Cosmology with Subaru Hyper Suprime-Cam imaging survey

(after 10 years involvement)

Chiaki Hikage
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On behalf of HSC WLWG

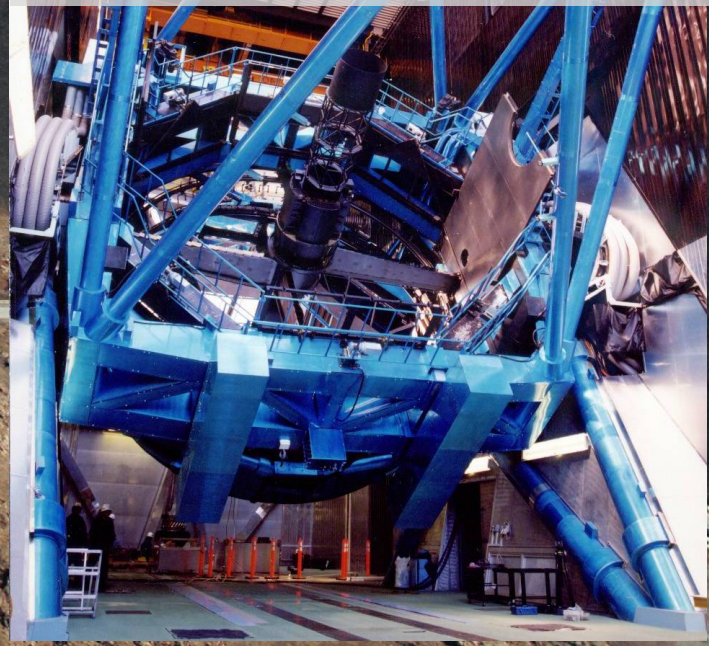
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

Subaru Telescope

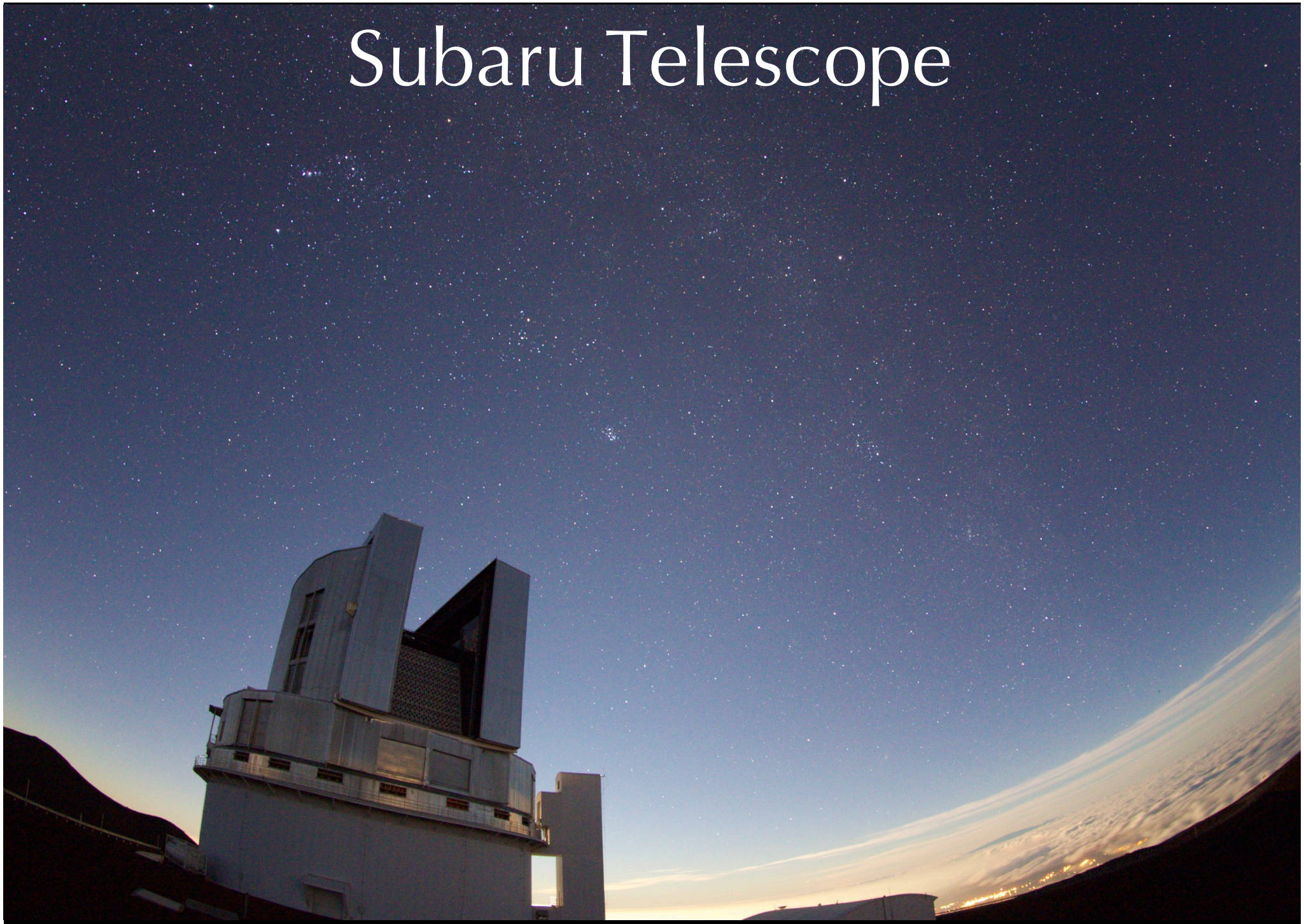
Prime-Focus Instrument



Subaru Telescope
(NAOJ)

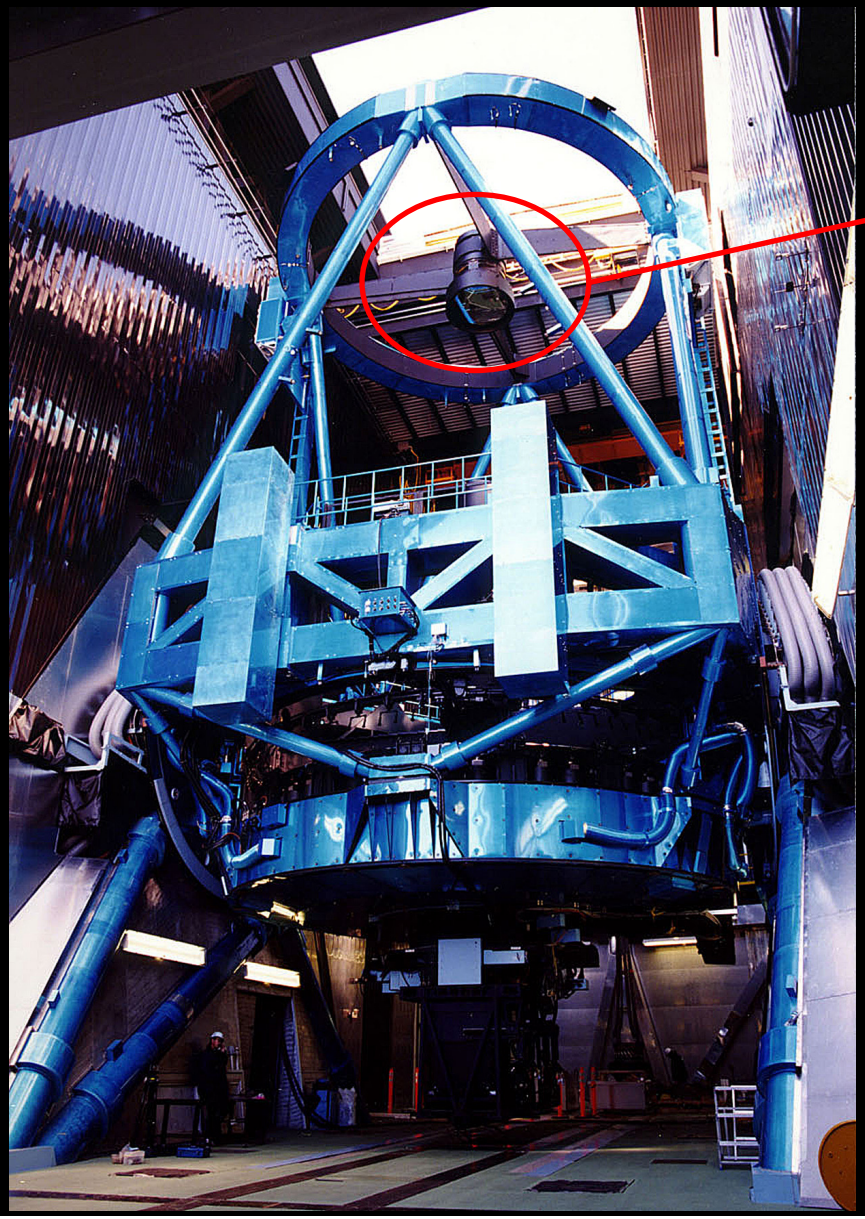
@ summit of Mt. Mauna Kea (4200m), Big Island, Hawaii

Subaru Telescope

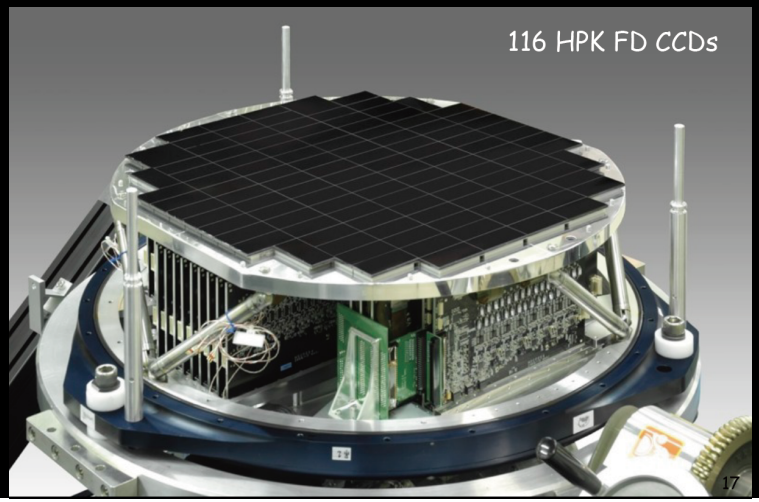


@ summit of Mt. Mauna Kea (4200m), Big Island, Hawaii

Hyper Suprime-Cam (HSC)



