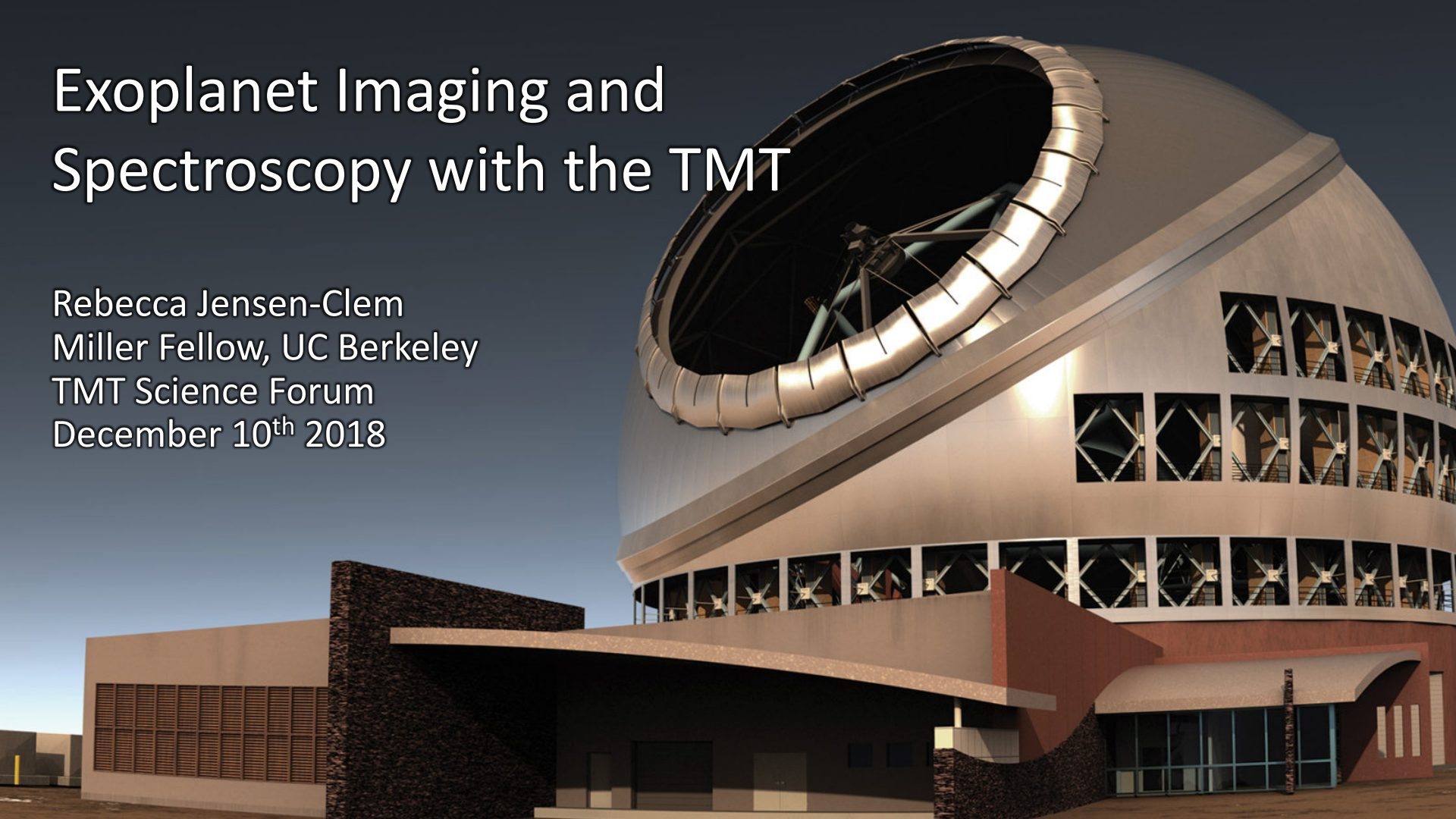
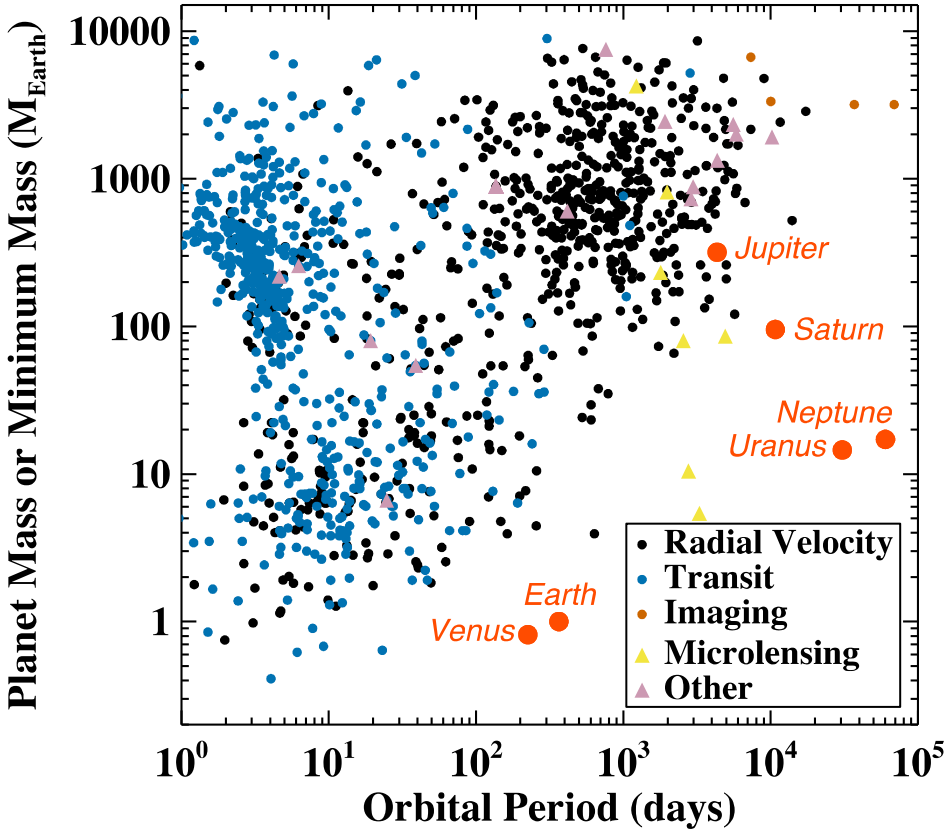
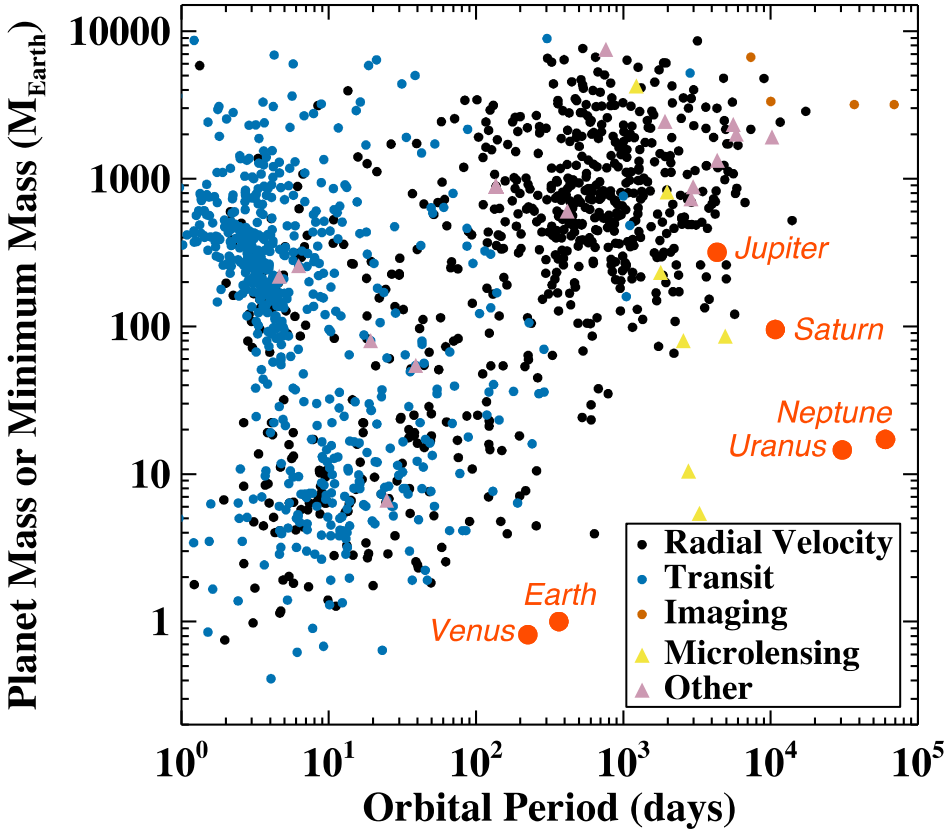
Exoplanet Imaging and Spectroscopy with the TMT

Rebecca Jensen-Clem
Miller Fellow, UC Berkeley
TMT Science Forum
December 10th 2018




Planet Mass or Minimum Mass (M_{Earth})
10000
1000
100
10
1
10^0
10^1
10^2
10^3
10^4
10^5
Orbital Period (days)
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
Radial Velocity
Transit
Imaging
Microlensing
Other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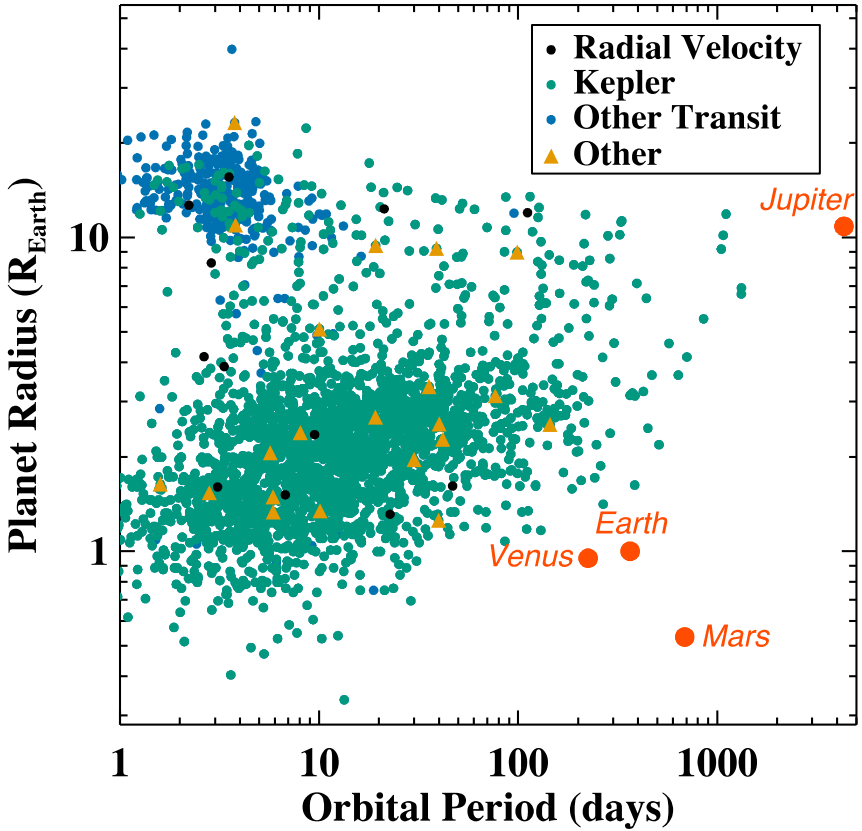
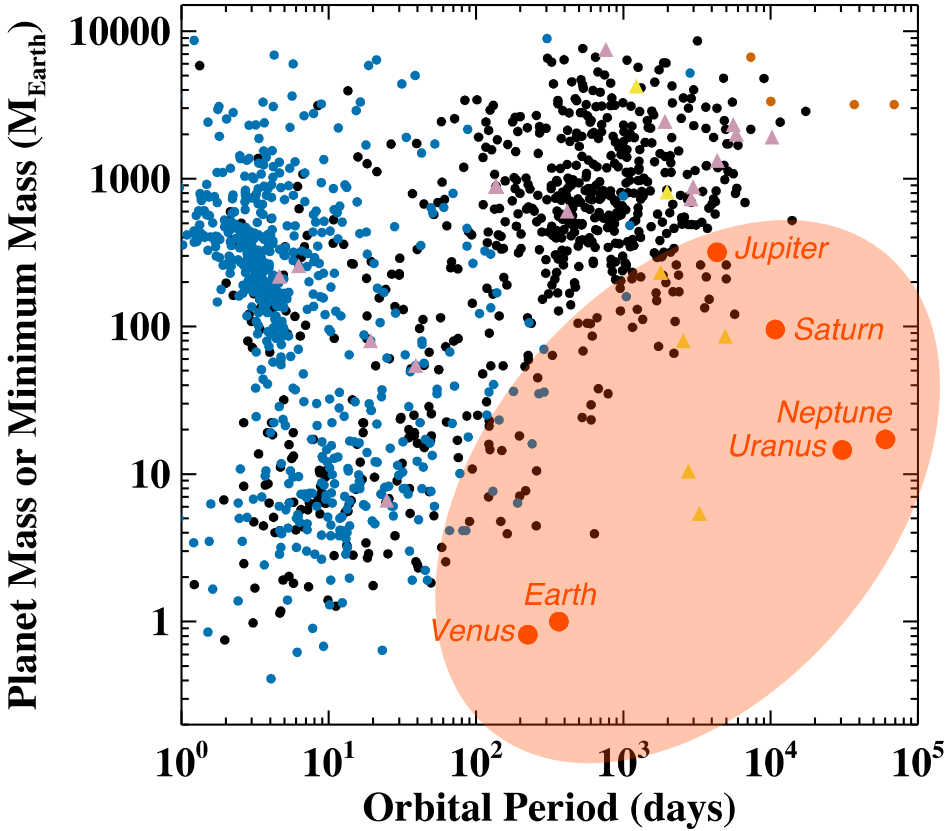

