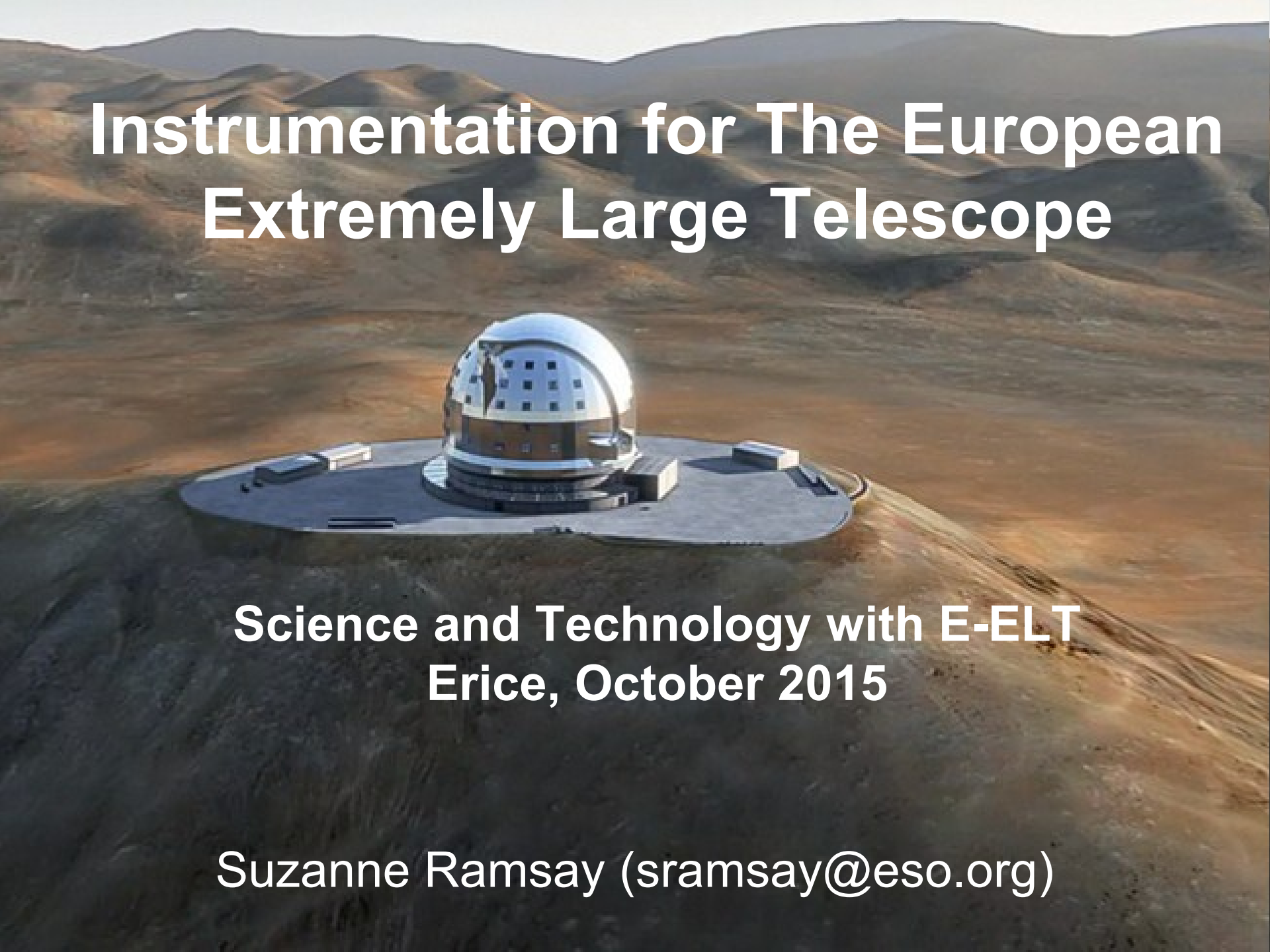
Instrumentation for The European Extremely Large Telescope



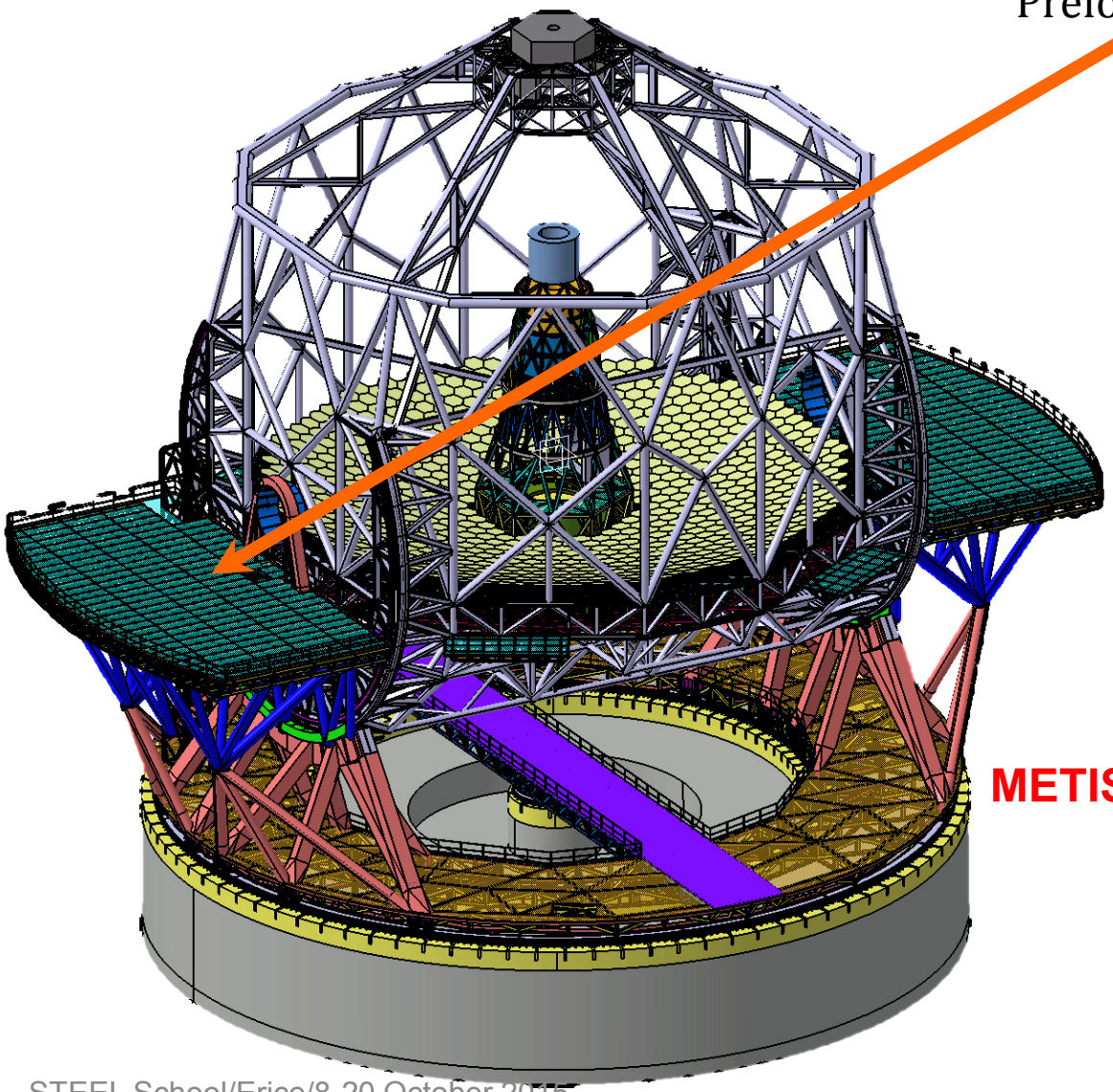
Science and Technology with E-ELT
Erice, October 2015

Suzanne Ramsay (sramsay@eso.org)

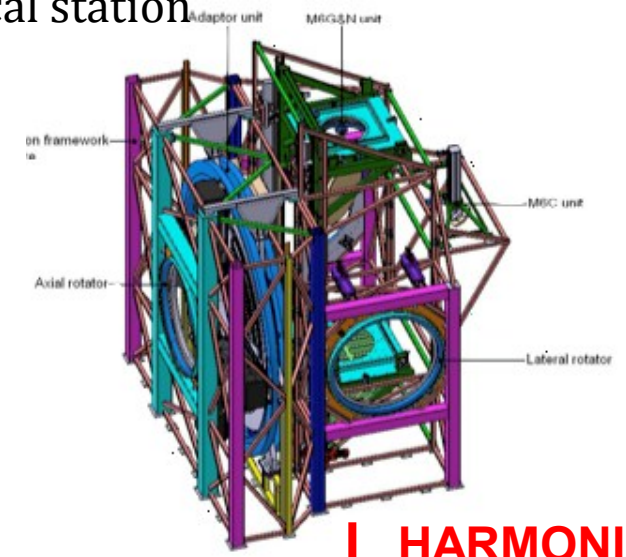
Outline of the talk

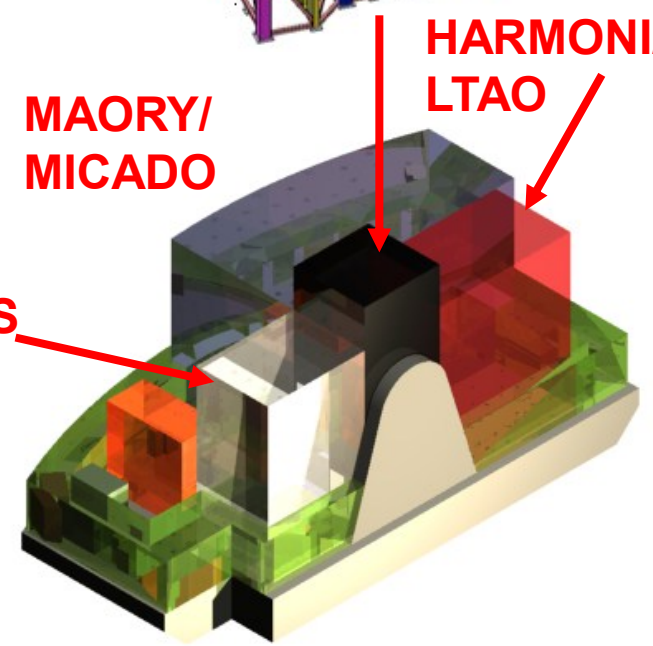
- The environment for instruments on the E-ELT
- The challenge of building instruments for extremely large telescopes
- Developing the roadmap for E-ELT instruments
- An overview of the instruments

The E-ELT: overview

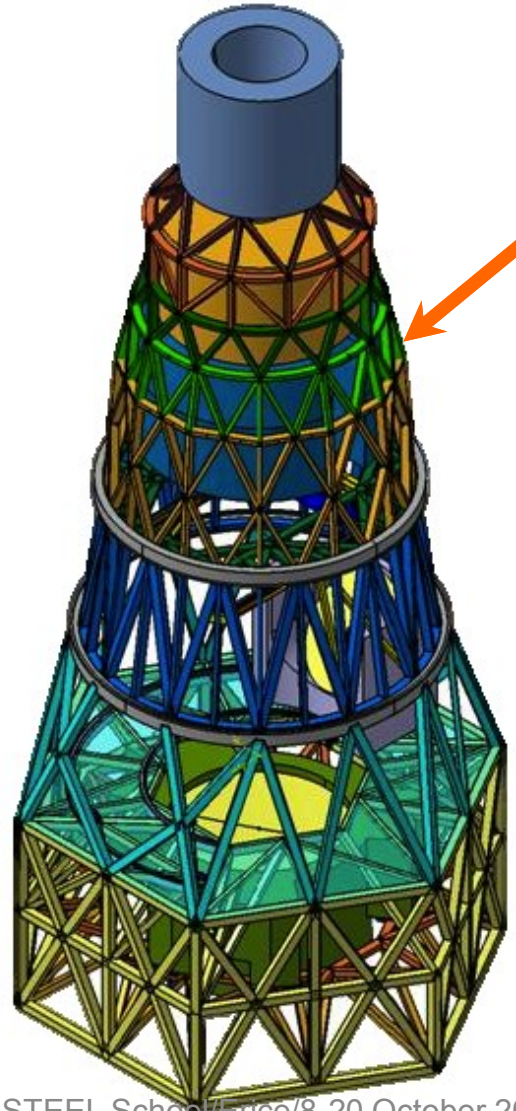


Prefocal station

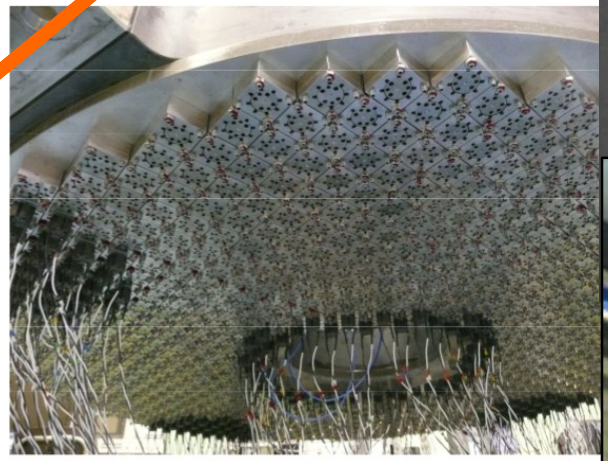


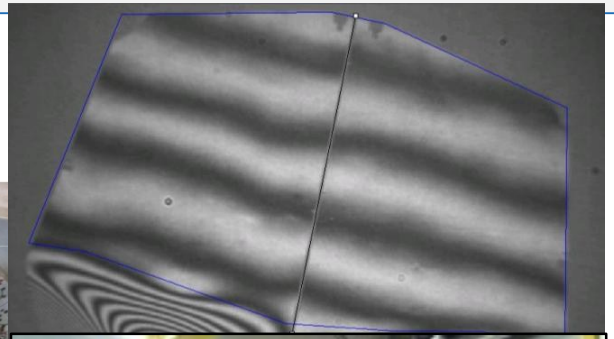


The E-ELT: M4

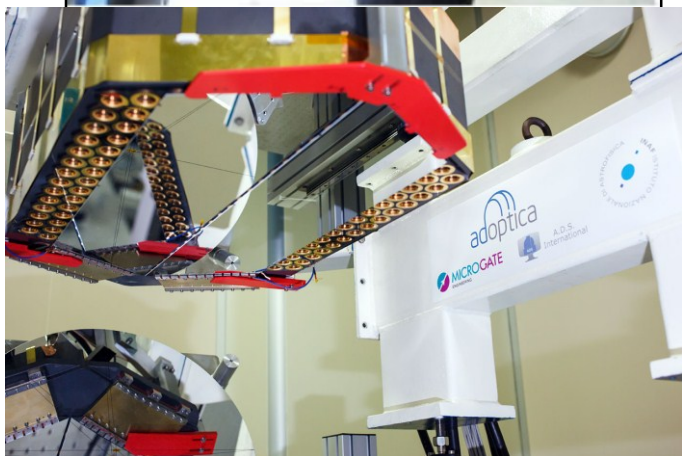


2.5m M4 unit





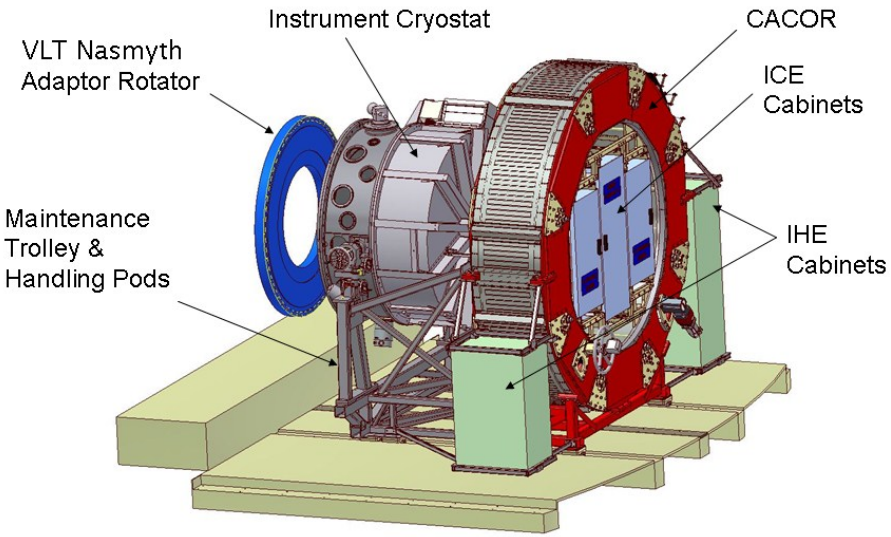
- The E-ELT is unique amongst ELTs in having a high order deformable mirror as part of the telescope optics

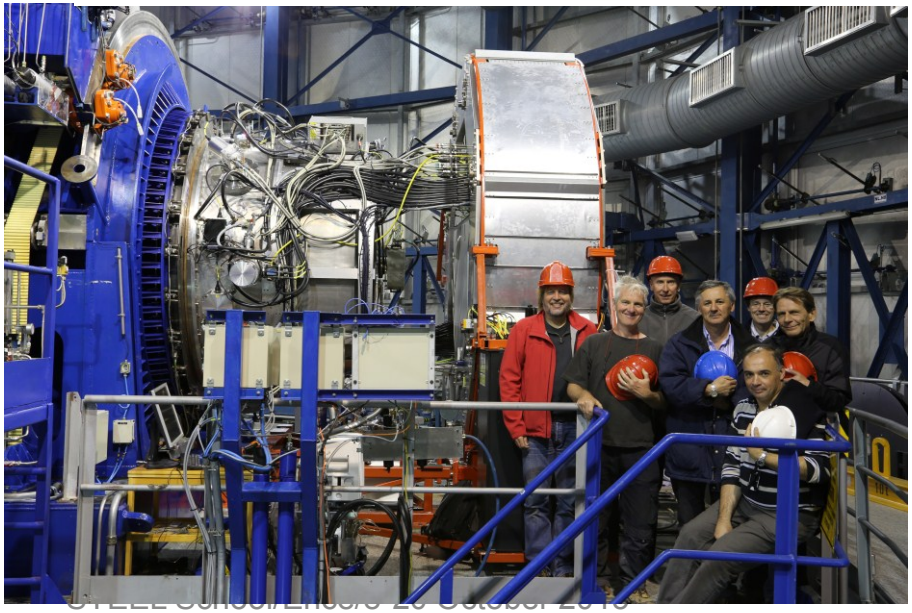


The challenge of building instruments for an ELT

- Instrument size typically increases with telescope size
  - VLT f-ratio: f/15 plate scale: 0.582mm/arcsec
  - E-ELT f-ratio: f/17.7 plate scale: 3.3mm/arcsec
- Some things get easier
  - Relaxed positioning tolerances
  - KMOS pick-off arms position to 0.2arcsecs = 120μm on VLT; would be 660μm on E-ELT
- Some things get harder….

