Windows on the Universe @ICISE, 8 Aug 2023

HSC Year 3 Weak Lensing Cosmology Results

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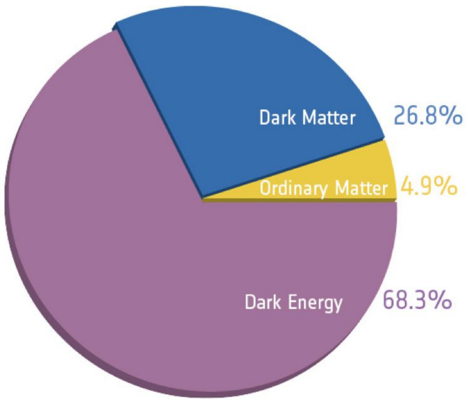
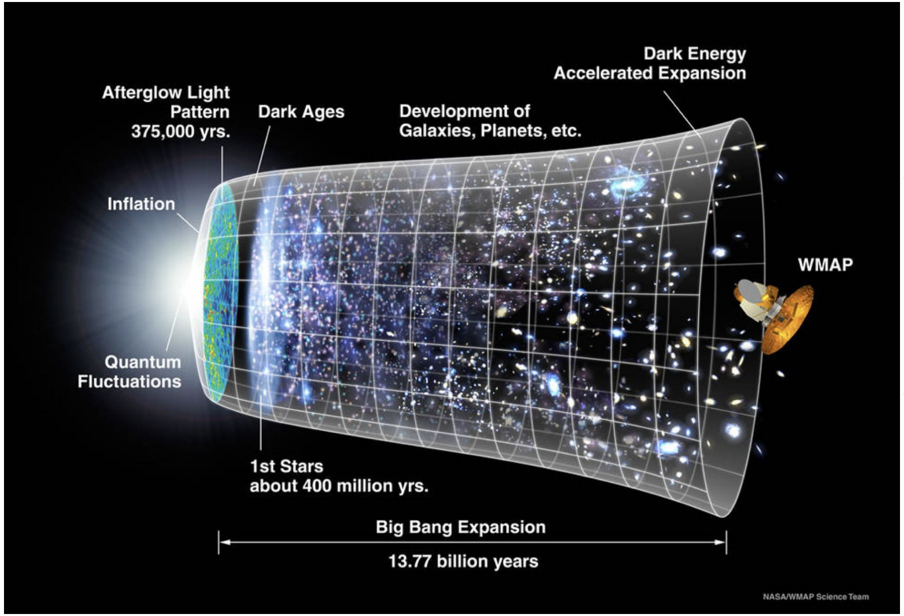
on behalf of The Hyper Suprime-Cam Subaru Strategic Program Collaboration

Observational cosmology

ΛCDM model: Standard model of the universe



credit: NASA



- Standard model of the universe
  - Cosmology constant (Λ) + Cold Dark Matter (CDM)
  - Inflation seeds fluctuation → Structure formation
- CMB, accelerating expansion (SNe), galaxy clustering
- ***Precision cosmology***: Determining cosmo param at percent level.

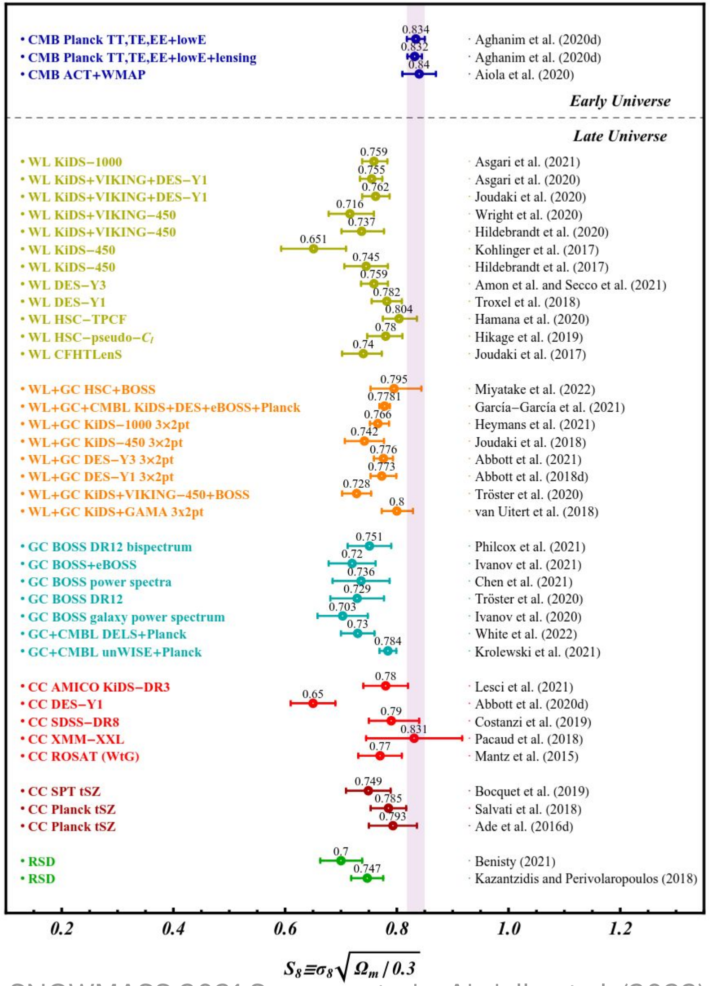
Testing ΛCDM with S_8

$$S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$$

- σ_8: Clumpiness of cosmic structure today.
- Ω_m: Energy density of matter (incl. dark matter).

S_8 tension?

Most **large scale structure probes** (weak lensing, galaxy clustering, galaxy clusters, etc...) prefer smaller S_8 compared to **CMB**, if we assume ΛCDM is correct.

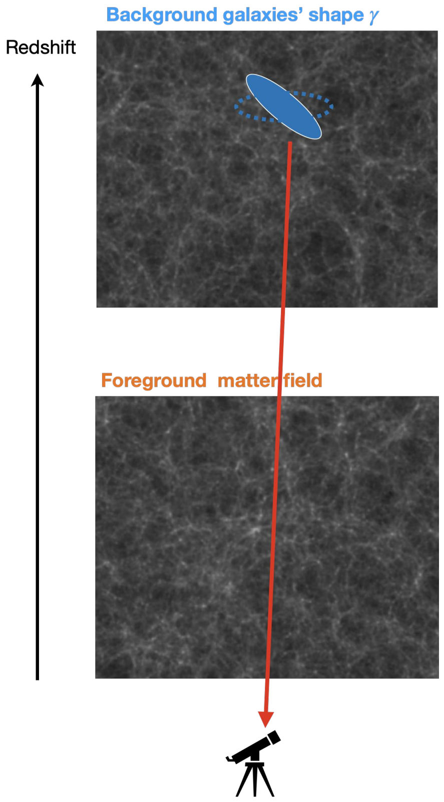


SNOWMASS 2021 Summer study: Abdalla et al. (2022)

CMB

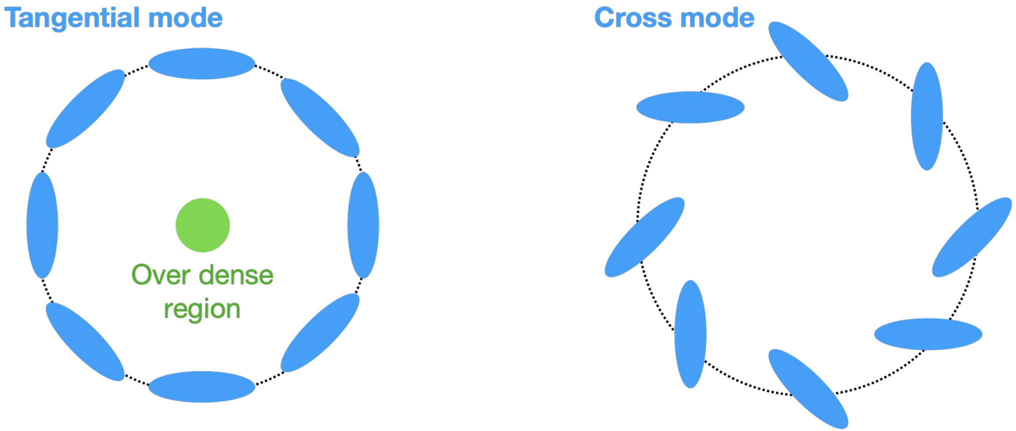
Large Scale Structure (LSS)

