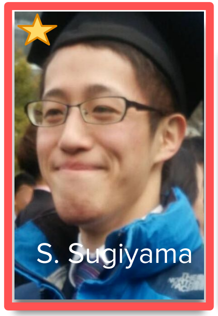
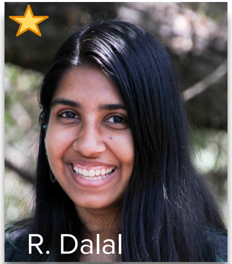
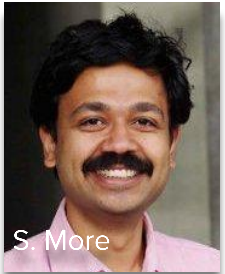
Cosmology from Galaxy Clustering and Weak Lensing with HSC-Y3 and SDSS using the Emulator-Based Halo Model

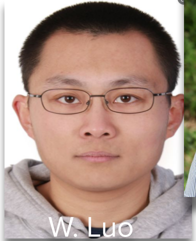
Hironao Miyatake (KMI, Nagoya University)
On behalf of the Hyper Suprime-Cam Subaru Strategic Program Collaboration

Weak lensing working group









And efforts of many more!

Key weak lensing group publications: HSC Year 3

Supporting papers

- The three-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey (**Li X.**, et al. 2022, PASJ, 74, 2)
- A General Framework for Removing Point Spread Function Additive Systematics in Cosmological Weak Lensing Analysis (**Zhang T.** et al. 2022, MNRAS submitted, arXiv:2212.03257)
- Weak Lensing Tomographic Redshift Distribution Inference for the Hyper Suprime-Cam Subaru Strategic Program three-year shape catalogue (**Rau, M.** et al. 2022, MNRAS, submitted, arXiv:2211.16516)

Cosmology papers

- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Two-Point Correlation Functions (**Li X.,** et al. 2023, PRD, arXiv:2304.00702)
- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Power Spectra (**Dalal R.,** et al. 2023, arXiv:2304.00701)
- Hyper Suprime-Cam Year 3 Results: Measurements of the Clustering of SDSS-BOSS galaxies, galaxy-galaxy lensing and cosmic shear (More S., et al. 2023, arXiv:2304.00703)
- Hyper Suprime-Cam Year 3 Results: Cosmology from Galaxy Clustering and Weak Lensing with HSC and SDSS using the Minimal Bias Model (**Sugiyama S.,** et al. 2023, arXiv:2304.00705)
- **Hyper Suprime-Cam Year 3 Results: Cosmology from Galaxy Clustering and Weak Lensing with HSC and SDSS using the Emulator Based Halo Model (Miyatake H., et al. 2023, arXiv:2304.00704)**

https://hsc-release.mtk.nao.ac.jp/doc/index.php/wly3/

Early career scientists leading the projects marked in bold

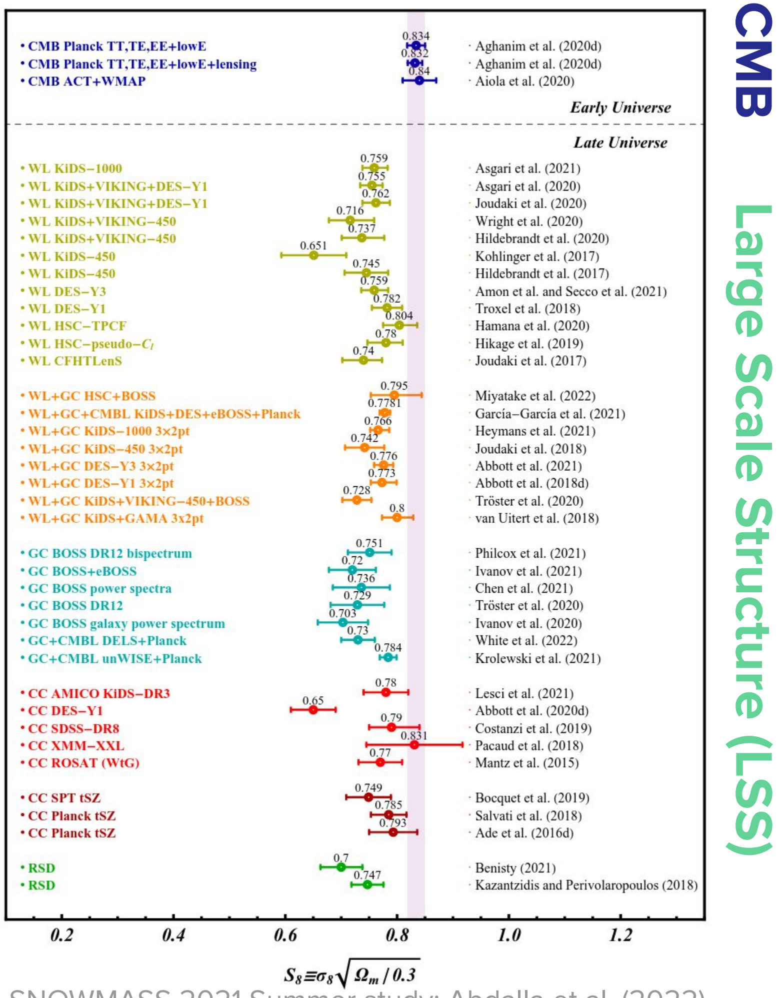
Testing ΛCDM using S_8

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

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

S_8 tension?

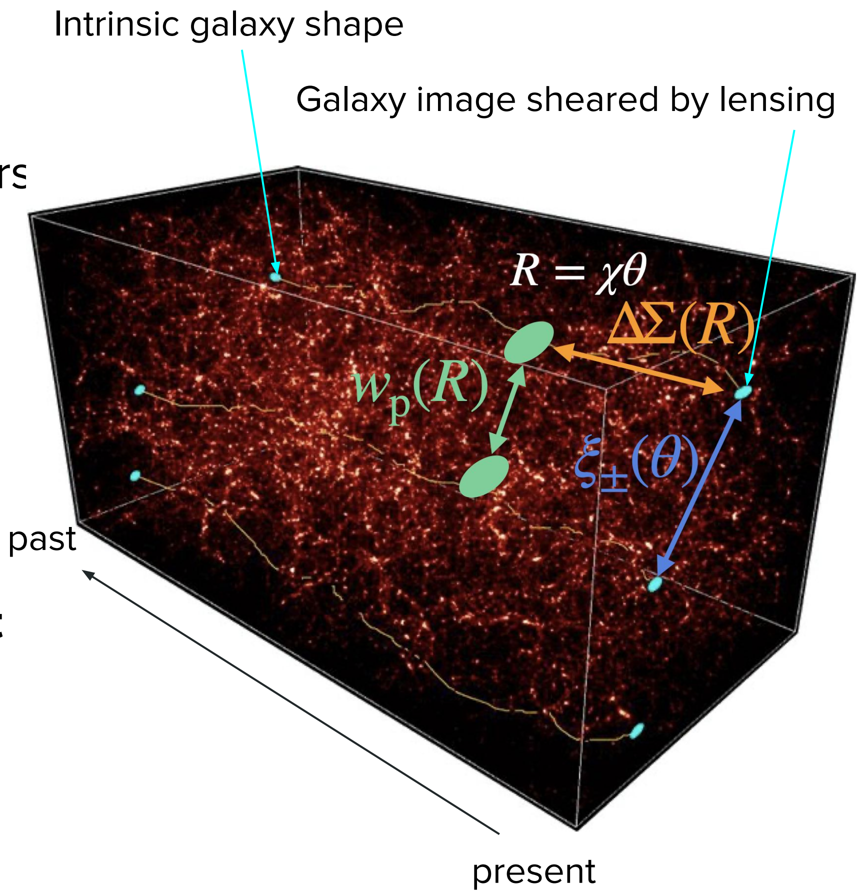
Most **large scale structure probes** (weak lensing, galaxy clustering, galaxy clusters, etc...) prefer smaller S_8 compared to **CMB**, if we assume ΛCDM is correct.



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

Weak Lensing Cosmology

- LSS is sensitive to cosmological parameters (Ω_m, σ_8) and $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$
- Weak Lensing, a subtle and coherent distortion of distant galaxies, probes the matter distribution (incl. dark matter)
- **Cosmic shear**
  - Auto-correlation of weak lensing shear
- **Galaxy-galaxy clustering x lensing: 2x2pt**
  - Auto-correlation of galaxy positions
  - Cross-correlation of galaxy positions and weak lensing shear
- **Cosmic shear + 2x2pt: 3x2pt**

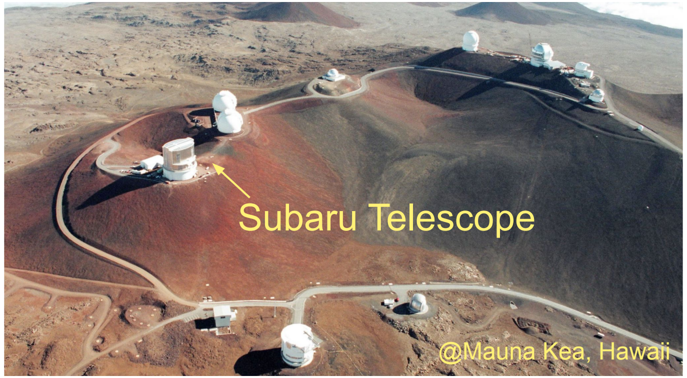


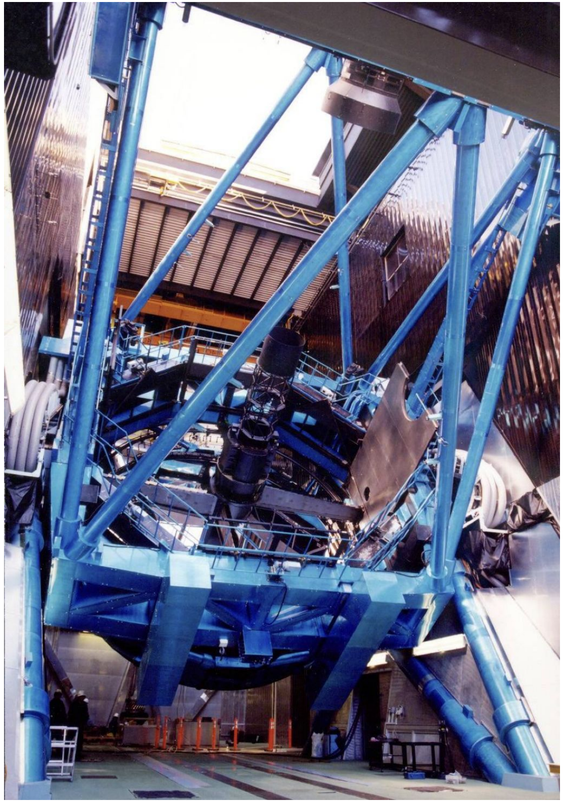
S. Colombi (IAP), CFHT Team

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.