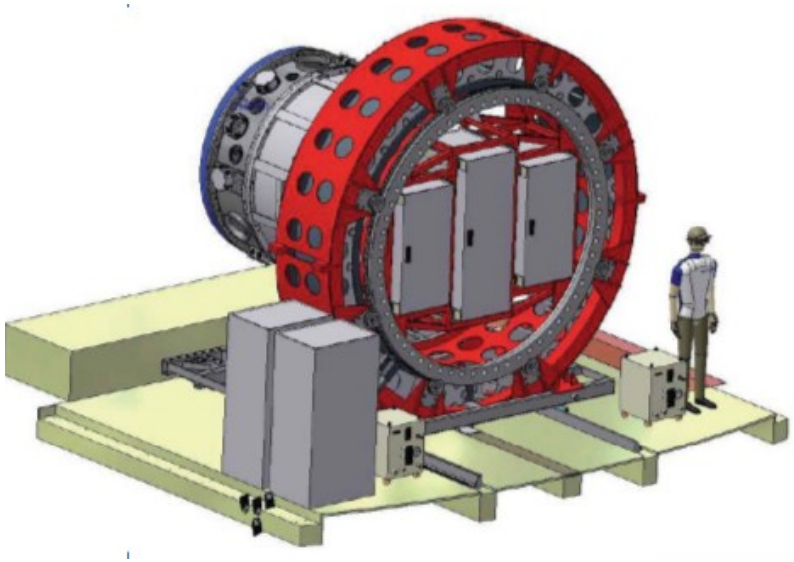
The challenge of building instruments for an ELT

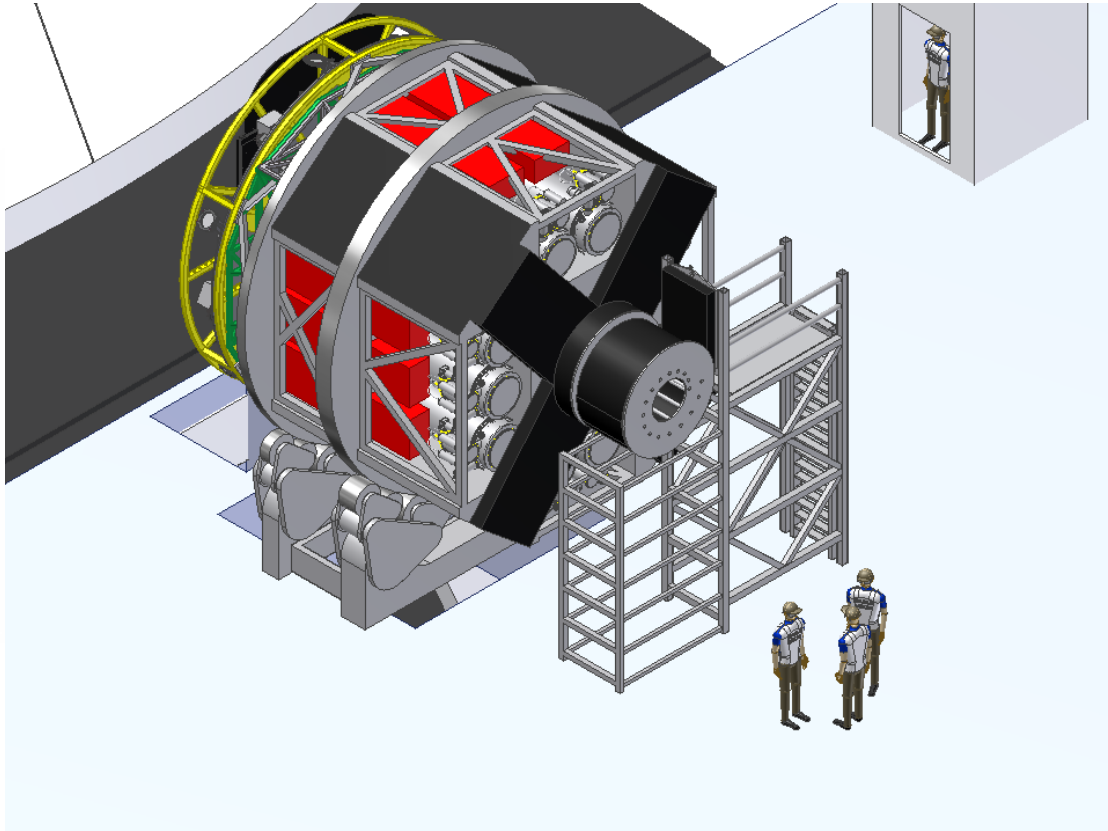




- KMOS on the VLT
  - Field of view of 7arcmin is ~200mm diameter
  - 5arcmin field on the ELT ~1m diameter

KMOS vs EAGLE





KMOS: 0.2arcsec pixels on 8-m telescope
EAGLE: 40mas pixels on a 39-m telescope

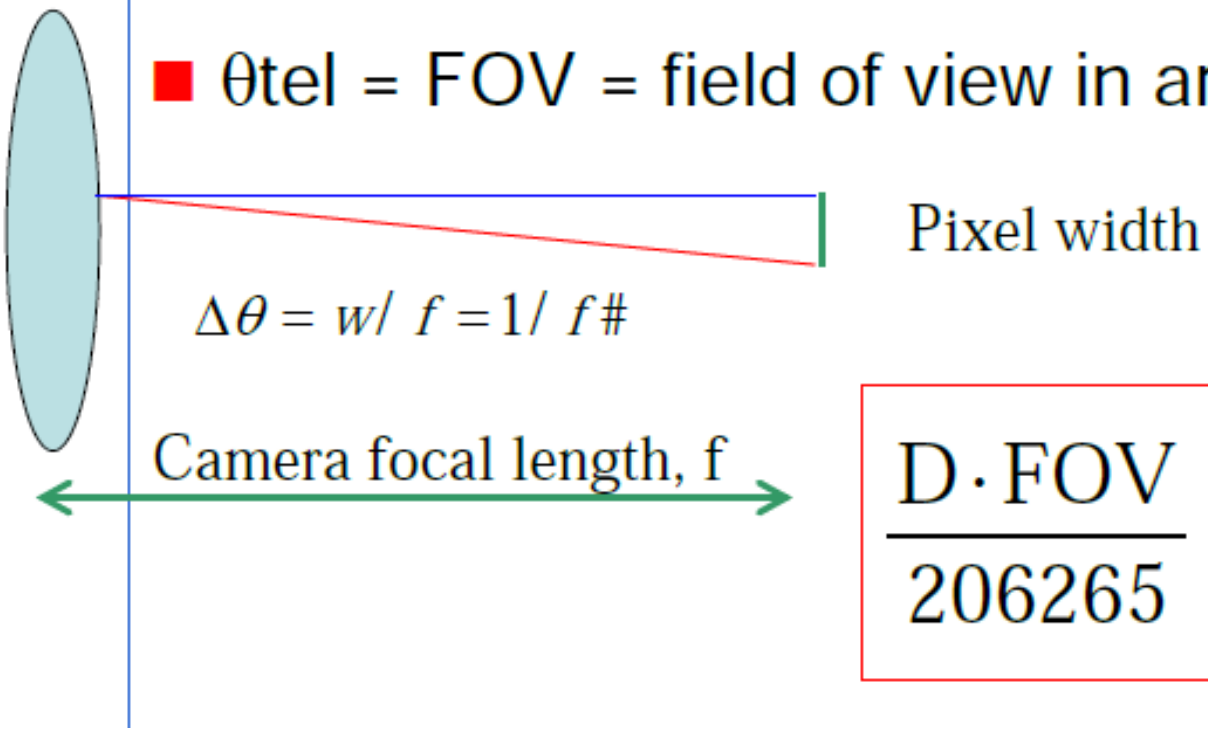
These instruments have the SAME AΩ product/étendue.

Conservation of Etendue

- Conservation of AΩ and the detector pixel size determines the camera f-number :

$$Dtel\theta_{\mathrm{tel}} = dpix\theta_{\mathrm{cam}}$$

- θtel = FOV = field of view in arcsec

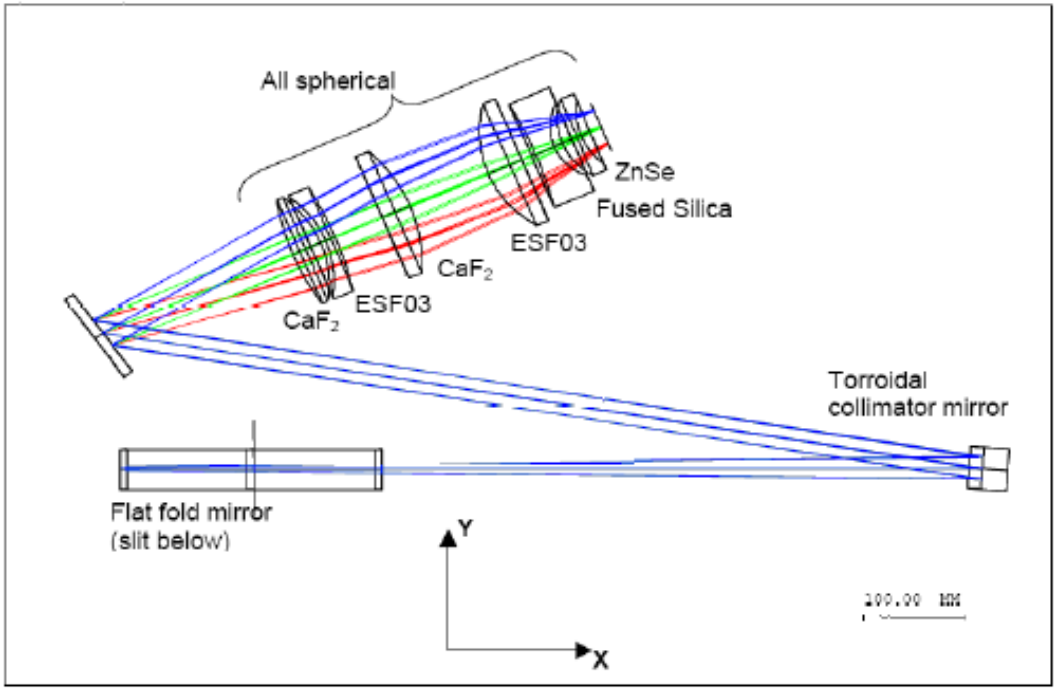


$$\frac{D \cdot FOV}{206265} = \frac{pixel_width}{f_number}$$

Case study: a seeing limited spectrograph (1) for VLT

- KMOS
- At the seeing limit
- FOV=0.2arcsecs
- 18μm pixels
- f2.3 on the 8m VLT

$$\frac{D \cdot FOV}{206265} = \frac{pixel_width}{f_number}$$



Case study: a seeing limited spectrograph (2) for ELT

- 0.4arcsecs/pixel
- 18 μm pixels
- ~f/0.5 on the E-ELT

- Alternatively:
- f/2 camera >> seeing disk is ~80 μm or 4-5 pixels

- Diffraction limited instruments:
  - H-band diffraction limited FWHM = 10mas
  - 0.005 arcsecs/18 μm pixel
- ~f/19 on the E-ELT

Oversampling implies larger focal plane>>larger instruments>>increased detectors costs>>power consumption etc….

At the diffraction limit

- Instruments sizes scale with the telescope
- Diffraction limited instruments
  - Set the field of view to match the diffraction limit:

$$\mathrm{FOV} = \frac{1.22\lambda}{\mathrm{D}}$$

$$\boxed{\frac{\mathrm{pixel_width}}{\mathrm{f_number}} \propto \lambda}$$

  - A diffraction limited instrument can go on any telescope

The challenge of building instruments for an ELT

- Can we build instruments
  - that will work?
  - meet the science case?
  - be reliable?
  - be affordable?

4.5 Extragalactic Massive Stars beyond the Local Group

The massive ($M > 8M_\odot$), young stellar populations of galaxies play a significant role in the chemical and dynamical evolution of their host systems – in particular via mass-loss from their stellar winds and ultimately as core-collapse supernovae. The current generation of 8-10m telescopes has enabled high-resolution spectroscopy of individual massive stars in Local Group galaxies, yielding their physical properties and chemical abundances. The main motivation of these studies has been to explore the dependence of stellar properties and stellar evolution on environment, particularly in the Magellanic Clouds which are metal-poor compared to the Milky Way (see

Notes on Design Requirements

Observation Type: Intermediate to high-resolution spectroscopy

Field of View: ~1′ (for e.g. NGC 3109/Sextans A)

Spatial Resolution: 0.1″ to 0.02″

Spectral Resolution: R=1000 to 10,000

Wavelength Range: Primarily V and R; IJHK of some use

Target Density: A few tens per field

Telescope Size: 30–100m

Observing time: A few hours for each system

Date constraint: None

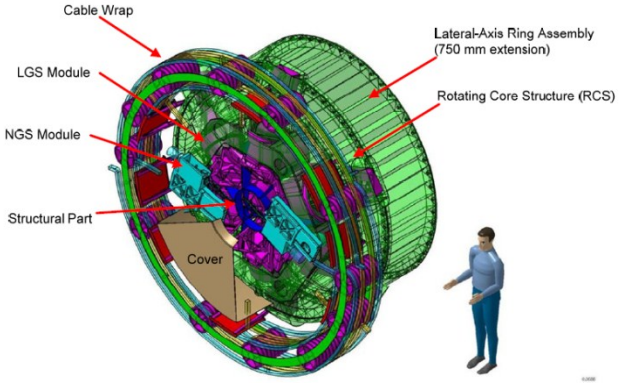
Other comments: MOS would improve efficiency

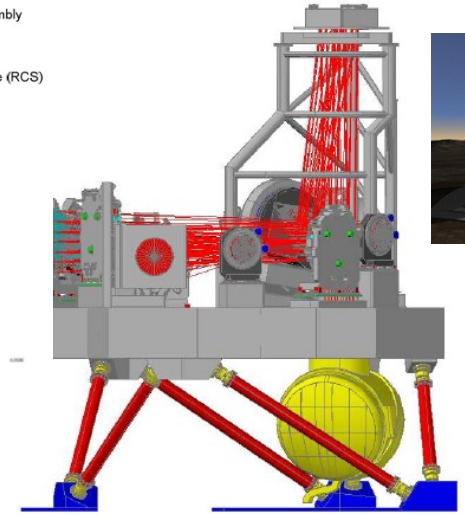
Early studies of instrument concepts

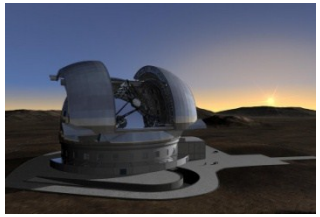
- The goal of the “Phase A” study programme was to carry-out a suitable number of instrument studies
  - to verify that instruments can be built at an affordable cost and that they properly address the highest priority scientific goals,
  - to work with the ESO community towards construction
  - to work with telescope and operation project offices to identify and define interfaces with the other subsystems and the observatory infrastructure.
- 9 instrument and 2 post-focal AO studies carried out by >300 scientists and engineers in 40 institutes throughout the ESO community

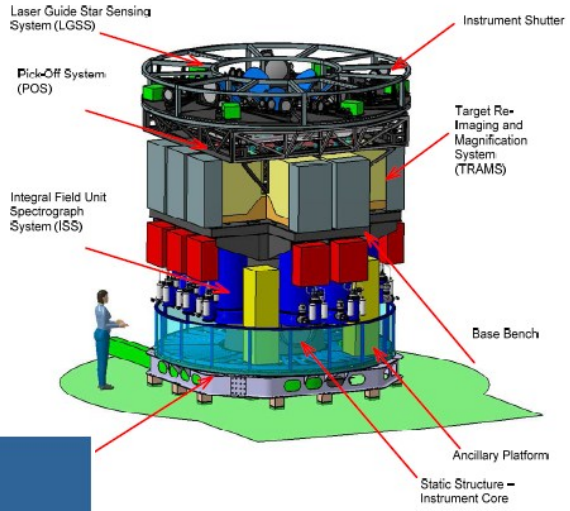
ELT Instrument Phase A studies

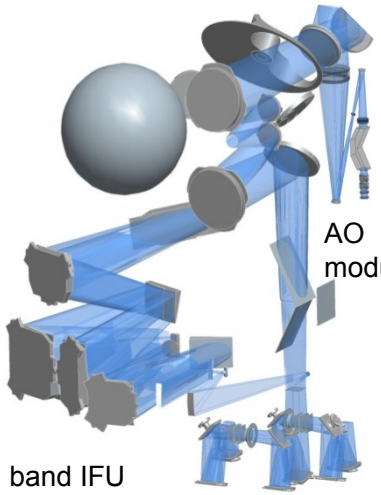
Name	PI	Institutes	Procurement of the Study	Responsible at ESO	Kick-off	Final Review
PFAO-ATLAS	T. Fusco (ONERA)	ONERA, LESIA, GEPI, LAM, UK ATC	Open call with initial module specifications	J. Paufique	19/09/08	2/02/10
PFAO-MAORY	E. Diolaiti (INAF OABo)	INAF-OABo, OAA, OAP, Univ. Bologna, ONERA	Direct negotiations with external institutes	E.Marchetti	09/11/07	10/12/09
CODEX	L. Pasquini (ESO)	ESO, INAF Trieste&Brera,IAC, IoA Cambridge, Obs. Genève.	ESO coordinates consortium of institutes which had done an FP6 E-ELT instrument study	N/A	16/09/08	23/02/10
EAGLE	J.G.Cuby (LAM)	LAM, GEPI, LESIA, ONERA, UK ATC, Univ. Durham	Direct negotiations with consortium of institutes that had done an FP6 E-ELT instrument study	S.Ramsay	27/09/07	27/10/09
EPICS	M.Kasper (ESO)	ESO, LAOG, INAF-OAPd, LESIA, NOVA ASTRON, Uni. Utrecht, ETHZ, ONERA, Univ-Oxford, FIZEAU, LAM	ESO coordinates consortium of institutes which had done an FP6 E-ELT instrument study	N/A	24/10/07	16/03/10
HARMONI	N. Thatte (Oxford)	Univ. Oxford, CRAL, CSIC-DAMIR, IAC, UK ATC	Open call with initial instrument specifications	J. Vernet	1/04/08	28/01/10
METIS	B.Brandl (Leiden)	NOVA Leiden&ASTRON, MPIA, CEA Saclay, KU-Leuven, UK ATC	Open call with initial instrument specifications	R.Seibenmorgen	07/05/08	17/12/09
MICADO	R.Genzel (MPE)	MPE, MPIA, USM, INAF-Padova, NOVA ASTRON, Leiden, Groningen, LESIA	Open call with initial instrument specifications	A. Richichi	28/02/08	30/11/09
OPTIMOS-DIORAMAS	O.LeFèvre (LAM)	LAM, STFC RAL, INAF IASF-Milano & OATs, Obs. Genève, IAC, Obs. Haute Provence	Open call for a new concept	S.Ramsay	3/11/08	30/03/10
OPTIMOS-EVE	F.Hammer (GEPI)	GEPI, NOVA ASTRON, RUN, Uni. Amsterdam, STFC RAL, INAF OATs&Brera, NBI Copenhagen	Open call for a new concept	S.Ramsay	3/11/08	30/03/10
SIMPLE	L. Origlia (INAF-OABo)	INAF – OABo, Arcetri, Roma, Univ. Bologna, UAO, TLS, PUC	Open call for a new concept	H.U.Käufl	30/10/08	04/03/10





