Mapping Other Worlds

Satellite Session Summary

Organizers: Daniel Apai and Nick Cowan

Speakers:

Esther Buenzli, MPIA (Invited Review)
Daniel Apai, U Arizona
Theodora Karalidi, U Arizona

Julien de Wit, MIT (Invited Review)
Nadine Afram, Kiepenheuer Institute

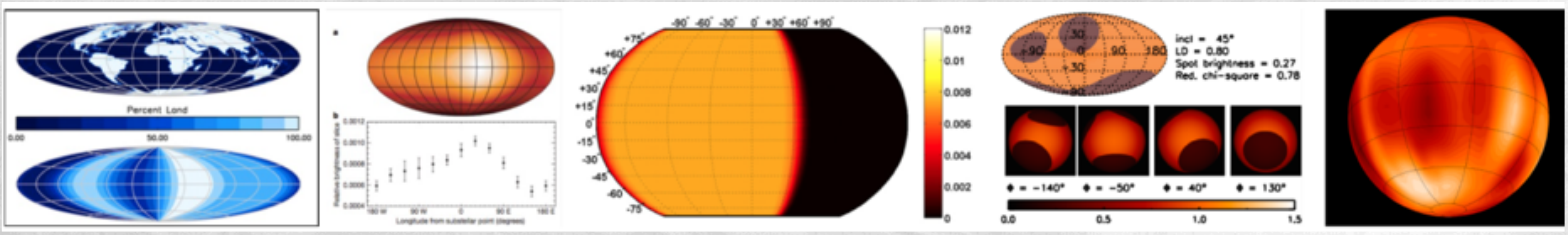
Yuka Fujii, ELSI Tokyo (Invited Review)
Joel Schwartz, Northwestern University
Nick Cowan, SSI/McGill

Mapping Other Worlds: Spatial Studies of Exoplanets and Ultracool Atmospheres

Brown Dwarfs

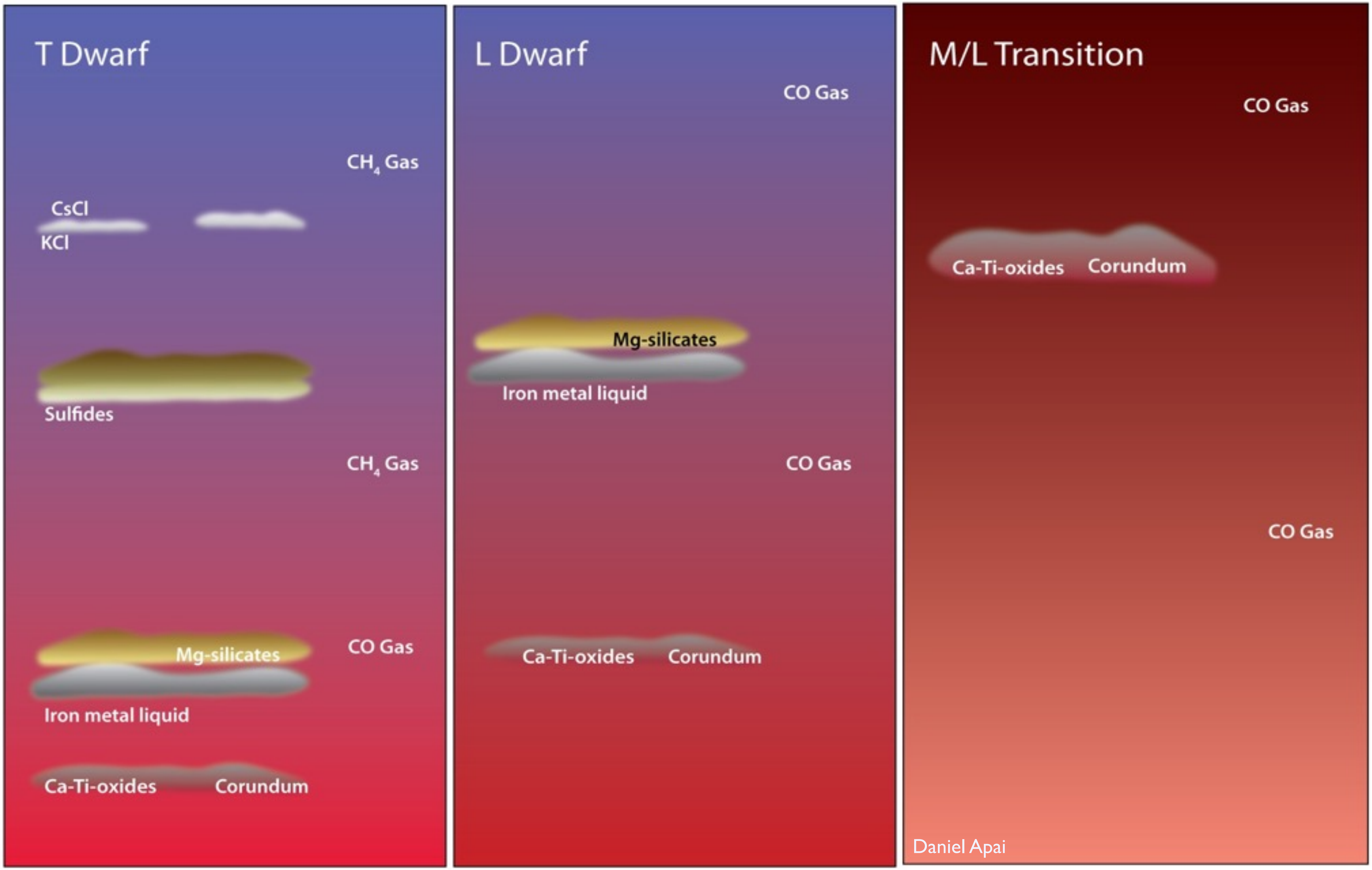
Transiting Exoplanets

Future Directly Imaged Earth-like Planets



Mapping Brown Dwarfs

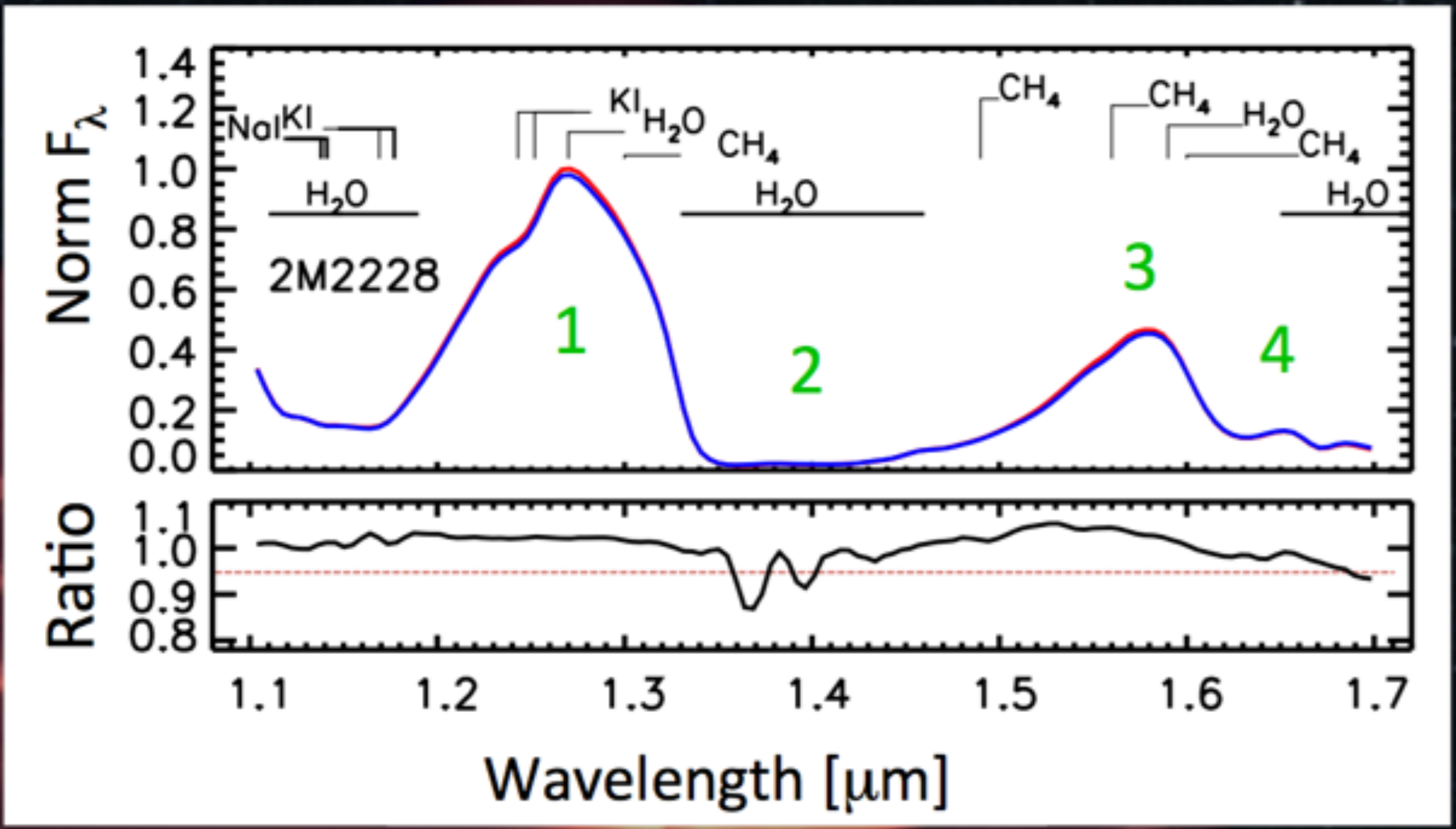
Esther Buenzli
Max Planck Institute for Astronomy


T Dwarf
CH_4 Gas
CsCl
KCl
Sulfides
CH_4 Gas
CO Gas
Mg-silicates
Iron metal liquid
Ca-Ti-oxides
Corundum
L Dwarf
CO Gas
Mg-silicates
Iron metal liquid
CO Gas
Ca-Ti-oxides
Corundum
M/L Transition
CO Gas
Ca-Ti-oxides
Corundum
CO Gas
Daniel Apai

