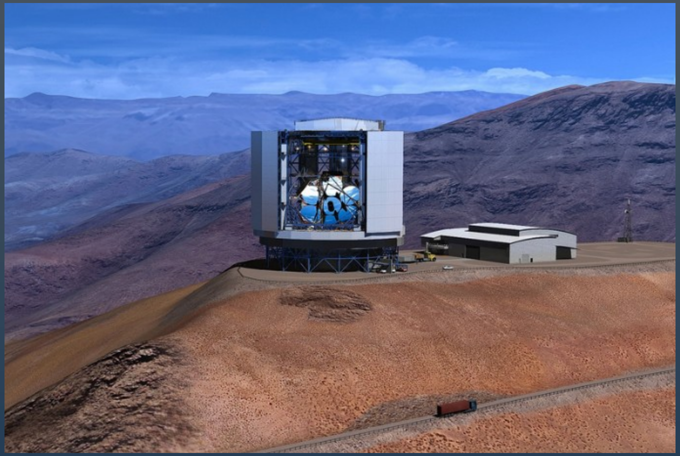
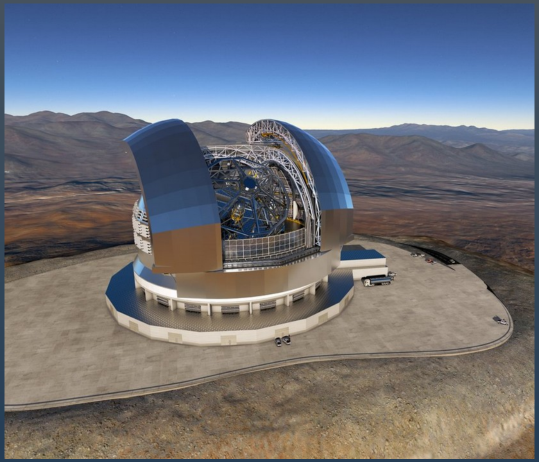
Studying Exoplanets with the ELTs





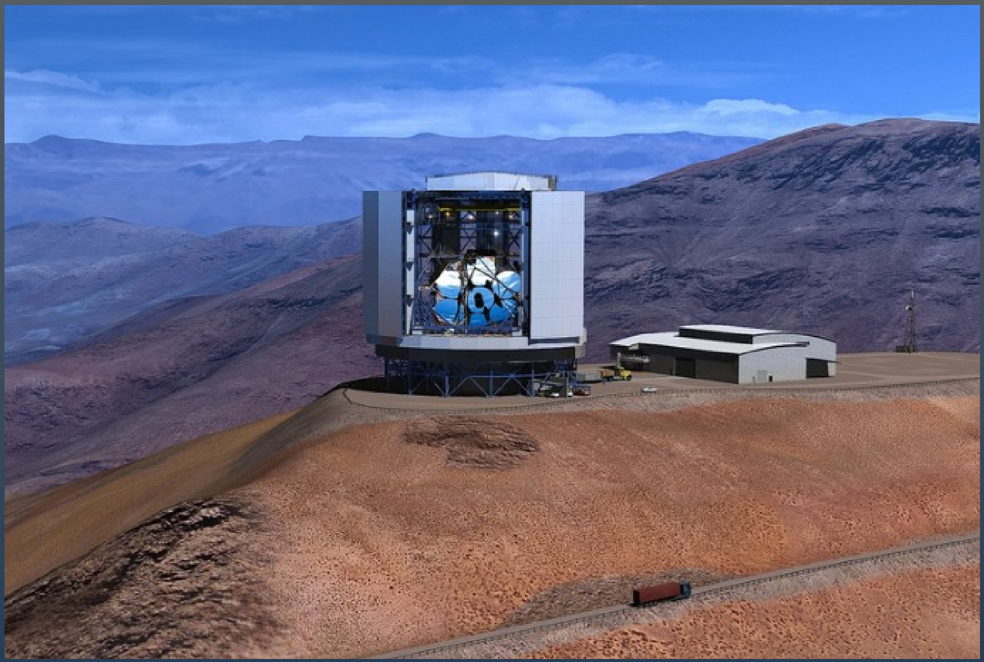
Jared Males
University of Arizona

The ELTs

- Extremely Large Telescopes
  - Note: this is both a class of telescope, and a specific telescope (a.k.a. the E-ELT)
- Current O/IR Telescopes:
  - 5 m: Hale (Palomar)
  - 6.5 m: MMT, Magellan (2x)
  - 8 m: Gemini, VLT (4x, single dish), Subaru, LBT (2x, single dish)
  - 10 m: Keck, GTC, SALT, HET
  - 22 m: LBT (dual aperture Fizeau mode)
    - (and interferometers like Keck-I, VLTI, Chara)

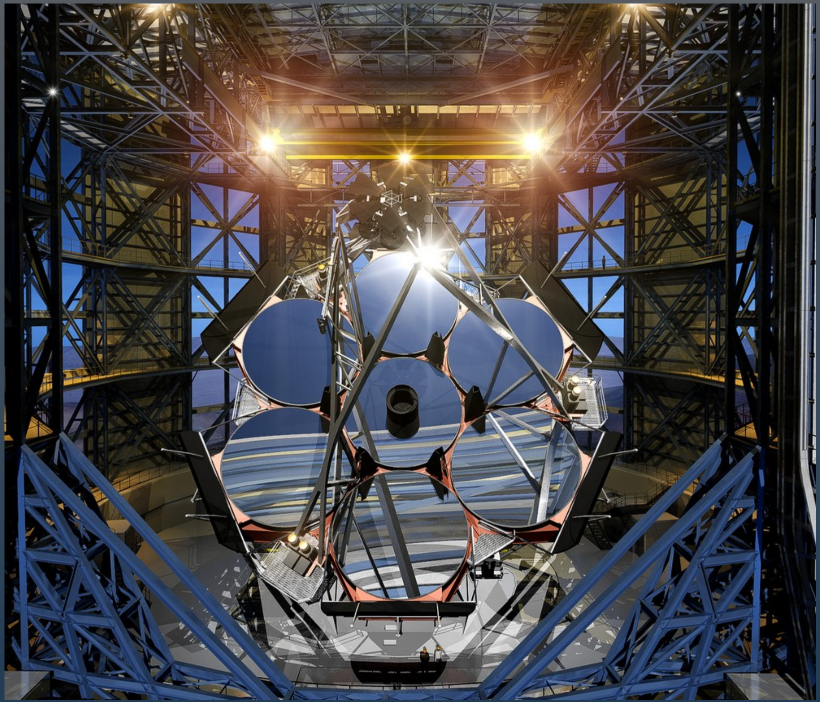
- Caveats:
  - I’m a GMT partisan.
  - I work on direct imaging instrumentation
    - Wavefront control, coronagraphy, image processing
  - So apologies to TMT, ELT, RV, Transits, and microlensing (etc.)

GMT



Giant Magellan Telescope

GMT



Diameter: 25.4 m
  Effective diameter: 24.5 m

Segment size: 8.4 m

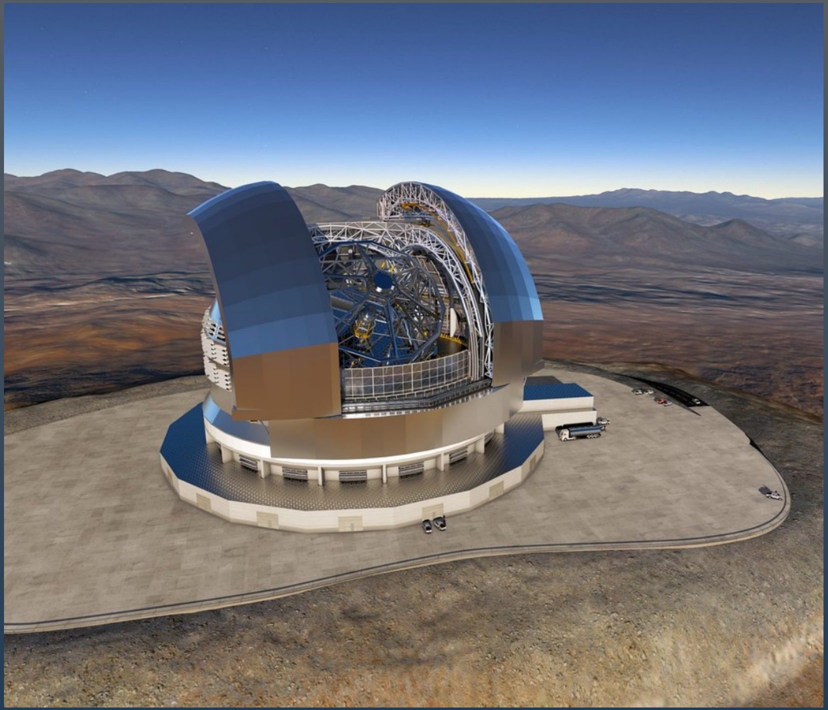
Collecting area: 368 m^2

Site: Cerro Las Campanas (Chile)
  Altitude: 2514 m (8248 ft)
  Median Seeing:

