Weak Lensing Cosmology with Subaru Hyper Suprime-Cam

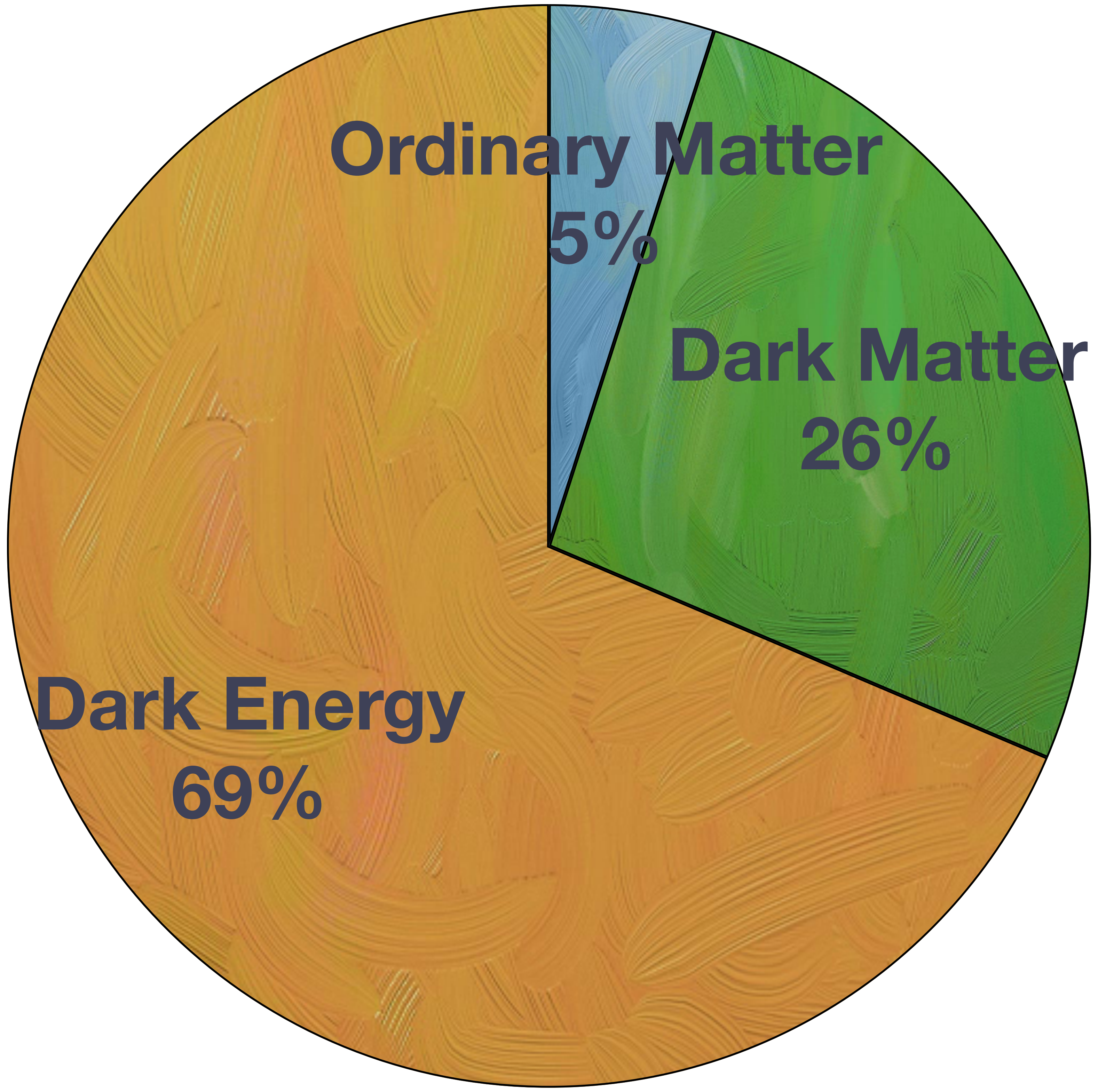
Hironao Miyatake
Nagoya University
On behalf of HSC Weak Lensing Working Group

Outline

- Large scale structure as a cosmology probe
- Subaru Hyper Suprime-Cam (HSC)
- HSC Y1 cosmology results
  - Cosmic shear
  - Galaxy-galaxy clustering x lensing (2x2pt)
- Ongoing HSC-Y3 cosmology analysis
- Summary

ΛCDM Model

- Cosmic evolution is governed by the cosmological constant Λ (or dark energy) and cold dark matter (CDM).
- ΛCDM model has been successful in explaining various cosmological observables such as CMB, distance measurements by type-Ia supernovae, and baryon acoustic oscillations.



Issues

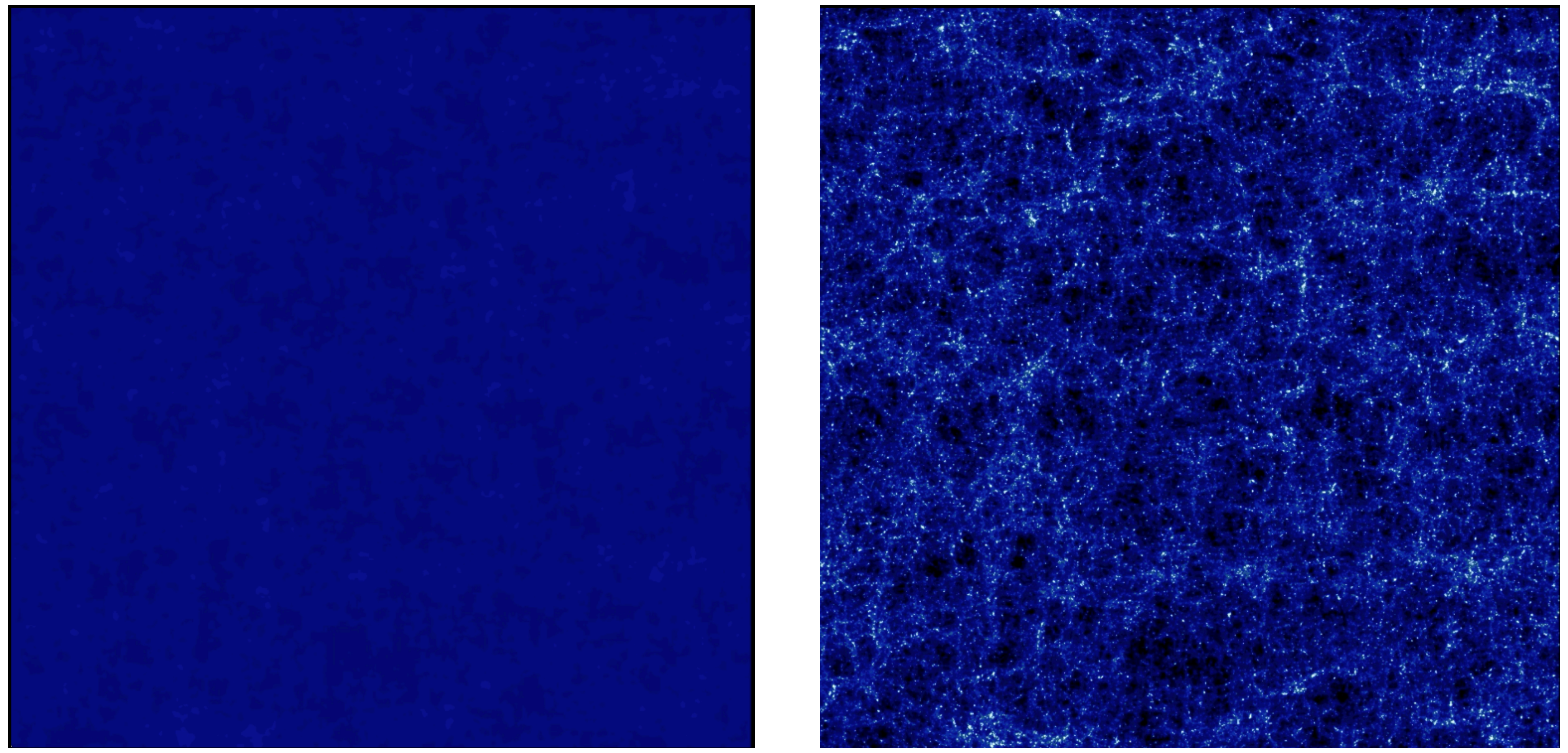
- 26% of the Universe is unknown matter: dark matter
- 69% of the Universe is unknown energy: dark energy
- Thus 95% of the Universe contents is unknown.

New physics?

Detailed Investigations of ΛCDM model is one of the most important studies in modern physics

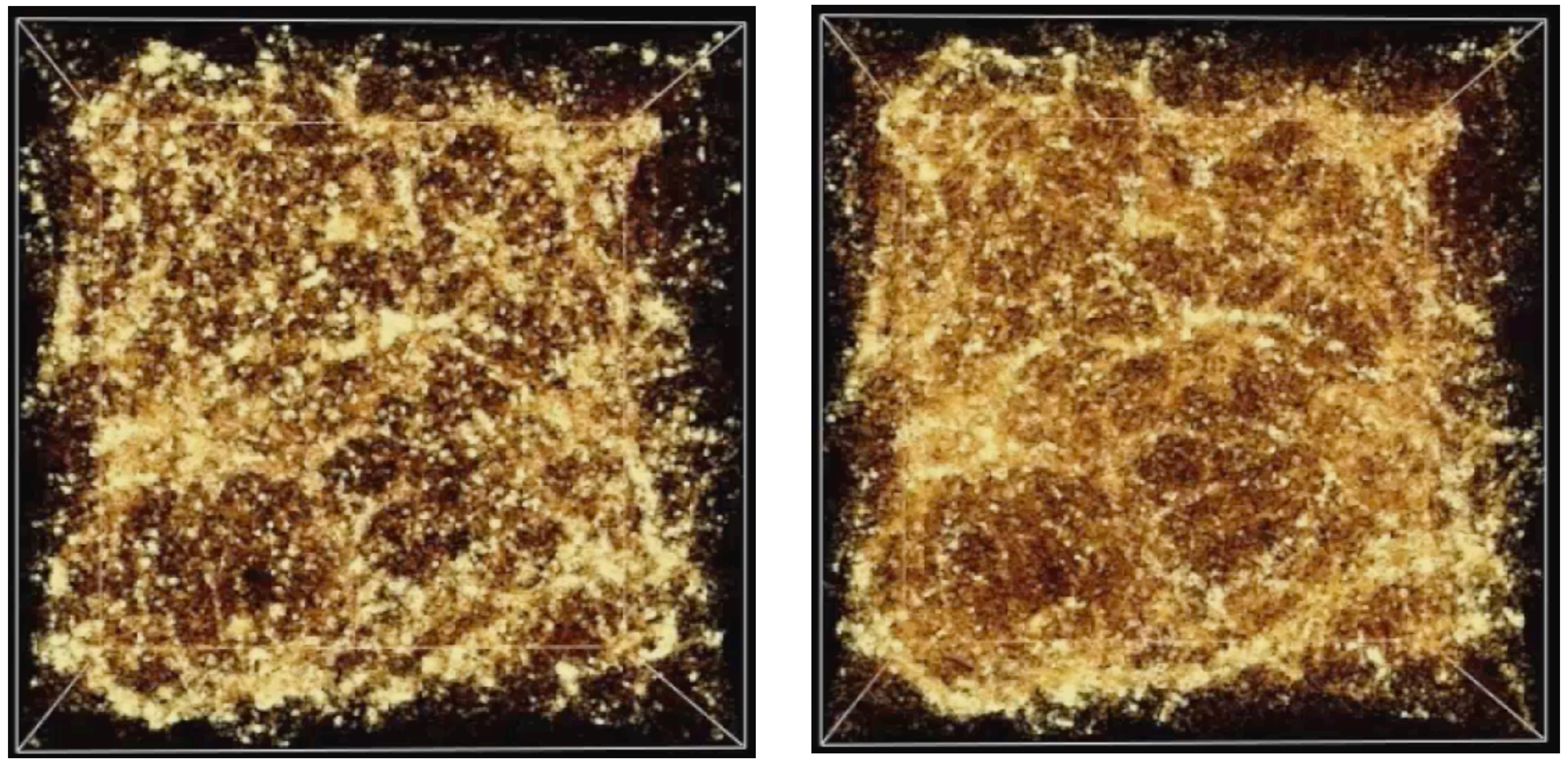
Large Scale Structure (LSS) of the Universe

w/o dark matter | w/ dark matter



credit: N. Yoshida

w/o dark energy | w/ dark energy



credit: ESA

- The nature of dark matter and dark energy is embedded in the growth of cosmic structure.
- Caution: dark matter makes up ~85% of the matter in the Universe, but we cannot directly observe it.

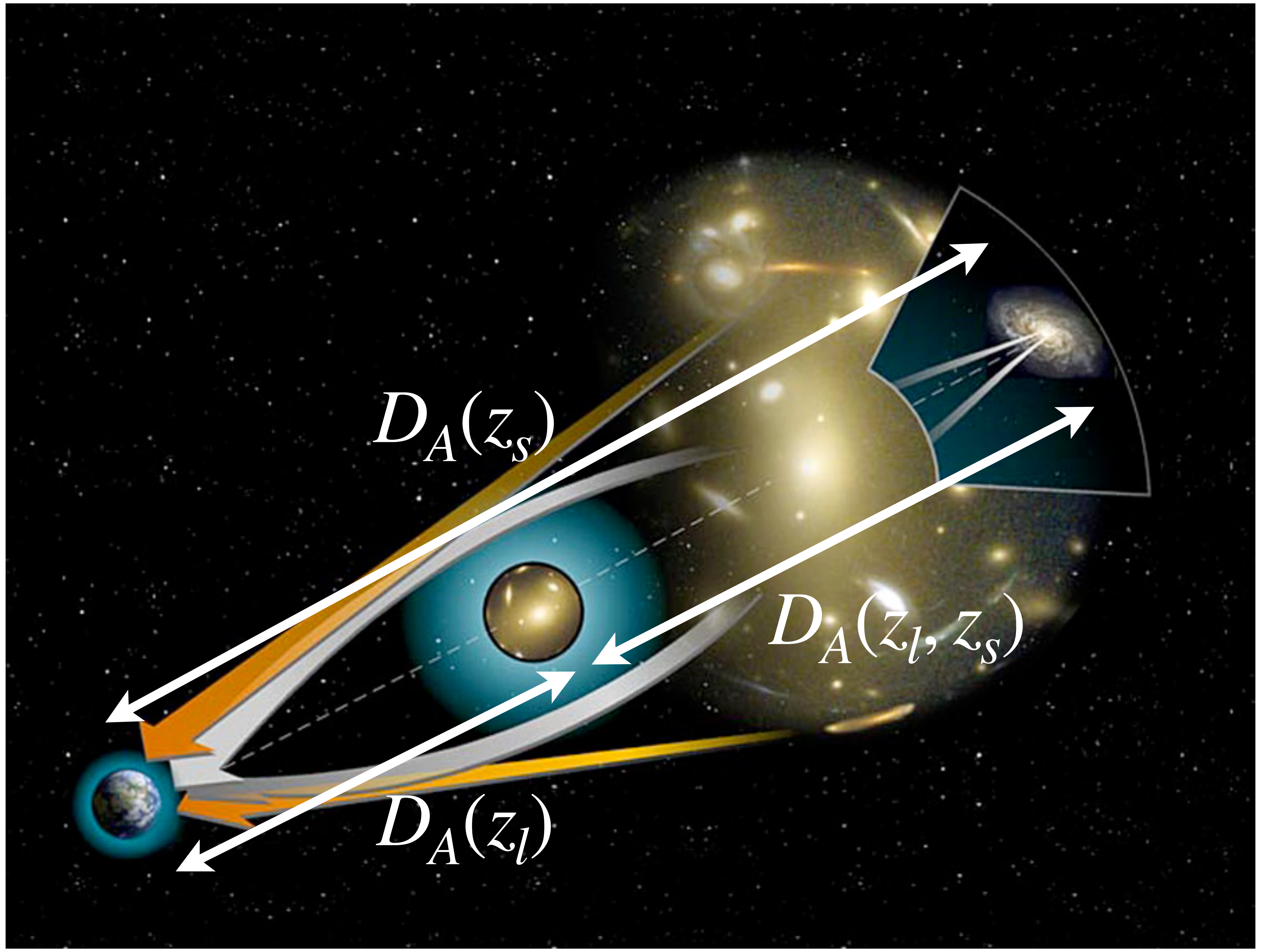
Weak Gravitational Lensing

$$\gamma \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

Weak lensing shear

Geometry of the Universe

Matter density fluctuation



Weak lensing enables us to map out dark matter distributions in the Universe

Weak Lensing Measurement

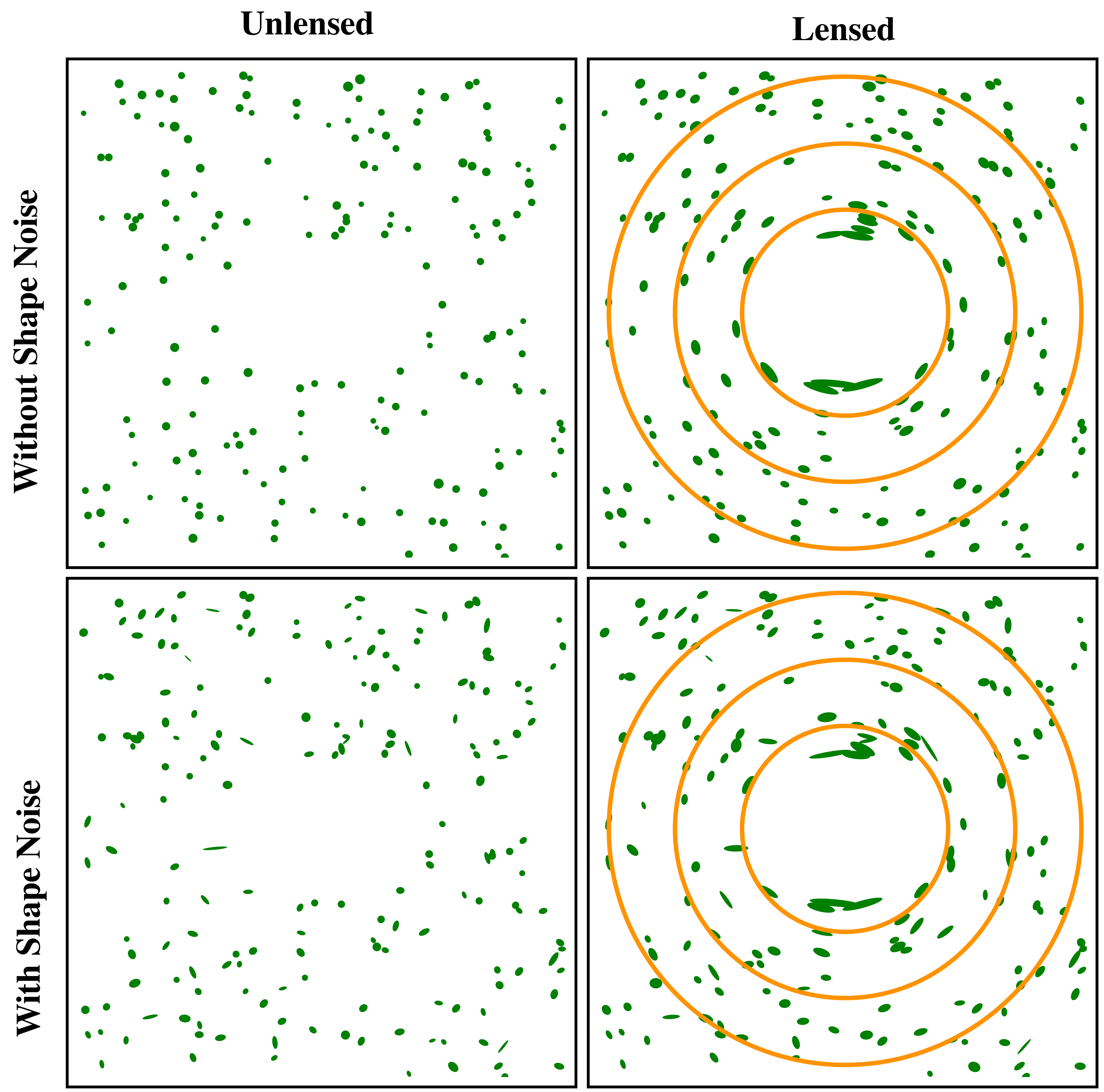
Example: weak lensing by a galaxy cluster

- Weak lensing tangentially distorts galaxy shapes by γ.
- Intrinsic galaxy shapes are beaten down (this is not the case if intrinsic alignment prominent) by averaging shapes of a number of galaxies.

$$\sigma_\gamma = \frac{\sigma_{\gamma,\mathrm{int}}}{\sqrt{N}}, \text{ where } \sigma_{\gamma,\mathrm{int}} \sim 0.3.$$

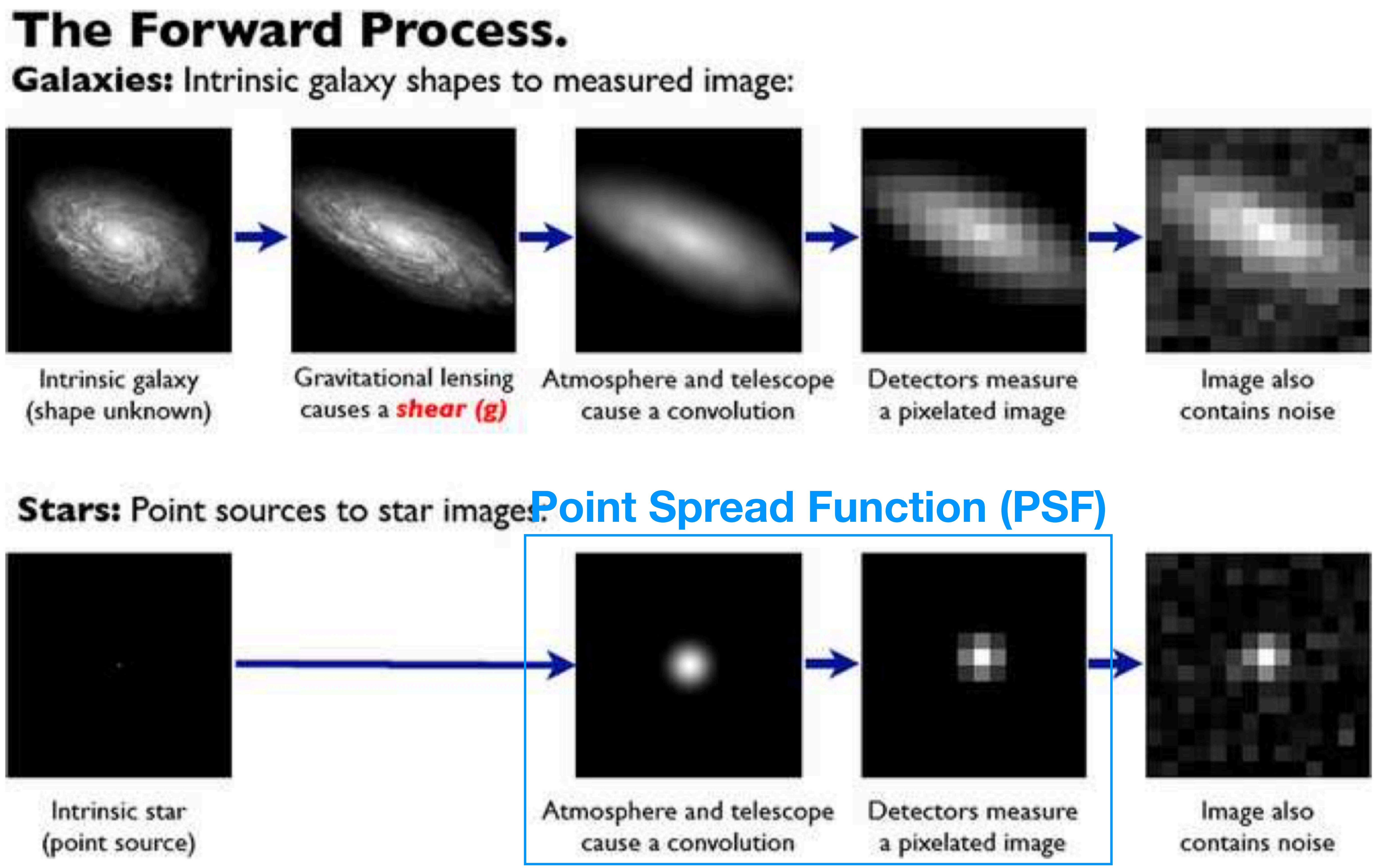
- To measure typical lensing signal ($\gamma \sim 0.01$) at 10 σ, one needs $\sim 100{,}000$ galaxies.

