COSMOLOGY WITH WEAK-LENSING SHEAR-SELECTED GALAXY CLUSTERS

Results from the three-year shear catalogue of the
Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP Y3)



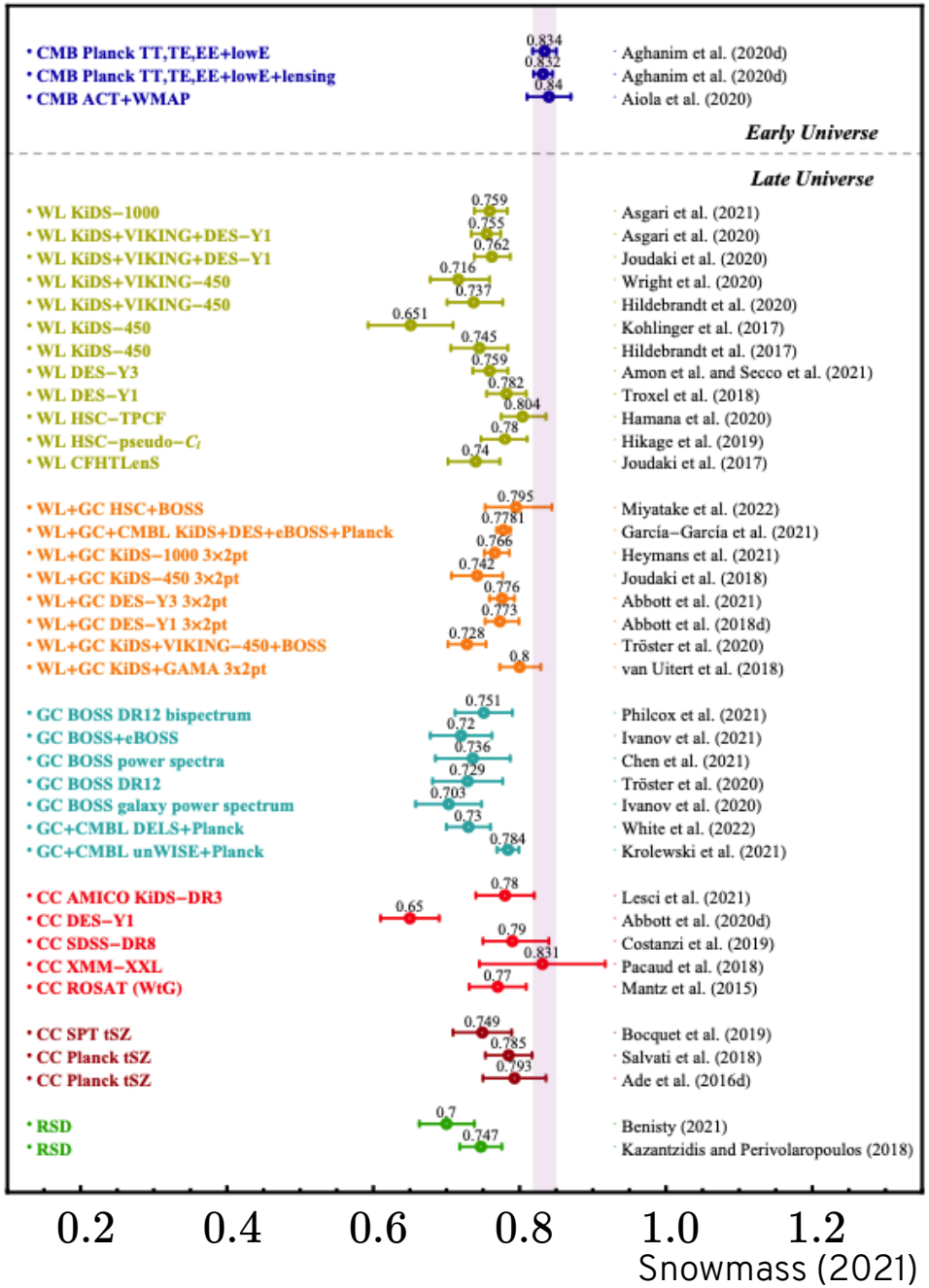
Kai-Feng Chen (MIT)
with I-Non Chiu (NCKU), Masamune Oguri (Chiba U.)
and the HSC WL collaboration

2406.11966

Nov. 1st, 2024 @ KIAS Workshop

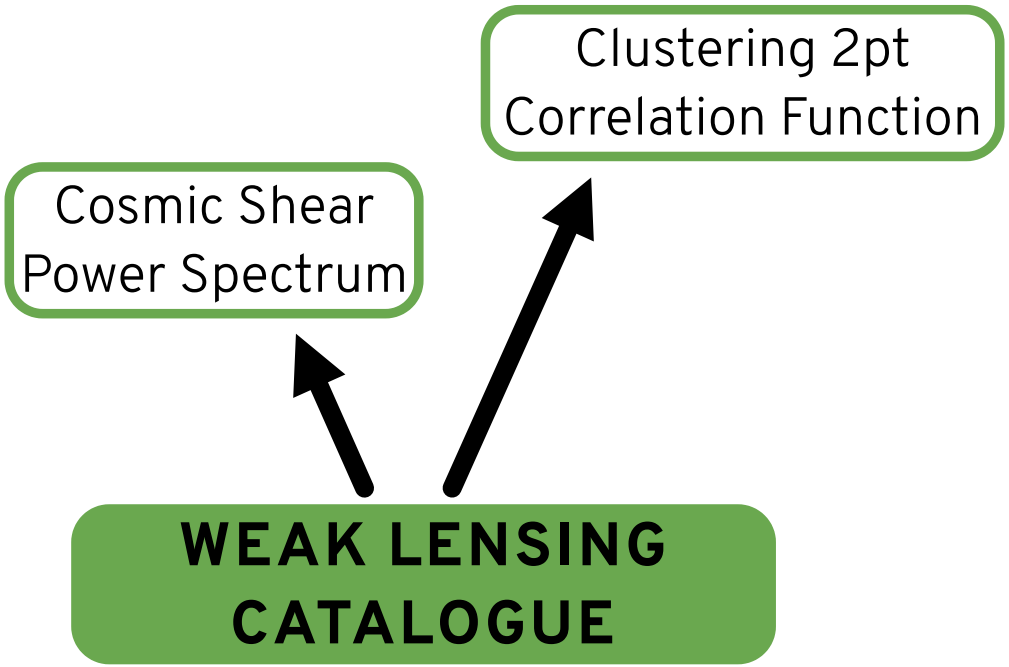
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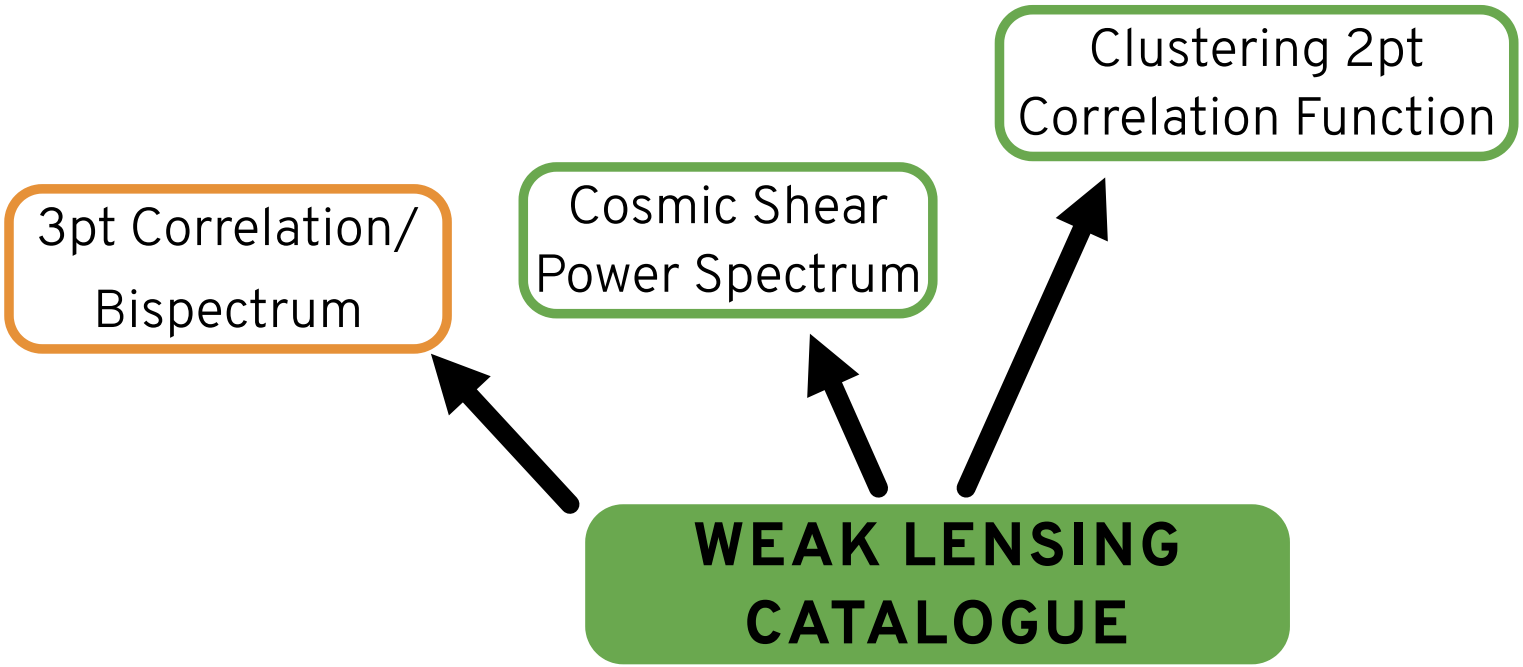
$$S_8 = \sigma_8 \times \sqrt{\Omega_m/0.3}$$

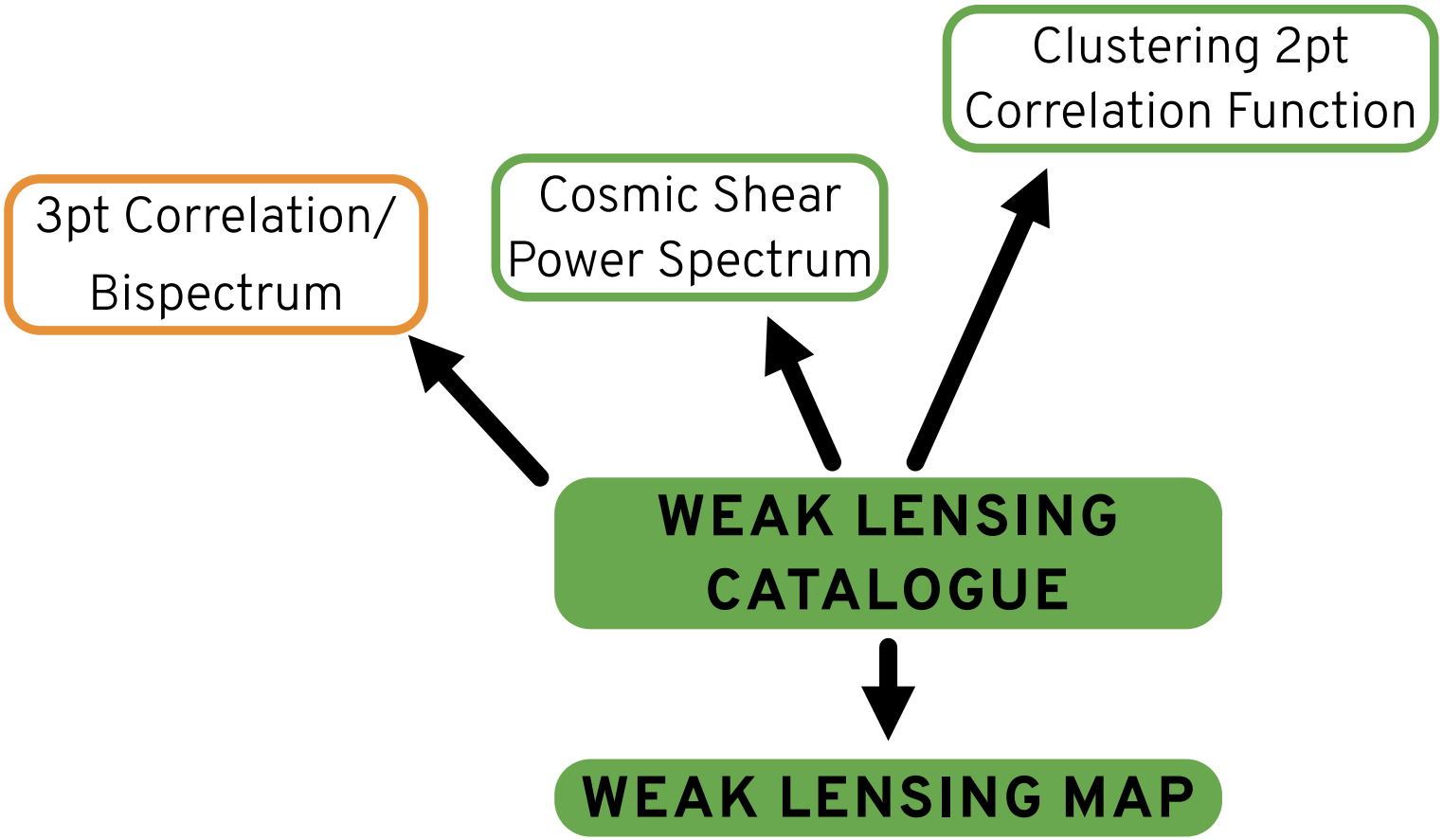


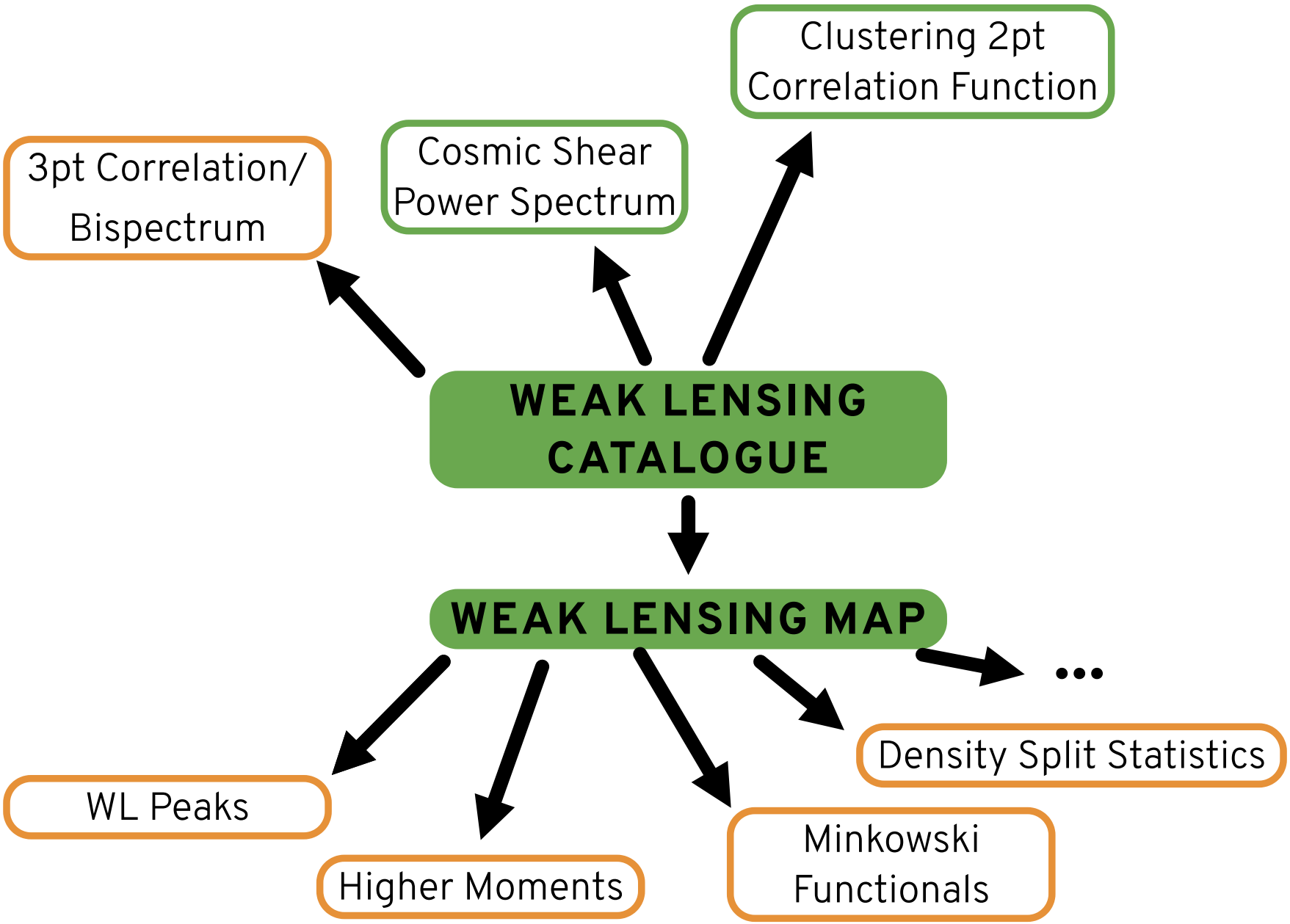
Snowmass (2021)

