Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam data

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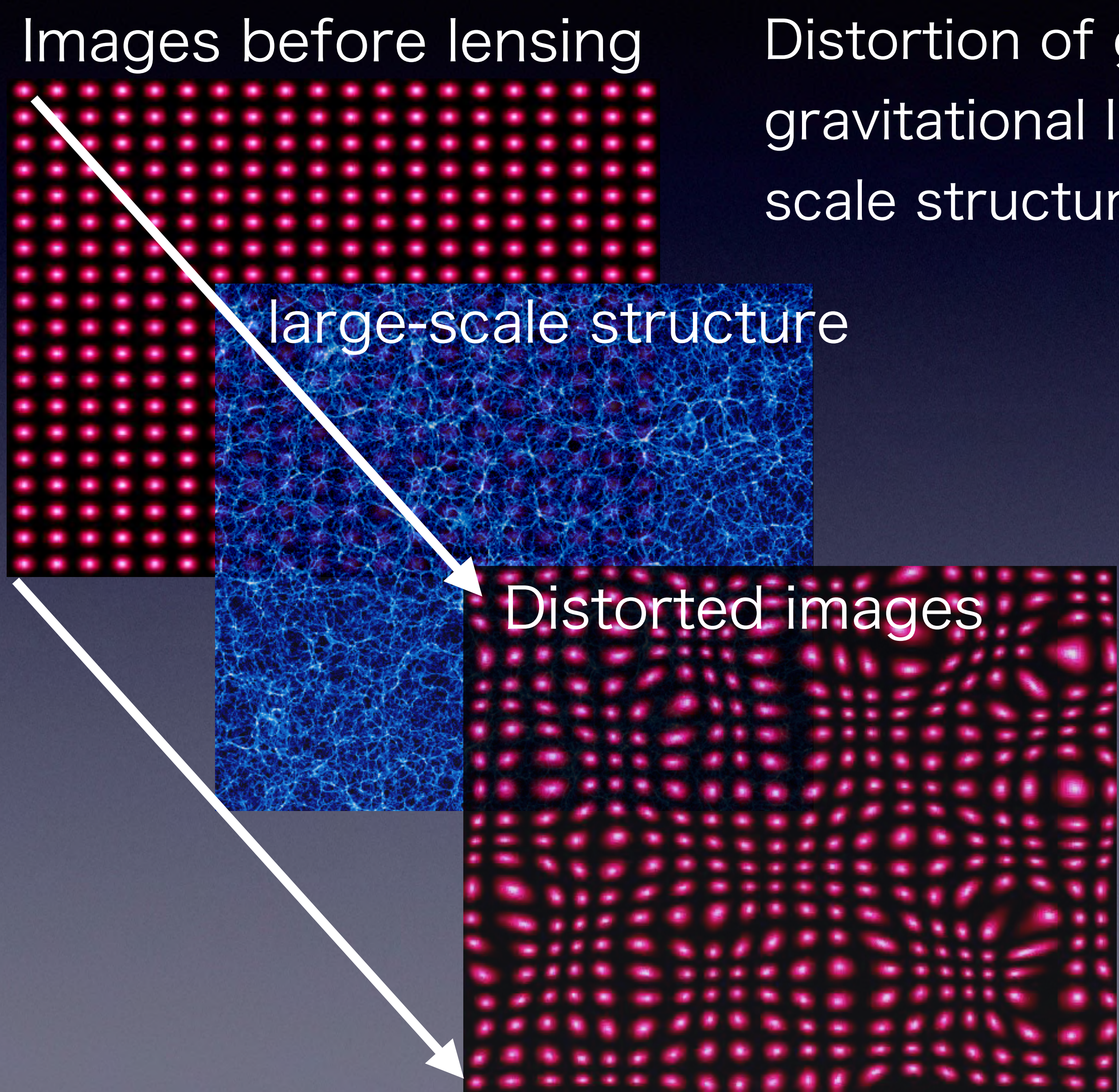
Cosmic shear



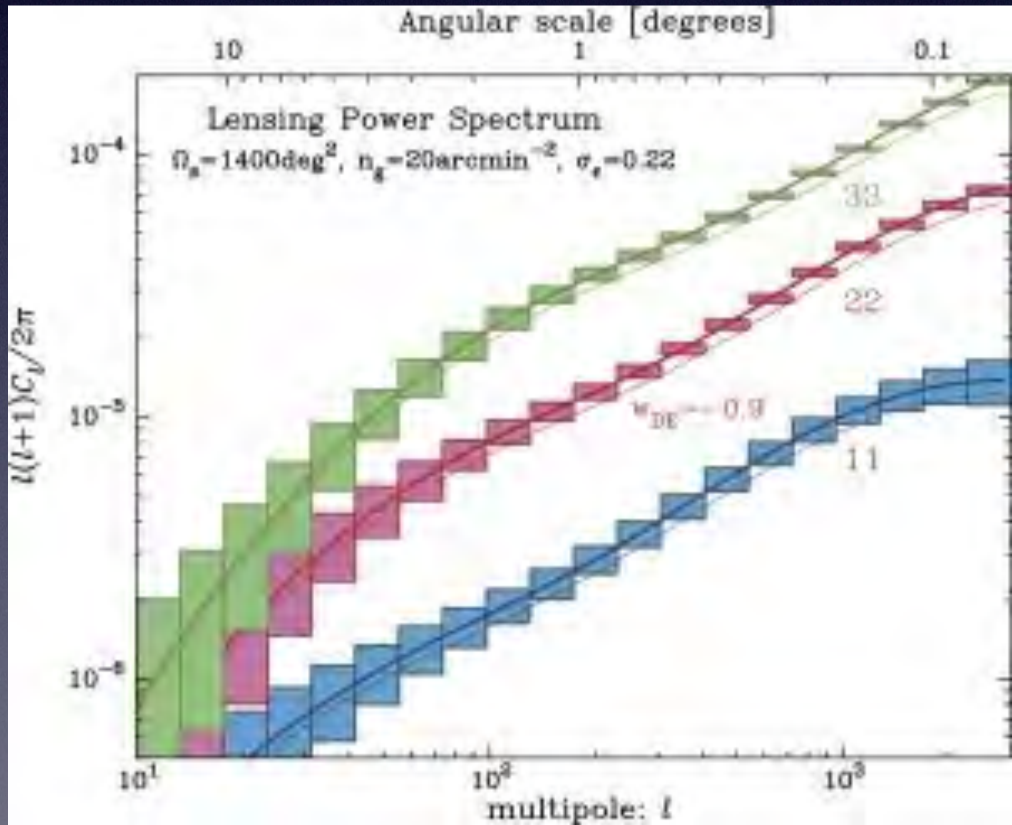
Distortion of galaxy images by weak gravitational lensing effect of large-scale structure

Coherent pattern of distortion in galaxy images , i.e., shear, becomes a **direct probe of matter density field**

Cosmic shear power spectrum

$$\gamma \propto \Omega_{m0} \int_0^{z_s} dz_L \frac{d_s(z_L)\, d_s(z_s - z_L)}{d_s(z_s)} \delta(z_L)$$

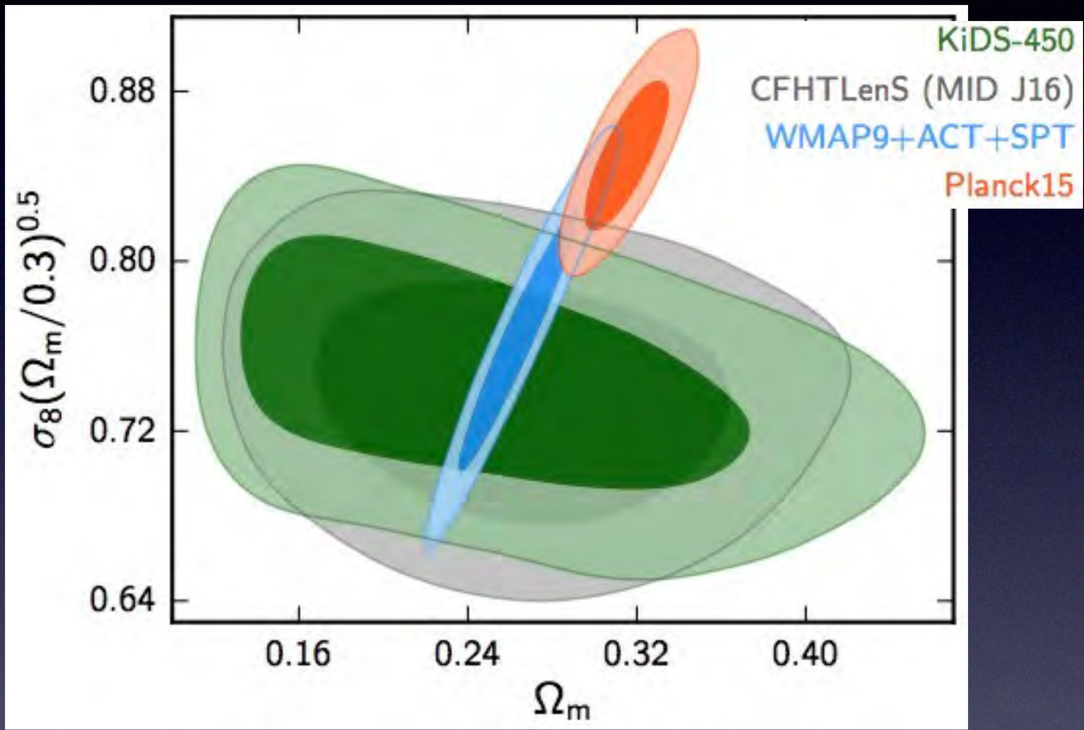
distance　　matter density field



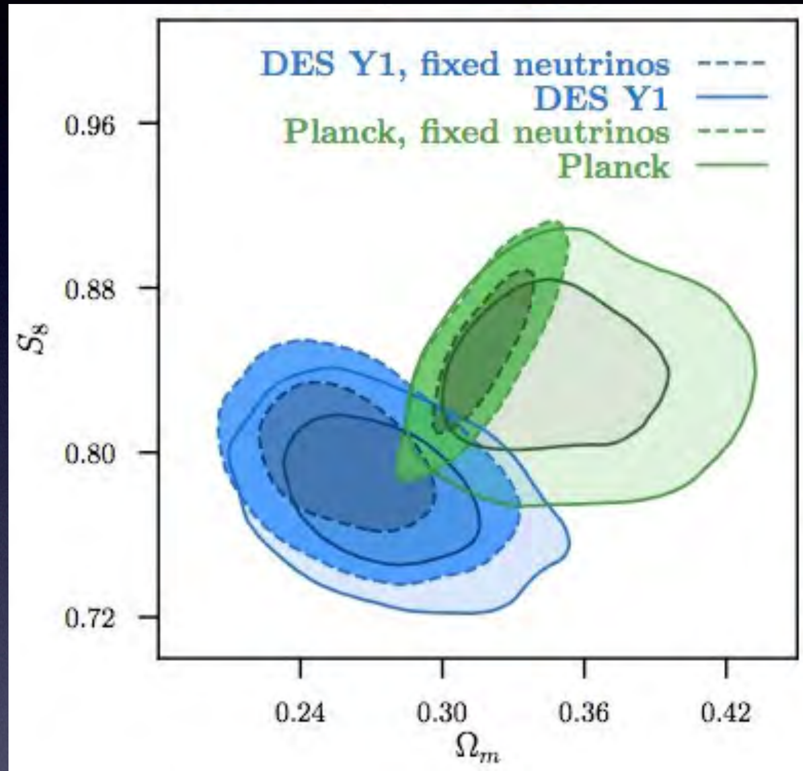
(c) HSC collaboration

- One can extract the information of the growth of structure by tomographic analysis
- Cosmic shear is sensitive to a combination of σ_8 and Ω_m
  $S_8 = \sigma_8(\Omega_m/0.3)^\alpha$　($\alpha \sim 0.5$)