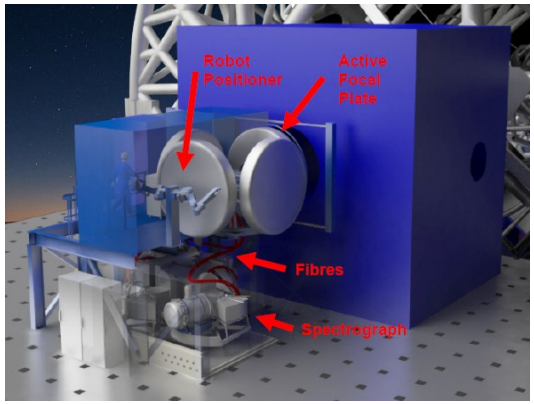




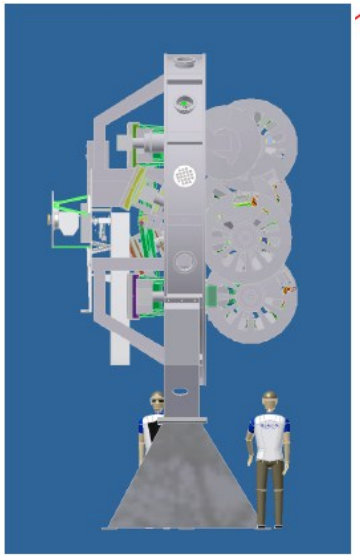


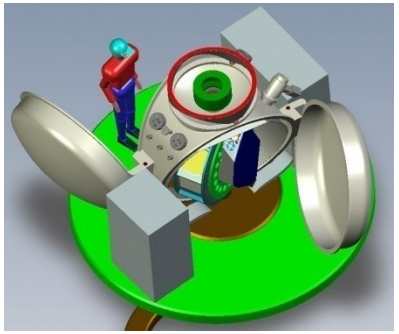
AO
module

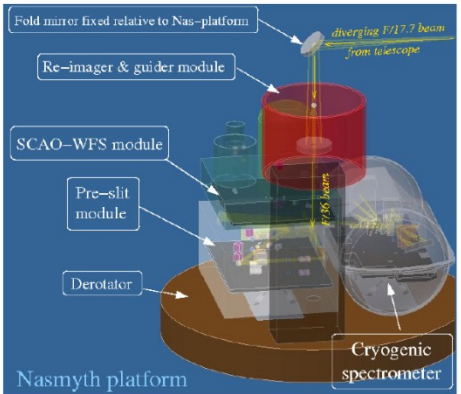
LM band IFU
spectrograph

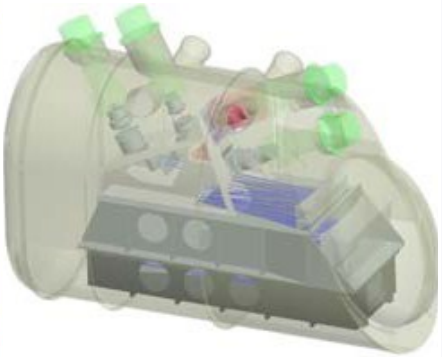


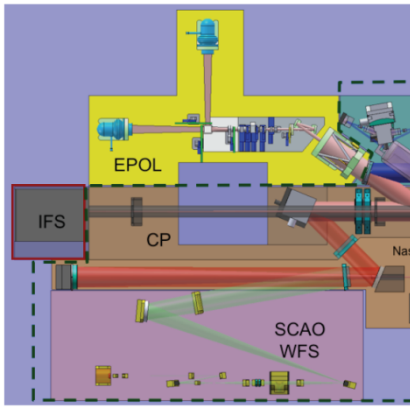
Imager (LM
and N-band
channels)

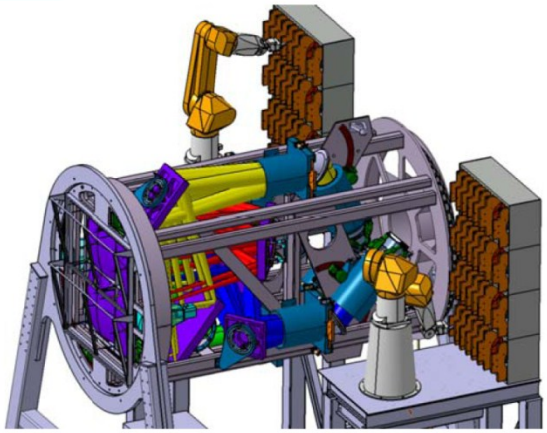












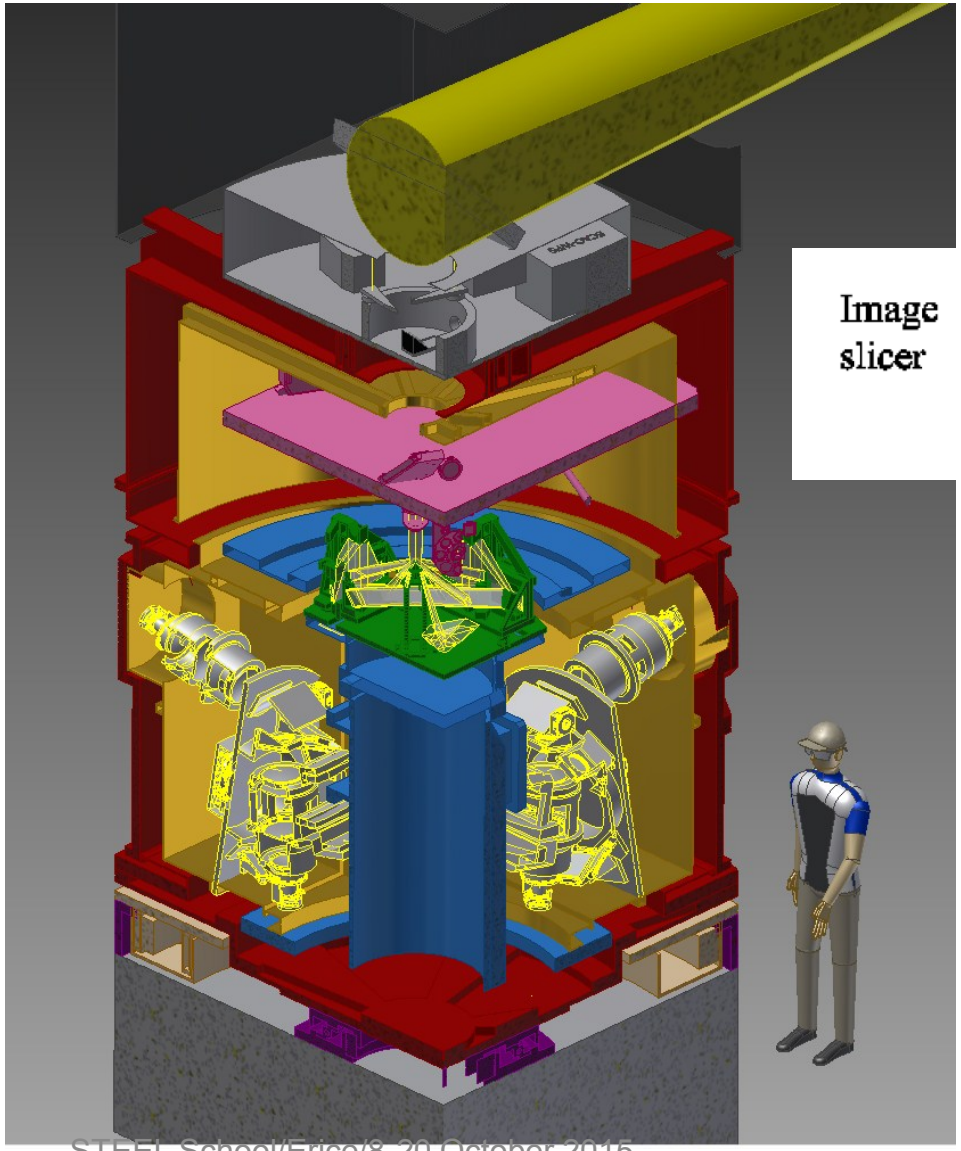
The E-ELT Instrument Roadmap

- Instruments selected in consultation with the ESO committess and community, based on
  - Scientific impact, return, flexibility
  - Complementarity to JWST, existing facilities
  - A plan to cover all observing conditions
- First light pair: ELT-IFU, ELT-CAM, both +AO

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-MOS	ELT-HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Cal for Proposals Start Phase A			
2016				Consortium Selection for construction		Call for proposals	
2017							
2018							TRL check
2019						Selection	Start when ready
2020							
2021							
2022							
2023							
2024							

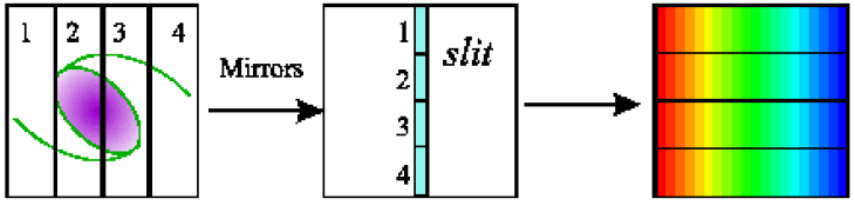
	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
	Decision point
	Development of Technical Specifications, Statement of Work, Agreement, Instrument Start.

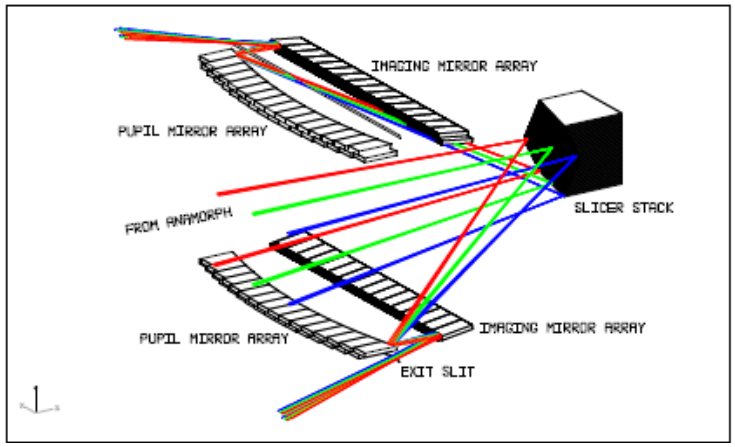
E-ELT IFU: HARMONI



PI: Niranjan Thatte, Uni. Oxford,

Consortium: UK ATC, CRAL, CSIC, IAC, RAL, IPAG, ONERA, LAM, ESO





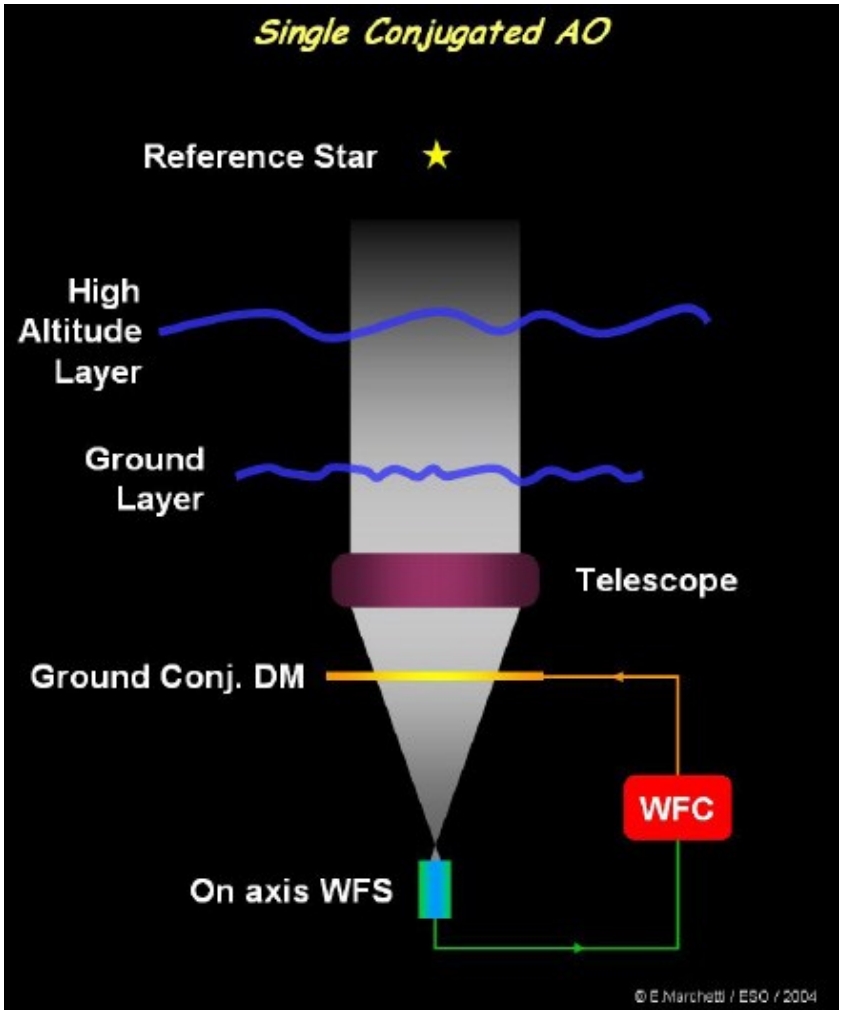
An image slicing integral field unit using arrays of mirrors.

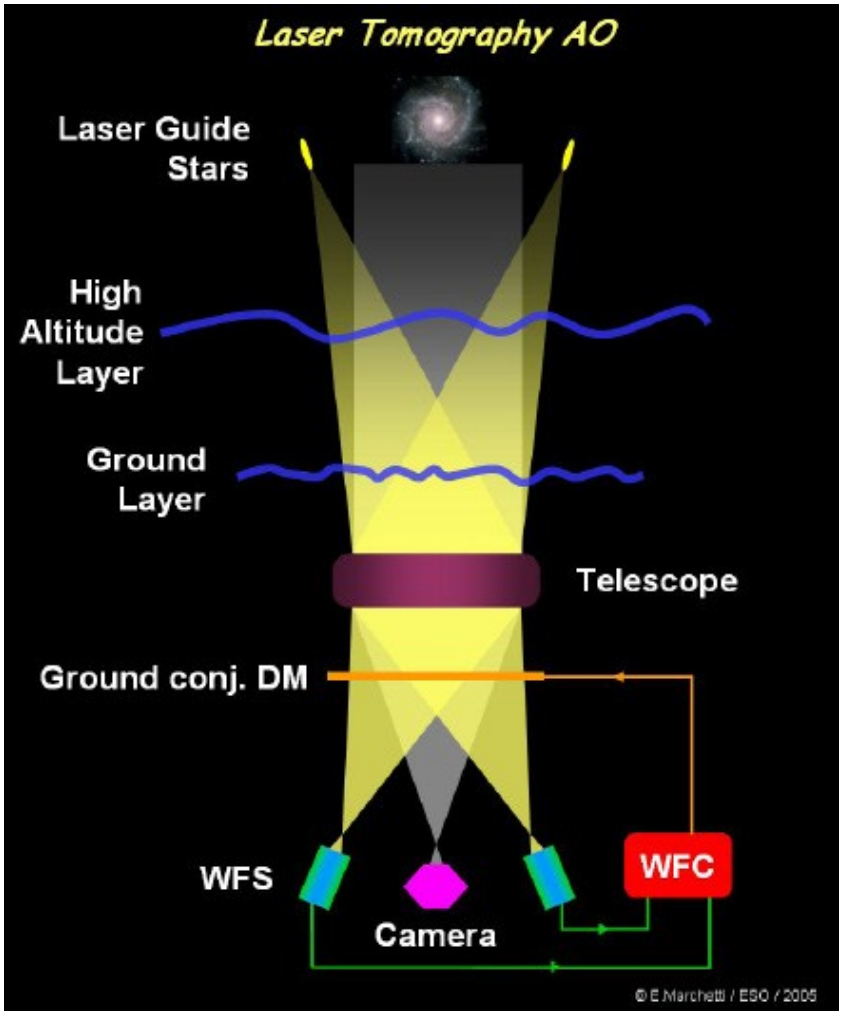
ELT-IFU: HARMONI

- Four spaxel scales / fields of view
  - 60x30mas == 6.5 x 9.1” FoV (Natural Seeing)
  - 20x20mas == 4.3 x 3.0” (LTAO faint sources)
  - 10x10mas == 2.1 x 1.5” (LTAO bright sources)
  - 4x4mas == 0.8 x 0.6” (SCAO / diffraction limit)
- 32 000 spaxels at all spatial scales (~ ½ MUSE)

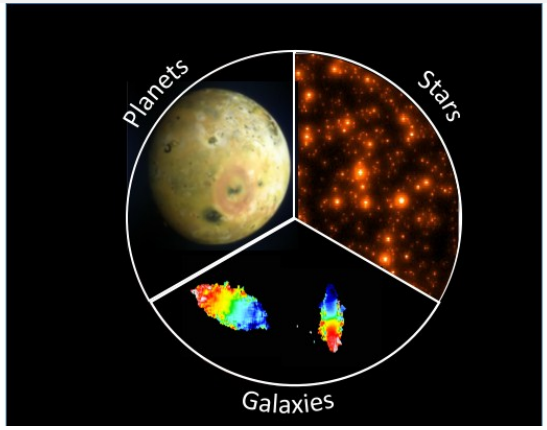
Bands	Wavelengths (µm)	R
“V+R” or “I+z+J” or “H+K”	0.45-0.8, 0.8-1.35, 1.45-2.45	~3000
“I+z” or “J” or “H” or “K”	0.8-1.0, 1.1-1.35, 1.45-1.85, 1.95-2.45	~7500
“Z” or “J_high” or “H_high” or “K_high”	0.9, 1.2, 1.65, 2.2 (TBD)	~20000

