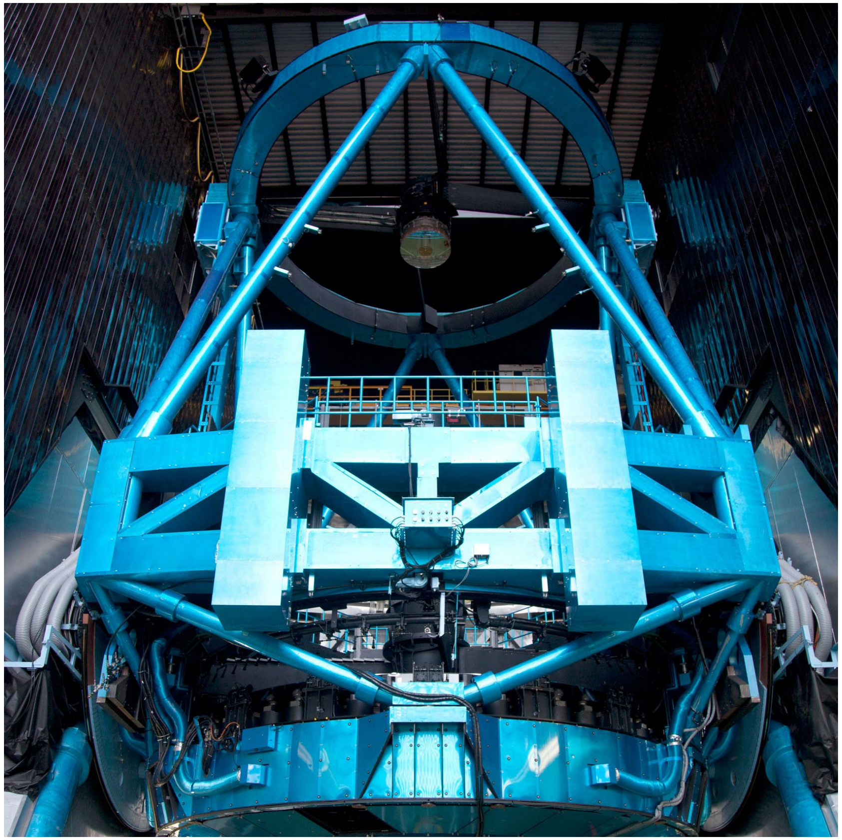
Olivier and the Subaru Prime Focus Spectrograph

Richard Ellis (UCL)



From Galaxies to Cosmology: A tribute to Olivier LeFèvre 5 July 2022

Subaru PFS – A Tortuous History

2002 – 2005: A Gemini Wide Field Survey instrument

- KAOS – the Kilo Aperture Optical Spectrograph – not practical on Gemini
- WFMOS – proposed as a Gemini-funded instrument on Subaru

2005 – 2009: Competitive WFMOS Concept Studies funded by Gemini

- Team A (Australia-led) vs Team B (Caltech/JPL-led)
- Team B wins but Gemini Board then immediately cancels the project!

2009 – 2011: Japanese government announces stimulus funds for science

- Hitoshi Murayama (Director IPMU) submits proposal for Subaru instrumentation (SuMIRE) linking HSC and PFS
  - Incorporates Caltech-led study of PFS
- Murayama secures $100M funding – big celebrations!
- Within two weeks, new government slashes award from $100M to $34M!
- Murayama sets out to find new partners visiting Olivier three times in 2010

2010-2011: PFS partnership established (including LAM which joined in May 2011)

PFS collaboration 2011

Caltech

Jet Propulsion Laboratory
California Institute of Technology

NAOJ

Academia Sinica

Princeton University

IPMU Institute for the Physics and Mathematics of the Universe

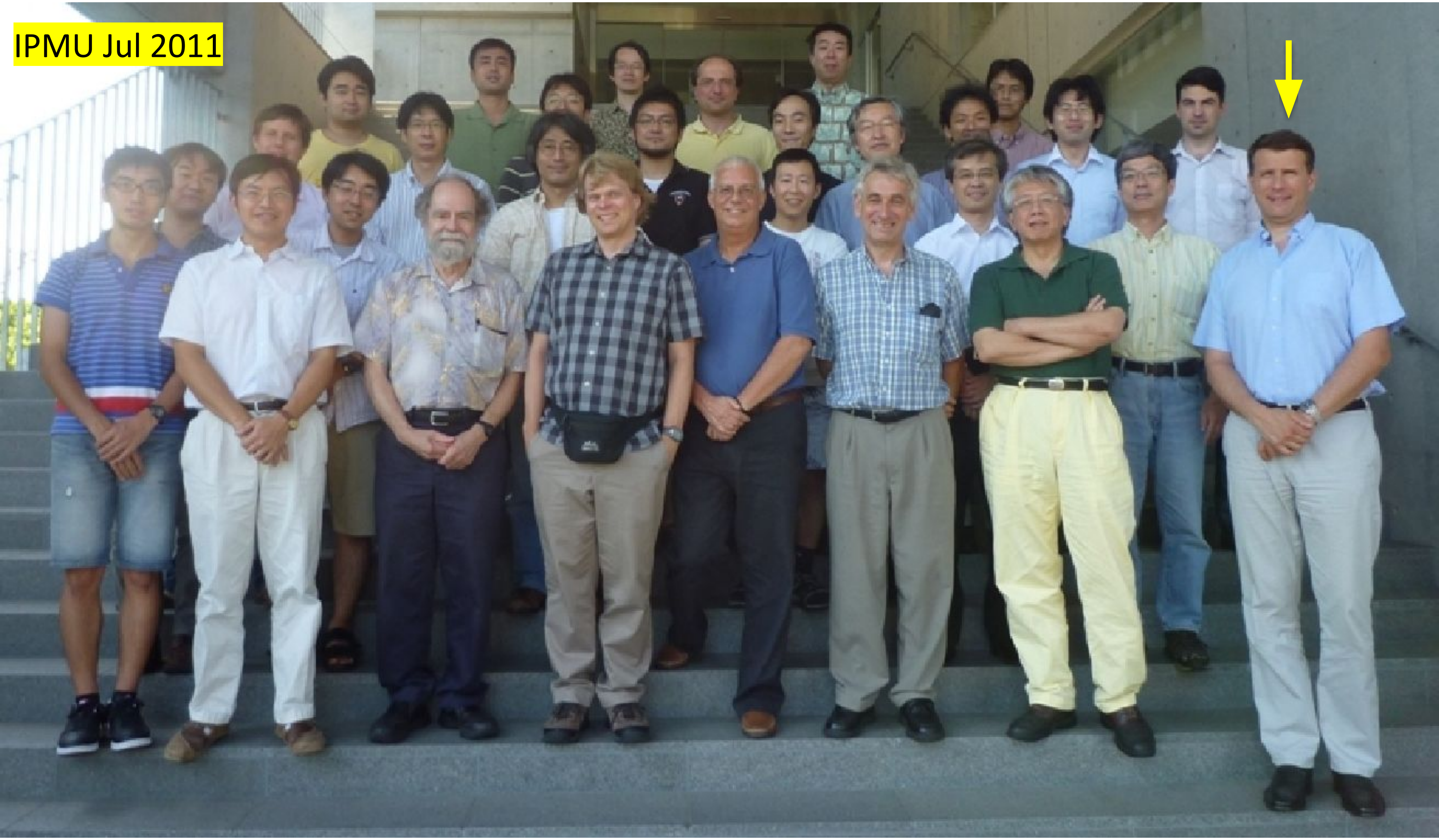
LNA Laboratório Nacional de Astrofísica

LAM Laboratoire d'Astrophysique de Marseille

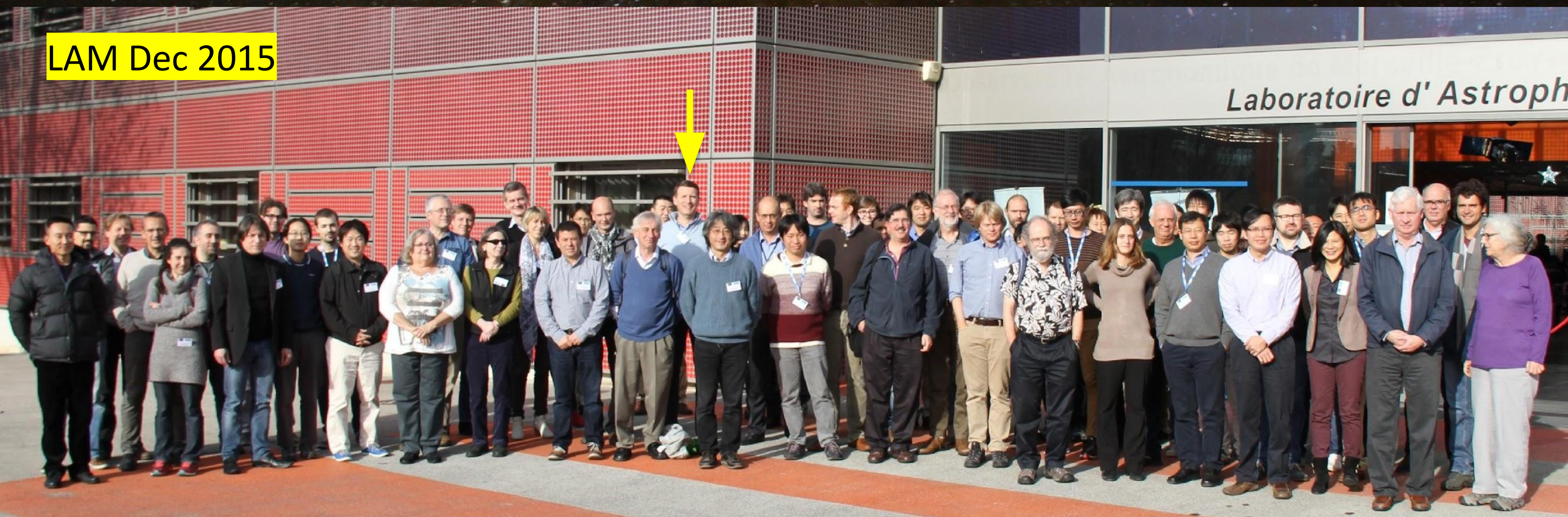
Royal Observatory Edinburgh

John Hopkins?