S_8 tension between Planck and cosmic shear

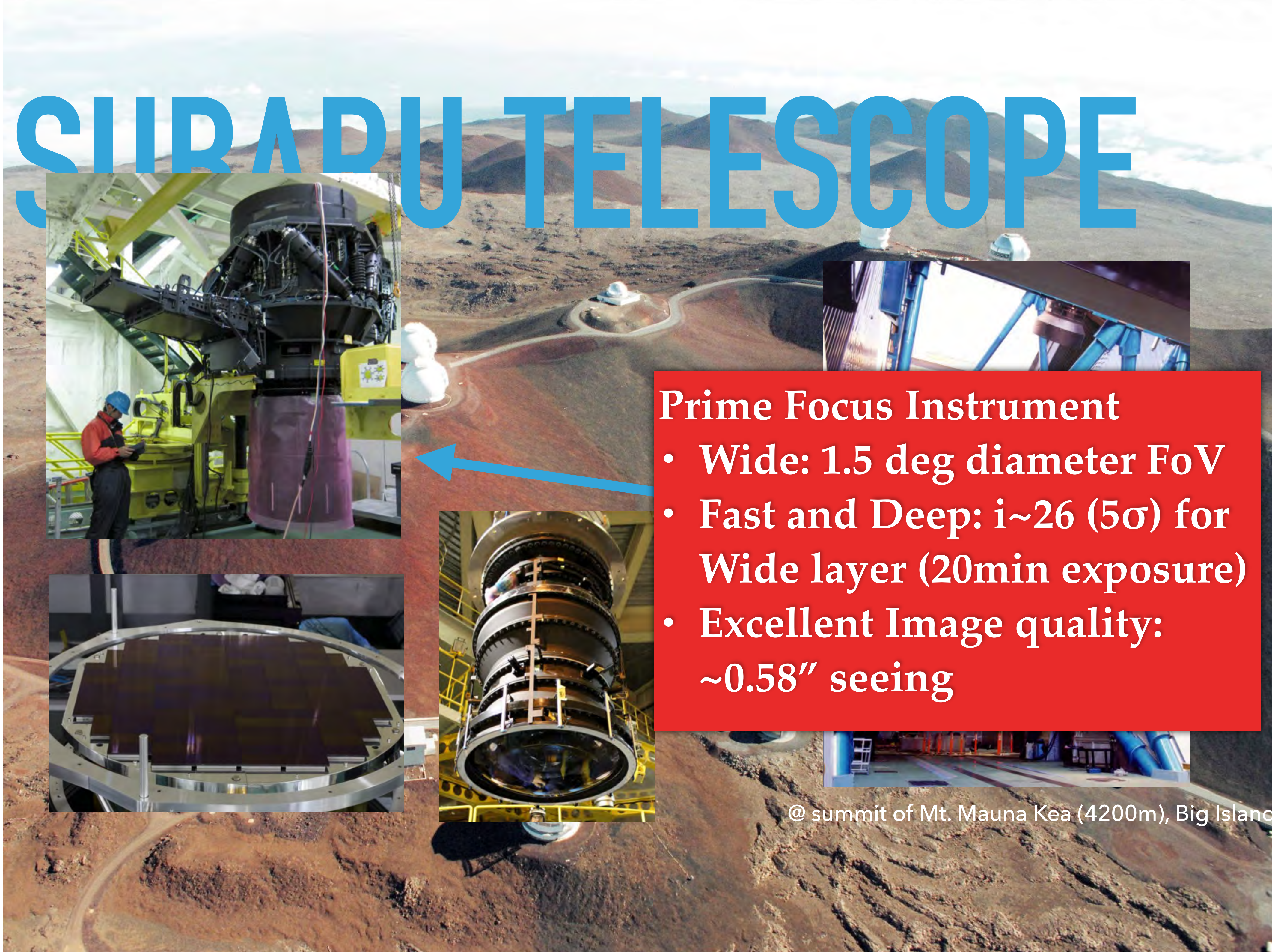


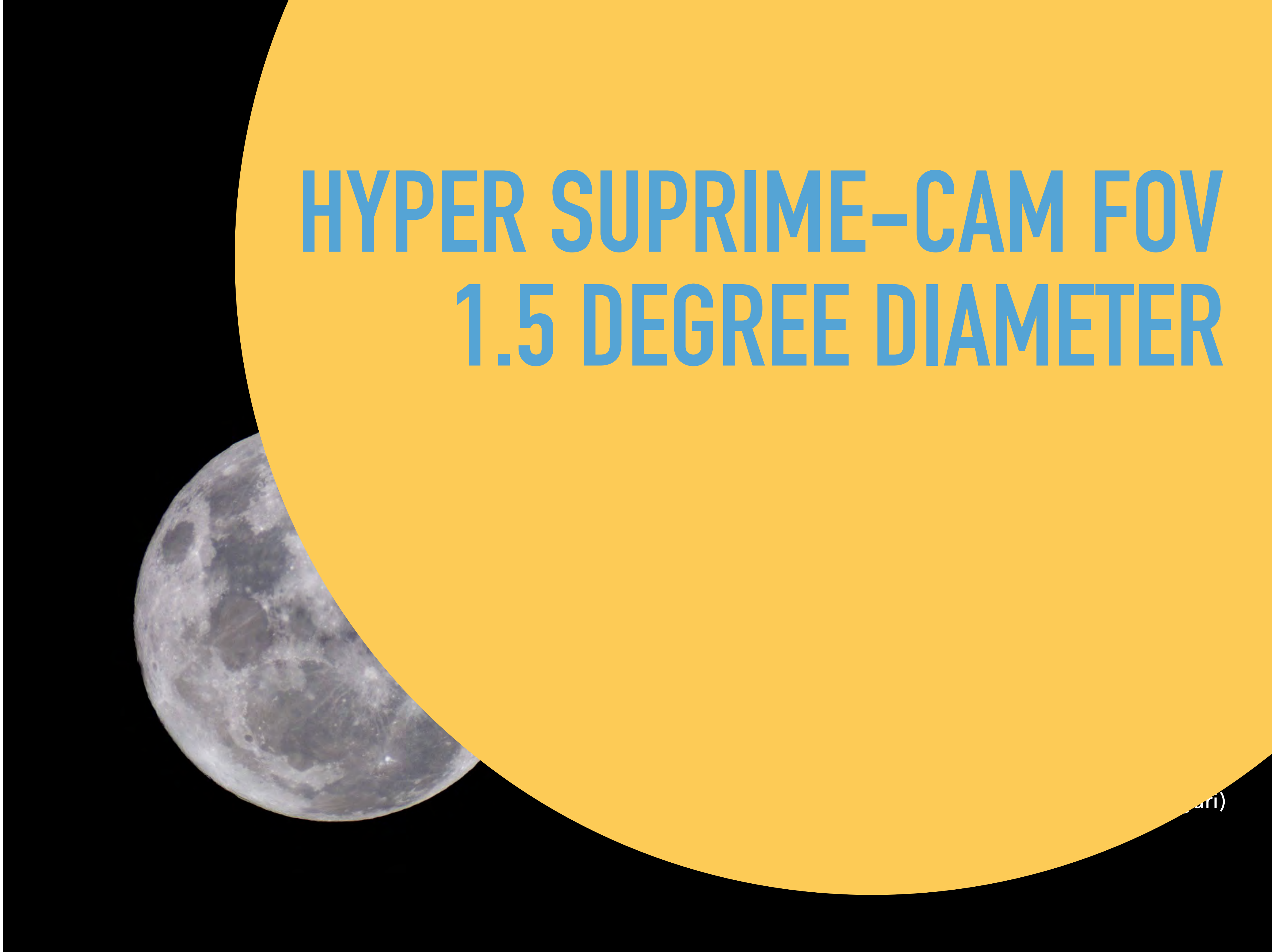
KiDS/CFHTLenS vs Planck
(Hildebrandt et al. 2017, Joudaki et al. 2017
Köhlinger et al. 2017)



DES vs Planck (Troxel et al. 2018,
DES collaboration et al. 2018)

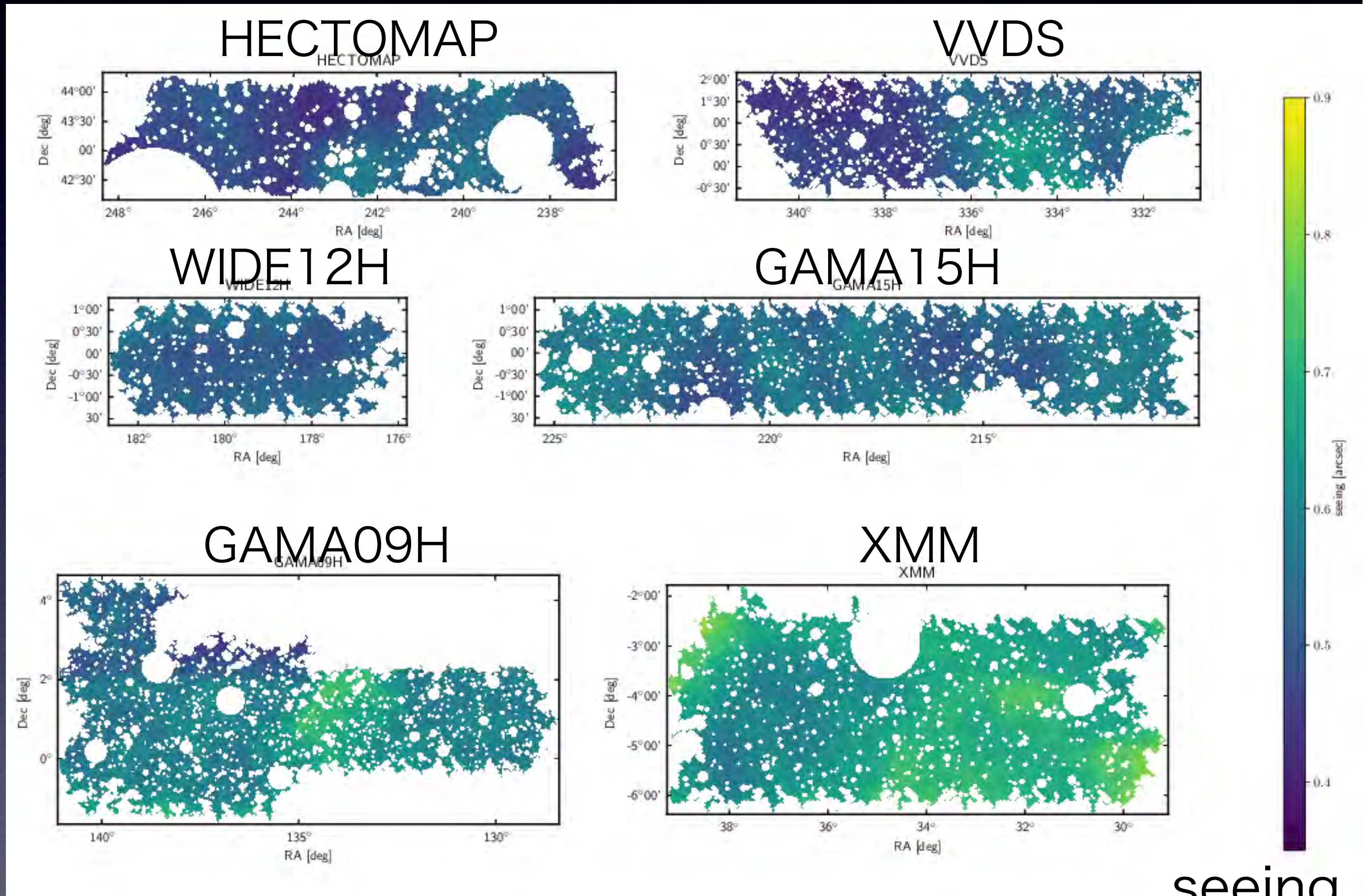
Some systematic or hints for physics beyond ΛCDM?


SUBARU TELESCOPE
Prime Focus Instrument
• Wide: 1.5 deg diameter FoV
• Fast and Deep: i~26 (5σ) for Wide layer (20min exposure)
• Excellent Image quality: ~0.58″ seeing
@ summit of Mt. Mauna Kea (4200m), Big Island


HYPER SUPRIME-CAM FOV
1.5 DEGREE DIAMETER

HSC Y1 shear catalog

- Data taken between Mar 2014 and Apr 2016
- 6 fields, 137deg^2
- HSM re-gaussianization method to measure galaxy shapes
- Selection for 1st year science (e.g., i<24.5, resolution>1/3)
- High number density: n_g=25gals/sq.arcmin
- Internal null tests of shear catalogs was done

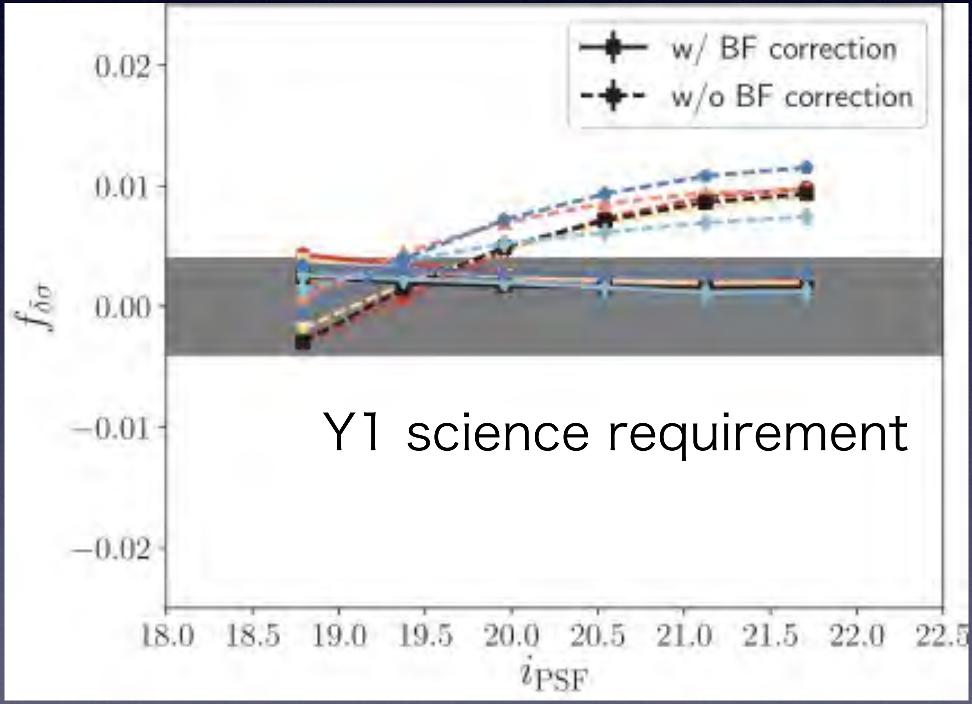


Map of i-band PSF FWHM

Mandelbaum, Miyatake et al. 2018

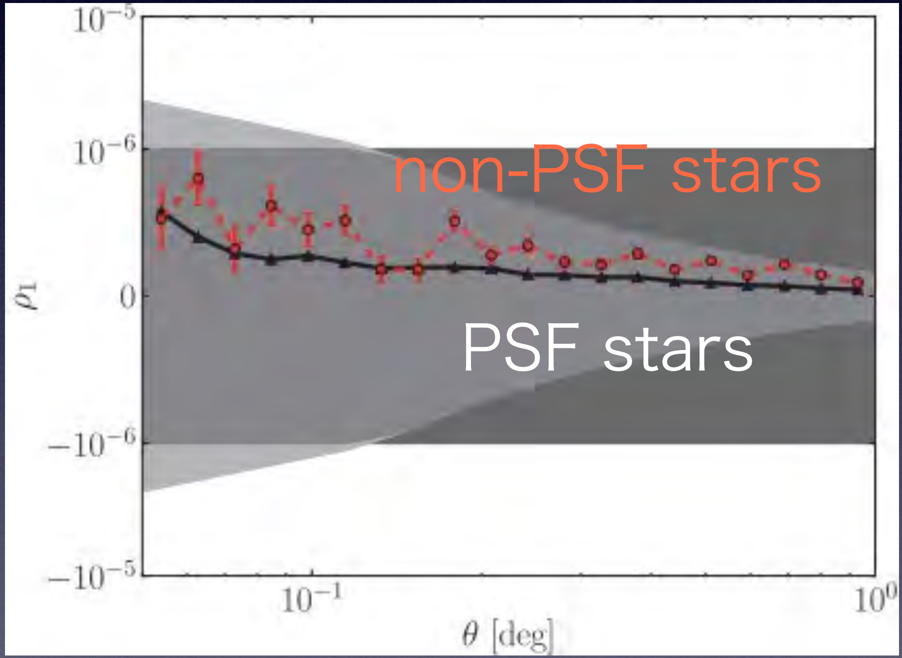
Shear catalog meets the HSC Y1 science requirements shown in shaded regions

fractional size residual



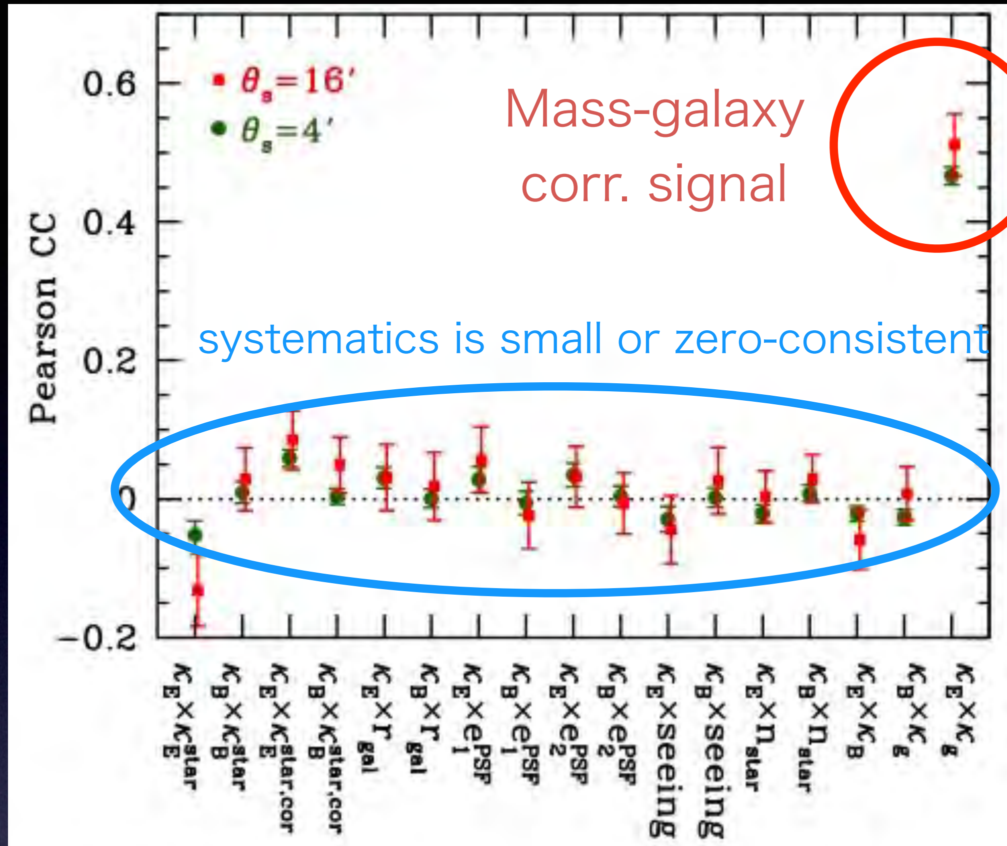
brighter-fatter effect must be corrected