Gravitational weak lensing



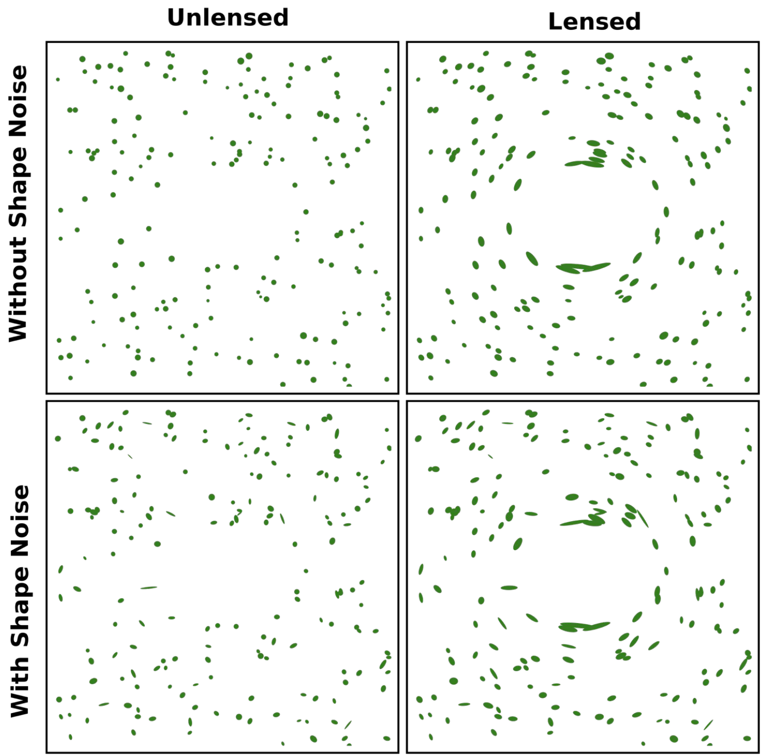
The shape distortion of background galaxy by the gravitational lensing effect by foreground matter distribution

$$\gamma \propto \Omega_\mathrm{m} \int \mathrm{d}z_\mathrm{l} \frac{D_A(z_\mathrm{l}) D_A(z_\mathrm{l}, z_\mathrm{s})}{D_A(z_\mathrm{s})} \delta_\mathrm{m} \propto \Omega_\mathrm{m} \sigma_8$$



Weak lensing gives coherent **tangential mode**
→ the foreground matter distribution

Statistical approach of weak lensing



By TallJimbo (Jim Bosch@Princeton)

$$\gamma \propto \Omega_\mathrm{m} \int \mathrm{d}z_\mathrm{l} \frac{D_A(z_\mathrm{l}) D_A(z_\mathrm{l}, z_\mathrm{s})}{D_A(z_\mathrm{s})} \delta_\mathrm{m}$$

Weak lensing signal below galaxy's intrinsic shape ellipticity

$$\gamma_{obs} = \gamma + \varepsilon_{int},\ \gamma \sim 0.01 \ll \varepsilon_{int} = 0.2$$

We can suppress the intrinsic shape term by using many galaxies (**statistics**!)

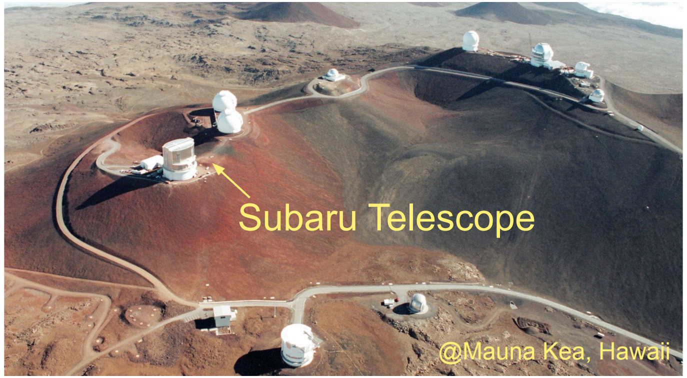
$$\gamma > \varepsilon/\mathrm{sqrt}(N)$$

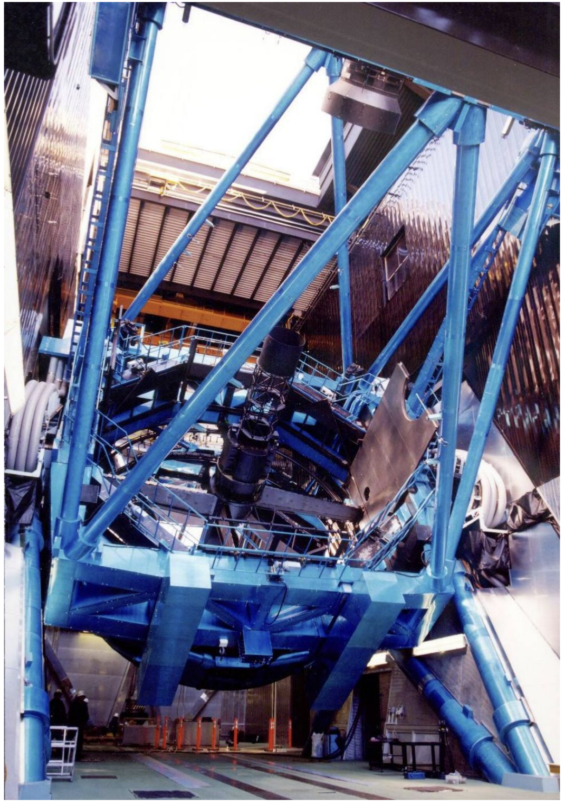
We will use the summary statistics of *two point correlation functions (2PCFs).*

Subaru Hyper Suprime-Cam (HSC)

- Wide FOV: 1.5 deg. Diameter
- Huge light-collecting power: 8.2m primary mirror
- Superb image quality: seeing~0.6”

HSC is one of the best “weak lensing machines” in the world.





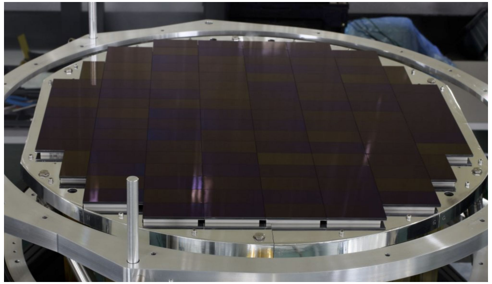
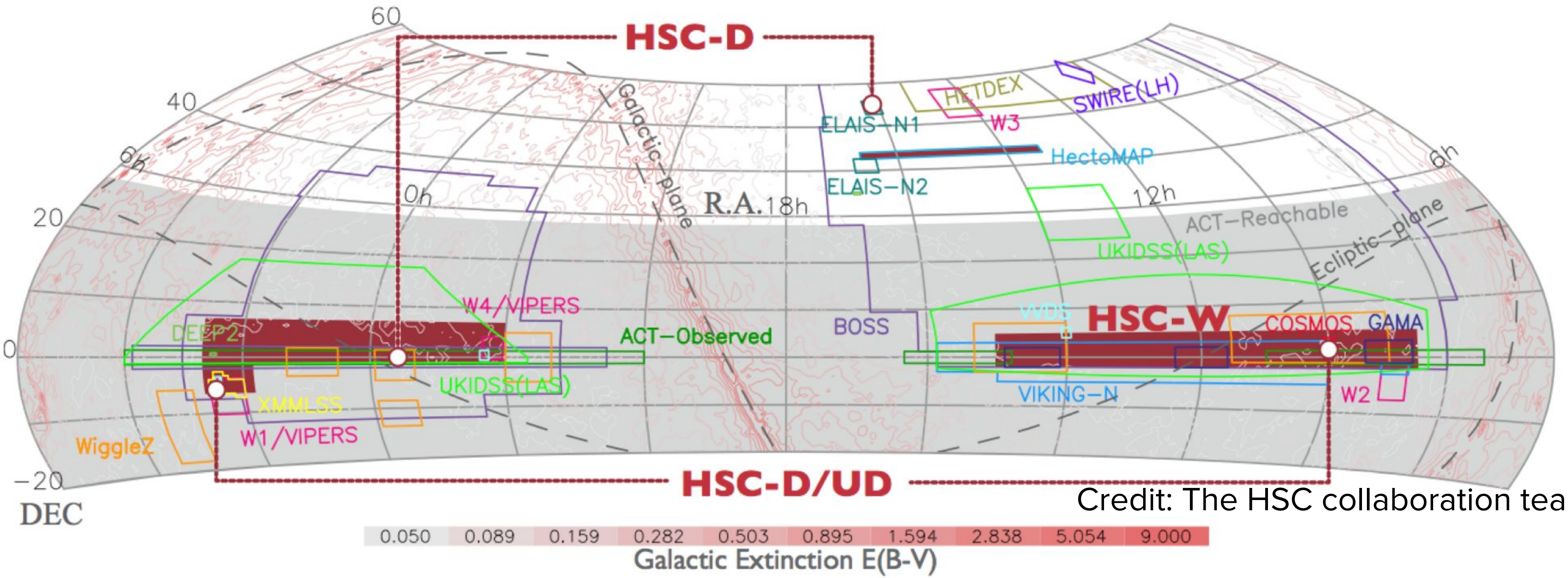