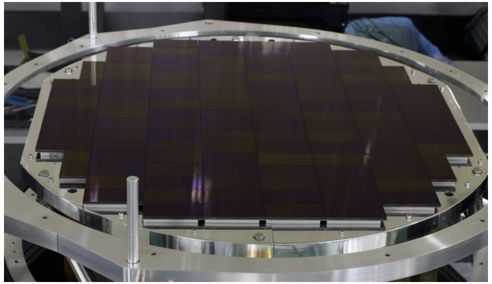
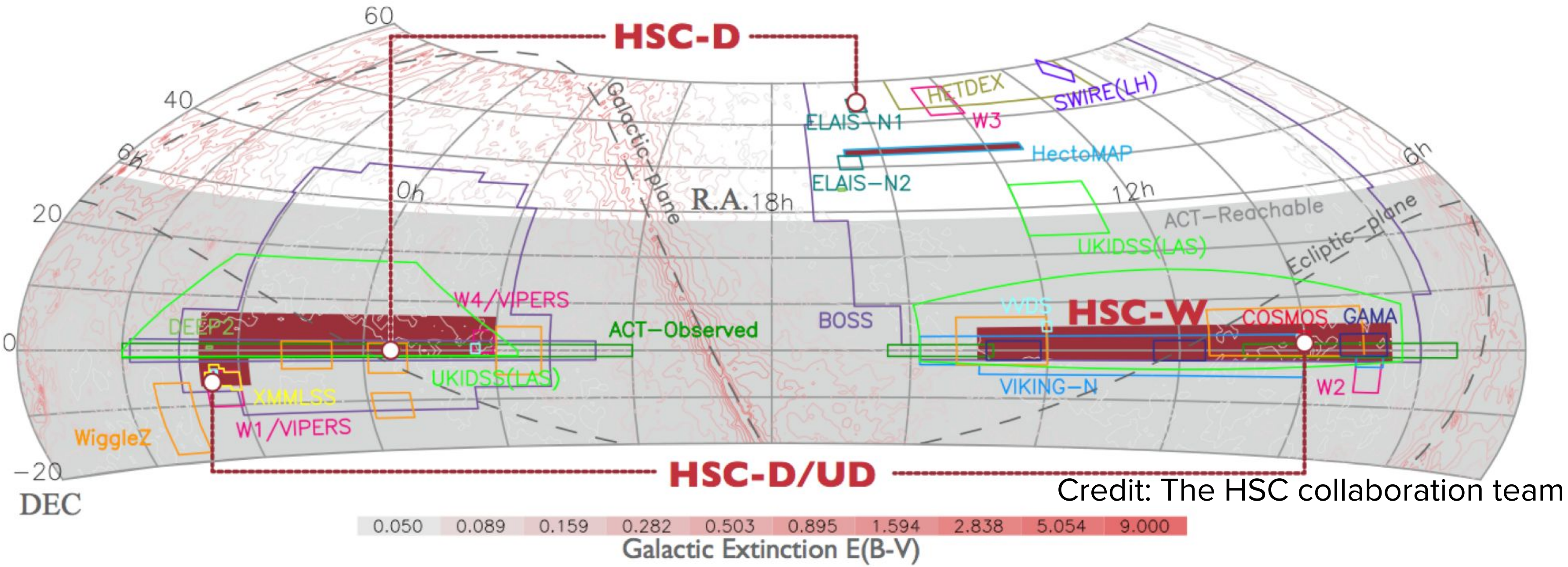


Photo credit: NAOJ / HSC Project

HSC Subaru Strategic Program (SSP) Survey

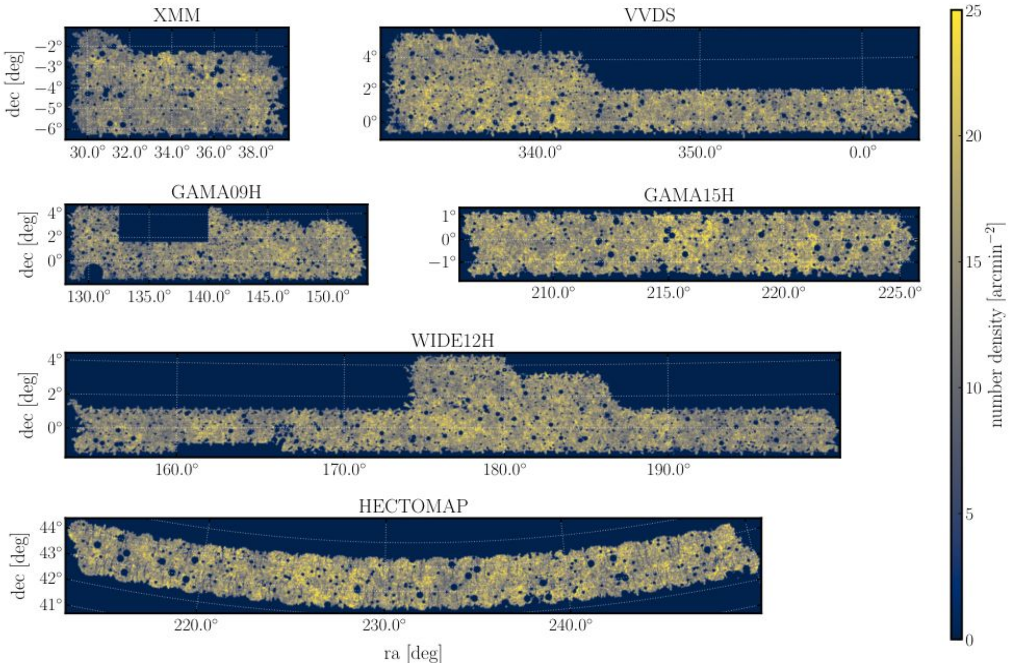


Credit: The HSC collaboration team

- 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 seminar, we will give results from the data taken until April 2019 (416 deg^2).**

HSC-Y3 Shape Catalog

Li+ (2022)



Using i-band HSC images
Magnitude cut: 24.5
Area: 416 (square degree)
Number of galaxies: 25 million
Number density: ~20 (/ square arcmin)
Seeing size: 0.6 arcsec
Calibrated with image simulation

Blind Analysis

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

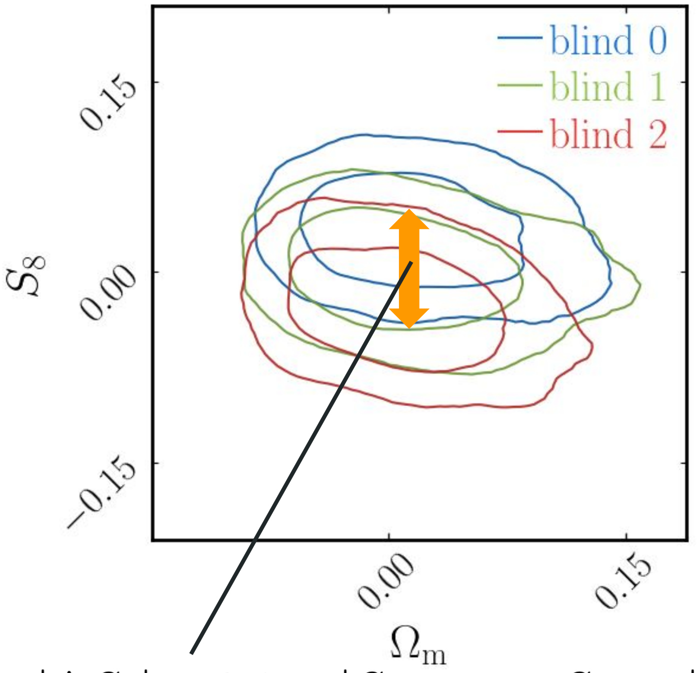
- Catalog-level blinding
  We prepare **three blinded catalogs** with slight offset of WL shear calibration. One of them is the true catalog.
- Analysis-level blinding
  When plotting a contour, we **blind the central value**.

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...

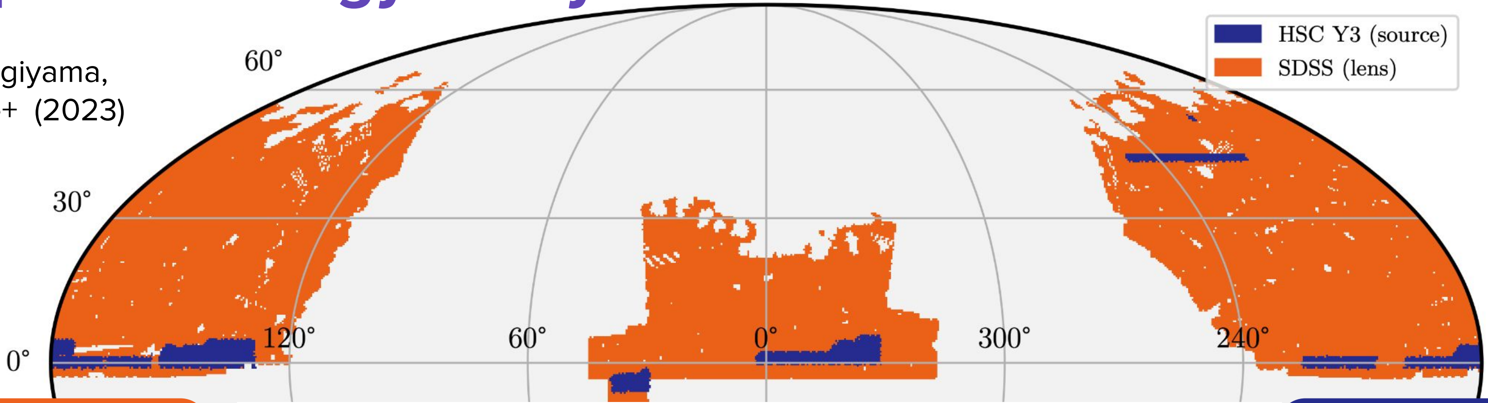
Unblind!



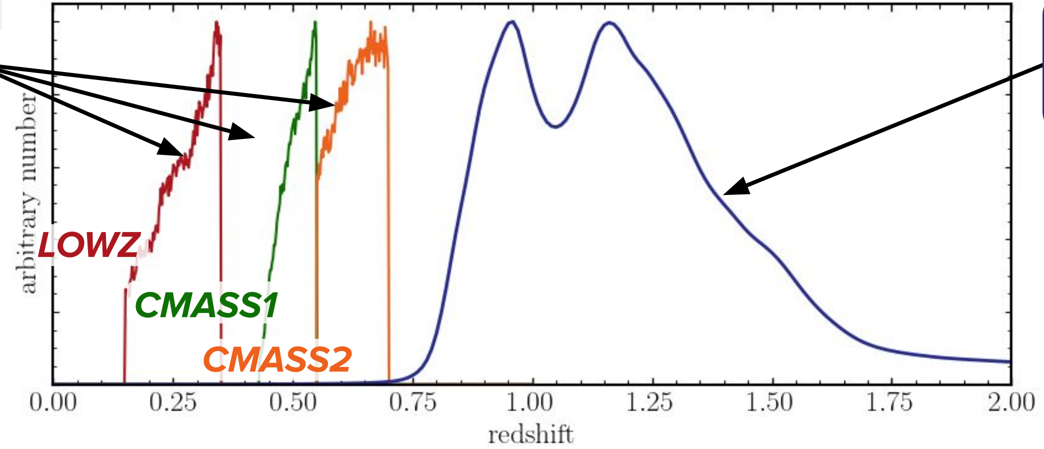
$$|\Delta S_8| \simeq 0.1 > |S_{8,\mathrm{CMB}} - S_{8,\mathrm{LSS}}|$$

