WEAK LENSING MASS MAPS AND COSMOLOGY FROM PEAK STATISTICS:

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

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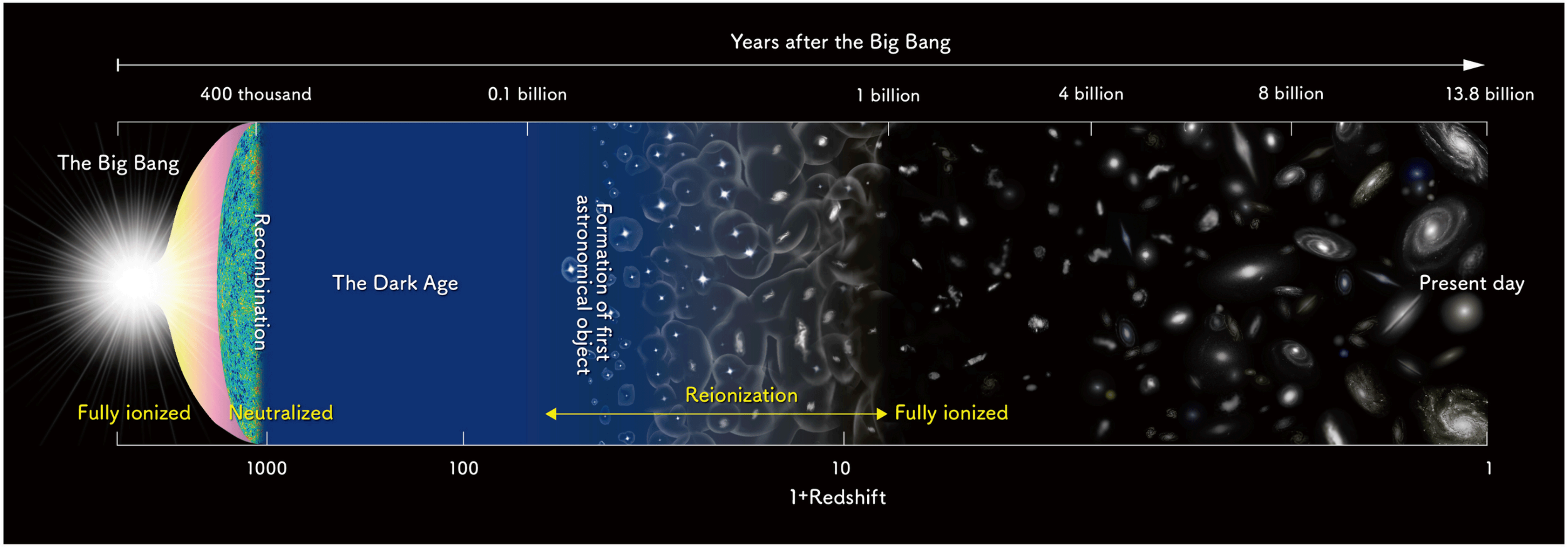
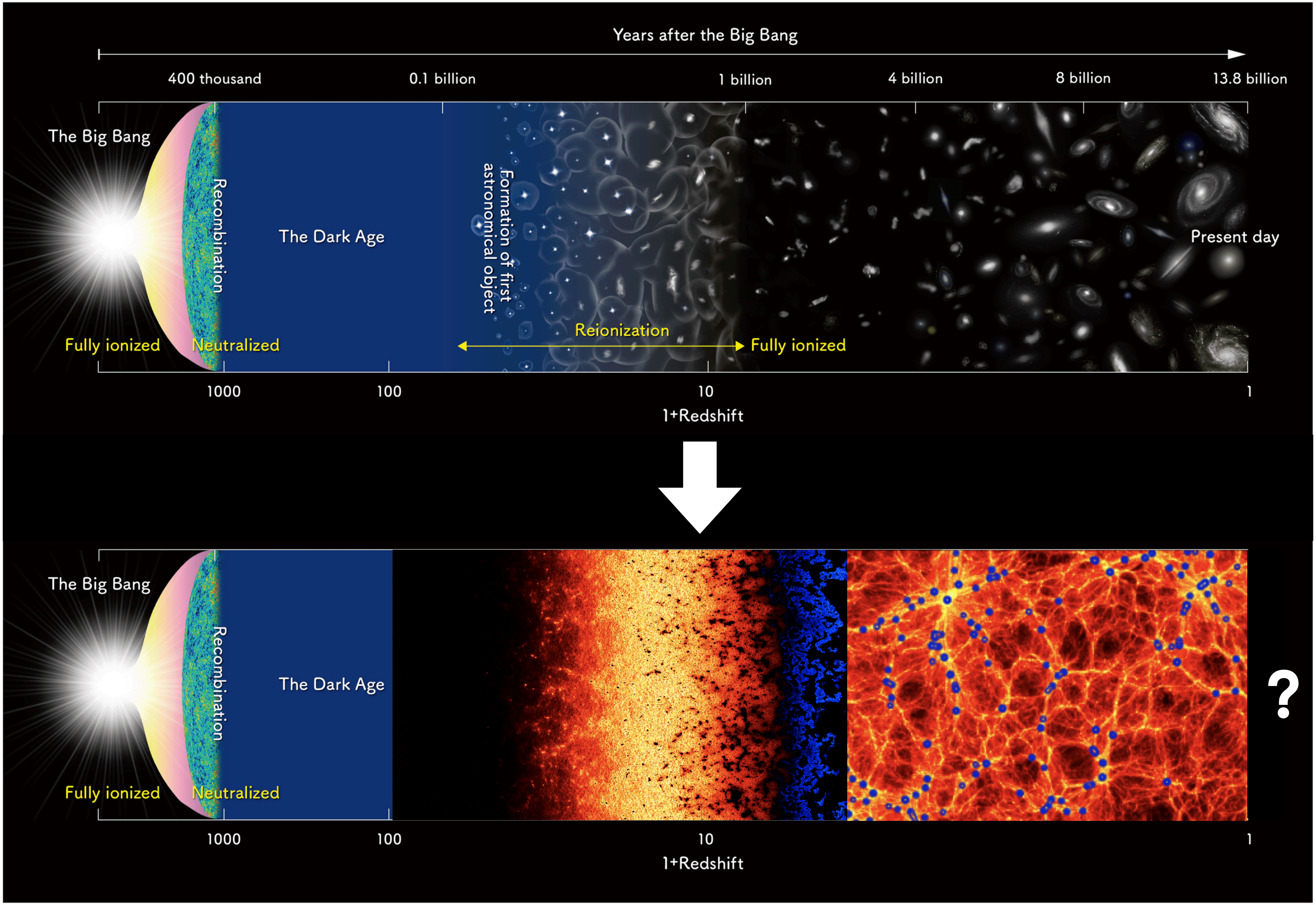
with I-Non Chiu (NCKU, Taiwan), Masamune Oguri (Chiba Univ., Japan)

and the HSC collaboration

Mar 20th @ Les Diablerets (Supported by Swiss National Science Foundation)


Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift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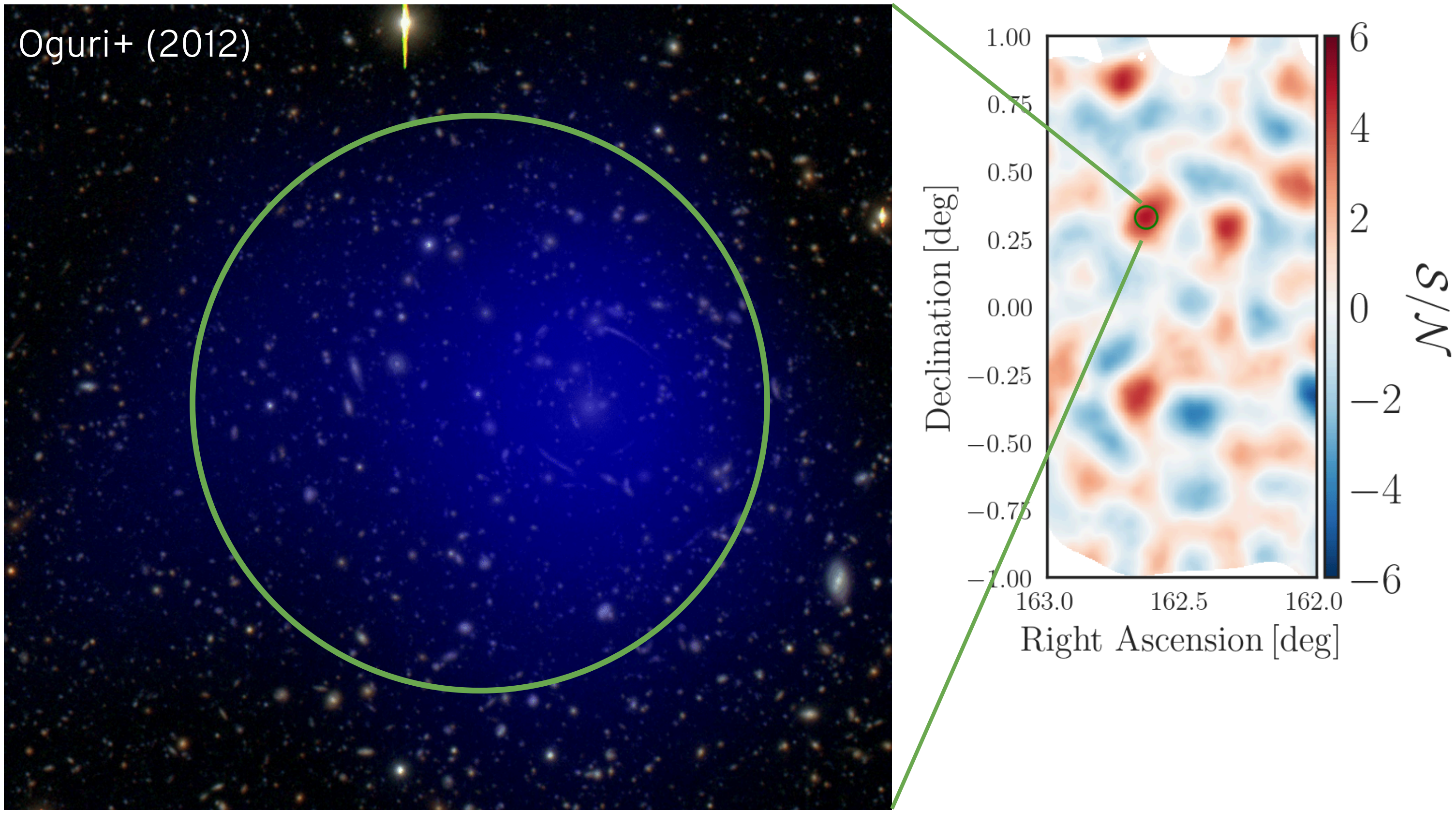
10
1
1+Redshift
The Big Bang
Recombination
The Dark Age
Fully ionized
Neutralized
?
1000
100
10
1
1+Redshift

MAPS IN THE NEABY UNIVERSE?
WEAK LENSING APERTURE MASS MAPS

- A map that measure the projected total mass within a certain aperture
- A compression of galaxy survey data

$$2 \times N_{\rm gal} \longrightarrow 2 \times N_{\rm pix} \quad (\sim 30 \text{ galaxies per arcmin}^2)$$

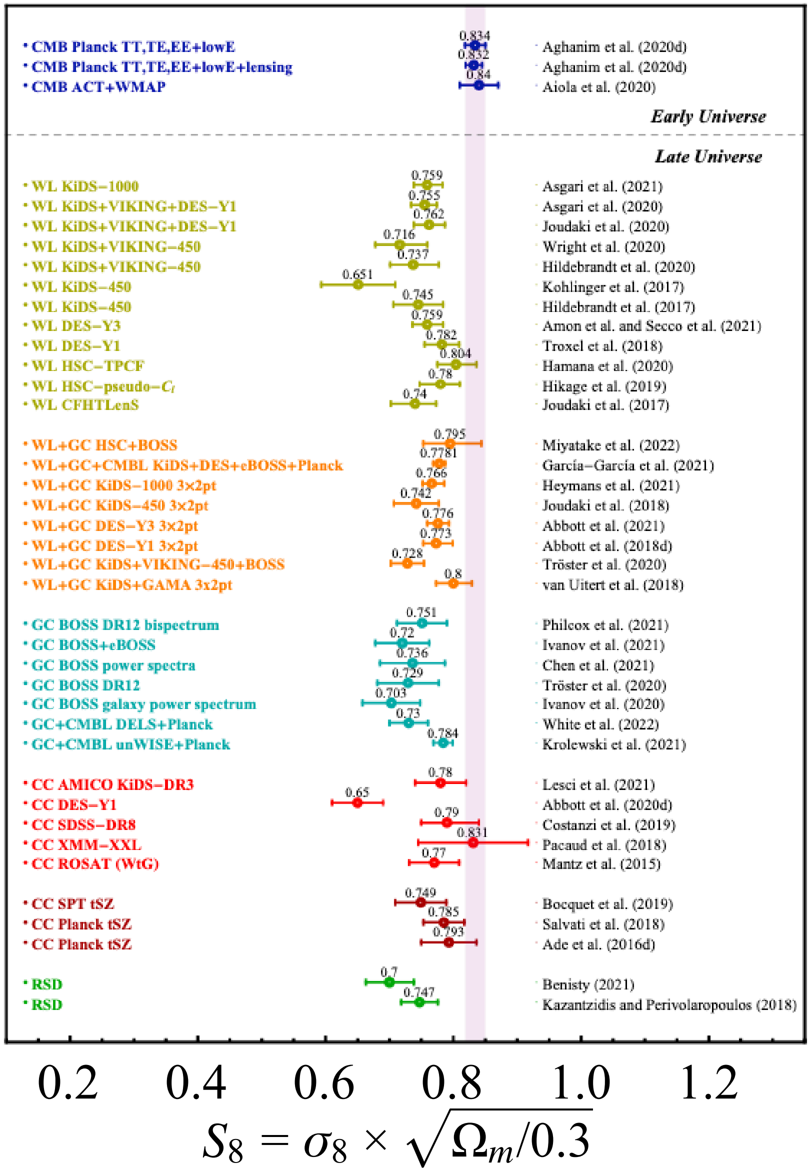
- Contains both Gaussian and non-Gaussian information