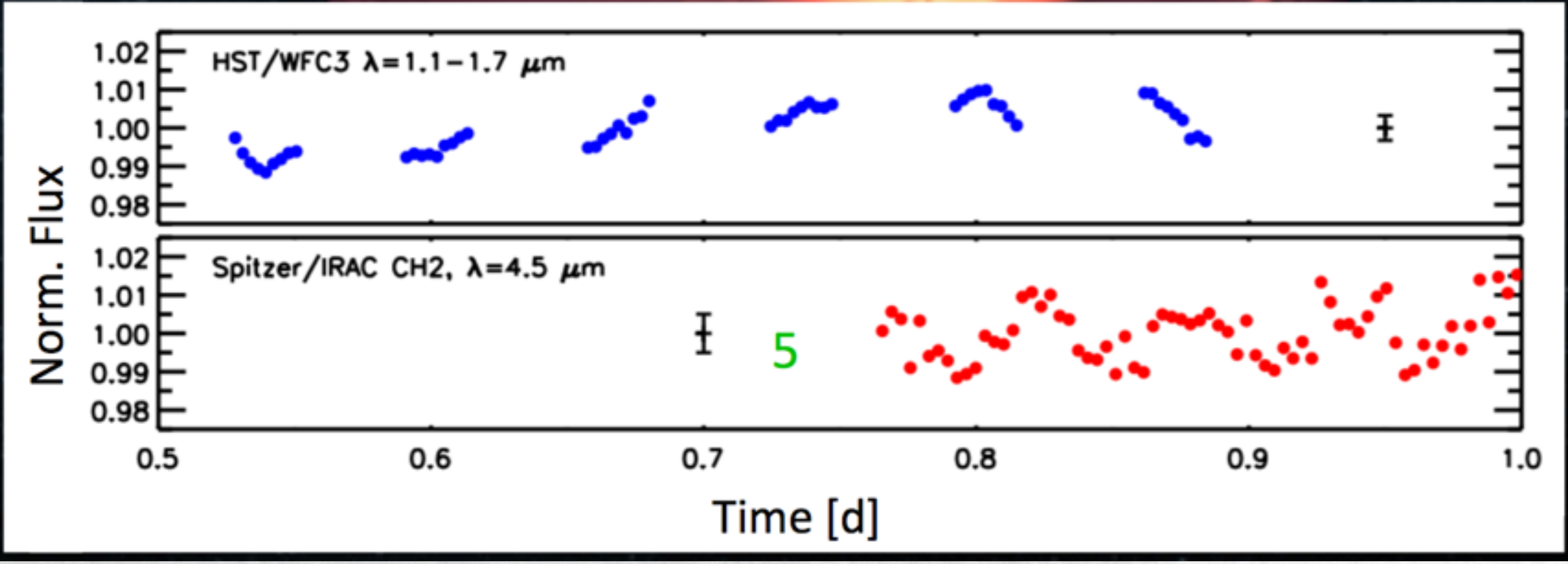
T6.5 dwarf 2M2228

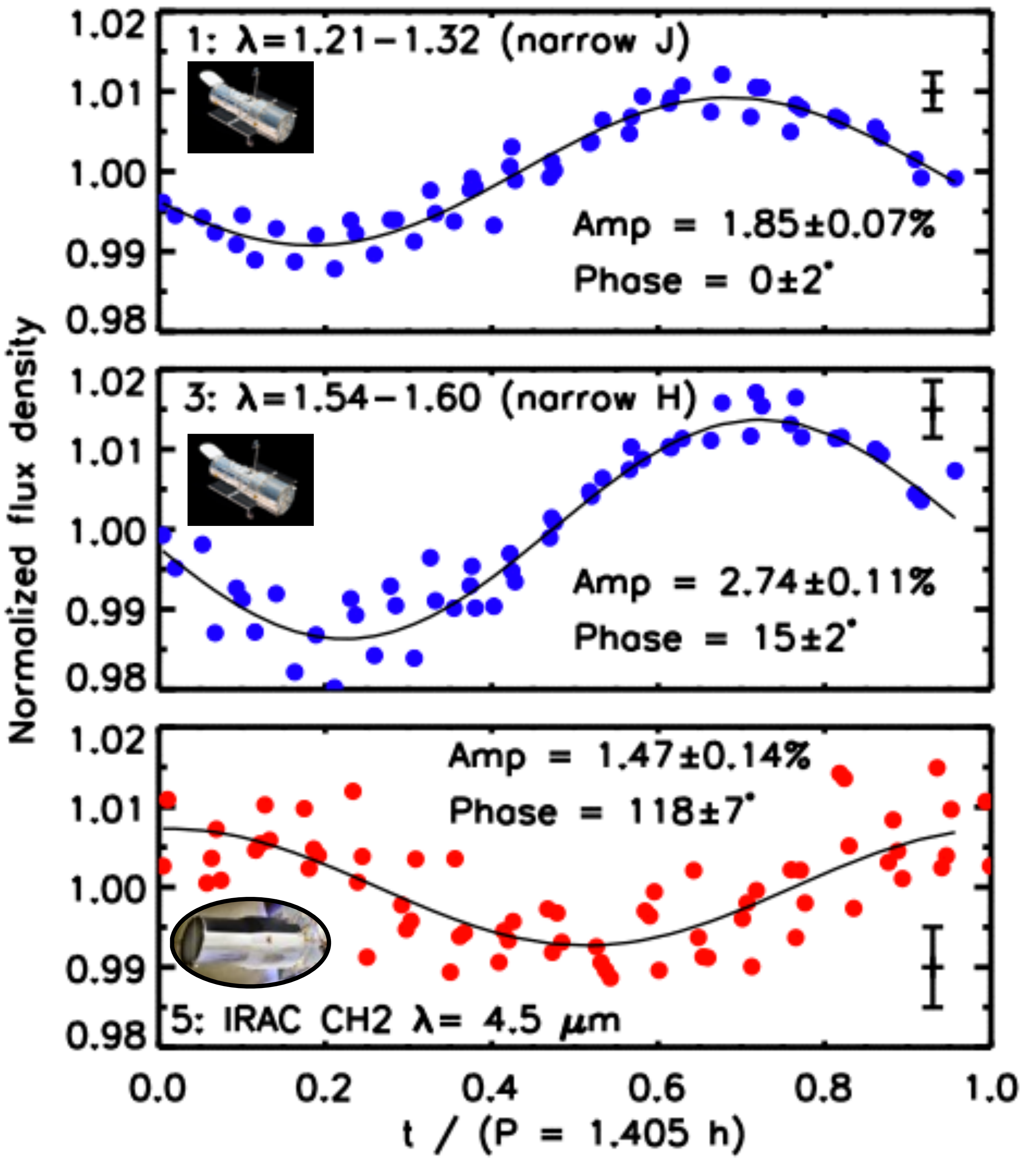
Min. and Max. Spectra

Ratio

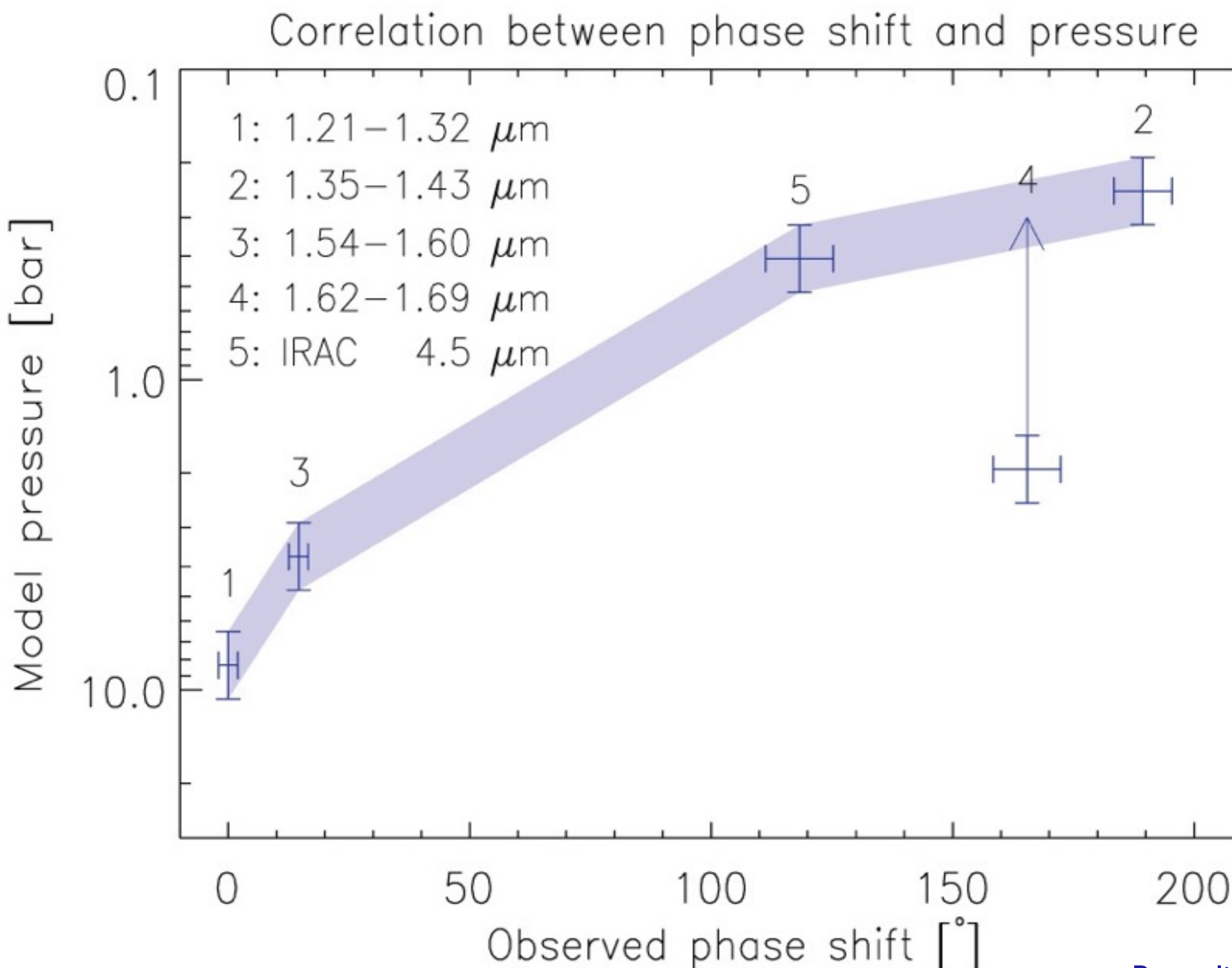


Buenzli et al. 2012

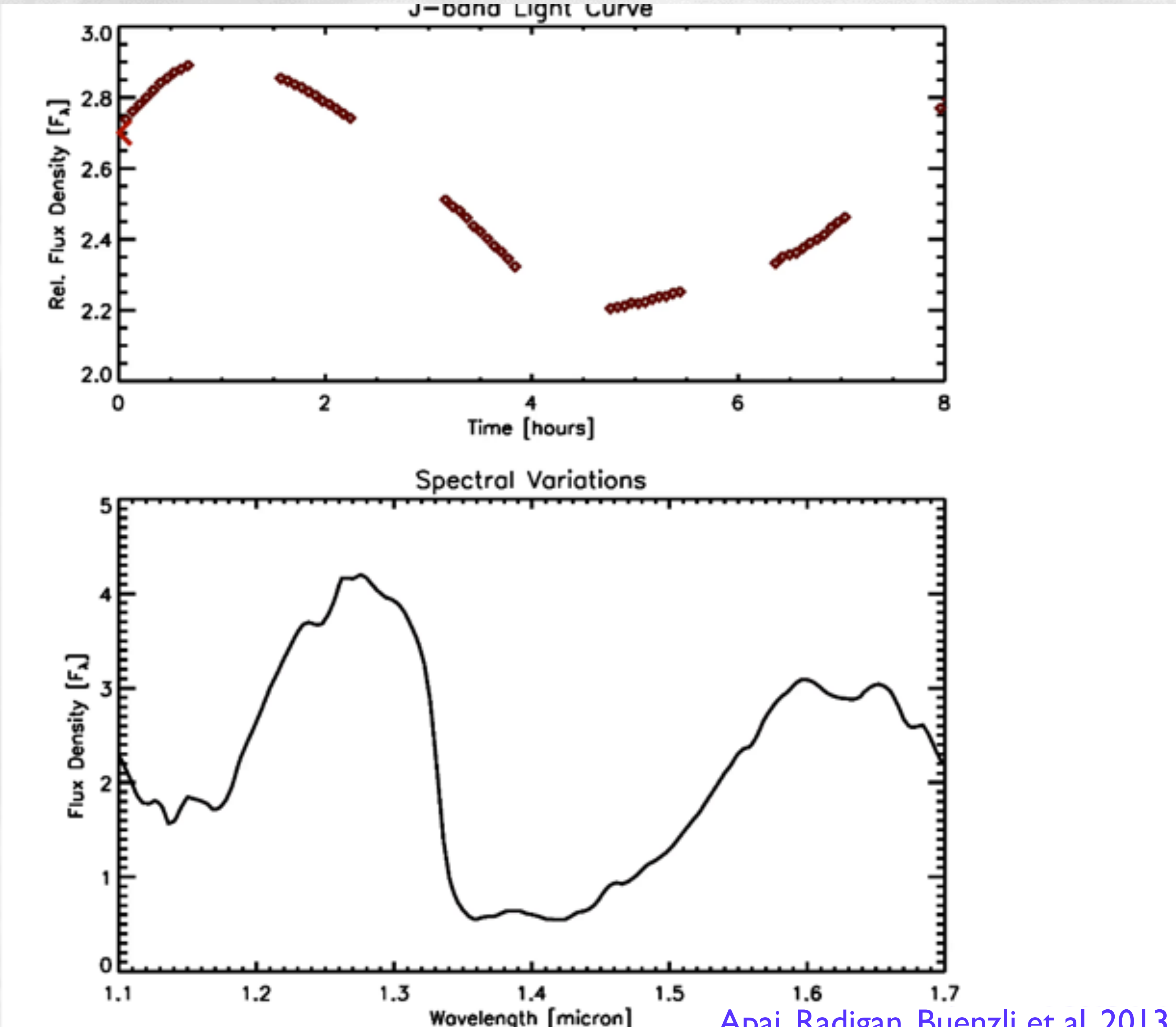




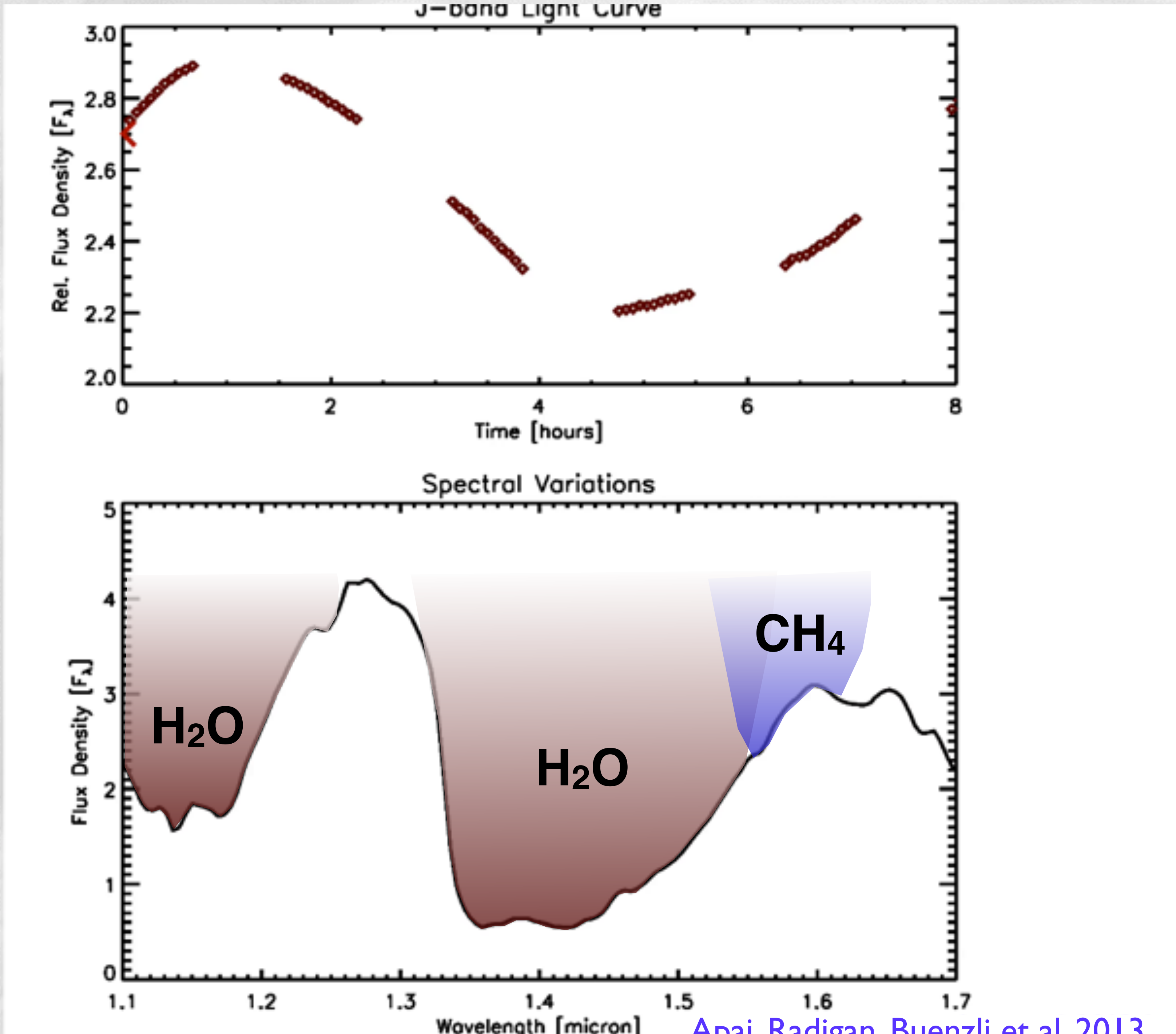
Buenzli, Apai et al. 2012 ApJ



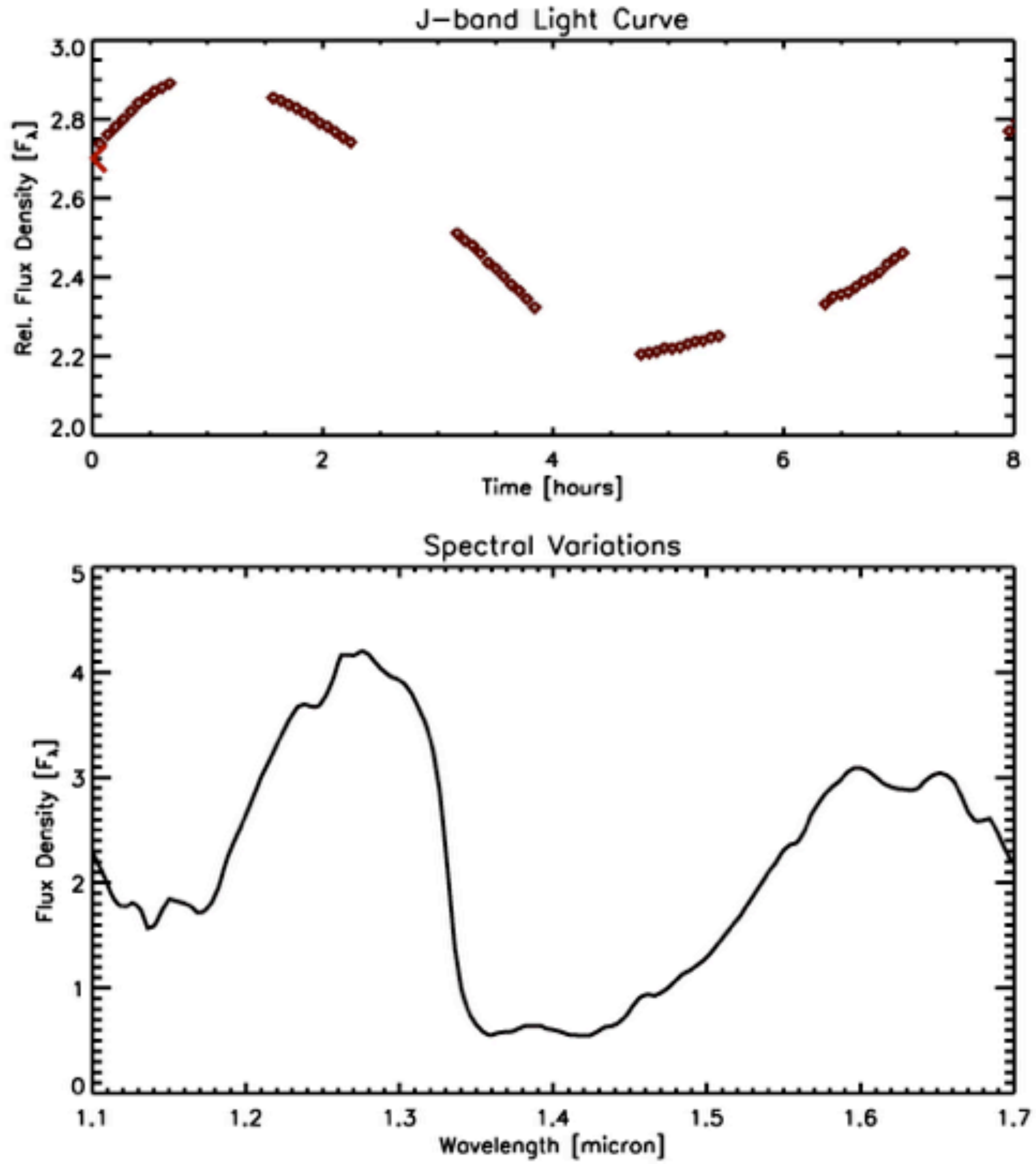
Buenzli et al. 2012



Apai, Radigan, Buenzli et al. 2013



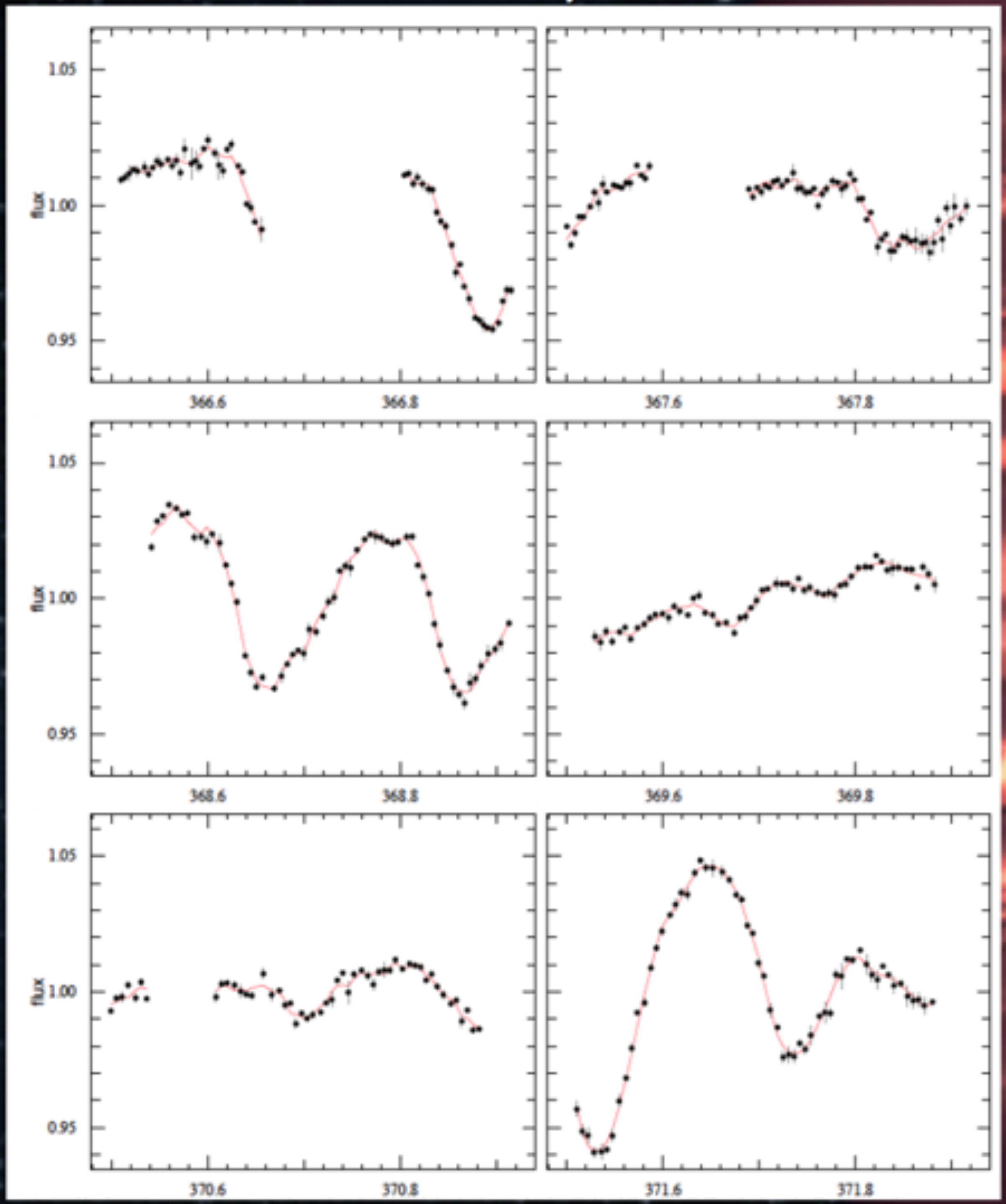
Apai, Radigan, Buenzli et al. 2013



Apai, Radigan, Buenzli et al. 2013

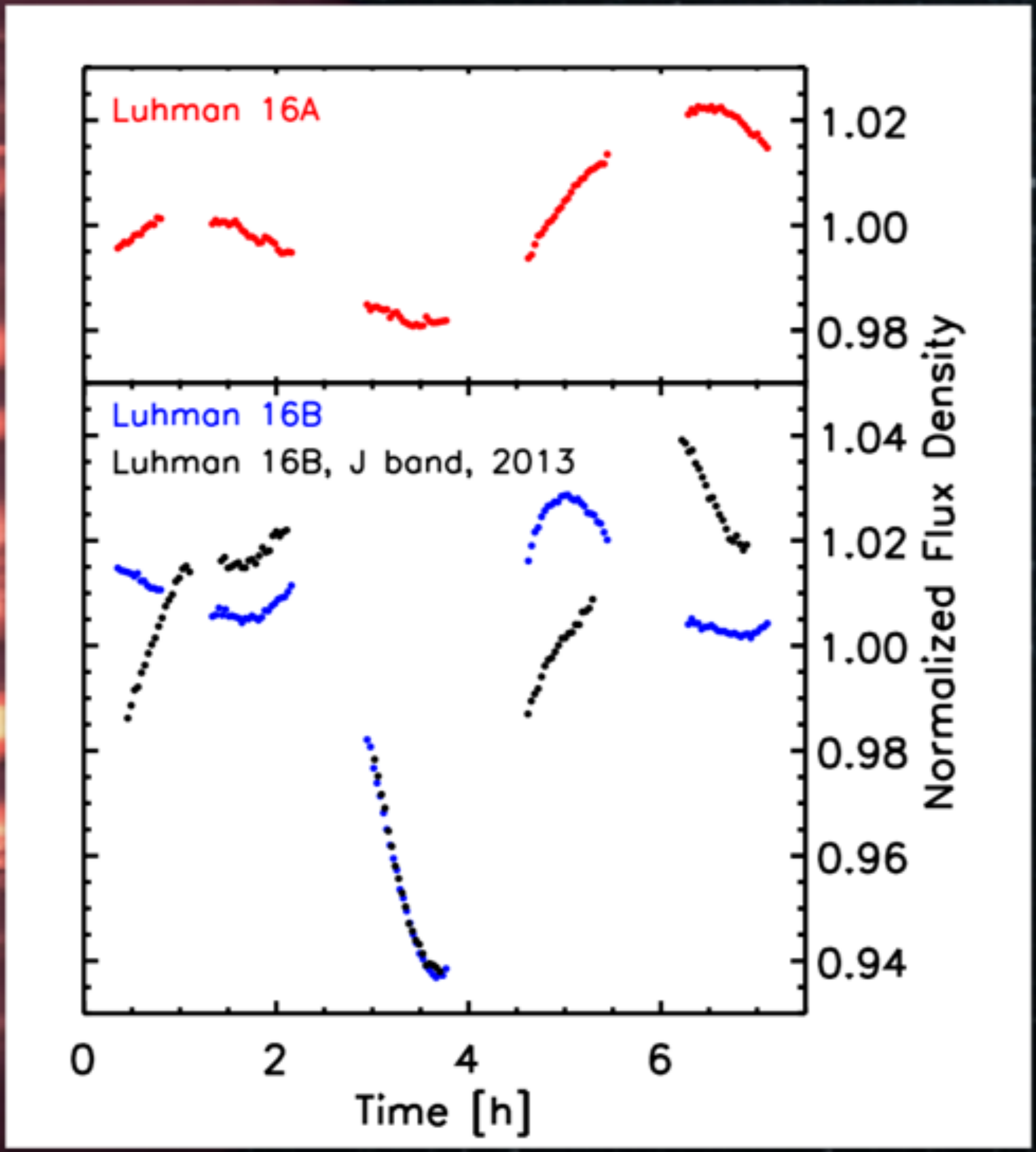
Luhman 16B – variability

Ground-based, unresolved

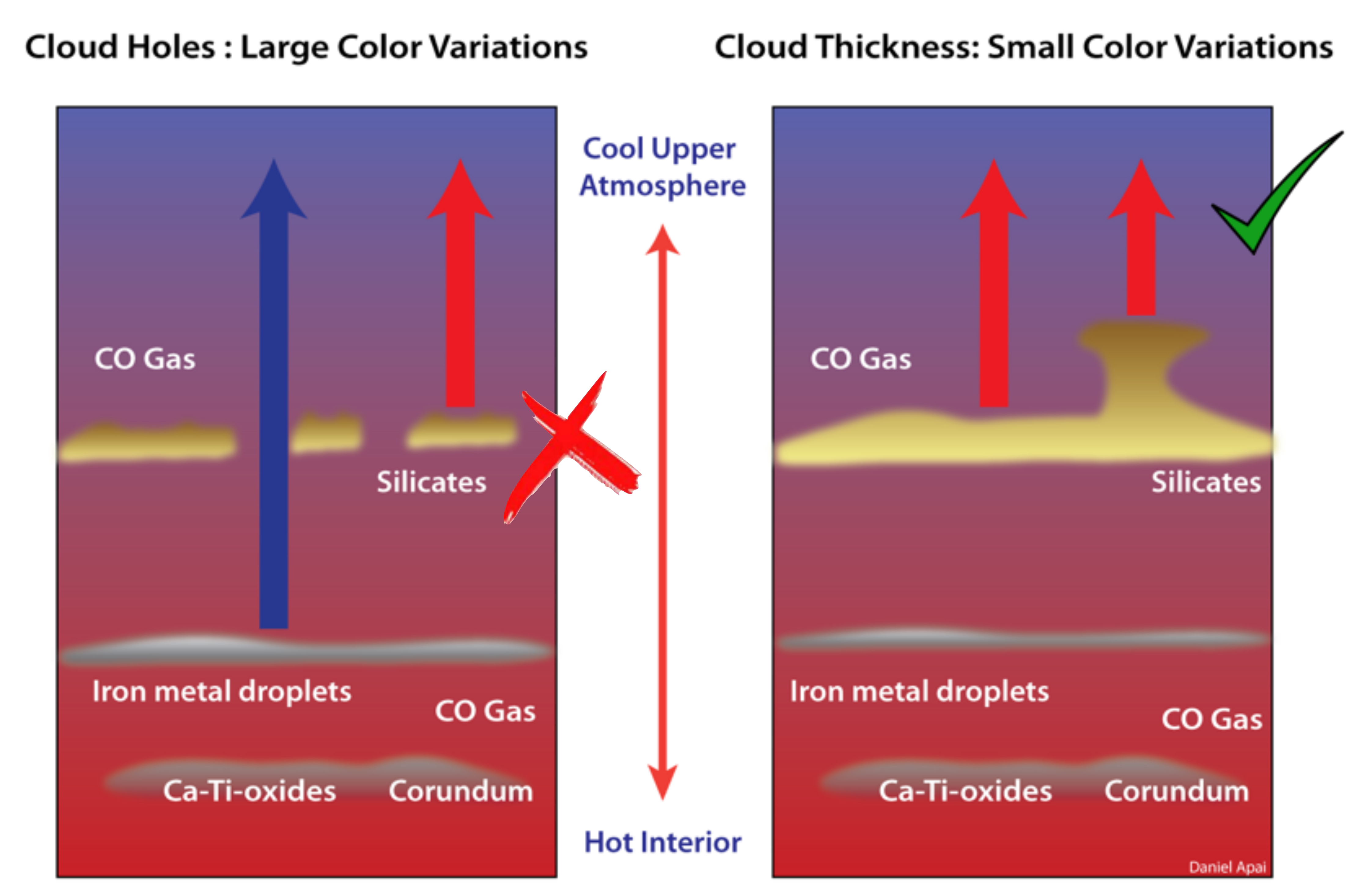


Gillon et al. 2013

HST resolved

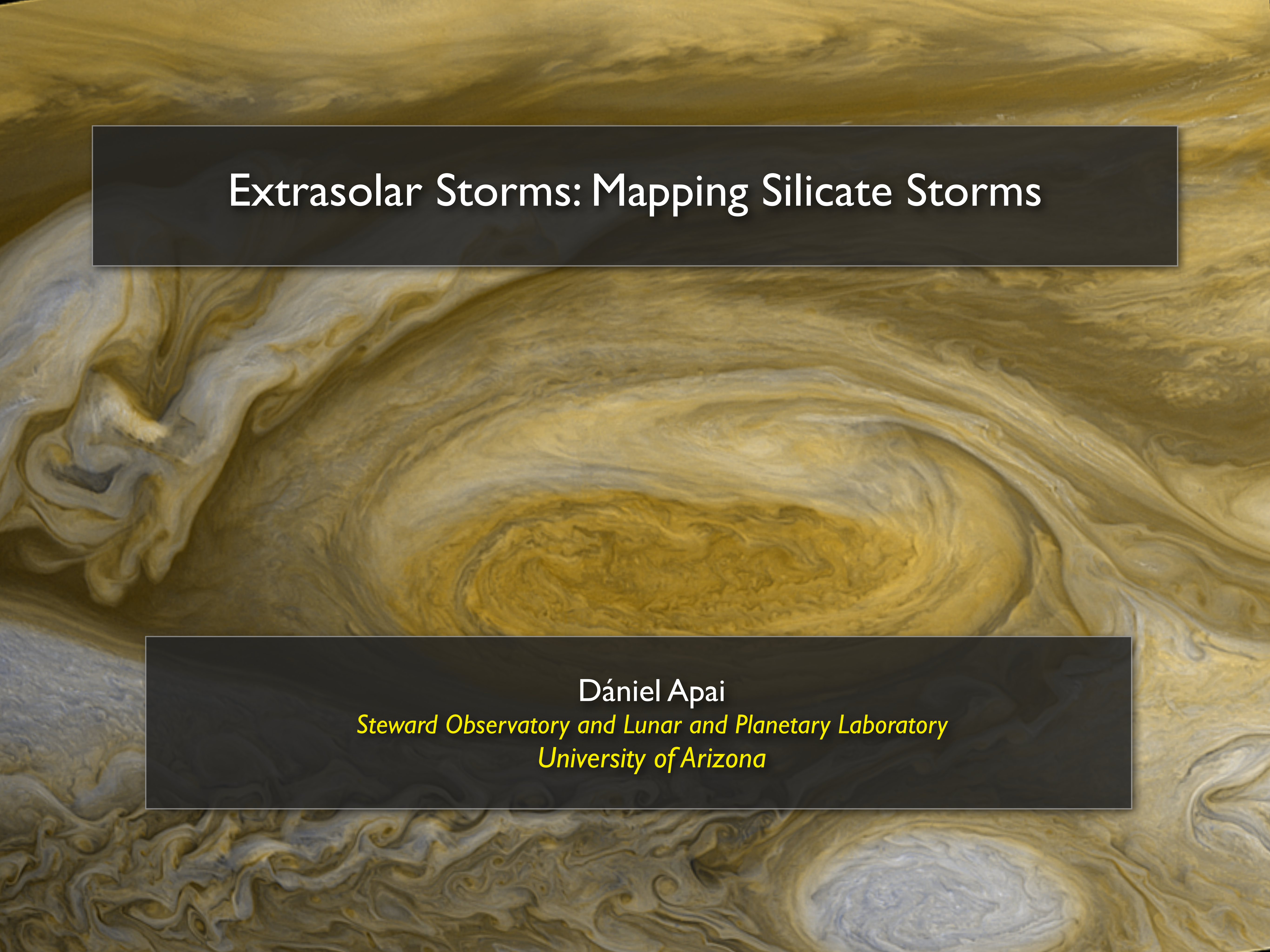


Buenzli et al. 2015, Buenzli et al. in prep.



1) First spectral maps of an ultracool atmosphere
2) Warm Thin - Cooler Thick clouds
3) Only a single type of thick cloud
4) Spectral signature of the difference

