Characterizing Planets with Direct Imaging

Victoria Meadows and the
NAI Virtual Planetary Laboratory Team

The University of Washington, California Institute of Technology, Jet Propulsion Laboratory, Pennsylvania State University, NASA Goddard Space Flight Center, University of Maryland, NASA Goddard Institute for Space Studies, University of Chicago, Weber State University, Adler Planetarium, NASA Ames Research Center, Stanford University, Rice University, Washington University at Saint Louis, Yale University, Australian Center for Astrobiology, University of Victoria, Laboratoire d’Astrophysique – Bordeaux

The NAI’s Virtual Planetary Laboratory

Earth as an Exoplanet

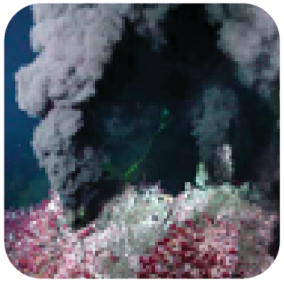
Earth Observations
GCM Results

Validation

Disk-averaged spectra over a full year for Earth and other planets

The Earth Through Time

Field Work
Lab Studies
Computer Models



Environmental constraints

Climate, Biosignatures

Disk-averaged spectra at several stages of evolution

The Habitable Planet

Planet Formation
1-D/3-D Climate/Chemistry
Orbital Dynamics
Stellar Observations

Habitability assessment

Disk-averaged spectra

Climate and limits of the habitable zone for plausible extrasolar planets

The Living Planet

Field Work
Lab Studies
Computer Models

Limits of photosynthesis

Impact of life on planetary environments

New biosignatures

Observer

Our Challenge

Direct Imaging

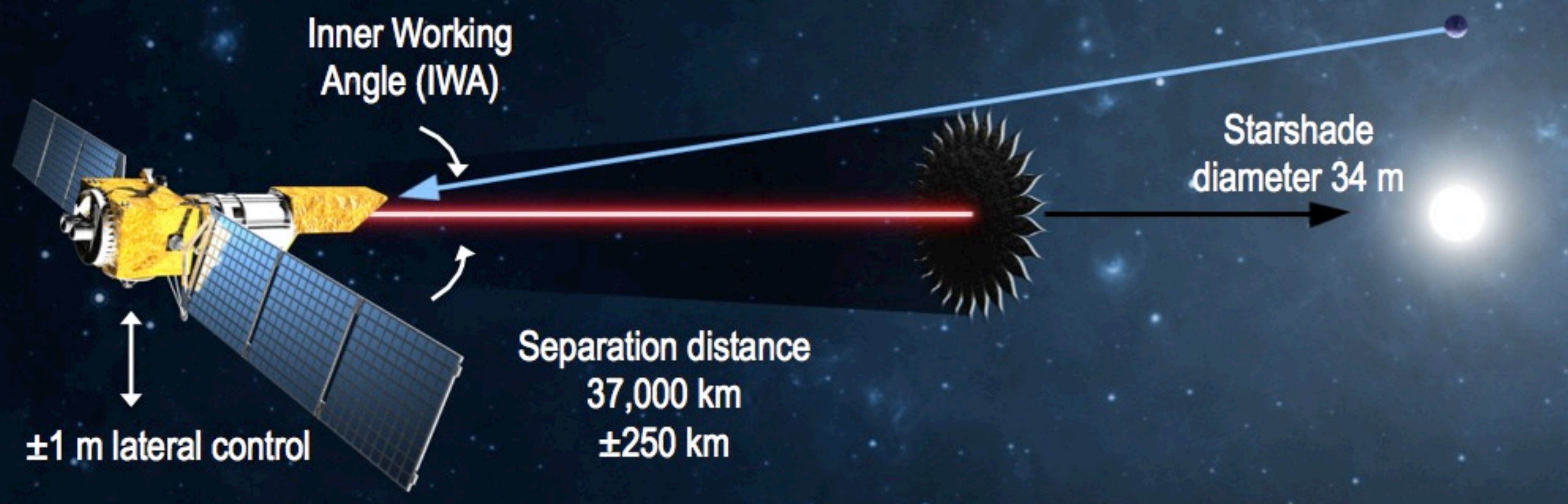
- Must suppress the light from the parent star so that the light from the smaller, fainter planet can be seen - at least 10^{-9} for Jupiter detection and 10^{-11} for Earth spectroscopy.
- Suppression techniques (e.g. coronography, interferometry) have inner and outer working angles that are ~2λ/D, where D = telescope diameter.
- The larger the telescope, or the shorter the wavelength, the closer in to the star we can see.

Direct Imaging

- Must also resolve planet and star as two separate images
- Angular resolution $\theta = 1.22\ \lambda/D$,
- Angular resolution improves with larger telescopes, shorter λ

Except…for external occulters

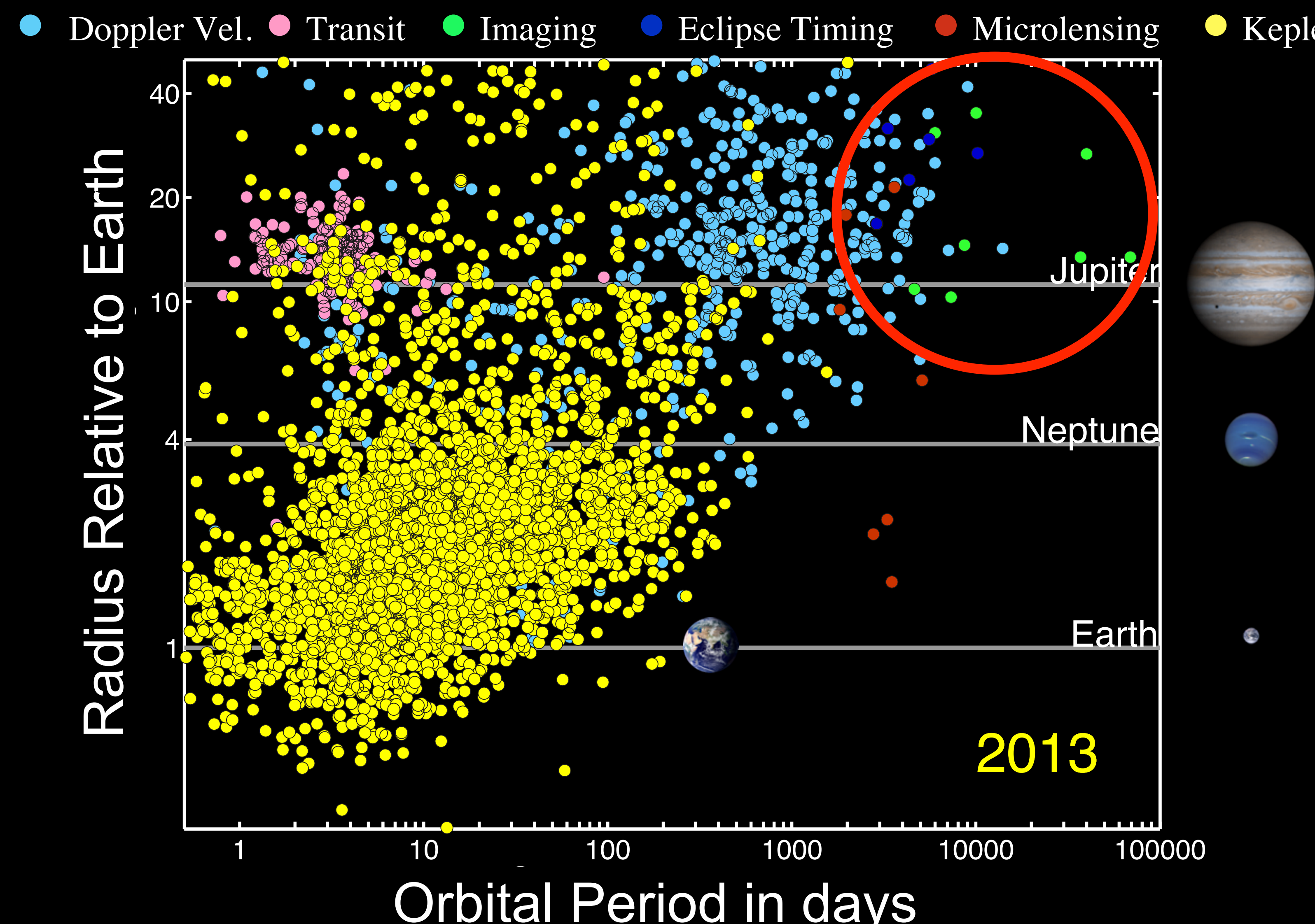
…where inner working angle is a function of starshade diameter and distance from the telescope



Telescope diameter 1.1 m

- Contrast and inner working angle are decoupled from the telescope aperture size
  - A simple space telescope can be used
  - No wavefront correction is needed
- No outer working angle

Direct Imaging. It's Hard. Why bother?



J. Fortney

Direct Imaging. It's hard. Why bother?

Aerosols can severely limit the altitude probed by transit spectra, hiding much of the atmosphere from study.

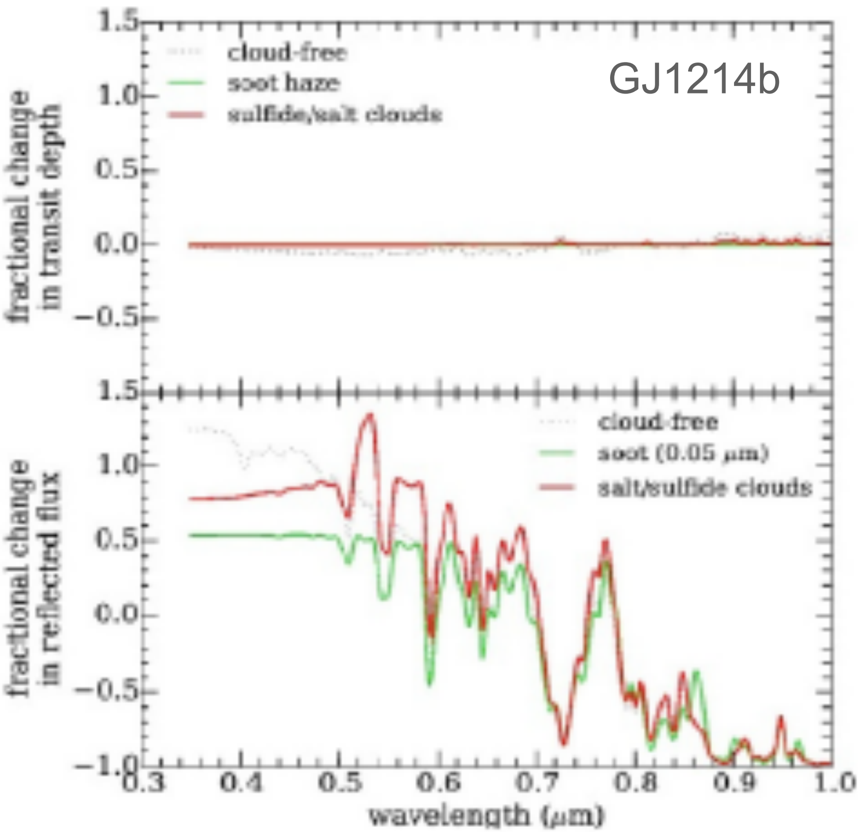
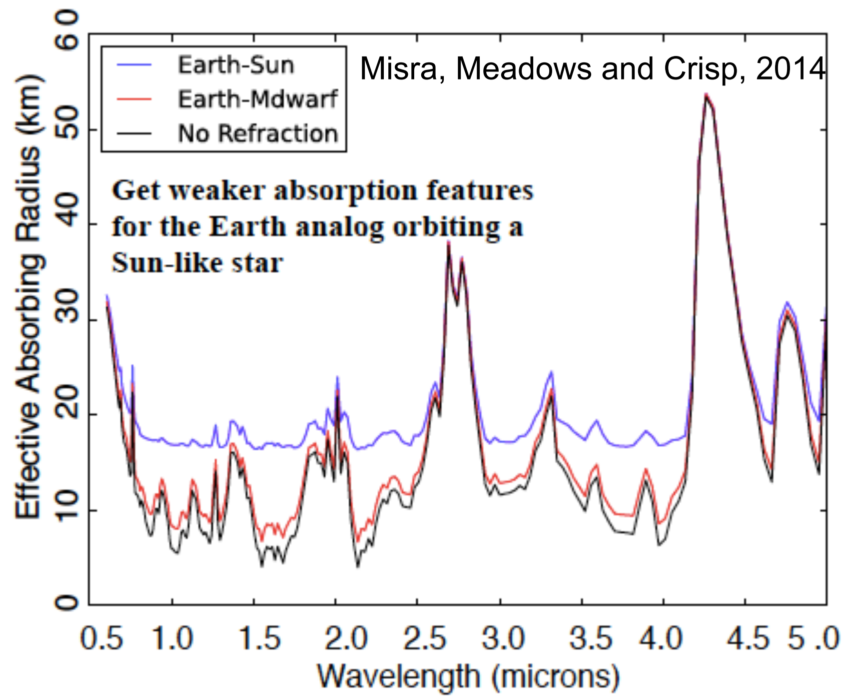


Figure by Caroline Morley in Stapelfeldt et al., 2015

Depending on observing geometry refraction also limits altitudes probed and favors close-in planets.



If you care about habitable planets….

Transit Transmission (Good for M Dwarf Planets)

vs

Direct Imaging (Good for G Dwarf Planets)

Transit Transmission

M dwarf HZ planets and close-in Jovians are good targets for transit transmission

- Planet close to the star (increasing the chance of a transit)
- Larger signal because the star is smaller (or the planet larger)
- There are more transits to observe
- Refraction has little effect on the altitudes probed.

However…

- The surface cannot be studied
- Aerosols can severely limit the altitudes probed
- Transiting planets are rare and so further away…on average.

Direct Imaging

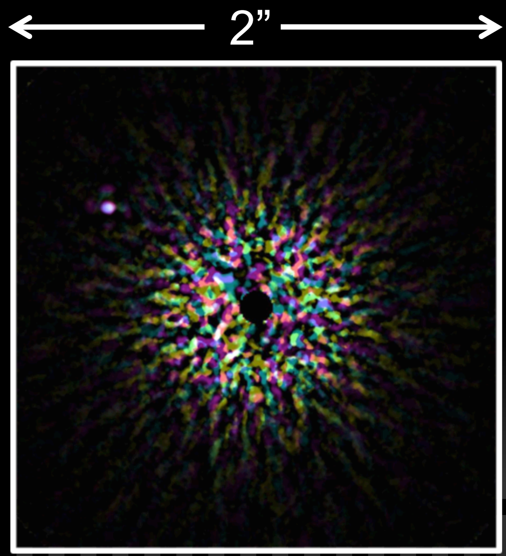
- Direct Imaging will allow us to obtain images and spectra of *planetary systems like our own*
  - At larger angular separation, direct imaging can characterize cool Jupiters and planets in the HZ of G dwarf stars, but *not* M dwarfs.
  - Will finally answer the age old question "Just how weird are we?"
- Can obtain direct (albeit spatially-unresolved) images of the planet – the planet does not have to transit.
- Can measure the planet's brightness as a function of phase, and obtain spectra
- Can probe atmosphere and surface. Less affected by haze

However,

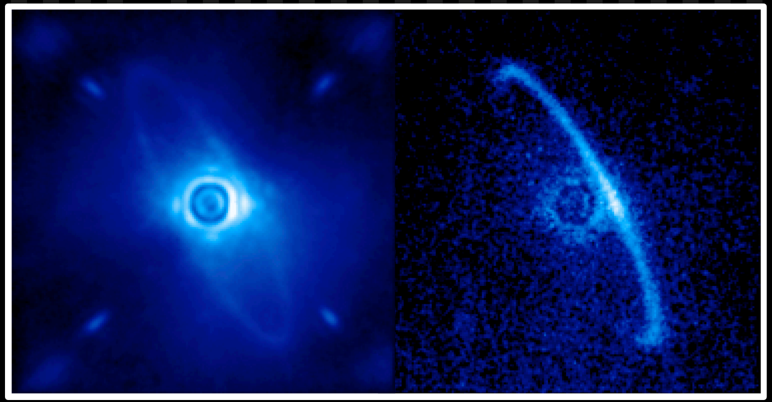
- We cannot determine size (at visible wavelengths)
- Technology to detect and characterize terrestrial planets in the HZ of their parent star is not yet available!

