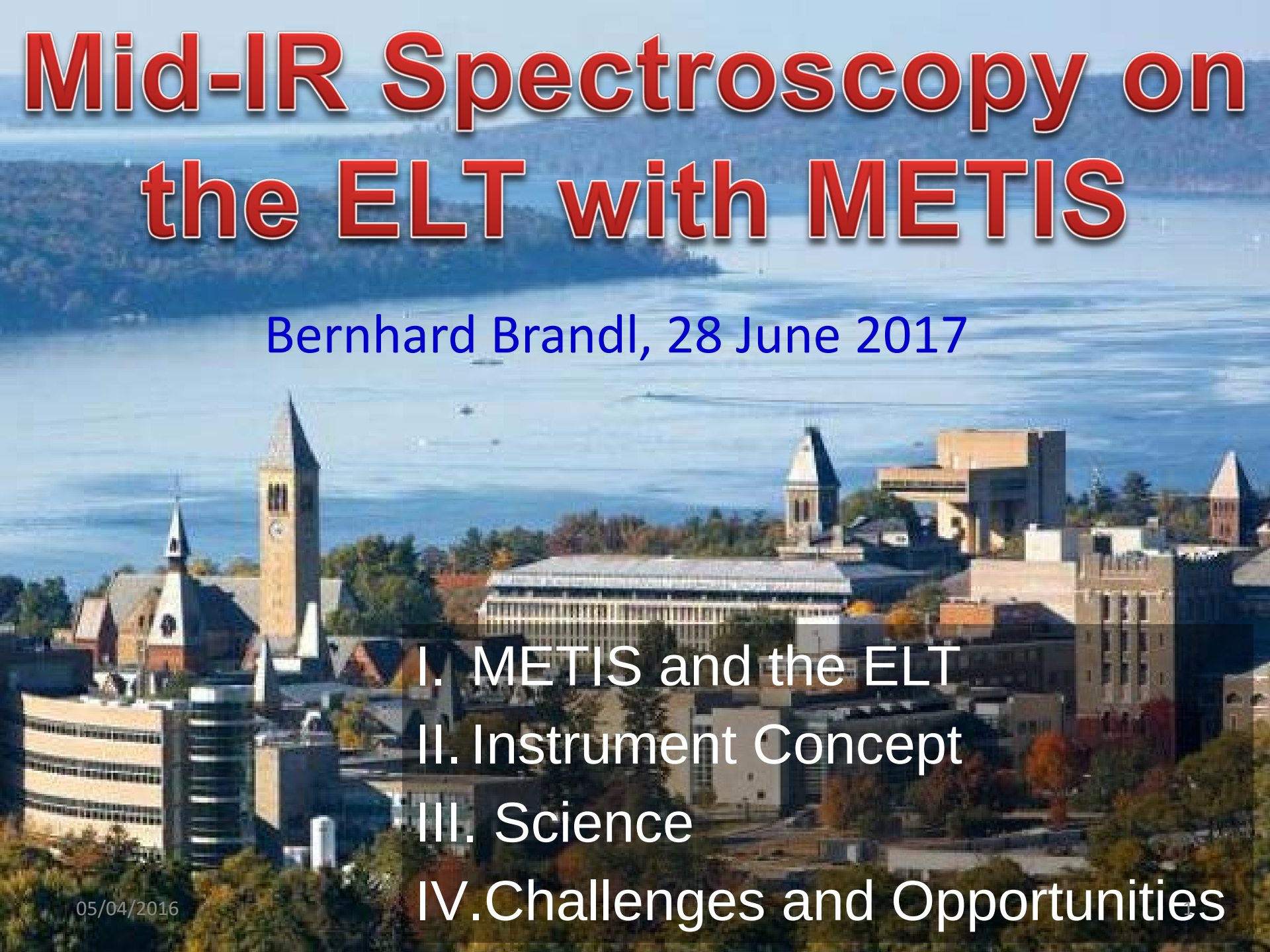
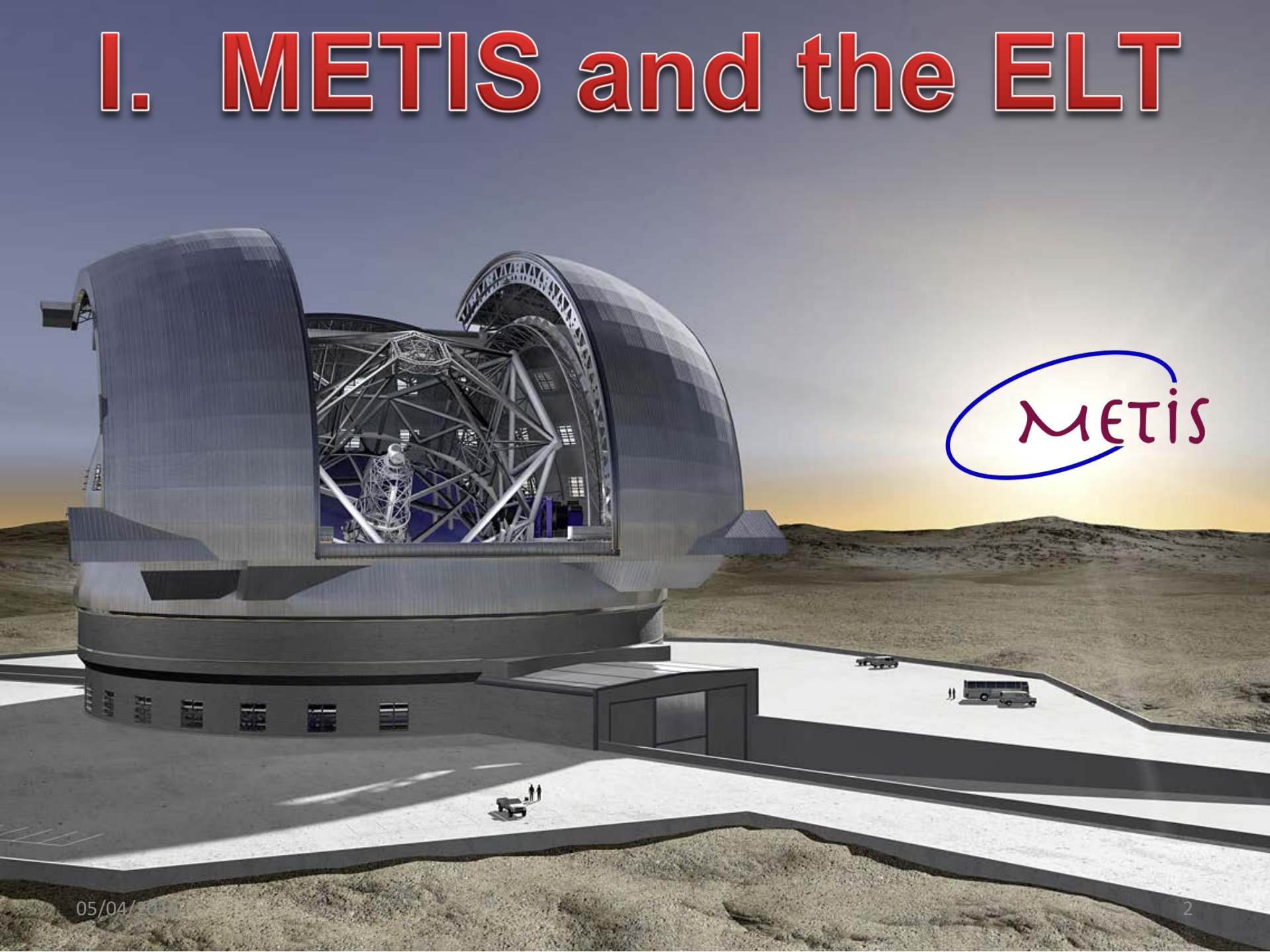
Mid-IR Spectroscopy on the ELT with METIS

Bernhard Brandl, 28 June 2017



I. METIS and the ELT
II. Instrument Concept
III. Science
IV. Challenges and Opportunities

I. METIS and the ELT

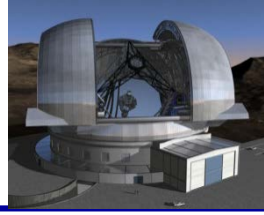


METIS = Mid-infrared ELT Imager and Spectrograph

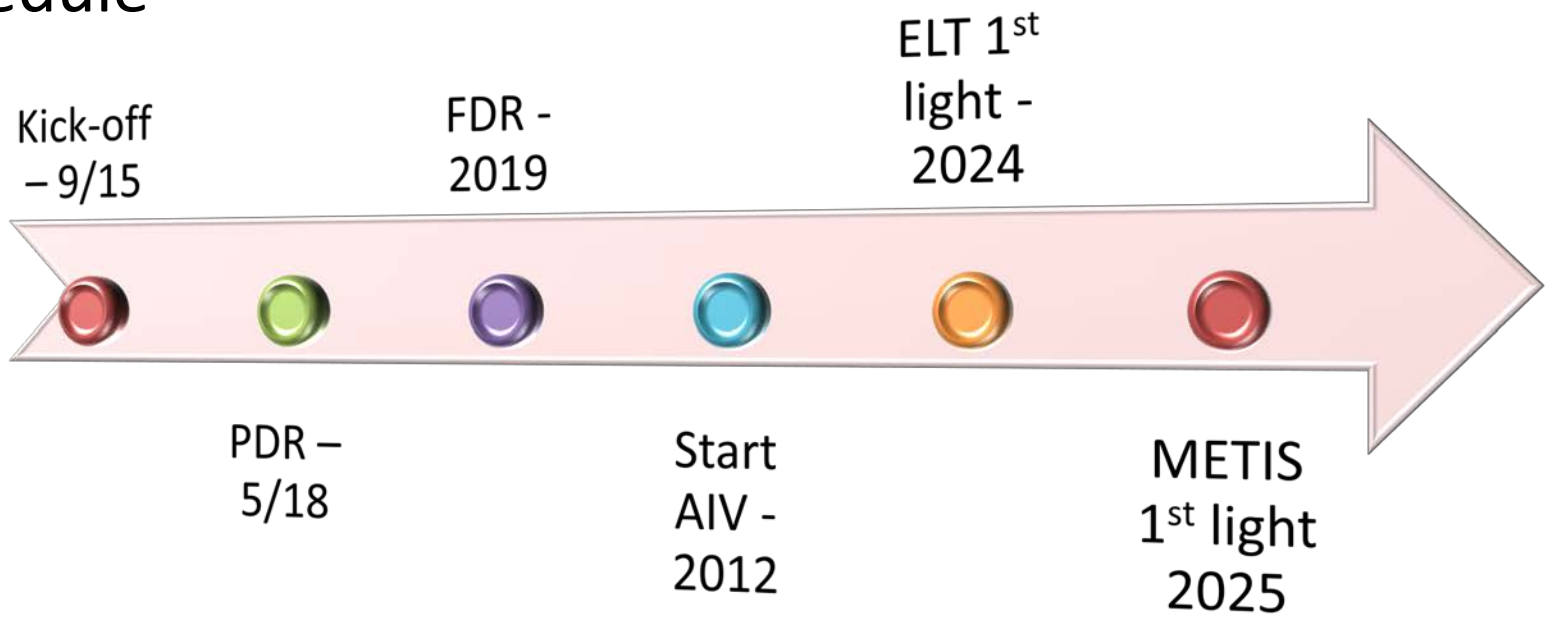
The only 1st-generation thermal/mid-IR instrument on any ELT

- **Imaging at 3 – 13 (19)µm.** The imager includes
  - low/medium resolution slit spectroscopy
  - coronagraphy for high contrast imaging
- **High resolution (R ~ 100,000) IFU spectroscopy at 3 – 5 µm**, including
  - a mode with extended (~300nm) instantaneous wavelength coverage.
- All observing modes work at the **diffraction limit** with single conjugate adaptive optics (SCAO) and eventually assisted by a LTAO system.

