Future Integral Field Spectrographs (at large telescopes)

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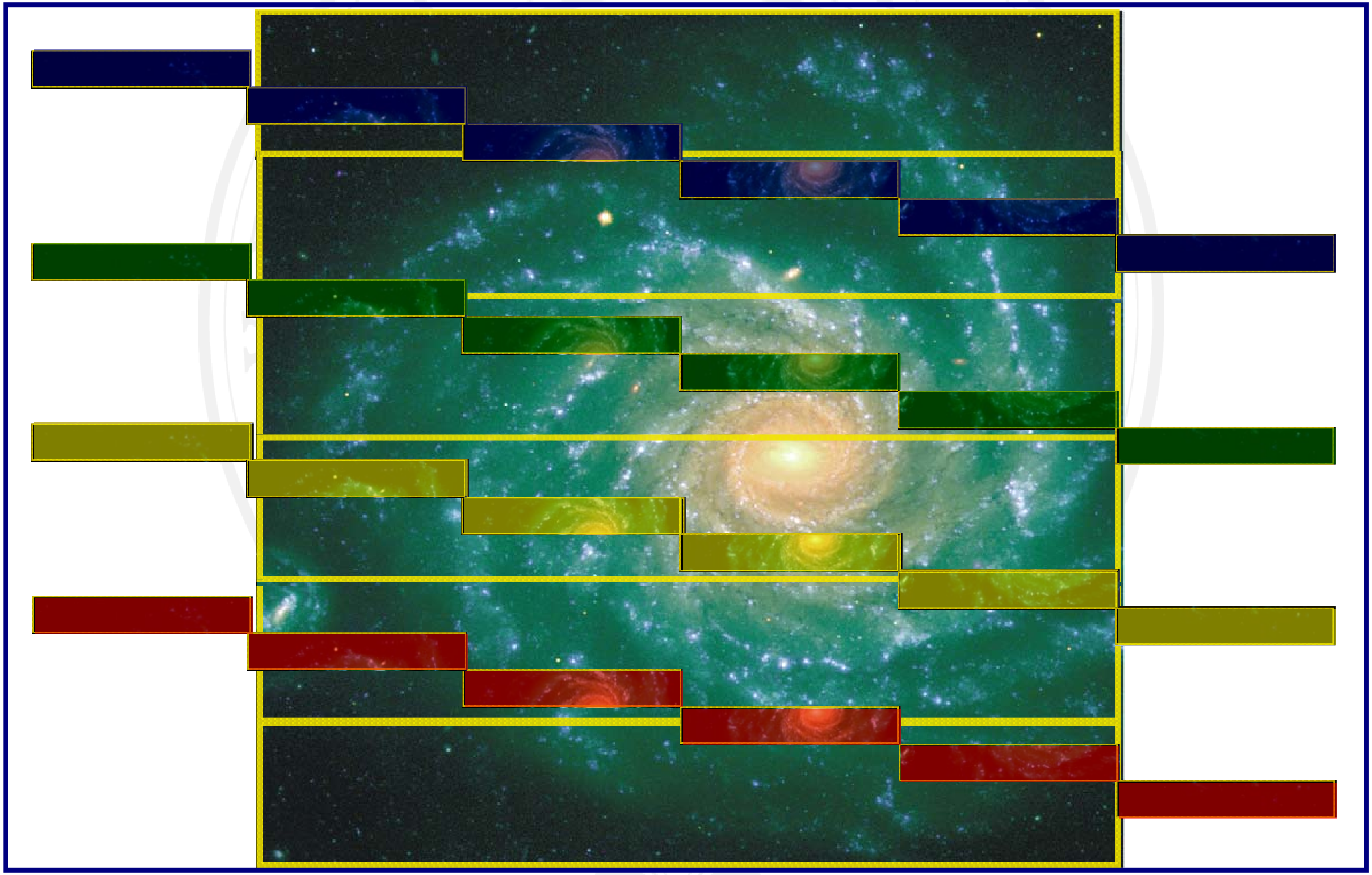
University of Oxford

Acknowledgements to the KMOS, MUSE, SPHERE, IRIS, HARMONI,EAGLE, NIRSpec, MIRI and other instrument consortia.

Proliferation of IFS at many observatories (big and small)

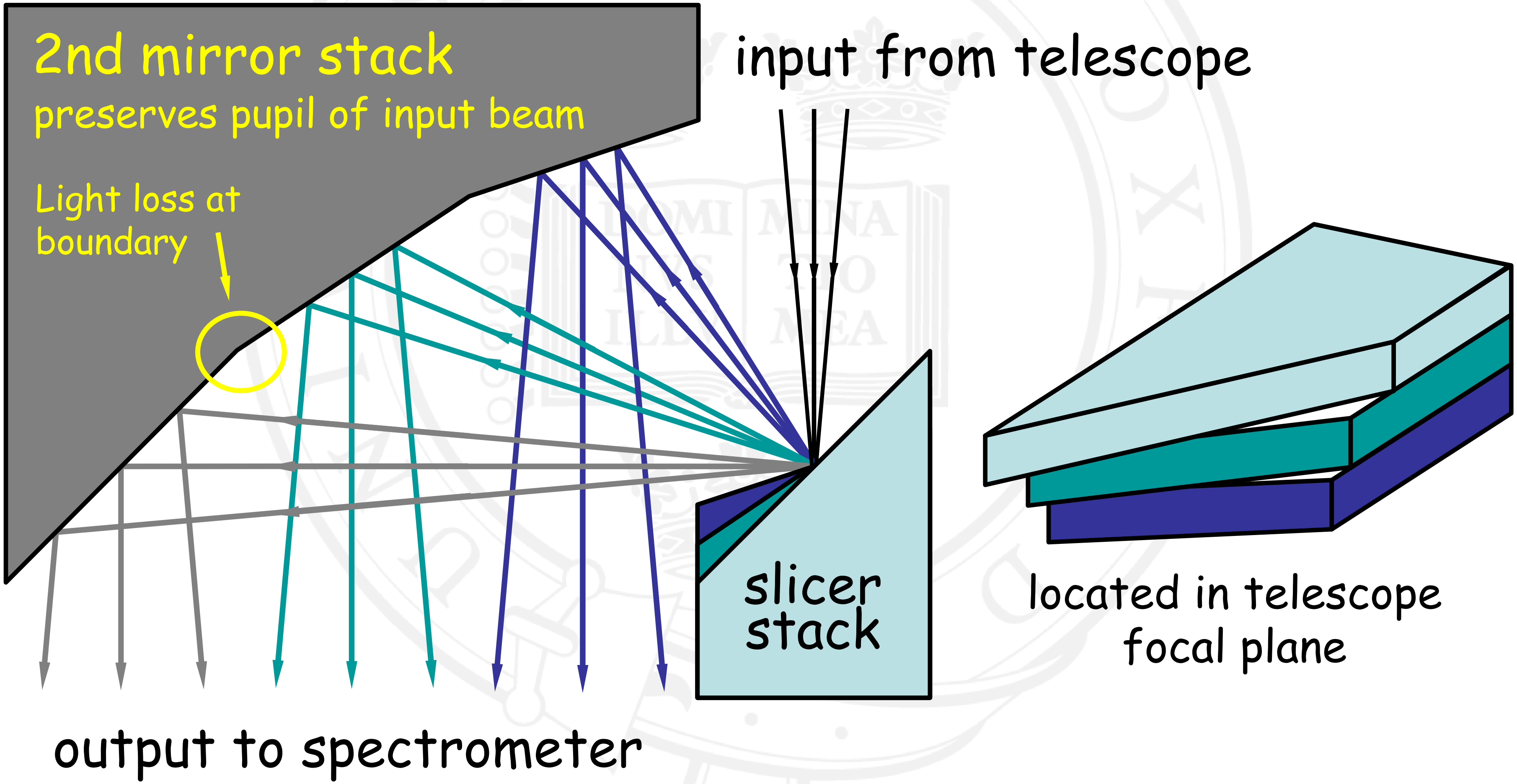
- SINFONI, FLAMES, VIMOS (ESO-VLT); GNIRS, NIFS (Gemini); OSIRIS (Keck); SAURON, OASIS (WHT) ….. to name but a few!
- Bigger and better – larger fields of view, more spaxels, higher throughput.
- More versatile – deployable IFS (warm now, cryogenic soon)
- Special purpose – high contrast planet finding applications
- Other wavelengths – mid-IR (JWST-MIRI), far-IR (Herschel-PACS)

Slicing the Image



Principle of the Image Slicer

(used in SINFONI, GNIRS, NIFS)



The Advanced Image Slicer

- Advanced image slicer (Content 1998) uses power on slicing and pupil mirrors to reduce slit length.
- Additional field optics required to place exit pupil at correct location