We need **so many galaxies** for weak lensing measurement



credit: J. Bosch

Galaxy Shape Measurement

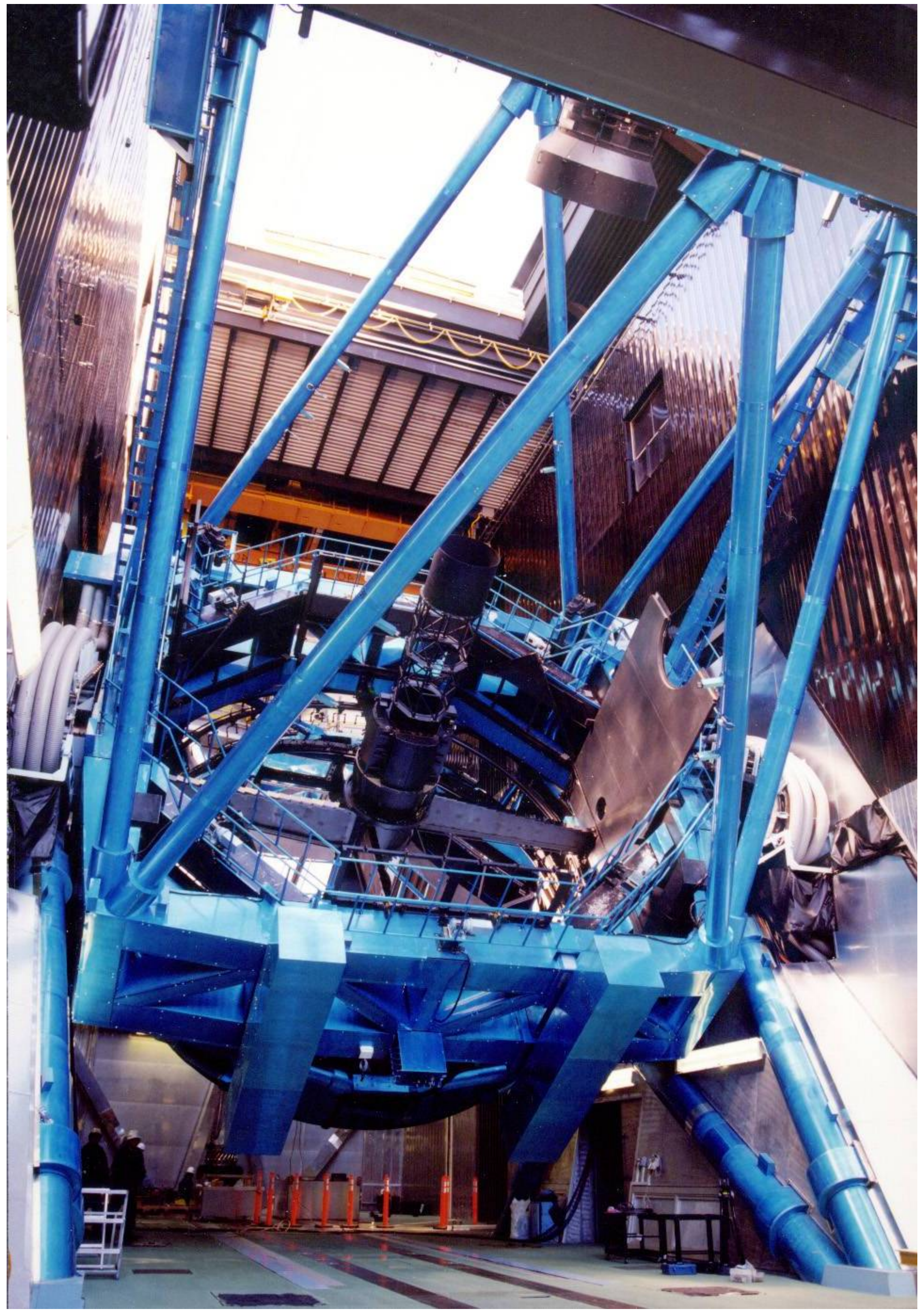


Good PSF is essential for weak lensing measurement

credit: S. Bridle

Subaru Hyper Suprime-Cam (HSC)

- Superb image quality: PSF~0.6”
  - SDSS PSF~1.0”
- Large Field-of-View: 1.5°diameter
  - ~7 x full moon
  - ~500 x Hubble Space Telescope
- 8.2 m primary mirror
  - ~11 x light collecting power of SDSS or Hubble



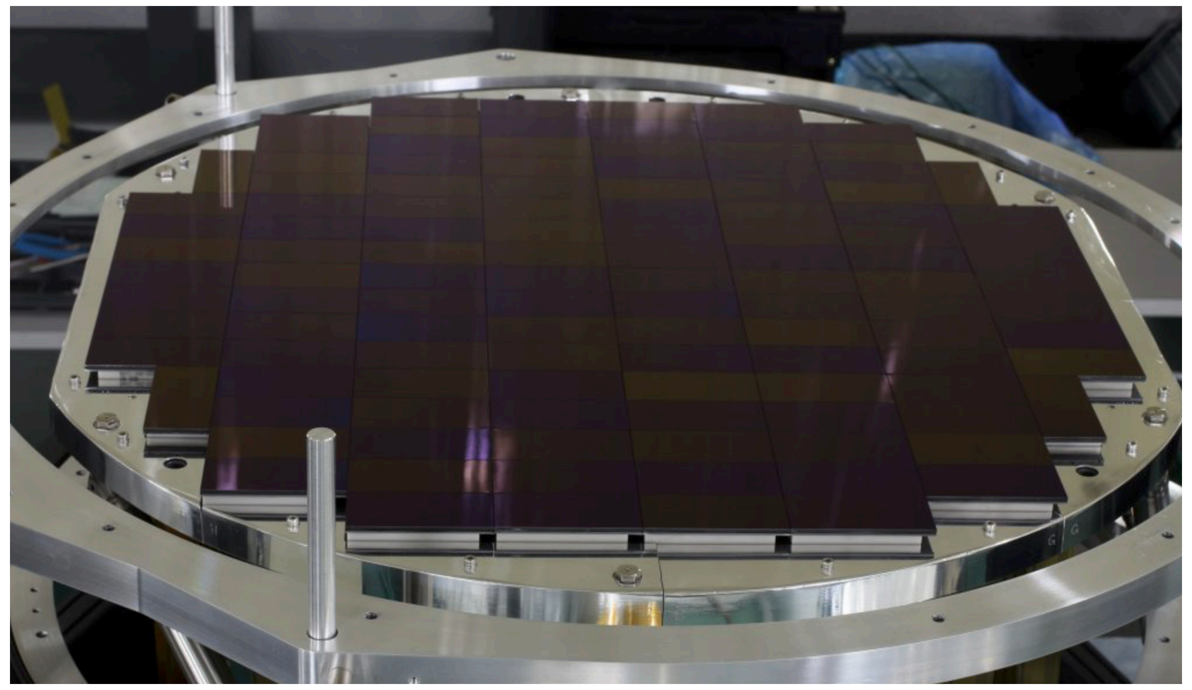
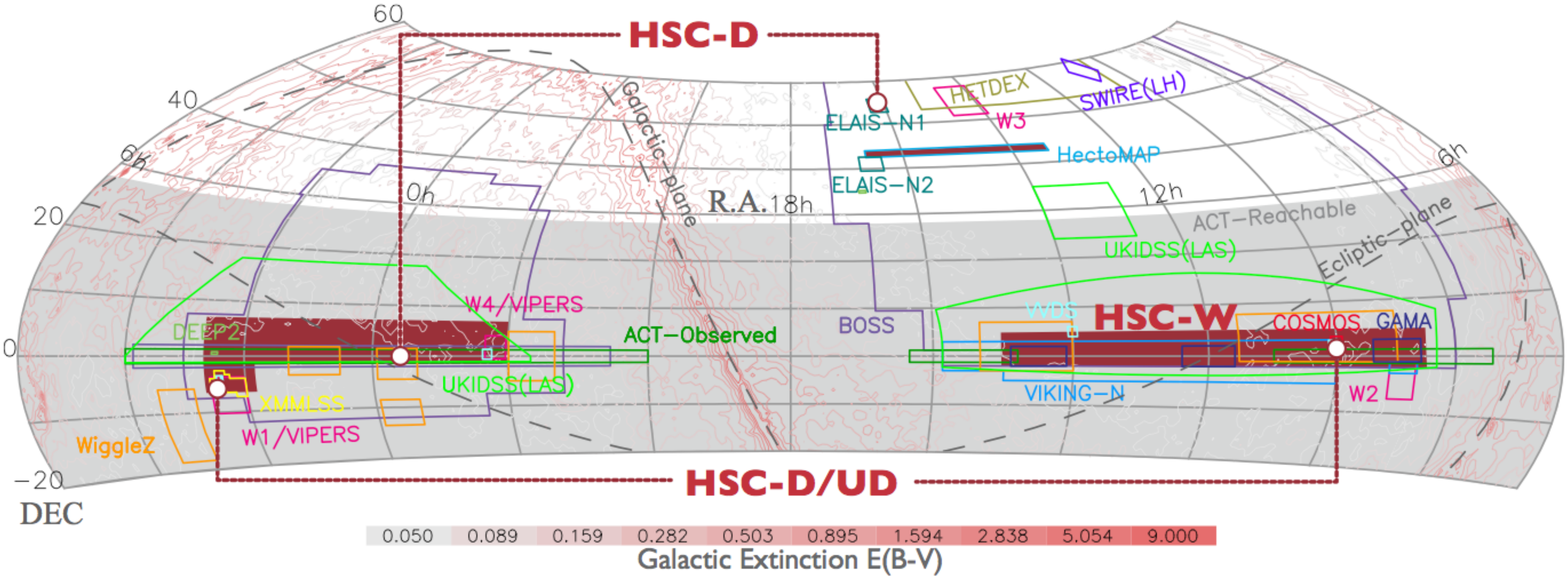


Photo credit: NAOJ, Miyazaki et al. (2018), Komiyama et al. (2018)

HSC SSP Survey

NAOJ National Astronomical Observatory of Japan · IPMU Institute for the Physics and Mathematics of the Universe · Princeton University · Academia Sinica Institute of Astronomy and Astrophysics



- Wide Layer (~1,100 deg^2, grizy, i_{lim}~26) is designed for weak lensing cosmology (10^8 galaxies).
- Overlaps with other major surveys (SDSS/BOSS, ACT, VIKING, GAMA, VVDS, etc…).
- Survey started in 2014 and complete at the end of 2021.
- Three data releases were made.

国立天文台 NAOJ National Astronomical Observatory of Japan

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

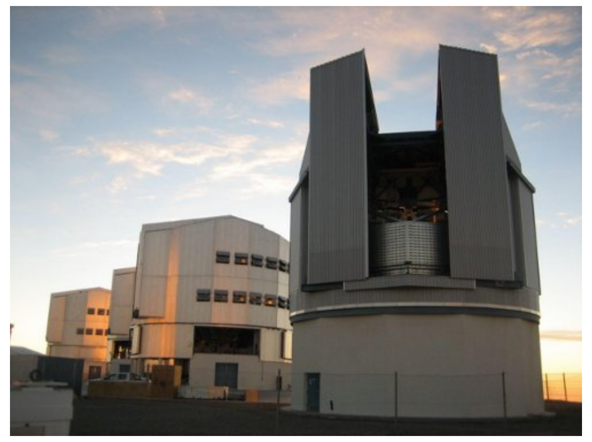
PRINCETON UNIVERSITY

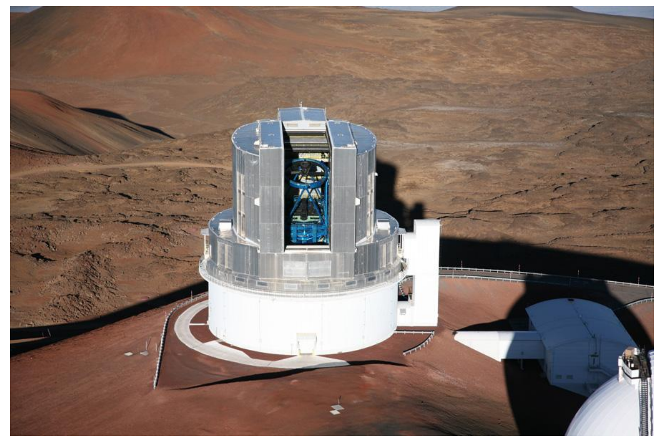
中央研究院 天文及天文物理研究所 ACADEMIA SINICA Institute of Astronomy and Astrophysics

Weak Lensing Surveys in 2010s

- HSC has small survey area, but goes to high redshift.
- DES has large survey area, but observes nearby universe.
- KiDS has a companion near-infrared survey.

These surveys are complementary





	KiDS (Europe)	DES (USA)	Subaru HSC (Japan)
Diameter of Primary Mirror [m]	2.6	4.0	8.2
Galaxy Number Density [arcmin^{-2}]	11	10	25
Survey Area [sq. deg]	1,300	5,000	1,100

All Sky ~41,253 [sq. deg]

2010 → 2020

Inspired by E. Krause   Credit: ESO, Fermilab/Reidar Hahn, NAOJ

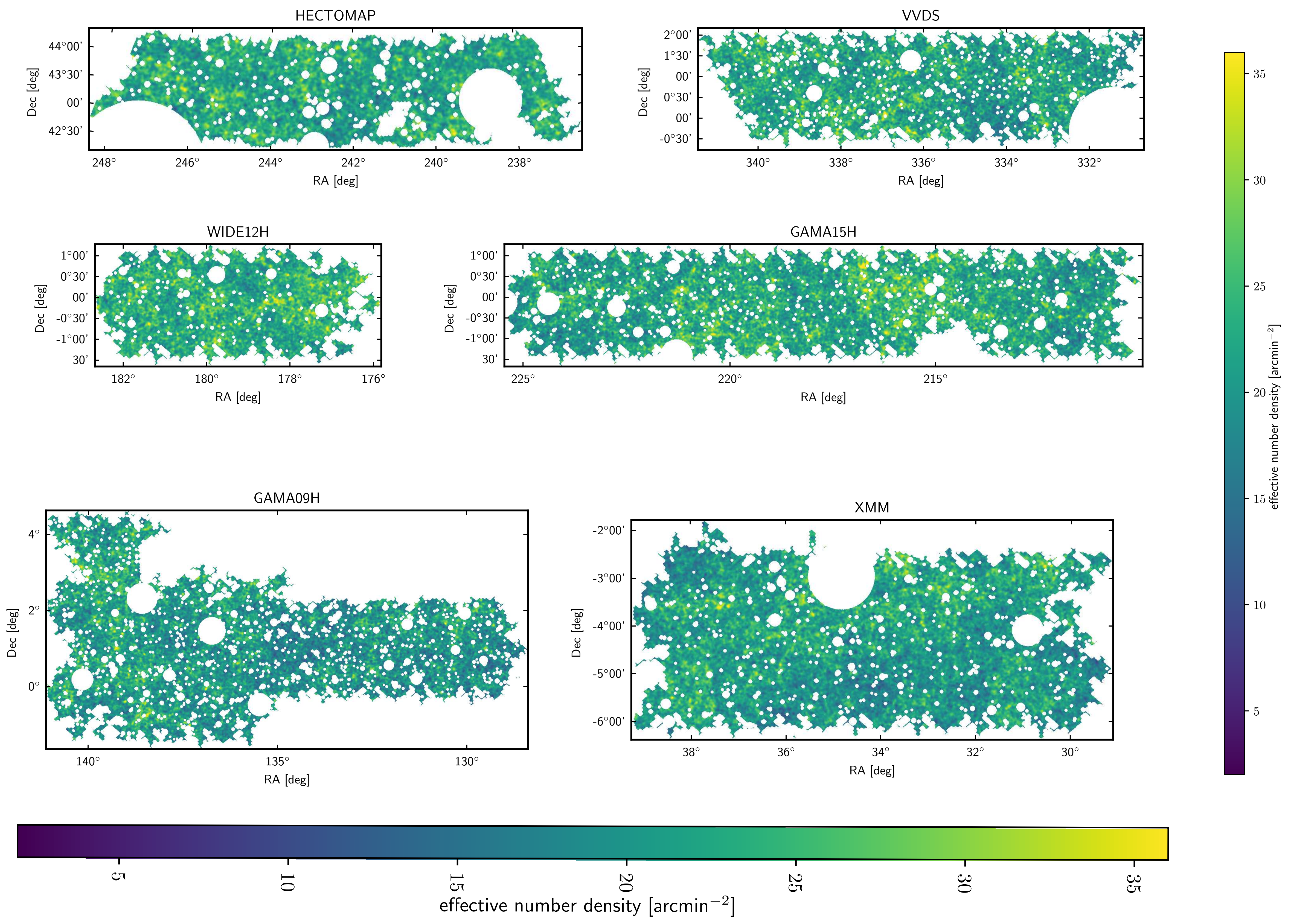
HSC-Y1 Results

HSC-Y1 Shape Catalog

- Wide Layer: 6 fields, ~170 deg^2
- Full-depth, full-color
- PSF FWHM ~ 0.6”
- 10^7 galaxies
- Number Density: n_g~ 23 gal/$arcmin^2$
  - DES: n_g~ 7 gal/$arcmin^2$
  - KiDS: n_g~ 10 gal/$arcmin^2$
- Shapes were measured by the reGaussianization method
- Calibrated against image simulations

  $$\hat{g} = (1+m)g^{\mathrm{true}} + c$$

- Publicly available



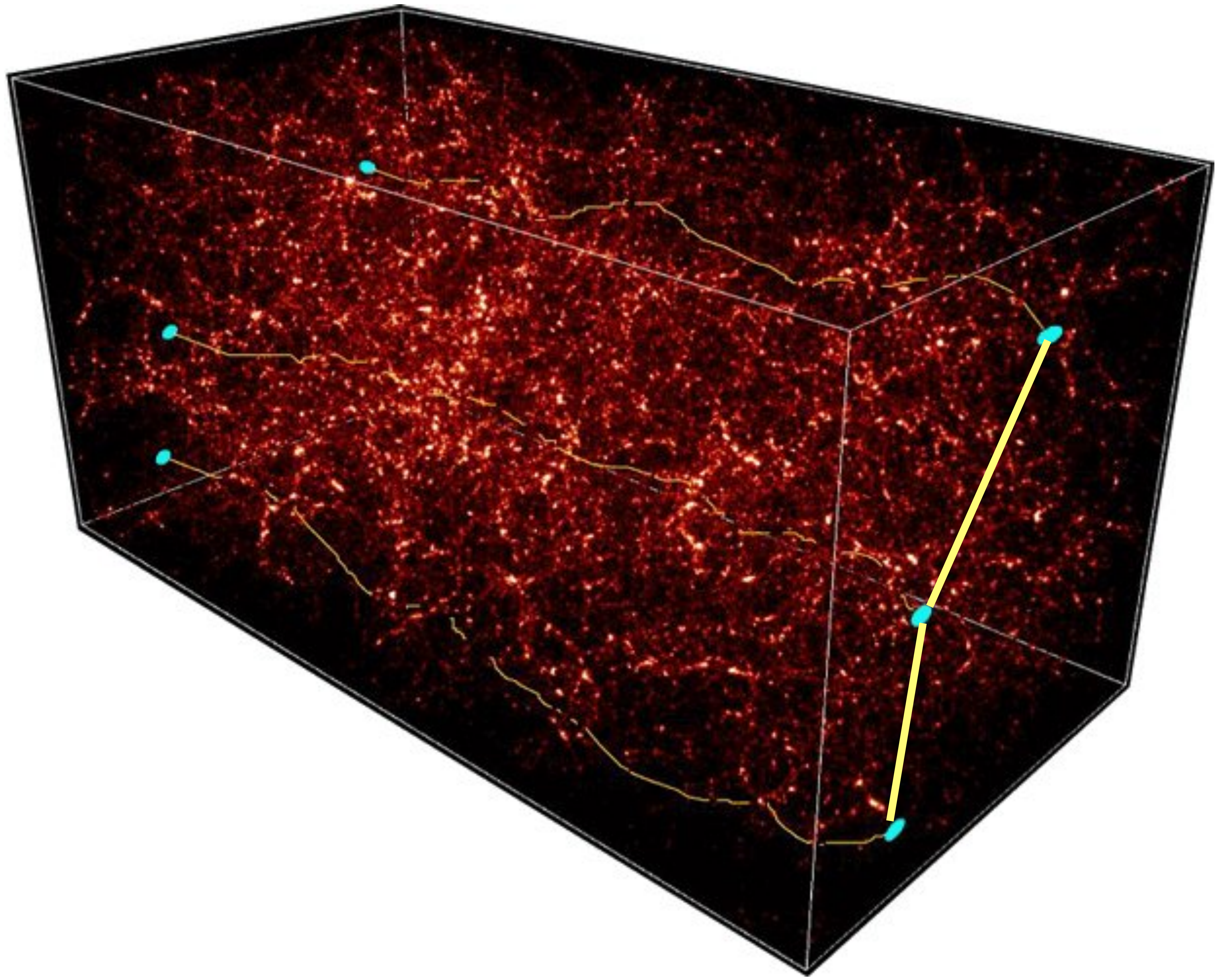
Mandelbaum, HM, et al. (2018a)
Mandelbaum et al., (2018b)

Cosmic Shear Analysis

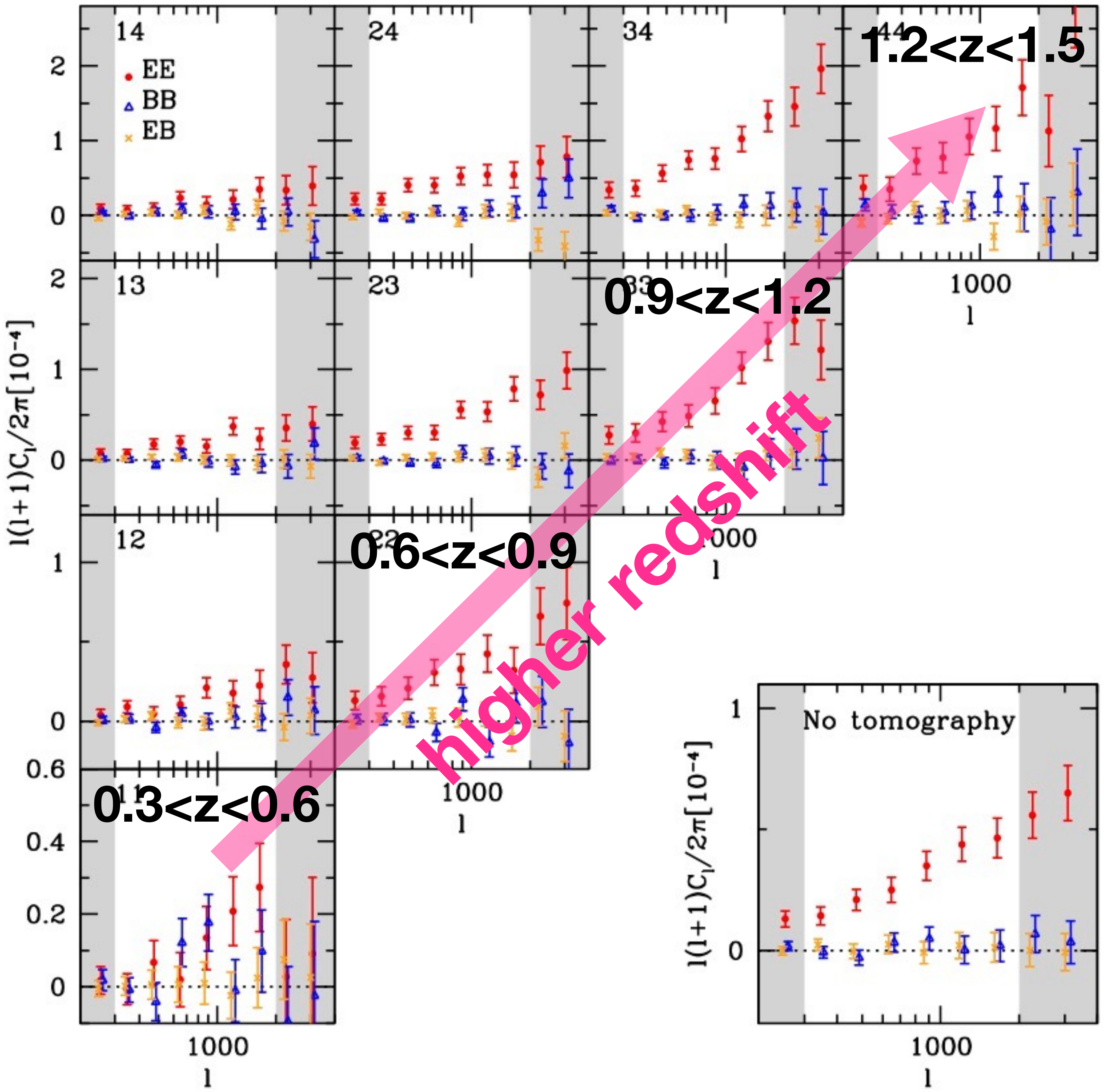
Cosmic Shear

- Auto-correlation of lensing shear (galaxy shapes).
- Directly measure matter correlation function: $\xi(r; \Omega_{\mathrm{m}}, \sigma_8) = \langle \delta_{\mathrm{m}}(r') \delta_{\mathrm{m}}(r' + r) \rangle_{r'}$

Matter energy density **Amplitude of matter power spectrum**



Fourier-space analysis



Parameter	symbols	prior
physical dark matter density	$\Omega_c h^2$	flat [0.03,0.7]
physical baryon density	$\Omega_b h^2$	flat [0.019,0.026]
Hubble parameter	h	flat [0.6,0.9]
scalar amplitude on $k = 0.05\mathrm{Mpc}^{-1}$	$\ln(10^{10}A_s)$	flat [1.5,6]
scalar spectral index	n_s	flat [0.87,1.07]
optical depth	τ	*flat [0.01,0.2]*
neutrino mass	$\sum m_\nu$ [eV]	fixed $(0)^\dagger$, fixed (0.06) or flat [0,1]
dark energy EoS parameter	w	fixed $(-1)^\dagger$ or flat $[-2,-0.333]$
amplitude of the intrinsic alignment	A_{IA}	flat $[-5,5]$
redshift dependence of the intrinsic alignment	η_{eff}	flat $[-5,5]$
baryonic feedback amplitude	A_B	fixed $(0)^\dagger$ or flat $[-5,5]$
PSF leakage	$\tilde{\alpha}$	Gauss (0.057, 0.018)
residual PSF model error	$\tilde{\beta}$	Gauss (−1.22, 0.74)
uncertainty of multiplicative bias m	$100\Delta m$	Gauss (0, 1)
photo-z shift in bin 1	$100\Delta z_1$	Gauss (0, 2.85)
photo-z shift in bin 2	$100\Delta z_2$	Gauss (0, 1.35)
photo-z shift in bin 3	$100\Delta z_3$	Gauss (0, 3.83)
photo-z shift in bin 4	$100\Delta z_4$	Gauss (0, 3.76)

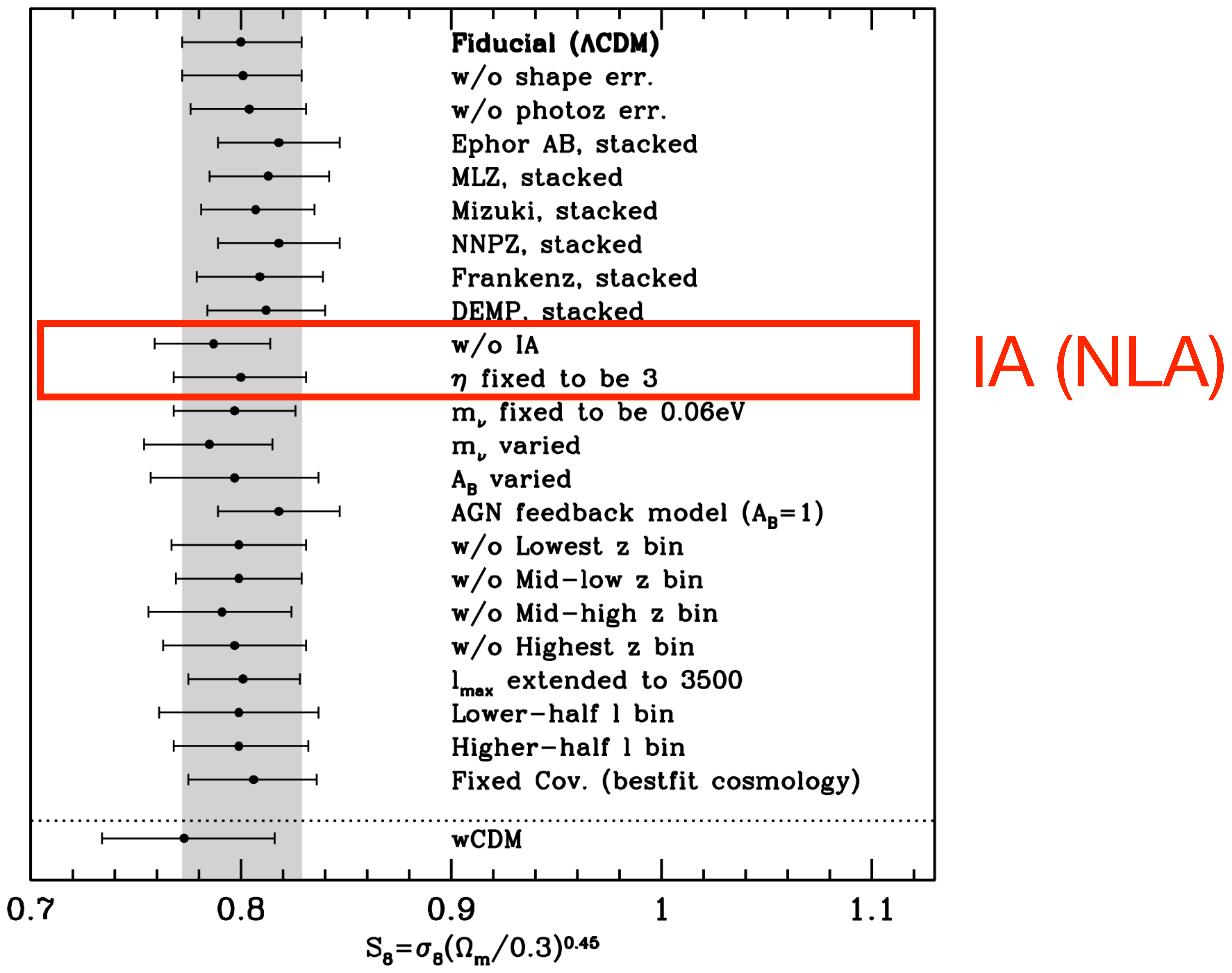
Cosmology Intrinsic alignment Baryonic effect

PSF modeling error Photo-z uncertainties

Hikage et al. (2018)

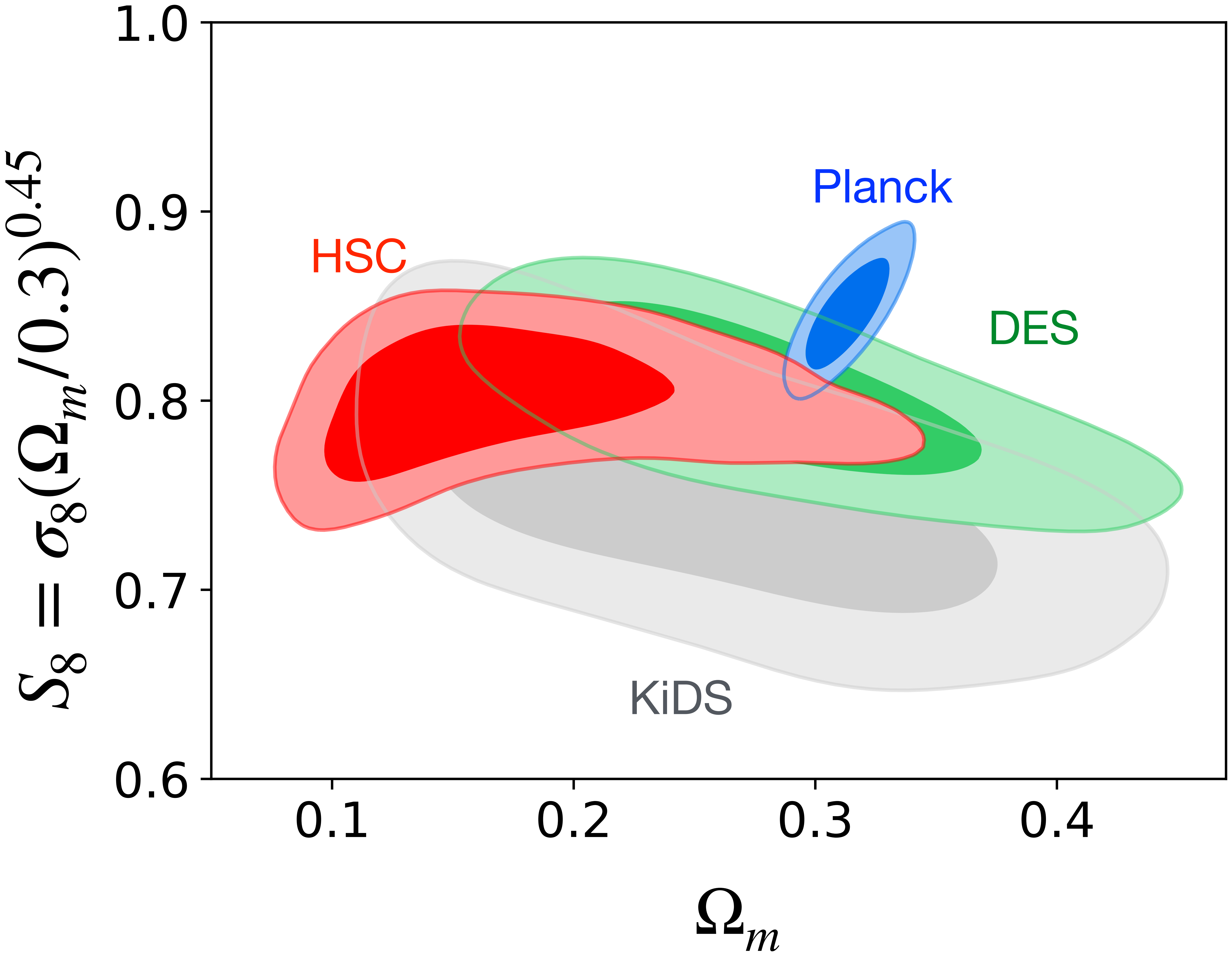
Blind Analysis

- We adopt “Blind Analysis” to avoid unconscious biases.
- We perform cosmological constraints with 3 blinded shape catalogs.
- We unblind our analyses after systematic tests.



