Exoplanet Science Cases

Mark Marley

Update

(Focus on Requirements Drivers)

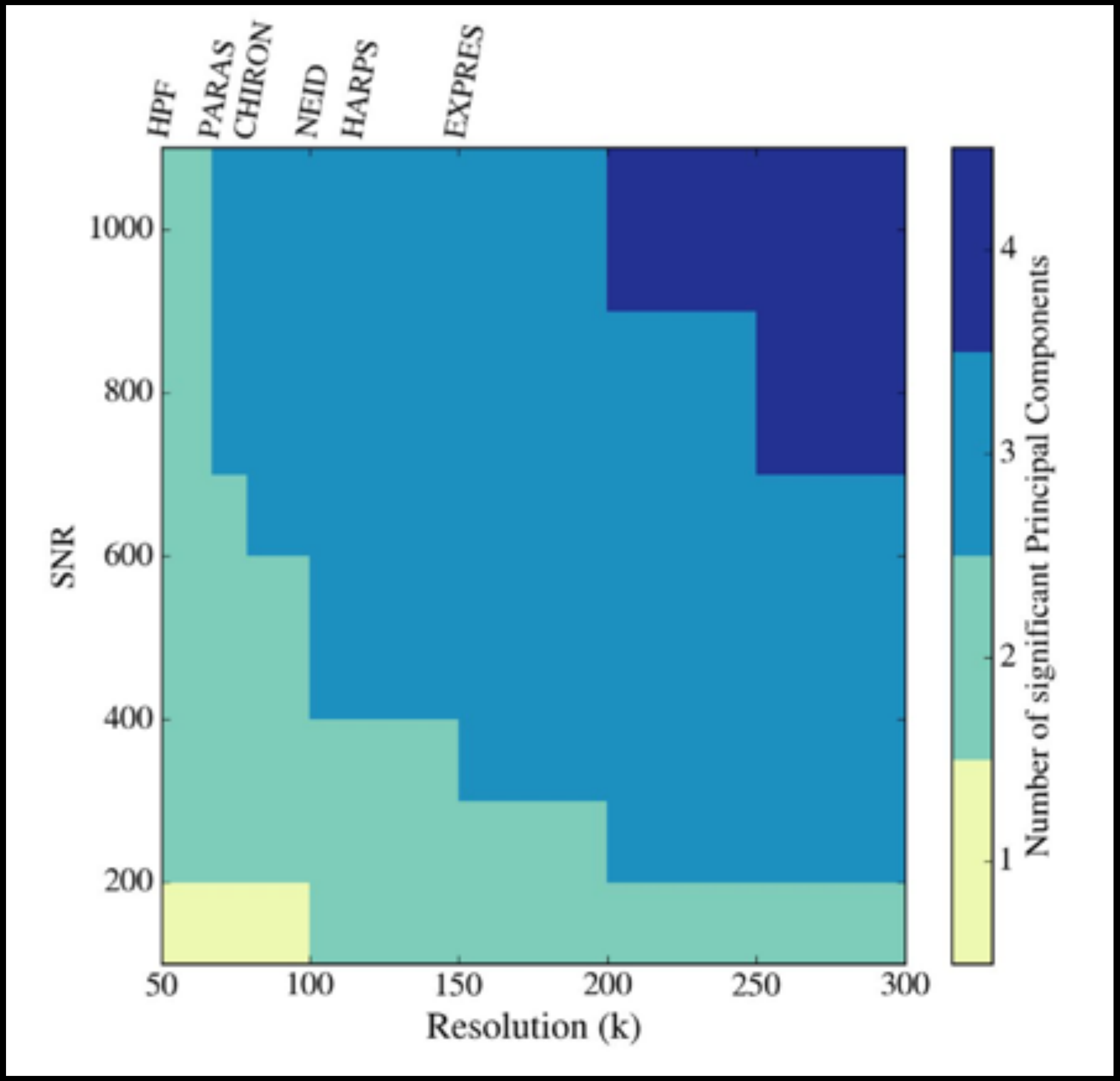
- Dozen solid contributions + SAG15 report
- Discovery
- Characterization
  - Transiting Planets
  - Direct Imaging
- Disk science

HZ Discovery

- Transiting HZ Earths - PLATO
- Find our own imaging targets
    - radial velocity (Fischer)
    - astrometry (Guyon)
    - blind imaging survey (Stark)

LUVOIR RV Survey (Fischer)

- Visible high resolution spectroscopy
- Need to resolve stellar velocity field
- Requires SNR > 700, R ~ 300K spectra
- What Δλ? Time requirement? RV reference?
- *M* sin *i* + imaging = *M*

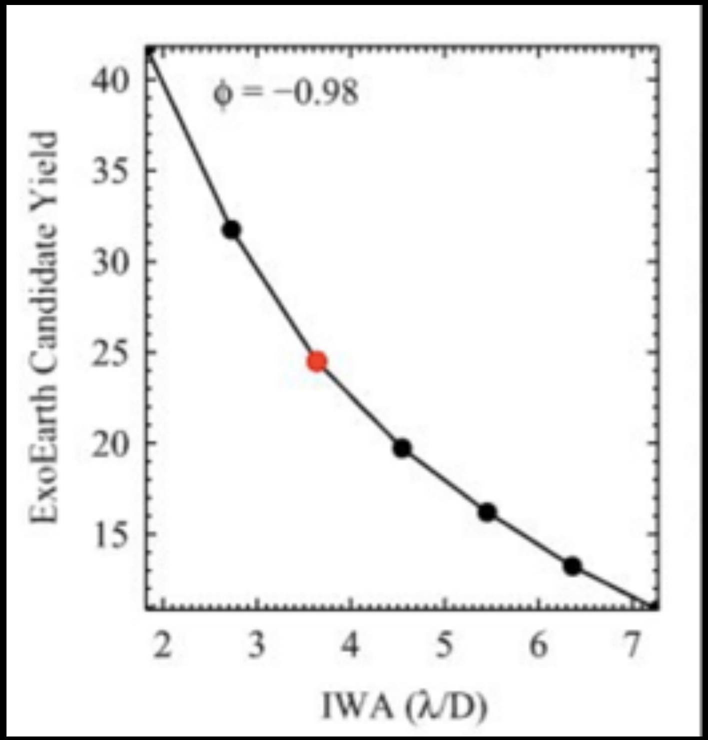


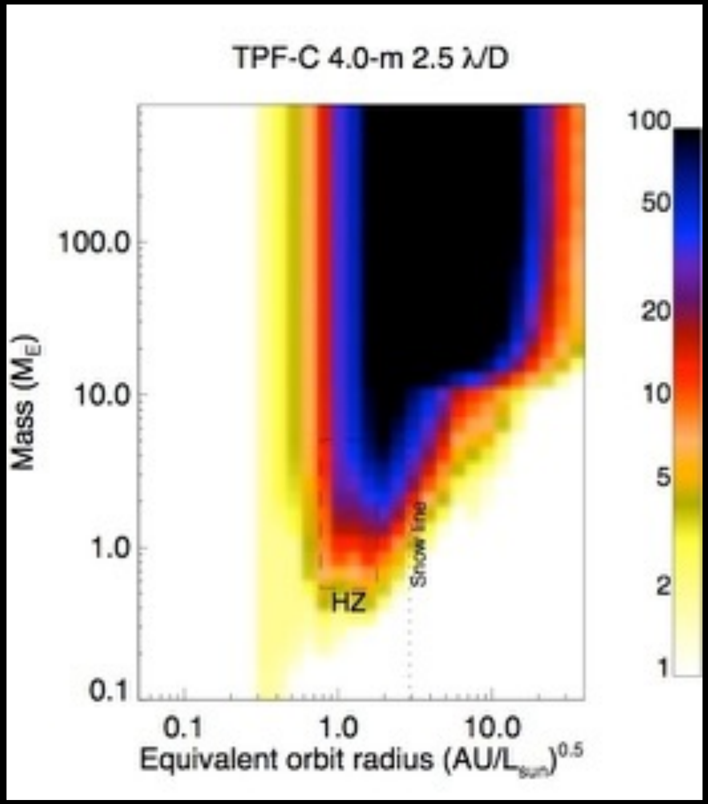
LUVOIR Astrometry (Guyon)

- 8 x 8 arcmin imaging, 10^{-6} pixel calibration floor, onboard metrology
- 20 nas in 1hr, search nearest 230 stars for a planet 0.1 $M_\oplus$ in the middle of HZ
- nearest 100~200 stars, an astrometric search can be conducted in 9 months (1 year orbital period)
- what is total observing time?
- lab effort to validate assumptions
- provides *M*

Blind Survey (Stark)

- Imaging survey
  - Detection coronagraph 10^{-10} raw contrast
  - 0.1 potentially habitable planets / star
  - 10 m telescope, 1 year time
  - Yields 25 potentially habitable planets
  - But no *M*
- Need self-consistent depth of search metrics for all surveys



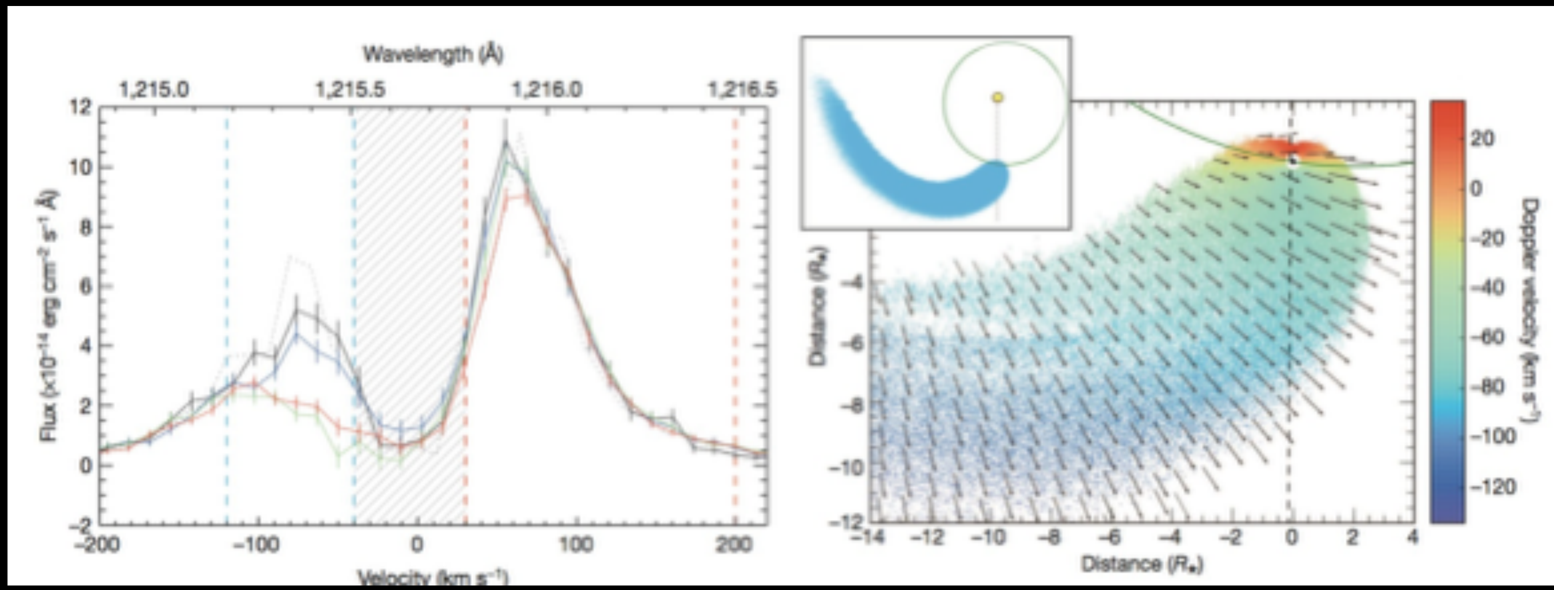


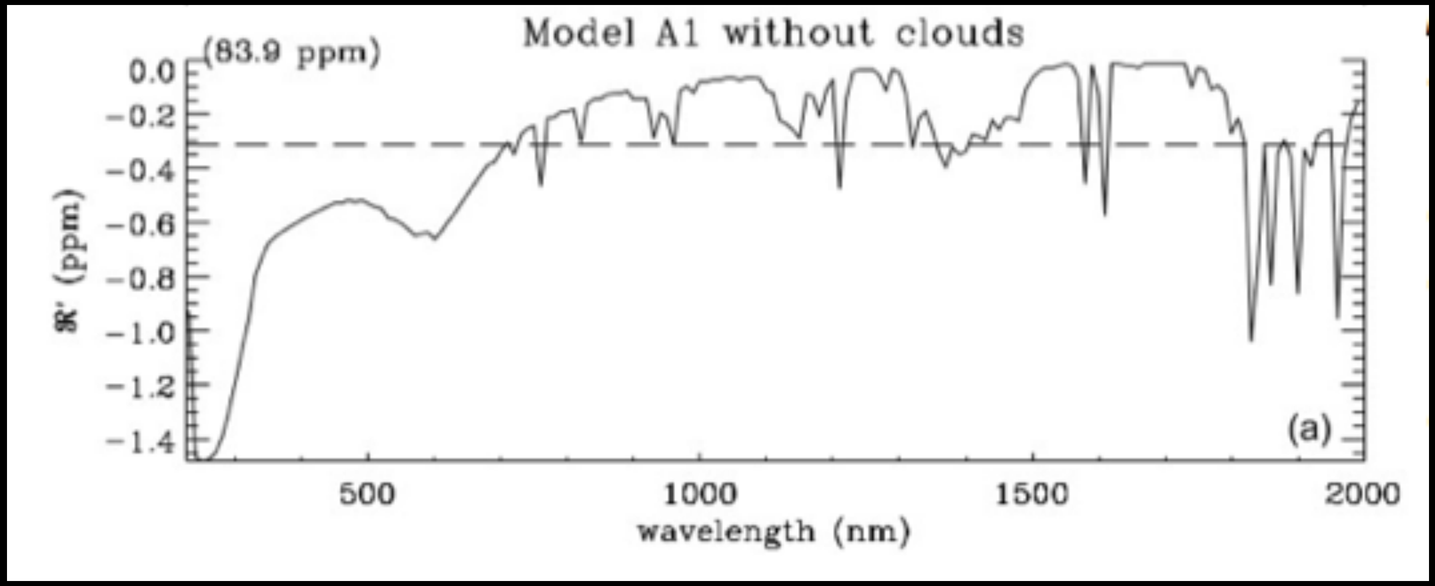
Characterization

- Transiting planets - beyond JWST (Fossati)
- Direct imaging
  - Habitable planets (Meadows+)
  - Others (SAG15, others)
  - Orbits