Photo credit: NAOJ / HSC Project

HSC-SSP: Subaru Strategic Program

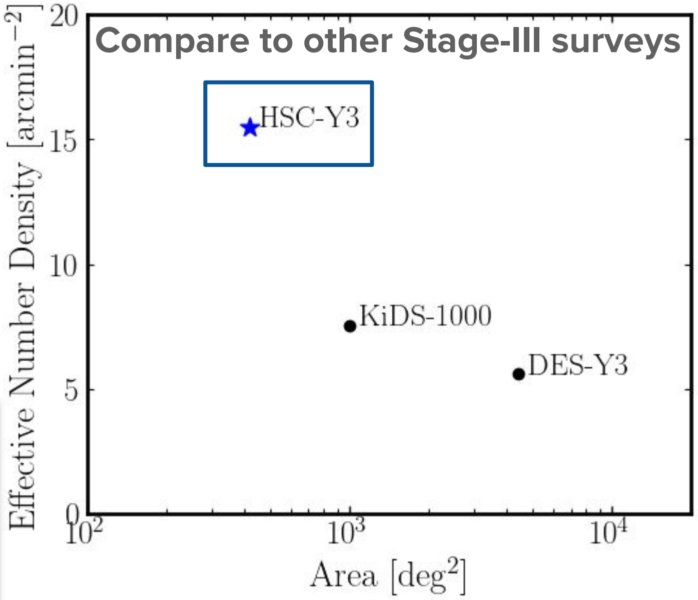


Credit: The HSC collaboration team

- Wide Layer (~1,100 deg^2, grizy, i_{lim}~26) is designed for weak lensing cosmology.
- Overlaps with other major surveys (SDSS/BOSS, ACT, VIKING, GAMA, VVDS, etc...).
- The survey started in 2014 and was completed in 2021.
- **In this talk, we will give results from the data taken until April 2019 (416 deg^2).**

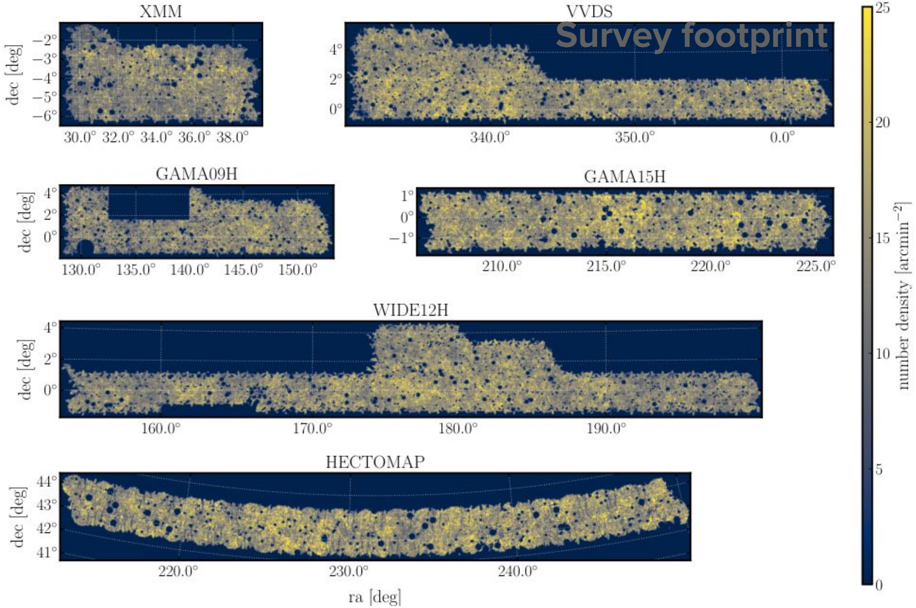
HSC-Y3 shape catalog

1. We measure shapes of 25 million galaxies;
2. The shear estimation is tested and calibrated with realistic image simulations;
3. We correct for PSF systematics in estimated shapes.

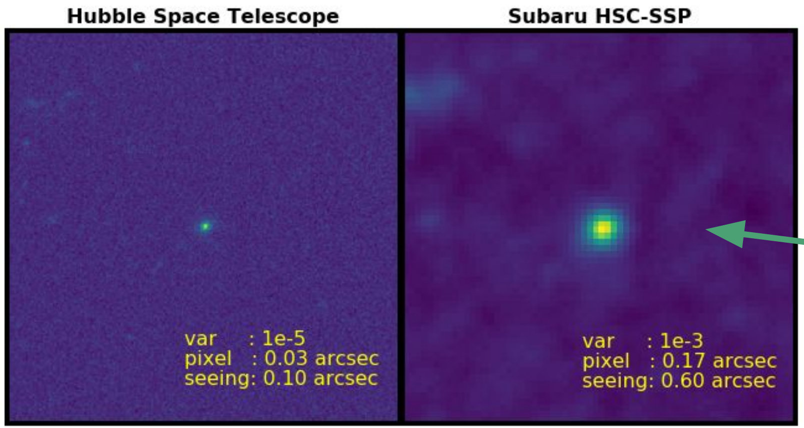


Li+ 2022

	DES Y3	KiDS-1000	HSC Year 3
Cosmic shear catalogue:			
Area [deg^2]	4143	777	416
Wavebands	*riz* (Wide) + *grizJHK$_s$* (Deep)	*ugriZYJHK$_s$*	*grizy*
$n_{\rm eff}$	5.59	6.22	14.96
$z_{\rm median}$	0.63	0.67	0.80



Calibrate shape estimation with image simulation



$$\hat{\gamma} = (1 + m)\gamma + c$$

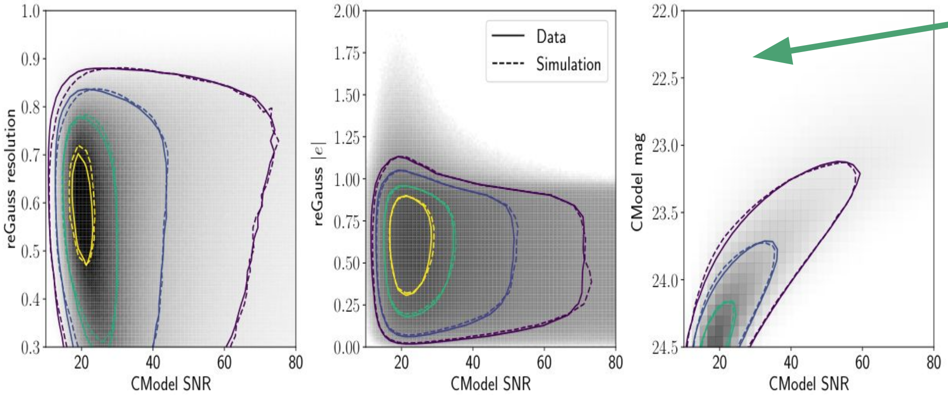
Measured shape   input shape

Quantify **biases** with **image simulations**.

