Exoplanet High Contrast Imaging Technologies Ground

KISS Short Course:
The Hows and Whys of Exoplanet Imaging

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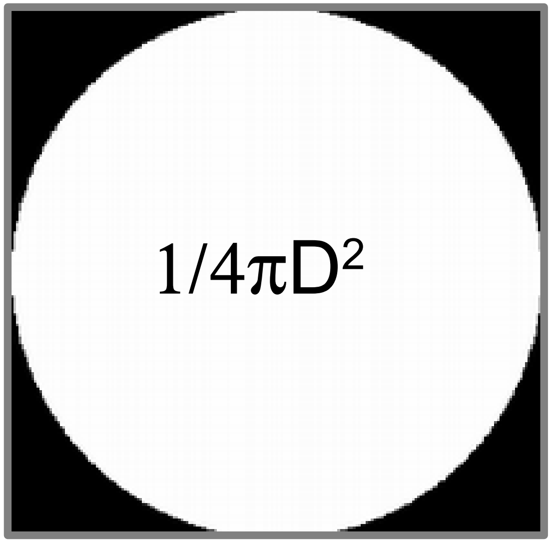
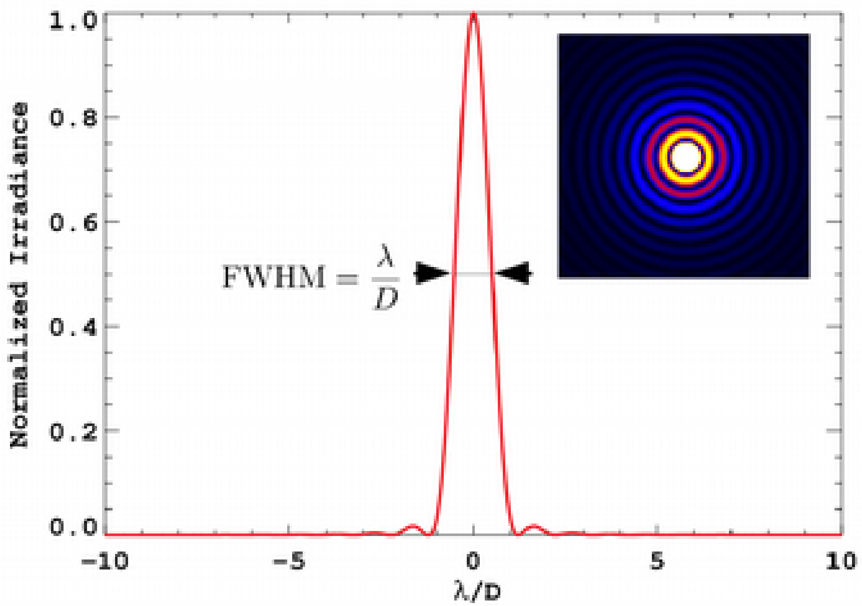
Telescope Diameter (Bigger is Better)

- Diameter:
  - Collecting area goes as D^2 -> more photons
  - Spatial resolution goes as 1/D -> sharper images (closer planets)

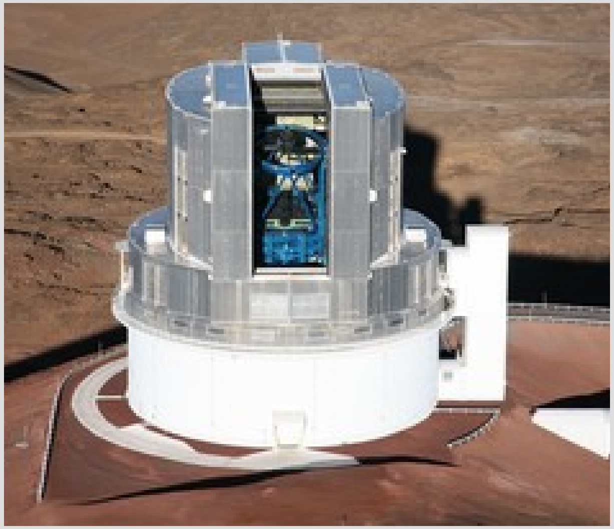




- Rule of thumb: it is easier to build large telescopes on the ground than to build them in space

Ground Based Telescopes

Magellan Clay 6.5 m



Subaru 8 m

Gemini-S 8 m

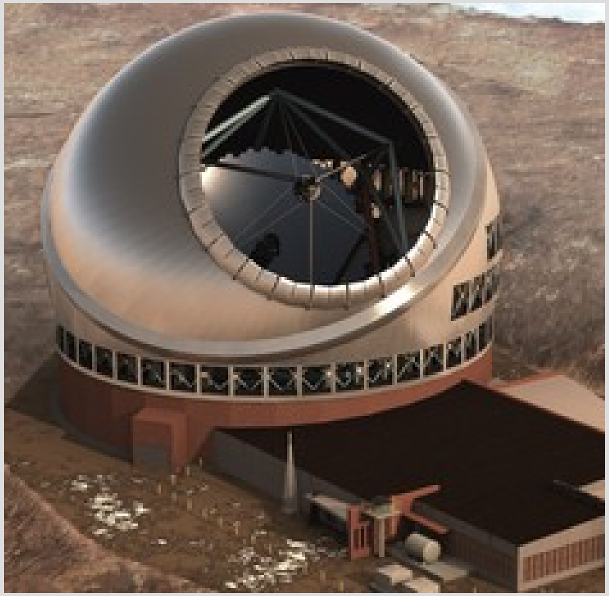
VLT 8 m (4)

Keck 10 m (2)

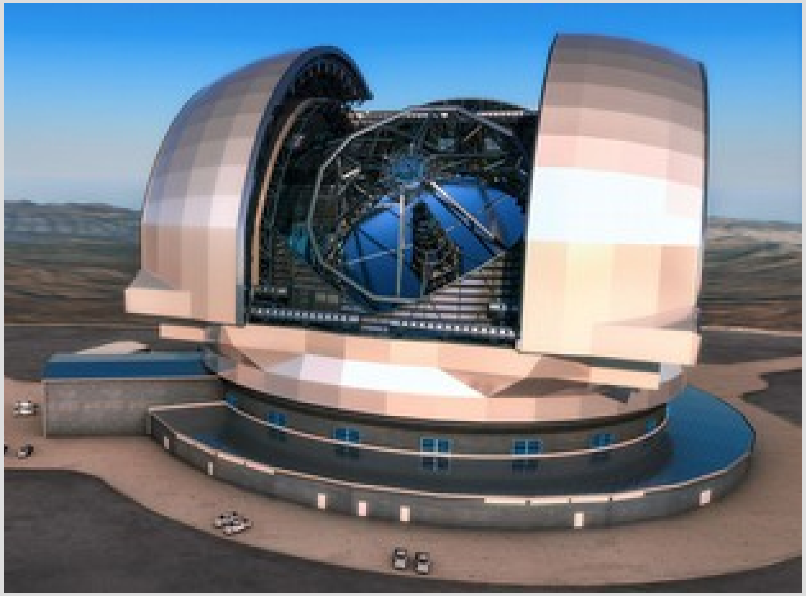
LBT 8x22 m

Ground Based Telescopes

GMT 24.5 m



TMT 30 m



E-ELT 39 m

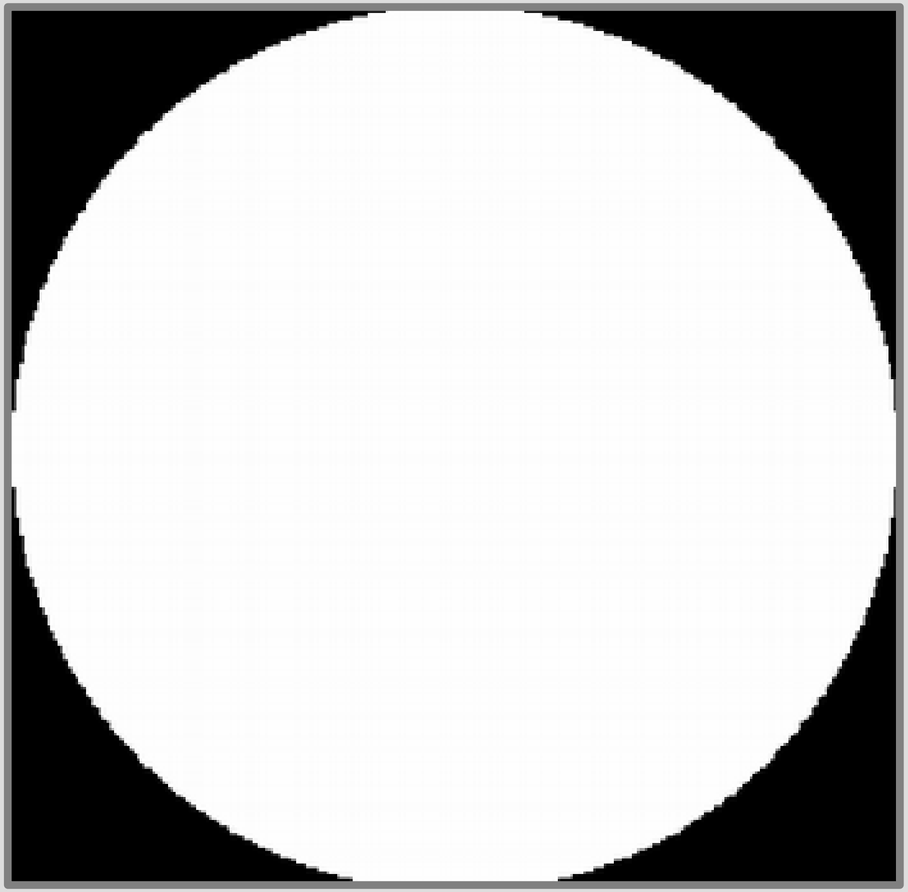
The future is under construction . . .

Turbulence

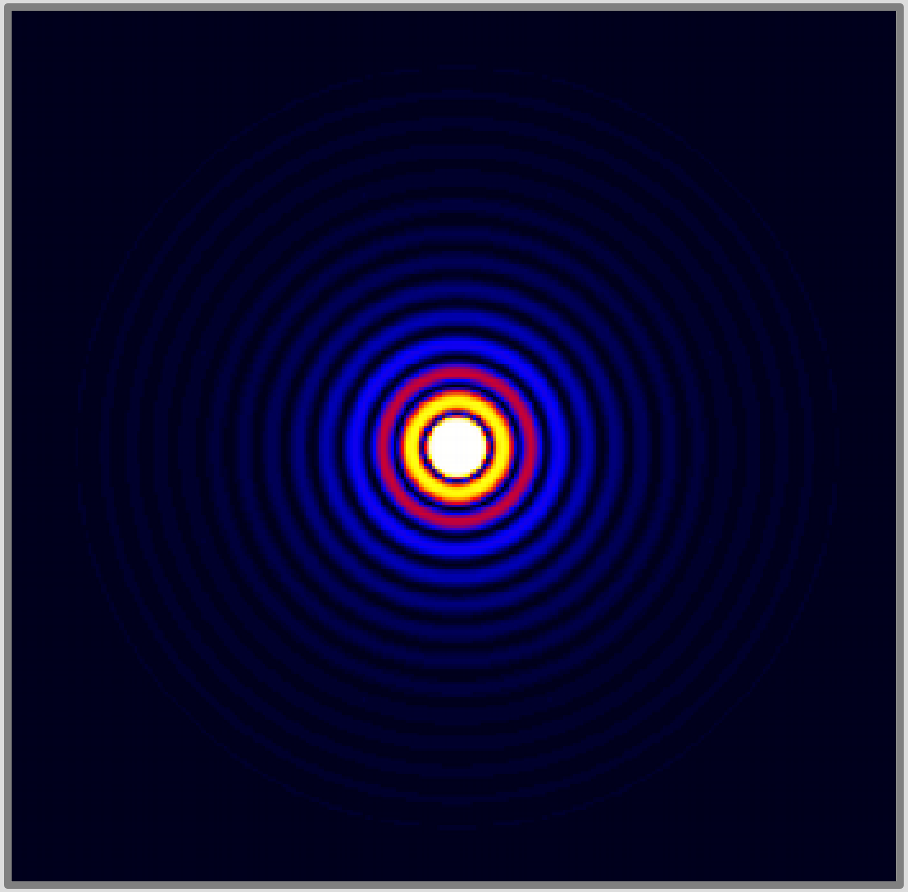
- There's a catch . . .
- Light must propagate through the Earth's atmosphere to reach a telescope on the ground.
- Temperature variations in the atmosphere cause index of refraction variations
- The characteristic scale of these variations, r0, is less than telescope diameter D (for large telescopes).
- Result: the wavefront reaching the telescope is no longer flat
  - This is why stars twinkle

