BlueMUSE
in a nutshell

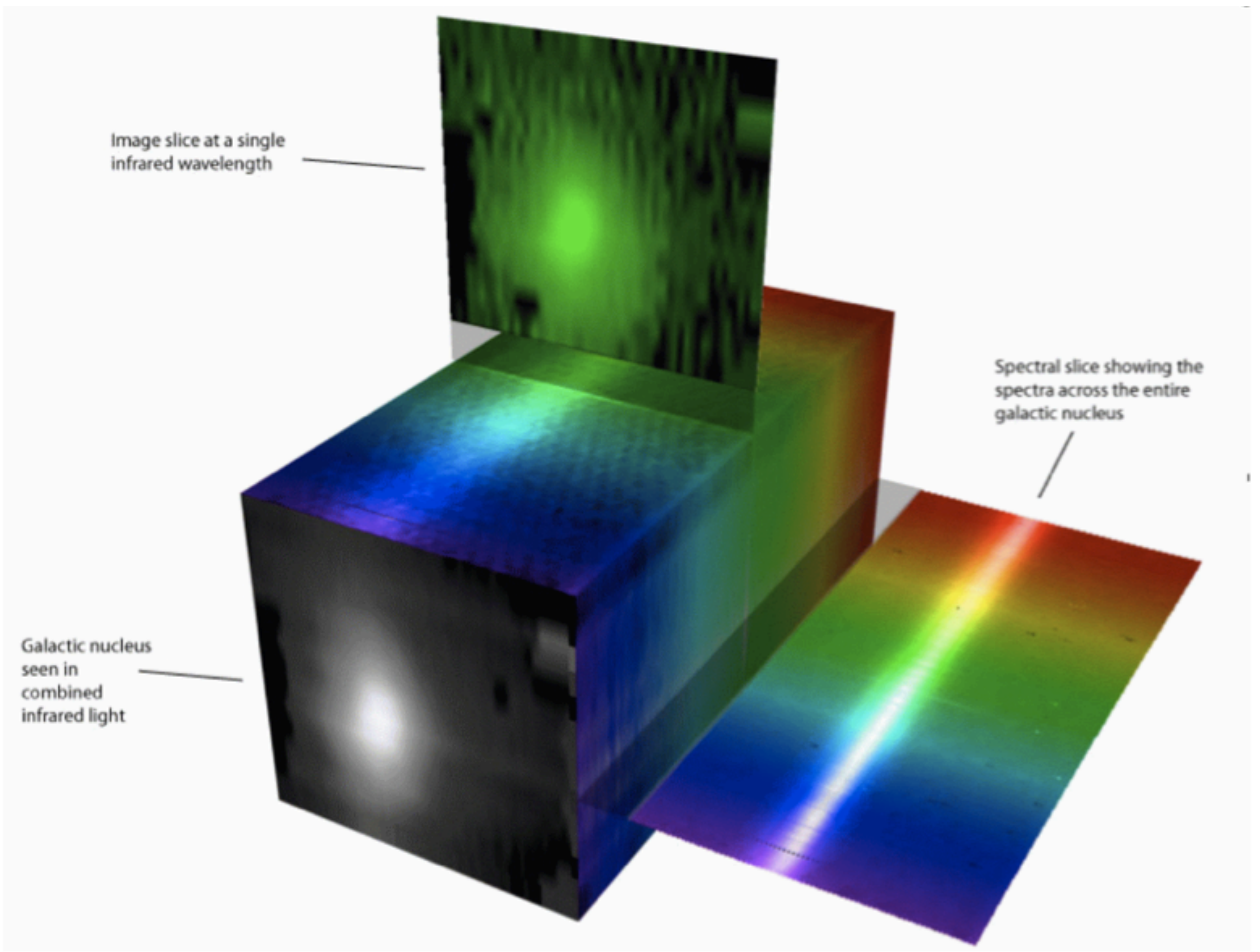
Johan Richard

(CRAL)

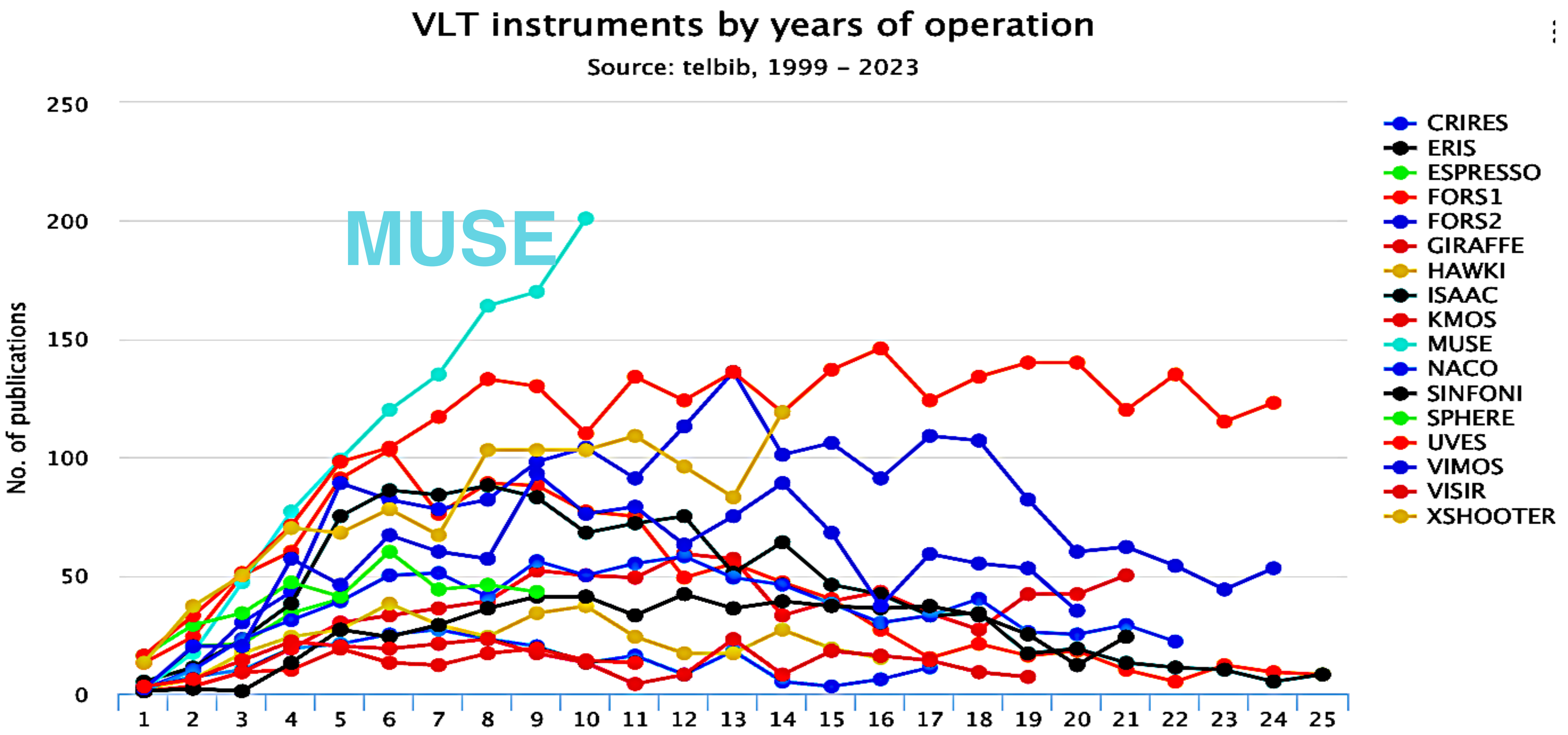
BlueMUSE online Science Team meeting, Apr 23-25th 2024

Why a panoramic IFS?

- <u>Spectroscopy of everything</u> and not only single sources
- Knowledge of the environment: neighbours, gaseous media (e.g. circumgalactic / intergalactic medium), …
- Remove bias from target selection for multi-object spectroscopy e.g. not all galaxies can be seen in broad band imaging

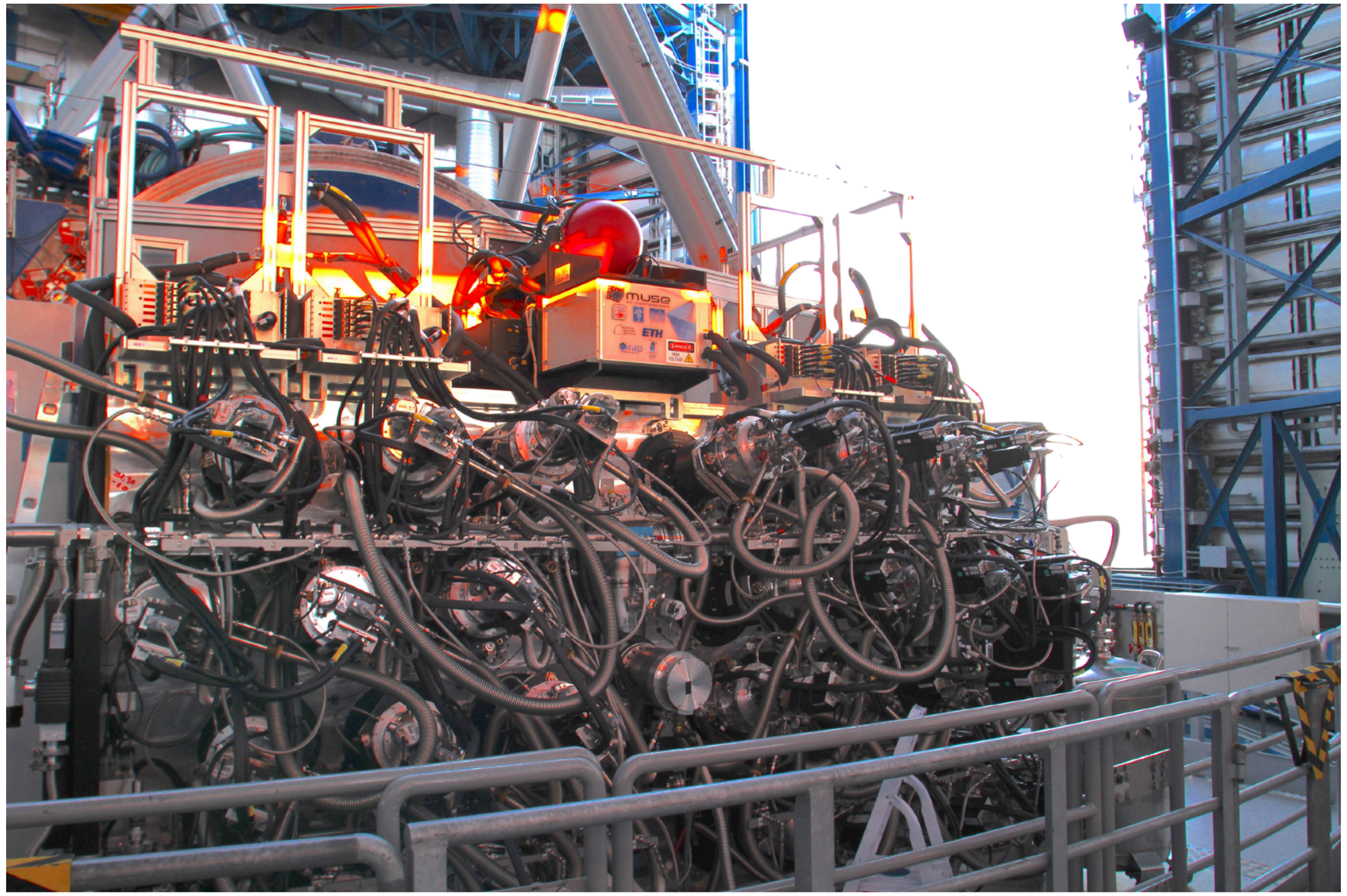


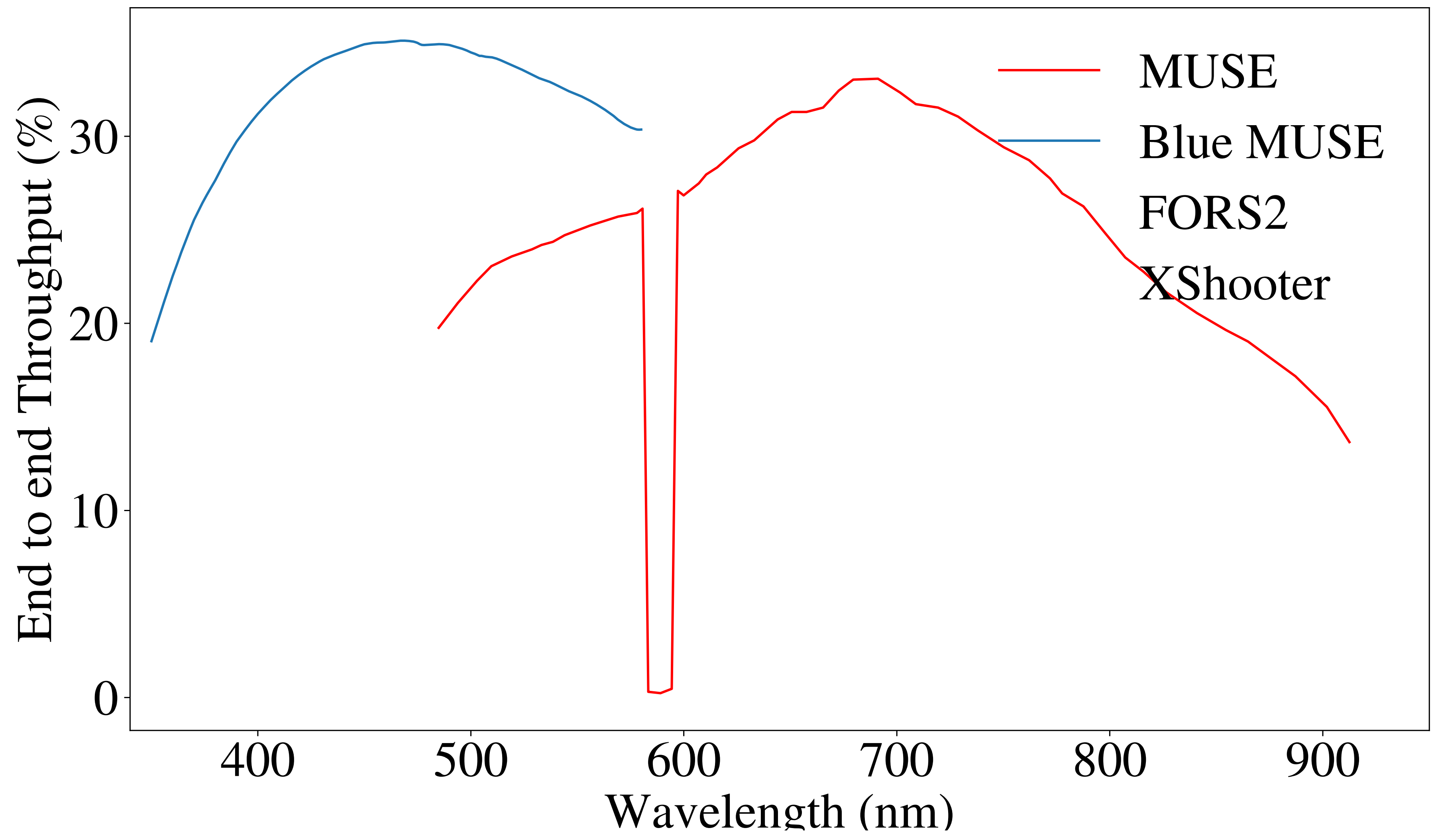
credits Churchill / MPIA

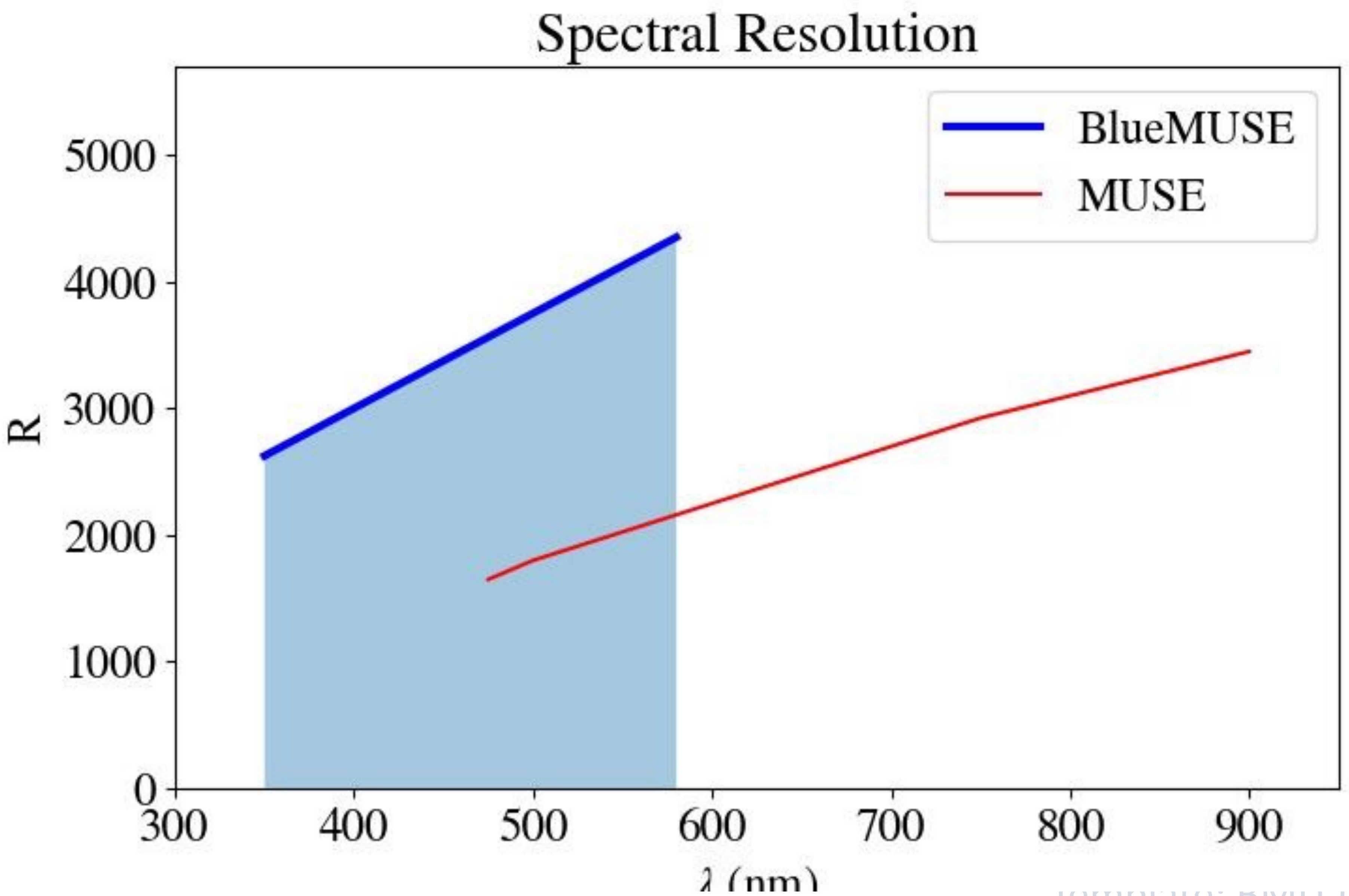


BlueMUSE main parameters

- A large field (**1 arcmin²**) Integral Field Spectrograph
- Optimised in the blue/UV **350-580 nm with R ~ 3500**
- With a high end-to-end throughput
- Very efficient in deep spectroscopy and crowded fields, high multiplexing capabilities
- Simple to use and operate!





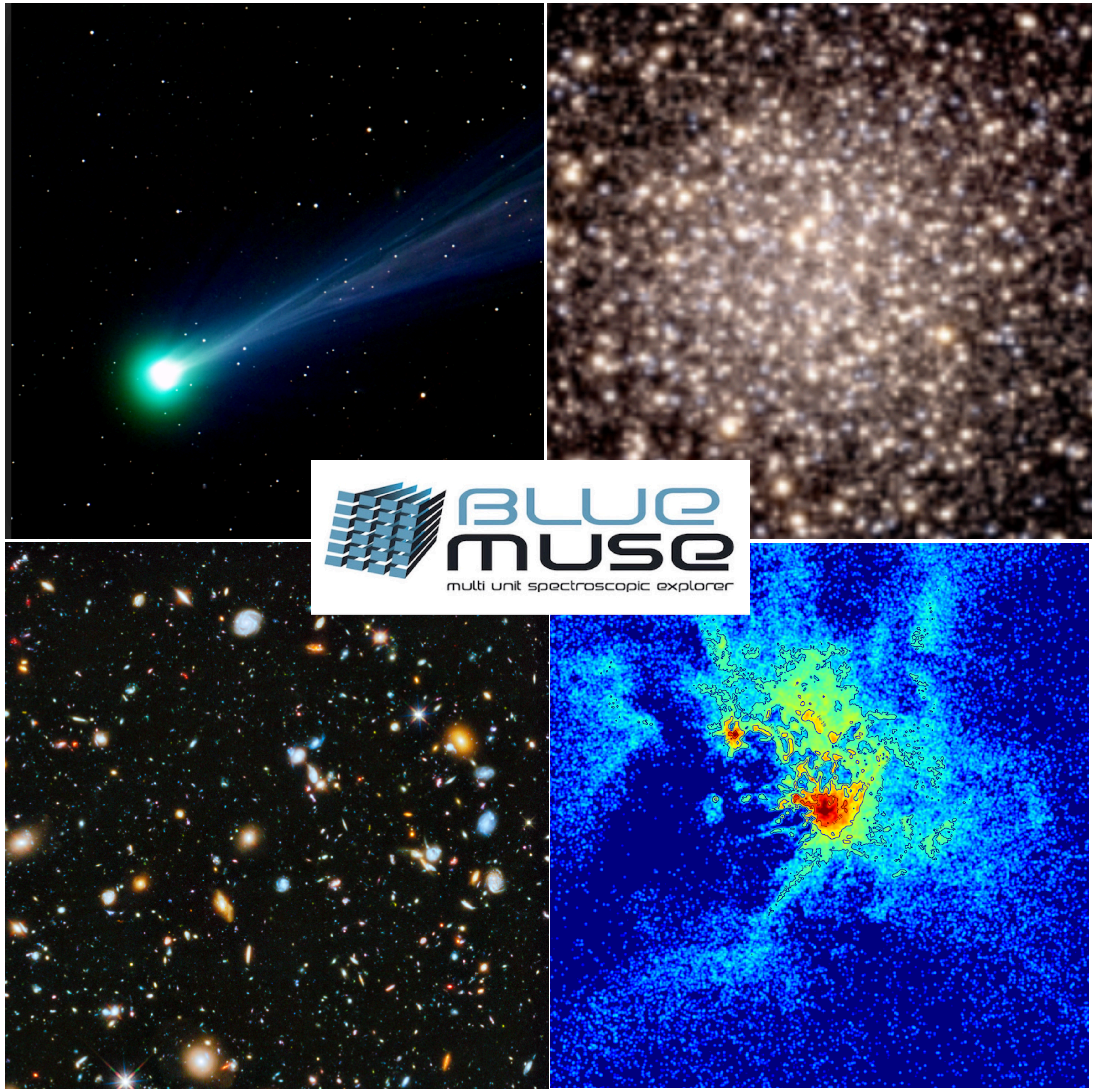


Science cases (white paper) Richard+2019

Local Volume SWG
(Adamo, Castro)

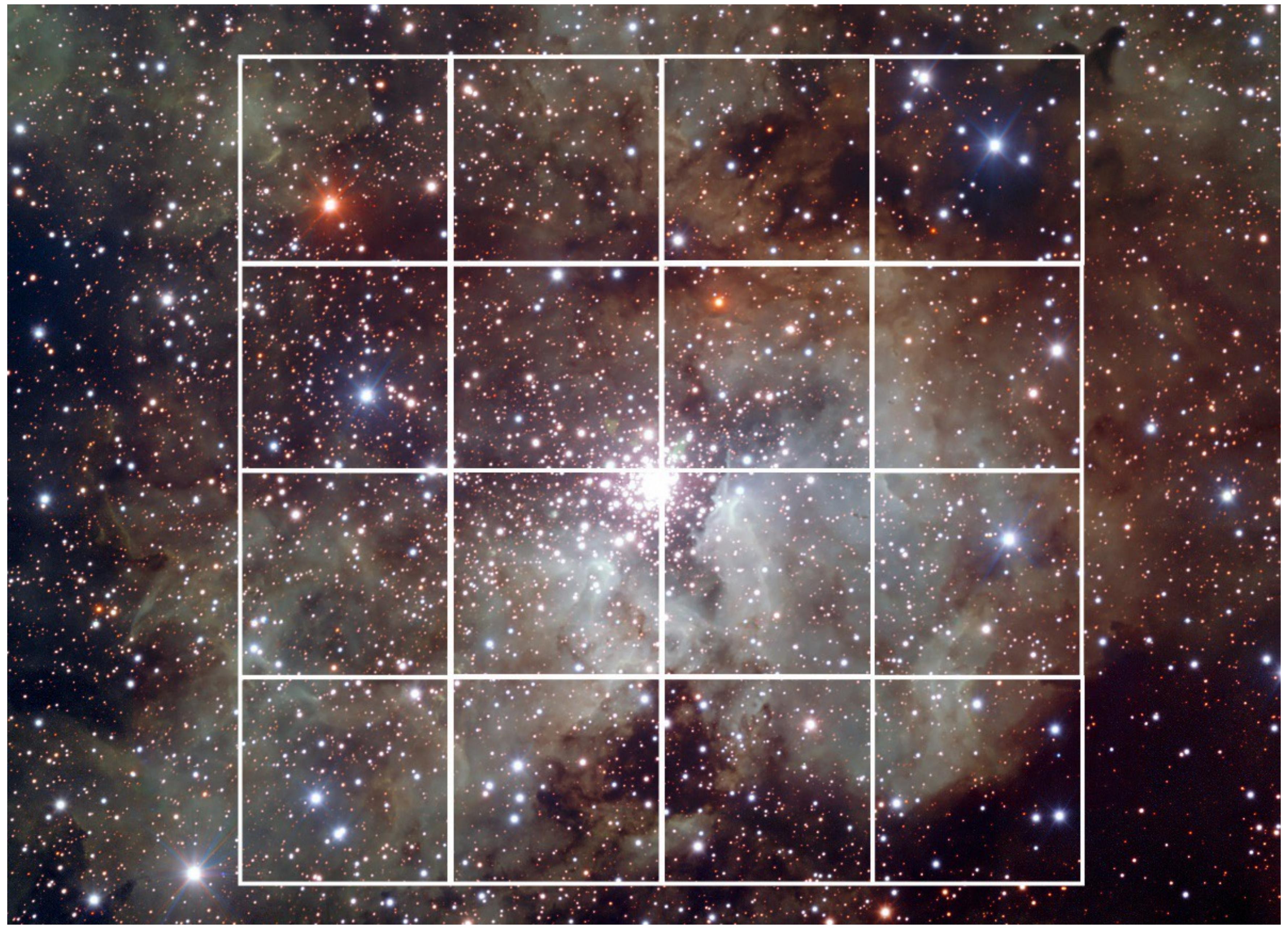
Nearby galaxies SWG
(Sanchez-Lopez, Krajnović)