First PFS Collaboration Meeting



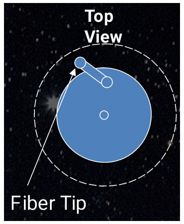

Tokyo Jan 2012

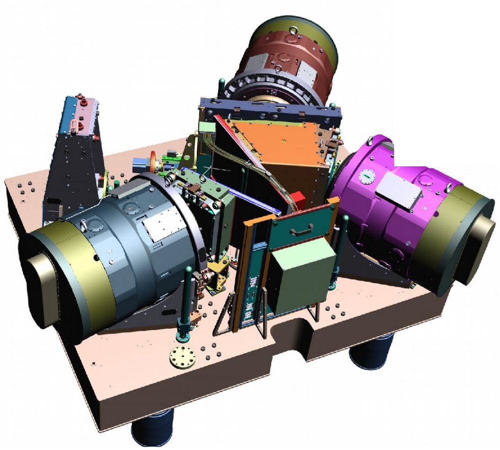

LAM Dec 2015
Laboratoire d' Astroph

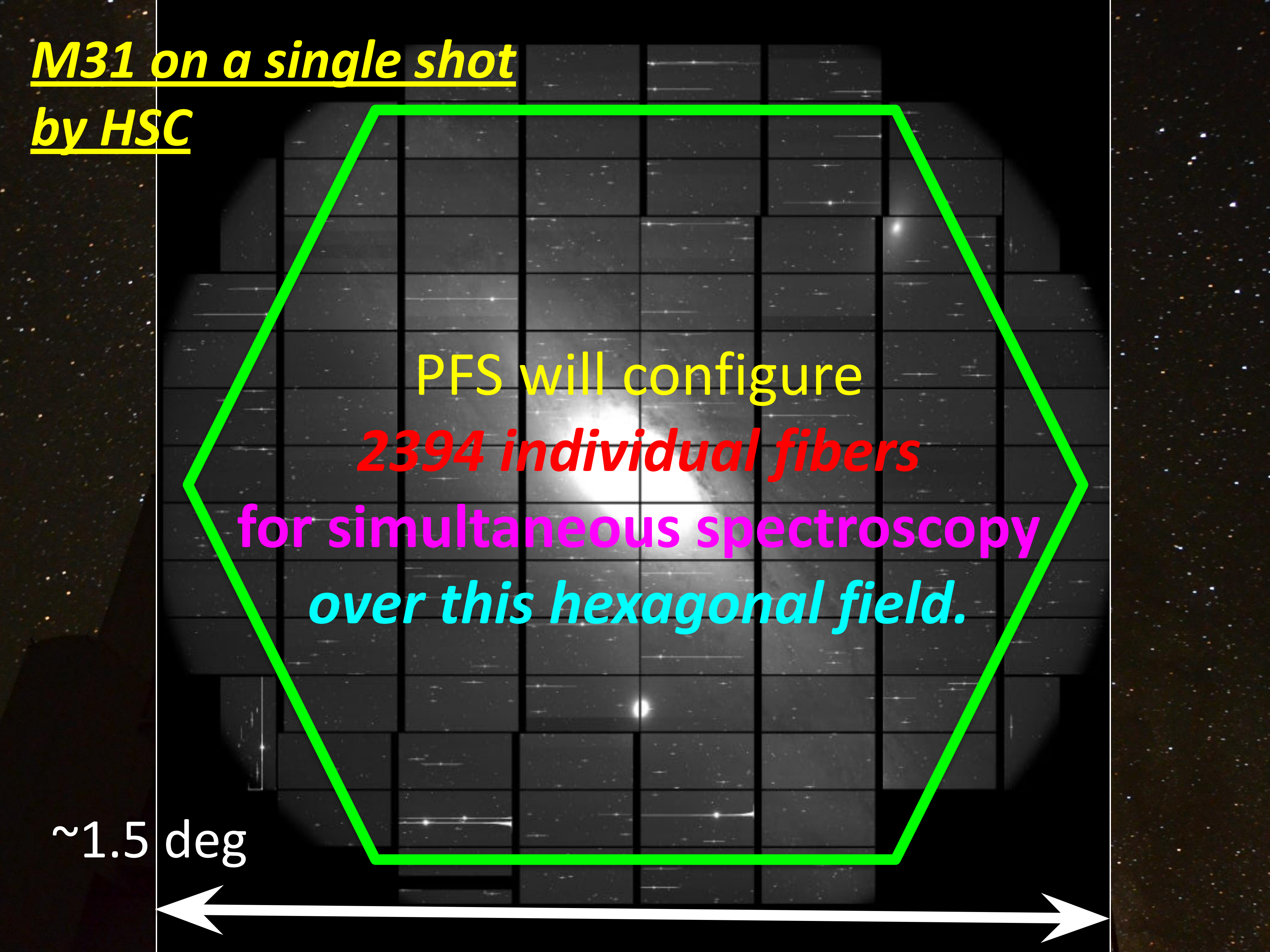
Olivier's Last Meeting

PFS: A Massively Multiplexed Spectrograph on a 8m Telescope

modules
tor drive

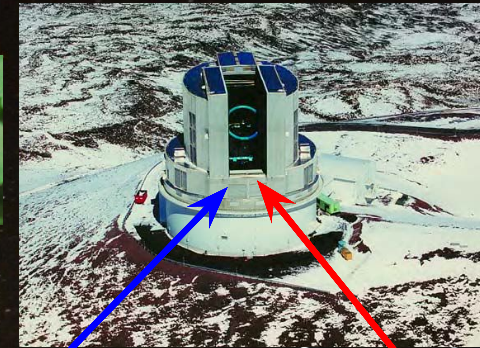





M31 on a single shot
by HSC
PFS will configure
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.
~1.5 deg

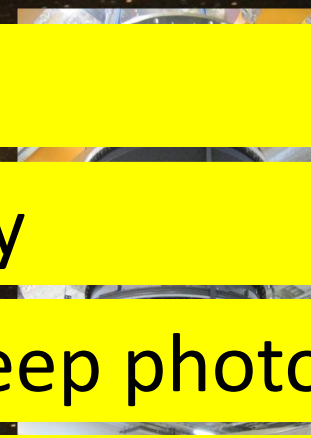
SuMIRe project

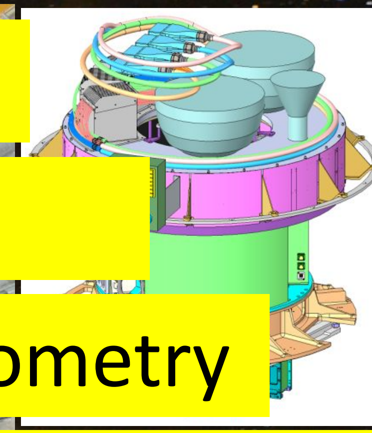
Subaru Measurement of Images and Redshifts



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

Same telescope





Same patches of sky

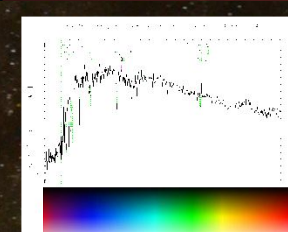
- ✔ 30
- ✔ 14

Clean target selection by deep photometry

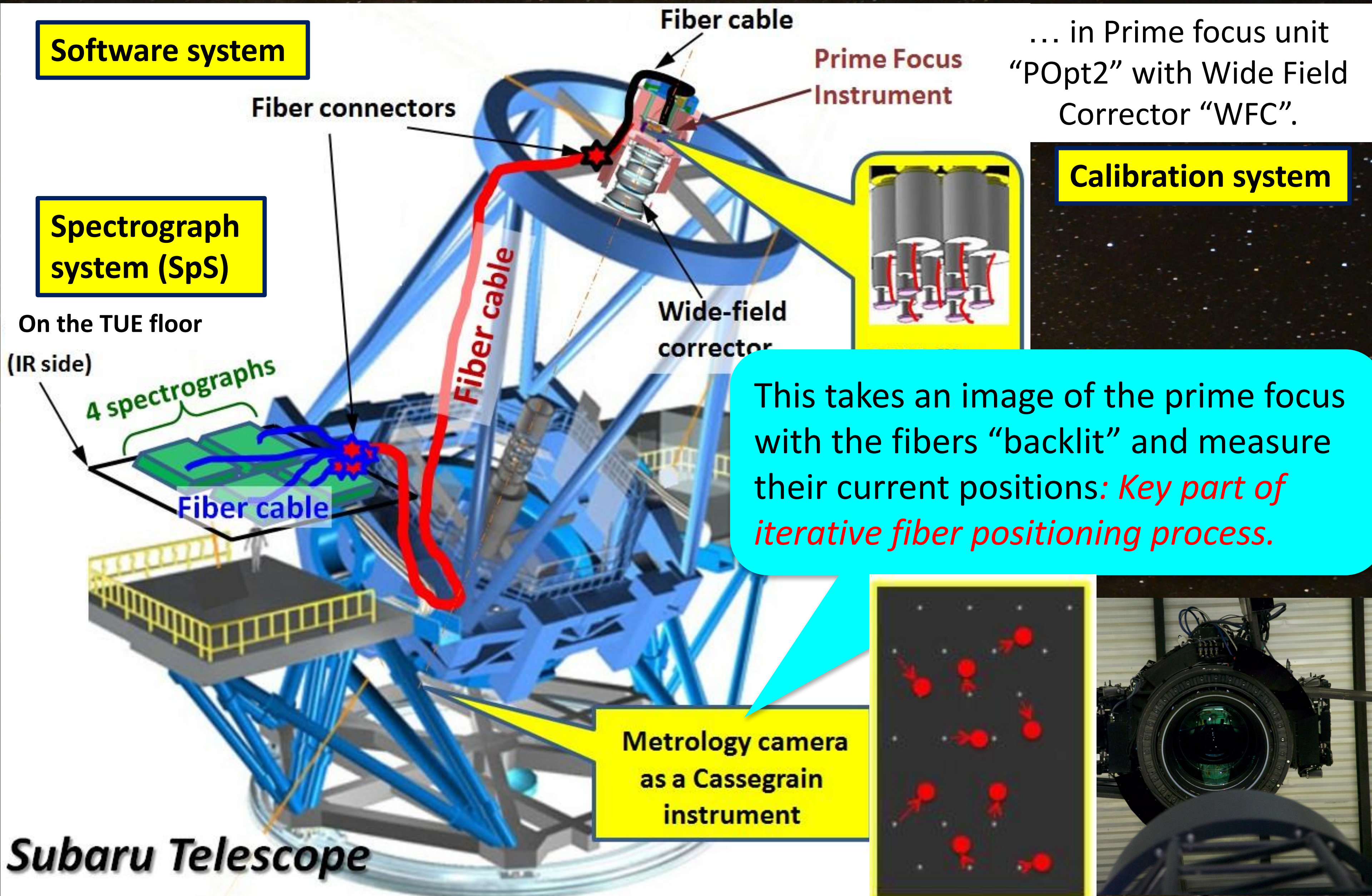
- *Follow-up*
  "Prime Fo

Joint analyses with spectroscopic information on top of deep & sharp images

- ✔ ~2400 o
- ✔ ~300-360 nights over ~5 years
- ✔ ~4M galaxy redshifts
- ✔ ~1M stars in MW halo/disks/satellites & M31.

