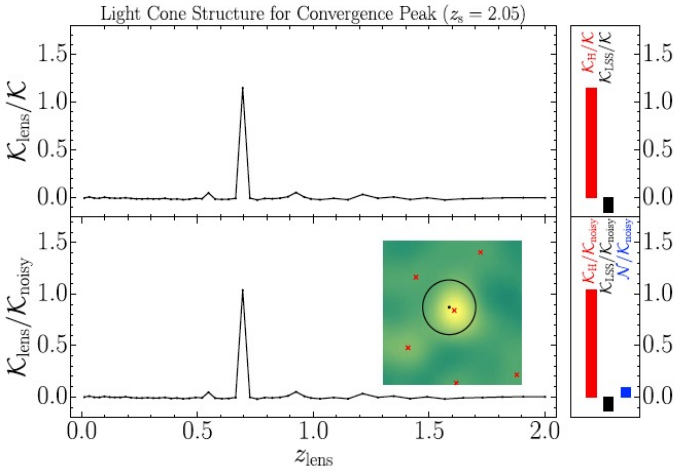
Assumption: Single massive halos contribute dominantly to WL peaks ($M \geqq M_* \sim 10^{14} h^{-1} M_{sun}$)

→ valid for high peaks – **theoretically similar to cluster abundance, but different observables without the need to calibrate the mass-observable relation**

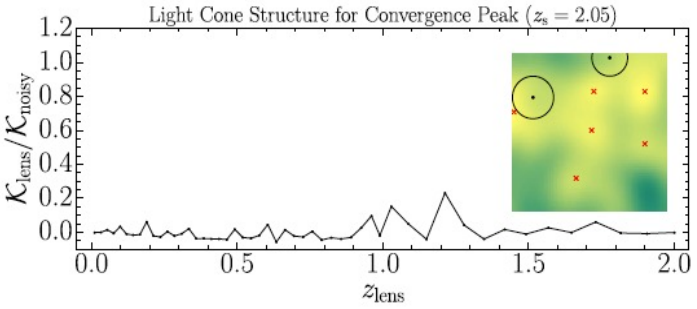
Including the shape noise and the LSS projection effects

→ adopt Gaussian approximation→ **forward modelling approach**





high peak



low peak

Physical ingredients: halo density profile, HMF, cosmic distances

Gaussian random field

$$\mathcal{K} = \mathcal{K}_{\rm H} + \mathcal{K}_{\rm LSS} + \mathcal{N} \qquad n_{\rm peak}(\nu)d\nu = n^{c}_{\rm peak}(\nu)d\nu + n^{n}_{\rm peak}(\nu)d\nu$$

$$n^{c}_{\rm peak}(\nu) = \int dz\, \frac{dV(z)}{dz d\Omega} \int_{M_*}^{\infty} dM\; n(M, z) \times \int_0^{\theta_{\rm vir}} d\theta (2\pi\theta) \hat{n}^{c}_{\rm peak}(\nu, M, z, \theta)$$

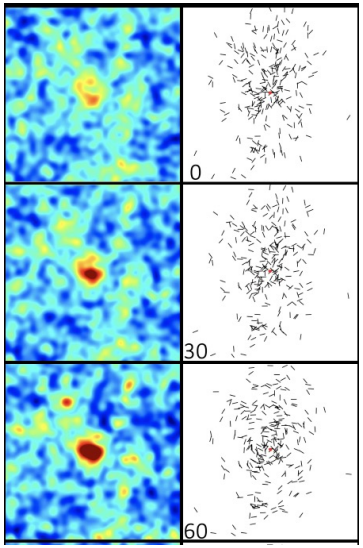
$$n^{n}_{\rm peak}(\nu) = \frac{1}{d\Omega} \times \left\{ n_{\rm ran}(\nu) \left[d\Omega - \int dz\, \frac{dV(z)}{dz} \int_{M_*}^{\infty} dM\; n(M, z)(\pi\theta^2_{\rm vir}) \right] \right\},$$

