Cosmology with Subaru galaxy survey(s)

Masahiro Takada (Kavli IPMU)

On behalf of Subaru HSC (and PFS) collaboration

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

CD3

@EAMA11, Niigata, Dec 2025

Kavli IPMU
Chiba, Japan



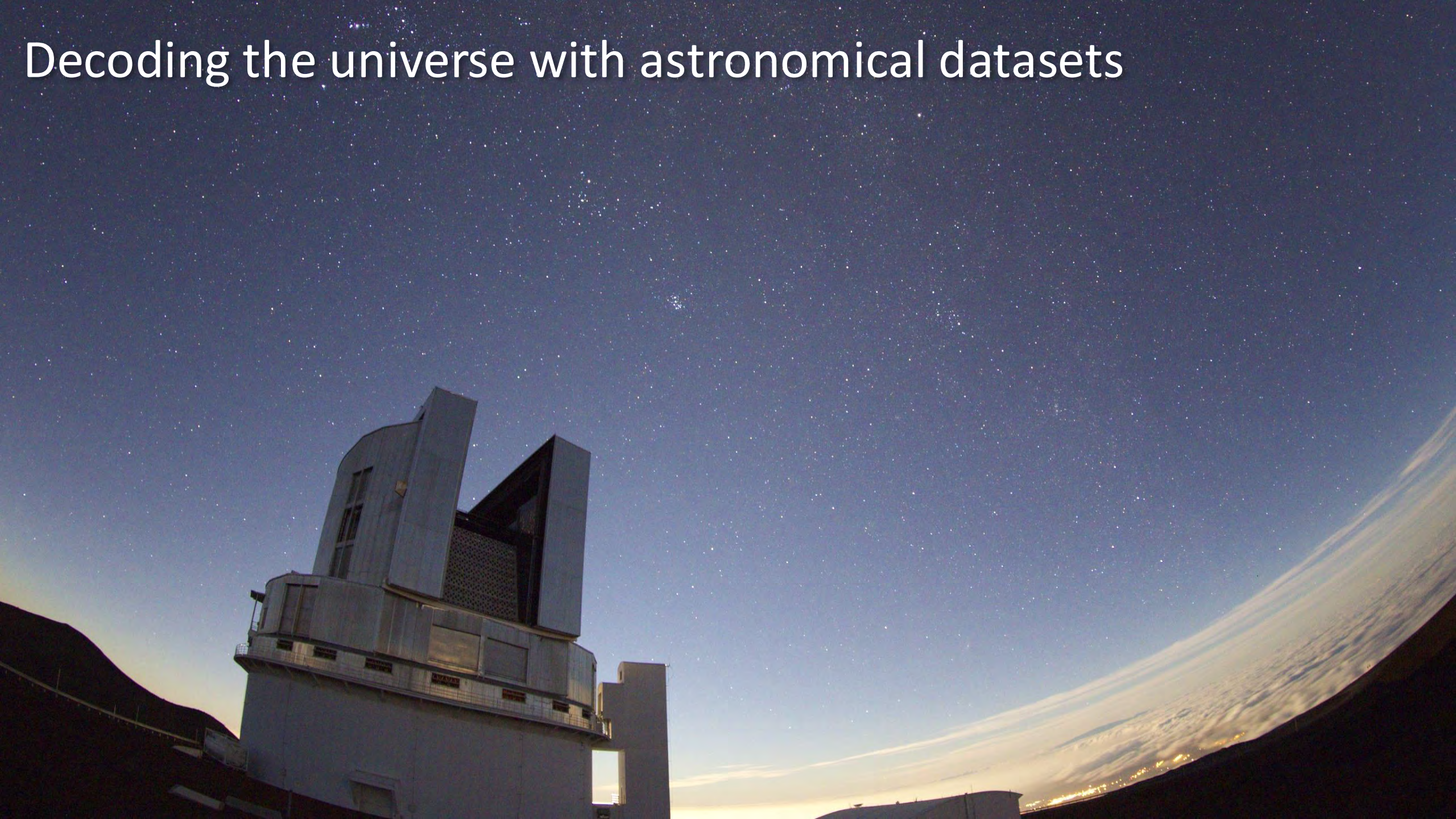




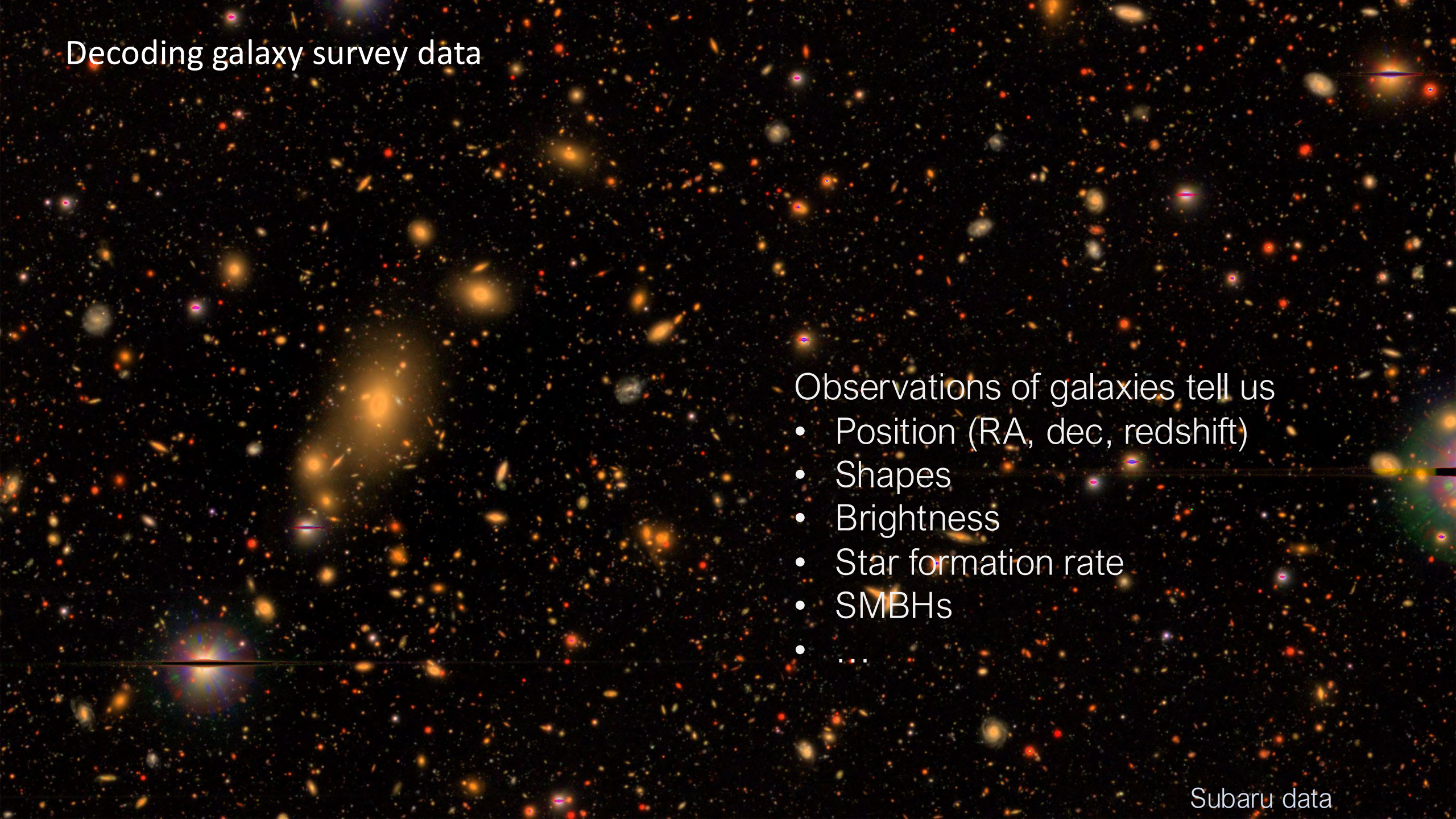
Teatime@3F Fujiwara hall


Subaru Telescope (NAOJ)
Prime-Focus Instrument
@ summit of Mt. Maunakea (4200m), Big Island, Hawaii

