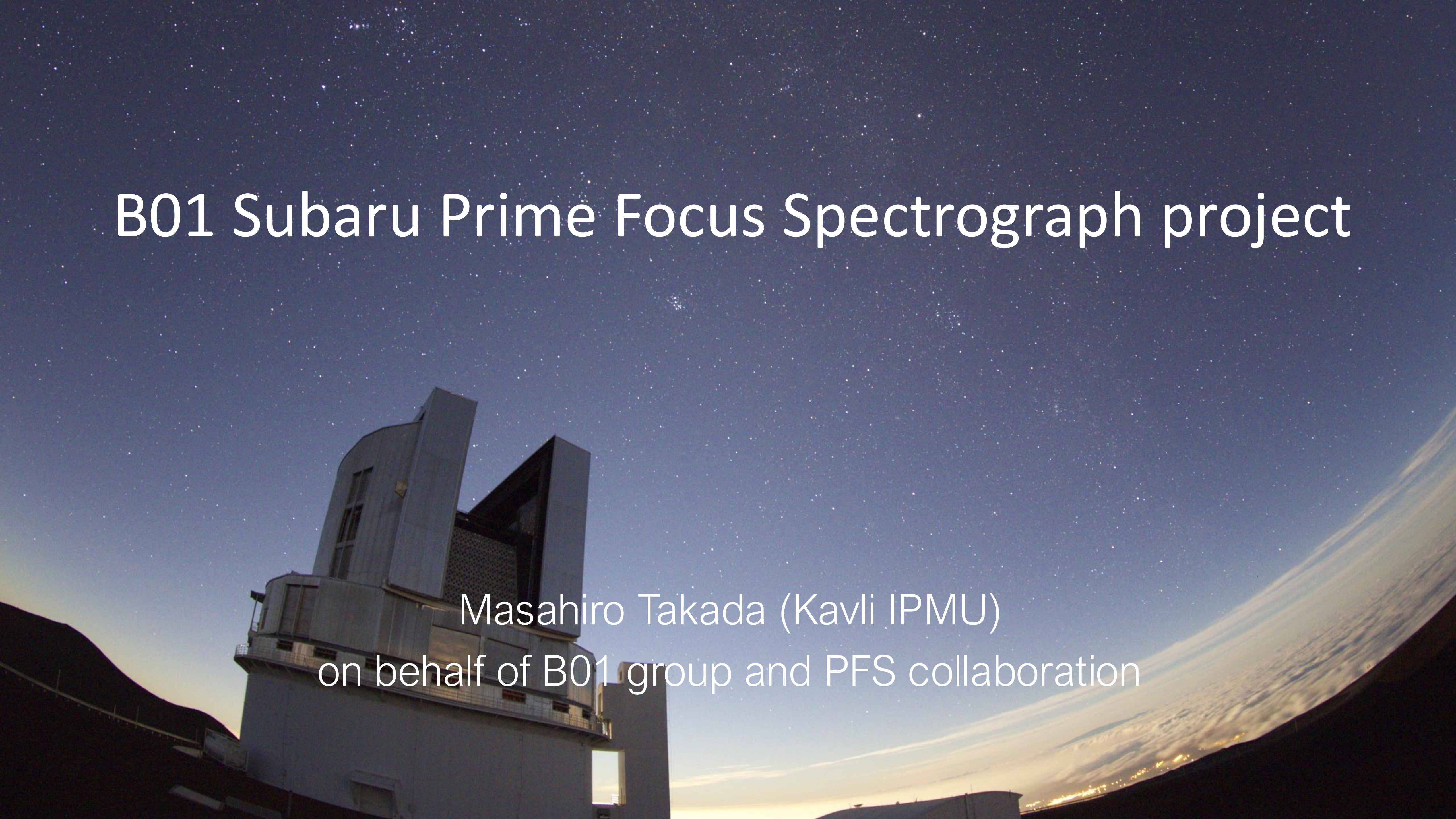
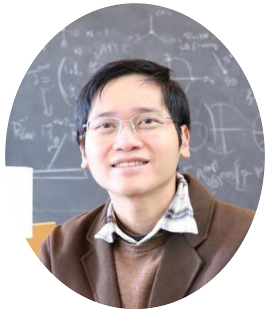
B01 Subaru Prime Focus Spectrograph project



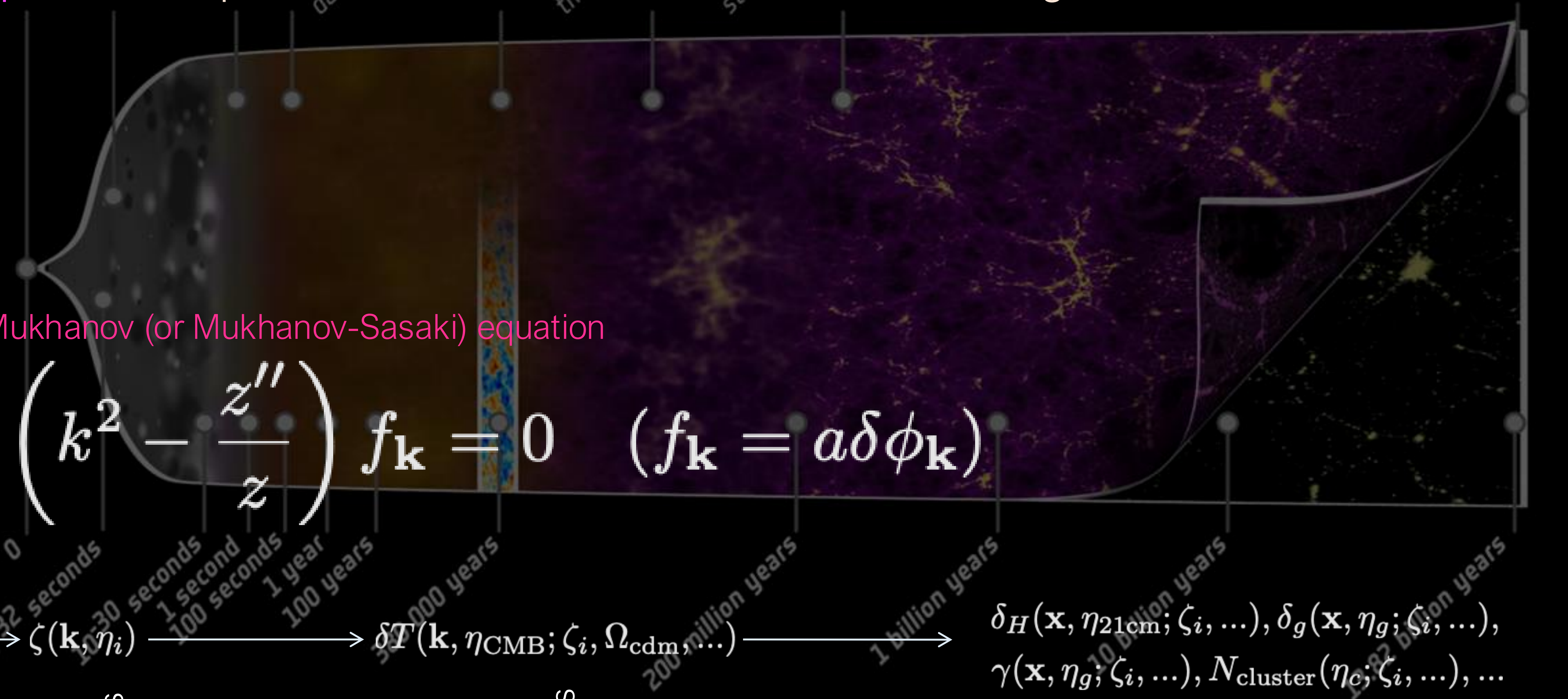
Masahiro Takada (Kavli IPMU)
on behalf of B01 group and PFS collaboration

B01 team members

- Masahiro Takada – management & overview (need Claude)
- Yuki Moritani (NAOJ) – instrumentation & data analysis
- Jingjing Shi (IPMU) – cosmology data analysis
- Kiyoto Yabe (NAOJ) – data analysis
- Leander Thiele (IPMU) – AI/ML cosmology
- Minh Nguyen (IPMU) – theory
- Collaborators: Atsushi Nishizawa (Gifu Shotoku),
  Jiaxi Yu (IPMU), PFS Cosmology WG members
- Students: Shintaro Nakano (IPMU),
  Shota Ogawa (IPMU), Shohei Kanda (Nagoya), …



From quantum to primordial fluctuations, and then cosmological observables



Sasaki-Mukhanov (or Mukhanov-Sasaki) equation

$$f''_{\mathbf{k}} + \left(k^2 - \frac{z''}{z}\right) f_{\mathbf{k}} = 0 \quad (f_{\mathbf{k}} = a\delta\phi_{\mathbf{k}})$$

$$\delta\phi(\mathbf{k}, \eta_i) \rightarrow \zeta(\mathbf{k}, \eta_i) \longrightarrow \delta T(\mathbf{k}, \eta_{\rm CMB}; \zeta_i, \Omega_{\rm cdm}, \ldots) \longrightarrow \begin{array}{l} \delta_H(\mathbf{x}, \eta_{21\rm cm}; \zeta_i, \ldots), \delta_g(\mathbf{x}, \eta_g; \zeta_i, \ldots), \\ \gamma(\mathbf{x}, \eta_g; \zeta_i, \ldots), N_{\rm cluster}(\eta_c; \zeta_i, \ldots), \ldots \end{array}$$