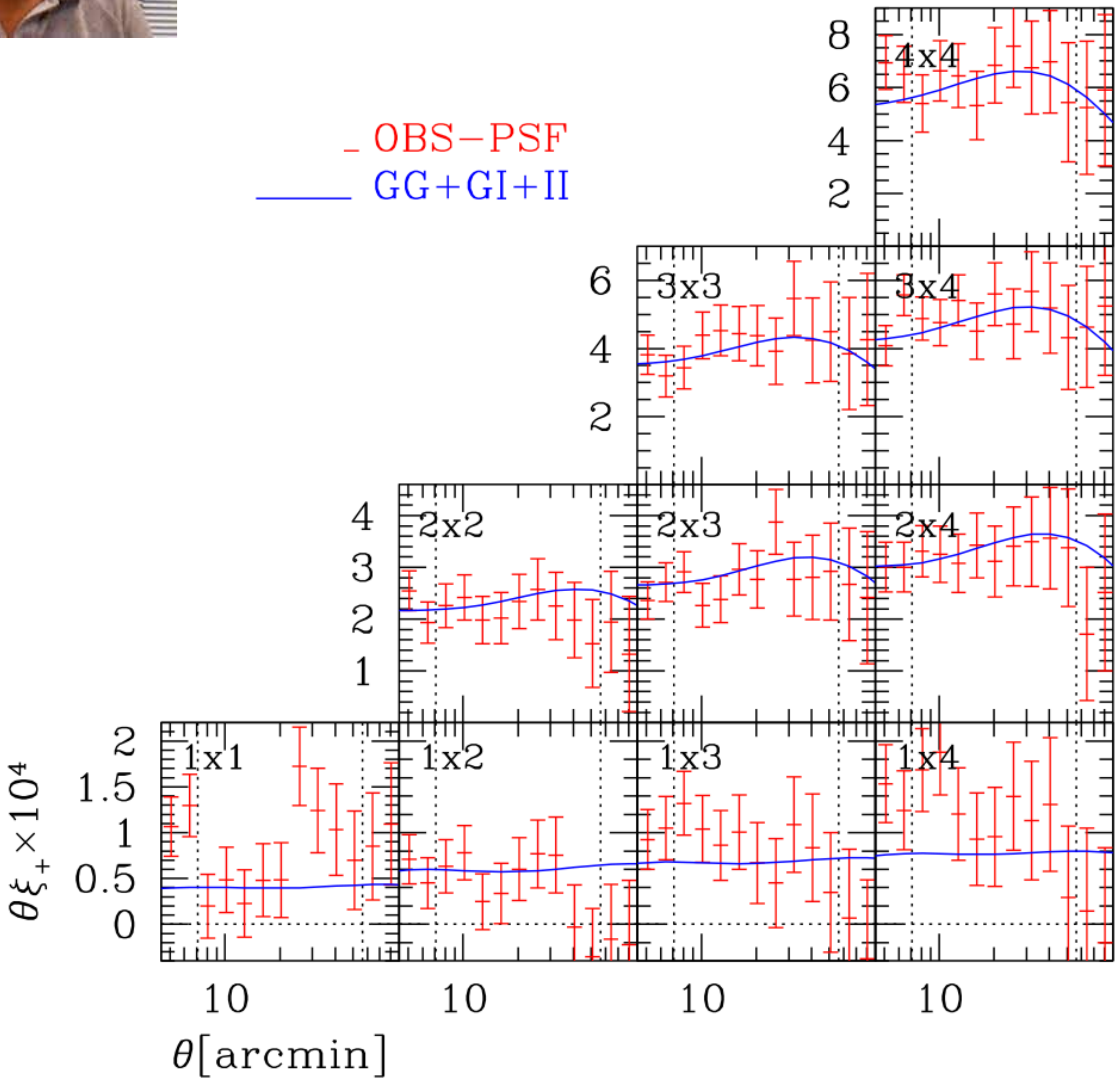
Hikage et al. (2018)

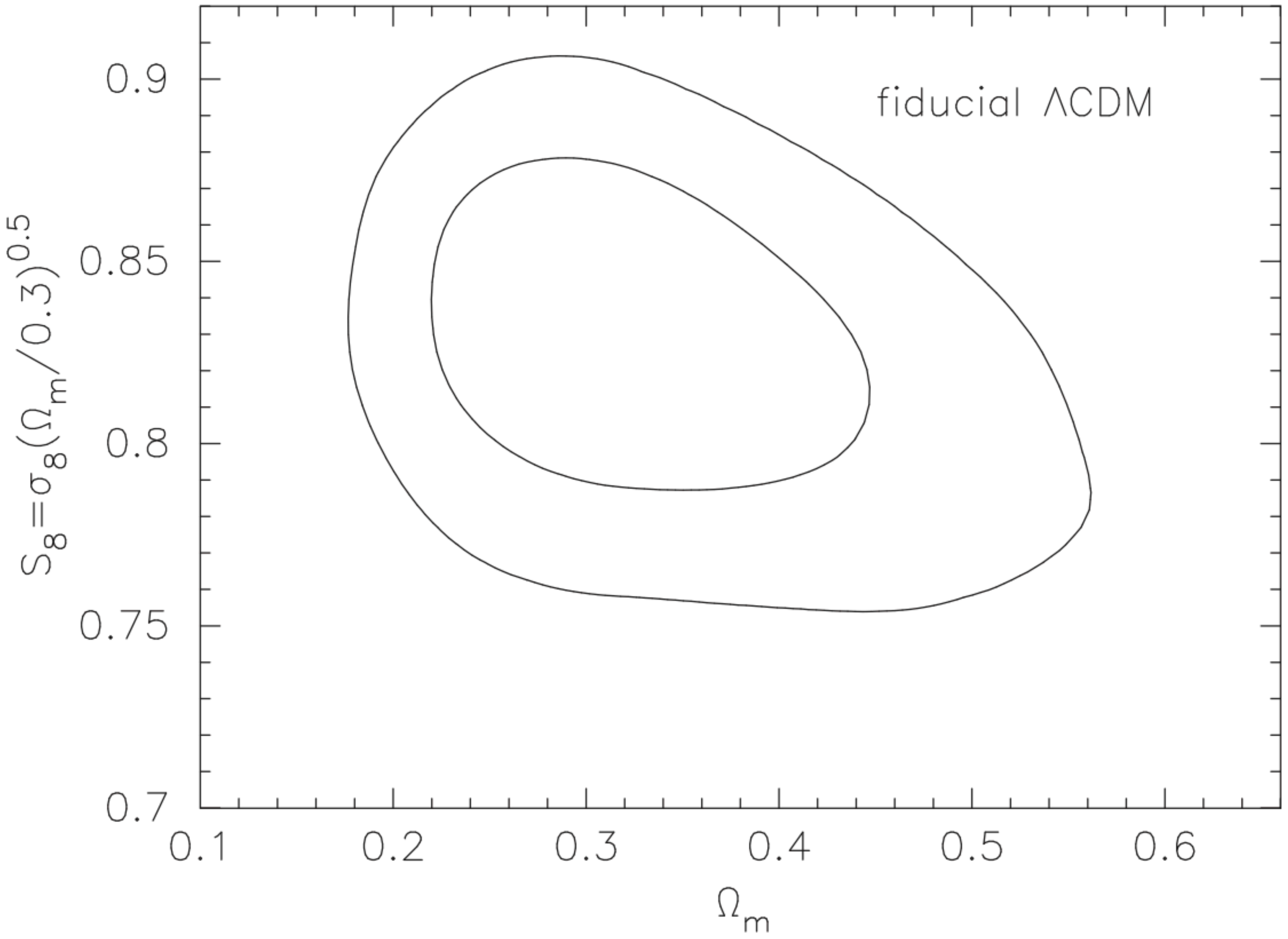
Cosmological Constraint

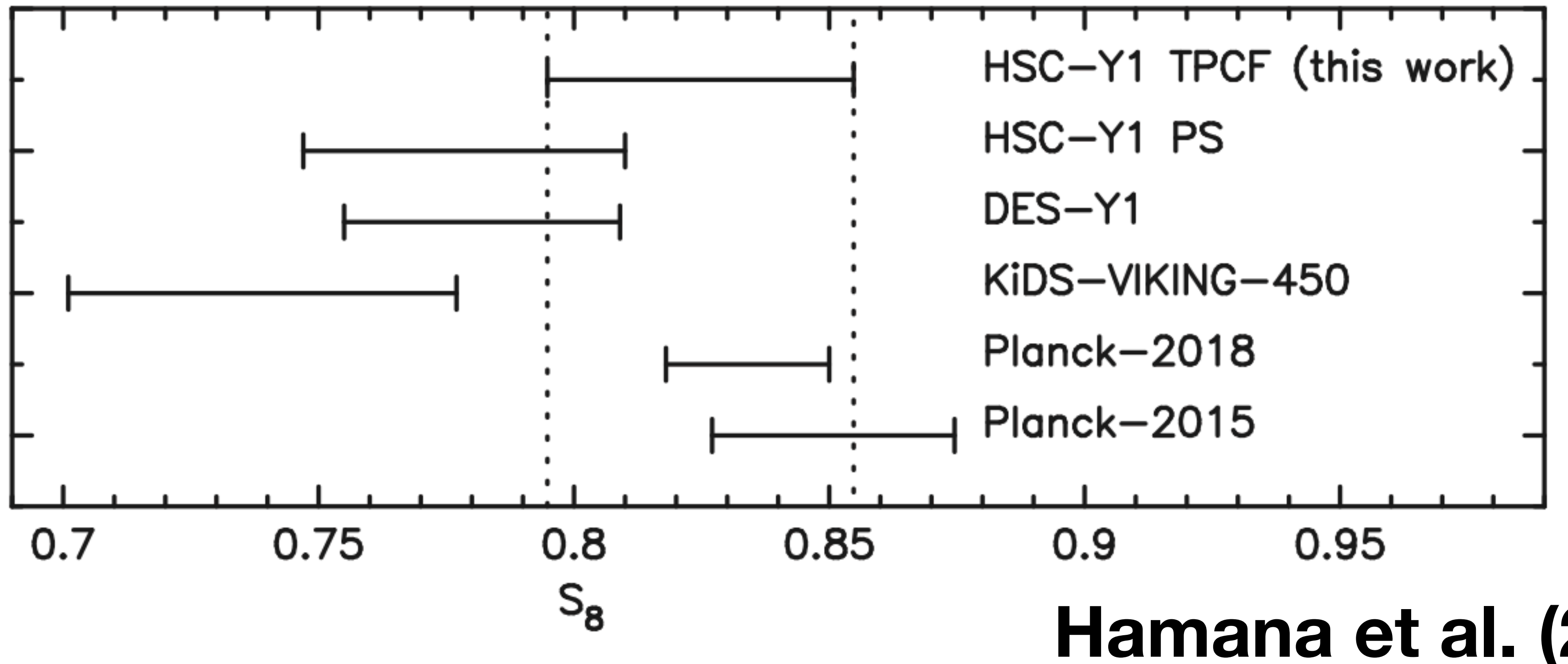


Hikage et al. (2018)

Real-space Analysis





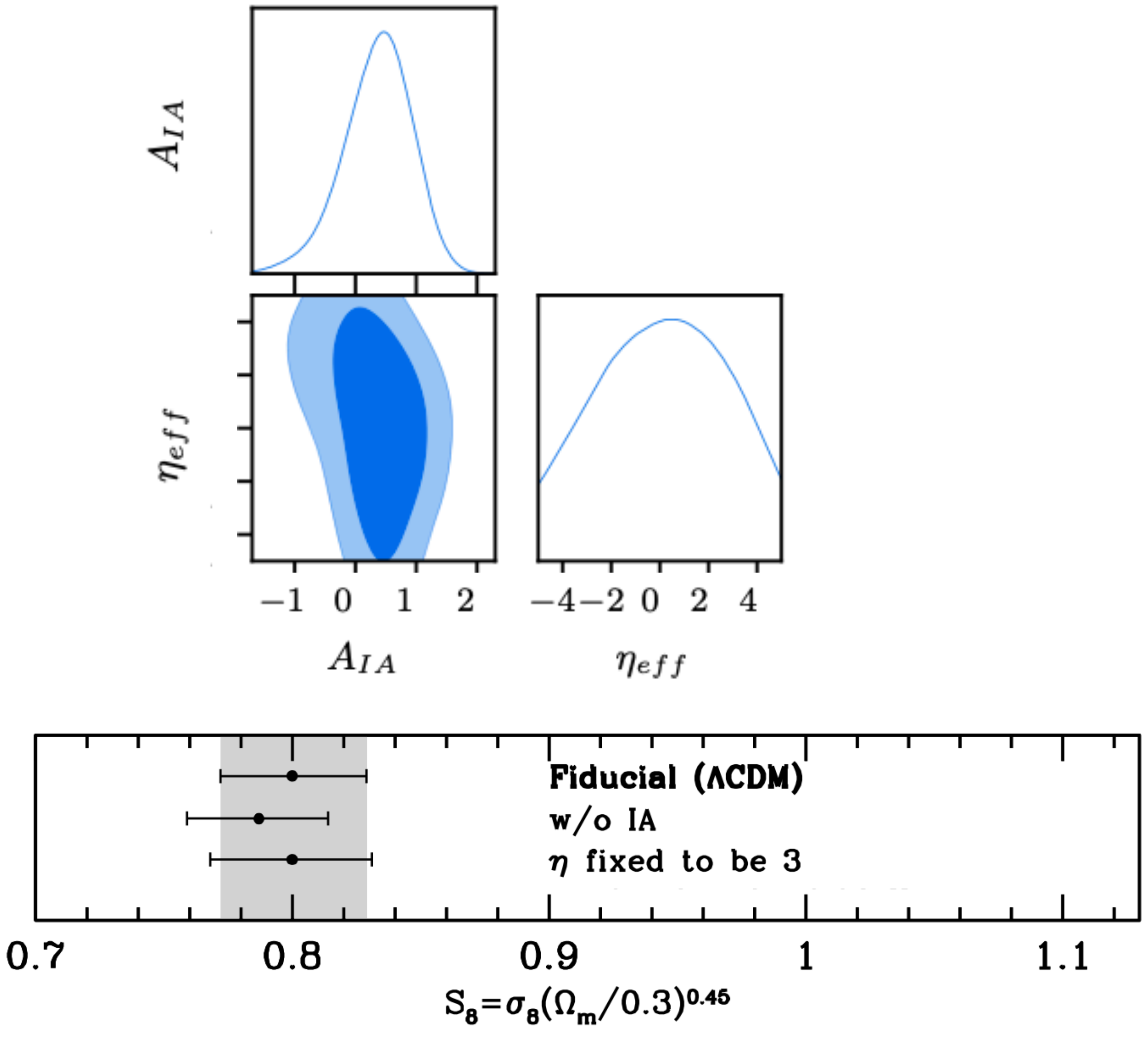


Hamana et al. (2019, 2022)

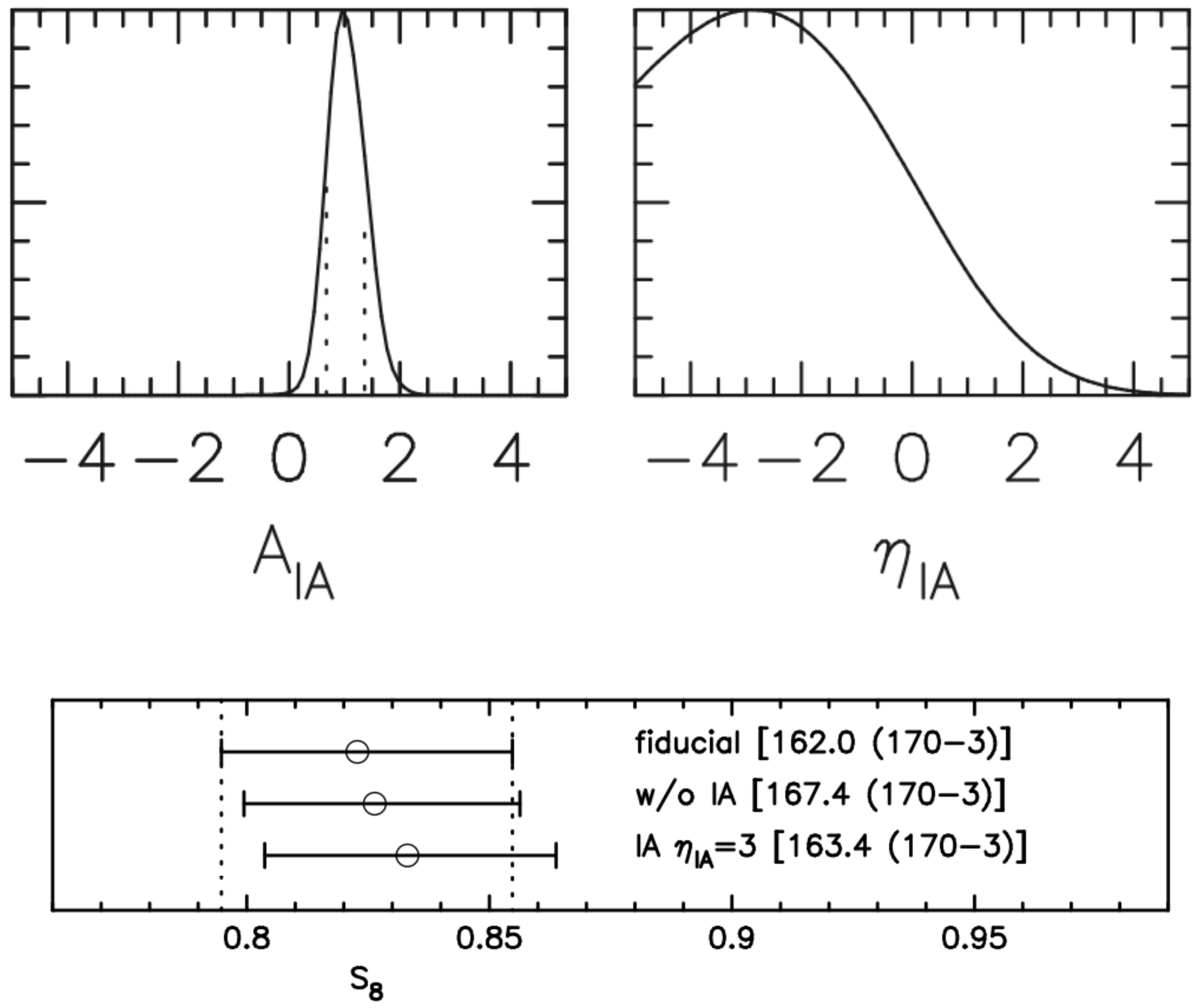
Intrinsic Alignments

$$F\left[\chi(z)\right] = -A_{\rm IA} C_1 \rho_{\rm crit} \frac{\Omega_m}{D_+(z)} \left(\frac{1+z}{1+z_0}\right)^{\eta_{\rm eff}}$$

Fourier-space analysis



Real-space analysis



Hikage et al. (2018)

Hamana et al. (2019, 2022)

Projected galaxy-galaxy clustering and galaxy-galaxy lensing (2x2pt)

Galaxy-galaxy Lensing x Galaxy-galaxy Clustering

Galaxy-galaxy clustering

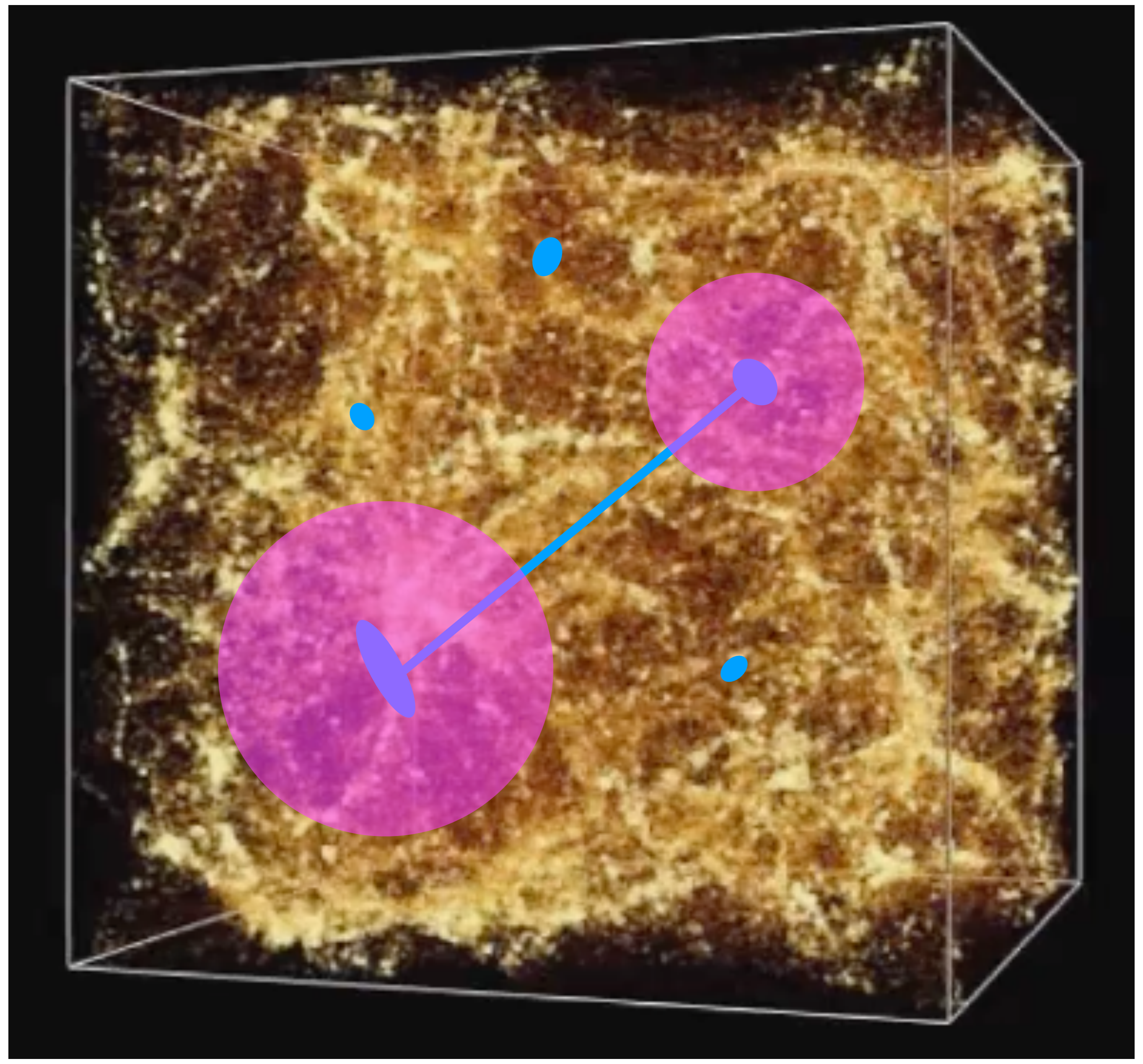
$$\xi_{\rm gg} = \langle \delta_{\rm g}\delta_{\rm g}\rangle \sim b^2\langle \delta_{\rm m}\delta_{\rm m}\rangle = \boxed{b^2\xi_{\rm mm}}$$

$\delta_{\rm g} \sim b\delta_{\rm m}$ at large scales

$$\boxed{\xi_{\rm mm}}$$

Galaxy-galaxy lensing

$$\xi_{\rm gm} = \langle \delta_{\rm g}\delta_{\rm m}\rangle \sim b\langle \delta_{\rm m}\delta_{\rm m}\rangle = \boxed{b\xi_{\rm mm}}$$

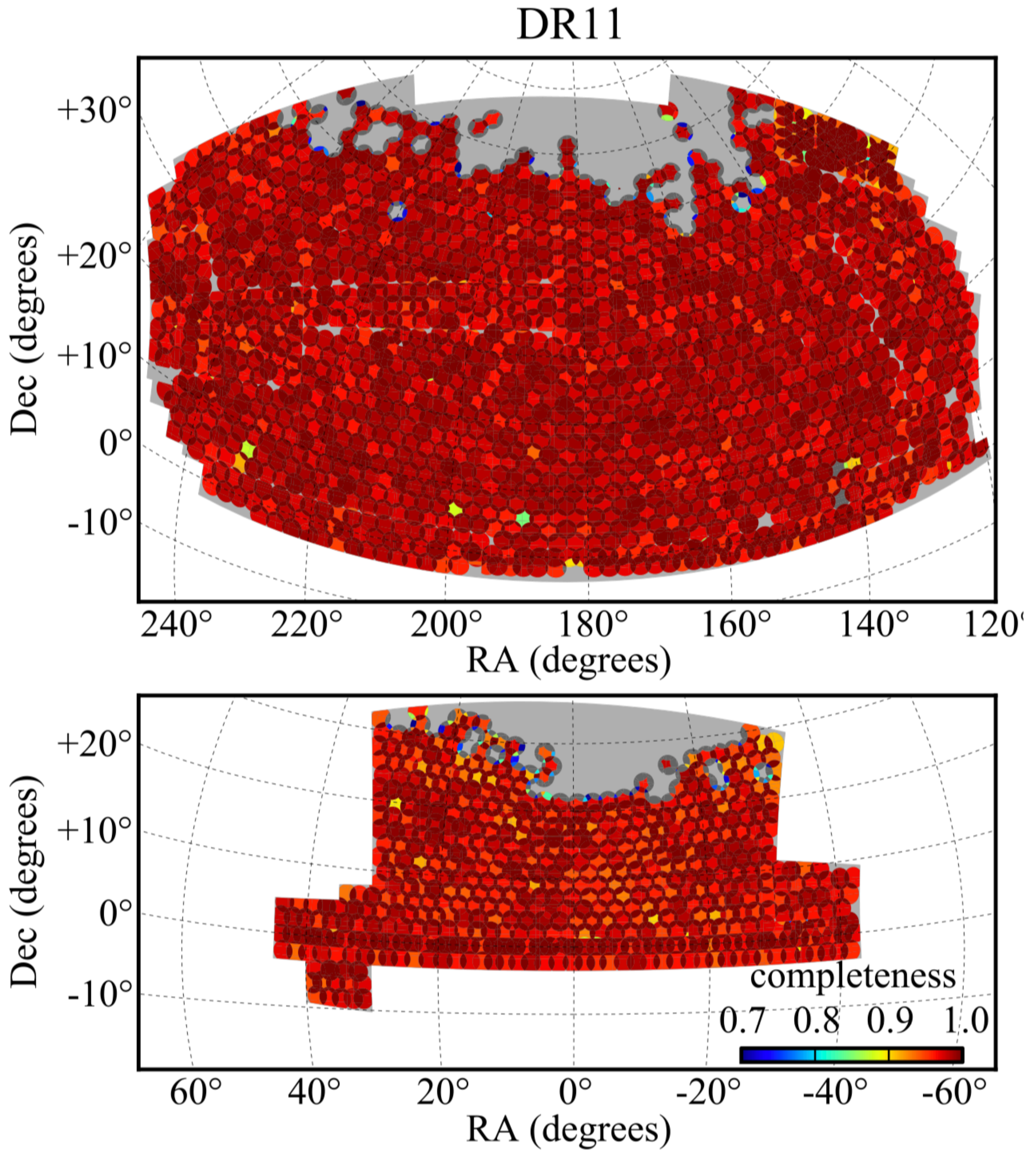


Robust against systematics in lensing measurement (shapes and photo-z) compared to cosmic shear.

