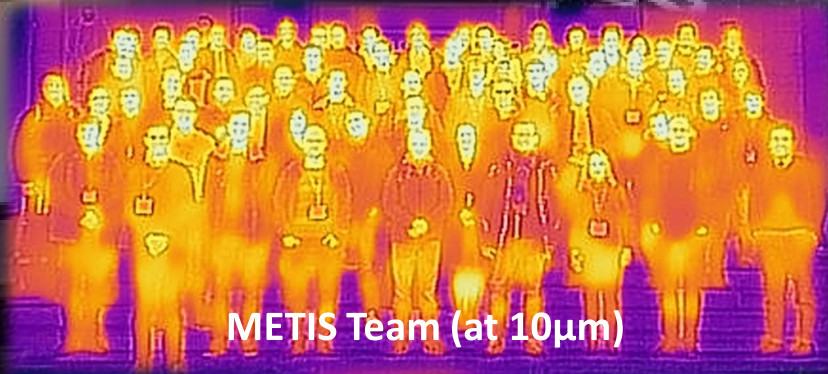
# Challenges for mid-IR Instruments on ELTs

Brandl, B.R.

# Challenges for mid-IR Instruments on ELTs

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

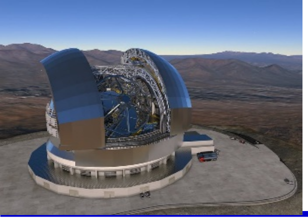

METIS Team (at 10μm)


Lorentz Center Workshop (Nov 2018)

**Bernhard Brandl (Leiden University / TU Delft)**

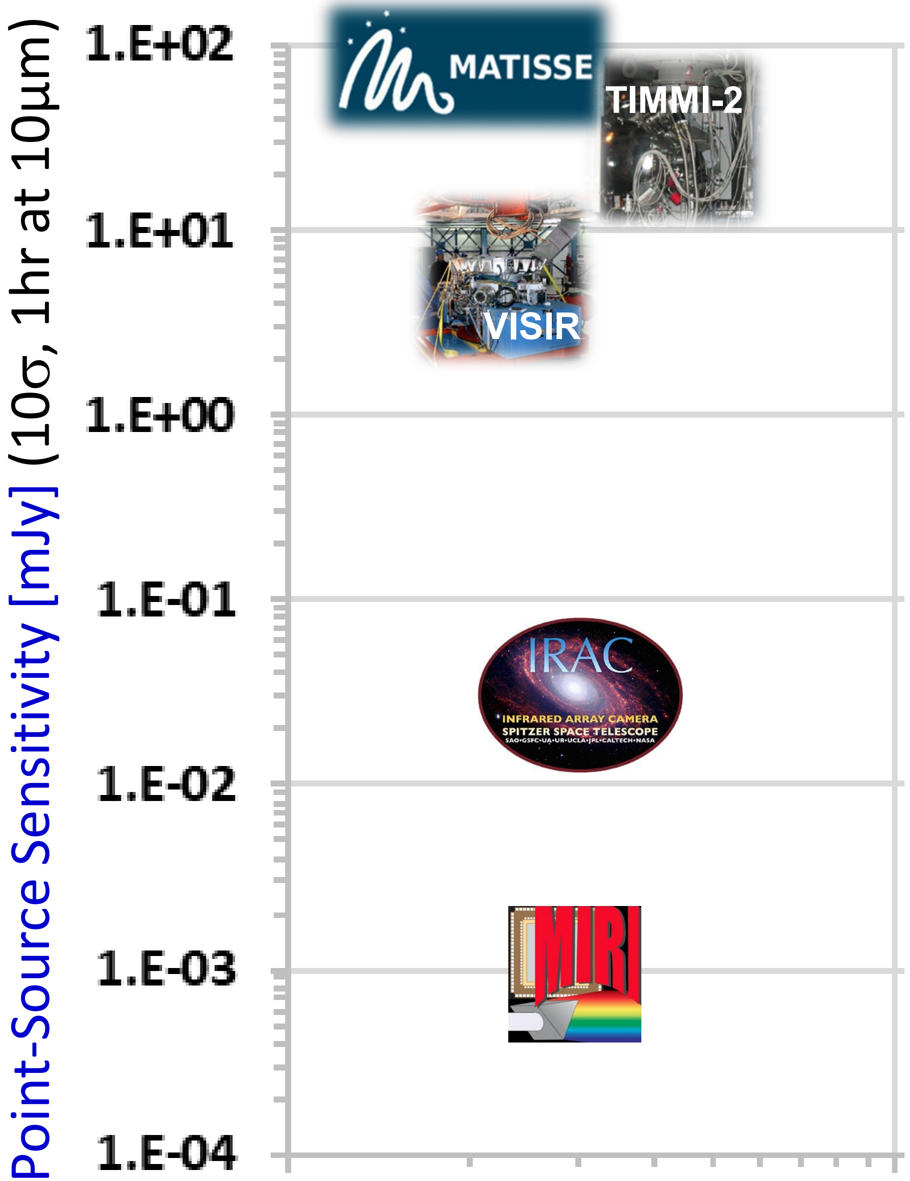
IR2020: Ground-based thermal infrared astronomy – past, present and future

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



# Main Challenge: achieving good Sensitivity

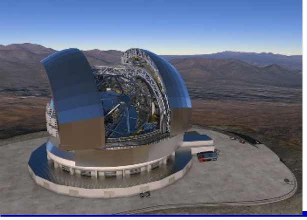
METIS
Mid-infrared ELT Imager and Spectrograph




Ground-based

Space-based


see talk by Chris Packham on Thursday



# The thermal Background

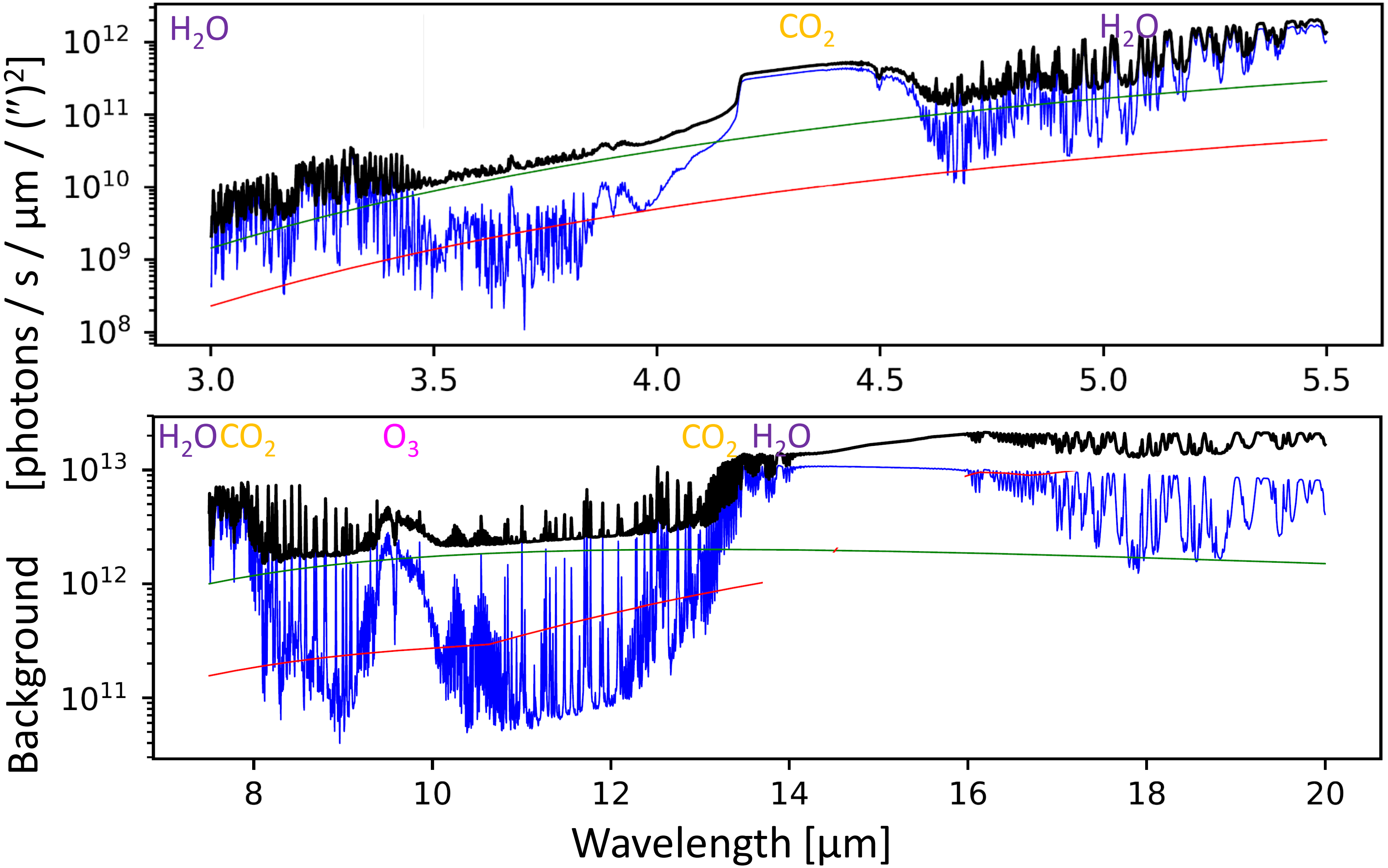
*Contributions from*:*

Sky

Telescope

Window

Total



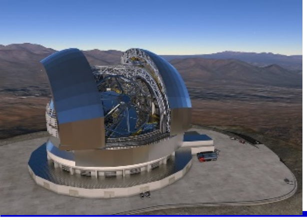

*Main absorbing molecules:*

$H_2O$

$CO_2$

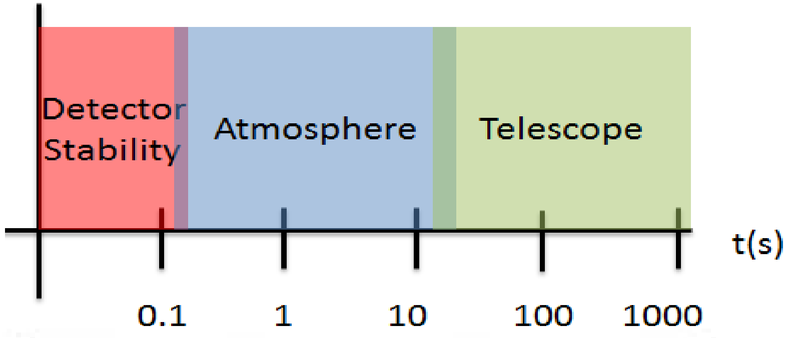
$O_3$

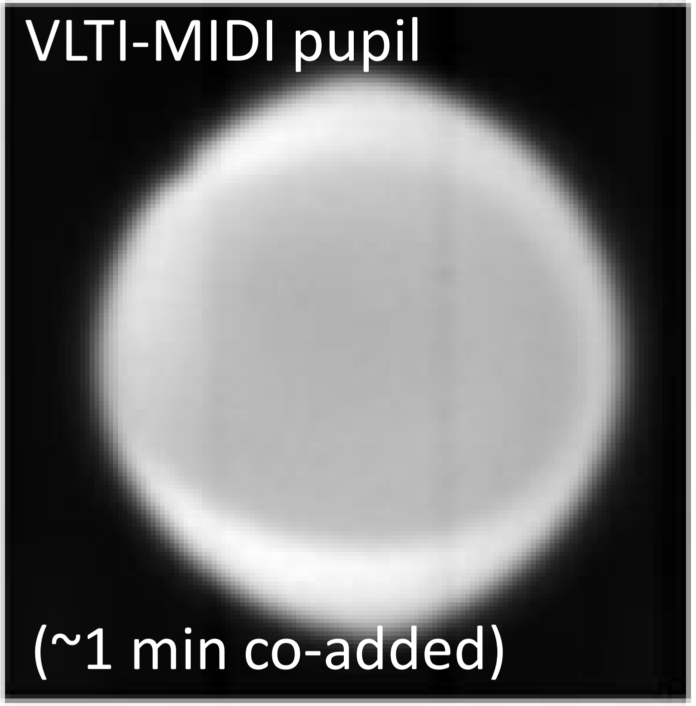
**Calculated for the ELT on Cerro Armazones*



