The ELT project

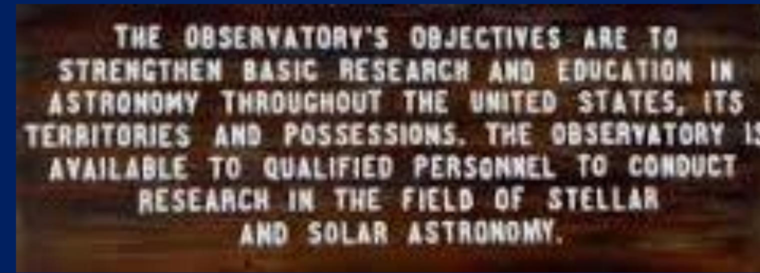
Ecole Evry Schatzmann 2017

Roscoff

120 m
100 m
80 m
60 m
40 m
20 m

3 Jun 1948
Inauguration of the Hale telescope

Kitt Peak, Arizona - 1958

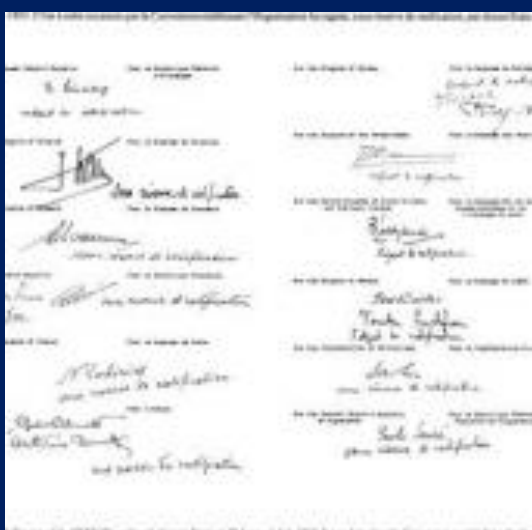


Beginning of the 50s', CERN creation in Europe

Lausanne, Dec 1949, Louis de Broglie propose the creation of an european laboratory for nuclear physics (Conférence européenne de la culture).

Florence, Jun 1950 (5e Conférence générale de l'UNESCO), resolution for allowing UNESCO to « assister et encourager la création de laboratoires régionaux pour accroître la coopération scientifique internationale ».

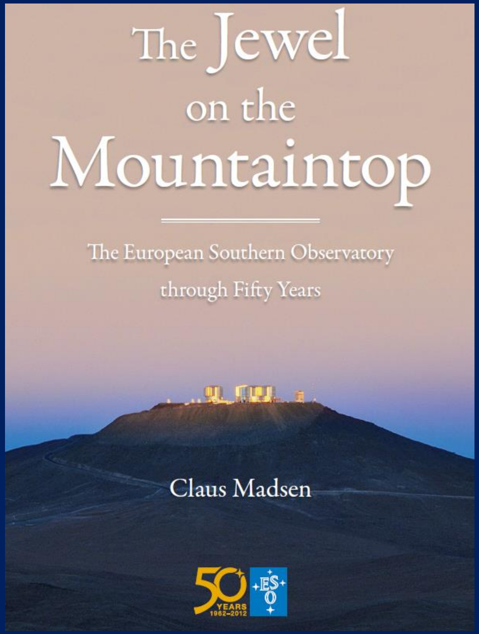
Paris, Dec 1951: First resolution for the foundation of the « Conseil européen pour la recherche nucléaire (CERN) » is voted.

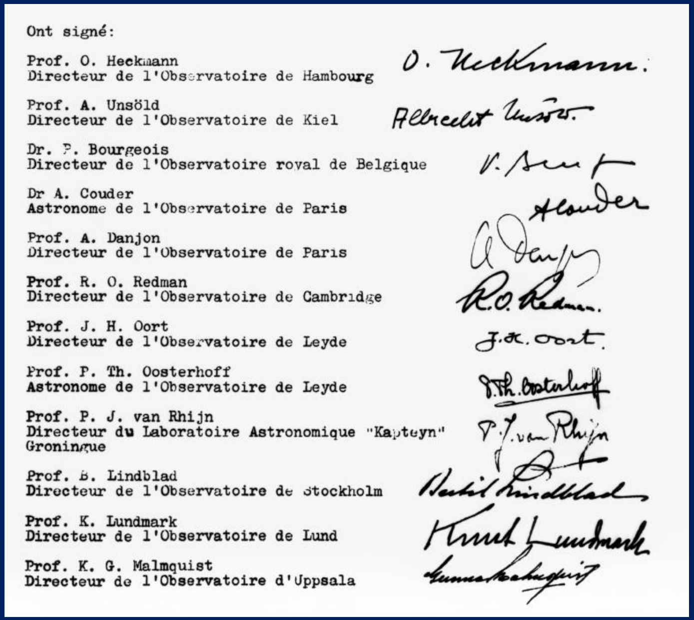


29 Sep 1954: birth of the European Organisation for Nuclear Physics (CERN acronym is preserved)

ESO: funded in 1962

Allemagne, Belgique, France, Pays-Bas et Suède





Ont signé:

Prof. O. Heckmann
Directeur de l'Observatoire de Hambourg

Prof. A. Unsöld
Directeur de l'Observatoire de Kiel

Dr. P. Bourgeois
Directeur de l'Observatoire royal de Belgique

Dr A. Couder
Astronome de l'Observatoire de Paris

Prof. A. Danjon
Directeur de l'Observatoire de Paris

Prof. R. O. Redman
Directeur de l'Observatoire de Cambridge

Prof. J. H. Oort
Directeur de l'Observatoire de Leyde

Prof. P. Th. Oosterhoff
Astronome de l'Observatoire de Leyde

Prof. P. J. van Rhijn
Directeur du Laboratoire Astronomique "Kapteyn" Groningue

Prof. B. Lindblad
Directeur de l'Observatoire de Stockholm

Prof. K. Lundmark
Directeur de l'Observatoire de Lund

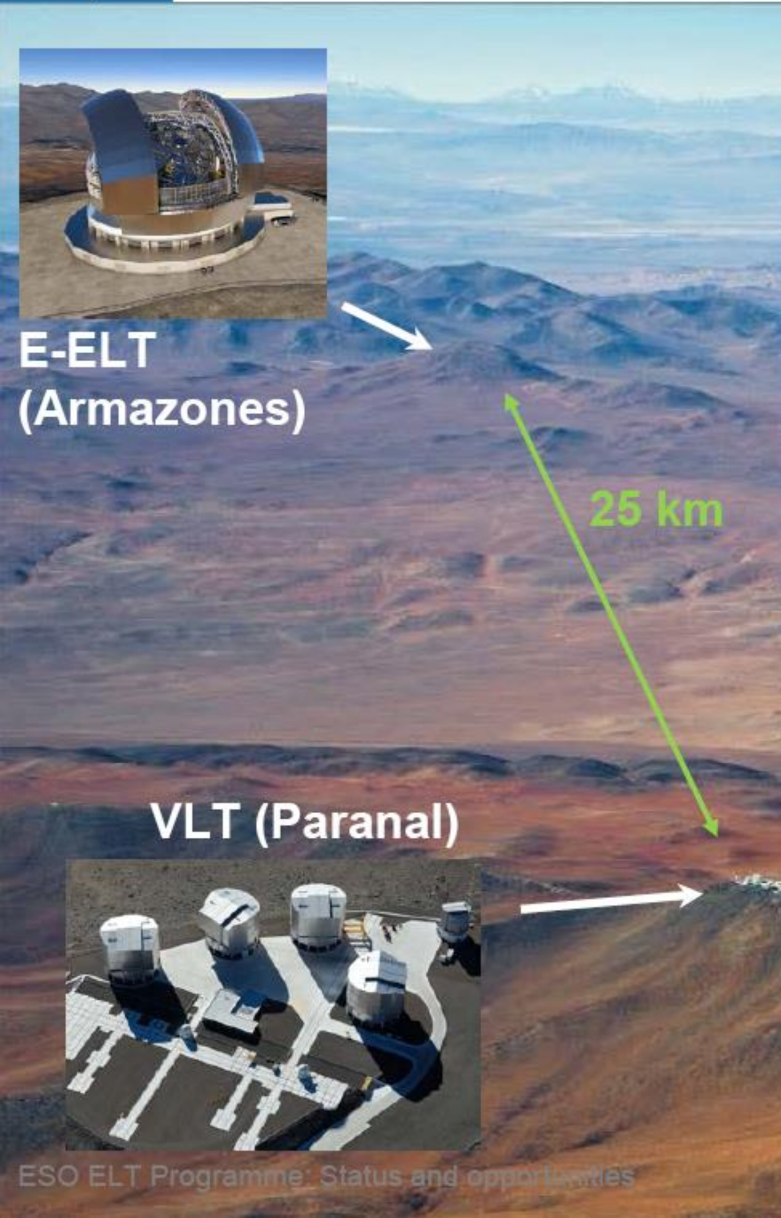
Prof. K. G. Malmquist
Directeur de l'Observatoire d'Uppsala

Otto Heckmann, ESO's first Director, wrote in his book *Sterne, Kosmos, Weltmodelle*:
"American astronomy, based on large instruments, seemed destined to remain a monologue, even though fruitful science demands dialogue, yes even controversy."

The situation in France in the 60s'

- Creation of ESO
- Vision of a national organisation to serve the big projects: Jean-François DENISSE, who was Président de l'Observatoire de Paris, Président of CNES and of INAG!
- Construction of the Nançay Radiotelescope and of the Paris Observatory calculator (linked to ESO programmes)
- Decisions for CFHT and IRAM

Armazones and Paranal

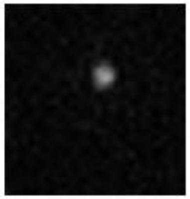


Armazones Site :

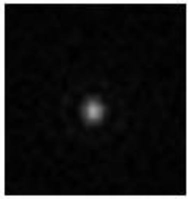
- Altitude: 3046 m
- c.a. 360 nights clear sky
- Very stable atmospheric and weather conditions
  - ➢ Rare and short-duration storms. Typ. 1/year, -10C (min), rain or snow fall, possibly high winds
- Very dry and high UV radiation
- Very active seismic area !

Why the ESO Observatories are in Chile?

- Excellent conditions in the Atacama Desert
  - Extremely dry
  - 90% clean sky
  - Low turbulence
  - Very limited light pollution



Poor site

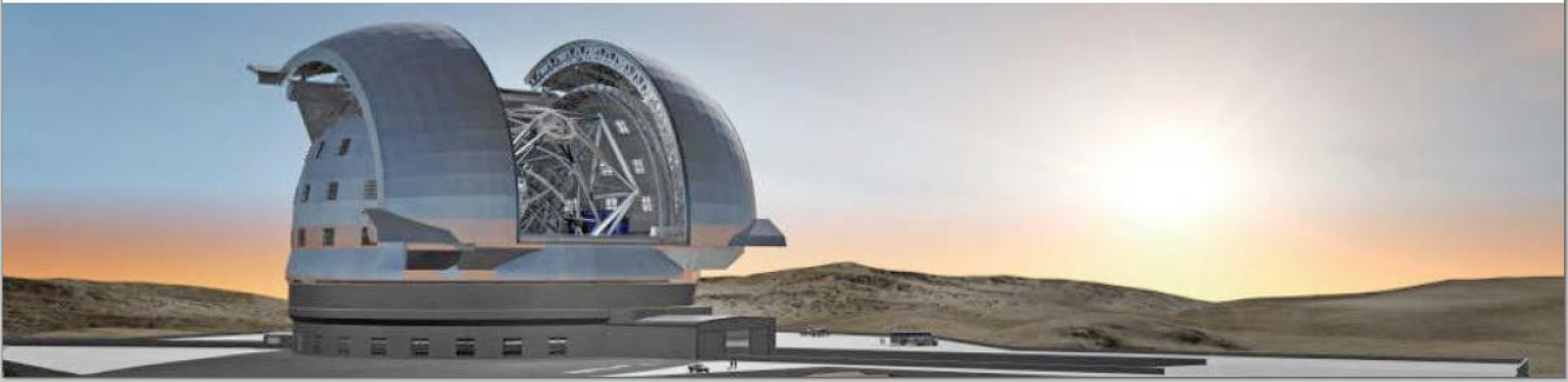


Chile

- Excellent vision to the Southern Hemisphere

And tomorrow, the ELT…

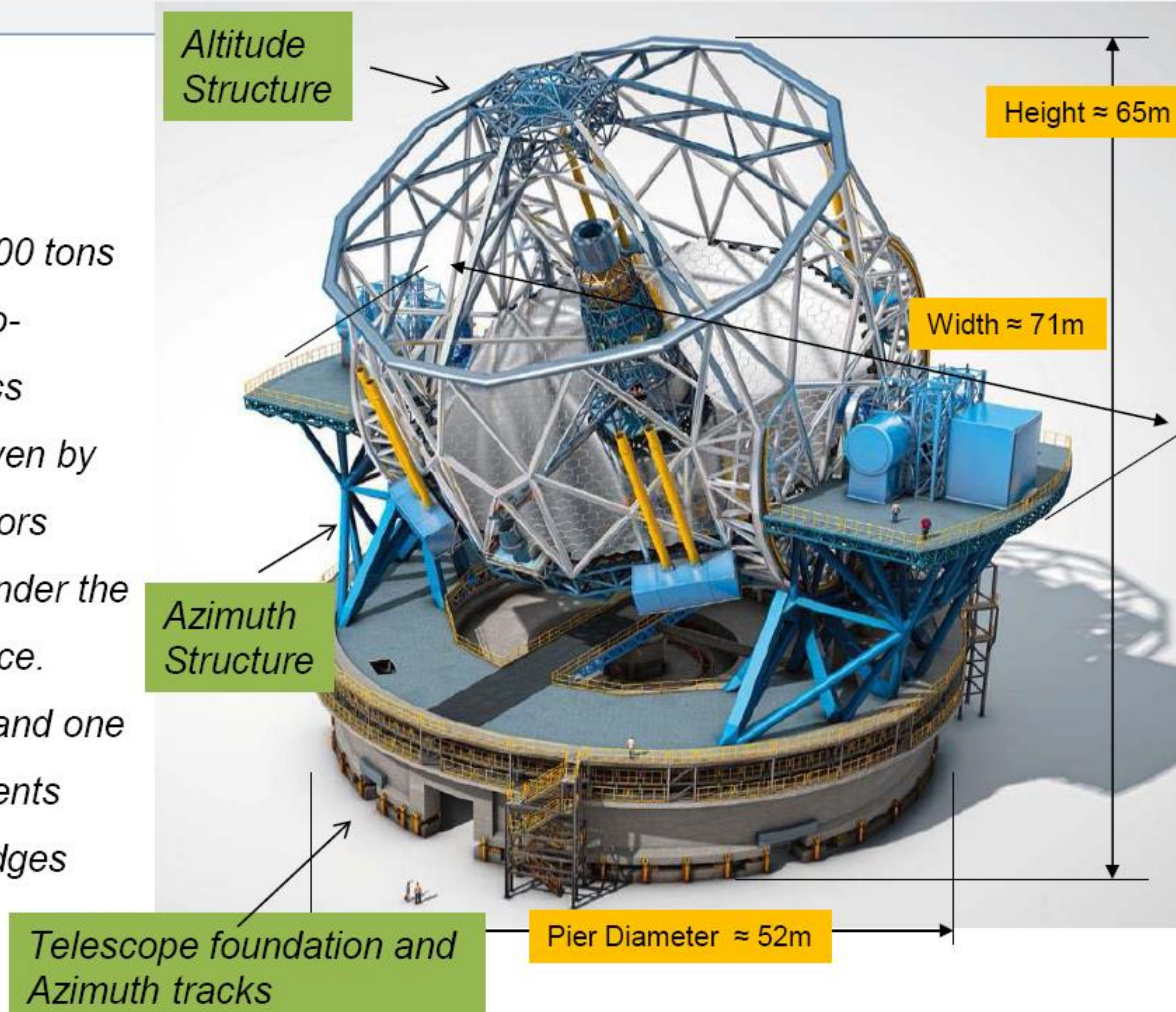
- Largest optical/infrared telescope in the world
  - 39m segmented primary mirror: transformational step
  - Science: exo-earths, deep universe, resolved populations
- Project
  - Construction 2014-2024, on Cerro Armazones
    - As *integral part* of the Paranal Observatory ('one more telescope')
  - ESO cost:
    - Total Capital cost (e.c. 2017): ~1157 MEUR incl. instr.s and contingency
    - Operation cost: ~50 MEUR / year



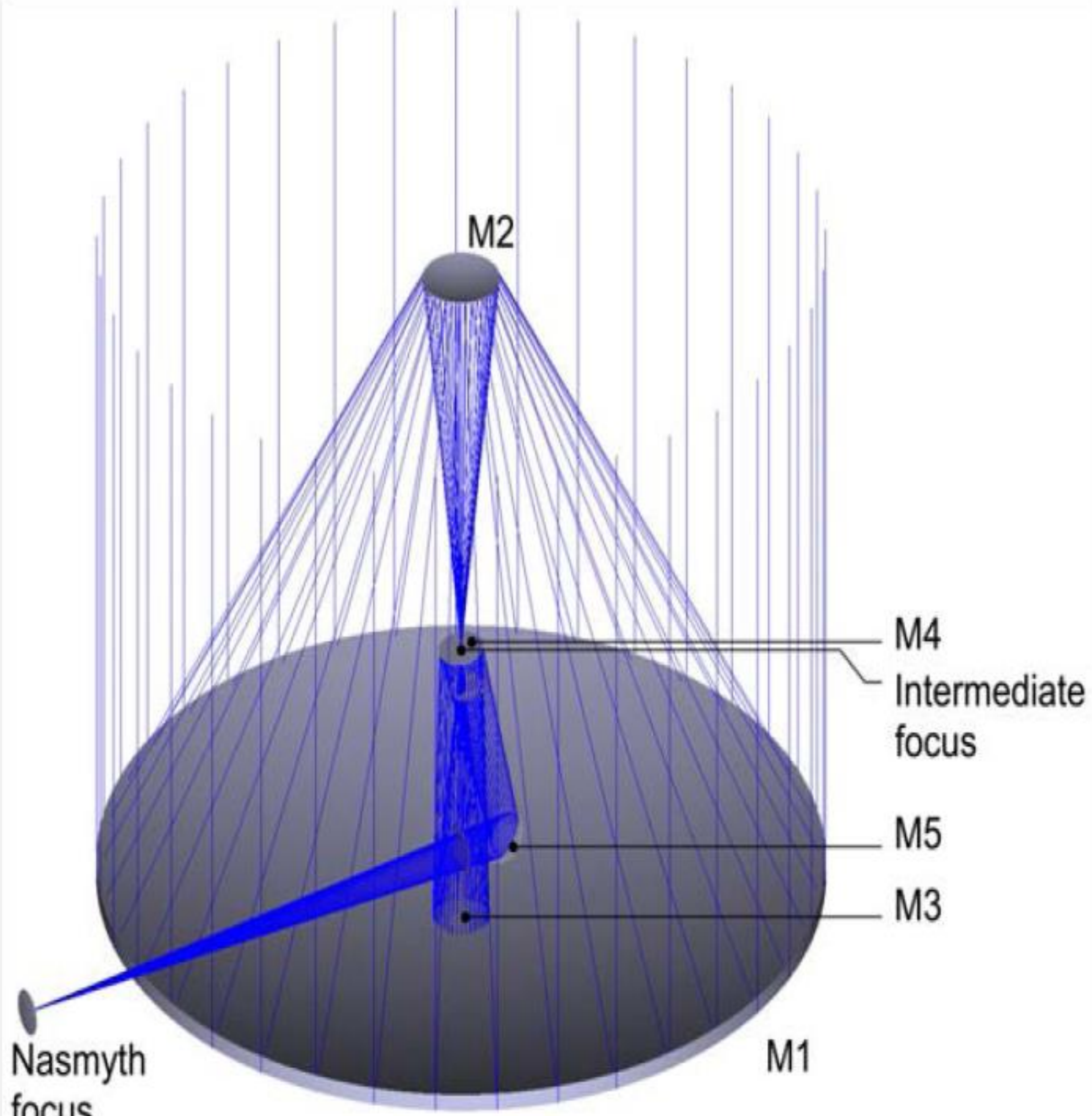
E-ELT - Overview

Telescope design

- *Altitude-Azimuth mount*
- *Main Structure about 3400 tons including 700 tons of opto-mechanics and electronics*
- *Hydrostatic bearings, driven by electrical direct drive motors*
- *Precision of 0.3 arcsec under the maximum wind disturbance.*
- *Two Nasmyth Platforms and one Coude Room for instruments*
- *Laser launch from M1 edges*



ELT Optomechanics



M1 Unit
39-m
Concave – Aspheric f/0.9
Segmented (798 Segments)
Active + Segment shape Control