$$\hat{n}^{c}_{\rm peak}(\nu, M, z, \theta) = \exp\left[-\frac{(\mathcal{K}^1_{\rm H})^2 + (\mathcal{K}^2_{\rm H})^2}{\sigma_1^2} \right] \times \left[\frac{1}{2\pi\theta_*^2} \frac{1}{(2\pi)^{1/2}} \right] \exp\left[-\frac{1}{2} \left(\nu - \frac{\mathcal{K}_{\rm H}}{\sigma_0} \right)^2 \right] \times \int_0^{\infty} dx \left\{ \frac{1}{[2\pi(1-\gamma^2)]^{1/2}} \times \exp\left[-\frac{[x + (\mathcal{K}^{11}_{\rm H} + \mathcal{K}^{22}_{\rm H})/\sigma_2 - \gamma(\nu - \mathcal{K}_{\rm H}/\sigma_0)]^2}{2(1-\gamma^2)} \right] \times F(x) \right\}$$

Extendable to include systematics into the model

→ photo-z errors, shear measurement errors, baryonic effects, **boost** & **IA effect**, …

IA changes the lensing profile of the halos



Source sample contains cluster member galaxies

$$\frac{\Sigma_{N_b}\gamma+\Sigma_{N_c}e}{N_b+N_c}\Big/\left(\frac{\Sigma_{N_b}\gamma}{N_b}\right)=\frac{N_b}{N_b+N_c}\left(1+\frac{\Sigma_{N_c}e}{\Sigma_{N_b}\gamma}\right)$$

dilution IA

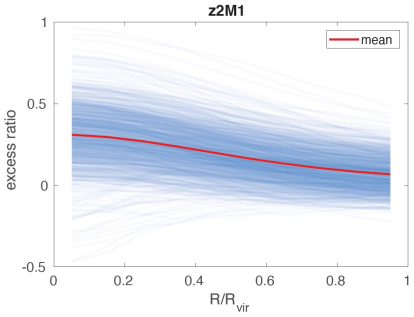
Calculating the lensing profile changes

-- Estimate the member excess ratio from clusters and the source galaxy catalog considering different bins of (z, M)

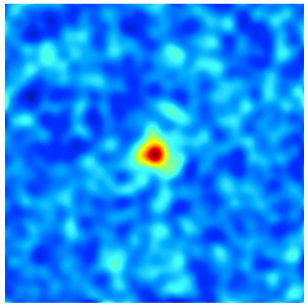
-- Single halo simulations without random shape noise to obtain the profile change

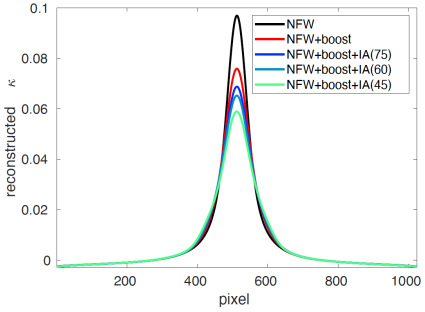
-- Adding random shape noise → noise change is calculated by considering the number density change and IA