The Project



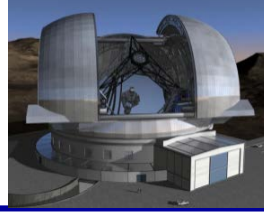
- Schedule

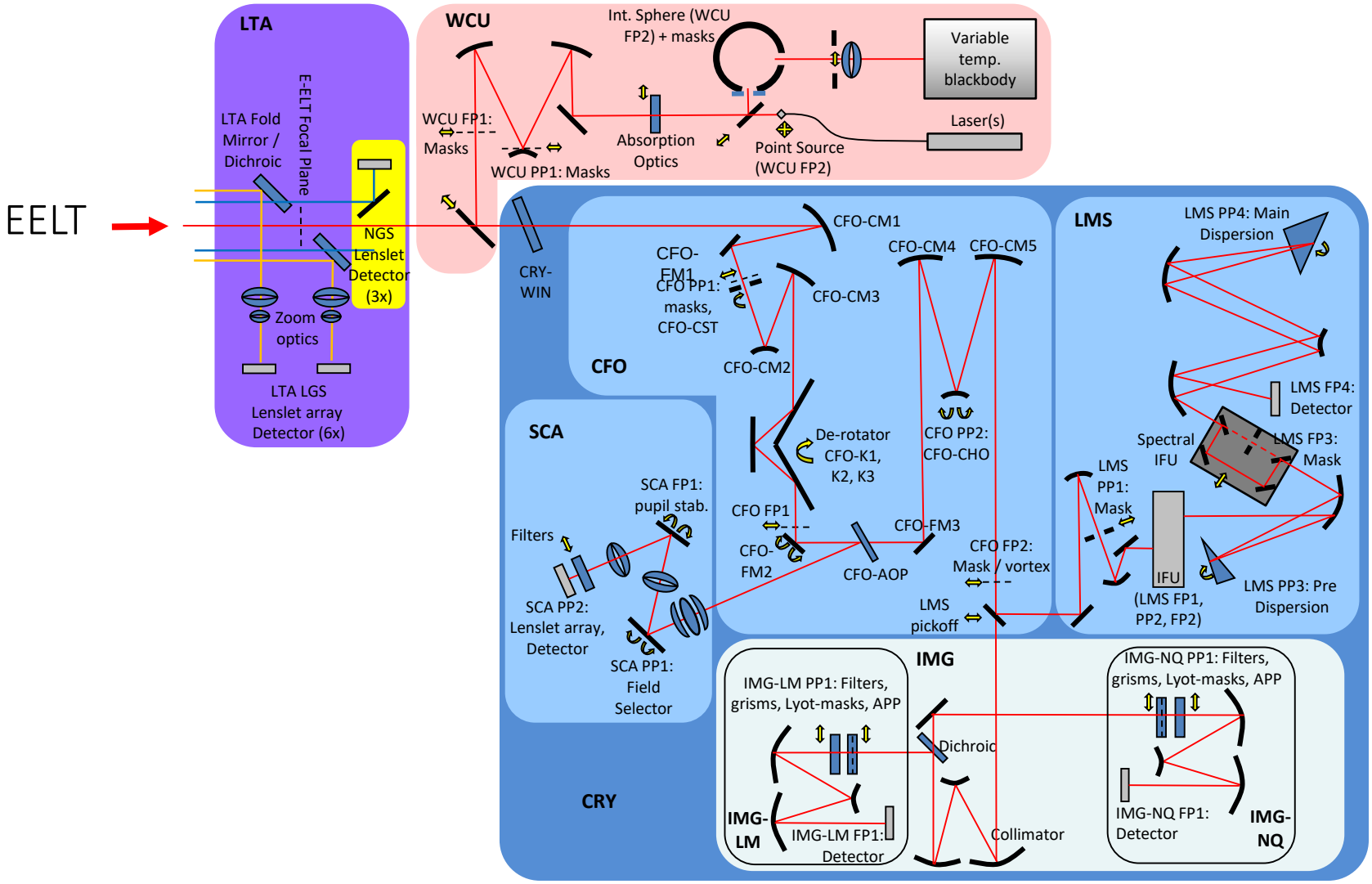


- Partners: 9 institutes from 8 countries

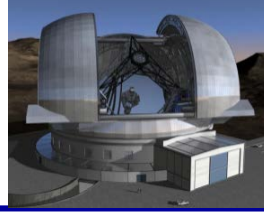
II. Instrument Concept

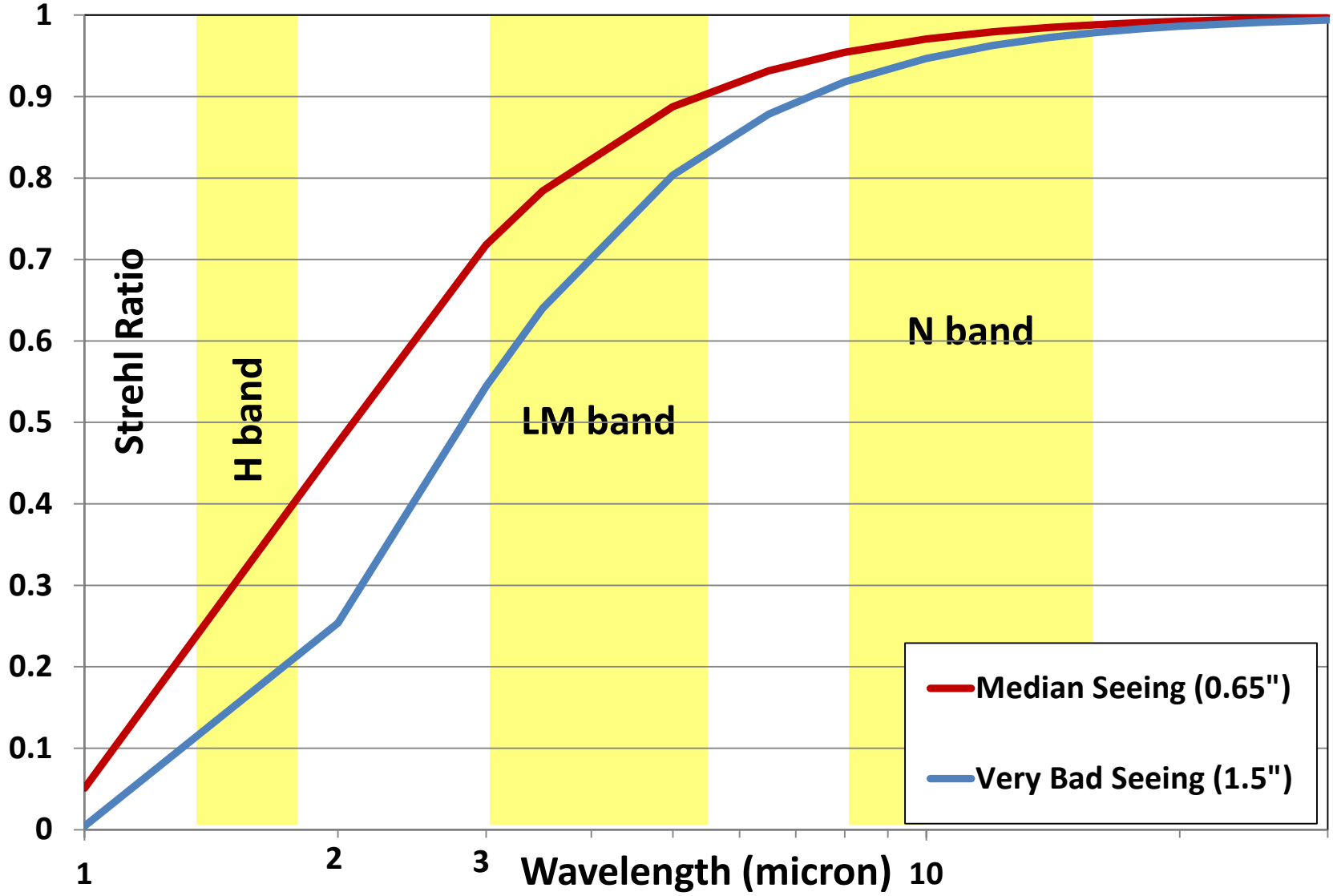
Optical Overview



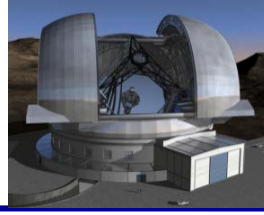


(SC)AO Performance

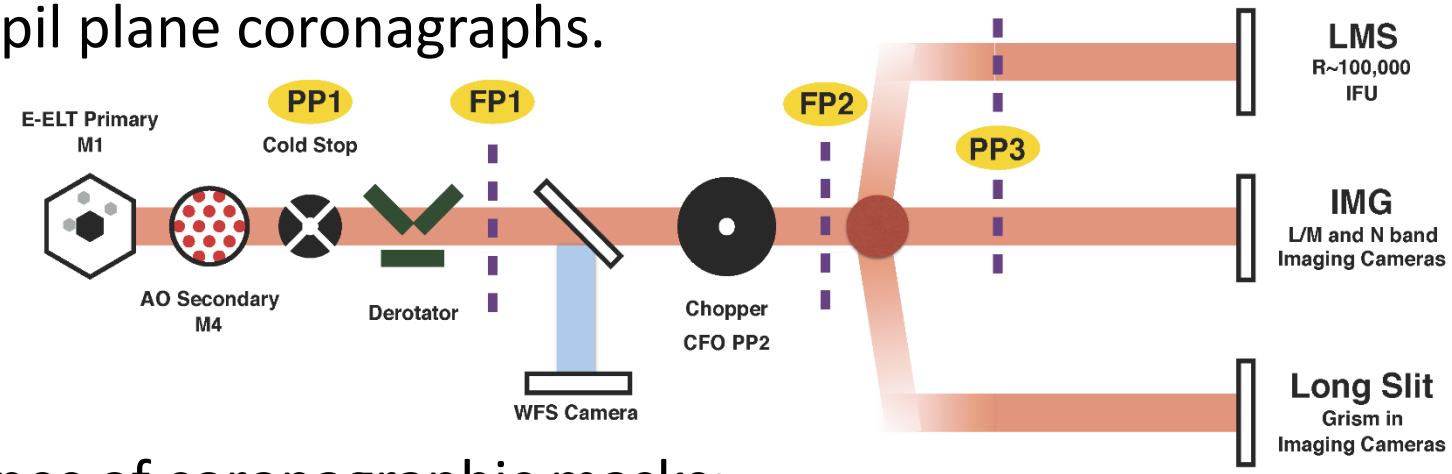




Coronagraphic Concept

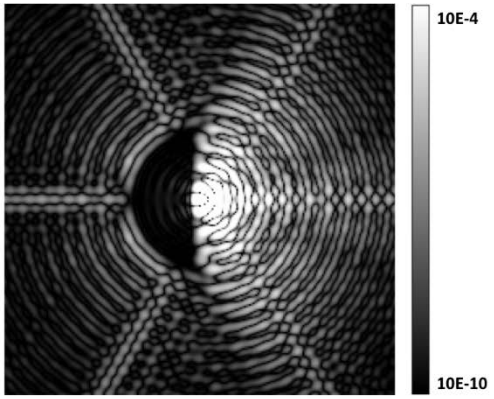


Four planes are available within the METIS fore-optics for focal plane and pupil plane coronagraphs.