Apai, Radigan, Buenzli et al. 2013; Buenzli et al. 2015; Buenzli et al. 2015 in prep.



Extrasolar Storms: Mapping Silicate Storms

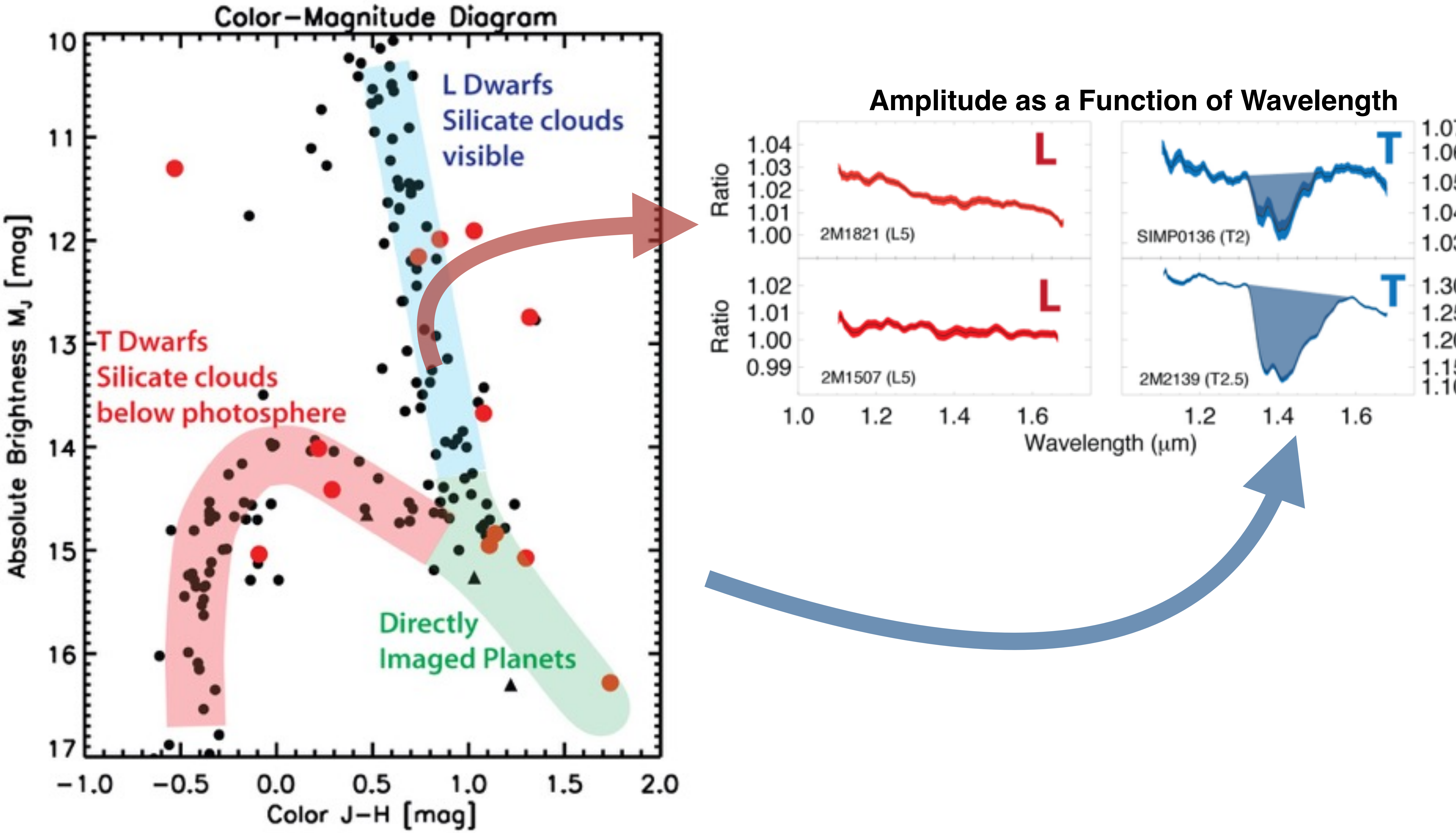
Dániel Apai
Steward Observatory and Lunar and Planetary Laboratory
University of Arizona

5 Hubble Space Telescope programs
PI Daniel Apai, ~220 orbits

Including:

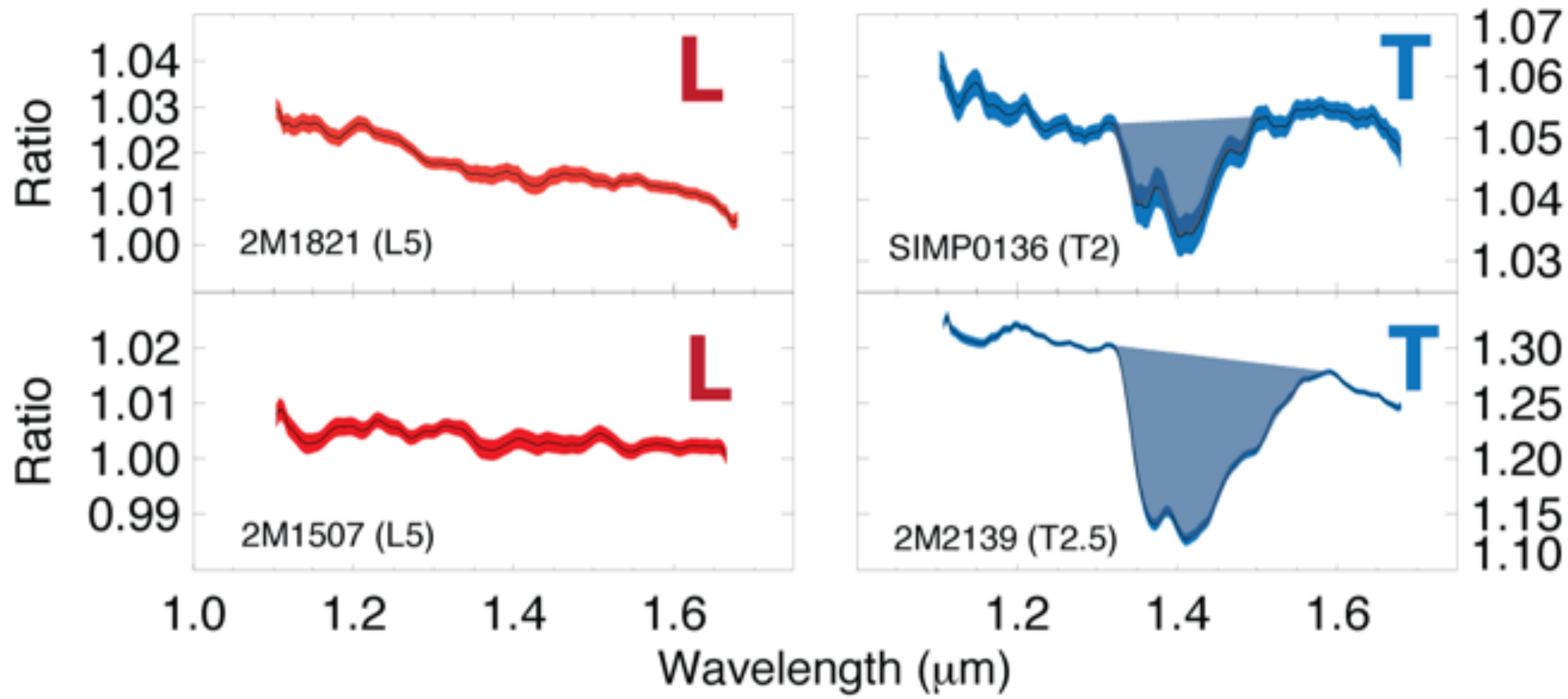
Cycle-9 *Extrasolar Storms*
PI: Daniel Apai 1,144 Spitzer hours + 24 HST orbits

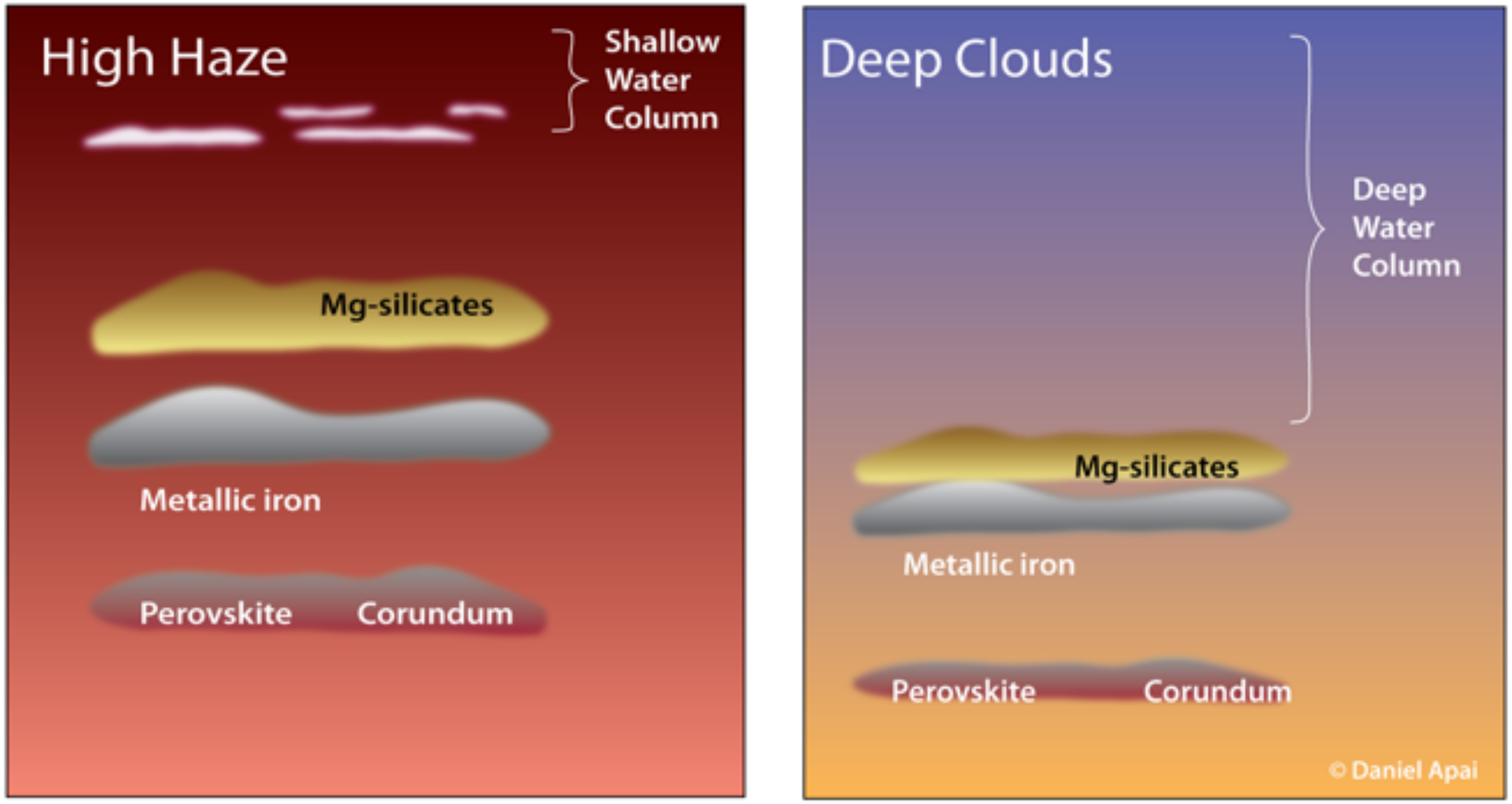
Cloud Atlas: Large Treasury Program
PI Daniel Apai, 112 orbits



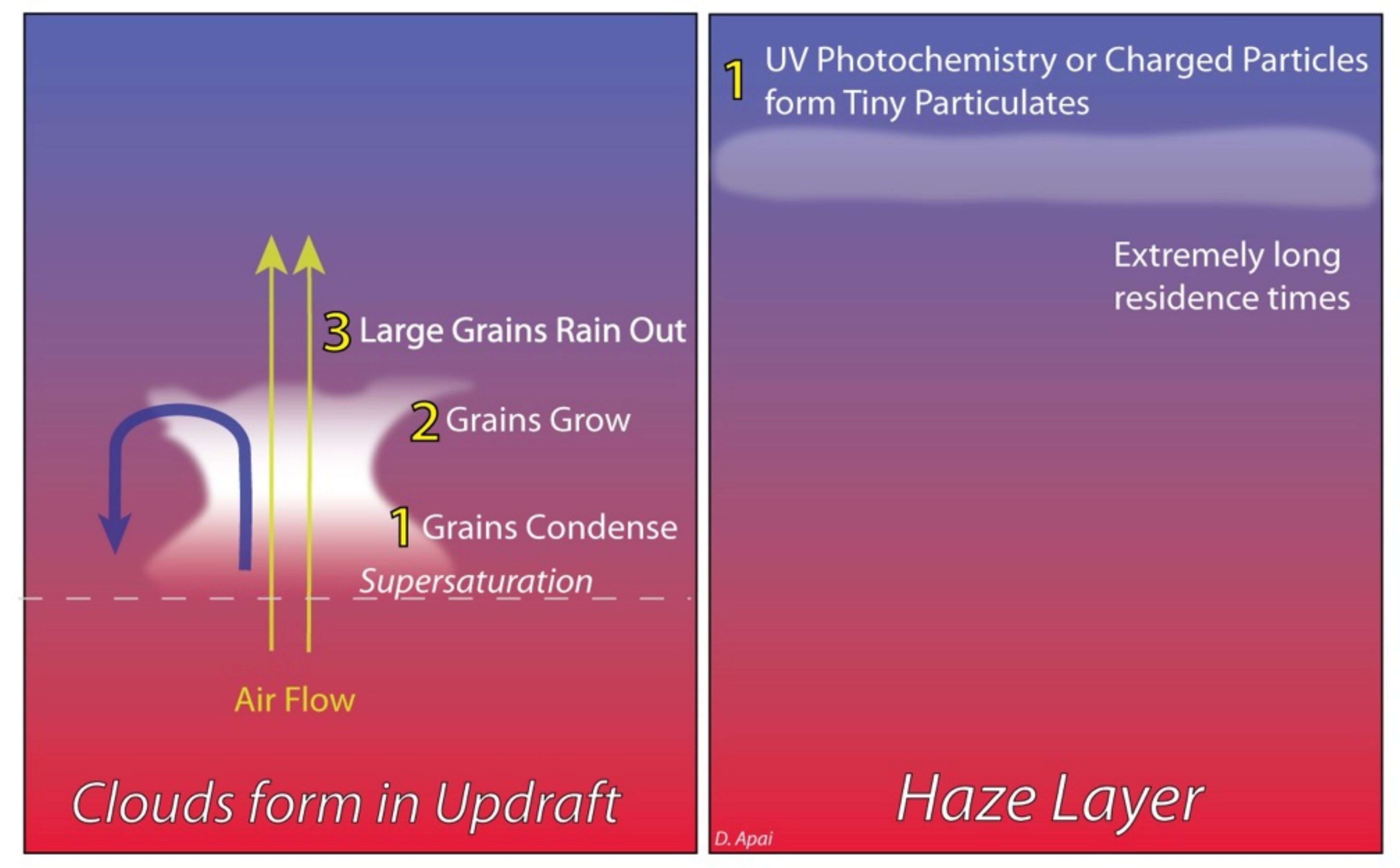
Yang, Apai et al. 2015 ApJ

Water-band Amplitude as Cloud Depth Probe

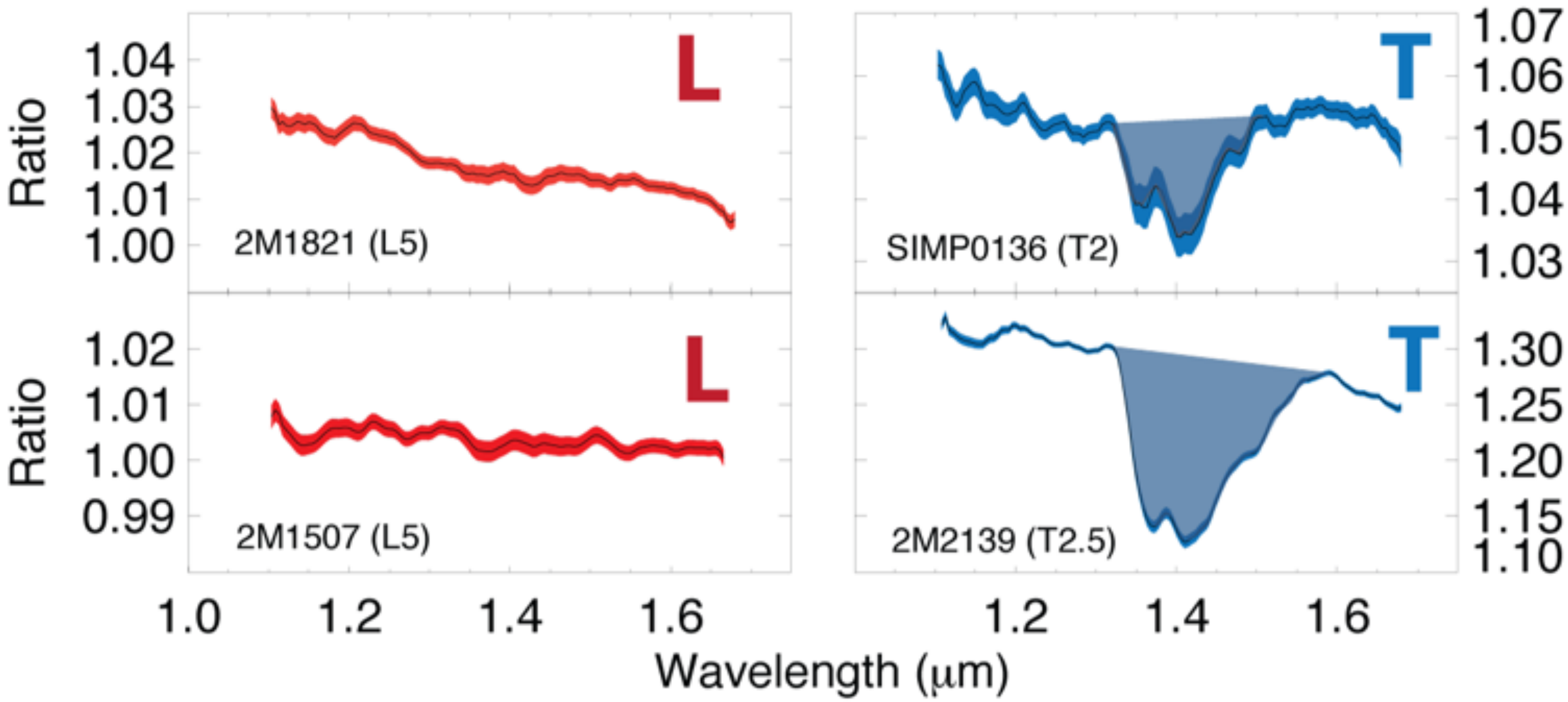




Yang, Apai et al. 2015 ApJ


3 Large Grains Rain Out
2 Grains Grow
1 Grains Condense
Supersaturation
Air Flow
Clouds form in Updraft
1 UV Photochemistry or Charged Particles form Tiny Particulates
Extremely long residence times
Haze Layer
D. Apai