HARMONI AO Modes



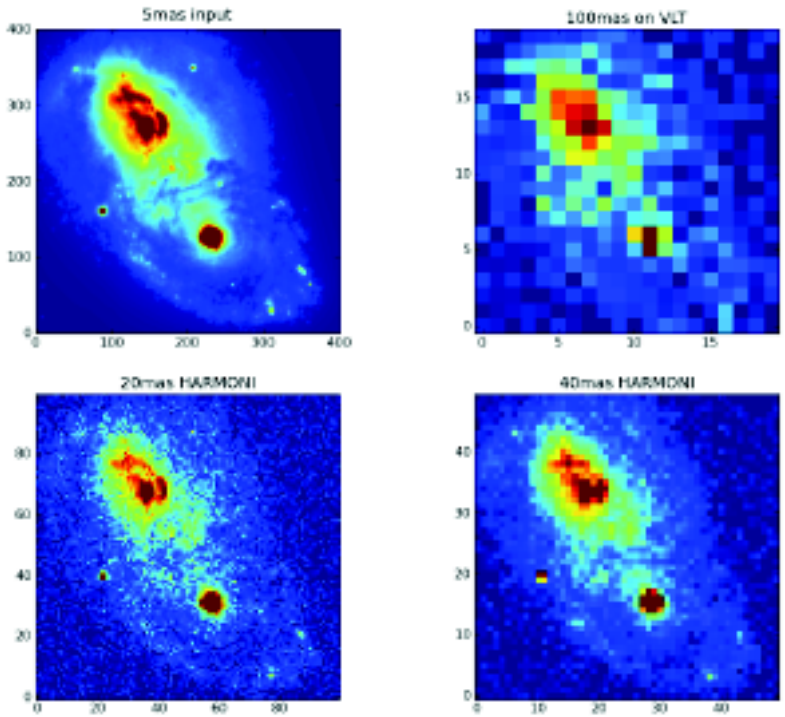


HARMONI Science



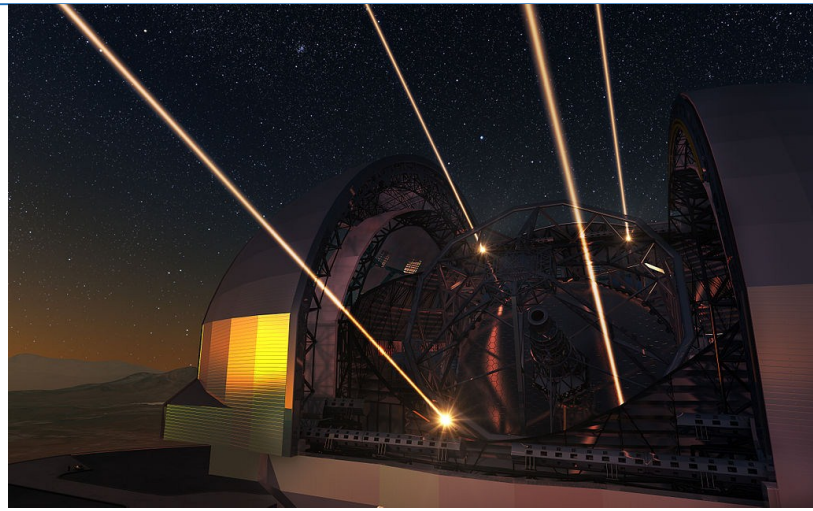
- Surveying ~50 Ultra-Luminous infrared galaxies discovered by *SPITZER*
  - Measure dynamical masses, kinematics, chemical composition
  - Characterise circumnuclear disk & rings
  - Measure shocks, winds, interactions with the intergalactic medium
  - Requires R~4000, 5-40mas scales, full wavelength range

Hα in z=2 ULIRG

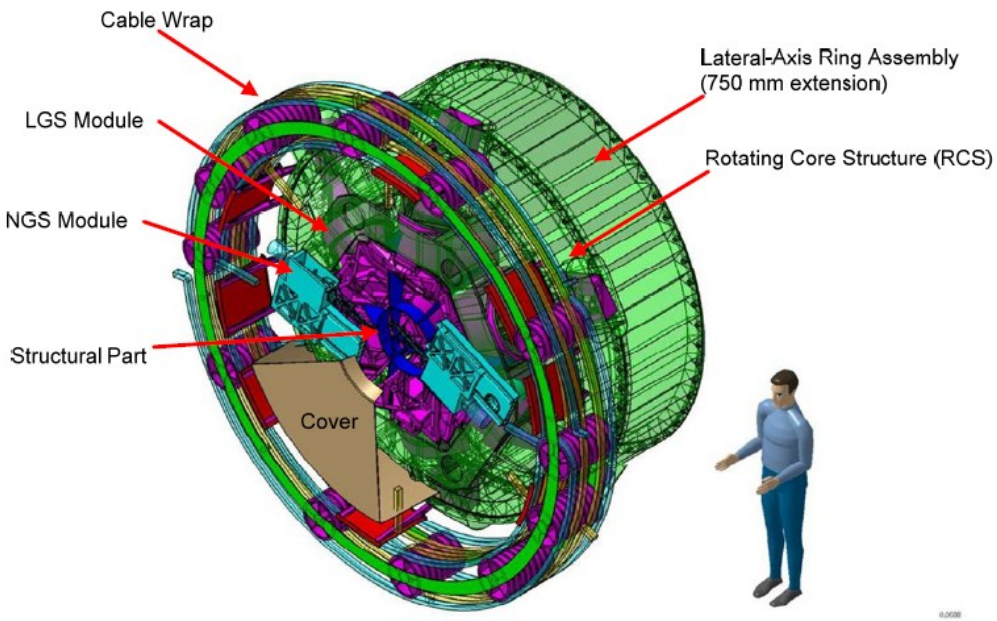


HARMONI LTAO

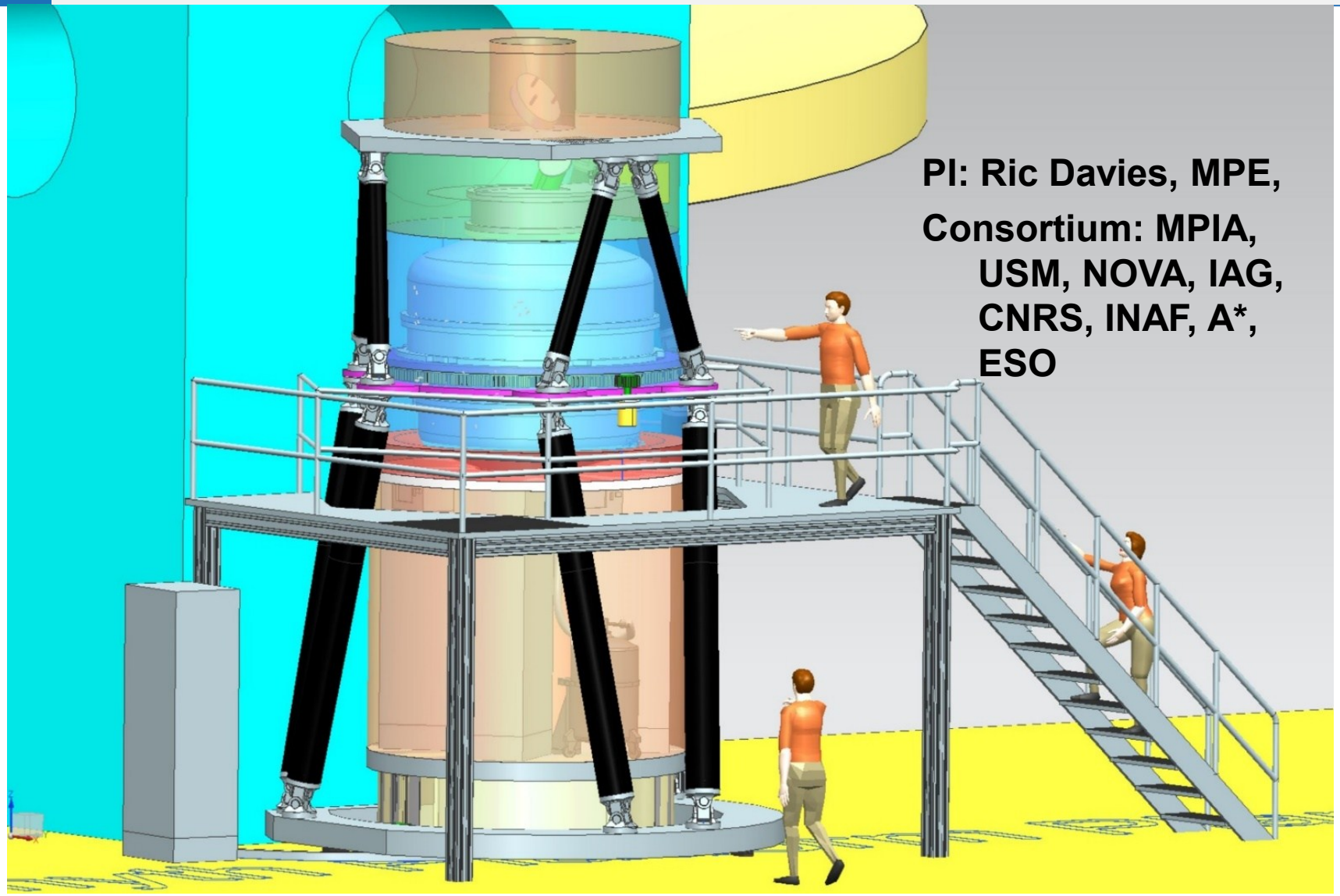
- Based on earlier 'ATLAS' Concept
  - Uses the telescope adaptive mirrors
  - No additional mirrors in the instrument optical path
  - 6 LGS, 2 NGS
  - Optimum laser asterism diameter?



- Performance
  - >50% strehl in K band
  - With 92% sky coverage
  - 30" field of view



ELT-CAM: MICADO



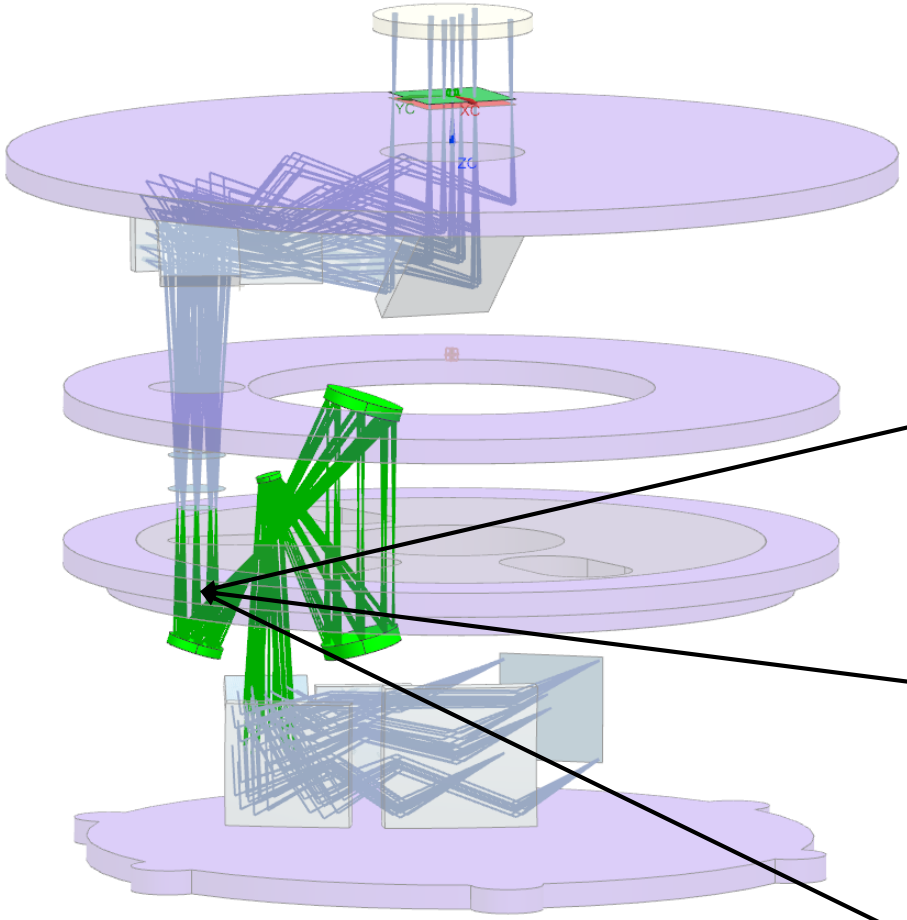
MICADO MODES

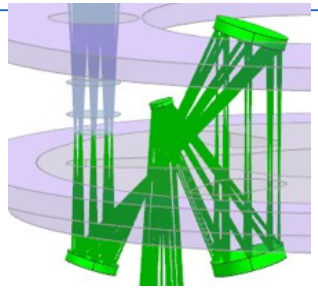
- Imaging through broad and narrow band filters covering 0.8-2.4μm, over an array of 3x3 $4k^2$ detectors, with pixel scales of 4mas (FoV ~53”) and 1.5mas (FoV ~20”)
- Astrometric imaging over the same fields, to 50μas precision across full field. Constraints on zenith distance, filter width, etc, are being assessed.
- Spectroscopy for single compact objects, through slits with length 3-4arcsec. Fixed format covers 0.8-1.4μm and 1.5-2.4μm (selectable via the sorting filter) at a resolution of ~8000.
- Coronagraphic imaging using SCAO and a coronagraph, with angular differential imaging. This will probably be for H and/or K bands where AO performance is best.

Goal:

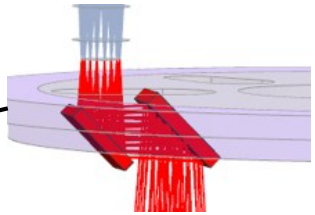
- Time Resolved Astronomy using windowing to enable rapid read-out of subarrays to achieve frame rates up to 250Hz (20x20 pixels).

MICADO optical concept

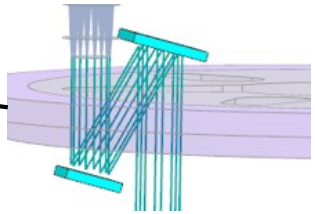




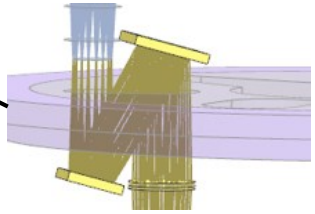
A. 1.5mas imager (4 fixed mirrors)



B. 4mas imager (2 flat fold mirrors)

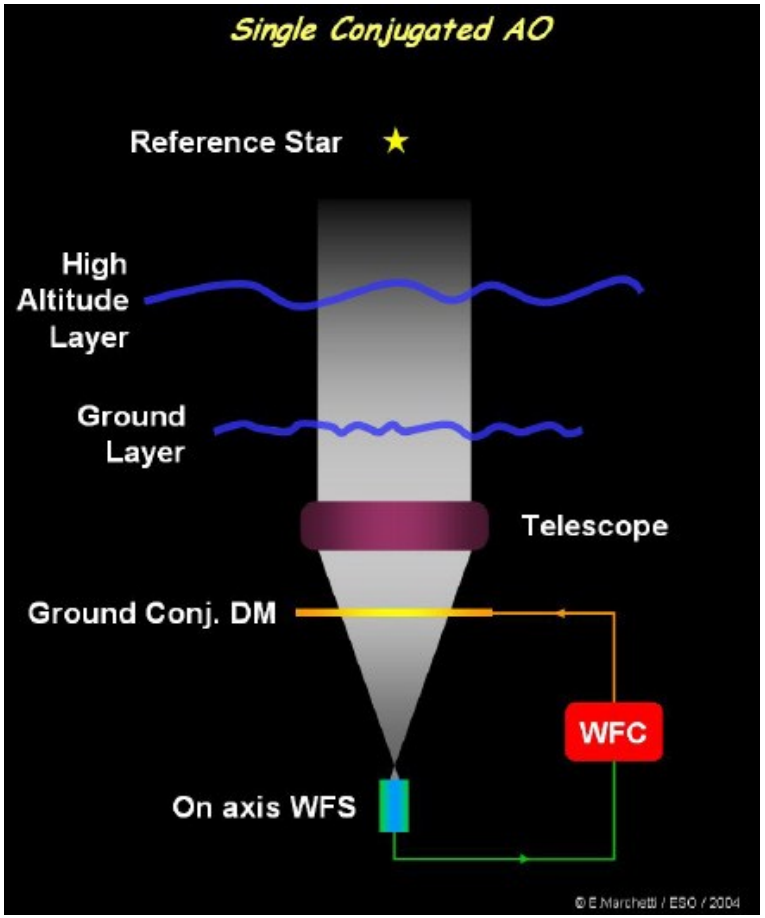


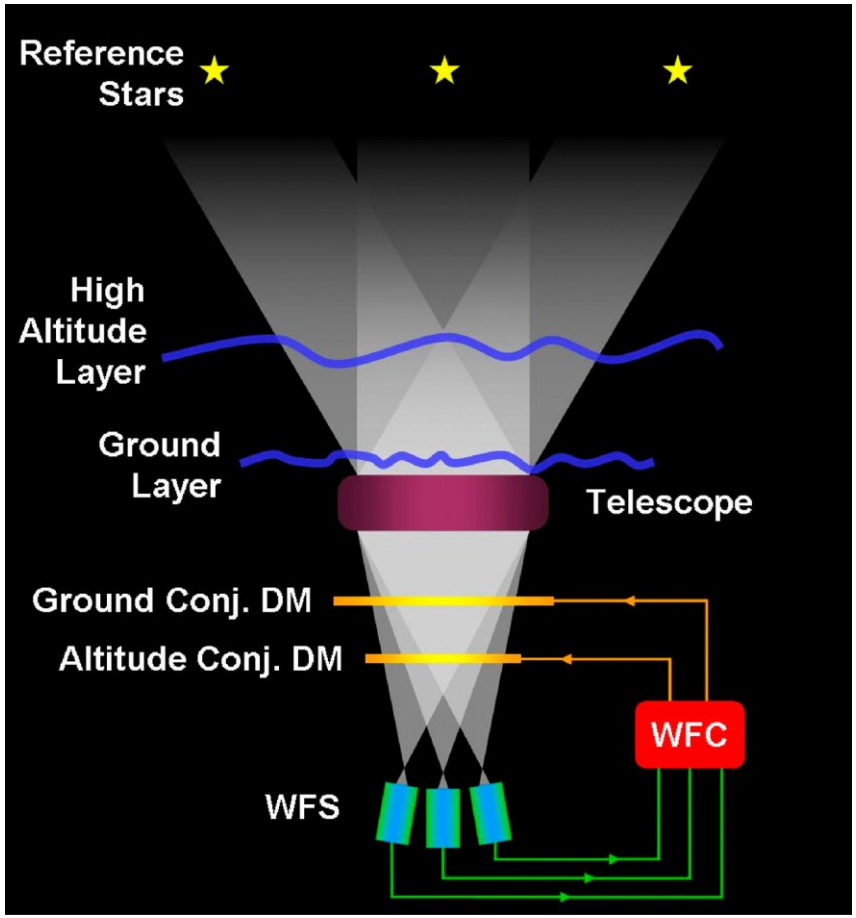
C. Cross-dispersed Spectroscopy (2 gratings)