Transits (Fossati)

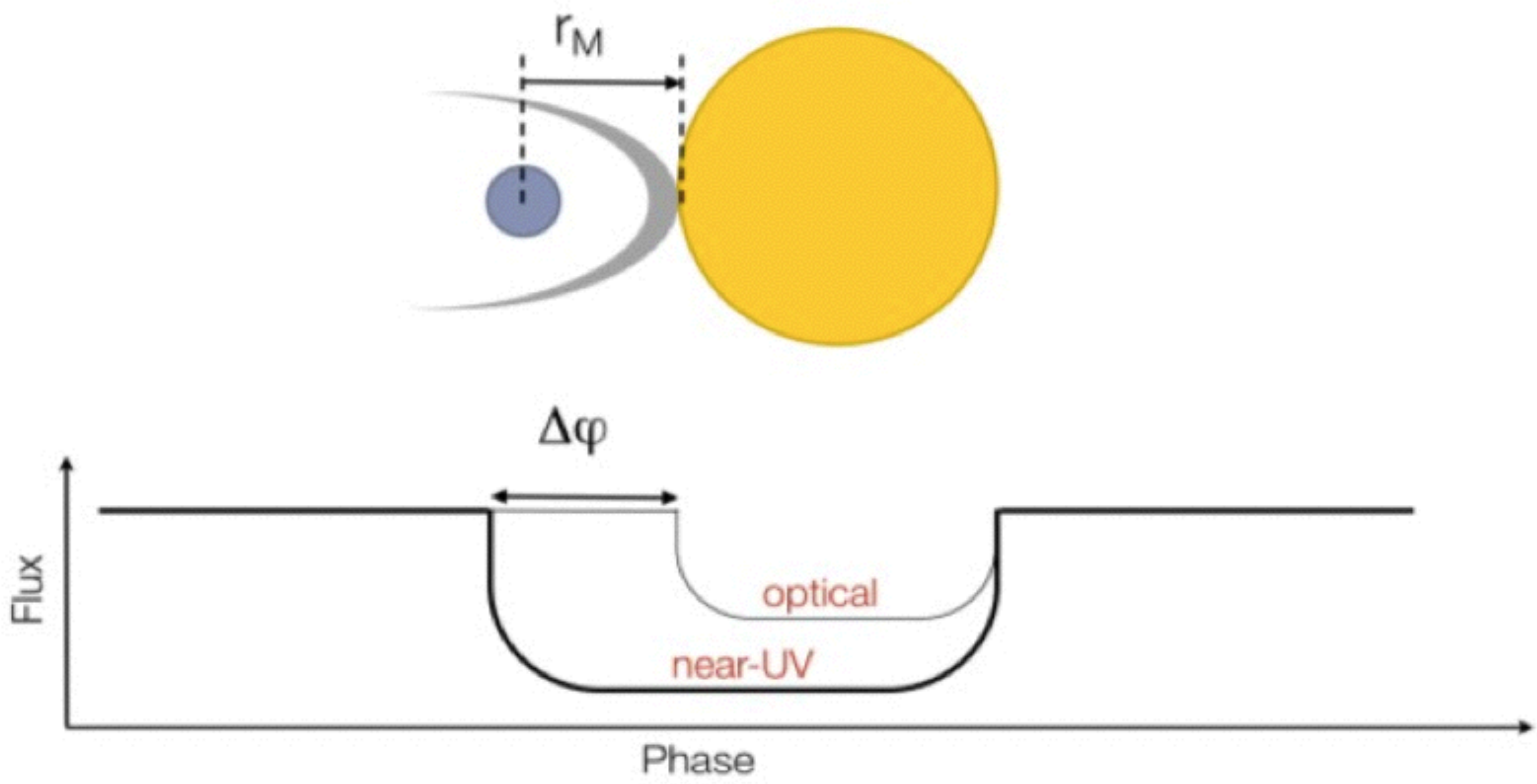
- Atmospheric escape from hot planets (UV spectra)
- Atmospheric characterization from transiting HZ Planets (optical, near-IR spectra) V < 7, 16-m mirror
    - binning
    - x-correlation





Escape

Observation Requirement	Major Progress	Substantial Progress	Incremental Progress
Wavelengths	100 – 1000 nm	100 – 1000 nm	100 – 1000 nm
Spatial resolution	0.1”	0.1”	0.1”
Spectral resolution	UV: 60,000 Optical: 100,000	UV: 30,000 Optical: 70,000	UV: 20,000 Optical: 50,000



Optical transits of best PLATO discoveries:

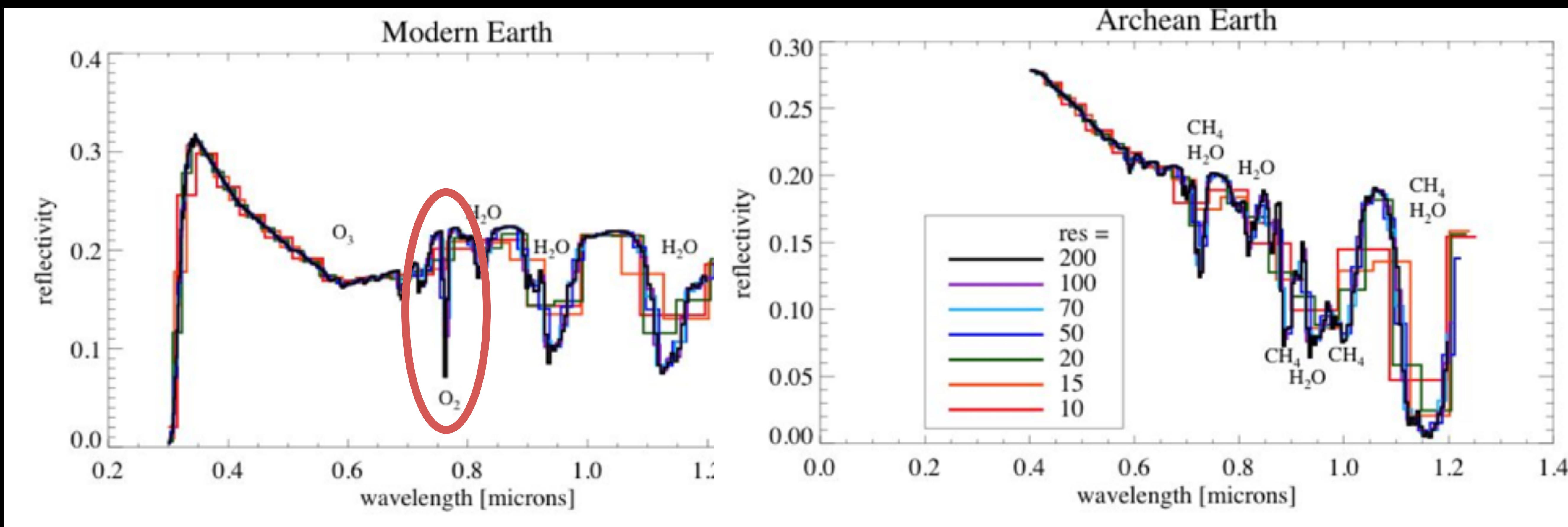
Observation Requirement	Major Progress	Substantial Progress	Incremental Progress
Wavelengths	200 – 1800 nm	200 – 1800 nm	200 – 1800 nm
Spatial resolution	0.1”	0.1”	0.1”
Spectral resolution	100,000	80,000	60,000
Field-of-view	N/A	N/A	N/A
Contrast	N/A	N/A	N/A
Telescope aperture	16m	8m	6m
Exposure time	14 – 30 h / target	14 – 30 h / target	14 – 30 h /target
Time resolution	N/A	N/A	N/A

Habitability

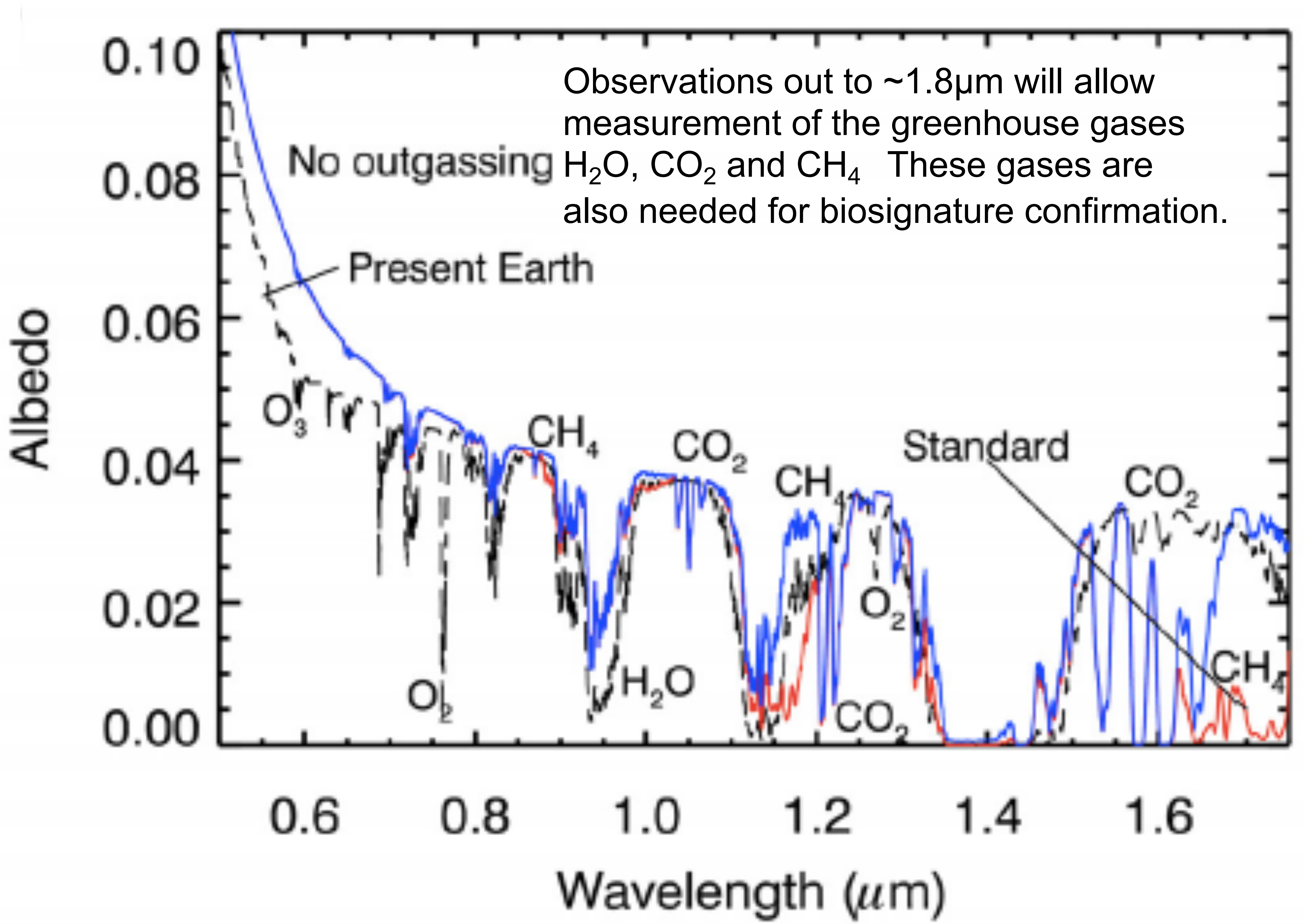
(Meadows+ VPL)