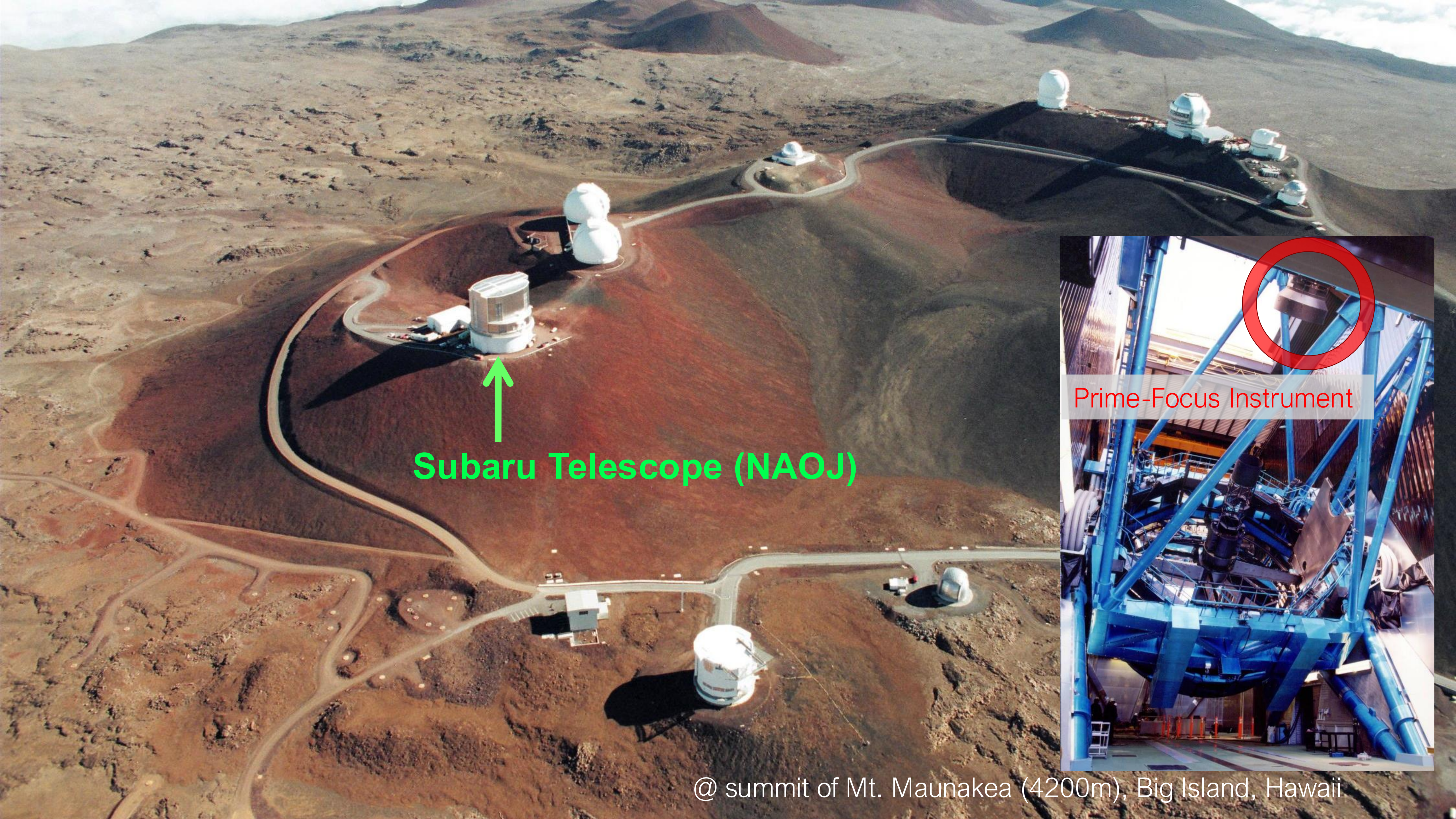
inflaton fluctuation

primordial curvature perturbations

CMB anisotropies

galaxy density field, weak lensing, 21cm, clusters of galaxies …

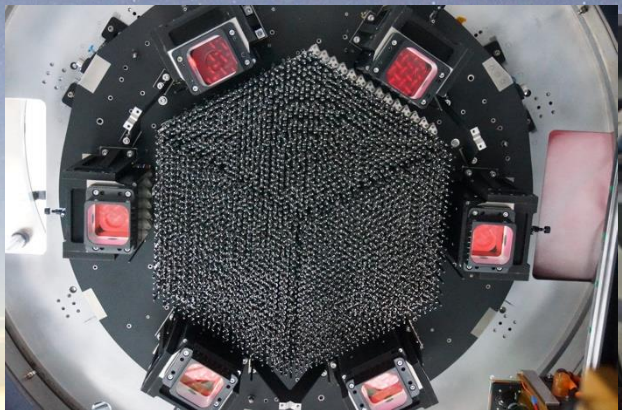
Kodama & Sasaki 84; Mukhanov+92



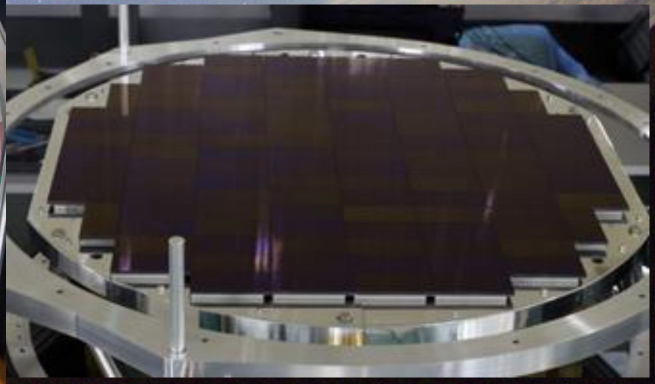
Subaru Telescope (NAOJ)
Prime-Focus Instrument
@ summit of Mt. Maunakea (4200m), Big Island, Hawaii

The strategic “upgrade” of Subaru (2006-)

Prime Focus Spectrograph (PFS): spectroscopy



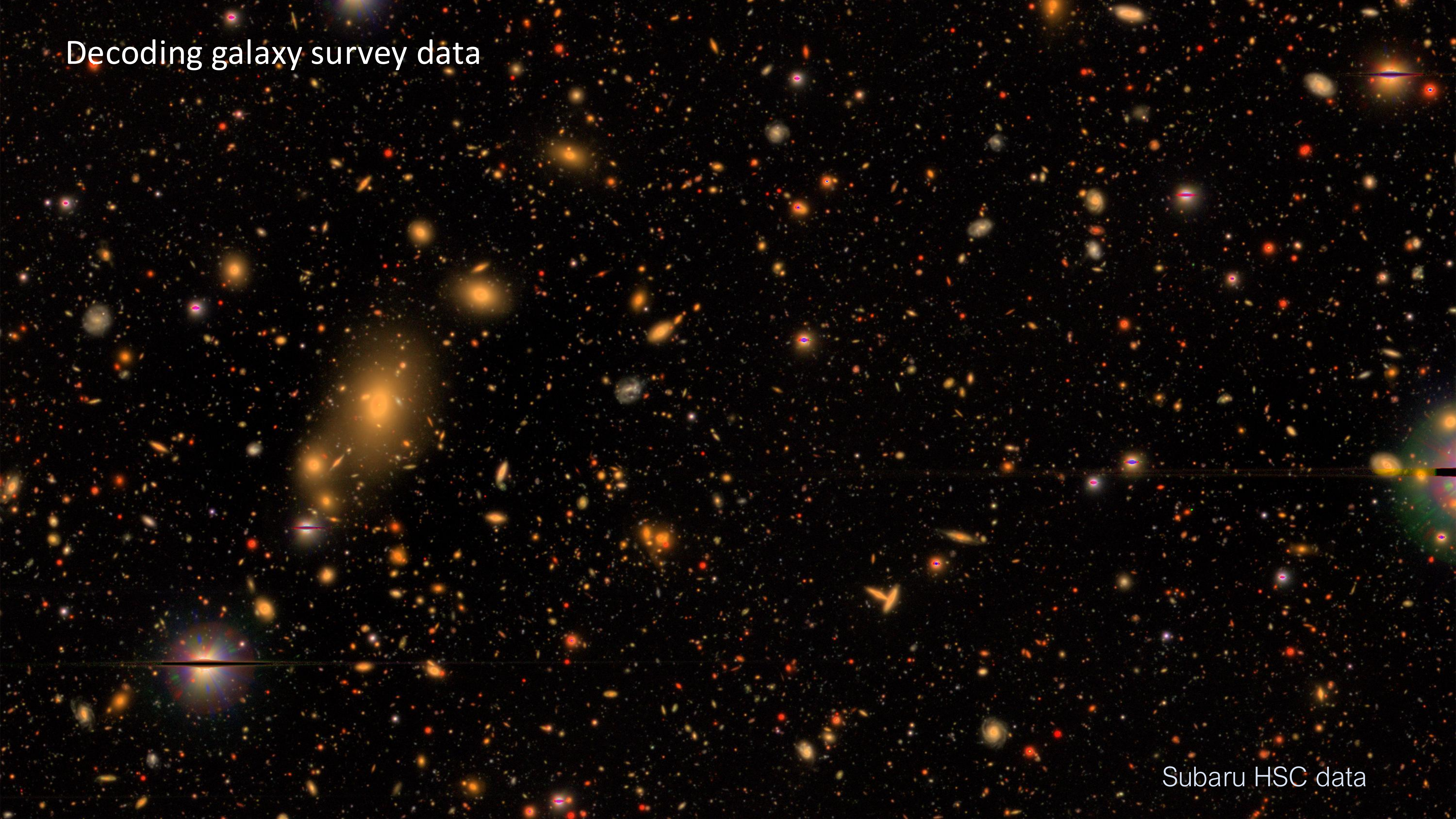
Hyper Suprime-Cam (HSC): imaging



HSC is working very well

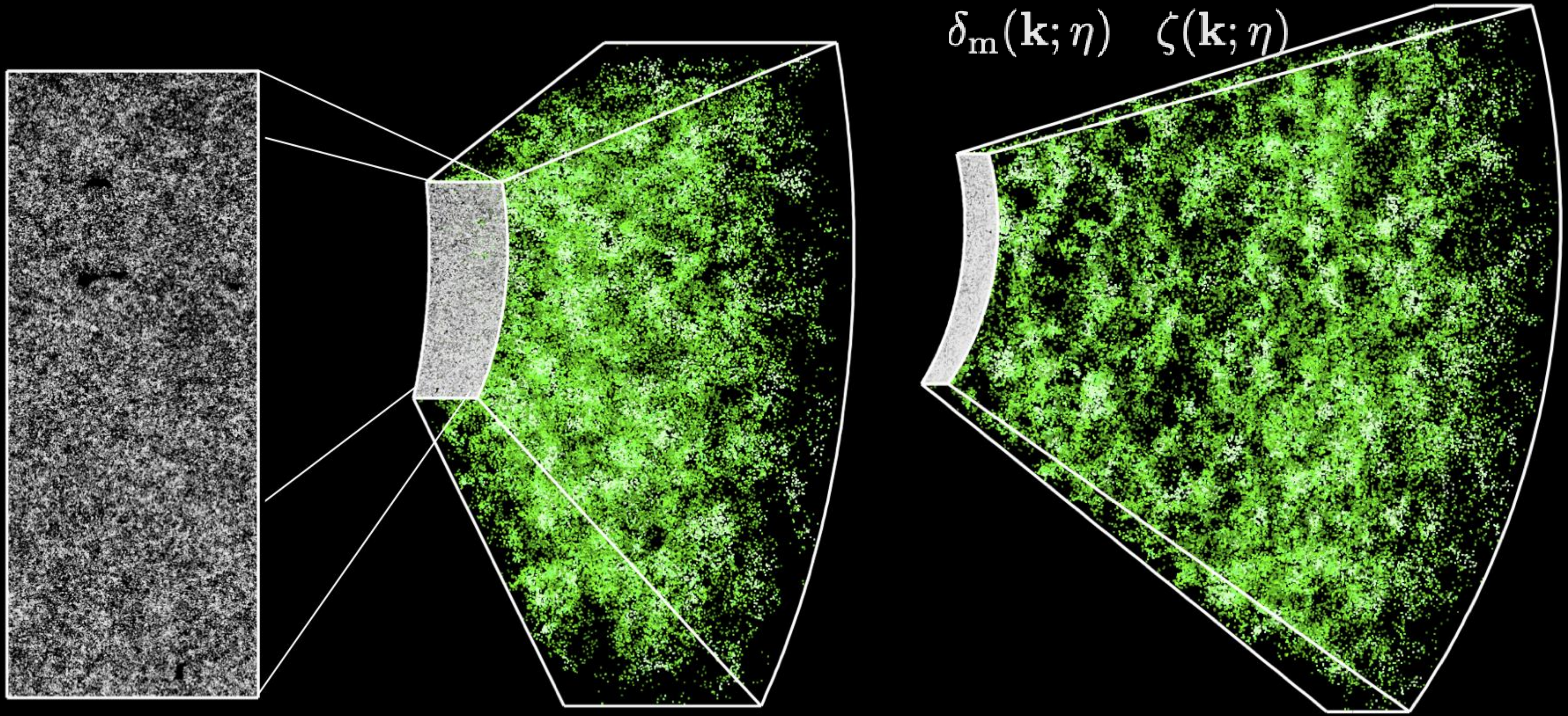
©HSC project

Decoding galaxy survey data



Subaru HSC data

Cosmology with spectroscopic galaxy survey, i.e., the three-dimensional distribution of galaxies