Decoding the universe with astronomical datasets



Decoding galaxy survey data

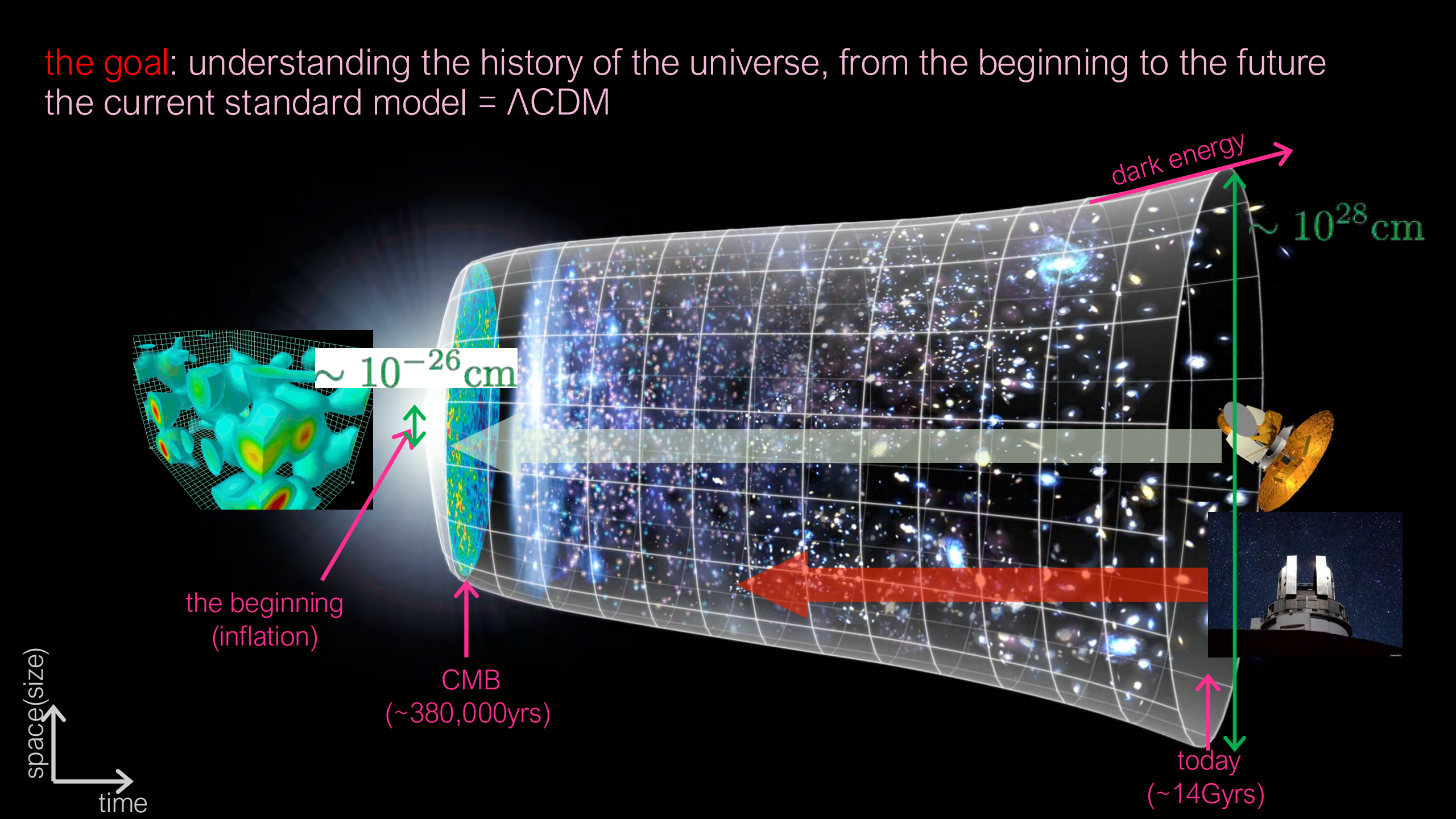


Observations of galaxies tell us

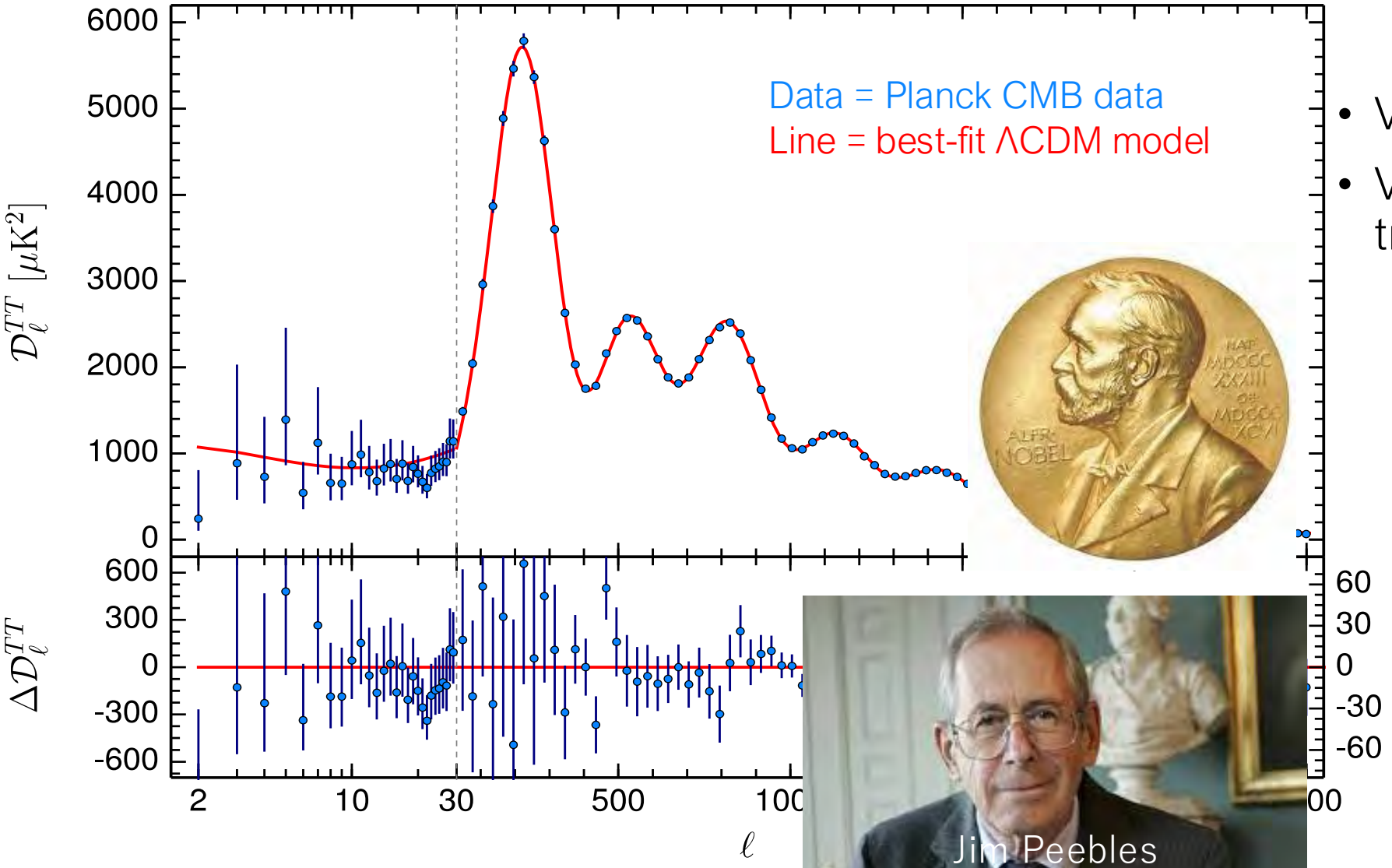
- Position (RA, dec, redshift)
- Shapes
- Brightness
- Star formation rate
- SMBHs
- …

Subaru data

the goal: understanding the history of the universe, from the beginning to the future
the current standard model = ΛCDM

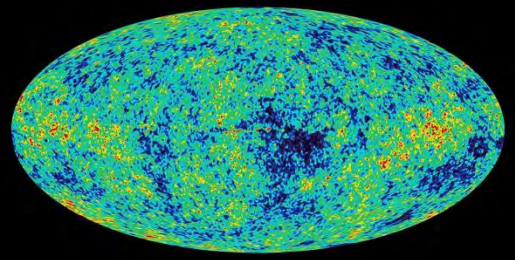


ΛCDM model: the standard model of the Universe



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

A stringent test of ΛCDM model



CMB at z~1000

ΛCDM extrapolation

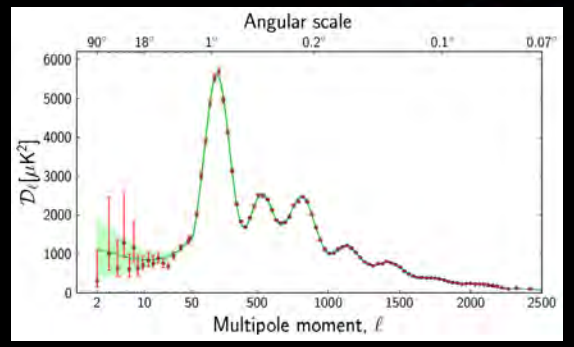
$$\sigma_8^{\rm CMB}(z\sim 0)$$
$$S_8^{\rm CMB}(z\sim 0)$$
$$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$$

time



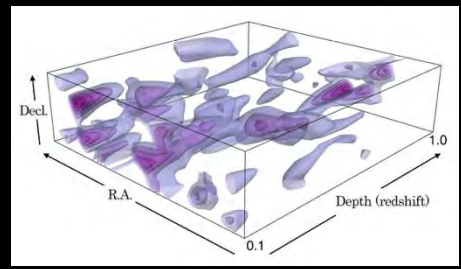
gravity (dark matter)

cosmic expansion (dark energy)



ΛCDM=~6 parameters

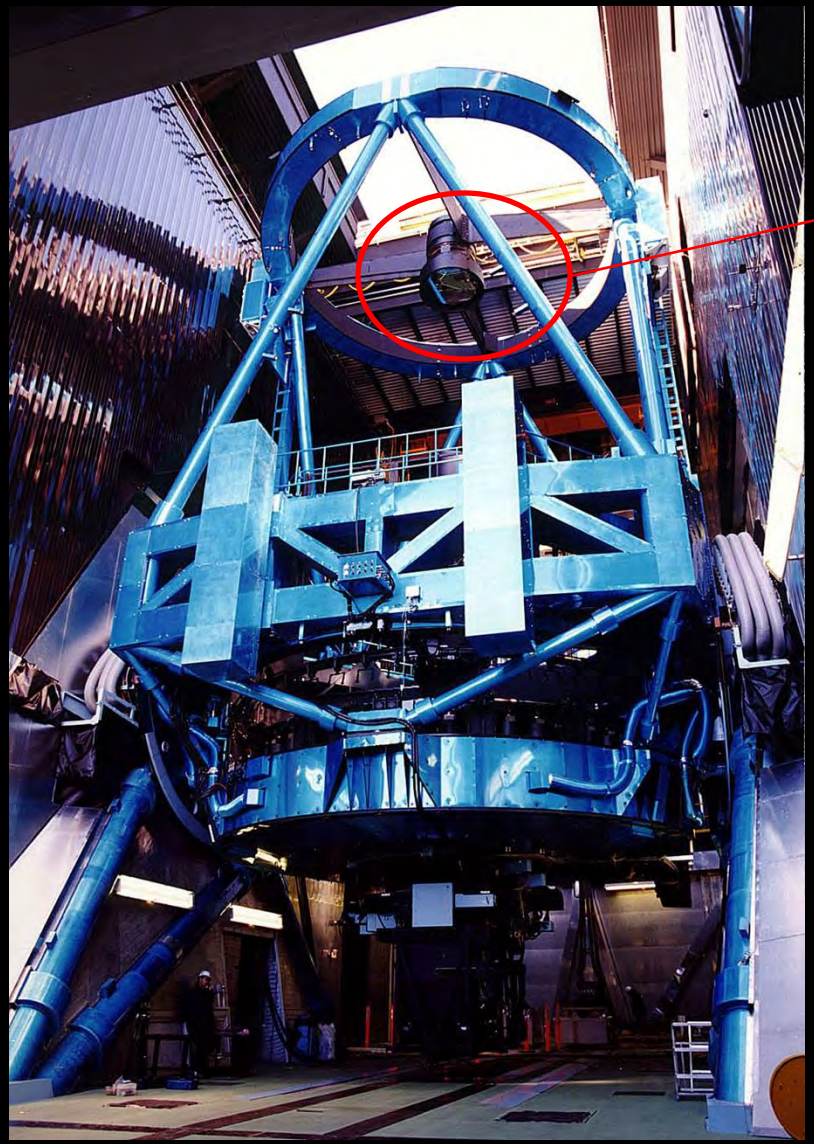




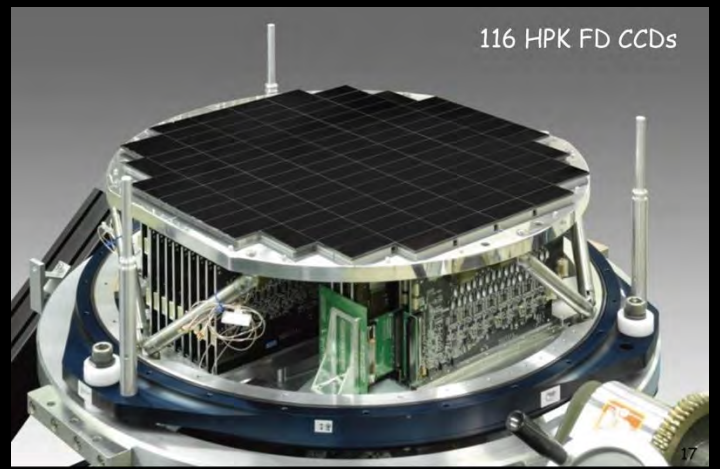
Galaxy surveys directly measure "**lumpiness**" of the late universe

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

Subaru Hyper Suprime-Cam (HSC)







- Built by NAOJ, Kavli IPMU, ASIAA, Princeton U.
- PI: Satoshi Miyazaki (NAOJ)
- Started in 2008, and then start the operation in 2014
- largest camera (before RO LSST camera)
- 3m high
- weigh 3 ton
- FoV = ~7 full moons
- 104 CCDs (~0.9G pixels)
- In operation since 2014

