SUBARU PRIME FOCUS SPECTROGRAPH

Overview of the project, instrumentation, and survey planning



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SuMIRe

Prime Focus Spectrograph

6th Galaxy Evolution Workshop at Kavli IPMU, Jun 5-7, 2019

Presentation outline

- Quick skimming of:
  - the project, collaboration, and instrumentation.

- General aspects of survey planning:
  - Its spirit!?
  - The current status
  - For your participations

- Then hopefully naturally connected to:
  - Kiyoto's and Miho's talks about some details of the current survey plan.
  - Discussion session

Highlighting a few important updates first

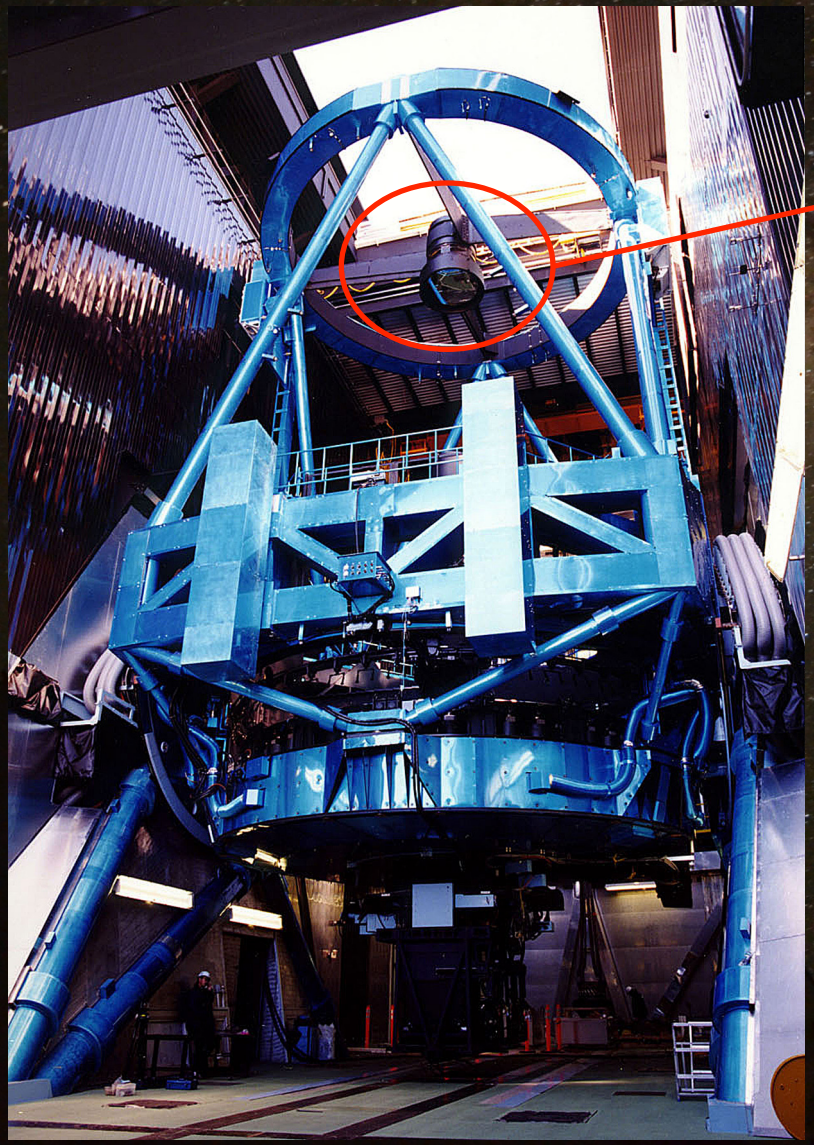
Maybe I have too many slides for the given timeframe …

- ***Technical*** – i.e. instrumentation
  - In April 2018, we delivered *the first PFS subsystem to Subaru*.
  - Two other subsystems aim to be partially delivered this year.
- ***Programmatic*** – i.e. finance & schedule
  - *~96% of total cost (US$~85M)* is secured. Fundraising is continuing (with *some recent success* e.g. private funds, new participants).
  - Pursuing to start engineering observation early 2020, and science operation from 2022.
- ***Scientific*** – i.e. survey planning
  - *The "SJ" has been refined a lot better*. Feasibility studies & survey simulations are actively ongoing to mature the "TJ".
  - A mechanism has been in place *for strategic, coherent integration* of bottom-up studies.

Now then, real contents are coming ☺



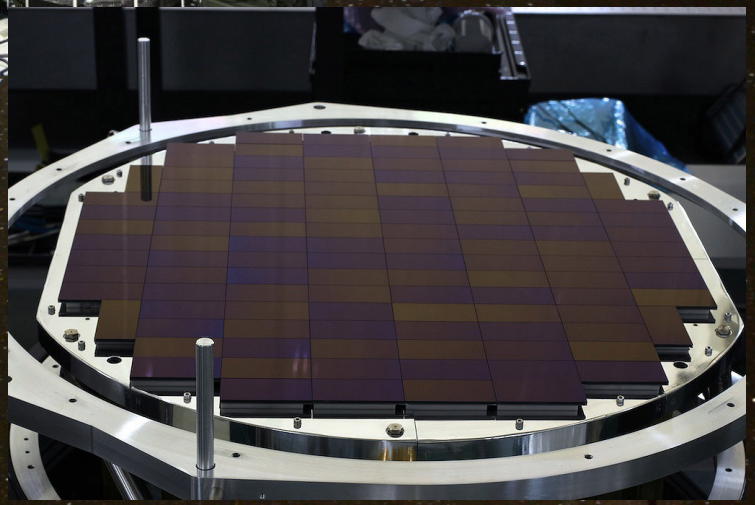
Subaru Telescope Prime Focus with Hyper Suprime Cam (HSC)





Largest camera

- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)



The history of Subaru Prime Focus Field of View



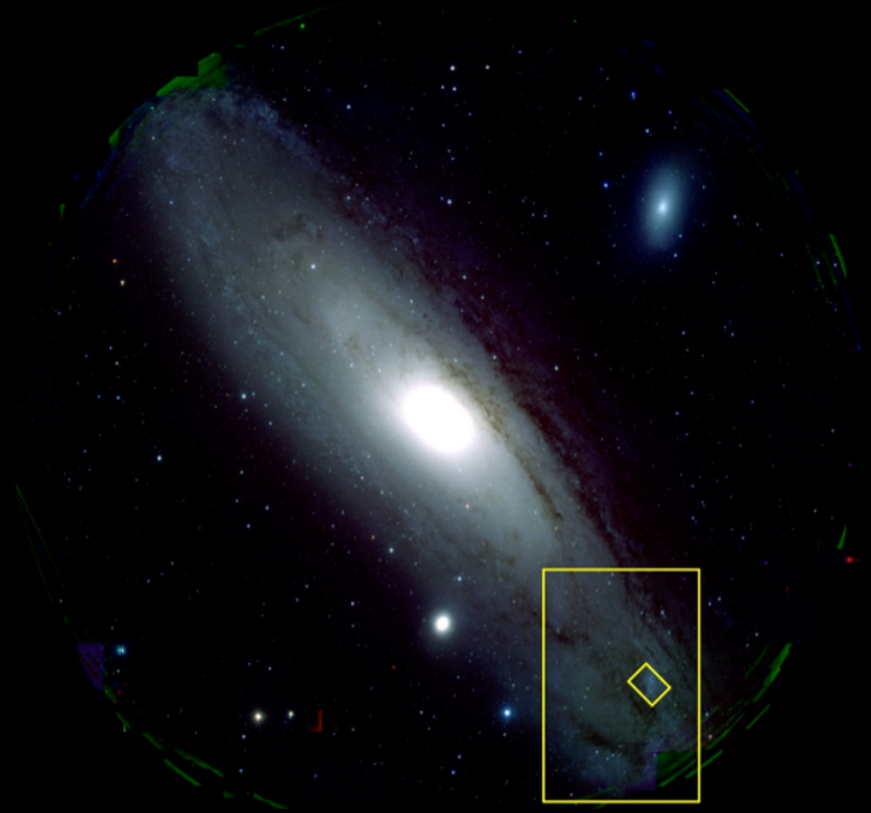
The full Moon
~0.5 deg diameter



Suprime-Cam
First Light
(Released Jan 1999)

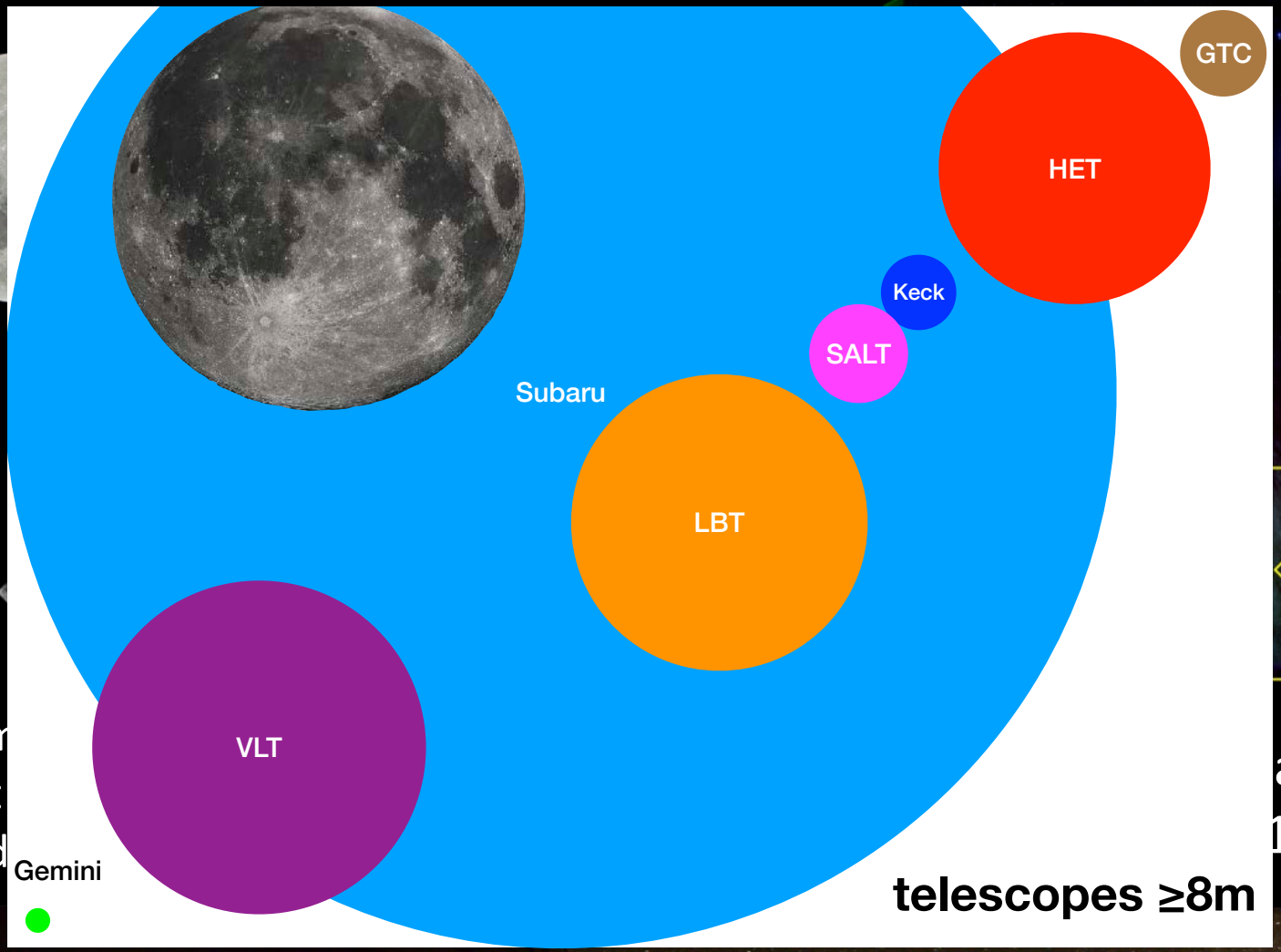


Suprime-Cam
Full operation
(Released Sep 2001)



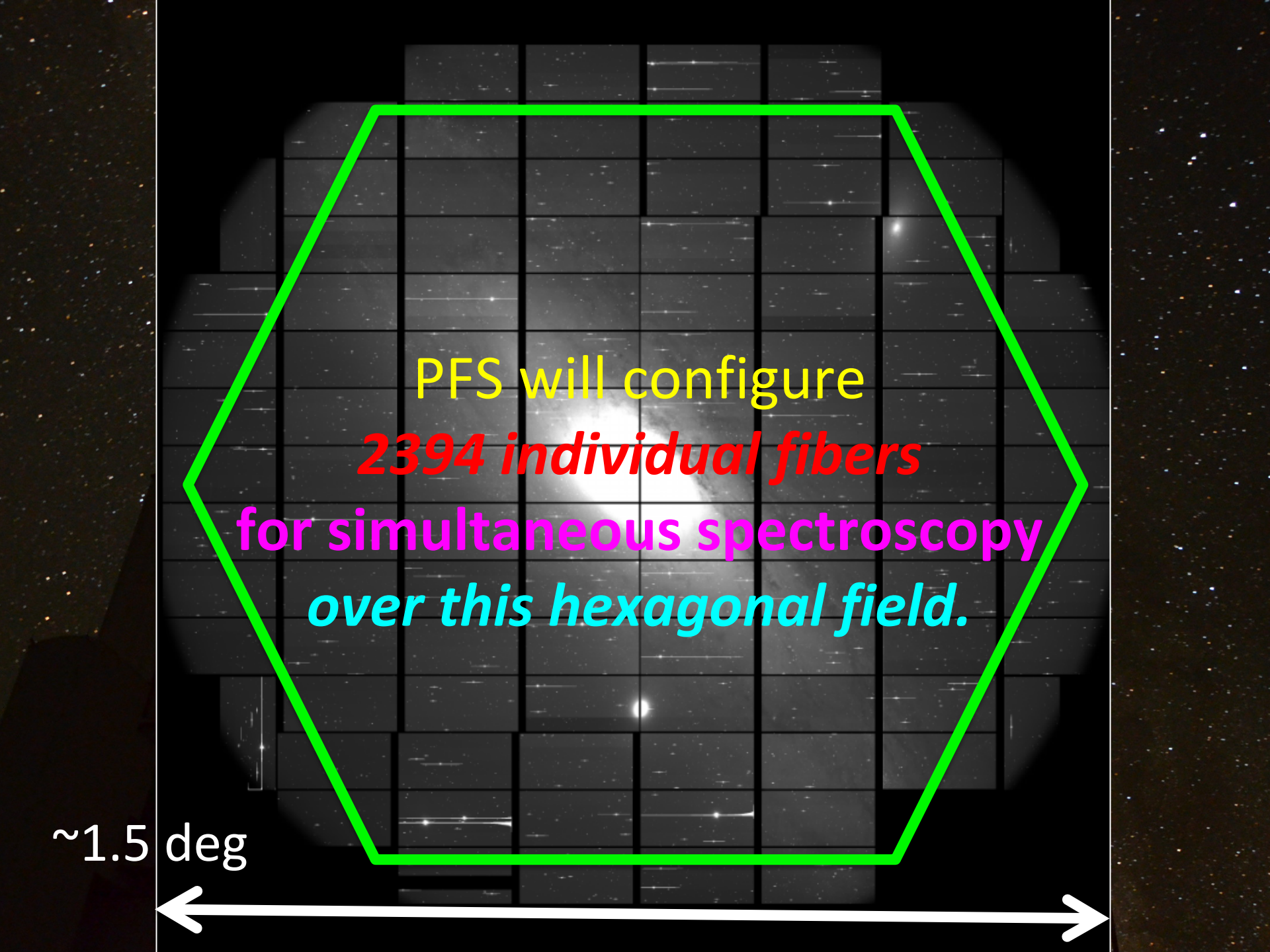
Hyper Suprime Cam
(Released Jul 2013)

The history of Subaru Prime Focus Field of View



Suprim
First
(Released

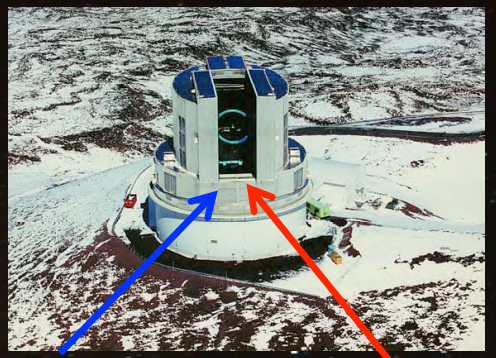
am
13)


PFS will configure
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.
~1.5 deg

SuMIRe project

Subaru Measurement of Images and Redshifts

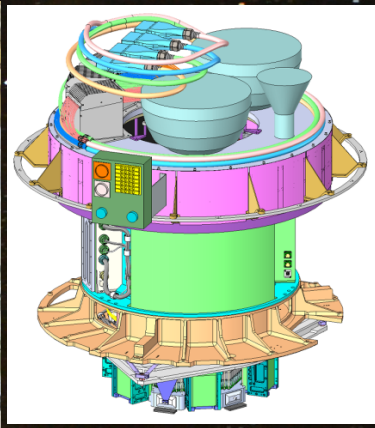




Exploiting the large light-collecting power of the Subaru Telescope & wide field at its prime focus:

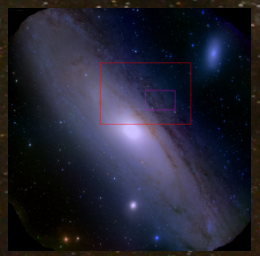
- *Imaging survey by "Hyper-Suprime Cam (HSC)"*
  - ✓ ~1 billion pixels
  - ✓ 300 nights from 2014 to 2019
  - ✓ 1400 sq. degrees, ~1 billion galaxies
- *Follow-up spectroscopic survey by "Prime Focus Spectrograph (PFS)"*
  - ✓ ~2400 optical fibers
  - ✓ ~300-360 nights over ~5 years
  - ✓ ~4M galaxy redshifts
  - ✓ ~1M stars in MW halo/disks/satellites & M31.