Coronagraph Spectroscopy

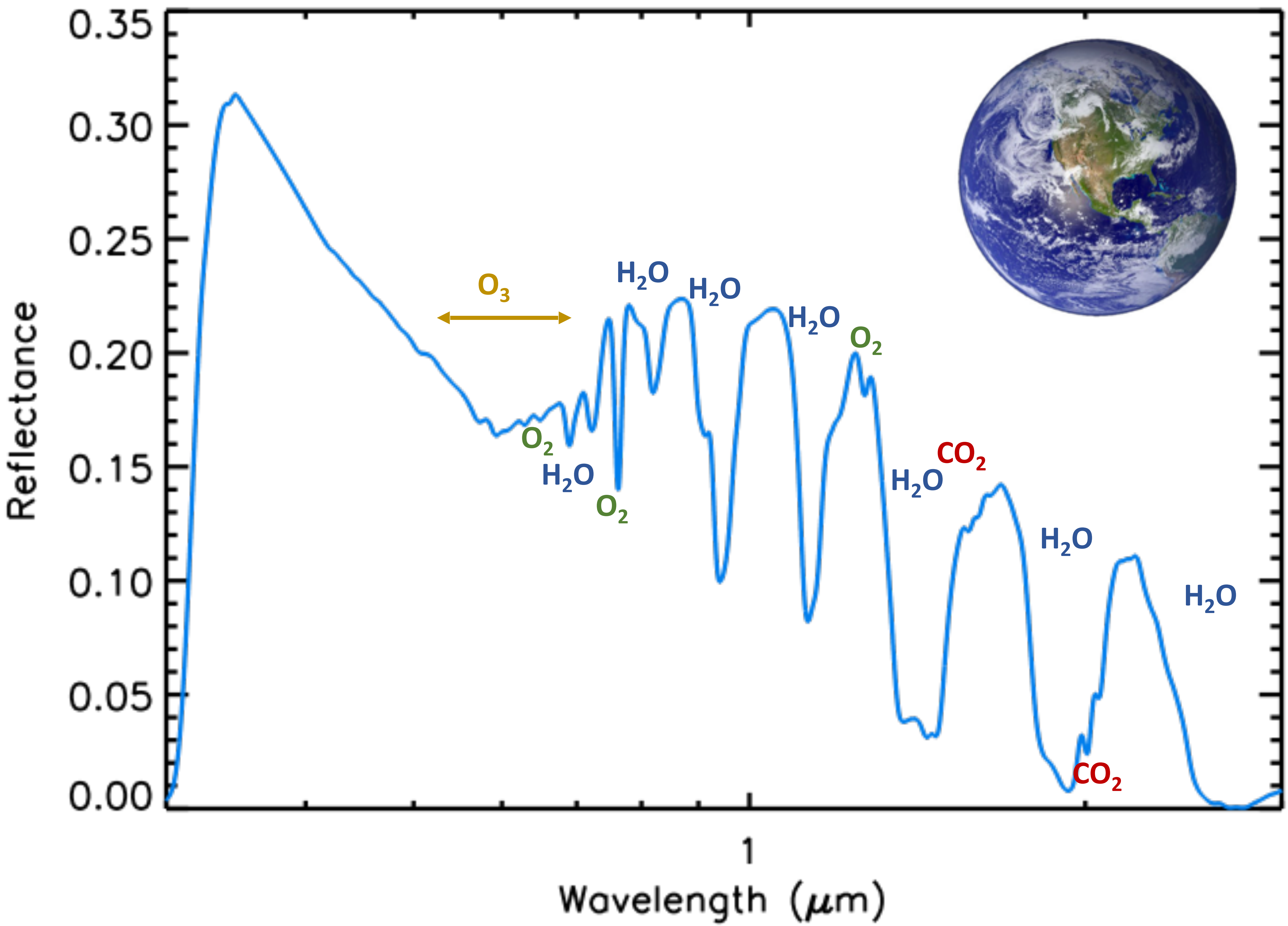
Optical R > 70



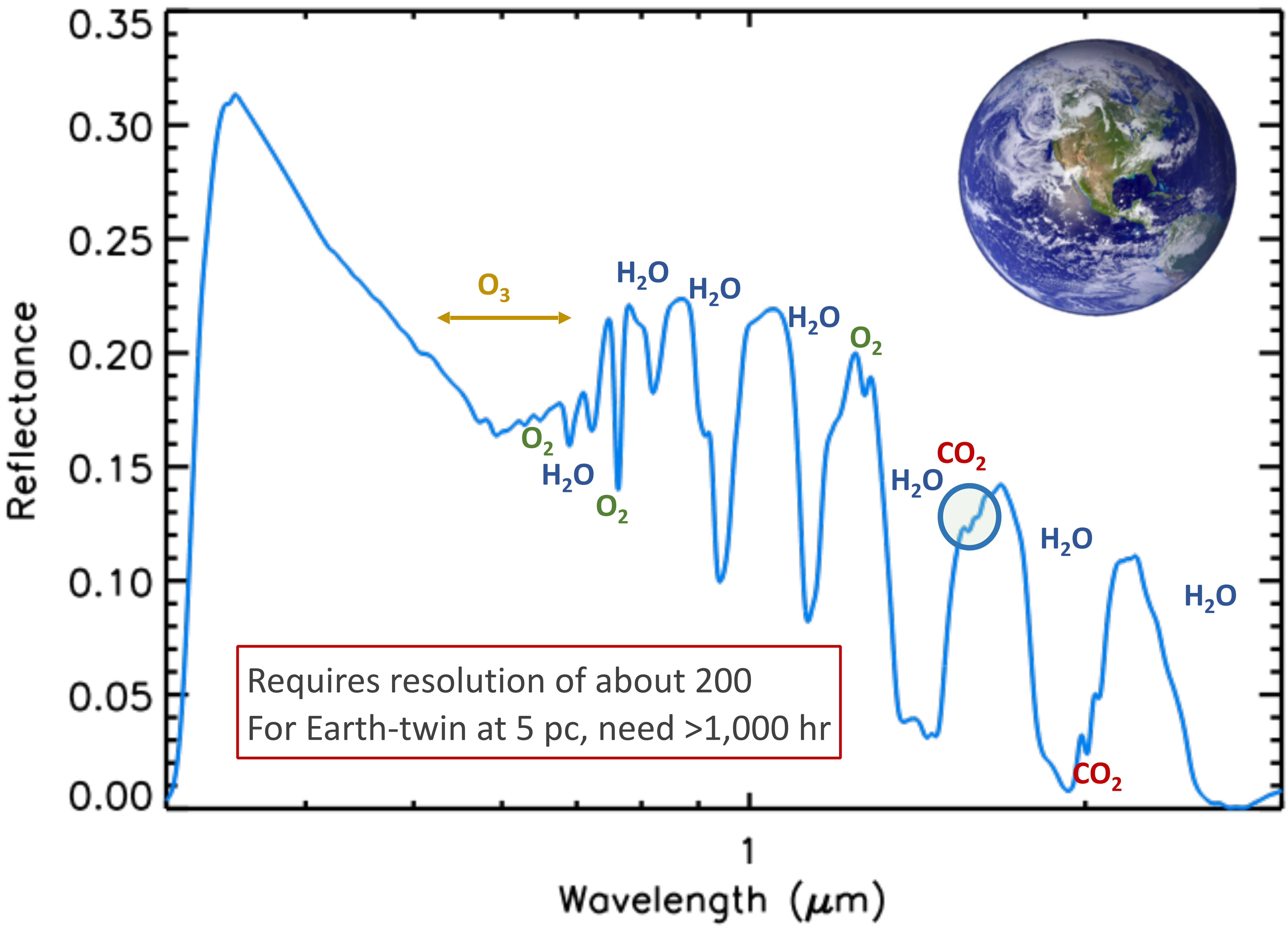
A census of greenhouse gases is important



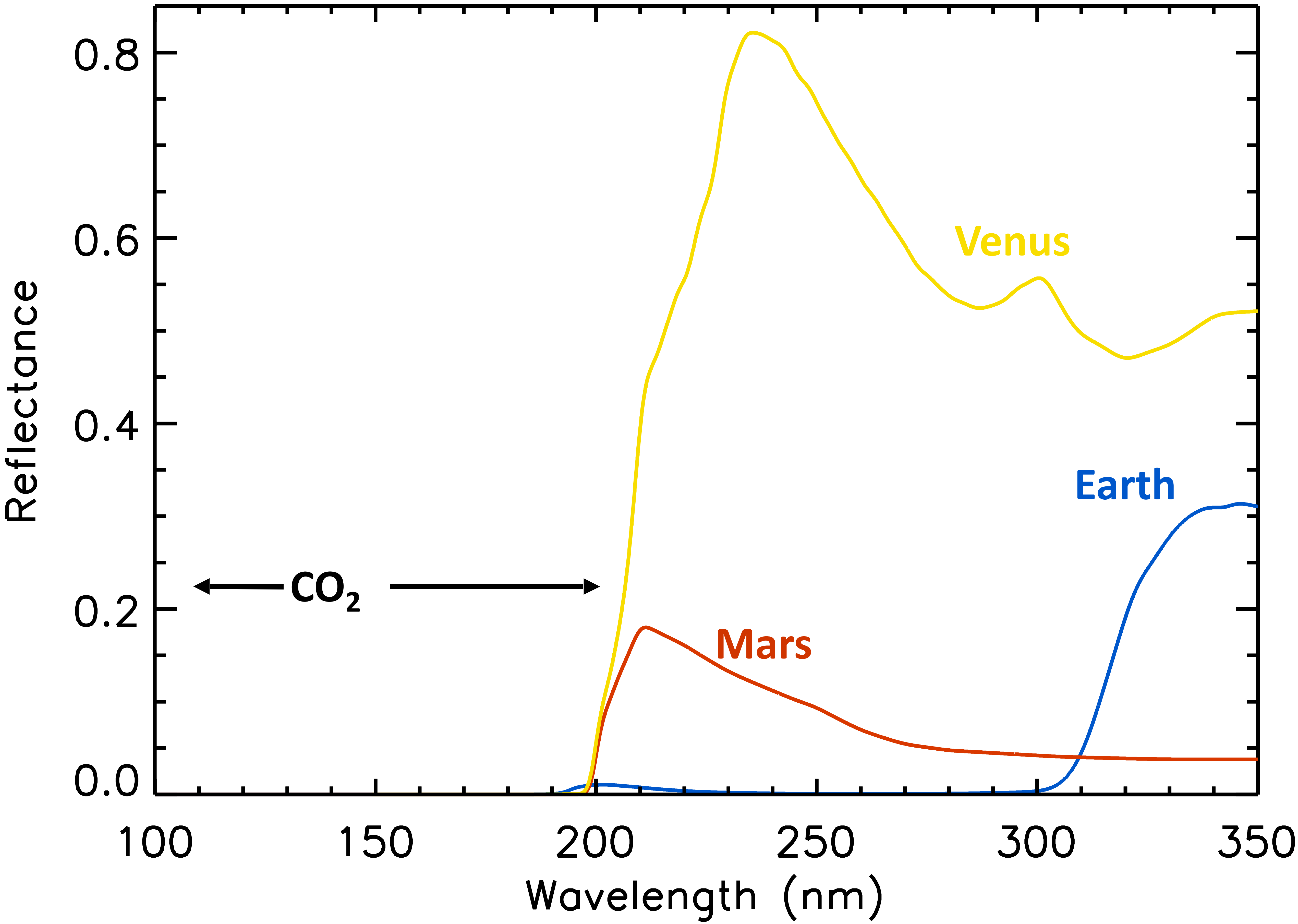
Segura, Meadows, Kasting, Crisp, Cohen, 2007



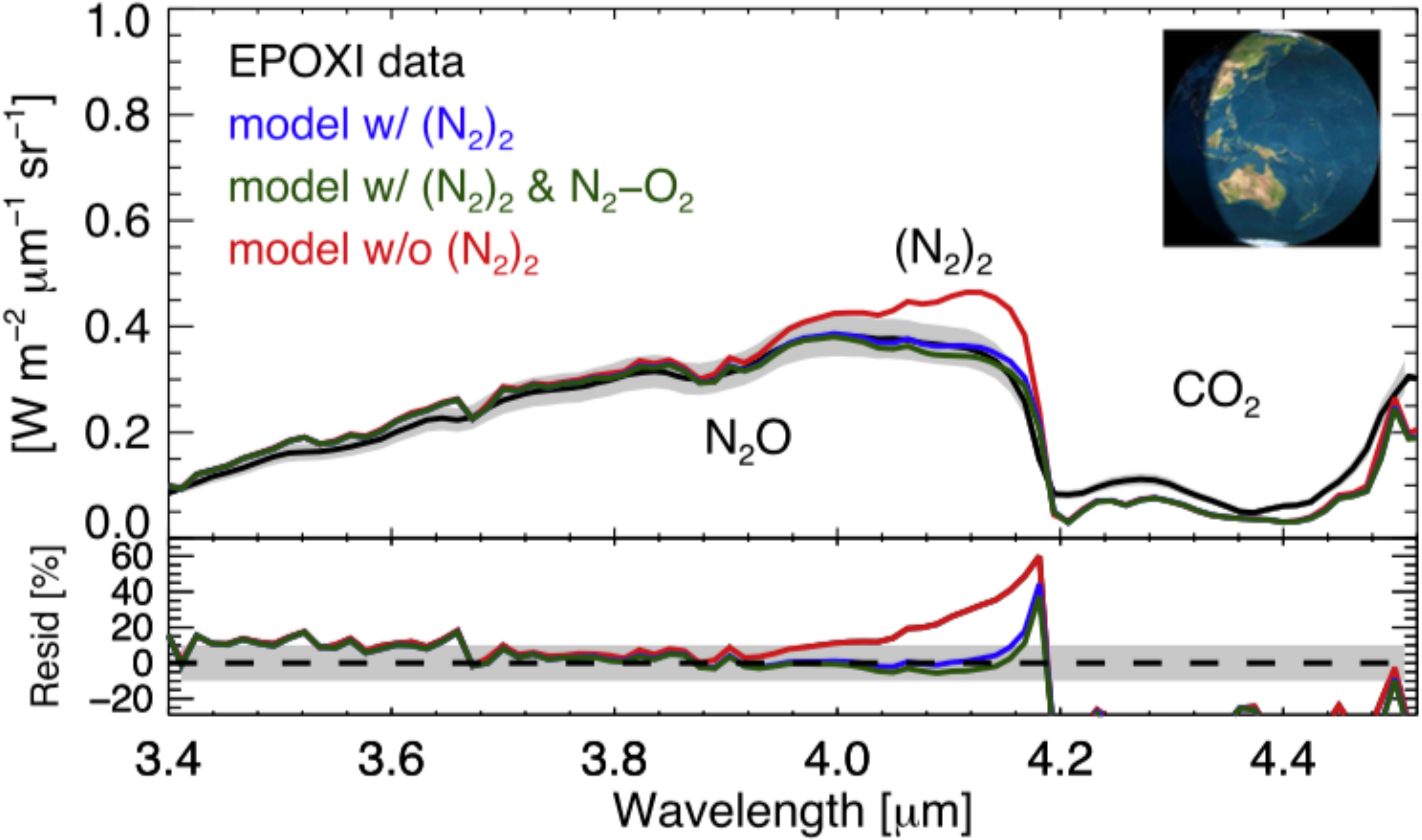
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Reflectance
1
Wavelength (μm)
O_3
O_2
H_2O
O_2
H_2O
H_2O
H_2O
O_2
H_2O
CO_2
H_2O
CO_2
H_2O


0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Reflectance
1
Wavelength (μm)
O3
H2O
H2O
H2O
O2
O2
H2O
O2
CO2
H2O
H2O
H2O
CO2
Requires resolution of about 200
For Earth-twin at 5 pc, need >1,000 hr