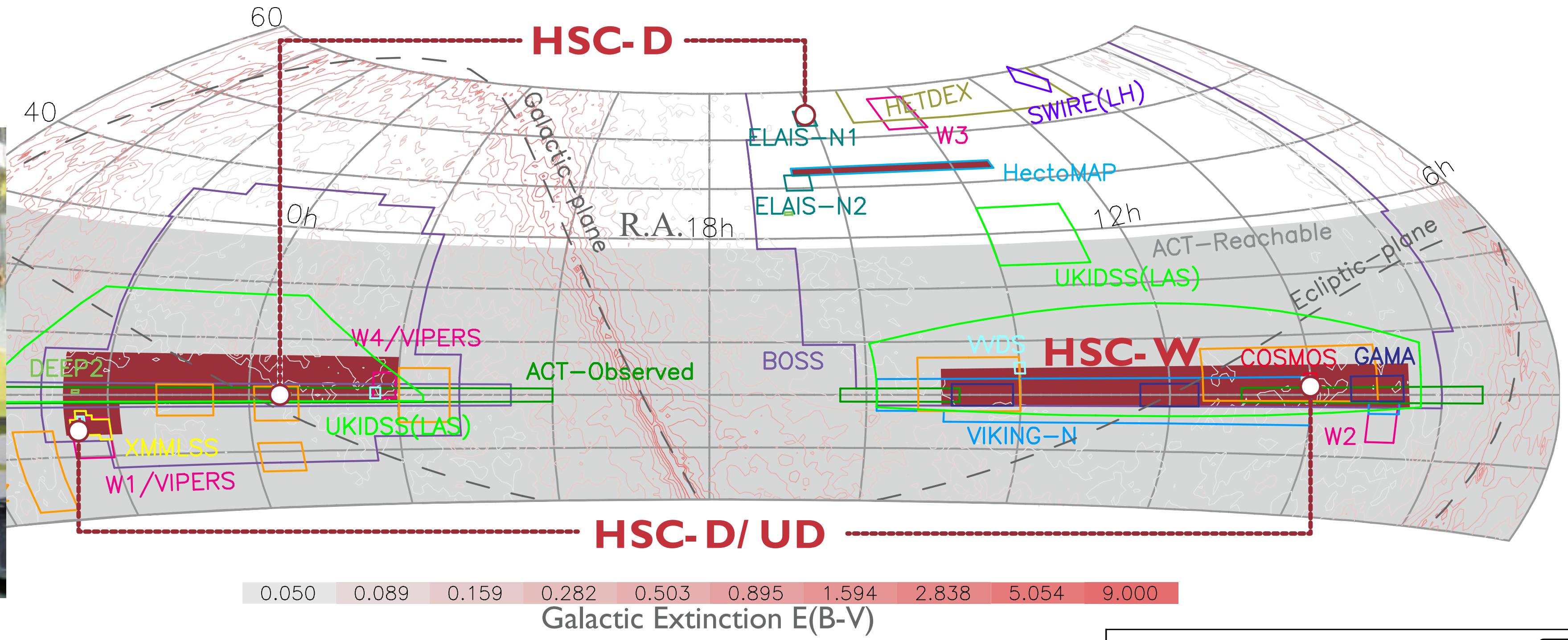


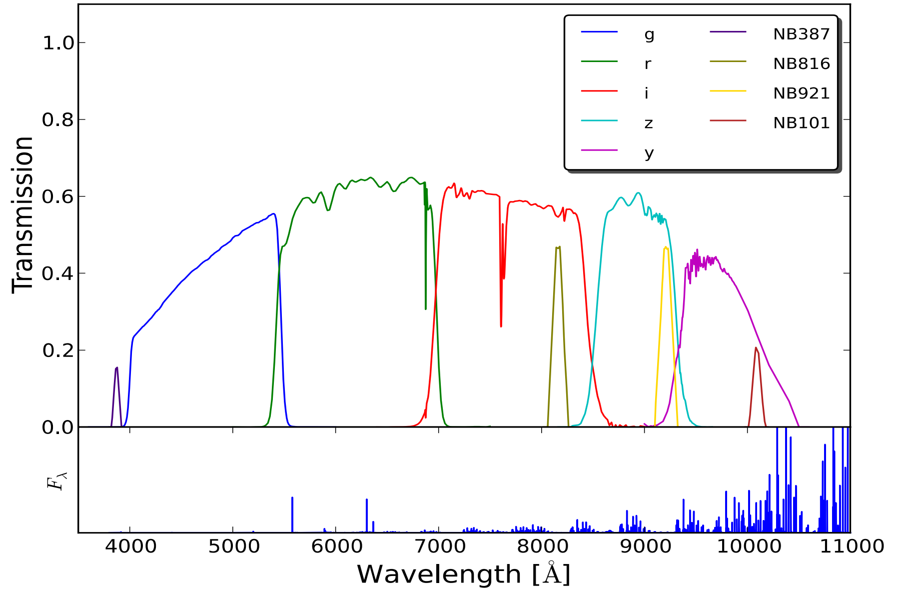
credit: SDSS

The position of each galaxy is given by (z, RA, dec)

Subaru wide solid-angle survey (2014-)

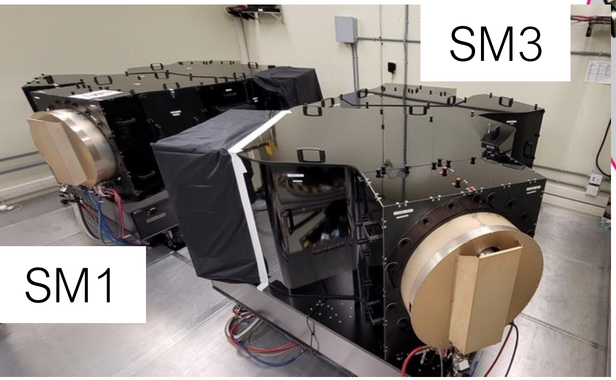
HSC (imaging)



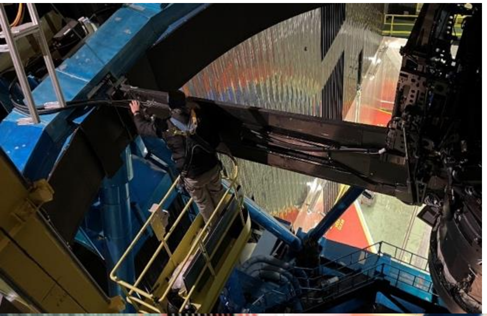


- HSC: 2014 – 2021 (HSC imaging data acquisition are done)
- Broad band filters (grizy) (plus NB filters for Deep/UD fields)
- HSC-Wide for cosmology (i~26, grizy, ~1100 deg^2)
- More area is available to observe, if we want

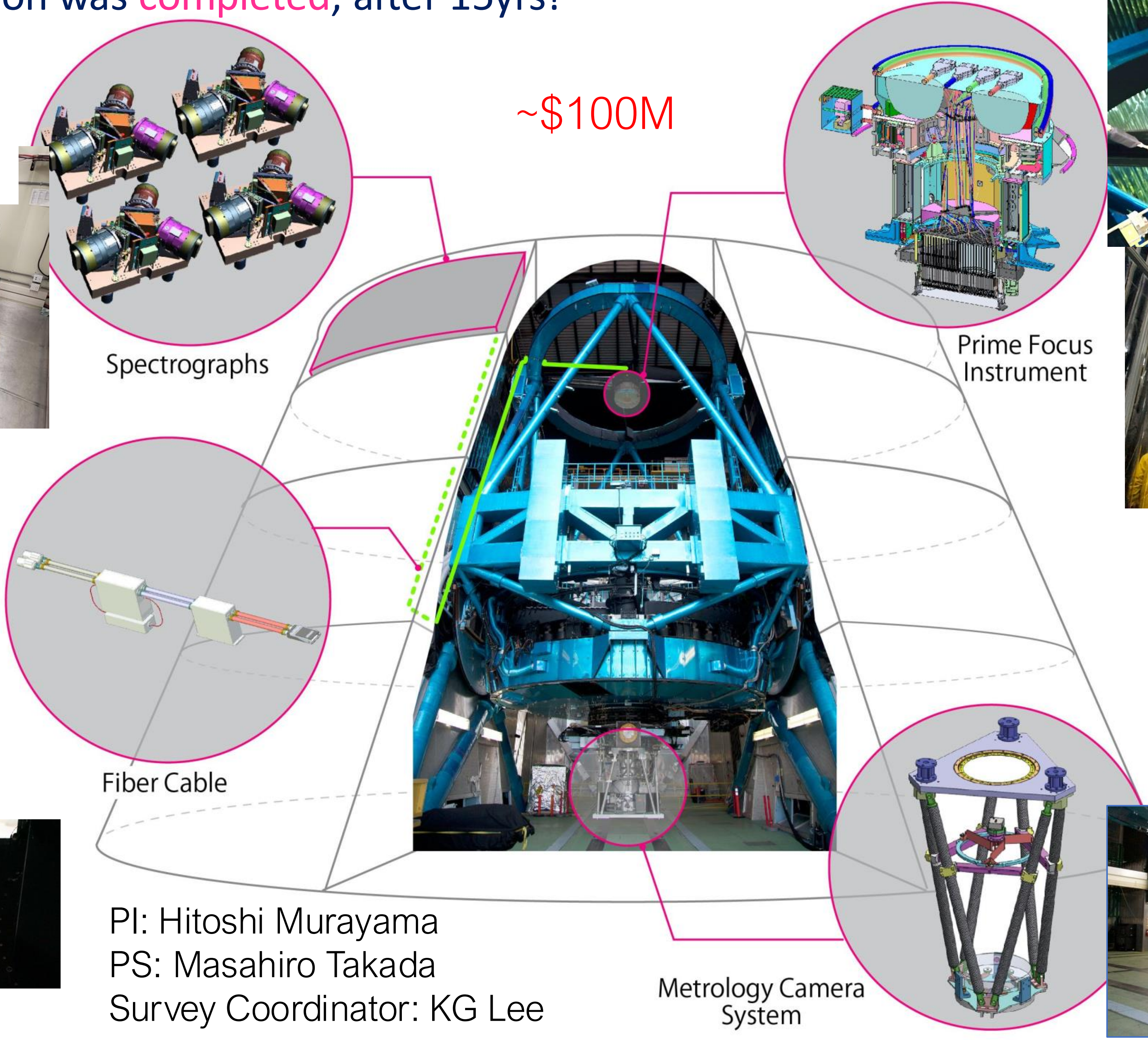
Subaru PFS construction was completed, after 15yrs!

