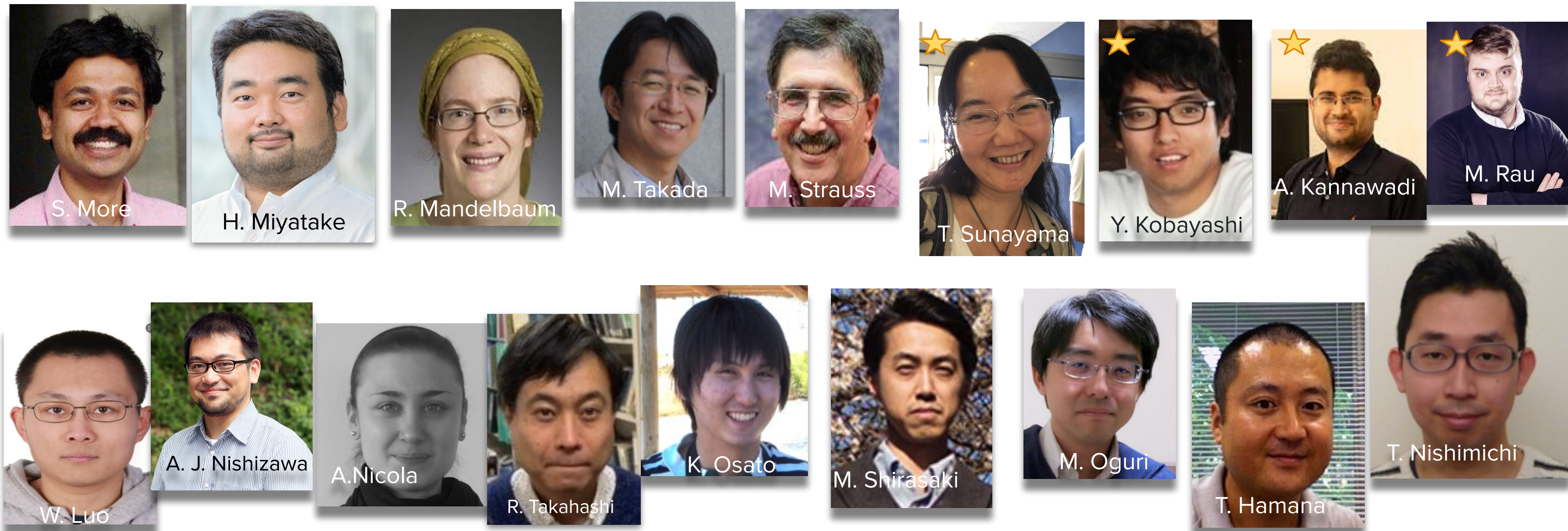
HSC Year 3 Weak Lensing Cosmology Results

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!

HSC Year 3 Weak Lensing Cosmology Results

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 525, 2441)
- Weak Lensing Tomographic Redshift Distribution Inference for the Hyper Suprime-Cam Subaru Strategic Program three-year shape catalogue (**Rau, M.** et al. 2022, MNRAS, 524, 5109)

Cosmology papers

- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Two-Point Correlation Functions (**Li X.**, et al. 2023, PRD, in press)
- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Power Spectra (**Dalal R.**, et al. 2023, PRD, in press)
- 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, PRD, in press)
- 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, PRD, in press)
- 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, PRD, in press)
- *Optical Cluster Cosmology with SDSS redMaPPer clusters and HSC-Y3 lensing measurements (**Sunayama T**, et al., 2023, arXiv:2309.13025)* ← **NEW!**

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

Early career scientists leading the projects marked in bold

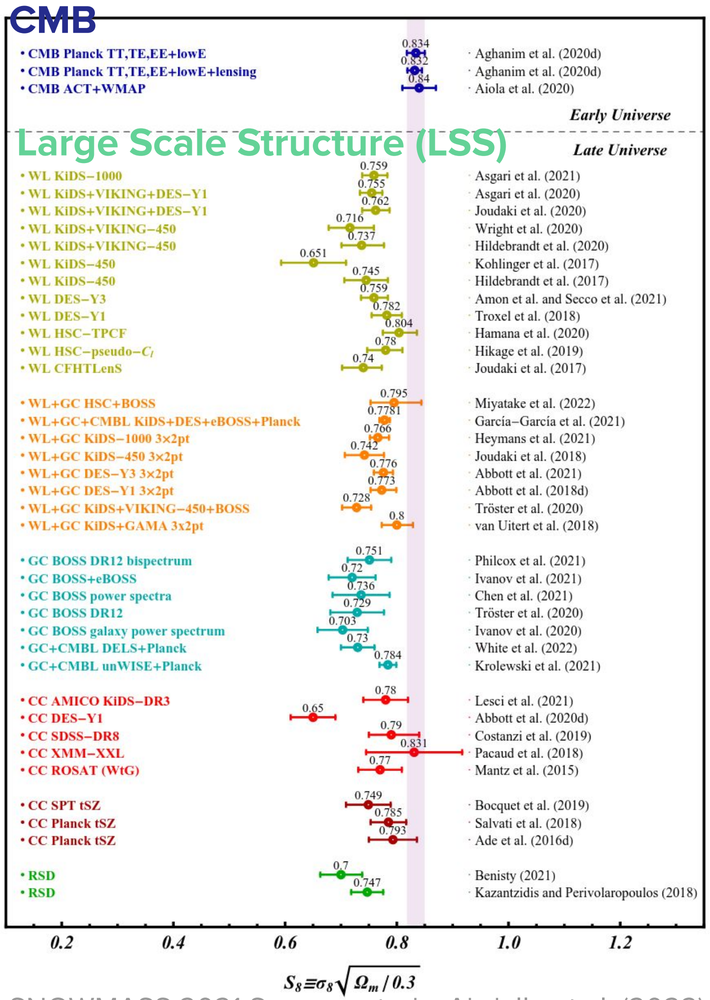
Testing ΛCDM using S_8

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

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

S_8 tension?

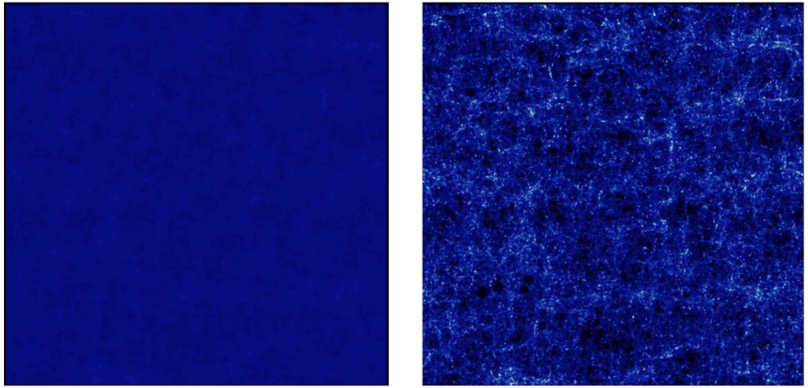
Most large scale structure probes (weak lensing, galaxy clustering, galaxy clusters, etc…) prefer smaller S_8 compared to **CMB**, if we assume ΛCDM is correct.



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

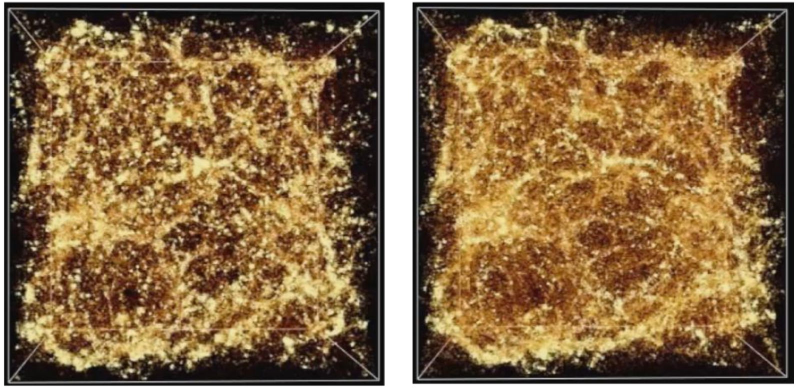
Large Scale Structure of the Universe

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 dark matter**.