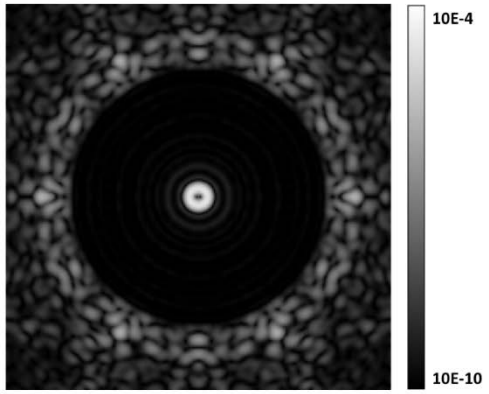


Two types of coronagraphic masks:

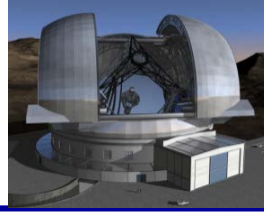
APP - very robust but not innermost IWA



Vortex - excellent IWA but vibration sensitive



Detectors



Subsystem	Type	Pixels
AO WFS (NIR)	Leonardo SAPHIRA	320 × 256
L/M band imaging	Teledyne HAWAII-2 RG	2048 × 2048
L/M IFU spectroscopy	Teledyne HAWAII-2 RG	4 × 2048 × 2048
N/Q band imaging *or*	Raytheon AQUARIUS	1024 × 1024
N band imaging	Teledyne Geosnap	2048 × 2048
N IFU spectroscopy	Raytheon AQUARIUS	2 × 1024 × 1024

METIS 2.9-5.3 µm Spectrograph

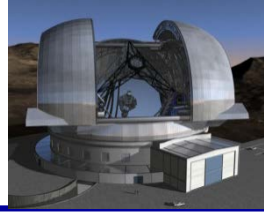
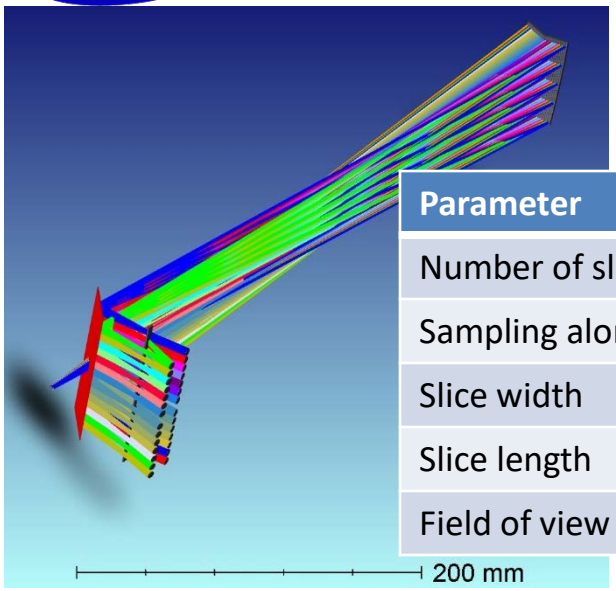
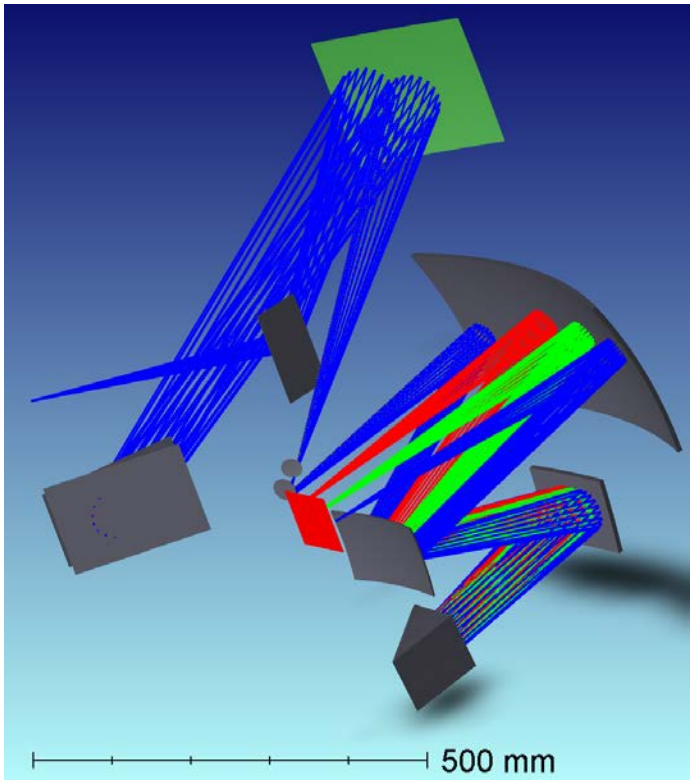


Image slicer



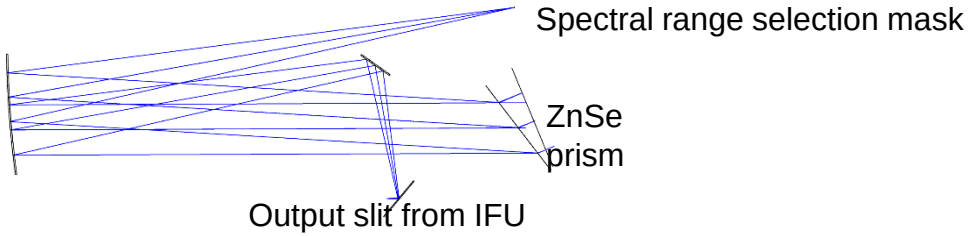
Parameter	Value
Number of slices	28
Sampling along slice	0.008″
Slice width	0.020″
Slice length	138 pix
Field of view	0.55″×1.08″

Main optics



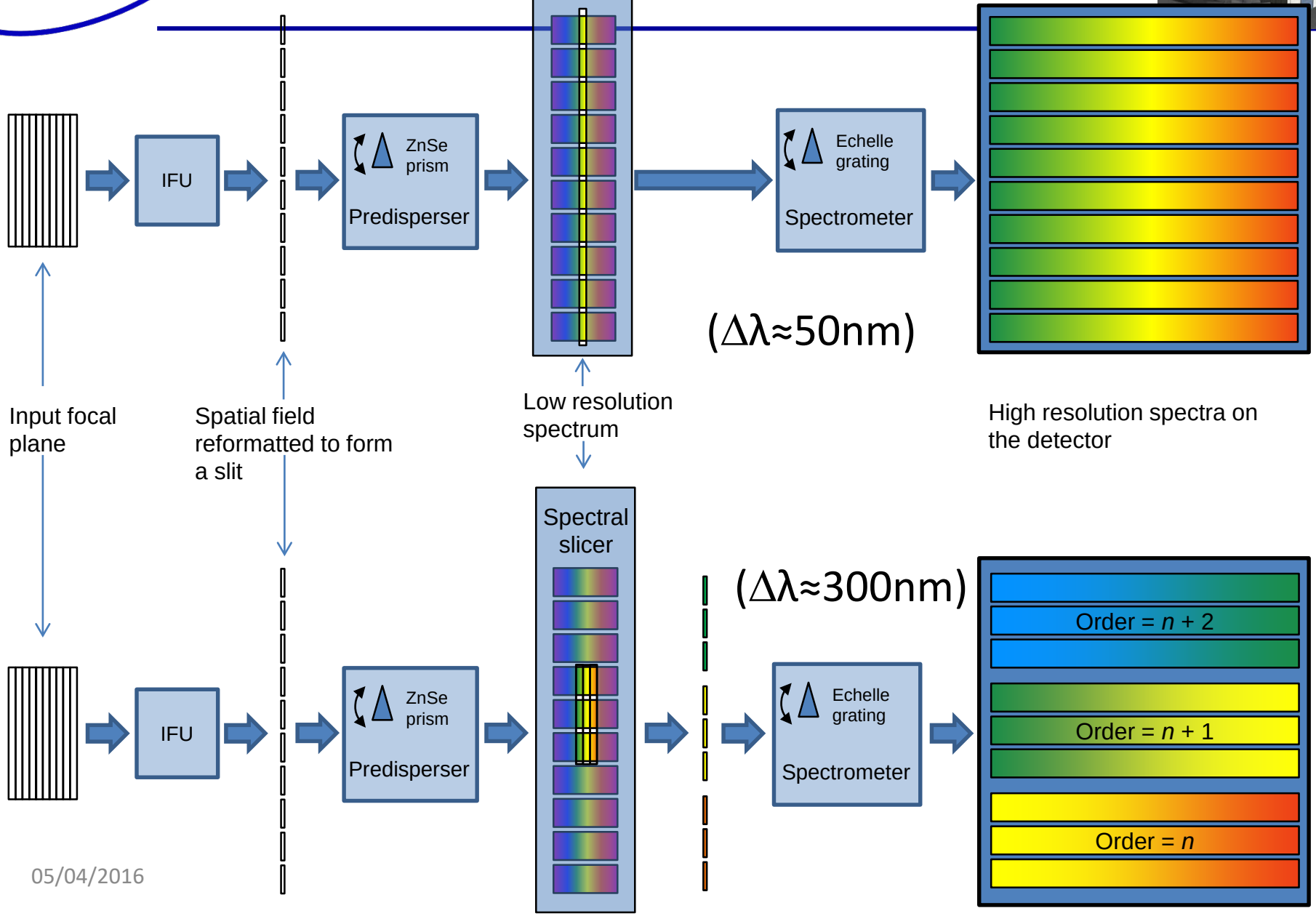
- all-reflective TMA design in double pass
- disperser: immersed Si echelle grating
- R > 100,000 for λ ≤ 4.8µm

Pre-disperser

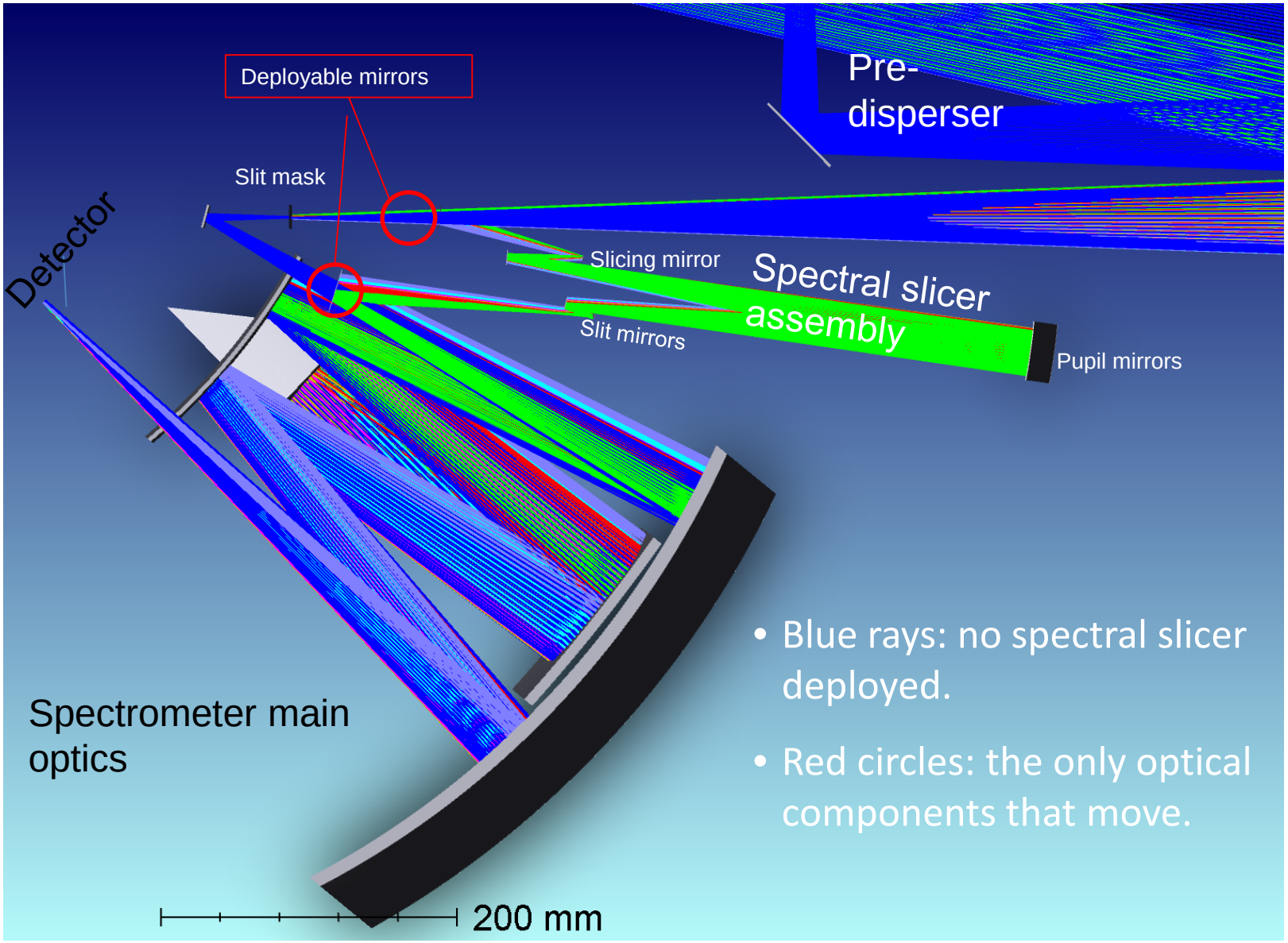


- produces a low resolution spectrum at slit mask for order sorting.
- double-pass monochromator design
- ZnSe prism used in reflection.