First Light: 2025

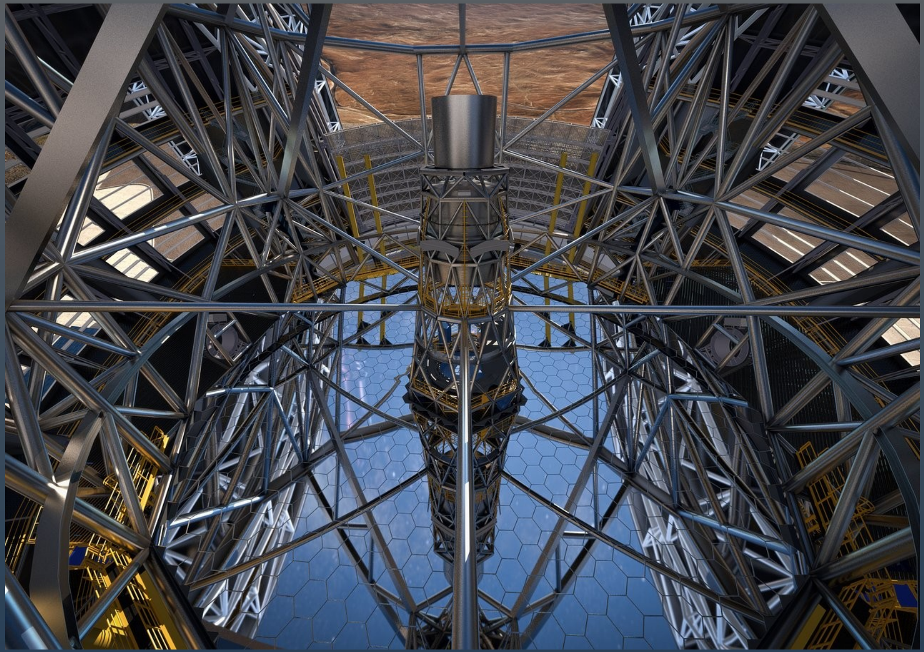
Organization: consortium of ASU, AAL (Australia), RSAA (Australia), Carnegie, FAPESP (Brazil), Harvard, KASI (Korea), Smithsonian, Texas A&M, U. Texas, U. Arizona, U. Chicago.

ELT



Extremely Large Telescope

ELT



Diameter: 39.3 m

Segment size: 1.4 m

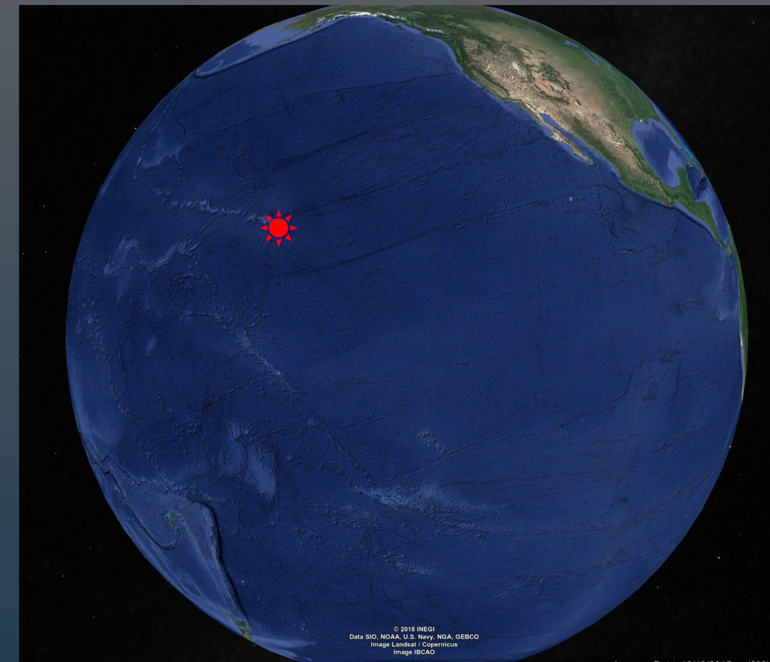
Collecting area: 978 m^2

Site: Cerro Armazones (Chile)
  Altitude: 3046 m (9993 ft)

First Light: 2025

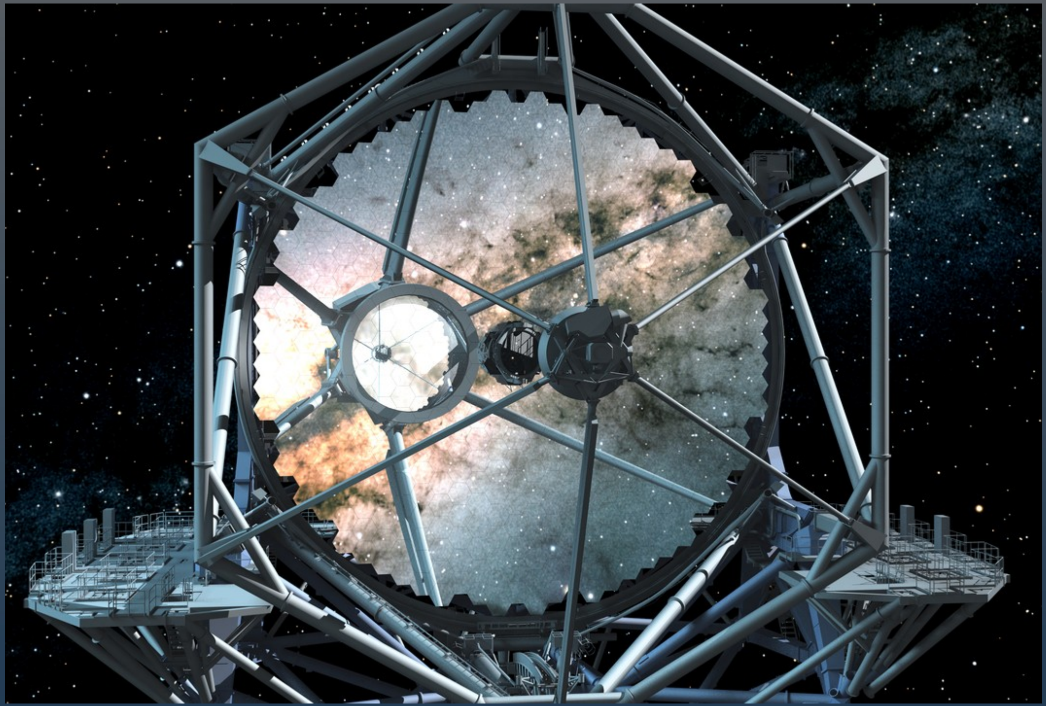
Organization: European Southern Observatory (ESO)

TMT



Thirty Mirror Telescope

TMT



Diameter: 30.0 m

Segment size: 1.44 m

Collecting area: 655 m^2

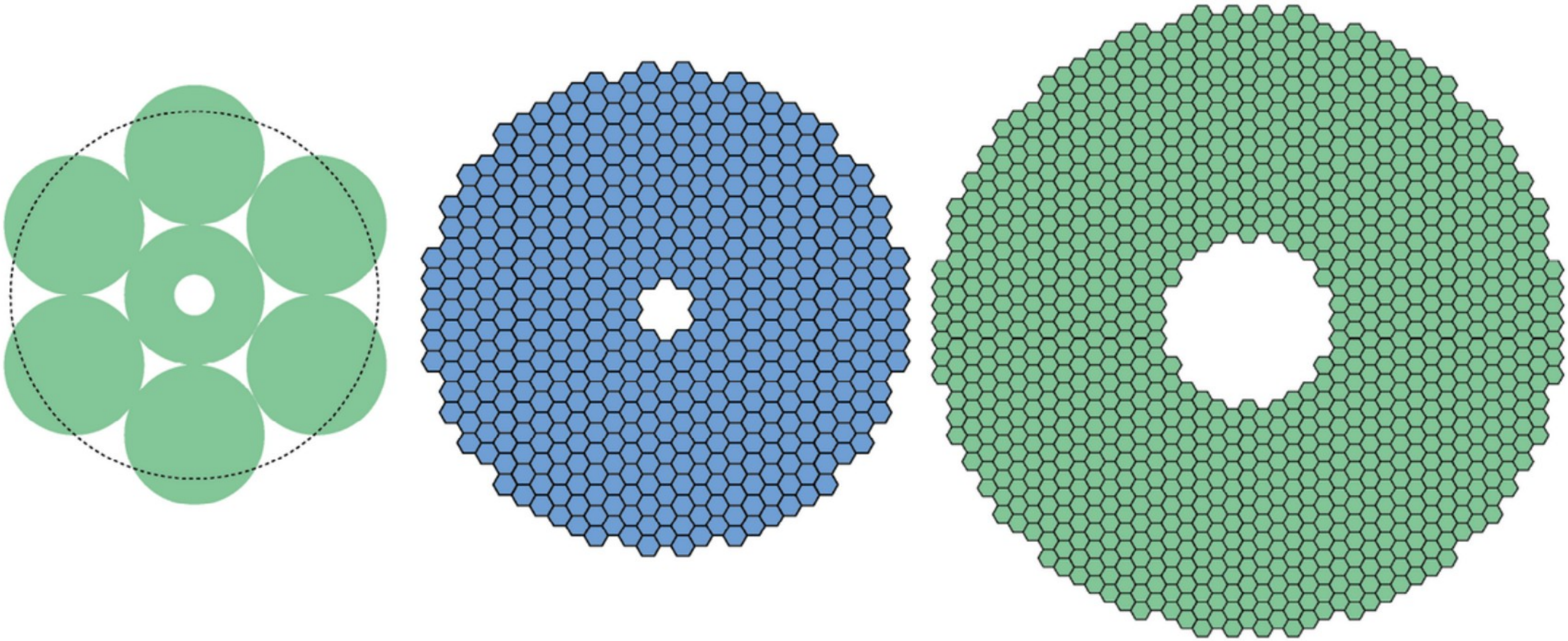
Site: Mauna Kea (Hawaii, USA)
  Altitude: 4050 m (13,290 ft)