COSMOLOGY WITH WEAK LENSING MASS MAPS

- WL surveys already have competitive constraints on S8 from power spectra/2pt correlation functions
- However, these constraints are in increasing tension with early-time measurement
- High-order statistics as an additional consistency test
  - Peak statistics
  - Higher moments in WL maps
  - 3pt-correlation/bispectra
  - Minkowski functionals
  - Density split statistics
  - Field-level inference

Snowmass (2021)

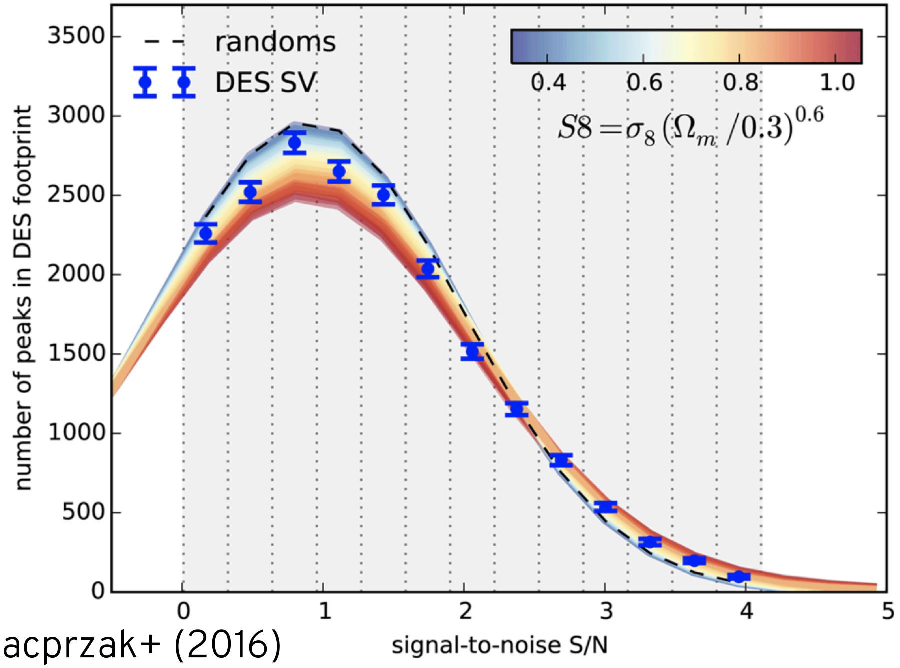


MID S/N PEAKS

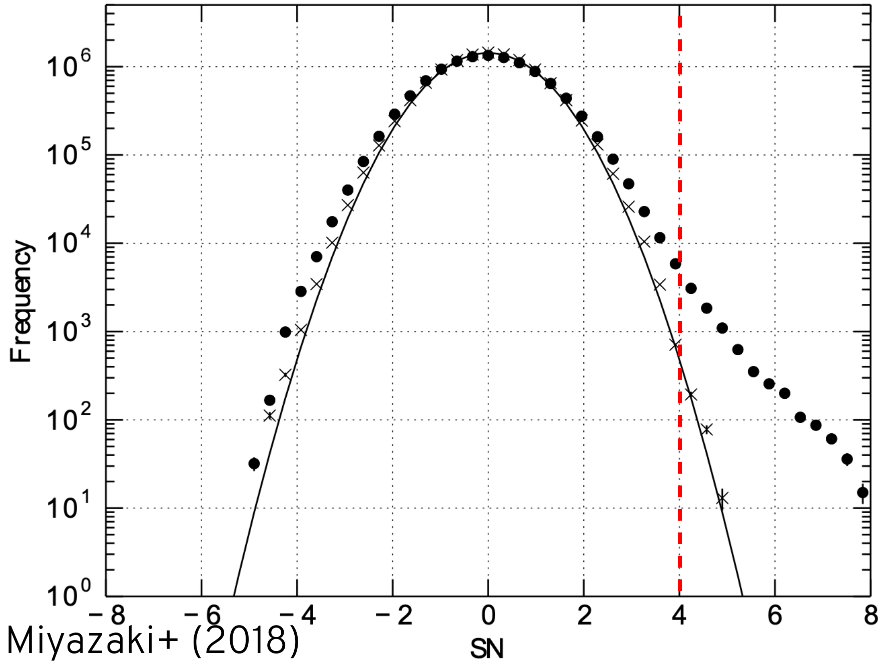
- Peaks from galaxy/group scale halos + random fluctuation
- The peak function can be modelled analytically or numerically
- More sensitive to systematics such as boost and dilution effect, intrinsic alignment, etc.

HIGH S/N PEAKS

- Peaks from massive halos (clusters)
- Could obtain redshift info through cross-matching
- Complicated mass--observable relation and selection function to model



Kacprzak+ (2016)



Miyazaki+ (2018)

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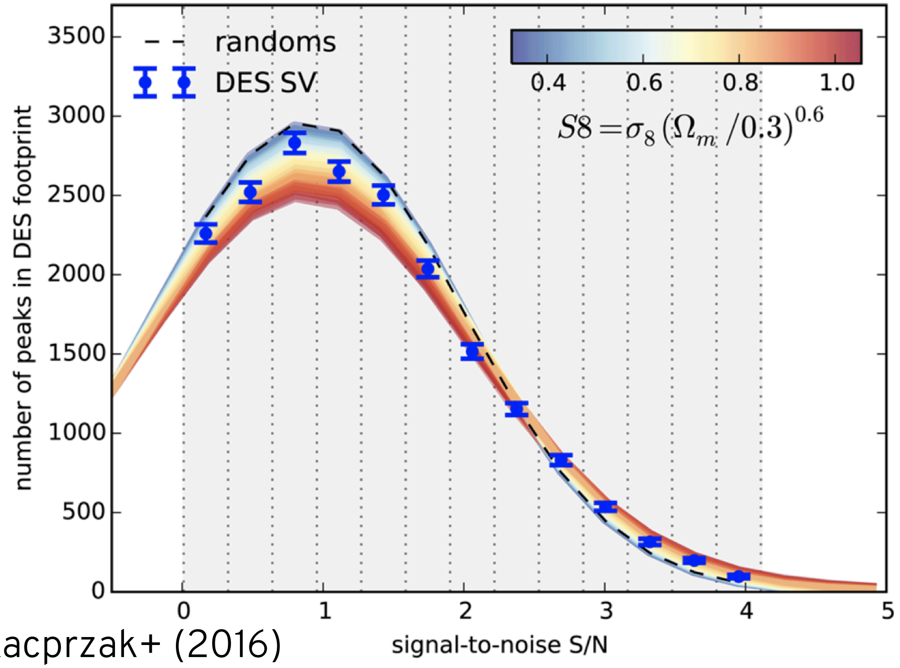

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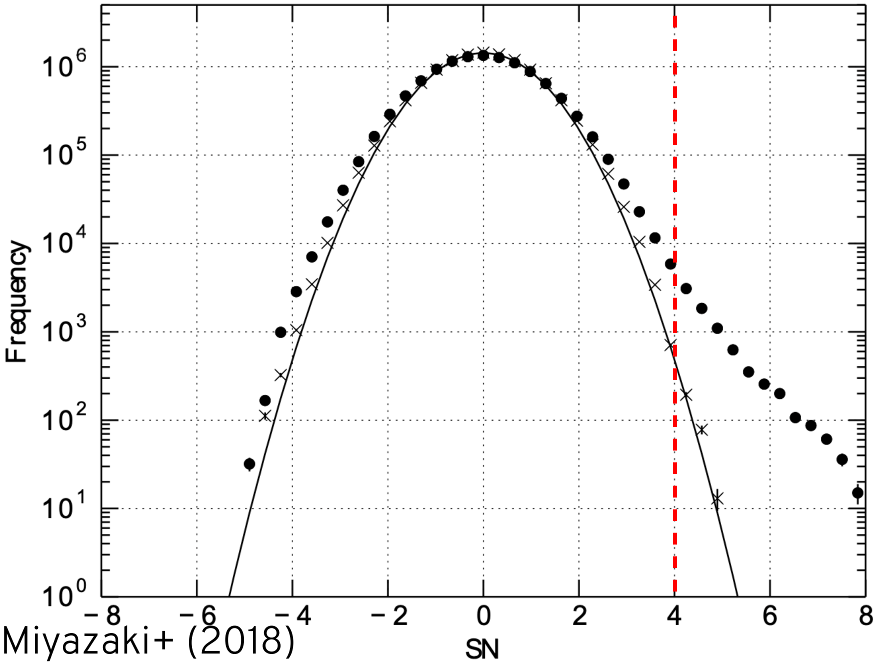
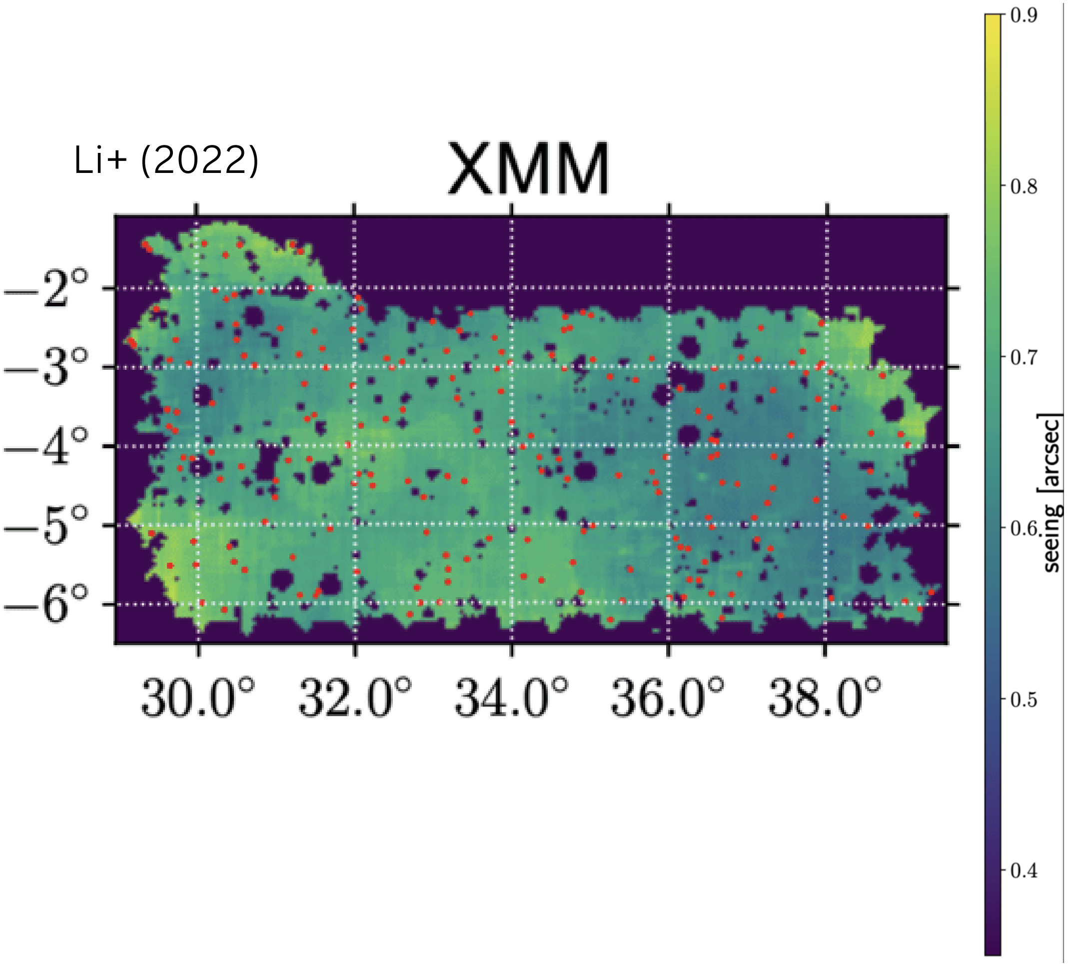


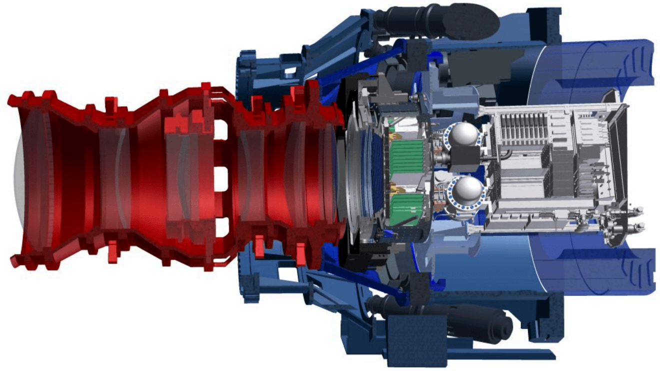
Miyazaki+ (2018)