Planet Radius (R_{Earth})
10
1
1
10
100
1000
Orbital Period (days)
Radial Velocity
Kepler
Other Transit
Other
Jupiter
Earth
Venus
Mars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Earth
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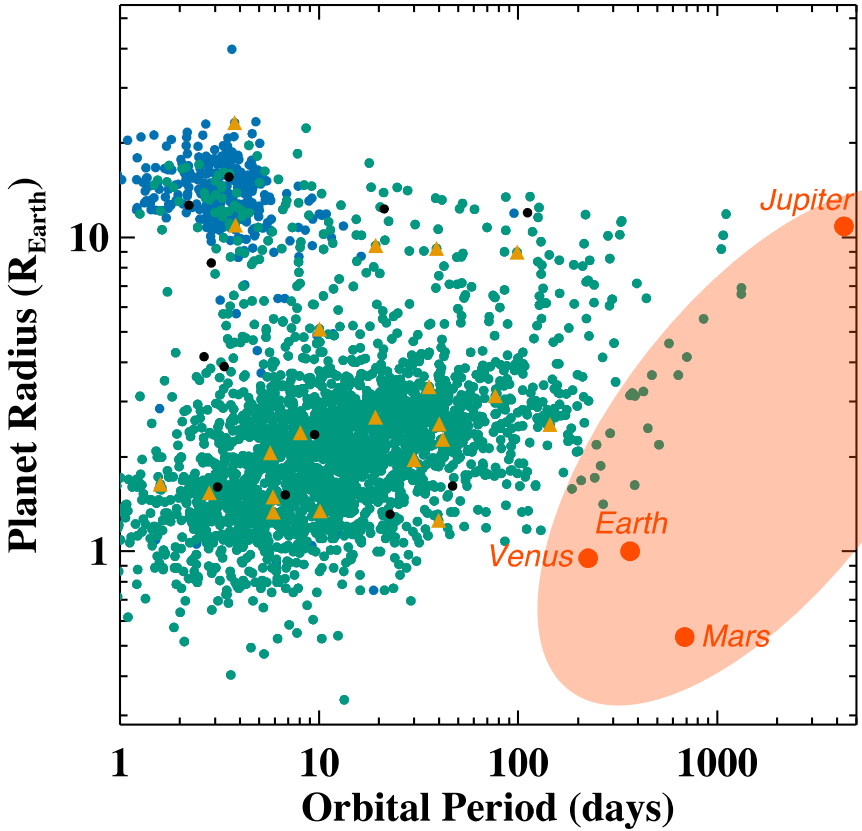
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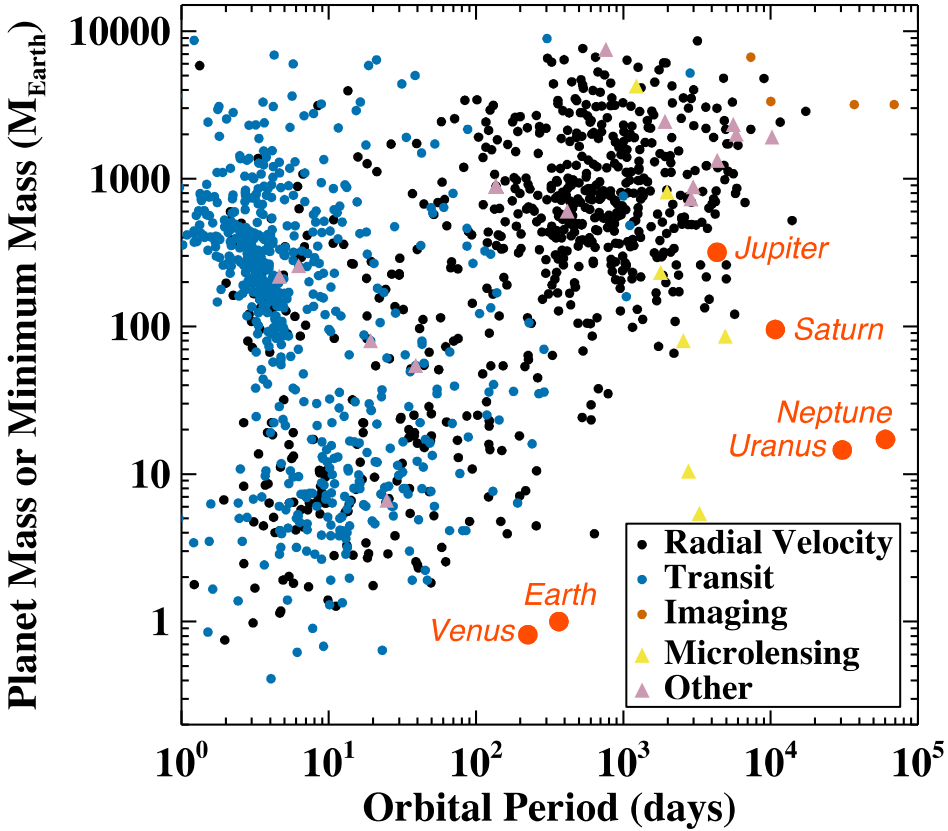
Earth
Venus
Mars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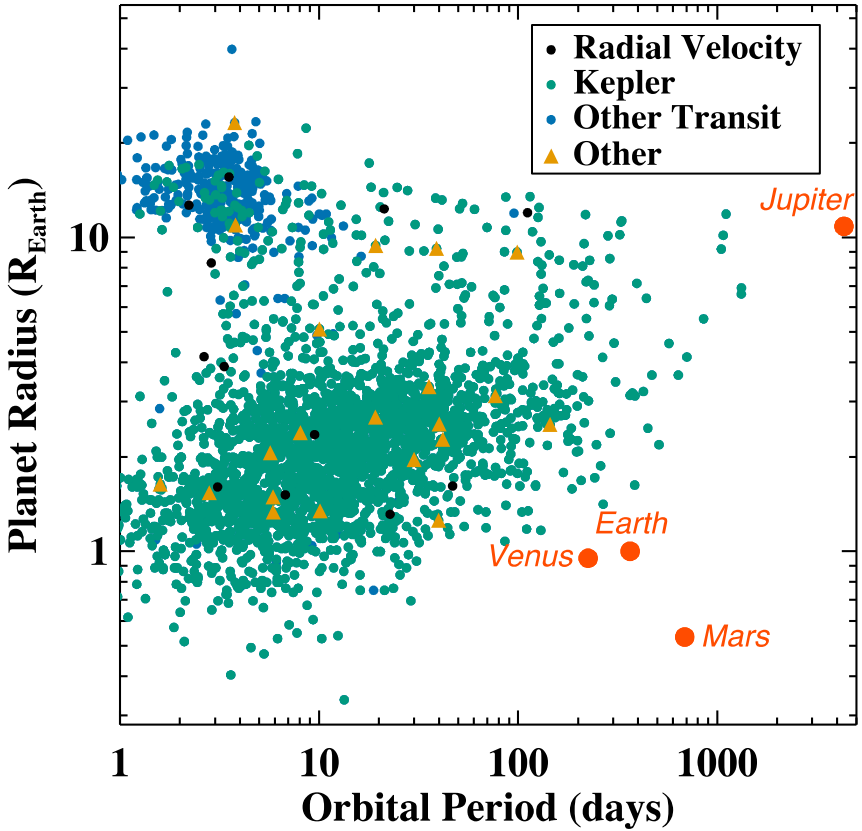
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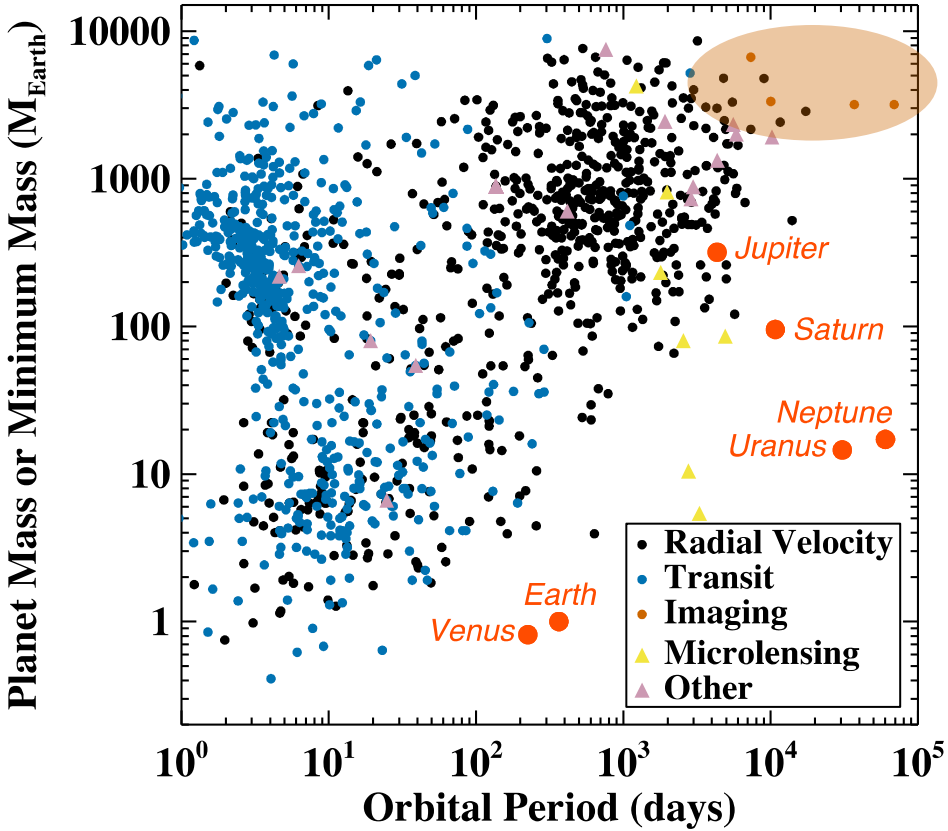
1
10
100
1000
Orbital Period (days)
Radial Velocity
Kepler
Other Transit
Other
Jupiter
Earth
Venus
Mars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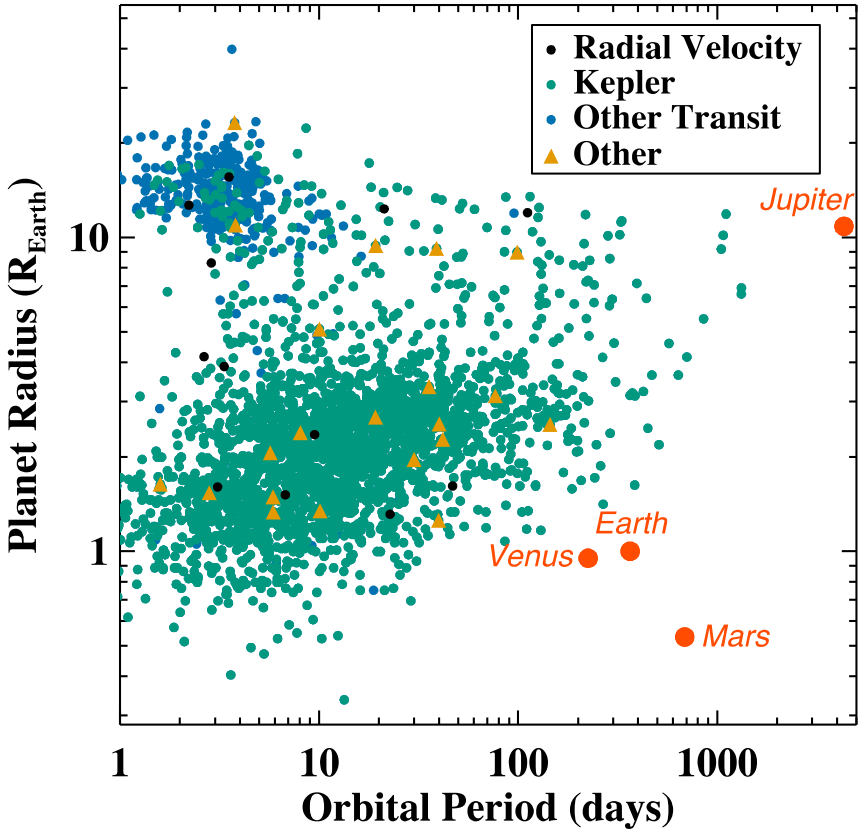
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1000
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Kepler
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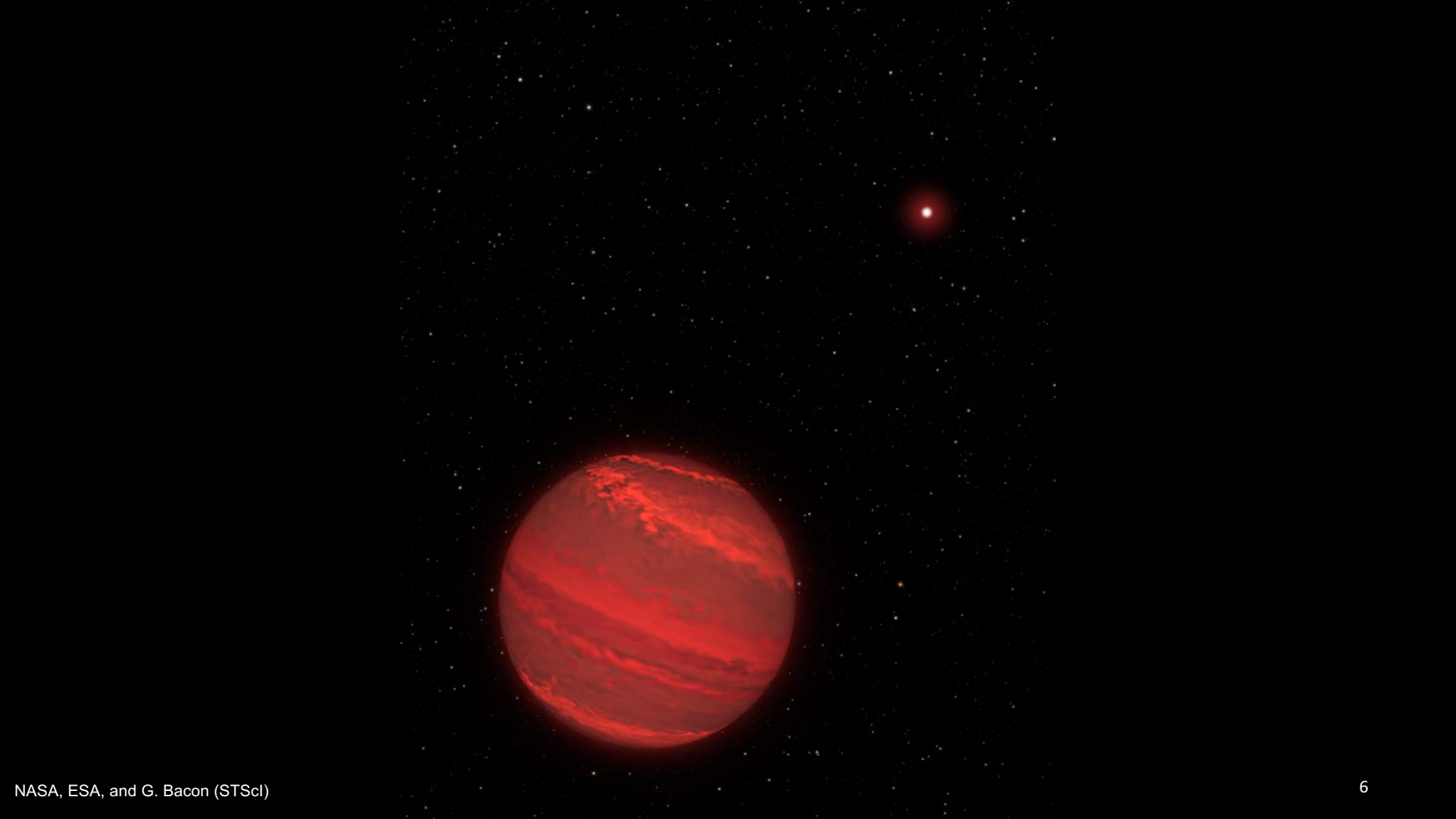
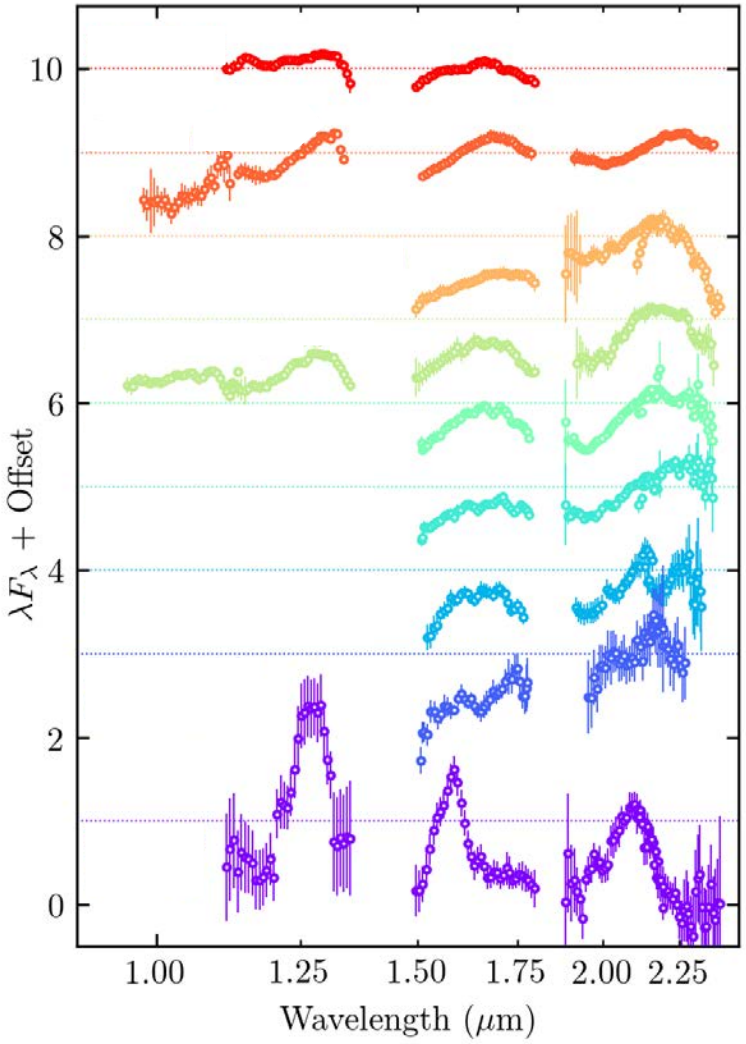
Mars



NASA, ESA, and G. Bacon (STScI)



HD 984 B (2700 K)

β Pic b (1750 K)

HD 206893 B (1300 K)

HR 2562 B (1200 K)

HR 8799 c (1200 K)

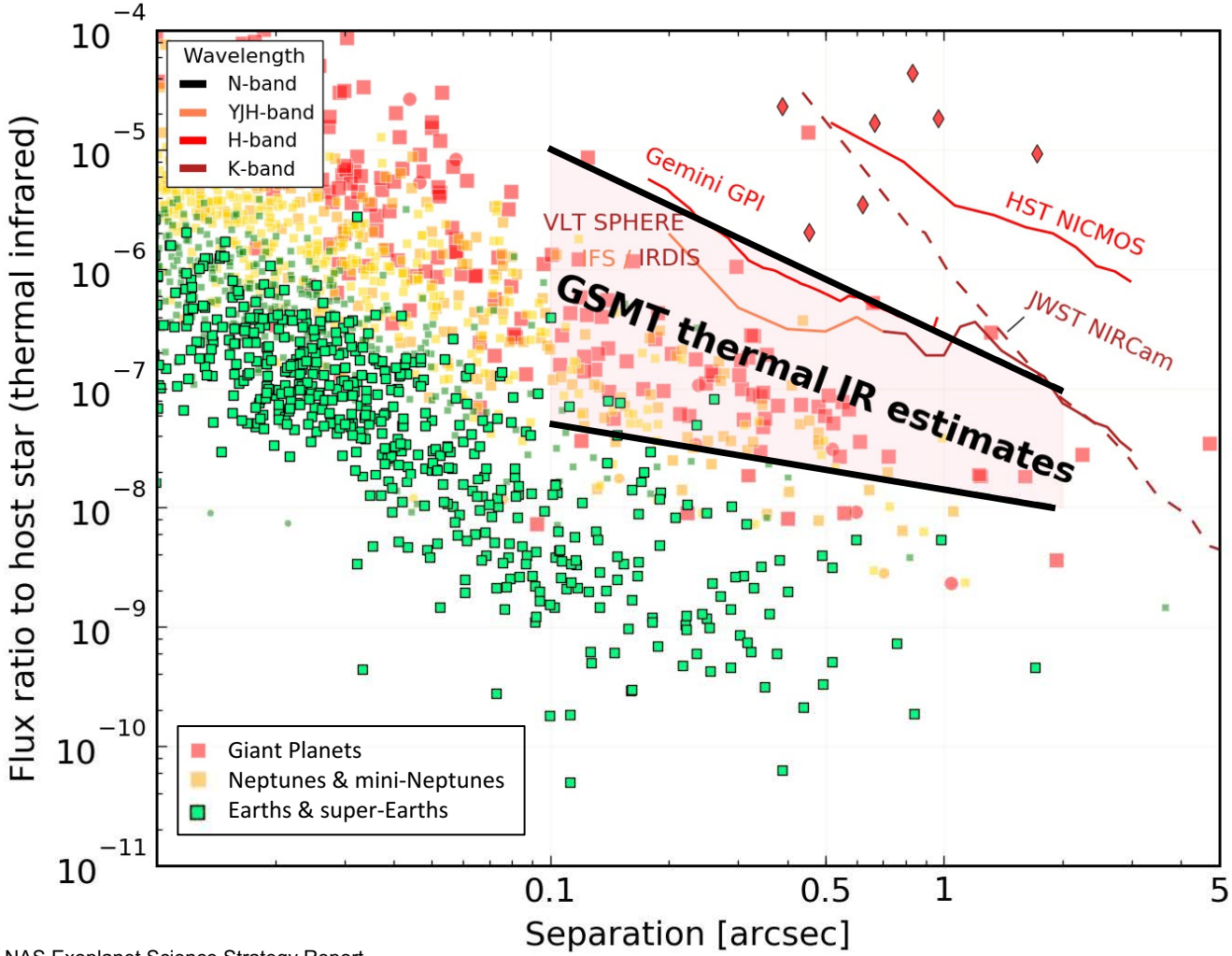
HR 8799 d (1200 K)

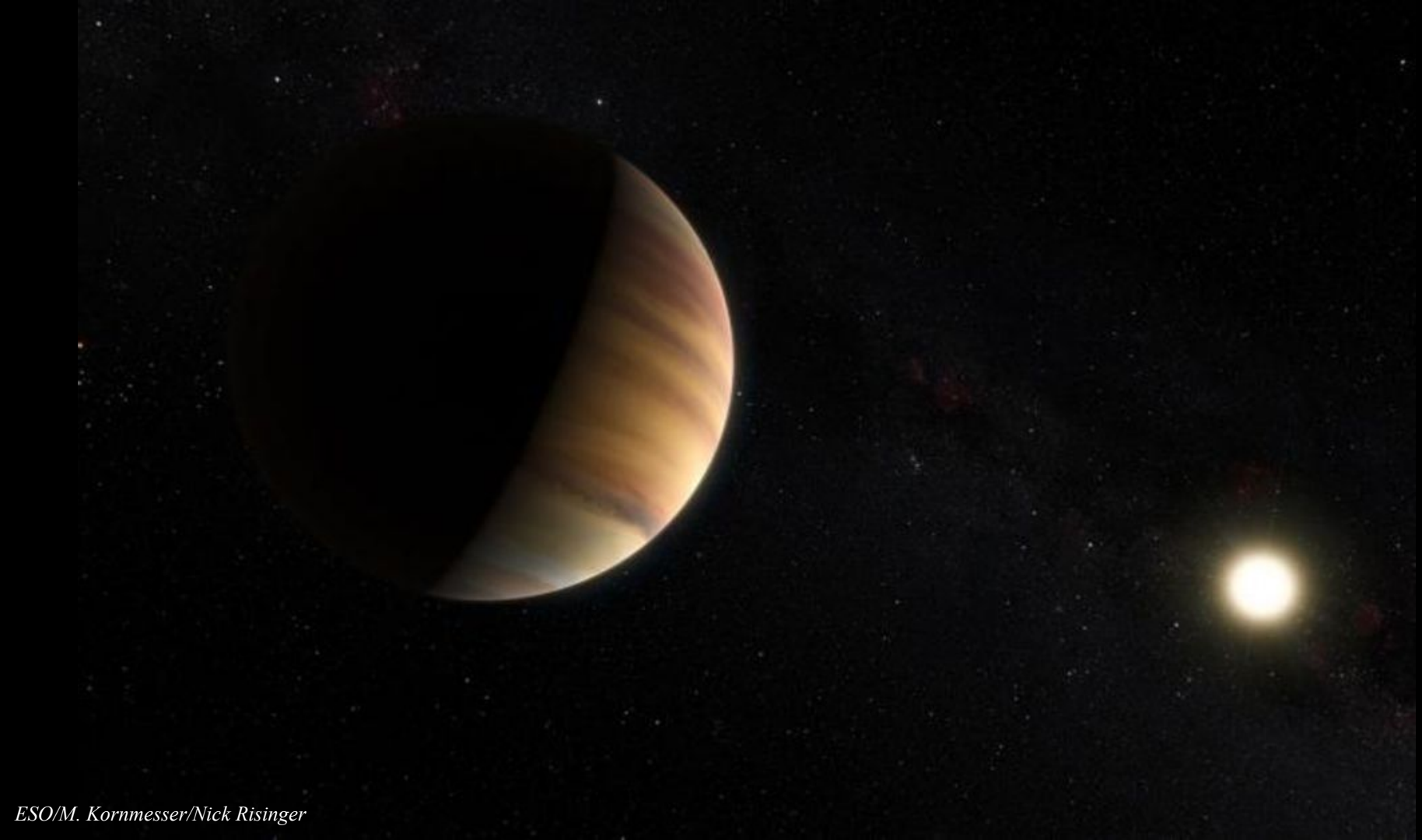
HR 8799 e (1200 K)

HD 95086 b (1100 K)

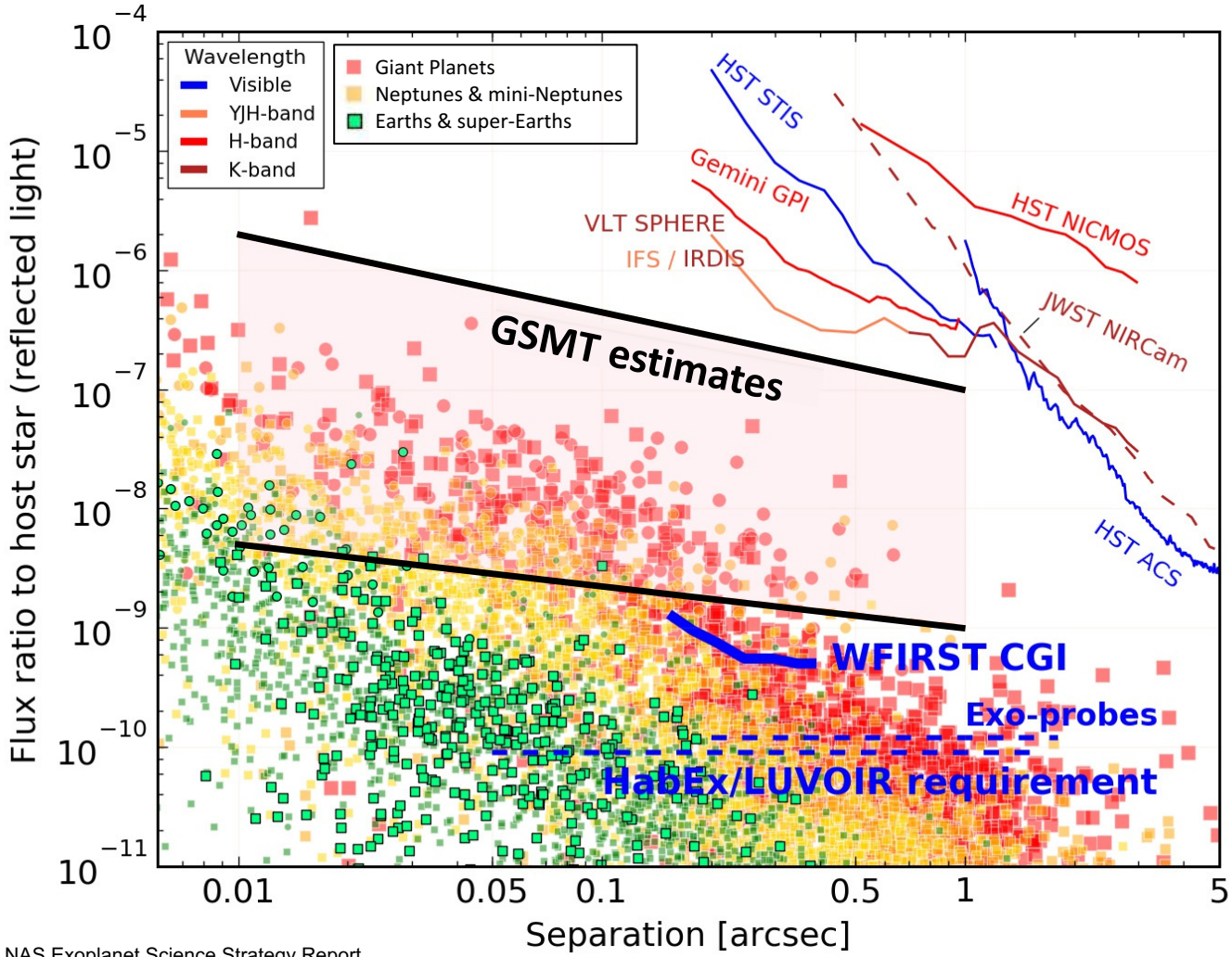
51 Eri b (700 K)