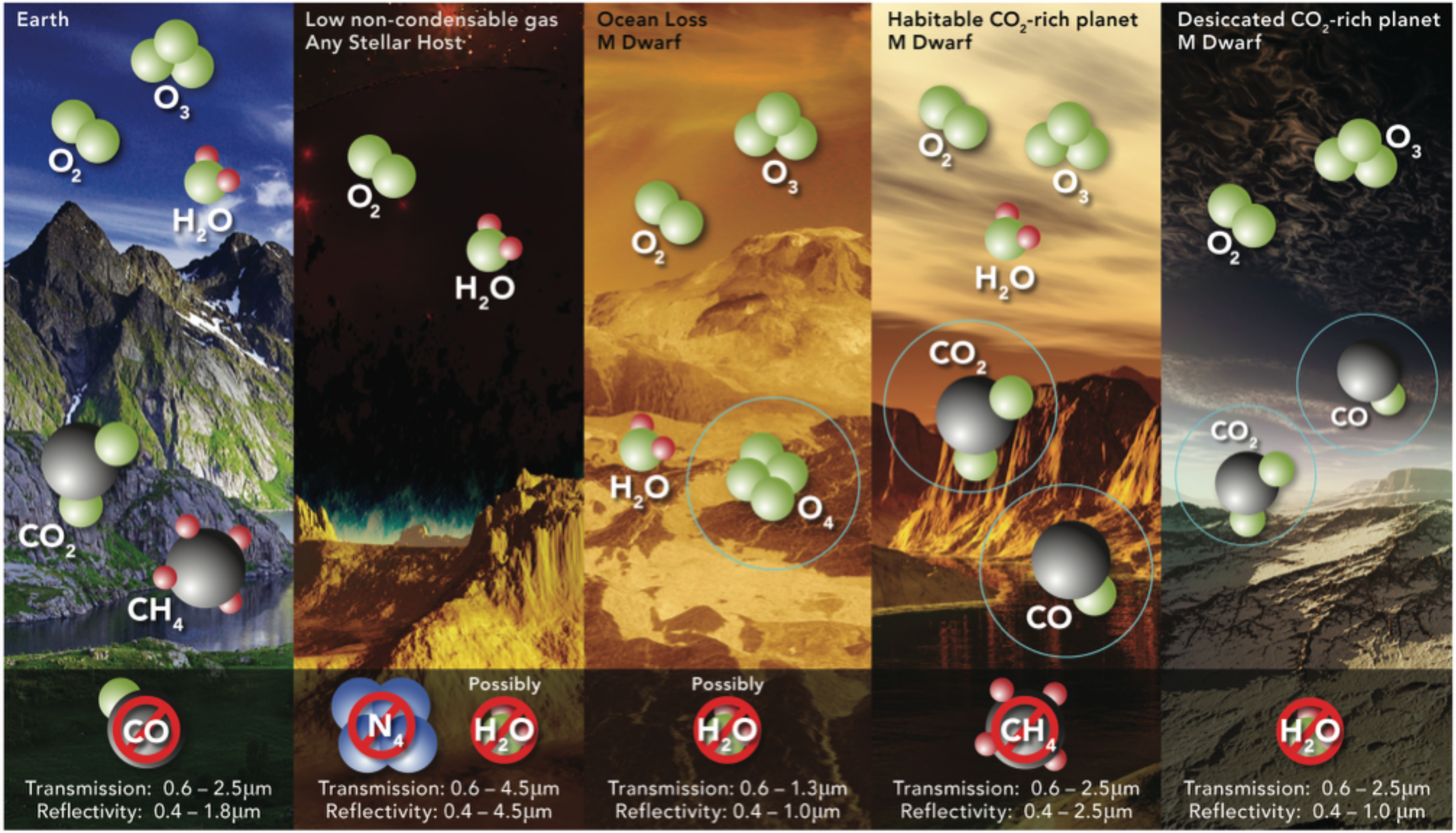
CO₂ Also in FUV



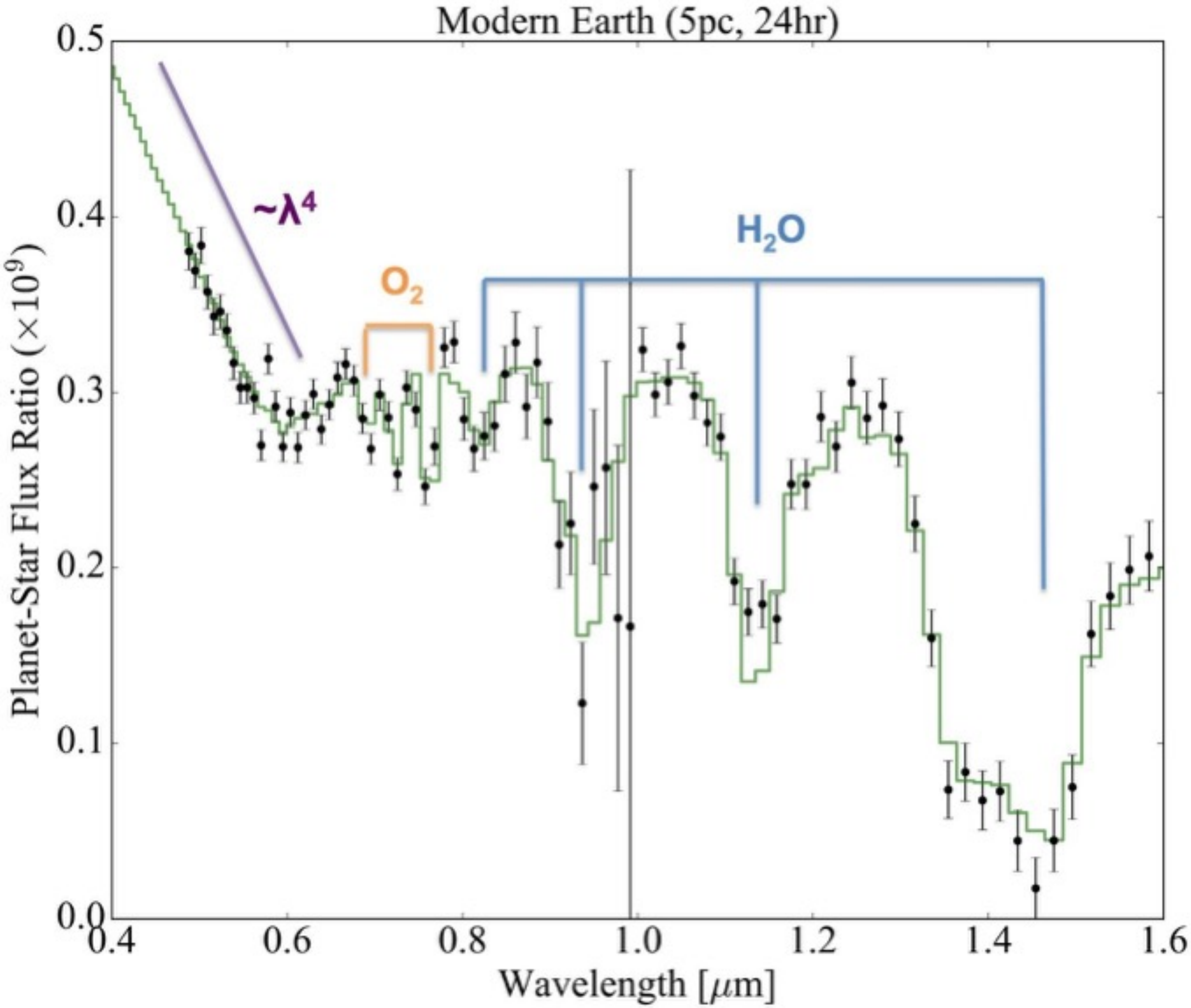
And thermal IR



Near-IR Permits False+ Exclusion



Hasler/Meadows/Domagal-Goldman



Modern Earth (5pc, 24hr)
Planet-Star Flux Ratio (×10^9)
Wavelength [μm]
~λ^4
O2
H2O
0.0
0.1
0.2
0.3
0.4
0.5
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Table 2: Spectral features sought

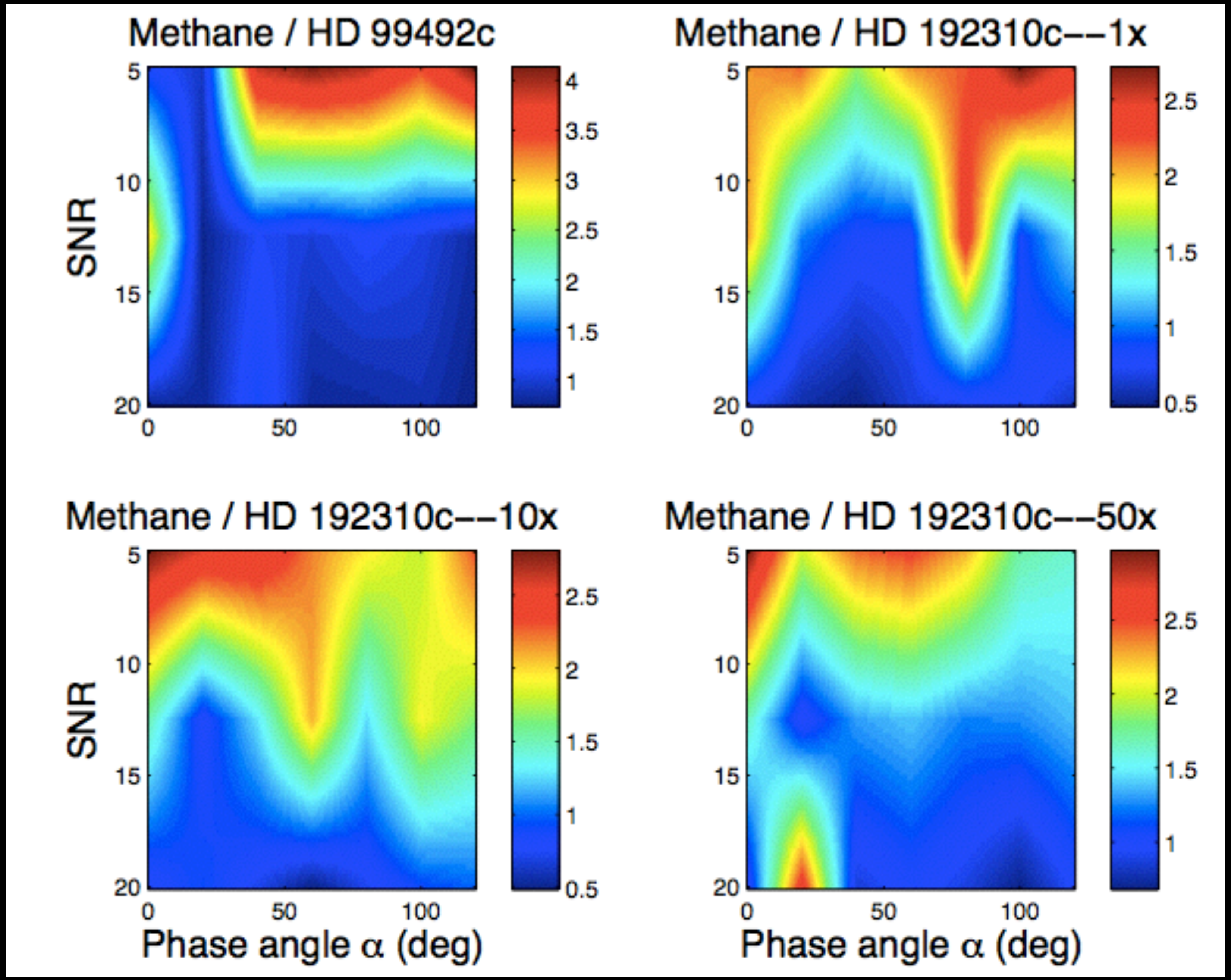
Molecules/Feature	0.2-1.8um	1.8-2.5um	2.5-5.0um
O_2	0.2, 0.69,0.76, 1.27		
O_3	0.2-0.3 (strong), 0.4-0.5		
O_4 (O_2-O_2)	0.45, 0.48, 0.53, 0.57, 0.63, 1.06, 1.27 (strong)		
CH_4	0.79, 0.89, 1.0, 1.1, 1.4, 1.7	2.31 (strong)	3.3 (strong)
CO_2 0.1 - 0.2	1.05, 1.21, 1.6	2.01	4.2 (strong)
N_2O		2.11, 2.25	2.6, 2.67, 2.97, 3.6, 3.9, 4.3, 4.5
CO	1.6	2.35	
H_2O	0.65,0.72,0.82,0.94,1.12,1.4	1.85, 2.5	
N_4 (N_2-N_2)			4.1
H_2	0.64-0.66, 0.8-0.85		
Ocean glint	0.8-0.9		
Vegetation Red Edge	0.6 (halophile) 0.7 (photosynthesis)		
Seasonal variability	CO_2 (1.6um), CH_4 (1.1 and 1.4um)		

LUVOIR; D = 16 m

Case	Max Elongation	λ_1 (OWA)	λ_2 (IWA)
Sun + Earth (10 pc)	0.10”	0.19 um	2.59 um
Sun + OHZ (10 pc)	0.17”	0.33 um	4.34 um
Sun + Jupiter (10 pc)	0.50”	0.97 um	12.9 um
Sun + Earth (5 pc)	0.20”	0.39 um	5.17 um
Sun + OHZ (5 pc)	0.34”	0.65 um	8.70 um
M4V + IHZ (3 pc)	0.04”	0.08 um	1.03 um
M4V + OHZ (3pc)	0.08”	0.16 um	2.06 um
α Cen A + Earth (1.34 pc)	0.75”	**1.45 um**	19.3 um
ProximaCen + IHZ	0.03”	0.06 um	0.83 um
ProximaCen + OHZ	0.06”	0.12 um	1.66 um