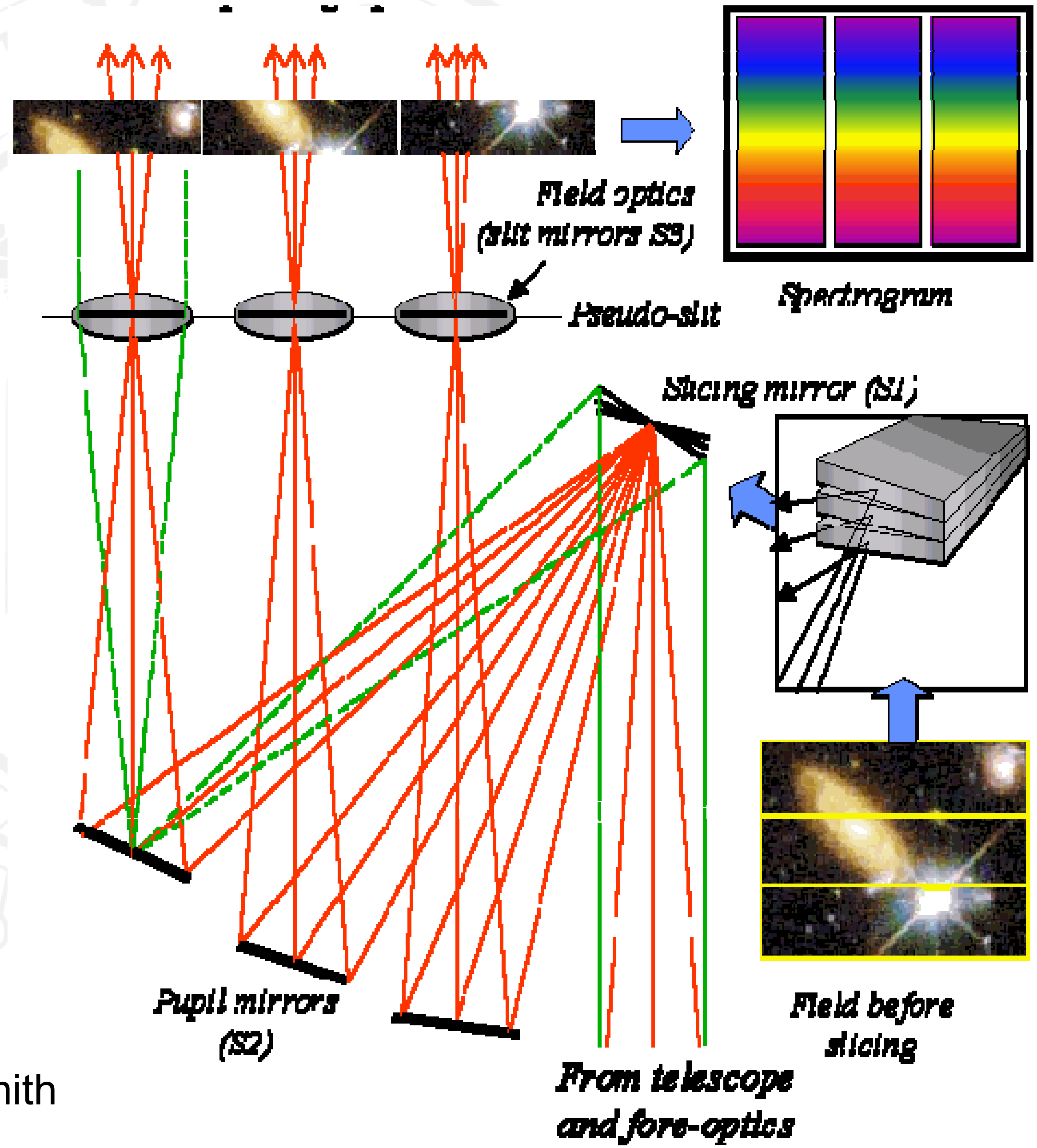
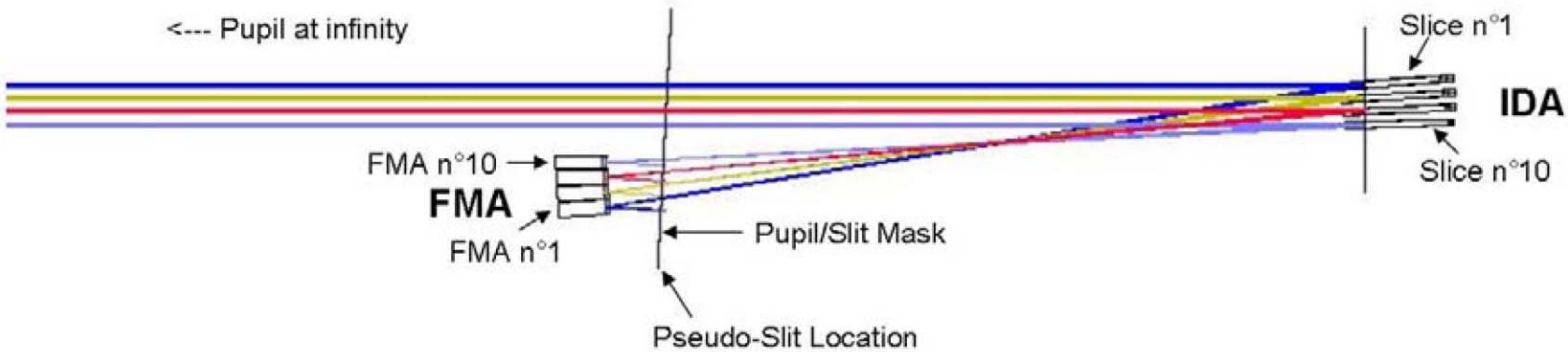
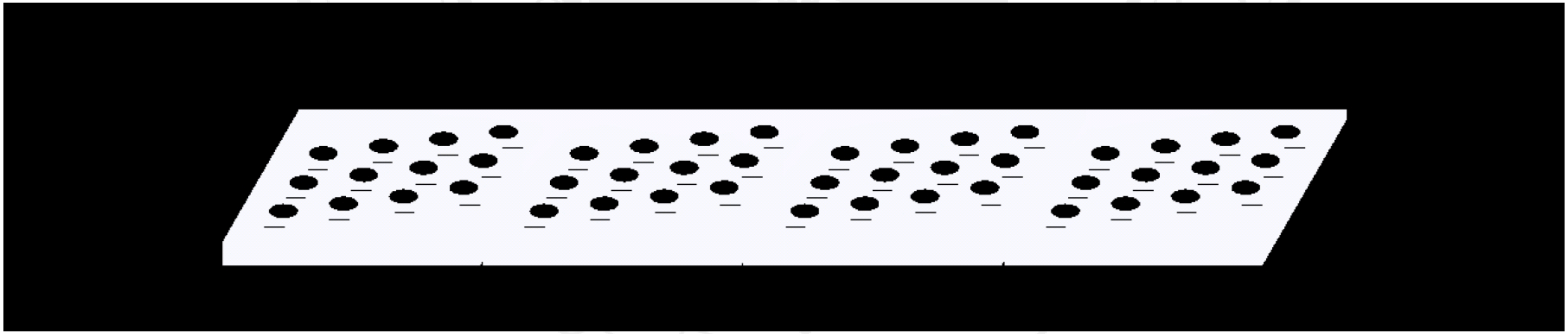


Figure courtesy J. Allington-Smith

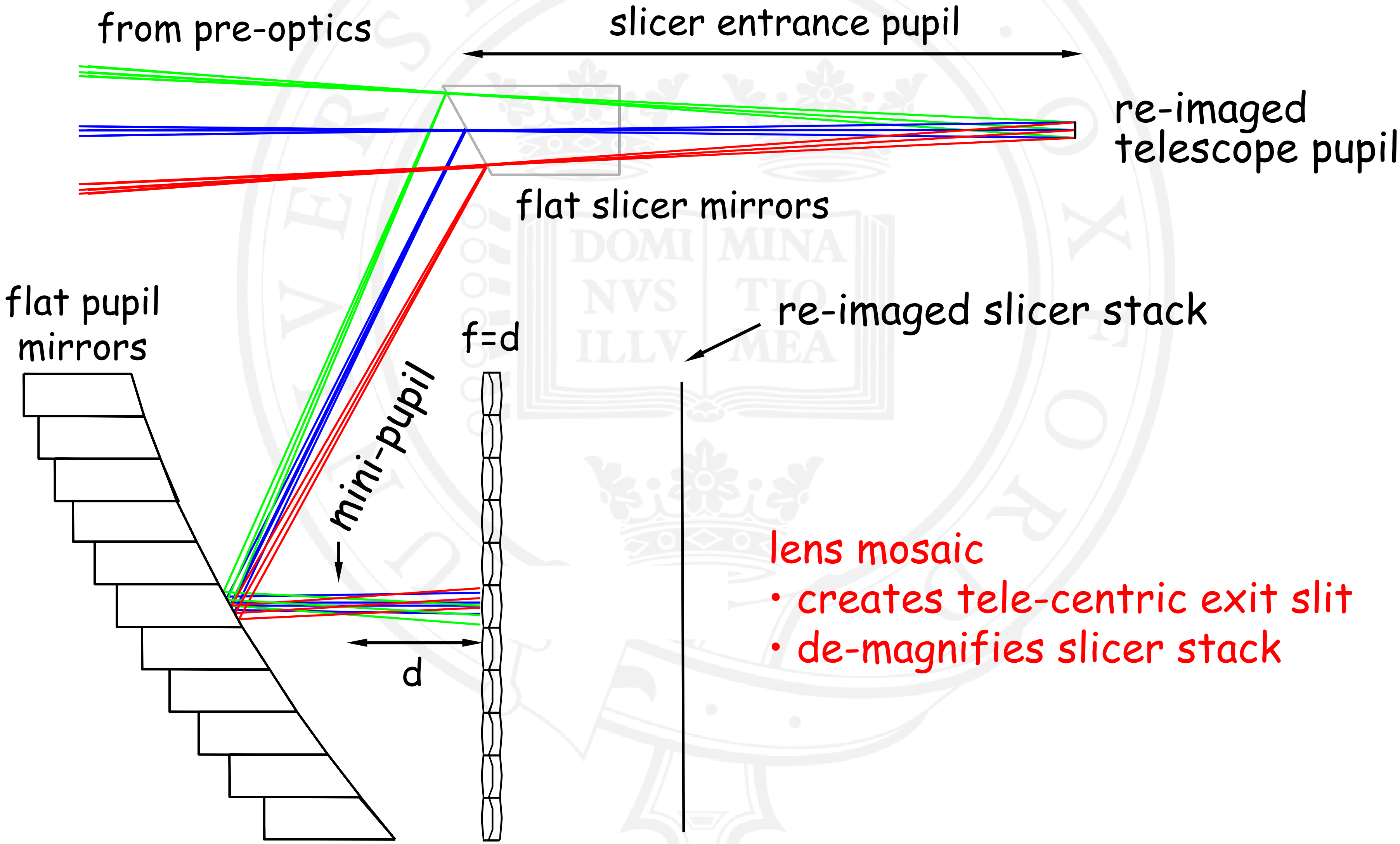
The MUSE image slicer





courtesy MUSE project (Bacon, Laurent, et al.)