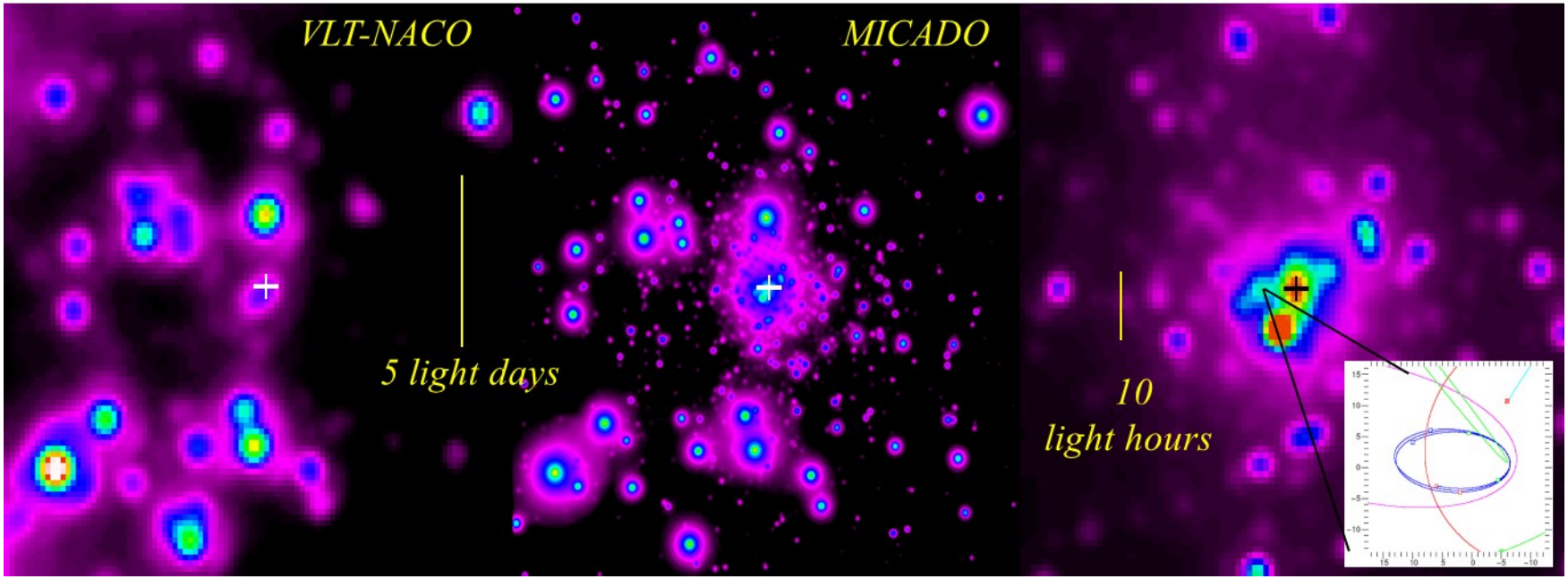
D. Pupil imager (2 flat fold mirrors + 1 lens)

MICADO AO MODES





Galactic centres near & far



- sensitivity >5mag fainter, resolution & astrometry 5x better than NACO@VLT
- density profile, luminosity function to <1M_{sun}, shape of IMF
- orbits of stars closest to BH: prograde & retrograde precession
- proper motions of ~1000 stars: phase-space clumping (disks)

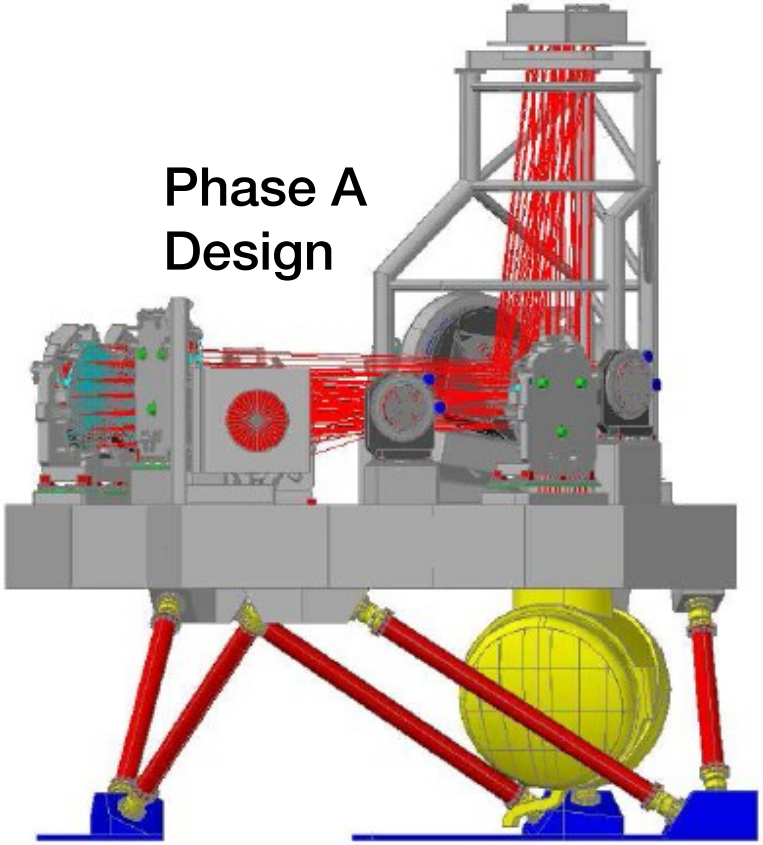
spectroscopy: - 3D orbits, stellar types, spectral properties of accretion events

ELT-MCAO: MAORY

- Multi-conjugate AO
  - 6 laser, 3 natural guide stars
  - MAORY deformable mirrors conjugated to 4km, 12.7km
  - Single DM initial, upgrade path to 2DMs
  - Two output ports for MICADO plus another future instrument
- Performance
  - 0.6 μm < λ < 2.4 μm
  - wide field - 2’, 1’ clear

PI: Emiliano Diolaiti

Consortium of INAF institutes +INSU IPAG



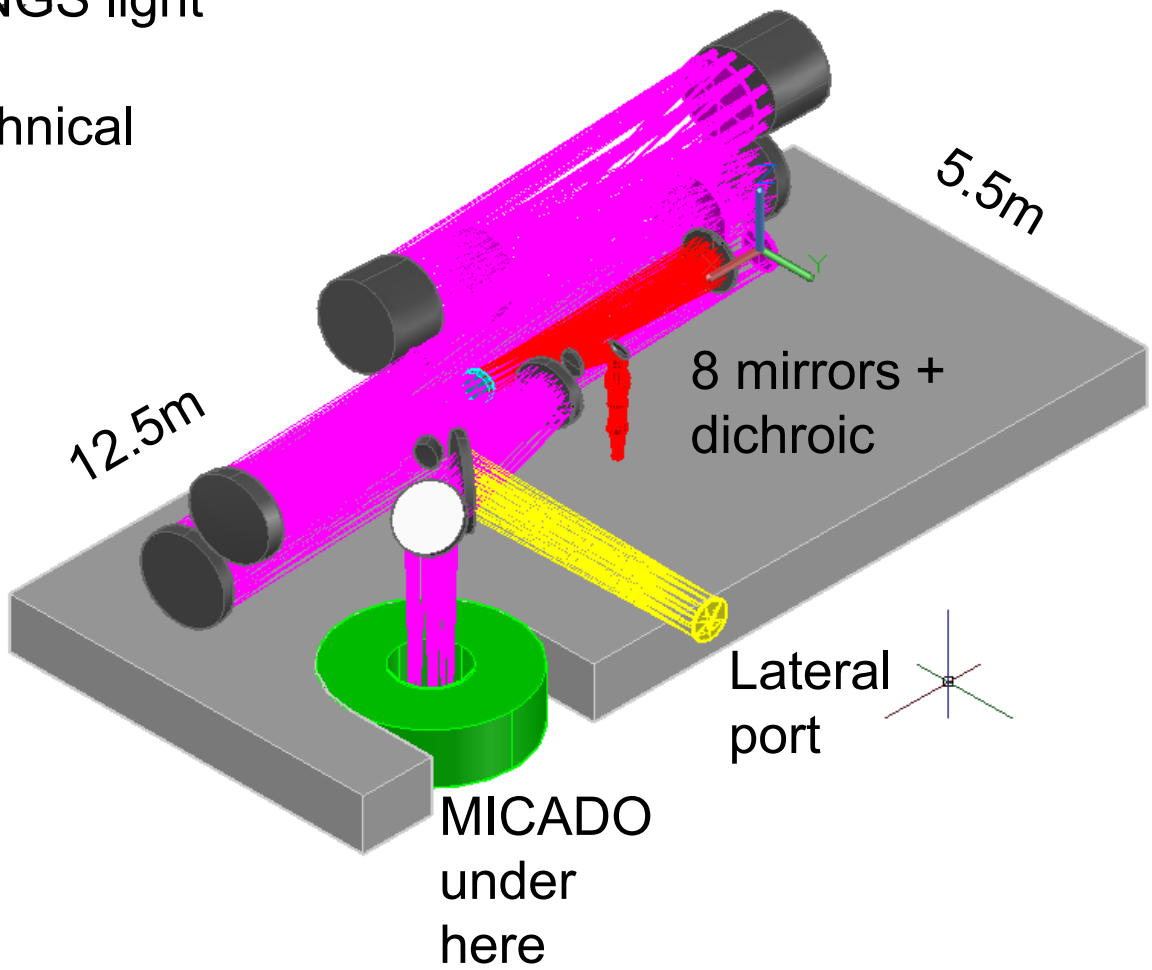
MAORY OPTICAL CONCEPT

- MICADO + NGS light
- Lateral port + NGS light
- LGS channel
- NGS WFS/ technical field

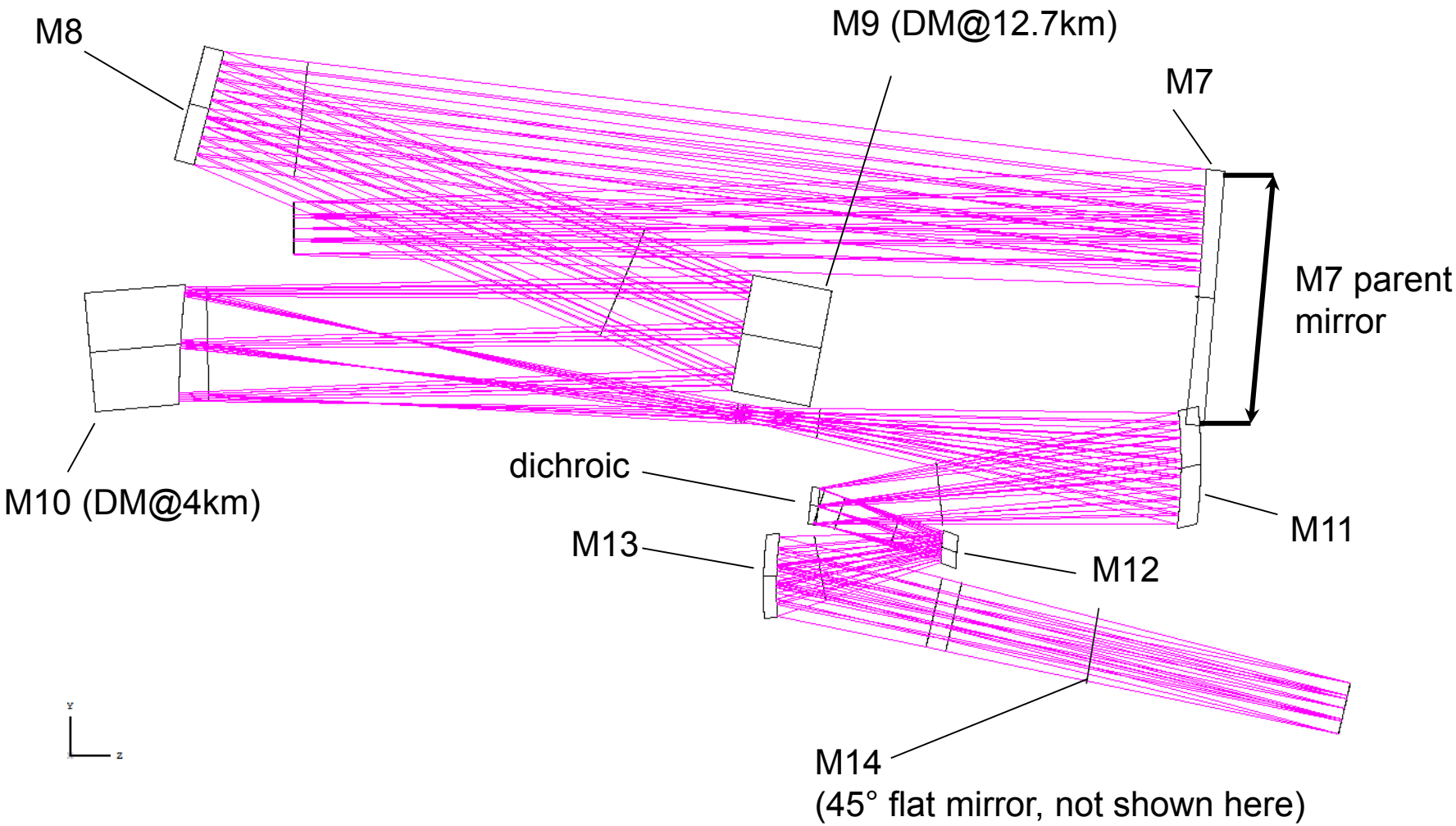
MAORY senses the natural guide star light in at near infrared wavelengths.

The stars are selected from an annular field around the science field.

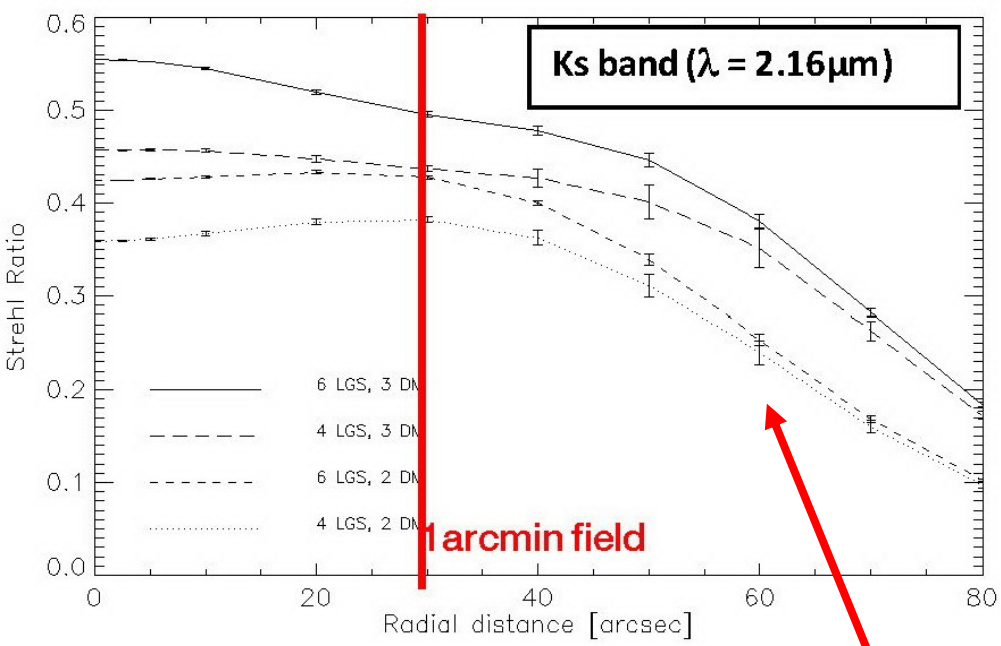
Sky coverage > 50% over the sky observable from E-ELT.



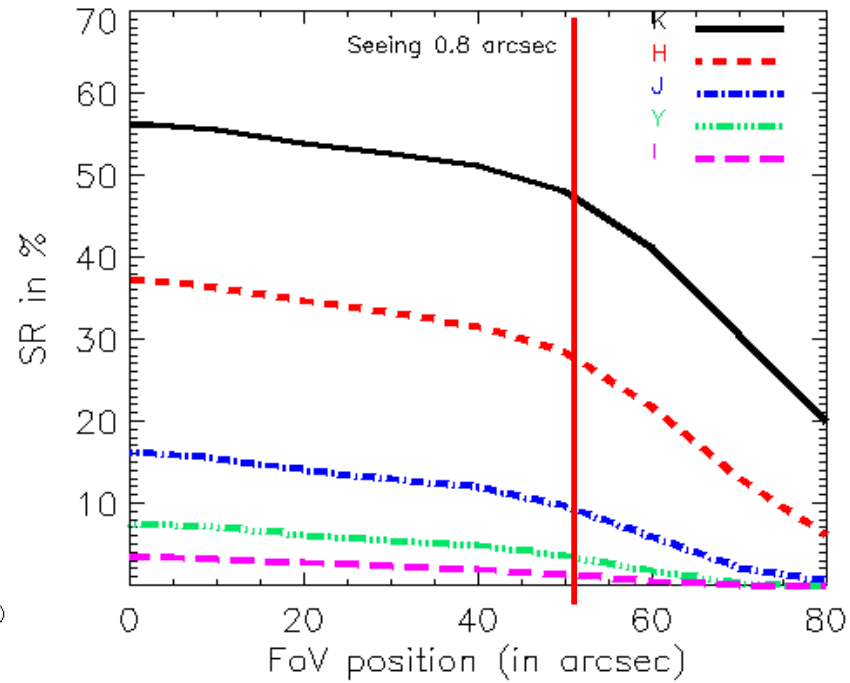
MAORY OPTICAL CONCEPT



Some MAORY simulation results



MICADO FOV



Baseline for MAORY is for one post-focal DM plus M4.

Upgrade path to a second DM.