1. We use galaxy image simulations (downgrading the high-resolution Hubble Space Telescope **(HST F814W)** images to the **HSC i-band images (PSFs and noises)**) to calibrate our shape estimation;

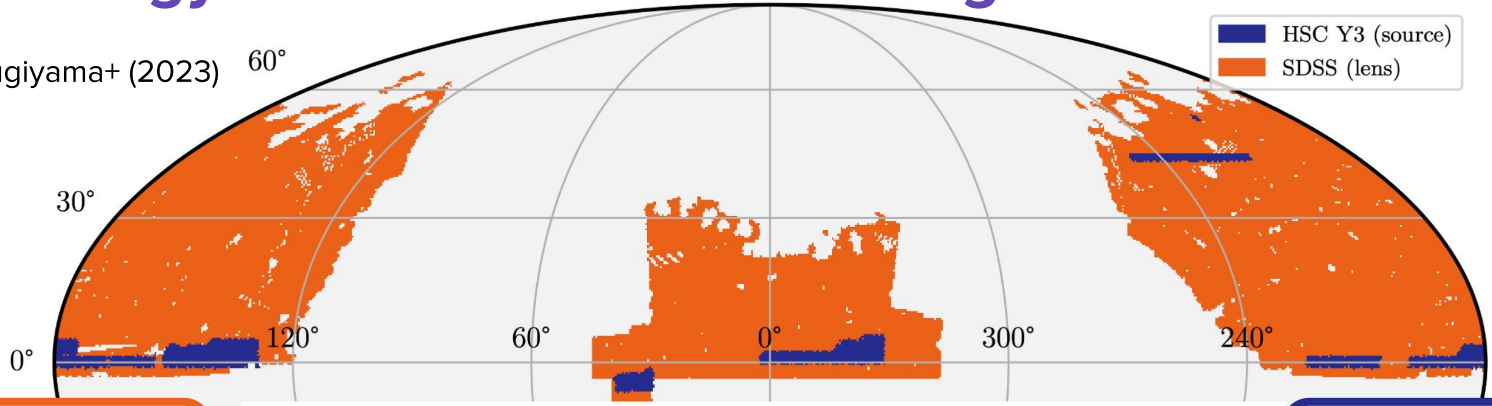
2. Our simulation matches the galaxy number histogram with an accuracy of **1%.**

Mandelbaum+ (2018), Li+ (2022)



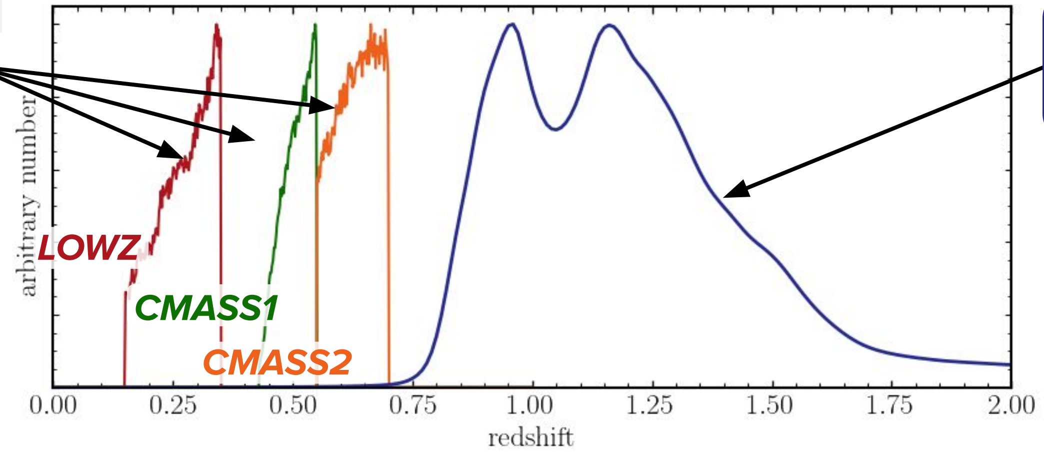
Cosmology with HSC x SDSS catalogs

More, Sugiyama+ (2023)

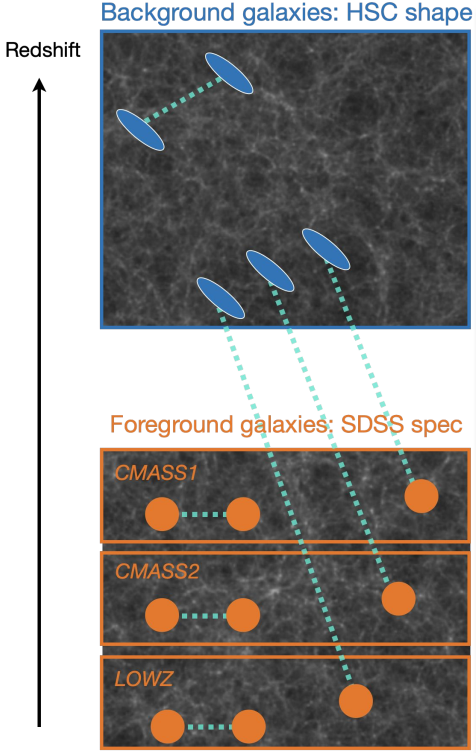


SDSS spec-z sample lens galaxies

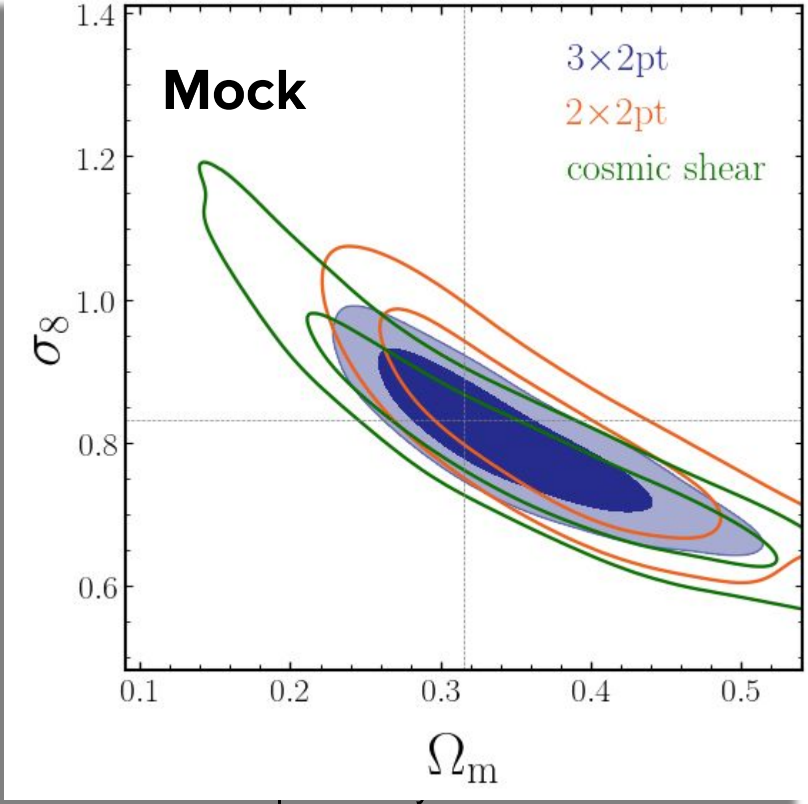
HSC shape sample source galaxies

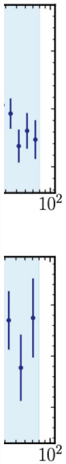


3x2pt analysis with HSC x SDSS catalogs



Credit: T. Nishimichi, edited by S. Sugiyama





$\delta_g = b\delta_m$ on large scales

$w_p \sim b^2 \xi_{mm}(r \,|\, \Omega_m, \sigma_8)$

$\Delta\Sigma \sim b\xi_{mm}(r \,|\, \Omega_m, \sigma_8)$

$\xi_\pm \sim \xi_{mm}(r \,|\, \Omega_m, \sigma_8)$

e, Sugiyama+ (2023)

les shown by shaded region.

These scales were used for the 3x2 pt cosmology analyses.

