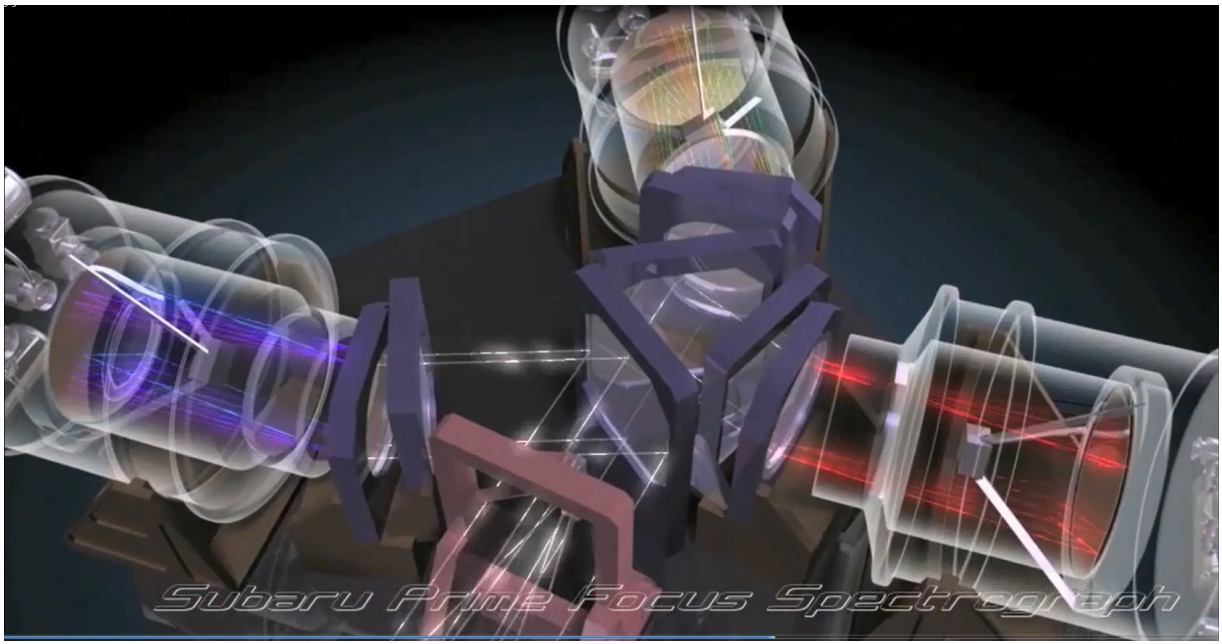
Subaru Prime Focus Spectrograph (PFS)

Masahiro Takada
Naoyuki Tamura
(Kavli IPMU)
on behalf of PFS Team



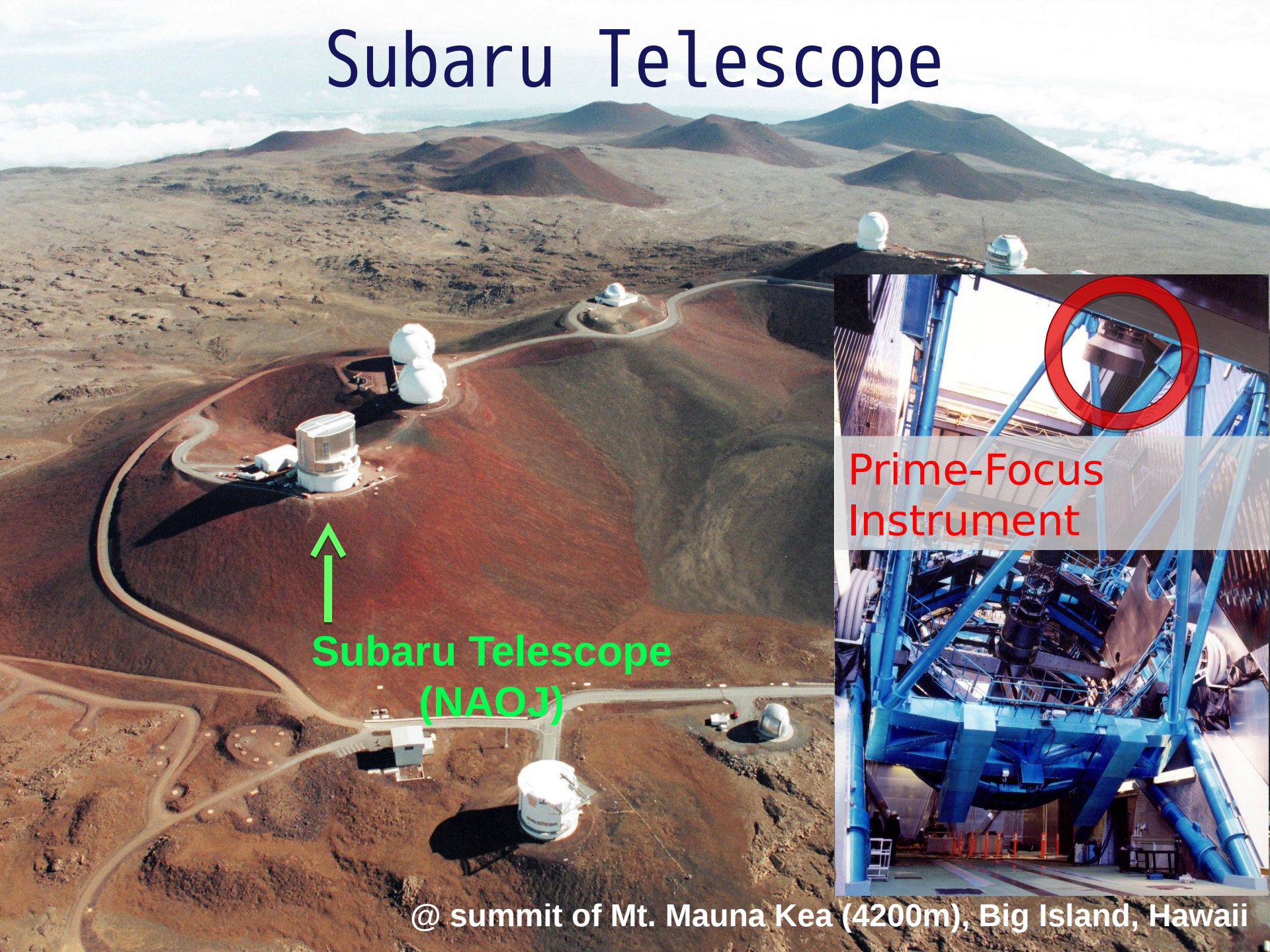
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

wpi

@MOS conference, La Palma, March 2015

Subaru Telescope

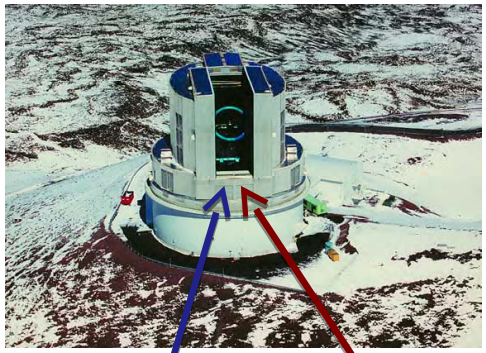


@ summit of Mt. Mauna Kea (4200m), Big Island, Hawaii

SuMIRe = Subaru Measurement of Images and Redshifts

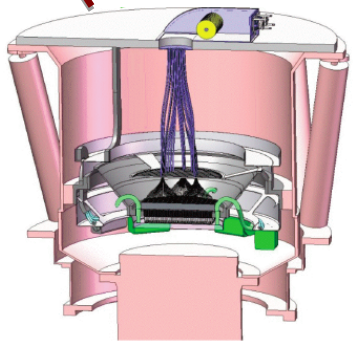
Murayama (Kavli IPMU Director)

- IPMU director Hitoshi Murayama funded (~$32M) by the Cabinet in Mar 2009, as one of the stimulus packages
- Build *wide-field* camera (Hyper Suprime-Cam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies
- Do SDSS-like survey at z>1

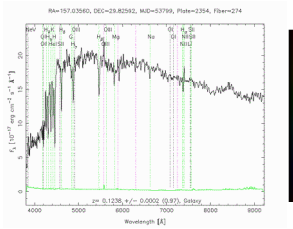


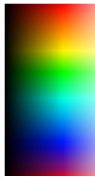
Subaru (NAOJ)

HSC



PFS





HSC Collaboration

International collaboration: Japan, Princeton, Taiwan

国立天文台 NAOJ

中央研究院 ACADEMIA SINICA 1928

PRINCETON UNIVERSITY

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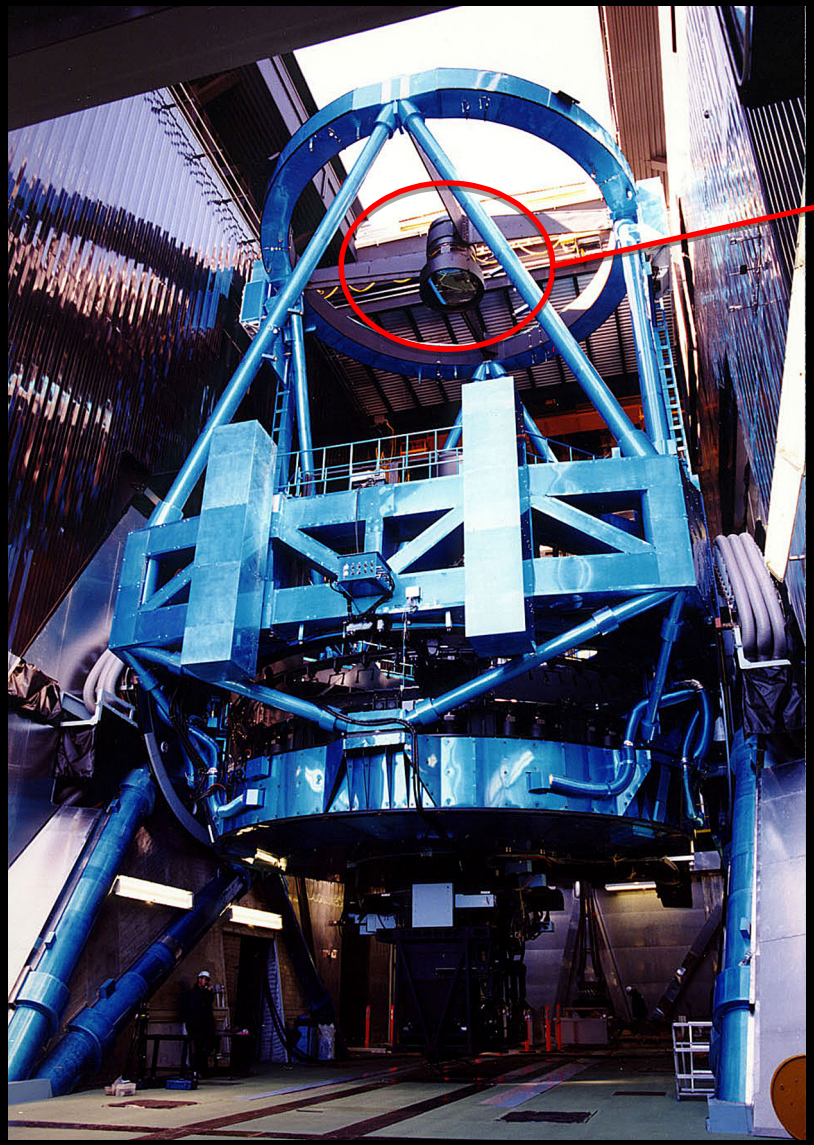
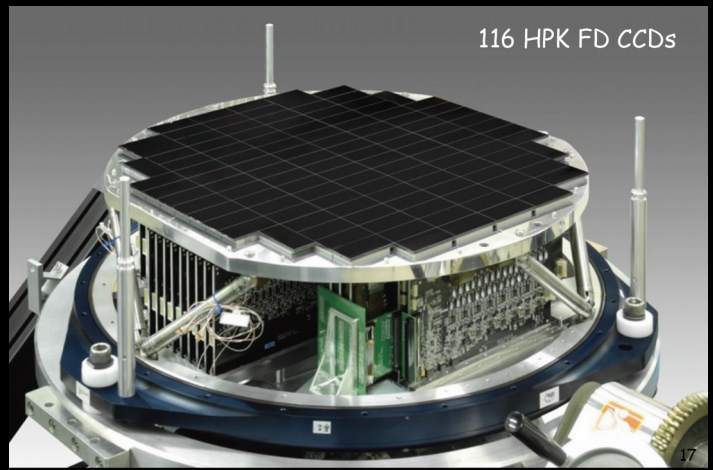
Hyper Suprime-Cam



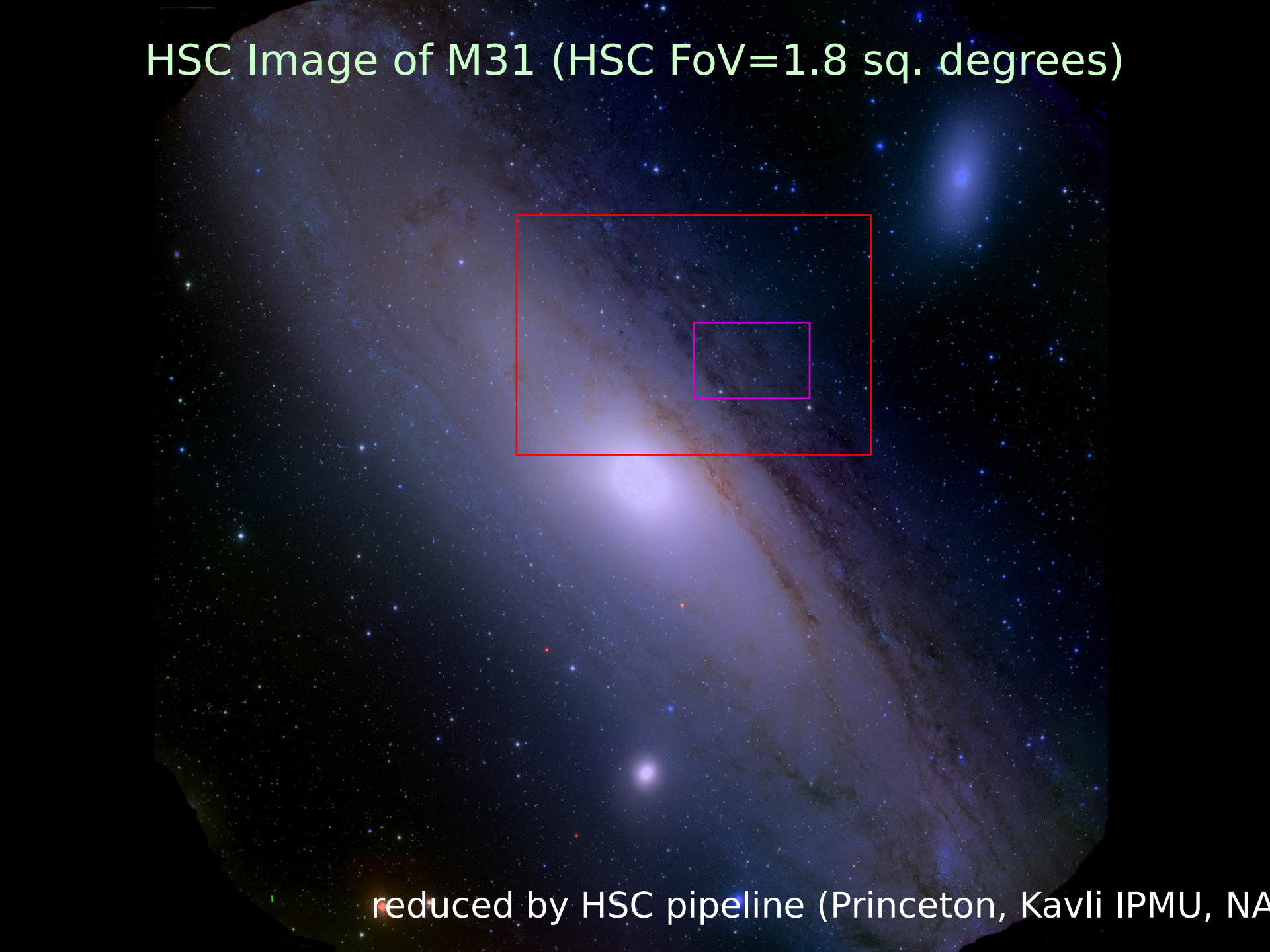
- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)



Hyper Suprime-Cam FoV

wid

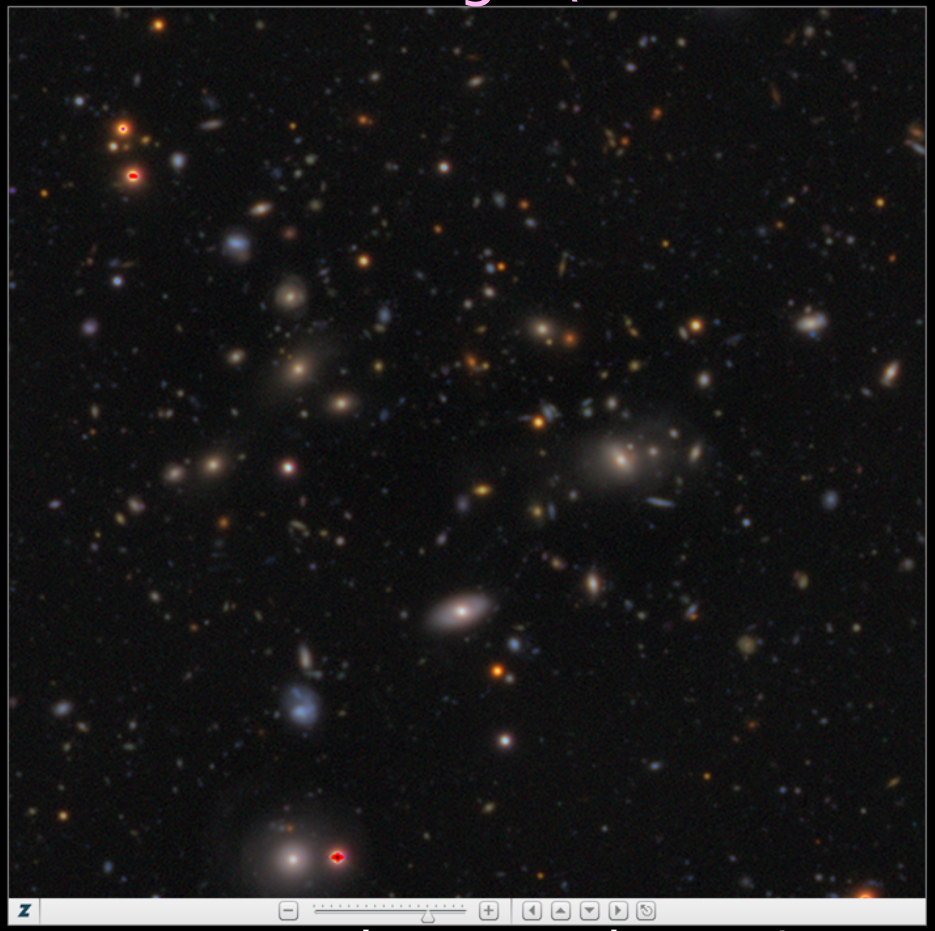
- **Fast**
- a co
  hese


HSC Image of M31 (HSC FoV=1.8 sq. degrees)
reduced by HSC pipeline (Princeton, Kavli IPMU, NA

HSC Survey finally started (March 2014)!