The Distant Universe SWG
(Urrutia, Swinbank, Jauzac)



Local Volume SWG

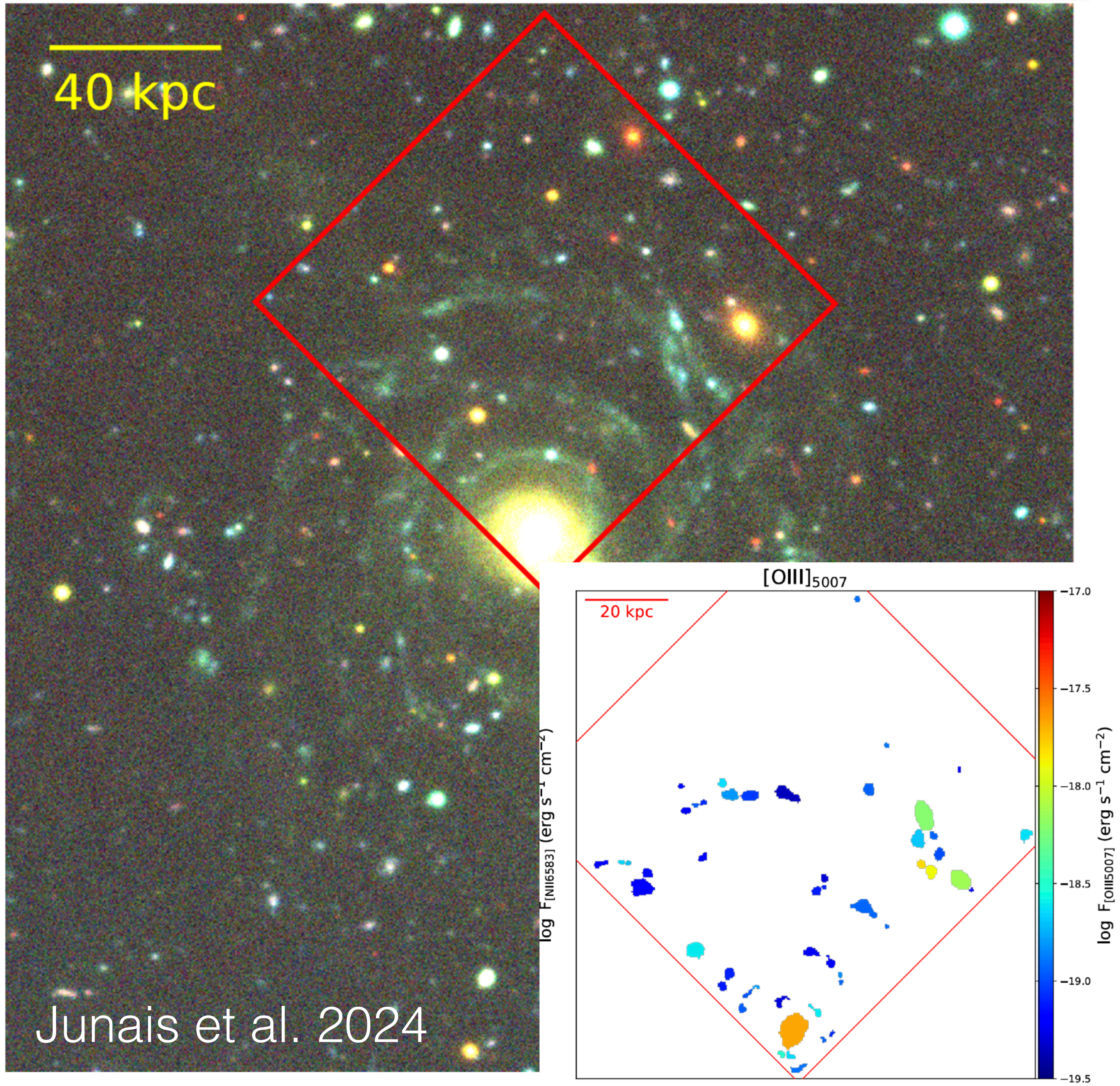
- Wolf-Rayet and OB stars evolution
- Comets
- Resolved HII regions, ionised nebulae, SNRs
- Globular clusters
- Ultra Faint Dwarf (UFD) galaxies (from ESO white paper)



See presentations tomorrow by:
N. Castro, B. Björgvinsson, C. Opitom

Nearby Galaxies SWG

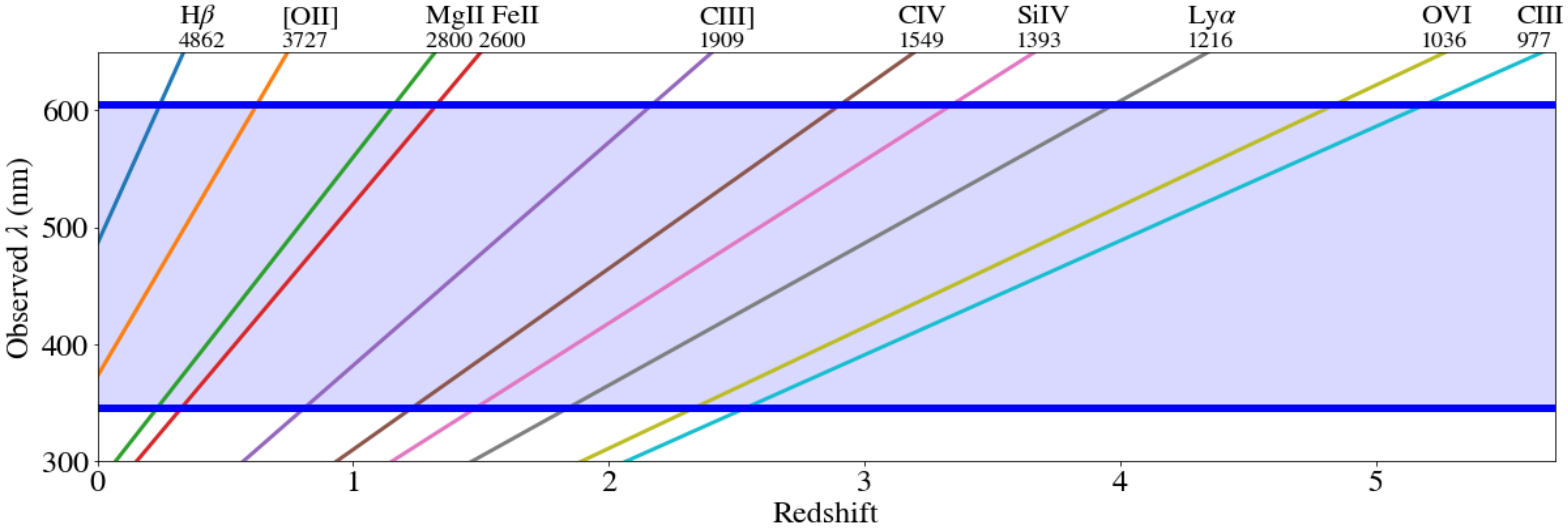
- <u>ISM and HII regions in Extreme starburst galaxies</u>
- Low surface brightness (LSB) galaxies
- Environmental effects in local galaxy clusters
- High order kinematics of cold stellar disks and dwarf galaxies
- PNs for stellar populations and kinematics of ell. galaxies + distances
- Soft X-ray sources and radiative shocks in metal-poor galaxies

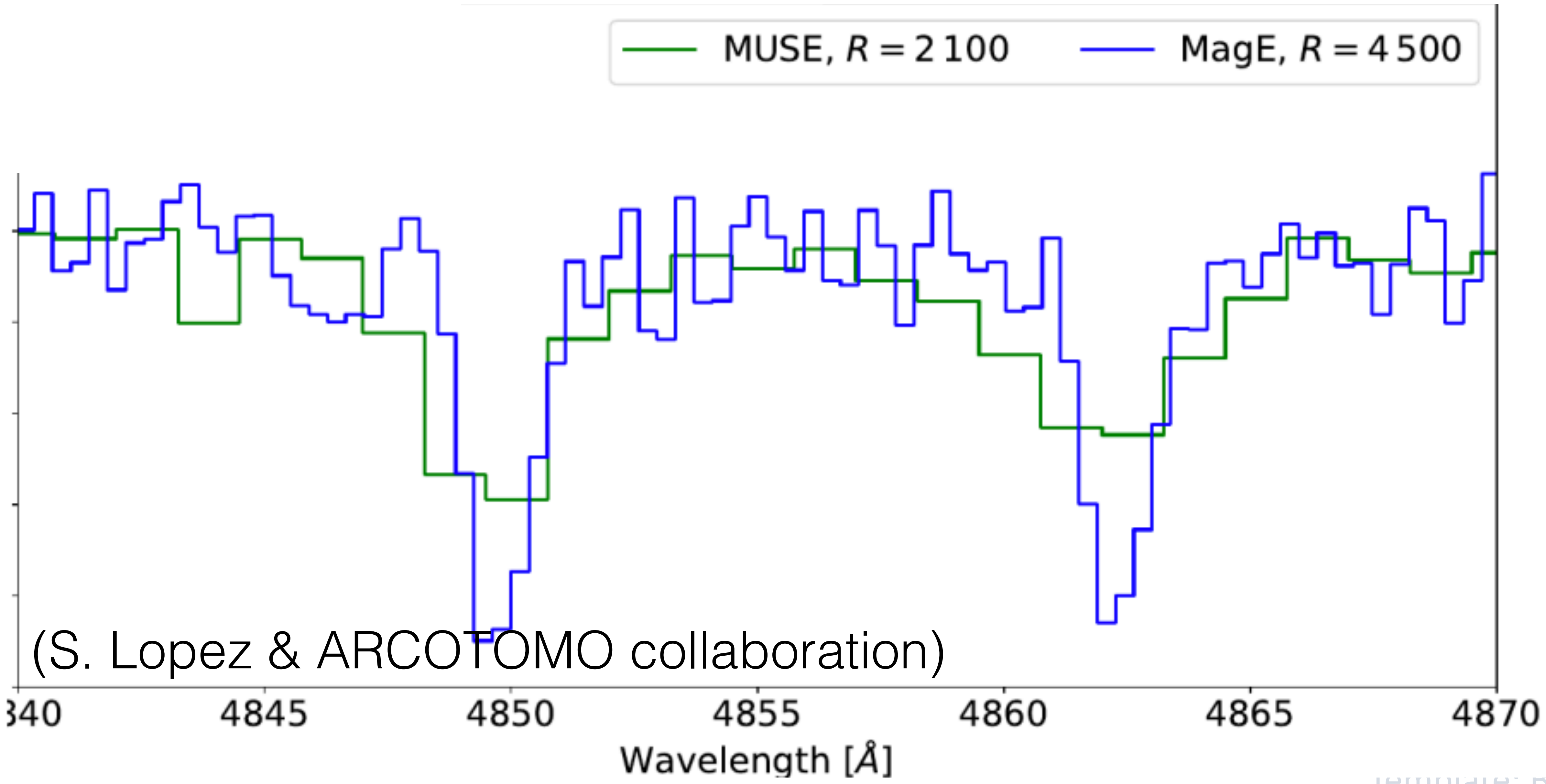


See presentations today by:
A. Lopez Sanchez, A. Bik, A. Lassen, D. Krajnović

Distant Universe SWG

- Deep fields
- Gas flows around and between galaxies
- Gravitational lensing by massive clusters
- Forming groups and clusters
- Lyman continuum leakers





(S. Lopez & ARCOTOMO collaboration)

See presentations tomorrow and Thursday:
S. Vergani, A.Verhamme, C. Simmonds, T. Urrutia, E. Daddi, A. Claeyssens

Requirements definition process

Science cases reports: summary

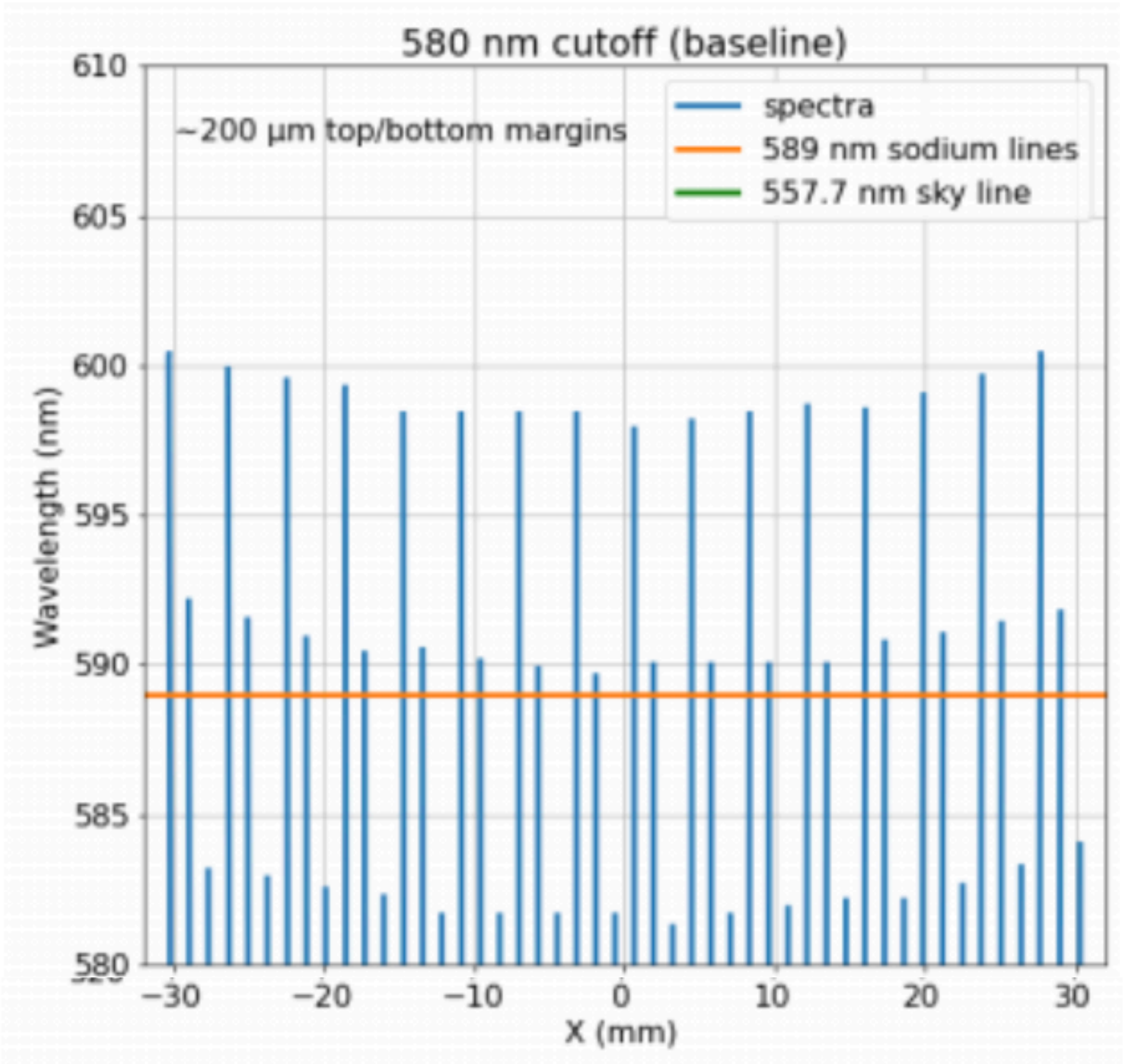
Science case	Wavelength Range (nm)	Average spectral Resolution	FoV (arcmin²)	Spatial sampling (“)
SWG1: Local Volume				
Wolf-Rayet (WR) and OB star evolution	350-580	>=3500	>1, goal 2	0.2<s<0.3
Resolved HII regions, SNRs, and PNe	350-580	>=3500, >2800 at 370 nm	>1, goal 2	0.2<s<0.3
Resolved stars in GCs and integrated light of star clusters	350-580 (goal 336)	>=3500	>1, goal 2	0.2<s<0.3
Comets	335-520	>1000	>1	0.2<s<0.3
SWG2: Nearby Galaxies				
ISM and HII regions in extreme starbursts	350-580	>=3500, >2800 at 370 nm	>1	0.2 < s < 0.3
Low Surface Brightness (LSB) galaxies	350-580	~ 3000	>1	0.2 < s < 0.3
Environmental effects in local galaxy clusters	350-580	~ 4000 Goal 30 km/s disp.	>1	0.2 < s < 0.3
High order kinematics of cold stellar disks and dwarf galaxies	375-575	~ 5000	>1	0.2 < s < 0.3
Elliptical galaxy stellar populations from integrated light spectroscopy in the far blue	336-480	Nominal Following wavelength range	>1	Not critical
Planetary nebulae for stellar populations and kinematics of elliptical galaxies + distances	Including 500.7 nm	x3 MUSE resolution =5500 at 500 nm.	>1	0.2 < s < 0.3
Soft X-ray sources and radiative shocks in metal-poor galaxies	340-580 (incl. 342.6 nm)	~3000	>1	0.2 < s < 0.3
SWG3: Distant Universe				
Gas flows around and between galaxies	350-580	2800 < R < 3700	>1, goal 2	0.2 < s < 0.3
Gravitational Lensing by massive clusters	350-580, goal 330-600	2500 < R < 4500	>1	0.2 < s < 0.3
Forming Groups and clusters	350-580		>1	>=0.3
Lyman-continuum leakers	350-600	R<3500	>1, goal 2	>=0.3
Derived TLR	**At least 350 – 580 nm**	**Min. R > 2600** **Average R>= 3500**	**>1 arcmin²**	**0.2” < s < 0.3”**

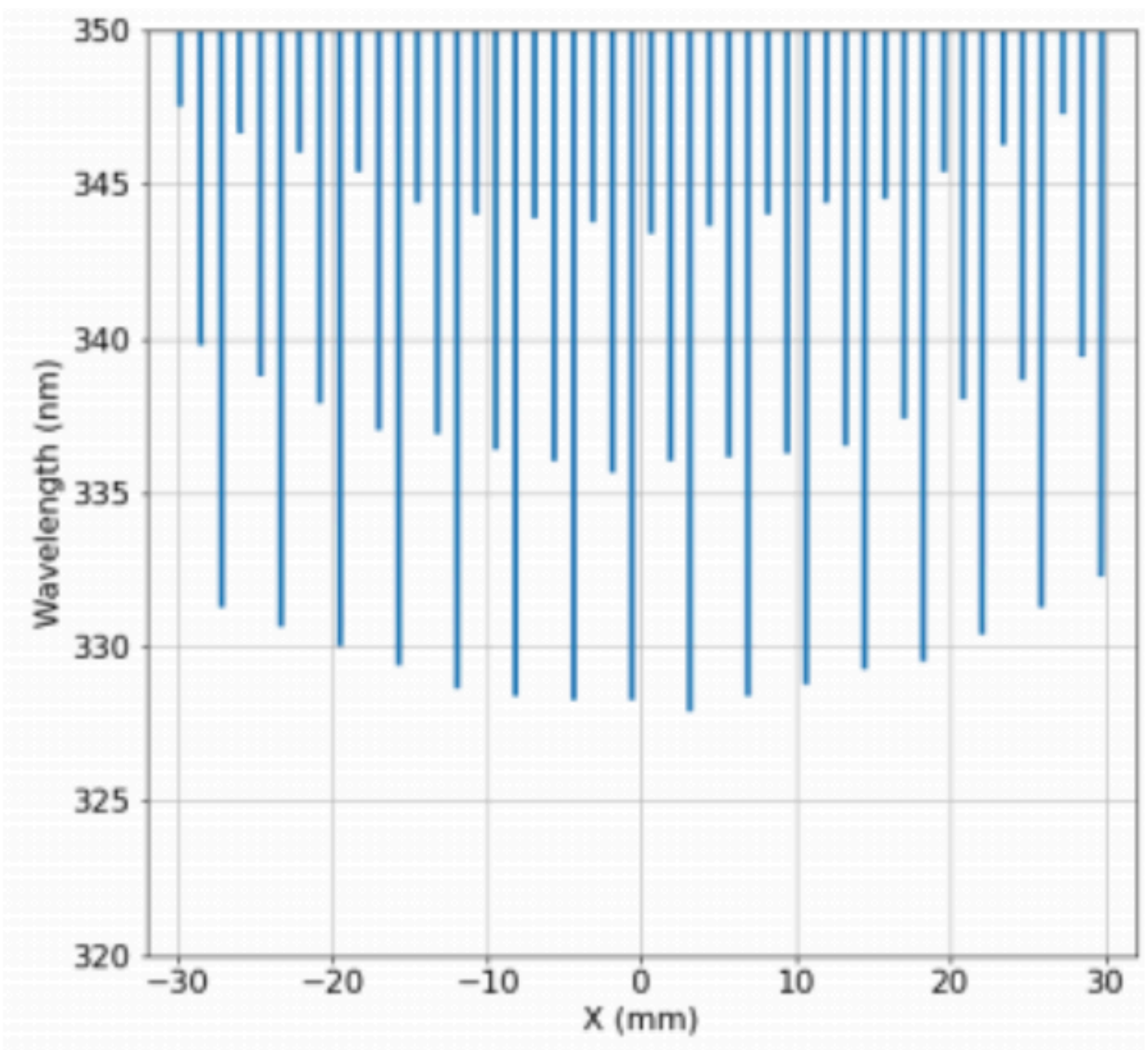
Reference Science case (blue) **TLR partially met** (yellow)

TLR on Wavelength Range

The **common wavelength coverage** of the BlueMUSE instrument (defined as the minimum wavelength range covered by the detector at any spatial position in the Field of View) shall fully contain the wavelength domain **350 nm < lambda < 580 nm.**

The ‘Extended wavelength range’ is the additional wavelengths acquired on the detector but only partially covered by the Field of View (approximately a third of the FoV). The limits in wavelength of the extended range are expected to be ~ 330 nm < lambda < 600 nm (goal).





All requirements shall be fulfilled over the common wavelength range.