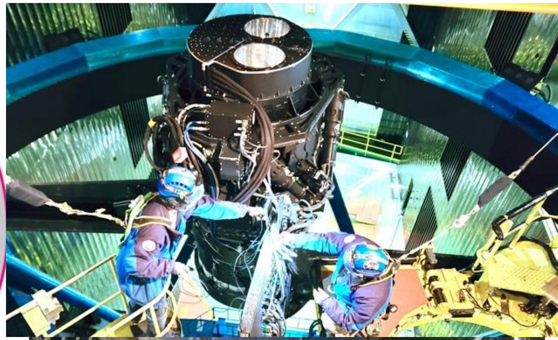


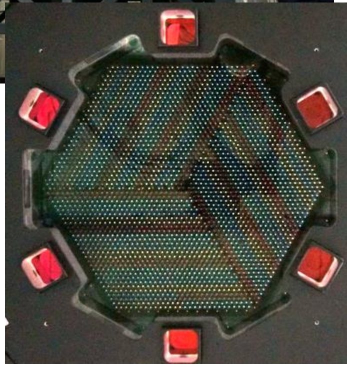
12 spectrographs

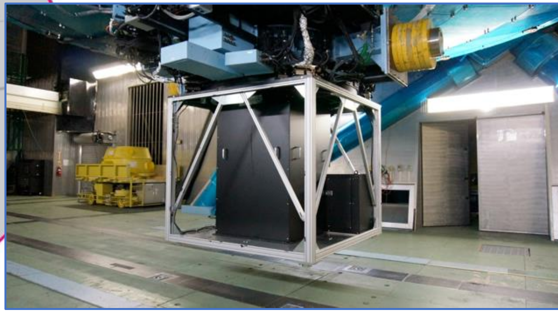


~$100M



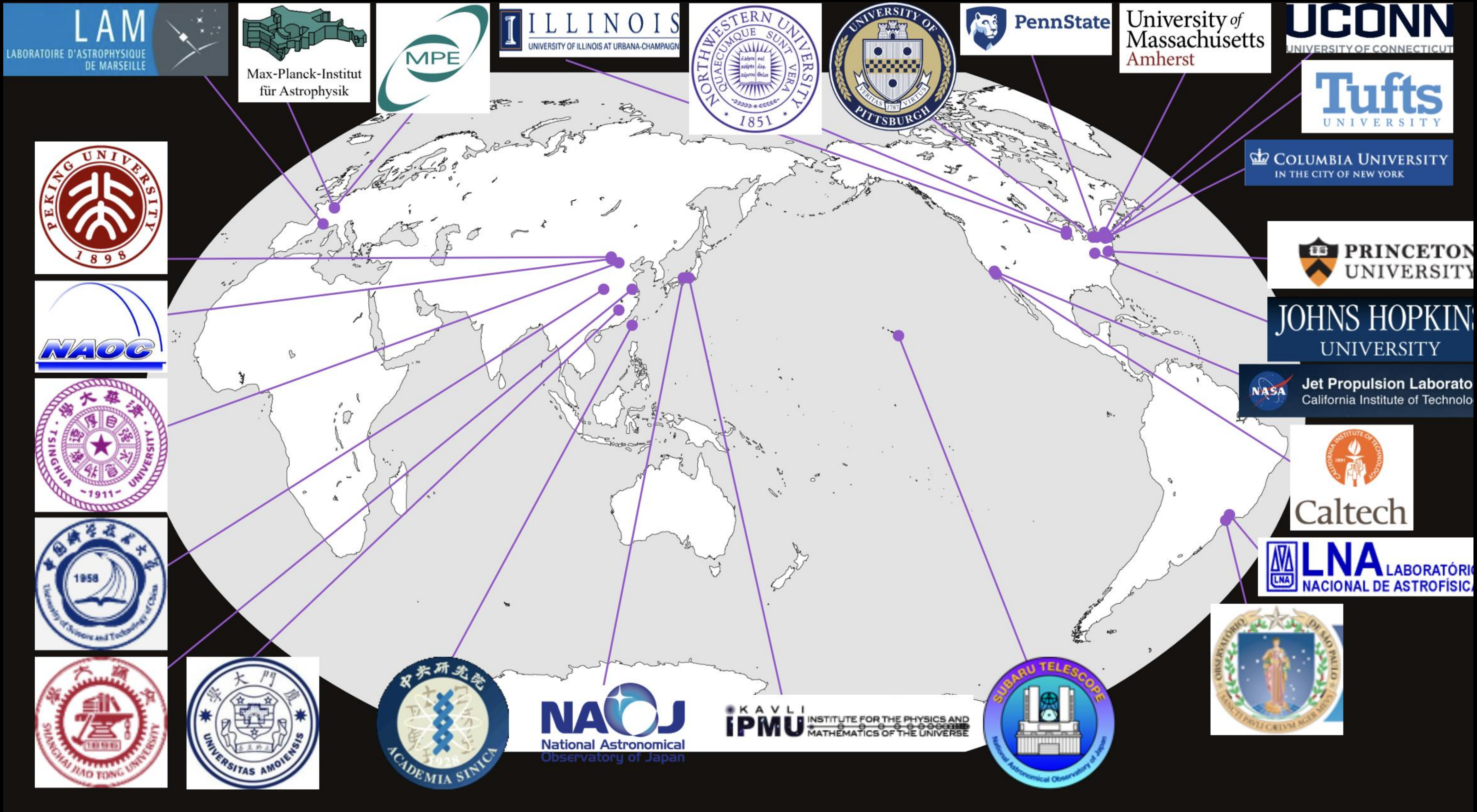




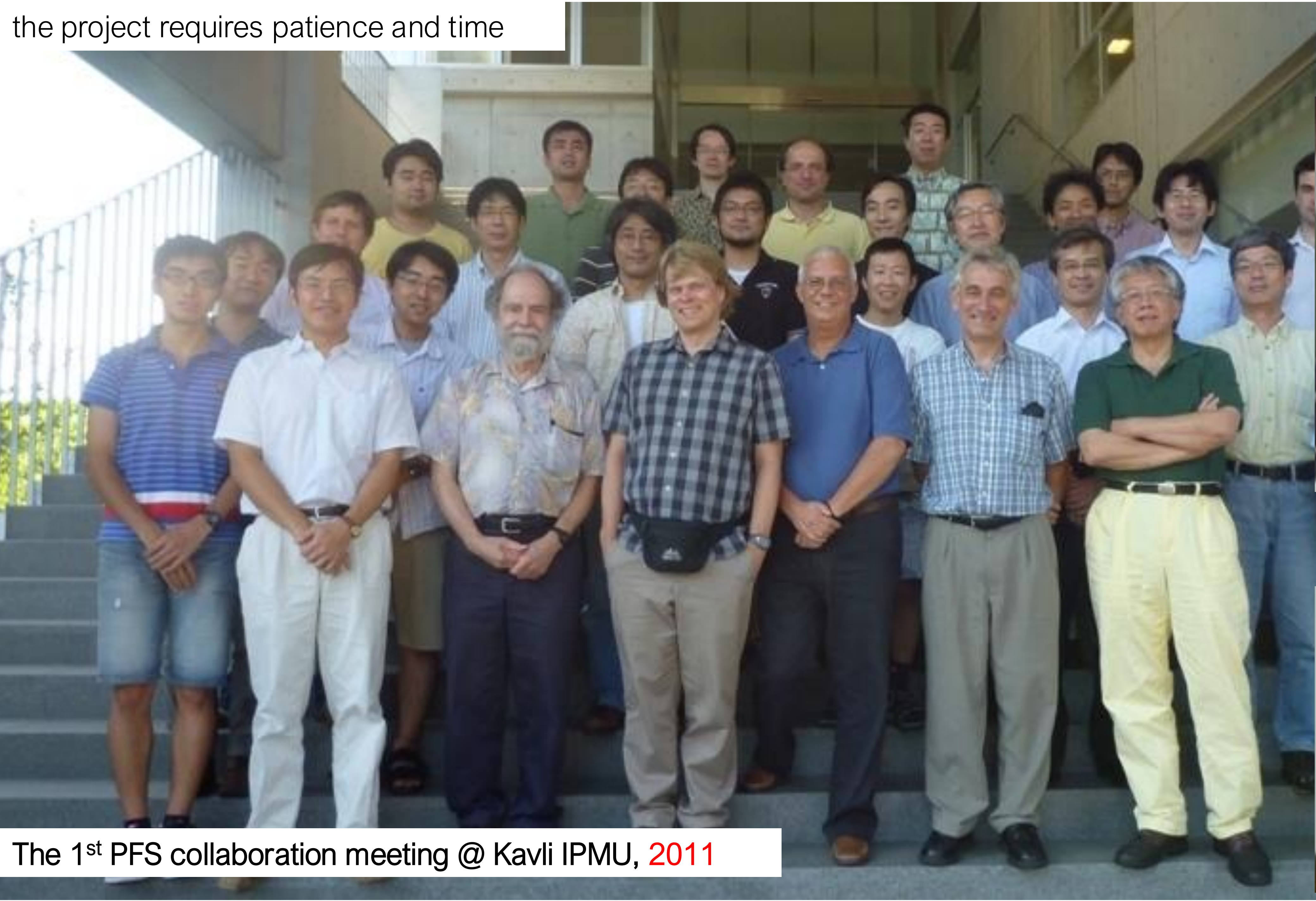


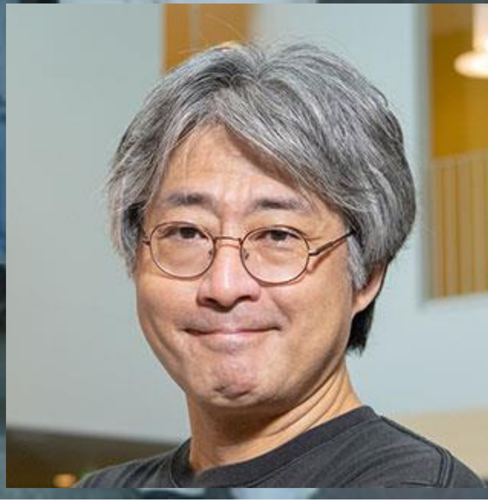
PI: Hitoshi Murayama
PS: Masahiro Takada
Survey Coordinator: KG Lee

PFS collaboration = Opportunities for collaboration & networking



the project requires patience and time





The 1st PFS collaboration meeting @ Kavli IPMU, 2011

@ Tokyo, Jan 2012

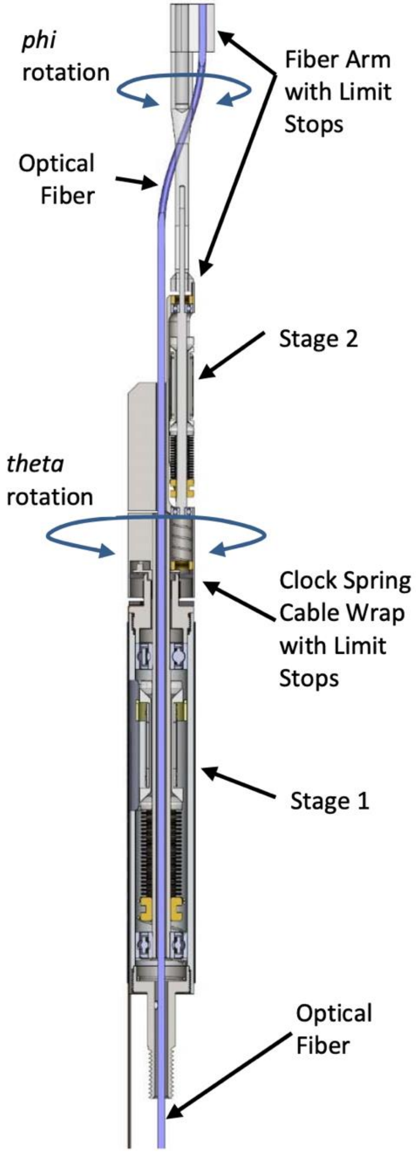
PI: Hitoshi Murayama
PS: Masahiro Takada
Survey Coordinator: KG Lee

Collaboration meeting @ Kavli IPMU, Jan 2025

Naoyuki Tamura (PM)
(Kavli IPMU → NAOJ)

Yuki Moritani
(Instrument Scientist)
(Kavli IPMU → NAOJ)

Kiyoto Yabe
(Software Scientist)
(Kavli IPMU → NAOJ)

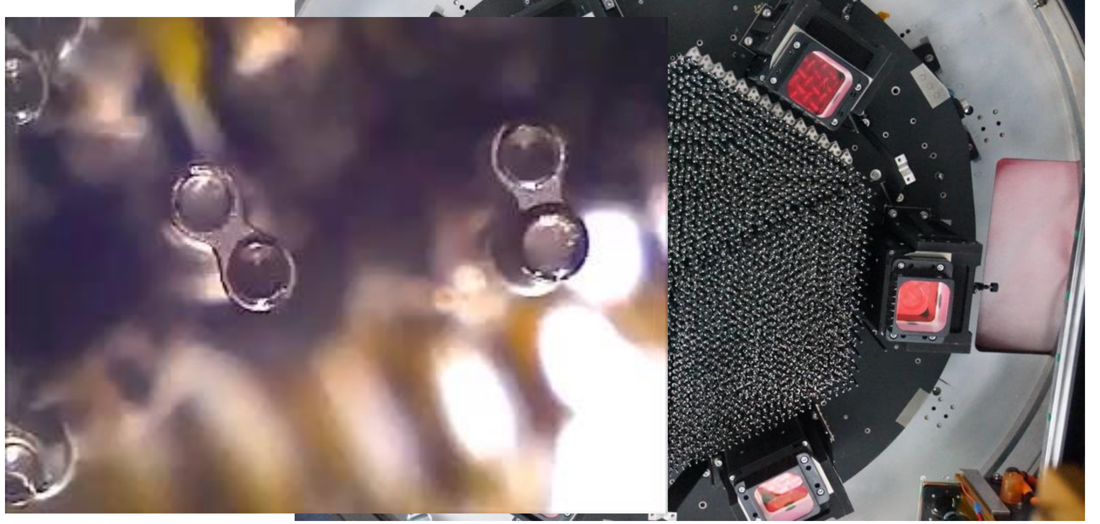


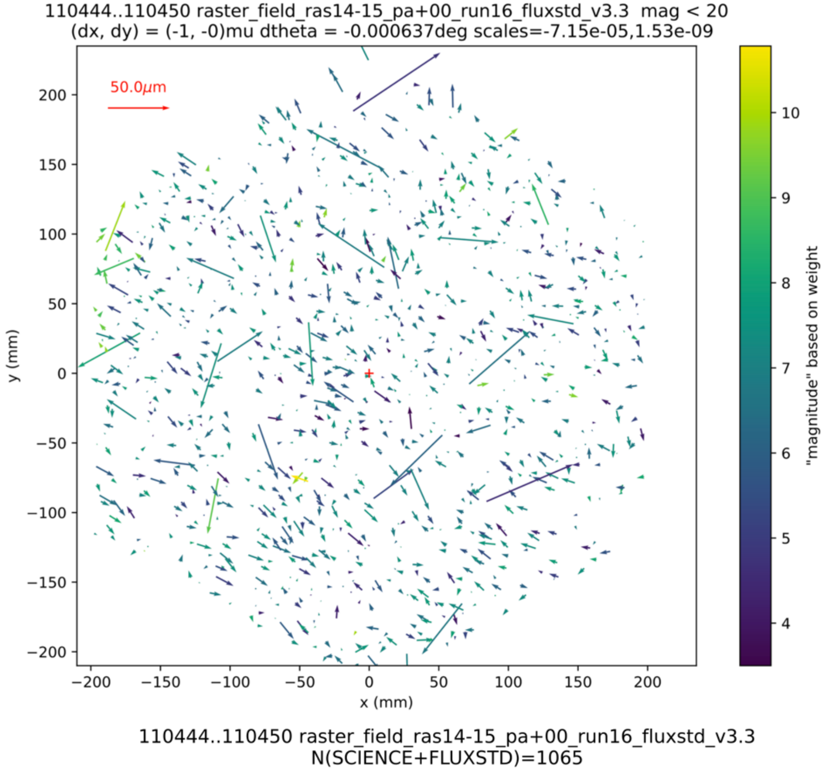
PFS fibers (cobras)