(5 years until 2019, 300 Subaru nights)

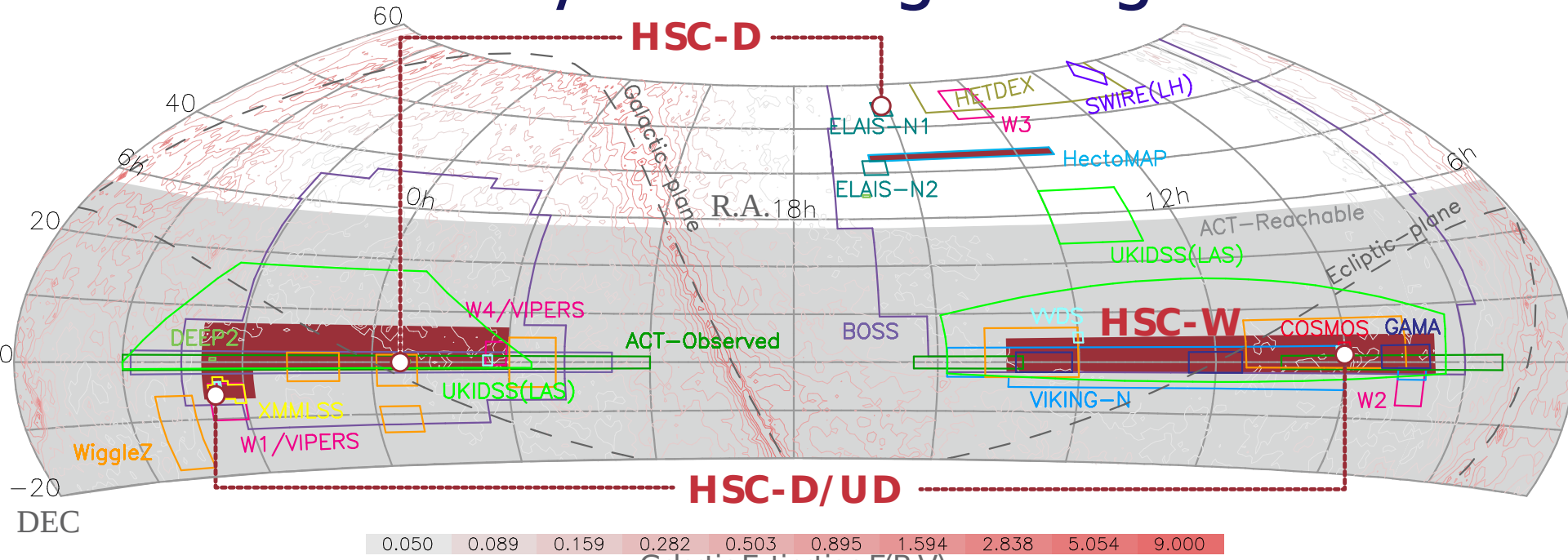
Subaru HSC image (riz: ~2.5 deg^2)



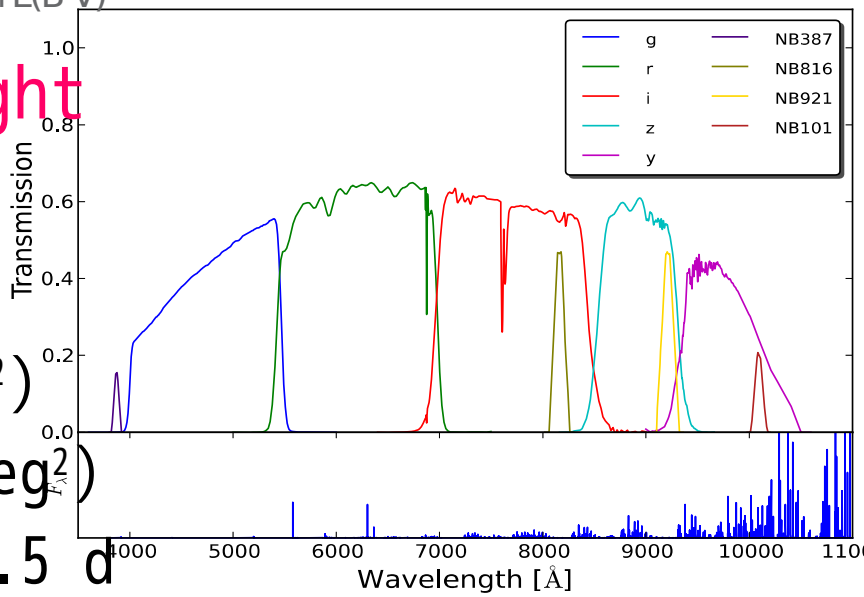
best seeing ~0.5’’
typically ~0.7’’

COSMOS HST (640 orbits: ~500h

HSC Survey: 300nights granted



- 2014 – 2019 (so far 21 nights)
- Three survey layers
  - Wide (i~26, grizy, 1400 deg^2)
  - Deep (i~27, grizy+NBs, 28 deg^2)
  - Ultra-D (i~28, grizy+NBs, 3.5 d



PFS Collaboration

Caltech

国立天文台 NAOJ

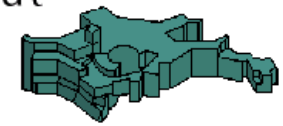
NASA JPL

中央研究院 ACADEMIA SINICA

PRINCETON UNIVERSITY

JOHNS HOPKINS UNIVERSITY

Max-Planck-Institut für Astrophysik



OBSERVATÓRIO DE SÃO PAULO
SANCTI PAVLI CÆLVM AGER MEVS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

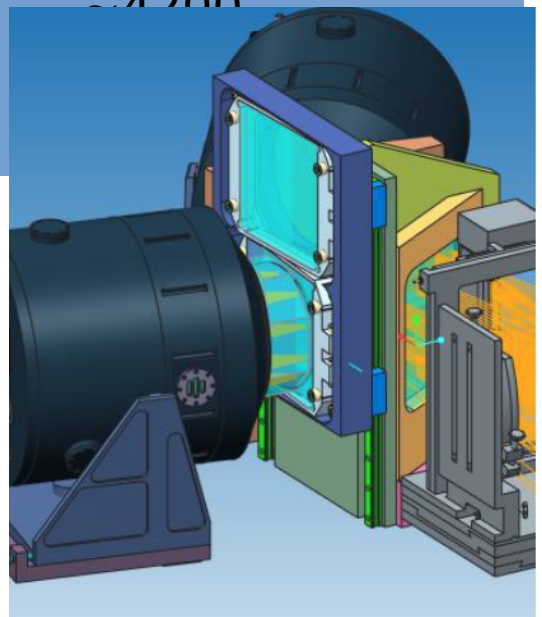
LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

PFS Parameters

roved by Preliminary Design Review (March, 2013)

Number of fibers	2400		
Field of view	1.3 deg (hexagonal-diameter of circumscribed circle)		
Fiber diameter	1.13'' diameter at center	1.03'' at the edge	
Spectrograph	Blue	Red	NIR
Wavelength range [nm]	380-650	630-970 (706-890)	940-1260
Central resolving power	~2350	~2900 (~5000)	~4200
Detector type	CCD	CCD	

- Share WFC with HSC
- 4 spectrographs for 600 fibers each
- λ=380-1260nm with 3 arms (⇔ 360-980nm for DESI)
- Fiber density: 2200/sq. degs (⇔ ~140 for 2.5m BOSS; ~600 for 4m DESI)
- The medium resolution mode (R~5000) for the red arm is also available



Scientific drivers: Three Pillars

All science cases are based on a spectroscopic follow-up of objects taken from the HSC imaging data

- Cosmology (~100 nights): 1400 sq. degrees
  - ~4M redshifts of emission-line galaxies
  - BAO at each of 6 redshift bins over 0.8<z<2.4
  - Cosmology with the joint experiment of WL and galaxy clustering (HSC/PFS)
- Galaxy Evolution (~100 nights): ~20 deg^2
  - A unique sample of galaxies (~0.5M) up to z~2, with the aid of the NIR arm
  - Dense sampling of faint galaxies (also many pairs of foreground/background gals)
  - Studying cosmic reionization with a sample of LAEs, LBGs and QSOs
- Galactic Archaeology (~100 nights): Milky Way/M31/dSphs
  - ~1M star spectra for measuring their radial velocities
  - Use the 6D phase-space structure, in combination with GAIA in order to study the origin of Milky Way (also use the M31 survey)

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Review

Review

Extragalactic science, cosmology, and Galactic archaeology with the Subaru Prime Focus Spectrograph

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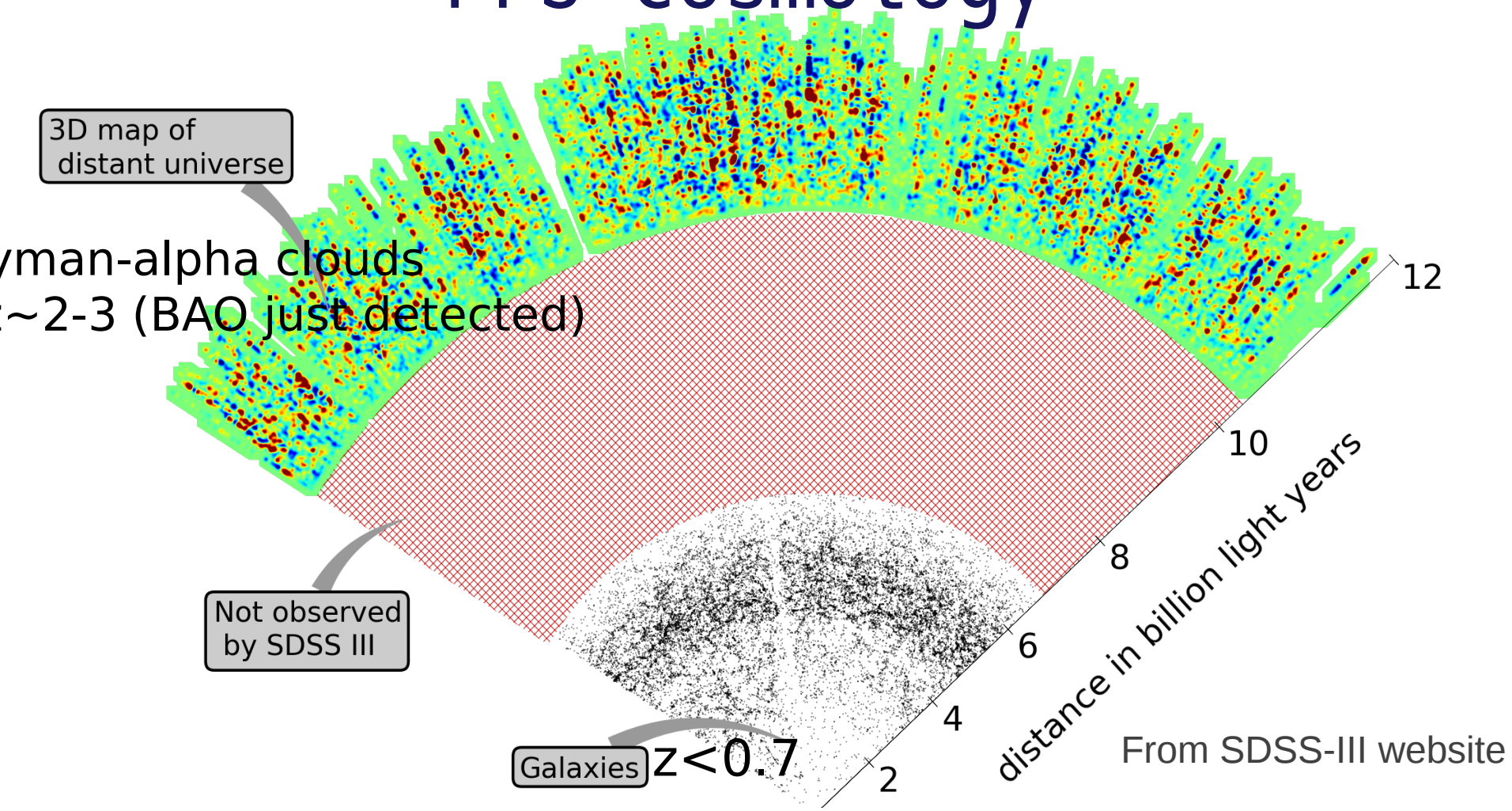
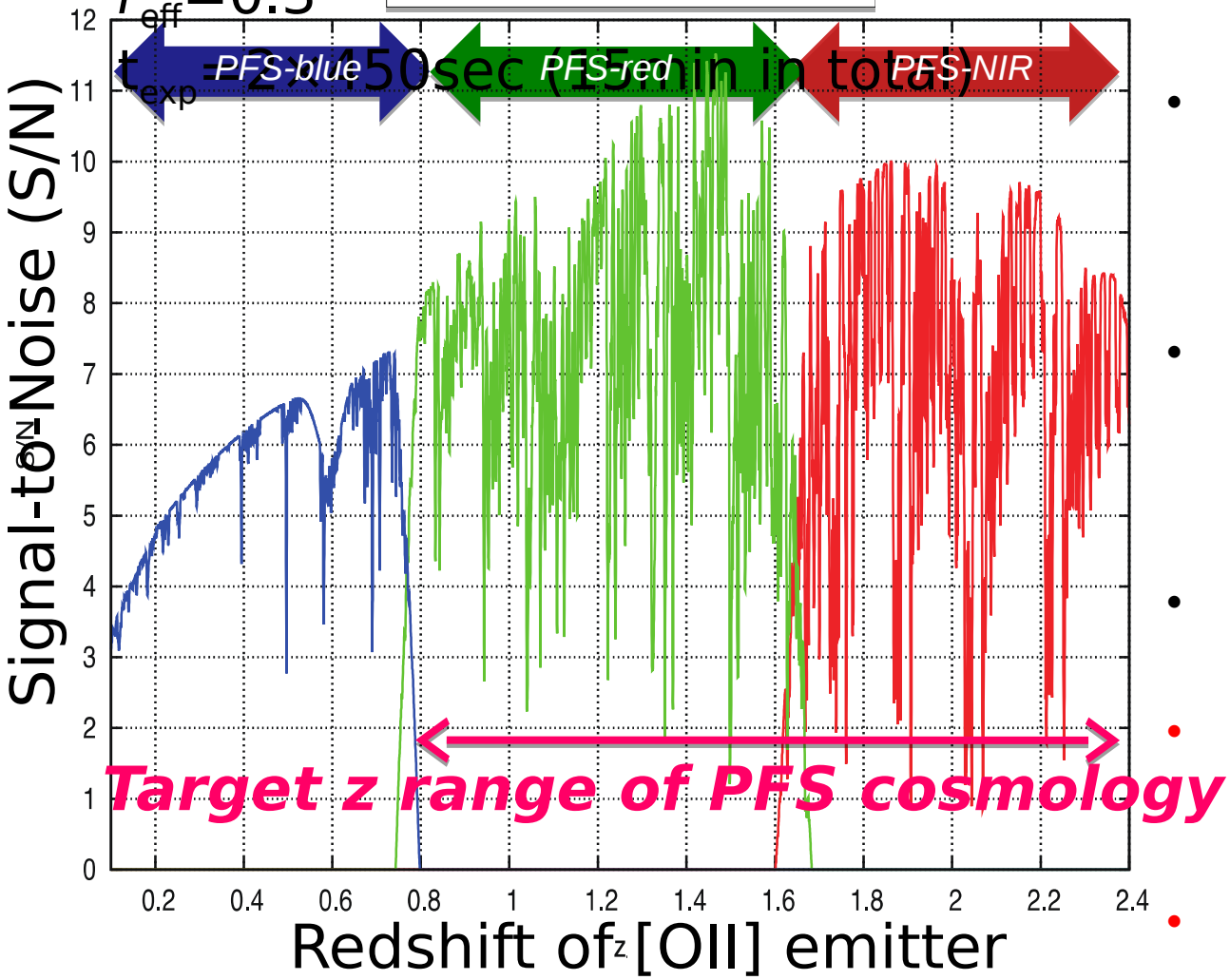
PFS Cosmology



- 0.7<z<2 universe not yet observed
- SuMIRe = Imaging & spectroscopic surveys of the *same* region of the sky with the *same* telescope