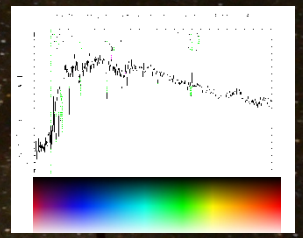








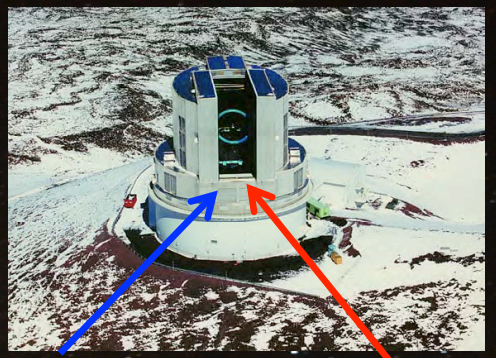




SuMIRe project

Subaru Measurement of Images and Redshifts





HSC PFS

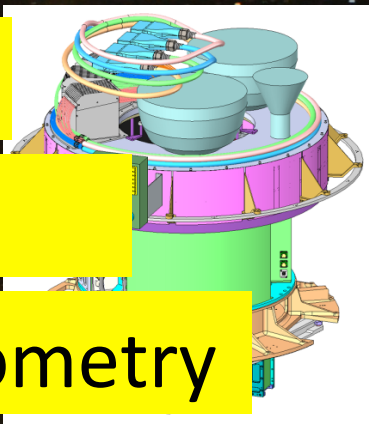
Exploiting the large light-collecting power of the Subaru Telescope & wide field at its prime focus:

Same telescope

Same patches of sky

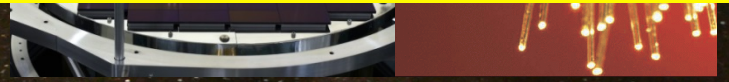
- ✓ 30
- ✓ 1400 sq. degrees. 1 billion galaxies

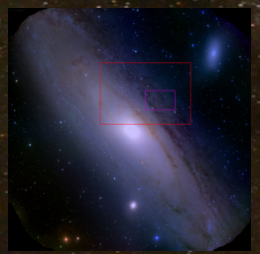
Clean target selection by deep photometry

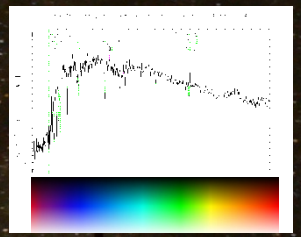


- *Follow-up*
- *"Prime Fo*
  - ✓ ~2400 optical fibers
  - ✓ ~300-360 nights over ~5 years
  - ✓ ~4M galaxy redshifts
  - ✓ ~1M stars in MW halo/disks/satellites & M31.

Spectroscopic information on top of detailed studies by deep & sharp images



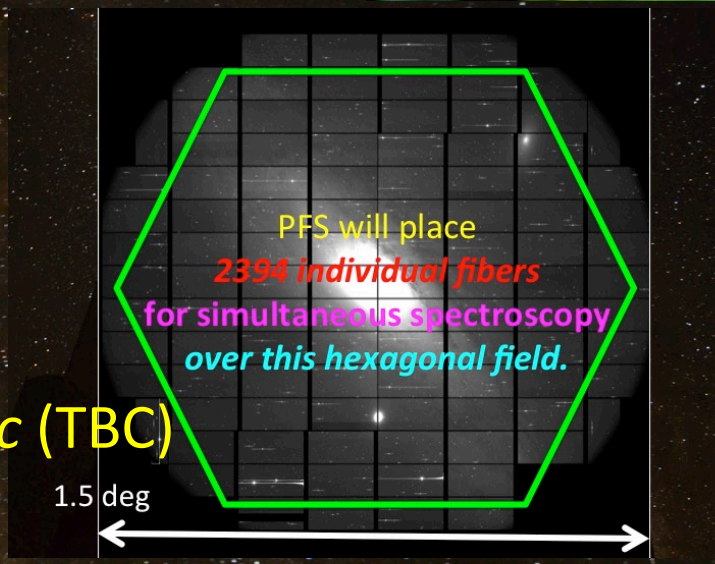




PFS - Fast facts



- Subaru *Prime Focus Spectrograph*:
  The spectroscopy part of the "SuMIRe" project.
  - Wide field: *~1.3 deg* diameter
  - High multiplicity: *2394 fibers*
    - Fiber diameter: ~1.05 arcsec
    - Fiber positioner pitch: ~85 arcsec
    - Minimum fiber separation: ~30 arcsec
  - Quick fiber reconfiguration: *~60- 120 sec* (TBC)
    - *Dynamic* survey strategy is allowed.
  - VIS-NIR coverage: *380-1260nm simultaneously*
    - Low resolution mode: ~2.5 A resolution
    - Medium resolution mode (around 800nm): ~1.6 A resolution



- The PFS instrument is being developed *to be a facility instrument on Subaru Telescope.*

The PFS collaboration



The *growing* PFS collaboration

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



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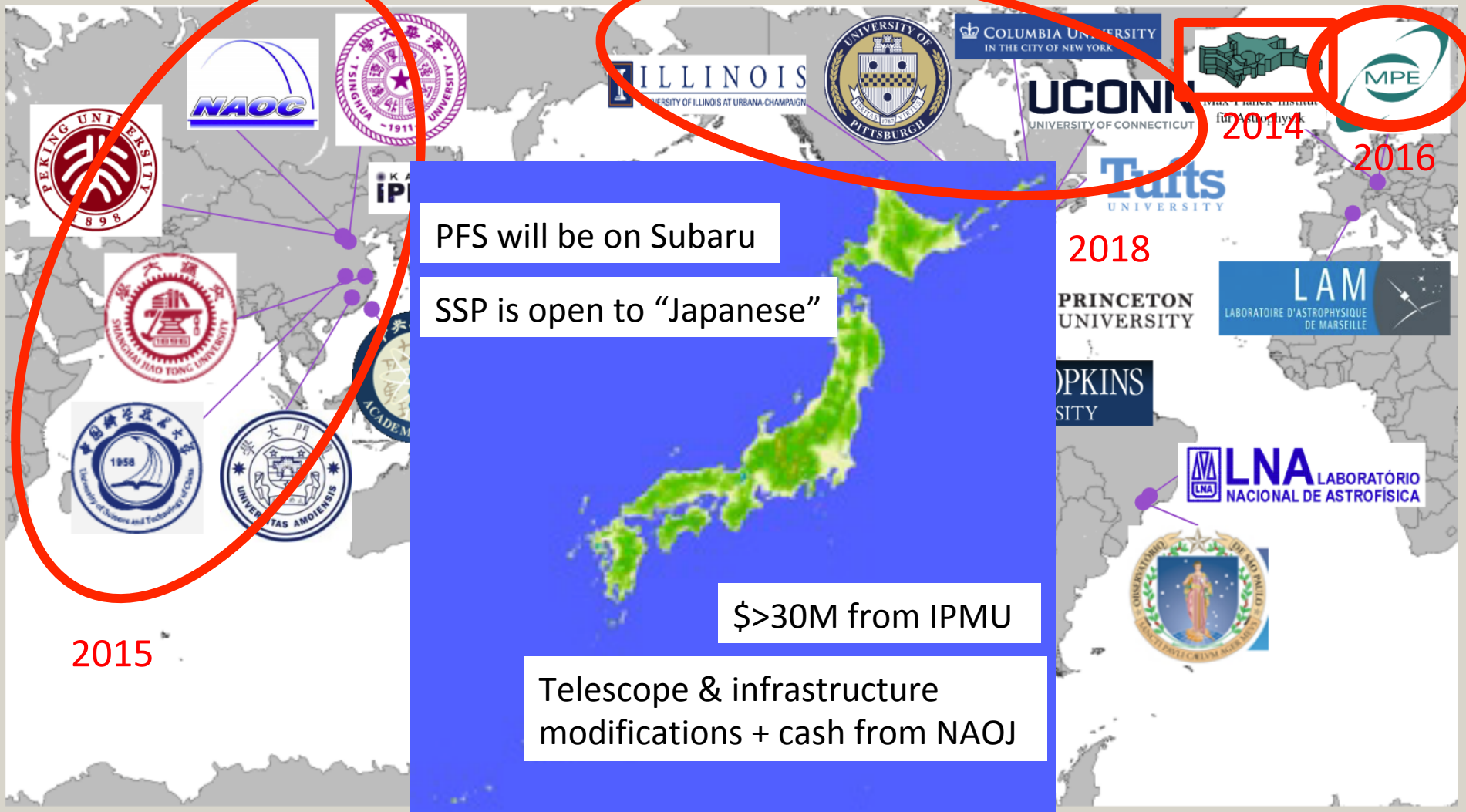


9th PFS collaboration meeting

- 5 days from Nov 27 to Dec 1 in 2017.
- At Kavli IPMU in Japan.
- ~130 participants (cf. ~80 is a typical number)



Dec 11, 2018
10th Collaboration Meeting



10th PFS collaboration meeting

Dec 10-14 2018 at Shanghai Jiao Tong University



Next collaboration meeting will be at Caltech from Dec 9 2019.

The PFS instrumentation



PFS subsystems distribution

Software system

Spectrograph system (SpS)

On the TUE floor
(IR side)

4 spectrographs

Fiber cable

Fiber connectors

Fiber cable

Prime Focus Instrument

Wide-field corrector

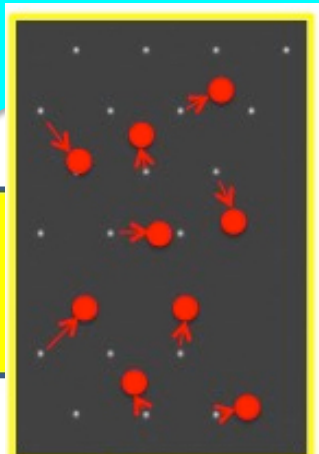
… in Prime focus unit "POpt2" with Wide Field Corrector "WFC".

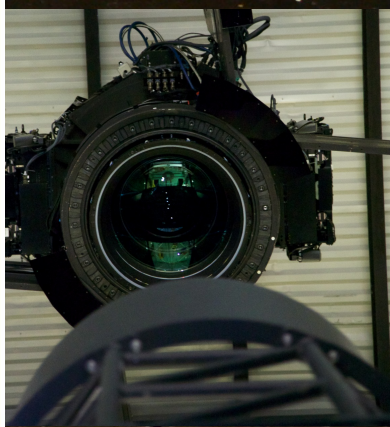
Calibration system



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

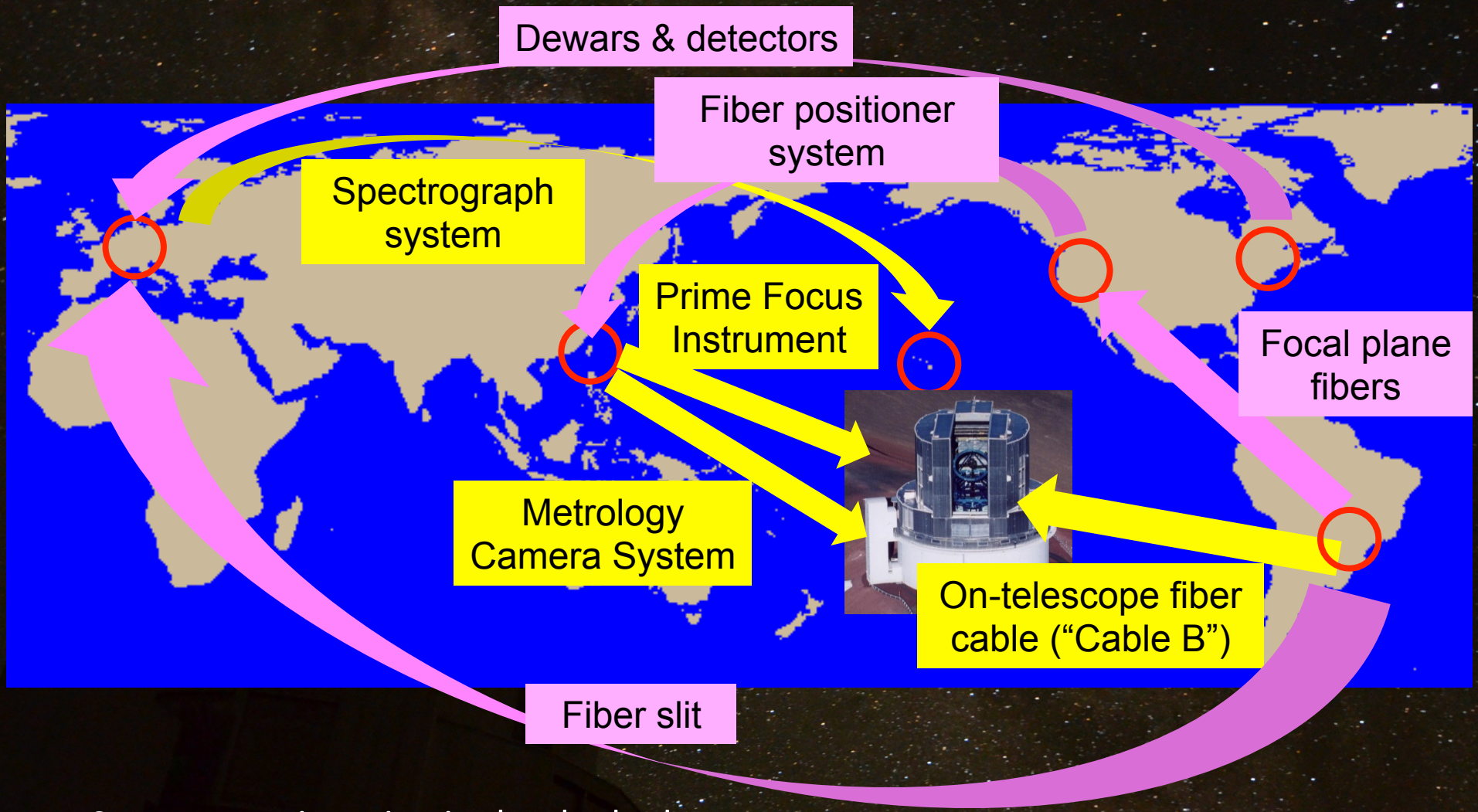
Metrology camera as a Cassegrain instrument





Subaru Telescope

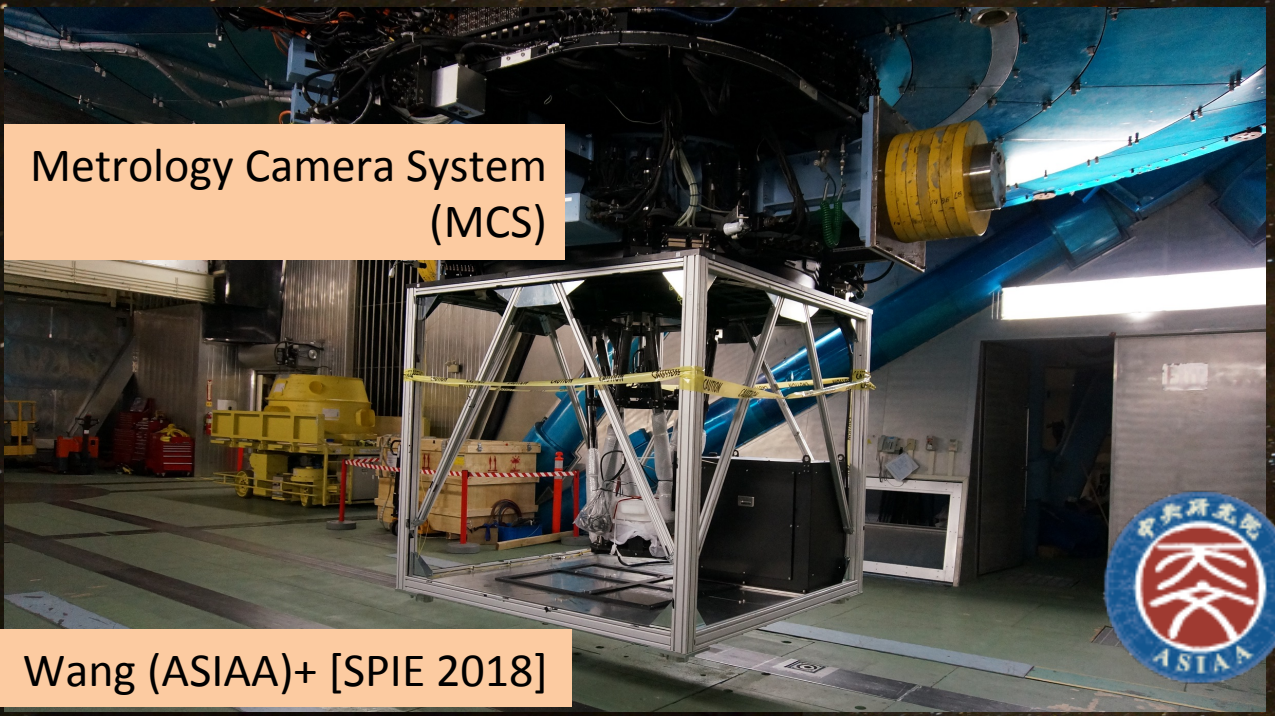
Logistics for PFS system integration



- 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.