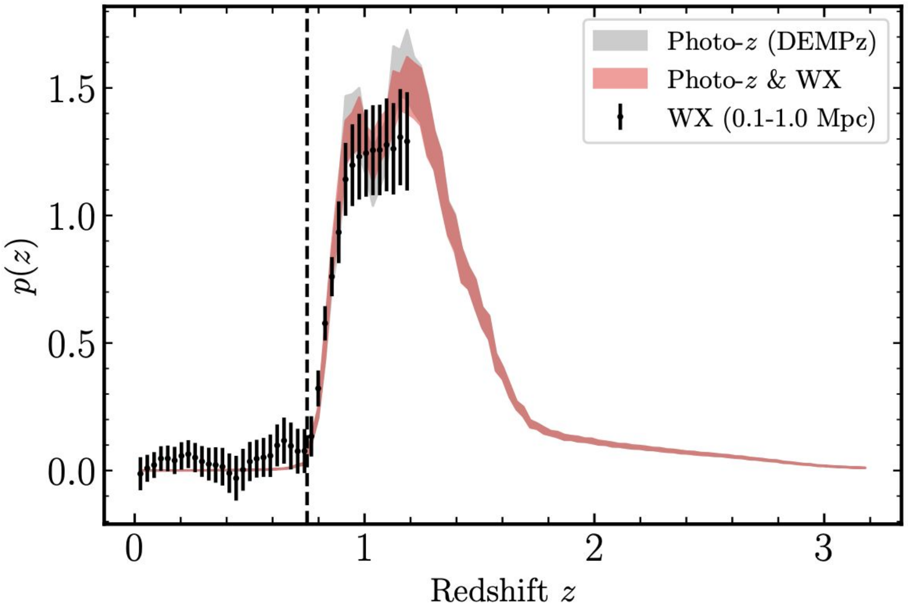
Photo-z calibration and its limitation at high redshift

Methodology:
Rau et al. 2023

Grey: photo-z likelihood (DeMPz) + cosmic variance

Black points: Clustering Redshift from cross-correlation between HSC source catalog and CAMIRA-LRG

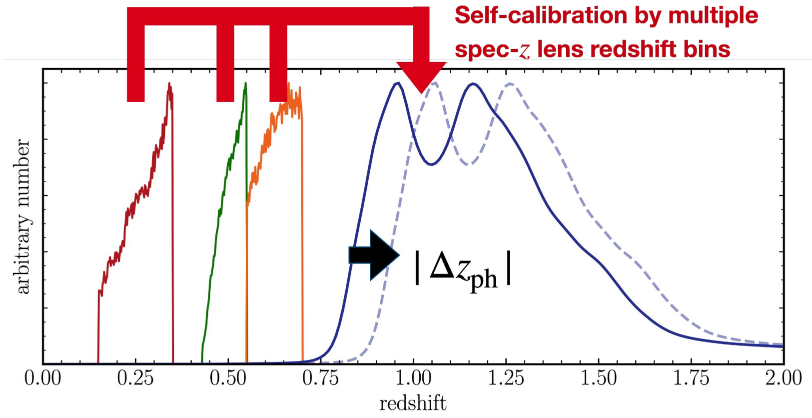
Red: joint posterior of the two

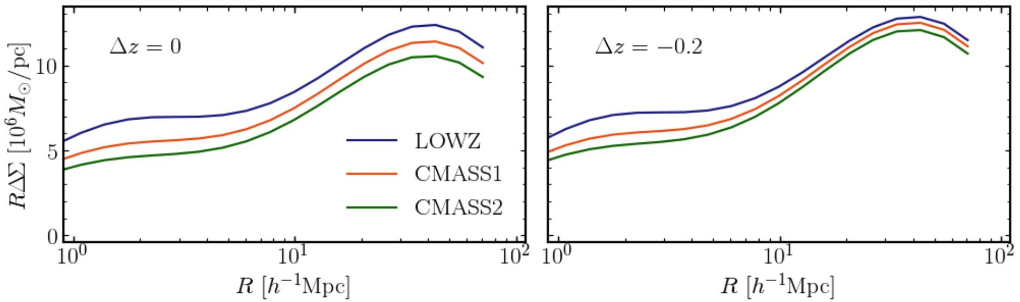


3x2pt source samples are at high redshift $z \gtrsim 1$, where

- photometric redshift estimate **may be inaccurate** due to the lack of spec-z training sample (COSMOS),
- Clustering redshift (CAMIRA-LRGs) is **not** available at z>1.2.

Photo-z self-calibration by galaxy-galaxy lensing signals





The ratios of g-g lensing signals in three different redshift bins inform us the mean source redshift (Oguri&Takada 2011).

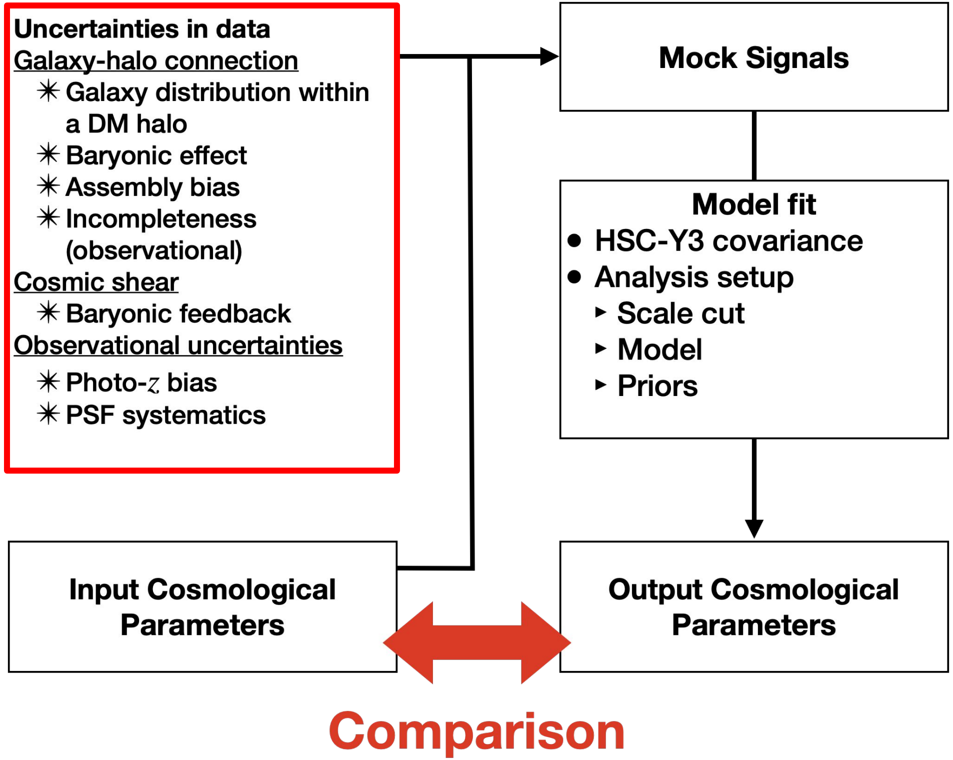
$$\frac{\Delta\Sigma(z_{l_1})}{\Delta\Sigma(z_{l_2})} = \frac{\Sigma_{\rm cr}(z_{l_1}, z_{\rm s}) w_{\rm gm}(z_{l_1})}{\Sigma_{\rm cr}(z_{l_2}, z_{\rm s}) w_{\rm gm}(z_{l_2})}$$

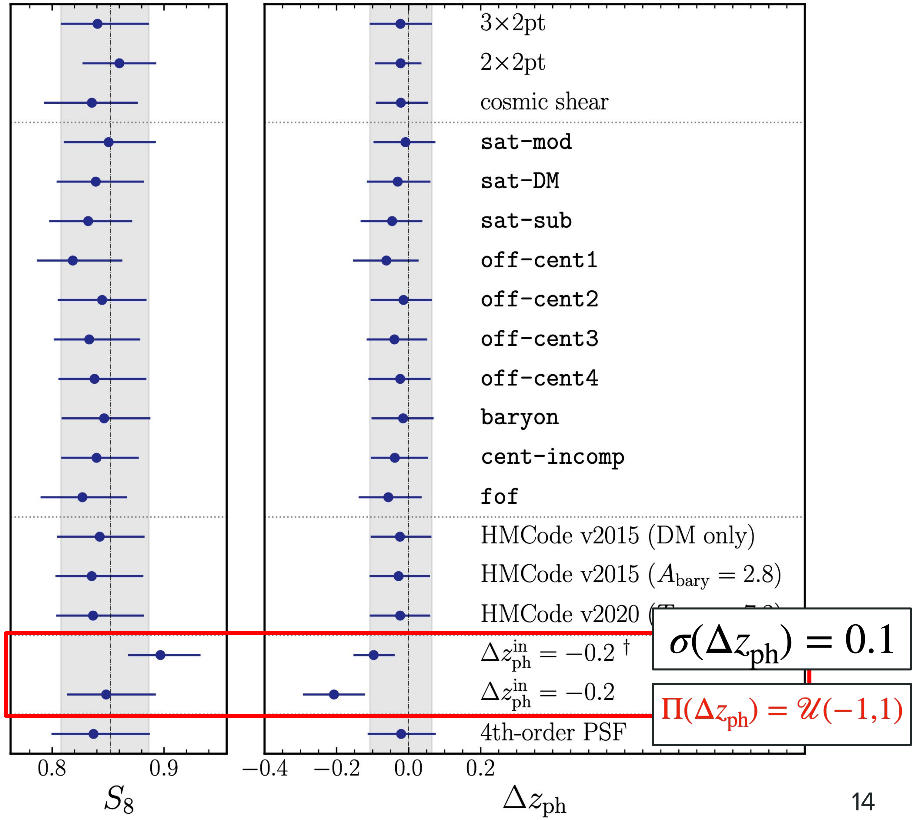
This dependence is imprinted in measured g-g lensing signals ➜ we do not have to rely on informative prior.

$$\Pi(\Delta z_{\rm ph}) = \mathcal{U}(-1,1)$$

We decided/validated this choice *before* unblinding.