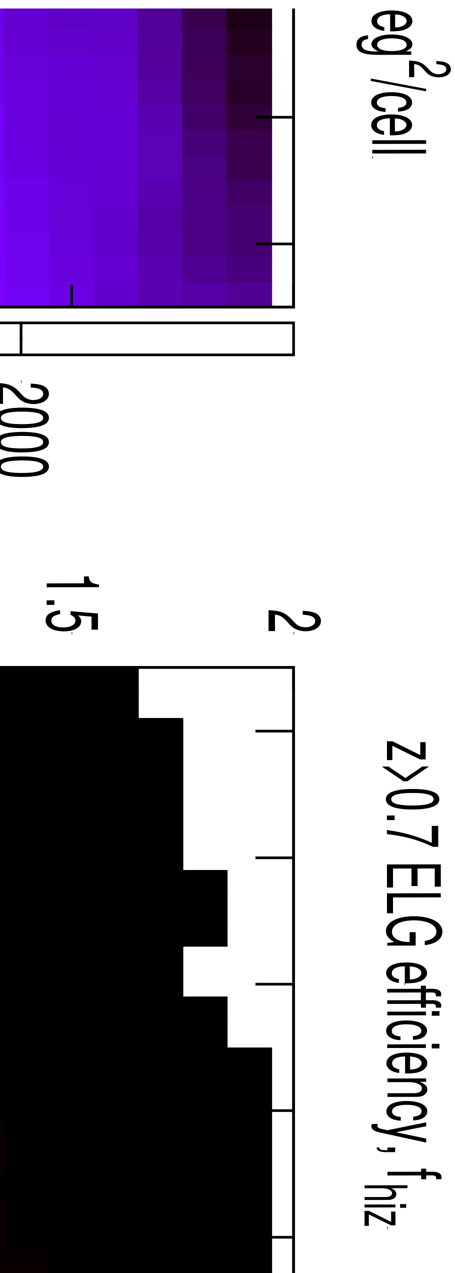
Unique capability of PFS

A working example:
$f_{[OII]}=5\times10^{-17}$erg/cm^2/s, σ_v=70 km/s,
r_{eff}=0.3''
t_{exp}=2×(450sec (15min in total)



- [OII] line (3727Å) feature used for cosmology survey
- Assuming baseline instrument parameters (fiber size, throughput, readout noise, etc.)
- *Conservative assumption*: 0.8'' seeing, at FoV edge, 26 deg. zenith angle
- *Included sky continuum & OH lines*
- The Red and NIR arms allow a wide redshift coverage, **0.8<z<2.4**
- LSS more linear at higher z

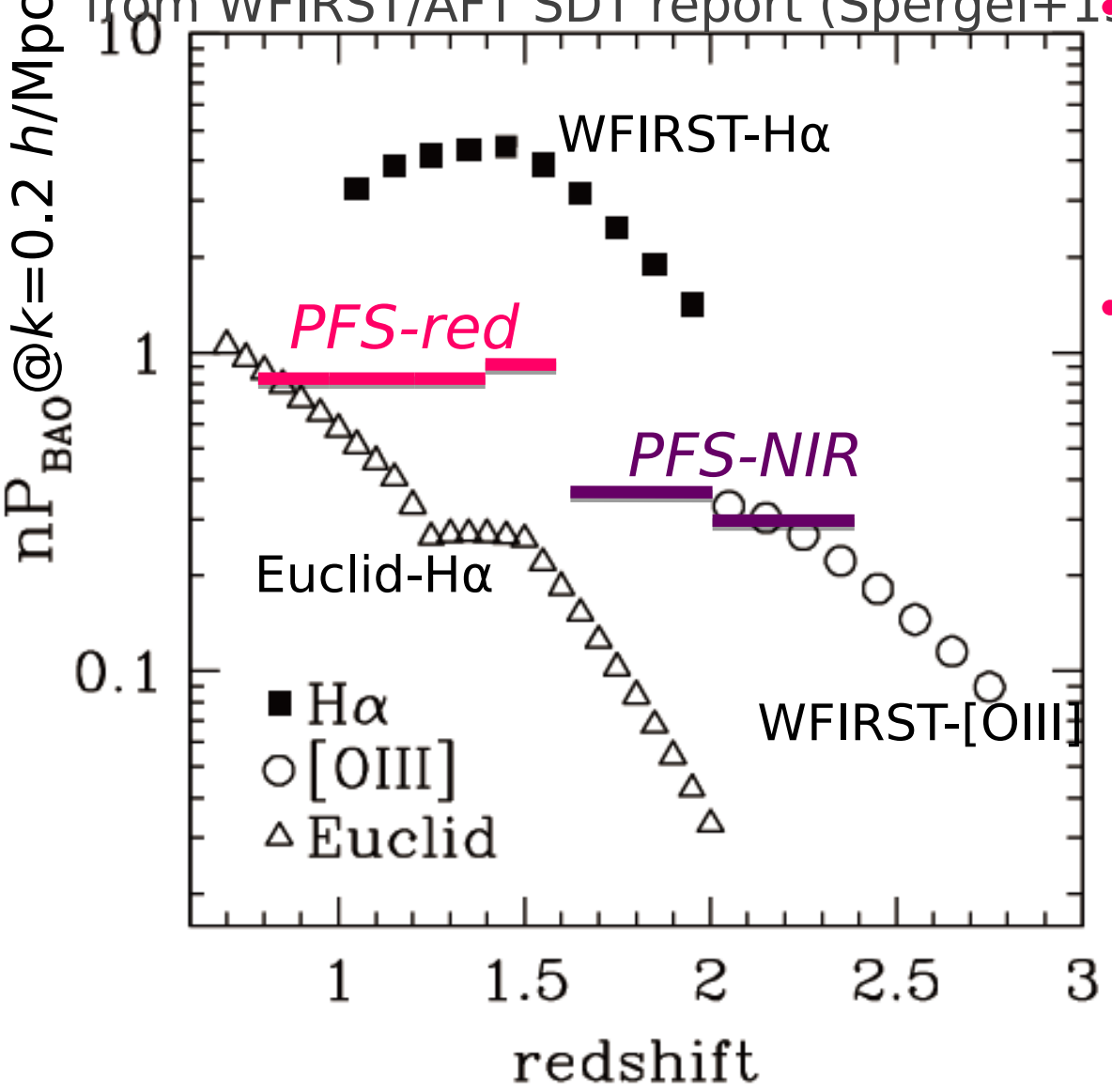
Target selection of [OII] emitters



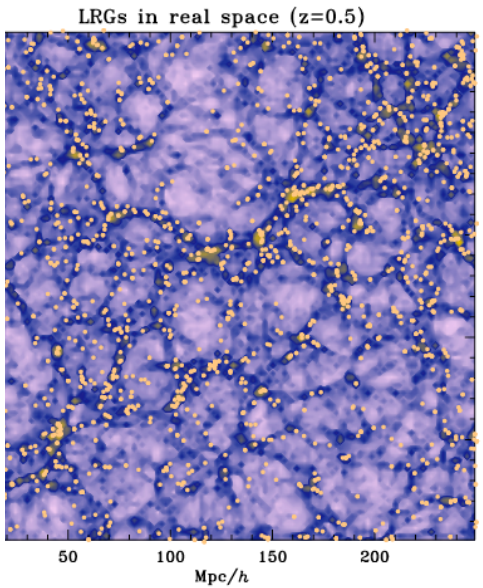
- Used mock catalog, based on the COSMOS 30 bands, zCOSMOS and DEEP2 (Jouvel et al. 2009, + further updates)
- Select blue galaxies from the HSC data (g~26)
- 7847 targets per the PFS FoV (1.3 deg. diameter)~ 3 × (# of PFS fibers)
- **~75%** success rate for 2 visits of each field

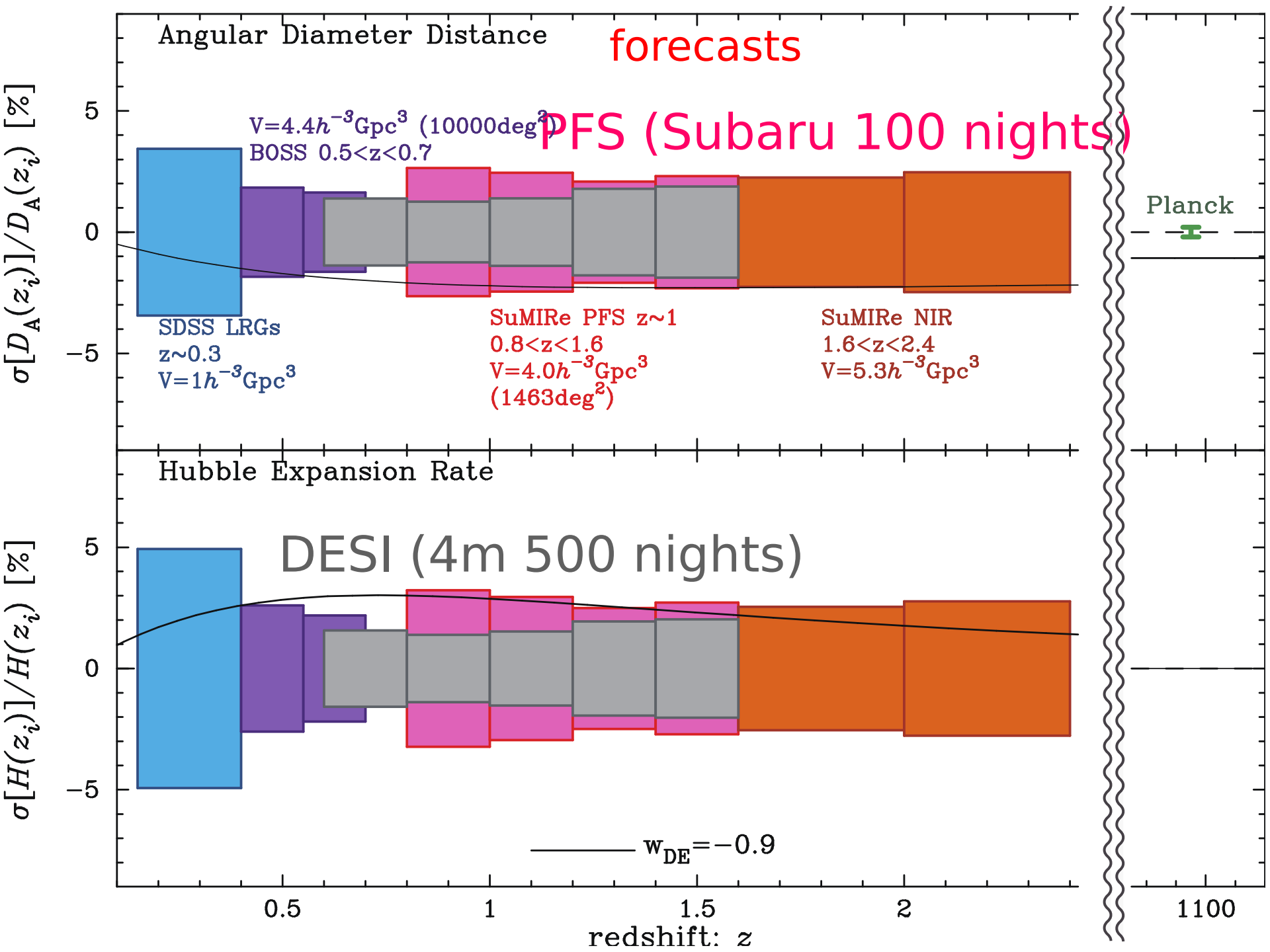
Dense sampling of LSS

from WFIRST/AFT SDT report (Spergel+13)



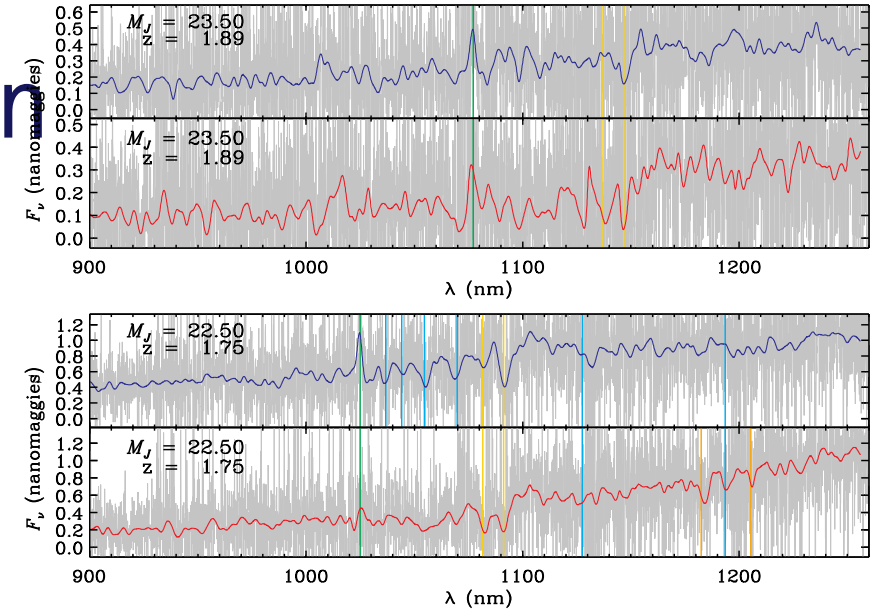
- *Fiber density: 2200 /sq. degs (⇔ ~140 for 2.5m BOSS; ~700 for 4m DESI)*
- *Galaxy BAO with NIR arm (z>1.6)* is unique until WFIRST/AFTA (~2025)




Angular Diameter Distance
forecasts
PFS (Subaru 100 nights)
V=4.4h^-3Gpc^3 (10000deg^2)
BOSS 0.5<z<0.7
SDSS LRGs
z~0.3
V=1h^-3Gpc^3
SuMIRe PFS z~1
0.8<z<1.6
V=4.0h^-3Gpc^3
(1463deg^2)
SuMIRe NIR
1.6<z<2.4
V=5.3h^-3Gpc^3
Planck
σ[D_A(z_i)]/D_A(z_i) [%]
Hubble Expansion Rate
DESI (4m 500 nights)
w_DE=−0.9
σ[H(z_i)]/H(z_i) [%]
5
0
−5
0.5
1
1.5
2
1100
redshift: z

PFS Galaxy Evolution

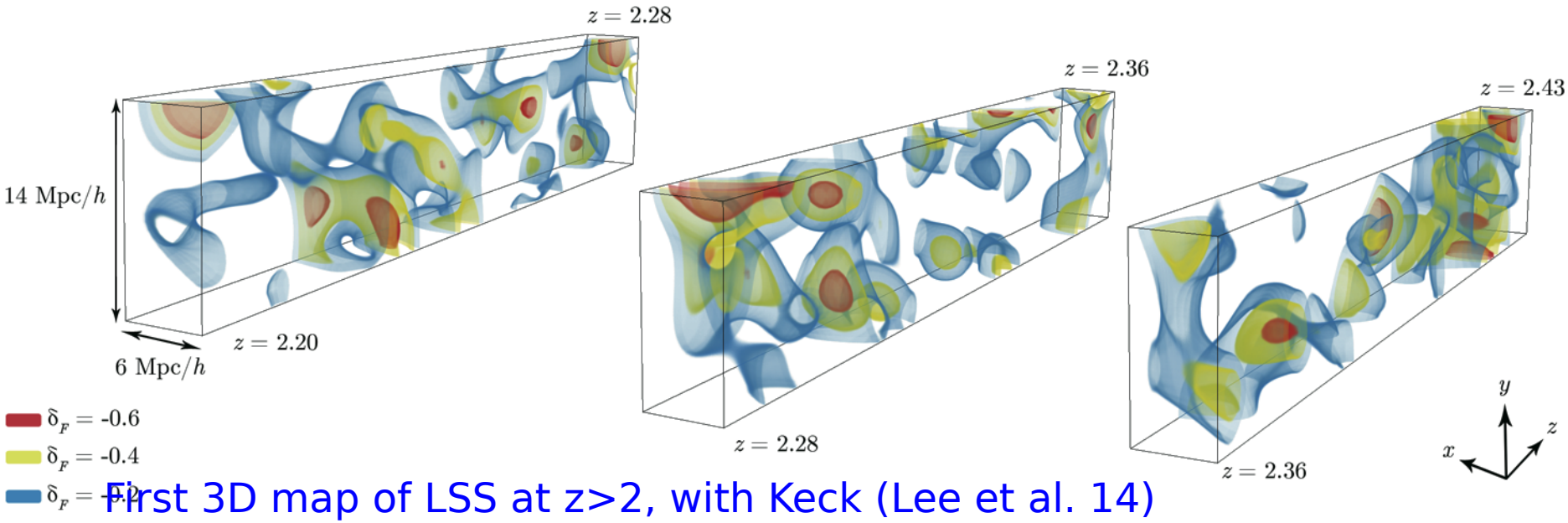
- PFS also enables a spectroscopic survey of “general” galaxies at z~1-2 for the HSC-Deep of ~20 sq. degrees (a detection of continuum in each spectrum)



A dense spec. survey of galaxies

PFS-Galaxy survey lives in a unique region of depth-area-redshift

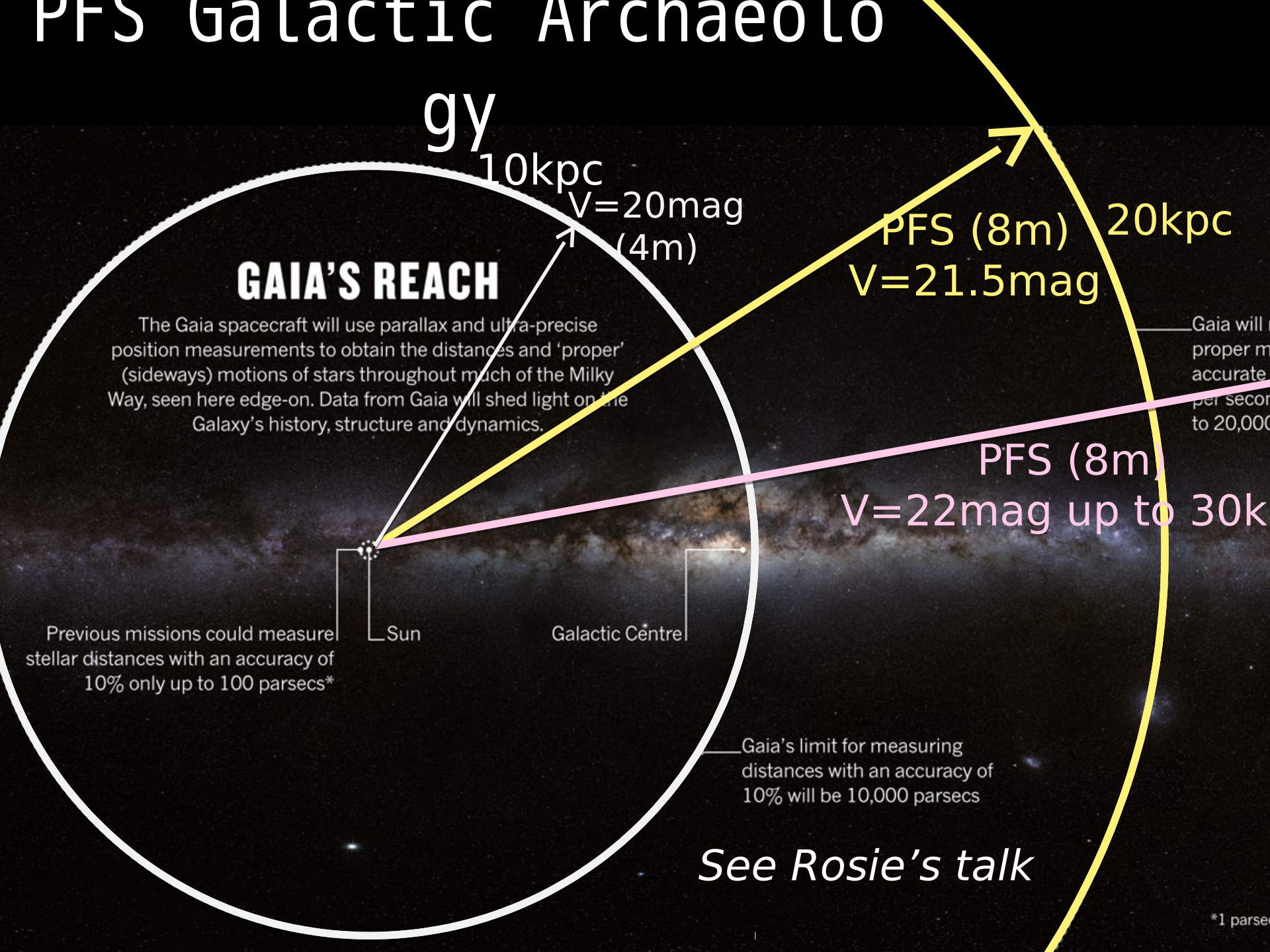
3D tomography of IGM at z>2 (as a part of PFS Galaxy)



