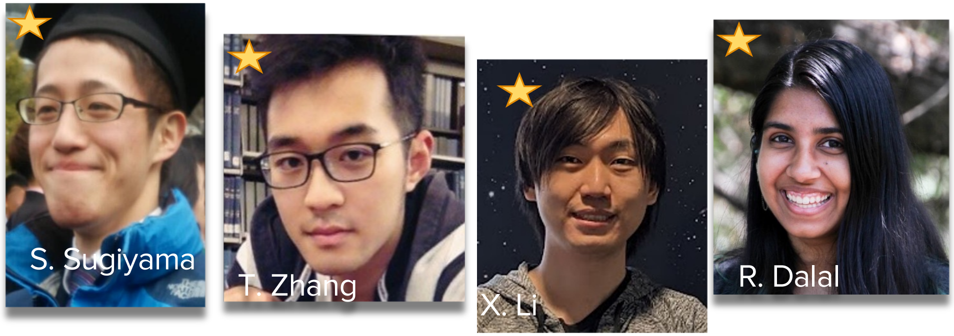
Subaru HSC Year 3 Cosmology results

Masahiro Takada (Kavli IPMU)

On behalf of Subaru HSC collaboration

Weak lensing working group



And efforts of many more!

Key weak lensing group publications: HSC Year 3

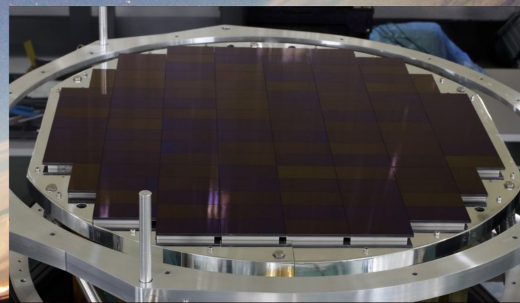
- The three-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey (**Li X.**, et al. 2022, PASJ, 74, 2)
- A General Framework for Removing Point Spread Function Additive Systematics in Cosmological Weak Lensing Analysis (**Zhang T.** et al. 2022, MNRAS submitted, arXiv:2212.03257)
- Weak Lensing 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)
- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Two-Point Correlation Functions (**Li X.,** et al. 2023, PRD, to be submitted)
- Hyper Suprime-Cam Year 3 Results: Cosmology from Cosmic Shear Power Spectra (**Dalal R.,** et al. 2023, PRD, to be submitted)
- Hyper Suprime-Cam Year 3 Results: Measurements of the Clustering of SDSS-BOSS galaxies, galaxy-galaxy lensing and cosmic shear (More S., **Sugiyama S**., et al. 2023, PRD, to be submitted)
- 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, to be submitted)
- 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., **Sugiyama S.**, et al. 2023, PRD, to be submitted)

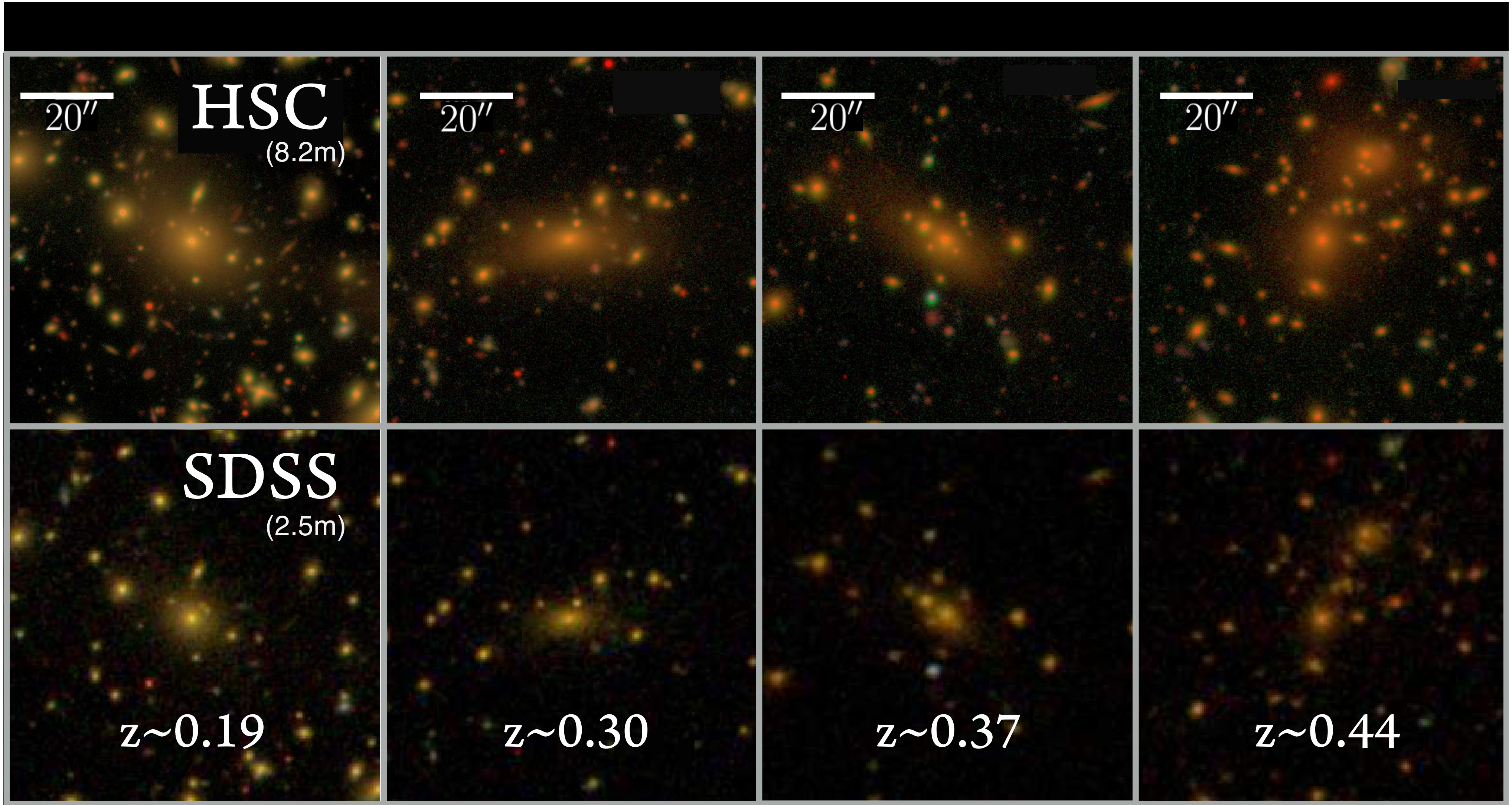
https://hsc-release.mtk.nao.ac.jp/doc/index.php/wly3/

Early career scientists leading the projects marked in bold

Subaru Telescope Hyper Suprime-Cam (HSC)

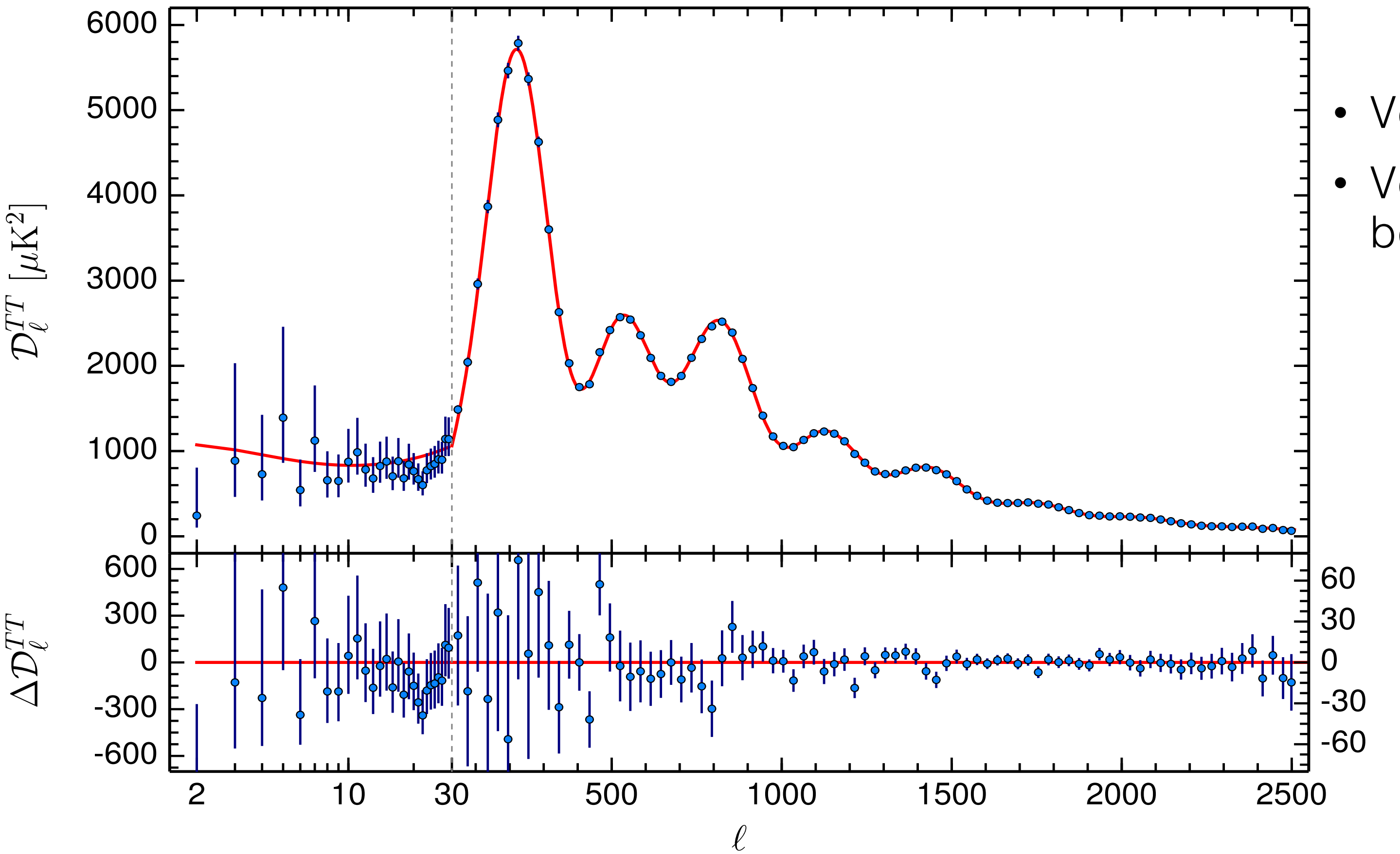
- Large aperture (8.2m)
- Wide field-of-view (1.5 deg. diameter)
- Excellent image quality (~0.6 arcsec)
- A precursor survey of Rubin LSST





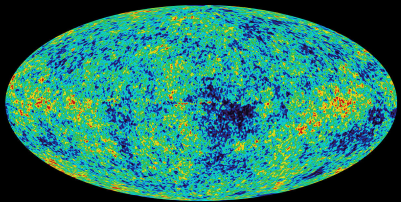
Huang et al. 2017

ΛCDM model: the standard model of the Universe



- Very successful
- Very simple! (too simple to be true?)
  - Dark matter
  - Dark energy
  - Baryon
  - Primordial fluctuations (ns and As) or inflation
  - (optical depth)

A stringent test of LCDM model



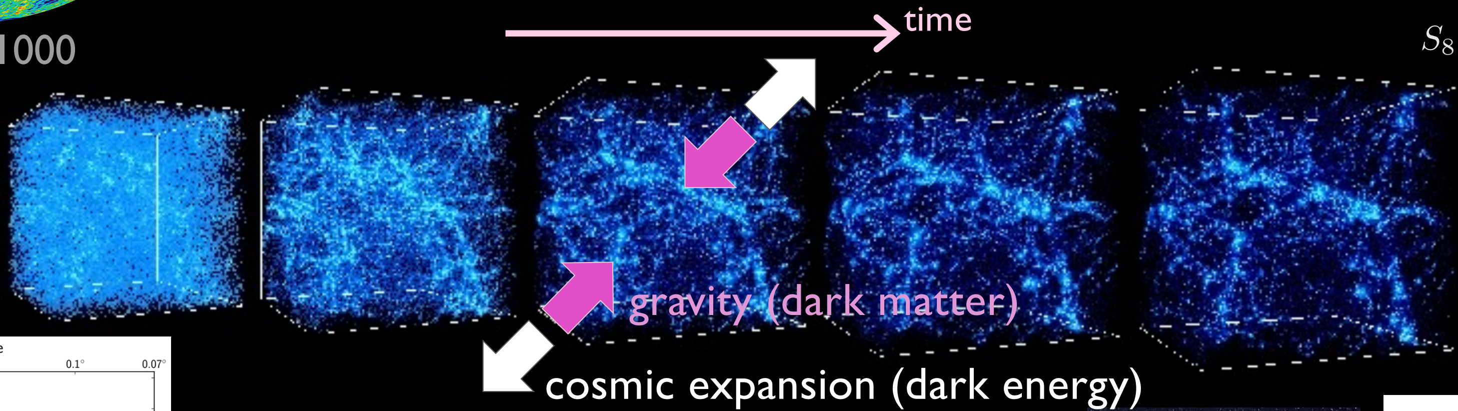
CMB at z~1000

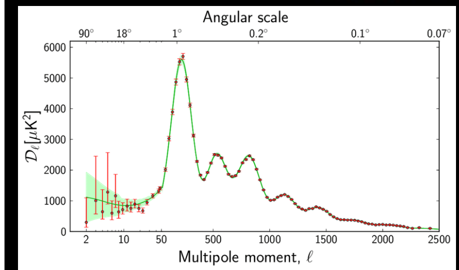
ΛCDM extrapolation

$\sigma_8^{\mathrm{CMB}}(z \sim 0)$

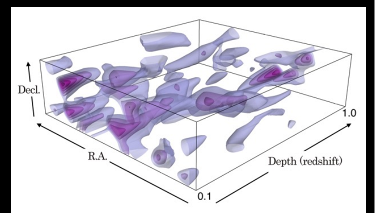
$S_8^{\mathrm{CMB}}(z \sim 0)$

$S_8 \equiv \sigma_8(\Omega_{\mathrm{m}}/0.3)^{0.5}$





ΛCDM=~6 parameters



Galaxy surveys directly measure "**lumpiness**" of the universe

$\sigma_8^{\mathrm{obs}}(z \sim 0), \quad S_8^{\mathrm{obs}}(z \sim 0)$

LSS-sigma8 vs. CMB-inferred sigma8

- sigma8, a parameter to which galaxy surveys (large-scale structure) is most sensitive to

$$\sigma_8^{\rm LSS} \equiv \left[\left\langle\left(\frac{\delta\rho_{\rm m}}{\bar{\rho}_{\rm m}}\right)^2_{8h^{-1}{\rm Mpc}}\right\rangle\right]^{1/2}$$

Matter (mainly dark matter) inhomogeneities at 8Mpc/h

- To infer sigma8 from the CMB observables (e.g. Planck), we need to assume the cosmological model to follow the time evolution of mass fluctuations over cosmic time from z~1000 to z=0 ⇒ extrapolation
- For flat ΛCDM model:

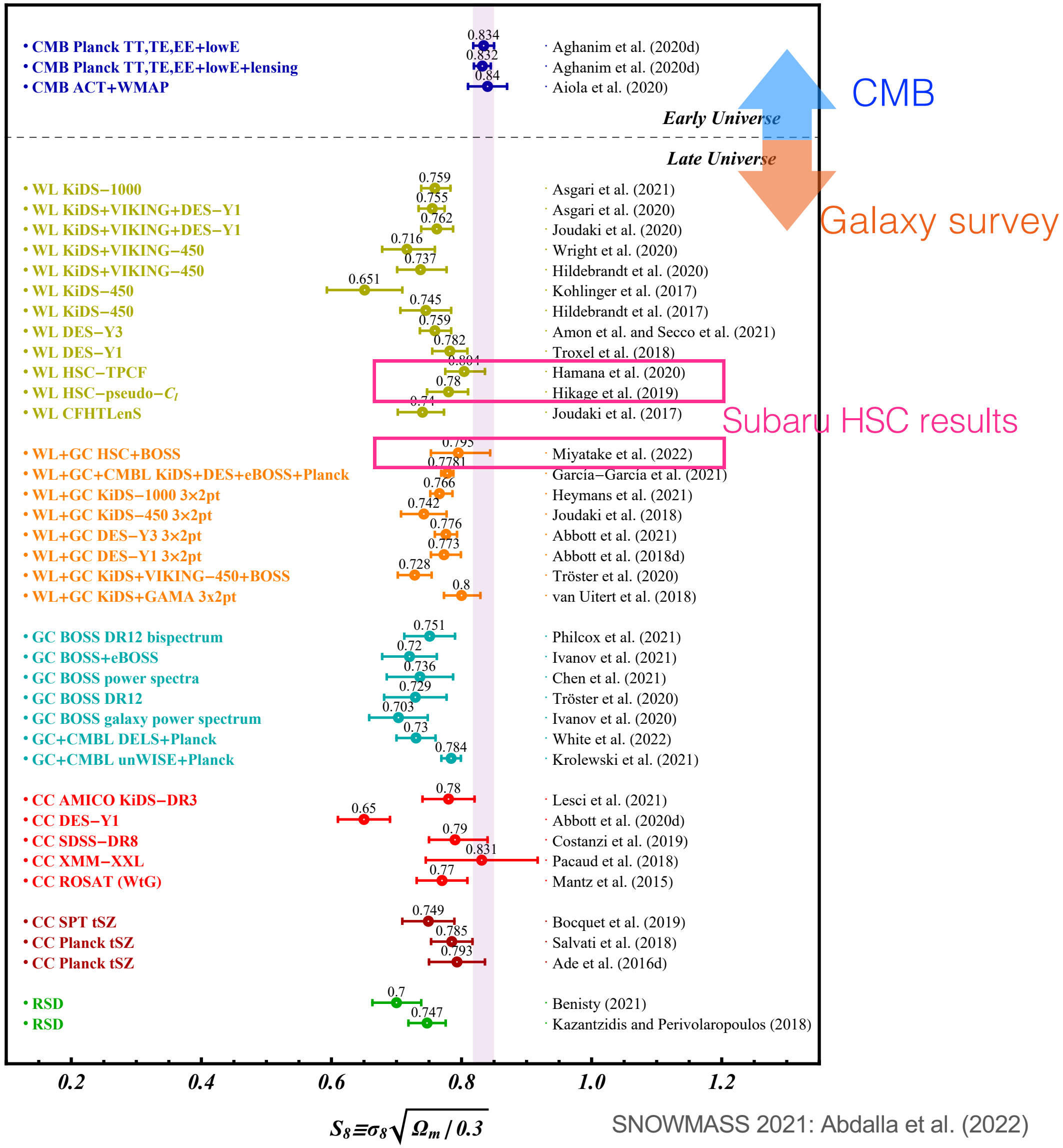
$$\sigma_8^{\rm CMB} \simeq 0.83\left(\frac{A_{\rm s}}{2.2\times 10^{-9}}\right)^{1/2}\left(\frac{\Omega_{\rm m}}{0.31}\right)^{0.24}\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)^{1/3}\left(\frac{\Omega_{\rm m}h^2}{0.14}\right)^{0.56}\left(\frac{h}{0.68}\right)^{0.69}$$

$A_{\rm s}, \Omega_{\rm m}h^2, \Omega_{\rm b}h^2$ CMB observables

S8-tension

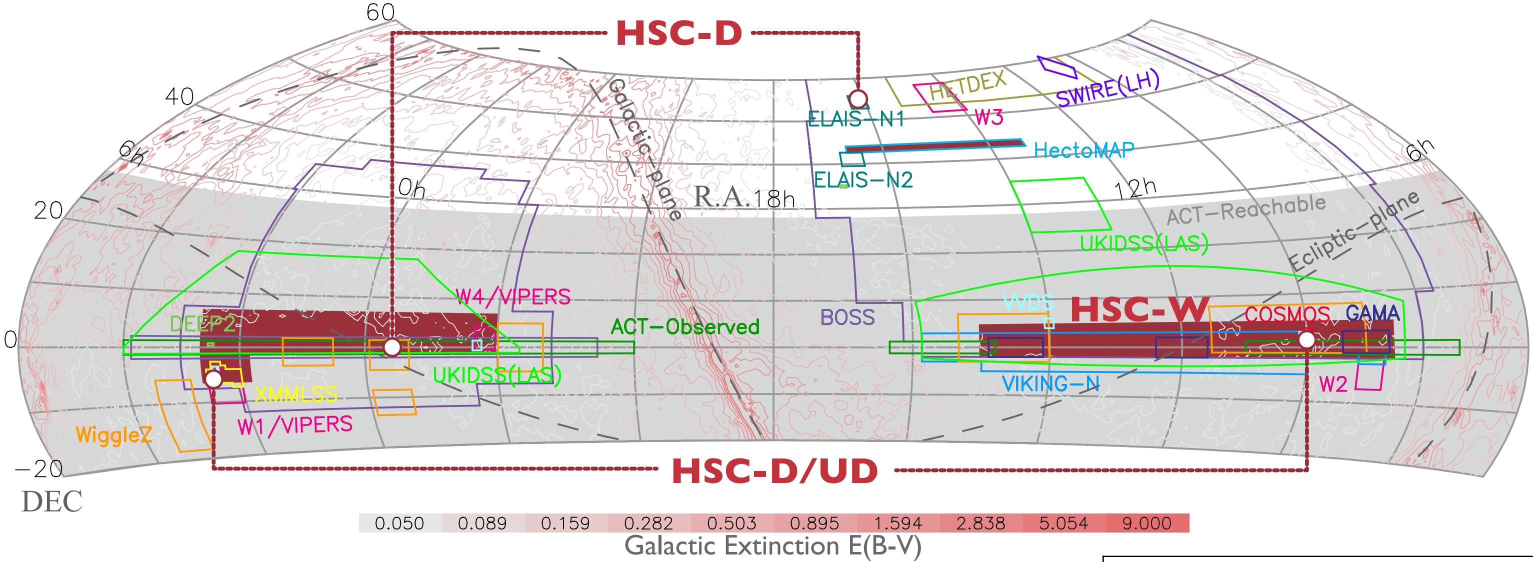
$$S_8 \equiv \sigma_8 \left(\frac{\Omega_\mathrm{m}}{0.3}\right)^{0.5}$$

- A parameter to characterize "lumpiness" of the late-time universe
- A parameter to which large-scale structure (LSS) probes are most sensitive
- S8 values from most LSS probes displays a tension with that from CMB – S8 tension
- Unknown systematics or New physics beyond ΛCDM?

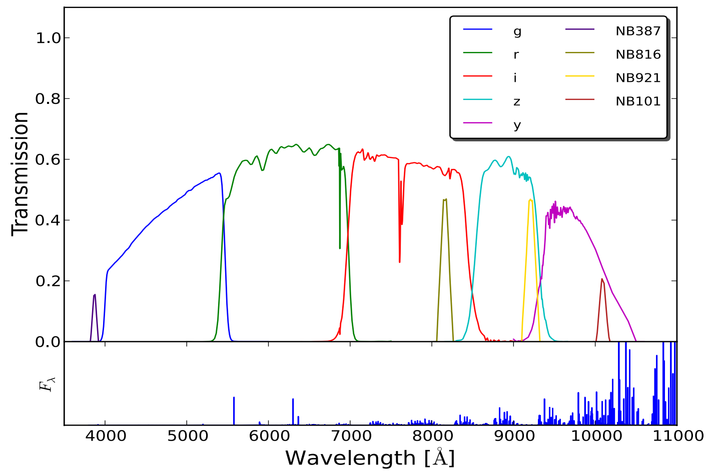


SNOWMASS 2021: Abdalla et al. (2022)

Subaru-Wide Survey (2014-2021)

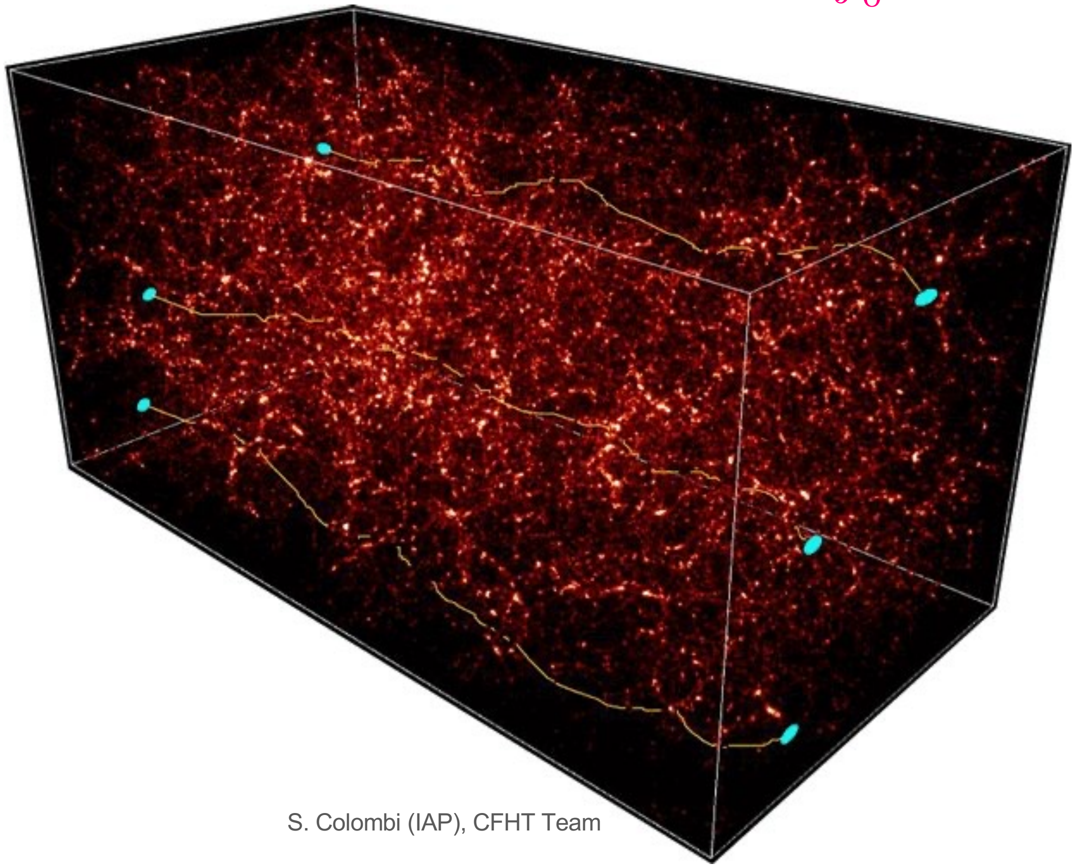


- HSC: 2014 – 2021 (HSC imaging done)
- HSC cosmology survey (i~26, grizy, ~1100 deg^2)
  - HSC-Year 3 weak data: ~416 sq. deg., i<24.5, n~16 arcmin^{-2} (Li et al. 22)



Weak gravitational lensing – a probe of dark matter distribution

$$\gamma = \frac{a-b}{a+b} \sim \Omega_{\rm m} \int_0^{\chi_{\rm s}} {\rm d}\chi\, \chi \left(1 - \frac{\chi}{\chi_{\rm s}}\right) \delta_{\rm m}(\chi, \chi\boldsymbol{\theta})$$

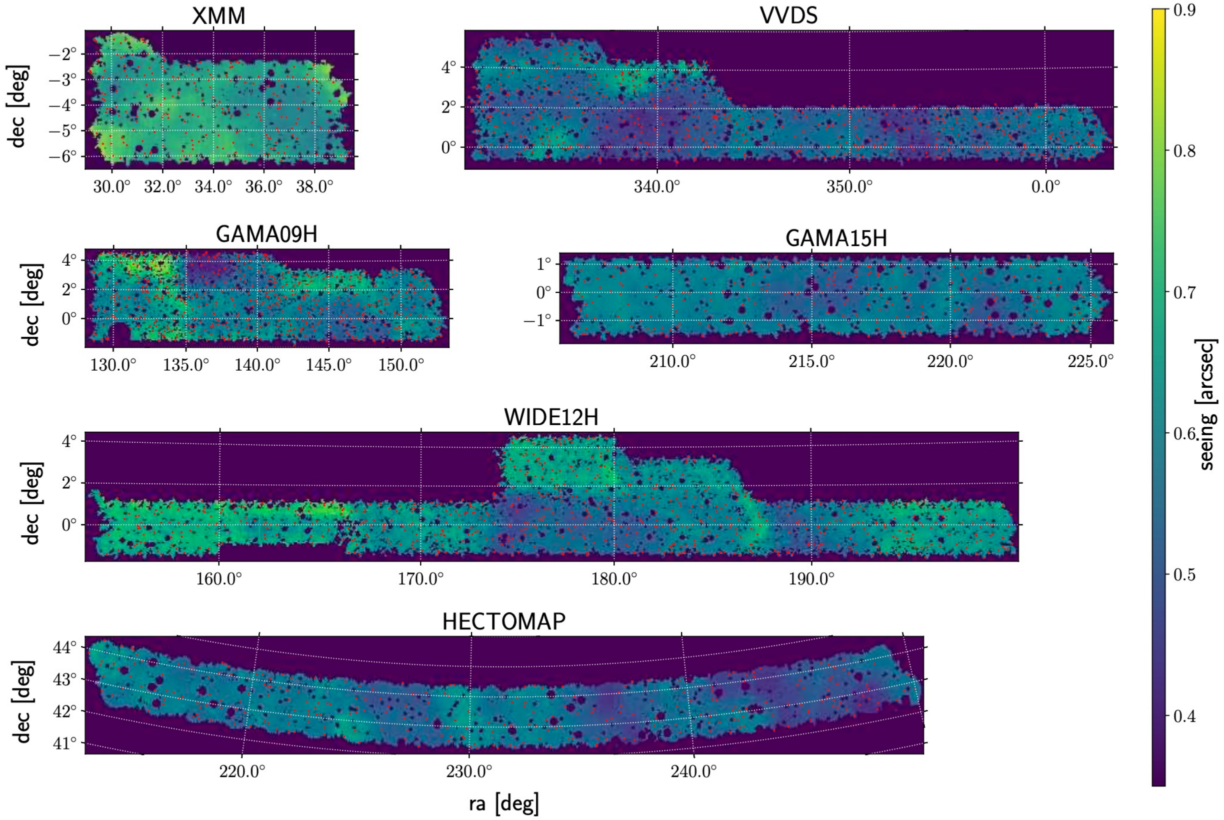


S. Colombi (IAP), CFHT Team

- An image of distant galaxy is distorted
- Lensing distortion (=ellipticity) is a tiny effect, ~ 1% in ellipticity amplitude
- If observed, it can probe the matter fluctuation field along the line-of-sight direction – a powerful way to probe DM distribution
- High-quality image like that of Subaru is crucial for accurate weak lensing measurement