Validation of model and analysis choices with mocks





Blind Analysis

We need to avoid **confirmation bias**: we may unconsciously correct systematics to match Planck cosmology.

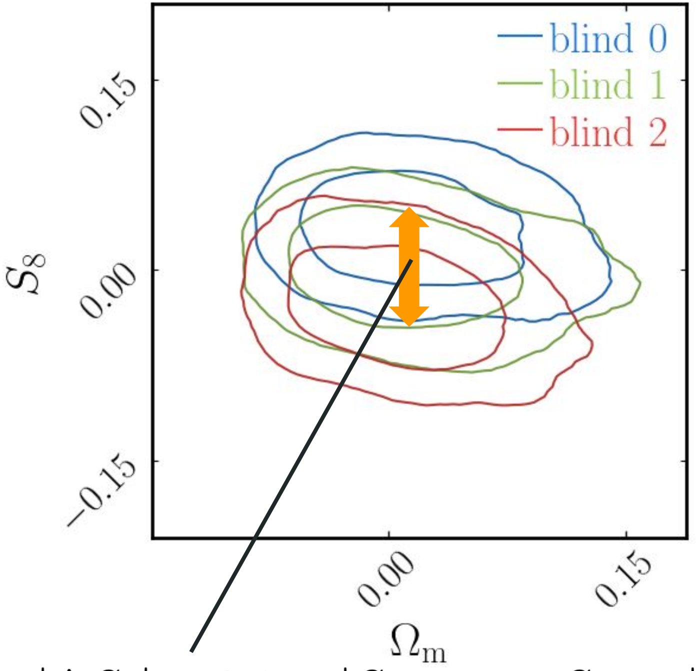
- **Catalog-level blinding**
  We prepare **three blinded catalogs** with slight offset of WL shear calibration. One of them is the true catalog.
- **Analysis-level blinding**
  When plotting a contour, we **blind the central value**.

Note: Different sets of blinded catalogs are used for different cosmology analyses.

Systematic tests

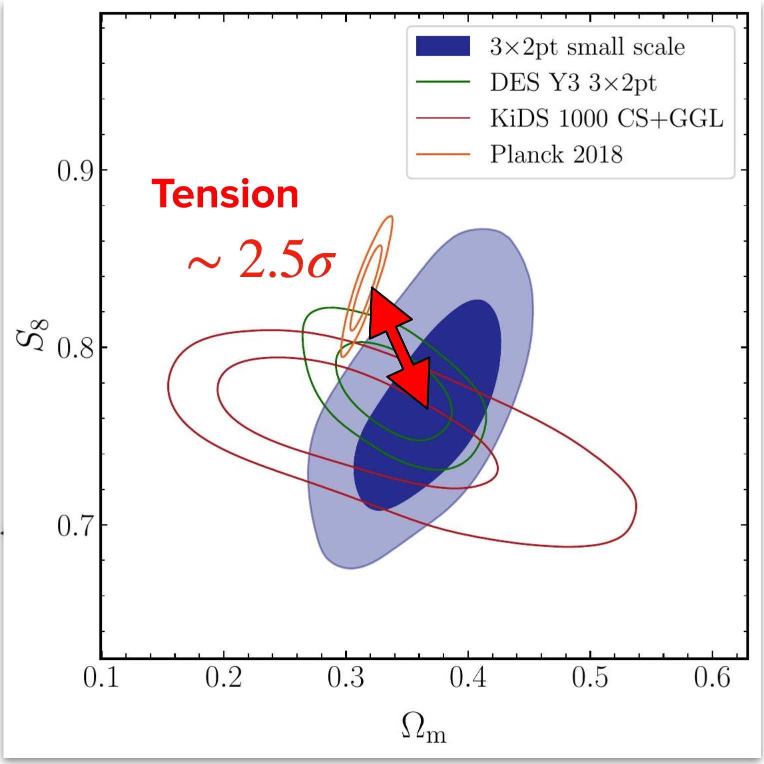
- Stress tests with various analysis choices
  e.g.) scale cuts, model variations, etc...

Unblind!



$$|\Delta S_8| \simeq 0.1 > |S_{8,\mathrm{CMB}} - S_{8,\mathrm{LSS}}|$$

Cosmology from HSC x SDSS 3x2pt without Δz prior



3x2pt analysis result for flat ΛCDM model

$$S_8 = 0.763^{+0.040}_{-0.036}$$

$$\Delta z_{ph} = -0.05 \pm 0.09$$

5% constraint!

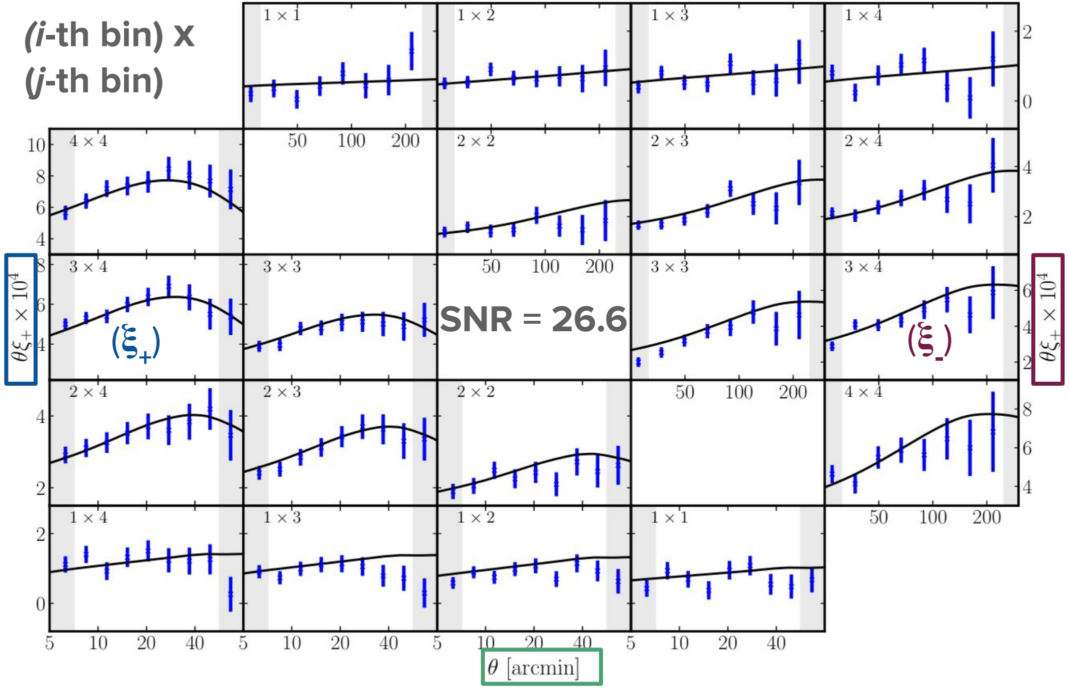
- We might have reached larger S_8 value if we were using the informative prior on Δz.
- After unblinding, we found our result is in 2.5 σ tension with Planck 2018.