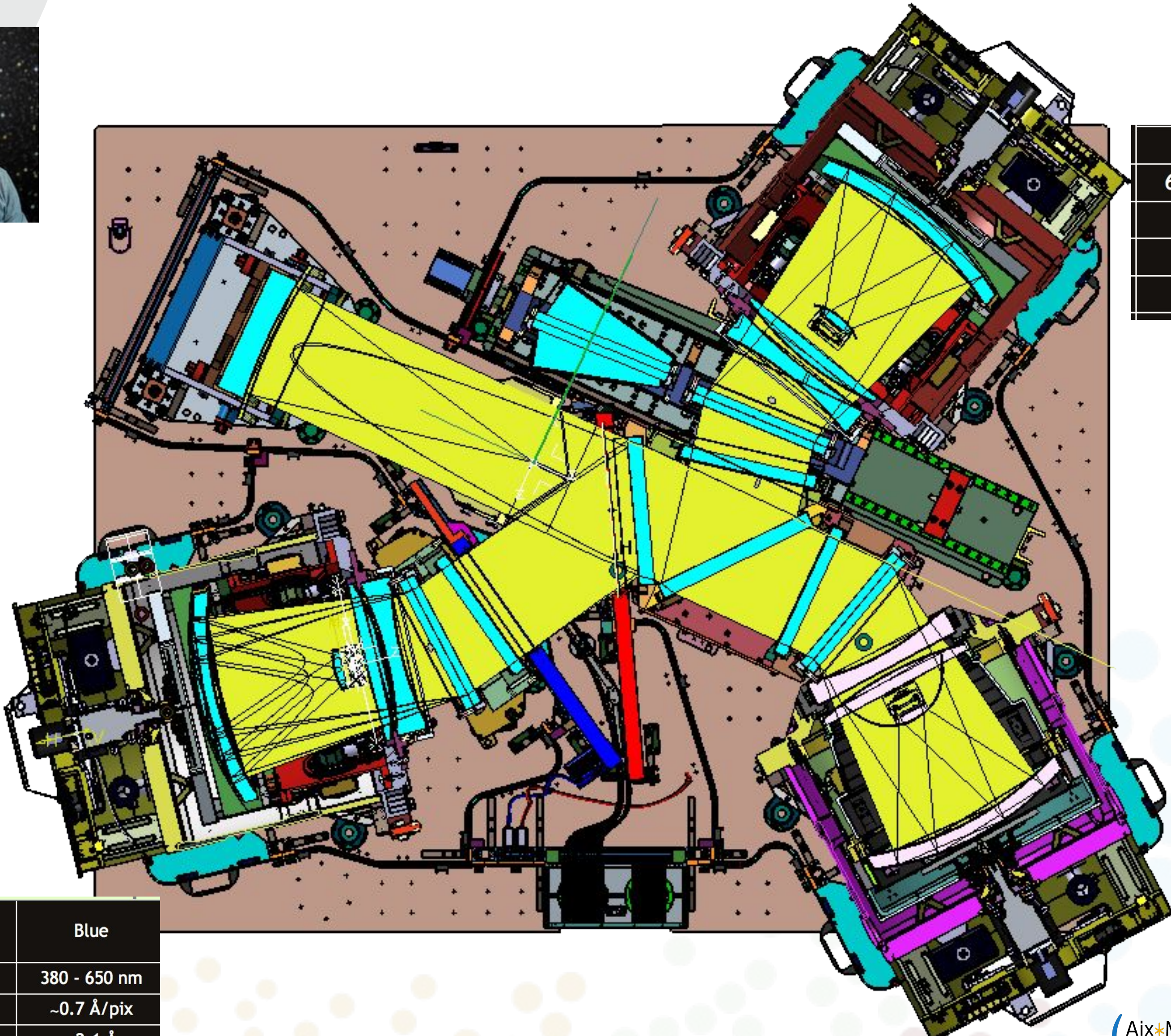


PFS subsystems distribution



Spectrograph System (SpS)

David Le Mignant (LAM)

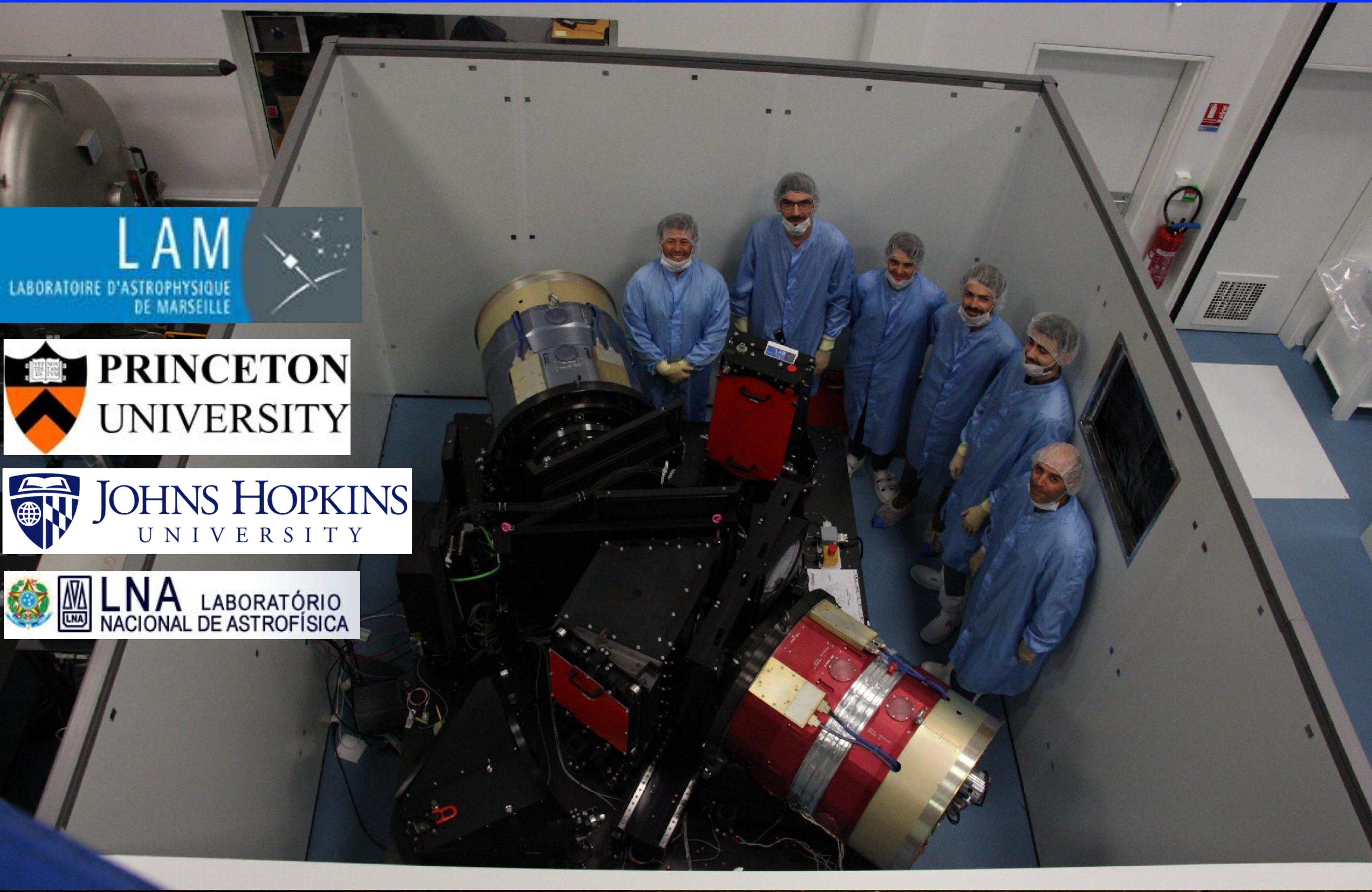


Low Res.	Mid. Res.
630 - 970 nm	710 - 885 nm
~0.9 Å/pix	~0.4 Å/pix
~2.7 Å	~1.6 Å
~3000	~5000

NIR
940 - 1260 nm
~0.8 Å/pix
~2.4 Å
~4300

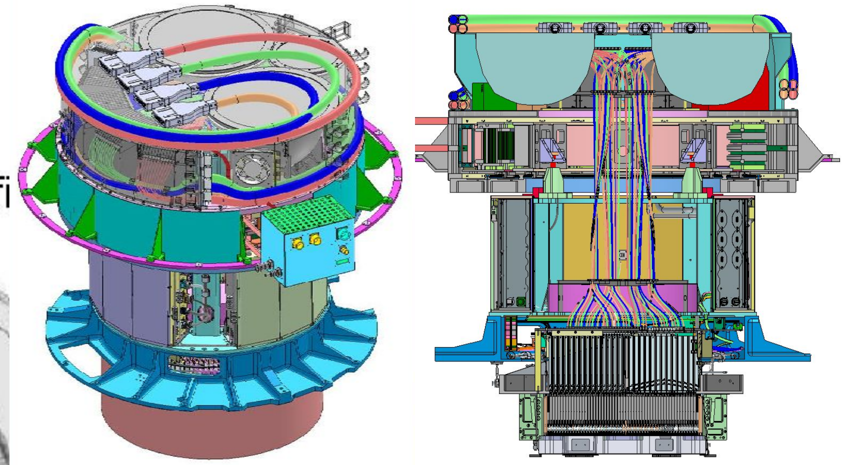
Spectral arms	Blue
Spectral coverage	380 - 650 nm
Dispersion	~0.7 Å/pix
Spectral resolution	~2.1 Å
Resolving power	~2300