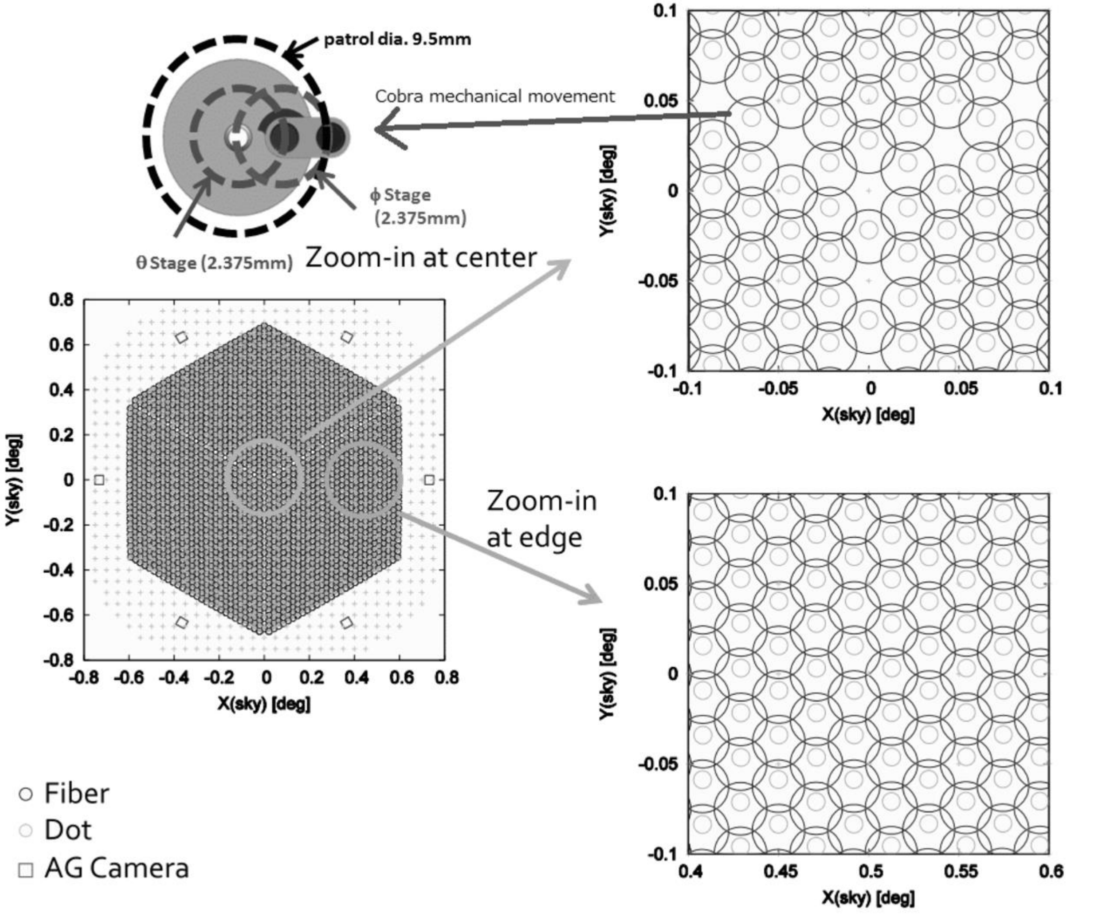
- Filling factor of fibers in PFS FoV

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

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



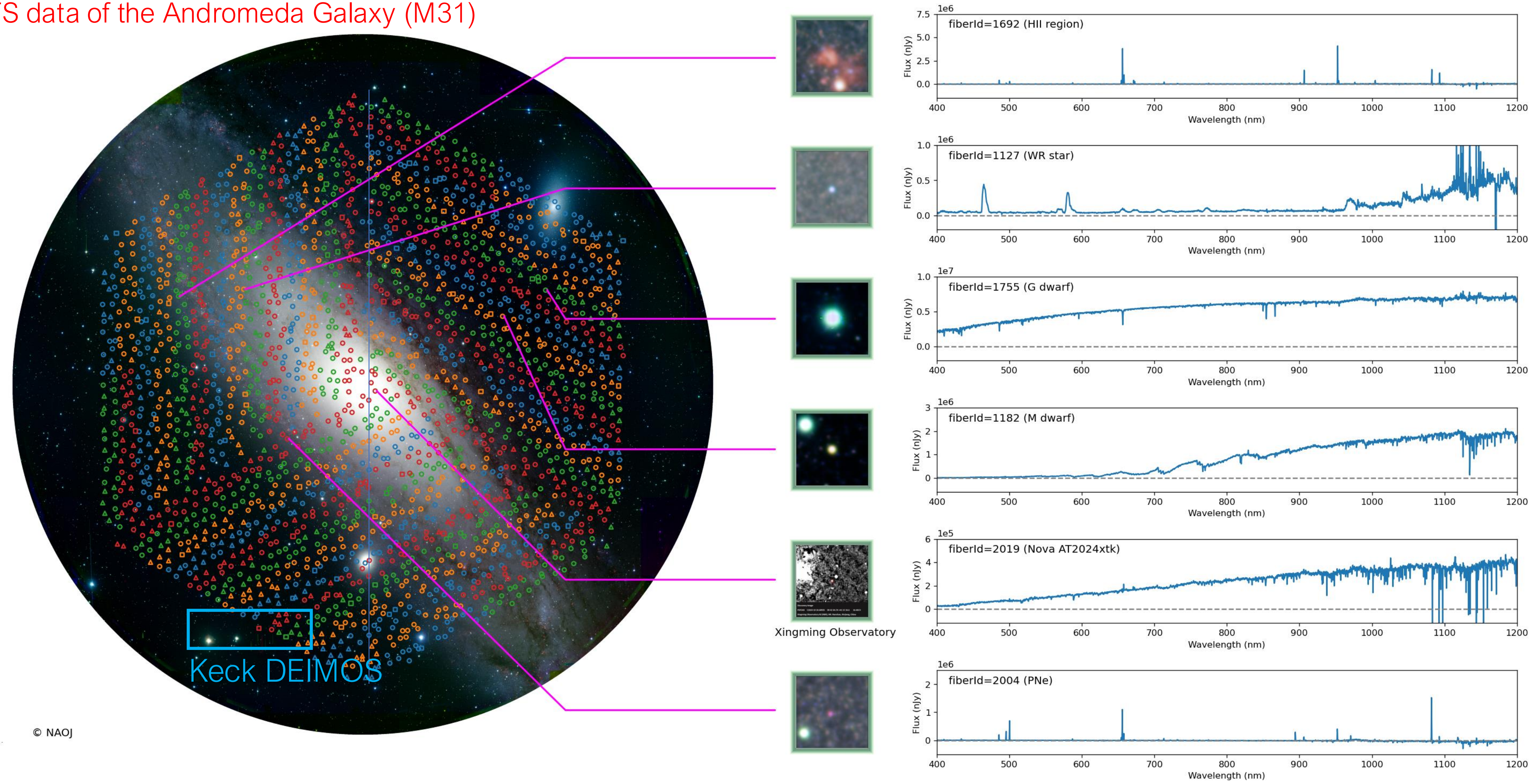




PFS spectroscopy-survey power > 1000 × Keck

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

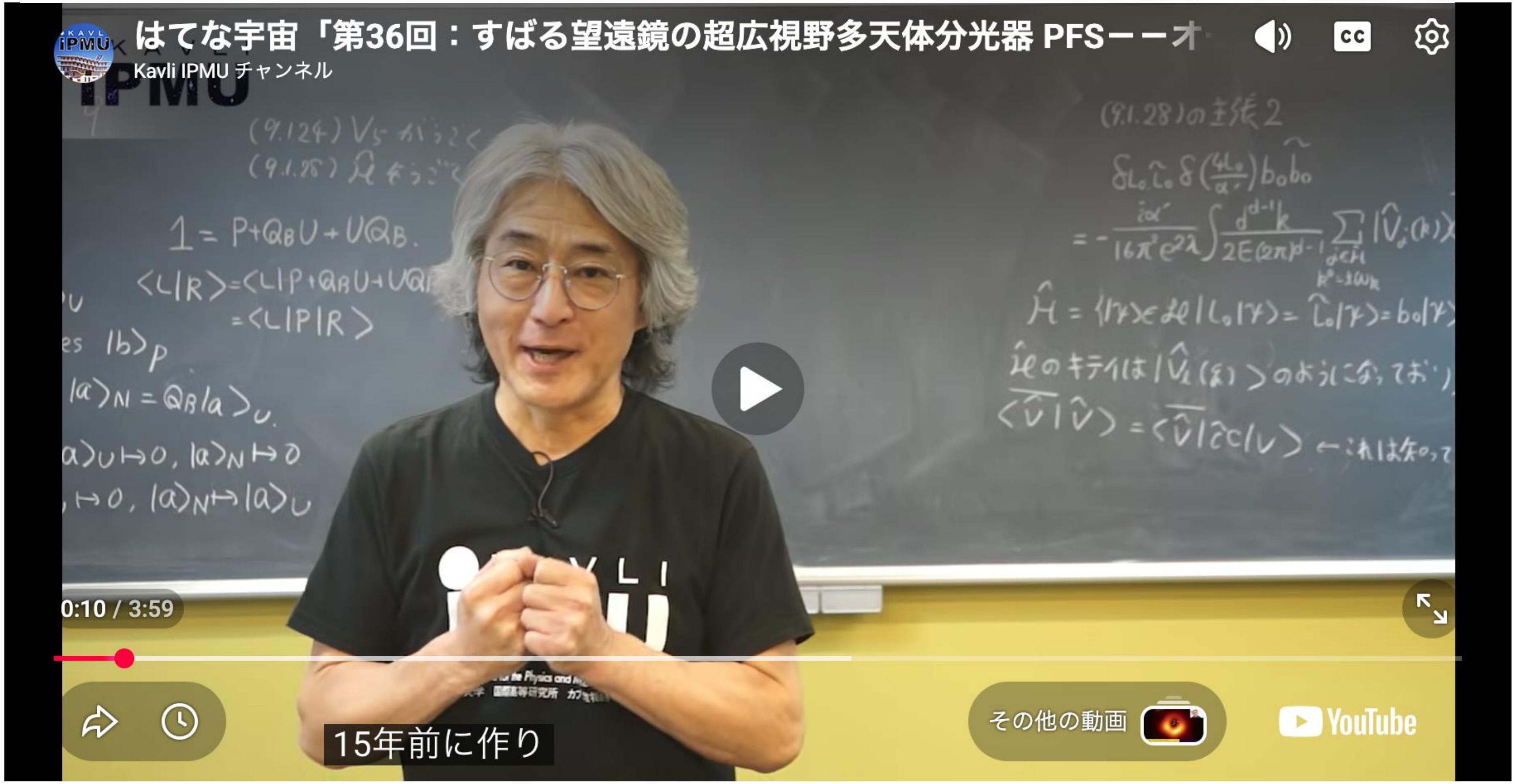
PFS data of the Andromeda Galaxy (M31)



A public outreach video introducing PFS “はてな宇宙” from Kavli IPMU

Share X ポスト

> **はてな宇宙「第36回：すばる望遠鏡の超広視野多天体分光器 PFS ーーオーノヒウラ 本格始動」**



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)

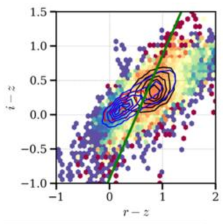
PFS compared to DESI

- Mirror size:
  8.2m vs. 4m
  (+Maunakea vs. Kitt peak)
- Fiber density:
  ~2000 deg^{-2} vs. ~600 deg^{-2}
- Wavelength coverage:
  [380,1260]nm vs. [360,960]nm
- Survey start:
  2025 vs. 2021
- Fiber reconfiguration time:
  both ~2min

The workflow of PFS cosmology observation/analysis

input

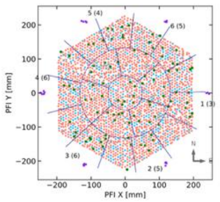
HSC image



target selection

Select star-forming galaxy candidates from the HSC catalog (+stars, sky)

uniform selection of the targets irrespective of observing conditions (deep HSC data helps)



fiber design

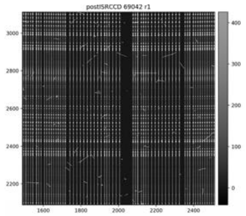
Designing the fiber configuration for each field (+stars, sky)

need to understand the properties of each fiber and the behavior of the fiber assignment …

observation

Execute the observation for allocated nights (remotely in most cases)