Weak Gravitational Lensing

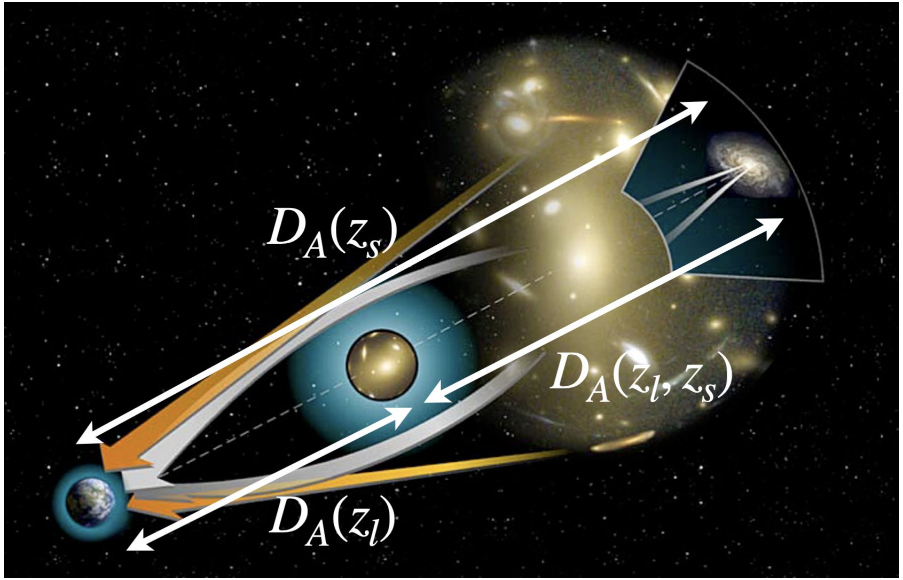
$$\underbrace{\gamma}_{\text{Weak lensing shear}} \propto \Omega_{\rm m} \underbrace{\frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)}}_{\text{Geometry of the Universe}} \underbrace{\delta(z_l)}_{\text{Matter density fluctuation}}$$

Weak lensing shear

Matter density fluctuation

Geometry of the Universe

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



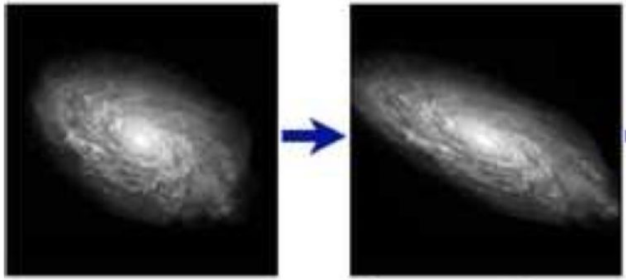
Weak Gravitational Lensing

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

Weak lensing shear

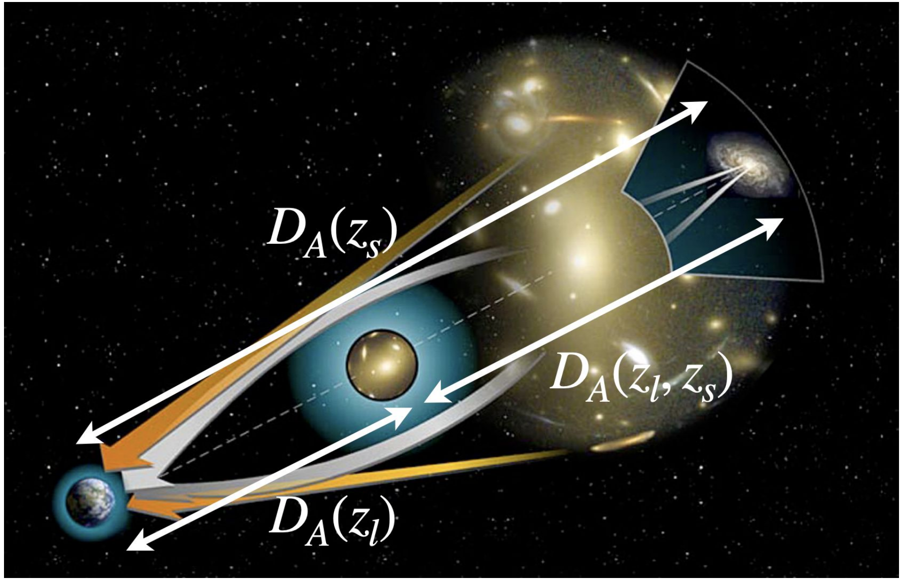
Matter density fluctuation

Geometry of the Universe



Intrinsic galaxy (shape unknown)

Gravitational lensing causes a **shear (g)**



Observables

γ : Average of **galaxy shapes**

- Calibration by image simulations (Mandelbaum+, 2015)
- Meta-calibration (Huff & Mandelbaum, 2017)

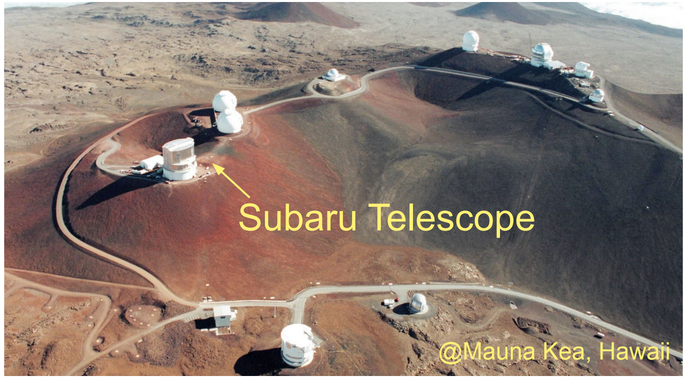
z_l, z_s : **Redshift** of lenses and sources

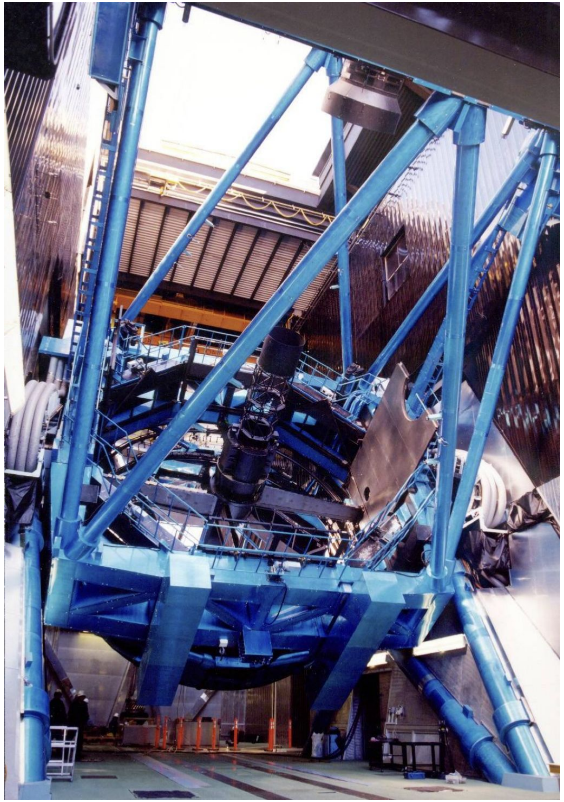
→ **Can be major systematics!**

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.