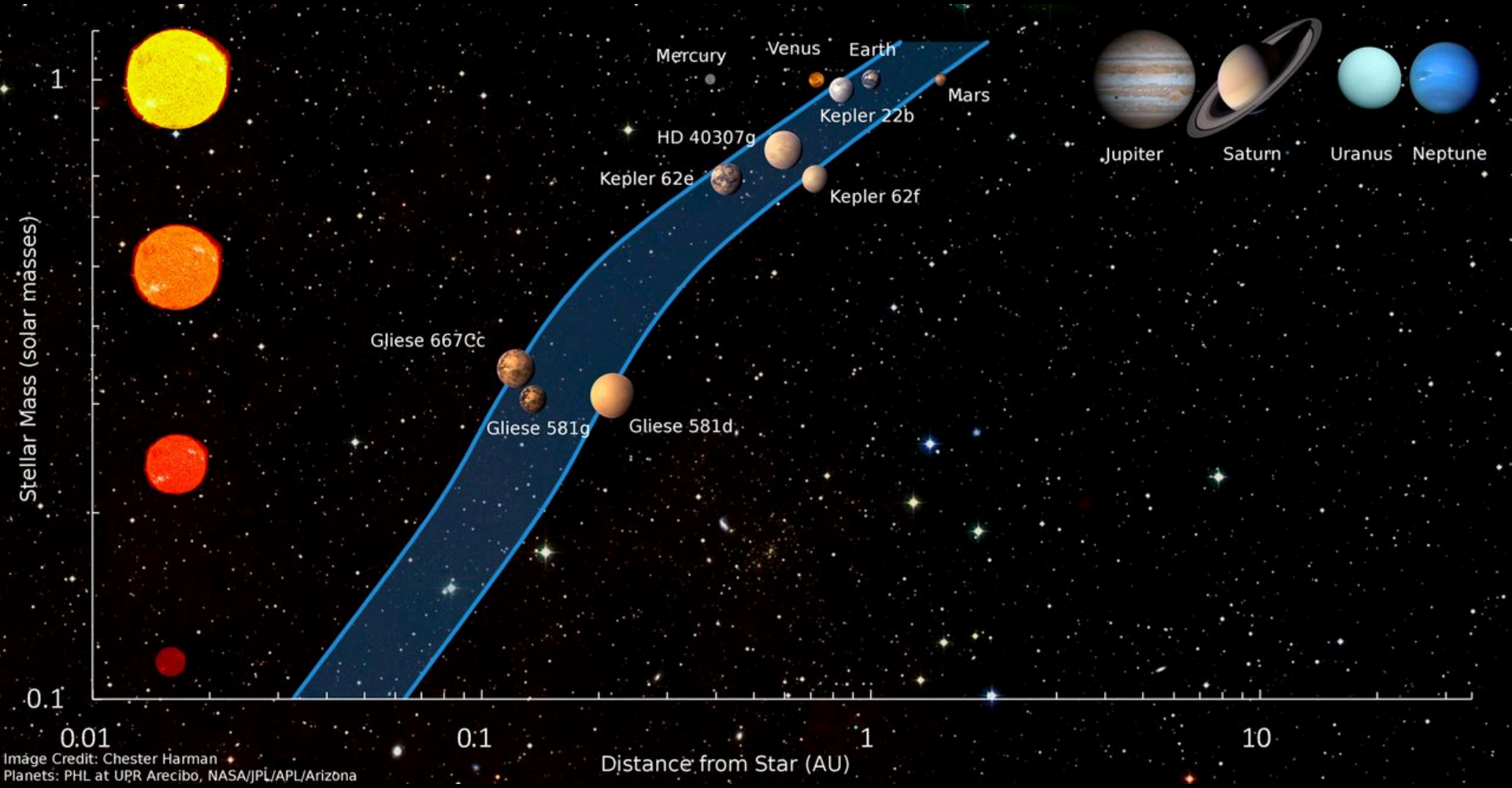
GPI/DeRosa


Wavelength
N-band
YJH-band
H-band
K-band
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
GSMT thermal IR estimates
Giant Planets
Neptunes & mini-Neptunes
Earths & super-Earths
Flux ratio to host star (thermal infrared)
Separation [arcsec]
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.1
0.5
1
5

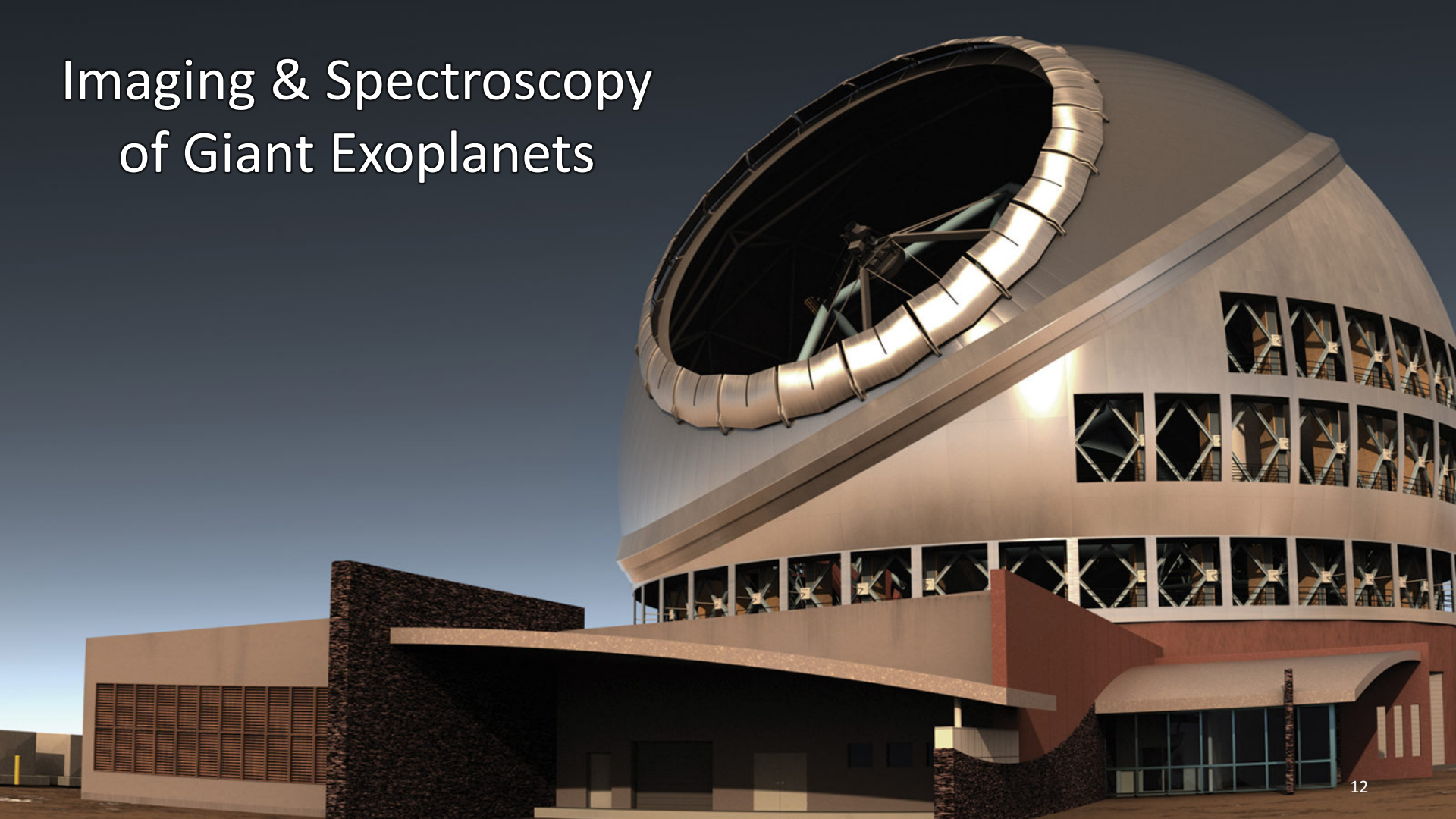


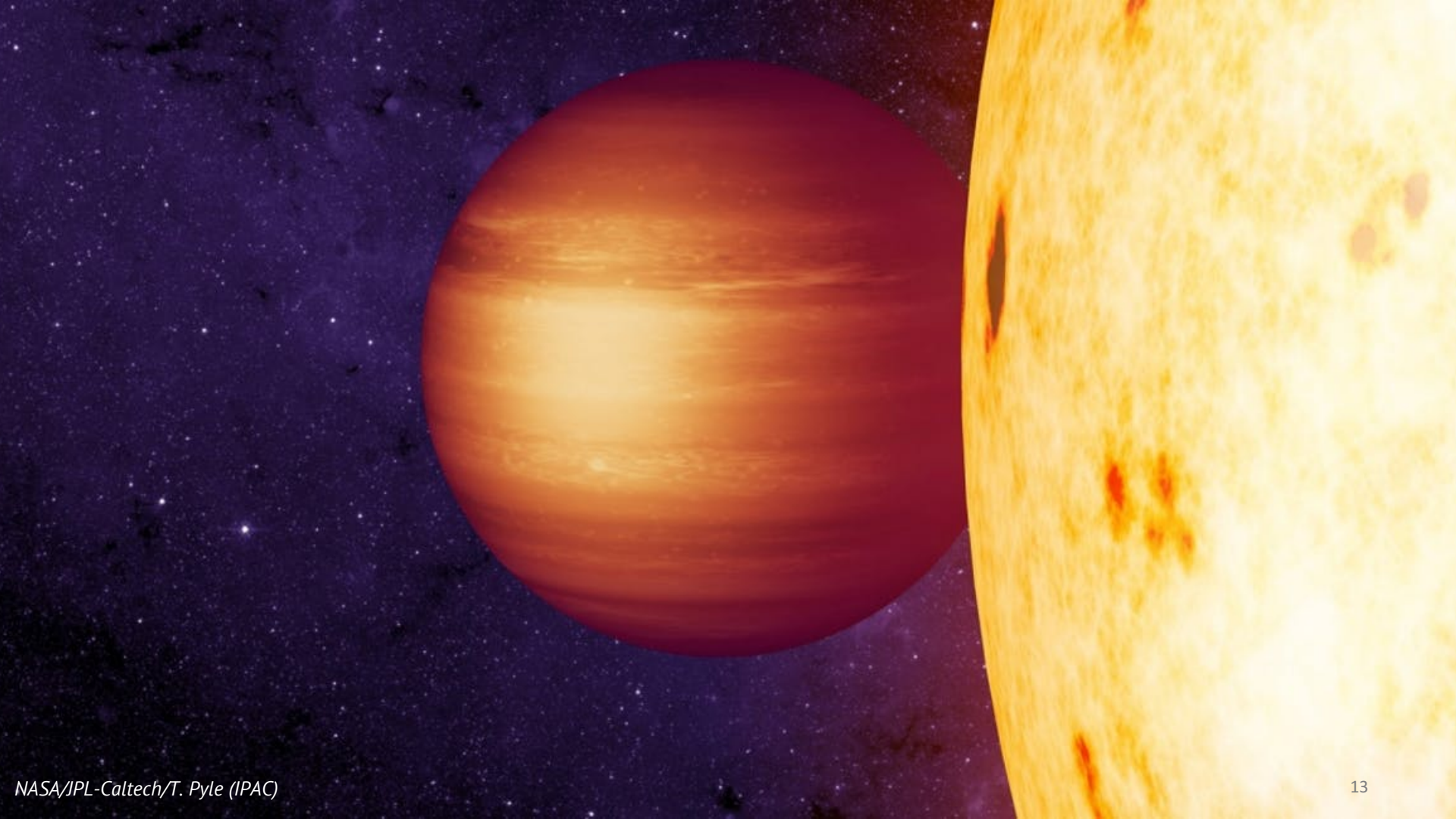
ESO/M. Kornmesser/Nick Risinger


Wavelength
Visible
YJH-band
H-band
K-band
Giant Planets
Neptunes & mini-Neptunes
Earths & super-Earths
HST STIS
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
HST ACS
GSMT estimates
WFIRST CGI
Exo-probes
HabEx/LUVOIR requirement
Flux ratio to host star (reflected light)
Separation [arcsec]
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
0.01
0.05
0.1
0.5
1
5

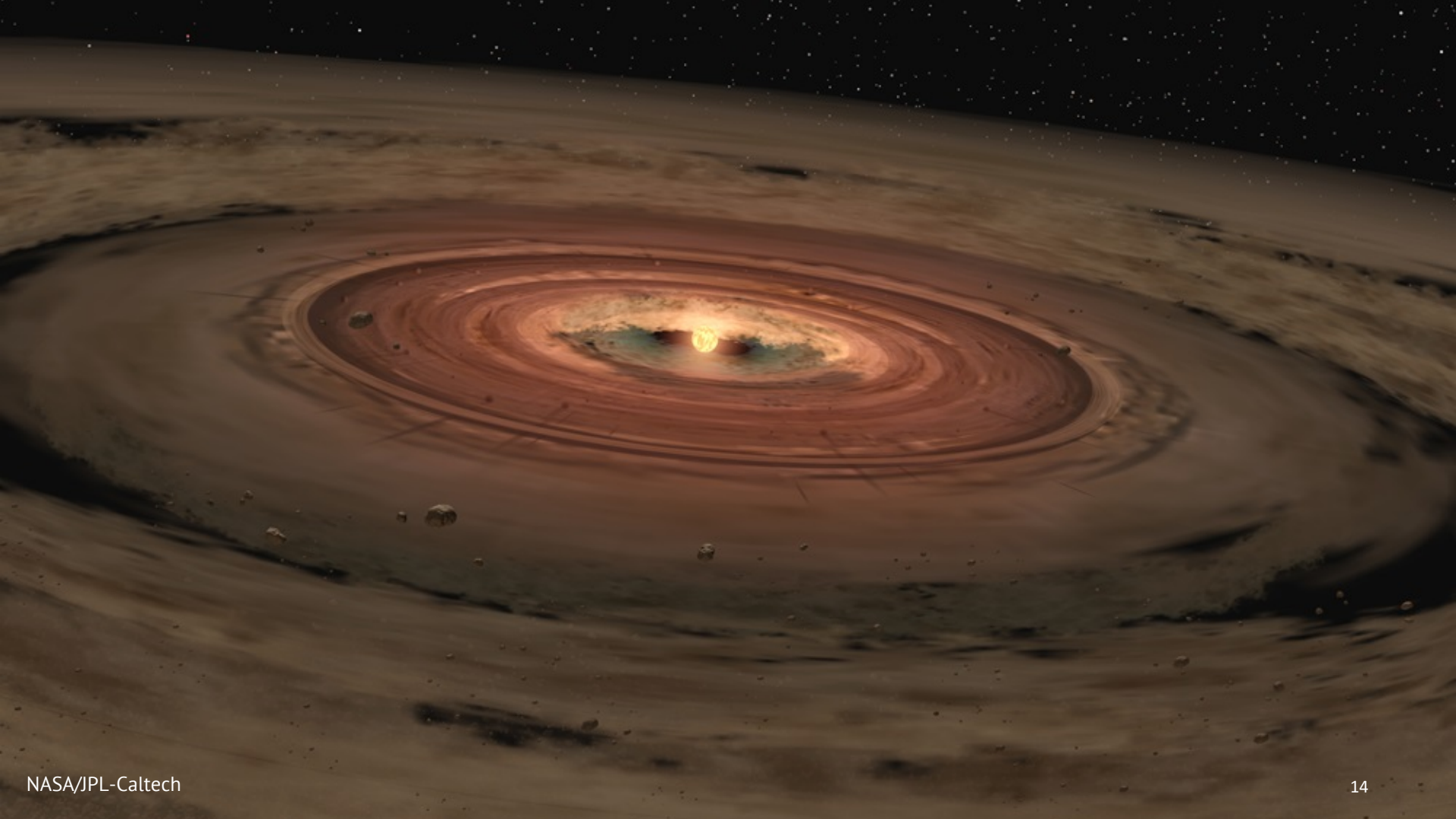

Mercury
Venus
Earth
Mars
Kepler 22b
HD 40307g
Kepler 62e
Kepler 62f
Gliese 667Cc
Gliese 581g
Gliese 581d
Jupiter
Saturn
Uranus
Neptune
Stellar Mass (solar masses)
1
0.1
0.01
0.1
1
10
Distance from Star (AU)
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL/APL/Arizona

Imaging & Spectroscopy of Giant Exoplanets

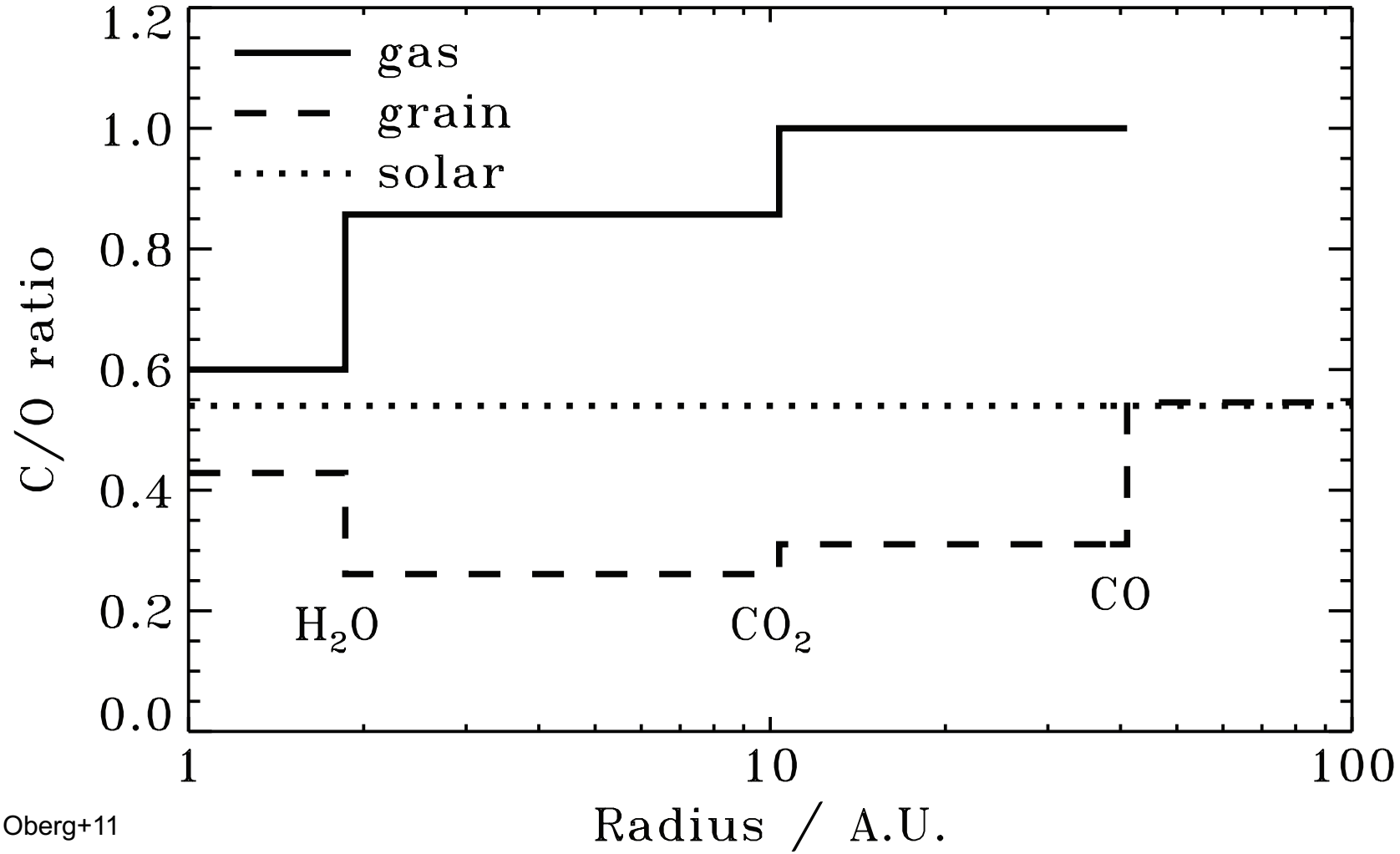




NASA/JPL-Caltech/T. Pyle (IPAC)



NASA/JPL-Caltech


gas
grain
solar
C/O ratio
1.2
1.0
0.8
0.6
0.4
0.2
0.0
H2O
CO2
CO
1
10
100
Radius / A.U.

