Cosmology with Subaru HSC and PFS

Masahiro Takada (Kavli IPMU)

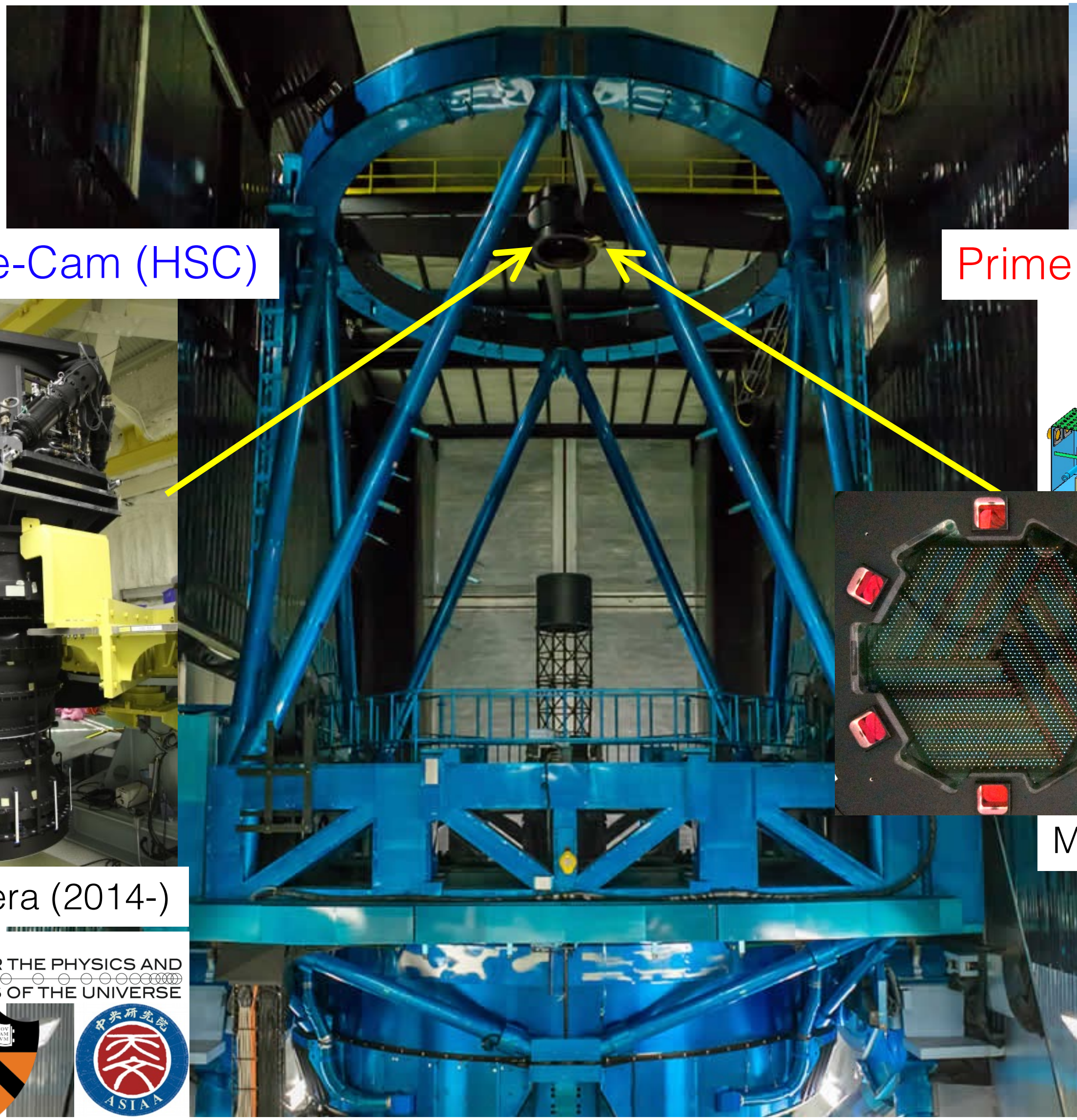
On behalf of Subaru HSC and PFS collaborations

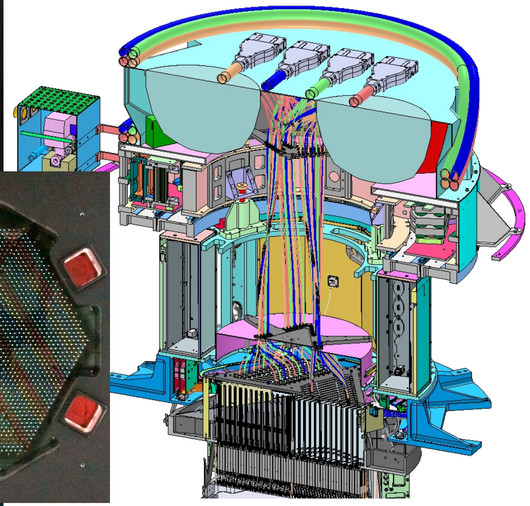
Subaru Telescope

- Large aperture (8.2m)
- Wide field-of-view (1.5 deg. diameter)
- Excellent image quality (~0.6 arcsec)
- HSC and PFS are powerful instruments for wide-area surveys (for HSC, it is so before LSST, but still unique for the northern hemisphere)

Hyper Suprime-Cam (HSC)

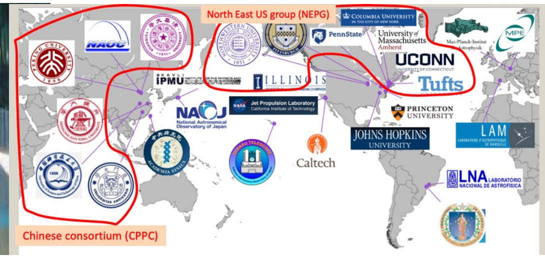
Prime Focus Spectrograph (PFS)





Imaging camera (2014-)

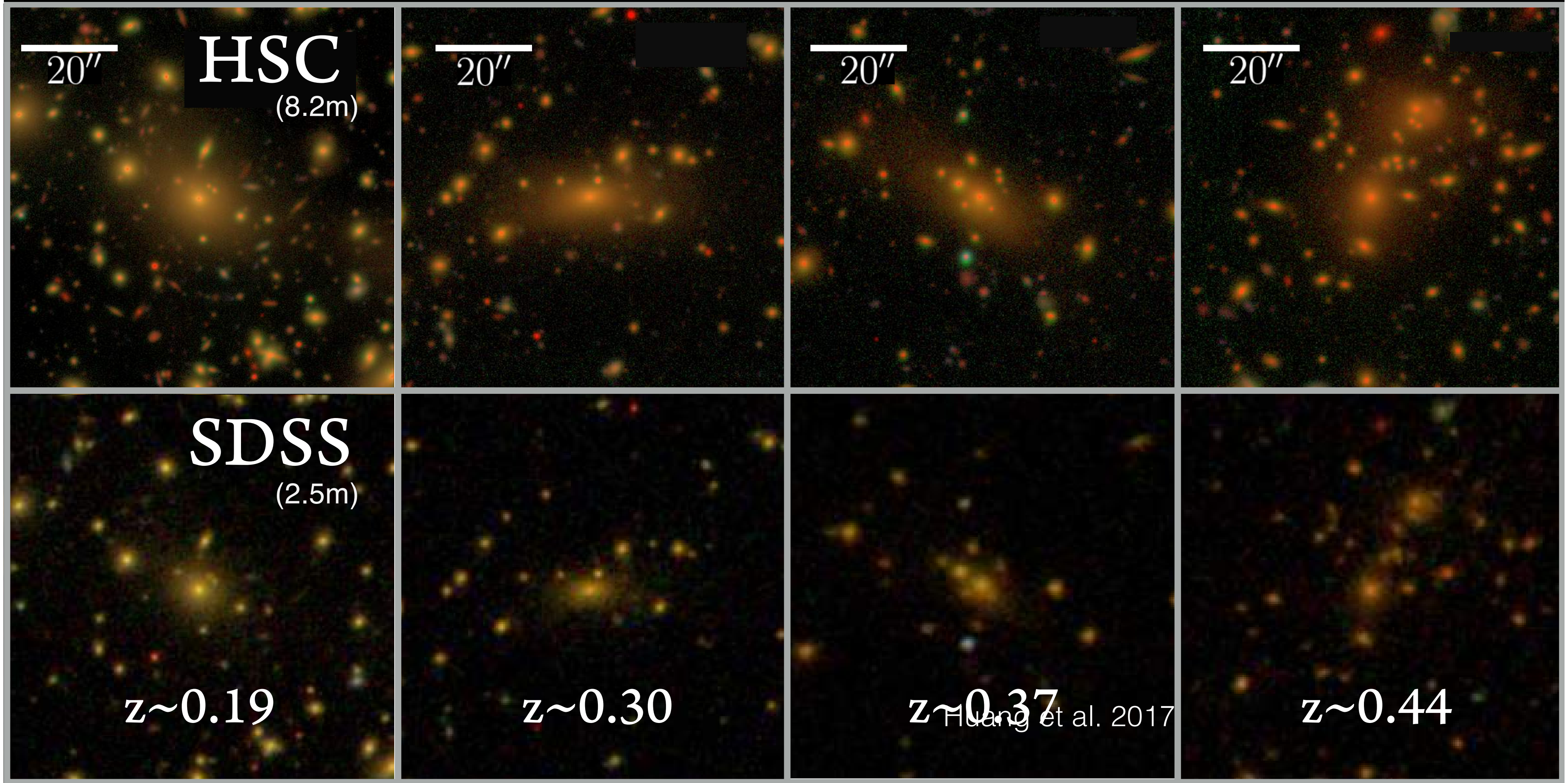
Multi-object spectrograph (2024-)



