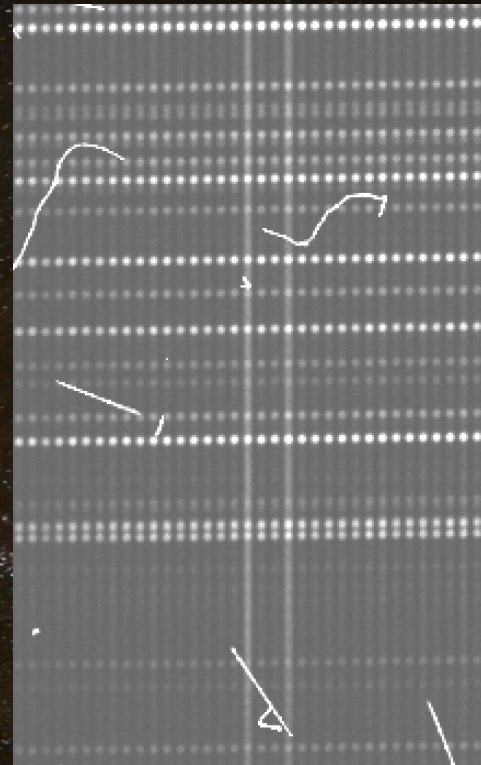
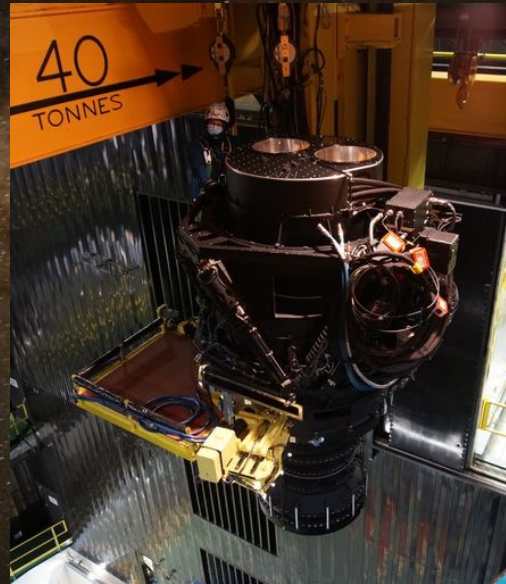
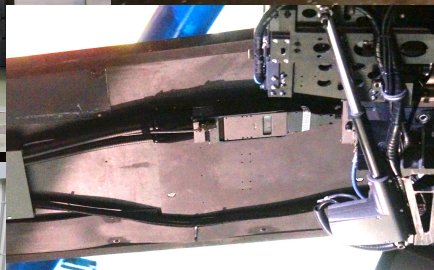
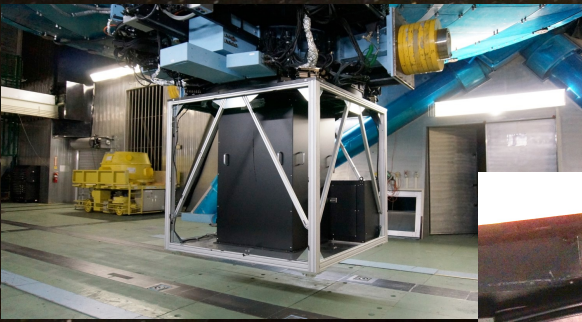


SUBARU PRIME FOCUS SPECTROGRAPH

Development of a next-gen facility instrument on Subaru telescope

The last phase has begun



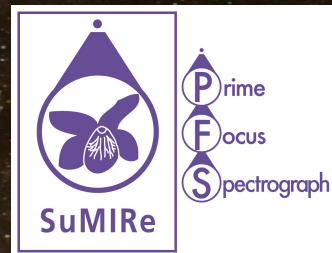
Naoyuki Tamura [Kavli IPMU]

Project Manager, Project Systems Engineer

On behalf of PFS Project Office & PFS collaboration

Prime Focus
Spectrograph

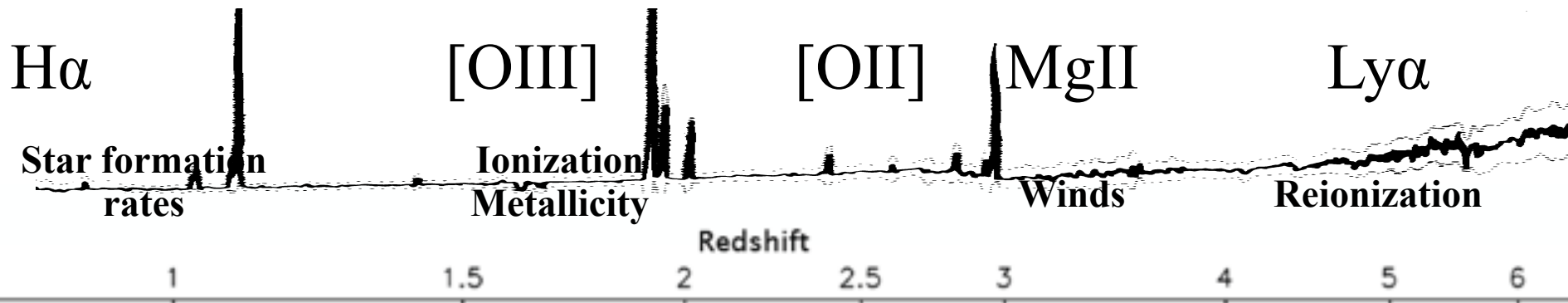
Mar 30 2022 JST
Dark Matter Symposium FY2021



M31 on a single shot
by HSC

PFS will configure
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.

Wide in wavelength range too:
380—1260nm at once with 3 cameras



PFS subsystems distribution

Software system

Spectrograph system (SpS)

Fiber connectors

Fiber cable

Prime Focus Instrument

... in Prime focus unit "POpt2" with Wide Field Corrector "WFC".