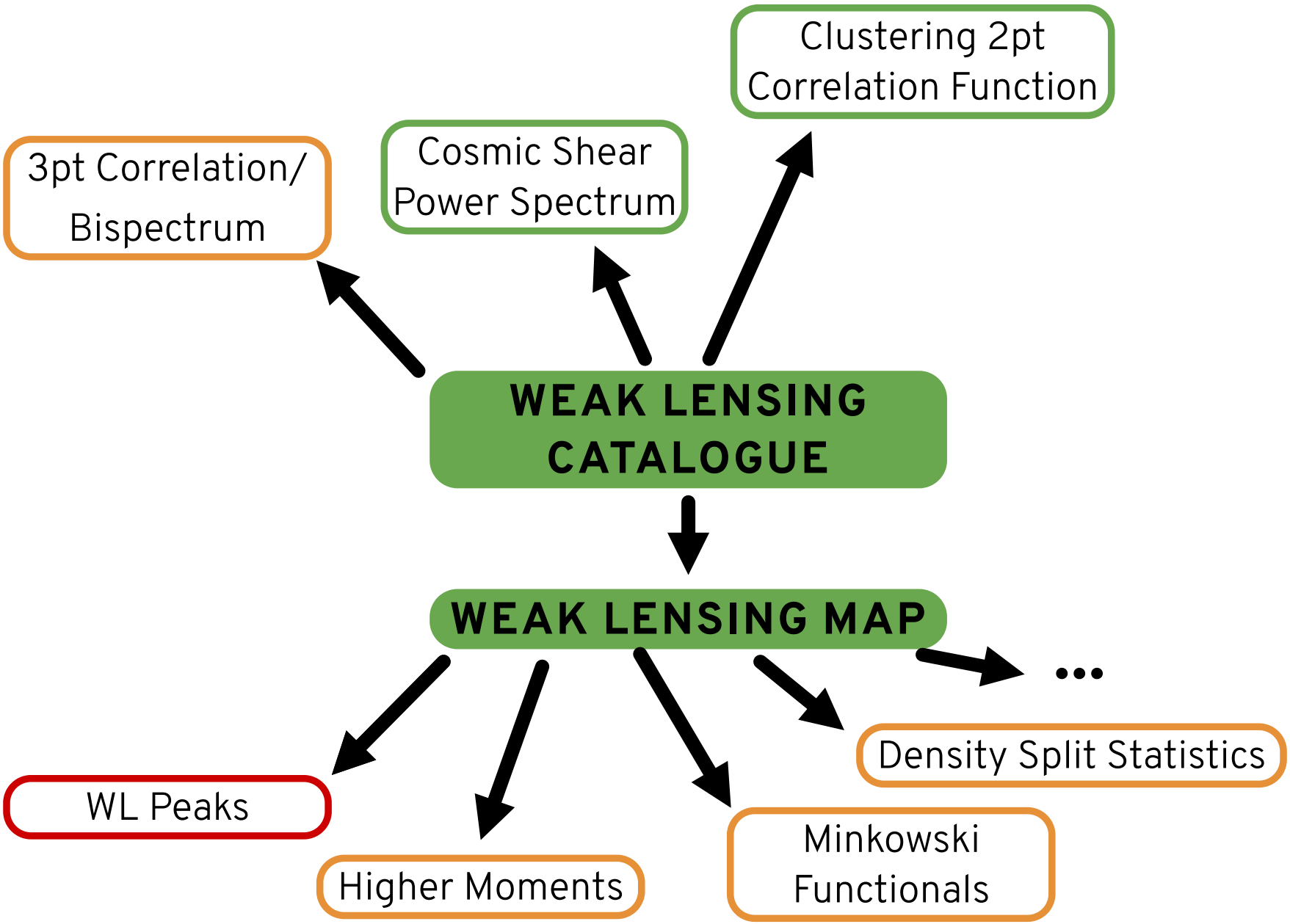
WEAK LENSING CATALOGUE


Clustering 2pt
Correlation Function
Cosmic Shear
Power Spectrum
WEAK LENSING
CATALOGUE

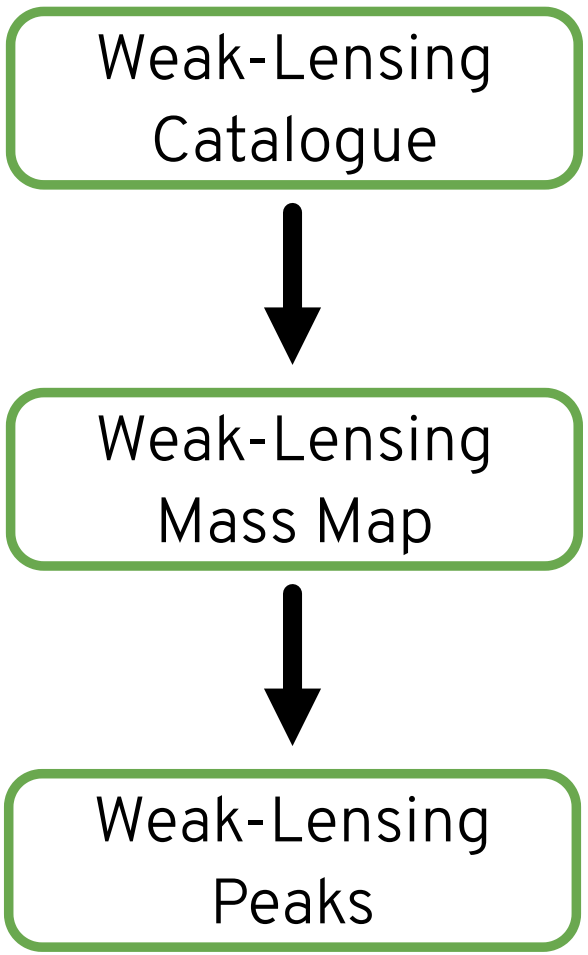

Clustering 2pt
Correlation Function
Cosmic Shear
Power Spectrum
3pt Correlation/
Bispectrum
WEAK LENSING
CATALOGUE


Clustering 2pt
Correlation Function
3pt Correlation/
Bispectrum
Cosmic Shear
Power Spectrum
WEAK LENSING
CATALOGUE
WEAK LENSING MAP


Clustering 2pt Correlation Function
Cosmic Shear Power Spectrum
3pt Correlation/ Bispectrum
WEAK LENSING CATALOGUE
WEAK LENSING MAP
...
Density Split Statistics
WL Peaks
Higher Moments
Minkowski Functionals


Clustering 2pt Correlation Function
Cosmic Shear Power Spectrum
3pt Correlation/ Bispectrum
WEAK LENSING CATALOGUE
WEAK LENSING MAP
...
Density Split Statistics
WL Peaks
Higher Moments
Minkowski Functionals

PEAKS FROM WEAK-LENSING MASS MAPS



Goal: Construct a conservative sample of WL peaks that is

- Purely due to high-mass galaxy clusters
- Free of baryonic effects

PEAKS FROM WEAK-LENSING MASS MAPS

Weak-Lensing Catalogue

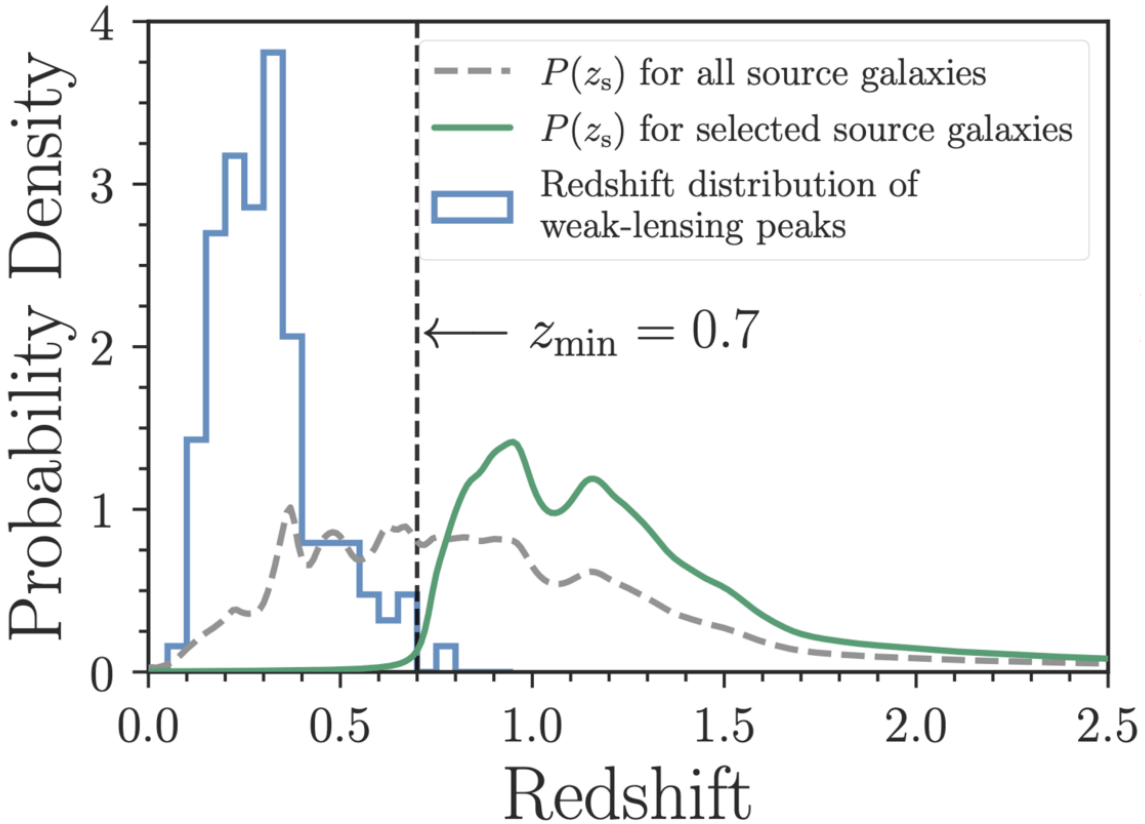
↓

Weak-Lensing Mass Map

↓

Weak-Lensing Peaks

Choose only background source galaxies (z > 0.7) to avoid dilution from member galaxies



Chen+ (2024)

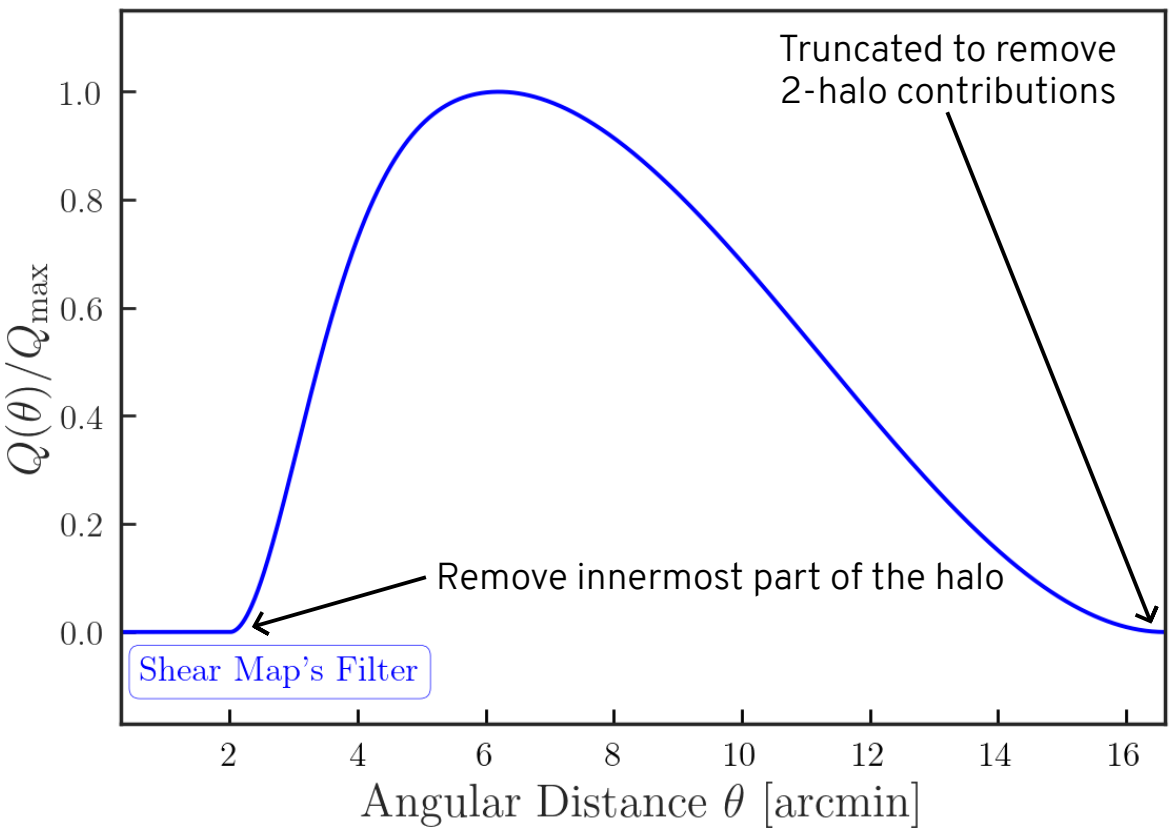
PEAKS FROM WEAK-LENSING MASS MAPS

Weak-Lensing Catalogue

Weak-Lensing Mass Map

Weak-Lensing Peaks

Choose a truncated isothermal filter to remove contributions from cluster center and outskirts



Chen+ (2024)

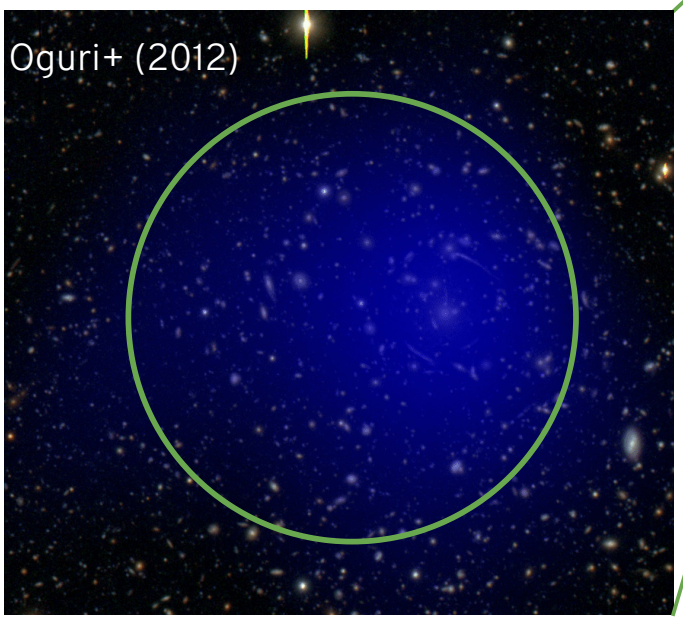
PEAKS FROM WEAK-LENSING MASS MAPS

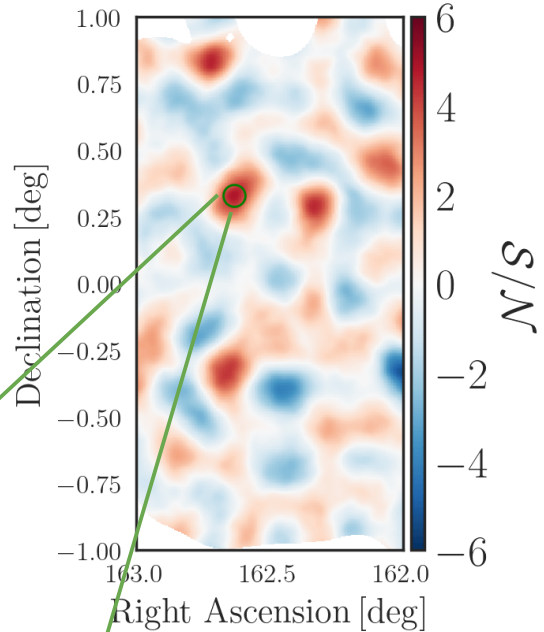
Weak-Lensing Catalogue

Weak-Lensing Mass Map

Weak-Lensing Peaks

Create WL signal-to-noise ratio maps with HSC-Y3 data (~500 sq deg)