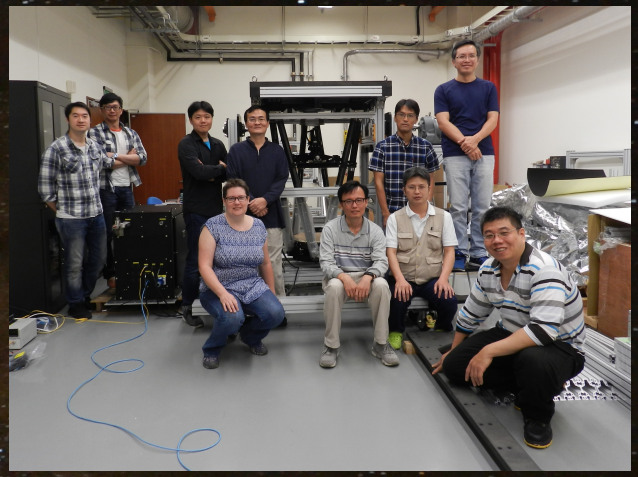
PFS subsystem at Subaru!

Delivered in April 2018
Subsequently re-integrated & tested.



Metrology Camera System (MCS)

Wang (ASIAA)+ [SPIE 2018]



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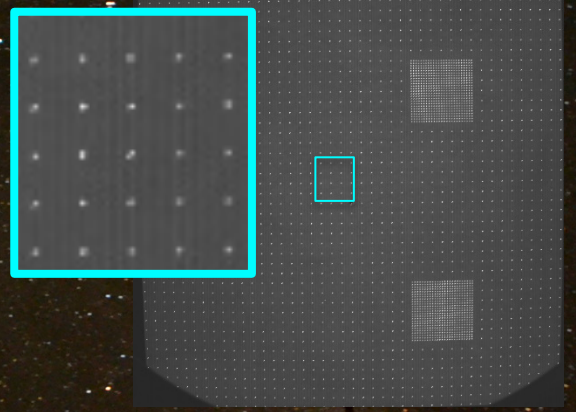
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

~6000 exposures on Oct 23-25 2018

- Imaged pinhole mask at Prime Focus that mimics backlit fibers.
- Operation software worked well.
- Motivated upgrade of data analysis rooutine.



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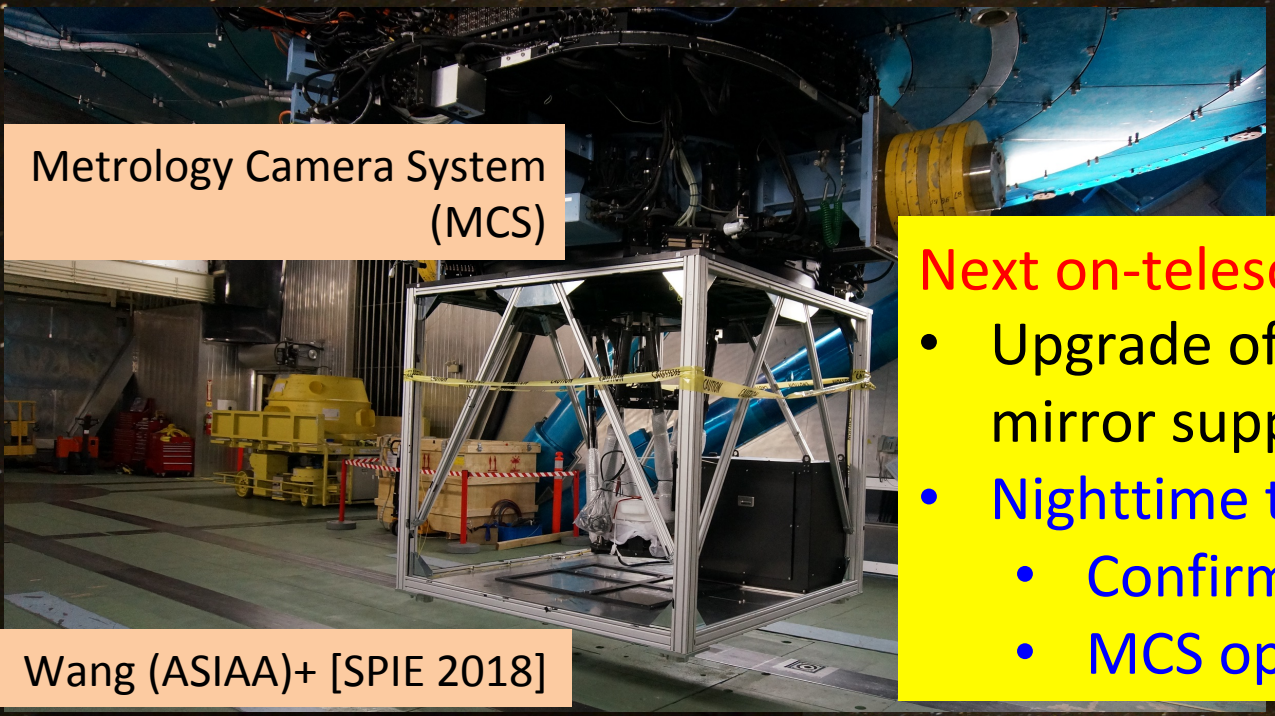

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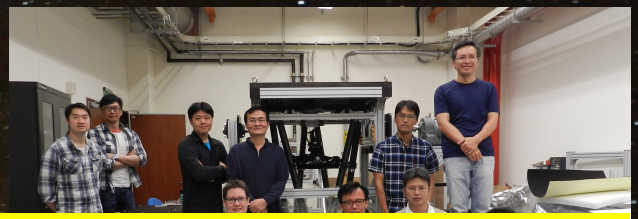

Next on-telescope runs in Aug:

- Upgrade of the MCS primary mirror support structure
- Nighttime test for:
  - Confirmation of image quality
  - MCS operation

~6000 exposures on Oct 23-25 2018

- Imaged pinhole mask at Prime Focus that mimics backlit fibers.
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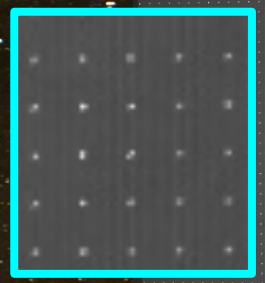
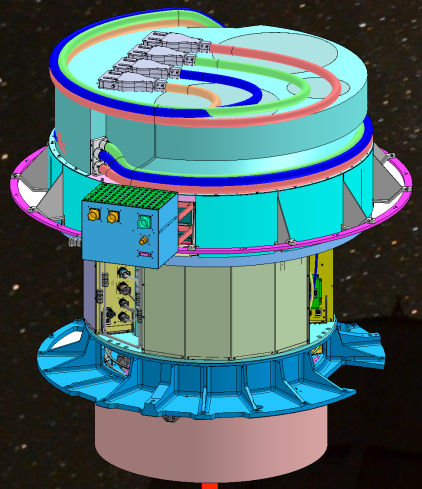
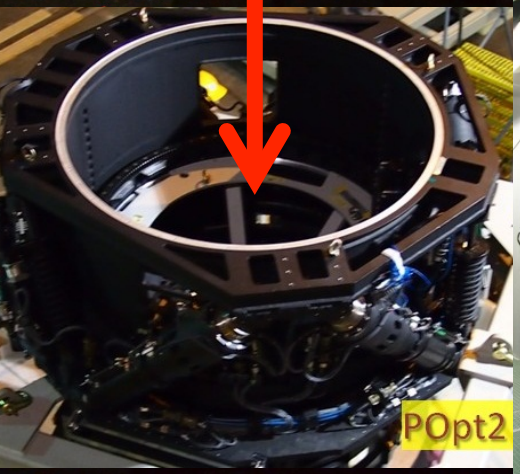


Prime Focus Instrument (PFI)

Sits in the prime focus unit “POpt2” and installed to the telescope

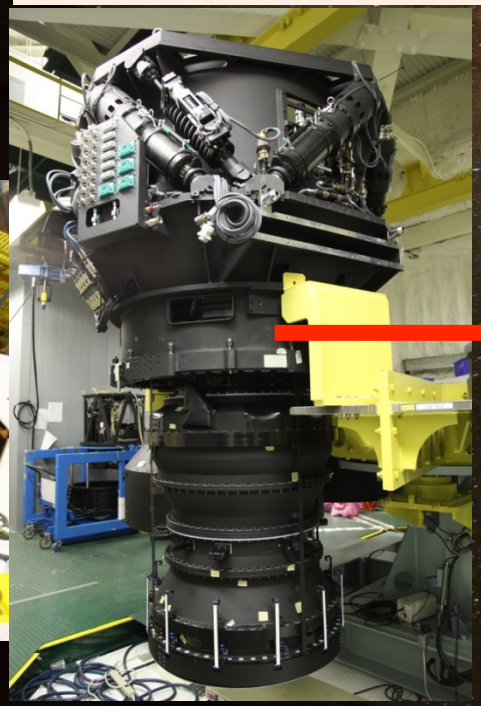


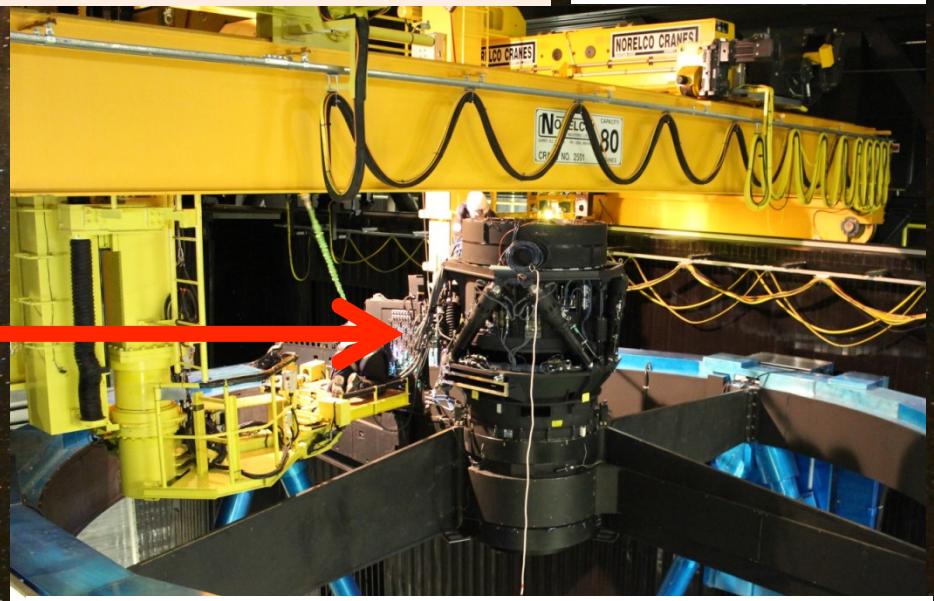


- Fiber positioner system
- Acquisition & Guide (AG) camera
- Fiber cable: “Cable C” & fixed fiducial fibers
- Fiducial fiber illuminator
- Field element (cf. Filter+dewar window@HSC)
- Cable wrapper
- Calibration lamp system

Wang (ASIAA)+ [SPIE 2016]

Caltech-JPL
LNA
ASIAA
IPMU/Princeton

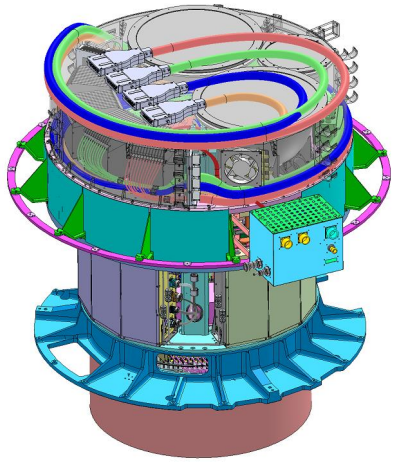


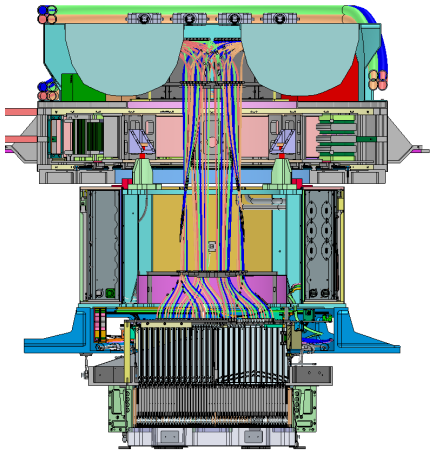


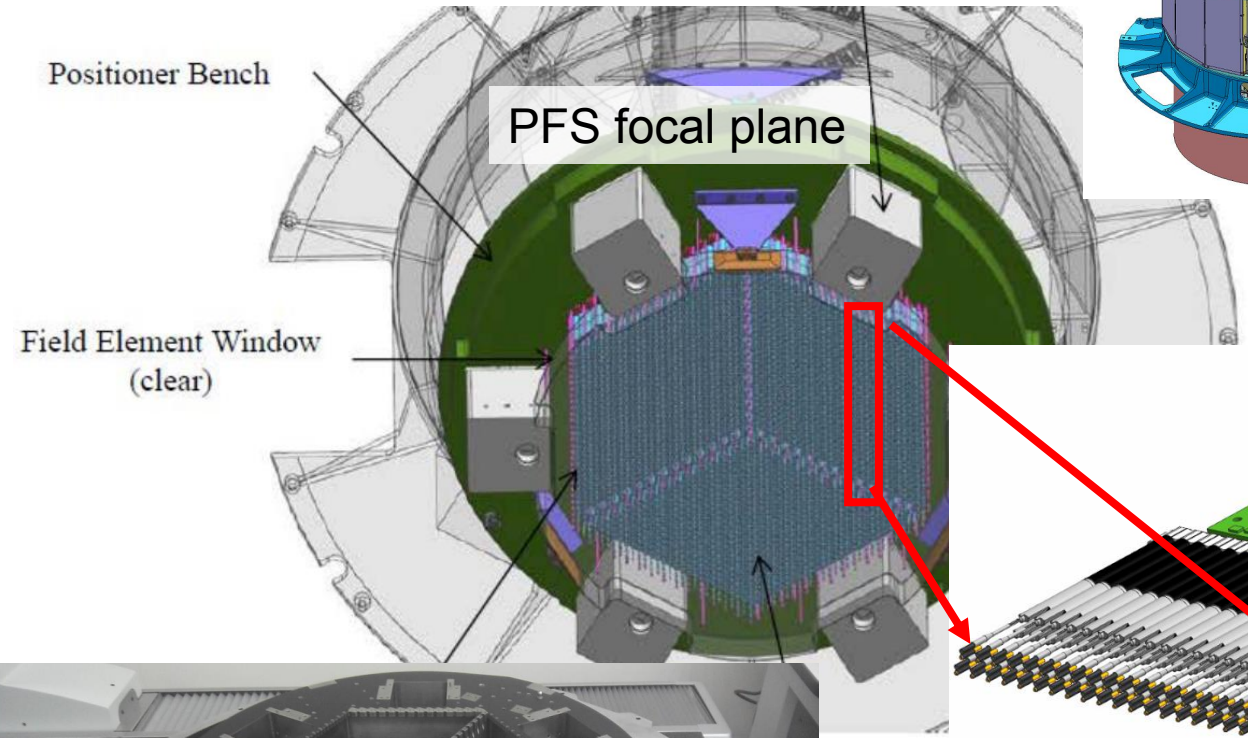
HSC builder’s blog
http://anela.mtk.nao.ac.jp/hscblog/builder/