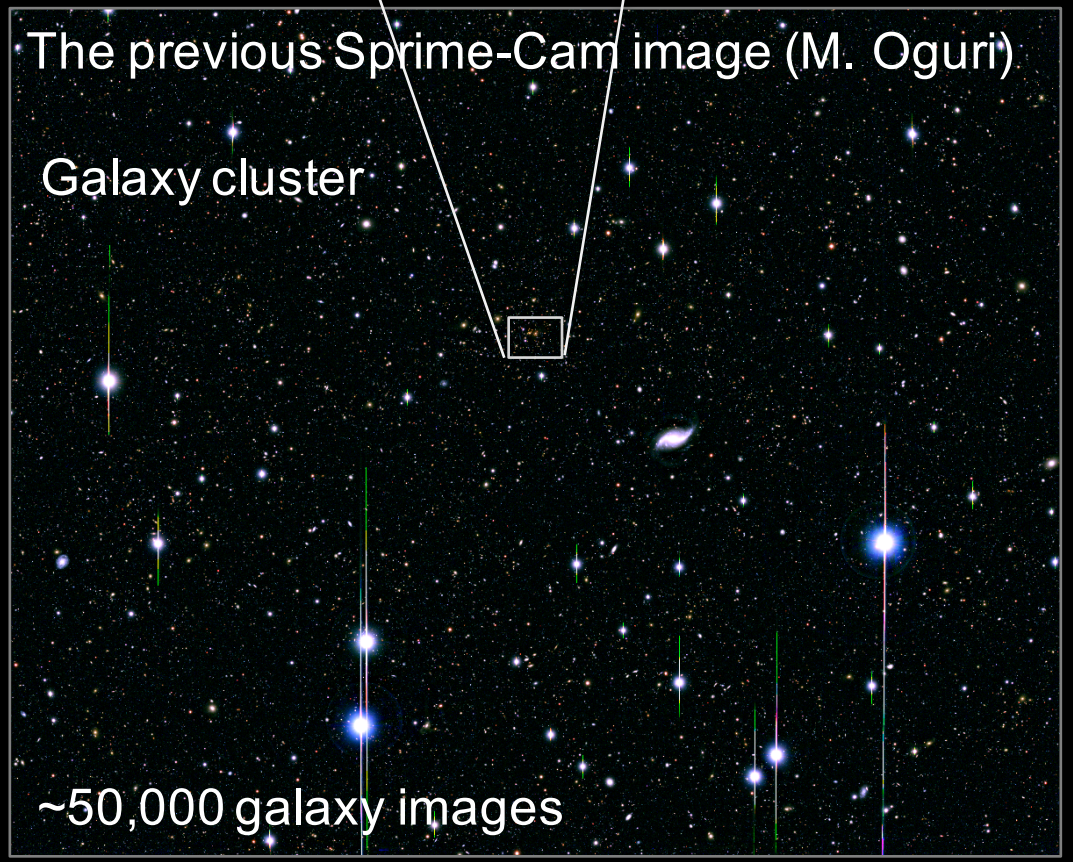
- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9G pixels)



Subaru Telescope: wide FoV & excellent image quality

- **Fast, Wide, Deep & Sharp**
- a cosmological survey needs these

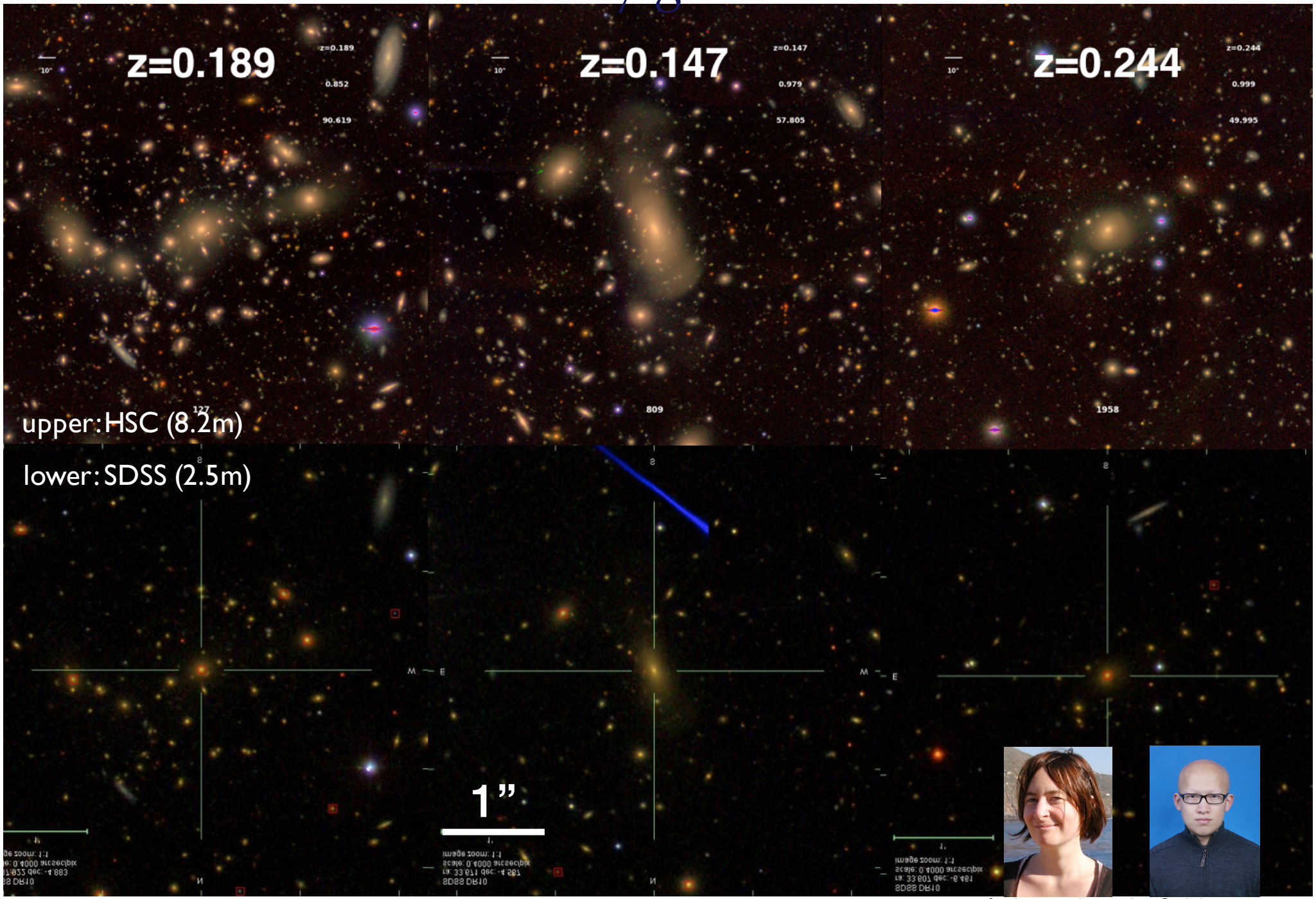
HST



Hyper Suprime-Cam FoV

- **Fas**
- a cos

Nearby galaxies



All data reduced by the HSC pipeline

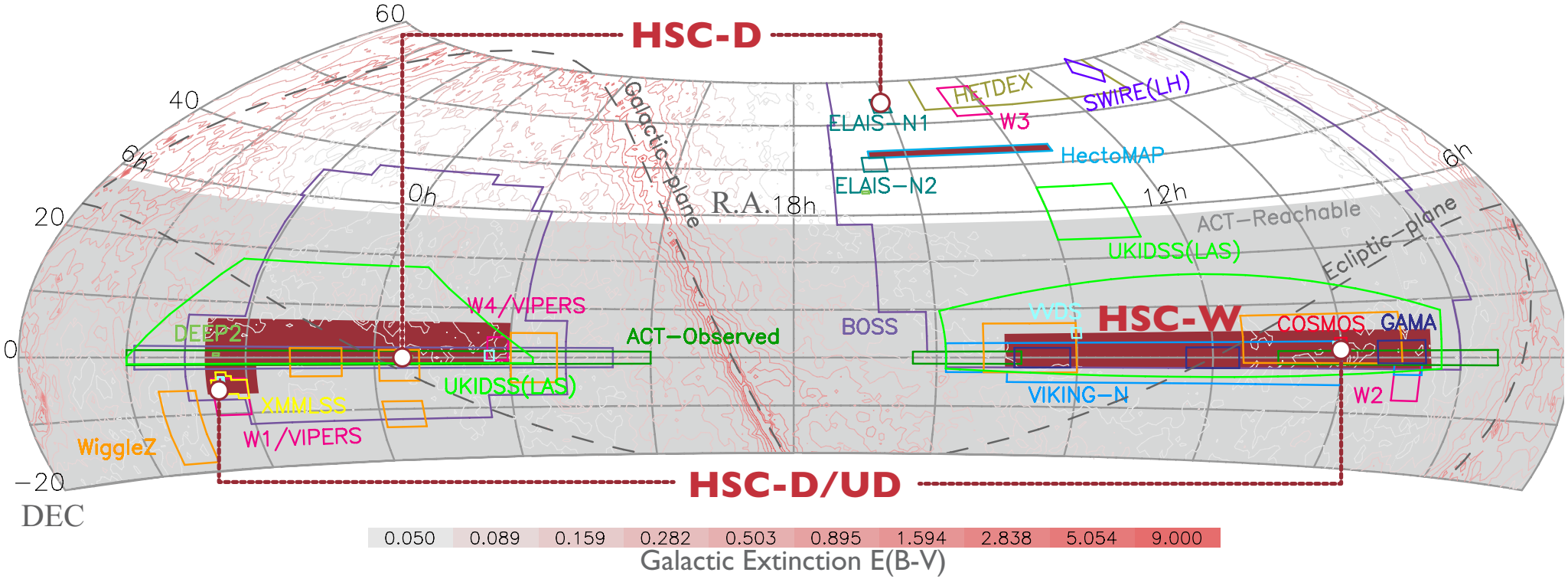
A. Leauthaud

S. Huang

Subaru-**300**-nights HSC project (2014 -)

