

## Challenges for mid-IR Instruments on ELTs (PPT)

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# Challenges for mid-IR Instruments on ELTs

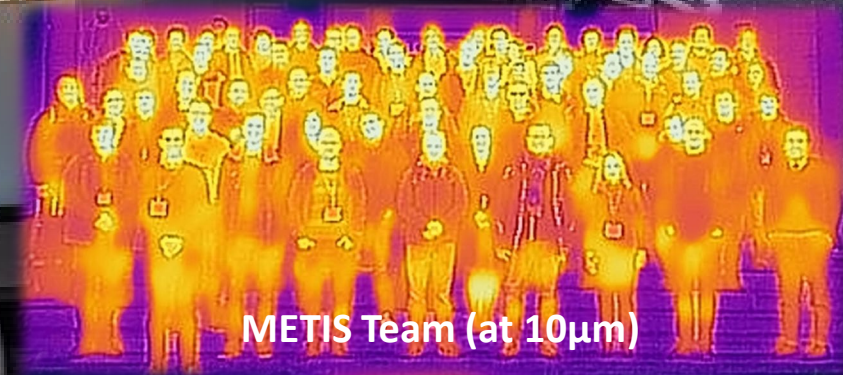
1. General MIR Challenges
2. Specific Challenges on ELTs
3. METIS (ELT) & MICHI (TMT)

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

IR2020: Ground-based thermal infrared astronomy

– past, present and future

Bernhard Brandl



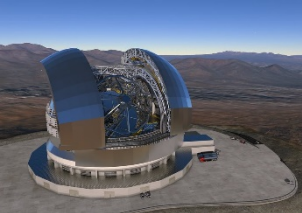


# 1. General MIR Challenges

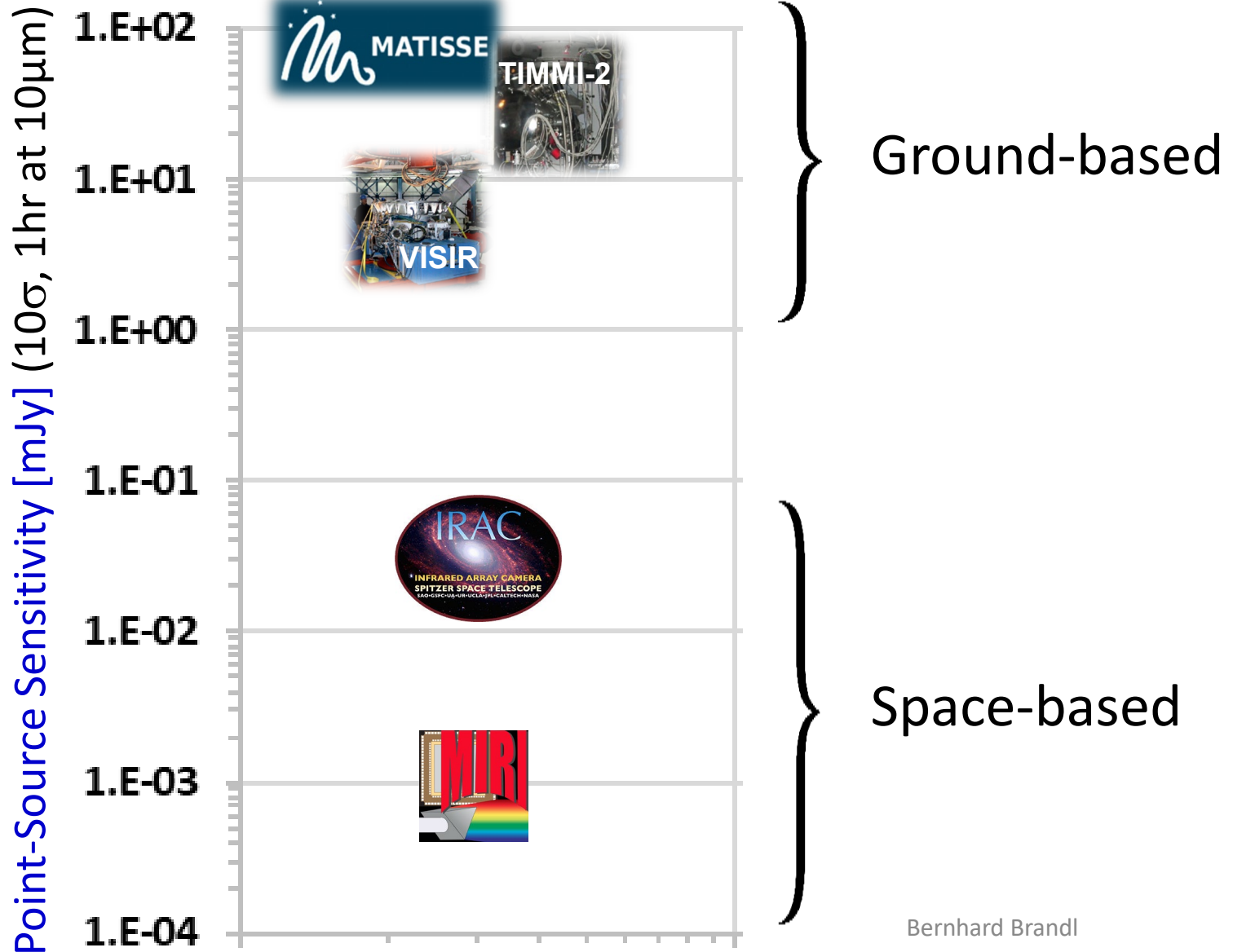
- Sensitivity
- Thermal Background
- Angular Resolution

## 2. Specific Challenges on ELTs

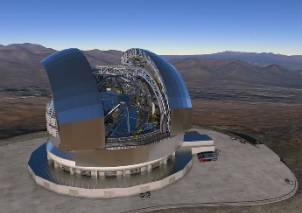
## 3. METIS (ELT) & MICHI (TMT)



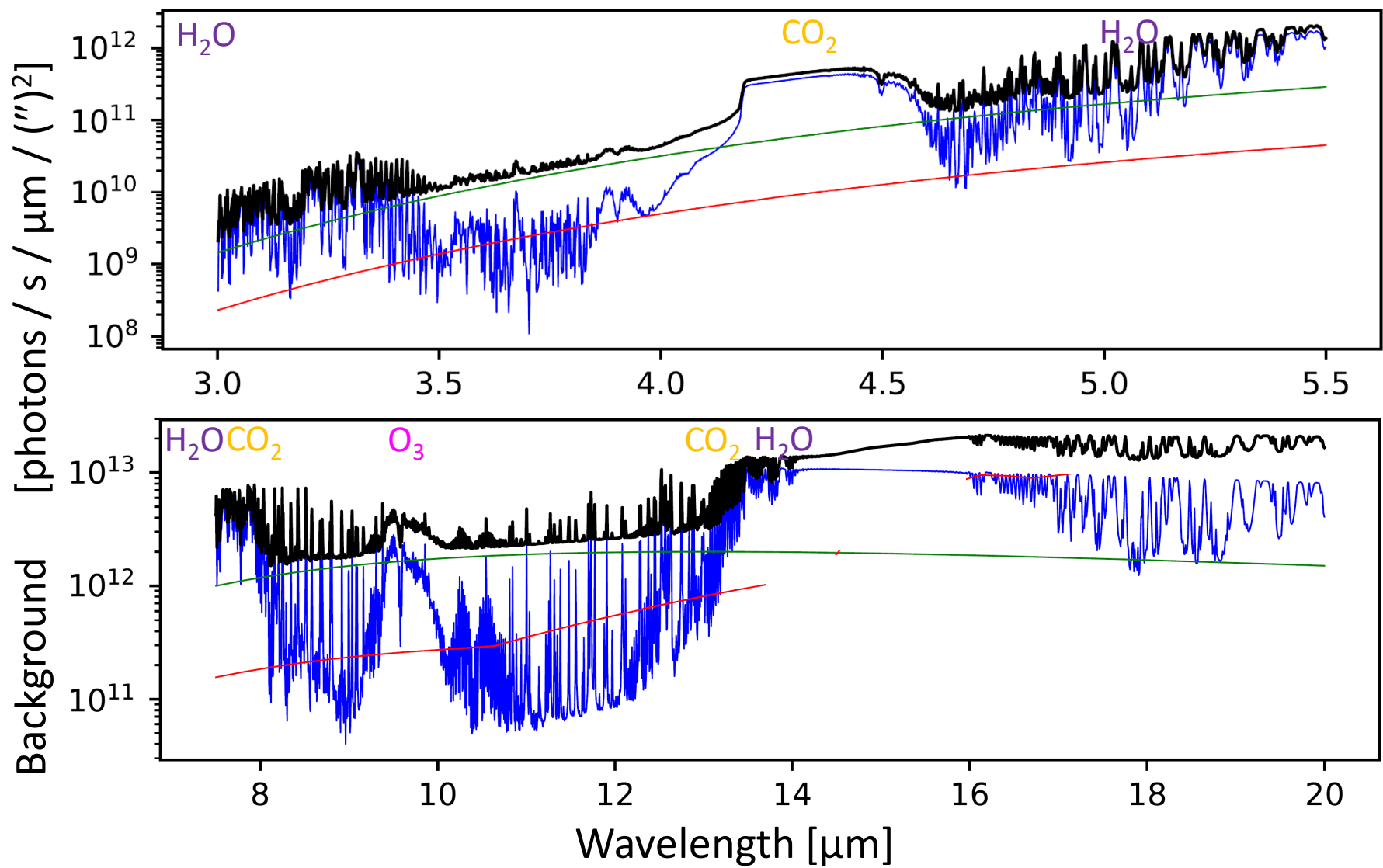
# Main Challenge: achieving good Sensitivity



see talk by Chris Packham on Thursday



# The thermal Background



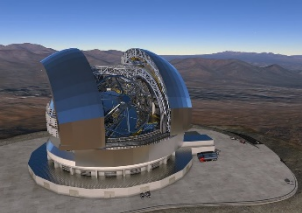
Contributions from\*:

- Sky
- Telescope
- Window
- Total

Main absorbing molecules:

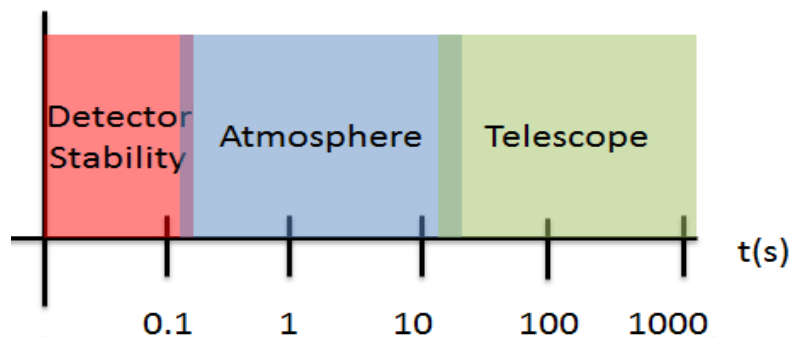
- $\text{H}_2\text{O}$
- $\text{CO}_2$
- $\text{O}_3$

\*Calculated for the ELT on Cerro Armazones

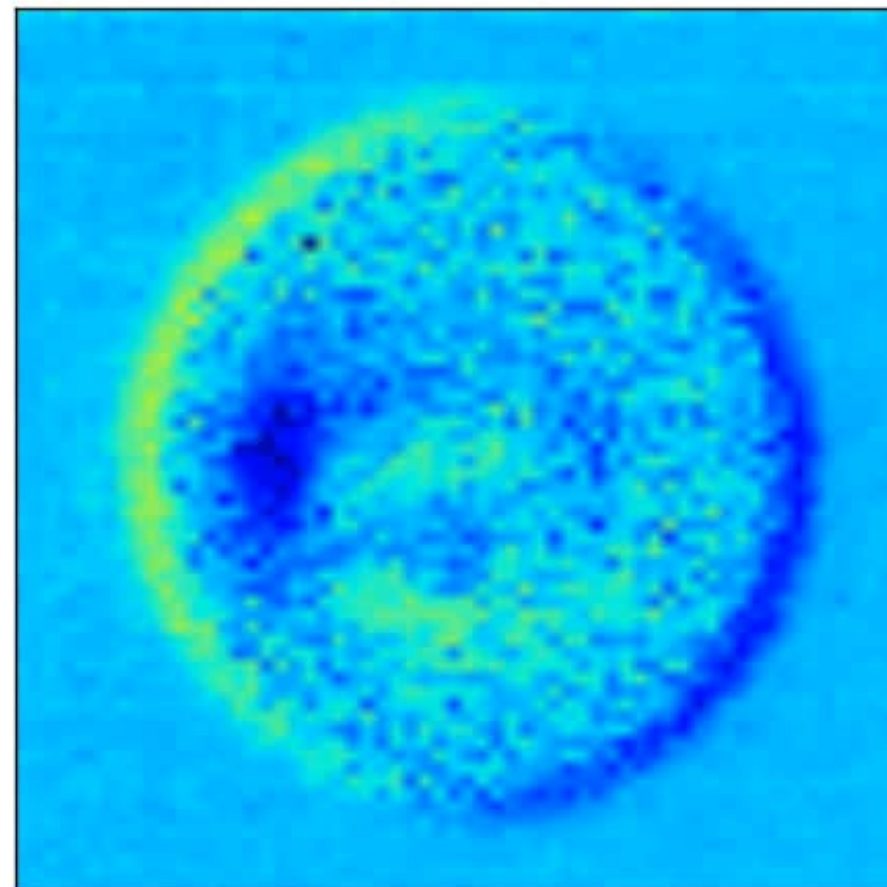


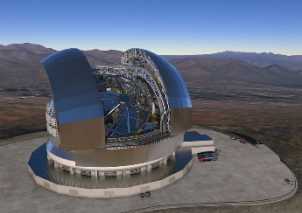
# The *variable* thermal IR Background

The thermal background is **non-uniform** ( $f_{\text{Telescope}}$ ) and **time-variable** ( $f_{\text{Air, Telescope}}$ )



Time series of MIDI chop-difference acquisition frames



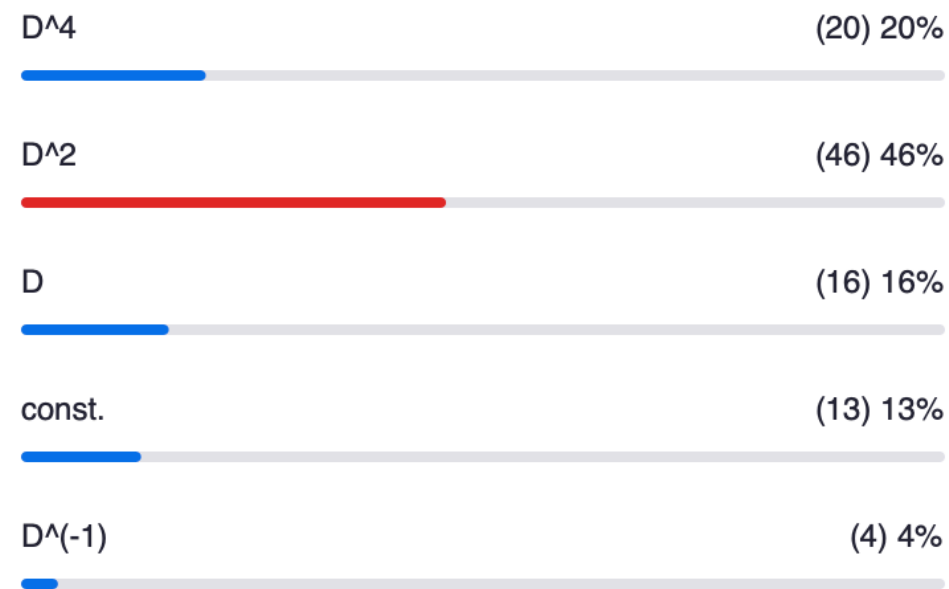


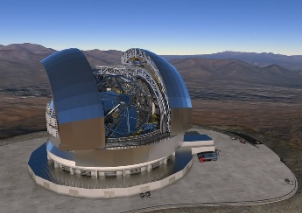
# Zoom Poll

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  $D$ ?