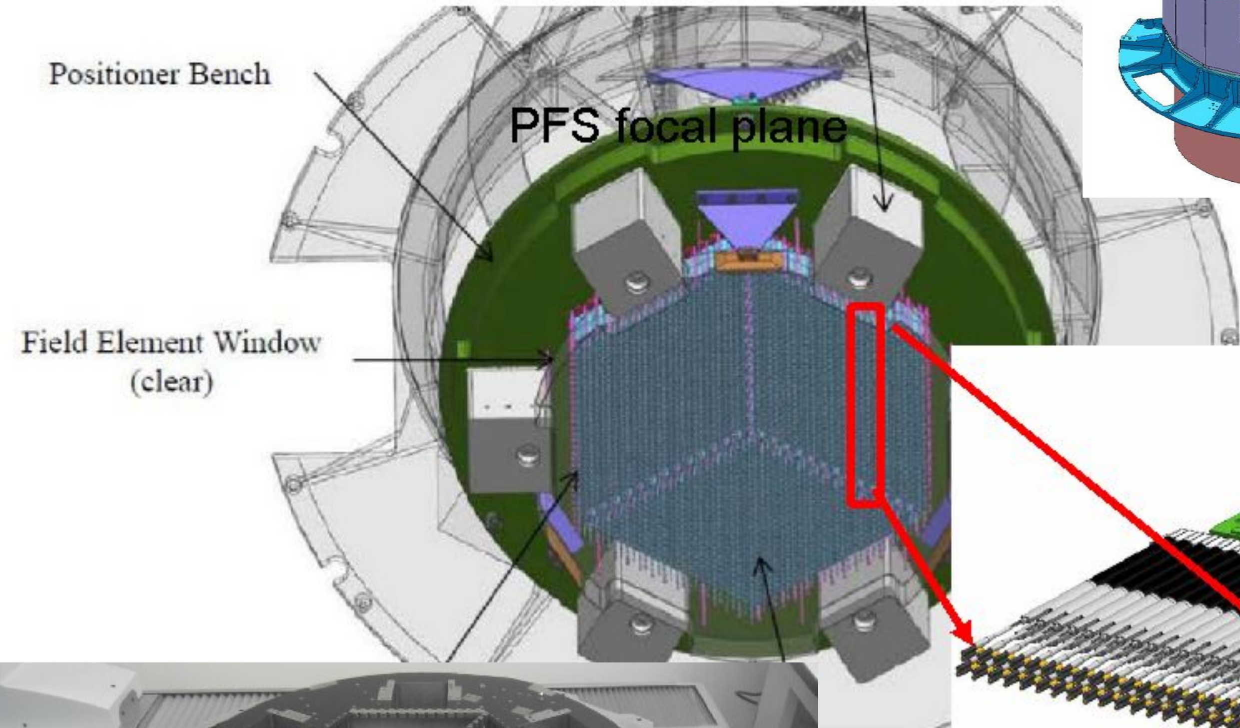
The Spectrograph Module #1 (SM1)



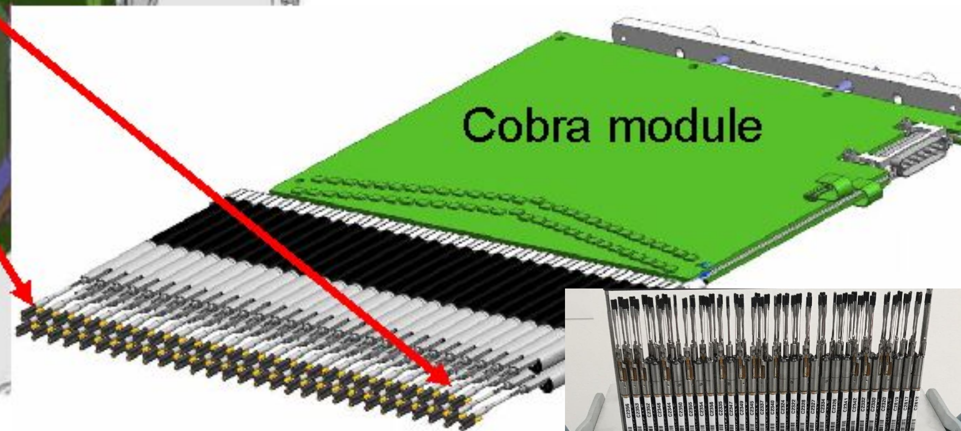
Prime Focus Instrument (PFI)

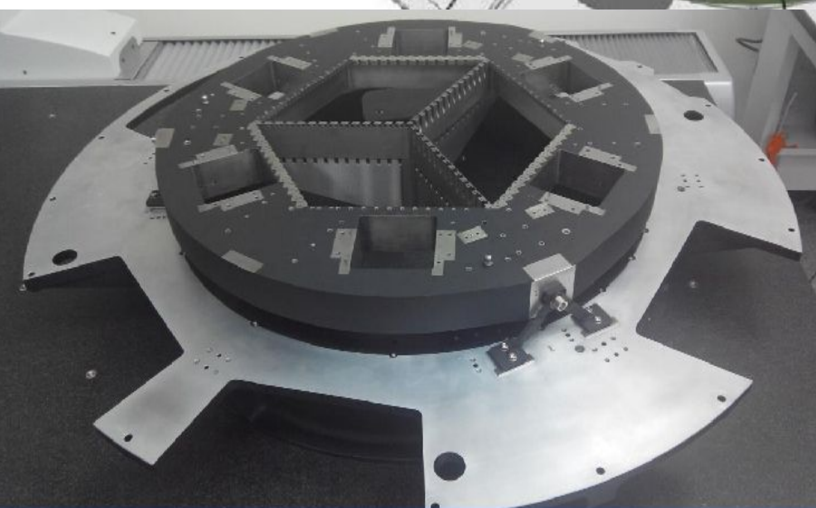
The focal plane will include 42 modules, each with 57 fi
Caltech is building and testing these modules





Each Cobra module includes 57 Cobra assemblies





中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

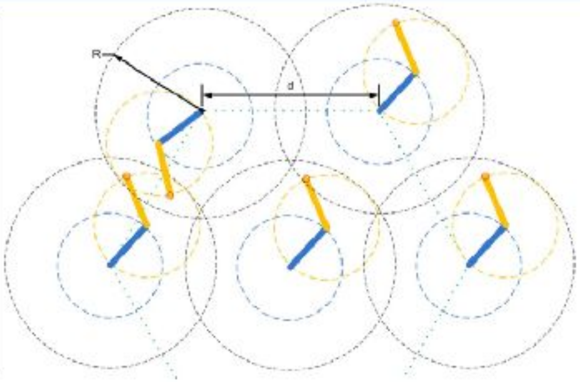
LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

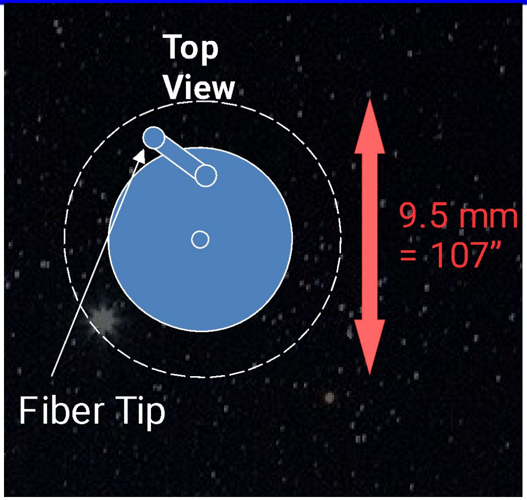
NASA JPL

Caltech

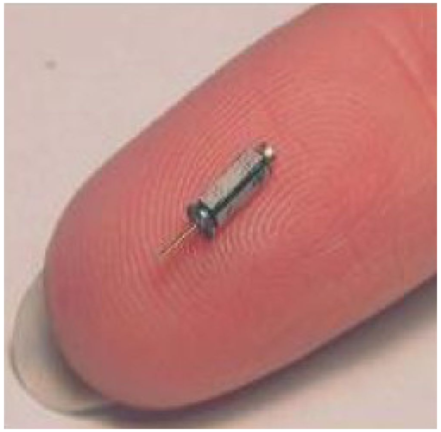
Focal plane: Fiber positioner "Cobra"

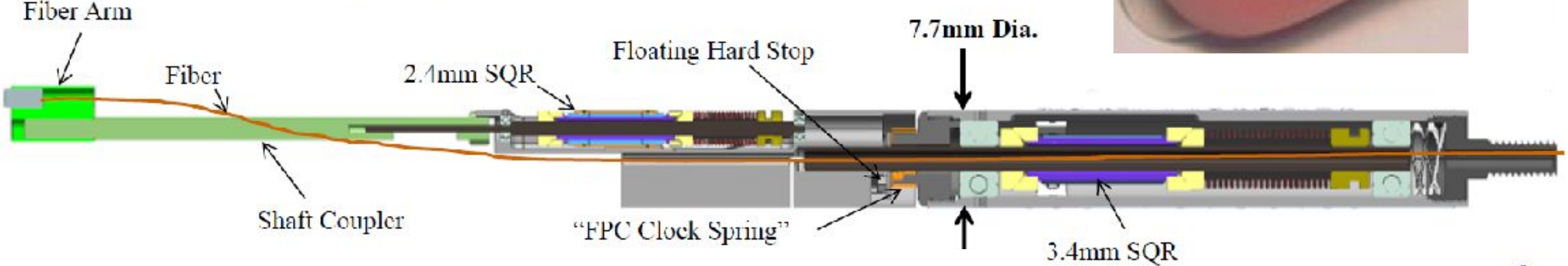
8mm pitch vs. 9.5mm diameter patrol area
→ Patrol areas are overlapped.

