Challenges for mid-IR Instruments on ELTs (PPT)

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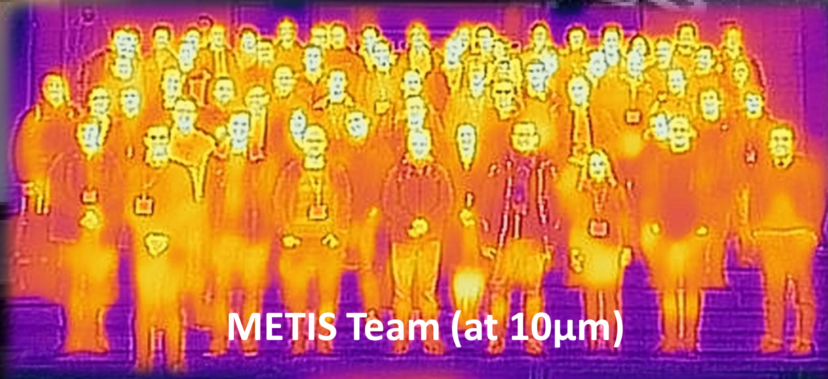
Challenges for mid-IR Instruments on ELTs

1. General MIR Challenges
2. Specific Challenges on ELTs
3. METIS (ELT) & MICHI (TMT)

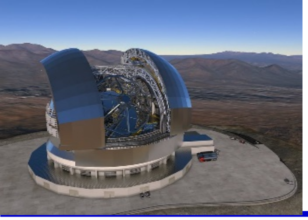
Bernhard Brandl (Leiden University / TU Delft)

IR2020: Ground-based thermal infrared astronomy – past, present and future

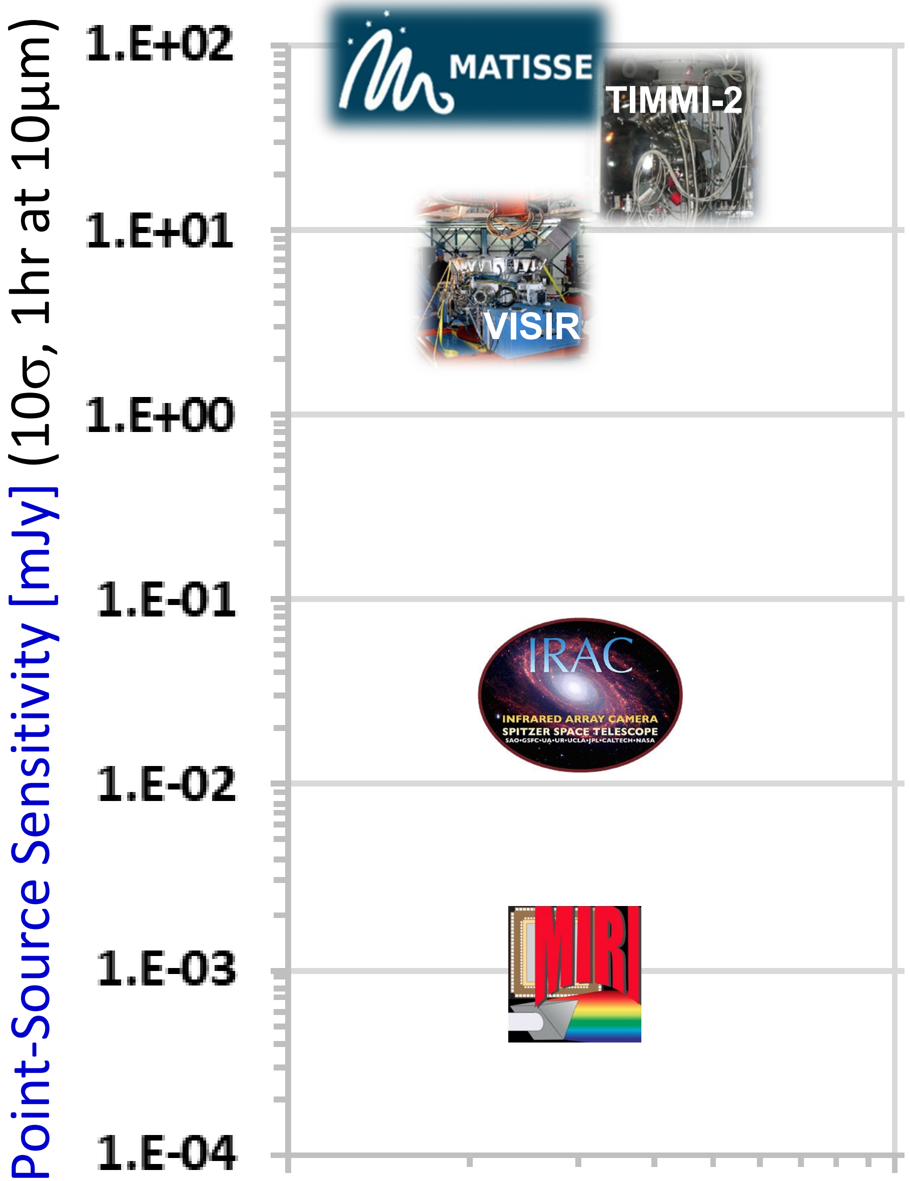

METIS Team (at 10μm)


Lorentz Center Workshop (Nov 2018)

1. General MIR Challenges
    - Sensitivity
    - Thermal Background
    - Angular Resolution
2. Specific Challenges on ELTs
3. METIS (ELT) & MICHI (TMT)



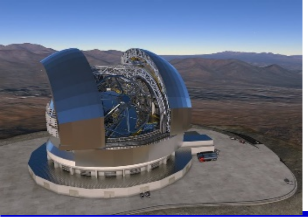
Main Challenge: achieving good Sensitivity



Ground-based

Space-based

see talk by Chris
Packham on Thursday



The thermal Background

Mid-infrared ELT Imager and Spectrograph

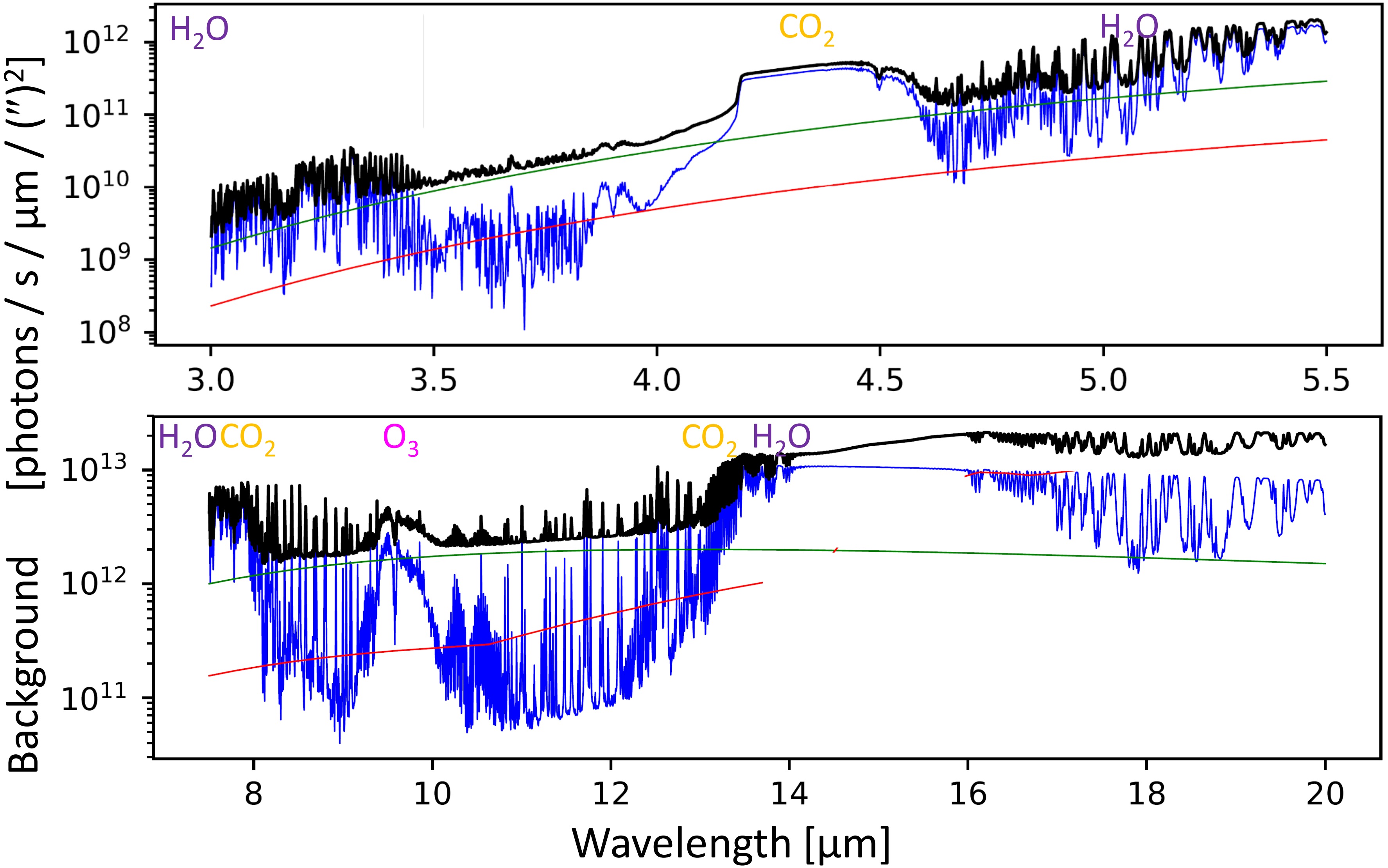
Contributions from:*

Sky

Telescope

Window

Total



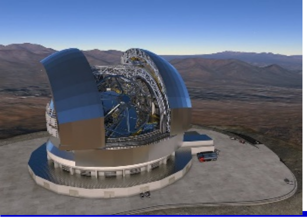
Main absorbing molecules:

H_2O

CO_2

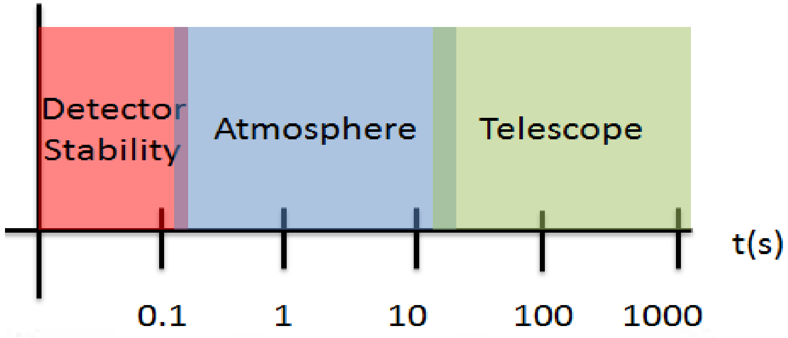
O_3

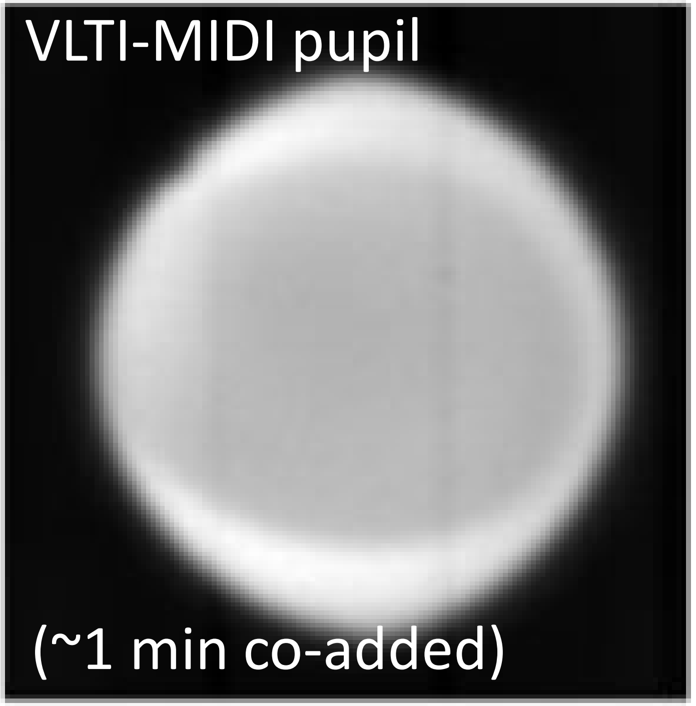
**Calculated for the ELT on Cerro Armazones*



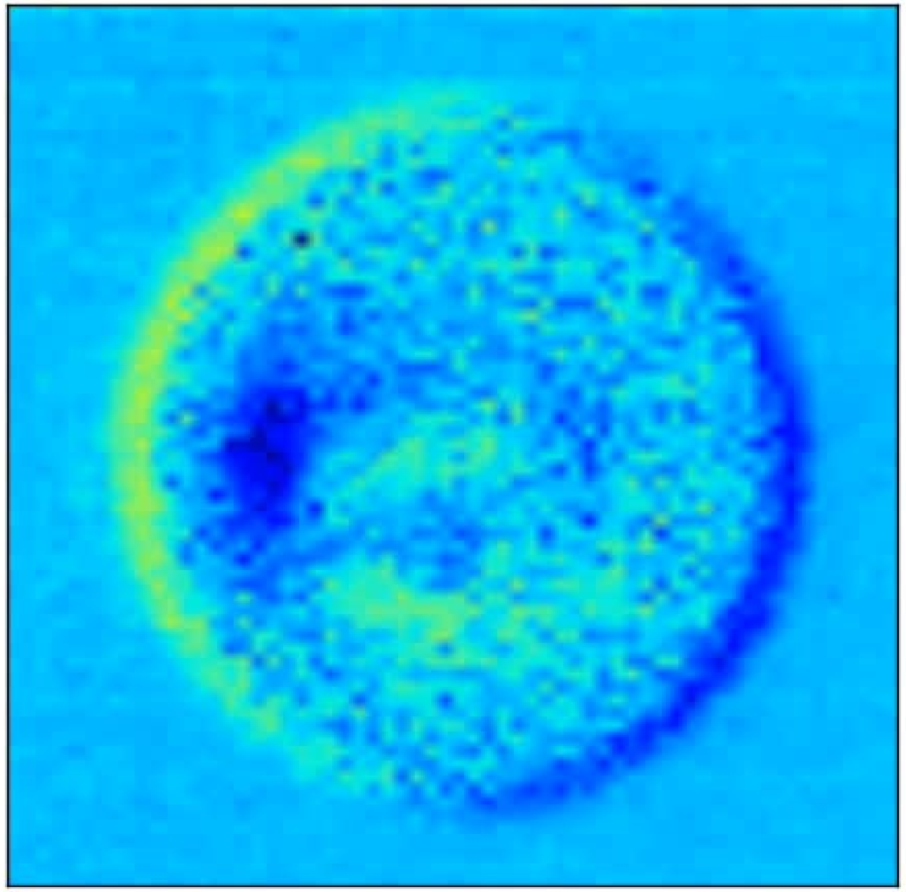
The *variable* thermal IR Background

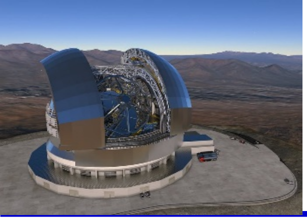
The thermal background is non-uniform (*f*{Telescope}) and time-variable (*f*{Air, Telescope})





Time series of MIDI chop-difference acquisition frames





Zoom Poll

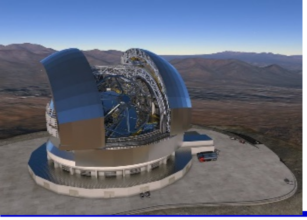
METIS
Mid-infrared ELT Imager and Spectrograph

Consider a camera with a pixel scale which is Nyquist-sampling the diffraction-limited PSF. We are imaging an object with uniform extended emission. How does the achievable signal-to-noise (S/N) per pixel depend on the telescope diameter D?