HSC x BOSS Measurement

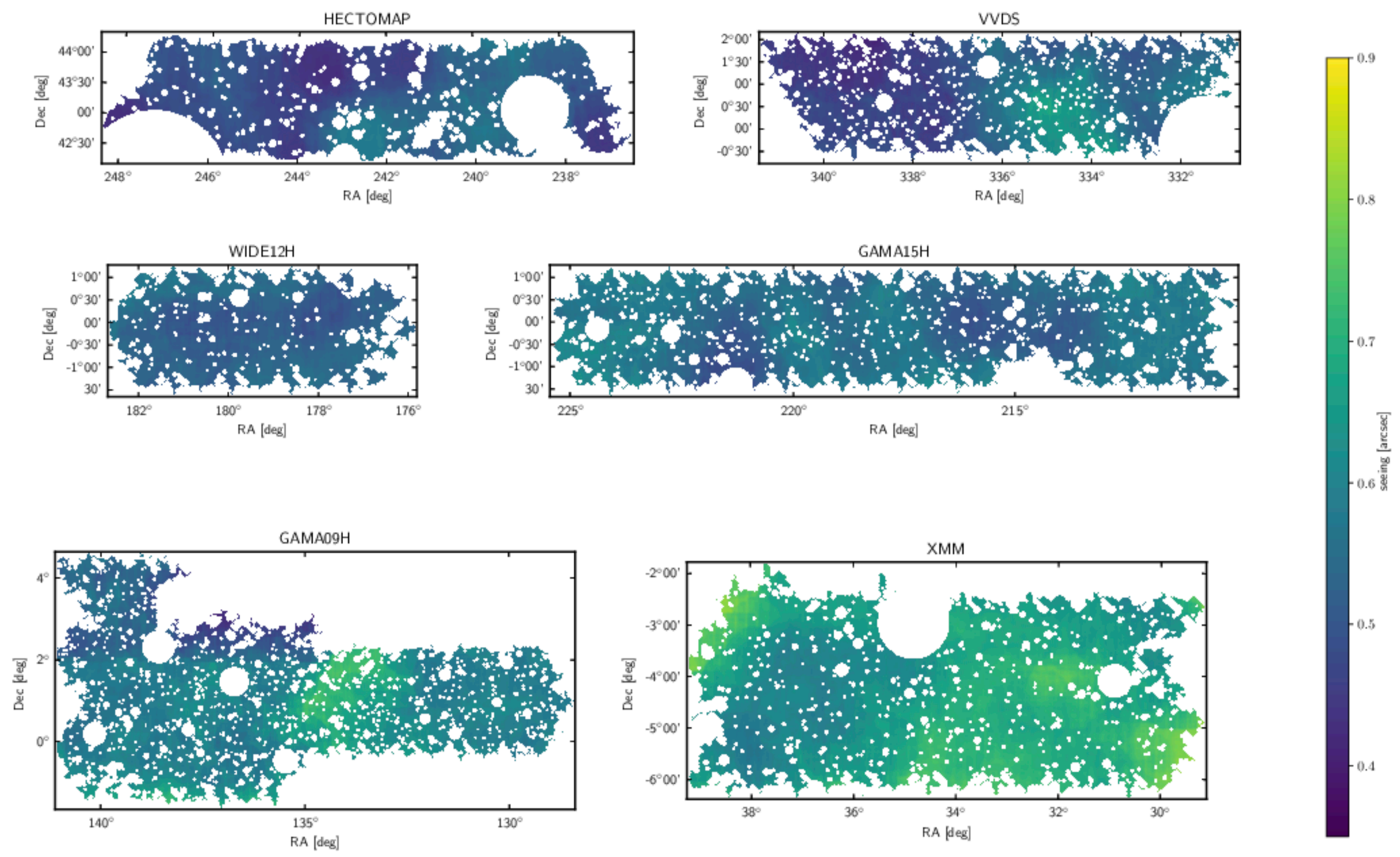
SDSS-III/BOSS spec-z sample

- Area ~ 8300 deg^2
- z = [0.15, 0.35], [0.47, 0.55], [0.55, 0.70]
- Luminosity cut is applied to obtain volume-limited sample.



HSC SSP-Y1 shape catalog

- Area ~ 137 deg^2 in total
- Single redshift bin with <z>~1.0. →**photo-z self calib.**
- Galaxy shapes are blinded.



g-g lensing signal

g-g clustering signal

Miyatake et al. (2022a)

Intrinsic Alignments

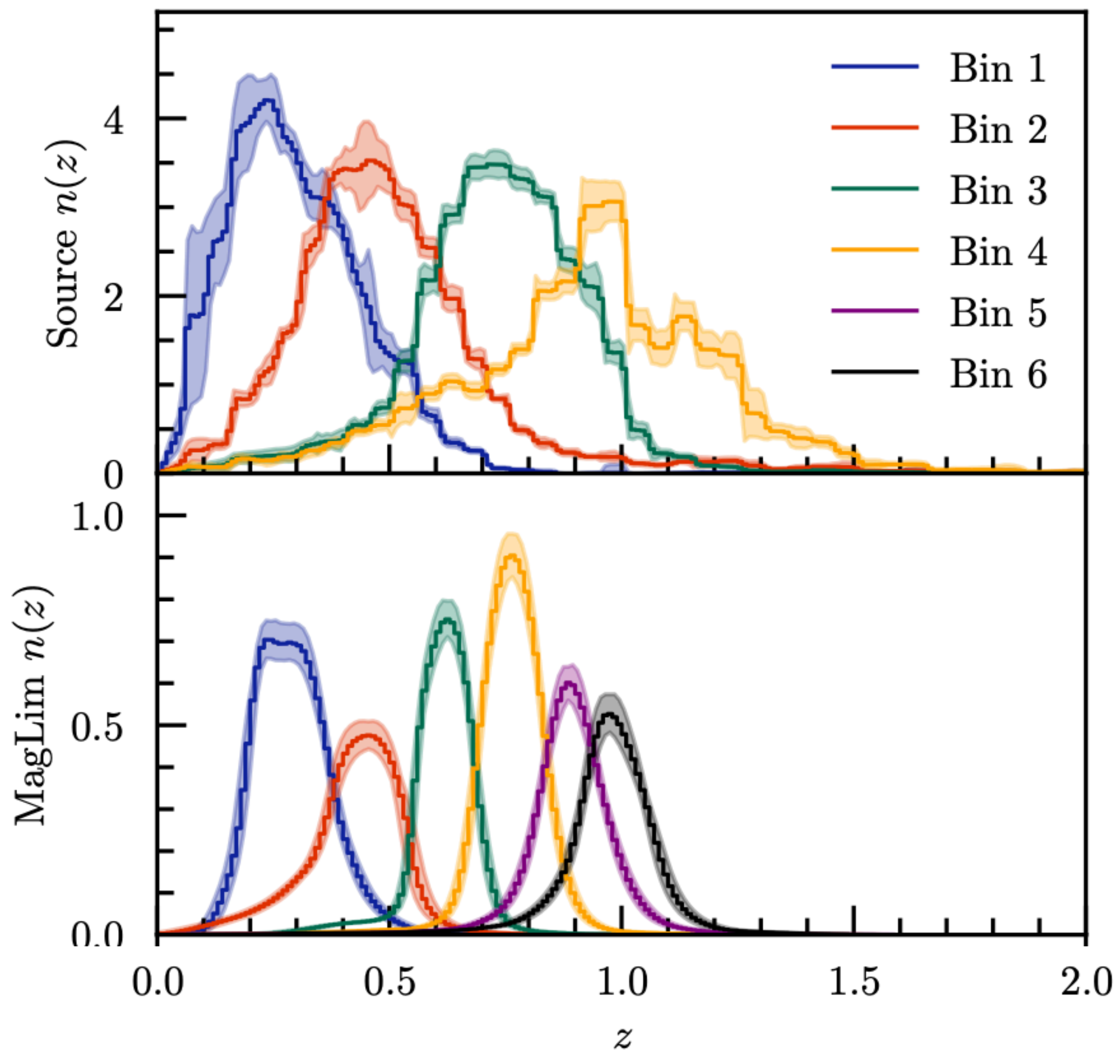
Since we use the *spectroscopic* sample for lens galaxies and our source galaxy selection is conservative,

$$\int_{z_{\mathrm{l,max}}+0.05}^{7} \mathrm{d}z_{\mathrm{s}}\ P_i(z_{\mathrm{s}}) \geq 0.99$$

$z_{\mathrm{l,max}}$=0.7 (highest redshift of the lens sample)

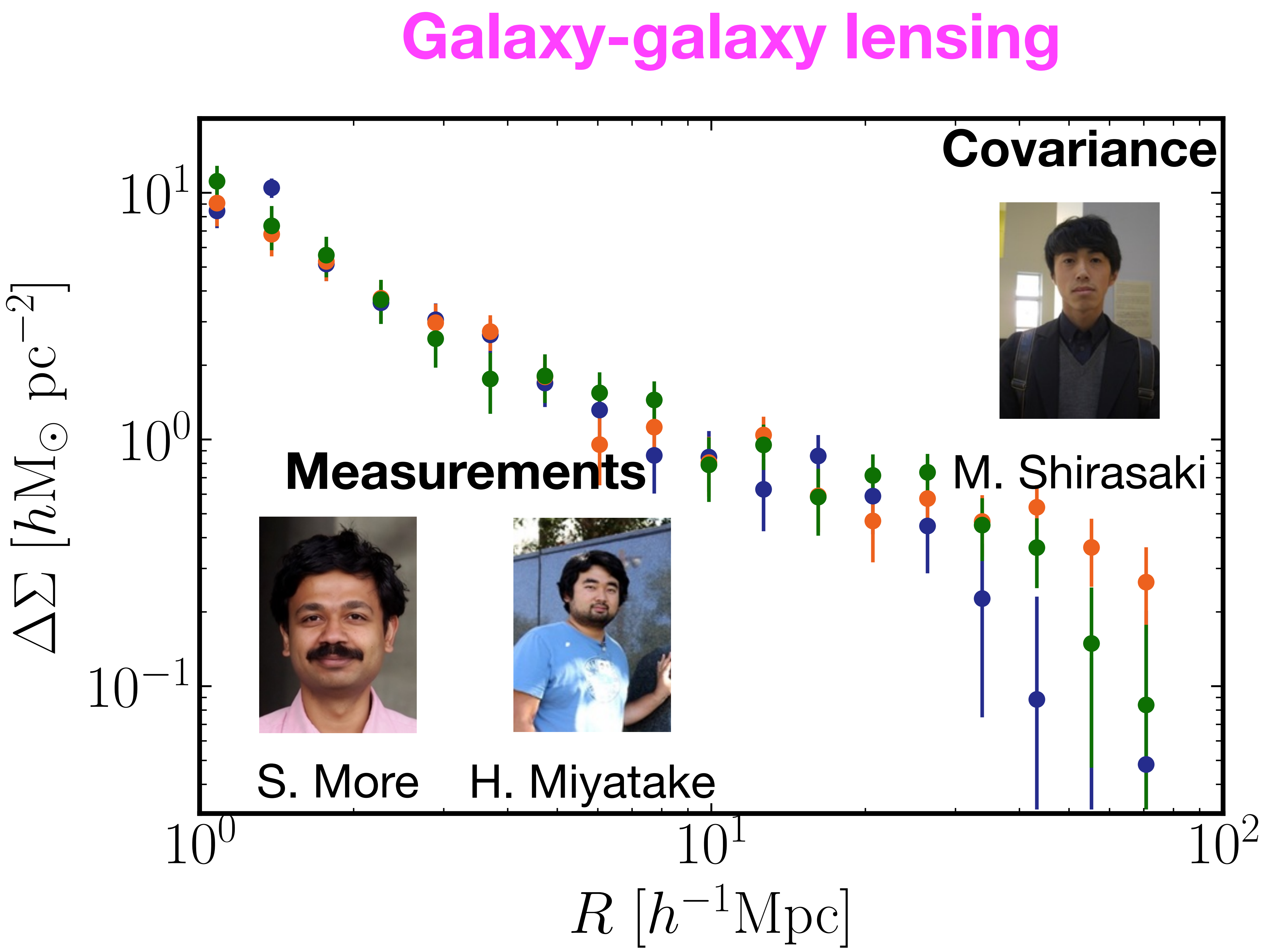
we do not have to care about intrinsic alignment.

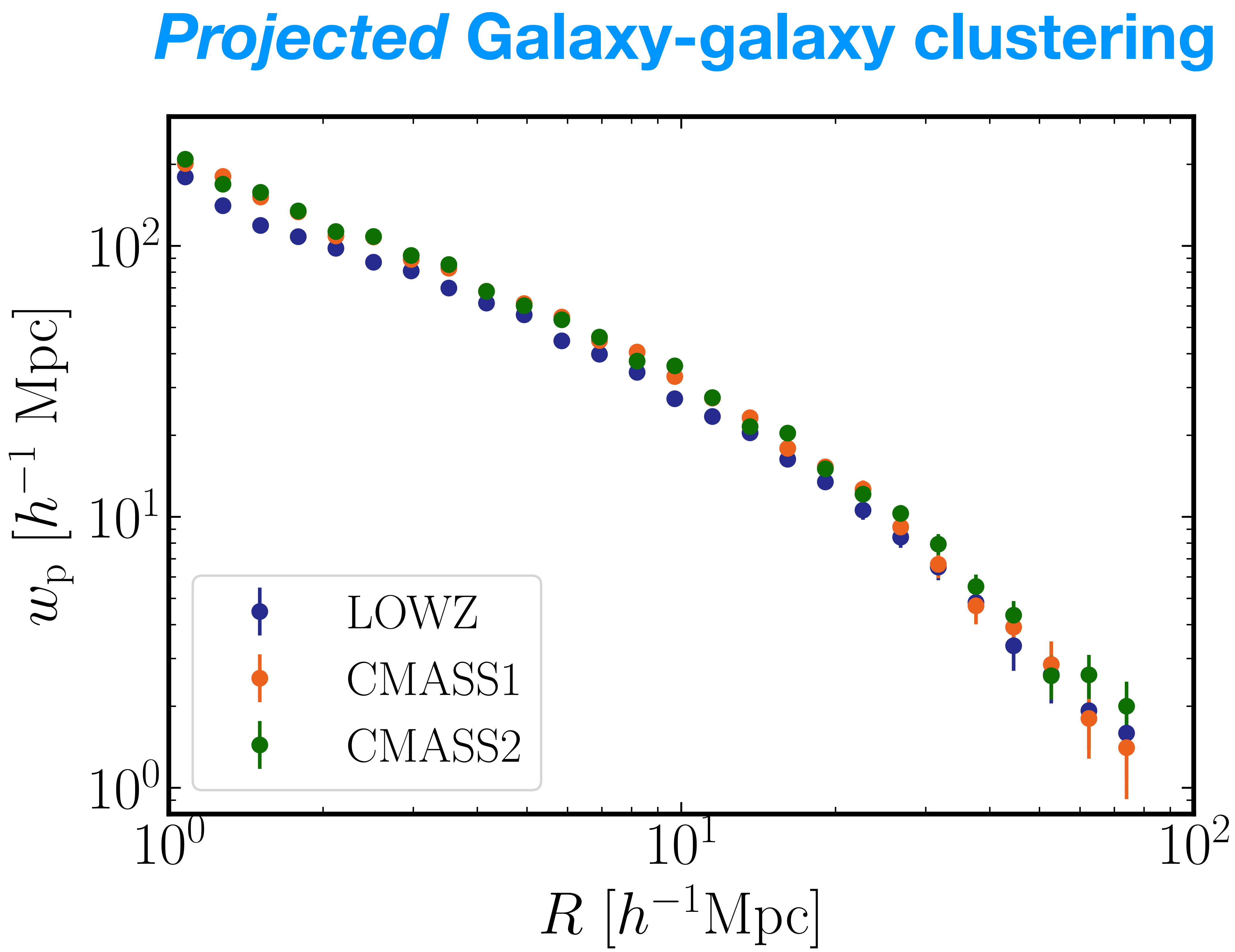
DES needs to account for intrinsic alignment, since they use *photometric* galaxies for lens samples.



DES-Y3 analysis (DES collaboration; 2022)

G-g lensing and clustering measurements by HSC-Y1 and BOSS





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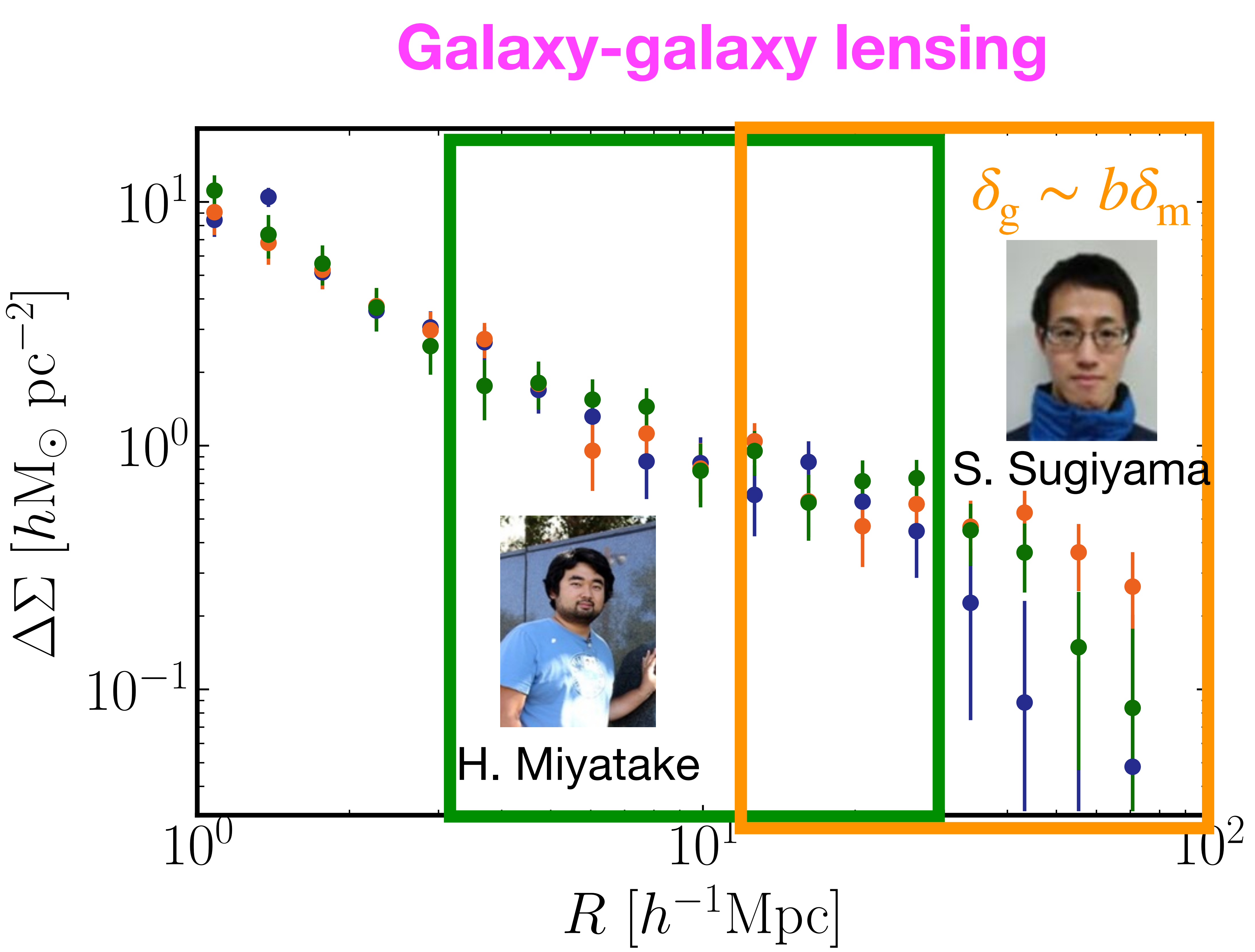
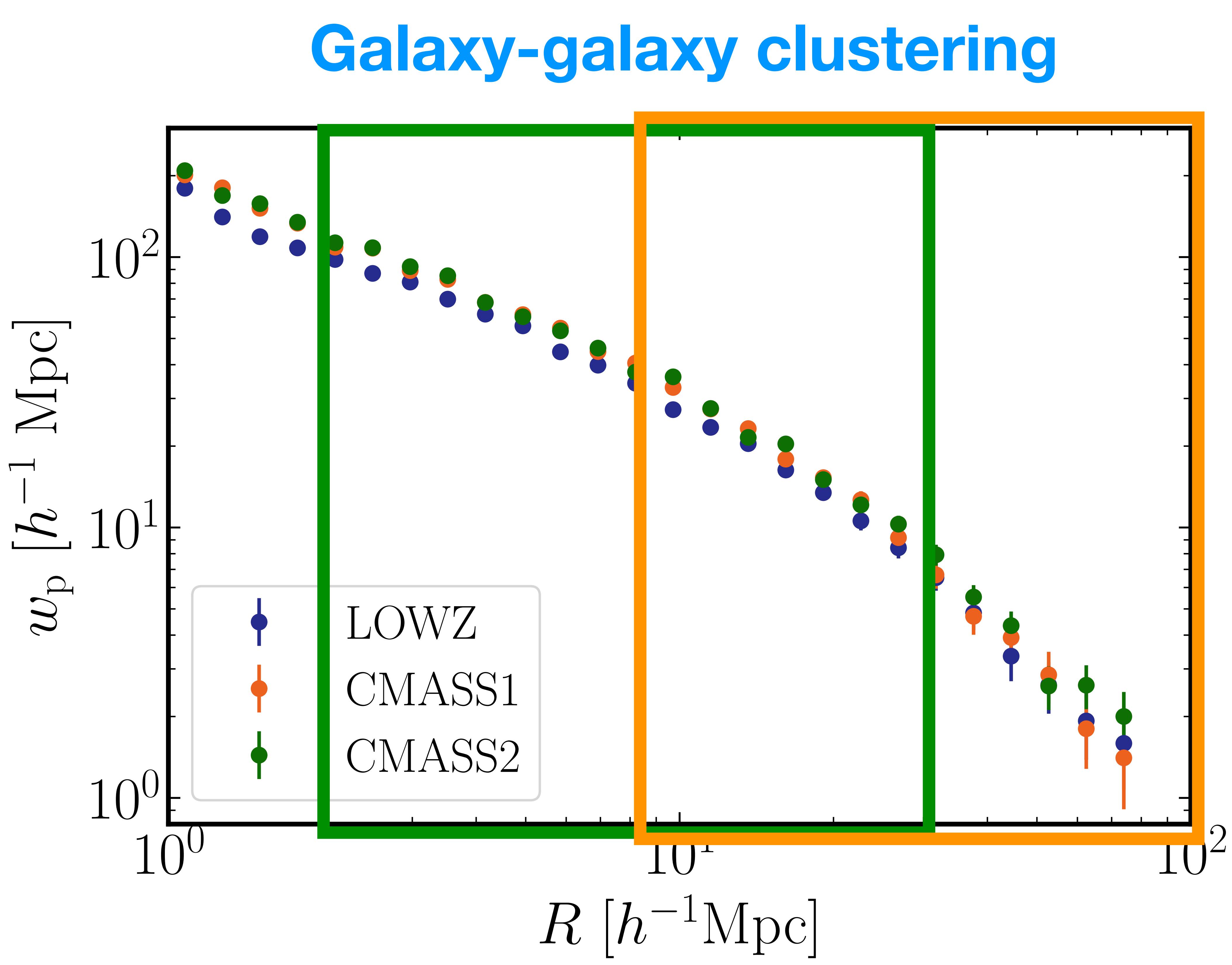


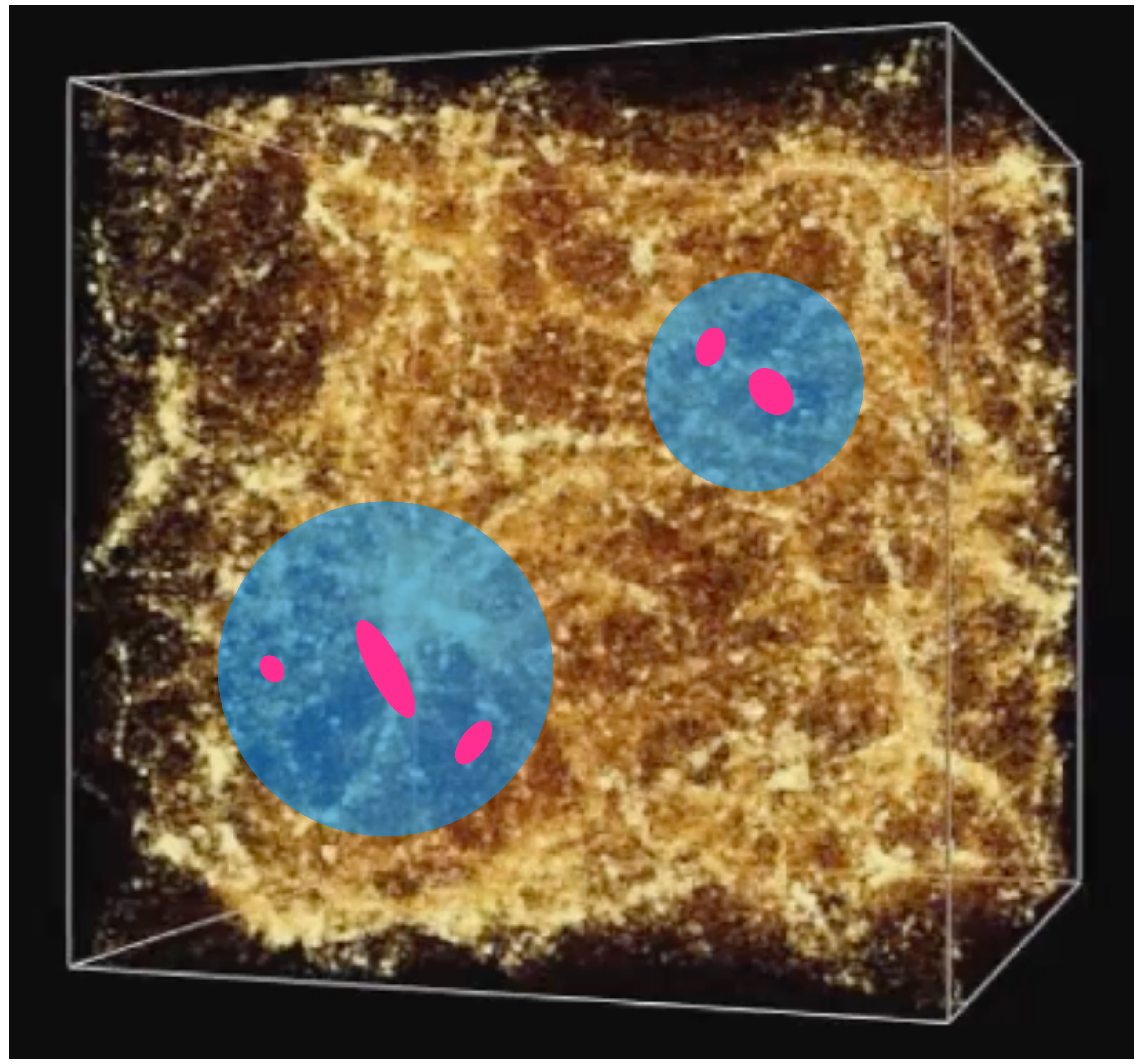


Large scale analysis (**same scale cut with DES-Y1**; Sugiyama et al., 2021)
→Less modeling systematics, less signal-to-noise