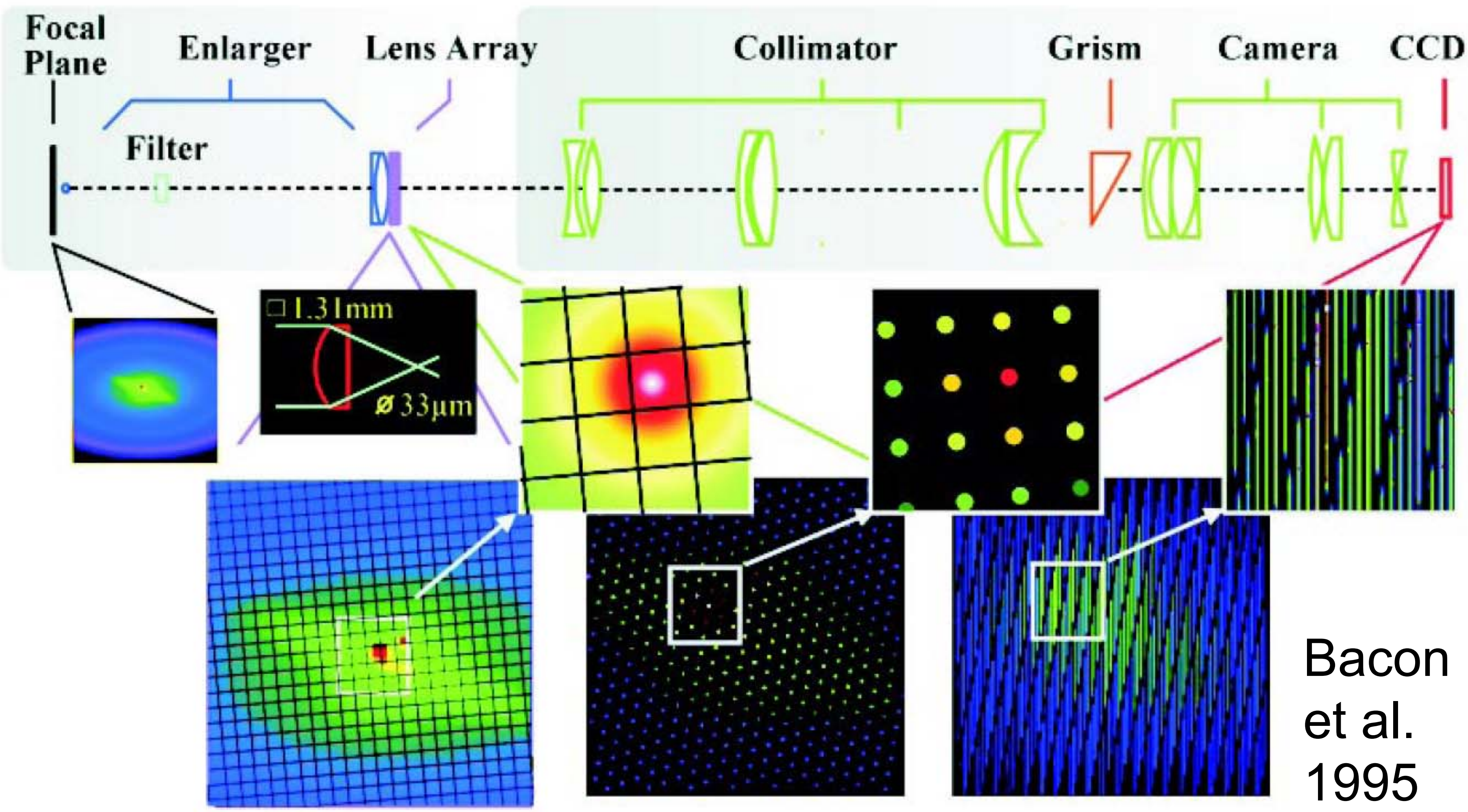
Image Slicer with de-magnification



lens mosaic

- creates tele-centric exit slit
- de-magnifies slicer stack

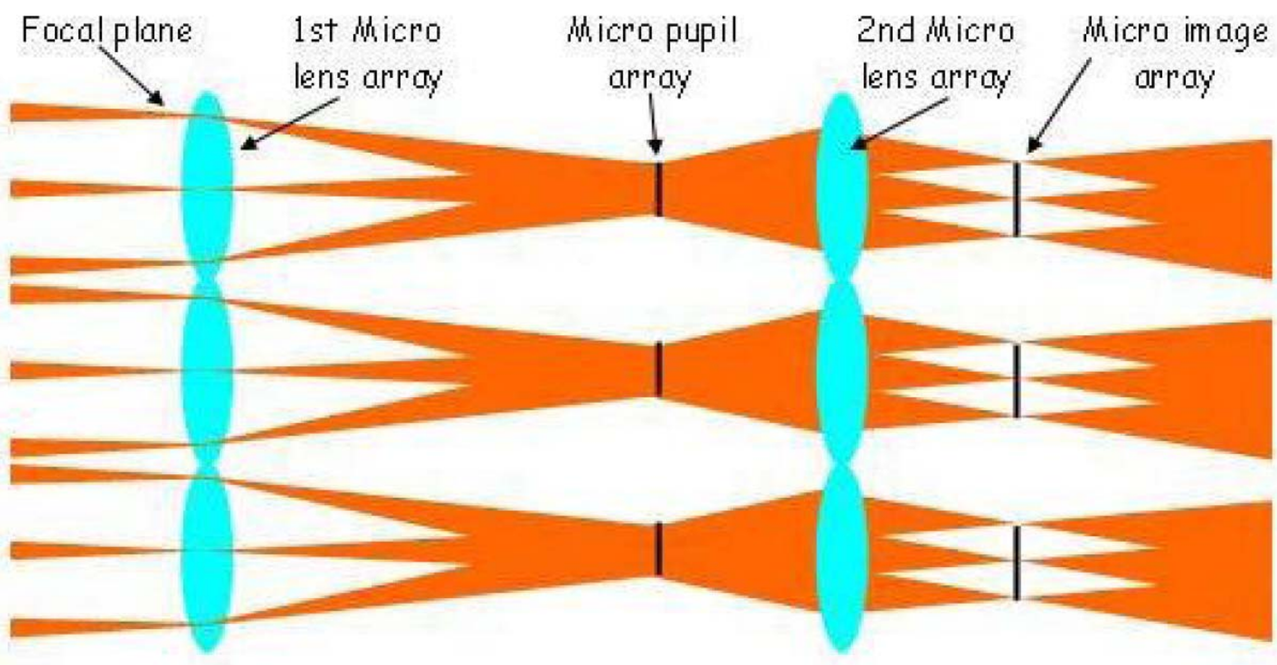
The TIGRE concept (also SAURON, OASIS, OSIRIS)



Bacon et al. 1995

The BIGRE concept

- Second set of lenslets to create dispersed focal planes rather than pupil planes. Necessary to avoid diffraction effects



Gratton, Antichi, et al. 2007

KMOS (VLT)

What is KMOS ?

- KMOS is a multiple-object cryogenic integral field spectrograph designed for intermediate resolution spectroscopy in the 0.8-2.5μm range
- 24 robotic pickoff arms patrol a 7.2 arcmin diameter field each of which feeds 2.8x2.8 arcsec FoV sampled at 0.2 arcsec to an image slicing IFU
- The IFUs are consolidated in groups of 8 which feed one of 3 identical spectrographs providing R~3500 spectra in the IZ, J, H & K bands

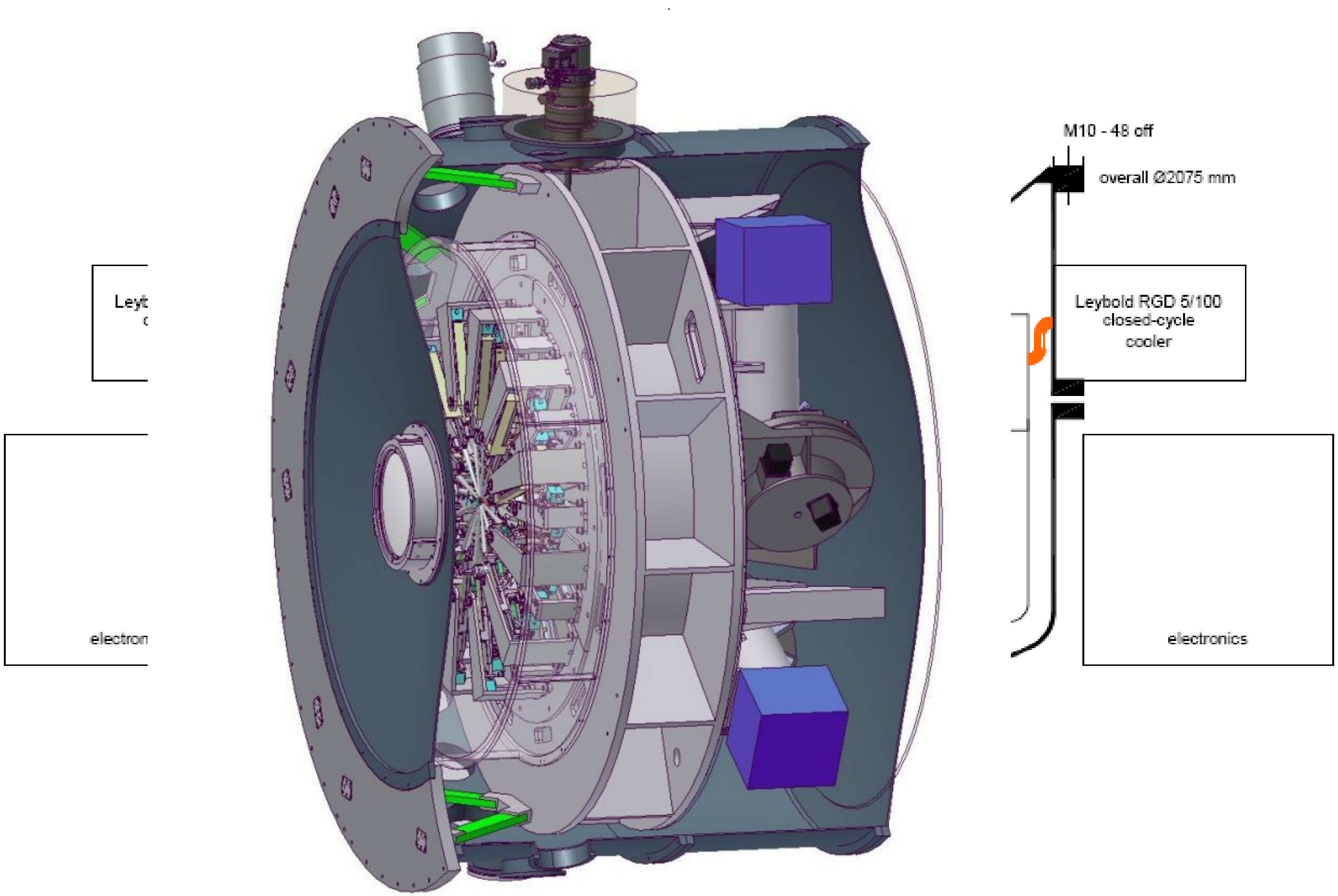
Top Level Scientific Drivers (KMOS)

- Investigate the physical processes which drive galaxy formation and evolution over redshift range $1<z<10$.
- Map the variations in star formation histories, spatially resolved star-formation properties, and merger rates
- Obtain dynamical masses of well-defined samples of galaxies across a wide range of environments at a series of progressively earlier epochs