High Strehl in the technical field>> fainter guide stars/higher sky coverage

Recall: dependence of Strehl ratio on wavelength is just atmospheric physics

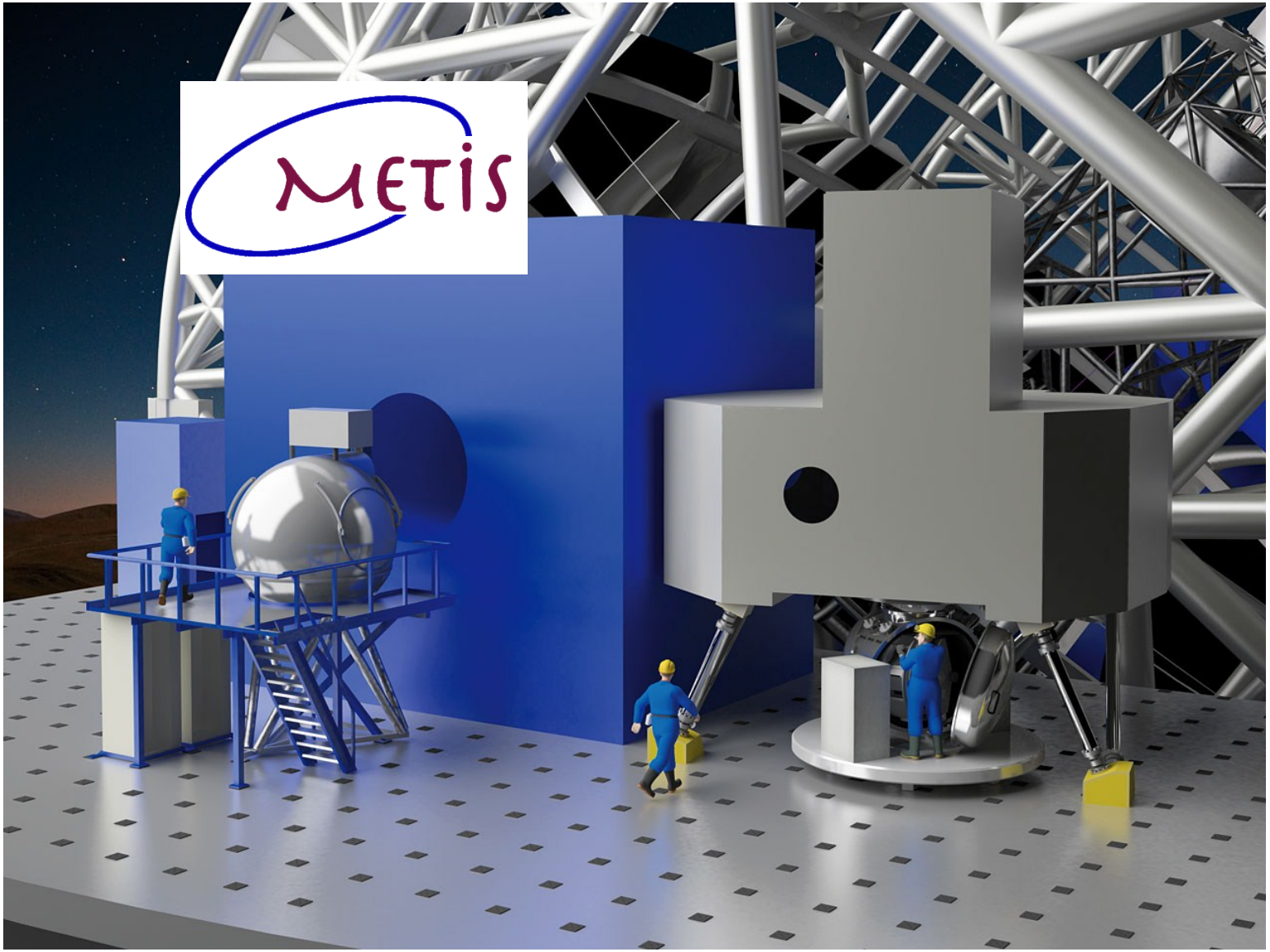
The E-ELT Instrument Roadmap

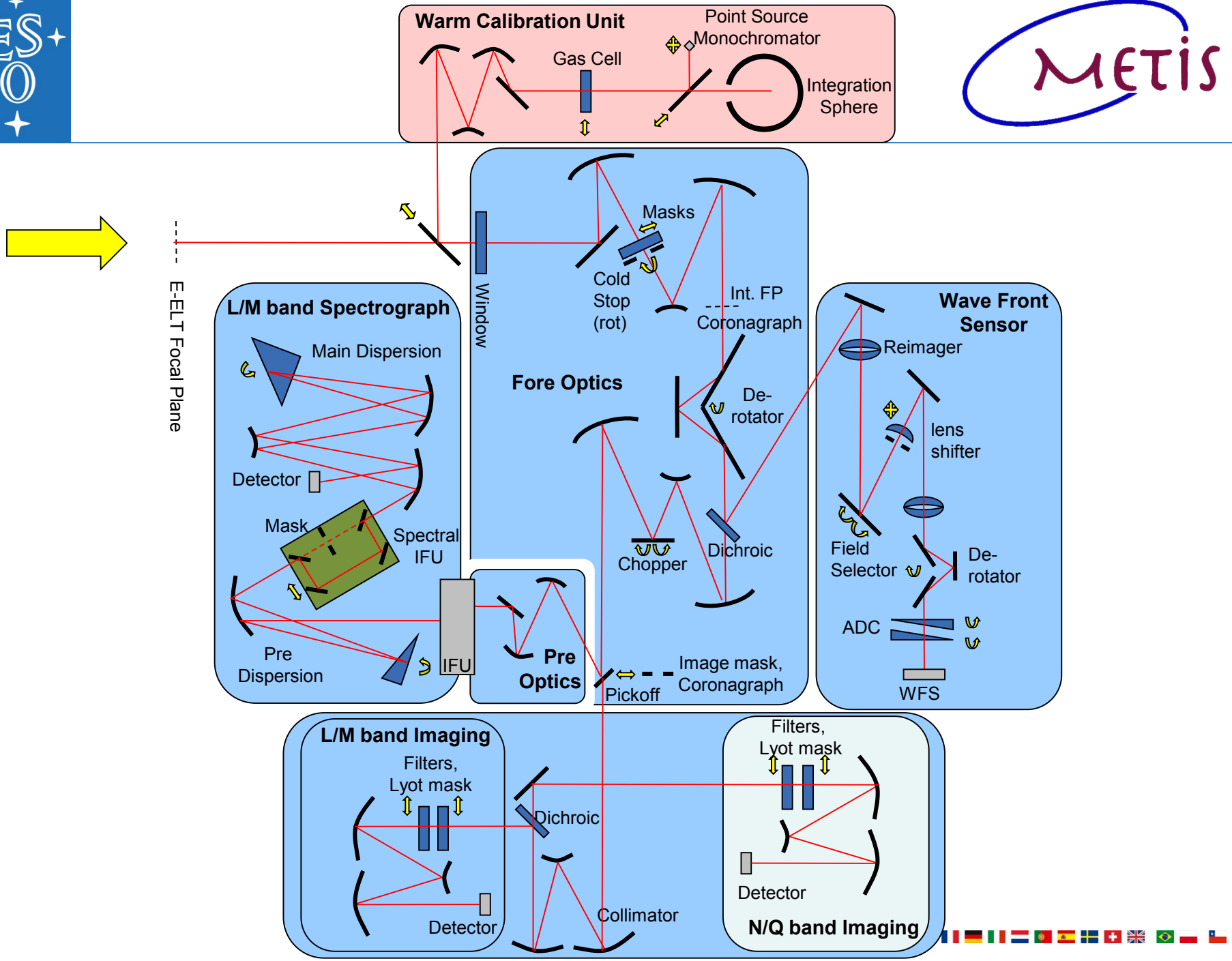
- Instruments selected in consultation with the ESO committess and community, based on
  - Scientific impact, return, flexibility
  - Complementarity to JWST, existing facilities
  - A plan to cover all observing conditions
- ELT-MIR: METIS

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-MOS	ELT-HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Cal for Proposals Start Phase A			
2016				Consortium Selection for construction		Call for proposals	
2017							
2018							TRL check
2019						Selection	Start when ready
2020							
2021							
2022							
2023							
2024							

	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
	Decision point
	Development of Technical Specifications, Statement of Work, Agreement, Instrument Start.

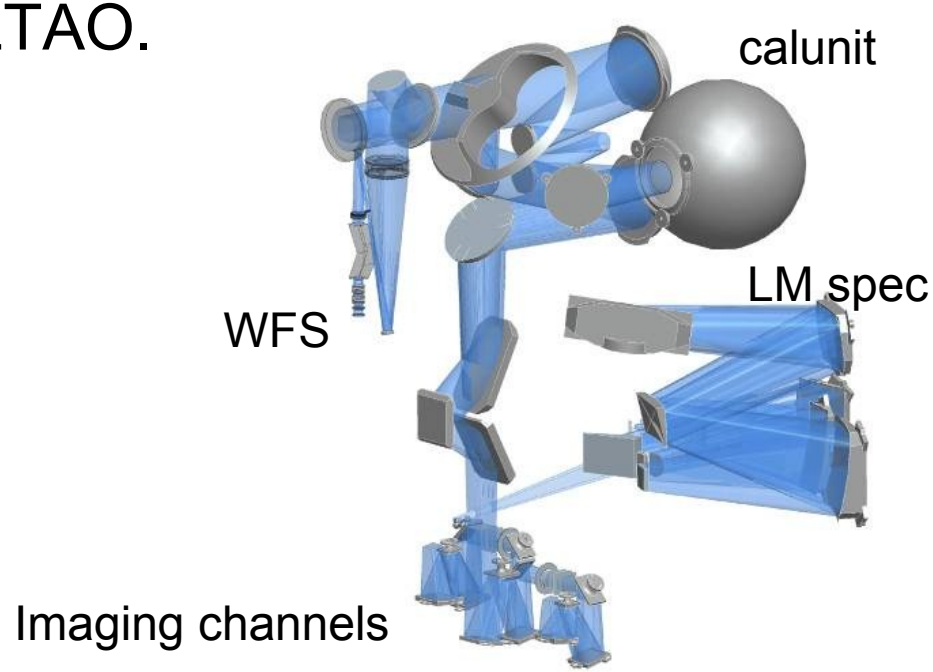
ELT-MIDIR: METIS

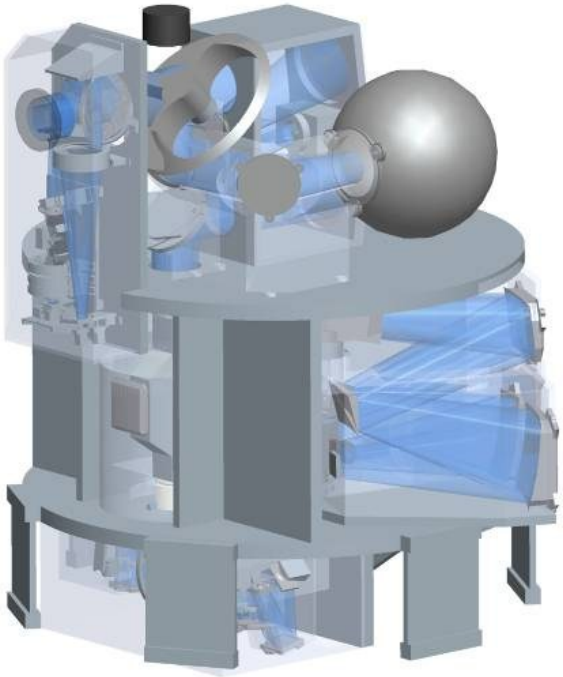



Warm Calibration Unit
Point Source
Monochromator
Gas Cell
Integration
Sphere
METIS
E-ELT Focal Plane
Window
Masks
Cold
Stop
(rot)
Int. FP
Coronagraph
Fore Optics
De-
rotator
Chopper
Dichroic
L/M band Spectrograph
Main Dispersion
Detector
Mask
Spectral
IFU
Pre
Dispersion
IFU
Pre
Optics
Pickoff
Image mask,
Coronagraph
Wave Front
Sensor
Reimager
lens
shifter
Field
Selector
De-
rotator
ADC
WFS
L/M band Imaging
Filters,
Lyot mask
Detector
Dichroic
Collimator
Filters,
Lyot mask
Detector
N/Q band Imaging

METIS MODES

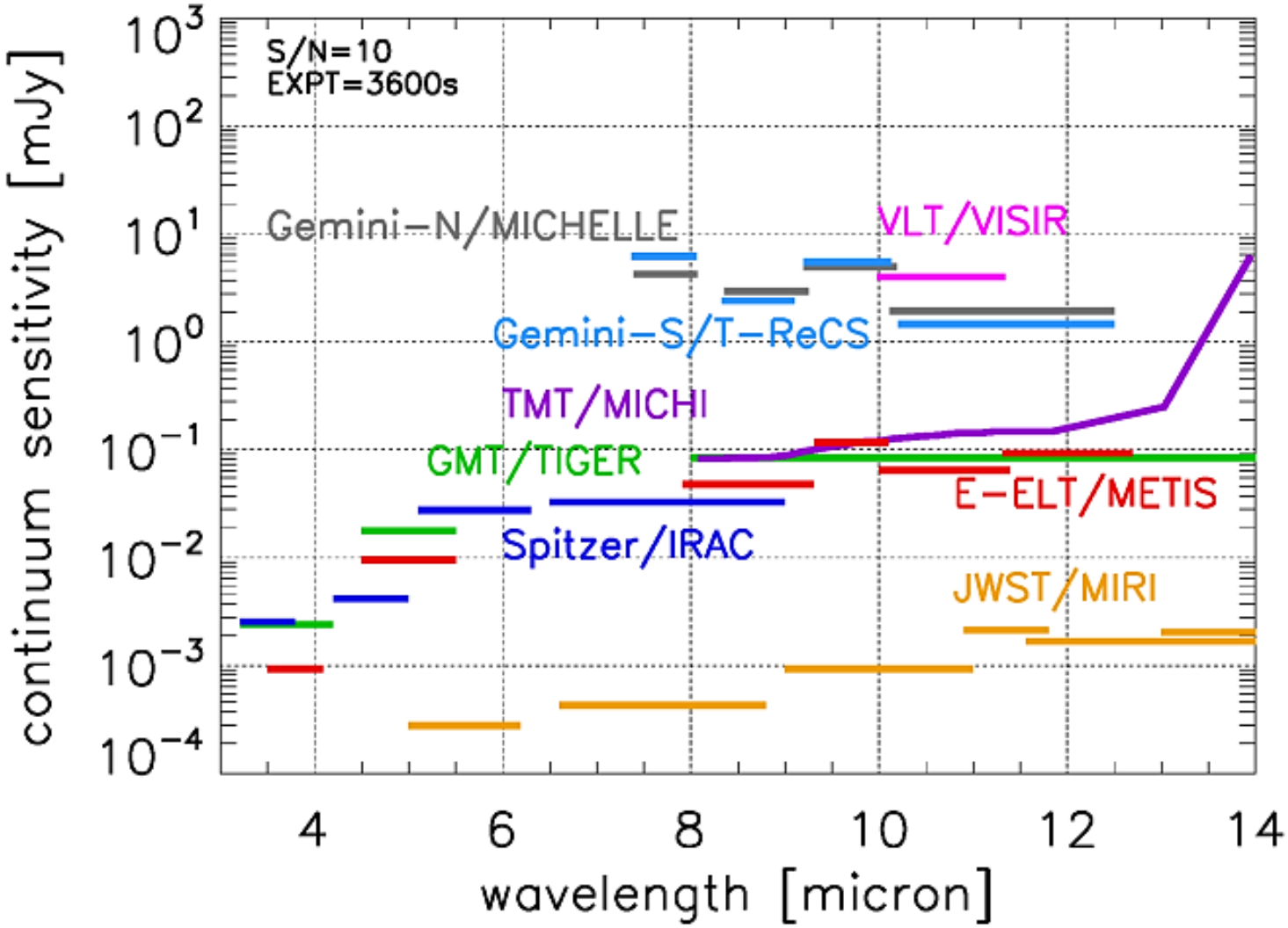
- **Imaging at 3 – 19 µm.** The imager includes low/medium resolution slit spectroscopy as well as coronagraphy for high contrast imaging.
- **High resolution (R ~ 100,000) IFU spectroscopy at 3 – 5 µm**
- **Diffraction limited observations** with SCAO (initially) and in future LTAO.





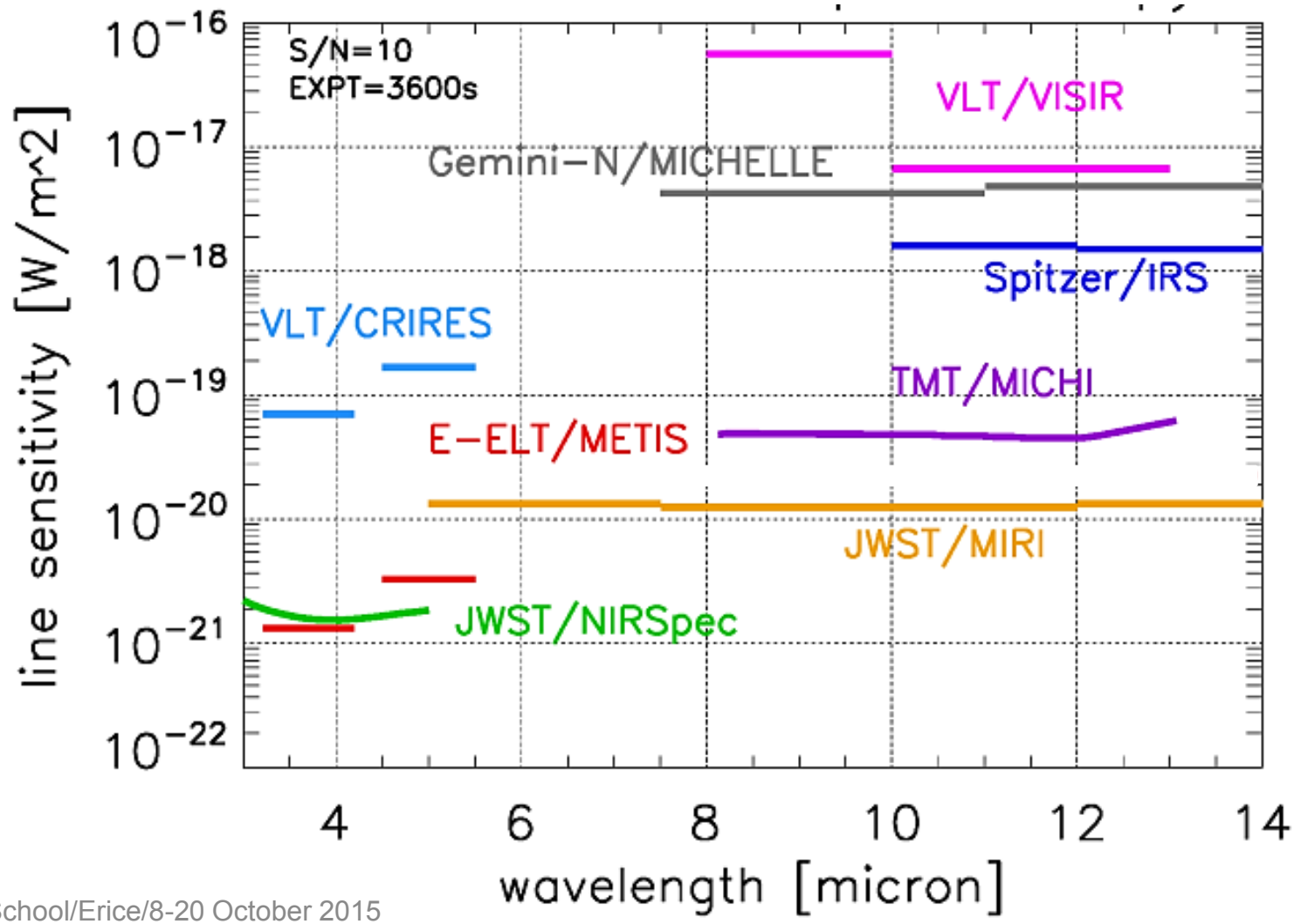
Imaging Point Source Sensitivity

Point Source Sensitivities (1hr, 10σ)