HSC Year 3 Cosmology Analyses

- HSC Year 3 data: ~416 sq. deg. ⇐ Year 1 ~140 sq. deg., a factor of 3 wider
- Galaxy shape catalog: Xiangchong Li (the former IPMU student), Miyatake et al. 22
- Used the sophisticated simulated data (using HST) for the calibration



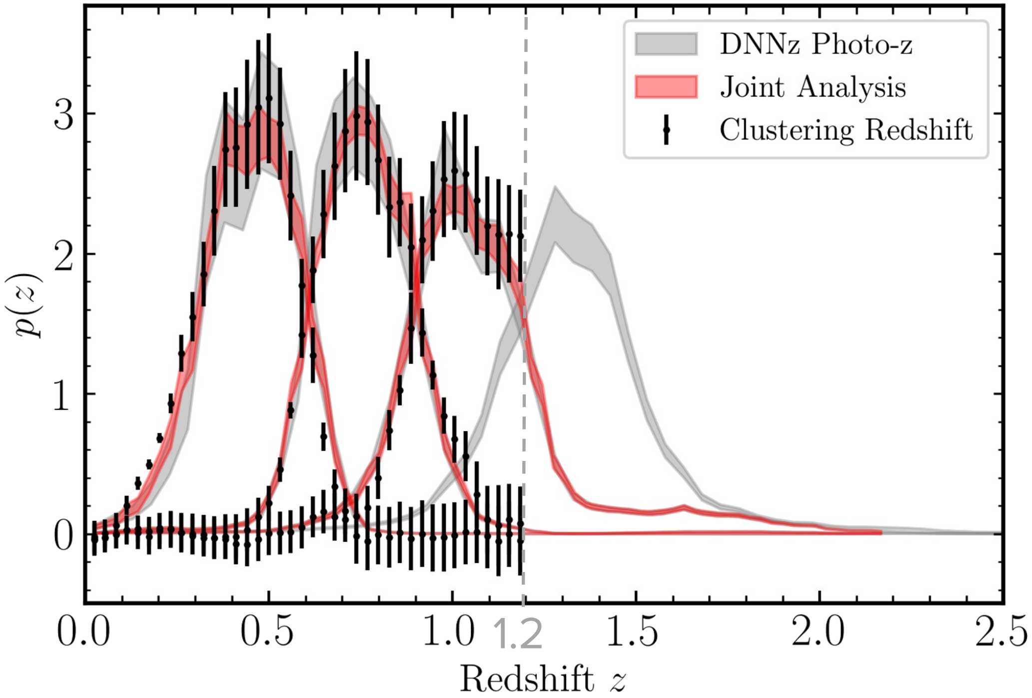
X. Li
(IPMU⇒CMU)

seeing ~0.6 arcsec
(⇔ ~0.9 arcsec for DES)

Rau+2022

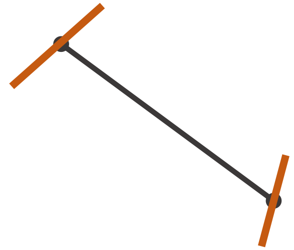
Redshift distribution inference

- **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 not calibrated by CAMIRA-LRG samples.

Cosmological dependence of cosmic shear



- Cosmic shear 2pt correlation function (power spectrum)

$$C_{i_s j_s}(\ell) = \int_0^{\chi_H} \mathrm{d}\chi \, \frac{q_{i_s}(\chi) q_{j_s}(\chi)}{\chi^2} P_m^{\mathrm{NL}}\left(k = \frac{\ell + 1/2}{\chi} : \chi\right)$$

nonlinear matter power spectrum

  - Here chi: comoving radial distance, i_s, j_s are the tomographic redshift bins and q(chi) is

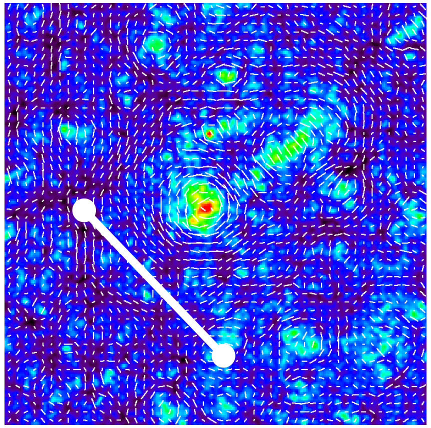
$$q_{i_s}(\chi) = \frac{3}{2}\Omega_{\mathrm{m}} H_0^2 \frac{\chi}{a(\chi)} \int_\chi^{\chi_H} \mathrm{d}\chi_s \, p_{i_s}(\chi_s) \frac{\chi_s - \chi}{\chi_s}$$

source redshift distribution

- In configuration space, $\xi_{+/-(i_s j_s)}(\theta) = \int \frac{\ell \mathrm{d}\ell}{2\pi} \, C_{i_s j_s}(\ell) J_{0,4}(\theta\ell)$

- Further need to include contributions of intrinsic alignments and baryonic physics effect in theory predictions

Cosmology inference: A test of ΛCDM model



- Bayesian inference

posterior — likelihood — prior

$$P(\boldsymbol{\theta}|\mathbf{d}) \sim \mathcal{L}(\mathbf{d}|\boldsymbol{\theta})\Pi(\boldsymbol{\theta})$$

parameters ($\boldsymbol{\theta}$), data ($\mathbf{d}$)

- Likelihood

$$-2\ln\mathcal{L}(\mathbf{d}|\boldsymbol{\theta}) = [\mathbf{d}-\mathbf{m}(\boldsymbol{\theta})]^T\,\mathbf{C}^{-1}\,[\mathbf{d}-\mathbf{m}(\boldsymbol{\theta})]$$

model ($\mathbf{m}$), covariance ($\mathbf{C}$)

data

- 2pt function
- High-precision measurement
- Systematics & null tests
- Unbiased estimator
- Data cuts

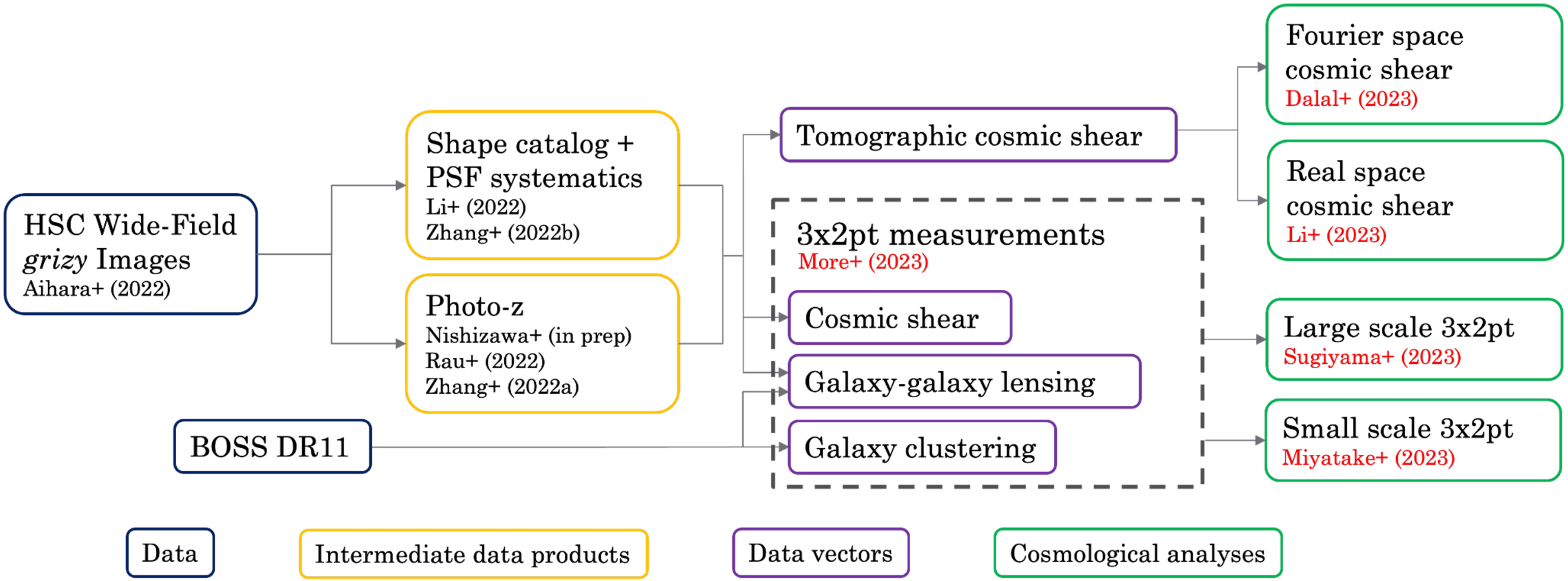
covariance

- Sample variance
- Mock catalogs/data

model

- Accurate model
- Nonlinear clustering & baryonic physics (with simulations)
- Nuisance paras to model systematic effects

We (international team) have developed the pipelines of these parts (not as easy as it sounds at all)



HSC Wide-Field
grizy Images
Aihara+ (2022)
Shape catalog +
PSF systematics
Li+ (2022)
Zhang+ (2022b)
Photo-z
Nishizawa+ (in prep)
Rau+ (2022)
Zhang+ (2022a)
BOSS DR11
Tomographic cosmic shear
3x2pt measurements
More+ (2023)
Cosmic shear
Galaxy-galaxy lensing
Galaxy clustering
Fourier space
cosmic shear
Dalal+ (2023)
Real space
cosmic shear
Li+ (2023)
Large scale 3x2pt
Sugiyama+ (2023)
Small scale 3x2pt
Miyatake+ (2023)
Data
Intermediate data products
Data vectors
Cosmological analyses

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

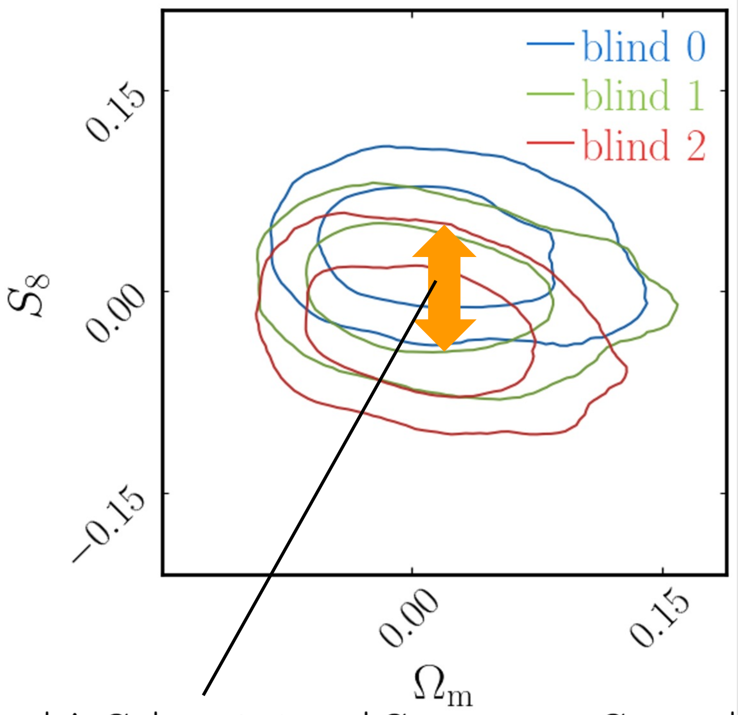
Note: Different sets of blinded catalogs are used for different cosmology analyses.

Systematic tests

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

Unblind!

- The team promises that the unblinded results would be published regardless of the outcome
- Cannot change/modify the analysis method after unblinding