3x2pt Cosmology Analysis with HSC x SDSS

More, Sugiyama, Miyatake+ (2023)



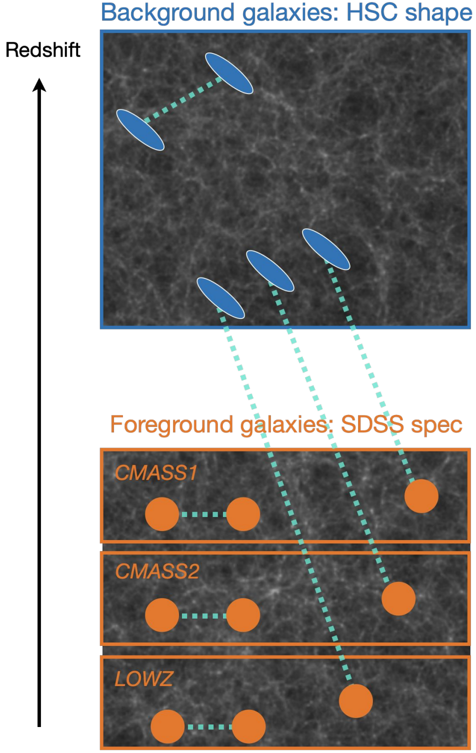
SDSS spec-z sample lens galaxies



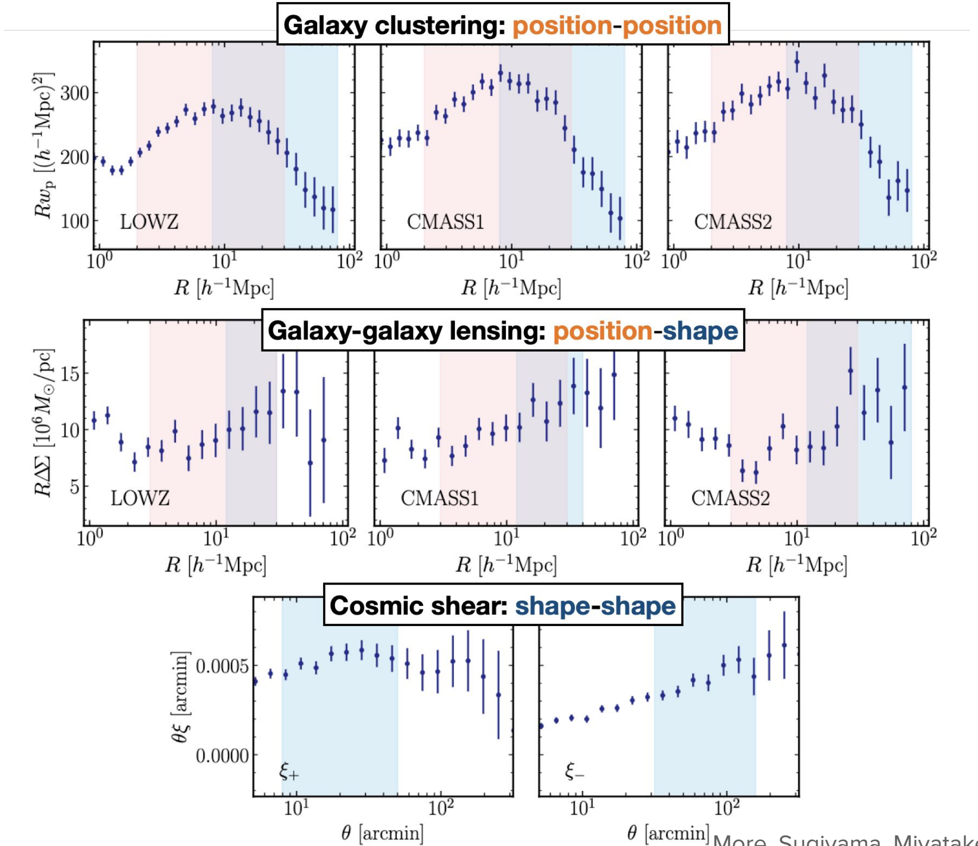
HSC shape sample source galaxies

Single source sample for 3x2pt analysis, which is different from tomographic cosmic shear source samples.

3x2pt Analysis: Measurements



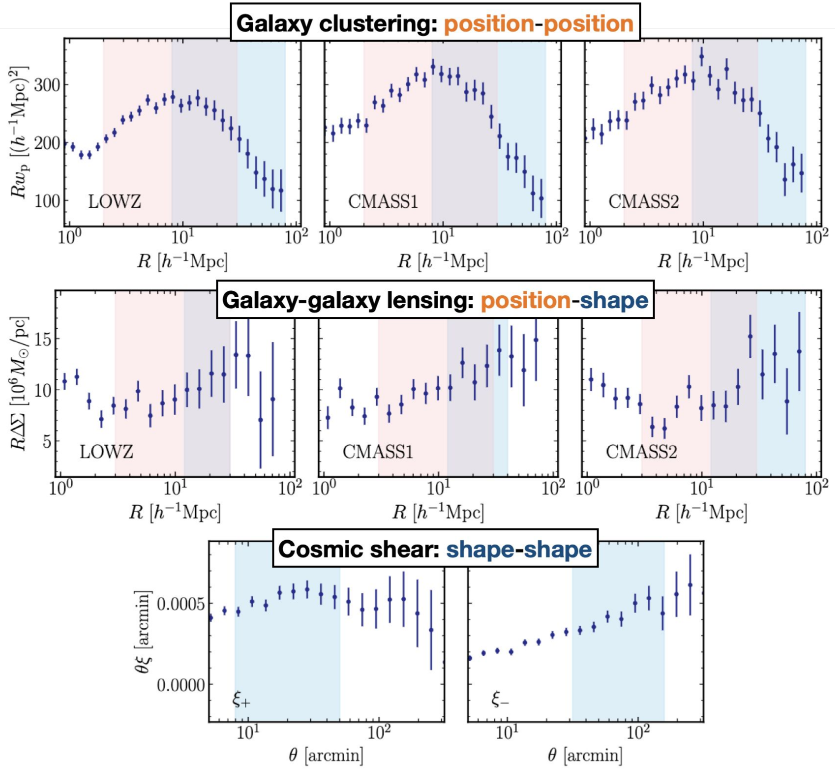
Credit: T. Nishimichi,
edited by S. Sugiyama



More, Sugiyama, Miyatake+ (2023)

Which Scale Do We Want to Use?

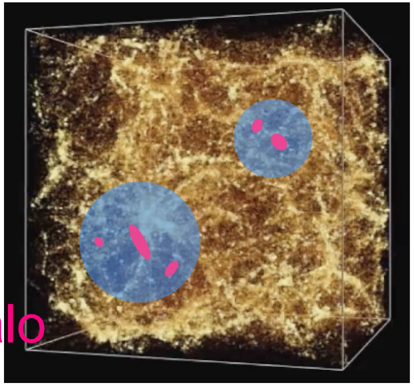
- At **large scales**, linear bias approximation $\delta_g = b\delta_m$ holds.
    - Clustering: $w_p \sim b^2 \xi_{mm}(r \mid \Omega_m, \sigma_8)$
    - Lensing: $\Delta\Sigma \sim b\xi_{mm}(r \mid \Omega_m, \sigma_8)$
- At **small scales**
    - We gain more signal-to-noise.
    - Modeling signals is challenging.
        - Non-linear regime
        - Galaxy-halo connection



More, Sugiyama, Miyatake+ (2023)

Credit: ESA

Modeling Small (Intermediate) Scales



dark matter
dark matter halos
galaxies

Challenges

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

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

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

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

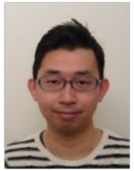
Projection onto 2-d

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

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

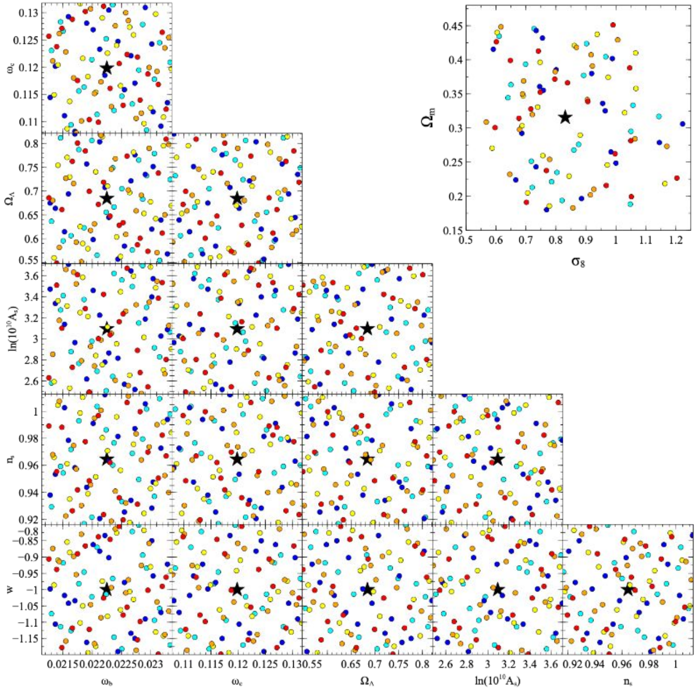
Uncertainties between galaxy-halo (g-h) connection
Analytical convolution of phenomenological model enables us to quickly change the g-h connection model if necessary

Dark Emulator: accurate non-linear model



T. Nishimichi (Kyoto)

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



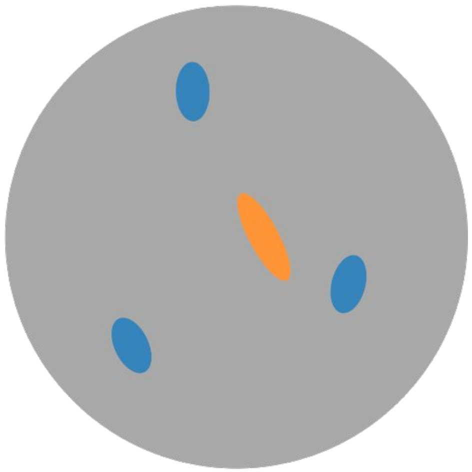
https://darkquestcosmology.github.io/

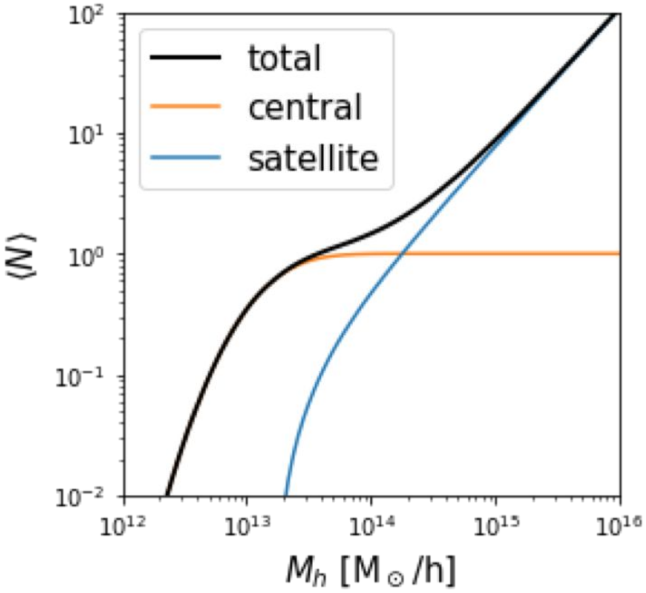
Nishimichi et al. (2019)