Subaru Tel

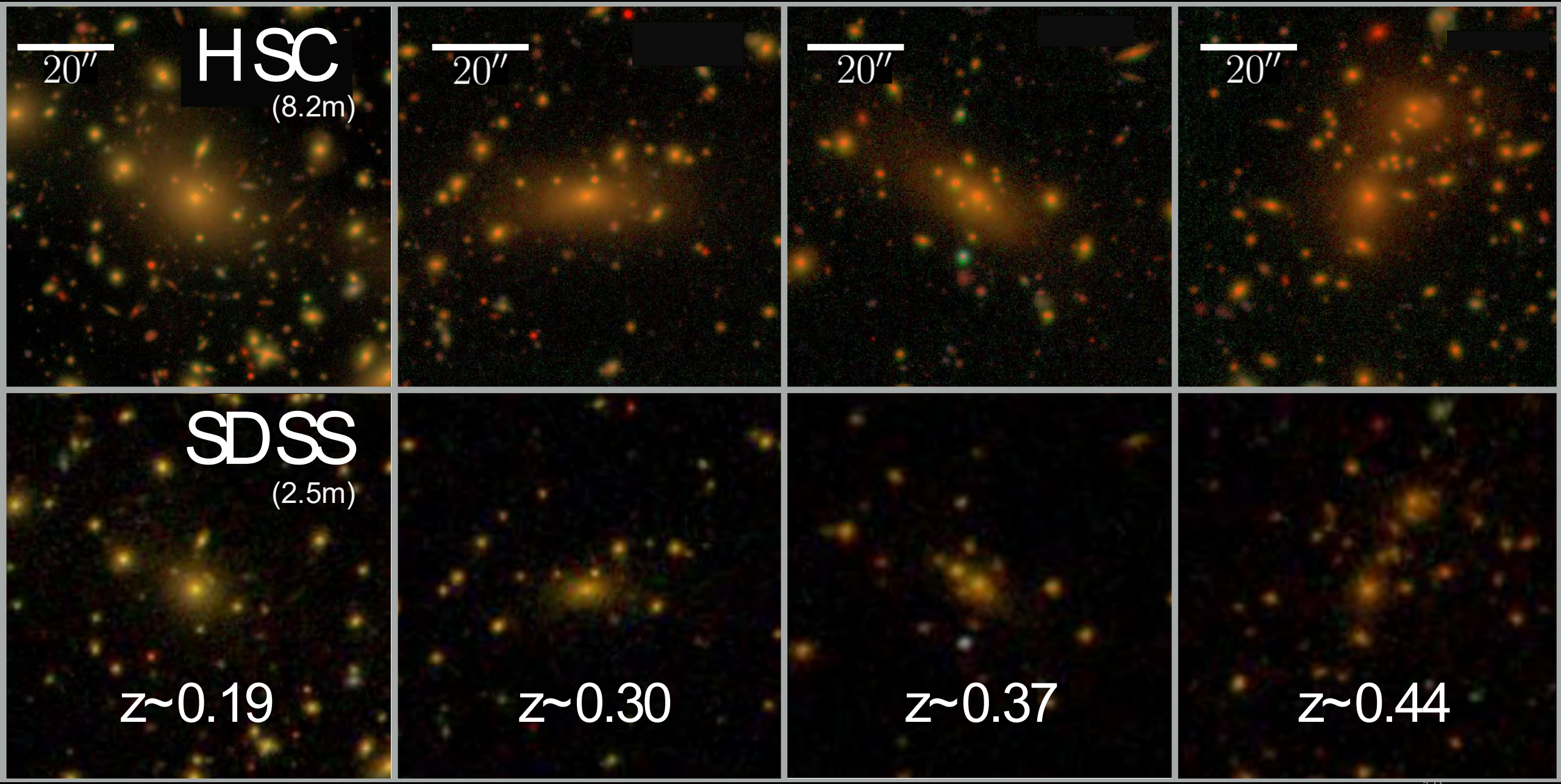
- Fast, Wide, De
- a cosmologica



Hyper Suprime-Cam FoV

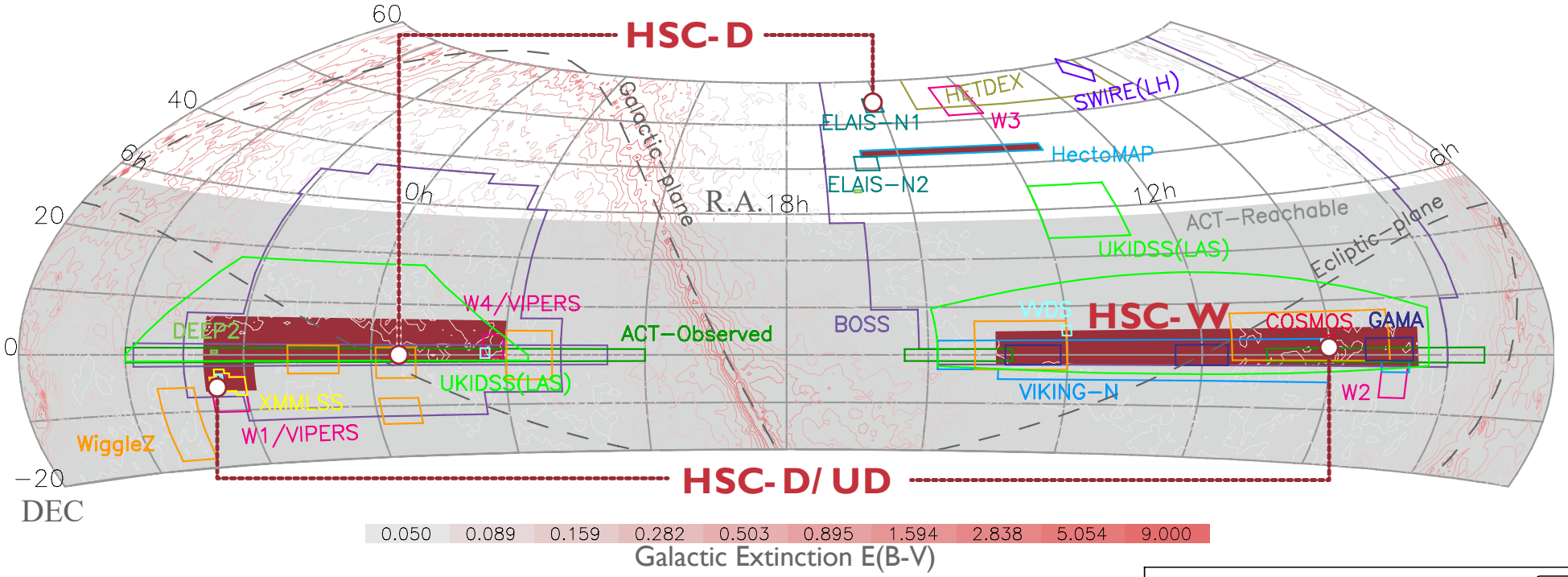


©HSC project

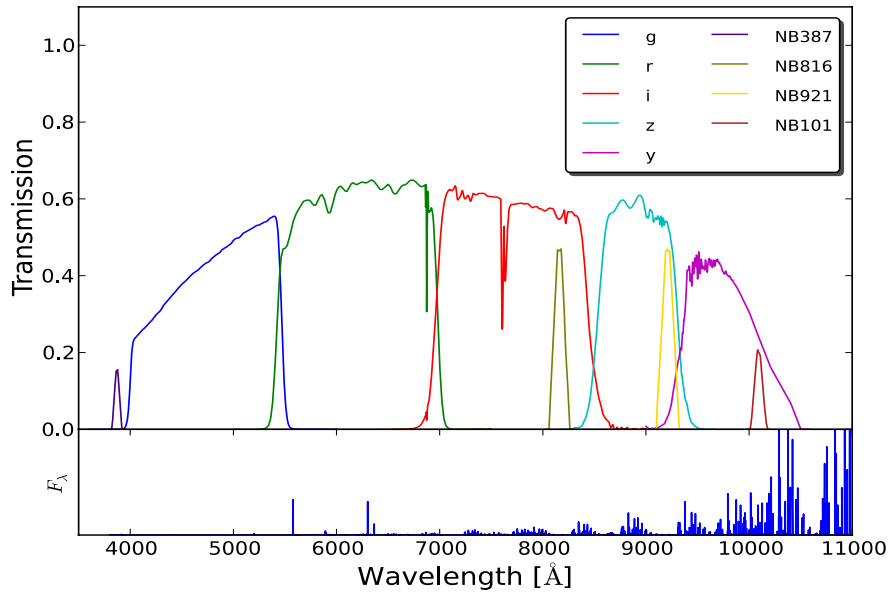


Huang et al. 2017

Subaru wide solid-angle survey (2014-)

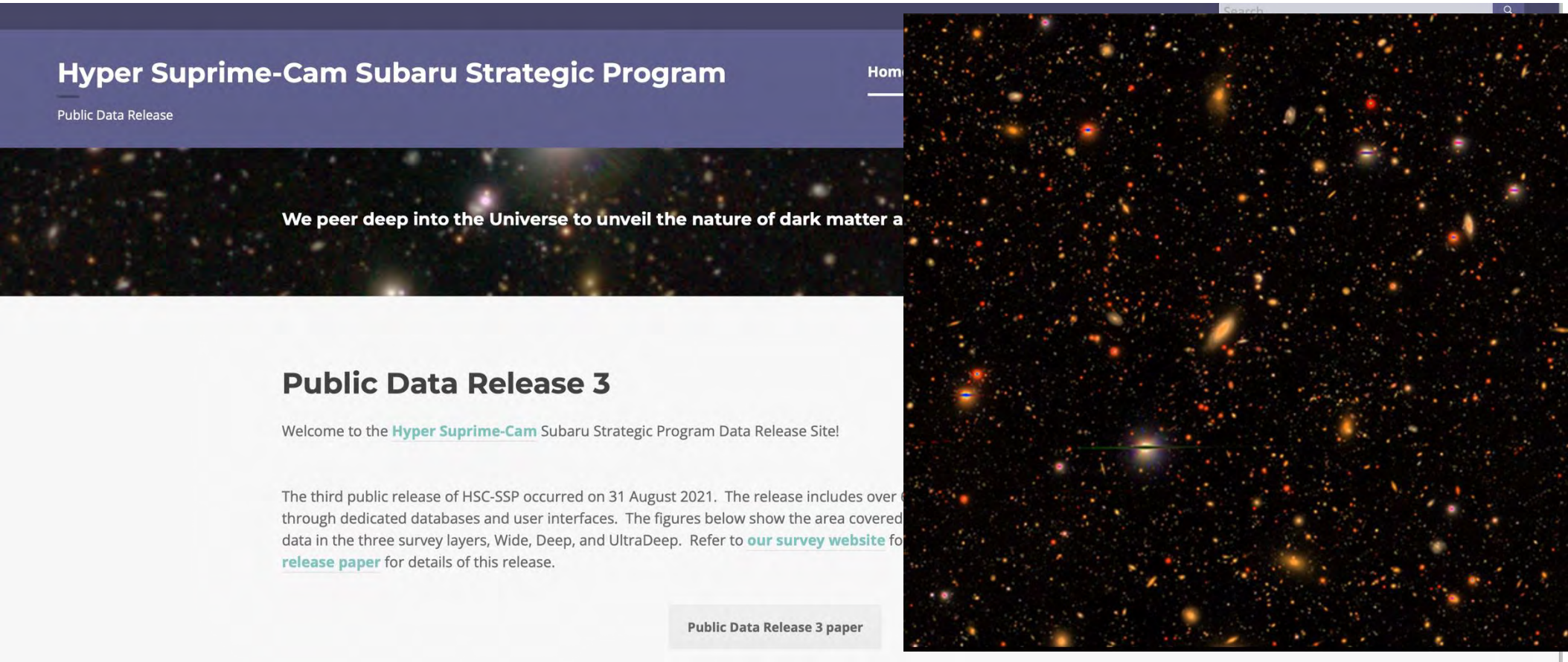


- HSC: 2014 – 2021 (HSC imaging data acquisition are done)
- Broad band filters (grizy) (plus NB filters for Deep/UD fields)
- Various science cases: cosmology, galaxies, AGN, the Milky Way structure, solar system, ….
- HSC-Wide for cosmology (i~26, grizy, ~1100 deg^2)



Public Data Release of HSC SSP: DR3

- DR3 (catalog, images, raw data): 278 Subaru nights, ~670 sq. deg., i~26, **~5×10^8 objects** ≃50yrs SDSS (final PDR will be in ~2024)
- Led by the NAOJ HSC team (Hisanori Furusawa, Masayuki Tanaka, …)
- https://hsc-release.mtk.nao.ac.jp/doc/
- Being used by LSST collaboration as its testbed



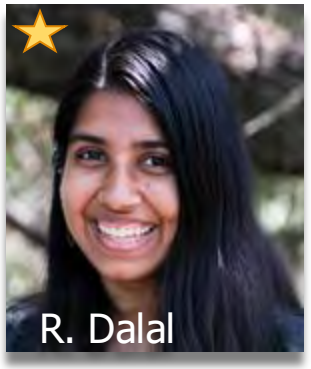
Weak lensing working group

★ junior scientists


S. Sugiyama


T. Zhang


X. Li


R. Dalal


S. More


R. Mandelbaum

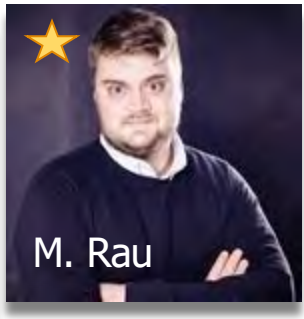

H. Miyatake


M. Takada


M. Strauss

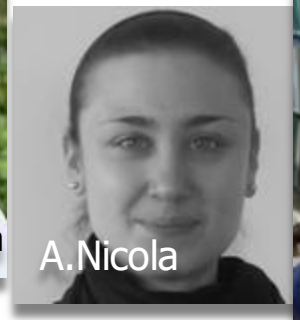

Y. Kobayashi


A. Kannawadi


M. Rau


W. Luo


A. J. Nishizawa


A.Nicola

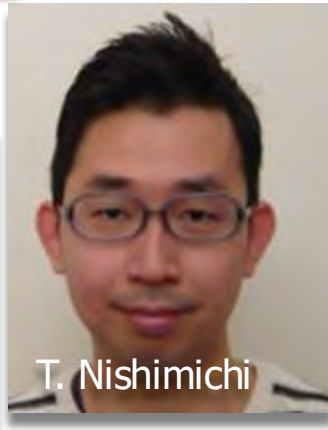

R. Takahashi


K. Osato


M. Shirasaki


M. Oguri


T. Hamana


T. Nishimichi

And efforts of many more!

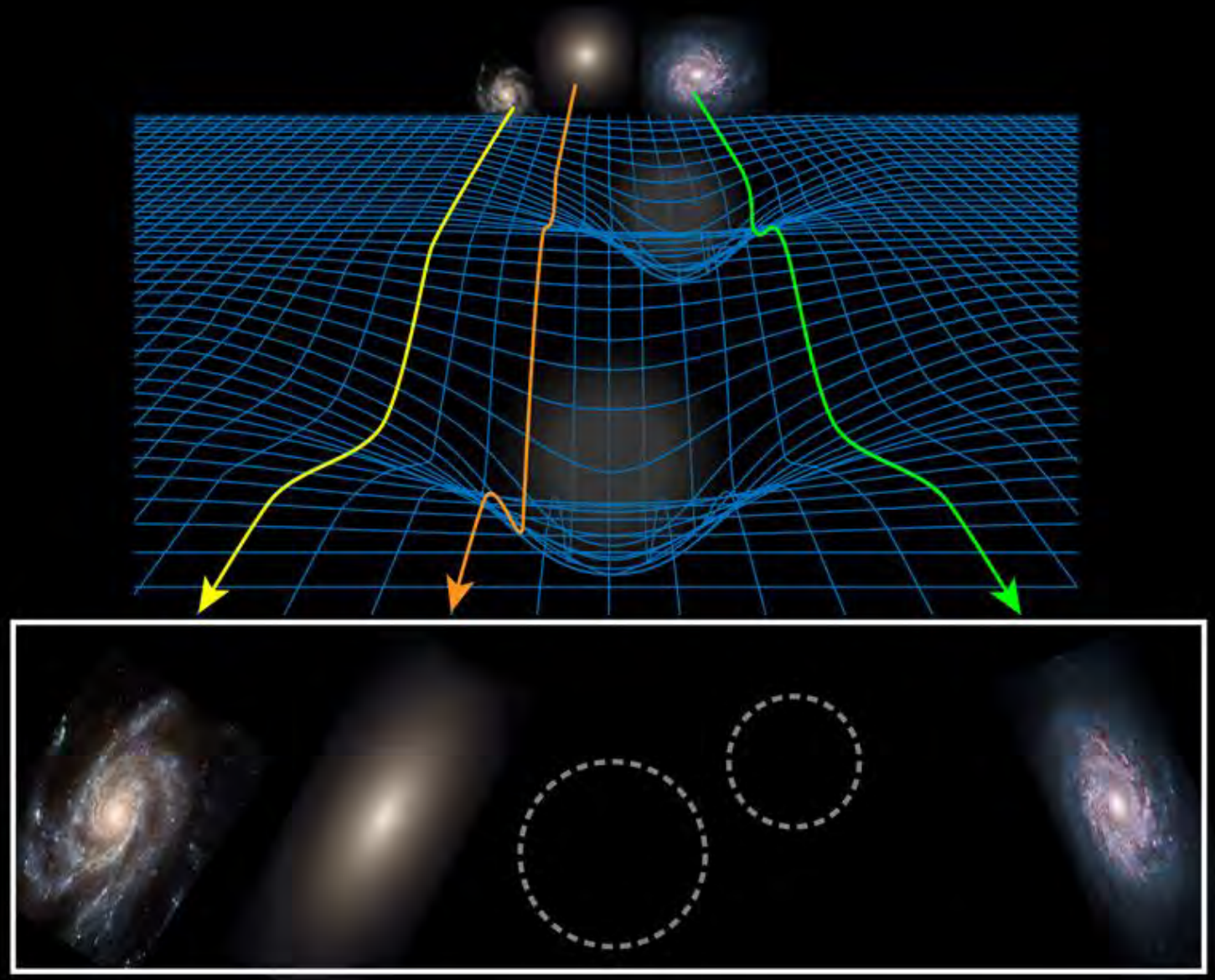
Key weak lensing group publications: HSC Year 3 (2023)