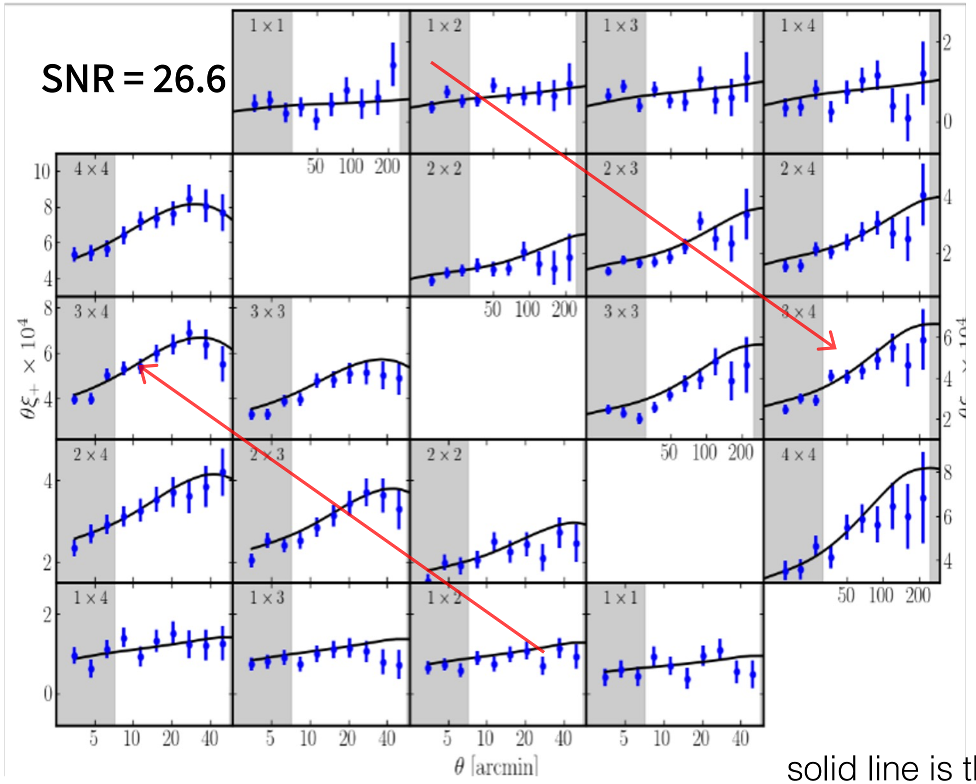


$$|\Delta S_8| \simeq 0.1 > |S_{8,\mathrm{CMB}} - S_{8,\mathrm{LSS}}|$$

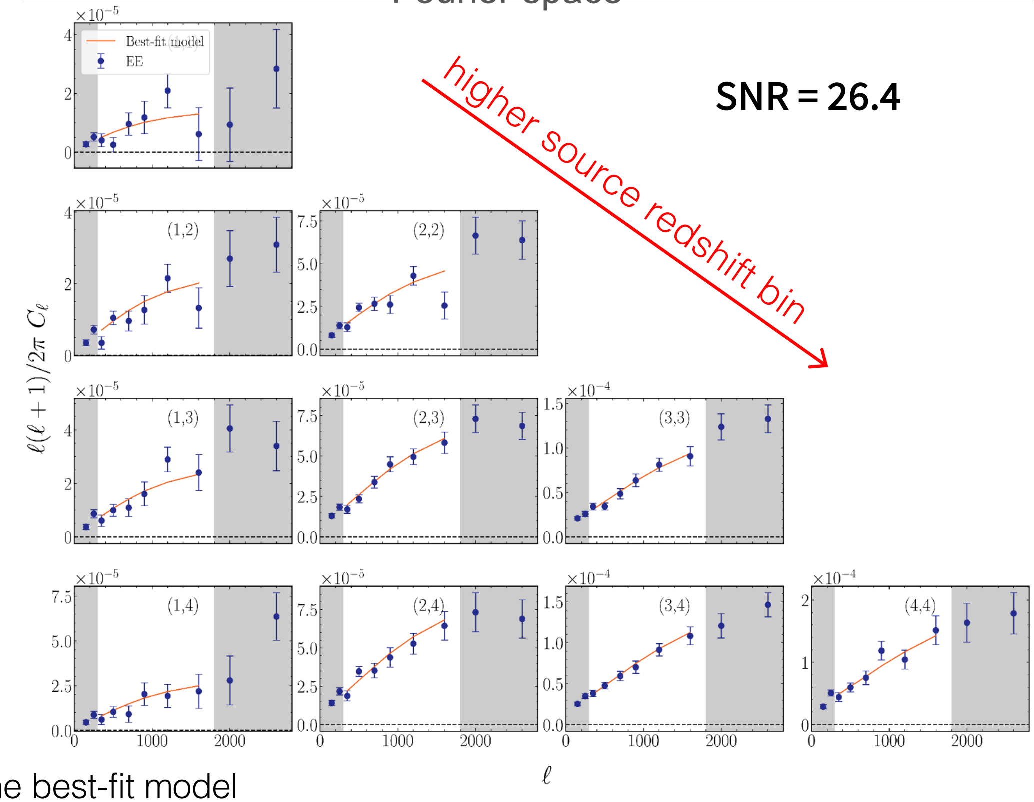
Cosmic shear tomography (configuration- and Fourier-space)

Li+; Dalal+

configuration space



Fourier space



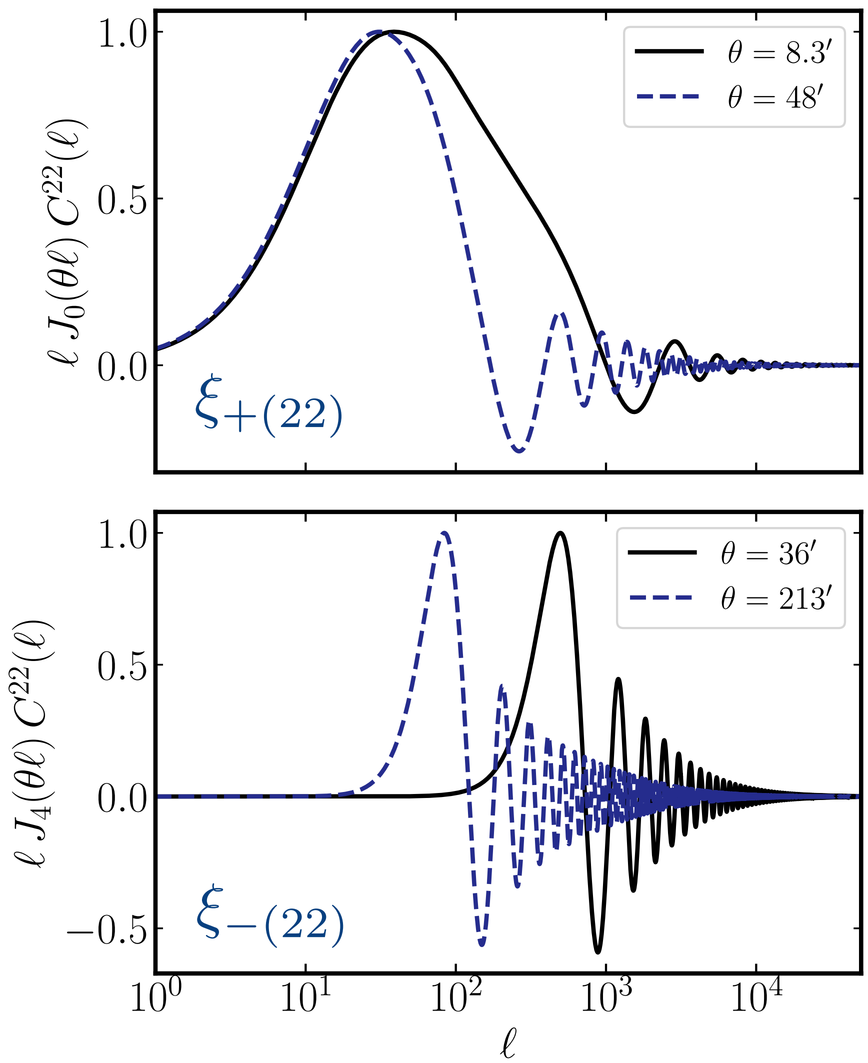
solid line is the best-fit model

Use unshaded angular/multipole range (i.e. scale cuts) for cosmology inference

Angular scale
vs.
multipole scale

$$\xi_{+/-(i_s j_s)}(\theta) = \int \frac{\ell \mathrm{d}\ell}{2\pi}\, C_{i_s j_s}(\ell) J_{0,4}(\theta\ell)$$

- ξ_+: $\theta>$ 7 arcmin
- ξ_-: $\theta>$ 30 arcmin
- C_ell: 300<ell<1800
- Fourier space analysis uses smaller-scale information



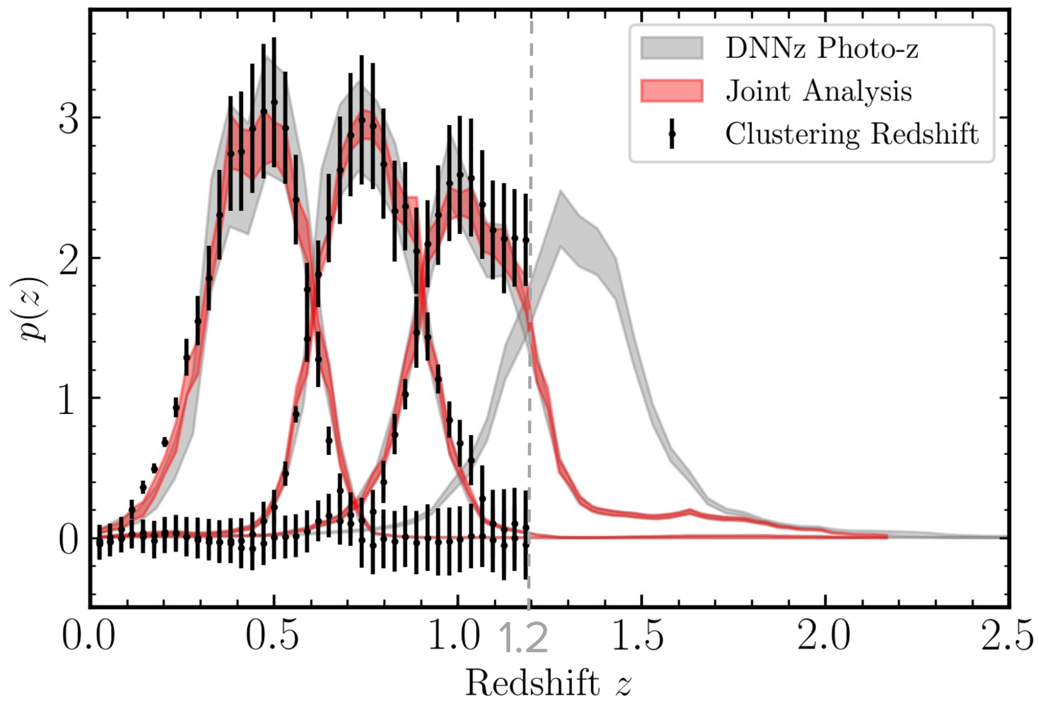
Rau+2022

Residual source redshift (photo-z) errors?

- Red: joint posterior of the two
- The redshift distribution inference gives an estimation of the mean redshift in each tomographic bin, to the precision of

$$\sigma(\bar{z}_{s(i_s)}) \simeq 0.01 - 0.02$$

- However …



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

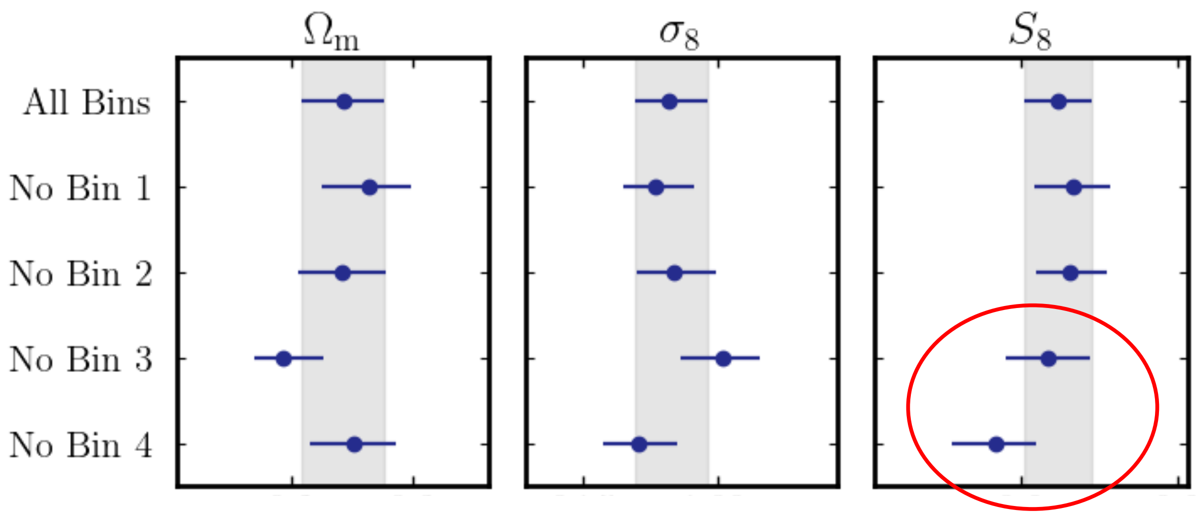
Residual source redshift (photo-z) errors? (contd.)

Li+

- If we employ the Gaussian prior inferred by the the redshift distribution inference, i.e.

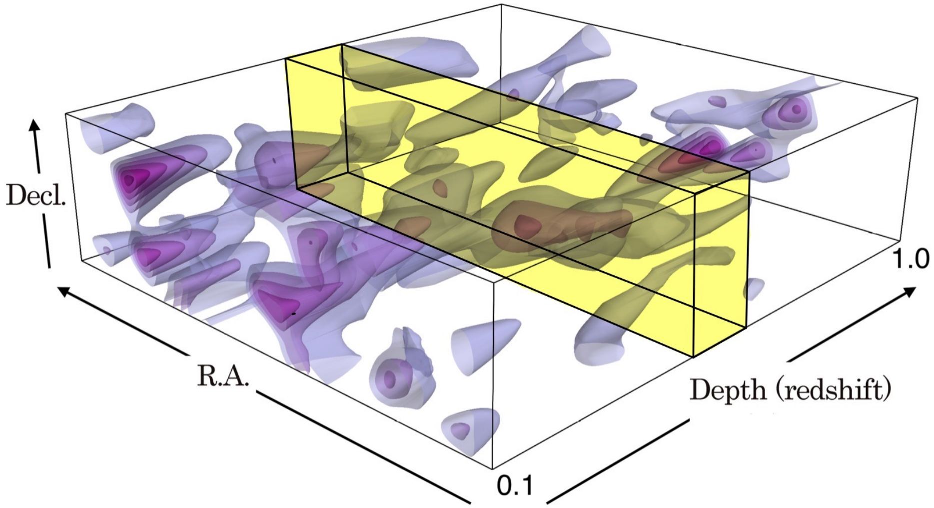
$$\sigma(\bar{z}_{s(i_s)}) \simeq 0.01 - 0.02$$

- we found, during the blinding analysis stage, that the internal consistency test (right plot) we failed
- HSC-Y1 cosmology analysis (Miyatake+22) also implied a residual systematic error in source redshifts at z>1



Our approach: "robust" vs. "precision" MT & Oguri 2011; Miyatake+21,22

- *Photometric redshift errors* are the most important systematic error; 5 colors (grizy) have limited information on galaxy properties
- Tomography using low-redshift galaxies that have either spec-z or more accurate photo-z
- Cross-correlation can be used to "calibrate" photo-z uncertainties for high-z HSC galaxies



- For each high-z HSC source galaxy, shear is

$$\gamma(\boldsymbol{\theta}; z_s) \sim \int_0^{z_s} d\chi\, W(\chi, \chi_s)\delta_m(\chi, \chi\boldsymbol{\theta})$$

- The cross-correlation with low-z large-scale structure tracers gives

$$\langle\gamma(\boldsymbol{\theta}; z_s)X(\boldsymbol{\theta}', z_l)\rangle \sim W(\chi_l, \chi_s)\xi_{mX}(\chi_l\Delta\theta; z_l)$$

$\delta_g(\mathbf{x}, z_l)$ SDSS spectroscopic galaxies

$\gamma(\boldsymbol{\theta}', z_l)$ low-z HSC galaxy shapes

- This method statistically allows for calibration of photo-z errors

cosmic shear cosmology: parameters and priors

Parameter	Prior
Cosmological parameters (Section IV A)	
Ω_m	$\mathcal{U}(0.1, 0.7)$
A_s ($\times 10^{-9}$)	$\mathcal{U}(0.5, 10)$
n_s	$\mathcal{U}(0.87, 1.07)$
h_0	$\mathcal{U}(0.62, 0.80)$
ω_b	$\mathcal{U}(0.02, 0.025)$
Baryonic feedback parameters (Section IV A)	
A_b	$\mathcal{U}(2, 3.13)$
Intrinsic alignment parameters (Section IV B)	
A_1	$\mathcal{U}(-6, 6)$
η_1	$\mathcal{U}(-6, 6)$
A_2	$\mathcal{U}(-6, 6)$
η_2	$\mathcal{U}(-6, 6)$
b_{ta}	$\mathcal{U}(0, 2)$
Photo-z systematics (Section IV C)	
Δz_1	$\mathcal{N}(0, 0.024)$
Δz_2	$\mathcal{N}(0, 0.022)$
Δz_3	$\mathcal{U}(-1, 1)$
Δz_4	$\mathcal{U}(-1, 1)$
Shear calibration biases (Section IV D)	
Δm_1	$\mathcal{N}(0.0, 0.01)$
Δm_2	$\mathcal{N}(0.0, 0.01)$
Δm_3	$\mathcal{N}(0.0, 0.01)$
Δm_4	$\mathcal{N}(0.0, 0.01)$
PSF systematics (Section IV E)	
$\alpha'^{(2)}$	$\mathcal{N}(0, 1)$
$\beta'^{(2)}$	$\mathcal{N}(0, 1)$
$\alpha'^{(4)}$	$\mathcal{N}(0, 1)$
$\beta'^{(4)}$	$\mathcal{N}(0, 1)$

baryonic effect

IA (TATT)

residual error in source redshift

shear error

PSF error

- We decided to use the uninformative flat prior on mean redshift of the z3 and z4 bins