Prime Focus Instrument (PFI)

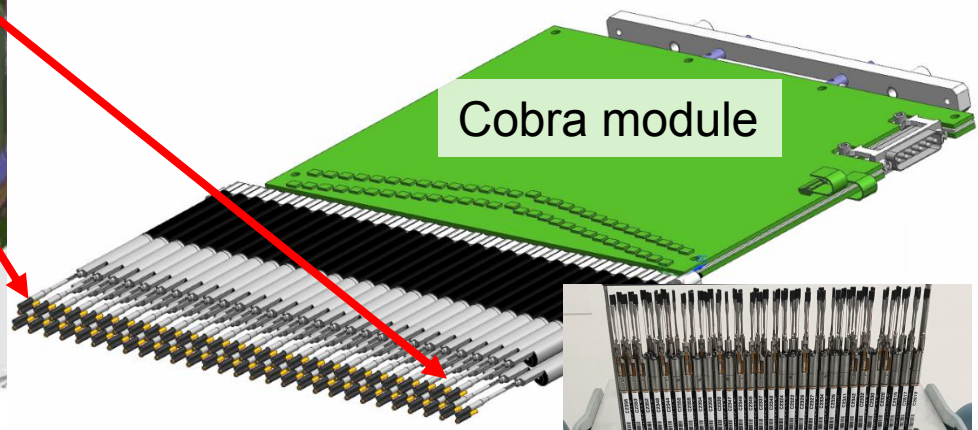
The focal plane will include 42 modules, each with 57 fi
Caltech is building and testing these modules

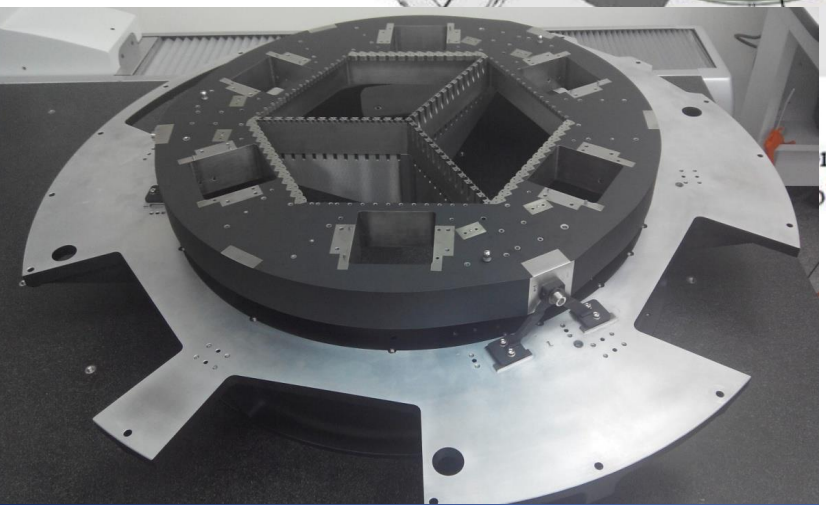






Each Cobra module includes
57 Cobra assemblies





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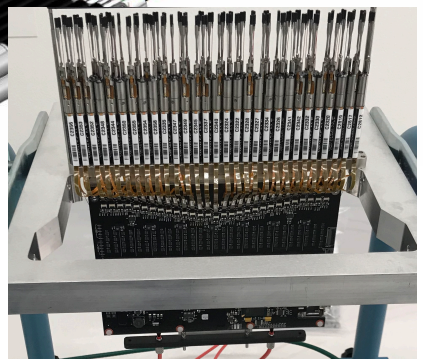

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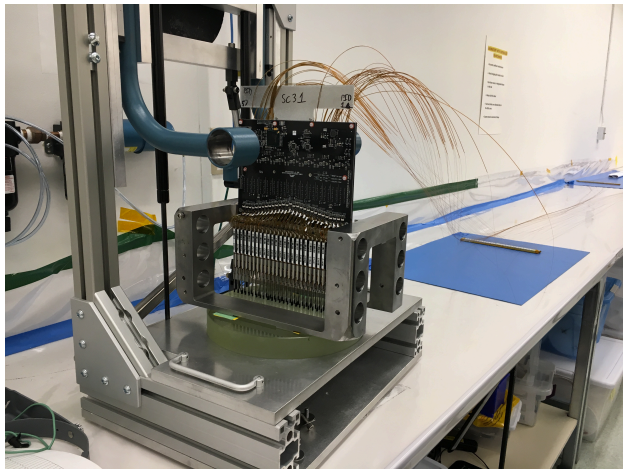
NASA JPL Caltech

Current status of PFI (1)

- In Pasadena (Caltech+LNA):
  - The 6 Cobra modules (2 spare and 4 science) were shipped to Taiwan.
  - The integration & test of next modules are steadily progressing.
  - The work in Caltech are expected to complete in this summer.







Currer

- In Pasadena (Caltech+L
  - The 6 Cobra modules (2
  - The integration & test o
  - The work in Caltech are

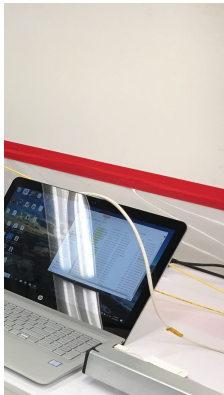


		Week of:	6/5/2019								Complete		
				4hrs	2+1day	2.5day					In Progress		
		St2, par	part 3	part 4	part 5,6	LNA/CI	CIT	Princet	CIT	CIT	Goal for the week		
inst order	Module Name	Board assembly	Power conn	Cobras	Fibers	MTP / FRD	Angle / Focus	Converge nce	Doc collection	Shipped	Current status	Fiber delivered total	Fiber + shaft coupler
1	Spare1	x	x	x	x	x	x	x	x	x	Shipped	57	57
2	Spare2	x	x	x	x	x	x	x	x	x	Shipped	114	114
3	SC01	x	x	x	x	x	x	x	x	x	Shipped	171	171
4	SC15	x	x	x	x	x	x	x	x	x	Shipped	228	228
5	SC29	x	x	x	x	x	x	x	x	x	Shipped	285	285
6	SC02	x	x	x	x	x	x	x	x	x	Shipped	342	342
7	SC16	x	x	x	x	x	x				Ready for conv (stored)	399	399
8	SC30	x	x	x	x	x	x				Ready for conv (stored)	456	456
9	SC03	x	x	x	x	x	x				Ready for conv (stored)	513	513
10	SC17	x	x	x	x	x					Focus error, rework (stored)	570	570
11	SC31	x	x	x	x	x	x				Ready for conv (stored)	627	627
12	SC04	x	x	x	x	x					Ready for angle/focus (stored	684	684
13	SC18	x	x	x	x	x	x				Ready for conv (stored)	741	741
14	SC32	x	x	x	x	x	x				Ready for conv (stored)	798	798
15	SC05	x	x	x	x	x	x				Ready for conv (stored)	855	855
16	SC19	x	x	x	x	x	x				Ready for conv (stored)	912	912
17	SC33	x	x	x	x	x					Ready for angle/focus (stored	969	969
18	SC06	x	x	x	x	x	x				Ready for conv (stored)	1026	1026
19	SC20	x	x	x	x	x	x				Ready for conv (stored)	1083	1083
20	SC34	x	x	x	x	x					Ready for angle/focus (stored	1140	1140
21	SC07	x	x	x	x						Bent shaft (repair)	1197	1197
22	SC21	x	x	x	x	x	x				Reday for conv (stored)	1254	1254
23	SC35	x	x	x	x	x	x				Ready for conv (stored)	1311	1311
24	SC08	x	x	x	x	x	x				Ready for conv (stored)	1368	1368
25	SC22	x	x	x	x	x	x				Ready for conv (stored)	1425	1425
26	SC36	x	x	x	x	x	x				Ready for conv (stored)	1482	1482
27	SC09	x	x	x	x	x	x				Ready for conv (stored)	1539	1539
28	SC23	x	x	x	x	x	x				Ready for conv (stored)	1596	1596
29	SC37	x	x	x	x	x	x				Ready for conv (stored)	1653	1653
30	SC10	x	x	x	x	x	x				Ready for conv (stored)	1710	1710
31	SC24	x	x	x	x	x	x				Ready for conv (stored)	1767	1767
32	SC38	x	x	x	x	x					Bent shaft & focus error (repa	1824	1824
33	SC11	x	x	x	x	x	x				Ready for conv (stored)	1881	1881
34	SC25	x	x	x	x	x	x				Ready for conv (stored)	1938	1938
35	SC39	x	x	x	x	x	x				Ready for conv (stored)	1995	1995
36	SC12	x	x	x	x	x	x				Ready for conv (stored)	2052	2052
37	SC26	x	x	x	x	x	x				Ready for conv (stored)	2109	2109
38	SC40	x	x	x	x	x	x				Ready for conv (stored)	2166	2166
39	SC13	x	x	x	x	x	x				Reday for conv (stored)	2223	2223
40	SC27	x	x	x	x	x					In test cube (ready for conv)	2280	2280
41	SC41	x	x	x	x	p					In conn station on table	2337	2337
42	SC14	x	x	x	x	x					Ready for conv (stored)	2394	2394
43	SC28	x	x	x	x	p					In conn station on table	2451	2451
44	SC42	x	x	x	p						In focus adjust fixture	2508	2508

CIT work	Cobras	Fiber threading	Shaft coupler bonding / curing	Fiber prot / move to table	MTP finish / Module FRD	move to test cube	Angle/Focus	move to storage	shipping
SC40								Thr	
SC27					x	x	x		
SC14					x	x	x	Thr	
SC41					TBD				
SC28				x	TBD				
SC42	x	x	x	Wed					
SC07	Repair module: Thr & Fri / Rebuild MTP: next week								

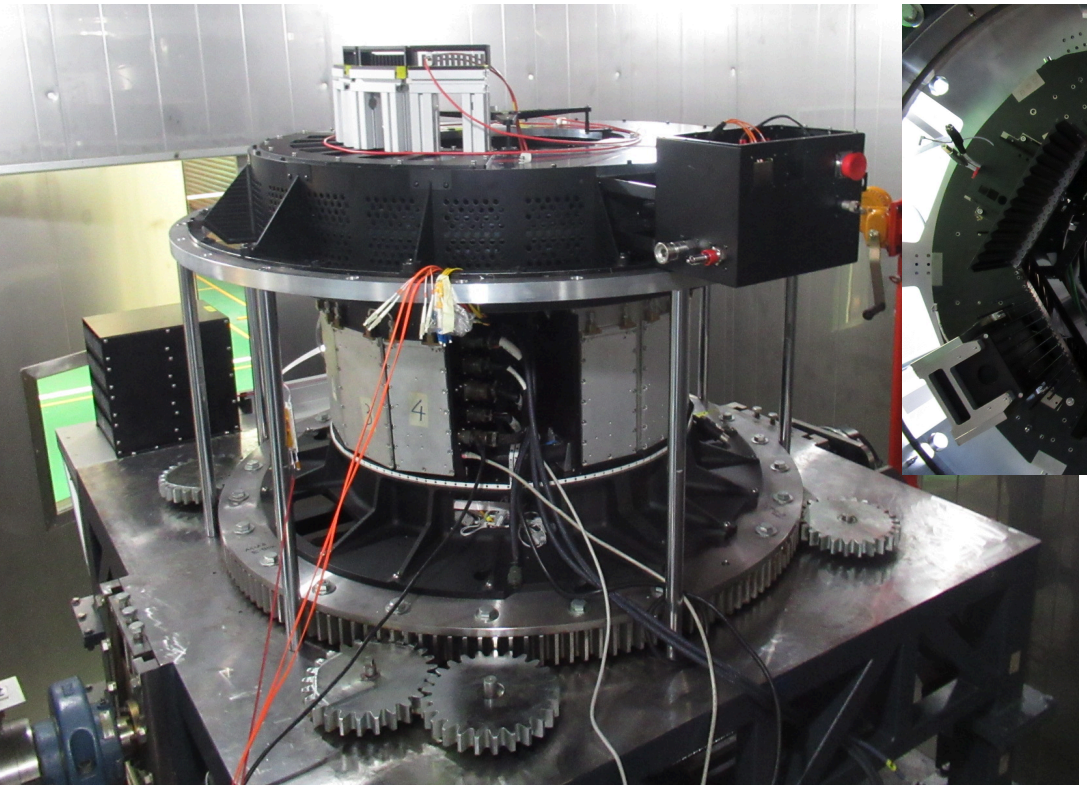
Other actions
Cobra connector / focus repair complete

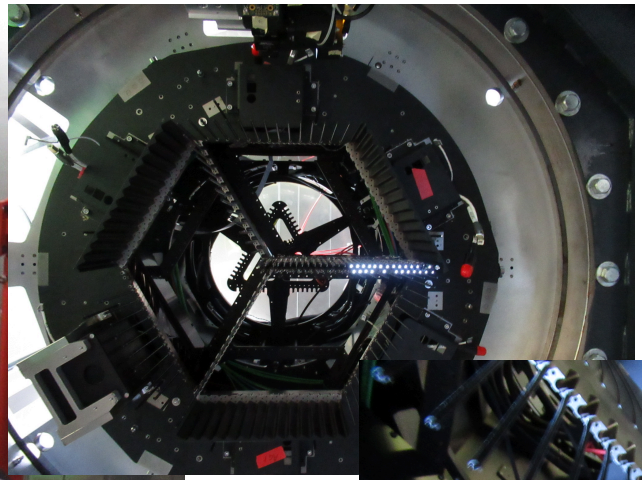


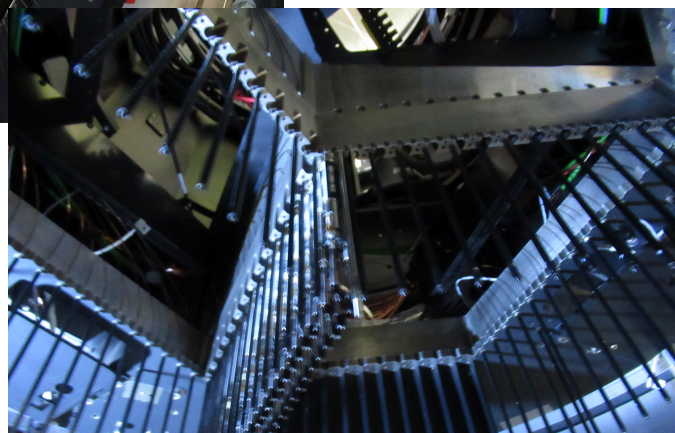


Current status of PFI (2)

- In Taiwan:
  - Cobra module installation procedure is being optimized:
    - Try and errors using the two spare modules.
    - We had a mini review meeting of the installation process on Mar 27-28. Responses to the issues and recommendations are under discussion now.
    - It seems possible to install a few modules per day.