First Light: 2027

Organization: consortium of Caltech, DST India, NAO-CAS (China), NINS/NAOJ (Japan), NRC Canada, U. California, AURA

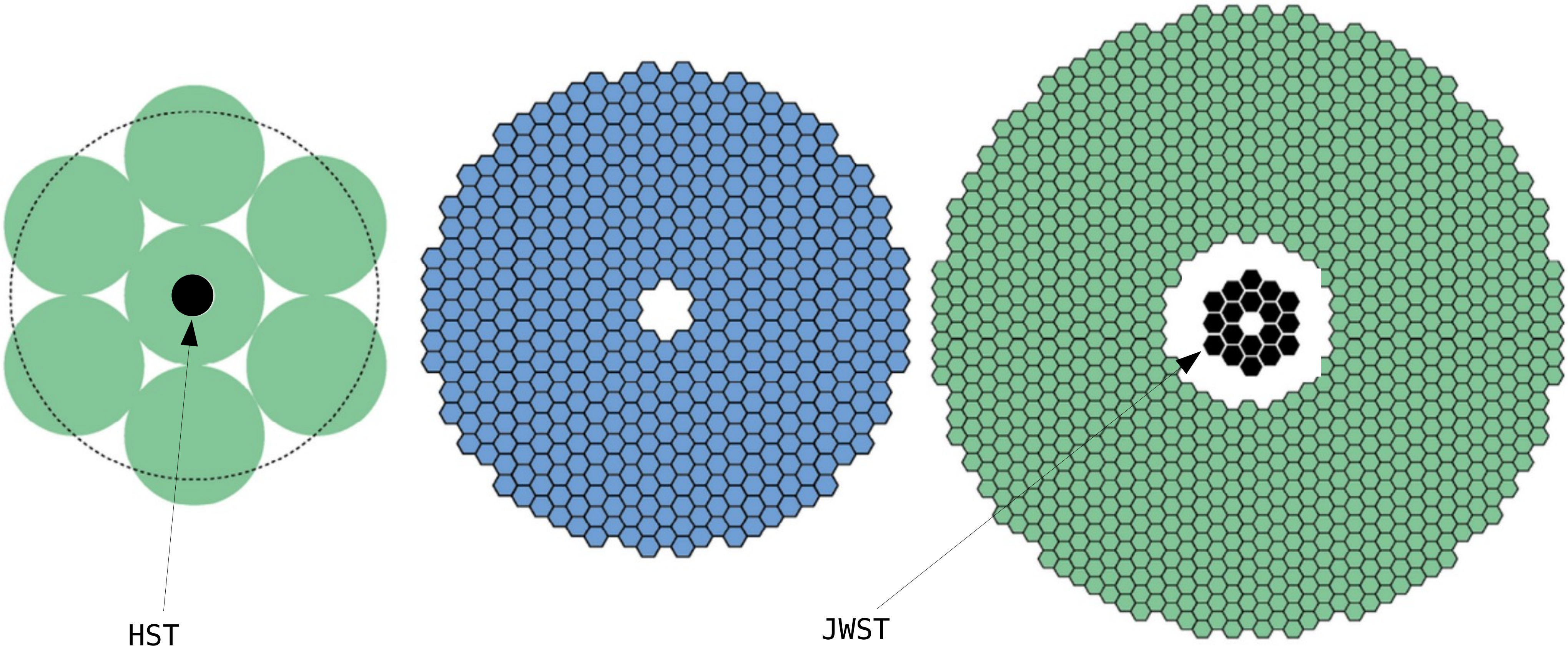
Note: not a space telescope

ELTs Are E.L.



Adapted from: https://commons.wikimedia.org/wiki/File:Comparison_optical_telescope_primary_mirrors.svg

ELTs Are E.L.



Why So Big?

For an unresolved or seeing limited source:

$$S/N = \frac{F_* \times A * t}{\sqrt{F_* \times A \times t}} \propto \sqrt{At} \propto D\sqrt{(t)}$$

key point: size of photometric aperture is independent of telescope diameter in this regime

Exposure Time (seeing limited)

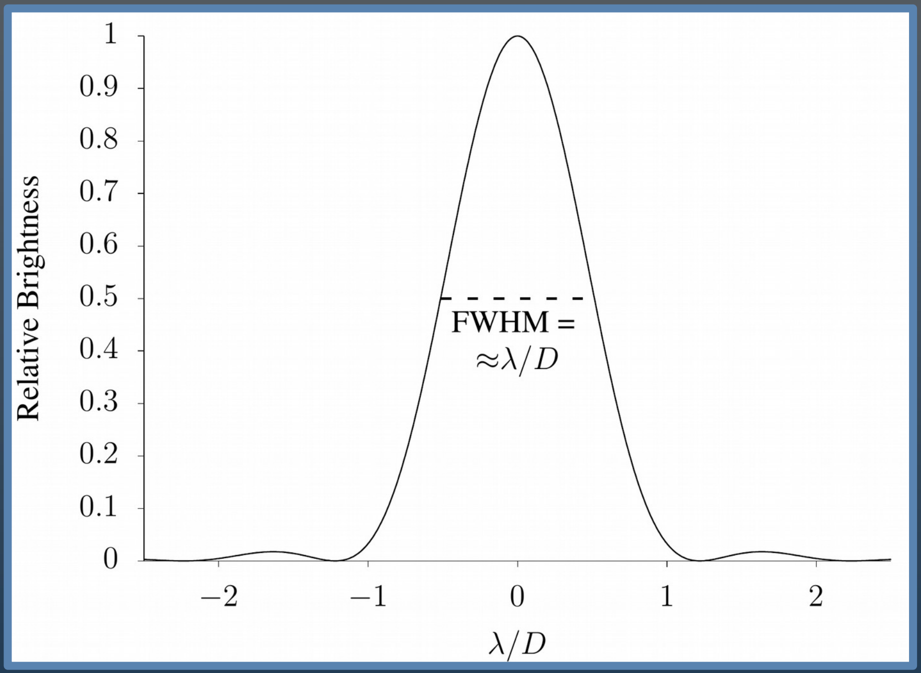
For an unresolved (or seeing limited) source:

$$S/N = \frac{F_* \times A * t}{\sqrt{F_* \times A \times t}} \propto \sqrt{At} \propto D\sqrt{(t)}$$

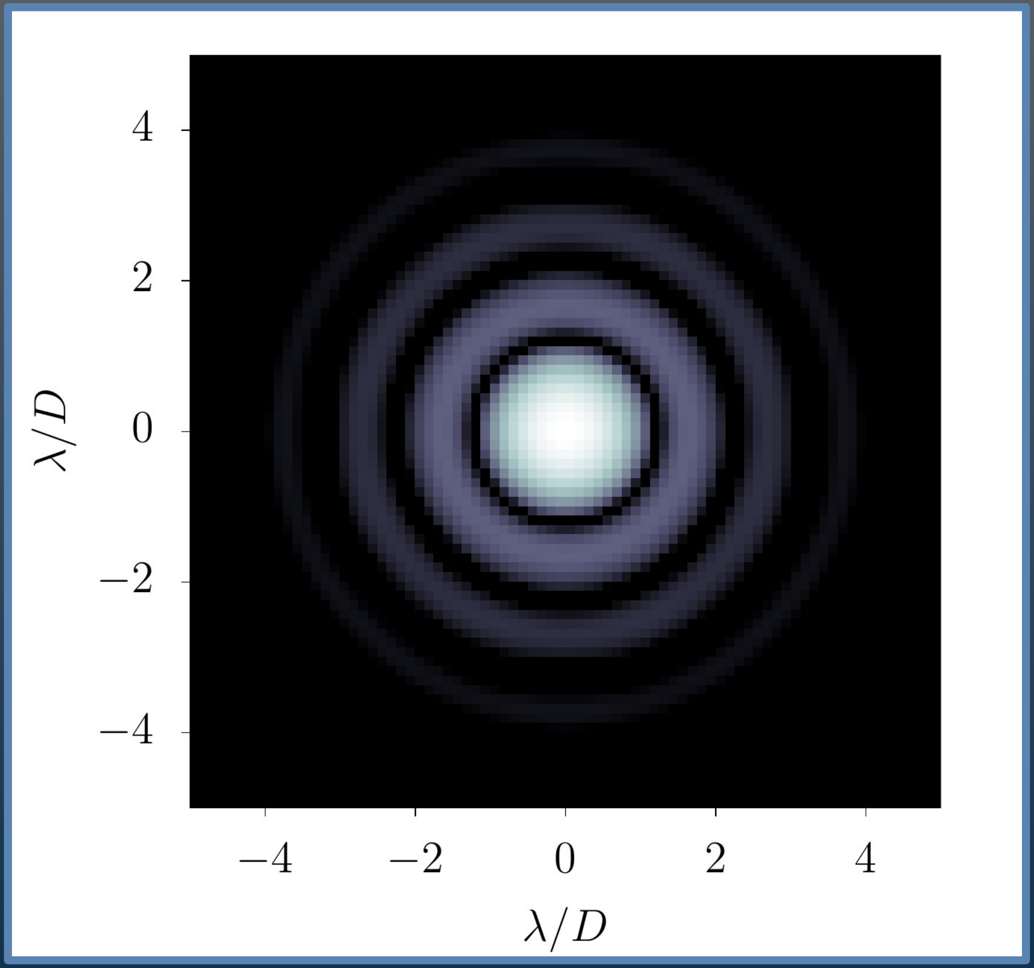
$$t(S/N) \propto D^2$$

Exposure time goes as diameter squared.