- $S/N \propto D^4$
- $S/N \propto D^2$
- $S/N \propto D$
- $S/N \propto \text{const.}$
- $S/N \propto D^{-1}$

1. Consider a camera with a pixel scale which is Nyquist-sampling the diffraction-limited PSF. We are imaging an object with uniform extended emission. How does the achievable signal-to-noise (S/N) per pixel depend on the telescope diameter D?

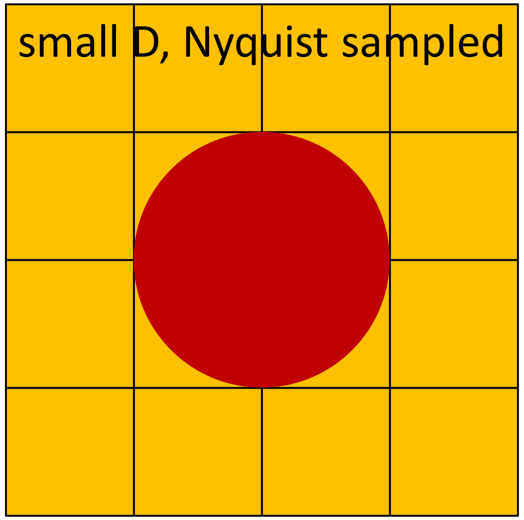
D^4	(20) 20%
D^2	(46) 46%
D	(16) 16%
const.	(13) 13%
D^(-1)	(4) 4%



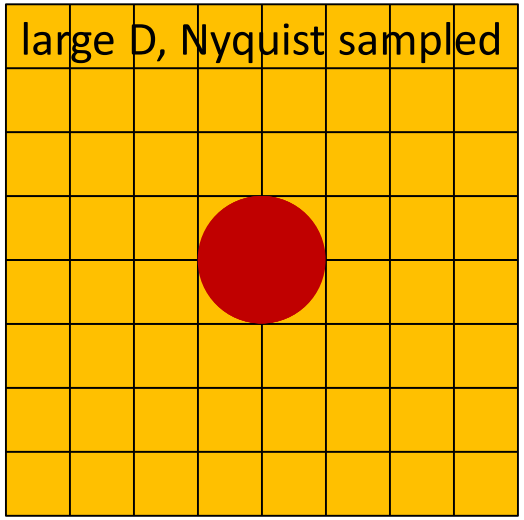
"Extended Source-Sensitivities"

Mid-infrared ELT Imager and Spectrograph

Point source



Background Star



Telescope aperture:

$$\left.\begin{array}{l} S \propto D^2 \\ B \propto D^2 \rightarrow N \propto D \end{array}\right\} S/N \propto D$$

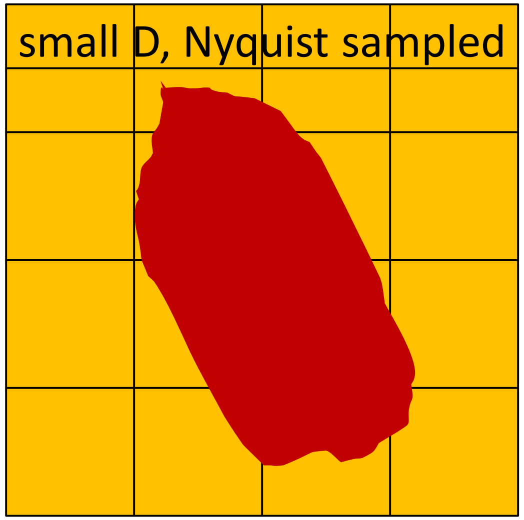
Pixel FoV:

$$\left.\begin{array}{l} S \propto \text{const} \\ B \propto D^{-2} \rightarrow N \propto D^{-1} \end{array}\right\} S/N \propto D$$

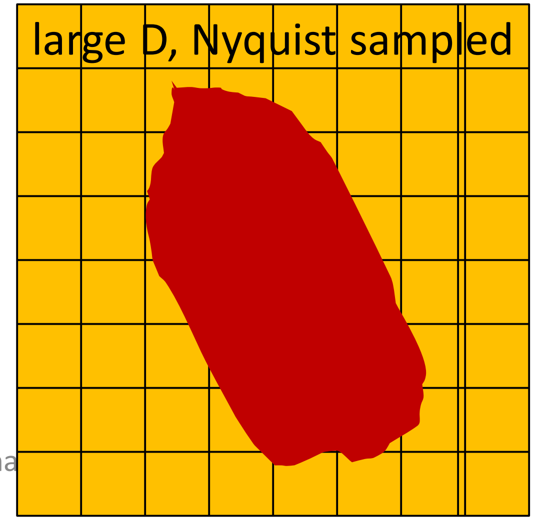
In total:

$S/N \propto D^2 \rightarrow t_{int} \propto D^{-4}$

Extended source



Background Galaxy



Telescope aperture:

$$\left.\begin{array}{l} S \propto D^2 \\ B \propto D^2 \rightarrow N \propto D \end{array}\right\} S/N \propto D$$

Pixel FoV:

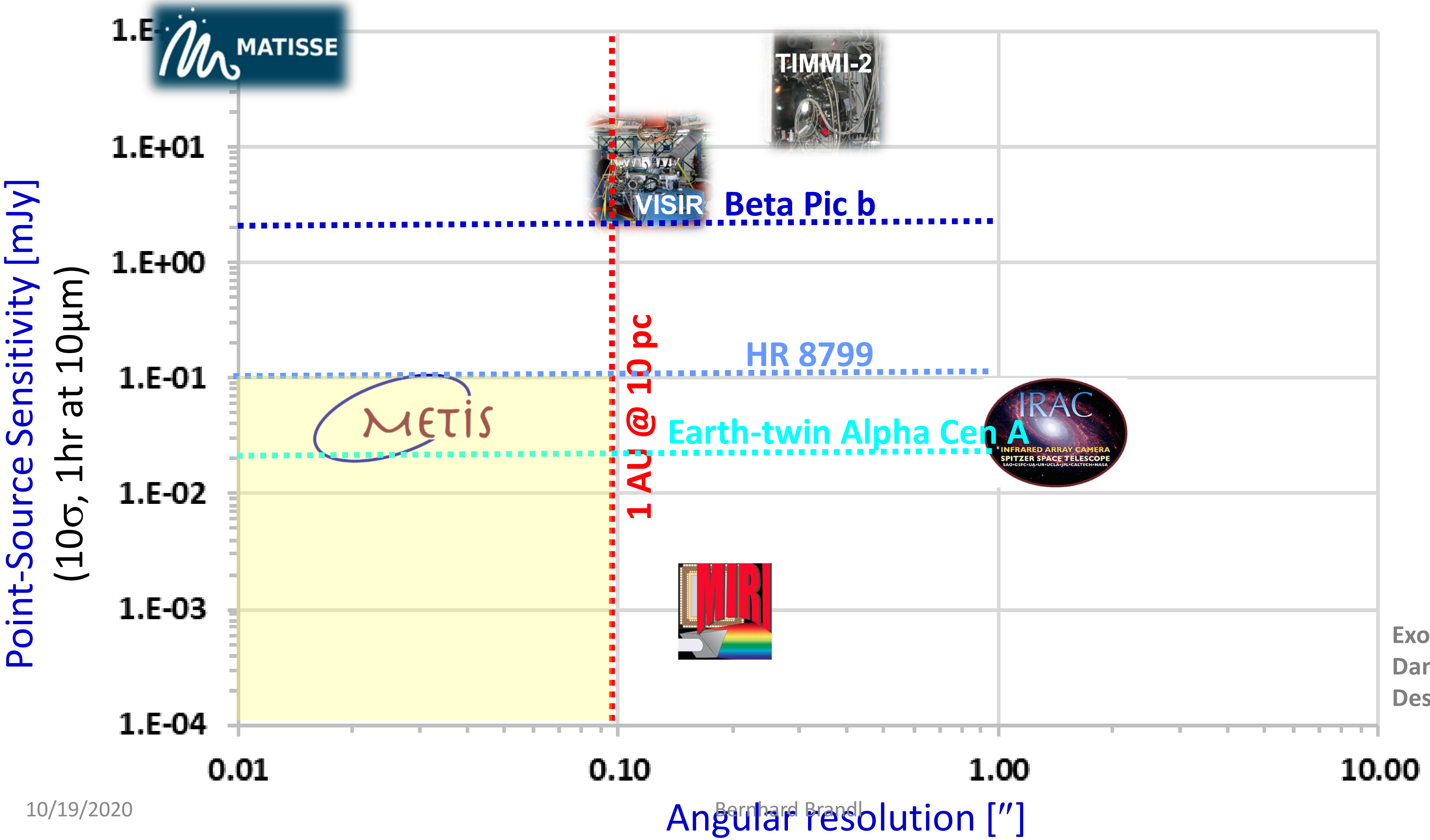
$$\left.\begin{array}{l} S \propto D^{-2} \\ B \propto D^{-2} \rightarrow N \propto D^{-1} \end{array}\right\} S/N \propto D^{-1}$$

In total:

$S/N \propto \text{const} \rightarrow t_{int} \propto \text{const}$

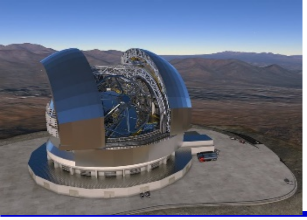
Resampling would regain sensitivity

Why Ground *can* make unique Contributions



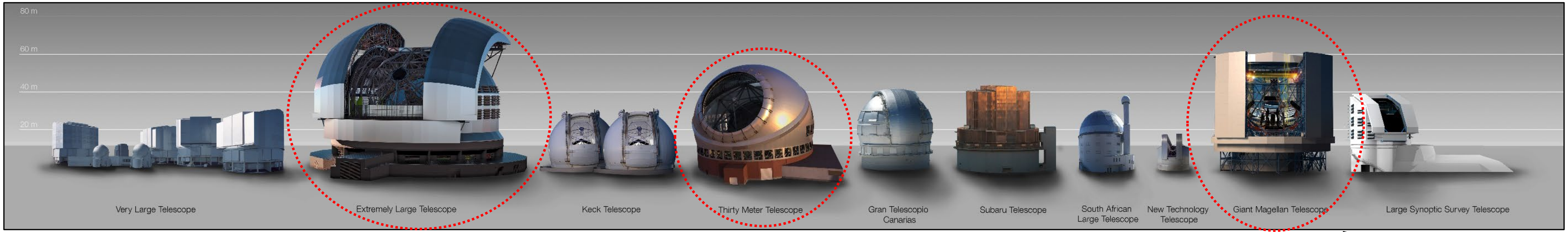
Exoplanet fluxes from Danielski et al. (2018) and Des Marais et al. (2001)

1. General MIR Challenges
2. Specific Challenges on ELTs
   - General considerations
   - Chopping/Nodding
   - Need for Adaptive Optics
3. METIS (ELT) & MICHI (TMT)



General Considerations for ELT Instruments

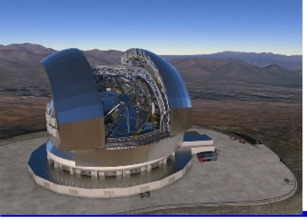
METIS
Mid-infrared ELT Imager and Spectrograph