Calibration system

On the TUE floor

Wide-field corrector

(IR side)

4 spectrographs

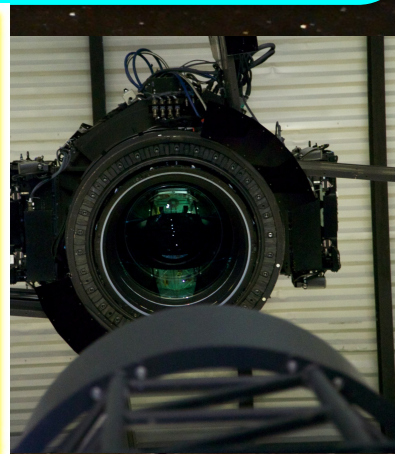
Fiber cable

Fiber cable

This takes an image of the prime focus with the fibers "backlit" and measure their current positions: *Key part of iterative fiber positioning process.*

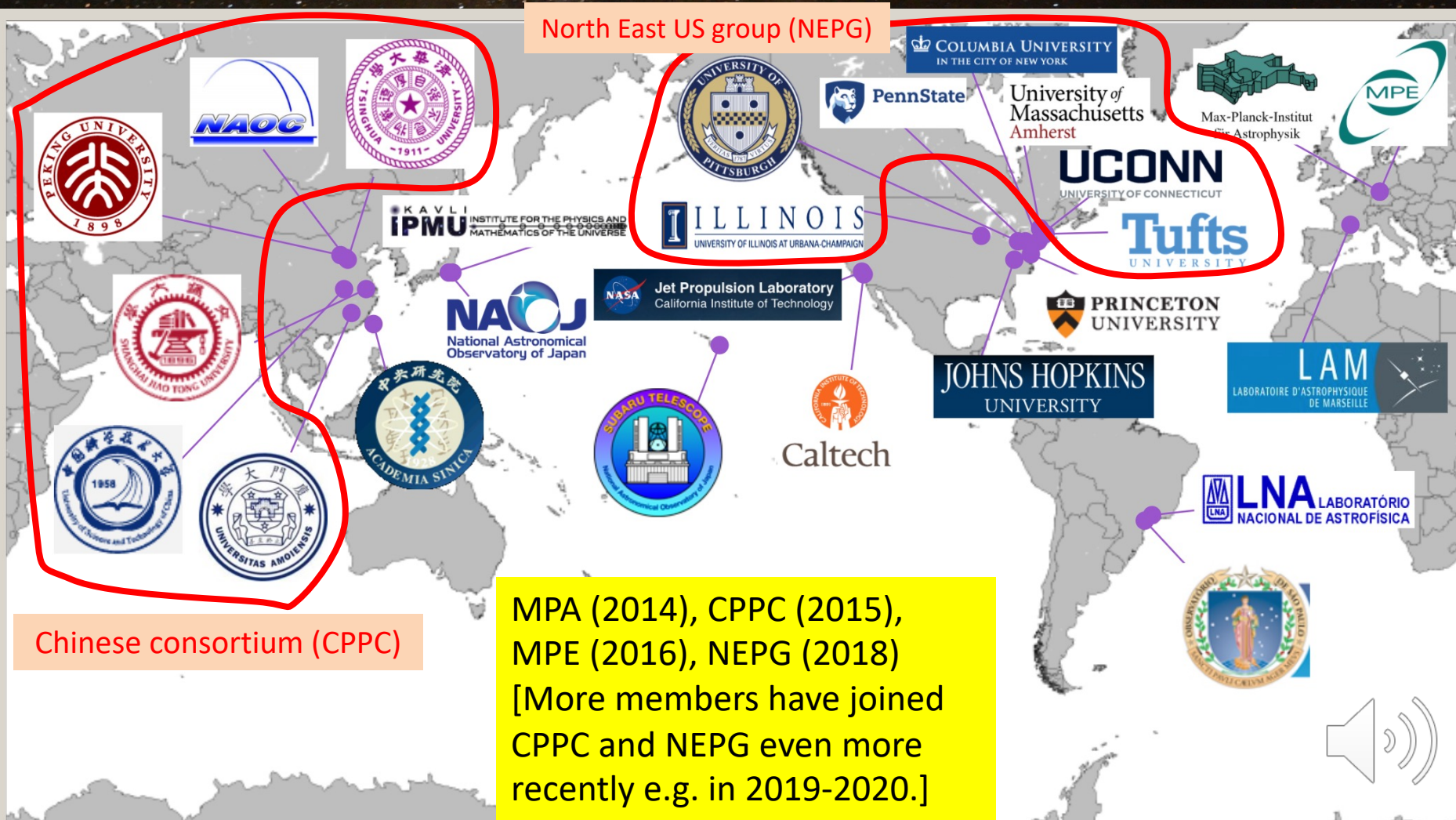
Metrology camera as a Cassegrain instrument