Flat Wavefronts

Pupil Plane

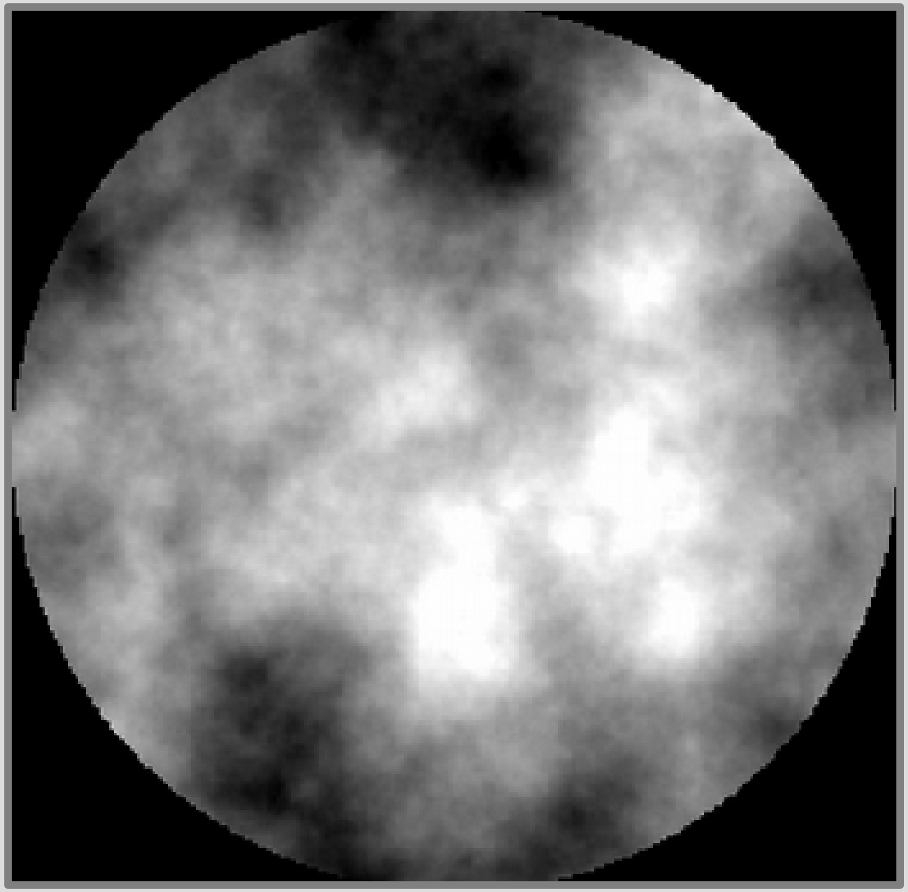


Focal Plane



Turbulence Degraded Wavefronts

Pupil Plane



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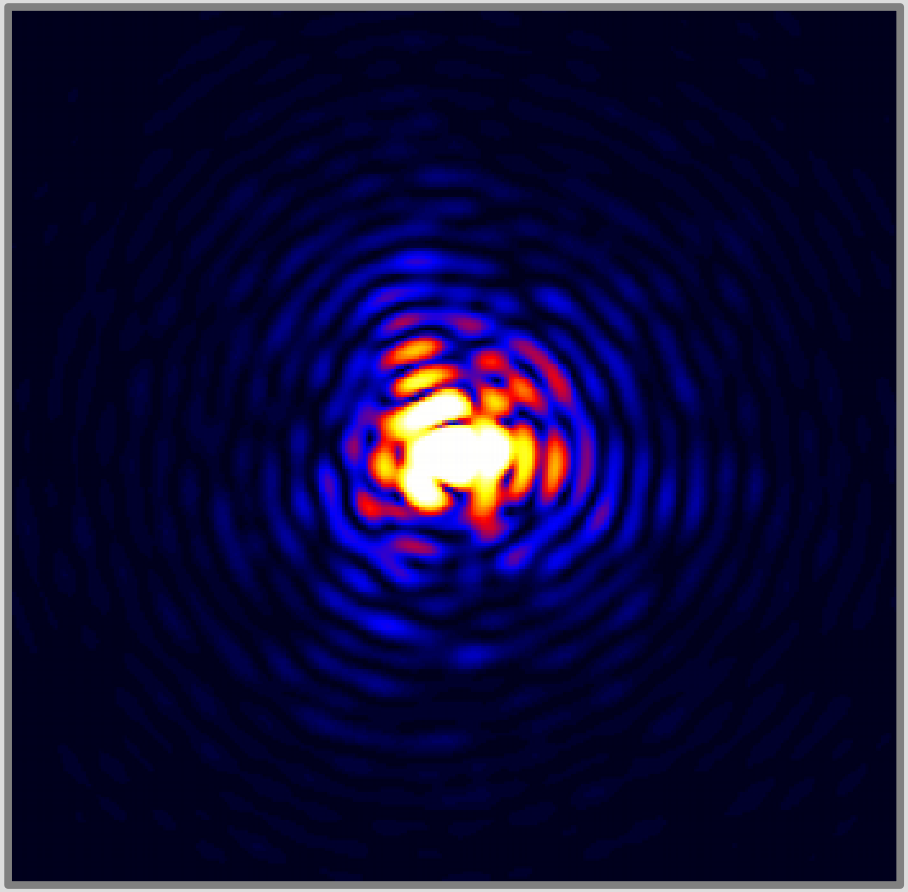
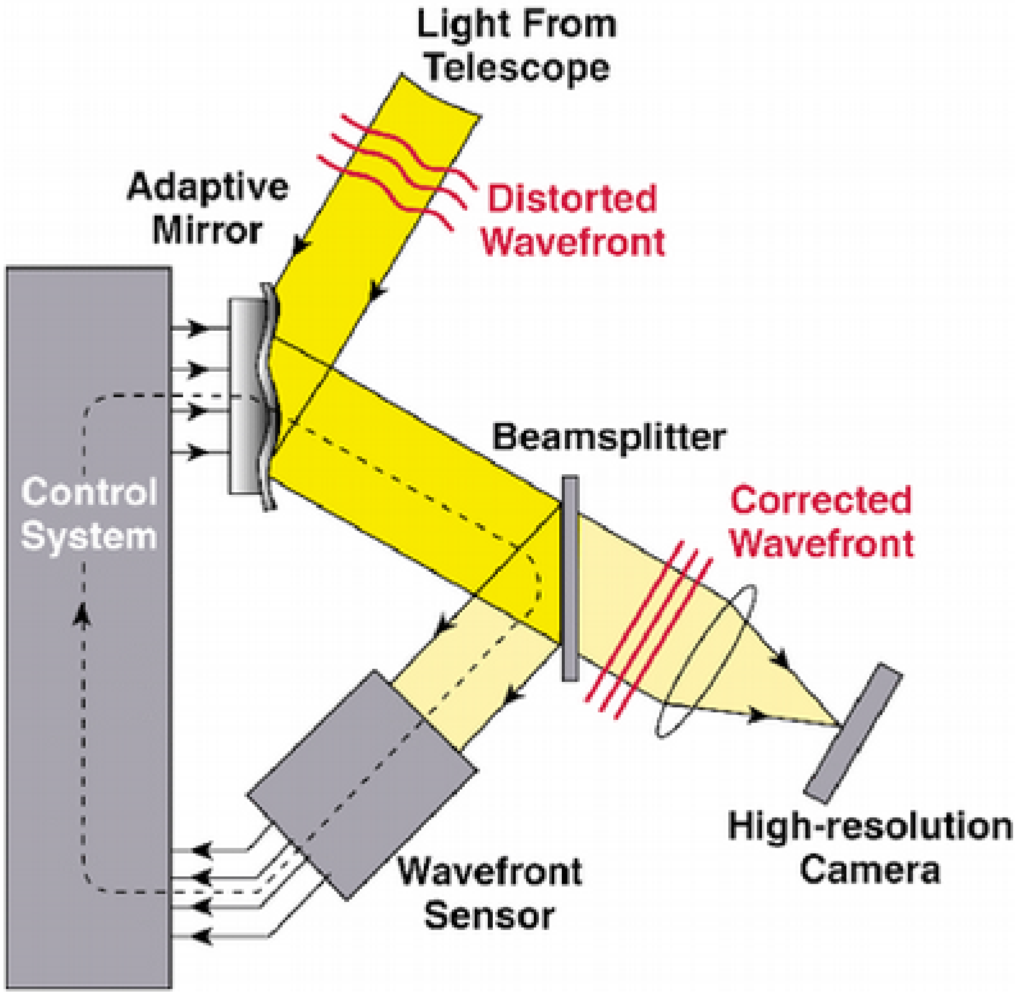


Adaptive Optics

- AO systems measure and correct the OPD caused by turbulence

- Key components
  - Wavefront sensor
  - Deformable mirror
  - Real time control system

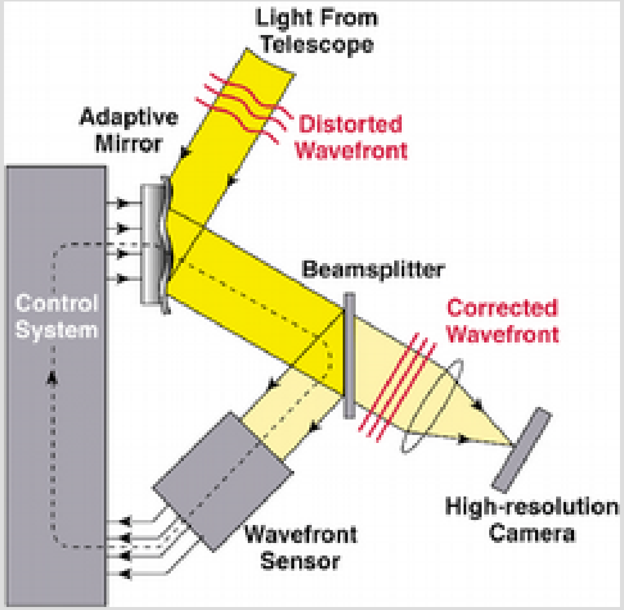
- Limited by:
  - Speed of components
  - Number of actuators (DOF)
  - Brightness of stars