METIS Spectral Slicing (1)

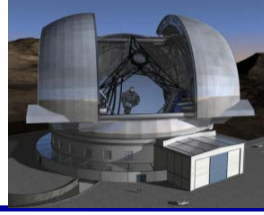


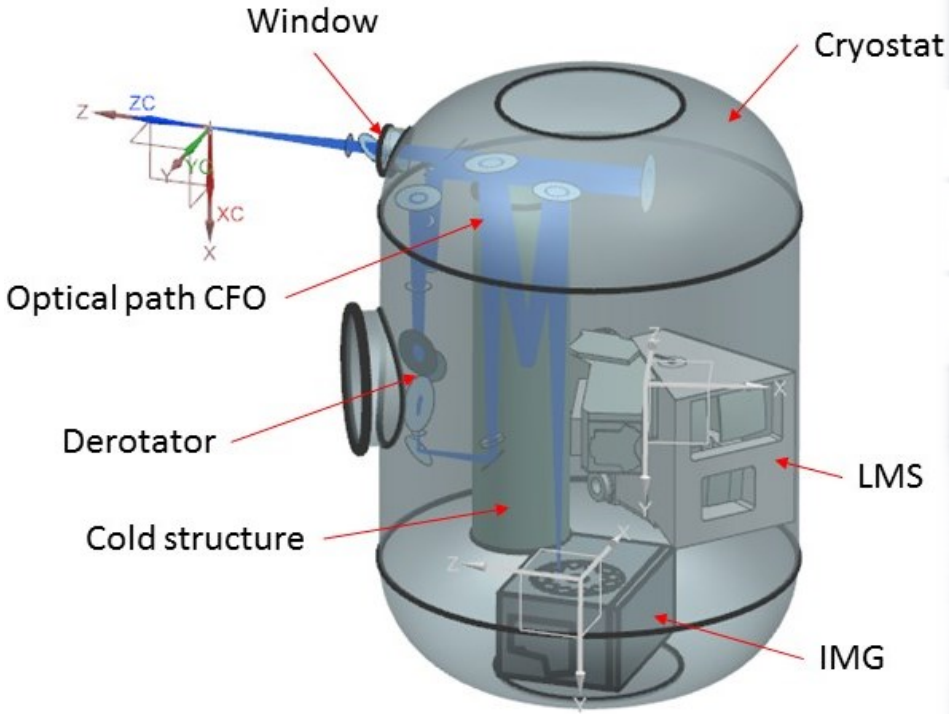
Spectral Slicing (2)



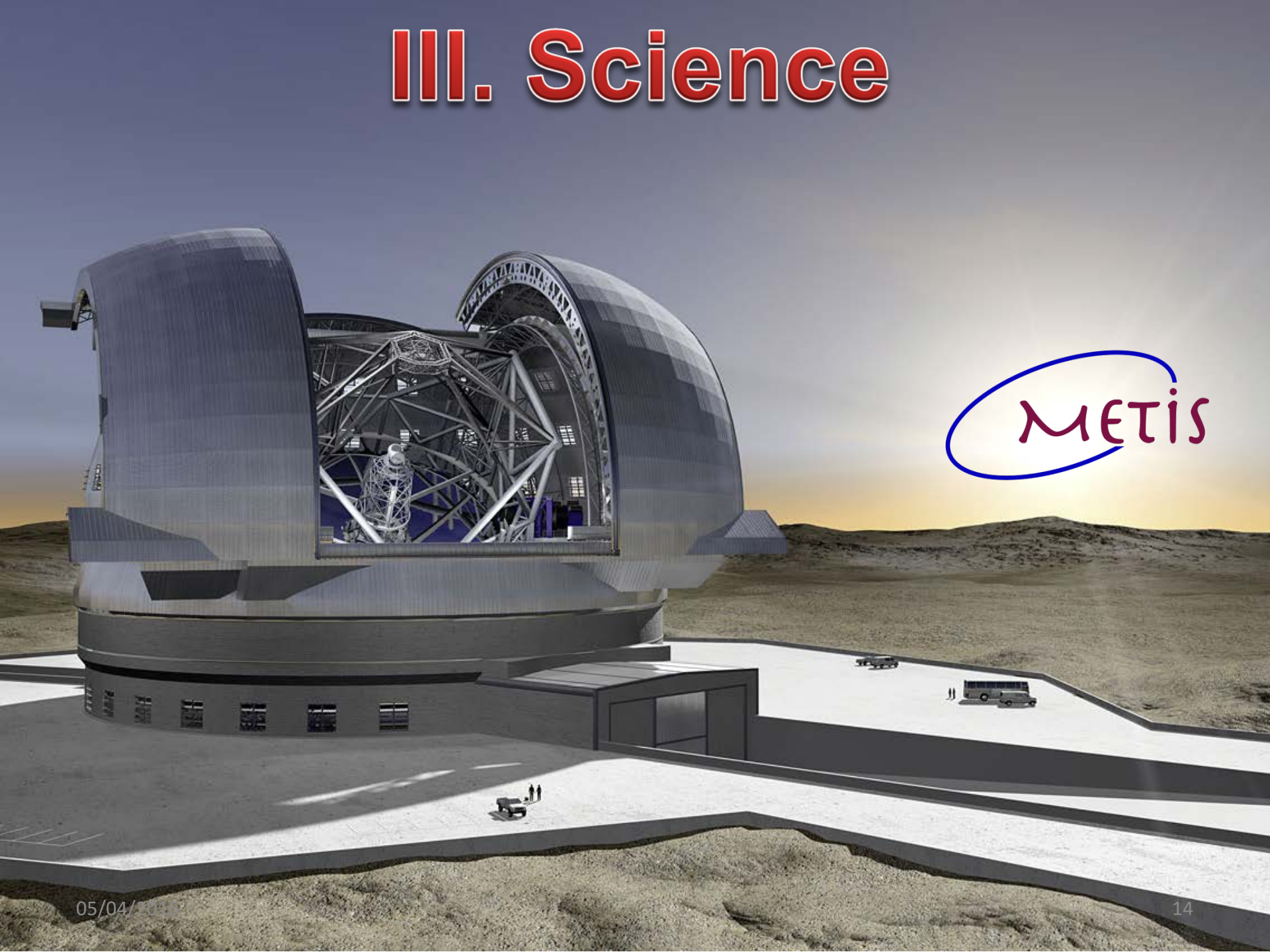
- Blue rays: no spectral slicer deployed.
- Red circles: the only optical components that move.

Packaging

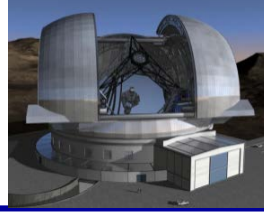


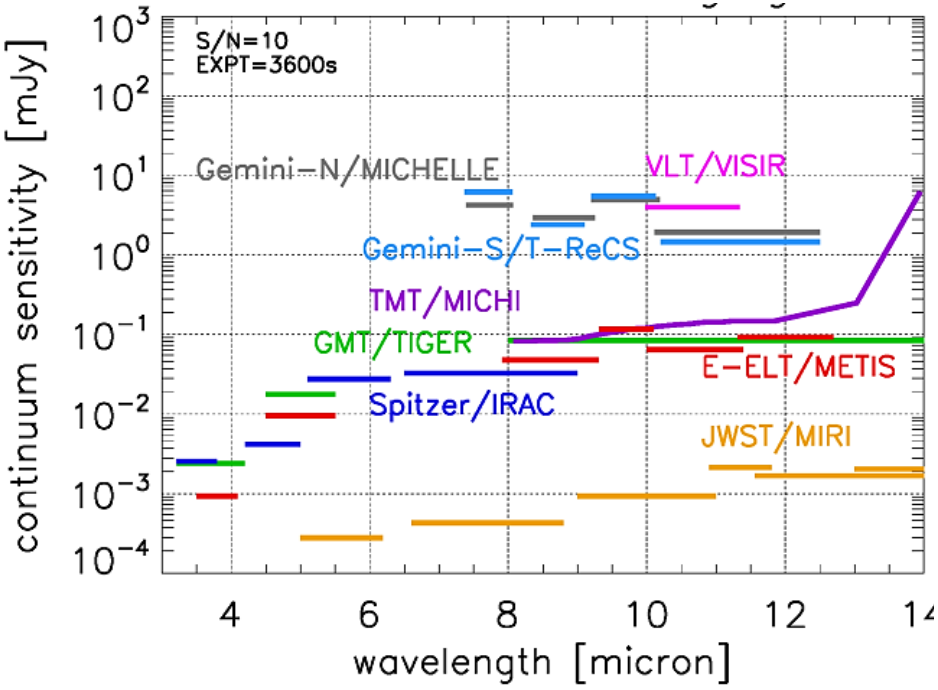

Window
Cryostat
ZC
YC
XC
Optical path CFO
Derotator
LMS
Cold structure
IMG

III. Science



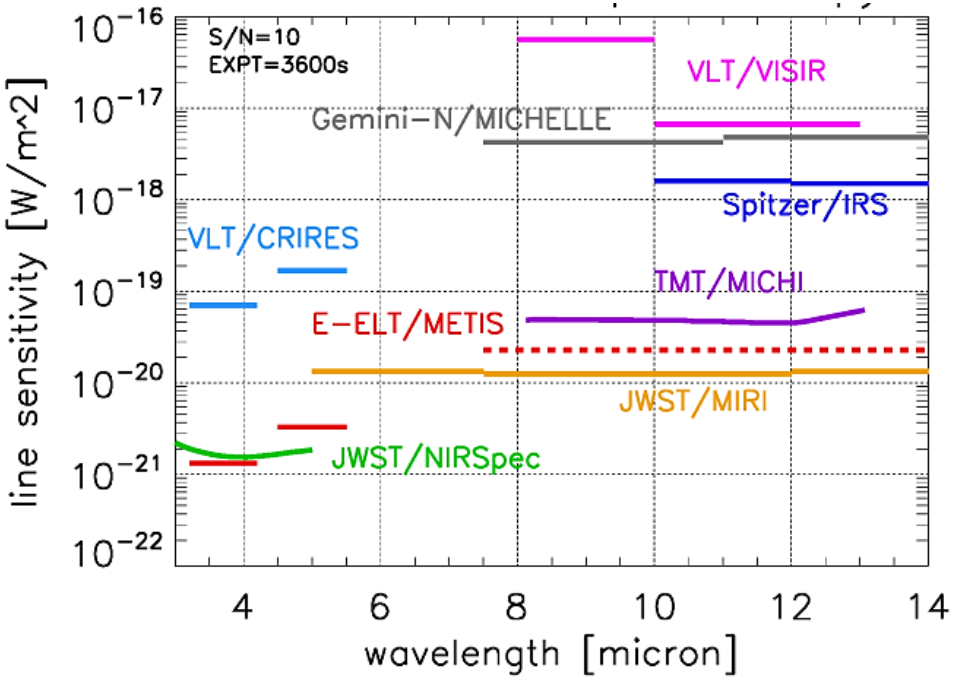
Sensitivity



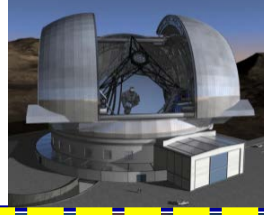


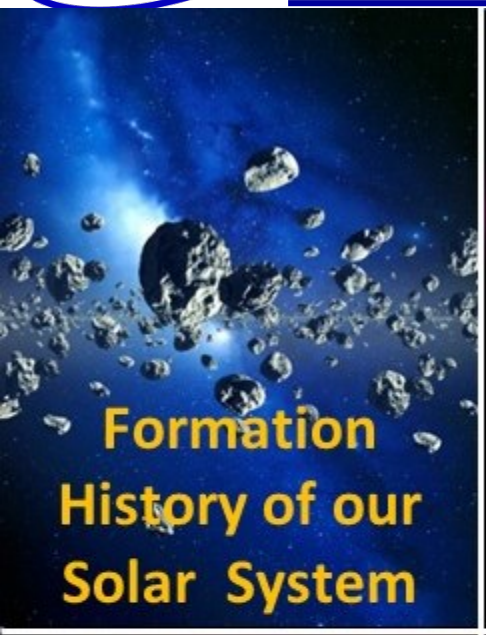
↑ Imaging point source sensitivity (1hr, S/N=10)

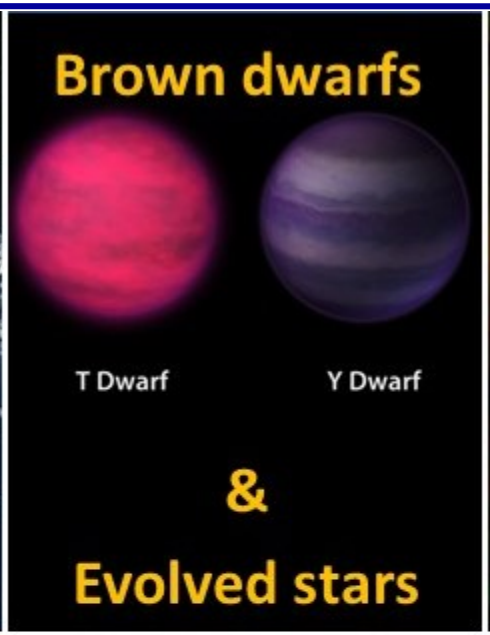
IFU *R=100,000* spectroscopy (1hr, S/N=10, PS, unresolved lines) ↓