Small scale analysis (Miyatake et al., 2021)
→Challenges in modeling, more signal-to-noise

Credit: ESA

Modeling Small-scale Signals



dark matter

dark matter halos

galaxies

Challenges

- Accurate modeling of non-linear regimes
- Proper treatment of uncertainties in galaxy-halo connection

Cosmo. Params.
$(\sigma_8, \Omega_\mathrm{m}, \ldots)$

$\xi_\mathrm{hh} = \langle \delta_\mathrm{h} \delta_\mathrm{h} \rangle$
$\xi_\mathrm{hm} = \langle \delta_\mathrm{h} \delta_\mathrm{m} \rangle$

$\xi_\mathrm{gg} = \langle \delta_\mathrm{g} \delta_\mathrm{g} \rangle$
$\xi_\mathrm{gm} = \langle \delta_\mathrm{g} \delta_\mathrm{m} \rangle$

Projection to 2-d

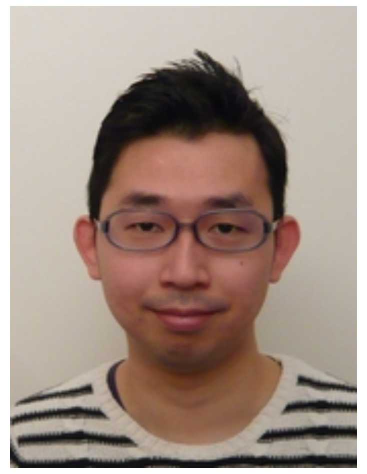
Observables

Clustering: $w_\mathrm{p}(R)$
Weak Lensing: $\Delta\Sigma(R)$

Modeling non-linear regimes
Prediction by **Dark Emulator**
achieved a few % accuracy

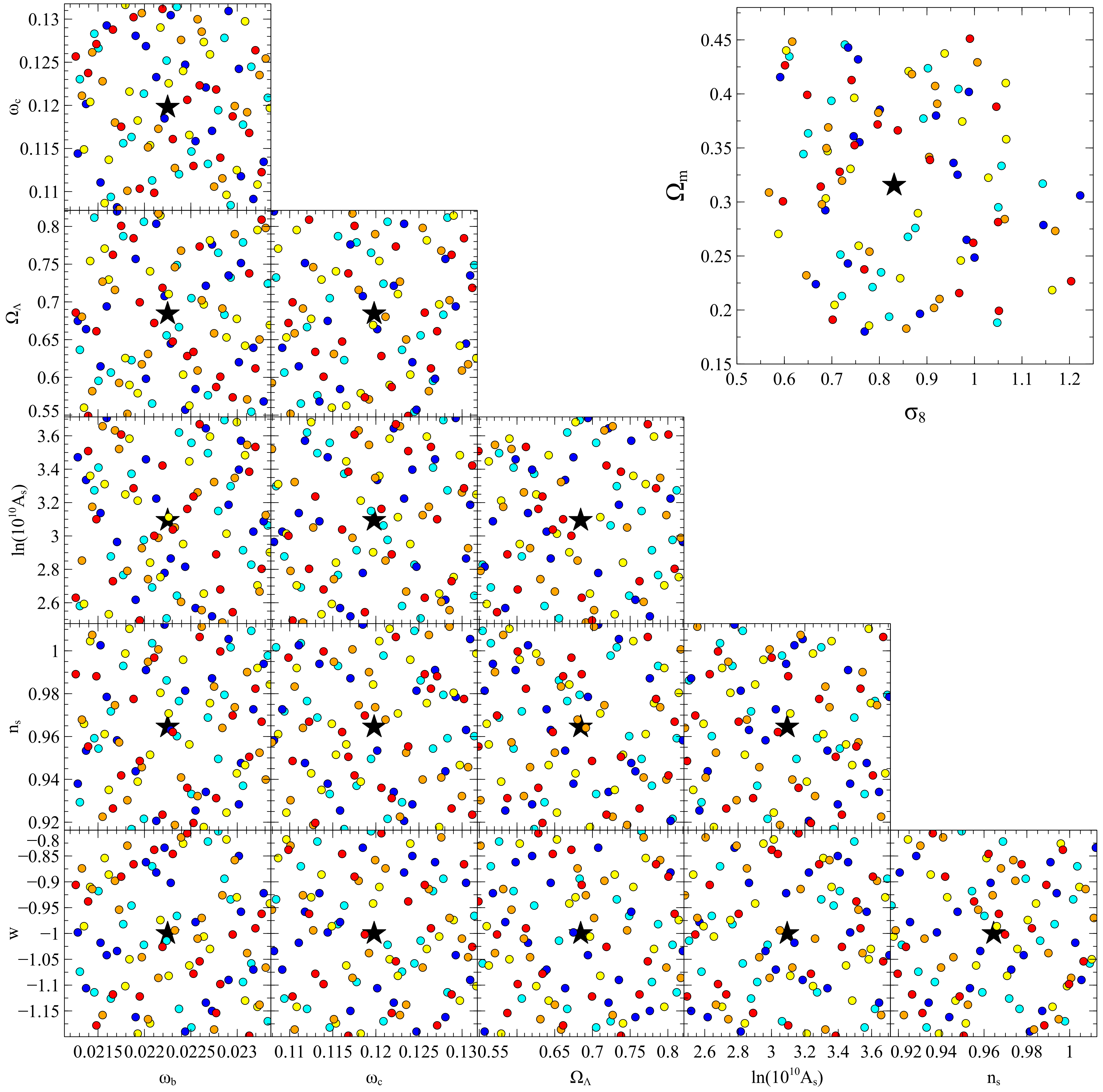
Uncertainties between galaxy-halo (g-h) connection
Analytical convolution of phenomenological model
enables us to **quickly change the g-h connection** model if necessary

Dark Emulator: accurate non-linear model



T. Nishimichi (Kyoto)

- Run N-body simulations under 101 sets of cosmological parameters.
  $\overrightarrow{C} = (\omega_b, \omega_c, \Omega_\Lambda, A_s, n_s, w)$
- Run the Rockstar halo finder.
- Measure correlation functions, i.e., $\xi_{\rm hh}(r; \overrightarrow{C})$ and $\xi_{\rm hm}(r; \overrightarrow{C})$.
- Interpolate correlation functions across the cosmological parameter sets using PCA and Gaussian process.
- Achieved an accuracy for $\xi_{\rm hh}(r; \overrightarrow{C})$ and $\xi_{\rm hm}(r; \overrightarrow{C})$ better than 2%.



Nishimichi et al. (2019)

DQ Project What's new? Overview Team Implementation Models Simulations Installation Publications Press Release Acknowledgements

Dark Quest Project Webpage

A suite of cosmological N-body simulations and a handy emulator to explore cosmological parameter space

pypi package 1.0.23 | Downloads 9194 | Anaconda.org 1.0.23 | Install with conda | downloads 69 total | license MIT_License | Last updated 29 Oct 2021

~10000 downloads!

What's new?

Dark Emulator is now publicly available! (March 19, 2021)

Overview

Dark Quest is a cosmological structure formation simulation campaign by Japanese cosmologists initiated in 2015. The primary goal of the project is to understand the complex parameter dependence of various large-scale structure probes, and provide a versatile tool to make predictions for parameter inference problems with observational datasets. The first series of simulations, Dark Quest. I. (DQ1), was completed in 2018 and we are now in the second phase (DQ2). A Gaussian-Process based emulation tool, Dark Emulator, was developed with the DQ1 database.

Our Team

Takahiro NISHIMICHI

YITP, Kyoto U / Kavli IPMU, U of Tokyo

PI of this project.

Taira OOGI

Chiba U

Participation in DQ1

Simulator

Yosuke KOBAYASHI

Kavli IPMU, U of Tokyo

Participation in DQ1 and DQ2

Mock galaxy database maintenance

Extension to redshift space

Masahiro TAKADA

Kavli IPMU, U of Tokyo

Participation in DQ1

Hironao MIYATAKE

Nagoya U

Participation in DQ1

Development of HOD modules

Cosmology challenge

Naoki Yoshida

Kavli IPMU, U of Tokyo

Participation in DQ1

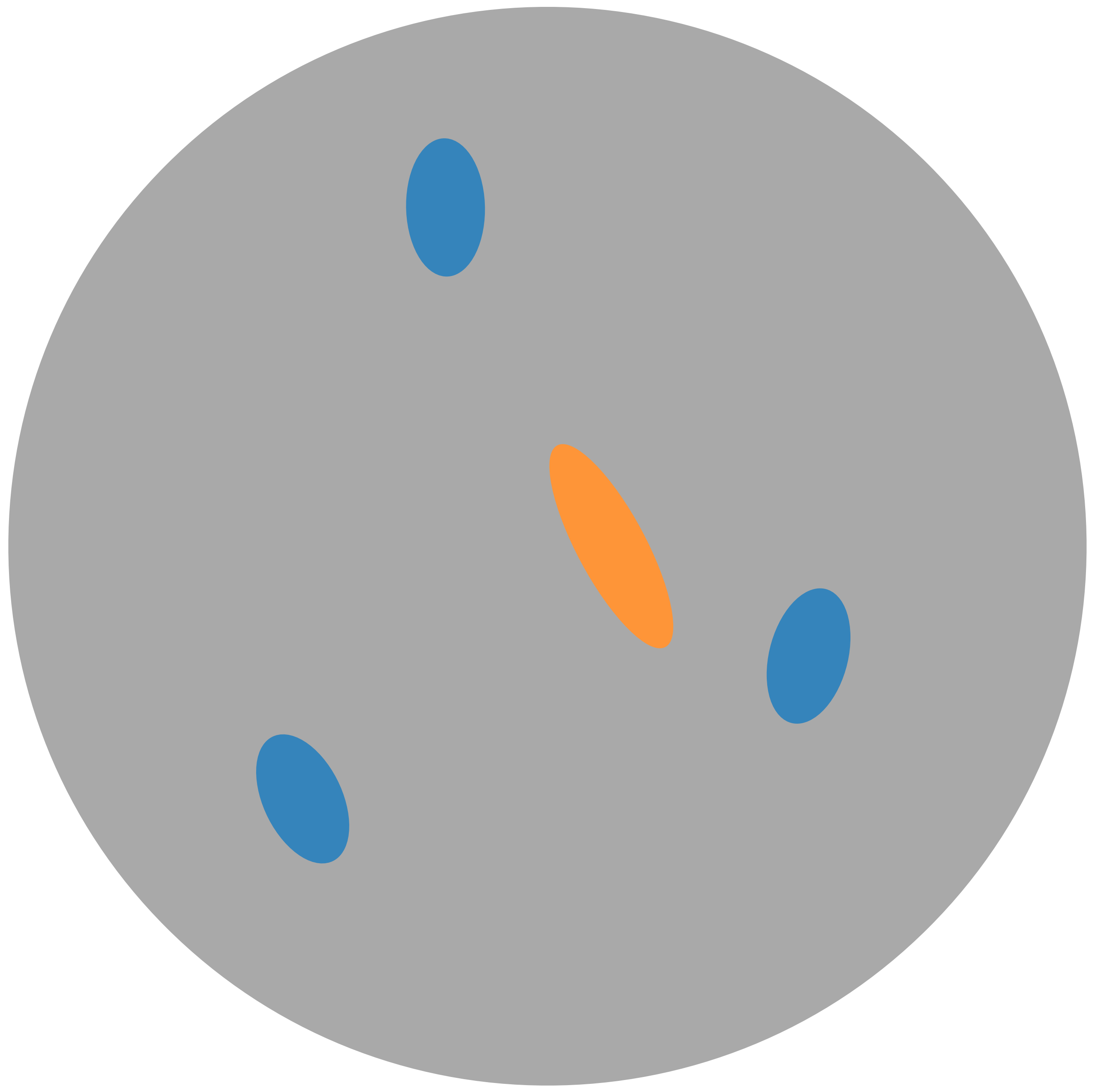
Ryuichi TAKAHASHI

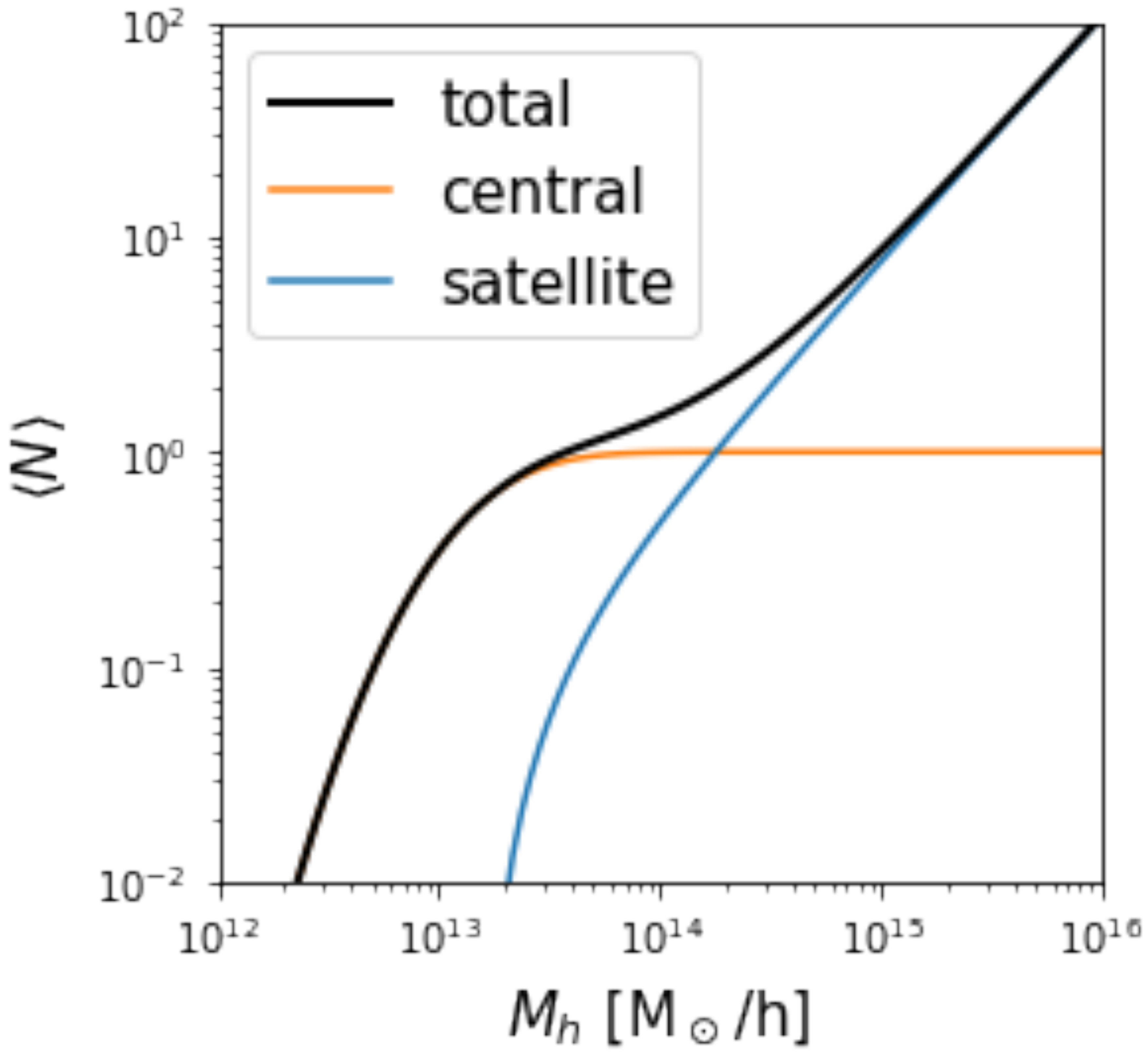
Hirosaki U

Galaxy-halo connection

- Use halo occupation distribution (HOD; 5 parameters) to distribute galaxies in a dark matter halo.

- Take into account the uncertainties in galaxy physics by marginalizing HOD parameters.





Cosmology challenge: Systematic tests with mocks

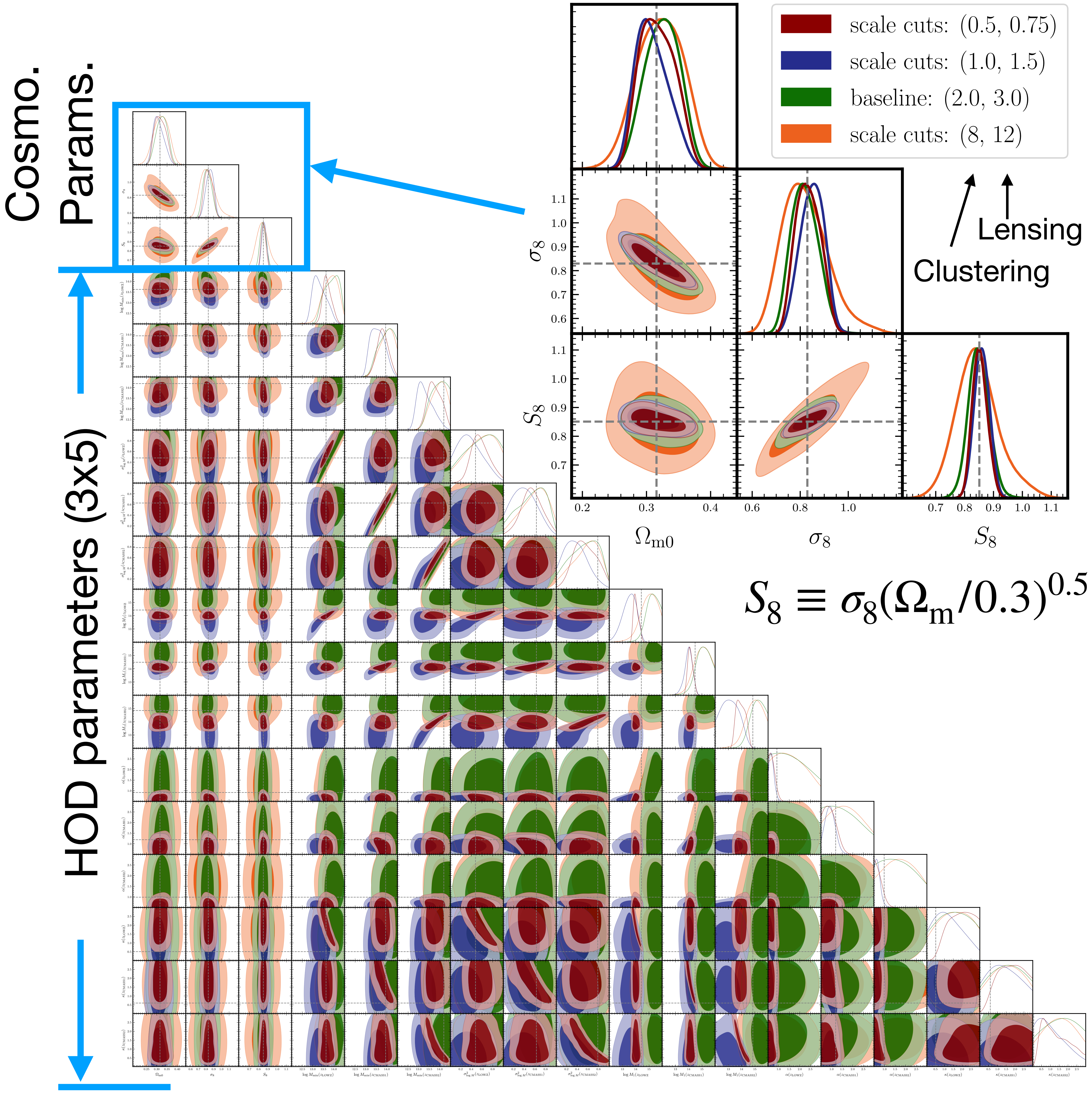
Y. Kobayashi (U. of Arizona)
led mock signal constructions

Mock Signals

Model fit
- HSC-Y1 covariance (Shirasaki et al., 2019)
- Different scale cuts

Input cosmological parameters ⟷ **Output cosmological parameters**

Compare



$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

Miyatake et al. (2022a)

Cosmology challenge: Systematic tests with mocks

Y. Kobayashi (U. of Arizona) led mock signal constructions

Uncertainties in galaxy physics
- Galaxy distribution within a DM halo
- Baryonic effect
- Assembly bias

Observational uncertainties
- Incompleteness

Theoretical uncertainties
- SO vs FoF

Mock Signals

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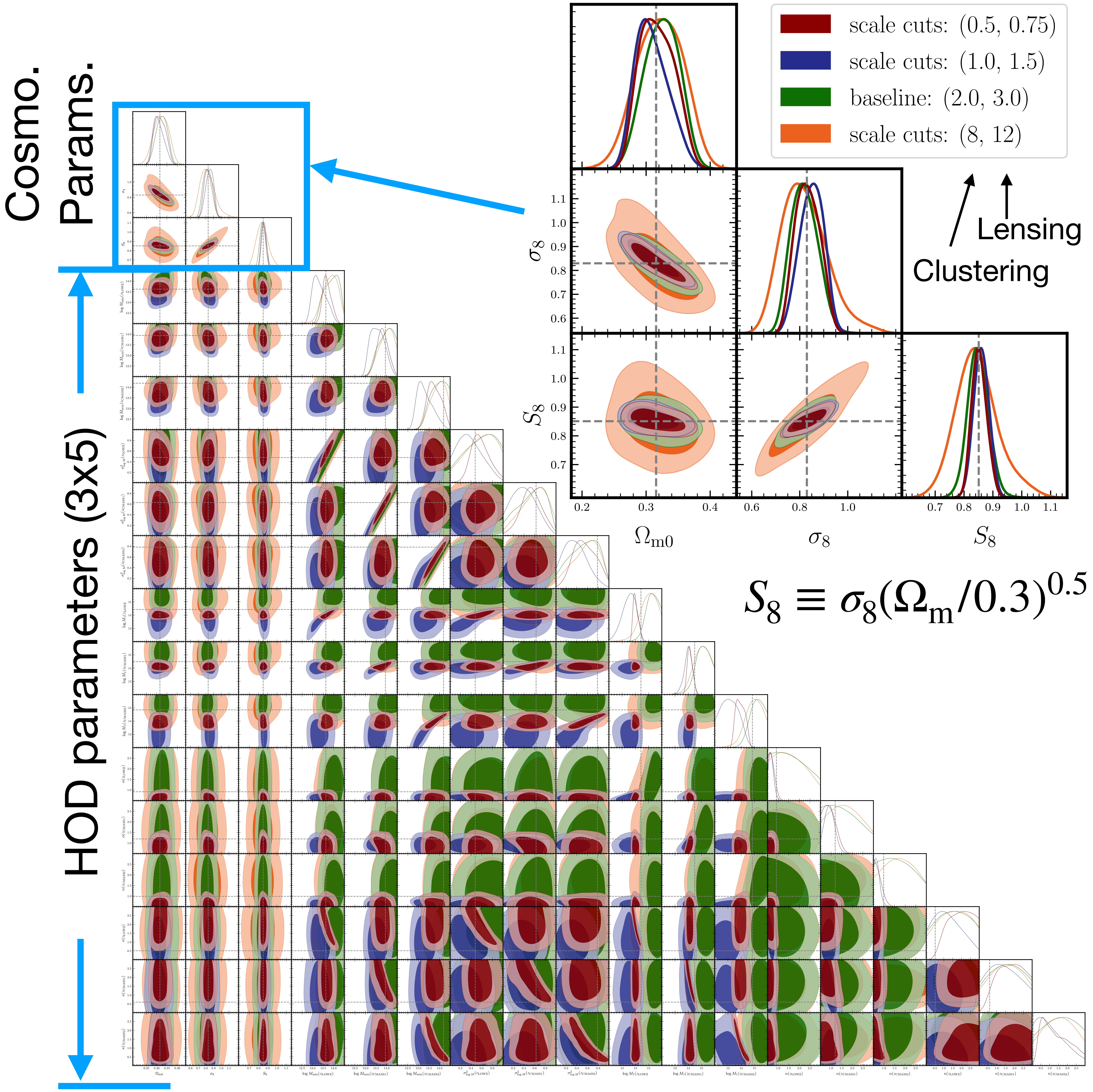