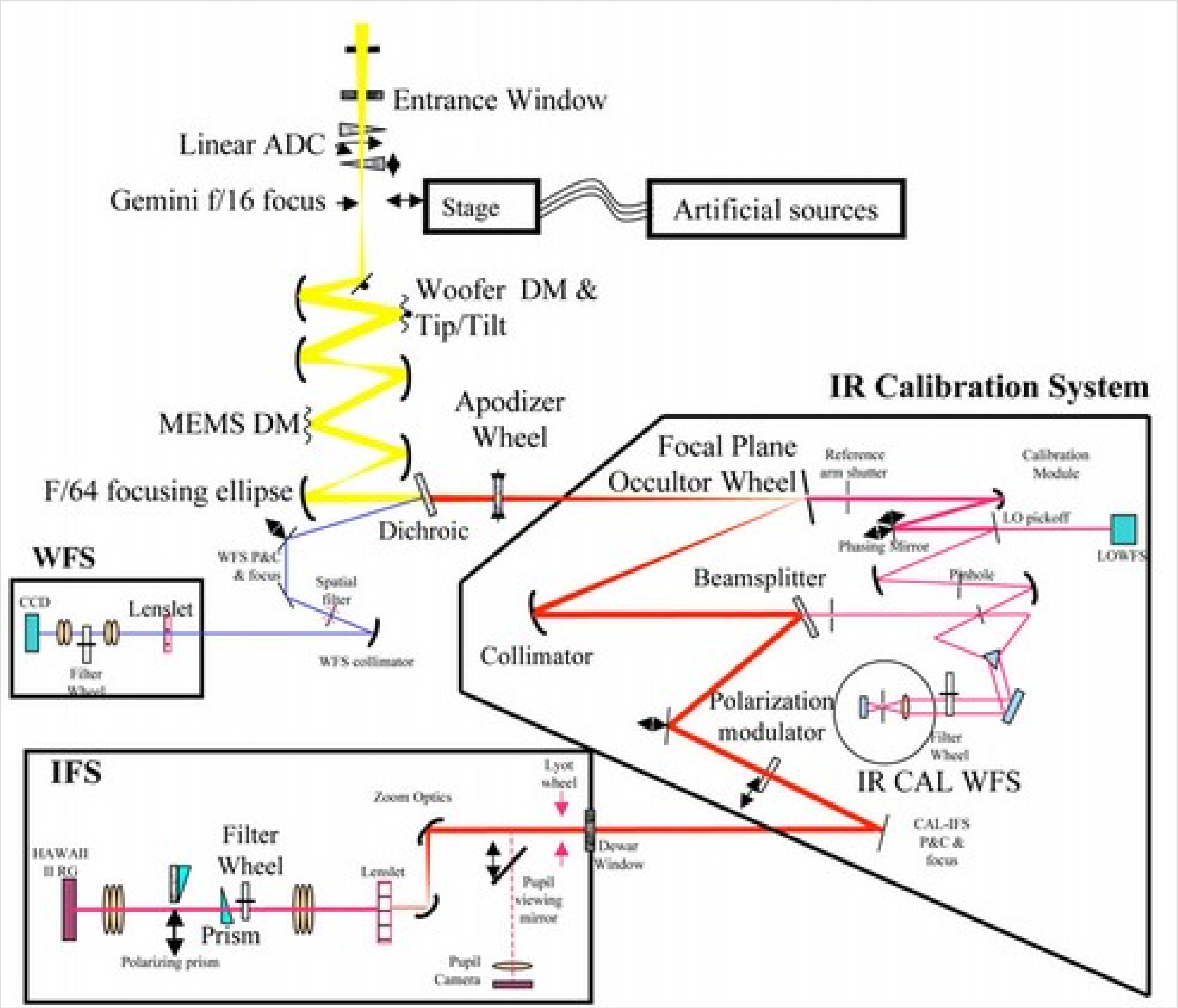
Courtesy of Claire Max

AO for Exoplanet Imaging

Generic AO System



Gemini Planet Imager (GPI)



See Macintosh+ (2014), Poyneer+ (2016)

AO for Exoplanet Imaging

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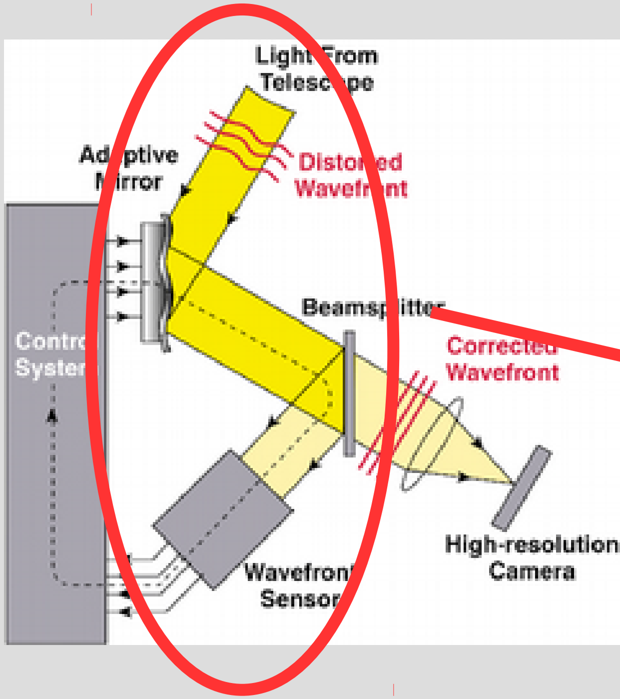

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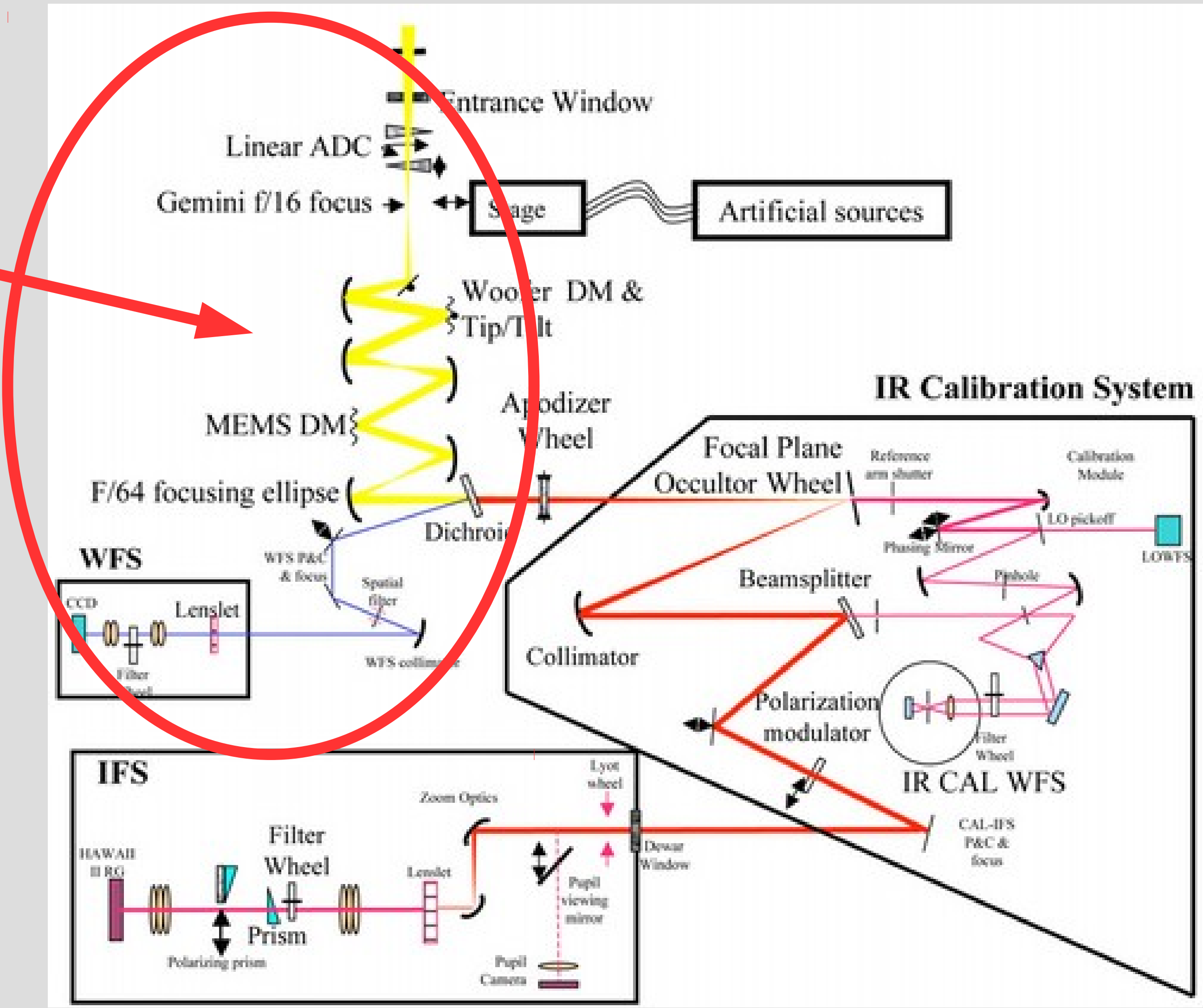

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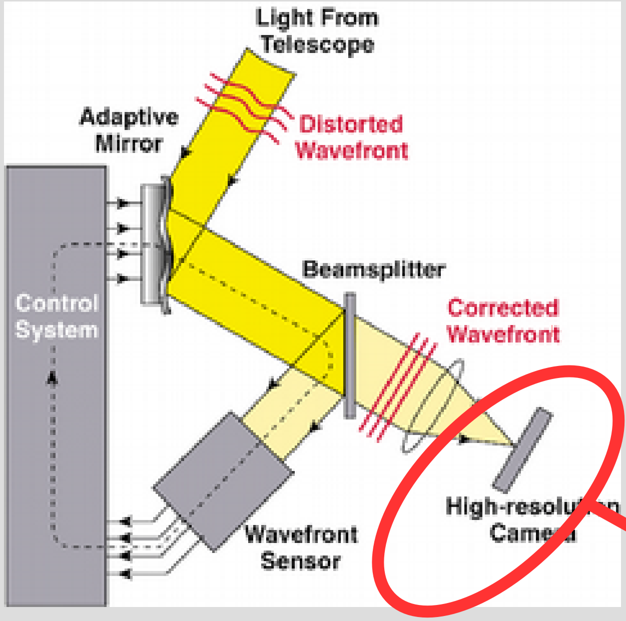