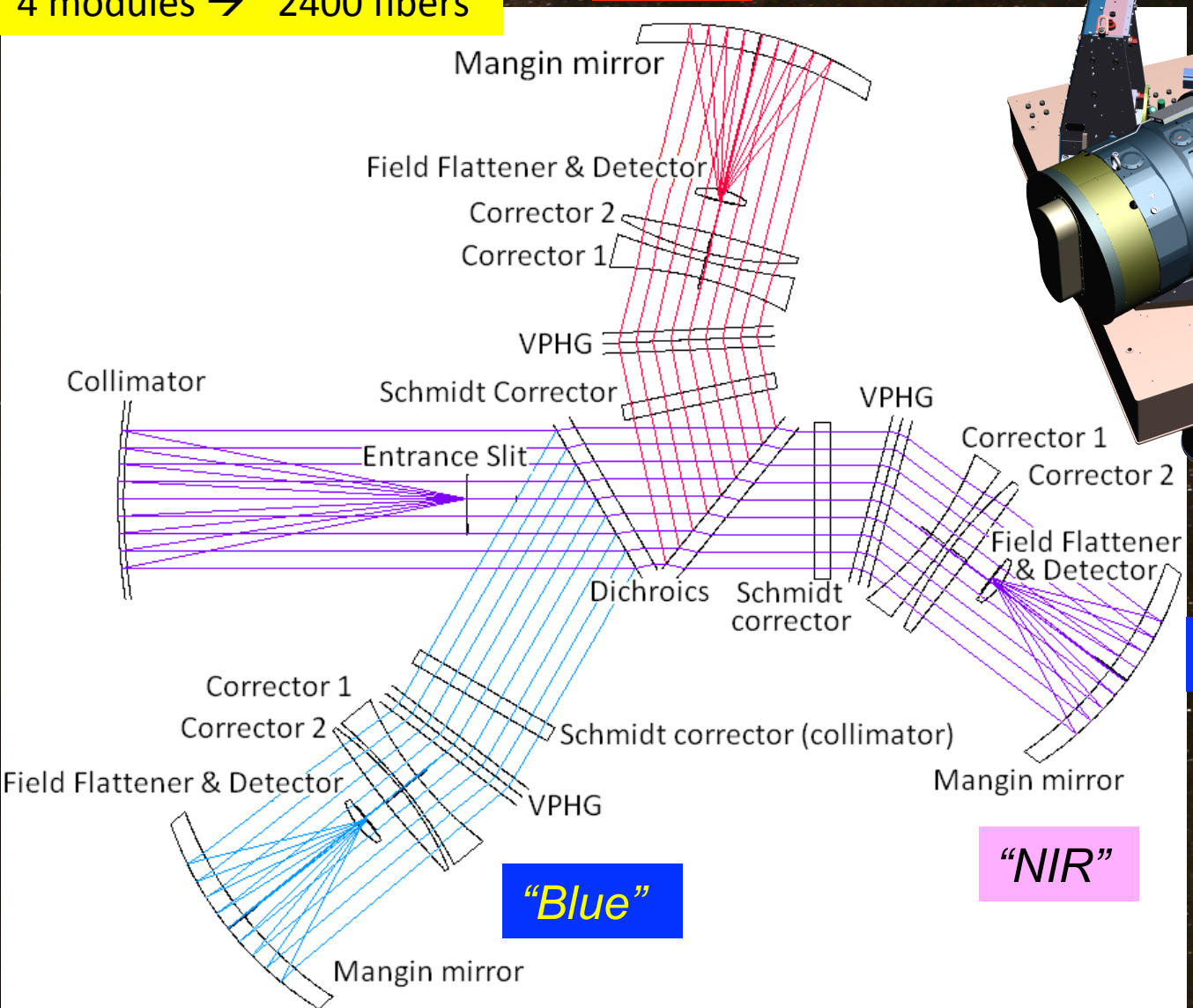


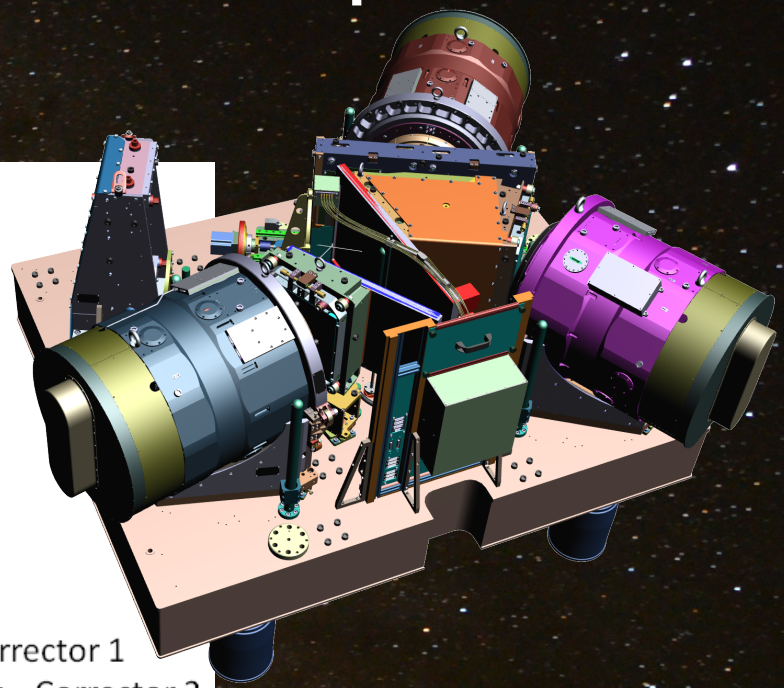




Spectrograph System (SpS)

1 module → ~600 fibers
4 modules → ~2400 fibers





Blue (380-650nm)

Red (630-970nm)

NIR (950-1280nm)

One channel – Working prototype with red camera only

One Channel Acceptance

Optical alignments

- Repositioning of the unit is ok
- Alignment procedure and quality are ok

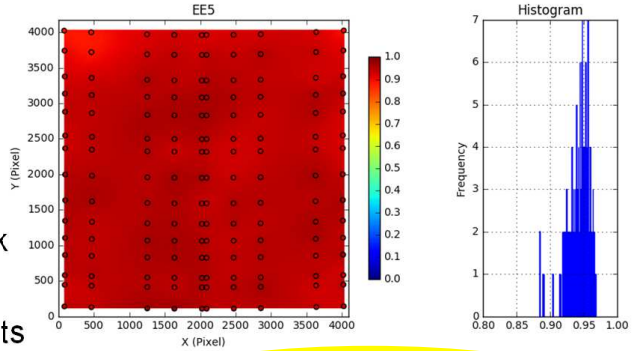
Optical performance is ok

- Image quality is well within requirements
- Image stability, ghosts within requirements

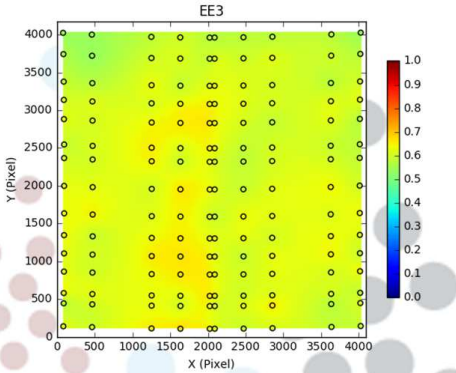
Thermal validation

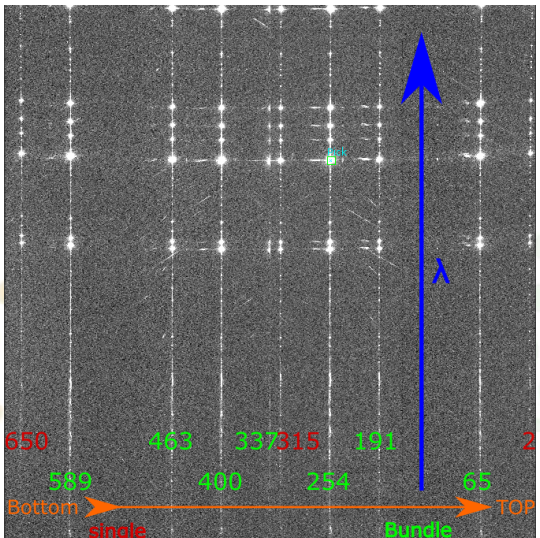
- Lot of improvements were done
- Better understanding of the system
- Final validation at cold confirm the performance

Under good control.



Meet the specs.



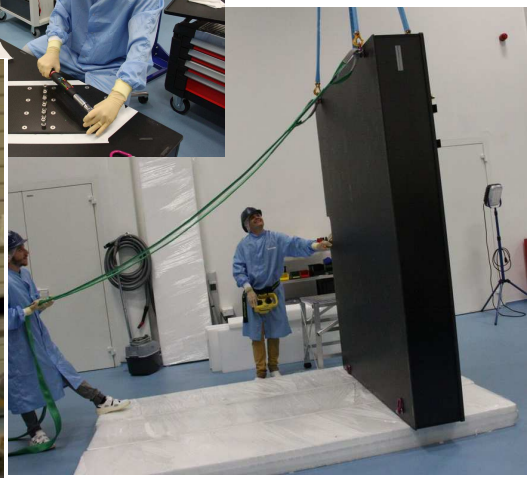


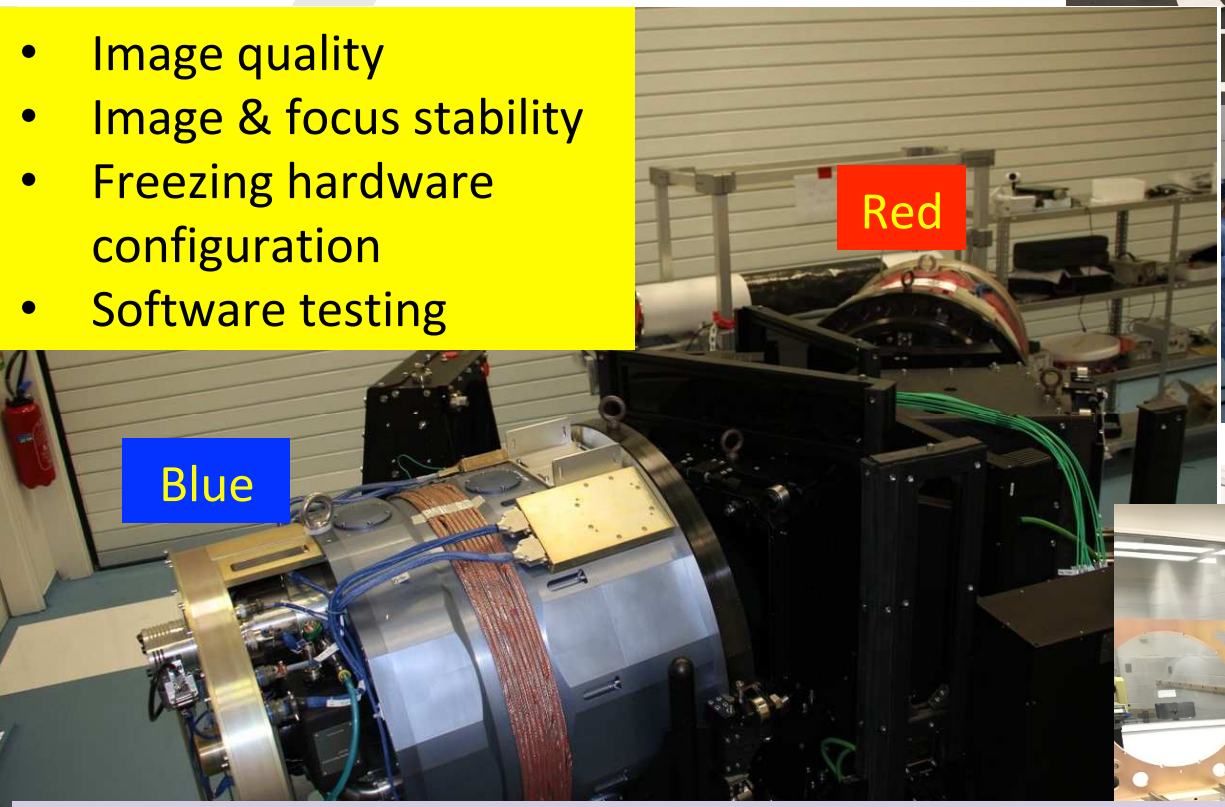
- ***SM1*** -- Spectrograph Module #1
- ***AIT*** – Assembly, Integration & Test

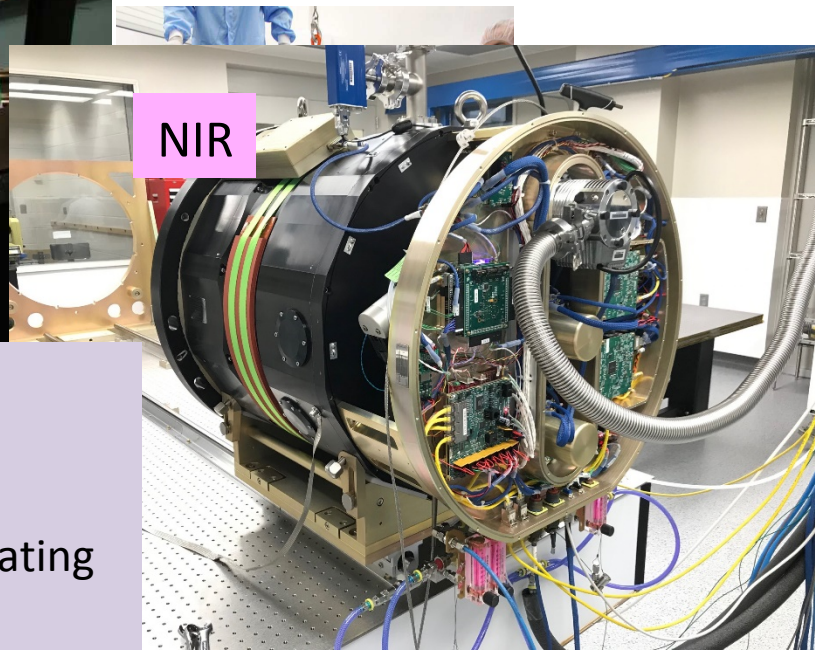
SM1 AIT activities at LAM

- Image quality
- Image & focus stability
- Freezing hardware configuration
- Software testing



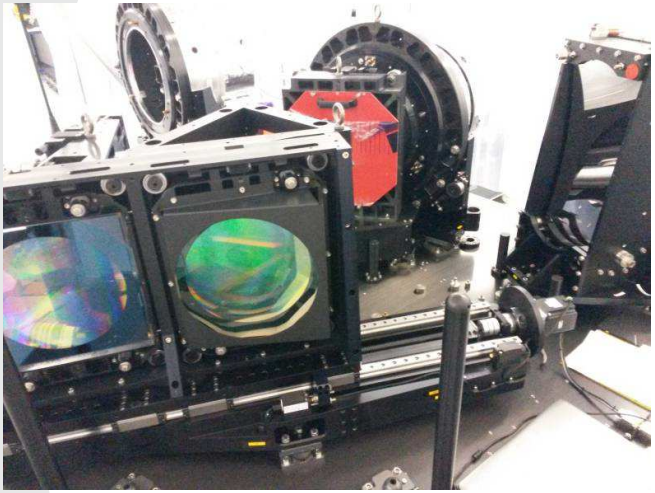


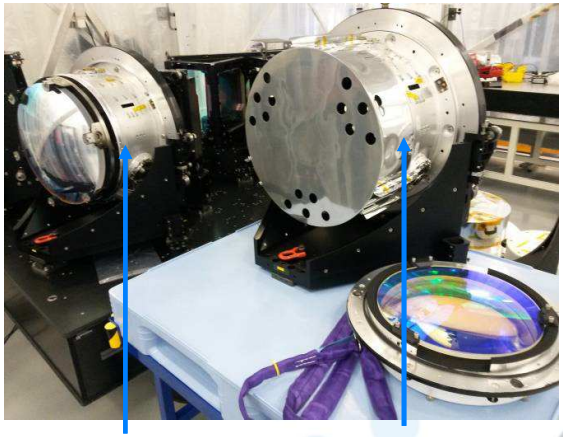




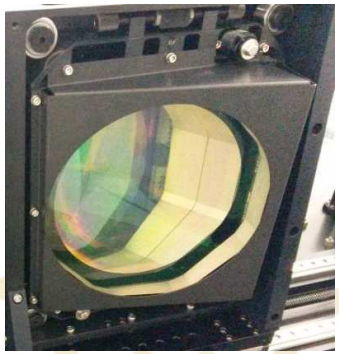
NIR camera is under AIT at JHU

- Thermal performance looks good.
- Delays in:
  - Procurement oof thermal radiation blocking coating
  - H4RG operation and characterization



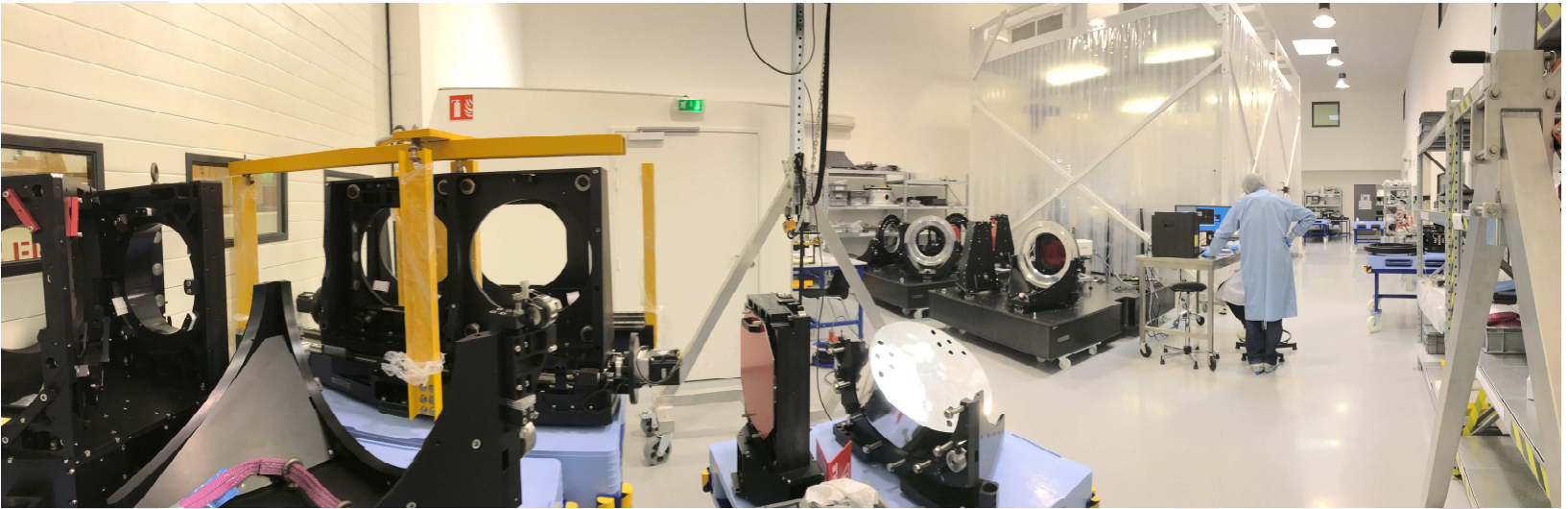


SM2 Blue Camera SM2 Red Camera



SM2 Medium resolution grating

The integrations of SM2, 3 & 4 ***ARE*** ongoing in parallel.