PEAKS FROM WEAK-LENSING MASS MAPS

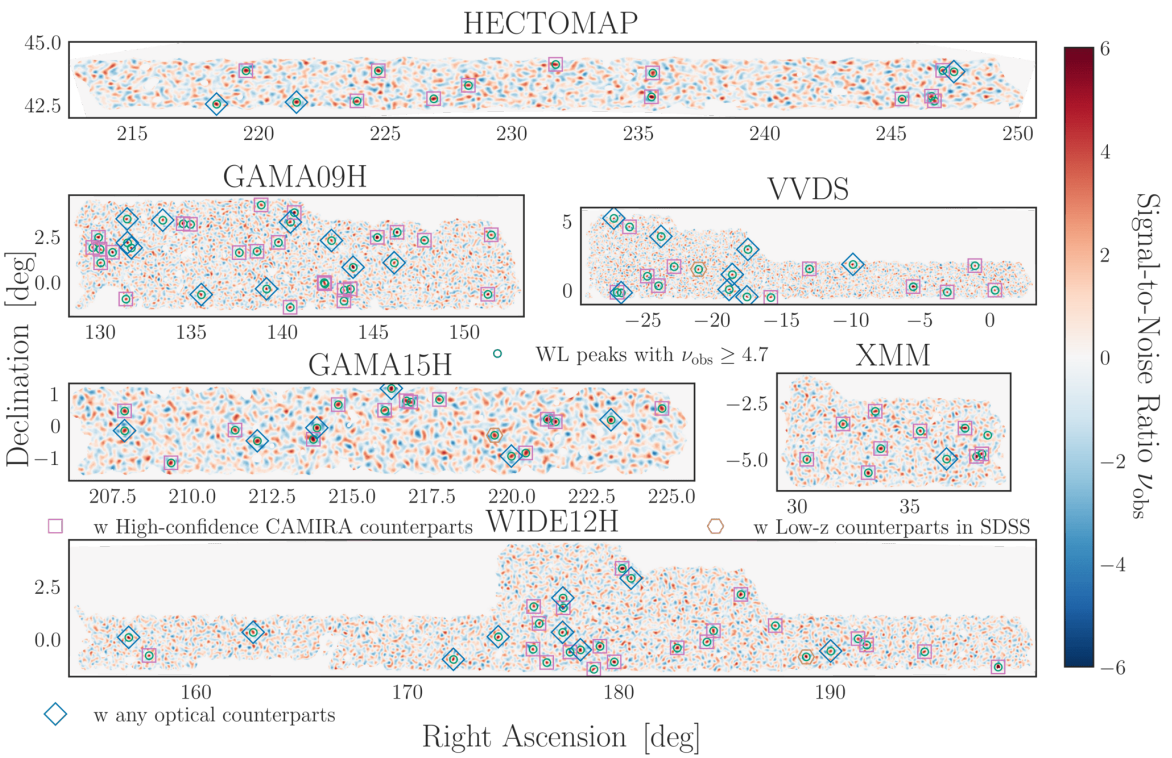
Weak-Lensing Catalogue

↓

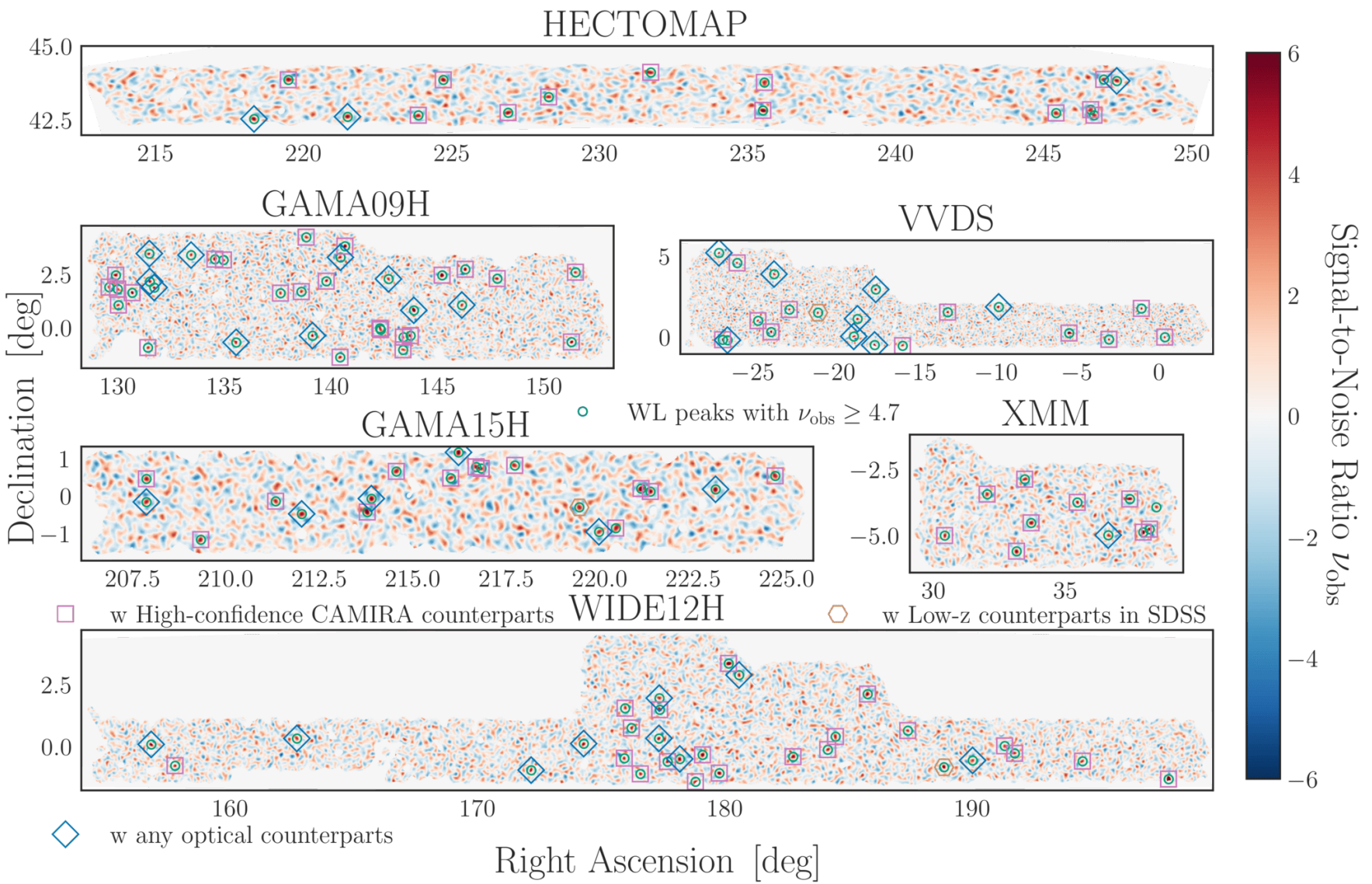
Weak-Lensing Mass Map

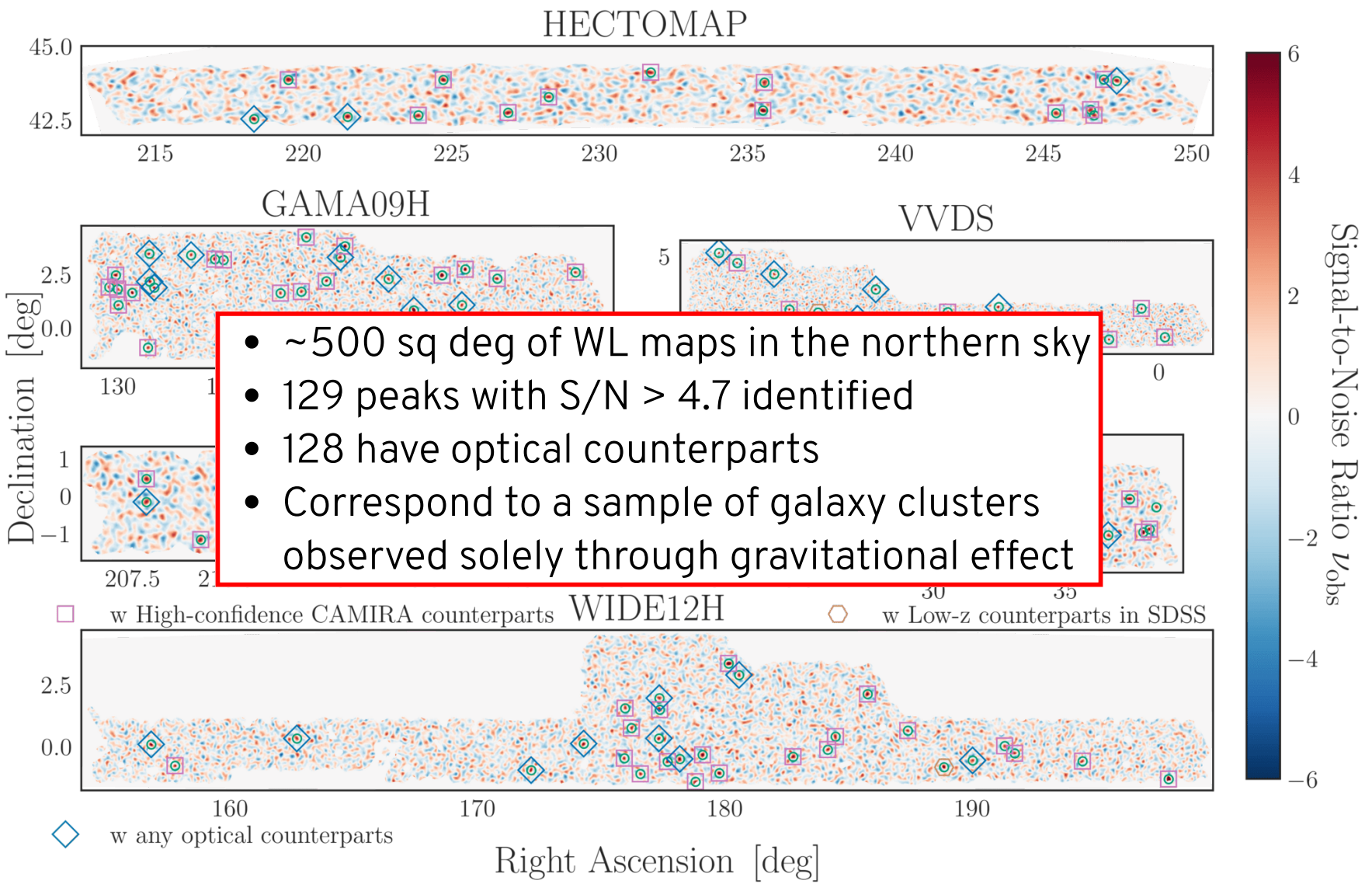
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Weak-Lensing Peaks



Chen+ (2024)

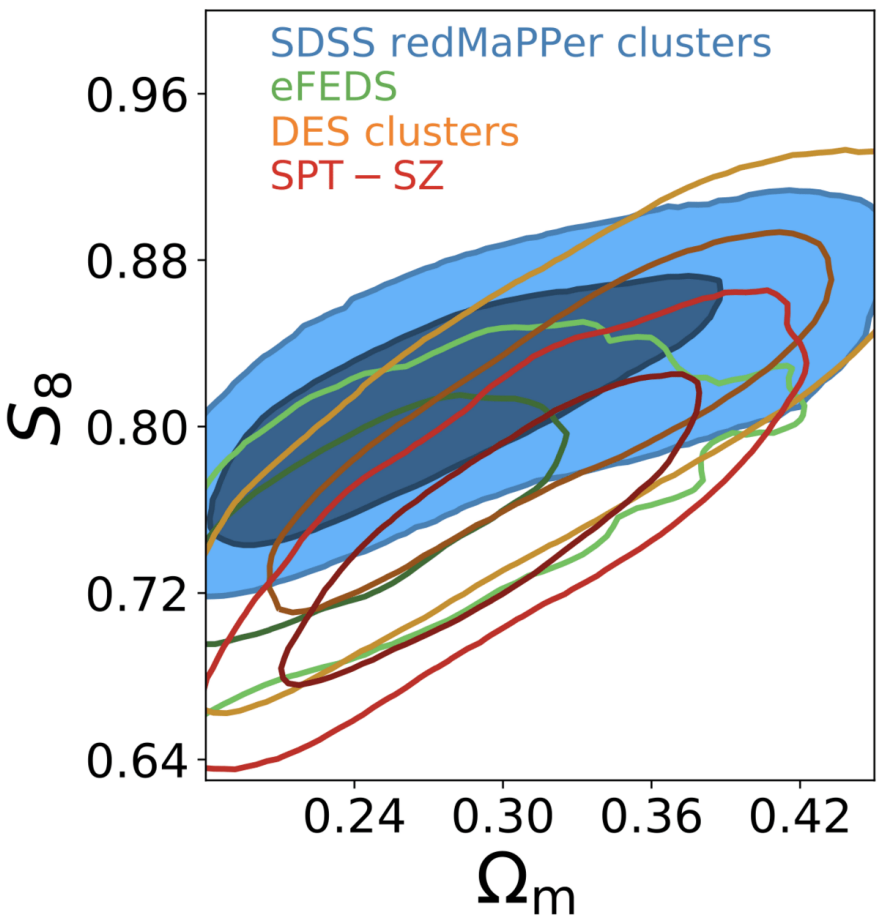

HECTOMAP
GAMA09H
VVDS
GAMA15H
XMM
WIDE12H
WL peaks with $\nu_{\rm obs} \geq 4.7$
w High-confidence CAMIRA counterparts
w Low-z counterparts in SDSS
w any optical counterparts
Declination [deg]
Right Ascension [deg]
Signal-to-Noise Ratio $\nu_{\rm obs}$



- ~500 sq deg of WL maps in the northern sky
- 129 peaks with S/N > 4.7 identified
- 128 have optical counterparts
- Correspond to a sample of galaxy clusters observed solely through gravitational effect

WHERE DOES OUR SENSITIVITY COME FROM?

Similar to Cluster Cosmology!



Sunayama+ (2023)

$$\#\ \text{of halos}(M, z)$$

$$=$$

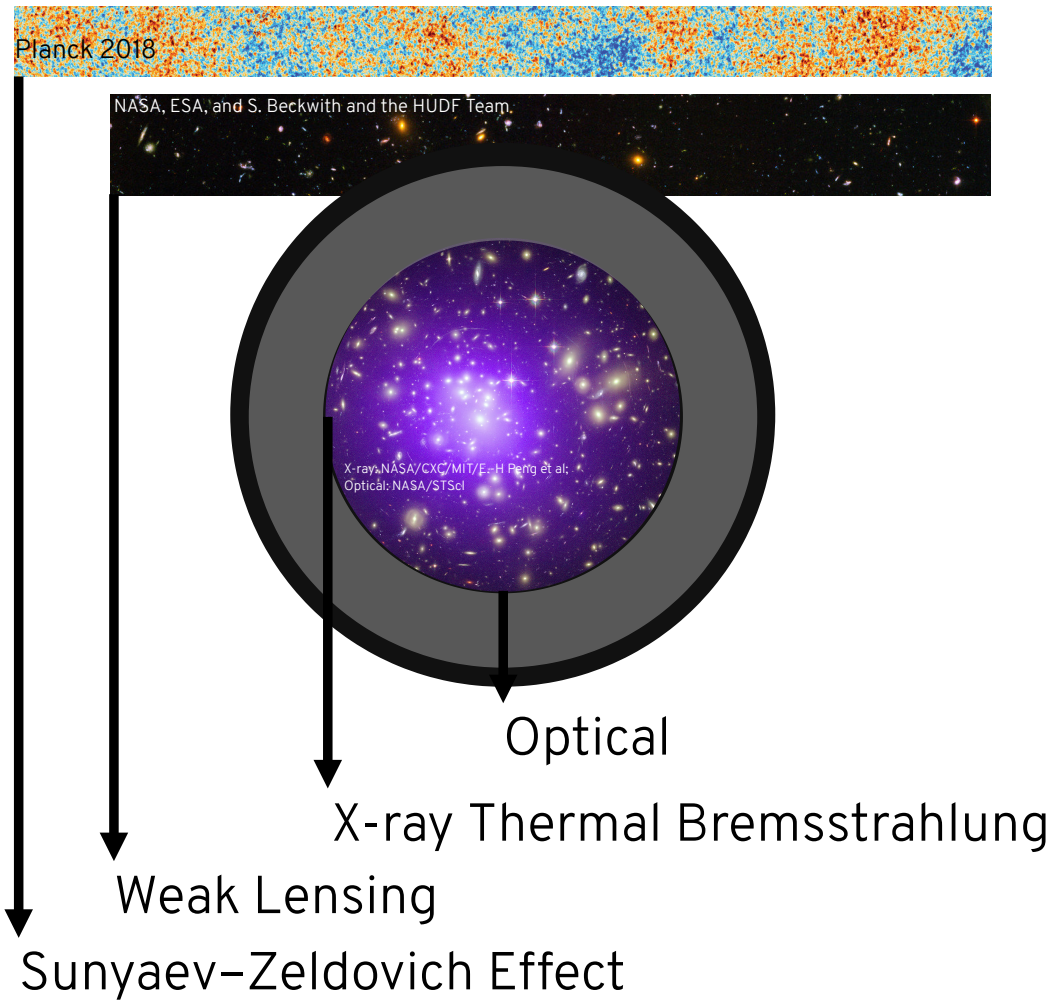
$$\text{Halo density}(M, z)$$

$$\times$$

$$\text{Volume}(z)$$

WHY USE WL PEAKS INSTEAD?