Oberg+11

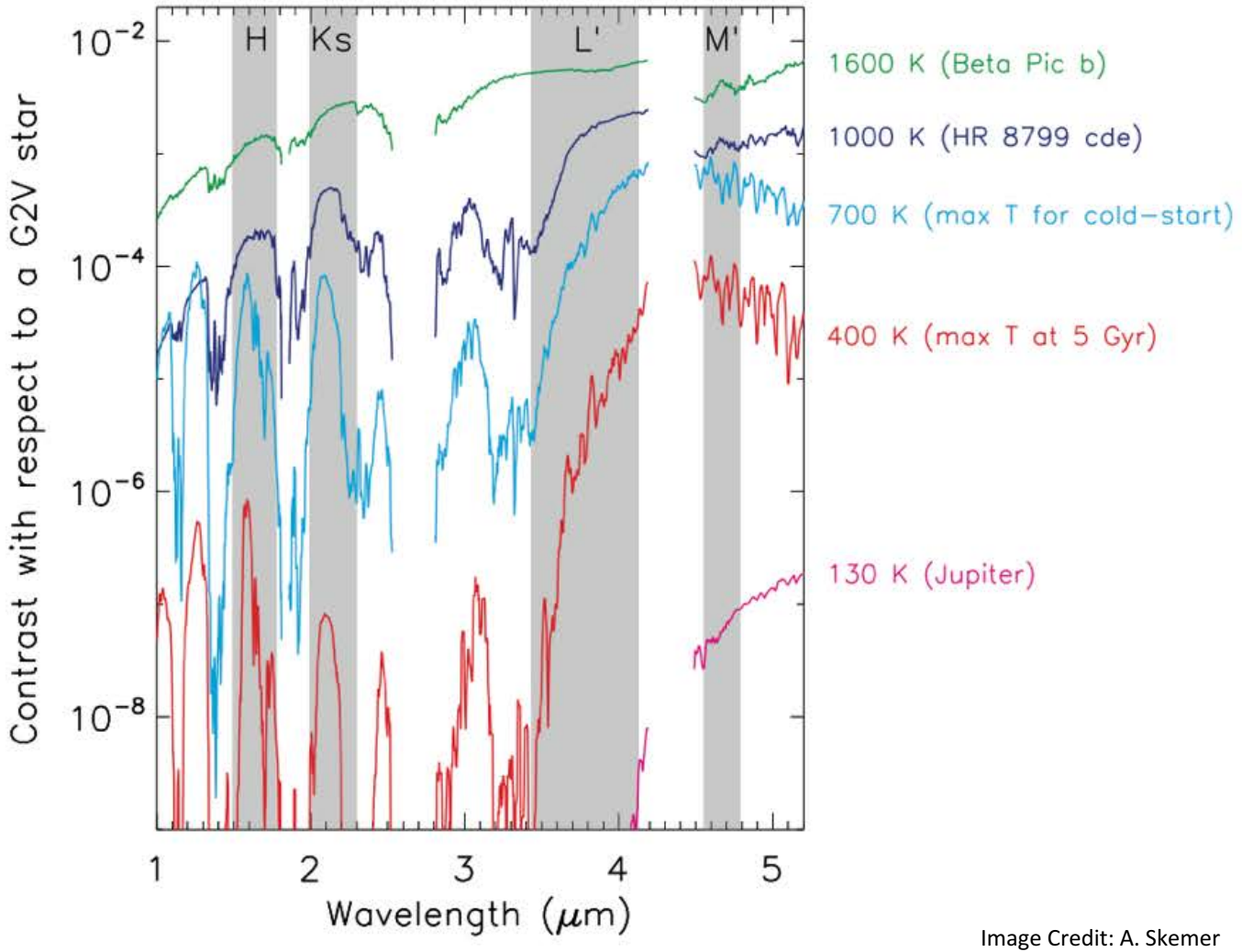


Image Credit: A. Skemer

Multiwavelength spectroscopy:

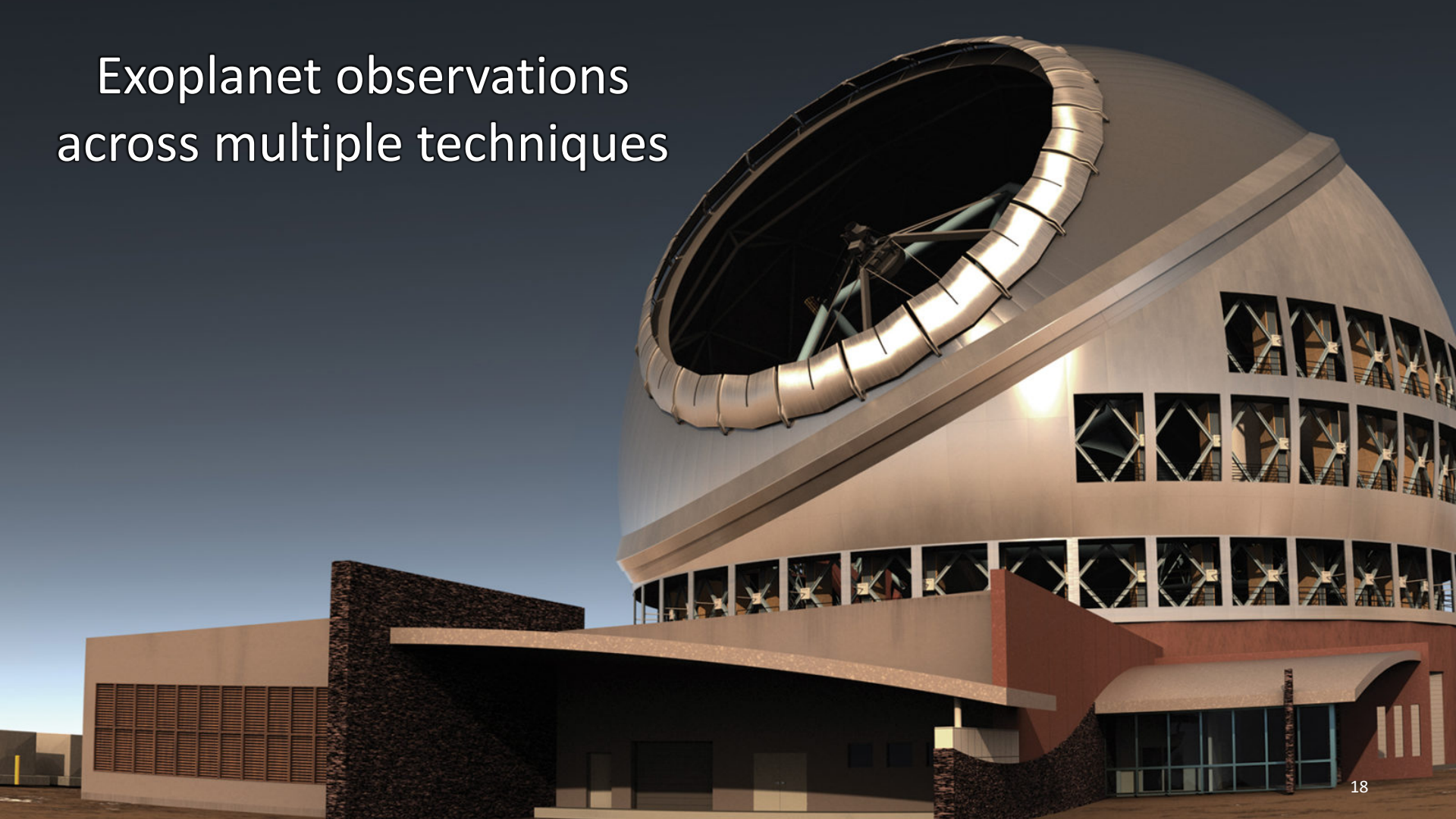
- <970nm: C & O abundances from e.g. CH_4 and H_2O features
- L & M bands: C & O abundances from e.g. CH_4, CO, CO_2 features
- 10um regime: nitrogen abundances from the NH_3 feature

How do volatile abundances vary with:

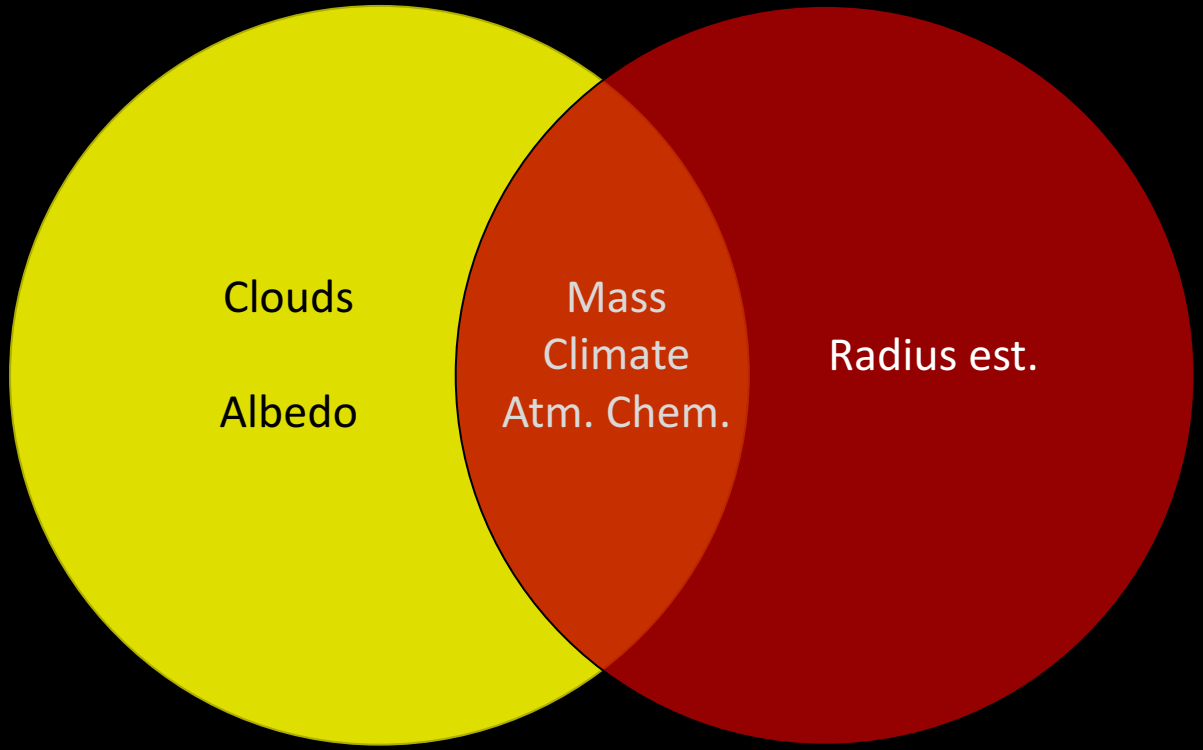
- Planet-star separation?
- Planet mass?
- Host star mass?
- Host star metallicity?

NASA/JPL-Caltech

Exoplanet observations across multiple techniques



Combining Reflected Light and Thermal Imaging



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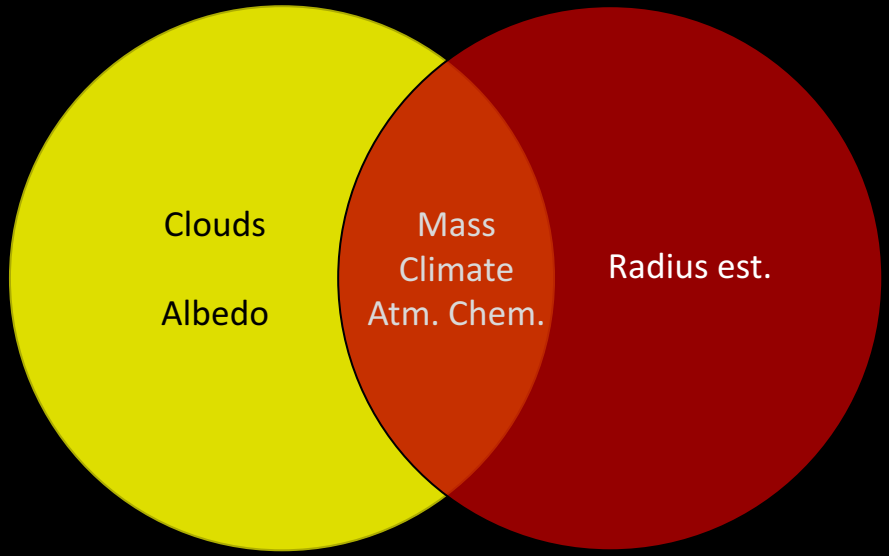
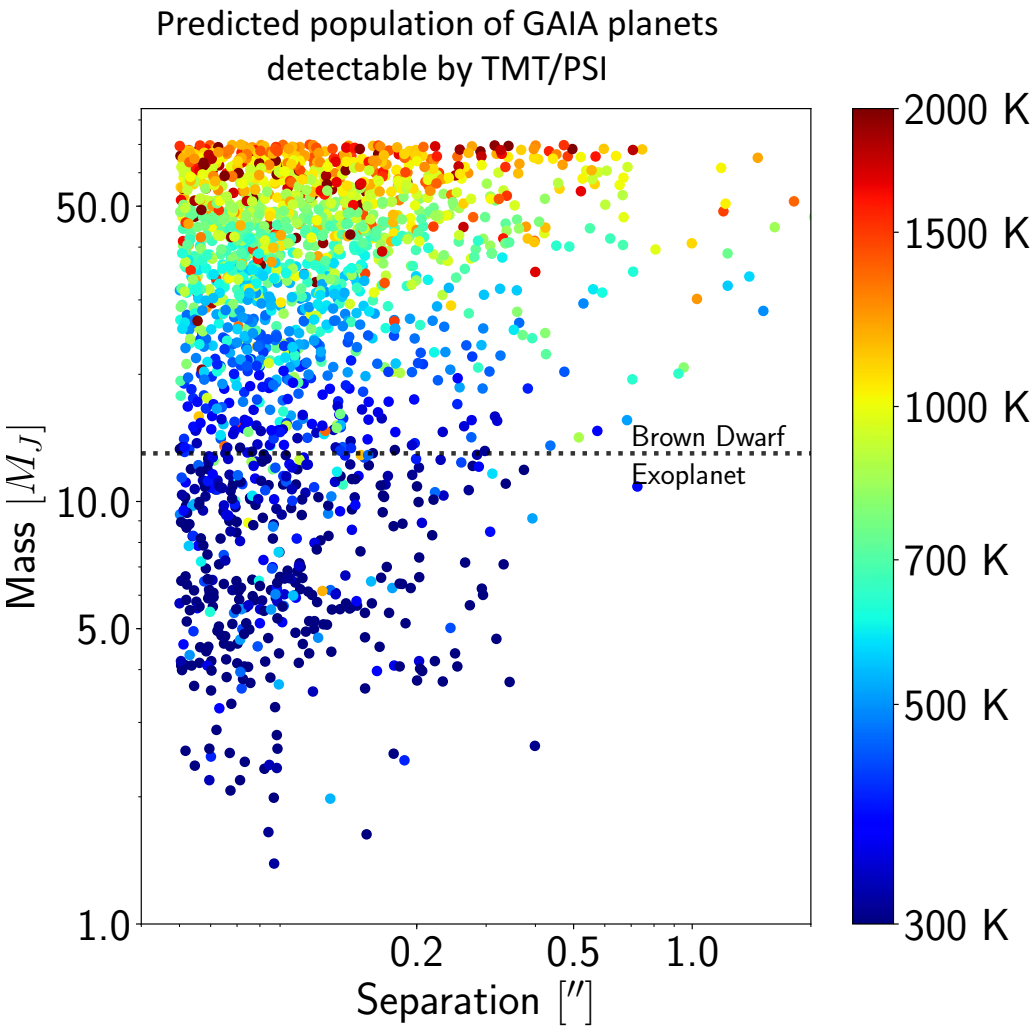


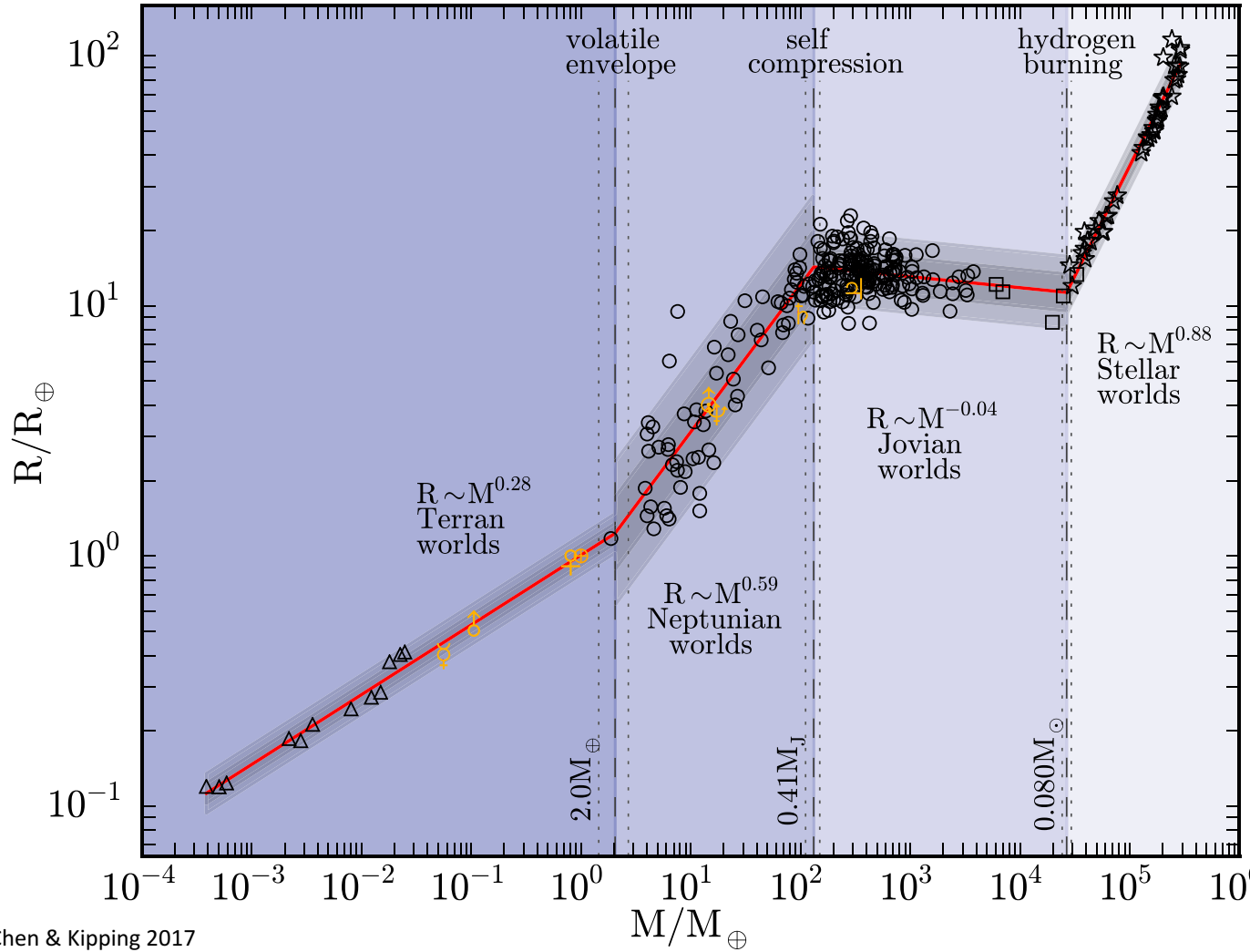
- Constrain phase angles via imaging
- Measure T_{eff} via thermal imaging to constrain radius
- Radius and phase angle will inform clouds' scattering phase functions
- Multi-λ observations inform cloud composition information



Overlap with non-imaging techniques

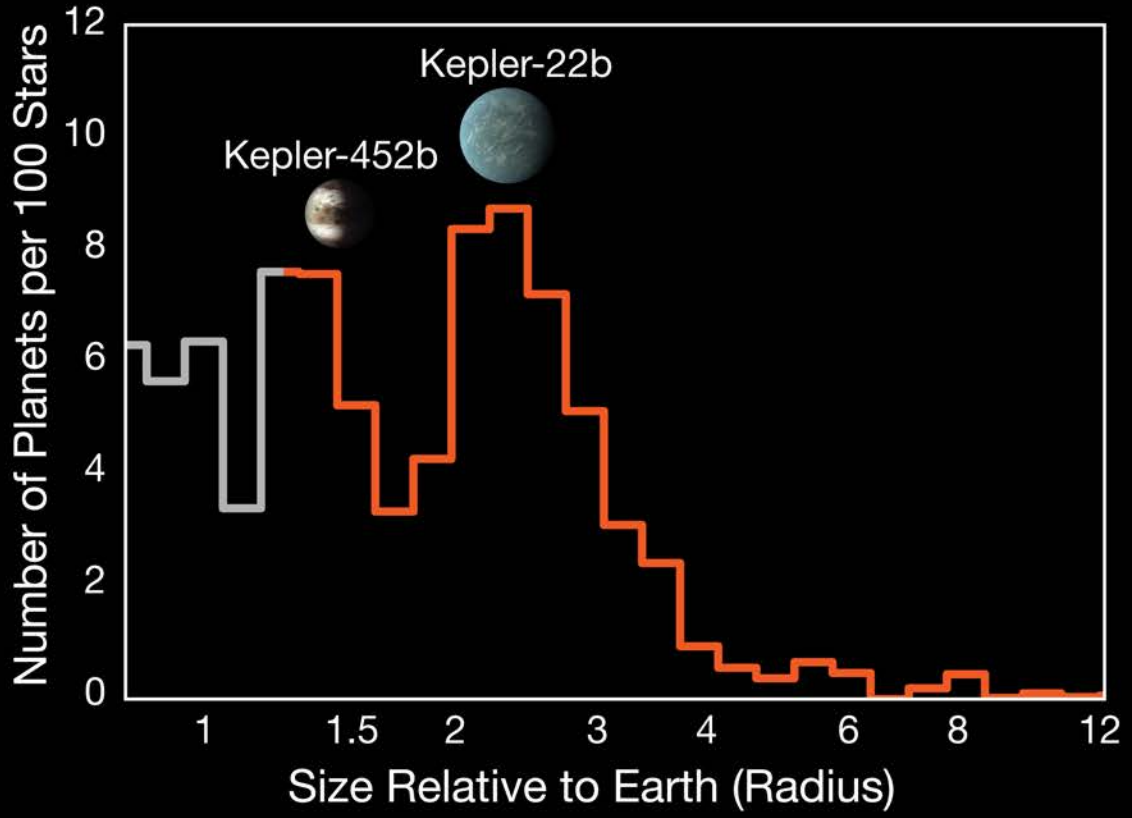
- Exoplanet masses via RV, astrometry, and imaging
- Bulk density constraints from radii estimates and masses
- Are planets' luminosities consistent with evolutionary models?
- Are the surface gravities derived from atm. models consistent with masses?