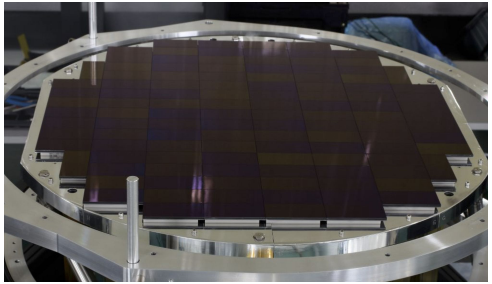
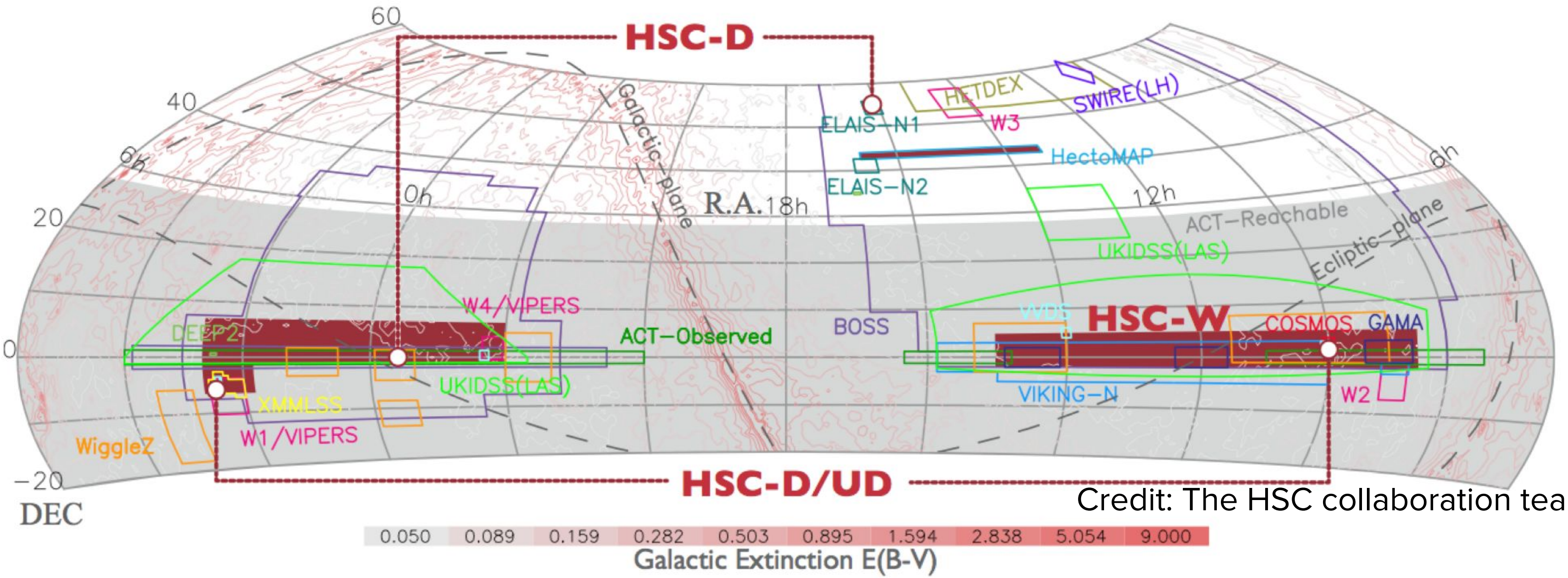


Photo credit: NAOJ / HSC Project

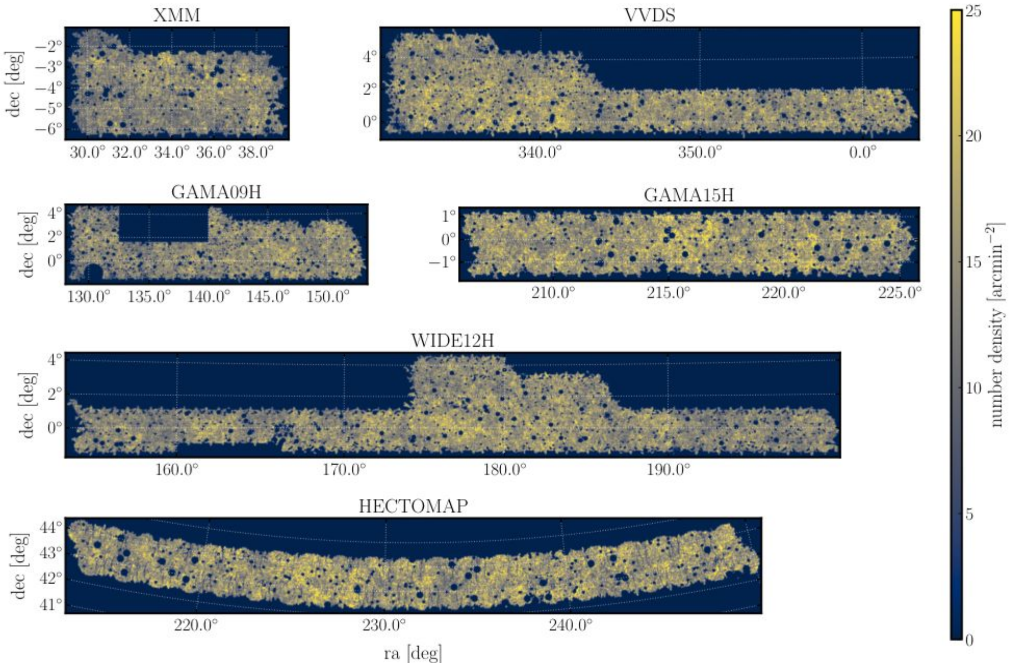
HSC Subaru Strategic Program (SSP) Survey



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 talk, 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

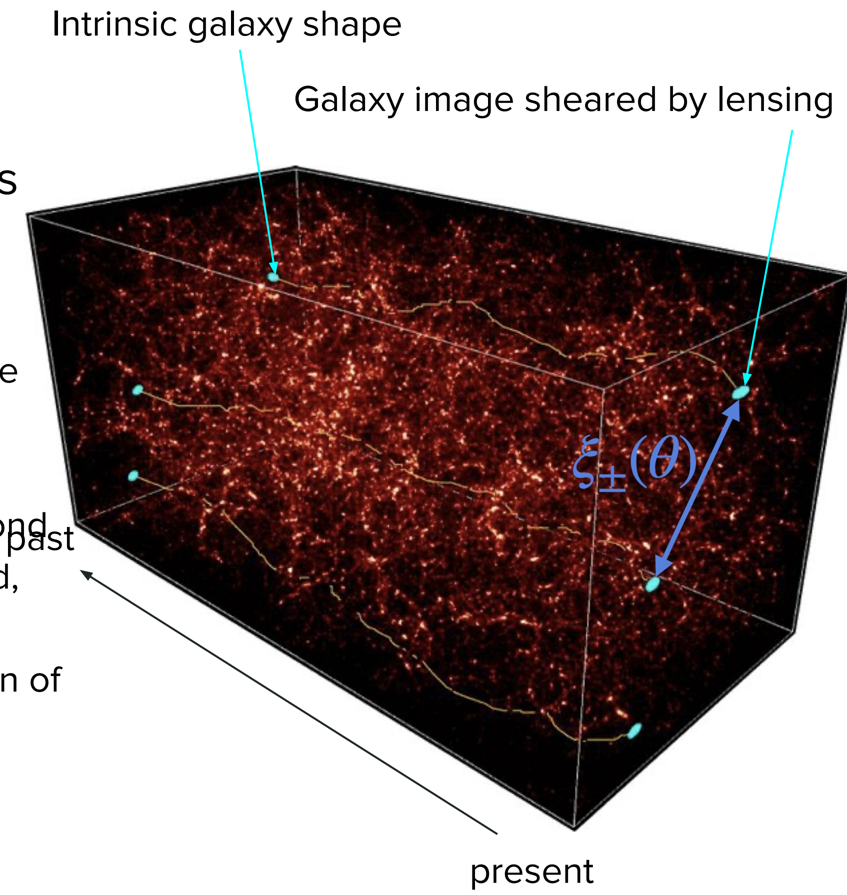
Result 1: Cosmic Shear


Li et al. (2023)


Dalal et al. (2023)

Weak Lensing Cosmology

- LSS is sensitive to cosmological parameters (Ω_m, σ_8) and $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$
- Cosmic shear
    - $\xi_{\pm}(\theta)$ (2 Point Correlation Functions) - measures the correlation of shapes of galaxies with an angular separation θ.
    - C_ℓ (Angular Power Spectrum) - measures the second moment of the Fourier transform of the shear field, as a function of multipole (ℓ).
    - We use four redshift bins to measure the evolution of large scale structure.