Current Status of Ground-based Systems

- Telescopes with adaptive optics systems can achieve diffraction limited observations.
- Primarily limited to infrared.
- Limited to contrasts ~10^6-10^7
- Systems take approach very similar to high contrast imaging from space
  - Adaptive optics, coronagraphy, integral field spectroscopy
- Gemini/GPI, Palomar/P1640, Subaru/SCExAO, VLT/SPHERE



Subaru/SEEDS, Carson et al. 2013



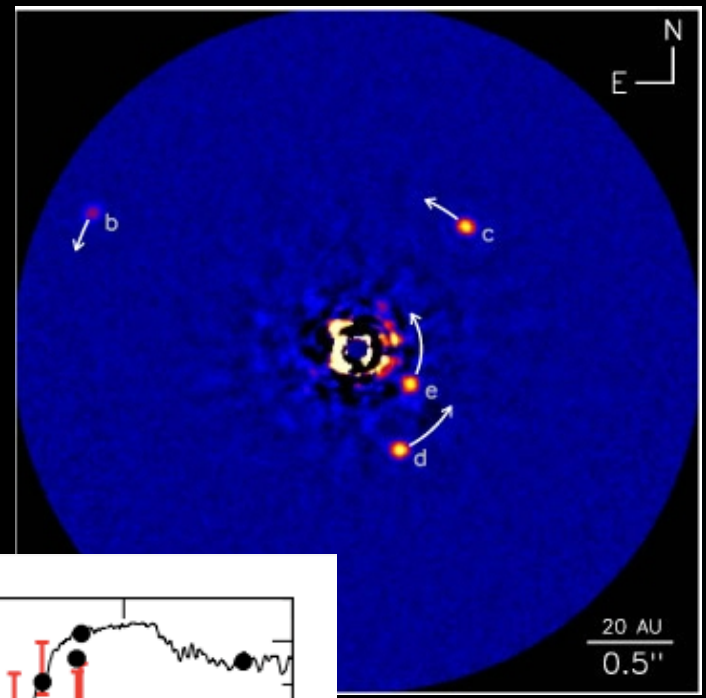
Gemini/GPI, M. Perrin & GPI team

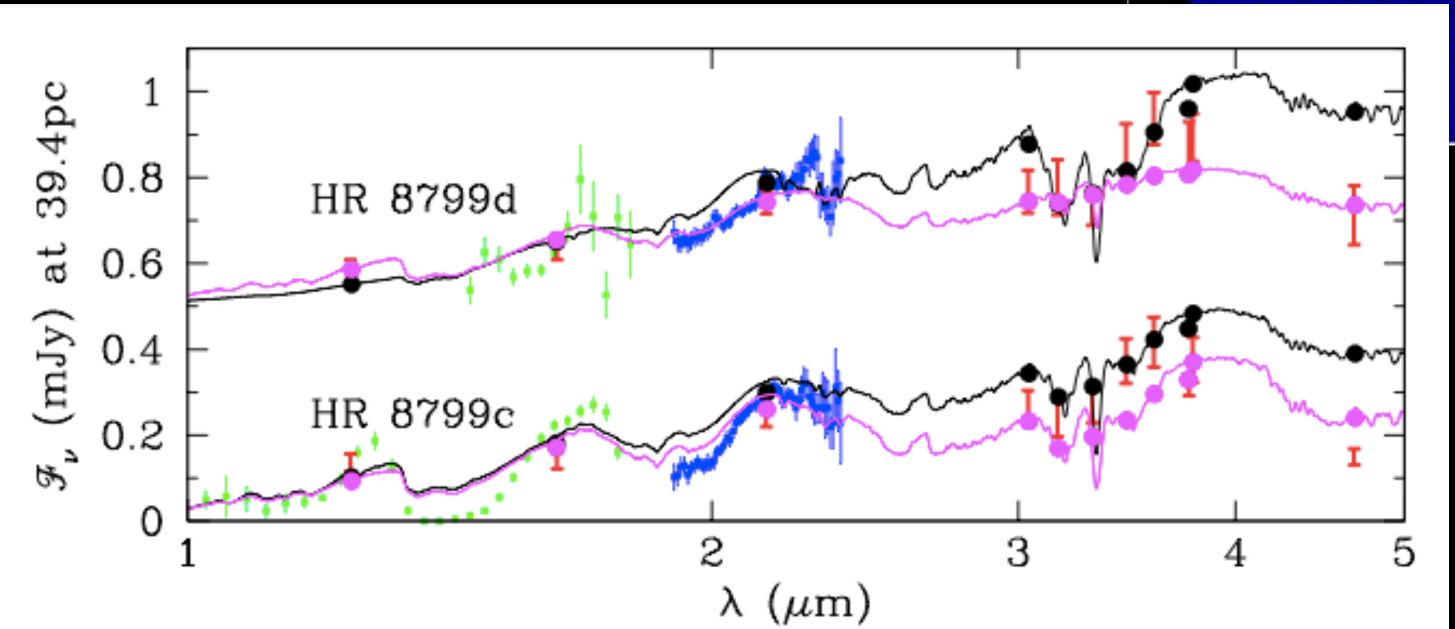
GPI: Direct Imaging and Spectroscopy of Young Giants

Spectra of young, hot planets that likely have very different environments to our cold Jovians.

No single atmospheric model fits all the data. Inferred planet radius is much smaller than that predicted by evolutionary models. Possible disequilibrium.

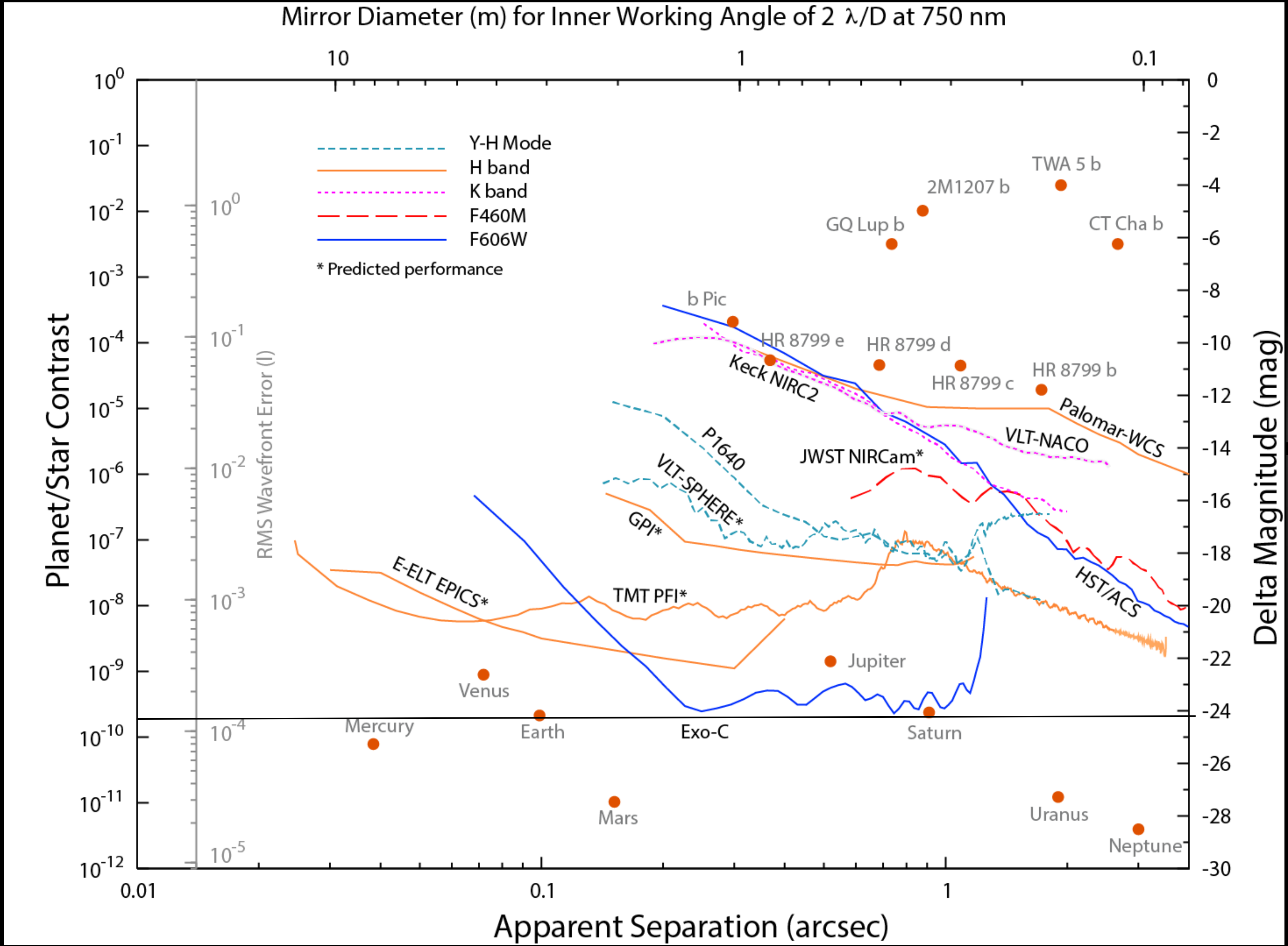
NRC/HIA, C. Marois, and Keck Observatory)





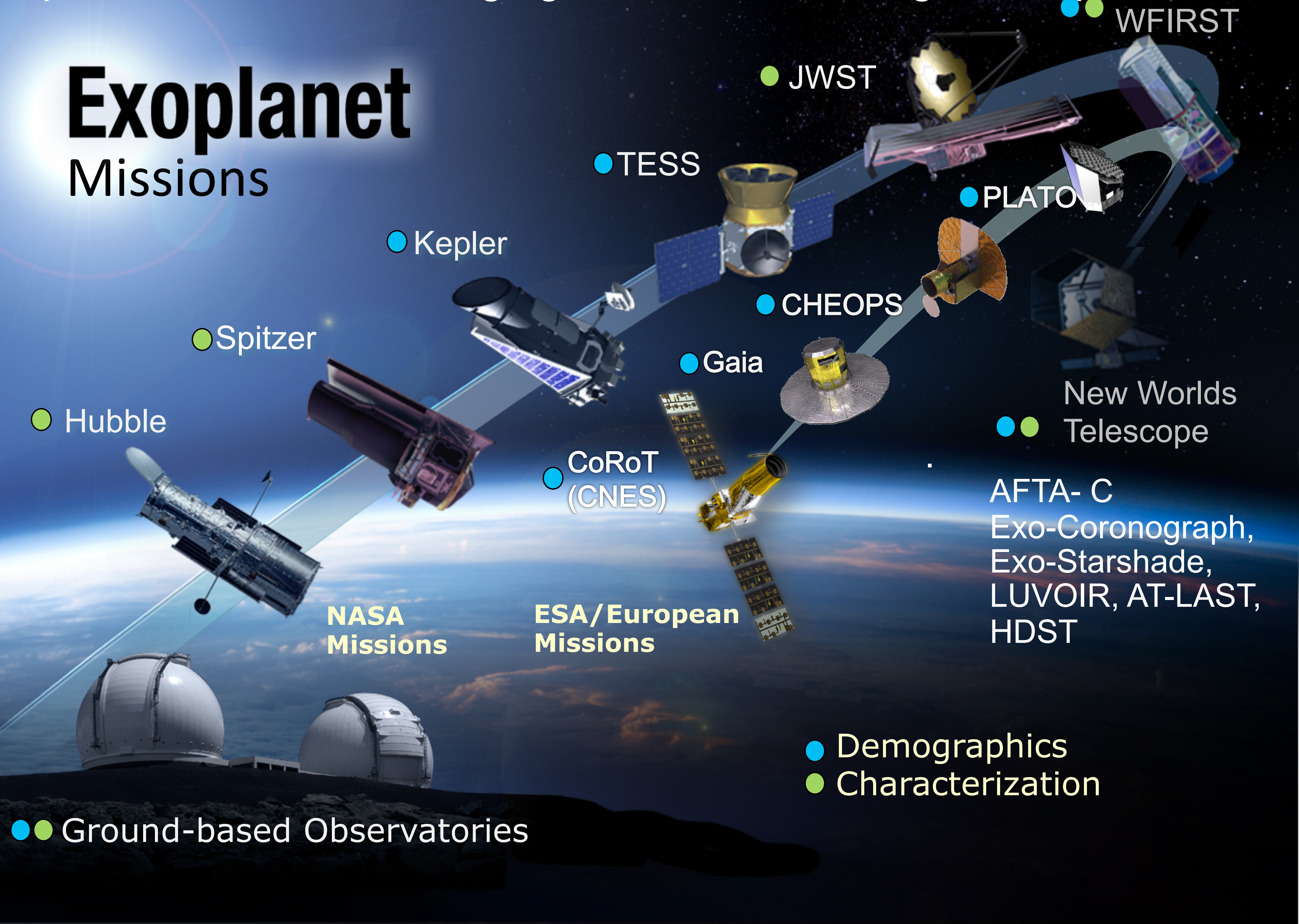
Ingraham et al., 2014

High Contrast Imaging Comparison



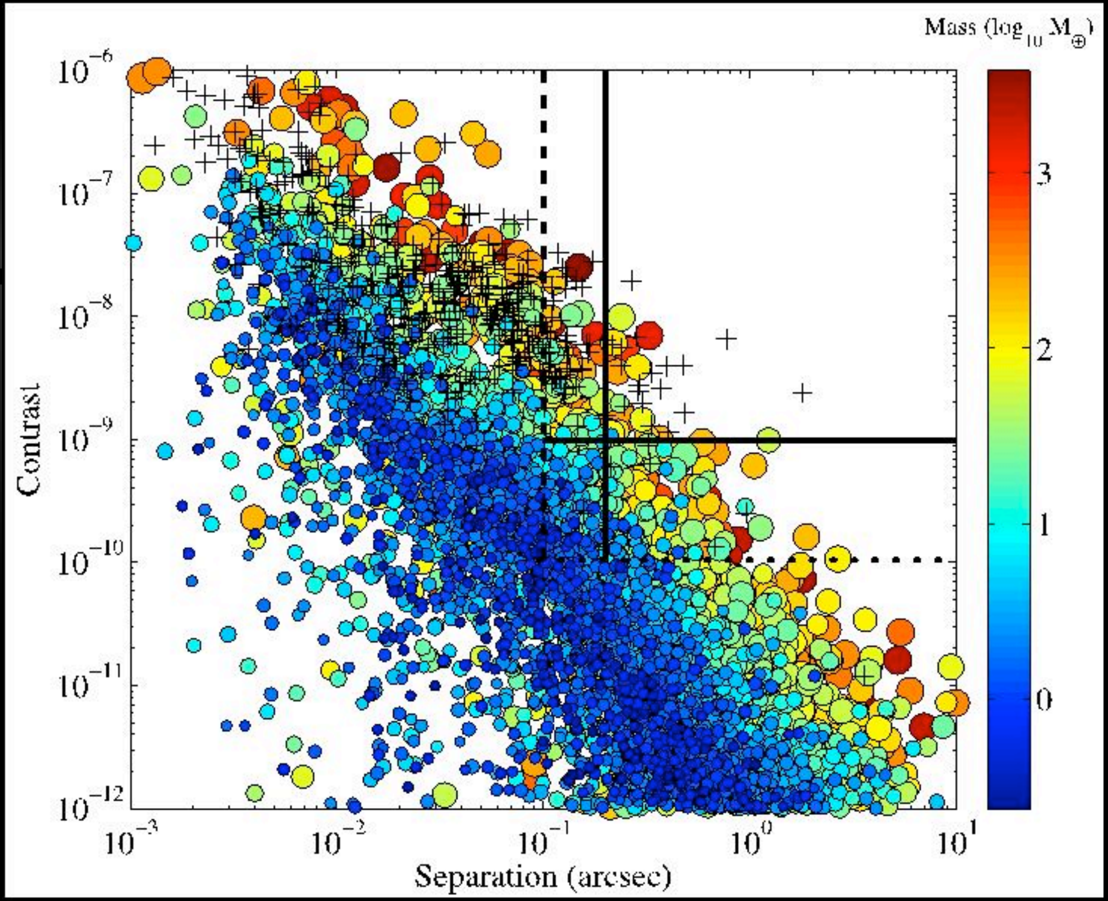
Stapelfeldt et al., 2015.