Figure credit: Briemeister, Skemer, Brandt, Savransky, Wang, Millar-Blanchaer



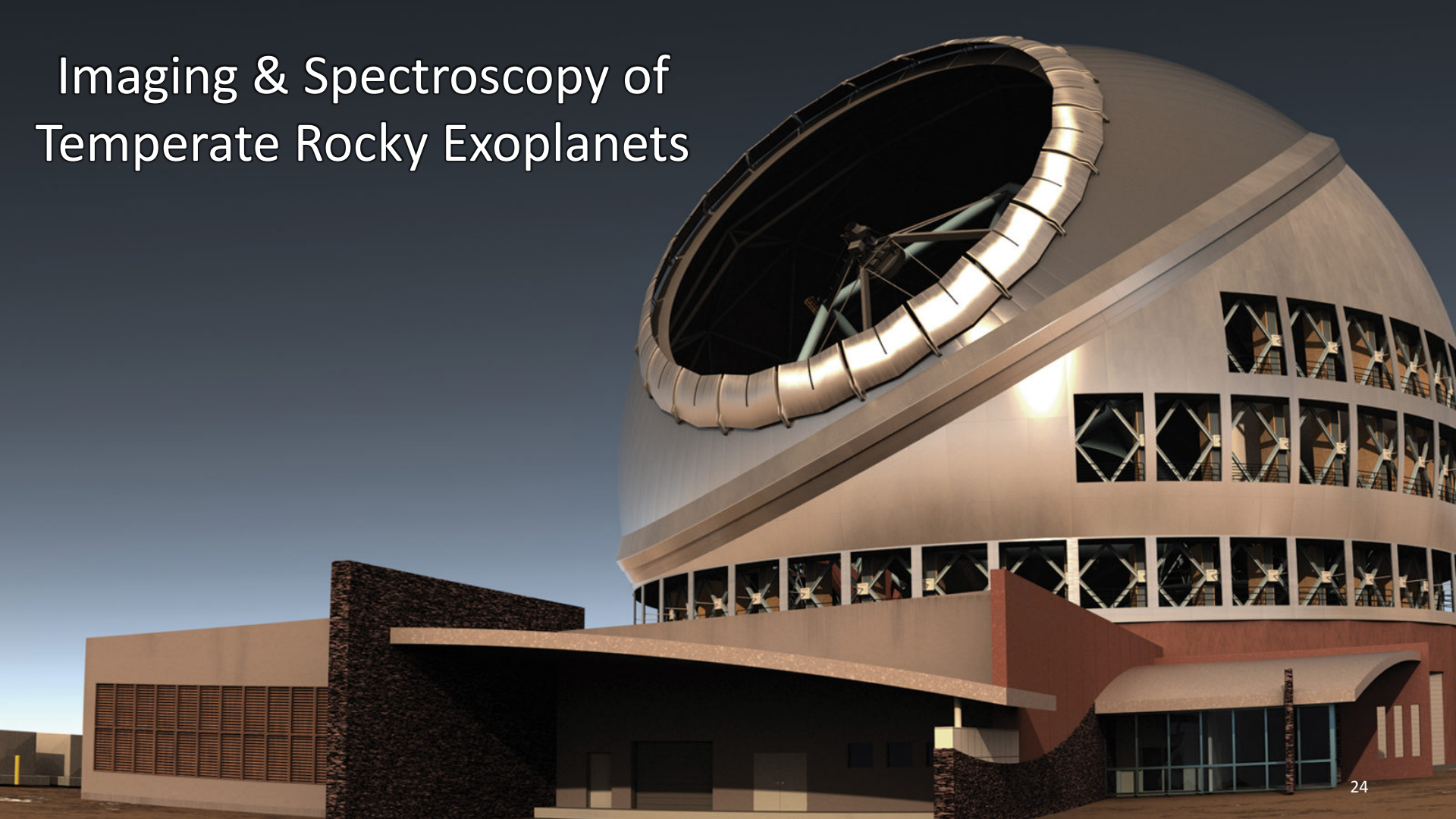
Chen & Kipping 2017

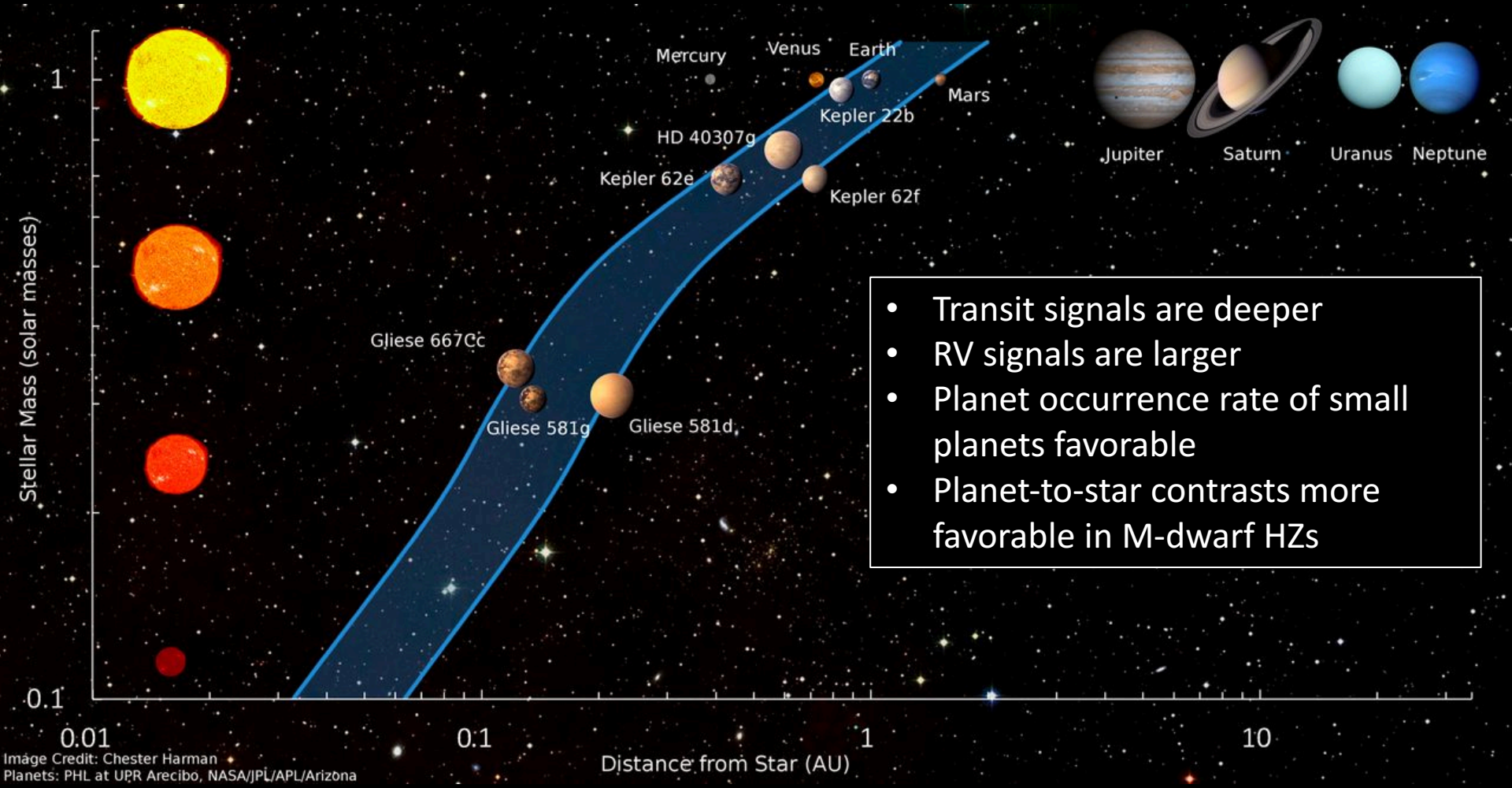
Small Planets Come in Two Sizes



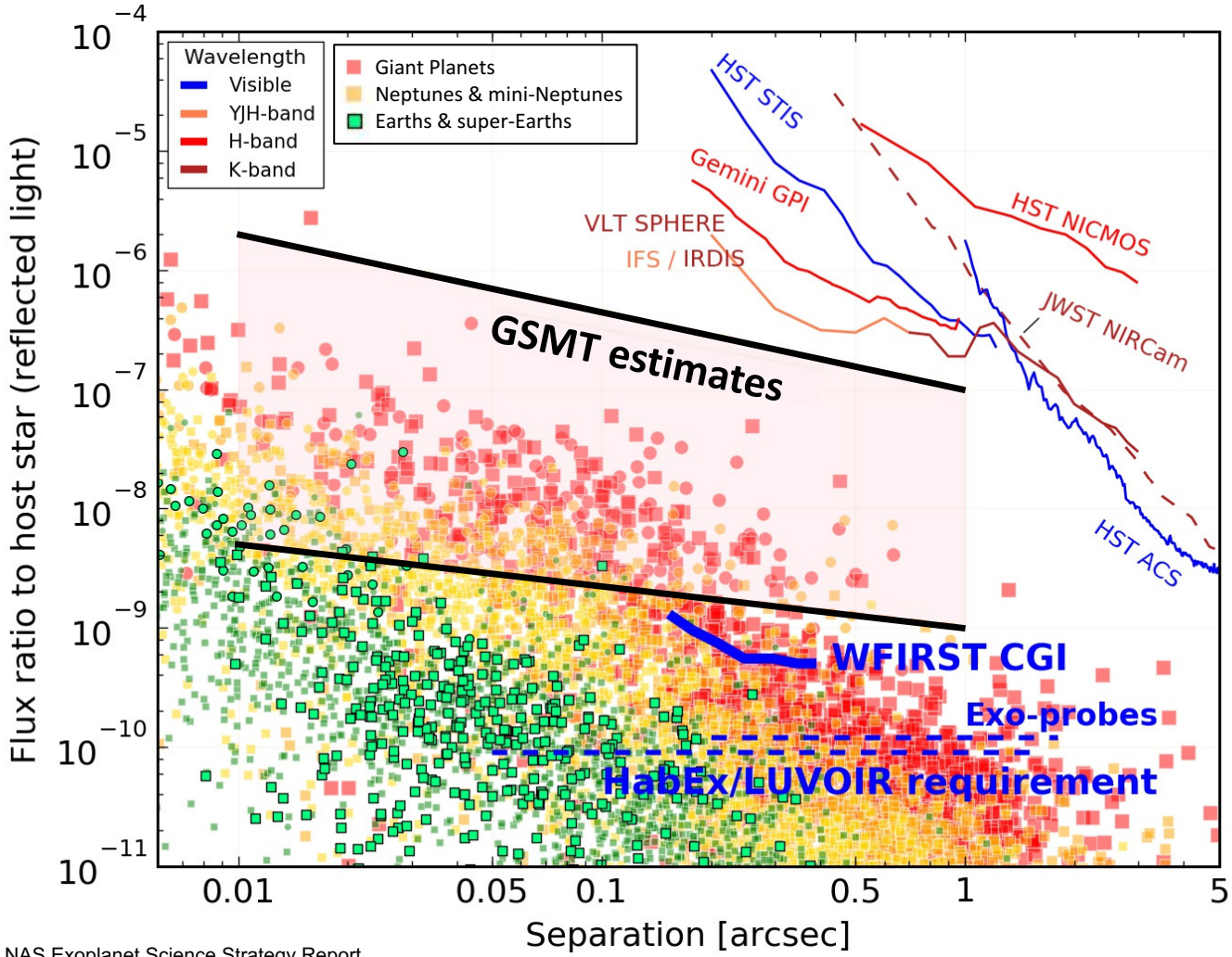
Caltech/Fulton+17

Imaging & Spectroscopy of Temperate Rocky Exoplanets





- Transit signals are deeper
- RV signals are larger
- Planet occurrence rate of small planets favorable
- Planet-to-star contrasts more favorable in M-dwarf HZs


Wavelength
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H-band
K-band
Giant Planets
Neptunes & mini-Neptunes
Earths & super-Earths
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Gemini GPI
VLT SPHERE
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10^-8
10^-9
10^-10
10^-11
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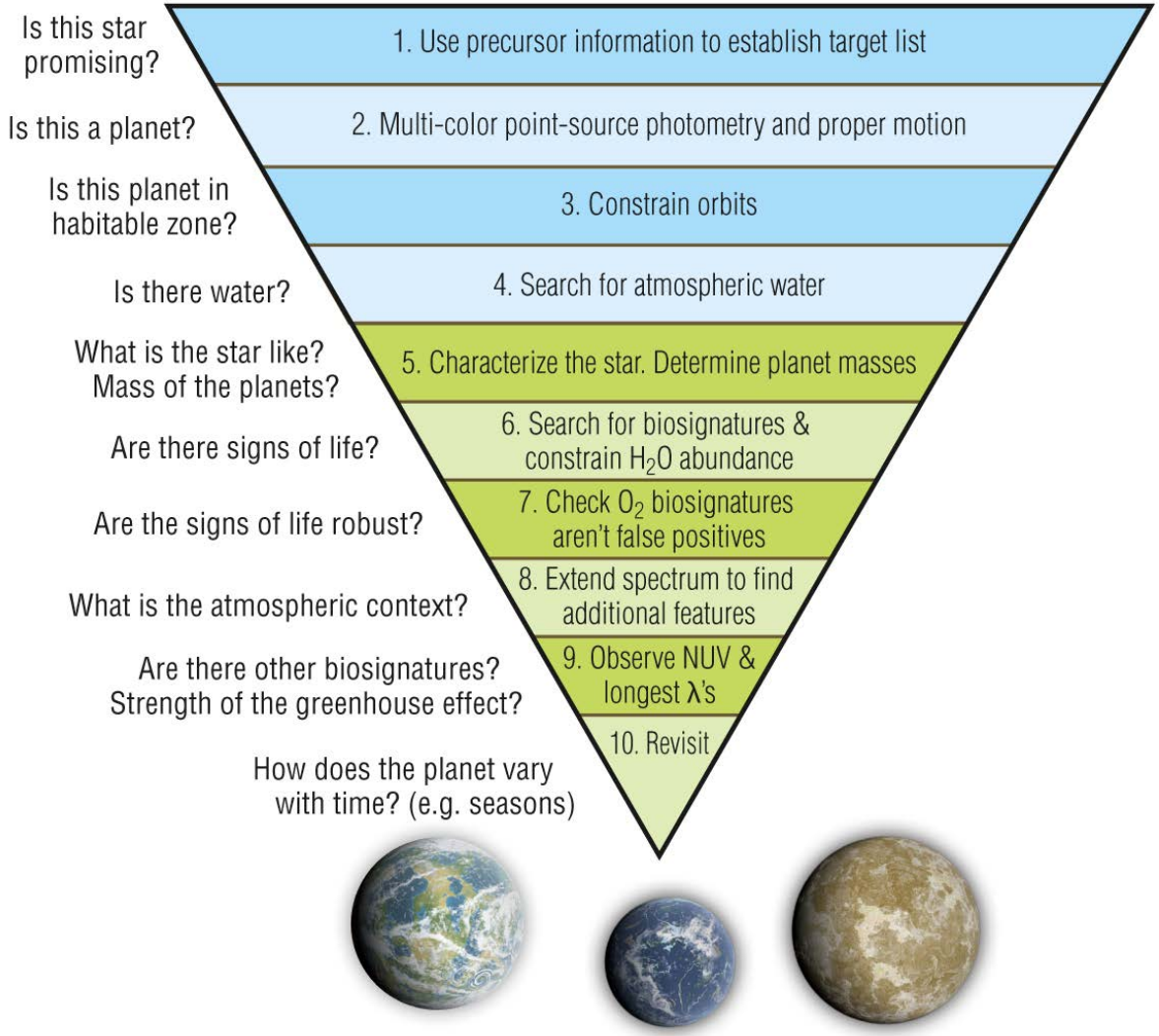
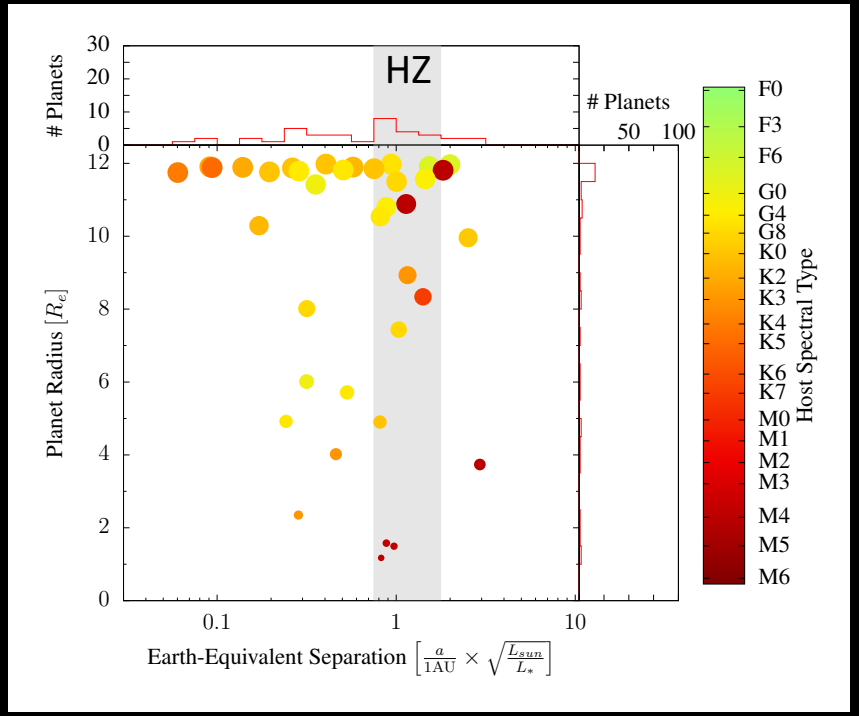
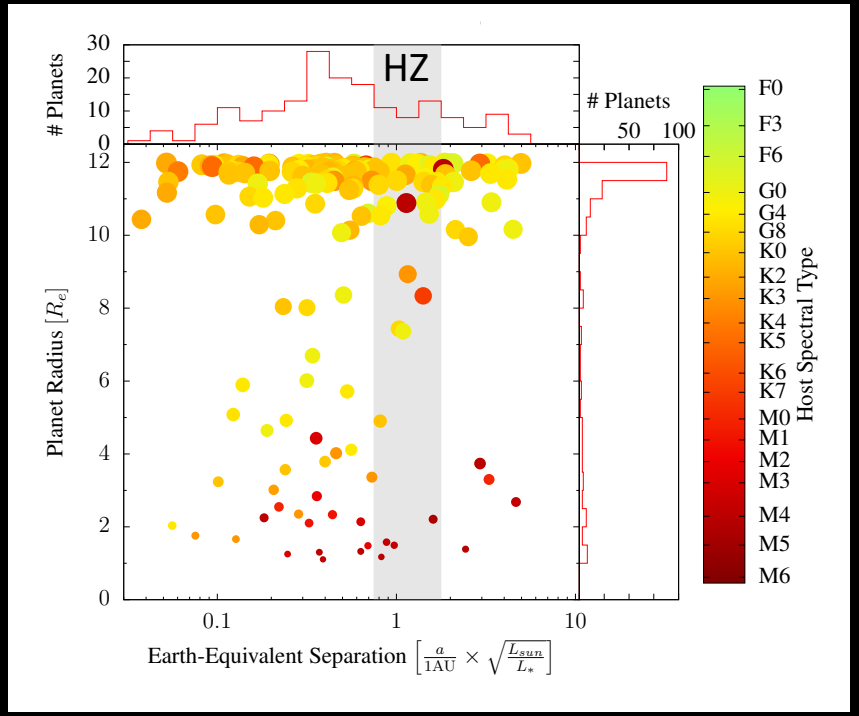
0.5
1
5