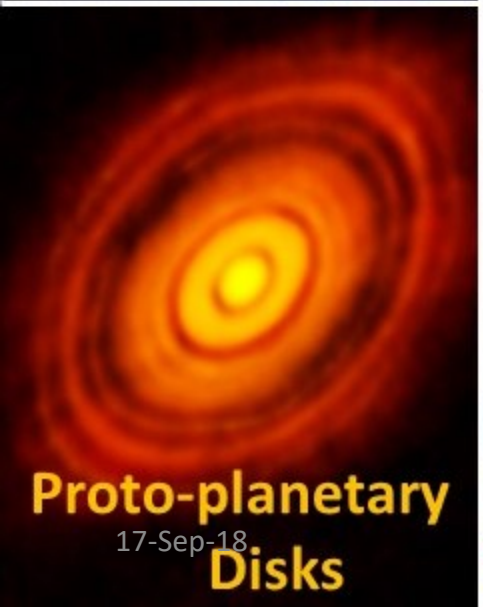


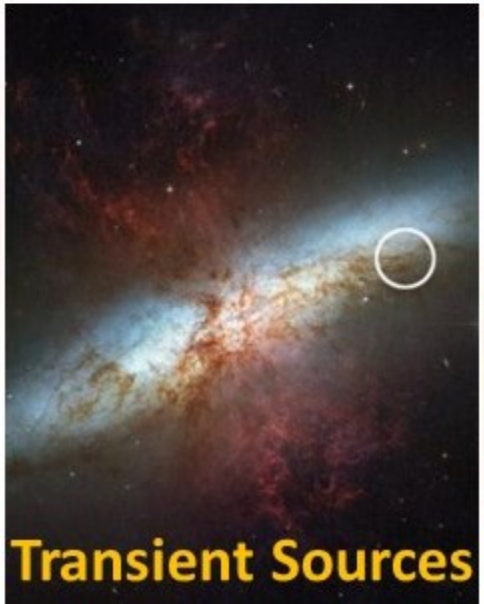
METIS Wide Range of IR Science

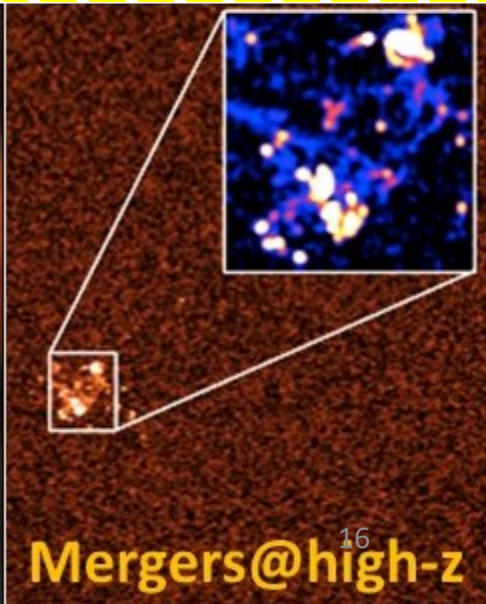




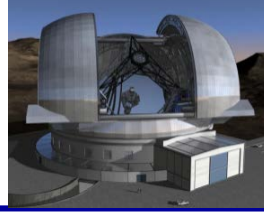


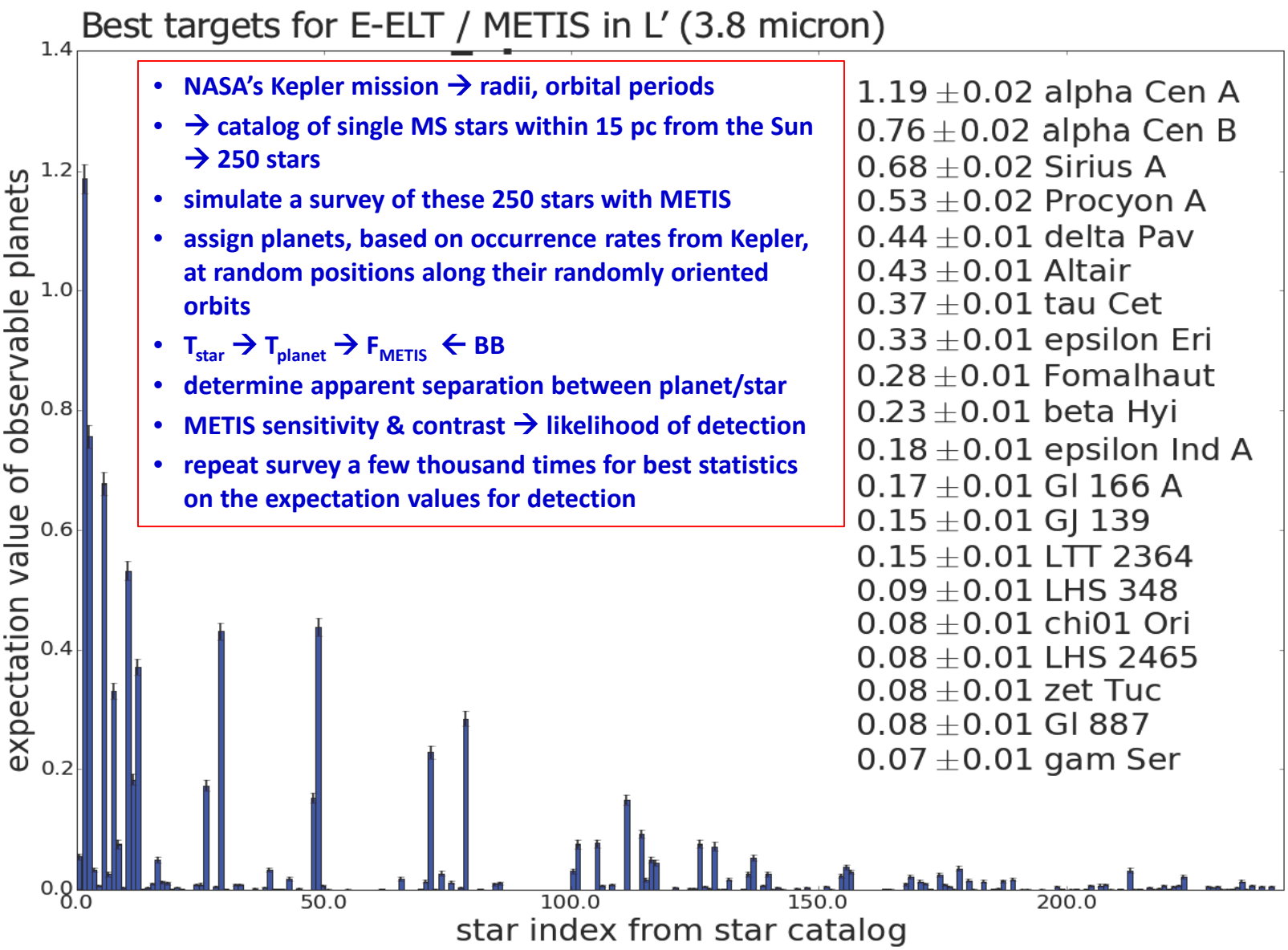






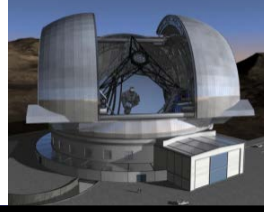
Imaging nearby Exoplanets



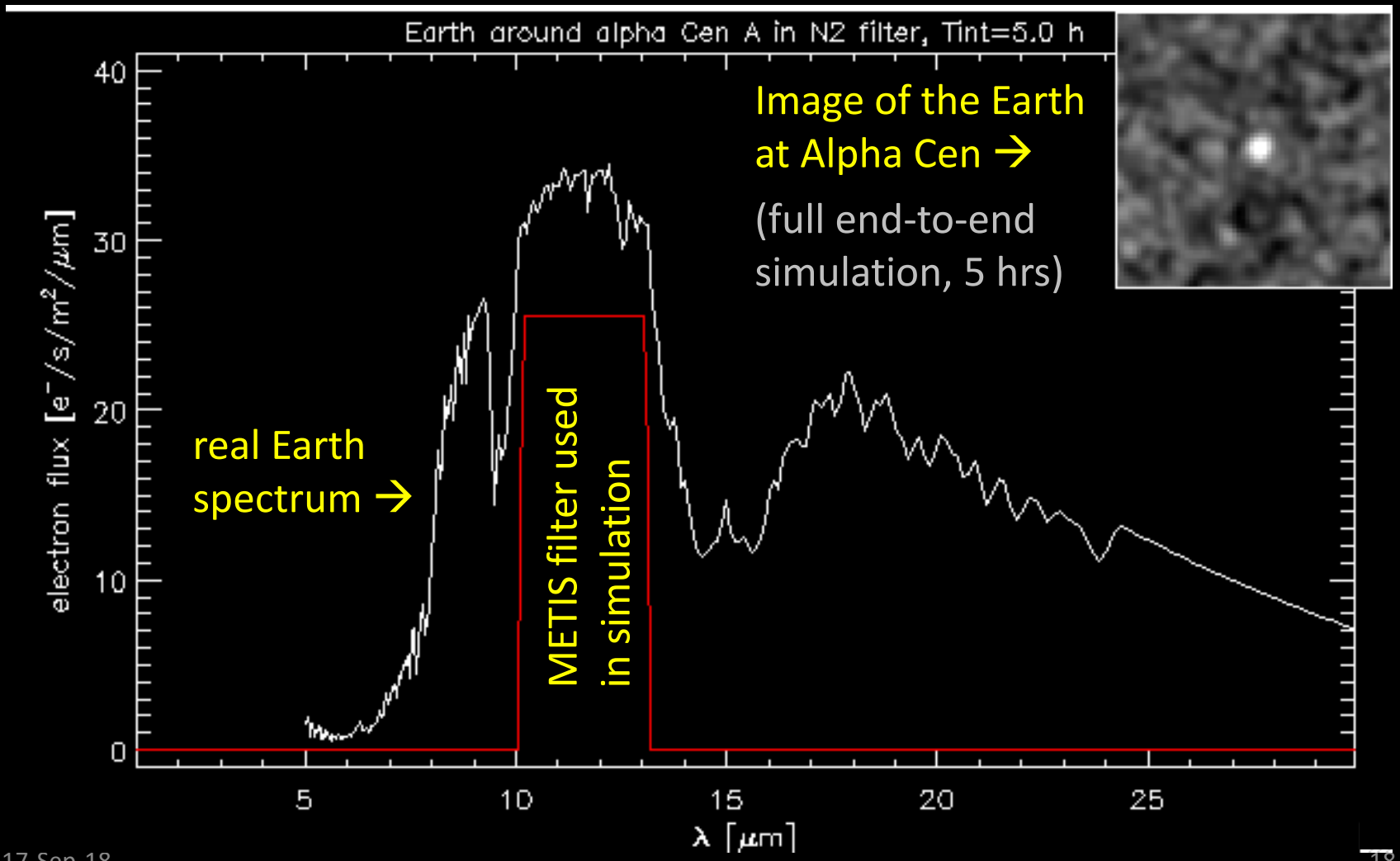


- NASA's Kepler mission → radii, orbital periods
- → catalog of single MS stars within 15 pc from the Sun → 250 stars
- simulate a survey of these 250 stars with METIS
- assign planets, based on occurrence rates from Kepler, at random positions along their randomly oriented orbits
- T_{star} → T_{planet} → F_{METIS} ← BB
- determine apparent separation between planet/star
- METIS sensitivity & contrast → likelihood of detection
- repeat survey a few thousand times for best statistics on the expectation values for detection

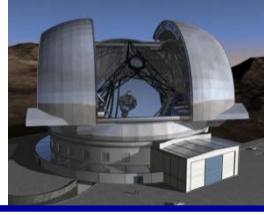
Earth @ Alpha Centauri



What would a habitable Earth around Alpha Centauri look like?