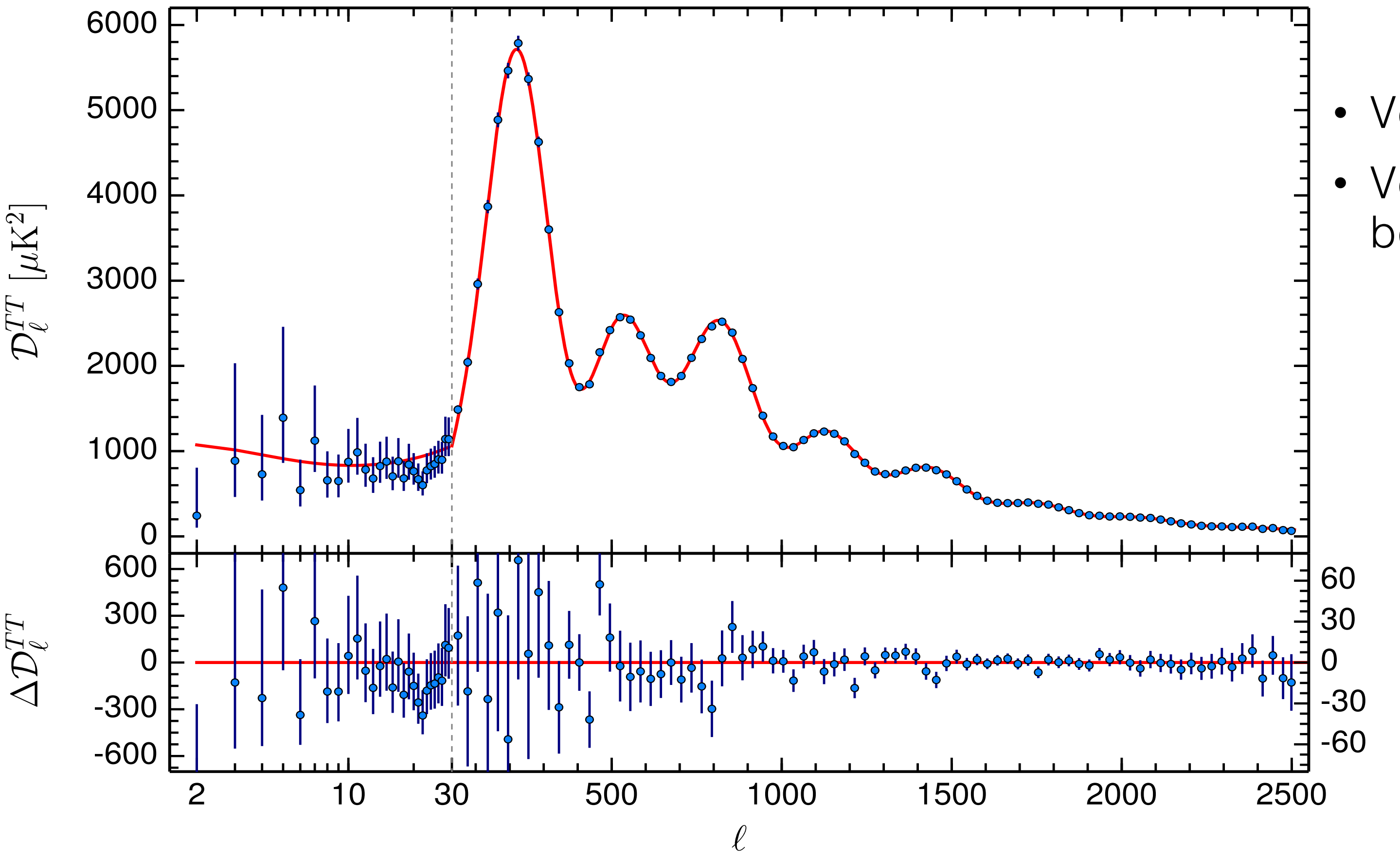
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

NAOJ

ASIAA

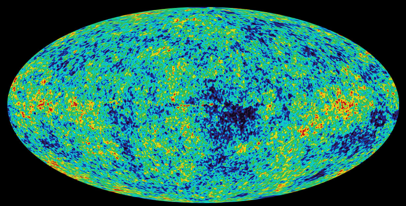

20″
HSC
(8.2m)
20″
20″
20″
SDSS
(2.5m)
z~0.19
z~0.30
z~0.37
Huang et al. 2017
z~0.44

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



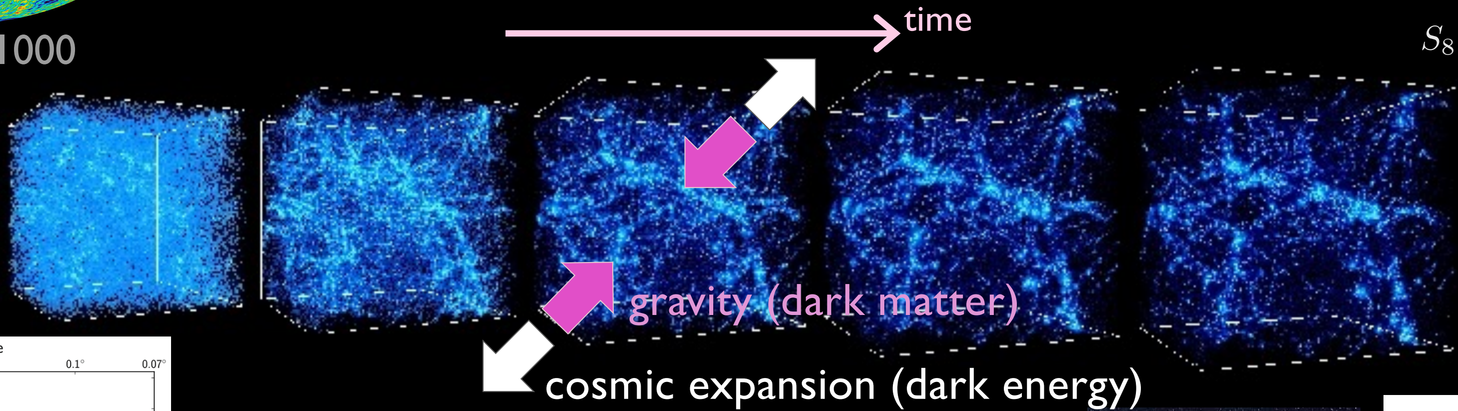
CMB at z~1000

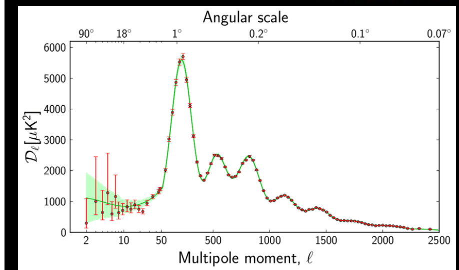
ΛCDM extrapolation

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

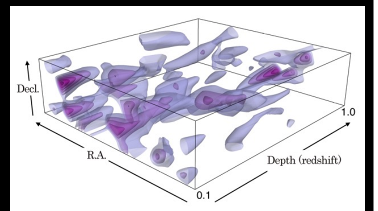
$S_8^{\rm CMB}(z\sim 0)$

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





ΛCDM=~6 parameters



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

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

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 LambdaCDM model:

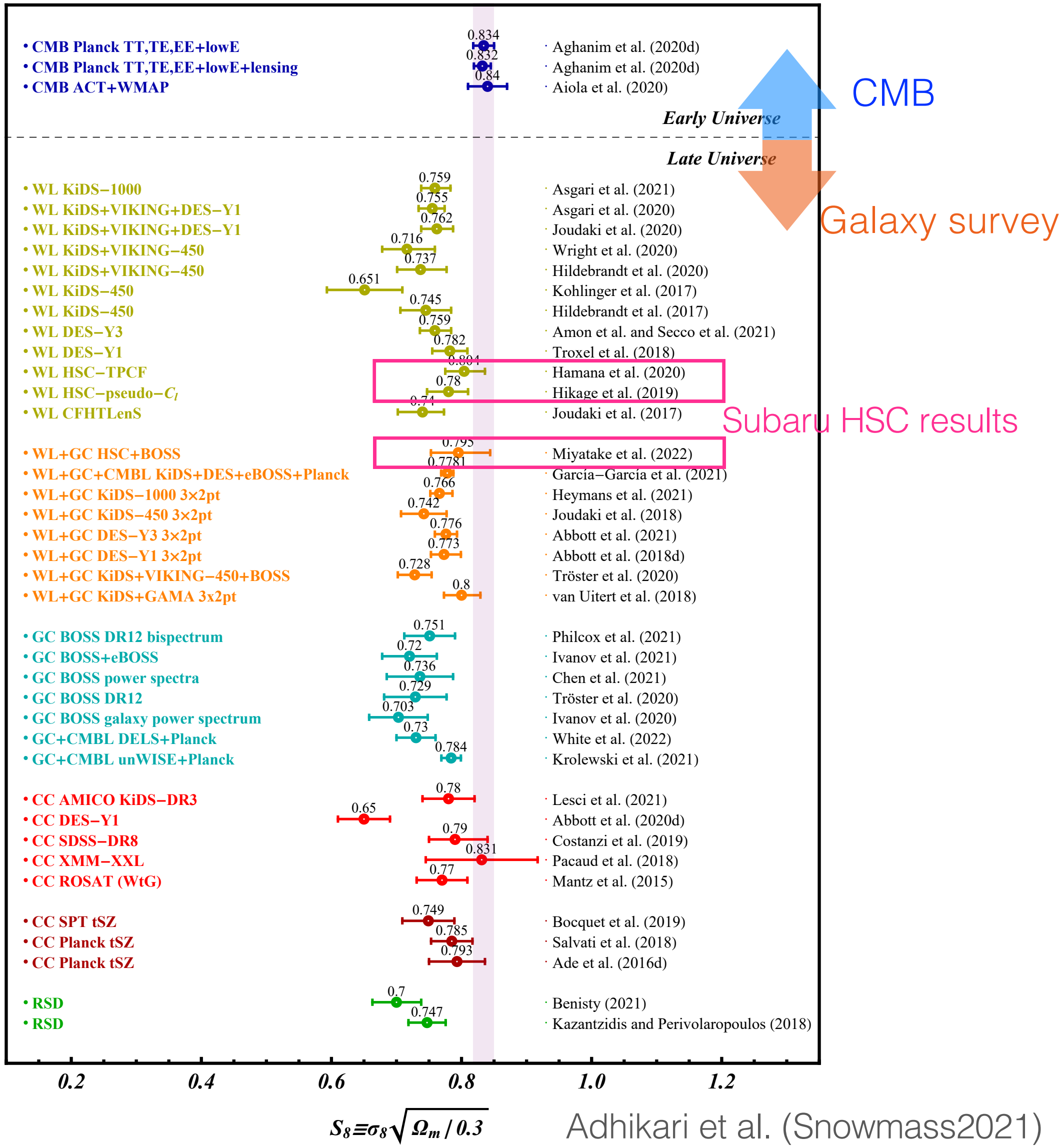
$$\sigma_8^{\rm CMB} \simeq 0.83\left(\frac{A_{\rm s}}{2.2\times 10^{-9}}\right)^{1/2}\left(\frac{\Omega_{\rm m}}{0.31}\right)^{0.24}\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)^{1/3}\left(\frac{\Omega_{\rm m}h^2}{0.14}\right)^{0.56}\left(\frac{h}{0.68}\right)^{0.69}$$