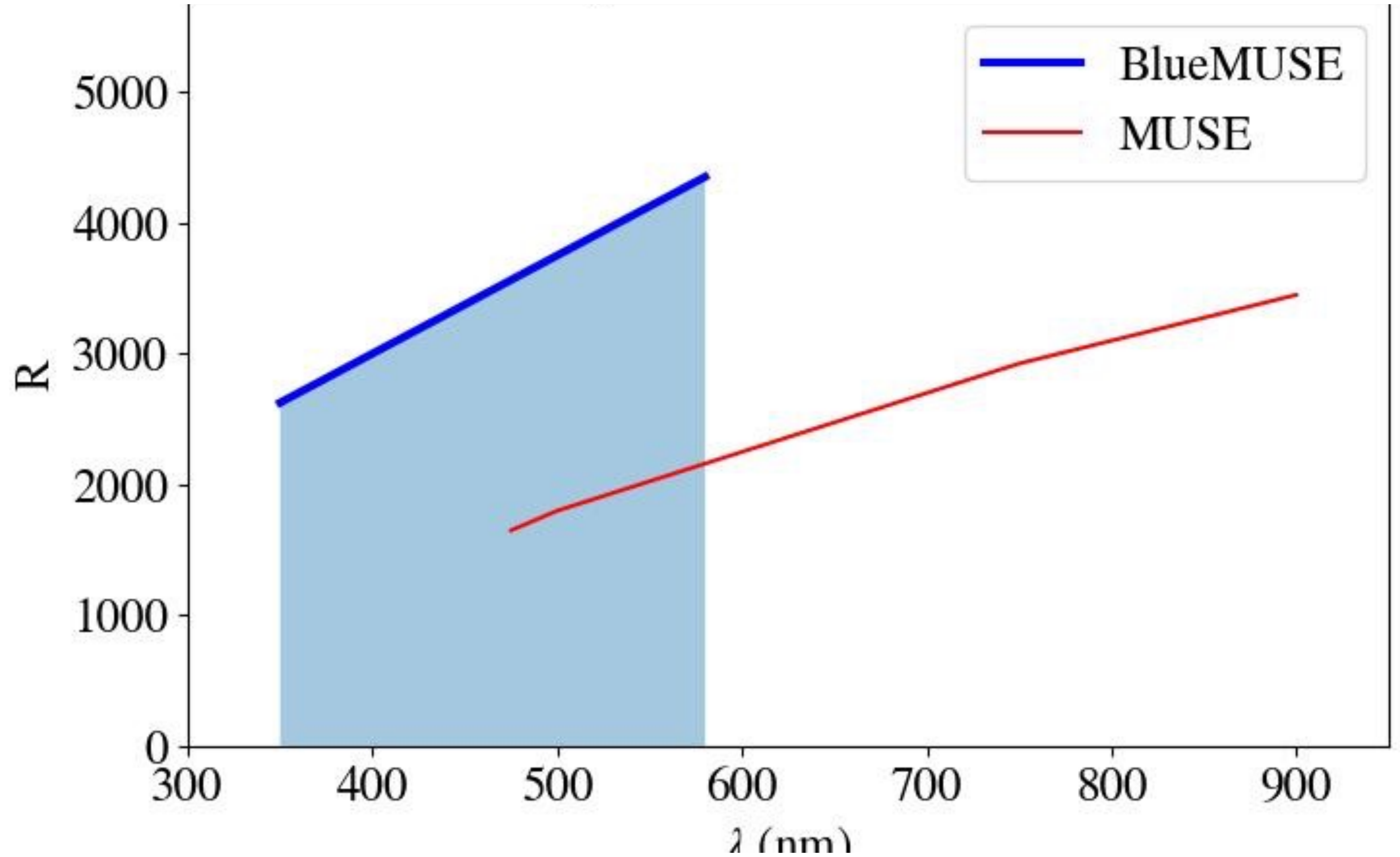
350 - 580 nm	all slices
~ 350 - 600 nm	1 / 3 slices
~ 340 - 590 nm	1 / 3 slices
~ 330 - 580 nm	1 / 3 slices

Spectral resolution and sampling

The **minimum spectral resolution** of the BlueMUSE instrument, defined as R=lambda / FWHM with the wavelength and FWHM of the line spread function, shall be higher than **2600**. The **average** spectral resolution across the common wavelength range **shall be higher than 3500.**

The **pixel sampling** of the BlueMUSE instrument detectors shall sample the LSF FWHM along the spectral direction by at least **2 pixels (goal: 2.5 pixels)** at any wavelength of the common range.

λ_{max} (nm)	R_{min}	R_{max}	R_{avg}
580 (baseline)	2600	4350	3500



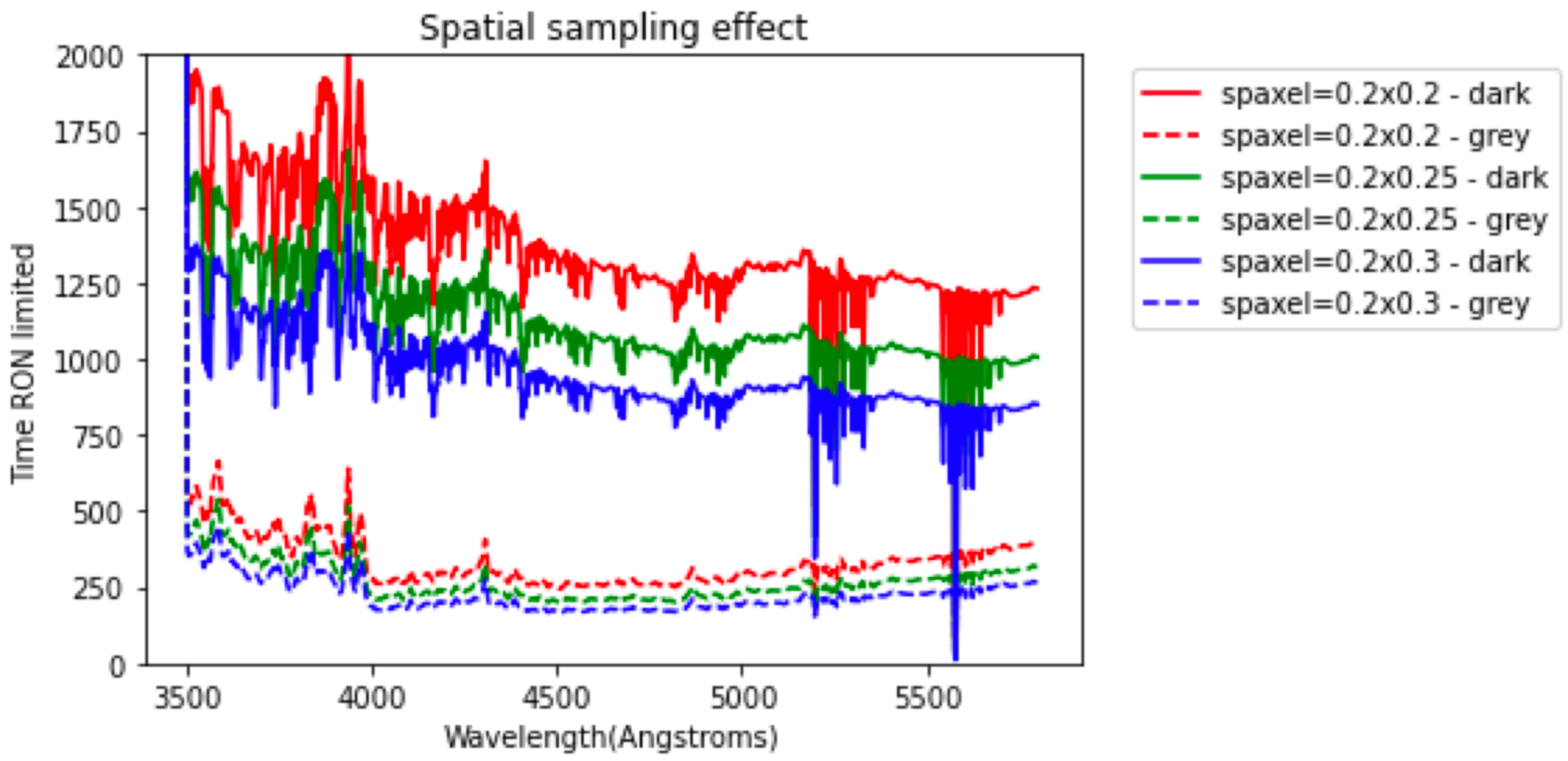
FoV and spatial sampling

The BlueMUSE instrument shall provide spectroscopy across a contiguous field-of-view (i.e. all spaxels in the field-of-view being illuminated) covering a **minimum area of 1x1 arcmin^2.** No gaps are accepted.

The spaxel size (spatial sampling) of the BlueMUSE instrument shall be **between 0.2 and 0.3” on a side.**

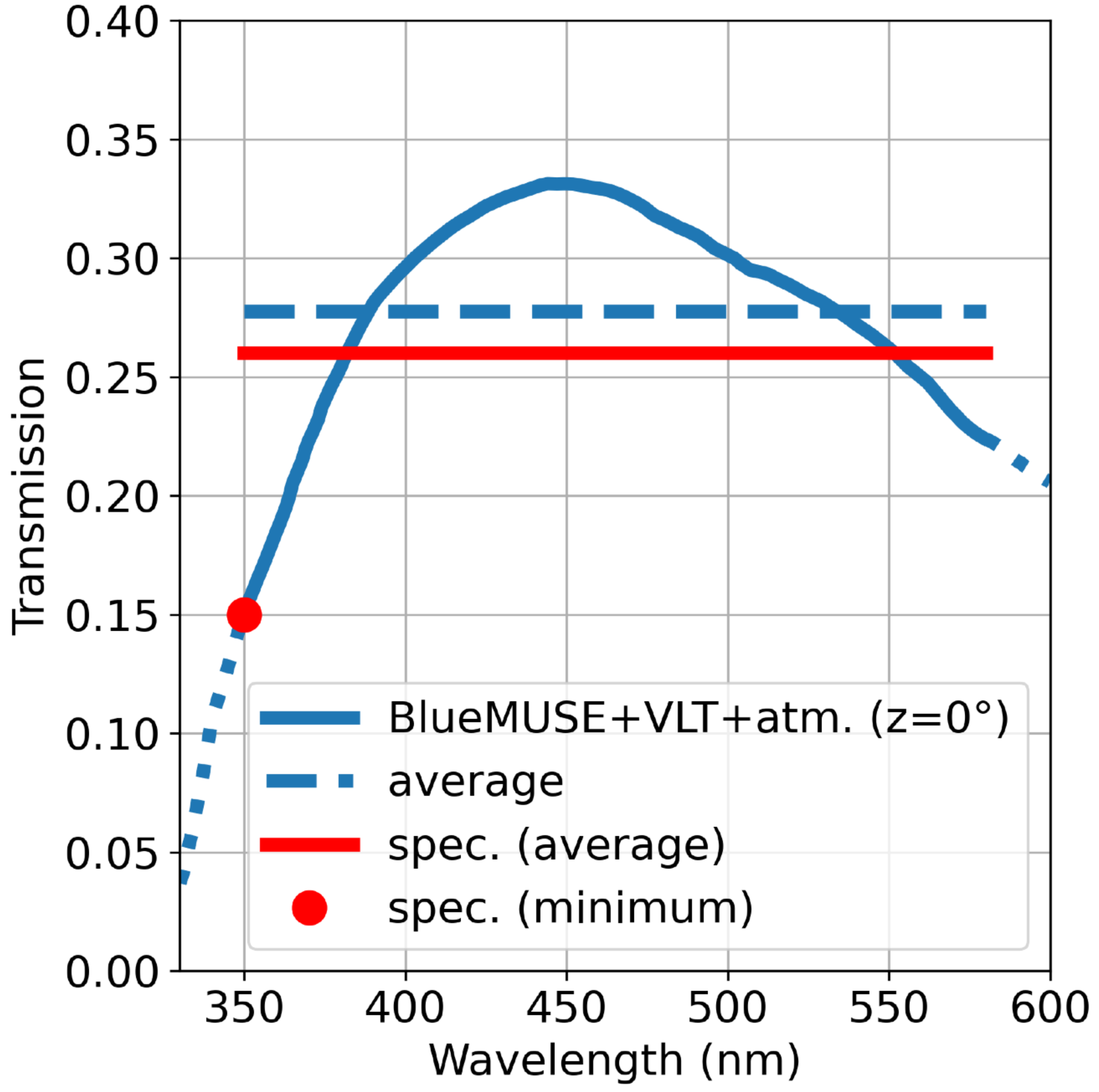
Current design option:
the use of **rectangular spaxels (0.2” x 0.3”)** has allowed for a significant simplification and cost reduction of the instrument, with only 16 channels / submodules.

It also helps reach background limit in < 1800 sec in dark time.



Throughput / ETC performances

TLR: minimum 15 %, average 26 % end to end.



@350nm:
XShooter ~ 13.8%
UVES ~ 5%
KCWI ~ 5%
(eq. ~ 9%)

ex. point source, constant 1e-17 erg/s/cm2/Å,
SNR=5 @350 nm in 1000 s

https://calc-bluemuse.univ-lyon1.fr/

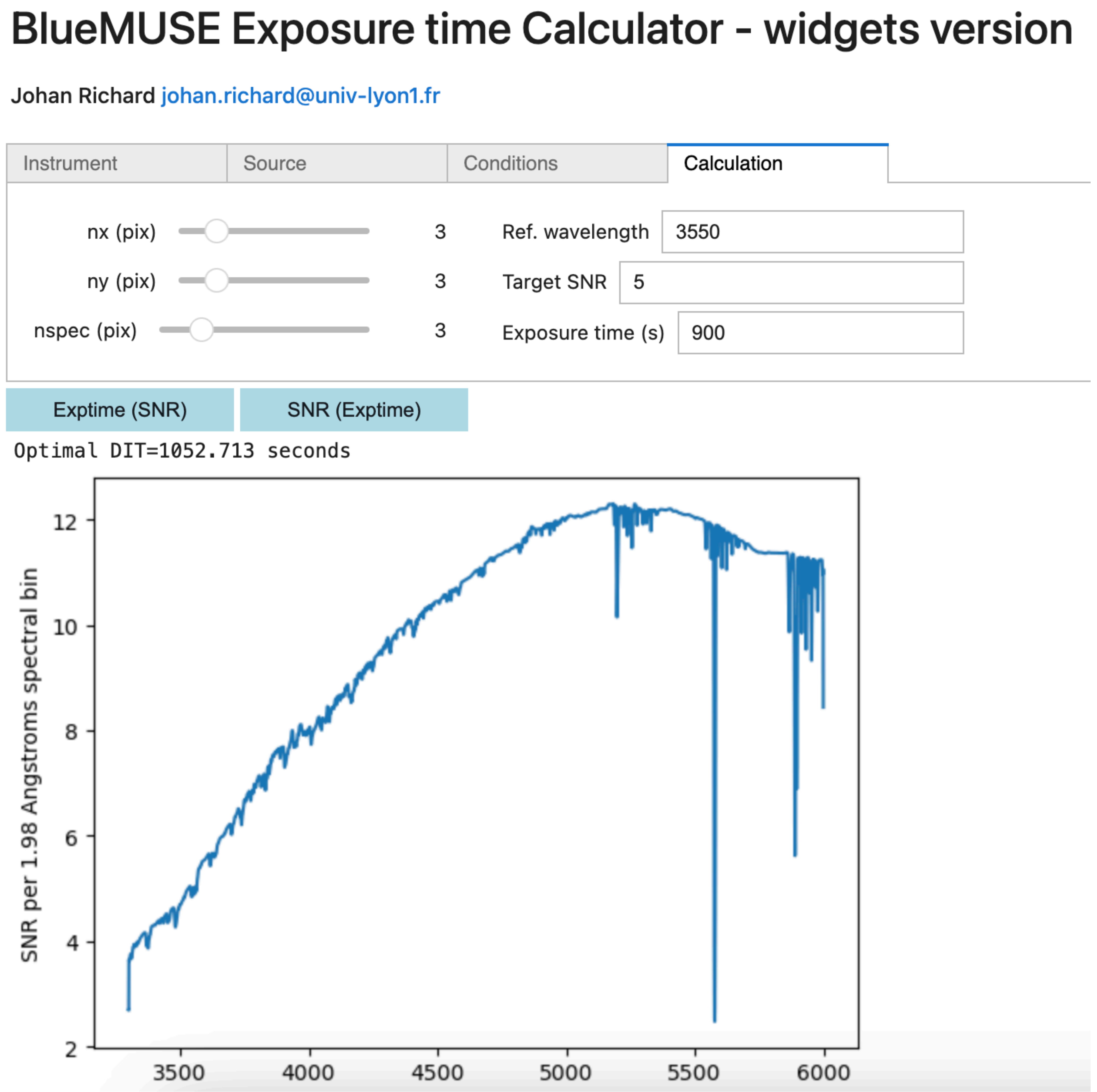
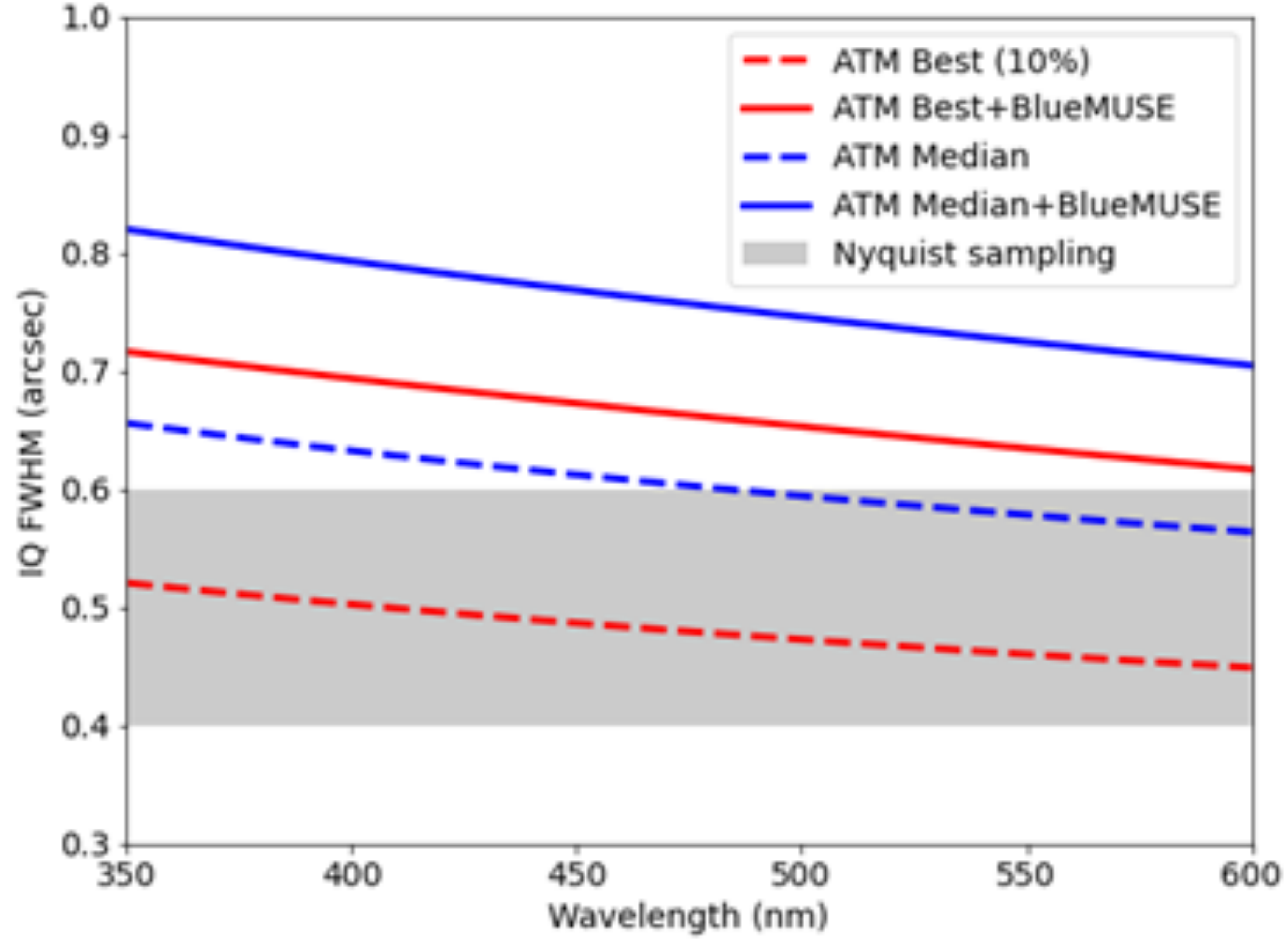
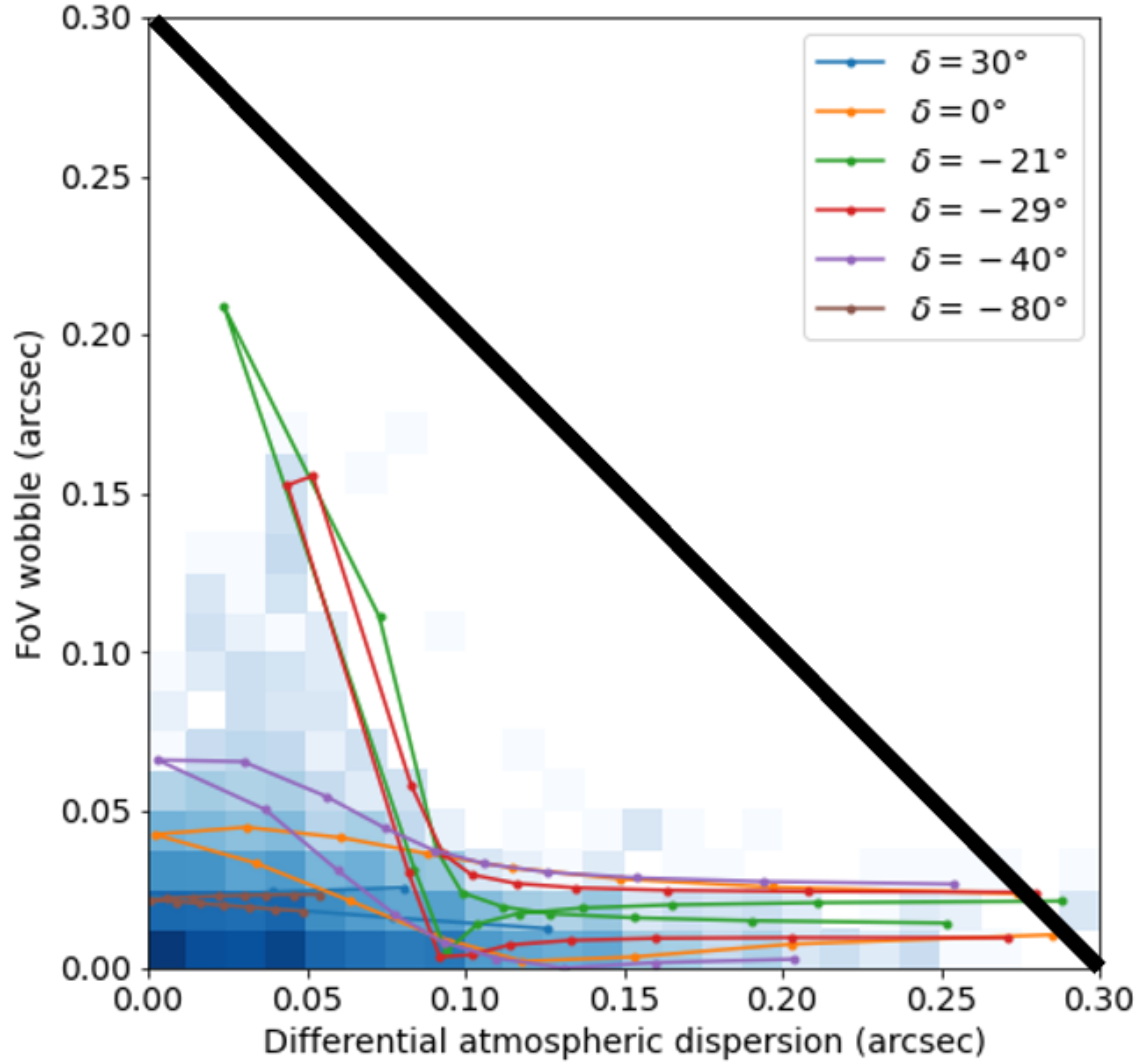


Image Quality and AD / wobble

The BlueMUSE instrument PSF (including all optical aberrations and contributions from derotator wobble and differential atmospheric dispersion during an exposure, but excluding telescope) shall have a FWHM lower than 0.42” in the common wavelength range.





Synergy with other facilities

Present and future IFUs on > 6m

Instrument / Telescope	Wavelength Range	Max FoV (arcmin2)	R	Technology	1st light
KCWI / Keck	0.35 - 0.56 um	0,05 - 0,19	1000 - 20000	Slicers	2010
MUSE / VLT	0.47 - 0.93 um	1	1800-3000	Slicers	2014
FOCAS / Subaru	0.37 - 1 um	0.036	3000 - 7000	Slicers	2018
ERIS / VLT	1 - 5 um	0.017	2000-4000, 8000	Slicers	2021
NIRSpec / JWST	0.9 - 5 um	0.0025	1000 - 2700	Slicers	2022
MIRI / JWST	4.9 - 28.3 um	0.015	1500 - 3500	Slicers	2022
KCWI-red (KCRM) / Keck	0.53 - 1.05 um	0,05 - 0,19	1000 - 20000	Slicers	2023
LLAMAS / Magellan	0.35 - 0.98 um	0.4	2200	Fibers / Lenslets	2024 ?
ROSIE / Magellan	0.39 - 0.9 um (3 settings)	0.749	2000	Slicers	?
SWIMS-IFU / TAO	0.9-2.5 um	0.053	1000	Slicers	2024
MIRMOS / Magellan	0.8 - 2.4 um	0.144	3700	Slicers	2025
HARMONI / ELT	0.5 - 2.5 um (> 3 settings)	0.015	3300-17300	Slicers	2029
GMTIFS / GMT	0.9-2.5 um	0.0022	5000-10000	Slicers	?
VLT/MAVIS	0.37 - 1 um	0.0025-0.01	5900 - 14700	Slicers	2030
BlueMUSE / VLT	0.35 - 0.58 um	1	2600-4500	Slicers	2032
MOSAIC / ELT	0.8 - 1.8 um	10 x 0,0011	5000	Fibers	2032
IRMOS / TMT	0.8 - 2.5 um	10 x 0,0025	2000 - 10000	Slicers	2030?