Water-band Amplitude as Cloud Depth Probe



1) First spectral maps of L dwarfs
2) No reduced amplitude in the water band
3) High haze in L dwarfs, deeper clouds in L/T dwarfs

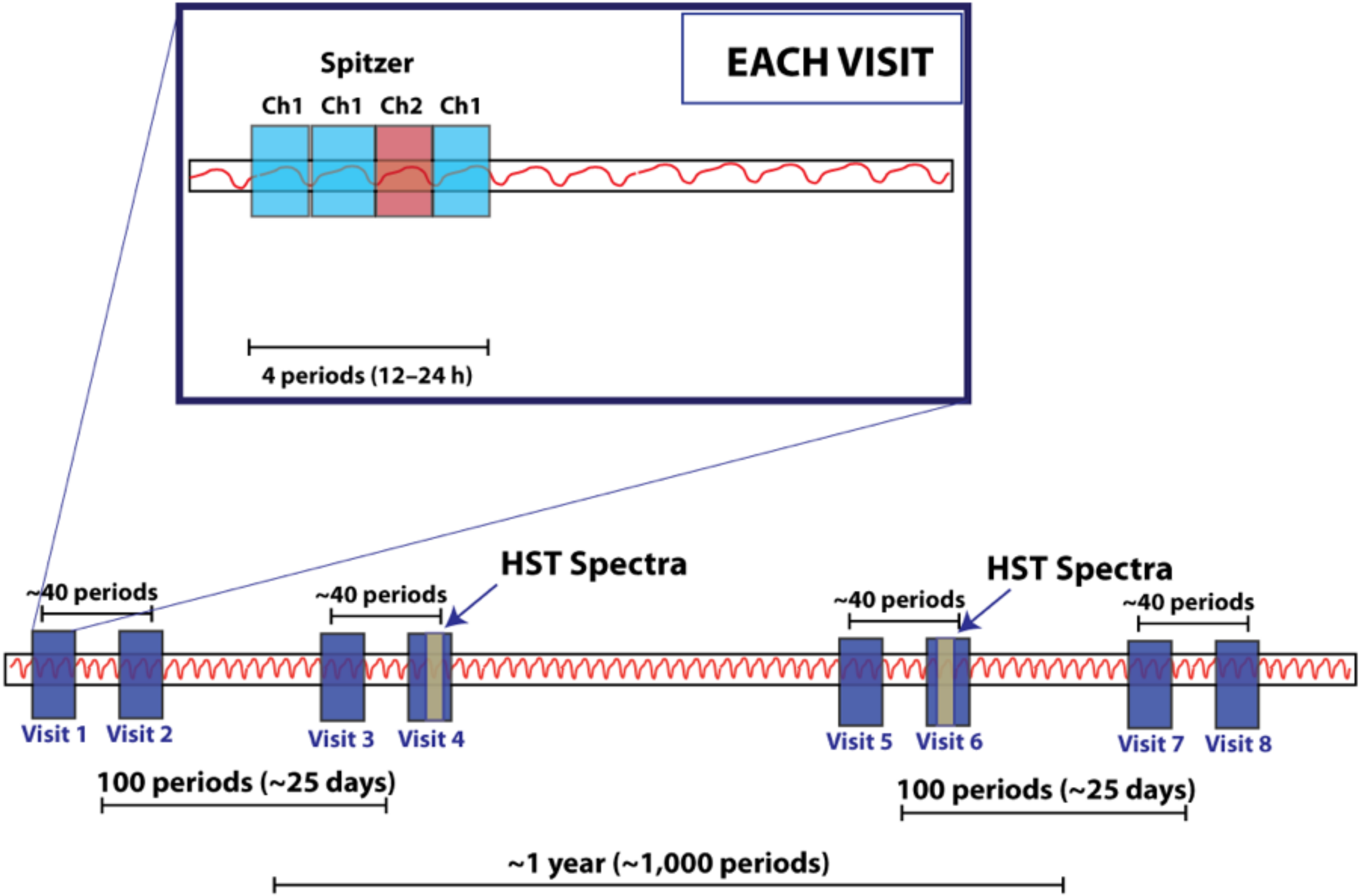
Yang, Apai et al. 2015 ApJ

What Physical/Chemical Processes Drive the Light Curve Evolution in Brown Dwarfs?

Extrasolar Storms

Exploration of Atmospheric Dynamics in Brown Dwarfs
PI: Apai
(1,144 hour Spitzer + 24 HST orbits)

Lightcurves Sampling Multiple Timescales



Extrasolar Storms Preliminary Results

1) All six targets variable
2) All show LC evolution
3) LC evolution timescale ~P_{rot}

Mapping Ultracool Atmospheres with Aeolous

Theodora Karalidi
University of Arizona

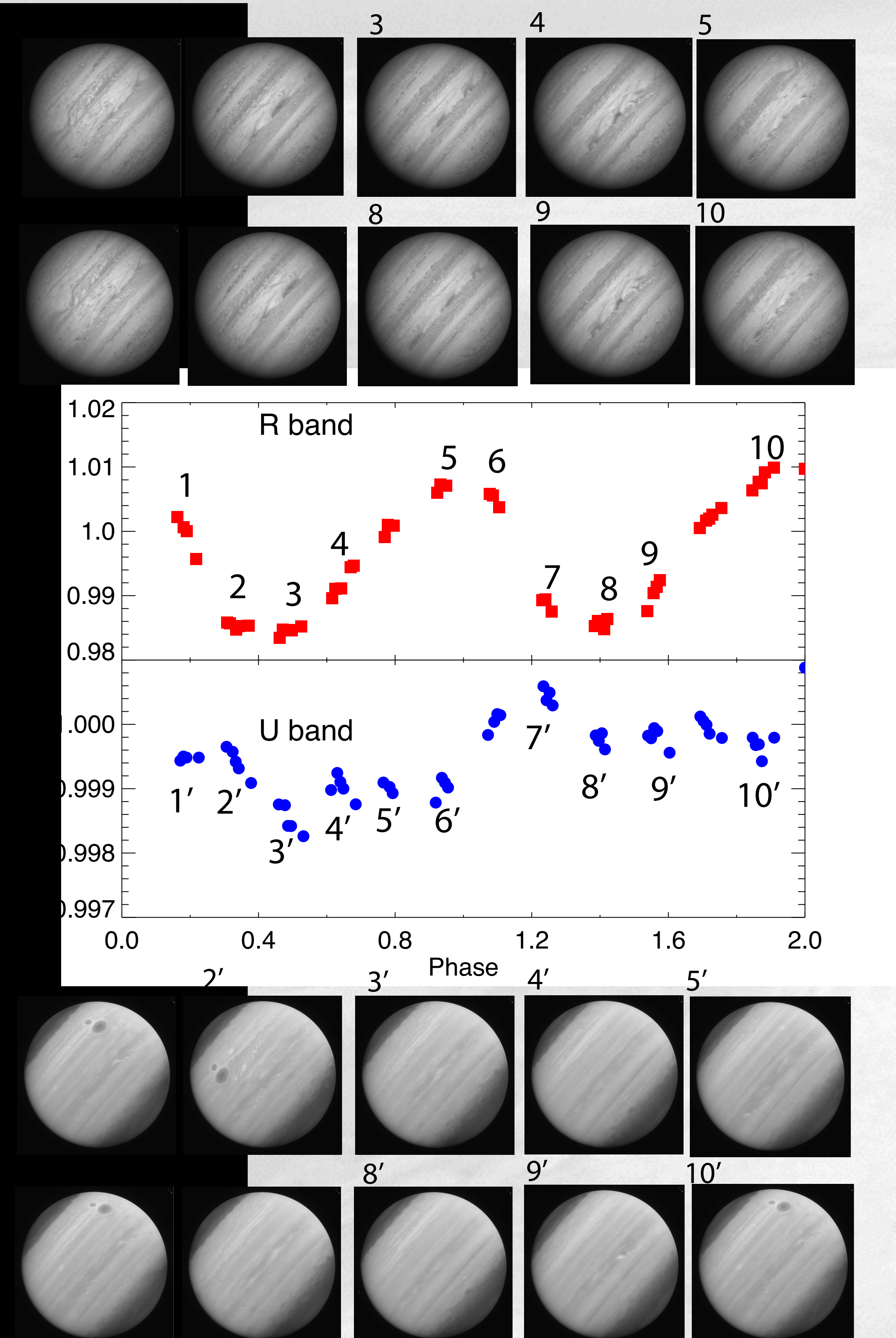
Aeolus

MCMC mapping code

Assume heterogeneities are elliptical spots (e.g. Great Red Spot)

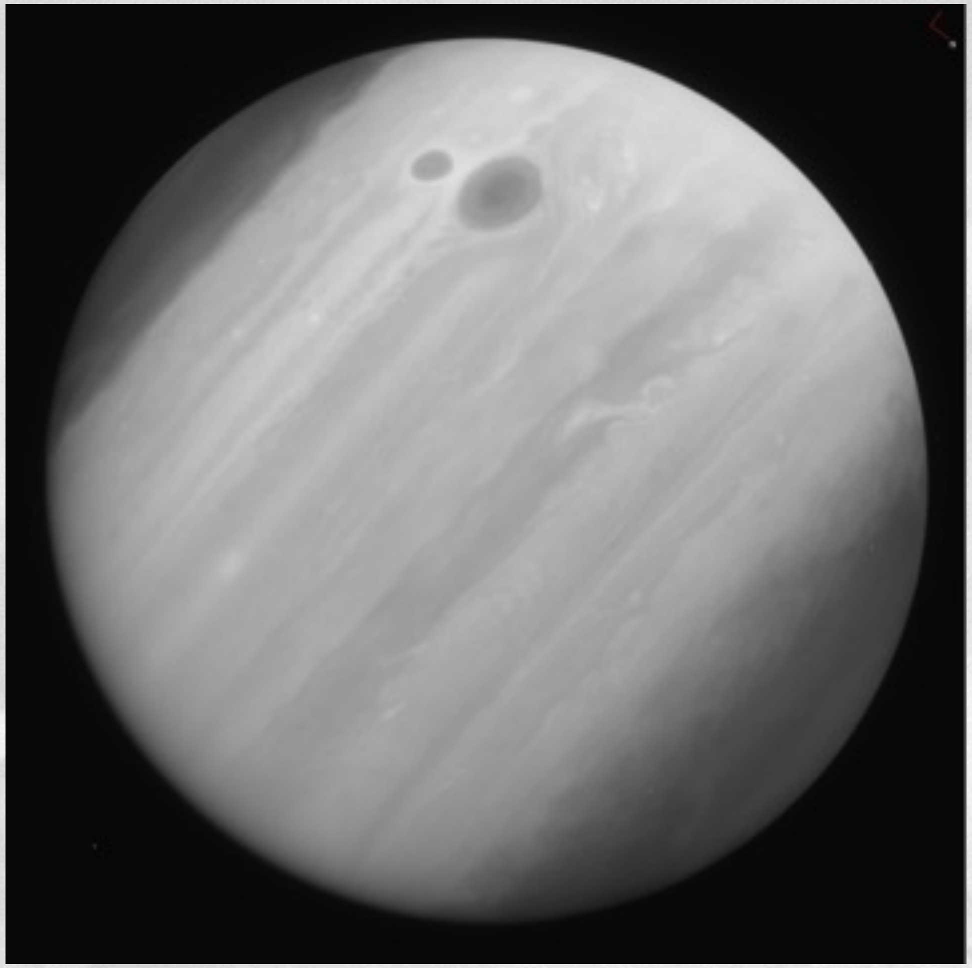
- Number of spots
- Location on disk
- Size of spot
- Contrast ratio to background TOA
- Inclination of brown dwarf/ (exo)planet
- Limb darkening

Karalidi, Apai et al., in prep.



lue) light curves of Jupiter. The uncertainties in the relative photometric measures (e
f the measured signal in either filter band. Corresponding snapshot images of Jupite
wn for helping the reader interpret the light curves.

Schneider and Vedovato



8

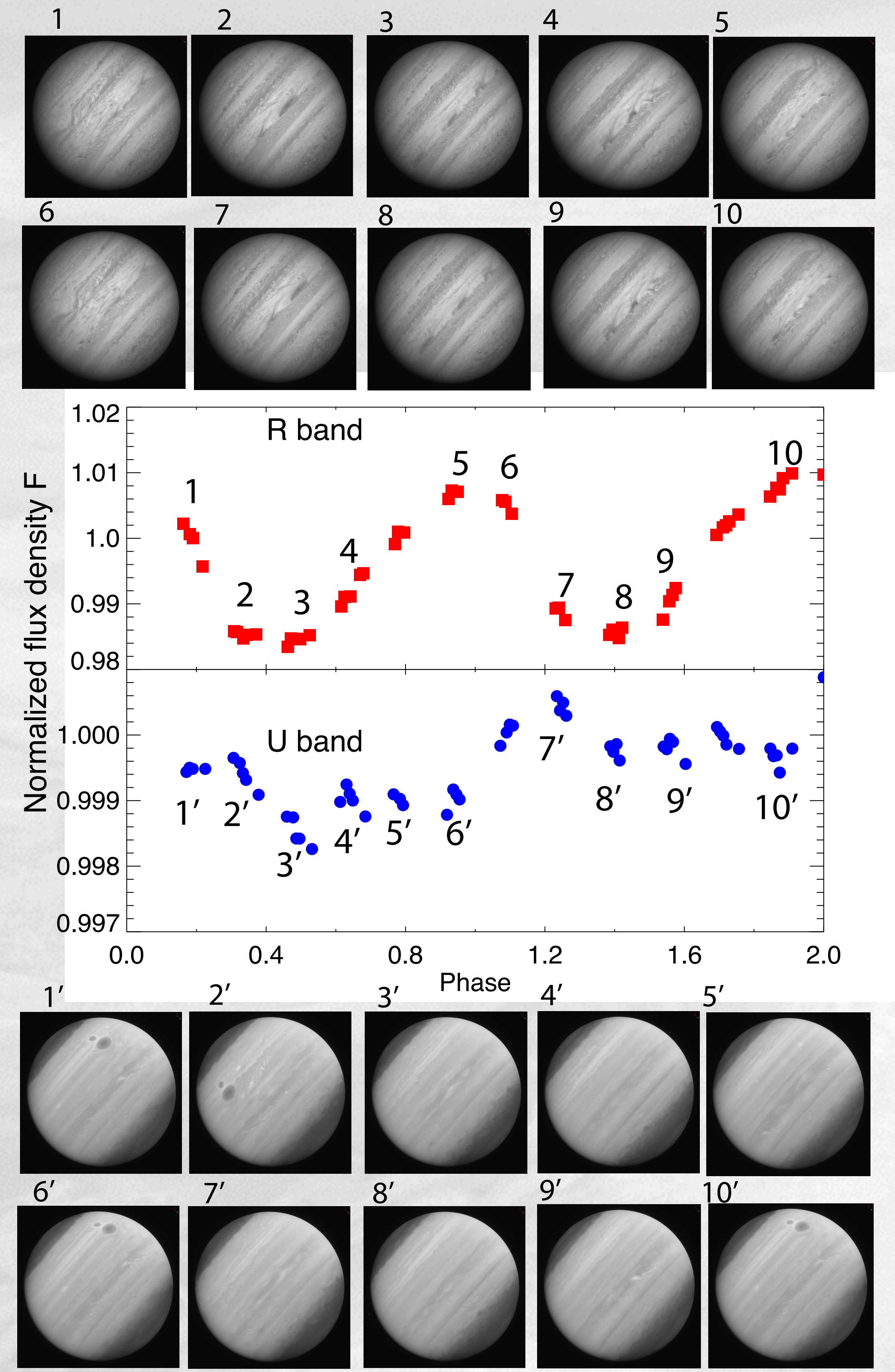
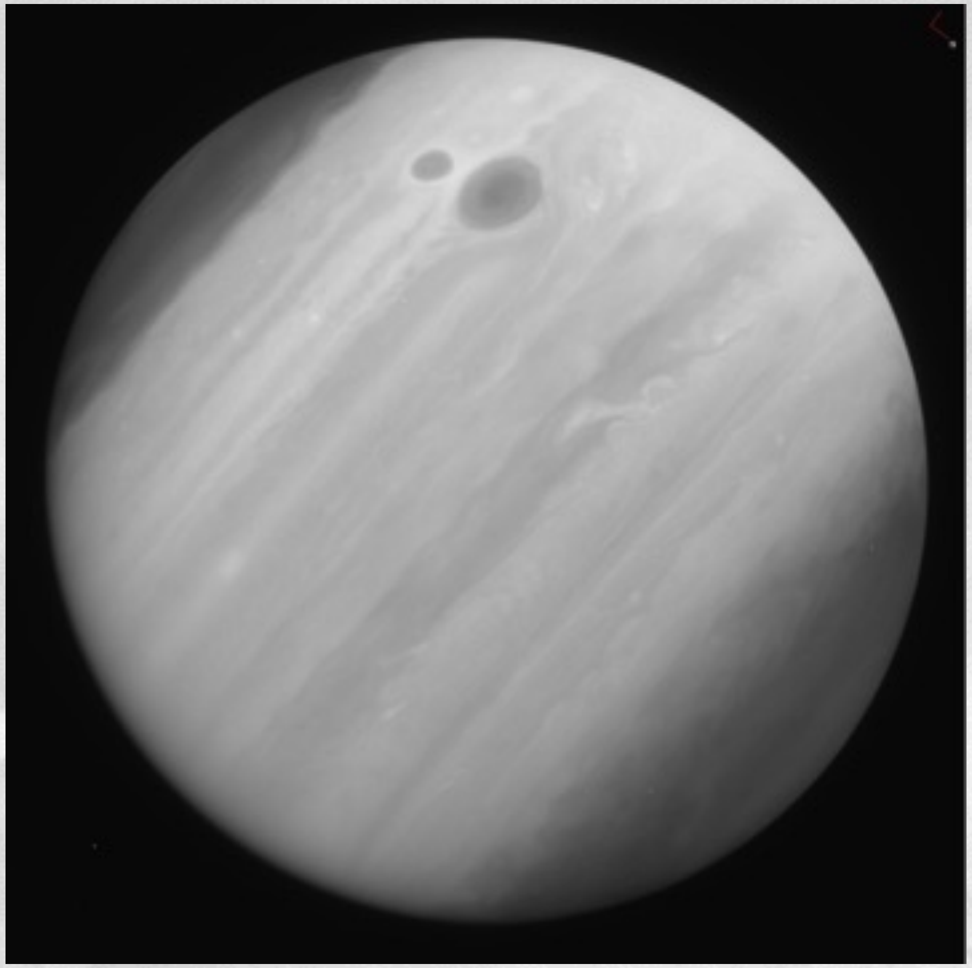


FIG. 5.— Normalized R (red) and U (blue) light curves of Jupiter. The uncertainties in the relative photometric measures (e are estimated as $1\sigma \leq 0.022\%\pm0.009\%$ of the measured signal in either filter band. Corresponding snapshot images of Jupite band (top) and U band (bottom) are shown for helping the reader interpret the light curves.