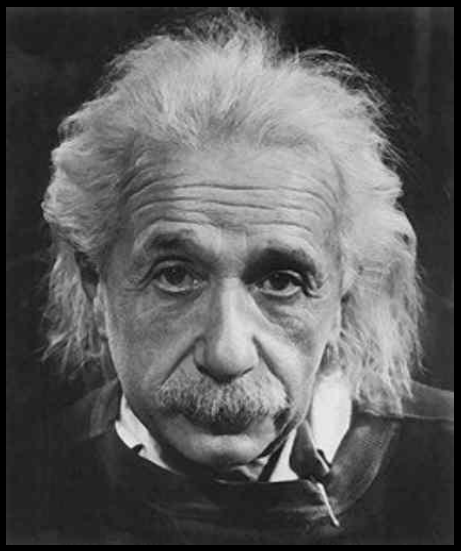
- The three-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey (**Li X.**, et al. 2022, PASJ, 74, 2)
- A General Framework for Removing Point Spread Function Additive Systematics in Cosmological Weak Lensing Analysis (**Zhang T.** et al. 2022, MNRAS submitted, arXiv:2212.03257)
- Weak Lensing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

Weak gravitational lensing



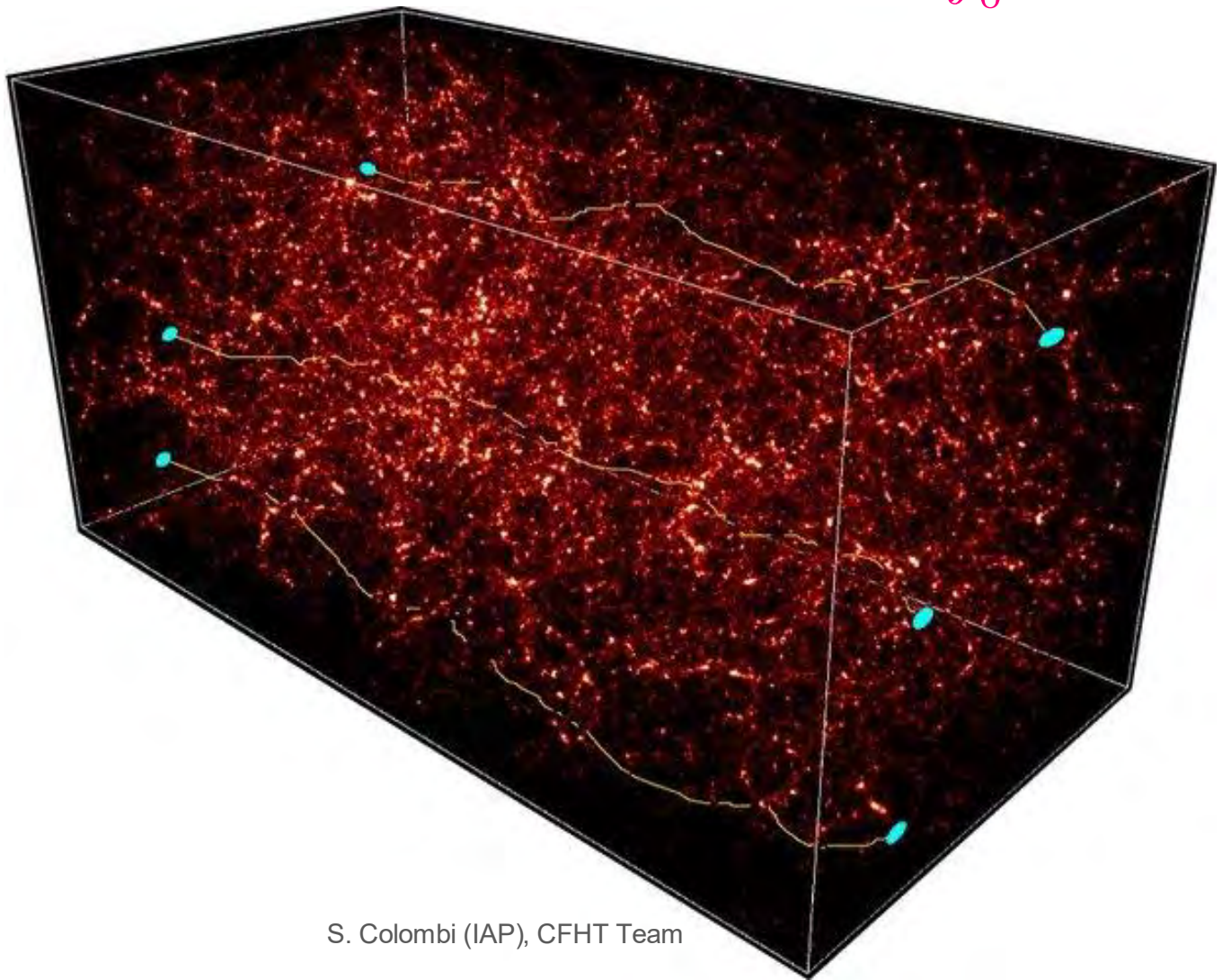


- Prediction of Einstein's gravity theory
- Gravity = Curved space-time
- Even light path, emitted from a distant galaxy, is bent by the intervening matter (mainly dark matter) distribution
- Can observe "distortion" in galaxy images

APS/**Alan Stonebraker**; galaxy images from STScI/AURA, NASA, ESA, and the Hubble Heritage Team

Weak gravitational lensing – a probe of dark matter distribution

$$\gamma = \frac{a-b}{a+b} \sim \Omega_{\rm m} \int_0^{\chi_{\rm s}} {\rm d}\chi\ \chi \left(1 - \frac{\chi}{\chi_{\rm s}}\right) \delta_{\rm m}(\chi, \chi\boldsymbol{\theta}) \sim \sigma_8 \Omega_{\rm m}^{0.5} \sim S_8$$

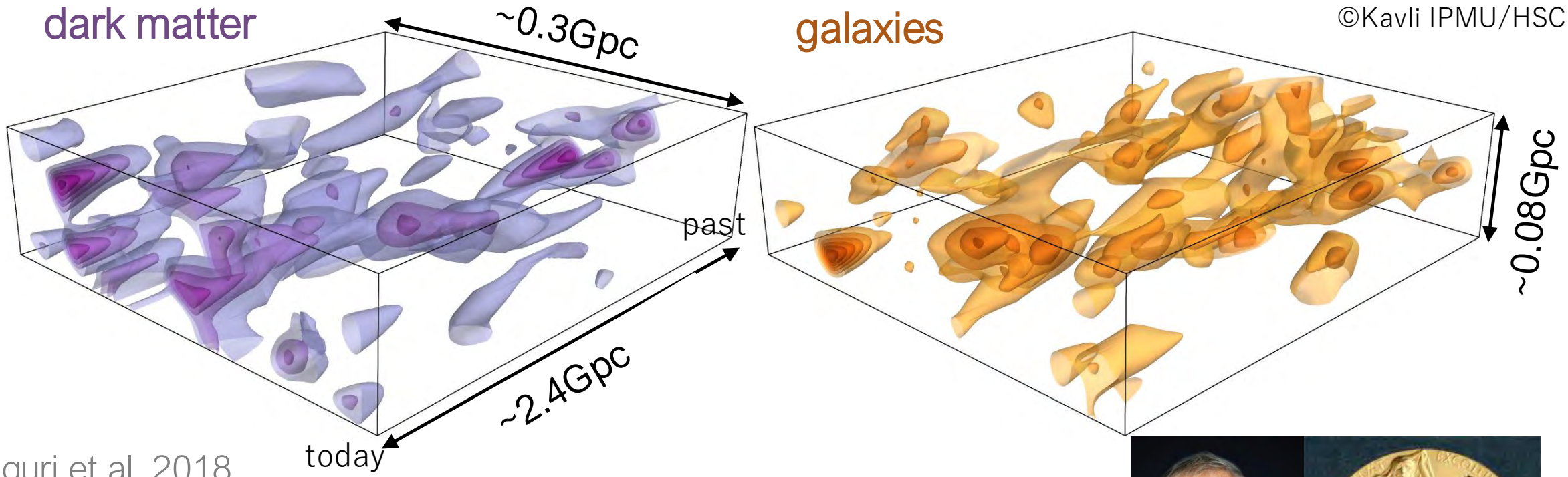


S. Colombi (IAP), CFHT Team

Ω_m: the amount of matter (incl. dark matter)
δ_m: the matter density fluctuation field

- 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

3D mass (mainly dark matter) map with Subaru HSC data



Oguri et al. 2018

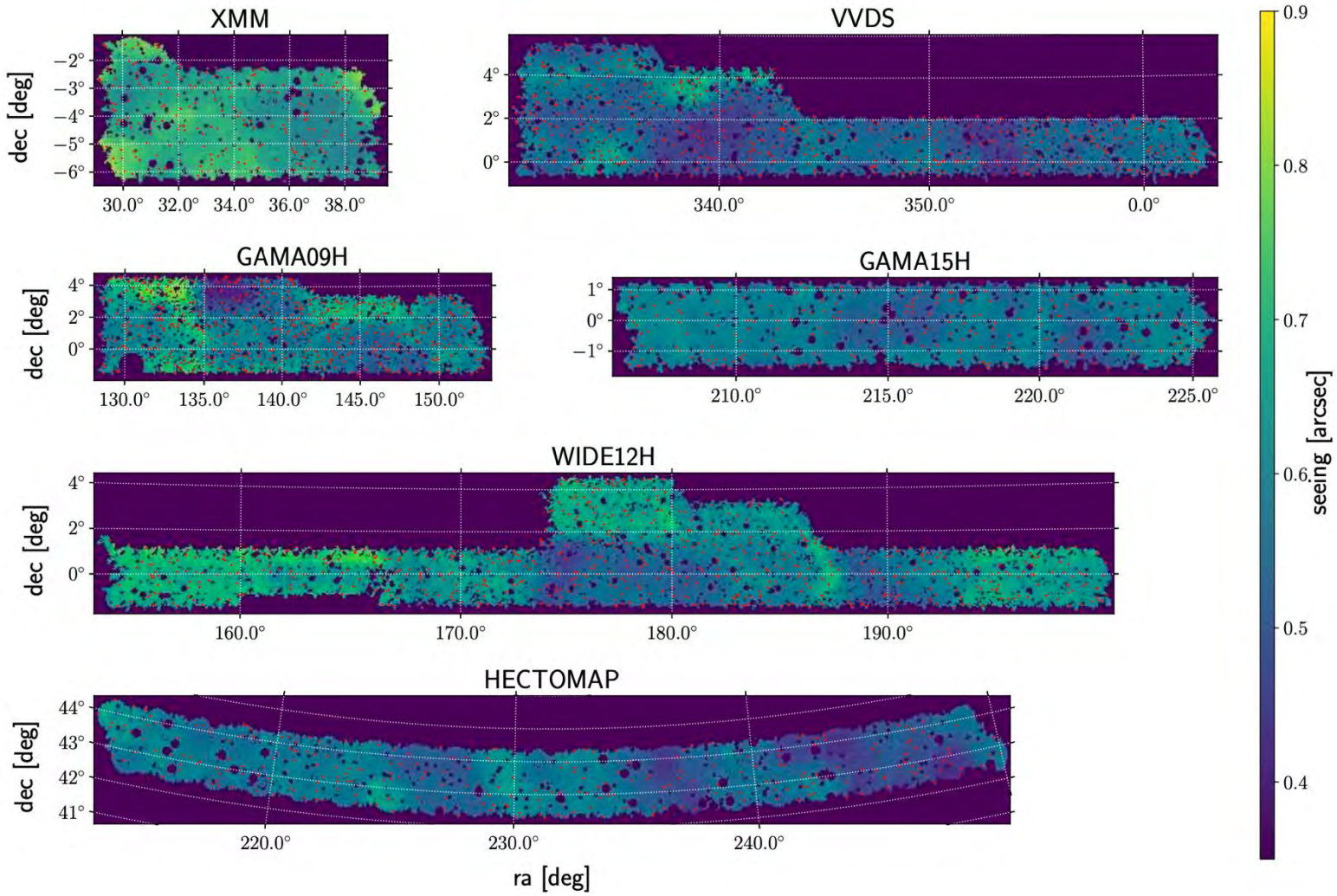
Galaxies form in regions where dark matter are dense (concentrated), as predicted by ΛCDM structure formation scenario



Jim Peebles (2019 Nobel Prize)