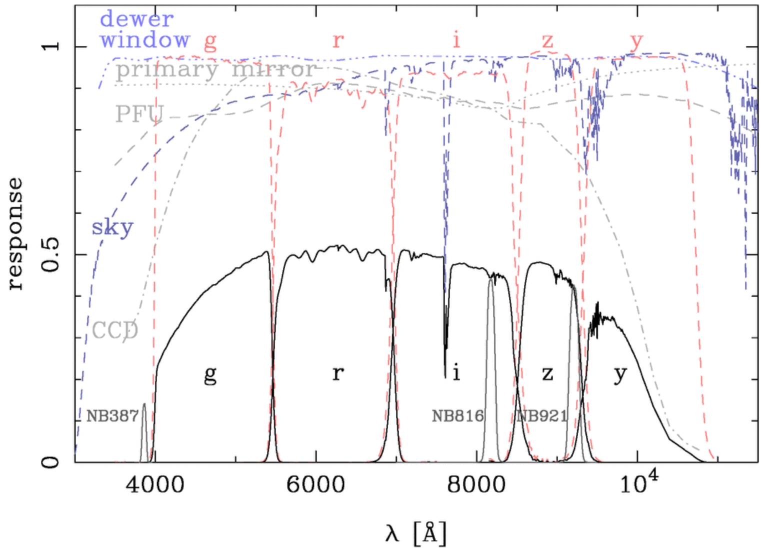
DATA: SUBARU HYPER SUPRIME-CAM

- HSC: 1.8 sq deg wide field camera on the 8.2m Subaru Telescope
- Collaboration between Japan, Taiwan and Princeton University
- Multi-band photometry with average i-band seeing at 0''.59
- Year-3 data: 35 million raw galaxies over ~450 sq deg

Li+ (2022)

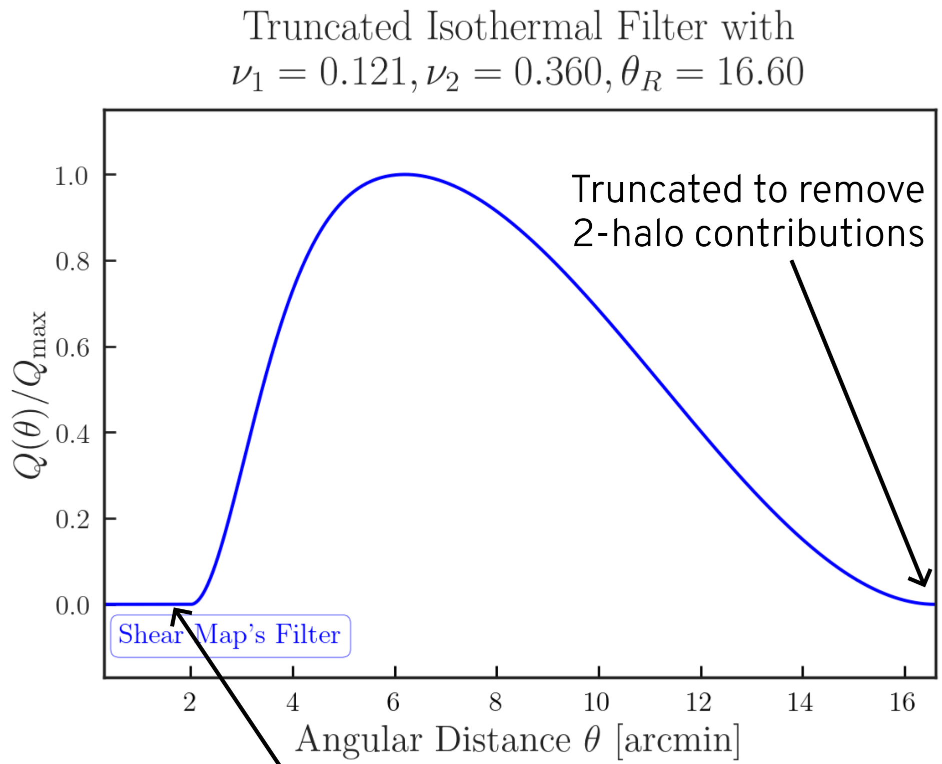




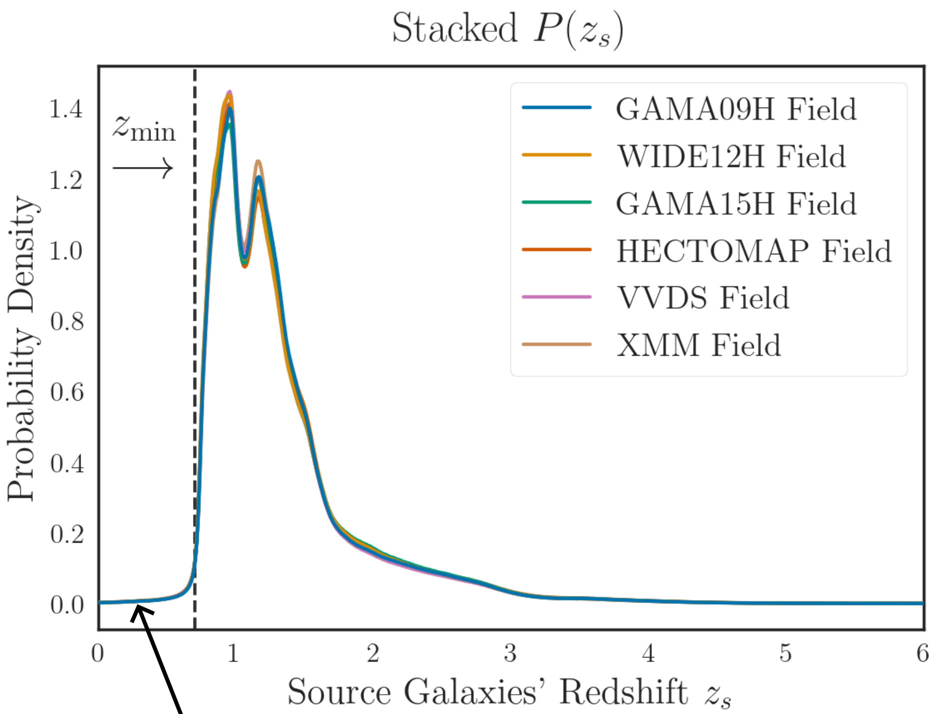


WEAK LENSING MAPS IN HSC

- Convolve galaxies' shear with a truncated isothermal profile (Schneider 1996) to maximise lensing signals from galaxy clusters
- Use only high-z (z > 0.7) source galaxies to avoid dilutions from cluster member galaxies



Remove innermost part of the halo



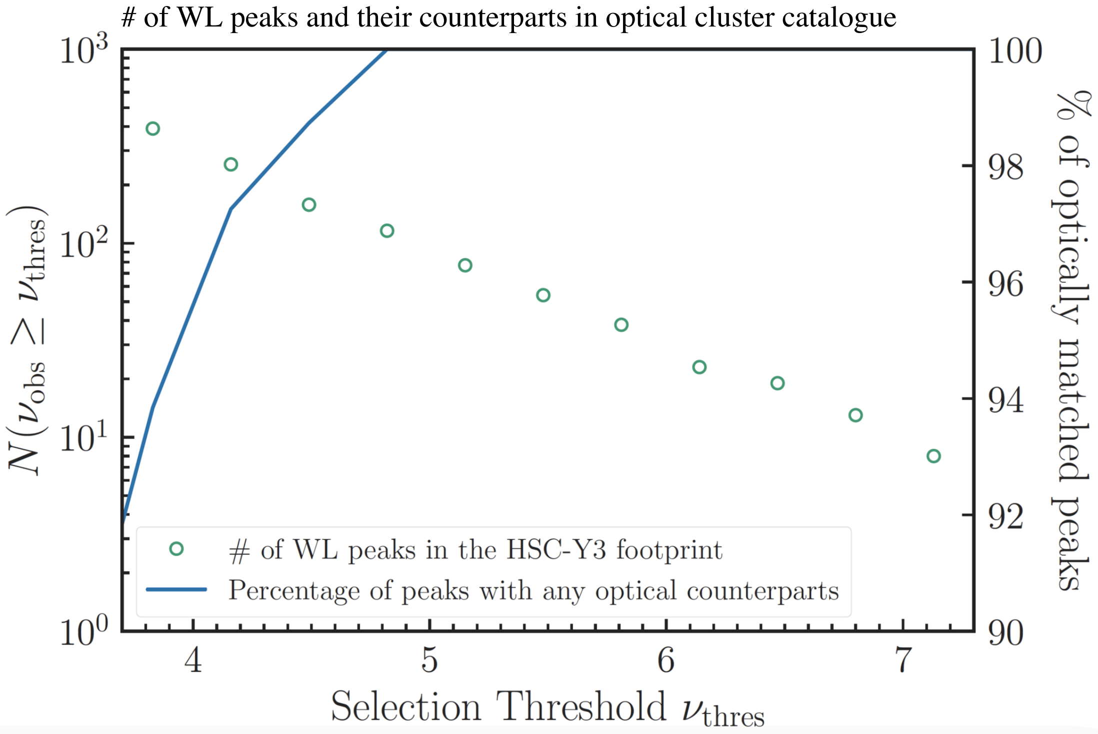
Chen+ (in prep.)

Remove source galaxies at low redshift to avoid dilutions from cluster member galaxies

GETTING THE OBSERVABLE

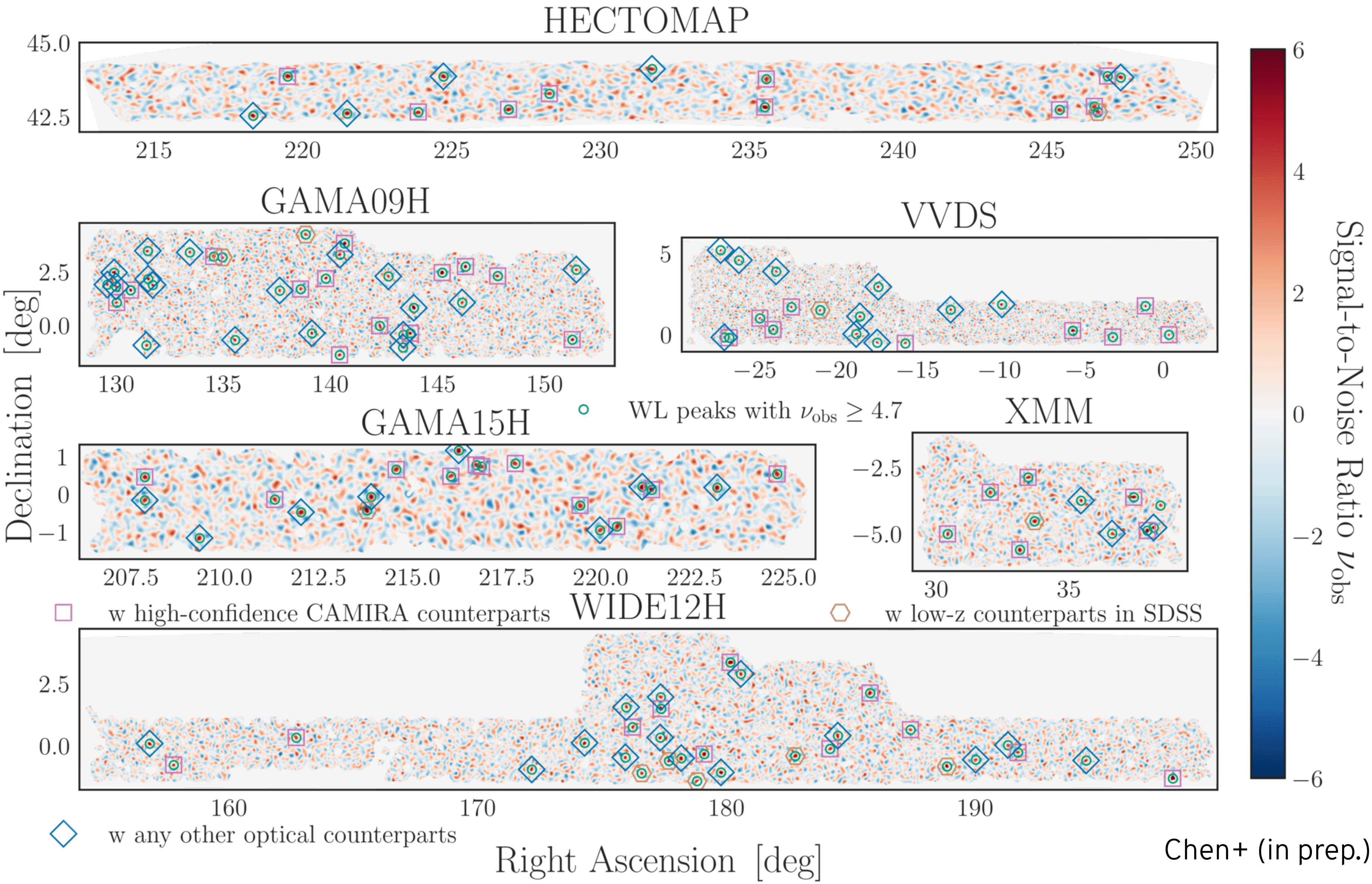
- Signal map (Aperture mass map)
- Noise map (Through randomise source galaxies shape)
- Masking
- Observable: Signal-to-Noise ratio map
- Peak Detection

$\Longrightarrow$ 130 peaks with S/N > 4.7



Chen+ (in prep.)