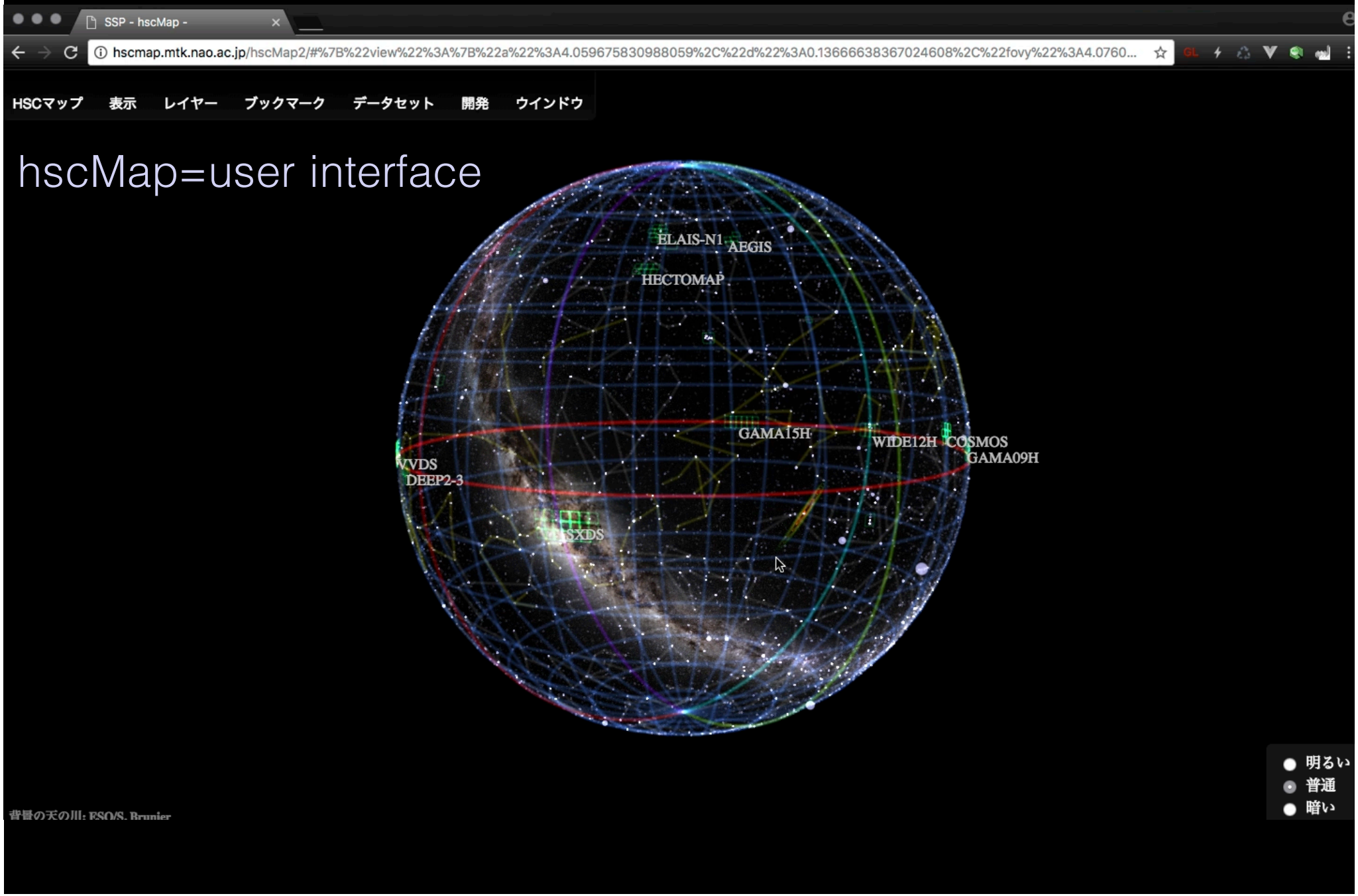
International collaboration (Japan, Taiwan, Princeton U.)

HSC Survey Fields



- **Subaru 300 nights** granted (2014 – 19)
- HSC Survey Fields selected based on
  - Overlap with SDSS regions and other interesting, external datasets (ACT CMB, NIR, spectroscopic surveys, …); Low dust extinction; Spread in RA
- The main scientific objectives are
  - Wide: Cosmology, Deep: galaxy evolution, UD: cosmic reionization

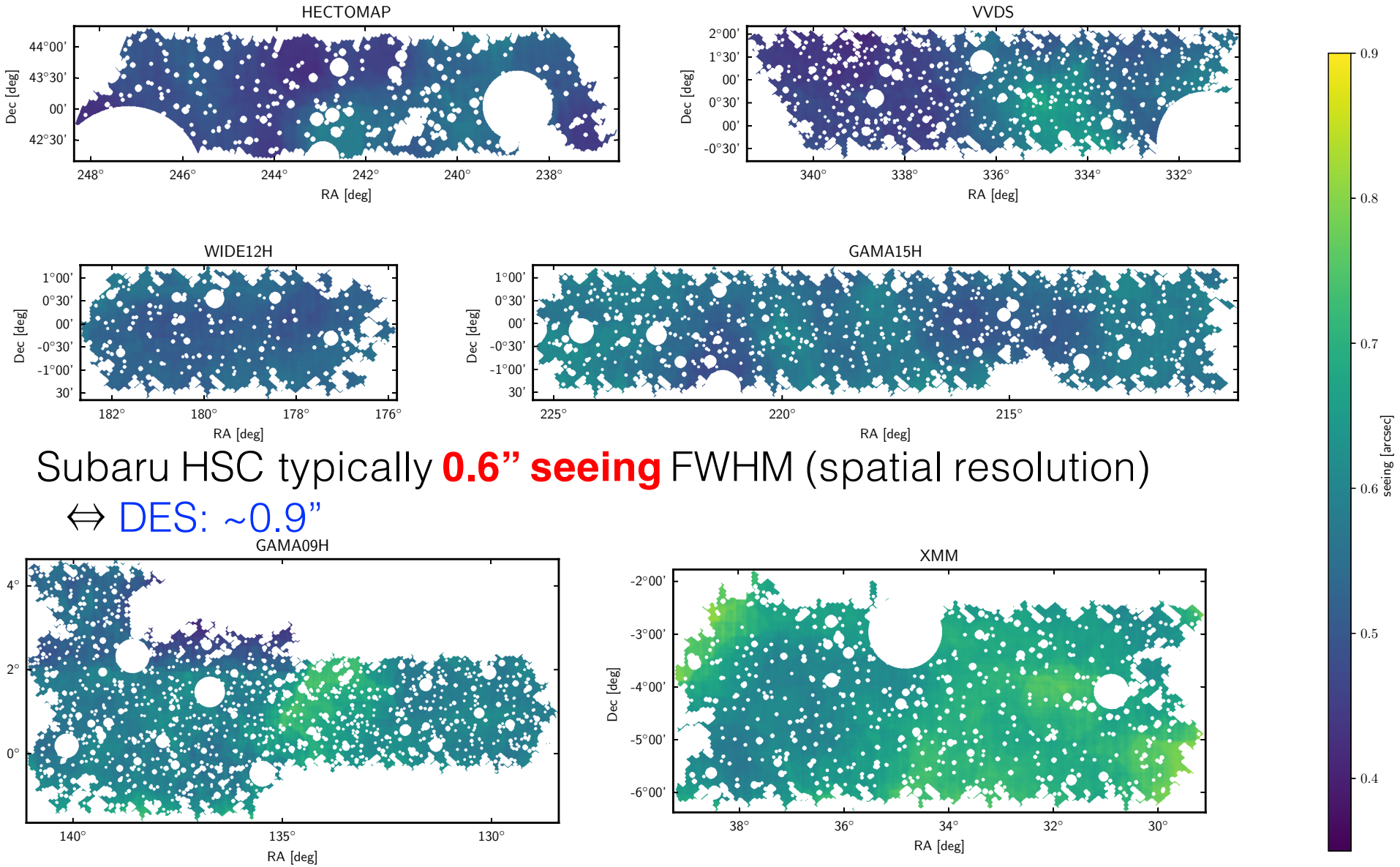
HDC Public Data Release 1 (Feb, 2017)



Subaru HSC = superb image quality

6 fields (~140 sq. deg. in total)

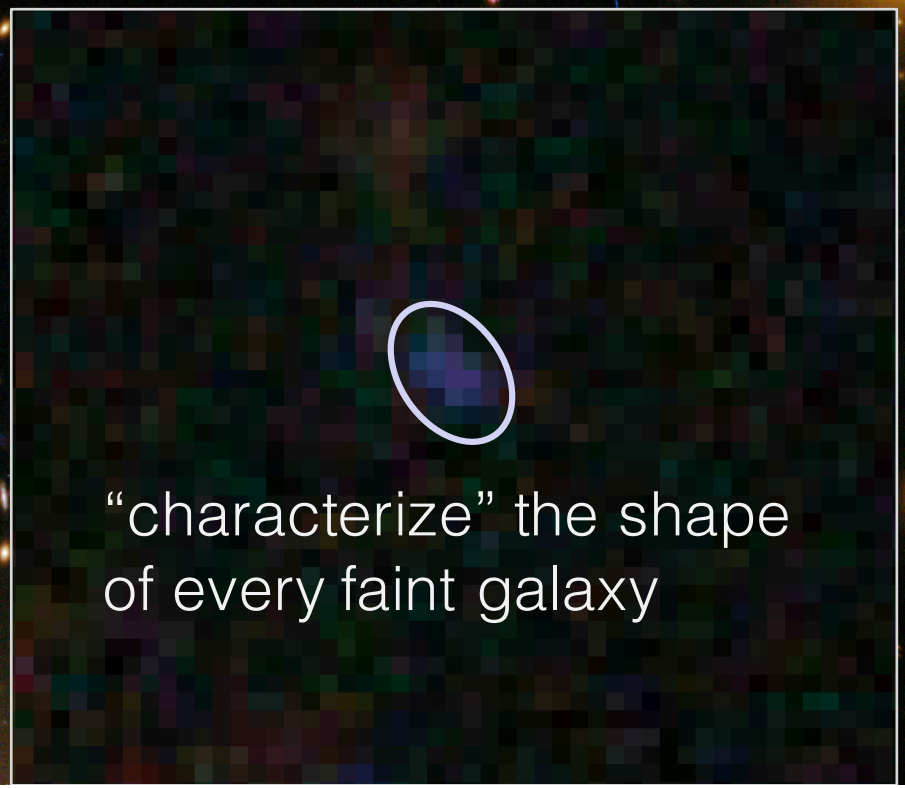
$n_{\rm eff} \simeq 22$ arcmin^{-2}



Subaru HSC typically **0.6" seeing** FWHM (spatial resolution)

⇔ DES: ~0.9"

Weak gravitational lensing (shear)