ELT time: 500 € / min

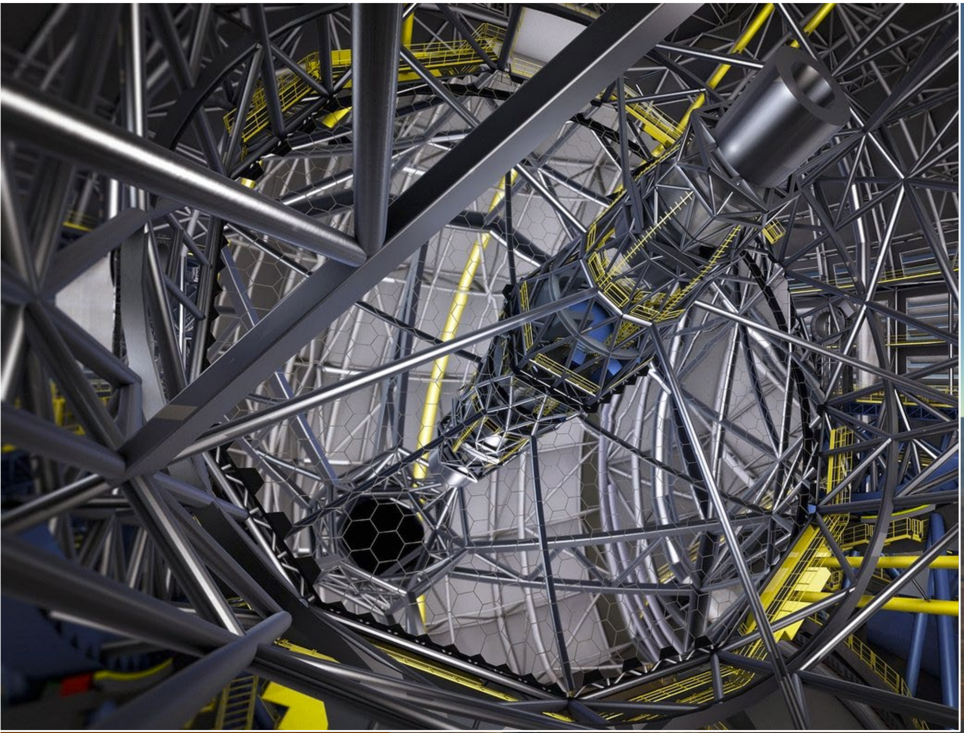
- Exploit the unique ELT discovery space (⇔ JWST, LSST, ALMA, …)
- "There will be only a few extremely large telescopes":
  - Each instrument must serve a large fraction of the community (no "PI-instruments")
  - Low complexity to ensure low risk, high efficiency, and reliable operation
  - High complexity because there will be only a few instruments on each ELT, and the resources in the community are limited ← high threshold for each ELT instrument

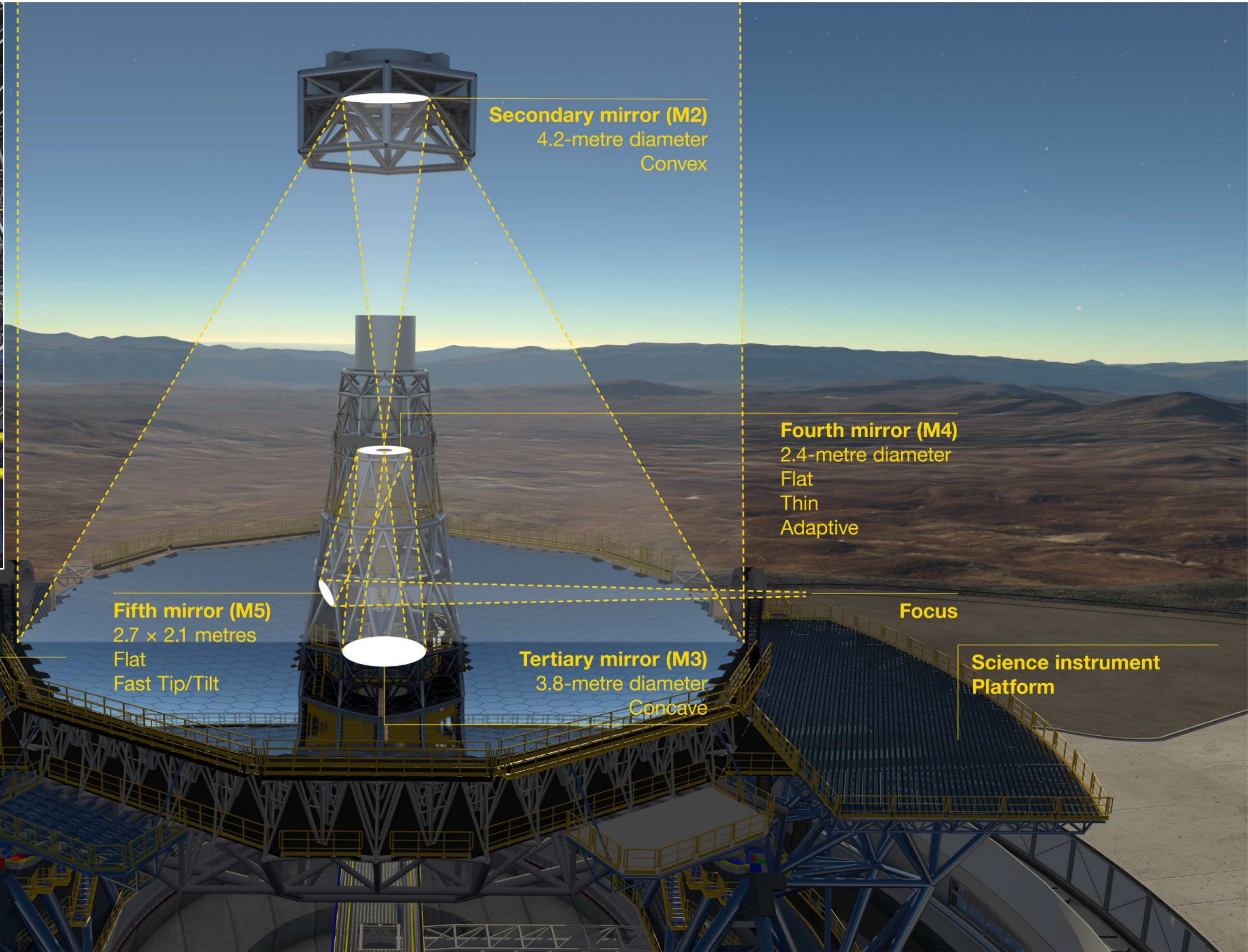
- Science operations aim at "space standards" (queue scheduling, pipeline processing, data archive, …)

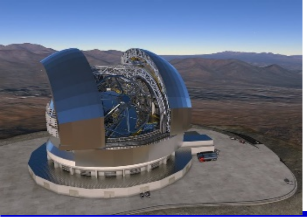


The (warm and complex) ELT Optics

Mid-infrared
ELT Imager and
Spectrograph

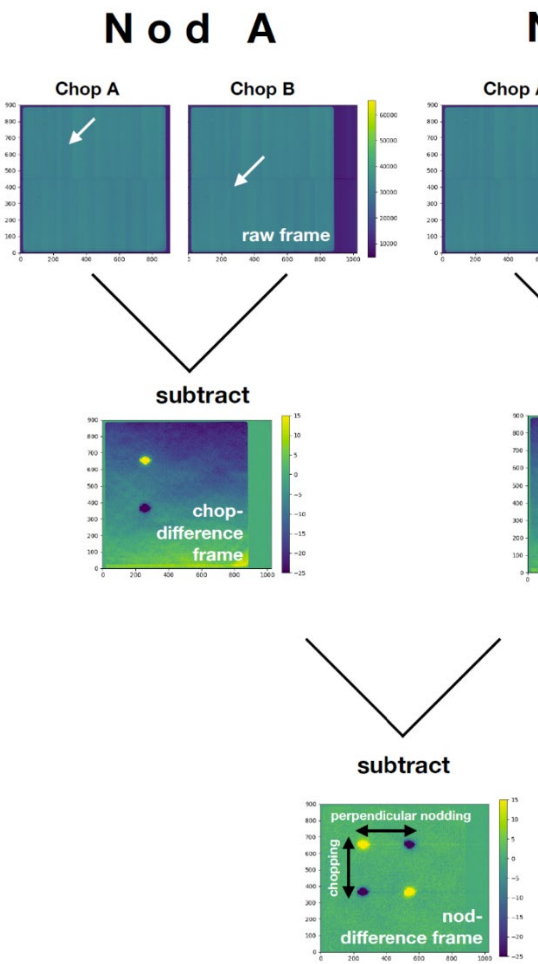






We have to re-invent chopping/nodding

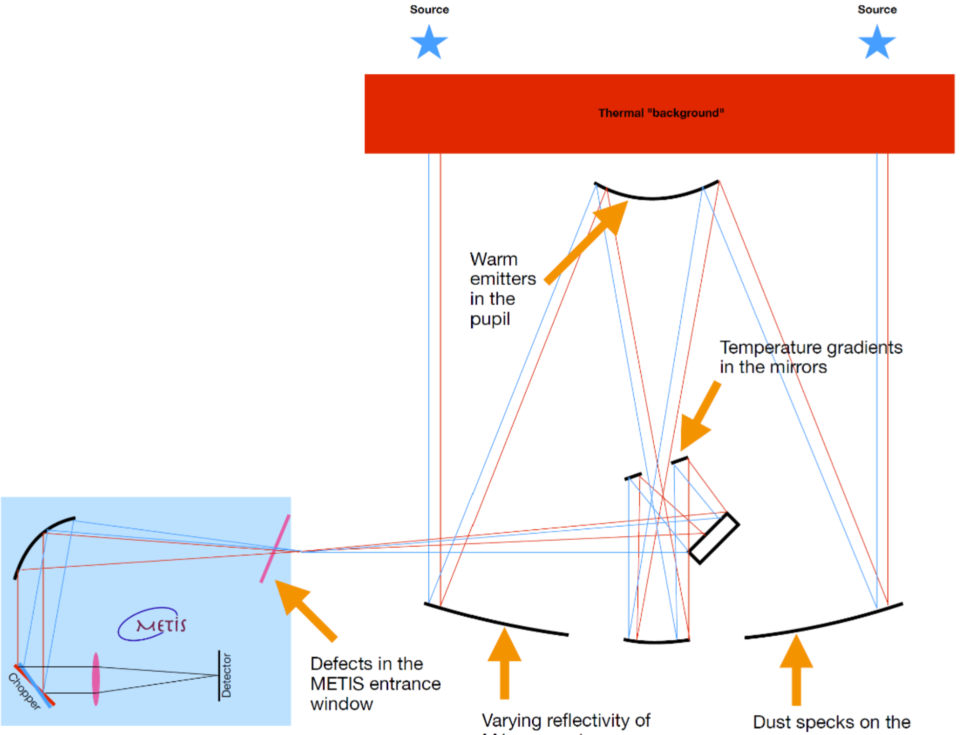
Classical chopping with M2:



Option #1: chopping mirror inside instrument

+ flexibility, accuracy

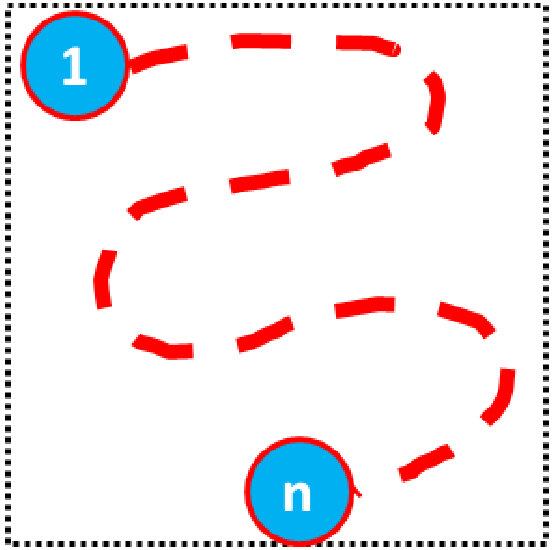
– beam wander upstream

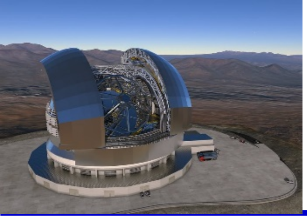


Slightly simplified optical sketch

Option #2?:

Alternatives, like "drift scanning" [TBC]



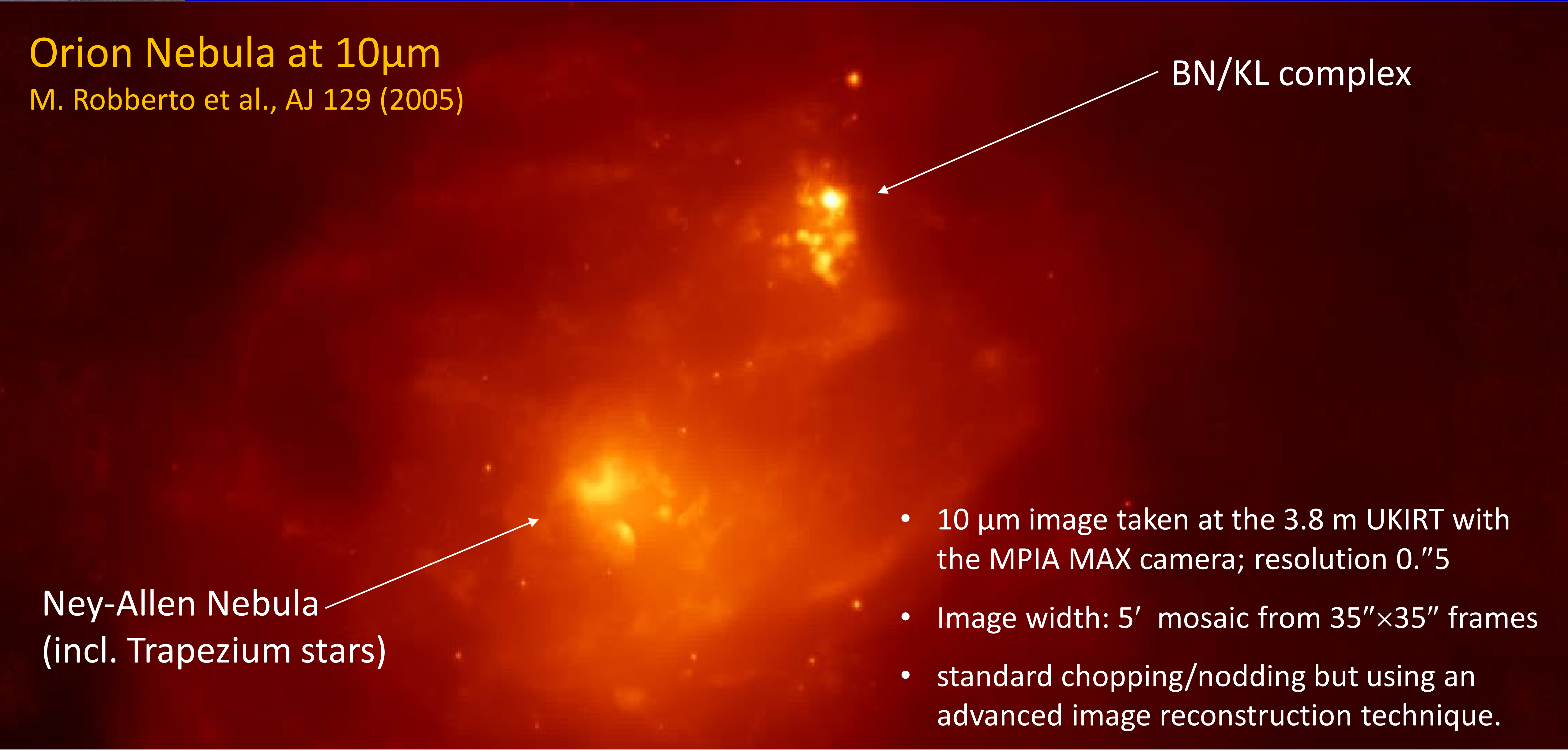


…and develop the Software to optimize it!