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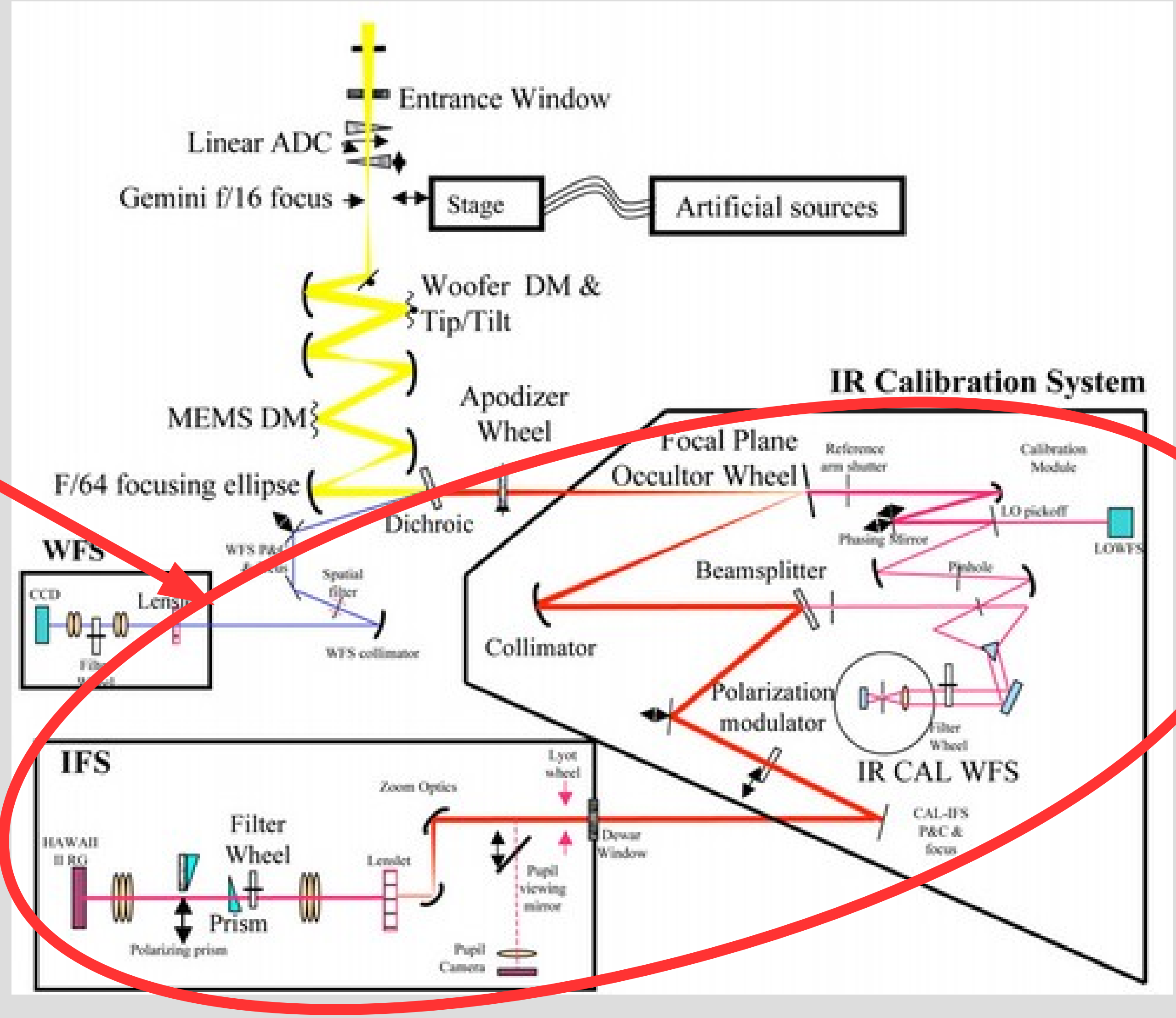

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AO for Exoplanet Imaging

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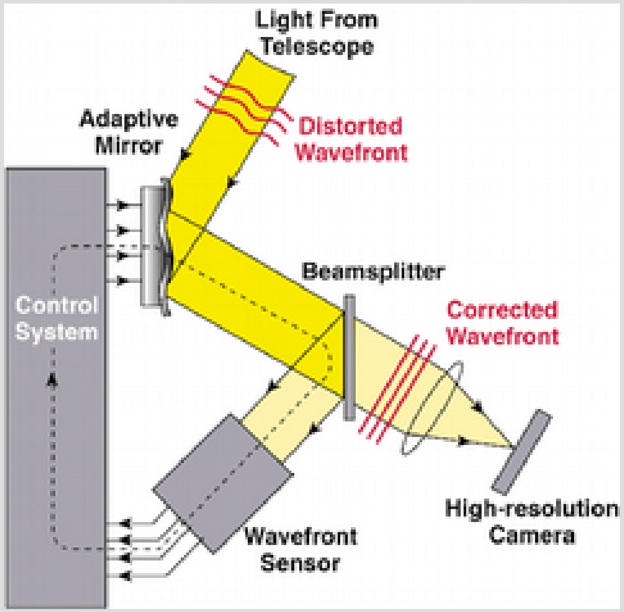

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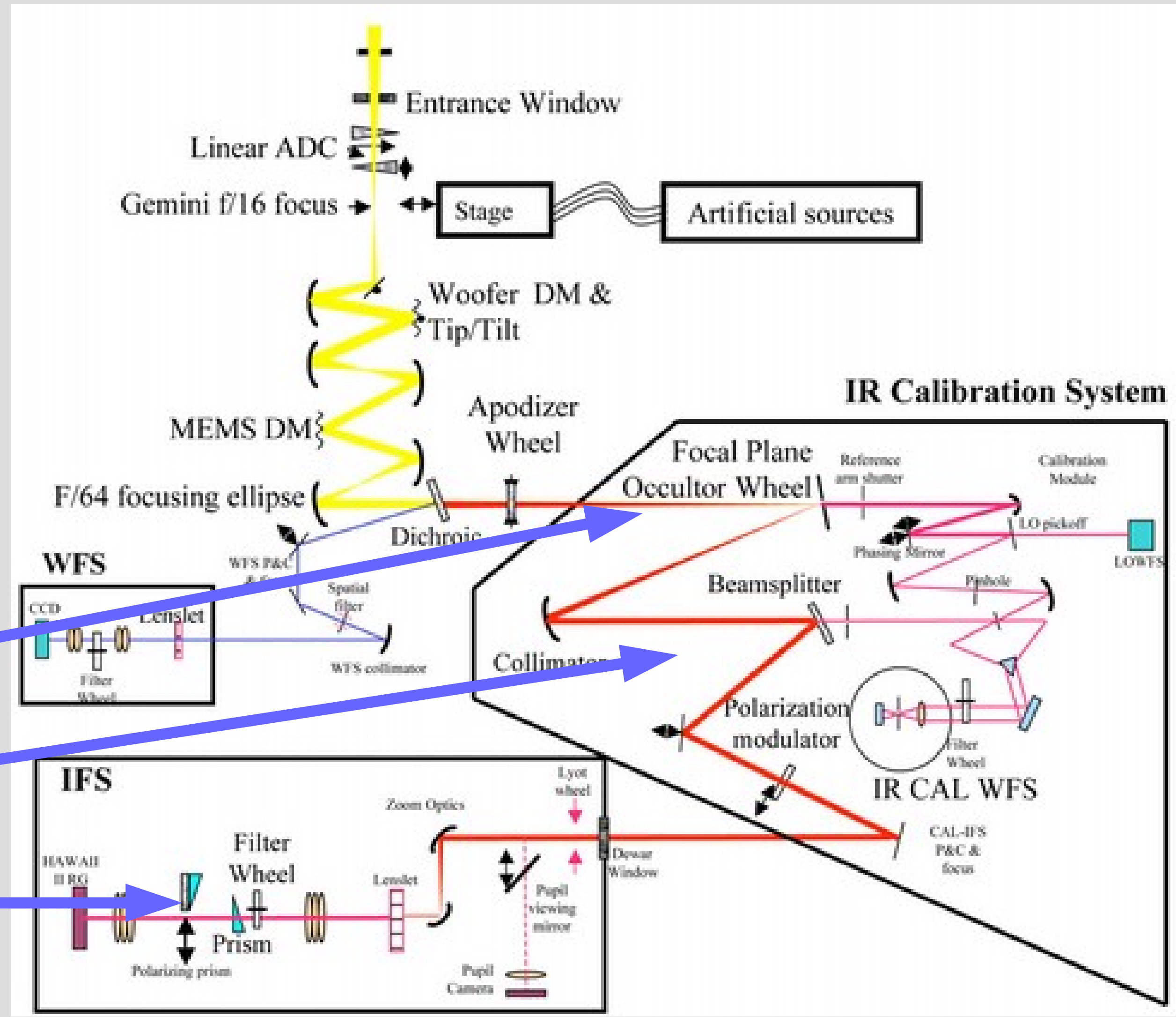


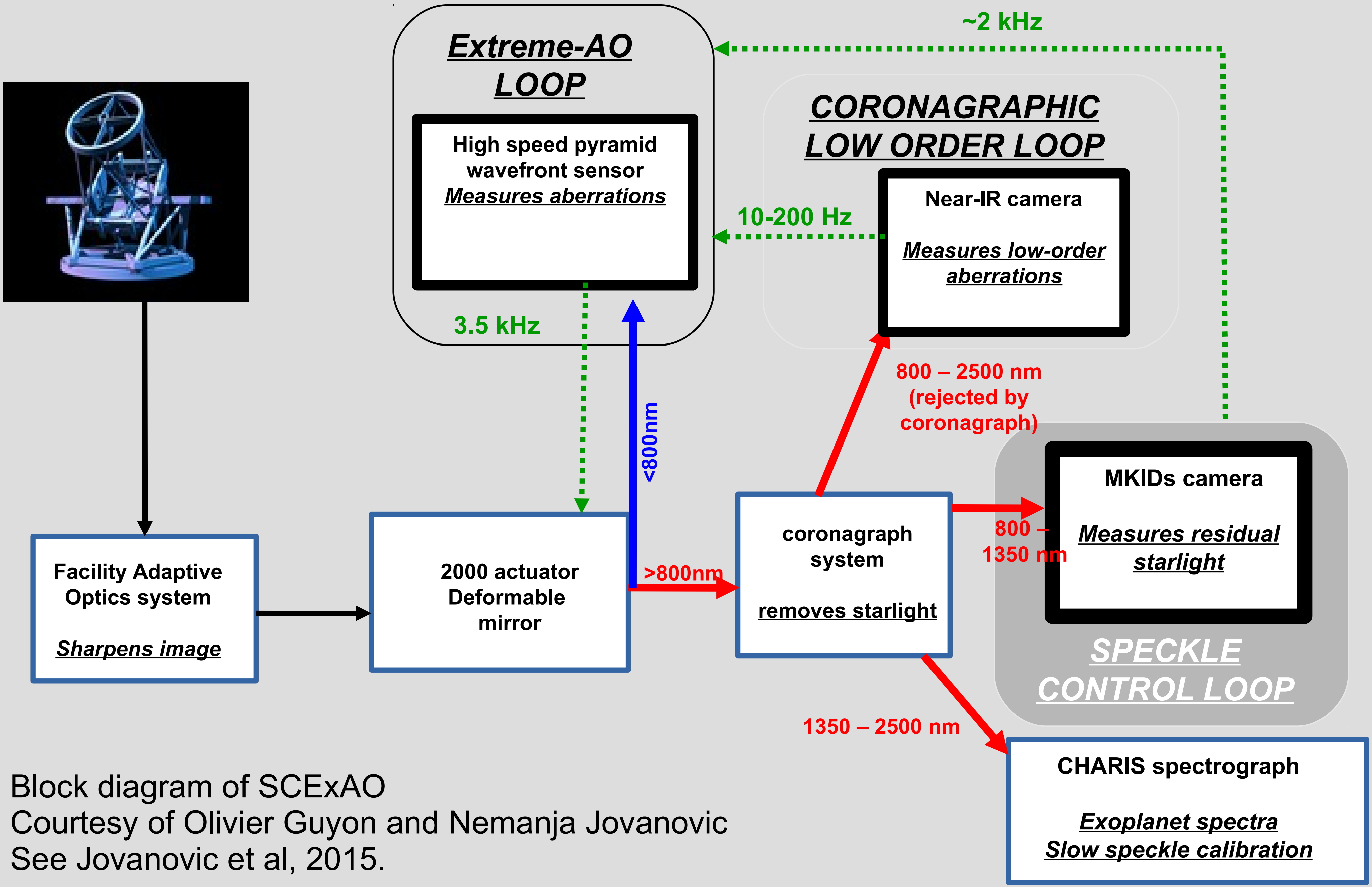
Coronagraph

Low-Order WFS

Integral Field Spectrograph

See Macintosh+ (2014), Poyneer+ (2016)

ExAO Block Diagram

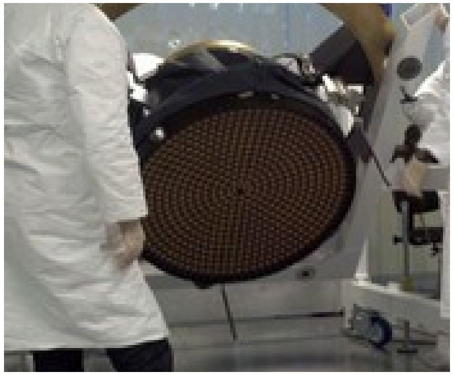


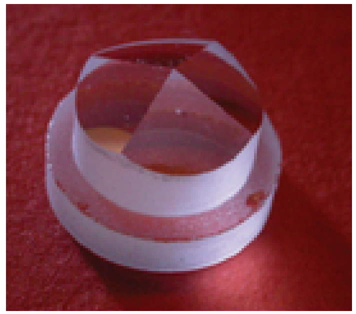
Block diagram of SCExAO
Courtesy of Olivier Guyon and Nemanja Jovanovic
See Jovanovic et al, 2015.