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

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  $D$ ?

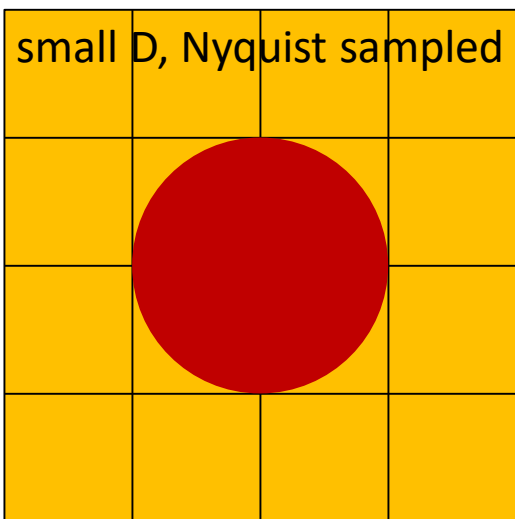




# “Extended Source-Sensitivities”

## Point source

## Extended source



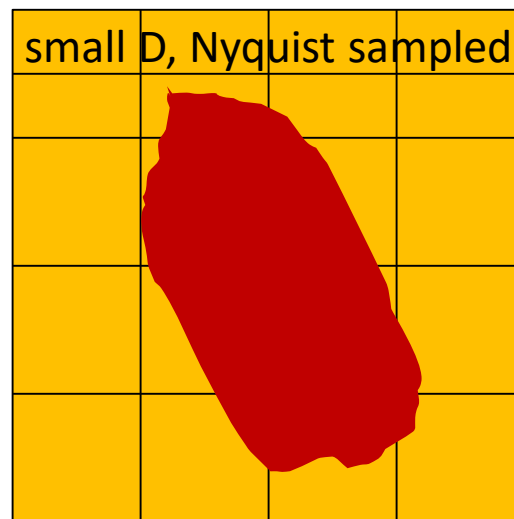
Telescope aperture:

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

Pixel FoV:

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

Background Star



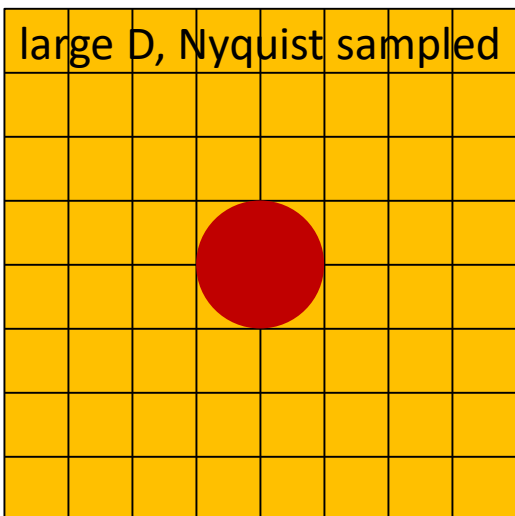
Telescope aperture:

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

Pixel FoV:

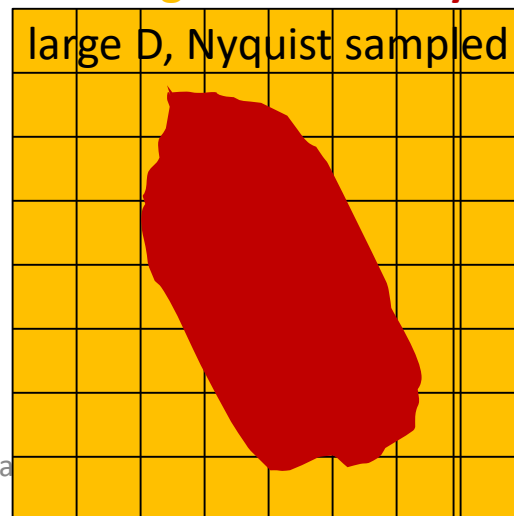
$$\left. \begin{aligned} S &\propto D^{-2} \\ B &\propto D^{-2} \rightarrow N \propto D^{-1} \end{aligned} \right\} S/N \propto D^{-1}$$

Background Galaxy



In total:

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

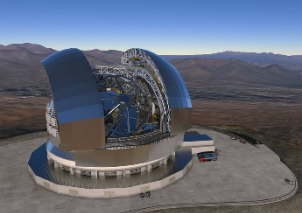


In total:

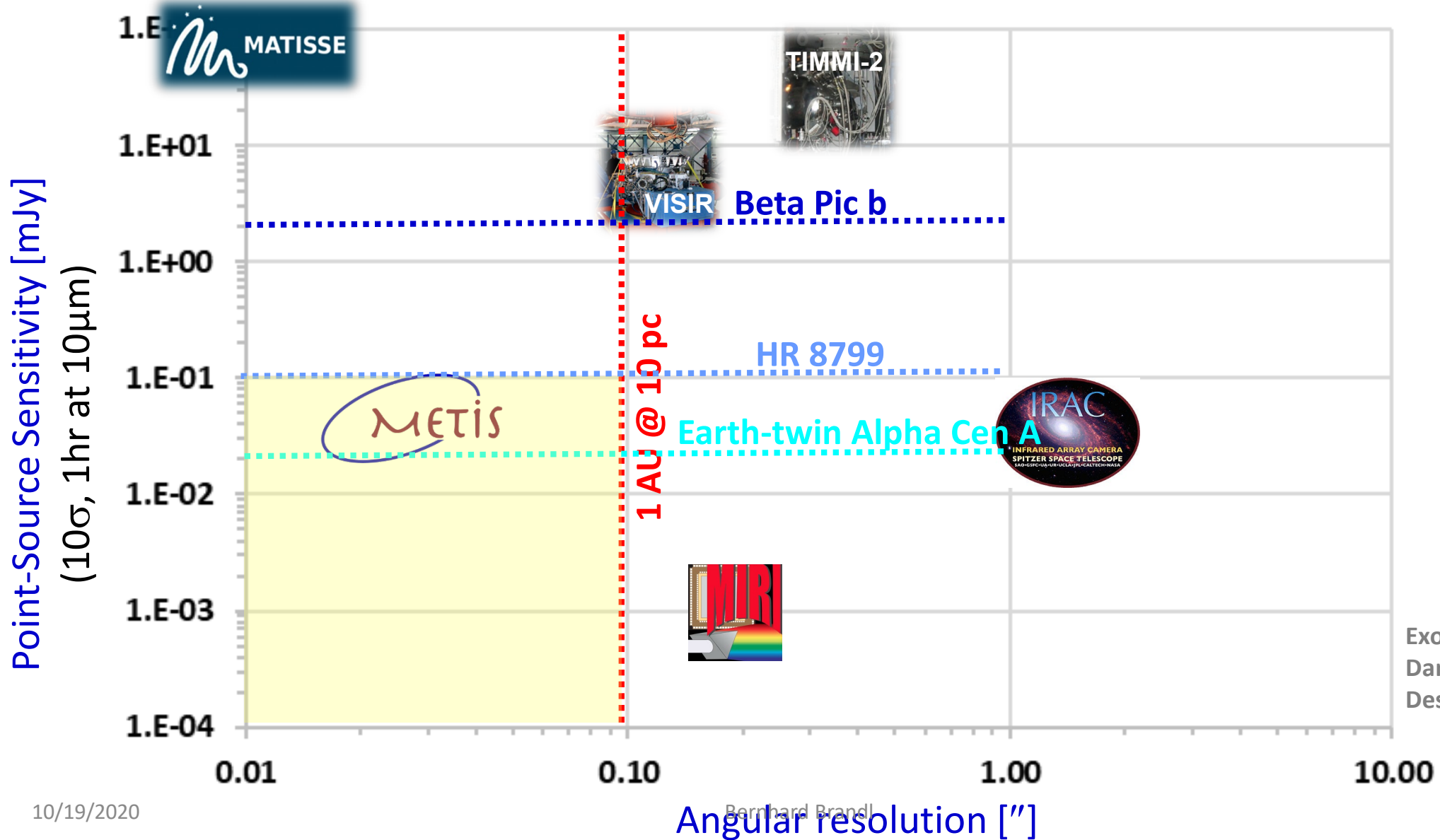
$$S/N \propto \text{const} \rightarrow t_{\text{int}} \propto \text{const}$$