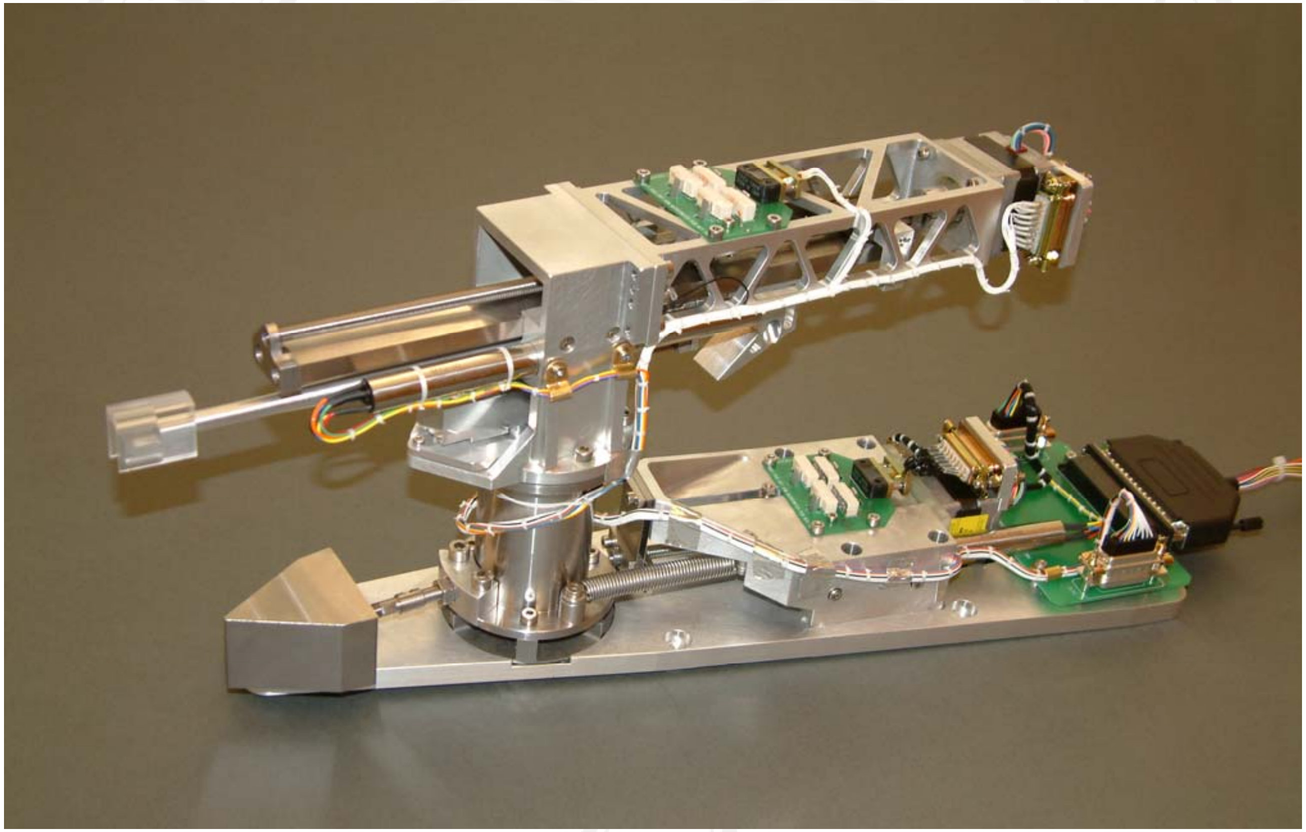
KMOS Science Cases

- How did galaxies form ?
- How did galaxies grow ?
- What are their masses as function of time ?
- How did galaxies acquire their angular mom. ?
- How does metallicity grow with time ?
- What is the role of mergers ?
- What is the role of AGN/feedback
- What is the role of environment ?

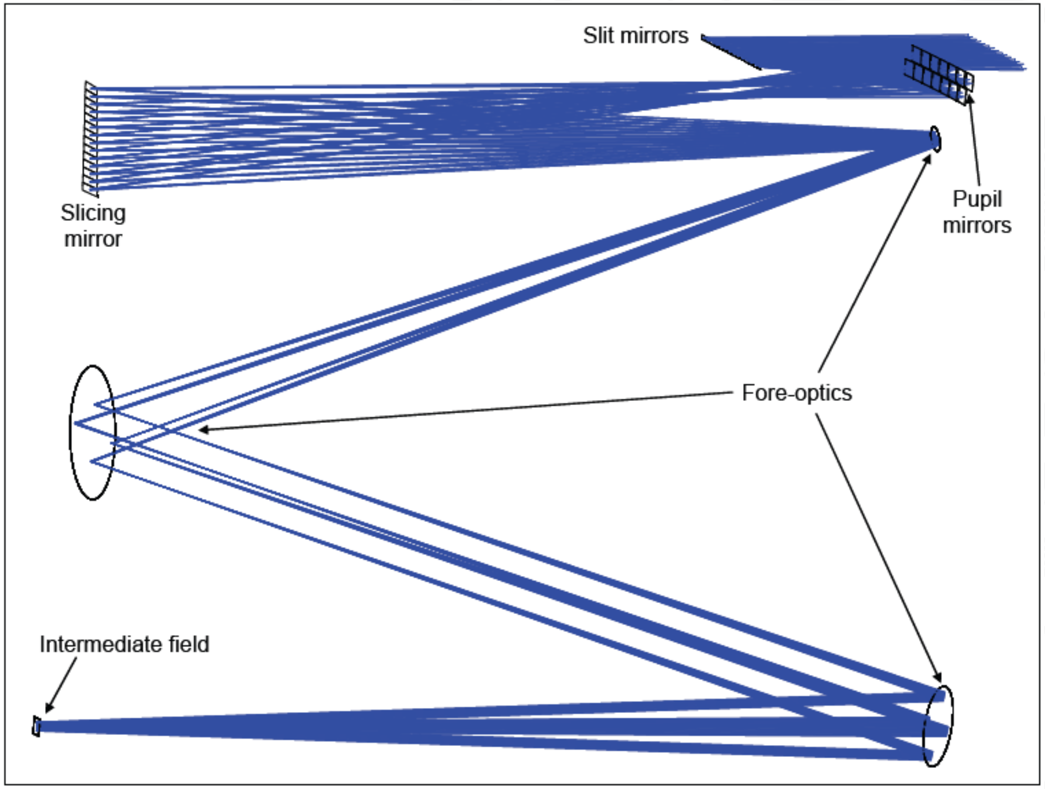
Systems Architecture

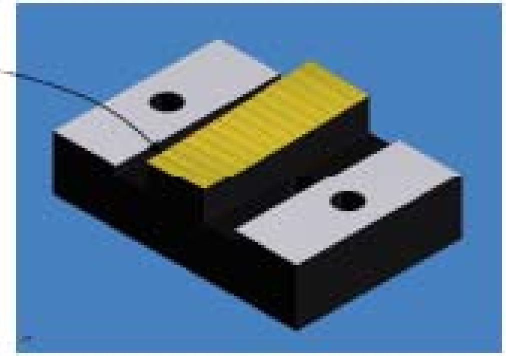


Prototype Pickoff Arm

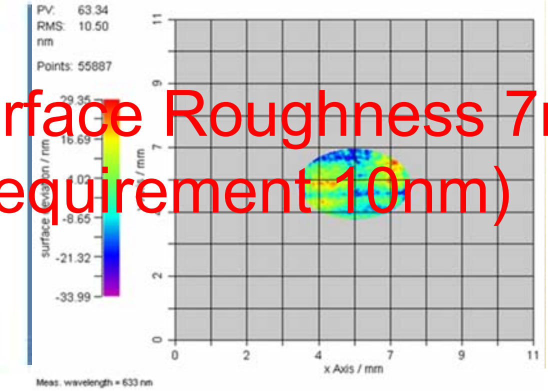


Integral field units



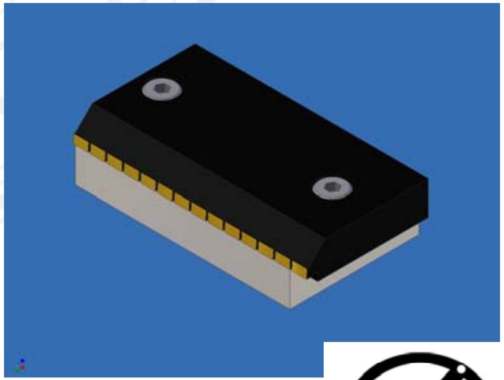


Slicing mirror



Surface Roughness 7nm (Requirement 10nm)

Pupil mirror



Slit mirror

3 identical sets of 8 IFUS
4 foreoptics designs (aspheric)
24 identical image slicer assemblies

Status and Schedule

- Phase B start July 2004
- Preliminary Design Review May 2006
- Final Design Review Sep 2007
- Prelim Acceptance Europe Sep 2010
- Prelim Acceptance Chile Mar 2011

MUSE (VLT)

Instrument Overview

Focus	Nasmyth B UT4
Deformable Secondary Mirror	1170 actuators
Laser guide stars	4 x 5-10 Watts
Instrument	Integral Field Spectrograph
Number of IFU units	24
Detectors	4k x 4k Deep depletion CCD
Simultaneous Wavelength Range	480 – 930 nm (nominal) 465 – 930 nm (extended)
Resolving Power	1750@465nm – 3750@930nm
Datacube Size	1570 MB

Wide Field Mode

Field of View	1x1 arcmin^2
Spatial Sampling	0.2x0.2 arcsec^2
Spectra/Exposure	90,000
Sky Coverage in AO	70% @ galactice pole 99% @ galactic equator
AO Energy gain wrt seeing	x2