Space-based Direct-Imaging Missions are being developed



NASA High Contrast Missions: AFTA-C

- AFTA is a NRO telescope given to NASA
- WFIRST mission concept benefits from larger aperture
- Coronagraph is second science camera



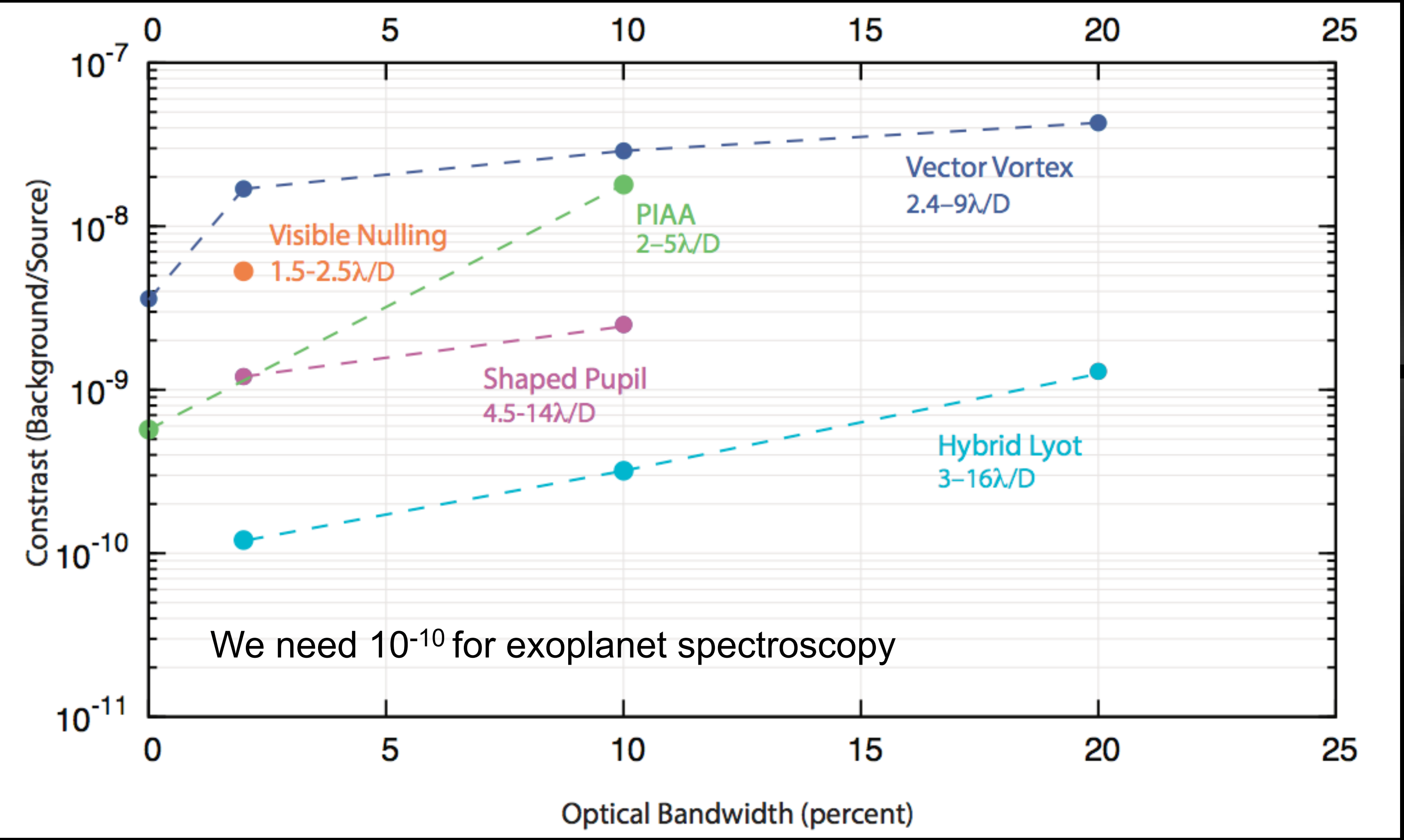
Sensitivity of the WFIRST-2.4m coronagraph for exoplanets.

Solid black lines mark the baseline technical goal of 1 ppb contrast and 0.2 arcsec inner working angle, while the dotted lines show the more aggressive goals of 0.1 ppb and 0.1 arcsec.

Terrestrials would only be detectable with the more aggressive goals but still challenging to observe them in their HZs

WFIRST website

High Contrast Imaging Technology Demos: Coronagraphs



ExEP 2014 Technology Plan

Internal Coronograph: Exo-C Concept

1.4m telescope, Earth-trailing

$\sim$2 λ/D inner working angle (0.15″ at 550 nm)

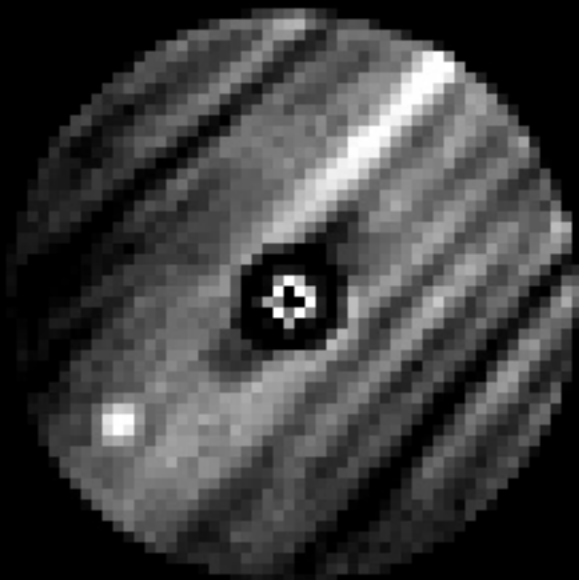
Filter imaging and R= 70 integral field spectroscopy from 0.45-1.0µm.

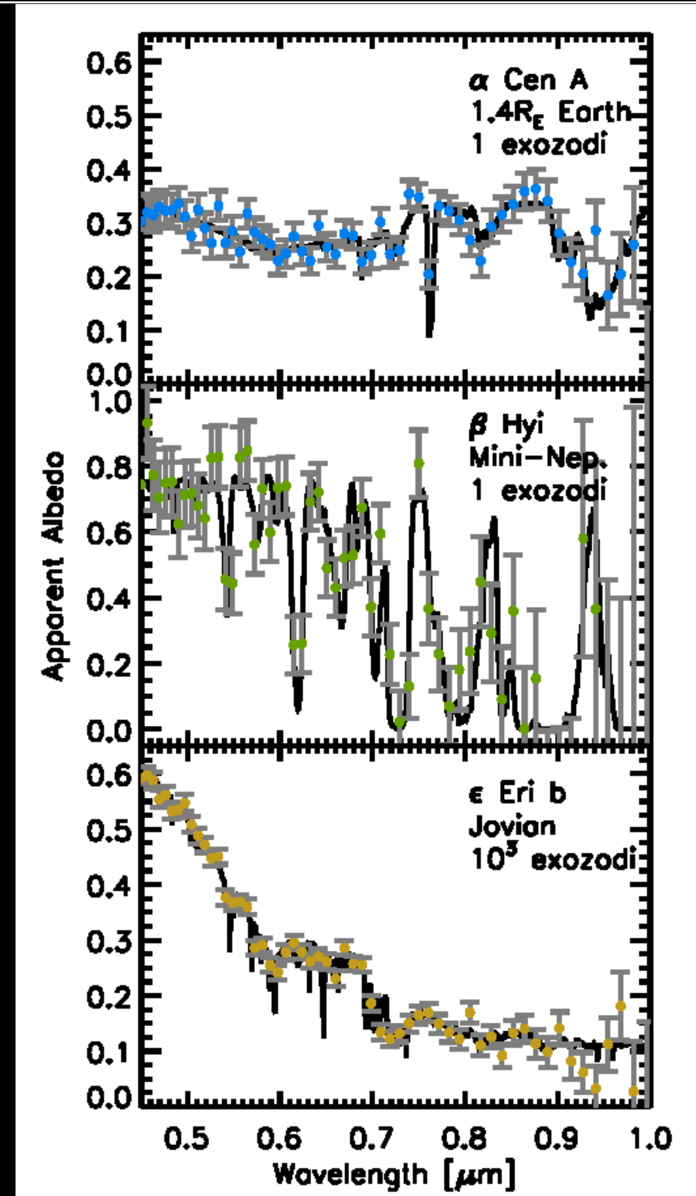
Multi-epoch surveys of hundreds of science targets

Possible spectra of Earth-like planets in the HZ.

Direct Imaging and Alpha Cen A

Simulated *5-day* V band Exo-C exposure of an Earth analog in the habitable zone of α Cen A (α Cen B is 8” away)





A disk-averaged spectrum of the planet can be obtained in ~28 days.

Ty Robinson

Science Questions: Jovians to Neptunes

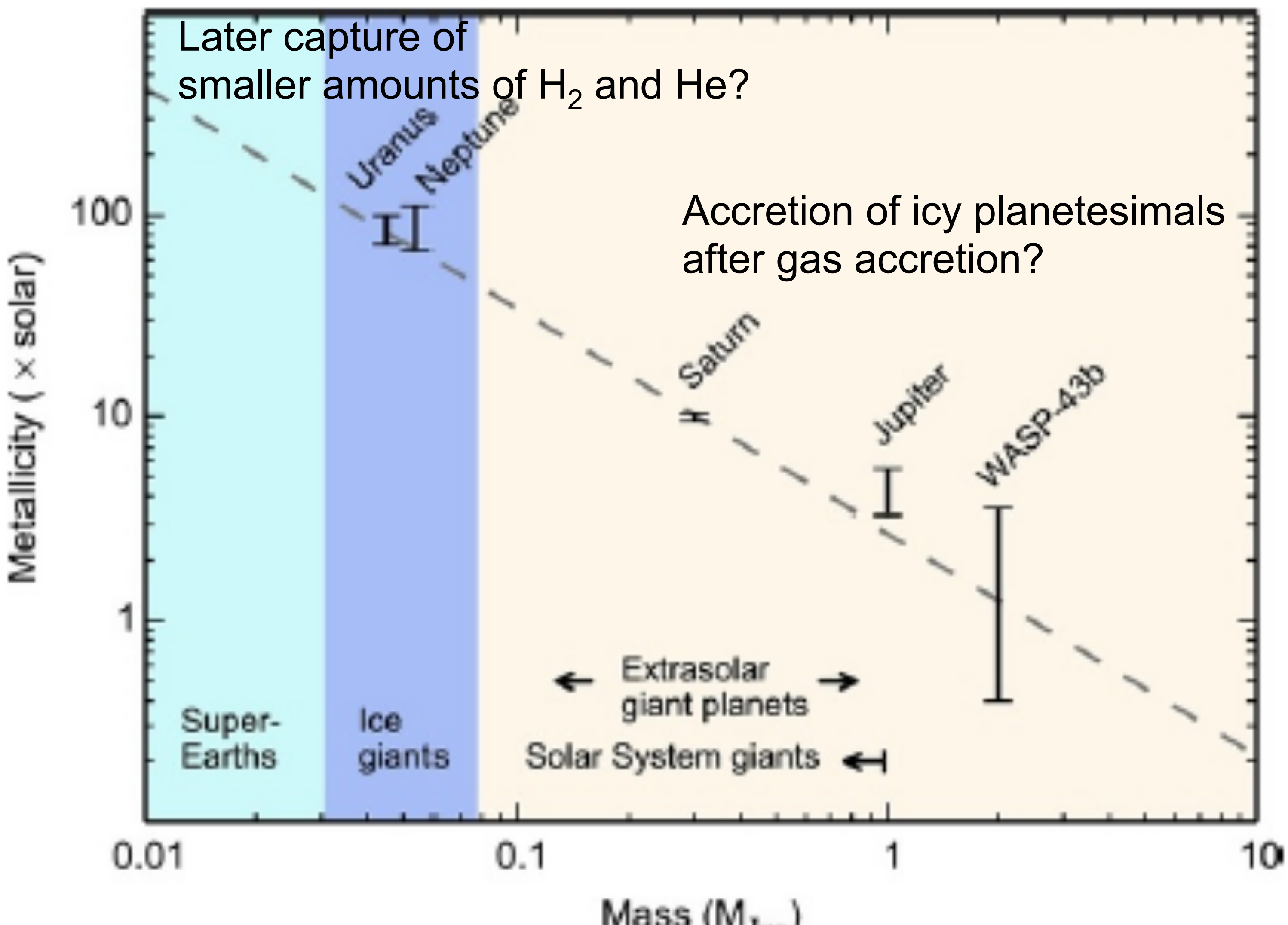
- How does the composition of gas and ice giant planets vary with planet mass, orbit and stellar mass and metallicity? What does this tell us about their formation and evolution?

- How do clouds affect giant planet atmospheres and vary with temperature and other planetary parameters?

- Direct Imaging will allow us to obtain images and spectra of *Jovians like our own* – older, cooler and further from the star.
  - Measure atmospheric constituents, CH_4, H_2O, NH_3, possibly H_2 and Na and K.
  - Measure the presence of clouds and cloud height by observing the relative depths of molecular absorption bands of differen strengths
  - Cloud thickness and height can give planetary temperature.
  - Search for Rayleigh and haze scattering.

Metallicity and mass: A correlation?