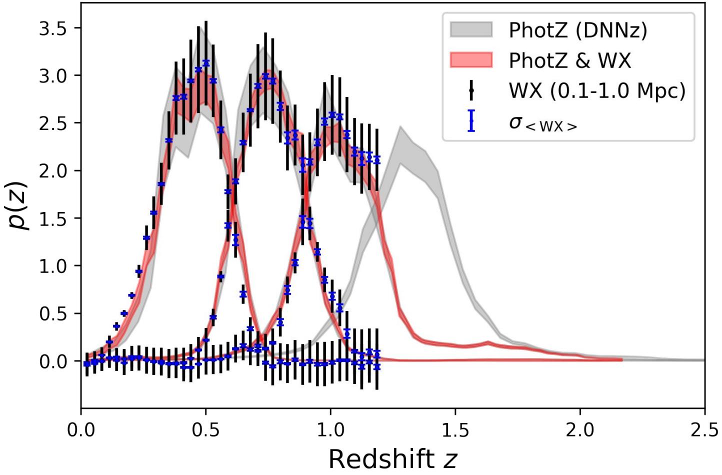
Tomographic cosmic shear: Real

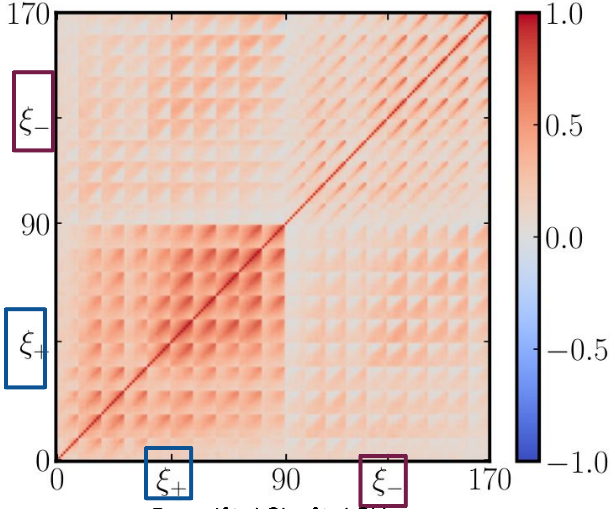
$\xi_{\pm}(\theta)$ (2 Point Correlation Functions)

Measured with **TreeCorr**

p-value of best-fit model: 0.28







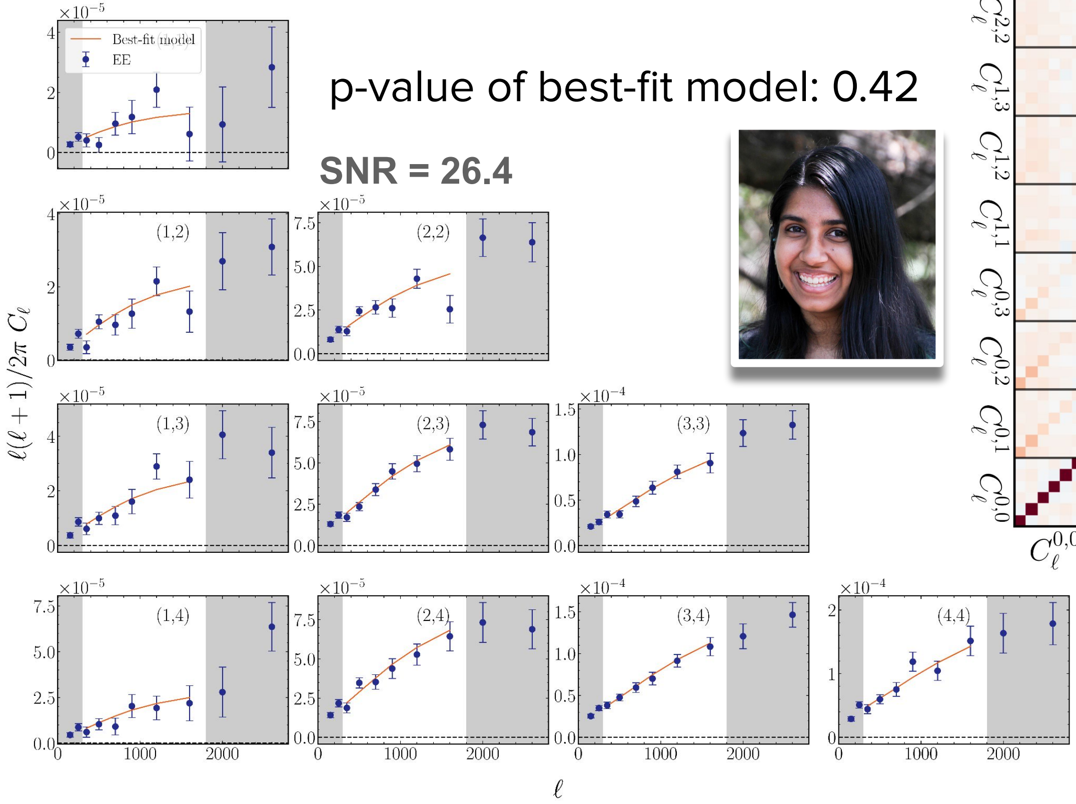
Cov($\xi_{\pm}(\theta)$, $\xi_{\pm}(\theta)$)