Subaru Telescope

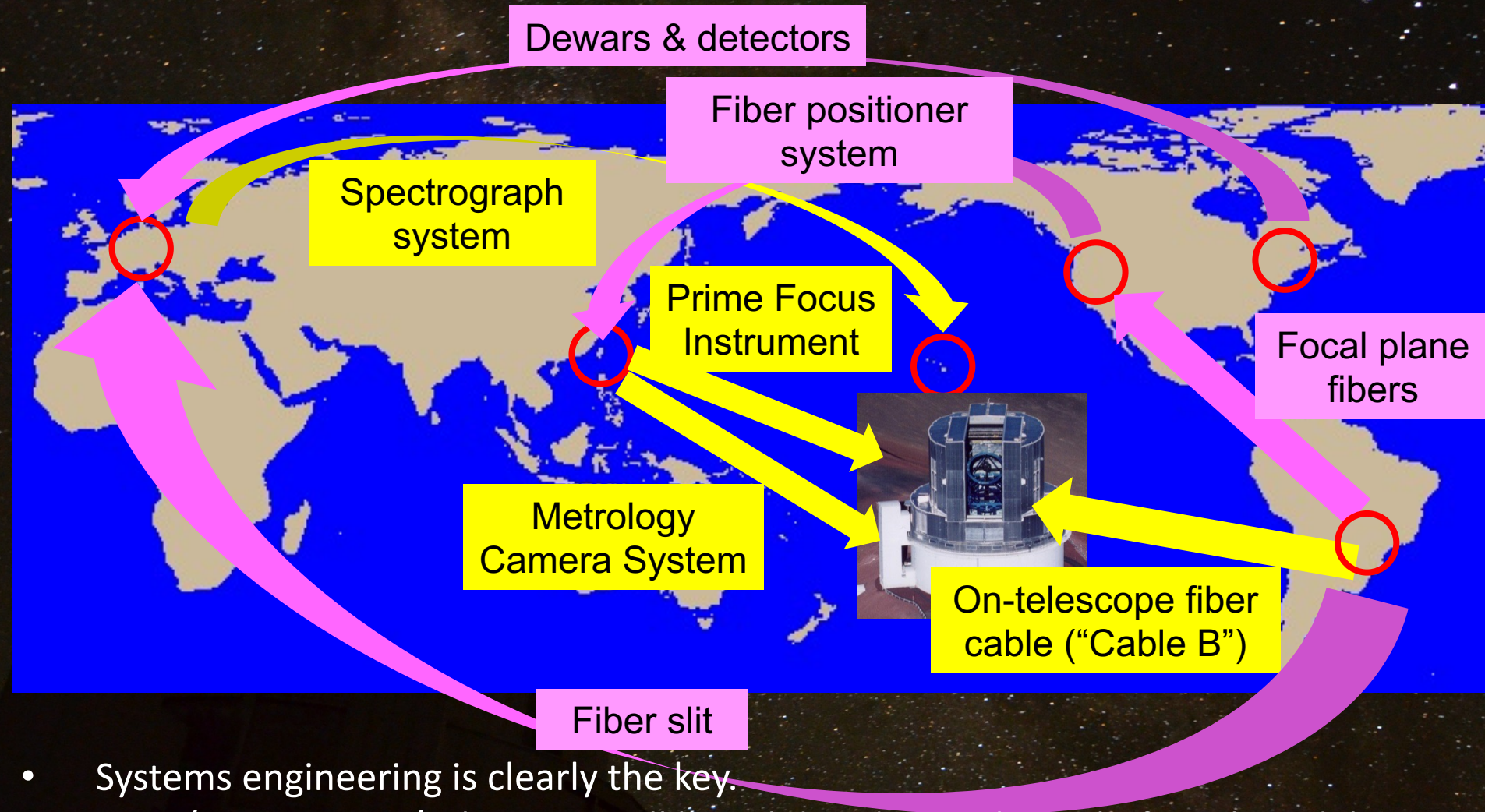


The growing PFS collaboration

Scientists & engineers in Japan & other 6 countries are co-working for instrument development & survey planning.



Logistics for PFS system integration



- Systems engineering is clearly the key.
- Parts/components/subsystem will be validated at each site before their delivery to other places for higher-level integration & finally to Subaru.
- Challenging especially under the circumstance due to COVID-19 ...

PFS subsystems distribution

The first spectrograph module has been fully assembled and tested, and is in operation in the dedicated clean room.

The 1st on-telescope fiber cable has been installed on the telescope.

READY!

Prime Focus Instrument (PFI) arrived at Subaru in June 2021.

2400 fibers steered by positioners

All fiber positioner modules have been installed onto PFI.

1st one is ... **READY!**

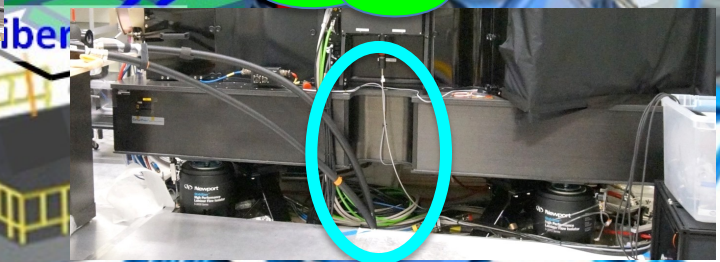
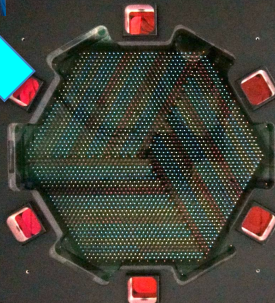
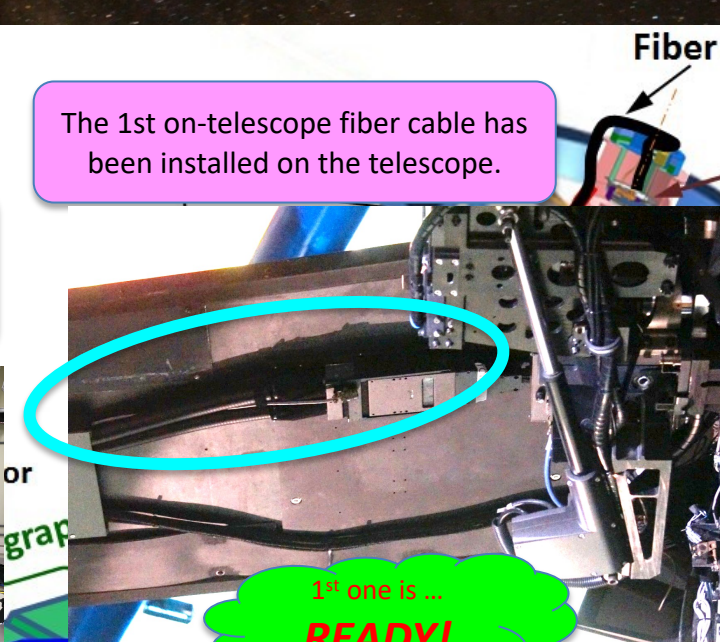
1st one is ... **READY!**

Metrology came as a Cassegrain instrument

READY!

The metrology camera that has been fully integrated and tested on the telescope.

Subaru Telescope



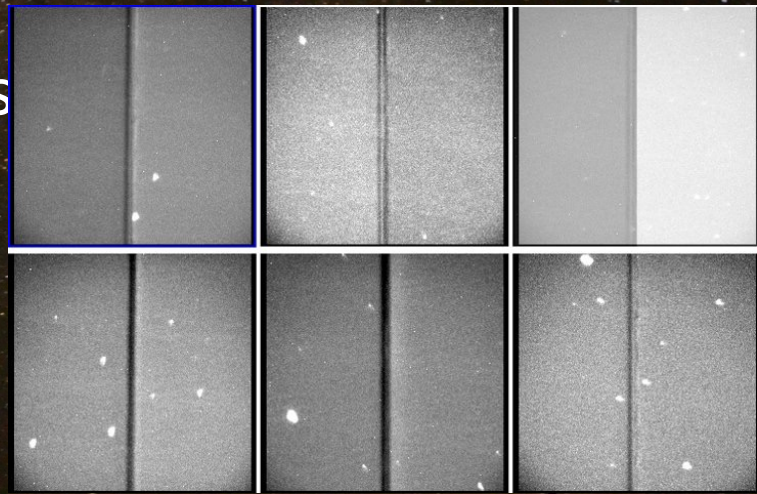
On-telescope on-sky tests started!!

- Hardware configuration
 - PFI, MCS, Cable B1 and SM1 w/ blue & red cameras
- Dates
 - (1) 9/13-26 2021
 - Kept the dome closed most of the time.
 - (2) 11/19-21 2021
- Progressed a lot in various aspects
- Next observations have been scheduled in May and June 2022.