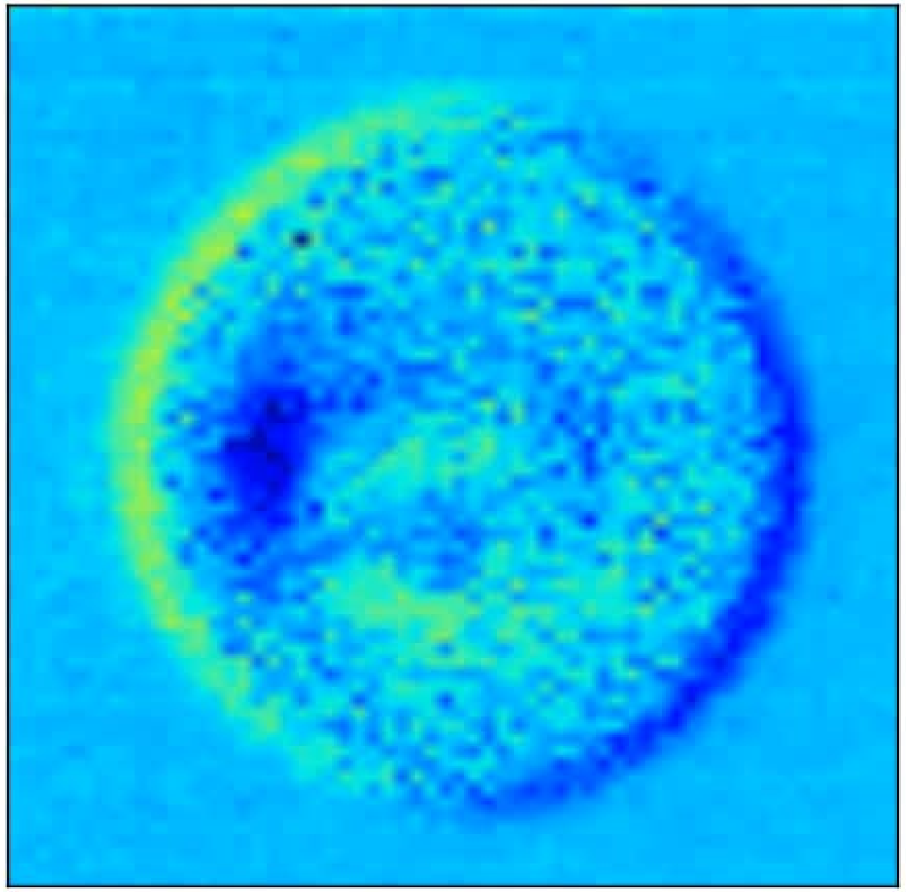
# The *variable* thermal IR Background

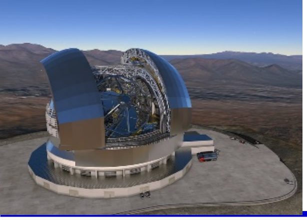
The thermal background is non-uniform ( *f*{Telescope}) and time-variable ( *f*{Air, Telescope})




Time series of MIDI chop-difference acquisition frames



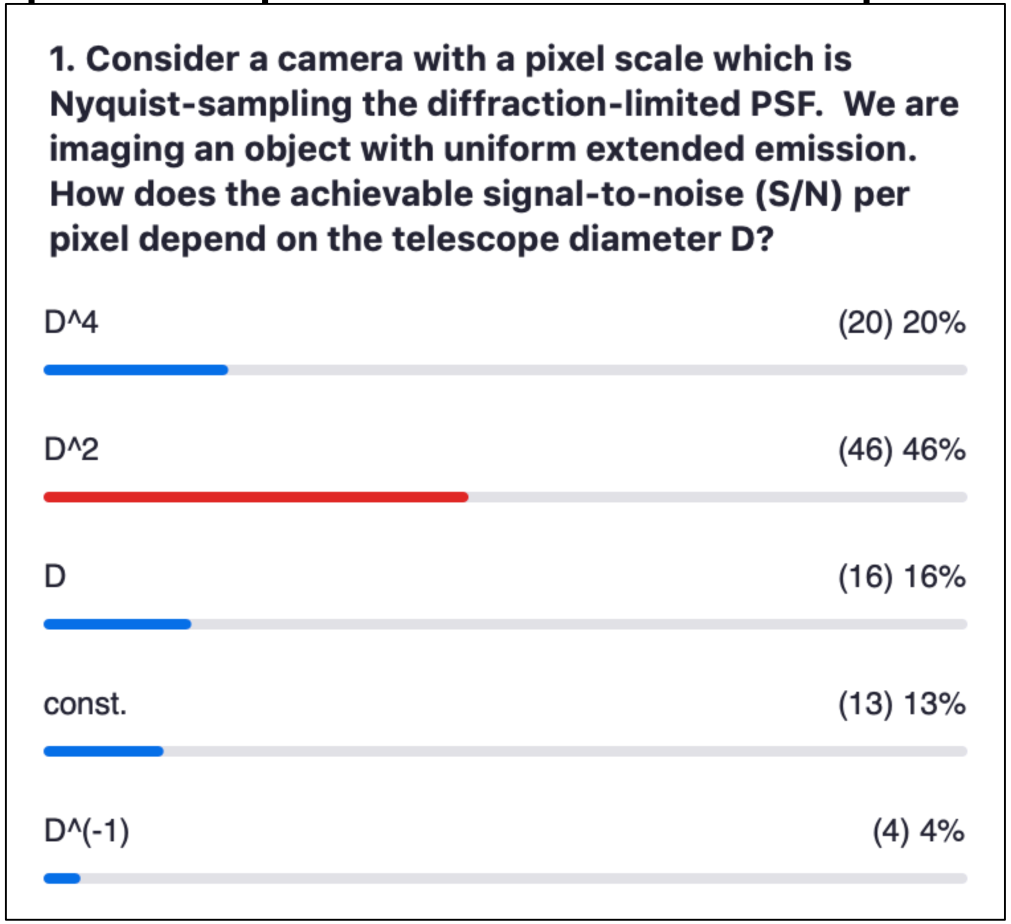


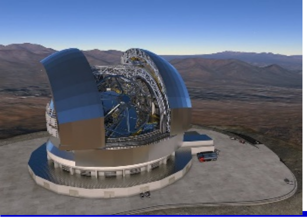
# Zoom Poll



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?

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

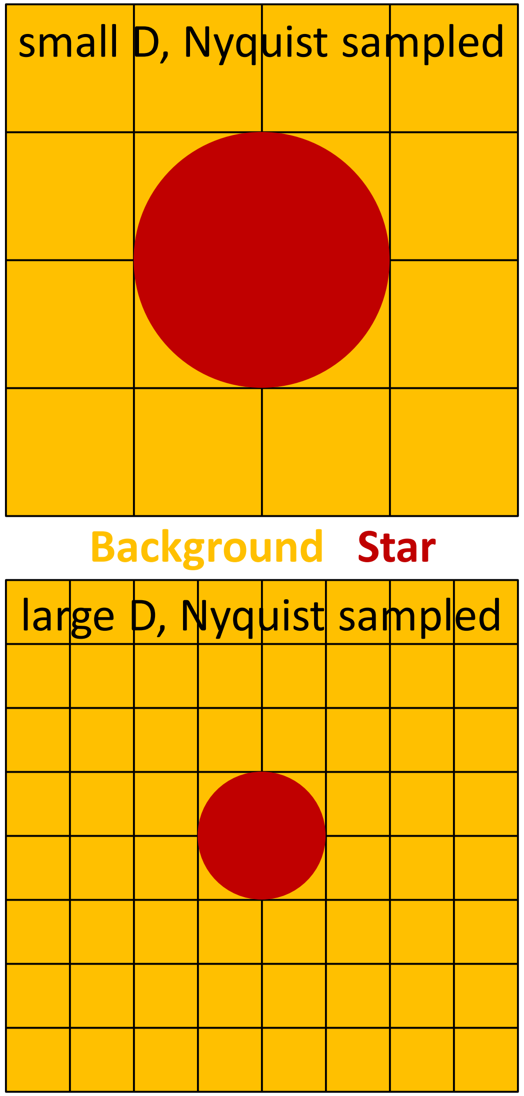




# “Extended Source-Sensitivities”

Mid-infrared ELT Imager and Spectrograph

## Point source




Telescope aperture:

$S \propto D^2$

$B \propto D^2 \rightarrow N \propto D$

} $S/N \propto D$

Pixel FoV:

$S \propto \text{const}$

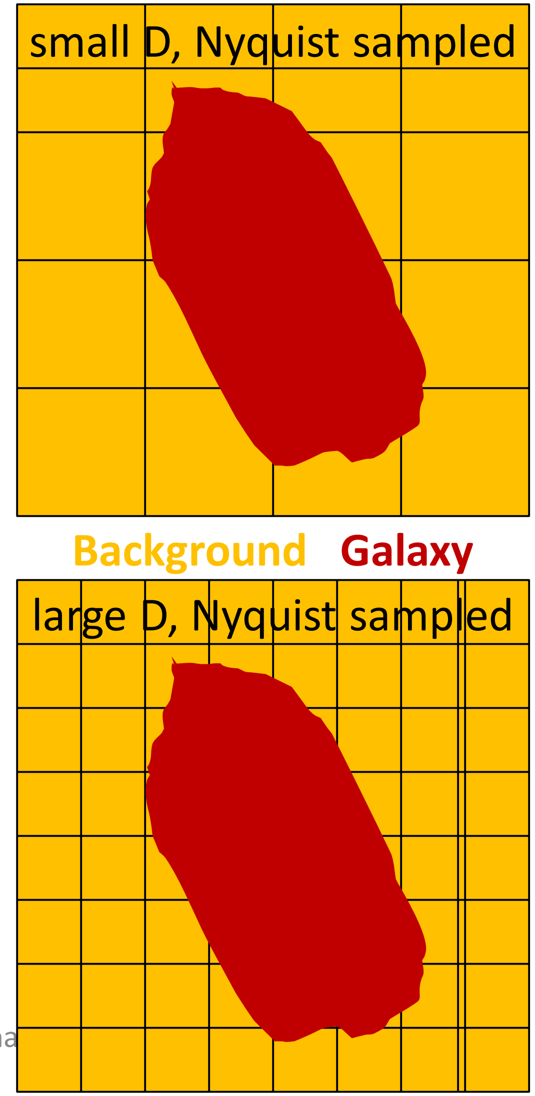
$B \propto D^{-2} \rightarrow N \propto D^{-1}$

} $S/N \propto D$

In total:

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

## Extended source




Telescope aperture:

$S \propto D^2$

$B \propto D^2 \rightarrow N \propto D$

} $S/N \propto D$

Pixel FoV:

$S \propto D^{-2}$

$B \propto D^{-2} \rightarrow N \propto D^{-1}$

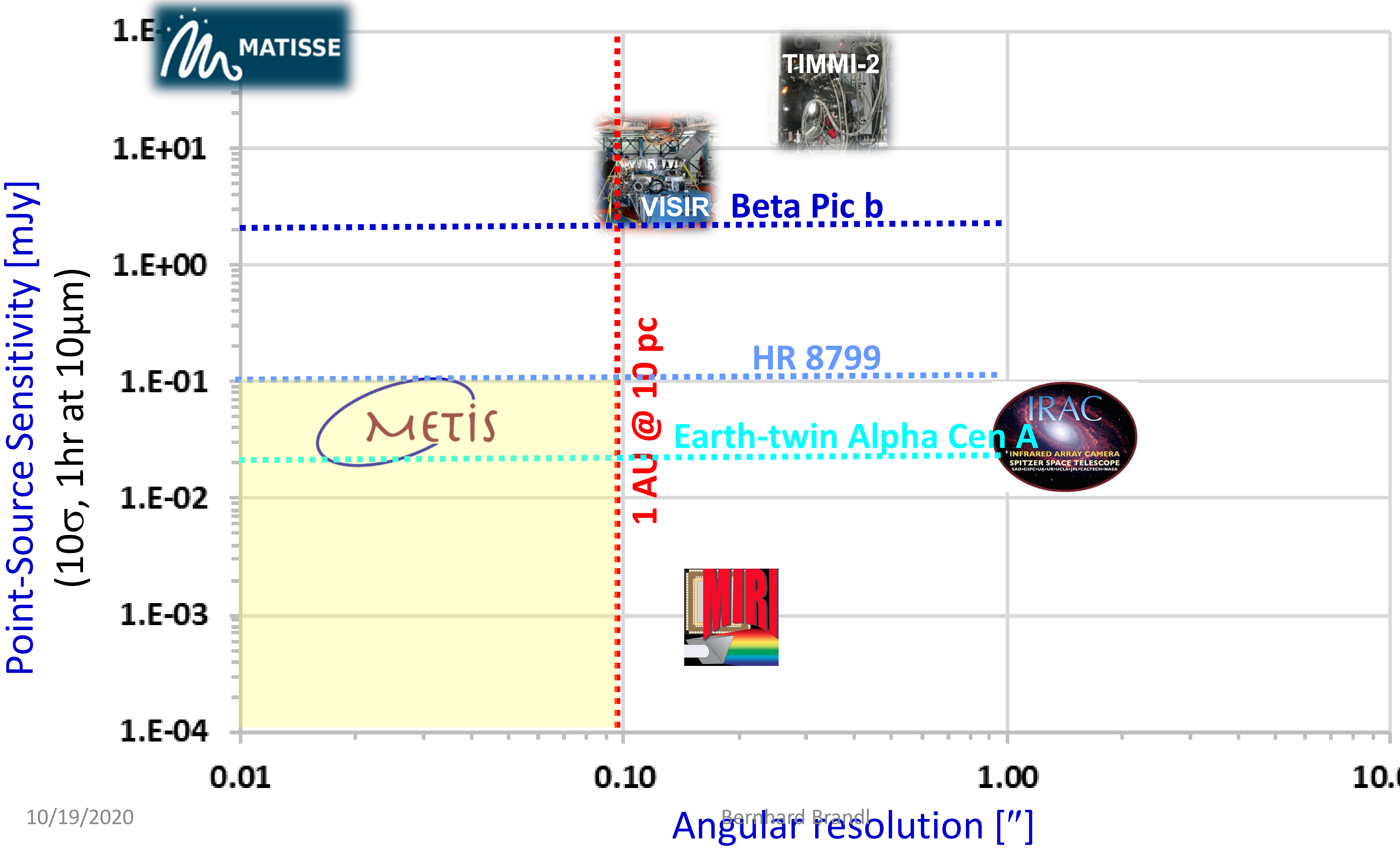
} $S/N \propto D^{-1}$

In total:

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

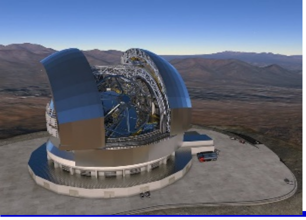
*Resampling would regain sensitivity*

# Why Ground *can* make unique Contributions



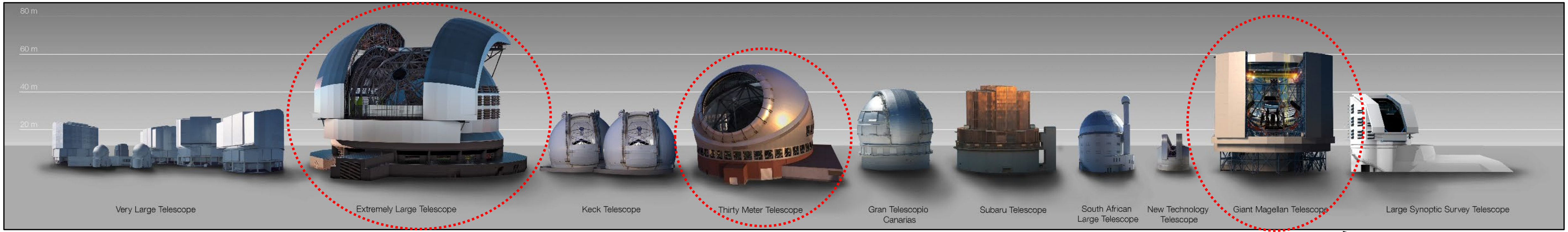

Exoplanet fluxes from Danielski et al. (2018) and Des Marais et al. (2001)

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



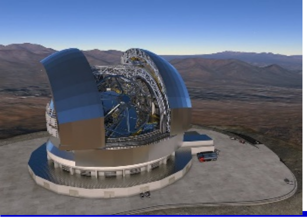
# General Considerations for ELT Instruments

METIS
Mid-infrared ELT Imager and Spectrograph

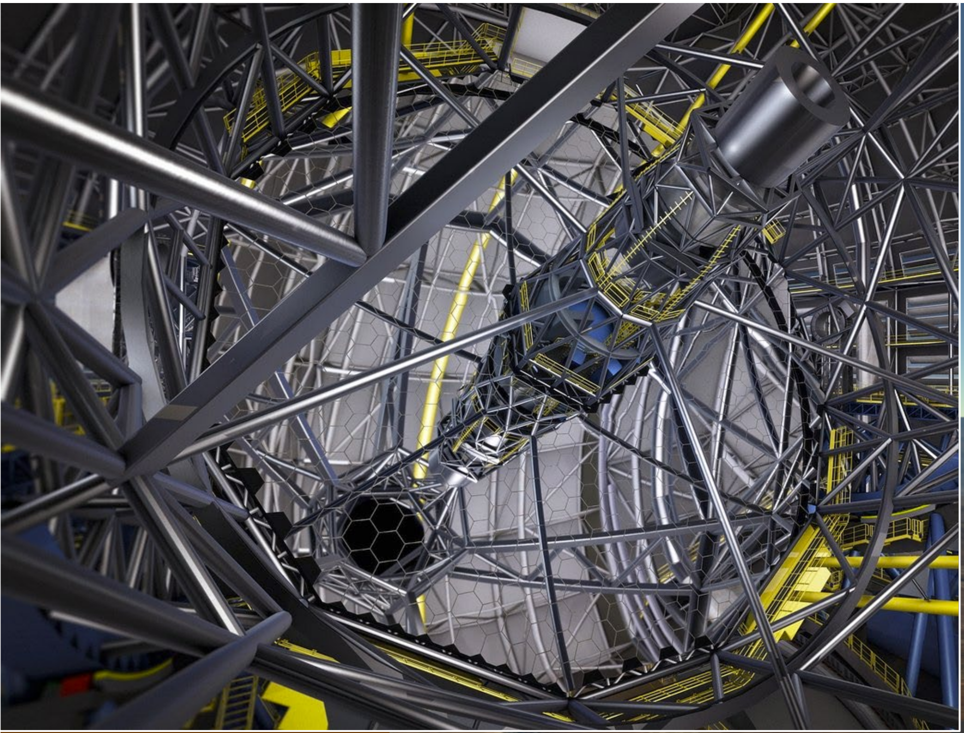


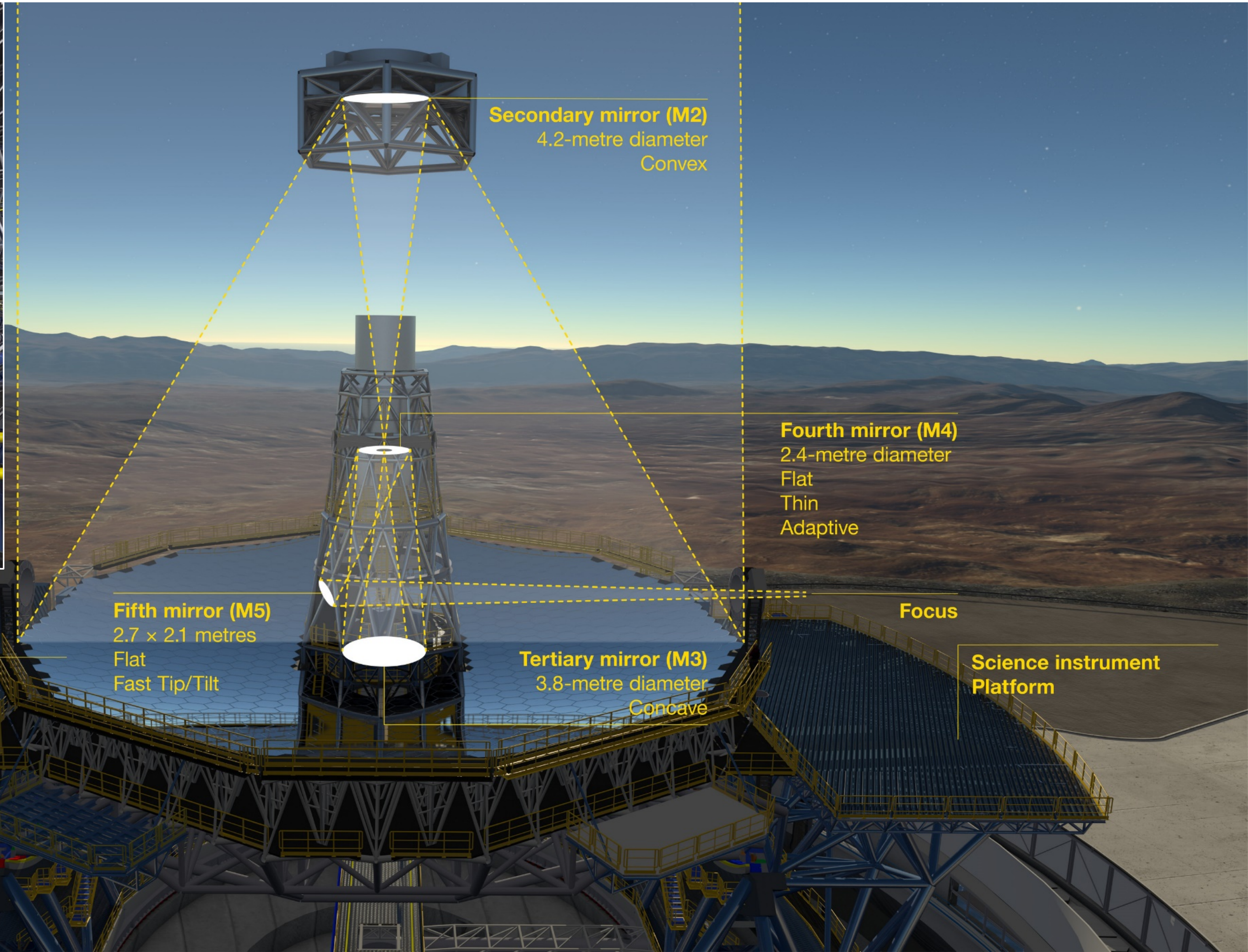

ELT time: 500 € / min

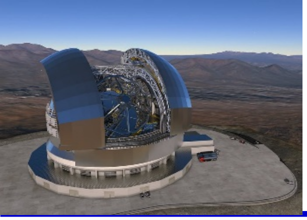
- Exploit the unique ELT discovery space (⇔ JWST, LSST, ALMA, …)
- "There will be only a few extremely large telescopes":
  - Each instrument must serve a large fraction of the community (no "PI-instruments")
  - Low complexity to ensure low risk, high efficiency, and reliable operation
  - High complexity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



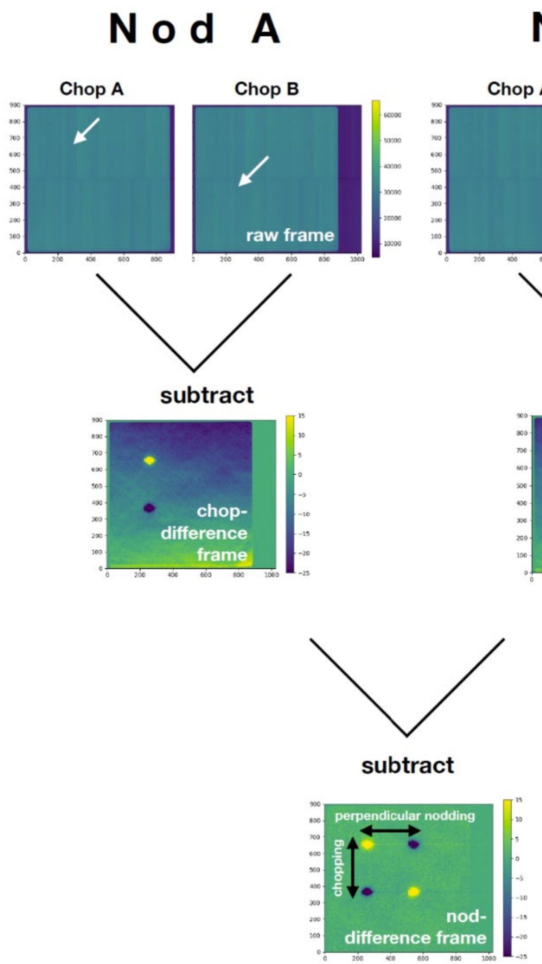




# We have to re-invent chopping/nodding

Mid-infrared ELT Imager and Spectrograph

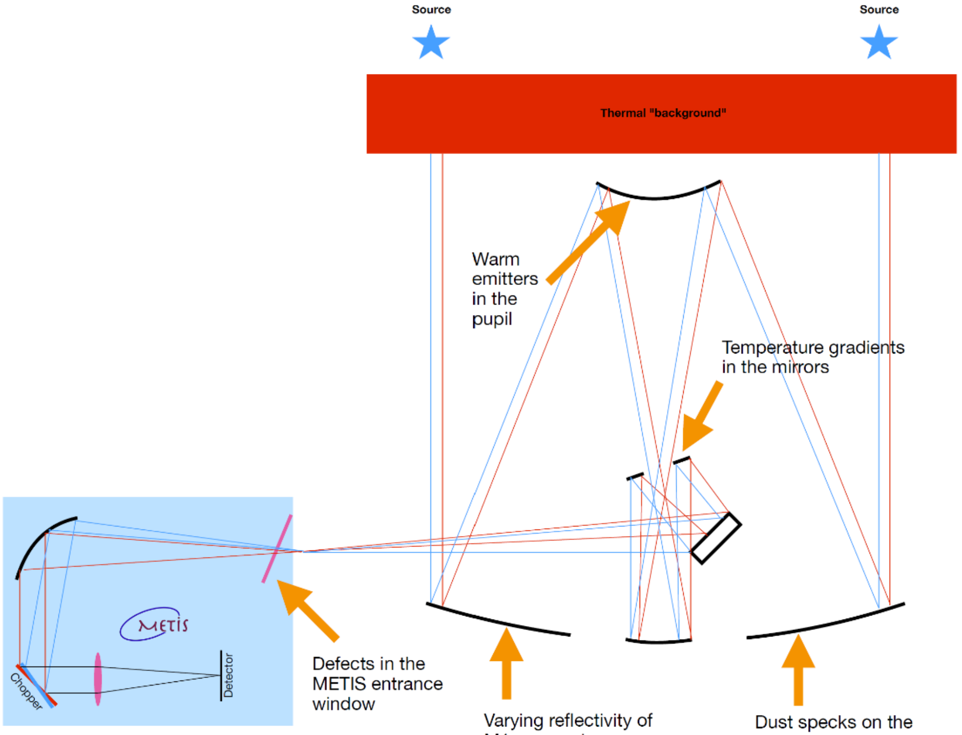
## Classical chopping with M2:




## Option #1: chopping mirror inside instrument

+ flexibility, accuracy

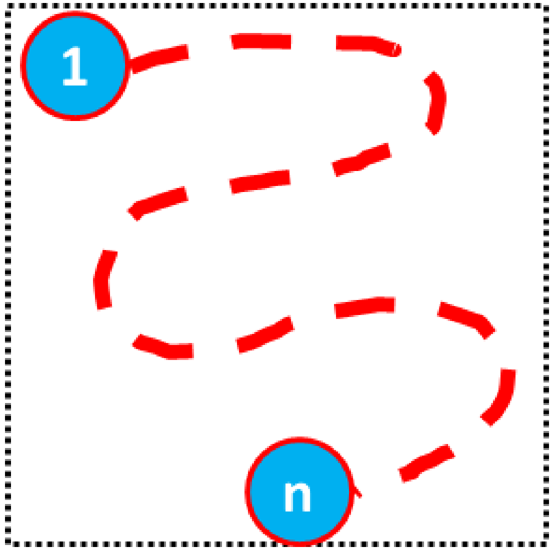
– beam wander upstream

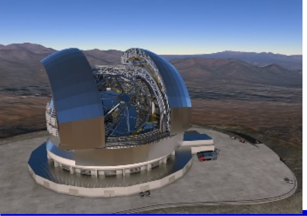


Slightly simplified optical sketch

## Option #2?:

Alternatives, like “drift scanning” [TBC]



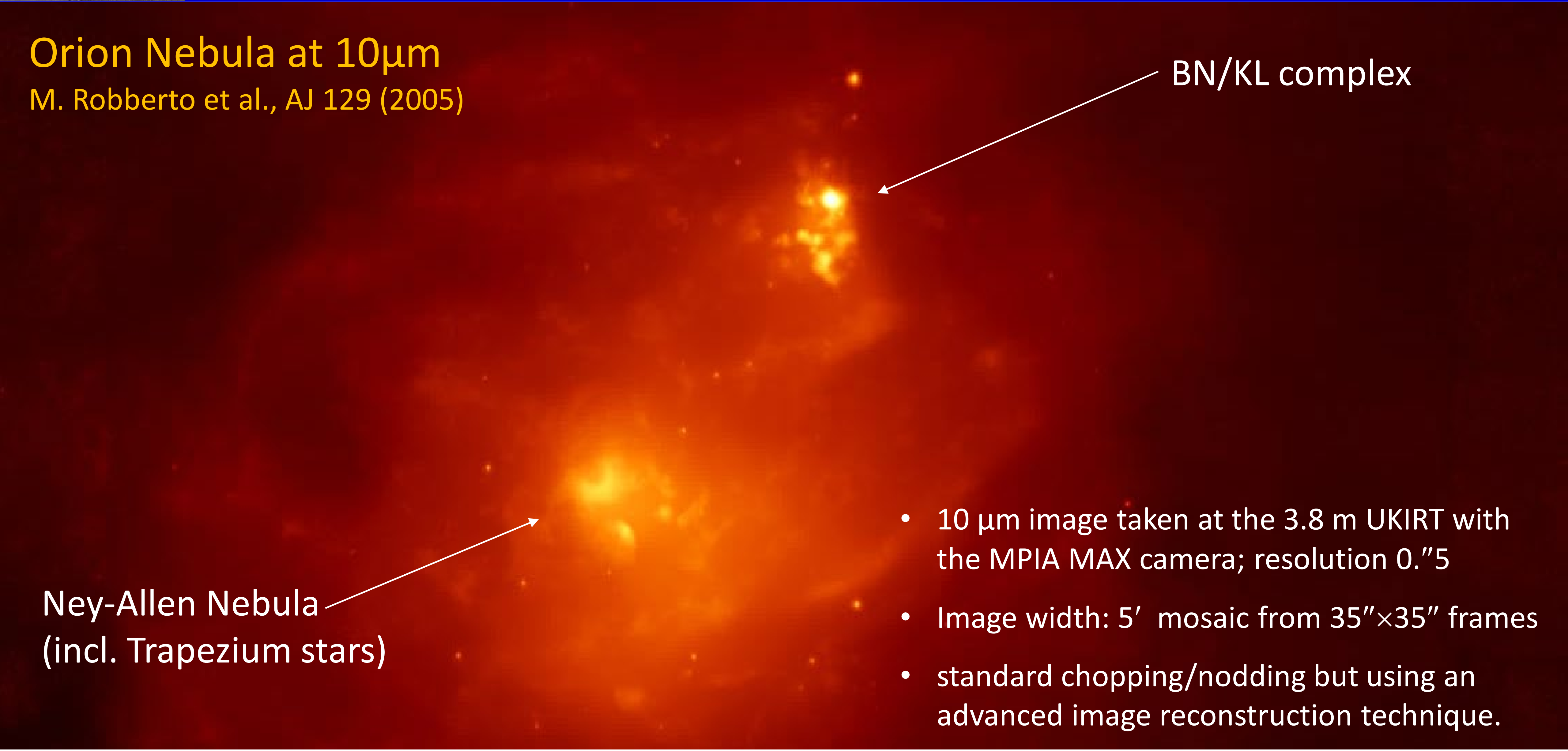


# …and develop the Software to optimize it!

METIS
Mid-infrared ELT Imager and Spectrograph

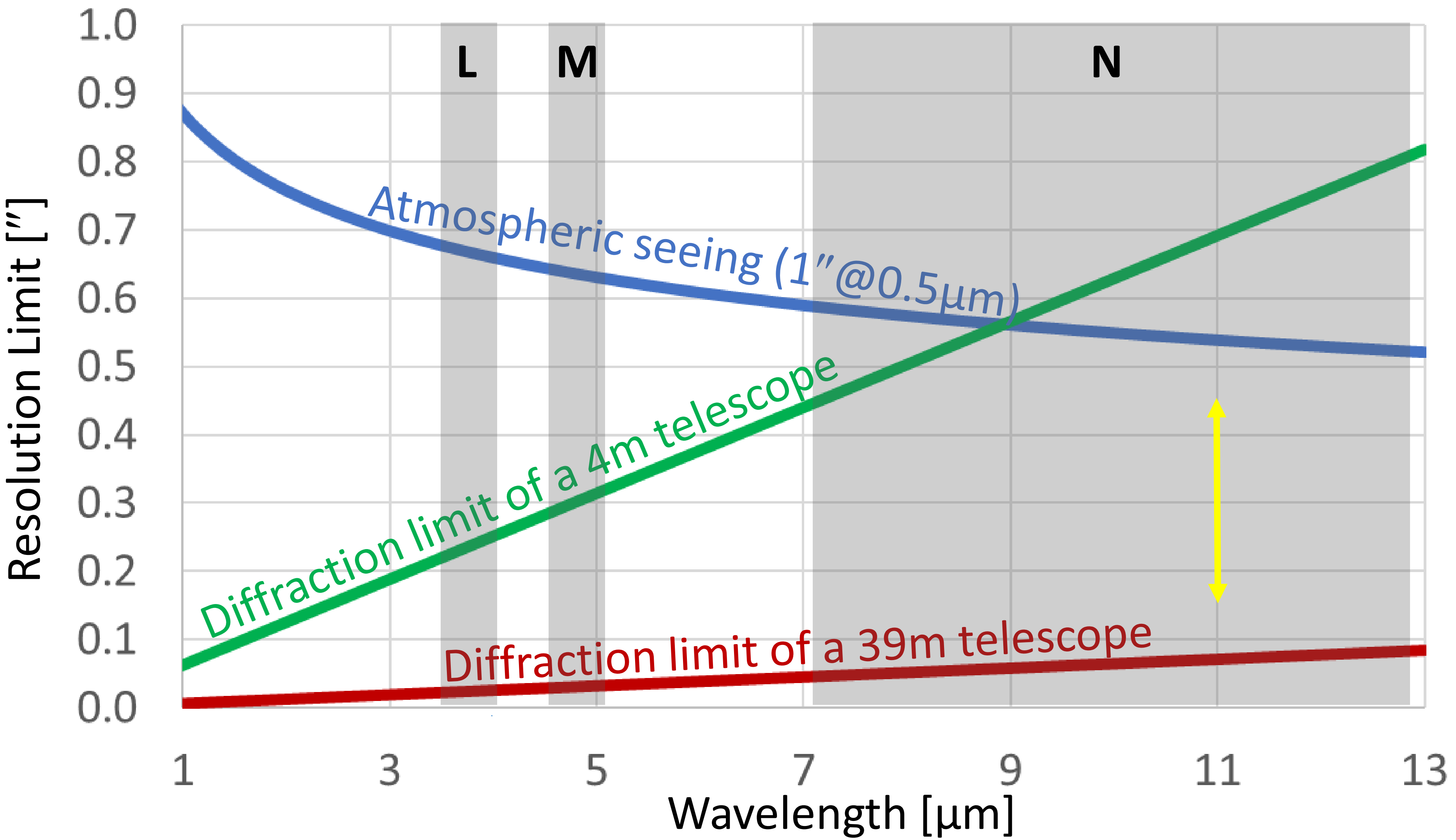
## Orion Nebula at 10µm

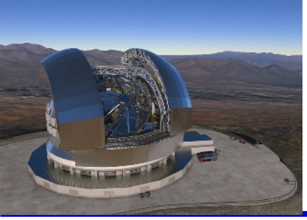
M. Robberto et al., AJ 129 (2005)




- 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

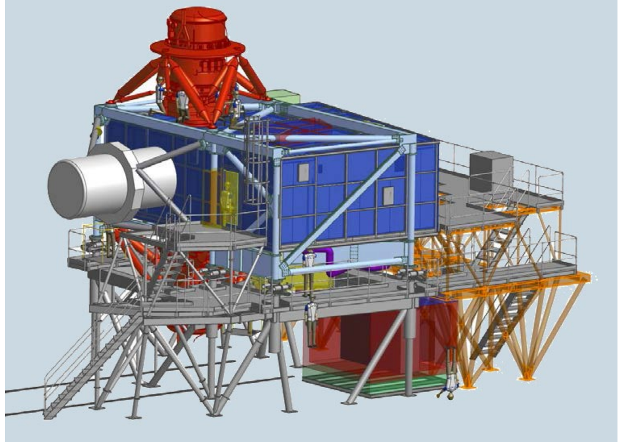
Mid-infrared ELT Imager and Spectrograph

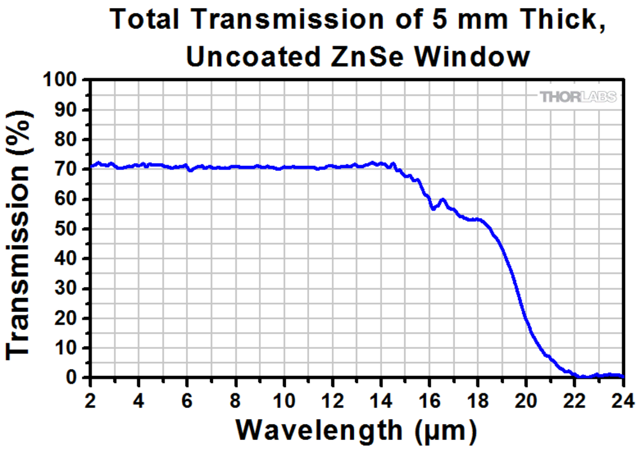
| | Telescope | Instrument | AO type | Deformable Mirror | Beam-splitter | Wavefront sensor | Telescope Mirrors | Laser guide stars |
|---|---|---|---|---|---|---|---|---|
| A | Classical | most | TBD | AO bench | warm | warm | 2 - 3 | TBD |
| B | TMT-NFIRAOS | IRIS,MODHIS | MCAO | AO bench | warm | -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 |

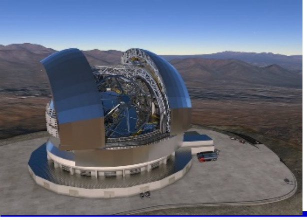
Crane et al. SPIE 10703 (2018)
Chun et al. SPIE 6272 (2006)
Bertram et al. SPIE 10703 (2018)

Goal: avoid warm dichroic

Problem: passing $\lambda$ = 0.5 µm – 28 µm through window



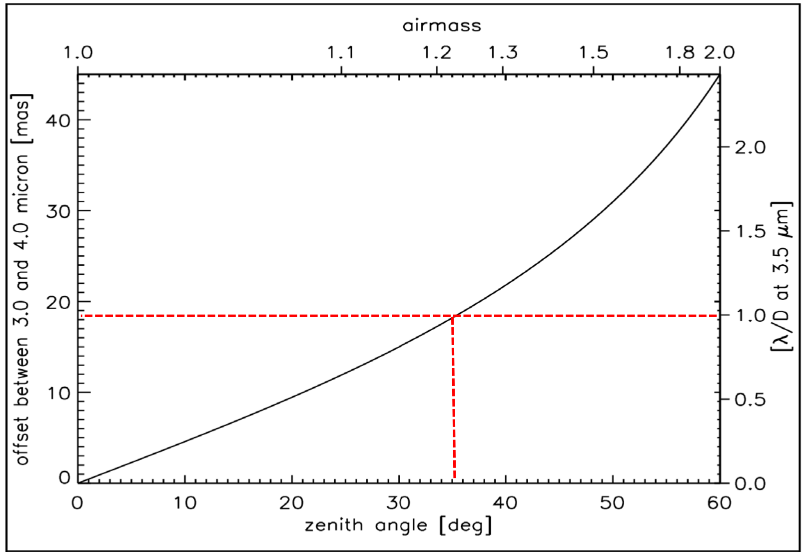




# Other atmospheric & optical Effects

Mid-infrared ELT Imager and Spectrograph

## Atmospheric dispersion



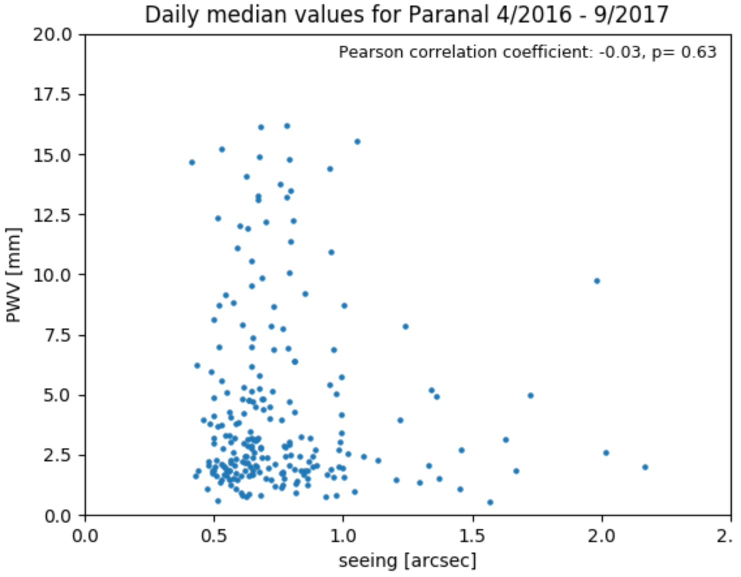

Spatial offsets. *Left*: offset as a function of wavelength at airmass=2.0 (z=60°). Right: total offset between 3.0 and 4.0 μm, as a function of zenith angle.