Present and future IFUs on > 6m

Instrument / Telescope	Wavelength Range	Max FoV (arcmin2)	R	Technology	1st light
KCWI / Keck	0.35 - 0.56 um				
MUSE / VLT	0.47 - 0.93 um				
FOCAS / Subaru	0.37 - 1 um				
ERIS / VLT	1 - 5 um				
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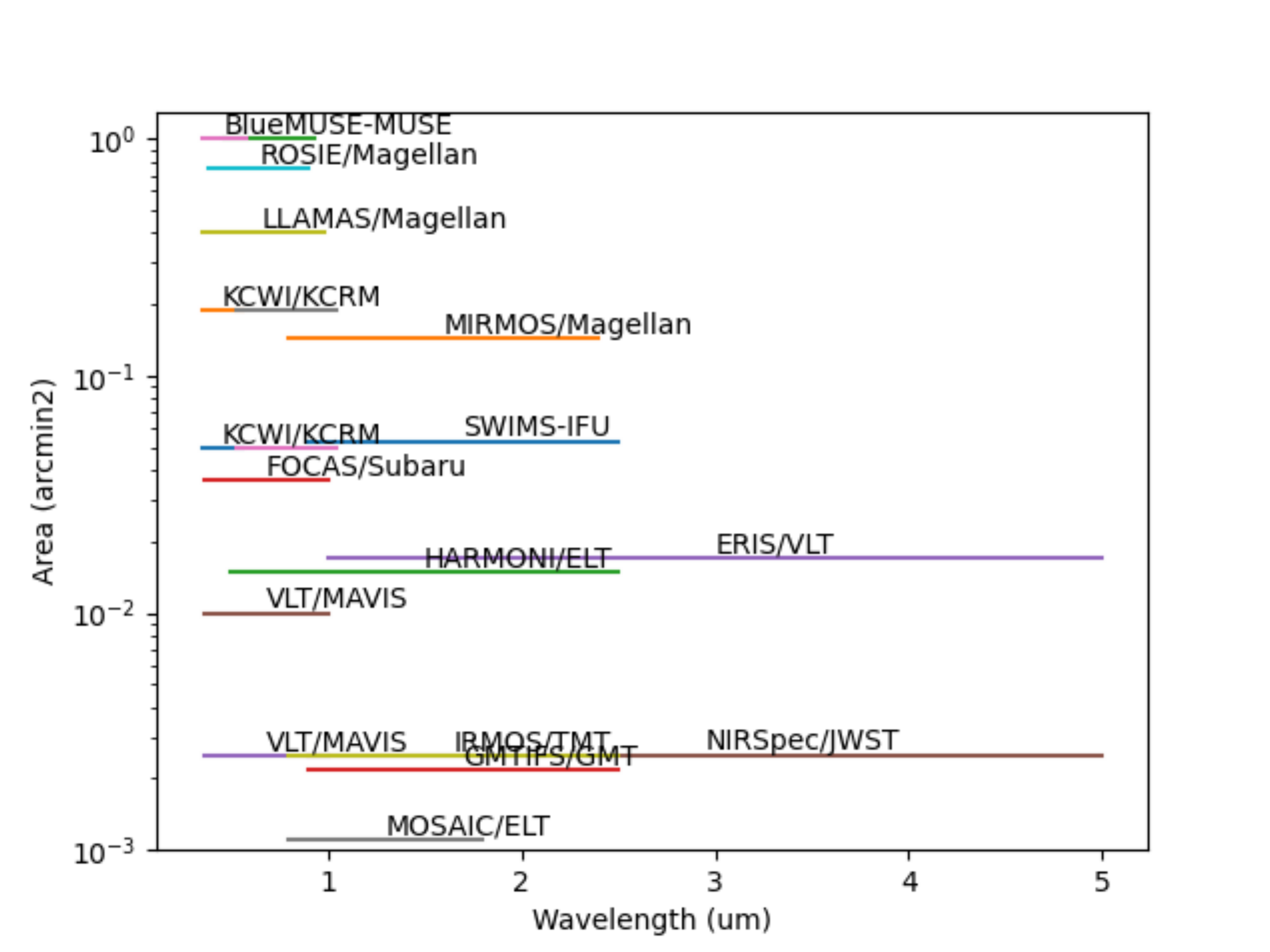
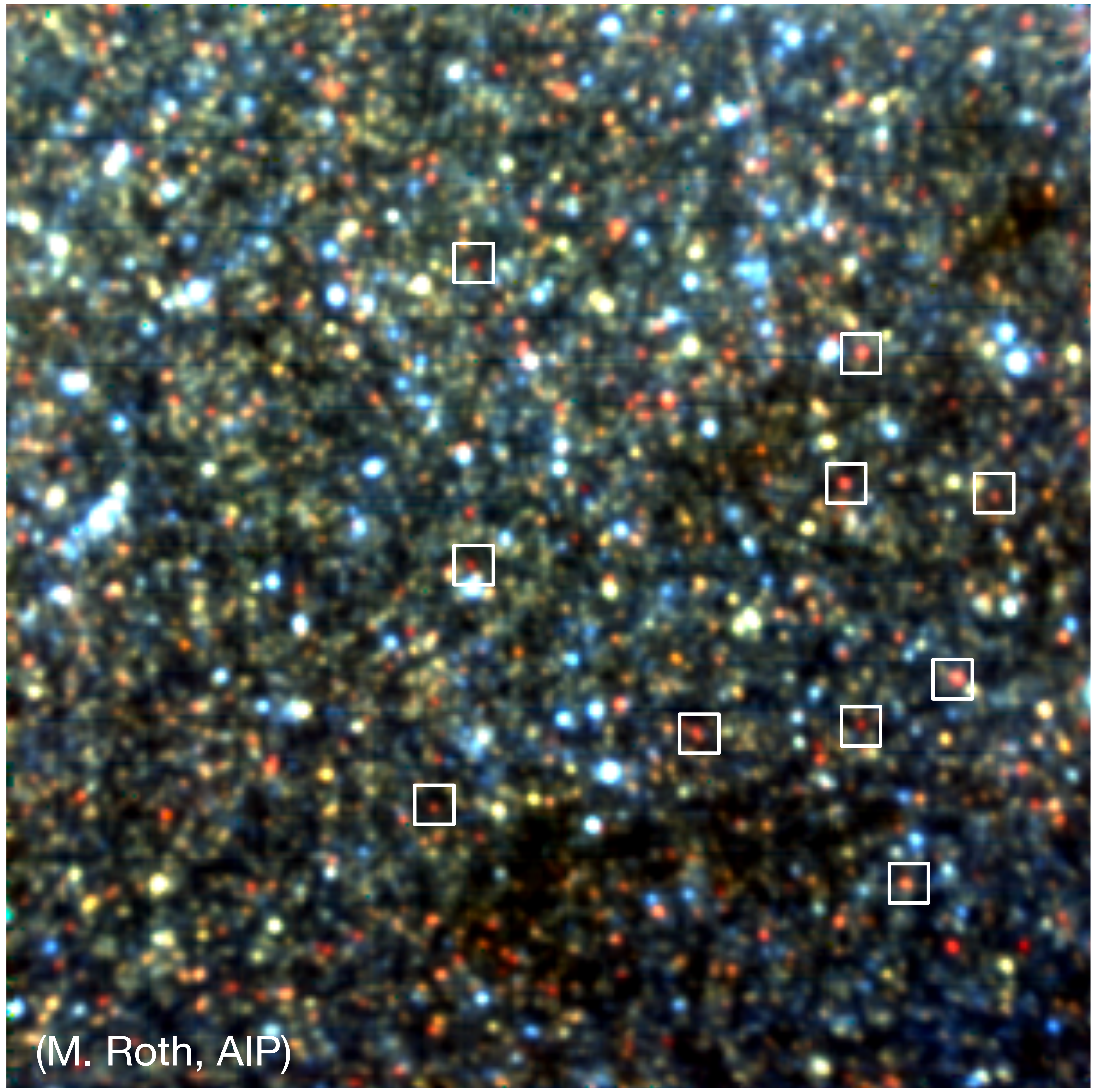
IRMOS / TMT	0.8 - 2.5 um				



Synergy with ELT instruments

MOSAIC

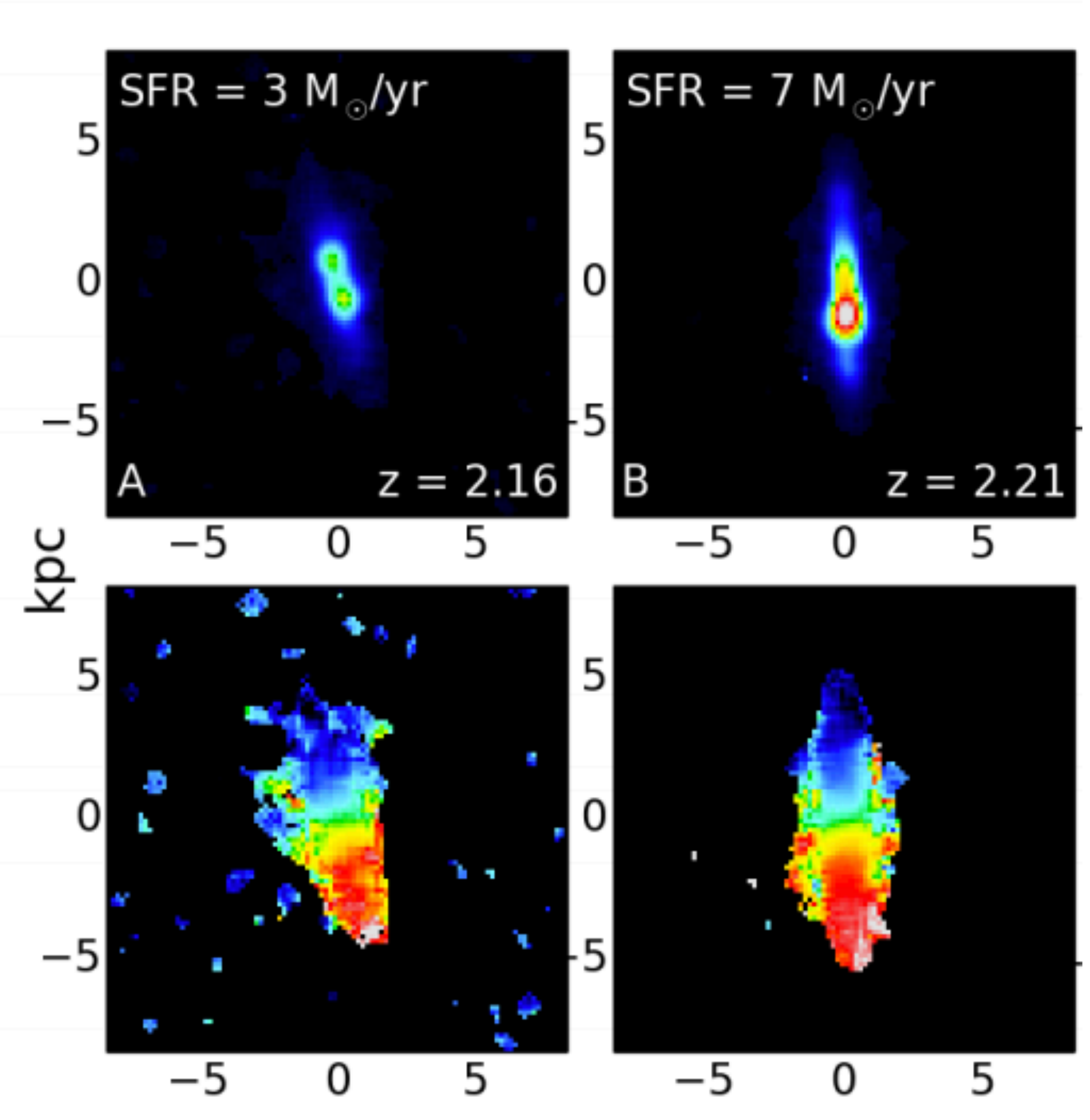
- Large multiplexing capability over a sky area comparable to a BlueMUSE
- e.g. Follow-up of massive stars at high resolution in HMM mode



(M. Roth, AIP)

HARMONI

- Follow-up observations of BlueMUSE-detected LAEs will give us access to the overall kinematics (dark matter content) and extended haloes, resolved abundances etc. to test galaxy formation models.



HARMONI Halpha simulations at z=2

Zieleniewski et al. 2015

Synergy with VLT2030 instruments

MAVIS

- Higher spatial resolution
- Imaging sensitivity
- λ coverage up to 1 micron
- Higher spectral resolution

CUBES

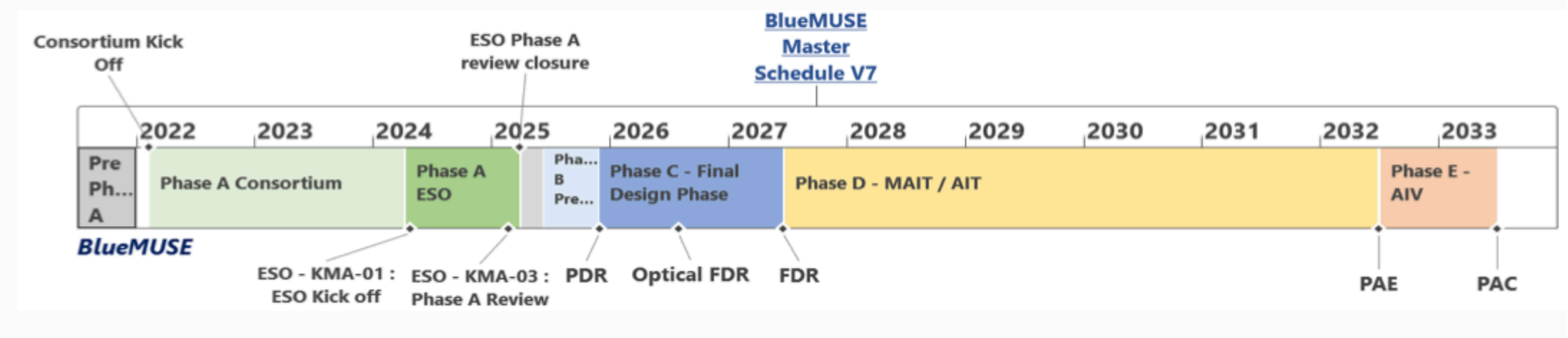
- Higher spectral resolution (de-blending of absorption lines)
- λ coverage down to 300 nm

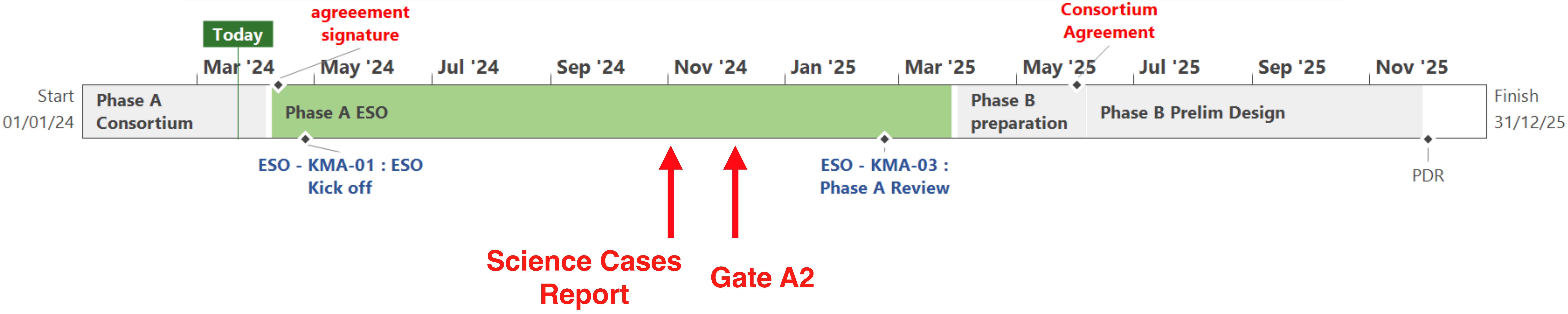
BLUE MUSE
multi unit spectroscopic explorer

- Large field, IFU, multiplexing
- λ coverage up to 580 nm / down to 350 nm
- High sensitivity to emission lines and low SB

Schedule + Phase A

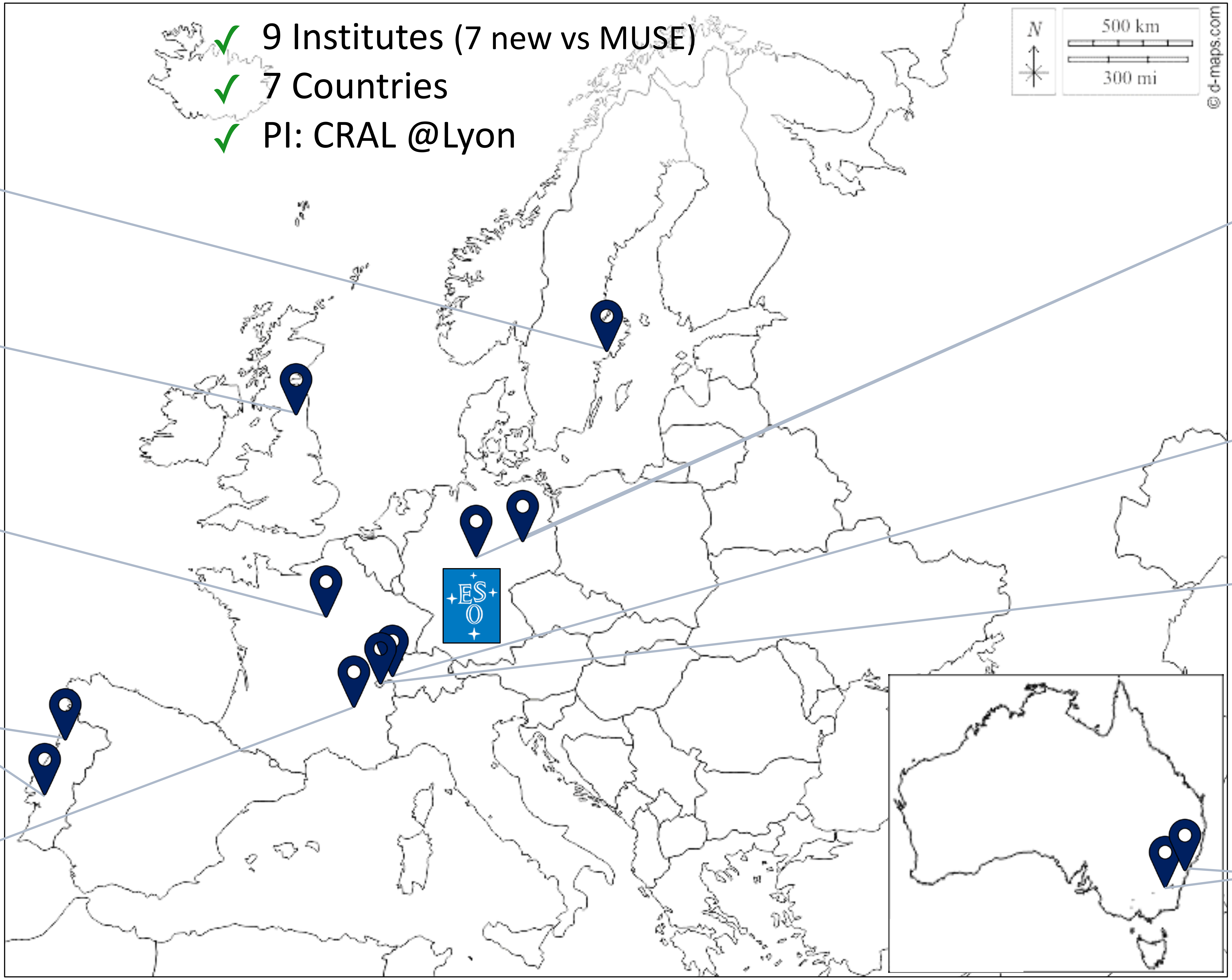
- Agreement between ESO and CNRS (for CRAL) signed Apr. 18th (?) by ESO
- Clear common objective from the project and ESO: Phase B (contract) to be discussed at ESO council in June 2025.





BlueMUSE Consortium

- ✓ 9 Institutes (7 new vs MUSE)
- ✓ 7 Countries
- ✓ PI: CRAL @Lyon



Stockholm University

Durham University

cea irfu AIM

ia instituto de astrofísica e ciências do espaço

CRAL CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

AIP Universität Potsdam

INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

EPFL

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES Département d'astronomie

AAO Astralis

BlueMUSE — Project organization

- Science team mailing lists (global + 1 per SWG)
- BlueMUSE science wiki https://bluemuse.univ-lyon1.fr/sciencewiki/
- BlueMUSE slack

ESO
Executive Board
Project Office
Science Team
Local Project Managers
Engineering team

Consortium partners and GTO

- Each consortium partner will contribute in the form of FTE (towards the design, manufacturing, testing of a subsystem) or in-kind cash contribution (only to purchase deliverable hardware systems and tools).

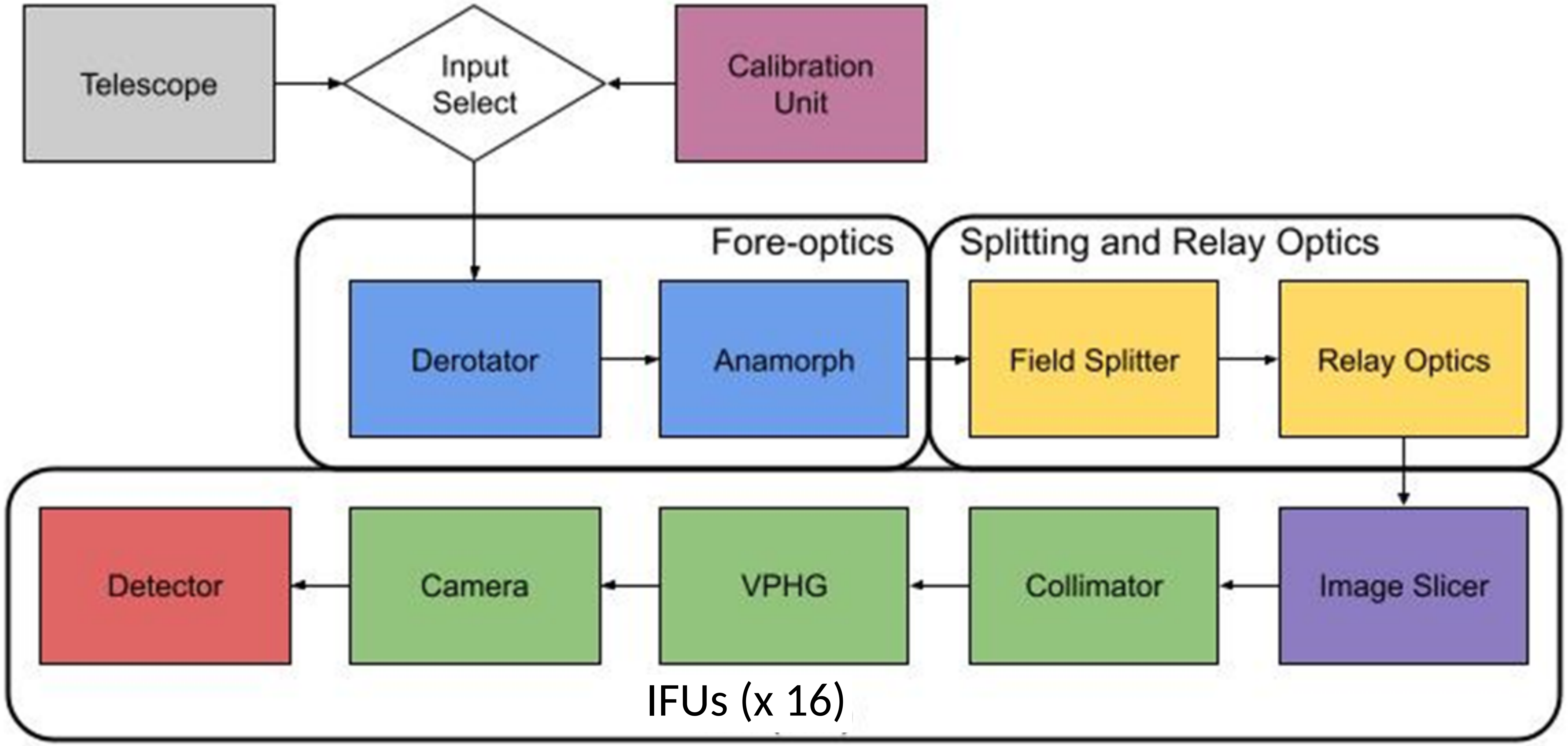
- Very first estimates show that individual partner contributions are relatively similar

- In return for this expected contribution, we can expect ~ 180 VLT nights of Guaranteed Time Observations (GTO).

- **We want to propose a use of BlueMUSE GTO where all the GTO nights are pooled in BlueMUSE science programmes as opposed to splitting and distributing GTO nights in proportion to each partner's contribution to the project.**

Return of Experience from MUSE consortium GTO by R. Bacon + discussion tomorrow!