Hybrid style →

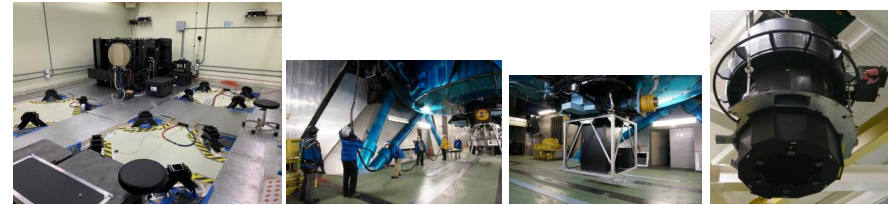
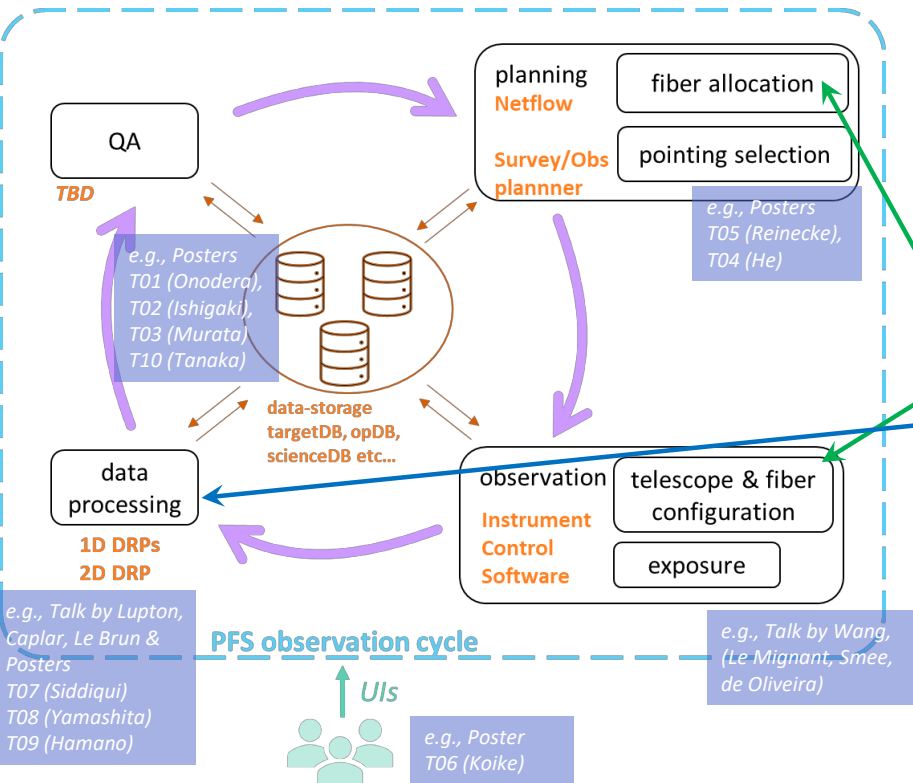


AG camera FIRST LIGHT !!



PFS operation and overview of commissioning flow

The ultimate goal is to optimize the PFS performance and validate the goodness for scientific use = establish this ↓



↓ We can start it w/ delivered subsystems We are here now.

1. Integrate PFS subsystems of which the performances have been validated by the PFS collaborators.
2. Operate the system and confirm their functions on the telescope.
3. Characterize the system, mainly
 - Calibrate the coordinate systems to put the fibers on the targets with required accuracy.
 - Characterize PSF/LSF of spectra for data processing
4. Evaluate the on-sky performance and validate it.
 - Firstly, we focus on verifying the performances at given telescope positions, rotation angles.
5. Finally stabilize the instrument performances.
 - We optimize software, re-configuration sequence, calibration and so on.
 - We validate the performance at any telescope pointing or time.

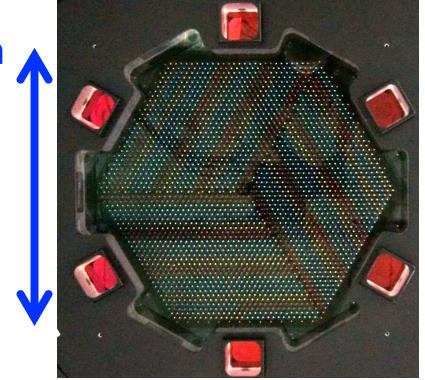


7mm between
Adjacent Cobras

On-telescope

Cobra target convergence

40cm



9

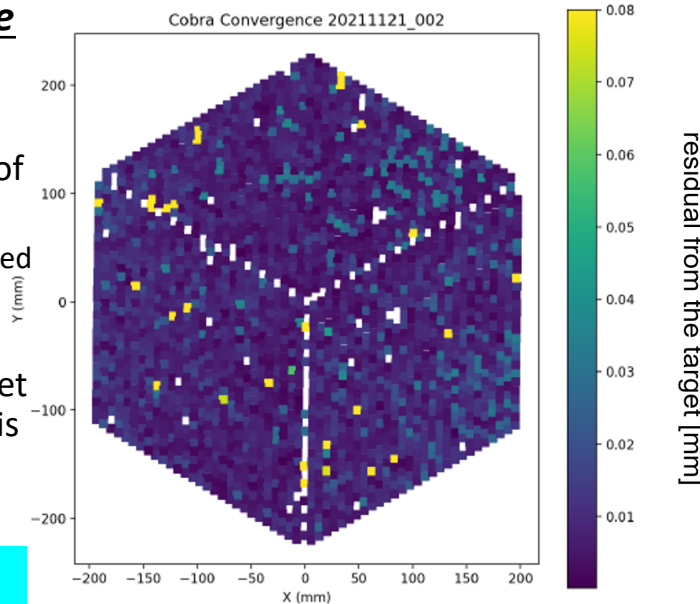
The fiber positioners "Cobra" are working well:

- The number of non-converged Cobras is typically several tens out of ~2350 (<5%).
 - Excluding the Cobras that are disabled due to known issues (broken, badly behaving, etc).
- The residual distance between target positions and Cobra final positions is **~10um** on PFI focal plane.

Improvements are in pursuit:

- ~100% convergence
- Stability & robustness

How these target positions can be set correctly need to be checked by on-sky observations.



↑Color-coded residual distances of the fibers from the targets **set in XY** over the PFI focal plane.