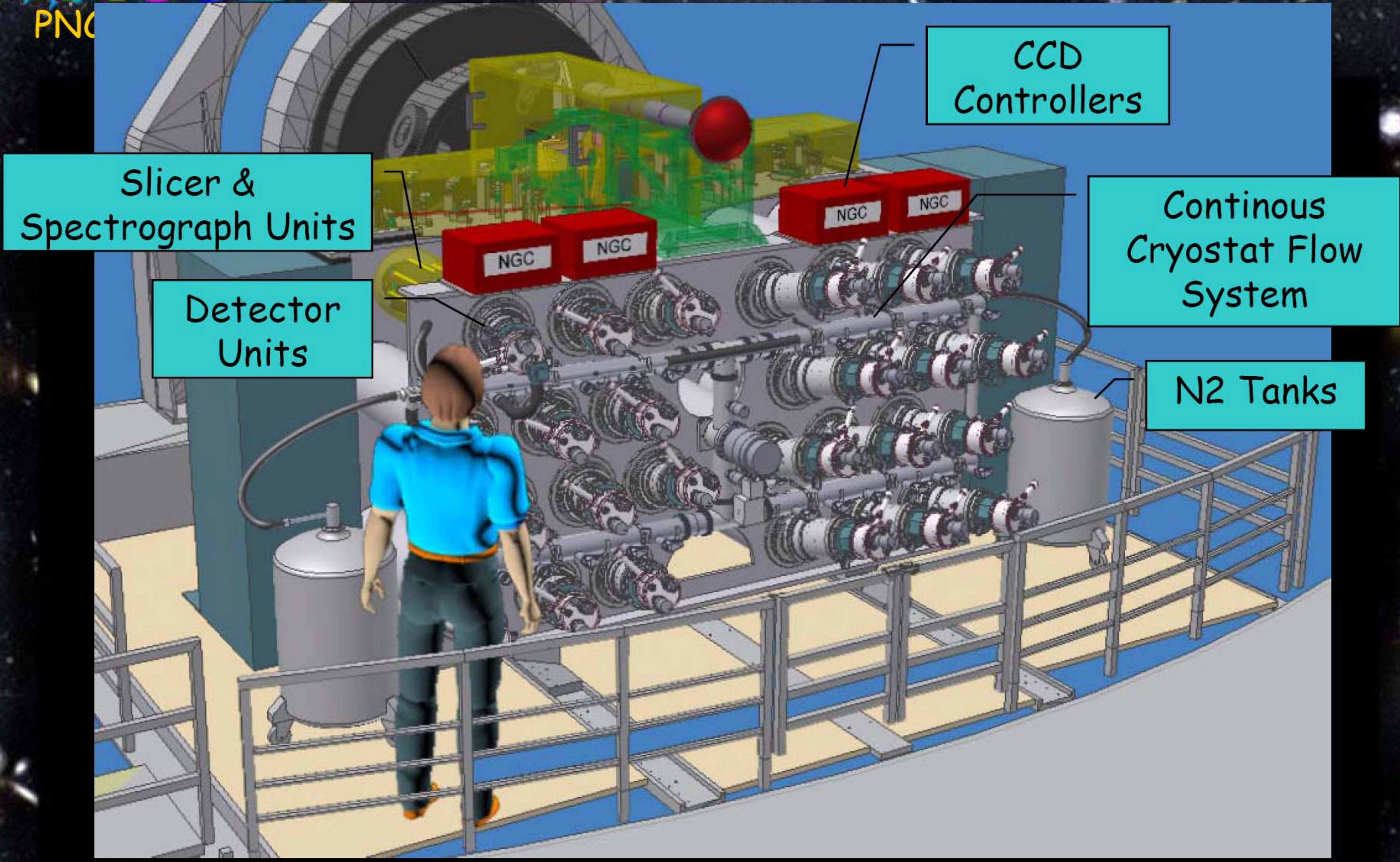
MUSE

Narrow Field Mode

[redacted]

Field of View	7.5x7.5 $arcsec^2$
Spatial Sampling	25x25 $milliarcsec^2$
Spectra/Exposure	90,000
Spatial resolution	5-10% Strehl Ratio @ 650nm 10%-20% Strehl Ratio @ 850nm

Instrument Design (2)



MUSE

Project Planning

[redacted]

Pre-Phase A & Phase A

2001	2002	2003	2004

- ESO Call for Idea
- KO phase A
- CDR
- Council Approval

Design Phase

2005	2006	2007	2008

- KO Jan.
- OPDR July
- PDR July
- OFDR Dec.
- FDR Nov.

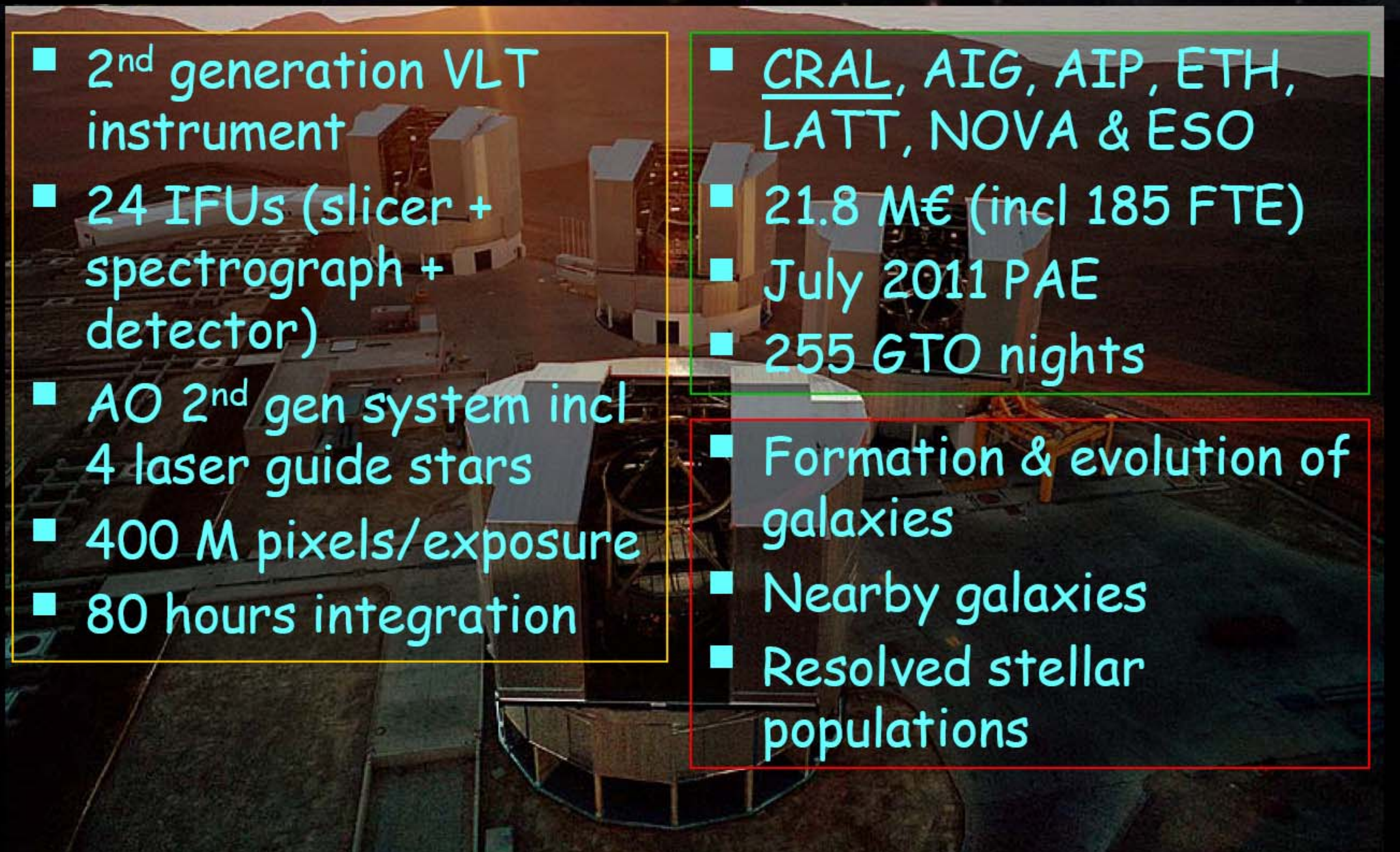
MAIT Phase / Commissioning

2009	2010	2011	2012

- IFU MIA Feb.
- S/S MIA Oct.
- PAE July
- PAC July

MUSE fast facts

[redacted]



- 2nd generation VLT instrument
- 24 IFUs (slicer + spectrograph + detector)
- AO 2nd gen system incl 4 laser guide stars
- 400 M pixels/exposure
- 80 hours integration

- CRAL, AIG, AIP, ETH, LATT, NOVA & ESO
- 21.8 M€ (incl 185 FTE)
- July 2011 PAE
- 255 GTO nights

- Formation & evolution of galaxies
- Nearby galaxies
- Resolved stellar populations

IRIS (TMT)

IRIS team

UCLA
(lenslet spectrograph and system)

John Cranfield
Glenn Fox
James Larkin (PI)
Ian Maclean
Alex Vaucher
Jason Weiss

CALTECH
(Slicer spectrograph, IRIS WFS)

Anna Moore (co-PI)
Rich Dekany
ME

UCSC
(ADC and Spectrograph optics)

Brian Bauman
Drew Phillips

Subaru
(Imager)

Tomonori Usuda
Masahiro Konishi
Ryuji Suzuki

HIA
(IRIS WFS, interface)

David Loop
Joeleff Fitzsimmons
Murray Fletcher
James Stilburn

IRIS Science Team

TBA (next week!)

courtesy Anna Moore (Caltech)

IRIS Requirements

- Spectrograph
  - Wavelength Range 0.8-2.5 microns
  - Spectral Resolution > 3500
  - Bandwidth: Complete bands at one time ~20%
  - IFS with Four Plate Scales
    - 0.004, 0.010, 0.025, 0.050 arcsec per sample
    - FOV > 64x64 spatial samples
      - 0.25"x0.25" to 3.2"x3.2"
  - >8,000,000 spatial/spectral pixels
- Imager
  - >15 arcsec field of view
  - 0.004 arcsec plate scale
  - Wavefront Error < 30 nm
  - Distortion correctable to 50 microarcsec.
  - Atmospheric Dispersion Correction < 1 milliarcsec