Observable–Mass Relation



$$\#\ \text{of halos}(M, z)$$

$$=$$

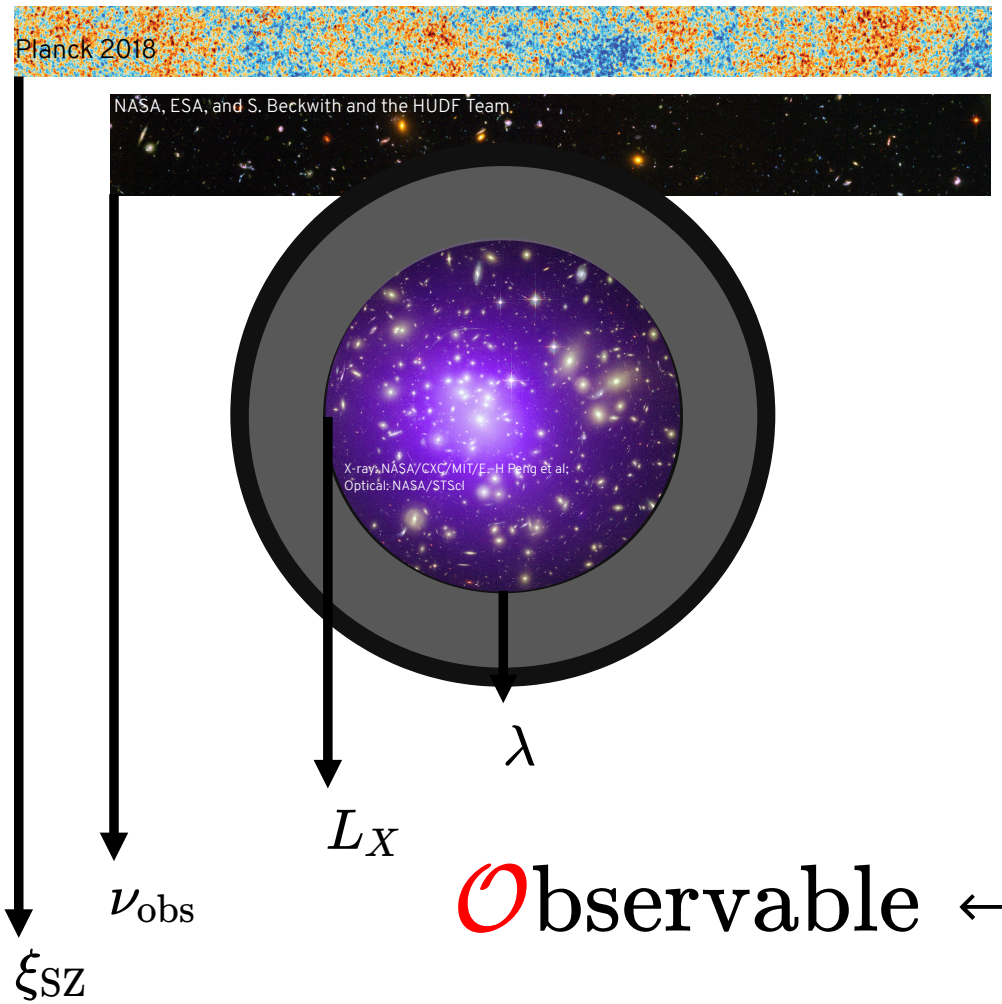
$$\text{Halo density}(M, z)$$

$$\times$$

$$\text{Volume}(z)$$

WHY USE WL PEAKS INSTEAD?

Observable–Mass Relation



$$\#\ \text{of halos}(M(\mathcal{O}), z)$$

$$=$$

$$\text{Halo density}(M, z)$$

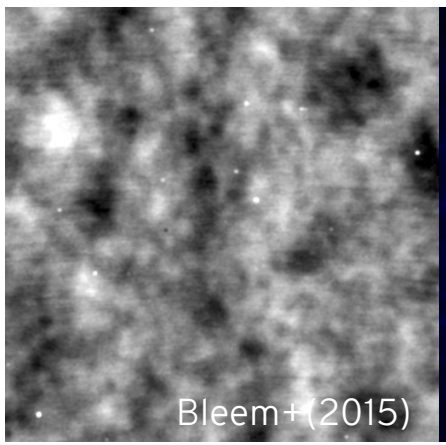
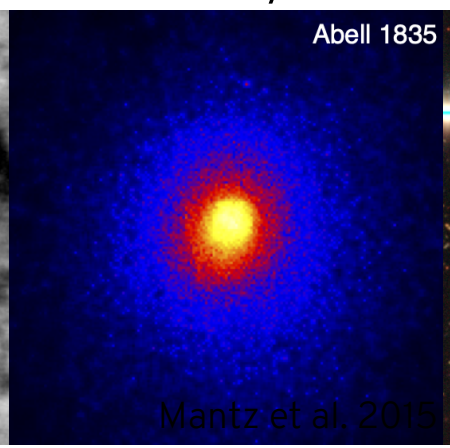
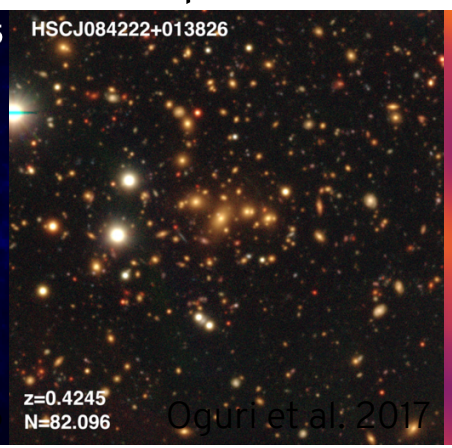
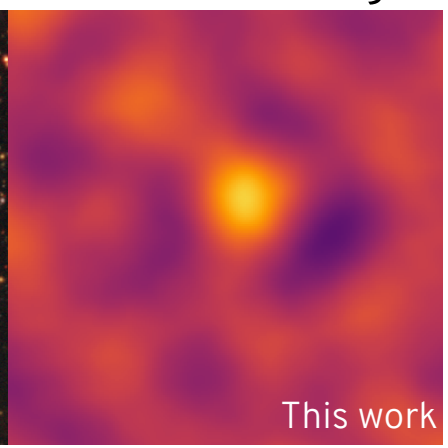
$$\times$$

$$\text{Volume}(z)$$

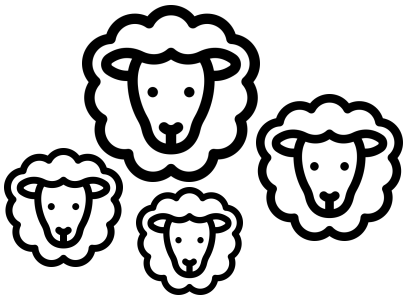
$$\mathcal{O}\text{bservable} \longleftrightarrow M\text{ass}$$

WHY USE WL PEAKS INSTEAD?

Direct Observable—Mass Relation!

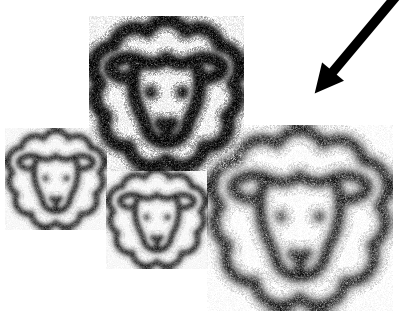
tSZ	X-ray	Optical	Weak Lensing
			
Bleem+(2015)	Mantz et al. 2015	Oguri et al. 2017	This work
$y_{\rm SZ} \propto n_e$	$L_{\rm X} \propto n_e^2$	$\lambda_{\rm rich} \propto M_*$	$M_{\rm aper} \propto M_{\rm 2D}$

THE WL MASS OBSERVABLE RELATION

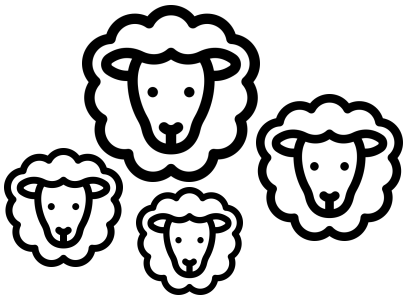


$(M_{200c}, z_{cl}, c_{200c})$

WL Signal-to-Noise Ratio

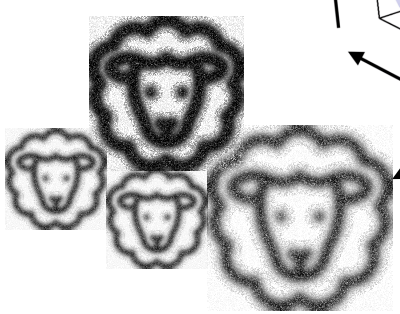


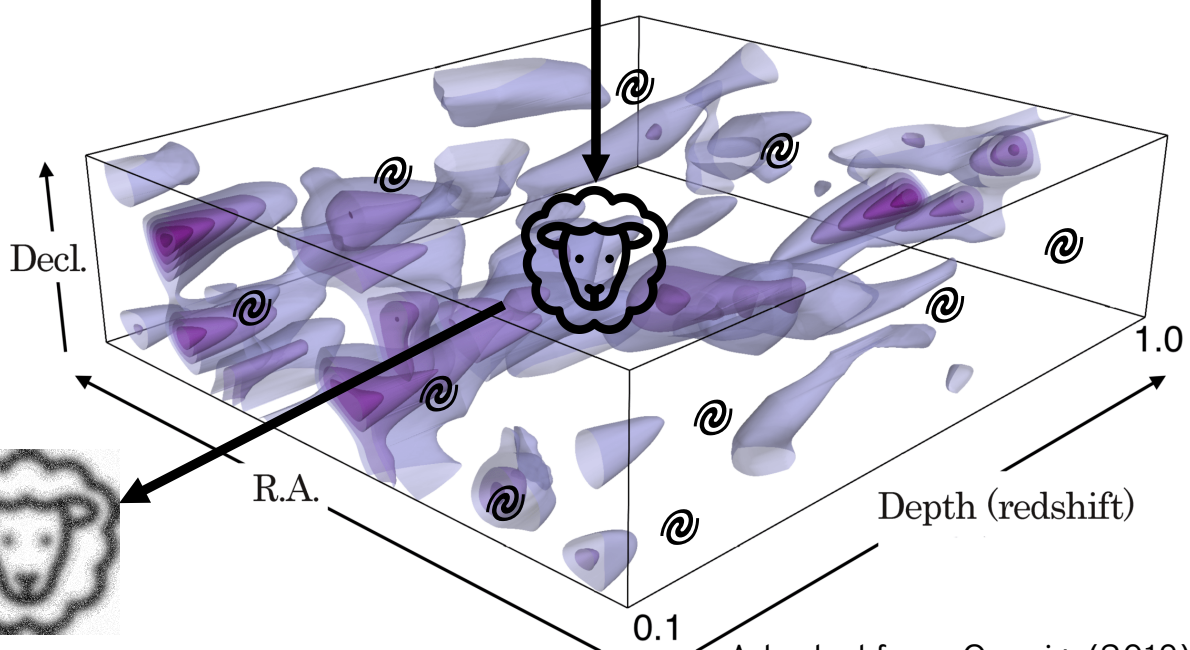
THE WL MASS OBSERVABLE RELATION



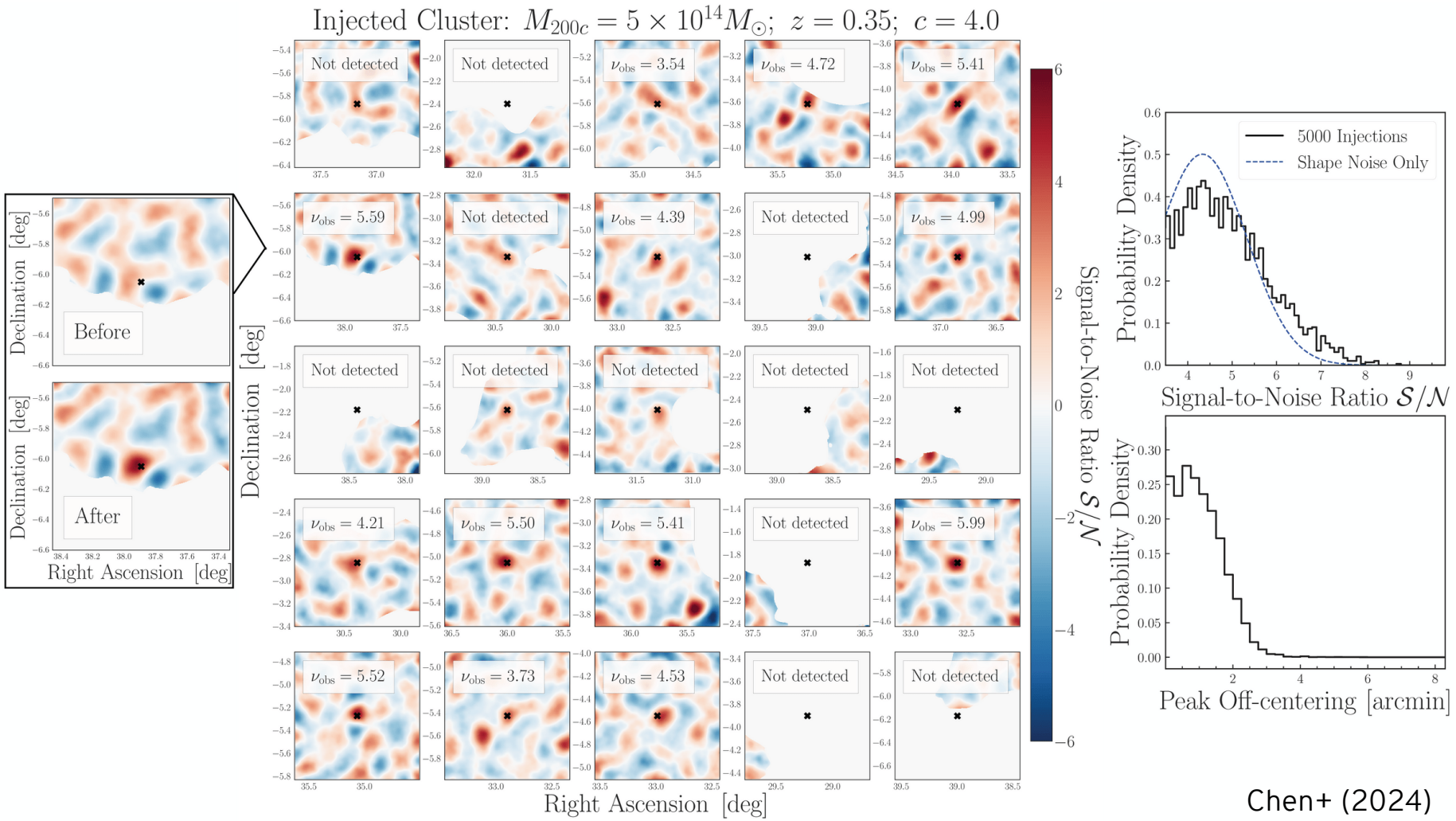
$(M_{200c}, z_{cl}, c_{200c})$

WL Signal-to-Noise Ratio





Adapted from Oguri+ (2018)


Injected Cluster: $M_{200c} = 5 \times 10^{14} M_\odot$; $z = 0.35$; $c = 4.0$
Not detected
$\nu_{\rm obs} = 3.54$
$\nu_{\rm obs} = 4.72$
$\nu_{\rm obs} = 5.41$
$\nu_{\rm obs} = 5.59$
$\nu_{\rm obs} = 4.39$
$\nu_{\rm obs} = 4.99$
$\nu_{\rm obs} = 4.21$
$\nu_{\rm obs} = 5.50$
$\nu_{\rm obs} = 5.41$
$\nu_{\rm obs} = 5.99$
$\nu_{\rm obs} = 5.52$
$\nu_{\rm obs} = 3.73$
$\nu_{\rm obs} = 4.53$
Declination [deg]
Right Ascension [deg]
Before
After
Signal-to-Noise Ratio $\mathcal{S}/\mathcal{N}$
5000 Injections
Shape Noise Only
Probability Density
Signal-to-Noise Ratio $\mathcal{S}/\mathcal{N}$
Peak Off-centering [arcmin]

Chen+ (2024)

MODELING PIPELINE

Take into account:

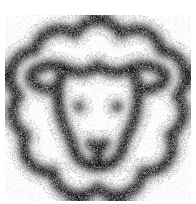
- Shape noise
- Non-uniform survey depth and geometry
- Uncorrelated Large-Scale Structure
- Chance projections
- Miss-centering



NFW-like halos



Chen+ (2024)



WL Peaks

MODELING PIPELINE

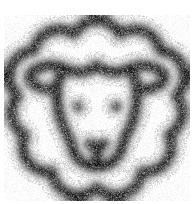


Real halos



NFW-like halos

Chen+ (2024)



WL Peaks

Take into account:

- Shape noise
- Non-uniform survey depth and geometry
- Uncorrelated Large-Scale Structure
- Chance projections
- Miss-centering

MODELING PIPELINE

Take into account:

- WL mass bias due to
  - deviation from NFW
  - halo triaxiality
- Photo-z uncertainties
- Scattering in mass-concentration relation



Real halos

Chiu+ (2024)

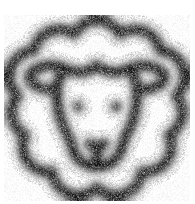


NFW-like halos

Take into account:

- Shape noise
- Non-uniform survey depth and geometry
- Uncorrelated Large-Scale Structure
- Chance projections
- Miss-centering

Chen+ (2024)