## PWV ⇔ seeing

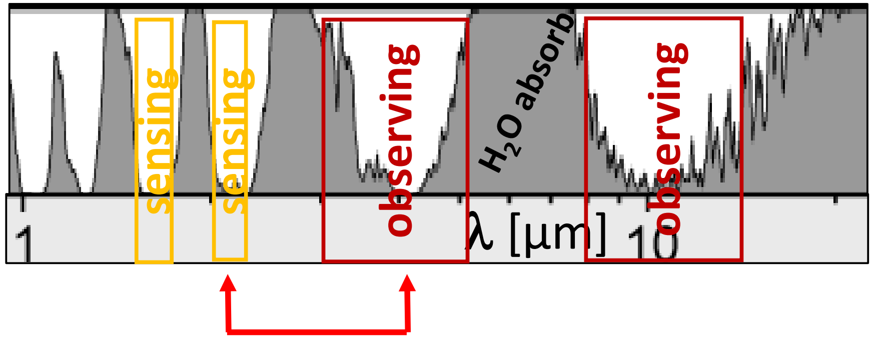
Good news: no correlation

→ scheduling

© ESO




## $H_2O$ vapor seeing

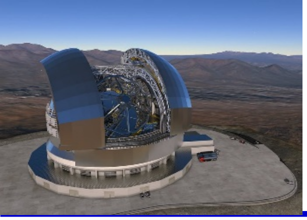



- small effect – not visible on 8m telescopes
- Potential impact on high contrast imaging/ coronagraphy

## 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

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

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centra
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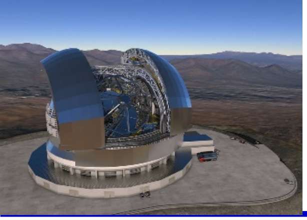


# Instrument Overview

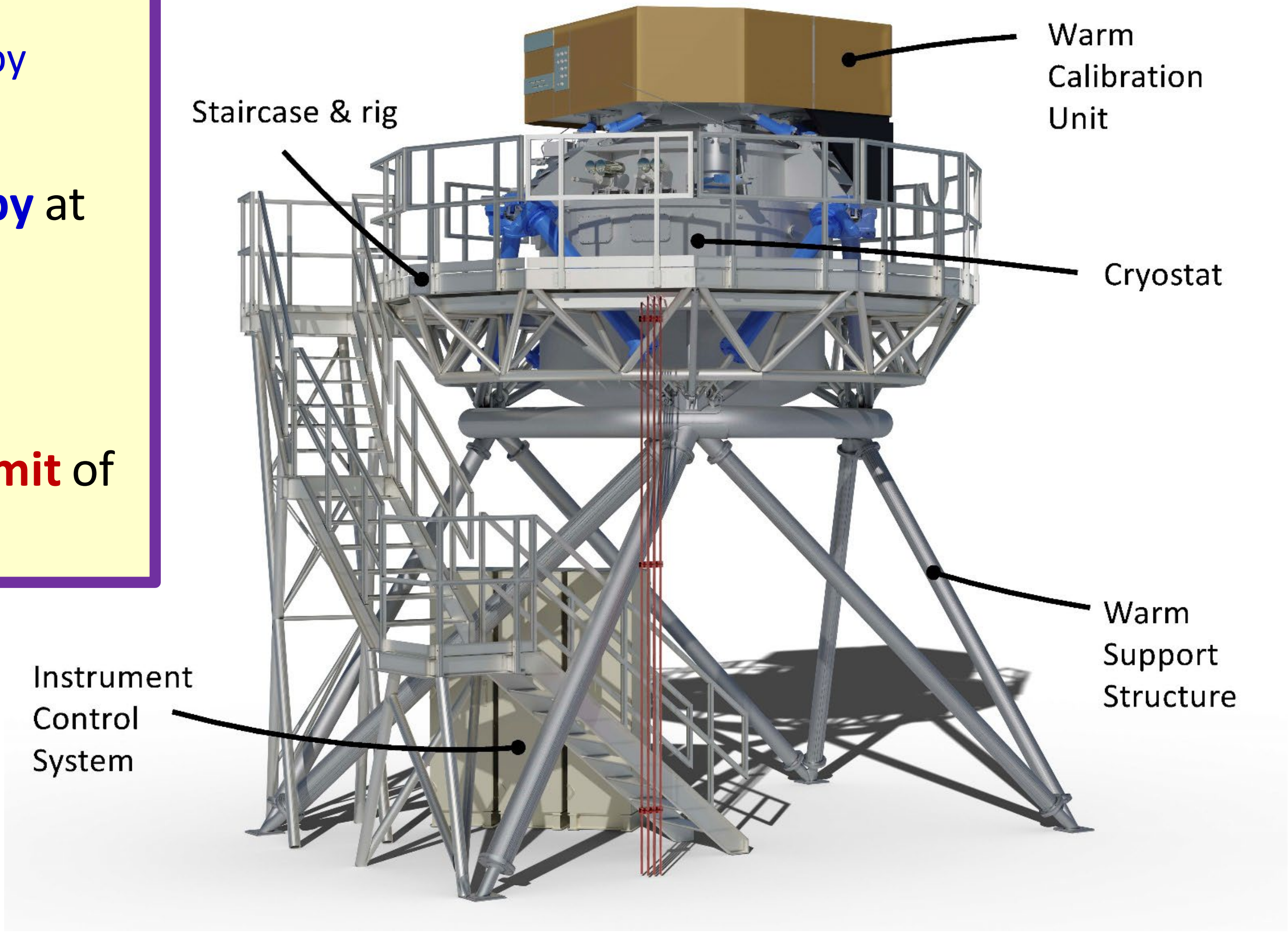
Mid-infrared ELT Imager and Spectrograph

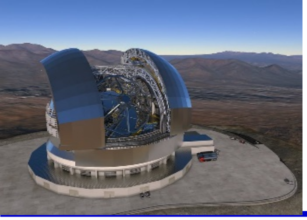
- ❑ **Imaging** over a FoV of 10.5″ × 10.5″ (3 – 5 µm) and 13.5″ × 13.5″ (8 – 13 µm), incl.:
  - low resolution (*R* ~ few 100s) longslit spectroscopy
  - coronagraphy for high contrast imaging
- ❑ **High resolution** (*R* ~ 100,000) **IFU spectroscopy** at 3 – 5 µm, over a FoV of ~ 0.93″ × 0.58″, incl.
  - 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)

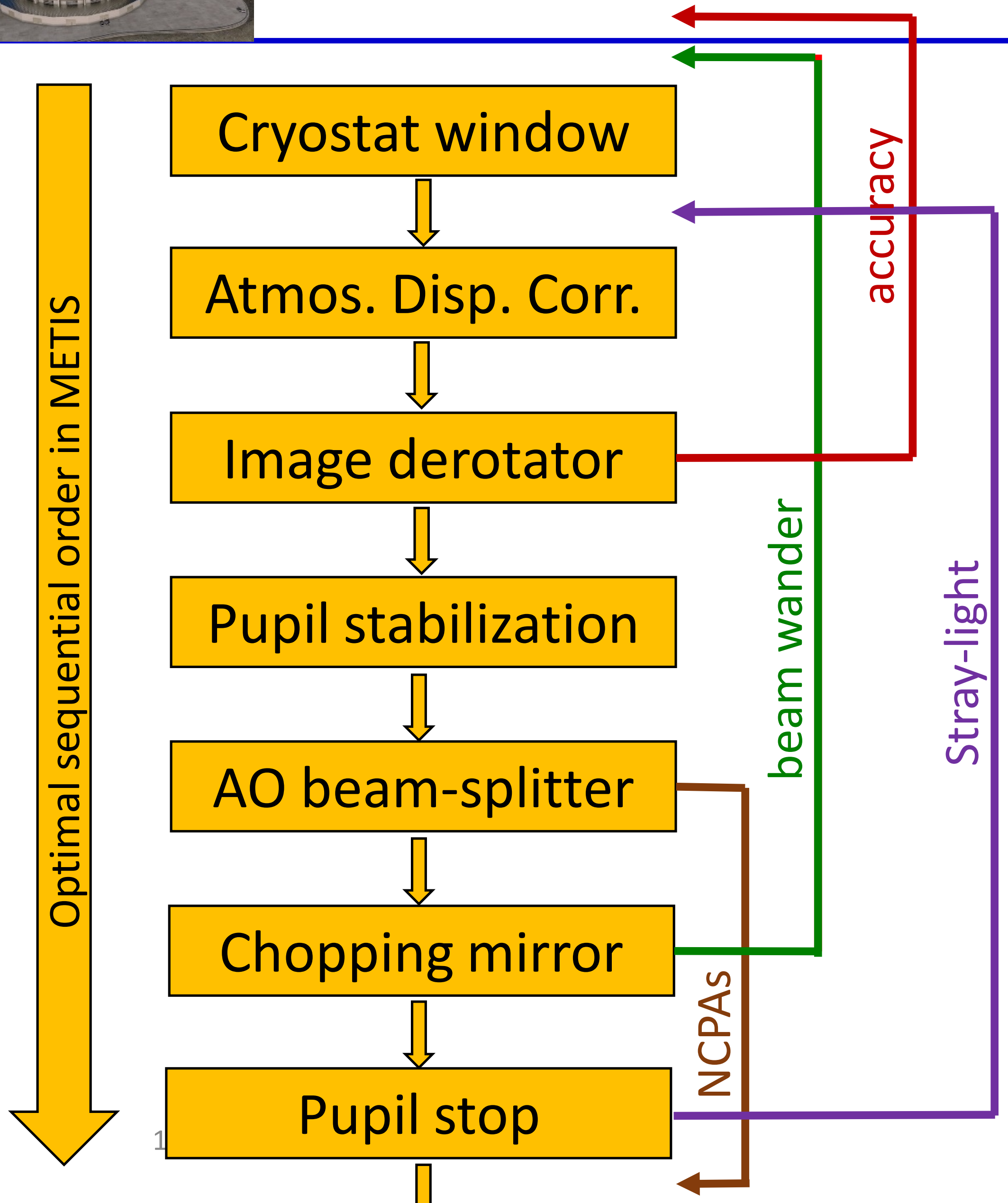
PS sensitivity (10-σ, 1hr)