*Resampling would regain sensitivity*





# Why Ground *can* make unique Contributions



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

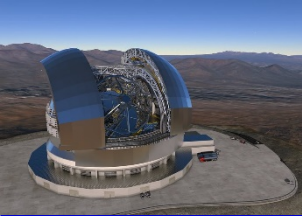


# 1. General MIR Challenges

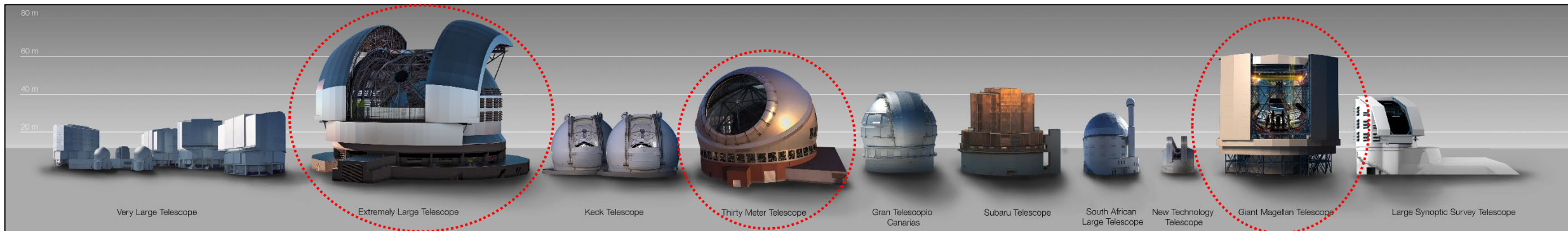
## 2. Specific Challenges on ELTs

- General considerations
- Chopping/Nodding
- Need for Adaptive Optics

## 3. METIS (ELT) & MICHI (TMT)

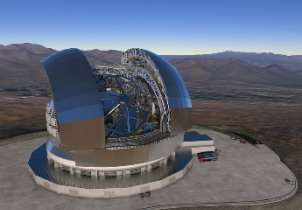


# General Considerations for ELT Instruments

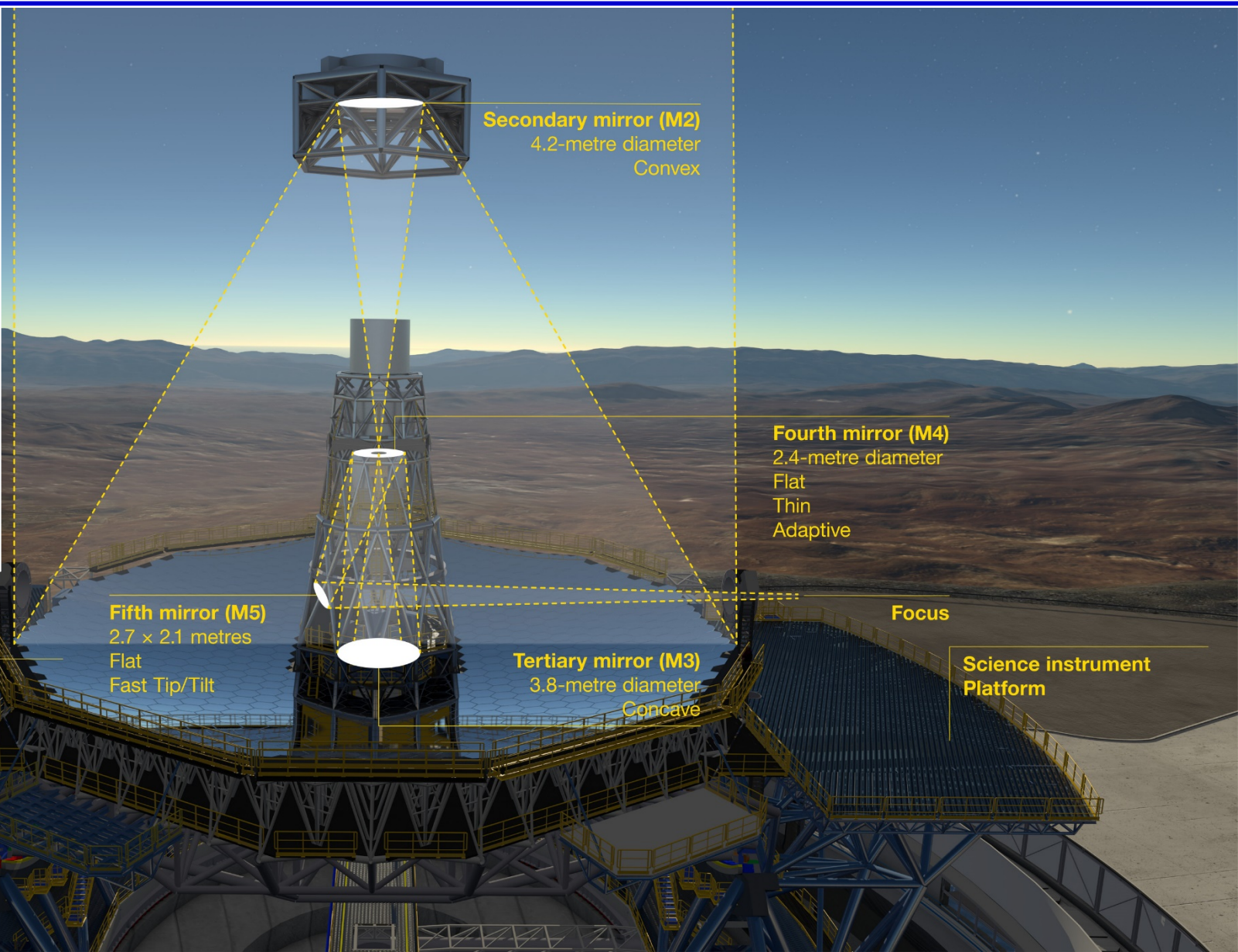
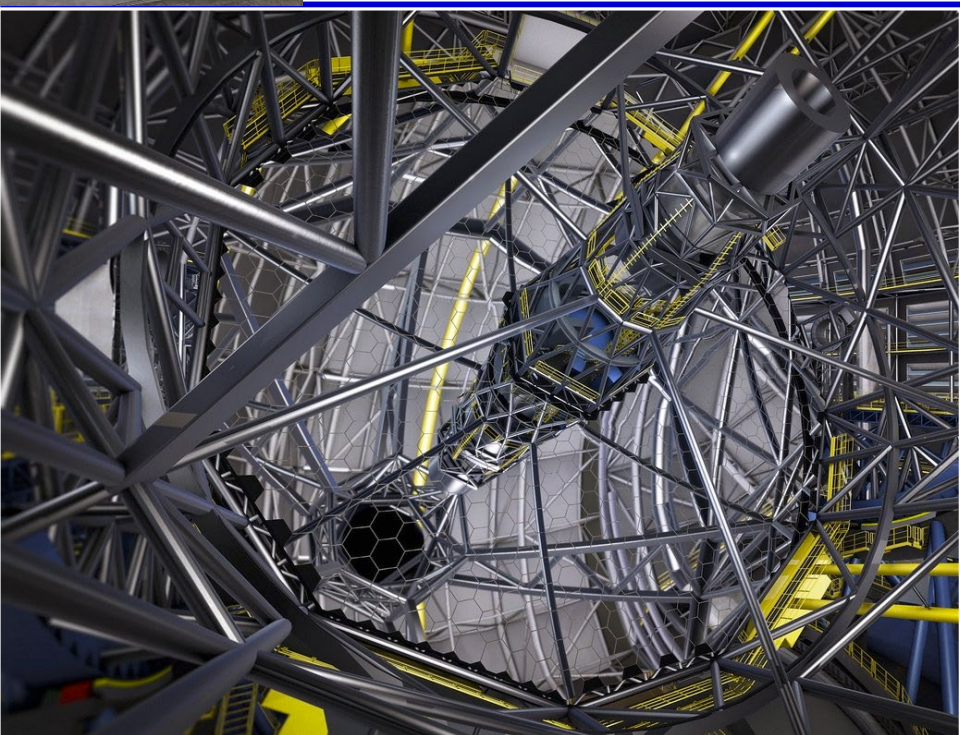


- Exploit the **unique ELT discovery space** ( $\Leftrightarrow$  JWST, LSST, ALMA, ...)
- “There will be **only a few extremely large telescopes**”:
  - Each instrument must serve a large fraction of the community (no “PI-instruments”)
  - Low complexity to ensure low risk, high efficiency, and reliable operation
  - High complexity because there will be only a few instruments on each ELT, and the resources in the community are limited  $\leftarrow$  high threshold for each ELT instrument
- **Science operations** aim at “space standards” (queue scheduling, pipeline processing, data archive, ...)

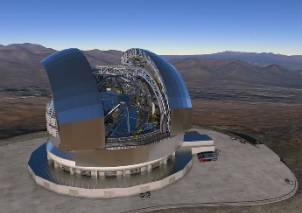
**ELT time:  
500 € / min**



# The (warm and complex) ELT Optics

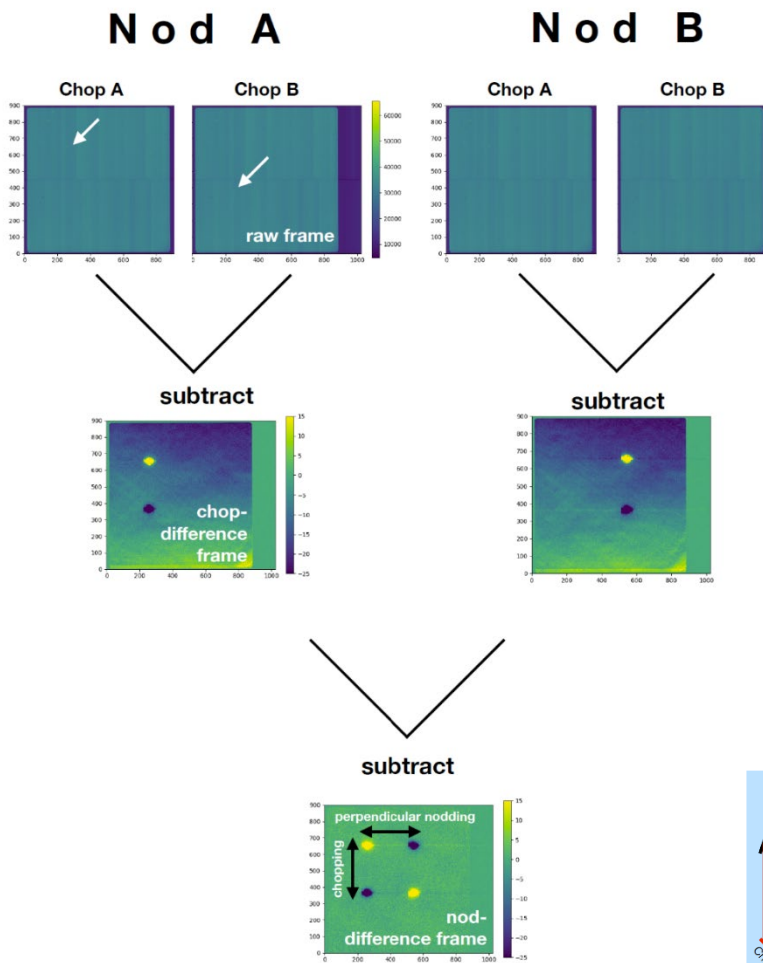


**Primary mirror (M1)**  
39-metre diameter  
Concave  
798 hexagonal segments  
Active



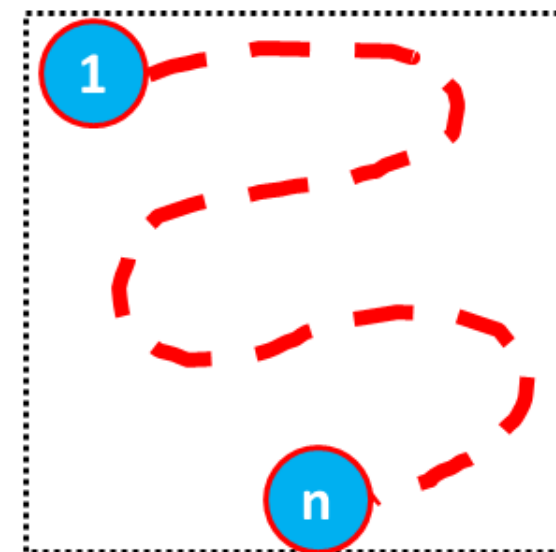
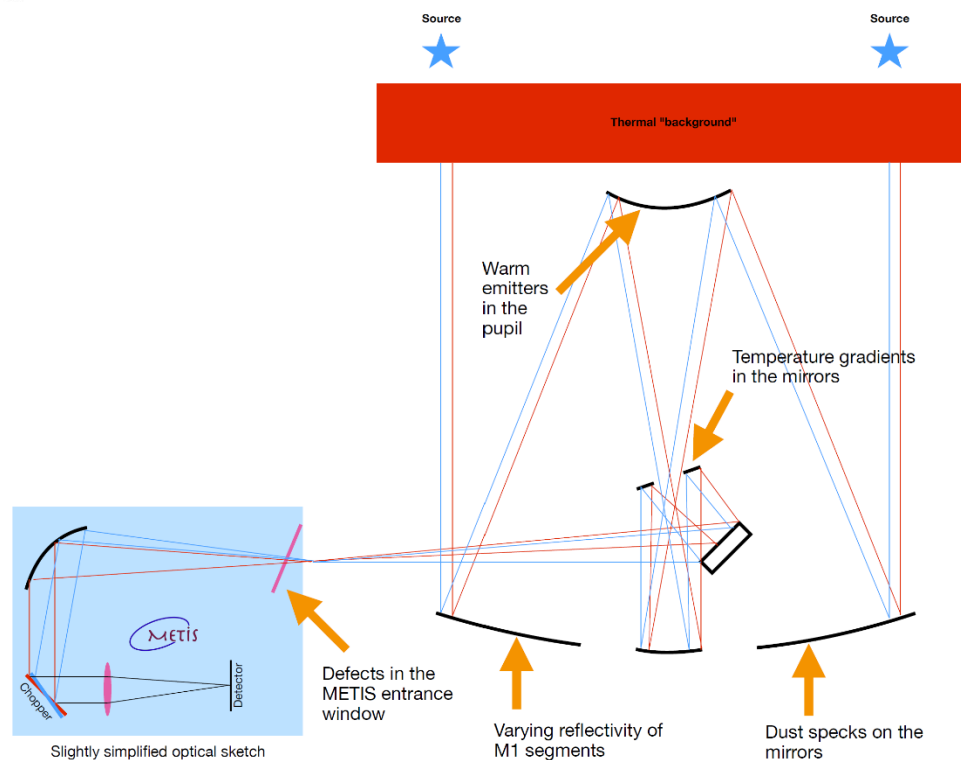
# We have to re-invent chopping/nodding

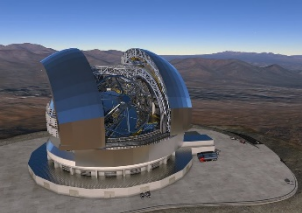
Classical chopping with M2:



**Option #1:** chopping mirror inside instrument  
 + flexibility, accuracy  
 – beam wander upstream

**Option #2?:**  
 Alternatives, like “drift scanning”  
 [TBC]

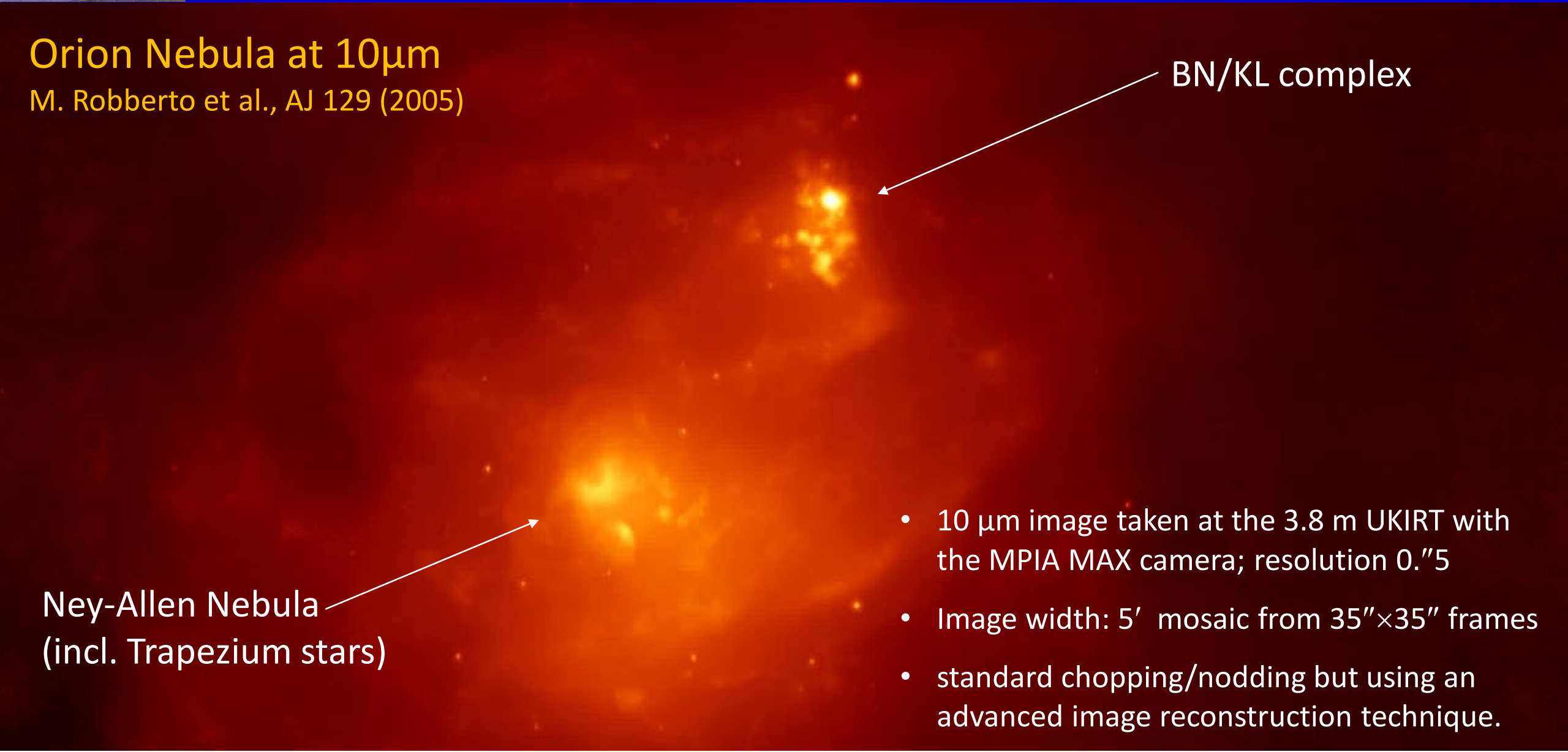




...and develop the Software to optimize it!