Spectrograph Clean Room (SCR)





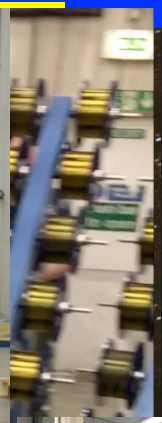
- "IR-side" 4th floor in the dome.
- Cabling & piping for facility resources are complete.
- Environmental control testing is under way.
- SCR readiness review in July (TBC)

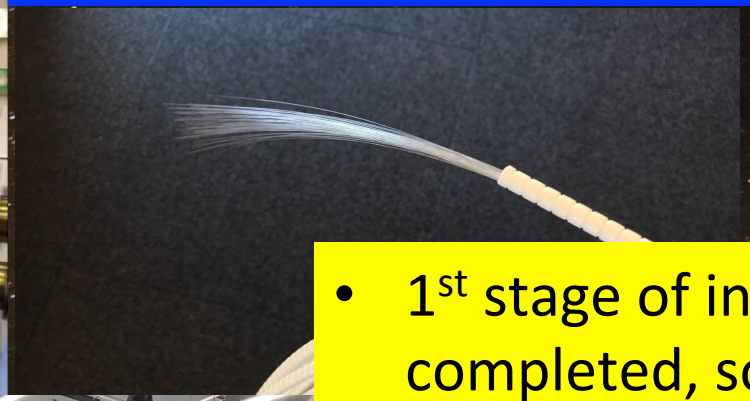
Updated strategy of Spectrograph System delivery

- The first spectrograph module (SM1) will be delivered from LAM to Subaru ***with no NIR camera***.
  - Recently we proposed this to Subaru and Subaru agreed.
  - SM3 and SM4 will be tested at LAM with the full set of cameras and delivered to Subaru. Meanwhile, SM1 and SM2 can hopefully be delivered to Subaru directly and retrofitted with NIR cameras.
  - By doing this, we can minimize delays of the start of engineering observations;
    - PFI delivery is still the critical path.
    - The commissioning willstart with PFI, one Cable B cable, and one SM having only blue and red cameras.
  - This should also help minimize delays of the end of commissioning.

On-telescope fiber cable: *Production* cables are now being assembled.



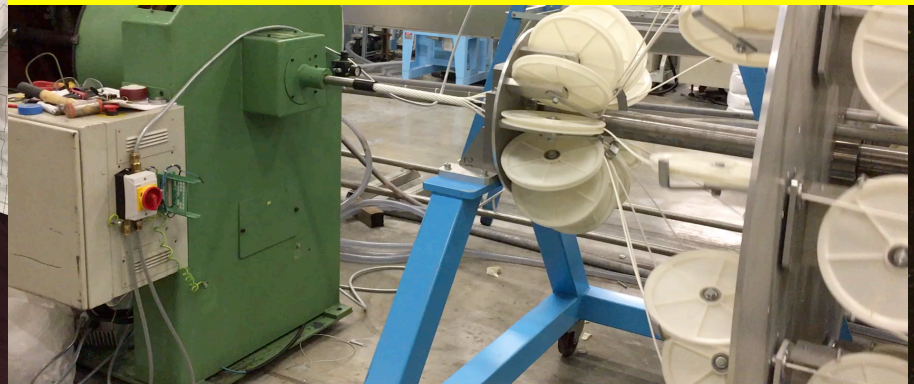






- 1st stage of integration and test is completed, so now the shipping of the cables is ongoing.
- 2nd stage will happen at LNA in Brazil.
- We willsoon schedule a readiness review of this 2nd process.





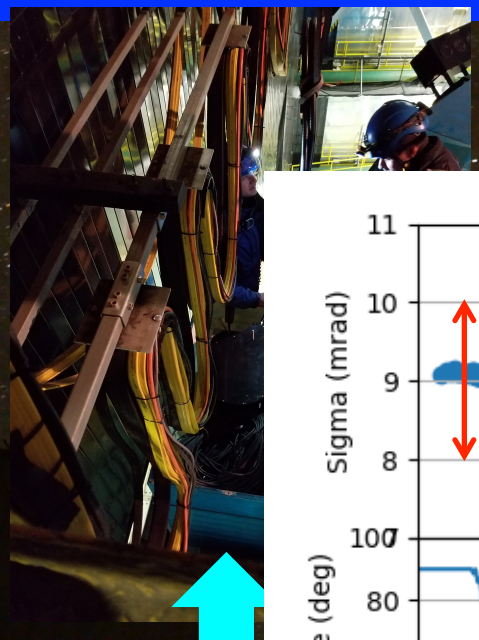


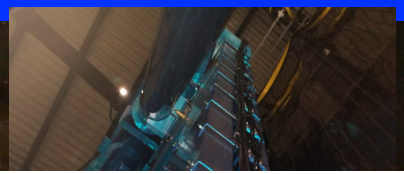
- Fibers are
- No race tr

Murray, Tamur

Prototype cable has been on the telescope.

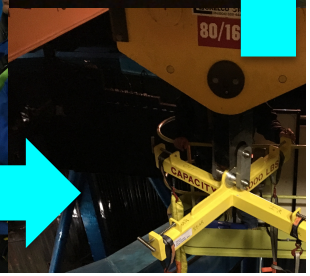




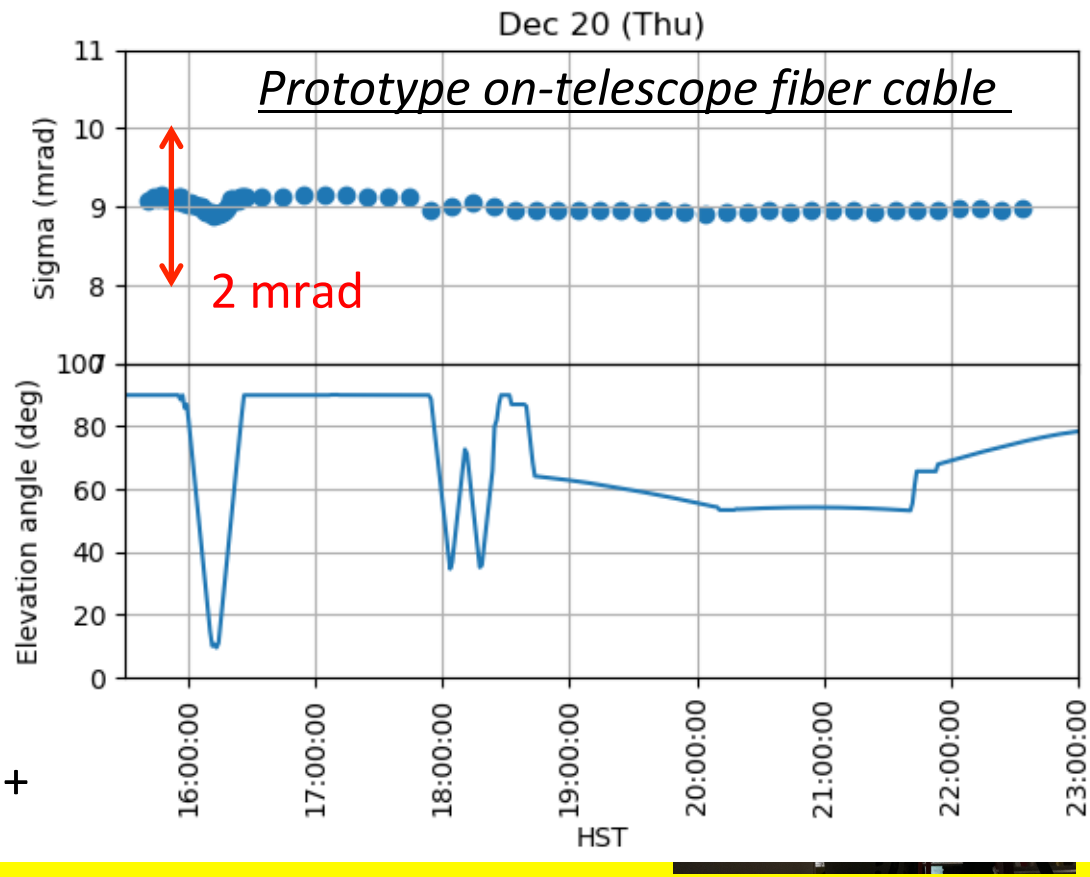








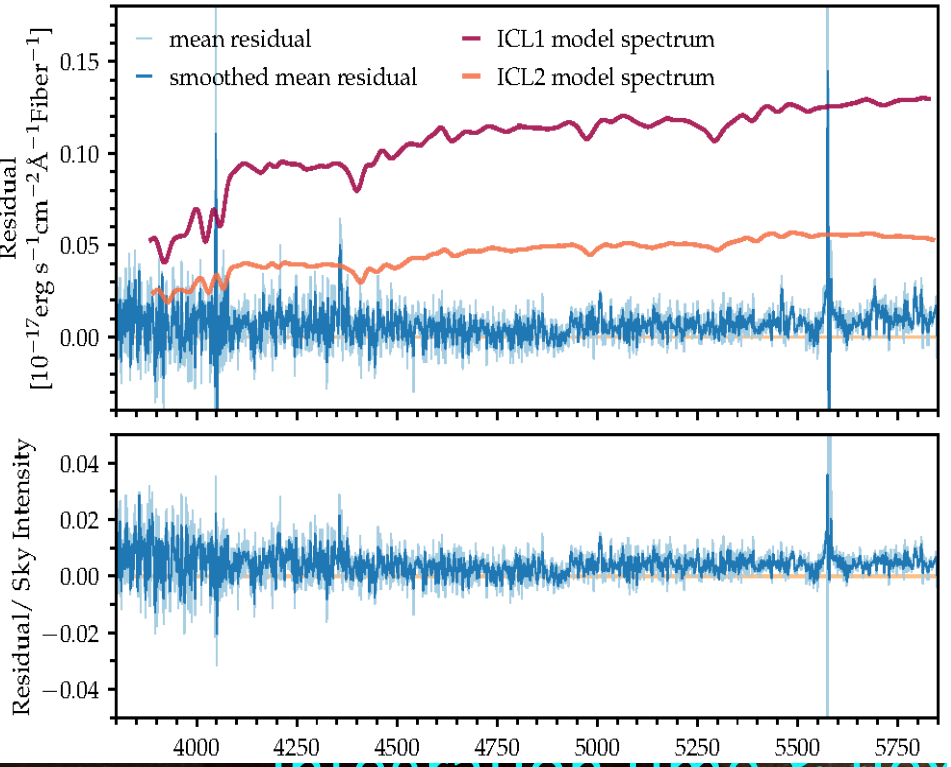
Murray, Tamura, Ferreira+



The cable installation, FRD measurement, and optimization of cable route & installation details were done in Jan, Feb, and Dec 2018.

PFS is a fiber-fed spectrometer.

- Needless to say, the optical performance of the fiber system is crucial.
- And, good sky subtraction:
  - No beam switch is desired to maximize on-source integration time & flexibility in fiber allocation.
  - We shouldn't give up challenging it just because it is a fiber instrument:
    - BOSS & eBOSS – 0.7% or even better
    - 2dF+AAOmega – Poisson noise limited
    - (MaNGA – Clean spectra of very low brightness ICL in the Coma cluster)



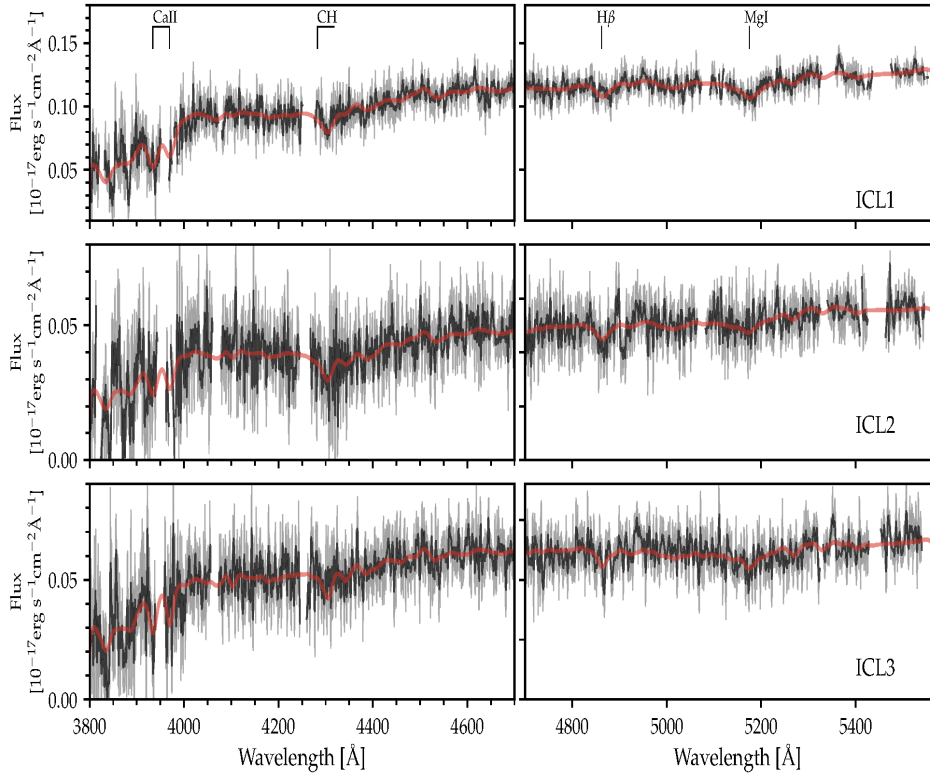


Figure 6. Stacked spectra (black) and best-fit model spectra (red) with parameters at minimum χ^2 from `alf` of IC
ICL2 (middle), and ICL3 (bottom). Spectra are smoothed with a 3 pixel box car filter for the purpose of better displ
shaded regions show the uncertainty of flux from the input spectra. Gaps in the black lines indicate pixels that ar
prior to the fitting, which are pixels contaminated by bright sky lines.

integration time & flex

– We shouldn't give up c
is a fiber instrument:

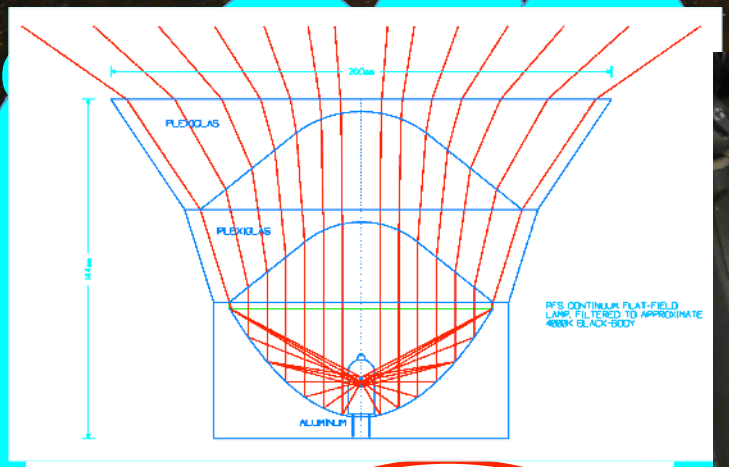
- BOSS & eBOSS – 0.7% or even better
- 2dF+AAOmega – Poisson noise limited
- (MaNGA – Clean spectra of very low brightness ICL in the Coma cluster)

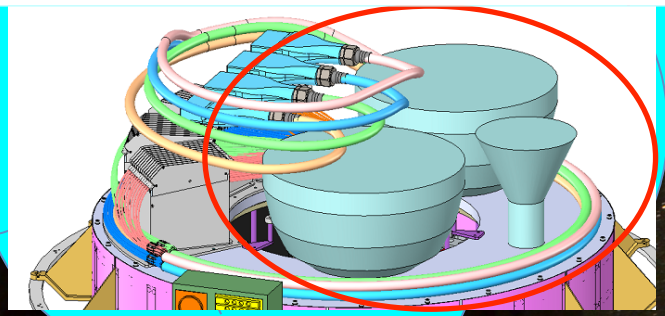
For good sky subtraction …

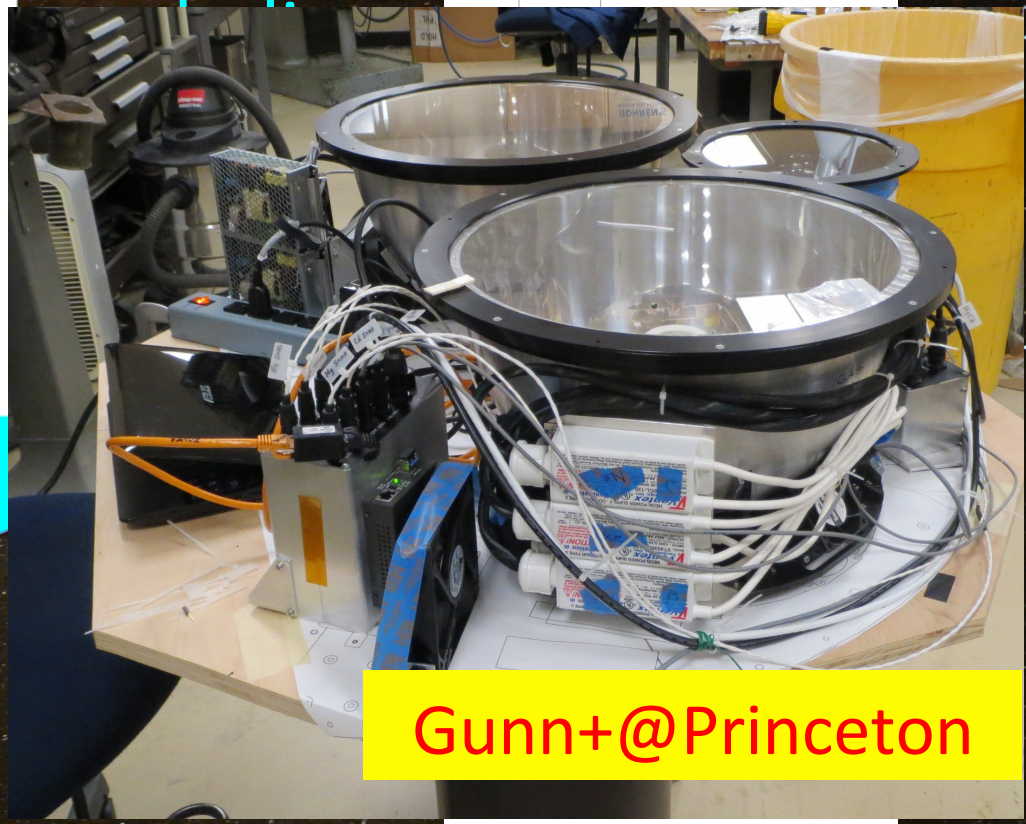
- The performance of data reduction pipeline is certainly crucial.
- But software can do only what it is told to do.
  - It has to know e.g. the instrument, the sky, and the data.
- Specific challenges are:
  - Characterization & calibration of instrument & sky
  - The instrument being easily characterizable
  - Sensitive & flexible algorithm to model 2D PSF

For good sky subtraction …

- …







Gunn+@Princeton

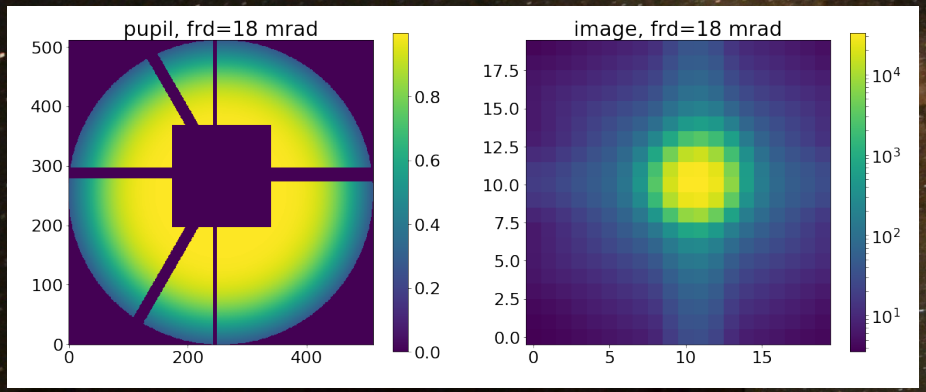
To illuminate the telescope pupil and focal plane *just like the sky does*.

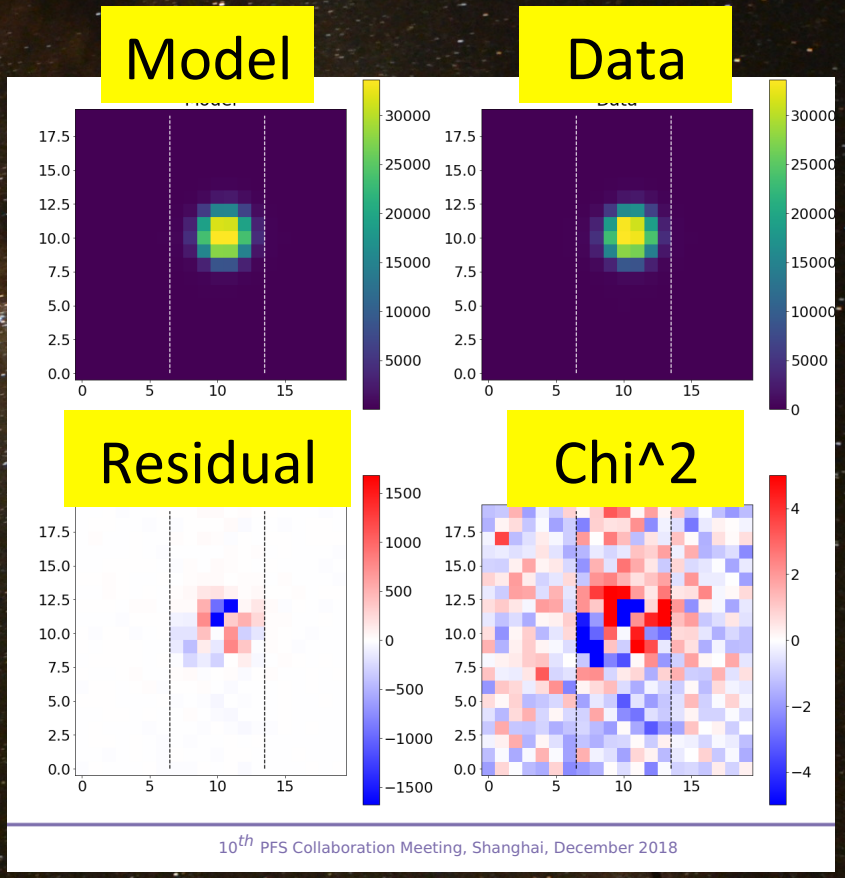
For good sky subtraction …

- "2D pipeline" development
  – Modeling in-focus images from de-focused images

PRINCETON UNIVERSITY

+IPMU, NAOJ



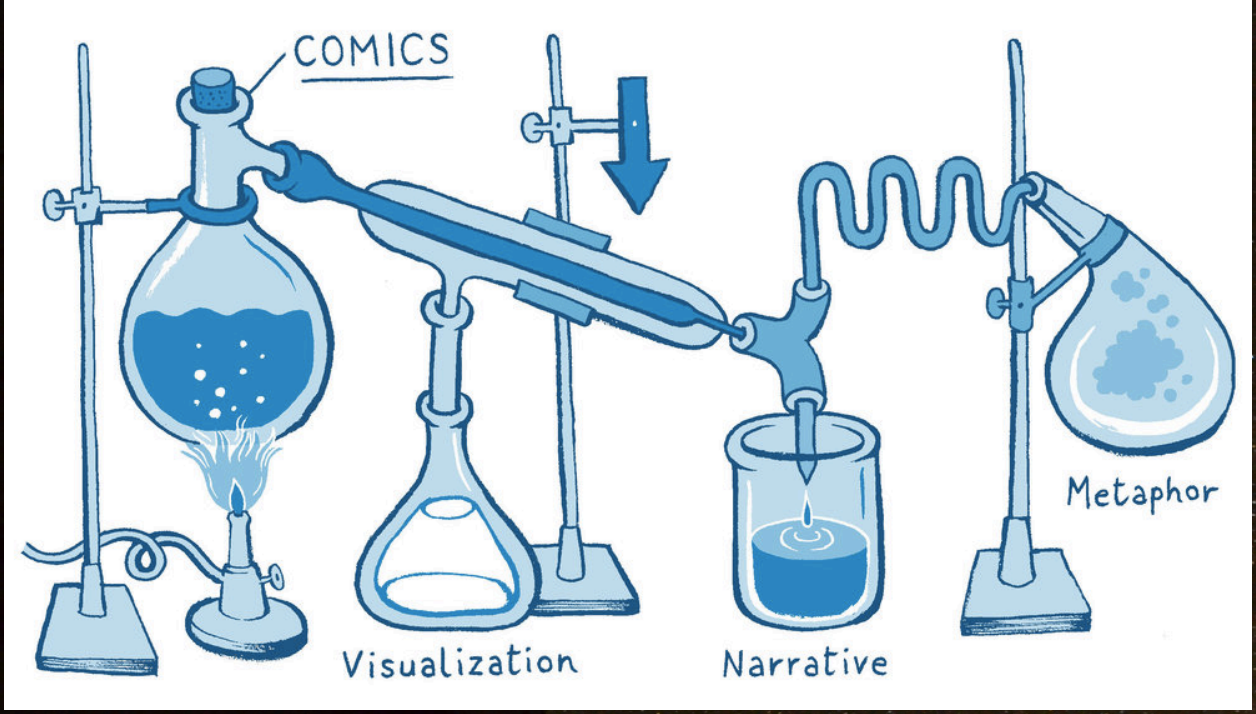


STILL PRELIMINARY

- Modeling is being improved to deal with data from the real SpS hardware.
- Residual will further be subtracted by PCA-like method – Tests underway.

(Caplar, Lupton, Gunn+)

Survey planning



To propose a large survey in the framework of Subaru Strategic Program (SSP)



Hitoshi Murayama
[PI of PFS project]

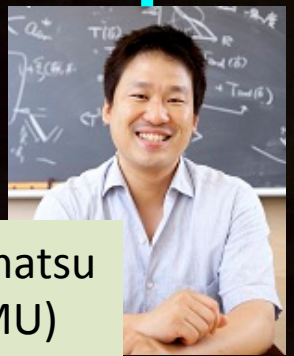
Survey integration team

Masahiro Takada
[Kavli IPMU]

Richard Ellis
[UCL]

Science working group co-chairs

Cosmology



Eiichiro Komatsu
(MPA/IPMU)

Galaxy/AGN evolution

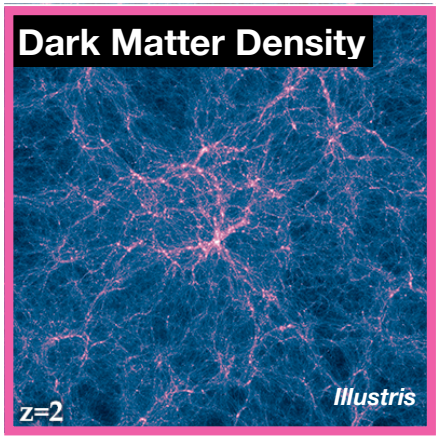


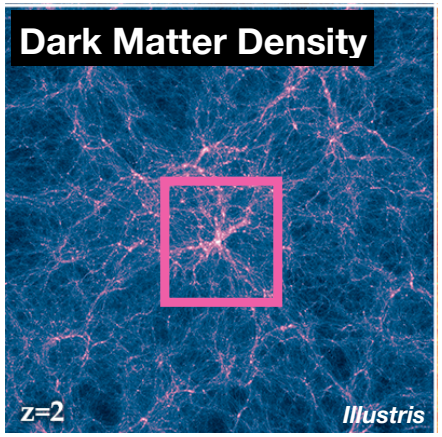
Jenny Greene (Princeton)

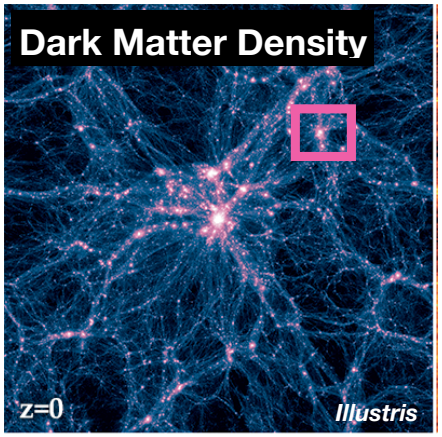
Galactic Archaeology



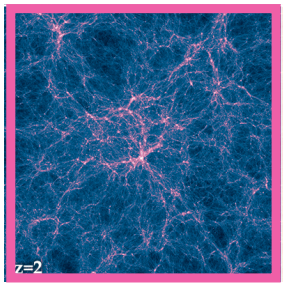
Masashi Chiba
(Tohoku U.)







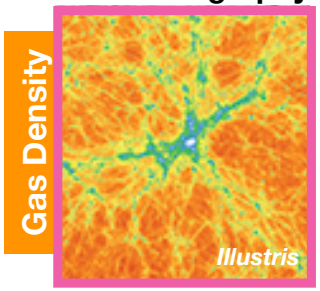
Cosmology and Large Scale Structure



* just illuminate emission line galaxies to probe LSS

Bezanson
Greene

IGM Tomography

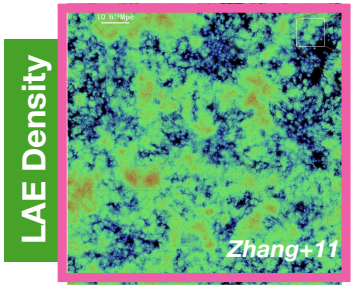


z~2

Galaxies in the Cosmic Web



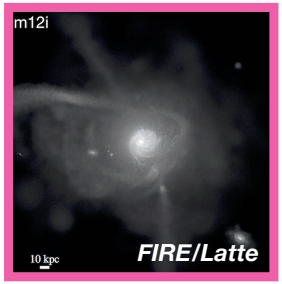
z~1.5



z~5

*Colored by sSFR in the same region

Stellar Streams



Galactic Archeology



*stars colored by chemical abundances

Murayama

Comprehensive Challenge on the Standard Model of the Universe and Beyond

3 pillars of PFS SSP

ΛCDM	Galactic Archaeology	Galaxy Evolution	Cosmology
General Relativity		✓	✓
Flat FRW metric			✓
Collisionless Dark Matter	✓		
Nearly Scale-invariant Adiabatic Gauissian Spectrum	✓	✓	✓
Hierarchical Structure Formation	✓	✓	✓
Cosmological Constant			✓
Massless Neutrinos	✓ (warm DM)		✓
Reionization from stellar formation		✓	

PFS SSP self-encompasses complementarity & independent checks.



