Exoplanet Spectrophotometry

(from Ground-, Airborne- and Space-based Observatories)

Dr. Daniel Angerhausen

(ORAU NPP fellow, NASA-Goddard, 667)

TDE workshop

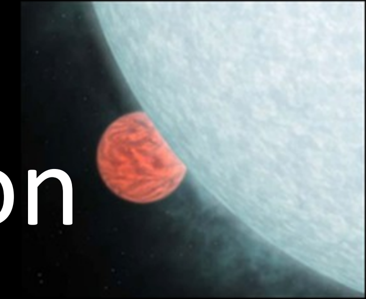
Nice, France

October 12, 2015

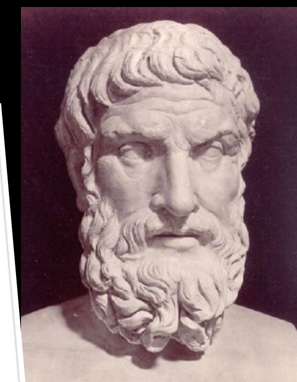
NASA POSTDOCTORAL PROGRAM

Administered by Oak Ridge Associated Universities

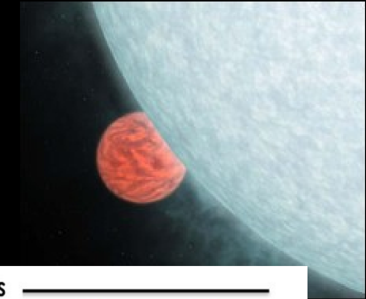
Exoplanets: A very old question

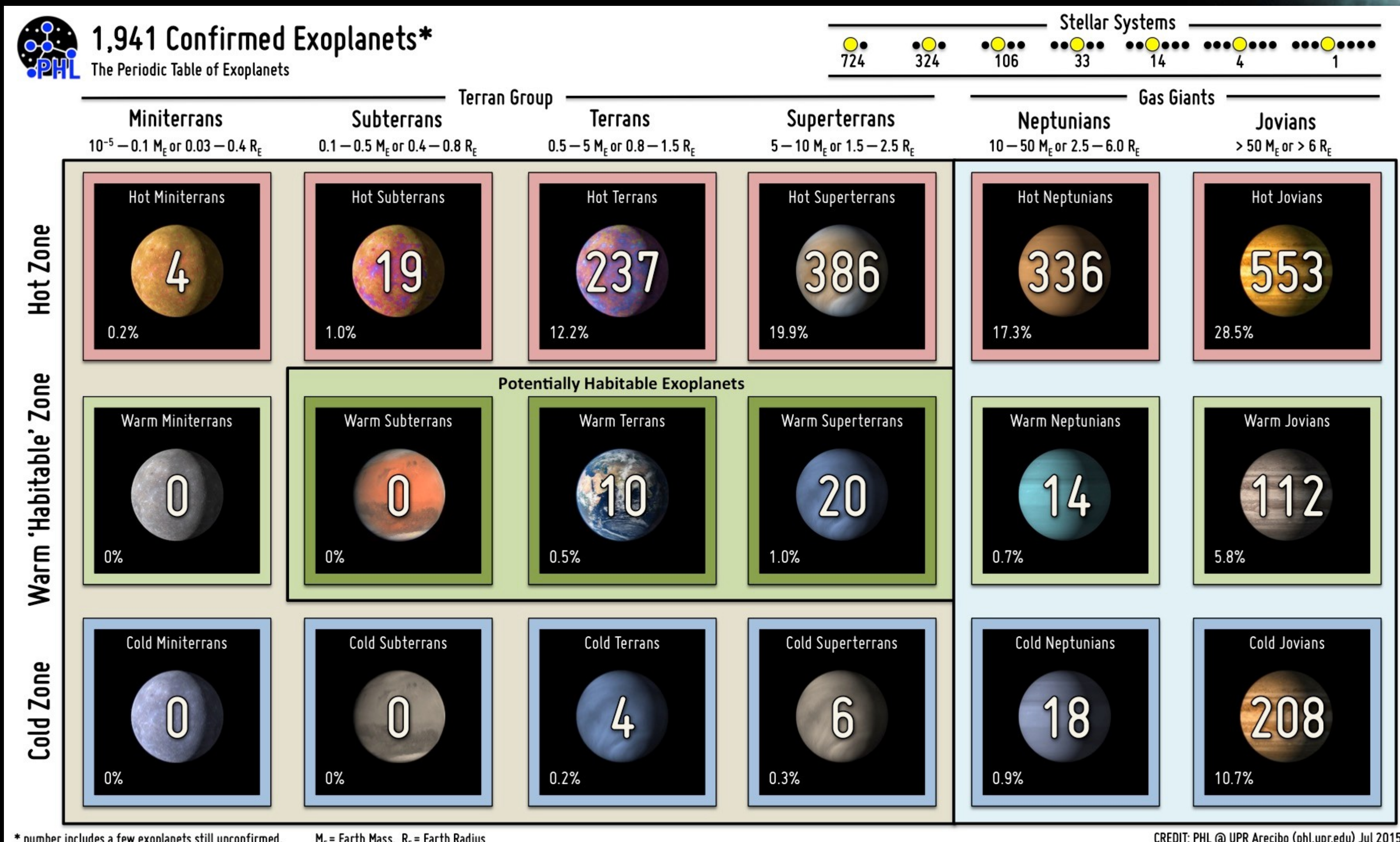


Epicurus ... like

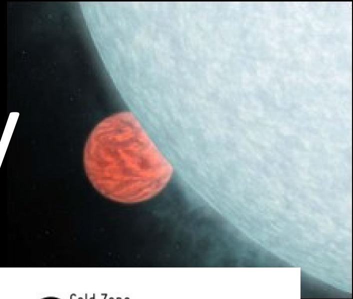


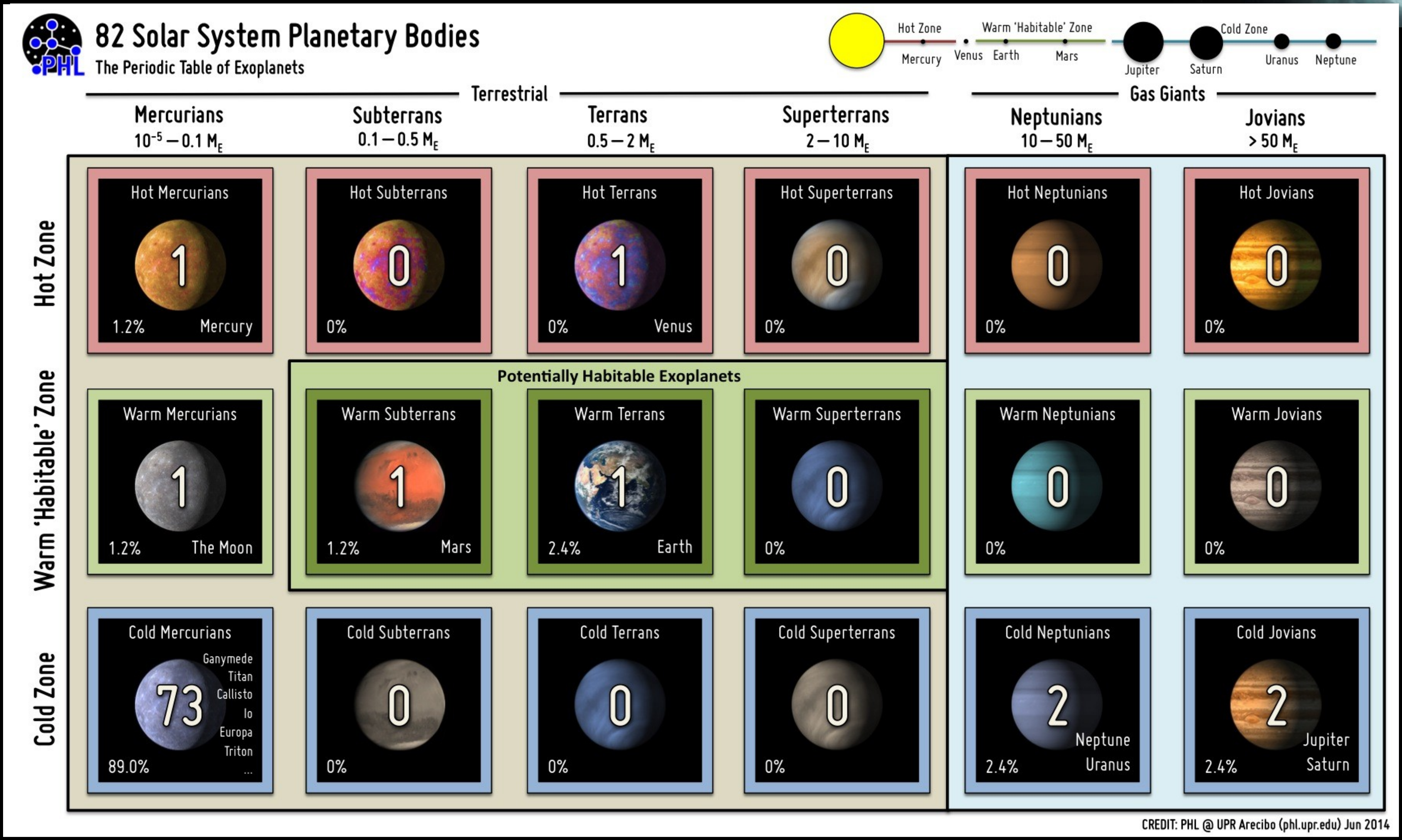