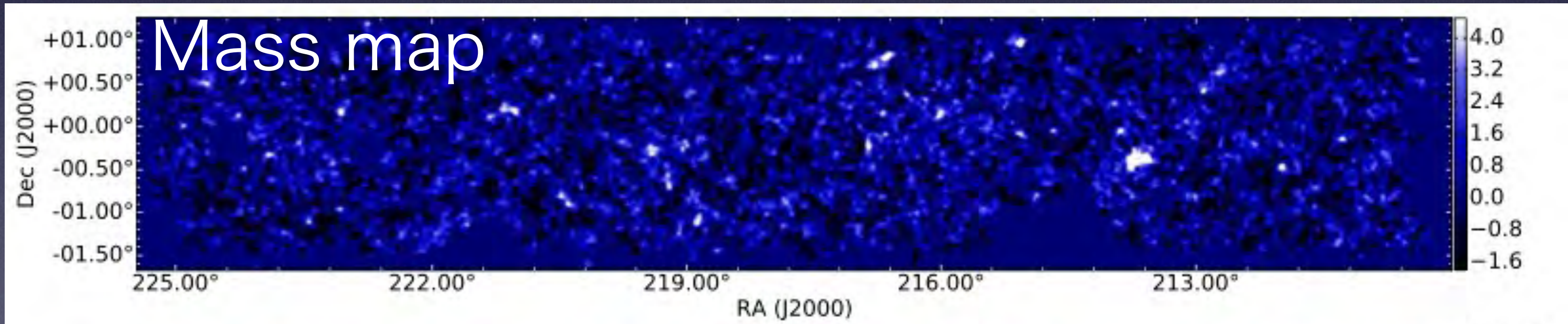
Correlations of PFS residual

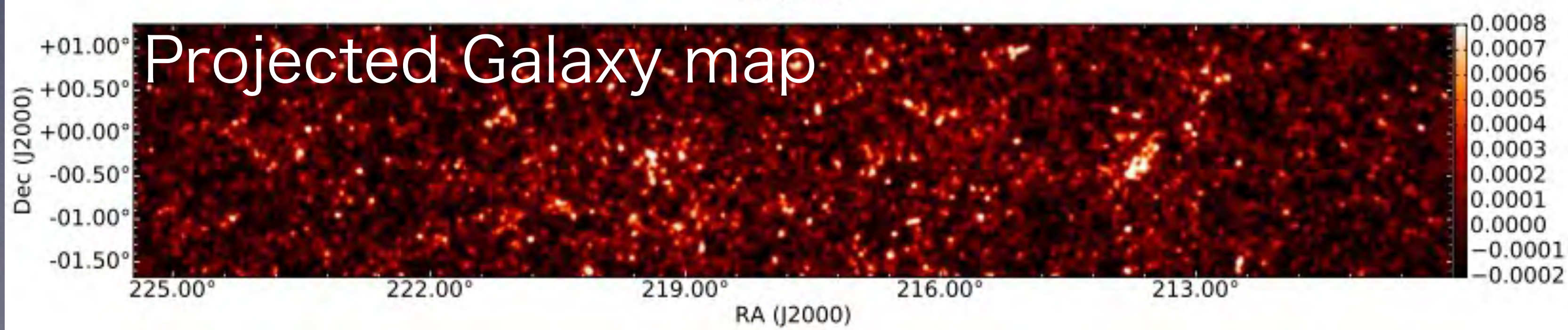


Mass map reconstruction

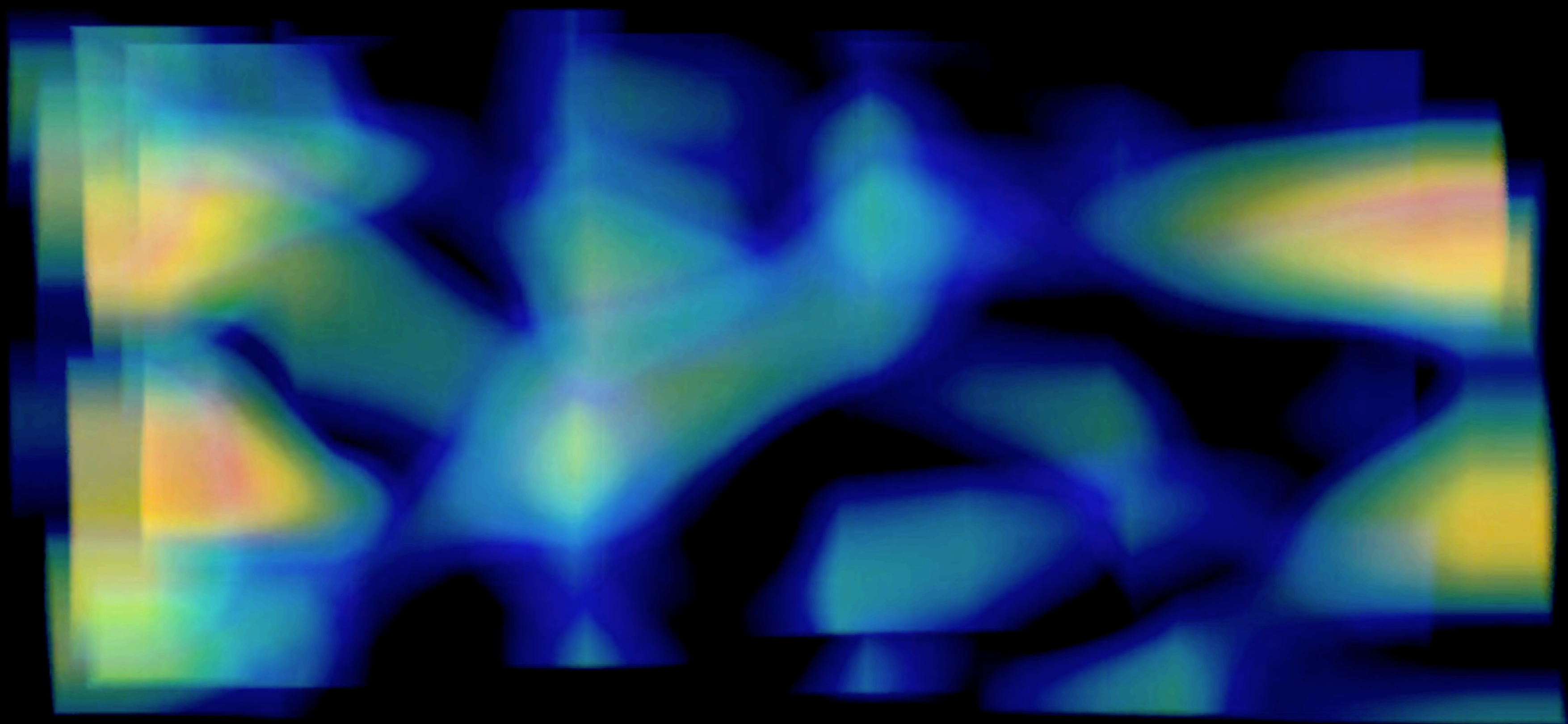
Oguri et al. 2018







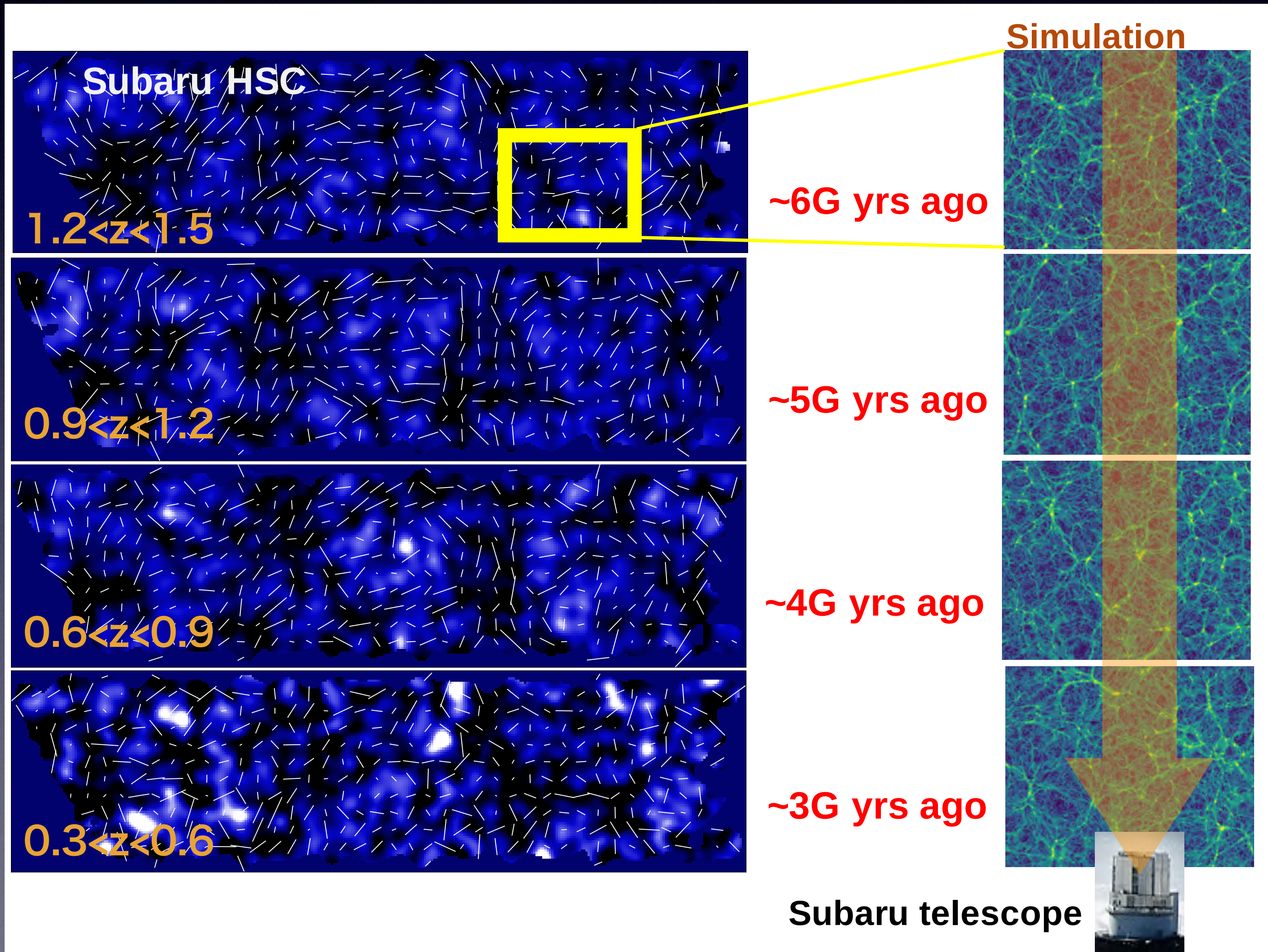
3D mass map



Oguri et al. 2018

tomographic analysis

We divide galaxy samples into 4 redshift bins to extract the information of the growth of matter structure in the expanding Universe



Properties of HSC Y1 shear catalog

4-bin tomographic sample

bin number	z range	$z_{\rm med}$	$N_{\rm g}$	$n_{\rm g}$ [arcmin^{-2}]	$n_{\rm g,eff}$ [arcmin^{-2}]
1	0.3 – 0.6	0.446	2842635	5.9	5.4
2	0.6 – 0.9	0.724	2848777	5.9	5.3
3	0.9 – 1.2	1.010	2103995	4.3	3.8
4	1.2 – 1.5	1.300	1185335	2.4	2.0
All	0.3 – 1.5	0.809	8980742	18.5	16.5

$$n_{\rm g,eff} = \sum_i e^2_{\rm rms,i}/(\sigma^2_{e,i} + e^2_{\rm rms,i})/\text{area}$$

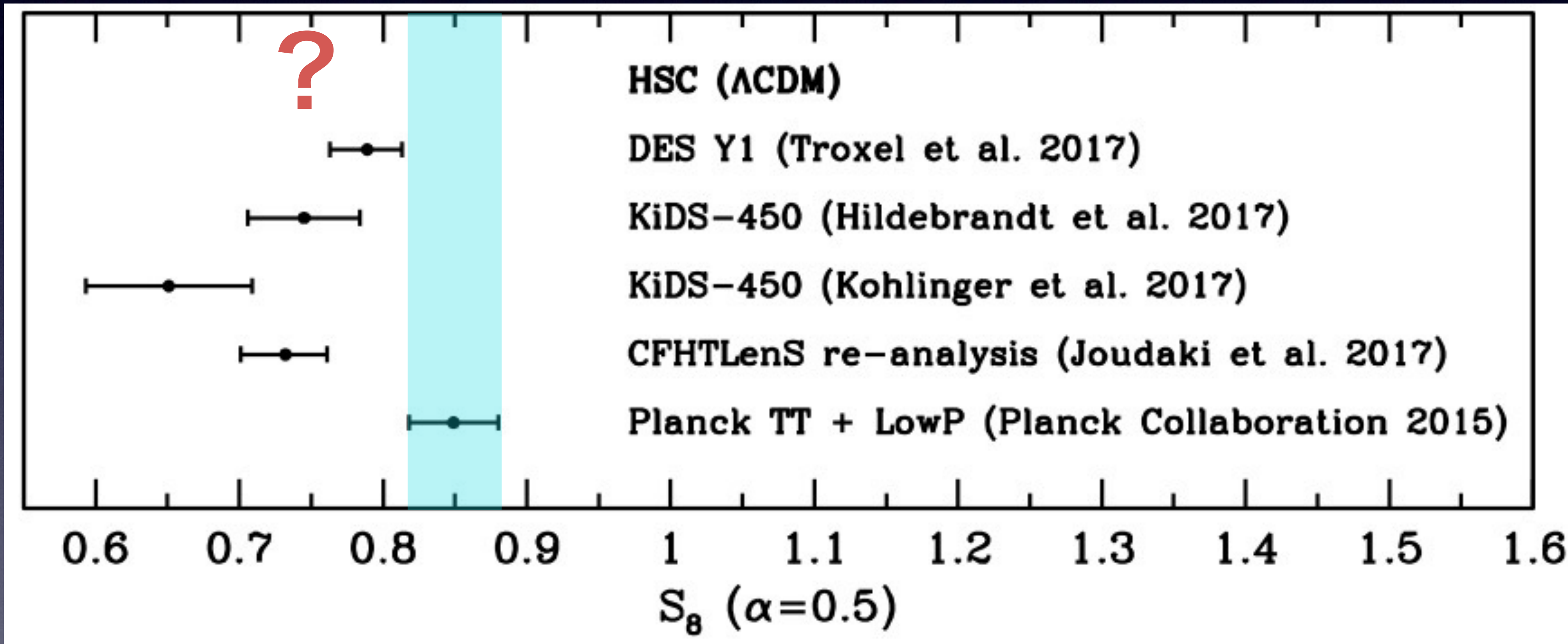
Comparison with other surveys

survey catalog	area [deg^2]	No. of galaxies	$n_{\rm g,eff}$ [arcmin^{-2}]	z range
KiDS-450	450	14.6M	6.85	0.1 – 0.9
DES Y1	1321	26M	5.14	0.2 – 1.3
HSC Y1	137	9.0M	16.5	0.3 – 1.5