Is this star promising?
1. Use precursor information to establish target list
Is this a planet?
2. Multi-color point-source photometry and proper motion
Is this planet in habitable zone?
3. Constrain orbits
Is there water?
4. Search for atmospheric water
What is the star like? Mass of the planets?
5. Characterize the star. Determine planet masses
Are there signs of life?
6. Search for biosignatures & constrain H_2O abundance
Are the signs of life robust?
7. Check O_2 biosignatures aren't false positives
What is the atmospheric context?
8. Extend spectrum to find additional features
Are there other biosignatures? Strength of the greenhouse effect?
9. Observe NUV & longest λ's
How does the planet vary with time? (e.g. seasons)
10. Revisit

Imaging Habitable Zone Exoplanets with the TMT

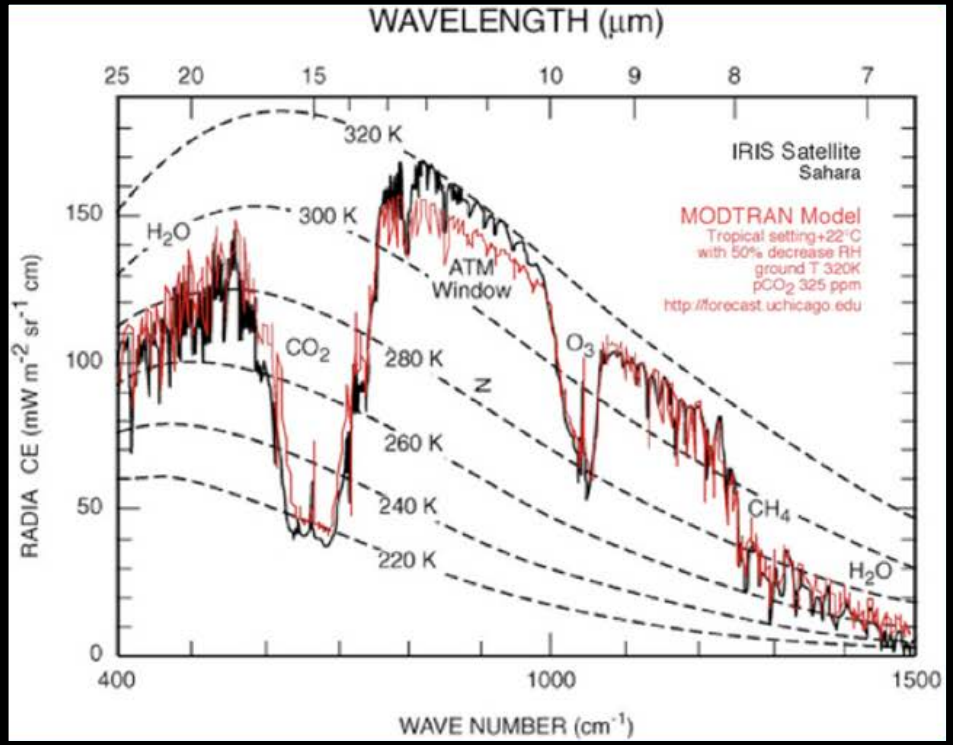


Pessimistic performance



Optimistic performance

Imaging Exo-Earths at 10um

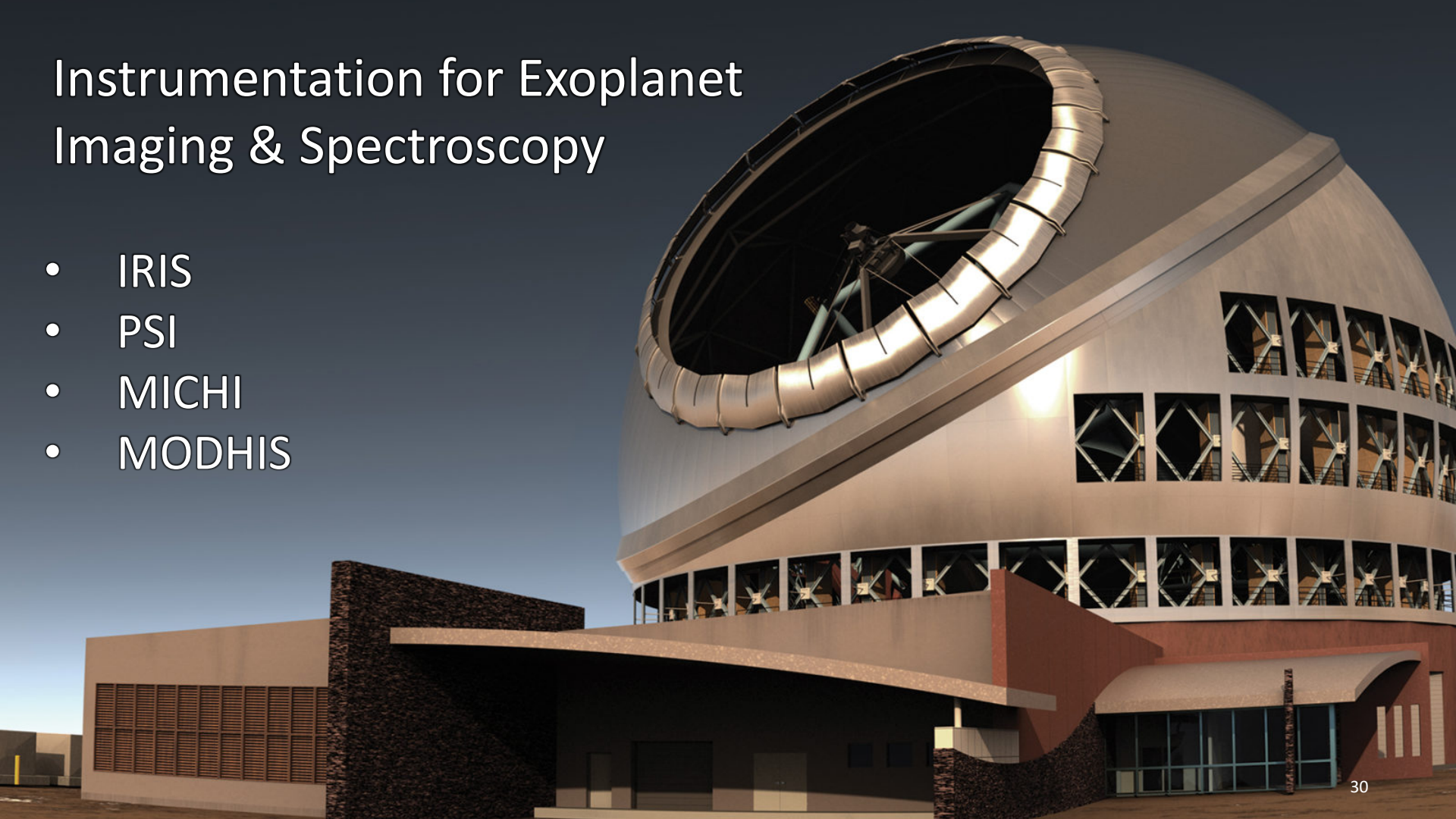


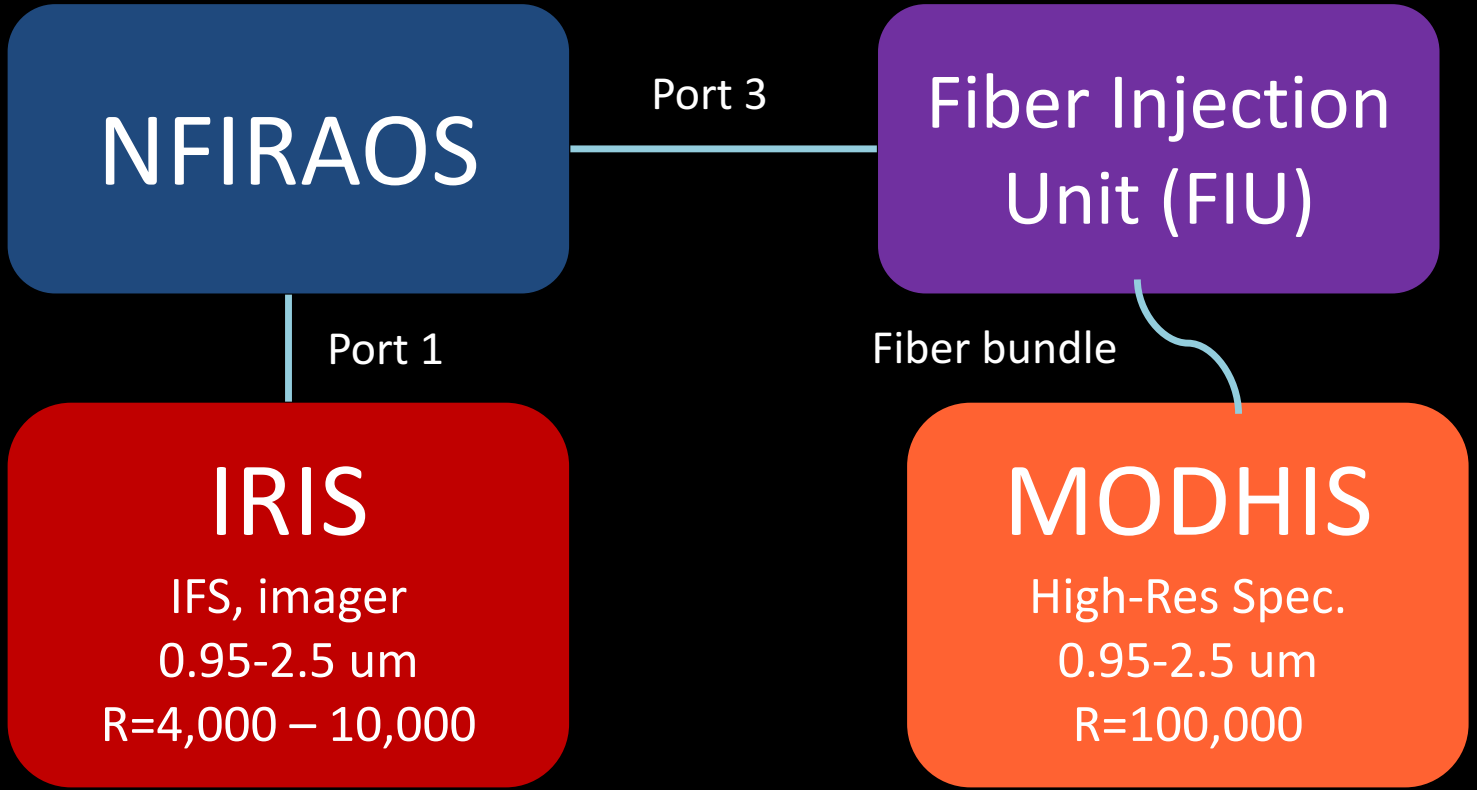
Packham+18/Hanel+72

- The TMT resolves the HZ at 10 μm out to 5 pc for G stars
- At 10 μm, contrast is >100X more favorable than in vis.
- Low res. spectra at 10 μm could enable biomarker detection (e.g. O_3, H_2O, O_2, CH_4 and CO_2)

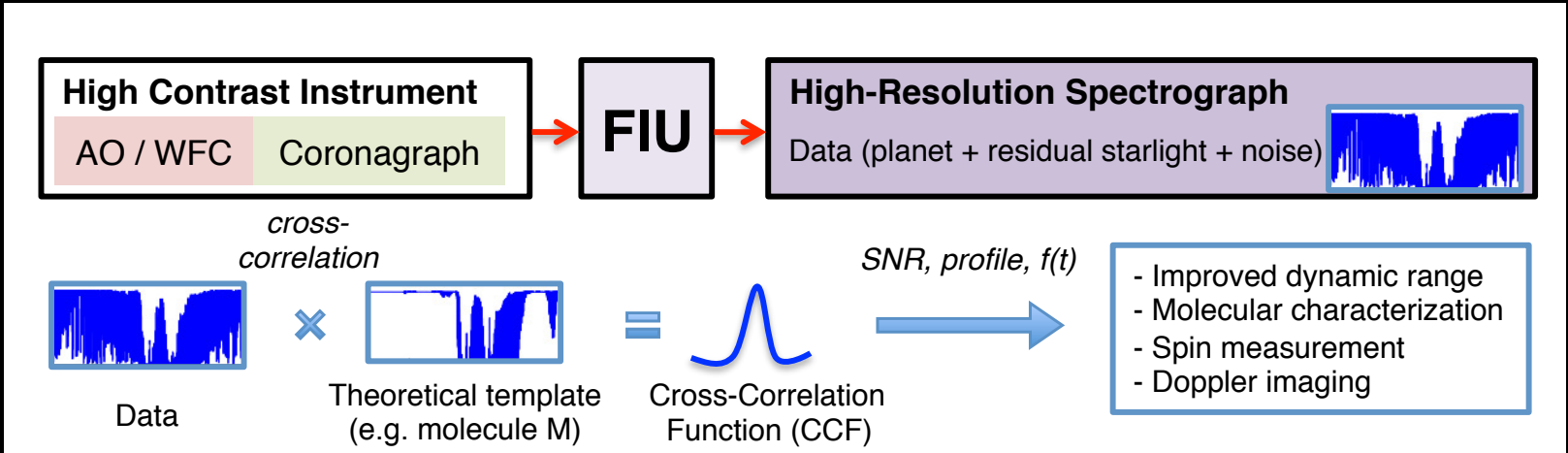
Instrumentation for Exoplanet Imaging & Spectroscopy

- IRIS
- PSI
- MICHI
- MODHIS

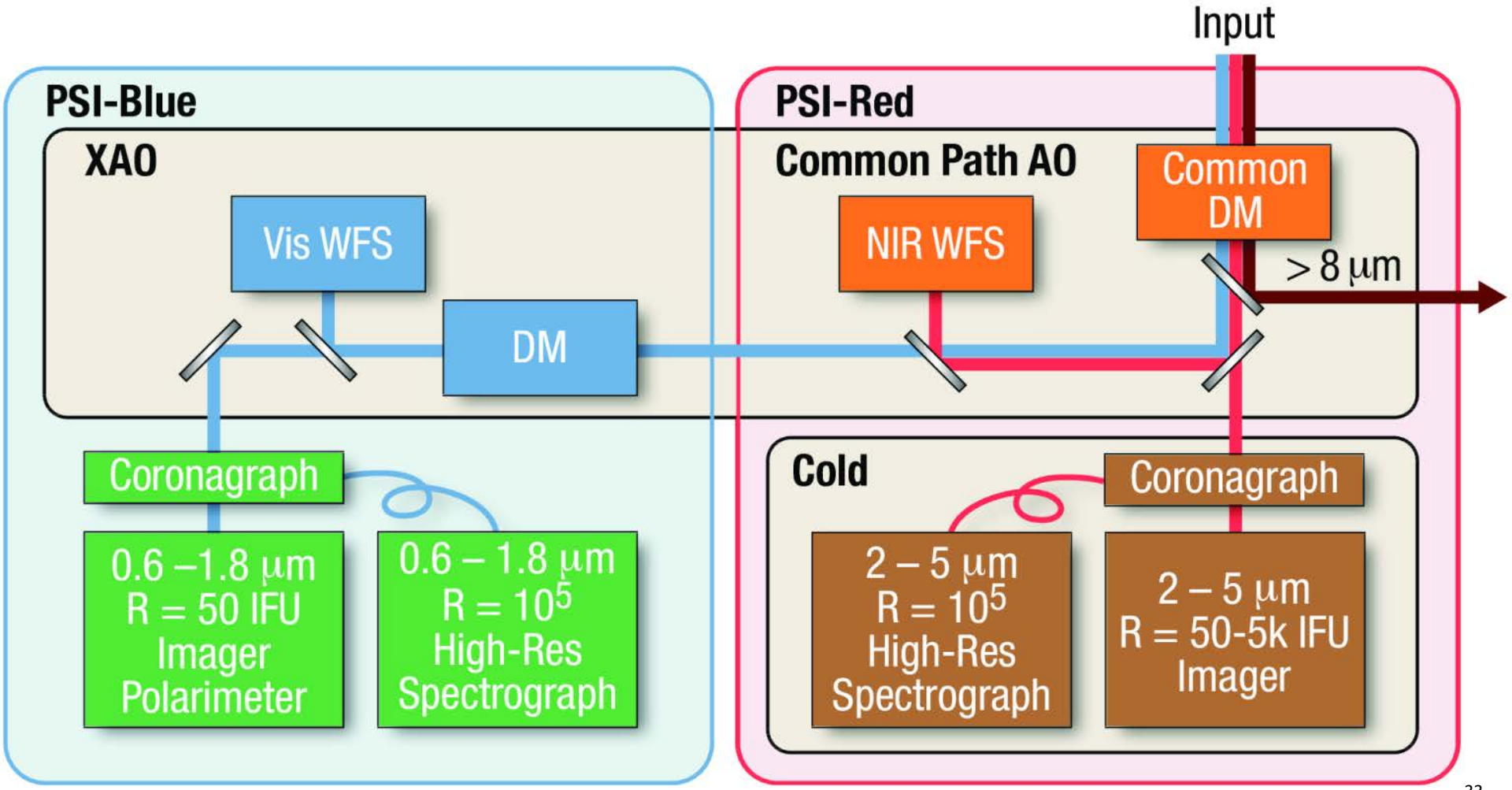


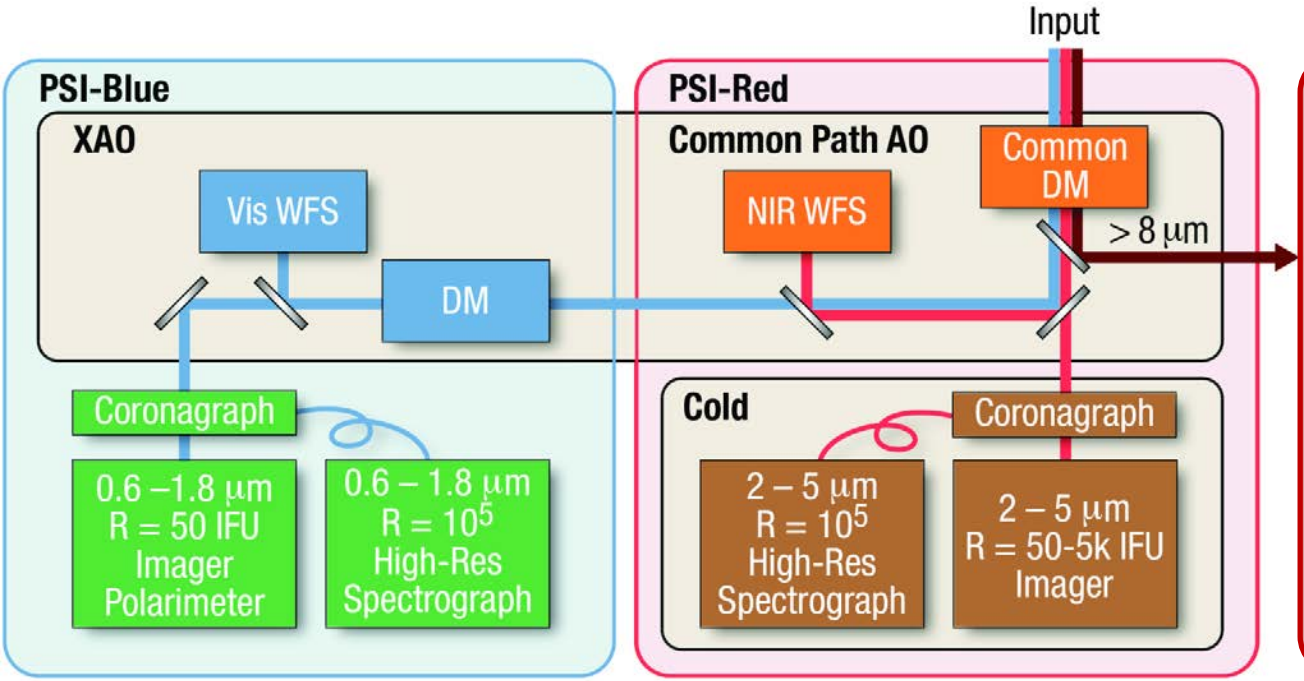

NFIRAOS
Port 3
Fiber Injection Unit (FIU)
Port 1
Fiber bundle
IRIS
IFS, imager
0.95-2.5 um
R=4,000 – 10,000
MODHIS
High-Res Spec.
0.95-2.5 um
R=100,000

Diffraction-limited High-resolution Spectroscopy



Mawet+17b

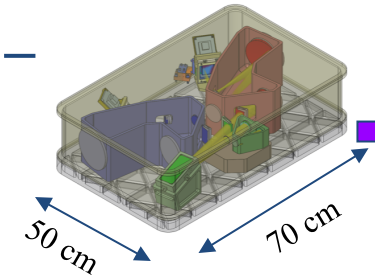

Input
PSI-Blue
XAO
Vis WFS
DM
Coronagraph
0.6 –1.8 μm
R = 50 IFU
Imager
Polarimeter
0.6 – 1.8 μm
R = 10^5
High-Res
Spectrograph
PSI-Red
Common Path AO
NIR WFS
Common
DM
> 8 μm
Cold
Coronagraph
2 – 5 μm
R = 10^5
High-Res
Spectrograph
2 – 5 μm
R = 50-5k IFU
Imager