S. Colombi (IAP), CFHT Team

Redshift distribution inference


Rau+2022

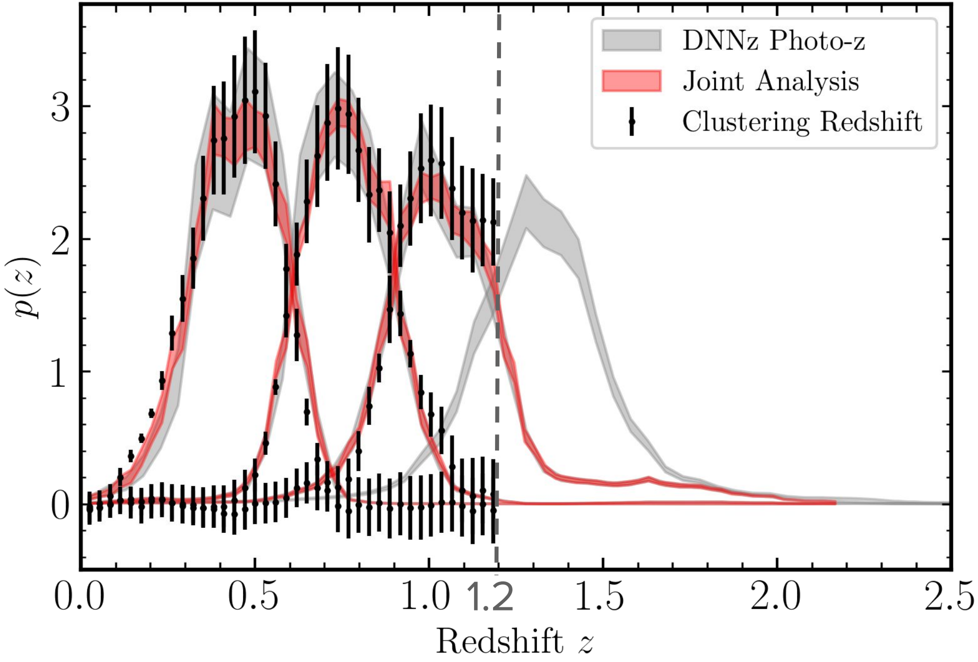
Grey: photo-z likelihood (DNNz) + cosmic variance

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

Red: joint posterior of the two

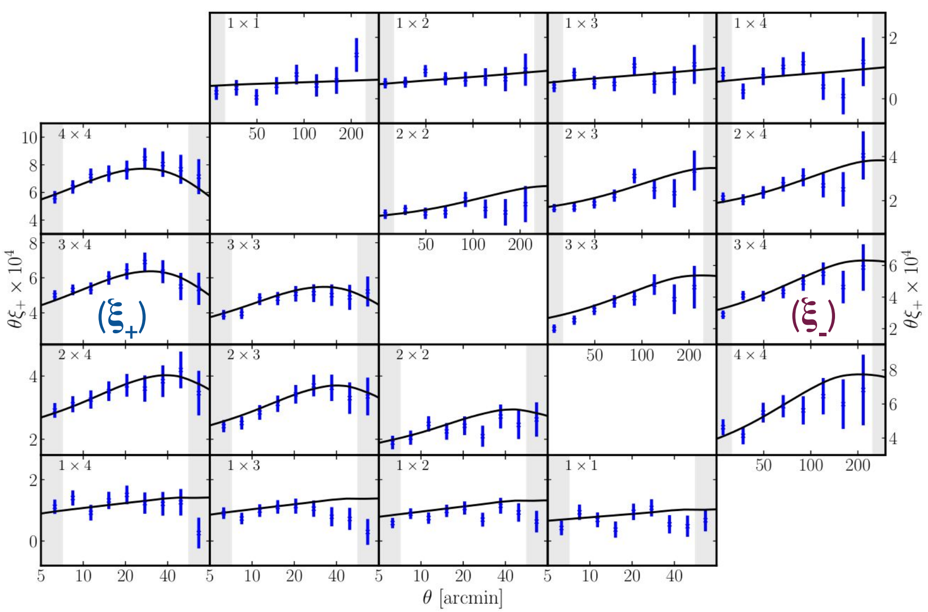
Source galaxies with z>1.2 are <u>not</u> calibrated by CAMIRA-LRG samples.

- Δz_1 , Δz_2: Gaussian prior σ~0.02
- Δz_3 , Δz_4: ***Uniform prior [-1, 1]***

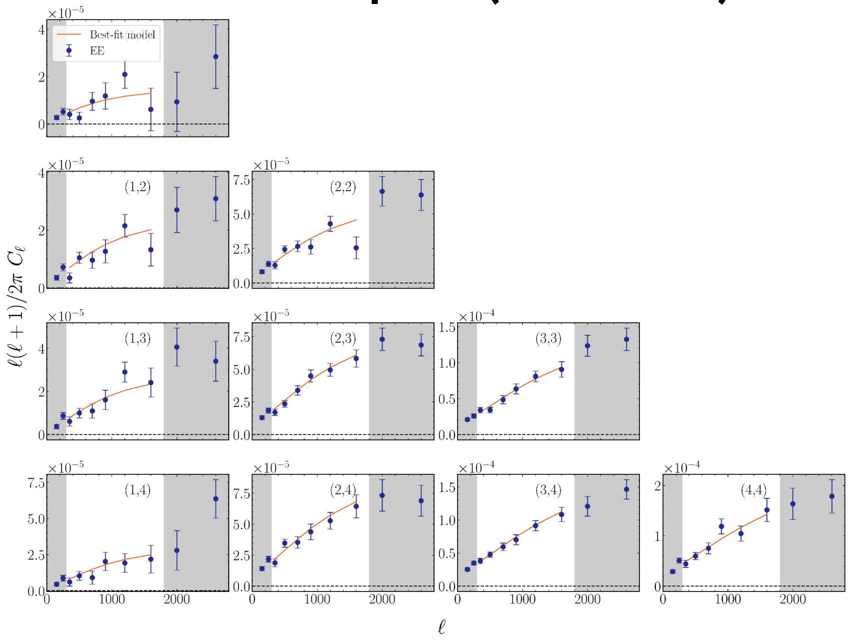


Measurements

Real Space (SNR=26.6)

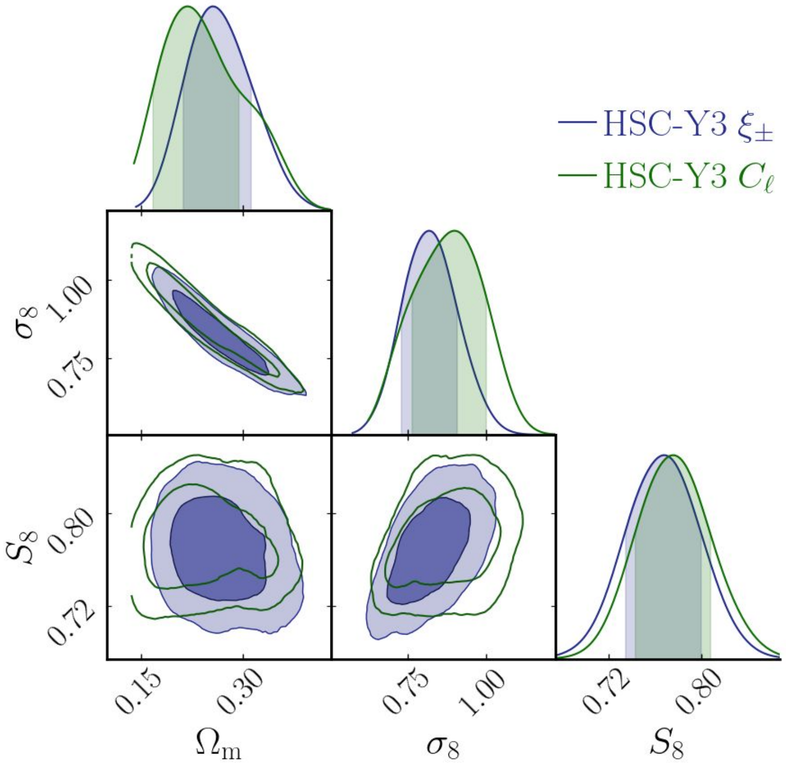


Fourier Space (SNR=26.4)