WL Peaks

MODELLING FOR INTRINSIC UNCERTAINTIES

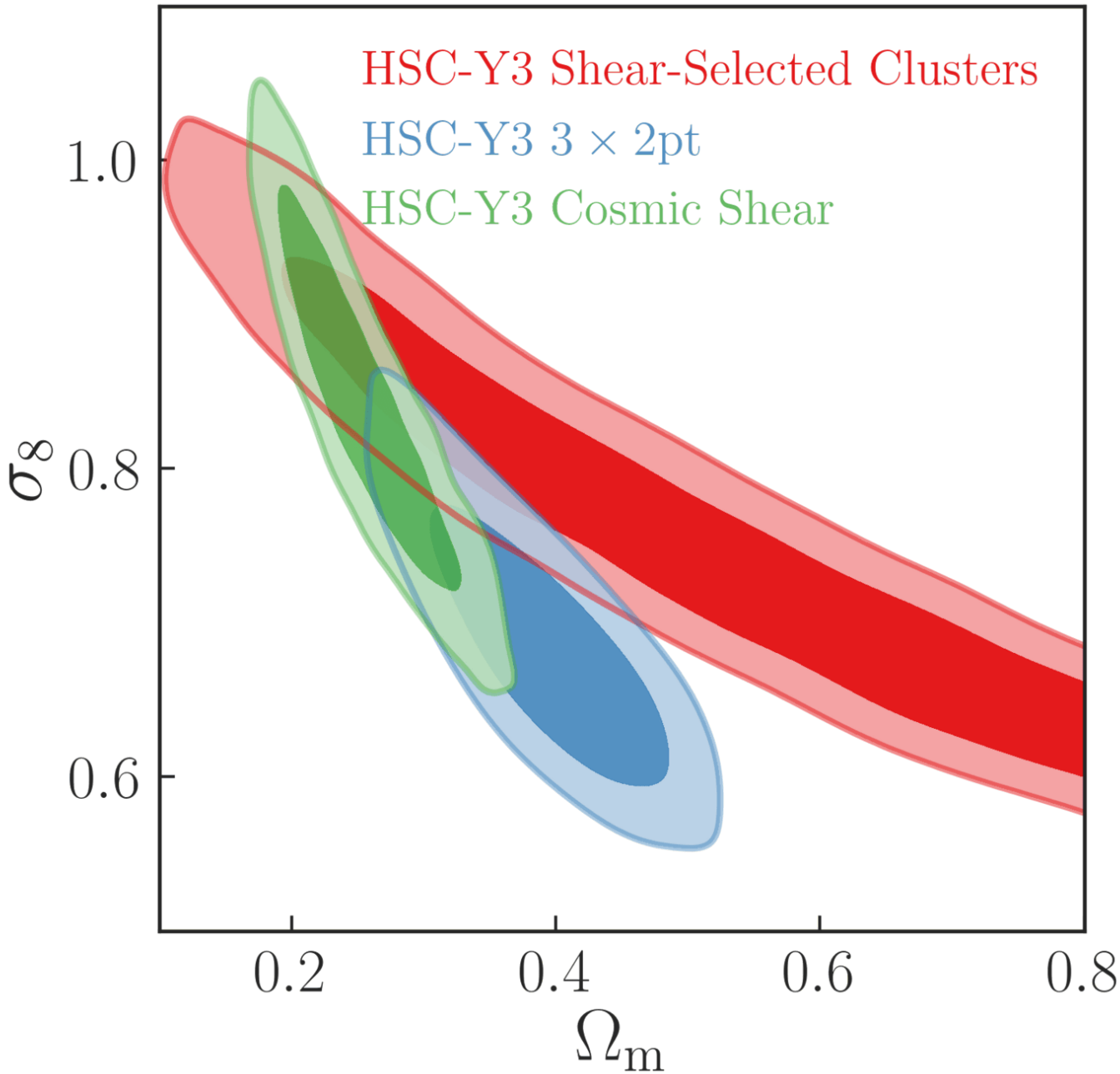
- Deviation of real halo from an NFW description (triaxiality, substructures...)
  - Model through a scaling relation between true mass and WL mass
  - Two types of models with priors from hydro simulation
- Photo-z bias
  - Two priors: Cosmic shear inferred and clustering measurement
- Scatter in the mass-concentration relation
  - Prior from Diemer & Joyce (2019)
- Truncation of up-scattering low S/N objects

Table 1. The priors used in the modelling. The first column contains the names of the parameters, while the second columns present the priors.

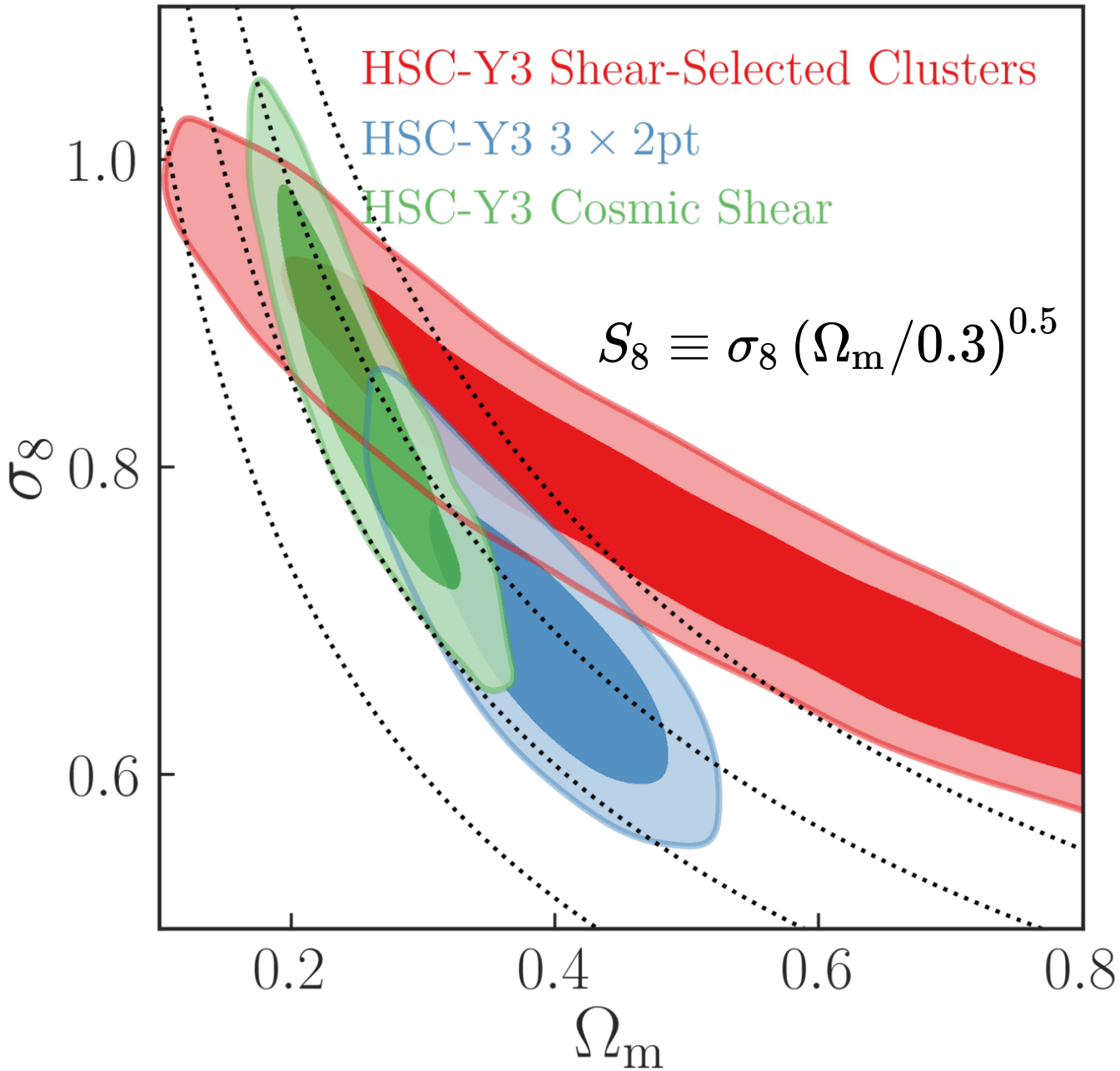
Parameter	Prior	
	Cosmology	
Ω_m	$\mathcal{U}(0.1, 0.99)$	
Ω_b	$\mathcal{U}(0.03, 0.07)$	
Ω_k	Fixed to 0	
σ_8	$\mathcal{U}(0.45, 1.15)$	
n_s	$\mathcal{U}(0.92, 1.0)$	
h	$\mathcal{U}(0.5, 0.9)$	
w	Fixed to -1 or $\mathcal{U}(-2.5, -1/3)$	
	Weak-lensing mass bias (Section 4.5)	
	M-z dependent bias	Constant bias
A_{WL}	$\mathcal{N}(0.903, 0.03^2)$	$\mathcal{N}(0.99, 0.05^2)$
B_{WL}	$\mathcal{N}(-0.057, 0.022^2)$	Fixed to 0
γ_{WL}	$\mathcal{N}(-0.474, 0.062^2)$	Fixed to 0
σ_{WL}	$\mathcal{N}(0.238, 0.037^2)$	
	Photo-z bias (Section 4.6)	
	Clustering-z	Cosmic-shear-informed
Δz	$\mathcal{N}(0, 0.008^2)$	$\mathcal{N}(-0.13, 0.05^2)$
	Concentration	
σ_c	$\mathcal{N}(0.3, 0.1^2)$	
	Up-scattering	
Δ	$\mathcal{U}(2, 4.5)$	

Chiu+ (2024)

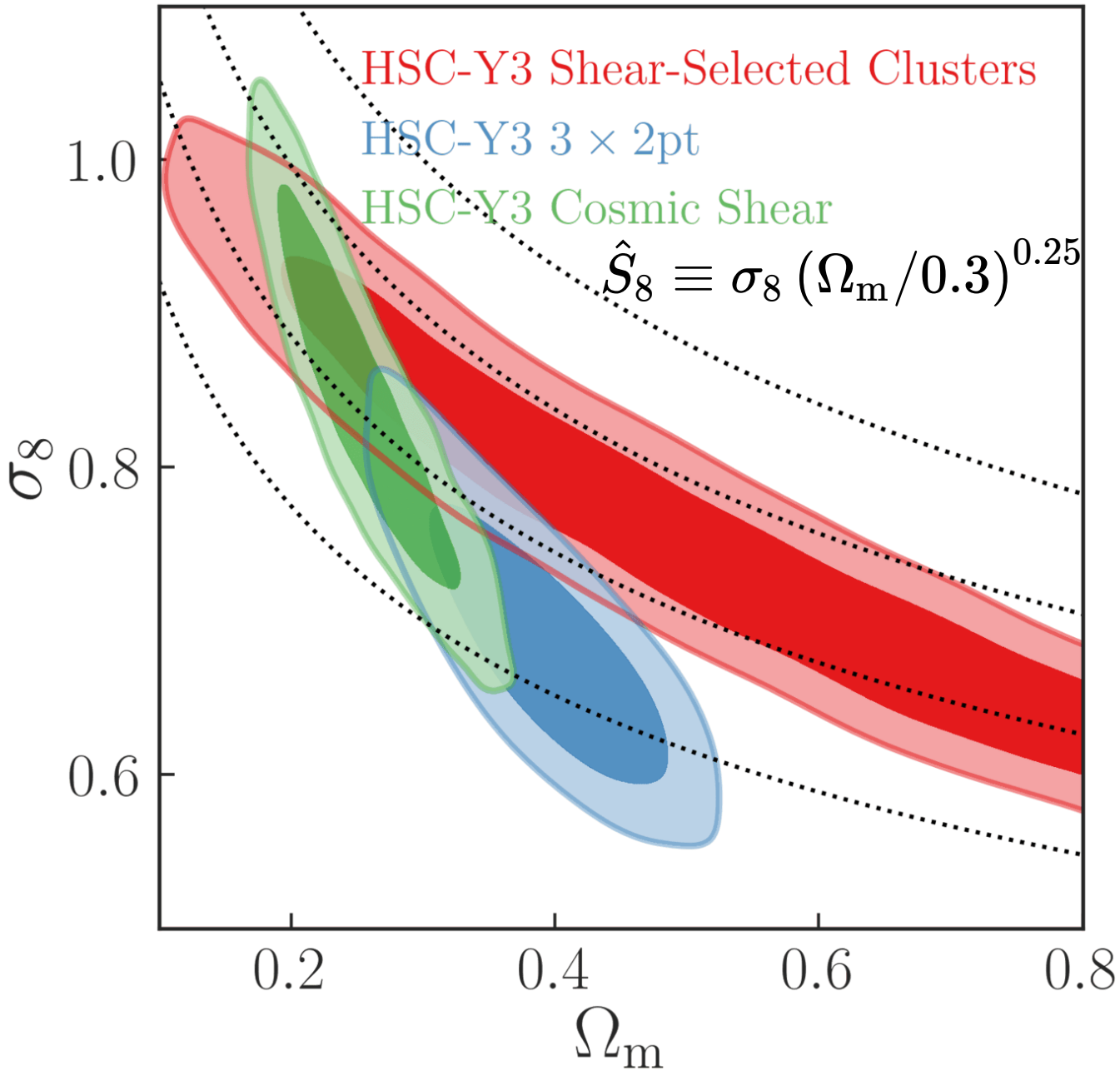
RESULTS

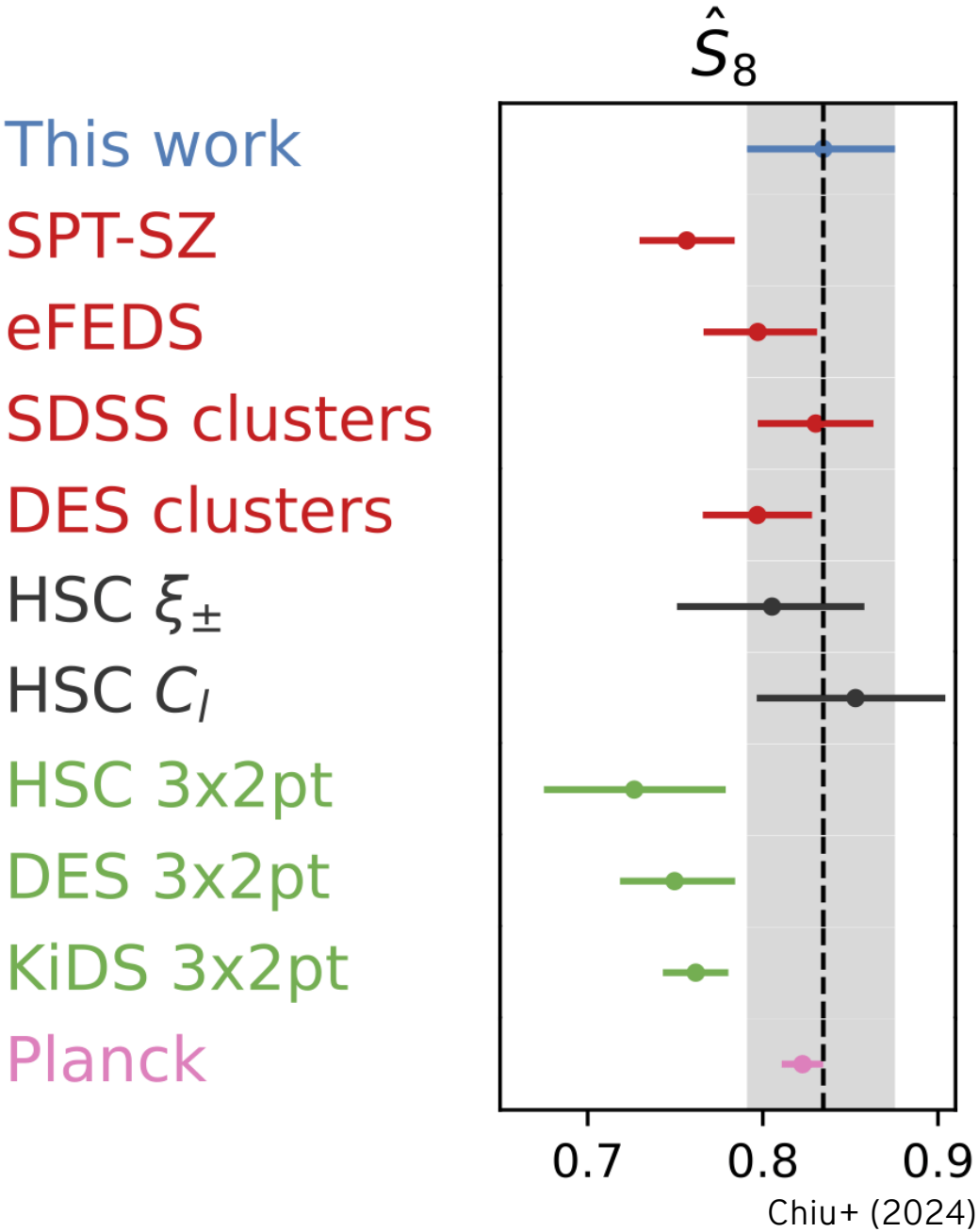

HSC-Y3 Shear-Selected Clusters
HSC-Y3 3 × 2pt
HSC-Y3 Cosmic Shear
1.0
0.8
0.6
σ_8
0.2
0.4
0.6
0.8
Ω_m

RESULTS


HSC-Y3 Shear-Selected Clusters
HSC-Y3 3 × 2pt
HSC-Y3 Cosmic Shear
$S_8 \equiv \sigma_8 \left(\Omega_\mathrm{m}/0.3\right)^{0.5}$
1.0
0.8
0.6
σ_8
0.2
0.4
0.6
0.8
Ω_m

RESULTS


HSC-Y3 Shear-Selected Clusters
HSC-Y3 3 × 2pt
HSC-Y3 Cosmic Shear
$\hat{S}_8 \equiv \sigma_8 \left(\Omega_\mathrm{m}/0.3\right)^{0.25}$
1.0
0.8
0.6
σ_8
0.2
0.4
0.6
0.8
Ω_m