M2 Unit
4-m
Convex Aspheric f/1.1
Passive + Position Control

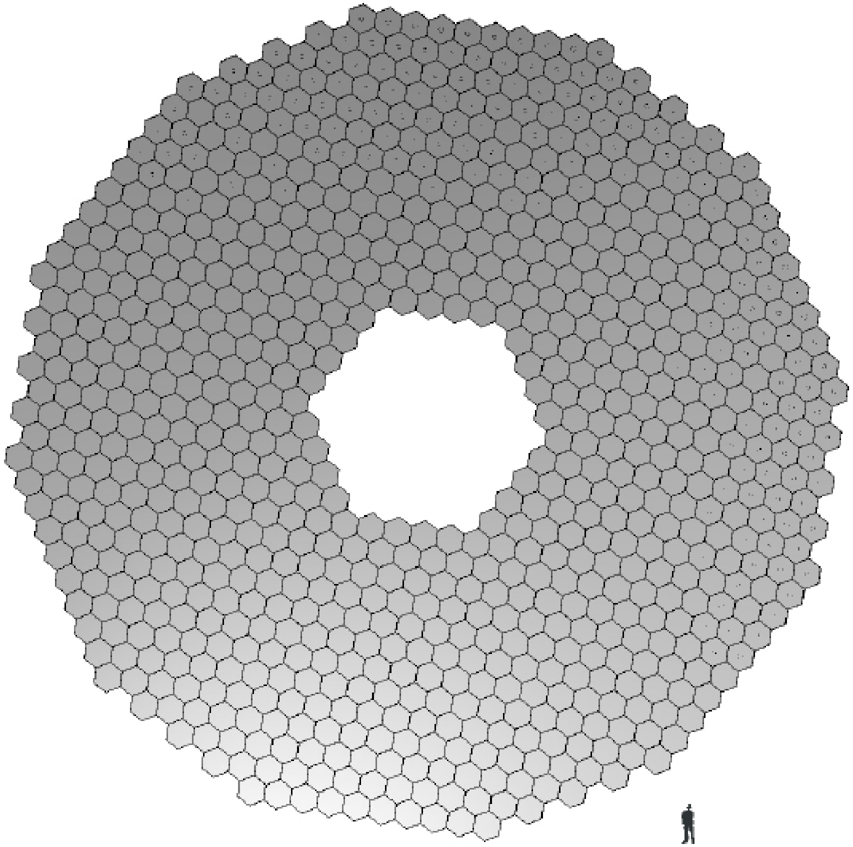
M3 Unit
4-m – Concave – Aspheric f/2.6
Active + Position Control

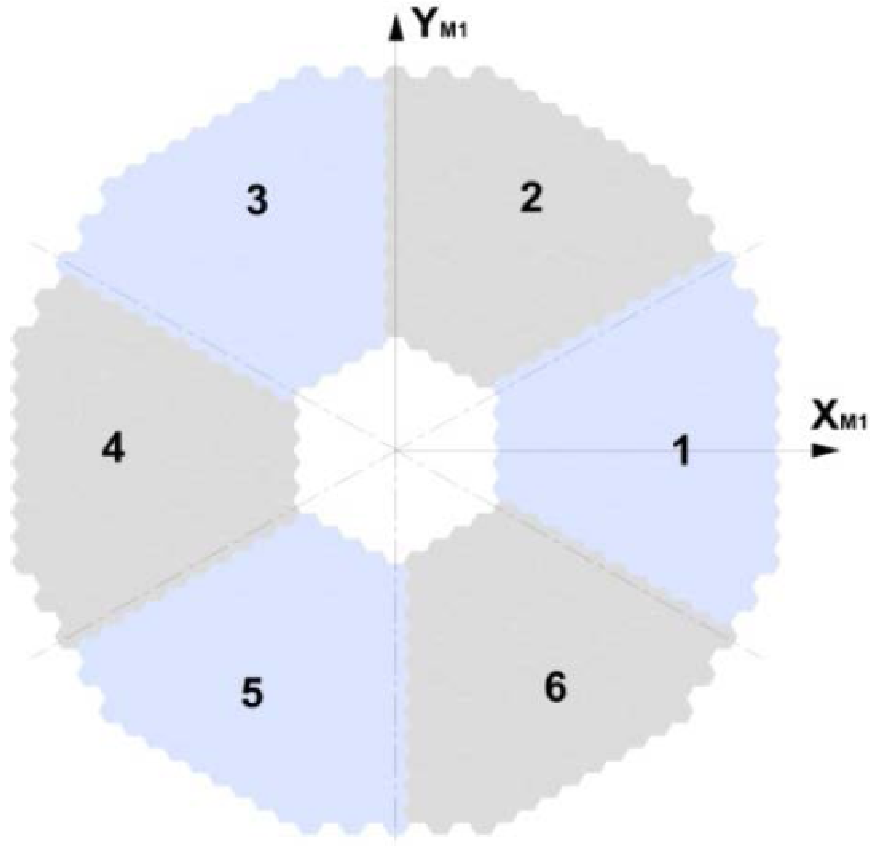
M4 Unit
2.4-m
Flat
Segmented (6 petals)
Adaptive + Position Control

M5 Unit
2.7x2.1-m
Flat
Passive + Fast Tip/Tilt

LGSU
(Laser Guide Star Units)
Laser Sources + Laser Beacons shaping and emitting

M1 Unit

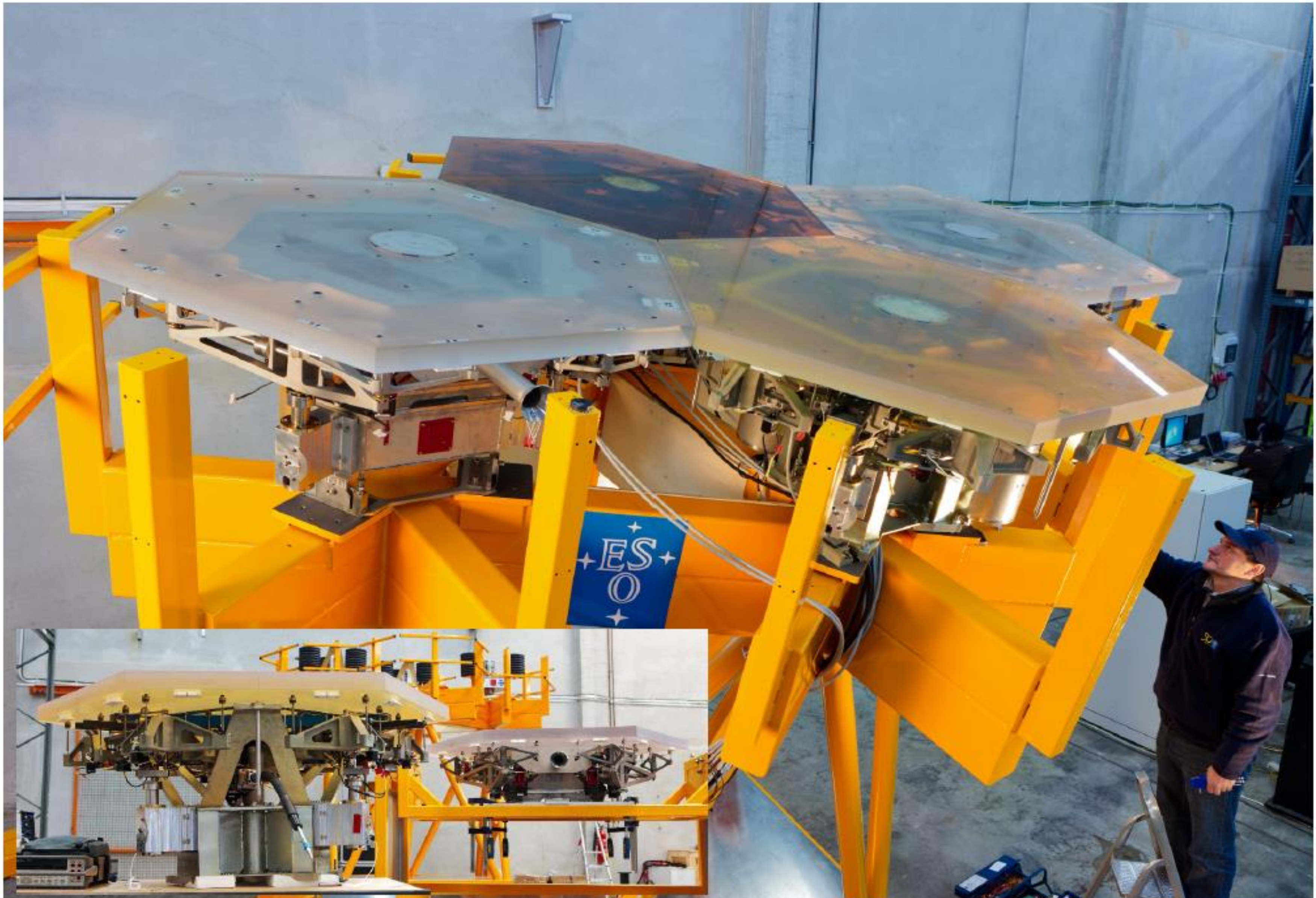




39-m diameter
6x133=798 segments (1.4-m)
+1x133 spare segments
Total: 931 segments

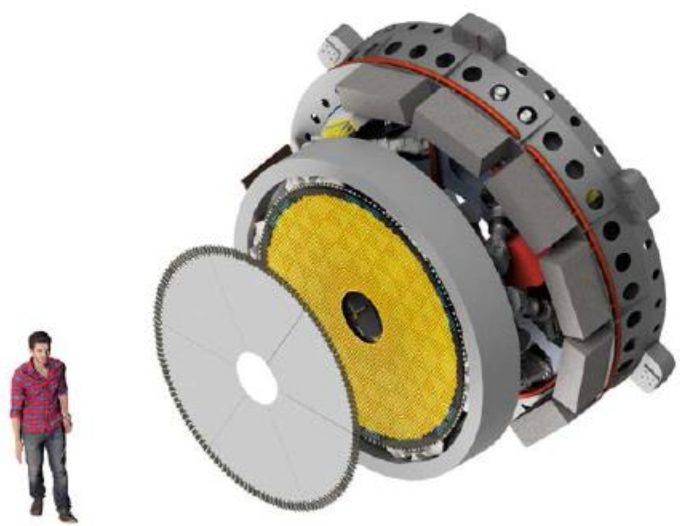
M1 Mirror	
Outer diameter (mm)	39146.0
Inner diameter (mm)	9418.4
M1 Optical Prescription	
Radius of curvature (mm)	68685
Conic constant	-0.996473

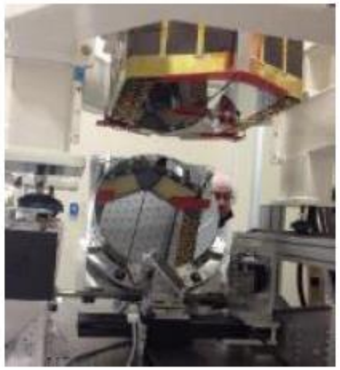
M1 Unit

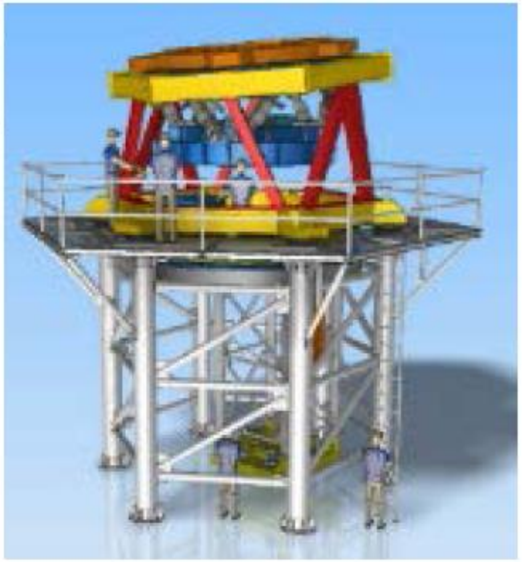


M4 Unit

- 2.4-m flat adaptive mirror – 6 thin-shell petals only 1.95mm thick!
- ~5300 contactless actuators driving the mirror shape at 1 kHz
- Contracts for Final Design and Manufacturing is running

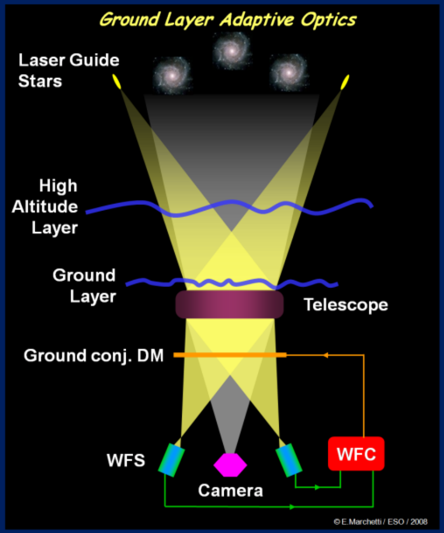




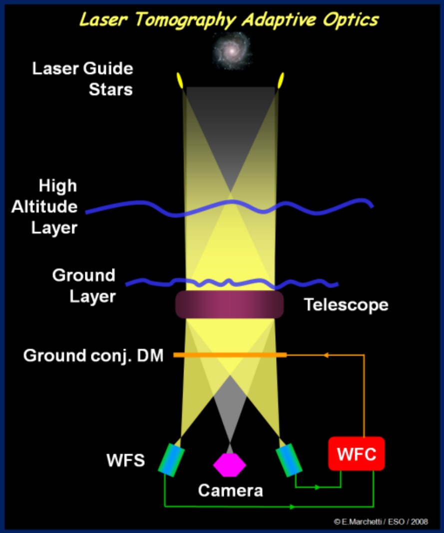


AO projects for the E-ELT

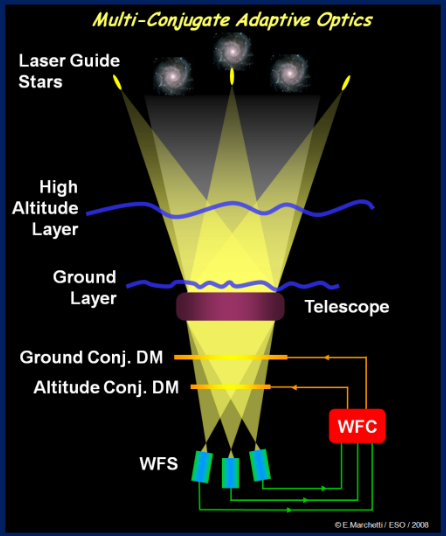
GLAO-LGS



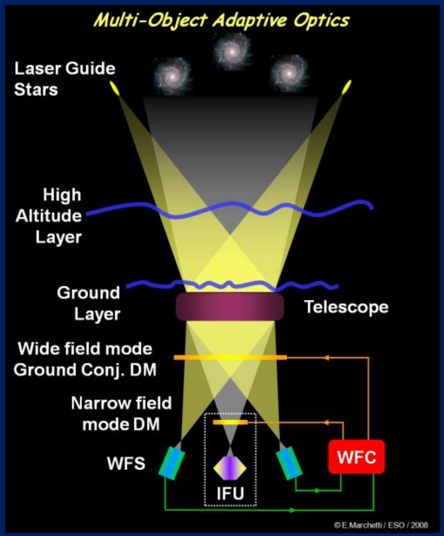
LTAO: ATLAS



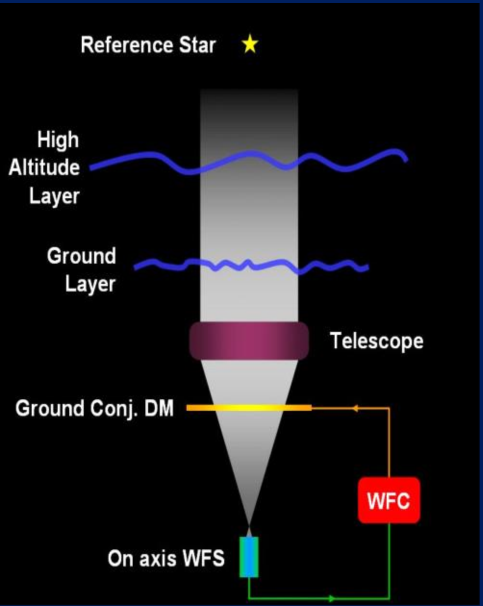
MCAO:MAORY



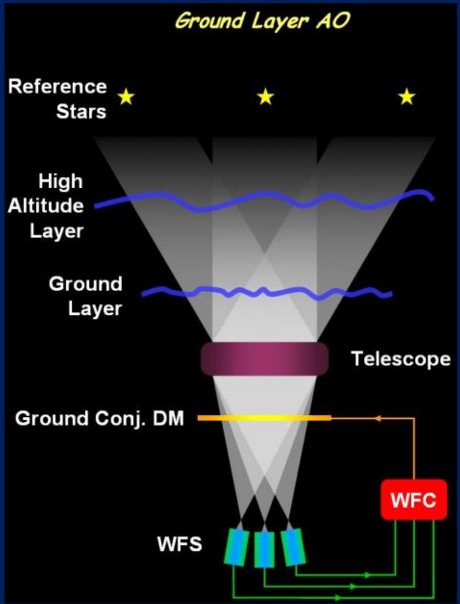
MOAO:EAGLE



XAO: EPICS

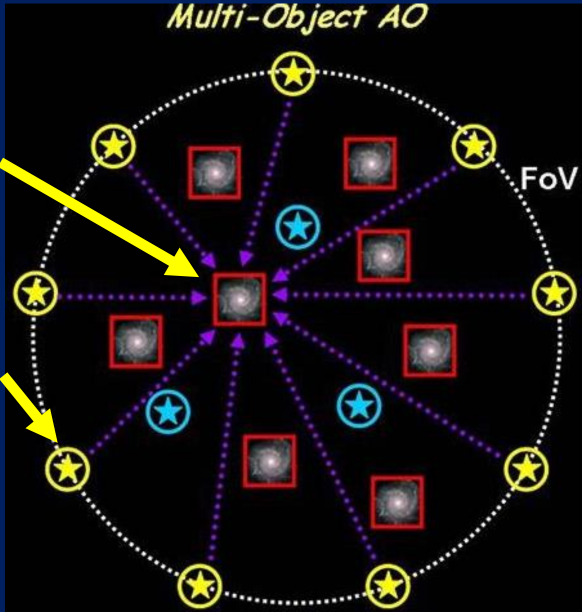


GLAO-NGS



Few” IFU

6-8 LGSs in Ø 7.2’



Expected performances

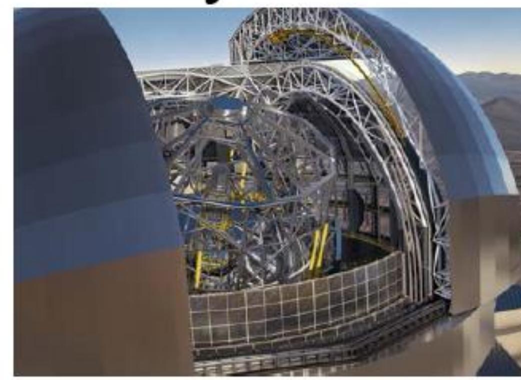
(seeing = 0.71 arcsec -- perf @ 2.2 µm – on axis perf)

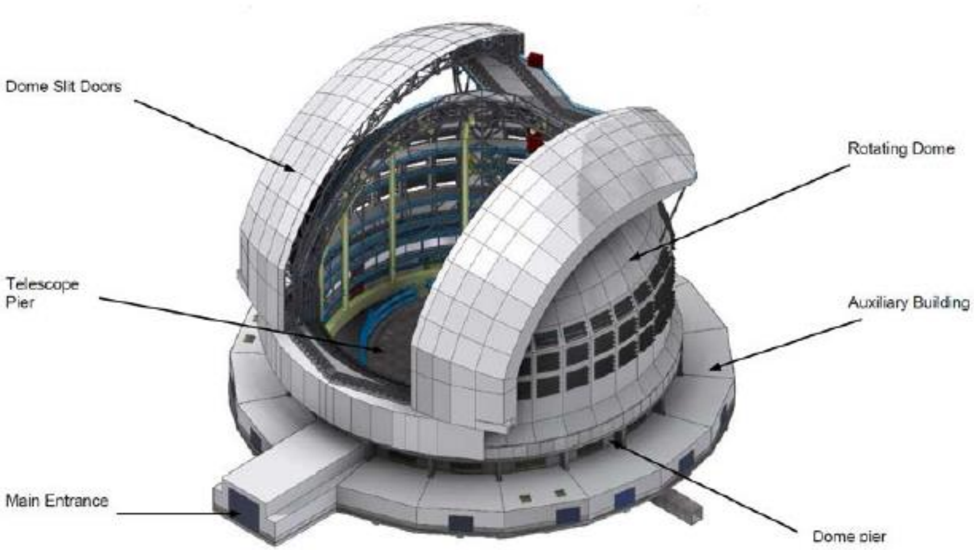
AO type	Nb N-LGSs	Strehl(K) %	% EE in 75mas	FWHM (mas)	Sky Coverage % (60° lat.)	PSF uniformity
SCAO-NGS (postfocal)	1 NGS on-axis	70 → 45	80	11 mas	2	anisoplanatism
NGS-GLAO (Telescope)	3 NGS	<0.3	<8-9	250	50	good
LGS GLAO (Telescope)	4LGS >4.2' 1 NGS	0.3	8-9	250	100	Very good
EAGLE (Postfocal)	6-8LGSs>7.2' 1 NGS	N/A	30	>11	100	Sporadic PSF uniformity
ATLAS (Postfocal)	6 LGSs>4.2' 2 IR NGSs	55	64	11	60	anisoplanatism
MAORY (postfocal)	6LGSs @ 2' 3 IR NGSs	50	58	11	60	Excellent
EPICS	1NGS on axis	90 in H	Few 10-9 contrast	11	Set of targets	N/A