Resolution



The diffraction limit (Sparrow Criterion)



Why So Big?

For a diffraction limited & background limited source:

$$S/N = \frac{F_* \times A * t}{\sqrt{F_{BG} \times \epsilon \times t}}$$

$$\epsilon \equiv \text{ area of PSF } \propto \left(\frac{\lambda}{D}\right)^2$$

Exposure Time (diffraction limited)

For a diffraction limited & background limited source:

$$S/N = \frac{F_* \times A * t}{\sqrt{F_{BG} \times \epsilon \times t}}$$

$$\epsilon \equiv \text{ area of PSF } \propto \left(\frac{\lambda}{D}\right)^2$$

$$S/N \propto D^2\sqrt{t}$$

$$t(S/N) \propto D^4$$

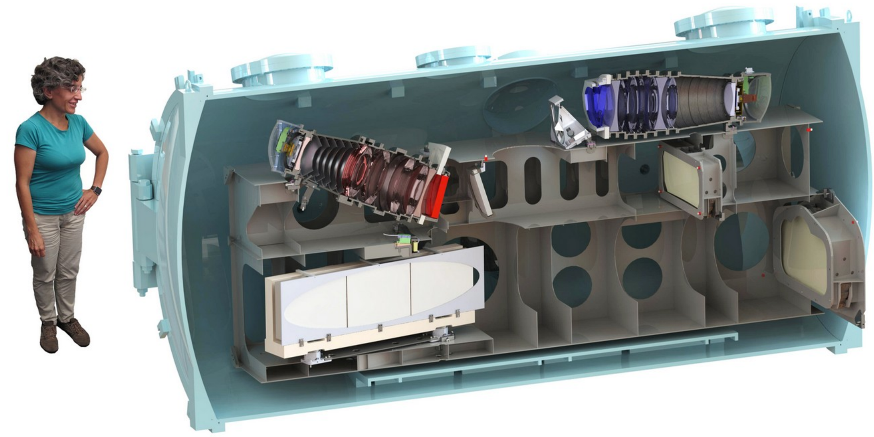
Exposure time goes as the 4^{th} power of diameter.

Taking Advantage of D

- Spectrographs
  - Radial velocity detection of exoplanets
  - Transit characterization of exoplanets
- Imagers
  - Photometric characterization
- Coronagraphs
  - High contrast detection and characterization

G-CLEF Spectrograph

- GMT-Consortium Large Earth Finder
  - Wavelength range: 350 nm to 900 nm
  - R = 19,000 to 108,000
  - A first-light instrument (2025)
- Key science:
  - precision radial velocity
  - detection of low-mass exoplanets

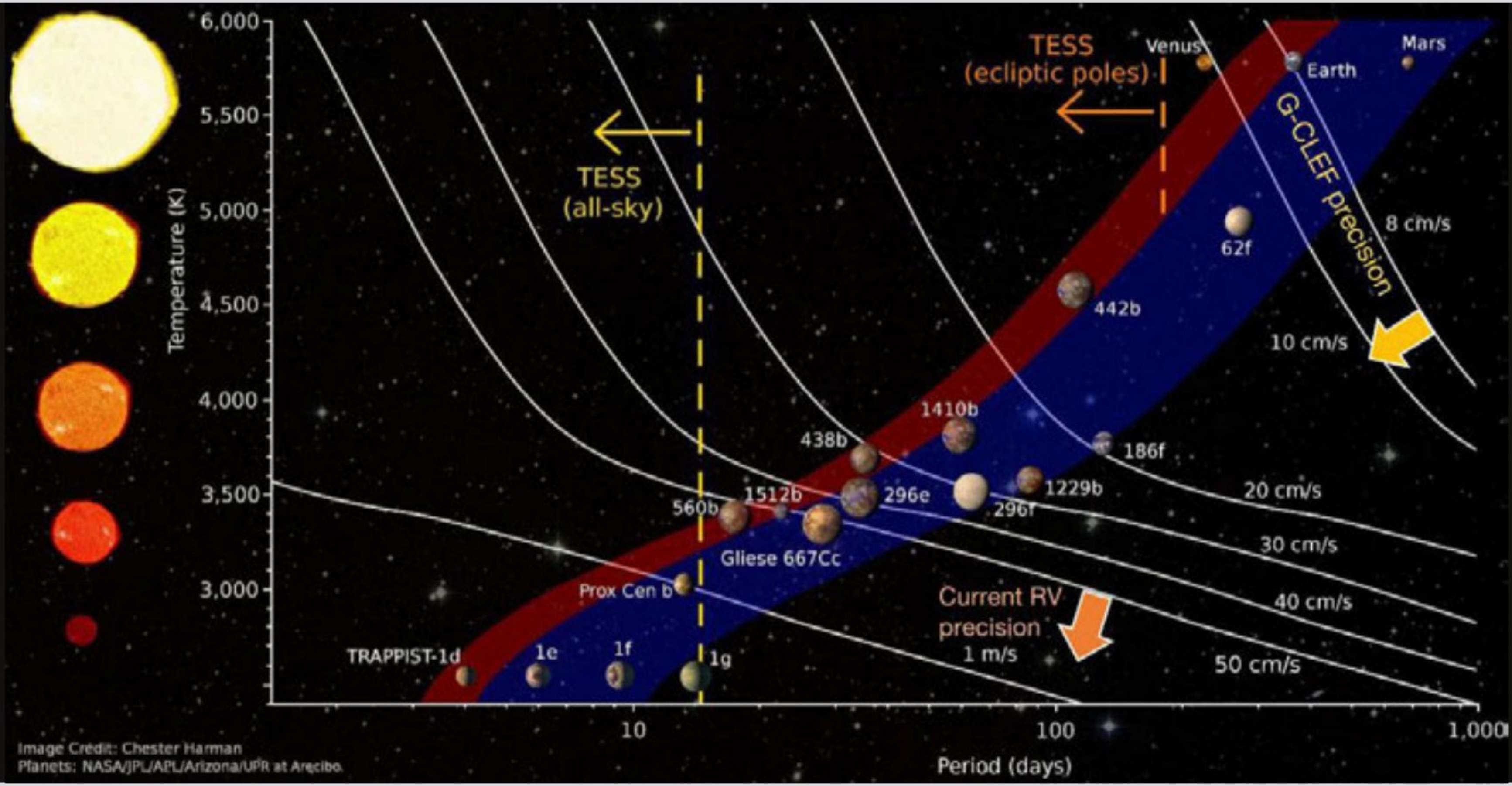


G-CLEF PRV

- Vacuum enclosed, gravity invariant (fiber fed)
- Diameter Advantage: consider an 11th mag TESS M-dwarf
  - 10 m: 1 hour = 1 m/s (photon noise limited)
  - GMT: 10 minutes (D^2!)
- Instrument noise floor: 10 cm/s
  - 20 min on a 9th mag star = 10 cm/s photon noise limited precition

    (see GMT science book for details)

G-CLEF PRV



From the GMT Science Book

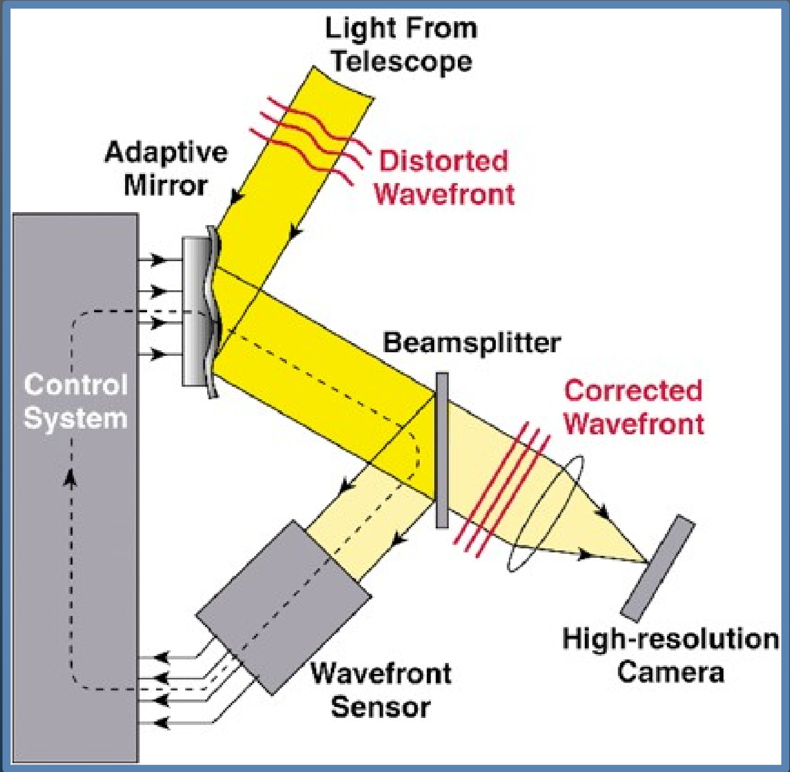
Similar TMT & ELT Instruments

- TMT Second Generation (proposed)
  - HROS (visible)
  - NIRES (near-IR)
- ELT - HIRES
  - 0.4 to 1.8 micron, R~100,000
  - Second gen, Phase A study complete