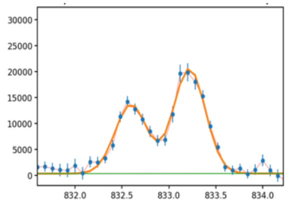
right decisions and uniform-depth exposures (dynamical exposures)



data reduction

data reduction (bias/flat, cosmic ray, sky subtraction, etc.)
2D & 1D spectrum extraction

precise data reduction (sky subtraction, wavelength calibration, flux calibration, …)



[OII] detection

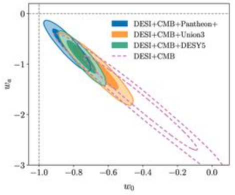
Identification of [OII] emitters from the data and redshift determination

precise identification of [OII] line, and selection function assessment, …

output

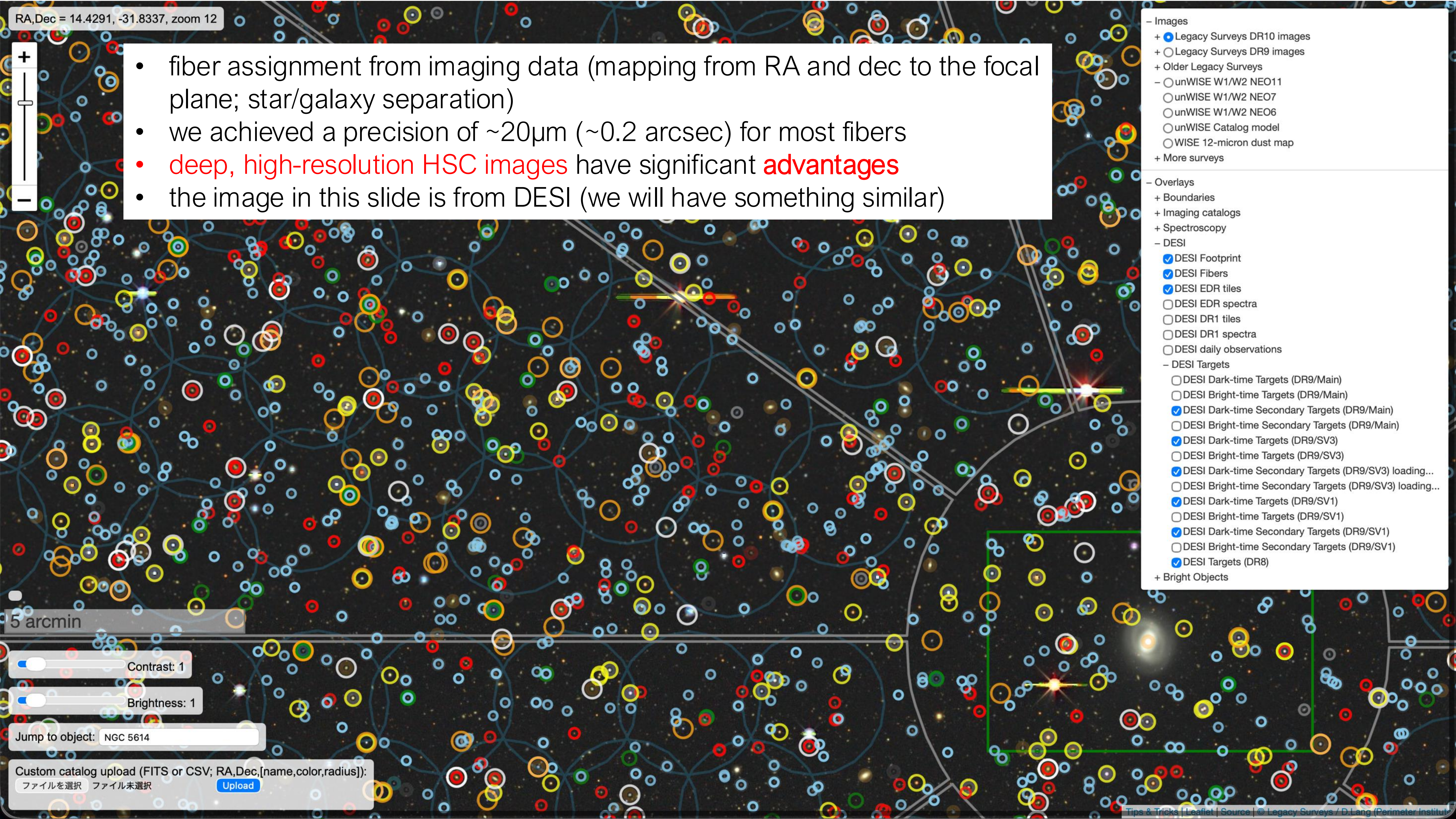
the PFS catalog of [OII] emitters

cosmology analysis

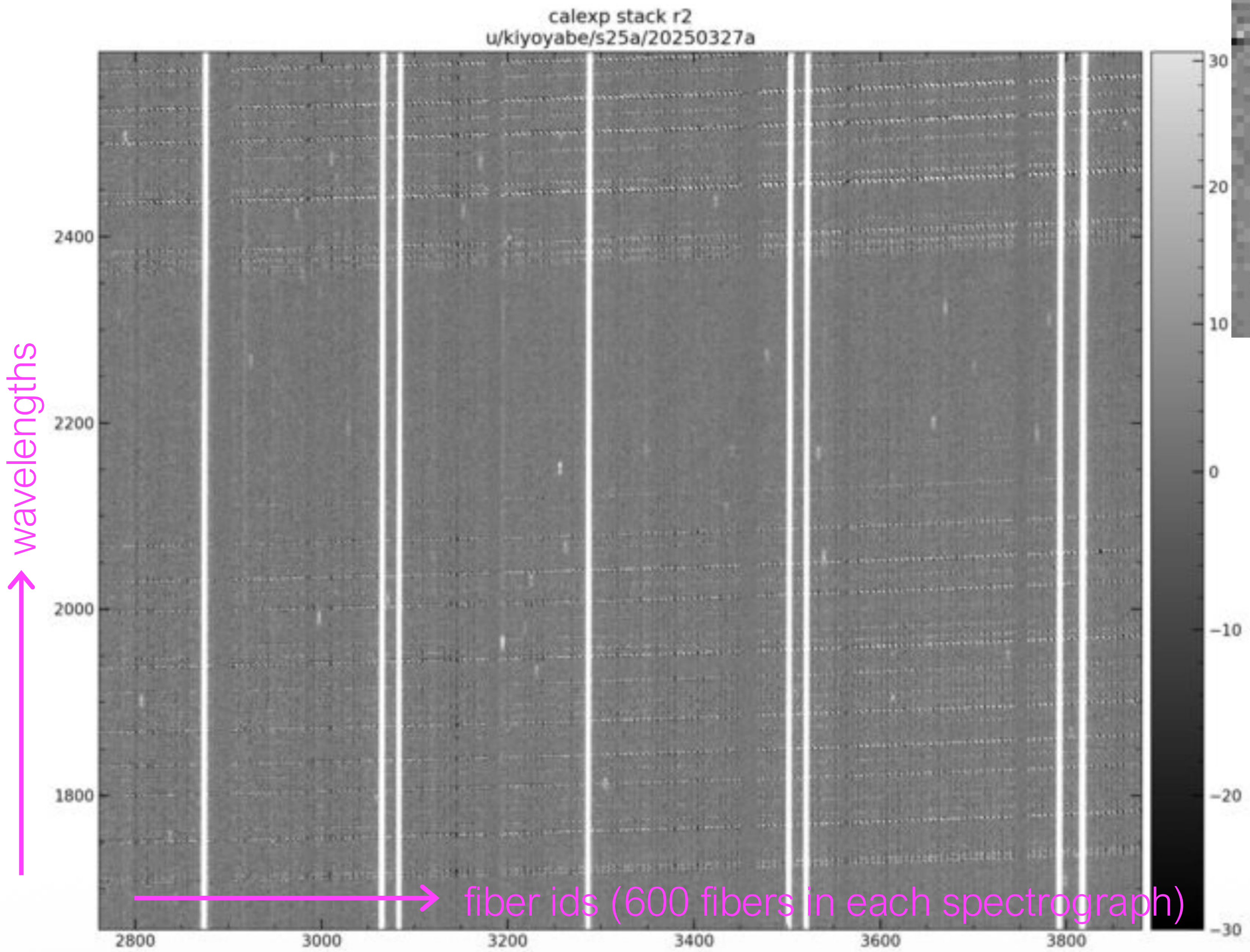


requirements

- fiber assignment from imaging data (mapping from RA and dec to the focal plane; star/galaxy separation)
- we achieved a precision of ~20μm (~0.2 arcsec) for most fibers
- deep, high-resolution HSC images have significant advantages
- the image in this slide is from DESI (we will have something similar)



2D PFS images



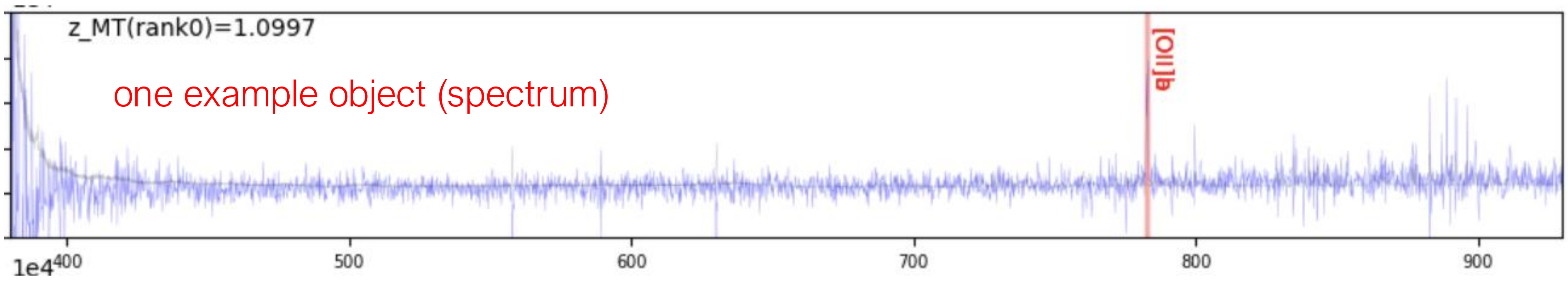
[OII] doublet

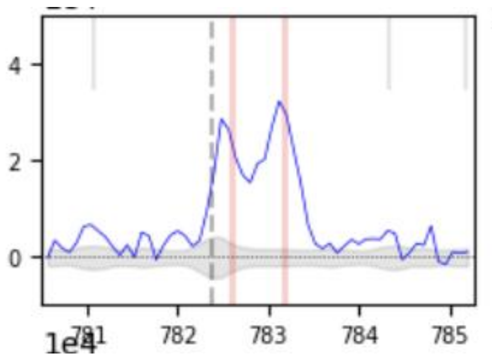
Note: quick data reduction was done. E.g., the sky background was subtracted (sky ~ 100 × signal)

credit: PFS project

2D ⇒ 1D spectrum

- basic data reduction (flat-fielding, bias subtraction, …)
- sky subtraction (sky ~ 100 × [OII])
- 2D ⇒ 1D spectrum: wavelength calibration, extraction of each spectrum (correcting for contribution from neighboring spectra), flux calibration…
- Identification of [OII] doublet (equivalent to redshift measurement)



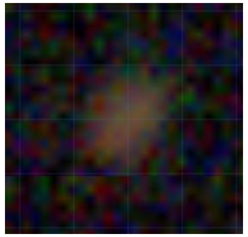


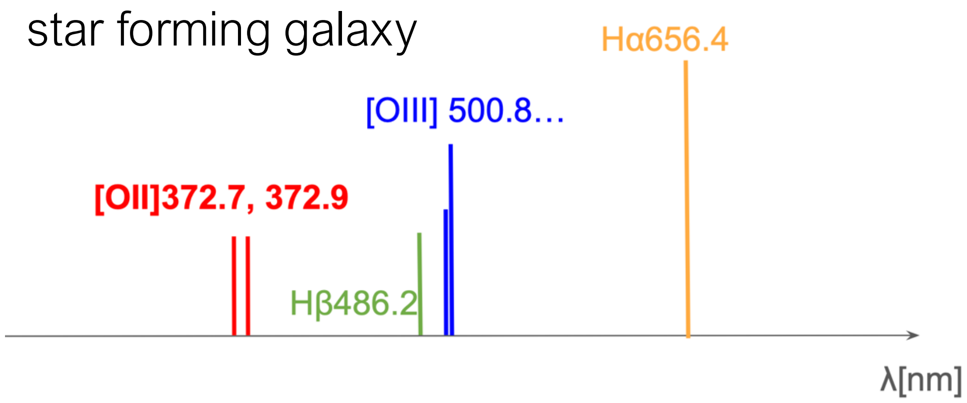
wavelength (blue + red arms; [380,930]nm