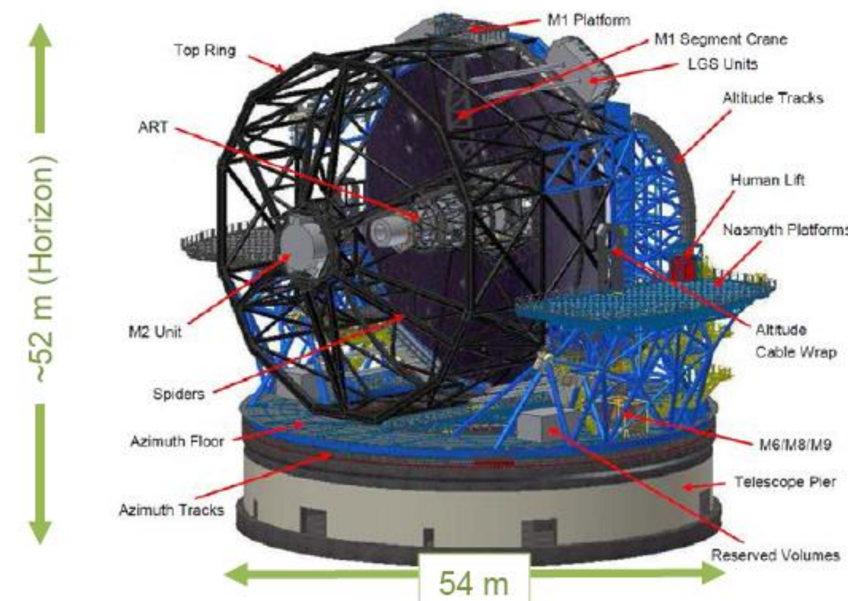
Access Road & Platform completed

Dome & Main Structure (DMS)

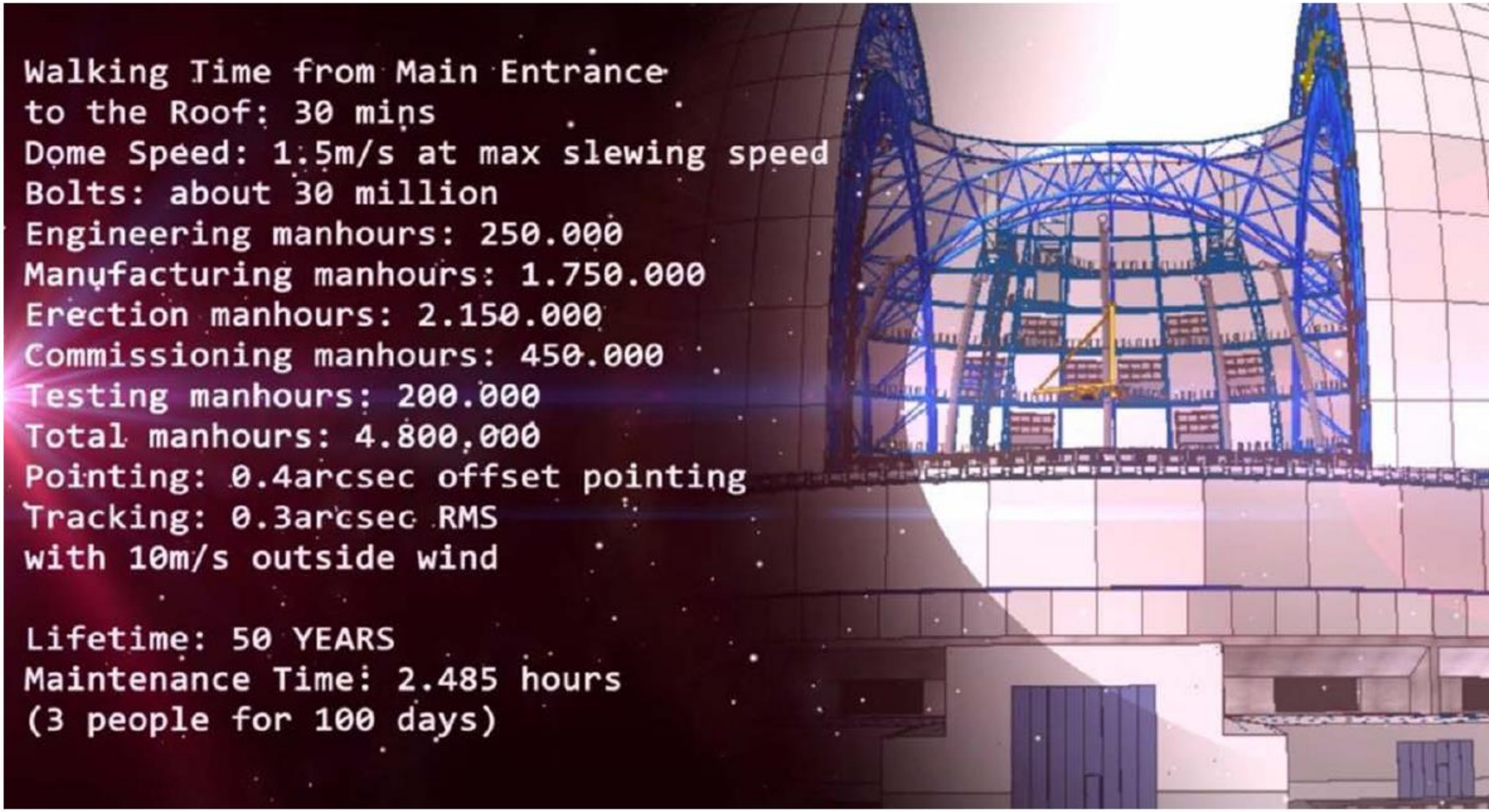
- Site hand-over and 1st Stone on 26th May 2017
- Dome PDR done 26-28 Jun 2017
- MS PDR scheduled Oct 2017







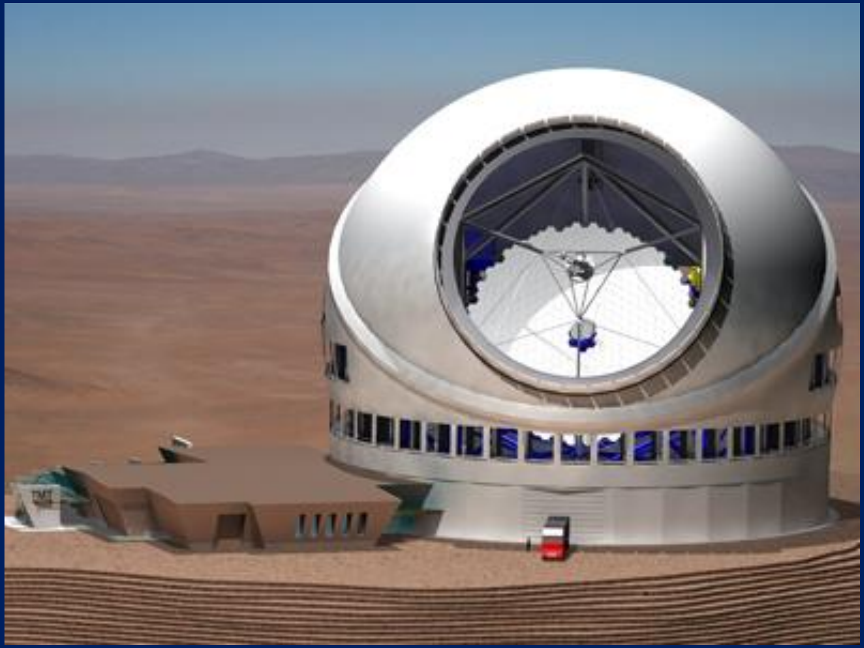
Some numbers from ACe…



Other International ELT projects

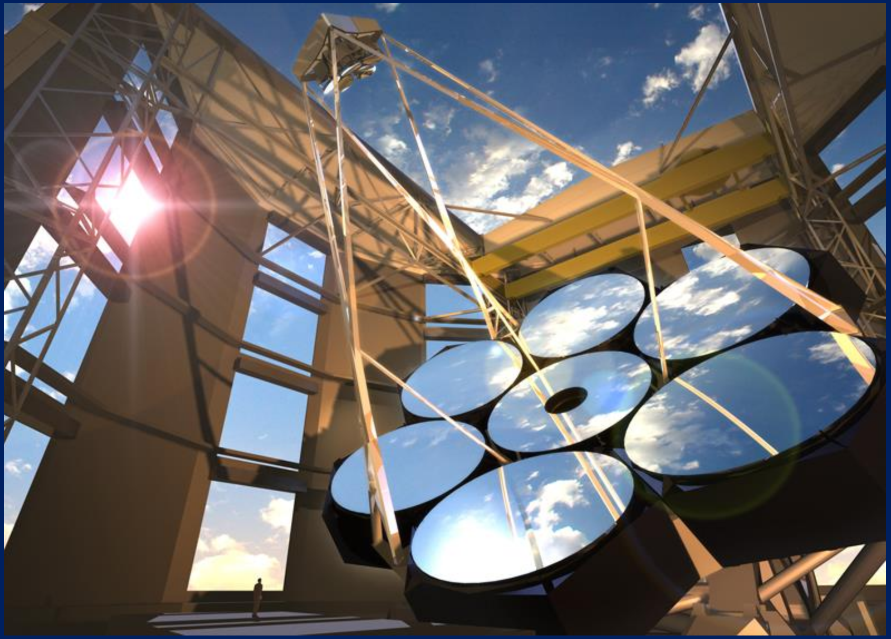
TMT

- 30m telescope
- Institutes in US, Canada, Japan, India, China
- Master agreement signed July 2013
- Groundbreaking Oct 2014 but…
- Maunakea difficulties today



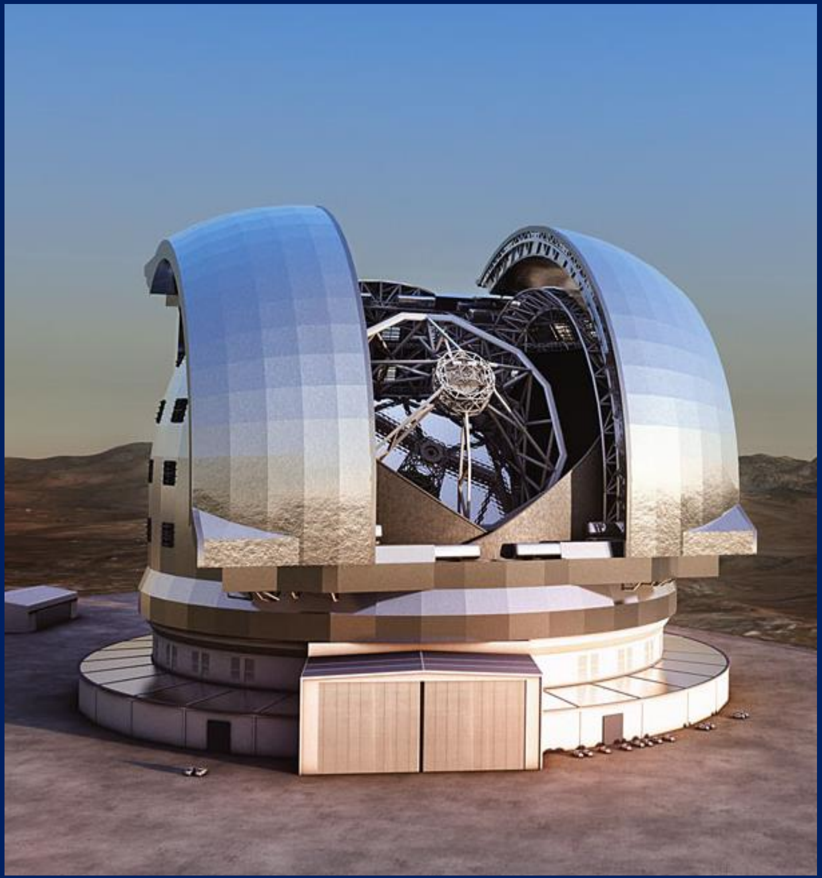
GMT

- 24m diameter (7x 8m segments)
- Collaboration of private US universities, Australia (ANU + AAL) + Korea
- 3rd mirror cast August 2013
- First light (4 segments) planned 2020?
- Funding issues on instruments



ELT Status

- 39m diameter telescope with adaptive optics built in
- Dec 2014: ESO Council gave green light for E-ELT construction in two phases
  - funding approved for Phase I
  - Still expectation that both phases will be completed
- Expected first light 2024



Dec 2014: green light for the construction

COUNCIL DECIDES:

1. That the construction of the full E-ELT is carried out **in two Phases** with Phase 1 as described in Section 6 of Council document ESO/Cou-1553 rev. 2 conf.

2. That the **construction period of Phase 1 may extend until 2026** for a cost-to-completion of **1012.5 MEUR in 2014 prices**. This **amount is fully funded** within the annual budgets of ESO without any additional contributions from the Member States, other than those currently approved for the E-ELT (additional contribution of 255 MEUR in 2012 prices and planned 2% increases year-on-year above inflation until 2021), and **does not require long-term loans** for investments from financial institutions.

3. **To authorize, independently of progress in the Brazilian ratification process, spending** on major items for Phase 1, i.e., the required procurement contracts with a single cost of more than 2 MEUR.

4. That a Council decision **to authorize the start of Phase 2, or some of its elements, is deferred until sufficient funding is available**, with the understanding that **if the Brazilian ratification procedure is completed before 2017 first light of the full E-ELT will be brought forward to 2024.**

5. That in accordance with the Terms of Reference of **the E-ELT Management Advisory Committee**, approved by Council on 4-5 March 2014 (doc. ESO/Cou-1509 conf. rev.), this Committee shall advise Council and the Director General on how and when external reviews shall be conducted. It shall meet first **in early 2015**.

But funds for phase 1 only

Phase 1 is identical to the baseline design in almost every aspect except the pre-focal station.

The M1 segments remain unchanged except for the total number procured. The rest of the optics, M2, M3, M4 and M5 are all unchanged.

The instrumentation suite provided by Phase 1 comprises:

1. MICADO together with the MAORY Multi Conjugate Adaptive Optics system and four sodium lasers to give full sky coverage.
2. HARMONI in Single Conjugate Adaptive Optics mode, and
3. METIS, also in Single Conjugate Adaptive Optics mode
4. Preliminary Design level funding of the LTAO module Competitive
5. Phase A studies for the MOS and HIRES instruments and their subsequent funding to Preliminary Design Level.

Phase 2 items (as of Dec'14)

Item	Material Cost MEUR	ESO FTE Cost MEUR	Total Cost MEUR	Impact if delayed	Recom-mendation	Priority for restoration in Phase 2
Power conditioning	11.0	1.0	12.0	Science efficiency (more technical downtime) but does not compromise either First Light or science operations	Phase 2 (if still needed)	6
Armazones support building	1.0	-	1.0	Impact on operations, not on science	Phase 2	7
Atmospheric monitoring	1.0	0.6	1.6	Minimal impact on operations	Phase 2	2
7th sector of M1 segments	19.7	0.1	19.8	No science impact in first five years	Phase 2	4
Inner 5 rings of M1 segments	29.8	-	29.8	26% loss of collecting area (but still the biggest ELT)	Phase 2	3
METIS (post PDR)	10.4	1.8	12.2	Significant impact on science and on community	Phase 1	
Second pre-focal station	9.3	0.1	9.4	No impact for first 2 (possibly 3) instruments	Phase 2	4
Descope First PFS	9.3	0.1	9.4	Reduced FOV and no GLAO	Phase 2	5
Defer 2 (of 6) Laser systems	2.8	0.7	3.5	Reduced Strehl compared to baseline	Phase 2	4
MAORY	14.7	4.9	19.6	Significant (SCAO only for MICAO)	Phase 1	
LTAO	9.6	0.4	10.0	Significant (SCAO only for HARMONI & METIS)	Phase 2	1
Adaptive M4	28.0	1.5	29.5	Severe – no AO on E-ELT	Phase 1	
Contingency (proportional)	10.0	-	10.0		Phase 2	
Grand Total	**156.7**	**11.2**	**167.8**			
Total Phase 2	***103.6***	***3.0***	***106.5***			

1) LTAO up to PDR within HARMONI contract.

2) Missing segments in option in the contracts but Australia agreement will soon permit to solve this important issue.

3) 2nd PFS is critical for the 2nd generation instruments (MOS, HIRES, +++)

4) Important to note that the 2nd gen instruments are in the operating budget

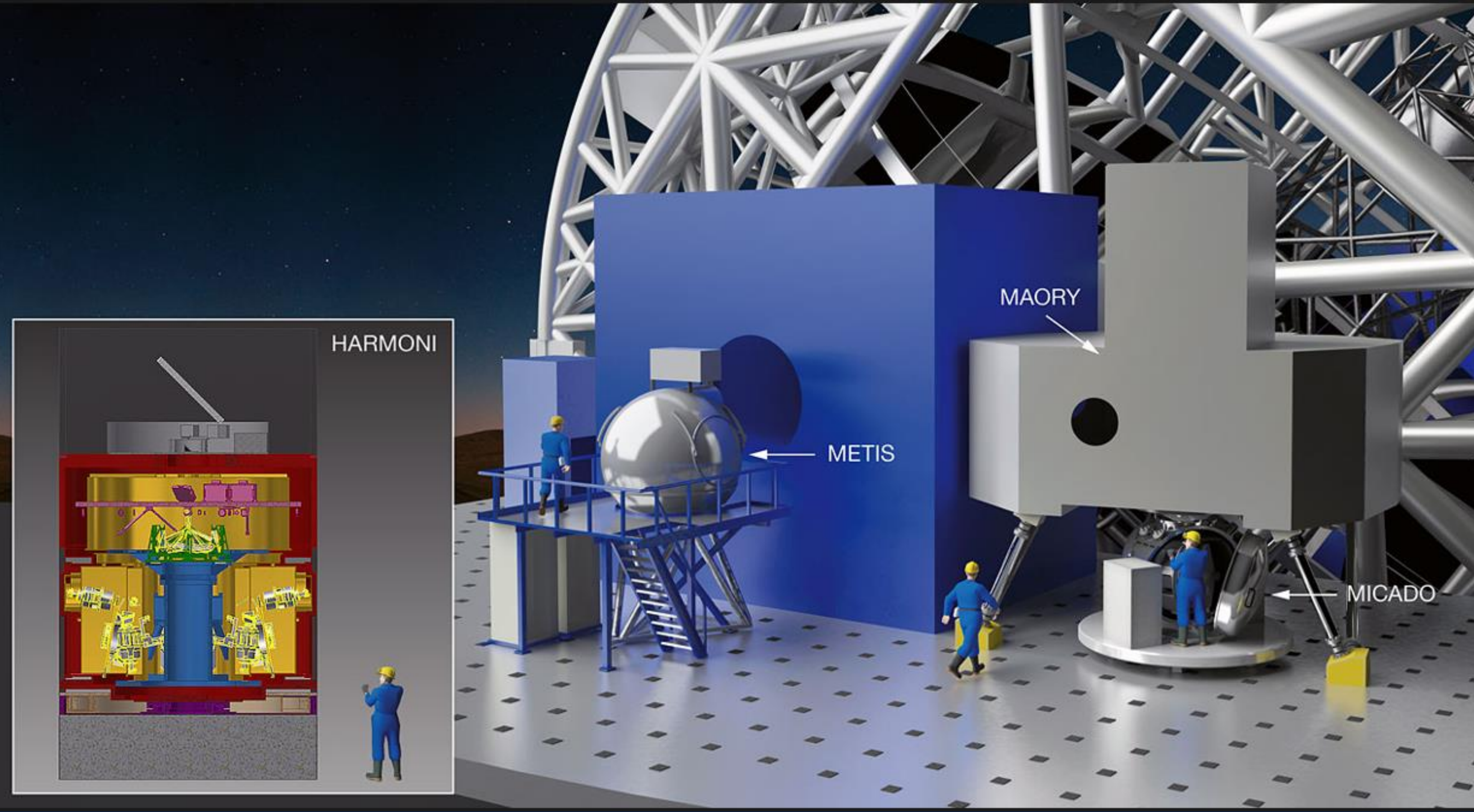
E-ELT Instrumentation Roadmap (Jan 2015)

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 X	
2017	PDR						
2018							TRL check
2019						Selection	Start when ready
2020							
2021							
2022							
2023							
2024							

- Pre-studies
- Decision point
- Development of tech specs, agreement, Instrument start