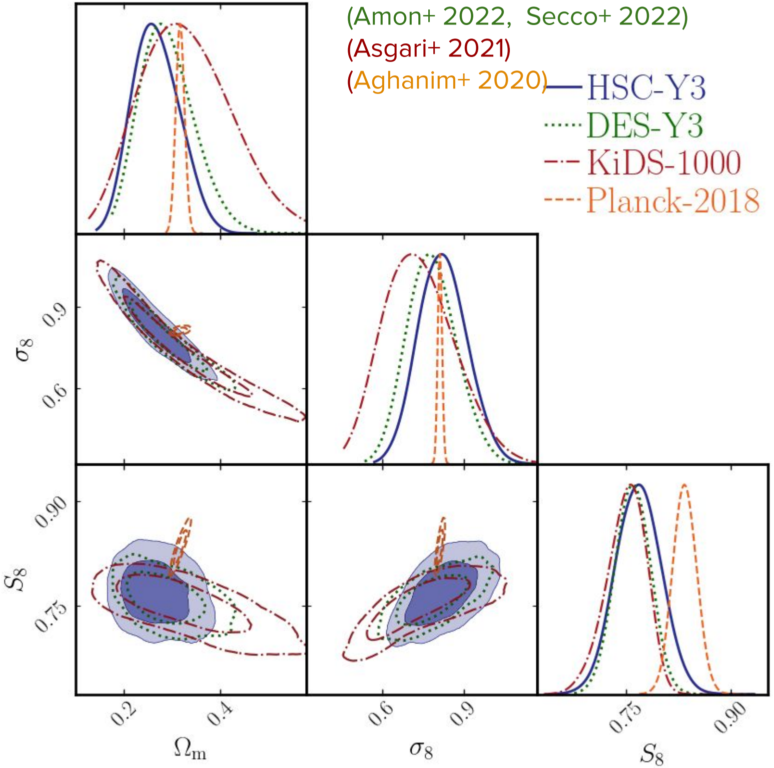


Comparison with Fourier Space analysis and Other Observations

Real space and Fourier space analyses are consistent with each other. Note that the two analyses rely on different scales.

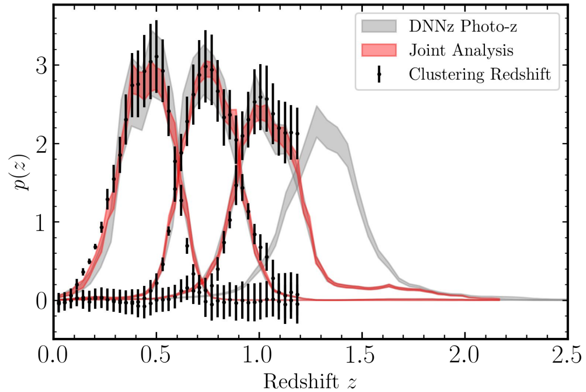


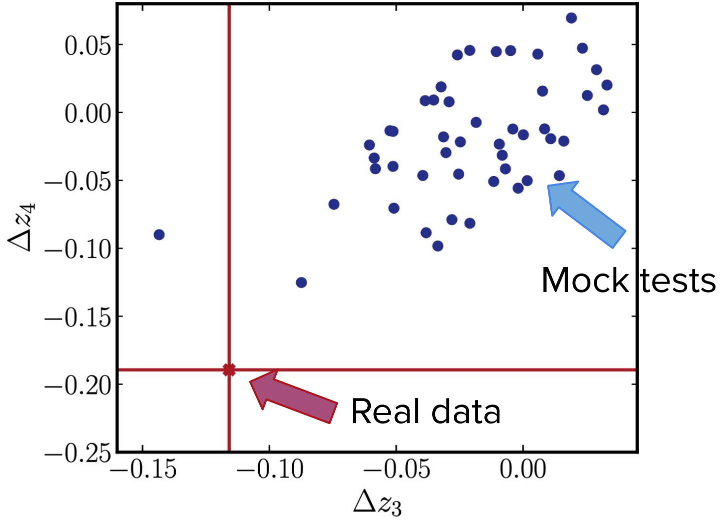
Our analysis is consistent with other weak-lensing analyses but has a **2σ** tension with ***Planck-2018***



Prior on Δz_3 and Δz_4

Rau+2022
Li+2023
Dalal+2023

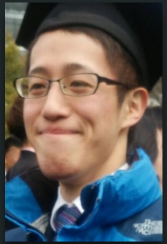




Comparing statistical spread of Δz3 and Δz4, versus the shift using a flat prior. (real space)

- Mock test to show that the shift in Δz_3 and Δz_4 is statistically significant.
  - Δz<0 means true redshift is shifted towards higher redshift.
- We use a flat prior for Δz_3 and Δz_4 Δz = [-1, 1]
- ***We made this decision before unblinding.***

Results2: 3x2pt Analyses

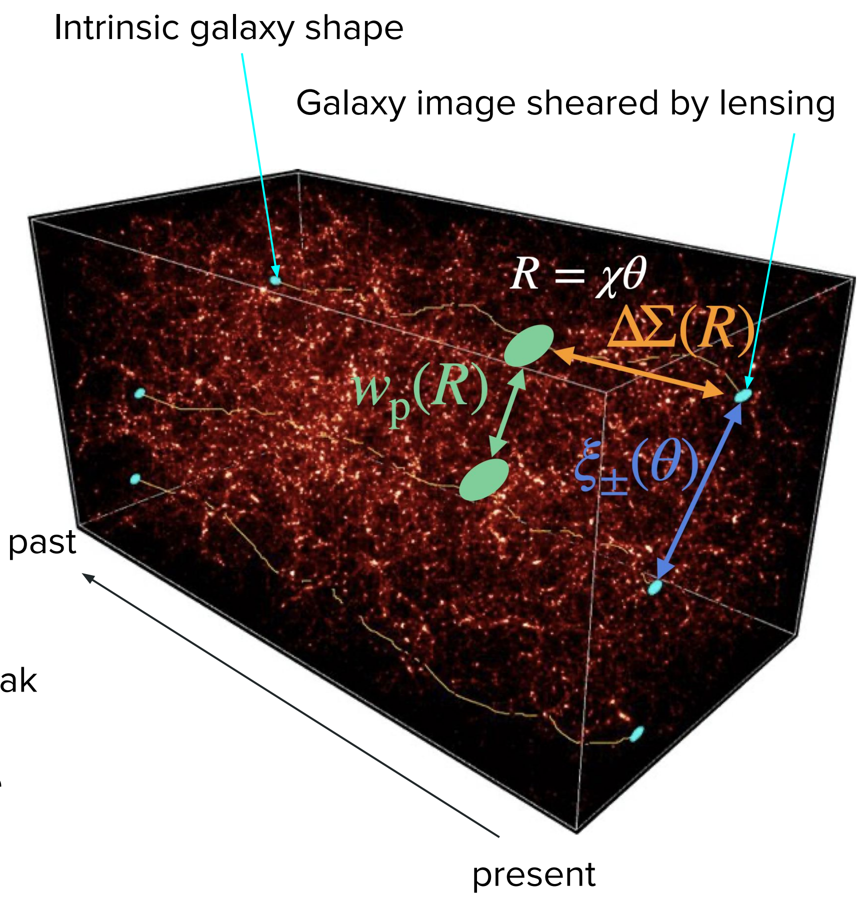

Sugiyama+ (2023)


More+ (2023)


Miyatake+ (2023)

3x2pt Analysis

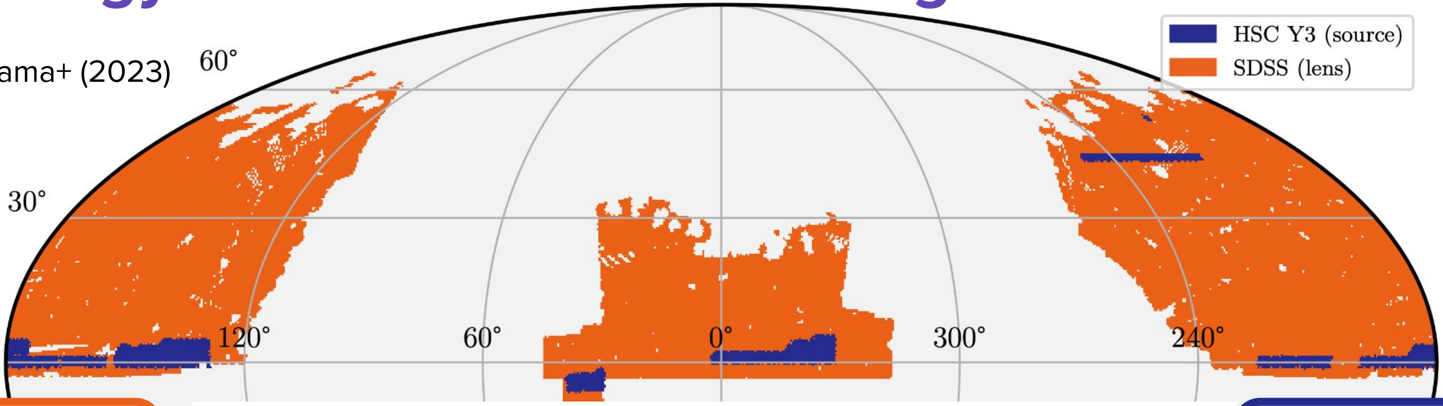
- LSS is sensitive to cosmological parameters $(\Omega_\mathrm{m}, \sigma_8)$ and $S_8 \equiv \sigma_8\sqrt{\Omega_\mathrm{m}/0.3}$
- **Cosmic shear + 2x2pt: 3x2pt**
  - **2x2pt: Galaxy-galaxy clustering x lensing**
    - Auto-correlation of galaxy positions
    - Cross-correlation of galaxy positions and weak lensing shear
  - We performed large-scale analysis and small-scale analysis.