8



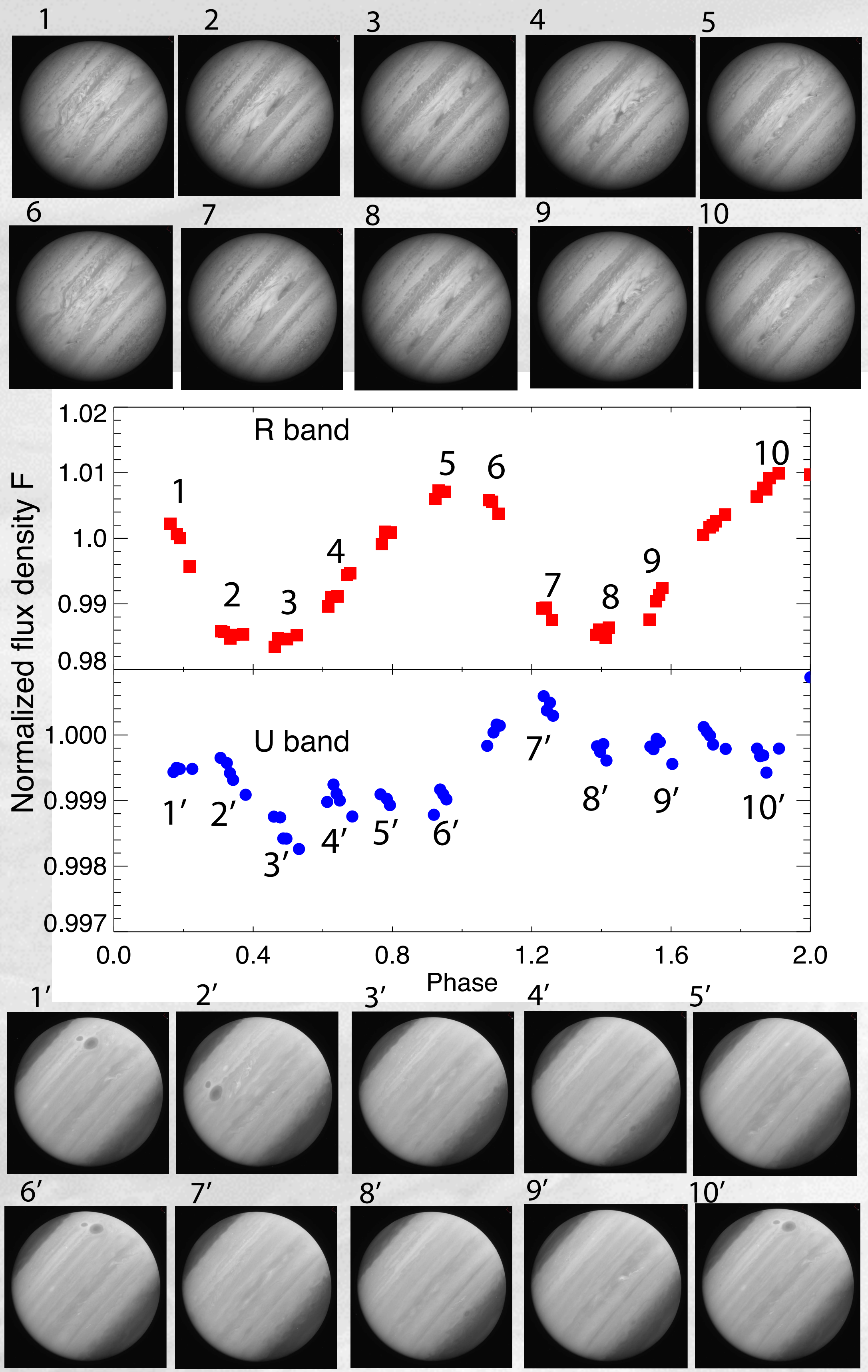
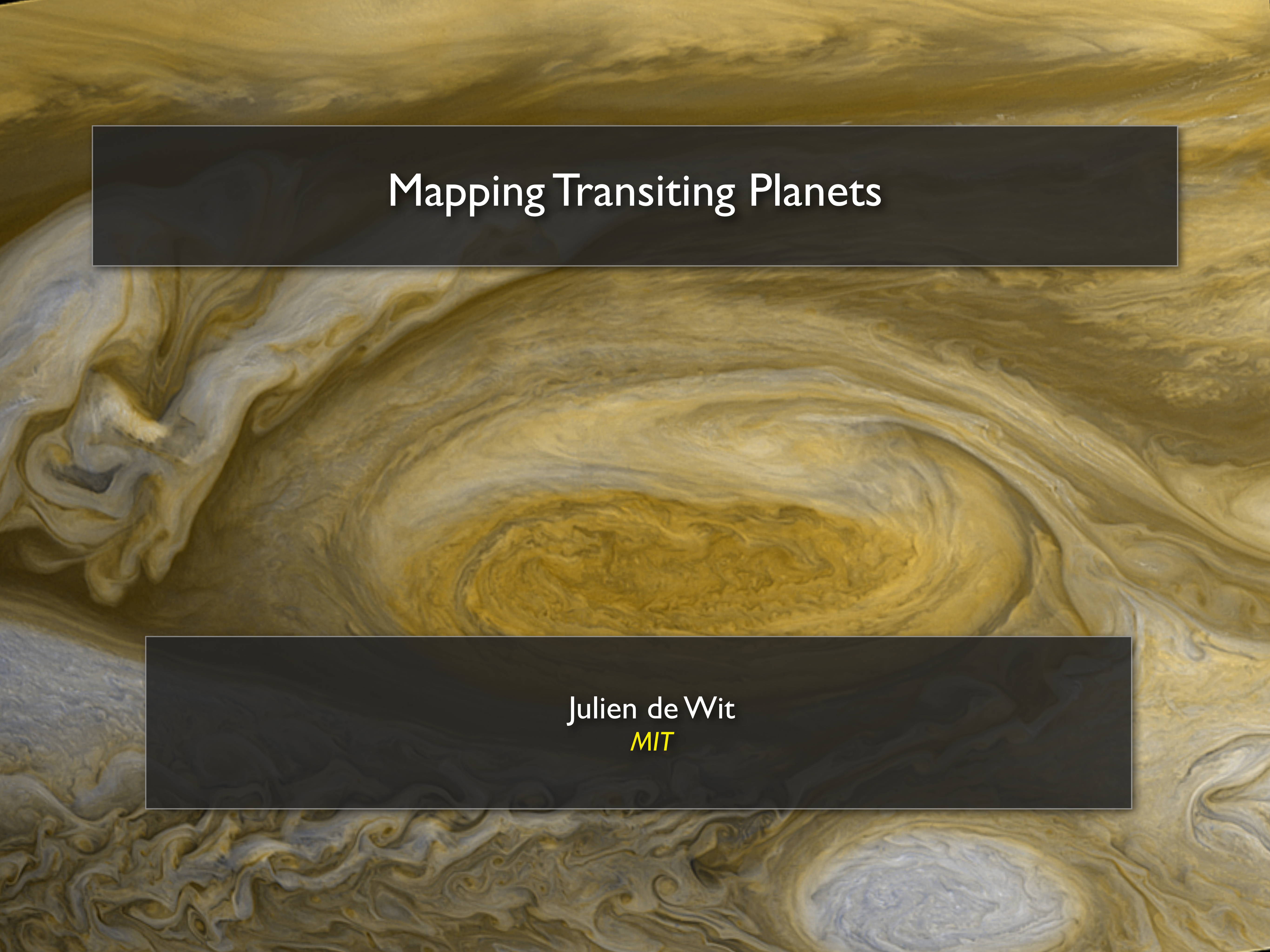


FIG. 5.— Normalized R (red) and U (blue) light curves of Jupiter. The uncertainties in the relative photometric measures (e are estimated as $1\sigma \leq 0.022\% \pm 0.009\%$ of the measured signal in either filter band. Corresponding snapshot images of Jupite band (top) and U band (bottom) are shown for helping the reader interpret the light curves.



Mapping Transiting Planets

Julien de Wit
MIT

How to Map Planets?

Monitoring the system flux variation over:

- Time

1. Phase-curve mapping (longitude)
2. Eclipse mapping (longitude & latitude)

- Wavelength

3. Multi-wavelength phase-curve mapping (altitude & longitude)
4. Multi-wavelength eclipse mapping (altitude, longitude & latitude)

→ 3D Maps

How to Map Planets?

1. Phase curves

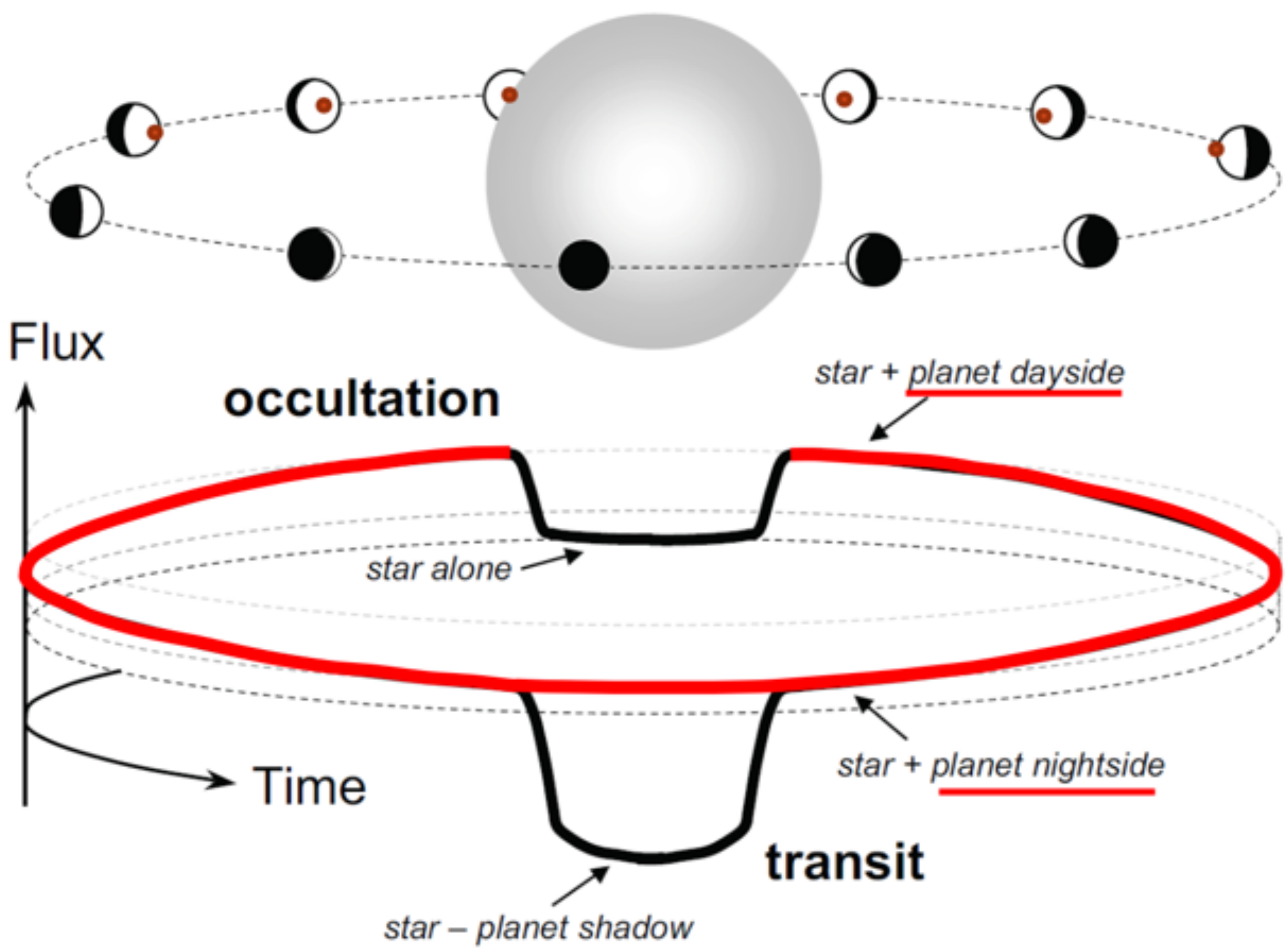
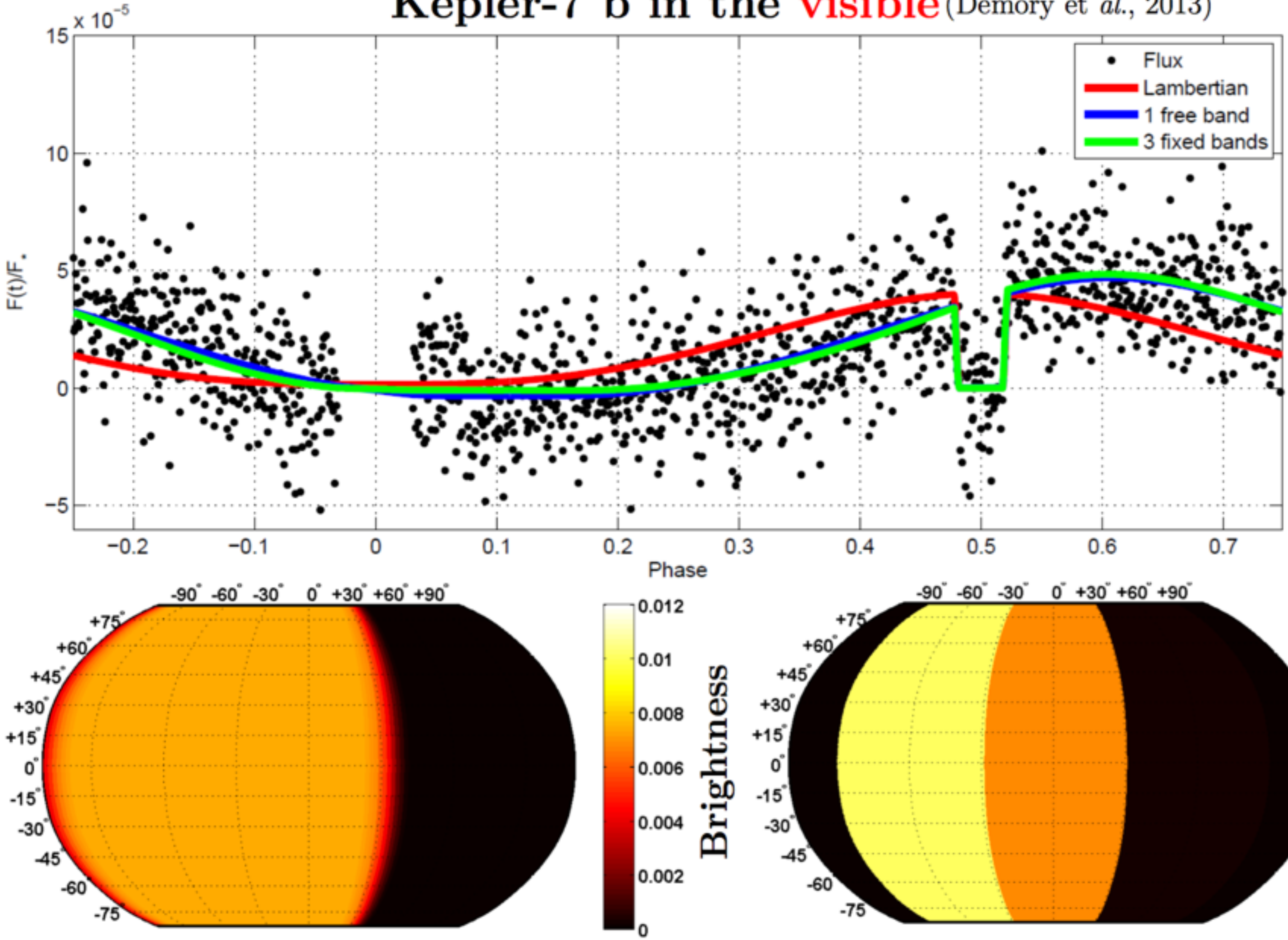


Figure from Winn (2010).

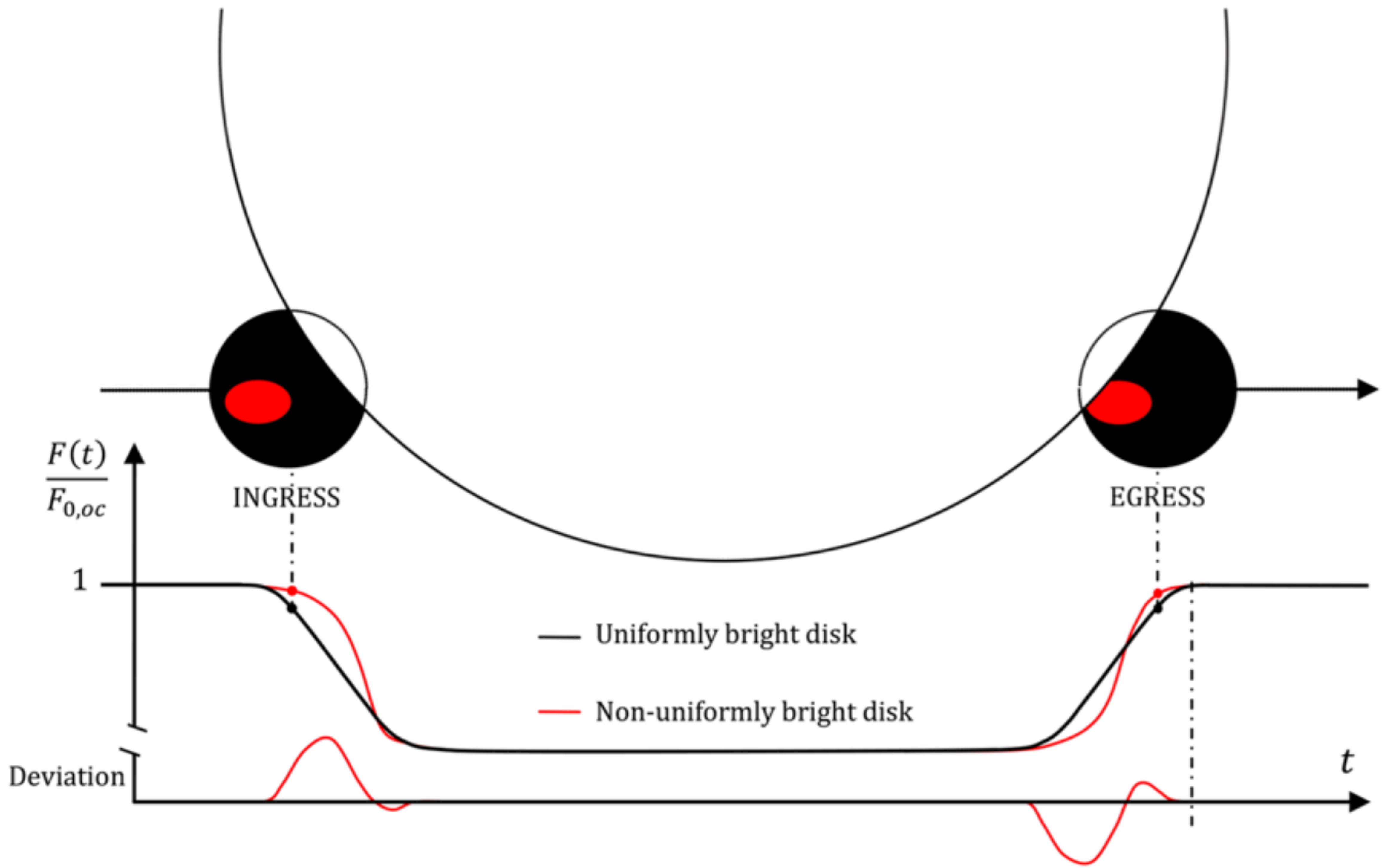
1. Phase curves

Kepler-7 b in the visible (Demory et *al.*, 2013)



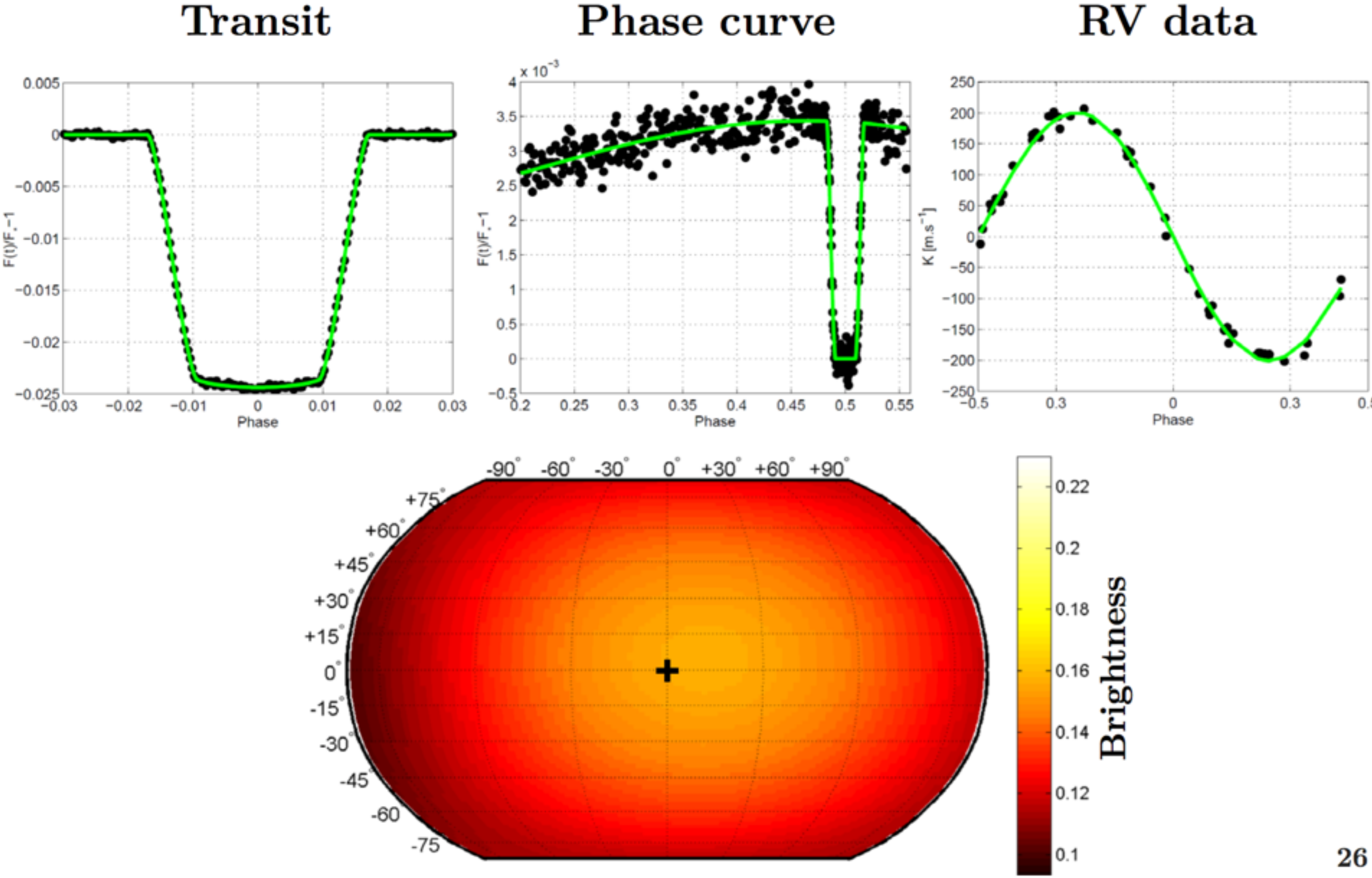
How to Map Planets?