## Orion Nebula at $10\mu\text{m}$

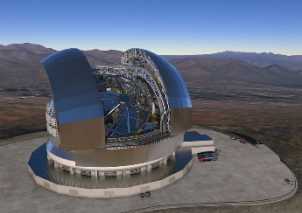
M. Robberto et al., AJ 129 (2005)



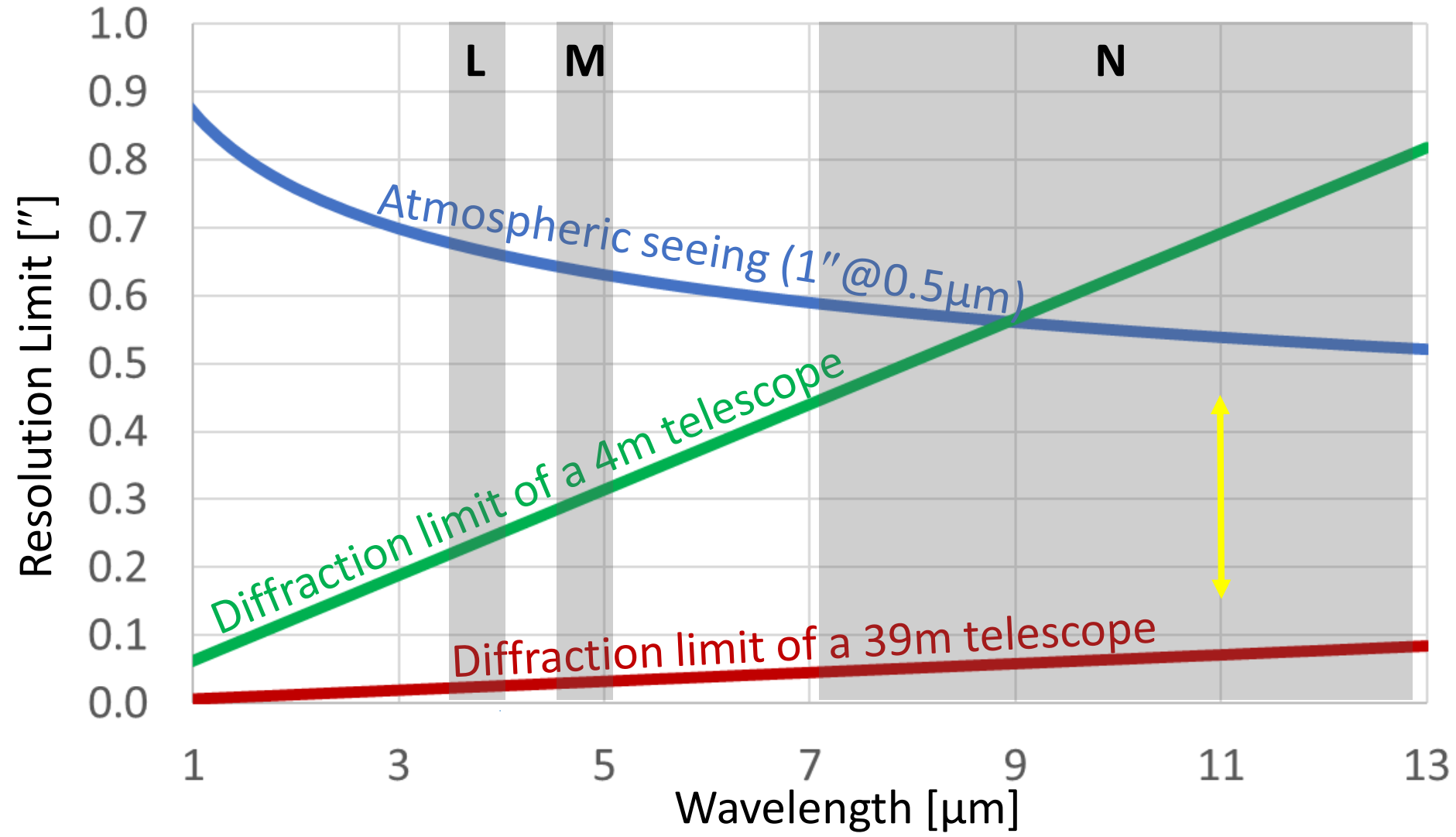
BN/KL complex

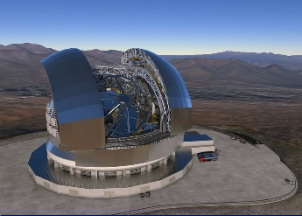
Ney-Allen Nebula  
(incl. Trapezium stars)

- $10\ \mu\text{m}$  image taken at the 3.8 m UKIRT with the MPIA MAX camera; resolution  $0.''5$
- Image width:  $5'$  mosaic from  $35''\times 35''$  frames
- standard chopping/nodding but using an advanced image reconstruction technique.



# The Need for Adaptive Optics





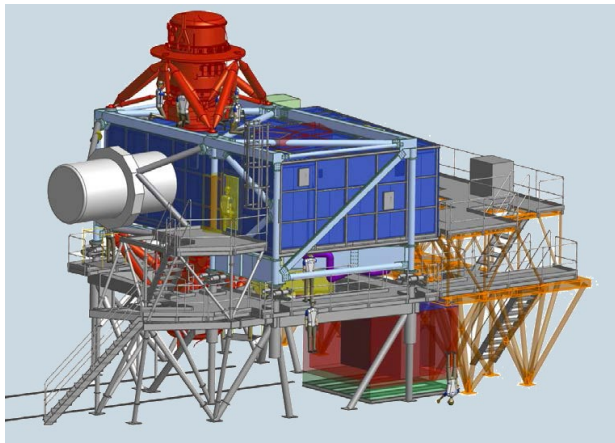
# How to implement AO on an ELT

	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

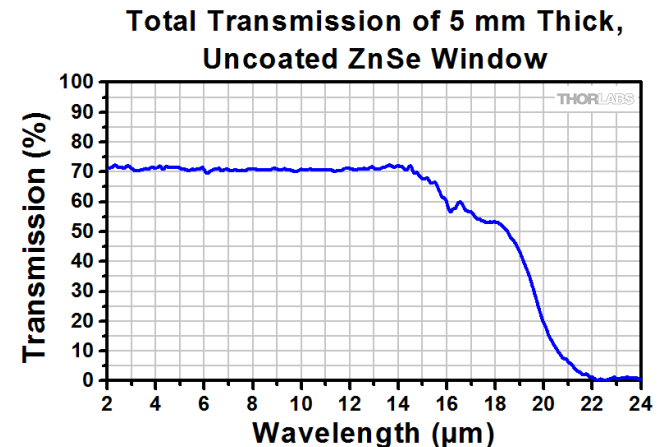
Crane et al. SPIE 10703 (2018)  
 Chun et al. SPIE 6272 (2006)  
 Bertram et al. SPIE 10703 (2018)

Goal: **avoid warm dichroic**

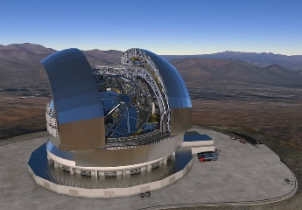
Problem: passing  $\lambda = 0.5 \mu\text{m} - 28 \mu\text{m}$  through window



Bernhard Brandl

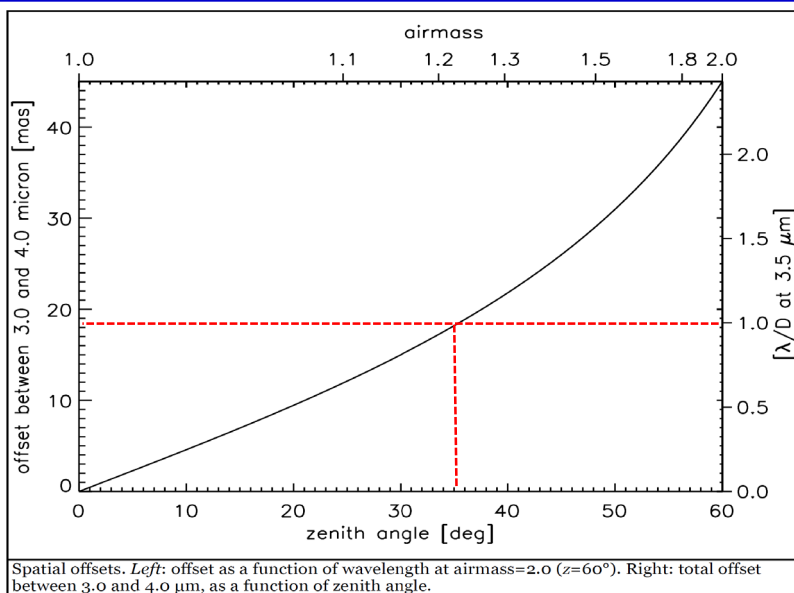
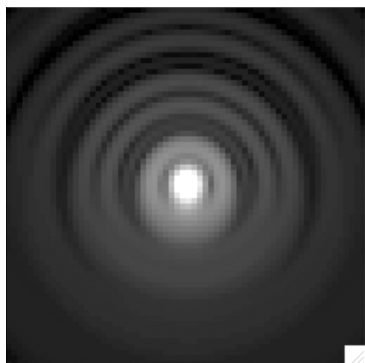






# Other atmospheric & optical Effects

## Atmospheric dispersion

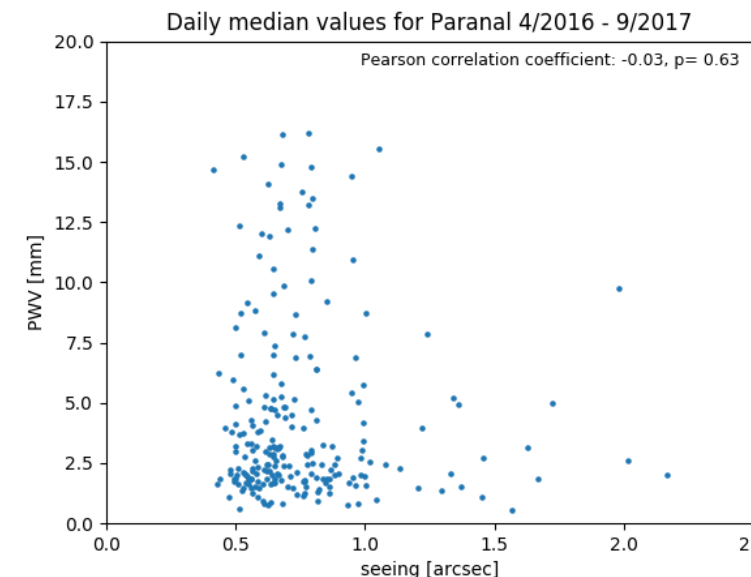


## PWV $\leftrightarrow$ seeing

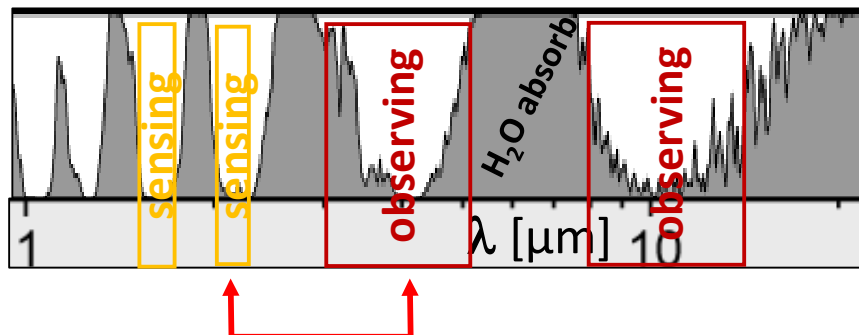
Good news: no correlation

$\rightarrow$  scheduling

© ESO



## H<sub>2</sub>O vapor seeing



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

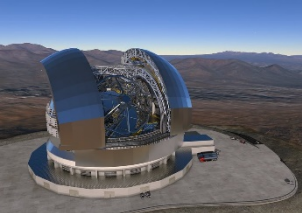
## Quality of the cold optics (usually Al)

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



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

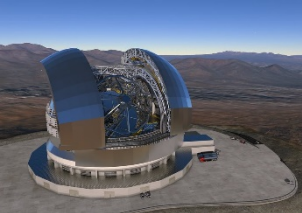
- Overview
- Design Considerations
- Optics & Coronagraphy
- Science Examples



# Project Overview

- The **M**id-IR **E**LT **I**mager and **S**pectrograph is one of three 1<sup>st</sup>-generation ELT science instruments on ESO's ELT
- Consortium of 12 partner institutions + ESO
- Total ~650 FTEs
- Prelim. Design Review (PDR) in 2019
- 1<sup>st</sup>-light in 2027





# Instrument Overview

☐ **Imaging** over a FoV of  $10.5'' \times 10.5''$  ( $3 - 5 \mu\text{m}$ ) and  $13.5'' \times 13.5''$  ( $8 - 13 \mu\text{m}$ ), incl.:

- low resolution ( $R \sim \text{few } 100\text{s}$ ) **longslit spectroscopy**
- **coronagraphy** for high contrast imaging

☐ **High resolution** ( $R \sim 100,000$ ) **IFU spectroscopy** at  $3 - 5 \mu\text{m}$ , over a FoV of  $\sim 0.93'' \times 0.58''$ , incl.