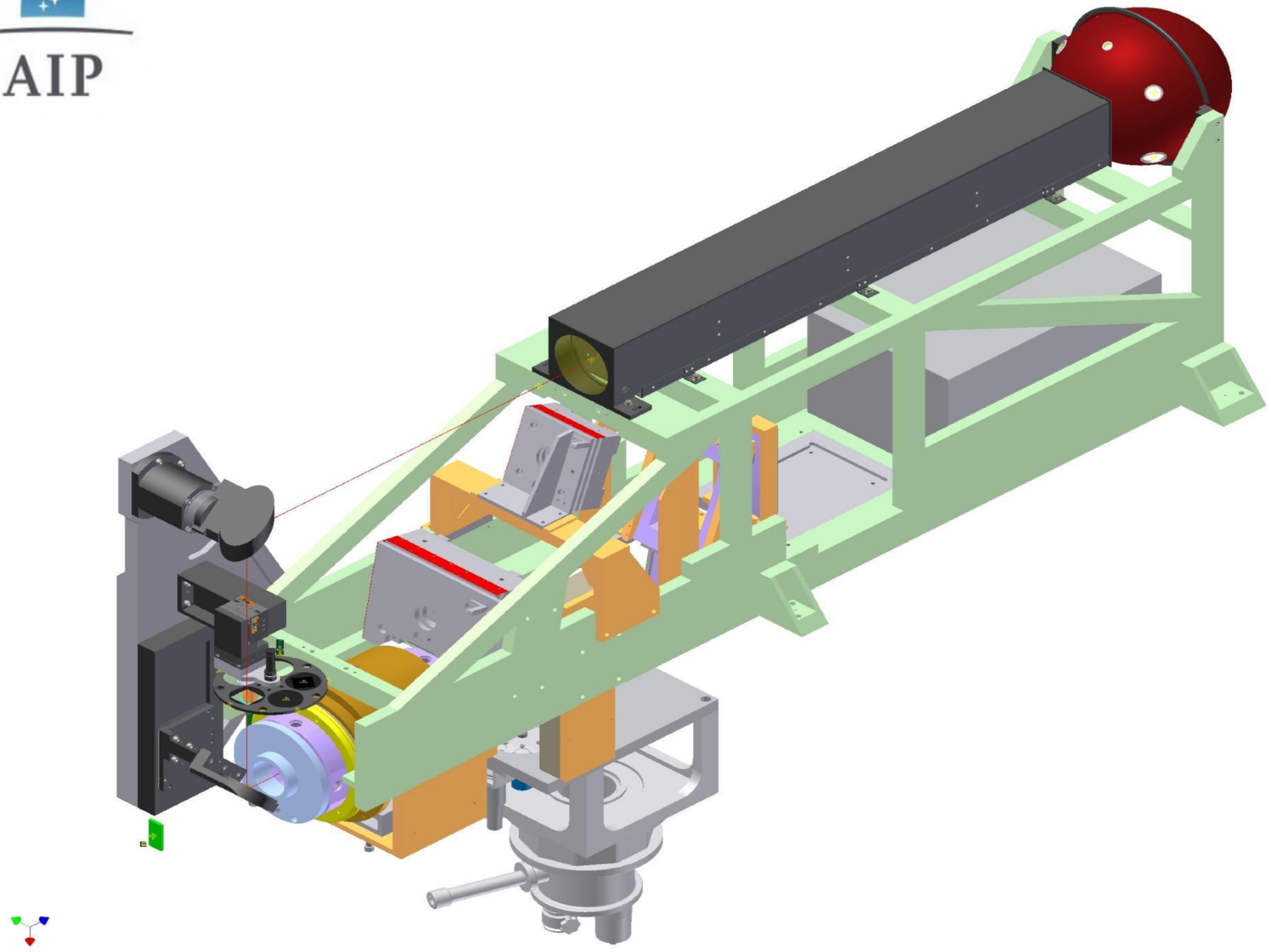
System architecture



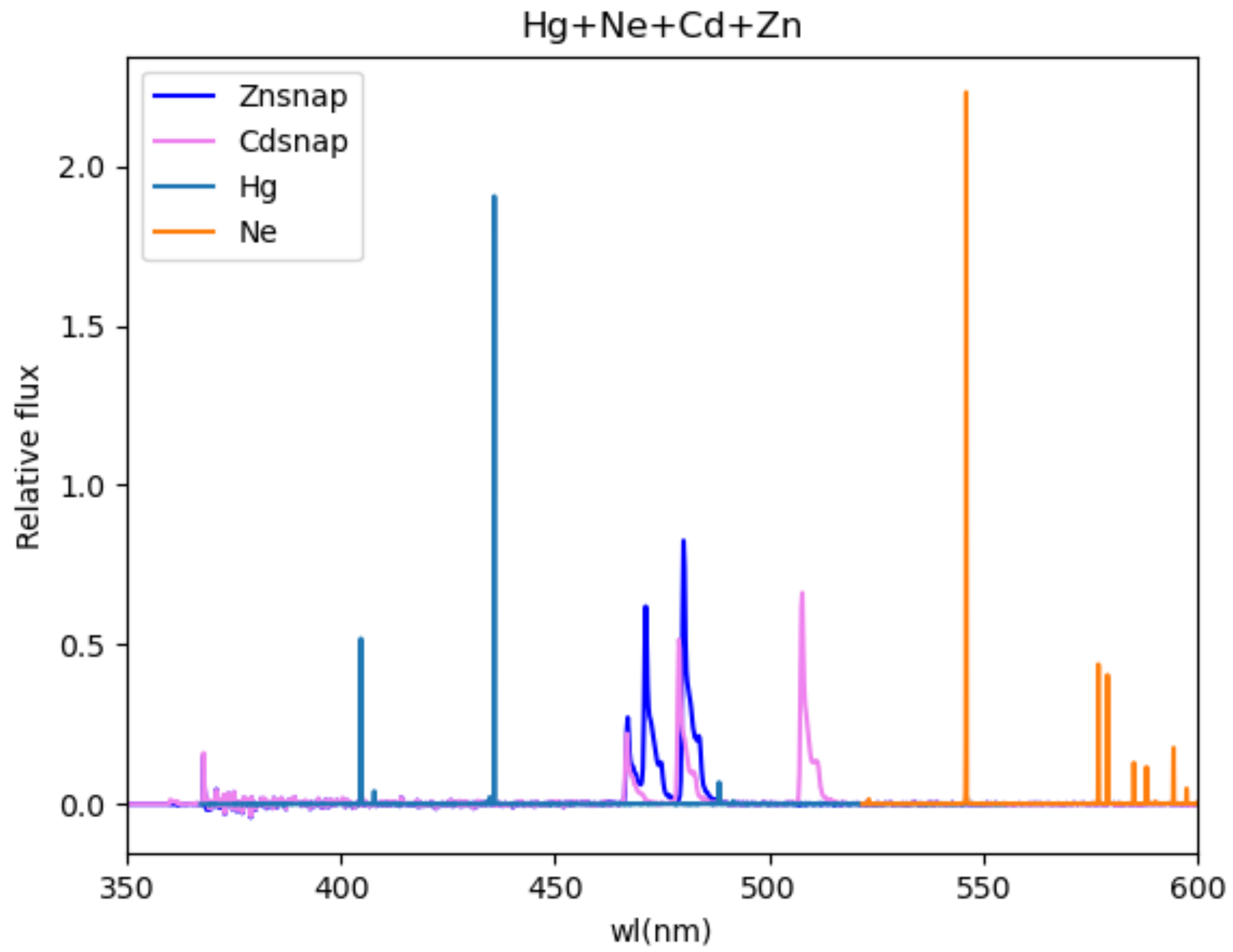
System breakdown

Calibration Unit

AIP



- Design based on MUSE, only little change expected.
- Challenge: getting adequate continuum and arc lamps for calibration.



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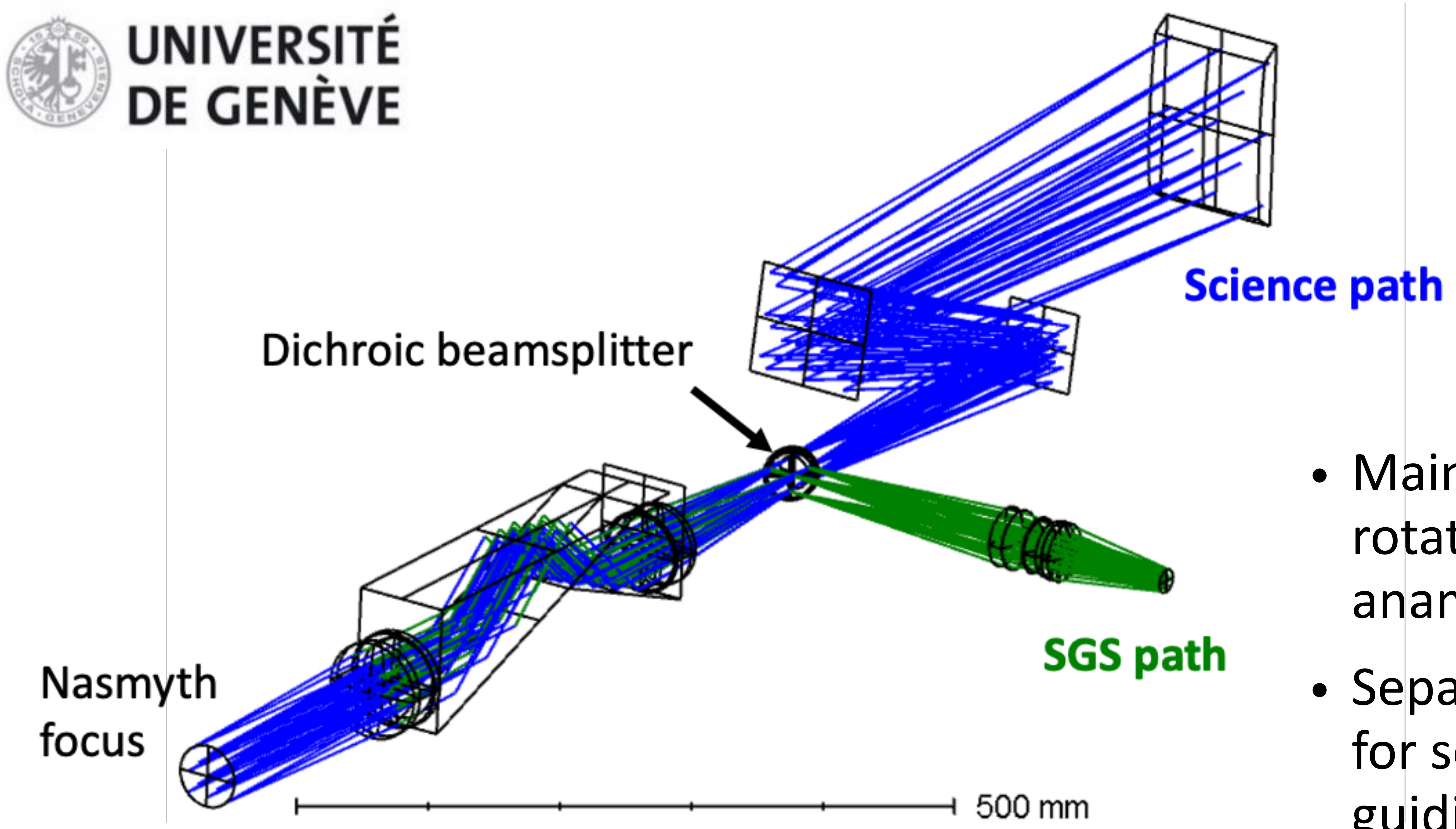
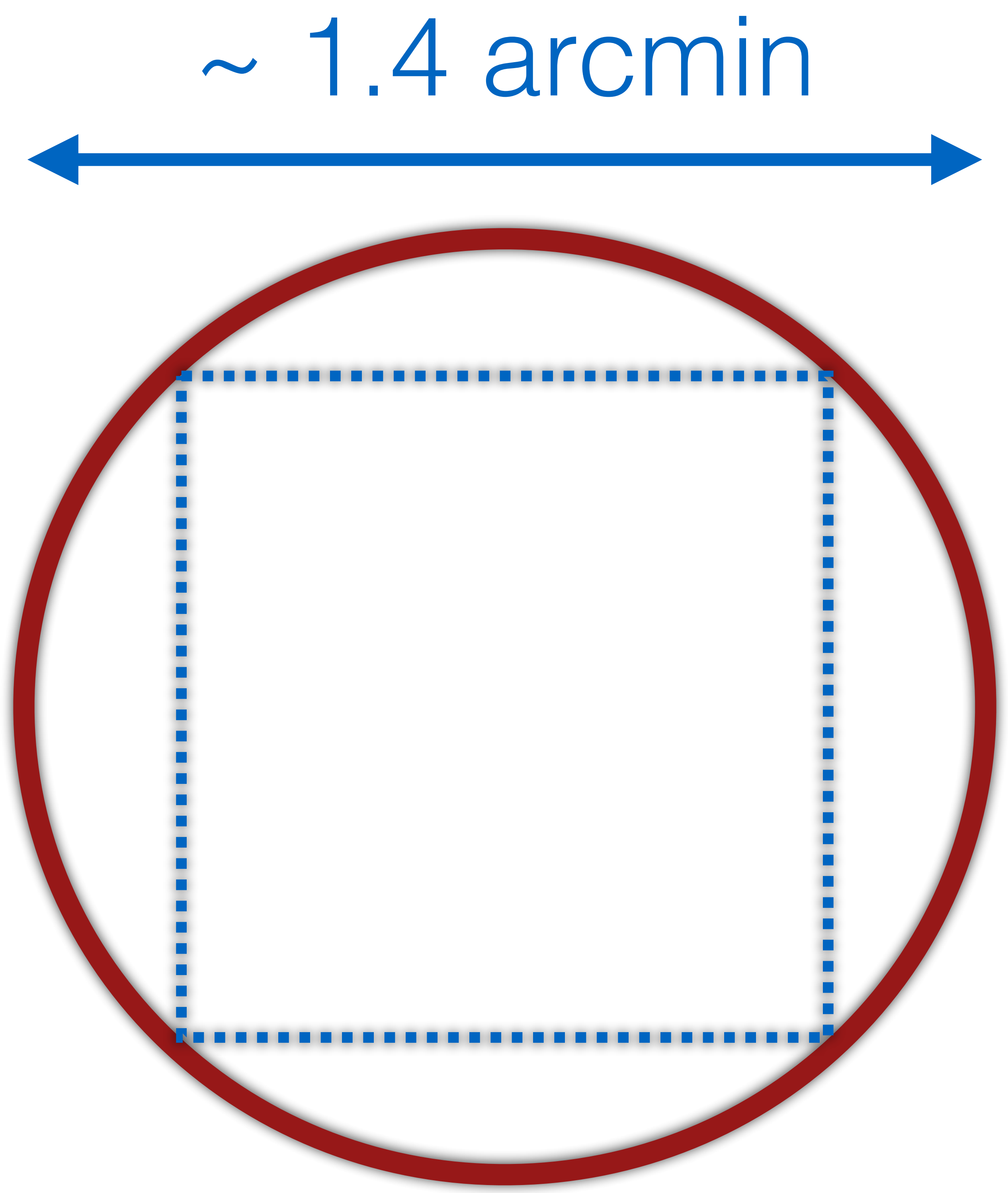
Fore-Optics



- Main functions: stabilise the field rotation and provide the correct anamorphosis / aspect ratio
- Separate a green path (> (600 nm) for secondary monitoring / guiding.

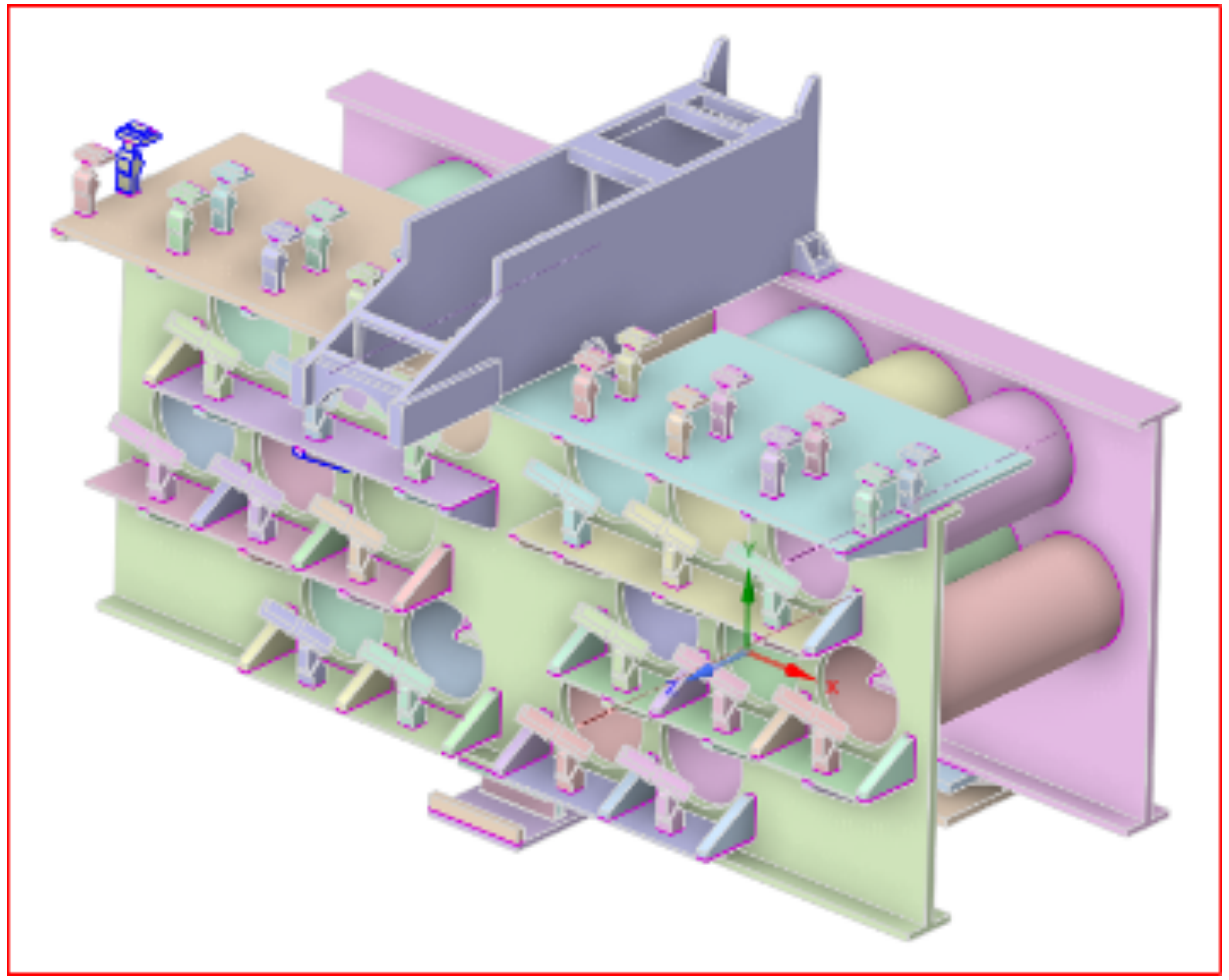
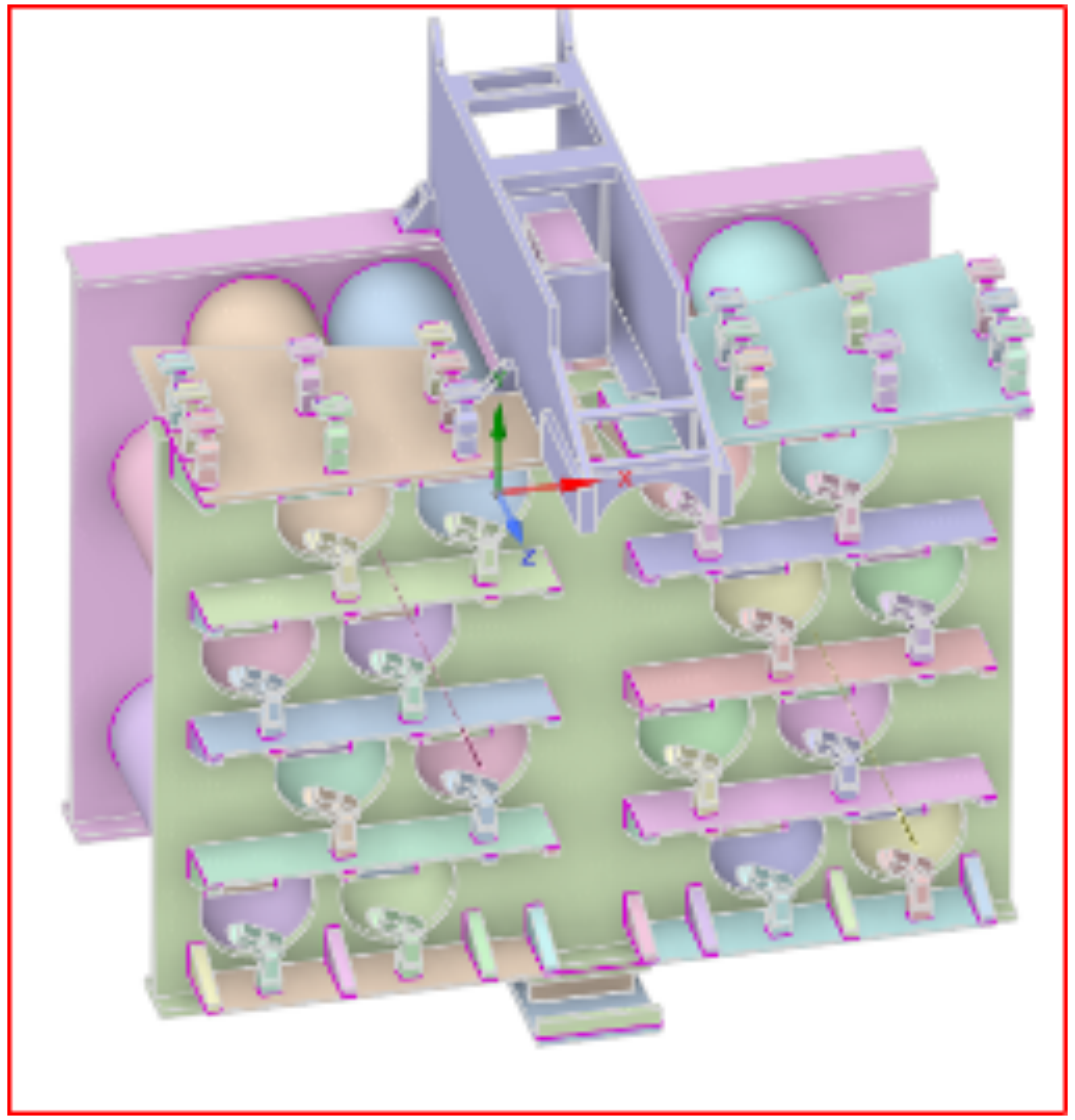
Monitoring camera / guiding system

UNIVERSITÉ DE GENÈVE



SGS	Specification	Comment
FoV	1.57 arcmin^2	1 arcmin^2 science FoV + 0.57 arcmin^2 “bananas”
Sampling	0.175 ”/px	0.0875 ”/px with 2 x 2 binning
Wavelength range	600 – 725 nm	R band
Transmission	80%	Nasmyth focus to SGS detector (included)
Exposure time	1 s	
Limiting AB magnitude	**20**	**R band** **SNR = 35 in 1.05 x 1.05” (6 x 6 px)**
Frame rate	> 0.1 Hz	5 s readout per frame

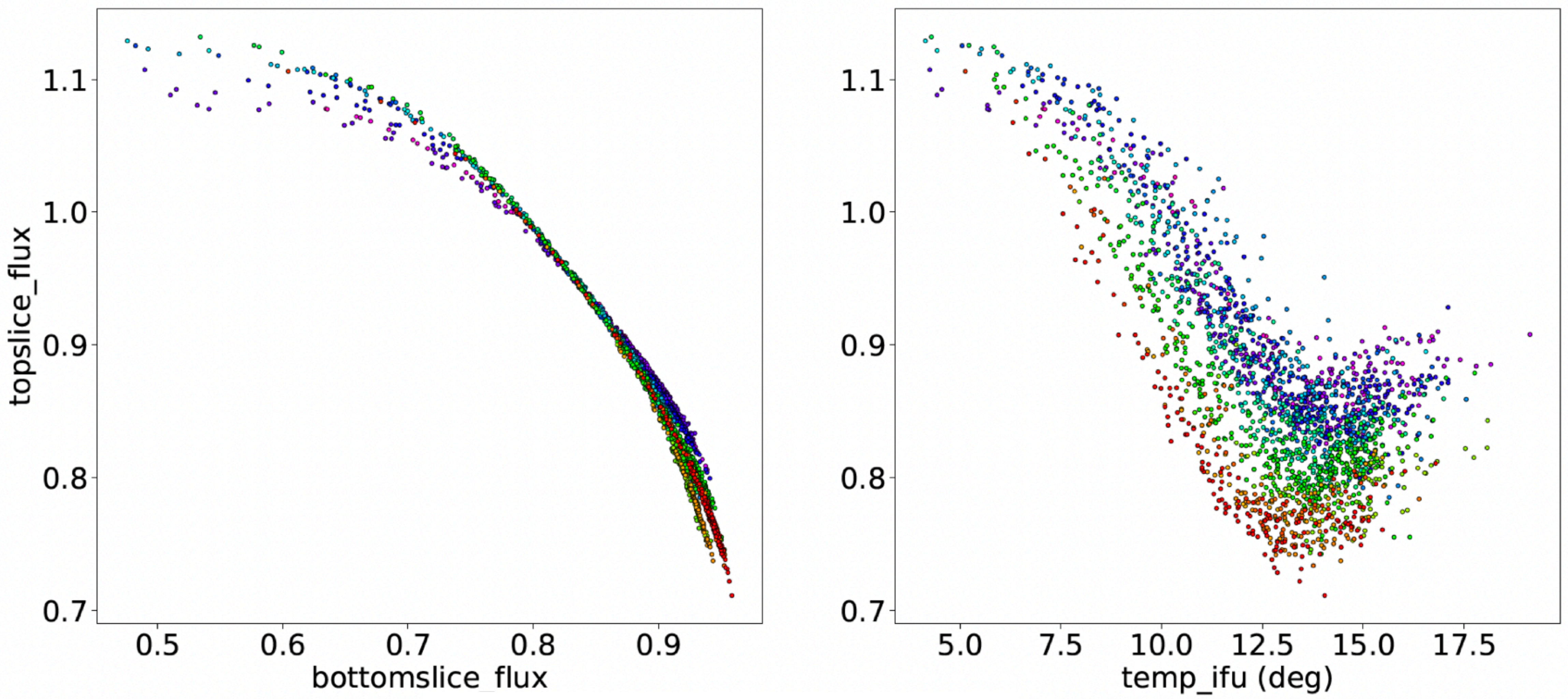
Structure and IFU organisation

- The BlueMUSE square FoV is divided into 16 rectangular sub-fields (~ 60" x 3.75")
- (long) optical relays feed light into 16 IFUs / modules
- Close link with the overall structure: ongoing work on architecture.