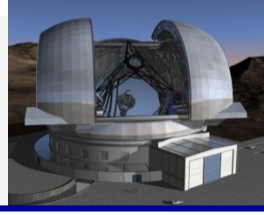


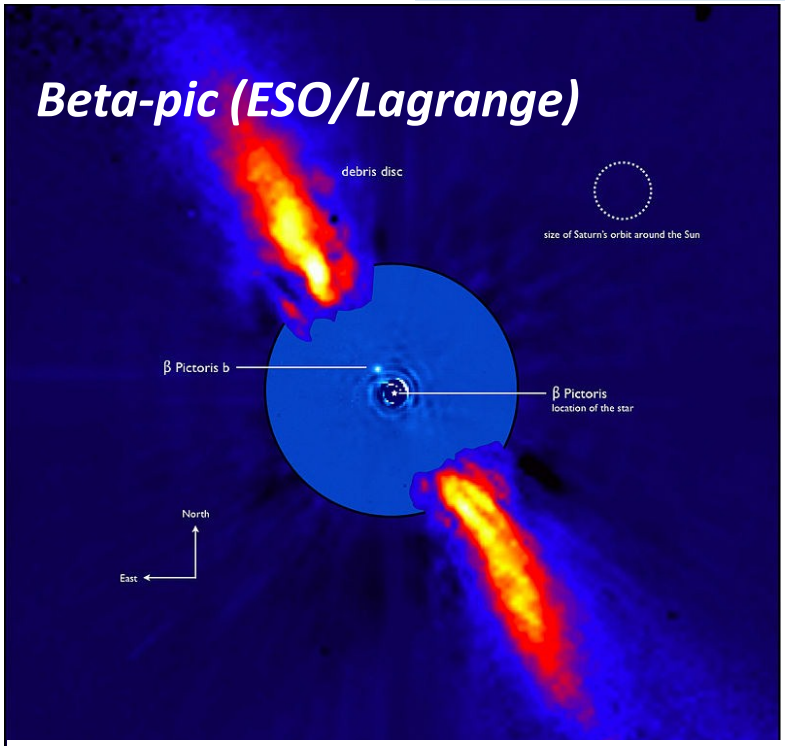
Spectroscopic Sensitivity

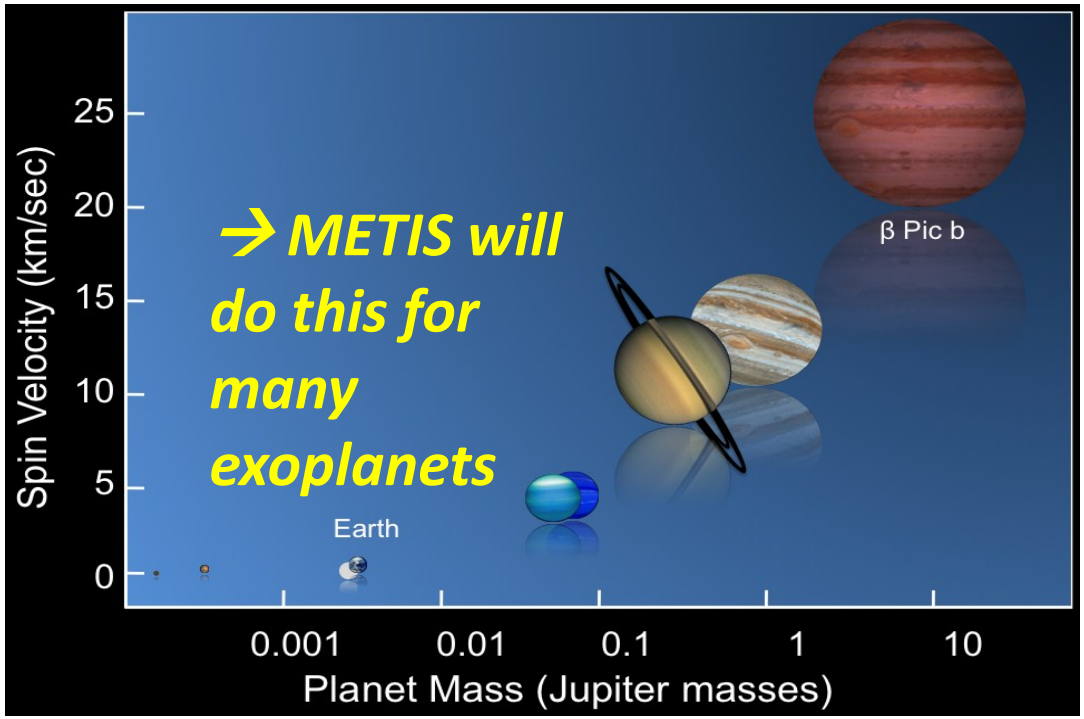
IFU *R=100,000* spectroscopy (PS, unresolved lines)

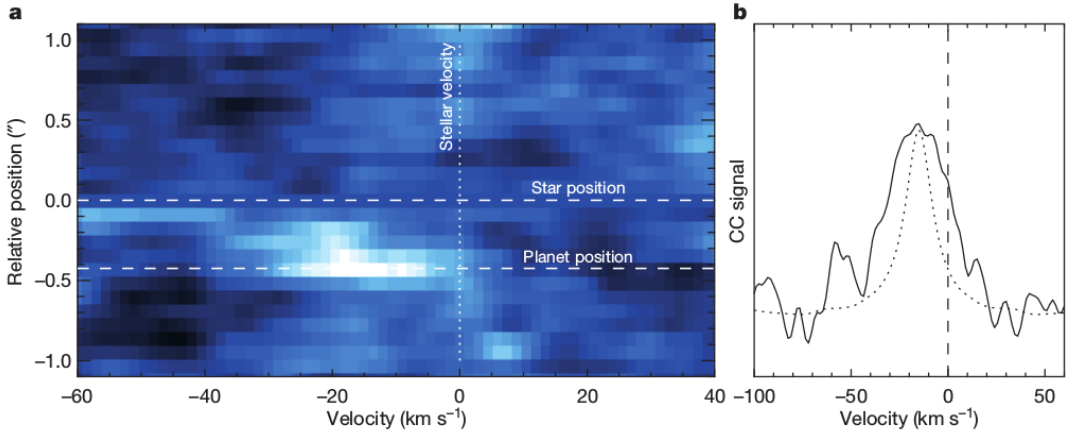


Planet Spin Rotation









First detection of exoplanet spin-rotation ***(Snellen, Brandl, et al., Nature 2014)***

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- ELT-MOS, -HIRES call for proposals

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EAGLE

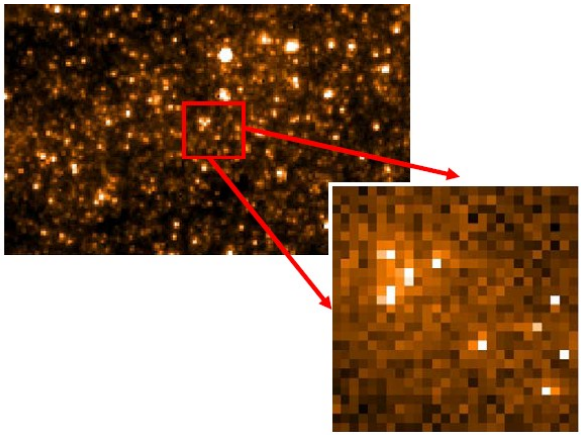
a wide-field multi-IFU AO assisted NIR spectrograph

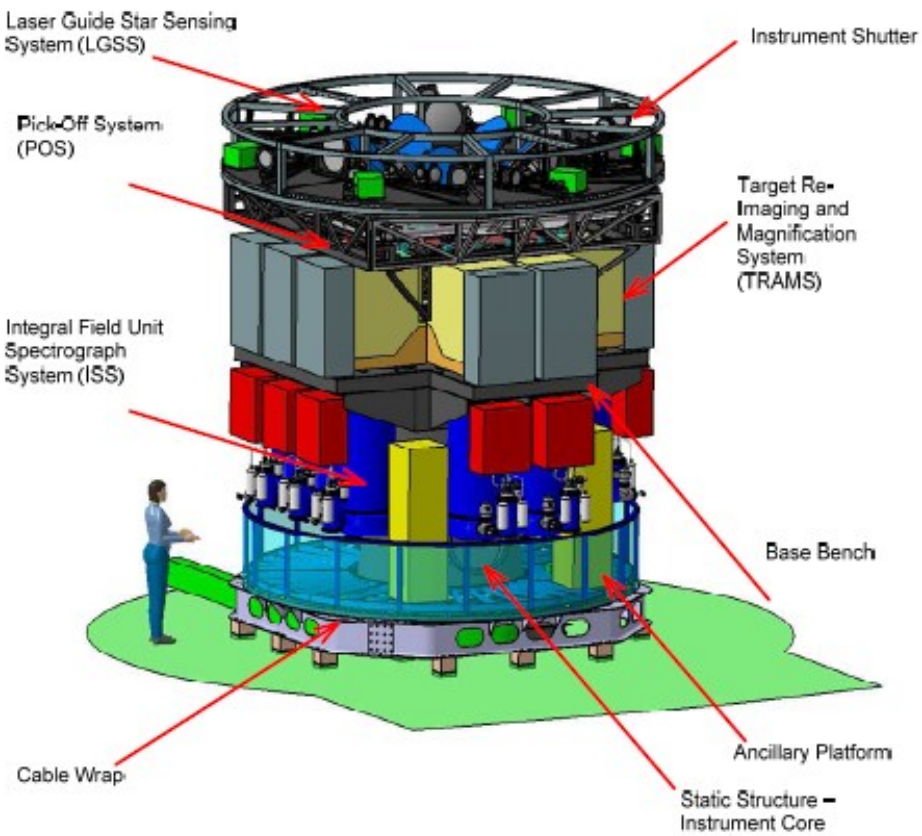
PI: Jean-Gabriel Cuby, Simon Morris

LAM, Uni. Durham, UK ATC, GEPI, ONERA, LESIA

At ESO: S Ramsay

- **Galaxy evolution via stellar archaeology: simulation of a single EAGLE IFU versus HST ACS**



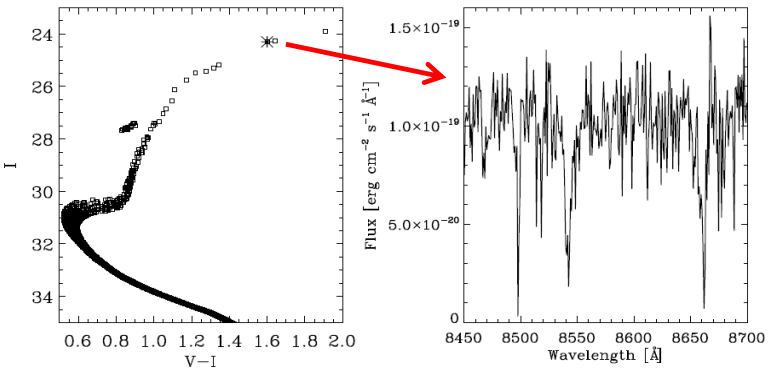


- Near-infrared: 0.8-2.45μm
- Patrol field 38arcmin^2
- 20-IFU fields 1.65”x1.65”
- R~4000,10000
- IQ:>30% EE in 75mas
- Multi-Object AO

OPTIMOS-EVE
optical-H band fibre MOS

PI: Francois Hammer

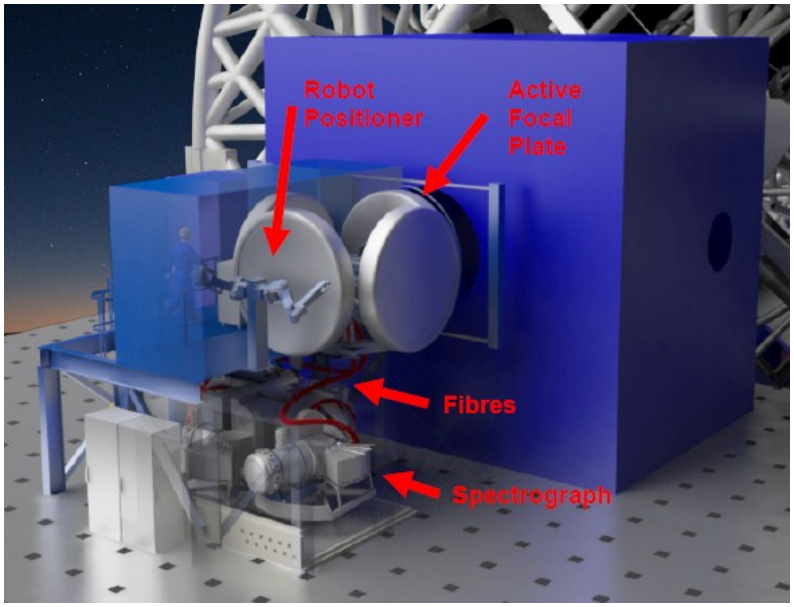
GEPI,NOVA, INAF, RAL, Nils Bohr I.

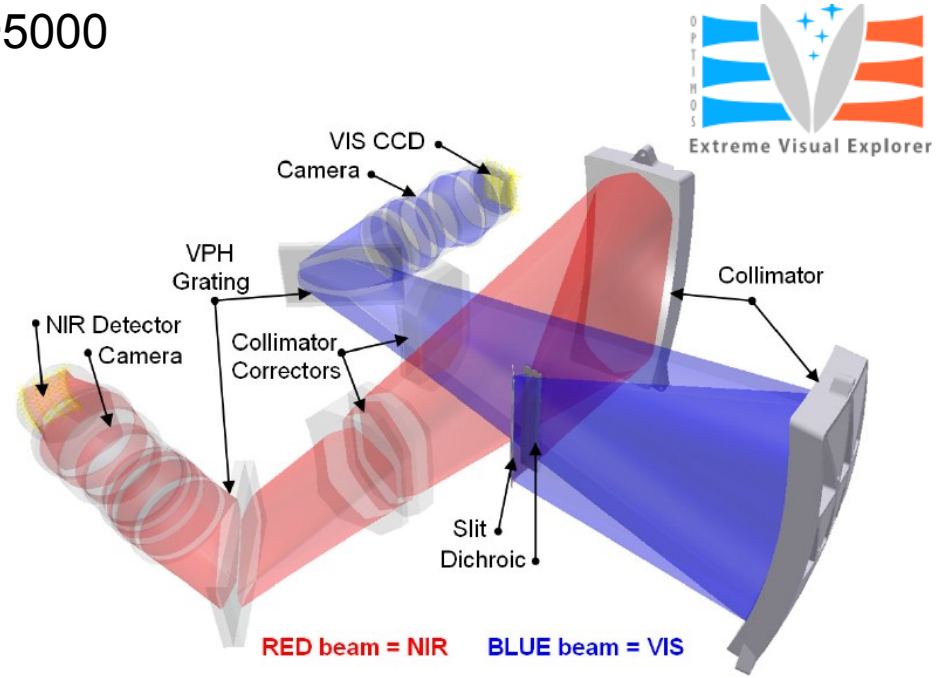


- 0.37μm-1.7μm
- Patrol field - ~7'
- 240 fibres /R~5000
- 70 fibres / R~15000

- 40 fibres / R~30000
- 30 IFUs 1.8" x 3"
- 1 IFU 7.8"x13.5"
- Both IFUs / R~5000

- Li abundance in stars in nearby galaxies





OPTIMOS-DIORAMAS

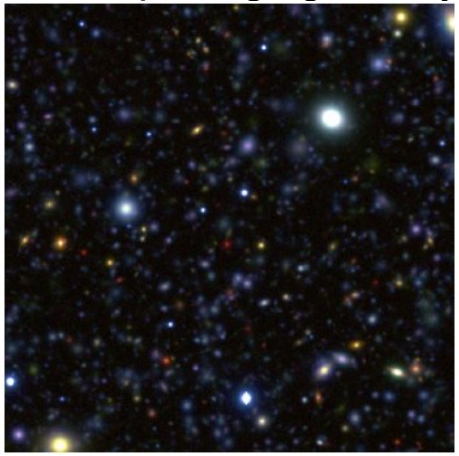
a wide field imaging multi-slit spectrograph

PI: Olivier Le Fèvre

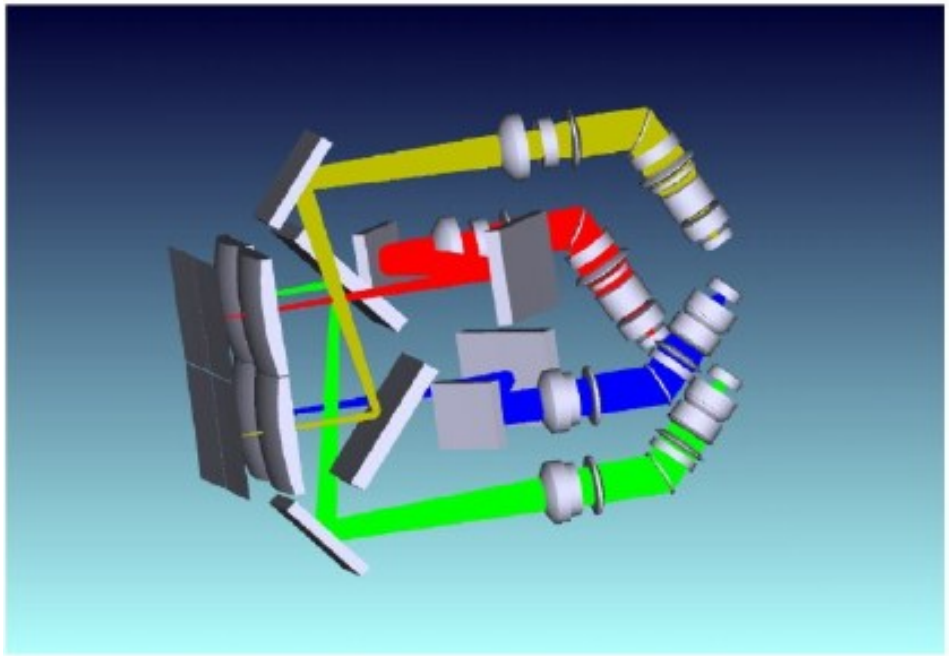
LAM, IASF-Milano, Obs. Haute Provence, Obs. Genève, IAC