"characterize" the shape
of every faint galaxy

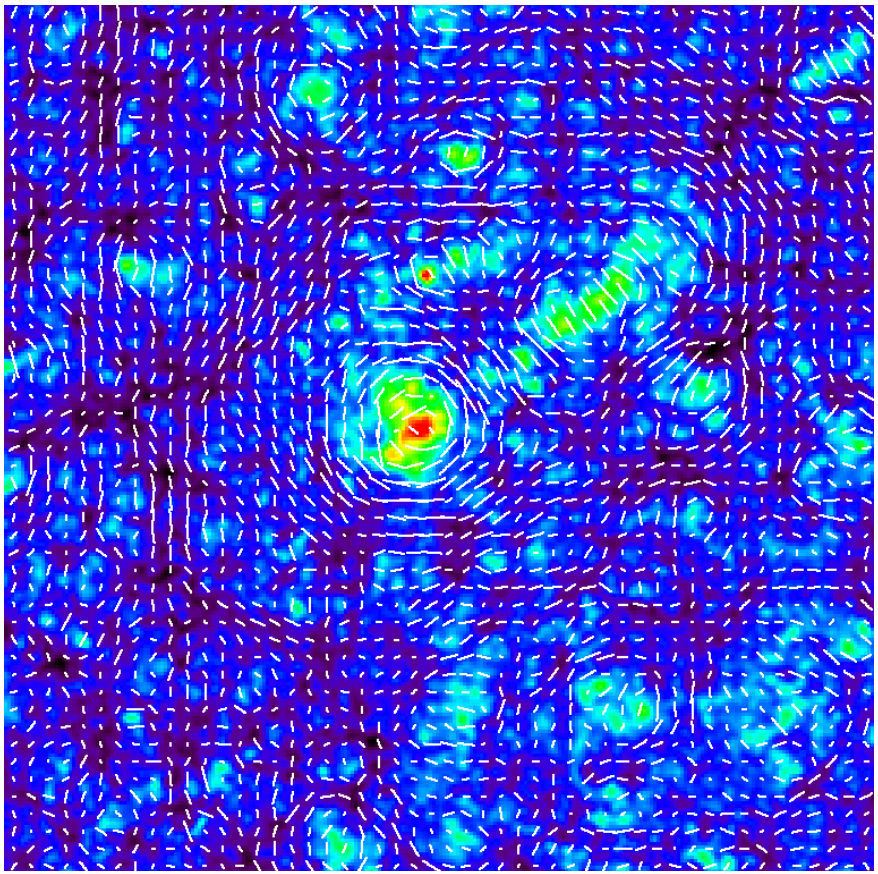
Weak lensing

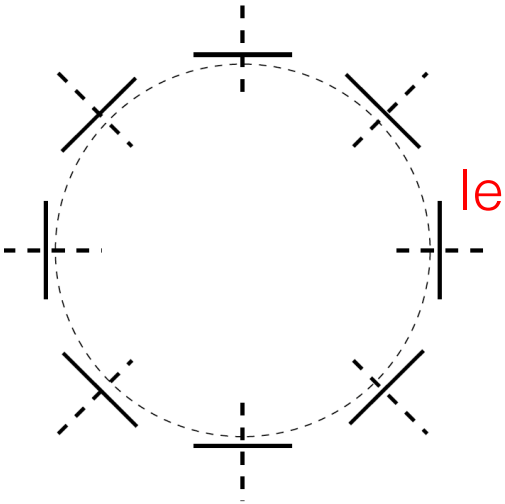
The signal is tiny: allows for a **direct reconstruction** of gravitational potential due to nonlinear matter distribution in the universe

shear $\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}_{\text{photon path}}(t)]$

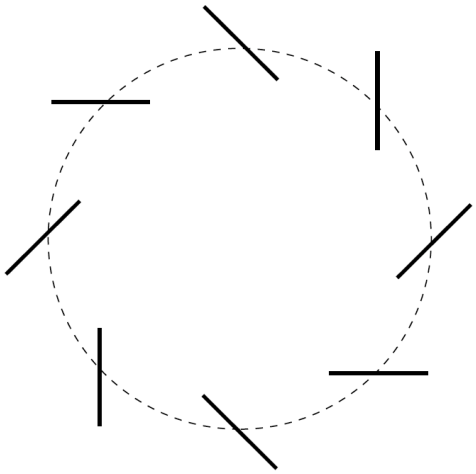
$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \bar{\rho}_m a^2 \delta_m(\mathbf{x}, t)$$

Simulated lensing map (color = 2D DM map, stick=shear)





lensing mode (E mode)



non-lensing mode (e.g., systematics) (B mode)

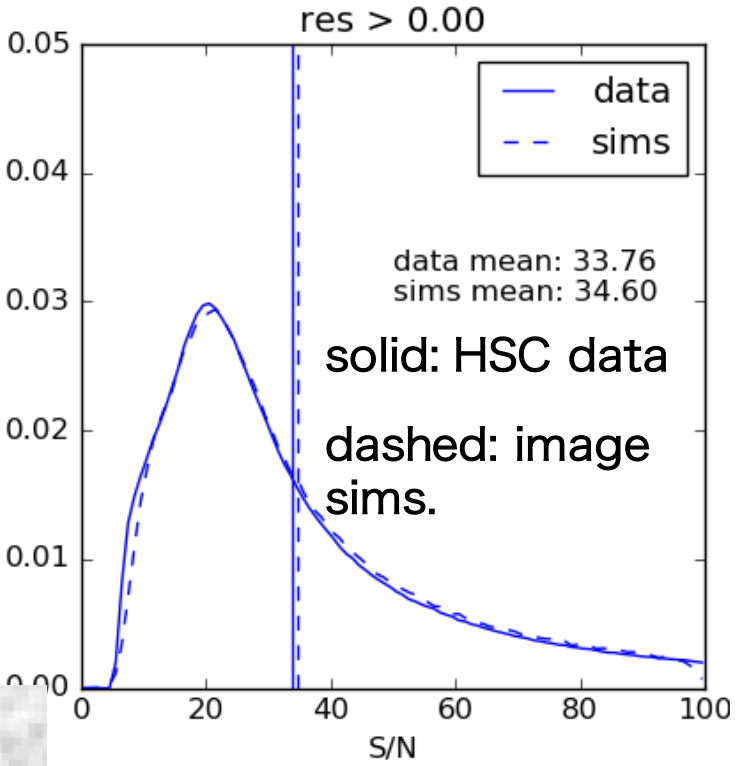
Mandelbaum, Miyatake+, PASJ 2018

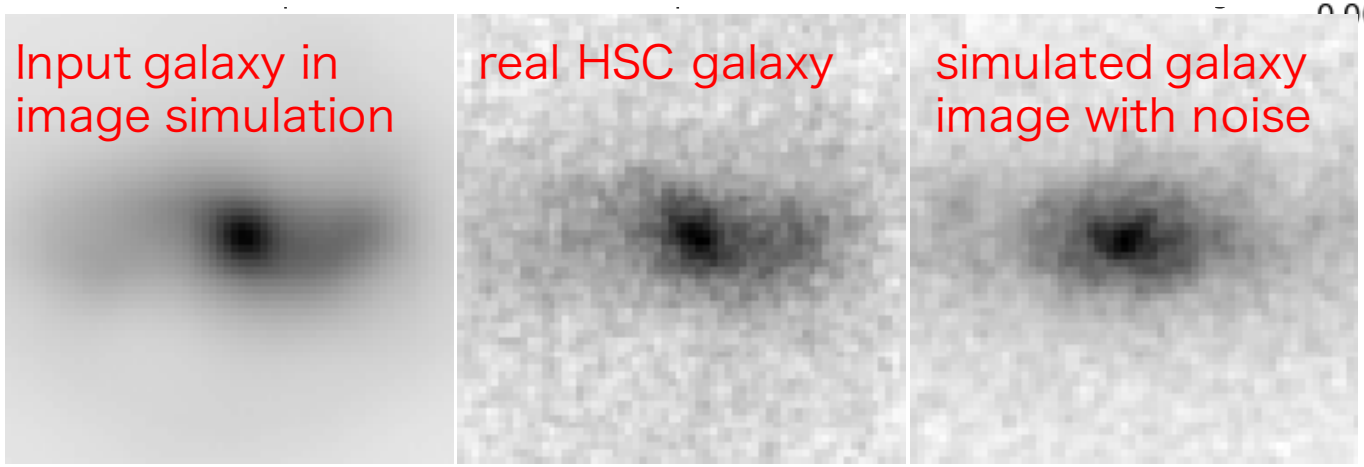
HSC galaxy shape catalog

R. Mandelbaum (CMU)

Hironao Miyatake (Nagoya/IPMU)

- Developed the pipeline for galaxy shape measurement
- Tested/validated the galaxy shape catalog with sophisticated image simulations
- **~10M galaxies (~20 gals/sq. arcmin., ~140 sq. deg.)**
- Ready to use for weak lensing science