HSC Year 3 galaxy shape catalog

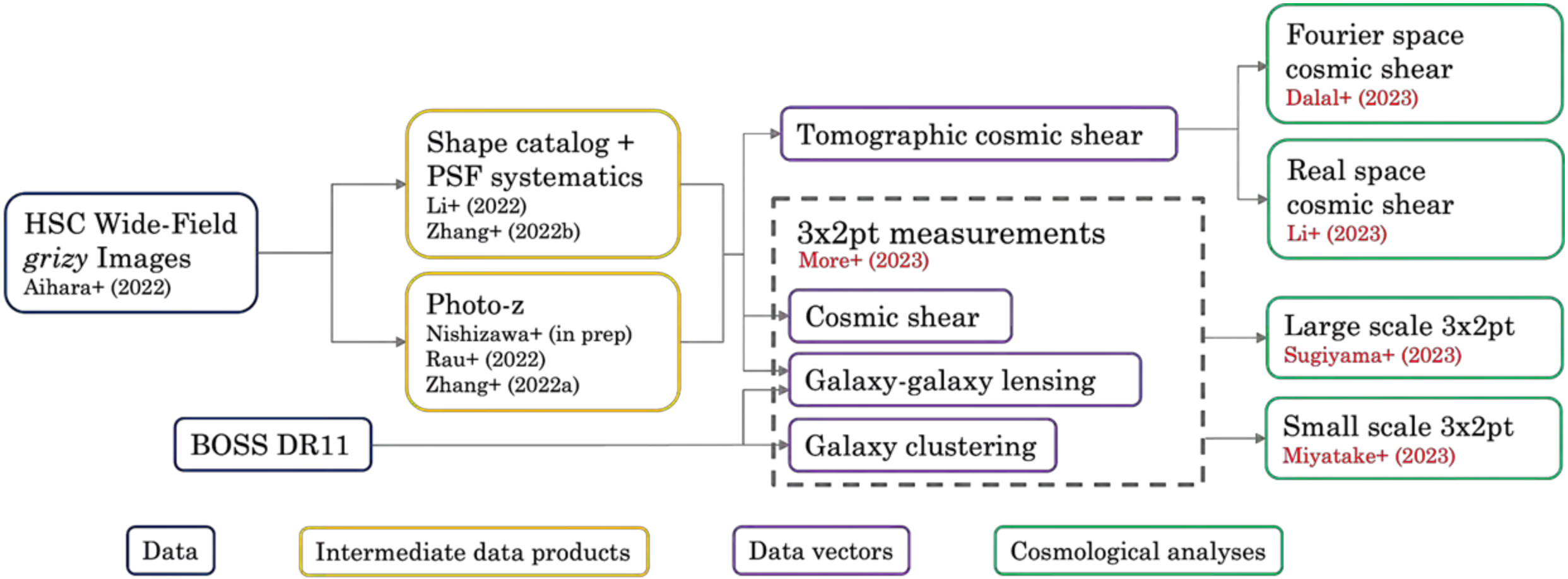
- HSC Year 3 data: ~416 sq. deg. ⇐ Year 1 ~140 sq. deg., a factor of 3 wider
- Galaxy shape catalog: Xiangchong Li (the former IPMU student), Miyatake et al. 22
- Used the sophisticated simulated data (using HST) for the calibration



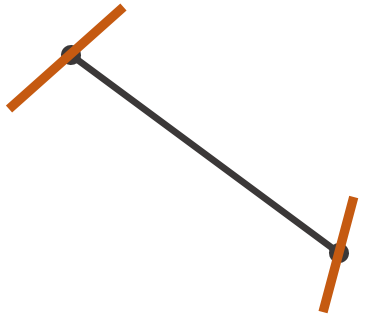
25M galaxies (shapes)

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

Many steps, many efforts, many works, ….



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

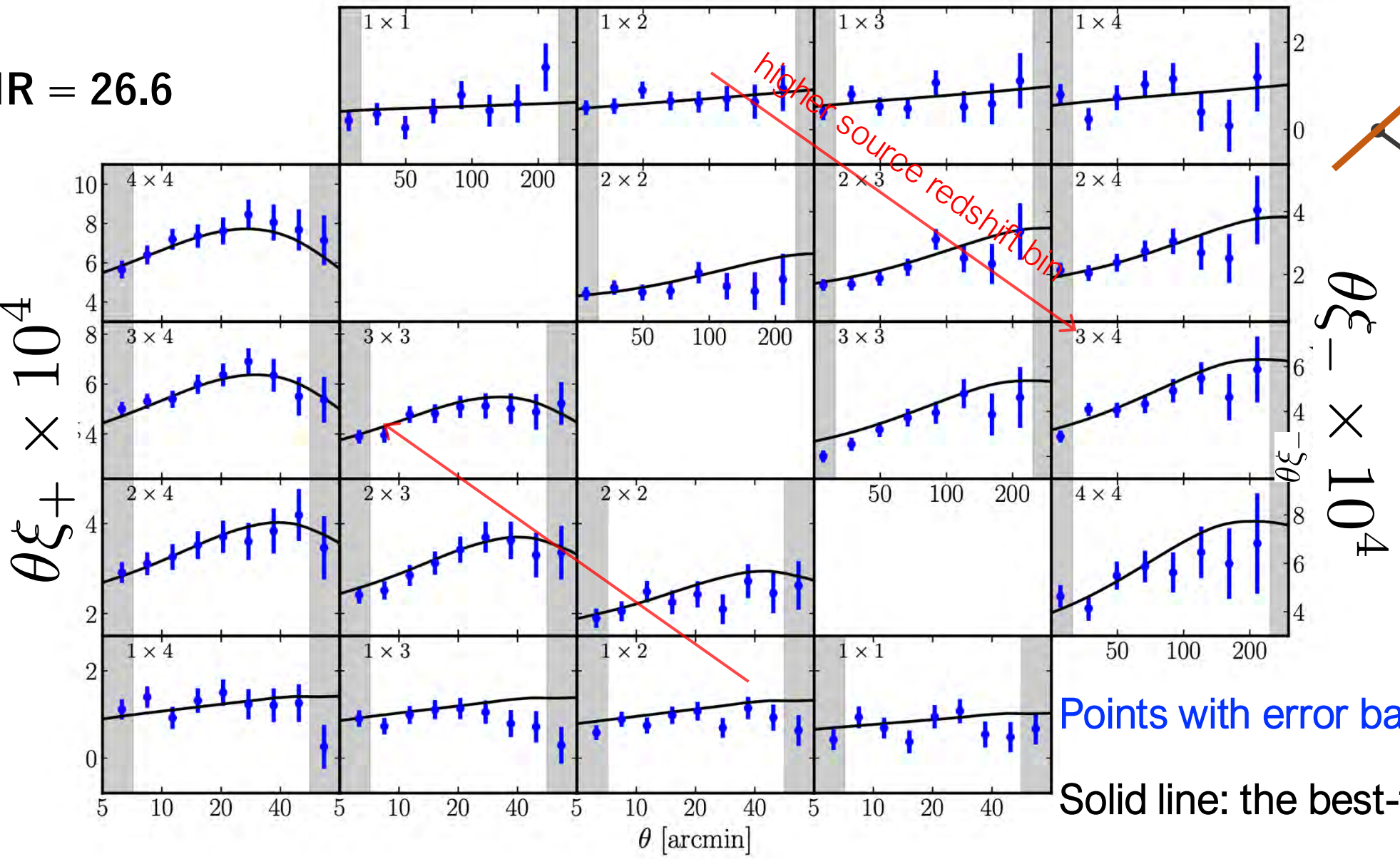
- In configuration space, $\xi_{+/-(i_s j_s)}(\theta) = \int \frac{\ell \mathrm{d}\ell}{2\pi} C_{i_s j_s}(\ell) J_{0,4}(\theta\ell)$