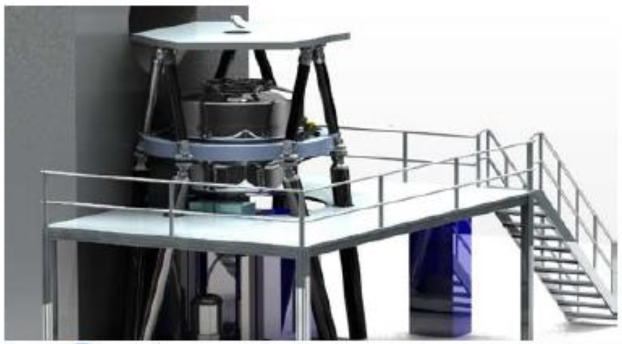
- Top level requirements being developed with PST
- Instrument science cases used as starting point
- Within each instrument, prioritisation of cases + modes still to be done

The first light instruments

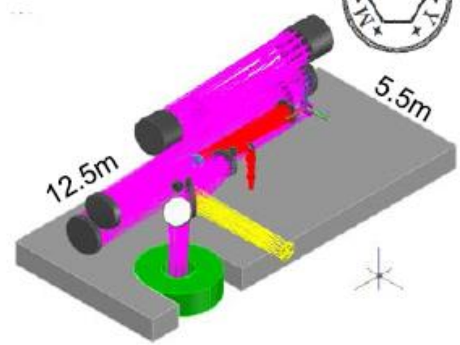


Instruments

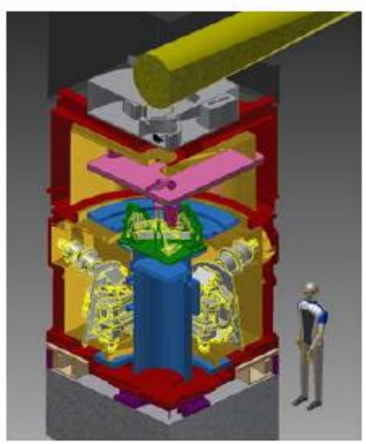
- MICADO, HARMONI, METIS, MAORY (design & construction on-going)
- MOS & HIRES (Phase A studies on-going)



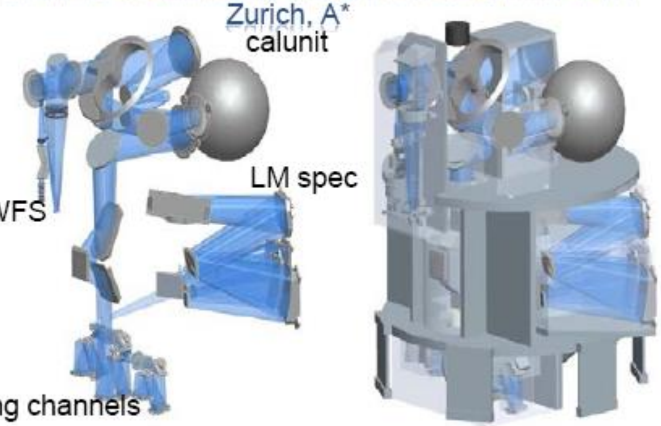
INAF OA Bologna
IASF Bologna
OA Arcetri
OA Brera
OA Capodimonte
OA Padova
INSU/CNRS-IPAG



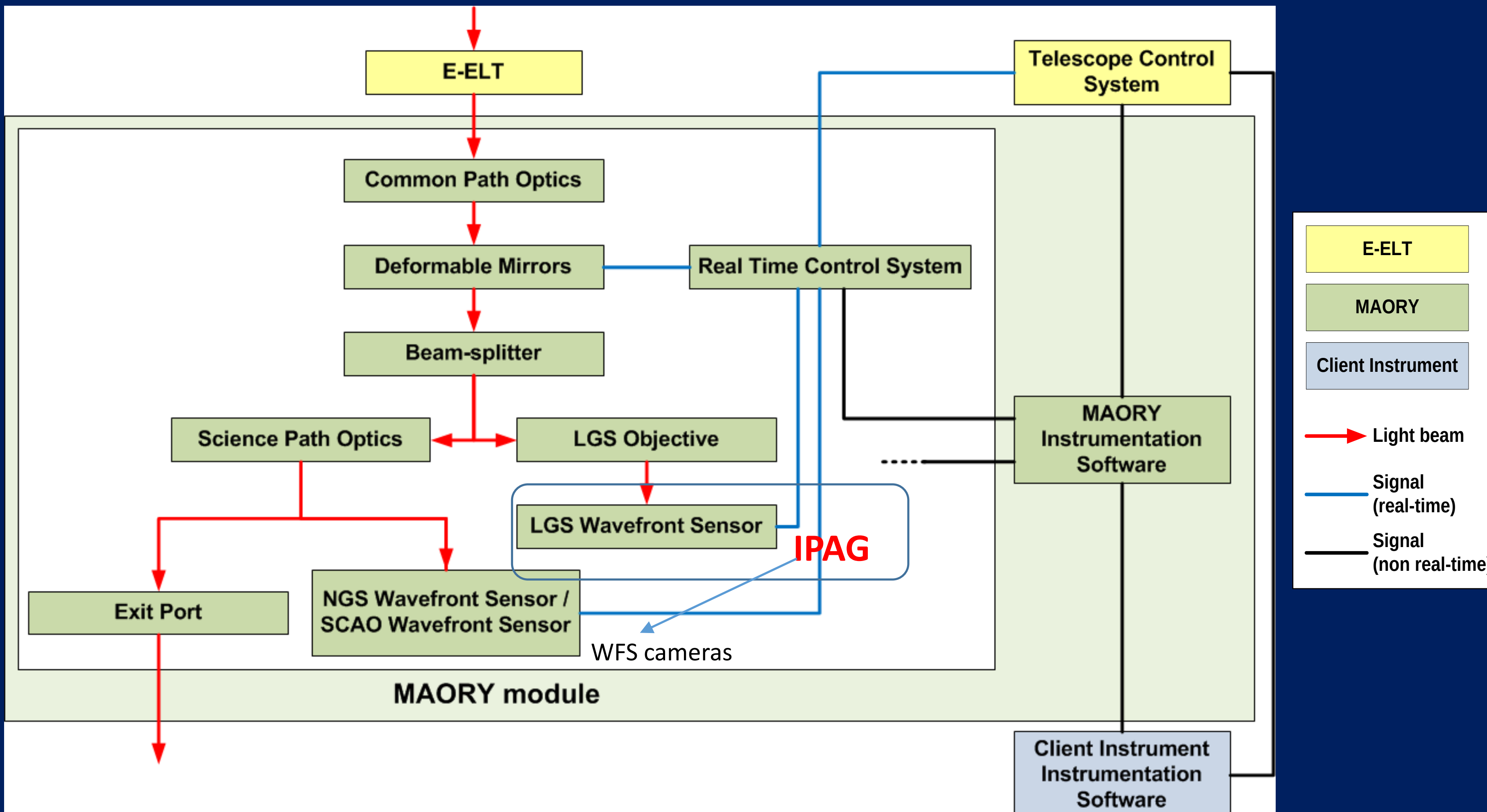
Uni. Oxford,
UK ATC,
CRAL,
CSIC,
IAC,
RAL,
IPAG,
ONERA,
LAM,
ESO

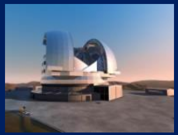


NOVA, MPIA, CEA-Saclay, UK ATC, K.U.Leuven, ETH Zurich, A*



MAORY functional block diagram

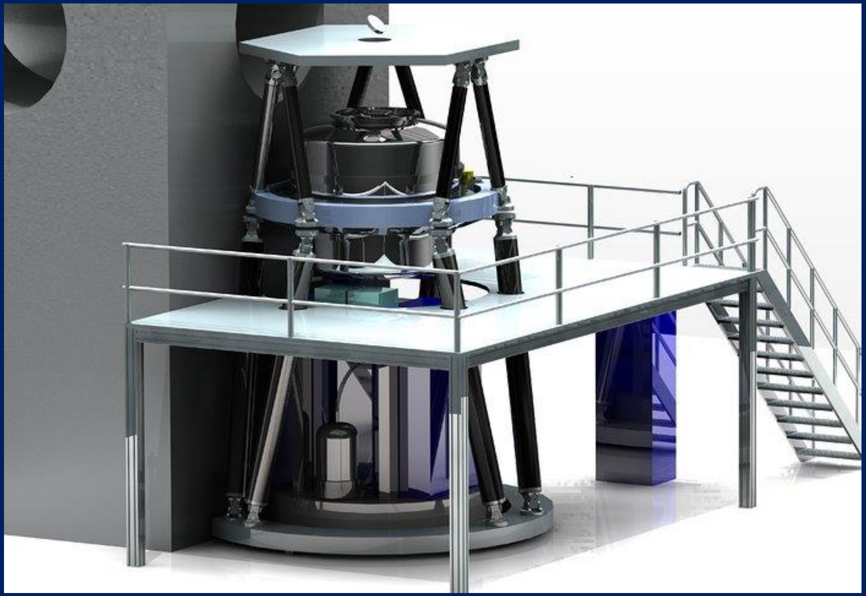


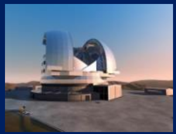


MICADO General Overview

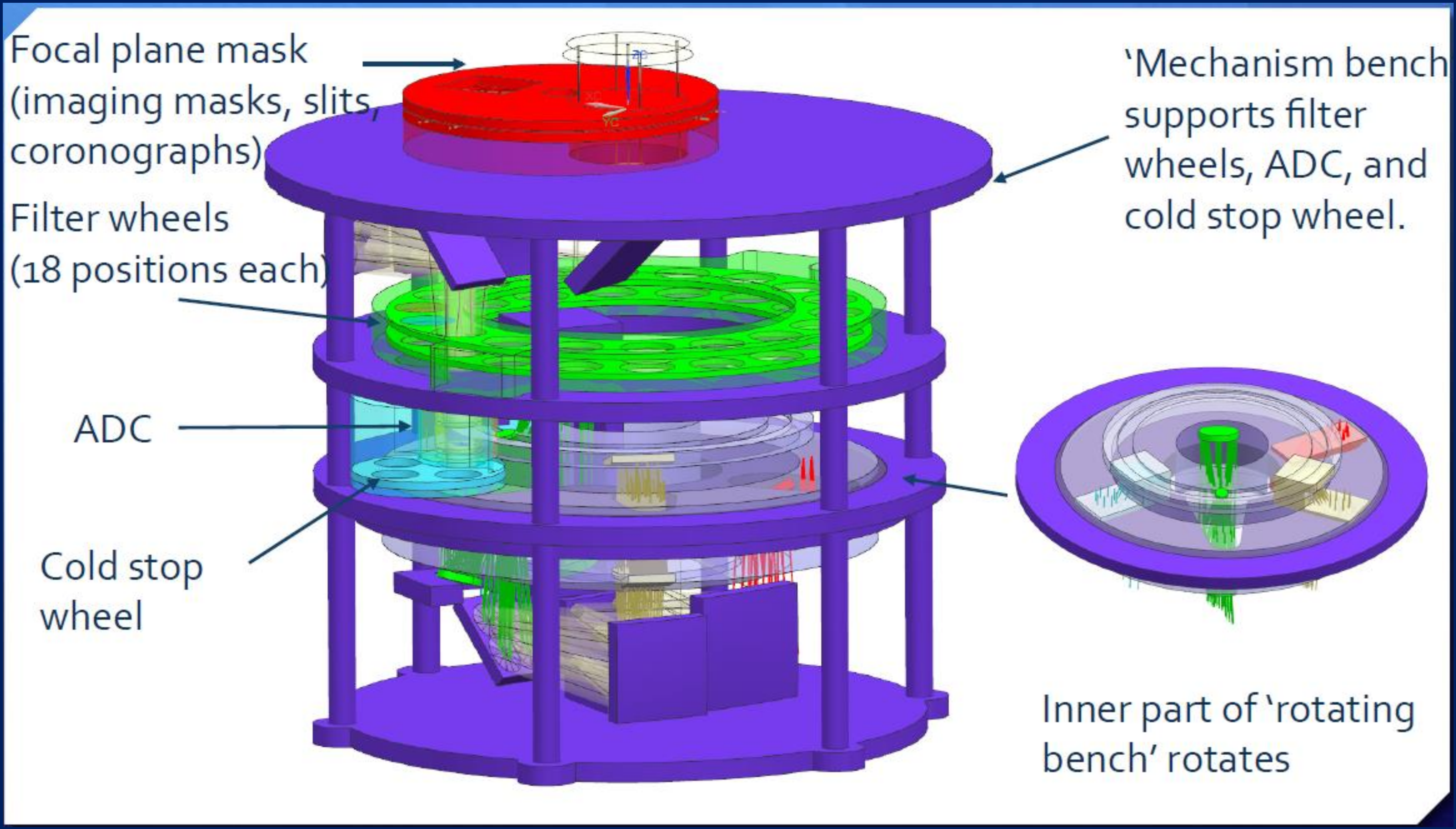
- First light general purpose Imaging Camera for the ELT
- **Multi-AO Imaging Camera for Deep Observations**

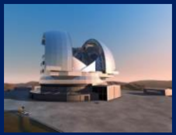
- R-K (0.8-2.4μm) FoV: 1′
- spectral resolution, 4000 to 8000
- SCAO/MCAO (MAORY) correction for diffraction limited imaging (small field/large field)
- Coronagraph, Pupil masks





MICADO principles

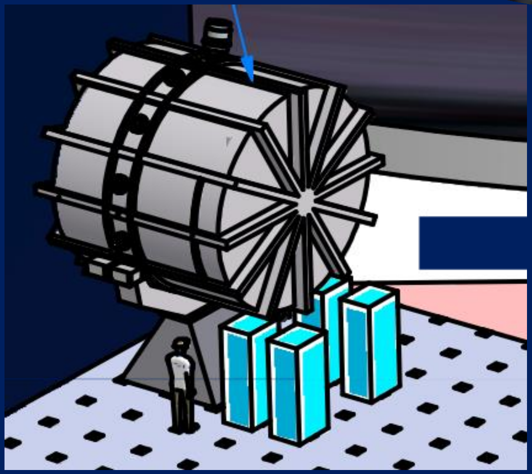




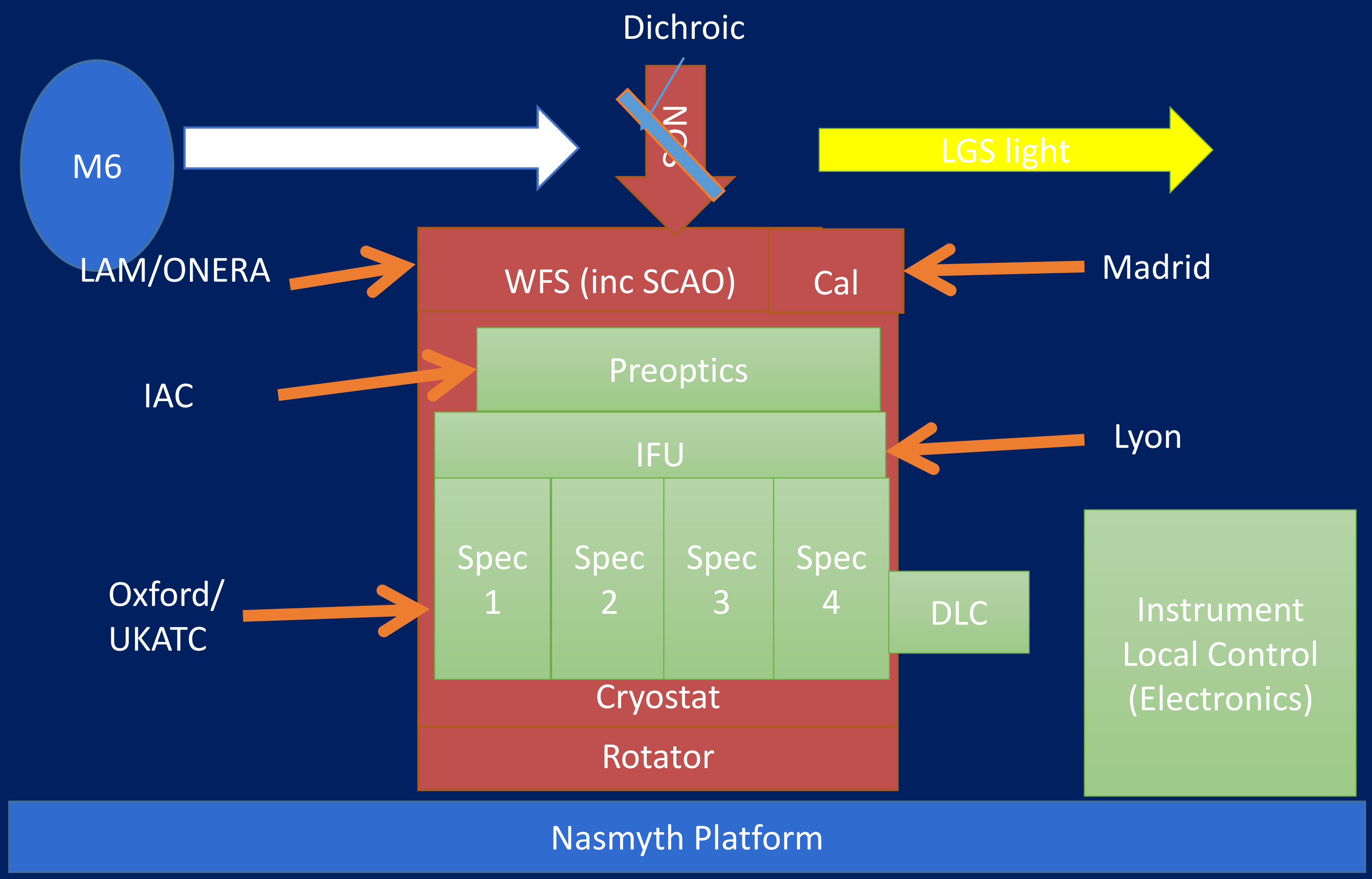
HARMONI General Overview

- First light general purpose Integral Field Spectrograph for E-ELT
  - Work horse instrument with wide appeal
  - Early 'highlight' science on key objects/projects
  - Low/no technology risks
- V-K (0.5-2.4μm) wavelength coverage
- Wide range of spectral resolutions
- Range of spatial resolutions from diffraction to seeing limited
- LTAO/SCAO correction