Commands & mechanisms for coordinated operation have been in place to routinely carry out the convergence process:

- Loading and ingesting pfsDesign
- Iterative moves of Cobras to the targets
 - Turn on fiber back illumination (PFI & SpS)
 - Centroiding backlit fiber spots on MCS images
 - Coordinate transformation to PFI coordinate
 - Moving Cobras towards the targets on PFI
 - Processing MCS images again and Judging the Cobra convergences

More works are needed for:

- Processing optimization
- Quality assurance
- Visualization

Current status: Data processing / instrument performance

Data processing

- Analysis of SuNSS spectra suggests that accuracy of sky subtraction $\sim 0.6\%$
 -> *Performance for PFS spectra is to be tested/developed.*
- A couple of on-sky PFI spectra taken (at zenith, w/o intentional target assignment)

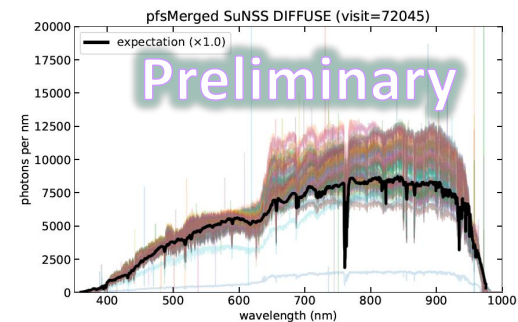
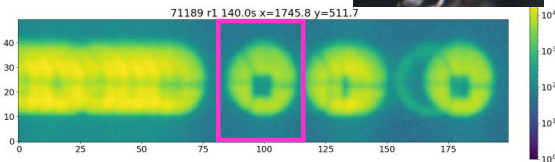
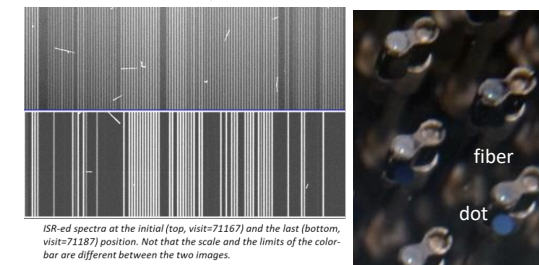
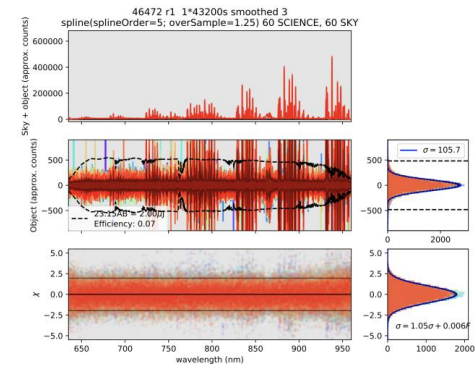
Calibration data with PFI is the keys for further development:

- Arc, flat to create good “detectorMap” which defines fiber- λ relations on each detector.
- Data for PSF modeling: spectra of isolated fibers!
- *In 2021* we partly succeeded in taking such a spectra. *We are developing the Cobra movement methods and the dot position, and will be tested at the next runs.*

Instrument Performance

- The spectra of stars/galaxies needs to be taken
- Throughput study using SuNSS: the data are under analysis
- Dependence of throughput across FoV has been checked using the PFI data
 → ETC will be updated.

In May and June, more calibration data and sky/target spectra will be taken including dark nights (hopefully), which will give us the idea about performance of sky subtraction, and how much it can be improved. In the S22B semester, we will validate instrument performance using dark nights more realistically.

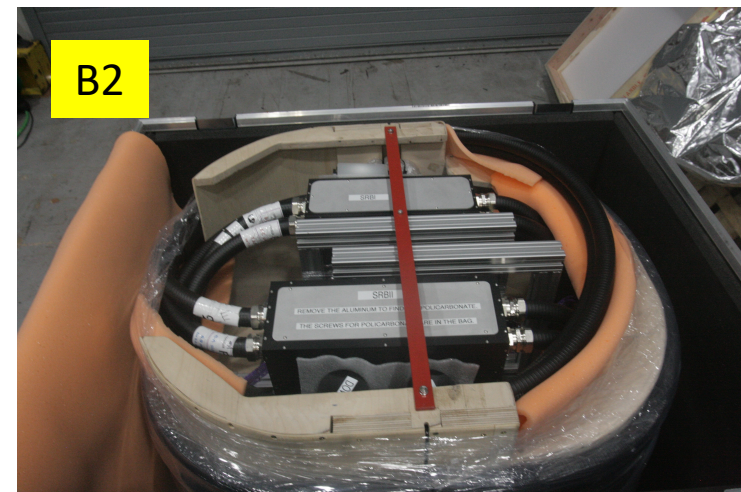


Overall project status

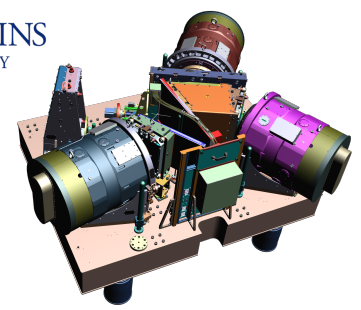
- Commissioning is ongoing:
 - Using PFI, MCS, Cable B#1, and SM1 B+R so far.
 - On-telescope test in Sep 2021, and engineering observation in Nov 2021.
 - May and June this year are the next.
- Still several hardware components need to be delivered to Subaru.
 - Cable B#3 & B#4
 - The rest of spectrograph system including all NIR cameras.

On-telescope fiber cable (“Cable B”)

- Second cable (“B2”)
 - Already at the Subaru summit.
 - Passed post-shipment inspections and optical continuity tests.
 - **Pre-installation optical tests and installation to the telescope will be carried out in the next two weeks.**
- Third & fourth cables (“B3” & “B4”)
 - Integration & test works are complete at LNA in Brazil.
 - **Passed the pre-ship review and will be shipped to the observatory soon.**
 - *These are the last works by the PFS team in Brazil.*