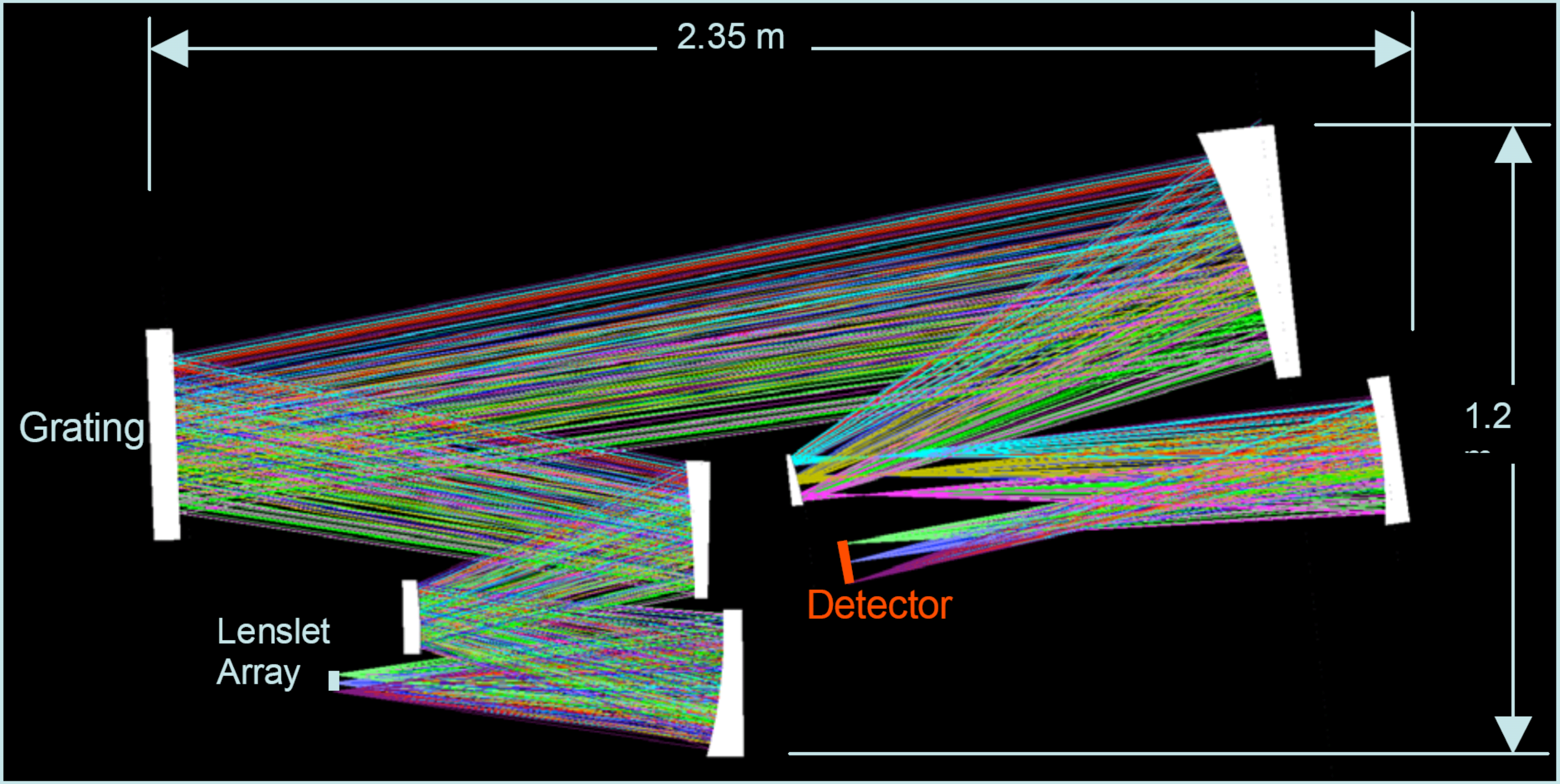
courtesy Anna Moore (Caltech)

Lenslet and Slicer Spectrograph

- Lenslet spectrograph offers excellent image quality (low wfe)
  - 0.004” and 0.009” scales
- Slicer offers 2x larger field of view and higher SNR
  - 0.025” and 0.050” scales

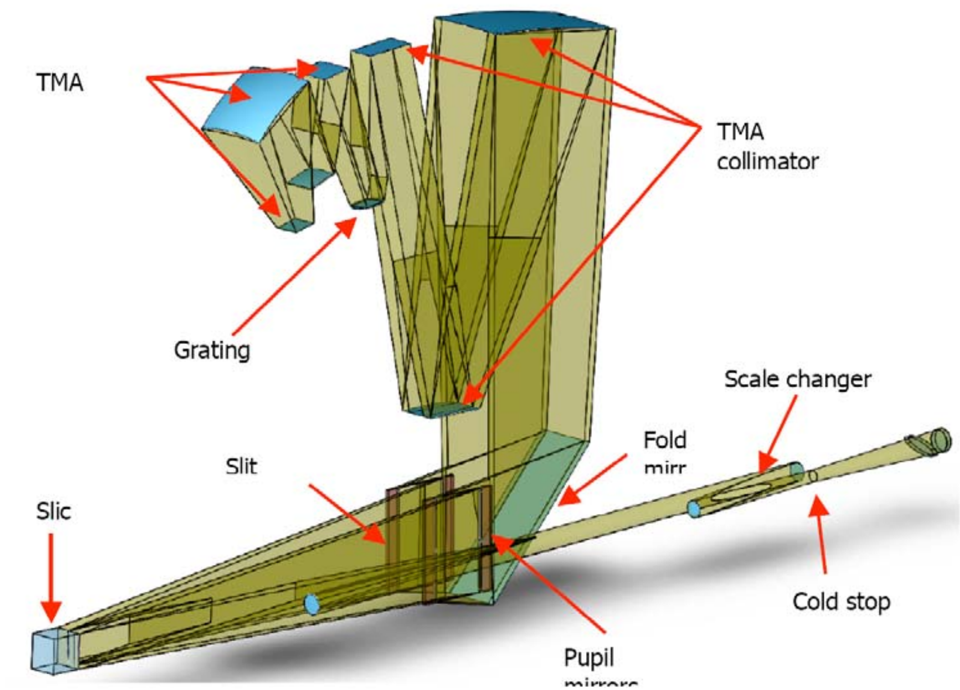
courtesy Anna Moore (Caltech)

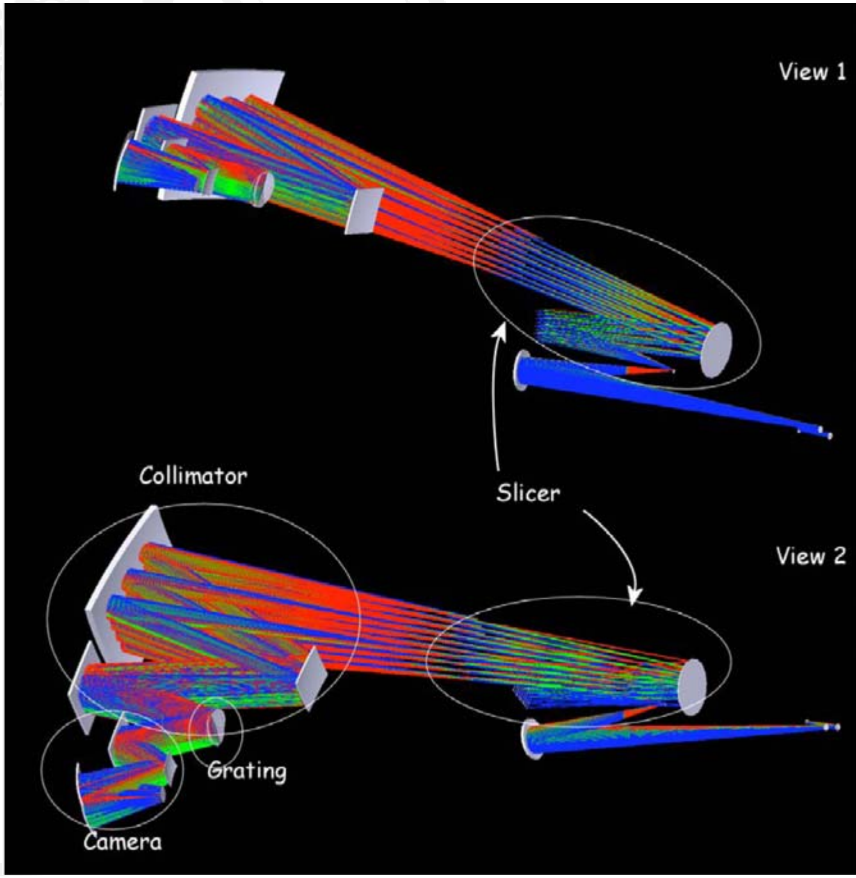
Lenslet design from IRIS feasibility study



courtesy Anna Moore (Caltech)

Slicer design from IRIS feasibility study





courtesy Anna Moore (Caltech)

IRIS Status

- Completed Feasibility study March 2006
- Now starting Conceptual study.
- Concept design review May 2009
- Goal is to deliver to HIA for integration with AO system in 2013.
- On sky 2016.

courtesy Anna Moore (Caltech)

HARMONI (E-ELT)

HARMONI: A single field, wide band, integral-field spectrograph for the E-ELT

HARMONI is a proposed optical-NIR, adaptive optics assisted, integral field spectrograph designed to exploit the early-light capabilities of the European ELT

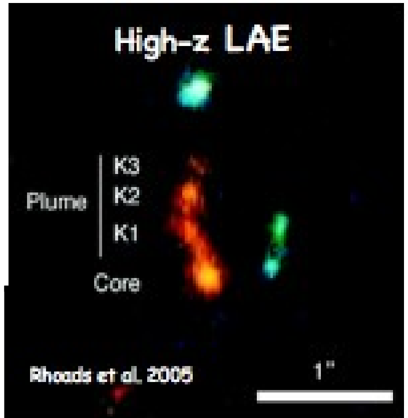
Phase A study: March ‘08 — Dec ’09

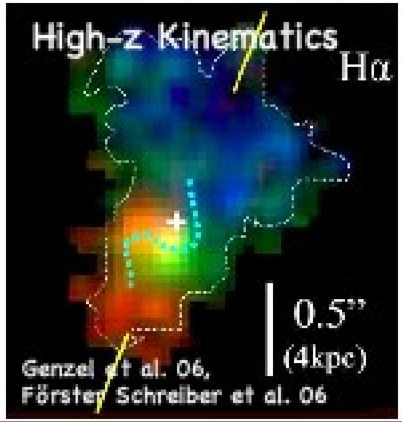
Oxford Physics

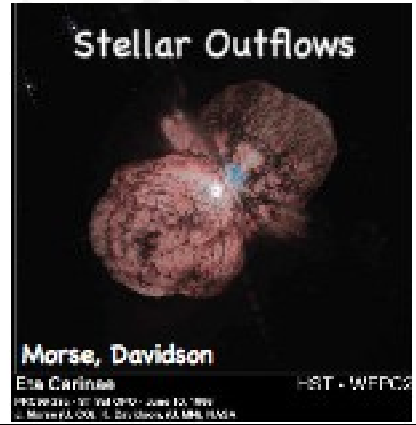
Science & Technology Facilities Council
UK Astronomy Technology Centre