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

S8-tension

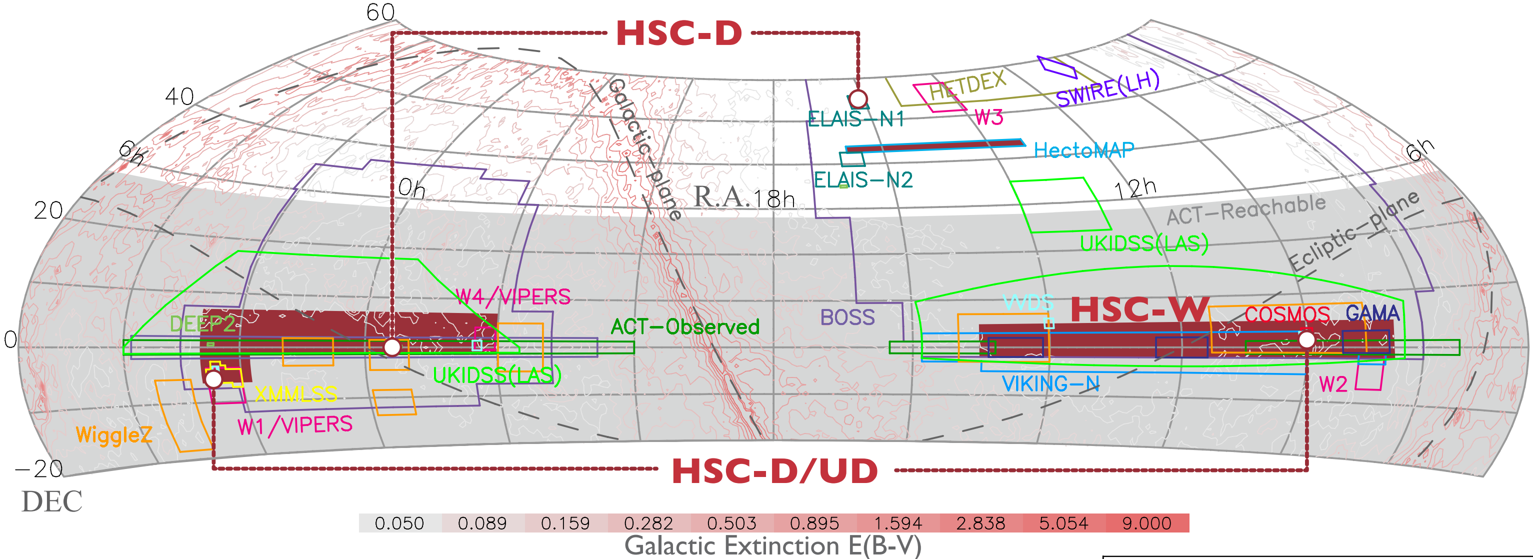
$$S_8 \equiv \sigma_8 \left(\frac{\Omega_\mathrm{m}}{0.3} \right)^{0.5}$$

- 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?
- Extensively discussed in P5 (Chair: Hitoshi Murayama)

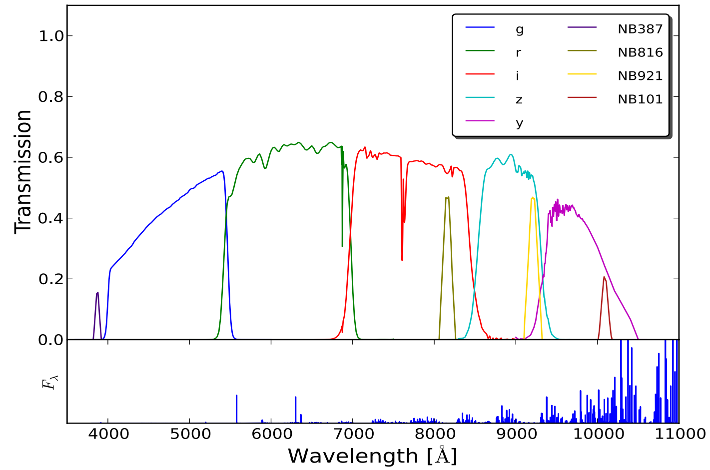


Adhikari et al. (Snowmass2021)

Subaru-Wide Survey (2014-2021)

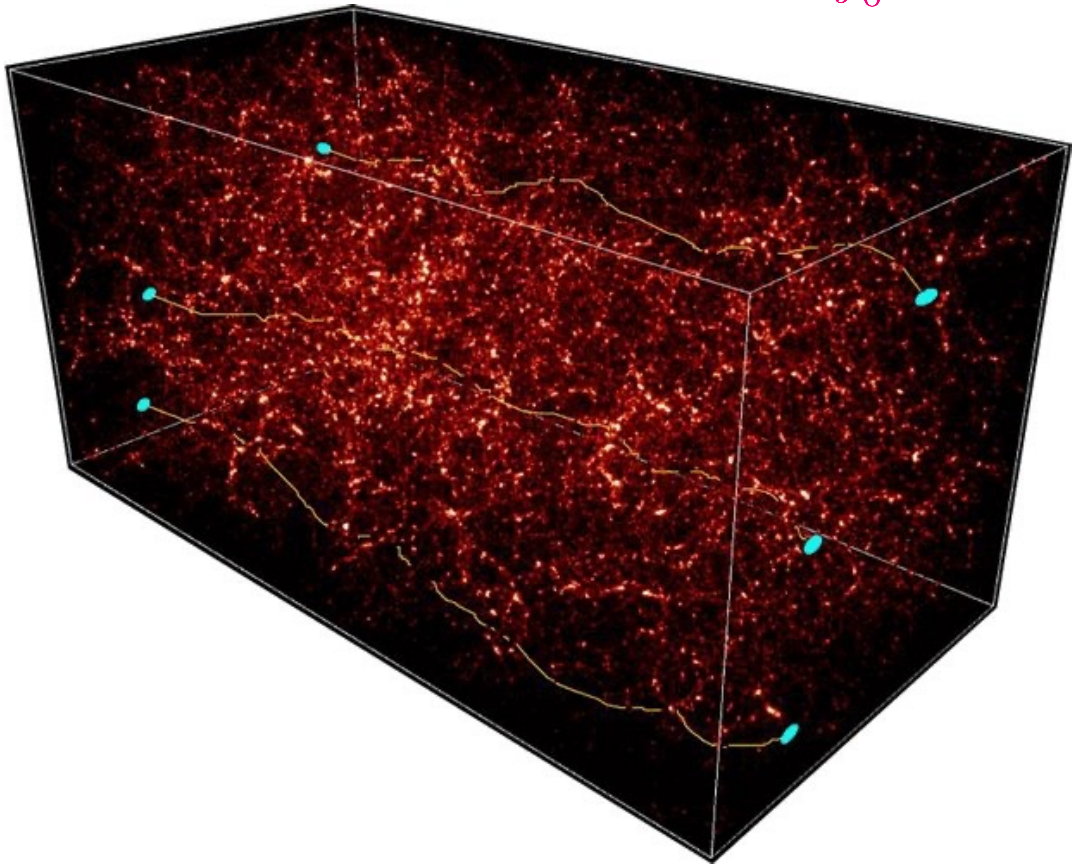


- HSC: 2014 – 2021 (HSC imaging done)
- HSC cosmology survey (i~26, grizy, ~1100 deg^2)
  - Weak lensing
- PFS cosmology survey (2024 -)
  - BAO, redshift-space distortion



Weak gravitational lensing – a probe of dark matter distribution

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



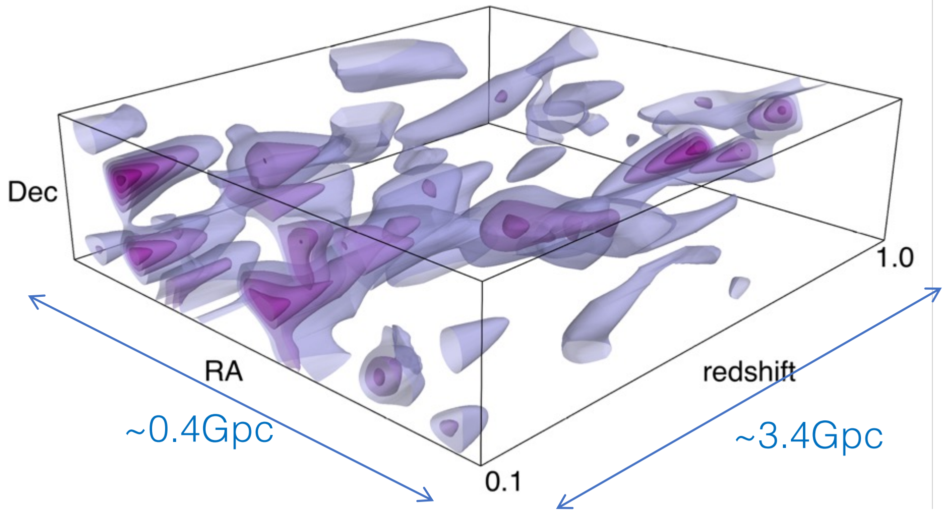
- An image of distant galaxy is distorted
- Lensing distortion (=ellipticity) is a tiny effect ~ 1% in ellipticity amplitude
- If observed, it can probe the matter fluctuation field along the line-of-sight direction – a powerful way to probe DM distribution
- High-quality image like that of Subaru is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