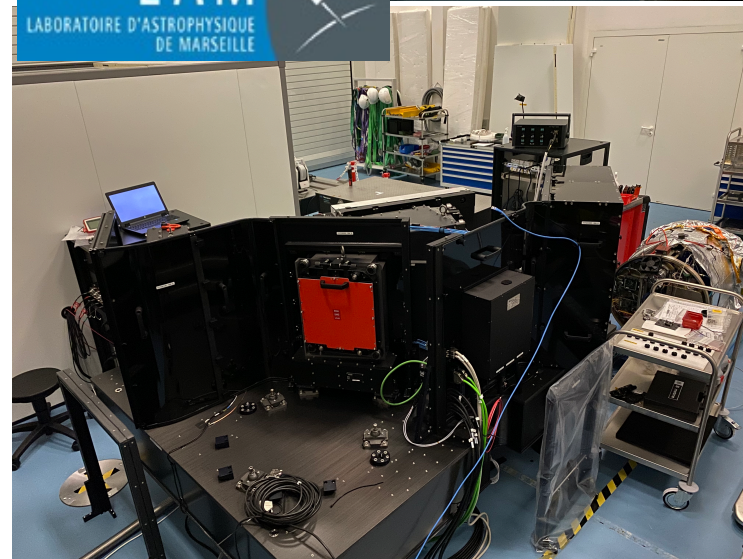
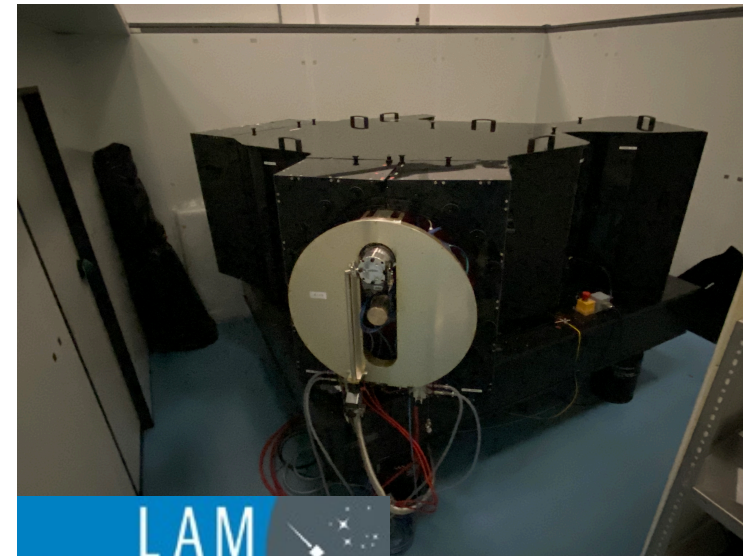


In total 4 cables were produced and they turned out to be very similar mechanically and optically.



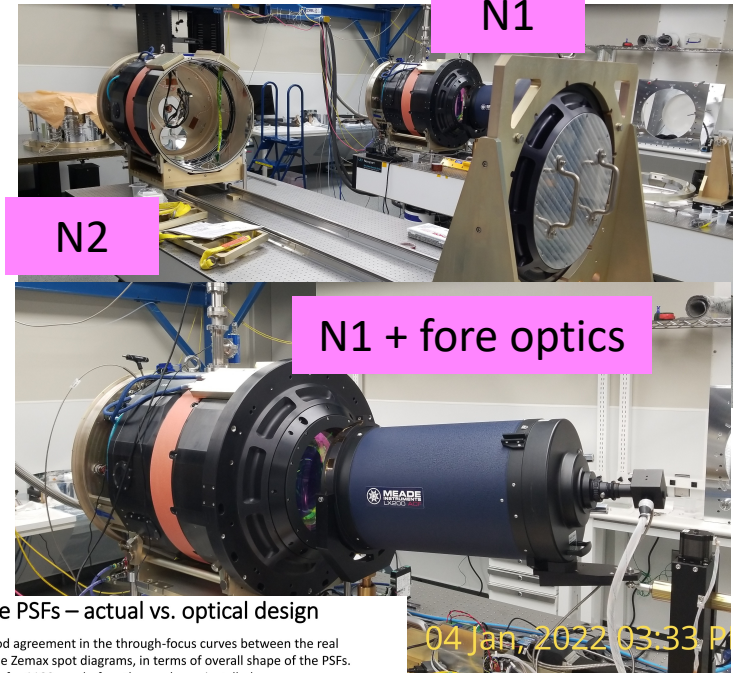
Spectrograph System (SpS)

- Spectrograph Module (SM) #2 and #3 are being integrated and tested.
- However, a while ago the team found an unexpected tilt offset of detector plane against the focal plane which has been stalling/slowing down the progress.
- The team is developing a method to accurately correct for this tilt offset and testing its robustness against e.g. thermal cycles. They have also put additional metrology processes during integration to be sensitive to such an error and its change.
- The goal is to deliver at least one SM (only w/ blue and red) and another one (w/ blue, red and NIR) to Subaru later this year.



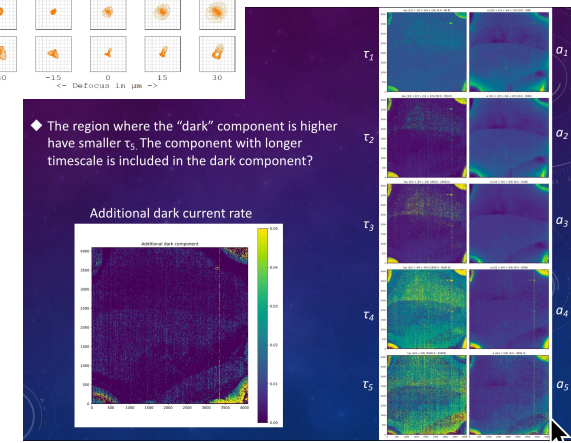
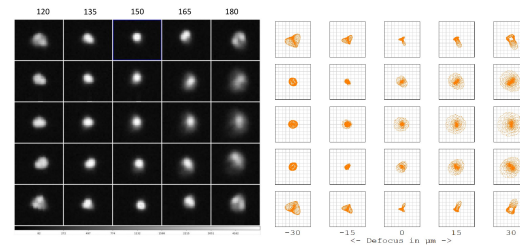
NIR Camera Unit (NCU)

- The 1st camera (#1) in the final 🙌 test campaign
 - So far the image quality looks good and as expected.
 - The thermal performance also looks good.
 - The special coating are applied on the two optics in the camera to suppress thermal radiation reaching the detector.
 - This coating process is nearly complete for all the 4 cameras.
- In parallel:
 - The 2nd camera (#2) is ready for alignment.
 - The 3rd cryostat testing is complete.
 - The 4th cryostat is to be tested.
 - The H4RG detector testing is being done in a dedicated dewar before its integration into the camera to measure QE, characterize persistence & take imaging flats.
- The goal is to deliver #1 to LAM in May, #2 to Subaru in ~Summer-Fall this year.



NIR1 Image PSFs – actual vs. optical design

We are seeing good agreement in the through-focus curves between the real image data and the Zemax spot diagrams, in terms of overall shape of the PSFs. This comparison is for 1180 nm, before the mask was installed.