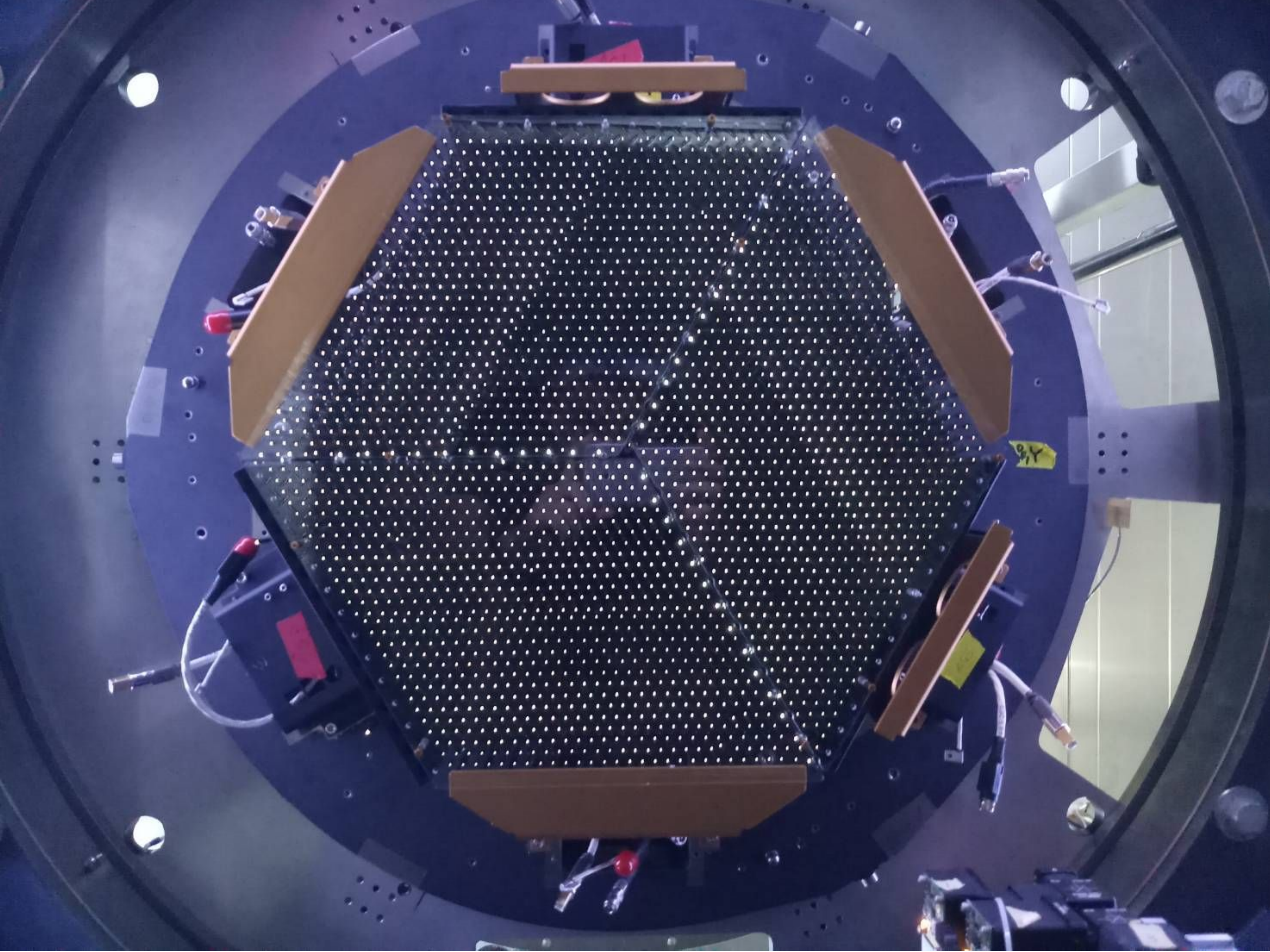


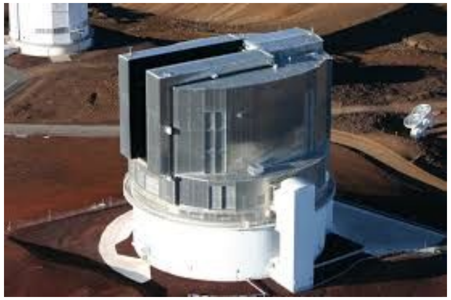


- Fiber is routed from the arm on the phi-stage through the center of the Cobra
  - Stages utilize hard stops to allow for full range of motion, yet prevent over twisting of the optic fiber
  - Protects fiber during handling and operation
- Piezo motors use phase shifted signals to excite the motor body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









Strategic Survey Programme (2024-2029)

Subaru supports long-term survey programmes (SSP) for all its major instruments

PFS SSP (360 nights) – spectroscopy of HSC-selected targets addressing 3 science questions

1. COsmology:
2. GAlactic archeology
3. GElaxy evolution

	Testing ΛCDM	Assembly history of galaxies	Importance of IGM
CO / GA / GE	• Nature & role of neutrinos • Expansion rate via BAO up to $z=2.4$ • PFS+HSC tests of GR • Curvature of space: Ω_K • Primordial power spectrum • Nature of DM (dSphs) • Structure of MW dark halo • Small-scale tests of structure growth	• PFS+HSC synergy • Absorption probes with PFS/SDSS QSOs around PFS/HSC host galaxies • Stellar kinematics and chemical abundances – MW & M31 assembly history • Halo-galaxy connection: M_*/M_{halo} • Outflows & inflows of gas • Environment-dependent evolution	• Search for emission from stacked spectra • dSph as relic probe of reionization feedback • Past massive star IMF from element abundances • Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

Data proprietary to PFS team and full Japanese community (including those overseas)

Publicly available via Subaru archive after 12 months

Science Programmes (brief summary..)

Cosmology:

BAO/RSD to higher z than other surveys + synergy with HSC lensing:
dark energy via growth of structure <u>and</u> geometry, neutrino mass etc

Colour-selected I < 26 galaxies 0.8 < z < 2.4: R~3000 spectra of [O II] emission over ~1400 deg^2.

Galactic archeology:

Nature of dark matter and assembly history of Milky Way and M31

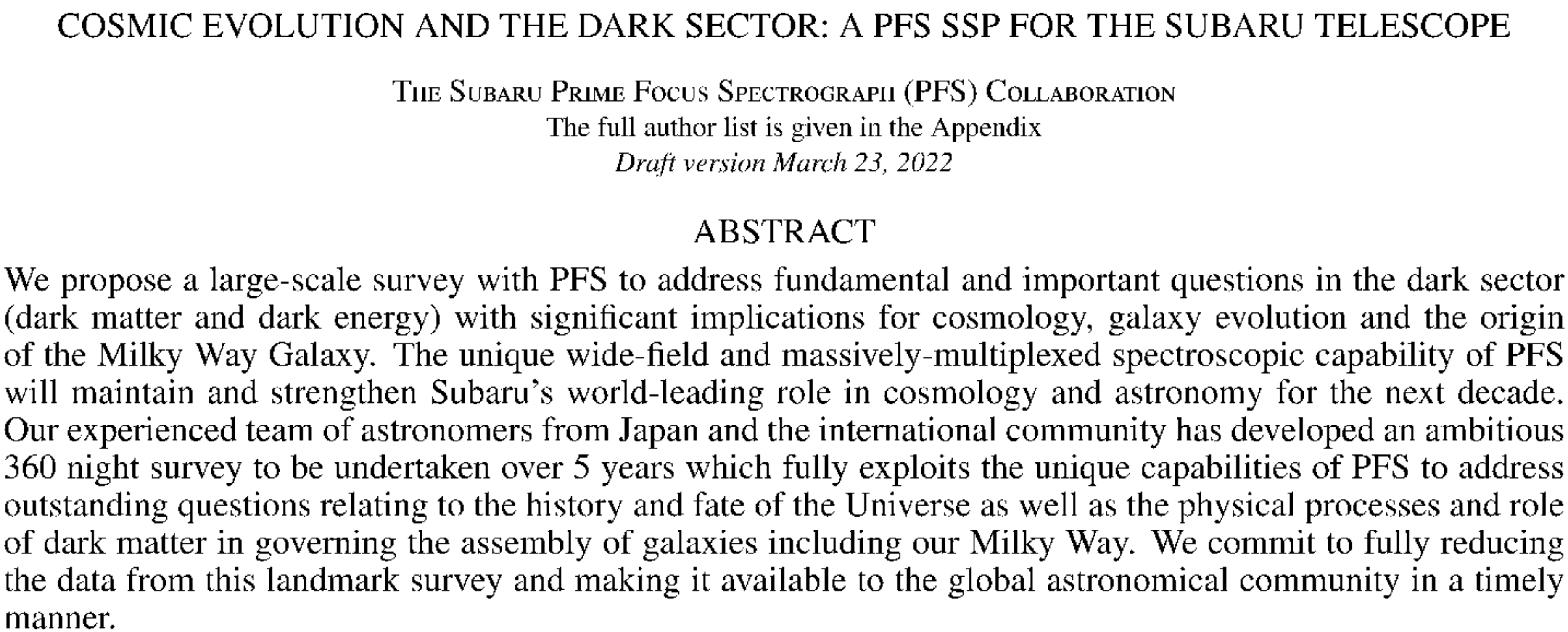
R~5000 spectra of Galactic dwarfs, halo of M31, outer disk & stellar streams

Galaxy Evolution:

Synergy between galaxies & cosmic web, tracing end of reionisation

(i) A SDSS-like survey over 0.7<z<1.7 down to y<24.3
(ii) Lyα tomography of 2.5<z<3.5 LBGs to y~24.3 with foreground associated galaxies over 2.1<z<2.5
(iii) Deep surveys of 3.5<z<7 LBGs and HSC-selected LAEs at z~2.2, 5.7, 6.6
(Olivier argued passionately for this aspect – John Silverman's talk)