Galaxies form where dark matter clusters

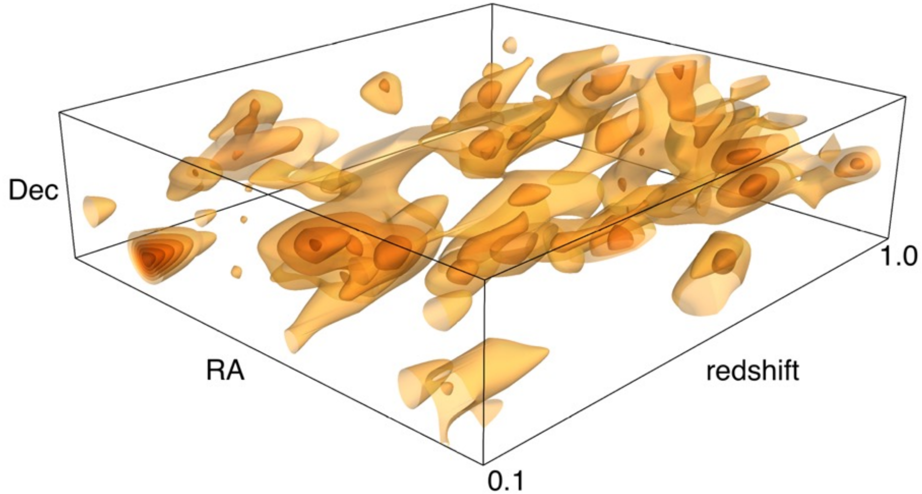
Jim Peebles (Nobel Prize: 2019)
Theory of structure formation

Oguri et al. 2018

"Observed" matter (mainly DM) distribution from HSC data



Observed galaxy distribution



A qualitative confirmation of ΛCDM structure formation scenario

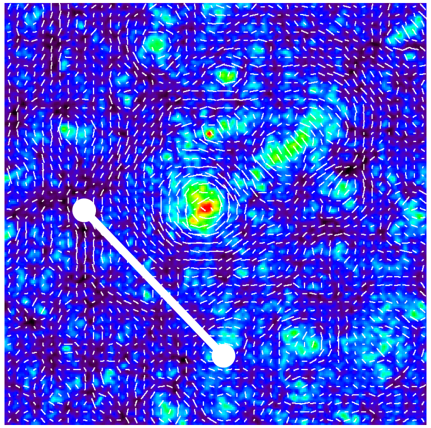
Cosmology inference: A test of ΛCDM model

- Bayesian inference

posterior likelihood prior

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

parameters data



- 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 covariance

data

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

covariance

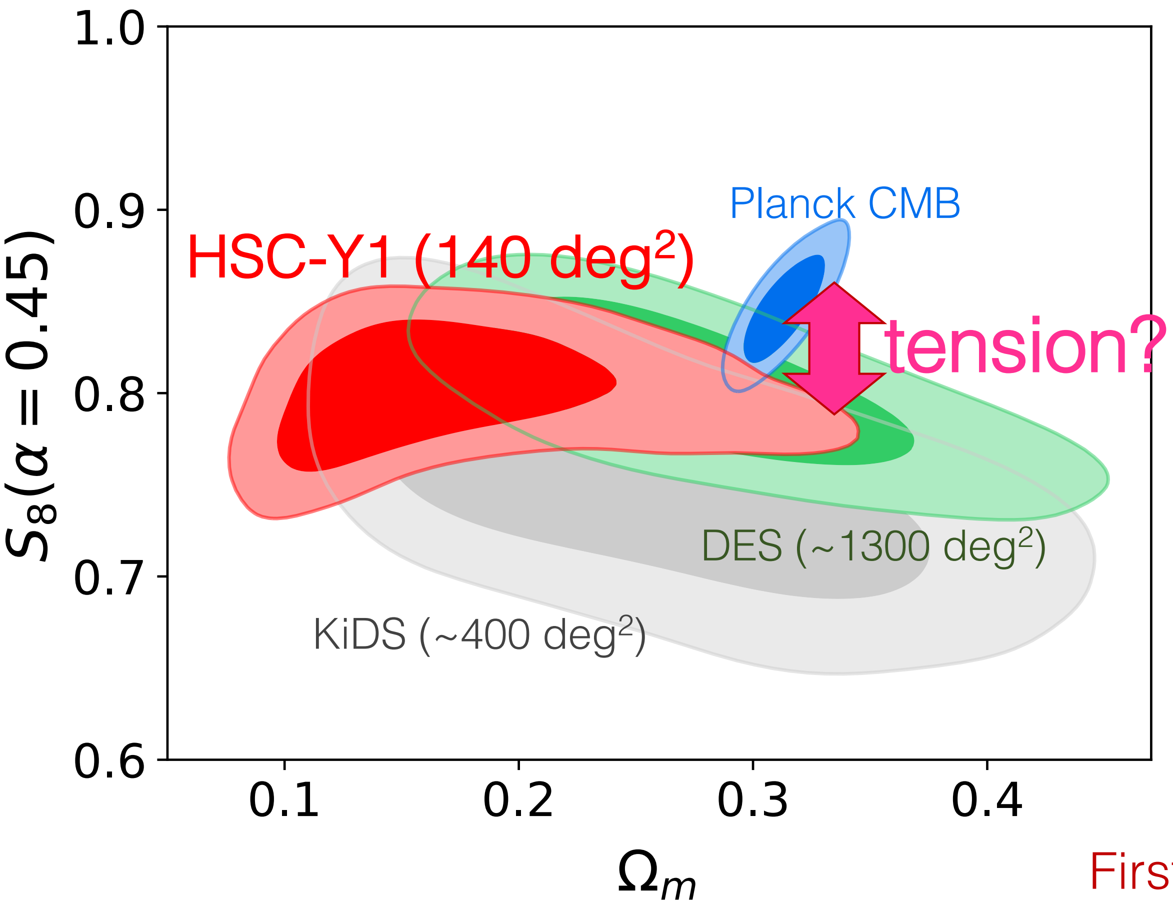
- Sample variance
- Mock catalogs/data

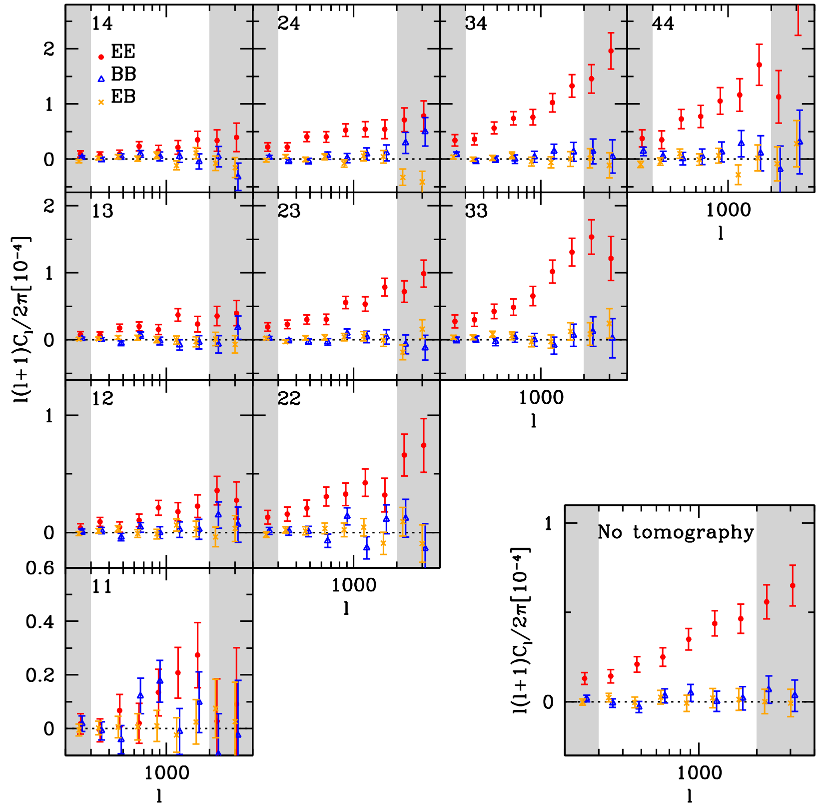
model

- 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-Year 1 cosmology result: Hikage+19