Galaxy-halo connection

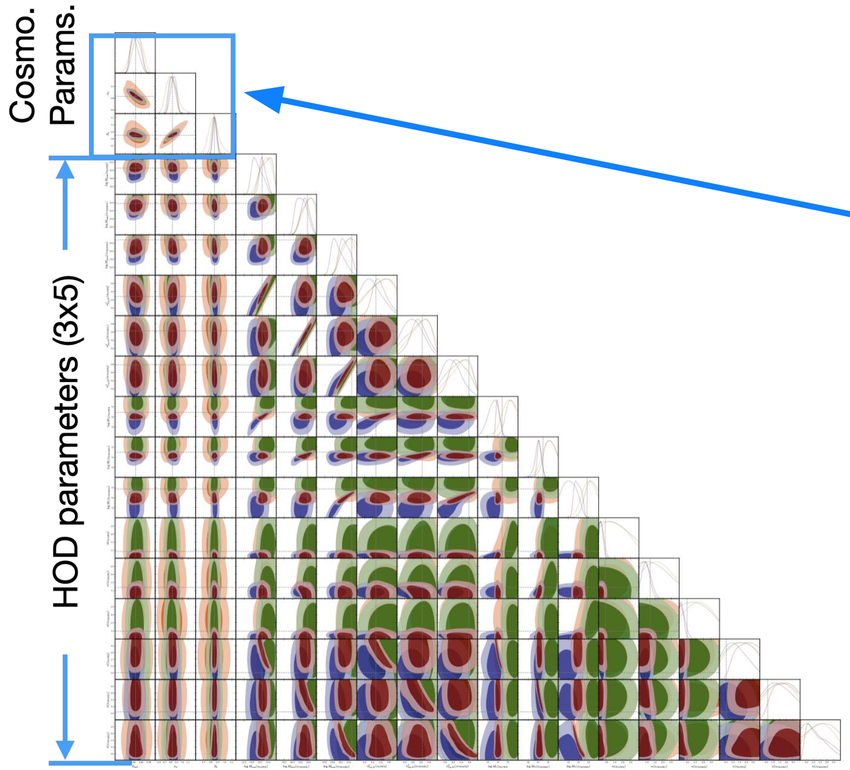
- Use halo occupation distribution (HOD; 5 parameters) to distribute galaxies in a dark matter halo.

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





Testing Emulator-Based Halo Model



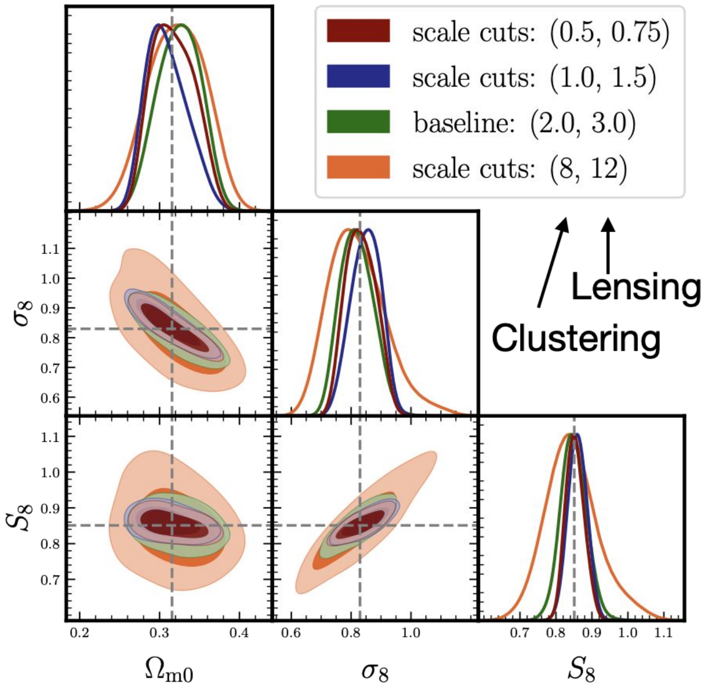
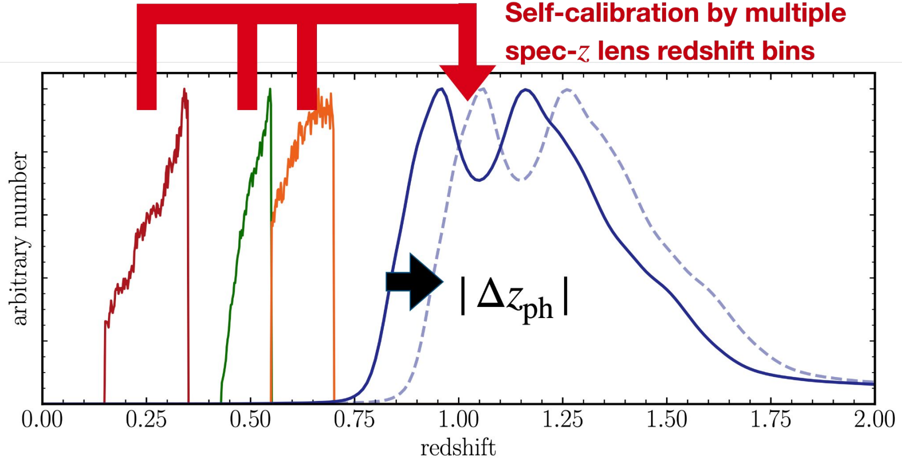


Photo-z calibration by multiple spec-z lens redshift bins



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

- photometric redshift estimate may be inaccurate,
- Cross calibrators (CAMIRA-LRGs) are not available.

Conventional approach:
Informative Gaussian prior with $\sigma(\Delta z_{\rm ph}) \sim 10^{-2}$

Our approach:
We adopt uninformative prior for the residual error in mean redshifts of our source sample:

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

$\Delta z_{\rm ph}$ is **self-calibrated** by galaxy-galaxy lensing signals of **three SDSS lens samples** (Oguri & Takada 2011).

Validation of model and analysis choices with mocks

Uncertainties in data

<u>Galaxy-halo connection</u>

- ✳ Galaxy distribution within a DM halo
- ✳ Baryonic effect
- ✳ Assembly bias
- ✳ Incompleteness (observational)