S. Colombi (IAP), CFHT Team

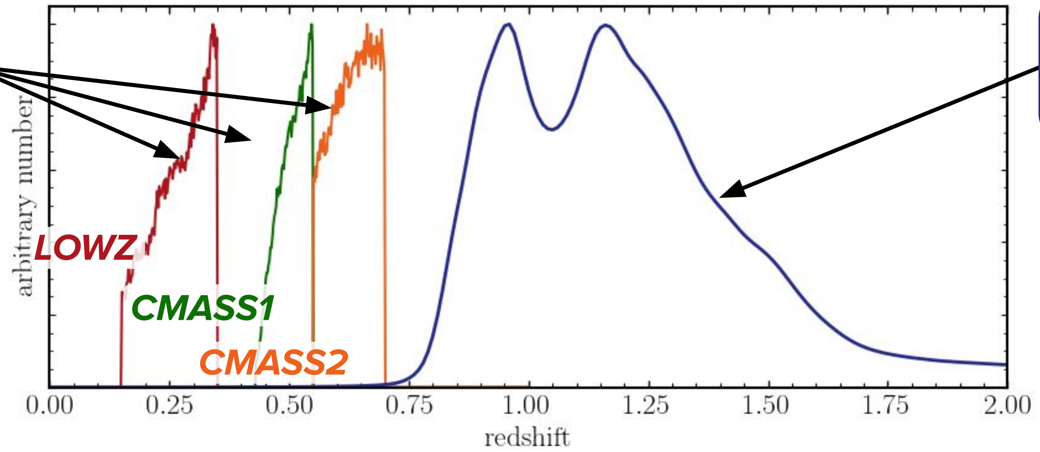
Cosmology with HSC x SDSS catalogs

More, Sugiyama+ (2023)



SDSS spec-z sample
lens galaxies

Luminosity cuts are applied to obtain (nearly) volume-limited sample.



HSC shape sample
source galaxies

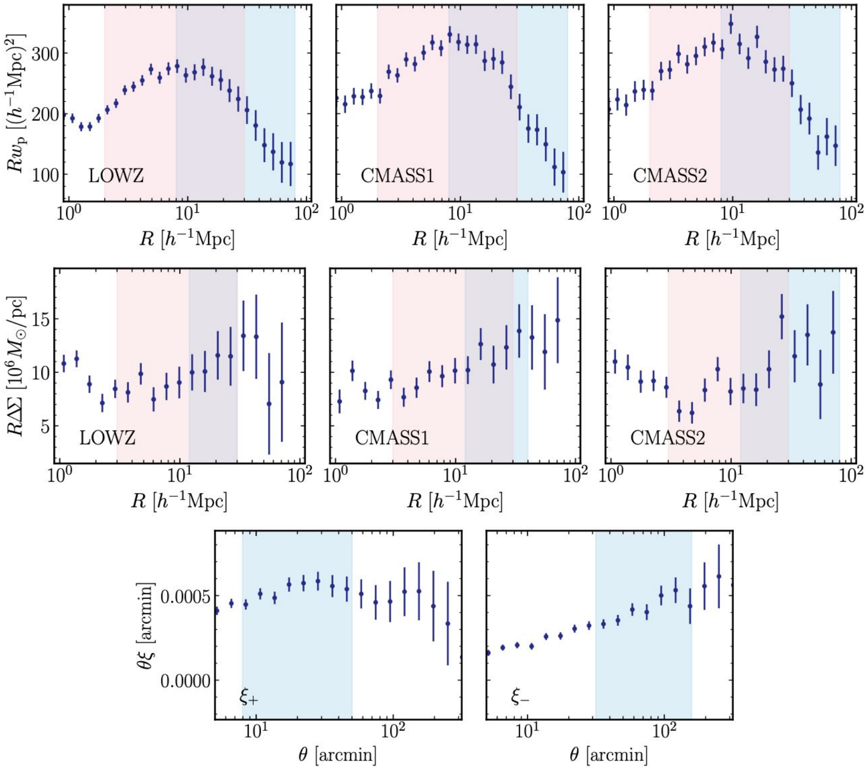
Single source sample for 3x2pt analysis, which is different from tomographic cosmic shear source samples.

Measurements

Small scale analysis: more S/N, difficulty in modeling
Large scale analysis: linear bias approx. holds

More+ (2023)

- Various systematic tests
  - Confirmed no redshift evolution in g-g lensing and clustering
  - g-g lensing: B-mode, boosts
  - g-g clustering: different luminosity cuts
  - cosmic shear: B-mode, imperfect PSF modeling/correction



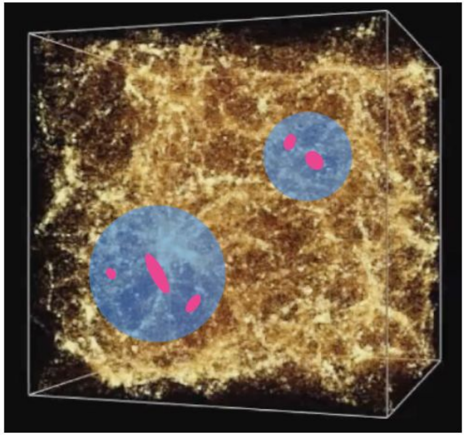
SNR~46

SNR~24

SNR~19

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. $(\sigma_8, \Omega_m, \dots)$ → $\xi_{hh} = \langle \delta_h \delta_h \rangle$, $\xi_{hm} = \langle \delta_h \delta_m \rangle$ → $\xi_{gg} = \langle \delta_g \delta_g \rangle$, $\xi_{gm} = \langle \delta_g \delta_m \rangle$ → (Projection to 2-d) → Observables

Observables

Clustering: $w_p(R)$

Weak Lensing: $\Delta\Sigma(R)$

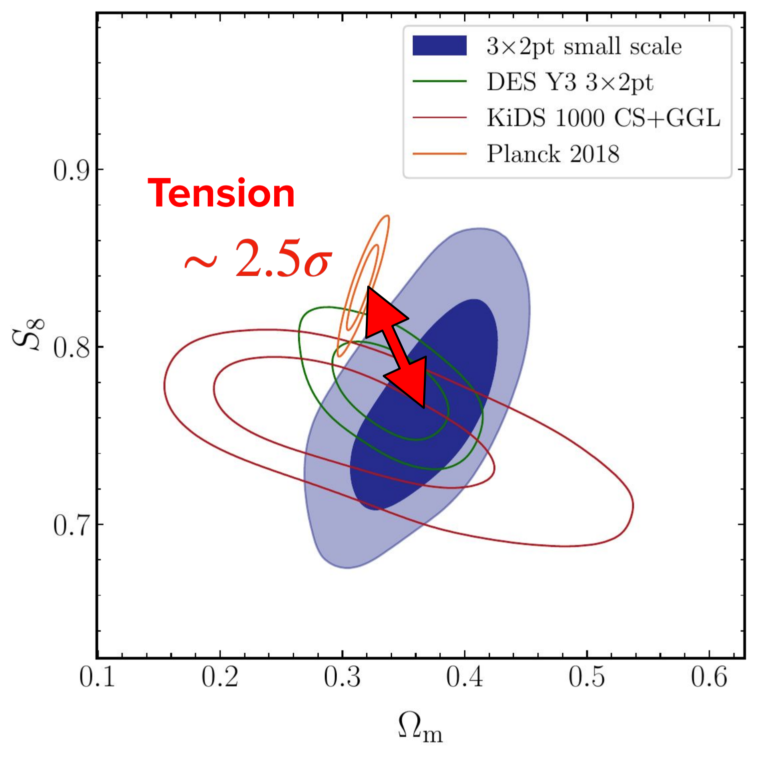
Projection to 2-d

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

Nishimichi+ (2019)
Miyatake+ (2022)

Cosmology from HSC x SDSS 3x2pt analyses



Small-scale analysis result for flat ΛCDM

$$\Omega_{\rm m} = 0.382^{+0.031}_{-0.047}$$

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

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

5% constraint!