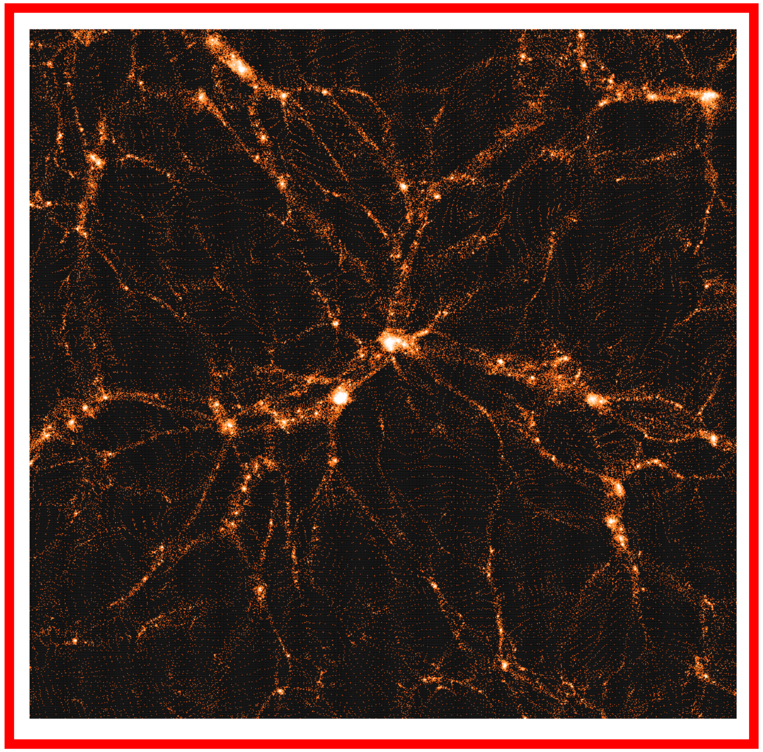




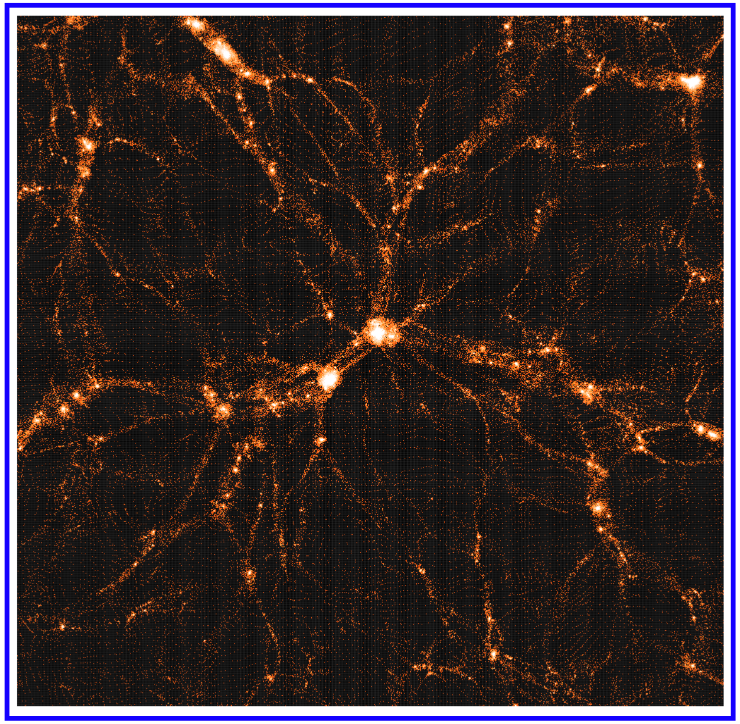
First Japan-led cosmology result!

Precision cosmology era

LSS probe (inc. HSC) preferred ΛCDM



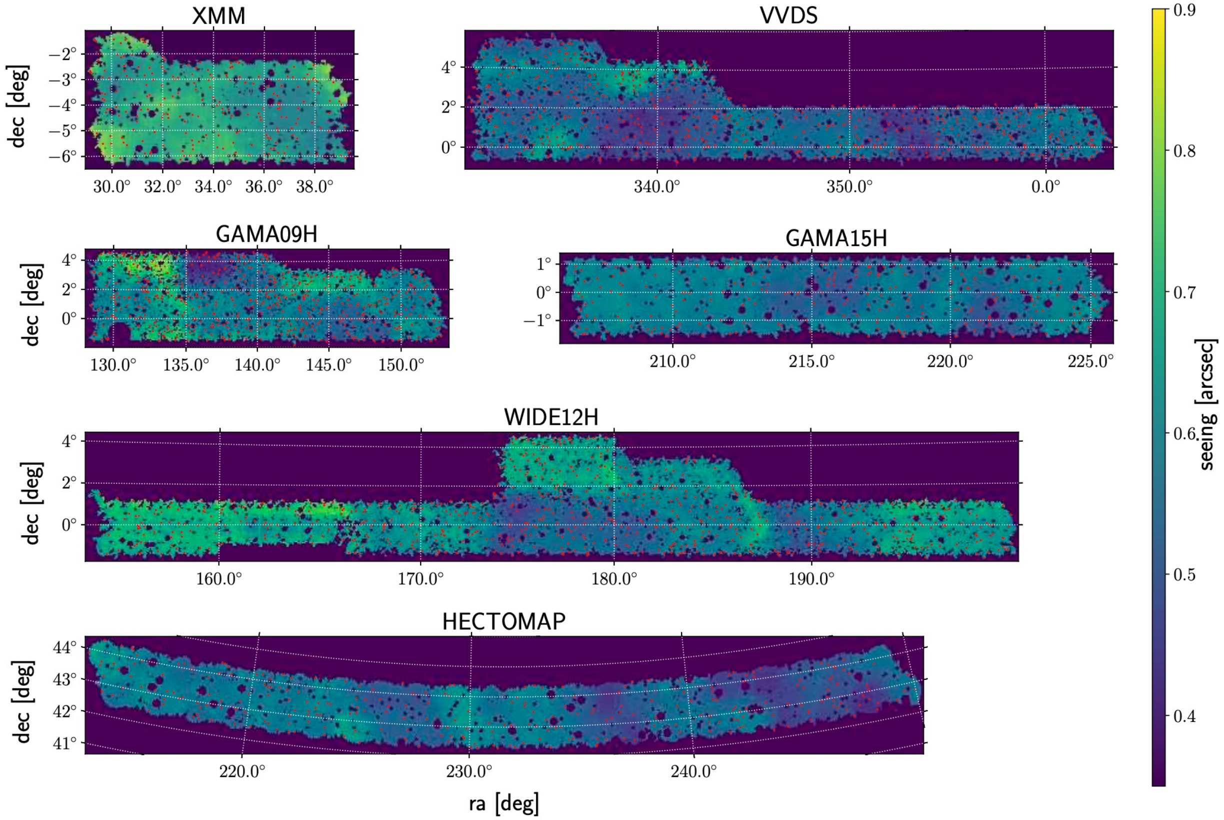
Planck CMB preferred ΛCDM



N-body simulations starting from the same initial seeds

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.]
- Used the sophisticated simulated data (using HST) for the calibration



X. Li
(IPMU⇒CMU)

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

HSC-Y3 blind cosmology analysis

- Being led by junior scientists in the international team (Japan, US, ..)
  - 4 cosmology analyses using the different methods and different parts of HSC data
- Two-tier blind analyses
  - Purpose: to avoid “confirmation bias”; e.g. reluctantly stop systematic tests/code debugging when the results accidentally look consistent with foreseen results such as Planck CMB
  - Catalog level: The analysis team must analyze the 3 catalogs that differ in terms of the multiplicative shear amplitude: $|\Delta\gamma|=0.05, 0.1 \sim |\Delta S8|$. One is the true catalog, but the team does not know which one is real
  - Analysis level: (i) any plot hides the value of cosmological parameters, (ii) the team is not allowed to compare the HSC result with external results (Planck), before unblinding
- Once the validation tests of methods and model and the internal consistency tests are passed, the results are “unblinded” if the collaboration agrees
  - The team promises that the unblinded results would be published regardless of the outcome
  - The analysis method cannot be changed or modified after unblinding
  - Sunao Sugiyama unblinded the results of his-led project on Dec 3, 2022 (2 weeks before the submission of his PhD thesis to U. Tokyo)

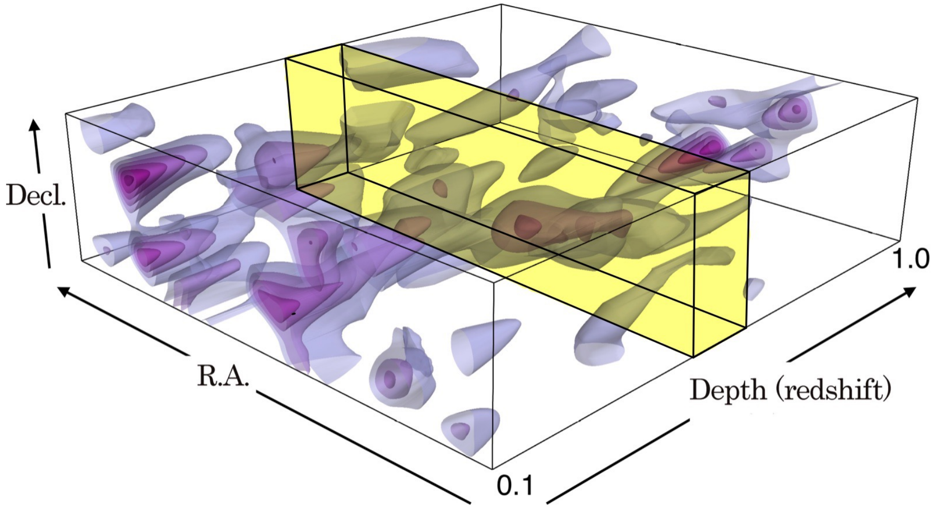
Sunao Sugiyama
(Kavli IPMU)

Xiangchong Li
(IPMU⇒CMU)

Roohi Dalal
(Princeton)

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

$$\gamma(\boldsymbol{\theta}; z_s) \sim \int_0^{z_s} \mathrm{d}\chi \, W(\chi, \chi_\mathrm{s}) \delta_\mathrm{m}(\chi, \chi\boldsymbol{\theta})$$