First 3D map of LSS at z>2, with Keck (Lee et al. 14)

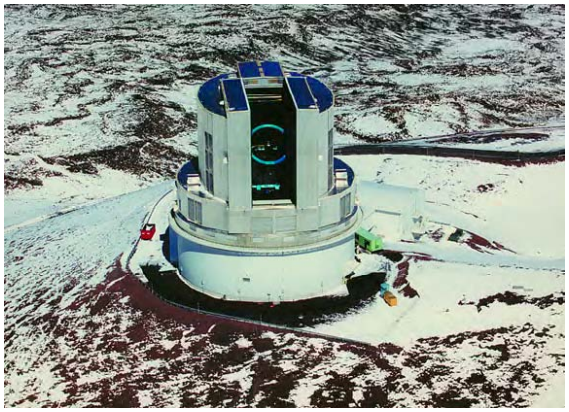
- Use LBGs as background light to probe the foreground IGM
- PFS can fill ~2000 fibers per pointing with g<24 LBGs and QSOs
- Just need a ~10nights survey with 4-5hrs per pointing, to map out ~0.1 $(Gpc)^3$ volume resolving <10Mpc scales
- *Give an understanding of physics on the interplays betwe*

PFS Galactic Archaeology

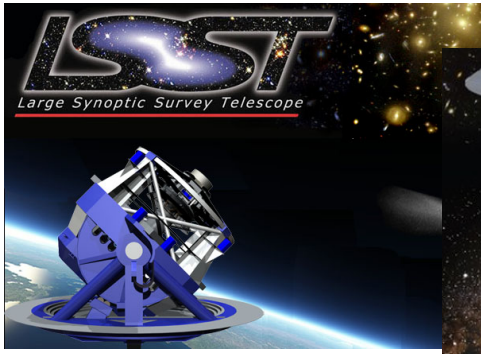


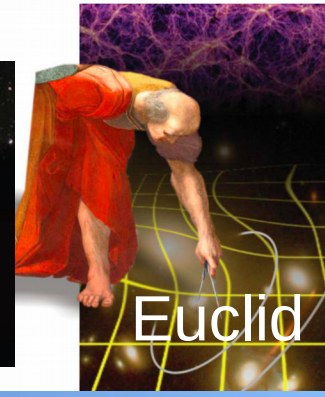
See Rosie's talk

Subaru Strategy in 2020 (TMT) era

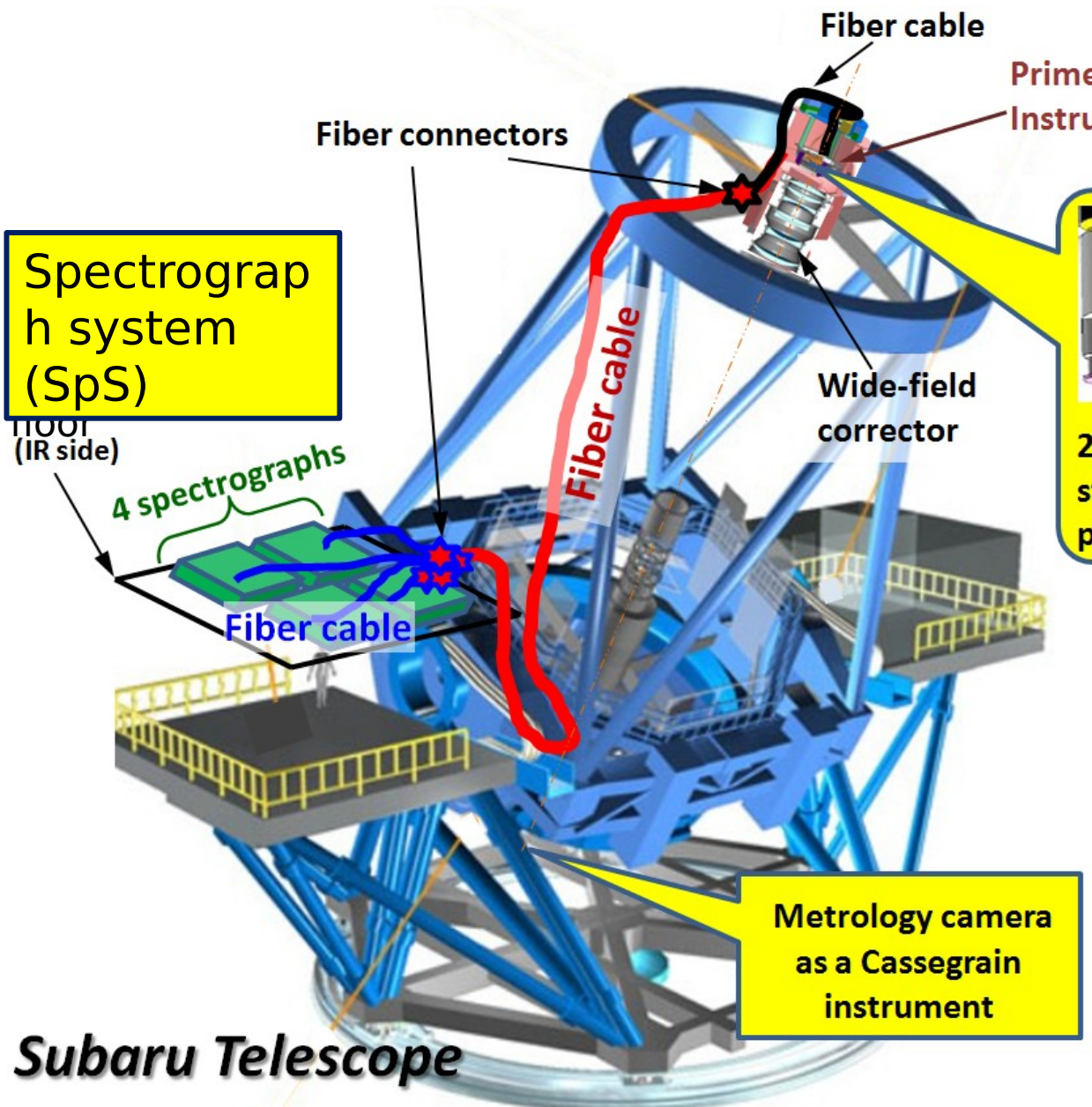


- HSC & PFS allow for making Subaru Tel. a unique facility in 2020era: target obs ⇒ survey telescope
- HSC, PFS, GLAO major instruments in 2020er
- Various synergies
  - GAIA (2013)
  - Euclid (2019)
  - LSST (2020? -)
  - WFIRST (2025?)
  - TMT& E-ELT (202?)





PFS subsystems distribution



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

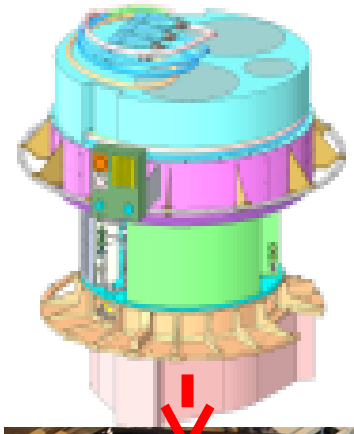
Spectrograph system (SpS)

POpt2 & WFC will be shared with Hyper Suprime Cam (HSC)

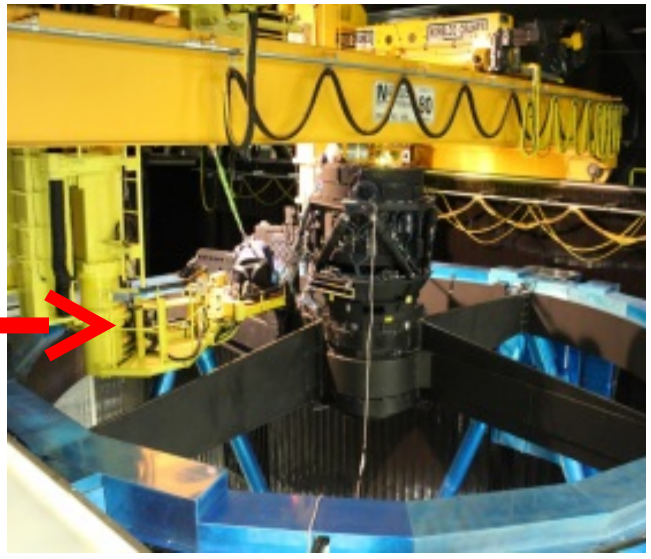
Software system

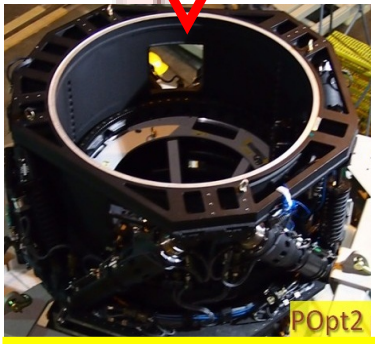
(Calibration system)

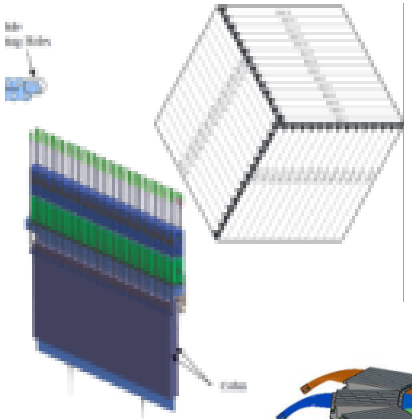
Prime Focus Instrument (PFI)



PFS shares the prime focus housing unit "POpt2" and Wide-Field Corrector "WFC" with HSC.

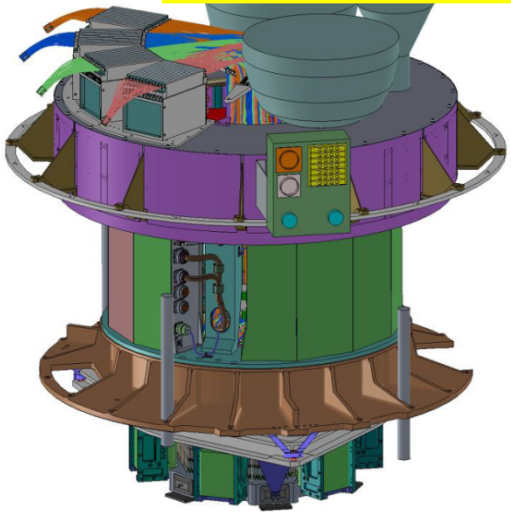




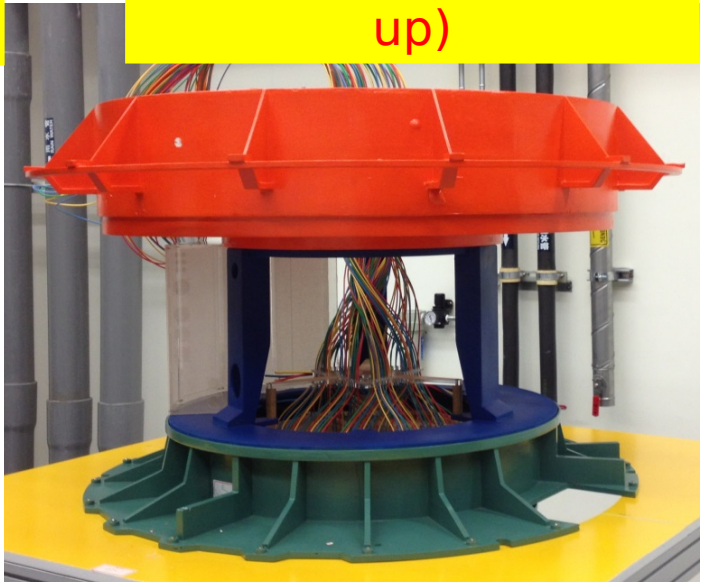


Hexagonal science field with 6 CCD cameras for AG.

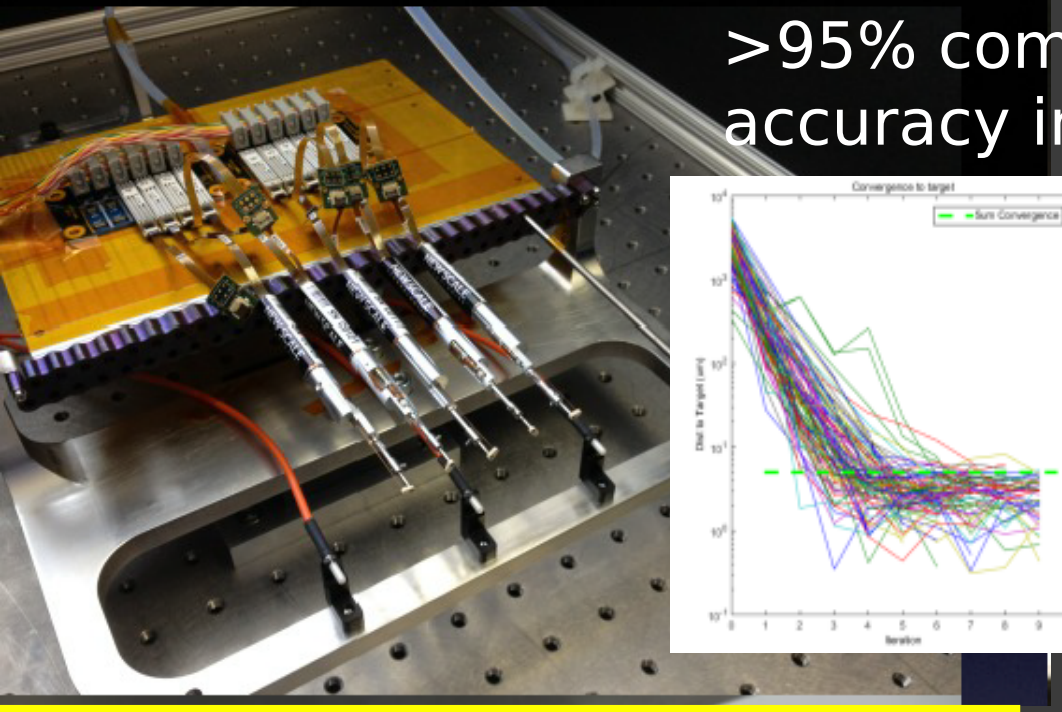
PFI (3D model)

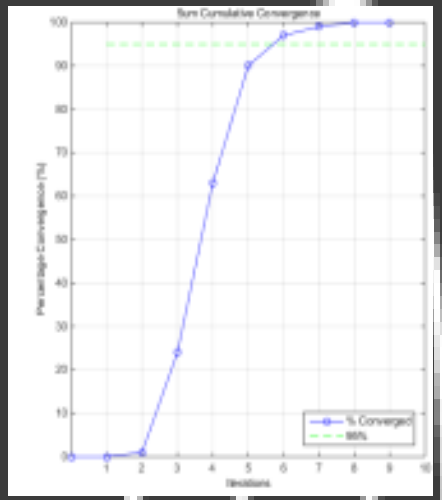


PFI (real-size mock-up)



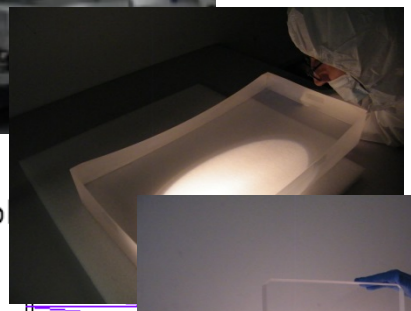
>95% comes to <5µm accuracy in ~6-7 iterations



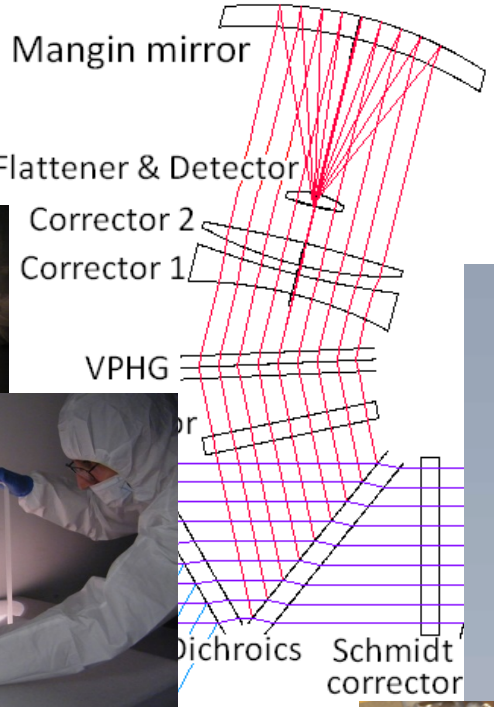


“Cobra” engineering model module

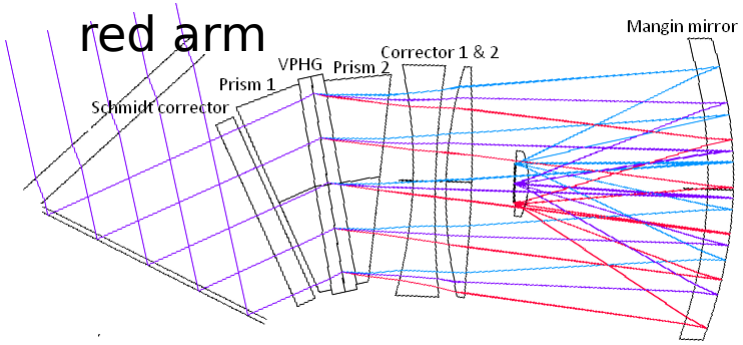
Spectrograph System (SpS)