<u>Cosmic shear</u>

- ✳ Baryonic feedback

<u>Observational uncertainties</u>

- ✳ Photo-z bias
- ✳ PSF systematics

Mock Signals

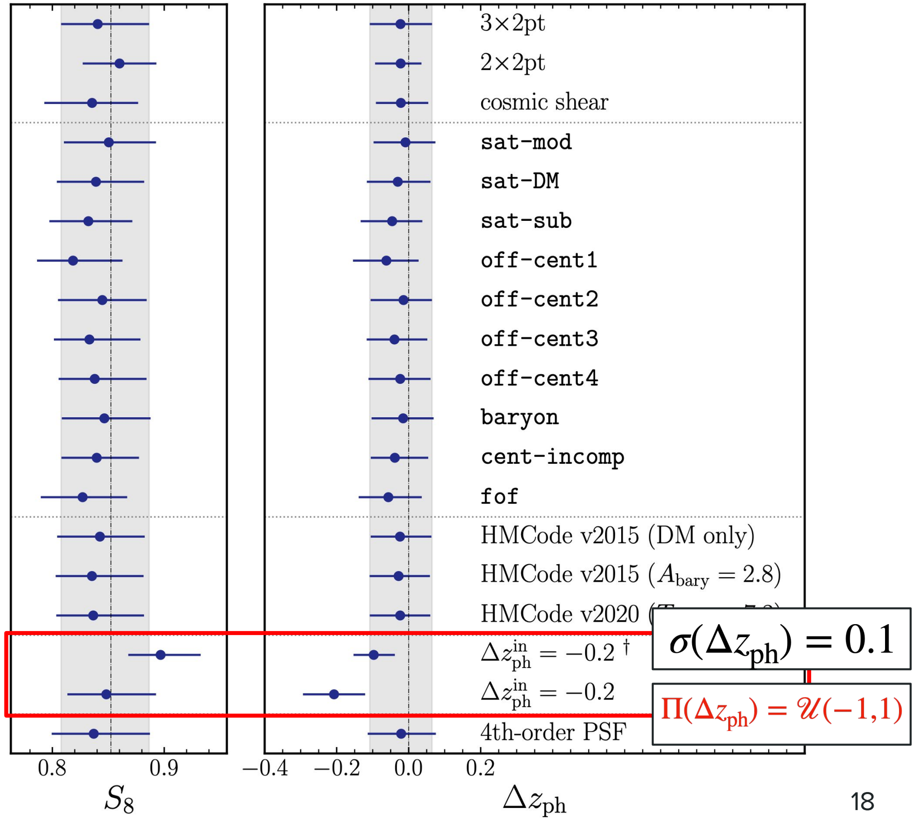
Model fit

- HSC-Y3 covariance
- Analysis setup
  - Scale cut
  - Model
  - Priors

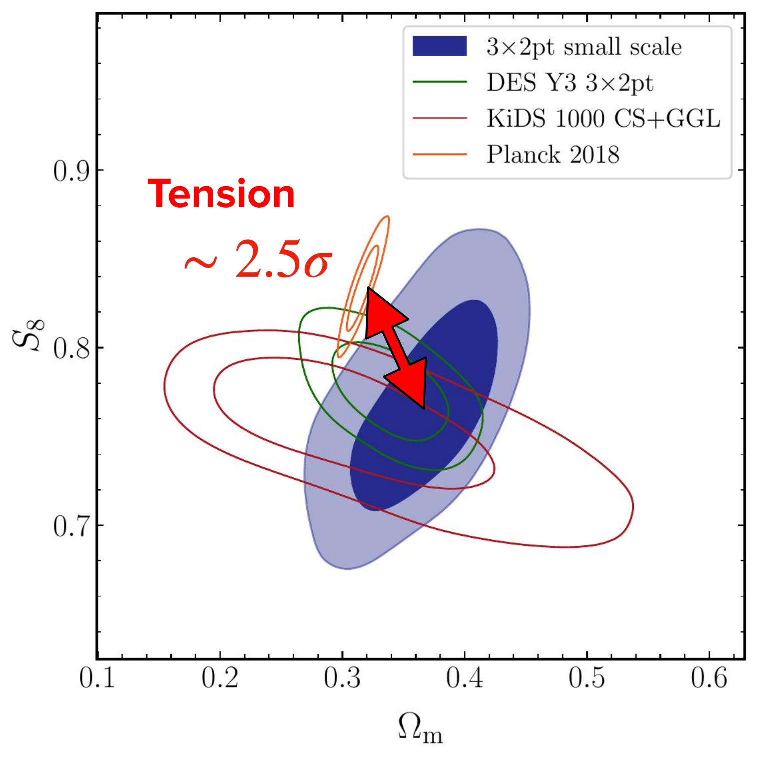
Output Cosmological Parameters

Input Cosmological Parameters

Comparison



Cosmology from HSC x SDSS 3x2pt analyses



Small-scale analysis result for flat ΛCDM

$$\Omega_m = 0.382^{+0.031}_{-0.047}$$

$$\sigma_8 = 0.685^{+0.035}_{-0.026}$$

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

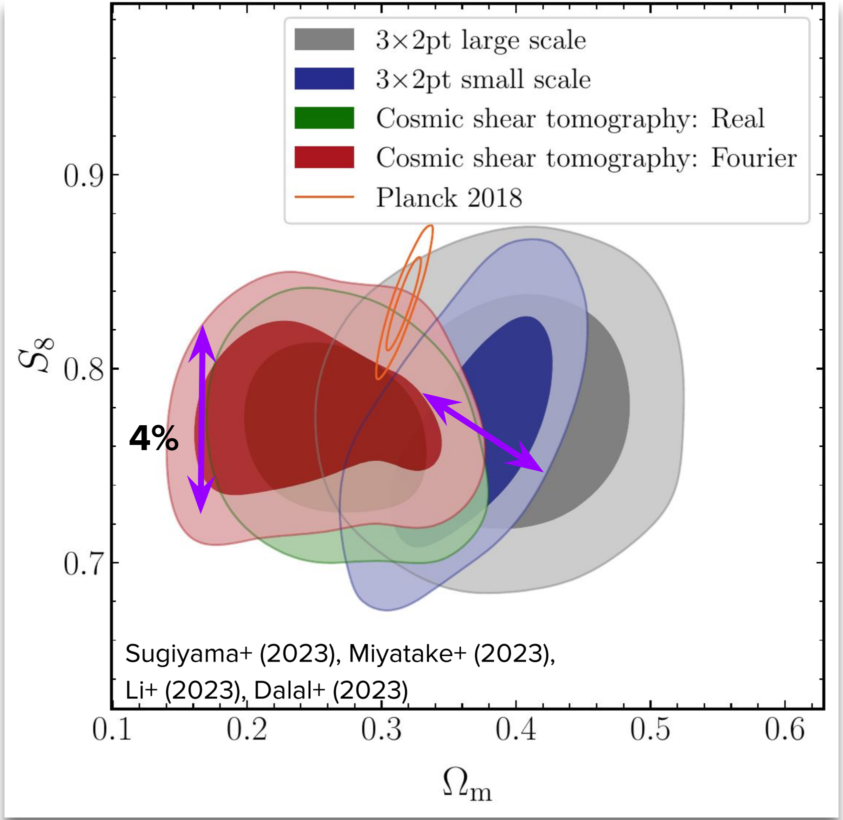
5% constraint!

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

- Significance of $\Delta z_{ph} < 0$ increases to 1.6σ when we adopt BAO prior on Ω_m
- Small-scale analysis is most sensitive to

$$S_8' \equiv \sigma_8(\Omega_m/0.3)^{0.22} = 0.721 \pm 0.028$$

HSC Year 3: Key Cosmology Results



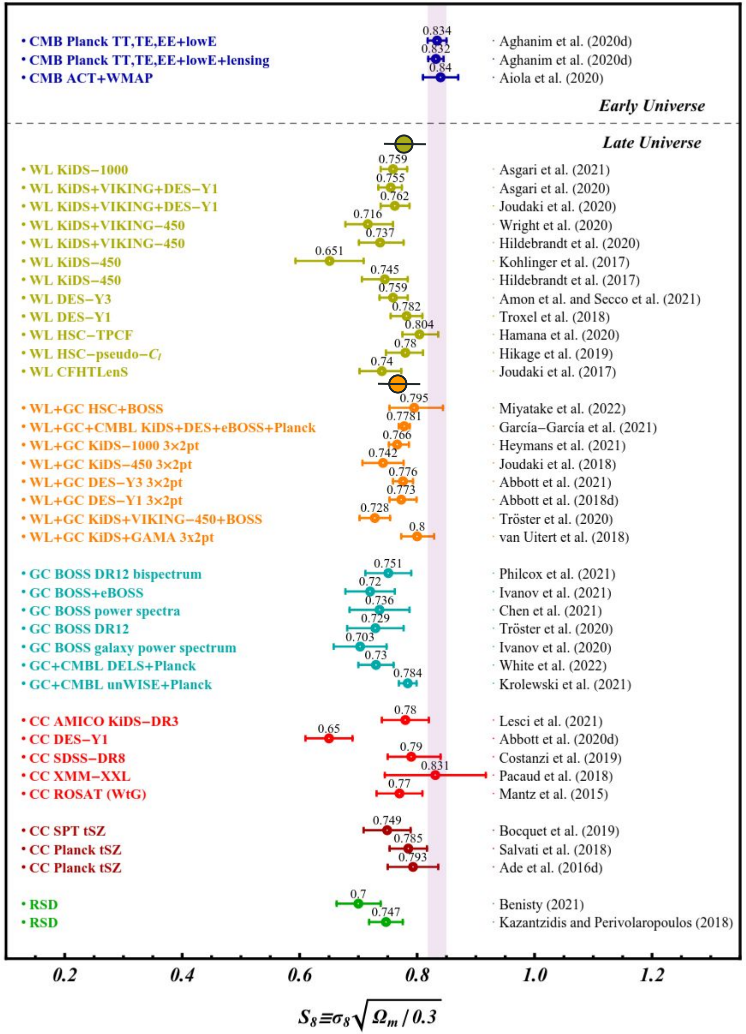
- Consistent cosmological constraints from blind analyses
  - Cosmic shear (Real and Fourier space)
  - 3x2 pt analysis (Linear and Quasi-linear scales)
- Conservative analyses in the presence of systematic uncertainties in the redshifts of source galaxies
  - Shear-ratio test currently in progress
-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

HSC-Y3 Cosmic shear analyses:

Dalal et al. (2023)
Li et al. (2023)

HSC-Y3 3x2 pt analyses:

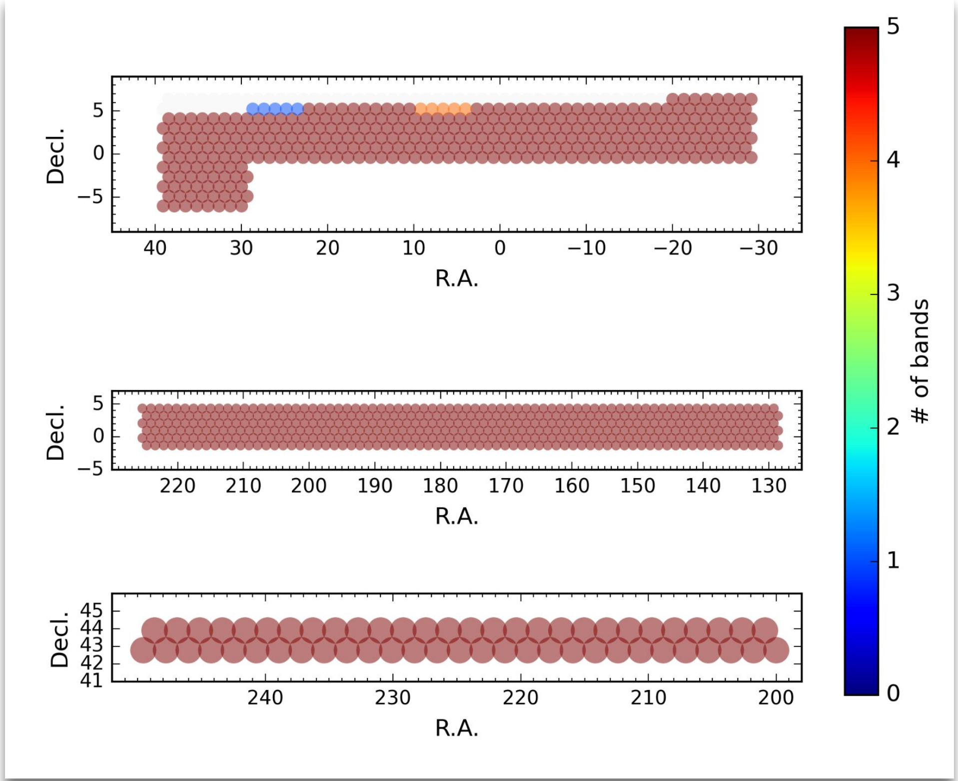
More et al. (2023),
Miyatake et al. (2023)
Sugiyama et al. (2023)



Are we reaching the limits of the standard cosmological model?

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

HSC survey: the future

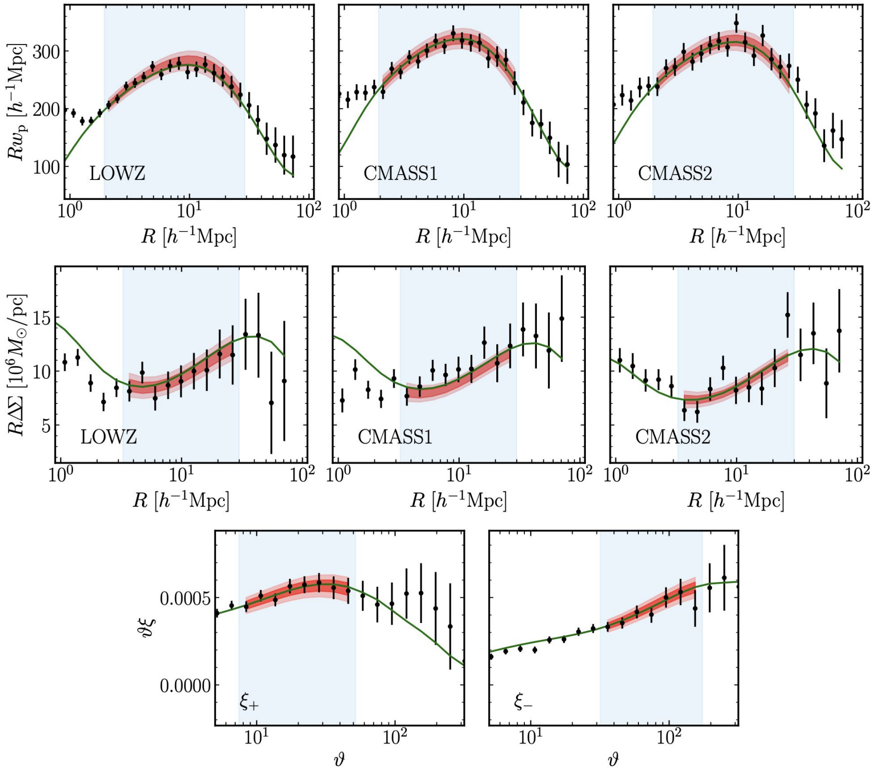


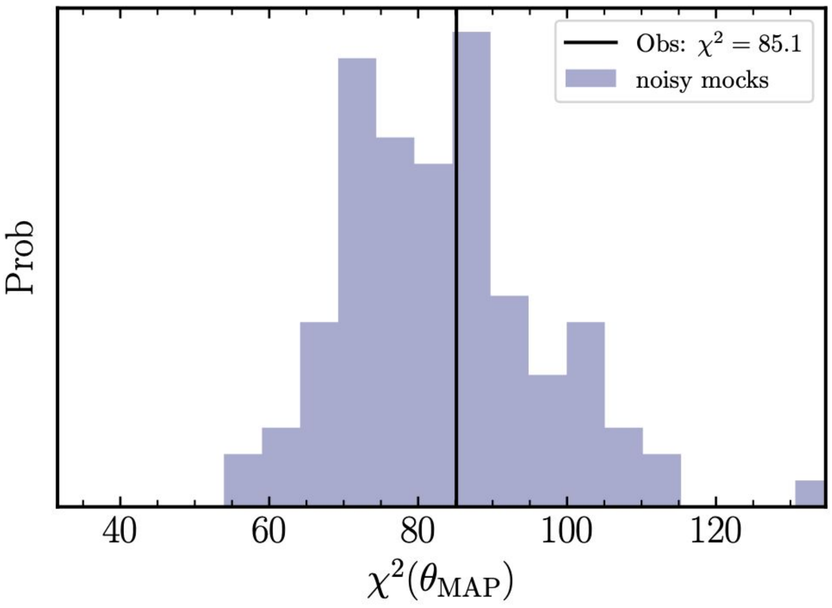
Credit: The HSC collaboration team

- Completed HSC survey has a full-depth full-color coverage of about 1087 deg^2
- Data currently being processed at NAOJ using the latest Rubin science pipelines
- Systematics challenges need to be overcome to leverage the statistical power
  - Blending of galaxies, PSF systematics, Source redshift uncertainties amongst others