Exoplanet Atmospheres



Transiting planets are observable:

- During **transit**
- Before/after **secondary eclipse**

Pilot study:
Brogi et al. 2012
CO - τ Bootis b

Day-side Spectroscopy

Transmission Spectroscopy

METIS will be able to do these studies on dozens of planetary systems

Carbon monoxide - 2.3μm

Orbital phase

0.8
0.6
0.4
0.2
0.0
-0.2

2.308 2.310 2.312 2.314
Wavelength (μm)

Observed

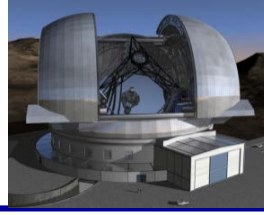
Orbital Phase
0.02
0.01
0.00
−0.01
−0.02

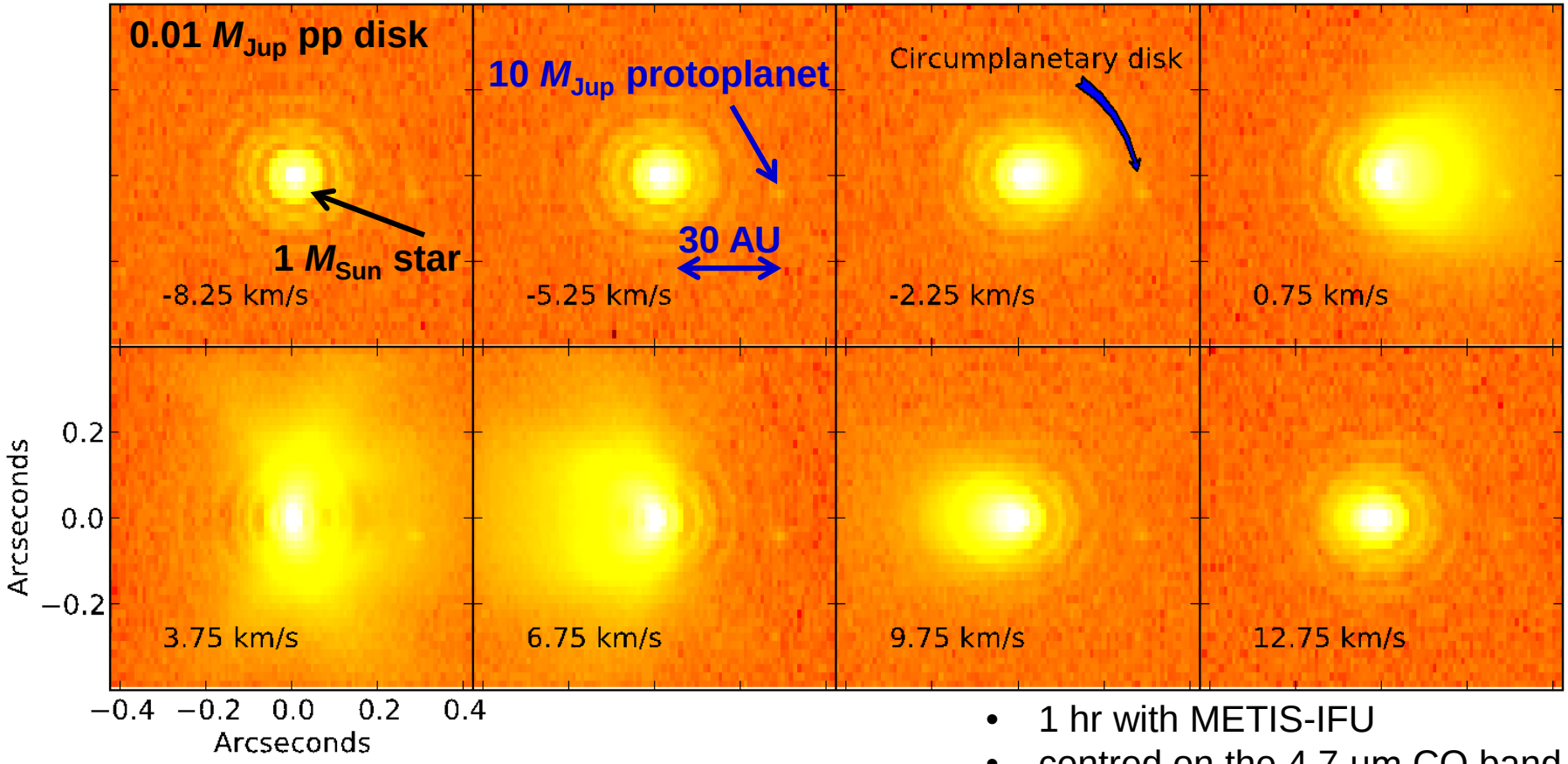
−60 −40 −20 0 20 40 60
Barycentric RV + 14.8 (km/s)

−60 −40 −20 0 20 40 60
Barycentric RV + 14.8 (km/s)

Pilot study:
Snellen et al. 2010
CO - HD209458b

METIS Spectral Imaging of Proto-Planets



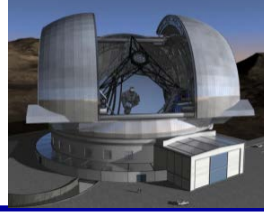


Pontoppidan et al. 2009

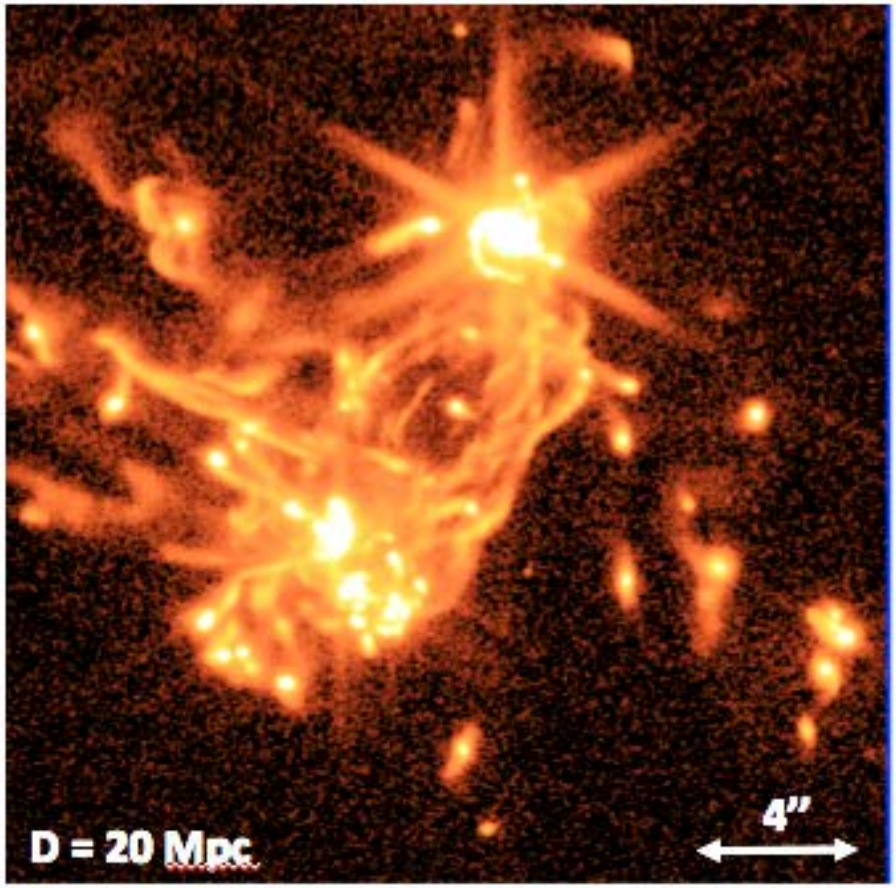
- 1 hr with METIS-IFU
- centred on the 4.7 μm CO band
- stack of 5 CO lines

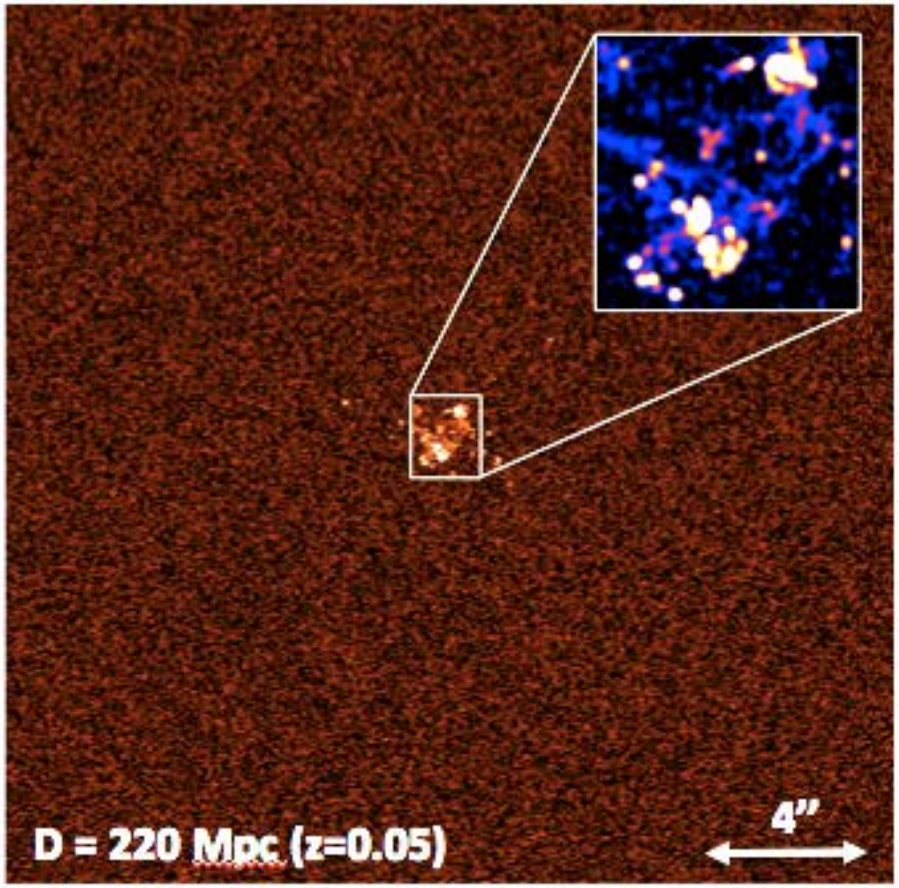
- broad line emission (←accretion) from the circum-planetary disk
- proto-planet clearly separated from the cooler circum-stellar disk