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

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

$\delta_\mathrm{g}(\mathbf{x}, z_l)$ SDSS spectroscopic galaxies

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

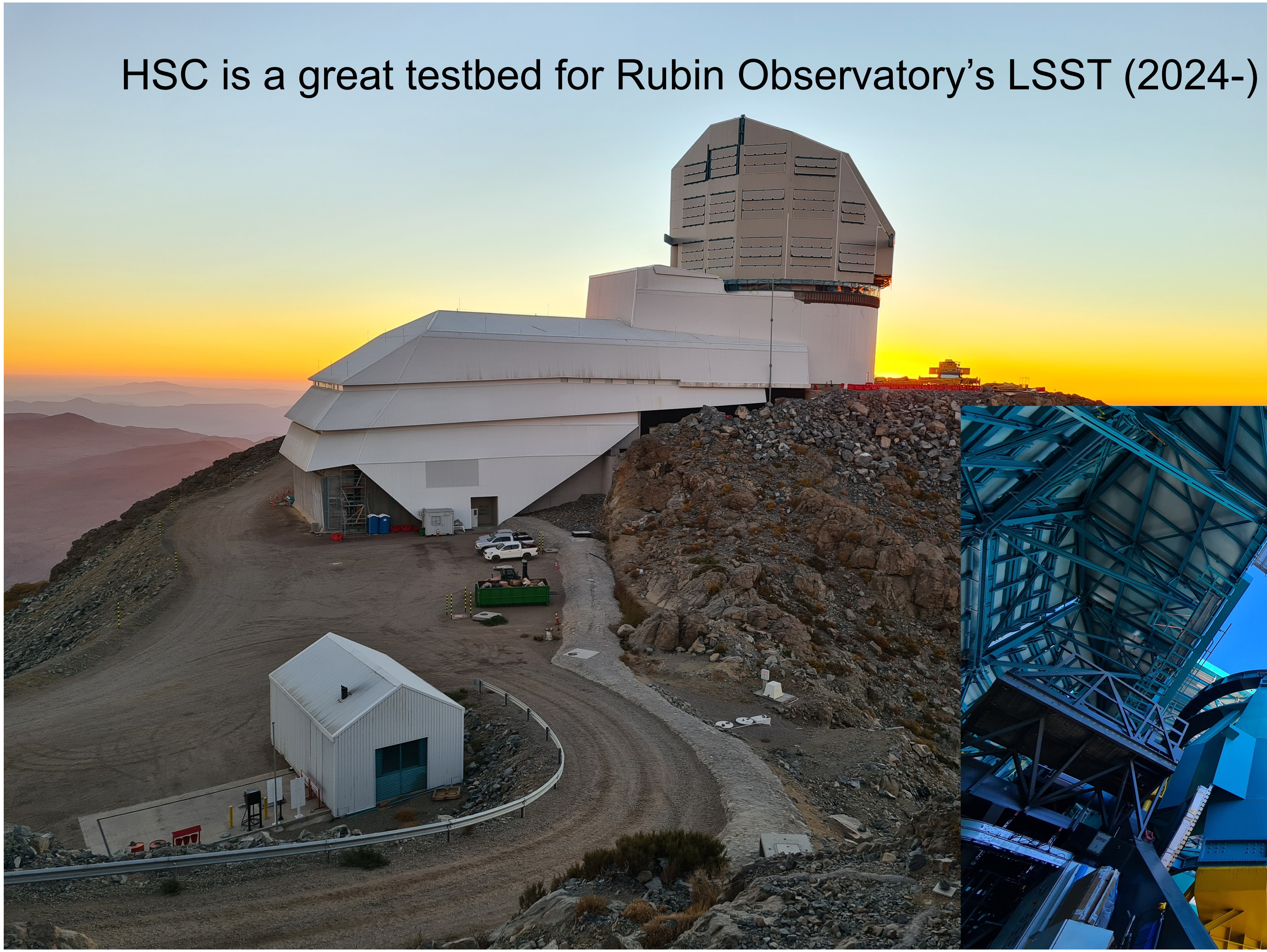
- This method statistically allows for calibration of photo-z errors

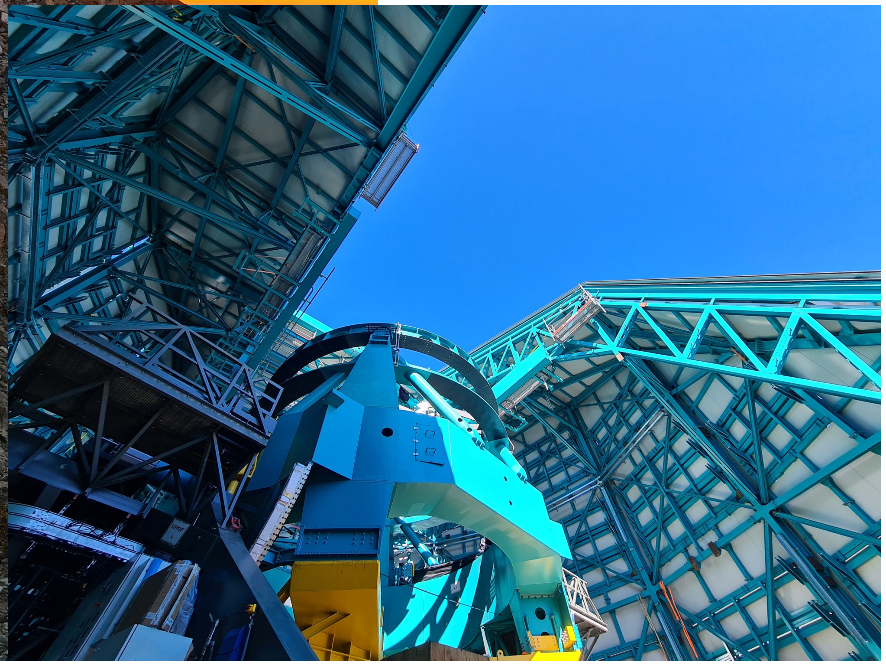
Announcement of HSC Year 3 Cosmology Results

- We will soon post a series of the papers presenting the HSC-Y3 cosmology results
- Junior scientists, including Dr. Sunao Sugiyama (Kavli IPMU, just graduated), played major roles in these works
- Webinar
  - 12am on April 4 (Tue) (the mid night of April 3) in JST
  - 11am on April 3 (Mon) in EDT – 8am on April 3 (Mon) in PDT
  - 5pm on April 3 (Mon) in Paris
  - If you are interested in joining, please let me know (you would have received the announcement email from the mailing list, LSST, DES, KiDS, …)
- Stay tuned!

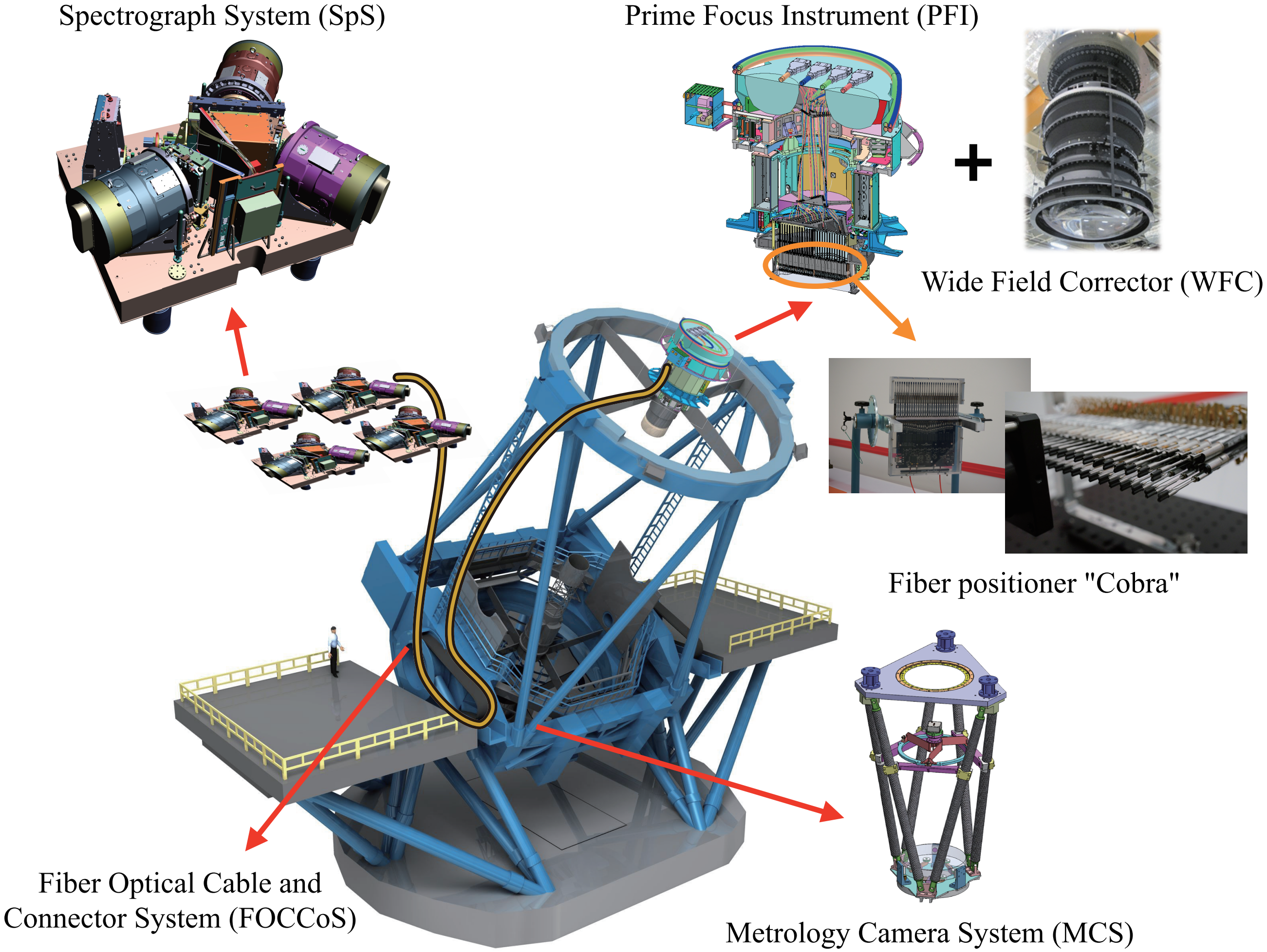
Sunao Sugiyama
(Kavli IPMU⇒UPenn)

HSC is a great testbed for Rubin Observatory's LSST (2024-)