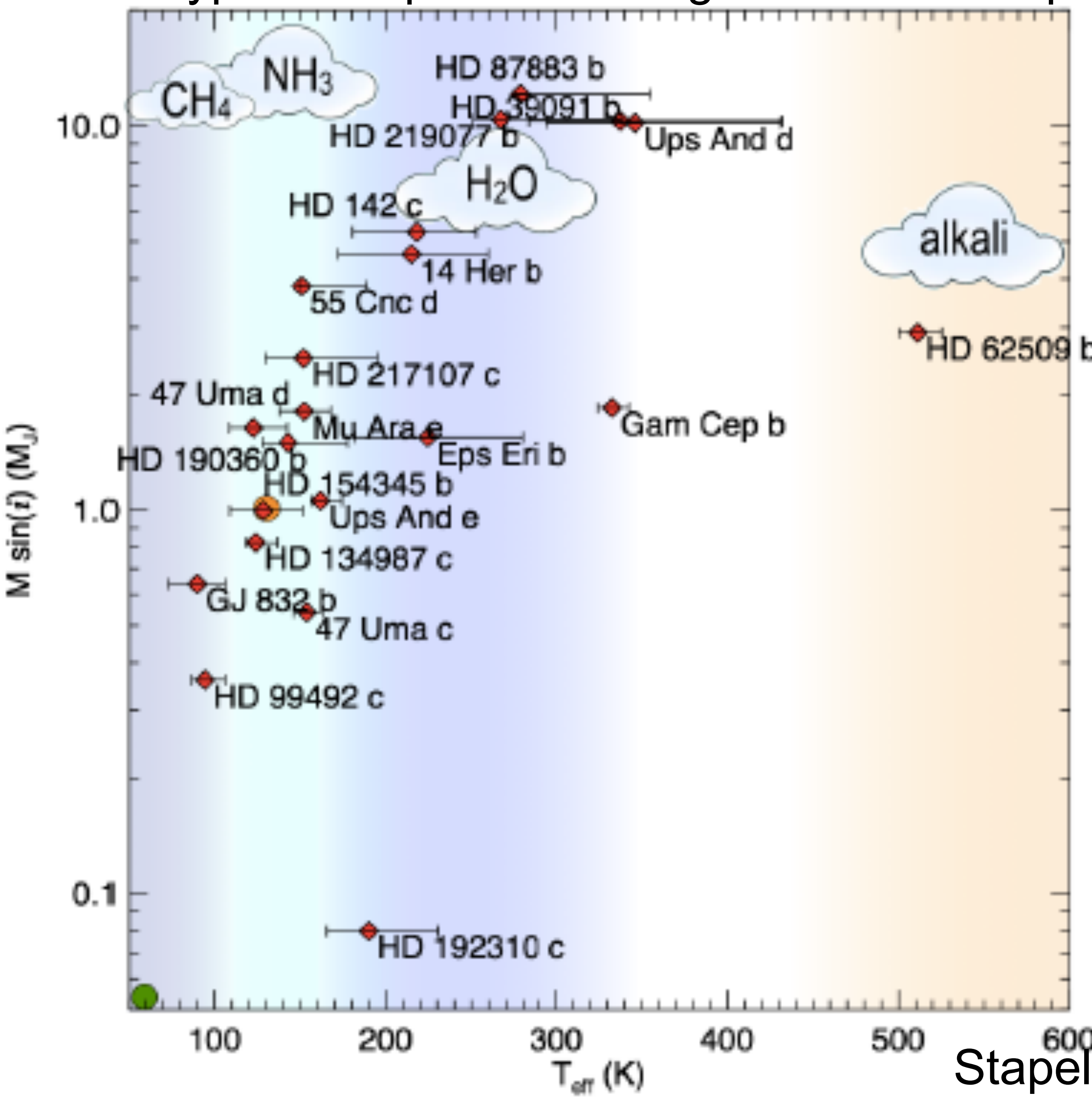
More data points would be hugely useful!



Stapelfeldt et al., 2015

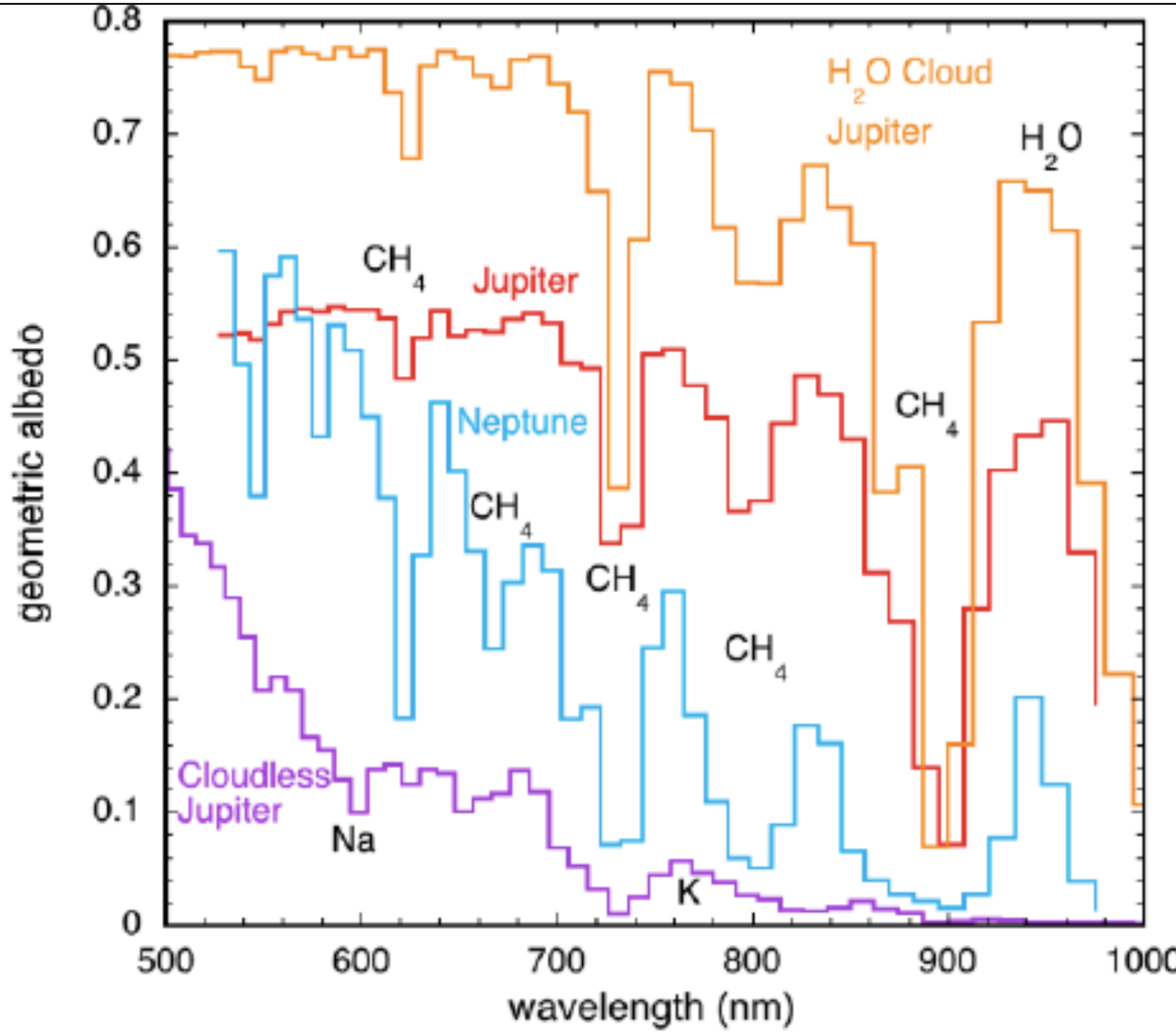
Temperature and Cloud Formation

A diversity of cloud types is expected among the known RV planets



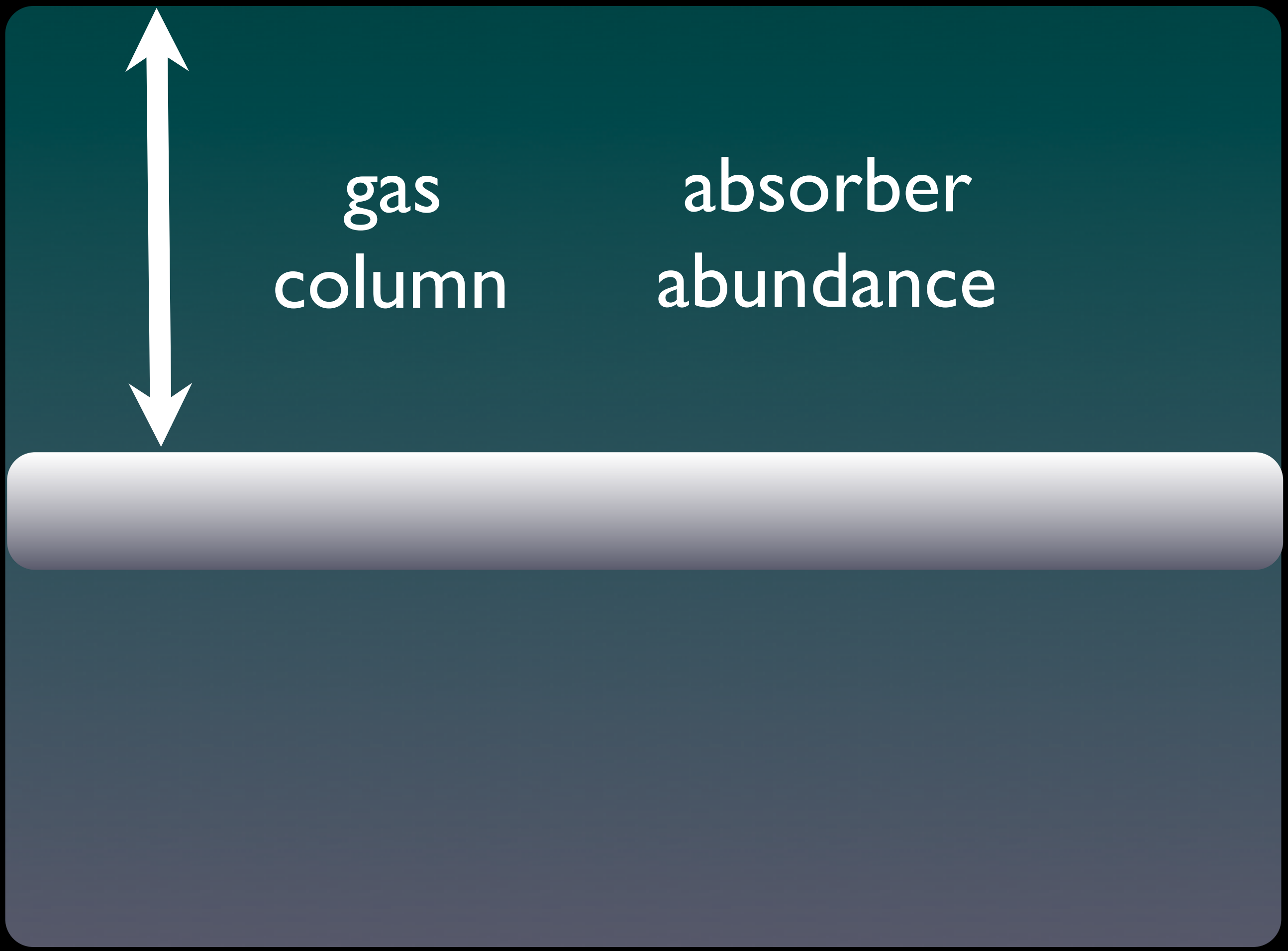
Stapelfeldt et al., 2015

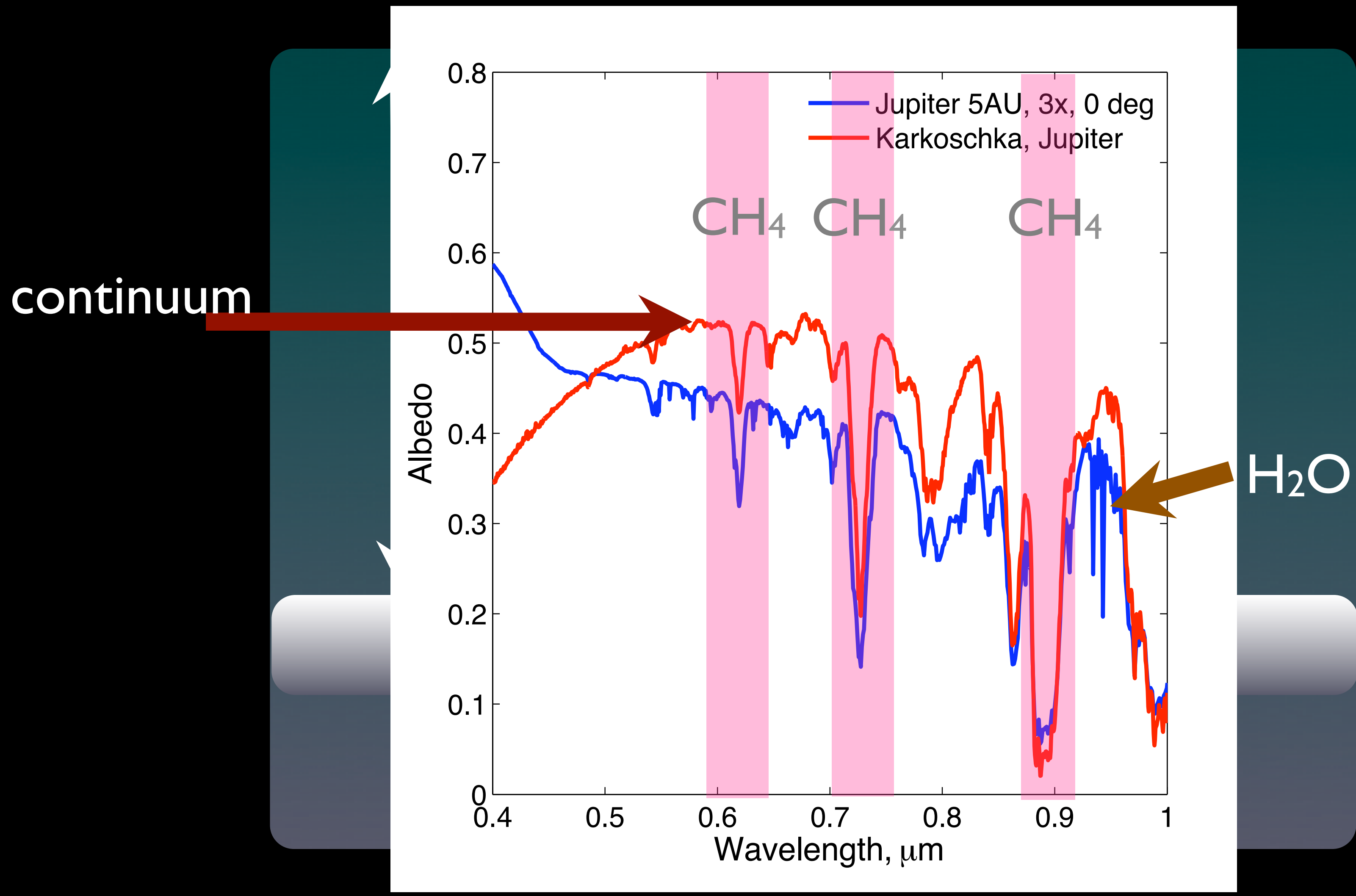
Gas and Ice Giant Spectroscopy



Clouds create a diversity of spectra.