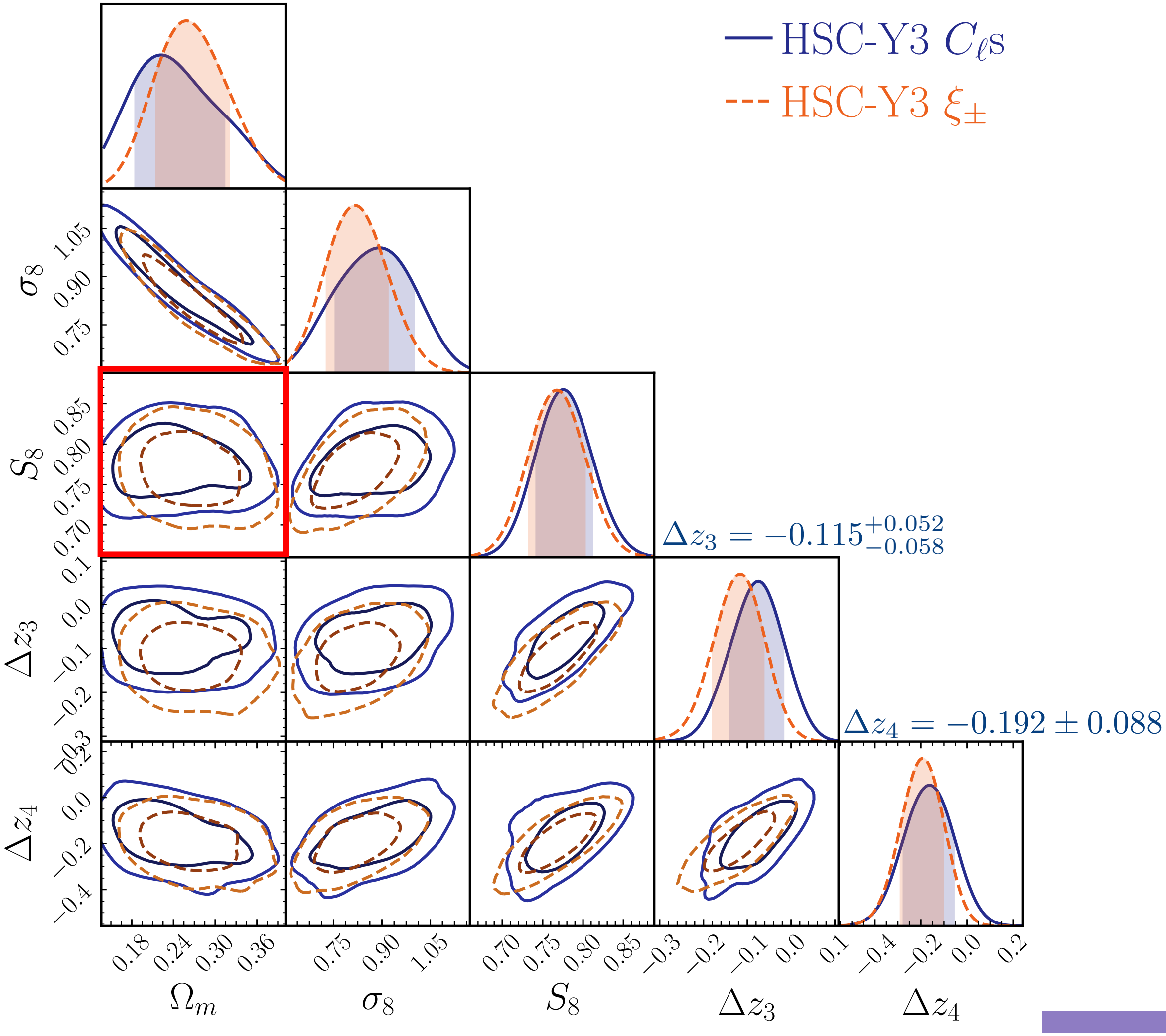
$$\Pi(\Delta z_{3,4}) = \mathcal{U}(-1.0, 1.0)$$

This is the first time; the previous WL cosmology work (DES and KiDS) employed the informative prior of sigma(Delta z)~0.01-0.02

- Include the parameter (A_b) to model the baryonic effects on the nonlinear matter power spectrum
- TATT IA model

HSC-Y3 cosmic shear cosmology results

Li+; Dalal+

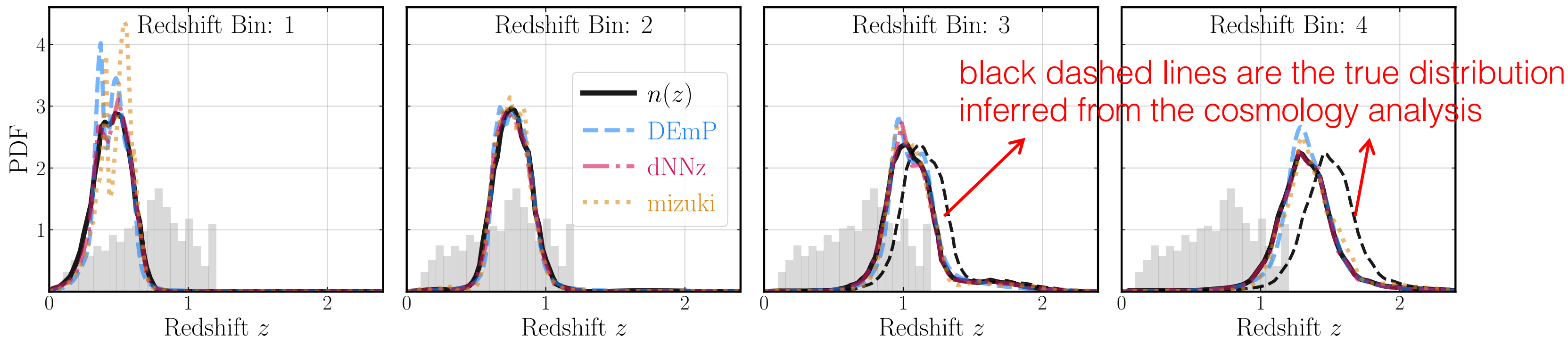


$$S_8(C_\ell) = 0.776^{+0.032}_{-0.033}$$

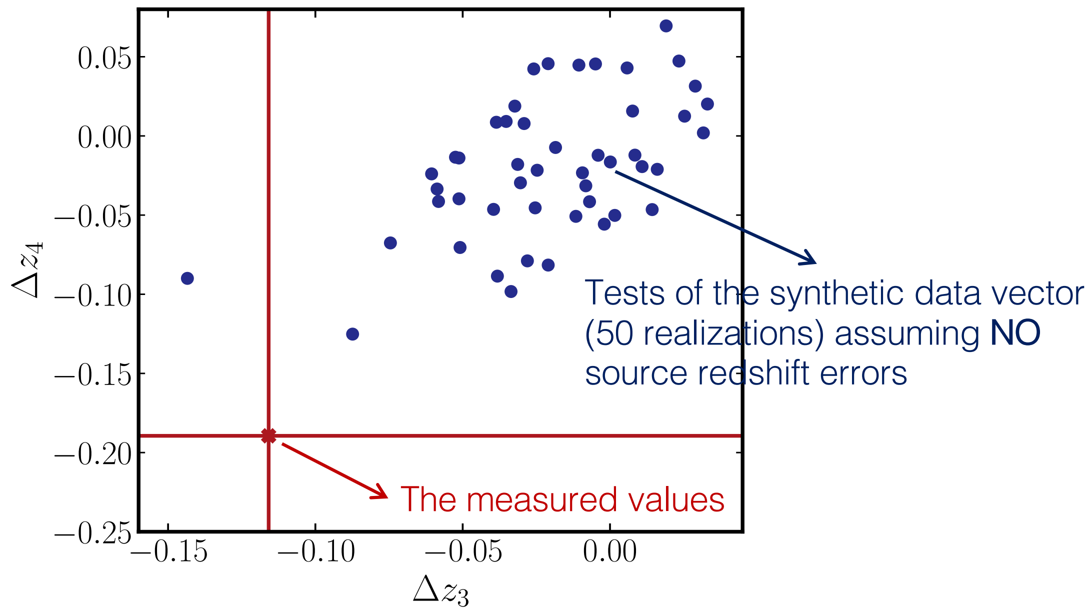
$$S_8(\xi) = 0.769^{+0.031}_{-0.034}$$

- 4% fractional precision of S8 measurement (even if using the uninformative, flat priors of dzs)
- After unblinding, we compared the two results, finding the consistent results of S8
- Including the marginalization over the baryonic effects and IA effects
- Implies non-zero dz3,4 values (implying the higher-redshift distribution of z3 and z4 bins than inferred by photo-z method)

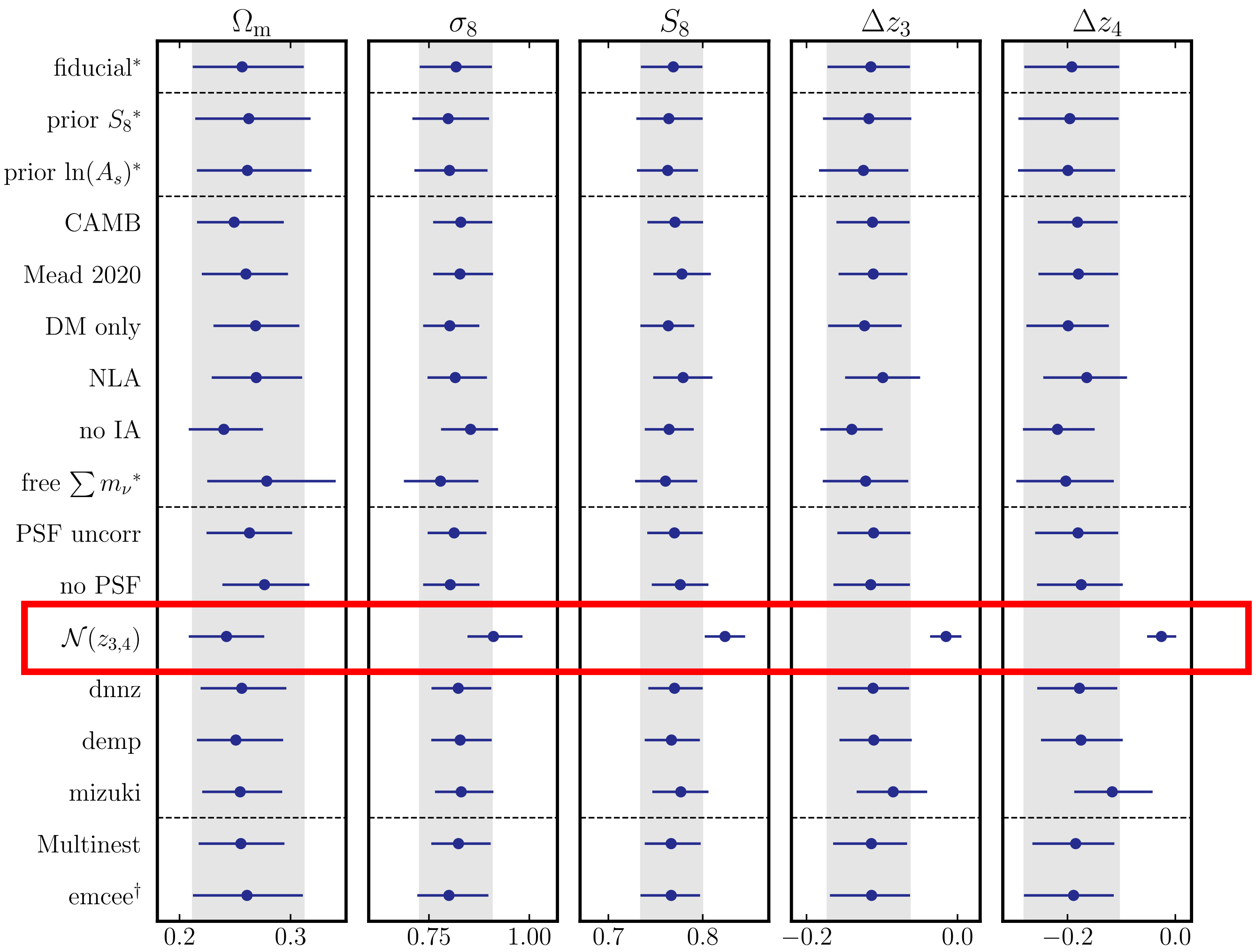
Residual errors in source redshift distribution (zs>1)



- The self-calibration method in cosmology analysis implies significant non-zero residual errors in the source redshifts of z3 and z4 bins



