Multi Unit Spectroscopic Explorer

Lyon

Leiden

Zurich

Potsdam

ESO

Toulouse

Göttingen

MUSE: A Second-Generation IFU for the VLT

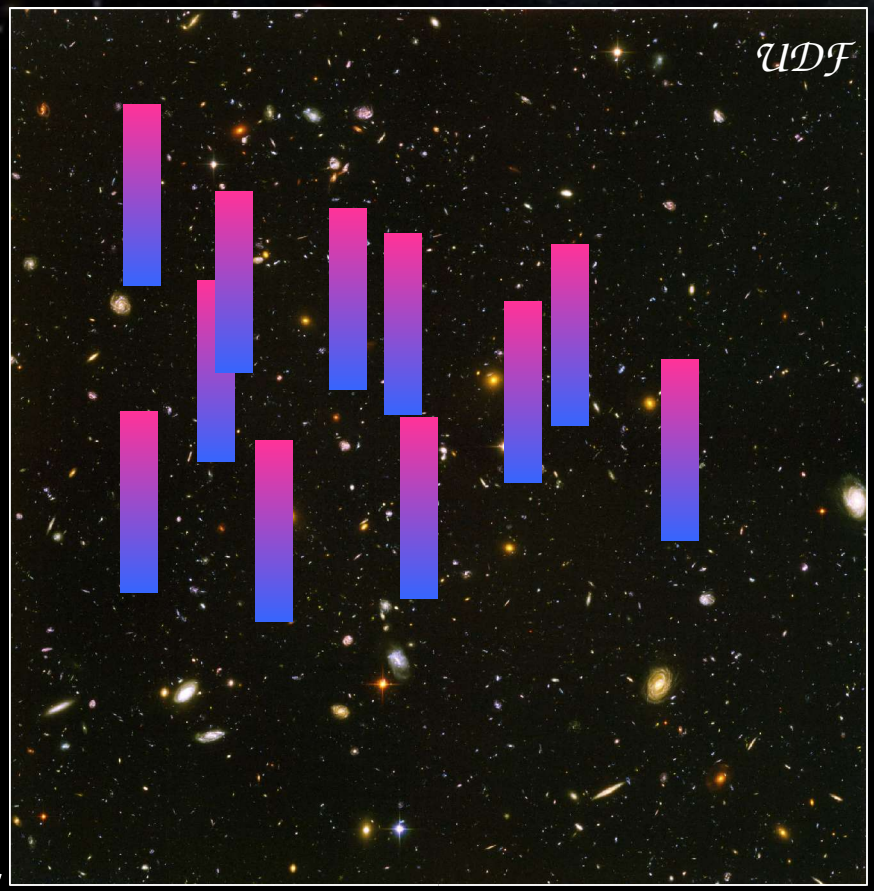
Richard McDermid

& MUSE collaboration

ESO Calibration Workshop

Survey Spectroscopy: Classical Approach

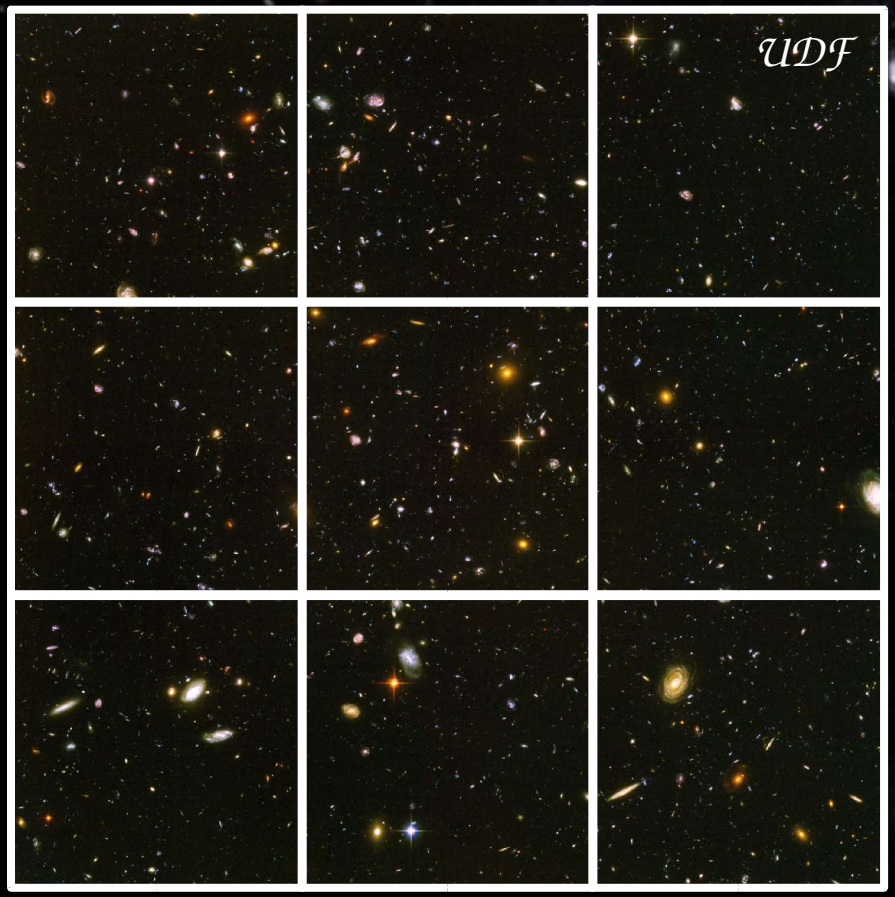
- *Imaging + MOS*
  - *1: Imaging*
  - *2: Selection*
  - *3: Spectroscopy*
- *Prerequisite*
  - *To see objects*
  - *To select objects*
- *Best for*
  - *Precise scientific question ⇒ efficient selection*
  - *Minimized spectrographic detector cost*



Survey Spectroscopy: New Approach

Get everything!

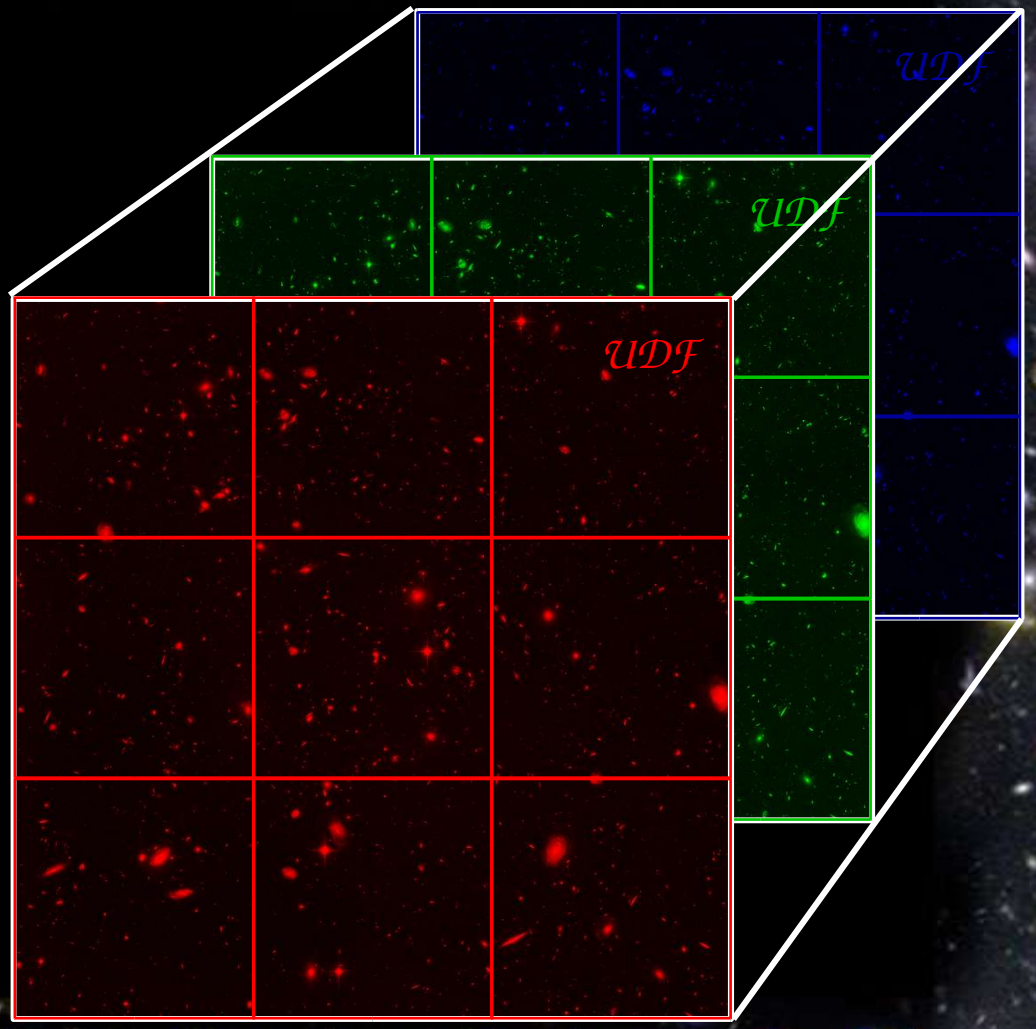
- *Eliminates pre-imaging*
- *Eliminates pre-selection*
- *Observe only once*
- *Large discovery space*



Survey Spectroscopy: New Approach

IFU can give best of both worlds:

- *Imaging: wide field of view and high spatial resolution*
- *Spectroscopy: wide, simultaneous spectral range and high resolving power*



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MUSE-WFM: The Big Step

Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 arcmin^2
Spatial sampling	0.2x0.2 arcsec^2
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	3.9 10^{-19}erg.s^{-1}.cm^{-2}

4096 pixels

370 10^6 pixels

90,000 spaxels

AO

Laser guide stars

High throughput

Stability

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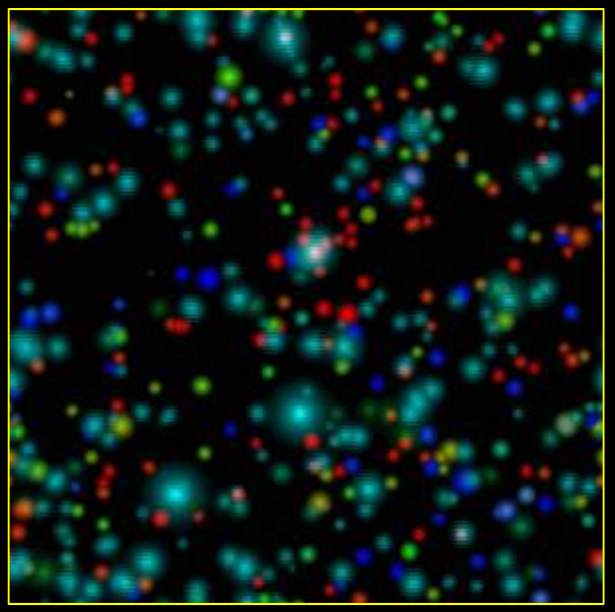
3D Deep Field: The Goal

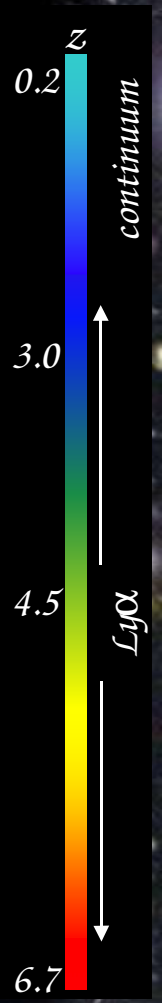
Comprehensive study of the faint galaxy population over a wide range of redshift

- *Wide range of redshift:*
  - *Lyα detectable z=2.8-6.7*
  - *Volume = 2.2 10^6 Mpc^3 ("Shallow Field" survey - 200 $arcmin^2$)*
- *Faint:*
  - *Progenitor of MW type galaxies up to z=6.7*
- *Comprehensive:*
  - *Statistics (luminosity function, clustering)*
  - *Star formation history*
  - *Diffuse ionized gas*
  - *Interaction with IGM*
  - *+ more*

1 arcmin



One deep field (80 hours)
> 400 galaxies



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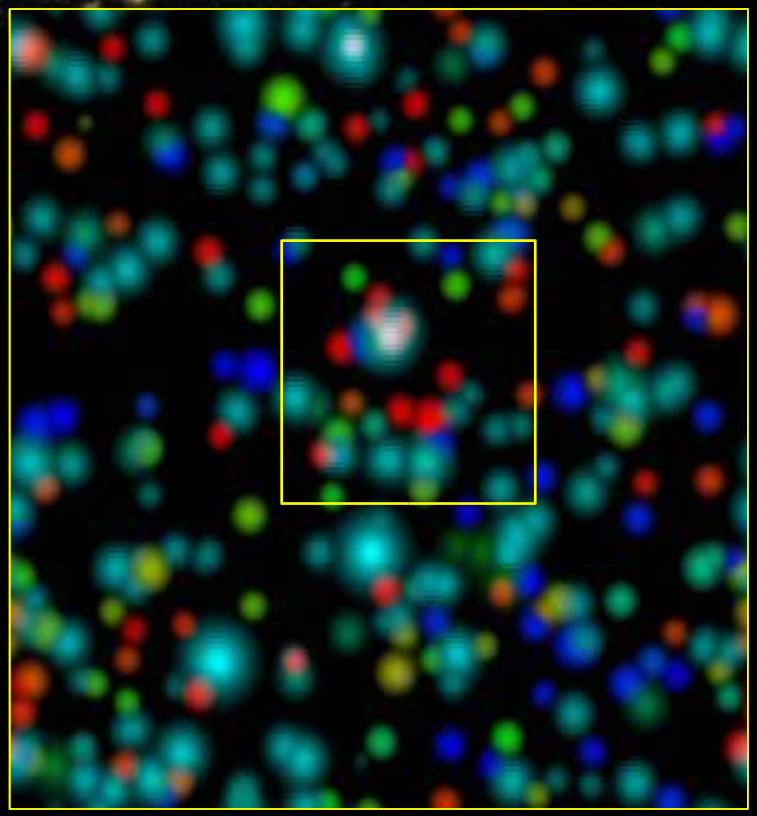
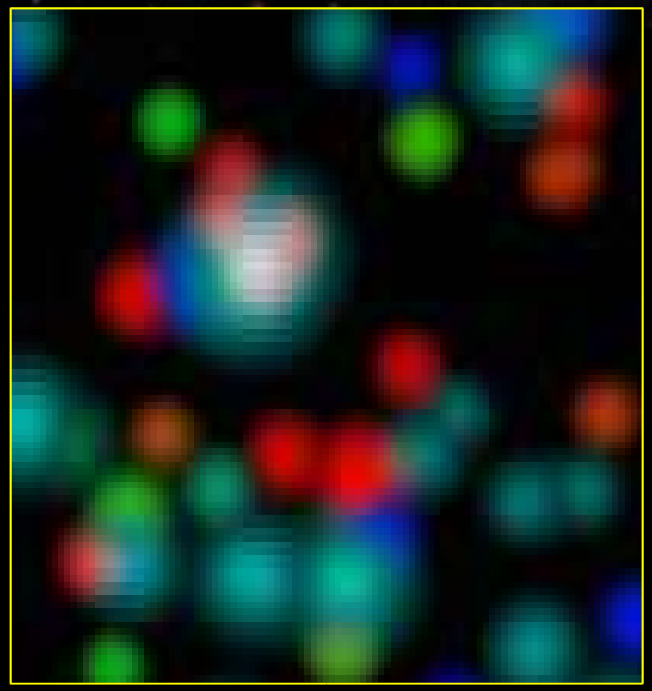
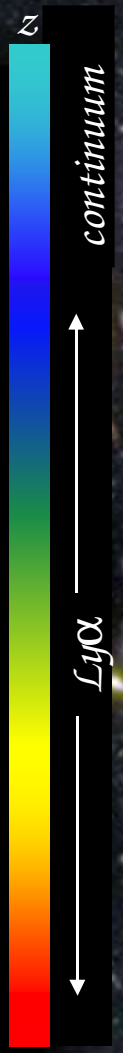
Effect of Spatial Resolution







Seeing limited observations in poor seeing conditions (1.1")

260 gal.arcmin^{-2} in total, 75 gal.arcmin^{-2} in z=[4-6.7]