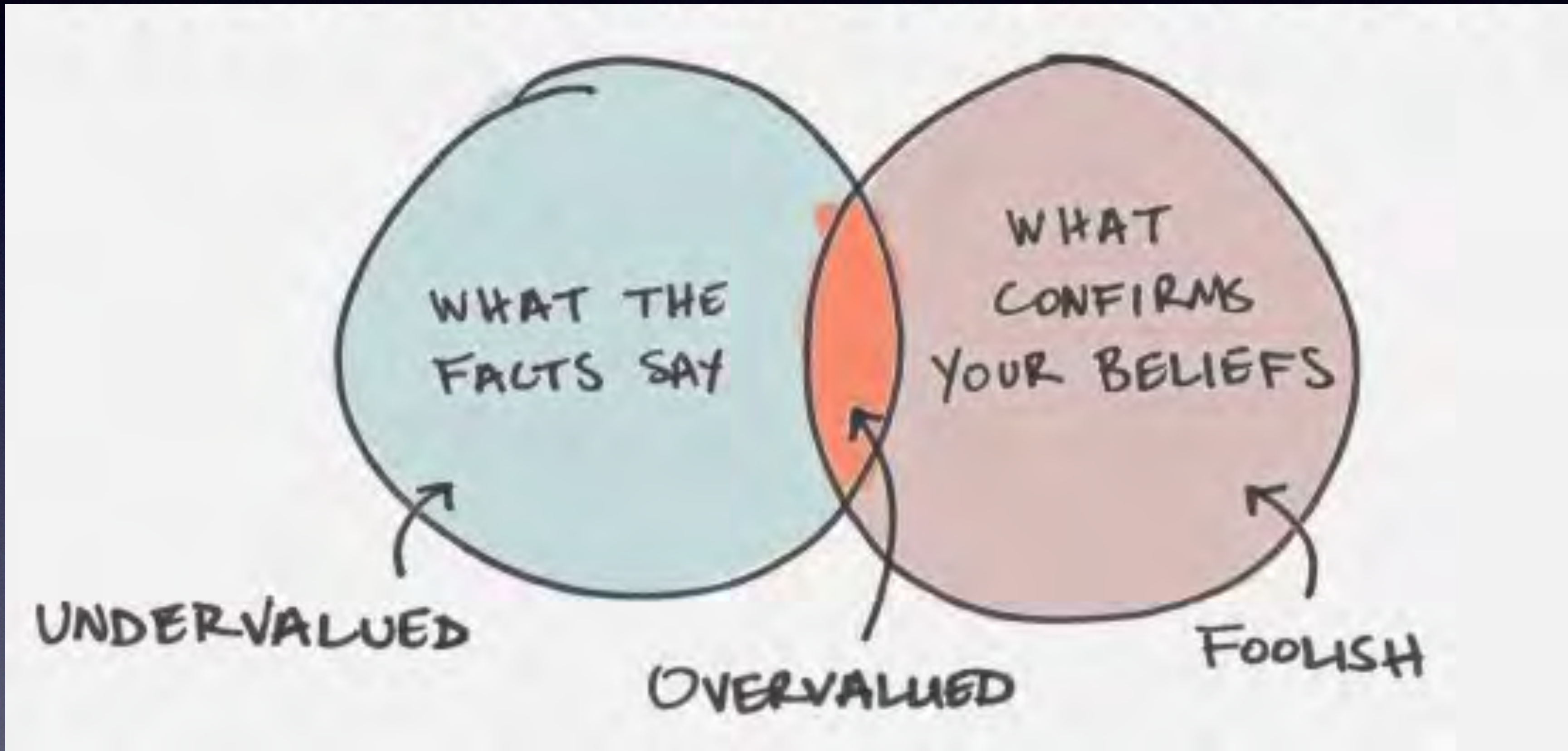
Higher number density → lower shape noise

Higher mean redshift → higher signal

How about S_8 from HSC survey ?



Confirmation Bias



People are biased toward confirming their existing beliefs

Comparison with other surveys may cause such bias

Blind analysis

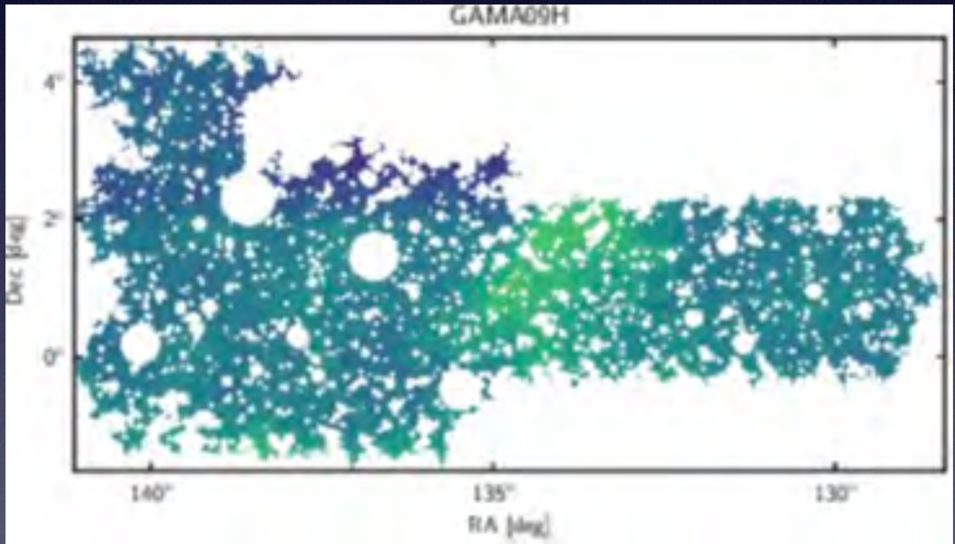
1. Catalog-level blinding:
   - Three catalogs with different values of shear bias are prepared: one is true, while other two are fake
   - No one can know which catalog is true by oneself. Unblinding needs two passwords from each analyst and the blinder-in-chief who is not involved in the analysis
2. Analysis-level blinding:
   - Central values of measured cosmological parameters are also blinded
   - No comparison with other datasets in the blinding phase

Systematics

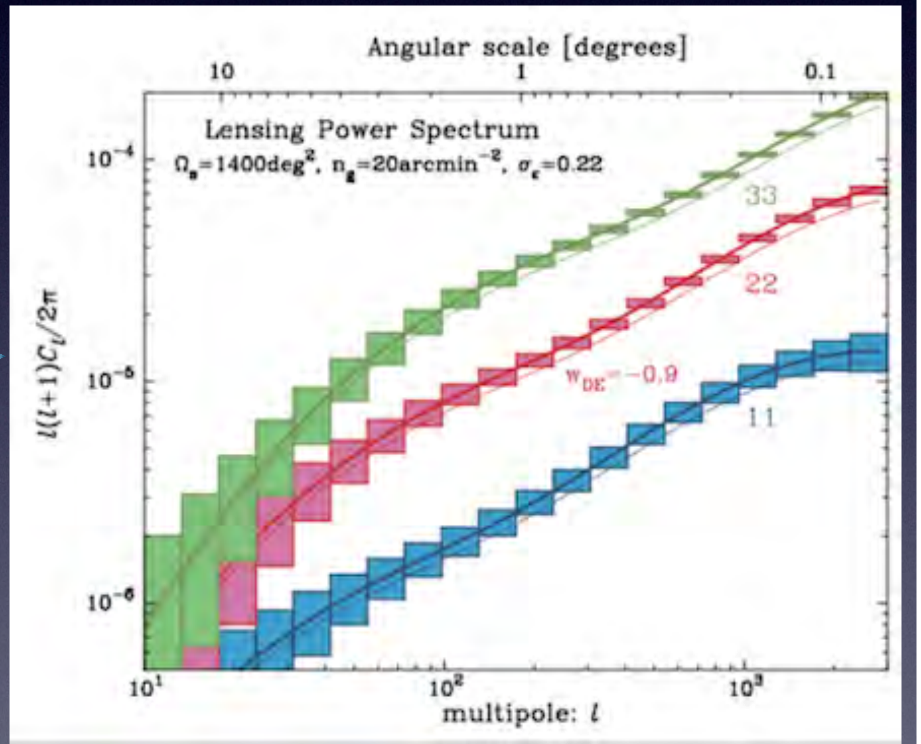
1. Survey geometry and inhomogeneity of data
2. PSF modeling error and leakage in shape measurement
3. Photo-z uncertainty
4. Intrinsic alignment
5. Baryon physics

1. Survey mask

Shear catalog has complicated survey geometry due to bright star masks



?



Can we get unbiased estimates of shear power spectra from such data?

Pseudo-Cl estimator

true mask obs noise

$$C_b = \mathbf{M}^{-1}_{bb'} \sum_{\mathbf{k}}^{k \in k'_b} P_{b'k} \left(\tilde{\mathbf{C}}_{\mathbf{k}} - \langle \tilde{\mathbf{N}}_k \rangle_{\mathrm{MC}} \right),$$

- Survey mask effect can be basically removed by multiplying the inverse of the convolution matrix (e.g.,Kogut et al. 2003)
- Shape noise spectrum is estimated by randomly rotating ellipticity data
- The estimator has been tested using simulations with complicated survey geometry (C.H., Hamana, Takada, Spergel 2009)

Mock shear catalogs

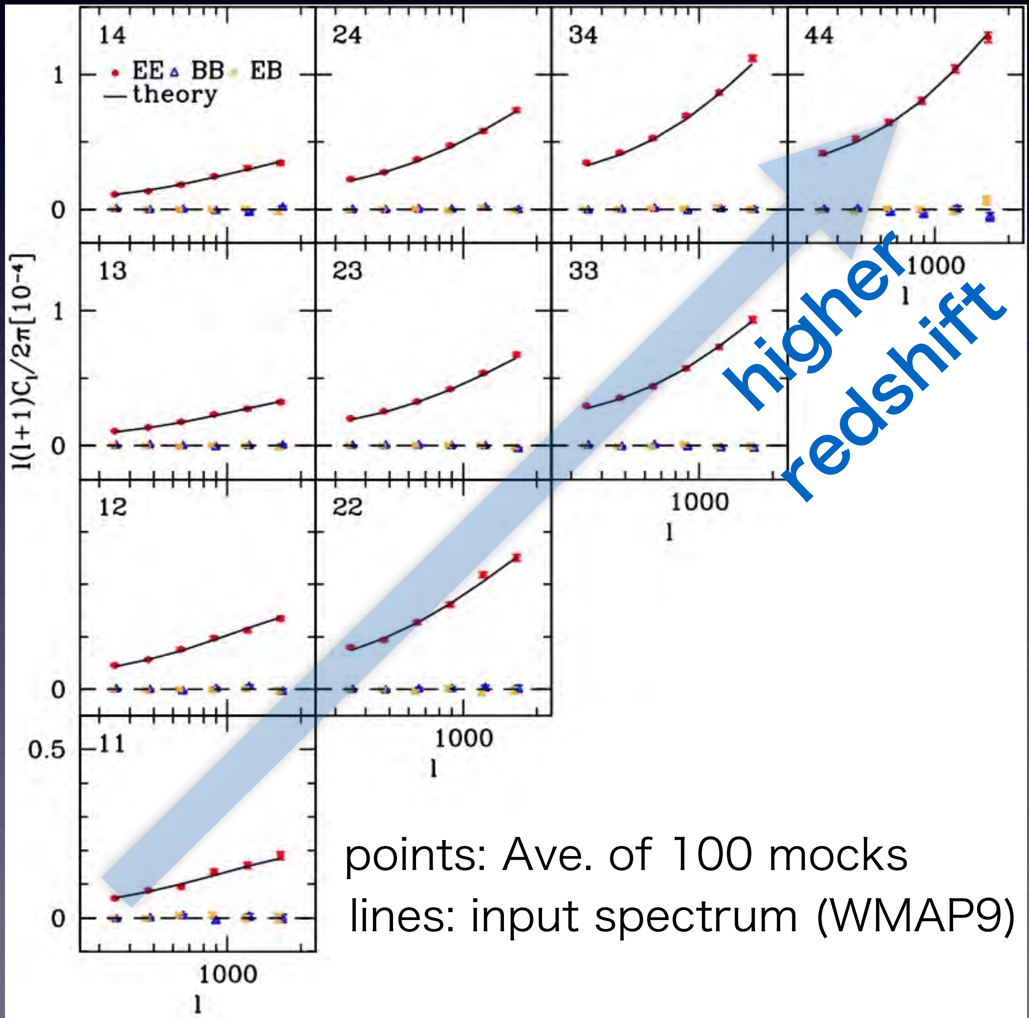
- We test pseudo-Cl method using HSC mock shear catalogs by Oguri+ 2018 (Shirasaki+ in prep), which are made from all-sky lensing simulations (Takahashi+ 2017)
  - Sky positions of sources are identical to data
  - Each source redshift is given from the photo-z PDF
  - Size of each source ellipticity is same as data, but the directions is randomly rotated
  - Convert observed ellipticities to simulated ones

$$\epsilon^{\rm lens} = \frac{\epsilon^{\rm int} + 2g + g^2\epsilon^{\rm int,*}}{1 + |g|^2 + 2{\rm Re}[g\epsilon^{\rm int,*}]}$$

(Seitz & Schneider 1995)

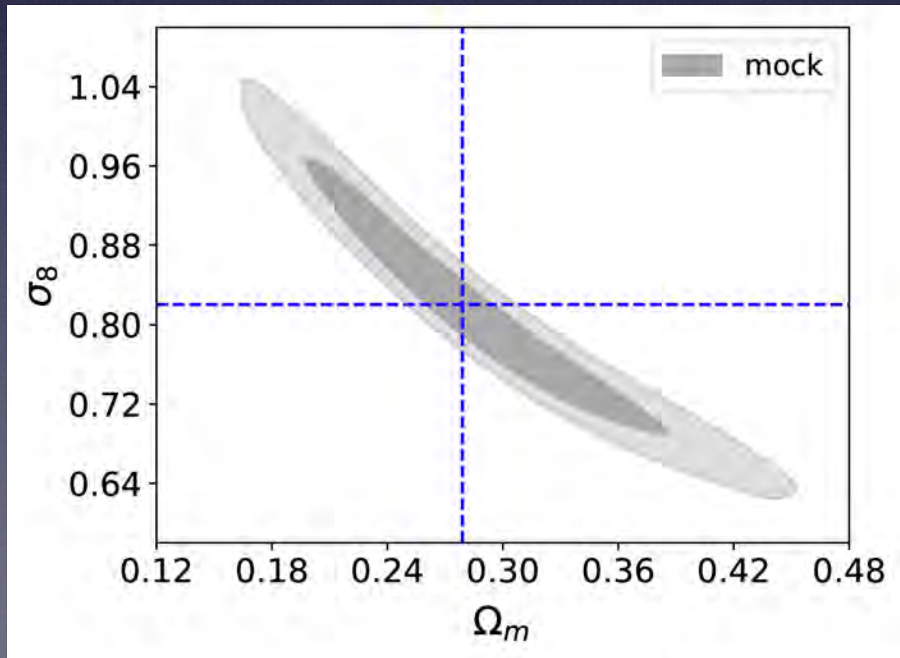
Testing pseudo-Cl method using mocks

Input spectrum is recovered

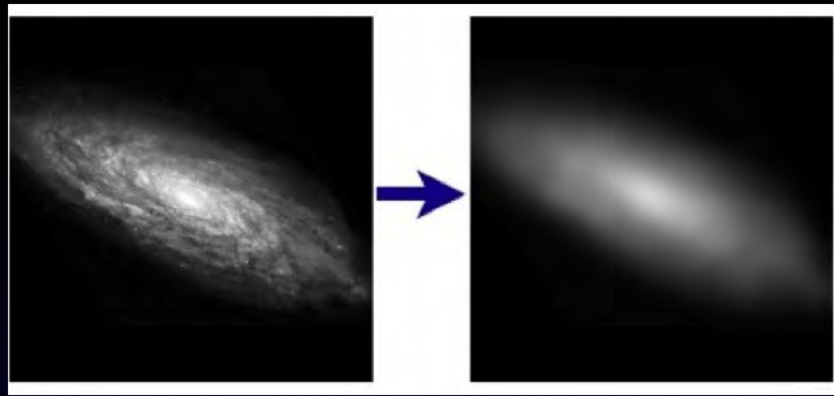


Input cosmology is recovered

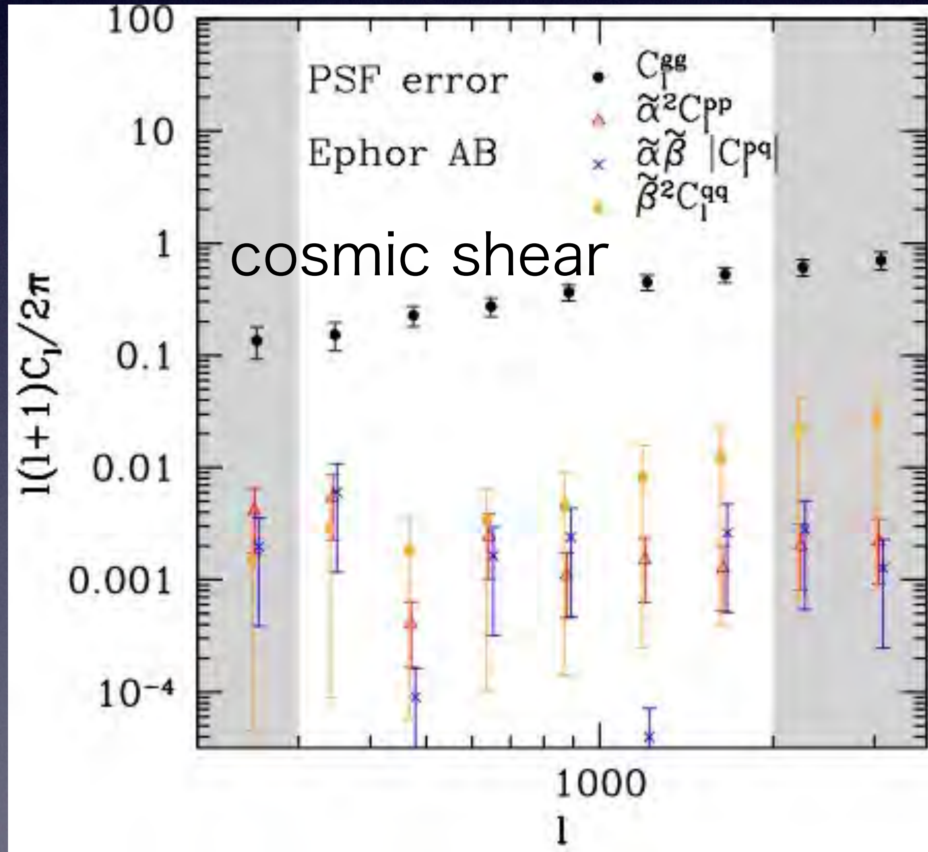
parameters	input values	fitted values
S_8	0.791	0.791±0.005
Ω_m	0.279	0.292±0.014
σ_8	0.82	0.801±0.020



2. PSF leakage and modeling error



- Shape errors & biases are estimated from the image simulations using HST COSMOS galaxy sample (Mandelbaum et al. 2018)
- The residual PSF model error and the deconvolution errors of the PSF model ('PSF leakage') are upto ~5% of signals.