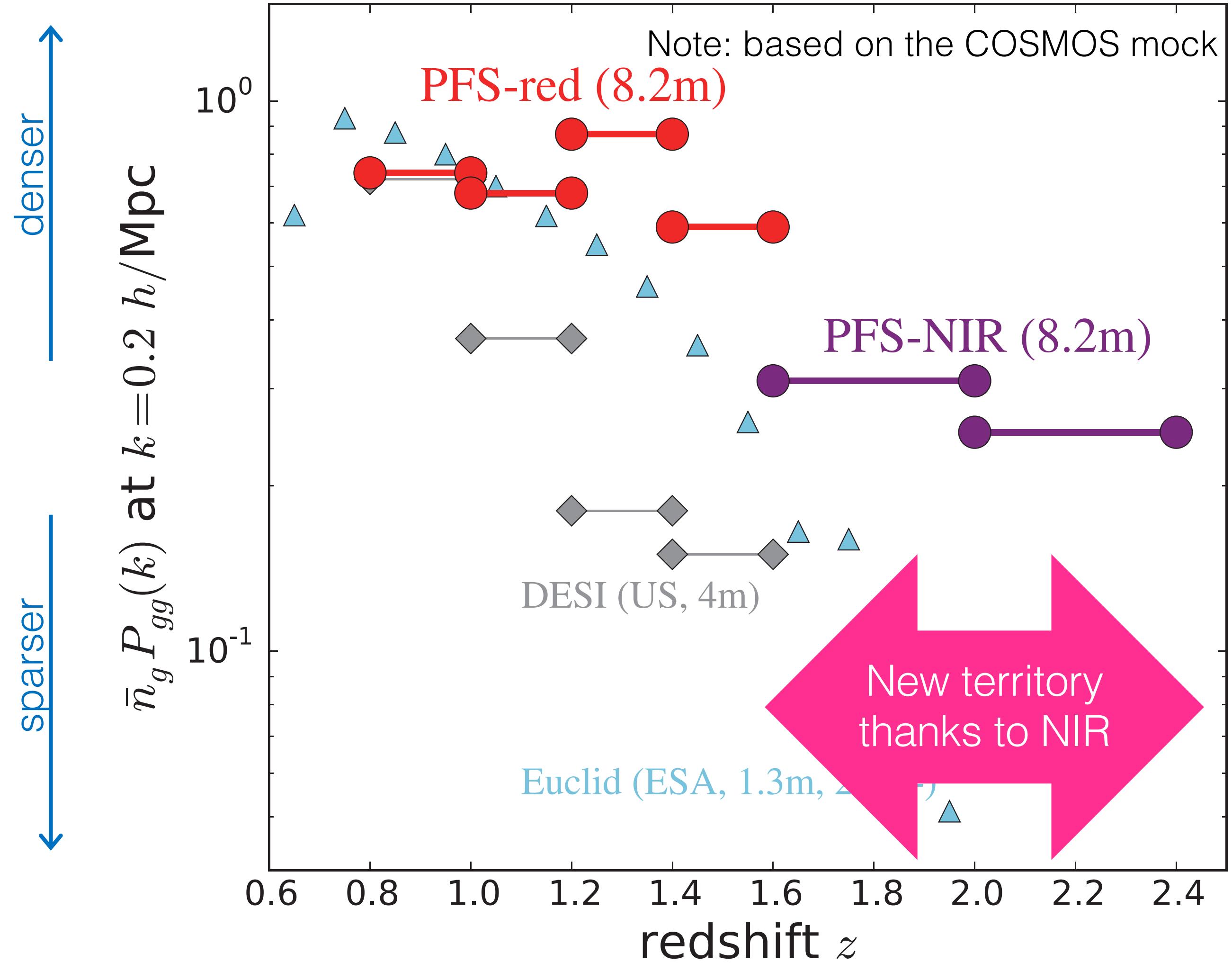


Subaru Prime Focus Spectrograph (see Naoyuki's talk)

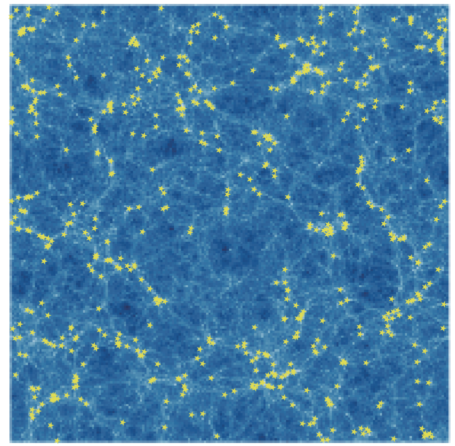


- ~$90M project, being led by Kavli IPMU (PI: Hitoshi Murayama, PM: Naoyuki Tamura, PS: MT)
- Institutes in 6 countries are involved (US, France, Taiwan, Brazil, Germany, China)
- Mentioned in several places of US Astro2020
- 2400 fibers, wide field-of-view, 8.2m collecting power
- We will start our large-scale surveys, from early **2024**
- PFS blog: https://pfs.ipmu.jp/blog/ja/

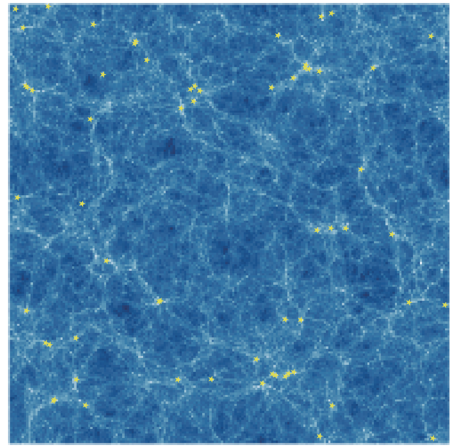
The power of 8.2m-aperture PFS



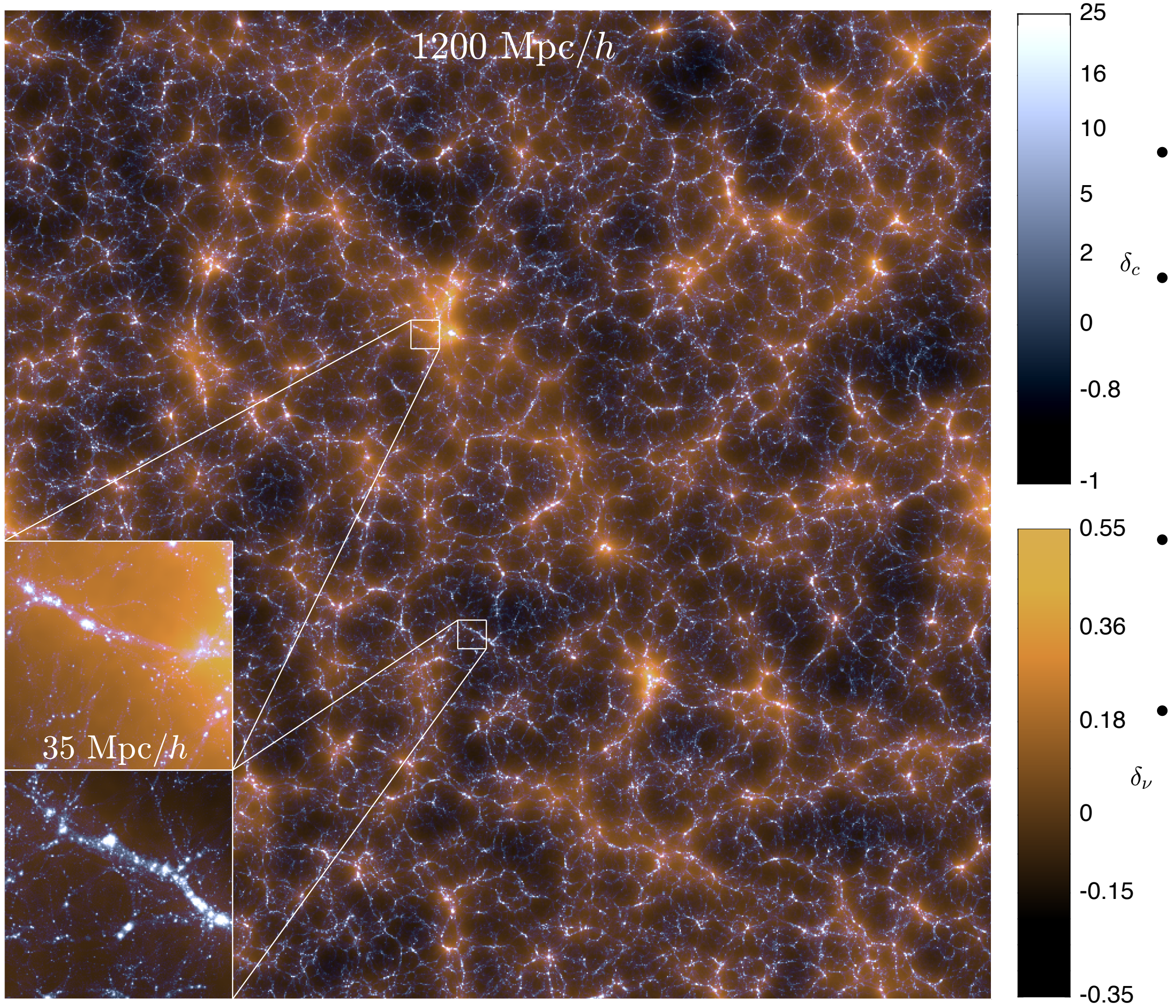
PFS (8.2m) for z~1.5 slice



4m-class tel.