For us, galaxies = numbers

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1	73979570428054640	0	213.7985	51.84384	8.504140E-29	4.593317E-31		21.5759	0.005864	21.6
2	73979570428054766	0	213.80921	51.84618	1.596781E-29	6.690010E-31		23.3919	0.045489	23.4
3	73979570428054794	0	213.[illegible]	51.[illegible]	[illegible]E-29	6.[illegible]		[illegible].5127	0.021113	22.5
4	73979570428054844	0	213.[illegible]	[illegible]	[illegible]E-29	7.[illegible]		23.[illegible]017	0.034431	23.2
5	73979570428055234	0	213.[illegible]0922	51.85532	1.222690E-29	4.107814E-31		23.6817	0.036477	23.6
6	73979570428055285	0	213.89554	51.85558	1.244757E-29	3.819837E-31		23.6623	0.033318	23.5
7	73979570428055331	0	213.80149	51.85738	7.723727E-31	2.396201E-30		26.6804	3.36838	24.2
8	73979570428055455	0	213.8055	51.85954	7.489265E-30	6.370268E-31		24.2139	0.092351	24.1
9	73979570428055529	0	213.79617	51.86112	1.142162E-29	6.177813E-31		23.7557	0.058726	24.0
10	73979570428055561	0	213.79818	51.86168	5.524251E-30	3.560247E-31		24.5443	0.069973	24.4
11	73979570428055570	0	213.88059	51.8612	7.356544E-30	3.634025E-31		24.2333	0.053634	24.1
12	73979570428055601	0	213.79551	51.86271	5.253717E-29	5.235109E-31		22.0988	0.010819	22.1
13	73979570428055610	0	213.82333	51.86247	1.097313E-29	3.973071E-31		23.7992	0.039312	23.7
14	73979570428055710	0	213.82804	51.86456	2.656856E-29	5.525464E-31		22.8391	0.02258	22.8
15	73979570428055791	0	213.79094	51.86662	1.471843E-29	9.626954E-31		23.4803	0.071015	23.9
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18	73979570428055959	0	213.79837	51.86971	9.101518E-30	5.423166E-31		24.0022	0.064694	24.0
19	73979570428055966	0	213.88424	51.86908	1.167941E-29	6.259547E-31		23.7314	0.05819	23.8
20	73979570428056010	0	213.79016	51.87074	6.363427E-30	4.339140E-31		24.3908	0.074035	24.3
21	73979570428056113	0	213.83133	51.87251	1.160774E-29	4.764544E-31		23.7381	0.044565	23.7
22	73979570428056185	0	213.78598	51.87434	1.052555E-28	8.382704E-31		21.3444	0.008647	21.4
23	73979570428056199	0	213.88646	51.87352	9.360481E-30	4.508771E-31		23.9718	0.052298	23.9
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26	73979570428056251	0	213.79243	51.87547	9.509173E-30	5.551205E-31		23.9546	0.063382	23.9
27	73979570428056257	0	213.88499	51.8749	-1.862690E-31	1.933658E-30				24.4
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29	73979570428056377	0	213.88431	51.8772	1.413942E-29	6.095634E-31		23.5239	0.046807	23.6
30	73979570428056383	0	213.79355	51.87816	2.612706E-29	5.893613E-31		22.8573	0.024491	22.7
31	73979570428056387	0	213.82763	51.87793	5.986320E-30	4.392153E-31		24.4571	0.07966	24.5
32	73979570428056520	0	213.79641	51.88102	1.180581E-29	6.598727E-31		23.7198	0.060686	23.9
33	73979570428056563	0	213.80574	51.8818	1.907350E-28	8.868550E-31		20.6989	0.005048	20.6
34	73979570428056601	0	213.82372	51.88231	1.067101E-28	1.064829E-30		21.3295	0.010834	21.4
35	73979570428056775	0	213.88284	51.88498	1.303106E-29	3.655387E-31		23.6126	0.030456	23.5
36	73979570428056779	0	213.82172	51.88564	1.089255E-29	5.317668E-31		23.8072	0.053005	23.8
37	73979570428056788	0	213.84372	51.88556	8.398296E-30	5.162690E-31		24.0895	0.066744	24.0
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41	73979570428056846	0	213.80921	51.88721	1.067762E-28	6.436782E-31		21.3288	0.006545	21.2
42	73979570428056850	0	213.83987	51.88708	4.627139E-29	9.125668E-31		22.2367	0.021413	22.4
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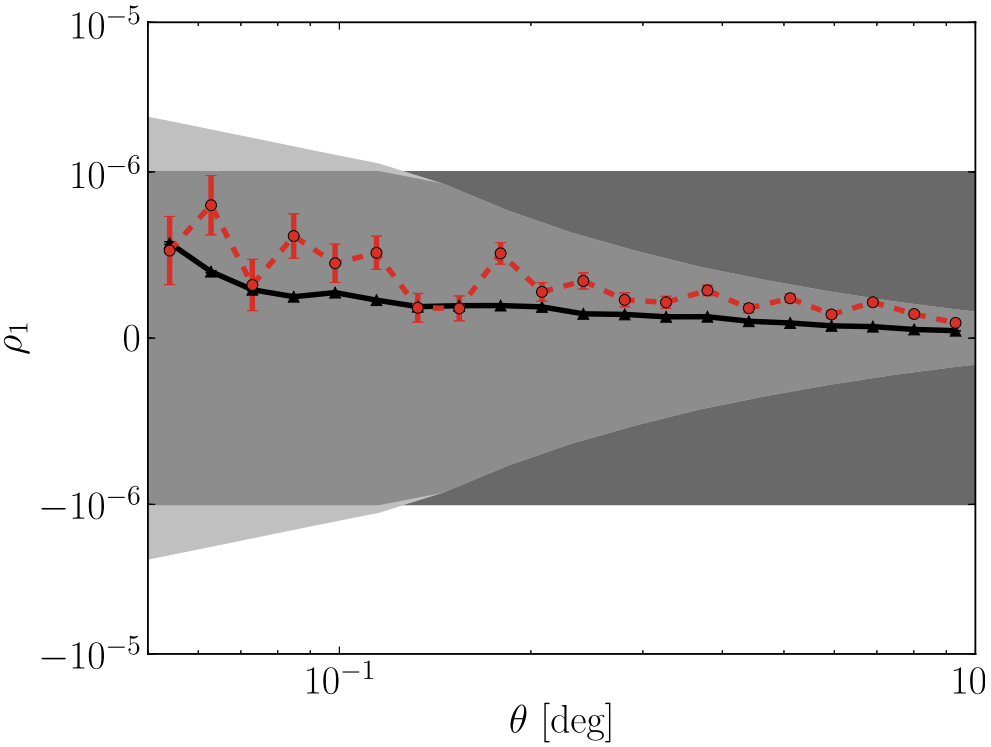
46	73979570428057101	0	213.80487	51.89223	1.388592E-29	5.331566E-31		23.5436	0.041687	23.5

null test, null test, null test ….

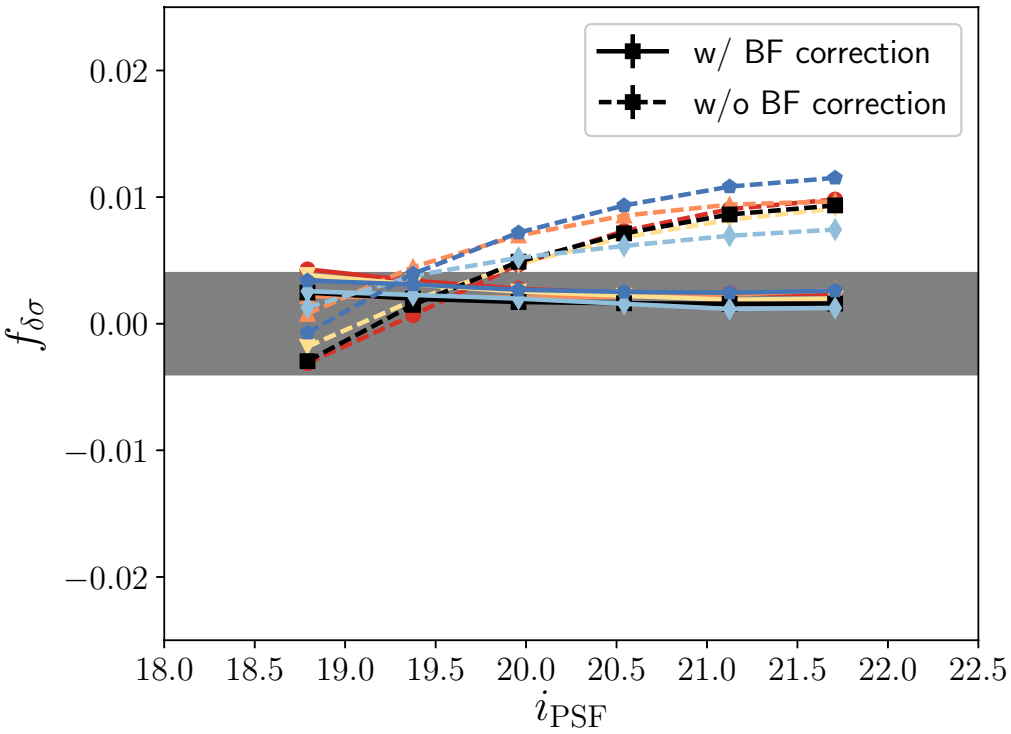
Mandelbaum, Miyatake et al. 2018

PSF-star ellipticity residual correlation



Light-gray region is the requirement for the 1st-year cosmic shear cosmology

PSF-star size residual



Grey region is the requirement

Note: might eventually be hit by ambiguous blends

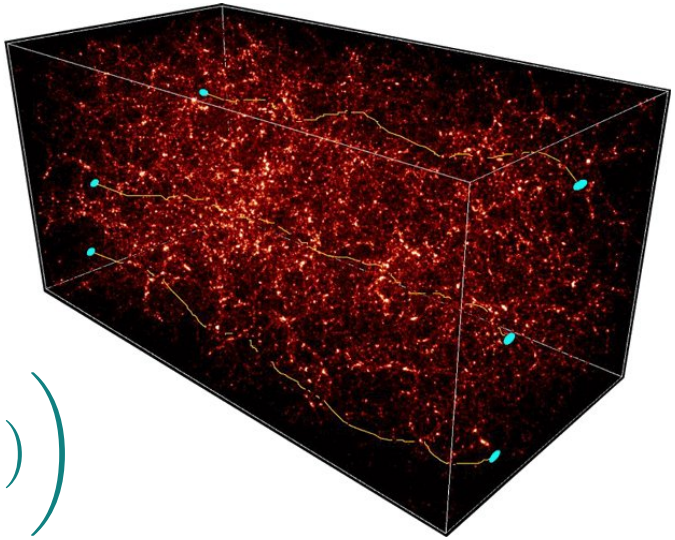
Unprecedented wide and deep 3D DM map

Oguri et al. 2018

(~7Gyr light years away)

one particular field (VVDS field)