SSP Proposal


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

ABSTRACT

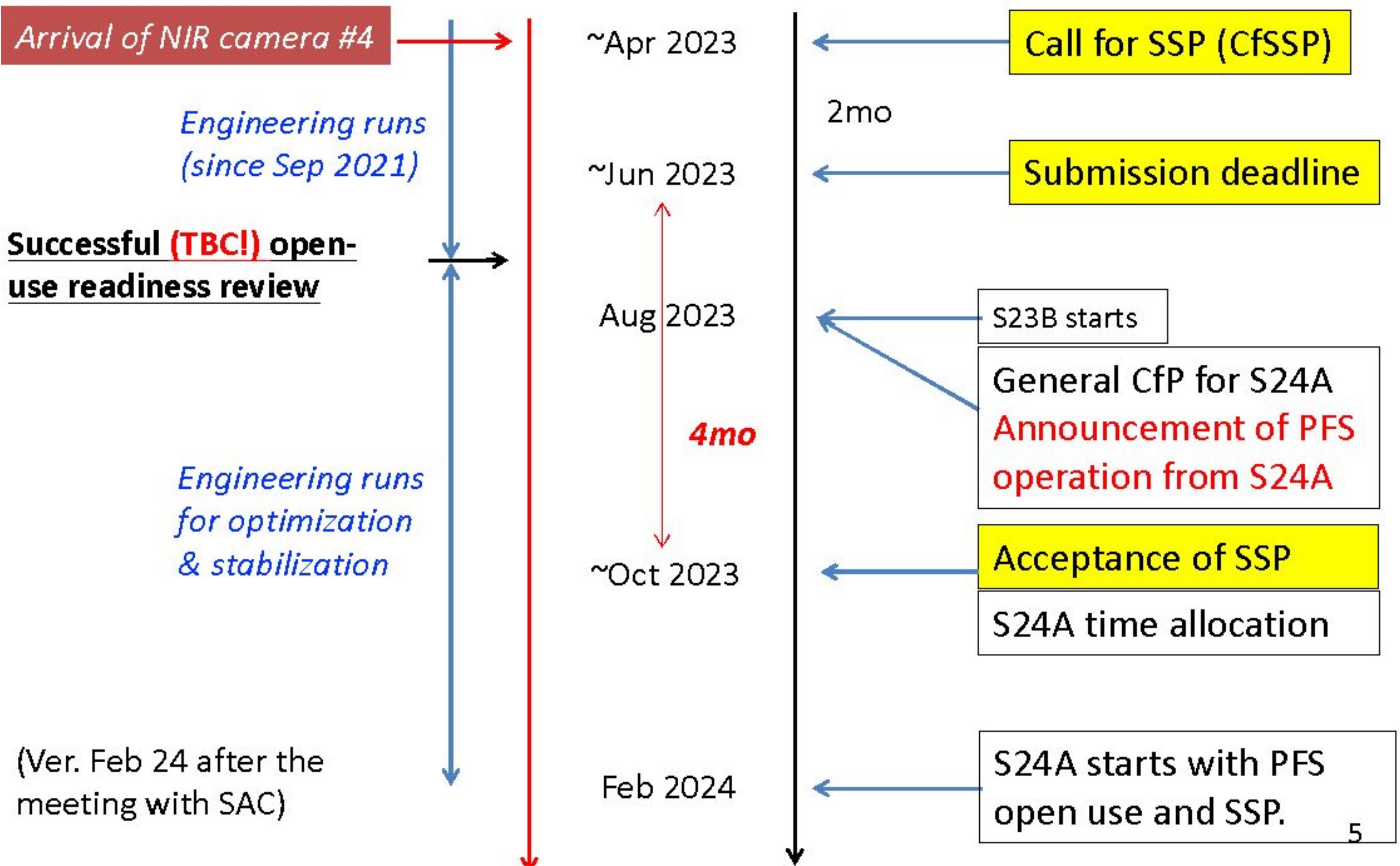
We propose a large-scale survey with PFS to address fundamental and important questions in the dark sector (dark matter and dark energy) with significant implications for cosmology, galaxy evolution and the origin of the Milky Way Galaxy. The unique wide-field and massively-multiplexed spectroscopic 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.

- In final form (30 pages) following two favourable external reviews

- Individual Working Groups are publishing their detailed plans shortly

GE plans: arXiv 2206.14908 (see John Silverman's talk)

PFS Timeline (Commissioning & Survey)



PFS in context

	Instrument/Telescope	Collecting Area m^2	Field of view deg^2	Multiplex
4m class funded	4MOST	10.7	4.00	1400
	Mayall 4m / DESI	11.4	7.08	5000
	WHT / Weave	13.0	3.14	1000
8-10m class funded/operational	**Subaru / PFS**	**52.8**	**1.25**	**2400**
	VLT / MOONS	52.8	0.14	500
	Keck / DEIMOS	76.0	0.015	150
Proposed and unfunded	Megamapper	28.0	7.06	20,000
	Keck / FOBOS	76.0	0.087	1800
	MSE @ CFHT	78.5	1.52	4000
	ESO Spectel	113.1	4.90	5000

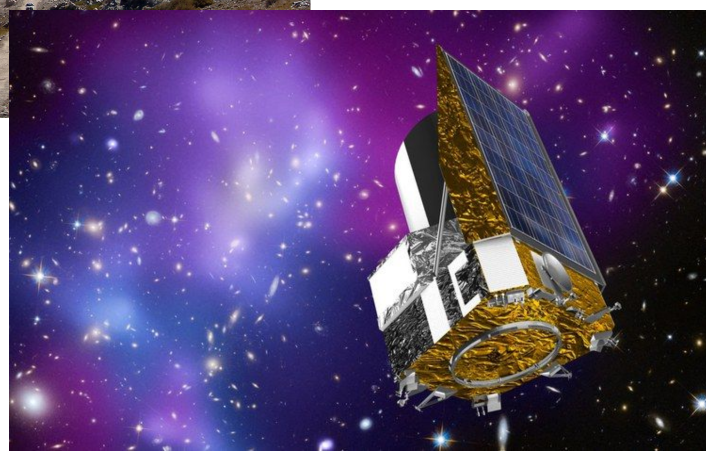
Plus: 8m aperture with largest field/multiplex gain on excellent Mkea site
Wide wavelength coverage 0.37 – 1.26 microns
Synergy with HSC survey e.g. weak lensing/targets

Minus: Not a dedicated telescope – survey time competes with regular use
No hi-res capability for certain stellar applications; R_{max} ~5000

A Decade of Deep Wide Field Imaging

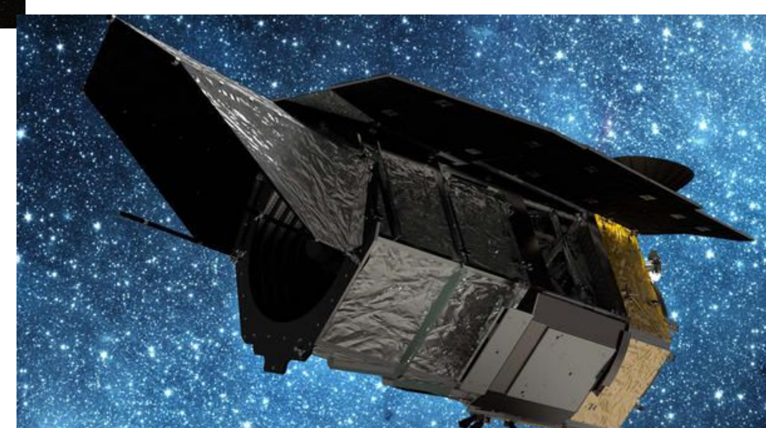
Significant investment in panoramic **DEEP** multi-color imaging in the 2020s

Vera C Rubin Observatory 6.5m (2022-2032):
ugrizy ~ 25-27 over 18000 deg^2 (wide-fast-deep survey)
ugrizy ~ 27-29 over ~38 deg^2 (4 deep drilling fields)



Euclid Space Tel 1.2m (2022-2029:
<riz>+YJH > 24 over 15000 deg^2
> 26 over 40 deg^2

Nancy G Roman Space Telescope (2026-2032):
YJH +F184 < 27 for 2000 deg^2 (wide field survey)
+ deep fields (strategy TBD following community input)



ESO Wide Field Spectroscopic Telescope (formerly SpecTel)

ESO community was polled on most important capabilities for research in 2020s and 2030s

A wide field spectroscopic telescope was the most desired unfunded facility (Messenger 161, Sep 2015)

Future of Multi-Object Spectroscopy ESO Working Group (2015-2017, Chair RSE)

Made scientific case for 10-12m dedicated spectroscopic telescope for programmes in extragalactic, Galactic and transient science.

Survey report : arXiv: 1701.01976

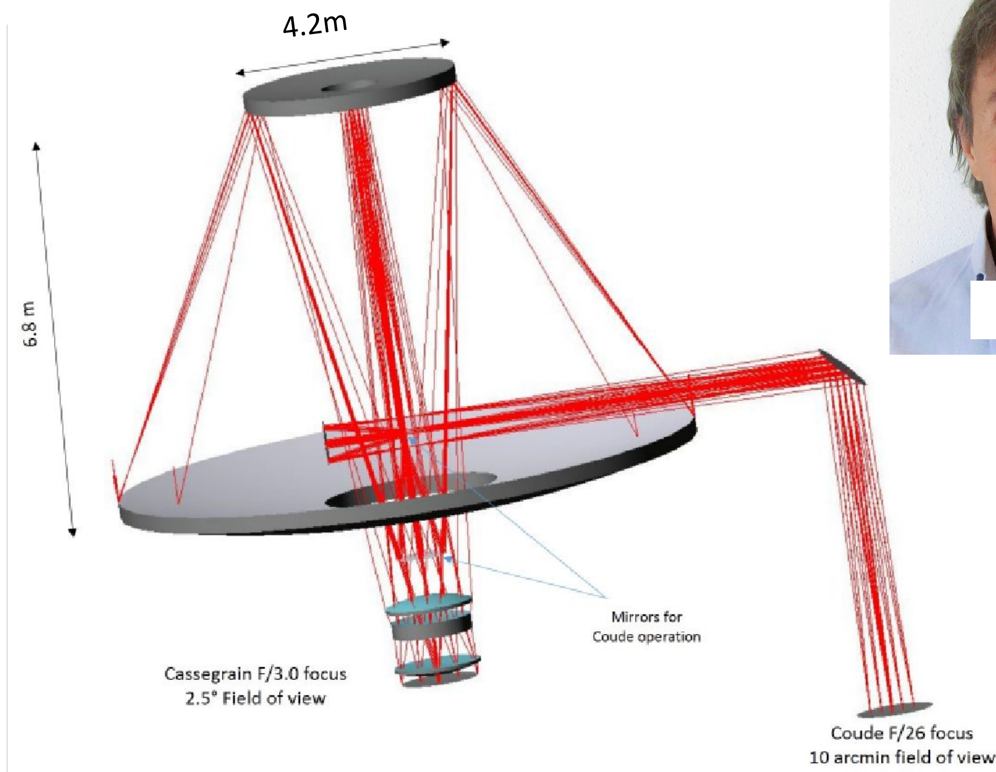
SpecTel: 10-12m Spectroscopic Survey Telescope

"Skunk works" design @ ESO

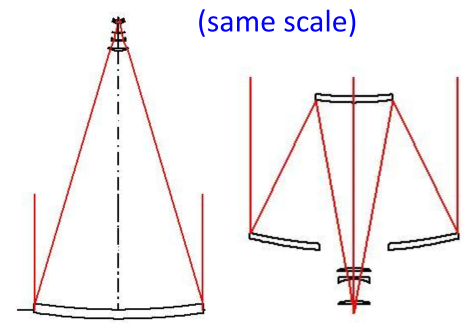
Cassegrain design is compact & flexible

11.4m f/0.6 primary (78 ELT segments) with a 5 deg^2 f/2.9 field ideal for fibres with good images from 360-1300nm.