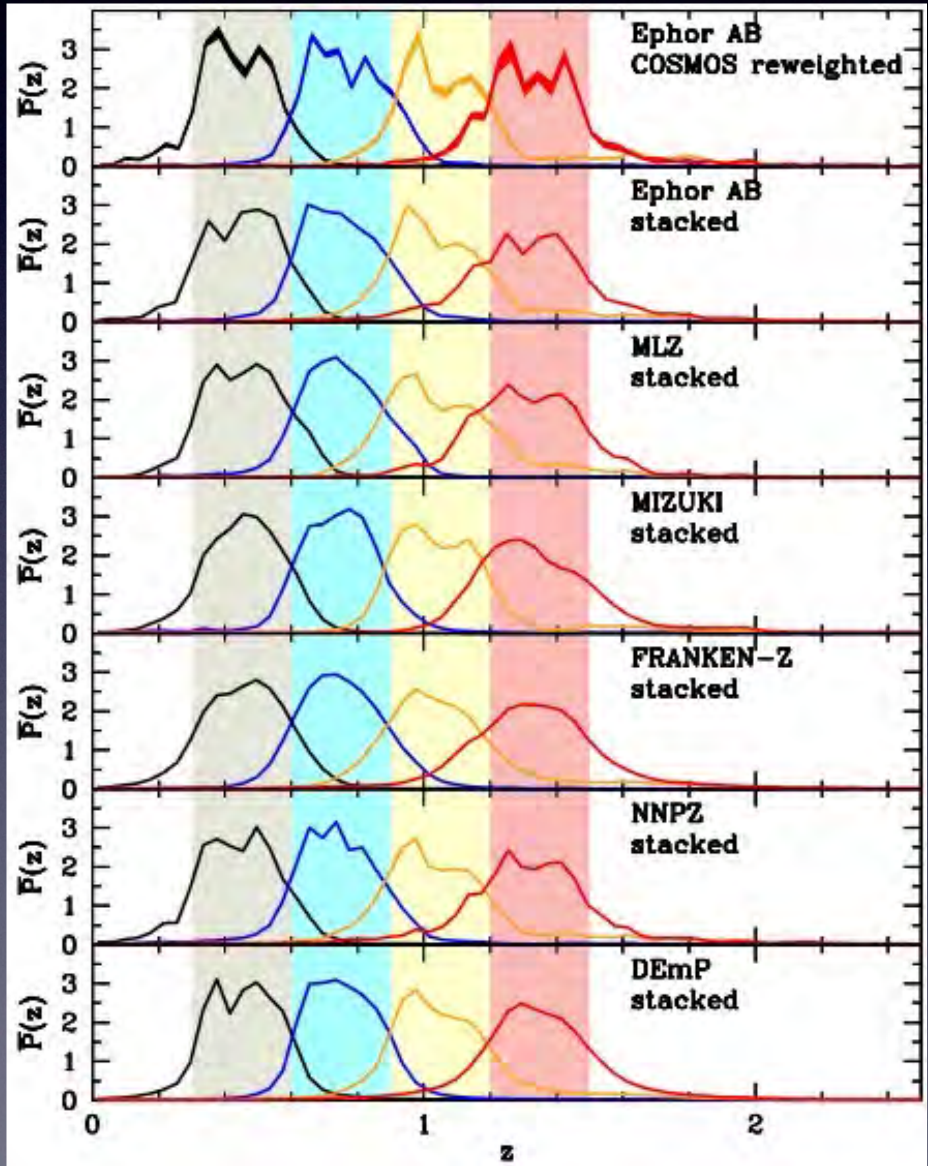
3. Photo-z distribution

- P(z) is estimated by reweighting COSMOS 30-band photoz data
- Stacked P(z) with different methods (e.g.,template fitting, neural network, self-organizing map) are used to estimate uncertainties of P(z)

$P_i(z) \rightarrow P_i(z+\Delta z_i)$

z range	$100\Delta z_i^{\rm method}$	$100\sigma_{\Delta z_i}^{\rm code}$	$100\sigma_{\Delta z_i}^{\rm tot}$
0.3 – 0.6	2.66	1.01	2.85
0.6 – 0.9	−1.07	0.83	1.35
0.9 – 1.2	−3.79	0.55	3.83
1.2 – 1.5	−3.20	1.98	3.76

comparison of p(z) in 4 tomographic bins from different estimates



4. Intrinsic alignment (IA)

- Galaxies are intrinsically aligned

$$\langle \gamma_i^{obs} \gamma_j^{obs} \rangle = \langle \gamma_i \gamma_j \rangle + \langle \gamma_i^I \gamma_j \rangle + \langle \gamma_i \gamma_j^I \rangle + \langle \gamma_i^I \gamma_j^I \rangle$$

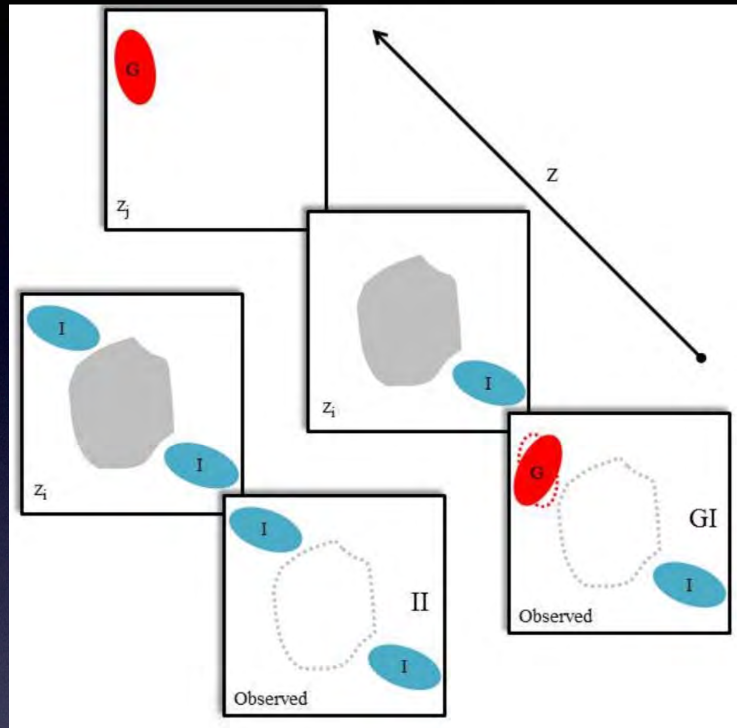
cosmic shear GI term II term

- We adopt the nonlinear alignment (NLA) model, which describes the measured IA signal upto ~1Mpc

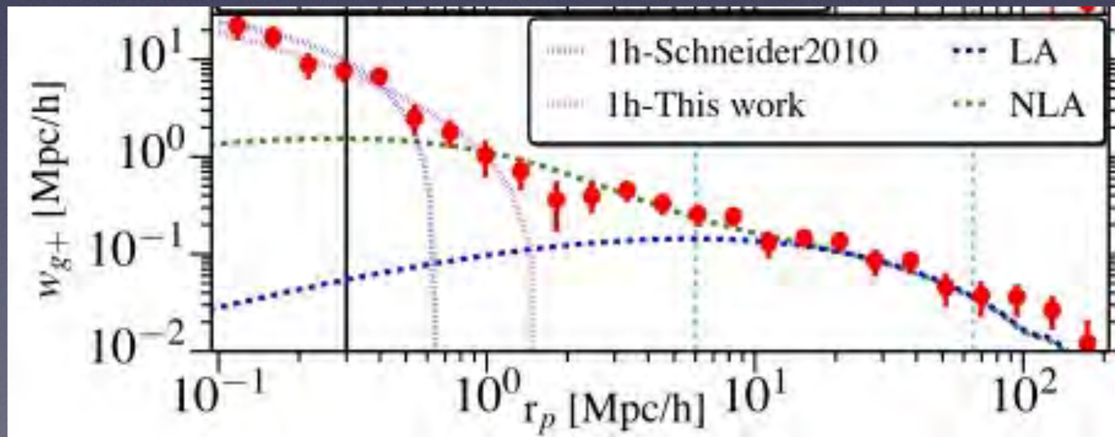
$$P_{\rm II}(k,z) = F^2(z) P_{\rm mm}^{\rm NL}(k,z)$$
$$P_{\rm GI}(k,z) = F(z) P_{\rm mm}^{\rm NL}(k,z).$$

$$F(z) = -A_{IA} C_1 \rho_{\rm crit} \frac{\Omega_m}{D(z)} \left(\frac{1+z}{1+z_0} \right)^{\eta}$$

- Amplitude and power-law index of z-evolution are fitted freely



Troxel et al. 2015

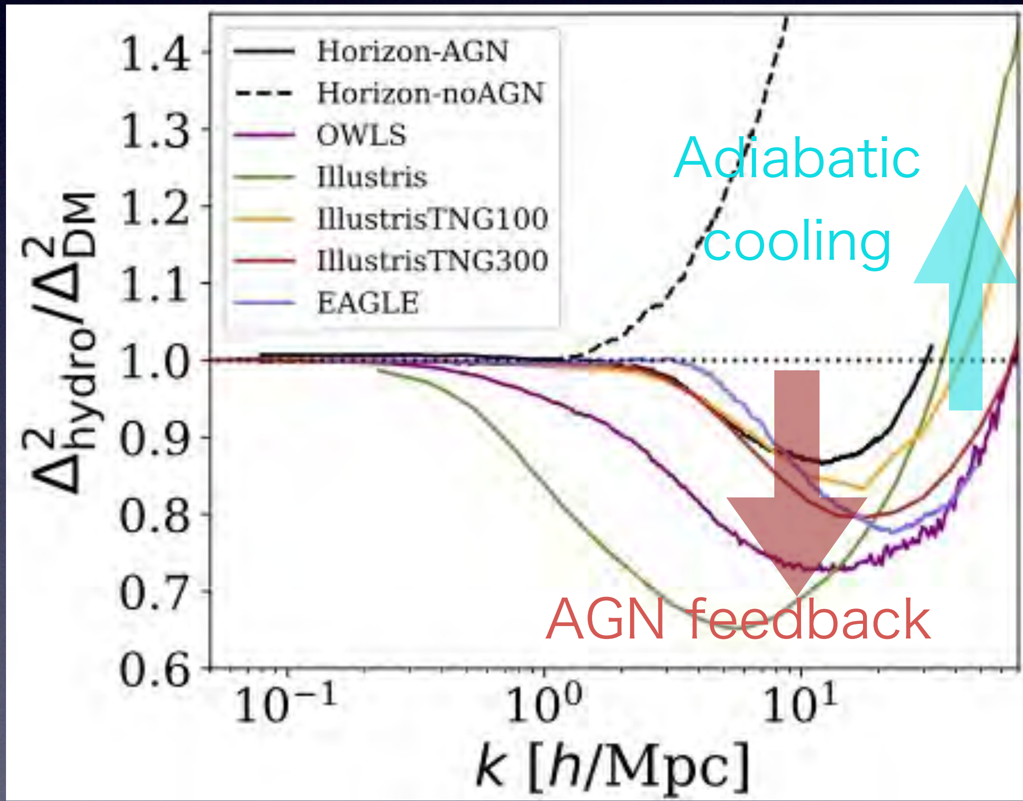


Singh & Mandelbaum 2014

5. Baryon physics

- Baryon physics (e.g., AGN feedback) may affect small-scale matter clustering, but the details of baryonic feedback are uncertain
- We don't use cosmic shear on subMpc scales
- We test the baryon impact on final result in the most extreme OWLS AGN feedback model (Harnois-Deraps et al. 2015, Mead et al. 2015)

The ratio of matter power spectrum between hydro-sim. and DM only sim.



Chisari et al. 2018

Parameters & Priors

Nested sampling likelihood analysis using “multinest" in MontePython

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	$A_{\rm IA}$	flat $[-5,5]$
redshift dependence of the intrinsic alignment	$\eta_{\rm eff}$	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