Meadows+

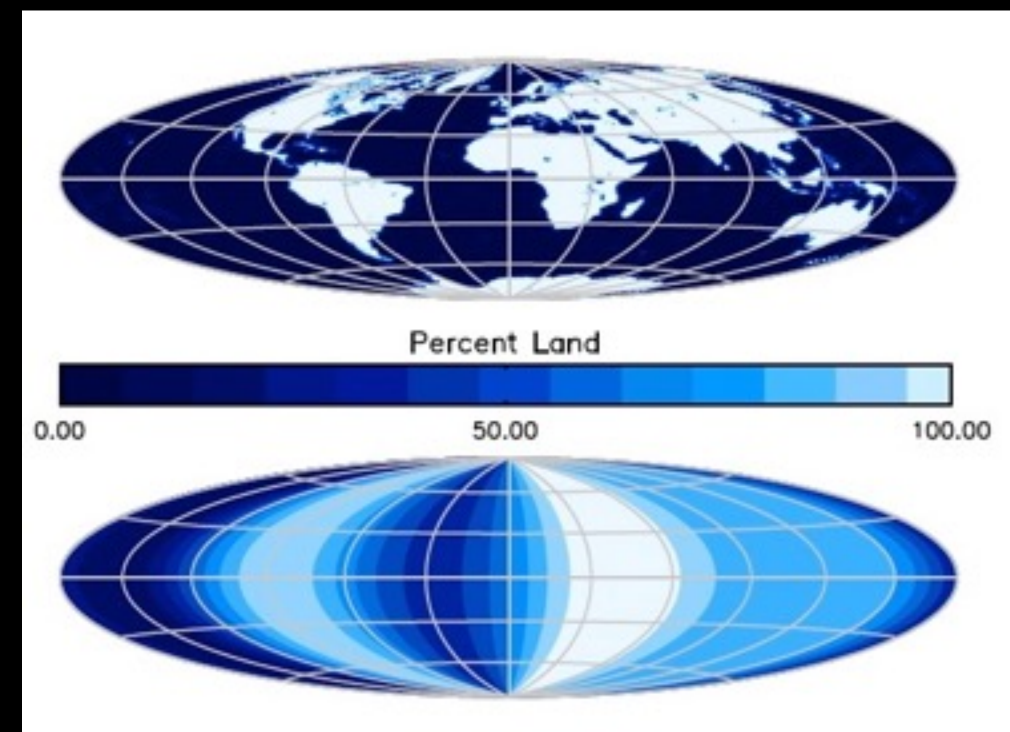
Need SNR > 20 for Useful Abundances

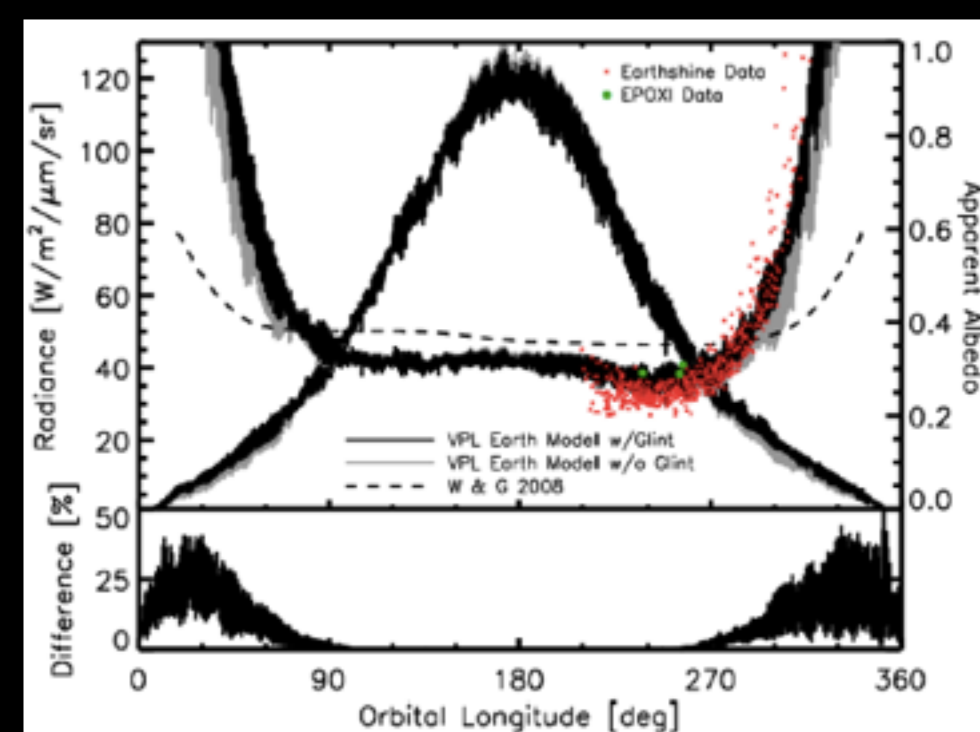


Nayak, Lupu, Marley+ (2016)

Other Signatures

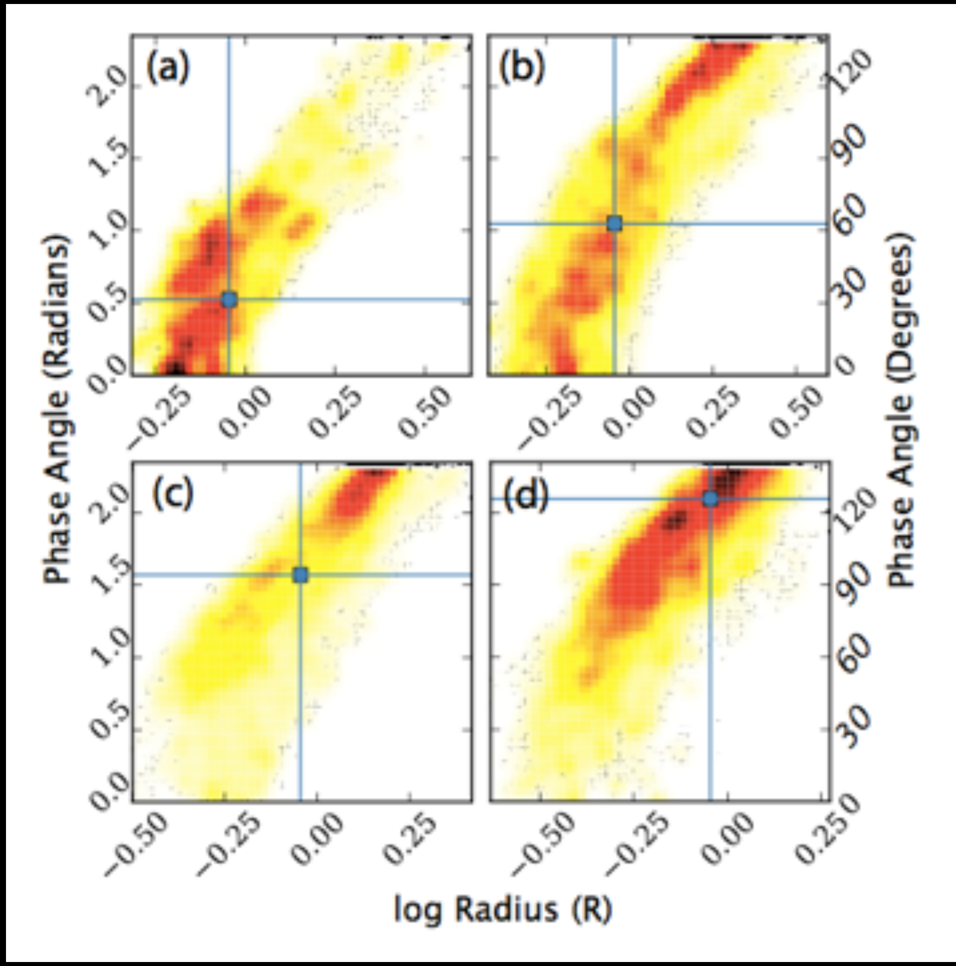
- Lightcurves (annual, daily)
- Glint
- Polarization





Crescent Phase Constrains Radius

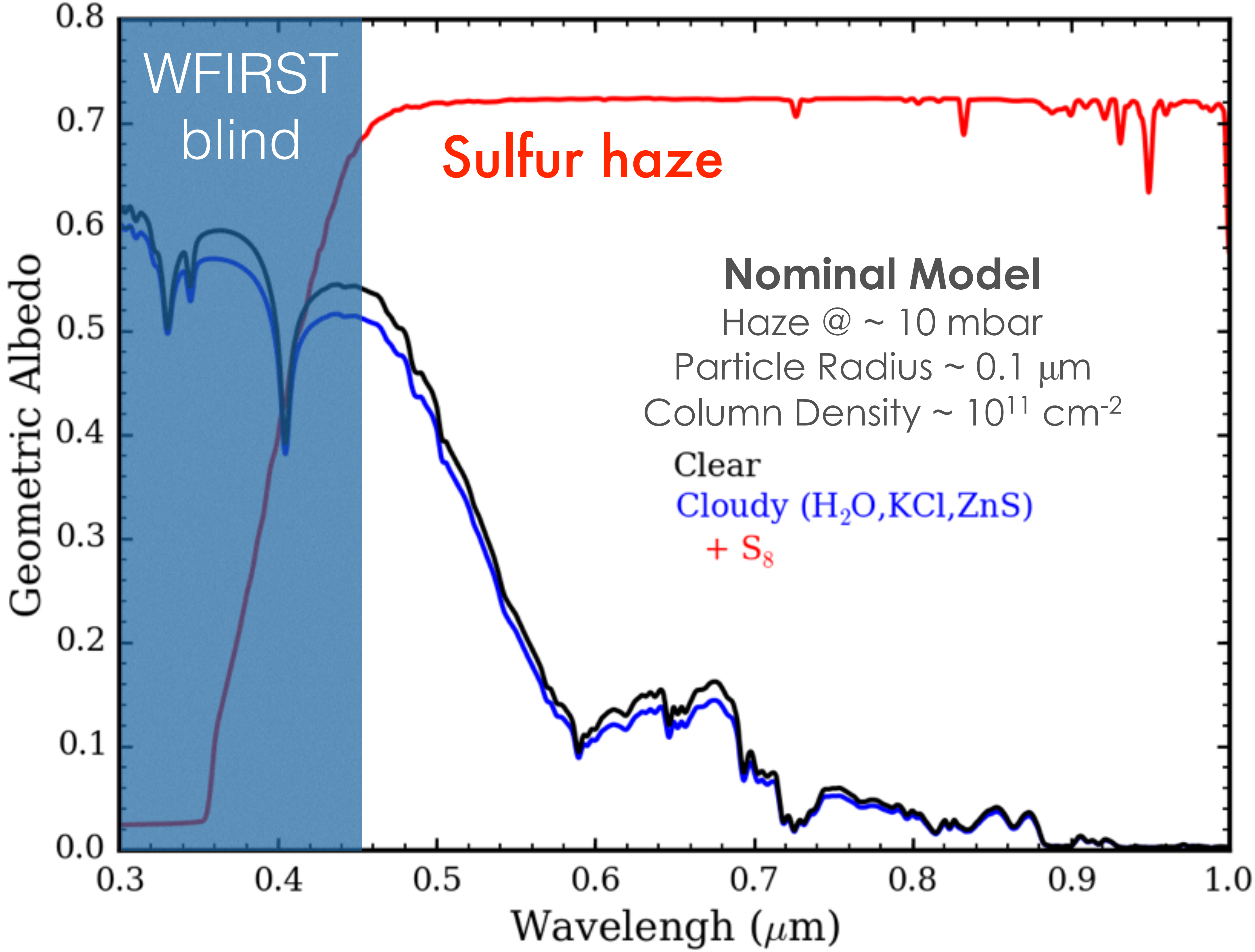
- Forward scattering at high phase angles minimizes albedo dependence
- Best radius constraints at crescent phases if planet is detectable



Nayak, Lupu, Marley+ (2016)

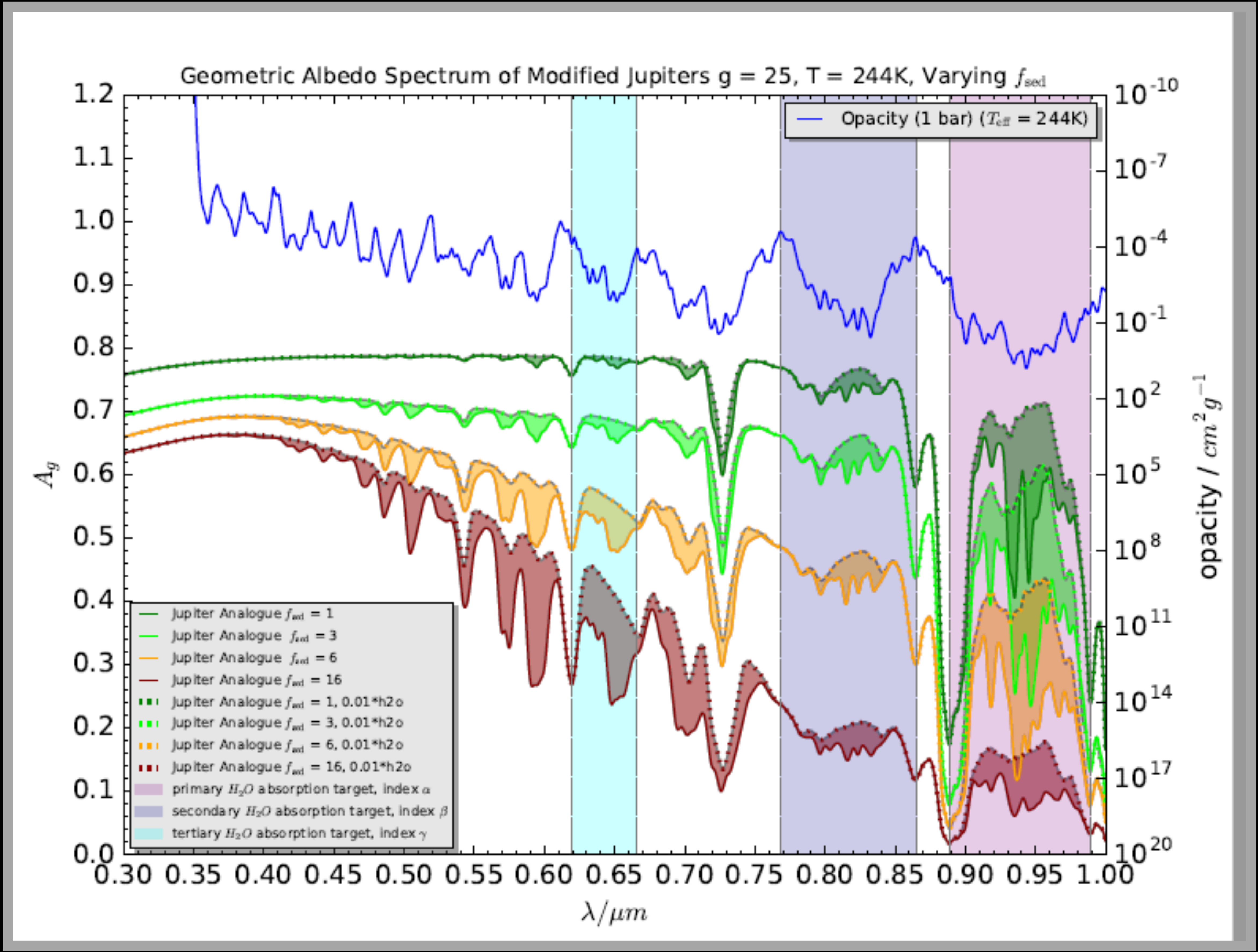
Selected Other Science

Hazey Warm Jupiters & Neptunes



H_2O in Warm Giants/Super-Earths

H_2O in Warm Giants/Super-Earths



Science Questions on Exoplanetary System Architectures & Population
A1. What is the diversity of planetary architectures? Are there typical classes/ types of planetary architectures? How Common are Planetary Architectures resembling the Solar System?
A2. What are the distributions and properties of planetesimal belts and eco-zodiacal disks in exoplanetary systems and what can these tell about the formation and dynamical evolution of the planetary systems?
Science Questions on Exoplanet Properties
B1. How do rotation periods and obliquity vary with orbital elements and planet mass/type?
B2. Which rocky planets have liquid water on their surfaces?
B3. What are the origins and composition of clouds and hazes in ice/gas giants and how do these vary with system parameters?
B4. How do photochemistry, transport chemistry, surface chemistry, and mantle outgassing effect the composition and chemical processes in terrestrial planet atmospheres (both habitable and non-habitable)?
Science Questions of Evolution and Processes that Change Exoplanets
C1. What processes/properties set the modes of atmospheric circulation and heat transport in exoplanets and how do these vary with system parameters?
C2. What are the Key Evolutionary Pathways for Rocky Planets?
C3. What types/which planets have active geological activity, interior processes, and /or continent-forming/resurfacing processes?