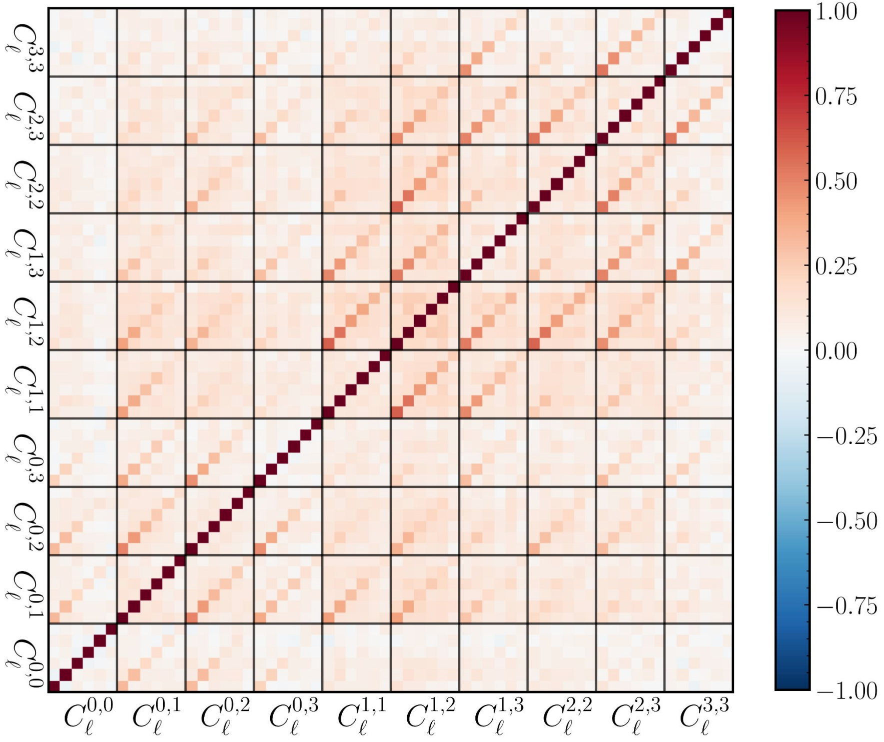
Tomographic cosmic shear: Fourier

Measured with **NaMaster**

p-value of best-fit model: 0.42

SNR = 26.4



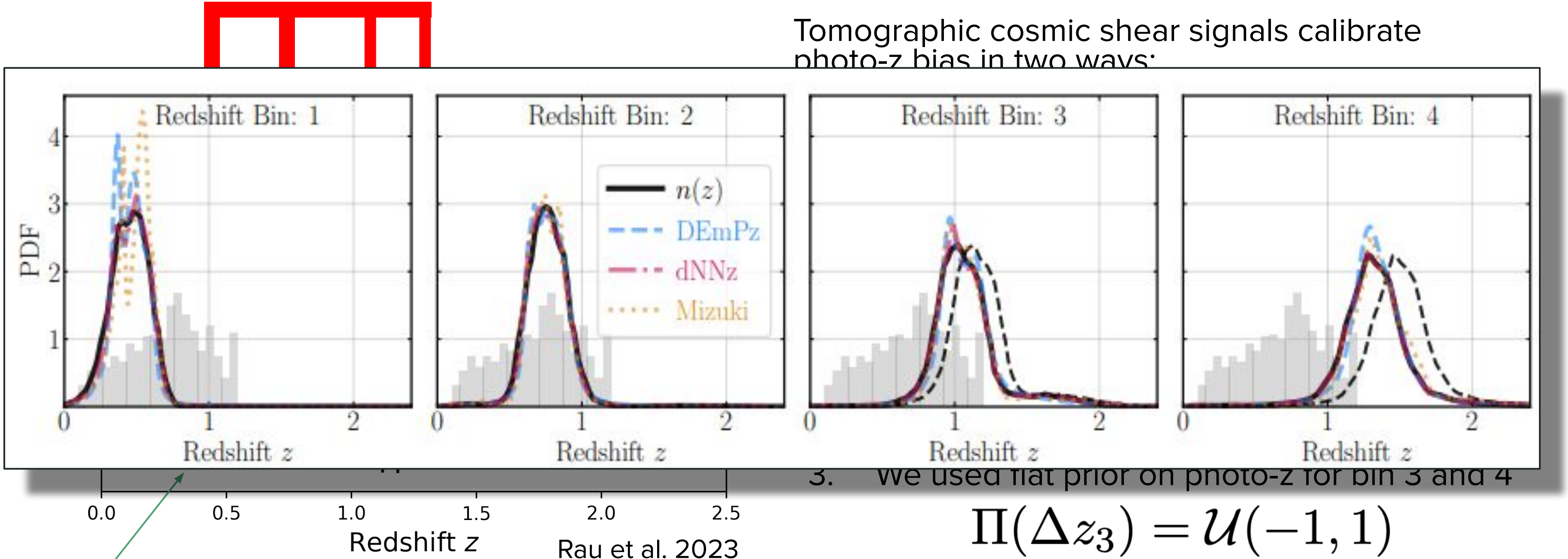


Covariances are measured from 1404 N-body + ray-tracing simulations

Takahashi+ (2017), Shirasaki+ (2019)

Photo-z self-calibration by tomographic cosmic shear signals

Tomographic cosmic shear signals calibrate photo-z bias in two ways:



Rau et al. 2023

The two lowest bins have reliable photo-z calibration.

3. We used flat prior on photo-z for bin 3 and 4

$$\Pi(\Delta z_3) = \mathcal{U}(-1, 1)$$

$$\Pi(\Delta z_4) = \mathcal{U}(-1, 1)$$

Fourier Space:

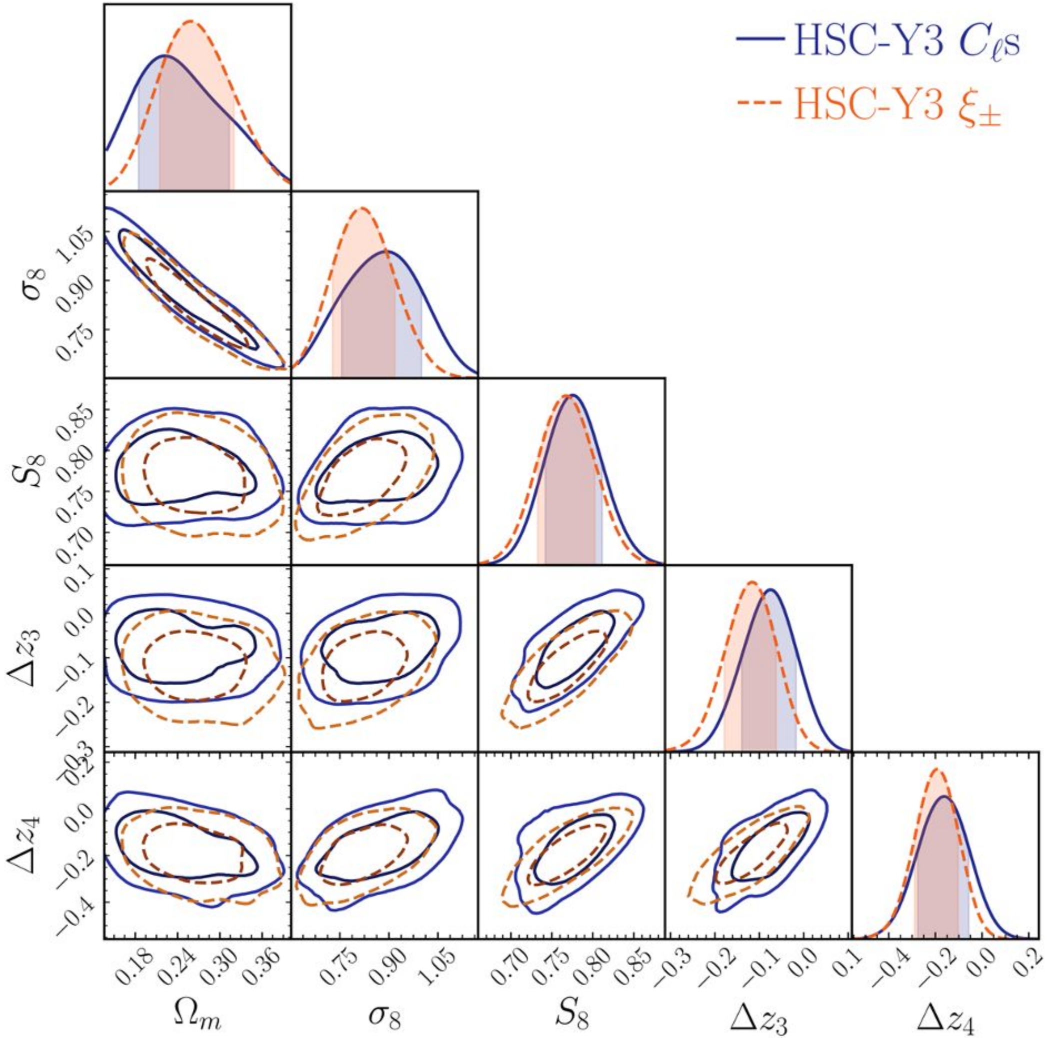
$$S_8 = 0.776^{+0.032}_{-0.033}$$

Real Space:

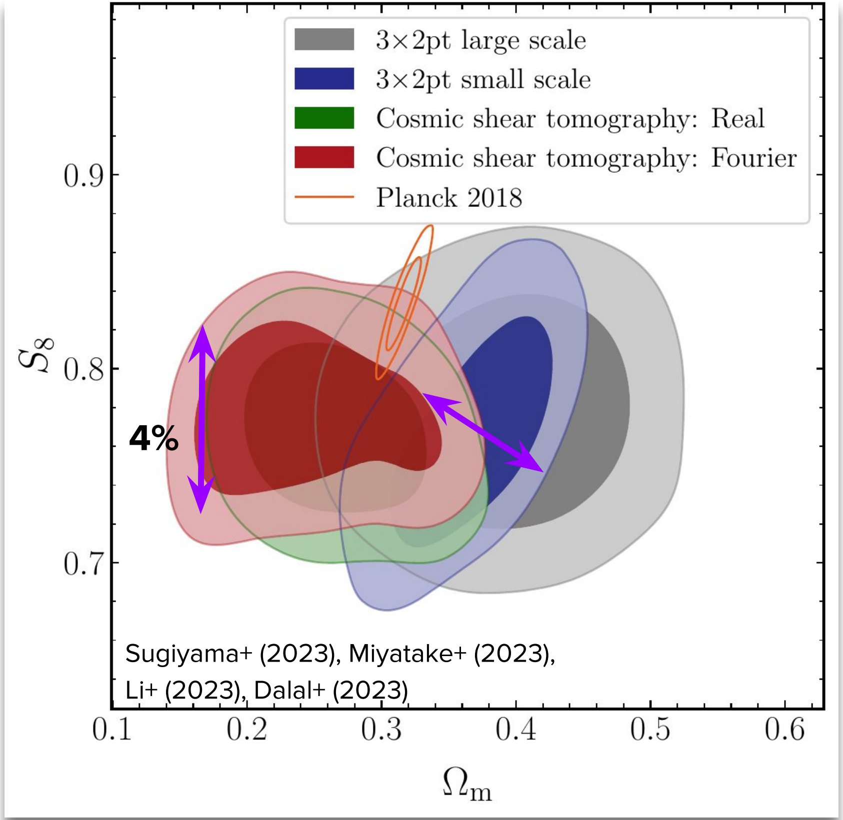
$$S_8 = 0.769^{+0.031}_{-0.034}$$

Marginalized 1D modes

We built our HSC likelihood with **CosmoSIS** (Joe Zunt), which will be public soon.



HSC Year 3: Summary of results



- Consistent cosmological constraints from blind analyses
  - Cosmic shear (Real and Fourier space)
  - 3x2 pt analysis (Linear and Quasi-linear scales)
- Conservative analyses in the presence of systematic uncertainties in the redshifts of source galaxies
  - Shear-ratio test currently in progress
- Difference from the CMB expectation in ΛCDM model context based on various tension metrics range from 2-2.5 sigma