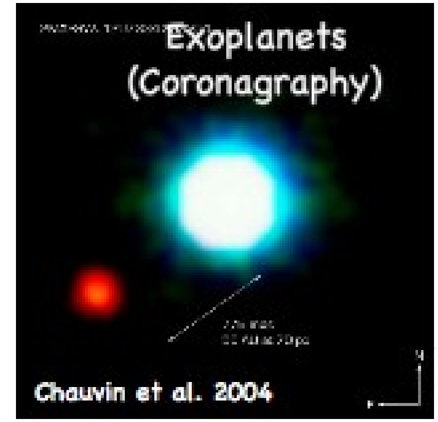
CSIC

CRA Lyon









DL, NIR Imager	imaging	Nasm./LTAO , MCAO	0.9-2.5	>30"	4	wide, n. bands	~ all	ONIRICA @ OWL
Narrow Field Spectrograph	spectroscopy	Nasm./SCAO , LTAO	0.6-2.5	1"/ 10":	20 / 50	3000, 20000:	~ all	Not studied
High Resolution Vis Spectrograph	spectroscopy	Coude/ GLAO	0.4 -0.8	Point source	=	150000	C2, C7	CODEX
Planetary Imager Spectrograph	imaging, spectroscopy	Nasm/ EXAO	0.6-1.75	~2" V ~4" H	>= Nyquist	>15	S3, S9	EPICS
NIR MOS	spectroscopy multiplex 20	Grav. Inv./ MOAO	0.8-2.5	>= 5'	30 - 50	3000 10000:	C4, C10	WFSPEC, MOMSI
NIR MOS, DL	Spectroscopy multiplex 20	Grav. Inv. or Nas/MCAO	0.8-2.5	>30"	1 - 30	3000 - 20000	G4, C9	MOMSI
MIR Imager	imaging (+limited spectroscopy	Nas or IF/ SCAO or LTAO	Mar-20	30"	6 - 20	w-n bands	S3, S9, S5, G9, C10	MIDIR

- Proven instrument concept delivering high quality science
- Early spectroscopic instrument to follow up faint sources discovered in deep imaging surveys (e.g. JWST), which is only possible with an ELT
- Narrow-field-of-view matched to early AO capabilities — near-diffraction limited over a small field
- Single object mode rather than survey mode à la MUSE

Single-Field Wide-Band Spectrograph (SFWBS)

Primary mode

- Integral Field
- Medium Spectral Resolution
- NIR
- GLAO & LTAO/MCAO

Optional modes

- Visible-red wave bands
- High Spectral Resolution

SPIFFI/SINFONI

- NIR: 1.0-2.5μm
- ≈ 2000 spectra
- R ≈ 2000 - 4000
- 0.25” - 0.025”
- 8”x8” - 0.8”x0.8”
- VLT/SINFONI AO module

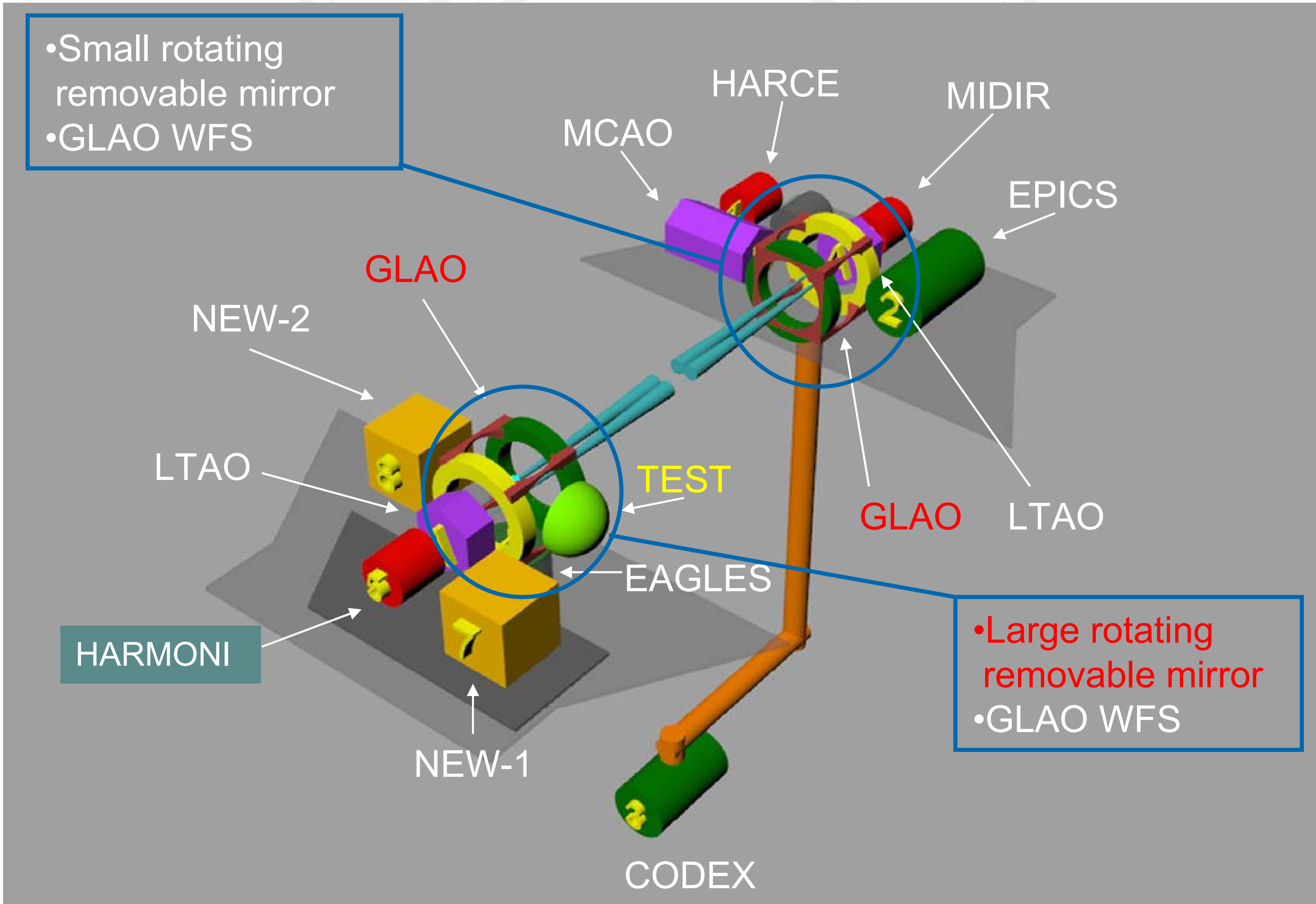
SWIFT

- I/z: 0.65-1.0μm
- ≈ 4000 spectra
- R ≈ 4000
- 0.235” - 0.08”
- 22”x10” - 7.5”x3.5”
- Palomar 5m / PALAO

Baseline Instrument Specifications

Field of view	5-10", likely 2:1 format; ~100x200 spaxels
Spatial pixel scales	At least 3: 50 mas, 4 mas, 15 mas(TBD)
Wavelength range	0.8-2.4μm, visible extension
Spectral resolution	R > 4000, 20000(?)
Simultaneous wavelength coverage	2K-4K spectra possible At least single band at medium/high res; goal: entire spectral range at once
IFU technology	Image slicer? (best fill factor on detector)
Throughput	>35% average, incl. detector Q.E. (similar to SINFONI)
AO performance	GLAO: 3-5x gain in EE in 50 mas spaxel (abs. value 3.7% at K with GLAO!) LTAO: K-60%, J-20%, NGS-19th mag. MCAO: K-50%(uniform), NGS-19th/20th