Stability

- MUSE has a significant sensitivity to ambient temperature
- We are studying different techniques to reduce this sensitivity for BlueMUSE, including:



(a) improvement on structure and possible thermal enclosure

(b) automatic adjustment of optical relays

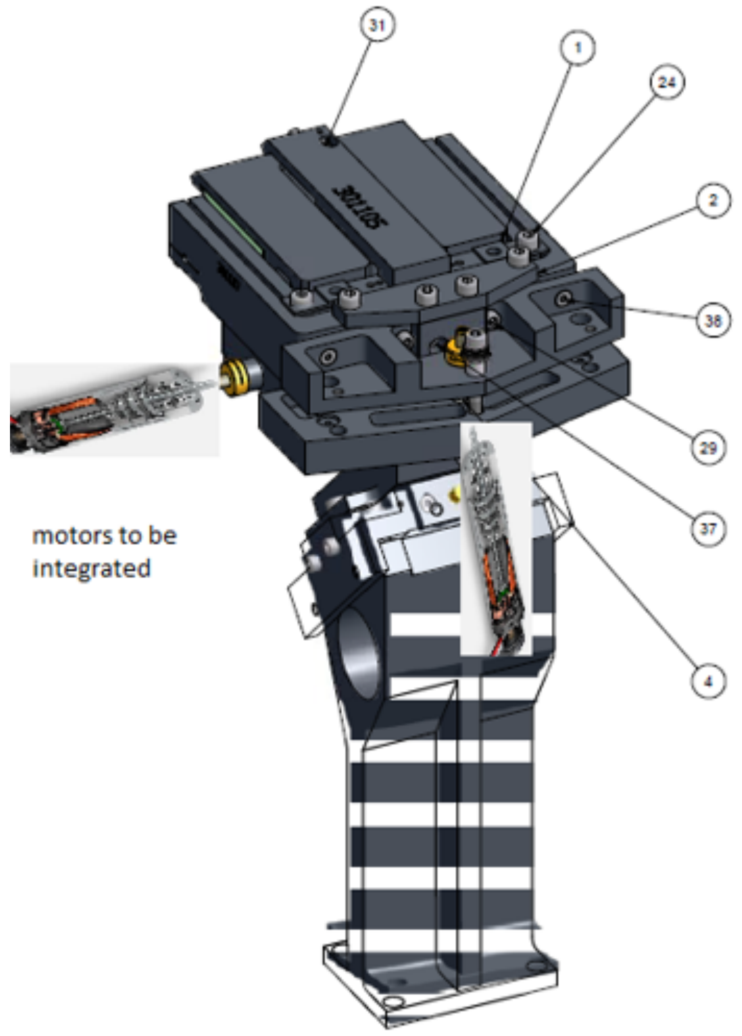
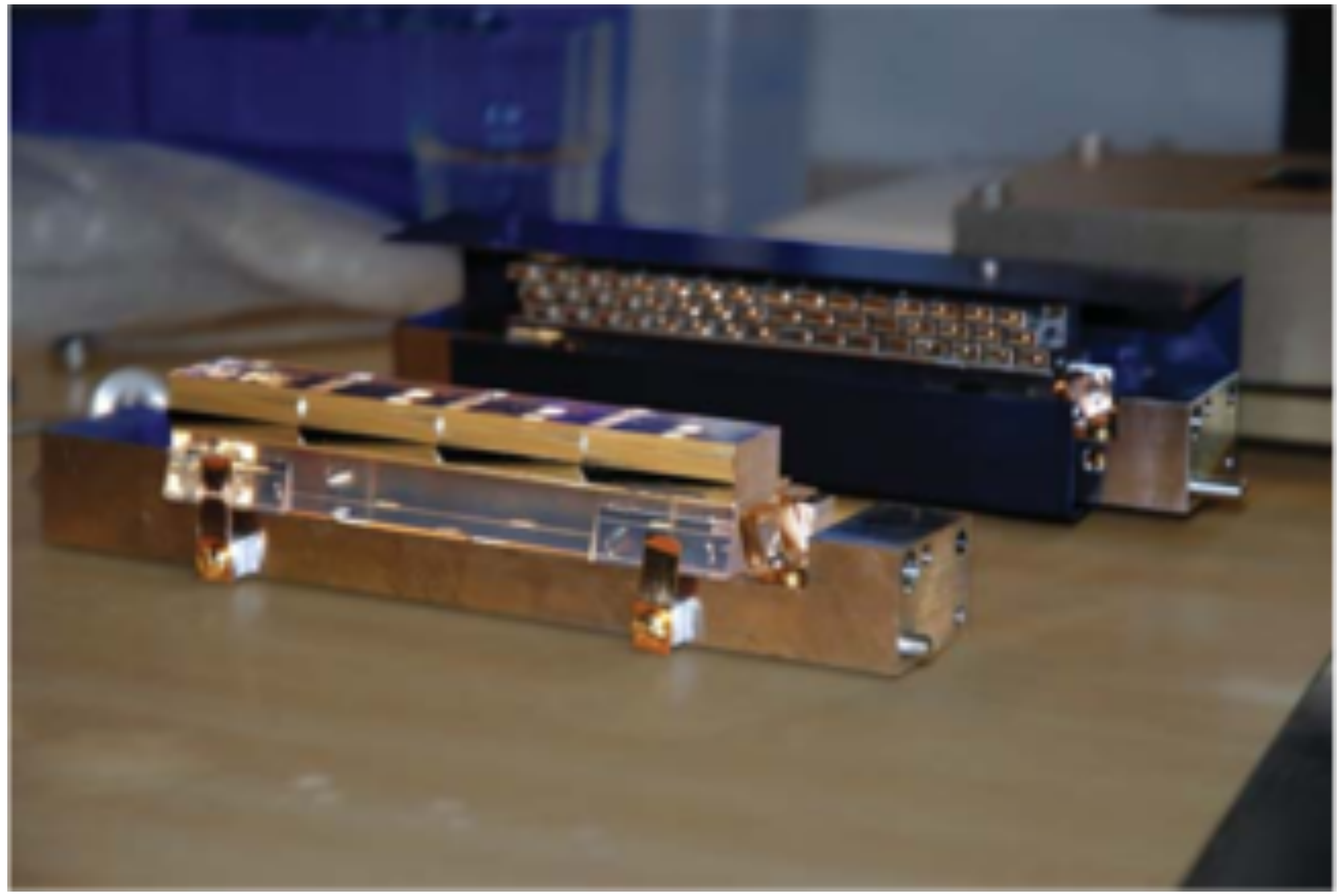
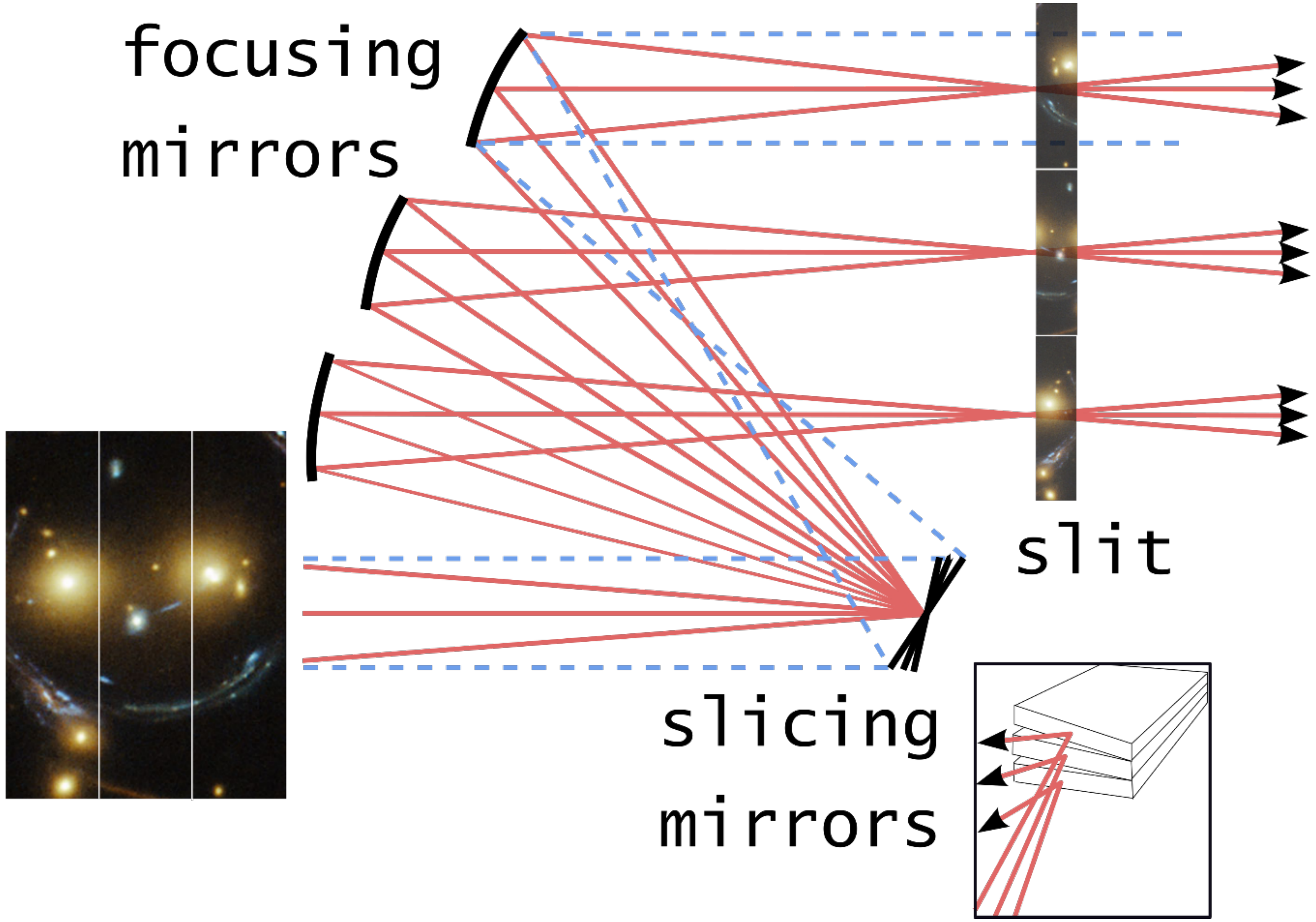


Image Slicer

- Transforms a rectangular FoV in a series of mini-slits, re-arranged along a pseudo-slit located at the entrance of the spectrograph
- Mirror-based (two 48-mirror arrays)
- Input and Output Telecentric

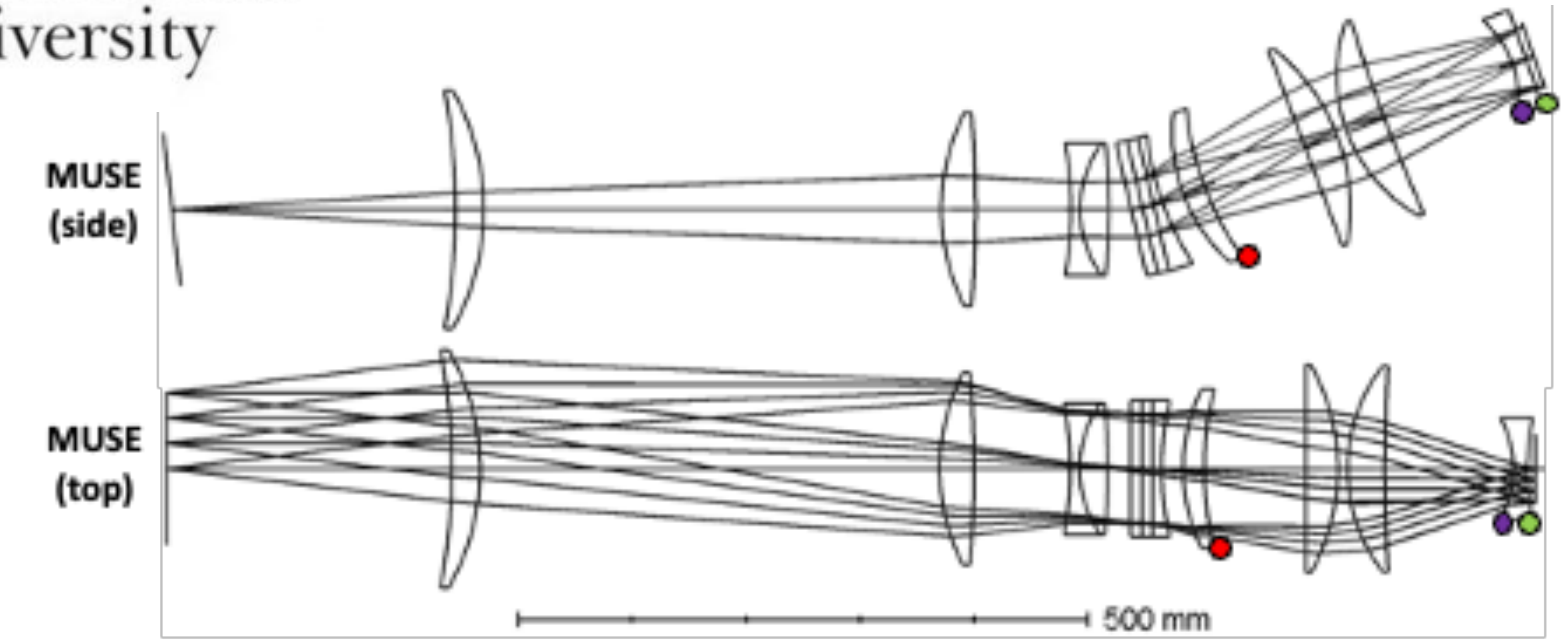


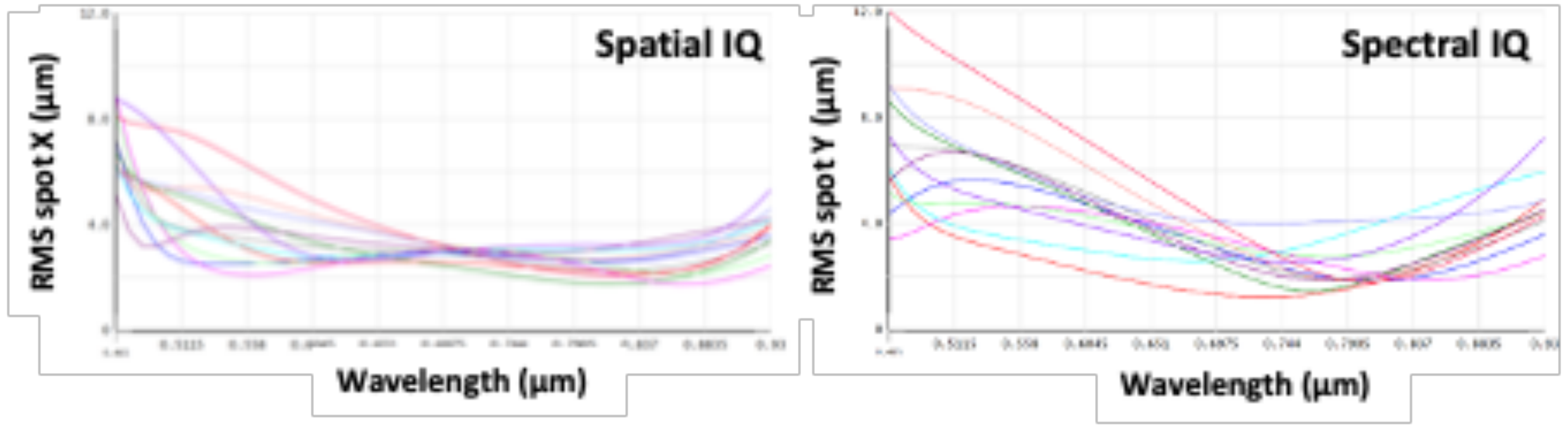
The MUSE Image Slicer



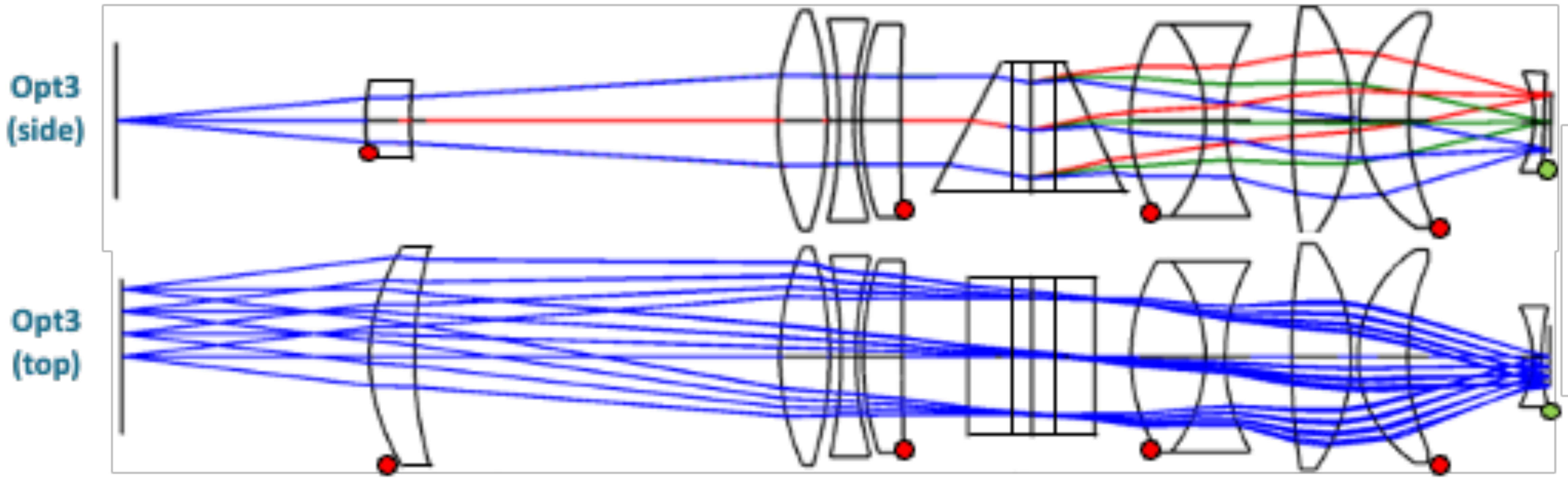
Spectrograph

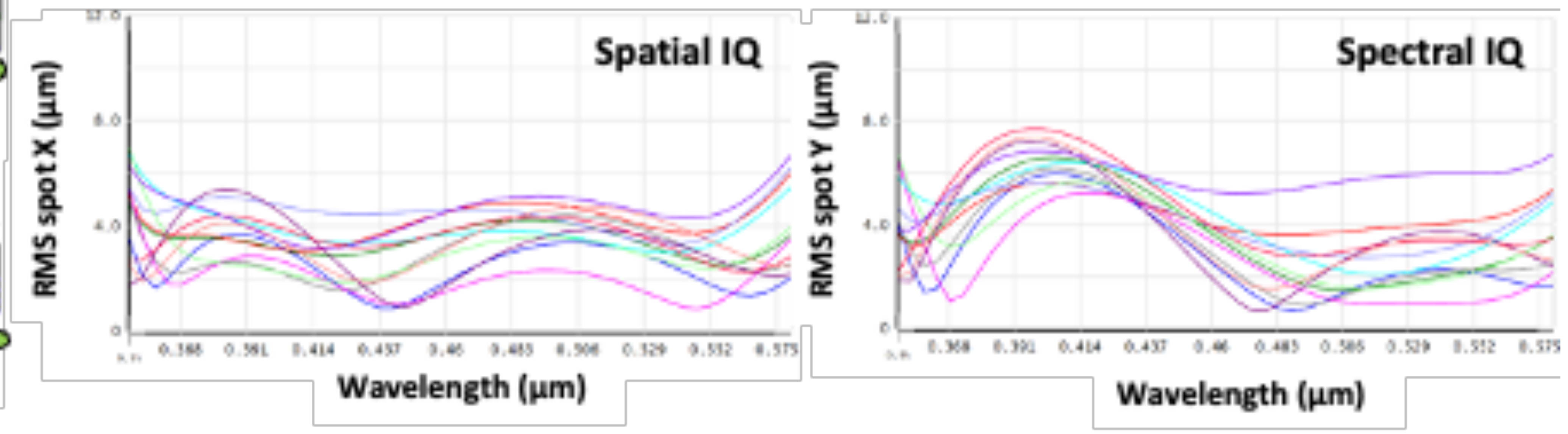
Optical Design





Transmission (99.0% coatings / excl. VPHG): **78.5% @465 nm**





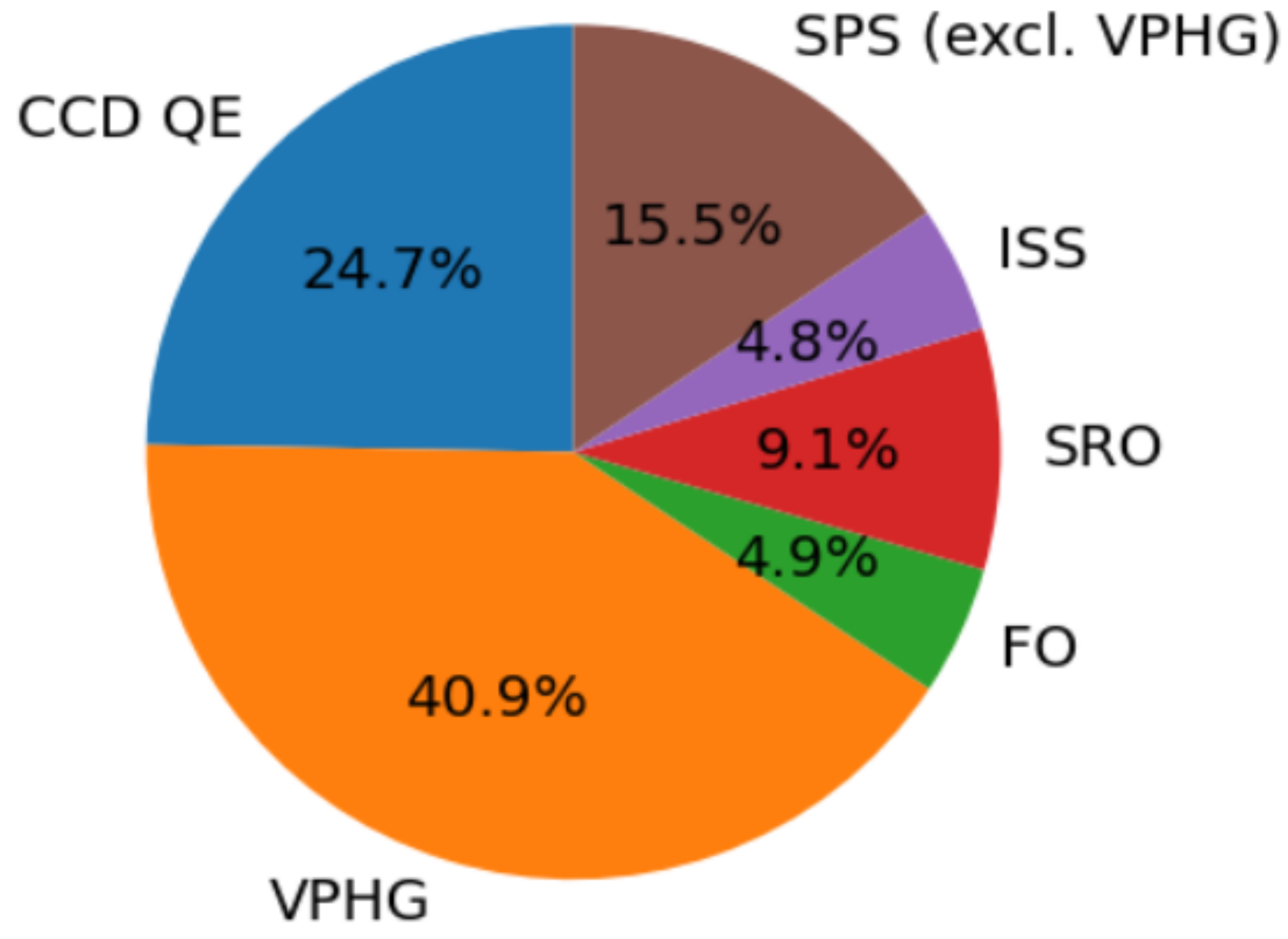
Transmission (99.0% coatings / excl. VPHG): **76.8% @350 nm**

- even asphere (red)
- cylinder (green)
- conic (purple)