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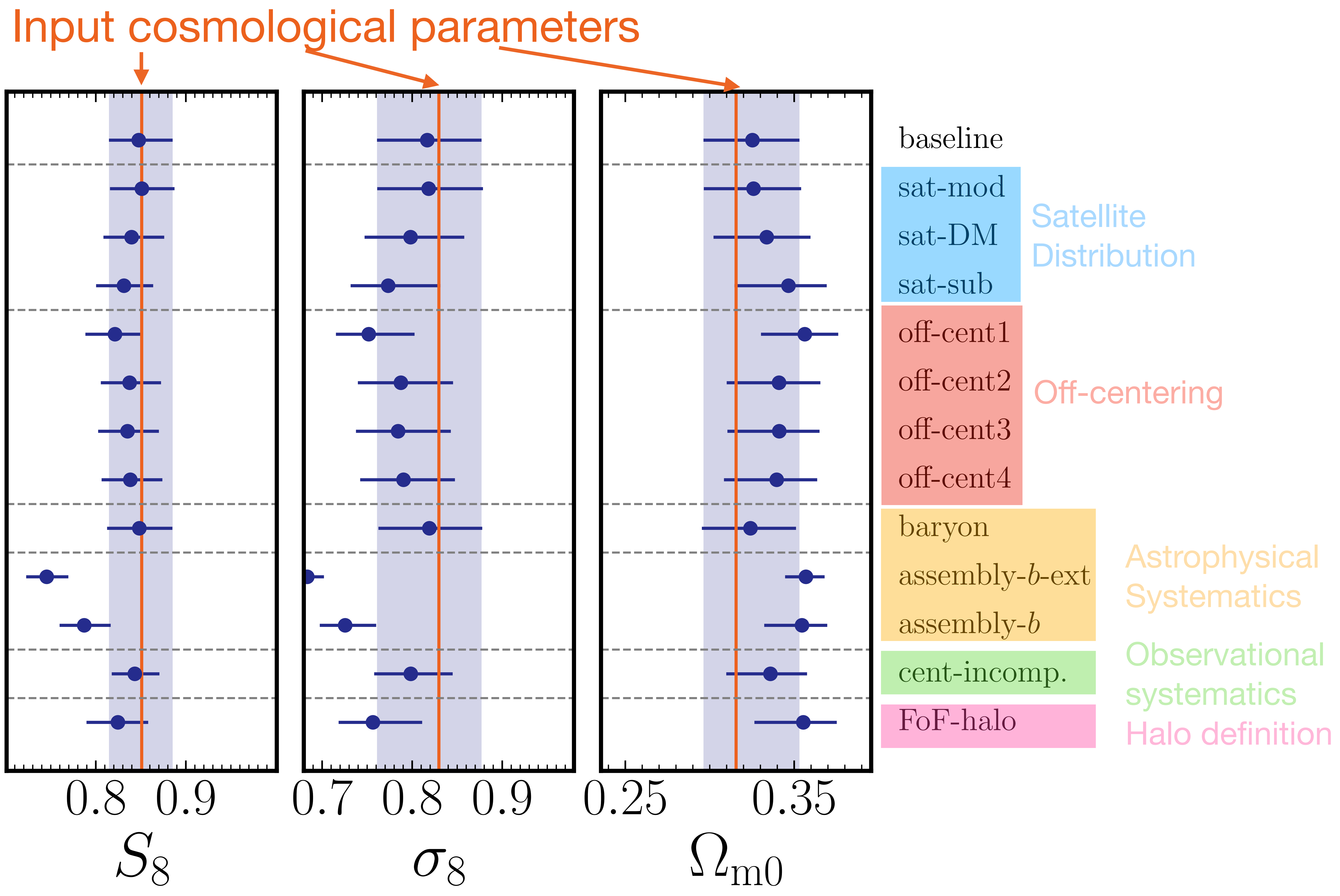
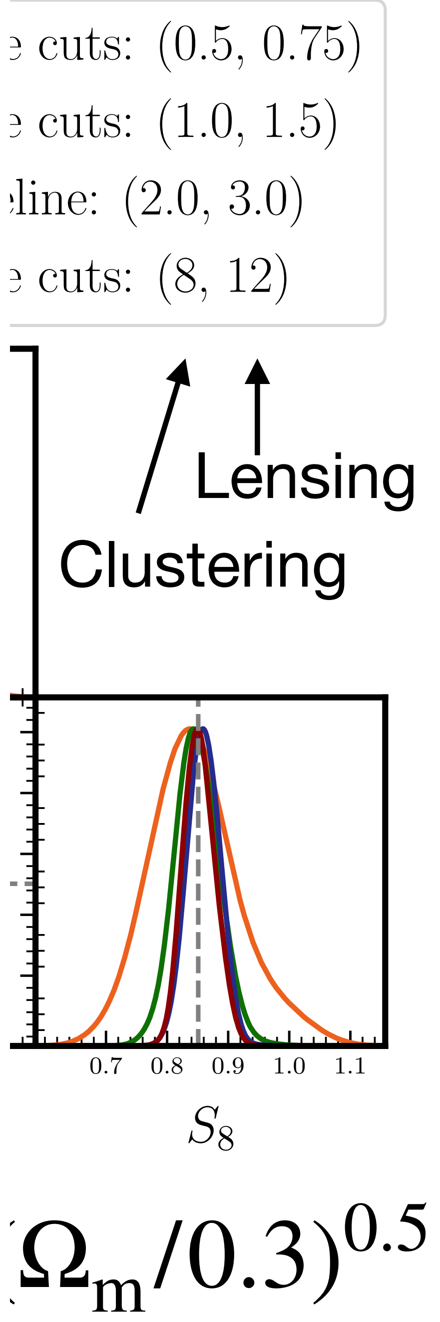
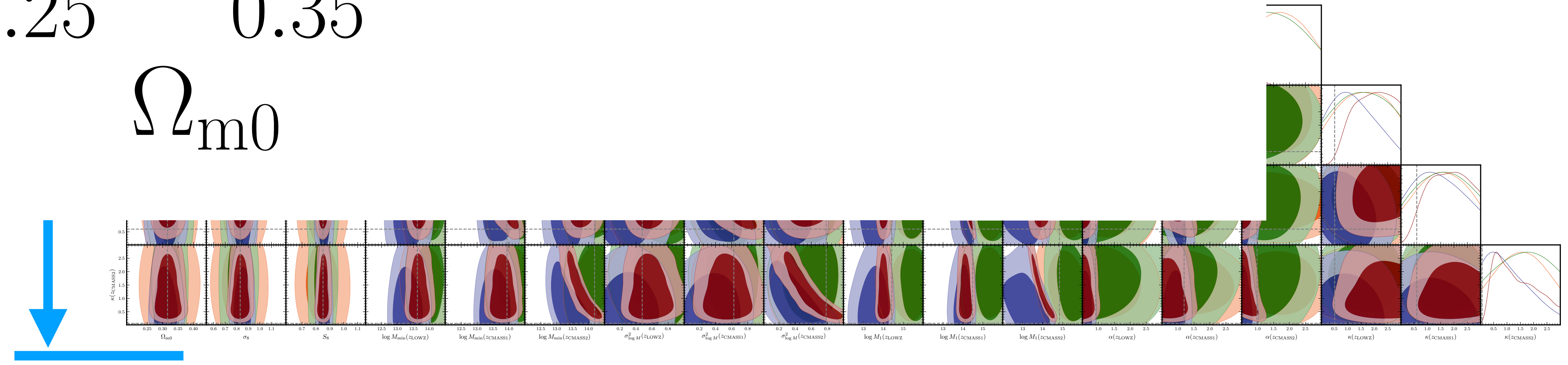


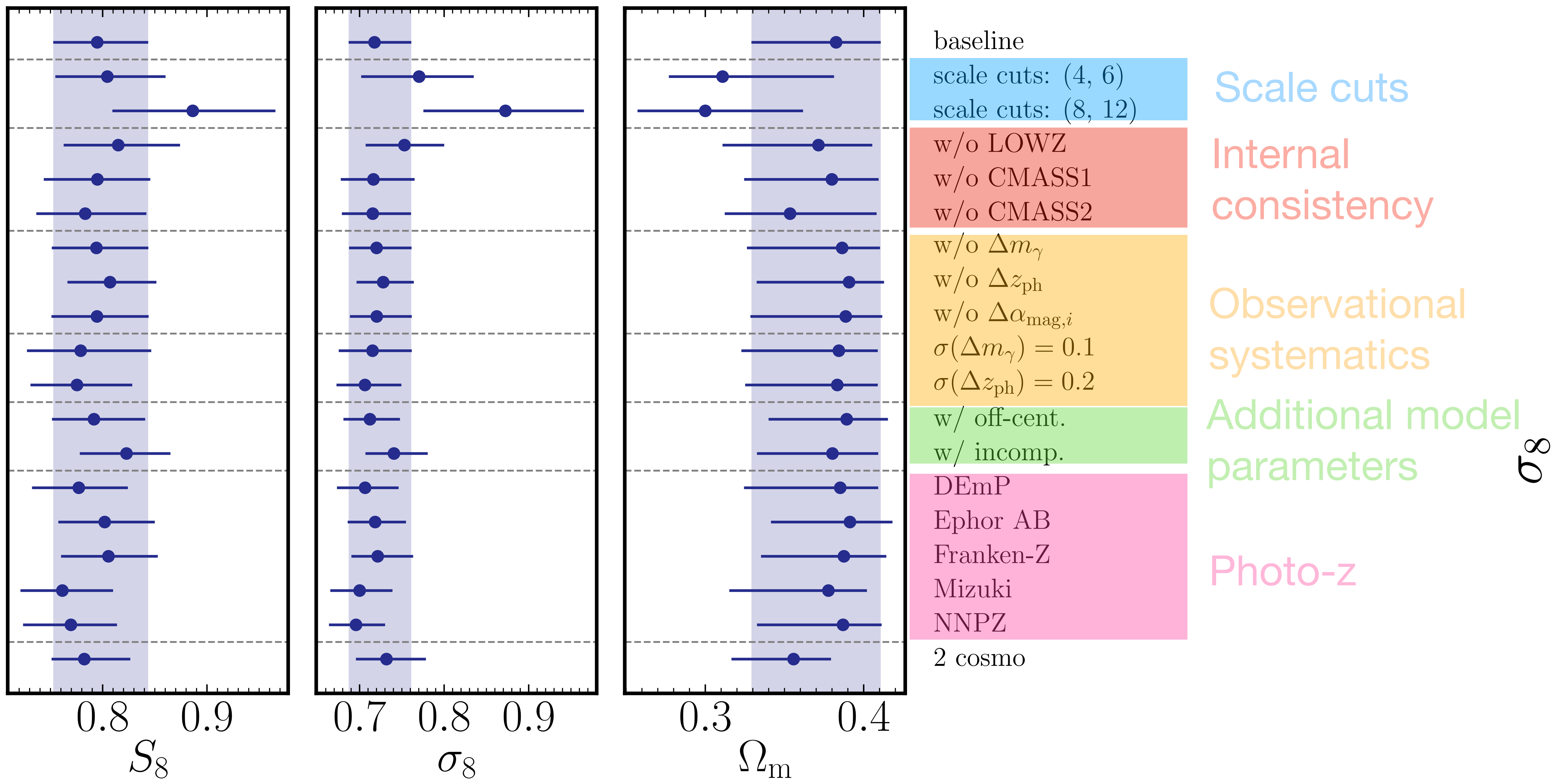


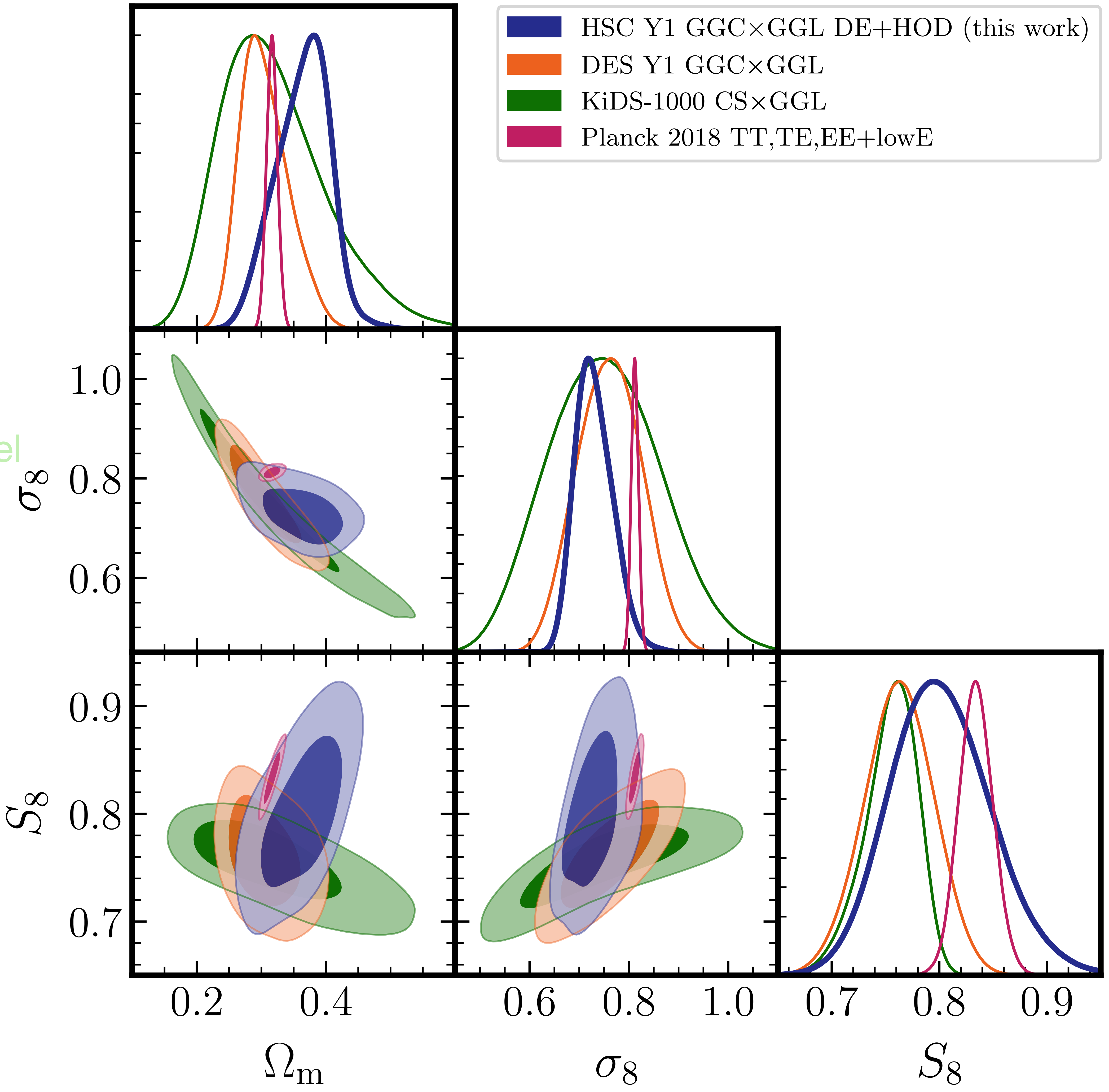
Comp



Miyatake et al. (2022a)

Analyzing real data





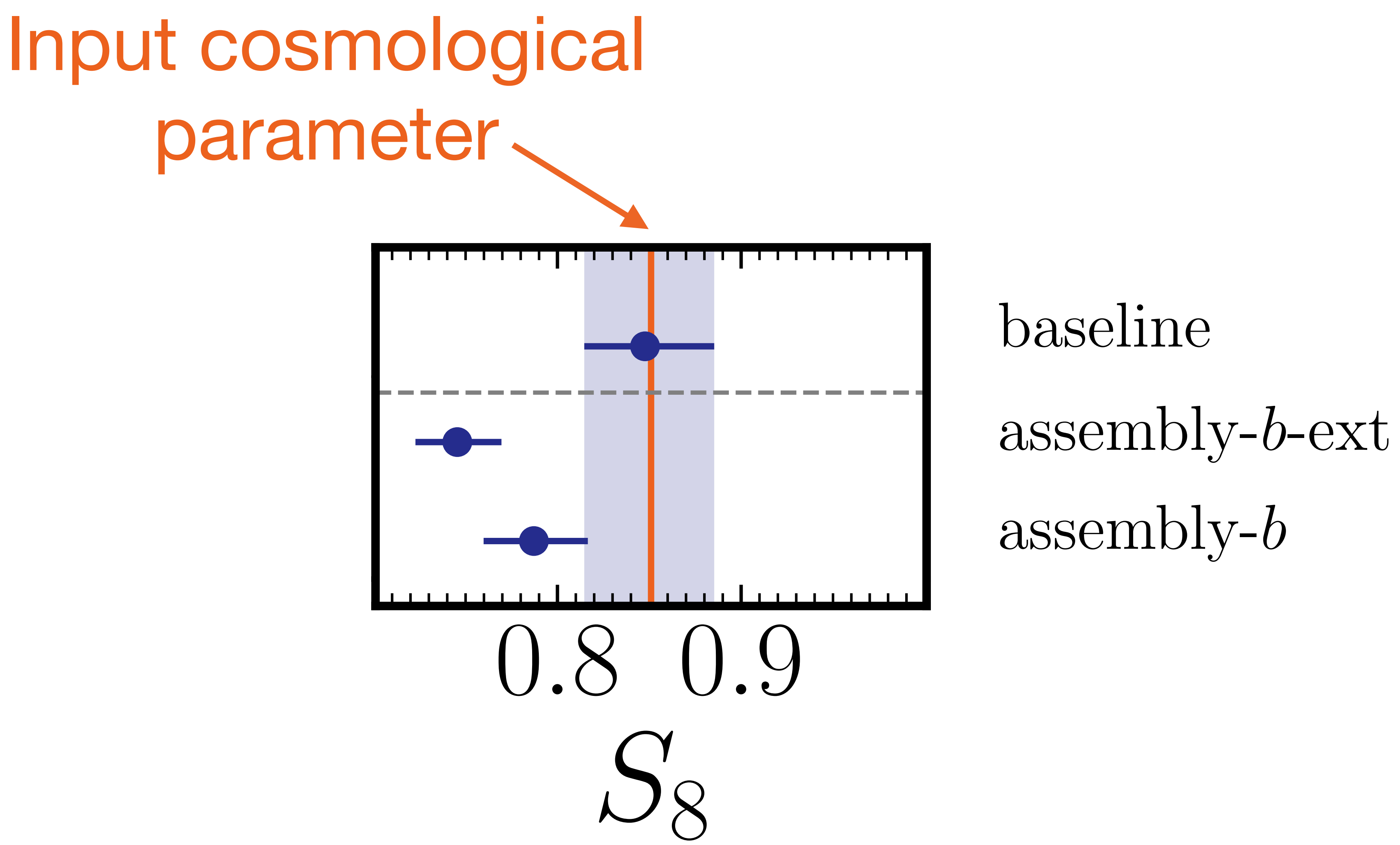
Systematic checks were done **before unblinding**

If we take the $\Omega_{\rm m} \sim 0.3$ slice (e.g., BAO, full shape clustering analysis), our constraint prefers S_8 lower than Planck.

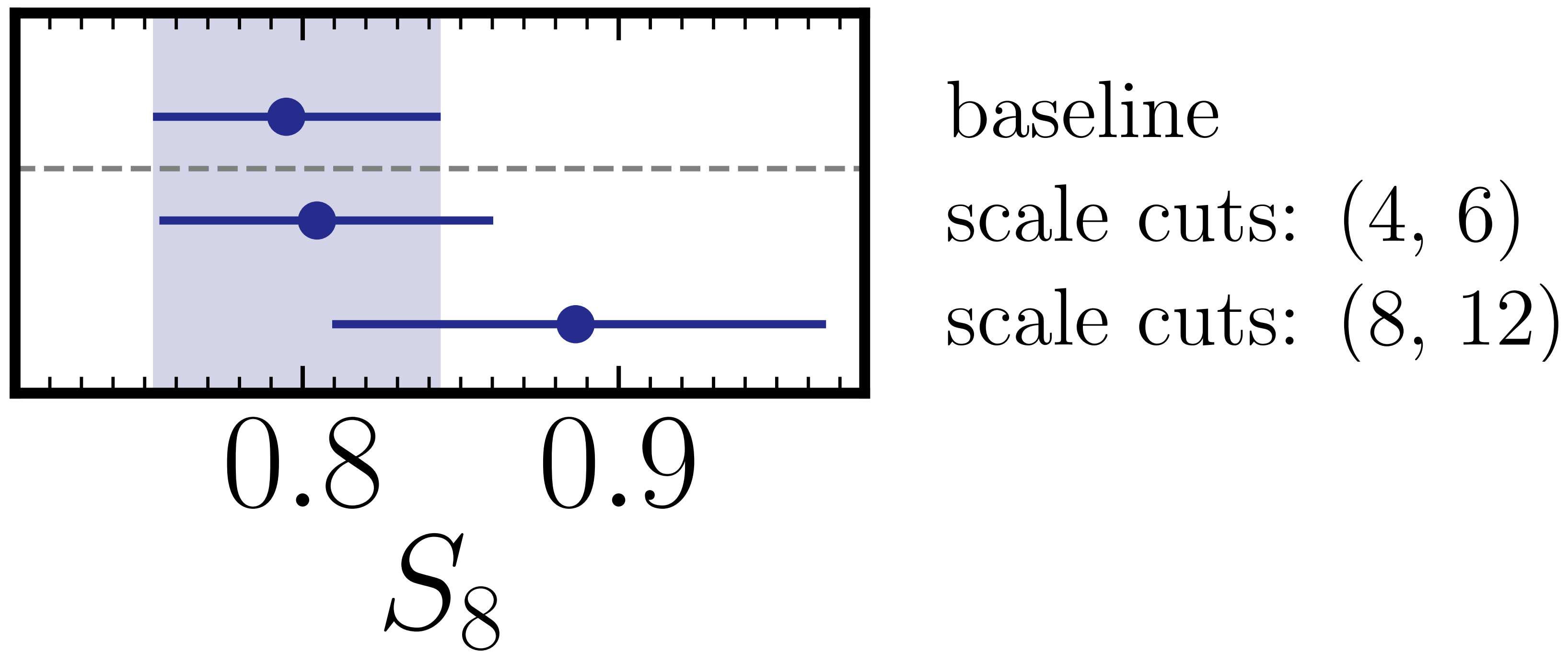
Miyatake et al. (2022b)

No Evidence of Assembly Bias

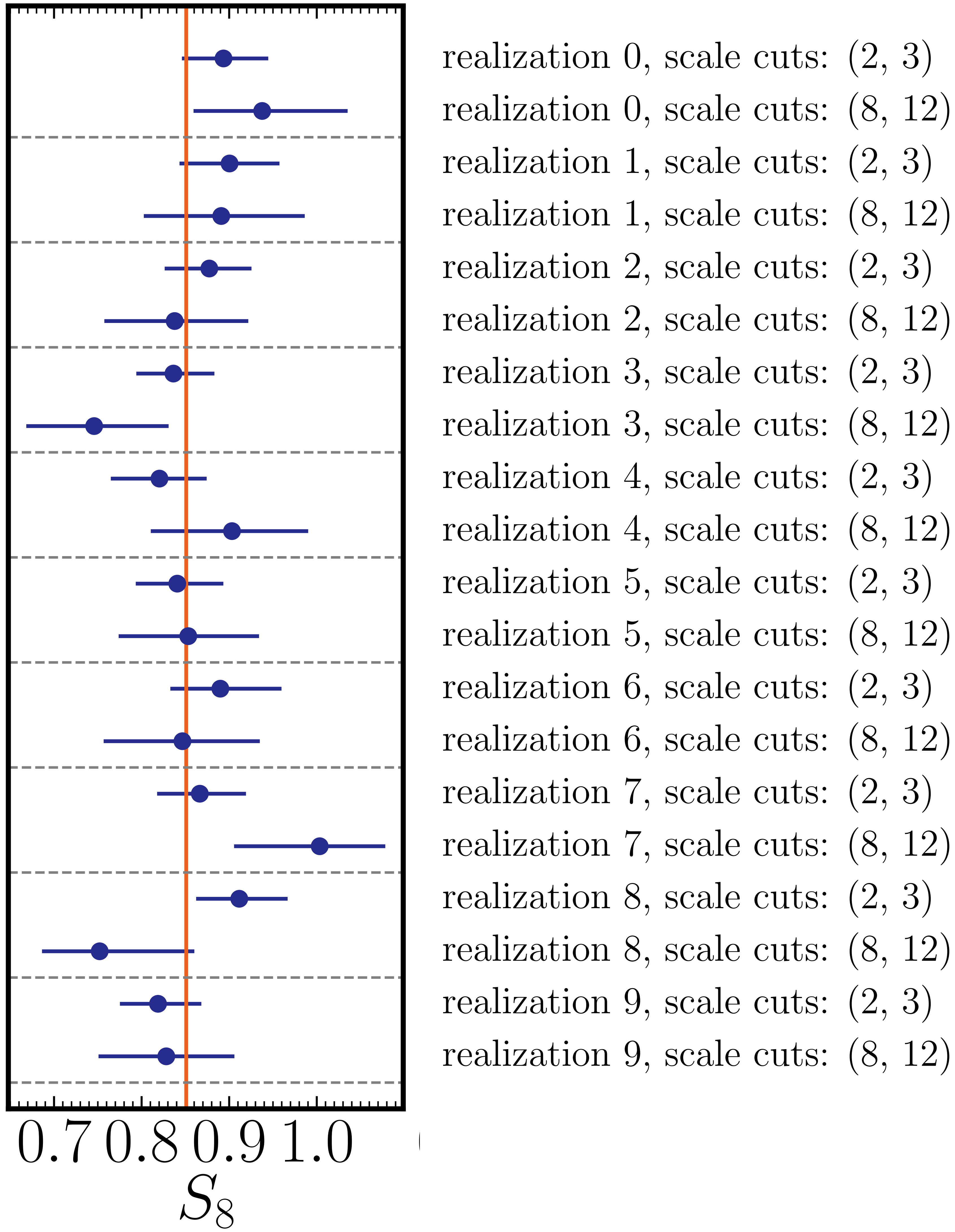
Mocks w/o noise



Real data



Baseline noisy mocks



Miyatake et al. (2022b)

Photo-z Self-calibration

Measurement

$$\Delta\Sigma(R) = \Sigma_{\rm cr}(z_{\rm l}, z_{\rm s}; \Omega_{\rm m})\,\gamma(R)$$

Theory

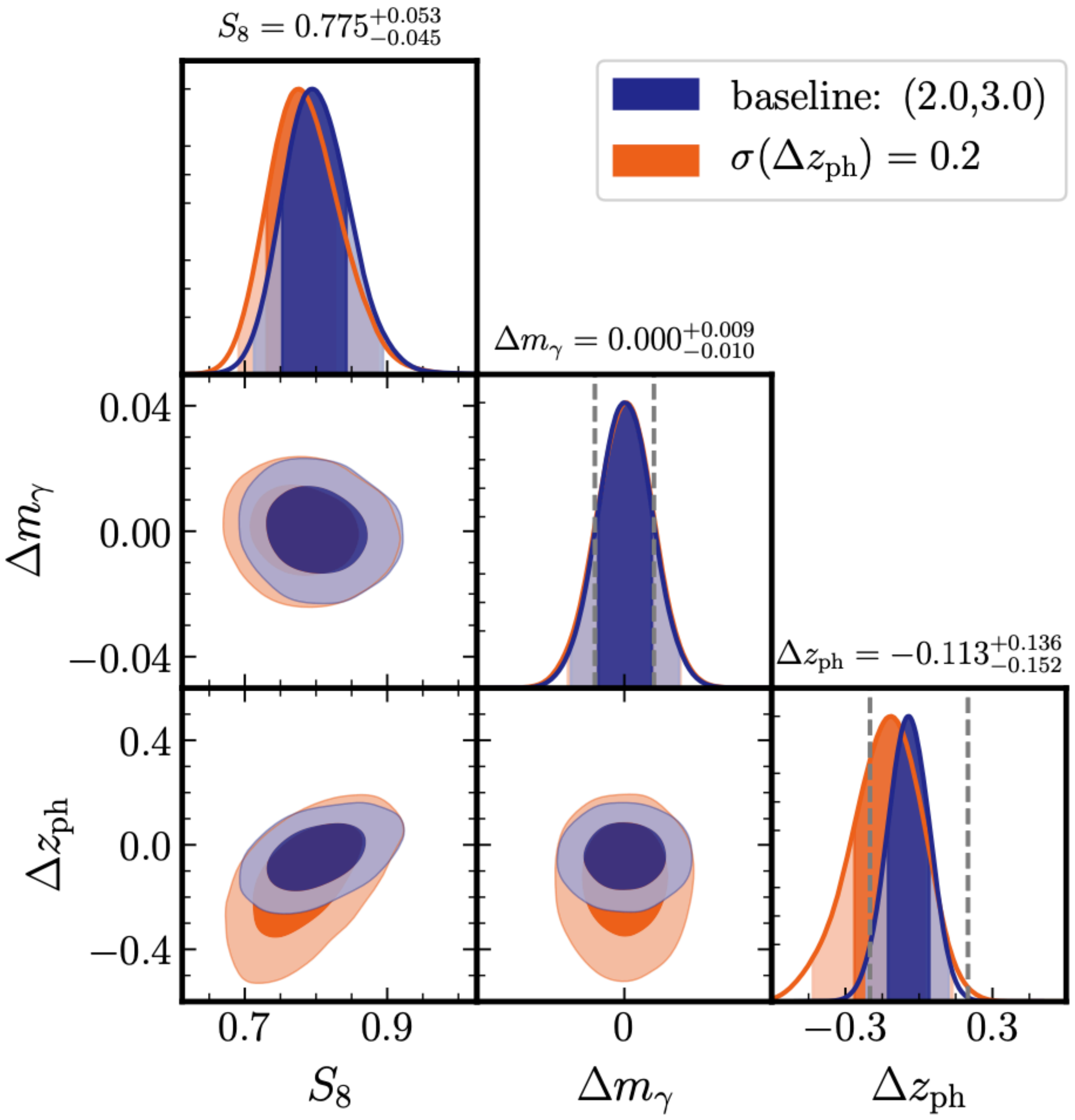
$$\Delta\Sigma(R) = \bar{\rho}_{\rm m0} \int_0^\infty \frac{k^2 dk}{2\pi^2} P_{\rm gm}(k; \sigma_8, \Omega_{\rm m}) J_2(kR)$$

$$\sigma_8(z) = \sigma_8 D_+(z_{\rm l}; \Omega_{\rm m}) / D_+(0; \Omega_{\rm m})$$

- Lensing kernel and growth rate have different redshift and Ω_m dependence.
- If we have multiple robust z_l and a single z_s, we can calibrate z_s.