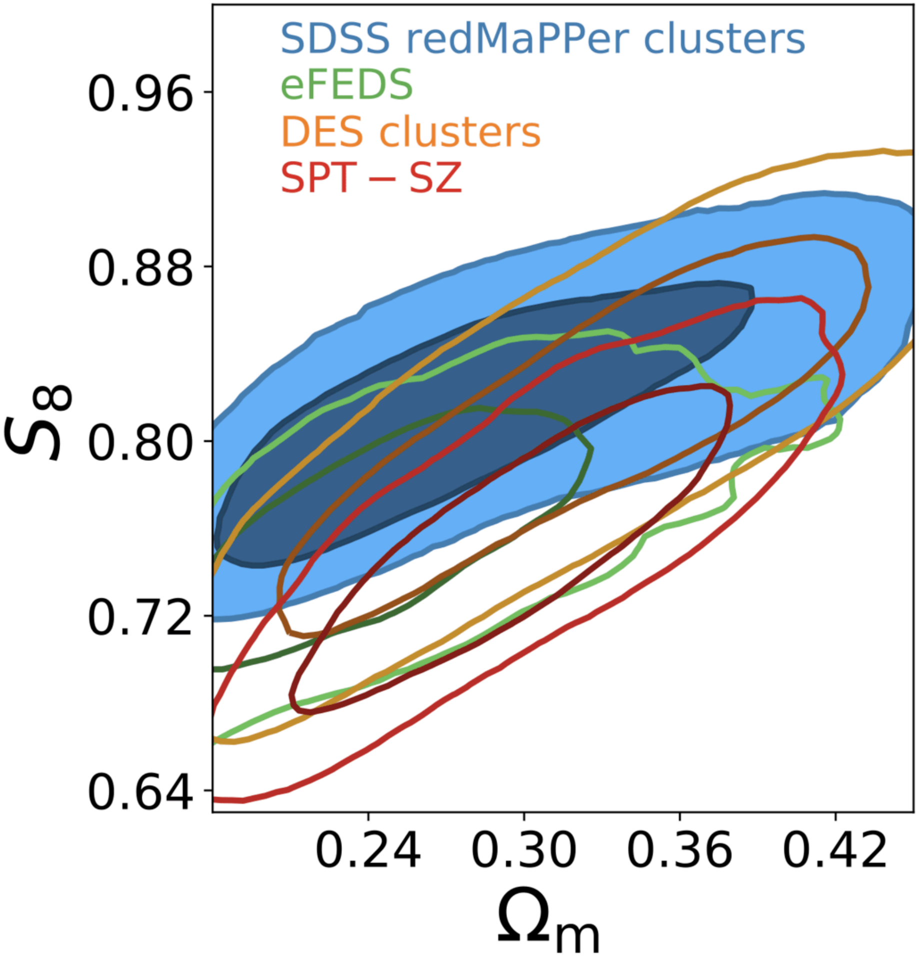
WEAK LENSING MAPS IN HSC



Chen+ (in prep.)

WHERE DOES OUR SENSITIVITY COME FROM?

Similar to Cluster Cosmology!

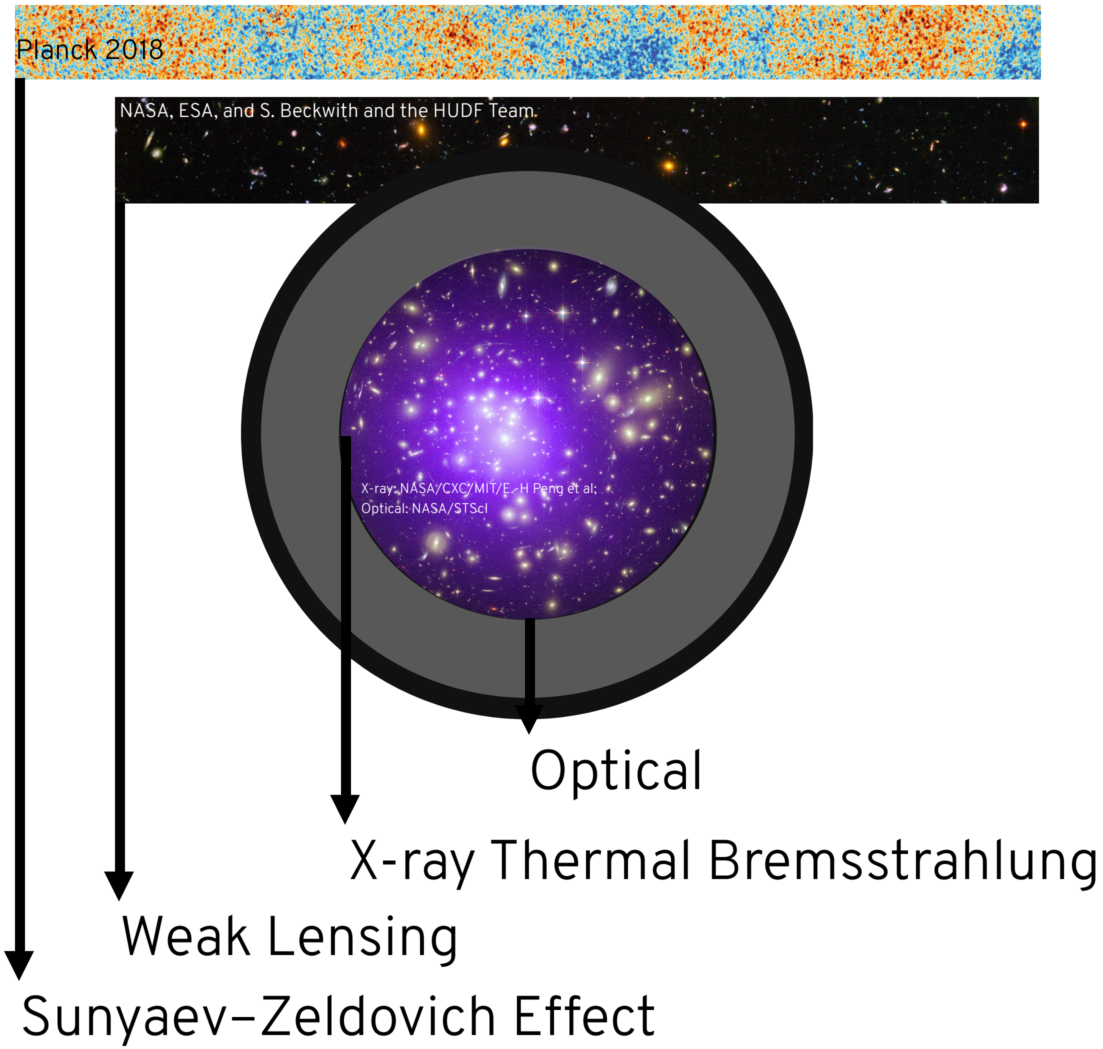


Sunayama+ (2023)

$$\#\text{ of halos}(M, z)$$
$$\parallel$$
$$\text{Halo density}(M, z)$$
$$\times$$
$$\text{Volume}(z)$$

WHY USE WL PEAKS INSTEAD?

Observable–Mass Relation



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

$$\|$$

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

$$\times$$

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

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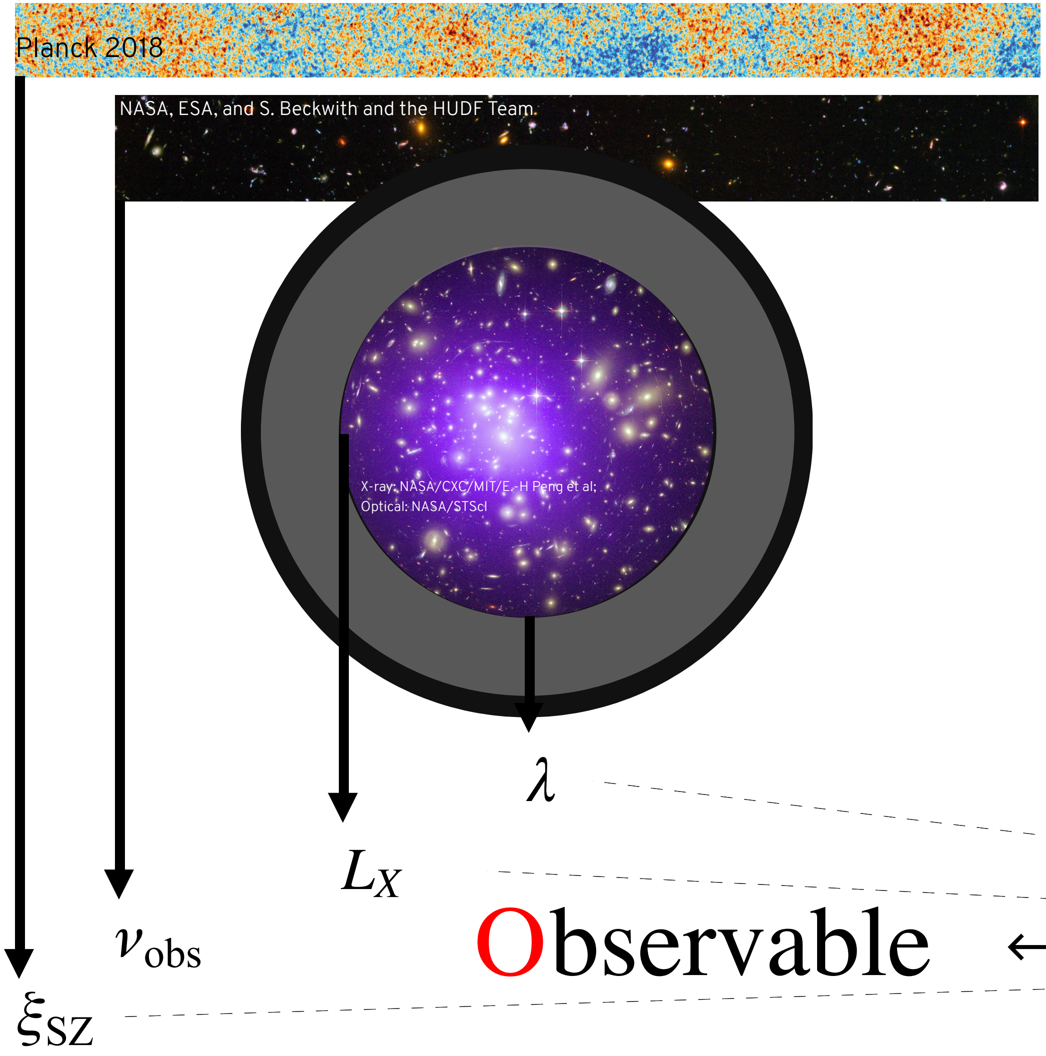
Observable–Mass Relation



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

$$\|$$

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

$$\times$$

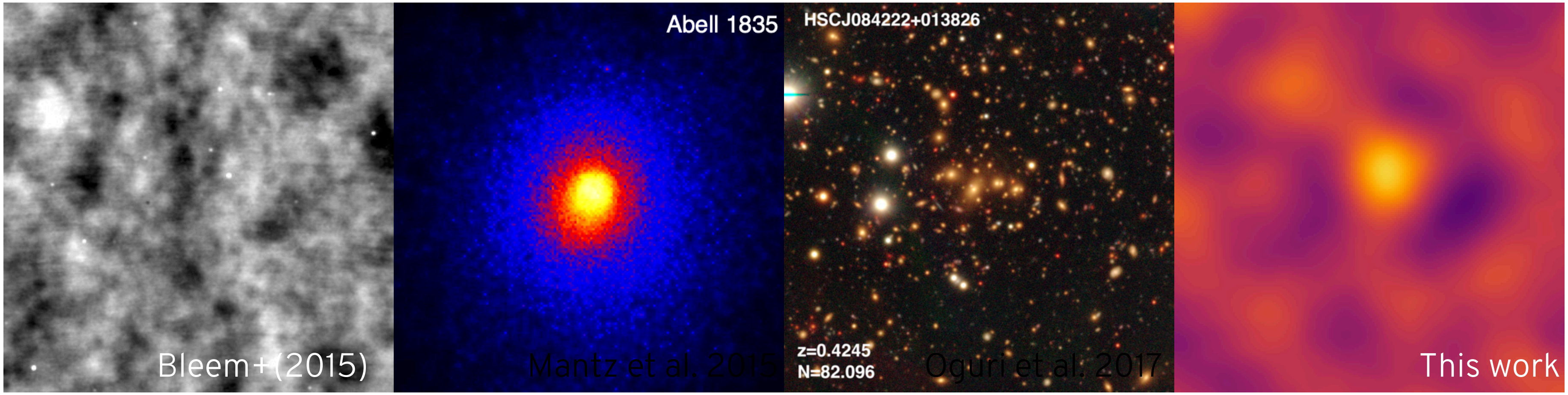
$$\text{Volume}(z)$$

Observable $\longleftrightarrow$ Mass

WHY USE WL PEAKS INSTEAD?

Direct Observable—Mass Relation!