COSMOS lens; Faure & Knieb

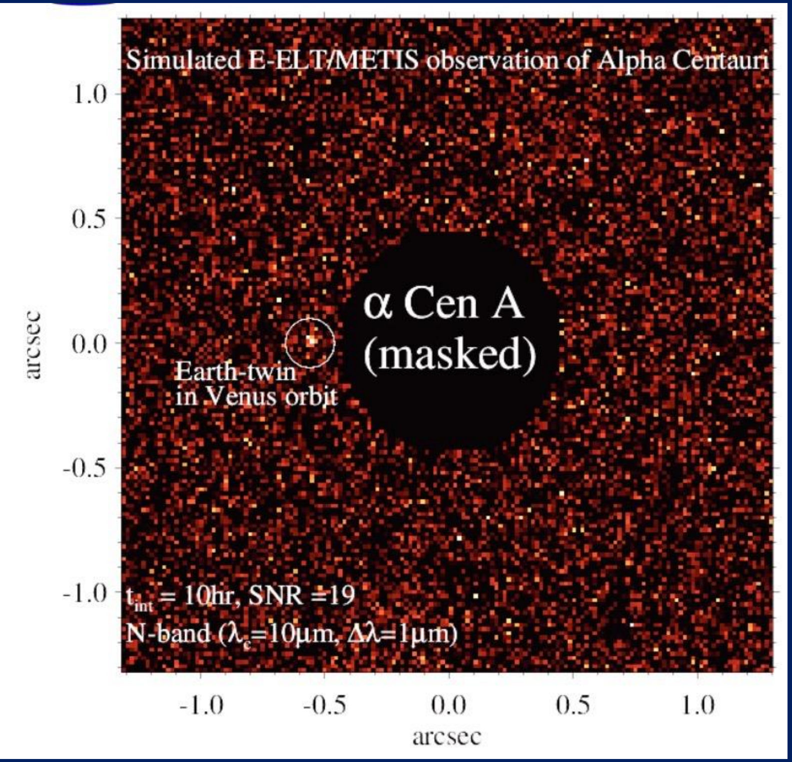


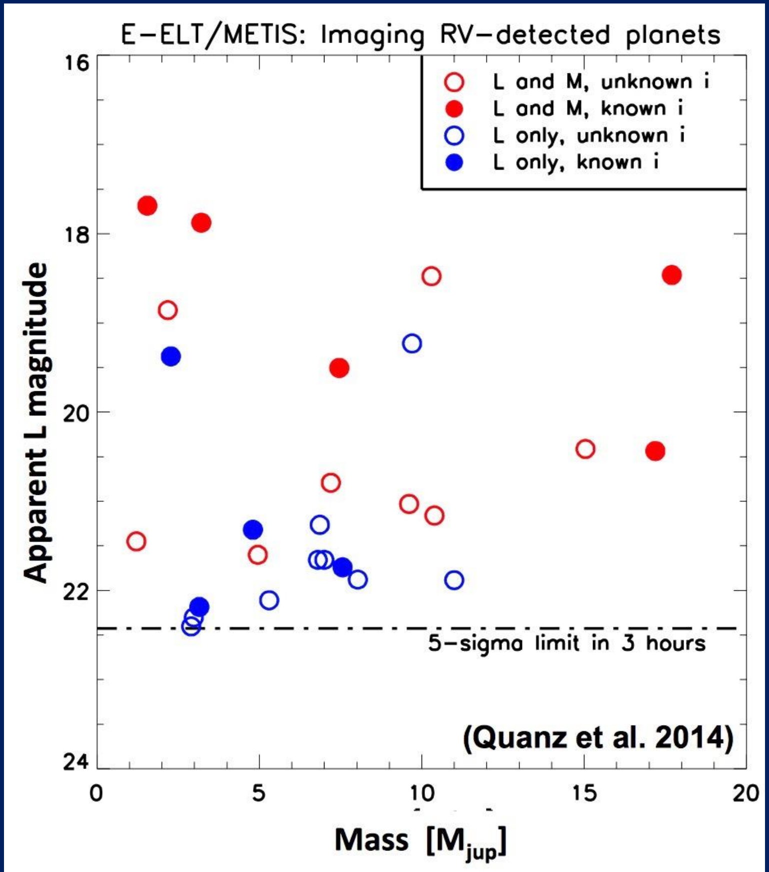
BASELINE HARMONI

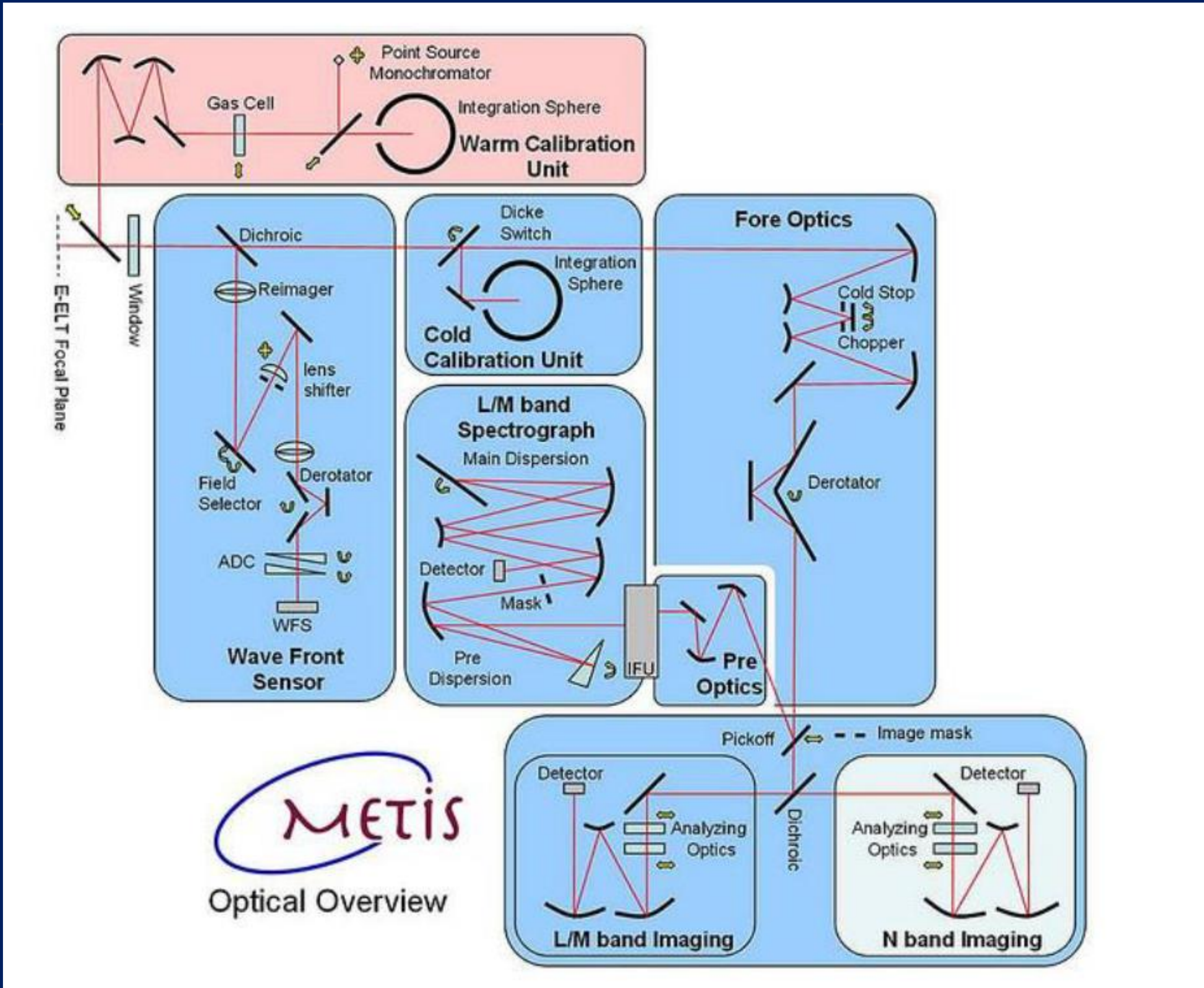


METIS

Imager L and M band
IFU spectrograph L/ M R=100000



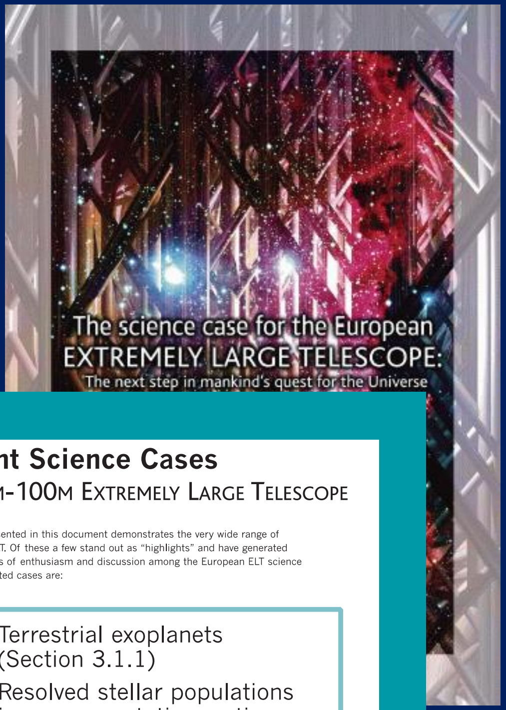


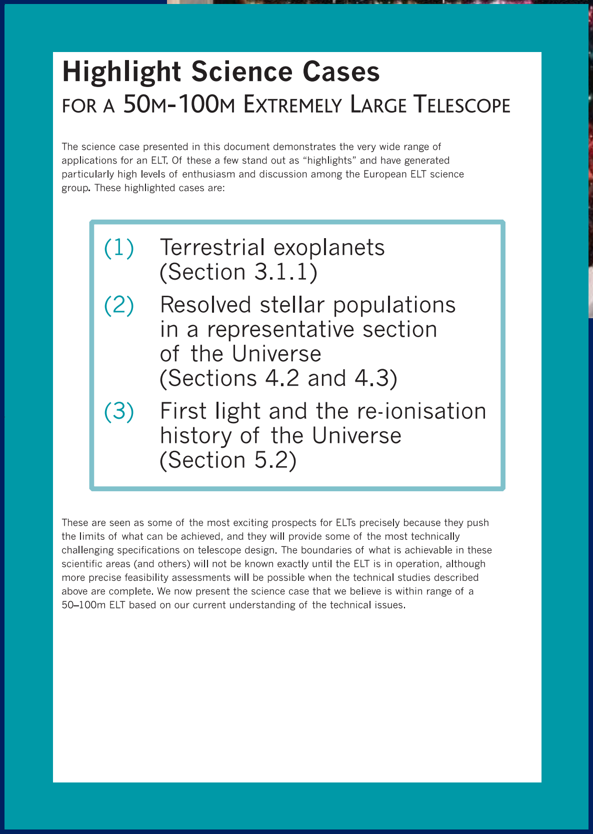


Point Source
Monochromator
Gas Cell
Integration Sphere
Warm Calibration Unit
E-ELT Focal Plane
Window
Dichroic
Reimager
lens shifter
Field Selector
Derotator
ADC
WFS
Wave Front Sensor
Dicke Switch
Integration Sphere
Cold Calibration Unit
L/M band Spectrograph
Main Dispersion
Detector
Mask
Pre Dispersion
IFU
Pre Optics
Fore Optics
Cold Stop
Chopper
Derotator
Pickoff
Image mask
Detector
Analyzing Optics
L/M band Imaging
Dichroic
Detector
Analyzing Optics
N band Imaging
METIS
Optical Overview

Some history (of science drivers)

- 1990s: Early work ELTs: OWL and Euro-50
  - Versatile, optical-IR telescopes
  - Excellent image quality, steerable, range of instrumentation
- Community meetings
  - E.g. Backaskog 1999
- 2005: OPTICON science case document
- 2006: E-ELT SWG formed
  - Chair M. Franx, later IH
  - Report in April 2006
- 2006: Marseilles meeting
  - Baseline 40m design presented
- 2011: Construction proposal published – Dec
  - Science case, DRM report
- 2012: SWG replaced by PST at end of Phase B
  - Chair G. Bono
- 2012: ESO Council approved E-ELT programme – June





Highlight Science Cases

FOR A 50M-100M EXTREMELY LARGE TELESCOPE

The science case presented in this document demonstrates the very wide range of applications for an ELT. Of these a few stand out as "highlights" and have generated particularly high levels of enthusiasm and discussion among the European ELT science group. These highlighted cases are:

(1) Terrestrial exoplanets (Section 3.1.1)

(2) Resolved stellar populations in a representative section of the Universe (Sections 4.2 and 4.3)

(3) First light and the re-ionisation history of the Universe (Section 5.2)

These are seen as some of the most exciting prospects for ELTs precisely because they push the limits of what can be achieved, and they will provide some of the most technically challenging specifications on telescope design. The boundaries of what is achievable in these scientific areas (and others) will not be known exactly until the ELT is in operation, although more precise feasibility assessments will be possible when the technical studies described above are complete. We now present the science case that we believe is within range of a 50–100m ELT based on our current understanding of the technical issues.

Science Working Group Report, April 2006

http://www.eso.org/sci/facilities/eelt/

Planets and Stars

Solar system comets

Extrasolar-system comets (FEBs)

Extrasolar planets:

- imaging
- radial velocities

Free-floating planets

Stellar clusters (inc. Galactic Centre)

Magnetic fields in star formation regions

Origin of massive stars

LMC field star population

Circumstellar disks, young and debris

Stellar remnants

Asteroseismology

Stars and Galaxies

Intracluster population

- Colour-Magnitude diagrams
- CaII spectroscopy of IRGB stars

Planetary nebulae and galaxies

Stellar clusters and the evolution of galaxies

Resolved stellar populations:

- Colour-Magnitude diagram Virgo
- abundances & kinematics Sculptor galaxies
- abundances & kinematics M31- CenA

Spectral observations of star clusters:

- internal kinematics & chemical abundances
- ages and metallicities of star cluster systems

Young, massive star clusters

- imaging
- spectroscopy

The IMF throughout the Local Group

Star formation history through supernovae

- search and light curves
- spectroscopy

Black holes/AGN

Galaxies and Cosmology

Dark energy: Type Ia SNe as distance indicators

- search and light curves
- spectroscopy

Dynamical measurement of universal expansion

Constraining fundamental constants

First light - the highest redshift galaxies

Galaxies and AGN at the end of reionization

Probing reionization with GRBs and quasars

Metallicity of the low-density IGM

IGM tomography

- bright LBGs and quasars
- faint LBGs

Galaxy formation and evolution:

Physics of high-z galaxies

- integrated spectroscopy
- high resolution imaging
- high spatial resolution spectroscopy

Gravitational lensing

Deep Galaxy Studies at z=2-5

Synergies with major facilities

- Sensitivity
- High angular resolution
  - matched to ALMA and SKA
  - 7x sharper images than JWST
- Follow-up of sources discovered by other telescopes
  - Spectroscopic and high angular resolution
  - Identification and physics

Slide from A. Verma

Exoplanets: Are we alone?

How do planetary systems form?

How common are systems like ours?

What atmospheres do planets have?

Are there other Earths?

Can we detect signs of life?

E-ELT

Direct Detection

Spatial resolution & sensitivity

Resolution of dusty disks in which they are forming

Indirect methods: Radial velocity and astrometry

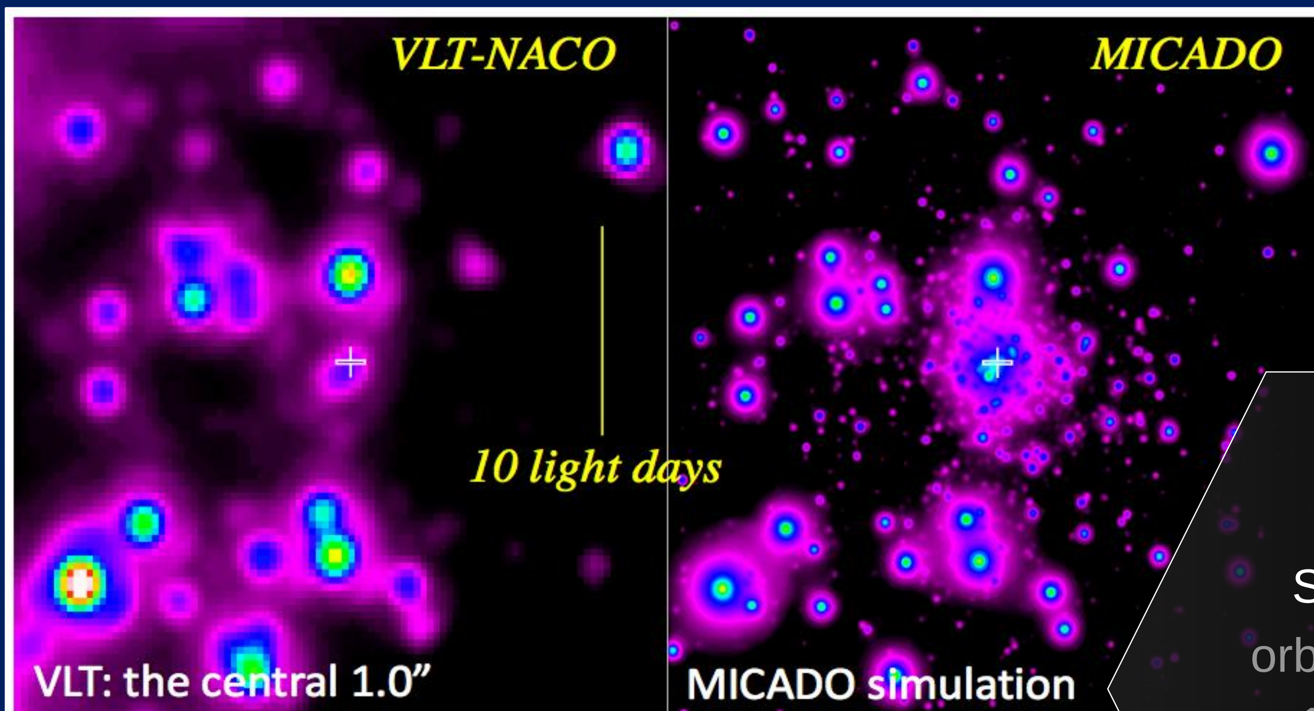
Potential to reach lower-mass planets, including Earth-mass

Characterise atmospheres

Constituent elements, signs of life

The Galactic Centre

AO observations imply supermassive Black Hole with mass of ~$3x10^6$ $M_\odot$
VLT (Genzel et al), Keck (Ghez et al)

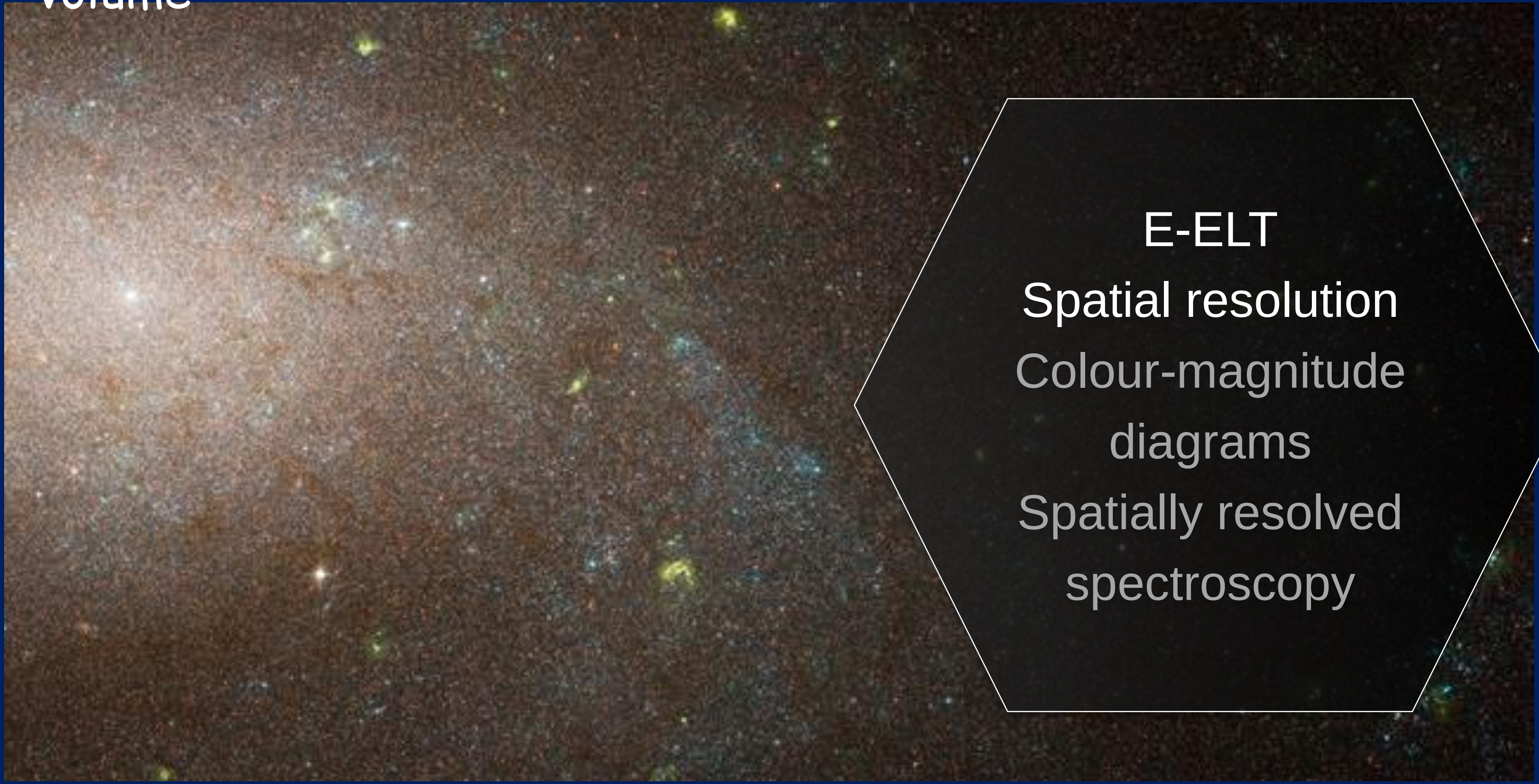


Simulations by MICADO group
e.g. Trippe et al 2010

E-ELT
Spatial resolution
orbits of stars at 100-1000 x BH event horizon: sensitive to SR and GR effects

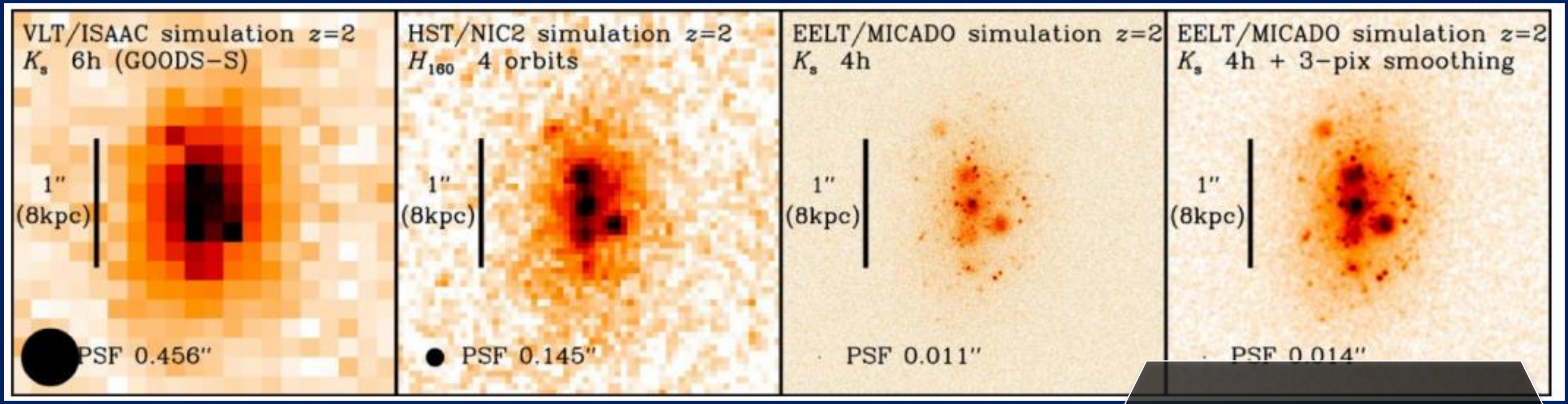
Resolved Stellar Populations

- Understand the merger history of galaxies by measuring properties of individual stars
- Aim for representative galaxies – implies representative volume