2D Excess fraction

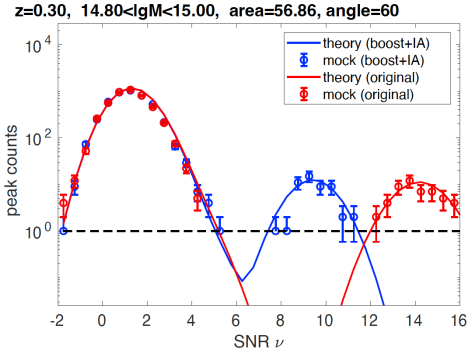


Profile change





One halo peak model & data



Overall model modifications

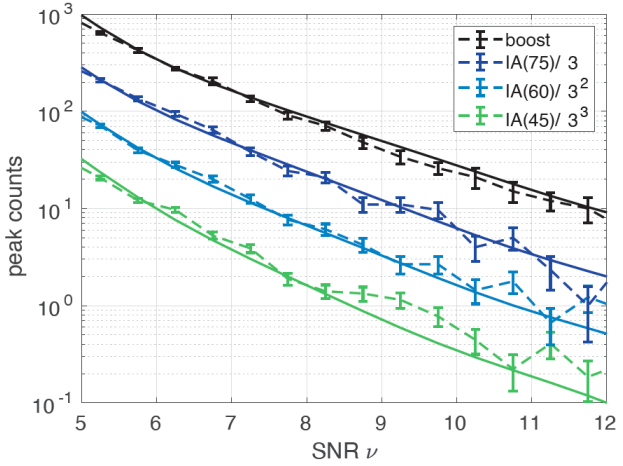
-- Include the profile change in the model from single halo simulations for different bins of (z,M)
-- Take into account the noise change
  -- single halo simulations → noise change inside massive halos
  -- galaxy number density change + II+GI from IA power spectrum model

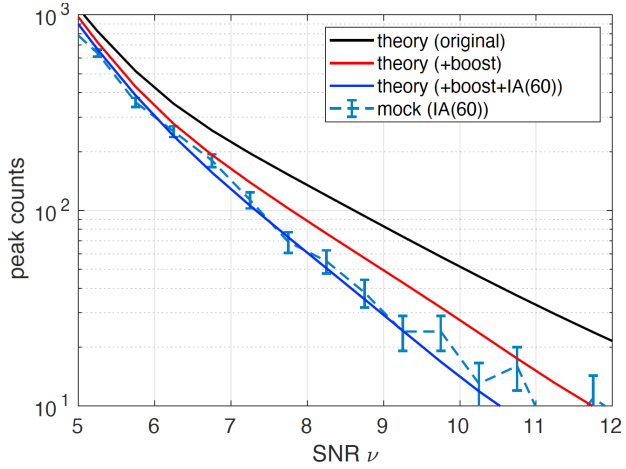
$$n_{\rm g} S_{\rm eff} = \sum n_{\rm g}^{\rm halo} S_{\rm eff}^{\rm halo} + n_{\rm g}^{\rm field} S_{\rm eff}^{\rm field}$$

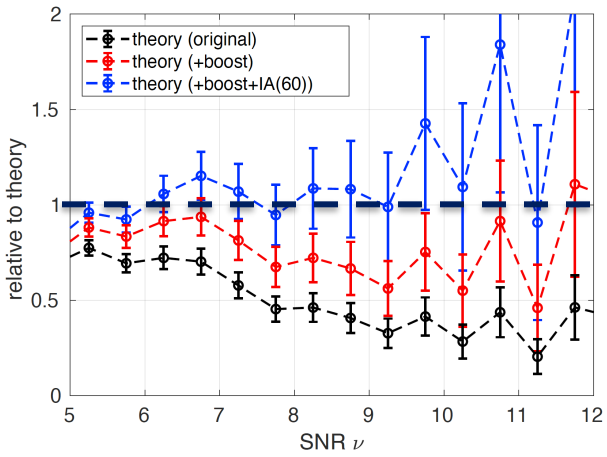
-- S/N scaling is considered
  -- S/N for 'observed' peaks can only be defined using average shape noise
  -- In model calculation, both in the halo regions and the field region, the noise is different from the average noise

Results： our model works very well for radially aligned satellites with dispersion σ>=45^o (Euclid-like redshift distribution with n_g=30 arcmin^{-2}, and area ~1400 deg^2)