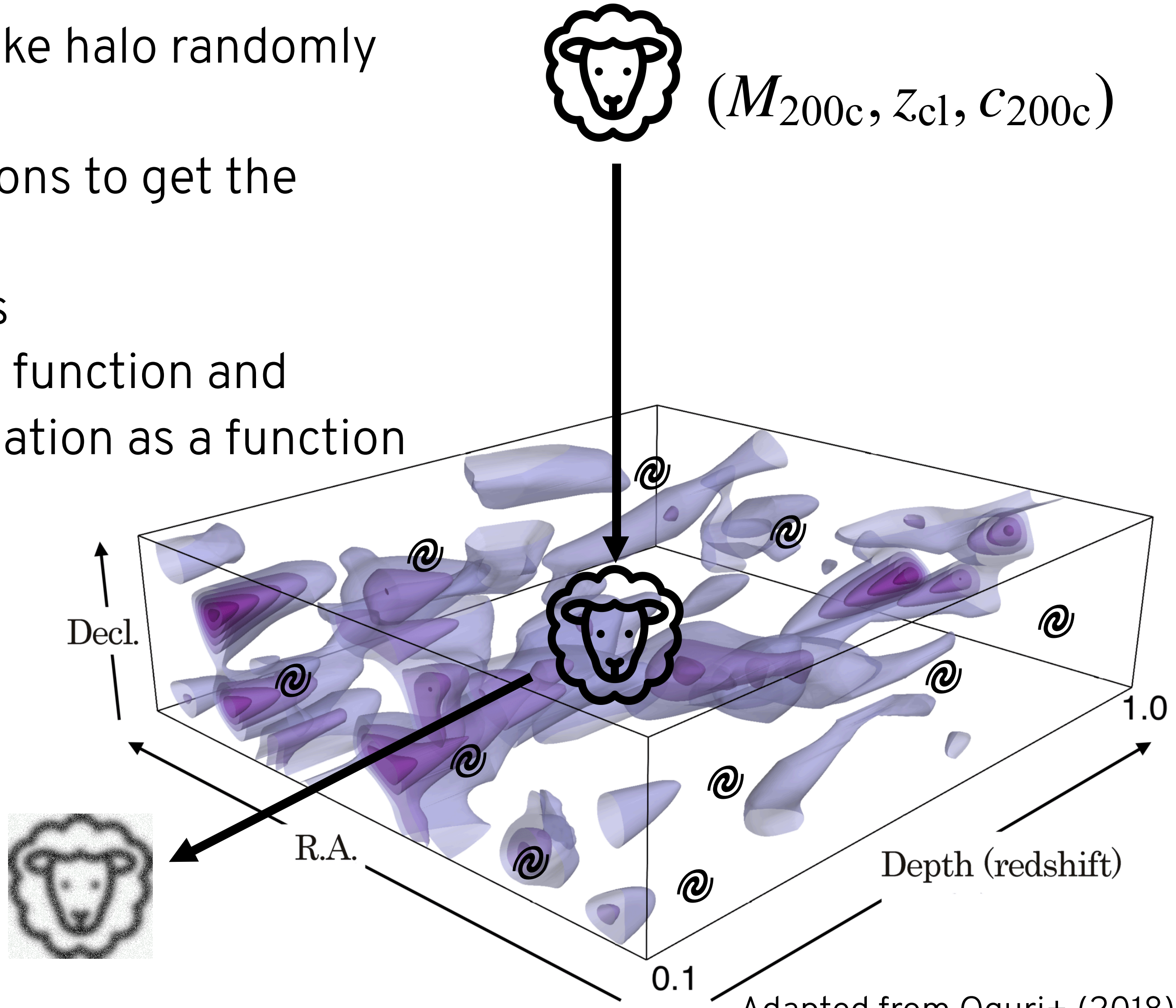
tSZ | X-ray | Optical | Weak Lensing



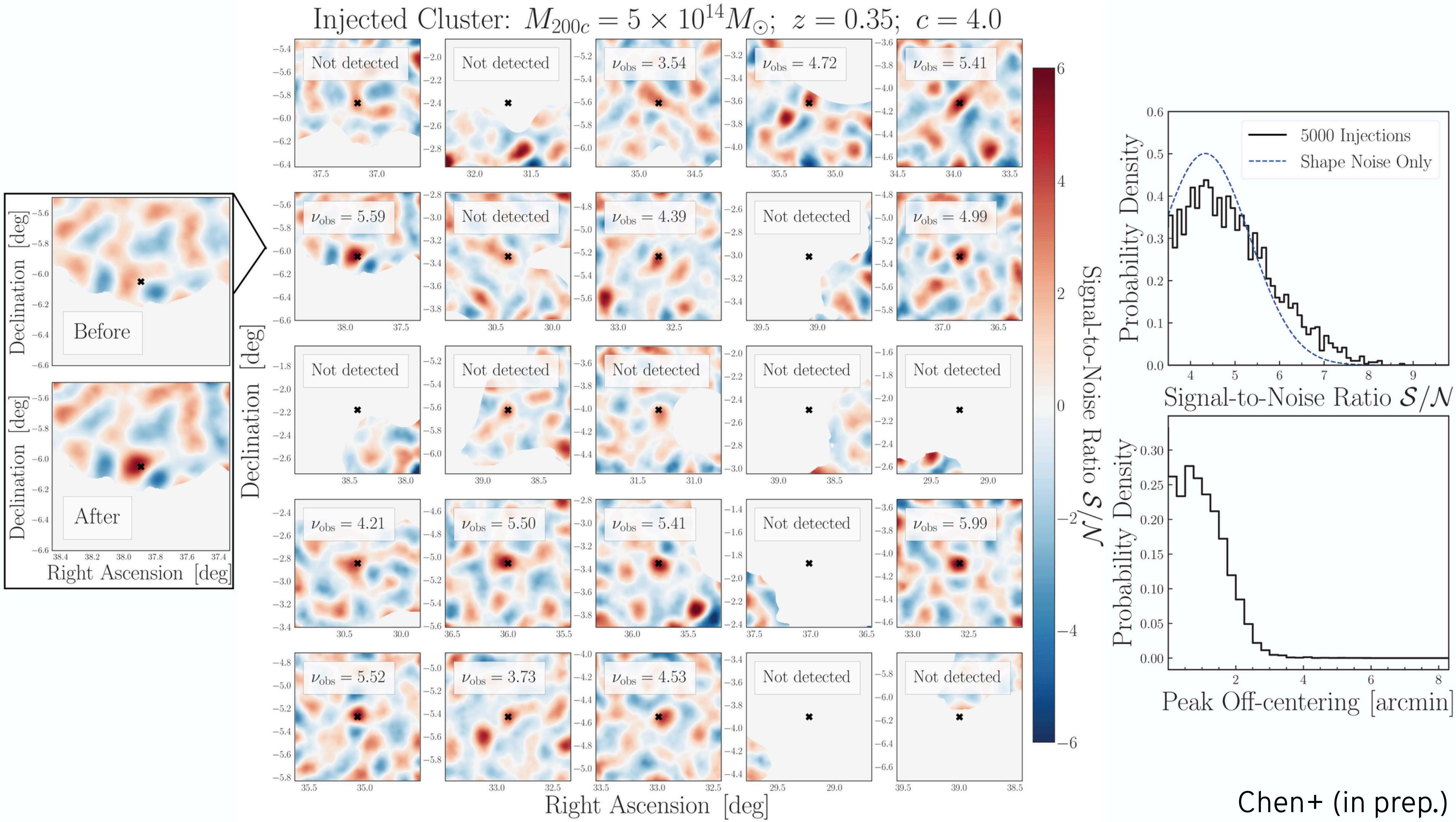
$y_{SZ} \propto n_e$ | $L_X \propto n_e^2$ | $\lambda_{rich} \propto M_*$ | $M_{aper} \propto M_{2D}$

THE MASS OBSERVABLE RELATION

1. Draw realisations of redshift for source galaxies to create semi-real 3D box
2. Paint a mock NFW-like halo randomly on to the sky
3. Run mock observations to get the observable
4. Repeat million times
5. Obtain the selection function and mass-observable relation as a function of halo properties



Adapted from Oguri+ (2018)

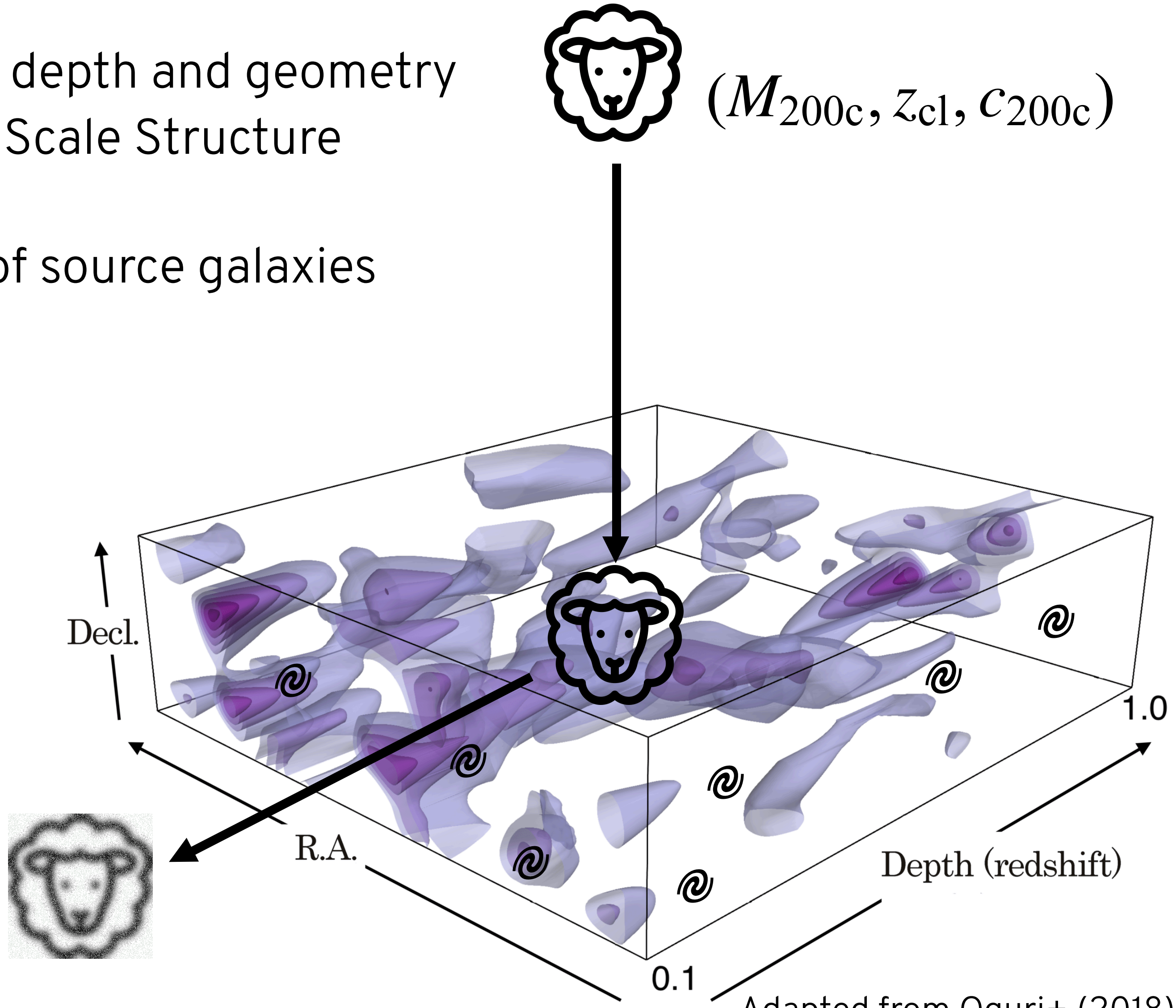

Injected Cluster: $M_{200c} = 5 \times 10^{14} M_\odot$; $z = 0.35$; $c = 4.0$
Before
After
Declination [deg]
Right Ascension [deg]
Not detected
$\nu_{obs} = 3.54$
$\nu_{obs} = 4.72$
$\nu_{obs} = 5.41$
$\nu_{obs} = 5.59$
$\nu_{obs} = 4.39$
$\nu_{obs} = 4.99$
$\nu_{obs} = 4.21$
$\nu_{obs} = 5.50$
$\nu_{obs}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

Chen+ (in prep.)