Backup slides

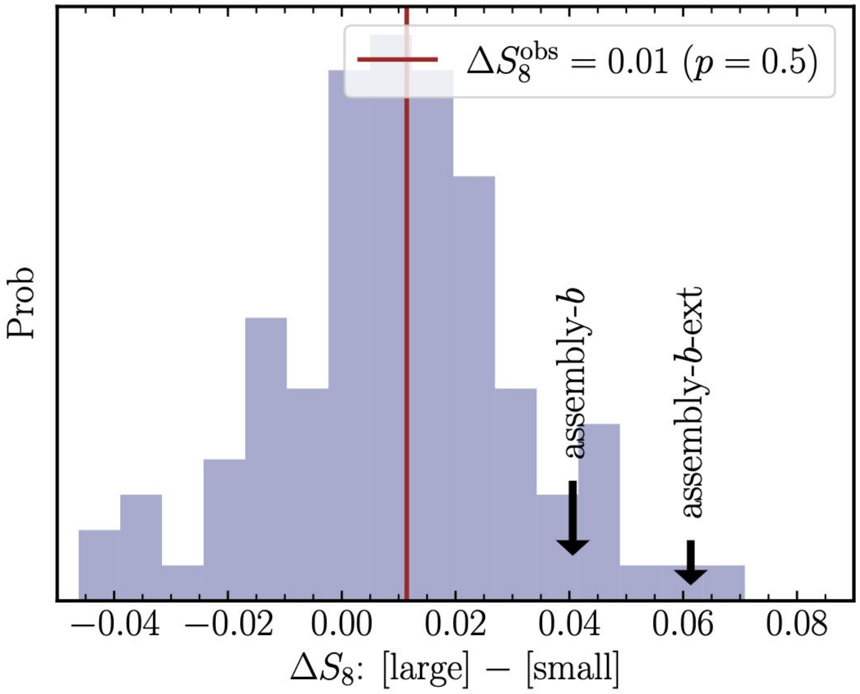
Model Fit





p-value = 0.41

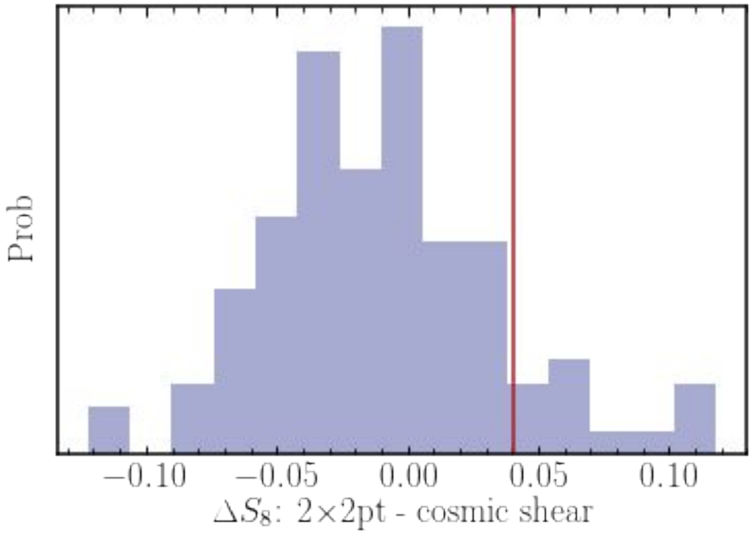
Agreement between 3x2pt large-scale and small-scale analyses



We tested the statistical agreement of the 3x2pt large-scale and small-scale analysis, using noisy mock analysis.

- Real data results are in a nice agreement.
- If galaxy clustering is affected by assembly bias, we can flag the presence of the effect by > 2σ level.

Consistency between Cosmic shear & 2x2pt



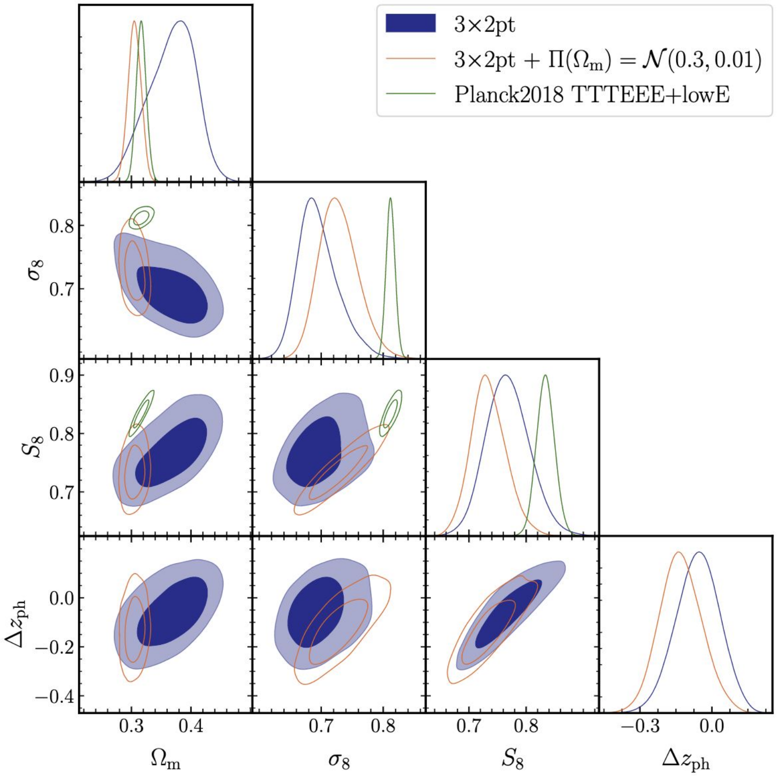
There is correlation between S8 estimates from cosmic shear & 2x2pt because both uses HSC galaxies.

We assess the correlation by running 100 noisy mock analyses (histogram).

We found S8 estimates from cosmic shear and 2x2pt are statistically consistent each other.

Here, cosmic shear is not tomographic cosmic shear,
tut the single source bin cosmic shear used in 3x2pt

Adding the BAO prior on Ω_m



We found relatively larger Ω_m value from HSC Y3 3x2pt analysis.

When we include BAO prior on Ω_m, we obtain

- Even smaller S_8 than baseline analysis.
- More significant photo-z bias parameter

$$S_8 = 0.732^{+0.027}_{-0.029}$$

$$\Delta z_{ph} = -0.133^{+0.077}_{-0.084}$$

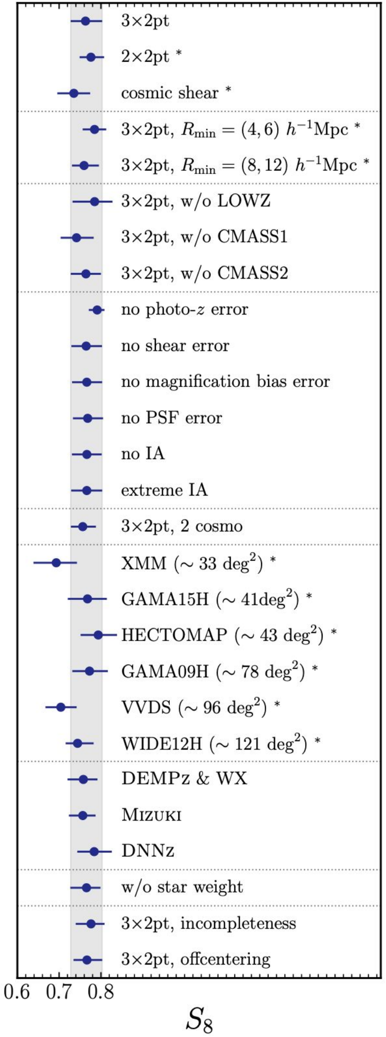
Internal consistency test of 3x2pt

We split the data vector, and analyzed by parts.

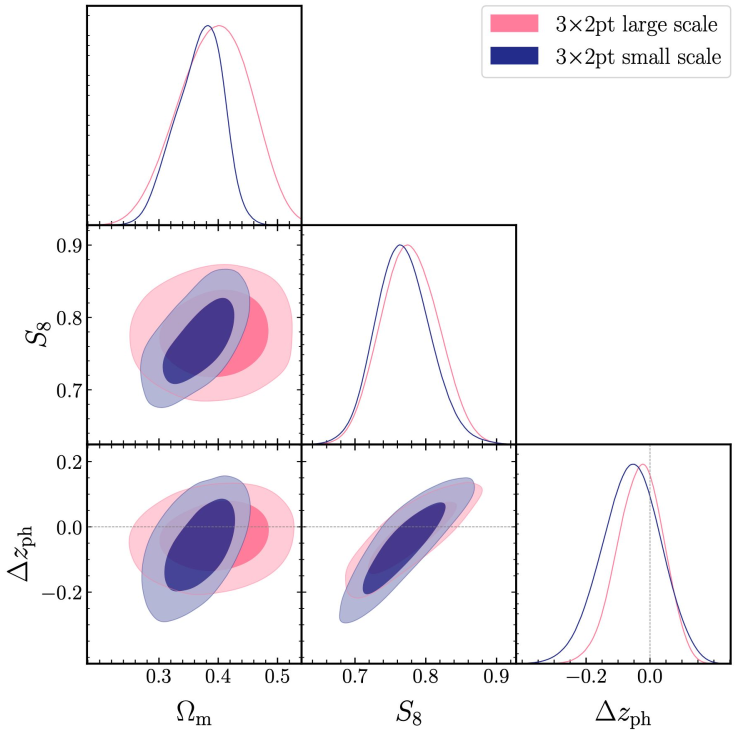
- Removing one lens sample
- Change scale cuts to larger scales (more conservative)
- Varying only two cosmological parameters (Ωm & S8)
- HSC field-by-field analysis.

Systematics

- No systematic parameter
  - photo-z , shear correction, magnification bias, PSF, IA, etc.
- Different photo-z methods
- Lens weights
- Extended model to HOD



Large-scale analysis result



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5% constraint!