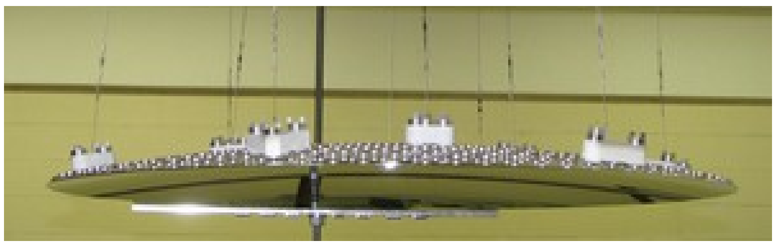
Ground Exoplanet Imagers Today

- MagAO
  - 6.5 m Magellan Clay, 0.5 um (VisAO) to 5 um (Clio)
- LBTI
  - 8x22 m LBT, 1-13 um imaging, IFS, nulling & Fizeau interferometry
- P1640
  - 5 m Palomar, 0.9-1.78 um IFS
- GPI
  - 8 m Gemini-S, 0.9-2.4 um IFS, polarimetry
- SPHERE
  - 8 m VLT, 0.5-2.32 um imaging, IFS, polarimetry
- SCExAO
  - 8 m Subaru, 0.5 – 2 um, many modes of observation

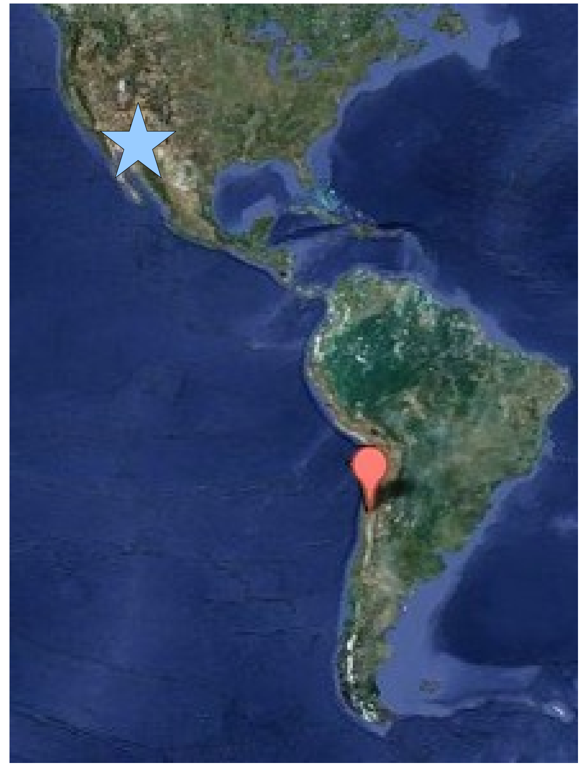
MagAO and LBTI

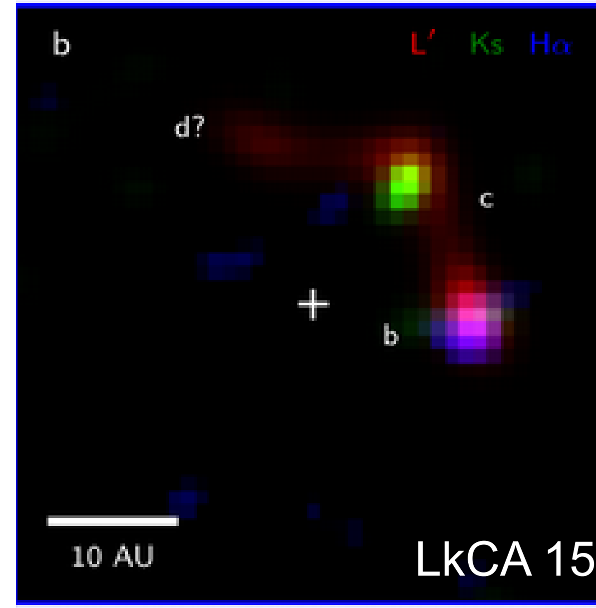






See Esposito+ (2011); Close+ (2012); Hinz+ (2013)

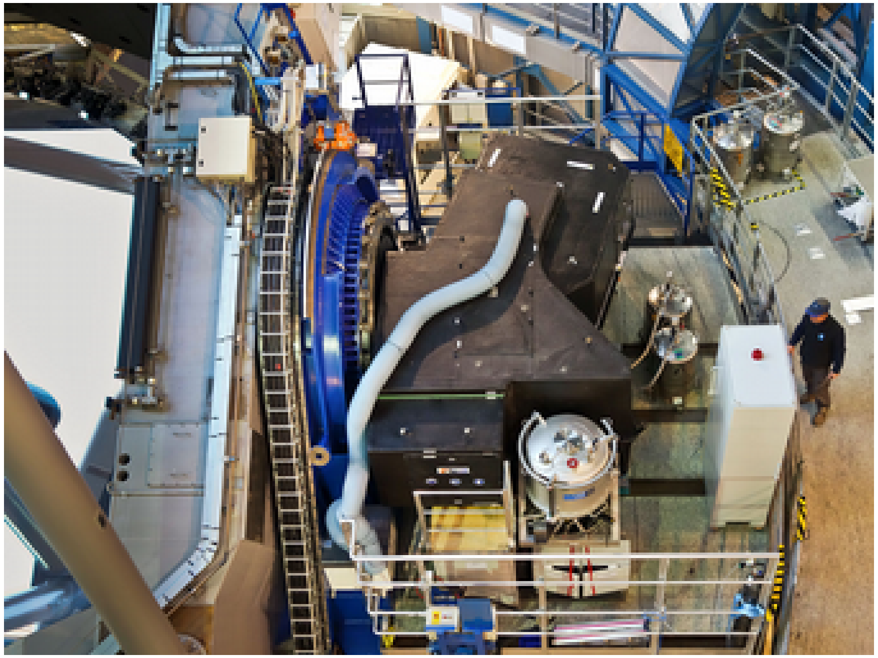


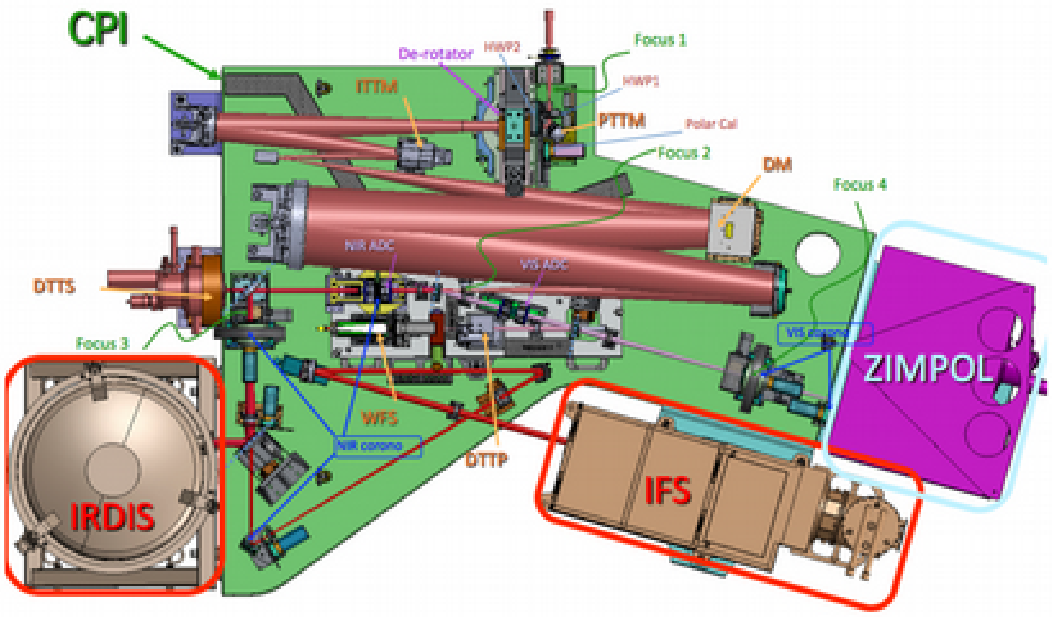


Steph Sallum (LBTI+NRM) and Kate Follette (MagAO+VisAO) [Sallum et al, *Nature*, 2015]

- Adaptive secondary mirrors
  - Minimum new optical surfaces, optimal for thermal-IR
  - 8x22 m Large Binocular Telescope, Mt. Graham, AZ
  - 6.5 m Magellan Clay Telescope, Las Campanas Obs., Chile

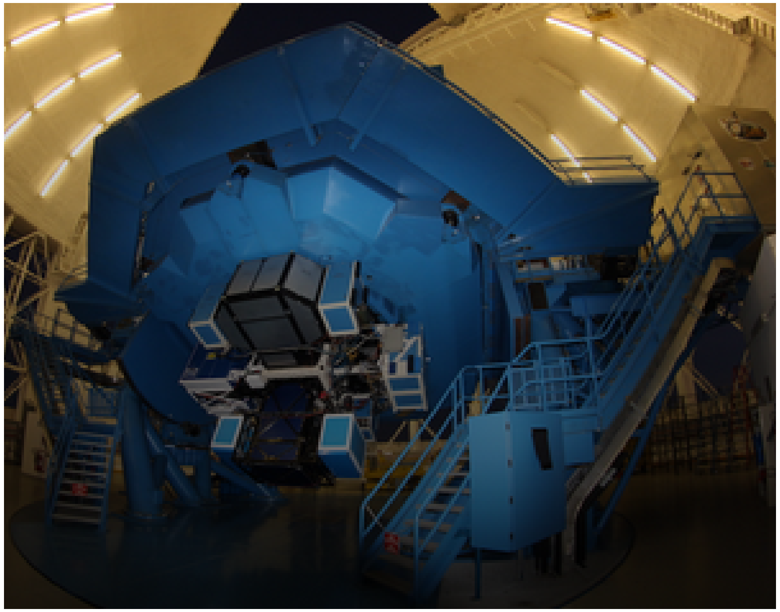
SPHERE

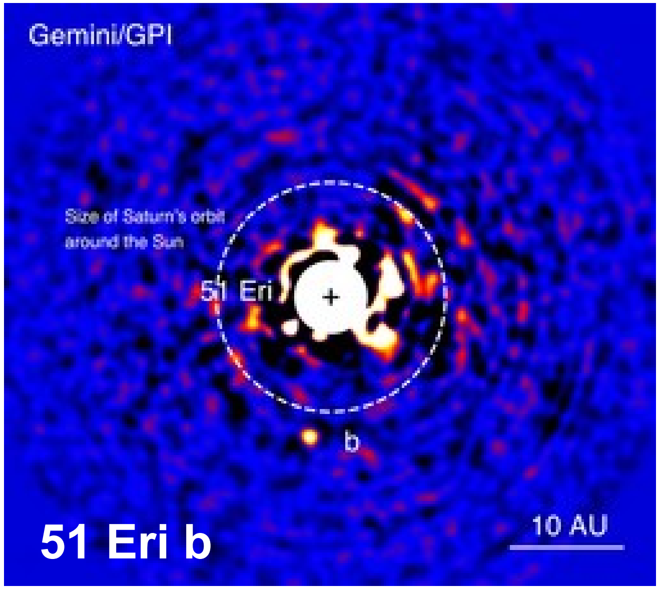




- Spectro-Polarimetric High-contrast Exoplanet Research
- At 8 m VLT (ESO)
- For more, see https://www.eso.org/sci/facilities/paranal/instruments/sphere/overview.html