Spectra reveal composition (metallicity), temperature and and cloud characteristics

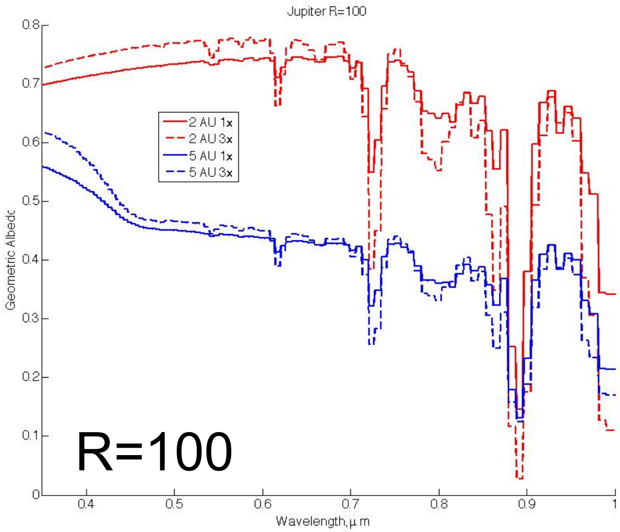

gas
column
absorber
abundance

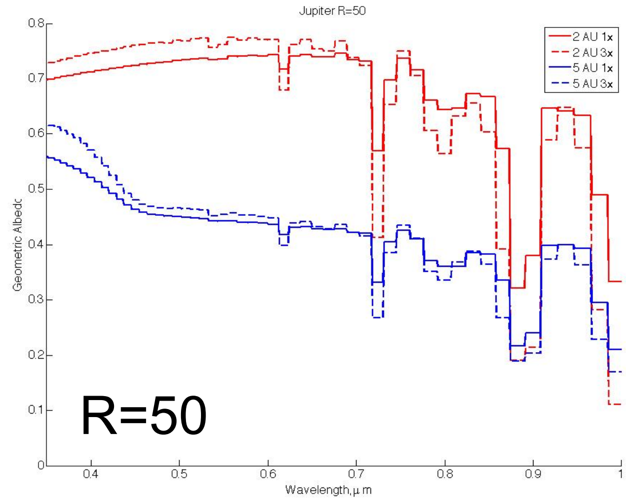


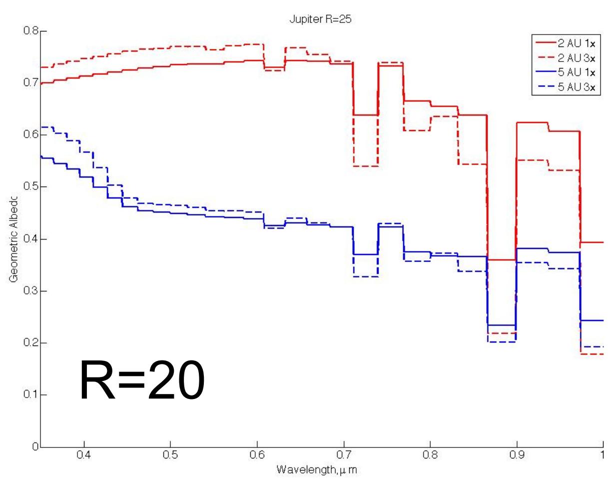
continuum
H2O
CH4
CH4
CH4
Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
Albedo
Wavelength, μm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1

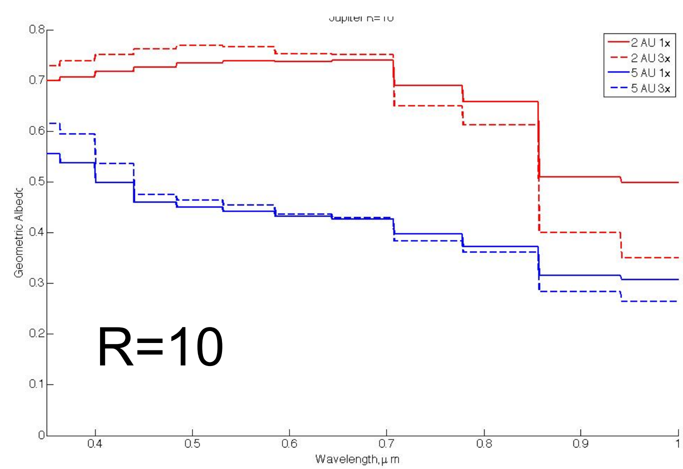
M. Marley

Spectral Resolution - Jupiter

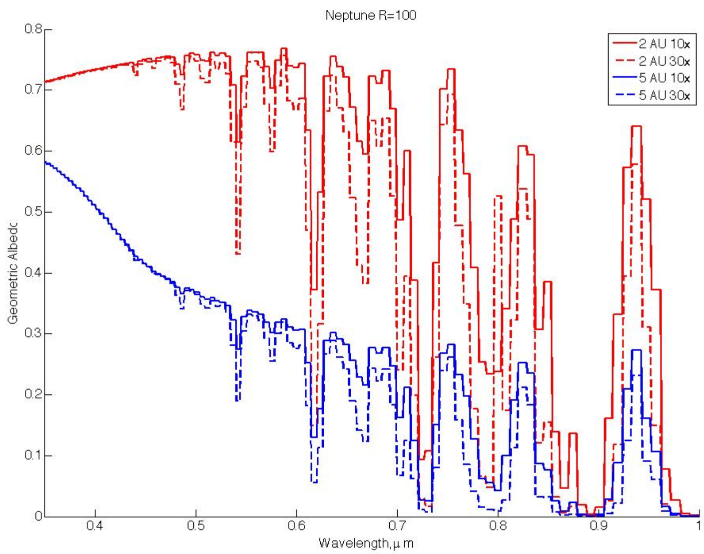


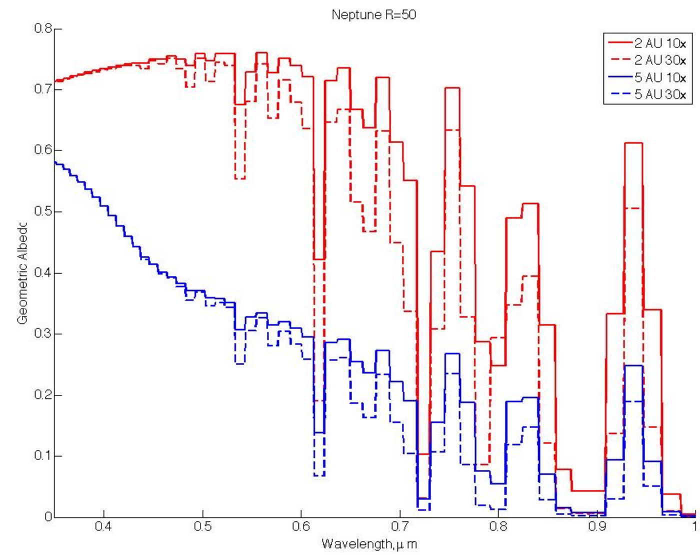


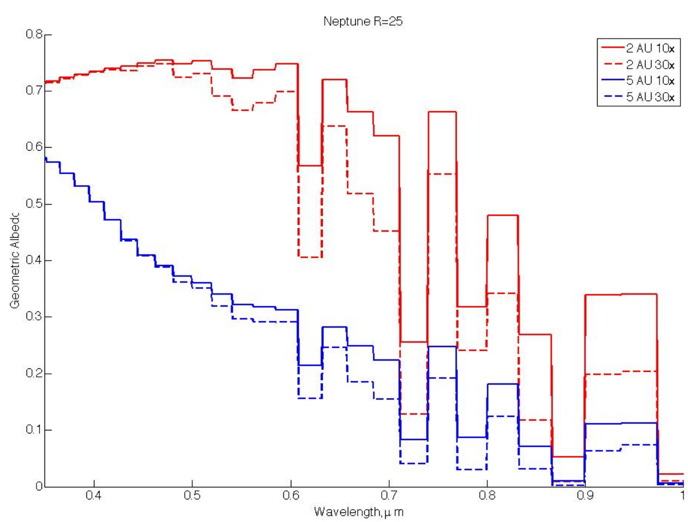


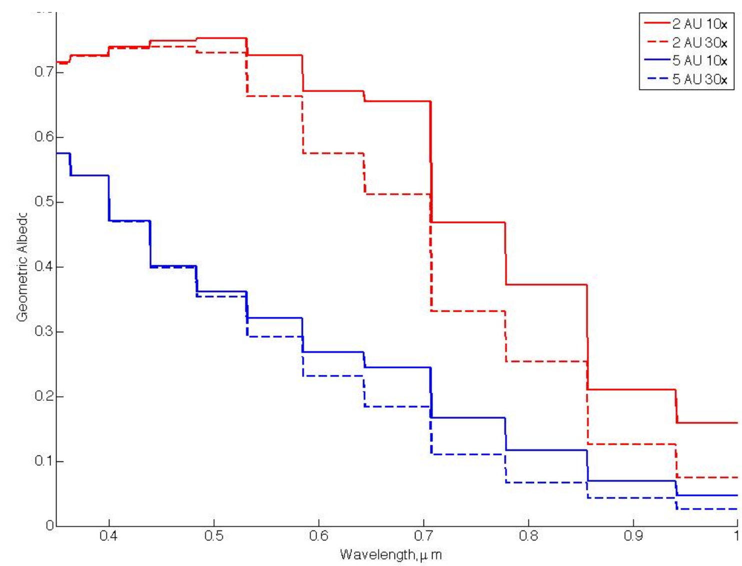


Spectral Resolution - Neptune









Sometimes, the spectral resolution is driven by the *continuum*…

Science Questions: Sub-Neptunes to Terrestrial

- What are the compositions of sub-Neptune planets and what does this tell us about their origin and evolution?

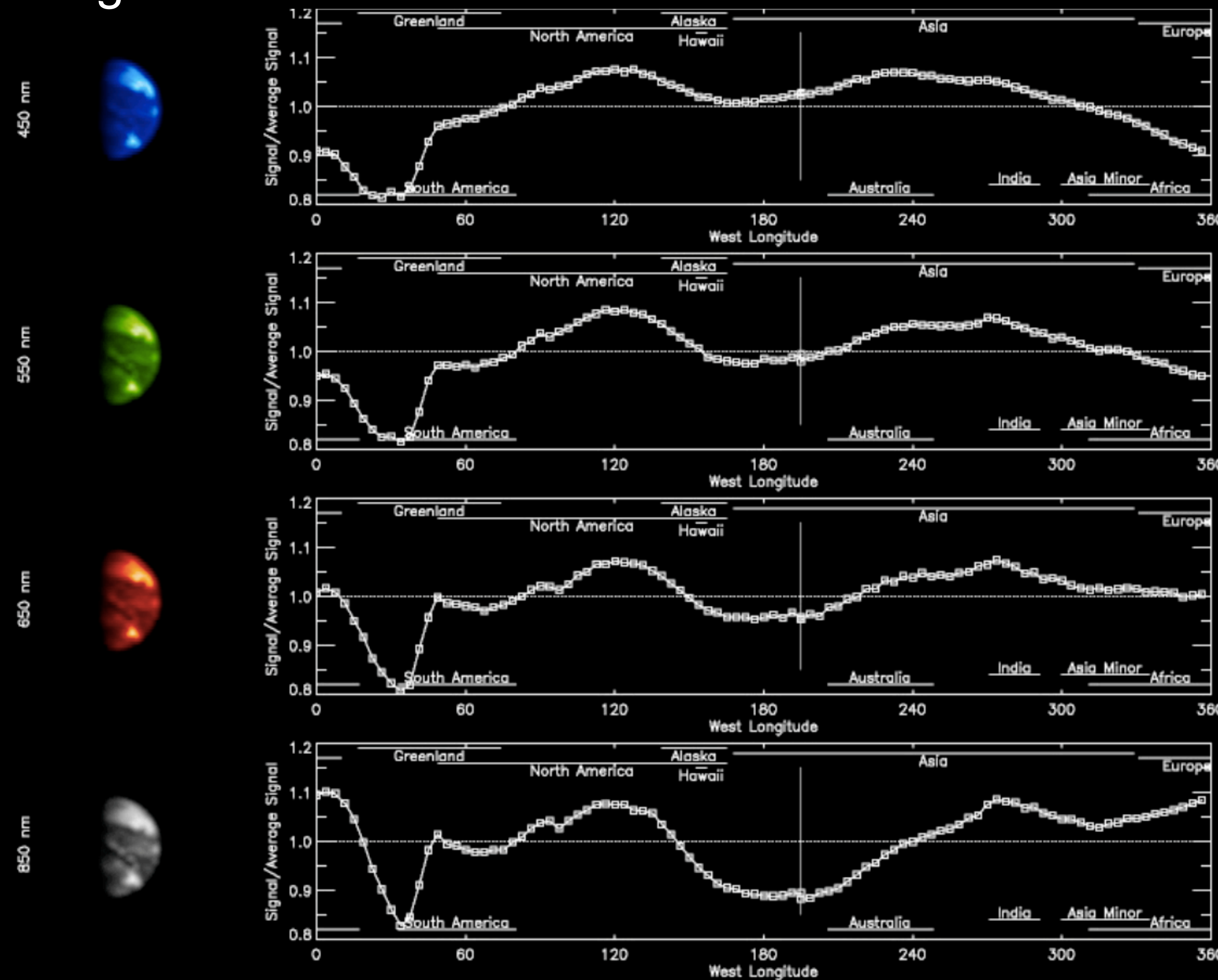
- What is the diversity of terrestrial planets? Are any of these planets able to support life or do they show signs of life?

- Direct Imaging will allow us to obtain images and spectra of *terrestrials like our own* – orbiting G-K dwarf stars.