HST image of NGC300, a spiral galaxy at 2 megaparsecs,

High-z galaxies



Simulated observations of a z=2 galaxy. MICADO science case

E-ELT

Resolution and sensitivity

Structure from high-resolution imaging

Dynamics and physics from spatially resolved spectroscopy

Reionisation

- QSO spectra and CMB constrain reionisation epoch 6 < z < 10
- Sources are beyond current detection limits
- Reionisation history unknown

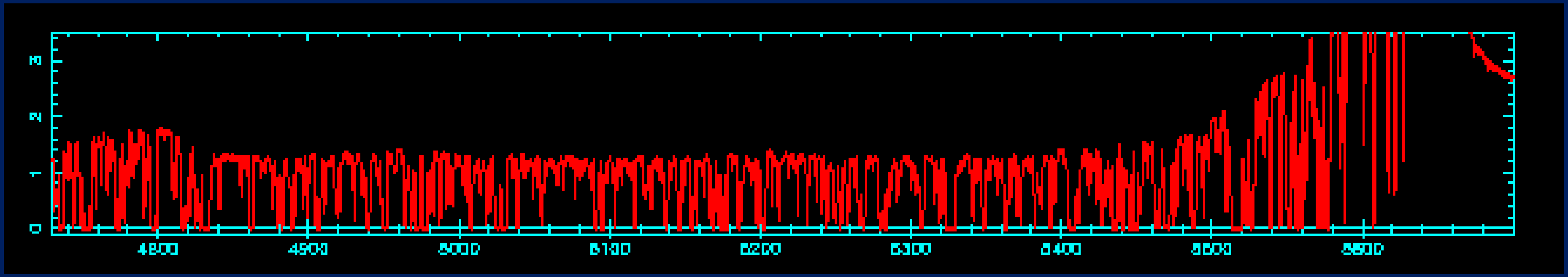
E-ELT

- Ly-α emission fraction in LBGs
- Absorption-line spectra of QSOs at z>6 (isotropy & homogeneity of reionisation)
- Enrichment of IGM

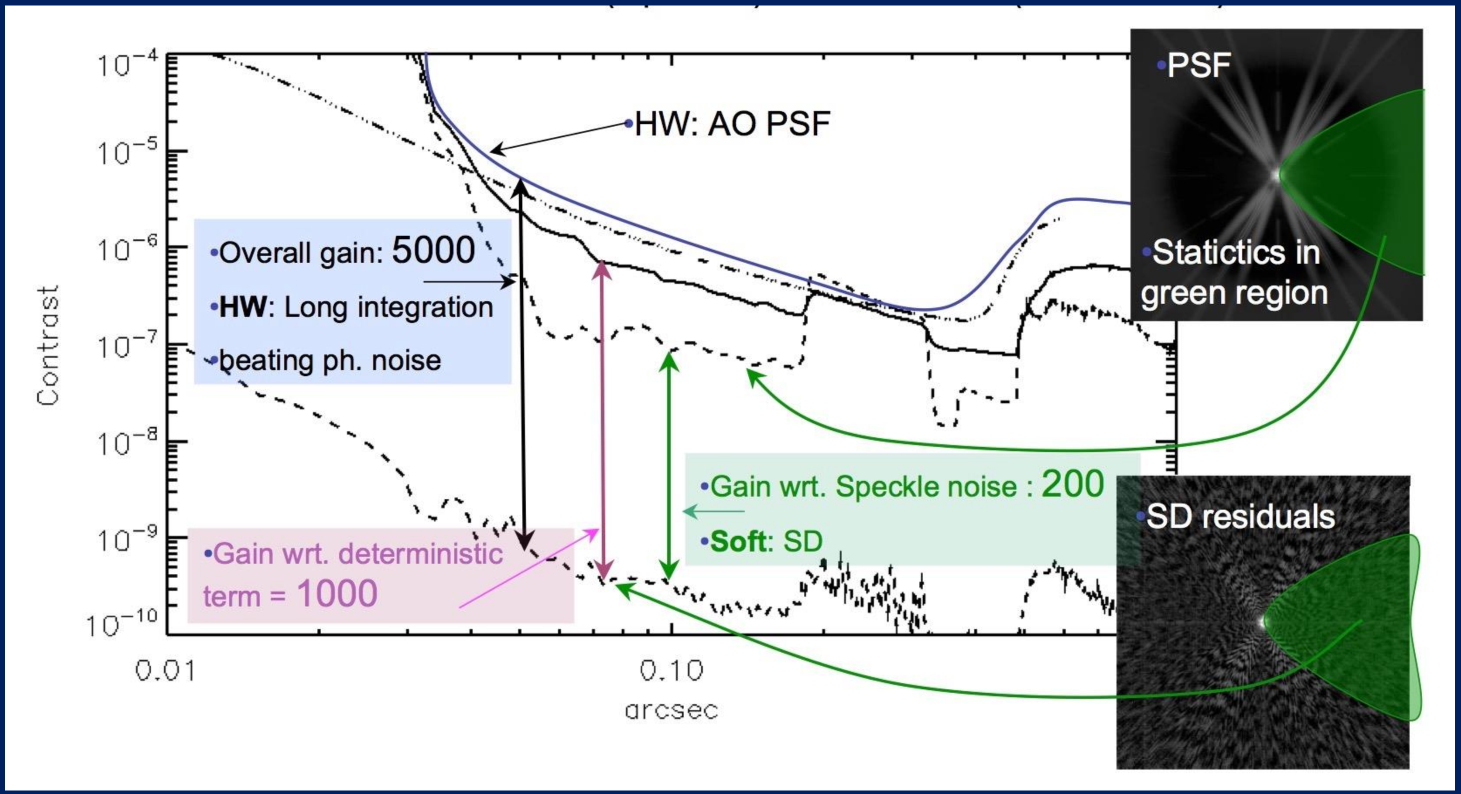
Image credit: Avi Loeb, 2006

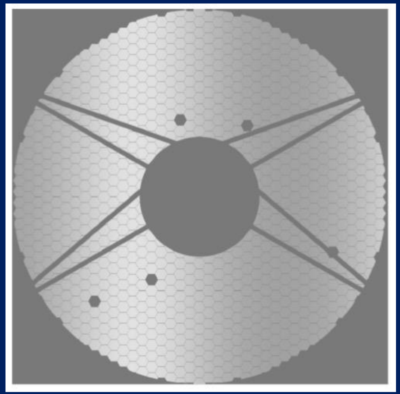
Cosmology and Fundamental physics

- Constancy of fundamental coupling constants
  - Test for variations of α, μ : variations expected in string theory
  - Possible detection of variation in α – or instrumental effect? (Whitmore et al 2015)
  - ESPRESSO then E-ELT will make leaps in sensitivity
  - Future constraints can provide constraints on Dark Energy models (e.g. Calabrese et al 2013)
- Sandage test (redshift drift)
  - Direct measurement of the changing expansion of the universe via precise measurements of Ly-α line positions with time
  - Very demanding stability (2cm/s absolute calibration)
  - (See Liske et al 2008)



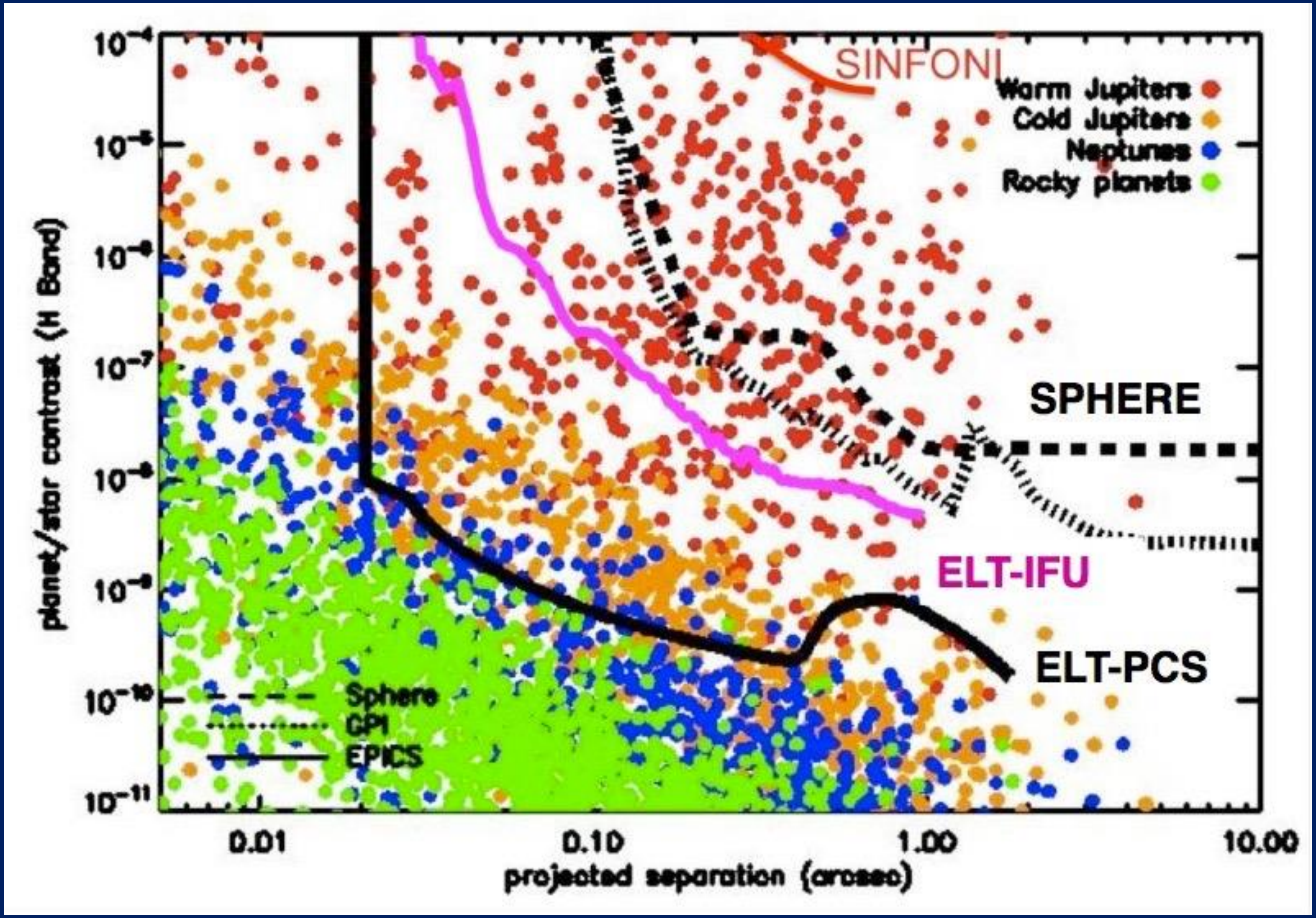
EPICS

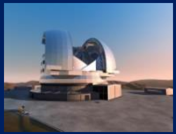


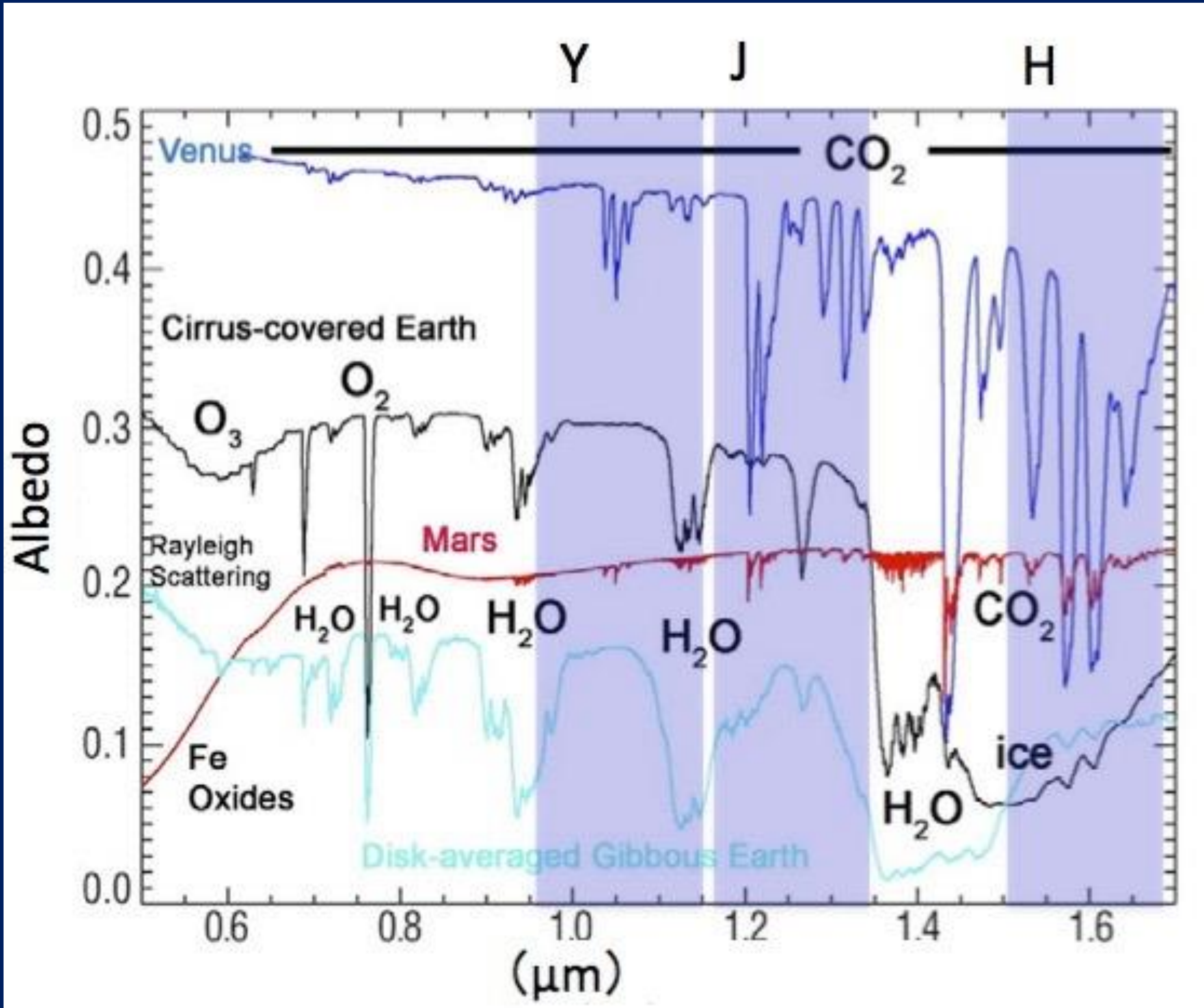


Brightness ratio at distance: [mas]	30	100	300	Limiting stellar Magnitude I band:
Science Case 1	10^{-6}	10^{-6}	10^{-6}	**9 (goal: 10)**
Science Case 2		**2 10^{-9} (goal 10^{-9})**	**10^{-9} (goal 4 10^{-10})**	7 (goal: 8)
Science Case 3	**10^{-8}**	**10^{-9}**	10^{-8}	7 (goal: 8)
Science Case 4	2 10^{-9} (goal 10^{-9})	10^{-9} (goal 4 10^{-10})	5 10^{-10} (goal 2 10^{-10})	5 (goal: 6)

EPICS


SINFONI
Warm Jupiters
Cold Jupiters
Neptunes
Rocky planets
SPHERE
ELT-IFU
ELT-PCS
Sphere
GPI
EPICS
planet/star contrast (H Band)
projected separation (arcsec)
0.01
0.10
1.00
10.00





Matsuo et al. (2013)

Improve XAO
10m class telescopes
mid-IR

Disks & lighter young GP
– 5 AU

E-ELT 1st gen. instruments
MICADO, HARMONI, METIS

Disks & young GP tens of AU in SFR
Inner components of disks
sub-Jup GP a few AU

XAO on the ELT

Super Earth in HZ

2018

2025

2030

JWST (mid-IR)

Light giant young planets
> 1" typ.

WFIRST (optical)
Detection down to super Earths
LR spectra
Disks

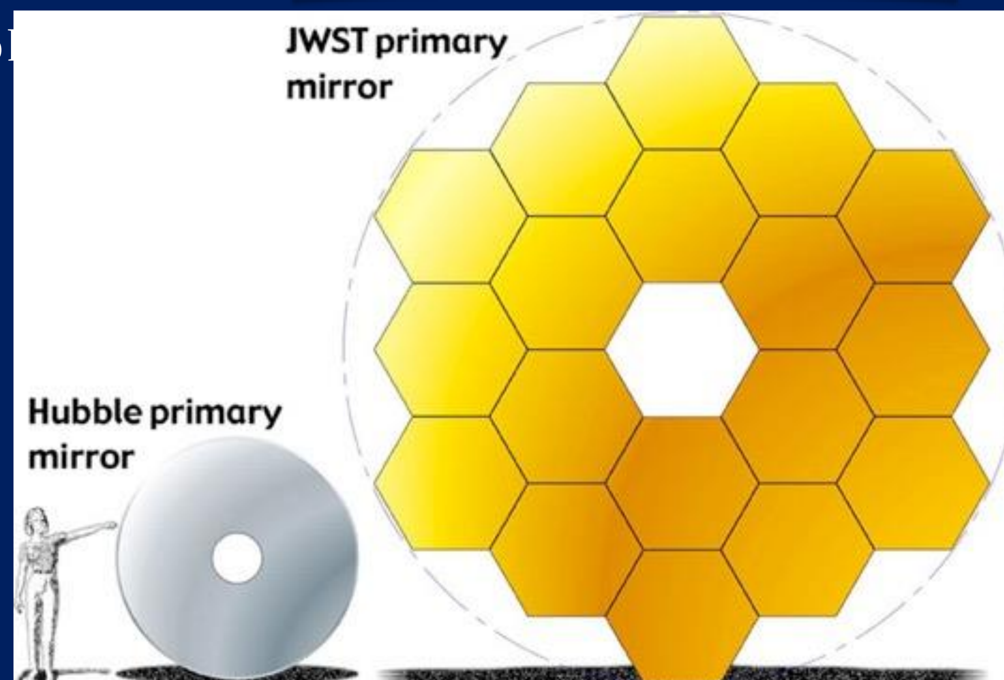
?

LUVOIR, HabEX
Earth in HZ
atmospheres,
Habitability

JWST

- Primary 6.6m (surface $25m^2$)
- Segmented, deployable
- Large solar panel => passive cooling (50K)
- Diffraction limited at $\lambda > 2\mu m$; R = 0.06 - 0.6''
- Spectral coverage : 0.6 - 28 µm
- Imaging, spectroscopy, Coronagrap
- Life time : 5 yrs (nominal) 10 ?

launch : end 2018



cost (1999) : $ 0.5 G$

....