Aug 2017@MPA

Survey planning

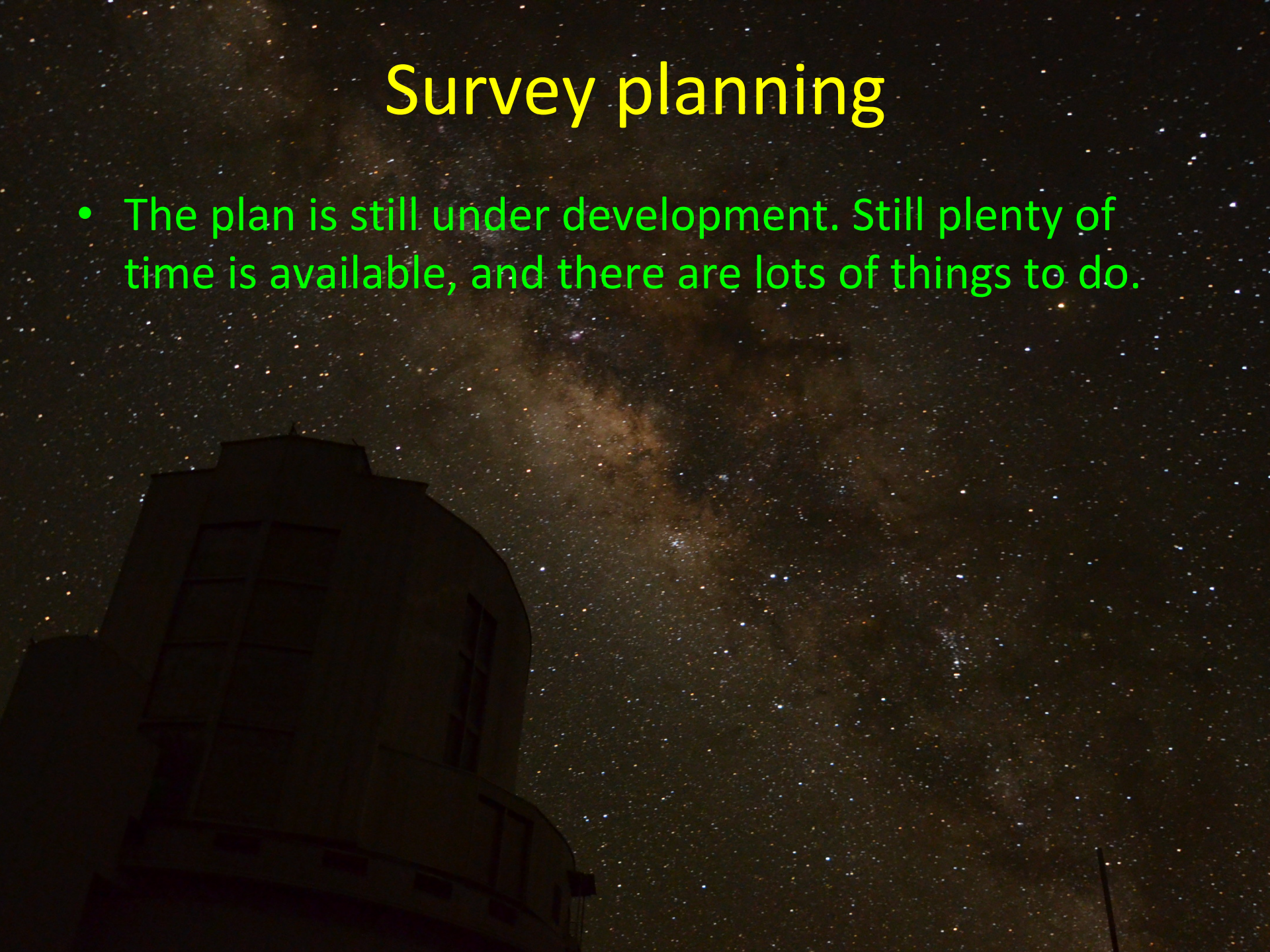


Sep 2018@Princeton

- Still largely bottom-up:
  - Each WG is actively having discussions at semi-regular telecons, ***occasional face-to-face meetings*** and by e-mail.
    - Annual PFS science meetings
    - Annual PFS general collaboration meetings
- Mechanism/process for strategic, coherent integration:
  - Critical review by the red team (with a few external members invited) in June 2017.
  - Survey integration team started being active & survey planning WG is actively upgrading survey simulations.
  - ***4-page document with a few "crisp" figures*** from each WG in Nov 2018.

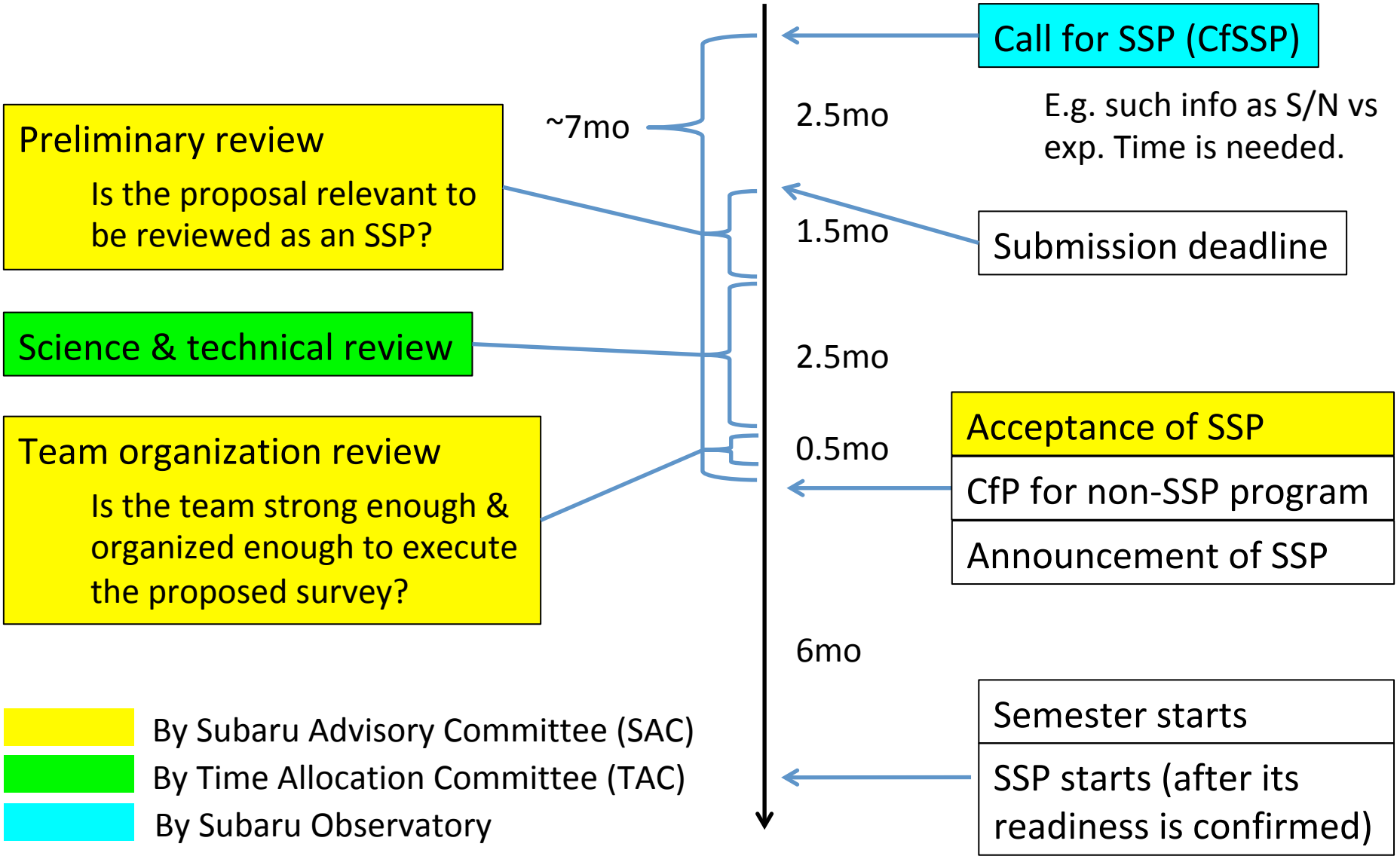
Survey planning

- The plan is still under development. Still plenty of time is available, and there are lots of things to do.



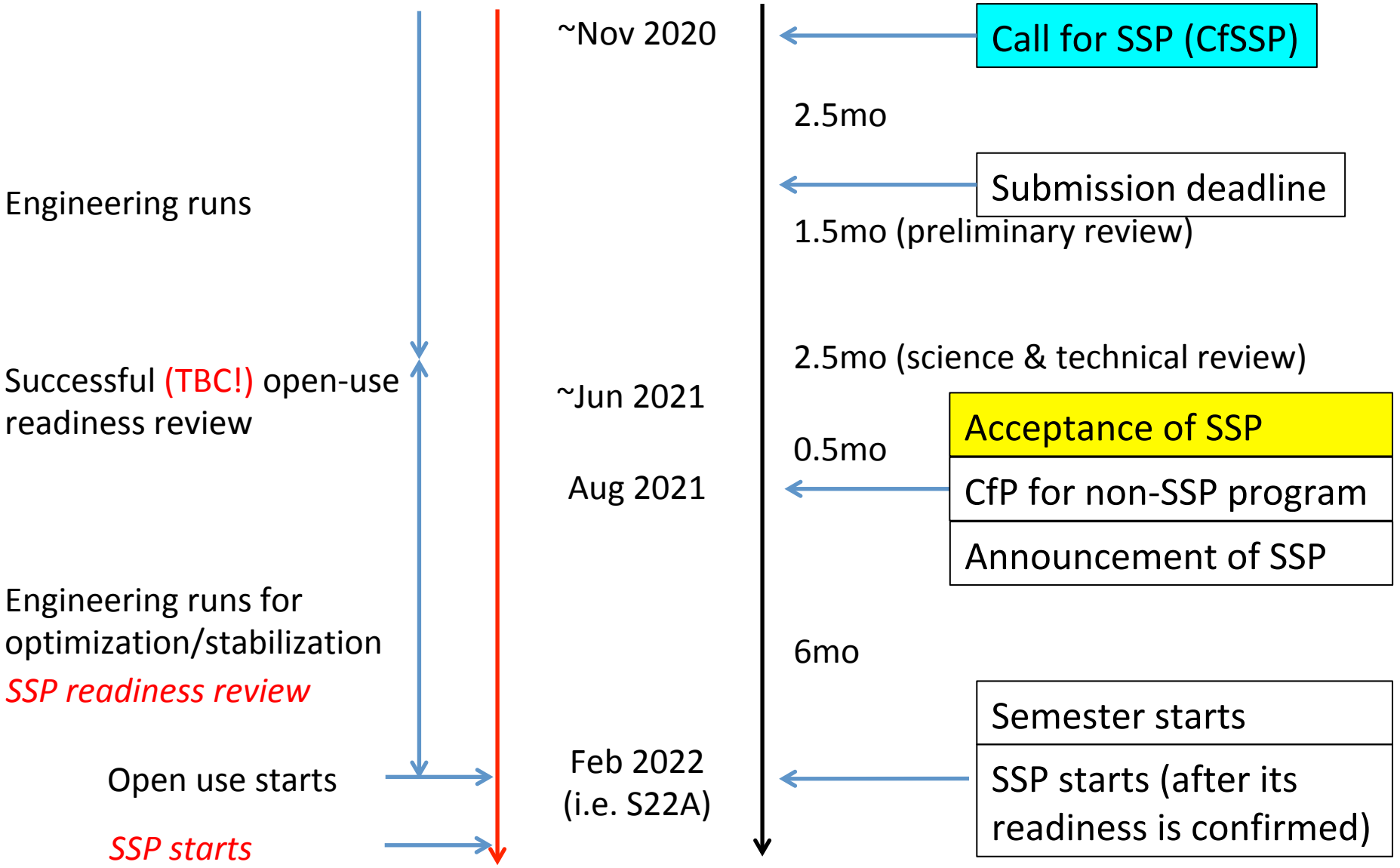
Review process of SSP proposal (speeded-up version)

[Still under discussion]



Commissioning vs. SSP proposal review process

[Always subject to updates …]

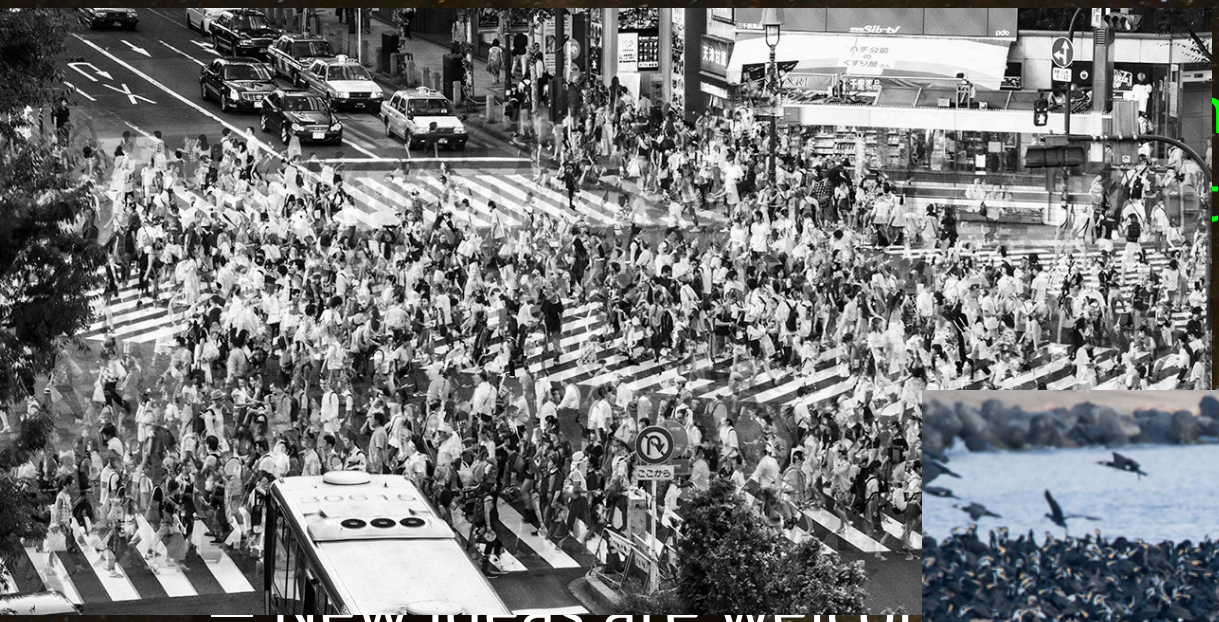


Survey planning

- The plan is still under development. Still plenty of time is available, and there are lots of things to do.

- The development is still based largely on bottom-up discussions:
  - New ideas are welcome!
  - Let's do together to be more efficient!
    - i.e. We desire to maximize scientific outputs per fiber per telescope time.
  - But we need to keep in mind that coherent integration is important.

Survey planning



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    per telescope time.
– But we need to keep in mind that coherent integration is important.

A model case of integration



- An AGN/QSO component
  - Matsuoka-san (ex. NAOJ, now Ehime) took the initiative of organizing meetings, telecons, etc.
  - The group came up with a set of key survey parameters such as:
    - Surface density of targets
    - Required S/N → integration time

    and contacted the cosmology and galaxy evolution WGs.
  - Yabe-san performed survey simulations, and found that it can be accommodated in the galaxy evolution survey component.

A model case of integration?



- Transient follow-up program (Yasuda-san)
  - In the galaxy evolution survey, several patches of the sky will be repeatedly observed to reach required integration time.
  - What if the target list is slightly modified to acc transients? How successfully can fibers be assigned?
  - Cadence observation???
  - Trying to simulate a survey using the survey simulator (see the Kiyoto's talk).
- Much smaller programs?
  - Maybe relevant as ancillary programs?
  - Maybe relevant data plan to be taken already …

Please, instead of observing PFS …

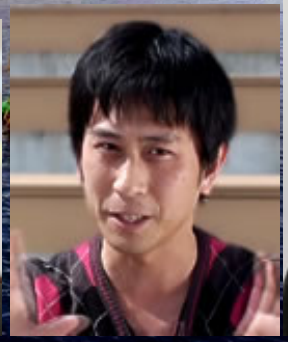


Jump into us & think about ***observing with PFS***



- Contact a WG.
- Not clear which WG ?
  - Contact Masahiro/us.
- Look forward to seeing your interesting ideas!















Two sessions ***dedicated to PFS*** have been scheduled recently:

- Plenary session in the afternoon of Nov 20 (Wed)
- Parallel science session in the morning of Nov 22 (Fri)

Please consider abstract submissions (by June 15, coming soon!!)

Summary – PFS has started coming!

More slowly than expected, but we are aggressively turning wheels.

And we will surely keep going.