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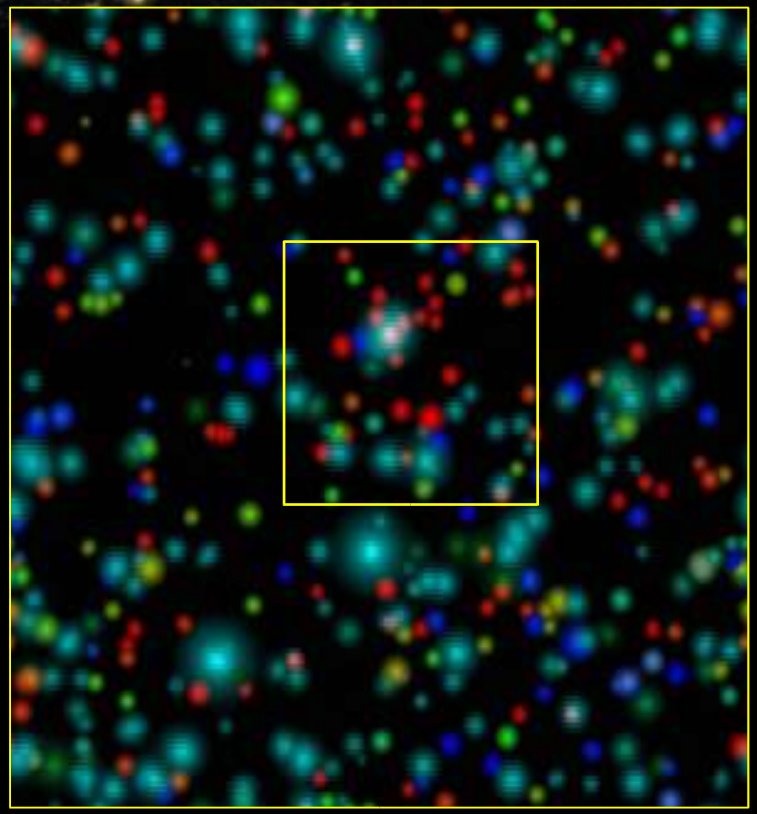
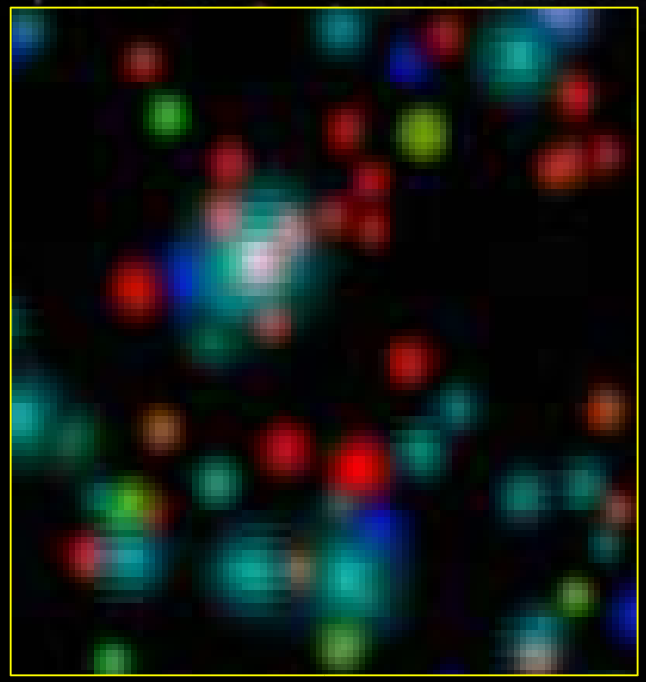
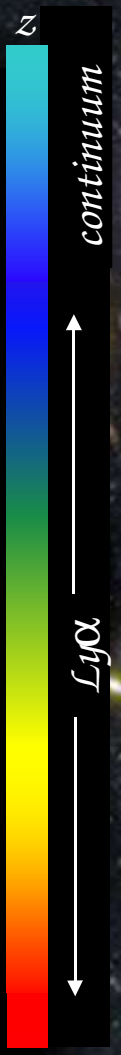
Effect of Spatial Resolution







AO observations in good seeing conditions (0.7")

420 gal.arcmin^{-2} in total, 132 gal.arcmin^{-2} in z=[4-6.7]

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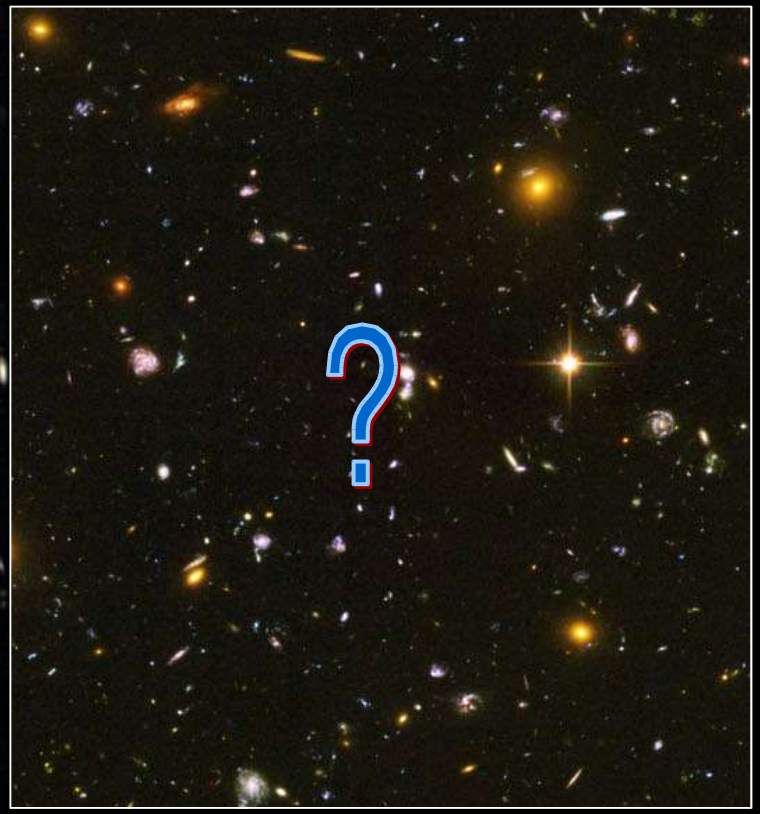
Richard McDermid (Leiden)

3D Deep Field: Simultaneity and Serendipity



- *High z Lyα emitters*
- *Reionization*
- *Intermediate z galaxies*
- *Fluorescent emission*
- *Feedback processes*
- *Gravitational lensing*
- *Spatially resolved spectroscopy*
- *Late forming pop III*
- *Active galactic nuclei*
- *Merger rate*
- *Development of dark halo*

All at once + the unknown !!

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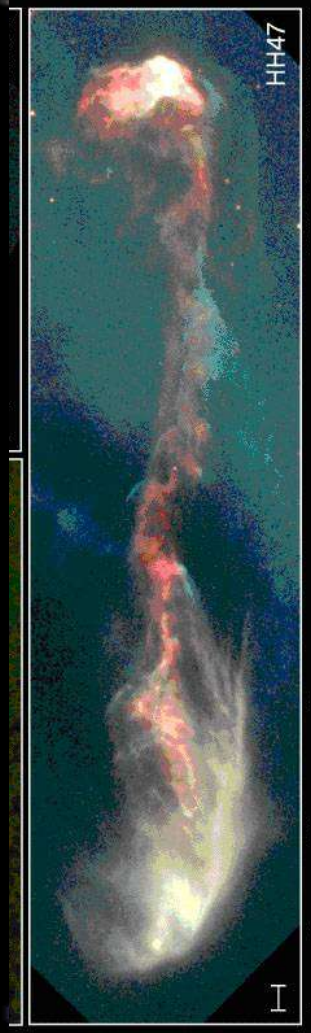
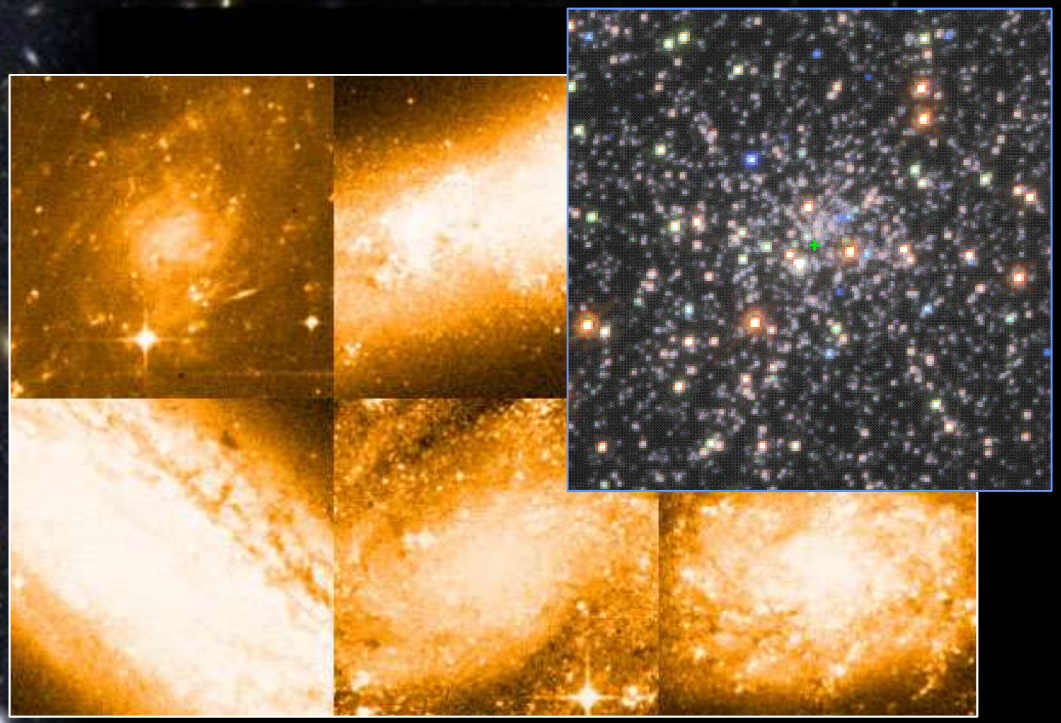
Stellar Jets in YSO



- *Broad line coverage + high spatial resolution + FOV*
- *Optical emission*
  - *Hβ, [OIII], [NI], [OI], [NII], Hα, [SII], [CaII], [FeII]*
- *Line fluxes and velocities*
- *Single flux calibration*
- *Magnetic field, shock conditions, jet density, origin of jet knots, low-velocity halo…*

Stellar Populations: Resolved Spectroscopy



- *Survey of nearby disk galaxies*
  - *25 exposures of 4 hour: 5x5 arcmin²*
- *Search for*
  - *Massive stars*
    - *1000/galaxy*
  - *Planetary nebulae*
    - *~100/galaxy*
  - *HII regions*
  - *Rare objects*
    - *Exotic stars (LBV, B[e])*
    - *SNR, novae, ultra-luminous X-ray source*
  - *Diffuse ISM*

- *Pre-ELT science*
- *GAIA complementarity*

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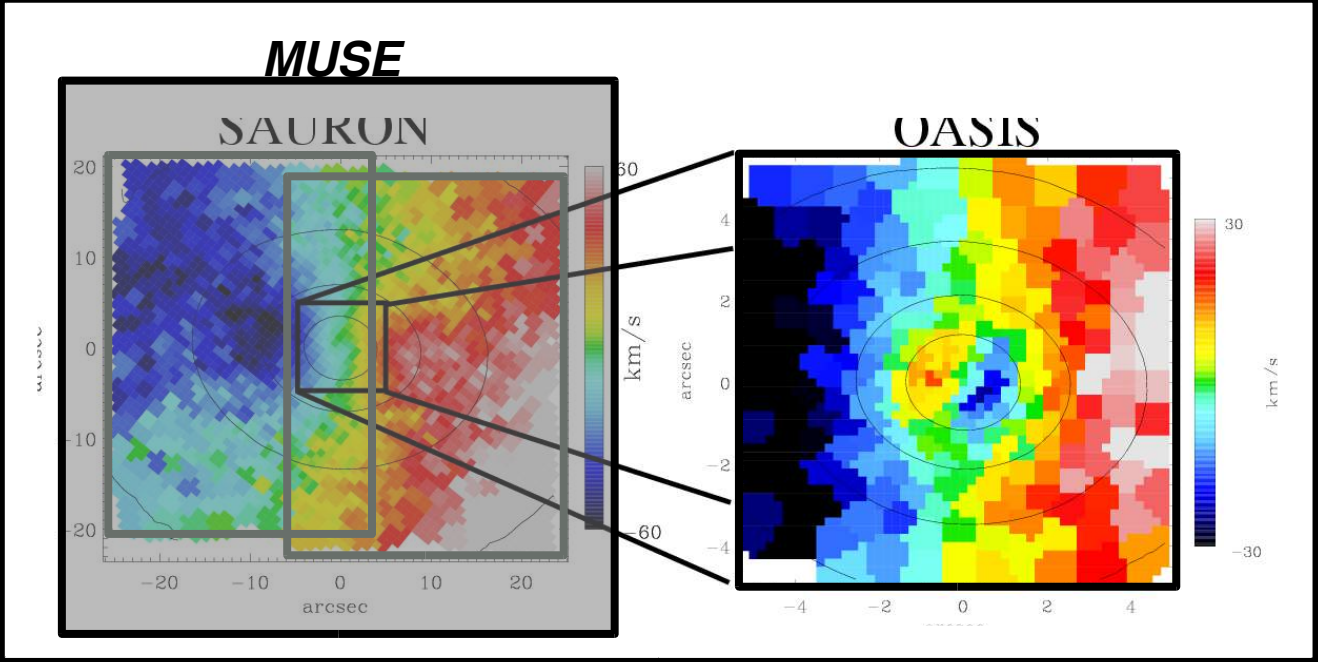
Nearby Galaxies

- *Sub-kiloparsec scale at 100 Mpc distance (Coma)*
- *Extend current studies (e.g. SAURON = Virgo) to different environments and large samples*



4hr SAURON + 1hr OASIS =< 1hr MUSE

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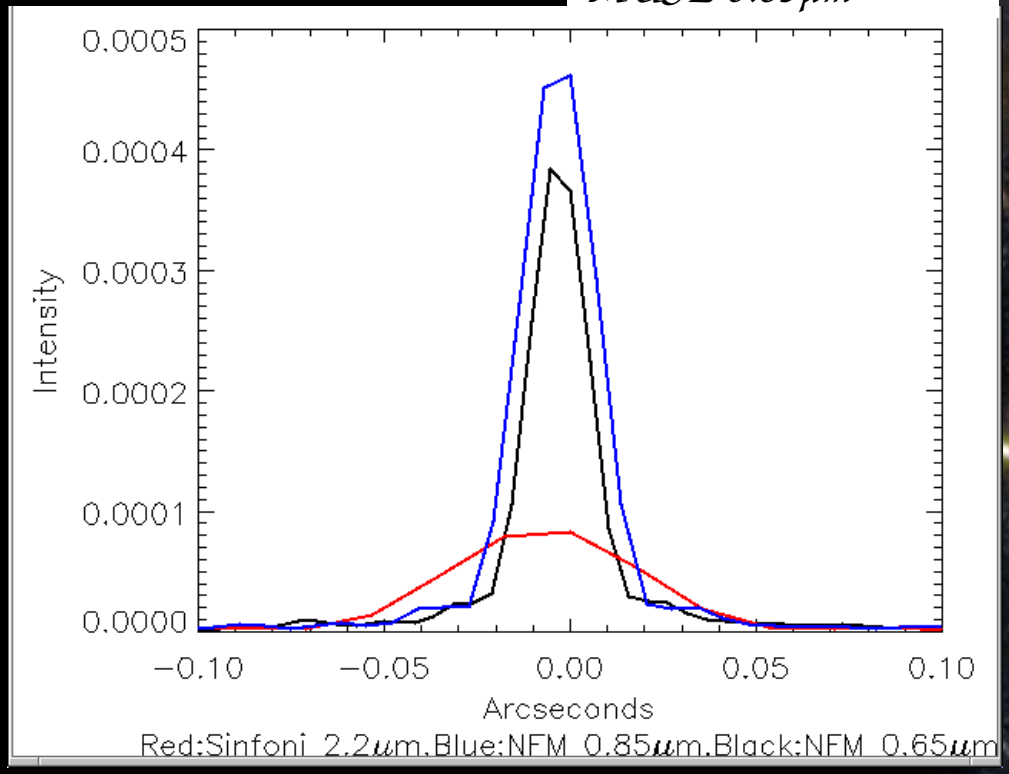
MUSE-Narrow Field Mode: Getting More from MUSE