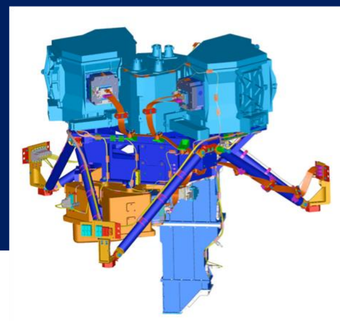
cost (2013): $ 8.8 G$

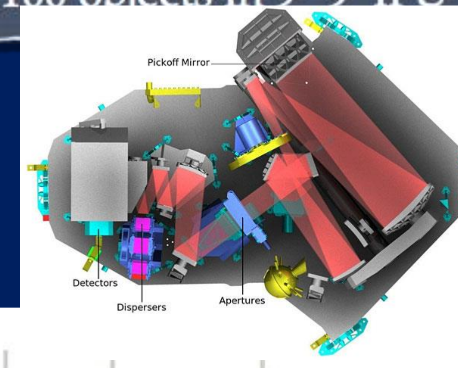
NIRCAM (US)
0.6 - 5 μm
2 x 2′*2′

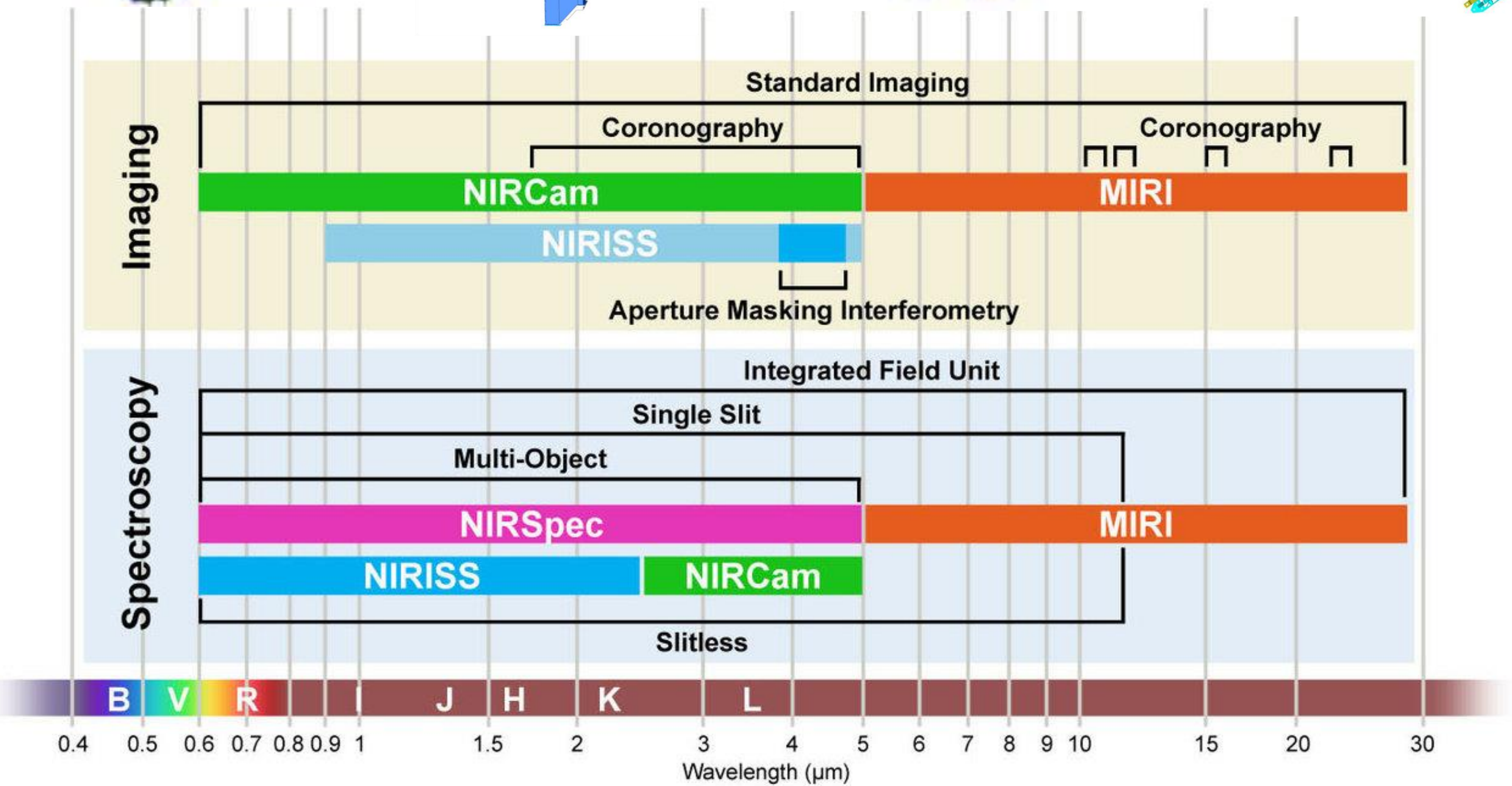
MIRI (Europe/US)
5 - 28 μm
74″*113″

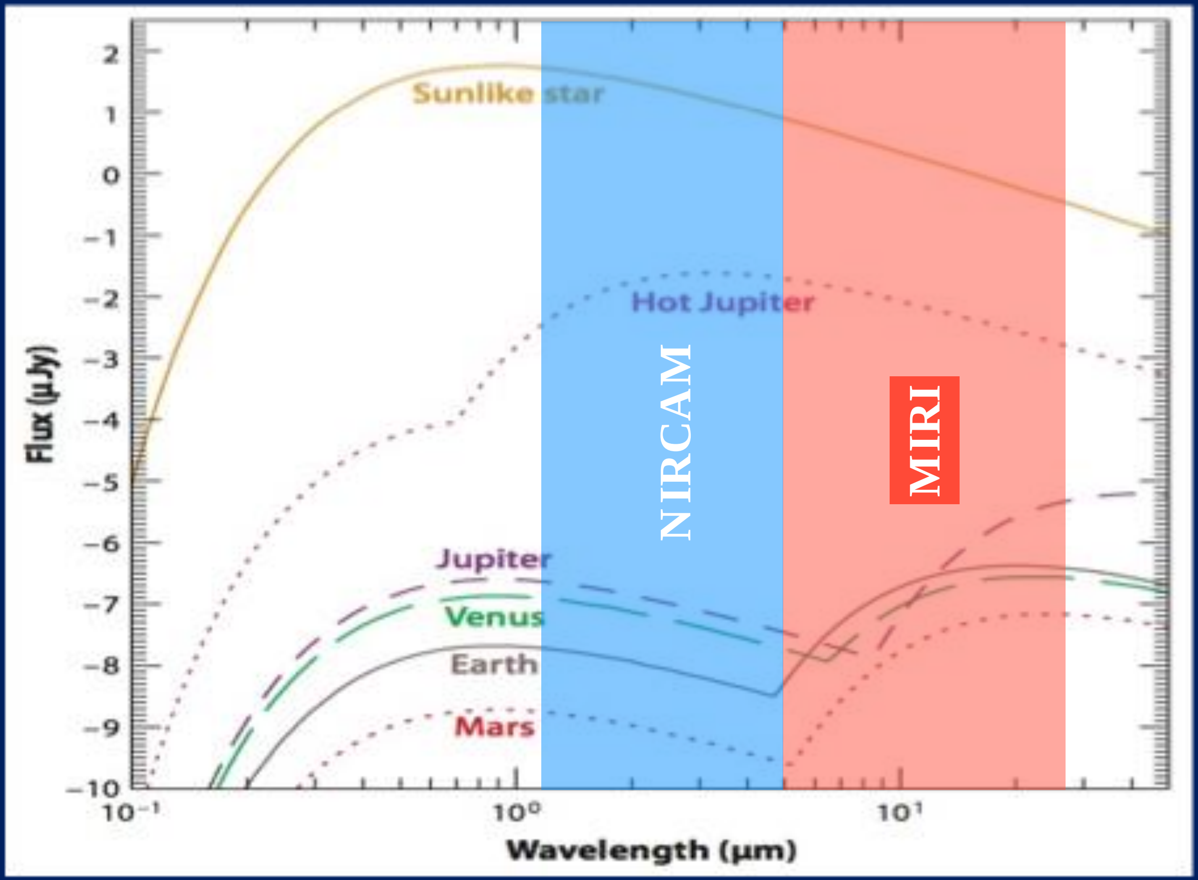
NIRISS (Canada)
1 - 5 μm

NIRSPEC (Europe)
0.7 - 5 μm
100 objects in 9′*9′ IFU



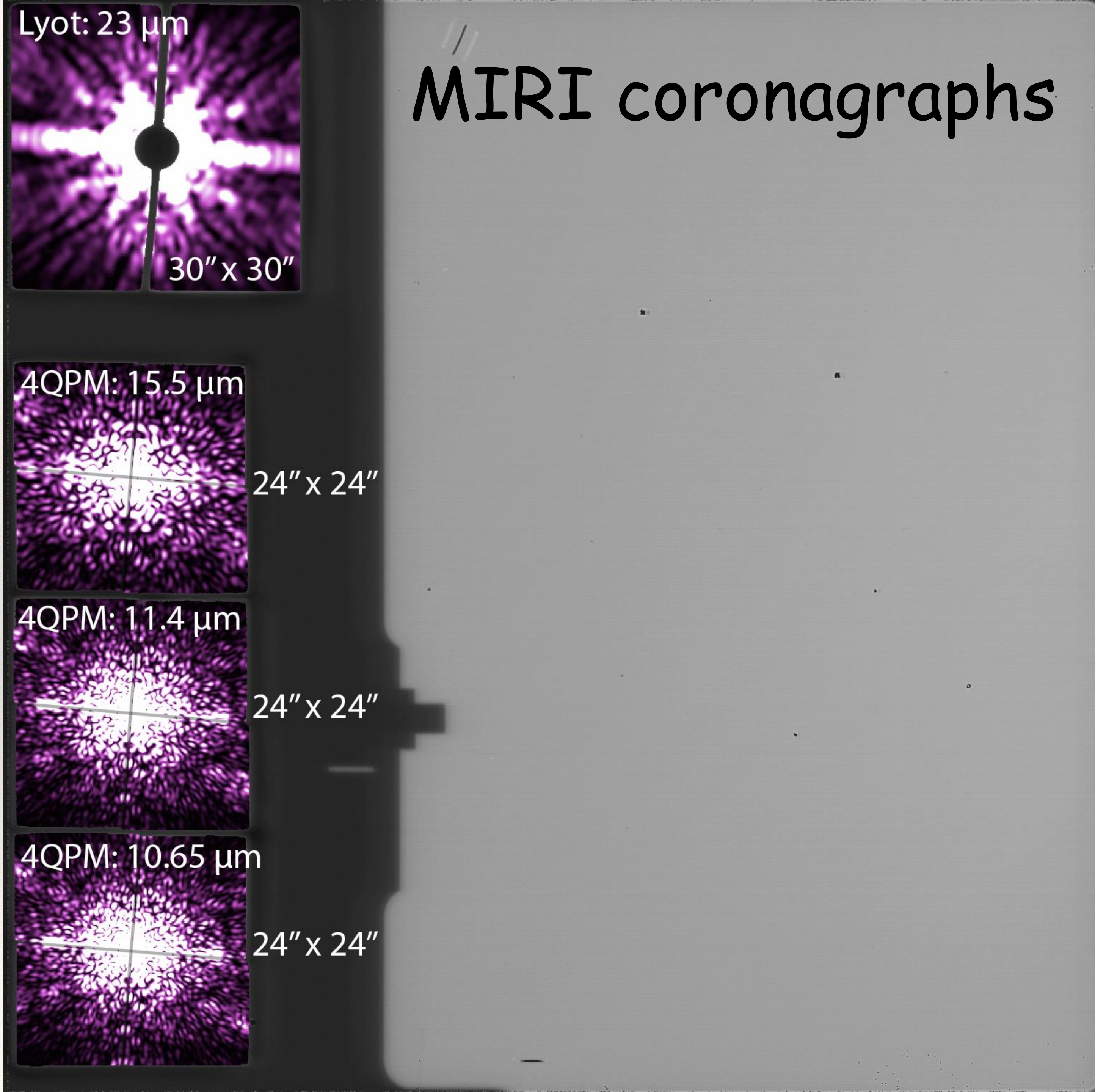




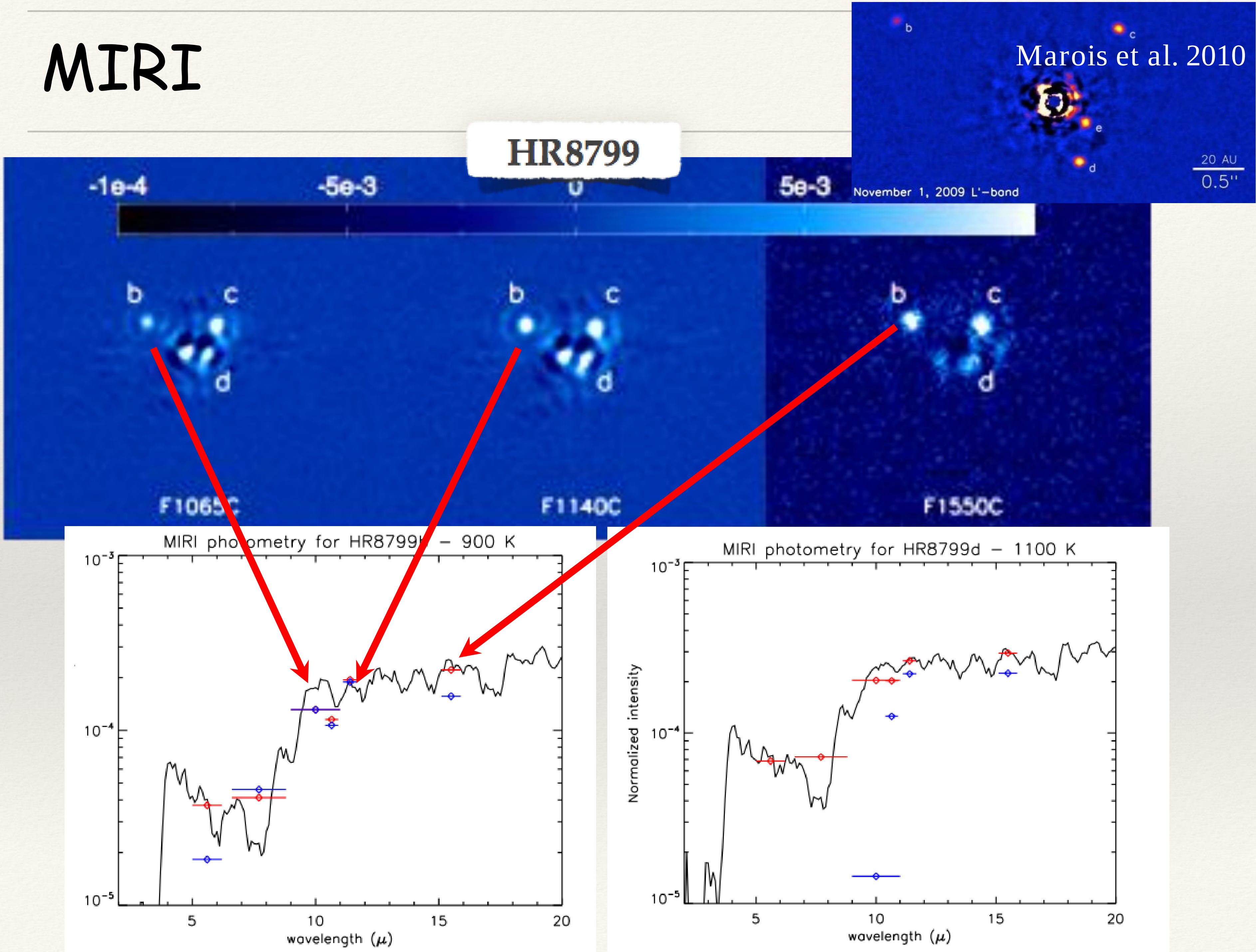


Seager et al. 2010

MIRI coronagraphs

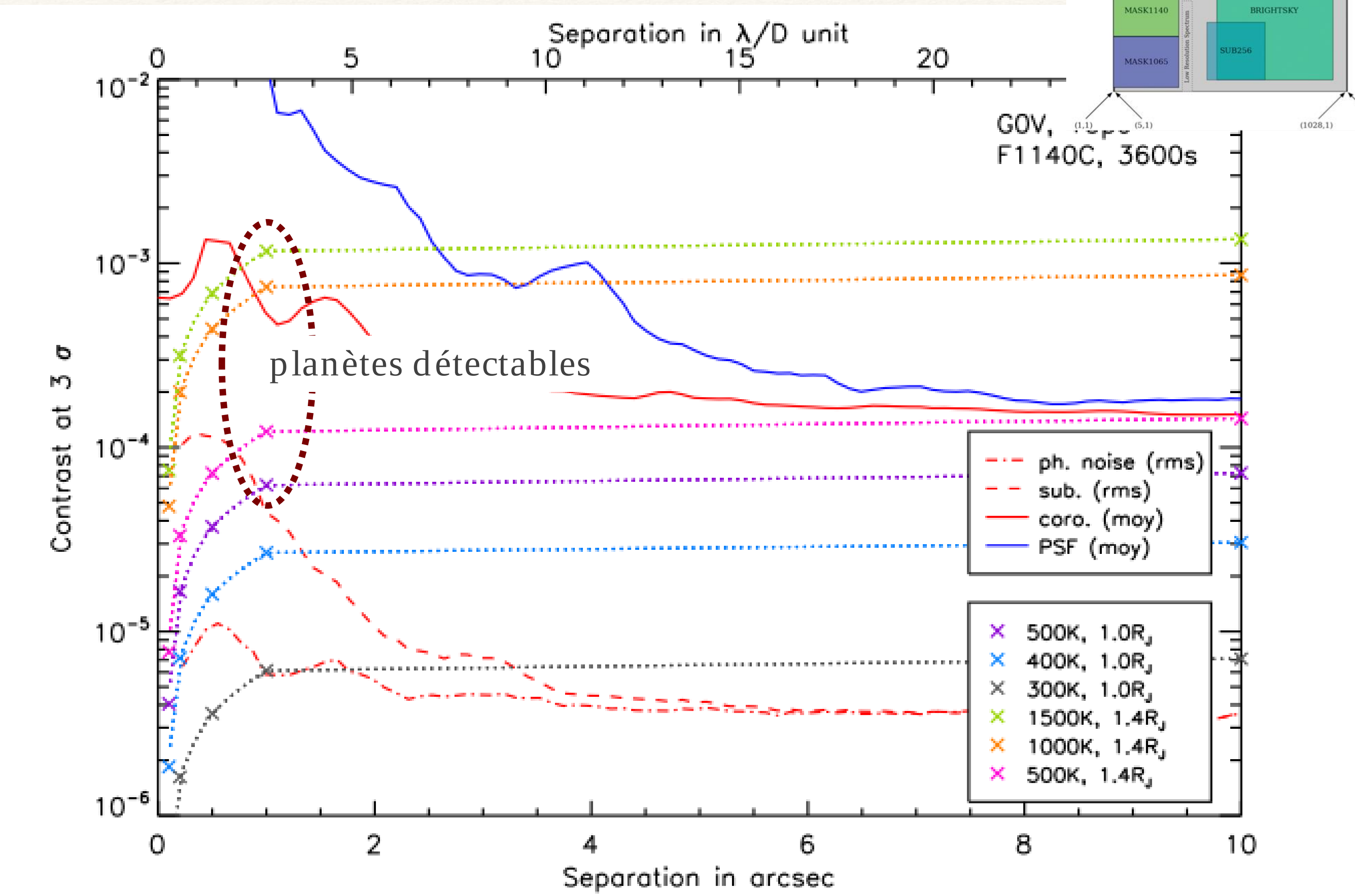


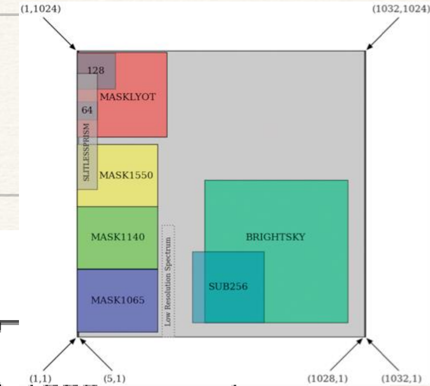
MIRI



HR8799
Marois et al. 2010
November 1, 2009 L'-band
20 AU
0.5''
b
c
d
e
-1e-4
-5e-3
0
5e-3
F1065C
F1140C
F1550C
MIRI photometry for HR8799b – 900 K
MIRI photometry for HR8799d – 1100 K
Normalized intensity
wavelength (μ)