METIS
Mid-infrared ELT Imager and Spectrograph

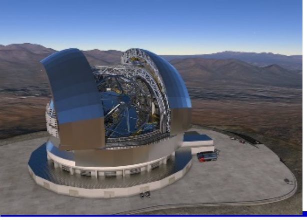
Orion Nebula at 10μm

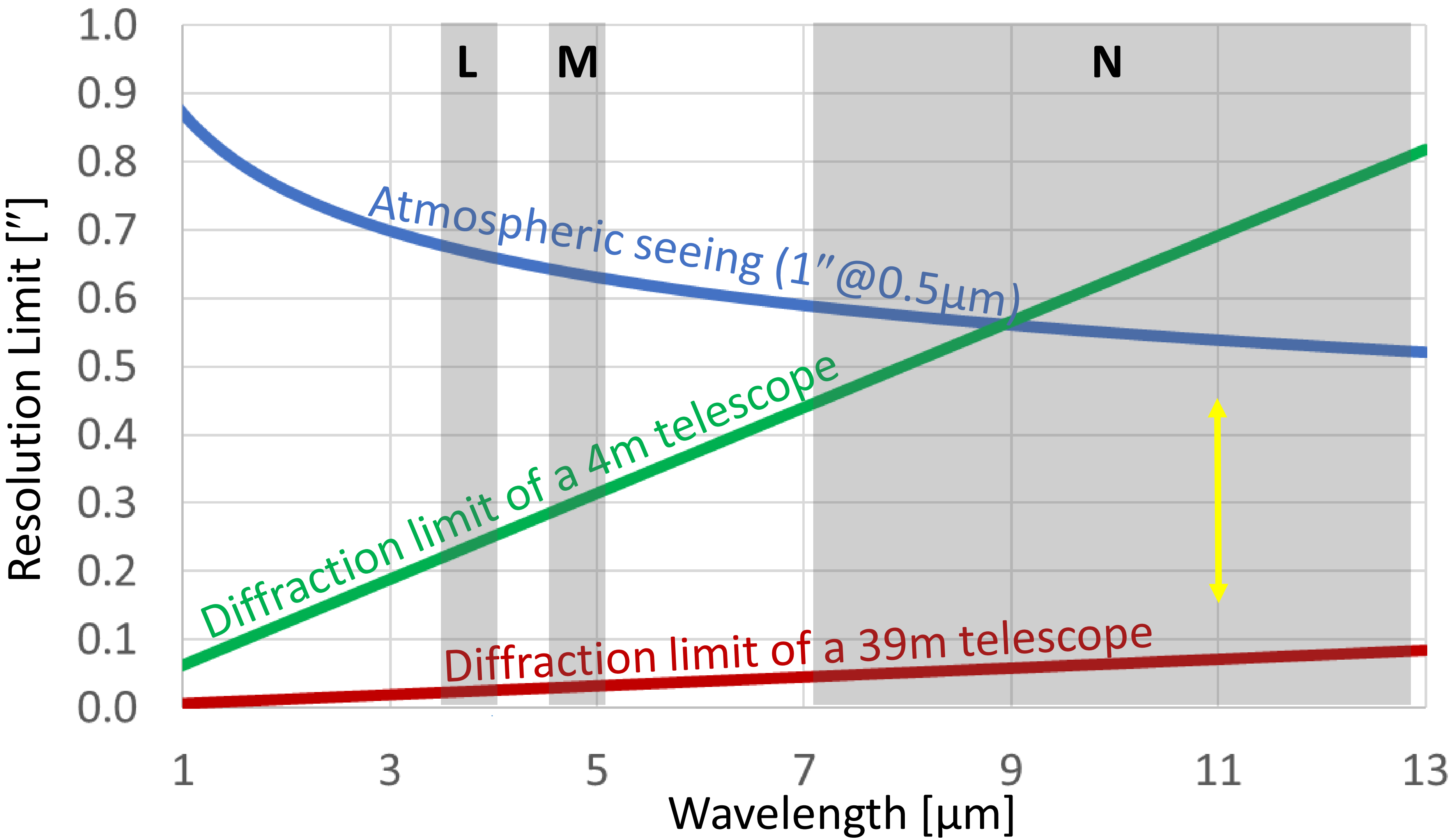
M. Robberto et al., AJ 129 (2005)

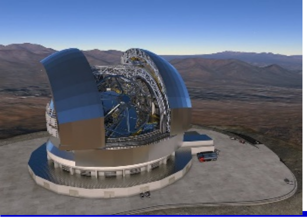


- 10 μm image taken at the 3.8 m UKIRT with the MPIA MAX camera; resolution 0.″5
- Image width: 5′ mosaic from 35″×35″ frames
- standard chopping/nodding but using an advanced image reconstruction technique.

The Need for Adaptive Optics







How to implement AO on an ELT

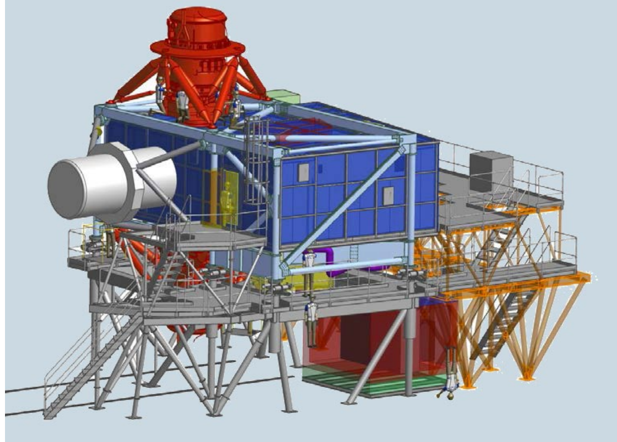
Mid-infrared ELT Imager and Spectrograph

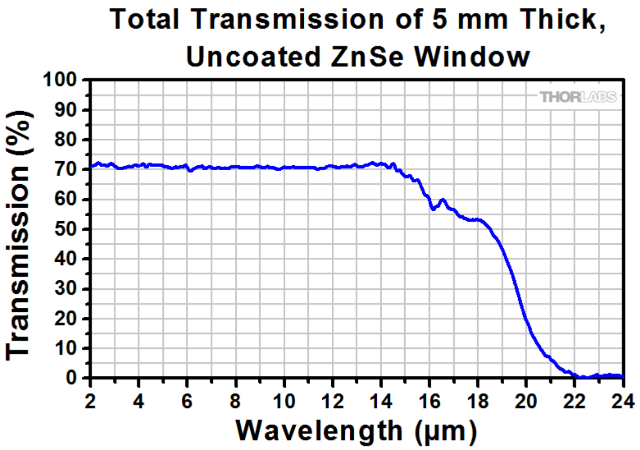
	Telescope	Instrument	AO type	Deformable Mirror	Beam-splitter	Wavefront sensor	Telescope Mirrors	Laser guide stars
A	Classical	most	TBD	AO bench	warm	warm	2 - 3	TBD
B	TMT-NFIRAOS	IRIS,MODHIS	MCAO	AO bench	warm	-30 deg C	3	Yes
C	TMT-MIRAO	MICHI	LTAO	AO bench	cold	cold	3	Yes
D	ELT	METIS	SCAO	Telescope	cold	cold	5 - 6	No

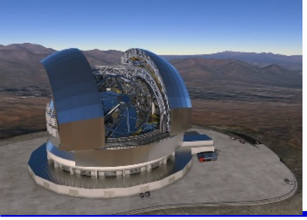
Crane et al. SPIE 10703 (2018)
Chun et al. SPIE 6272 (2006)
Bertram et al. SPIE 10703 (2018)

Goal: avoid warm dichroic

Problem: passing $\lambda = 0.5\ \mu m - 28\ \mu m$ through window



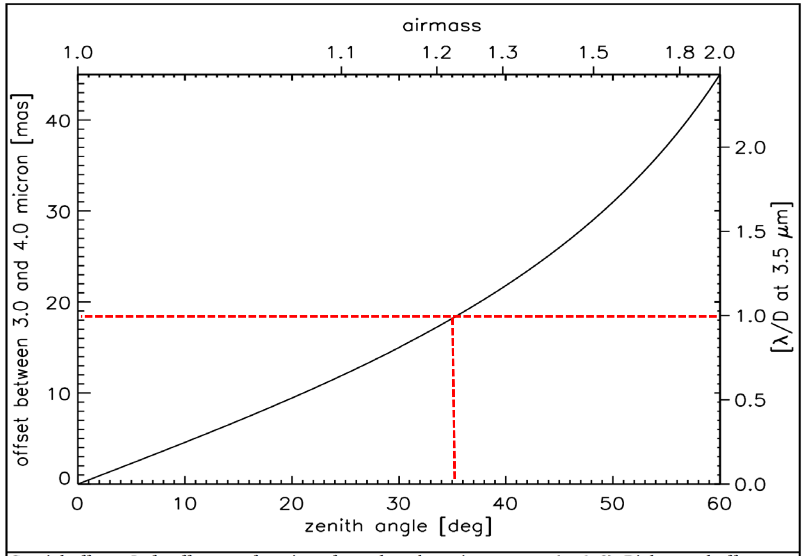




Other atmospheric & optical Effects

Mid-infrared ELT Imager and Spectrograph

Atmospheric dispersion

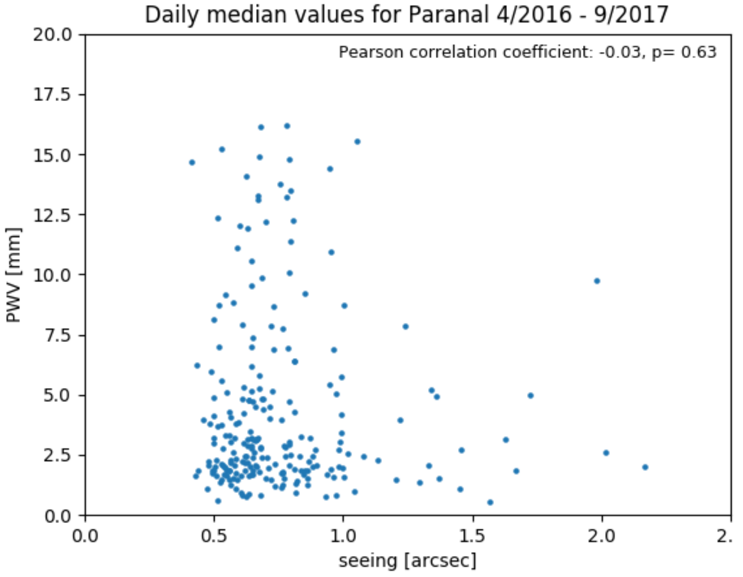


Spatial offsets. *Left*: offset as a function of wavelength at airmass=2.0 (z=60°). Right: total offset between 3.0 and 4.0 μm, as a function of zenith angle.

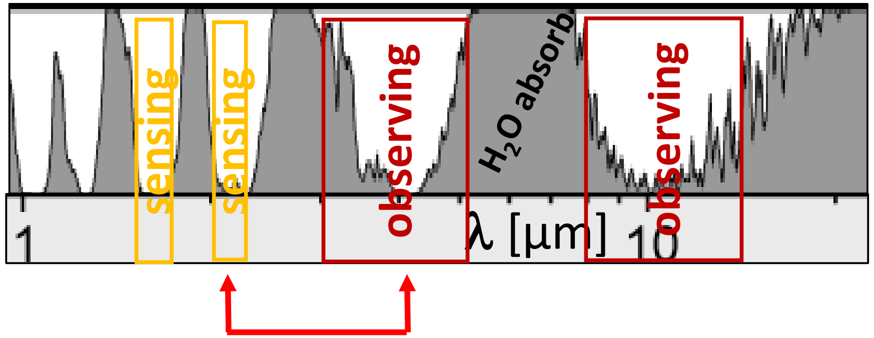
PWV ⇔ seeing

Good news: no correlation

→ scheduling



H_2O vapor seeing

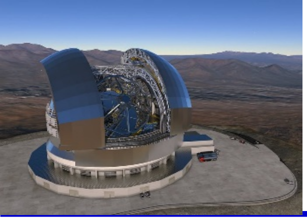


- small effect – not visible on 8m telescopes
- Potential impact on high contrast imaging/ coronagraphy

Quality of the cold optics (usually Al)

- Active pupil alignment (ELT/METIS: 5 pupils)
- mirror surface figure ≤ 15 nm
- mirror surface roughness ≤ 2 nm

1. General MIR Challenges
2. Specific Challenges on ELTs
3. METIS (ELT) & MICHI (TMT)
    - Overview
    - Design Considerations
    - Optics & Coronagraphy
    - Science Examples

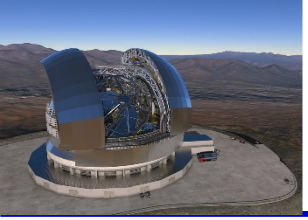


Project Overview

METIS
Mid-infrared ELT Imager and Spectrograph

- The Mid-IR ELT Imager and Spectrograph is one of three 1st-generation ELT science instruments on ESO's ELT
- Consortium of 12 partner institutions + ESO
- Total ~650 FTEs
- Prelim. Design Review (PDR) in 2019
- 1st-light in 2027