- *Changing spatial scale*
  - *0.2 ⇒ 0.025 arcsec*
  - *FOV: 7.5x7.5 arcsec²*
- *Changing AO optimisation & configuration*
- *Spatial resolution*
  - *Diffraction limited*
  - *Strehl > 10% @ 0.65 μm*

- *Sinfoni*
  - *0.025 arcsec*
  - *0.8x0.8 arcsec²*
  - *1-2.5 μm*
  - *Strehl 30%@K*

SINFONI 2.2μm
MUSE 0.85μm
MUSE 0.65μm



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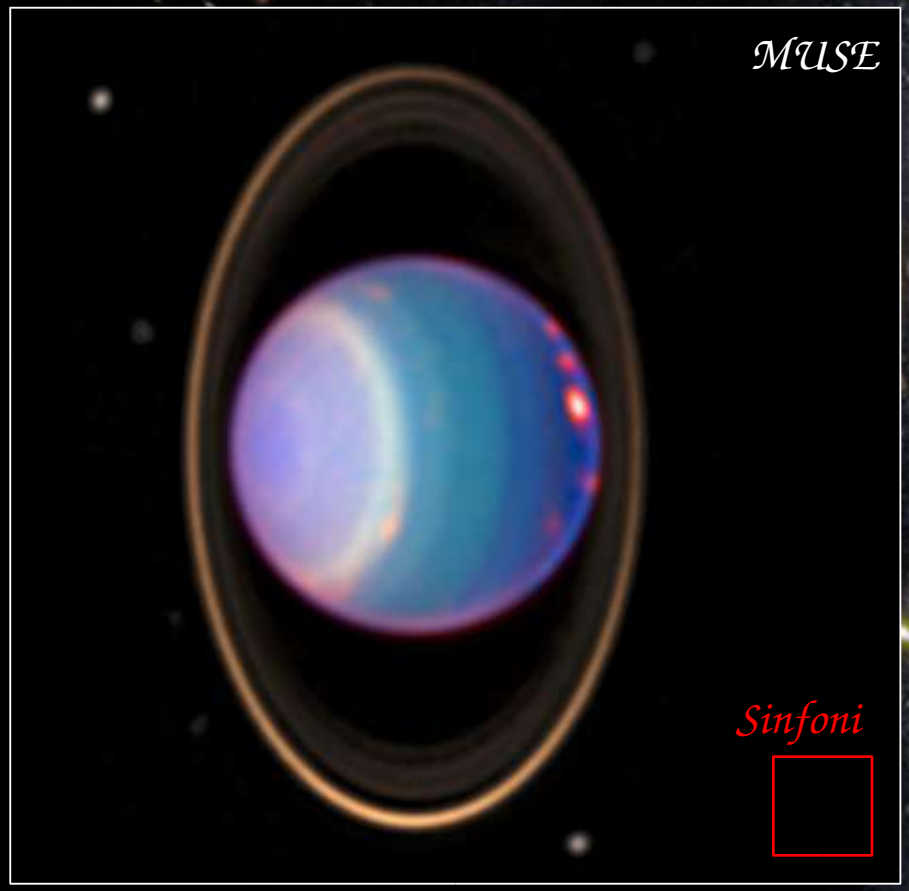
Planetary Atmospheres

Temporal changes on Uranus:

- *300 km/pixel*
- *Global monitoring*
- *3D atmospheric structure:*
  - *CO, C2H2, NH3, HC3N, CH4*



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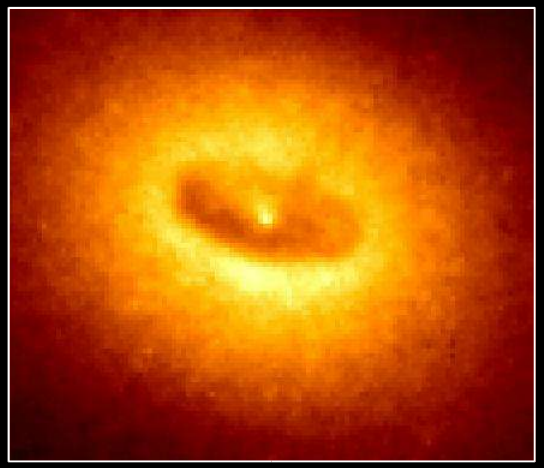
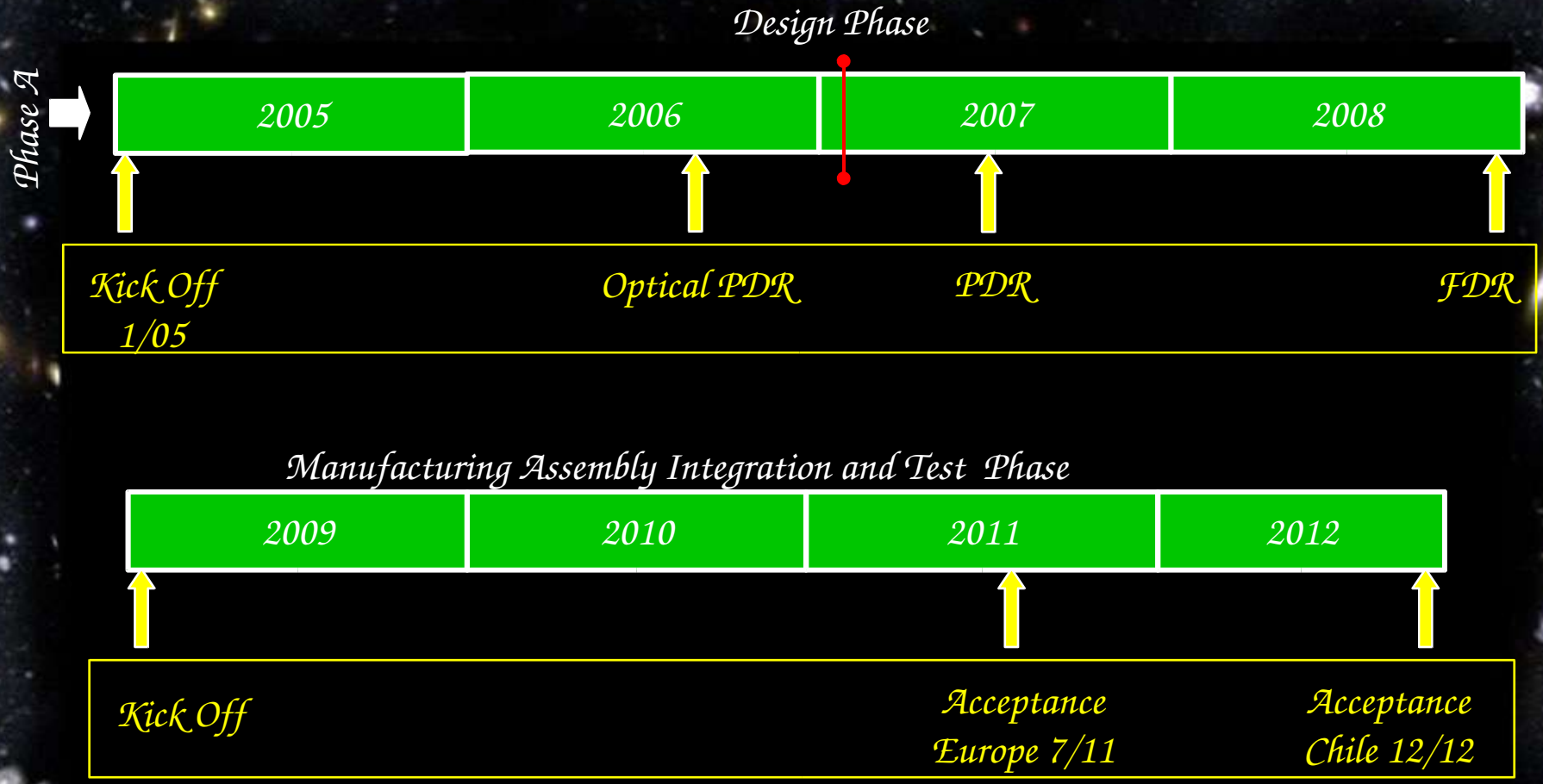
AGN environment

- *Circum-nuclear gas disk*
- *Emission cone*
- *Stellar populations*



Schedule/Milestones



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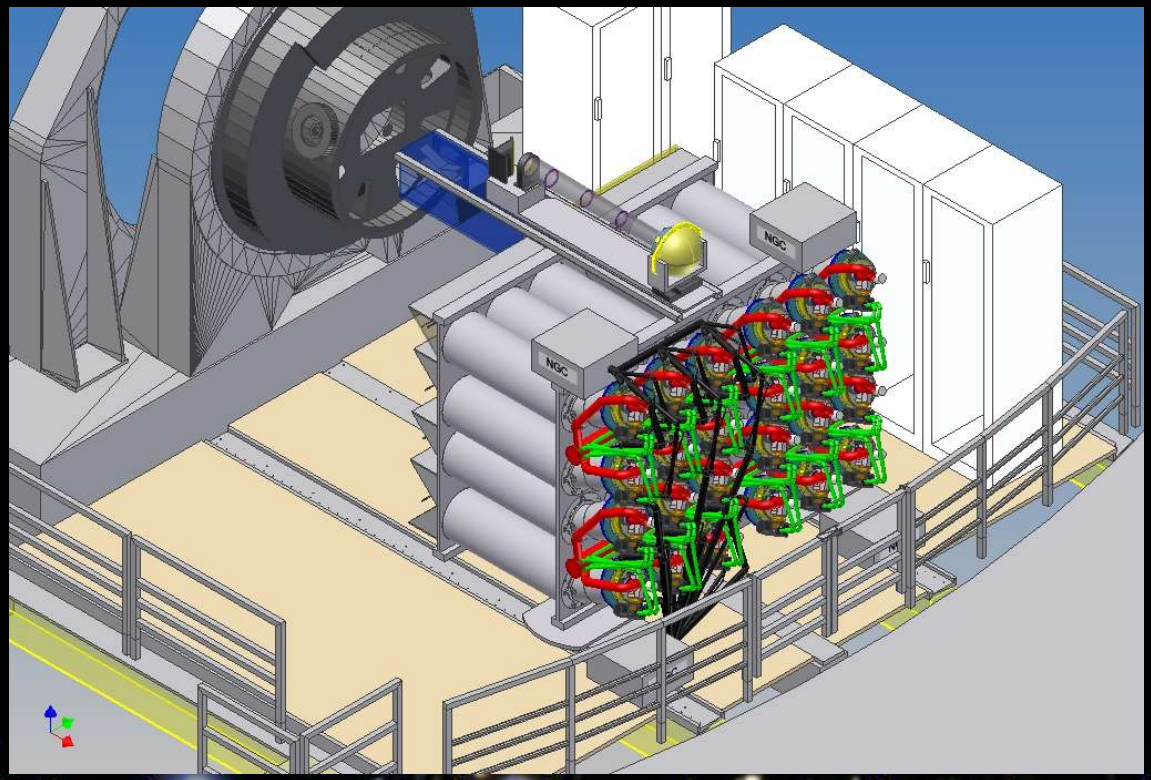
Instrument Description



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Challenge & Innovation

- *Challenge*
  - *Achieve high throughput*
  - *Achieve high spatial resolution*
  - *Achieve high optical quality*
  - *And keep cost under control*
- *Innovation*
  - *Slicer: advanced concept, diamond machining*
  - *Spectrograph: modular concept suited to serial industrial production*
  - *Grating: VPH with broad response*
  - *AO: ground layer correction*

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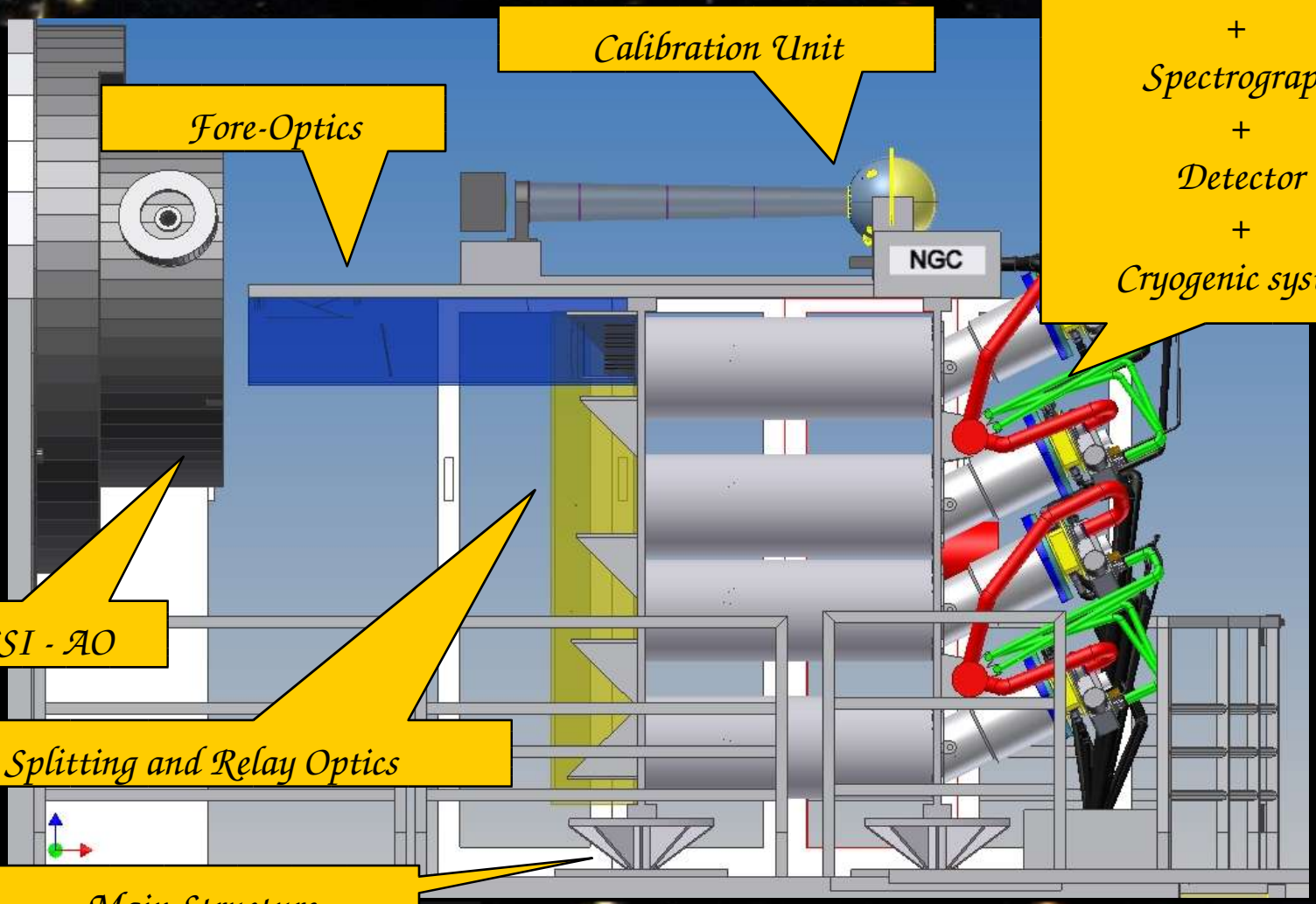
MUSE System Overview



24 IFUs
=
Image Slicer
+
Spectrograph
+
Detector
+
Cryogenic system

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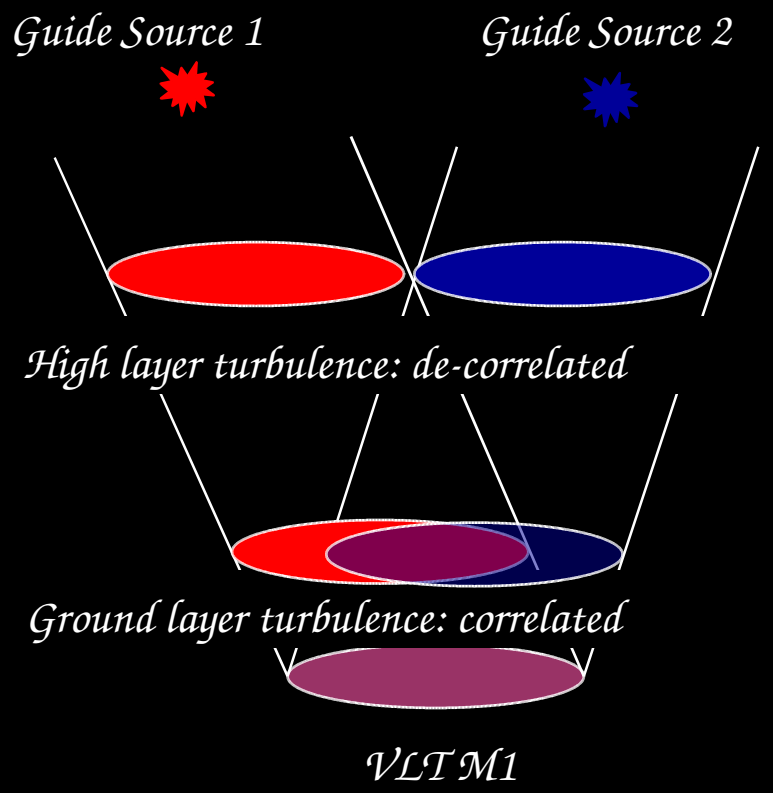
GALACSI AO System