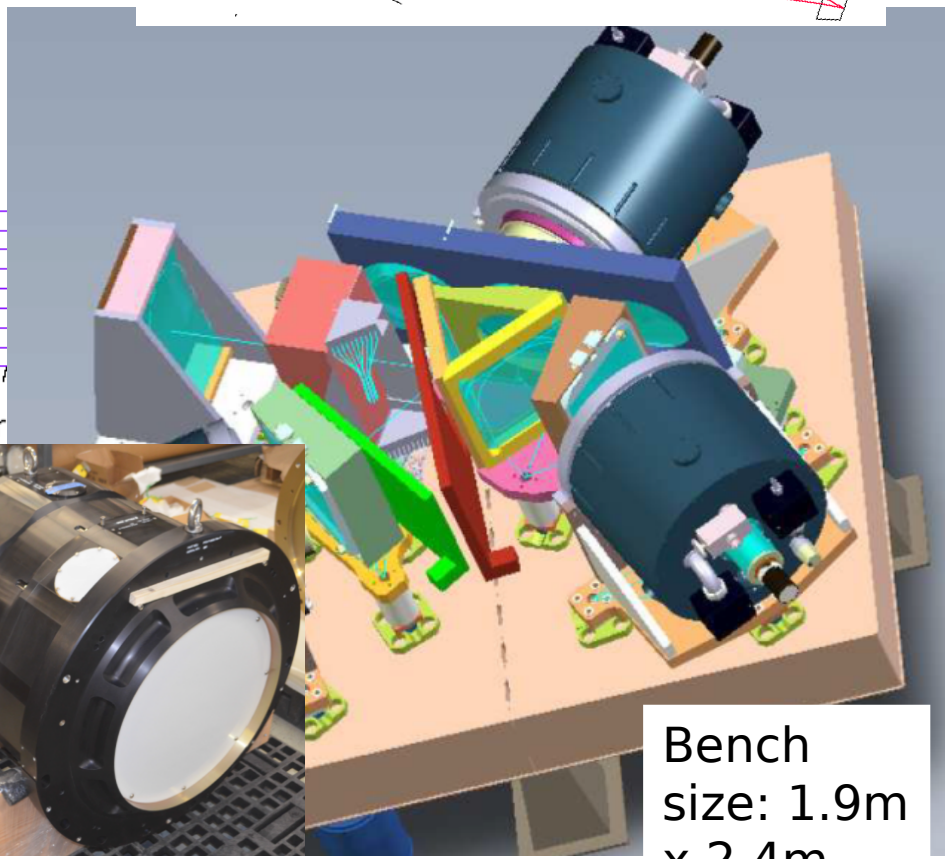


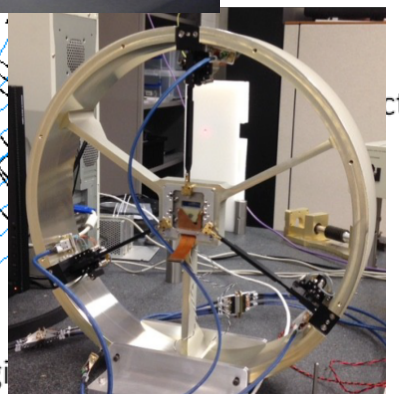
"Red"

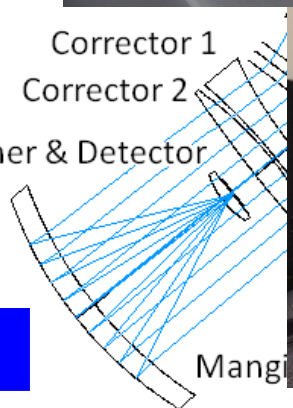


Mid. Res mode in the red arm









"Blue"

Bench size: 1.9m x 2.4m

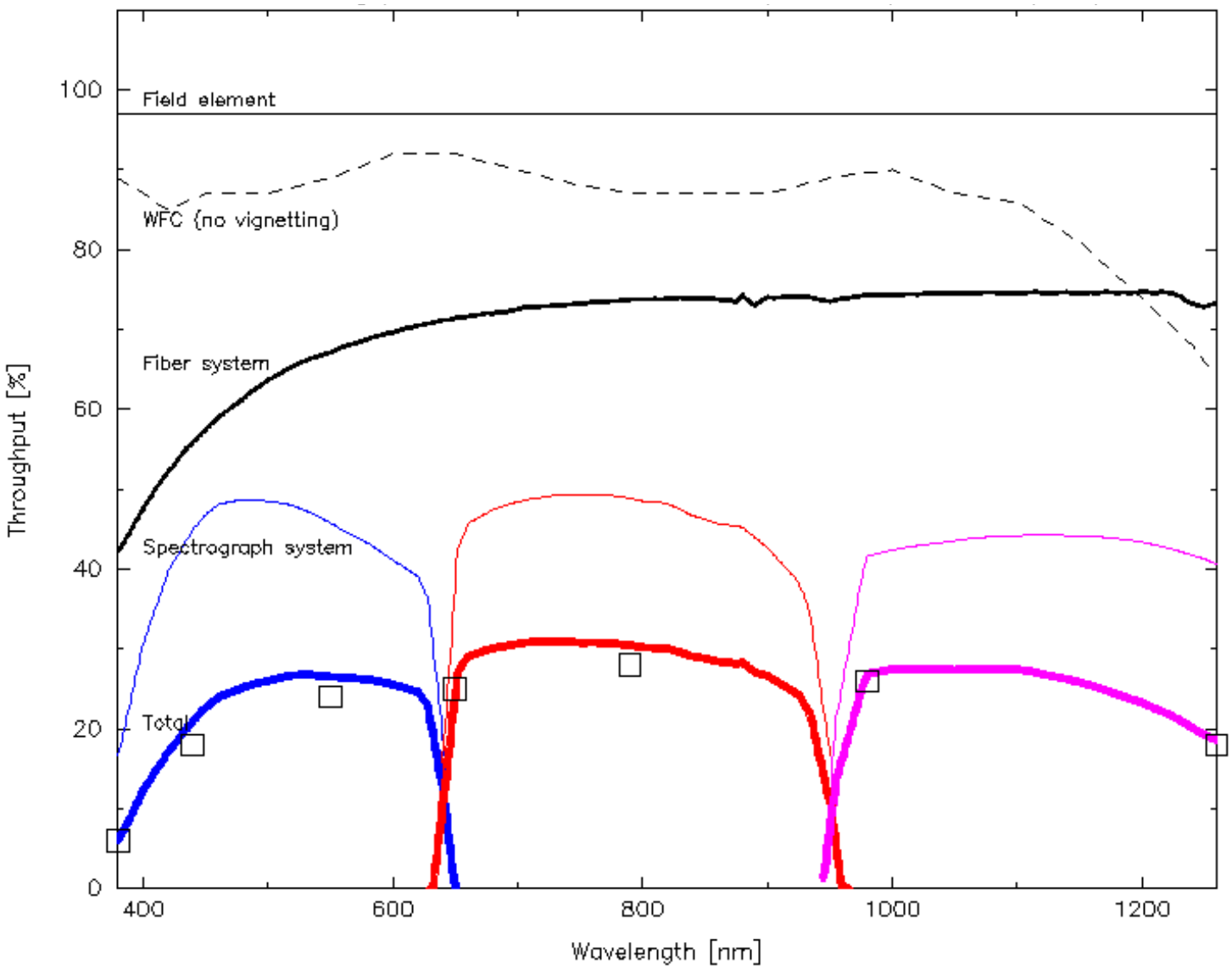
A summary of PFS focal plane

		Current situation	Notes
Optical configuration		WFC ✉ Field Element ✉ Microlens ✉ Fiber	
Mech. configuration		POpt2 + PFI	
Input F/# to Fiber		2.8	With microlens
# of science fibers		2394	Min. ~2350 [TBC] fully operational at delivery
# of fixed fiducial fibers		99	~50-50 split to interleavedd & perimeter
Input fiber core diameter		127um	~1.1 arcsec w/ microlens
Field of view		1.3 deg	Hexagonal , ~1.4 deg on chord
Positioner pitch		8mm	Positioner dia. 7.7mm
Positioner patrol field		9.5mm diameter	
Reconfiguration time		~60 sec	TBC
AG camera	Number	6 (one on each side of hex. Field)	One on each side of hex. field
	Format	1K x 1K CCD, 13um pixel size	5.5 sq. arcmin per camera
	Sensitivity	S/N=100 in 4 sec for r`=18.5 (AB)	>=1 star per camera

A summary of SpS

		Blue	Red		NIR
			Low Res	Mid Res	
Collimator F/#		2.5			
Camera F/#		1.1			
# of science fibers		597 or 600			
Operating temperature		+5 degC			
Input fiber core diameter		129um			
Wavelength coverage		380-650nm	630-970nm	710-885nm	940-1260nm
Resolving power		~2300	~3000	~5000	~4300
Detector	Type	CCD (Hamamatsu, with a new blue coating)	CCD (Hamamatsu, with the same coating as HSC)		H4RG (Teledyne, 1.7um cutoff)
	Format	(4K x 2K) x 2	(4K x 2K) x 2		4K x 4K
	Pixel size	15um			
	Readout noise	~4 e-/pix			4 e-/pix
	Dark	~0.4 e-/pix/hour			0.01 e-/pix/s
Thermal background		None			0.006 e-/pix/s

“Baseline” throughput model



Field Element

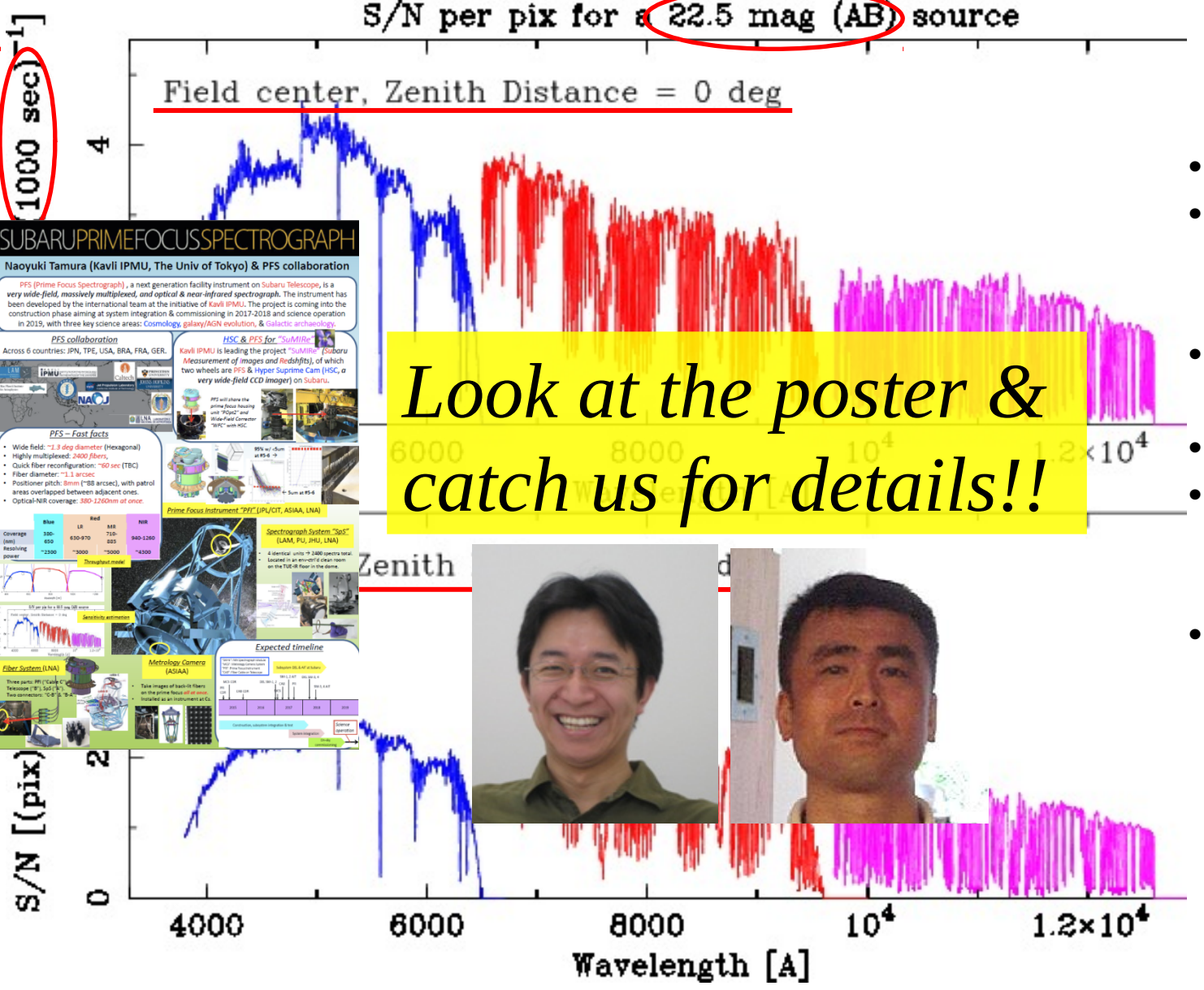
WFC transmission

Fiber system

Spectrograph system

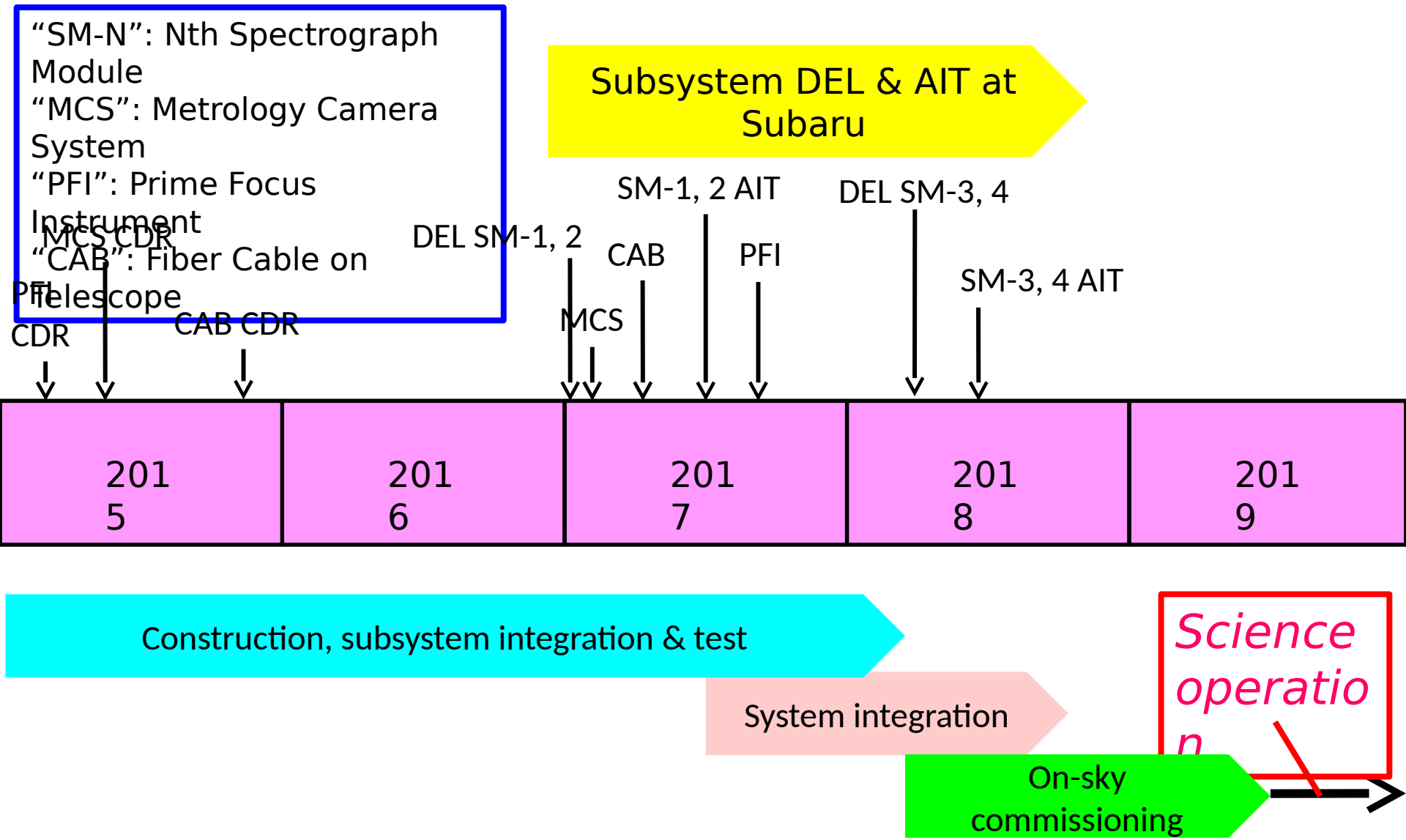
Total (instrument only)

Sensitivity estimation – Under way



- 1 pix: ~0.8A
- “Baseline” throughput is assumed.
- Gunn’s sky model
- Dark night
- Detector & thermal noises as specified.
- Point source: ~0.7 arcsec FWHM (✉ ~85% energy input at the field center with no x-y error).