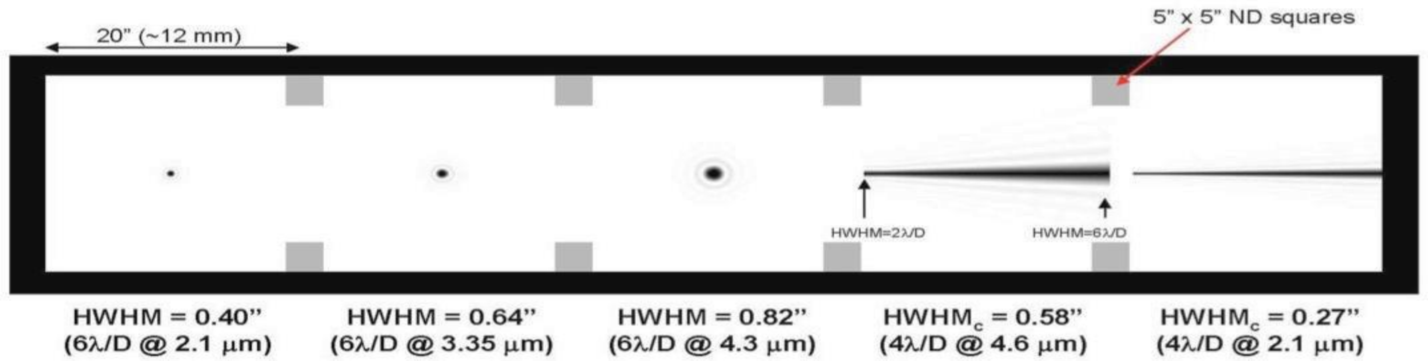
MIRI



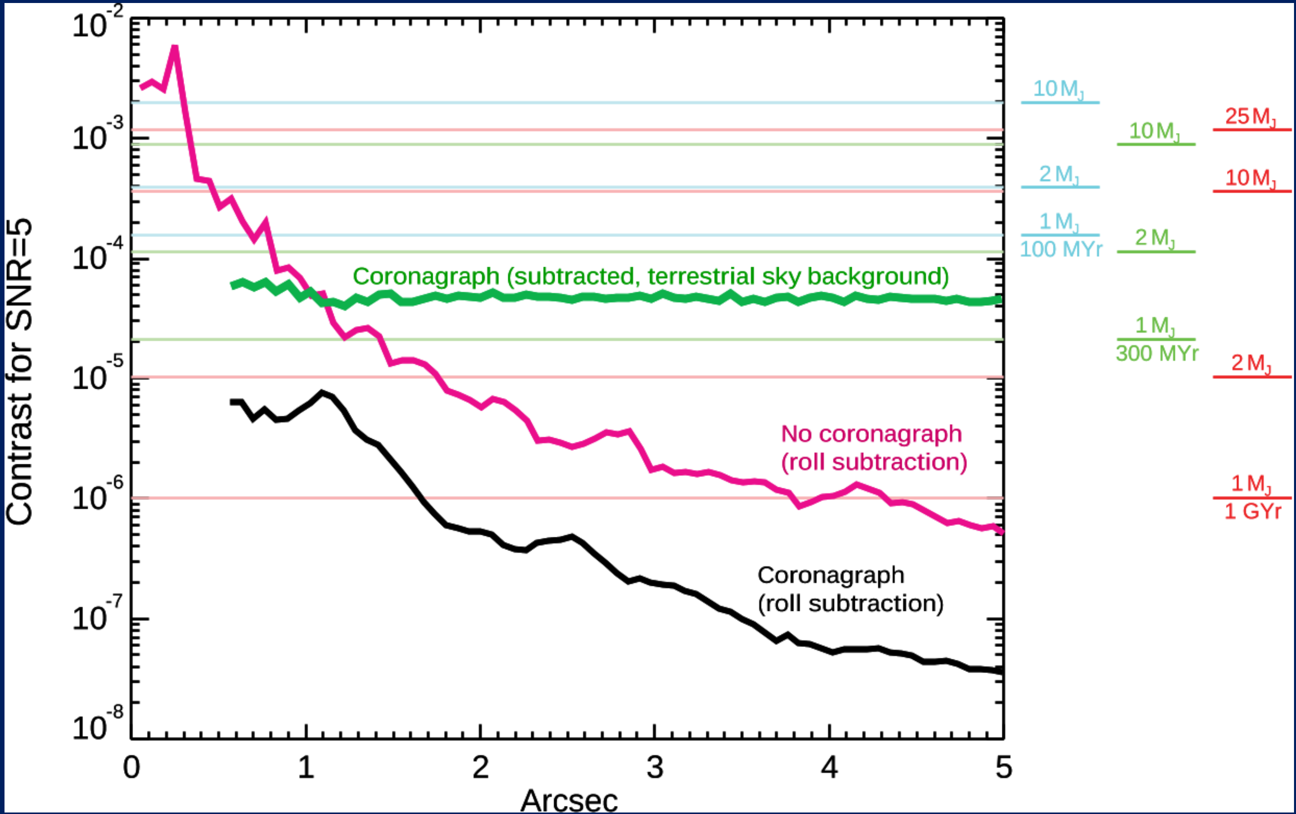


Simus A. Boccaletti

NIRCAM

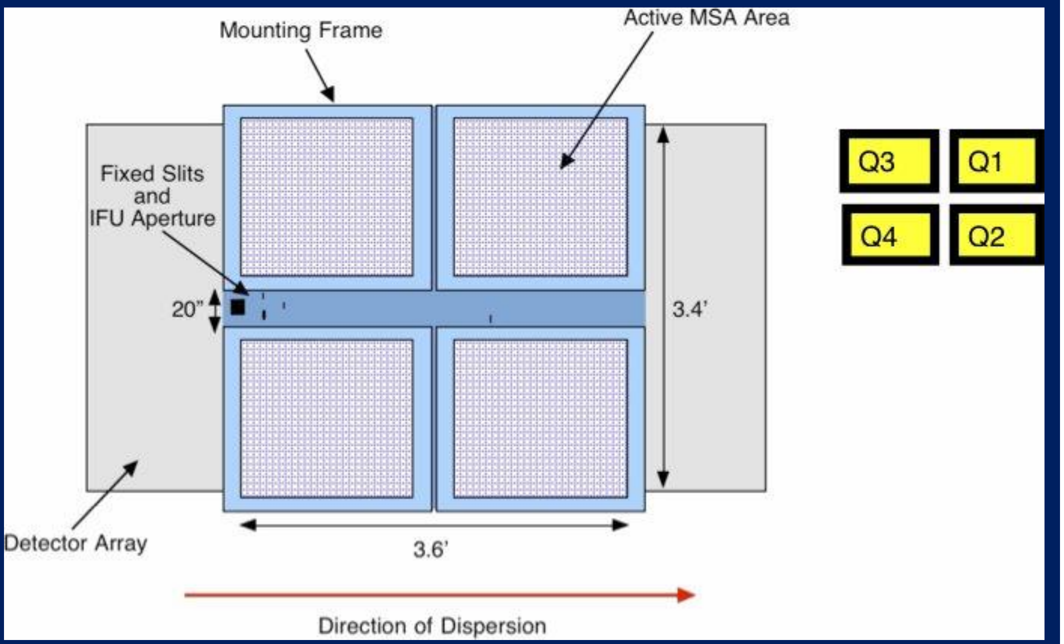


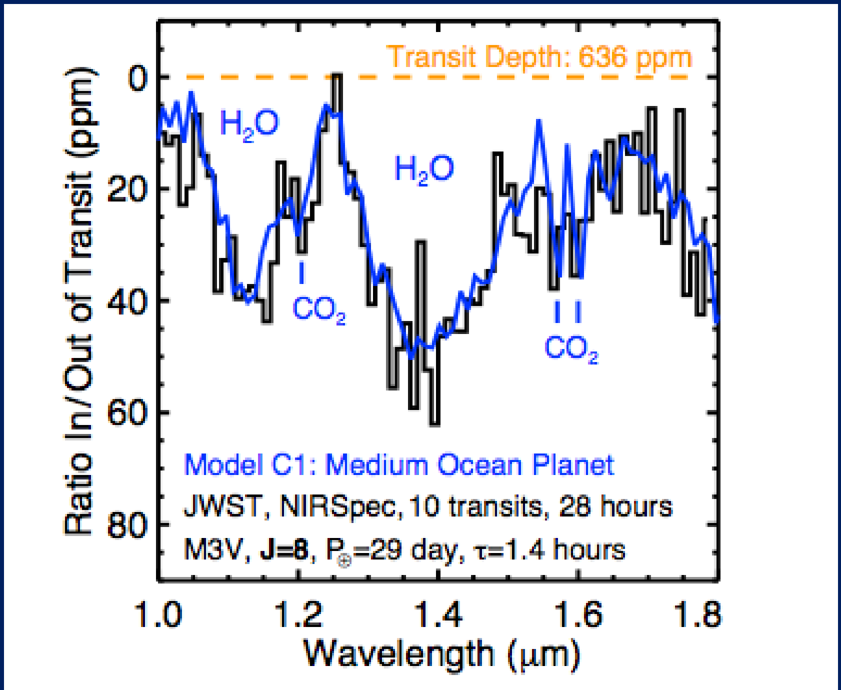
20" (~12 mm)
5" x 5" ND squares
HWHM=2λ/D
HWHM=6λ/D
HWHM = 0.40" (6λ/D @ 2.1 μm)
HWHM = 0.64" (6λ/D @ 3.35 μm)
HWHM = 0.82" (6λ/D @ 4.3 μm)
HWHM_c = 0.58" (4λ/D @ 4.6 μm)
HWHM_c = 0.27" (4λ/D @ 2.1 μm)



Contrast for SNR=5
Arcsec
Coronagraph (subtracted, terrestrial sky background)
No coronagraph (roll subtraction)
Coronagraph (roll subtraction)
10 M_J
2 M_J
1 M_J
100 MYr
10 M_J
2 M_J
1 M_J
300 MYr
25 M_J
10 M_J
2 M_J
1 M_J
1 GYr

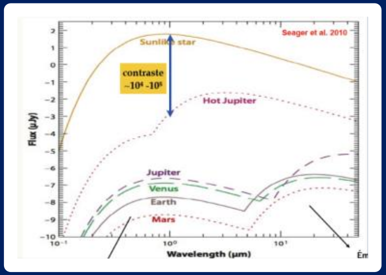
NIRSPEC

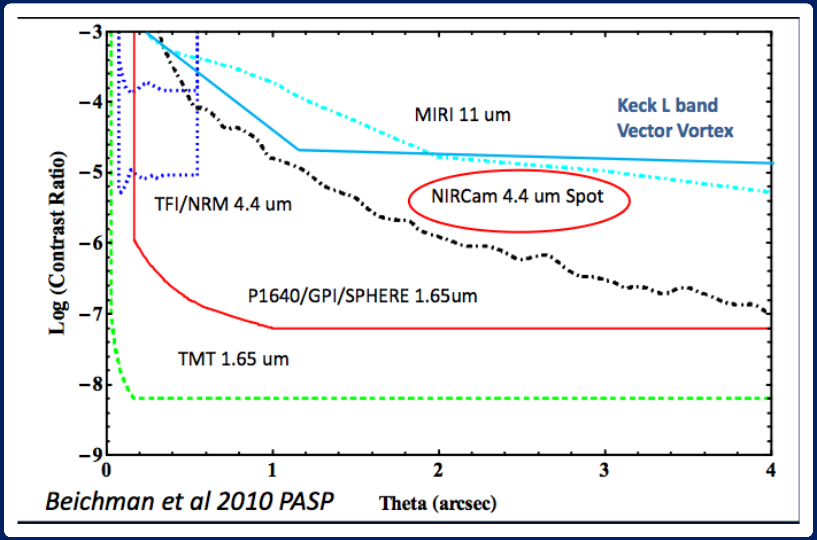


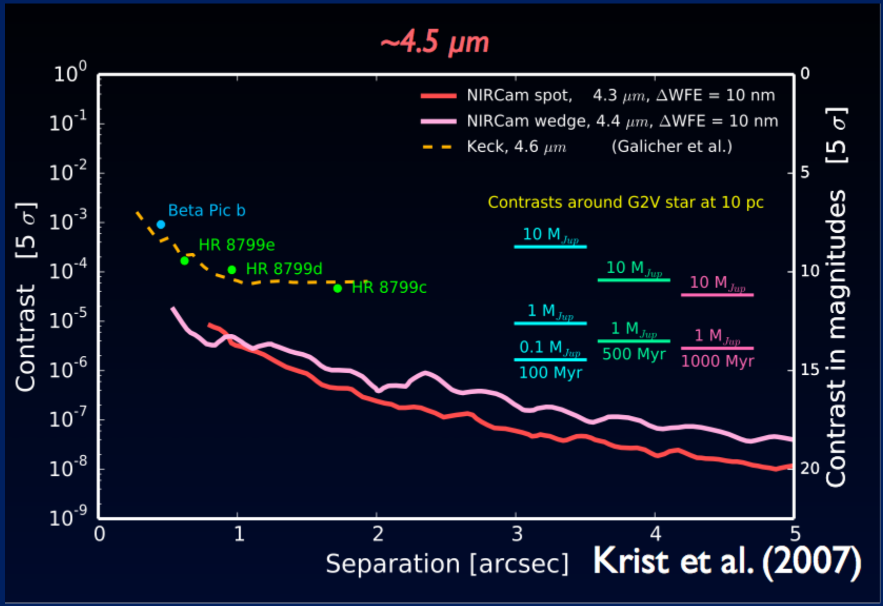


0.6 - 5 mic
microshutter 200mas
R = 100, 1000, 2700

Exoplanets Imaging JWST

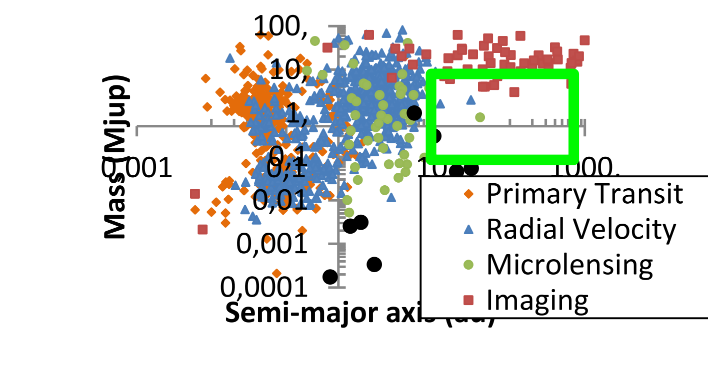






Complementarity ground & space

- JWST : light planets further than 1"
- Ground AO : planets within 1"



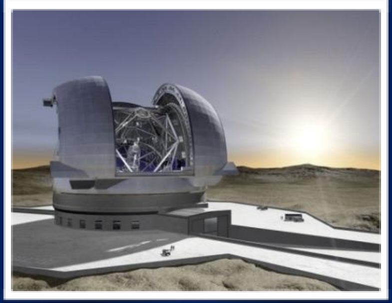
Niche for JWST

- **Light**, young giant planets (0.2 MJup, 10 AU)
- >2MJup planets few au from **<2Gyr, close (<10pc) M dwarfs**

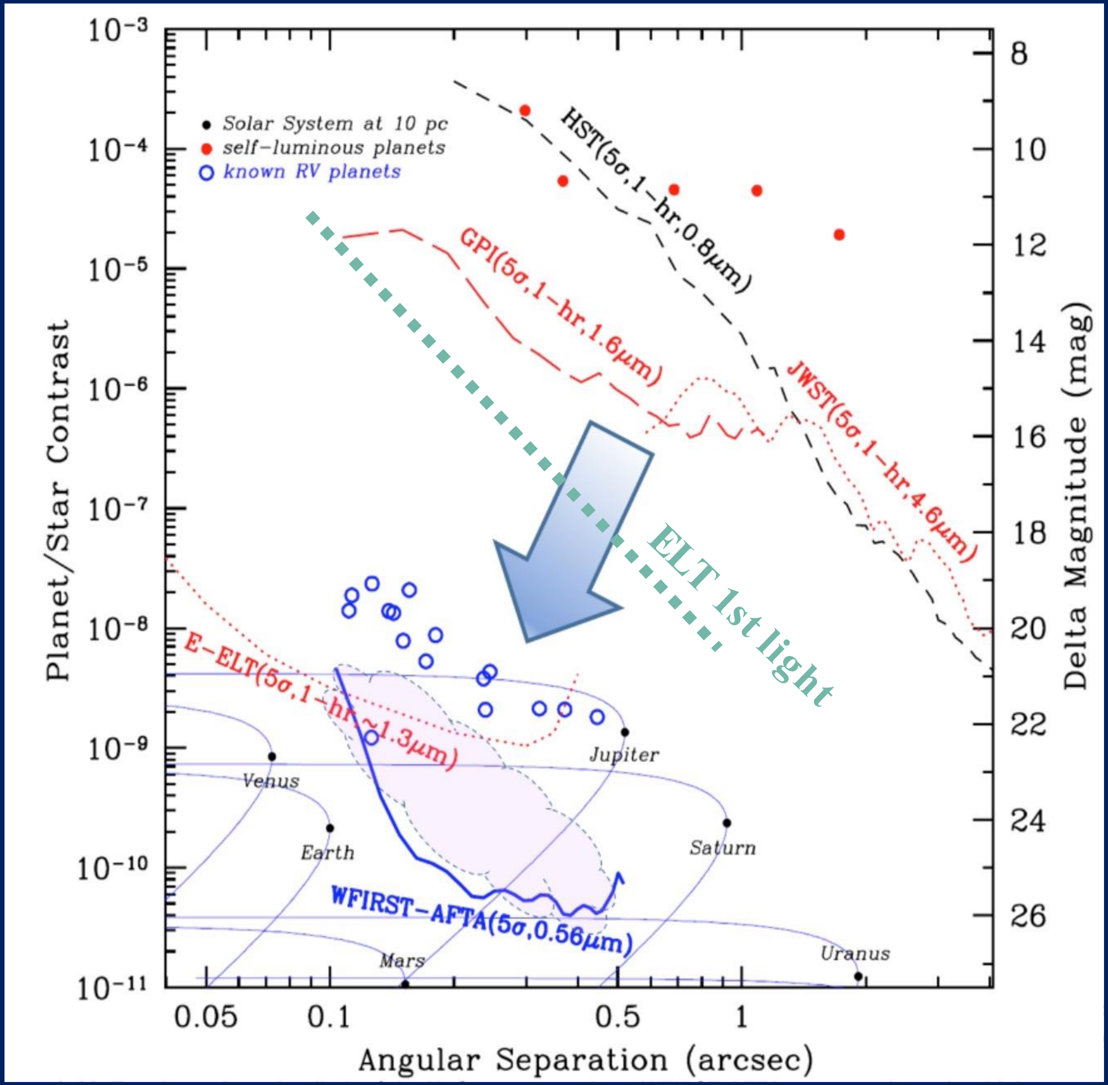
Beichman, 2010

Direct imaging of exoplanets
Longer term future

ELTs



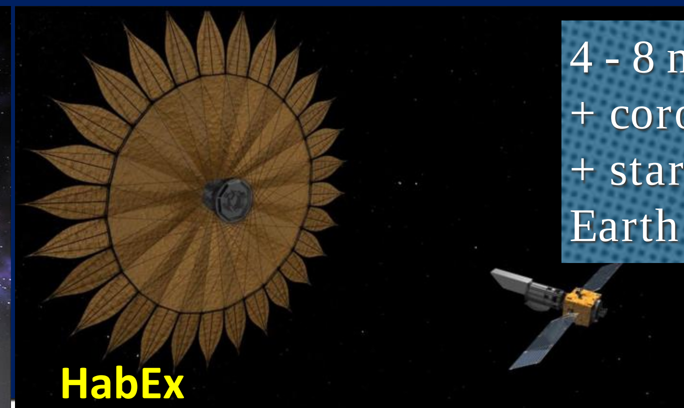
Large aperture,
Near-IR



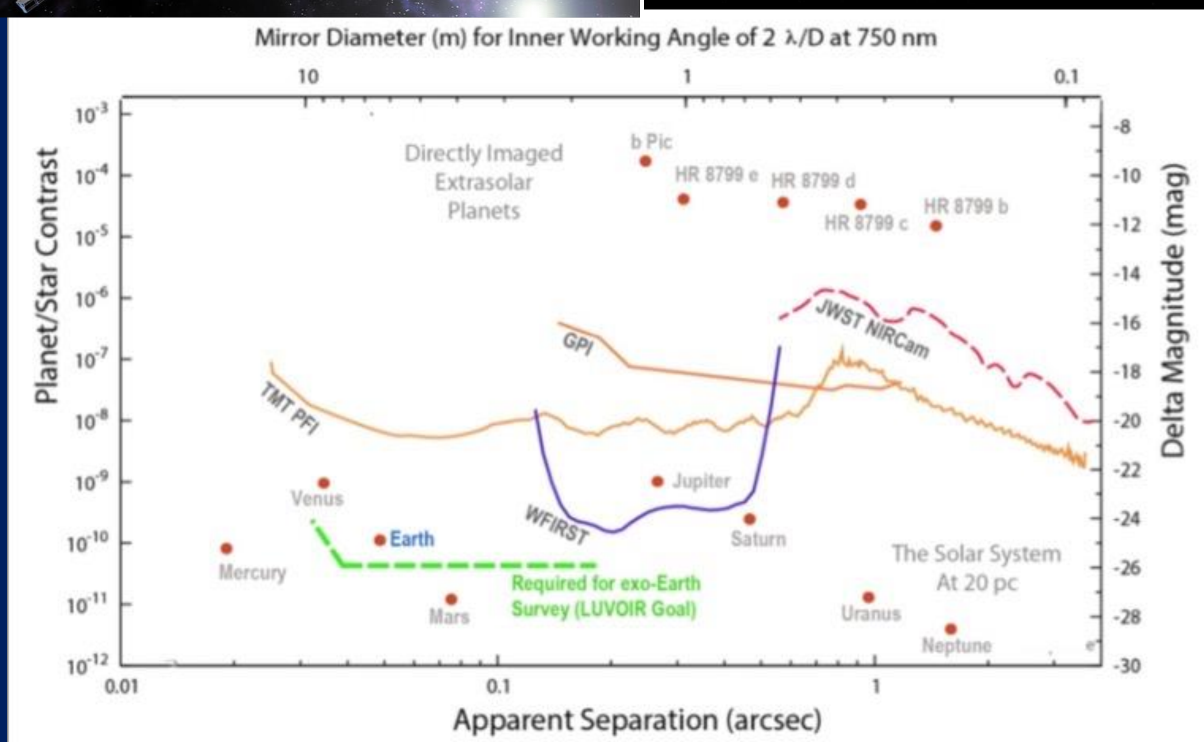
WFIRST
Small aperture
Optical

Concept studies for the Astro decadal 2020
4 missions selected in 2016 for studies

10 - 12 m telescope
+ coronograph
Earth like planets



4 - 8 m telescope
+ coronograph
+ starshade
Earth like planets



Thanks to Anne-Marie Lagrange, Roberto Tamai, Isobel Hook, Yann Clénet, Roland Bacon, Philippe Feautrier, Pierre-Olivier Lagage