THE MASS OBSERVABLE RELATION

Take into account:

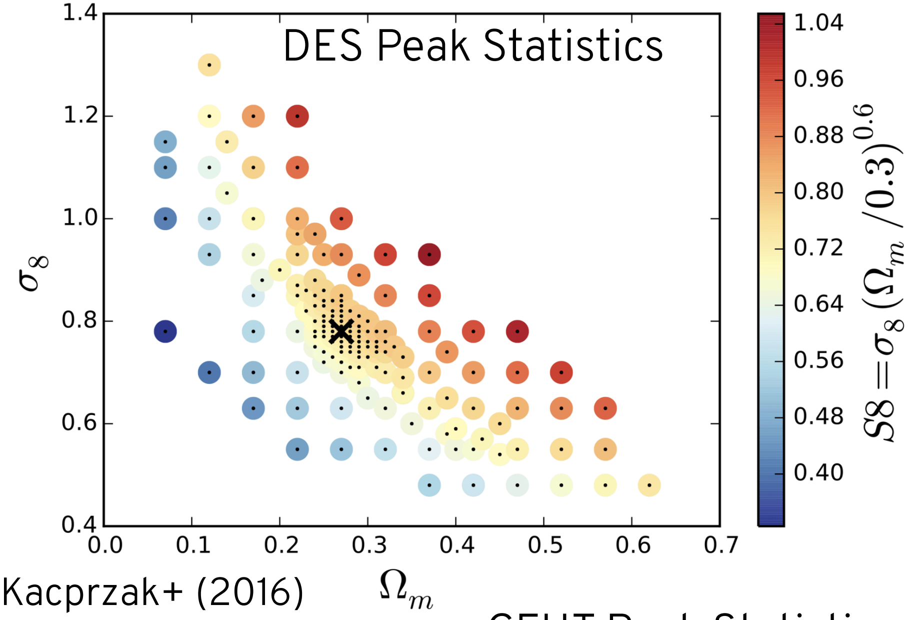
- Shape noise
- Non-uniform survey depth and geometry
- Uncorrelated Large-Scale Structure
- Chance projections
- Intrinsic alignment of source galaxies



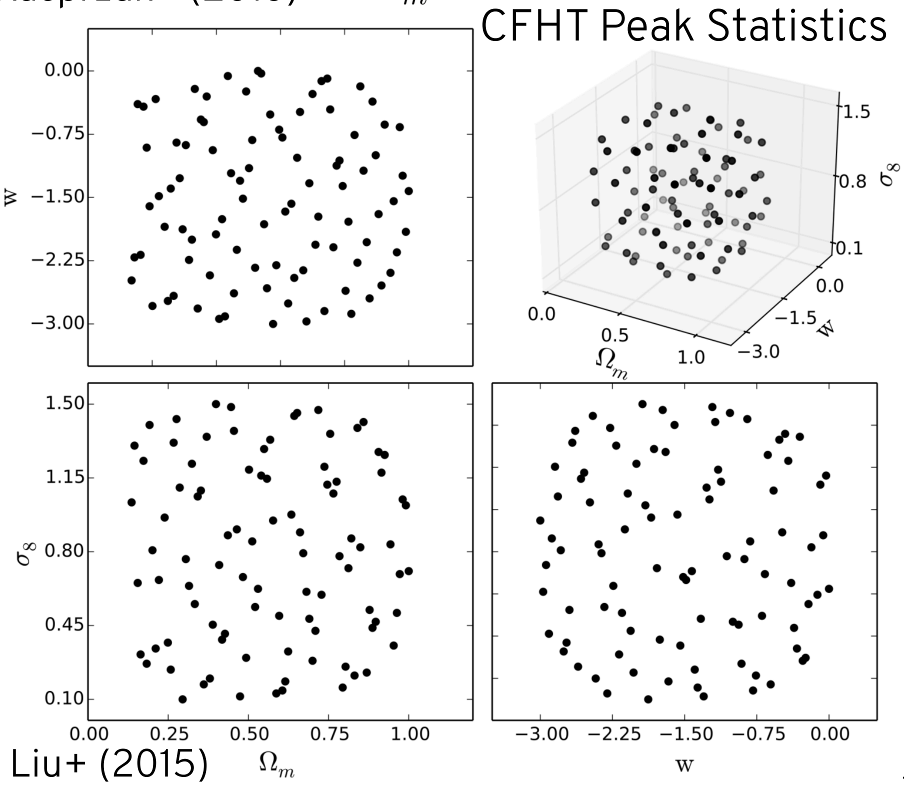
Adapted from Oguri+ (2018)

CHALLENGE

- Similar strategies exist in the literature for painting into numerical simulations
- Difficult to do millions of injections for every cosmology we sample
- Existing approach:
  - emulator
  - analytic modeling
- Are there other ways?



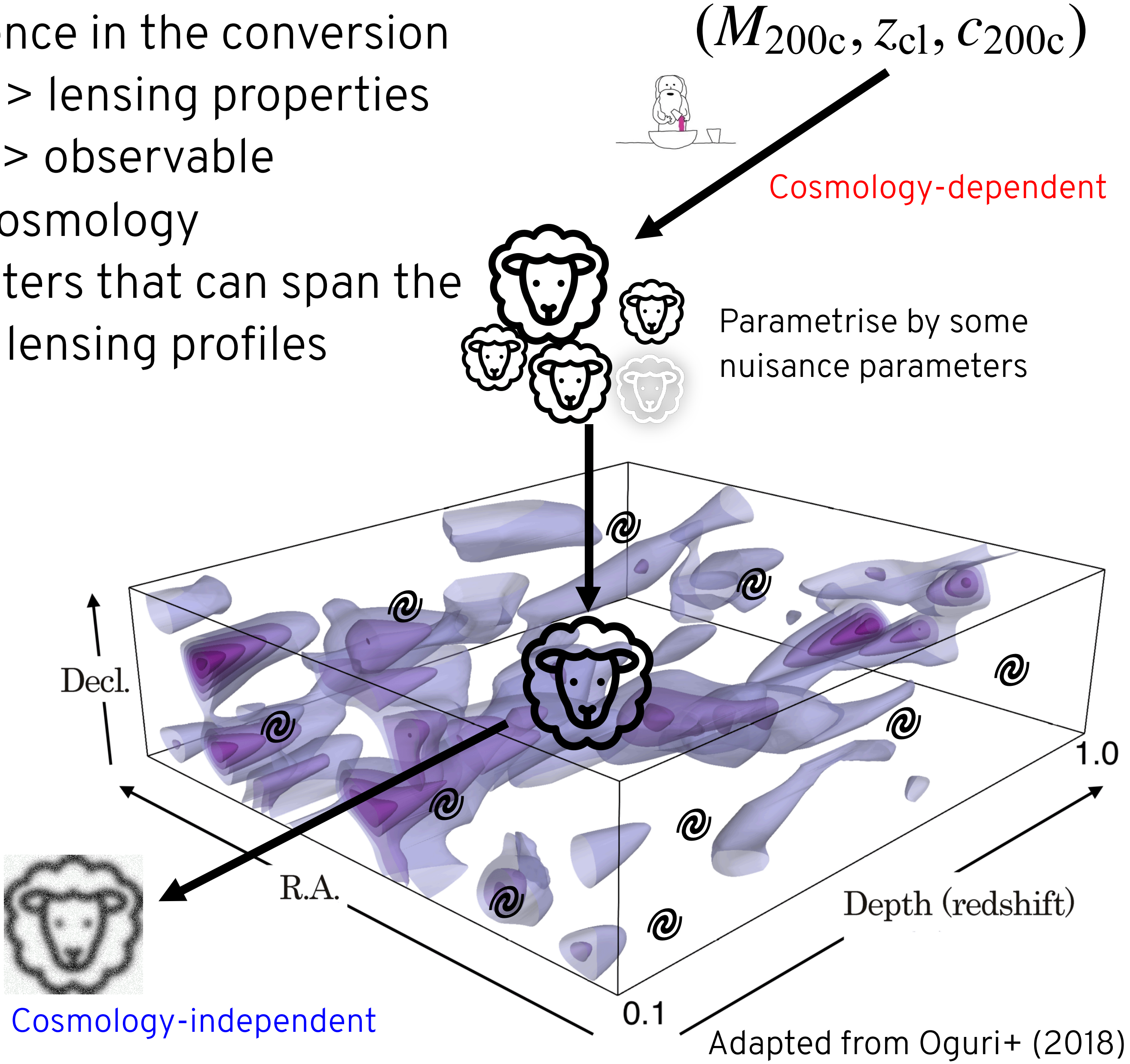
Kacprzak+ (2016)



Liu+ (2015)

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

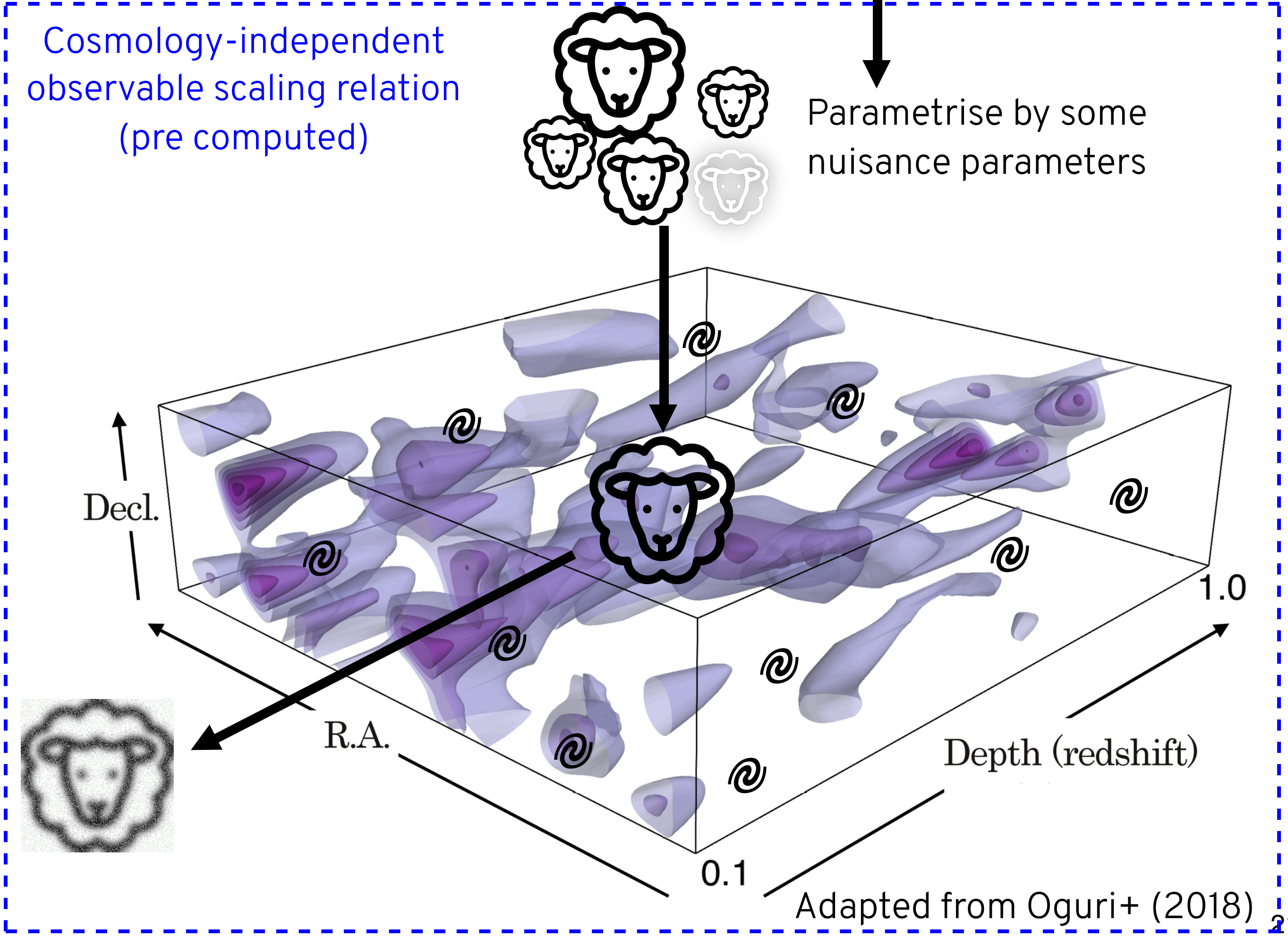


FULL PIPELINE

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

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

Cosmology-dependent



Data

Poisson Likelihood

$$\frac{\mathrm{d}N}{\mathrm{dO_{WL}}}$$

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

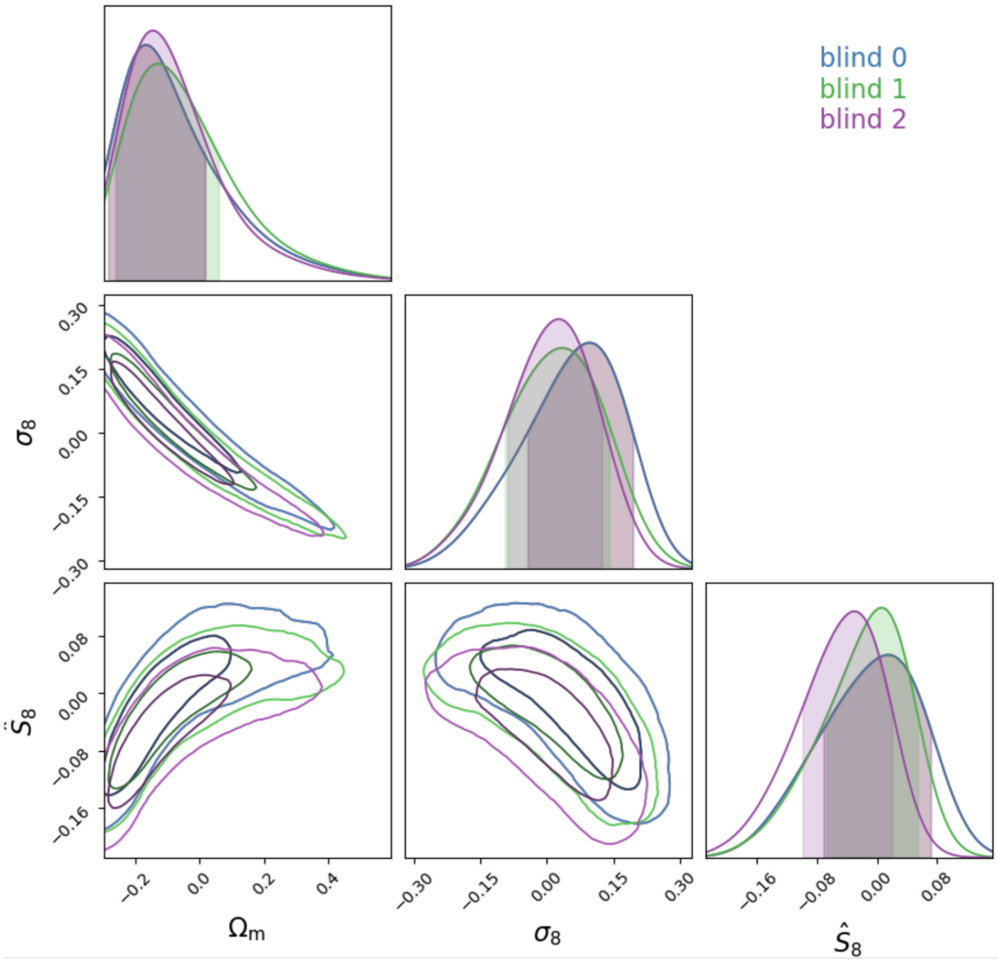
Table 1. The priors used in the modelling. The first column contains the names of the parameters, while the second columns present the priors.