- Search for surface inhomogeneity (time-resolved multi-wavelength photometry)
- Search for an ocean (phase dependent photometry and spectra).
- Measure atmospheric constituents, CH_4, H_2O, NH_3, CO_2, O_2, CO, N_2 (spectra).
- Measure the presence of clouds and aerosols (spectra and phase dependence),
- Temperature and Pressure determination (MIR spectra, NIR spectra)

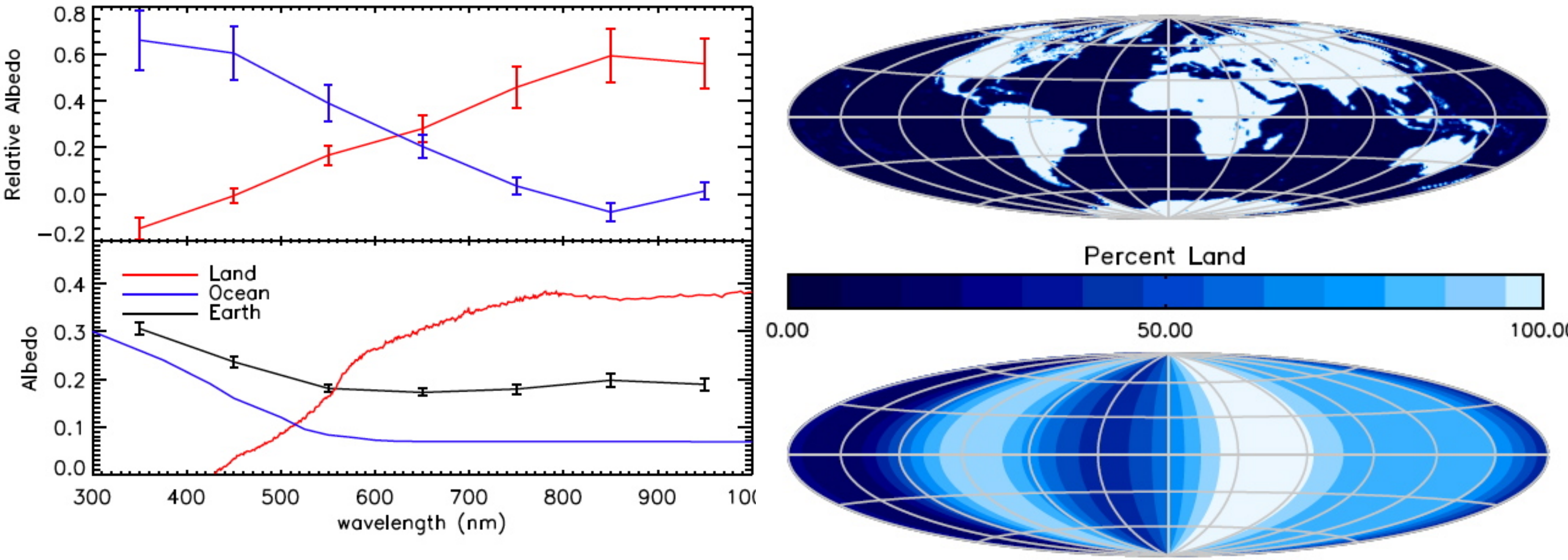
Time-Resolved Multi-Wavelength Photometry

EPOXI lightcurves of Earth



Livengood et al., 2011

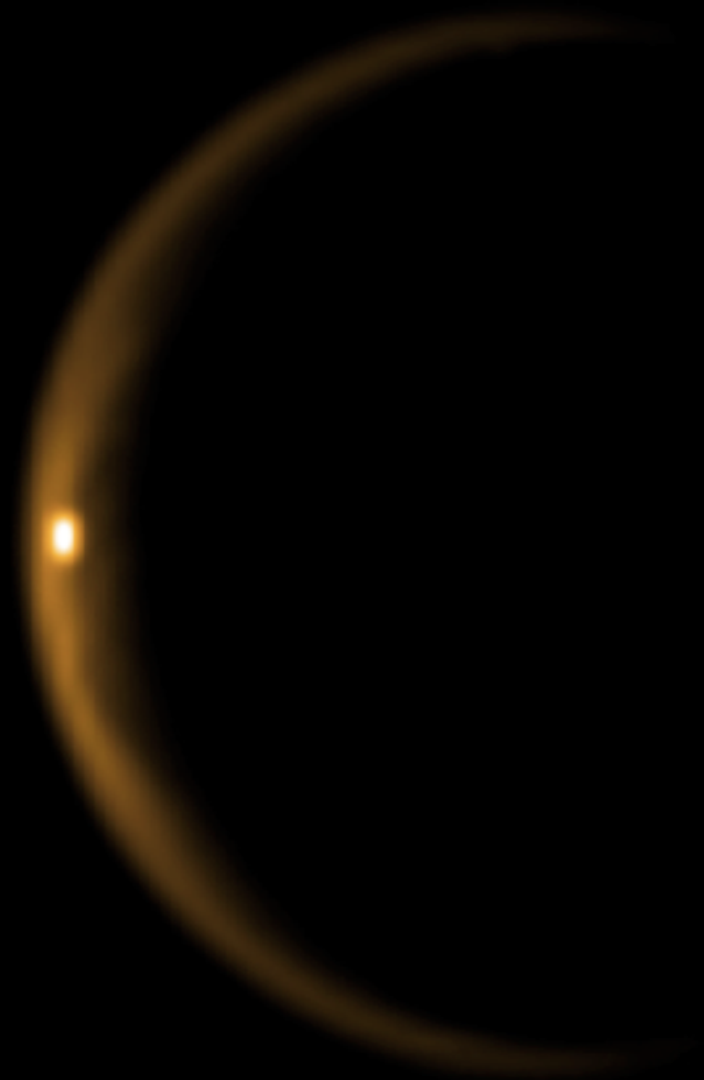
The Pale Blue Dot does not have to stay that way…



Cowan, Agol, Meadows, Robinson et al., 2010

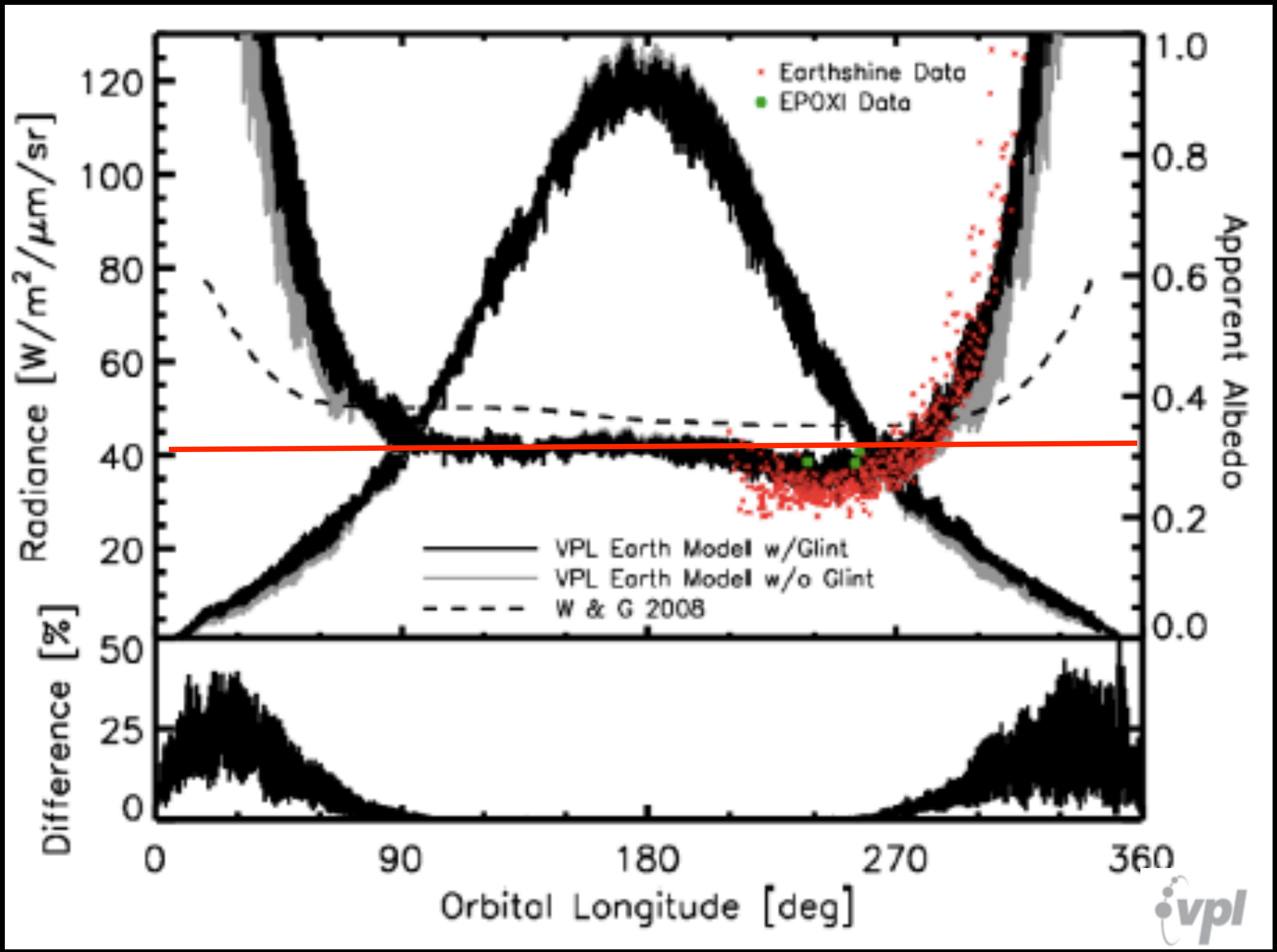
Multi-wavelength, time dependent photometry can be used to map the planet! Take that, lack of spatial resolution.

Detecting Surface Liquid



Stephan et al., 2010

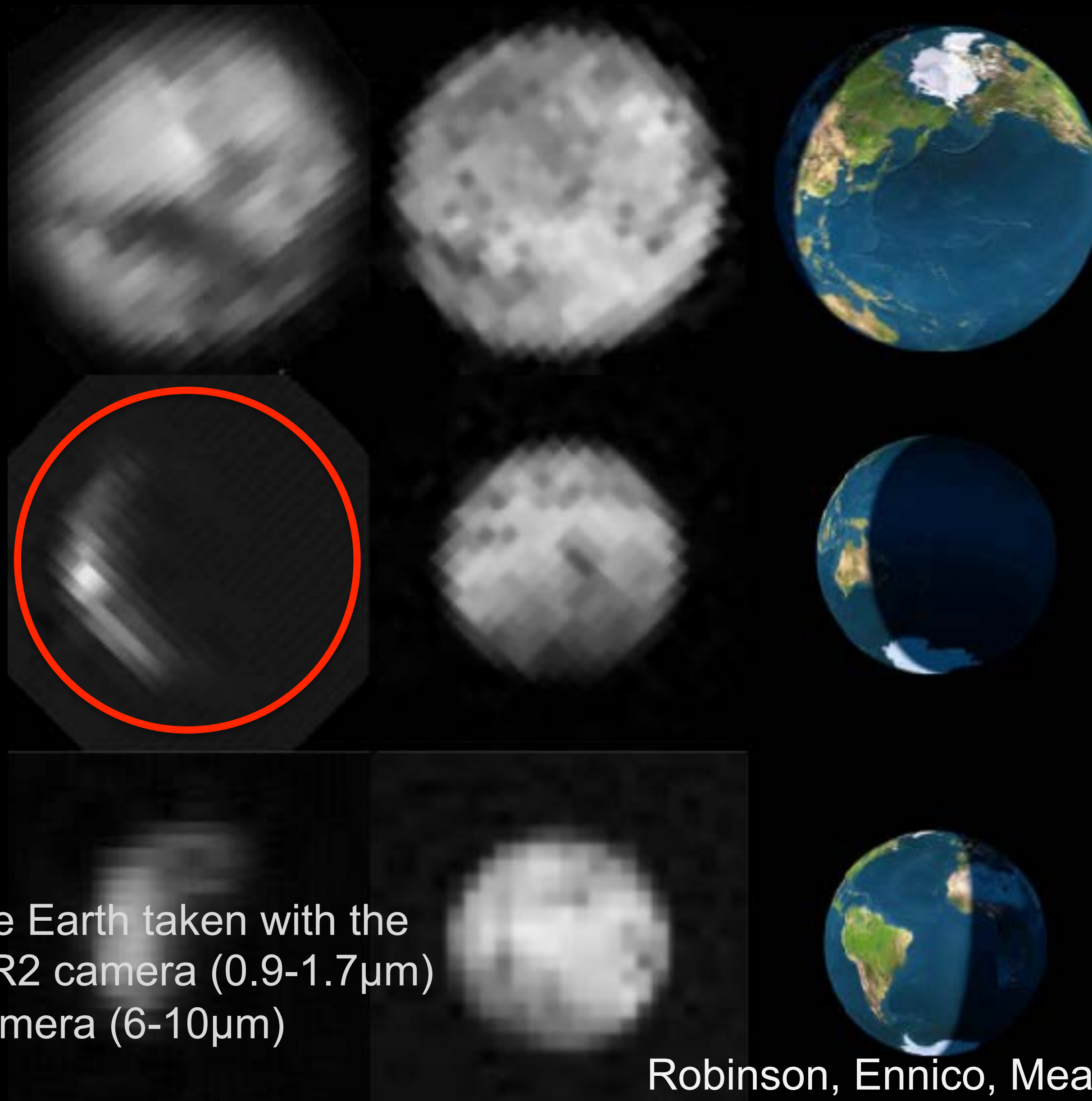
Glint Predictions From The VPL Earth Model



http://vpl.astro.washington.edu/spectra/planetary/earth_orbit.htm

Robinson, Meadows, & Crisp (2010)

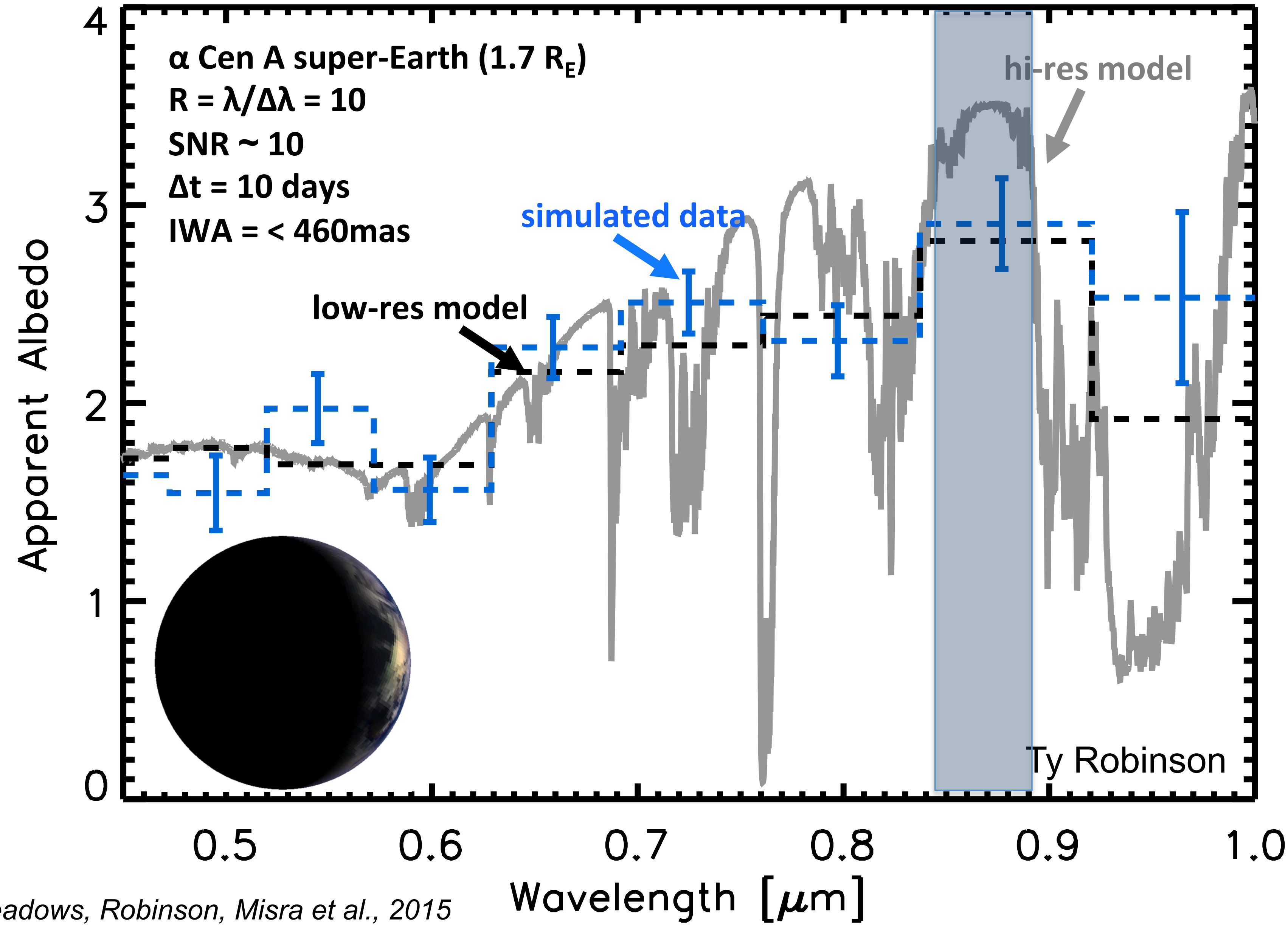
LCROSS Observations of Earth Glint



Images of the Earth taken with the LCROSS NIR2 camera (0.9-1.7μm) and MIR1 camera (6-10μm)