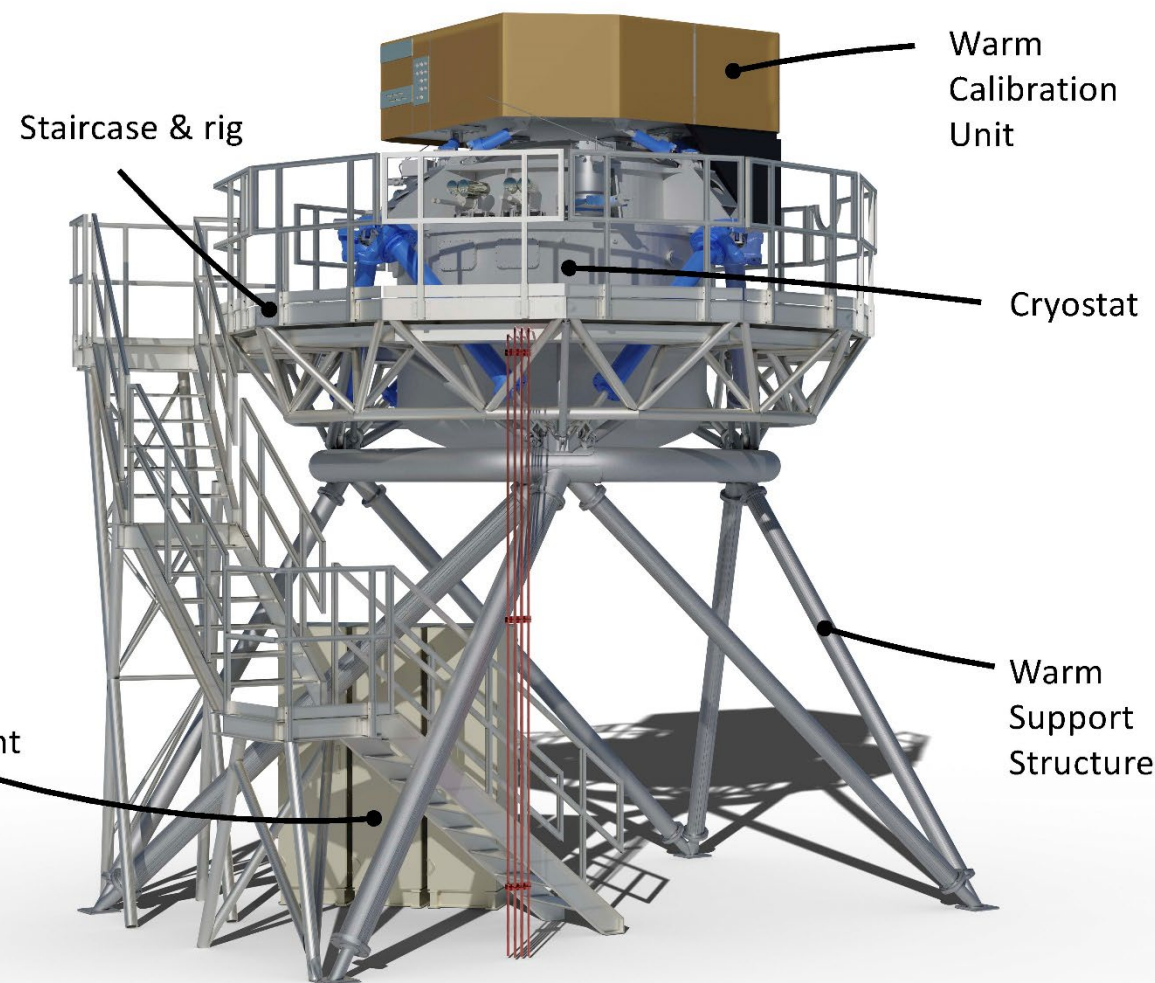
- a mode with extended  $\Delta\lambda_{\text{instant}} \sim 300 \text{ nm}$
- **coronagraphy** for high contrast IFU spectroscopy

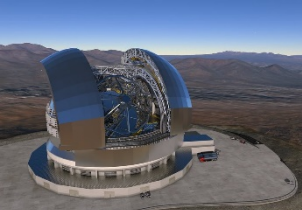
☐ All observing modes work at the **diffraction limit** of the 39m ELT with a single conjugate AO system.

Brandl et al. SPIE 10702 (2018)

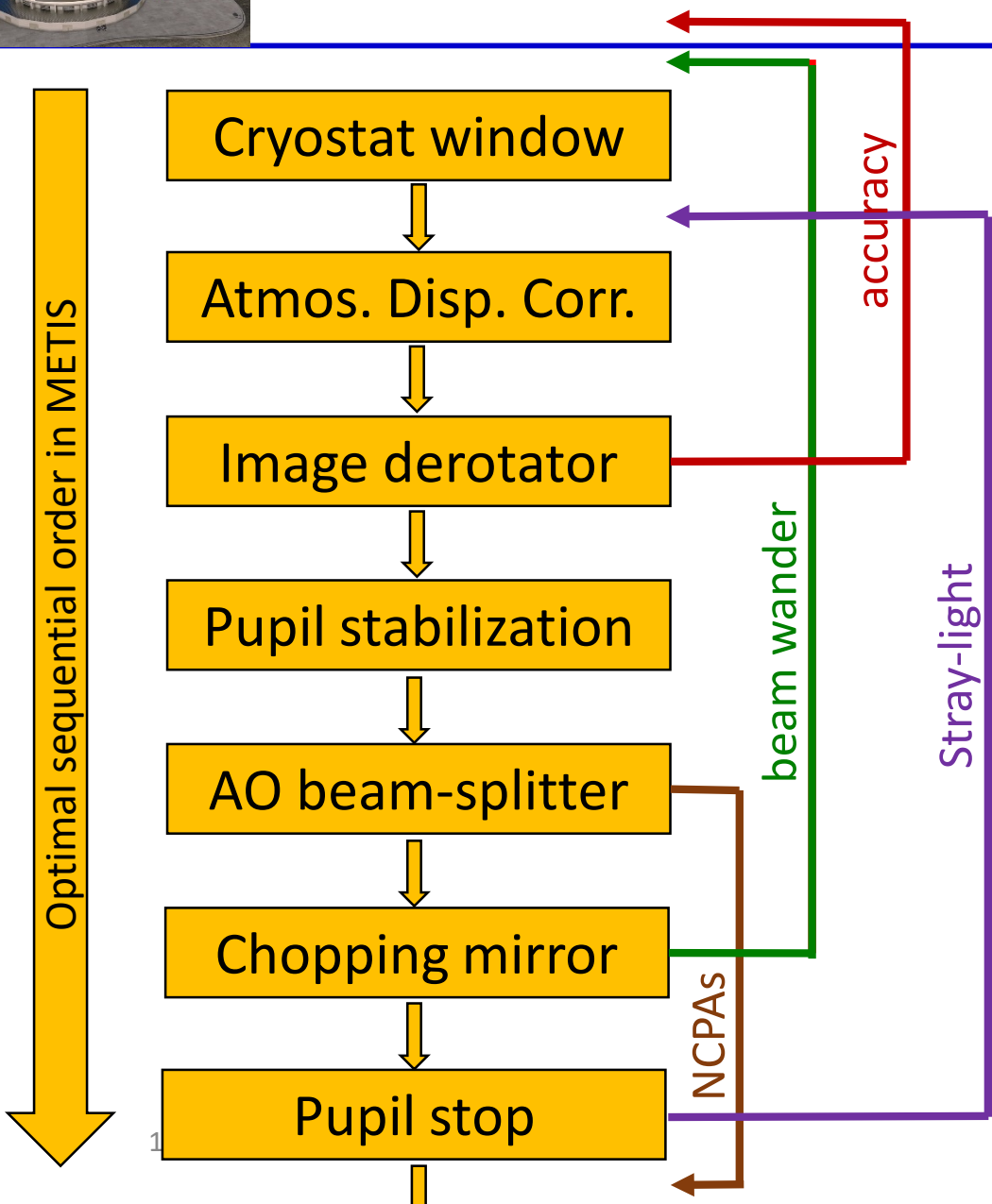
PS sensitivity ( $10\text{-}\sigma$ , 1hr)

$\lambda$	F	mag
<b>L</b>	$1 \mu\text{Jy}$	21.2
<b>M</b>	$8 \mu\text{Jy}$	18.3
<b>N</b>	$50 \mu\text{Jy}$	14.8



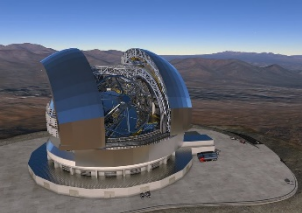


# Design Considerations

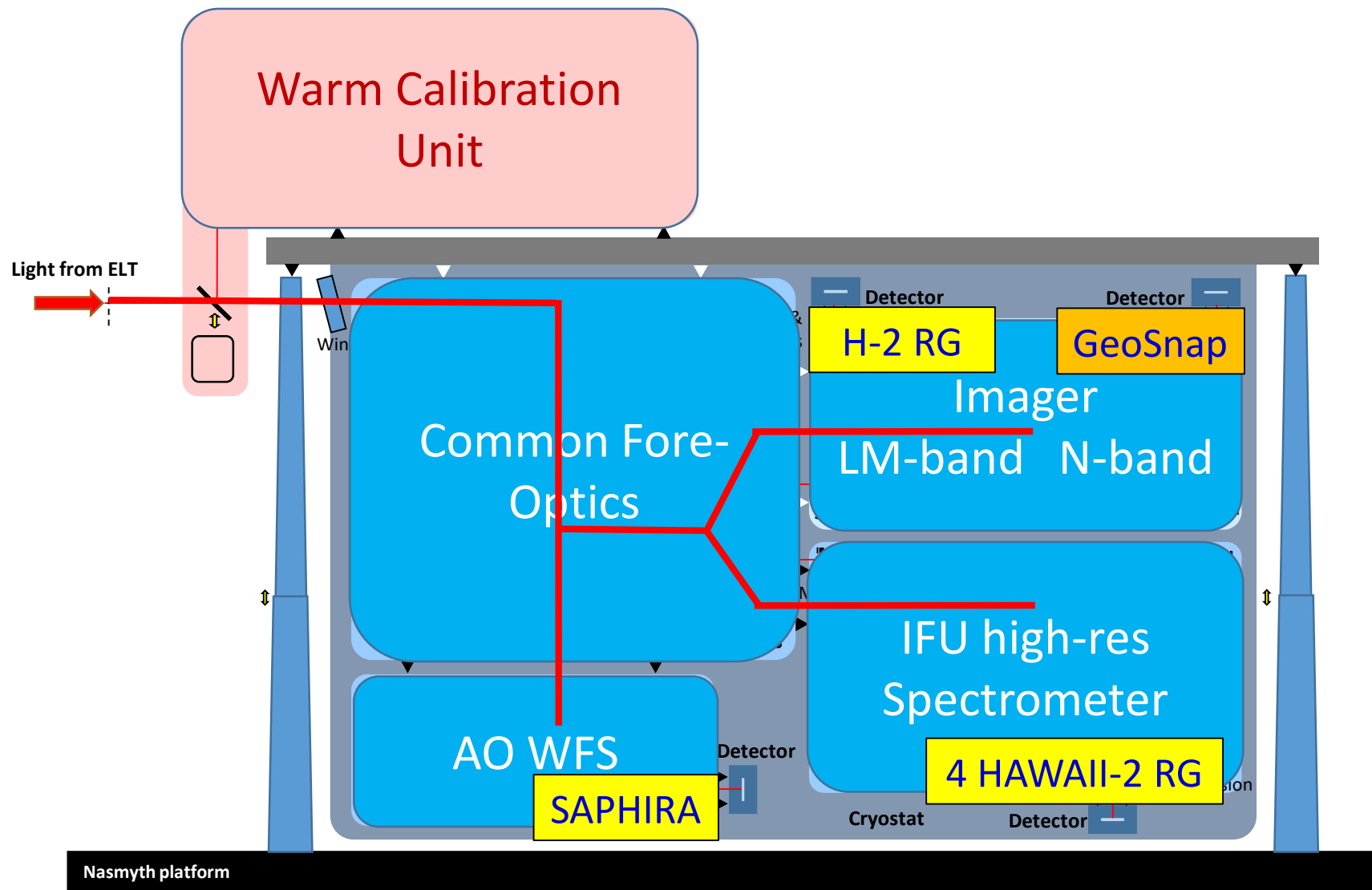


## Conceptual considerations:

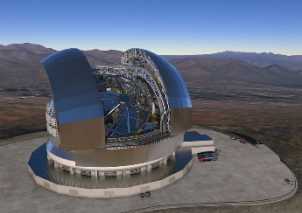
- Spectrograph concept (IFU  $\leftrightarrow$  cross-dispersed)
- Type of AO wavefront sensor (pyramid  $\leftrightarrow$  Shack-Hartmann)
- Imaging: required field of view (incl. chopping)