Science with PFS in the dark sector of the universe

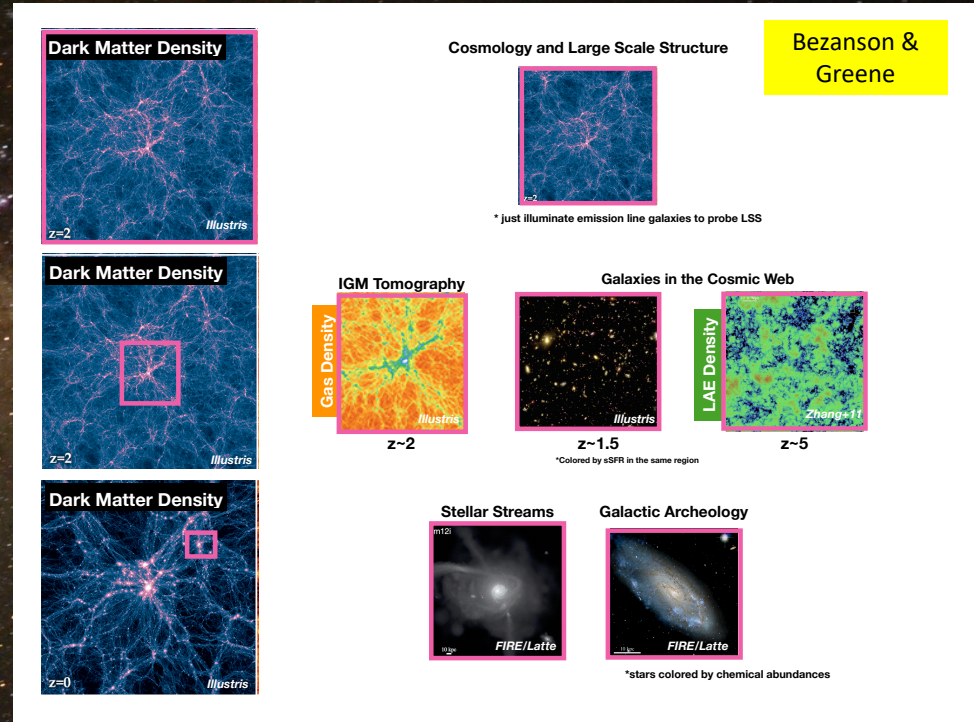
Comprehensive challenges to the major questions of modern astronomy & cosmology by three pillar survey components:

PFS large-sky survey in the framework of Subaru Strategic Program (SSP).

- ~360 nights for ~5 years
- Three pillars
 - Cosmology
 - Galaxy & AGN evolution
 - Galactic Archaeology

Timeline:

- System integration & survey planning are ongoing.
- On-sky commissioning from late 2021 to mid 2023.
- Science operation from 2024.
- \$100M project, \$1M shortage



	Testing Λ CDM	Assembly history of galaxies	Importance of IGM
CO	<ul style="list-style-type: none"> • Nature & role of neutrinos • Expansion rate via BAO up to $z=2.4$ • PFS+HSC tests of GR 	<ul style="list-style-type: none"> • PFS+HSC galaxy association • Absorption probes with PFS QSOs and HSC host galaxies 	<ul style="list-style-type: none"> • Search for emission from stacked spectra
GA	<ul style="list-style-type: none"> • Curvature of space: Ω_K • Primordial power spectrum 	<ul style="list-style-type: none"> • Stellar kinematics and chemical abundances – MW & M31 assembly history 	<ul style="list-style-type: none"> • dSph as relic probe of reionization feedback • Past massive star IMF from element abundances
GE	<ul style="list-style-type: none"> • Nature of DM (dSphs) • Search of MW dark halo • Small-scale tests of structure growth 	<ul style="list-style-type: none"> • Halo-galaxy connection: M_*/M_{halo} • Outflows & inflows of gas • Environment-dependent evolution 	<ul style="list-style-type: none"> • Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

PFS 360-night SSP survey: Proposal under development

COSMIC EVOLUTION AND THE DARK SECTOR: A PFS SSP FOR THE SUBARU TELESCOPE

THE SUBARU PRIME FOCUS SPECTROGRAPH (PFS) COLLABORATION

The full author list is given in the Appendix

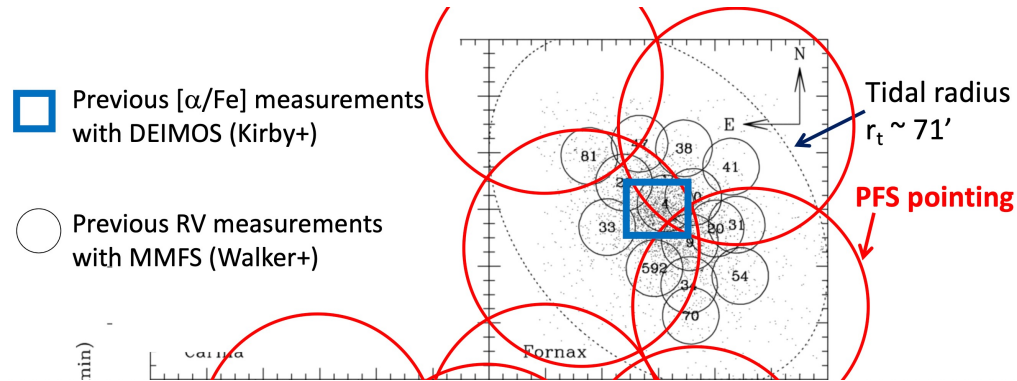
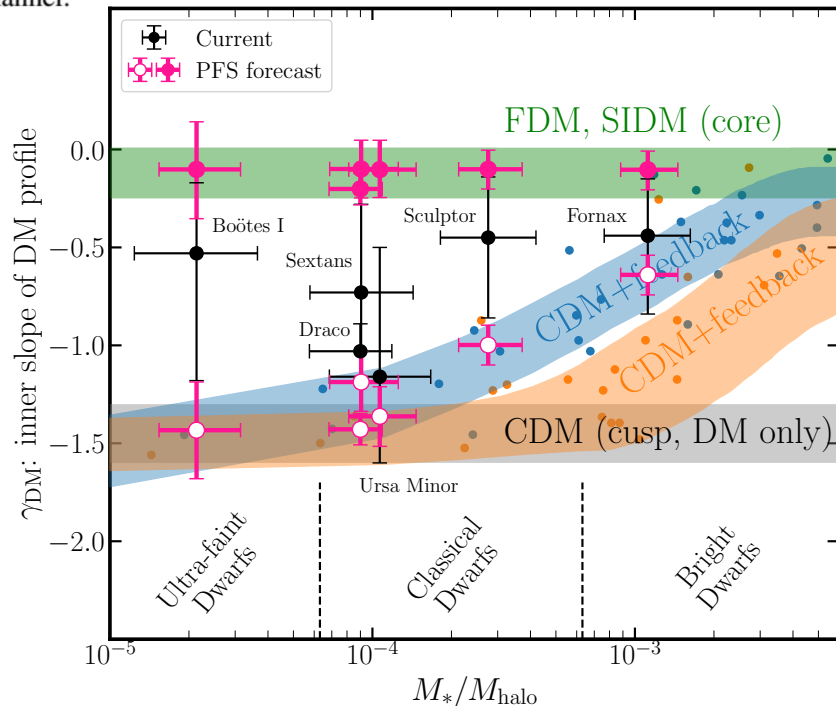
Draft version March 23, 2022