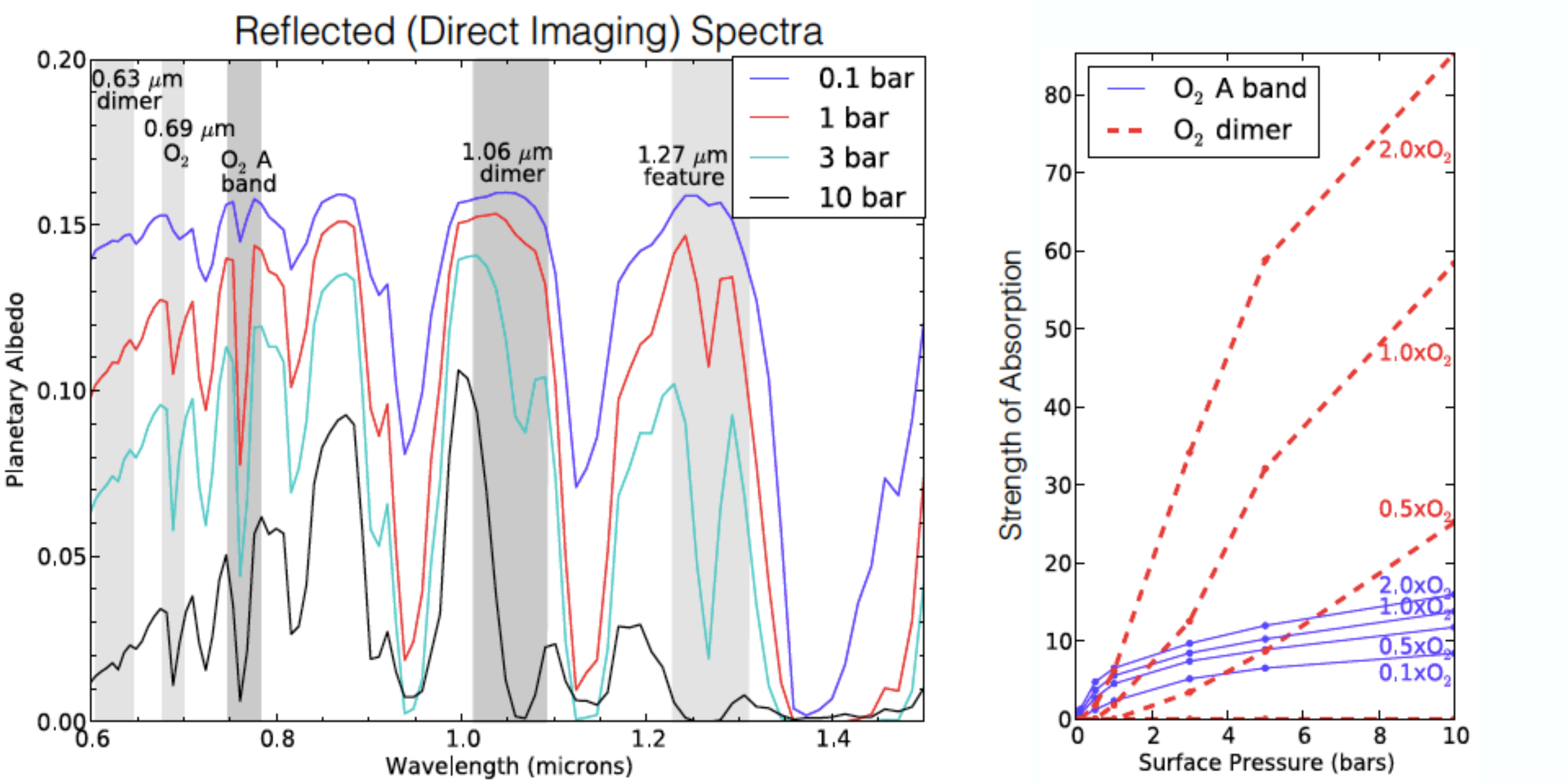
Robinson, Ennico, Meadows et al., 2014

Detecting Glint for Earth orbiting α-Cen A



Meadows, Robinson, Misra et al., 2015

Dimer Molecules as Pressure Indicators

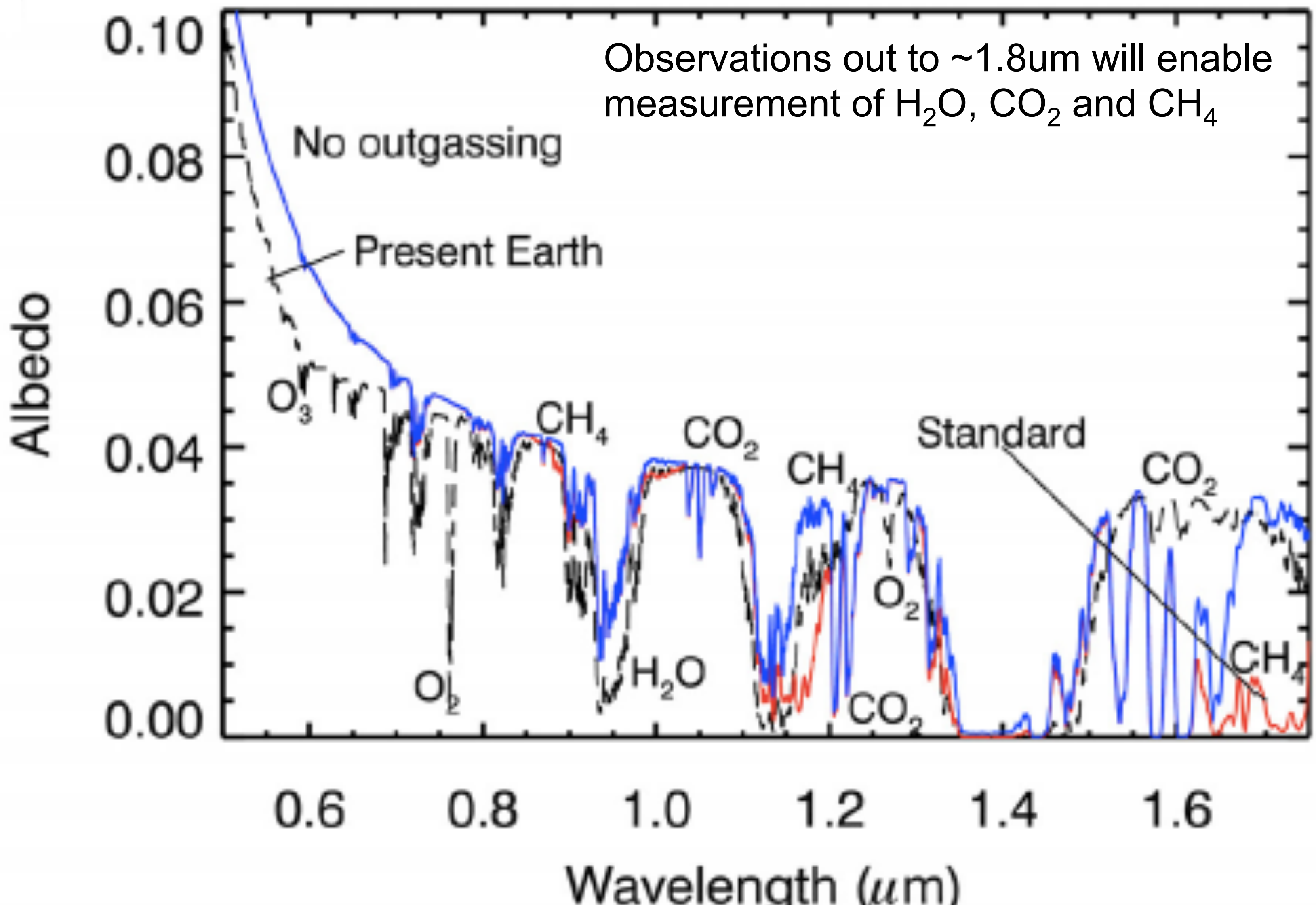


Misra, Meadows, Claire, Crisp (2014).

Absorption from collisional pairs increases more strongly with atmospheric pressure than absorption from the monomer

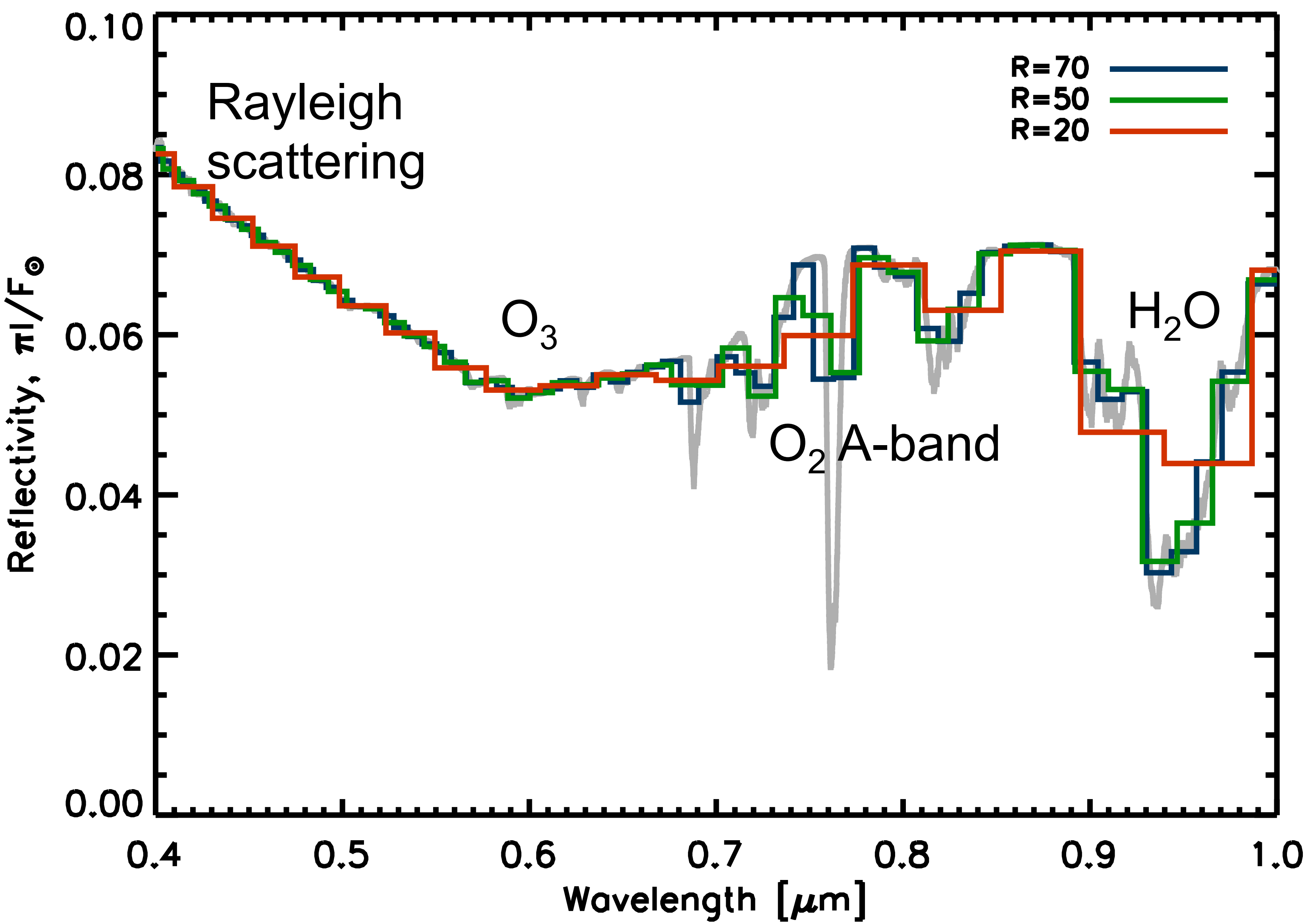
A census of greenhouse gases is important

There are no missions planned that can obtain direct thermal T measurements



Segura, Meadows, Kasting, Crisp, Cohen, 2007

Spectral Resolution – Earth



Photosynthesis is Earth’s Dominant Metabolism

Oxygen is its calling card!

Cyanobacteria - oxygenic photosynthesizers - may have evolved < 2.7Gya.
Cyanobacteria are responsible for the large O_2 fraction in our atmosphere
Our abundant O_2 is the most detectable sign of life on this planet
It is also considered the most robust against false positives
O_2 is likely to be the first biosignature we try to detect.