Adaptive Optics

- THE PROBLEM with ground-based telescopes: the atmosphere
- Impact of atmospheric turbulence:
  - Random variations in temperature cause variations in index of refraction (the speed of light), causing phase and amplitude (scintillation) variations in the incoming wavefront
  - Best sites (MKO, LCO) routinely deliver 0.5" "seeing" at 500 nm
  - GMT resolution at 500 nm: 0.004"
- Remember this key fact: when seeing limited, the spatial resolution of a large telescope is independent of D, and sensitivity (exposure time to S/N) goes only as D^2.
  - Realizing the full promise of the ELTs *requires* adaptive optics (AO)

Adaptive Optics

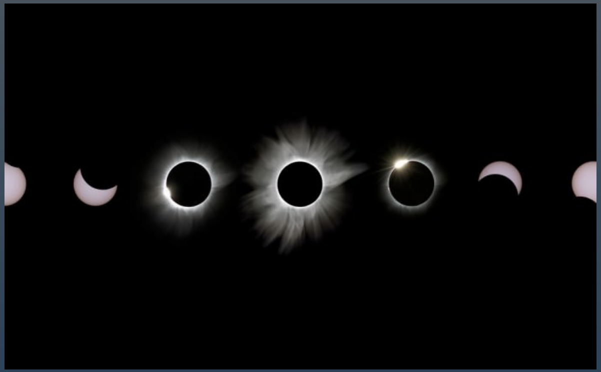


- Wavefront Sensor
  - Measure the aberrations
- Control System
  - Calculates wavefront
  - Sends commands
- Wavefront Corrector
  - (Deformable mirror)
  - Removes the aberration

Coronagraphs

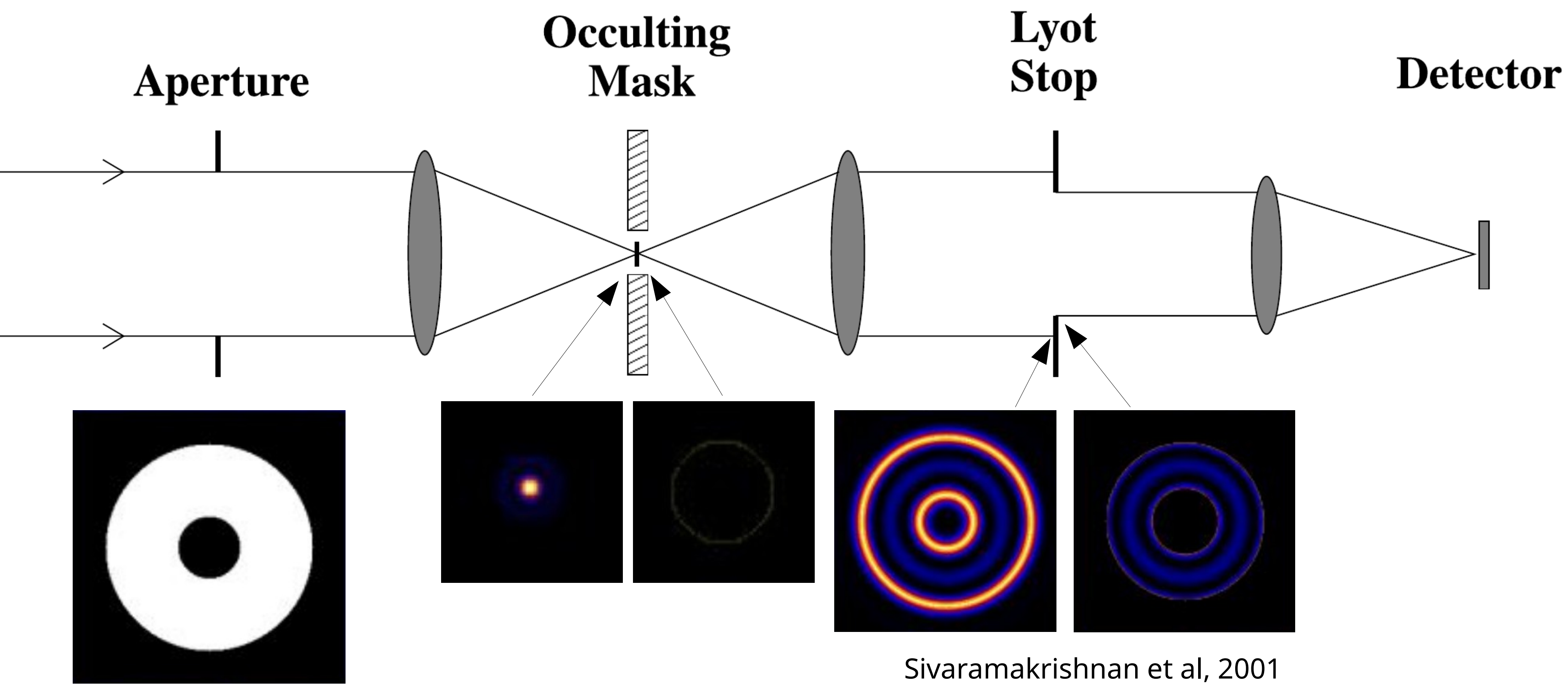
We need a way to block the star's light, without blocking the planet…

Thumb courtesy of
of Olivier Guyon



Note: none of these techniques work for our purposes.

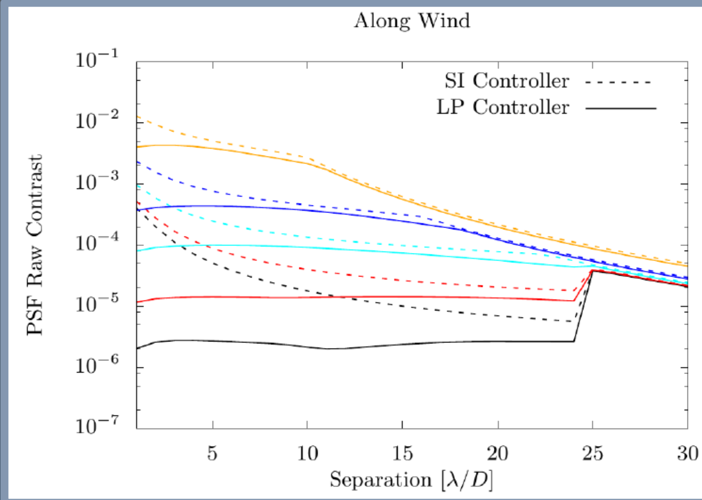
The Basic Lyot Coronagraph



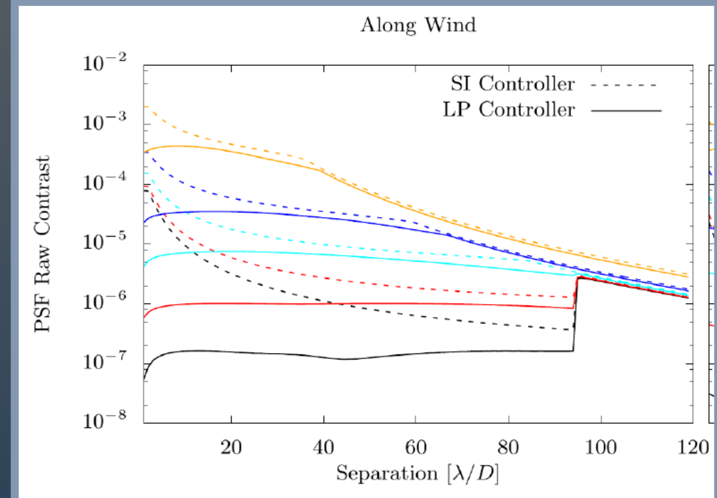
Sivaramakrishnan et al, 2001
http://lyot.org/background/coronagraphy.html

D^2 In Contrast

6.5 m Contrast



25.4 m Contrast



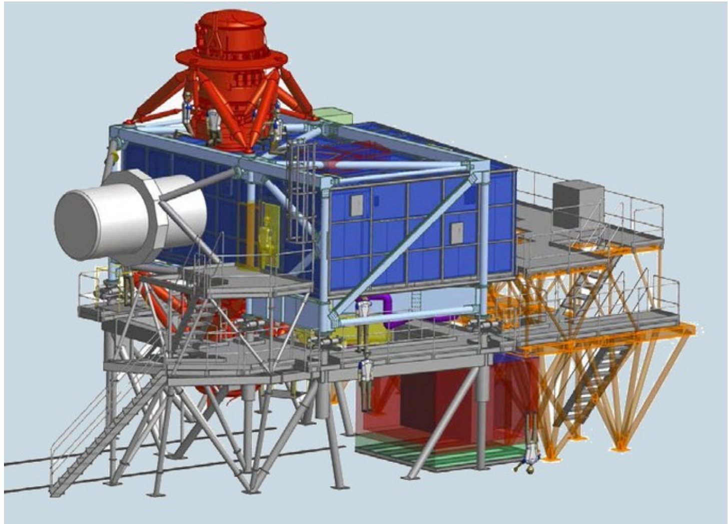
Post-coronagraph contrast scales as D^2, so root(t)-limited exposure time scales as D^4