NOVA
cea
LIÈGE université
ETH zürich
Universität zu Köln
Max-Planck-Institut für Astronomie Heidelberg
KU LEUVEN
UNIVERSITY OF MICHIGAN
ASIAA
centra
center for astrophysics and gravitation
UKRI
Science and Technology Facilities Council
UK Astronomy Technology Centre
ESO



Instrument Overview

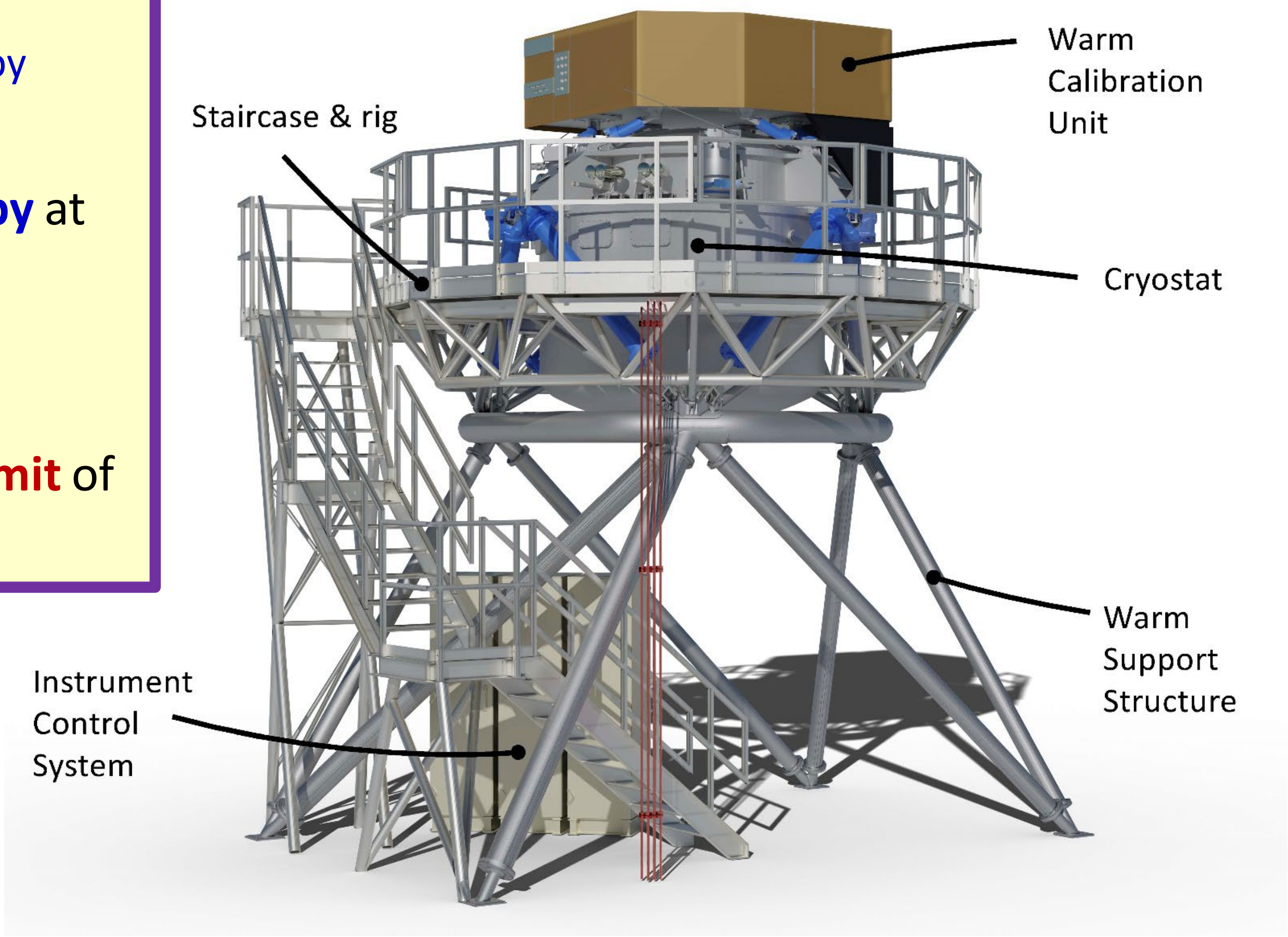
METIS
Mid-infrared ELT Imager and Spectrograph

- **Imaging** over a FoV of 10.5″ × 10.5″ (3 – 5 μm) and 13.5″ × 13.5″ (8 – 13 μm), incl.:
  - low resolution (*R* ~ few 100s) longslit spectroscopy
  - coronagraphy for high contrast imaging
- **High resolution** (*R* ~ 100,000) **IFU spectroscopy** at 3 – 5 μm, over a FoV of ~ 0.93″ × 0.58″, incl.
  - a mode with extended $\Delta\lambda_{instant}$ ~ 300 nm
  - coronagraphy for high contrast IFU spectroscopy
- All observing modes work at the **diffraction limit** of the 39m ELT with a single conjugate AO system.

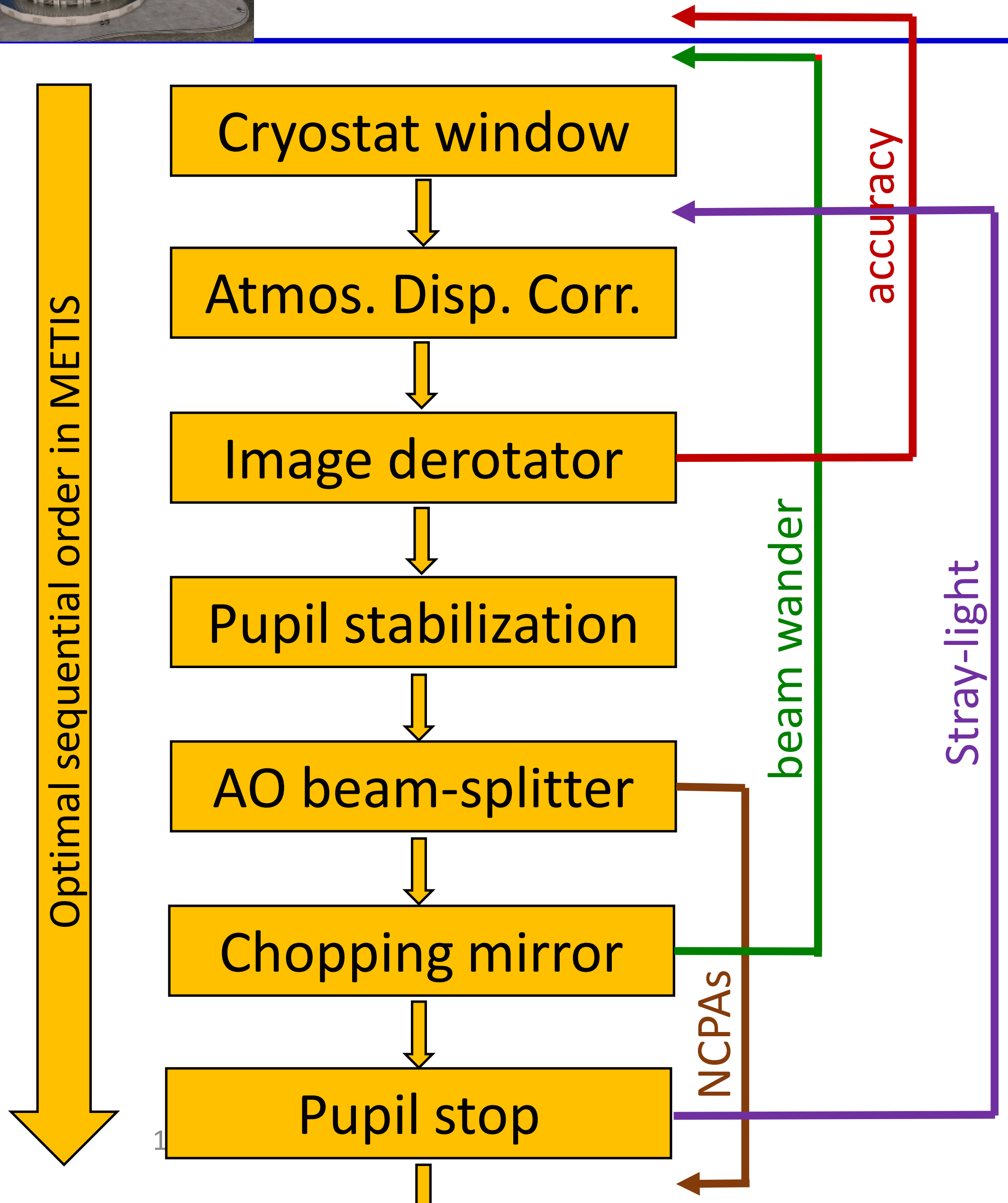
Brandl et al. SPIE 10702 (2018)

PS sensitivity (10-σ, 1hr)

λ	F	mag
L	1 μJy	21.2
M	8 μJy	18.3
N	50 μJy	14.8



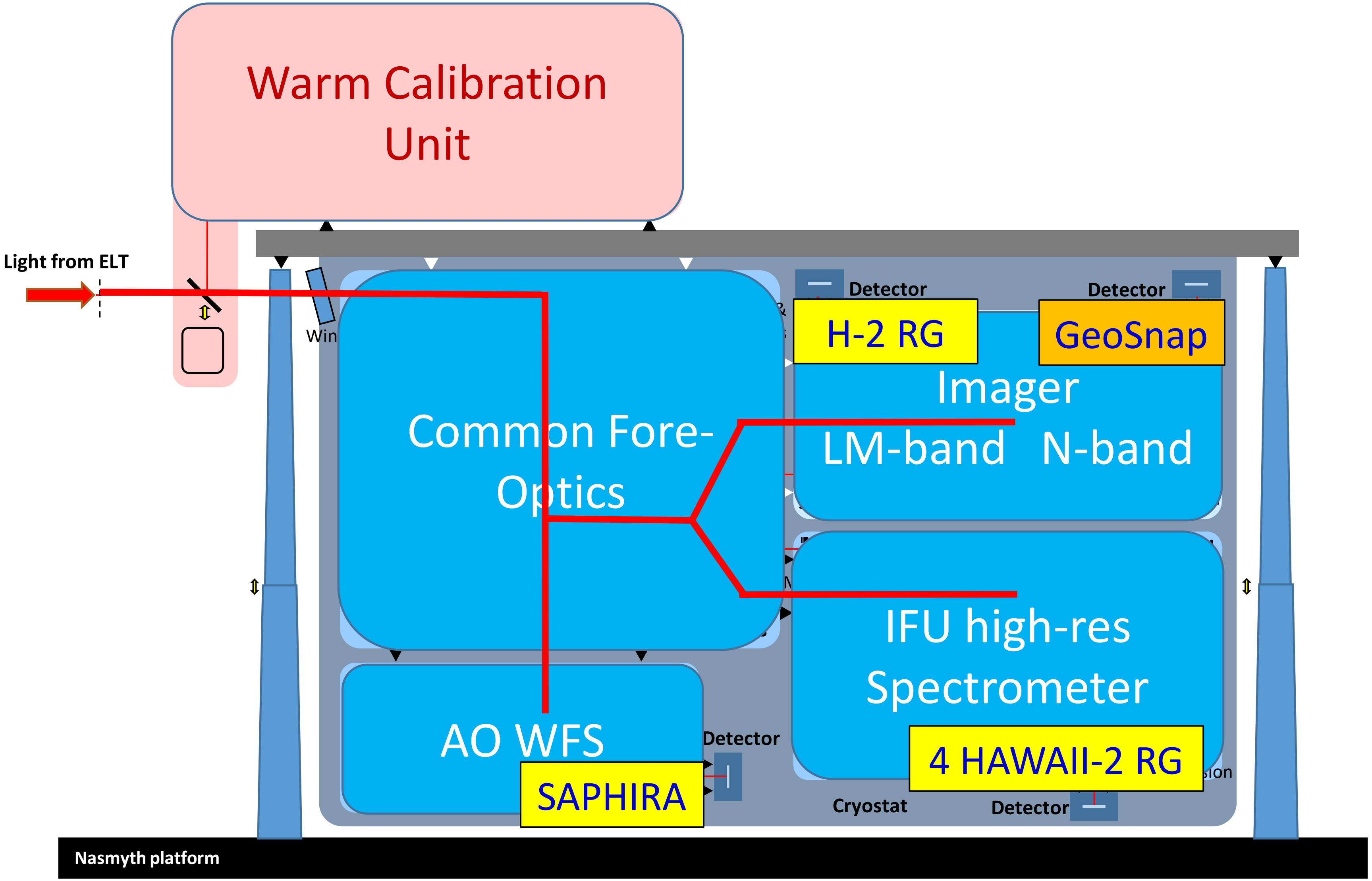
Design Considerations



Conceptual considerations:

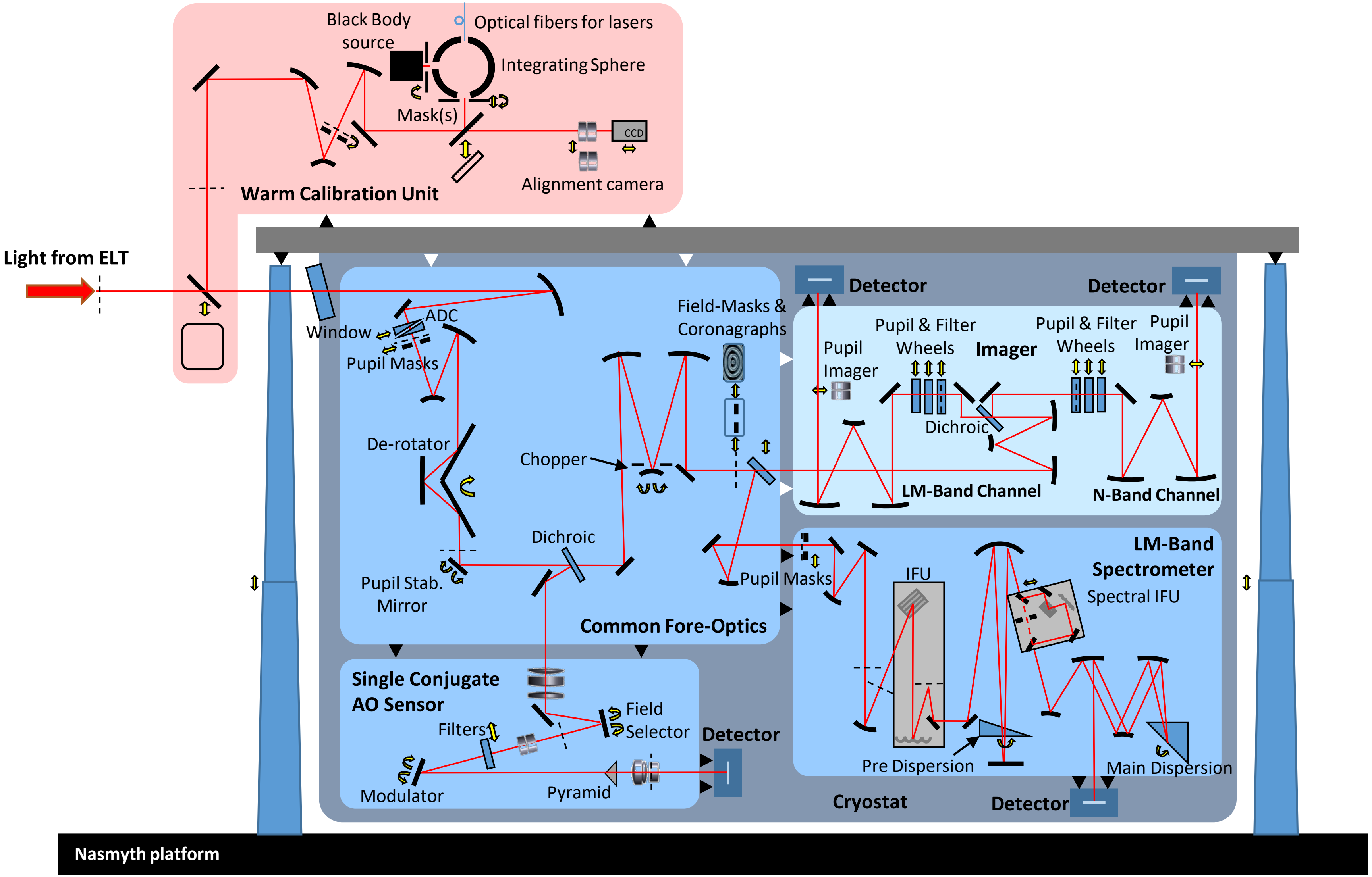
- Spectrograph concept (IFU ⇔ cross-dispersed)
- Type of AO wavefront sensor (pyramid ⇔ Shack-Hartmann)
- Imaging: required field of view (incl. chopping)

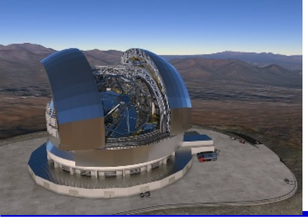
Optical Concept



See talks by Dani Atkinson and Michael Meyer on Friday afternoon

Optical Concept

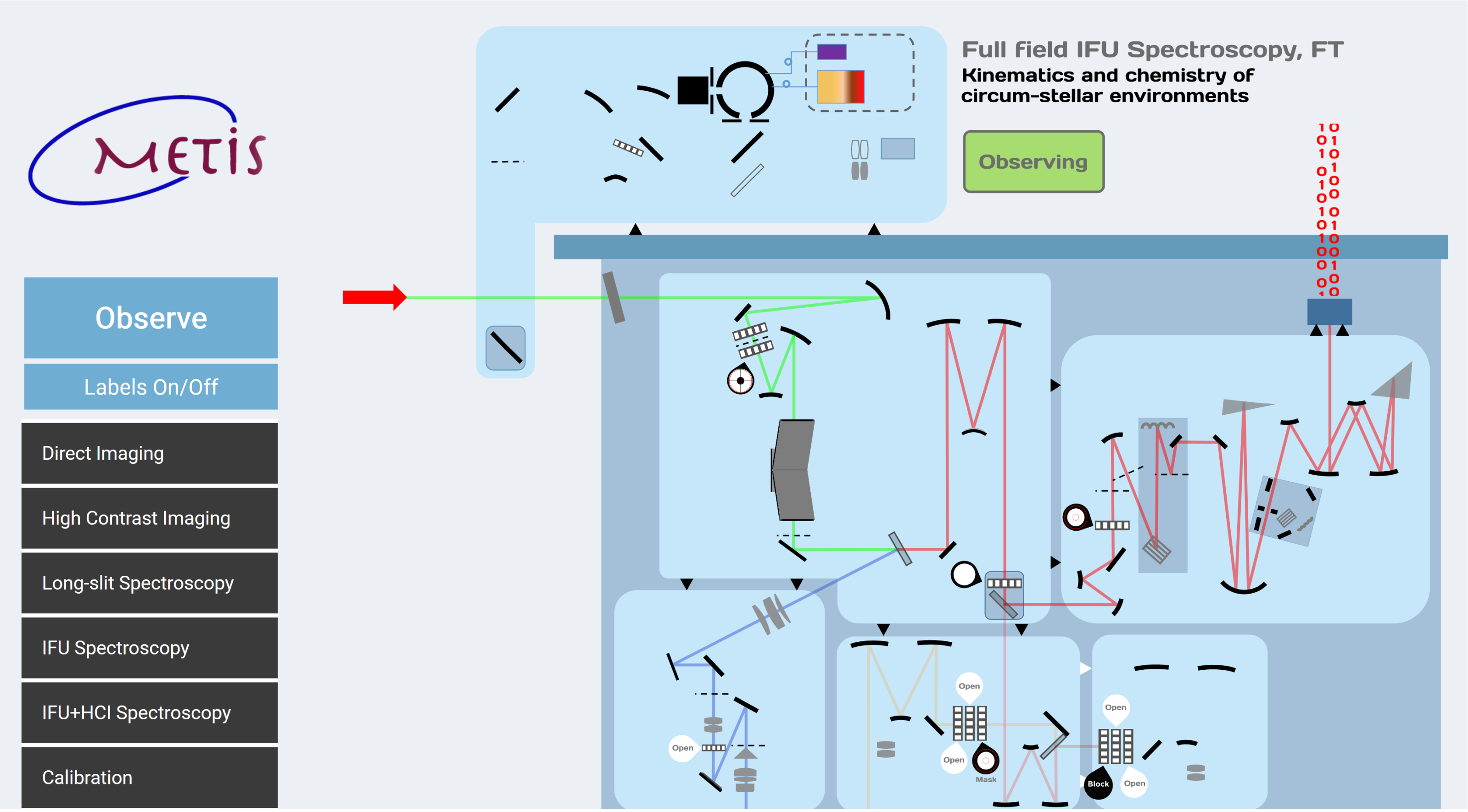


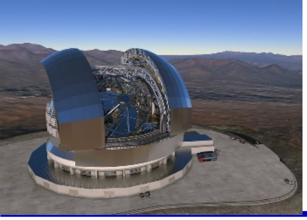


METIS Website

Please visit the METIS website https://metis.strw.leidenuniv.nl/

Lots of info … and a very instructive App:





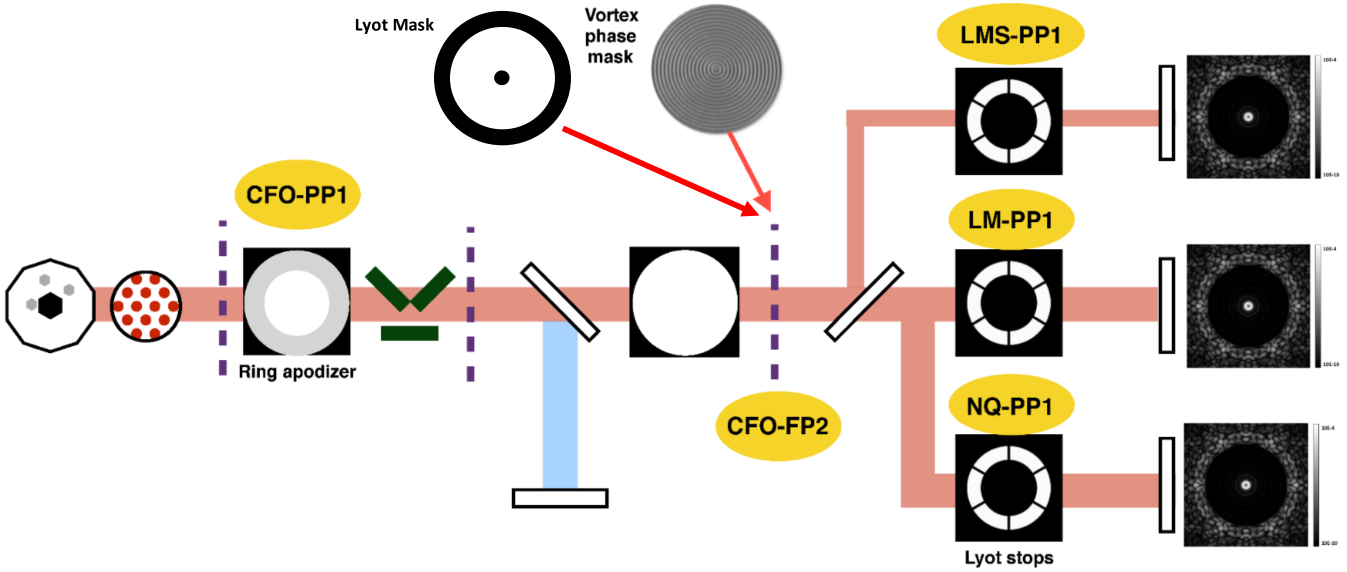
Coronagraph Concepts

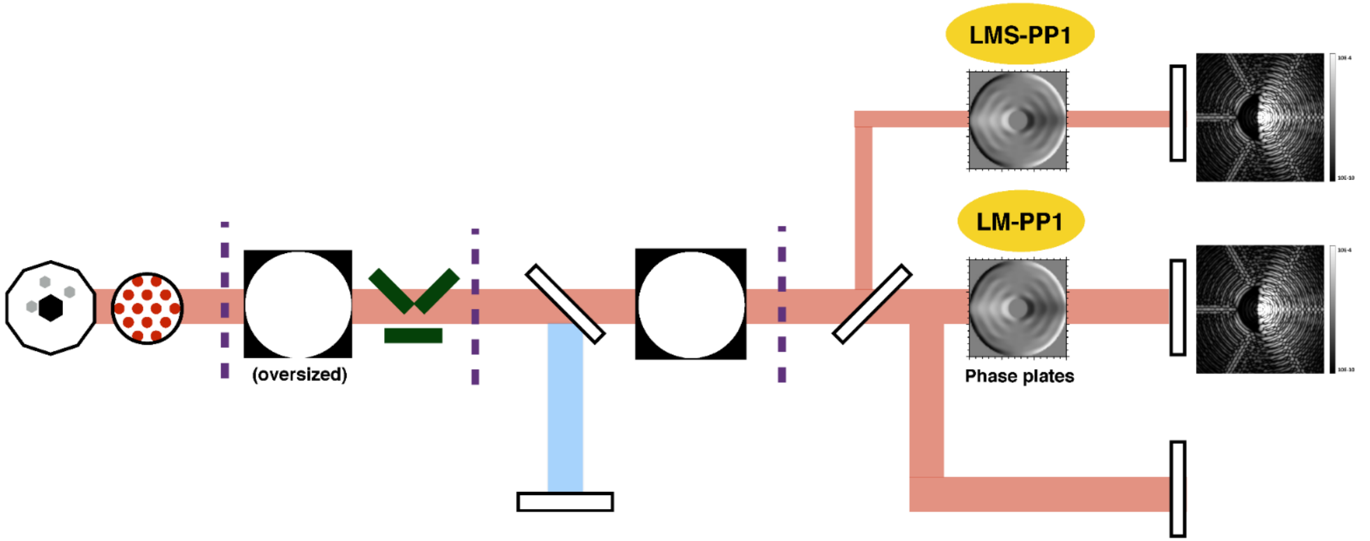
Mid-infrared ELT Imager and Spectrograph

Three different solutions:

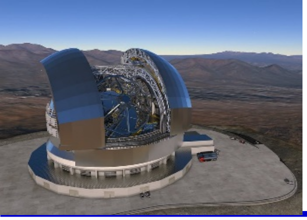
1. Vortex phase mask (focal plane) for <u>highest contrast</u>
2. Classical (or Apodized) Lyot Mask for <u>resolved stars</u>
3. Apodized phase plate (pupil plane) for <u>best stability</u>

…depending on the actual boundary conditions on the ELT





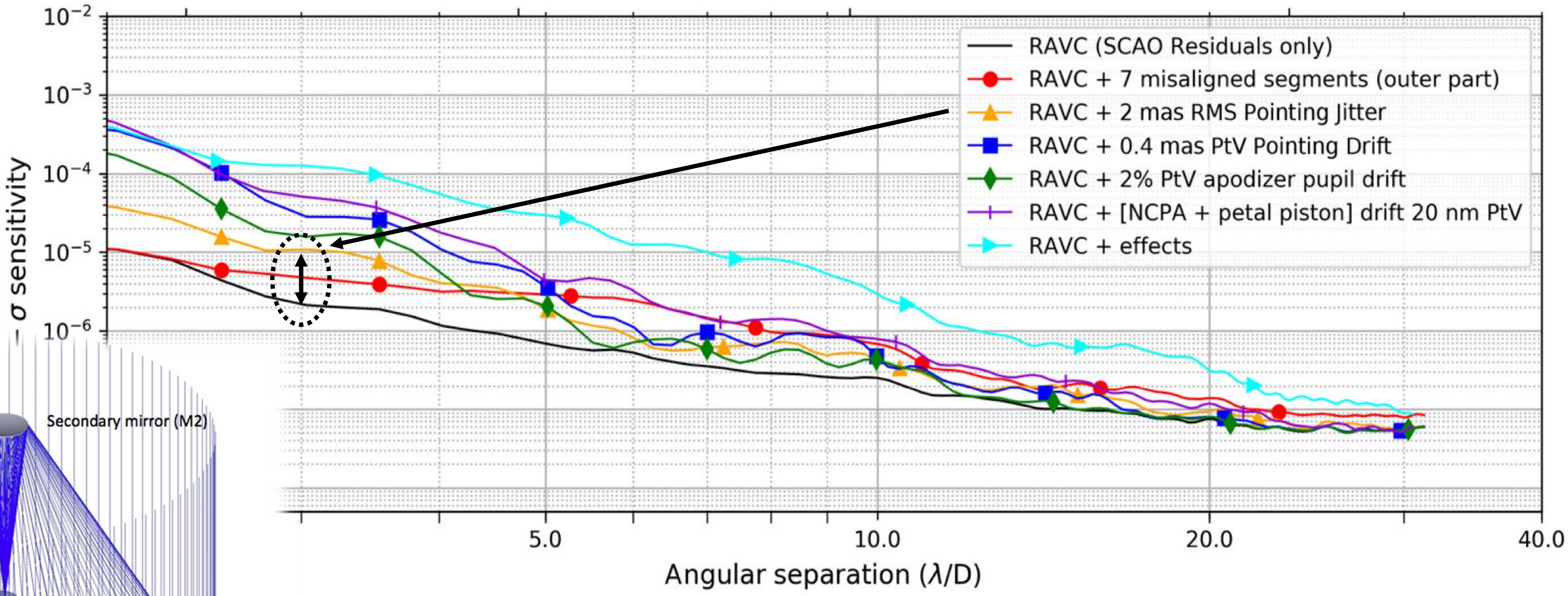
Kenworthy et al. SPIE 10702 (2018)