Milestones and Status

SAG15 approved: Oct 2015

Advanced draft: Sep 2016

Final draft: Dec 2016

Report submission: Feb 2017

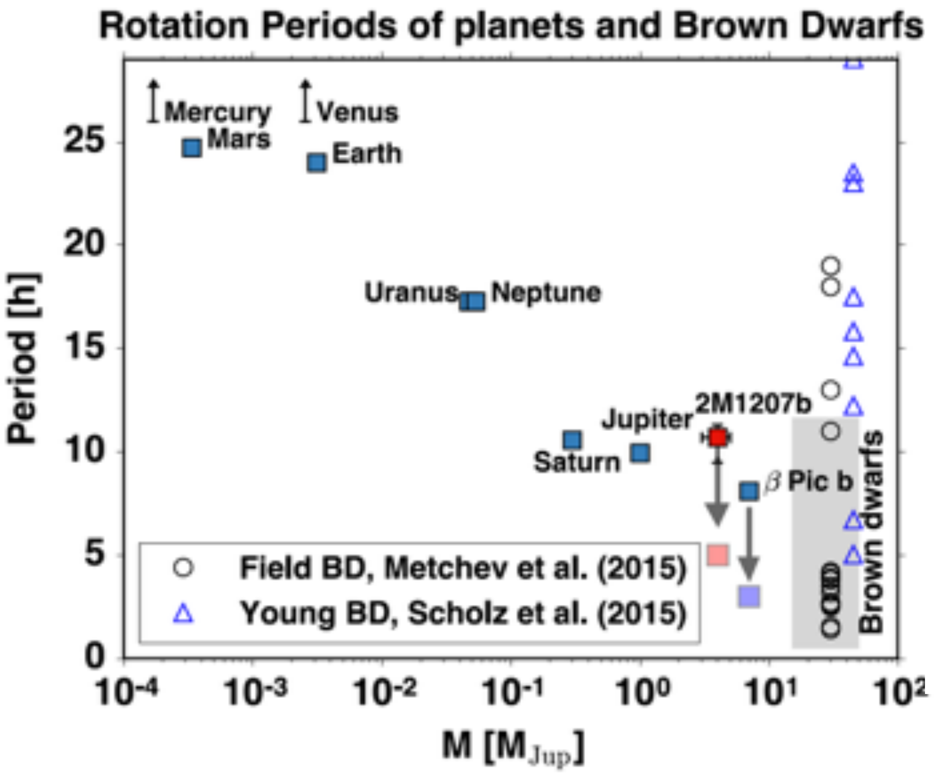
Manuscript submission: March 2017

Monthly telecons ongoing + workshop sessions

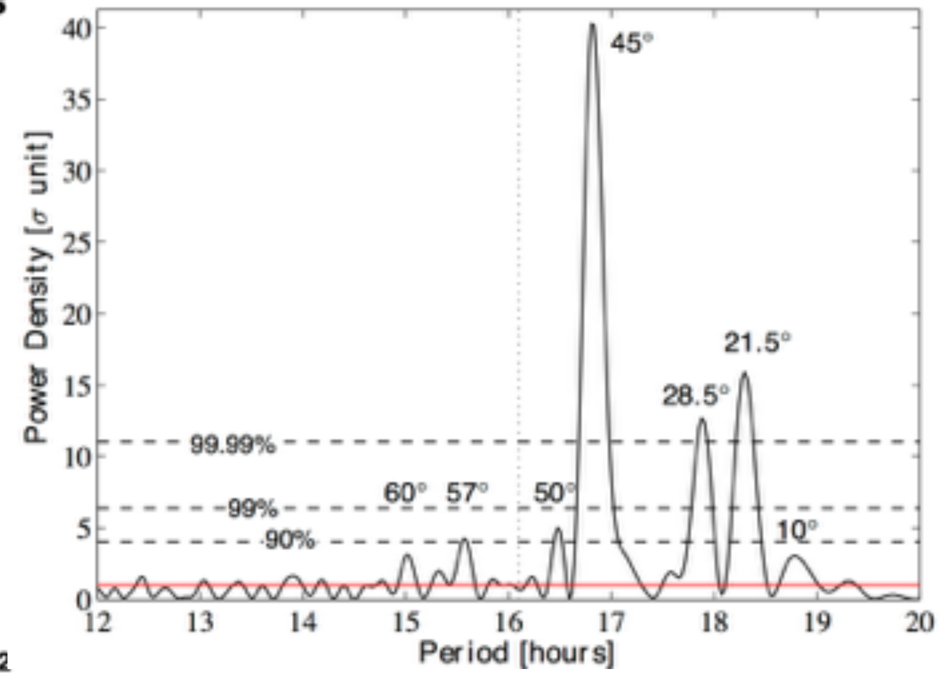
Contribution from ~40+ community members

All drafts on website, report open to input

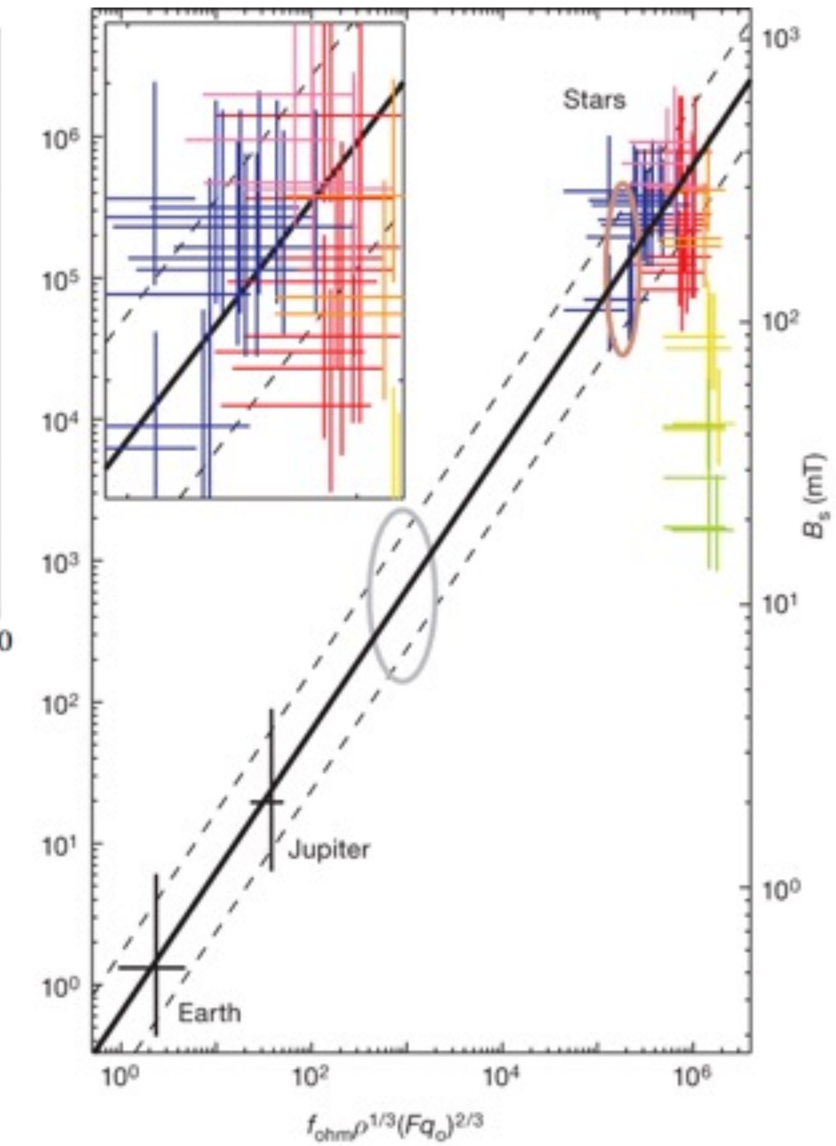
B1. How do Rotational Periods and Obliquity vary with orbital elements and planet mass/composition?



Zhou et al. 2016

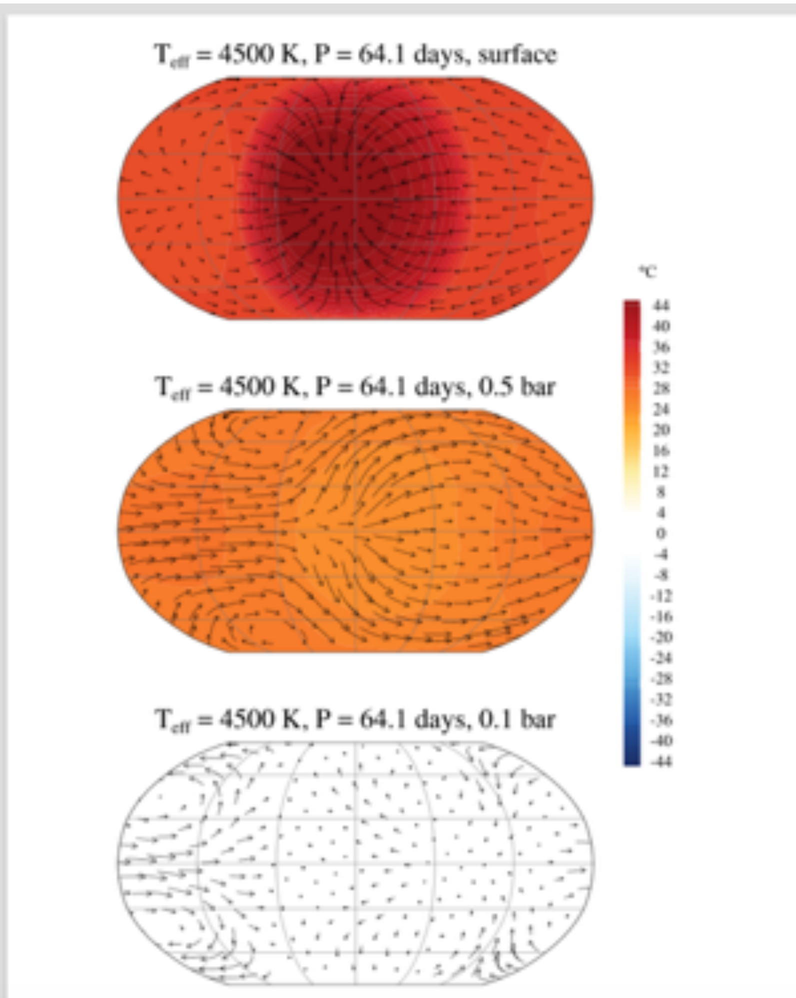


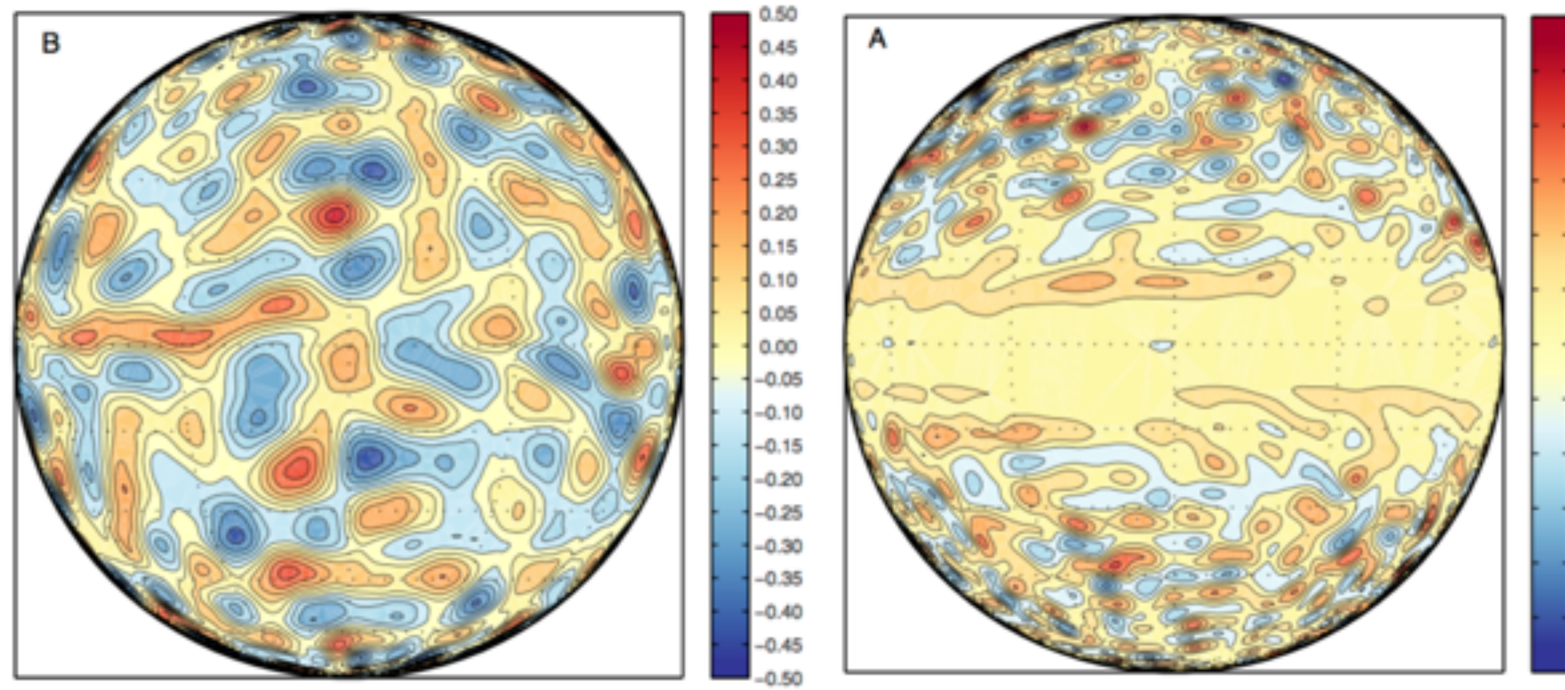
Simon et al. 2016



Christensen et al. 2009

C1. What processes/properties set the modes of atmospheric circulation and heat transport in exoplanets and how do these vary with system parameters?