Latest version 3/23

ABSTRACT

We propose a large-scale survey with PFS to address fundamental and important questions in the dark sector (dark matter and dark energy) with significant implications for cosmology, galaxy evolution and the origin of the Milky Way Galaxy. The unique wide-field and massively-multiplexed spectroscopic capability of PFS will maintain and strengthen Subaru's world-leading role in cosmology and astronomy for the next decade. Our experienced team of astronomers from Japan and the international community has developed an ambitious 360 night survey to be undertaken over 5 years which fully exploits the unique capabilities of PFS to address outstanding questions relating to the history and fate of the Universe as well as the physical processes and role of dark matter in governing the assembly of galaxies including our Milky Way. We commit to fully reducing the data from this landmark survey and making it available to the global astronomical community in a timely manner.

- Bottom-up discussions in the individual WGs.
- Integration by survey simulation & integration team
- “Friendly” review by external experts
- Collaboration-level discussions at PFS collaboration meetings and science meetings.



Large potential of PFS to judge the validity of of FDM and SIDM thanks to its wide field coverage and high multiplicity (K. Hayashi+)

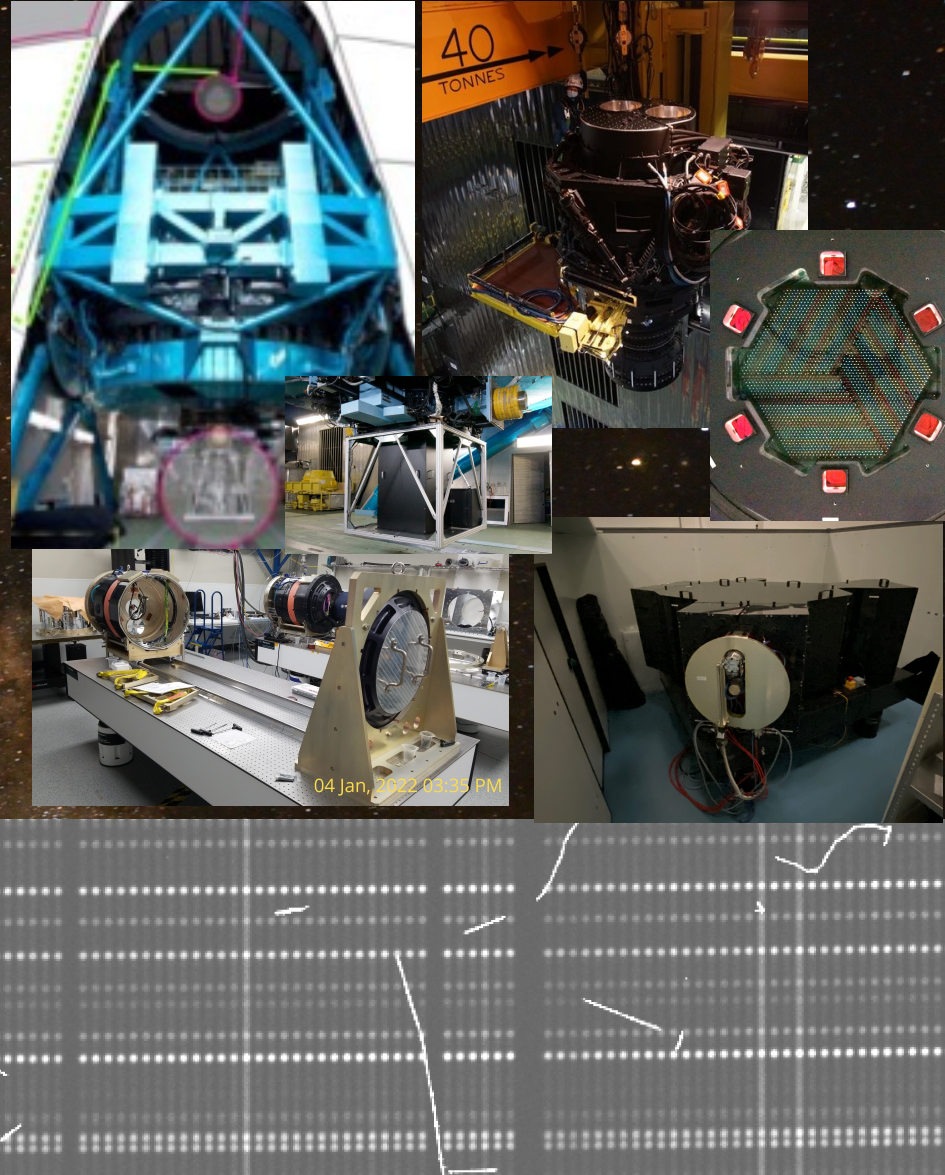
PFS is now coming out of the 4th corner for its scientific operation from 2024.

Commissioning started:

- After PFI arrival in June 2021, engineering tests and observations were carried out with PFI, MCS, CAB1 & SM1 B+R in Sep and Nov 2021.
- While various progresses were made, troubles delayed going beyond. But persistent efforts are ongoing towards formal First Light & continued success in the next runs in May & June 2022.

Remaining hardware is upcoming:

- Cable B3 & B4 passed pre-ship review.
- At least one SM in summer, and the other later this year.
- 1st NIR camera to LAM in May, and 2nd one to Subaru in ~Summer-Fall.



- ✓ Official web site - <https://pfs.ipmu.jp/>
- ✓ Membership registration - https://pfs.ipmu.jp/research/regist_collab.html
- ✓ Blog - <https://pfs.ipmu.jp/blog/>
- ✓ Instagram - https://www.instagram.com/pfs_collaboration/