GPI

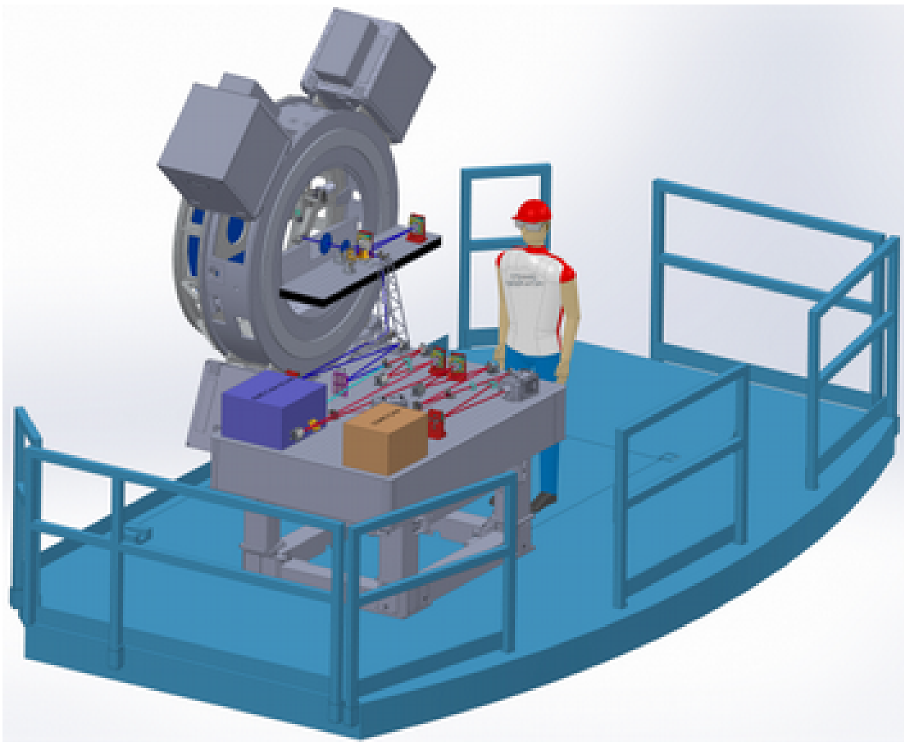


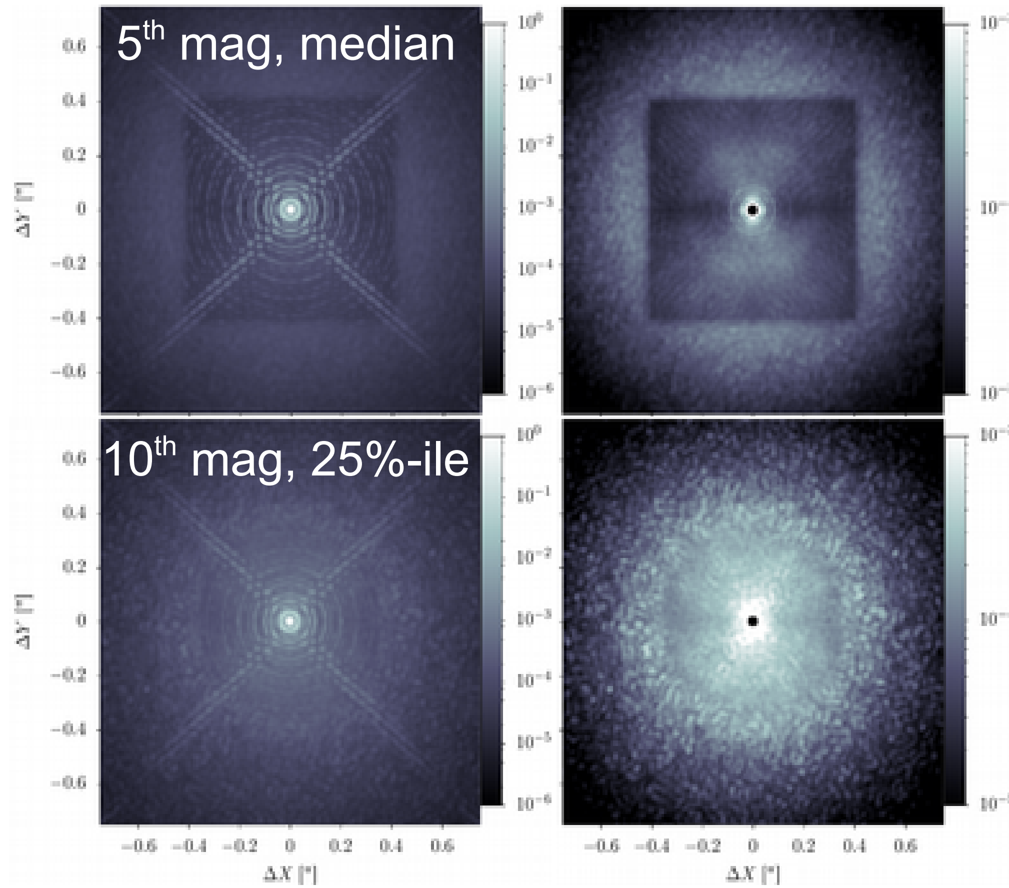


Macintosh+, 2015

- Gemini Planet Imager (GPI) on Gemini South (Chile)
- See also Poyneer+ (2016), and http://planetimager.org/

Introducing MagAO-X





Images at Hα (656 nm)

- A new Extreme-AO system for Magellan
- 2000 actuators, 3.6 kHz
- Goal: 1 λ/D coronagraphy in the visible (see Males+, SPIE, 2016)
- Status: recommended for funding by NSF-AST (MRI), in preliminary design phase.

Limits of Ground Based AO

- Technology keeps getting better
  - Fast, high order DMs are readily available
  - Low (near zero) noise, fast detectors are becoming ubiquitous
    - From visible (EMCCD) to IR (APD arrays)
    - With energy resolution (MKIDS)
- Fundamental limit: photon noise
  - Stars are only so bright
  - Limits number of actuators: can not correct all errors
  - Limits system speed: always behind the wind
  - Overall limit on image quality achievable from ground
- Key metric (for exoplanets): Contrast
  - Ratio of detectable planet brightness to star brightness

Discussing Contrast Limits

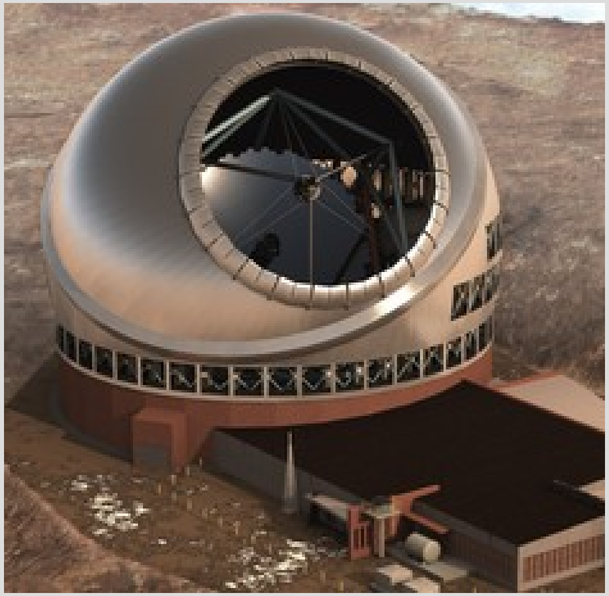
- Space and Ground people sometimes mean different things

- Typical usage:
  - Space: raw post-coronagraph & WFC contrast
    - No dependence on integration time, etc.
  - Ground: final contrast, after post-processing
    - Includes hours of integration, weeks/months/years of post-processing work

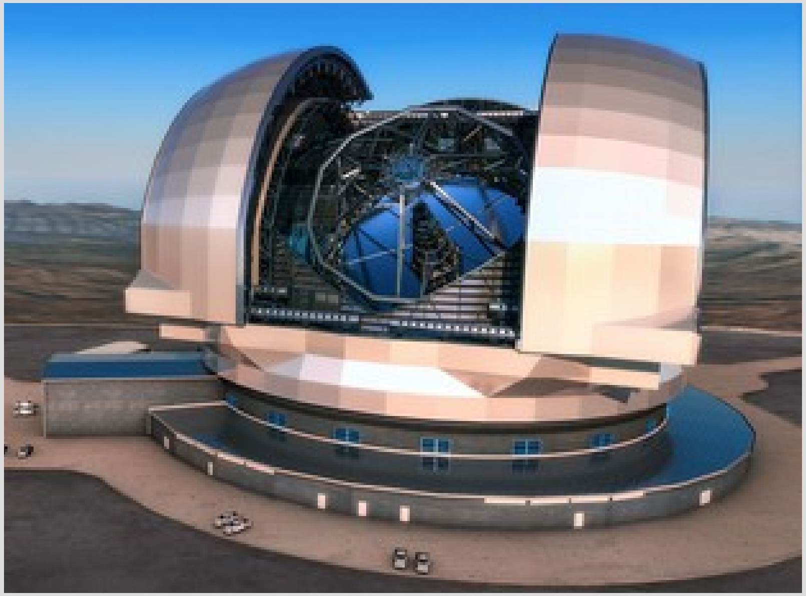
- Result: space people tend to think that ground people are crazy