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





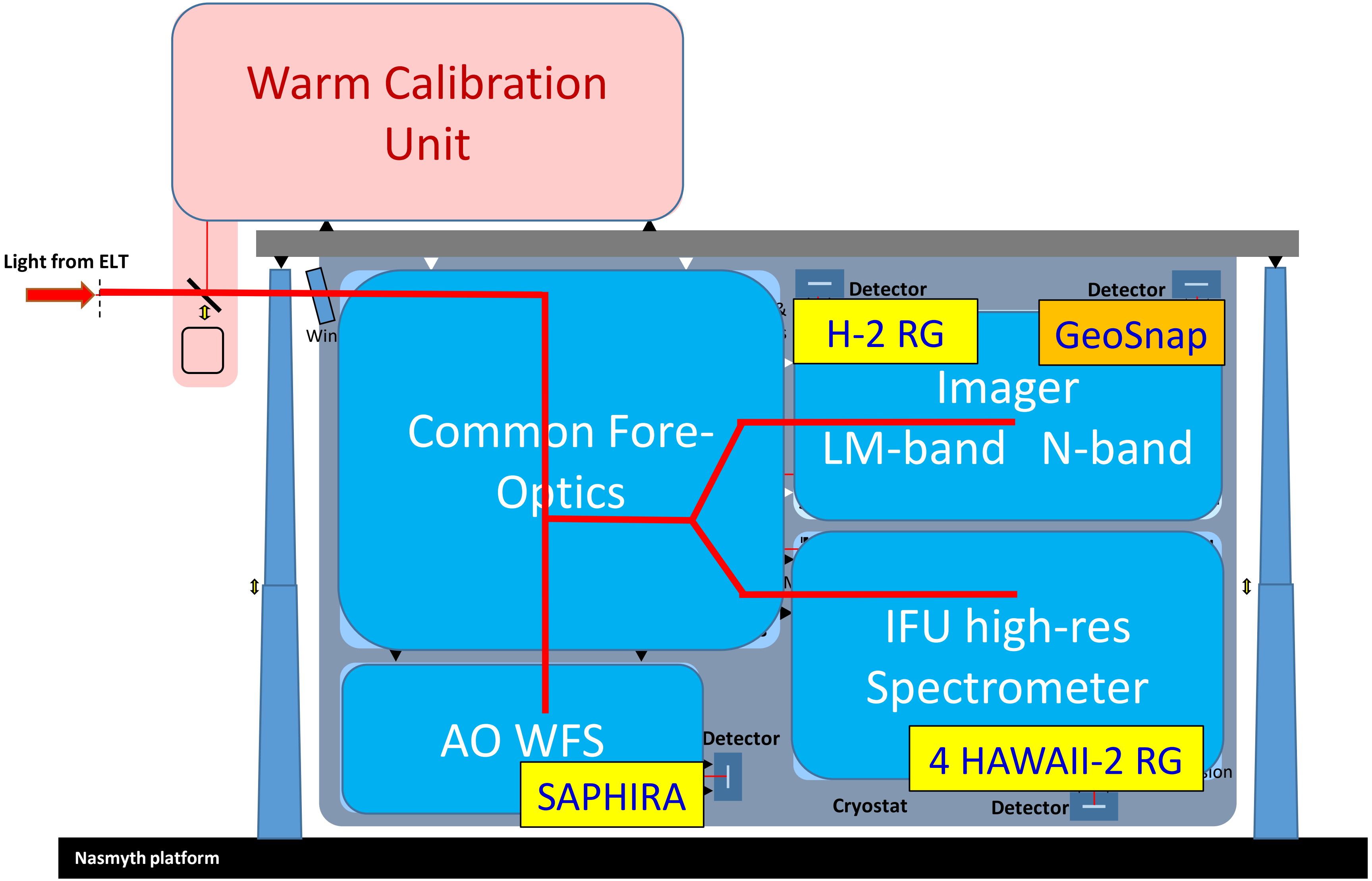
# Design Considerations




Conceptual considerations:

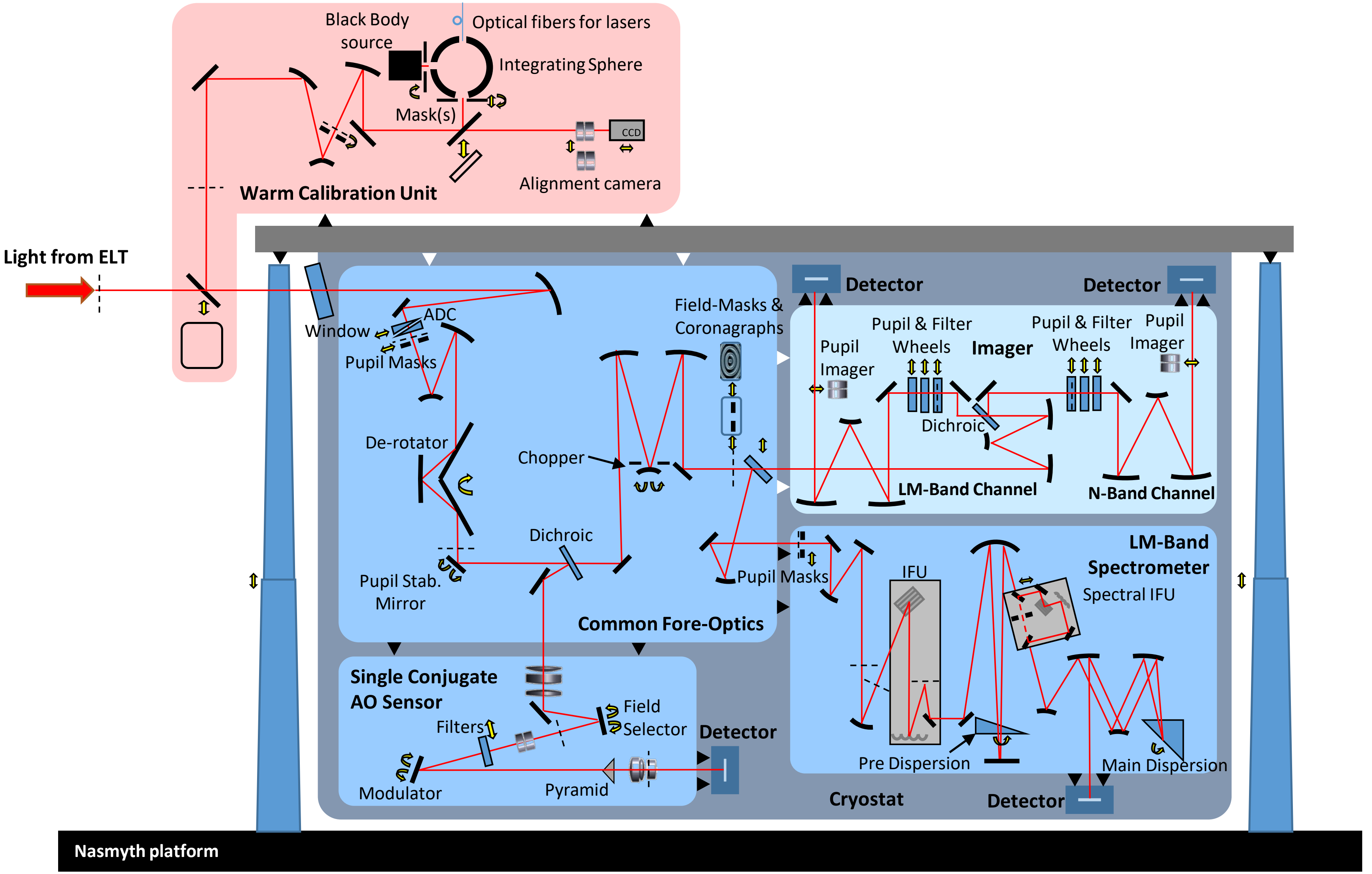
- Spectrograph concept (IFU ⇔ cross-dispersed)
- Type of AO wavefront sensor (pyramid ⇔ Shack-Hartmann)
- Imaging: required field of view (incl. chopping)

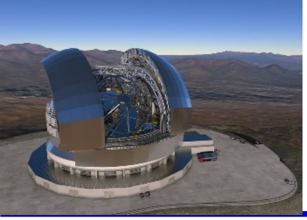
# Optical Concept




See talks by Dani Atkinson and Michael Meyer on Friday afternoon

# Optical Concept





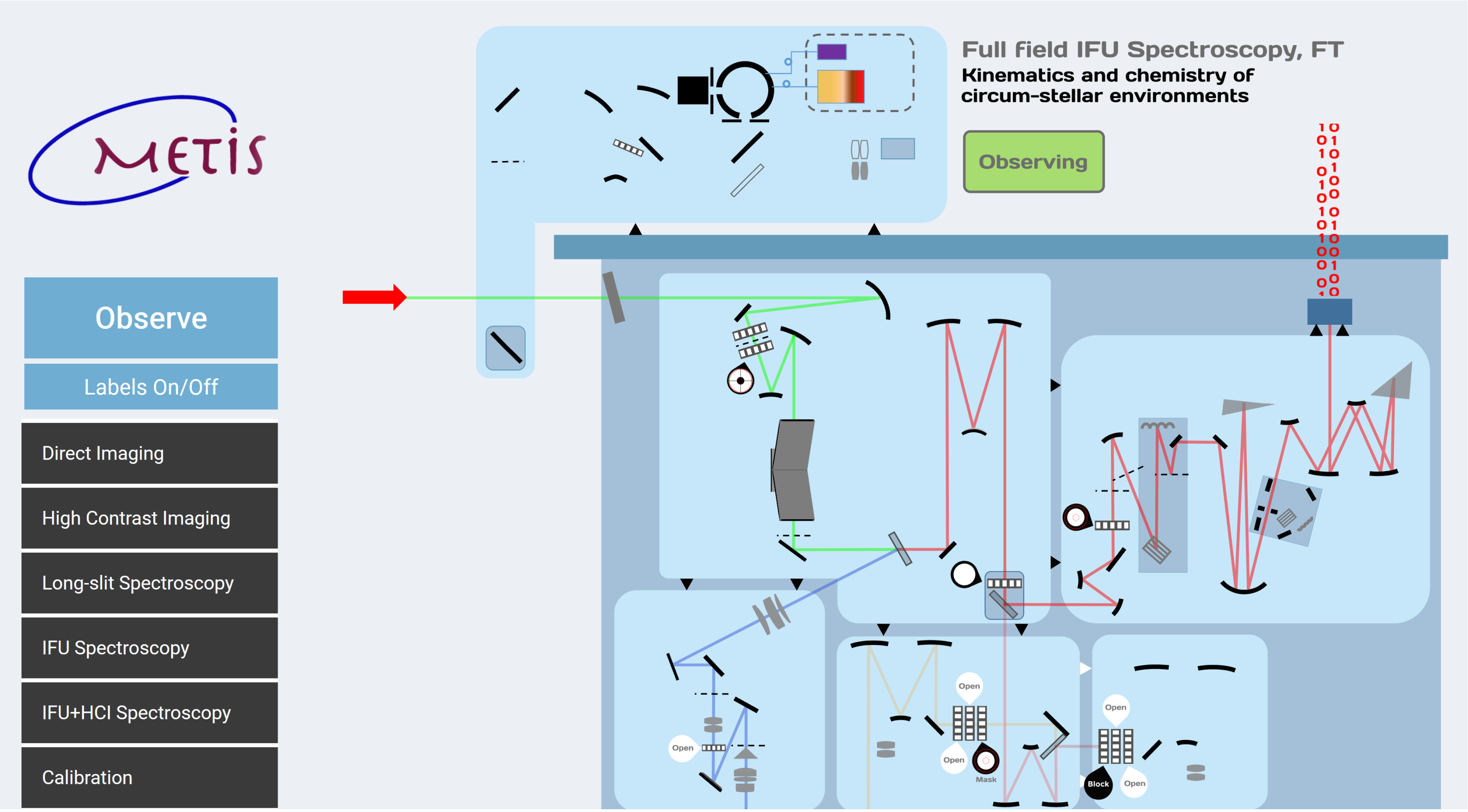
# METIS Website

Mid-infrared ELT Imager and Spectrograph

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

Lots of info … and a very instructive App:

- Home
- Science
- Design Concept
- SimMETIS
- Publications
- Consortium
- Team members
- Jobs
- Outreach
- Contact
- Wiki