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	U$(2, 4.5)$	

Chiu+ (in prep.)

BLINDED ANALYSIS

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



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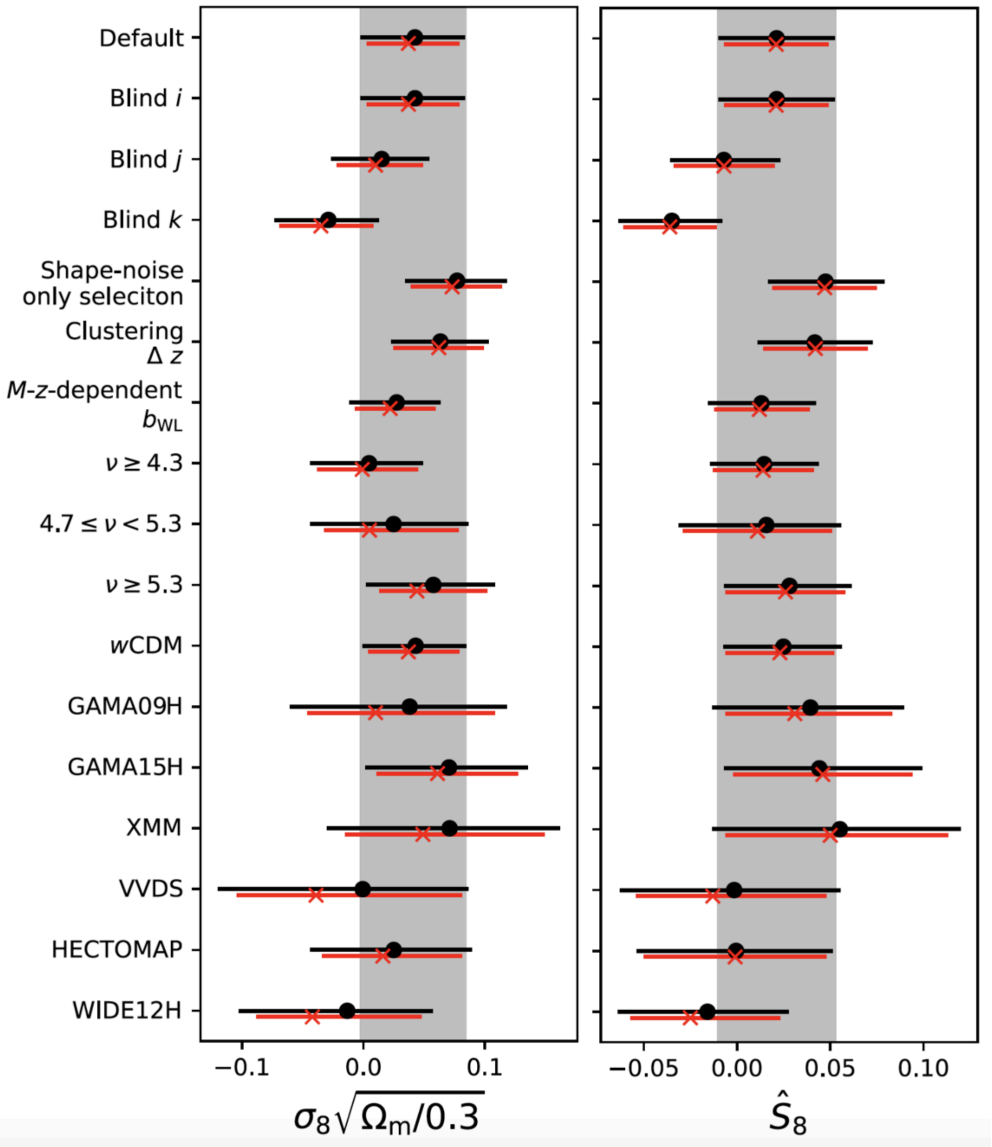
CONSISTENCY CHECKS

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



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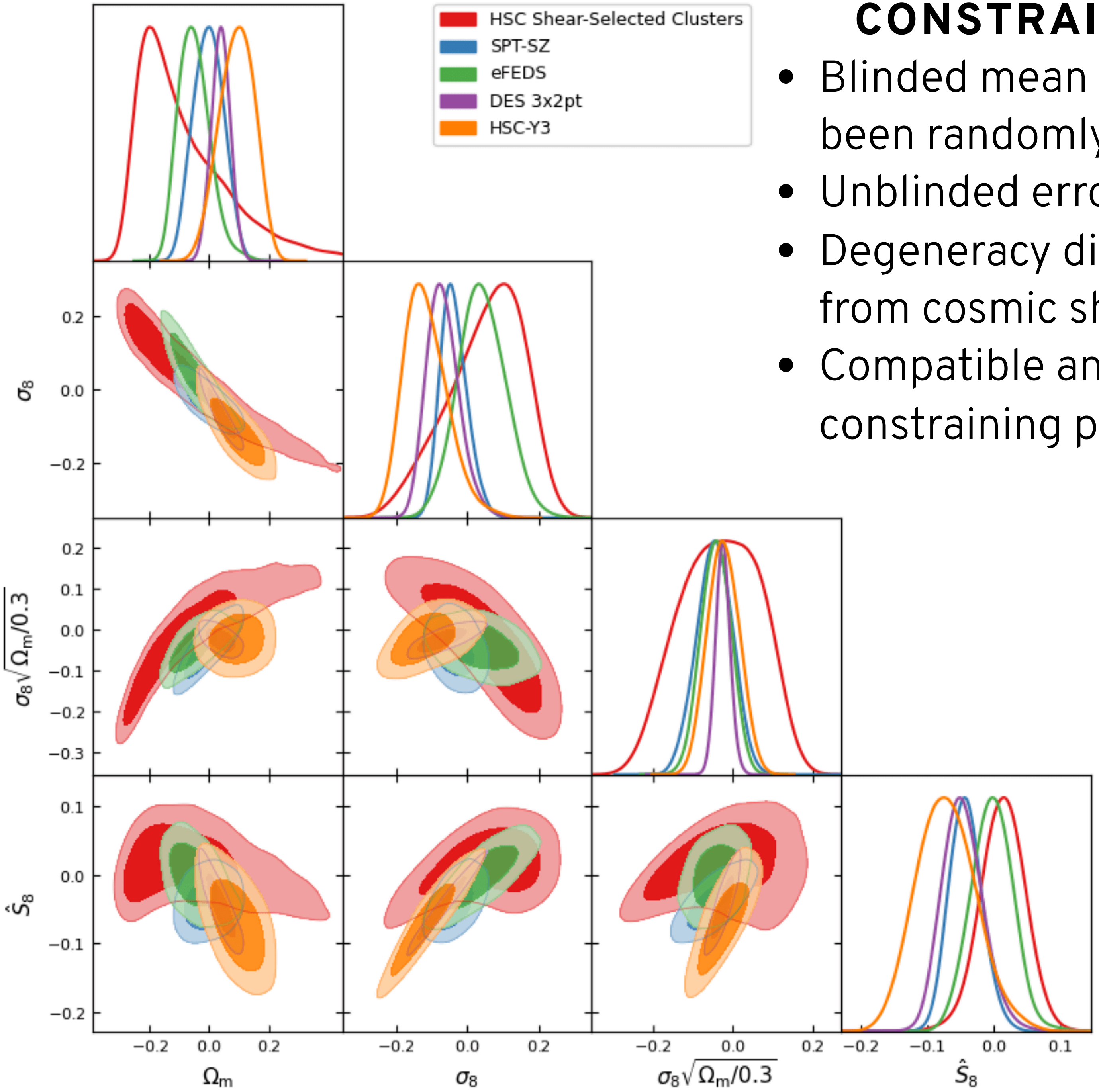


CONSTRAINING POWER

- Blinded mean (contours have all been randomly shifted)
- Unblinded error bar
- Degeneracy direction different from cosmic shear
- Compatible and complementary constraining power

Chiu+ (in prep.)

SUMMARY

- WL maps can be useful data product to study!
- A new WL probe that sits between peak statistics and cluster cosmology
- Novel modelling framework that is comprehensive and computationally efficient
- May complement existing 2-pt probes through adding higher-order information
- Future: Combine with redshift obtained from optical cluster catalogues to break degeneracy

BACKUP SLIDES

QUANTITATIVELY

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

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

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

$$= \iint \mathrm{d}\hat{M}_\varkappa \mathrm{d}\theta_s {\color{green}P(\nu|\hat{M}_\varkappa,\theta_s)}{\color{orange}[P(\hat{M}_\varkappa|\theta_s,M,z,p)\times P(\theta_s|M,z,p)]}$$

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

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

θ_s : Cluster characteristic angular size

QUANTITATIVELY

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

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

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

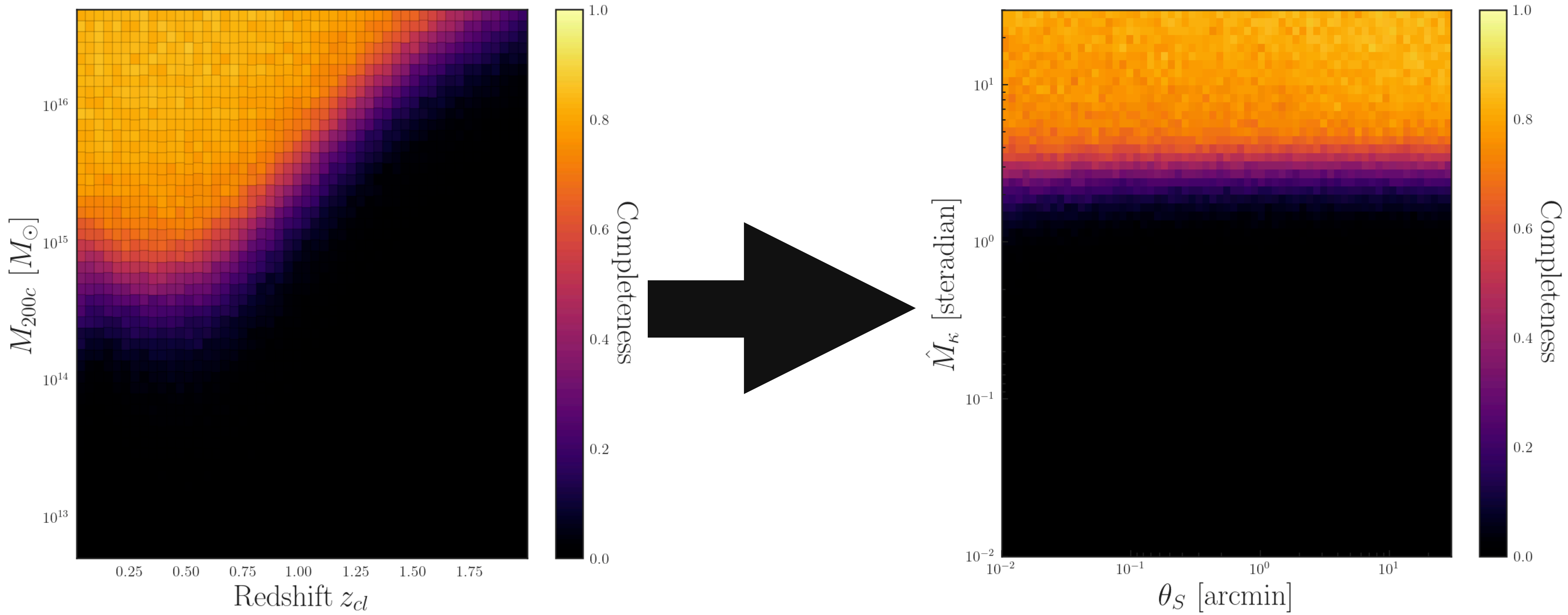
$$= \hat{M}_\varkappa \frac{\int_0^{x_{\mathrm{out}}} U(\theta - x\cdot\theta_S)f(x)x\mathrm{d}x}{\int_0^{x_{\mathrm{out}}} U(x\cdot\theta_S)f(x)x\mathrm{d}x}$$