- Good agreement between small & large-scale analysis.
- Small-scale analysis is most sensitive to

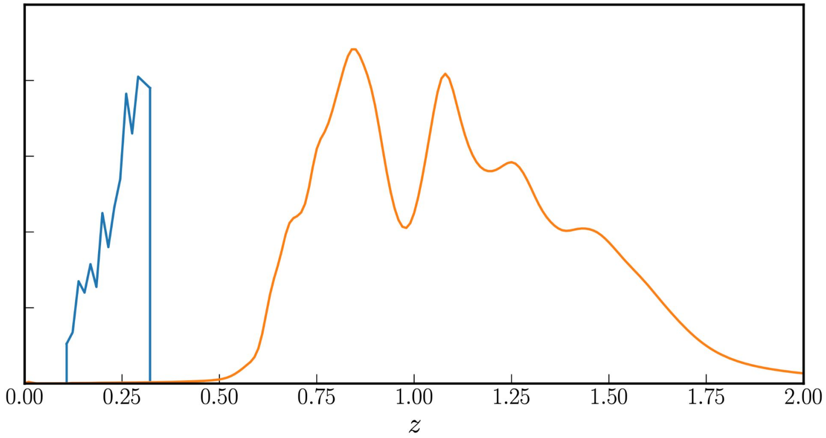
$$S_8' \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.22} = 0.721 \pm 0.028$$

Results3:
Cluster Cosmology with WL calibrations

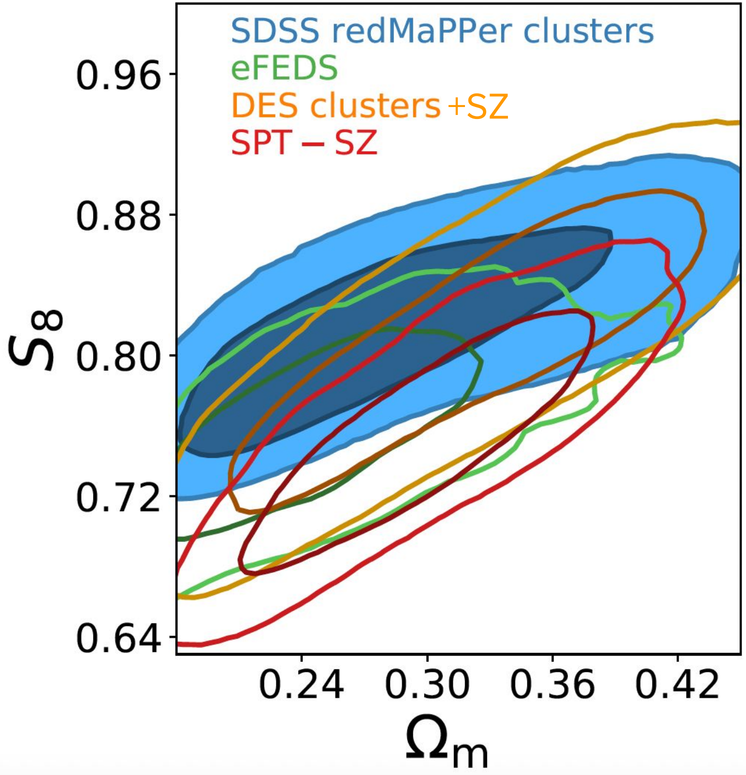

Sunayama+ (2023)

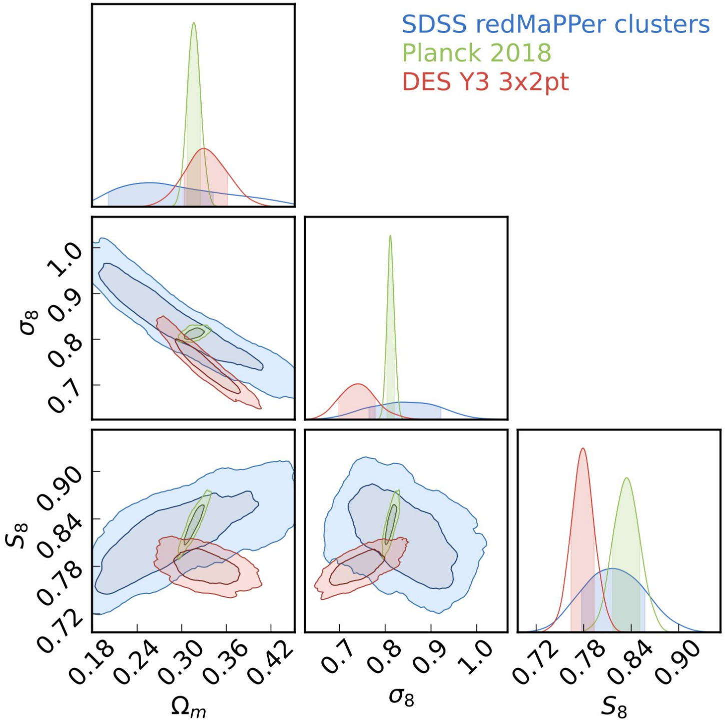
Cluster cosmology with SDSS clusters and HSC WL mass calibration

- Cluster abundance is sensitive to S_8.
- SDSS redMaPPer clusters at $0.1 < z < 0.33$.
- Conservative selection for HSC source galaxies.
- Calibrated projection effect by combining cluster-clustering. (Sunayama+ 2020, Park+ 2022).