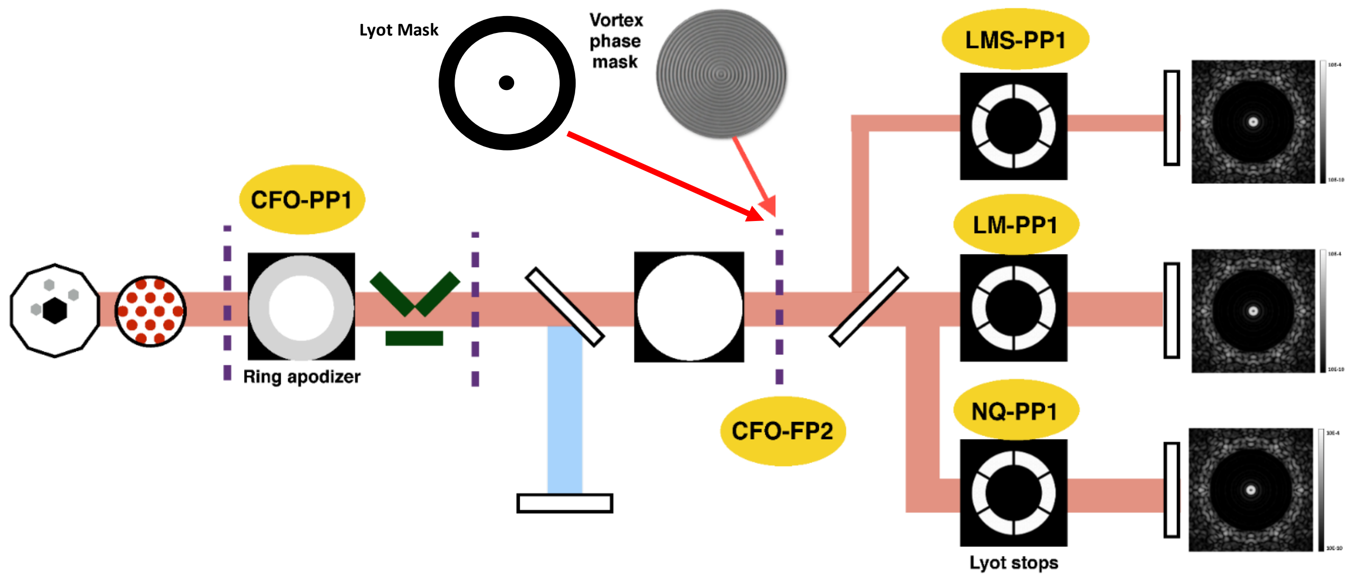


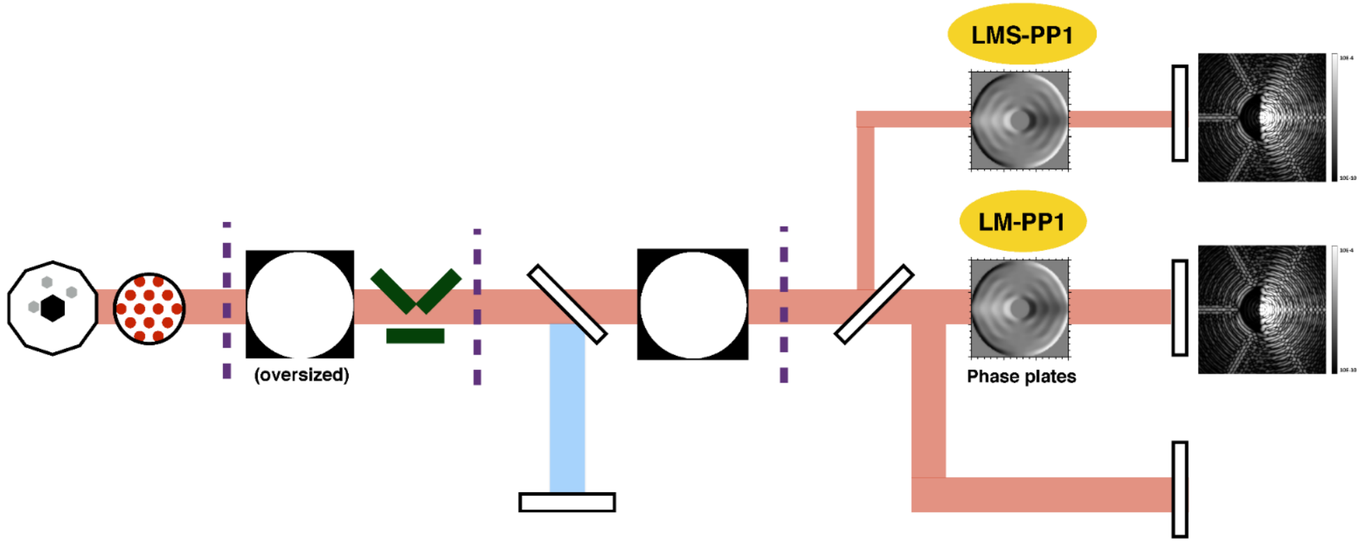
# Coronagraph Concepts

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>

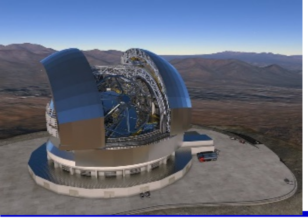
*...depending on the actual boundary conditions on the ELT*



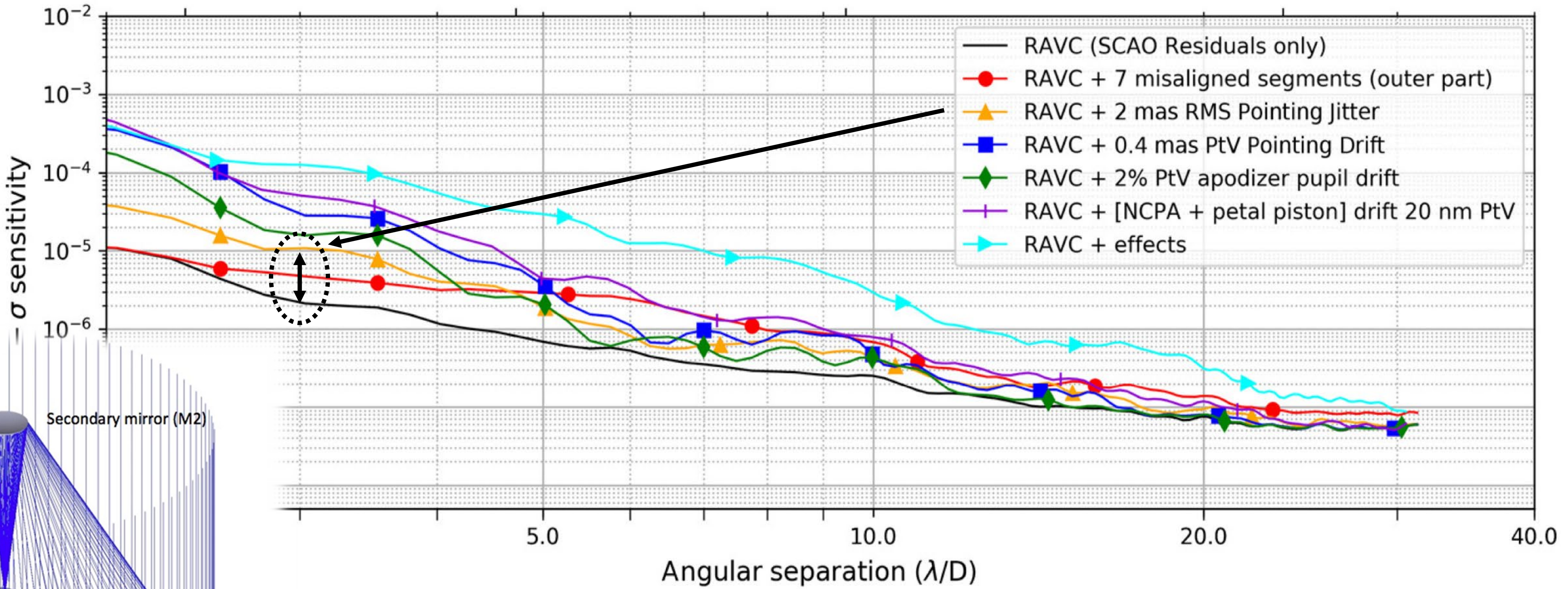


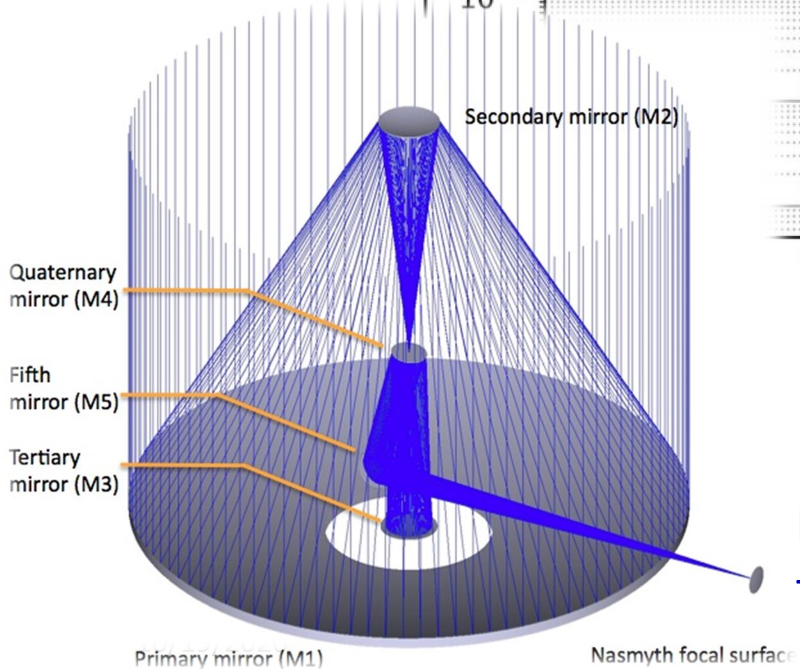

Kenworthy et al. SPIE 10702 (2018)



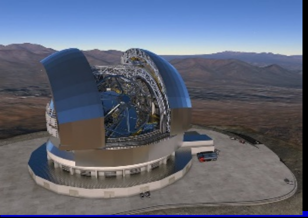
# Coronagraphic Performance

Carlomagno et al. JATIS Vol.6 (2020)



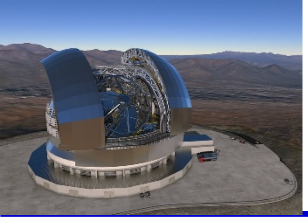




Example: 0.″002 pointing jitter requires M4+M5 to keep the source steady to within 6.6 µm in the telescope focal plane, which is > 20 m from M5.



# Science Case Overview

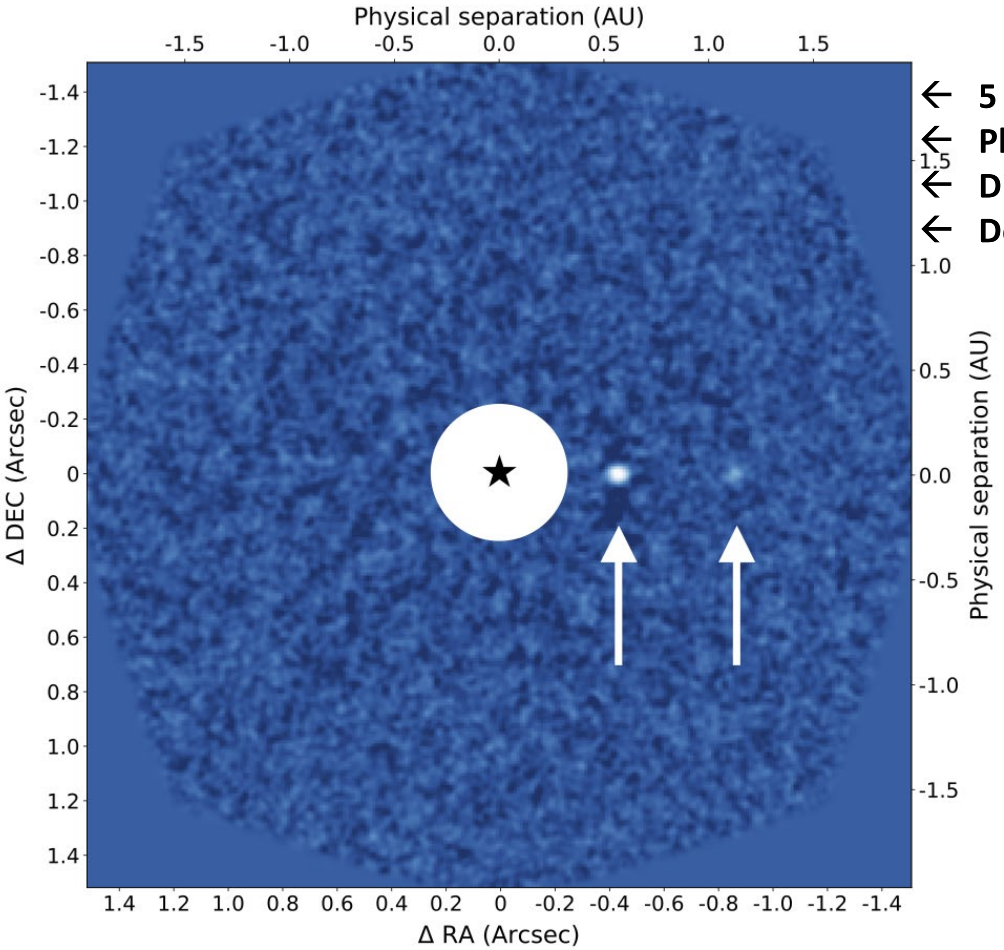
METIS
Mid-infrared ELT Imager and Spectrograph



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

## Simulation: direct imaging of Alpha Cen A at 10µm

METIS N2 band - Alpha Cen A

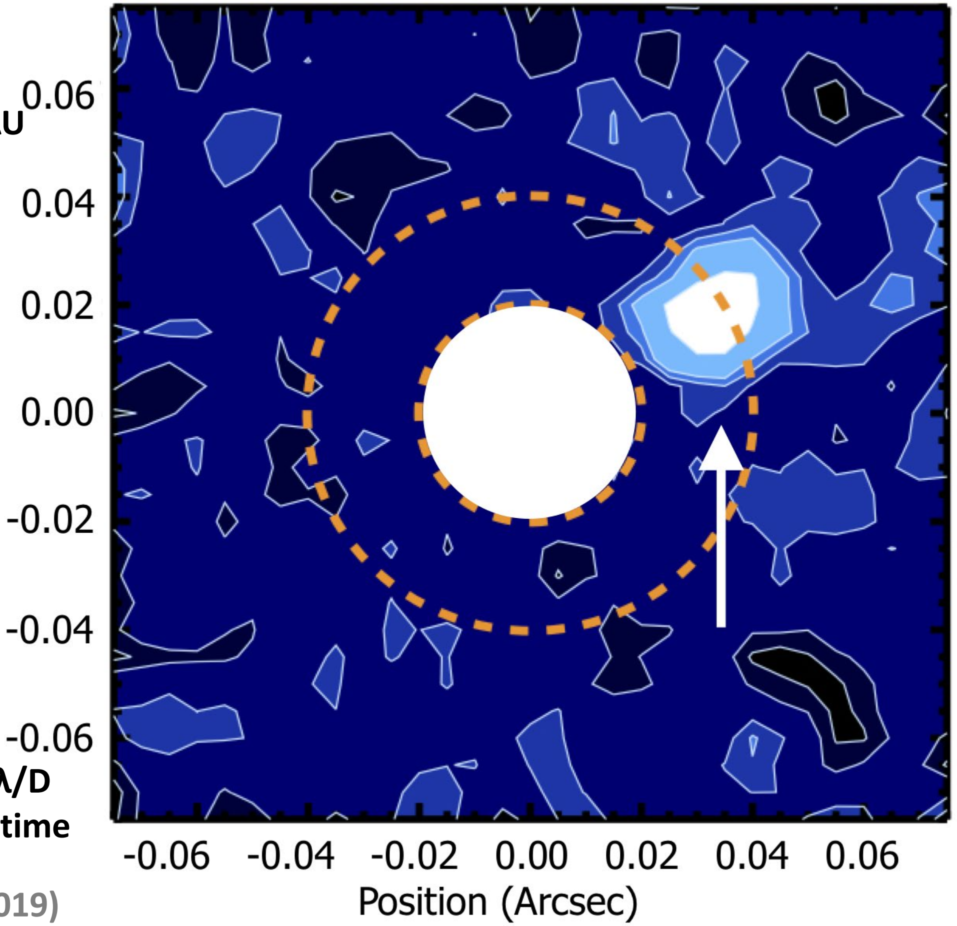



- ← 5 hours on-source time
- ← Planets of Earth radius and albedo
- ← Dist: 1.1 AU (Earth twin)and 0.55 AU
- ← Detection S/N ~6 and ~10