This work
SPT-SZ
eFEDS
SDSS clusters
DES clusters
HSC $\xi_{\pm}$
HSC C_l
HSC 3x2pt
DES 3x2pt
KiDS 3x2pt
Planck
$\hat{S}_8$
0.7
0.8
0.9

Chiu+ (2024)

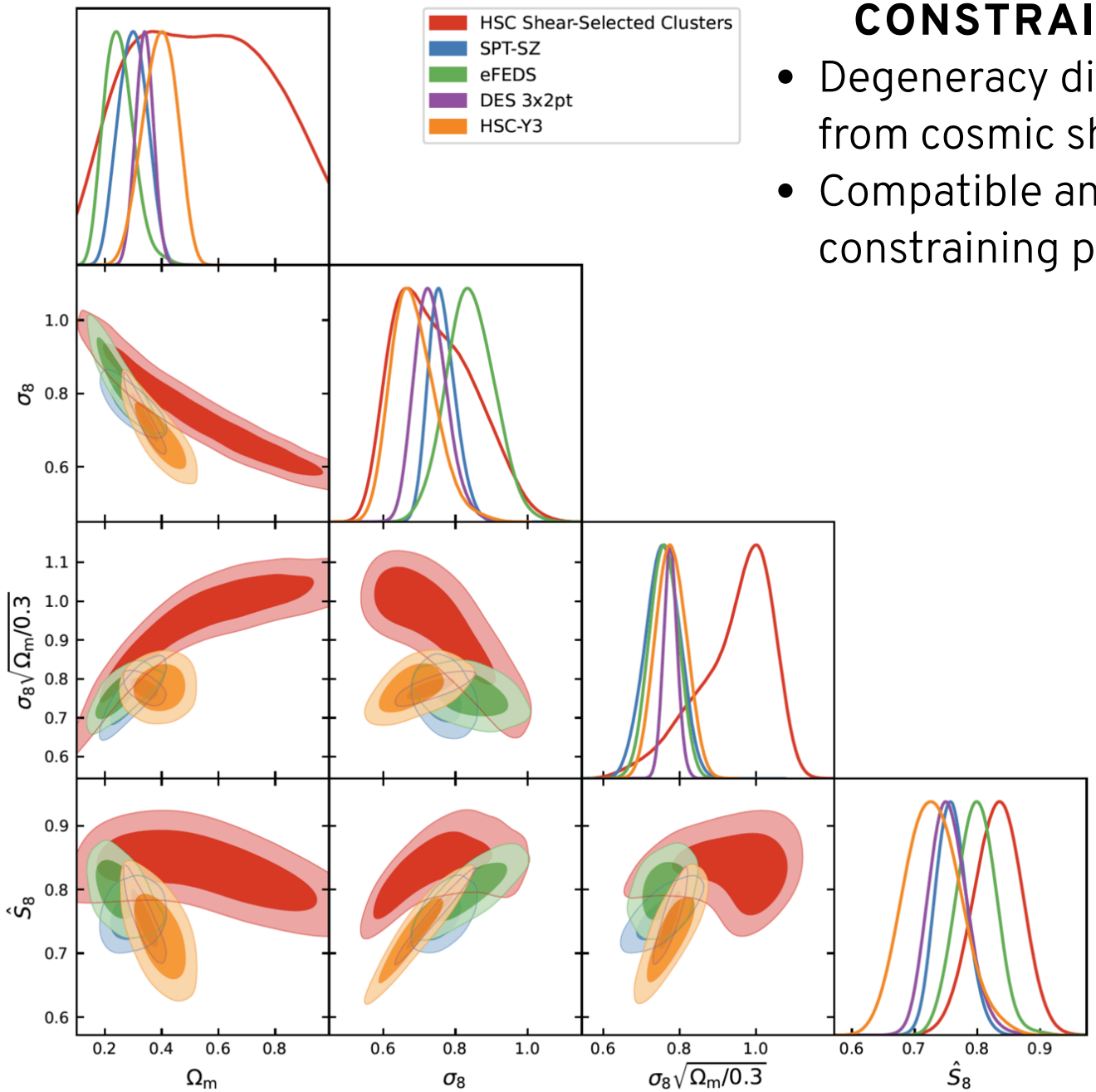
SUMMARY

- Construct a galaxy cluster sample solely from weak-lensing data
- Provide competitive late-universe constraints from higher-order statistics
- Complement existing 2-pt probes and shed light to potential systematics
- Current Status:
  - Consistent with Planck, most cluster probes, and HSC cosmic shear
  - Slight tension with 3x2pt measurements
- Future: Combine with redshift obtained from optical counterpart to break parameter degeneracy

BACKUP SLIDES

CONSTRAINING POWER

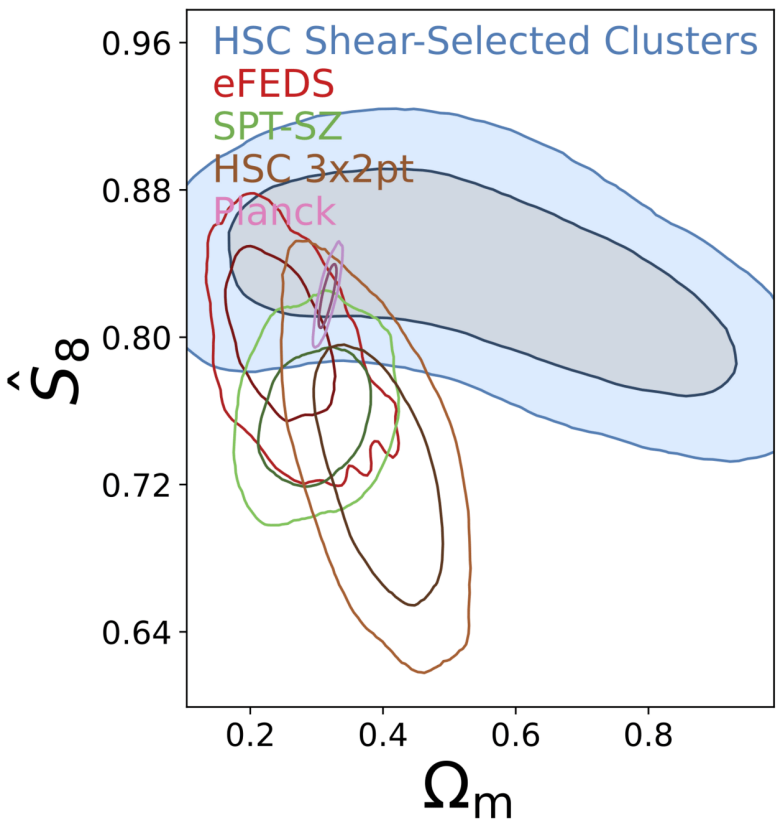
- Degeneracy direction different from cosmic shear
- Compatible and complementary constraining power

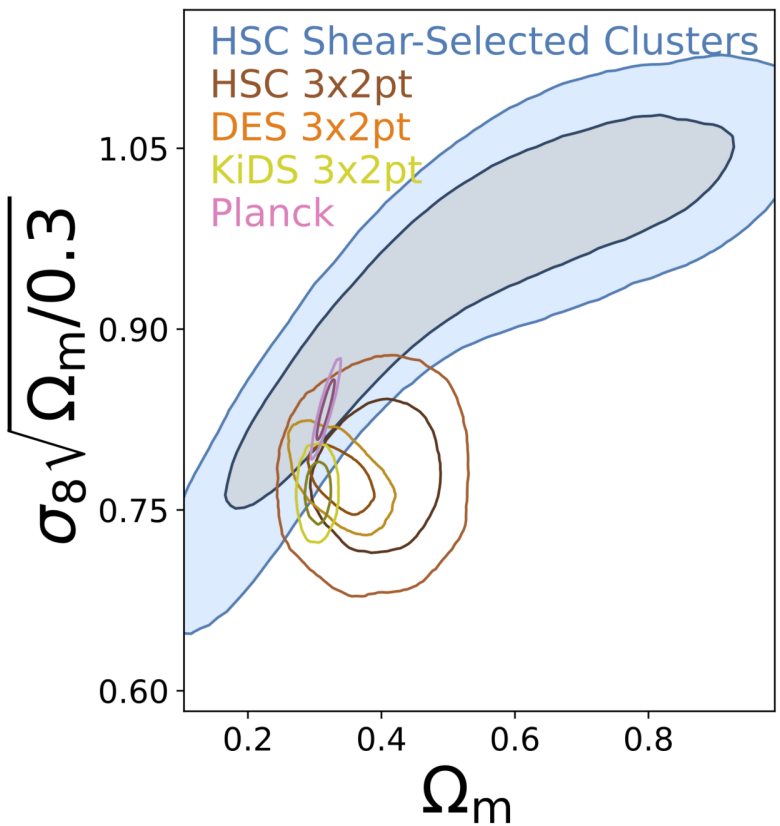


Chiu+ (in prep.)

CONSTRAINING POWER

- Prefer slightly higher S8
- Similar to those from CMB, CMB lensing and X-ray selected Cluster Number Count
- Consistent with HSC cosmic shear only
- In slight tension with HSC 3x2 pt analysis

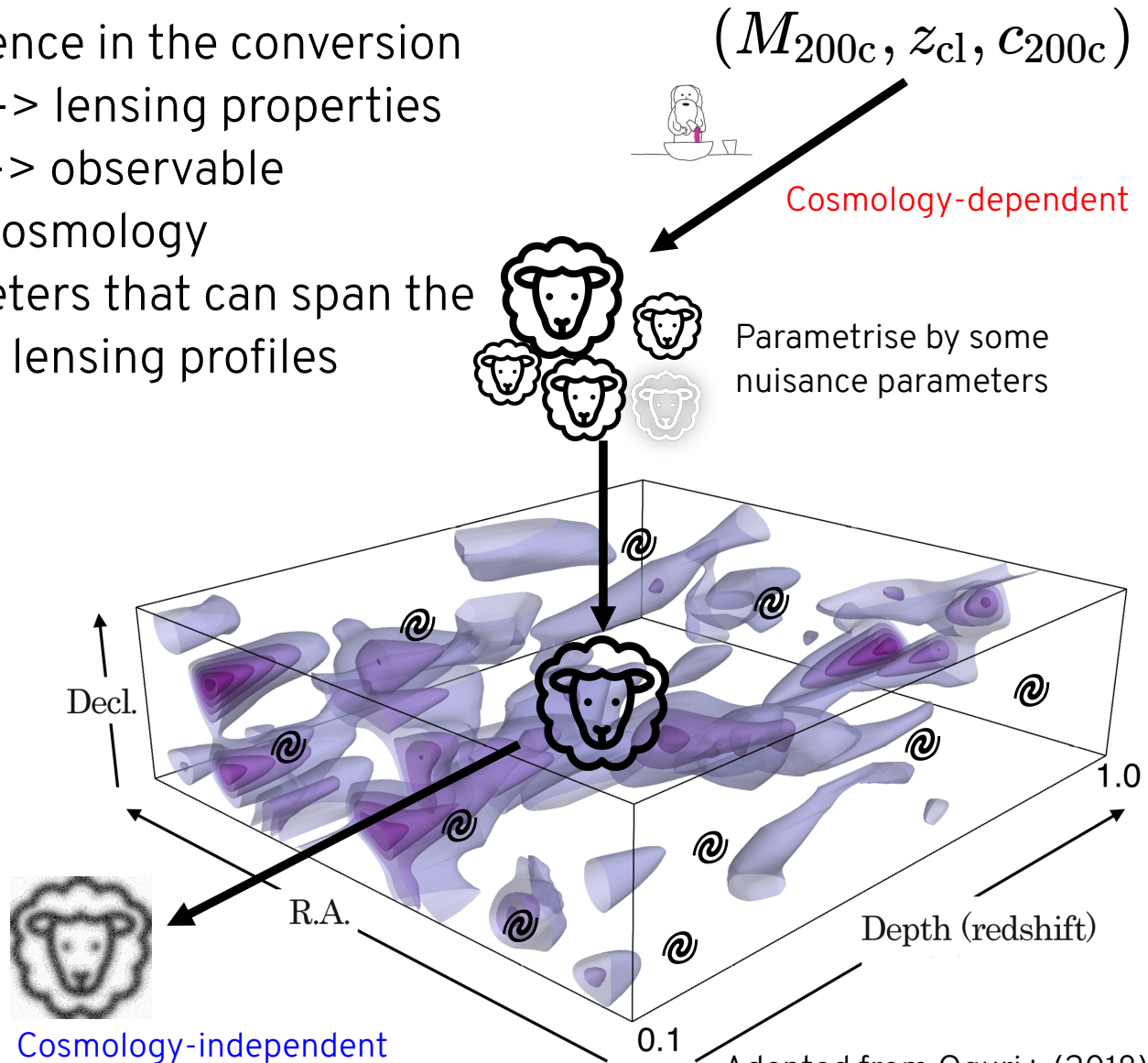




Chiu+ (in prep.)

NEW PARAMETRISATION OF THE MASS OBSERVABLE RELATION

- Cosmology dependence in the conversion physical properties -> lensing properties
- Lensing properties -> observable
  Not so sensitive to cosmology
- Need to find parameters that can span the space of all possible lensing profiles



FULL PIPELINE

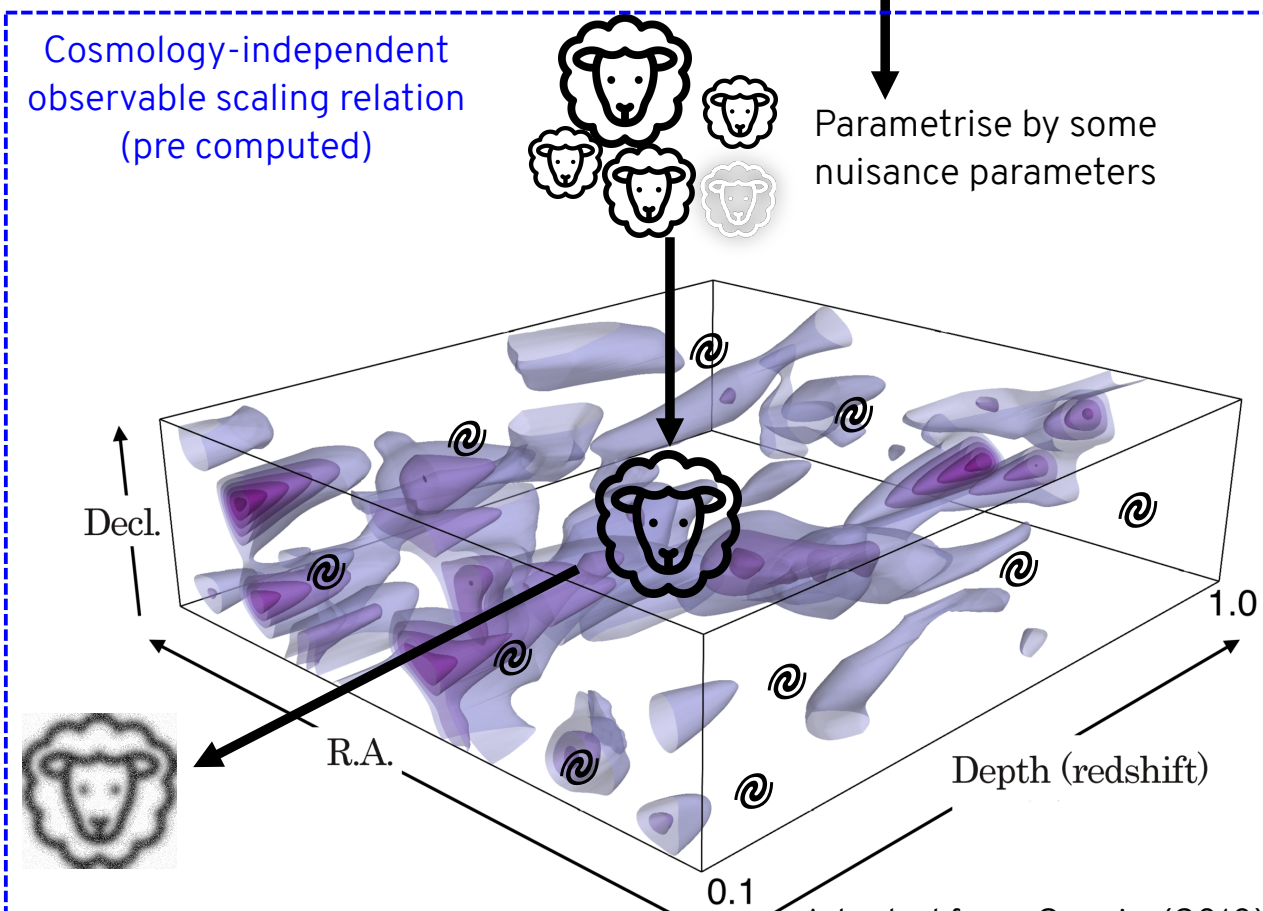
$$\Rightarrow \frac{\mathrm{d}N}{\mathrm{d}M\mathrm{d}z}\left(M, z \middle| \mathbf{p}\right)$$

(M_{200c}, z_{cl}) — Modelling the deviation from NFW-like halo (intrinsic uncertainties) → (M_{WL}, z_{cl}, c_{WL})

Cosmology-dependent

Cosmology-independent observable scaling relation (pre computed)