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

Cosmic shear tomography

Li+23; Dalal+23

SNR = 26.6



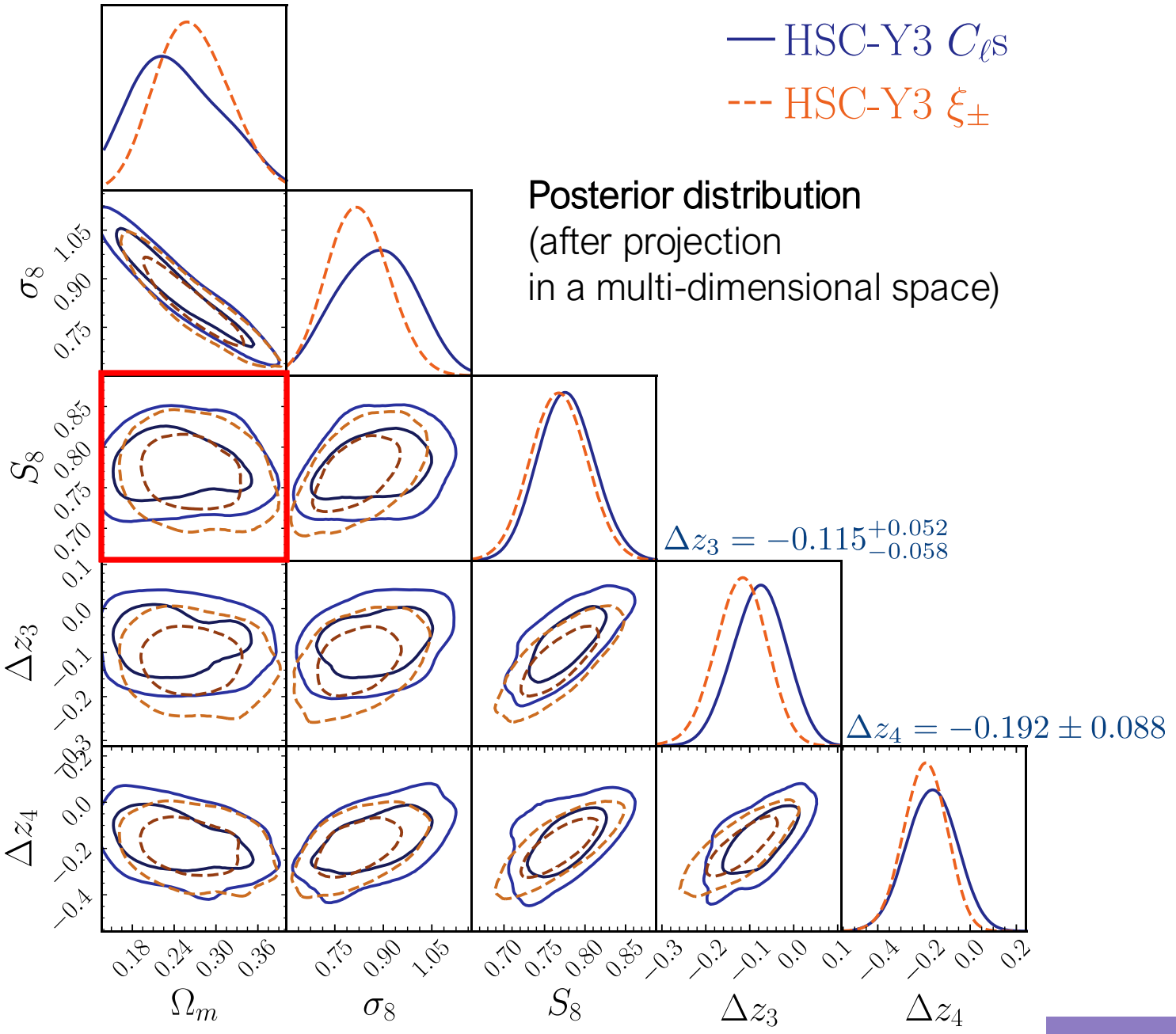
Points with error bars: HSC

Solid line: the best-fit ΛCDM model

Use unshaded angular scale range (scale cuts) for cosmology inference

HSC-Y3 cosmic shear cosmology results

Li+; Dalal+

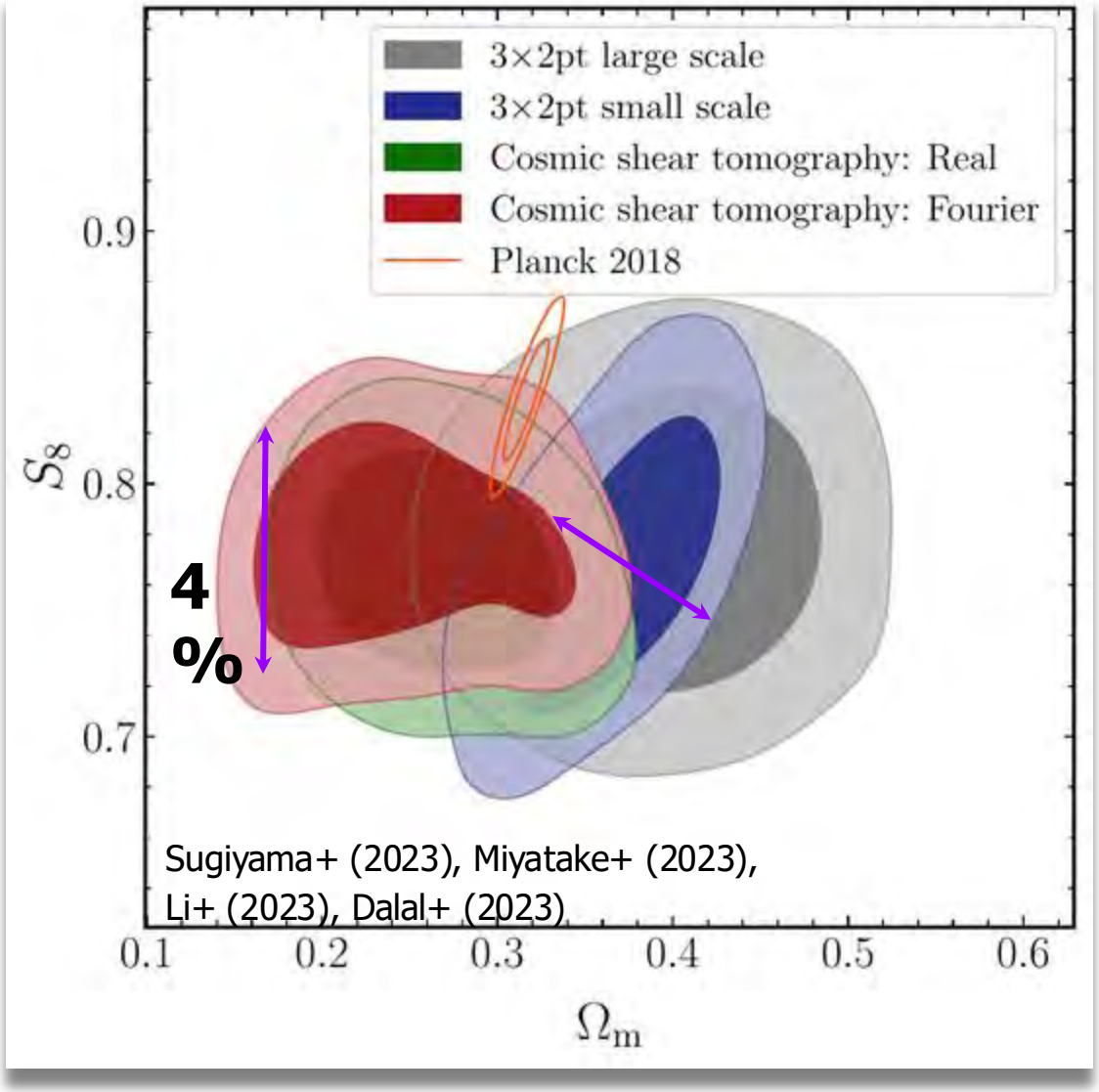


$$S_8(C_\ell) = 0.776^{+0.032}_{-0.033}$$

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

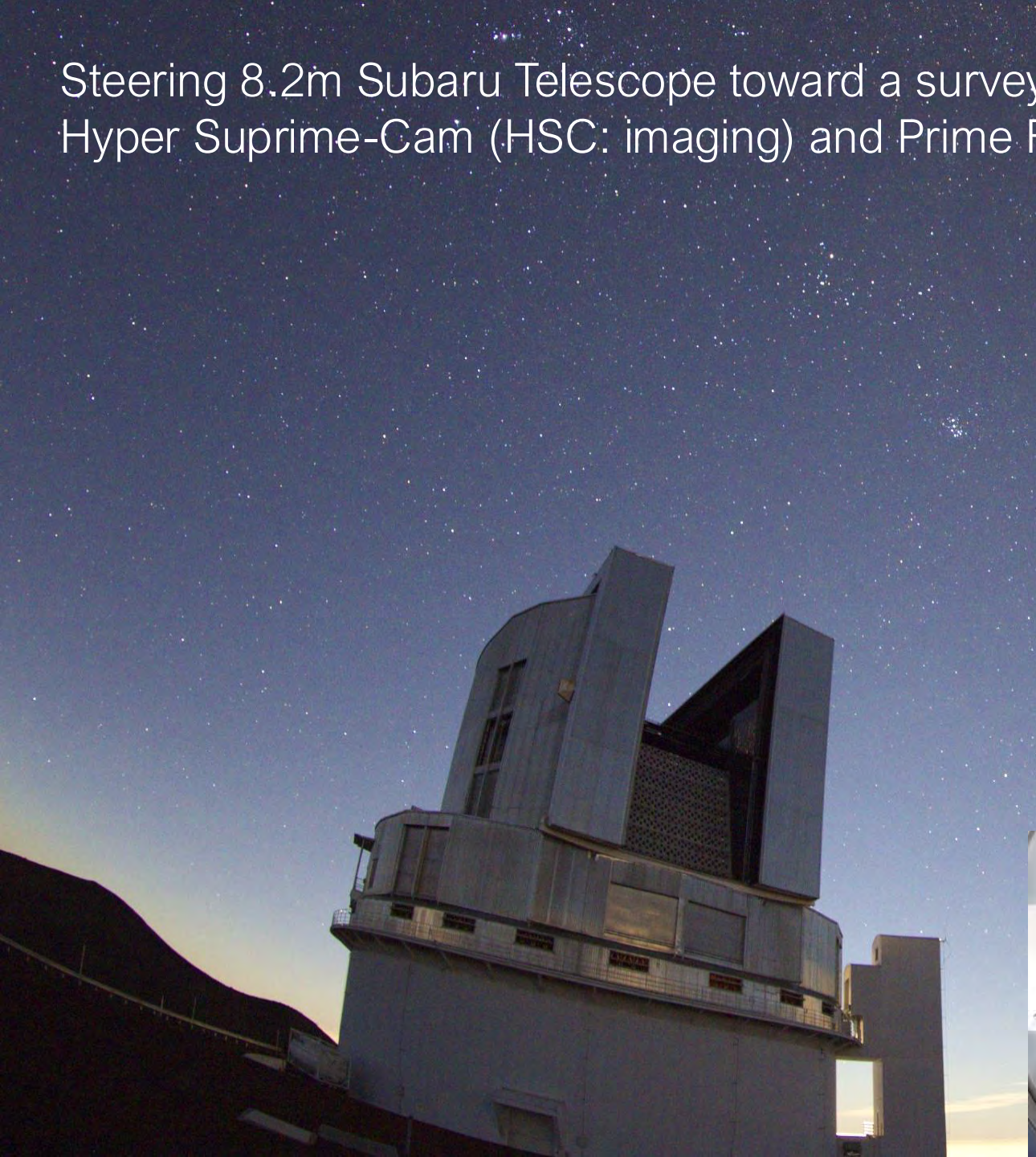
- 4% fractional precision of S8 measurement (even if using the uninformative, flat priors of dzs)
- After unblinding, we compared the two results, finding the consistent results of S8
- Including the marginalization over the baryonic effects and IA effects
- Implies non-zero dz3,4 values (implying the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

Summary of HSC Year 3 cosmology results



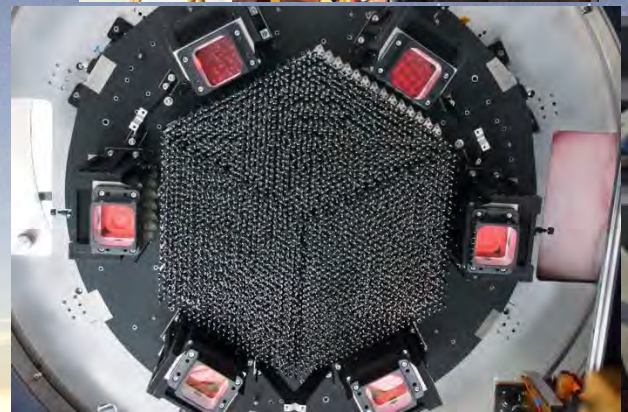
- Compare the cosmic shear and the 3x2pt result, after the unblinding
- Consistent cosmological constraints from the blind analyses
  - Cosmic shear (Real and Fourier space)
  - 3x2pt analysis (Linear and Quasi-linear scales)
- Conservative analyses in the presence of systematic uncertainties in the 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

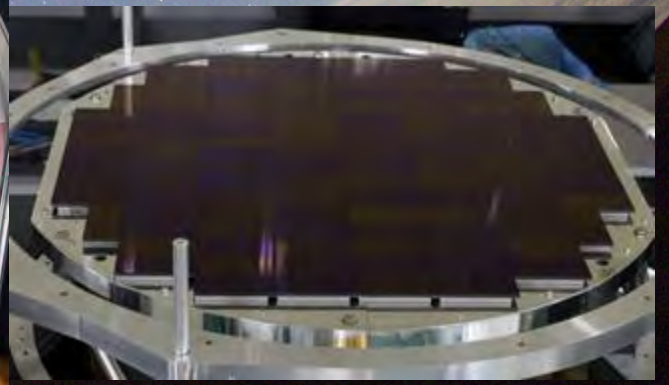
Steering 8.2m Subaru Telescope toward a survey-type telescope in a coming decade: Hyper Suprime-Cam (HSC: imaging) and Prime Focus Spectrograph (PFS: spectroscopy)



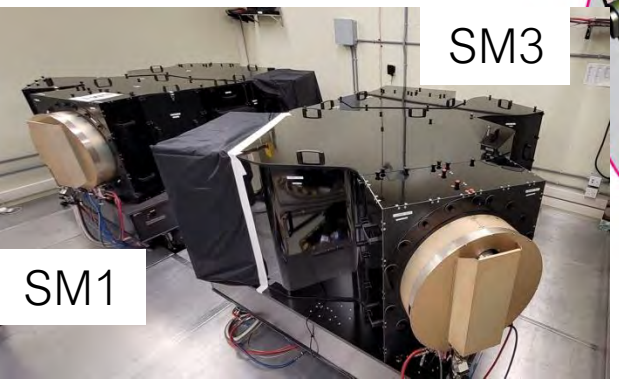




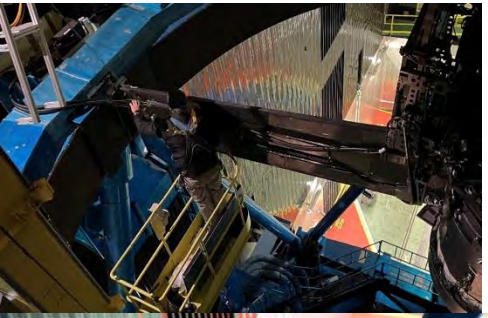




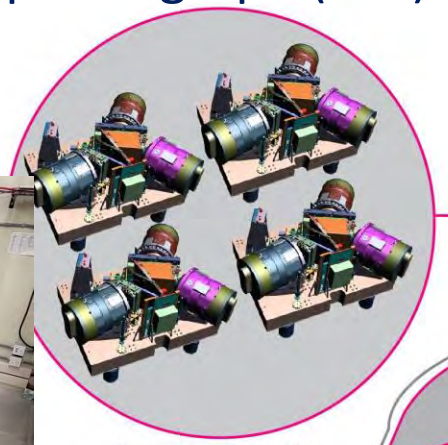
Subaru Prime Focus Spectrograph (PFS) completed, after 15yrs!

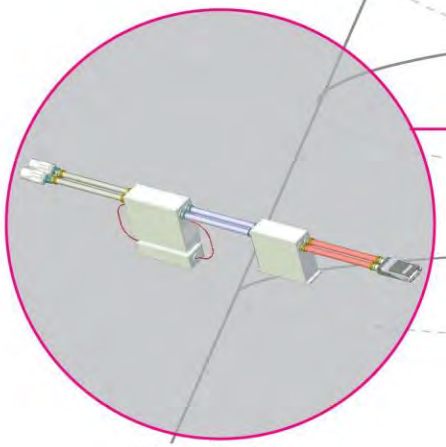


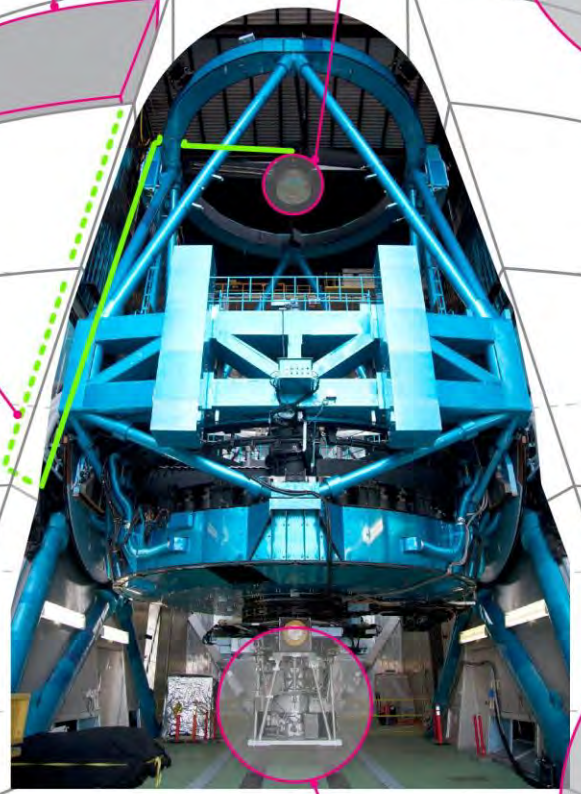
All 12 spectrographs installed by the end of this year