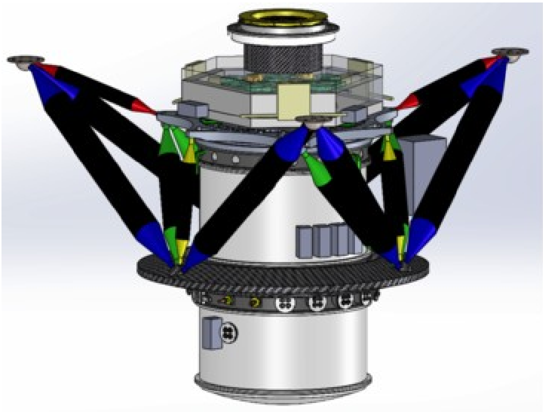
(assuming equivalent AO systems)

From Males and Guyon (2018) (https://ui.adsabs.harvard.edu/abs/2018JATIS...4a9001M/abstract)

TMT: NFIRAOS & IRIS

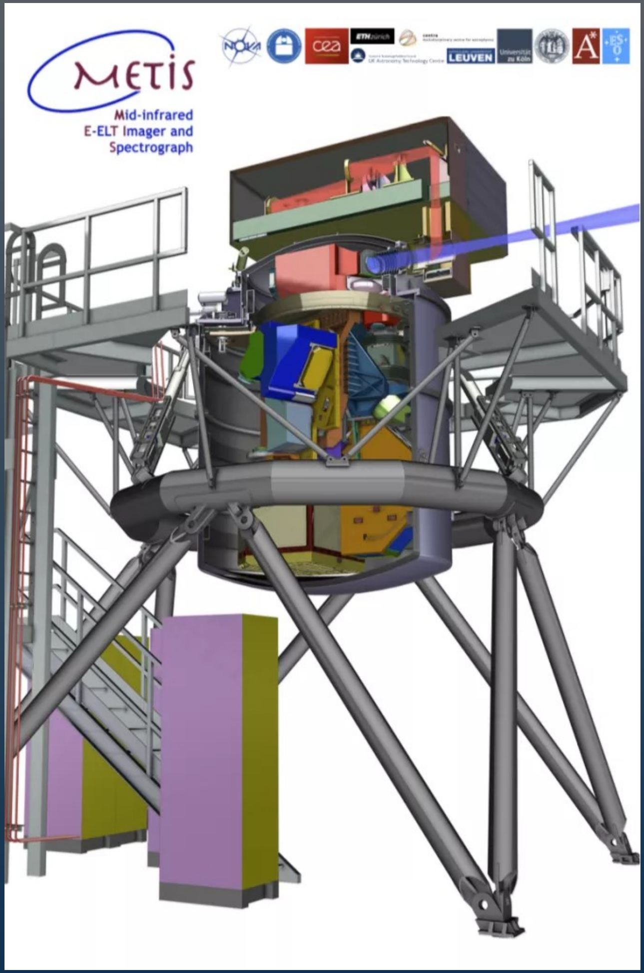
- First generation exoplanet science with TMT
- Narrow-Field Infrared Adaptive Optics System
  - Wavelength Range: J/H/K
  - DM: 60x60 and 76x76
  - LGS mode
- Feeds IRIS (Infrared Imaging Spectrograph)
  - https://www.tmt.org/page/iris
  - Imager & integral field spectrograph
  - 0.84 to 2.4 microns
  - Spatial resolution as fine as 0.006”
  - Spectral resolution R=4000 to 8000



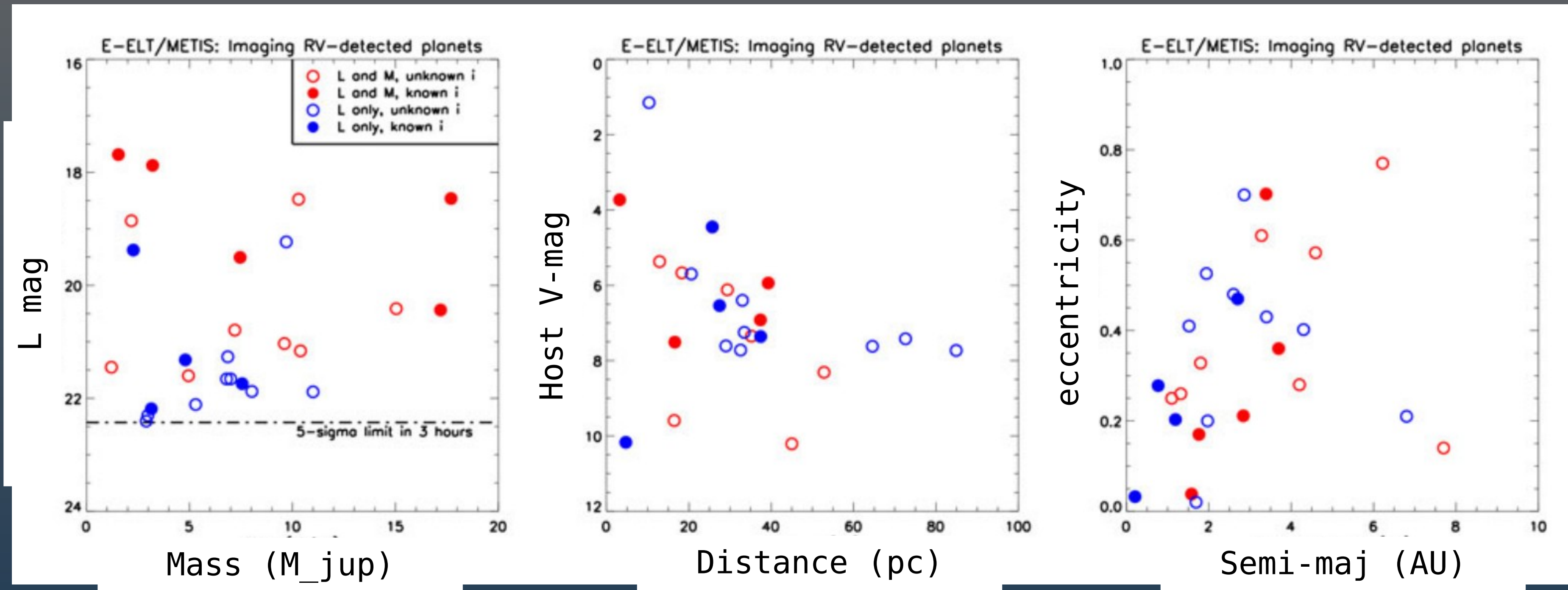


ELT: METIS

- Mid-Infrared ELT Imager and Spectrograph
  - First generation AO fed imager and spectrograph
  - 3-13 microns
  - R~100,000 @ L and M bands (3-5 microns)
- These wavelengths background limited
  - Taking advantage of D^4 sensitivity scaling



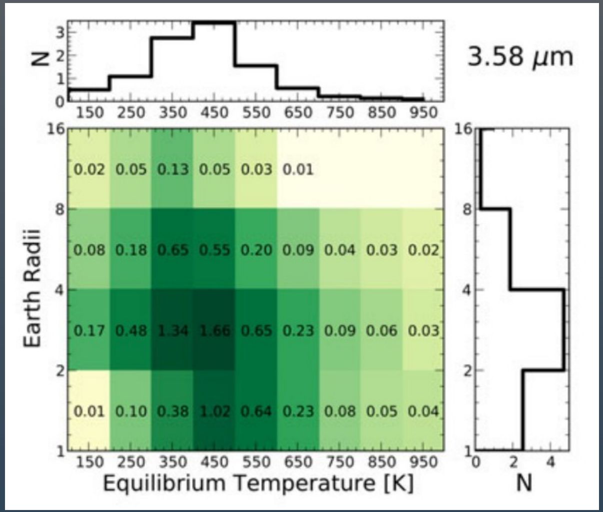
ELT-METIS: Known RV Planets

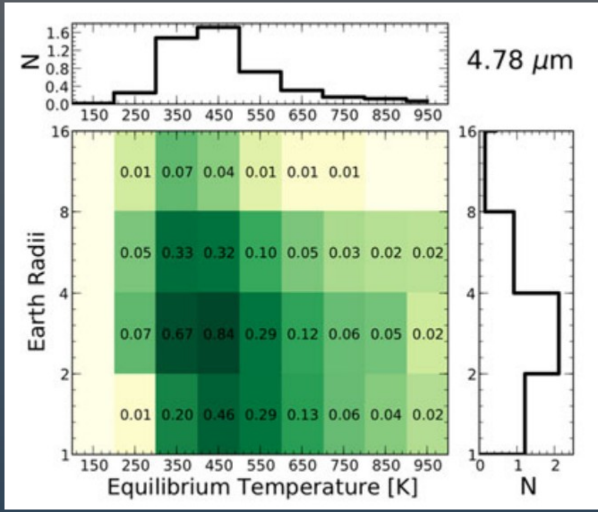


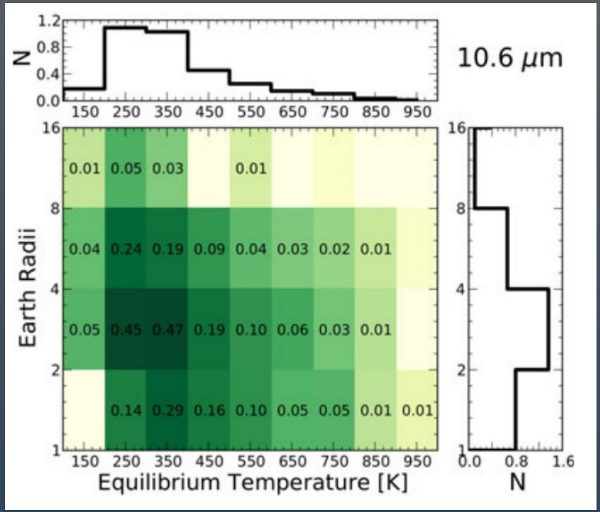
Properties of currently (2015) known RV planets detectable by METIS.