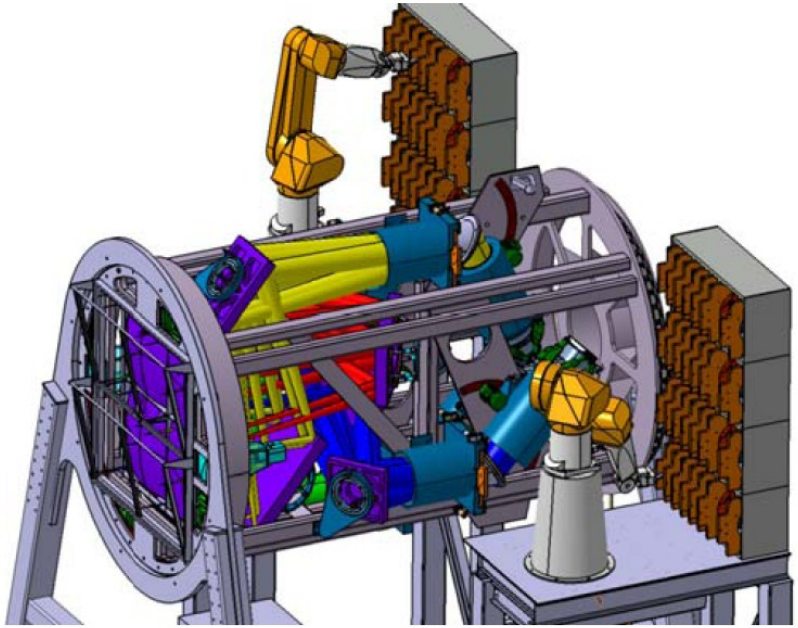
- MOS and Imager over 6.8'x6.8' FOV
- Standard visible and NIR filters for imaging
- 480 slits in the visible range, 120 for NIR
- R~300, 1000, 2500 visible; 400,800,3000 for NIR

Ultradeep imaging surveys



1/15 of the total field for imaging





E-ELT-MOS

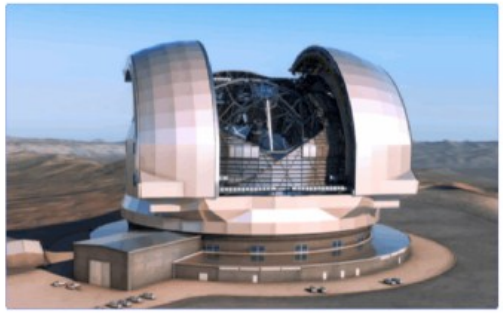
- Top Level Requirements
  - 0.4-2.45um wavelength range
  - 1 000 < R< 15 000
  - Multiplex ~>400 and 2-100 (AO)
  - Seeing limited or MOAO-type resolution

MOSAIC

Proposed instrument concept.

Community white paper
Astro ph/1501.04726 January 2015

The Science Case for Multi-Object Spectroscopy on the European ELT



European Organisation for Astronomical Research in the Southern Hemisphere
Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR THE ELT-MOS

ESO-204696 Version 1

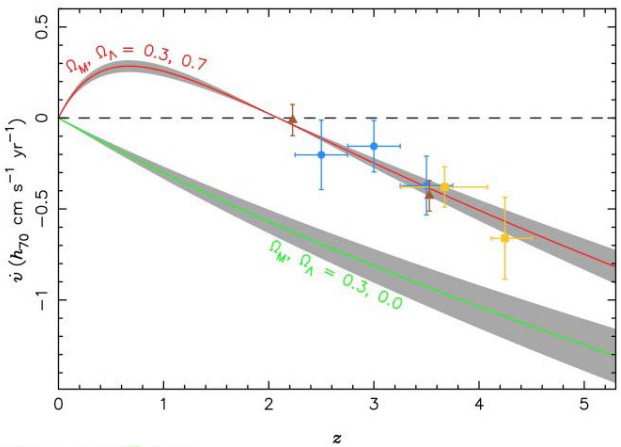
2014-1-23

Owner	P. Padovani	16/2/2014
Programme Scientist	J. Spyromilio	14/4/14
Programme Manager	R. Tamai	14 Feb 2014
	Name	Date / Signature

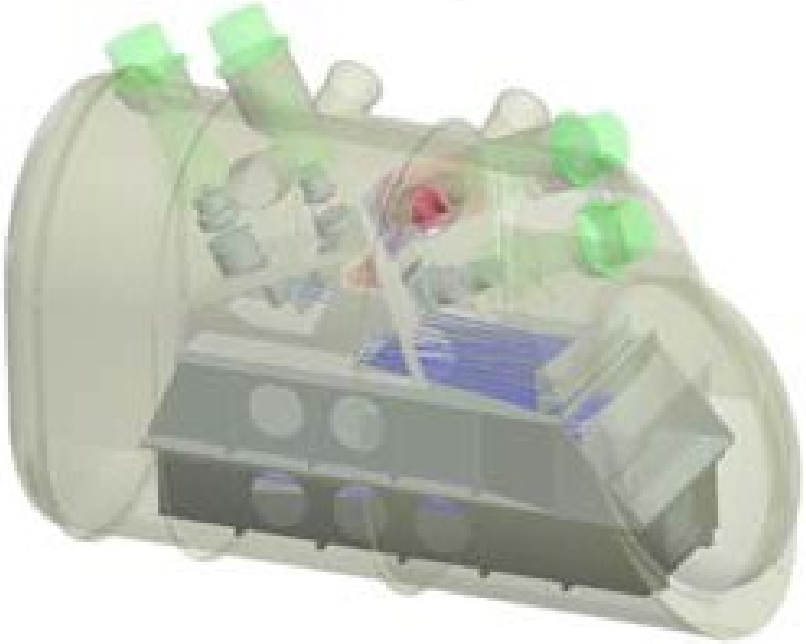
CODEX

high stability, high resolution visible spectrograph

- PI: Luca Pasquini, ESO
- Geneve Observatory, IAC, INAF-Trieste and Brera, IoA Cambridge



- field of view (0.82”)
- 0.37-0.71μm
- Dual beam spectrograph
- R~130,000
- ~2cms^{-1} Doppler precision over 30yrs
- no adaptive optics
- located in the coudé room



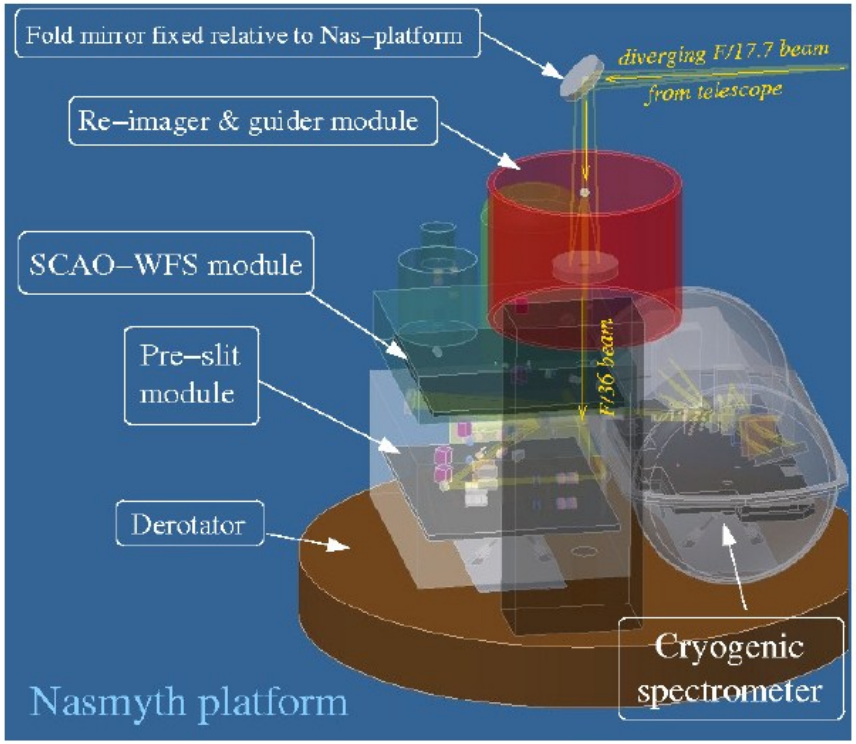
SIMPLE

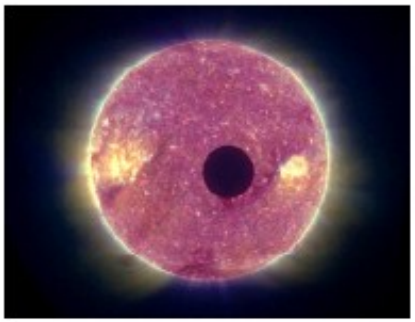
high resolution NIR spectrograph

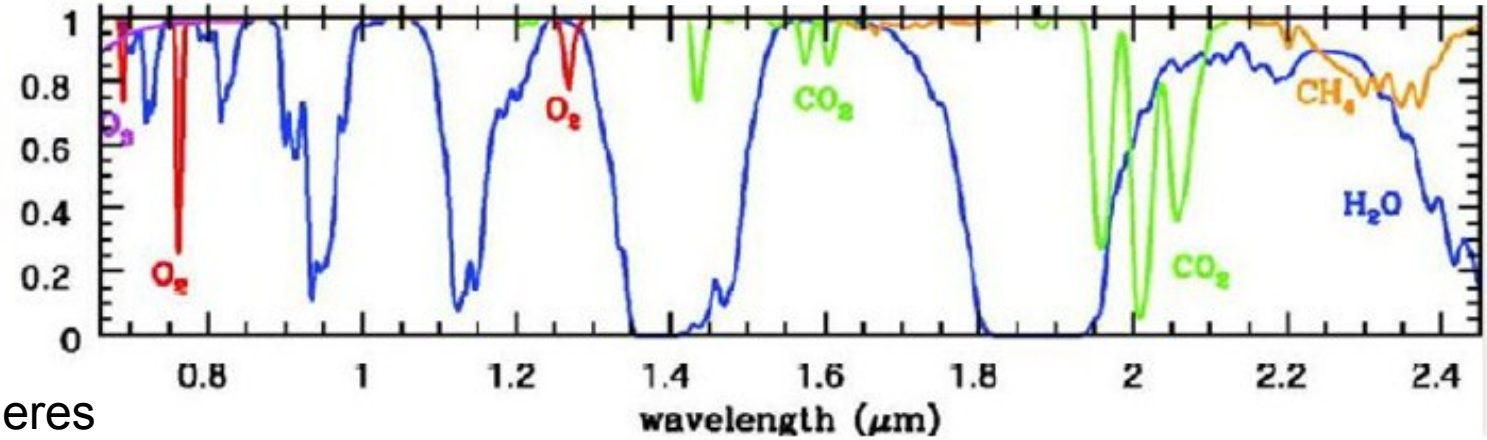
PI: Livia Origlia
INAF,UAO, TLS, PUC

At ESO H-U Kaufl

- 0.84-2.5μm
- Complete spectrum
- R~130,000
- Slit: 27x450mas
- SCAO on-board, MCAO or LTAO



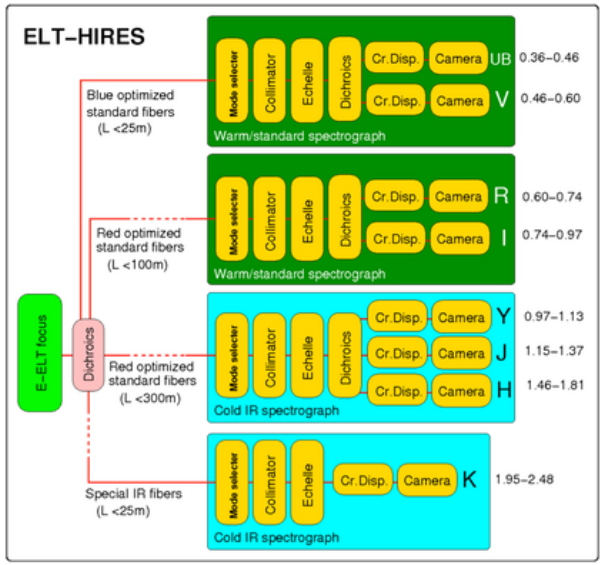




Exoplanet atmospheres

ELT-HIRES

- Instrument Top Level Reqs
  - 0.37-2.5um wavelength range
  - 100 000 < R< 200 000
  - Diffraction limited resolution >1u
  - Also seeing limited performance



Proposal from the HIRES initiative, see also talk by Livia Origlia.

European Organisation for Astronomical Research in the Southern Hemisphere
Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR ELT-HIRES

ESO-204697 Version 1

30/01/2014

Owner	J. Liske	10/02/2014
Programme Scientist	J. Spyromilio	14/2/14
Programme Manager	R. Tamai	14/2/2014
	Name	Date / Signature

The E-ELT Instrument Roadmap

- Instruments selected in consultation with the ESO committess and community, based on
  - Scientific impact, return, flexibility
  - Complementarity to JWST, existing facilities
  - A plan to cover all observing conditions
- ELT-6: an instrument for the unknown

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-MOS	ELT-HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Cal for Proposals Start Phase A			
2016				Consortium Selection for construction		Call for proposals	
2017							
2018							TRL check
2019						Selection	Start when ready
2020							
2021							
2022							
2023							
2024							

	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
	Decision point
	Development of Technical Specifications, Statement of Work, Agreement, Instrument Start.

The E-ELT Instrument Roadmap

- Instruments selected in consultation with the ESO committess and community, based on
  - Scientific impact, return, flexibility
  - Complementarity to JWST, existing facilities
  - A plan to cover all observing conditions
- ELT-planetary camera and spectrograph

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-MOS	ELT-HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Cal for Proposals Start Phase A			
2016				Consortium Selection for construction		Call for proposals	
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2023							
2024							

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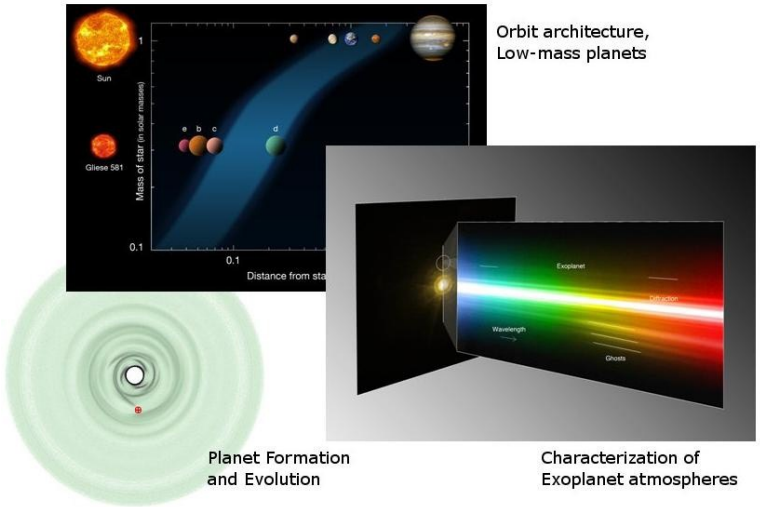
EPICS

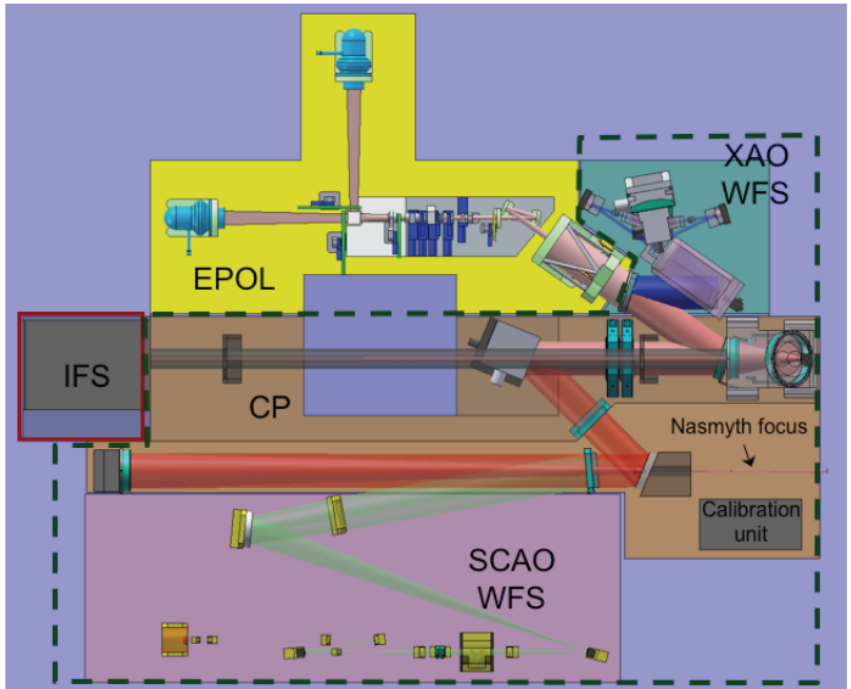
- **PI: Markus Kasper, ESO**
- **LAOG,LESIA, Uni. Nice, LAM,ONERA, Uni.Oxford, INAF, ETH Zurich, NOVA**

IFS 0.95-1.65μm
FOV: 0.8" x 0.8"/2.33mas
0.8" x 0.014" long slit
R = 125, 1400 and 20000

EPOL 0.6-0.9μm
Coronagraphic polarimeter
FOV: 2" x 2"/1.5mas

Contrast ratios – 10^{-8} – 10^{-9}
XAO – very high (90%) Strehl





Some useful links

- Links to ELT pages
  - E-ELT: ww.eso.org/sci/facilities/eelt
  - TMT: www.tmt.org
  - GMT: www.gmto.org
  - Messenger Vol. 140 summarises Phase A instrument concepts

- Some past and future science conferences
  - Shaping the E-ELT Science and Instrumentation (Feb 2013) www.eso.org/sci/meeting/2013/eelt2013.html
  - Expolanet observations with E-ELT (Feb 2014) www.eso.org/sci/meeting/2014/exoelt2014.html
  - Speed and Sensitivity (May 2014) astro.nuigalway.ie/speedandsensitivity
  - Early E-ELT Science: Spectrscopy with HARMONI (Jul2015) harmoni2015.physics.ox.ac.uk
  - Science and Technology with E-ELT (www.eso,org/sci/meetings/2015/EELT_EriceSchool2015.html)