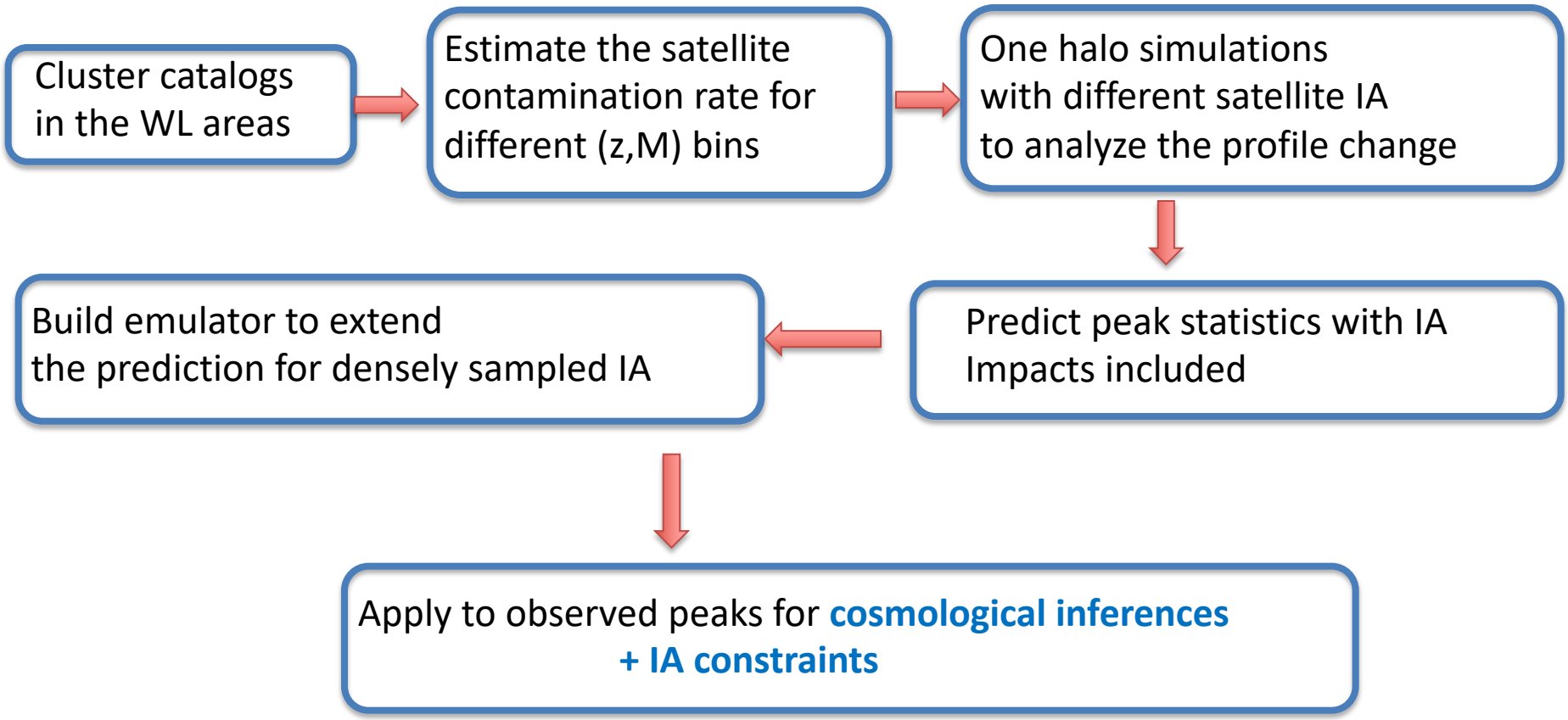
→ A theoretical tool to probe satellite IA with WL high peak statistics







Workflow for observational analyses



- **Summary and discussion**

- Statistics beyond 2pt statistics are important in WL cosmology
- WL peak statistics are complementary means to probe non-Gaussian info.
- IA is one of the major systematics

  -- closely related to cluster satellites' contaminations in source catalog

  -- sensitive to satellite IA
- By modeling the IA impacts on WL peak statistics properly

  -- mitigate the bias on cosmological parameter constraints

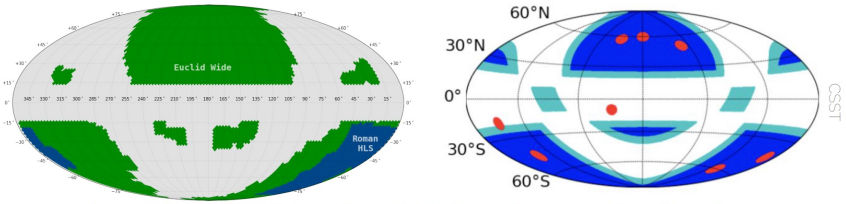
  -- probe satellite IA, thus their formation and evolution from WL peak analyses