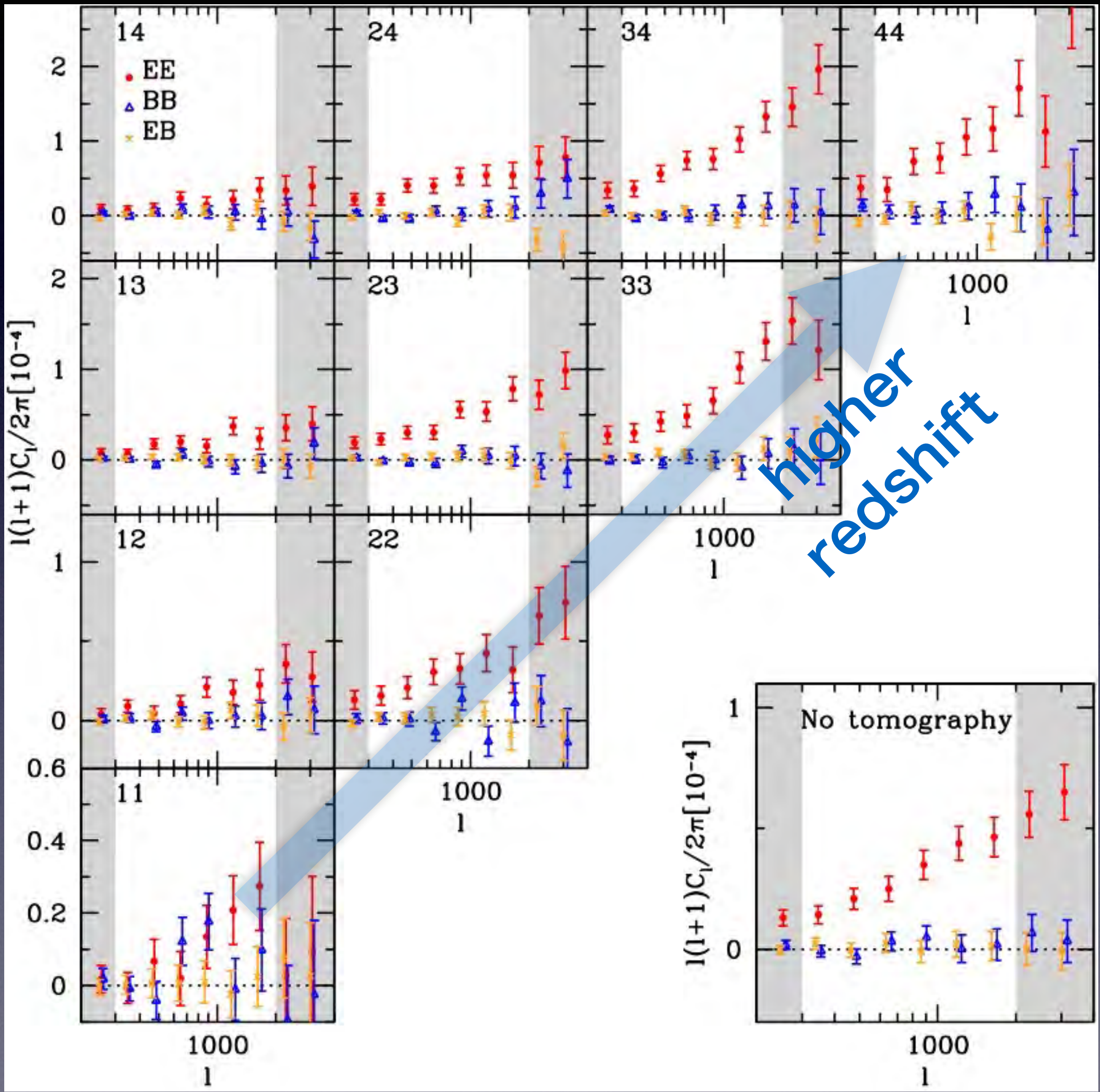
Baryonic effect

shear
measurement error

**photo-z
uncertainties**

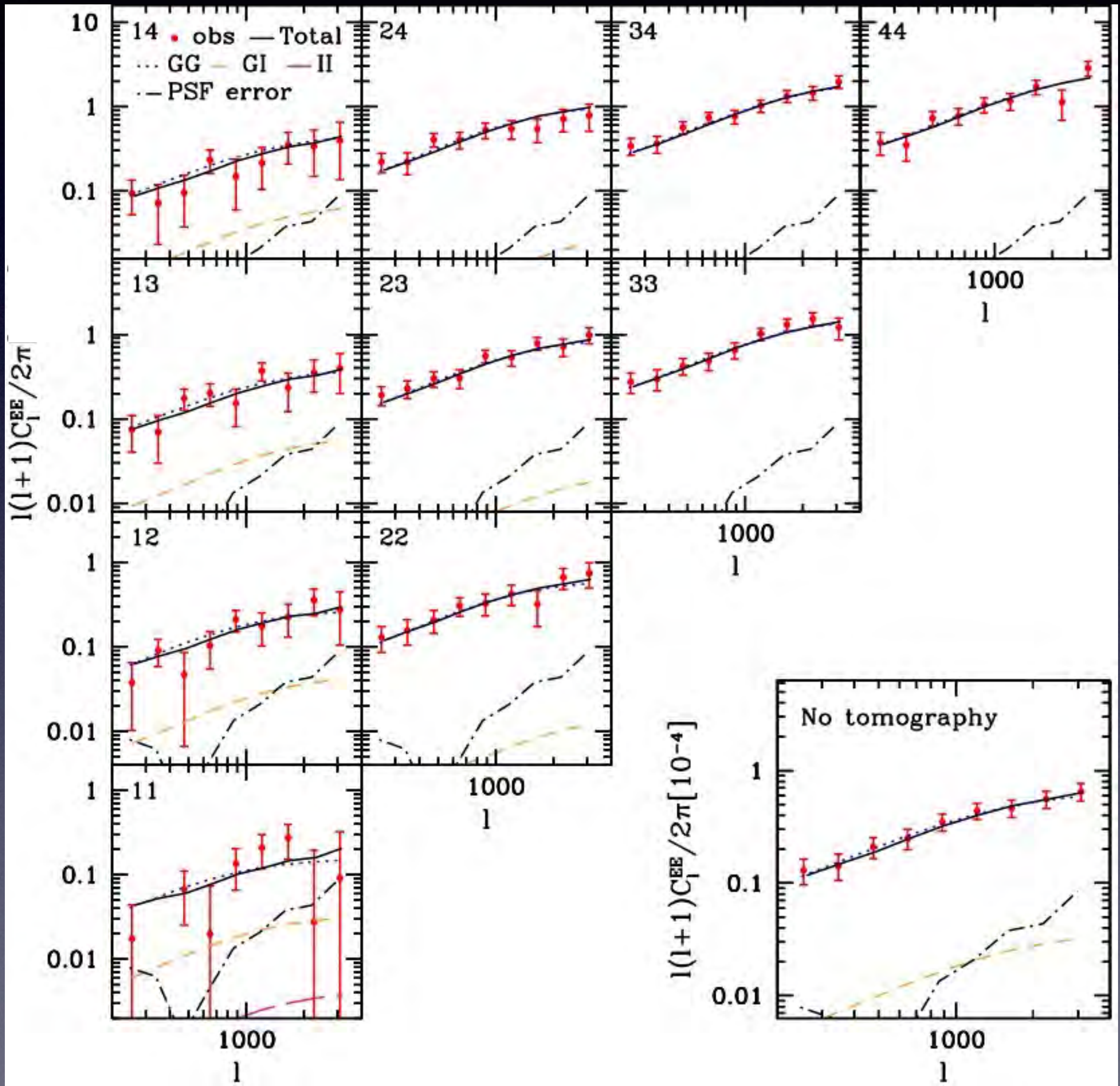
Fiducial setup: 5 cosmological and 9 nuisance parameters

Shear power spectra of HSC Y1 data



- 4-bin tomographic analysis in z range from 0.3 to1.5
- Focus on the scale 300<l<1900 to avoid potential systematic effects
- S/N of cosmic shear (EE mode) is ~16
- BB & EB signals are consistent with zero

Model fitting



Excellent fits of our modeling

χ^2_{min}=45.4 against effective d.o.f=57.1 (p-value is 0.87)

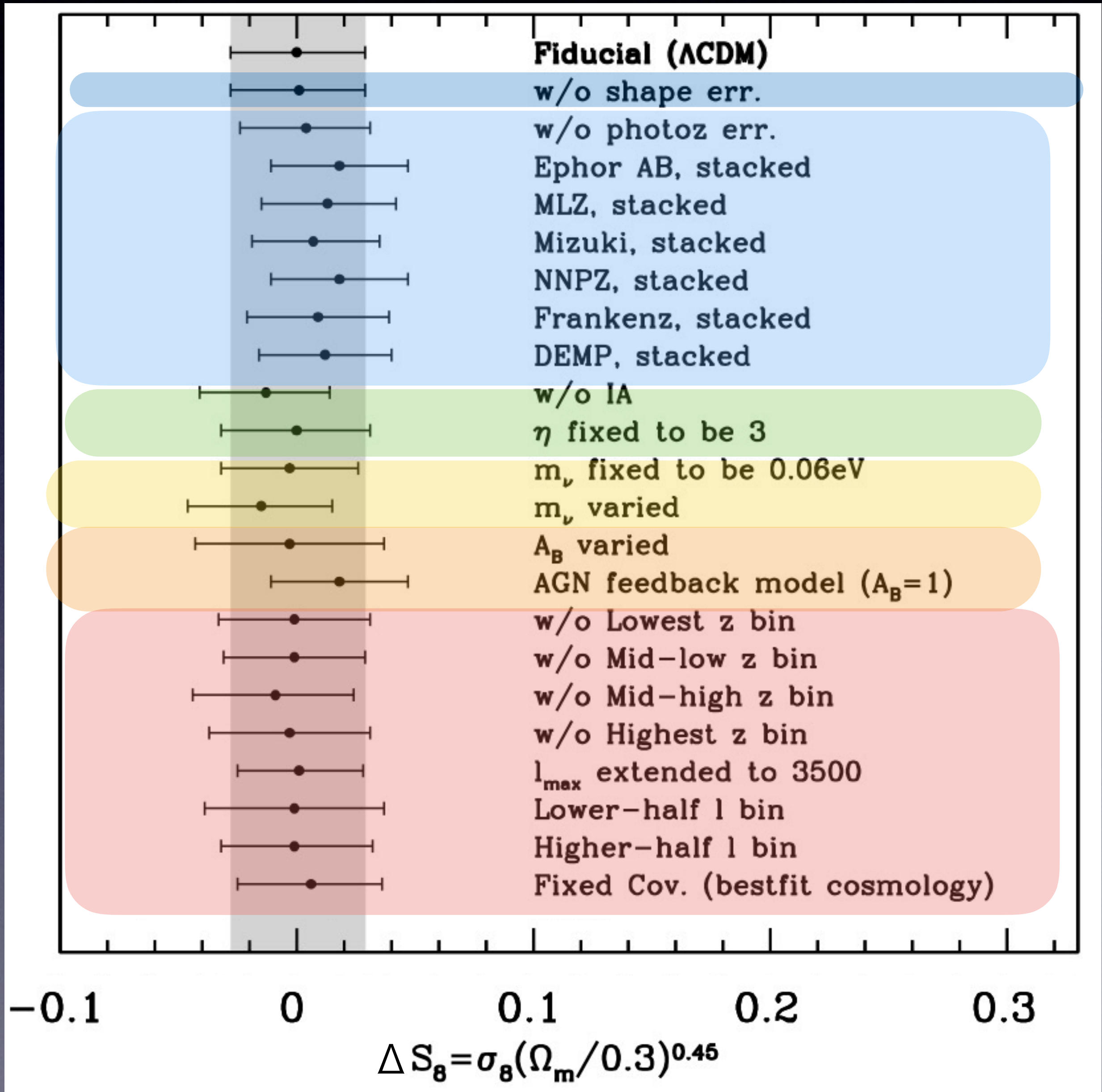
Definition of d.o.f (Raveri & Hu 2018)

$$\mathrm{DOF} = N_{\mathrm{data}} - N_{\mathrm{eff}}$$

$$N_{\mathrm{eff}} = N_{\mathrm{para}} - \mathrm{tr}[\mathcal{C}_{\mathrm{prior}}^{-1}\mathcal{C}_{\mathrm{post}}]$$

Robustness of S8 constraints

Systematic test was done before unblinding



shape error: <0.1 σ

Photo-z error: ~0.6 σ

Intrinsic alignment: <0.5 σ

Massive neutrino: < 0.5 σ

Baryonic effect: < 0.6 σ

No significant internal inconsistency

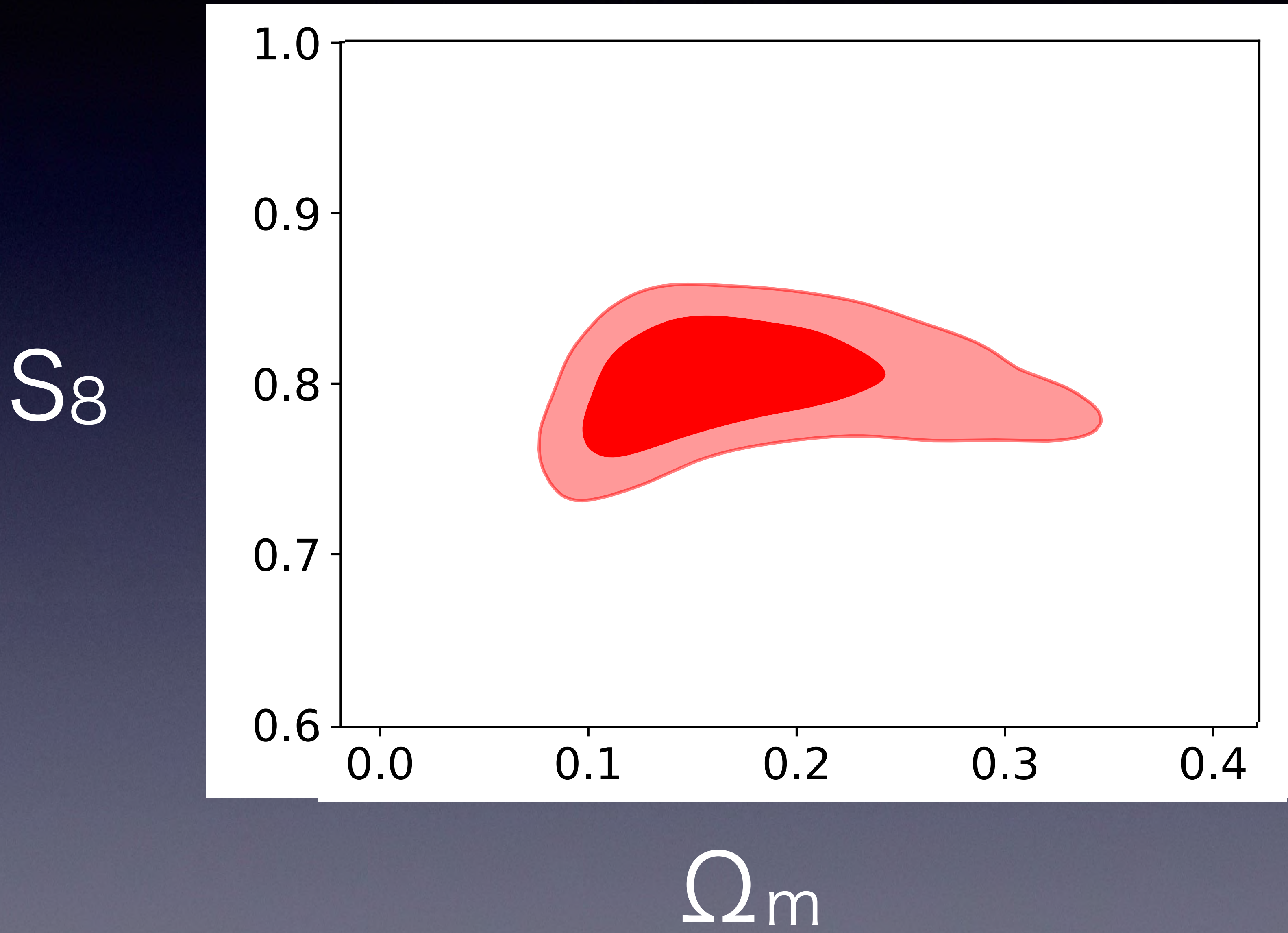
Our constraint is robust against various systematics