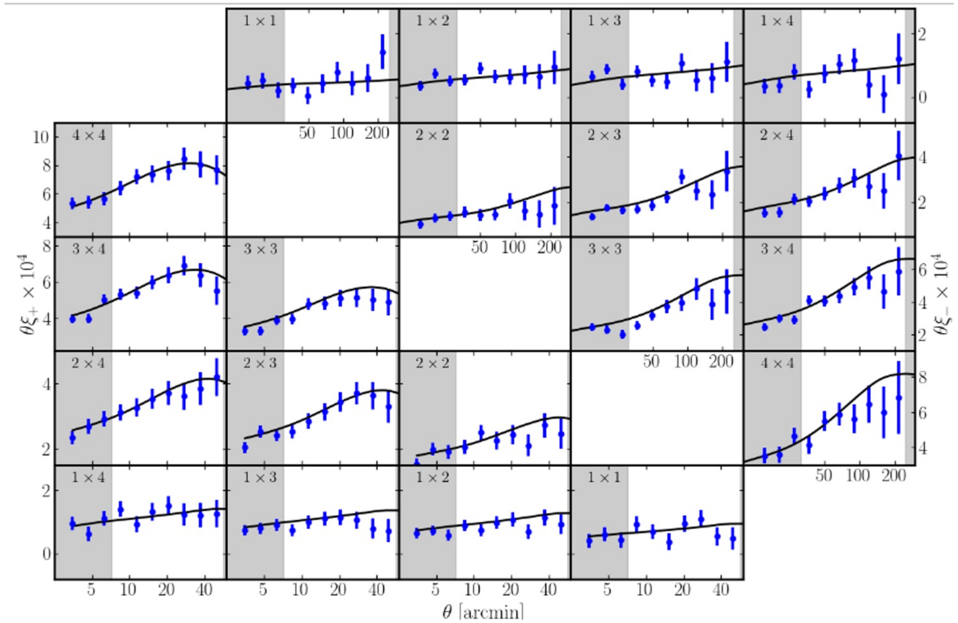
Validation/internal consistency tests



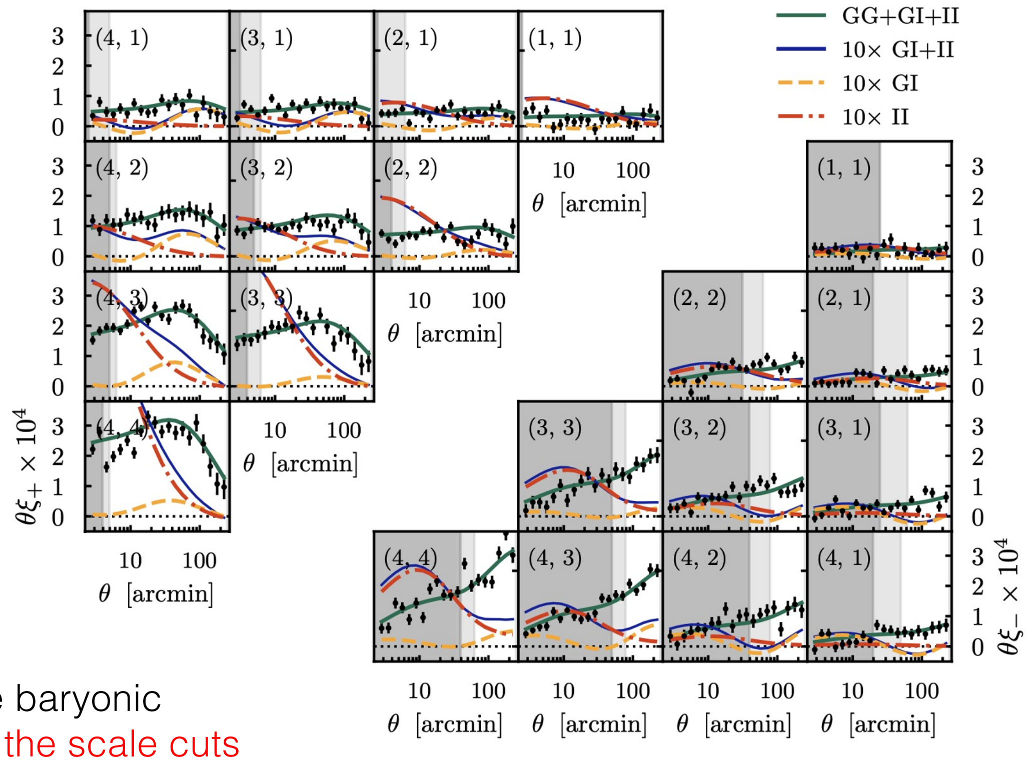
The case using the Gaussian priors of z3 and z4 bins, inferred from the photo-z inference method

Cosmic shear data themselves DO NOT display strong baryonic feedback effects

HSC-Y3 cosmic shear (Li+):
line is the best-fit DM-only prediction



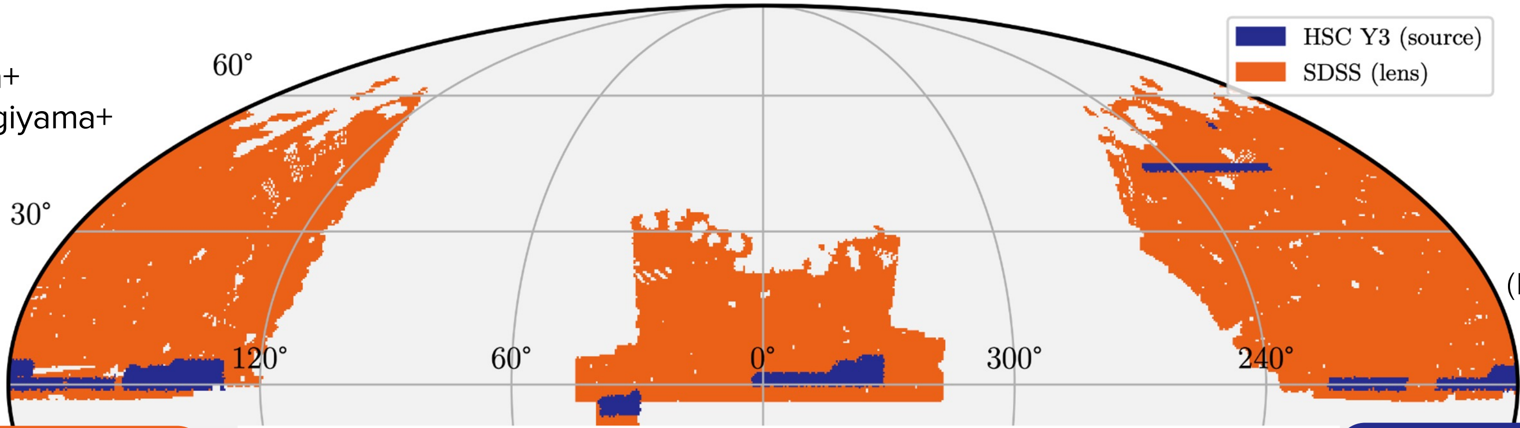
DES-Y3 (Secco+): line is the DM-only model



The best-fit model (DM-only for DES and the reasonable baryonic effect for HSC-Y3) can fit the data at scales even below the scale cuts

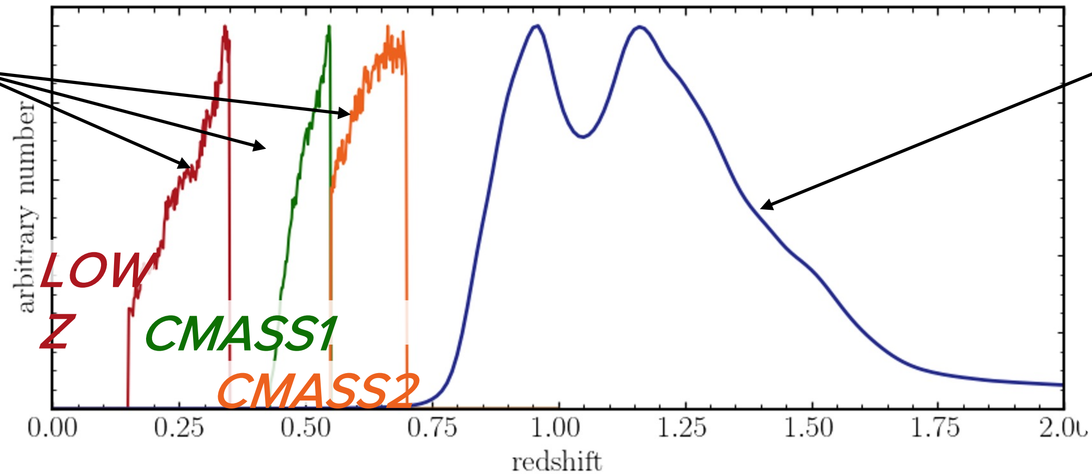
HSC-Y3 3x2pt cosmology with HSC x SDSS catalogs

Sugiyama+
More, Sugiyama+



Sunao Sugiyama
(Kavli IPMU⇒UPenn)

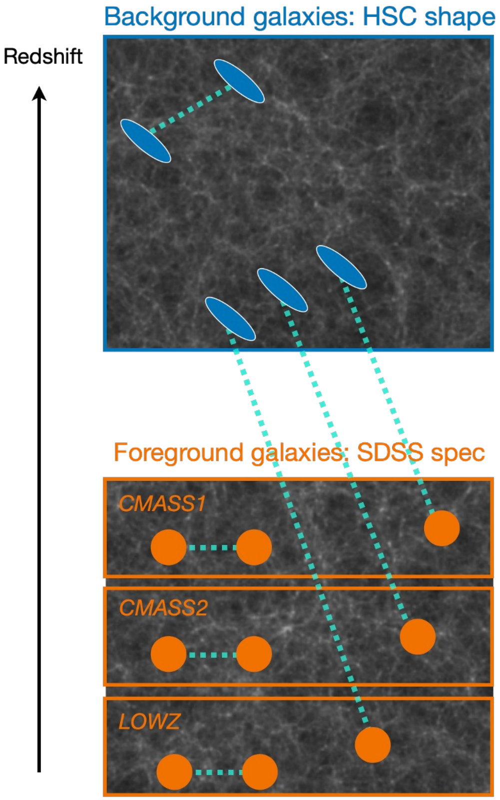
SDSS spec-z sample lens galaxies



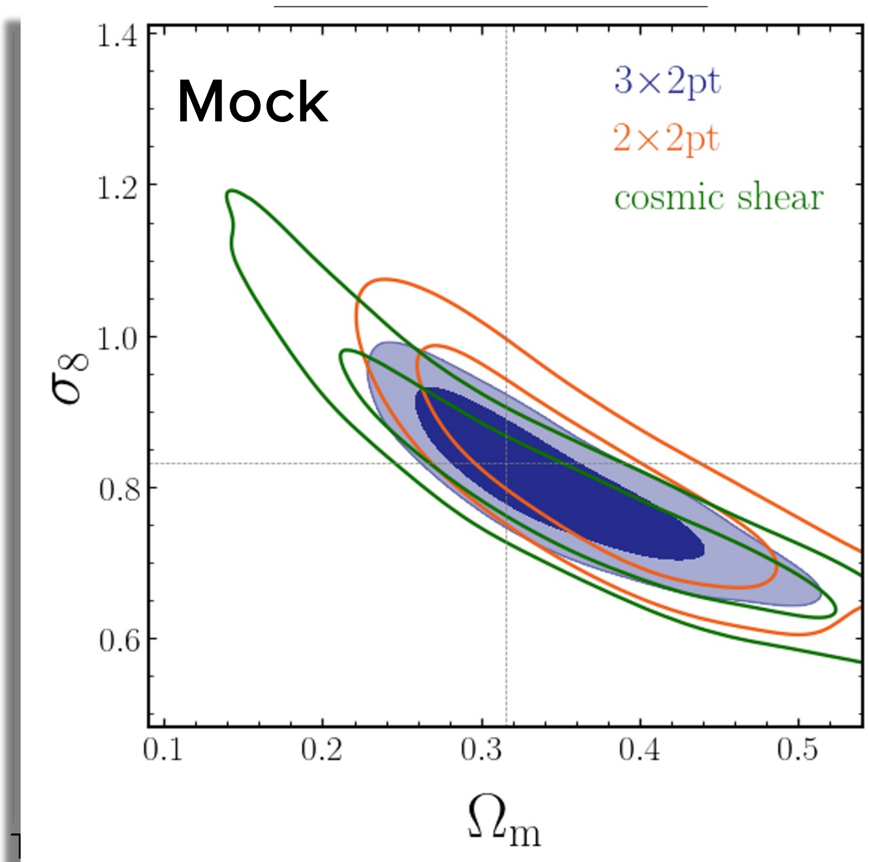
HSC shape sample source galaxies

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

3x2pt analysis with HSC x SDSS catalogs



Credit: T. Nishimichi,
edited by S. Sugiyama



$\delta_g = b\delta_m$ on large scales

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

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

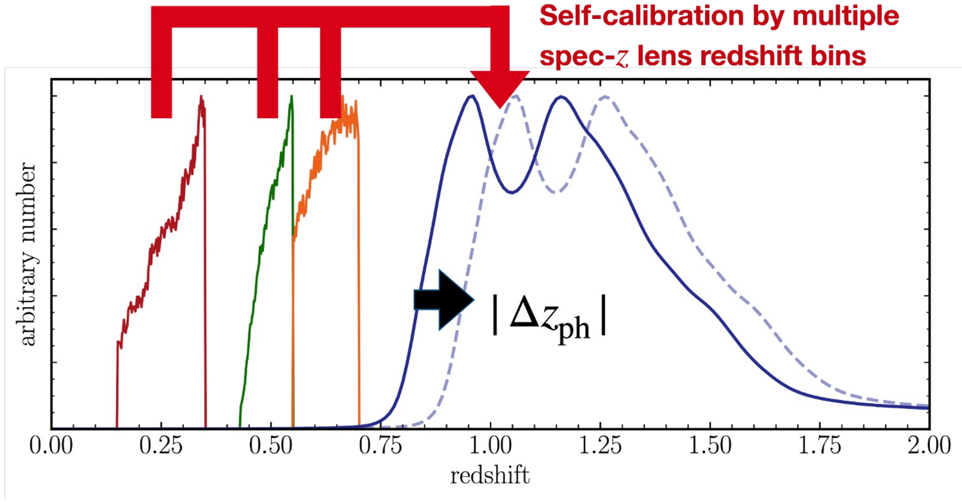
$\xi_\pm \sim \xi_{mm}(r \,|\, \Omega_m, \sigma_8)$

ugiyama+ (2023)

s shown by shaded region.

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

Self-calibration of residual source redshift error with multiple SDSS spec-z bins



The 3x2pt HSC source sample is 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 $\sigma(\Delta z_{ph}) \sim 10^{-2}$

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

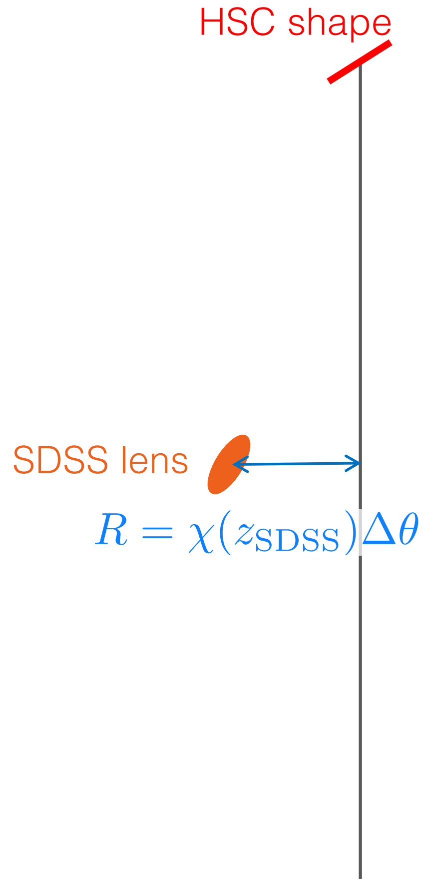
$$\Pi(\Delta z_{ph}) = \mathcal{U}(-1,1)$$

Δz_{ph} is self-calibrated by galaxy-galaxy lensing signals of three SDSS lens samples (Oguri & Takada 2011).

In this analysis, the self-calibration is based on spec-z SDSS lenses. For cosmic shear analyses of Li+ and Dalal+, the self-calibration is based on low-z photometric HSC galaxies.