GALACSI = Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging

- Multiple guide sources increase sky area sampled
- Concentrate on ground layer to expand corrected field beyond isoplanatic patch



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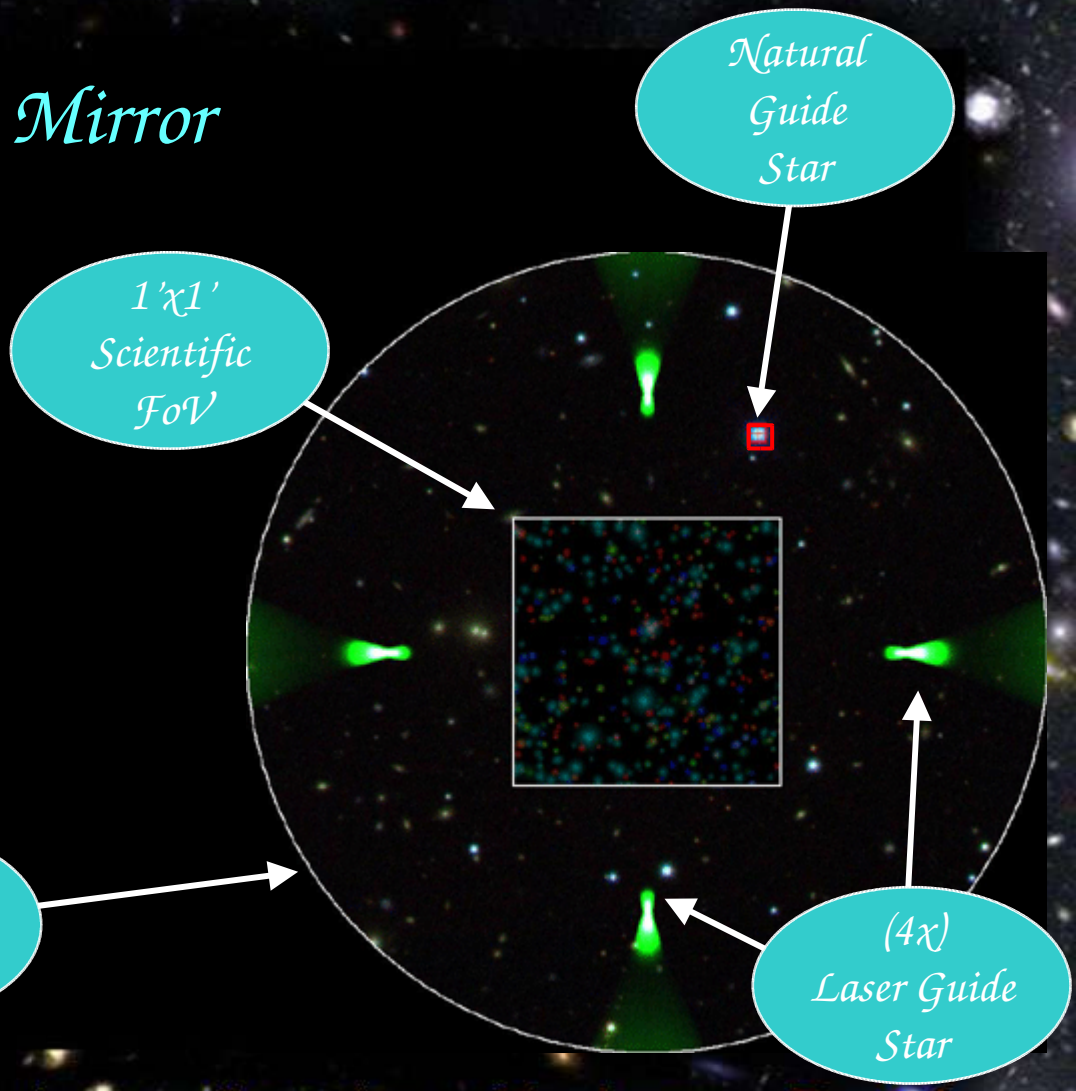
GALACSI WFM

- *Deformable Secondary Mirror*
  - *~1170 actuators*
  - *~500 Hz*
- *4 LGS, 1 NGS*
  - *NGS pick-up in 3-4'*
  - *Sky coverage 50-80%*
  - *Near-uniform PSF*



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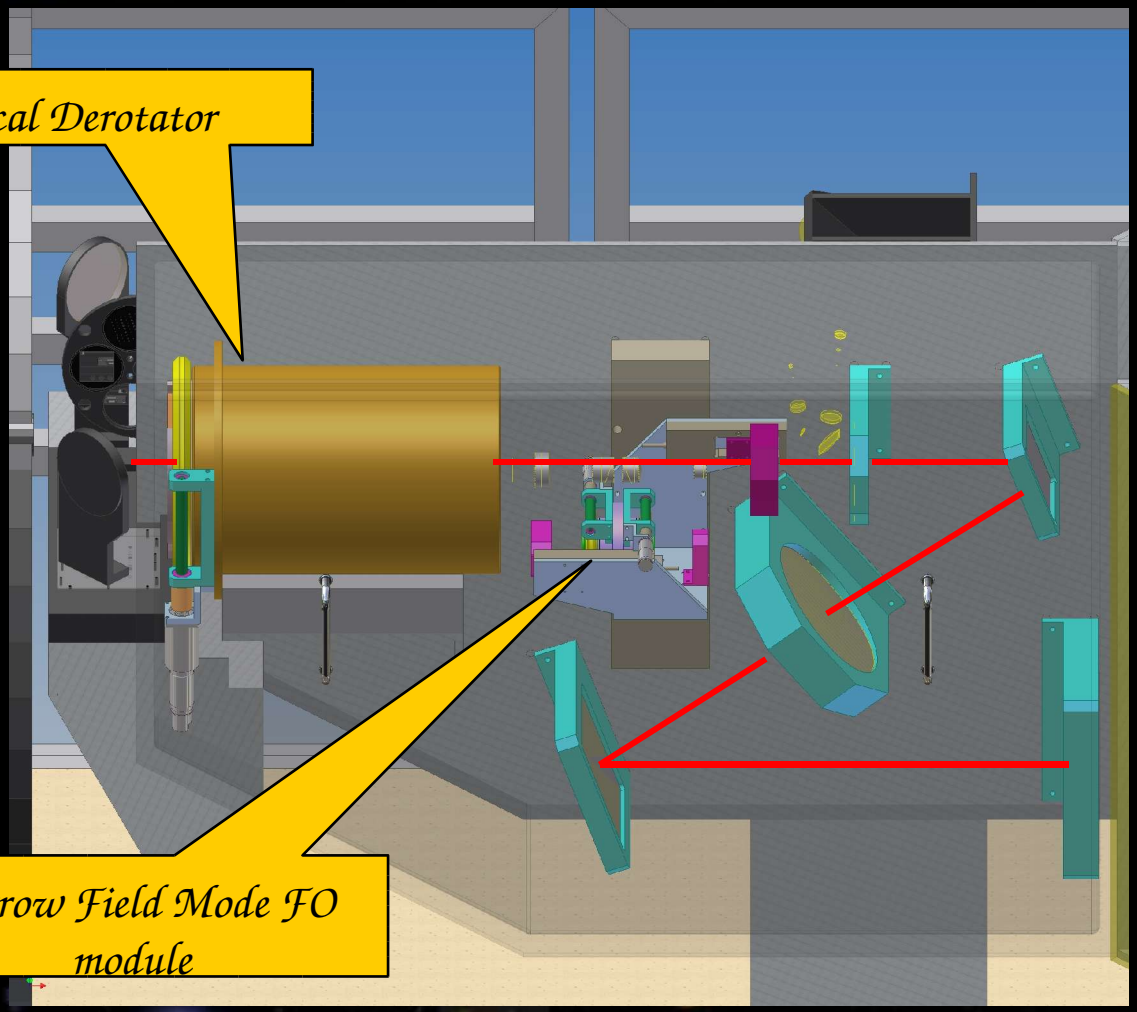
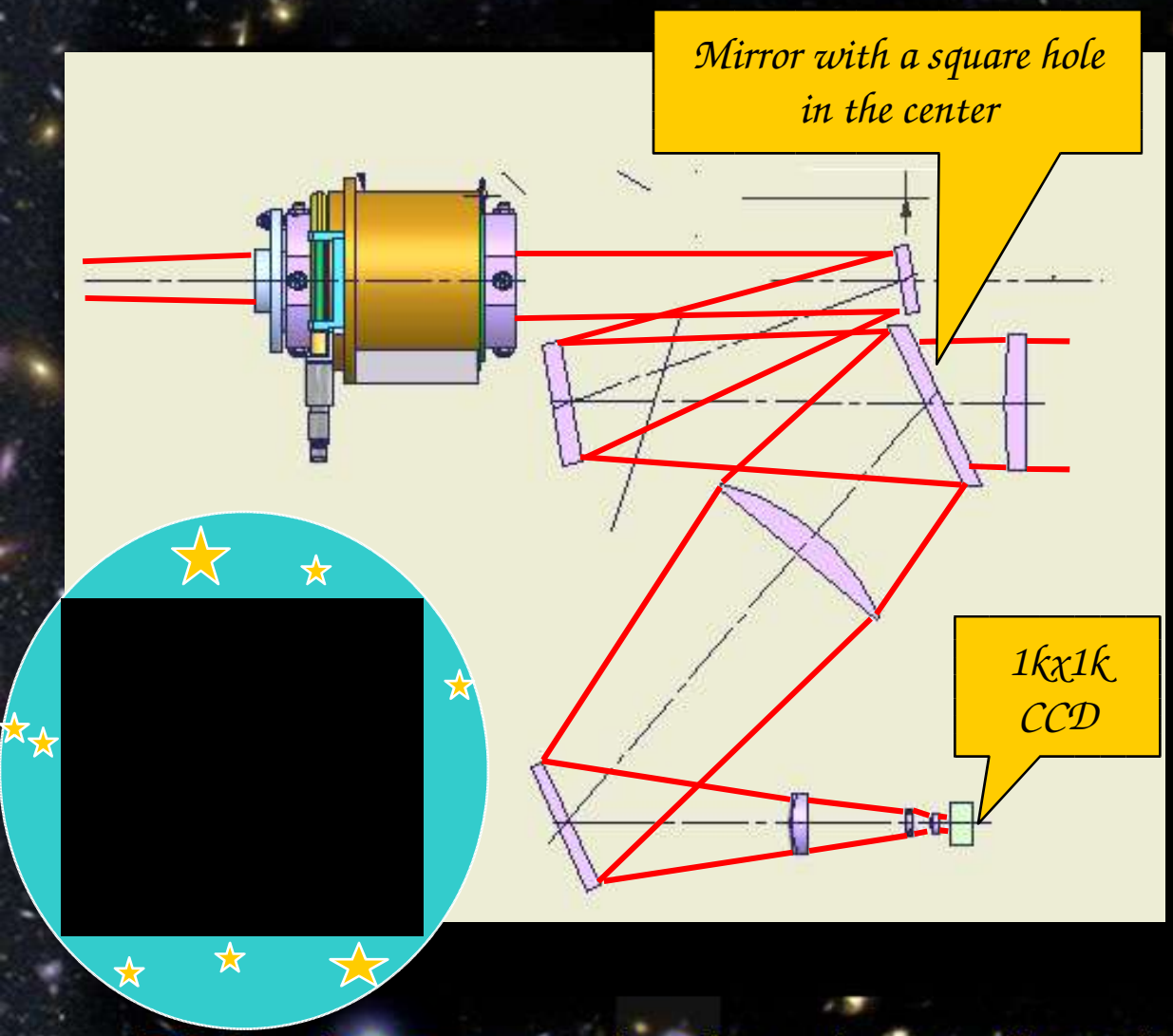
Fore Optics



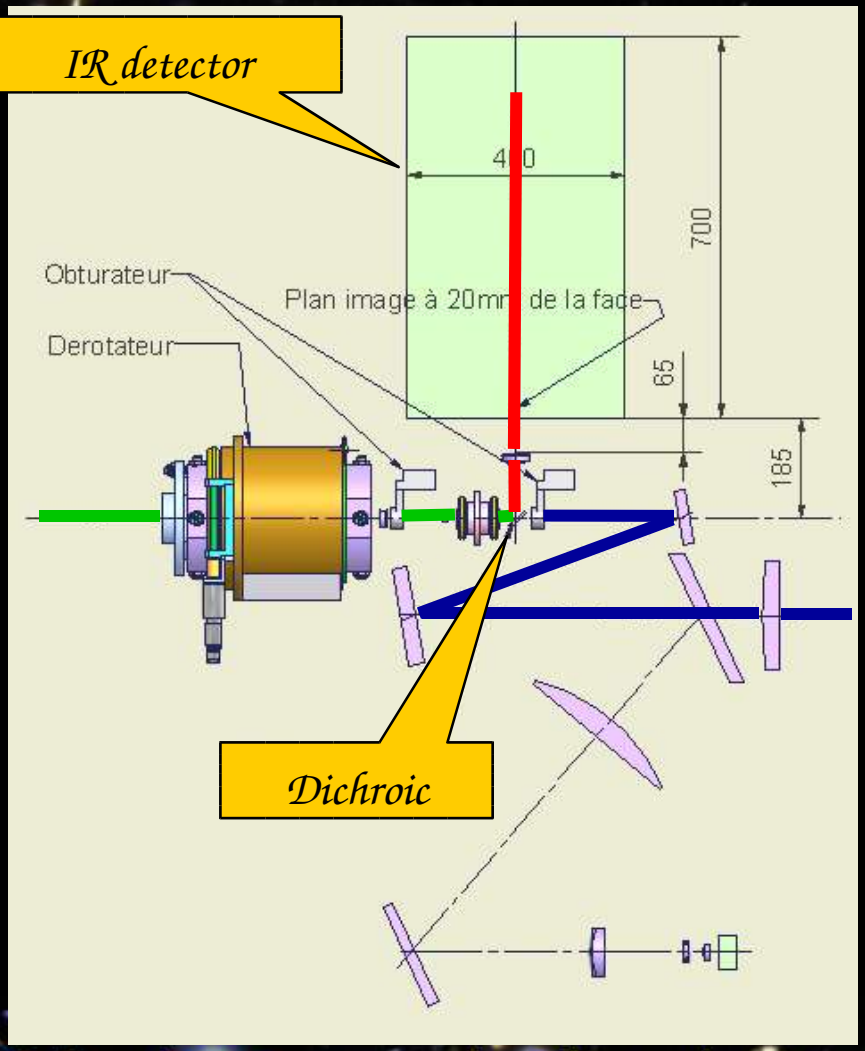
- Derotate
- Enlarge
- Anamorphose
- Na Notch Filter
- Blue cutoff Filter
- Light Stop
- ADC (NFM)
- IR Dichroic (NFM)