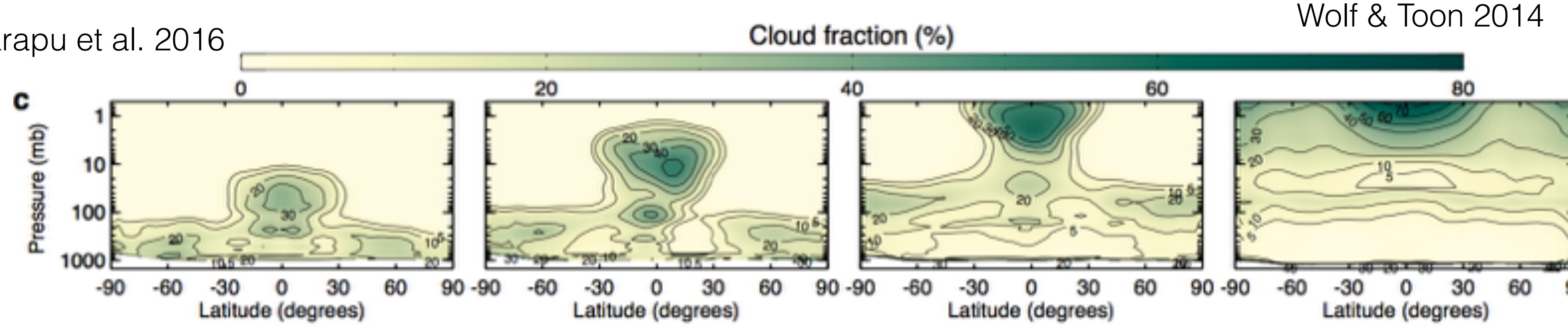




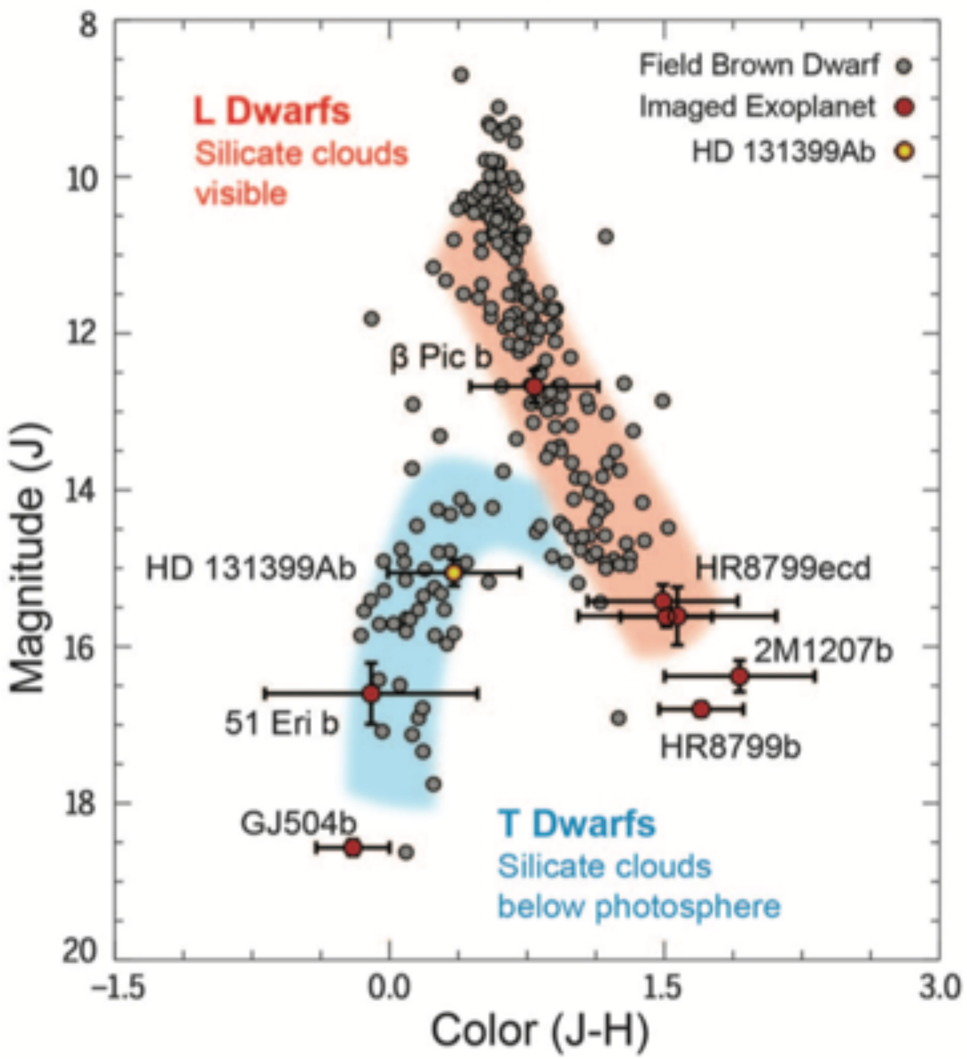
Zhang & Showman 2014

Kopparapu et al. 2016

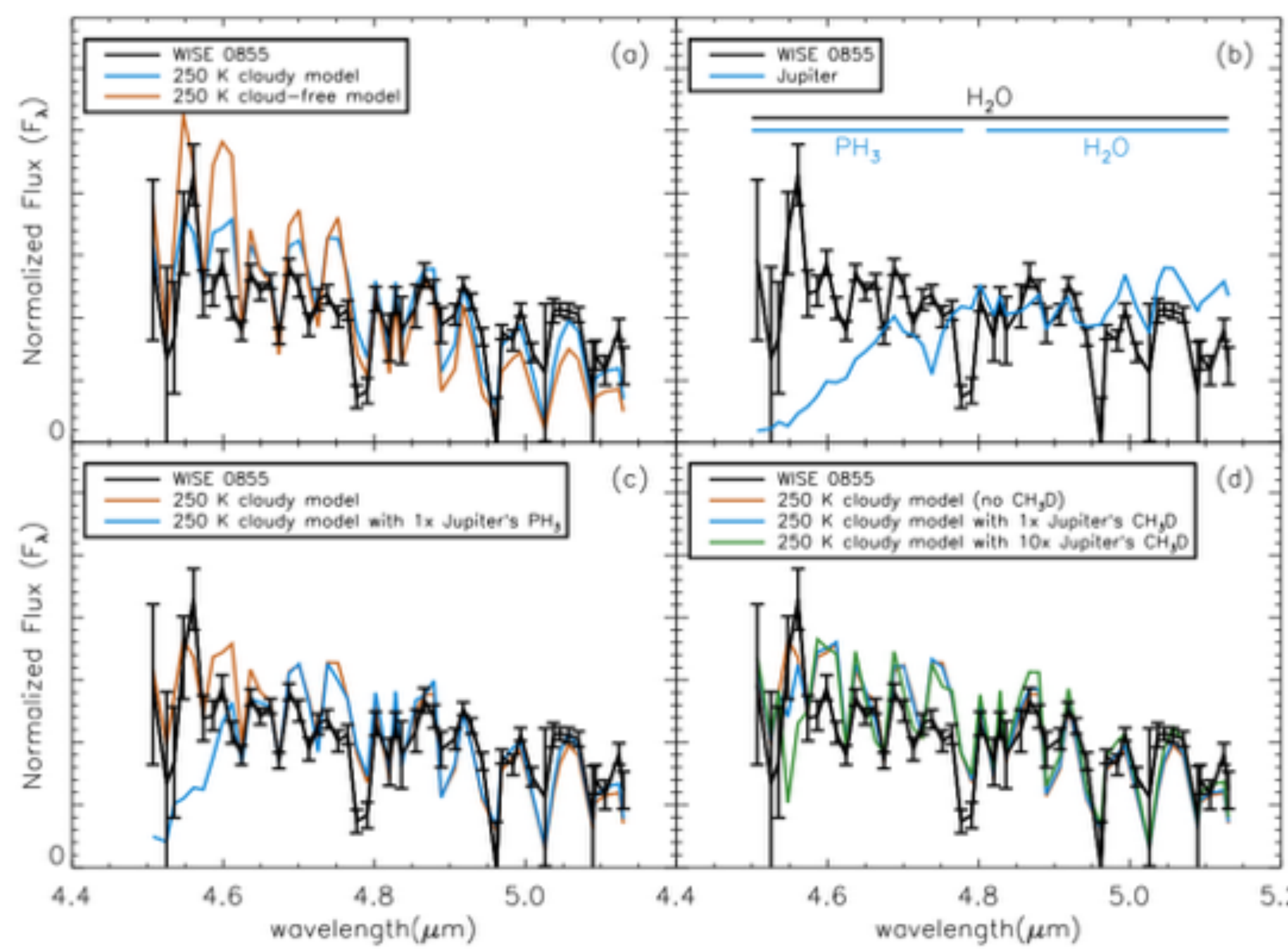
Wolf & Toon 2014



B3 What are the origins and composition of clouds and hazes in ice/gas giants and how do these vary with system parameters?



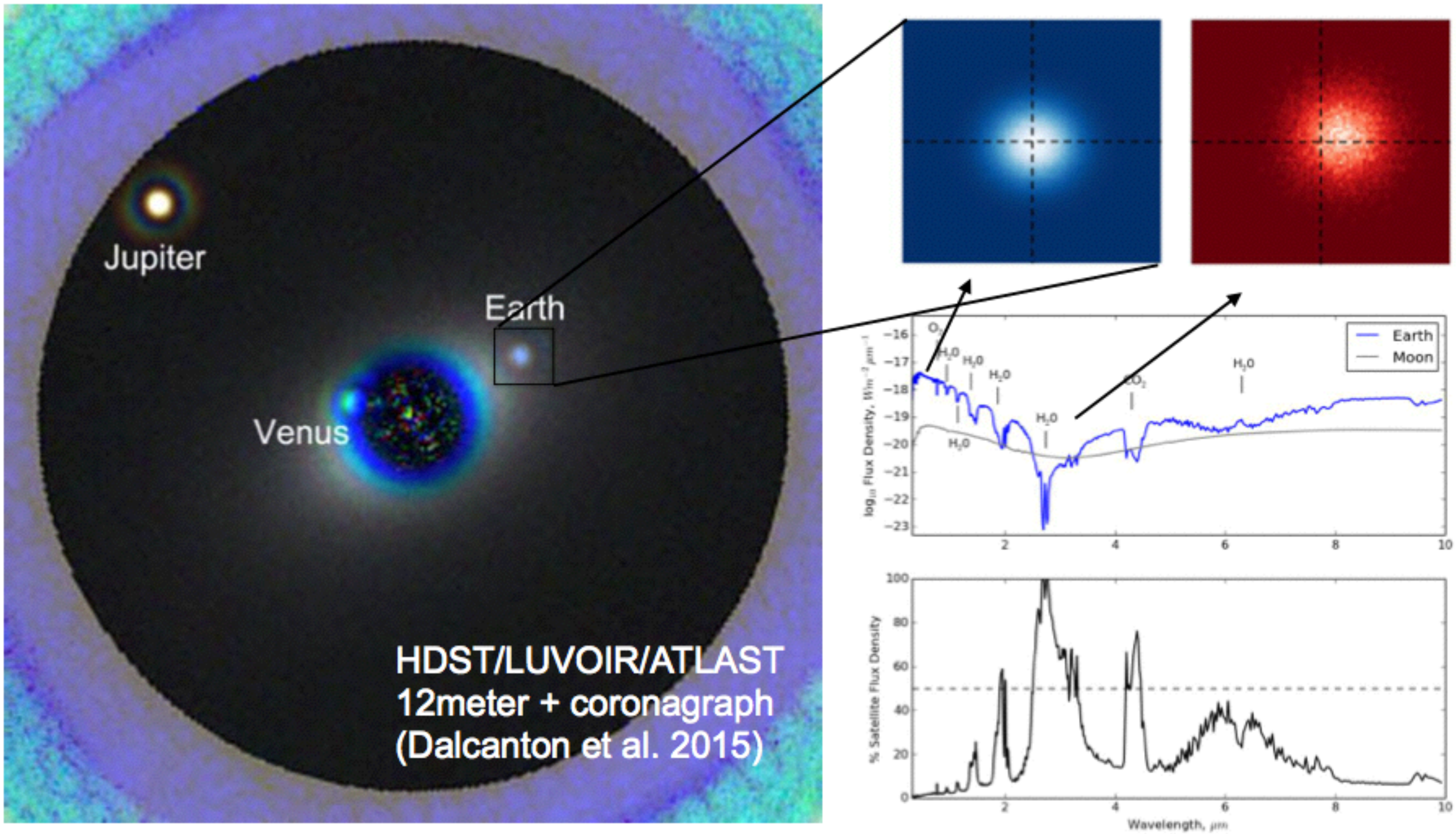
Wagner et al. 2016; Dupuy & Liu 2012



Skemer et al. 2016

1) What are vertical structures of single and multi-layer clouds formed from different condensates?
2) What are the grain size distributions and compositions (single-species or compound grains) in the clouds?
3) Under what conditions do photochemically{ and charged particle-driven haze layers form? How complex can chemistry get in haze layers?
4) How do condensate clouds form and evolve as a function of fundamental atmospheric parameters?