2. Eclipse mapping



2. Eclipse Mapping:

HD 189733 b in the infrared (de Wit et *al.*, 2012)



3. Multi-channel phase curves

WASP-43 b in the near-infrared (Stevenson et al., 2014)

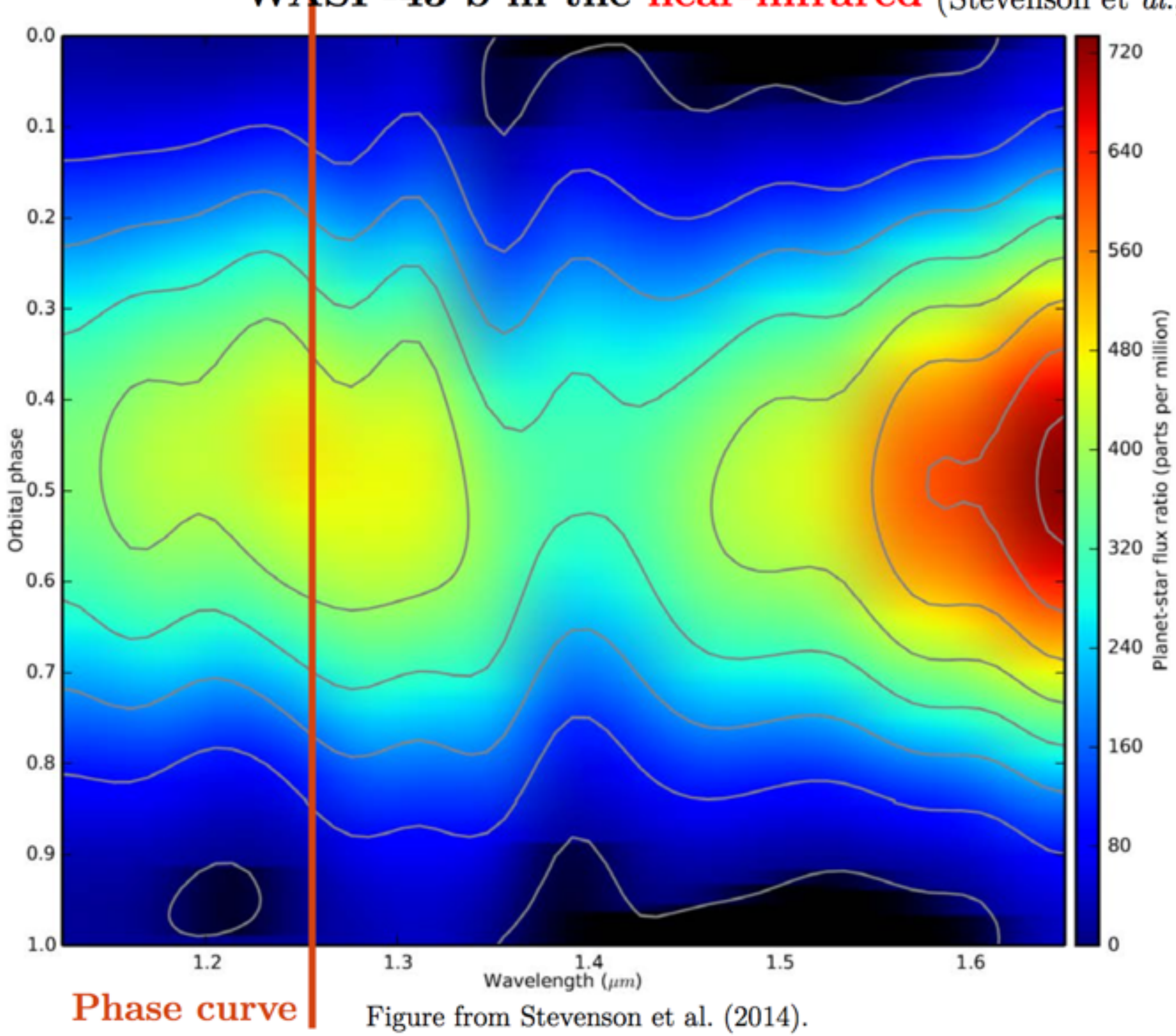


Figure from Stevenson et al. (2014).

3. Multi-channel phase curves

From emission spectra...

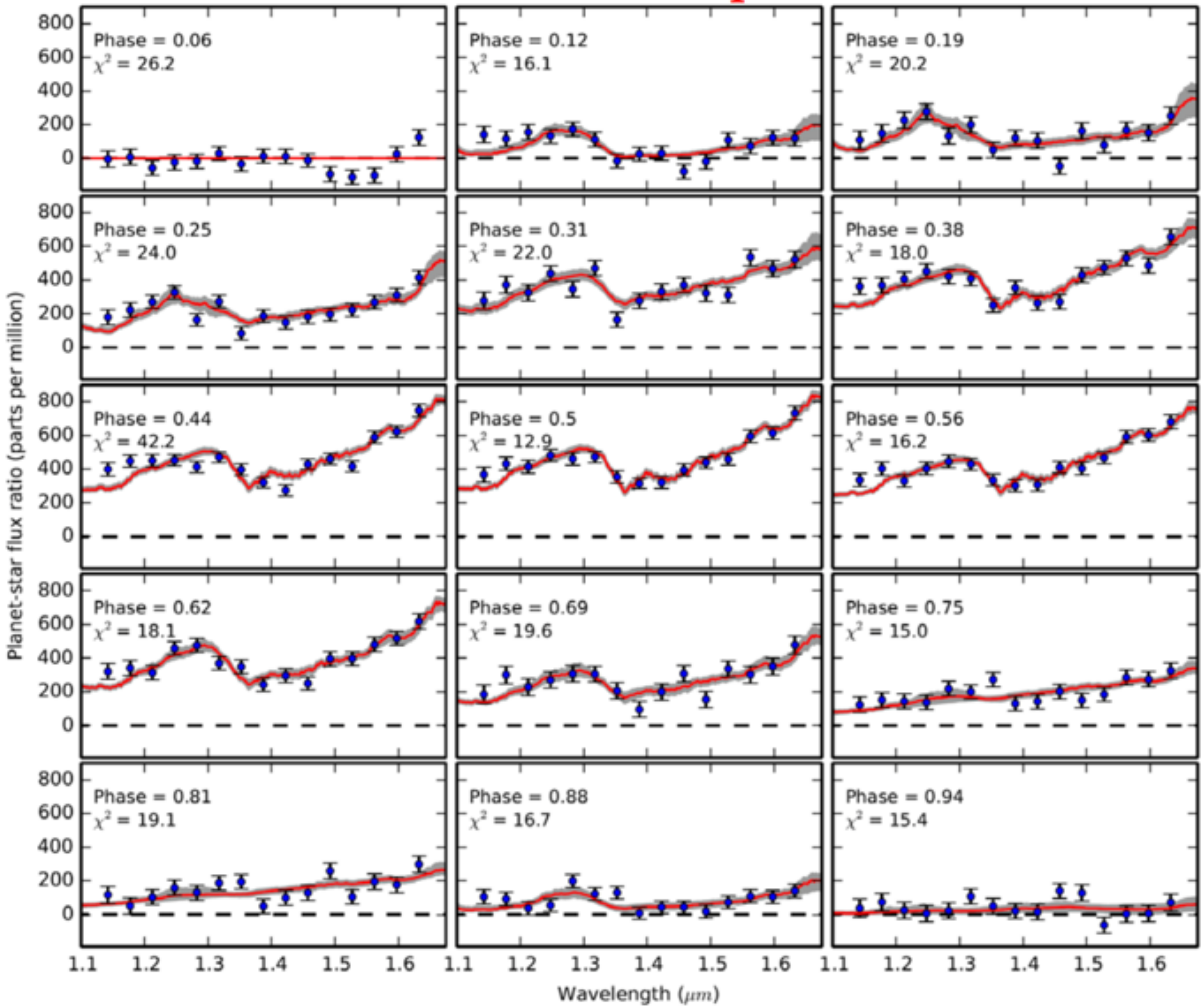


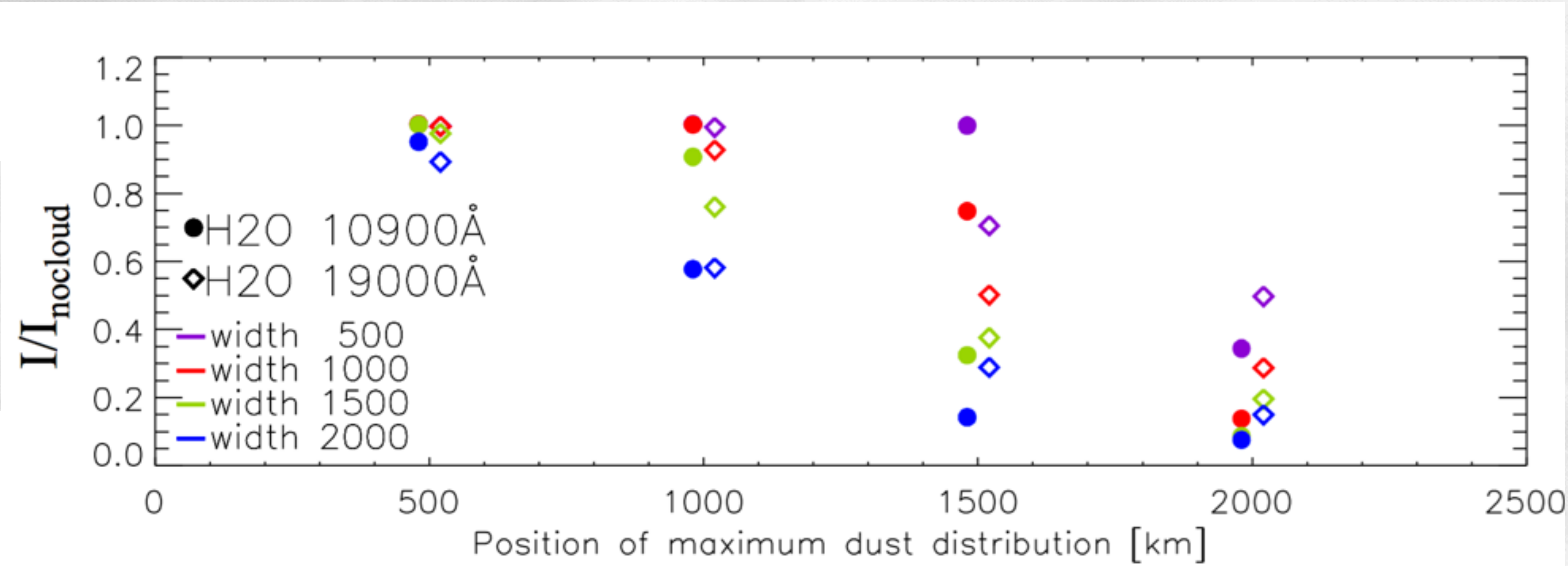
Figure from Stevenson et al. (2014).

Effects of Clouds on Reflection Properties of Hot Jupiters

Nadine Afram
Kiepenheuer Institute

Clouds important in exoplanetary atmosphere

- model molecular spectra with/out clouds
- vary cloud parameters (dust density, dust size, cloud position, cloud extension)
- study changes in molecular signal due to cloud parameter change, as molecules are formed at different depths => info about cloud

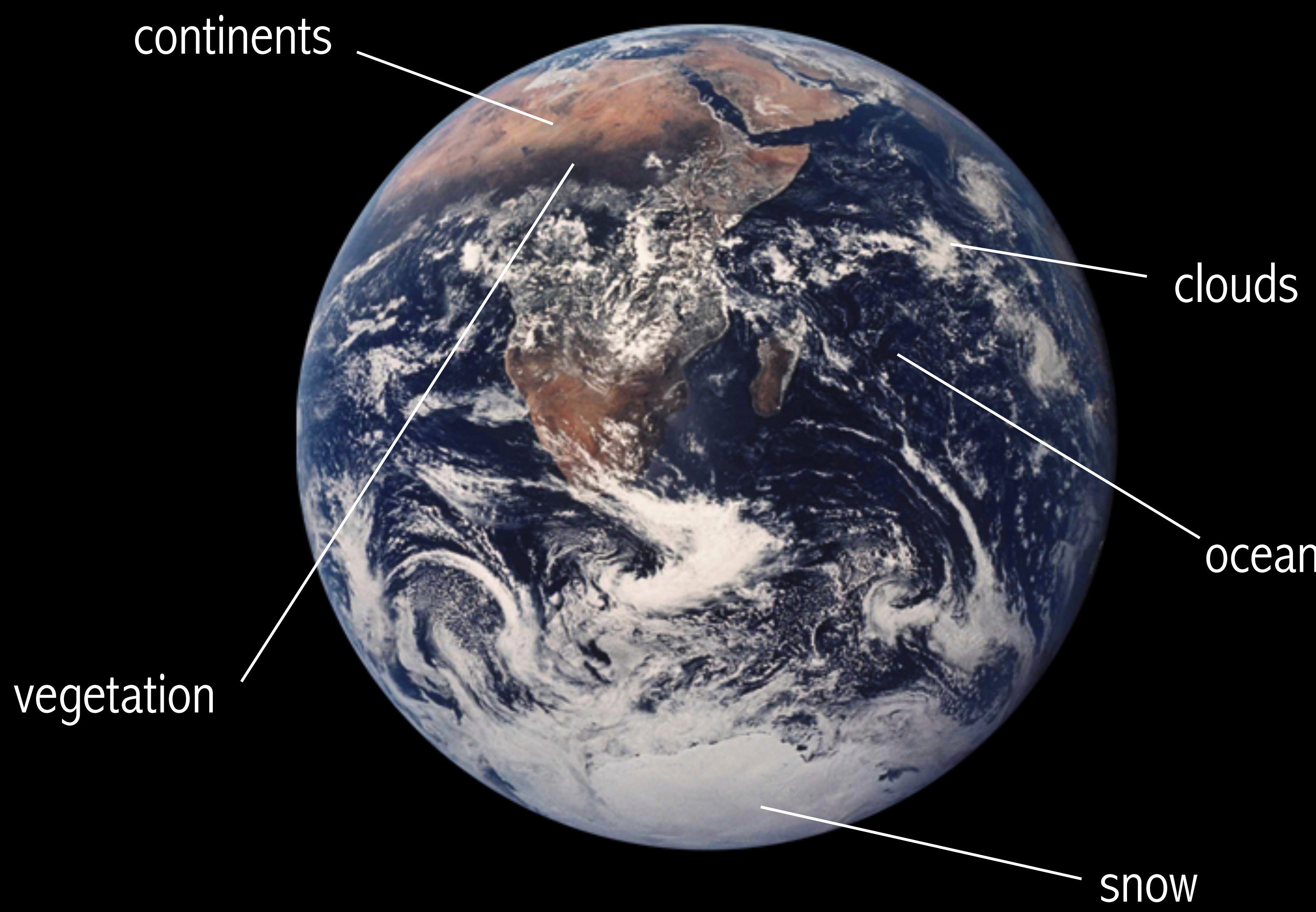


10 nm dust size

Mapping Earth-like Planets

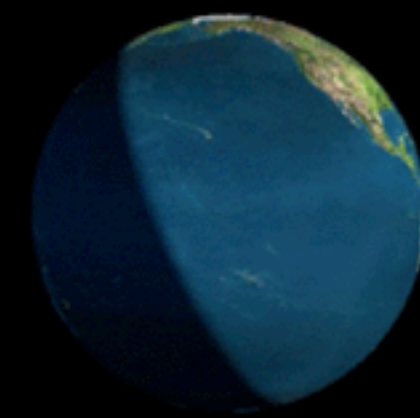
Yuka Fujii
ELSI Tokyo

Heterogeneous Surfaces !

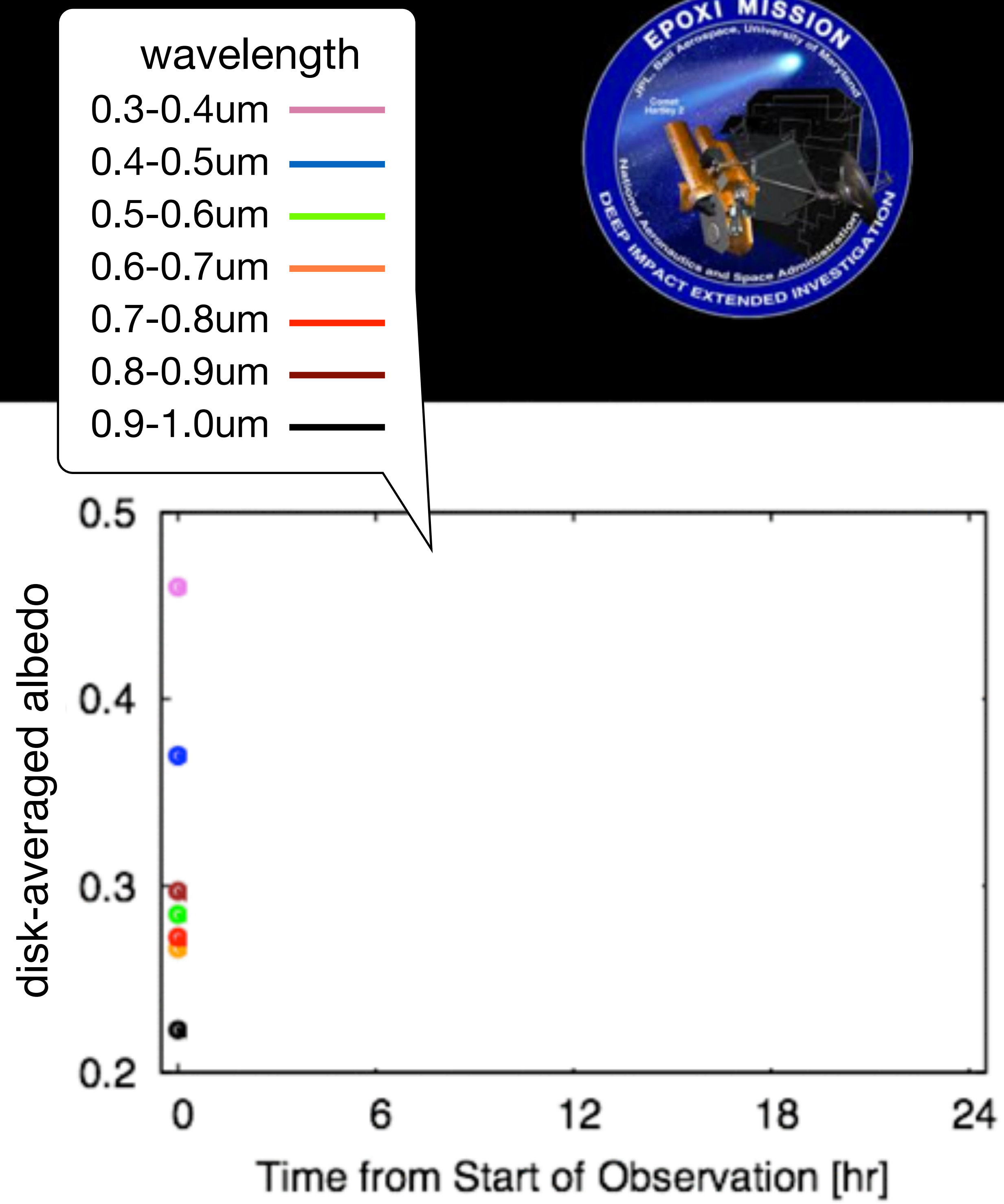


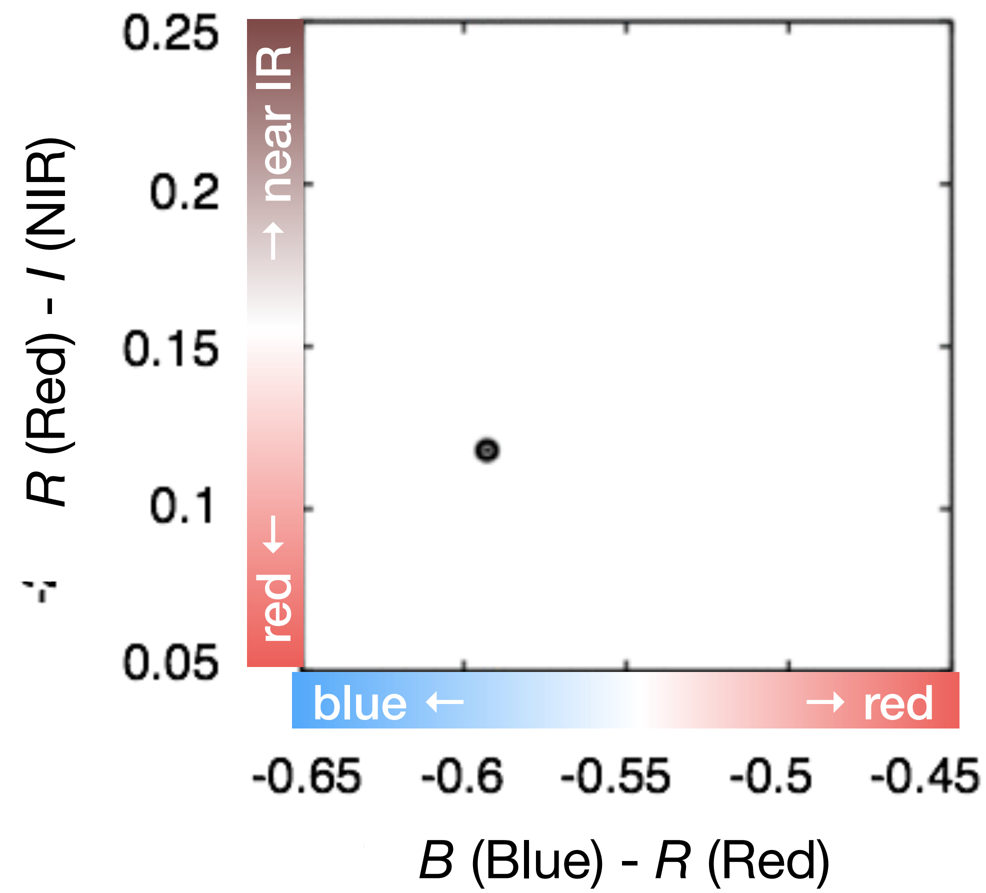
Daily Variation of Disk-Integrated Colors of Earth