Oguri & Takada et al. (2013)

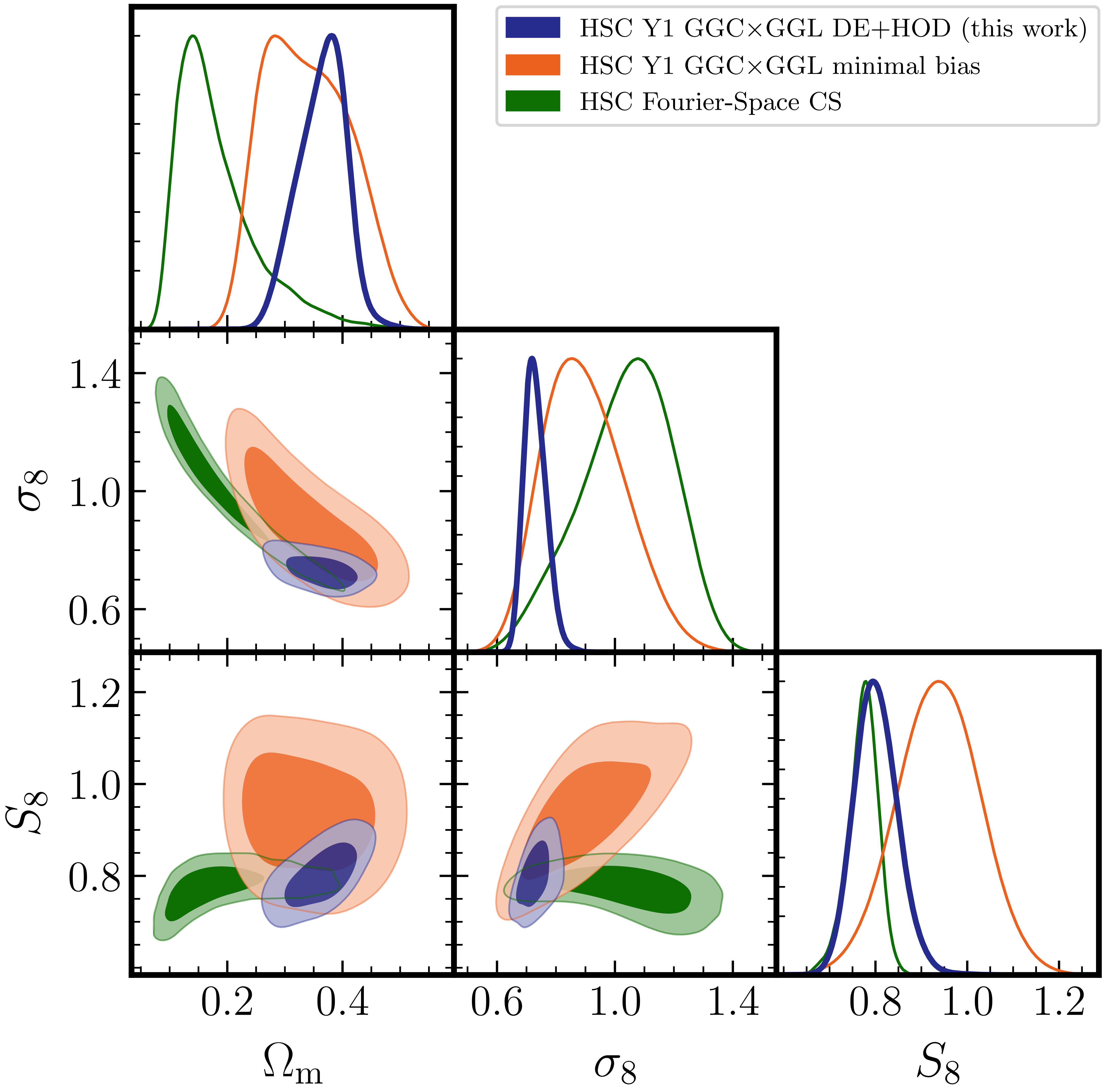
Photo-z Self-calibration



Miyatake et al. (2022b)

Comparison with other HSC-Y1 cosmology analyses

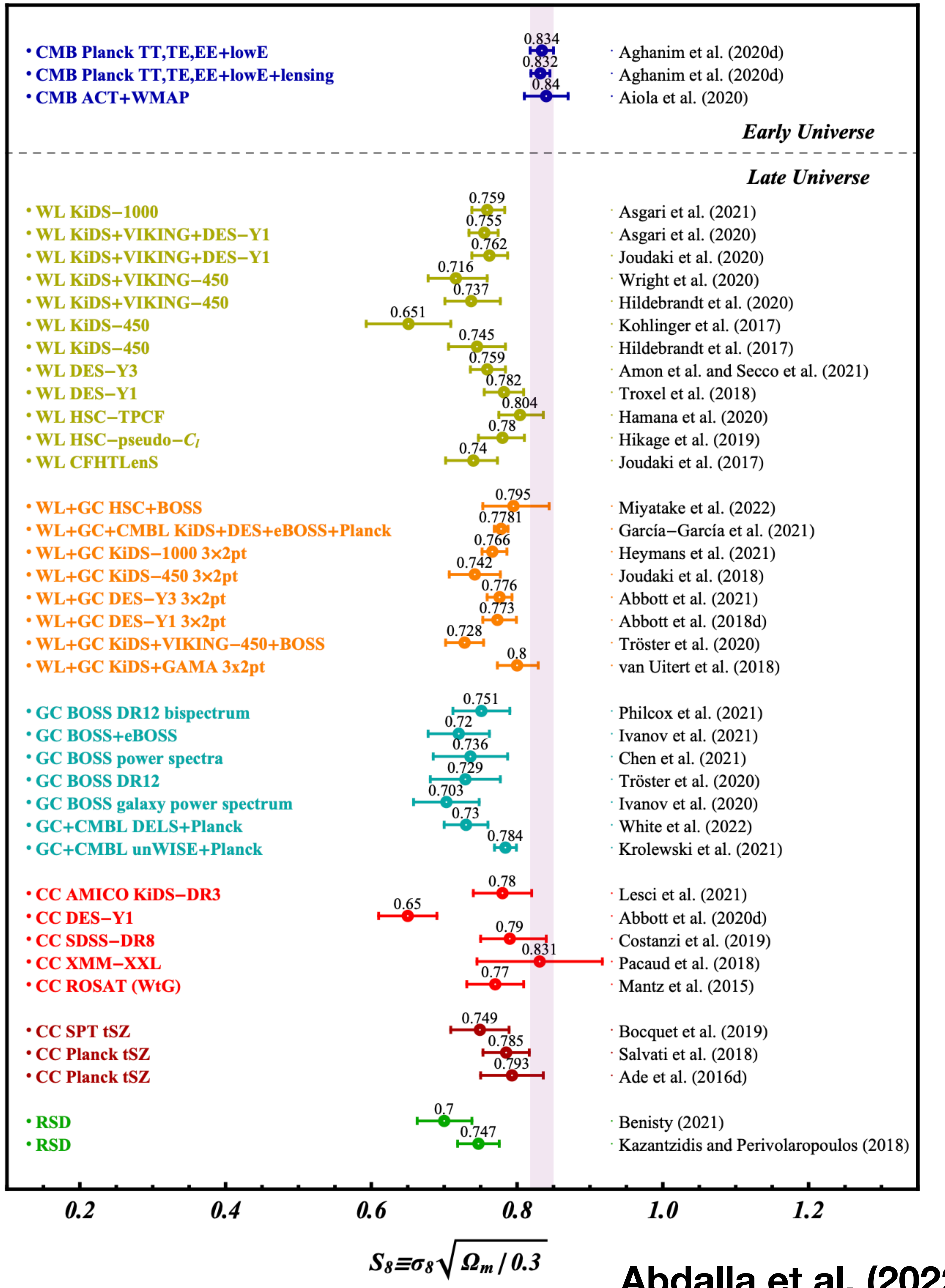
- Consistent with the 2x2pt large scale analyses (Sugiyama et al., 2022).
- Combining with cosmic shear (3x2pt), we can get more stringent constraints.



Miyatake et al. (2022b)

S_8 Tension

Late universe probes (weak lensing, galaxy clustering, cluster count, RSD) consistently yield S8 smaller than an early universe probe (CMB).

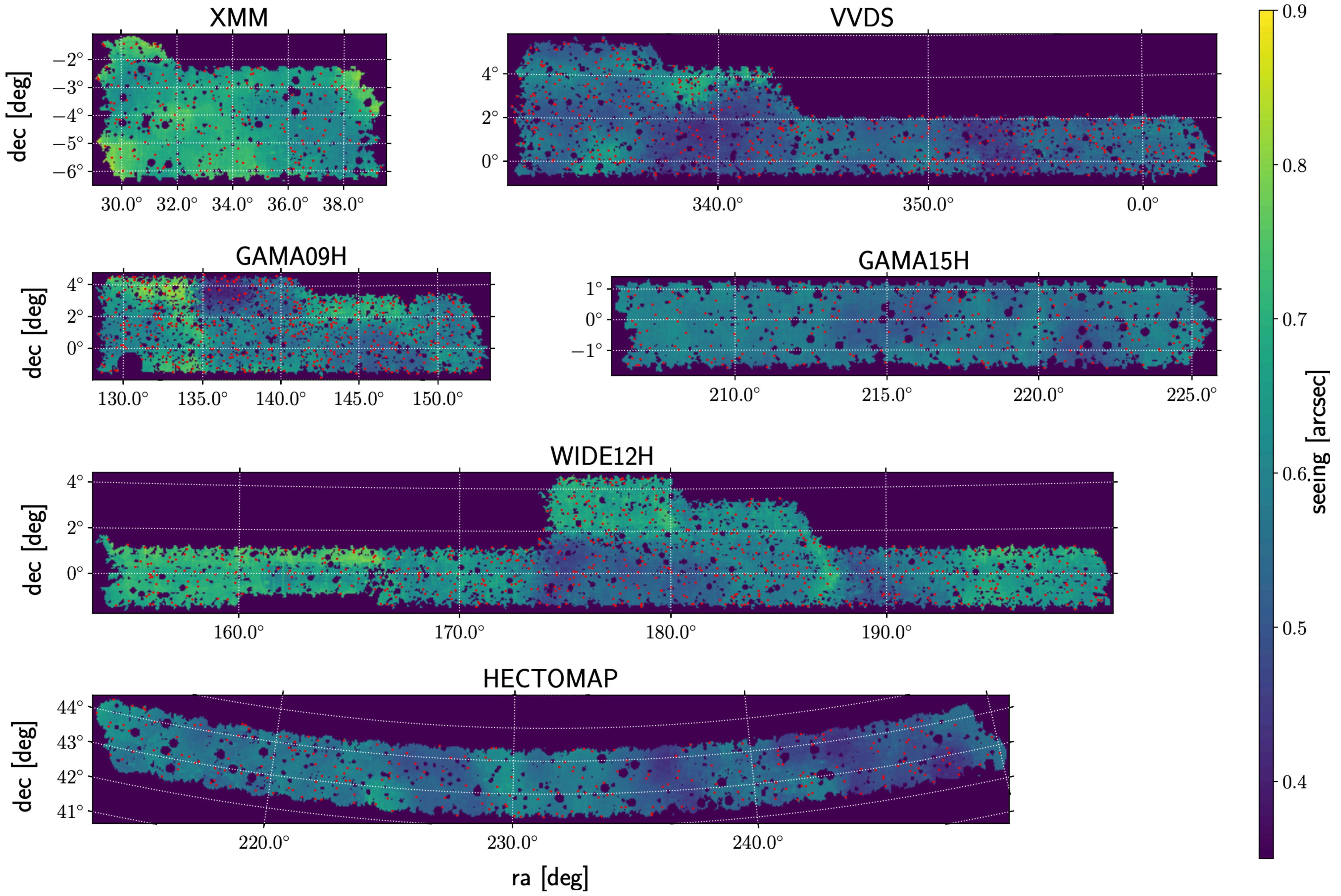


Abdalla et al. (2022)

HSC-Y3 Analysis

HSC-Y3 Shape Catalog

- Construction of Y3 shape catalog is done.
  - Seeing remains ~0.6”
  - Area: 170deg^2 → 430 deg^2.
  - 10^7 galaxies → 3×10^7 galaxies

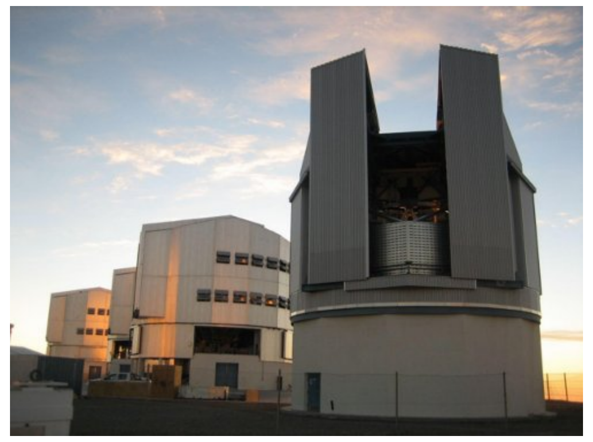


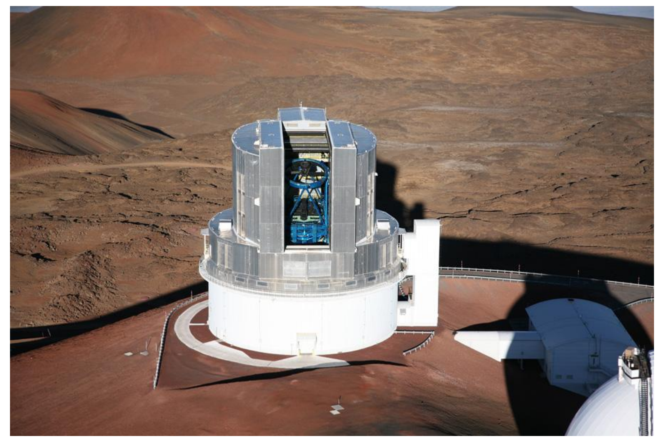
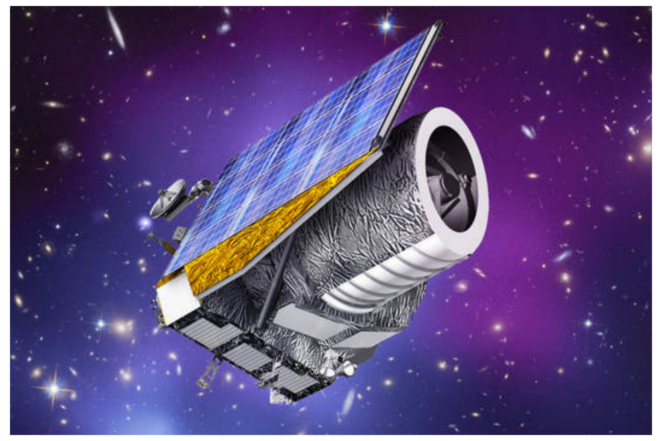
Li, HM, et al. (2022)

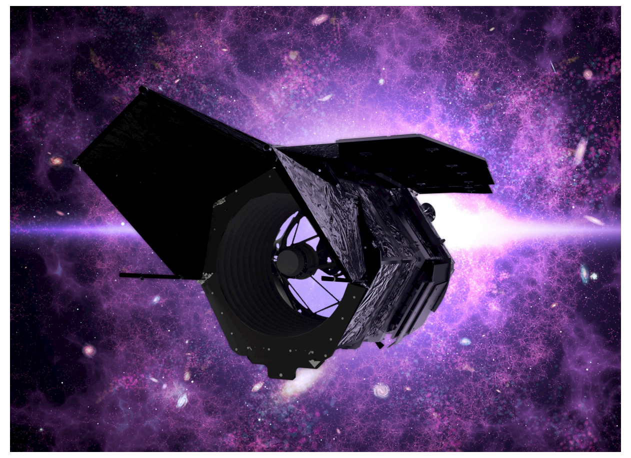
HSC-Y3 Cosmology Analysis

- Cosmic shear in real space (Xiangchong Li)
- Cosmic shear in Fourier space (Roohi Dalal)
- 3x2pt (2x2pt + cosmic shear) analysis
  - Measurements (Surhud More)
  - Large-scale analysis (Sunao Sugiyama)
  - Small-scale analysis (Hironao Miyatake)

Weak Lensing Surveys: Now and Future





	KiDS (Europe)	DES (USA)	Subaru HSC (Japan)	Euclid (Europe)	Rubin Observatory's LSST (USA)	Roman Space Telescope (USA)
Primary Mirror [m]	2.6	4.0	8.2	1.2	8.4	2.4
Galaxy Number Density [arcmin^{-2}]	11	10	25	30	30	50
Survey Area [sq. deg]	1,500	5,000	1,400	15,000	18,000	2,200

All sky ~41,253 [sq. deg]

2010 — 2020 — 2030

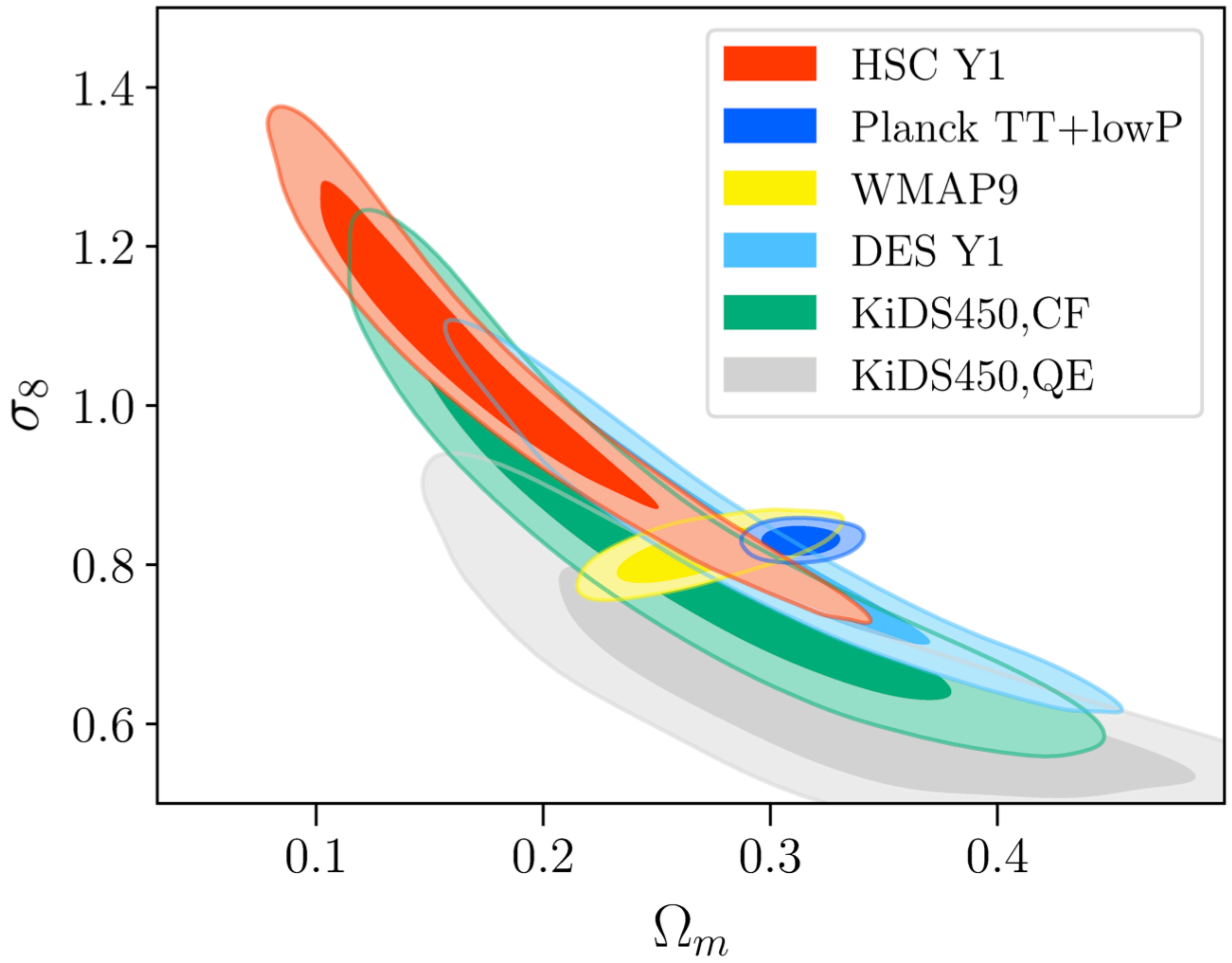
Inspired by E. Krause   Credit: ESO, Fermilab/Reidar Hahn, NAOJ, ESA/C. Carreau, Rubin Obs/NSF/AURA, NASA

Summary

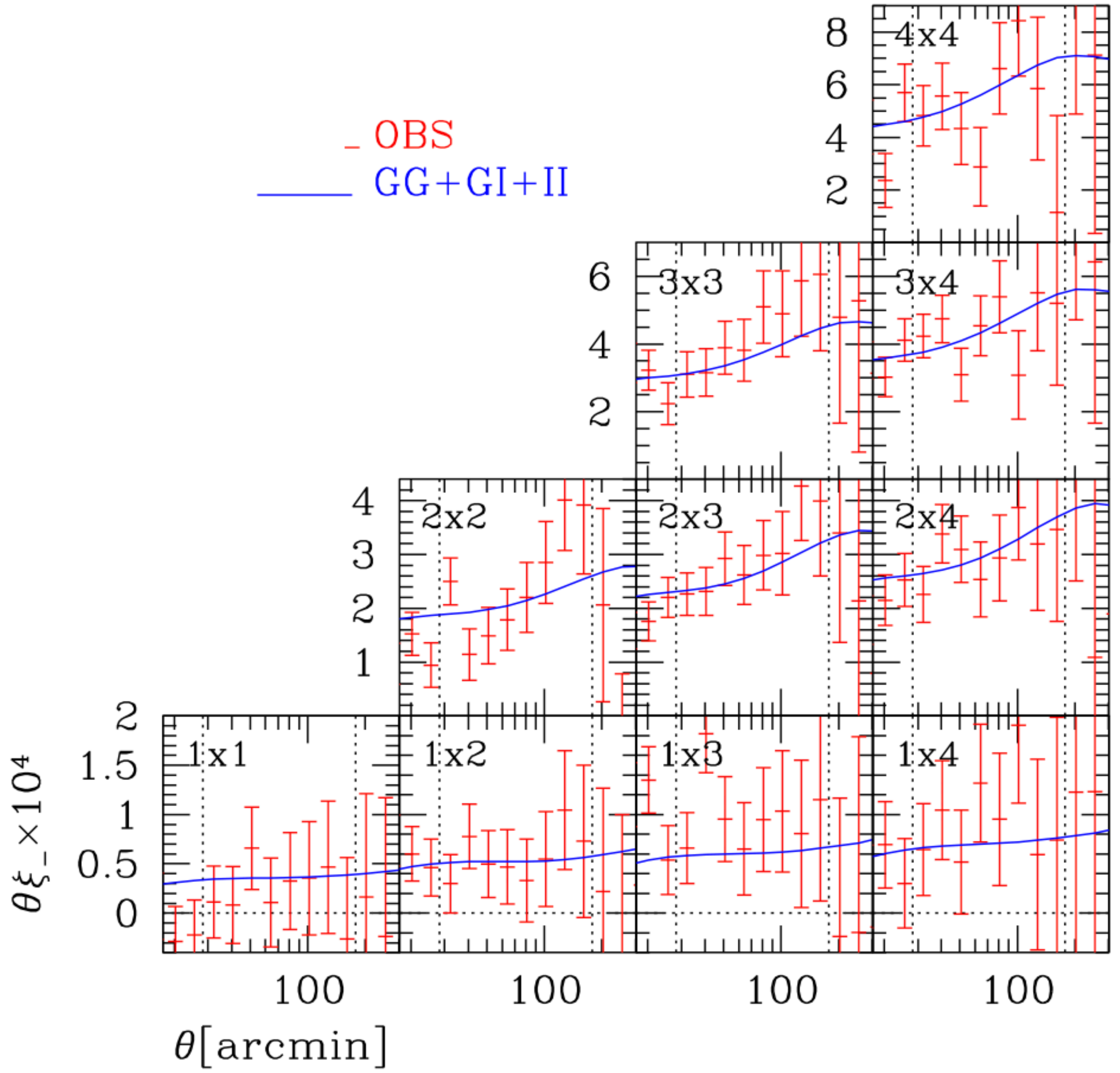
- Subaru HSC is one of the best telescopes to carry out weak lensing cosmology.
- HSC-Y1 cosmology results
  - Cosmic shear
  - Galaxy-galaxy clustering x lensing (2x2pt)
    - Used down to small scales using robust model by dark emulator x HOD.
  - S_8 tension exists?
- HSC-Y3 cosmology analysis
  - Cosmic shear x galaxy-galaxy clustering x lensing (3x2pt) analysis is going on!
- Combining 3D galaxy-galaxy clustering (full-shape and IA) with galaxy-galaxy lensing will have much more constraining power.