Advantage of the use of spec-z SDSS lens sample

$$\gamma \sim \Omega_{\rm m} \int {\rm d}\chi\, \chi \left(1 - \frac{\chi}{\chi_{\rm s}}\right) \delta_m(\chi, \chi\boldsymbol{\theta})$$



- Galaxy-galaxy lensing: cross-correlation of foreground SDSS lens galaxy positions with shapes of background HSC galaxies
- The use of spec-z SDSS lens galaxy allows us to measure the g-g lensing as a function of projected separation (not angle)

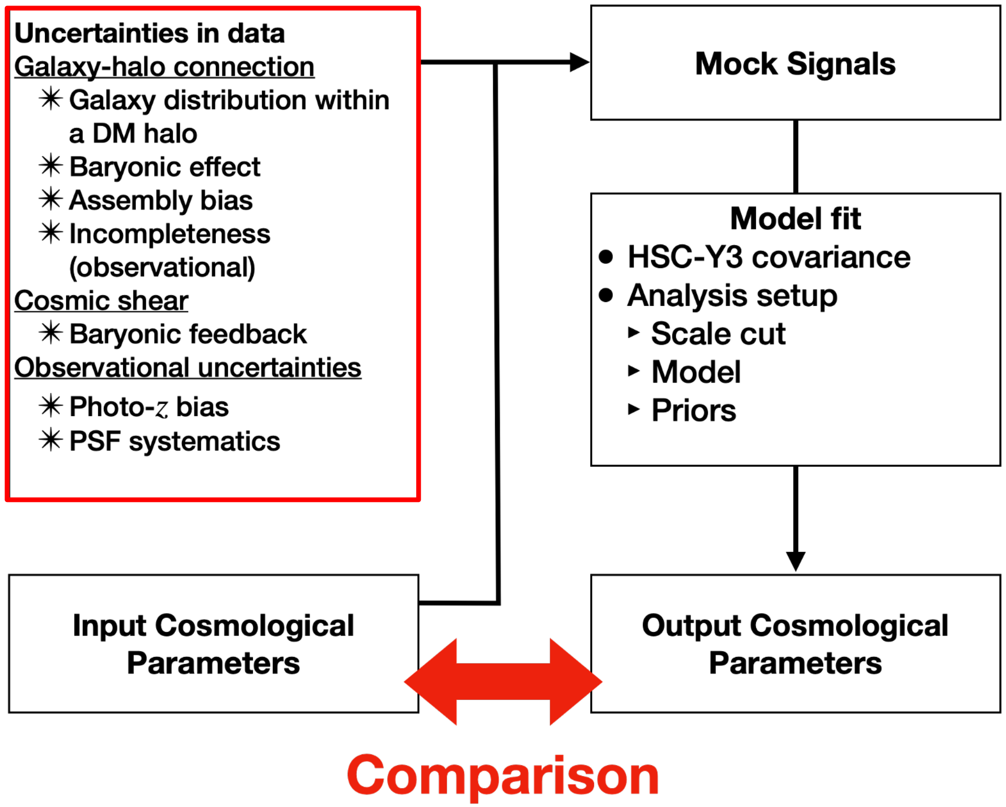
$$\widehat{\Delta\Sigma}(R) = \left.\frac{\sum_{\rm ls} w_{\rm ls} \left\langle \Sigma_{\rm cr}^{-1} \right\rangle_{\rm ls}^{-1} e_{+,{\rm ls}}}{2\mathcal{R} \sum_{\rm ls} w_{\rm ls}}\right|_{R=\chi(z_{\rm l})\Delta\theta_{\rm ls}}$$

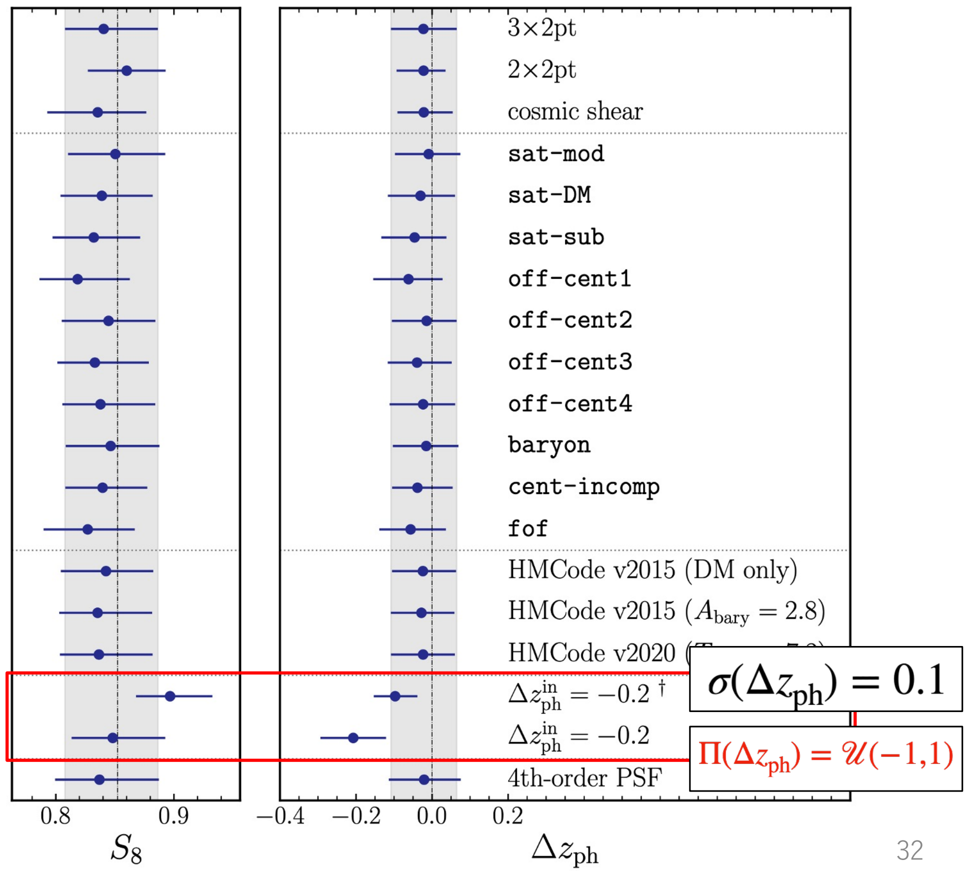
- Theory expectation: g-g lensing probes the projected average mass distribution around the lens galaxies (galaxy-matter cross-correlation)

$$\Delta\Sigma(R) = \langle \Sigma_{\rm gm} \rangle (< R) - \Sigma_{\rm gm}(R)$$

- HSC-Y3 3x2pt analysis uses the g-g lensing information at R>3Mpc/h (greater than virial radii of massive halos)
- Model: use the Dark Emulator (Nishimichi+19) to model the galaxy-matter cross-correlation, combined with halo occupation distribution to model galaxy-halo connection
  - Also use the PT based model, for cross check

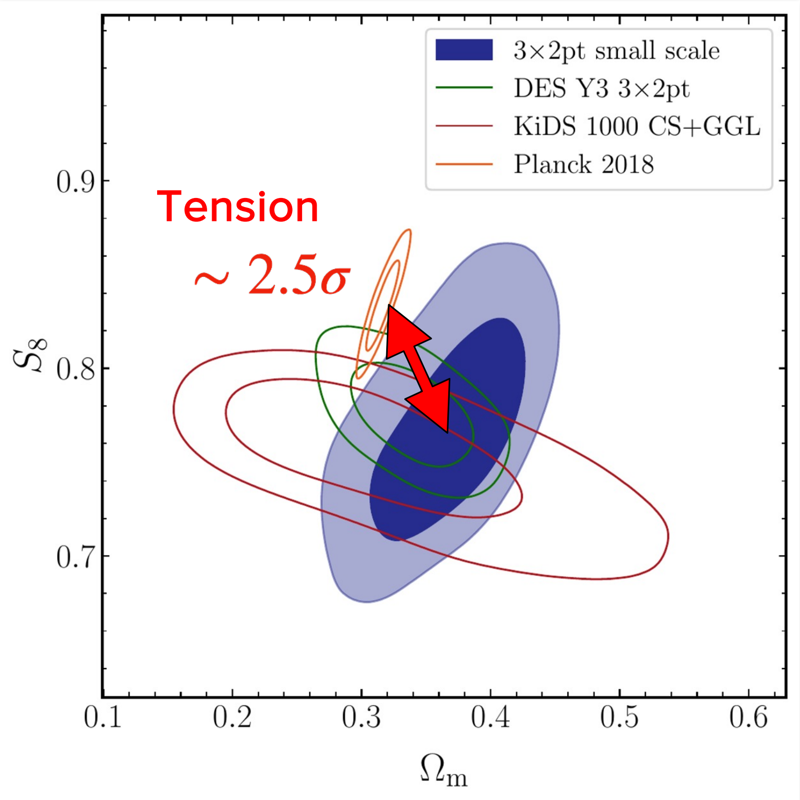
Validation of model and analysis choices with mocks





Sugiyama+

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!

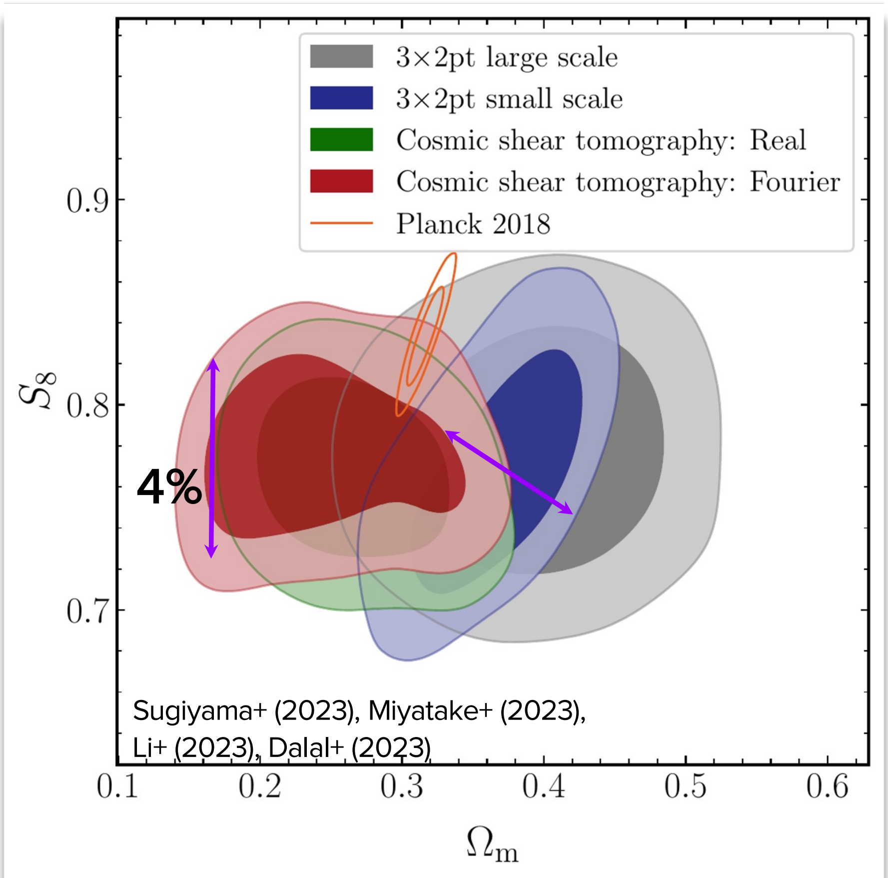
$$\Delta z_{\rm ph} = -0.05 \pm 0.09$$

- Good agreement between small & large-scale analysis.
- Significance of $\Delta z_{\rm ph} < 0$ increases to 1.6σ when we adopt BAO prior on $\Omega_{\rm m}$
- Small-scale analysis is most sensitive to

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

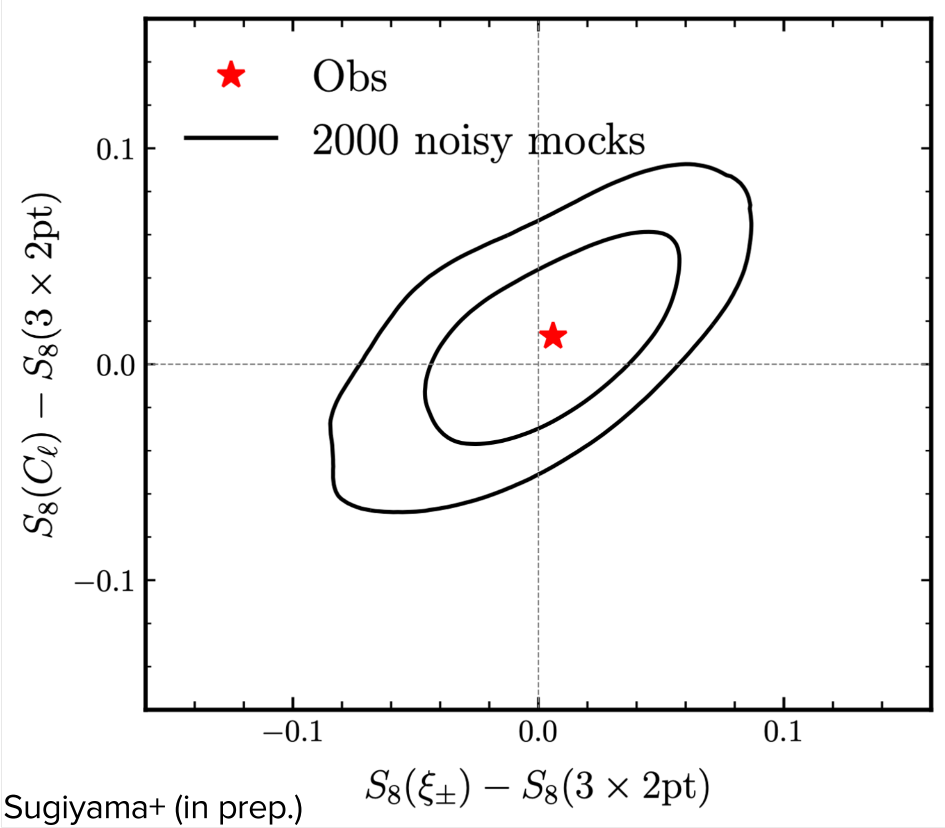
4% fractional error

Summary of HSC Year 3 cosmology results



- Compare the cosmic shear and the 3x2pt result, after the unblinding
- Consistent cosmological constraints from the blind analyses
  - Cosmic shear (Real and Fourier space)
  - 3x2pt 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

Internal consistency of HSC results



S. Sugiyama+ (in prep.)

We test internal consistency of the results from three HSC projects.

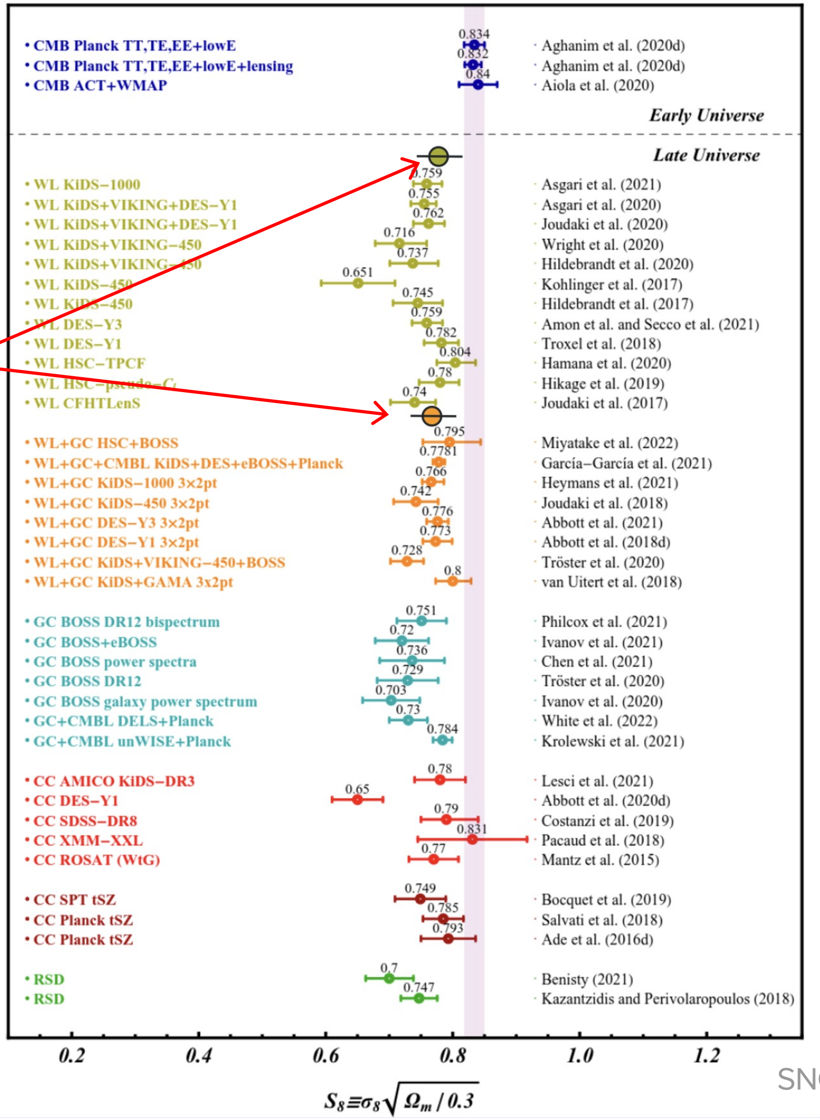
We run simulated analyses on 2000 noisy mocks, taking account of cross-covariance between different projects' probes.