※ NASA's EPOXI mission, Scattered light in UV/VIS/NIR



t = 0 hr

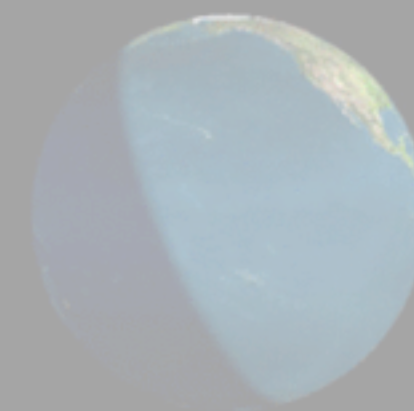




Daily Variation of Disk-Integrated Colors of Earth

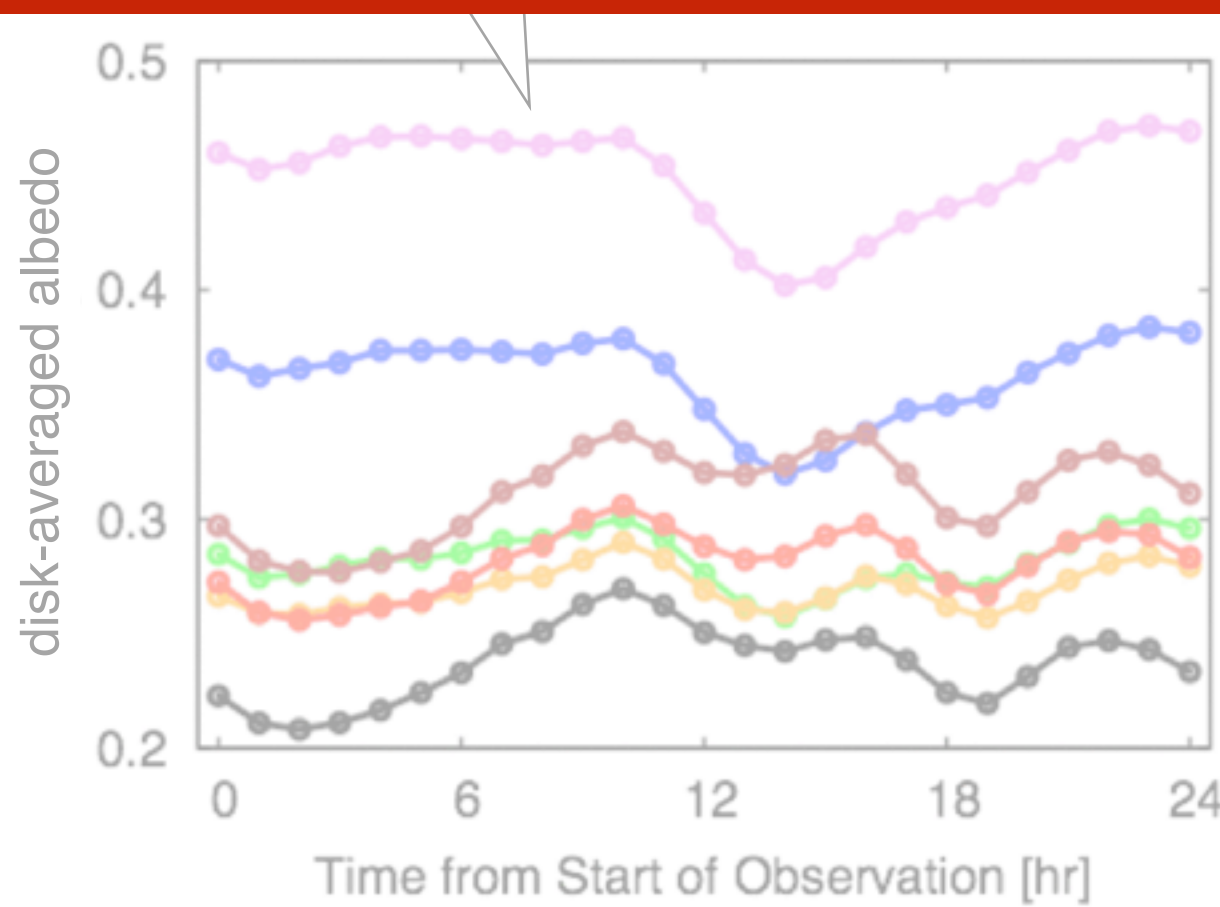
※ NASA's EPOXI mission, Scattered light in UV/VIS/NIR

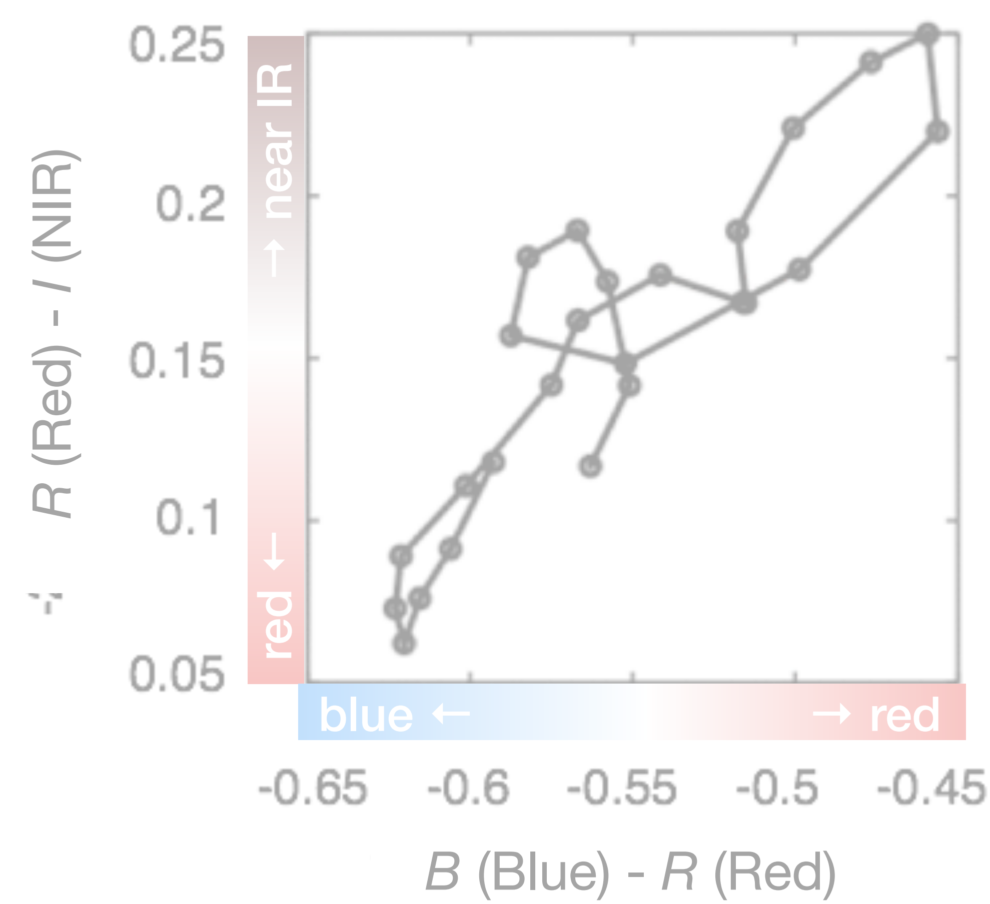
wavelength
0.3-0.4um
0.4-0.5um
0.5-0.6um



AGENDA

How can we retrieve surface characteristics properly from these data?





Mapping from **Daily** Color Variation

※ input: EPOXI data of the Earth

- Mapping of “Red” Component

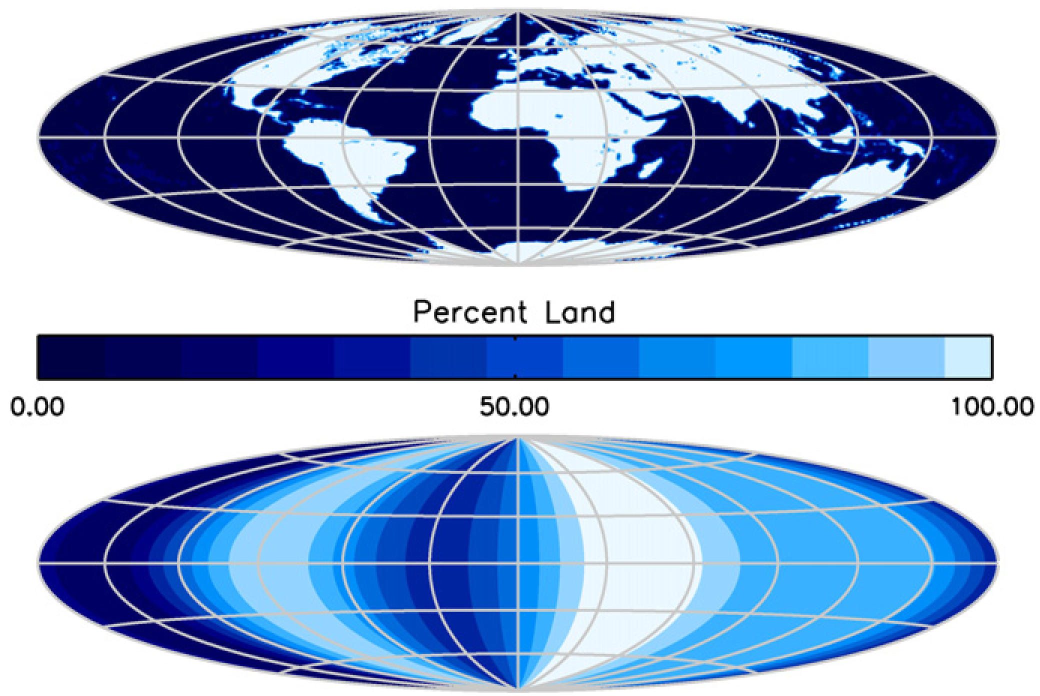
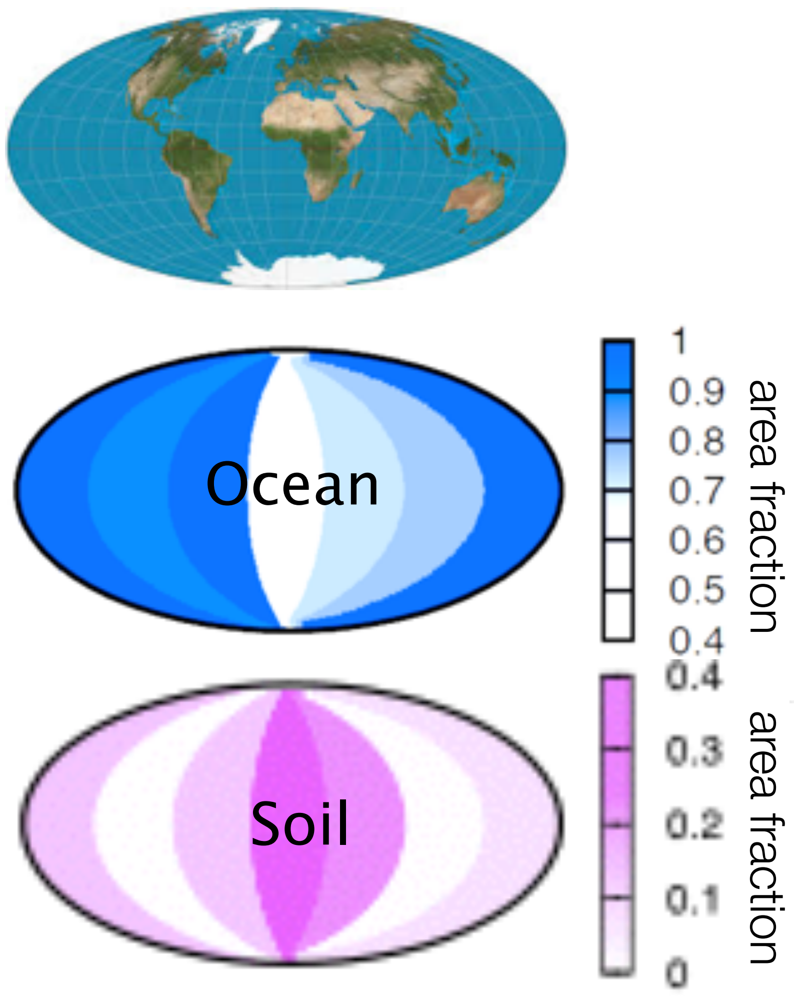


Figure 10. Aitoff projection showing the land distribution on Earth in a cloud-free MODIS map (top panel) and the distribution of land as determined from the June disc-integrated EPOXI light curves (bottom panel). The EPOXI map has a longitudinal resolution of approximately 60°; it has no latitudinal resolution, but is weighted toward the equator due to viewing geometry.

Cowan et al. (2009, 2011)

- Assuming a surface composed of clouds/ocean/snow/soil/vegetation



Fujii et al. (2010, 2011)

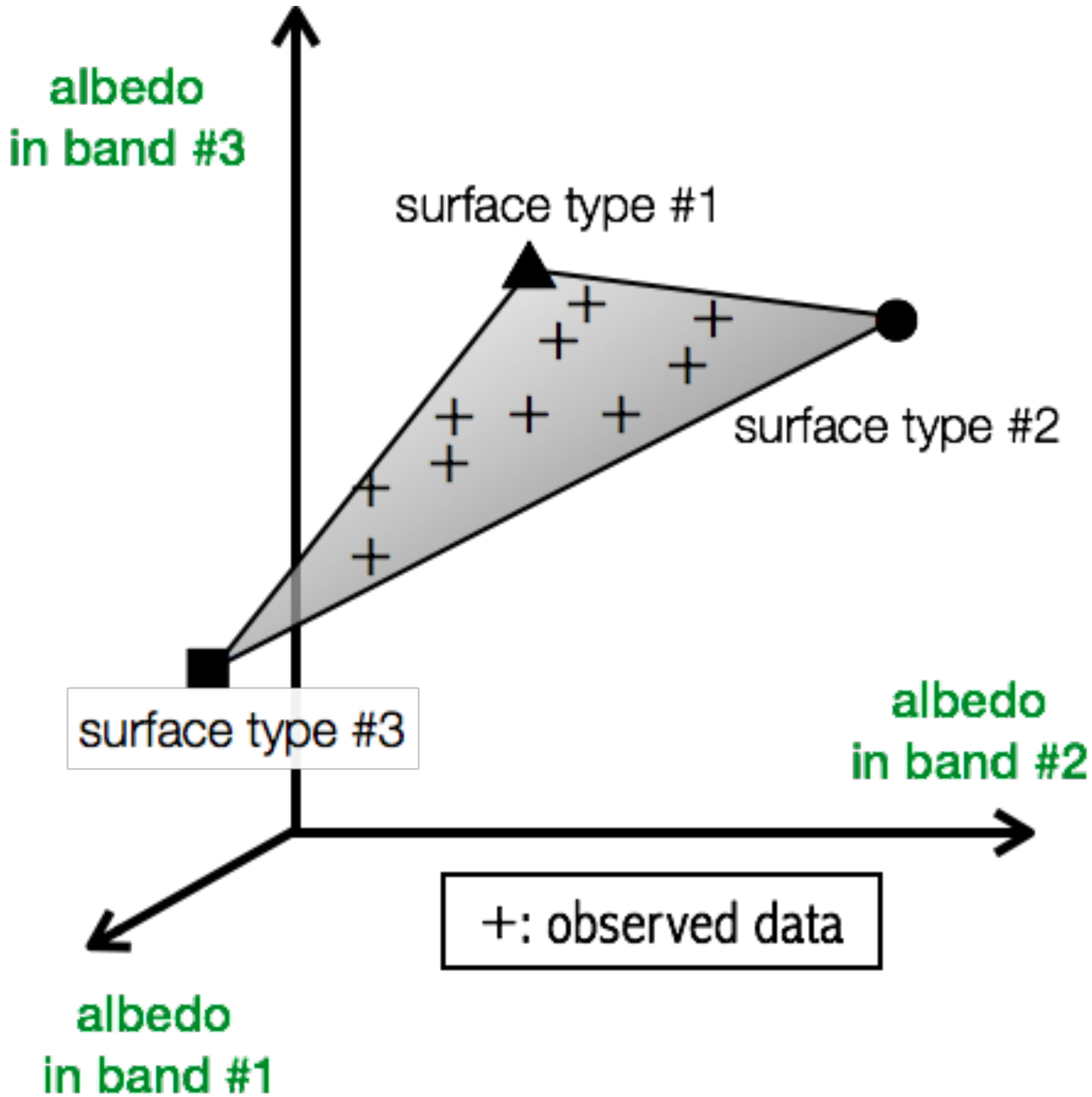
Finding "Unmixed" Colors

$$q(t;\lambda) = \sum_{l,k} W_l(t)\, f_{lk}\, a_k(\lambda)$$

data (planetary albedo) — kernel — fraction — albedo

constraints:

$$\Sigma_k(Wf) = 1, \quad Wf > 0$$



Cowan et al. (2009, 2011, 2013)

Mapping from **Yearly** Color Variation : SOT

video from YouTube: https://www.youtube.com/watch?v=9n04SEzuvXo

$$q(t;\lambda) = \sum_m W_m(t)\ a(\lambda)$$

data — observed

kernel — computed

local albedo — unknown

- spin rotation —moves longitude of sub-stellar/sub-observer point
- orbital motion —moves latitude of sub-stellar/sub-observer point

→ **2D scan** of surface (spin-orbit tomography: SOT)

Kawahra and Fujii (2010, 2011), Fujii and Kawahara (2012)

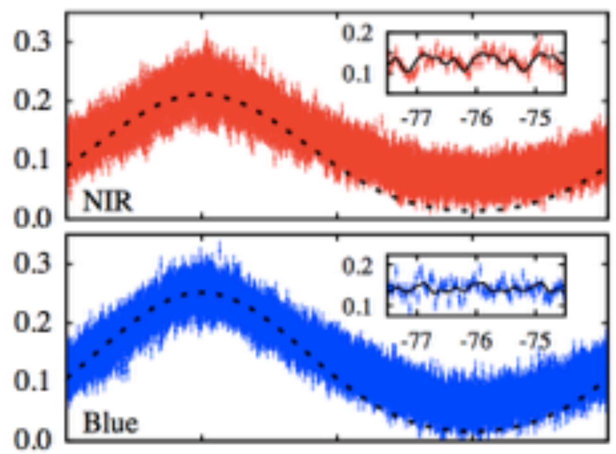
Demonstration of SOT — Result
Retrieved Albedo Contrast