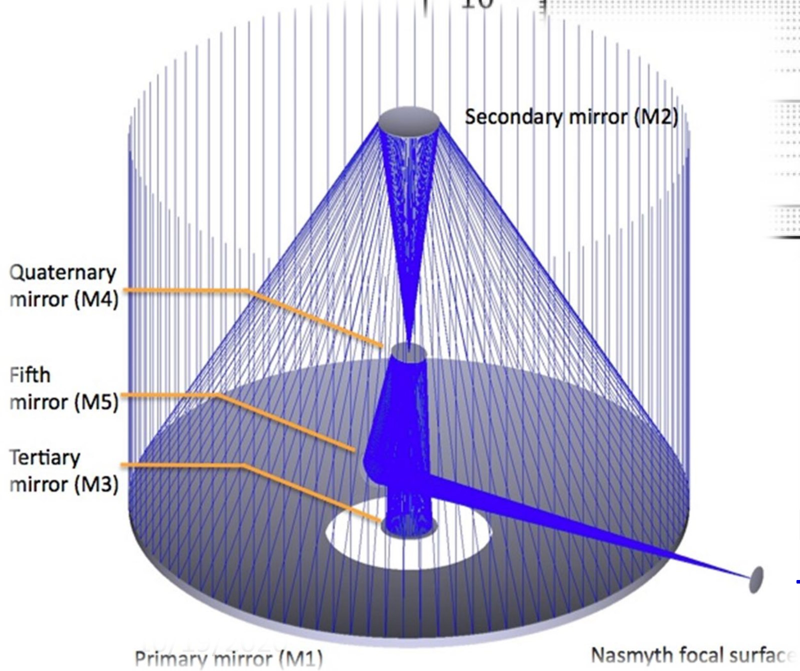


Coronagraphic Performance

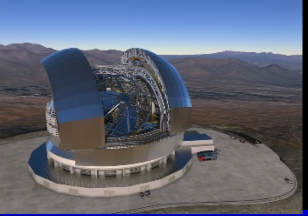
METIS
Mid-infrared ELT Imager and Spectrograph

Carlomagno et al. JATIS Vol.6 (2020)

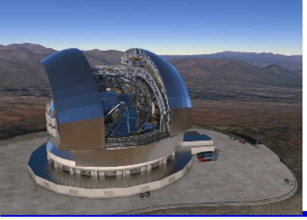




Example: 0.″002 pointing jitter requires M4+M5 to keep the source steady to within 6.6 µm in the telescope focal plane, which is > 20 m from M5.



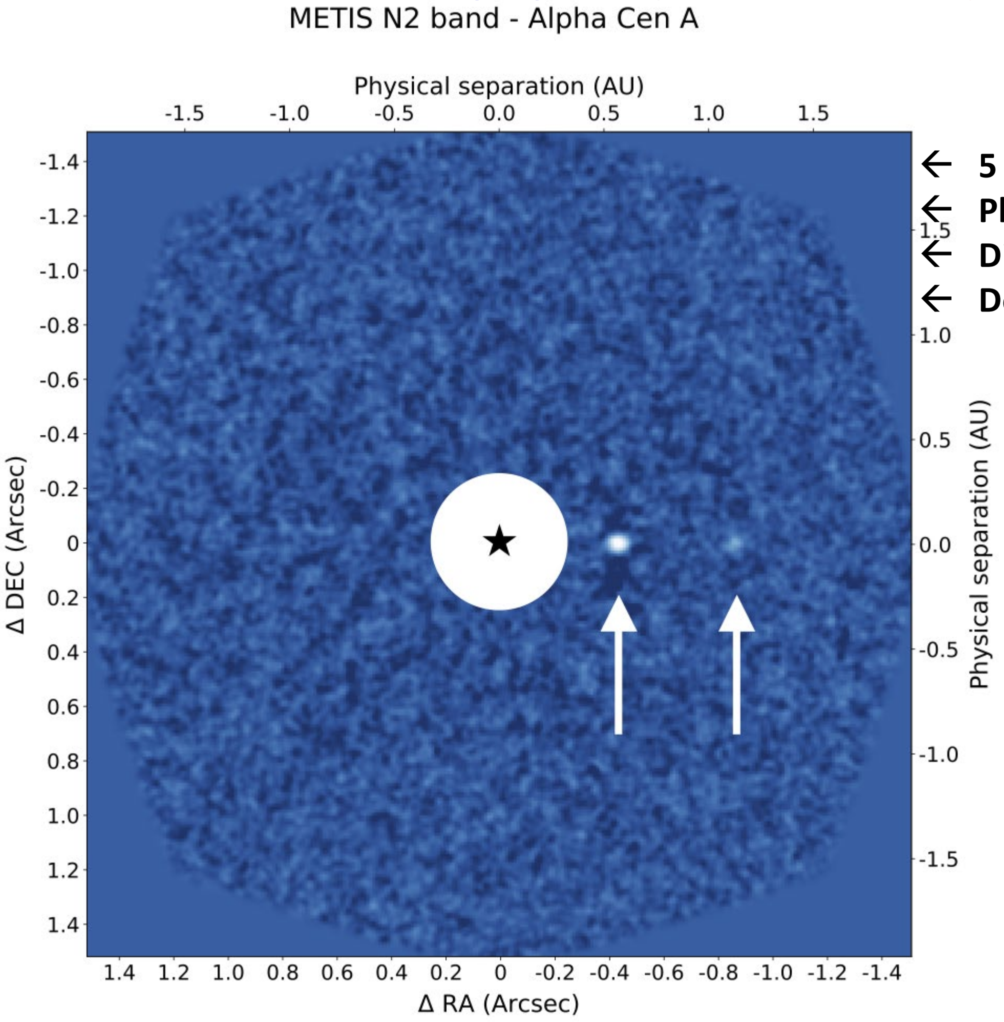
Science Case Overview



An Earth-like Planet in the Alpha-Cen system?

Mid-infrared ELT Imager and Spectrograph

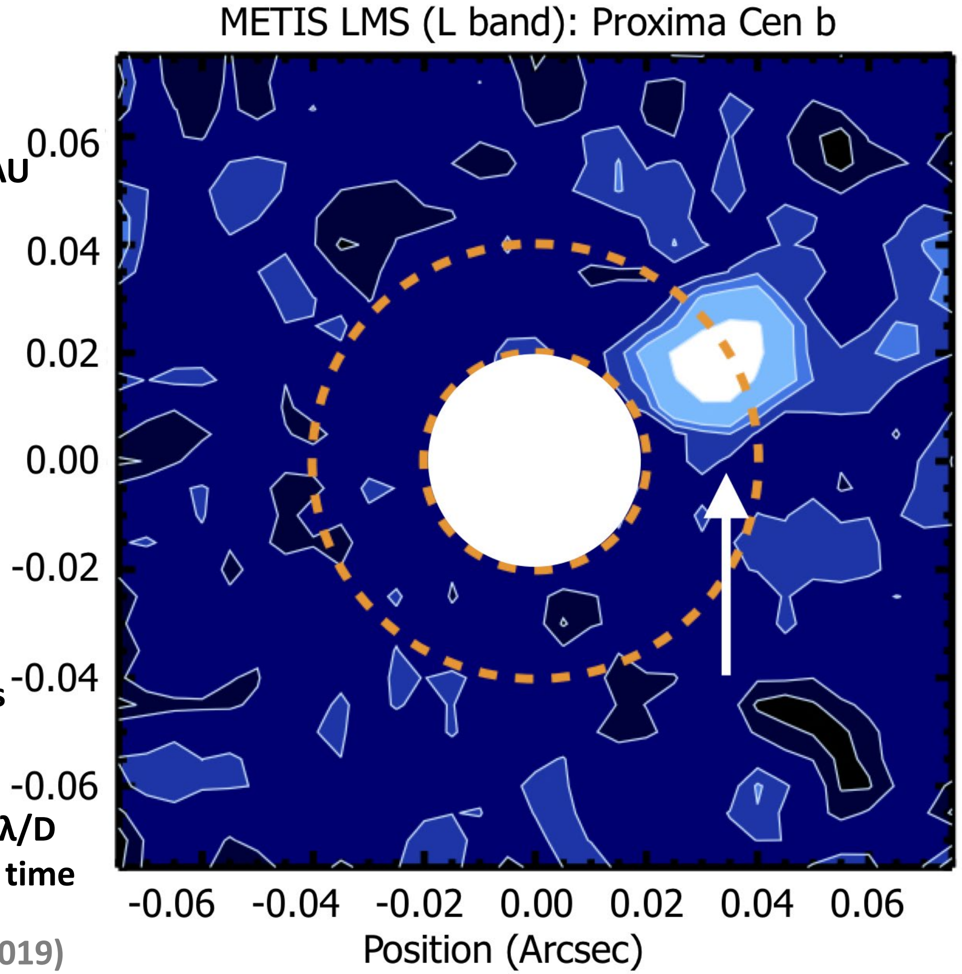
Simulation: direct imaging of Alpha Cen A at 10µm



- ← **5 hours on-source time**
- ← **Planets of Earth radius and albedo**
- ← **Dist: 1.1 AU (Earth twin)and 0.55 AU**
- ← **Detection S/N ~6 and ~10**

Quanz et al. (2015)

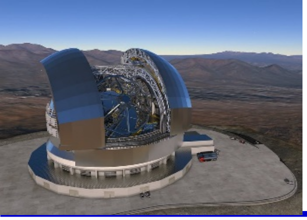
Simulation: IFU spectroscopy of Proxima Cen b at 3.8 µm



- → **1.1 R_{Earth} planet radius**
- → **Bond albedo of 0.3**
- → **50% illumination**
- → **contrast of 1:500 at 2 λ/D**
- → **10 hours of observing time**

Quanz et al. "METIS Science Case" (2019)

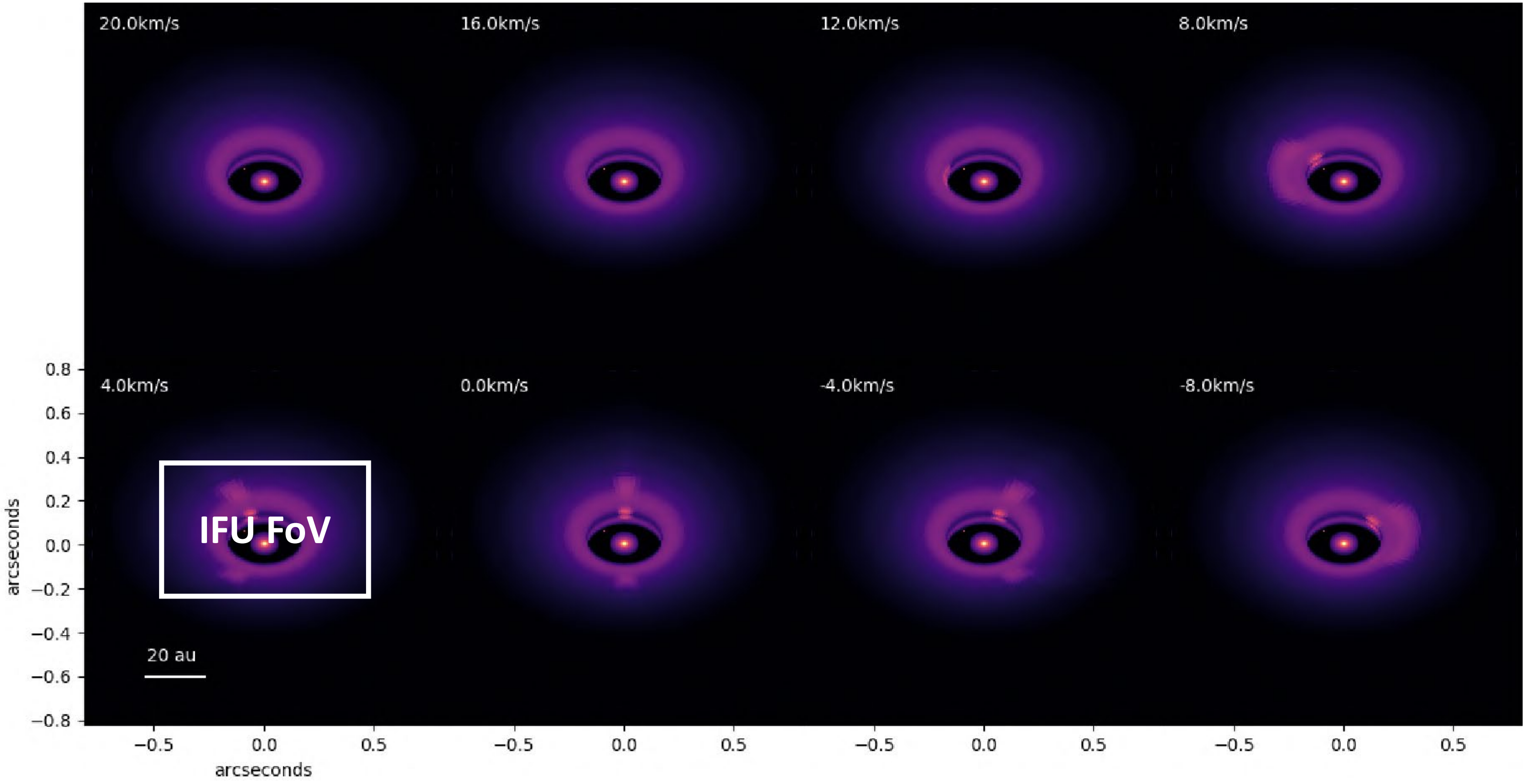
Snellen et al. (2015)