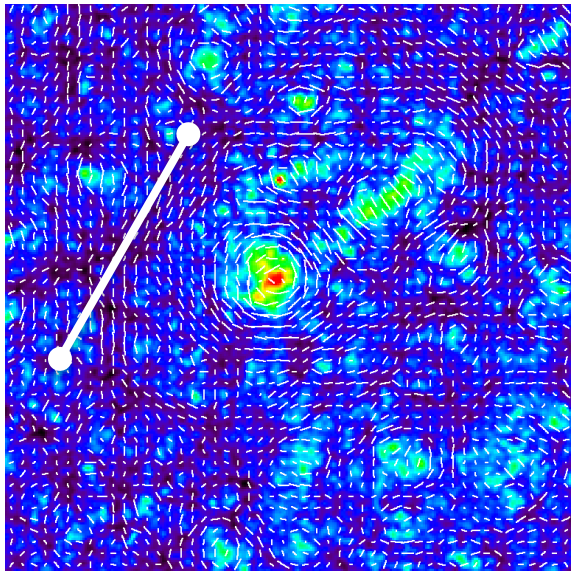
Cosmic shear cosmology



- Pros
  - Can measure “total” matter power clustering

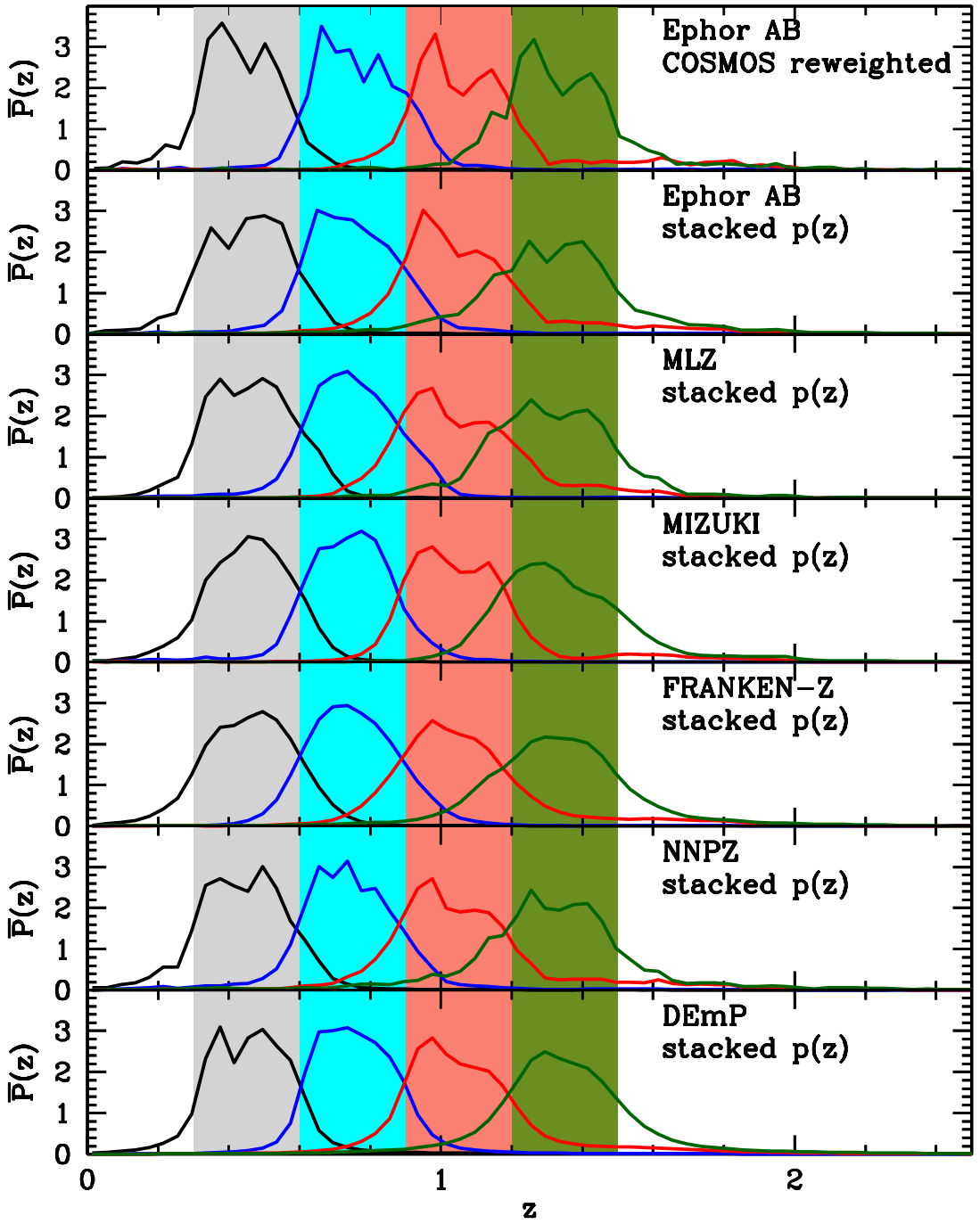
$$C_\ell = \int \mathrm{d}\chi \; W_{\mathrm{GL}}(\chi)^2 \chi^{-2} P_{\mathrm{m}}^{\mathrm{NL}}\left(k = \frac{\ell}{\chi}; z(\chi)\right)$$

- Cons
  - All the systematic errors additively contribute the measurements (⇔ g-g lensing)
  - Challenges: Photo-z errors and baryonic physics
  - HSC data are very deep compared to DES: precursor of LSST



Cosmic shear tomography

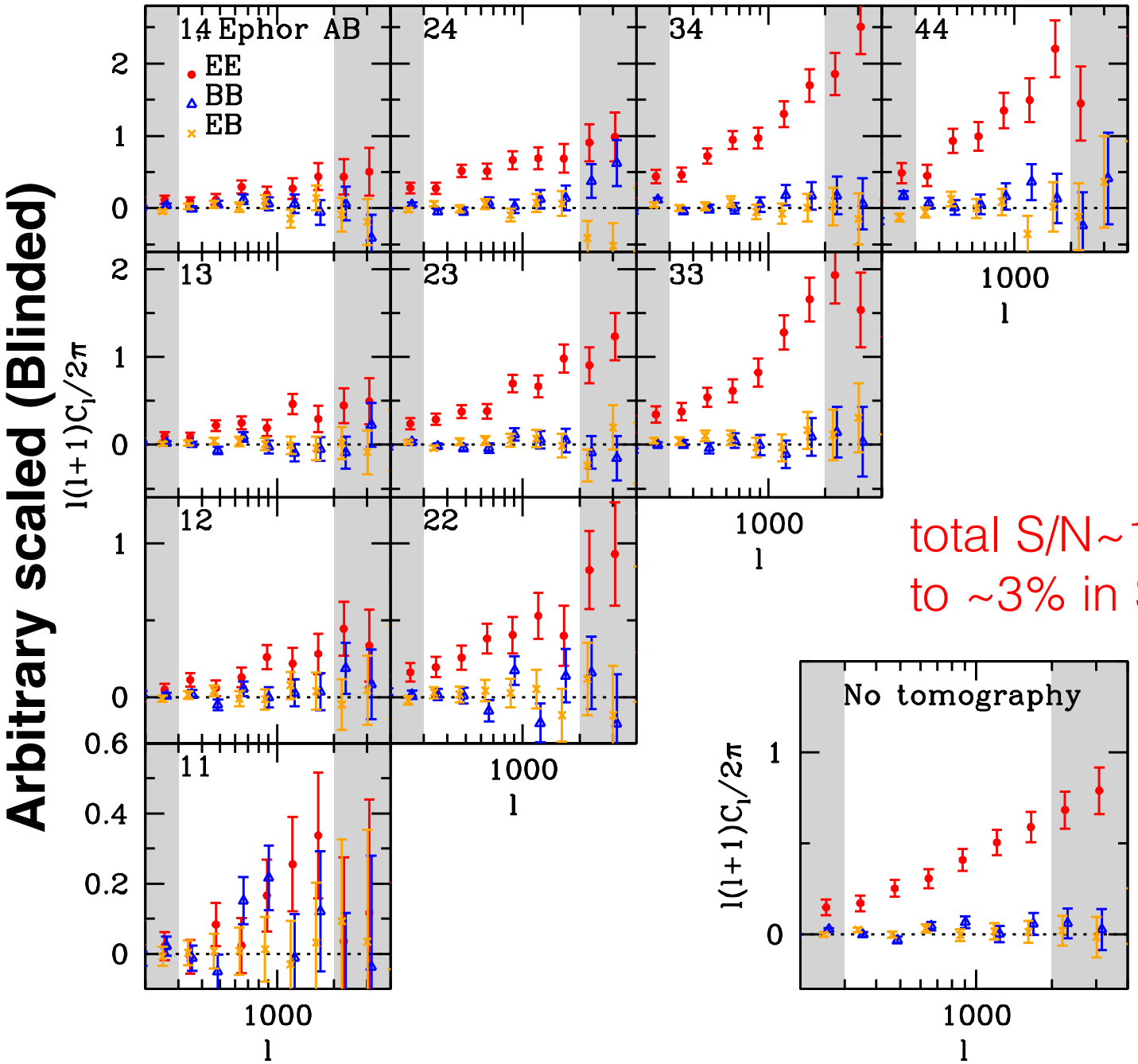
- Used photo-z's of each galaxy to have **4 tomographic bins**
- Used the **HSC-Wide depth data of COSMOS field** for galaxies after the WL cut to calibrate the photo-z errors
- Test the results against the different photo-z catalogs



Pseudo-power spectrum estimator
(Hikage, MT, Hamana, Spergel 11)