Parametrise by some nuisance parameters



Data

Poisson Likelihood

$$\frac{\mathrm{d}N}{\mathrm{d}\mathcal{O}_{WL}}$$

Adapted from Oguri+ (2018)

QUANTITATIVELY

$$\frac{\mathrm{d}N(\nu|p,\nu_{\mathrm{thres}})}{\mathrm{d}\nu}$$

$$= \iint \mathrm{d}M\mathrm{d}z \left[\frac{\mathrm{d}n(M,z|p)}{\mathrm{d}M\mathrm{d}z} V(z|p) \times \underline{P(\nu|M,z,p)} \Theta(\nu > \nu_{\mathrm{thres}}) \right]$$

$$\underline{P(\nu|M,z,p)} = \iint \mathrm{d}\hat{M}_\kappa \mathrm{d}\theta_s P(\nu|M_\kappa,\theta_s) P(\hat{M}_\kappa,\theta_s|M,z,p)$$

$$= \iint \mathrm{d}\hat{M}_\kappa \mathrm{d}\theta_s P(\nu|\hat{M}_\kappa,\theta_s) \left[P(\hat{M}_\kappa|\theta_s,M,z,p) \times P(\theta_s|M,z,p) \right]$$

$M_\kappa(\theta)$: True observed lensing signal profile

$\hat{M}_\kappa$: Estimated peak lensing signal

θ_s : Cluster characteristic angular size

QUANTITATIVELY

$$P(\nu|M,z,p) = \iint \mathrm{d}\hat{M}_\kappa \mathrm{d}\theta_s P(\nu|M_\kappa,\theta_s) P(\hat{M}_\kappa,\theta_s|M,z,p)$$

$$= \iint \mathrm{d}\hat{M}_\kappa \mathrm{d}\theta_s P(\nu|\hat{M}_\kappa,\theta_s) \Big[P(\hat{M}_\kappa|\theta_s,M,z,p) \times P(\theta_s|M,z,p) \Big]$$

$$M_\kappa(\theta) \approx 2\pi\rho_s r_s^3 D_A^{-2} \langle \Sigma_c^{-1} \rangle \int_0^{x_{\rm out} := \theta_{\rm out}/\theta_S} U\left(\theta - x\cdot\theta_S\right) f(x) x \mathrm{d}x$$

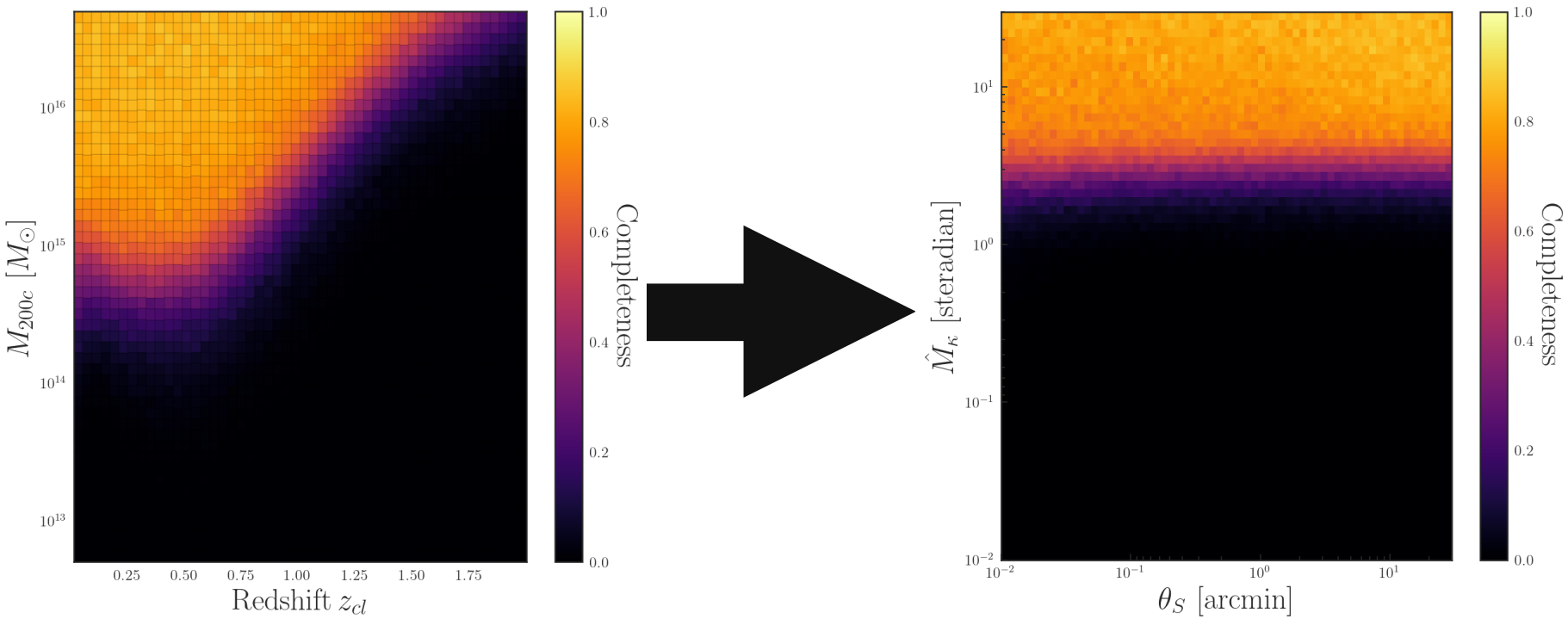
$$= \hat{M}_\kappa \frac{\int_0^{x_{\rm out}} U\left(\theta - x\cdot\theta_S\right) f(x) x \mathrm{d}x}{\int_0^{x_{\rm out}} U\left(x\cdot\theta_S\right) f(x) x \mathrm{d}x}$$

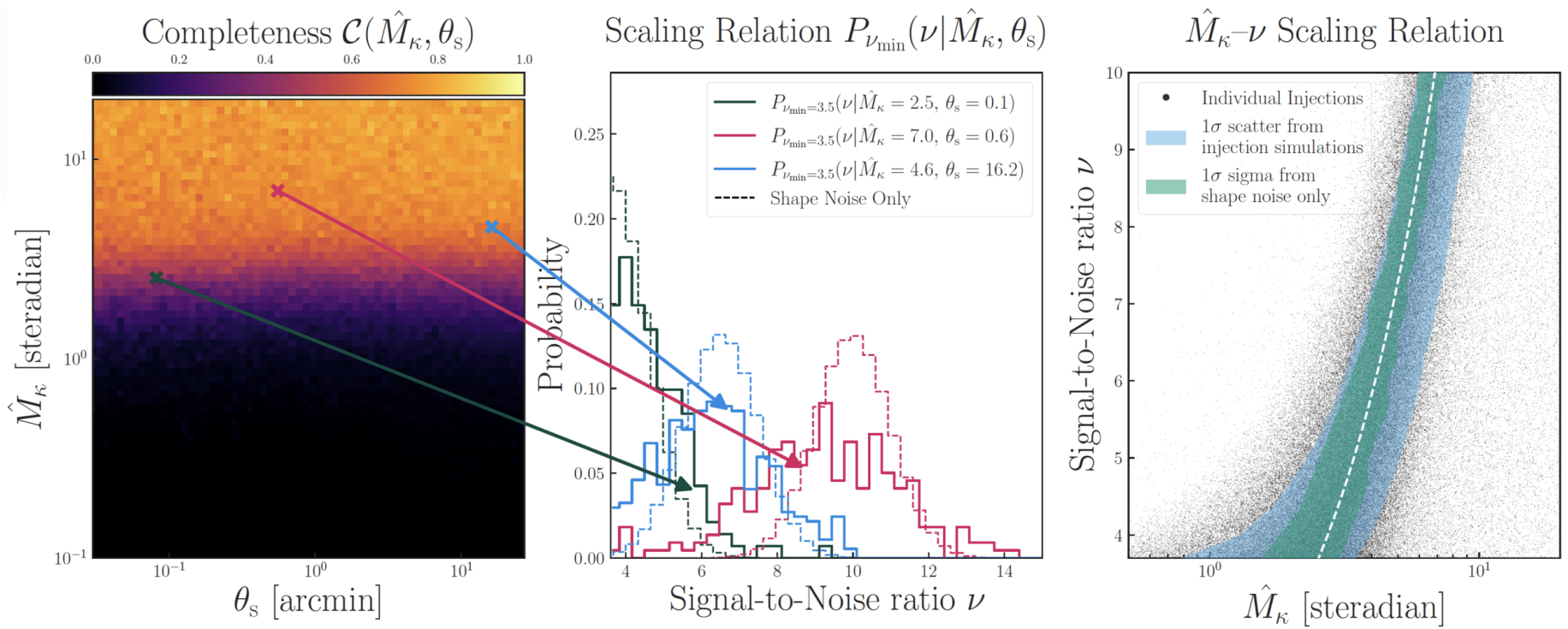
$M_\kappa(\theta)$: True observed lensing signal profile

$\hat{M}_\kappa$: Estimated peak lensing signal

θ_s : Cluster characteristic angular size

RE-PARAMETRIZED SELECTION FUNCTION




Completeness $\mathcal{C}(\hat{M}_\kappa, \theta_S)$
$\hat{M}_\kappa$ [steradian]
θ_S [arcmin]
Scaling Relation $P_{\nu_{\rm min}}(\nu|\hat{M}_\kappa, \theta_S)$
$P_{\nu_{\rm min}=3.5}(\nu|\hat{M}_\kappa = 2.5,\ \theta_S = 0.1)$
$P_{\nu_{\rm min}=3.5}(\nu|\hat{M}_\kappa = 7.0,\ \theta_S = 0.6)$
$P_{\nu_{\rm min}=3.5}(\nu|\hat{M}_\kappa = 4.6,\ \theta_S = 16.2)$
Shape Noise Only
Probability
Signal-to-Noise ratio ν
$\hat{M}_\kappa$–ν Scaling Relation
Individual Injections
1σ scatter from injection simulations
1σ sigma from shape noise only
Signal-to-Noise ratio ν
$\hat{M}_\kappa$ [steradian]

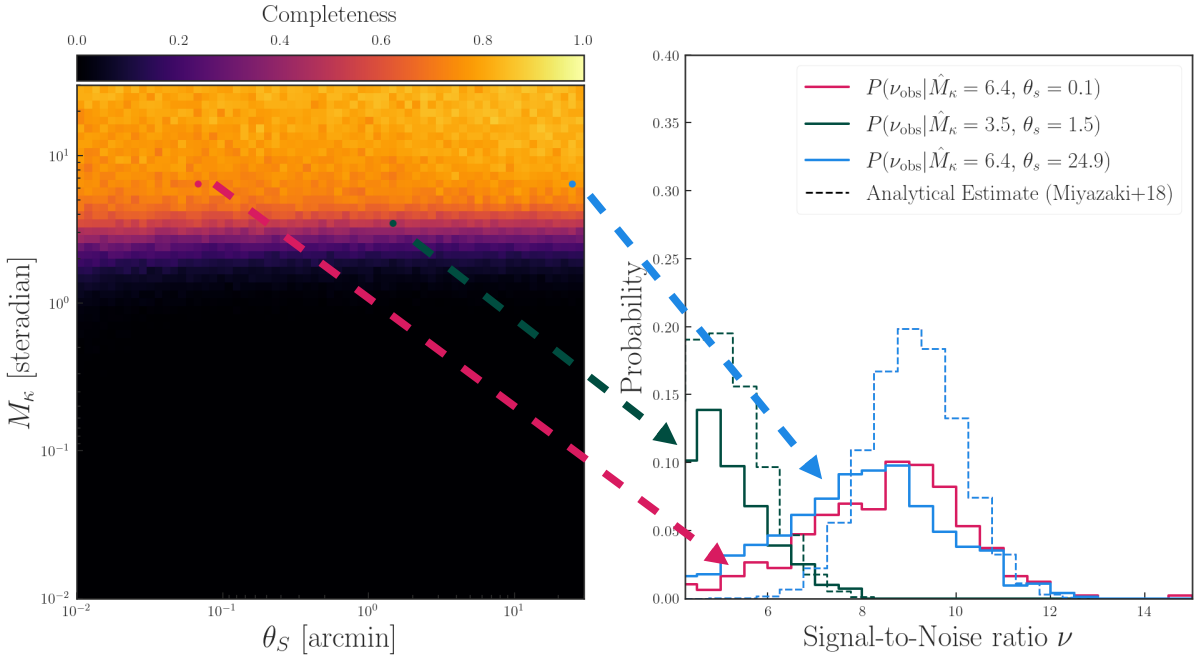
VALIDATION

- Use one ~22 square degree field from HSC-Y1
- Mock clusters sampled uniformly on the $\hat{M}_\kappa$–θ_s space
- Generate $P(\nu_{\rm obs}|\hat{M}_\kappa, \theta_s)$ for various cosmological parameters to validate our assumption

Vanilla

$h = 0.7,\ \Omega_c = 0.25,\ \sigma_8 = 0.8$

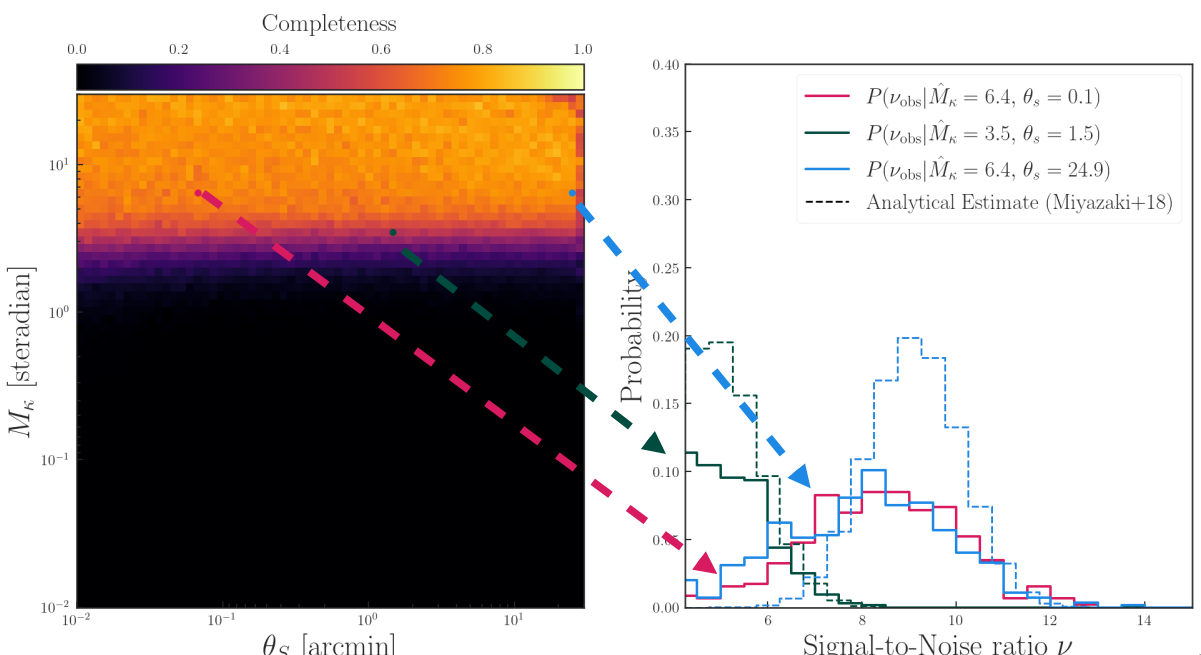
$n_s = 0.95,\ w_0 = -1.0$



Exotic

$h = 0.7,\ \Omega_c = 0.20,\ \sigma_8 = 0.65$

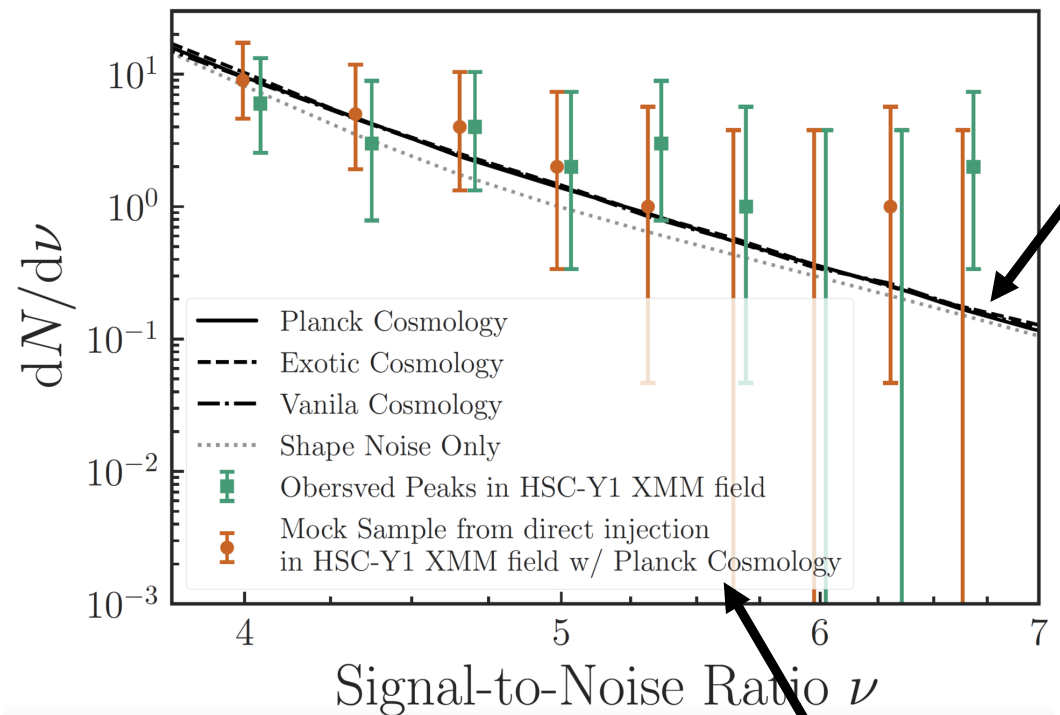
$n_s = 1.05,\ w_0 = -1.5$

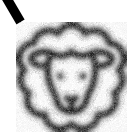


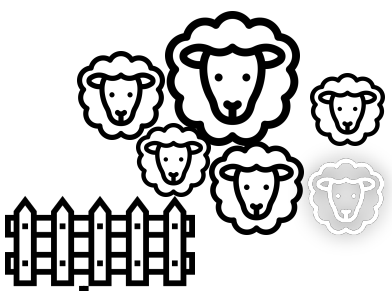
NUMBER COUNT

- Three sets of cosmology
- Compare to a mock observation
- Compare to actual number count