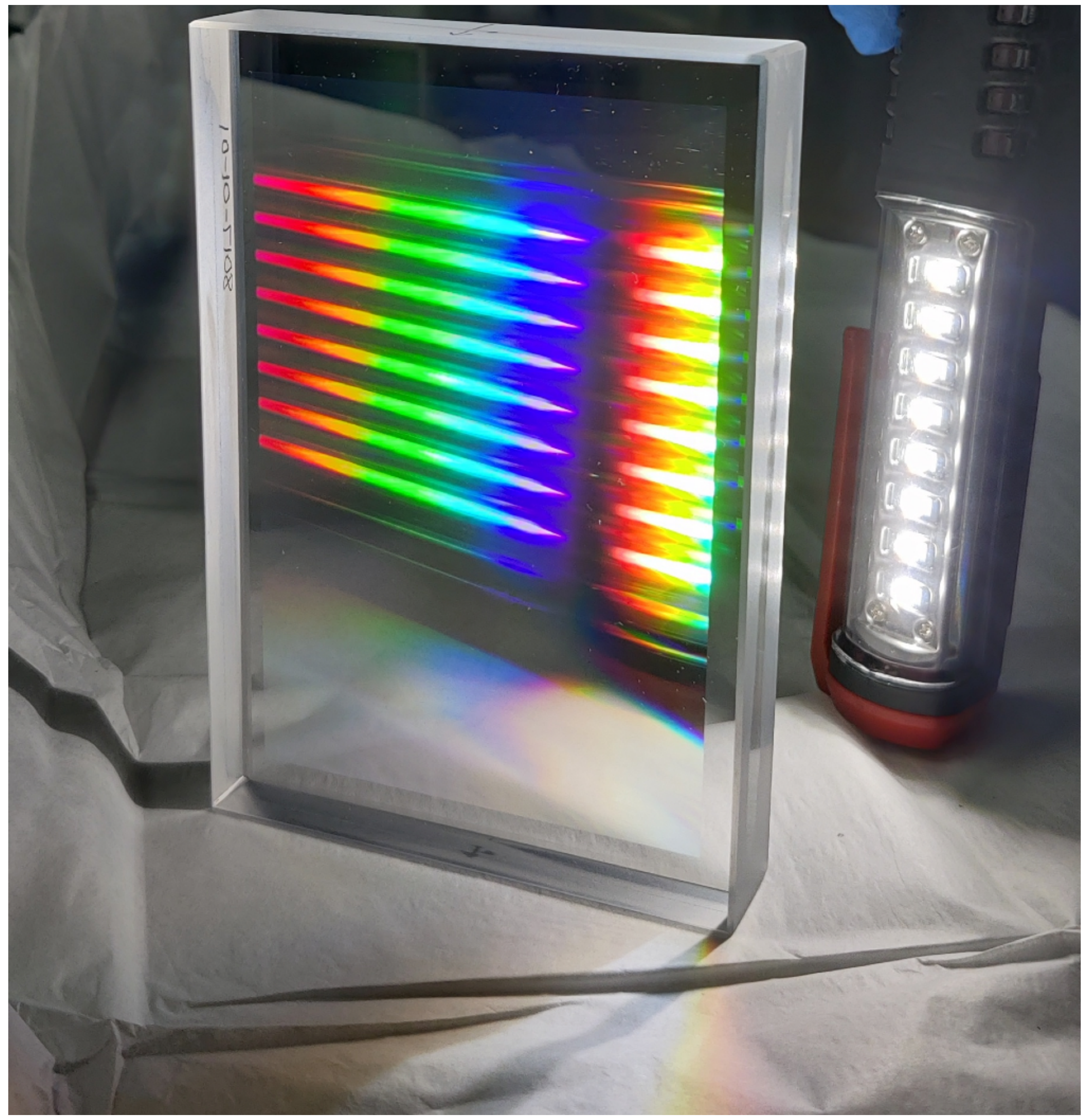
Spectrograph

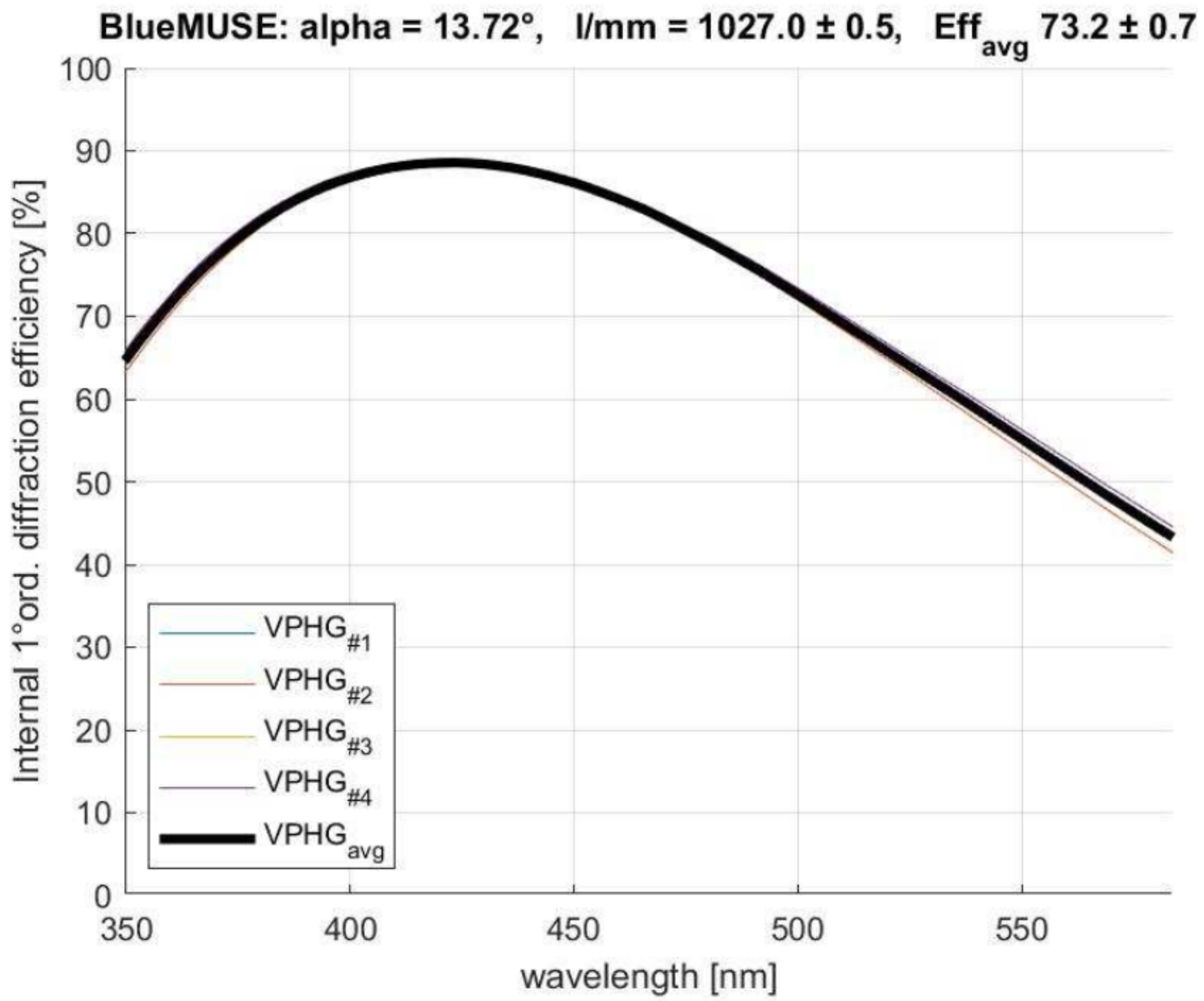
Challenge: high transmission at blue wavelengths

- Everything drops in transmission below 370 nm:
  atmosphere, telescope, most glasses, grating, CCD ….
- Importance of VPH grating: first prototypes received and tested!



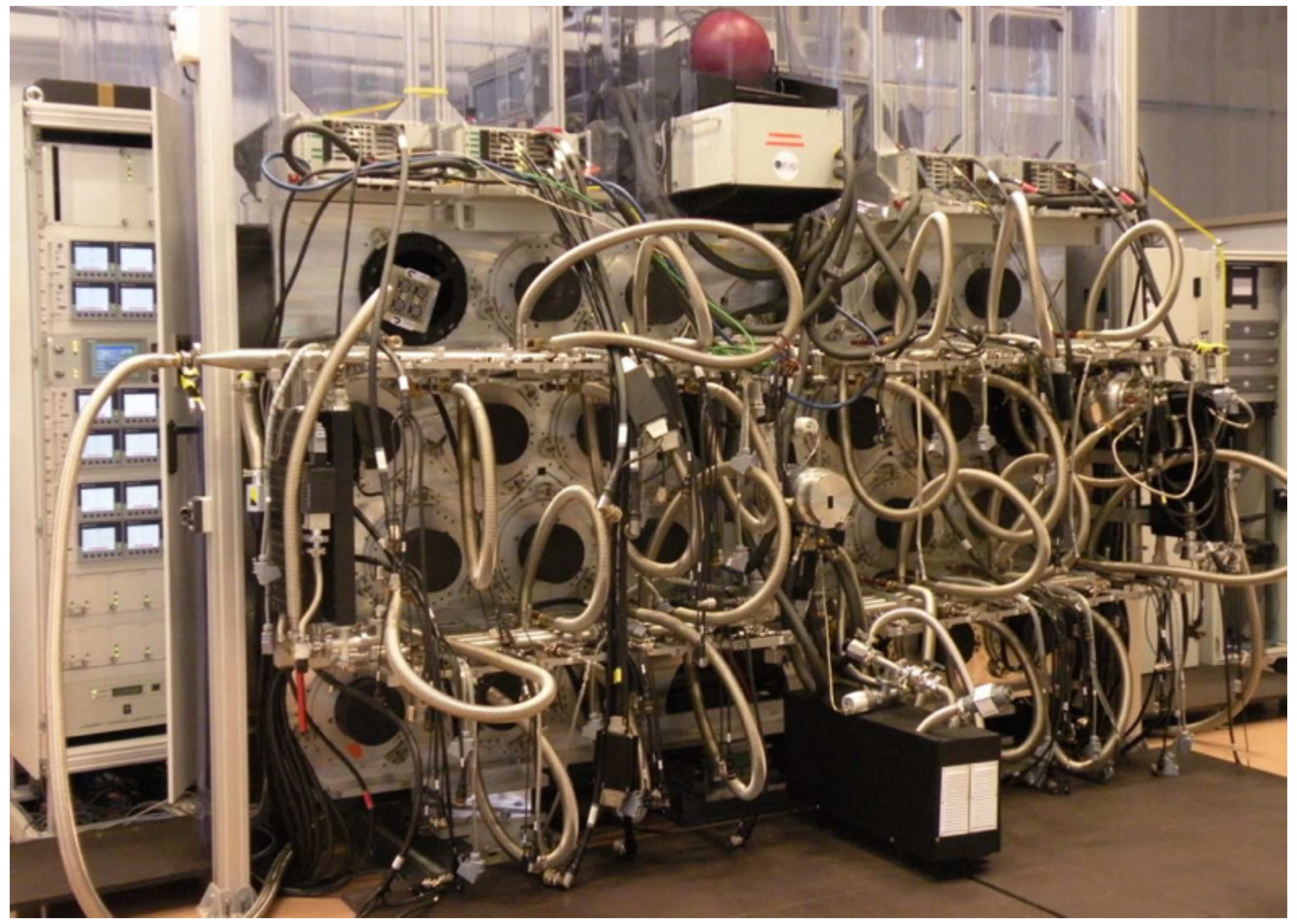
at 350 nm



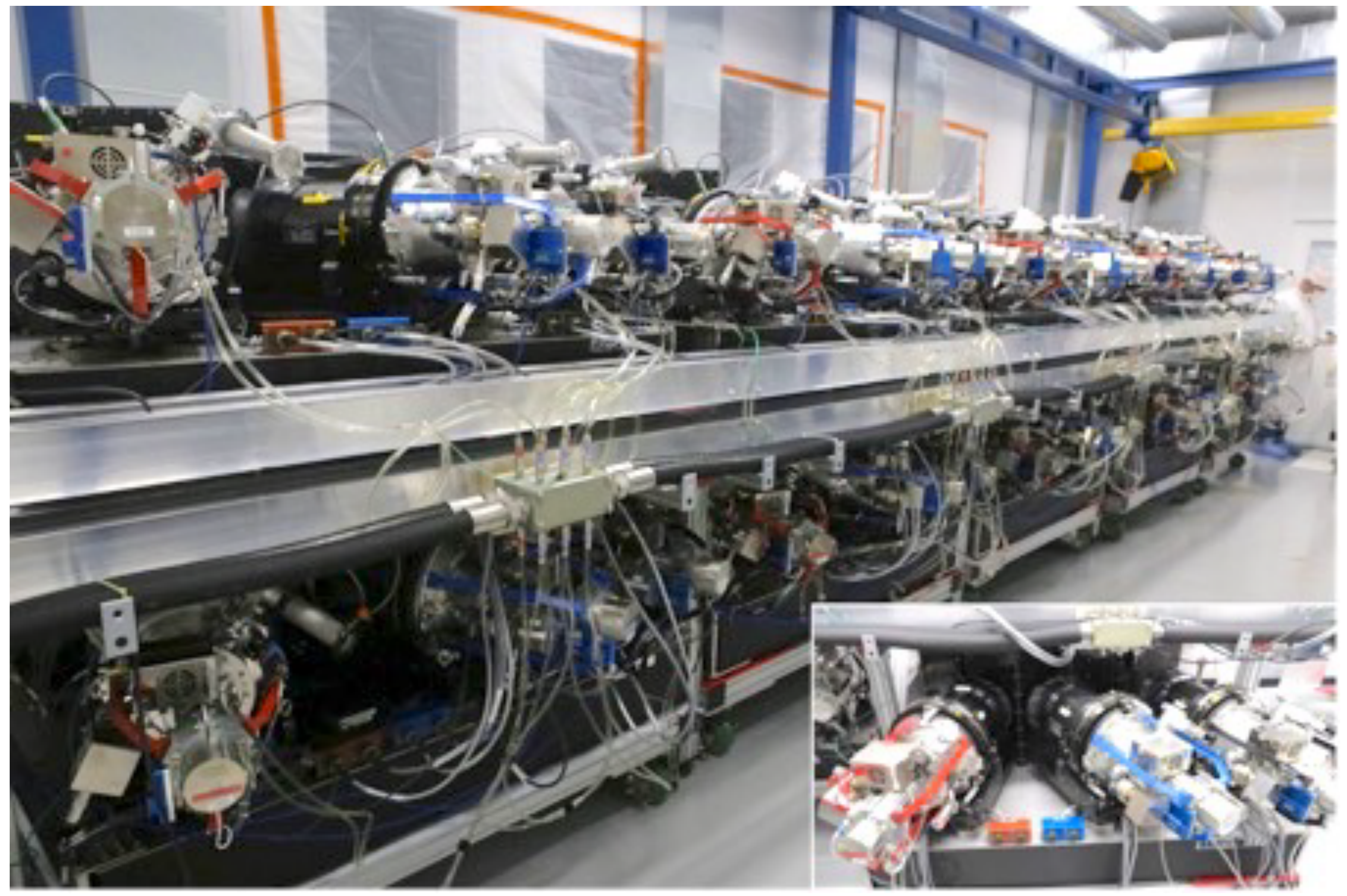


Detector / Cryogenics

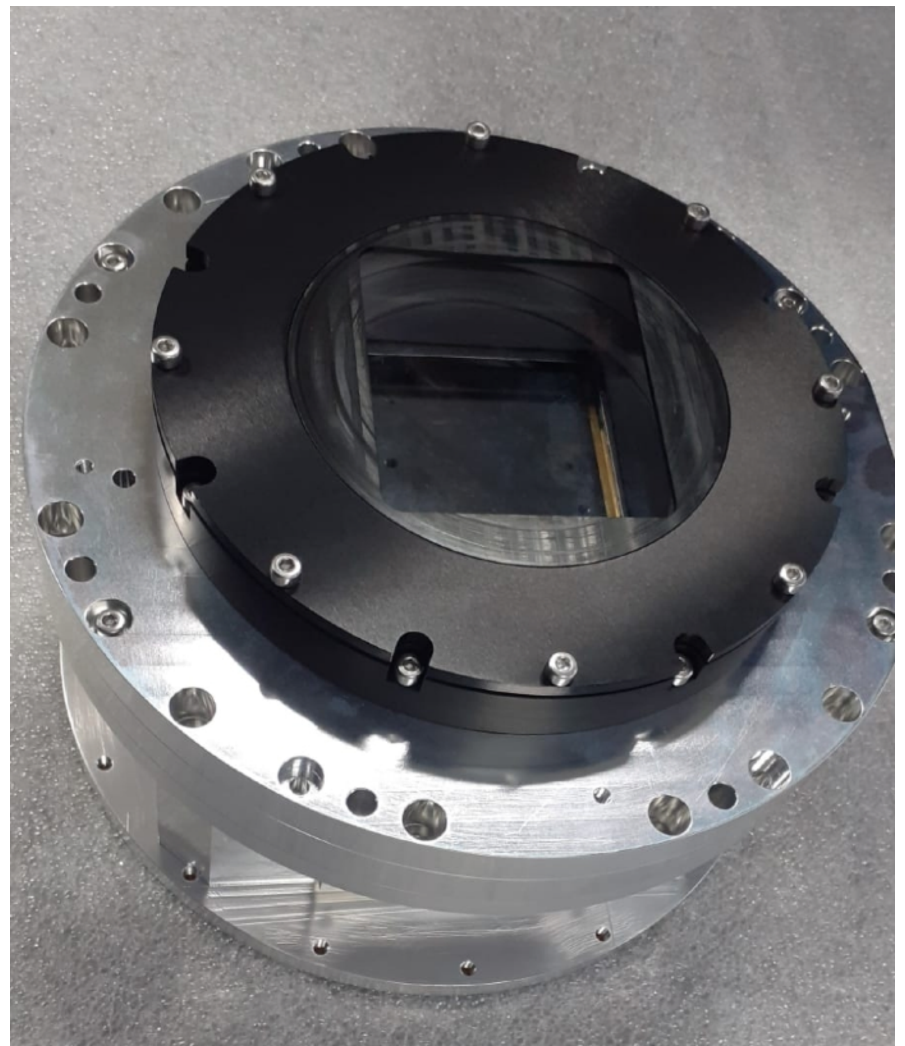
- MUSE used CFC design with liquid nitrogen.
- Current study for BlueMUSE: pulse-tube technology based on DESI design.

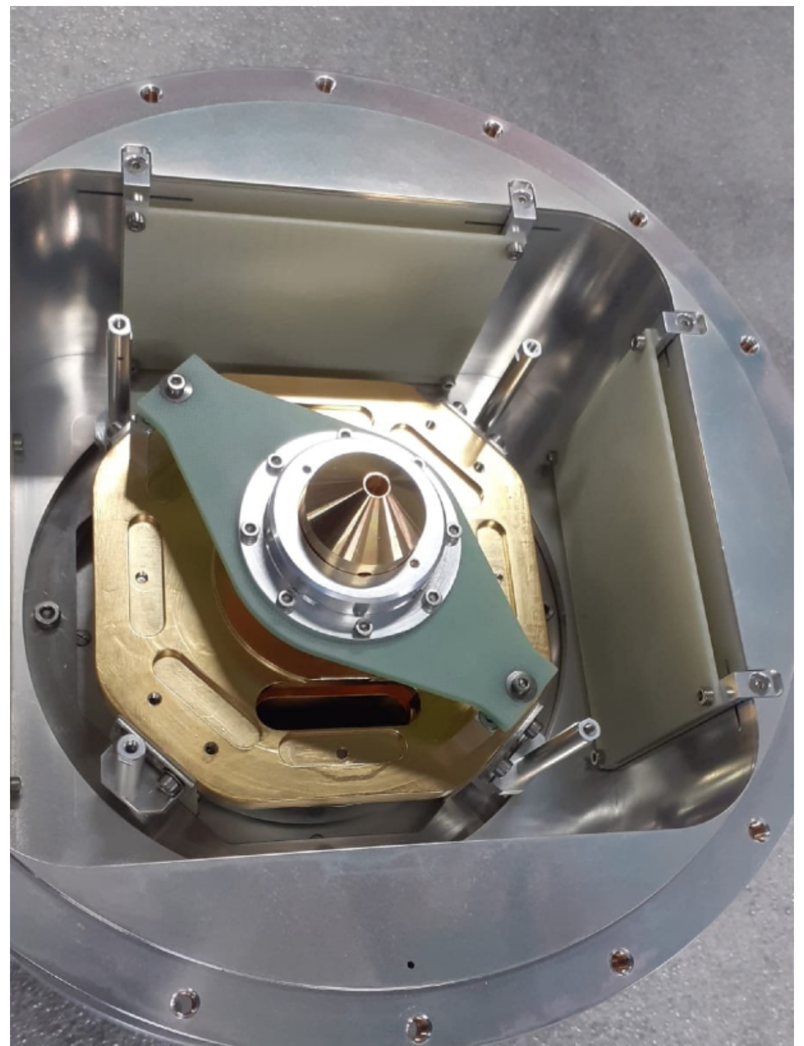


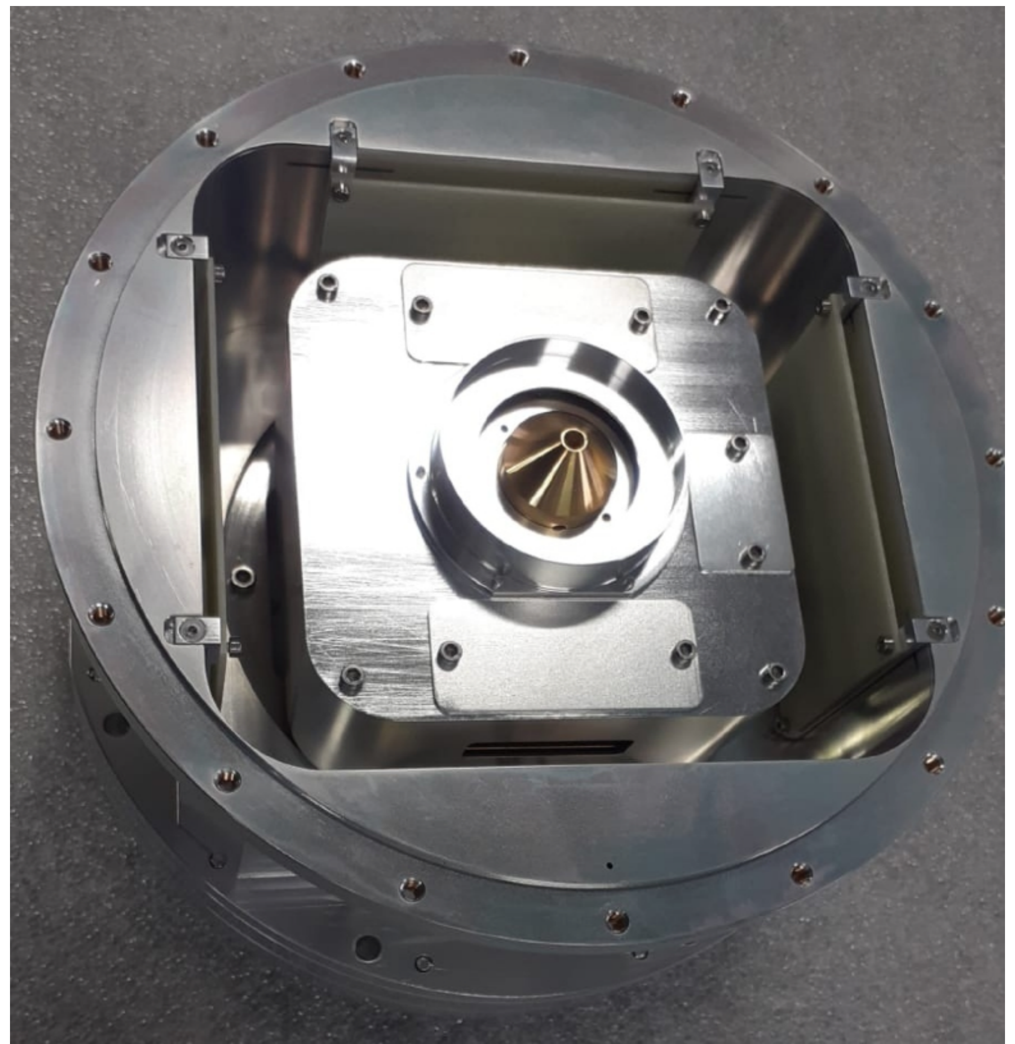
MUSE VCS



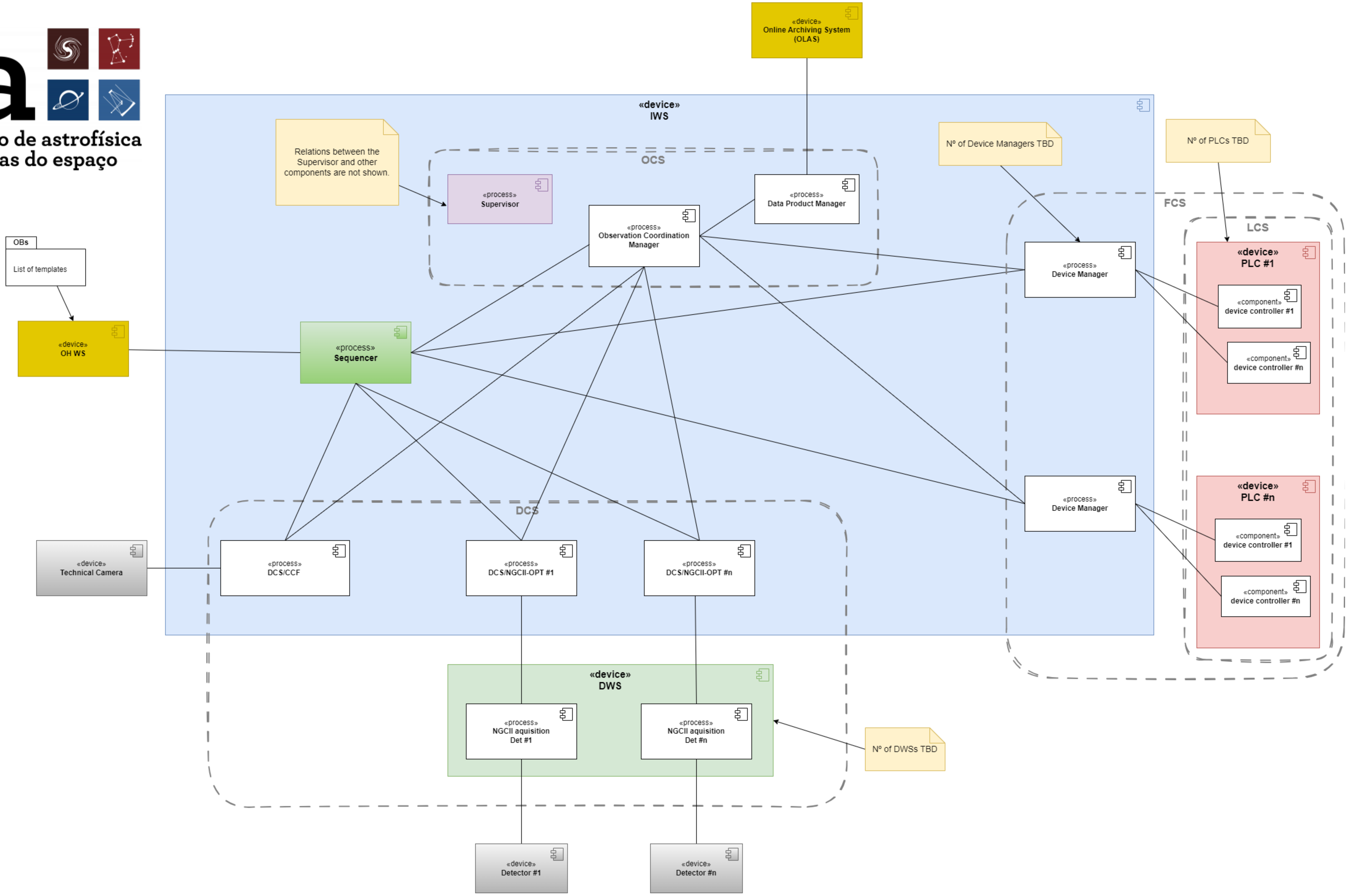
DESI cryostats







Control Software and electronics



- Only 1 mode compared to MUSE, but possible automatic realignments.
- Ongoing work on architecture design, needs to abide by the ELT framework.