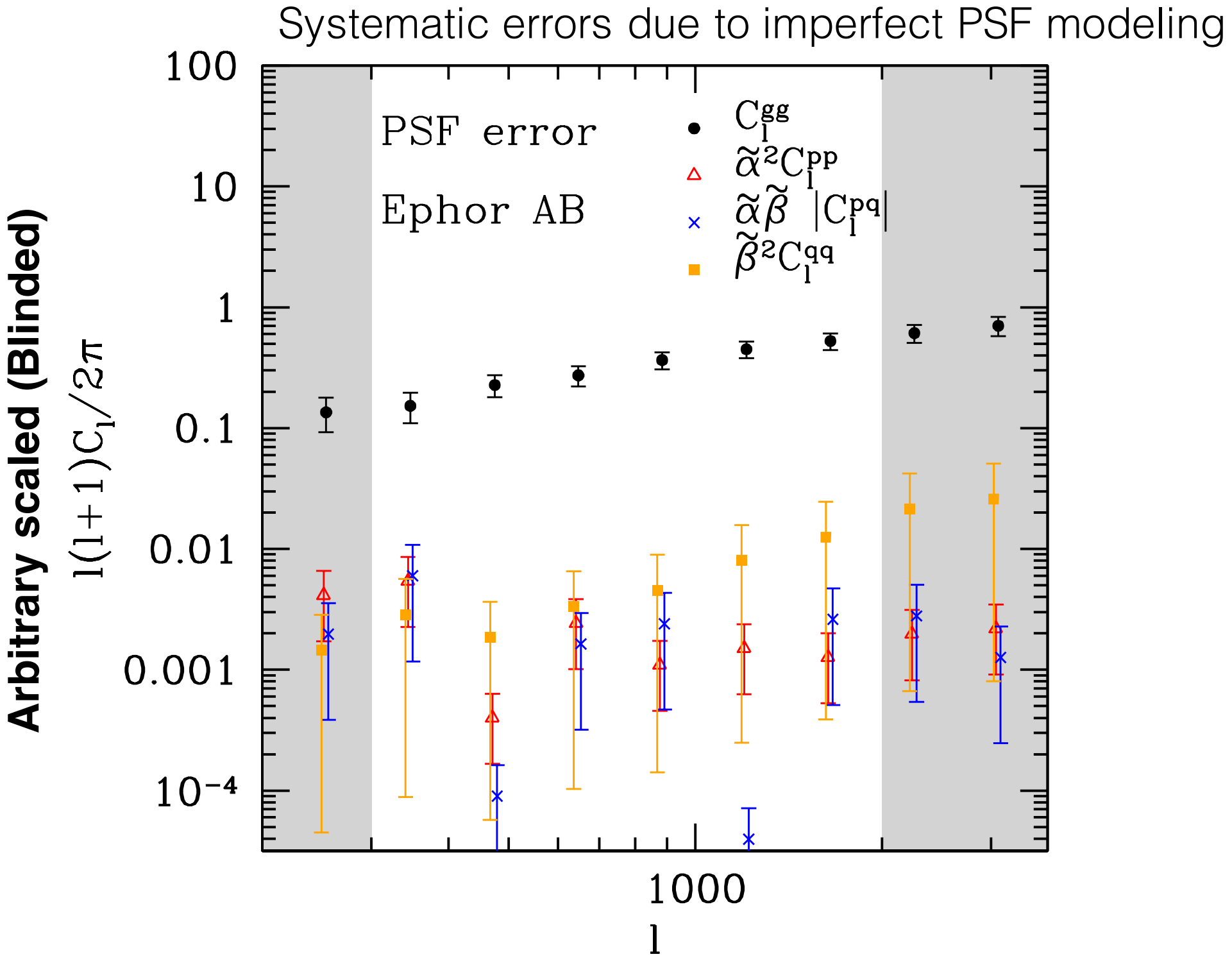
$$\tilde{E}_{\ell m} \pm i\tilde{B}_{\ell m} = \int \mathrm{d}^2\mathbf{n}\; w(\mathbf{n})\,[\gamma_1(\mathbf{n}) \pm i\gamma_2(\mathbf{n})]\,Y_{\ell m}(\mathbf{n})$$

$$\hat{C}_l^{EE} = \mathbf{M}^{-1}_{ll'}\left[C_{l'}^{EE} - N_{l'}\right]$$

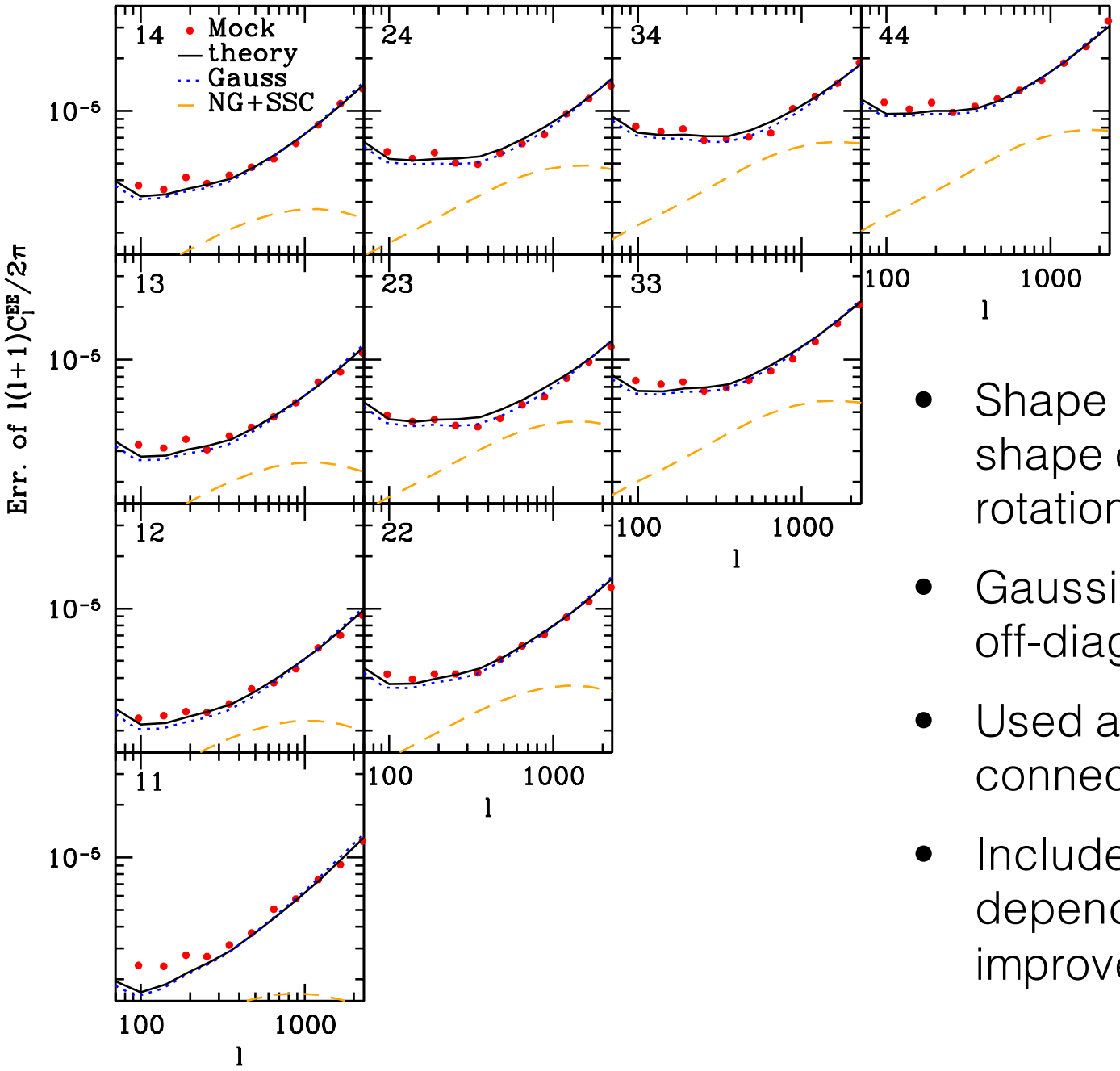


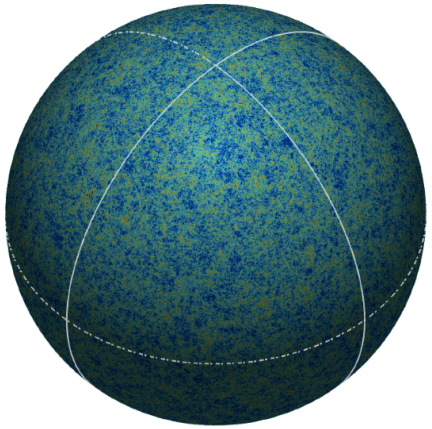
137 sq. deg.
0.3<z<1.5
300<ell<1900
n_eff~16.5 arcmin^{-2}

total S/N~16, corresponding to ~3% in S_8


Systematic errors due to imperfect PSF modeling
PSF error
Ephor AB
C_l^{gg}
$\tilde{\alpha}^2 C_l^{pp}$
$\tilde{\alpha}\tilde{\beta}\ |C_l^{pq}|$
$\tilde{\beta}^2 C_l^{qq}$
Arbitrary scaled (Blinded)
$l(l+1)C_l/2\pi$
100
10
1
0.1
0.01
0.001
10^{-4}
1000
l