Known Exoplanets today



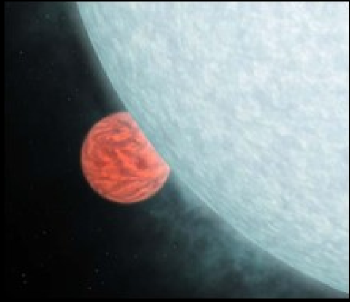


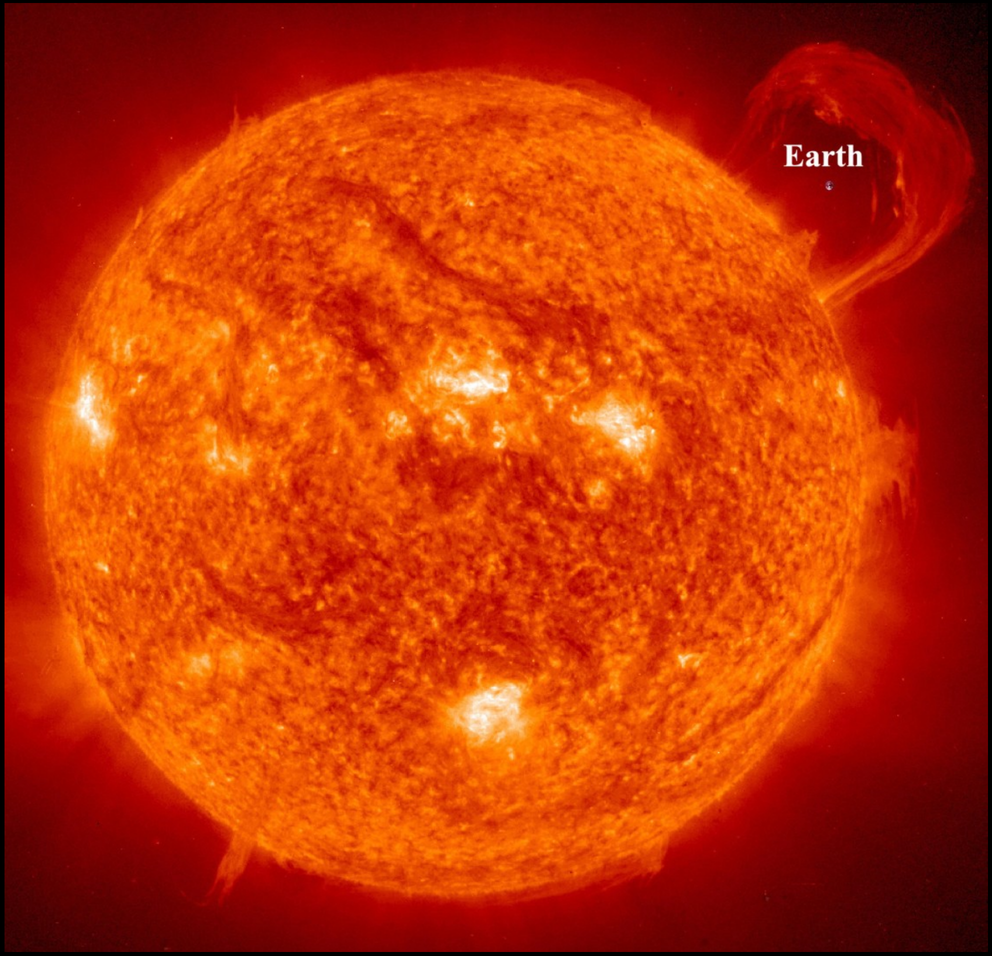
Known Solar system today





Why is it so difficult?