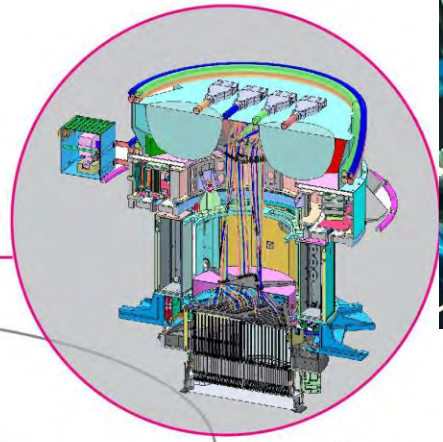


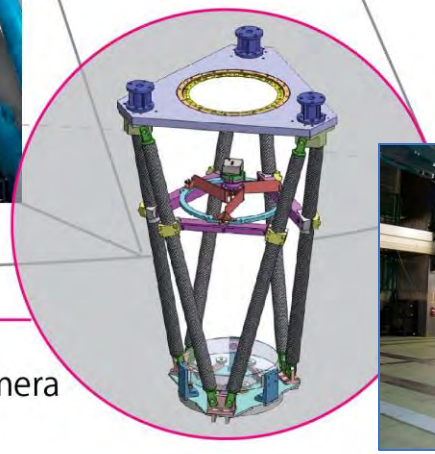


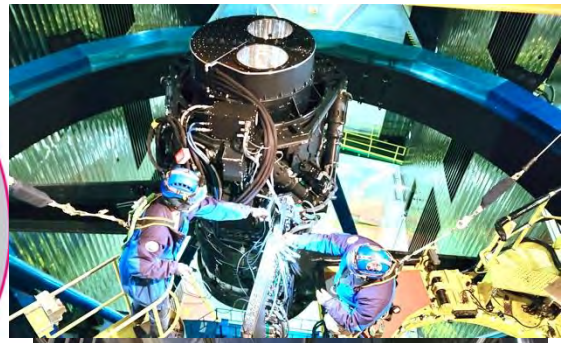




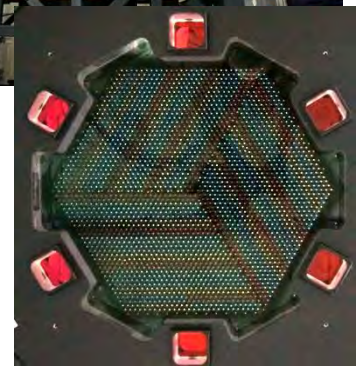






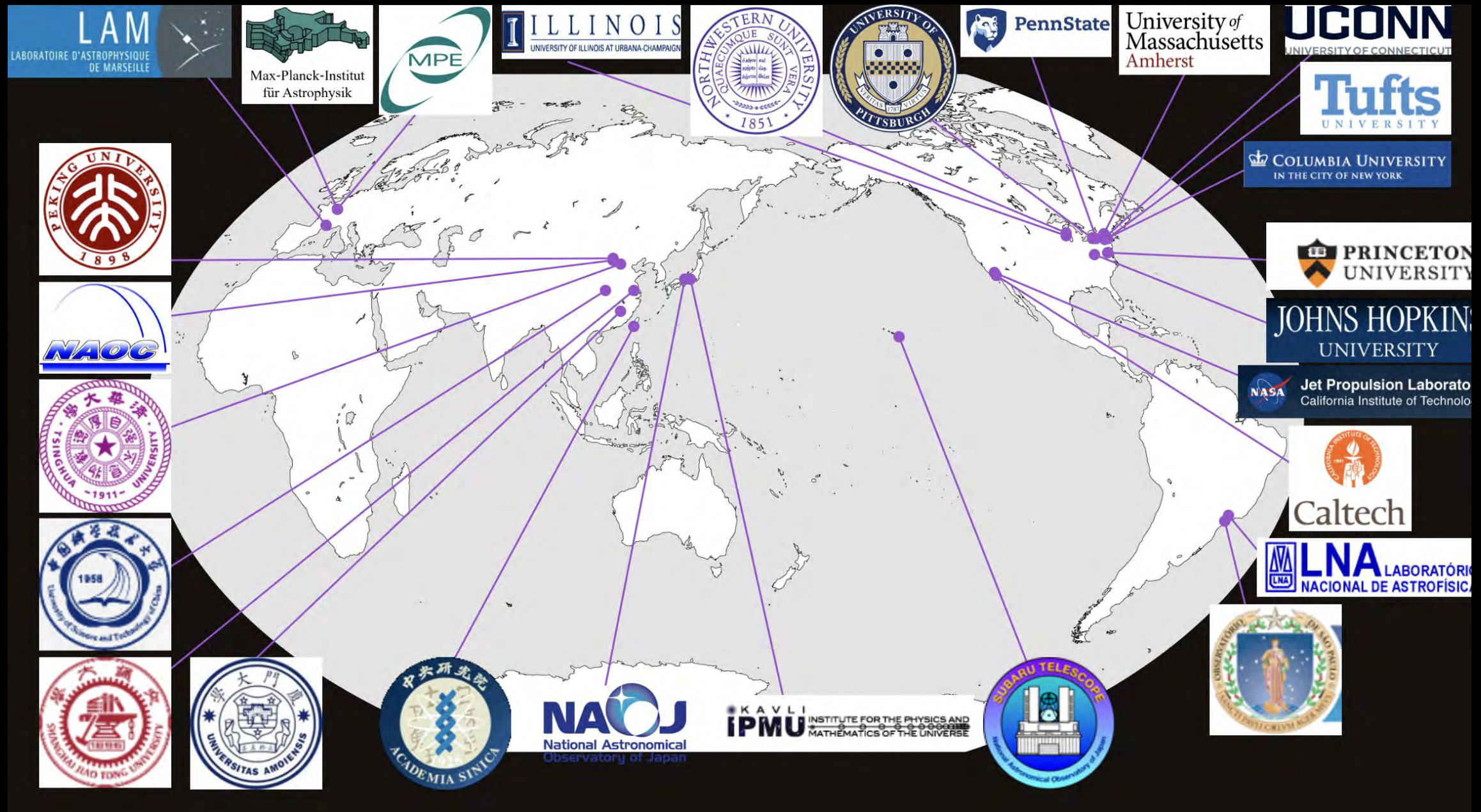








PFS collaboration = Opportunities for collaboration & networking





The 1st PFS collaboration meeting @ Kavli IPMU, 2011



@ Tokyo, Jan 2012

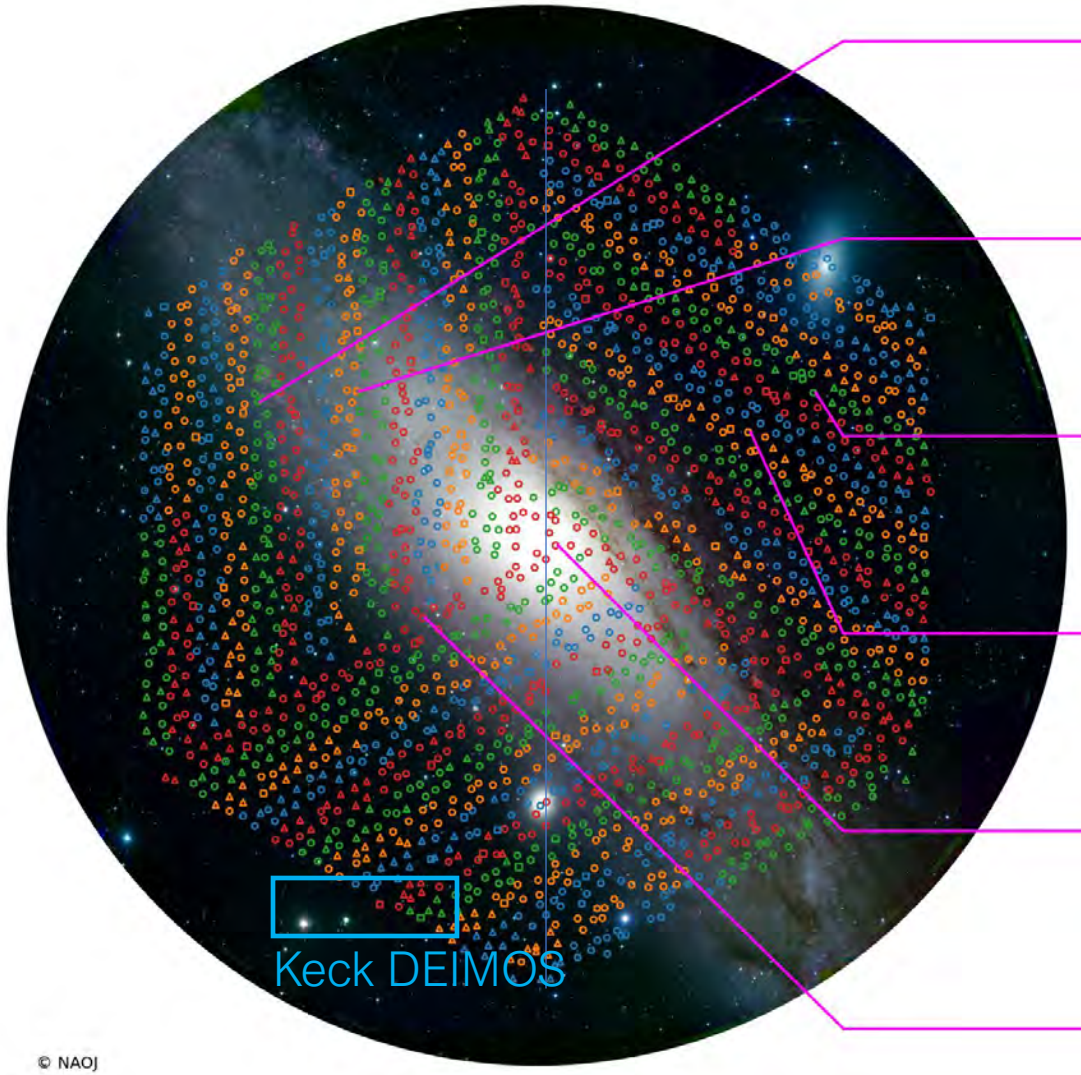


@ Kavli IPMU, Jan 2025

PFS spectroscopy-survey power > 1000 × Keck

$$(\text{tel. ap.}) \times \text{FoV} \times (\#\ \text{of spectra}) \times (\#\ \text{of each spectrum elements})$$

PFS data of M31 (updated by Robert yesterday)





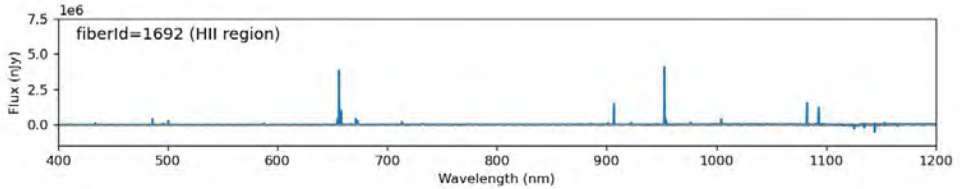


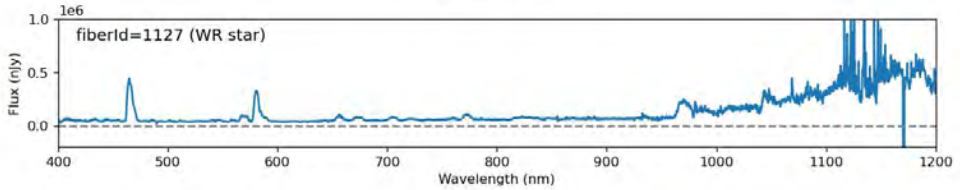


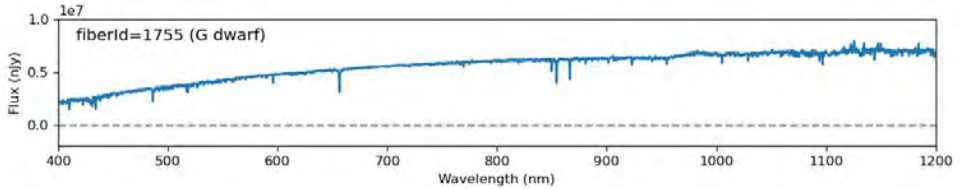


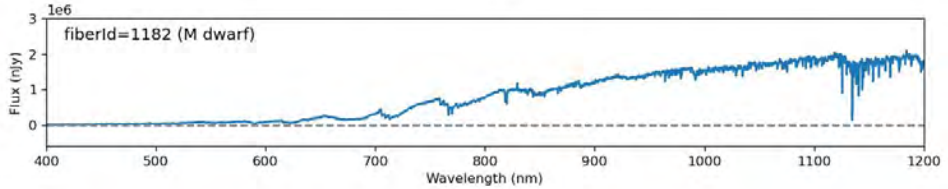


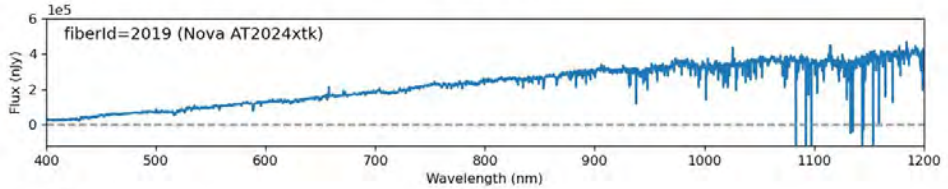


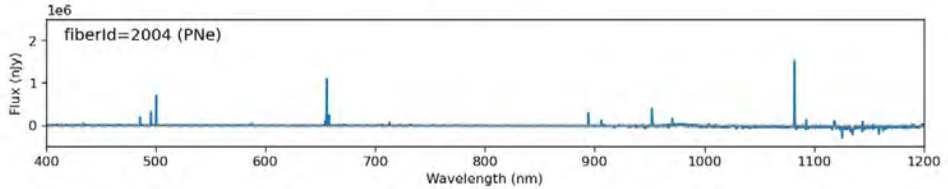












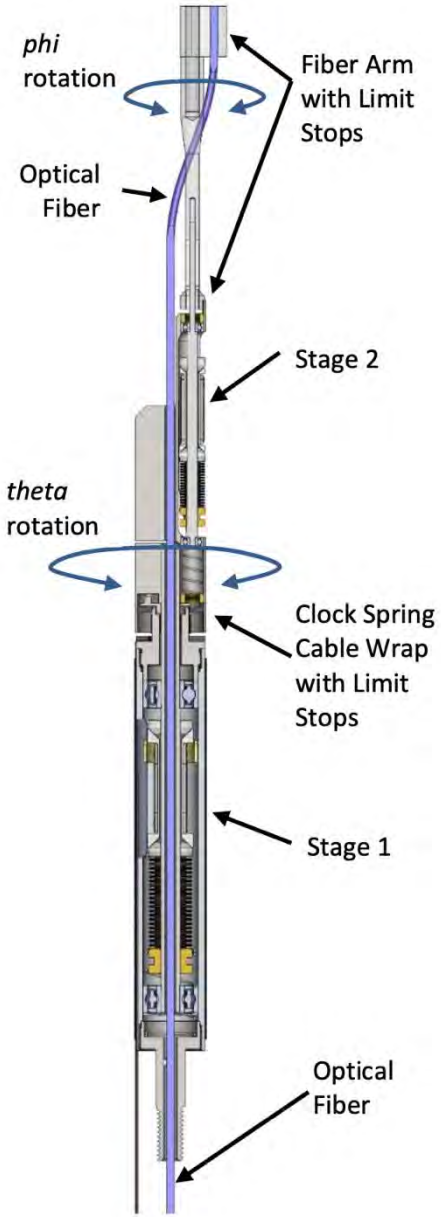
PFS instrument parameters

Prime Focus Instrument				
Field of view	~1.38 deg (hexagonal - diameter of circumscribed circle)			
Field of view area	~1.25 deg^2			
Input F number to fiber	2.8			
Fiber core diameter (1)	127 μm (1.12 arcsec at the FoV center, 1.02 arcsec at the edge)			
Positioner pitch	8 mm (90.4 arcsec at the FoV center, 82.4 arcsec at the edge)			
Positioner patrol field	9.5 mm diameter (107.4 arcsec at the FoV center, 97.9 arcsec at the edge)			
Fiber minimum separation (2)	~30 arcsec			
Fiber configuration time	~60-120 sec. [TBC]			
Number of fibers	Science fibers	Fixed fiducial fibers		
	2394	96		
Fiber density	~2000 deg^{-2} / ~0.6 $arcmin^{-2}$			
Number of A&G camera (3)	6			
Field of view of A&G camera	~5.1 $arcmin^2$ per one camera			
Sensitivity of A&G camera	r'~20.0 AB mag for S/N~30 (100) in 1 (10) sec. exposure			
Spectrograph				
Spectral arms	Blue	Red		NIR
		Low Res.	Mid. Res.	
Spectral coverage	380 - 650 nm	630 - 970 nm	710 - 885 nm	940 - 1260 nm
Dispersion	~0.7 Å/pix	~0.9 Å/pix	~0.4 Å/pix	~0.8 Å/pix
Spectral resolution	~2.1 Å	~2.7 Å	~1.6 Å	~2.4 Å
Resolving power	~2300	~3000	~5000	~4300
Spectrograph throughput (4)	~52% (@500nm)	~52% (@800nm)	~47% (@800nm)	~35% (@1100nm)