continents/vegetation

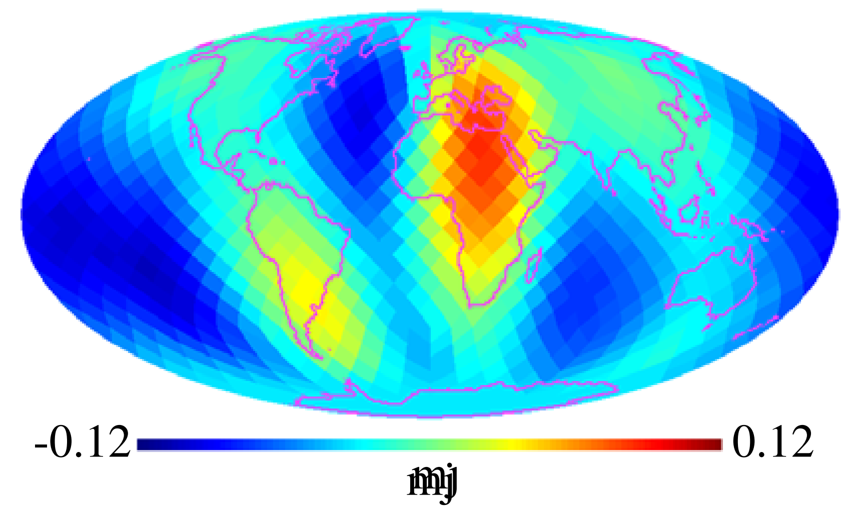
If SN = 100

NIR

Blue

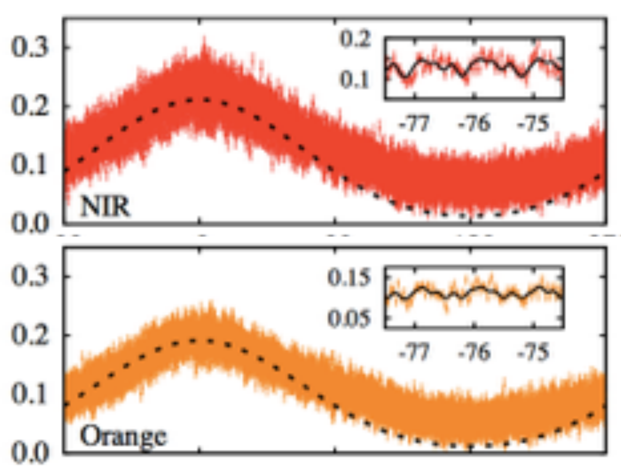


SOT

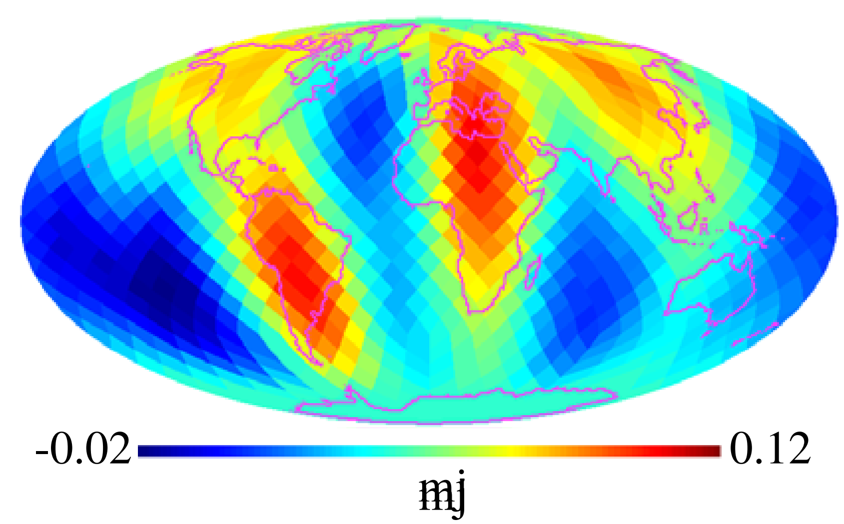


NIR

Orange



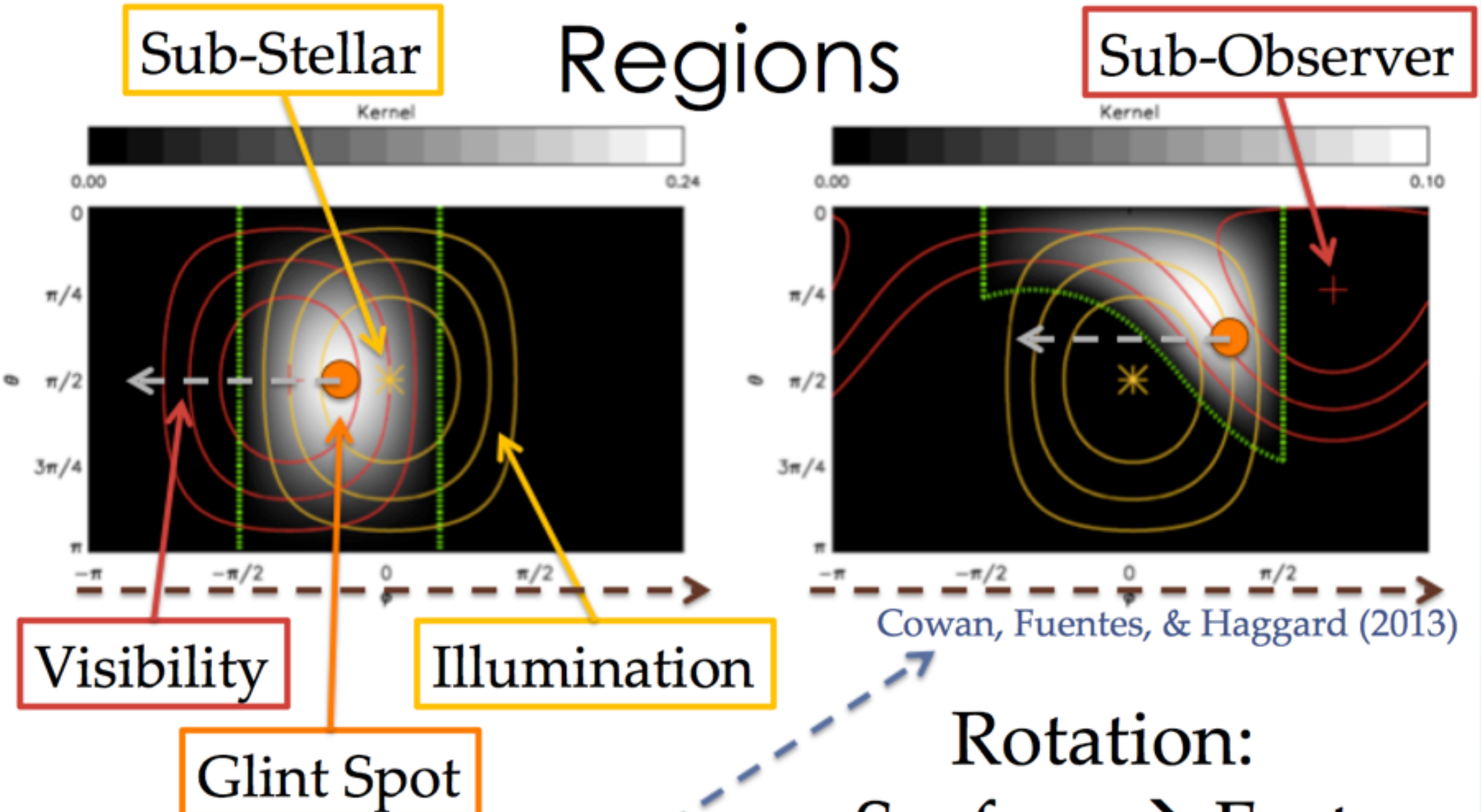
SOT



Inferring Obliquity from the Kernel of Reflection

Joel Schwartz
Amherst College

The Kernel Defines Probed Regions

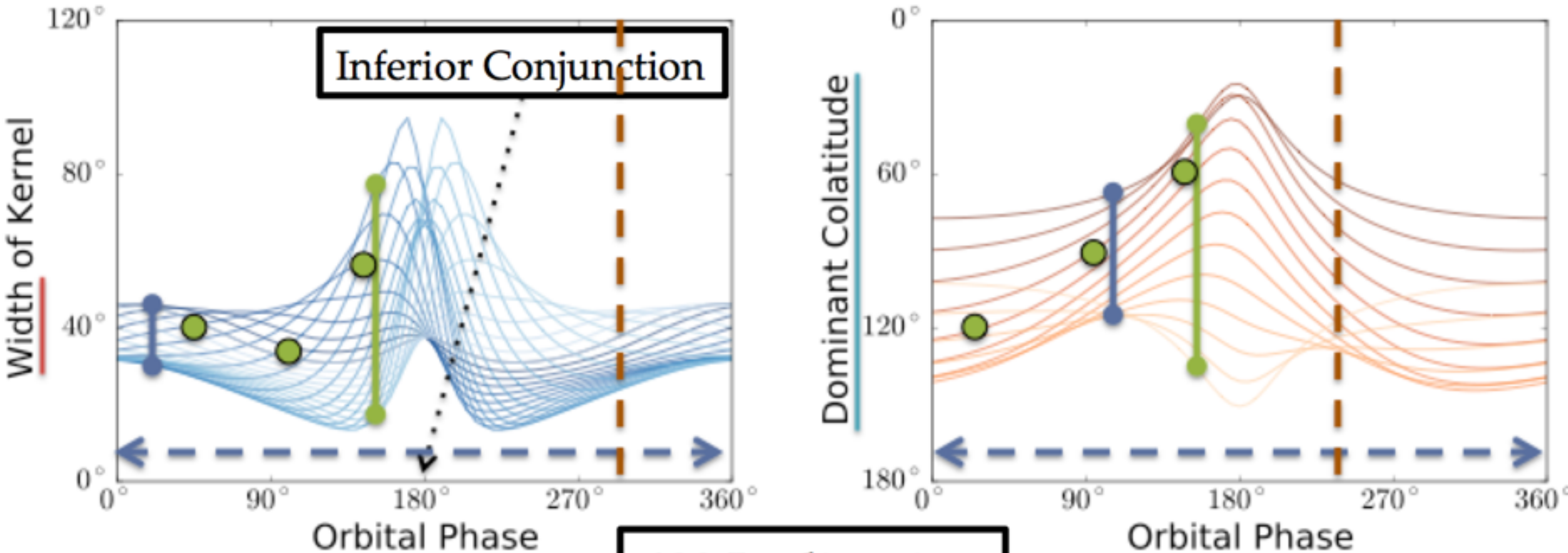


$$K \overset{\theta,\phi,G,t}{\propto} (V \times I)$$

Rotation:
Surface → East
Glint Spot → West

Kawahara & Fujii (2010)

Viewing Geometry Determines the Orbital Evolution



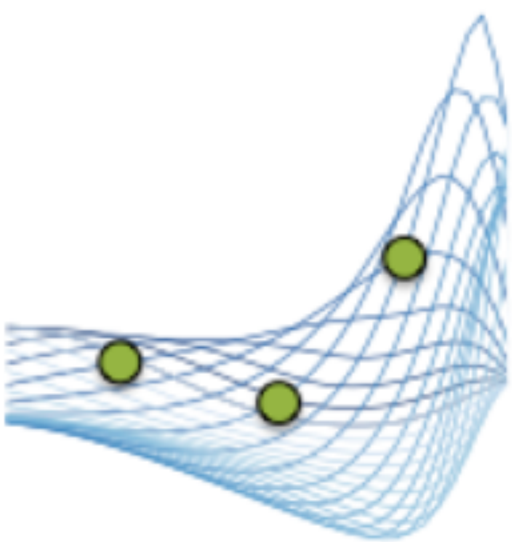
Reflected Light/Thermal Methods → ✔ Obliquity

e.g. Kawahara & Fujii (2010, 2011); de Kok, Stam, & Karalidi (2011), Cowan, Fuentes, & Haggard (2013)

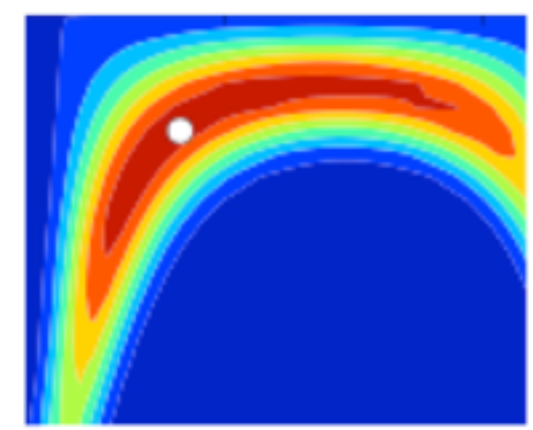
Sparse Kernel Widths/Locations → ✔ Obliquity

Takeaways…

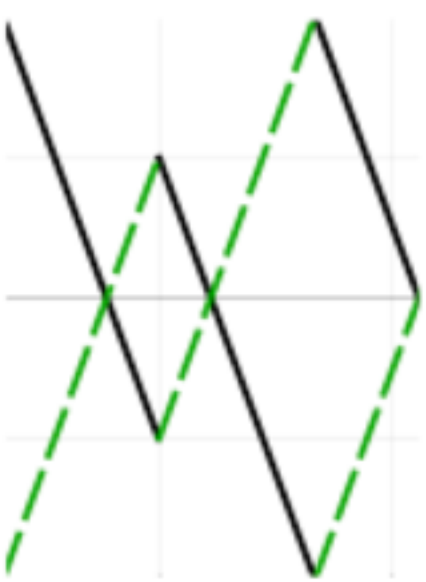
- **Kernel**: **Width** & **Dominant Latitude**



- ***Obliquity***: Encoded in **Characteristics**



- **Pro**/**Retro**grade Spin: Specific **Degeneracy**



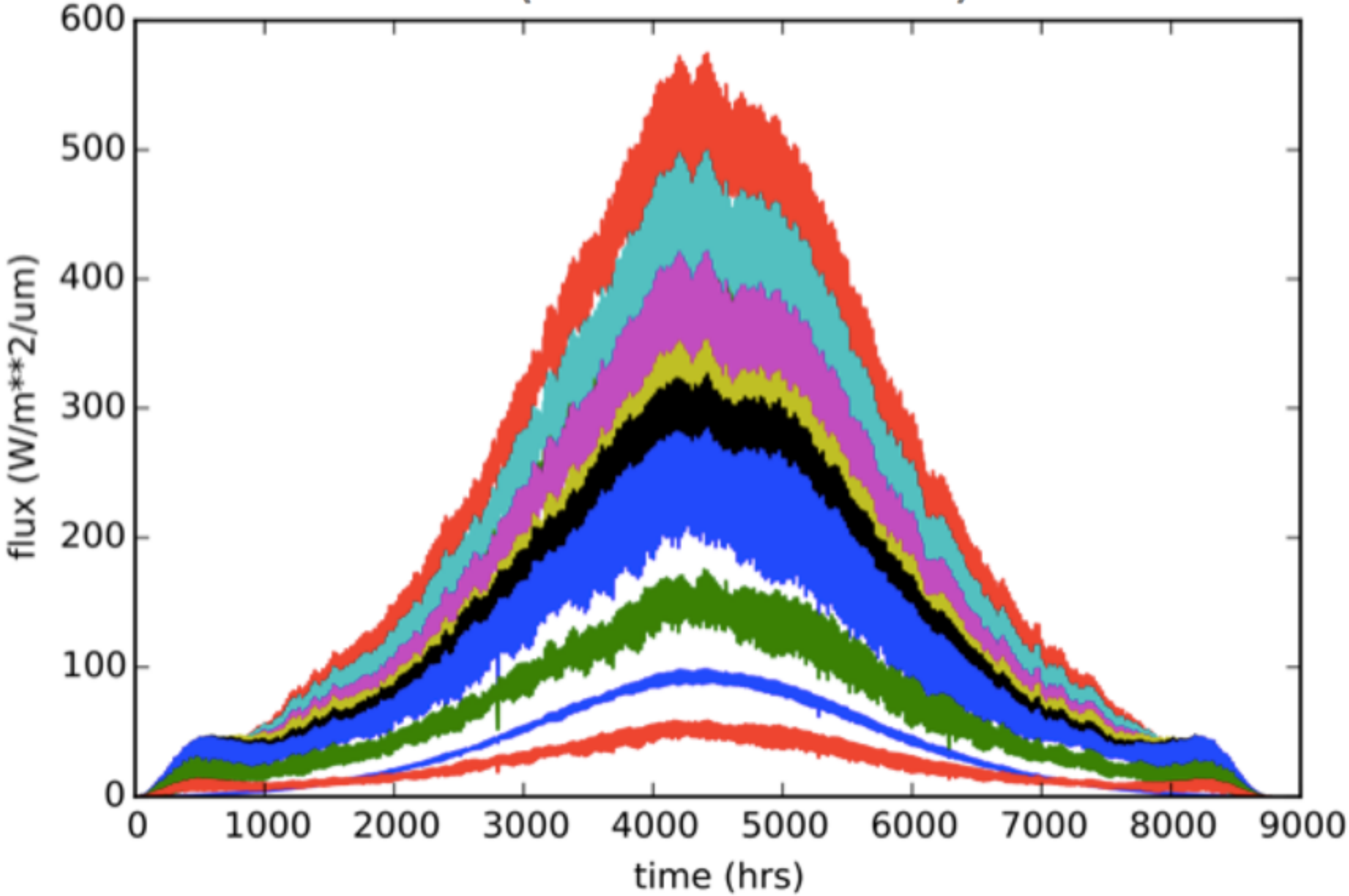
Cloud-free Maps of Exoplanets

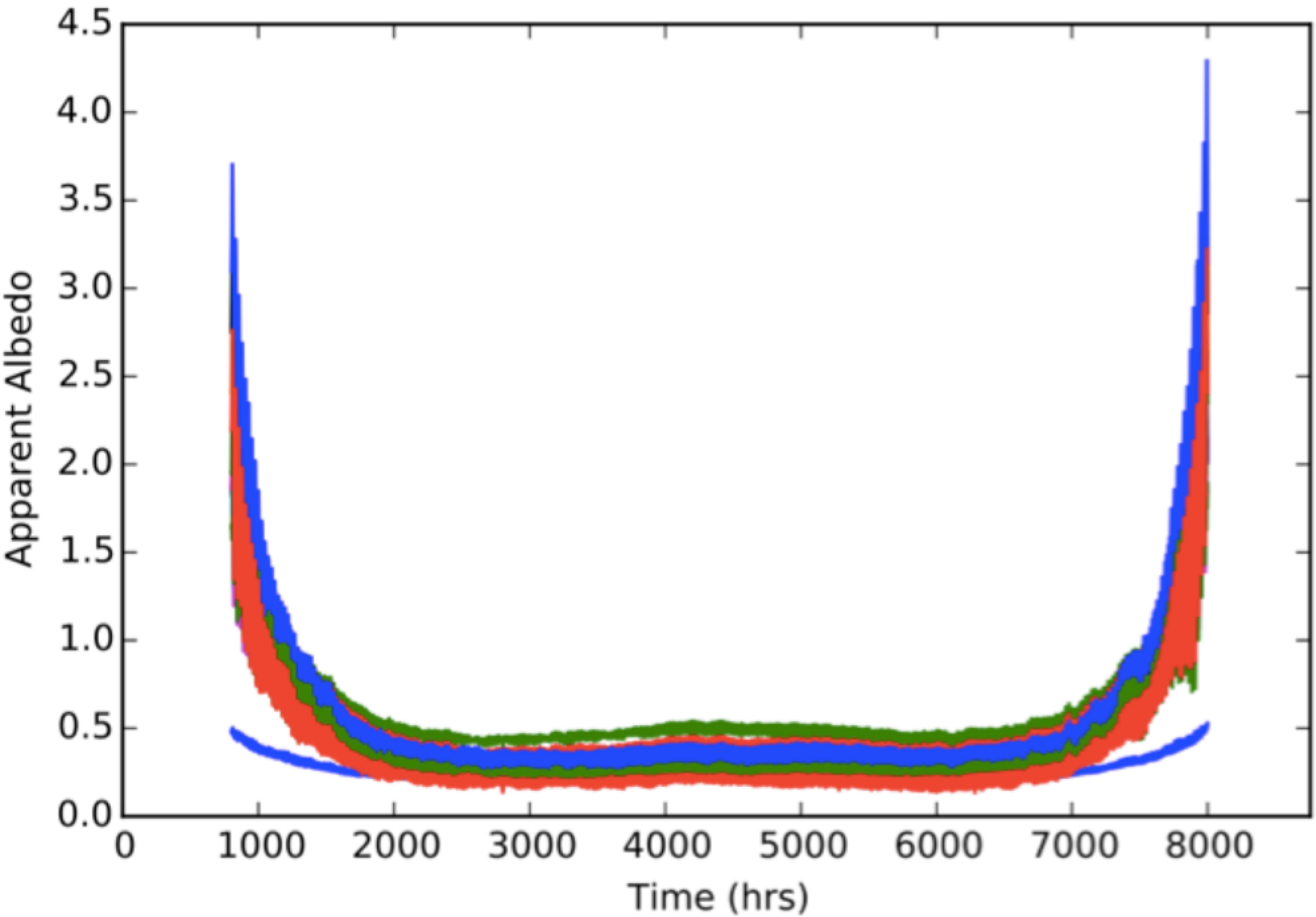
Nick Cowan
Amherst College / SSI / McGill

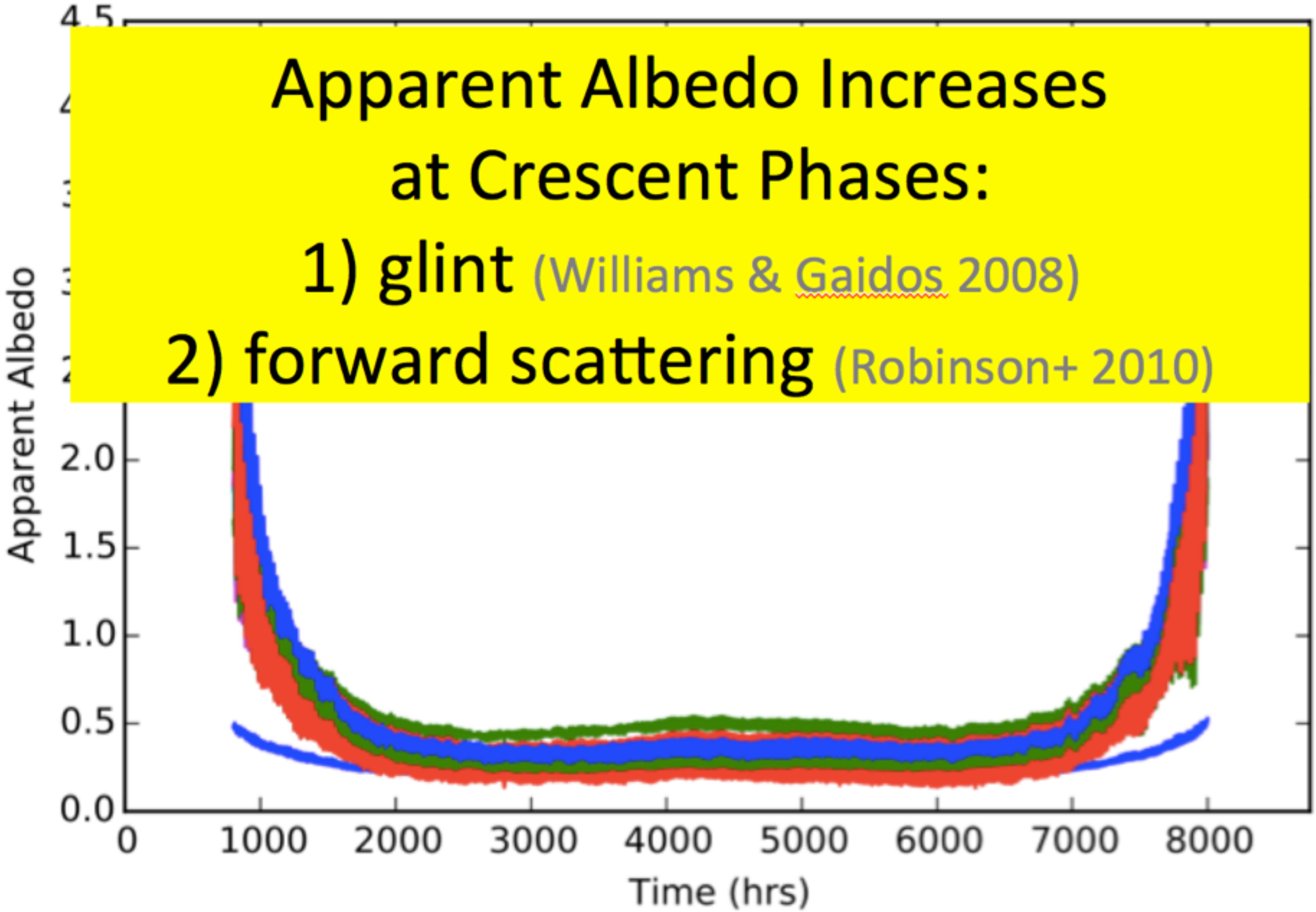
Cloud-Free Maps of Exoplanets (work in progress)

Nick Cowan (Amherst -> SSI -> McGill)

Virtual Planetary Laboratory 3D Earth Model (Robinson+2011)




4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Apparent Albedo
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (hrs)


Apparent Albedo Increases
at Crescent Phases:
1) glint (Williams & Gaidos 2008)
2) forward scattering (Robinson+ 2010)
Apparent Albedo
2.0
1.5
1.0
0.5
0.0
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (hrs)

Key Points:

Brown Dwarfs: Rich data on cloud types, properties, depth, structure, dynamics

2D Constraints/map already published
3D Maps and Time-evolving 3D maps are in the works

Hot Jupiters: 2D and 3D maps emerging

Future Earth Observations: 2D maps possible, identification of oceans, continents, ice/cloud, vegetation, obliquity

No Specially Designed Telescopes are Necessary