HSC results are fairly consistent with each other!

S8 tension!

CMB

HSC-Y3

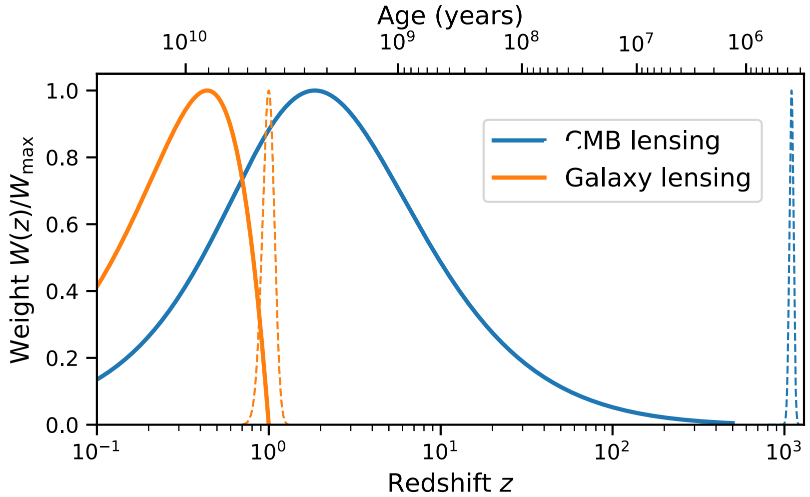


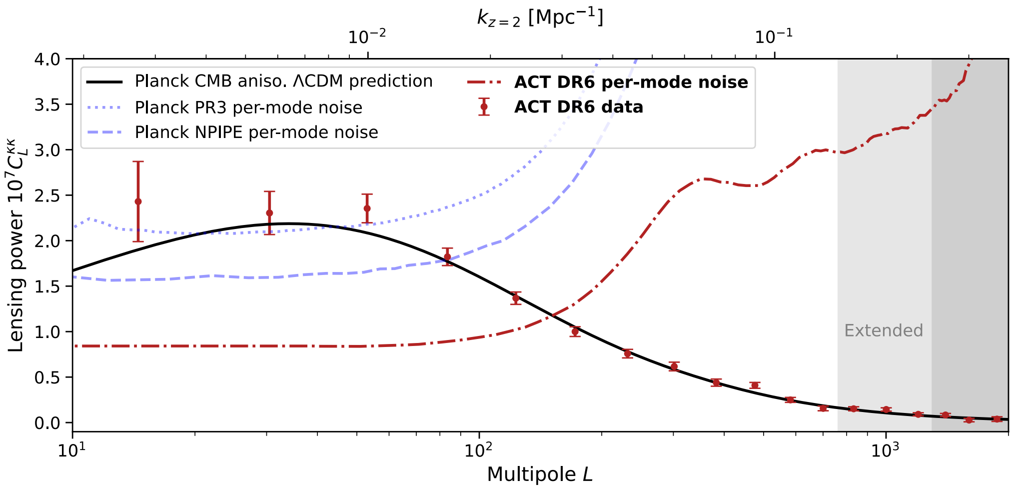
Galaxy weak lensing (k~1 h/Mpc, z<1)

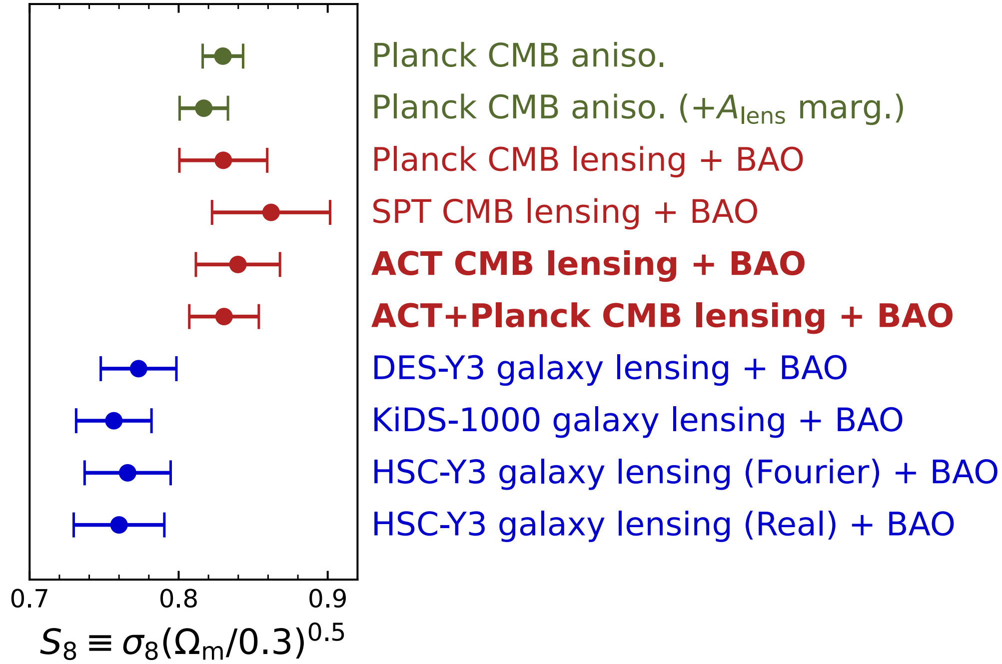
Redshift-space galaxy clustering (k~0.1 h/Mpc, z<1)

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

However, ACT DR6 CMB lensing result came out …



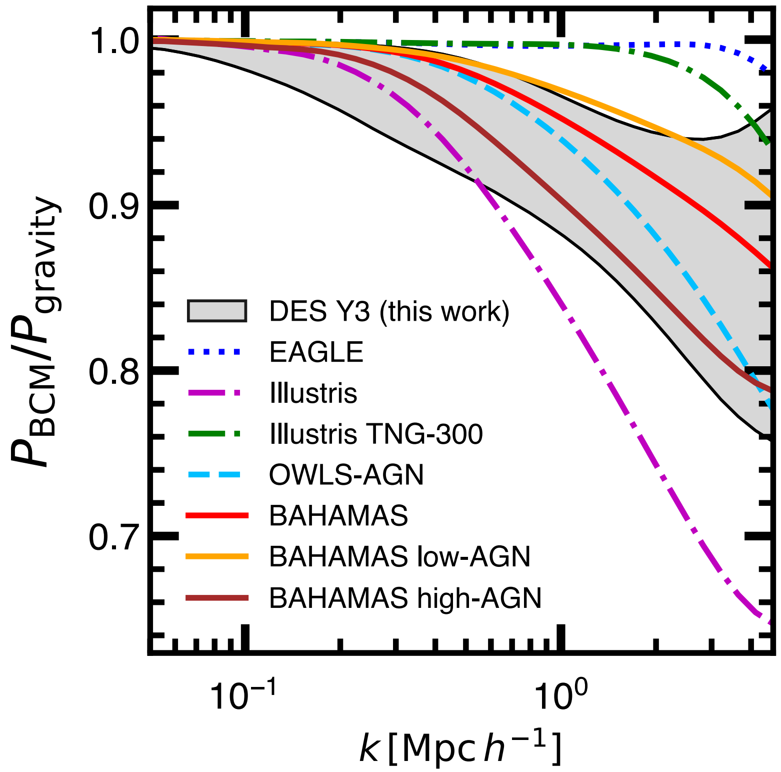


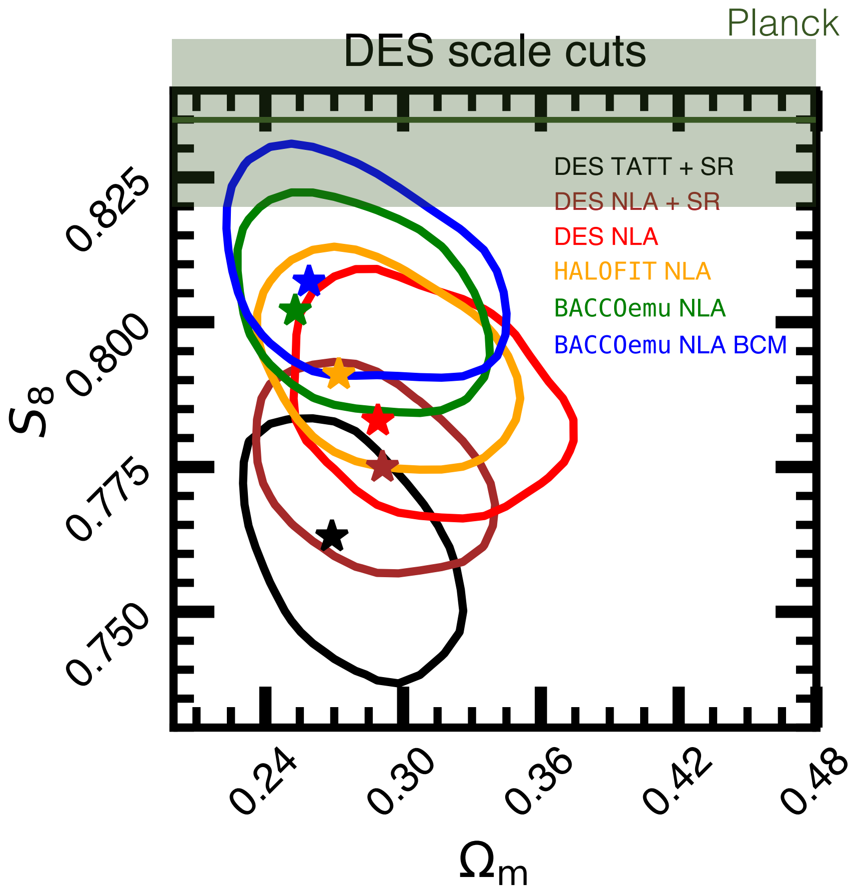


- Now S8 values inferred from CMB and galaxy lensing are in tension
- CMB lensing inferred cosmology (ACT and SPT) is consistent with Planck

All due to baryons?

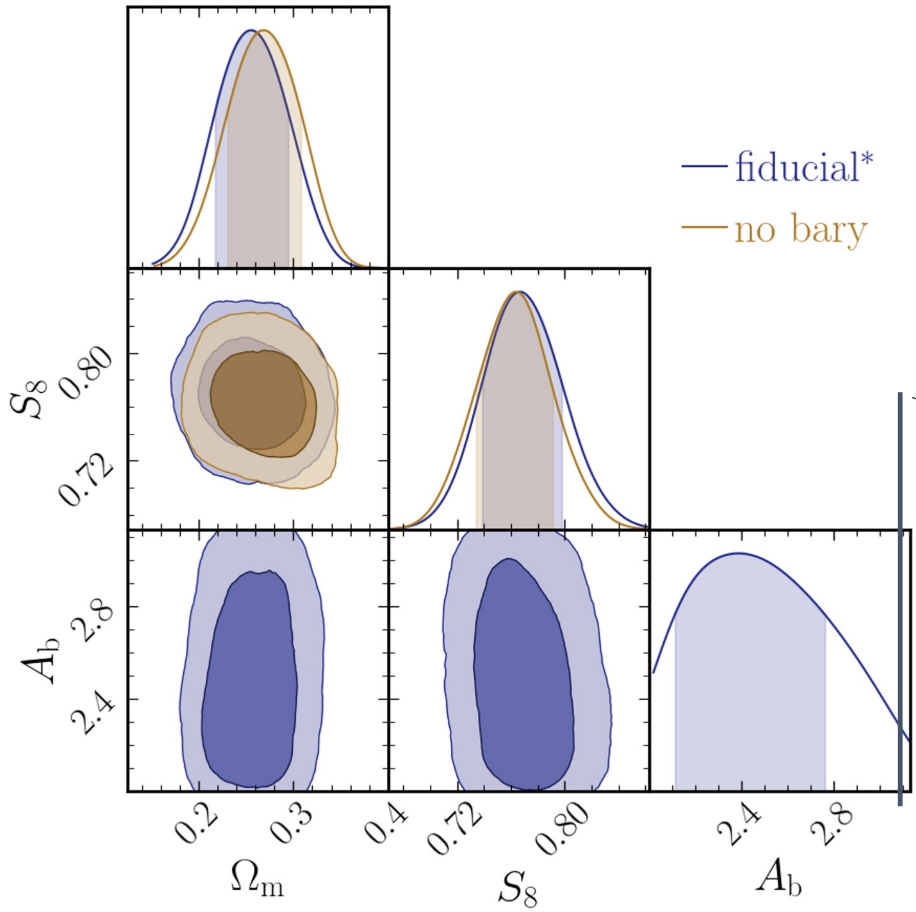
- Arico+ 23 reperformed cosmology inference analysis of DES-Y3 cosmic shear data using more flexible baryonification model





Baryonic Feedback

Li+



Note that 3x2pt result is less affected by baryonic effect

No baryonic feedback (3.13)

Summary: HSC-Y3 cosmology results

- Subaru HSC Year 3 results: 416 sq. deg., ~16 gals/arcmin^2: 3 analyses
  - Real-space cosmic shear tomography: Xiangchong Li+
  - Fourier-space cosmic shear tomography: Roohi Dalal+
  - 3x2pt cosmology (HSC+SDSS): Sunao Sugiyama+ (PT), Miyatake, Sugiyama+ (halo model)
- We tried to implement robust cosmology analysis for flat ΛCDM model
  - Blind analysis (catalog and analysis levels)
  - Employed uninformative flat prior of residual systematic error in the mean source redshift for galaxies at z>1
  - Performed various validation tests and internal consistency tests
- Achieved ~4% fractional precision of S8: S8~0.76-0.78±0.03, in 2-2.5σ tension with Planck cosmology
  - Found a hint of residual redshift error, at the level of |Δz|~0.1
- However, now ACT lensing, consistent with Planck, came out
- New physics or something else – very exciting!