- Stage IV surveys are coming soon (Euclid is observing already)

  Explore the synergy is important

Potential synergy between CSST and Euclid in WL cosmology (Liu,D.Z. et al. 2023)

CSST and Euclid will survey nearly the same sky area of about 15000 deg^2 with similar high resolutions, but the bands are different



Project	Orbit /Site	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num filters	spectr um
			deg^2	"	10^9	deg^2	nm		
CSST 2m	LEO	~2024	1.1	0.15	2.5	17500	255—1000	7	Y
Euclid 1.2m	L2	2022	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	N Y
Roman Space Telescope RST 2.4m (WFIRST)	L2	~2024	0.28	>0.2	0.3	2400	927—2000	4	Y
Rubin Observatory LSST 8.4m	Chile	2022	9.6	~0.7	3.2	18000	320—1050	6	N

Adapted from Hu Zhan

Cosmology with CSST, Euclid & Roman, 24 June 2021

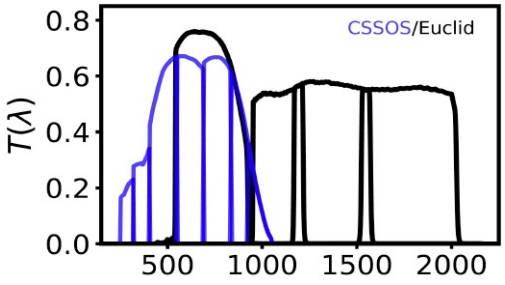
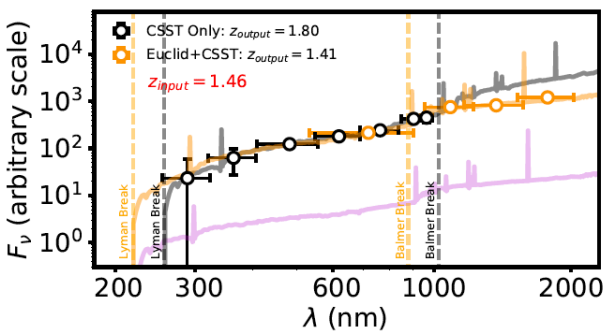
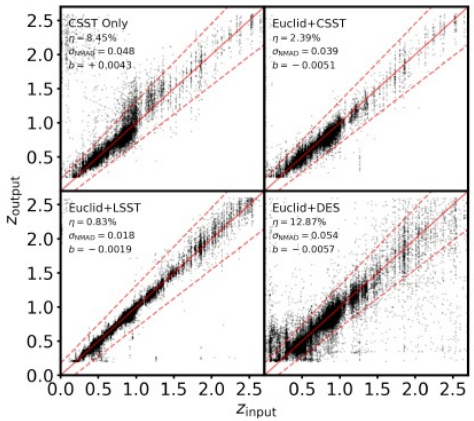
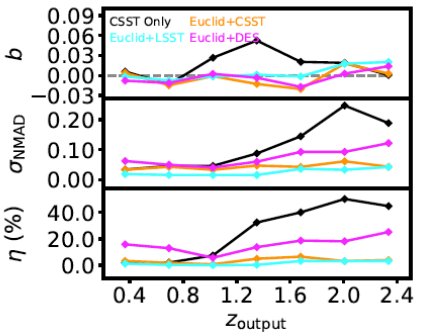


Table 2. Photo-z statistics in different cases.

Combination	Bias	σ_{NMAD}	η
CSST-only	+0.0043	0.048	8.45%
Euclid+CSST	−0.0051	0.039	2.39%
Euclid+LSST-like	−0.0019	0.018	0.83%
Euclid+DES-like	−0.0057	0.054	12.87%







Thank you