From Quanz et al (2015) (https://ui.adsabs.harvard.edu/abs/2015IJAsB..14..279Q/abstract)

ELT-METIS: Small Planets



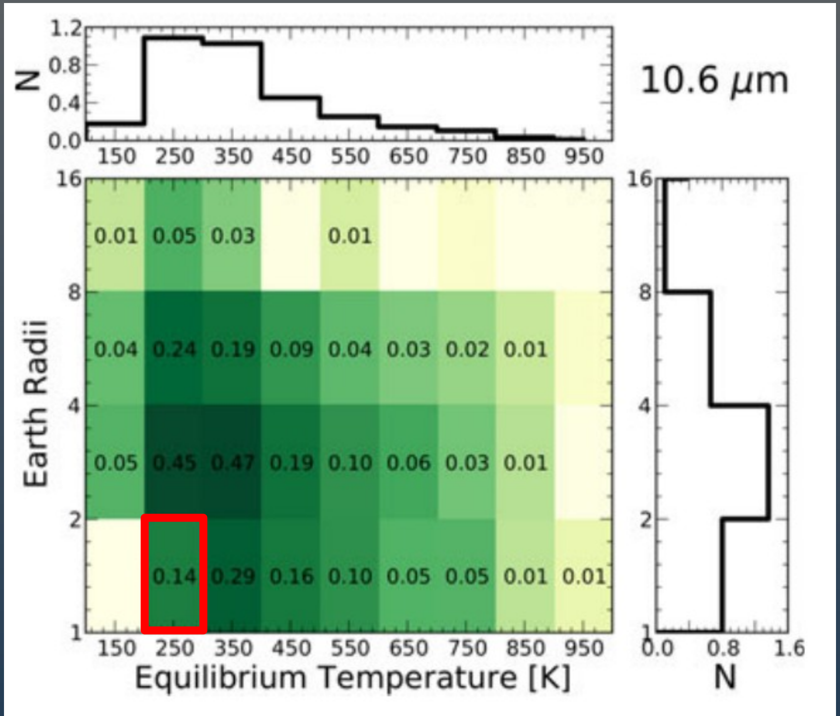




Plots show probability of METIS detecting a planet with 15 pc

From Quanz et al (2015) (https://ui.adsabs.harvard.edu/abs/2015IJAsB..14..279Q/abstract)

ELT-METIS: Small Planets



Plot shows probability of METIS detecting a planet with 15 pc

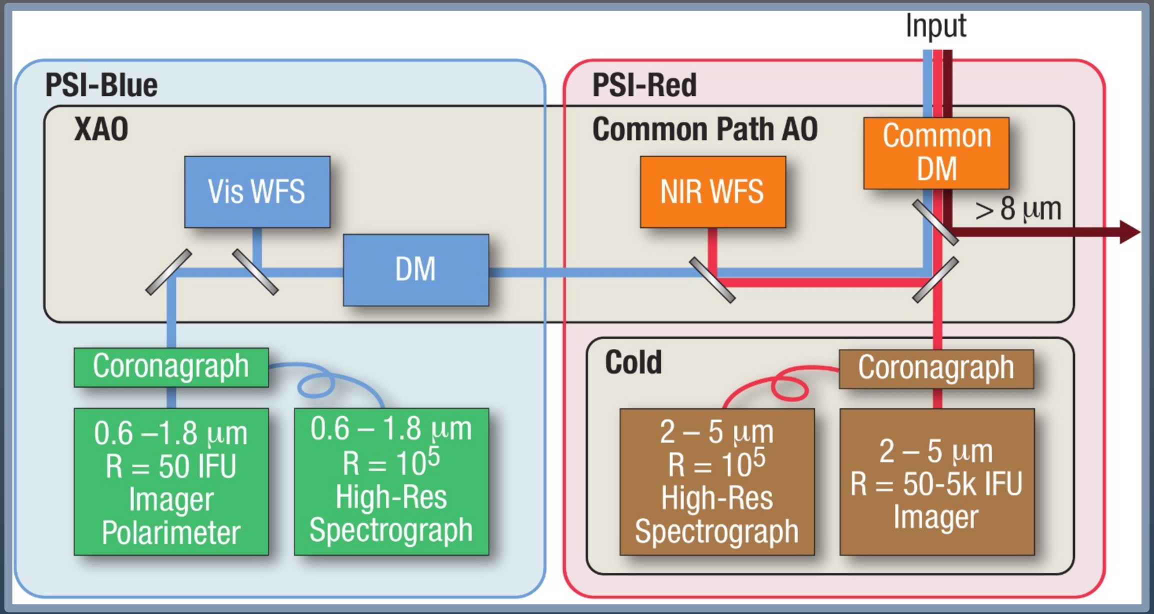
METIS will be sensitive to small, temperate, potentially habitable planets.

From Quanz et al (2015) (https://ui.adsabs.harvard.edu/abs/2015IJAsB..14..279Q/abstract)

Temperate Planets

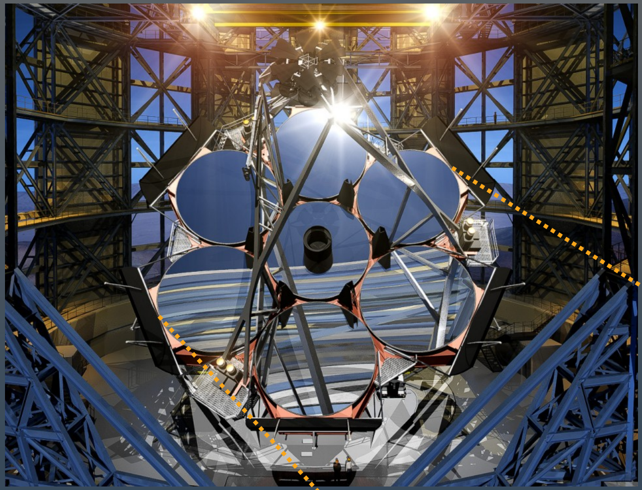
- Detecting planets closer to stars (i.e. in the HZ)
  - planet:star flux ratios from 1e-7 (M6) to 1e-10 (G2)
  - Separations from 0.1” to λ/D (~0.005”)
- What we need:
  - “extreme” adaptive optics (ExAO)
  - Coronagraphs to suppress the star’s light

Extreme-AO: TMT PSI



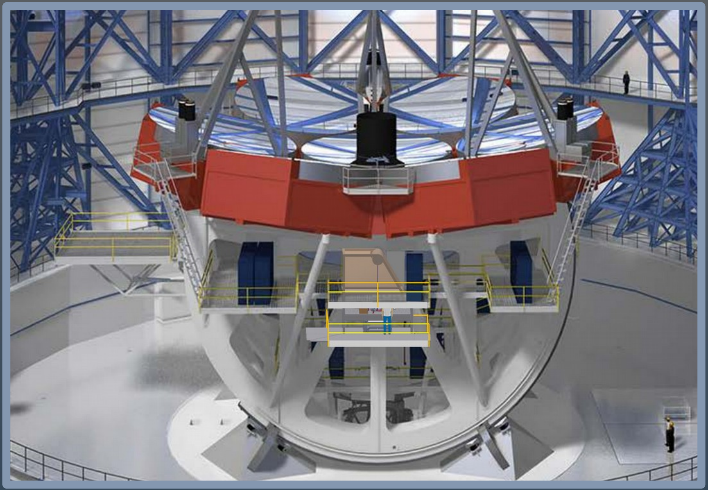
- Proposed 2nd gen. ExAO+coronagraph for TMT
  - ~600 nm to 10 microns
  - PSI-blue optimized for reflected light imaging of temperate exoplanets
- Background:
  - Astro2020 APC w.p. by Fitzgerald et al.
  - NAS w.p. “Direct Imaging in Reflected Light: Characterization of Older, Temperate Exoplanets With 30-m Telescopes” (arxiv.org/abs/1808.09632)
  - SPIE 2018 papers (Fitzgerald+, Guyon+, Stelter+, Skemer+)

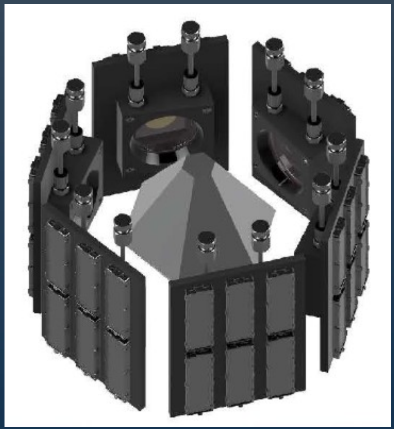
GMagAO-X

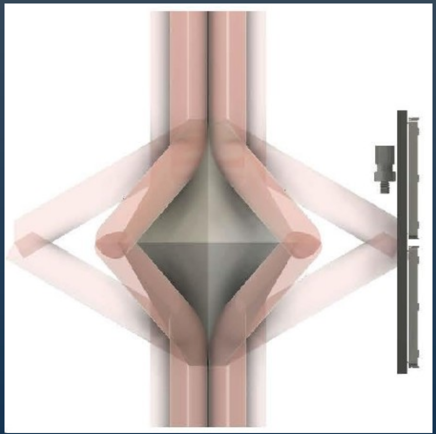


- BMC 3K MEMS
  - 1 per segment
  - 21,000 total actuators
- 62 across
  - 60 across pupil
  - 14.0 cm pitch
- Equivalent monolith:
  - 184x184 = 33,856
  - This does not exist (yet)
- > 80% Strehl at 1 micron