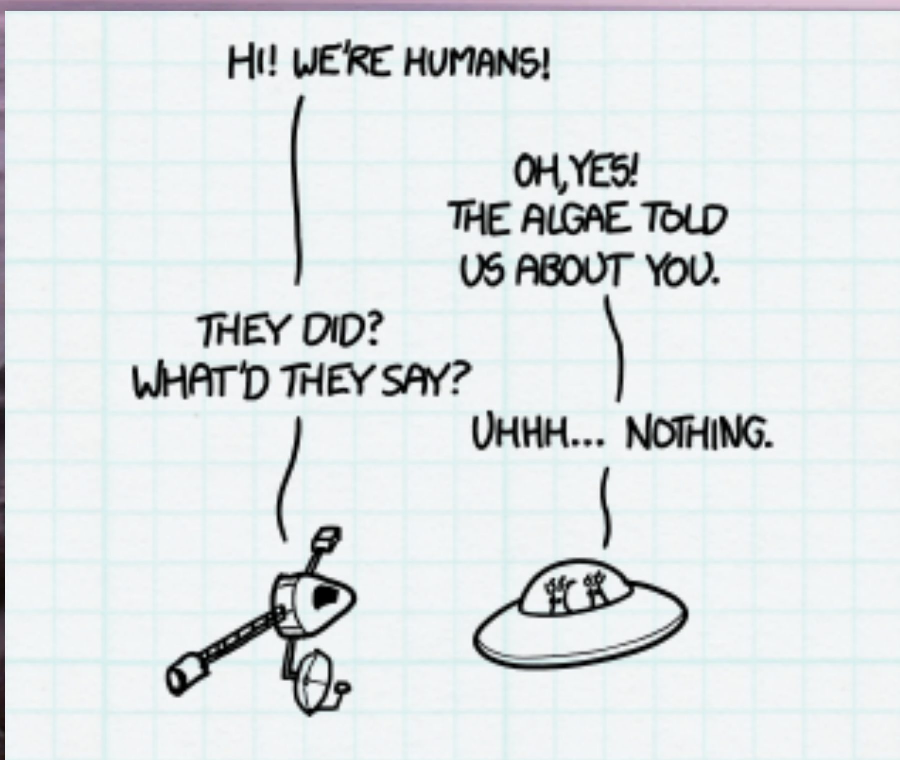
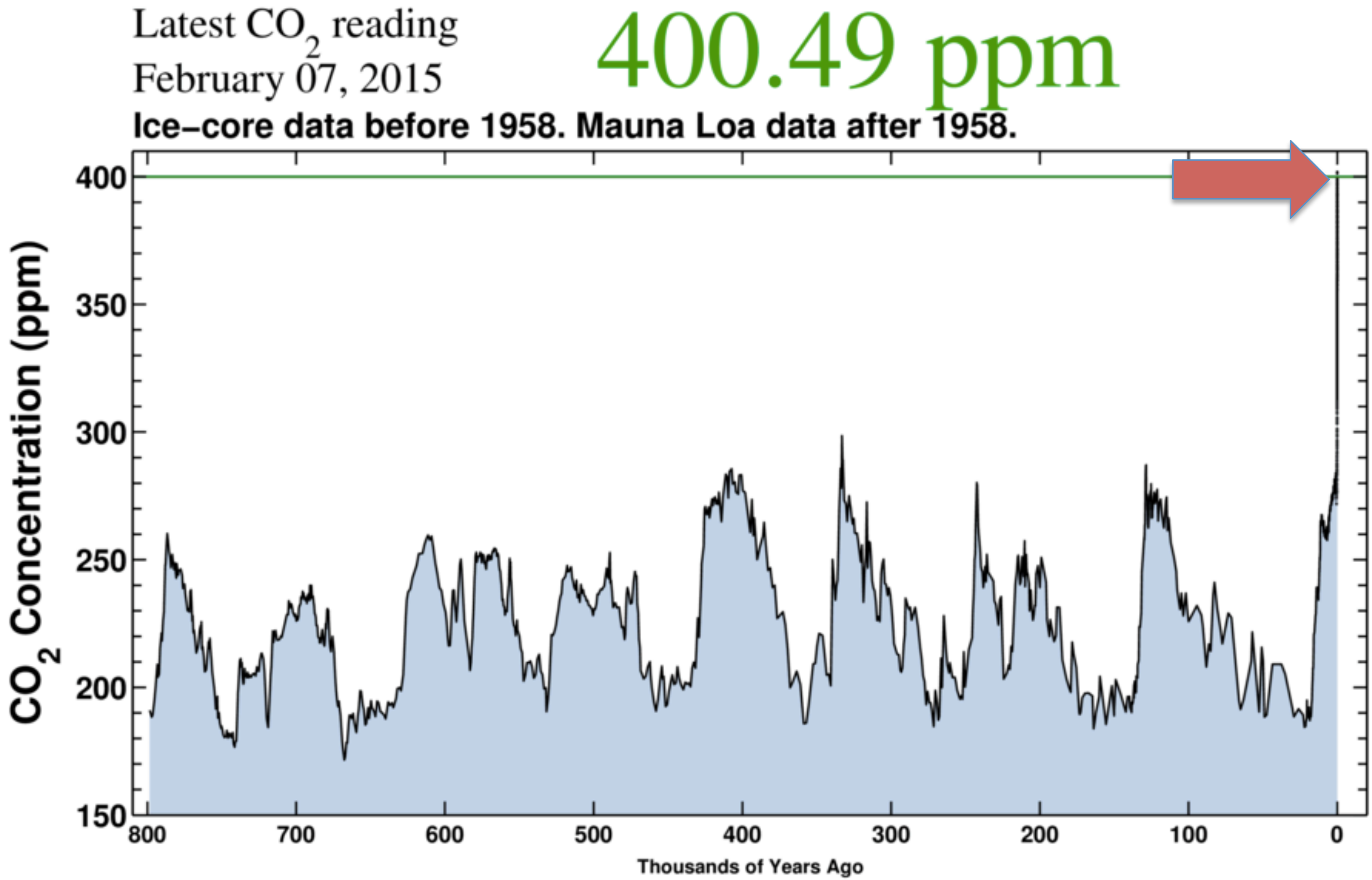
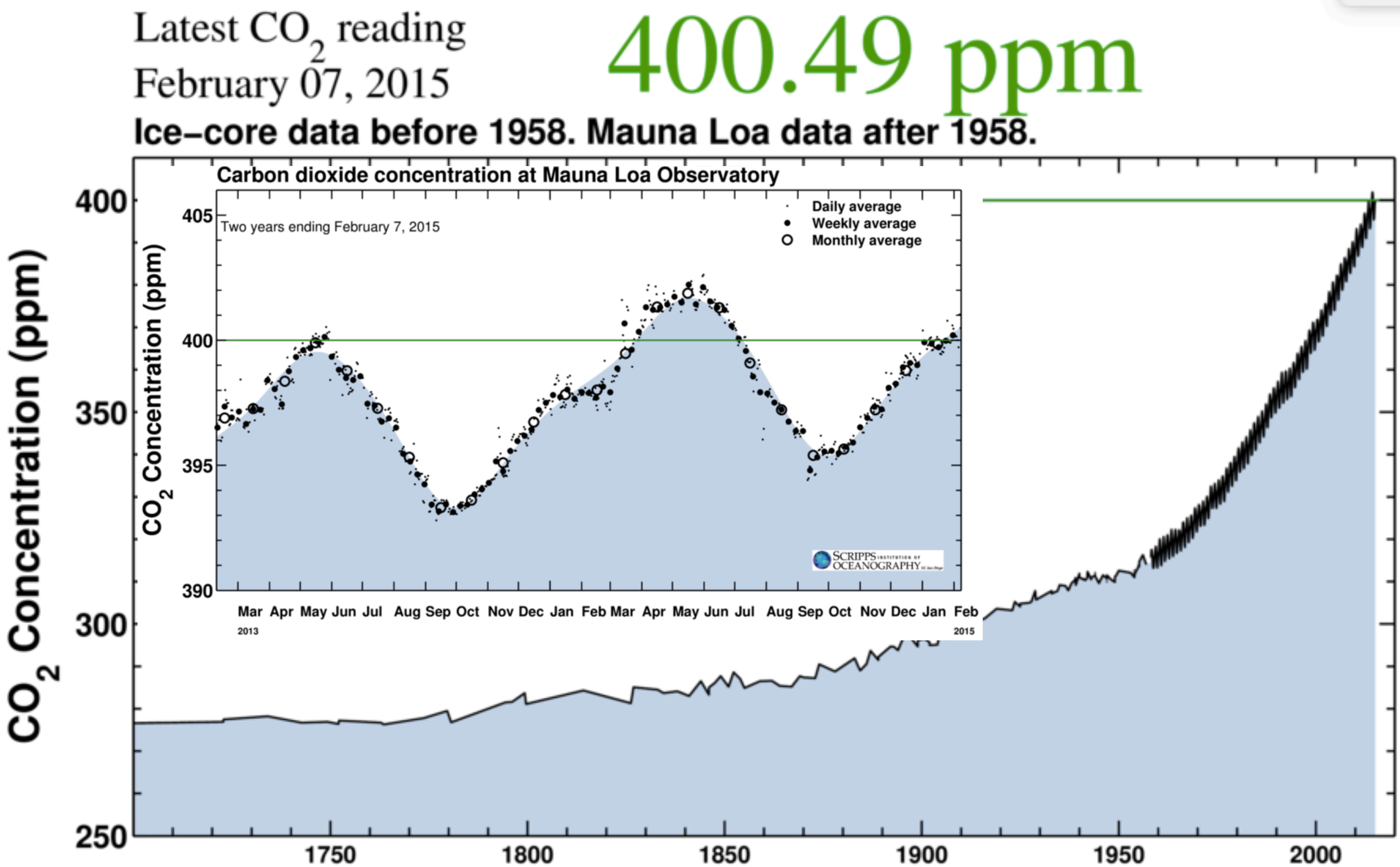


Photo: Frans Lanting

How to detect humans

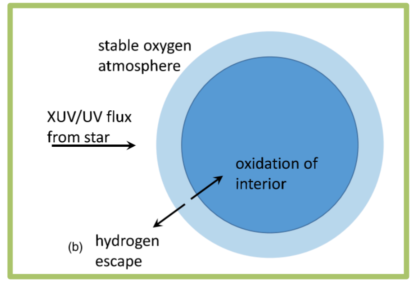


CO_2 as a Biosignature/Technosignature

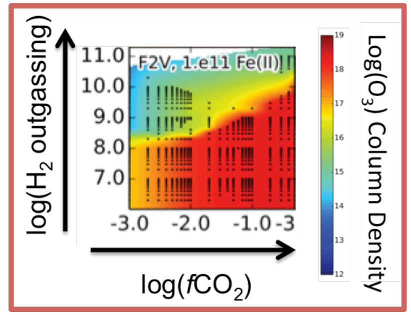


Abundant O_2 may not indicate a biosphere

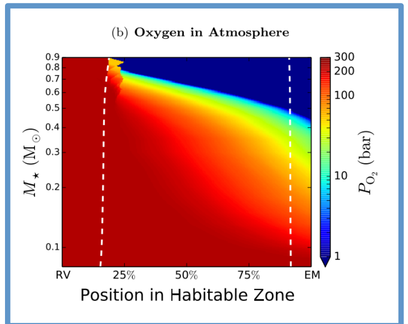
1. H Escape from Thin N-Depleted Atmospheres (Wordsworth & Pierrehumbert 2014)



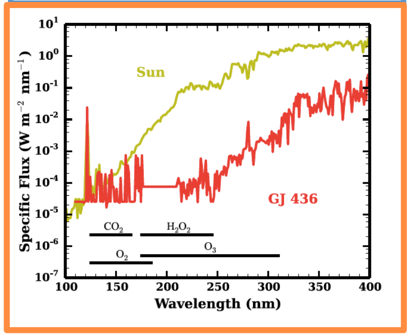
2. Photochemical Production of O_2/O_3 (Domagal-Goldman, Segura, Claire, Robinson, Meadows 2014)



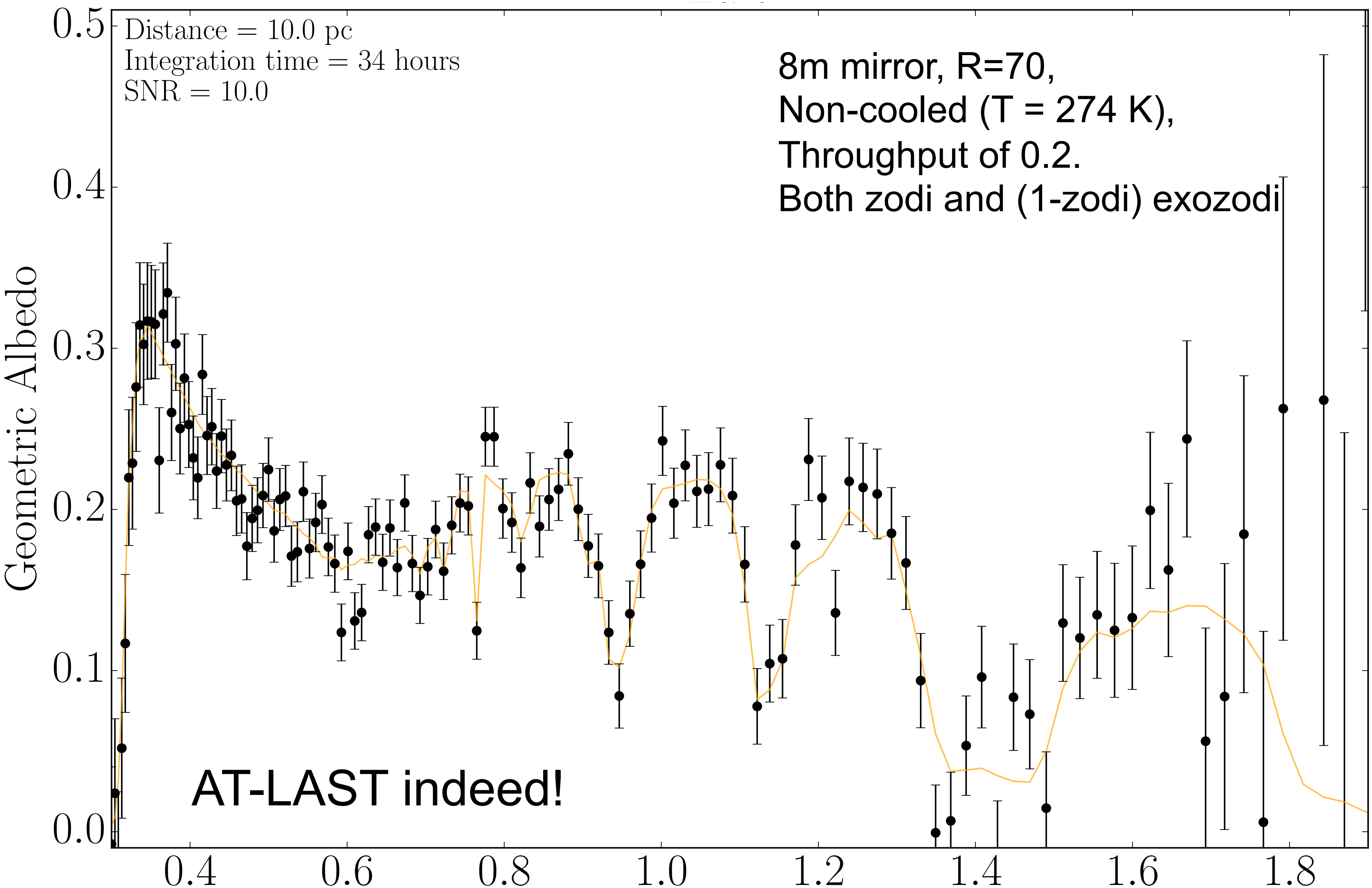
3. O_2-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2014)



4. CO_2 Photolysis in Dessicated Atmospheres (Gao, Hu, Robinson, Li, Yung, 2015)



And one day….



J. Lustig-Yaeger, G. Arney

(Really) General Summary

- Direct Imaging is needed to characterize other planetary systems like our own.

- Direct imaging observations of Jovian through sub-Neptune objects will help us understand the nature and formation of these objects.

- Direct imaging observations of terrestrial planets will address the place of Earth in planetary and cosmic scheme of things (Are We Weird?) and potentially reveal the global impact of life on an exoplanet (Are We Alone?).

The Virtual Planetary Laboratory

With Thanks To…
Eric Agol (UW)
Rika Anderson (NAI-NPP/WHOI)
John Armstrong (Weber State)
Giada Arney (UW)
Rory Barnes (UW)
John Baross (UW)
Cecelia Bitz (UW)
Bob Blankenship (WUStL)
Linda Brown (NASA-JPL/Caltech)
Roger Buick (UW)
David Catling (UW)
Benjamin Charnay (NAI-NPP/UW)
Mark Claire (U. St. Andrews)
David Crisp (NASA-JPL/Caltech)
Pan Conrad (NASA-GSFC)
Russell Deitrick (UW)
L. Drake Deming (U. Maryland)
Feng Ding (U. Chicago)
Shawn Domagal-Goldman (NASA-GSFC)
Peter Driscoll (UW)
Peter Gao (Caltech)
Colin Goldblatt (U. Victoria)
Chester (Sonny) Harman (PSU)
Suzanne Hawley (UW)
Tori Hoehler (NASA-Ames)
Jim Kasting (PSU)
Nancy Kiang (NASA-GISS)
Ravi Kopparapu (PSU)
Monika Kress (SJSU)
Rodrigo Luger (UW)
Jacob Lustig-Yaeger (UW)
Victoria Meadows (UW)
Amit Misra (UW)
Niki Parenteau (NASA-Ames)
Ray Pierrehumbert (U. Chicago)
Tom Quinn (UW)
Sean Raymond (Lab. Astrophysique Bordeaux)
Tyler Robinson (NAI-NPP/NASA Ames)
Eddie Schwieterman (UW)
Antigona Segura (UNAM)
Janet Seifert (Rice U.)
Holly Sheets (U. Maryland)
Aomawa Shields (NSF/UCLA/Harvard)
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