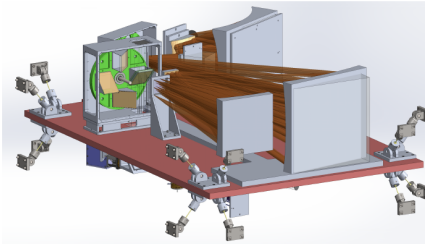
MICHI
Mid-IR Camera,
High-disperser &
IFU spectrograph
未知

Tech development roadmap part 1

HISPEC -> MODHIS

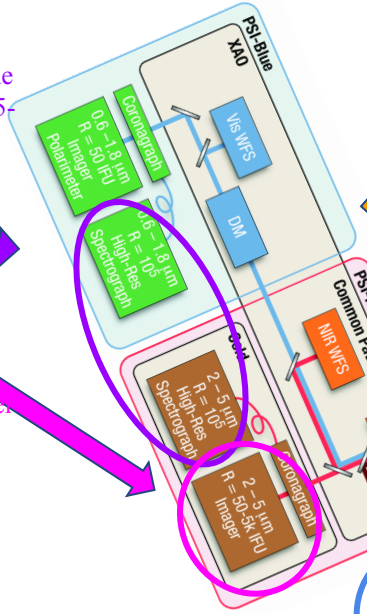


SCALES

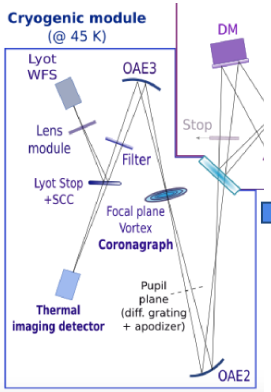


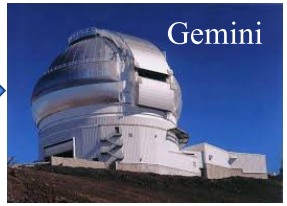
Upgrade to include the 0.6-0.9 and 2.5-5.0 micron

Upgrade to include other imaging/spectroscopic modes



TIKI



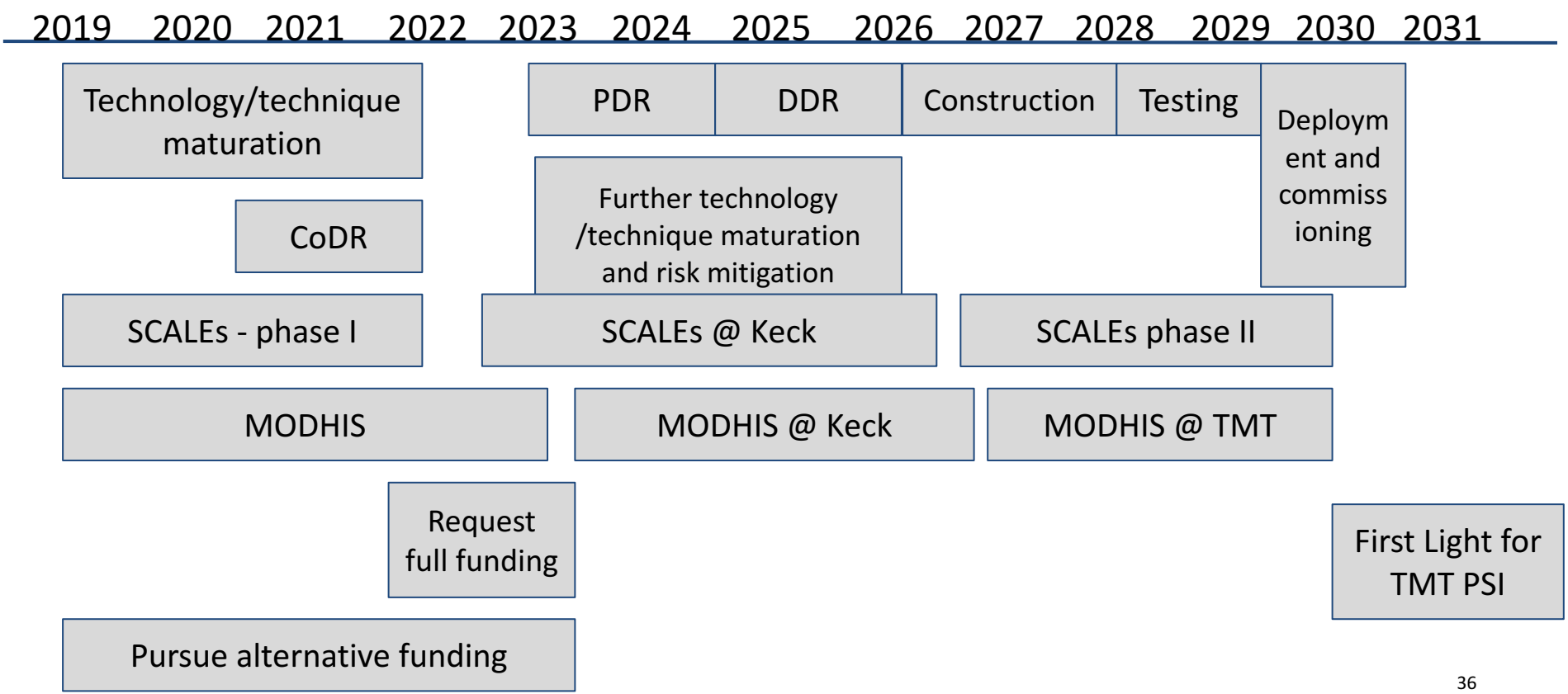


Upgrades to improve performance

Slide credit: Nem Jovanovic

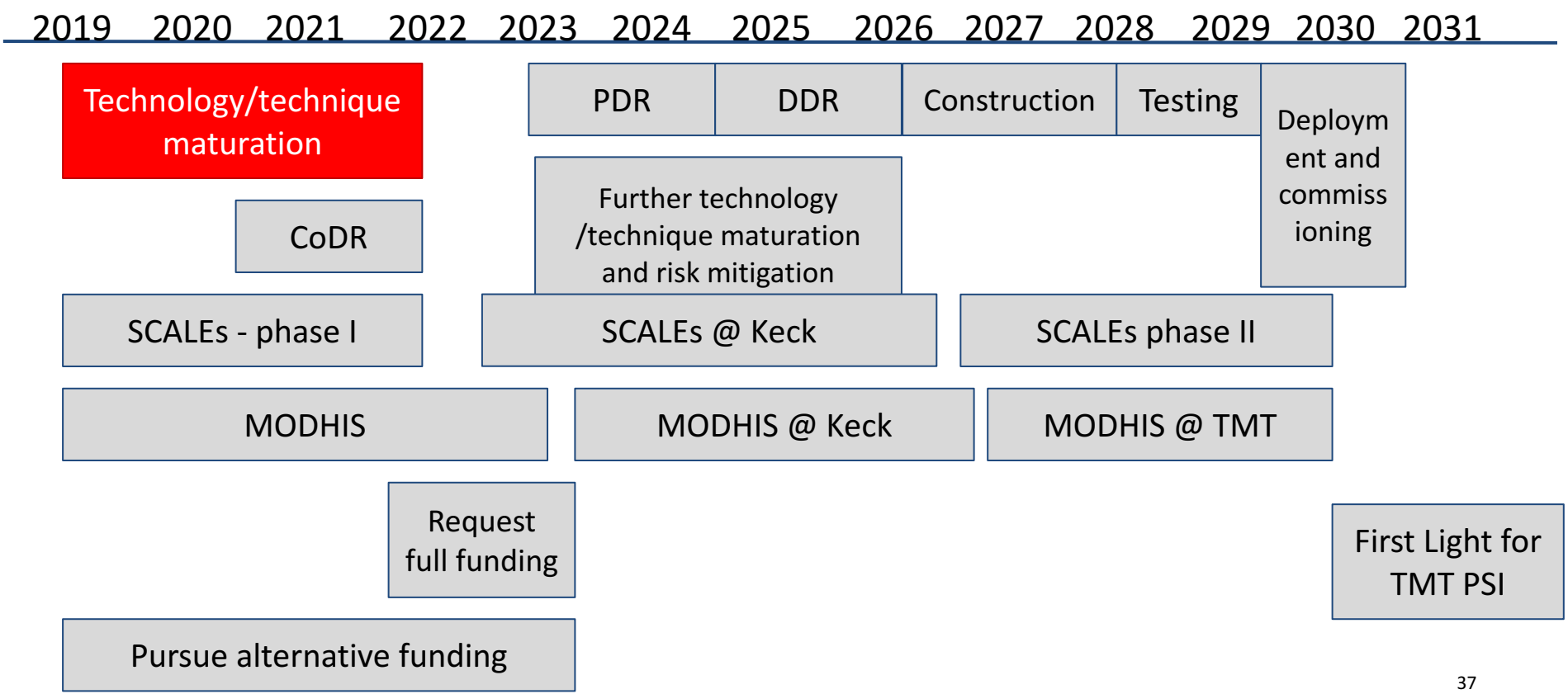
PSI/MODHIS Timeline

Slide credit: Nem Jovanovic



Timeline

Slide credit: Nem Jovanovic

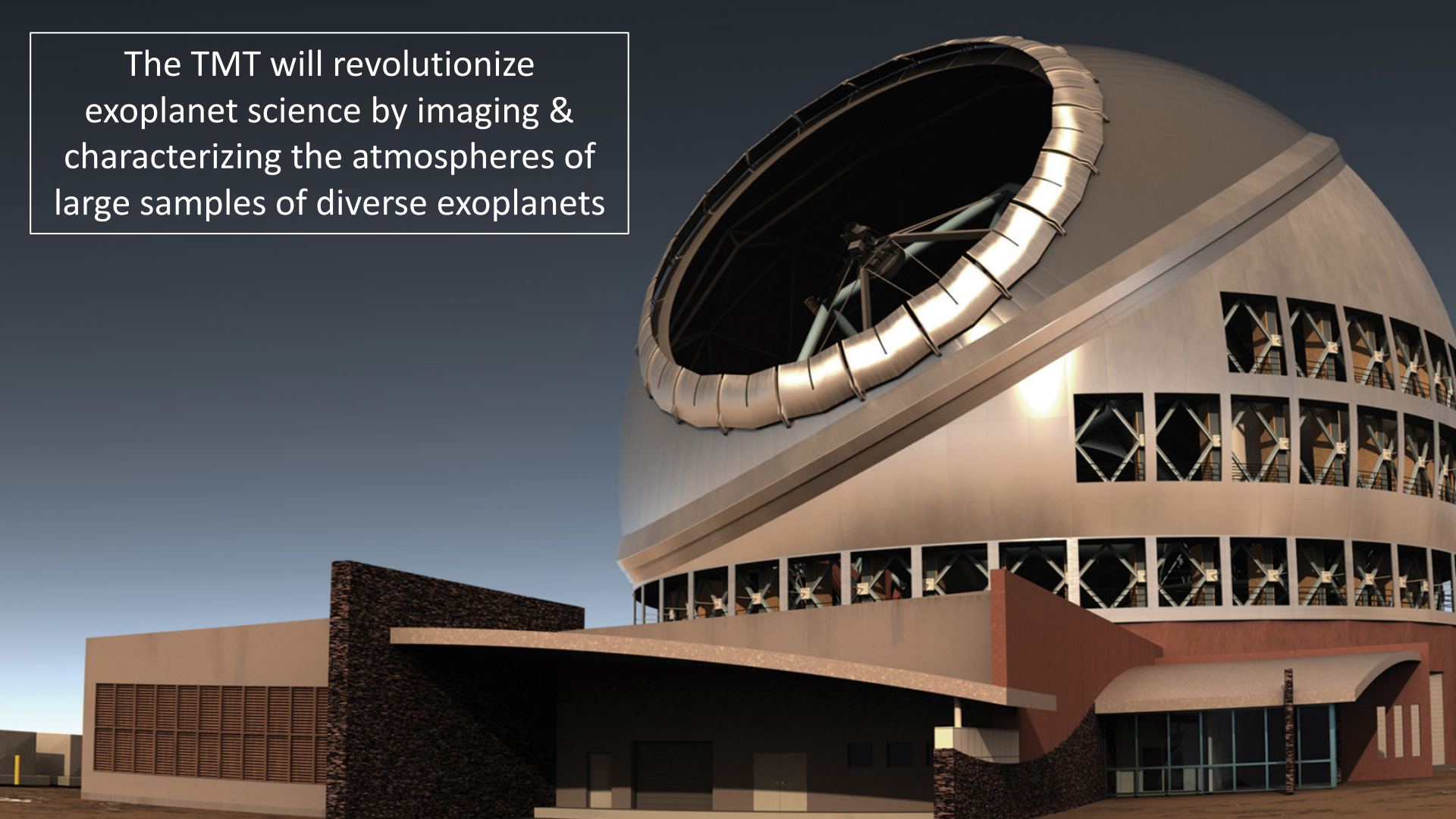


Timeline

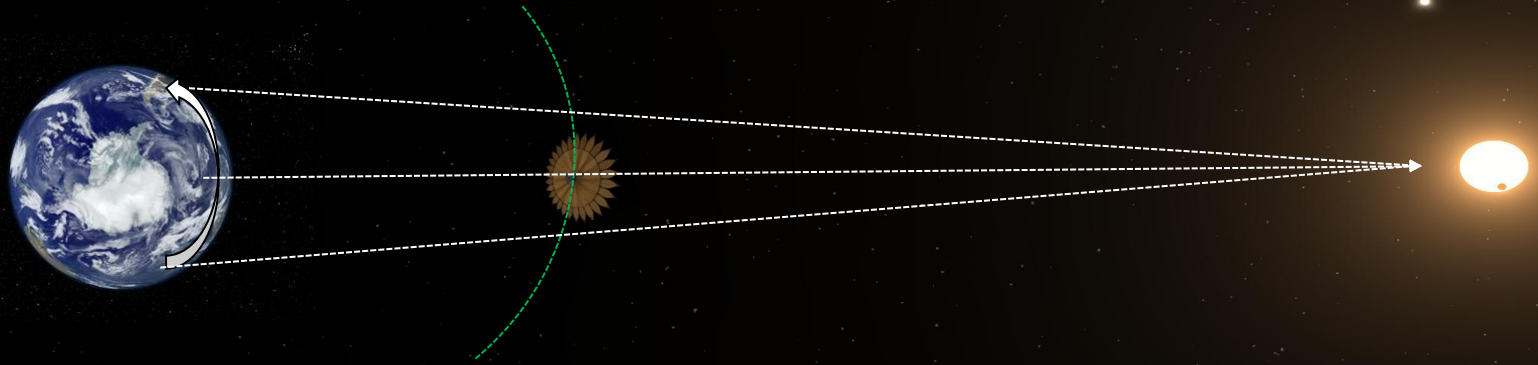
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

Technology/technique maturation

1. **Deformable mirror technology development**
2. **Focal plane wavefront sensing**
3. **Predictive wavefront control**
4. **Sensor fusion**
5. **Understanding the atmosphere**


The TMT will revolutionize exoplanet science by imaging & characterizing the atmospheres of large samples of diverse exoplanets

Starshade actively matches transverse velocity and acceleration of observatory; no radial constraints

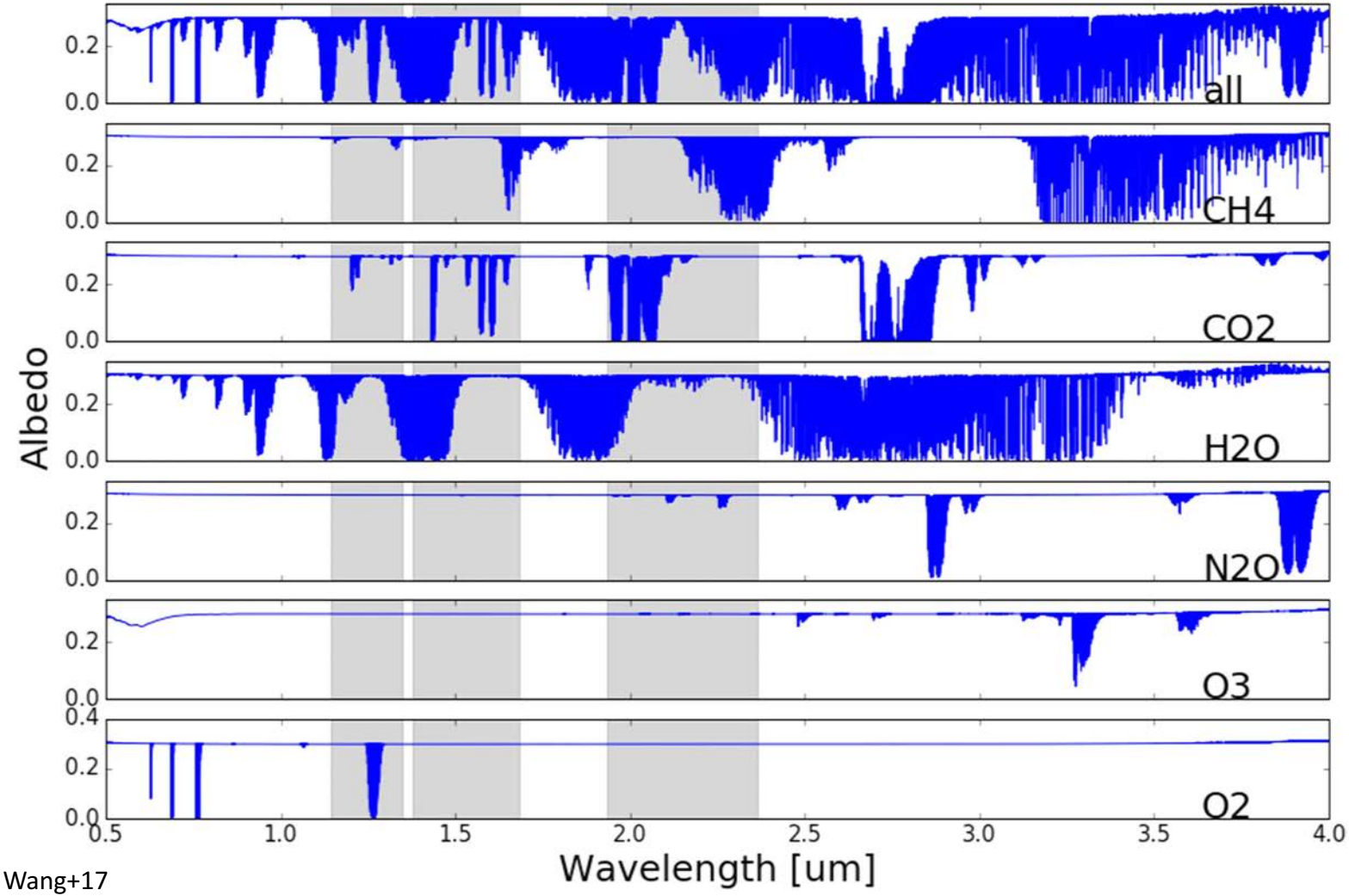


Slide Credit: Mather & Peretz

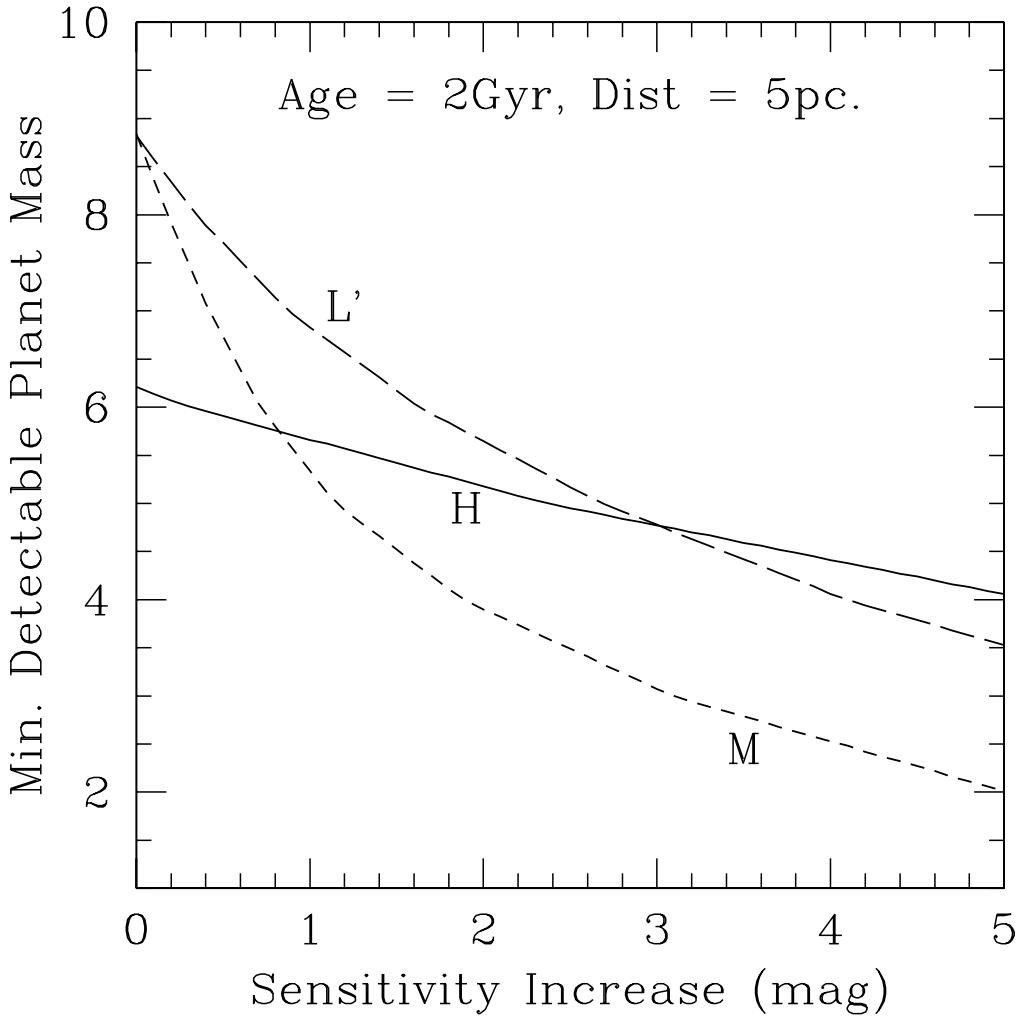
The TMT will revolutionize exoplanet science by imaging & characterizing the atmospheres of large samples of diverse exoplanets

Thank you!