WFM Fine Guiding System



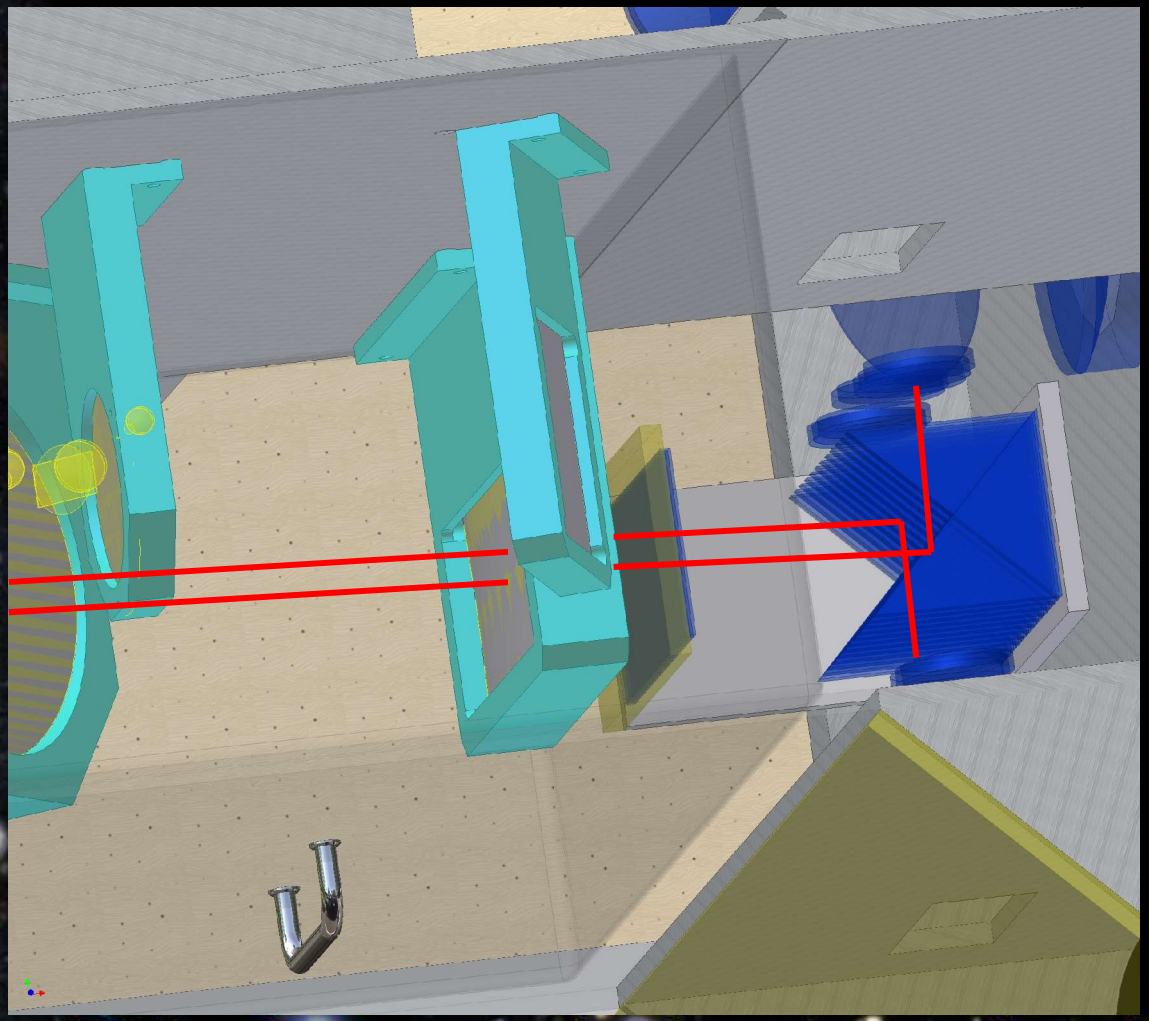
- *Correct for relative motions between GALACSI and Nasmyth Platform:*
  - *Thermal drift*
  - *De-rotator wobble*
- *Use stars in the 4 outer 'bananas'*
- *Cross-correlation at 1 - 0.1 Hz*

NFM Fine Guiding System

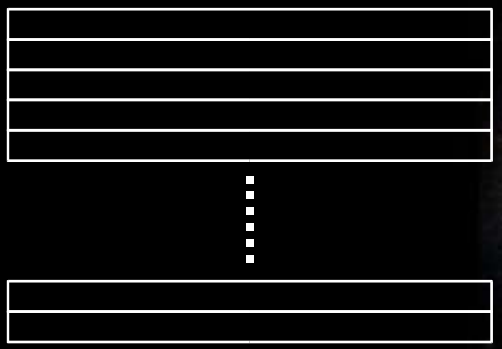


- *NFM uses on-axis guiding to maximise performance*
- *Tip/Tilt + Focus on the object using WFS IR 1-1.7 µm*

Field Splitter



- *Split the FoV in 24 sub-fields*
- *Shutter*



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Relay Optics

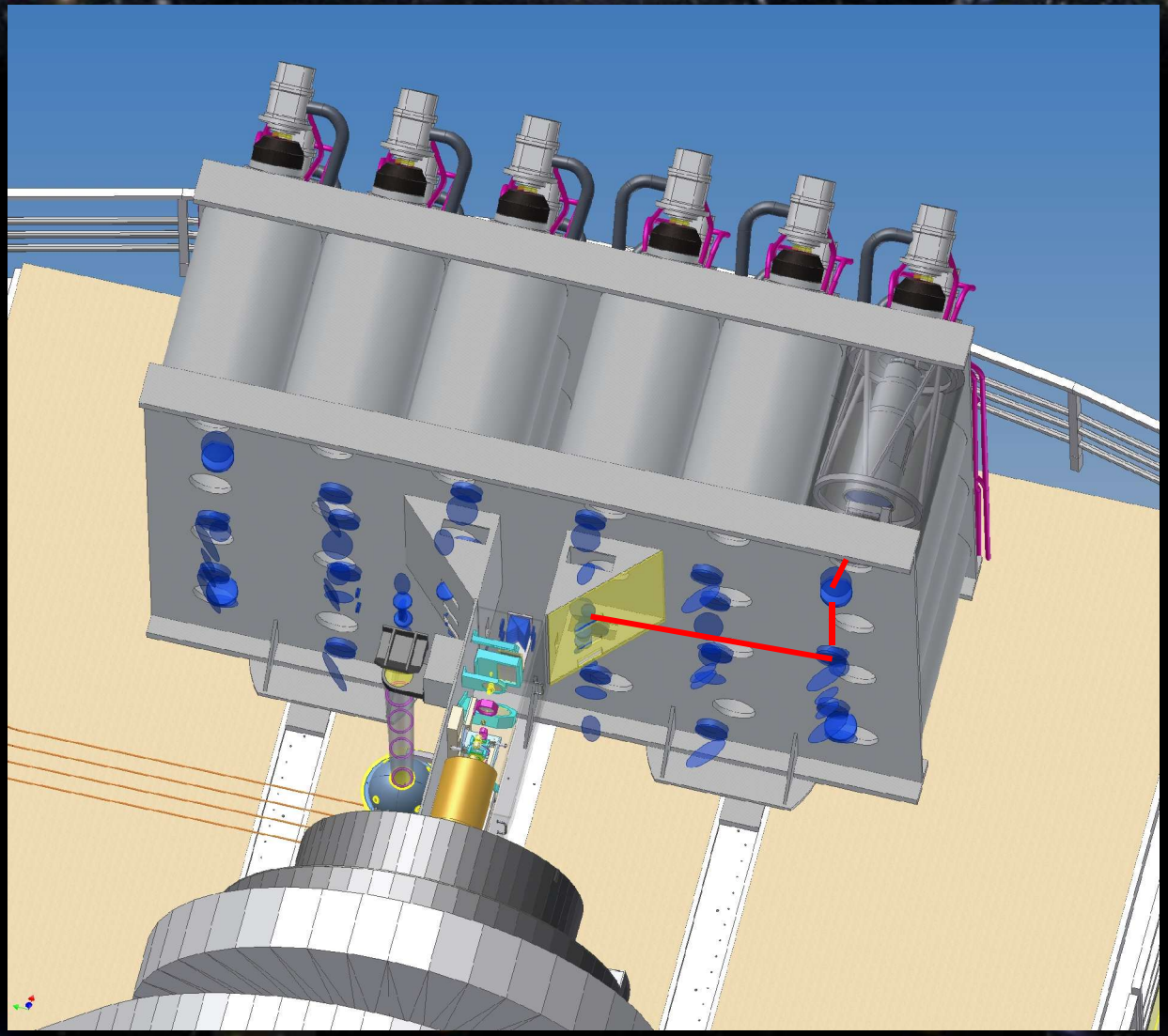

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Image Slicer

- *Image Dissector Array*
  - *4x12 thin off-axis spherical mirrors*
    - *33x0.9 mm*
    - *Sharp edge < 10 µm*
    - *Tilt accuracy < 1 arcmin*

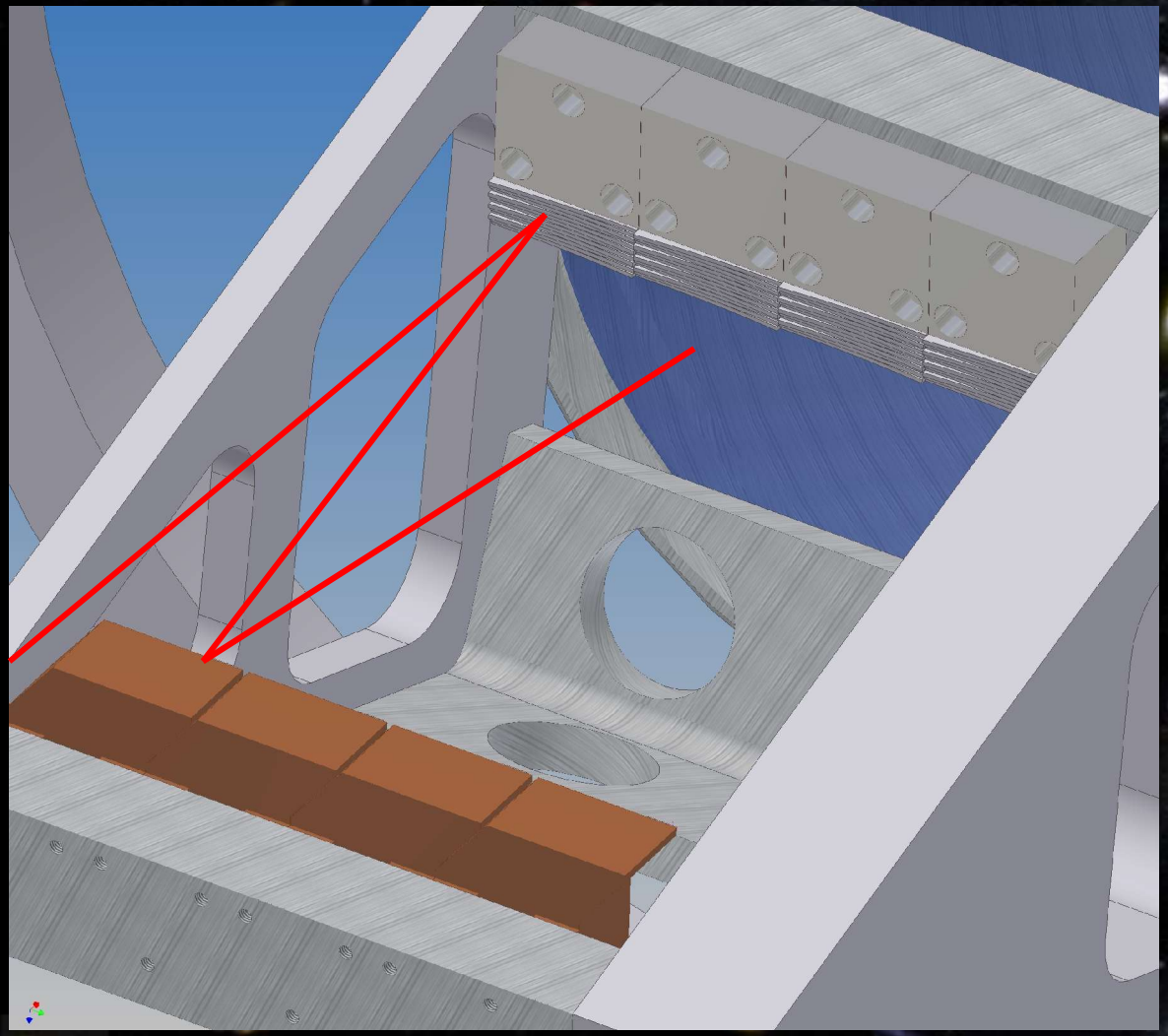
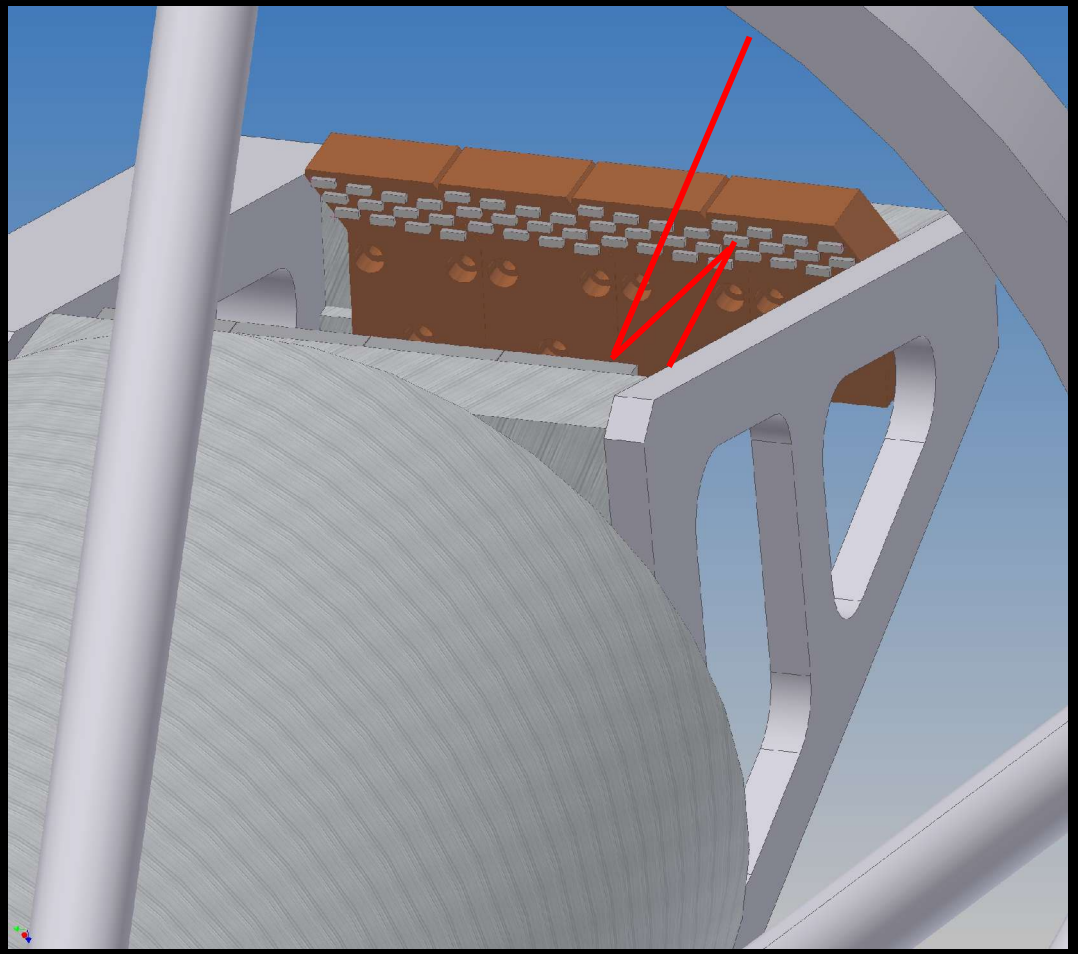
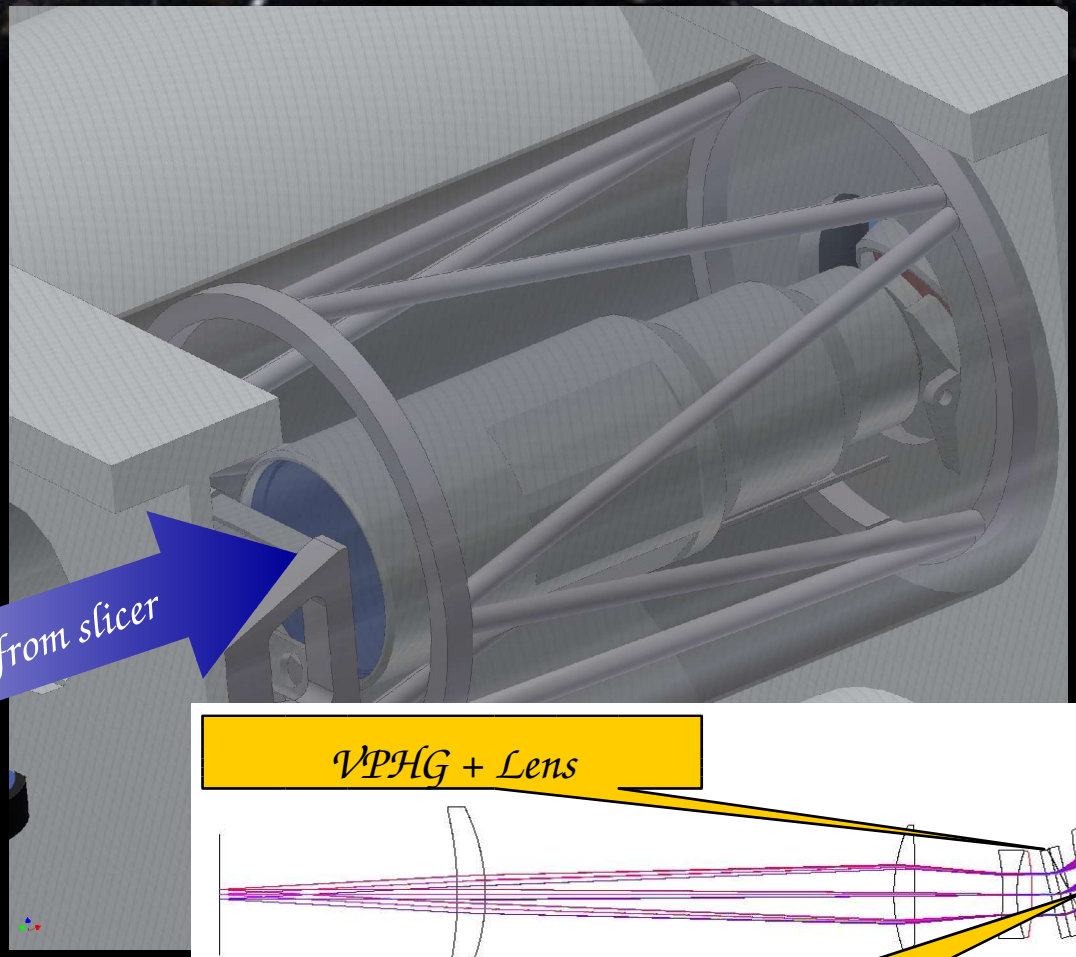