Covariance

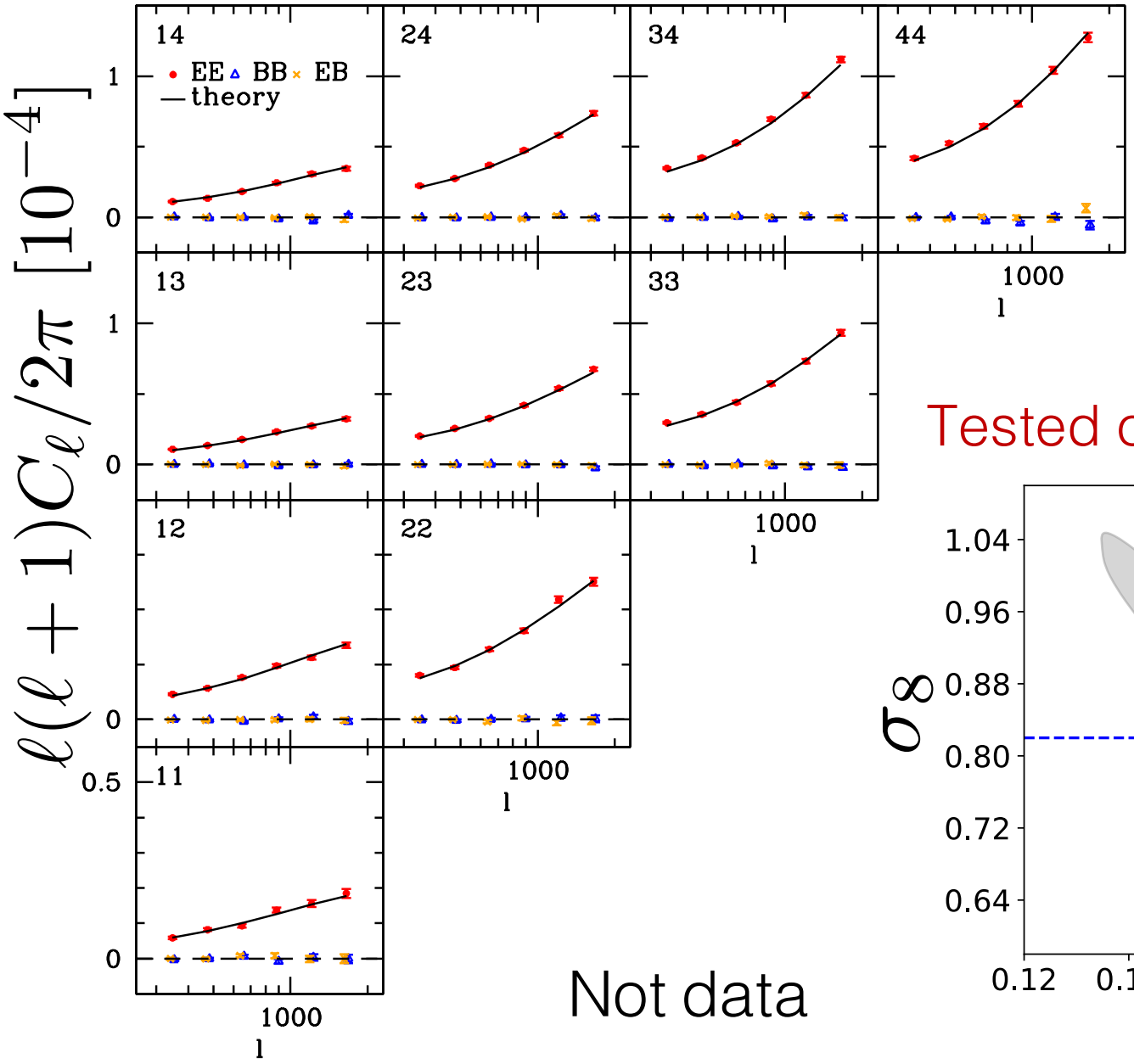


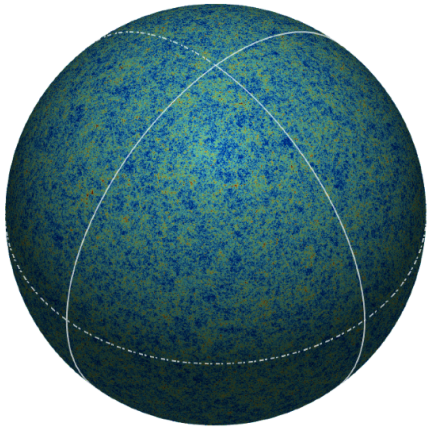


Takahashi + 18

- Shape noise – used the real shape catalog (after random rotations)
- Gaussian term also include off-diagonal terms
- Used analytical formula for connected NG and SSC
- Include the cosmological dependences (~10% improvement in S_8)

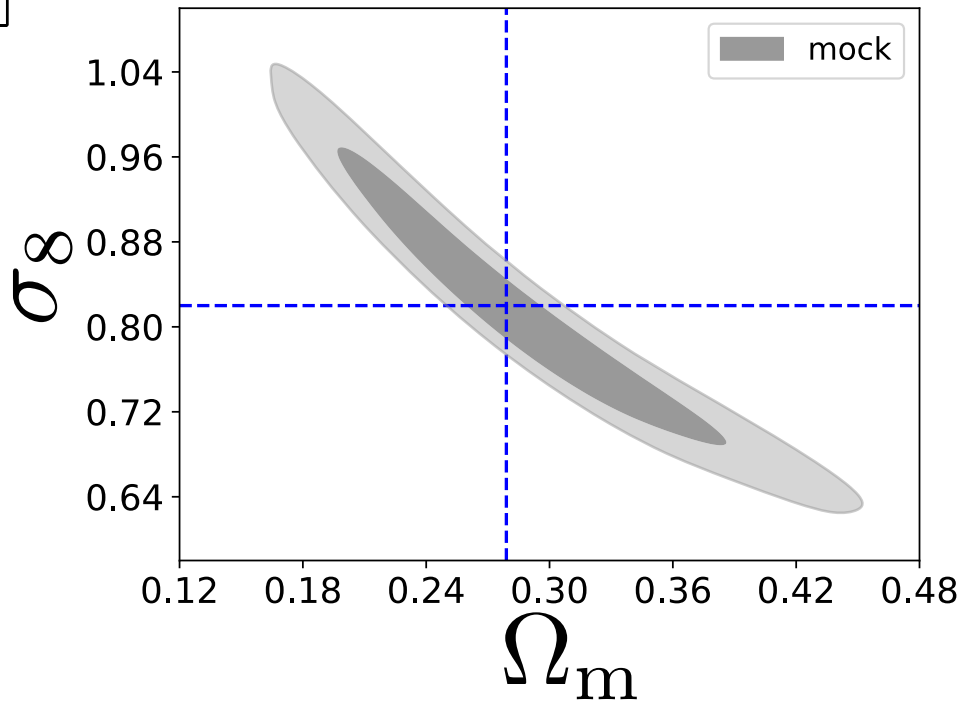
Mocks very important!





$C_\ell^{\rm theory} \leftrightarrow C_\ell^{\rm sim}$

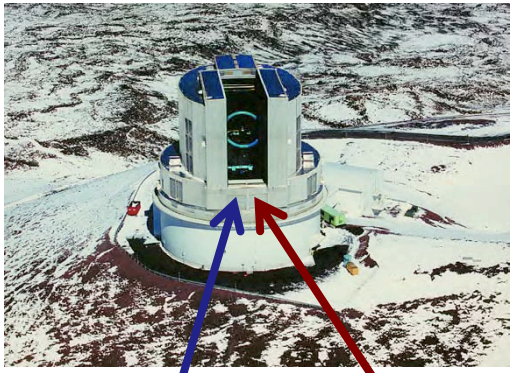
Tested our analysis pipeline



Not data

Hitoshi Murayama (IPMU Director)

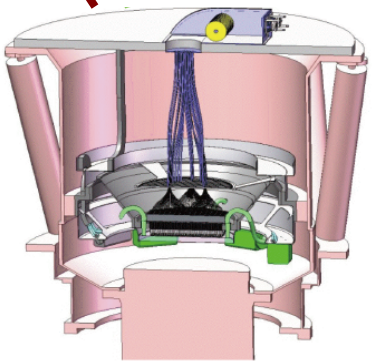
SuMIRe = Subaru Measurement of Images and Redshifts



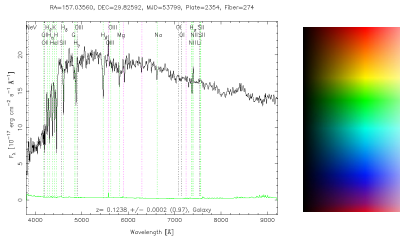
Subaru (NAOJ)

- IPMU director Hitoshi Murayama funded by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper SuprimeCam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies

HSC

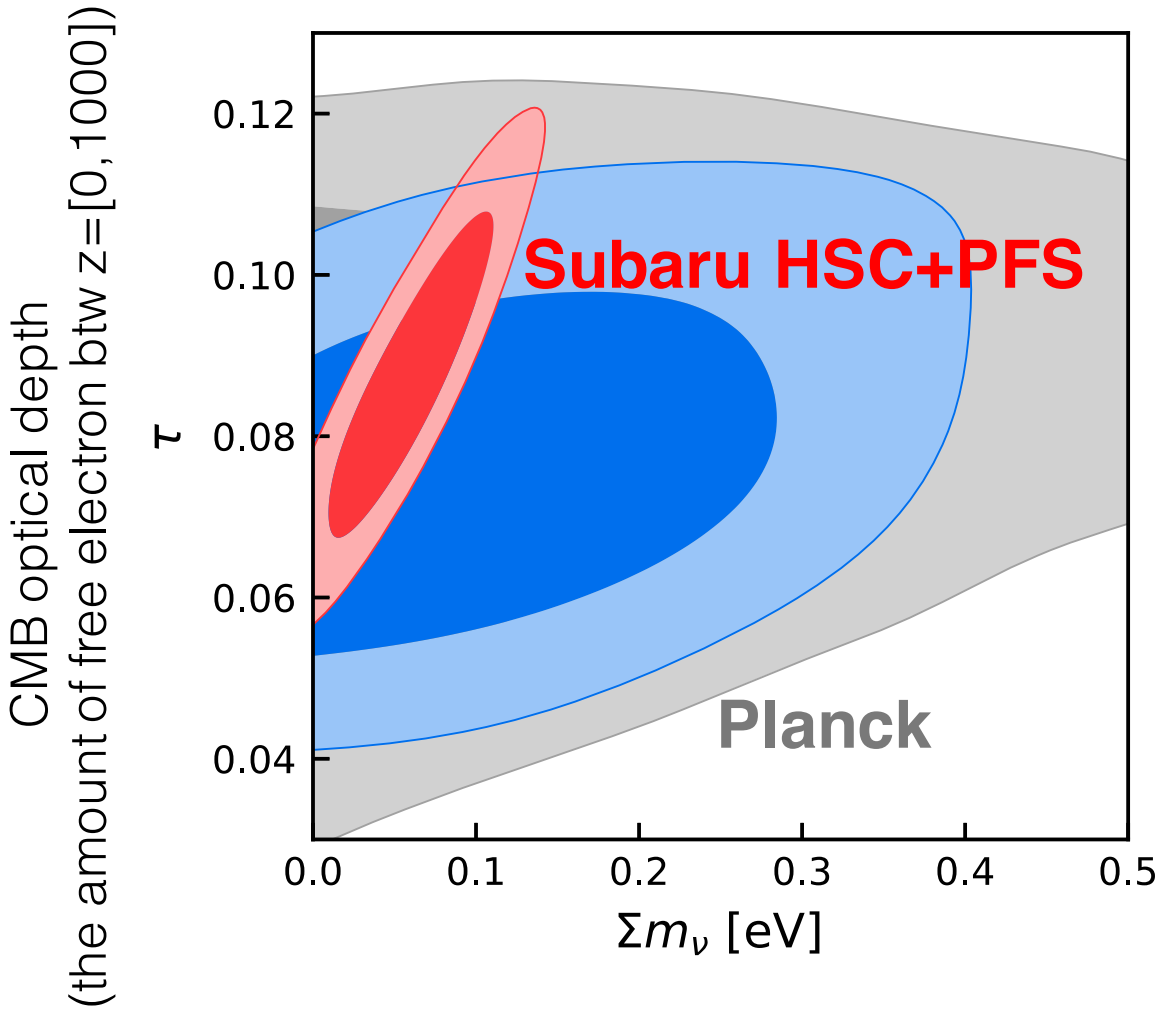


PFS



Cosmology goal for neutrino mass

- Forecasts for Subaru surveys (aimed at achieving by 2025)



$m_{\nu,\,tot}$<0.1eV (95%CL) with Subaru

Note: limited by an accuracy of CMB optical depth (stat. + sys.~0.02)

Future (till 2030):
$m_{\nu,\,tot}$<0.03eV (95CL) with CMB exp.
⇔ HK/DUNE (till 2030, after 5-years operation.)

$\sigma(N_{eff})$~0.027

summary

- Subaru Hyper Suprime-Cam: very deep and superb image quality, a precursor survey of LSST
- Subaru HSC cosmic cosmology analysis was unblinded (catalog level and analysis level), and the paper will come soon (Hikage et al.)
- Combined probe cosmology (g-g lensing and g-g clustering), from HSC and BOSS, is in working progress
- Further plan to include “RSD” information from BOSS
- Towards “robust” cosmology