SSCs in Galaxy Mergers

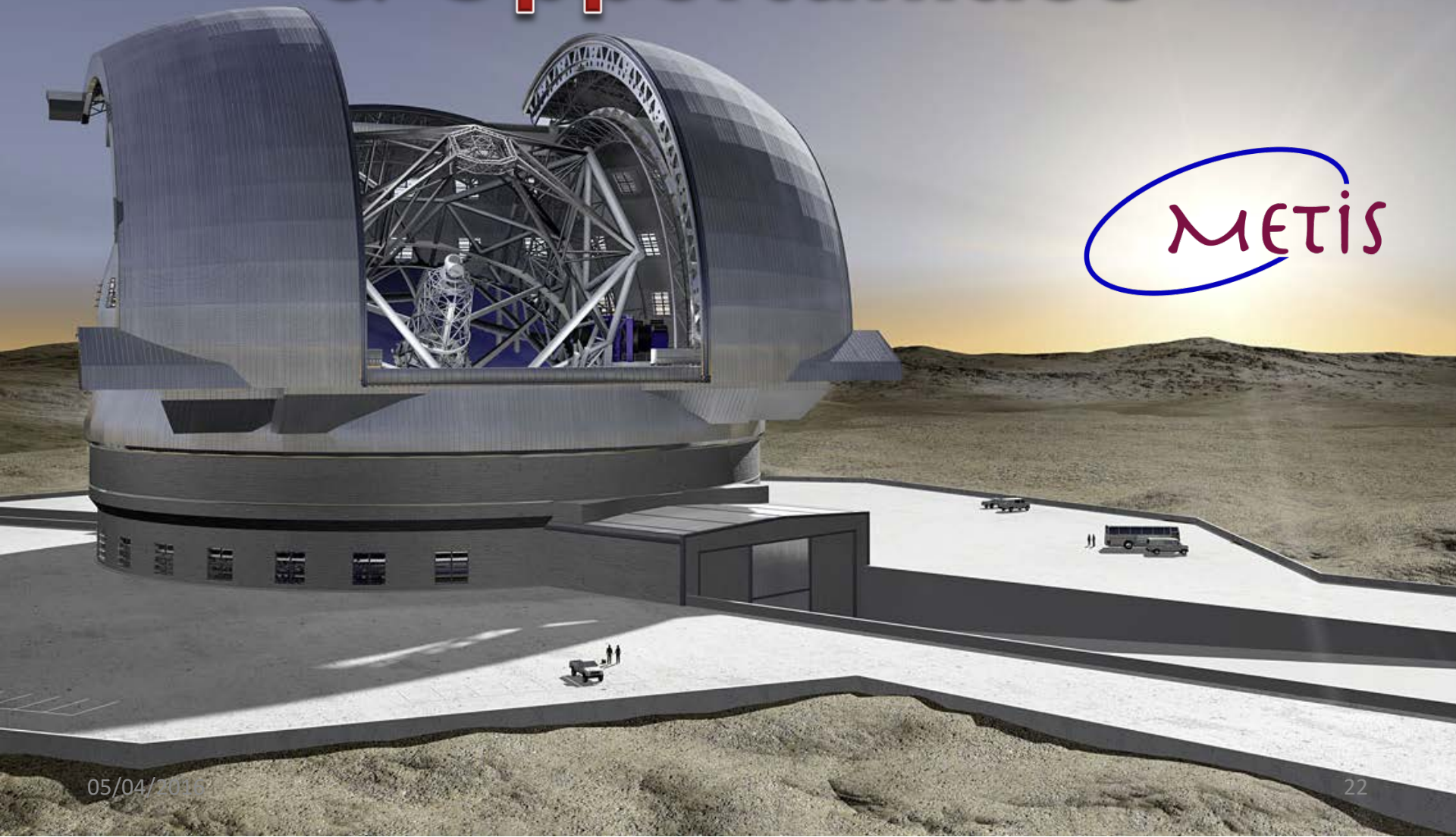


- Simulation of merger @ N-band by Renaud et al. (2014)
- Left: *D* (20 Mpc) and total F_ν (2 Jy) of the Antennae galaxies
- Right: object moved to *D* = 220 Mpc (*z* = 0.05)

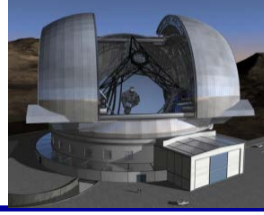




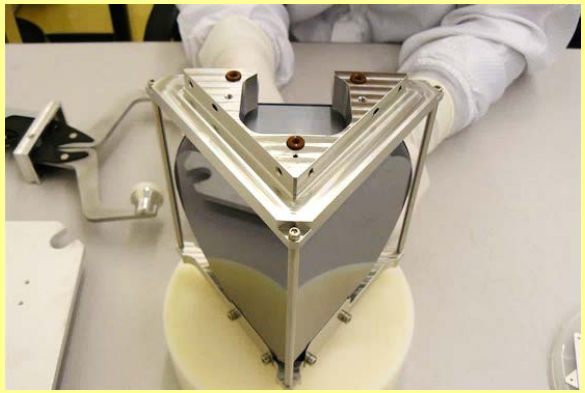
IV. Challenges & Opportunities

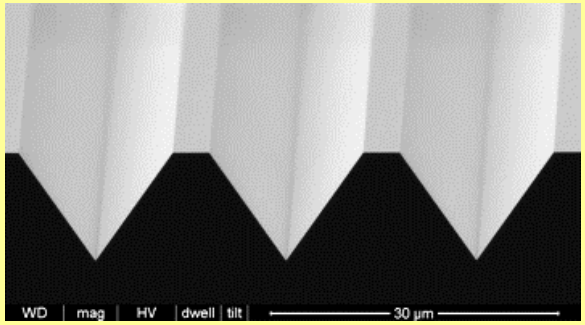


Development of Novel Components

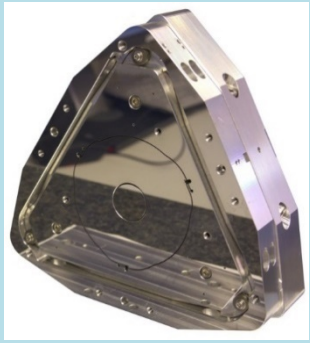


Immersed gratings

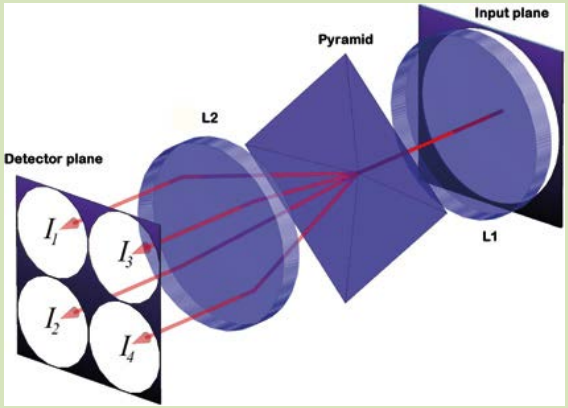




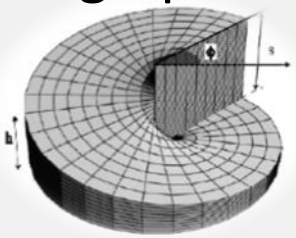
Cryo. beam-chopper



Cryo. AO modulator

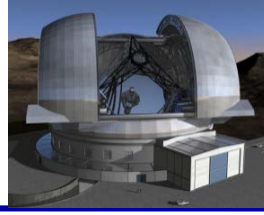


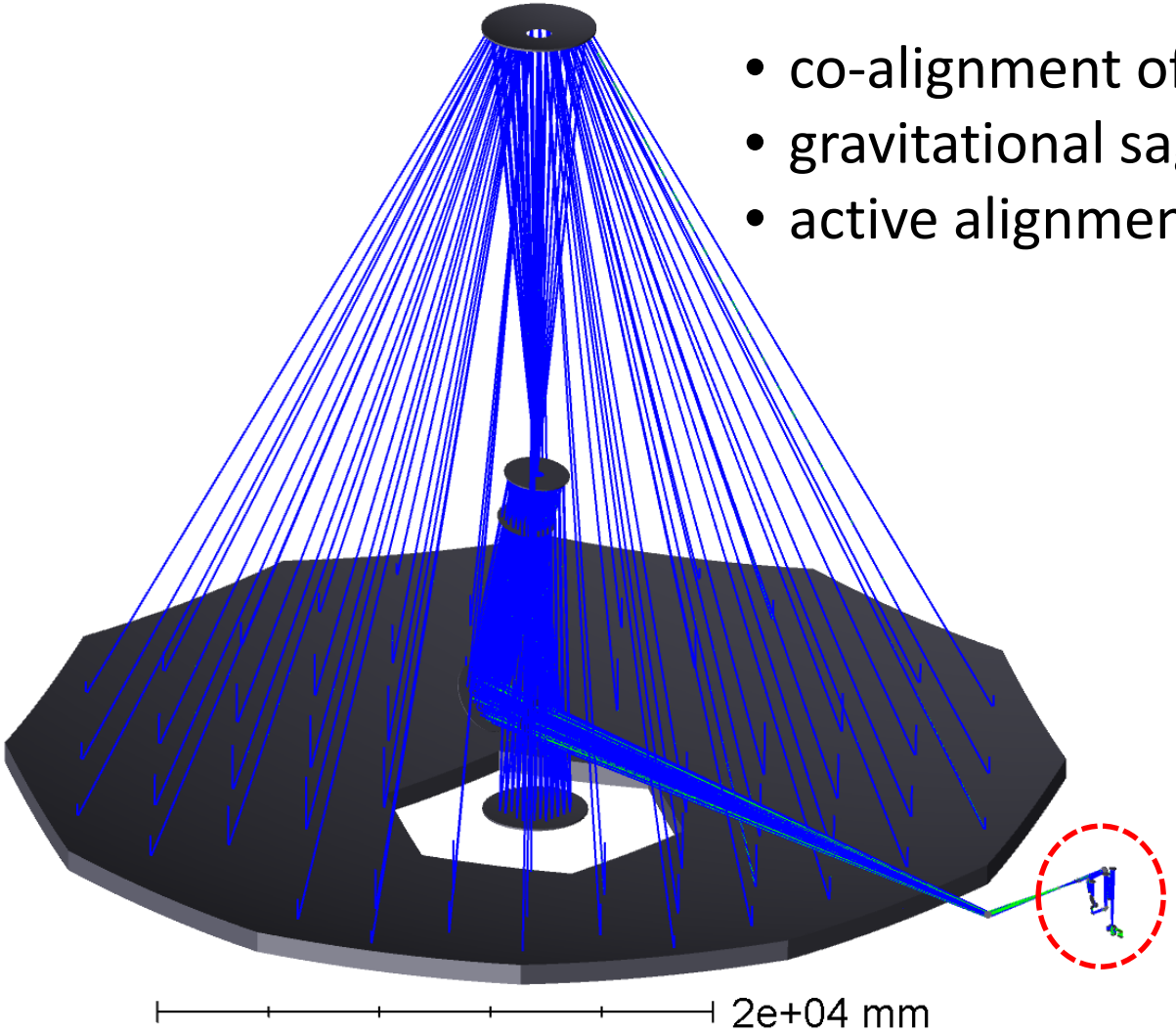
Coronagraphic masks



Cryo-mechanisms

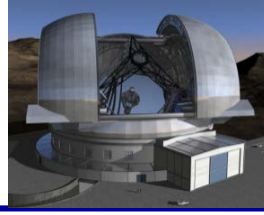
METIS Challenge: Alignment & Control



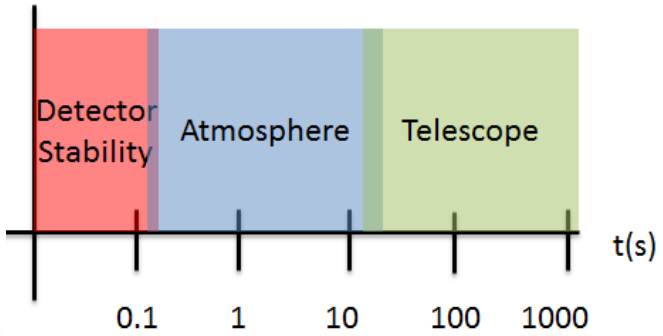


- co-alignment of 5 pupils (2 EELT + 3 instr.)
- gravitational sagging + vibrations
- active alignment & control → 90% SR

Background Calibration

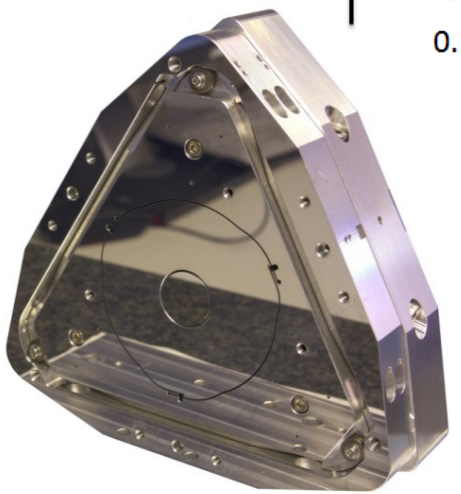


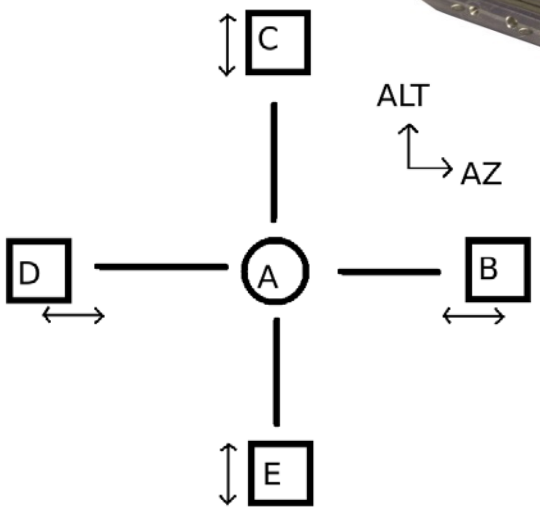
Reaching the photon shot-noise limit in the thermal IR on the E-ELT is arguably the biggest challenge for METIS

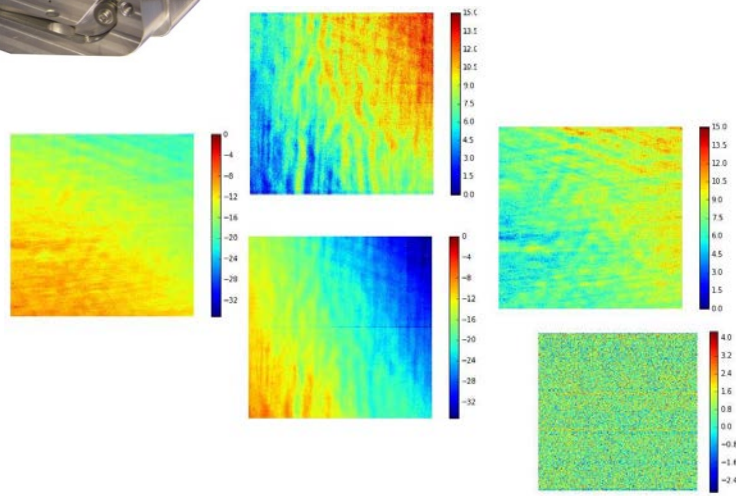


Calibration schemes:

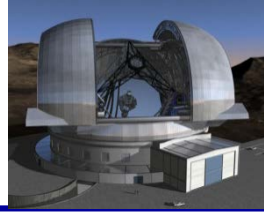
- Classical chopping/nodding
- Novel chopping strategies
- Drift scanning
- etc.