Neutrinos slows down structure formation

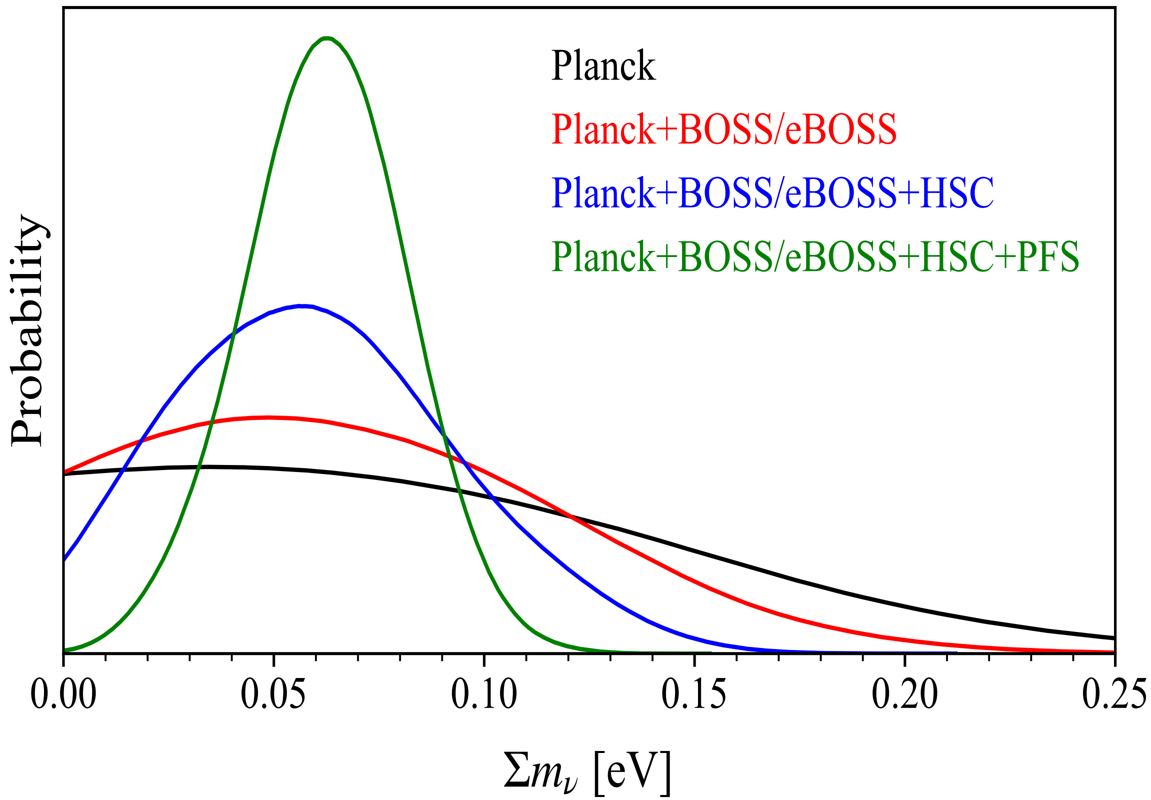


Yu+ Nature, 2017

- Neutrinos are a part of dark matter
- Neutrinos slow down structure formation (also see Saito, MT & Taruya PRL 16 for the analytical work)
- The effect on structure formation is now well understood
- Galaxy distribution can be used to explore the neutrino characteristic signature

Scientific objectives with PFS cosmology

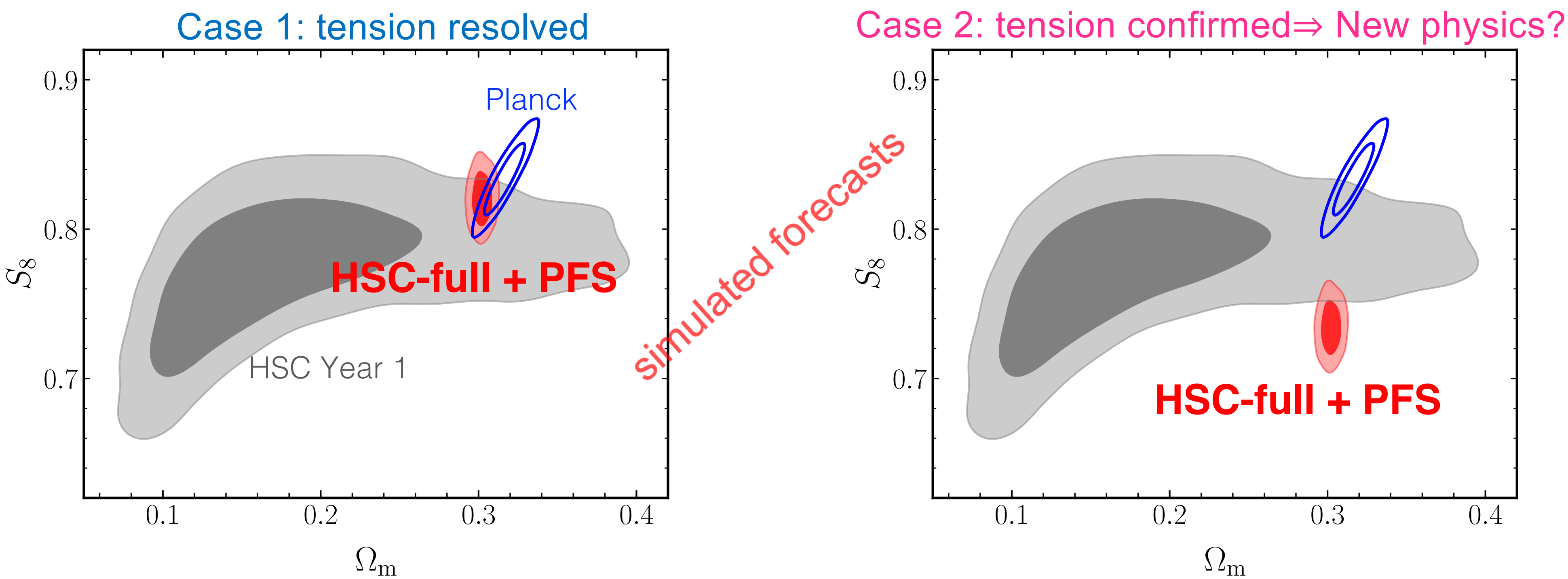
Forecast!



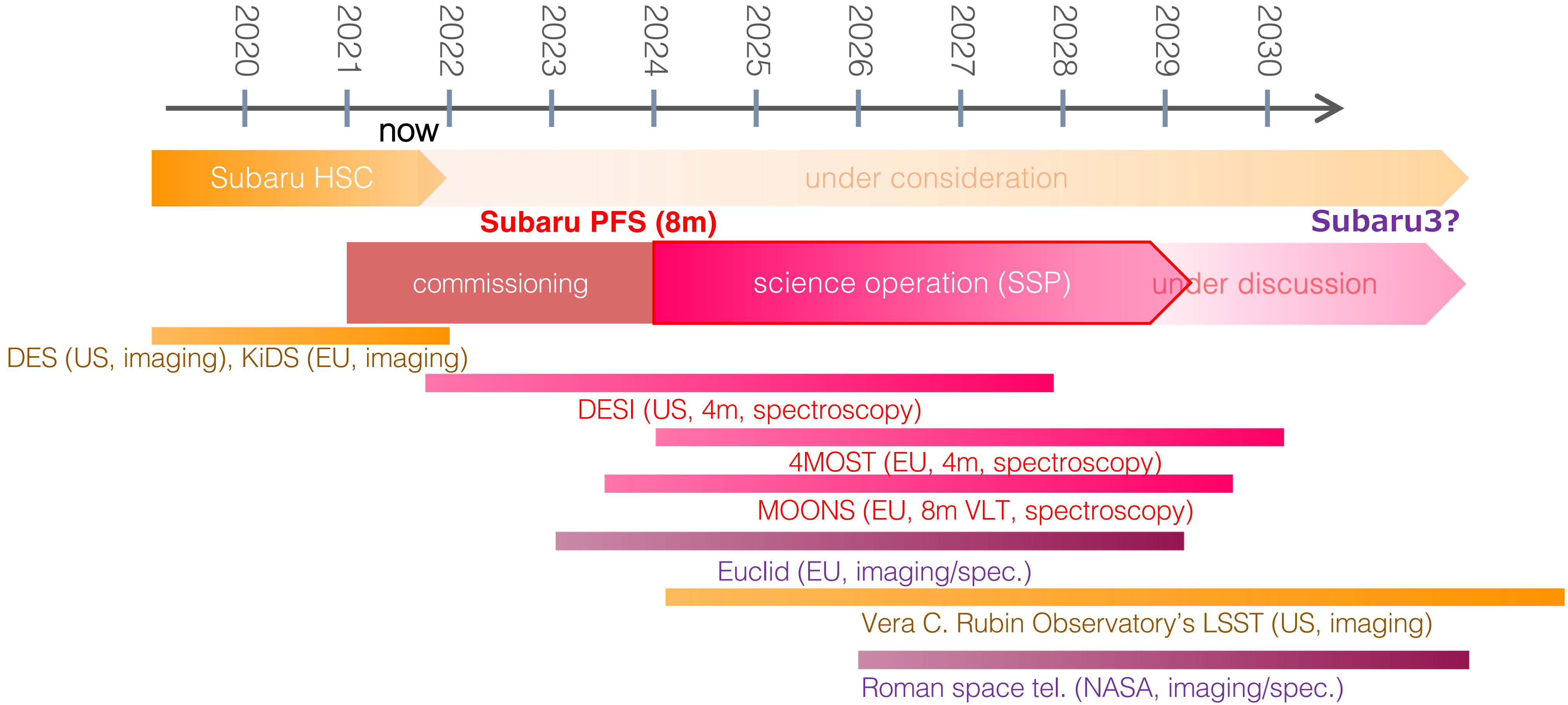
- ~100 Subaru nights, starting from 2024
- High-precision measurements of BAO and galaxy clustering
- Achieve the precision of σ(m_nu,tot)~0.02eV to weigh the sum of neutrino mass
- Dark energy …

Complementarity of HSC and PFS

- PFS spectroscopic catalog of galaxies at z>1 will be a perfect calibration data of HSC photo-z's at z>1
- PFS will not only constrain the cosmo paras, but also improve the HSC constraint



Landscapes in 2020s cosmology



Summary

- The ΛCDM framework is facing challenges: sigma8- and/or H0-tension
  - Inconsistencies between the ΛCDM models inferred from the early (CMB) and late (galaxy surveys) universe datasets
  - Systematics or New physics beyond ΛCDM model?
- Subaru Telescope is one of the most important instruments for carrying out wide-area galaxy survey cosmology – HSC/PFS
  - HSC is the first Japan-led cosmology project
  - PFS and HSC are a great combination for cosmology
- Subaru HSC Year 1 cosmology indicates the sigma8-tension
- Subaru HSC Year 3 cosmology results using a factor of 3 larger dataset than that of Year 1 will come soon (April 3)
  - Will be “robust” cosmology results!
  - Stay tunes