Unblinding in Jun 26, 2018

Two passwords of Blinder-in-Chiefand me are necessary to unblind the catalogs

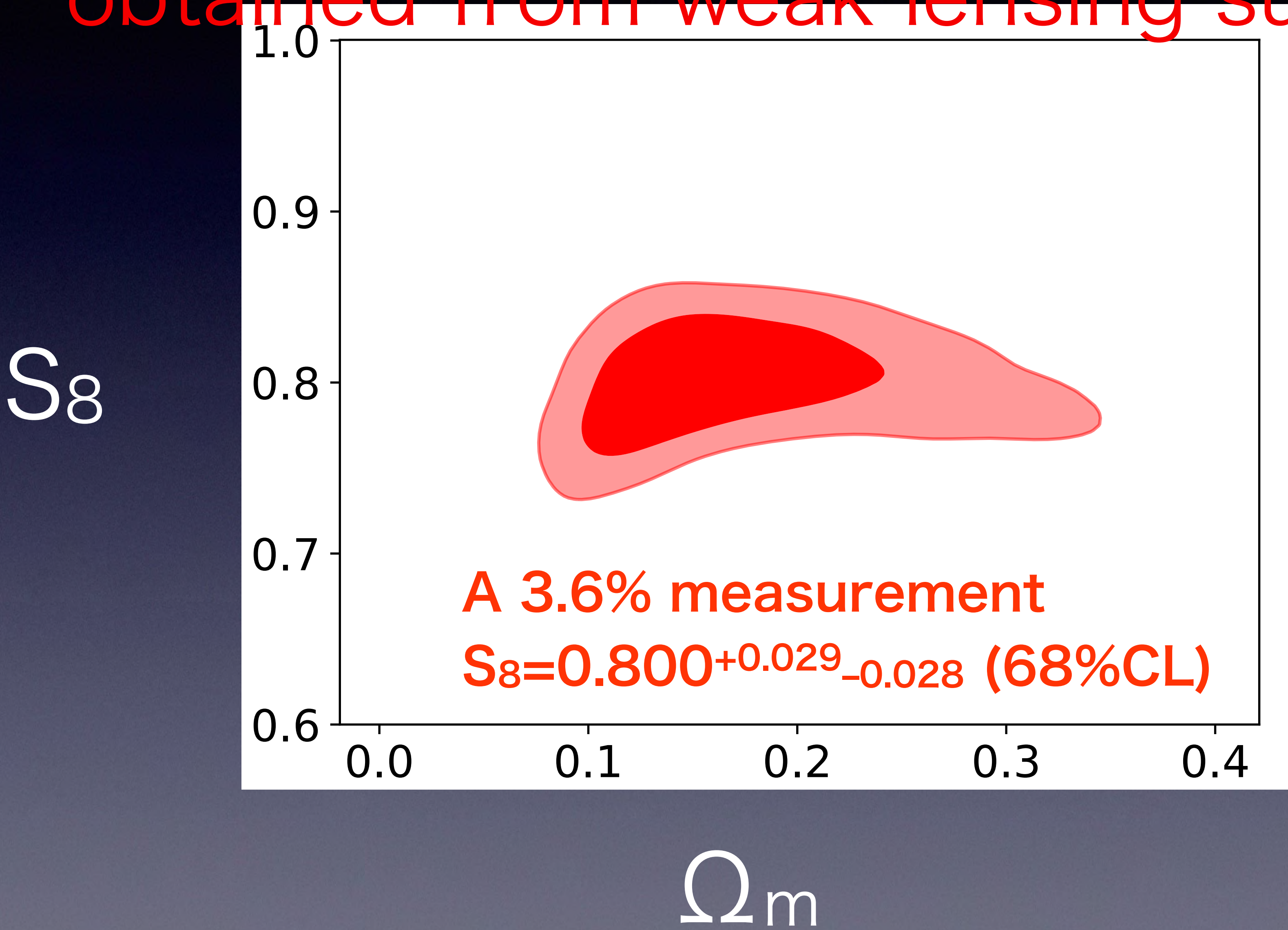
We decided not to change the unblinded results whatever they are

BInder-in-chief: Jim Bosch (Princeton) is not involved in the analysis team

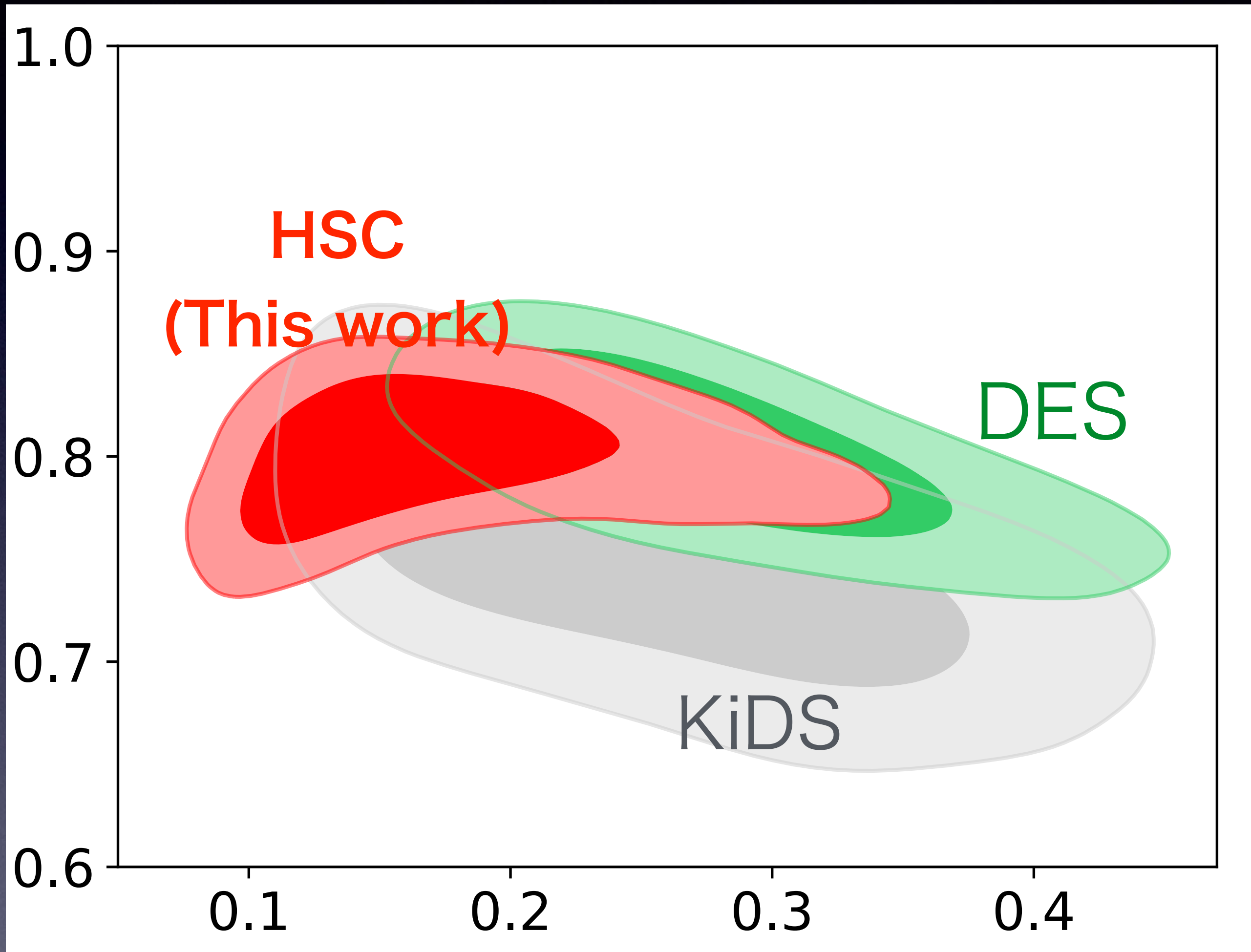


S8
1.0
0.9
0.8
0.7
0.6
0.0
0.1
0.2
0.3
0.4
Ωm

One of the tightest constraints ever obtained from weak lensing surveys



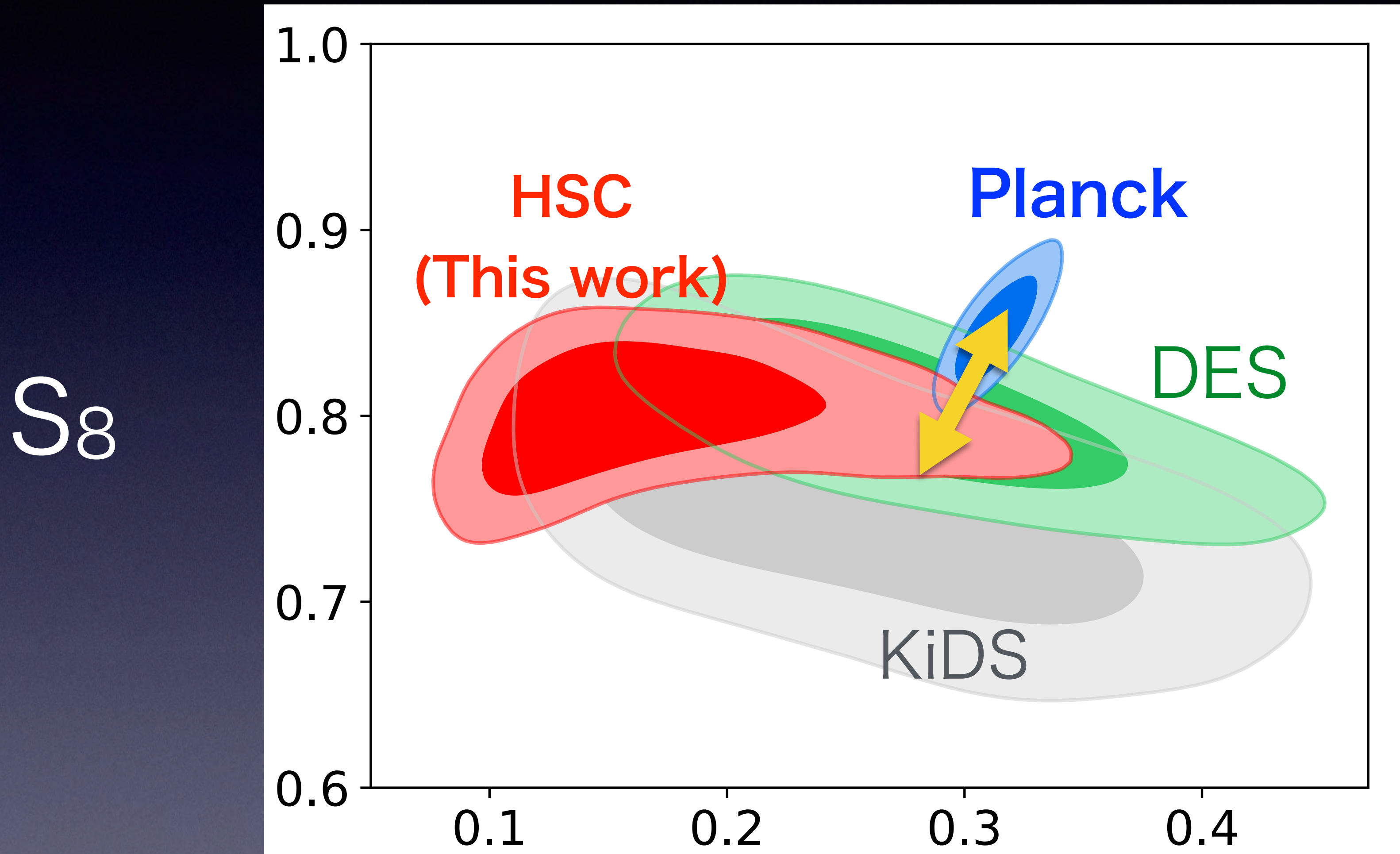
Consistent with other lensing surveys



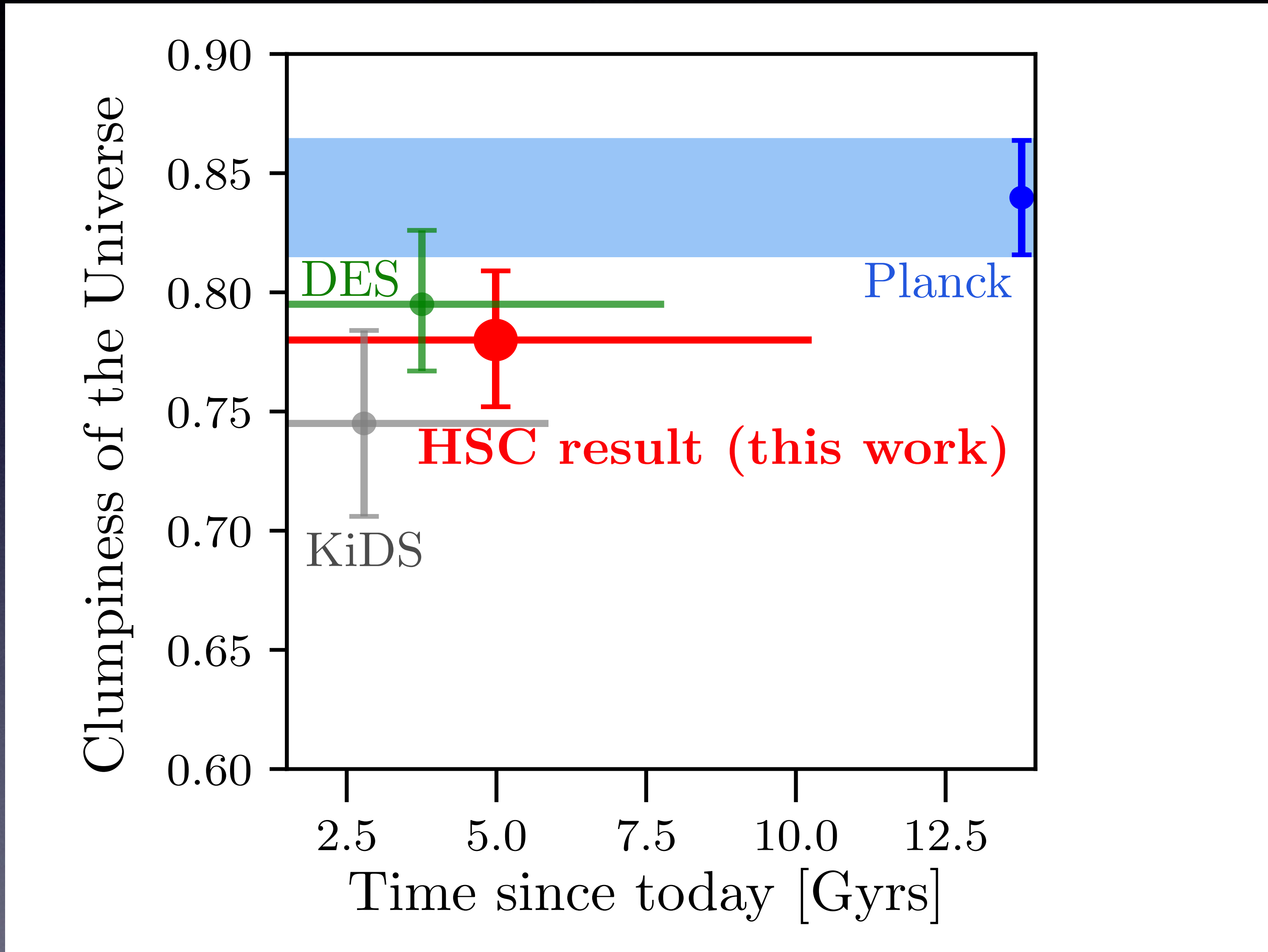
S8

Ωm

Consistent with Planck



Consistency is evaluated using Bayesian Evidence test and minimum χ^2 based statsitcis (Raveri & Hu 2018)



S_8 from the three WL surveys are systematically lower than Planck→Additional parameter beyond ΛCDM is necessary?