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

Large-scale analysis result for flat ΛCDM

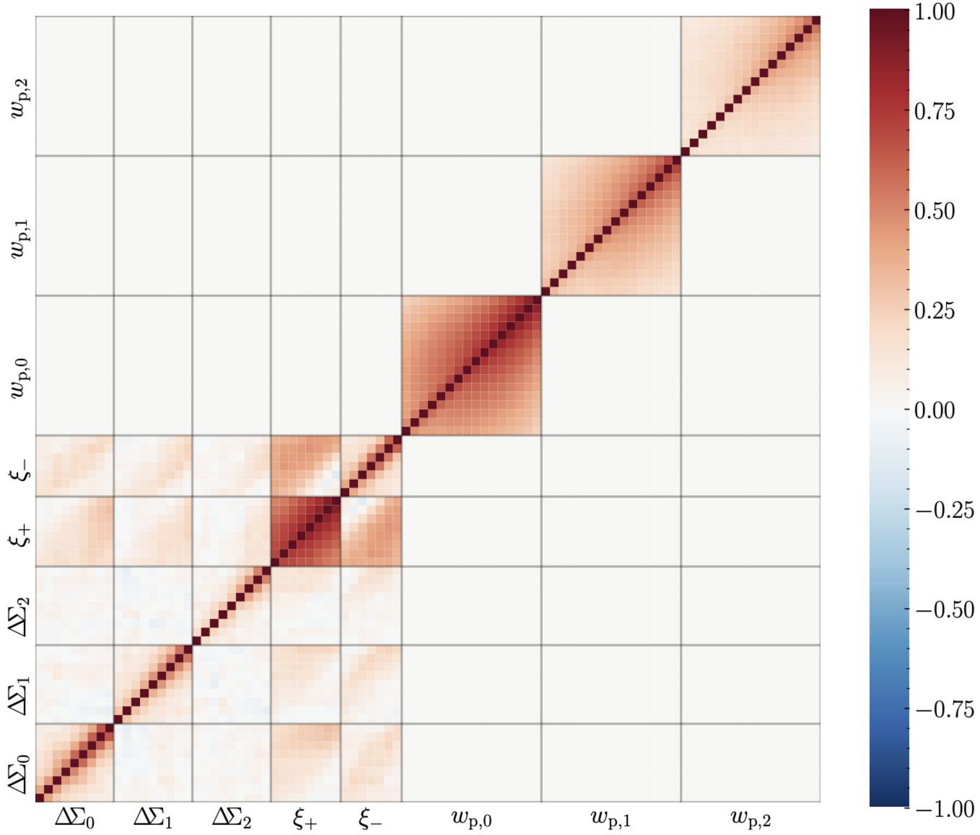
$$\Omega_m = 0.401^{+0.056}_{-0.064}$$

$$\sigma_8 = 0.666^{+0.069}_{-0.051}$$

$$S_8 = 0.775^{+0.043}_{-0.038}$$

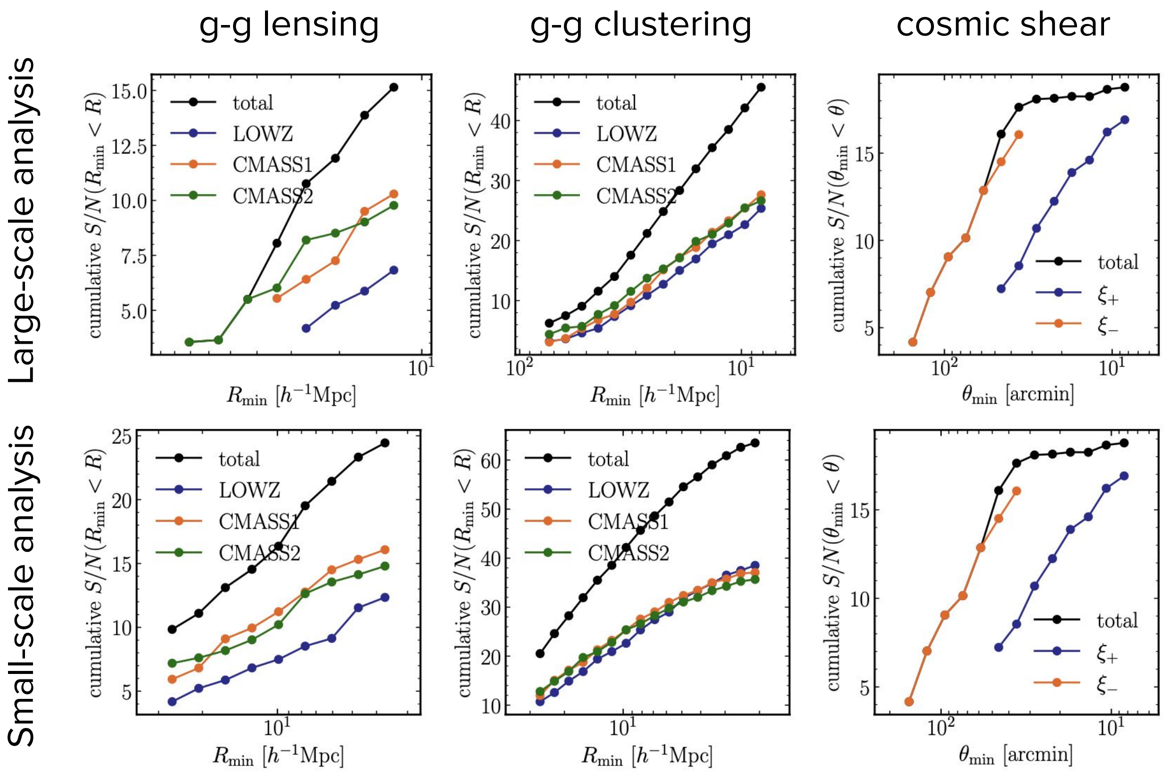
5% constraint!

Covariance

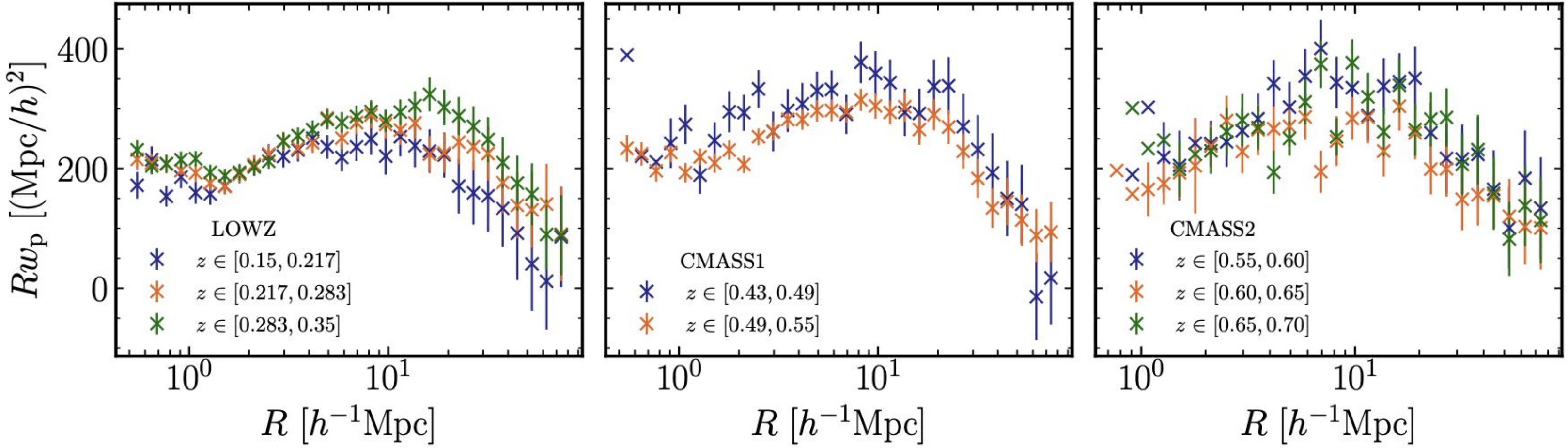


$w_{p,2}$
$w_{p,1}$
$w_{p,0}$
ξ_-
ξ_+
$\Delta\Sigma_2$
$\Delta\Sigma_1$
$\Delta\Sigma_0$
$\Delta\Sigma_0$
$\Delta\Sigma_1$
$\Delta\Sigma_2$
ξ_+
ξ_-
$w_{p,0}$
$w_{p,1}$
$w_{p,2}$
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