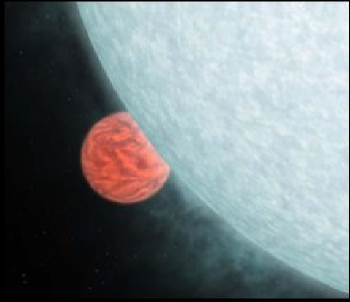


-stars are bigger than planets

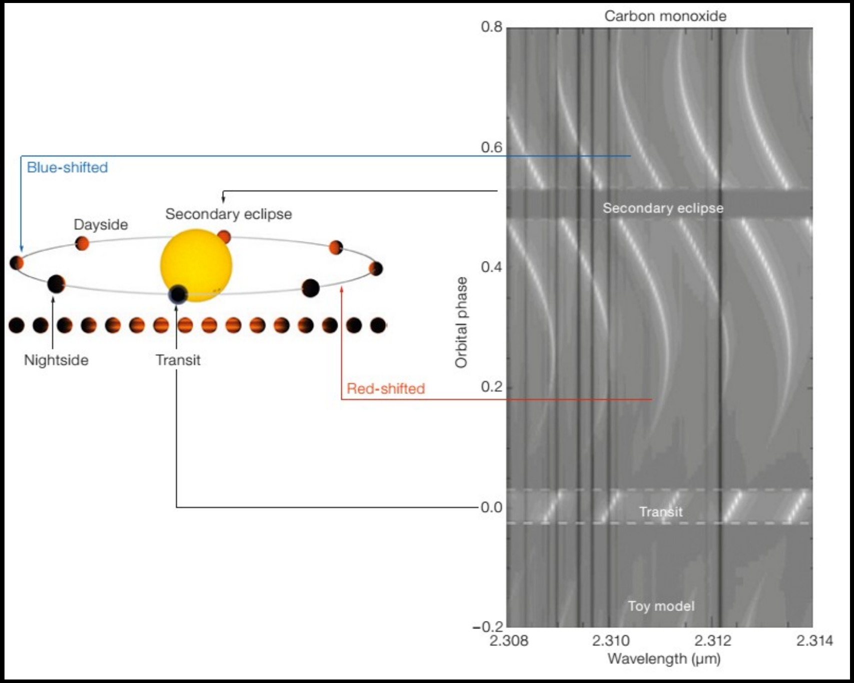
-stars are brighter than planets

>>> indirect methods or methods that cancel out the stellar contribution

Methods

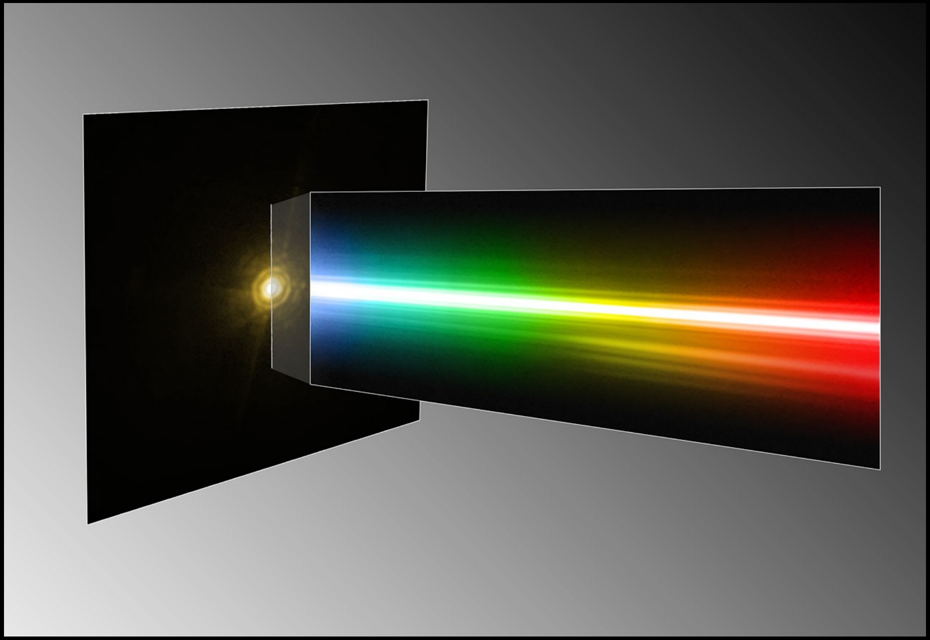


High Spectral Resolution



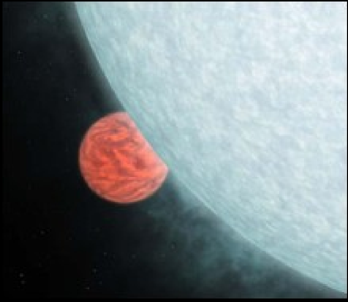
-work by Snellen, Brogi et al.
-qualititive method
-potentially biosignature with ELTs