Gravity-invariant f/26 Coudé focus with 10 arcmin FOV suitable for a on-axis "Super-MUSE"

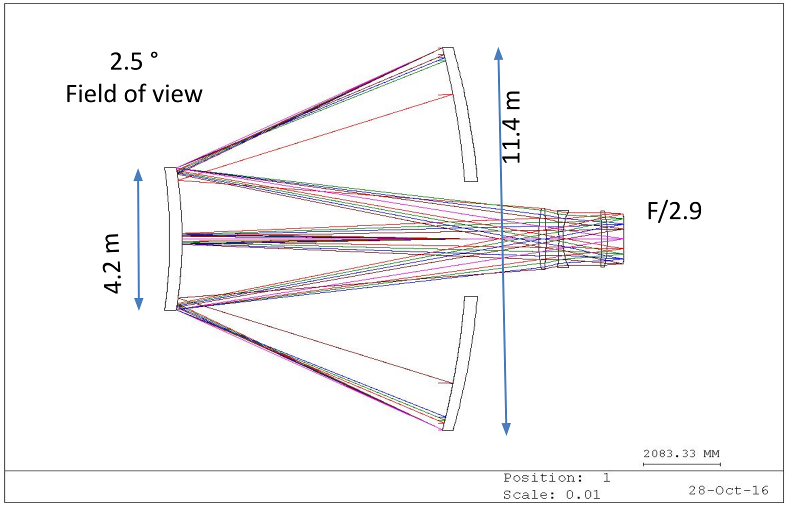


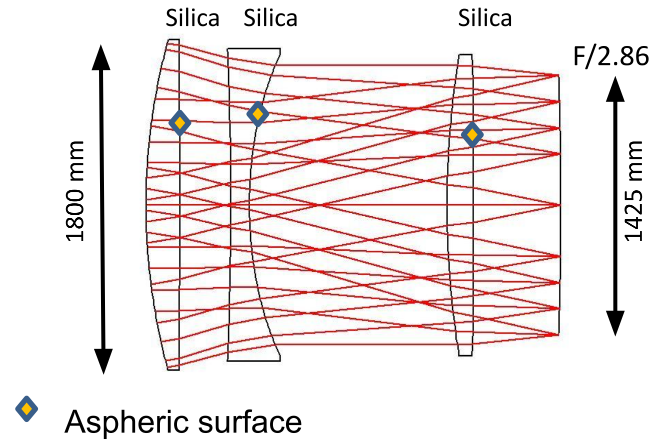
MSE and ESO study (same scale)



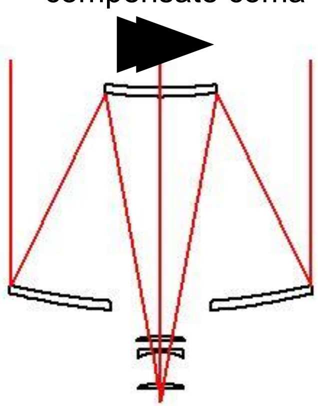
Pasquini et al arXiv 1606.06494, 1708.03561

Corrector with Innovative ADC

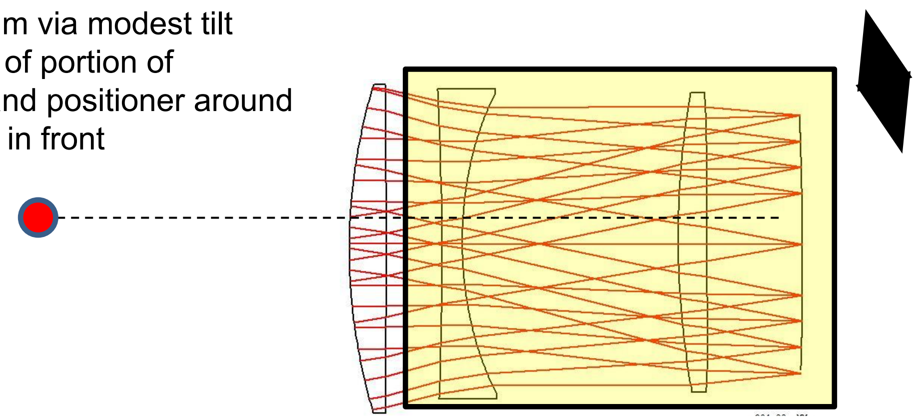




M2 translation to compensate coma



ADC operates over 360-1300nm via modest tilt (<0.3 deg) of portion of corrector and positioner around a point 5m in front

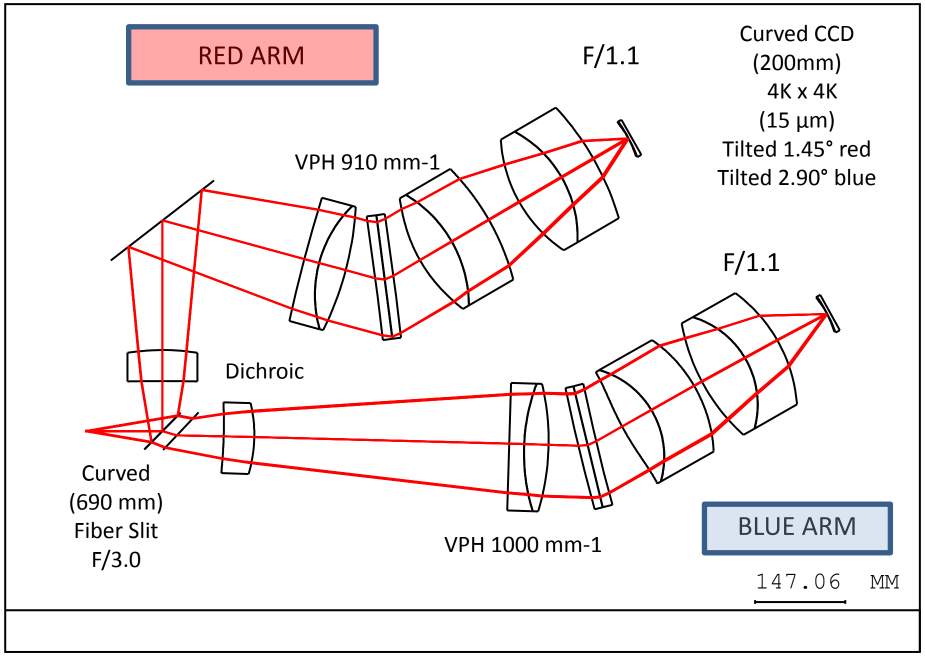


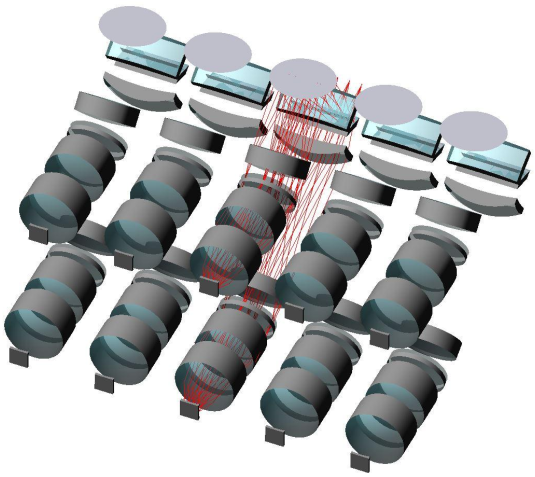
Low Resolution Spectrographs

Two-arm spectrograph design accommodating 650 fibres at R~2600

f/3.0 collimator with dichroic splitting λλ380-690nm and 680-1000nm

f/1.1 camera feeding two curved 4K CCDs





Multiplex of N~20,000 would require 30 such spectrographs and 60 4K CCDs!