PFS compared to DESI

- Mirror size:
  8.2m vs. 4m
  (+Maunakea vs. Kitt peak)
- Fiber density:
  ~2000 deg^{-2} vs. ~600 deg^{-2}
- Wavelength coverage:
  [380,126]nm vs. [360,960]nm
- Survey start:
  2024 vs. 2021

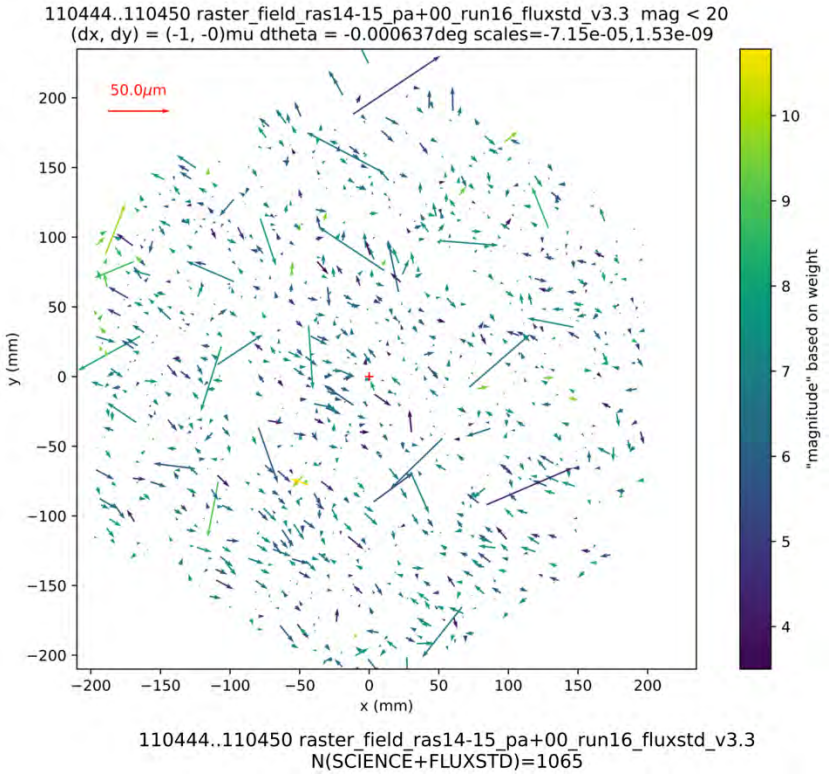
PFS fibers (cobras)

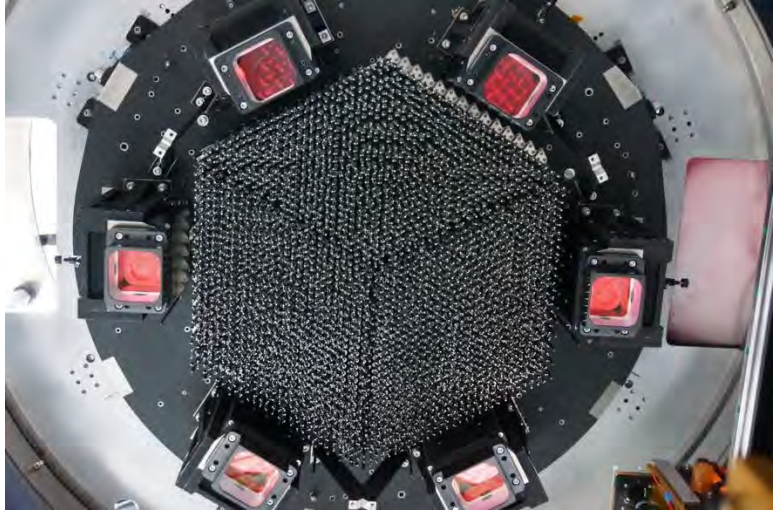


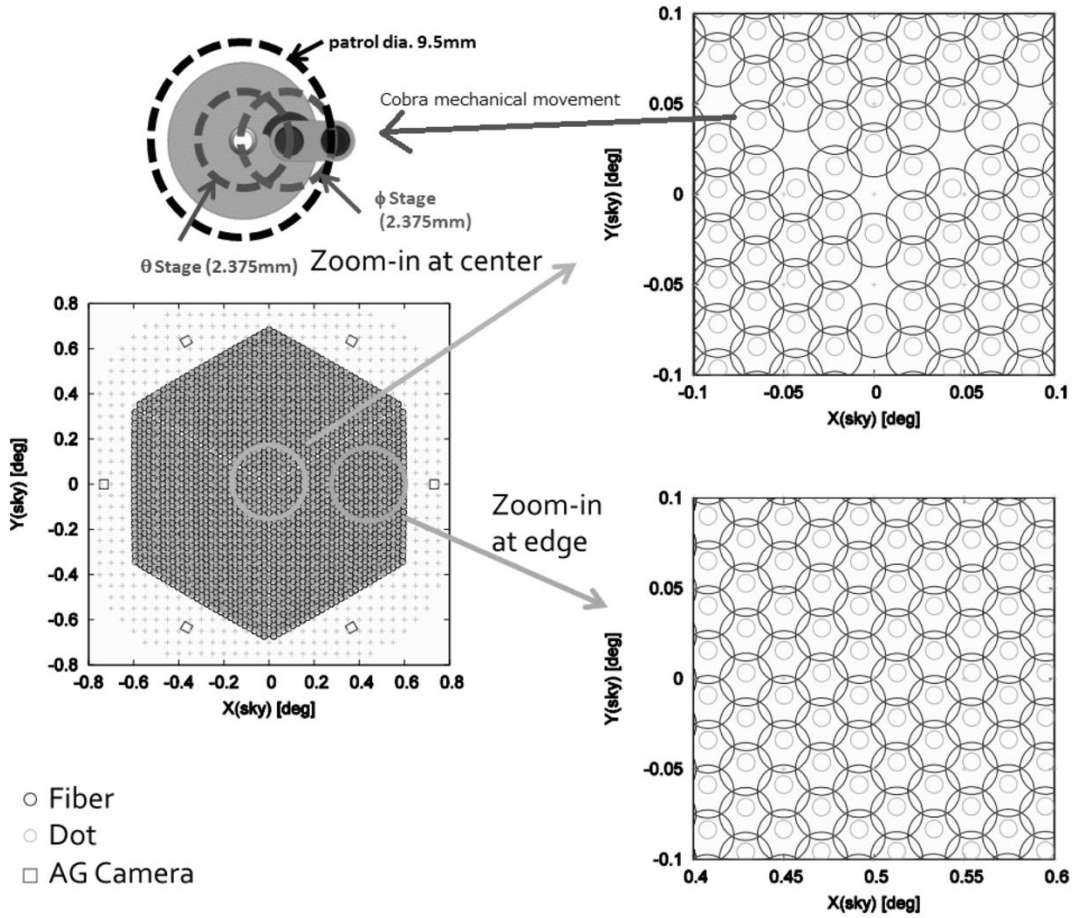
- Filling factor of fibers in PFS FoV

$$f \simeq \frac{2400 \times \pi r_{\rm fiber}^2}{\rm FoV} \simeq 0.01\%$$

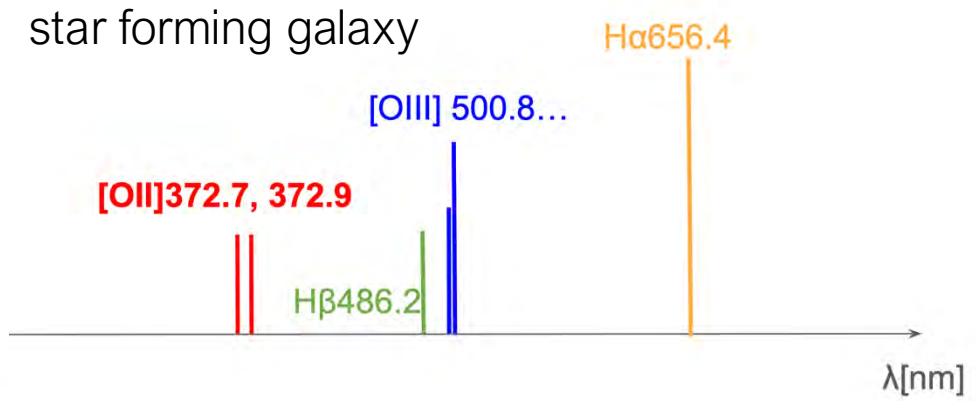
- Achieved a positioning precision of ~20μm (~0.2arcsec) for each cobra

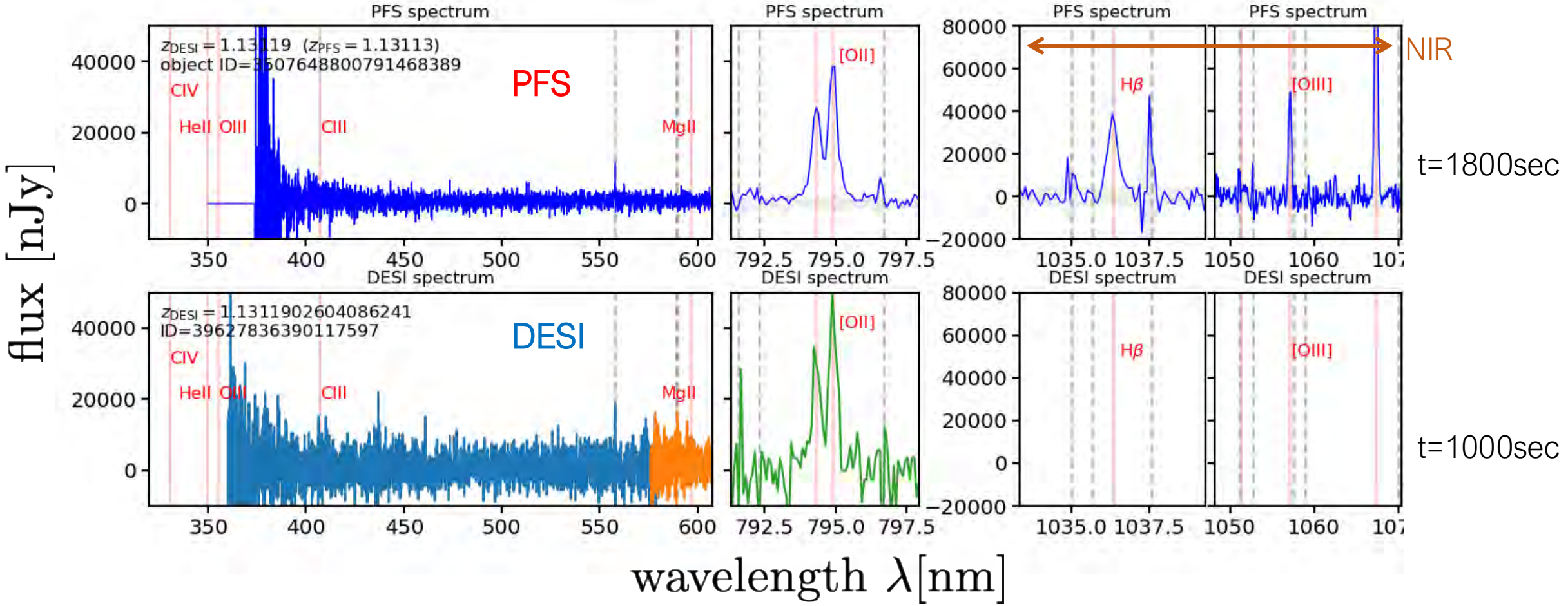






PFS spectrum vs. DESI spectrum (we have 1.6K matched galaxies)





summary

- The 8.2m Subaru Telescope remains one of the most powerful facilities in the world, especially for survey astronomy/cosmology enabled by the strategic HSC and PFS (initially started around 2003, by Subaru Director, Satoshi Miyazaki-san)
- A strong cosmology community has now been established in Japan – multiple-generations of scientists and a strong international network
- The high-quality HSC data, in both depth and in superb image quality, have enabled the stringent test of the standard model, ΛCDM
- The wide-FoV, multi-object fiber-fed spectrograph, Prime Focus Spectrograph (PFS), is finally in operation, after more than 15-years of construction
- The 360-night PFS program was approved to carry out cutting-edge studies of cosmology, galaxy evolution and Galactic archaeology