Spectroastrometric detection of exomoons (Agol, Jansen, Lacy, Robinson & Meadows 2015)



EUV/FUV Stellar Characterization
(France)

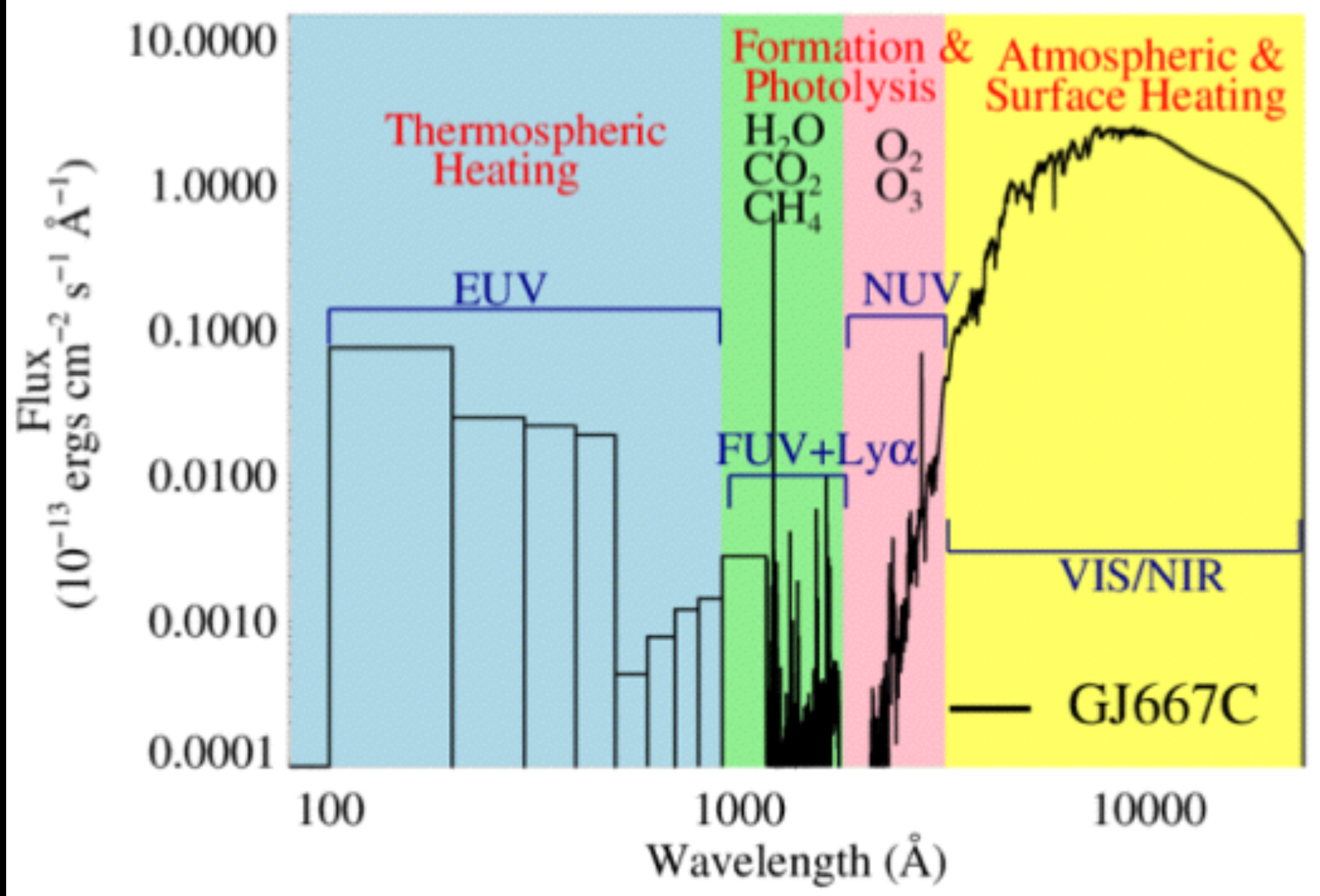
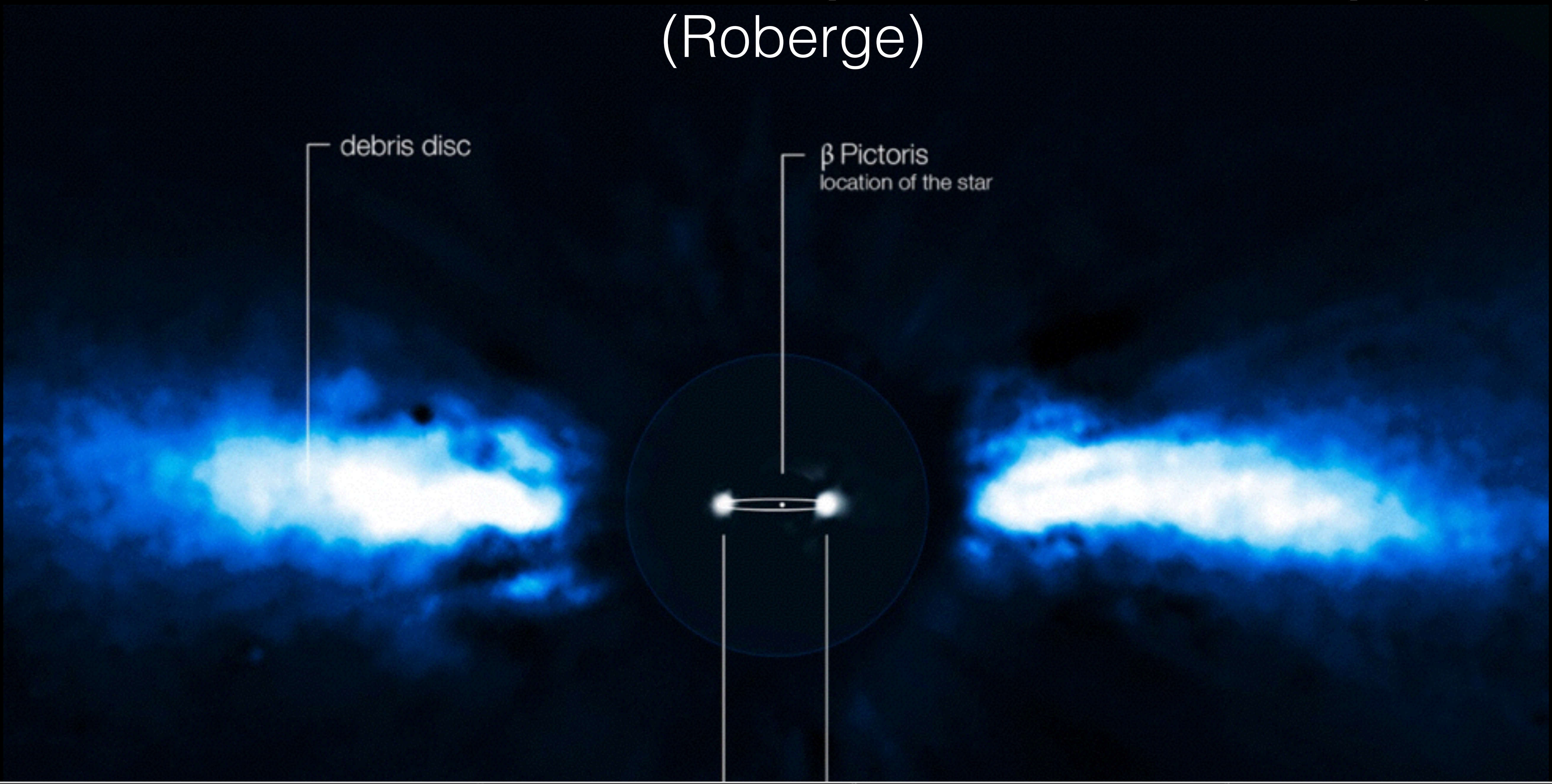


***Figure 1**: HST spectrum of GJ 667C, illustrating the influence of each spectral bandpass on the atmosphere of an Earth-like planet orbiting this star (France et al. 2013, 2016; Linsky et al. 2014). GJ 667C hosts a super-Earth mass planet located in the HZ..*

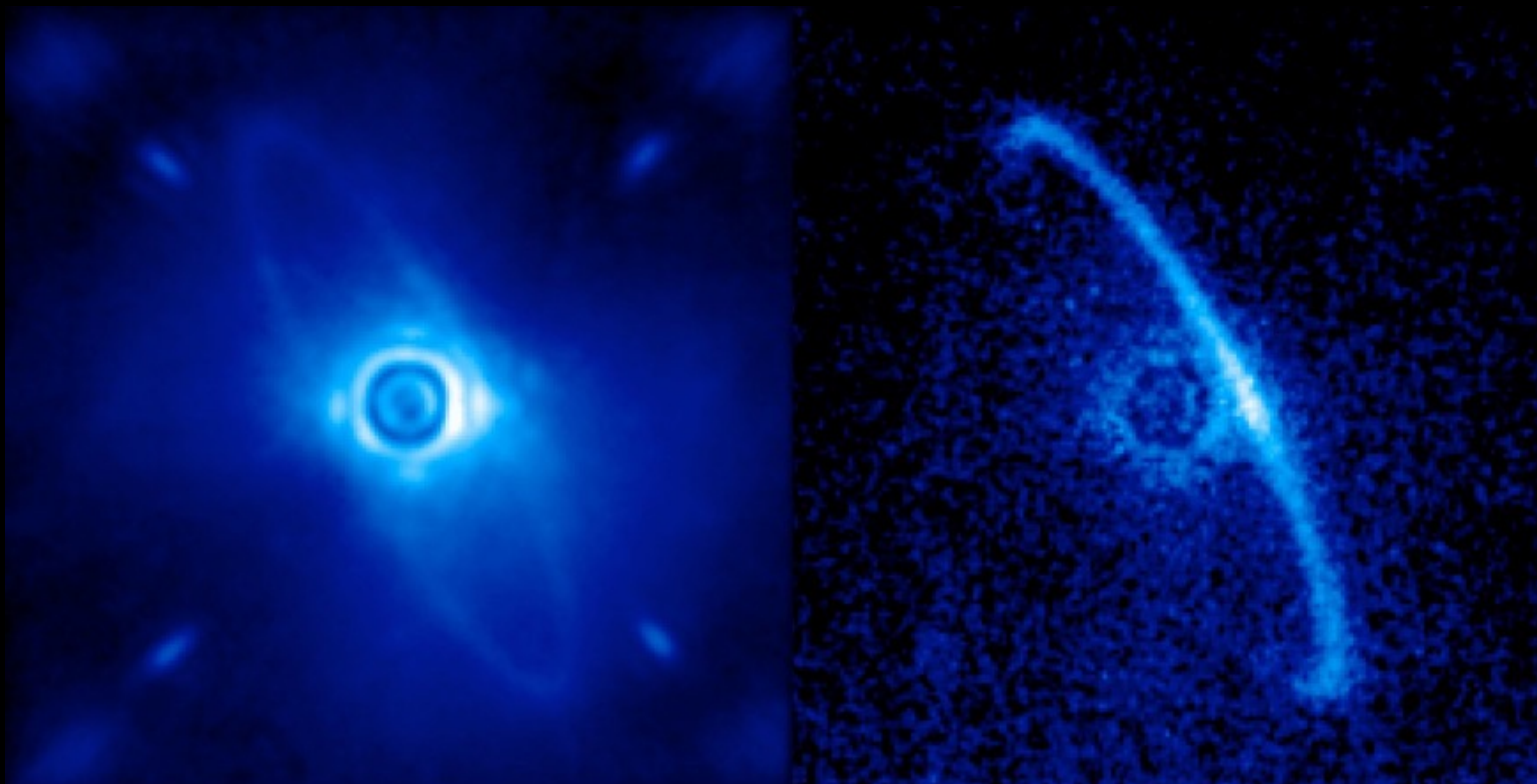
Debris Disk Spectroscopy

(Roberge)



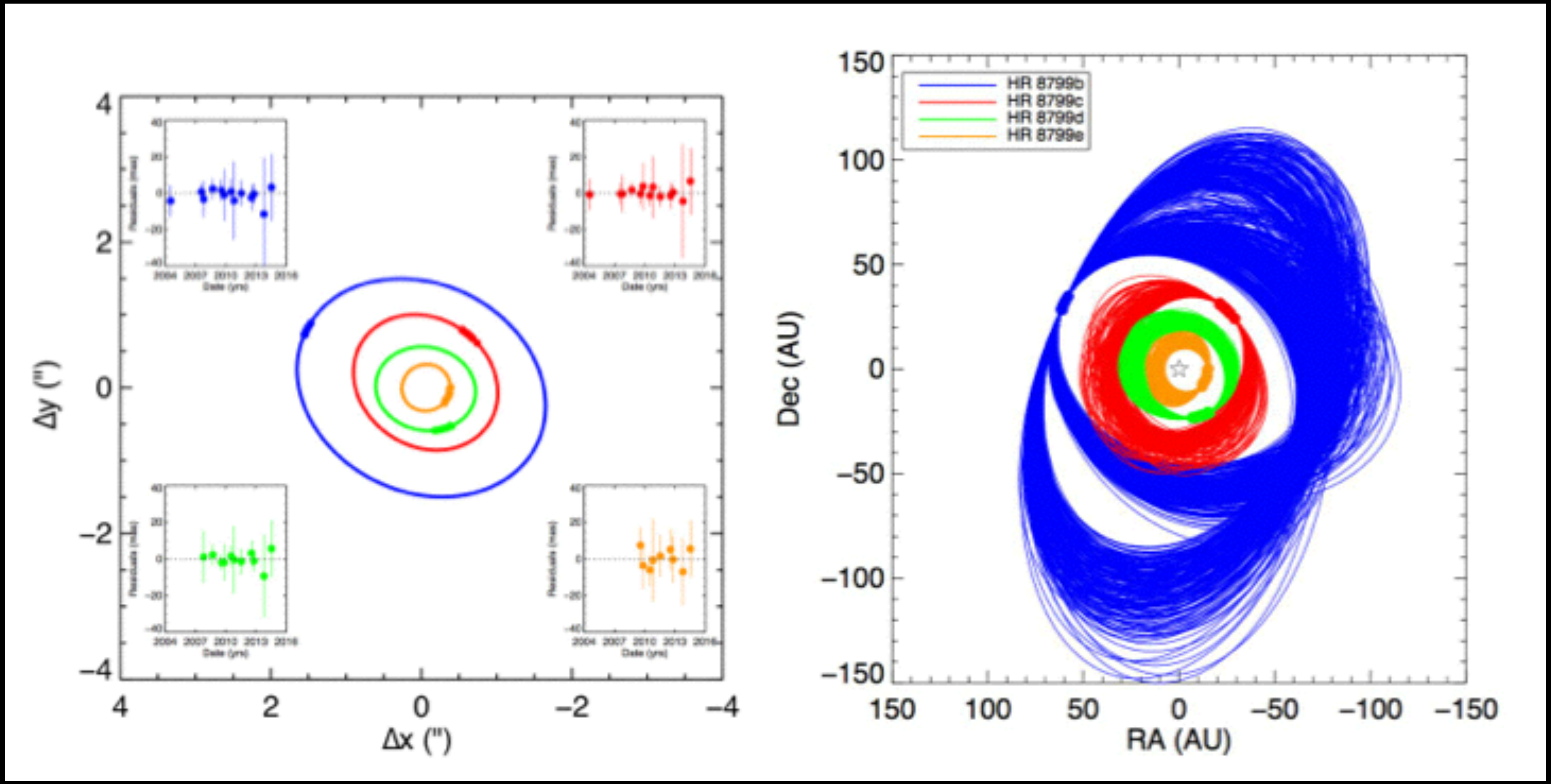
Observation Requirement	Major Progress	Substantial Progress	Incremental Progress
Wavelengths	1200 A – 8700 A	1200 A – 8700 A	1200 A – 3000 A
Spatial resolution	Not applicable	Not applicable	Not applicable
Spectral resolution	> 200,000	> 100,000	> 100,000

Disk Polarization (Sparks)



Summary

- Science motivation generally very solid
  - high resolution R~200,000 spectrograph
  - coronagraph(s) (wish for 0.1 to 1.8 to 2.3 to 5(!?) μm)
- Need more:
  - specific search capabilities for requirements
  - search method comparisons & optimization
  - transit science requirements (cadence, data storage…)



Δy (")
Δx (")
Date (yrs)
Residuals (mas)
HR 8799b
HR 8799c
HR 8799d
HR 8799e
Dec (AU)
RA (AU)