Image Slicer

- *Focusing Mirror Array*
  - *4x12 off-axis spherical mirrors*
    - *6x2 mm*



Spectrograph



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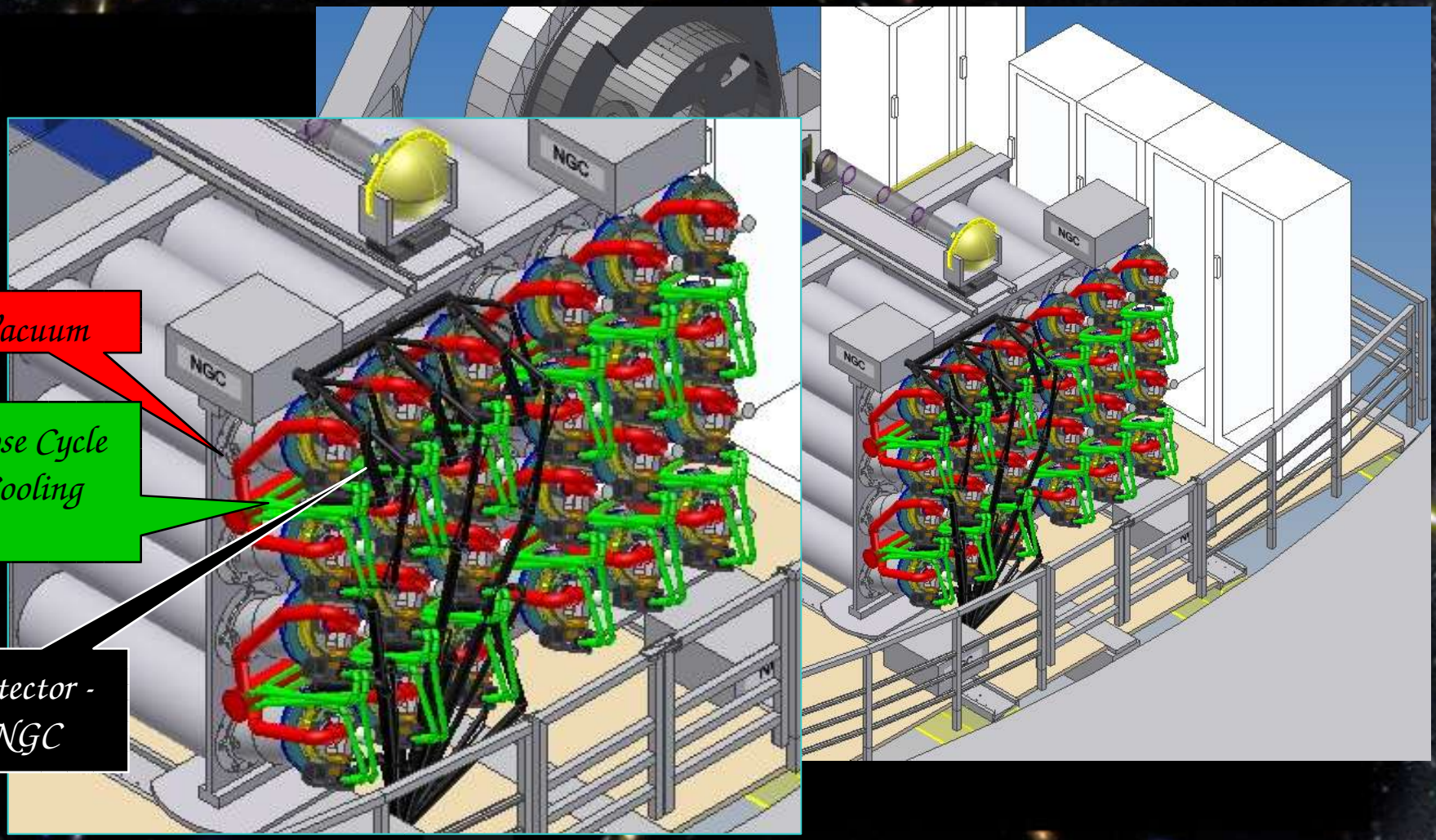
CCD Heads



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Operations

3 operating modes:

1) No AO WFM:

- *Point and shoot*

2) AO WFM:

- *AO setup*
- *Shoot*

3) AO NFM:

- *AO setup*
- *Fine centering*
- *Shoot*

Calibrations:

- *No night calibrations foreseen, except for spectrophotometric standard stars*
- *Twilight sky flats*
- *Daytime internal calibrations*
  - *Flats, Arcs, Bias, …*

MUSE Data: Challenges

Volume:

- *One exposure = 90,000 spectra on $4x10^8$ pixels -> 100s Gb/night of raw data*
  - *Transfer to archive/user*
  - *Storage/backup*
- *Need real-time quality checking & image reconstruction*
  - *Too many pixels for visual inspection*
  - *Need automatic data quality assessment*
- *24 separate images to reduce and combine into final data-cube*
  - *Parallel image processing*
  - *Tracking associated files from one exposure - database*
  - *Common calibrations: flat-field, astronometry, PSF…*

MUSE Data: Challenges

- *Calibration:*
  - *Full octave domain:*
    - *Arc line coverage*
    - *Uniform continuum source*
  - *Astrometry / field distortions*
    - *Large field – distortions become important*
    - *Thermal variations?*
    - *Calibrate with pinhole mask or on-sky*
  - *Coupling with AO:*
    - *PSF variations*
    - *Acquisition*
    - *Common calibration*
  - *Reliance on day calibrations*
    - *Regular stability monitoring*

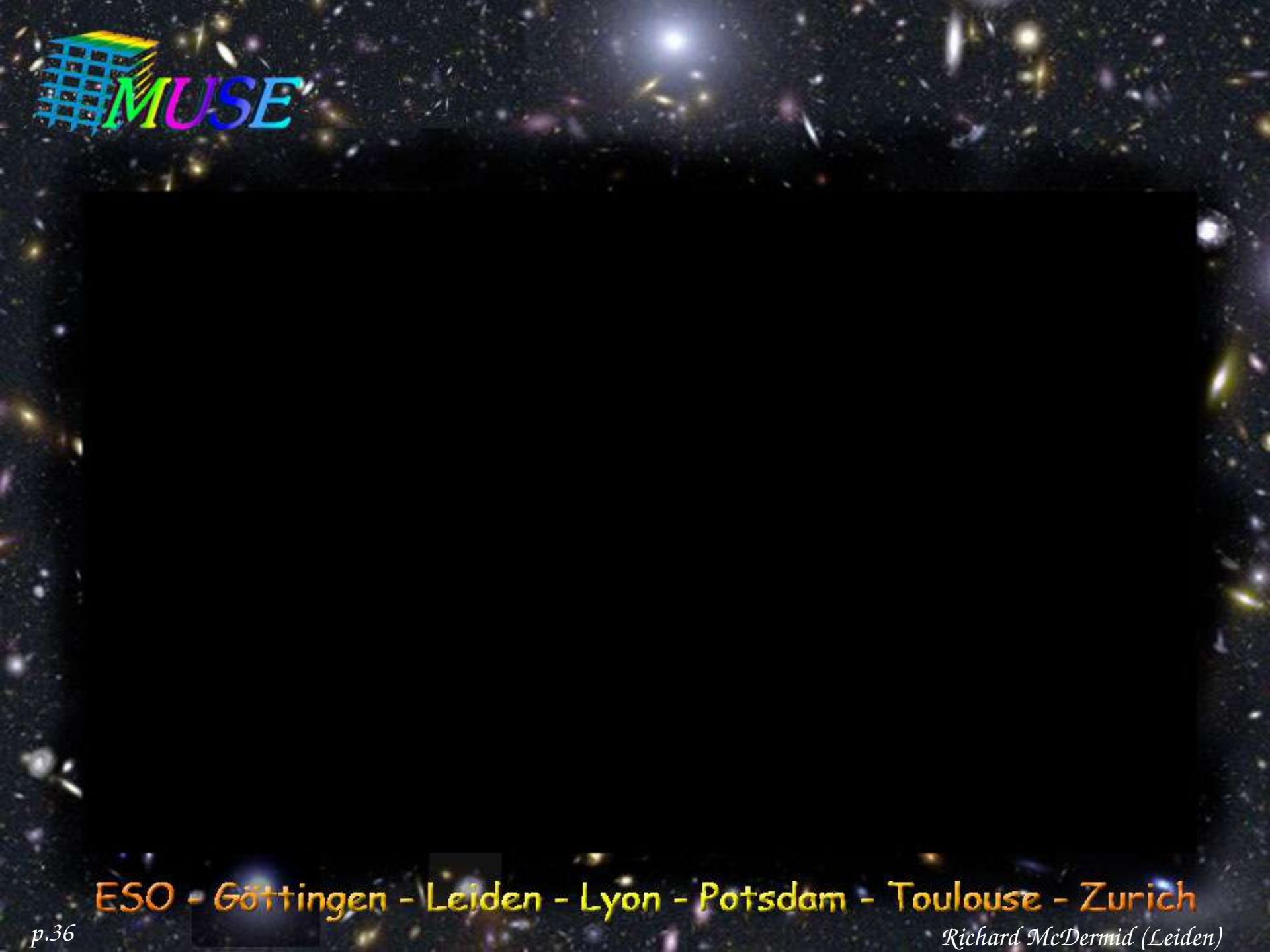
MUSE Data: Challenges

Analysis:

- *Mosaicing "blank" fields*
  - *No common reference sources*
  - *Use information from NGS-WFS or fine-guiding system*
- *PSF varies with field, wavelength, time:*
  - *PSF reconstruction crucial for some cases (extended sources)*
  - *Homogenize before combining exposures*
  - *Deconvolution in 3D?*
- *New/maturing analysis techniques:*
  - *Crowded field spectroscopy*
  - *Spectral background subtraction for faint emission lines*
  - *Automated faint source detection -> reliable error spectra*

"Hmmm.... I think there is a problem on pixel 192,379,482. You know, the one in spectrum 78,269? Maybe we should retake the OB?"