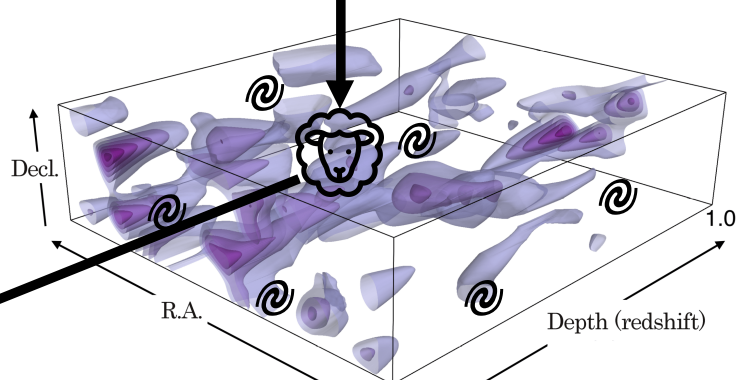
$$\frac{\mathrm{d}N(\nu|p,\nu_{\mathrm{thres}})}{\mathrm{d}\nu} = \iint \mathrm{d}M\mathrm{d}z \left[\frac{\mathrm{d}n(M,z|p)}{\mathrm{d}M\mathrm{d}z} V(z|p) \times P(\nu|M,z,p)\Theta(\nu > \nu_{\mathrm{thres}})\right]$$







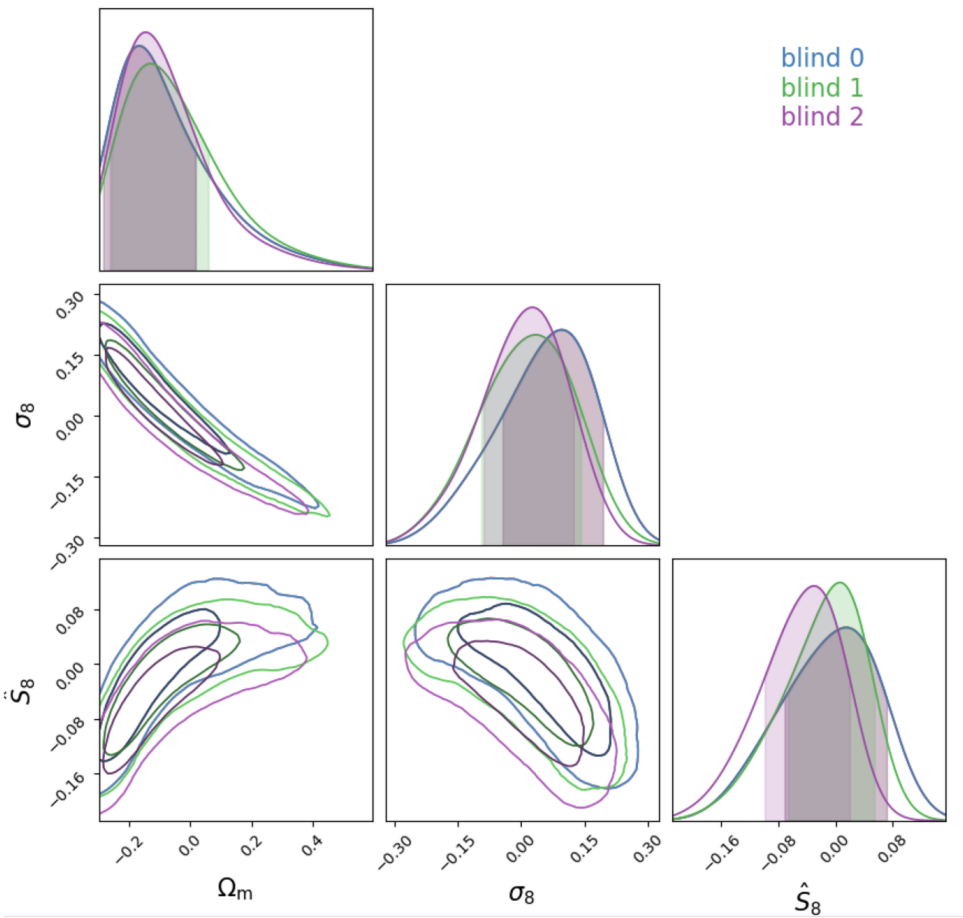
Bocquet+ (2016)



Adapted from Oguri+ (2018)

BLINDED ANALYSIS

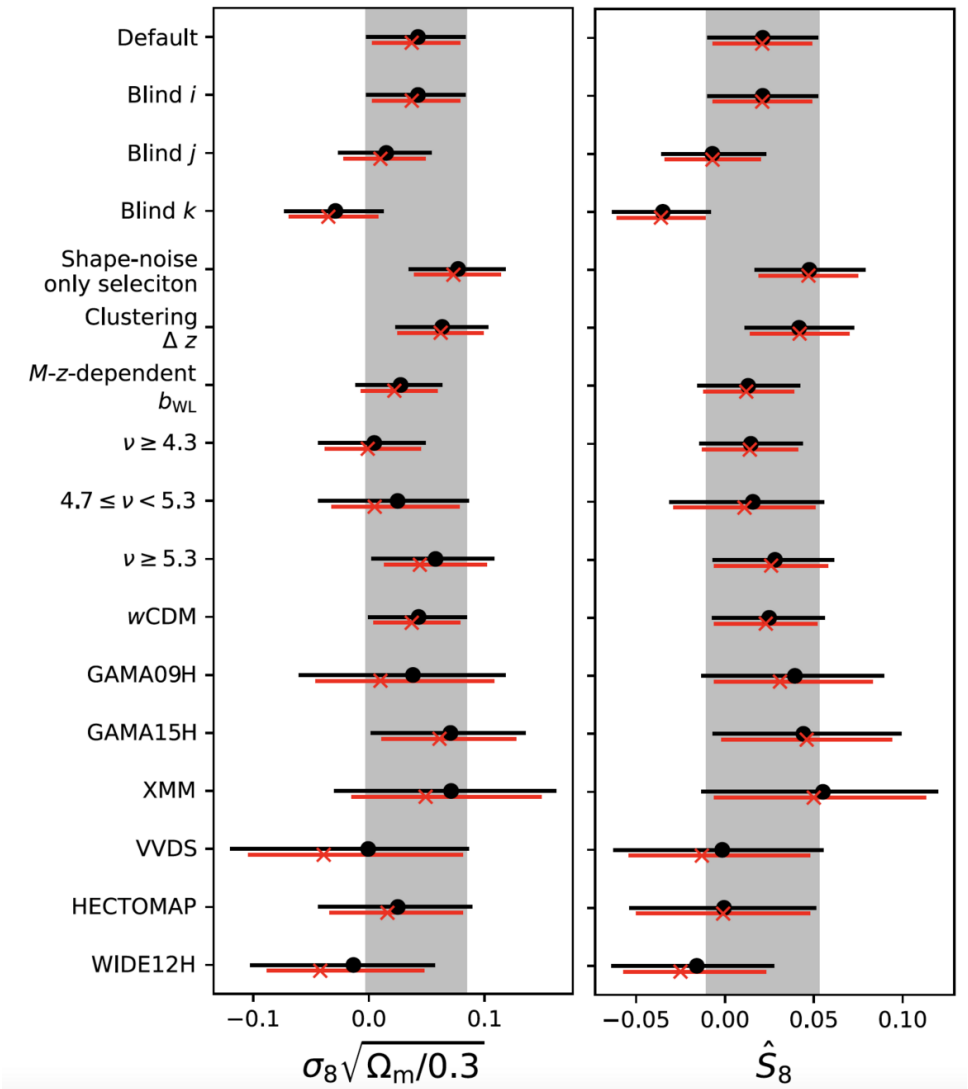
- Catalogue level blinding through shifting multiplicative bias
- Collaboration-level blinding
- All the analyses ran three times



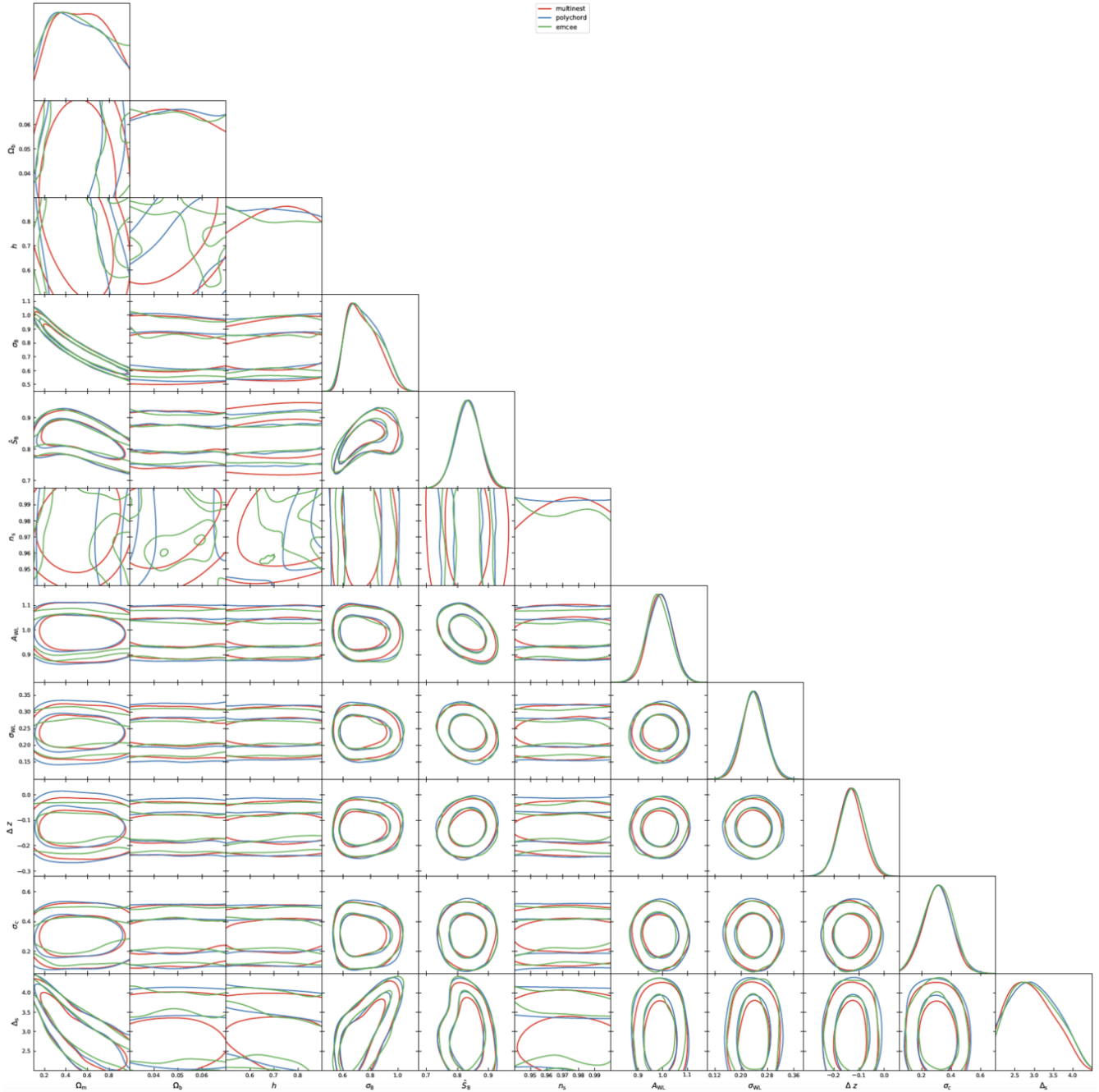
Chiu+ (in prep.)

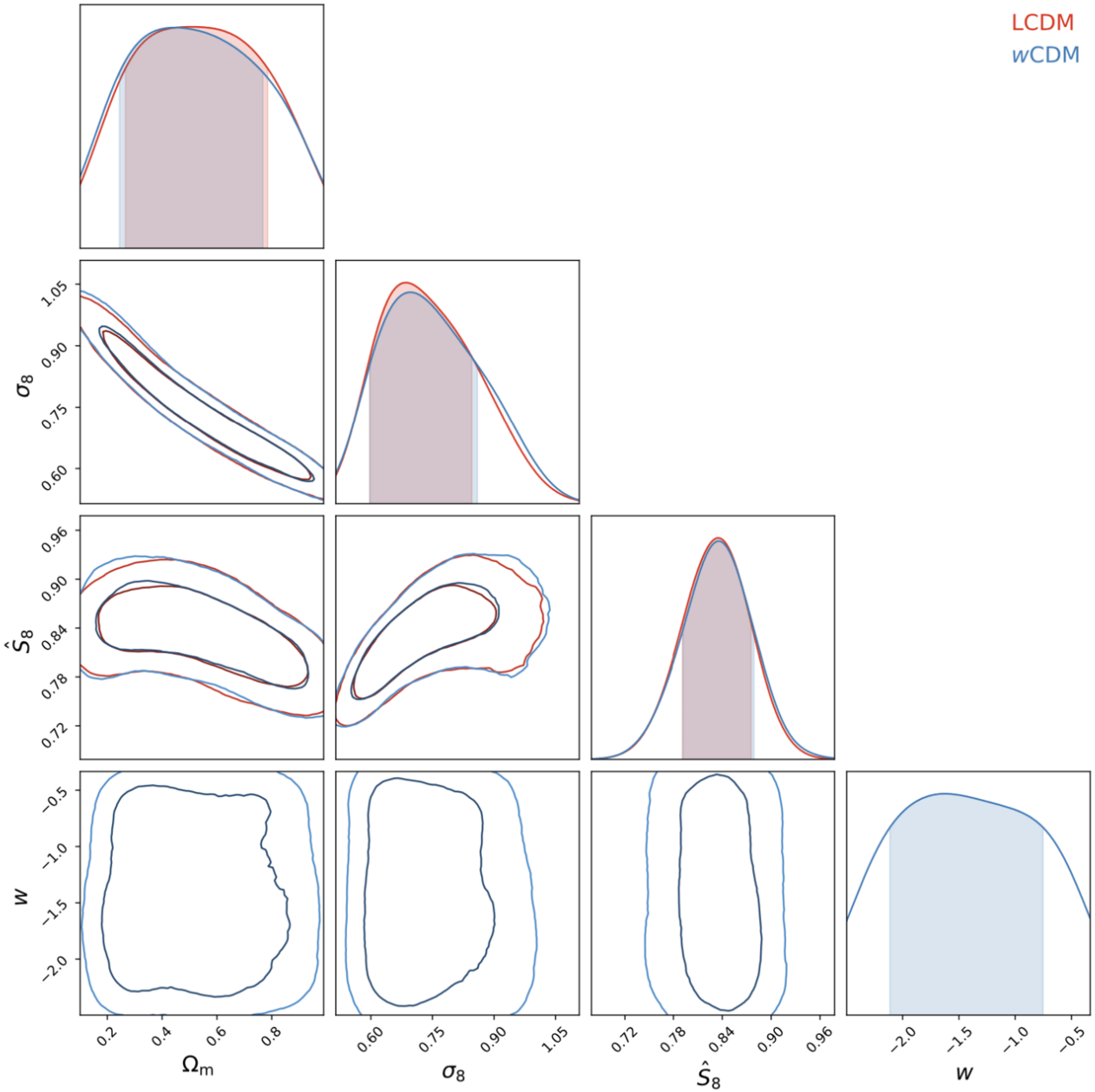
CONSISTENCY CHECKS

- Consistency across subset of data
- Consistency across different selection threshold
- Consistency across different modelling frameworks
- Consistency across different numerical packages



Chiu+ (in prep.)


multinest
polychord
emcee
Ω_m
Ω_b
h
σ_8
$\hat{S}_8$
n_s
A_{WL}
σ_{WL}
Δz
σ_c
Δ_s


LCDM
wCDM
Ω_m
σ_8
$\hat{S}_8$
w
0.2
0.4
0.6
0.8
0.60
0.75
0.90
1.05
0.72
0.78
0.84
0.90
0.96
−2.0
−1.5
−1.0
−0.5