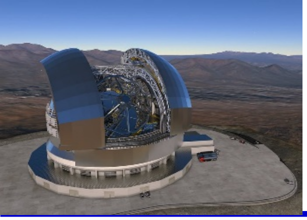
Proto-planetary Disks and Planet Formation

Radiative transfer simulations of CO v(1-0) emission at 4.7 µm

Quanz et al. "METIS Science Case" (2019)



- ← HD100546 (c) system
- ← CO v(1-0)P08 4.7µm channel maps
- ← M_* = 2.4 *Mo*
- ← M_p = 5 M_J, T_P = 1000 K
- ← M_{CPD} = 5x10^{-2} M_J
- ← t_{int} = 1 hr



Proto-planetary Disks and Planet Formation

Mid-infrared ELT Imager and Spectrograph

Radiative transfer simulations of CO v(1-0) emission at 4.7 μm

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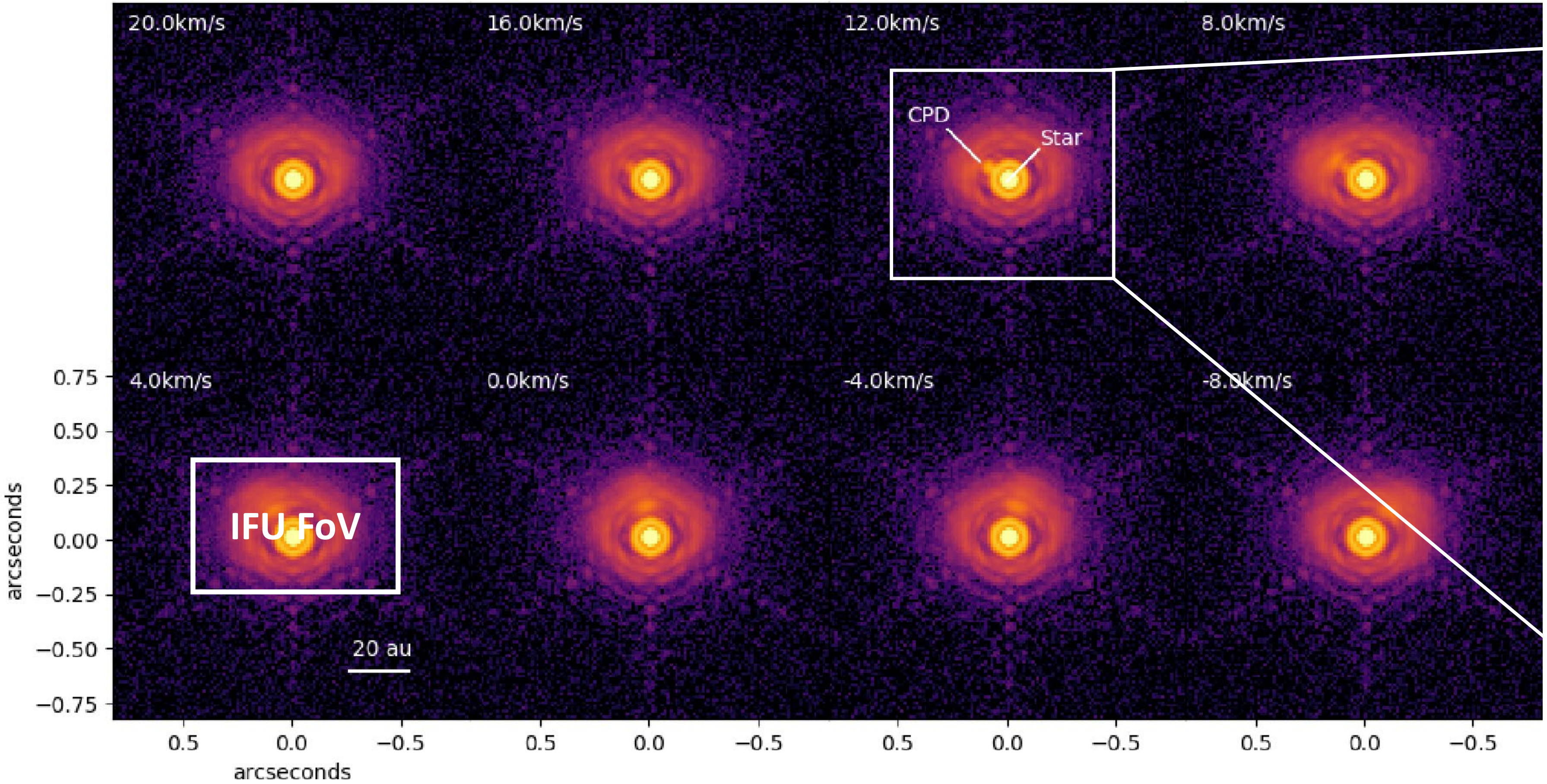

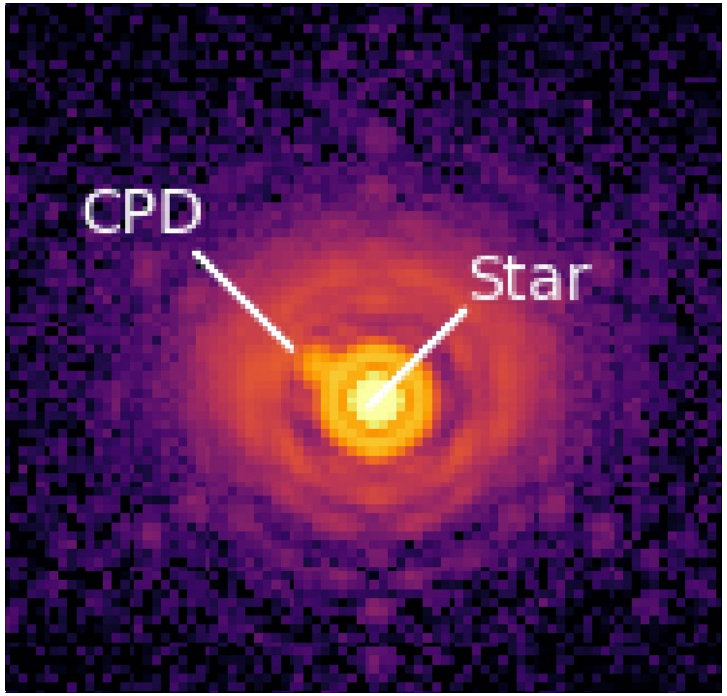

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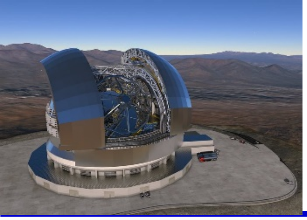
- ← $M_{CPD} = 5\text{x}10^{-2}\ M_J$
- ← $t_{int} = 1$ hr

Simulated METIS observations of the same model

1. General MIR Challenges
2. Specific Challenges on ELTs
3. METIS (ELT) & MICHI (TMT)
    - TMT instruments
    - MICHI overview
    - MICHI ⇔ METIS



TMT Instruments & MICHI

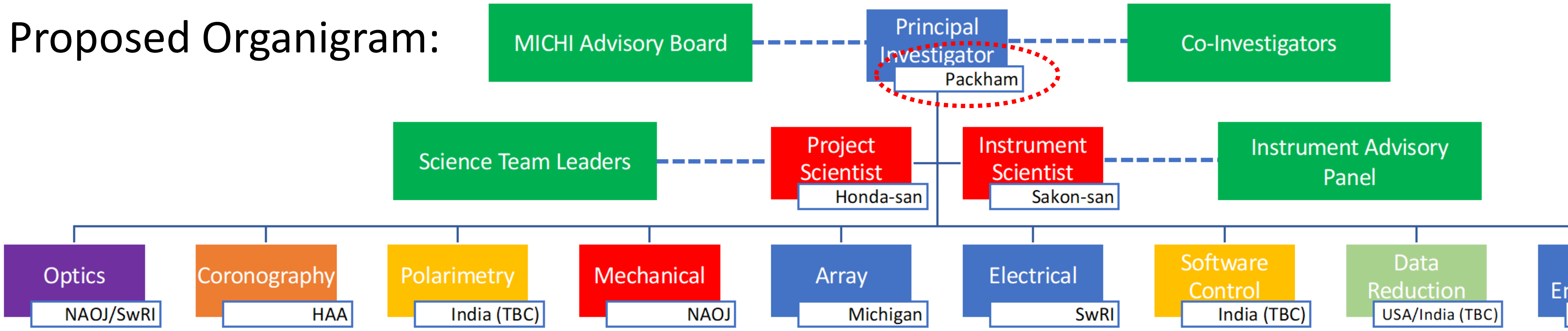
- Wide-field visible MOS (WFOS)
- [diff-ltd] IR imager & spectrometer (IRIS)
- [diff-ltd] High resolution IR MOS (MODHIS)
- AO feed to multiple instruments (NFIRAOS)

1^{st} light

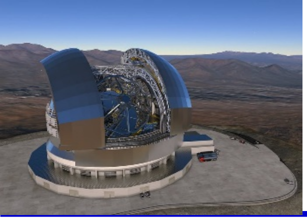
- proposed 2^{nd} generation: PSI, HROS, IRMOS, NIRES, ARISE, and:

  Mid-IR Camera, High-disperser & IFU spectrograph (MICHI, 未知)

Proposed Organigram:



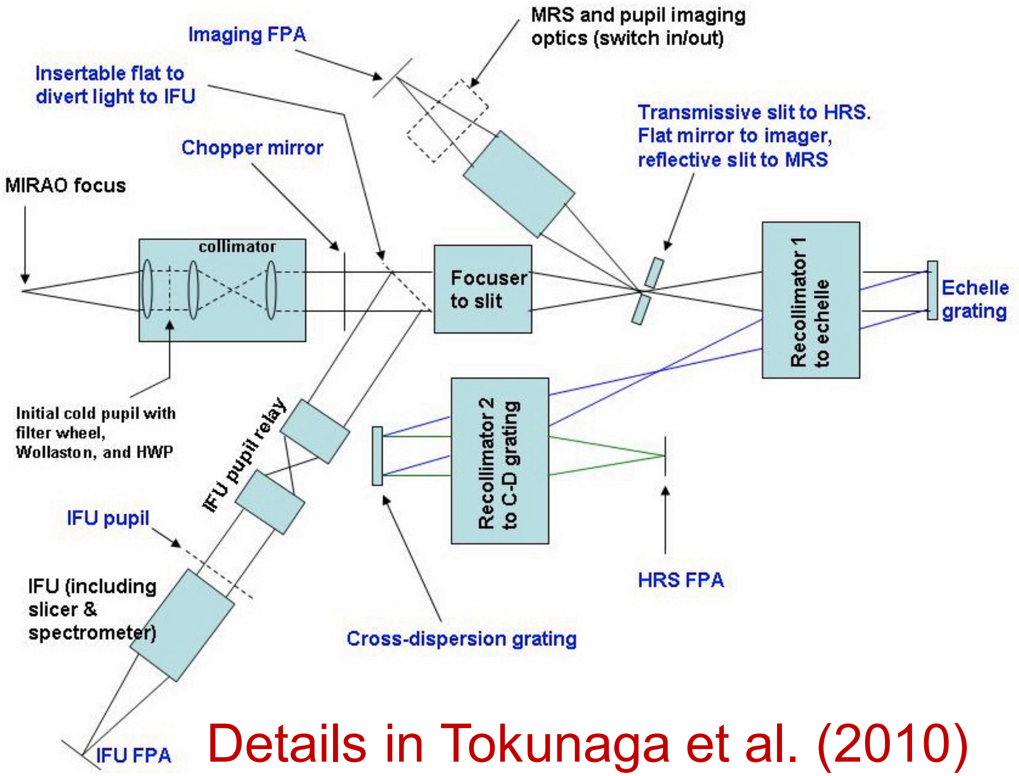
see talk by Chris Packham on Thursday



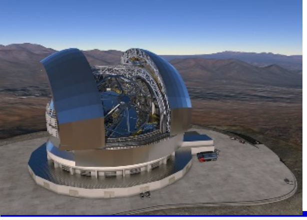
MICHI Overview

Instrument capabilities optimized to 3 – 14 µm:

- Diffraction-limited imaging at L, M, N
- Long slit R~600 spectroscopy at L, M, N
- High resolution R>100,000 cross-dispersed spectroscopy at L, M, N
- IFU R~1000 spectroscopy at LM *or* N
- Polarimetry (Imaging & long-slit spectrometry) at L, M, N [TBC]



Details in Tokunaga et al. (2010) and https://michi.space.swri.edu/



METIS ⇔ MICHI

METIS and MICHI will have many common aspects, driven by similar science goals. However, there are significant differences, which make them rather complementary instruments:

- The current METIS baseline does not include laser guide star capability
- Mauna Kea (likely location of MICHI) is the premier site for thermal-IR
- METIS covers the southern, MICHI the northern hemisphere
- METIS focuses on the unique combination of high resolution spectroscopy & IFU & coronagraphy
- While the METIS design is frozen, the MICHI design could still be optimized for JWST discovery follow-up
- MICHI may offer polarimetry and high spectral resolution at N band

Conclusions:

- Numerous challenges still to be addressed
- ELT-METIS & TMT-MICHI will be transformational for ground-based mid-IR astronomy
- Nowadays, ground-based IR astronomy even wins the Nobel Prize!