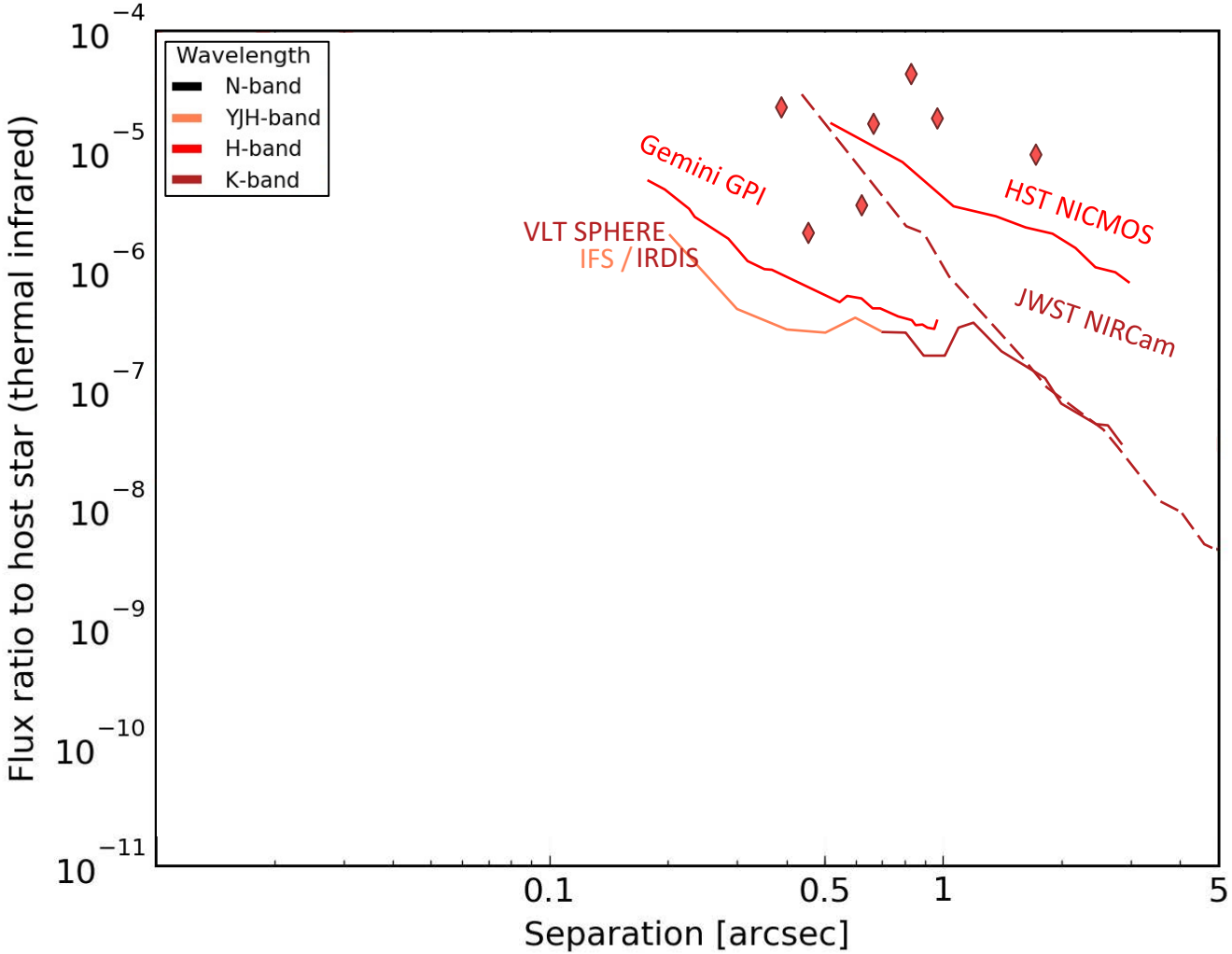
Extra slides

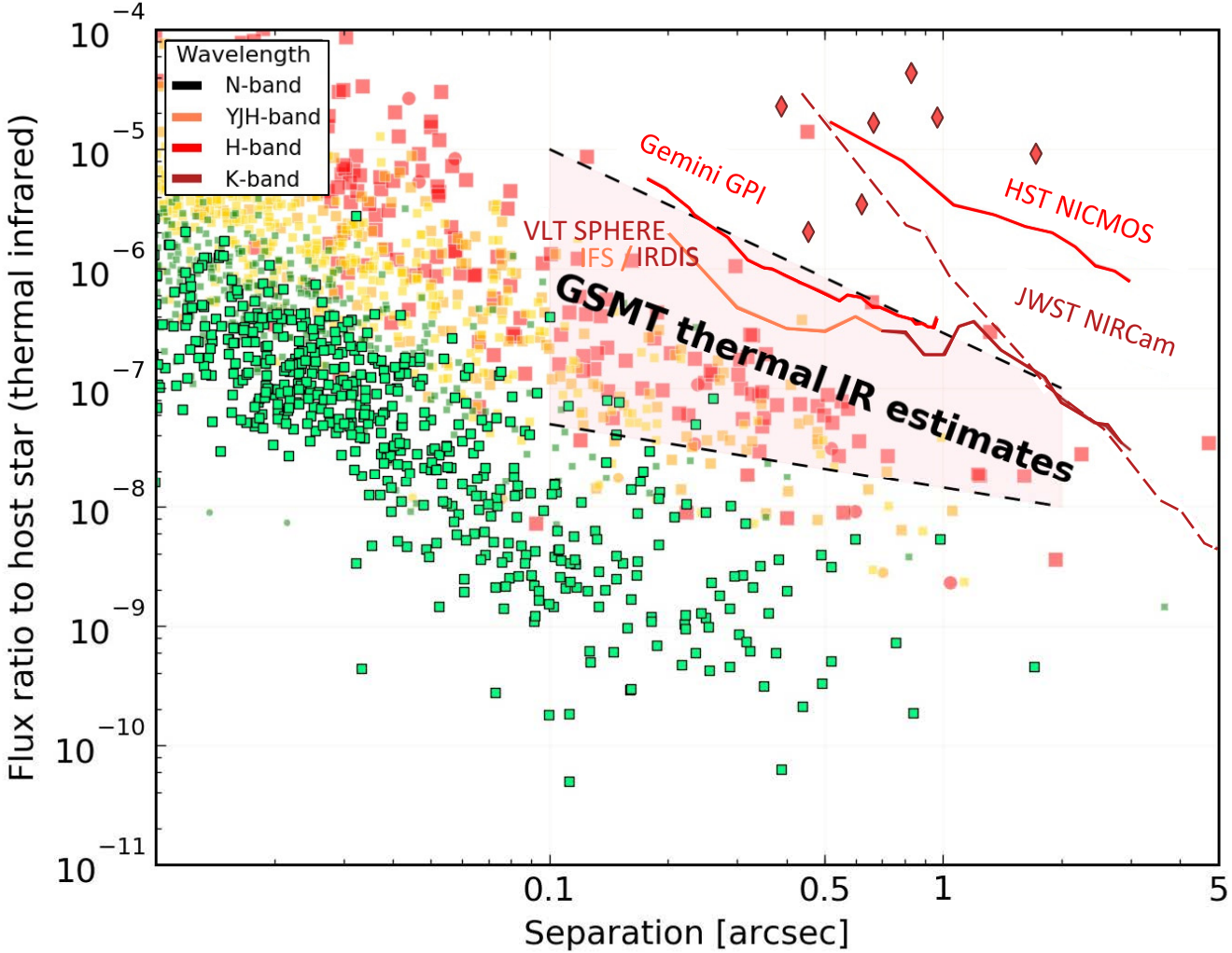

Albedo
all
CH4
CO2
H2O
N2O
O3
O2
0.0
0.2
0.4
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Wavelength [um]

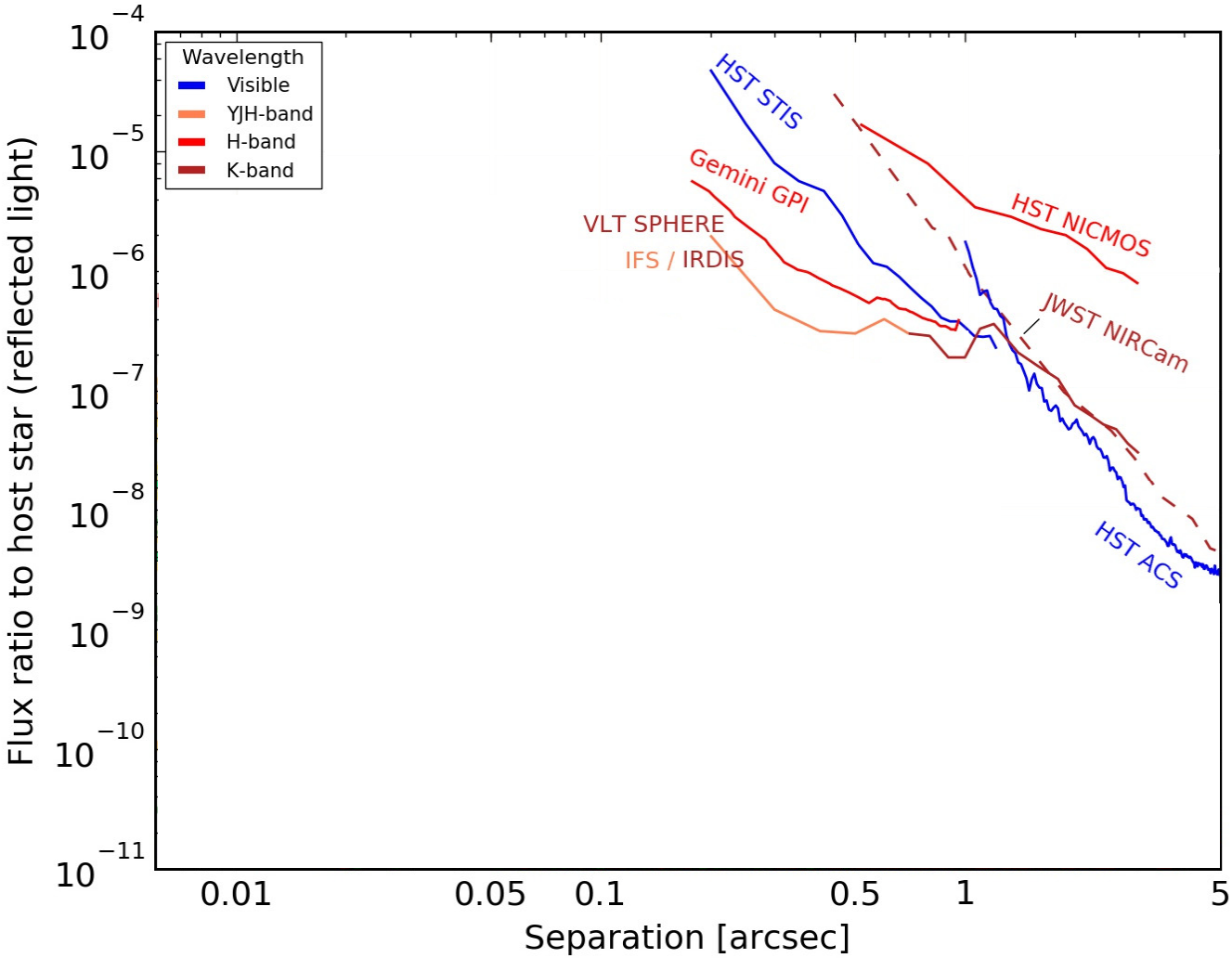
Wang+17

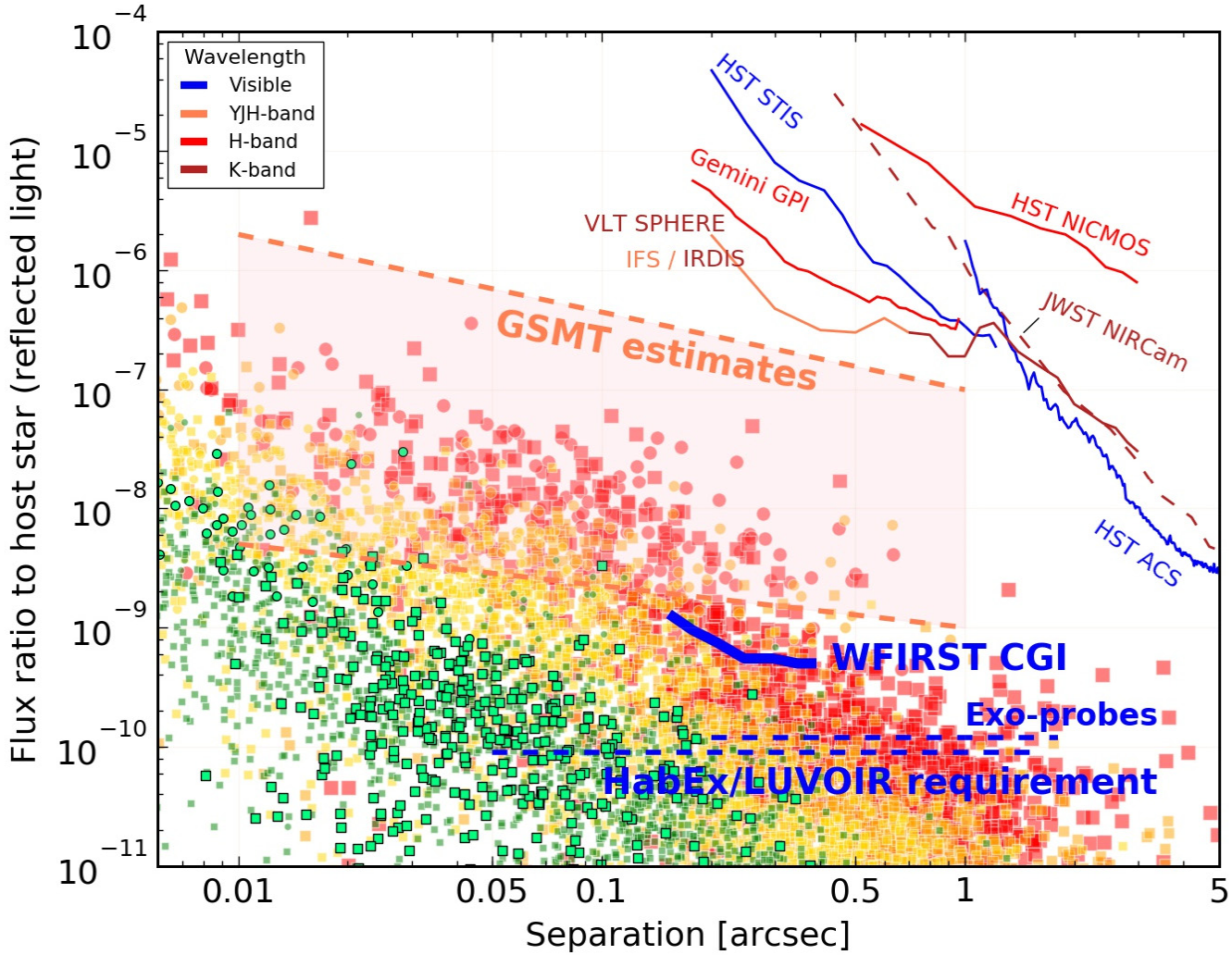

Age = 2Gyr, Dist = 5pc.
Min. Detectable Planet Mass
Sensitivity Increase (mag)
L'
H
M
10
8
6
4
2
0
1
2
3
4
5

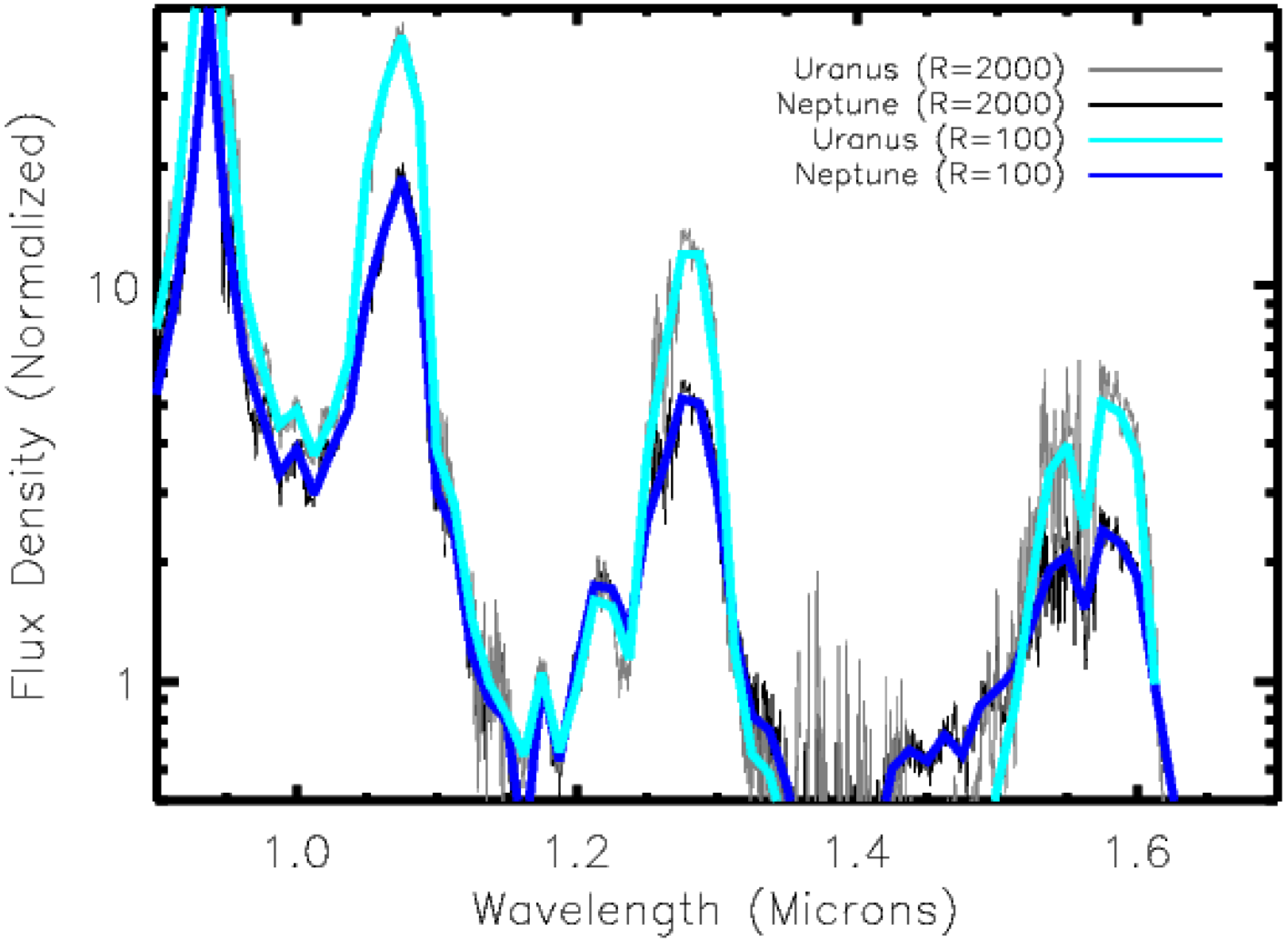
Heinze+10


Wavelength
N-band
YJH-band
H-band
K-band
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
Flux ratio to host star (thermal infrared)
Separation [arcsec]
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.1
0.5
1
5


Wavelength
N-band
YJH-band
H-band
K-band
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
GSMT thermal IR estimates
Flux ratio to host star (thermal infrared)
Separation [arcsec]
0.1
0.5
1
5


Wavelength
Visible
YJH-band
H-band
K-band
HST STIS
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
HST ACS
Flux ratio to host star (reflected light)
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.01
0.05
0.1
0.5
1
5
Separation [arcsec]


Wavelength
Visible
YJH-band
H-band
K-band
HST STIS
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
JWST NIRCam
HST ACS
GSMT estimates
WFIRST CGI
Exo-probes
HabEx/LUVOIR requirement
Flux ratio to host star (reflected light)
Separation [arcsec]
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.01
0.05
0.1
0.5
1
5


Uranus (R=2000)
Neptune (R=2000)
Uranus (R=100)
Neptune (R=100)
Flux Density (Normalized)
10
1
1.0
1.2
1.4
1.6
Wavelength (Microns)