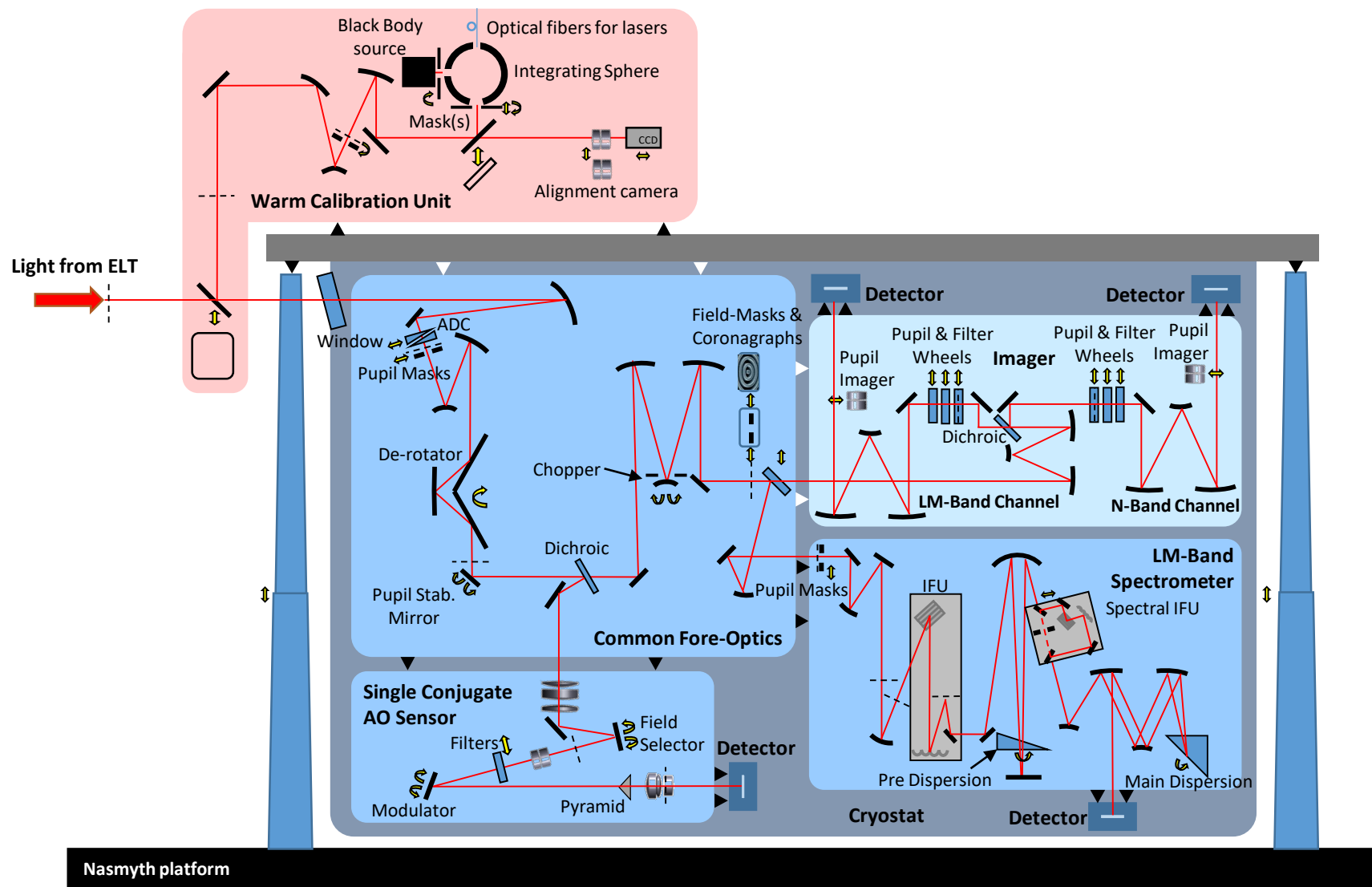
# Optical Concept

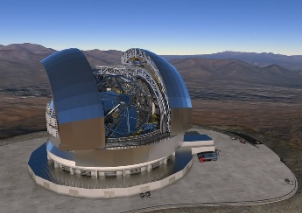


See talks by Dani Atkinson and Michael Meyer on Friday afternoon



# Optical Concept





# METIS Website

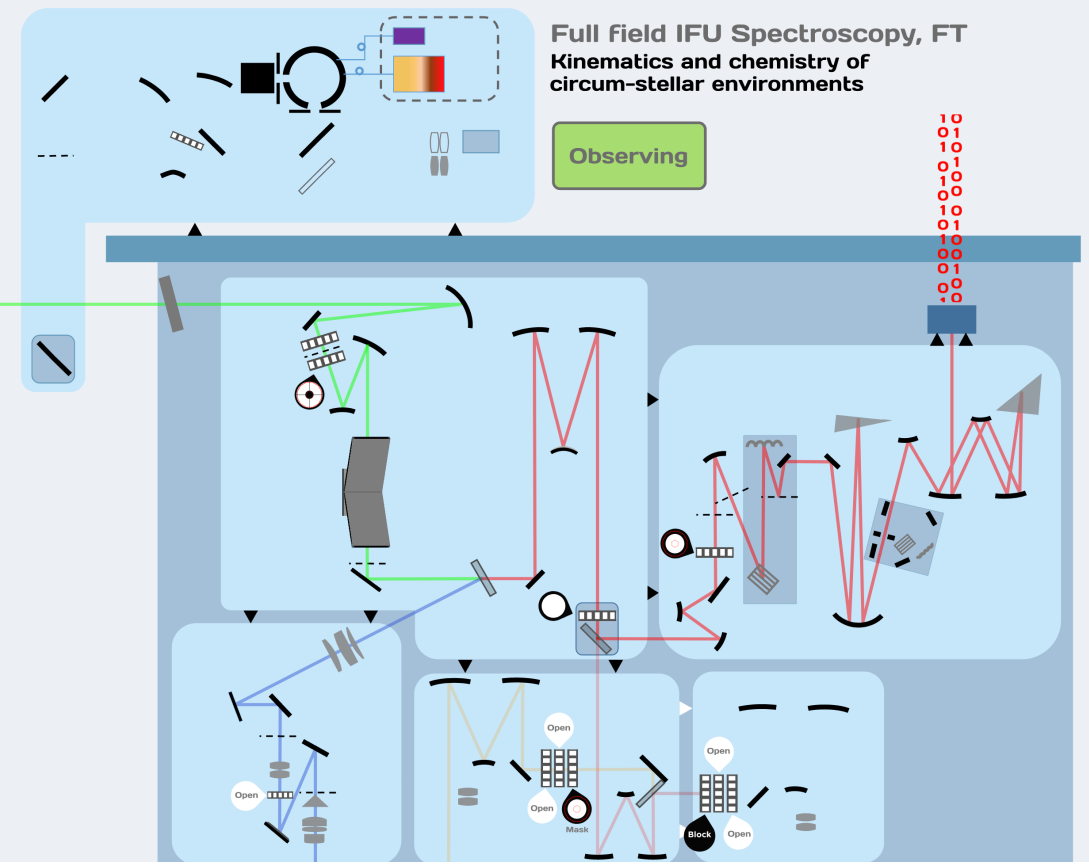
Please visit the METIS website <https://metis.strw.leidenuniv.nl/>

Lots of info ... and a very instructive App:

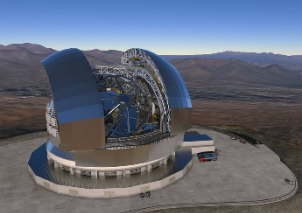
- Home
- Science
- Design Concept
- SimMETIS
- Publications
- Consortium
- Team members
- Jobs
- Outreach
- Contact
- Wiki



- Observe
- Labels On/Off
- Direct Imaging
- High Contrast Imaging
- Long-slit Spectroscopy
- IFU Spectroscopy
- IFU+HCI Spectroscopy
- Calibration





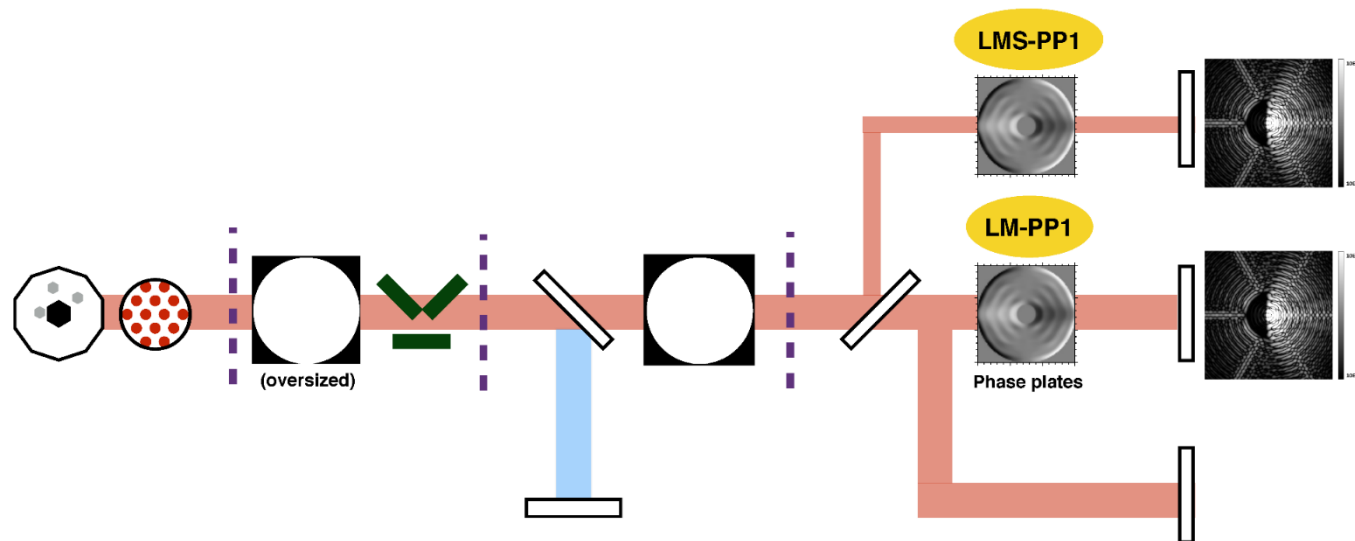
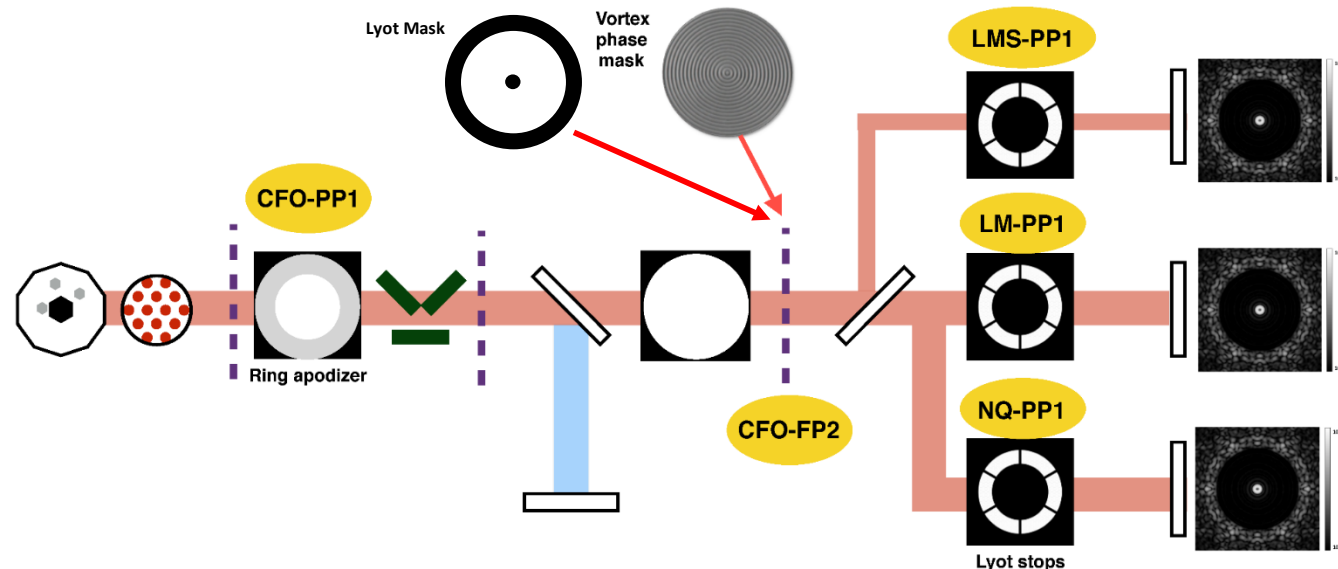


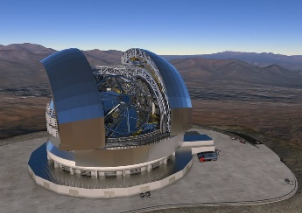
# Coronagraph Concepts

Three different solutions:

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

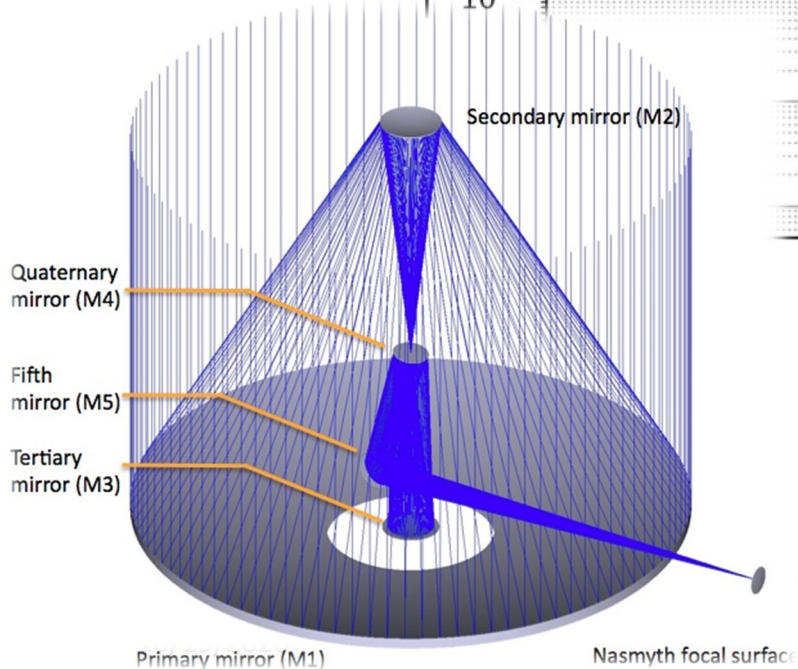
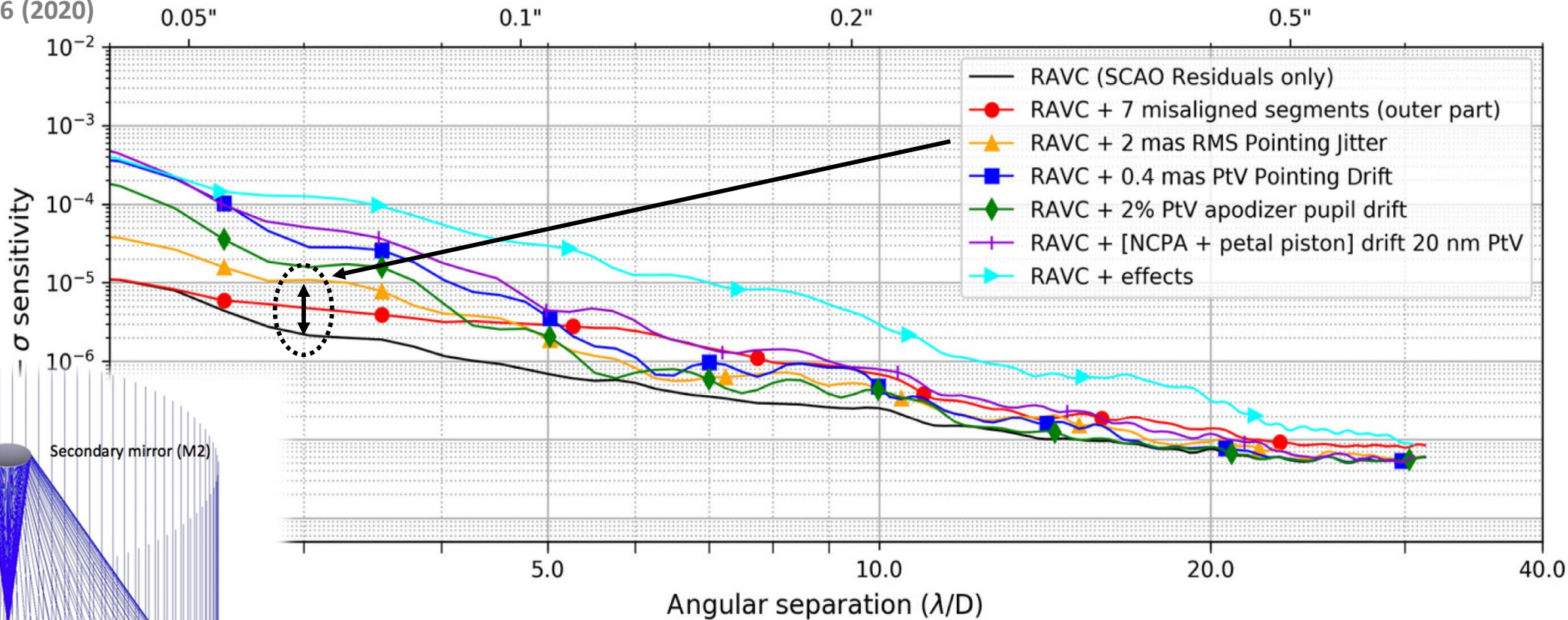
*...depending on the actual boundary conditions on the ELT*





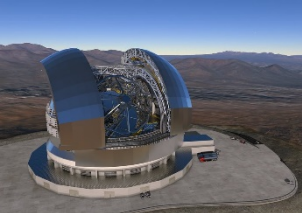
# Coronagraphic Performance

Carlomagno et al. JATIS Vol.6 (2020)

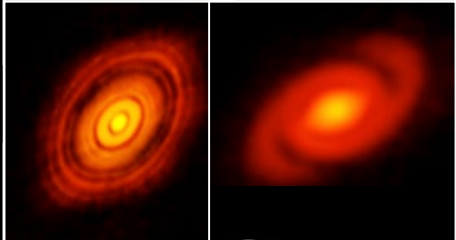


Example: 0."002 pointing jitter requires M4+M5 to keep the source **steady to within 6.6 μm** in the telescope focal plane, which is > 20 m from M5.

# Science Case Overview



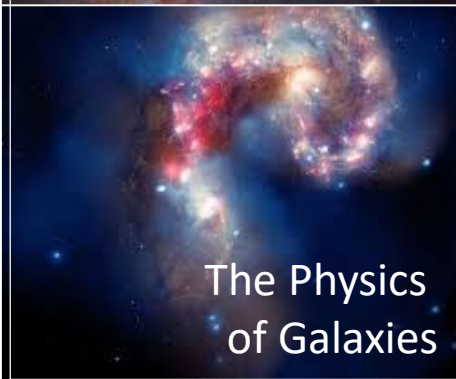
Circumstellar  
Disks



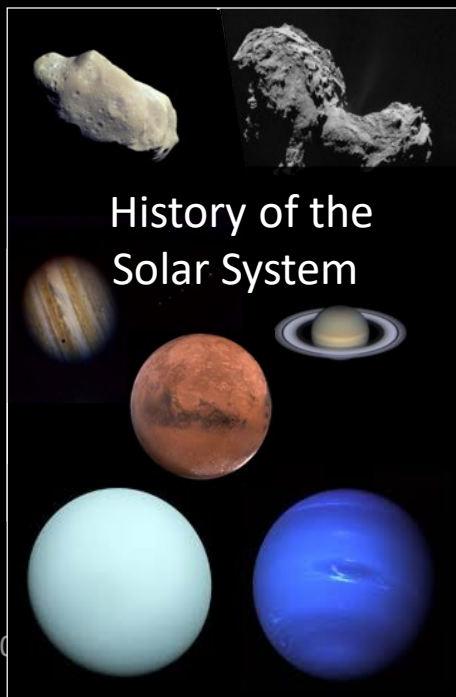
Exoplanets



Star Formation &  
Stellar Clusters



The Physics  
of Galaxies



History of the  
Solar System



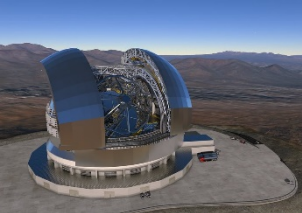
Active  
Galactic Nuclei



Evolved  
Stars

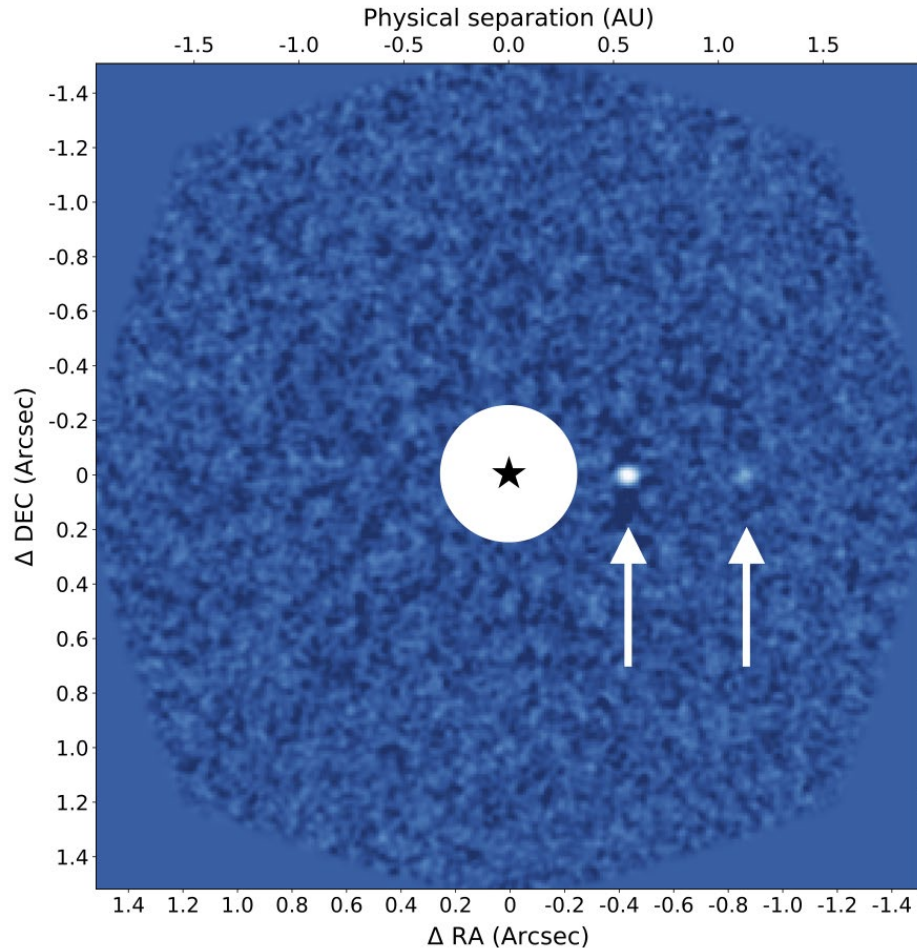


The Galactic  
Center



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

**Simulation: direct imaging of Alpha Cen A at 10 $\mu$ m**  
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

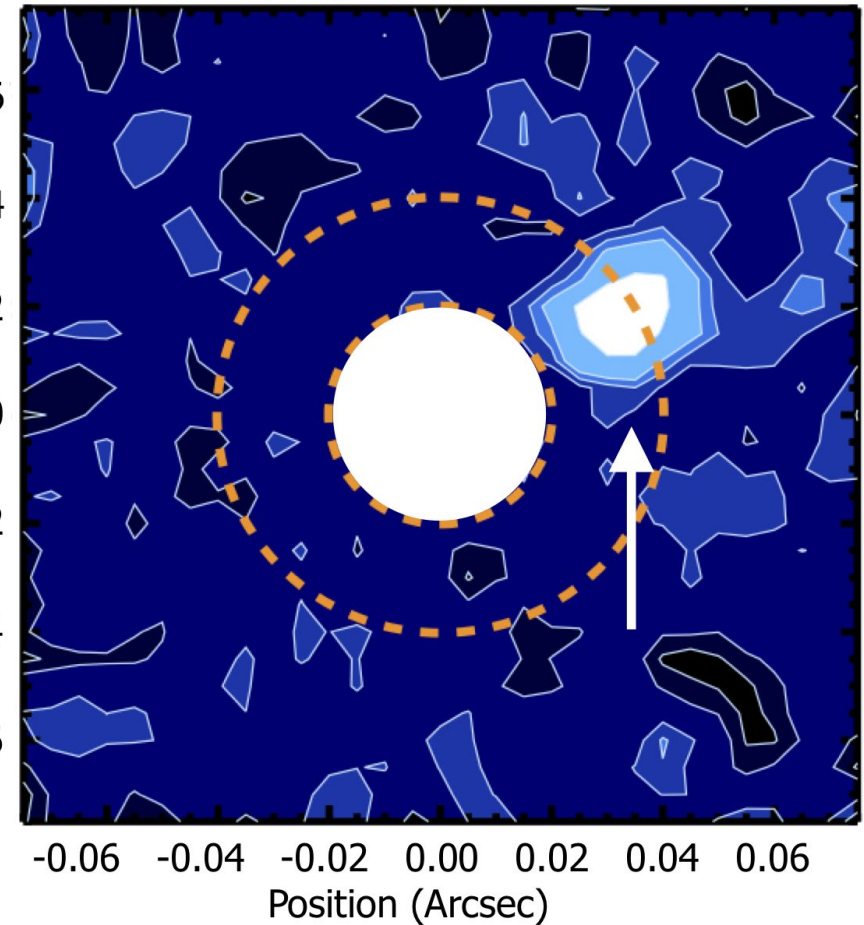
- 1.1  $R_{\text{Earth}}$  planet radius
- Bond albedo of 0.3
- 50% illumination
- contrast of 1:500 at  $2 \lambda/D$
- 10 hours of observing time

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

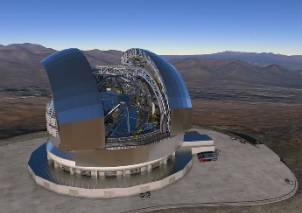
Bernhard Brandl

**Simulation: IFU spectroscopy of Proxima Cen b at 3.8  $\mu$ m**

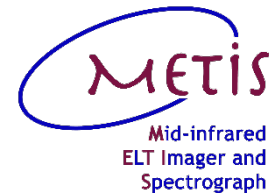
METIS LMS (L band): Proxima Cen b



Snellen et al. (2015)