GMagAO-X





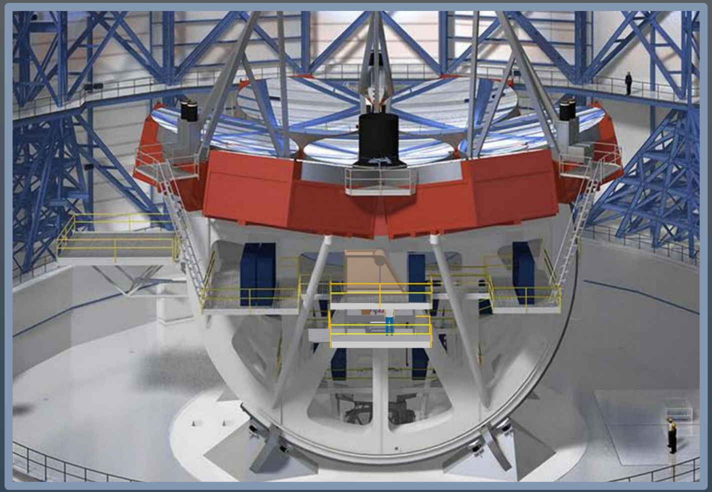


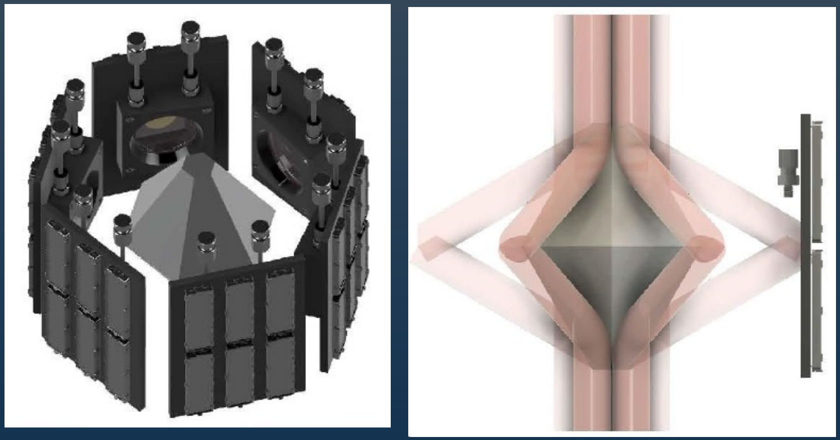
GMagAO-X Concept
opto-mech design by A. Hedglen and L. Close

- BMC 3K MEMS
  - 1 per segment
  - 21,000 total actuators
- 62 across
  - 60 across pupil
  - 14.0 cm pitch
- Equivalent monolith:
  - 184x184 = 33,856
  - This does not exist (yet)
- > 80% Strehl at 1 micron

Key Point: we can place a P.O. for these today – no tech. dev. required.

GMagAO-X





GMagAO-X Concept
opto-mech design by A. Hedglen and L. Close

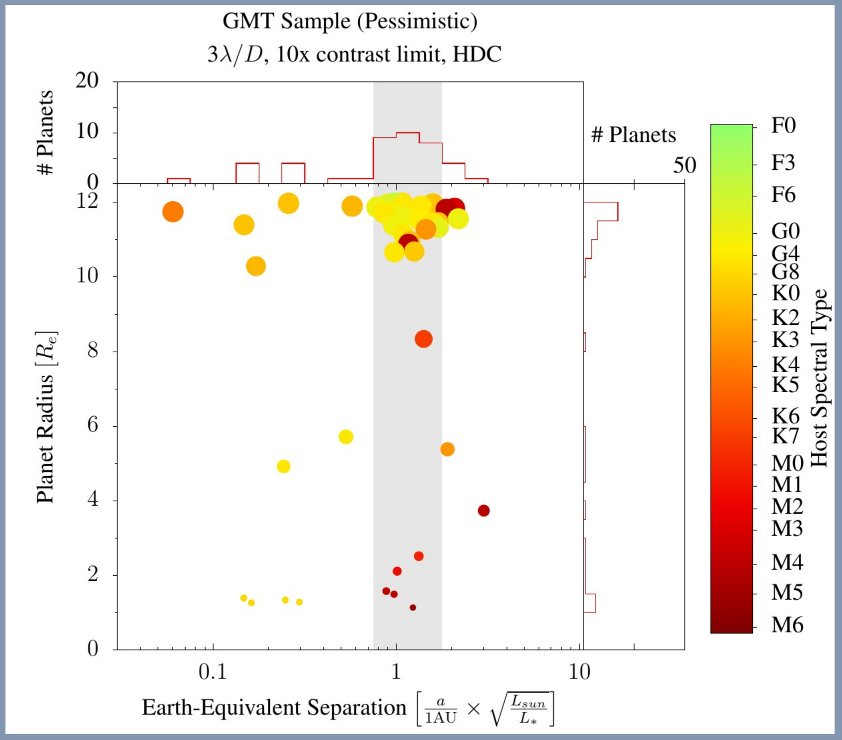
- GMagAO-X proposed for GMT as a potential first-light capability
- Use of existing COTS technology will allow rapid development
- Key challenge: imaging with a dissambled pupil
    - Phasing testbed planned at UA beginning Fall '19
- See our Astro2020 APC w.p.: "GMagAO-X: extreme adaptive optics & coronagraphy for GMT at first light" (Males+)

What to do with GMagAO-X and PSI

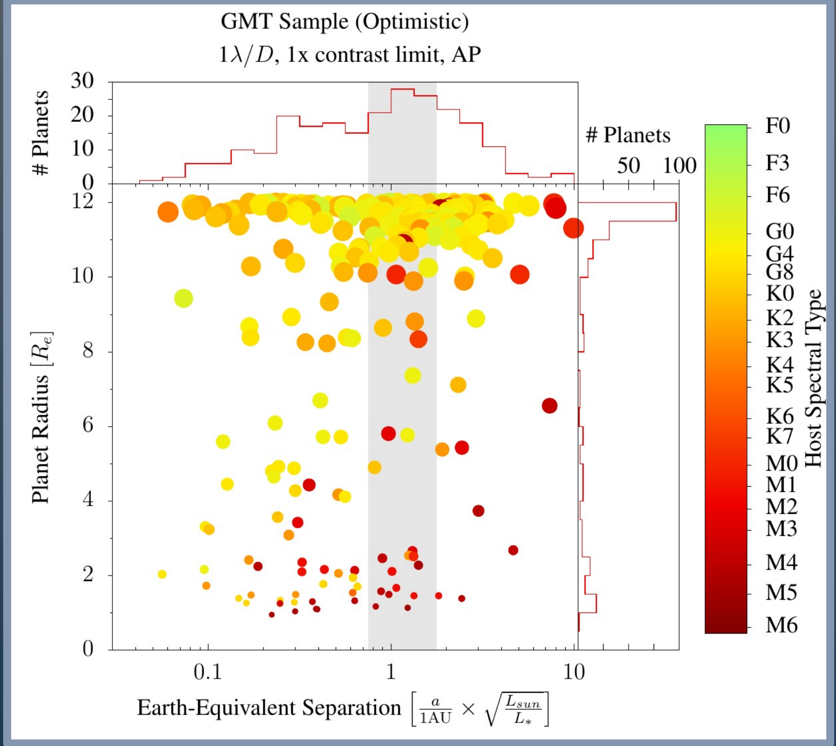
- "Temperate" planets in reflected light
- Assumptions:
  - Observe known-from-RV planet hosts (NExScI database)
  - Includes mass-radius conversion
  - Albedo models: Cahoy+ (2010)
  - Orbits taken into account
  - Science and WFS both @ 800 nm
  - 10% throughput
  - In 25%-ile conditions for LCO
  - 28x 10 hr survey

Temperate Planets in Reflected Light

Pessimistic Performance



Optimistic Performance



GMagAO-X will enable characterization of
~40 up to ~200 exoplanets in reflected light

Exoplanets With The ELTs

- Significant advance in sensitivity is coming
  - Diameters of 25, 30, and 39 m are game changing
- Will continue “today’s” exoplanet studies
  - Radial Velocity
  - Transit Spectroscopy
  - Direct Imaging:
    - Young thermally self-luminous planets
    - Circumstellar disks
- Will enable exciting new science
  - Multi-wavelength, multi-technique, sensitivity to temperate, potentially habitable, exoplanets

More Info

- GMT
  - https://www.gmto.org/
  - science book: https://www.gmto.org/2018/08/gmt-2018-science-book-released/
- TMT
  - https://www.tmt.org/
- ELT
  - https://www.eso.org/sci/facilities/eelt/
- The White Paper Deluge
  - Astro2020 Science and APC w.p.
  - NAS w.p.
  - US-ELT papers