Ground Based Telescopes

GMT 24.5 m



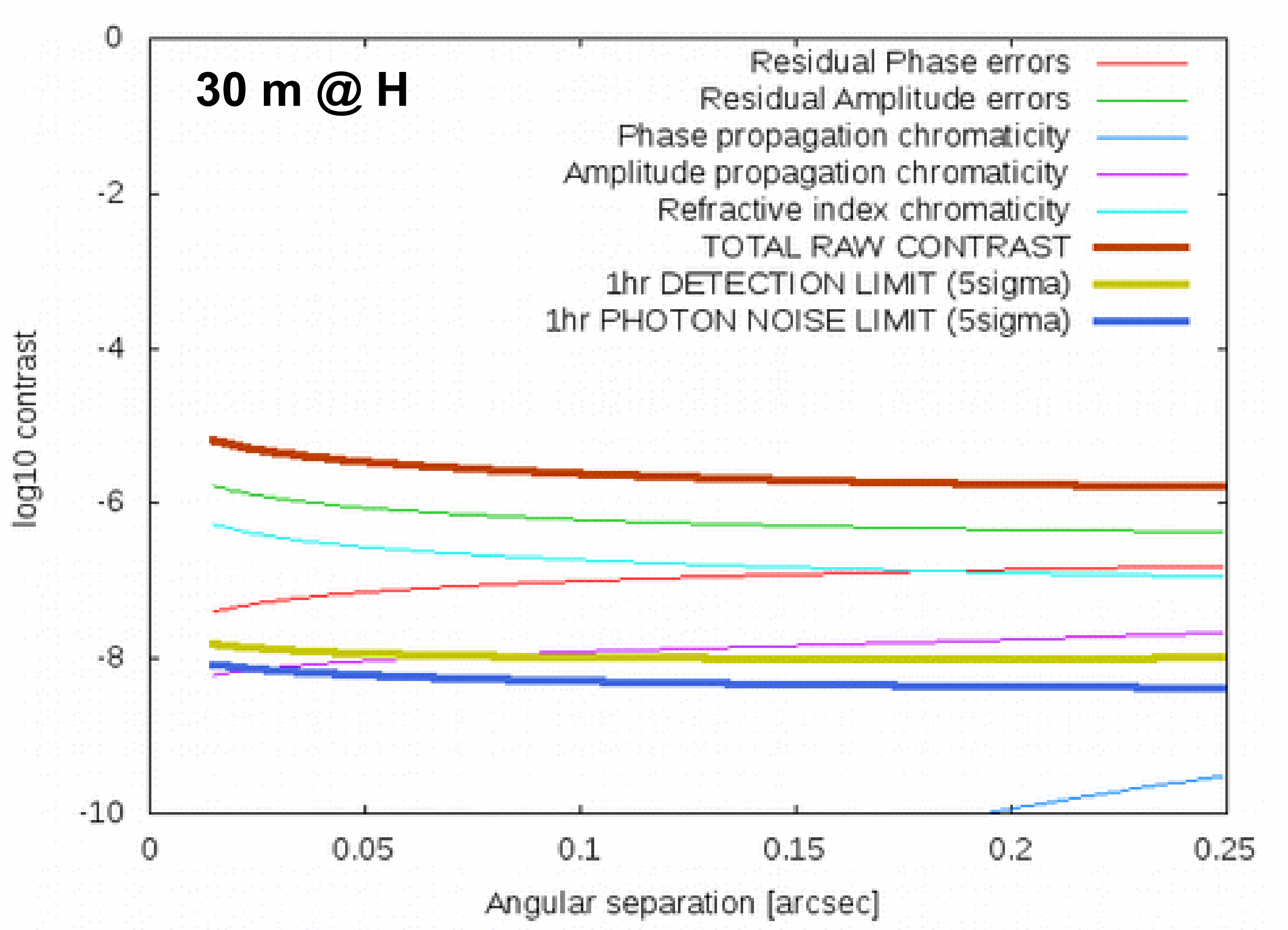
TMT 30 m



E-ELT 39 m

- The Extremely Large Telescopes will change the game
  - Diameters of 25, 30, and 39 m dramatically improve IWA
- ELTs will image smaller planets than we can today
  - And spectroscopically characterize them
- ELTs should be able to probe the HZs of nearby M-dwarfs

Ground-based Contrast Limits



Assumptions:

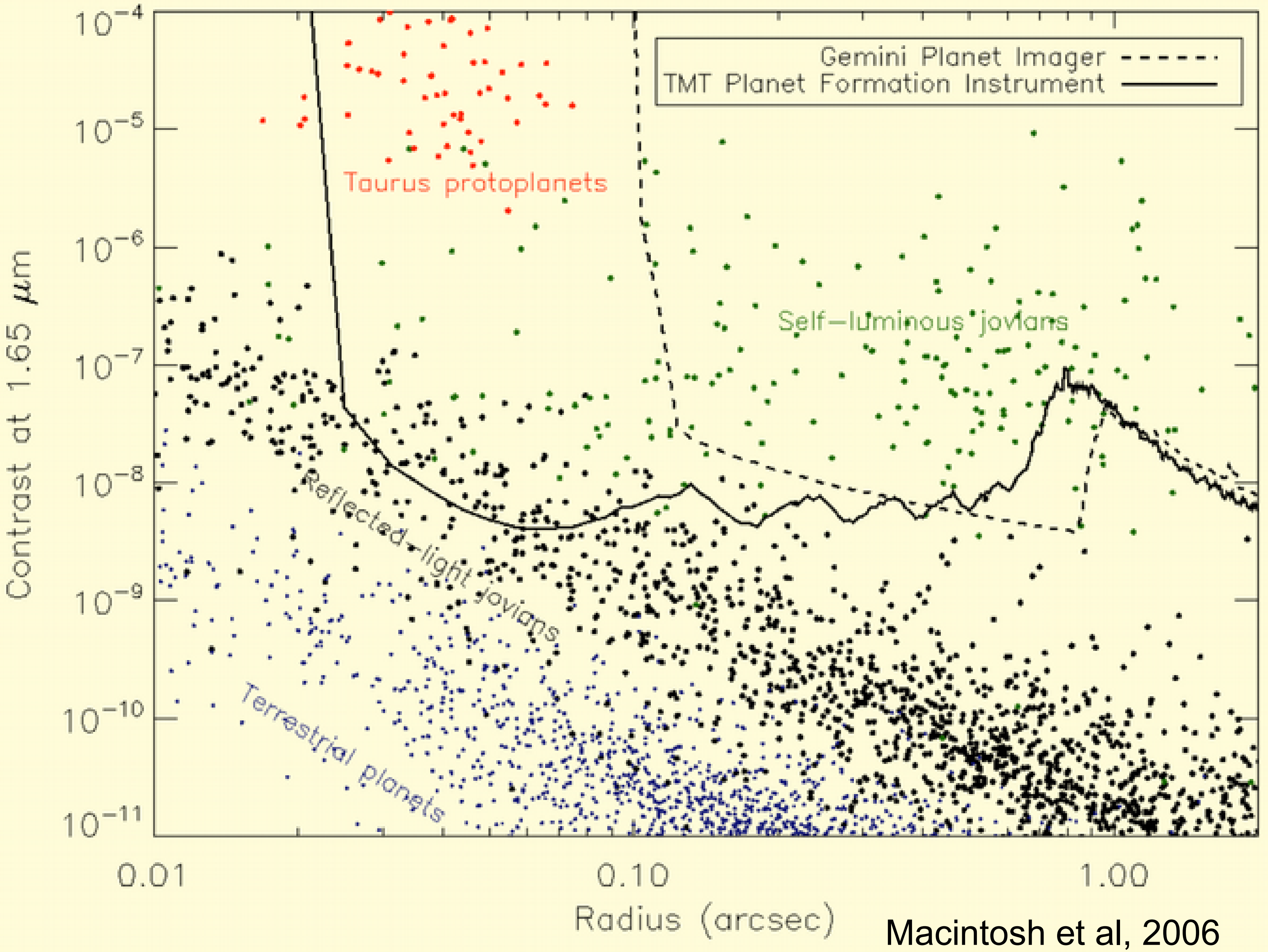
I mag = 8 (WFS > 100 targets)
H mag = 6 (Science)

Noiseless detector
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere

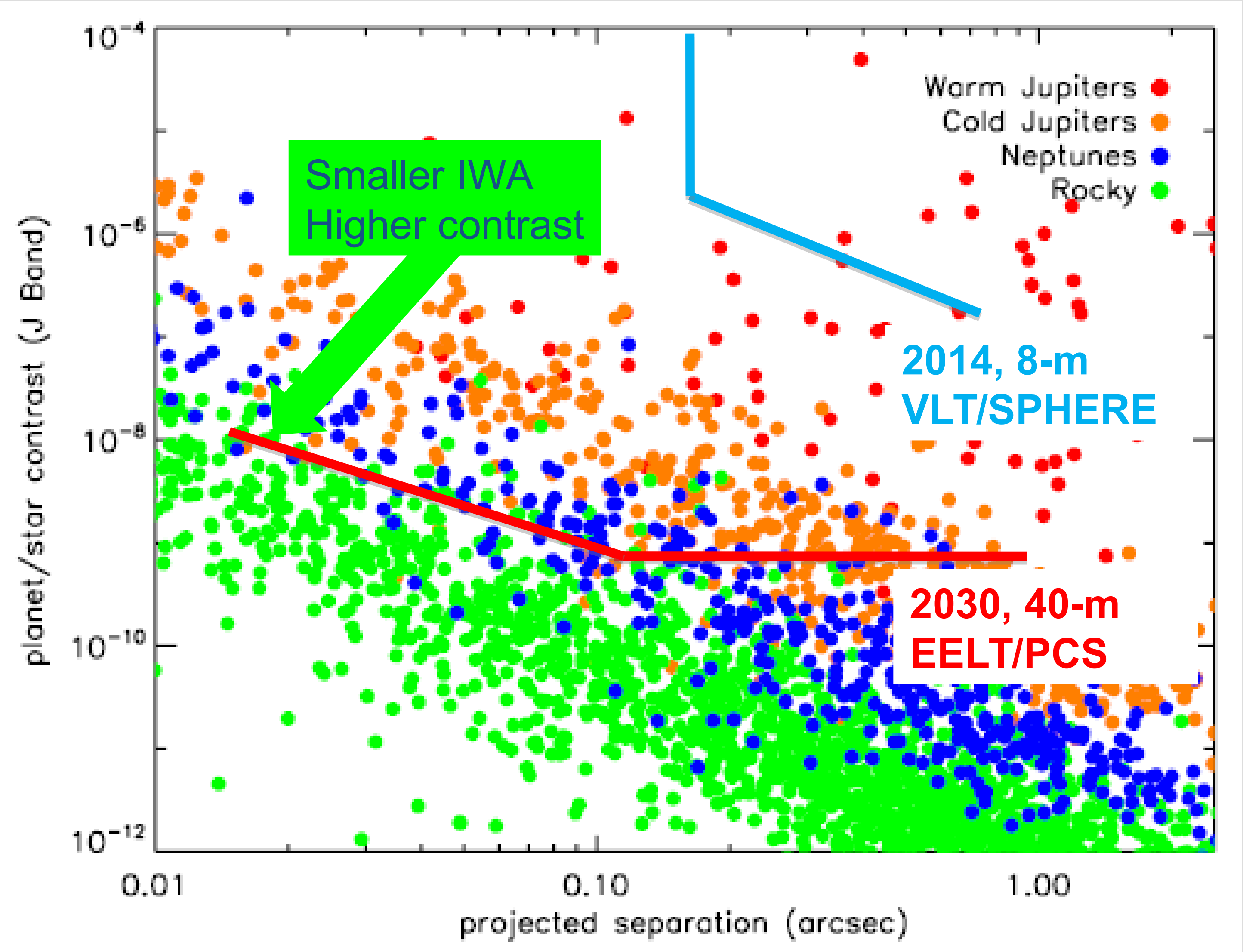
Analysis for 30 m TMT by Olivier Guyon (See Guyon, 2005, 2012)