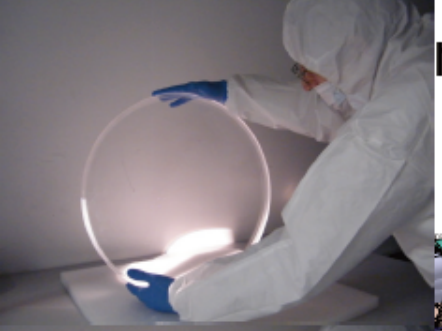
Project timeline

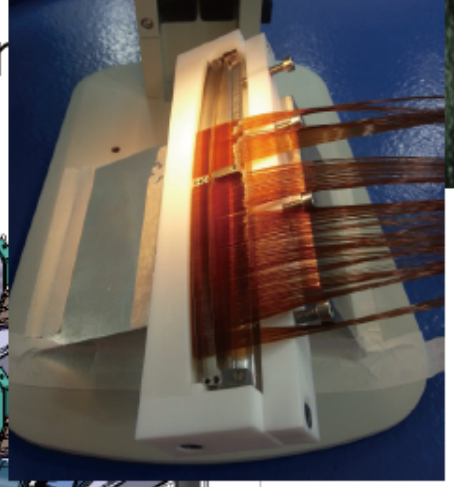
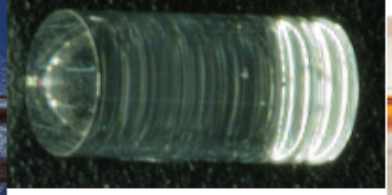
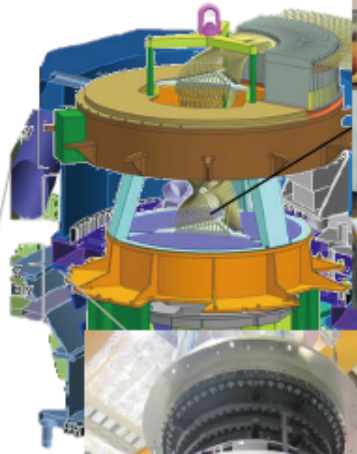


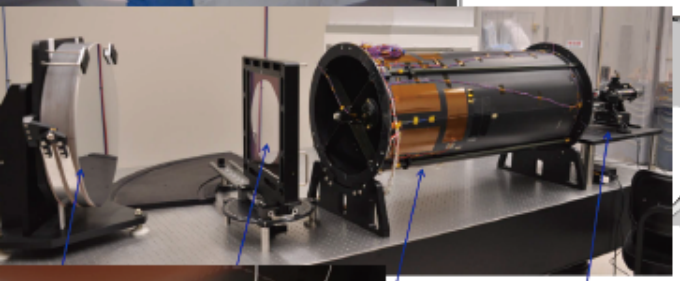
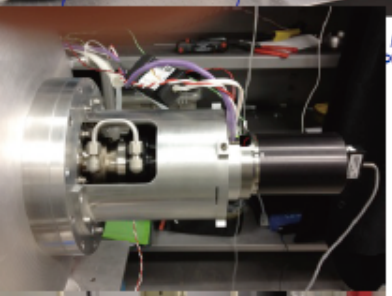
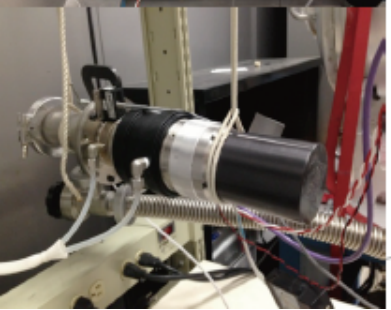
@ PFS collaboration meetin

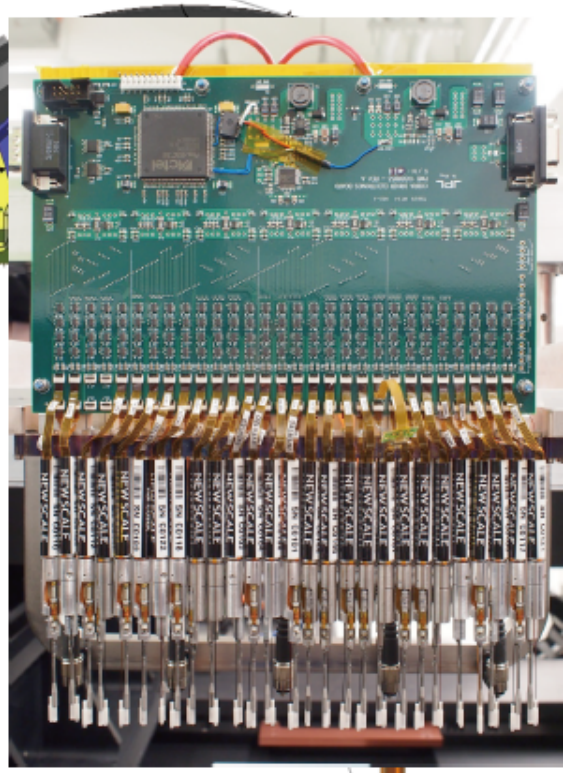
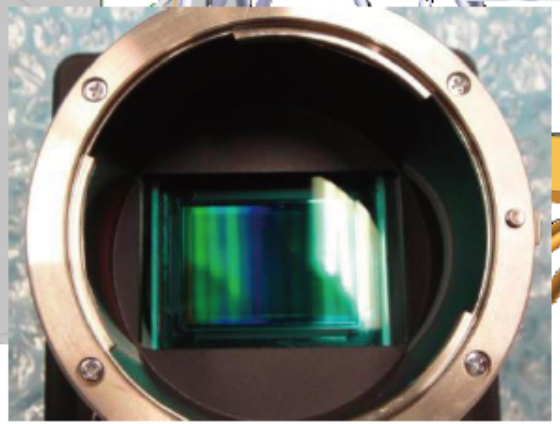
Subau Prime Focus Spectrograph (PFS)

- PFS is one of the key, strategic instruments of Subaru
- Subaru will switch to a survey-type operation in 2020 (TMT) era
- Almost fully funded (more than 90% of ~$80M)
- PFS science drivers: cosmology, galaxy, GA: ~300 Subaru nights
- Unique capability: 1.3deg FoV, 2394 fibers, lambda=380 – 1260nm, R~2000 (blue), 3000 (red), 4000 (NIR)
- Complementary to 4m MOS



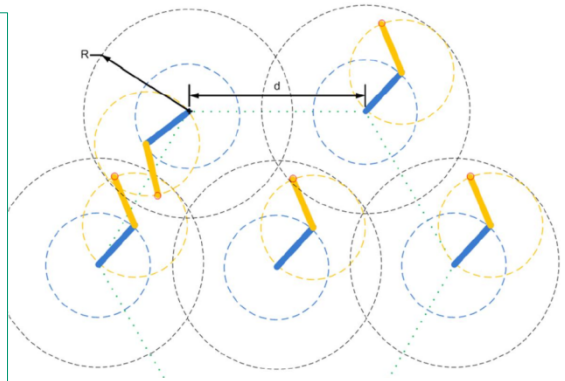




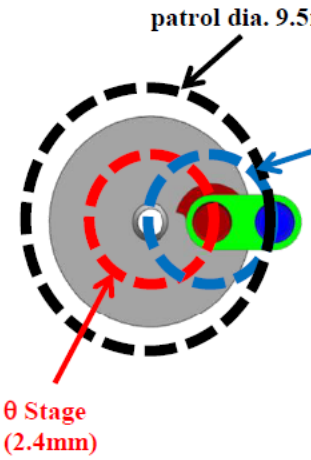




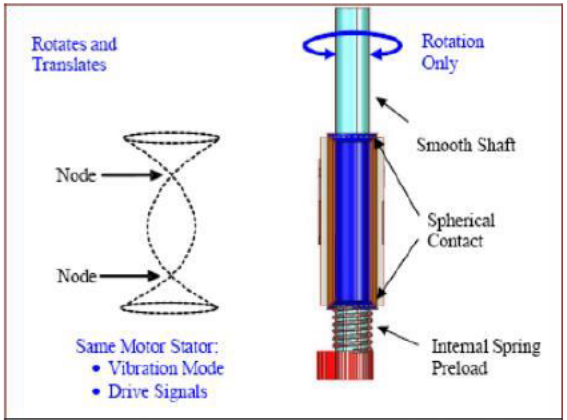



LASER UNEQUAL PATH
INTERFEROMETER (LUPI)

Fiber positioner "Cobra"

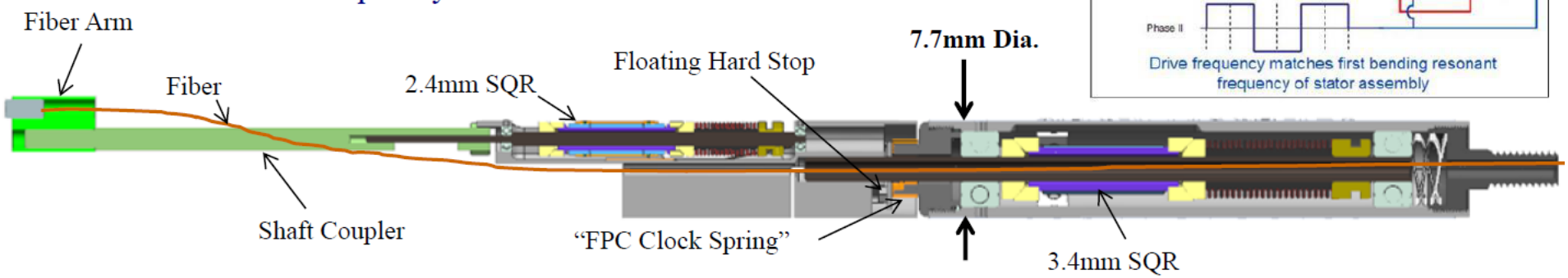
Positioners with a 8mm pitch.
✉ Patrol areas have some overlaps.

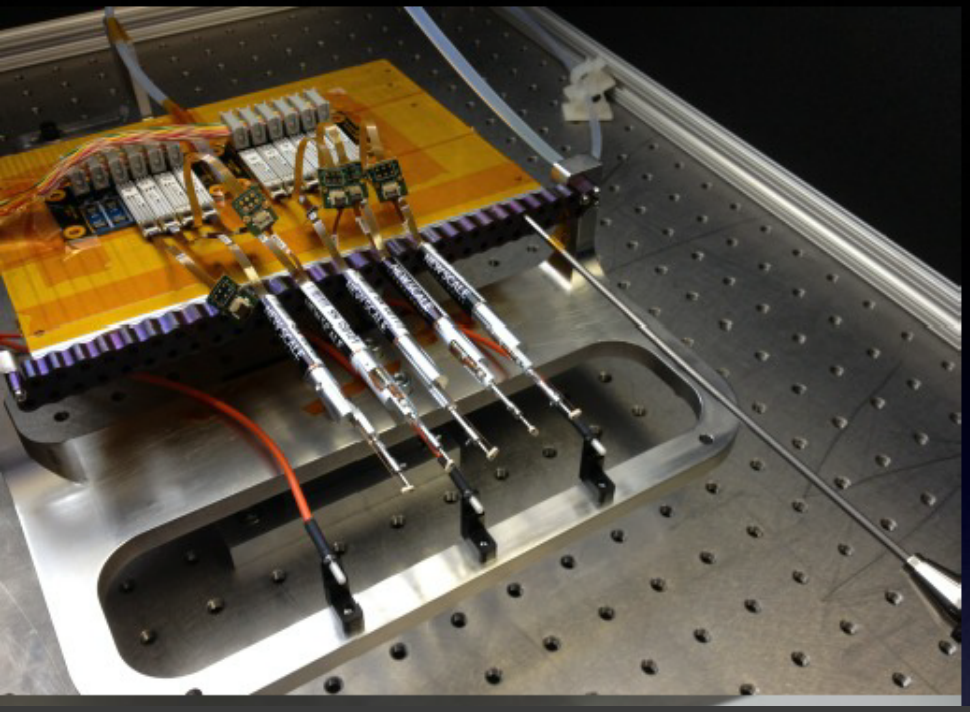




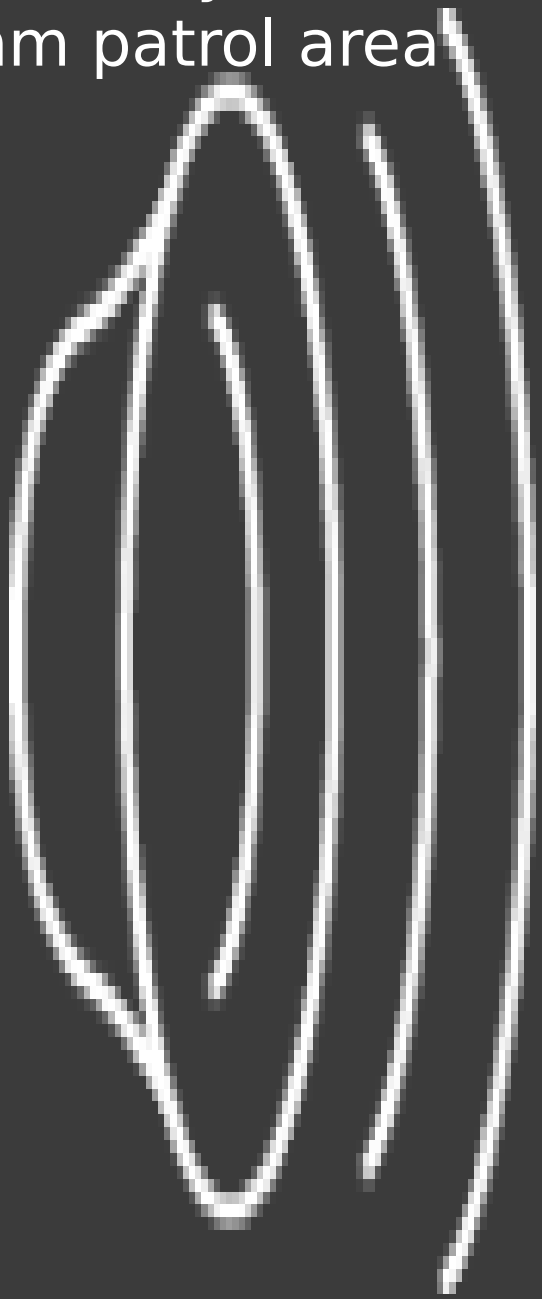


- Fiber is routed from the arm on the phi-stage through the center of the Cobra
  - Stages utilize hard stops to allow for full range of motion, yet prevent over twisting of the optic fiber
  - Protects fiber during handling and operation
- Piezo motors use phase shifted signals to excite the motor body at the first bending resonant frequency





5μ accuracy in 7 iterations
9.5mm patrol area



A summary of PFS focal plane

		Current situation	Notes
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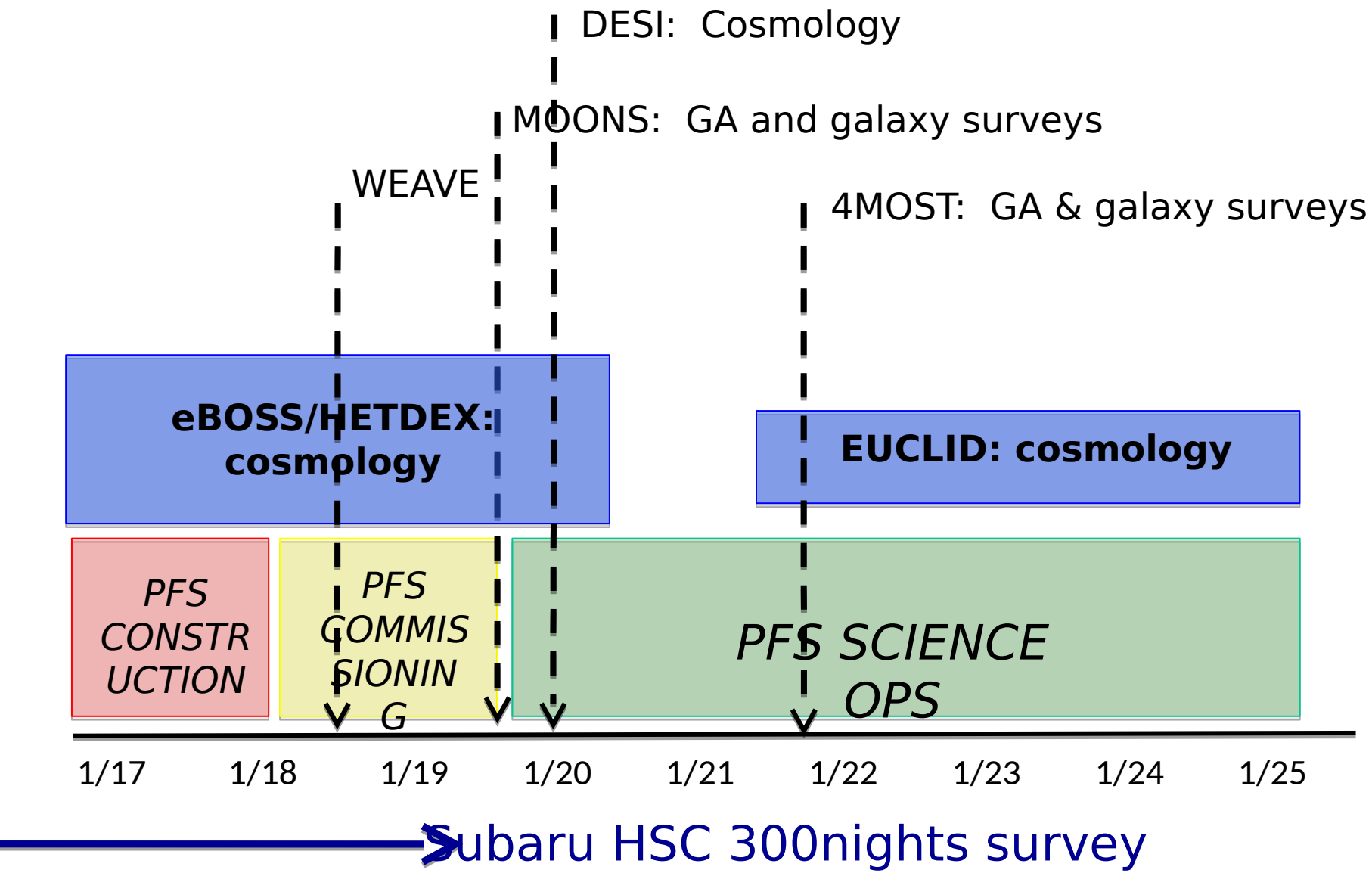
Input fiber core diameter		127um	~1.1 arcsec w/ microlens
Field of view		1.3 deg	Hexagonal , ~1.4 deg on chord
Positioner pitch		8mm	
Positioner patrol field		9.5mm diameter	
Reconfiguration time		~60-70 sec	
AG camera	Number	6 (one on each side of hex. Field)	One on each side of hex. field
	Format	1K x 1K CCD, 13um pixel size	5.5 sq. arcmin per camera
	Sensitivity	S/N=100 in 4 sec for r`=18.5 (AB)	>=1 star per camera