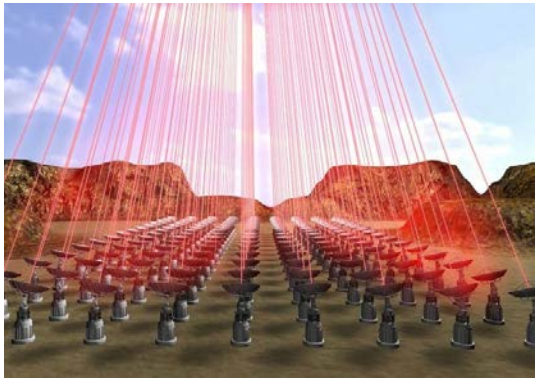


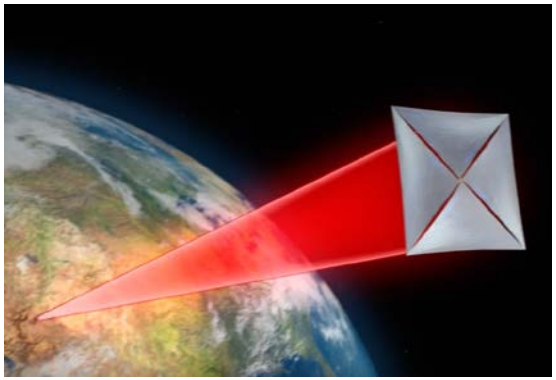


Breakthrough Initiative



- In July 2015, Milner launched the Breakthrough Initiatives:
  - Breakthrough Listen
  - Breakthrough Message
  - Breakthrough Starshot
  - Breakthrough Watch



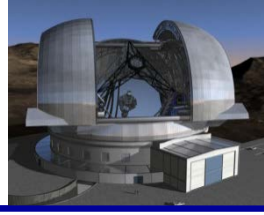


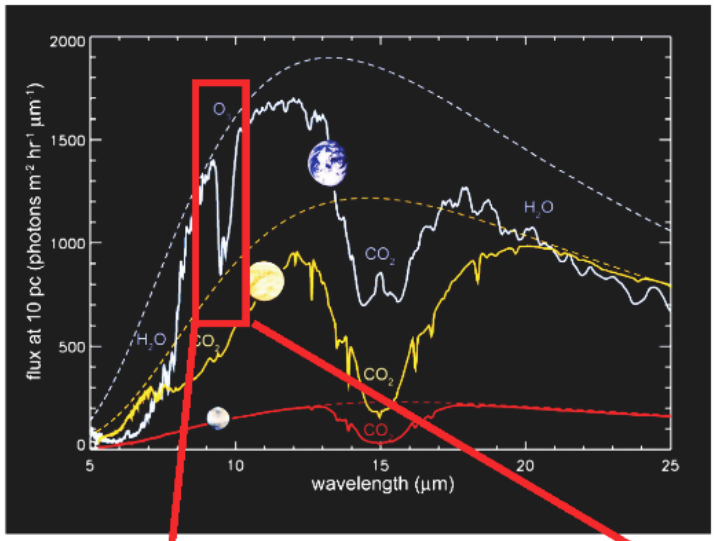
⟹ α Cen

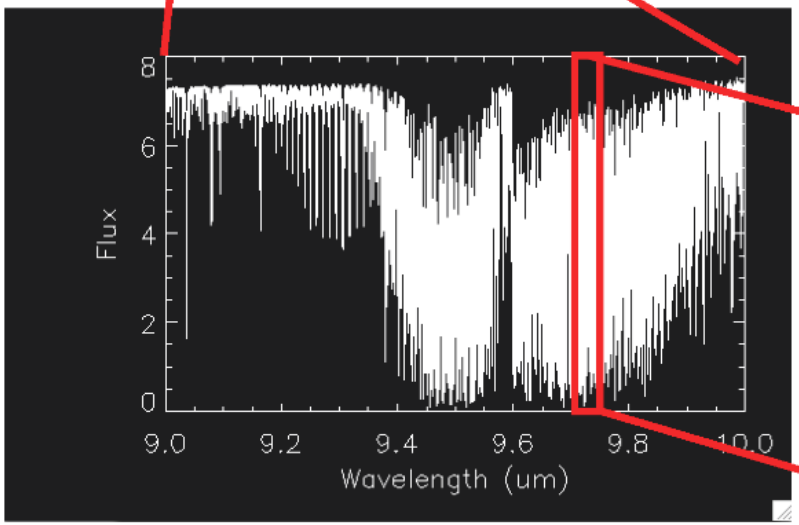
- https://breakthroughinitiatives.org/Instruments/4

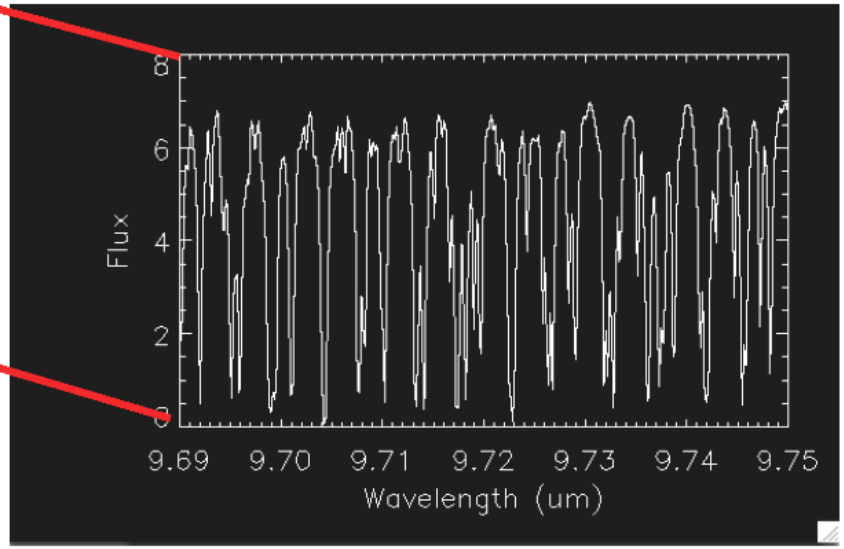
The developments for VISIR will also be beneficial for the future METIS instrument, to be mounted on the European Extremely Large Telescope (E-ELT), which is now under construction in Chile. The knowledge gained and proof-of-concept developed with the VISIR instrument will be directly transferable to the new telescope, due to see first light in 2024. The huge size of the E-ELT should allow METIS to detect and study exoplanets the size of Mars orbiting Alpha Centauri, if they exist, as well as other potentially habitable planets around other nearby stars.

Proxima Cen b @ 9.6µm



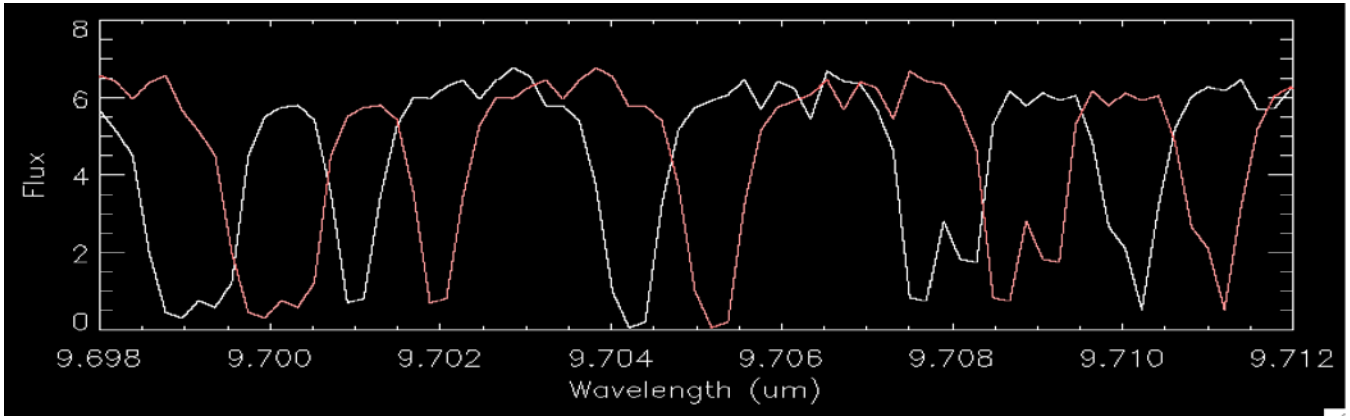




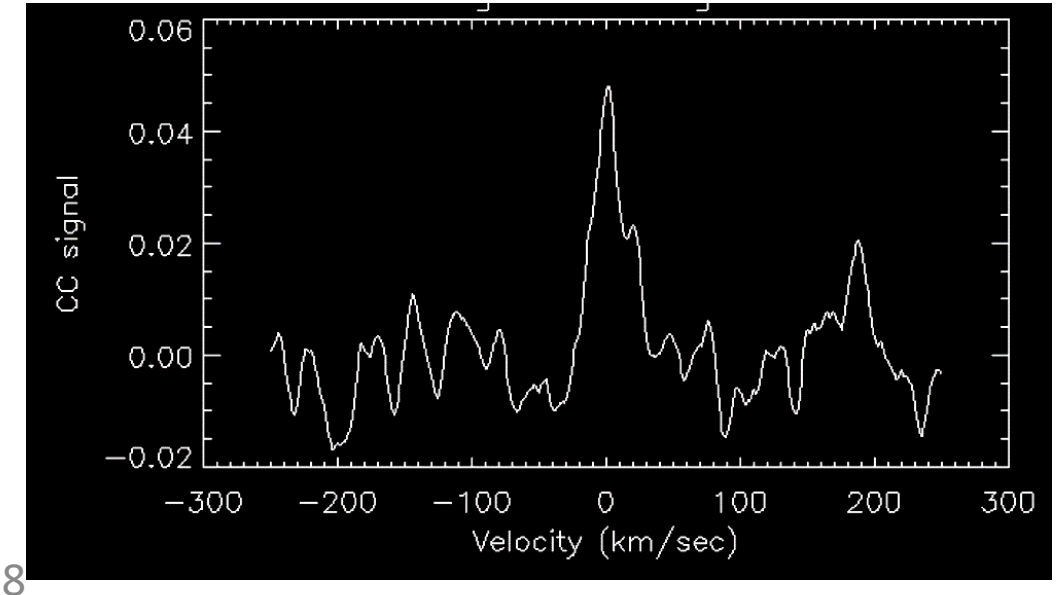


Upper left: the spectral features in the atmospheres of Earth, Venus and Mars. The ozone absorption at 9.6 µm is very pronounced in the Earth's spectrum. Lower left: Zoom into the spectral window around the ozone feature. Lower right: The complexity of the absorption bands demonstrates the need for high spectral resolution. The spectrum is shown at the METIS resolution of R ~ 100,000.

Ozone in Proxima Cen b



Although the Earth's atmosphere shows a similar ozone absorption spectrum than Proxima Cen b, the two can be distinguished by Doppler shift.



Ozone signal after three nights of METIS@E-ELT observations [TBC]. The cross-correlation with the ozone template spectrum was performed over a wavelength range of 9.4 – 9.8µm.

Surface of Exoplanet Proxima Cen b (artist conception)