Evaluation of consistency between different datasets

- Bayesian Evidence: the probability of observing dataset D in the basic model M

$$P(\vec{D}|H) = \int d^N\theta P(\vec{D}|\vec{\theta}, M) P(\vec{\theta}|M)$$

likelihood prior

- Evidence ratio

$$R = \frac{P\left(\vec{D}_1, \vec{D}_2|M\right)}{P\left(\vec{D}_1|M\right) P\left(\vec{D}_2|M\right)}$$

two datasets share the same cosmological parameters

two datasets have different cosmological parameters

M: ΛCDM, wCDM, ΛCDM+ν…

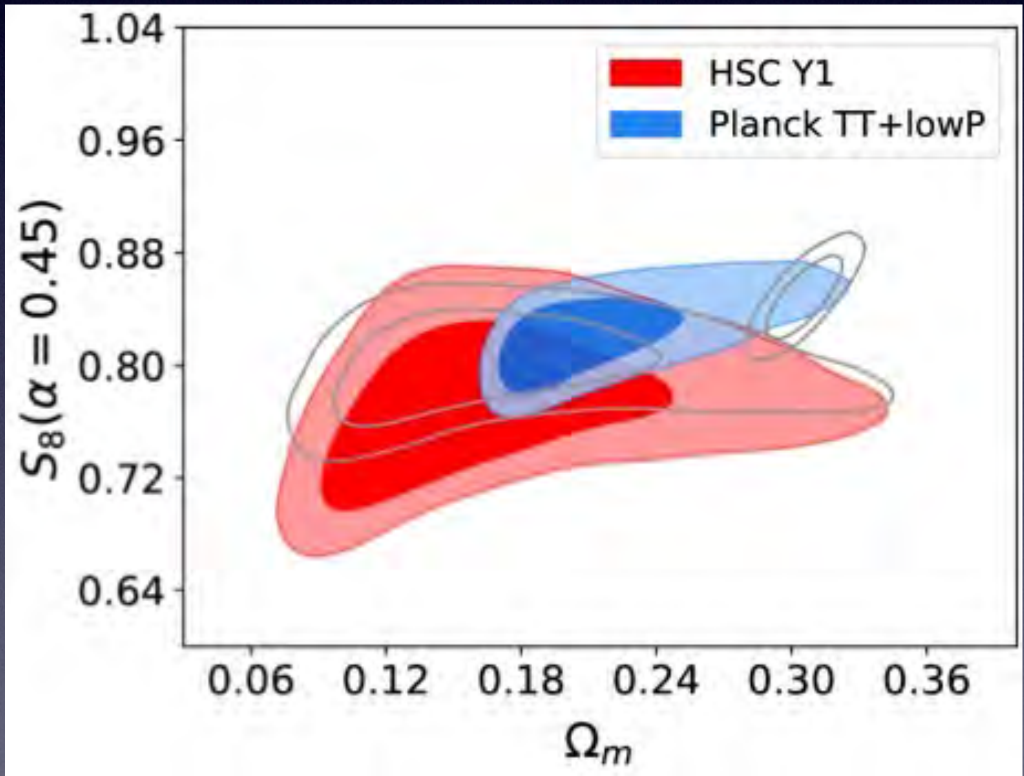
ref. Marshall et al. 2006, DES cosmology paper

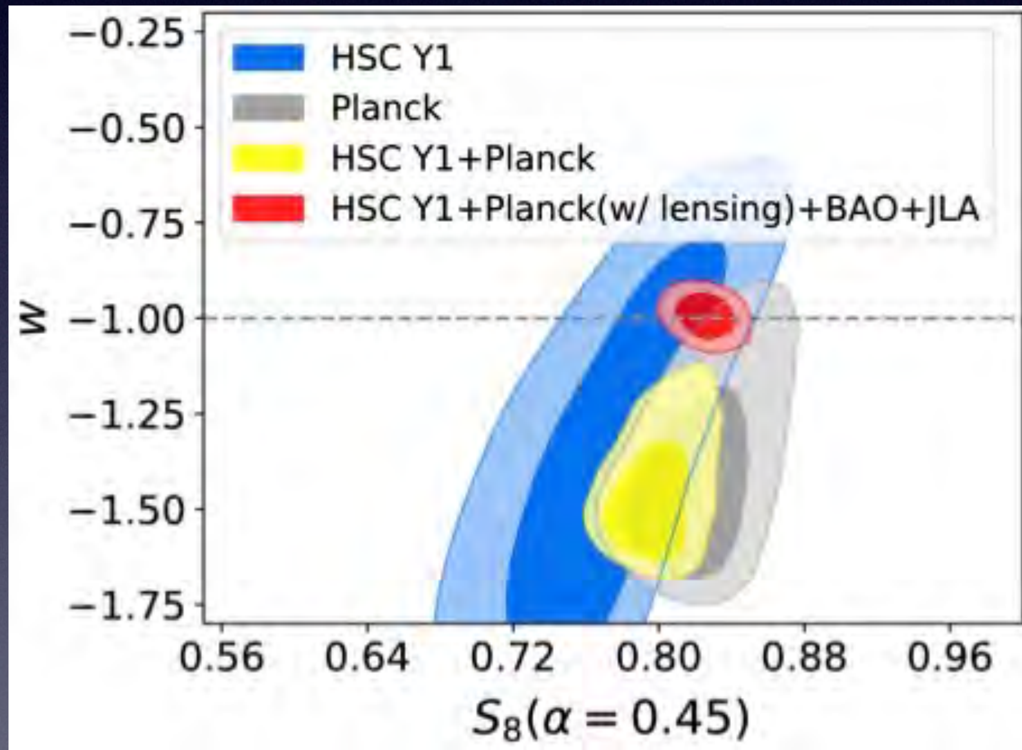
Jeffreys' Scale of Evidence for Bayes Factors

Bayes factor	Interpretation
$B_{ij} < 1/10$	Strong evidence for $\mathcal{M}_j$
$1/10 < B_{ij} < 1/3$	Moderate evidence for $\mathcal{M}_j$
$1/3 < B_{ij} < 1$	Weak evidence for $\mathcal{M}_j$
$1 < B_{ij} < 3$	Weak evidence for $\mathcal{M}_i$
$3 < B_{ij} < 10$	Moderate evidence for $\mathcal{M}_i$
$B_{ij} > 10$	Strong evidence for $\mathcal{M}_i$

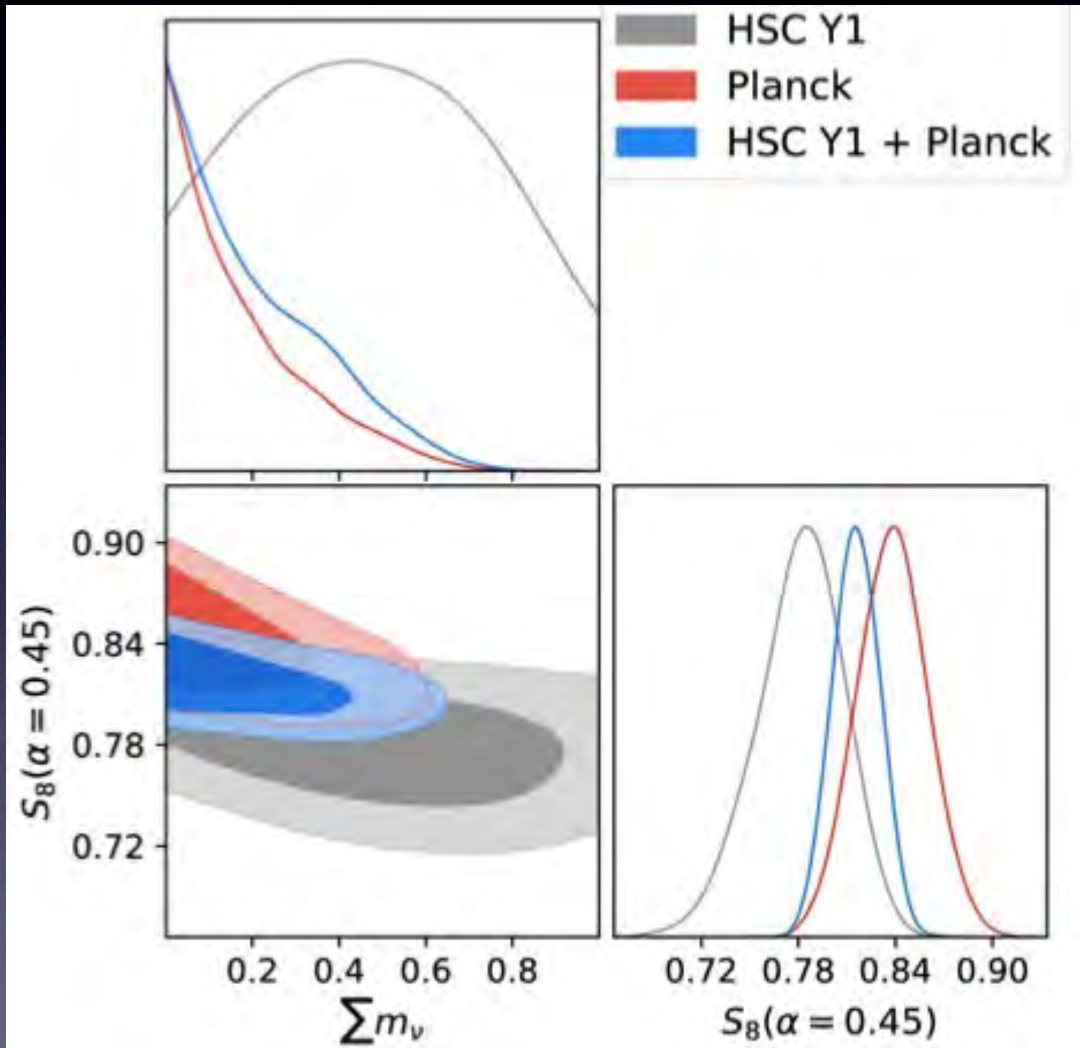
wCDM

wCDM model increases overlapped region between HSC and Planck, but has no significant preference to favor wCDM



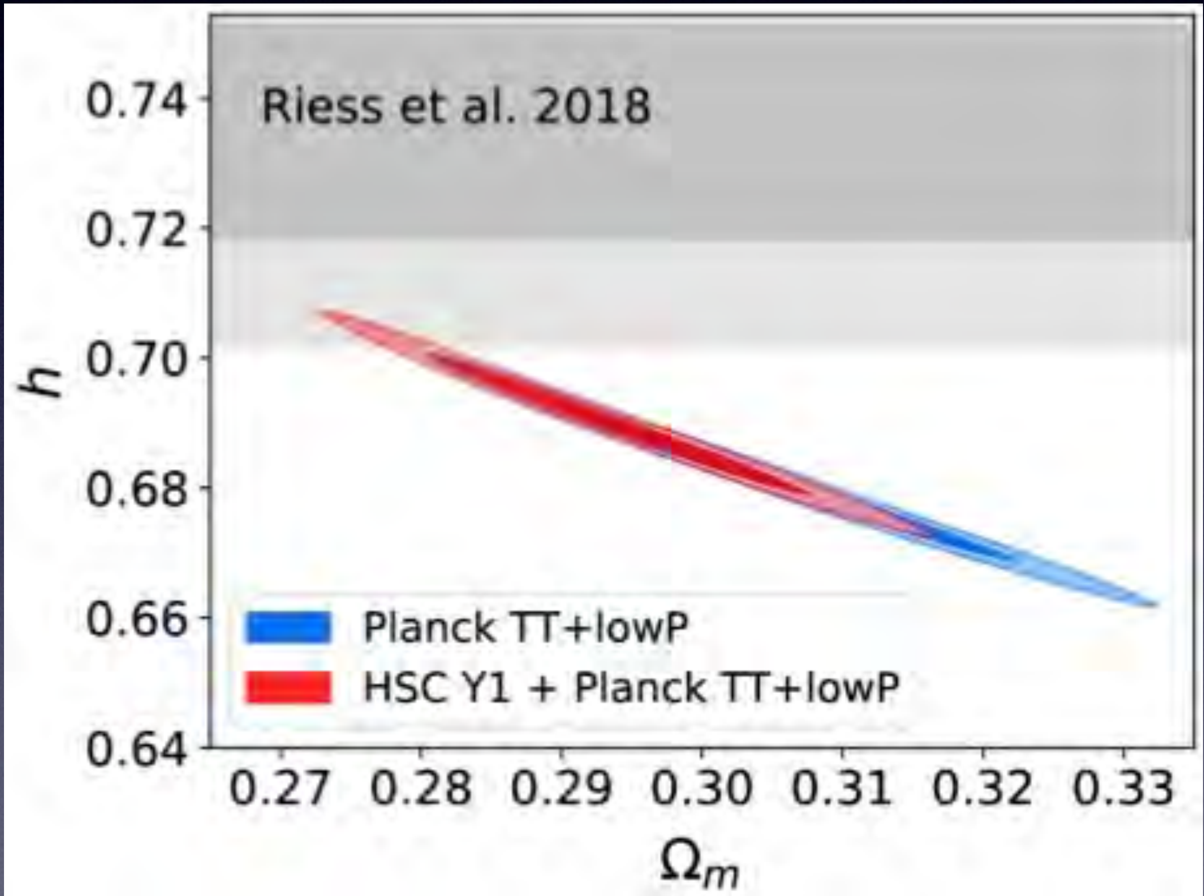


Neutrino mass



Cosmic shear favors massive neutrino mass

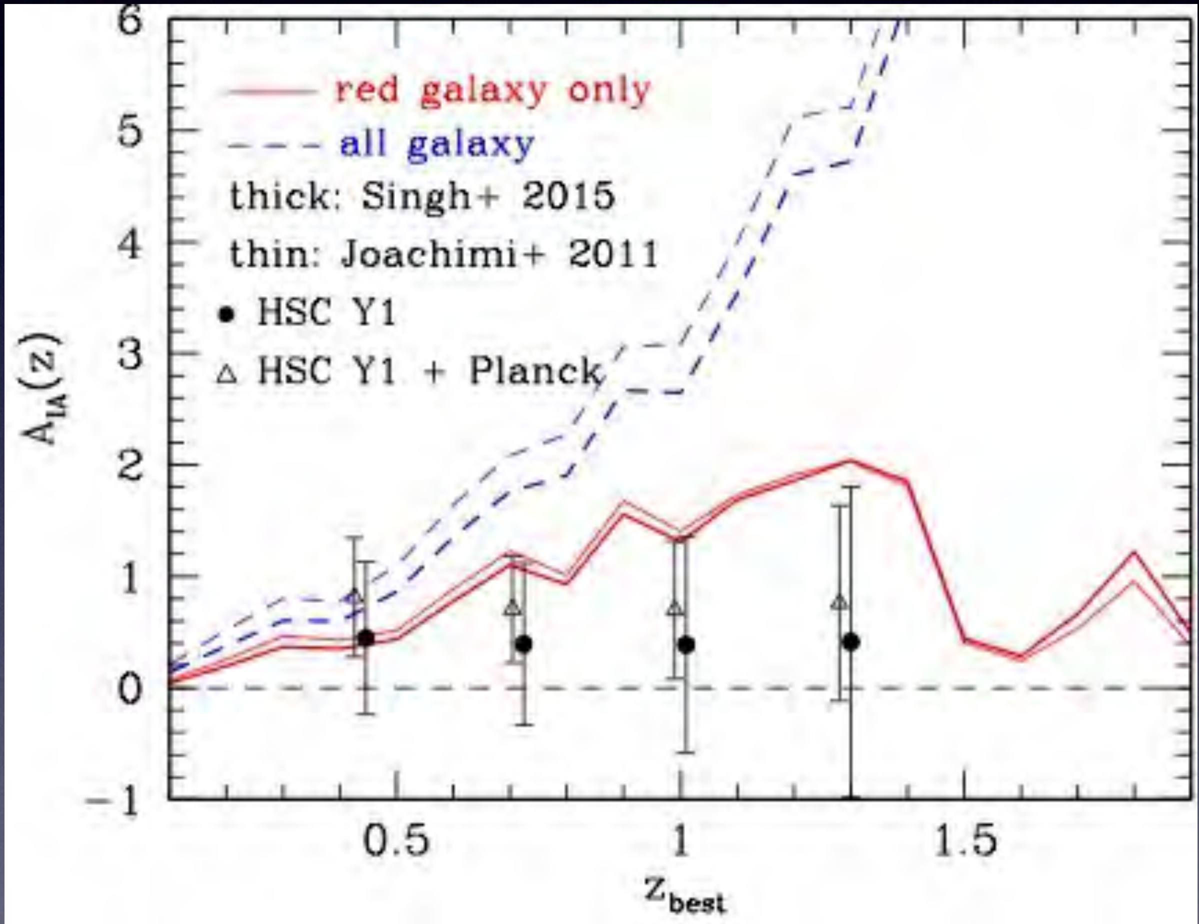
H_0 tension



Low Ω_m value of cosmic shear measurements push up H_0 value

H_0 tension is slightly alleviated by combining Planck with HSC ($3.7\sigma \rightarrow 3.1\sigma$)

Intrinsic Alignment



Consistent with IA amplitudes extrapolated from bright red galaxies (Joachimin+ 2011, Singh+ 2015)

No evolution signal of IA

IA amplitudes of blue galaxies is not comparable to red ones

Summary

- First cosmological analysis from Hyper Suprime-Cam survey
- Blind analysis to test various systematics, such as shear measurement, photo-z, intrinsic alignment, baryon feedback
- 3.6% measurement on $S_8 = \sigma_8 (\Omega_m/0.3)^{0.45} = 0.800^{+0.029}_{-0.028}$ from cosmic shear power spectra
- The value is consistent with Planck, but is lower at ~2σ level as other lensing surveys such as DES and KiDS shows
- This is just from 11% of HSC planned survey. Upcoming data should clarify the situation