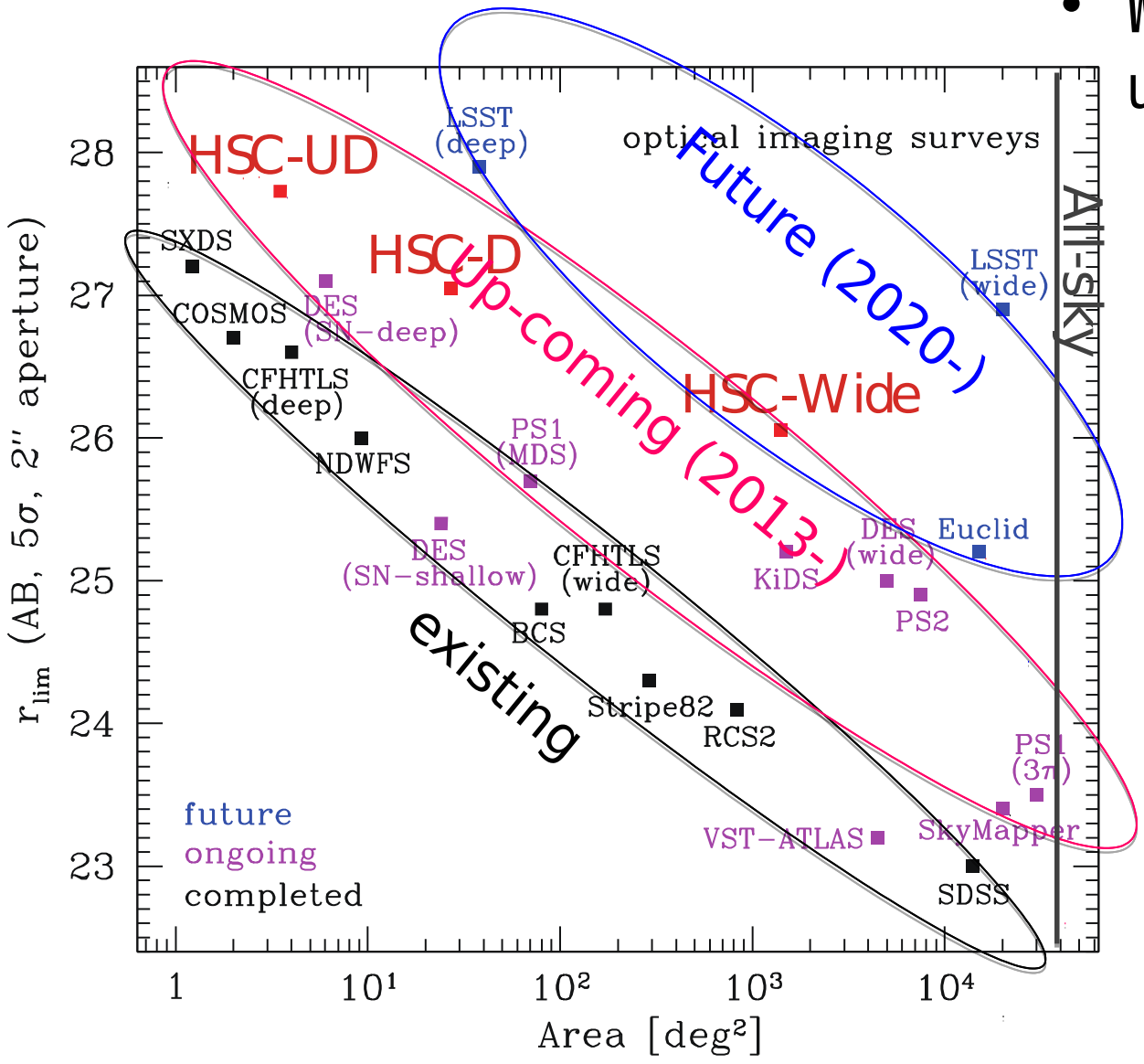
The Competition: Schedules



Project history & Current status

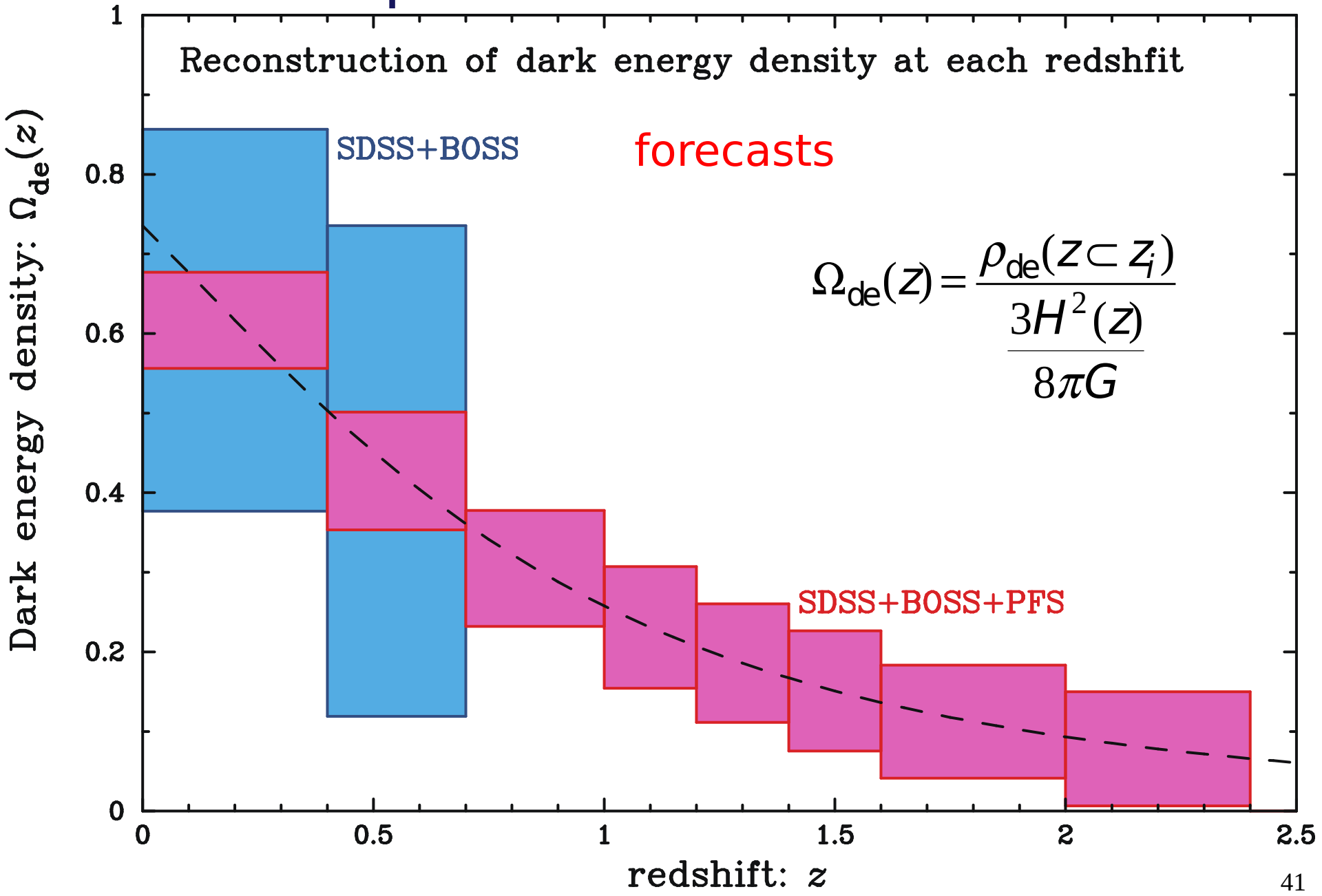
- Apr 2011: Project Office was established. Design study activities were formalized.
- Mar 2012: Conceptual Design Review (CoDR) @ Hilo
- Feb 2013: Preliminary Design Review (PDR) @ Hilo
- Mar 2013 – Present: A hybrid of critical design phase & production phase
    - Critical Design Review is held at subsystem level (i.e. no project CDR).
        - Mar 2014: Cable A & Spectrograph System (SpS) CDR
        - Early 2015: Metrology camera, PFI, fiber positioner system, Cable C
        - Late 2015: Cable B
- 2017-- : System integration & commissioning
- ASAP: Start open use (i.e. science operation)

Survey parameters of HSC SSP Survey



- Wedding-cake-type survey
  - Wide (1400 degs, i~26): Cosmology
  - Deep (28 degs, i~27): Galaxy evolution
  - Ultradeep (3 degs, i=27.7): cosmic reionization
  - *Each is new and unique in parameter space*
  - *See Aihara's talk for*

Model-independent DE reconstruction

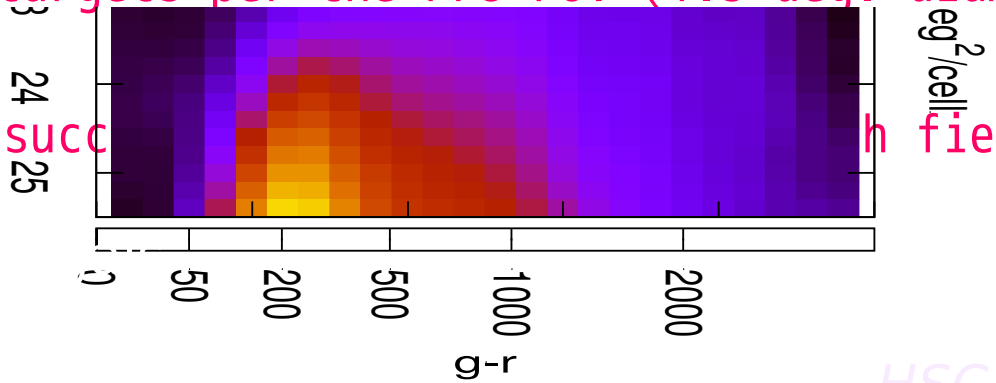


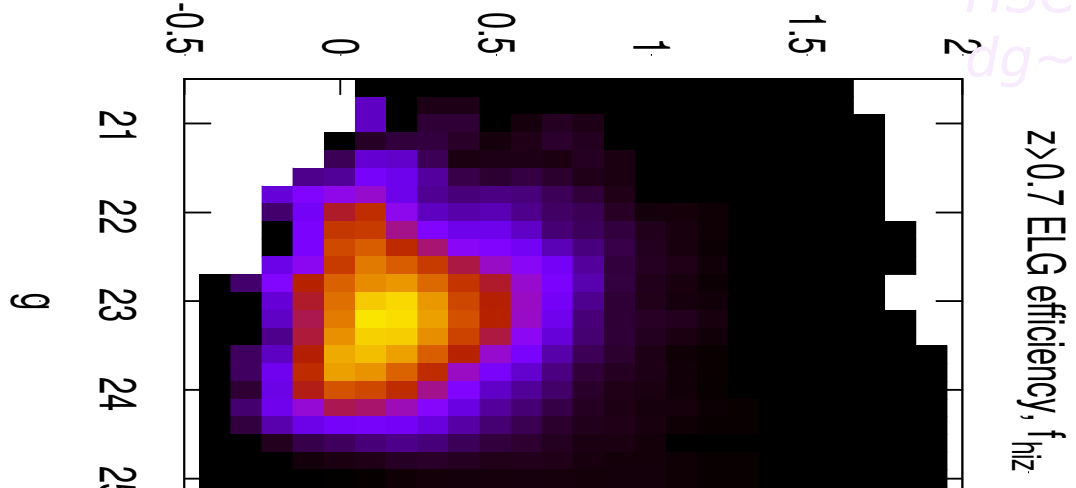
Target selection of [OII] emitters

- Mock Catalog, based on the COSMOS 30 bands, zCOSMOS and DEEP2 (Jouvel et al. 2009, + further updates)
- The wide *z*-range allows an efficient target selection based on the color cut:

$$22.8<g<24.2 \;\&\; -0.1<g-r<0.3$$

- 7847 targets per the PFS FoV (1.3 deg. diameter)~ 3×(# of PFS fibers)
- **~75%** succ… …h field



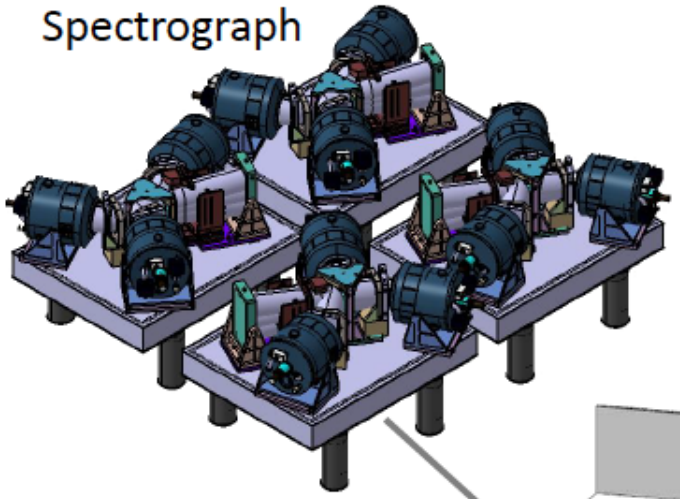


HSC (g~26) with dg~0.25

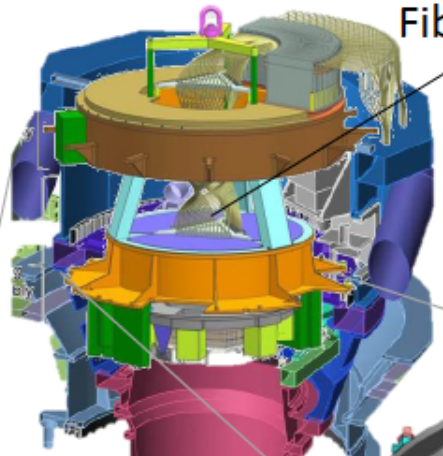
Prime Focus Spectrograph (PFS)

Prime Focus Instrument

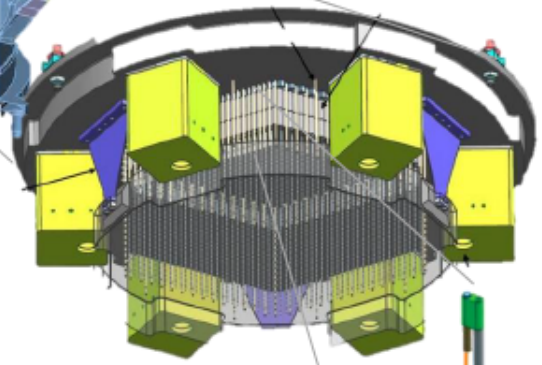
Spectrograph



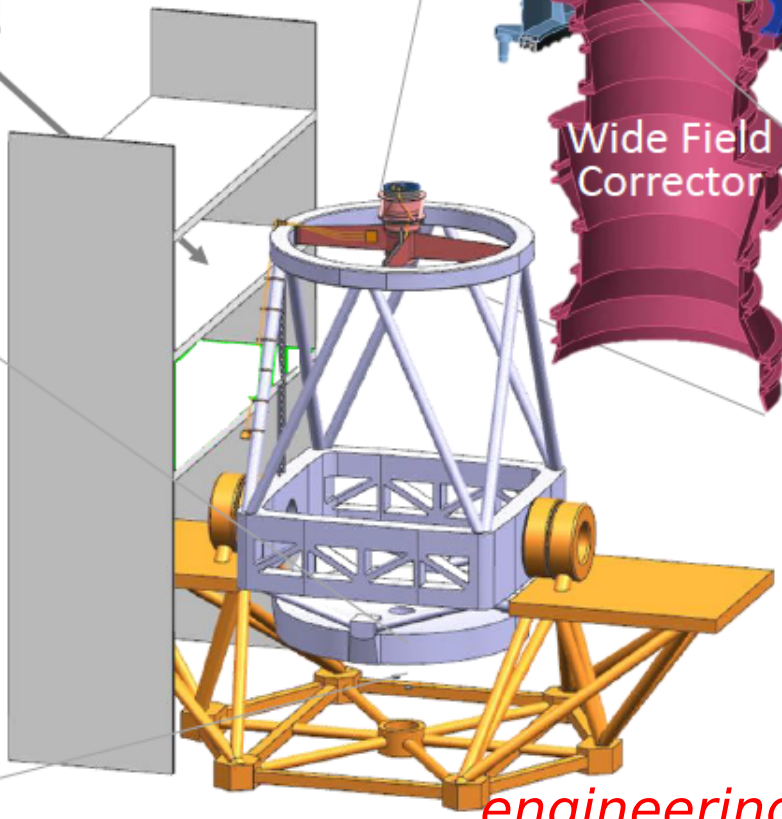
Fiber Cable



Wide Field
Corrector



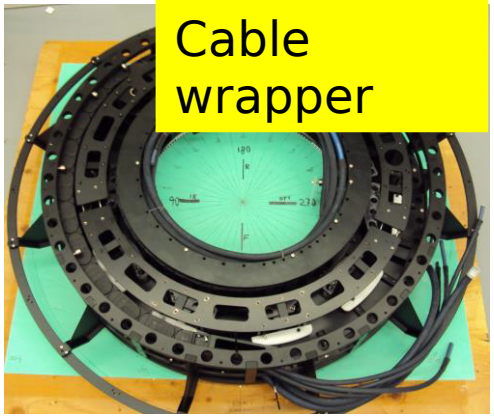
Metrology camera



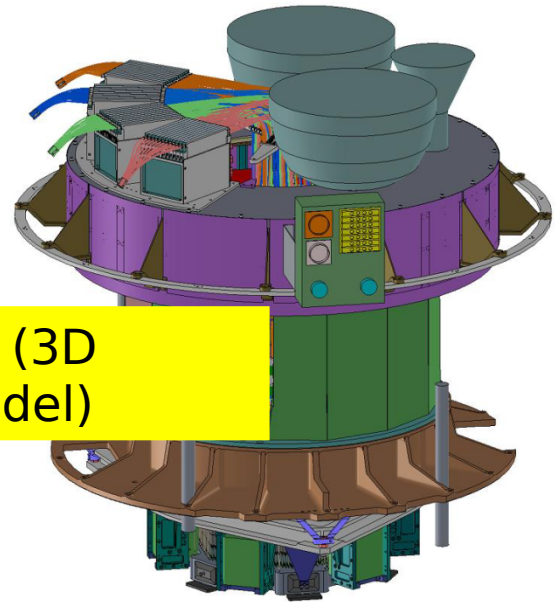
Fiber Positioner
(from bottom)

engineering first light in 2017-18

Models & Prototypes

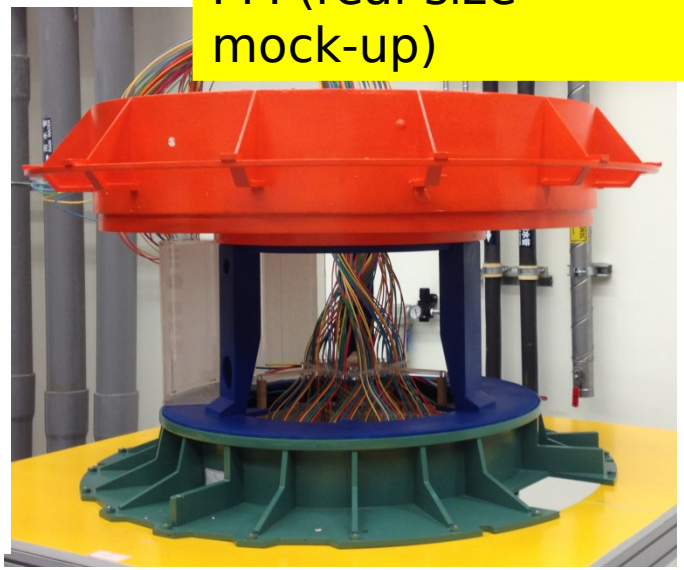


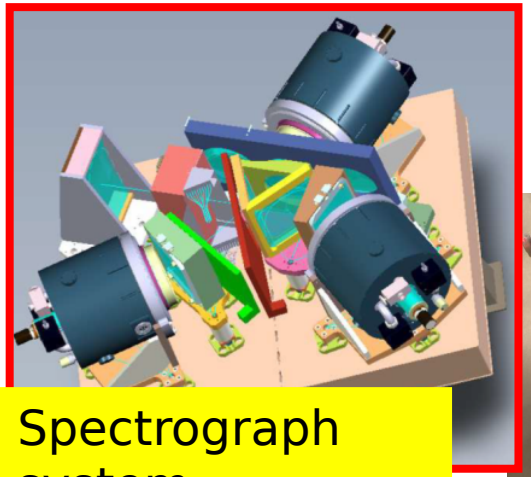
Cable wrapper



PFI (3D model)