The E-ELT focal stations

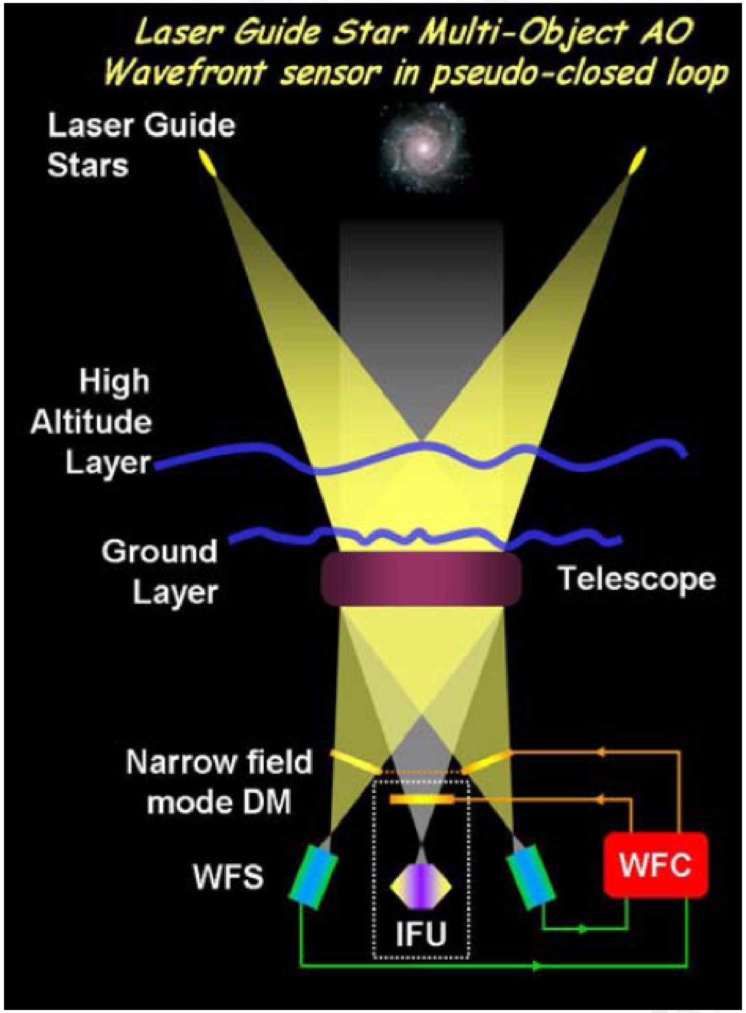


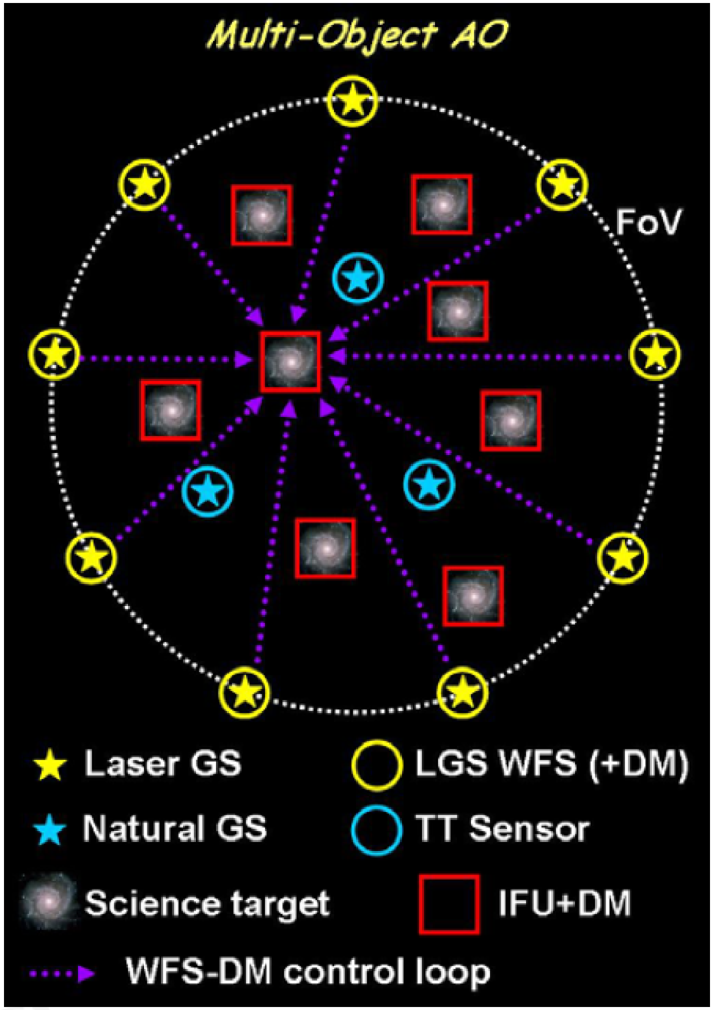
EAGLE (E-ELT)

EAGLE Science Requirements

- High spatial resolution (~ 75 milliarcsec):
  - Requires AO
- Extended sources (~2x2 arcsec):
  - For galaxies, clustered stellar objects etc
  - Integral Field Units needed
- Source counts for statistics:
  - Multi-object instrument (20+)
- Efficiency:
  - Wide-field (5 arcmin) to ensure all channels are used
- Spectral coverage:
  - From Calcium Triplet, through to K band
- Spectral resolution:
  - R~4,000 (to resolve OH lines, one atmos. band in ~2000 pix)
  - R~10,000 for precise velocities/abundances of stellar pops.

Multi-Object Adaptive Optics





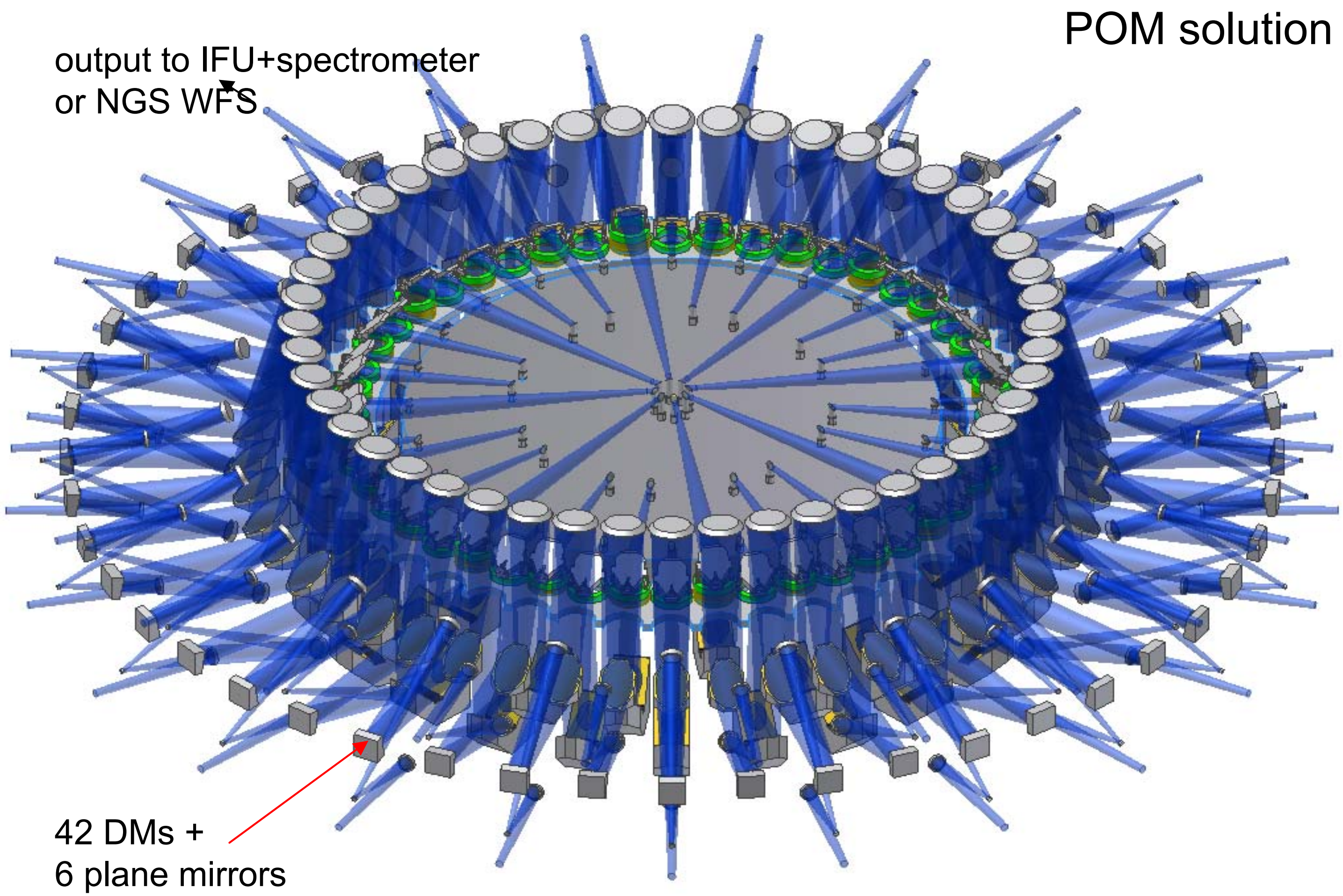
EAGLE Science Requirements

Parameter	Requirement
Patrol Field	5 arcmin diameter
Science subfield (IFU FOV)	> 1.5 arcsec
Multiplex	20 to 60
Spatial Resolution	30% EE in 75mas (H-band)
Spectral resolution	4,000 & 10,000
Wavelength range	0.8-2.5 µm

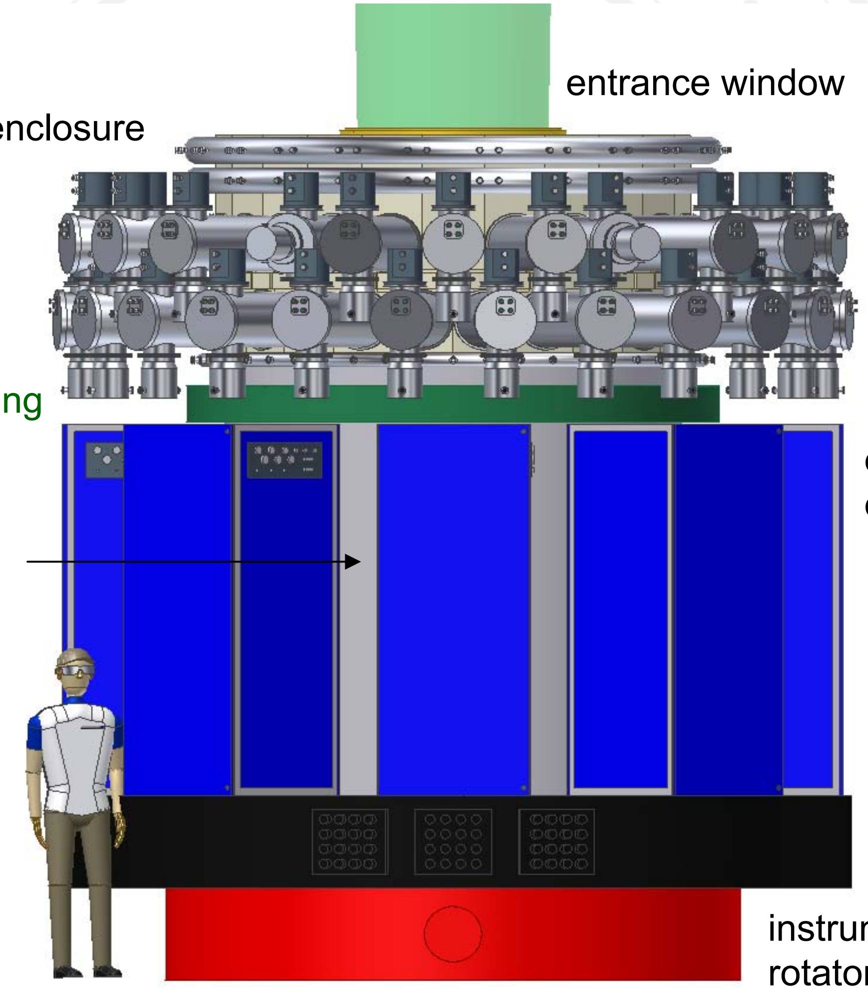
EAGLE Phase A Study

- French/UK instrument 50%/50% split
  - French PI: Jean-Gabriel Cuby (Marseille)
  - UK co-PI: Simon Morris (Durham)
  - Project Scientist: Matt Lehnert (Paris)
  - Instrument Scientist: Chris Evans (UK ATC)
- 2 year study, formally started Sept. 2007
- Phase 1 review with ESO in July
- Funding:
  - UK: STFC ELT funding
  - STFC PPRP bid (ELT R&D in “medium-high” priority from STFC programmatic review)
  - France: CNRS & other channels
  - Additional funding via EU-FP7
  - ESO

EAGLE Target Acquisition System



Mechanical Support and Packaging



4600mm high
4400mm diameter

Summary

- In the next decade, IFS observations well become the main mode of observing at large and small telescopes, at many different wavelengths, on the ground and in space.
- AO (LTAO, MCAO, MOAO) and large telescopes will provide a D^4 advantage, thus dramatically improving the sensitivity of these new instruments.
- These instruments are increasingly complex, require ~200 person-years of effort, cost >10M€, and weigh ~10 tons.
- The funding for none of these is automatic, if You think that these super-IFS are critical to achieving Your science goals, You need to actively lobby to get these instruments built.
- There will be a fantastic amount of software required to reduce and analyse these data properly, we really need to make a concerted effort to make sure all the tools we need are ready in time.