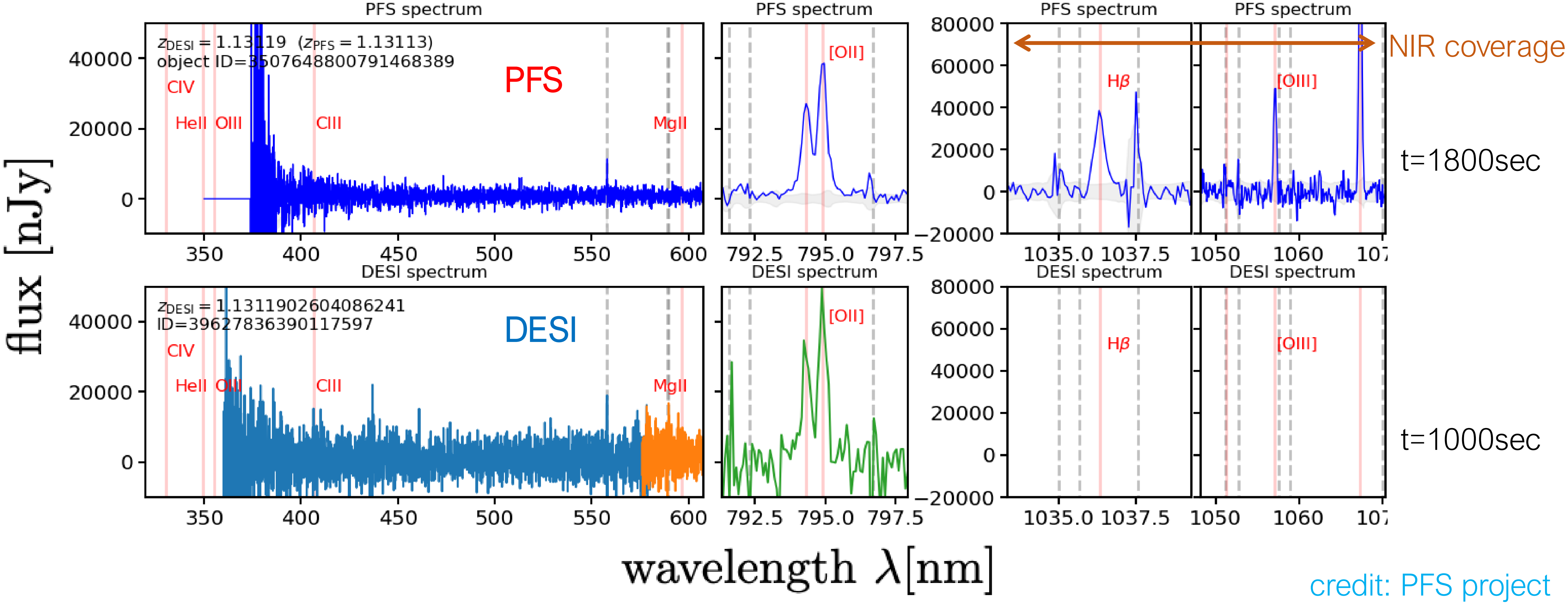
credit: Atsushi Nishizawa

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

an example galaxy

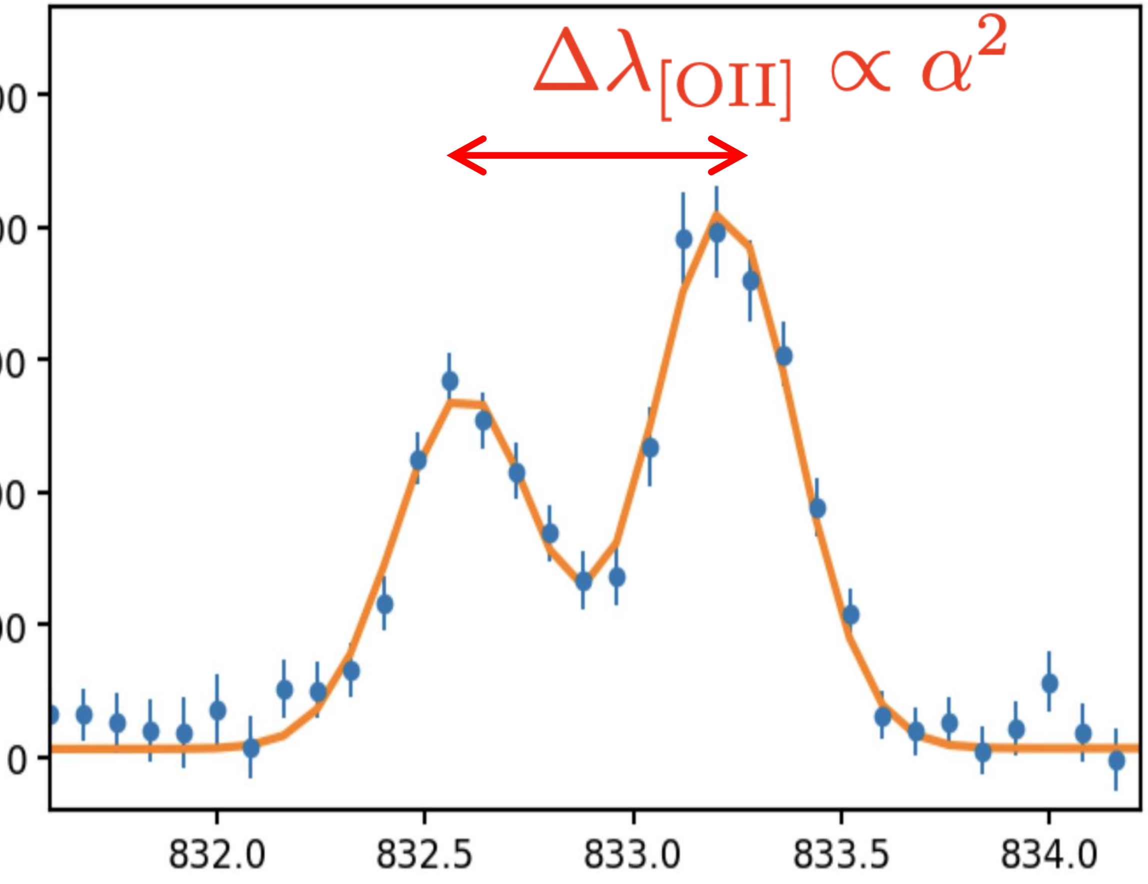






credit: PFS project

search for time variation in fine-structure constant (⇔ C01)



wavelength

- For each galaxy (note the absolute wavelength calibration)

$$\frac{\Delta\lambda}{\lambda} = 2\frac{\Delta\alpha}{\alpha} \sim 10^{-4}$$

- PFS galaxies at z~1

$$\sim 8 \text{ Gyr ago} \sim 10^{10} \text{ yr}$$

- Therefore, we have for each galaxy

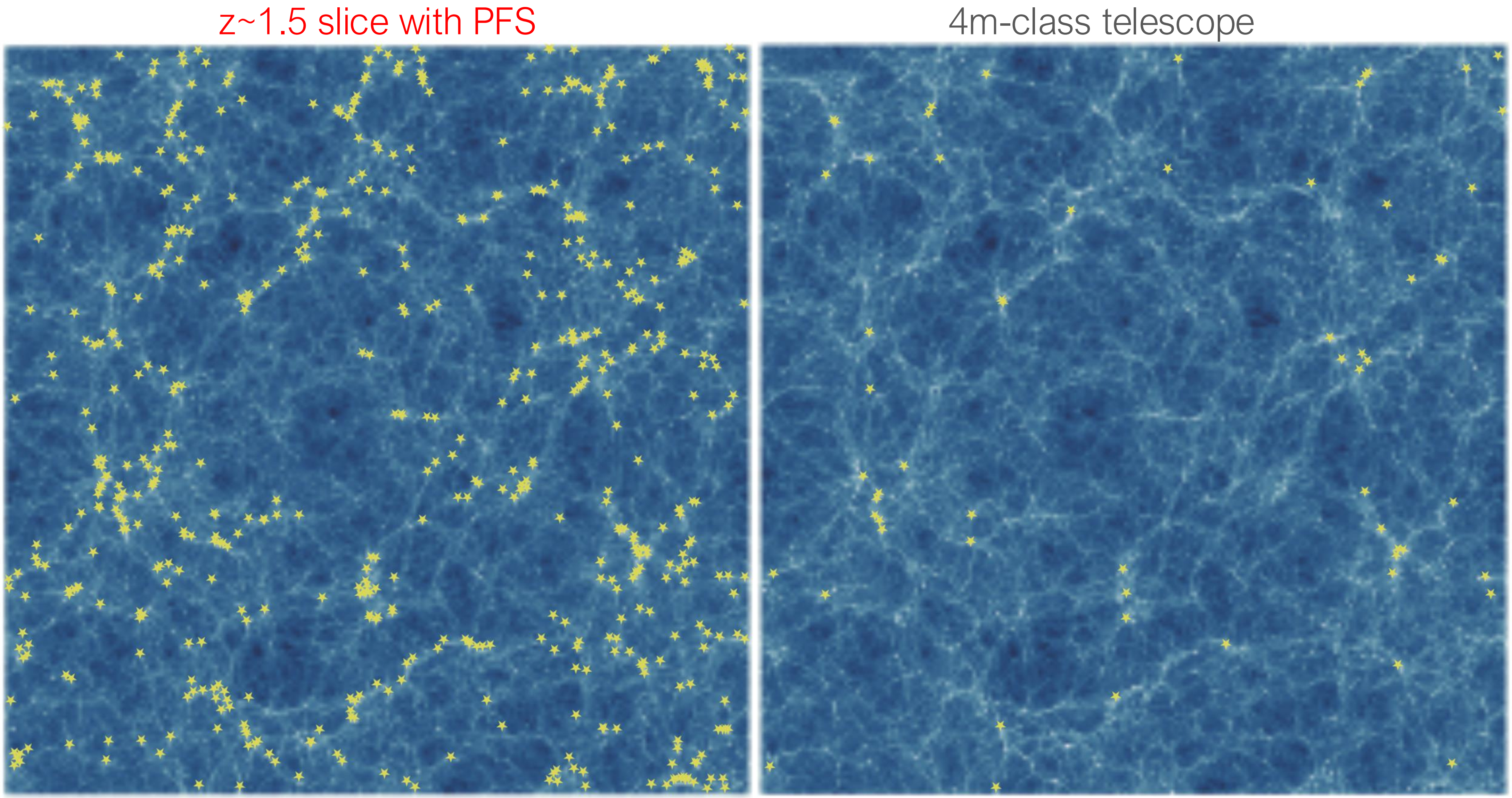
$$\frac{\dot{\alpha}}{\alpha} \sim 10^{-14} \text{ yr}^{-1}$$

- With ~10^6 galaxies, we have

$$\frac{\dot{\alpha}}{\alpha} \sim 10^{-17} \text{ yr}^{-1} \quad (\leftrightarrow 10^{-18} \text{ yr}^{-1} \text{ from C01})$$

Shohei Kanda (grad student at Nagoya), Nishizawa, MT, ...