Cluster cosmology with SDSS clusters and HSC WL mass calibration

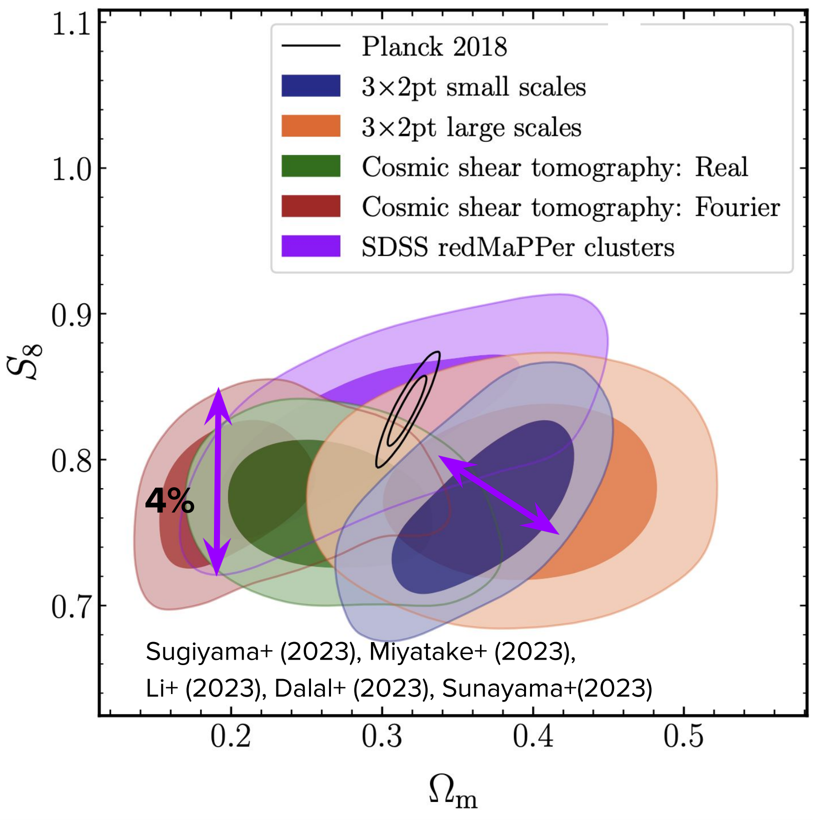




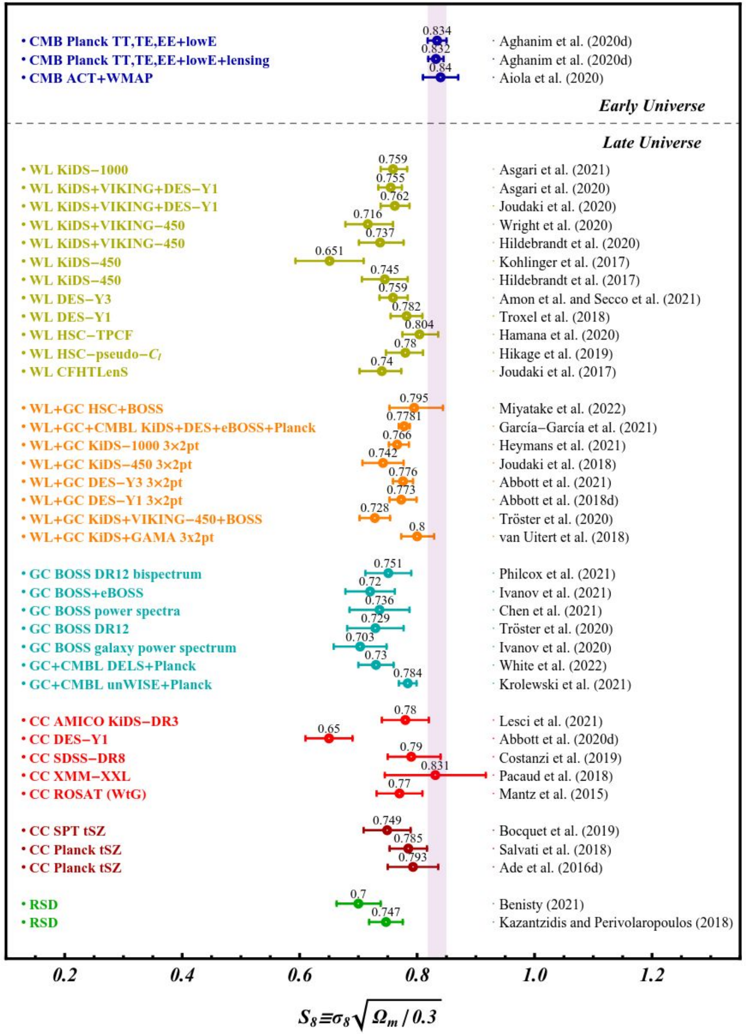
Sunayama+ (2023)

Summary

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)
  - Optically-selected clusters
- Conservative analyses in the presence of systematic uncertainties in the redshifts of source galaxies
- Difference from the CMB expectation in LCDM model context based on various tension metrics is ~2.5 sigma.



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

HSC-Y3 Cosmic shear analyses:

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

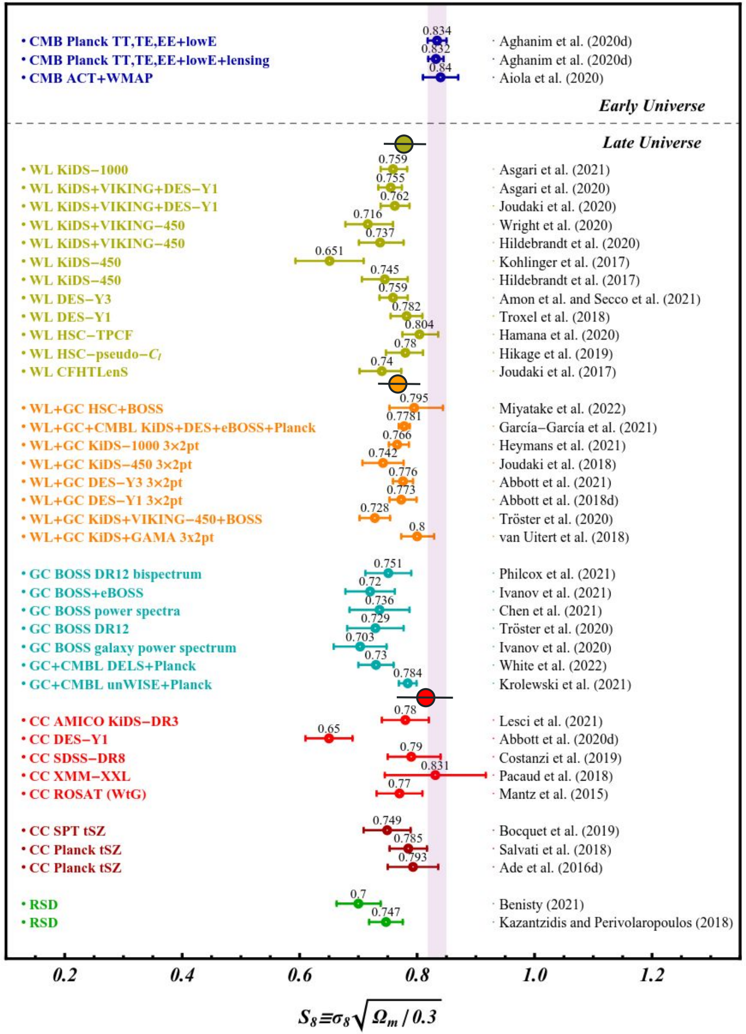
HSC-Y3 3x2 pt analyses:

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

SDSS cluster cosmology with HSC-Y3 WL calibration:

Sunayama et al. (2023)

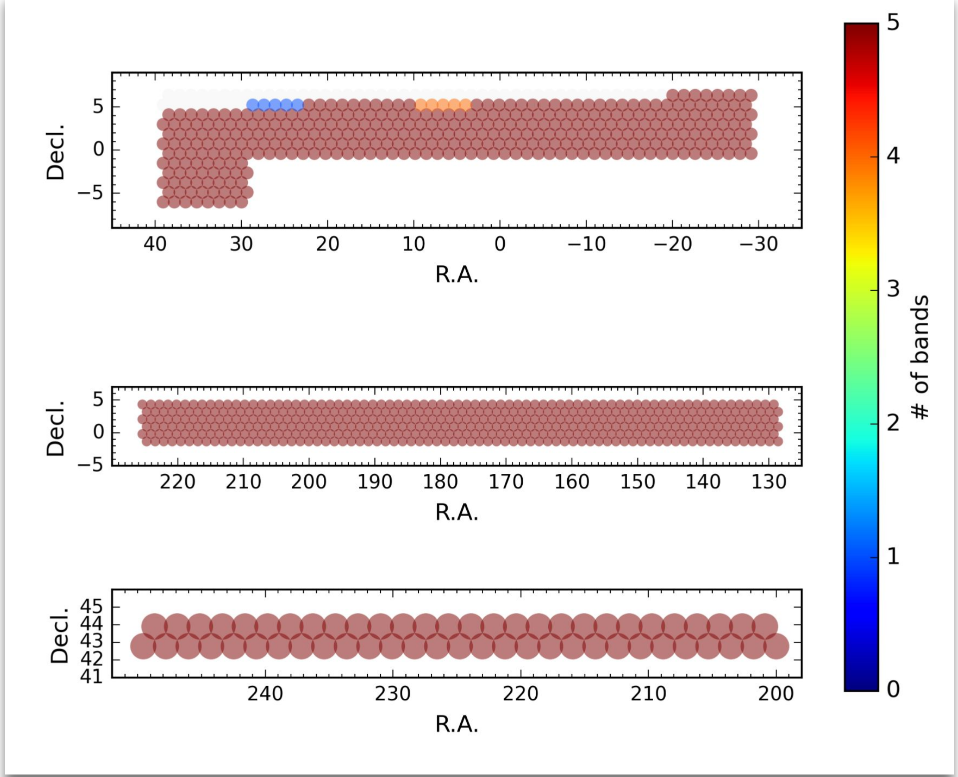
SNOWMASS 2021 Summer study: Abdalla et al. (2022)



Are we reaching the limits of the standard cosmological model?

ACT DR6 CMB lensing result is consistent with Planck Primary CMB

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