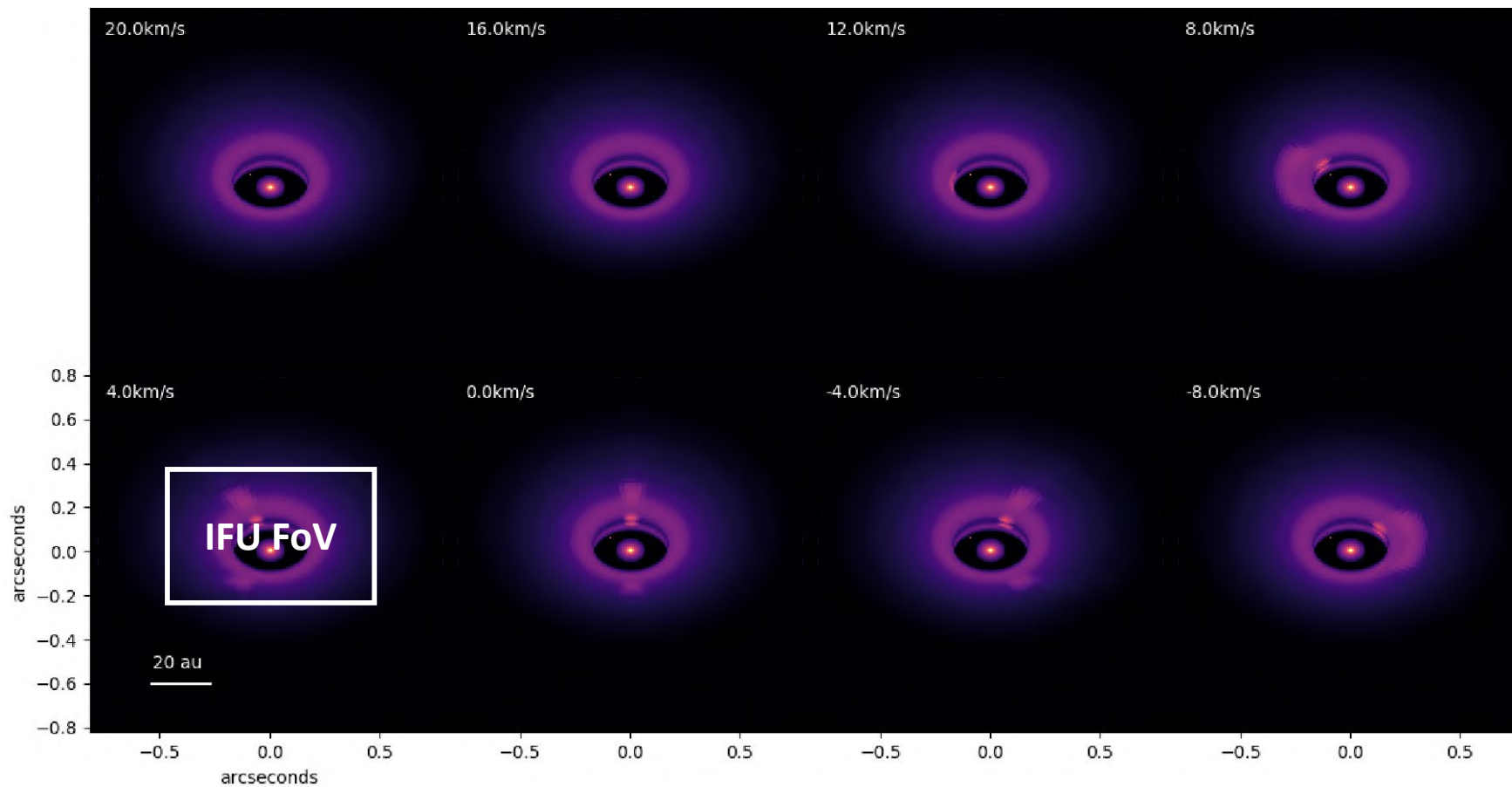


# Proto-planetary Disks and Planet Formation

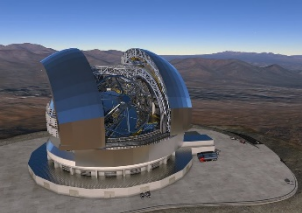


## Radiative transfer **simulations** of CO v(1-0) emission at 4.7 $\mu\text{m}$

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



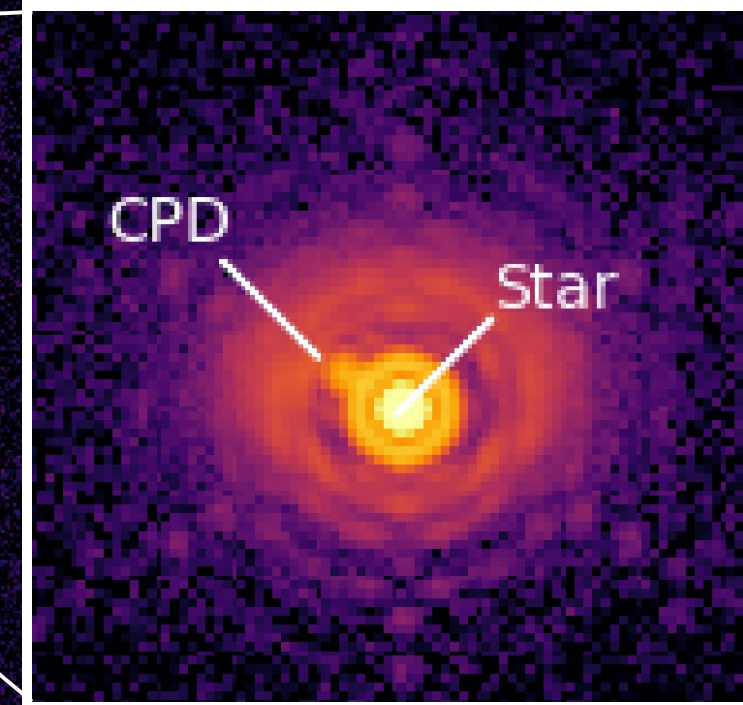
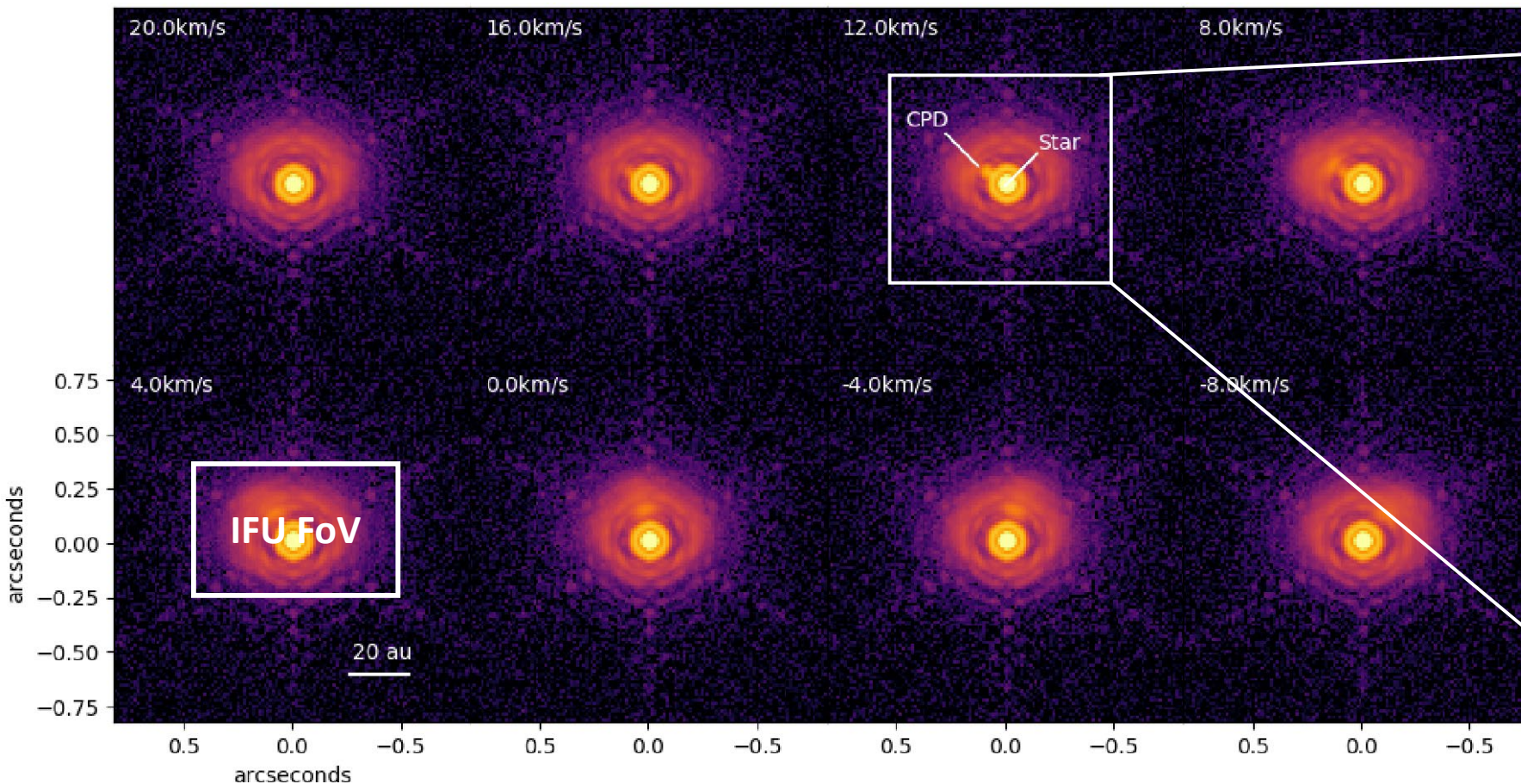
- ← HD100546 (c) system
- ← CO v(1-0)P08 4.7 $\mu\text{m}$  channel maps
- ←  $M_* = 2.4 M_\odot$
- ←  $M_p = 5 M_J$ ,  $T_p = 1000 \text{ K}$
- ←  $M_{\text{CPD}} = 5 \times 10^{-2} M_J$
- ←  $t_{\text{int}} = 1 \text{ hr}$



# Proto-planetary Disks and Planet Formation

Radiative transfer **simulations** of CO v(1-0) emission at 4.7  $\mu\text{m}$

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

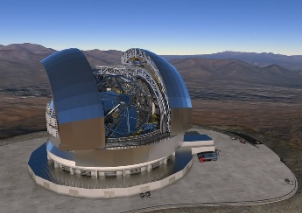


Simulated **METIS observations** of the same model

- ← HD100546 (c) system
- ← CO v(1-0)P08 4.7 $\mu\text{m}$  channel maps
- ←  $M_* = 2.4 M_{\odot}$
- ←  $M_p = 5 M_J, T_p = 1000 \text{ K}$
- ←  $M_{\text{CPD}} = 5 \times 10^{-2} M_J$
- ←  $t_{\text{int}} = 1 \text{ hr}$

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

- TMT instruments
- MICHI overview
- MICHI ↔ METIS



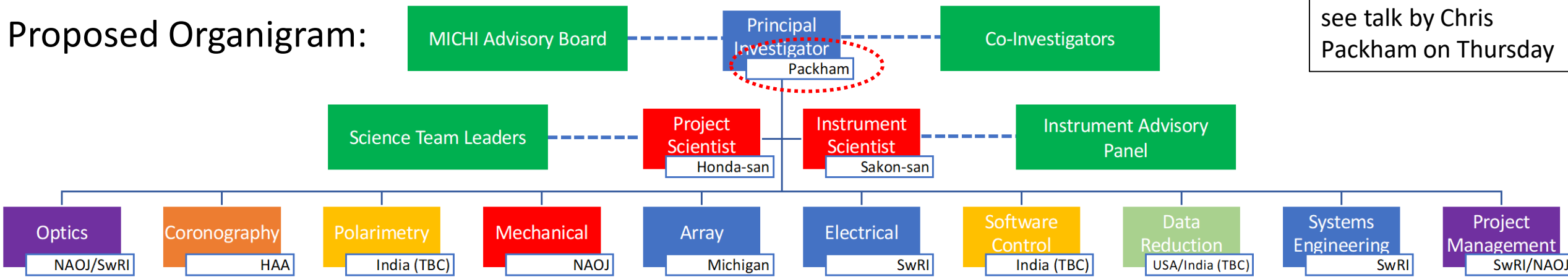
# TMT Instruments & MICHI



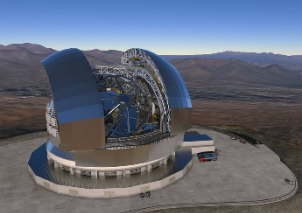
- Wide-field visible MOS (WFOS)
  - [diff-ltd] IR imager & spectrometer (IRIS)
  - [diff-ltd] High resolution IR MOS (MODHIS)
  - AO feed to multiple instruments (NFIRAOS)
- } 1<sup>st</sup> light
- proposed 2<sup>nd</sup> generation: PSI, HROS, IRMOS, NIRES, ARISE, and:  
Mid-IR Camera, High-disperser & IFU spectrograph (MICHI, 未知)

see talk by Chris Packham on Thursday

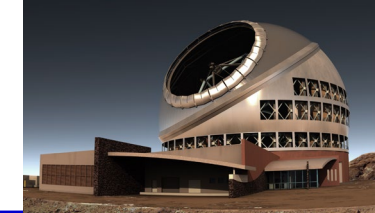
Proposed Organigram:





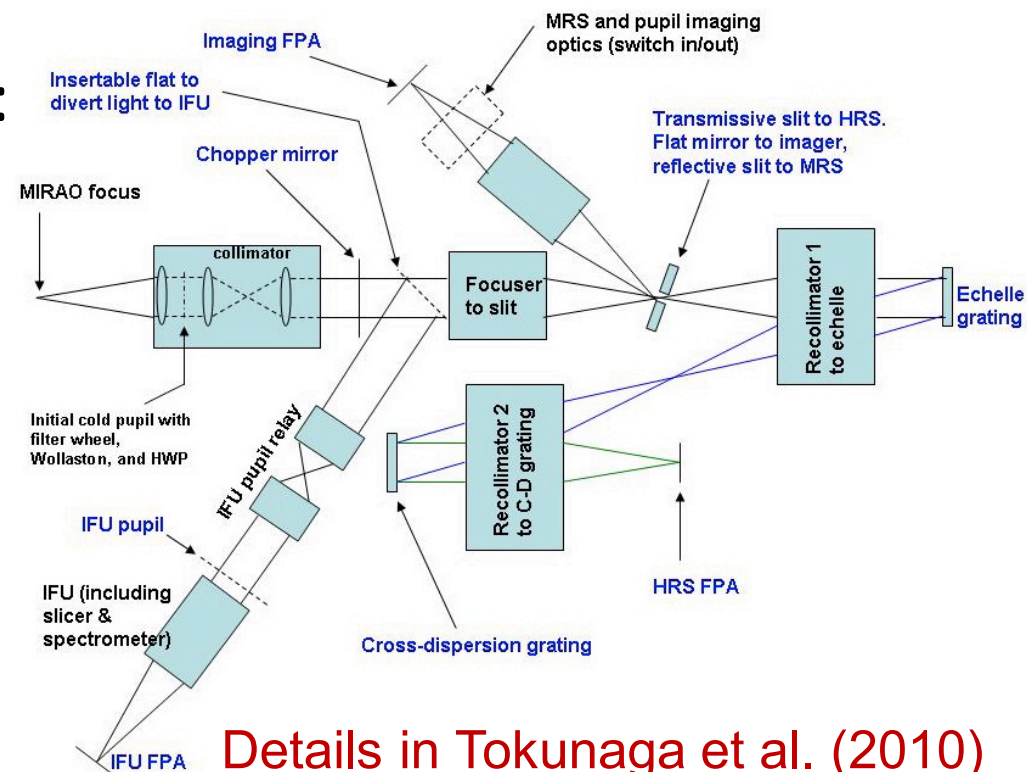


# MICHI Overview

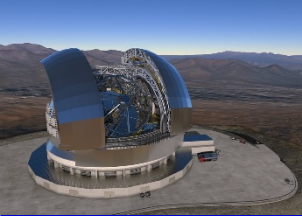


Instrument capabilities optimized to 3 – 14  $\mu\text{m}$ :

- Diffraction-limited **imaging** at L, M, N
- Long slit  **$R \sim 600$  spectroscopy** at L, M, N
- High resolution  **$R > 100,000$  cross-dispersed spectroscopy** at L, M, N
- **IFU  $R \sim 1000$  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!