Ground-based Contrast Limits



Macintosh et al, 2006

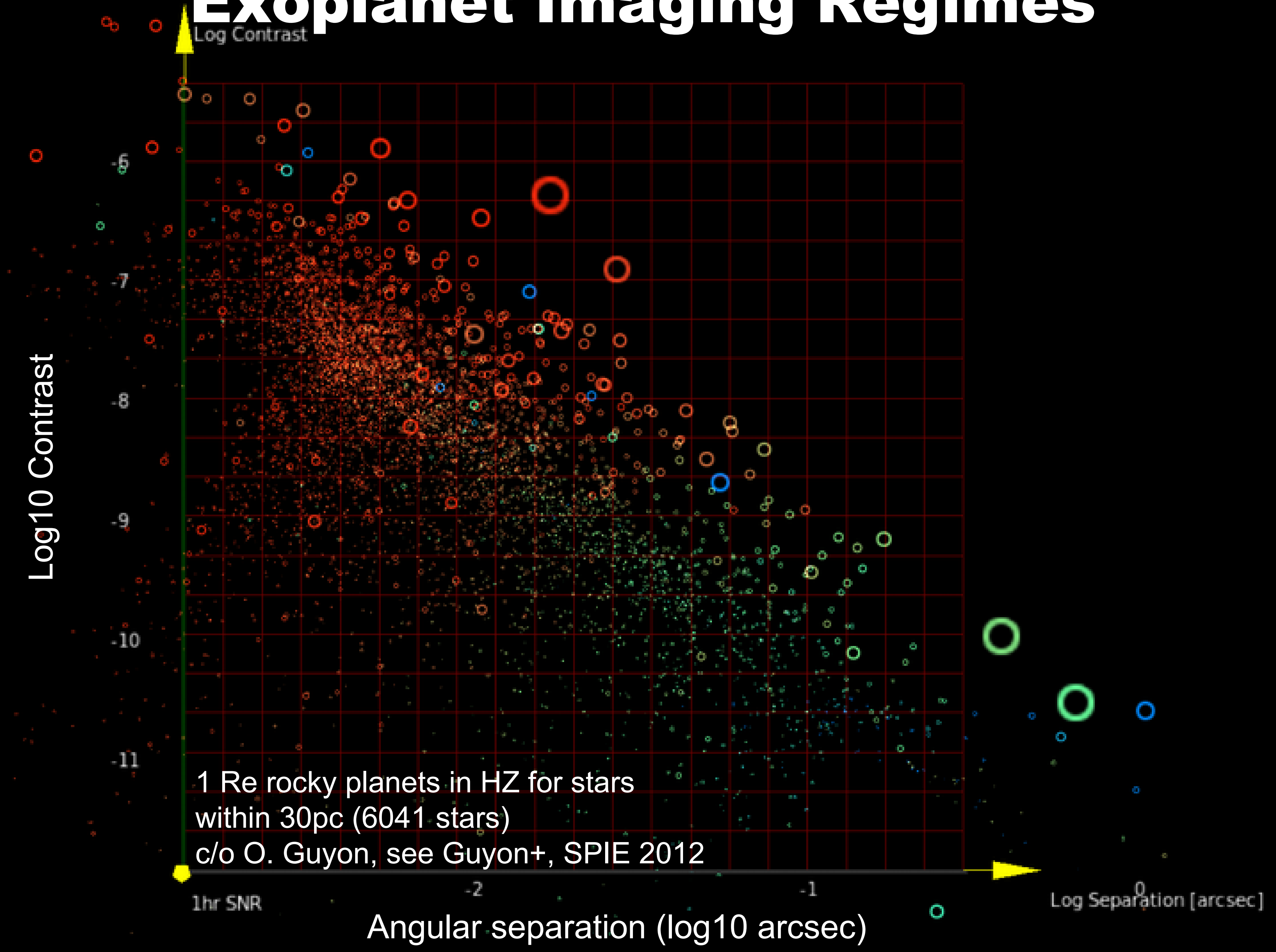
Ground-based Contrast Limits



Bonavita et al. 2012

Courtesy of Markus Kasper

Exoplanet Imaging Regimes



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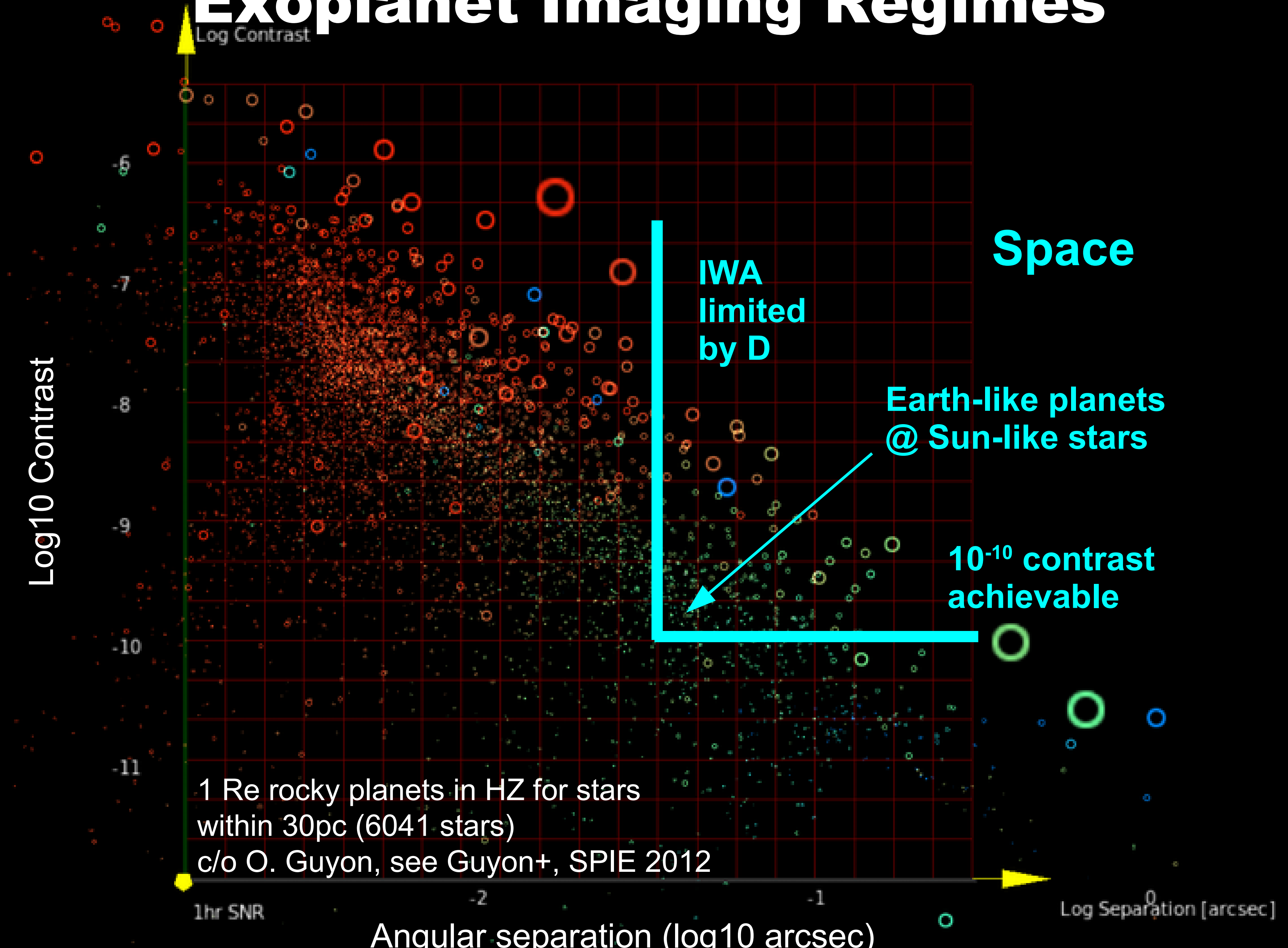
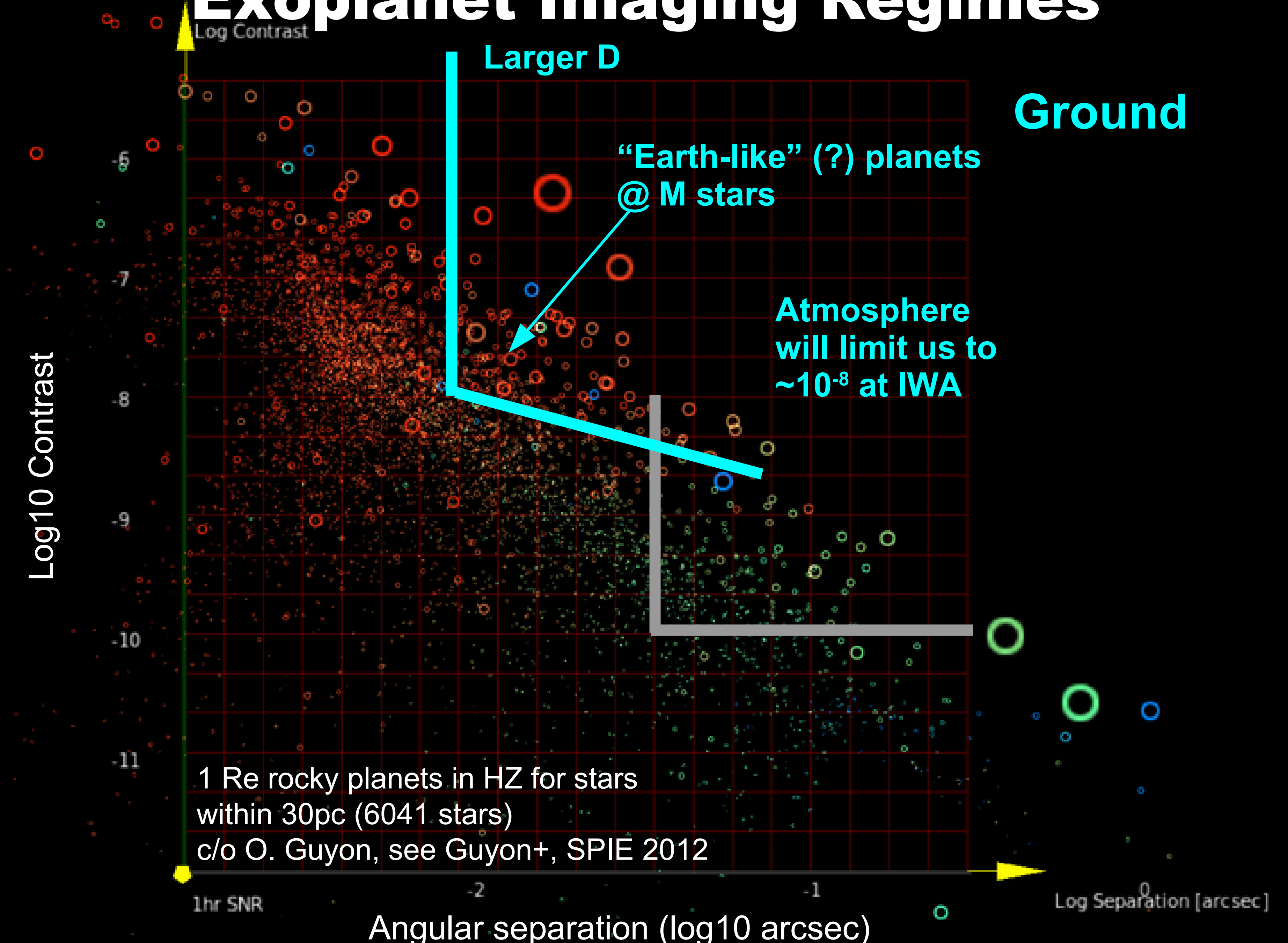


Exoplanet Imaging Regimes



High Contrast Imaging on the Ground

- We have built, and are building, large telescopes on the ground
  - Current generation, 5-10 m, with AO, studying exoplanets right now
  - Next generation, 25-39 m, probing the HZs of nearby stars in the next 10-15 years.
- Atmospheric turbulence is the big challenge on the ground
  - Adapative optics
- Post-AO ground exoplanet imagers are similar to space-based
  - Similar coronagraphy problem
  - Post-coronagraphic wavefront control
  - Post-processing
- Ground and Space are not really in competition
  - Different strengths, different weaknesses
  - Will study complimentary planet populations