PFS cosmology survey: a 3D map of "emission-line" galaxies



blue: dark matter, yellow: galaxies (mock)

required tasks toward PFS cosmology

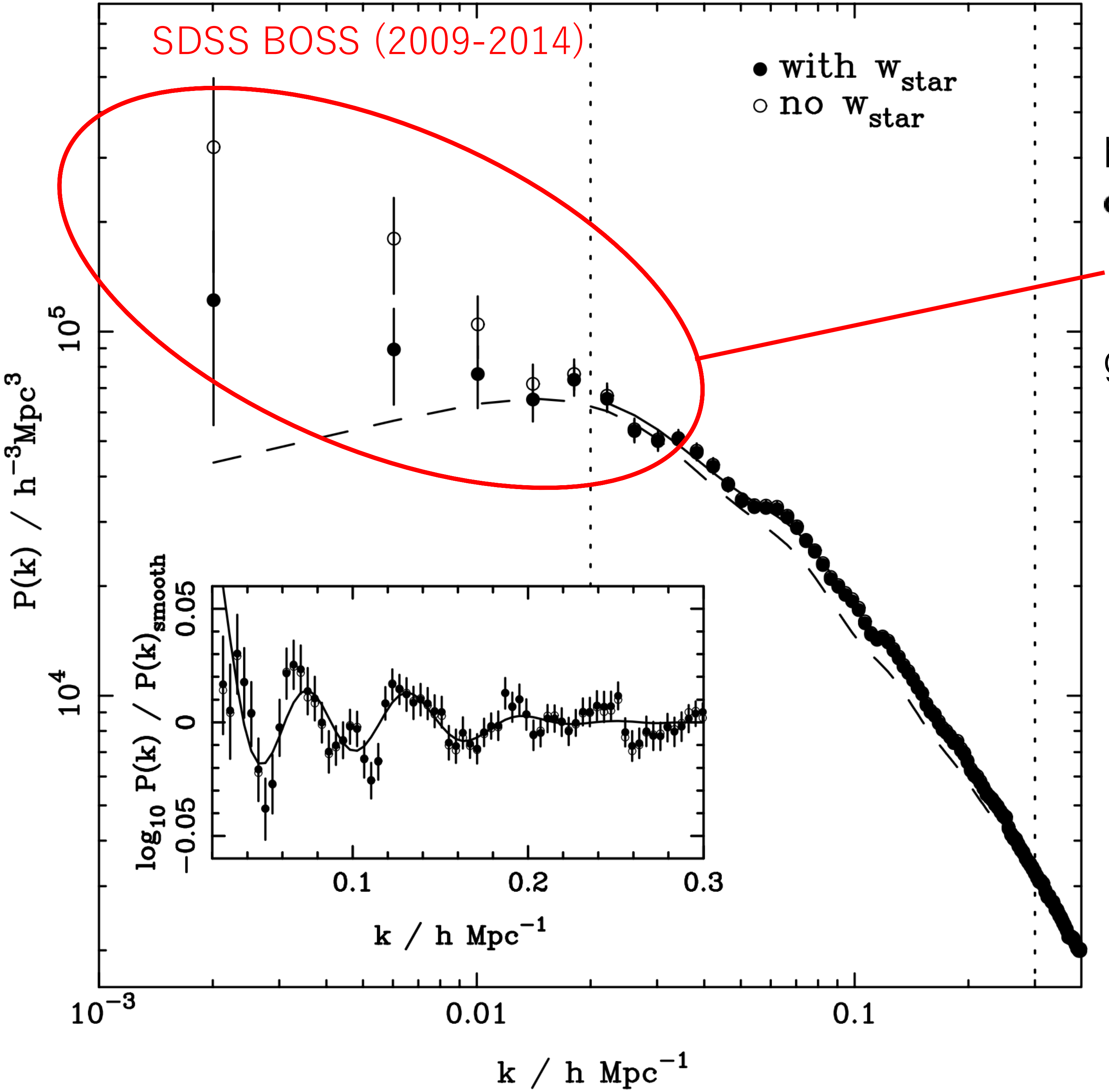
- Execution of observations (targets, fiber design, observation) – Jingjing, Shintaro, Shota, …
- Identification and selection of [OII] emitter candidates – Masahiro, Atsushi, …
- Construction of the large-scale structure catalog and the characterization of the survey selection function – Jingjing, Shintaro, …

← where we are now

- Clustering measurements – the PFS Cosmology WG
  - Development of clustering analysis pipeline
- Cosmological inference – the PFS Cosmology WG

← aim to achieve the first-year PFS BAO measurement in 2027

Ross+2012



primordial non-Gaussianity (PNG)?

$$\Phi(\mathbf{x}) = \phi_g(\mathbf{x}) + f_{\rm NL}\left(\phi_g(\mathbf{x})^2 - \langle\phi_g^2\rangle\right)$$

galaxy bias on linear scales (Dalal+08)

$$b(k) = b_1 + f_{\rm NL}\frac{b_1 - 1}{\mathcal{M}(k)}$$

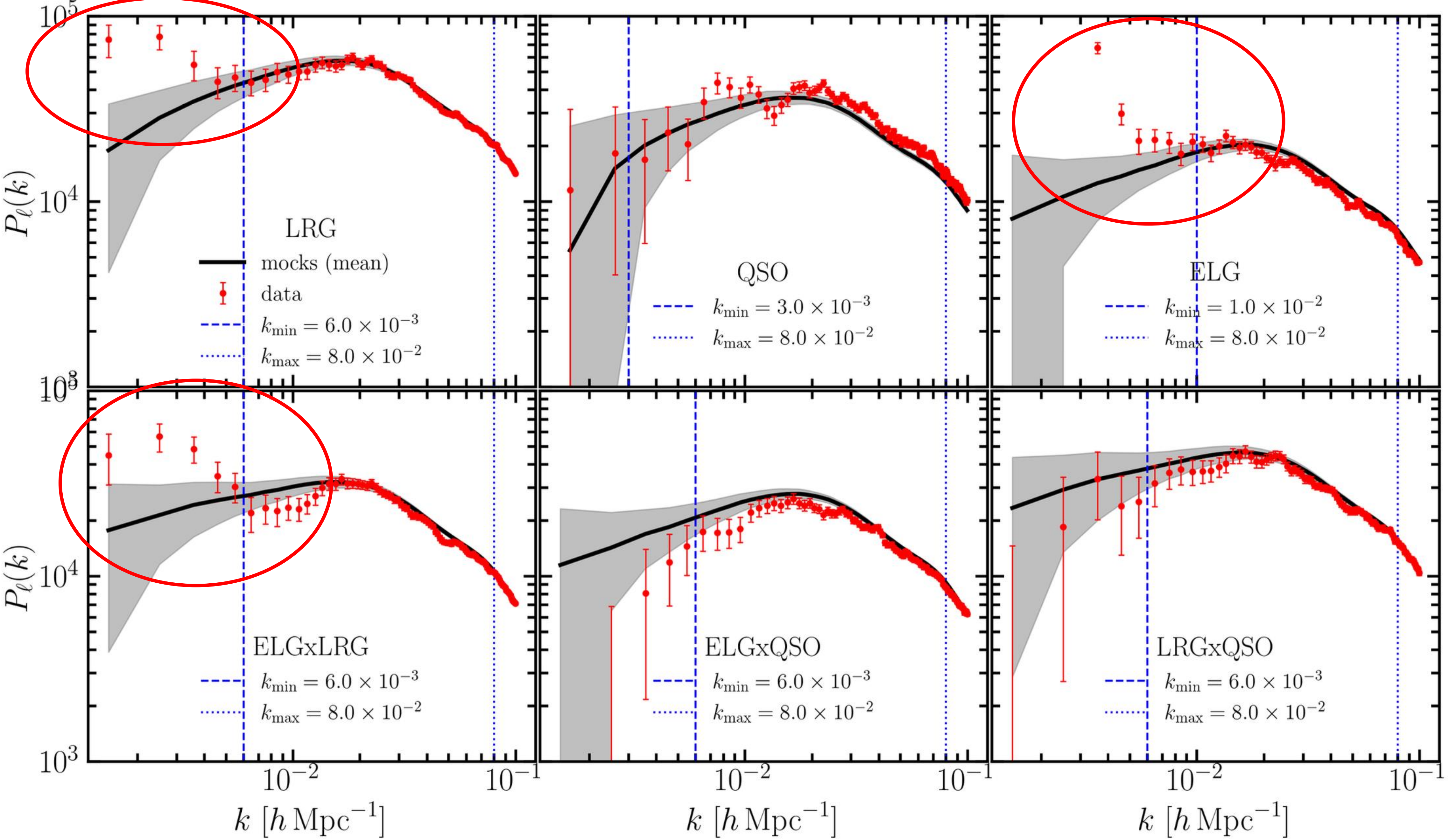
$$\propto \frac{f_{\rm NL}}{k^2}$$

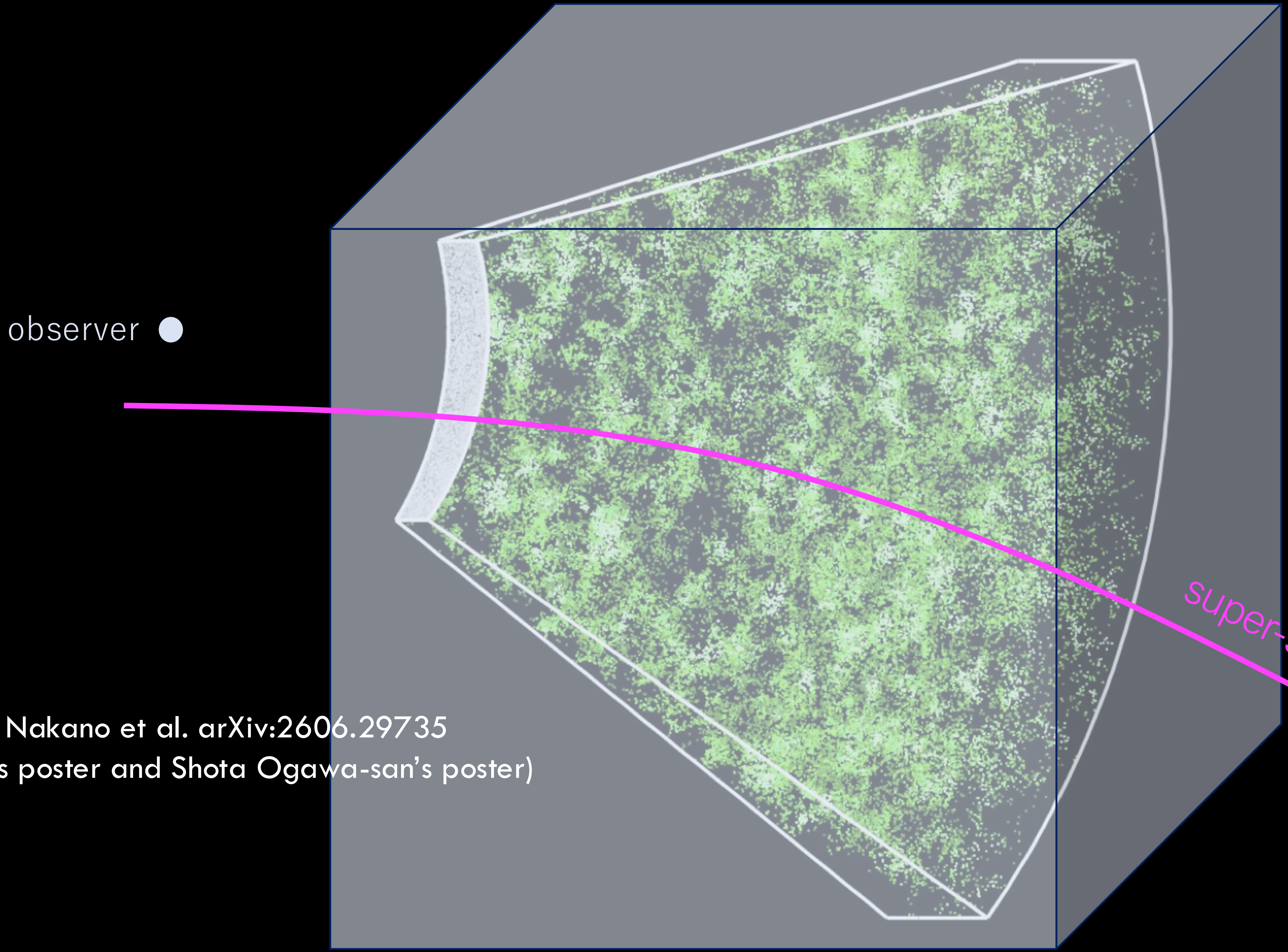
$$P_{\rm g}(k) = b(k)^2 P_{\rm m}(k)$$

- Signal (Physical) … or Systematics?
- Also see Rezaie, Ross+24; Rosado-Marin+26 for DESI imaging & DR1 results

Note: k_eq is also VERY interesting

DESI DR1 Rosado-Marin, Ross+ 26 (DESI 2021-)





Shintaro Nakano
(U. Tokyo/IPMU)

See Shintaro Nakano et al. arXiv:2606.29735
(see Shintaro's poster and Shota Ogawa-san's poster)

Goals of B01 team

- Construction of the high-fidelity PFS large-scale structure catalog (development of the pipeline in 2026; the first-year catalog in 2027)
  - Not only will PFS enable BAO and galaxy clustering analyses, but it will also provide a wide range of synergies with HSC weak lensing and CMB observations
- Measure BAO scales with PFS, to confirm or falsify DESI results (~2027 for the first-year data, and then ~2030 for final-year data)
  - A blind analysis is needed
- Search for PNG and primordial features from PFS (and the public DESI)
- Seach for time-variations in fine-structure constant from PFS [OII] doublets (2027-)
- Many other science cases and new ideas welcome!