€9M ERC Infrastructure Proposal

- After 5 years, ESO agrees to support a ERC proposal for conceptual design study

- Proposal submitted 19 April 2022
  - 3 year study (2023-2026) leading to CDR and science white paper
  - €3M requested + institutional funds/FTEs of ~€6M
  - PI Roland Bacon (Lyon), Co-PIs Vincenzo Mainieri (ESO), Sofia Randich (INAF)
  - 9 international partners, 18 institutions (including LAM)
  - Outcome late September 2022

- Science case and requirements very similar to 2017 report
  - 10m class aperture
  - FOV 5 deg^2
  - Larger multiplex N~20,000 (low res)
  - Optical facility (NIR would be an upgrade)
  - IFU is in baseline and simultaneous operation with MOS

SpecTel now WST (Wide Field Spectroscopic Telescope)

Some differences with 2017 requirements:

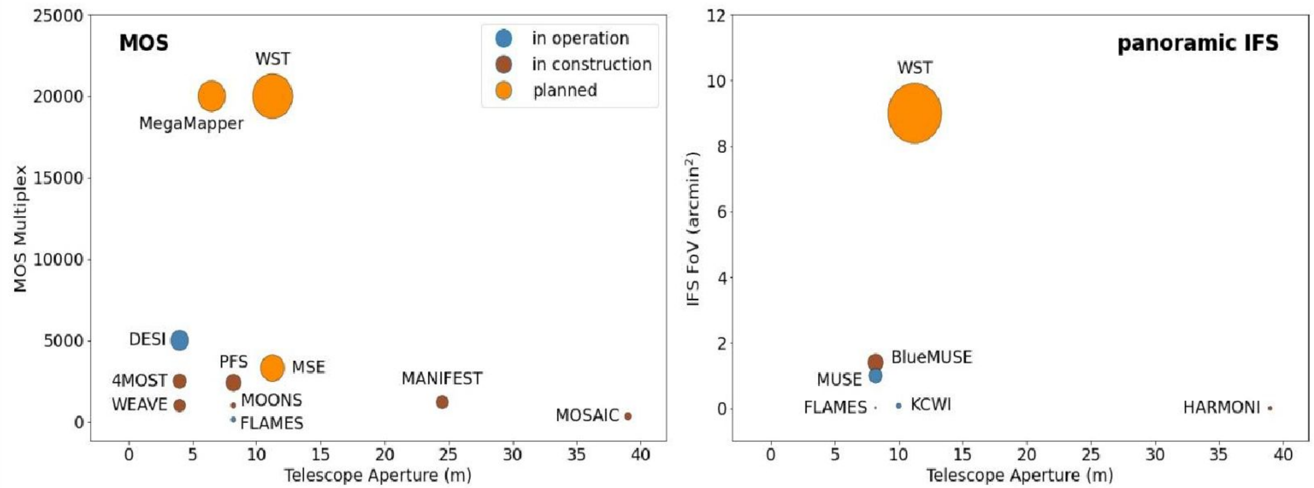
- ***Telescope aperture***: 10-12m driven by R~40,000 spectra of V~17 stars & R~3000 spectra of AB~24 galaxies. Competitive with PFS/MSE.
- ***Field of view:*** 5 deg^2 driven by surface density of V~17 stars, LBGs and rarity of transients
- ***Multiplex gain:*** N~20,000 (previously 5000) driven by need to fully utilise FOV and complete science programmes on <5 year timescales
- ***Spectral resolutions***: R~1000-3000 (galaxies, transients) R~20,000-40,000+ (stars)
- ***Wavelength Range***: 360-1000nm: blue important for stars and Lya forest; IR extension optional
- ***Super-MUSE:*** extragalactic applications (previously an optional upgrade with additional focal station)

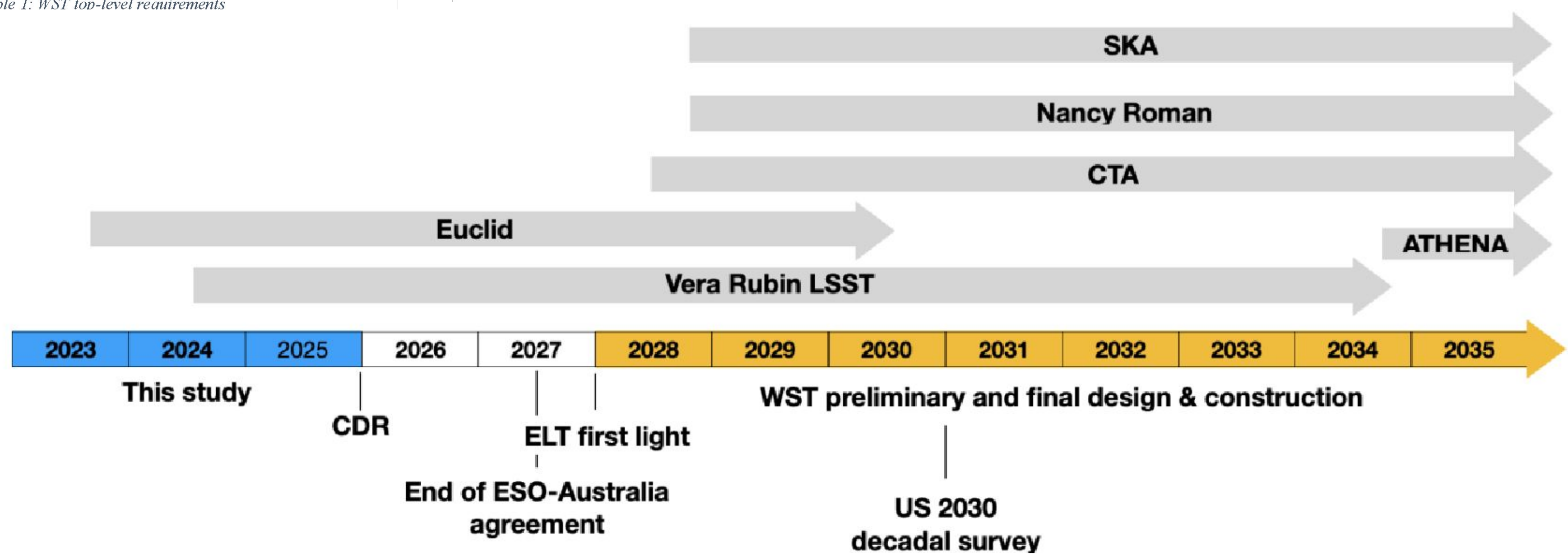
Science Capability in Context & Timeline

Main difference with SpecTel is larger multiplex gain (x4) and simultaneous MOS+IFS

1	Telescope diameter > 10m
2	Telescope Field of view > 5 deg^2
3	MOS spectral resolution Medium-res (MR) R=2000-7000, High-res (HR) R~40000
4	MOS multiplex MR>20000, HR>2000
5	MOS spectral range MR 350-970nm HR 3 regions in 350-970nm
6	IFS Field of view > 3x3 $arcmin^2$
7	IFS spectral resolution R=3000-5000
8	IFS spectral range 370-970nm
9	Simultaneous operation of IFS and MOS

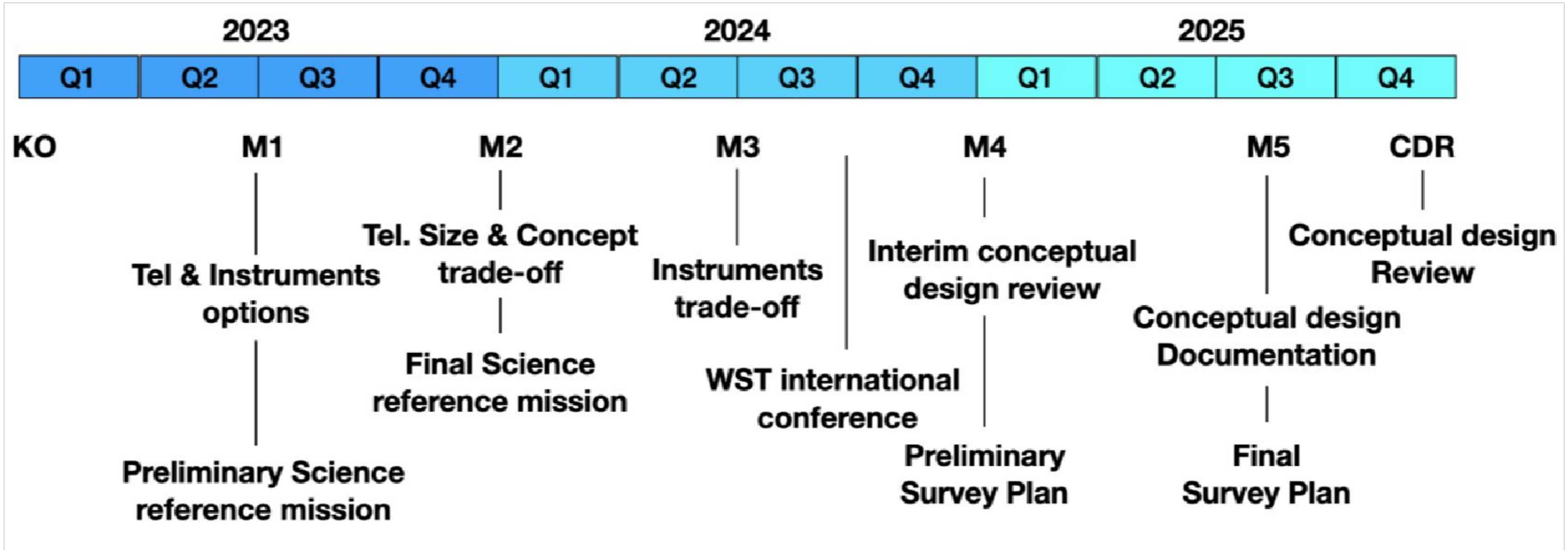
Table 1: WST top-level requirements





Work Packages & Study Timeline

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
1	Project Office	1	CNRS	103	1	36
2	Science	4	ESO	348,8	1	36
3	Telescope	10	UKRI	177	1	36
4	Instrumentation	4	ESO	315	1	36
5	Operations	2	INAF	90	1	36
6	General Facilities	2	INAF	55,5	1	36
				1089,3		



Challenges & Innovations

Challenges:

- Total budget tight for such a complex conceptual study
- Scientific benefit of including IFS in baseline for simultaneous use with MOS will need justifying
- Increasing multiplex to N~20,000 for a 10 m aperture is ambitious cost-wise
- Some regret loss of near-IR (e.g. c.f. PFS/MOONS) but it would be costly
- Sky subtraction with fibres for faintest applications will need demonstrating (PFS)

Innovation:

- For a facility completing in 2035, important to consider new technologies that will reduce cost / improve performance
- Improvements in telescope optics, corrector/ADC & fibre positioning
- Curved detectors would significant simplify spectrograph designs
- CMOS detectors would reduce detector cost if feasible in large formats

Hopefully it will eventually happen!

Olivier LeFèvre (1960 – 2020)

Huge legacy of articles exploiting current and future massively-multiplexed spectrographs

CFHT MOS (1994 - 1995)

CFRS (1995 - 1997)

CFRS+LDSS (1998 – 2000)

VVDS(2004 - 2013)

VIPERS (2013 – 2019)

zCOSMOS (2007 - 2022)

FMOS (2013 – 2019)

VUDS (2014 -2022)

ALPINE (2016 - 2022)

VANDELS (2018 - 2022)

JWST (2019 -

Euclid (2020 -

LATIS (2020 -

PFS (2014 –