Poster P33: *"The MUSE Data Reduction Pipeline – Plans and Status"*
Peter Weilbacher et al.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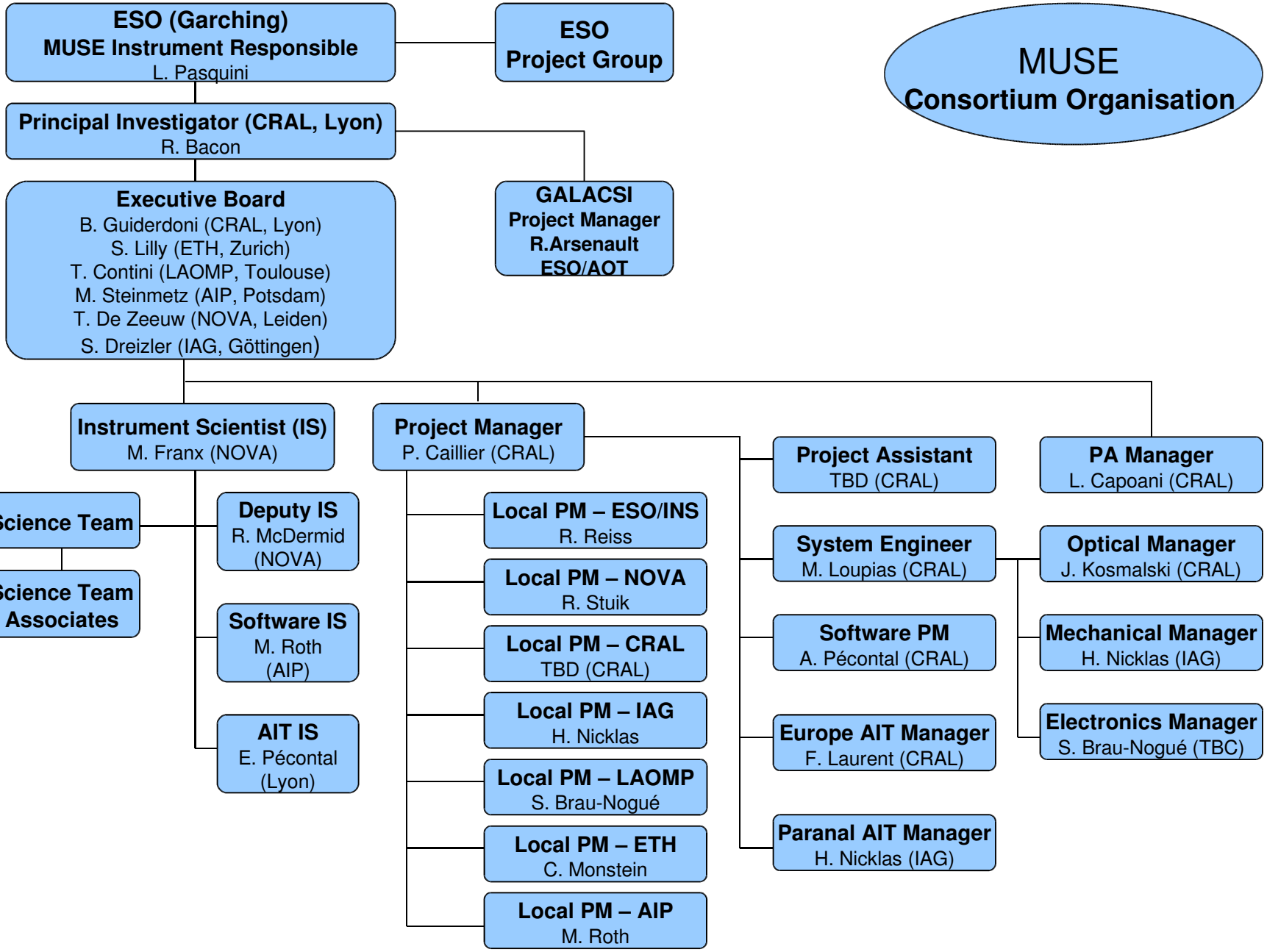
MUSE
Consortium Organisation
ESO (Garching)
MUSE Instrument Responsible
L. Pasquini
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Project Group
Principal Investigator (CRAL, Lyon)
R. Bacon
Executive Board
B. Guiderdoni (CRAL, Lyon)
S. Lilly (ETH, Zurich)
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M. Steinmetz (AIP, Potsdam)
T. De Zeeuw (NOVA, Leiden)
S. Dreizler (IAG, Göttingen)
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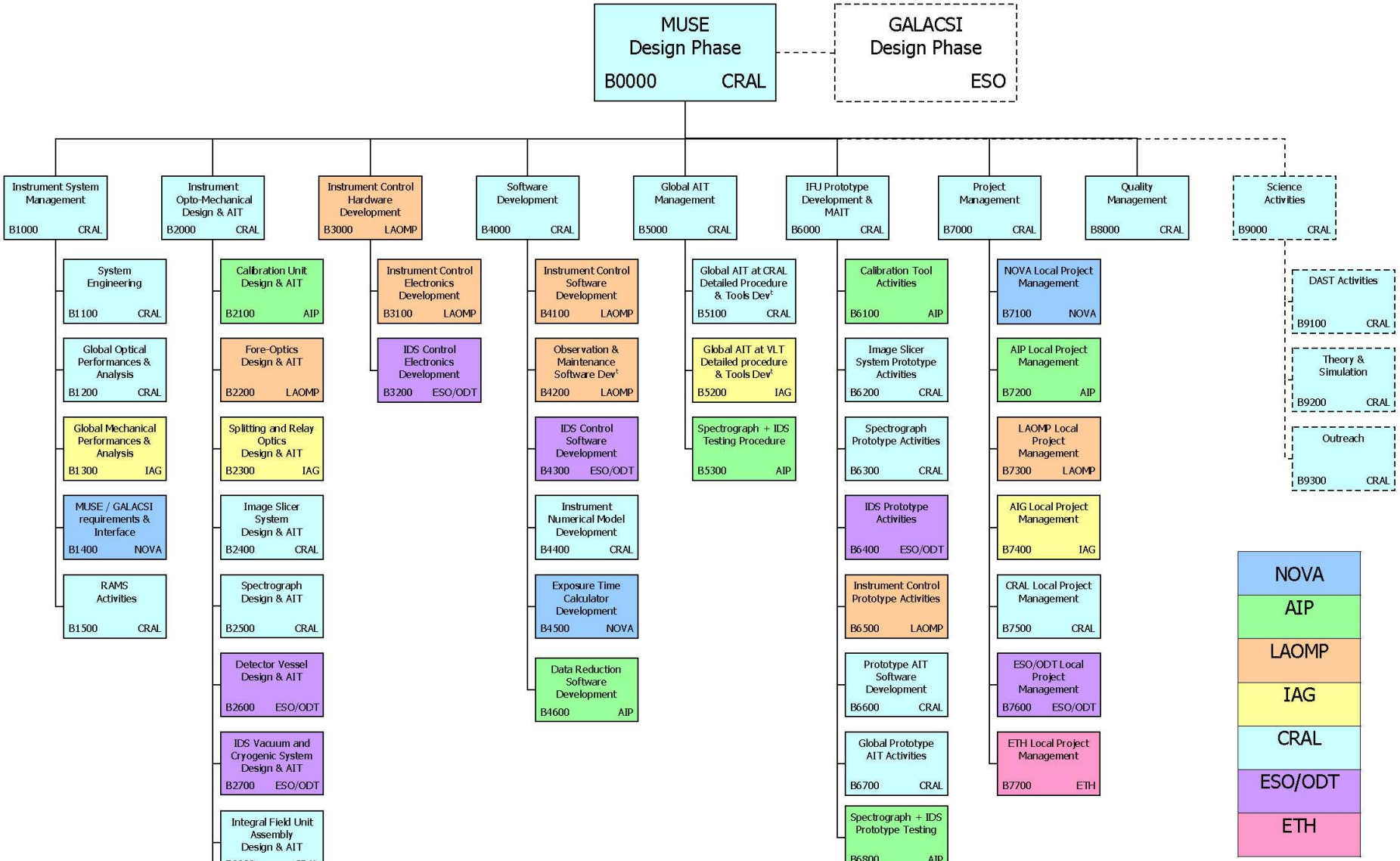
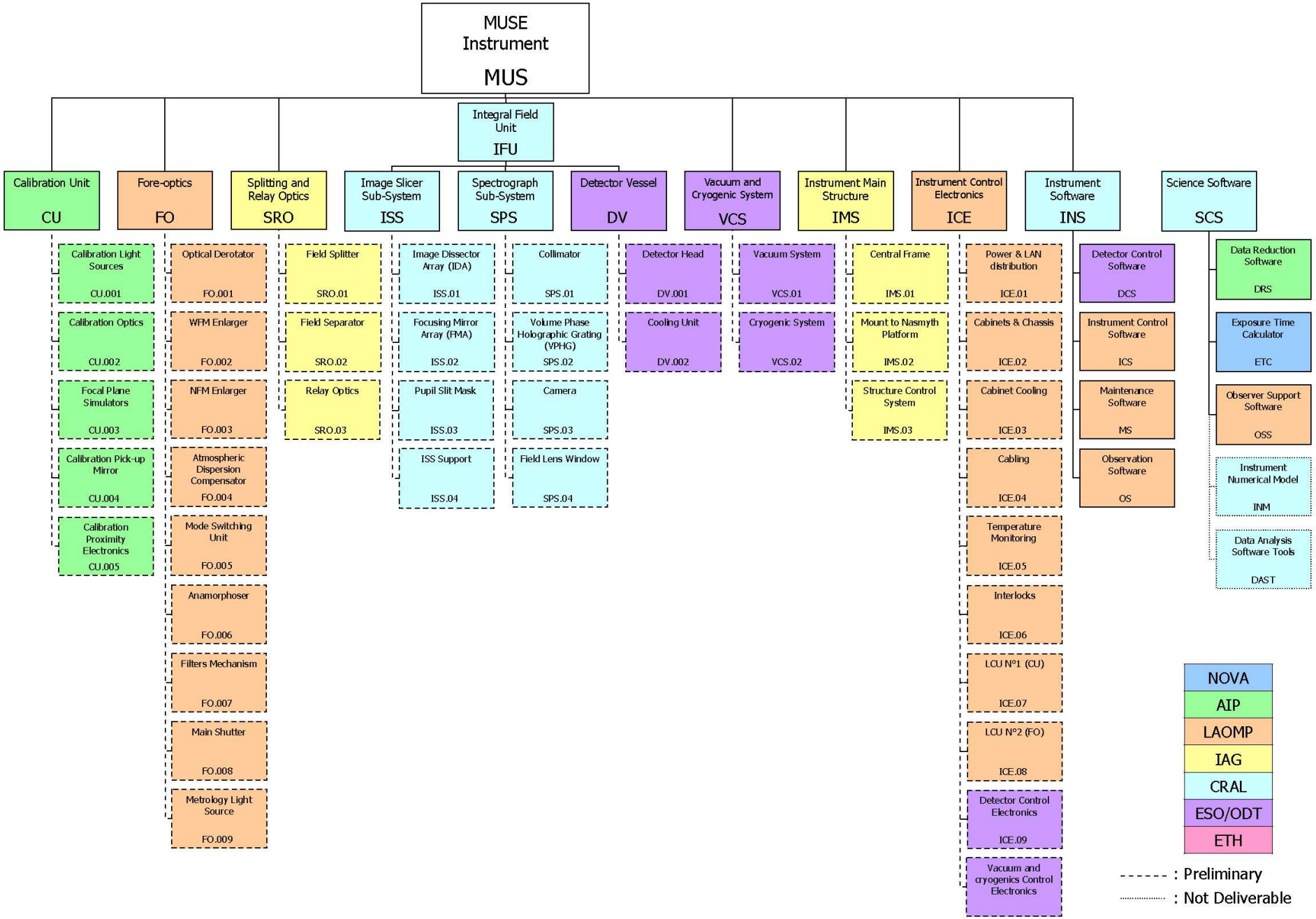
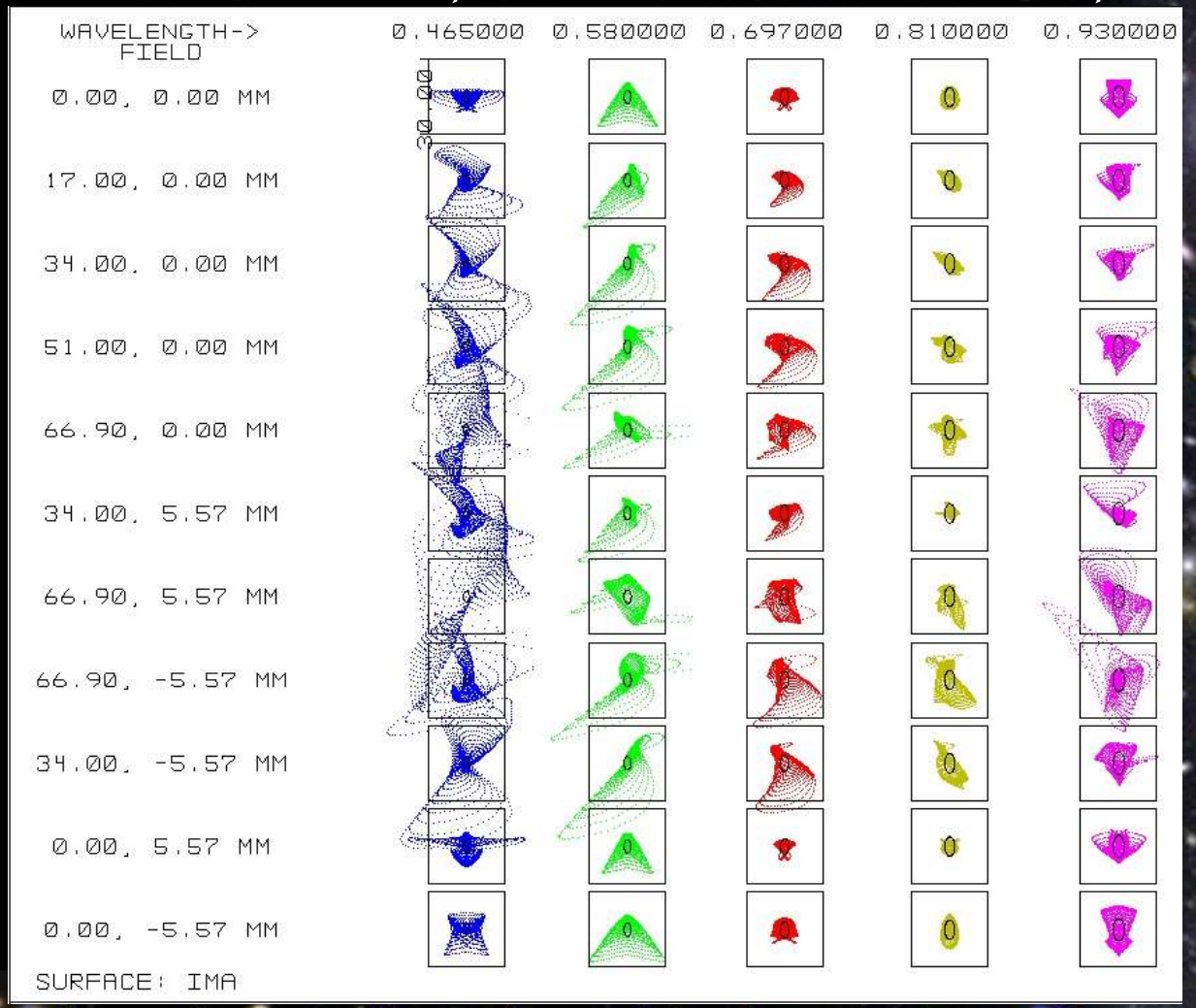
ESO/AOT
Instrument Scientist (IS)
M. Franx (NOVA)
Project Manager
P. Caillier (CRAL)
Project Assistant
TBD (CRAL)
PA Manager
L. Capoani (CRAL)
Science Team
Science Team Associates
Deputy IS
R. McDermid (NOVA)
Software IS
M. Roth (AIP)
AIT IS
E. Pécontal (Lyon)
Local PM – ESO/INS
R. Reiss
Local PM – NOVA
R. Stuik
Local PM – CRAL
TBD (CRAL)
Local PM – IAG
H. Nicklas
Local PM – LAOMP
S. Brau-Nogué
Local PM – ETH
C. Monstein
Local PM – AIP
M. Roth
System Engineer
M. Loupias (CRAL)
Software PM
A. Pécontal (CRAL)
Europe AIT Manager
F. Laurent (CRAL)
Paranal AIT Manager
H. Nicklas (IAG)
Optical Manager
J. Kosmalski (CRAL)
Mechanical Manager
H. Nicklas (IAG)
Electronics Manager
S. Brau-Nogué (TBC)


MUSE Design Phase
B0000 CRAL
GALACSI Design Phase
ESO
Instrument System Management
B1000 CRAL
System Engineering
B1100 CRAL
Global Optical Performances & Analysis
B1200 CRAL
Global Mechanical Performances & Analysis
B1300 IAG
MUSE / GALACSI requirements & Interface
B1400 NOVA
RAMS Activities
B1500 CRAL
Instrument Opto-Mechanical Design & AIT
B2000 CRAL
Calibration Unit Design & AIT
B2100 AIP
Fore-Optics Design & AIT
B2200 LAOMP
Splitting and Relay Optics Design & AIT
B2300 IAG
Image Slicer System Design & AIT
B2400 CRAL
Spectrograph Design & AIT
B2500 CRAL
Detector Vessel Design & AIT
B2600 ESO/ODT
IDS Vacuum and Cryogenic System Design & AIT
B2700 ESO/ODT
Integral Field Unit Assembly Design & AIT
B2800 CRAL
Instrument Main Structure Design & AIT
B2900 IAG
Instrument Control Hardware Development
B3000 LAOMP
Instrument Control Electronics Development
B3100 LAOMP
IDS Control Electronics Development
B3200 ESO/ODT
Software Development
B4000 CRAL
Instrument Control Software Development
B4100 LAOMP
Observation & Maintenance Software Dev^t
B4200 LAOMP
IDS Control Software Development
B4300 ESO/ODT
Instrument Numerical Model Development
B4400 CRAL
Exposure Time Calculator Development
B4500 NOVA
Data Reduction Software Development
B4600 AIP
Global AIT Management
B5000 CRAL
Global AIT at CRAL Detailed Procedure & Tools Dev^t
B5100 CRAL
Global AIT at VLT Detailed procedure & Tools Dev^t
B5200 IAG
Spectrograph + IDS Testing Procedure
B5300 AIP
IFU Prototype Development & MAIT
B6000 CRAL
Calibration Tool Activities
B6100 AIP
Image Slicer System Prototype Activities
B6200 CRAL
Spectrograph Prototype Activities
B6300 CRAL
IDS Prototype Activities
B6400 ESO/ODT
Instrument Control Prototype Activities
B6500 LAOMP
Prototype AIT Software Development
B6600 CRAL
Global Prototype AIT Activities
B6700 CRAL
Spectrograph + IDS Prototype Testing
B6800 AIP
Project Management
B7000 CRAL
NOVA Local Project Management
B7100 NOVA
AIP Local Project Management
B7200 AIP
LAOMP Local Project Management
B7300 LAOMP
AIG Local Project Management
B7400 IAG
CRAL Local Project Management
B7500 CRAL
ESO/ODT Local Project Management
B7600 ESO/ODT
ETH Local Project Management
B7700 ETH
Quality Management
B8000 CRAL
Science Activities
B9000 CRAL
DAST Activities
B9100 CRAL
Theory & Simulation
B9200 CRAL
Outreach
B9300 CRAL
NOVA
AIP
LAOMP
IAG
CRAL
ESO/ODT
ETH
------- : Activities related to MUSE Project but not included