Science Software

Data Reduction Software (DRS):
General philosophy followed from MUSE data reduction software

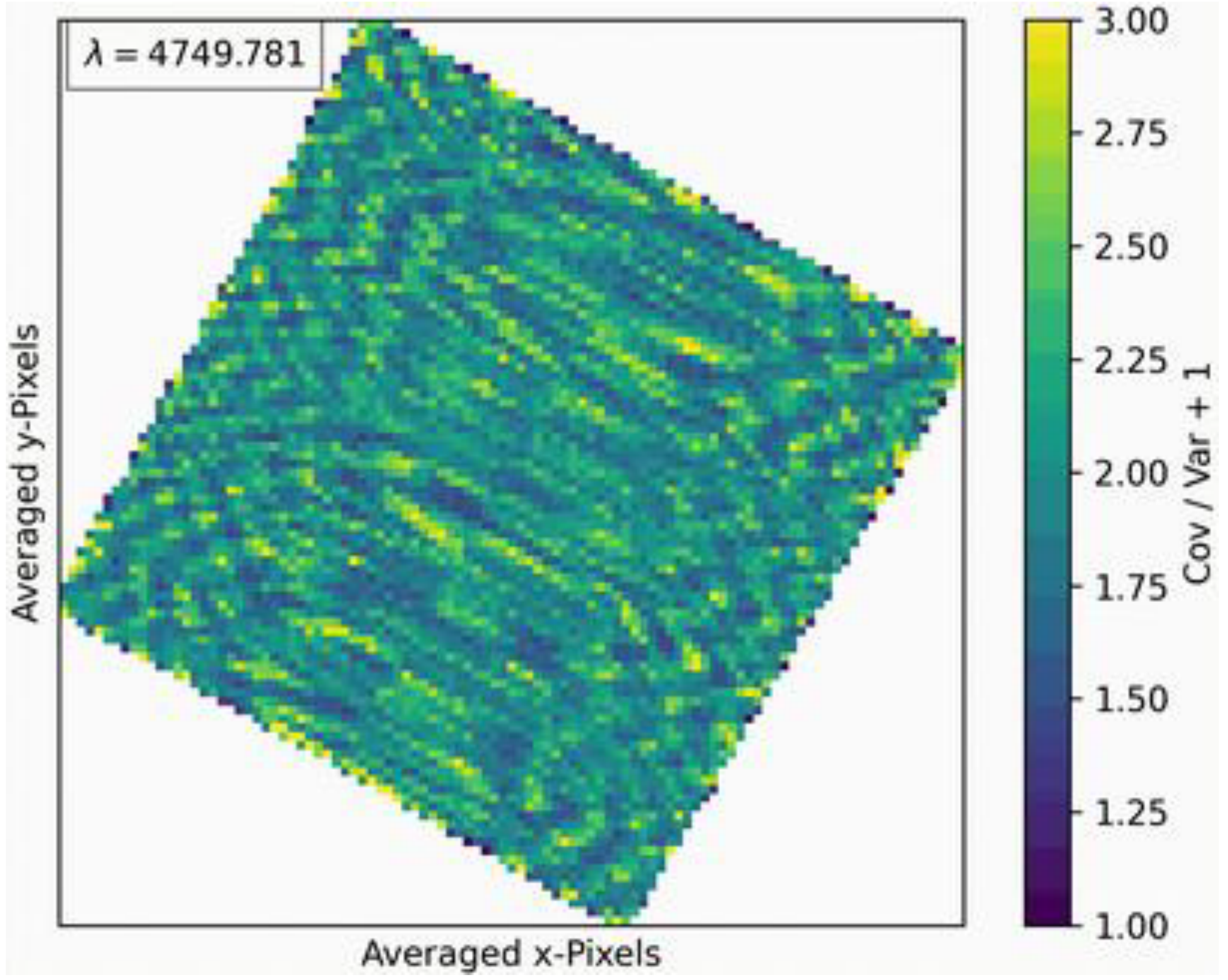
- propagate detector pixel information (and associated variance) until the very last step of reduction - single step interpolation into a data cube.

Rectangular spaxels

Interpolation steps need to be updated to account for field rotation with rectangular spaxels (current simplification in MUSE pipeline). Mostly a challenge on speed / accuracy.

Covariance propagation

Covariance propagation as an improvement for more accurate error estimates. - under investigation.



LSF propagation

Propagation of more precise LSF estimate through the reduction, together with final data cube.

BlueMUSE and MUSE combination

The BlueMUSE instrument shall be supported by a Data Flow System and a Data Reduction Software (DRS) providing science-grade data products as defined in AD5. **The data provided by the BlueMUSE shall allow the combination with MUSE data during data reduction process.** The DRS shall enable the processing of the 'Extended wavelength range'. The data products are in physical units and information on signal, error and data quality is provided as a minimum.

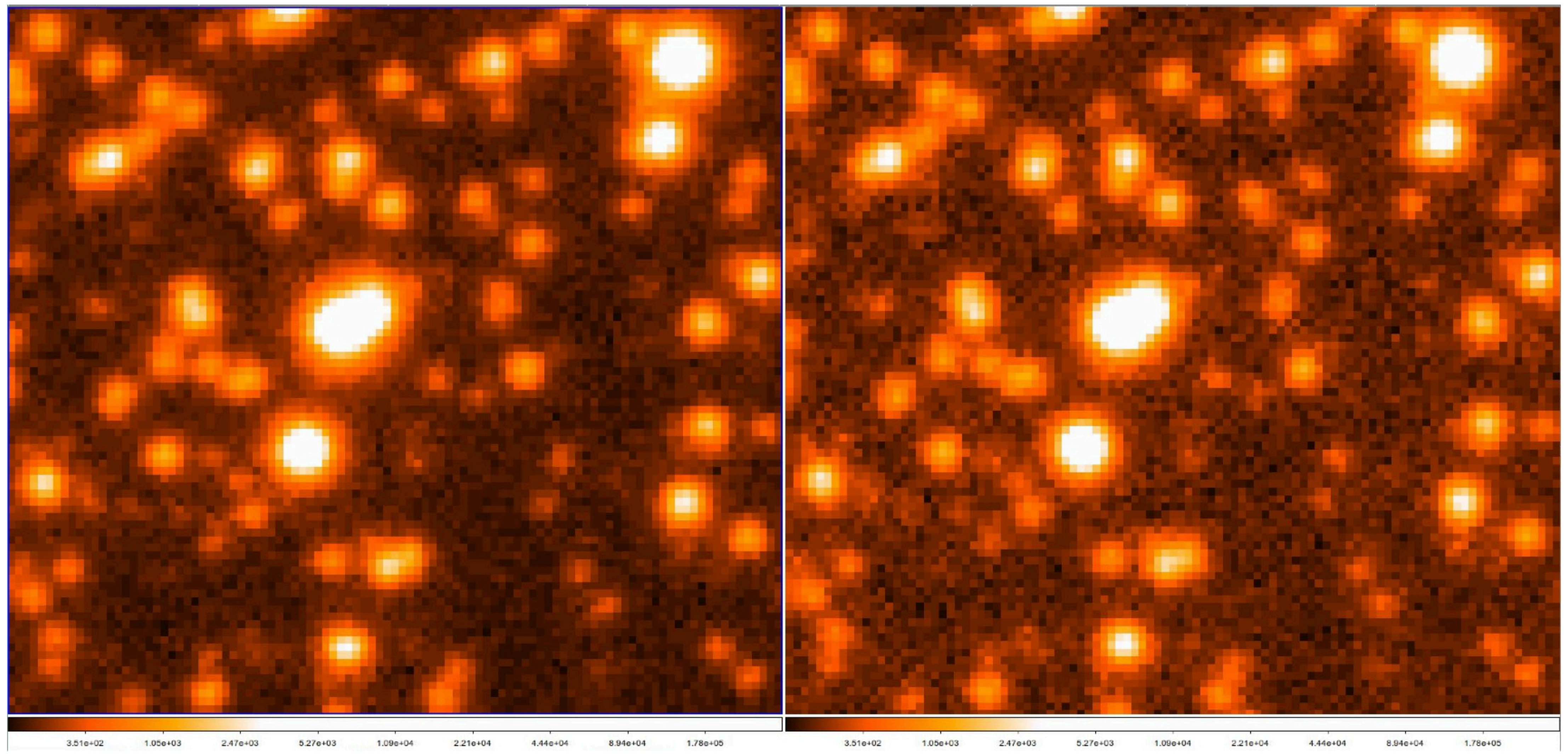
- Need to clarify what is (1) meaningful (2) useful to science users
- BlueMUSE pipeline could ingest (only calibrated) MUSE pixel tables for combination
- However: strong differences in LSF, spatial PSF. How about the overlap region (480-580nm)?

BlueSi

BlueSi is a software tool to produce (idealised) BlueMUSE data cubes from astrophysical scenes:

- reproduce some of the effects (PSF, LSF, transmission, idealised noise)

- can be used to test performances
- can be use to test the effects of rectangular spaxels

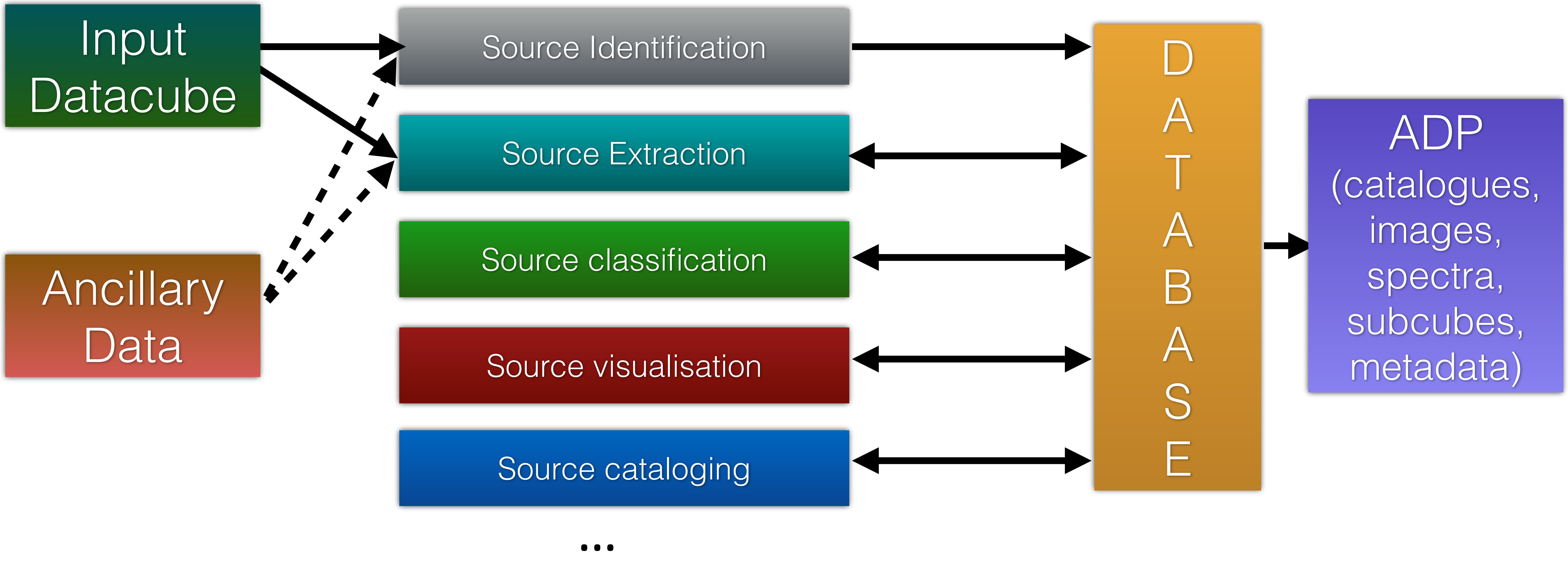


See dedicated presentation by M. Wendt and N. Castro on Thursday !

Data Analysis Software (DAS)

Software to produce advanced data products (ADP)

- Tools to help explore the richness of BlueMUSE (and MUSE) data

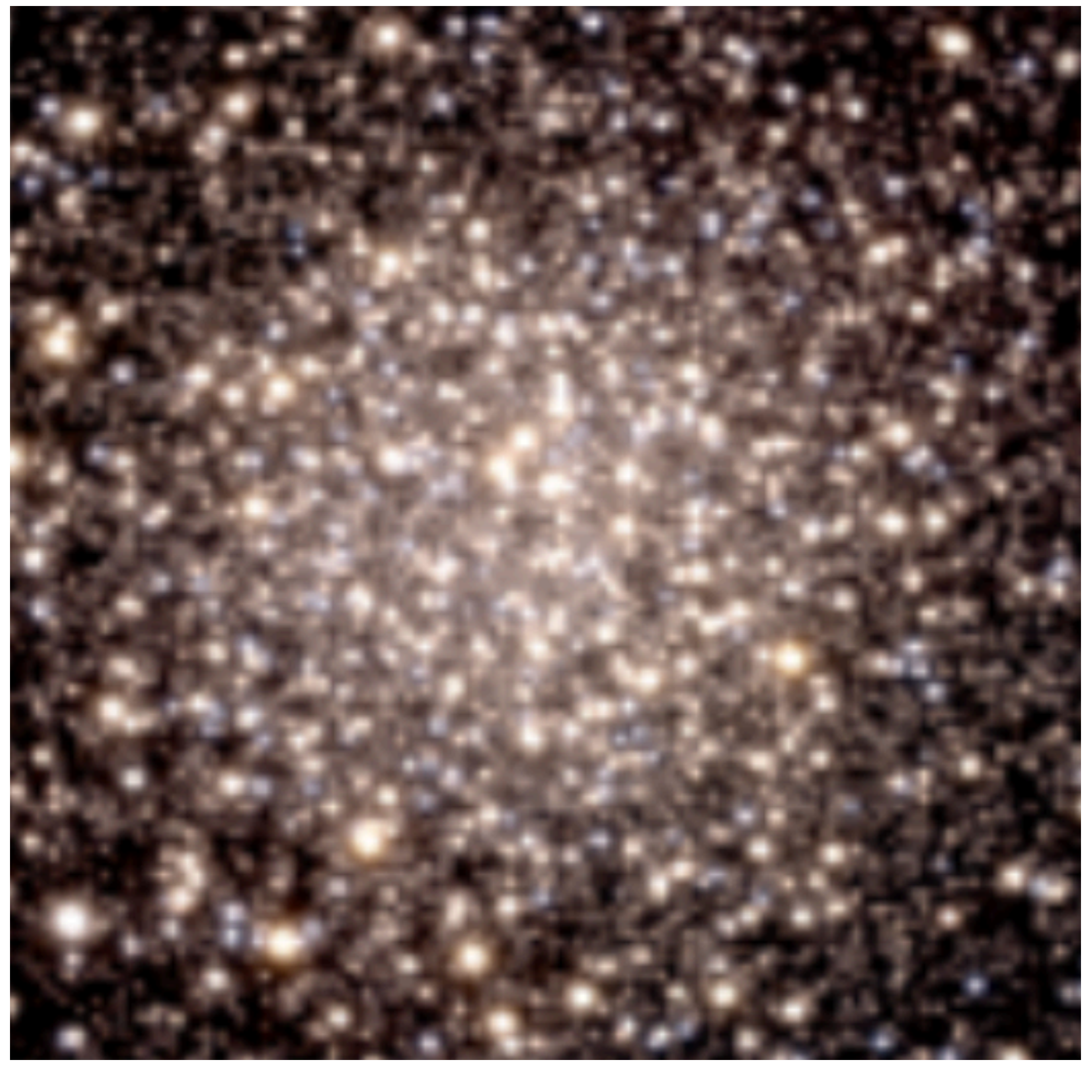
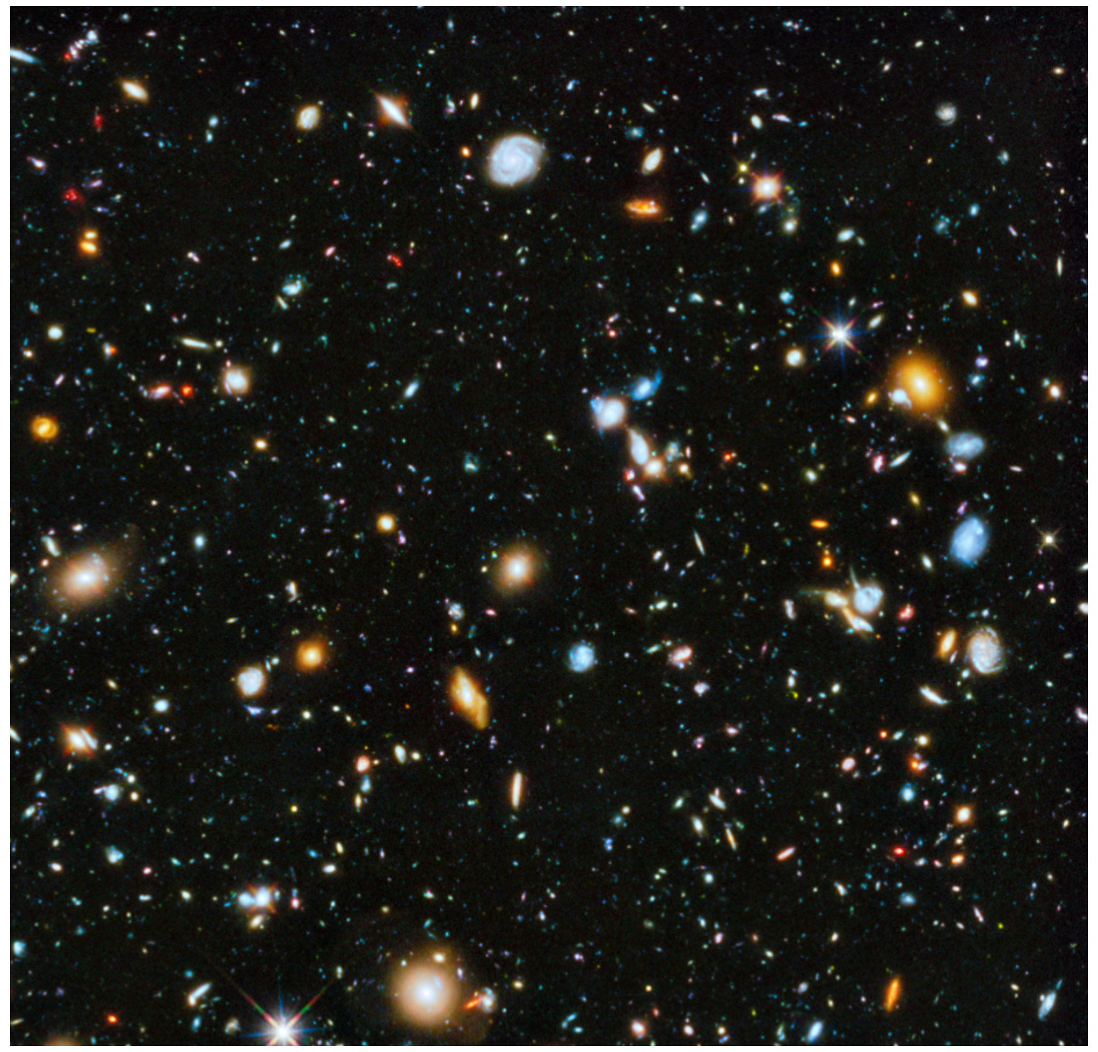
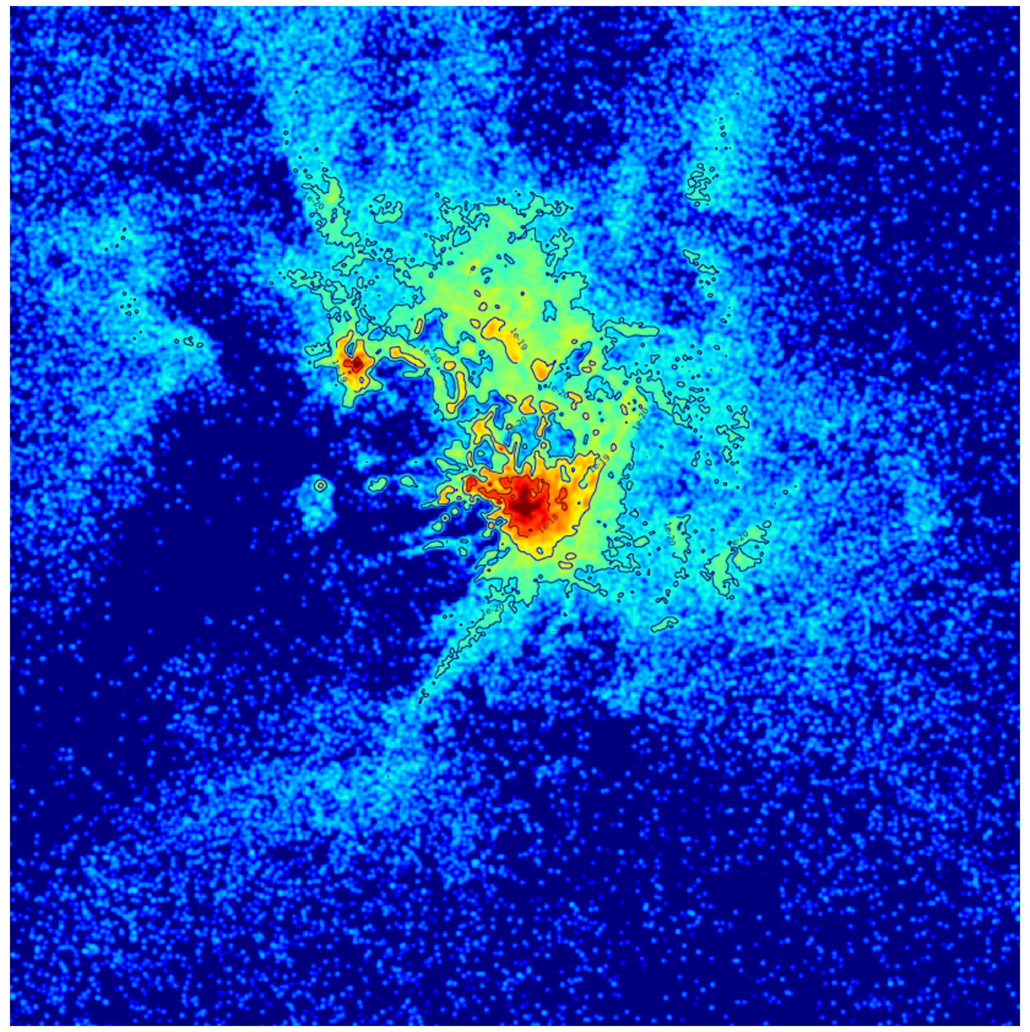


See dedicated presentation by M. Hayes on Thursday !

Conclusions

- We are just entering the ESO Phase A of BlueMUSE, we do benefit from all the previous developments and we are progressing on the prototyping activities.

- We have a first design architecture for most subsystems, one of the main activities during Phase A will be to produce the technical specifications per subsystem and ensure we are designing the right instrument to our science requirements.

Next Steps - input from science team

- On the science side the main Phase A activity is to **consolidate the science report** which is an update of the white paper accounting for the selected TLRs.

- We encourage the science team to think about possible (simple) simulations with BlueSi to test the feasibility of science cases.

- Input from the science team will also be very useful for specific activities:
  - Data Analysis Software
  - Draft of Calibration Plan and Operation Plan
  - Data Reduction System