Quanz et al. (2015)

## Simulation: IFU spectroscopy of Proxima Cen b at 3.8 µm

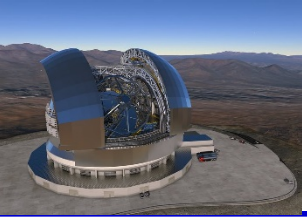
METIS LMS (L band): Proxima Cen b




- → 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)

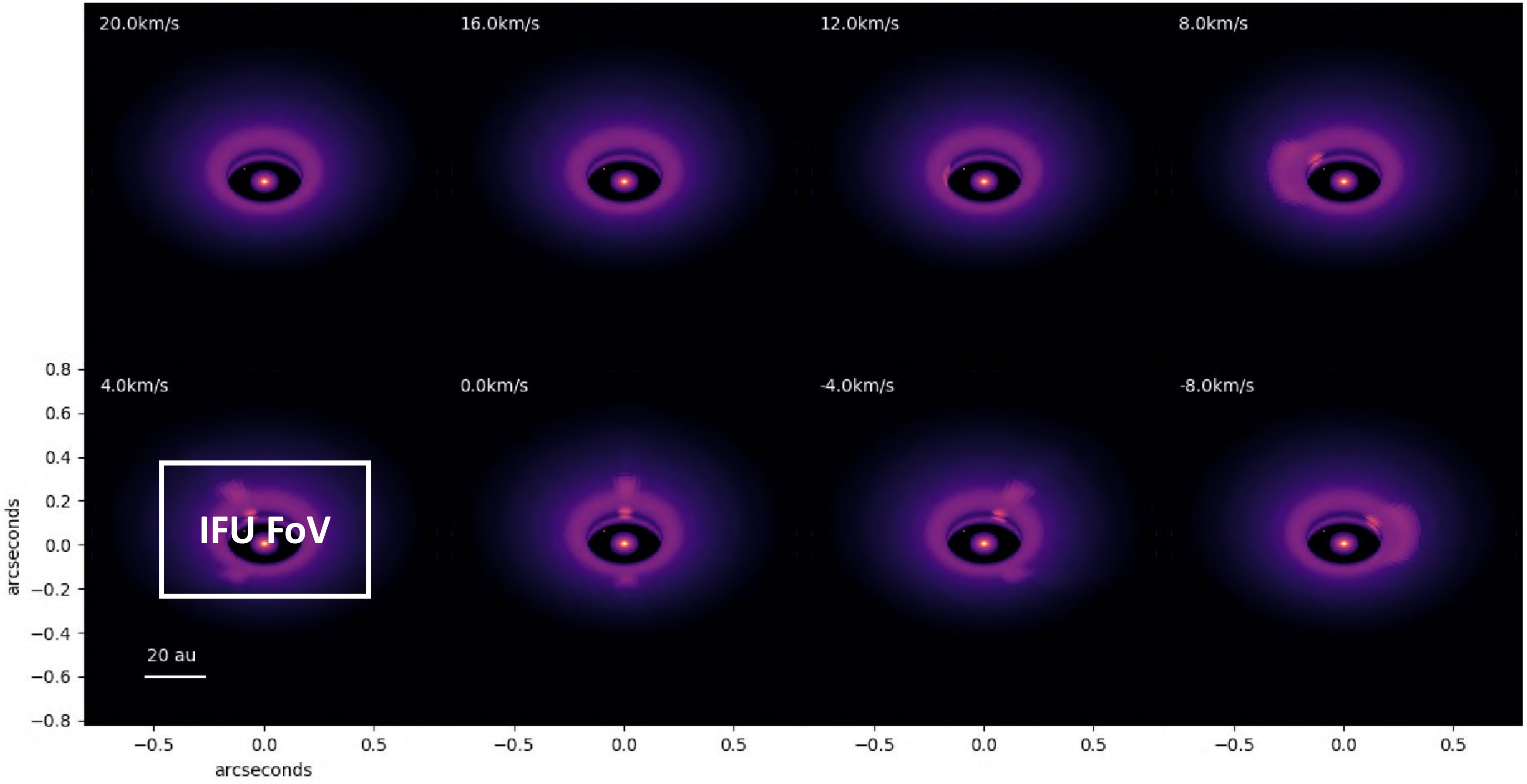


# Proto-planetary Disks and Planet Formation

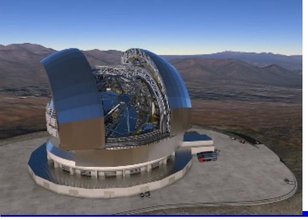
Mid-infrared ELT Imager and Spectrograph

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

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



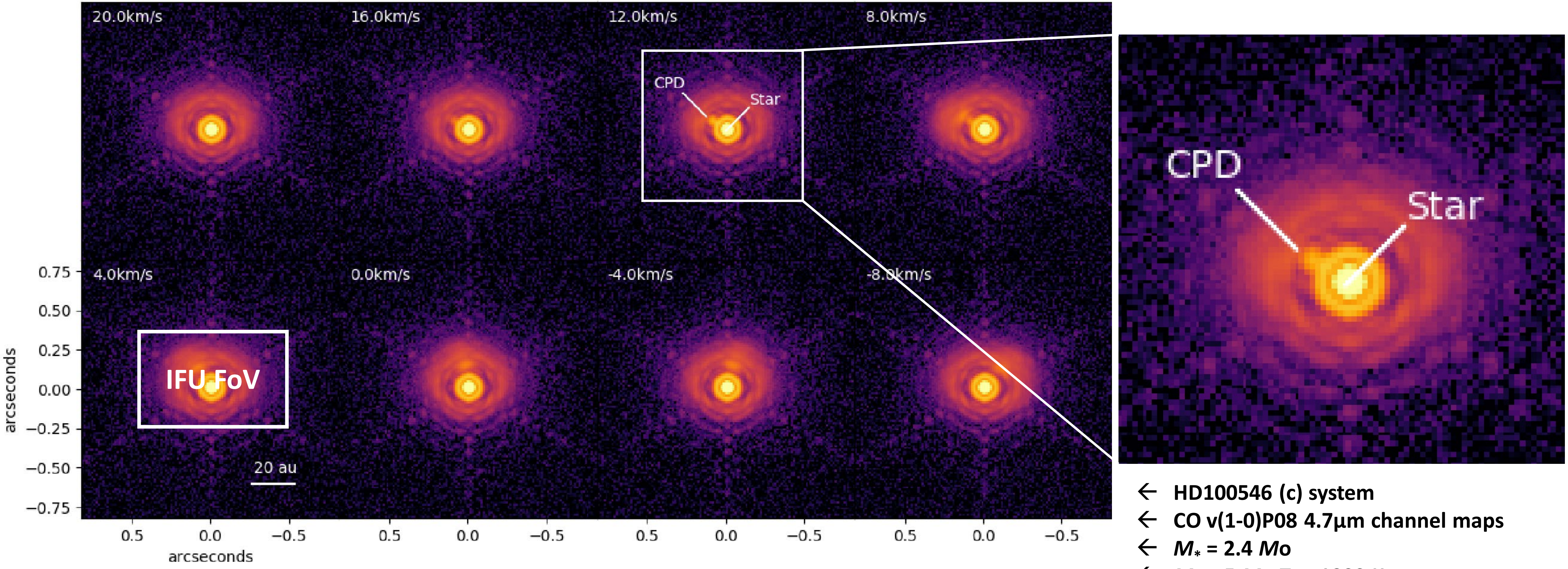

- ← HD100546 (c) system
- ← CO v(1-0)P08 4.7µm channel maps
- ← $M_*$ = 2.4 *Mo*
- ← $M_p$ = 5 $M_J$, $T_P$ = 1000 K
- ← $M_{CPD}$ = 5x10$^{-2}$ $M_J$
- ← $t_{int}$ = 1 hr



# Proto-planetary Disks and Planet Formation

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

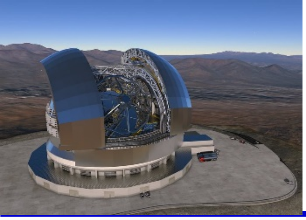
Quanz et al. "METIS Science Case" (2019)




Simulated METIS observations of the same model

- ← 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

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)

} 1st light

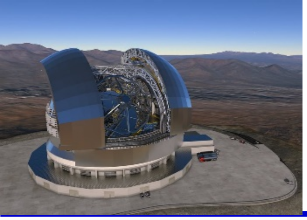
- proposed 2nd generation: PSI, HROS, IRMOS, NIRES, ARISE, and:

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

Proposed Organigram:

MICHI Advisory Board
Principal Investigator
Packham
Co-Investigators
Science Team Leaders
Project Scientist
Honda-san
Instrument Scientist
Sakon-san
Instrument Advisory Panel
Optics
NAOJ/SwRI
Coronography
HAA
Polarimetry
India (TBC)
Mechanical
NAOJ
Array
Michigan
Electrical
SwRI
Software Control
India (TBC)
Data Reduction
USA/India (TBC)
Systems Engineering
SwRI
Project Management
SwRI/NAOJ

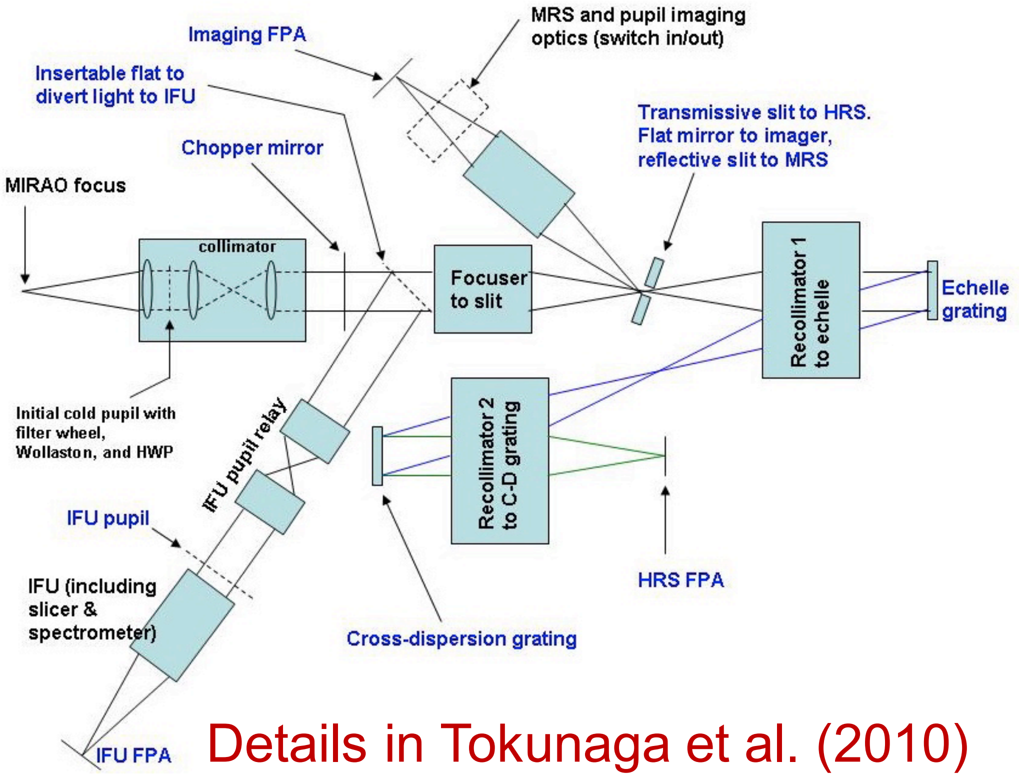
see talk by Chris Packham on Thursday



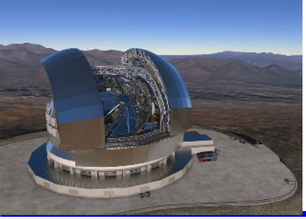
# MICHI Overview

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!