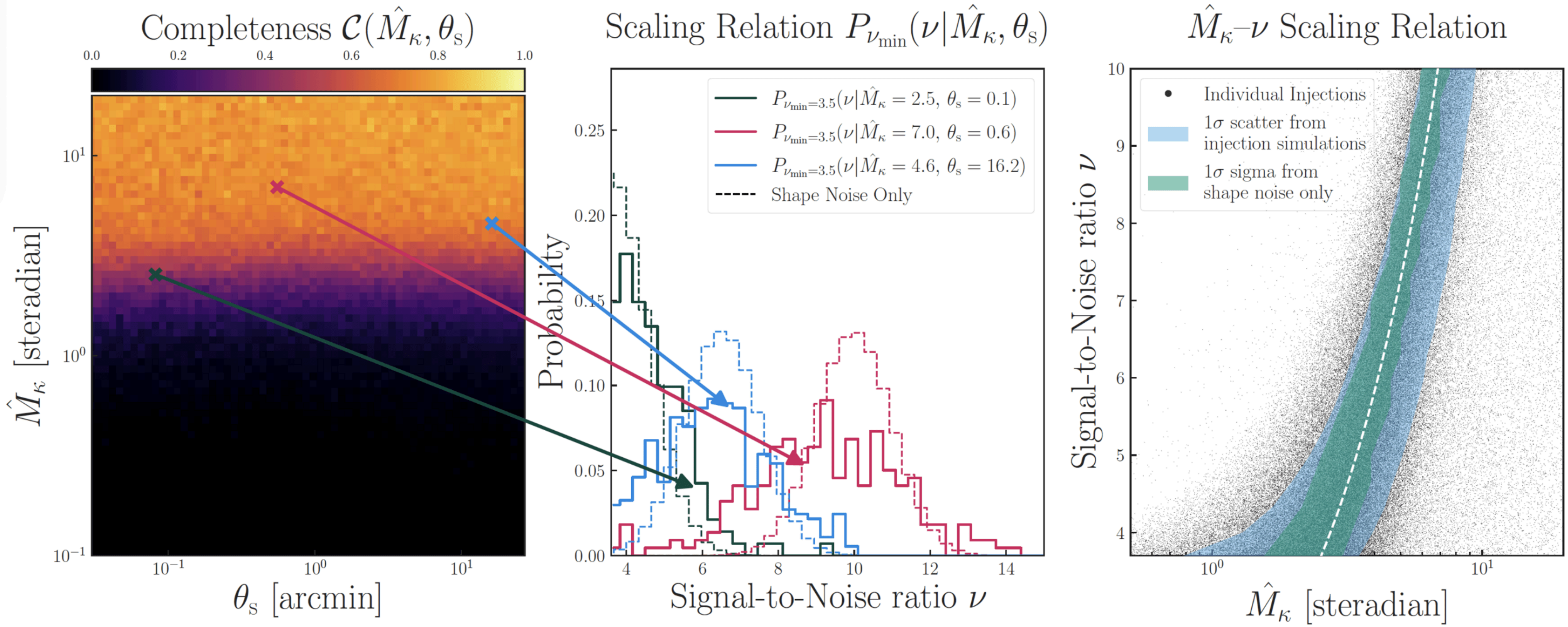
$M_\varkappa(\theta)$: True observed lensing signal profile

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

θ_s : Cluster characteristic angular size

RE-PARAMETRIZED SELECTION FUNCTION




Completeness $\mathcal{C}(\hat{M}_\kappa, \theta_s)$
0.0
0.2
0.4
0.6
0.8
1.0
$\hat{M}_\kappa$ [steradian]
θ_s [arcmin]
Scaling Relation $P_{\nu_{min}}(\nu|\hat{M}_\kappa, \theta_s)$
$P_{\nu_{min}=3.5}(\nu|\hat{M}_\kappa = 2.5, \theta_s = 0.1)$
$P_{\nu_{min}=3.5}(\nu|\hat{M}_\kappa = 7.0, \theta_s = 0.6)$
$P_{\nu_{min}=3.5}(\nu|\hat{M}_\kappa = 4.6, \theta_s = 16.2)$
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]

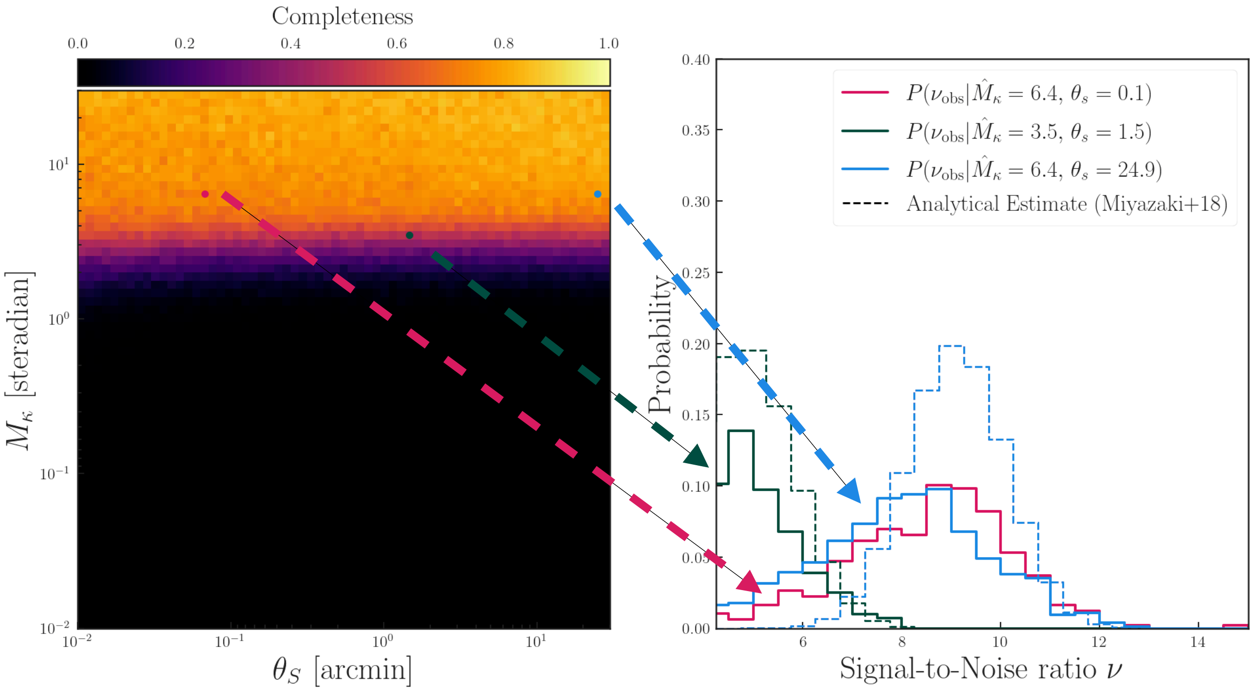
VALIDATION

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

Vanilla

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

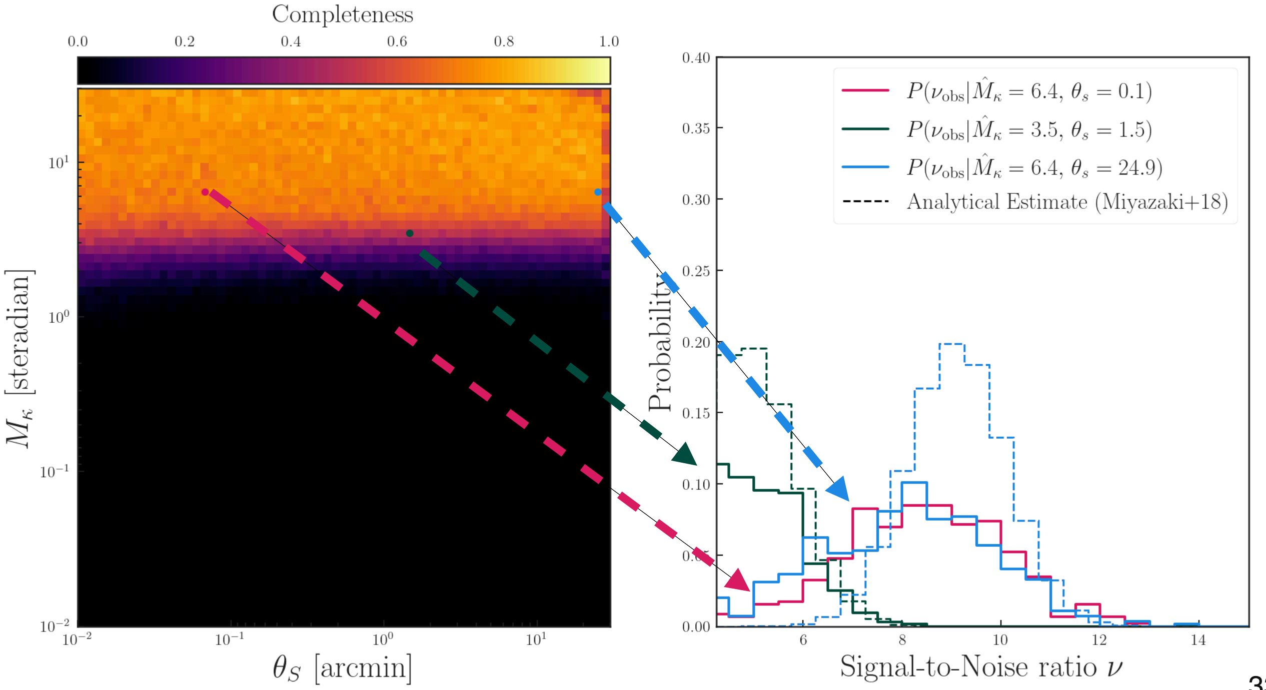
$n_s = 0.95,\ w_0 = -1.0$



Exotic

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

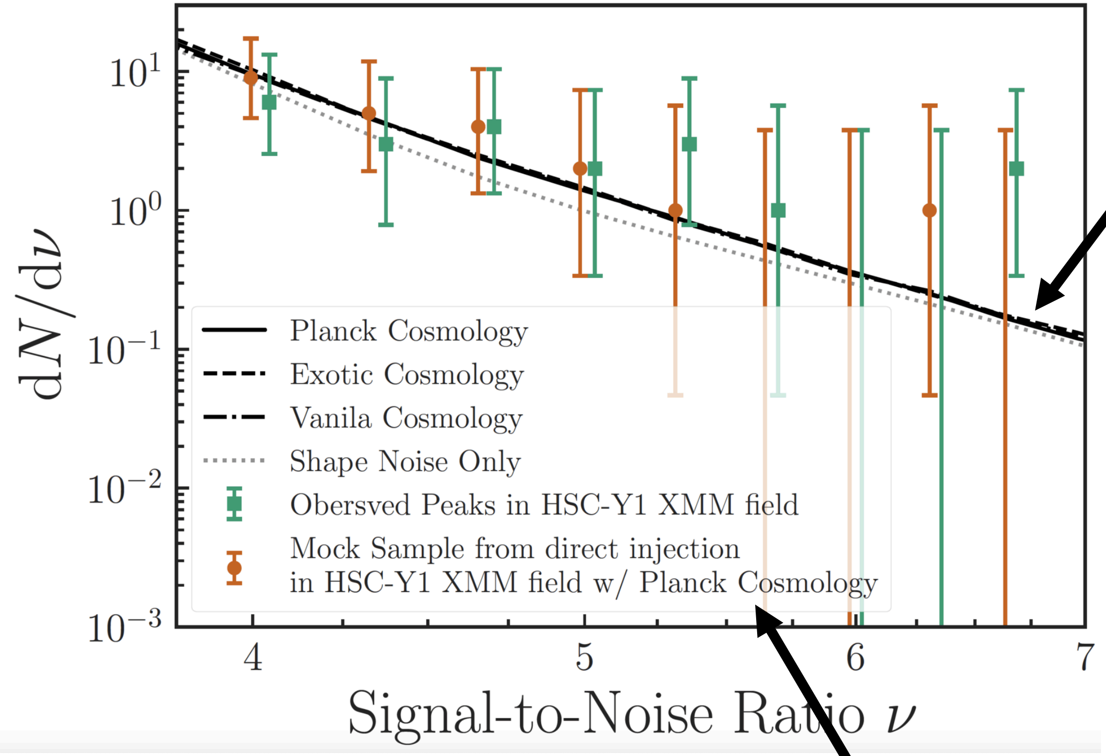
$n_s = 1.05,\ w_0 = -1.5$

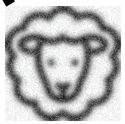


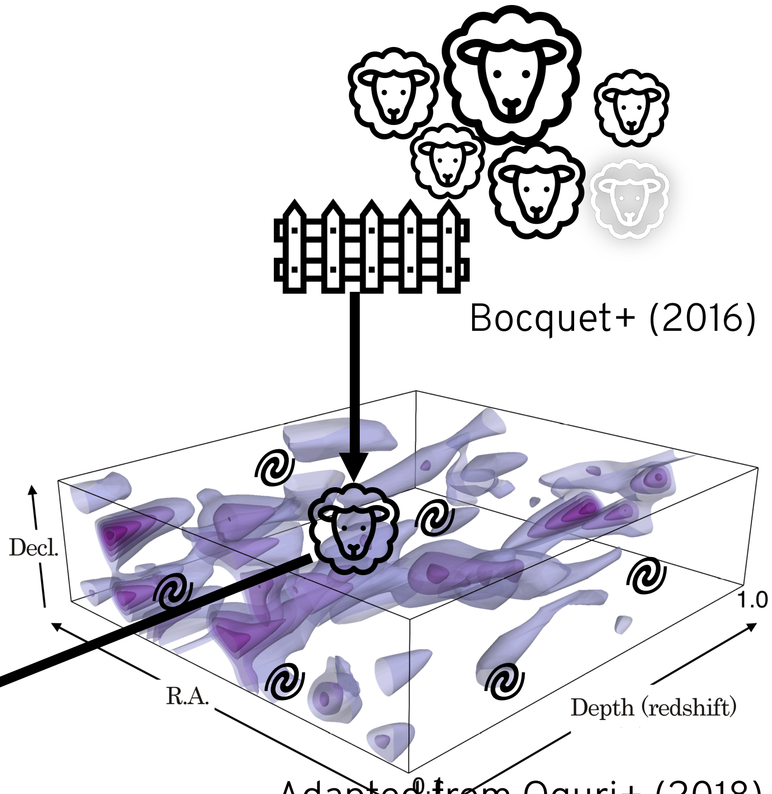
NUMBER COUNT

- 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)