Backup Slides

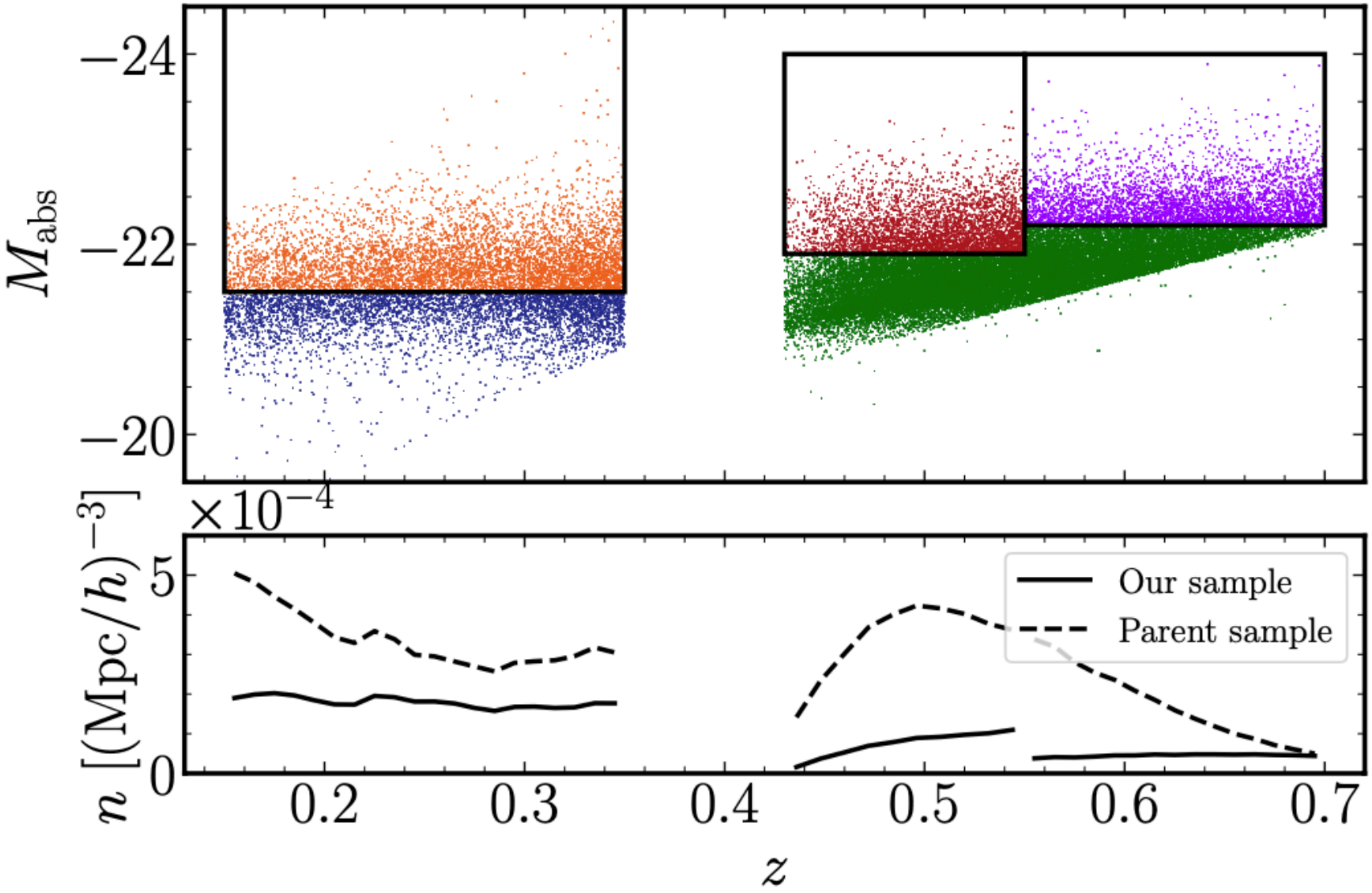
Fourier-space CS σ_8-Ω_m



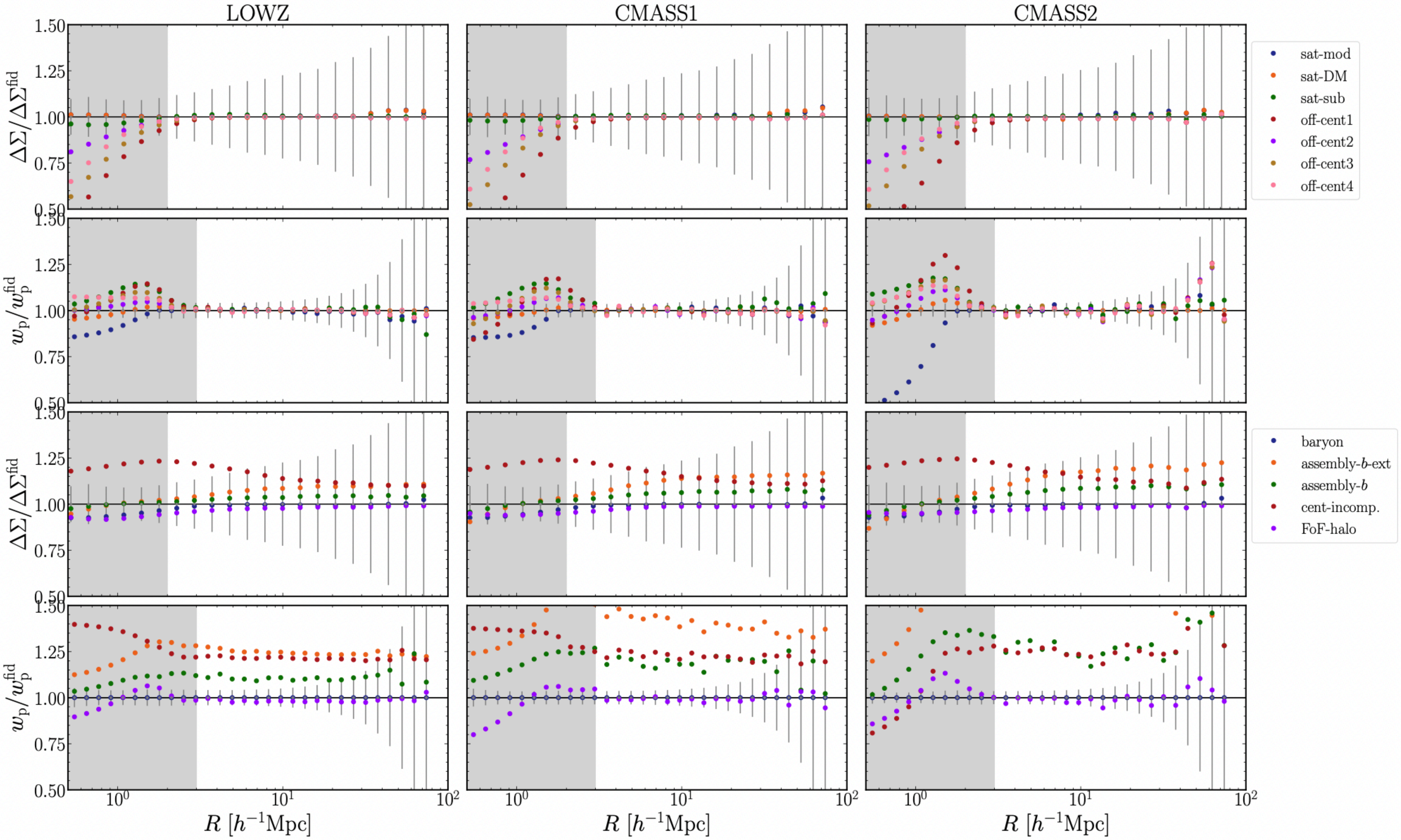
Real-space ξ-



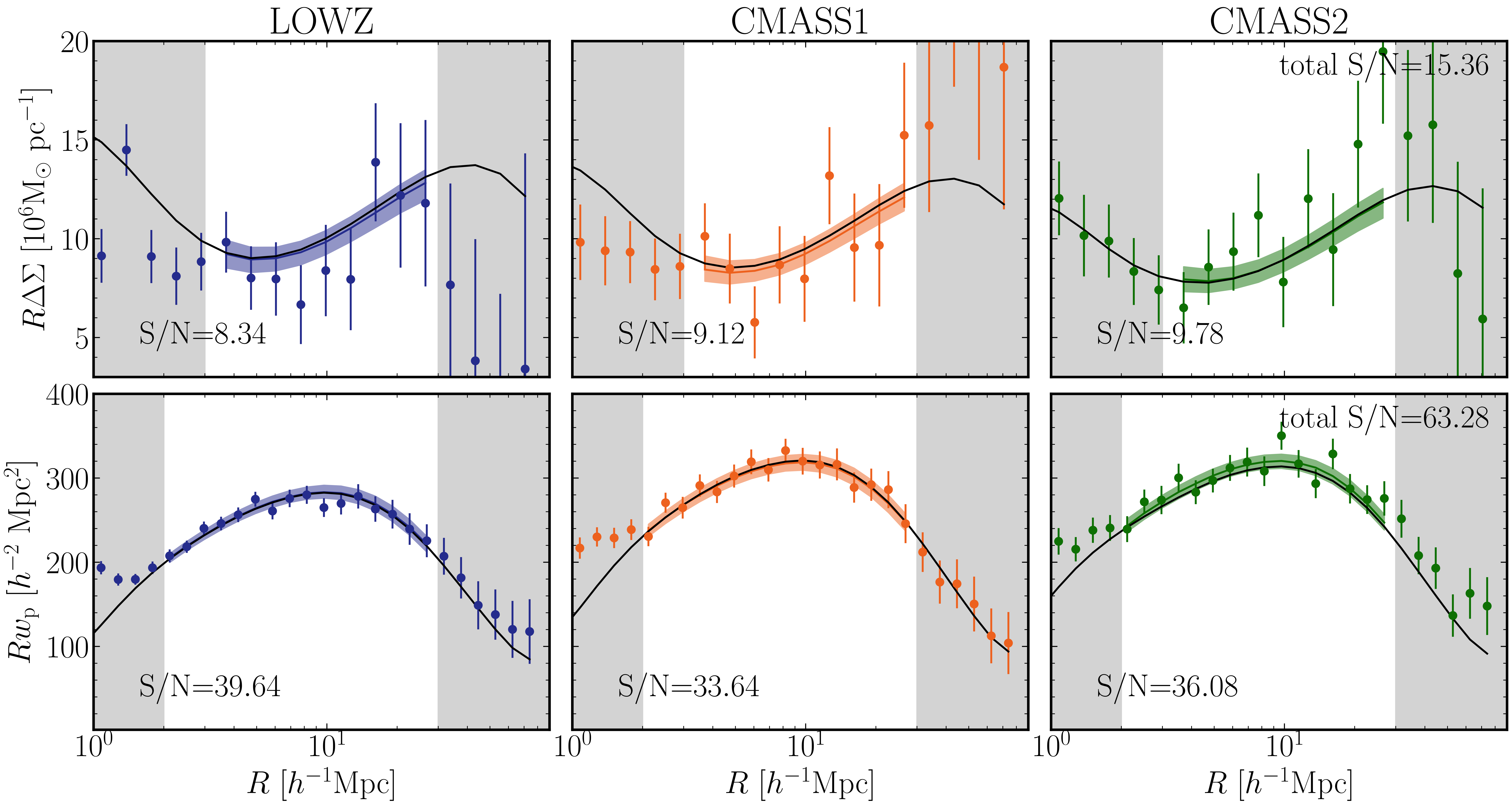
OBS
GG+GI+II
4x4
3x3
3x4
2x2
2x3
2x4
1x1
1x2
1x3
1x4
$\theta\xi_{-} \times 10^4$
θ[arcmin]
100



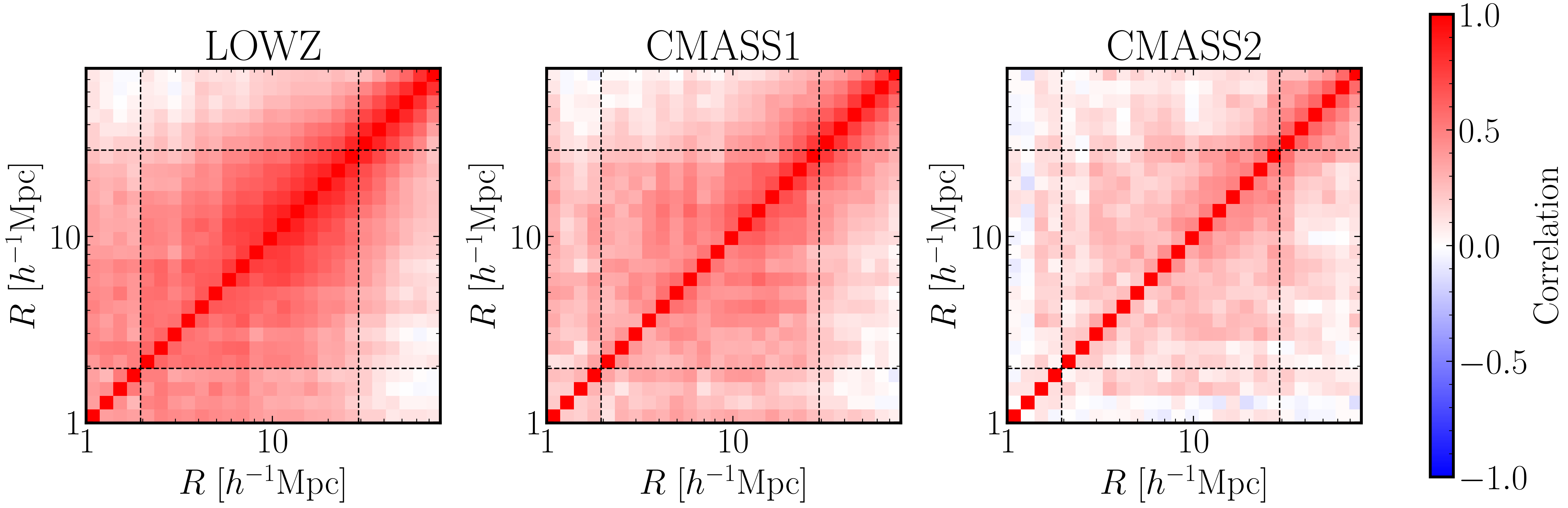
$M_{\rm abs}$
−24
−22
−20
$n\ [(\mathrm{Mpc}/h)^{-3}]$
$\times 10^{-4}$
5
0
Our sample
Parent sample
0.2
0.3
0.4
0.5
0.6
0.7
z

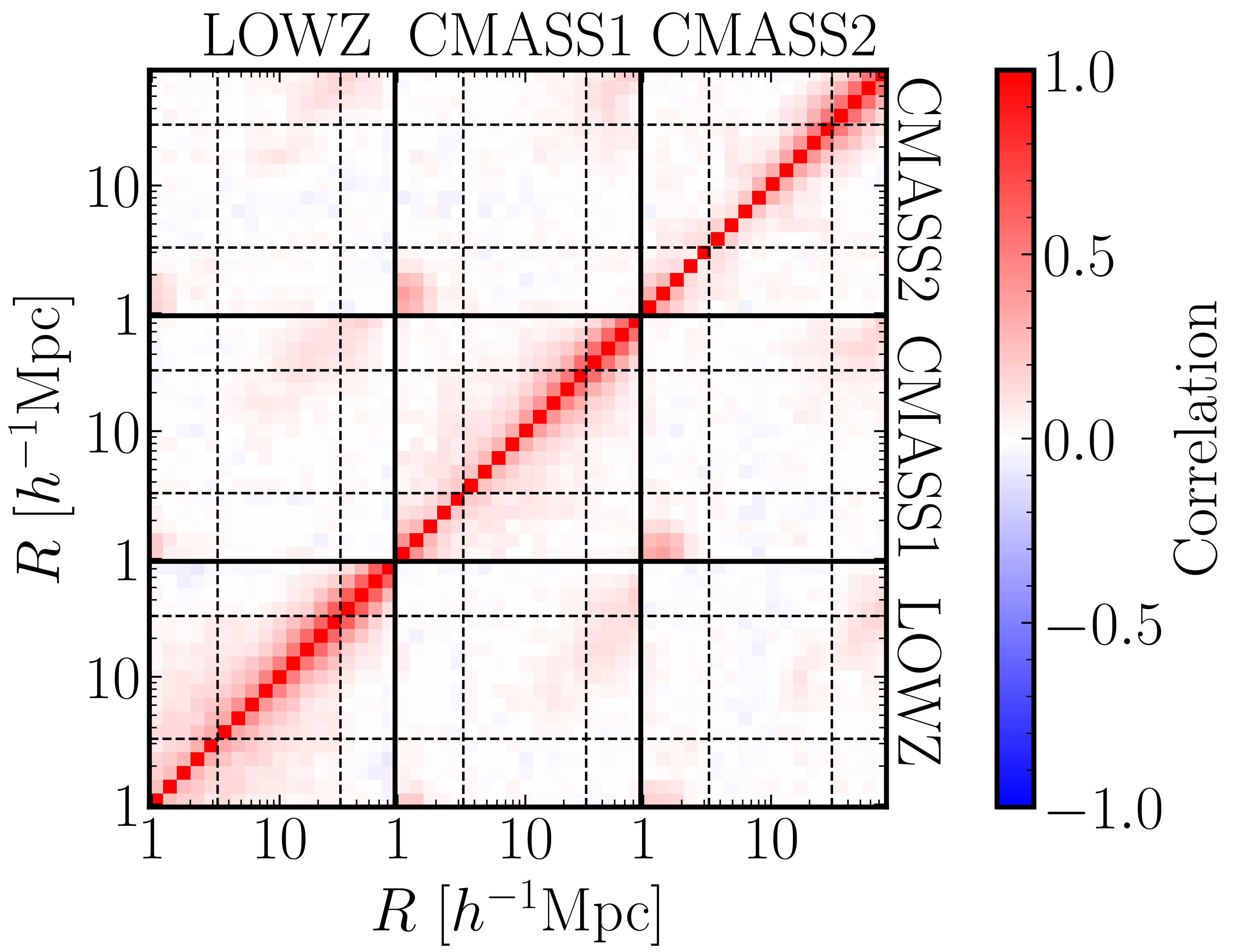


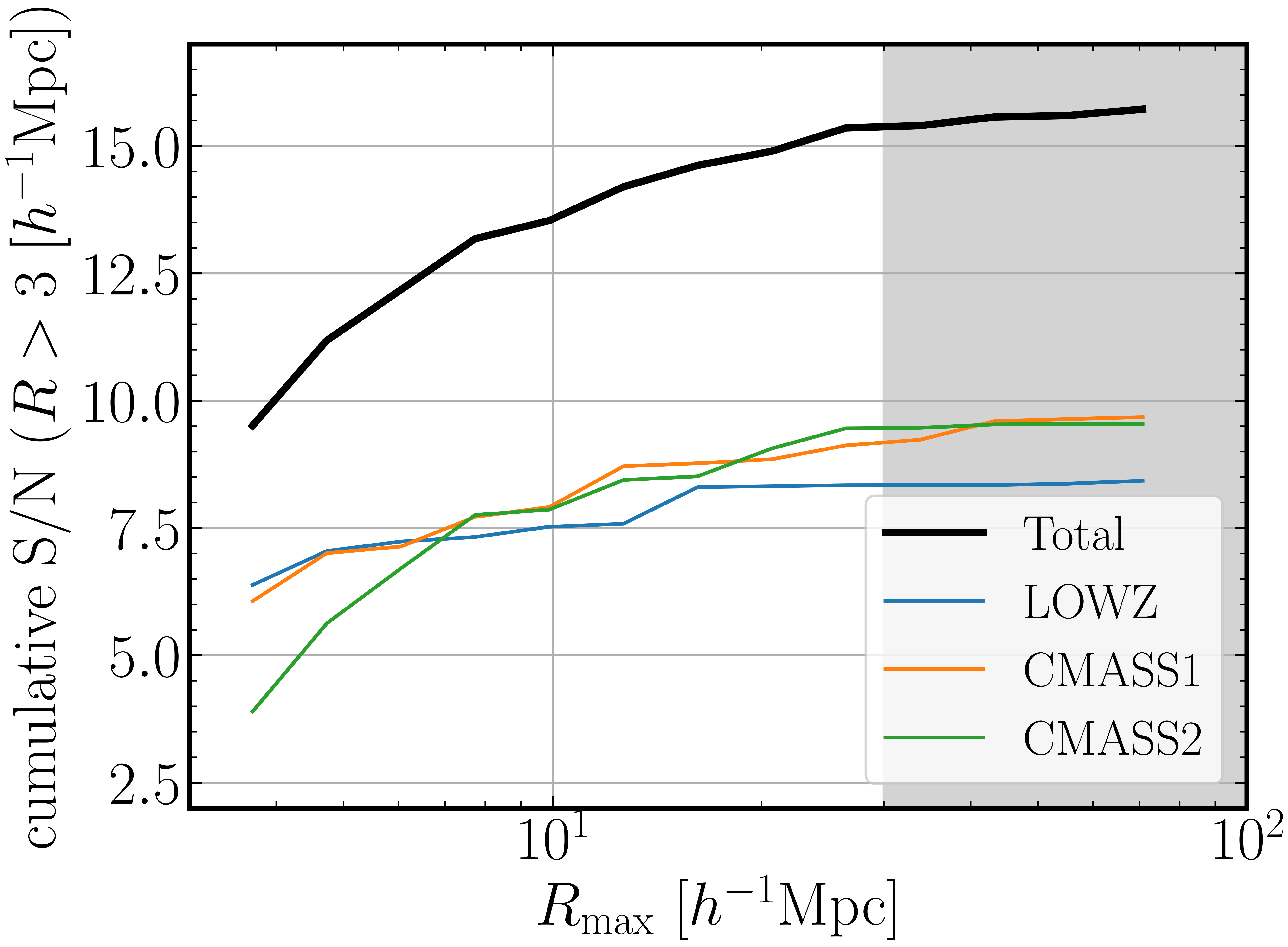
LOWZ
CMASS1
CMASS2
$\Delta\Sigma/\Delta\Sigma^{\rm fid}$
$w_{\rm p}/w_{\rm p}^{\rm fid}$
sat-mod
sat-DM
sat-sub
off-cent1
off-cent2
off-cent3
off-cent4
baryon
assembly-b-ext
assembly-b
cent-incomp.
FoF-halo
R [h^{-1}Mpc]



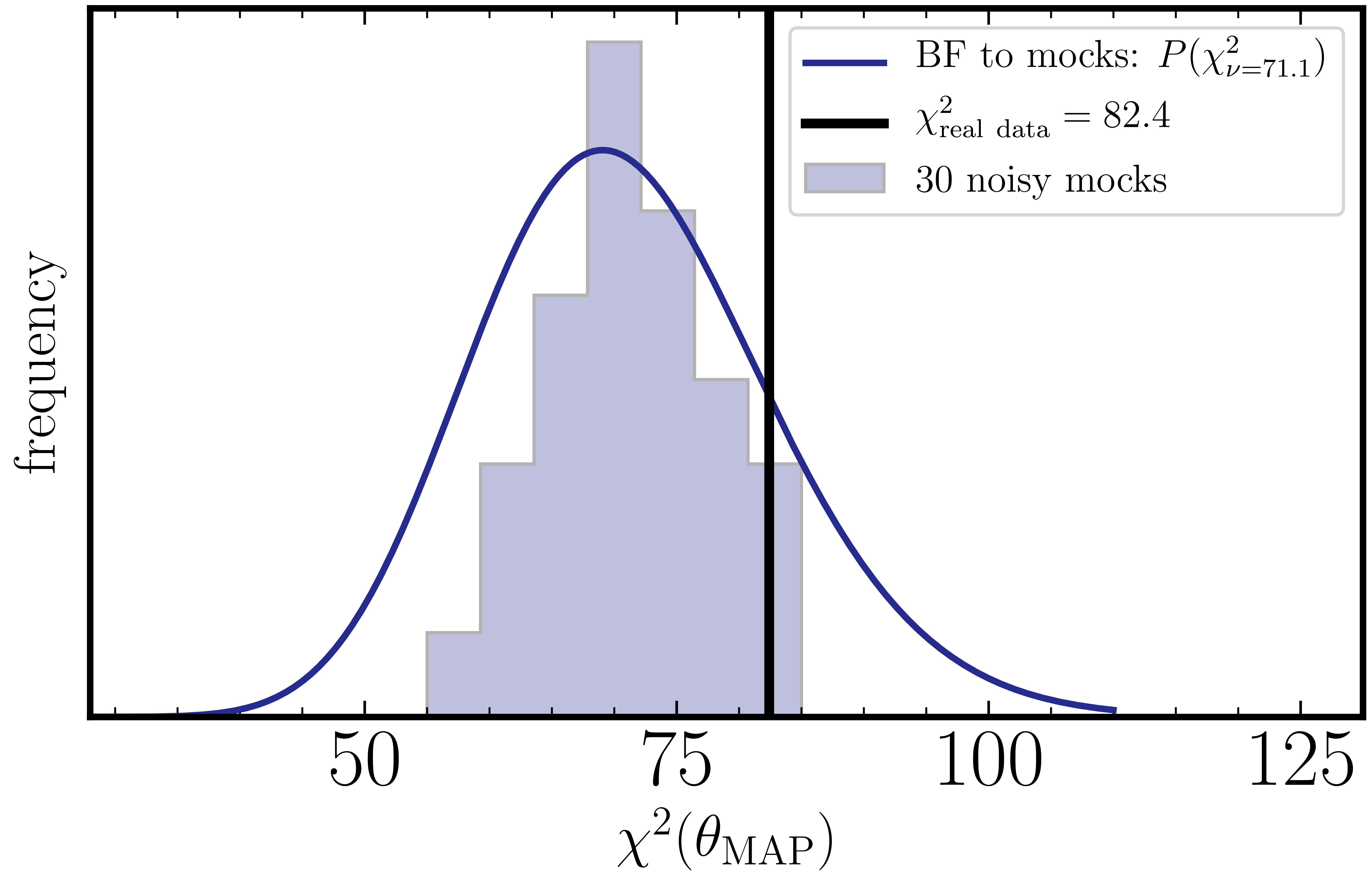
LOWZ
CMASS1
CMASS2
total S/N=15.36
S/N=8.34
S/N=9.12
S/N=9.78
total S/N=63.28
S/N=39.64
S/N=33.64
S/N=36.08
$R\Delta\Sigma\ [10^6 \mathrm{M}_\odot\ \mathrm{pc}^{-1}]$
$Rw_\mathrm{p}\ [h^{-2}\ \mathrm{Mpc}^2]$
$R\ [h^{-1}\mathrm{Mpc}]$


LOWZ
CMASS1
CMASS2
R [h^{-1}Mpc]
1
10
Correlation
1.0
0.5
0.0
−0.5
−1.0

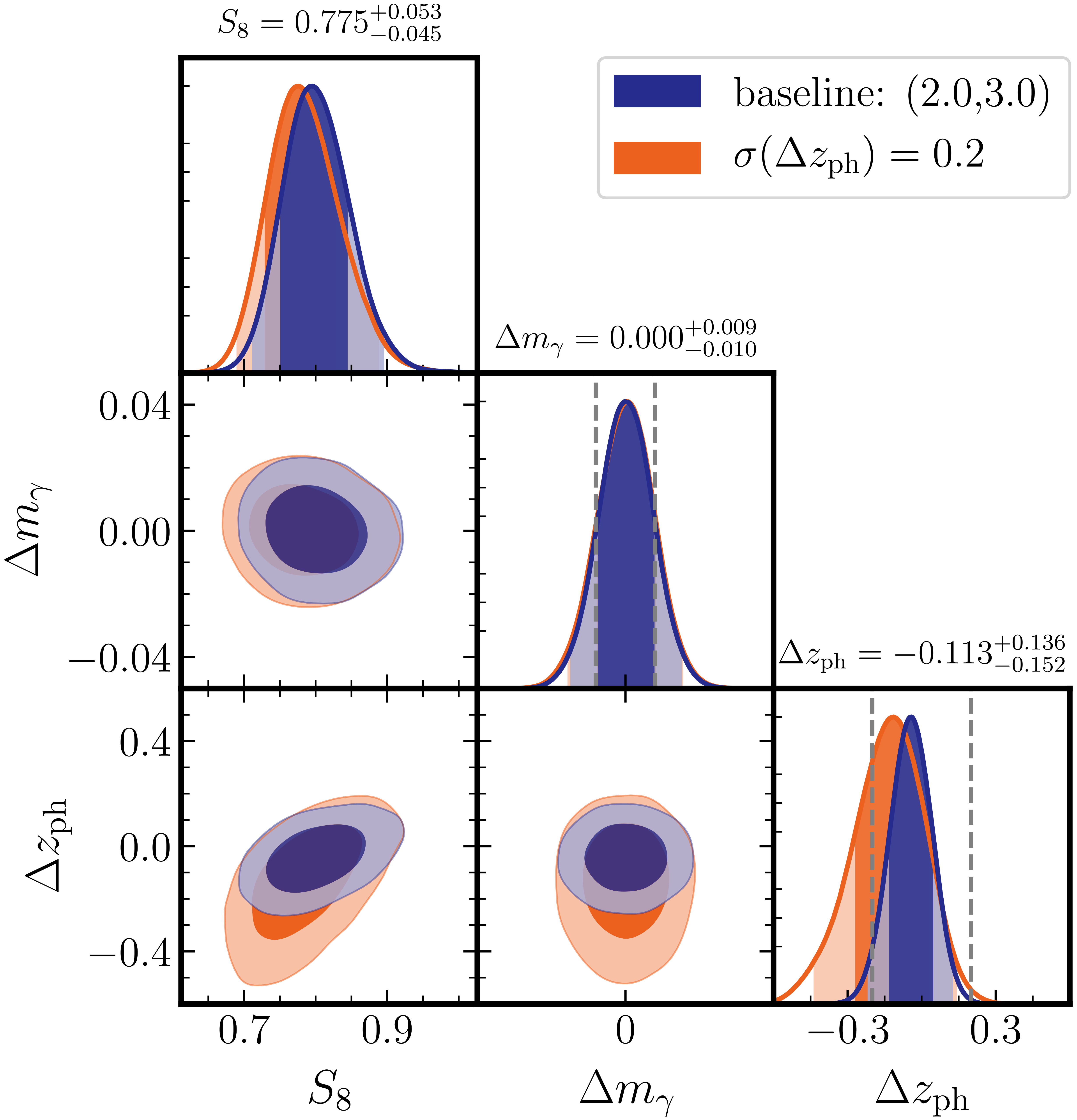

LOWZ
CMASS1
CMASS2
R [h^{-1}Mpc]
1
10
Correlation
1.0
0.5
0.0
−0.5
−1.0



cumulative S/N ($R > 3$ [h^{-1}Mpc])
15.0
12.5
10.0
7.5
5.0
2.5
10^1
10^2
$R_{\rm max}$ [h^{-1}Mpc]
Total
LOWZ
CMASS1
CMASS2



BF to mocks: $P(\chi^2_{\nu=71.1})$
$\chi^2_{\rm real\ data} = 82.4$
30 noisy mocks
frequency
50
75
100
125
$\chi^2(\theta_{\rm MAP})$



$S_8 = 0.775^{+0.053}_{-0.045}$
baseline: (2.0,3.0)
$\sigma(\Delta z_{\rm ph}) = 0.2$
$\Delta m_\gamma = 0.000^{+0.009}_{-0.010}$
$\Delta z_{\rm ph} = -0.113^{+0.136}_{-0.152}$
Δm_γ
0.04
0.00
−0.04
$\Delta z_{\rm ph}$
0.4
0.0
−0.4
0.7
0.9
0
−0.3
0.3
S_8
Δm_γ
$\Delta z_{\rm ph}$