MUSE Instrument
MUS
Integral Field Unit
IFU
Calibration Unit
CU
Calibration Light Sources
CU.001
Calibration Optics
CU.002
Focal Plane Simulators
CU.003
Calibration Pick-up Mirror
CU.004
Calibration Proximity Electronics
CU.005
Fore-optics
FO
Optical Derotator
FO.001
WFM Enlarger
FO.002
NFM Enlarger
FO.003
Atmospheric Dispersion Compensator
FO.004
Mode Switching Unit
FO.005
Anamorphoser
FO.006
Filters Mechanism
FO.007
Main Shutter
FO.008
Metrology Light Source
FO.009
Splitting and Relay Optics
SRO
Field Splitter
SRO.01
Field Separator
SRO.02
Relay Optics
SRO.03
Image Slicer Sub-System
ISS
Image Dissector Array (IDA)
ISS.01
Focusing Mirror Array (FMA)
ISS.02
Pupil Slit Mask
ISS.03
ISS Support
ISS.04
Spectrograph Sub-System
SPS
Collimator
SPS.01
Volume Phase Holographic Grating (VPHG)
SPS.02
Camera
SPS.03
Field Lens Window
SPS.04
Detector Vessel
DV
Detector Head
DV.001
Cooling Unit
DV.002
Vacuum and Cryogenic System
VCS
Vacuum System
VCS.01
Cryogenic System
VCS.02
Instrument Main Structure
IMS
Central Frame
IMS.01
Mount to Nasmyth Platform
IMS.02
Structure Control System
IMS.03
Instrument Control Electronics
ICE
Power & LAN distribution
ICE.01
Cabinets & Chassis
ICE.02
Cabinet Cooling
ICE.03
Cabling
ICE.04
Temperature Monitoring
ICE.05
Interlocks
ICE.06
LCU N°1 (CU)
ICE.07
LCU N°2 (FO)
ICE.08
Detector Control Electronics
ICE.09
Vacuum and cryogenics Control Electronics
Instrument Software
INS
Detector Control Software
DCS
Instrument Control Software
ICS
Maintenance Software
MS
Observation Software
OS
Science Software
SCS
Data Reduction Software
DRS
Exposure Time Calculator
ETC
Observer Support Software
OSS
Instrument Numerical Model
INM
Data Analysis Software Tools
DAST
NOVA
AIP
LAOMP
IAG
CRAL
ESO/ODT
ETH
------ : Preliminary
..... : Not Deliverable

Spectrograph

- *Cheap Glasses*
- *Axial chromatism corrected by CCD and field lens window tilt*
- *Image Quality*
  - *85% ensquared energy within 15x30 µm (30x30 µm at 0.465 µm)*
- *Athermal design*
  - *dZ/DT = 0.04µm/°C*



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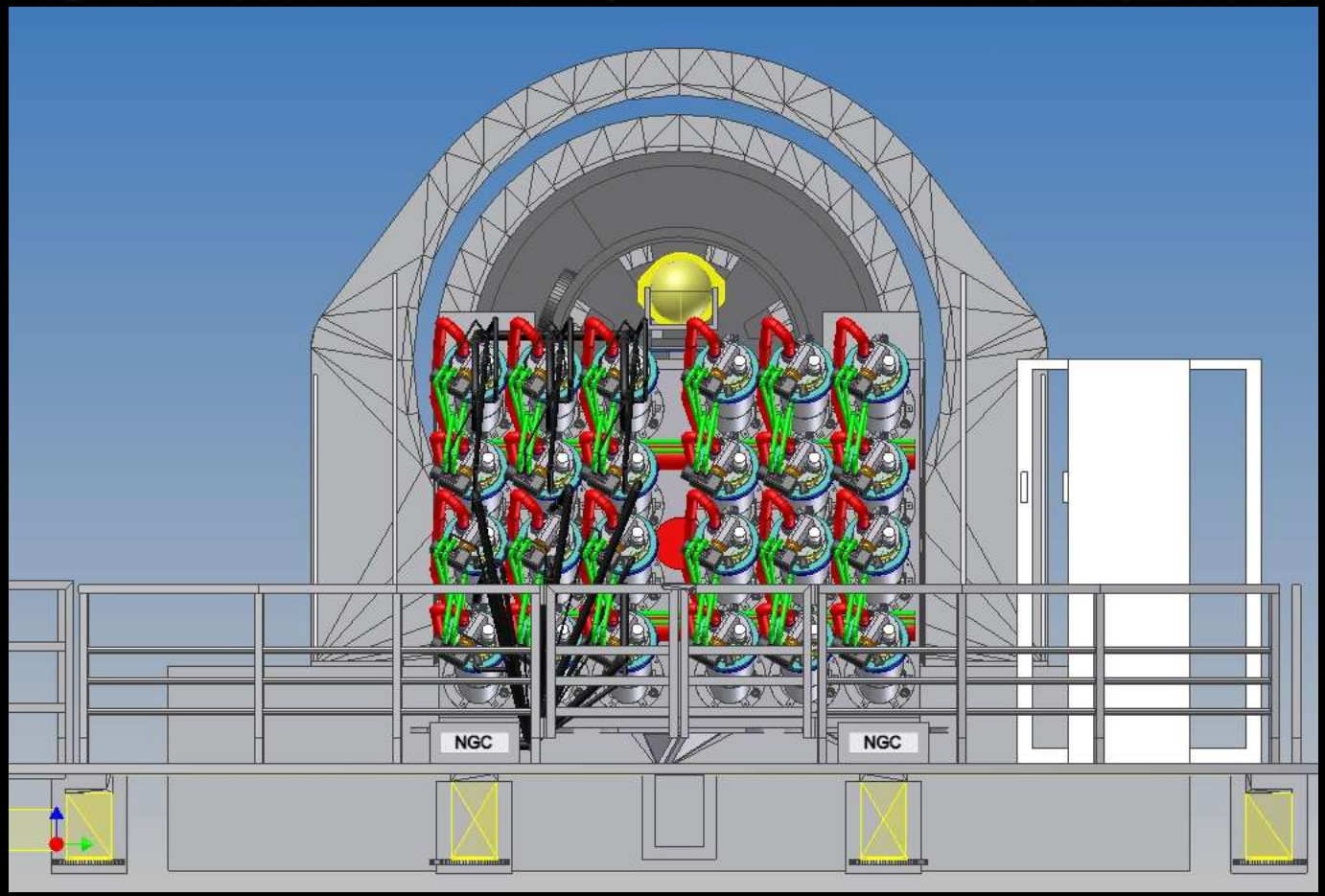
MUSE



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Maintenance

- *No moving part in the 24 IFUs*
- *Few moving parts in the Fore Optics*
  - *Filter*
  - *Derotator*
  - *Shutter*
  - *ADC in NFM*
  - *NFM/WFM switch*
  - *Imaging mirror*

The MUSE Collaboration

Roland Bacon (PI), Bauer S., Boehm P., Boudon D., Brau-Nogué S., Caillier P., Capoani L., Carollo C.M., Champavert N., Contini T., Daguisé E., Dallé D., Delabre B., Devriendt J., Dreizler S., Dubois J., Dupieux M., Dupin J.P., Emsellem E., Ferruit P., Francois M., Franx M., Gallou G., Gerssen J., Guiderdoni B., Hahn T., Hofmann D., Jarno A., Kelz A., Koehler C., Kollatschny W., Kosmalski J., Laurent F., Lilly S.J., Lizon J.L, Loupias M., Manescau A., McDermid R.M., Monstein C., Nicklas H., Parès L., Pasquini L., Pécontal-Rousset A., Pécontal E., Pello R., Petit C., Picat J-P., Popow E., Quirrenbach A., Reiss R., Renault E., Roth M., Schaye J., Soucail G., Steinmetz M., Stroebele S., Stuik R., Weilbacher P., Wisotzki L., Wozniak H., de Zeeuw P.T.

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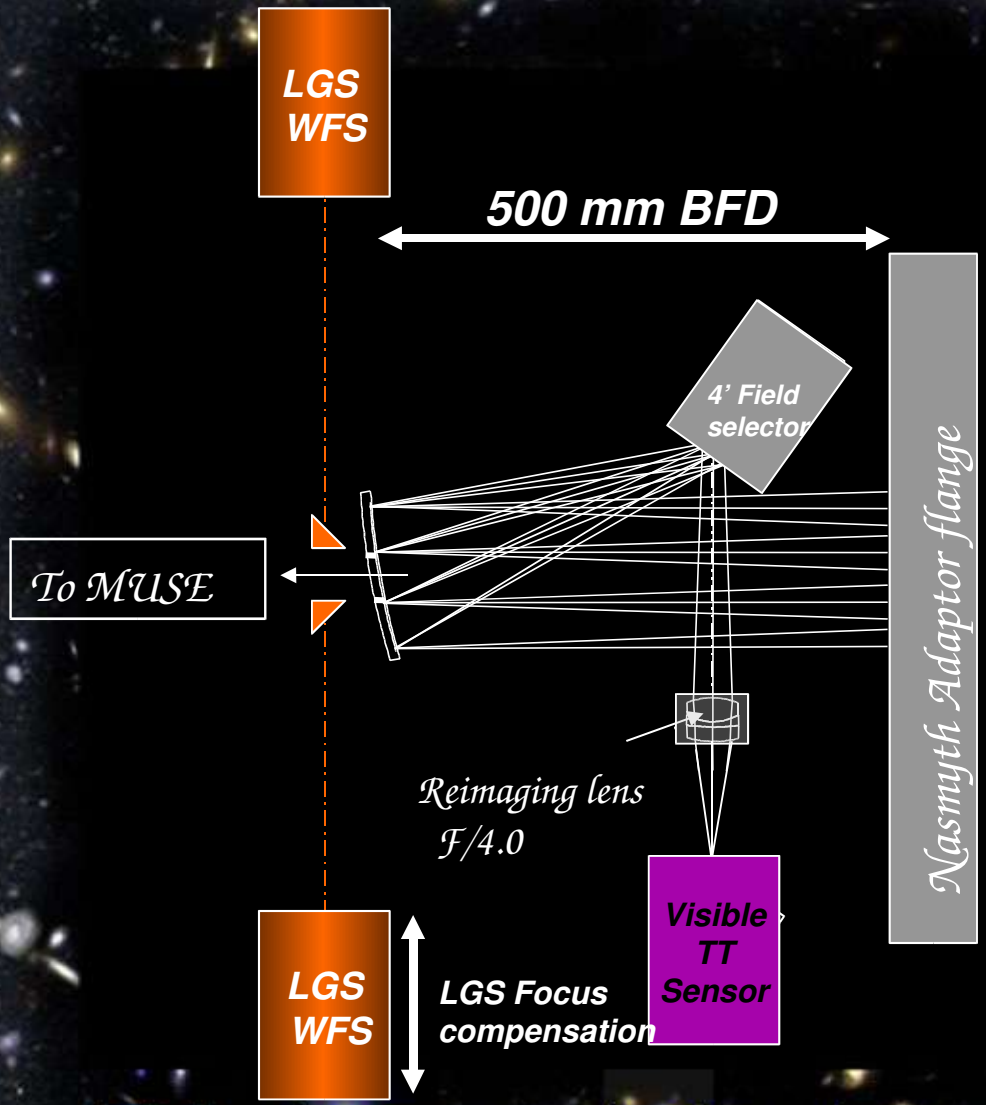
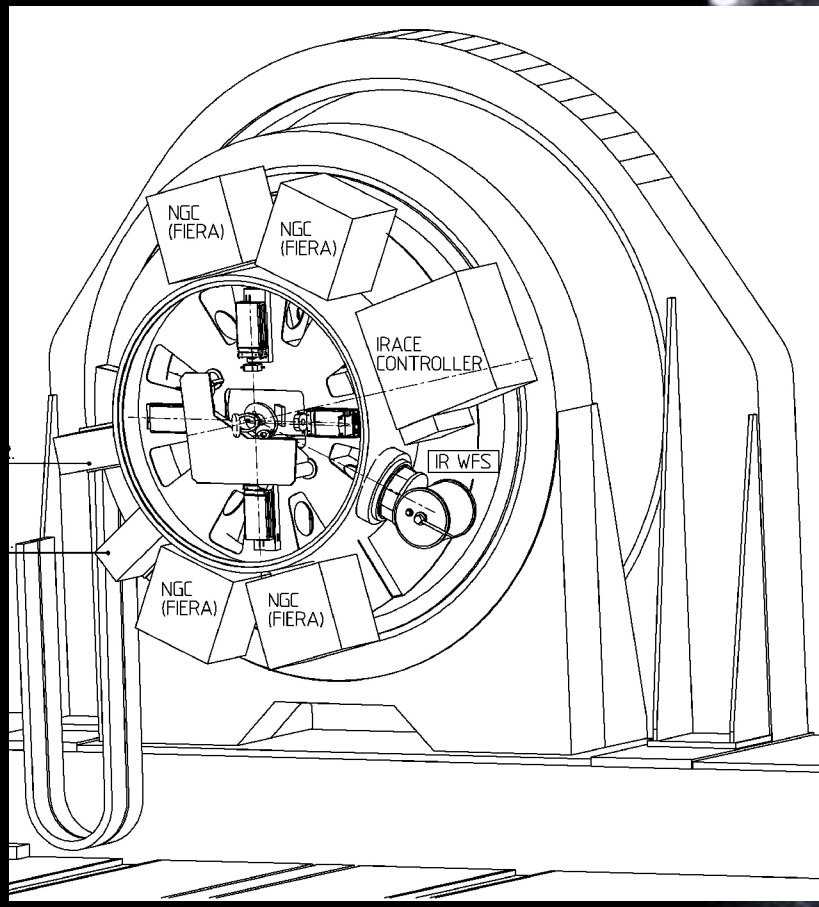
GALACSI Opto-Mechanics





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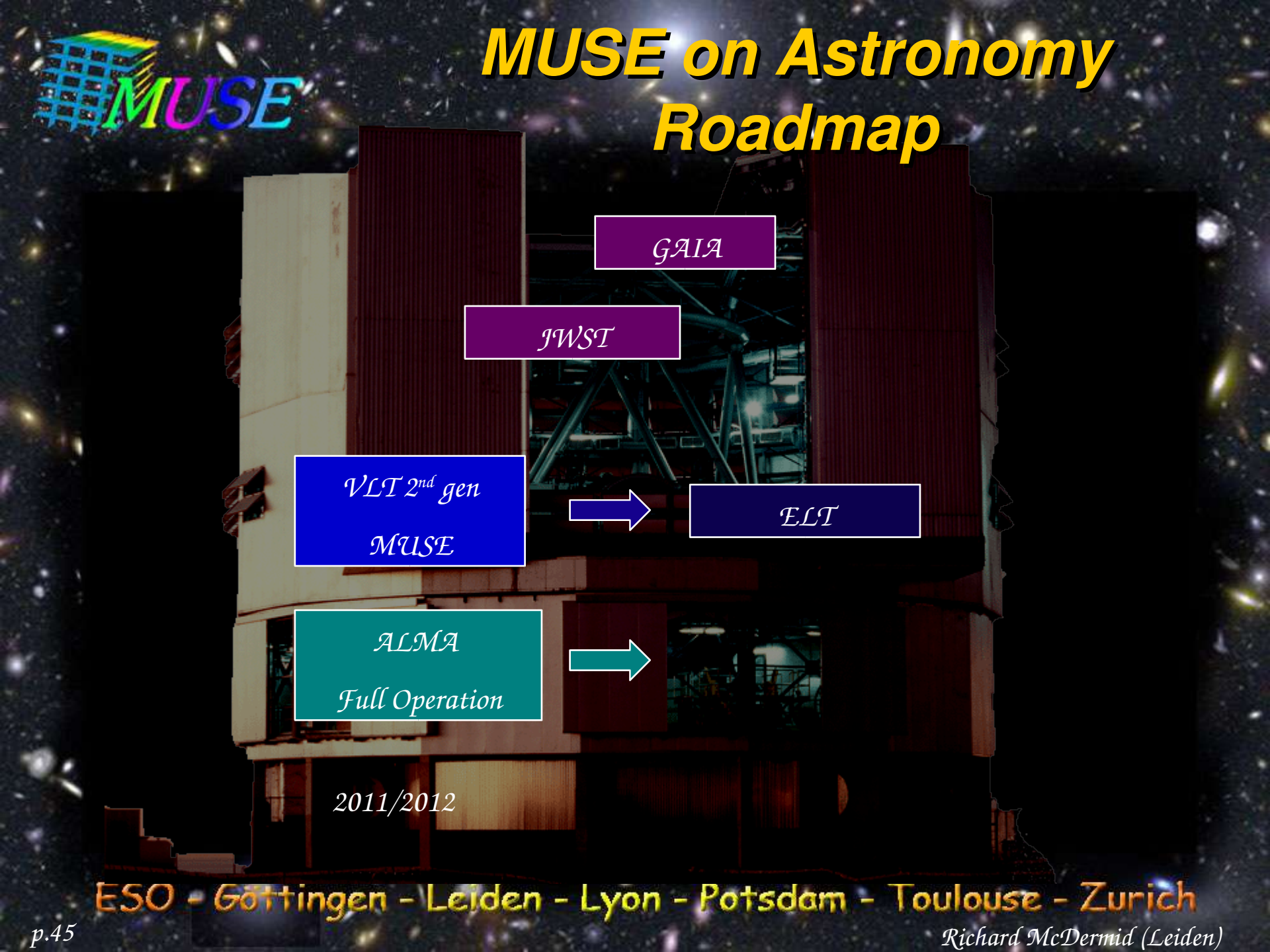
MUSE on Astronomy Roadmap



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