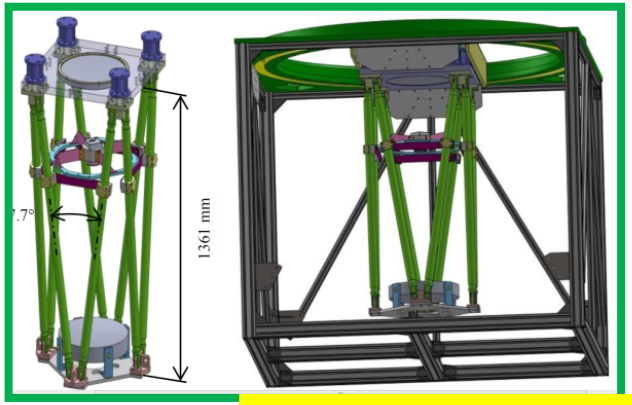
PFI (real-size mock-up)



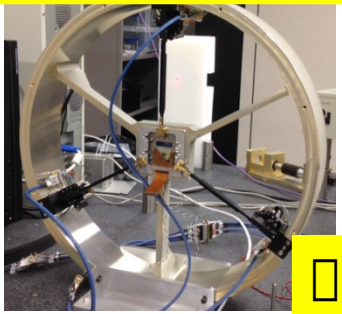


Spectrograph system

Fiber positioners “Cobra”



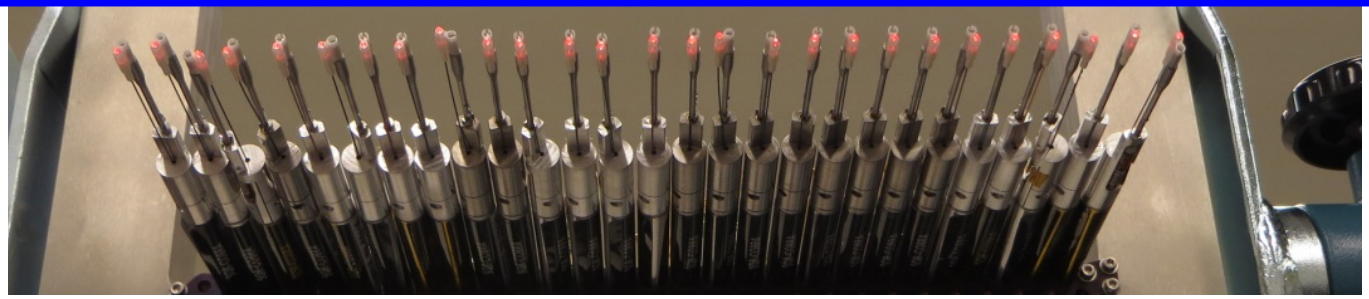
Metrology camera

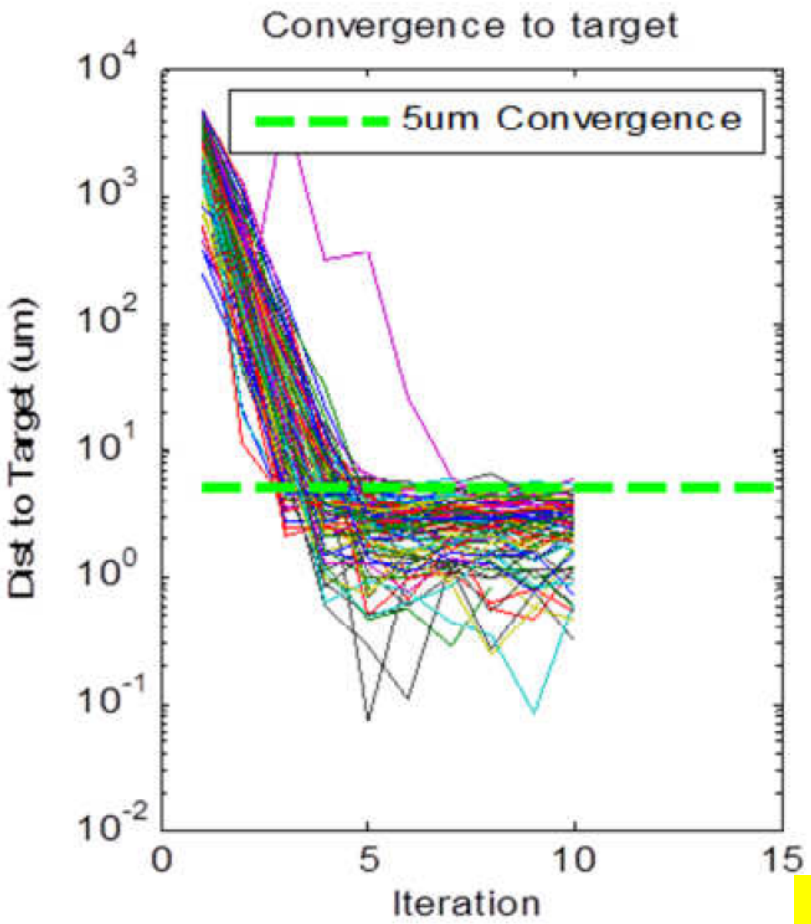


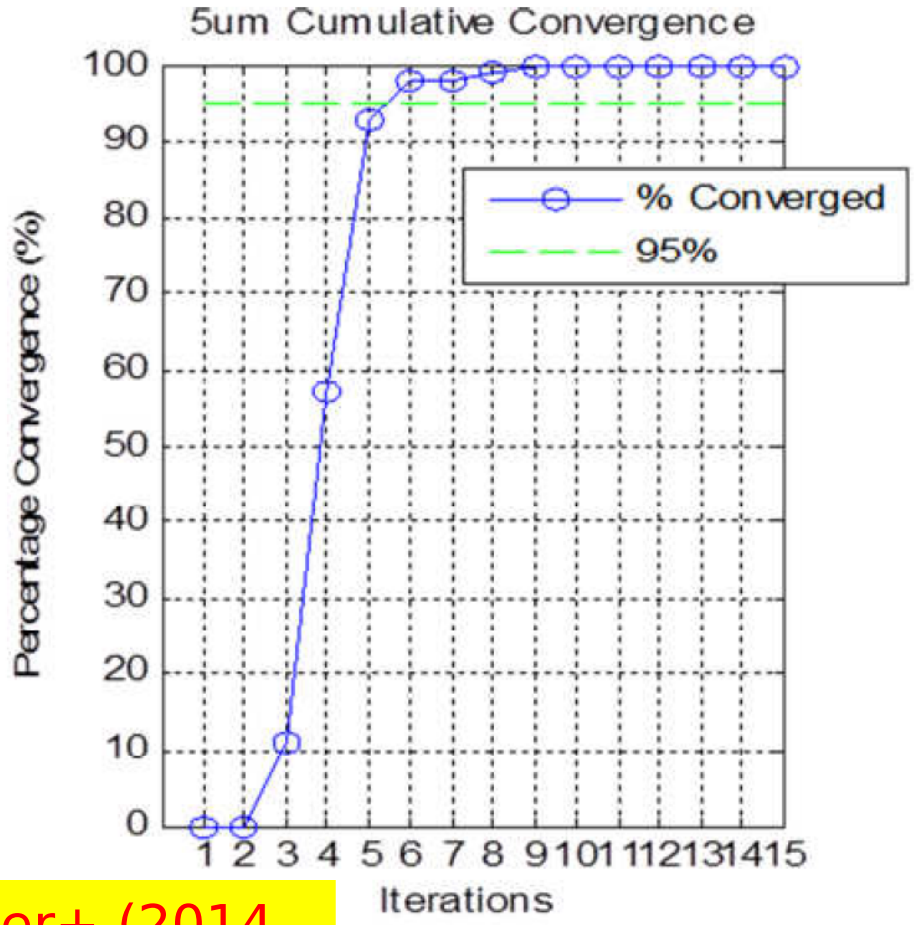
Fiber connectors

Detector focus

Cobra "Engineering model" performance



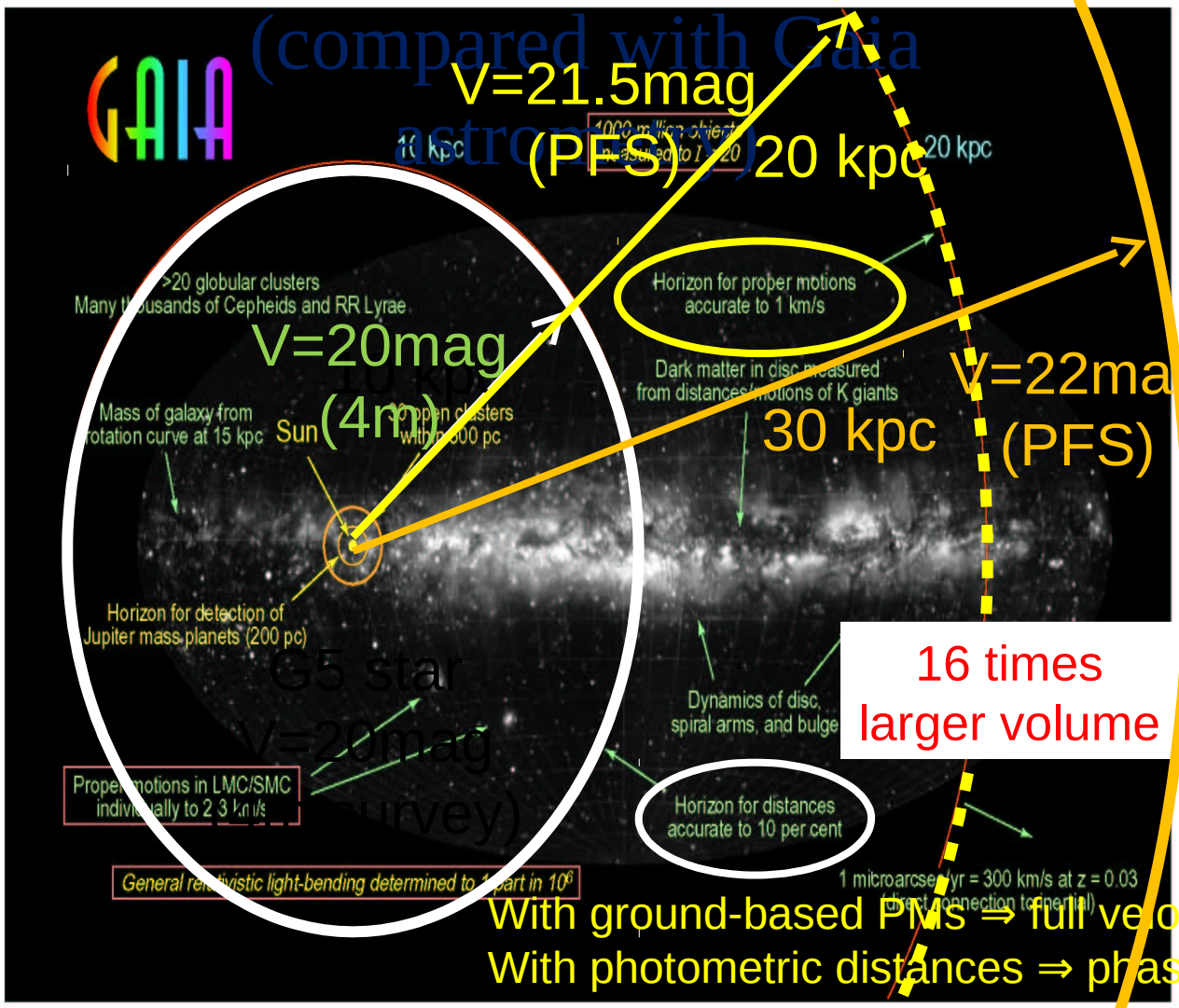




Fisher+ (2014,

4m vs. 8m spectroscopic survey (G5V)

(compared with Gaia astrometry)



With ground-based PMs ⇒ full velocities

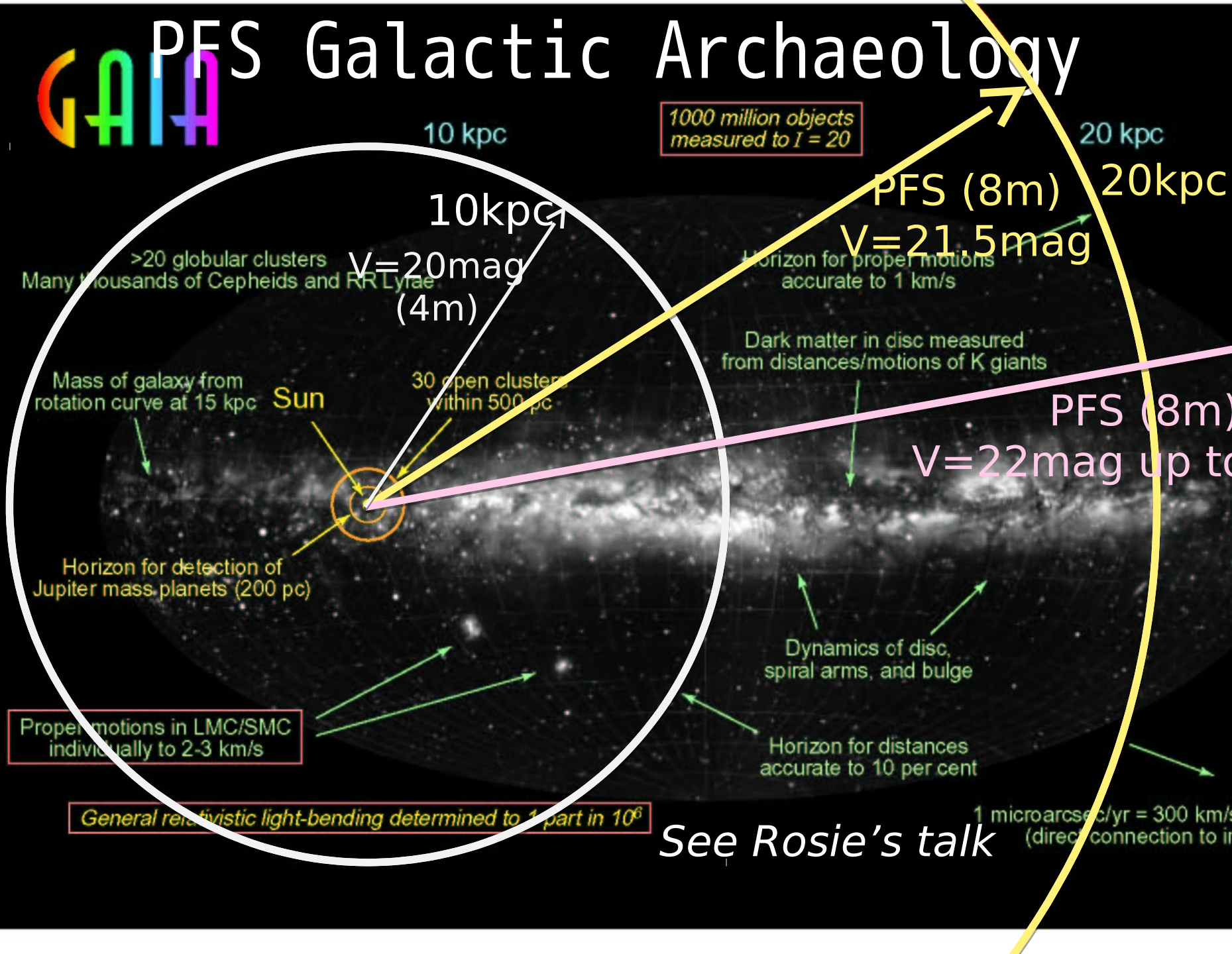
With photometric distances ⇒ phase-space

10μas = 10% distance @10kpc, 10μas/yr = 1km/s @20kpc

6th PFS Collaboration meeting @ Taipei

Banquet

PFS Galactic Archaeology



See Rosie's talk