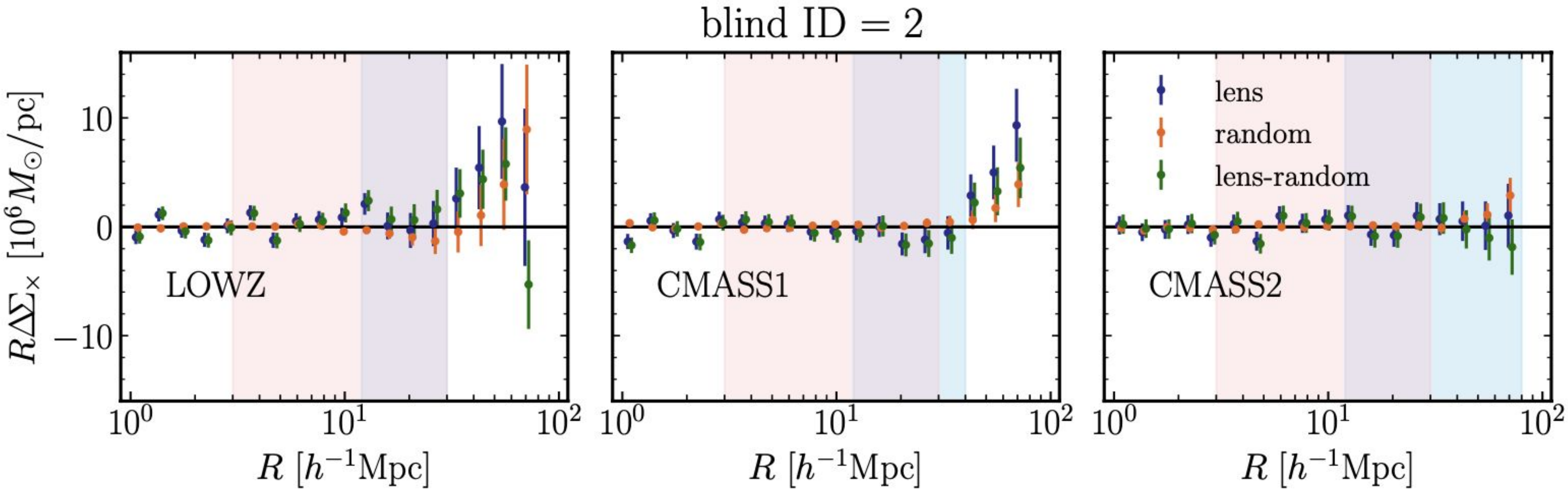
Cumulative SN



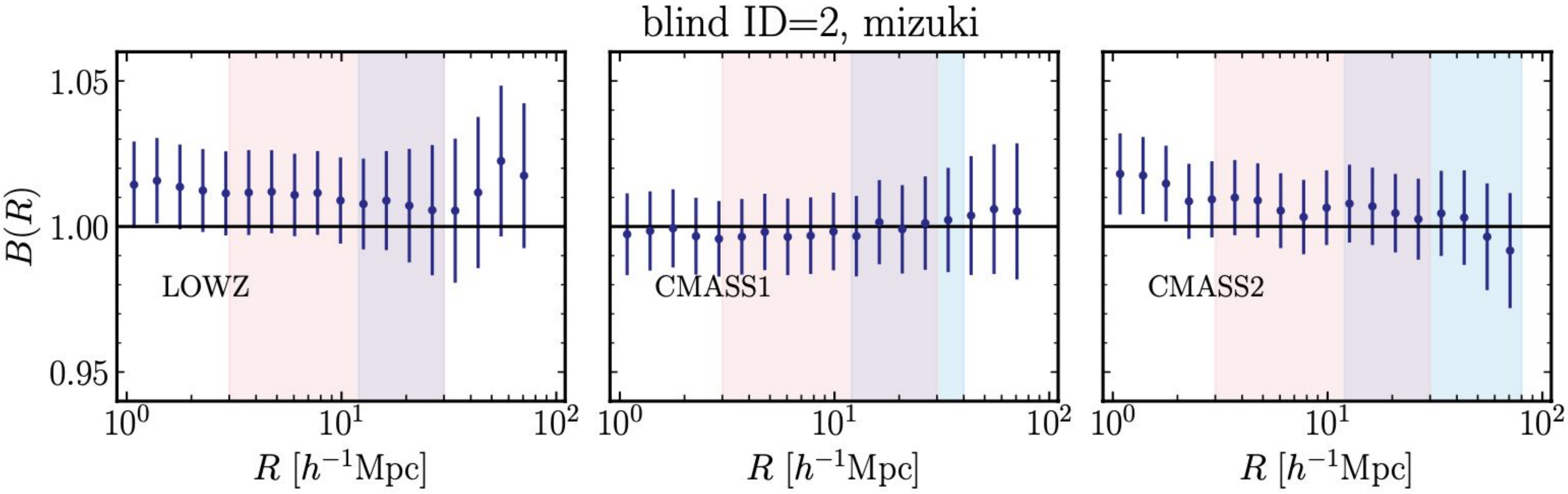
Clustering Measurements with Fine Redshift Bins



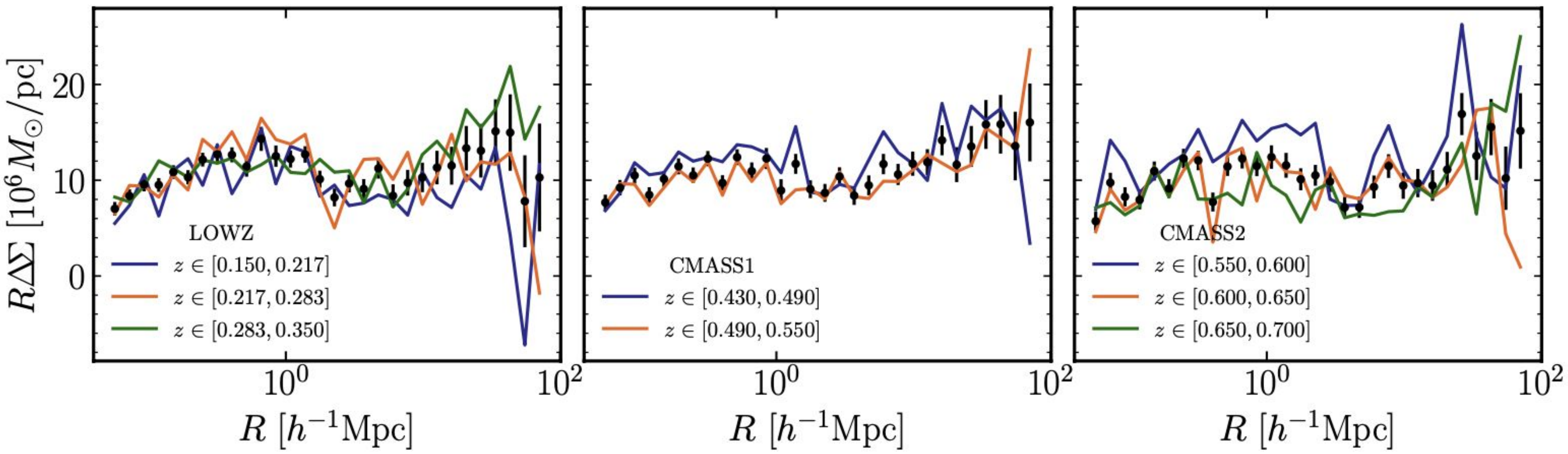
B-mode Signal of Galaxy-galaxy Lensing



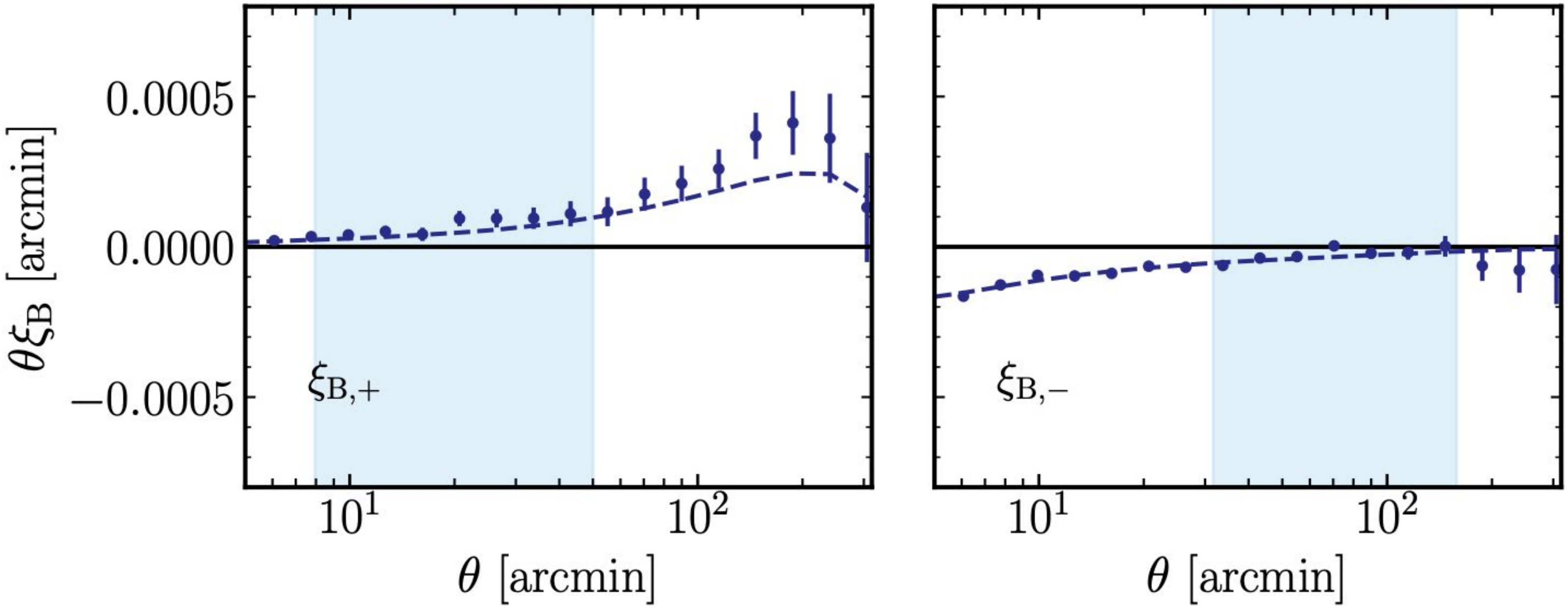
Boost Factor of Galaxy-galaxy Lensing



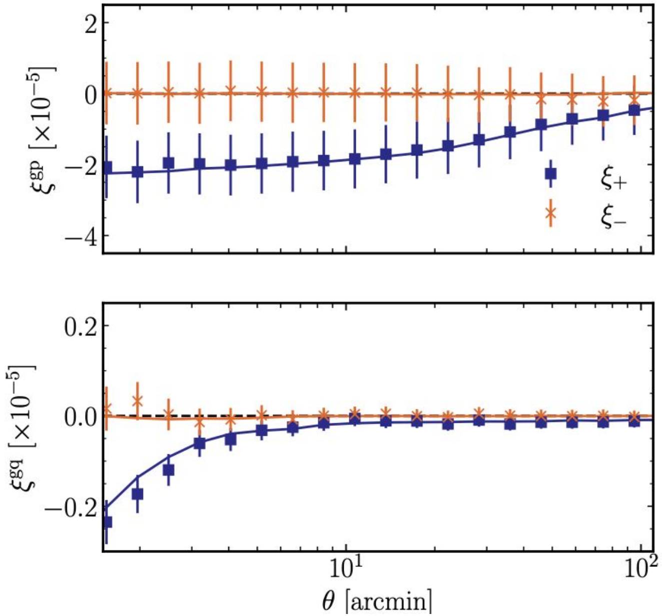
G-g Lensing Measurements with Fine Redshift Bins



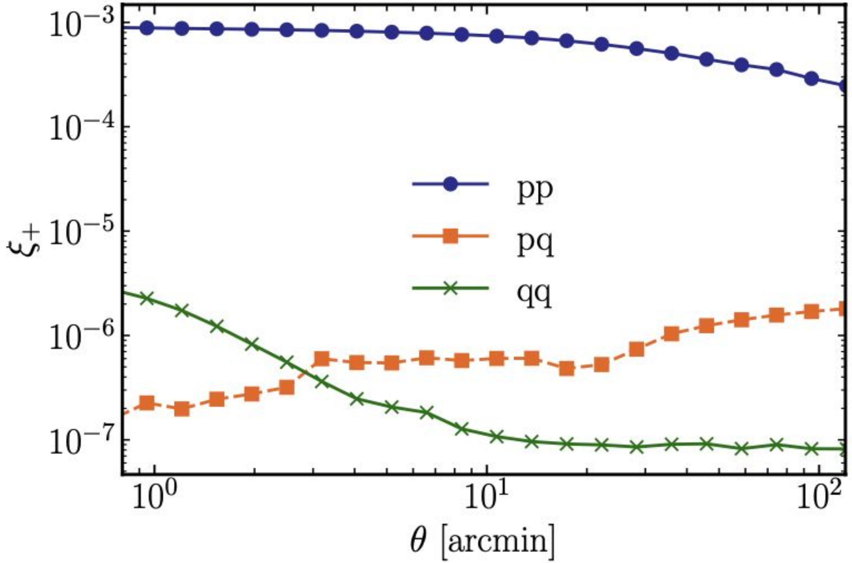
B-mode Signal of Cosmic Shear



PSF Systematics in Cosmic Shear



$$\xi_{\pm}^{gp} = \alpha_{psf}\xi_{\pm}^{pp} + \beta_{psf}\xi_{\pm}^{pq},$$
$$\xi_{\pm}^{gq} = \alpha_{psf}\xi_{\pm}^{pq} + \beta_{psf}\xi_{\pm}^{qq}.$$



$$\xi_{psf,\pm}(\vartheta) = \alpha_{psf}^2\hat{\xi}_{\pm}^{pp}(\vartheta) + 2\alpha_{psf}\beta_{psf}\hat{\xi}_{\pm}^{pq}(\vartheta) + \beta_{psf}^2\hat{\xi}_{\pm}^{qq}(\vartheta)$$

PSF Systematics in Cosmic Shear