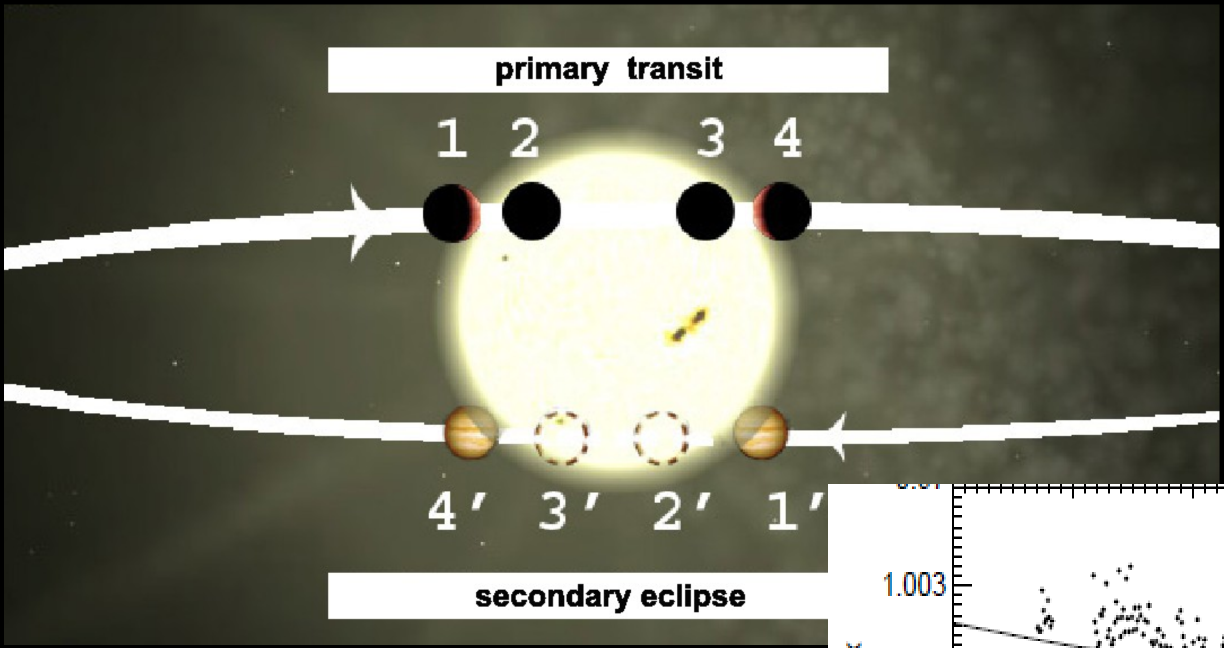
Direct Imaging



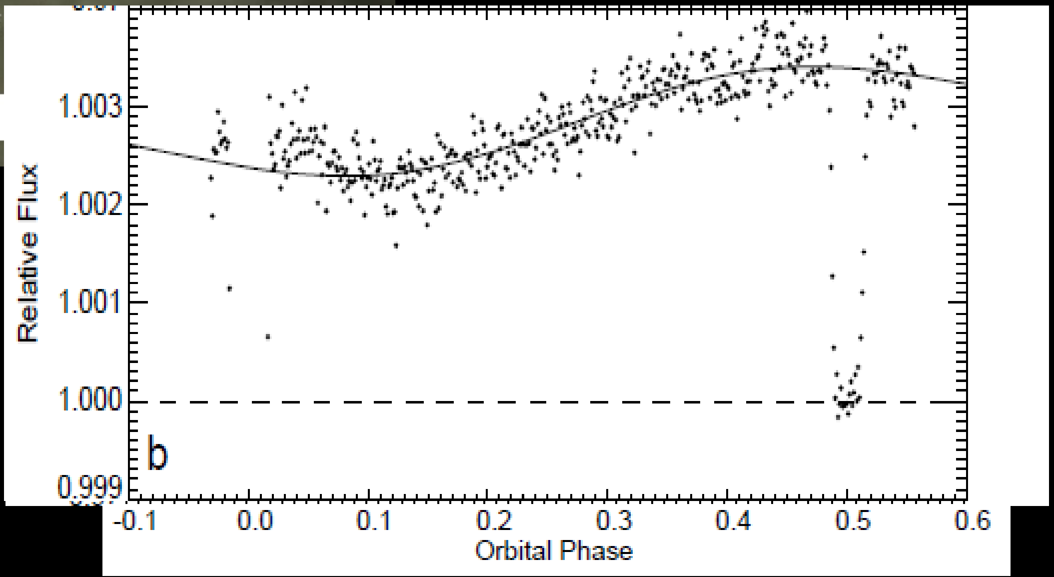
-GPI, SPHERE, P1640 ….
-next talk by Masayuki Kuzuhara

Differential photometry



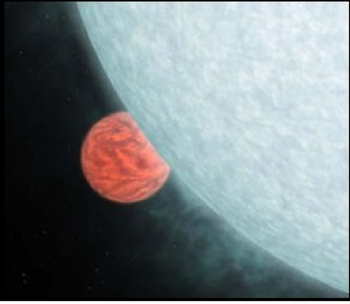


Differences between observations
In and out of occultation reveal
information about the planet



Example: half-orbit lightcurve of
HD189733b at 8 micron
with Spitzer
(Knutson et al. 2007)

Space-based: *Kepler*



INSIDE Rensselaer

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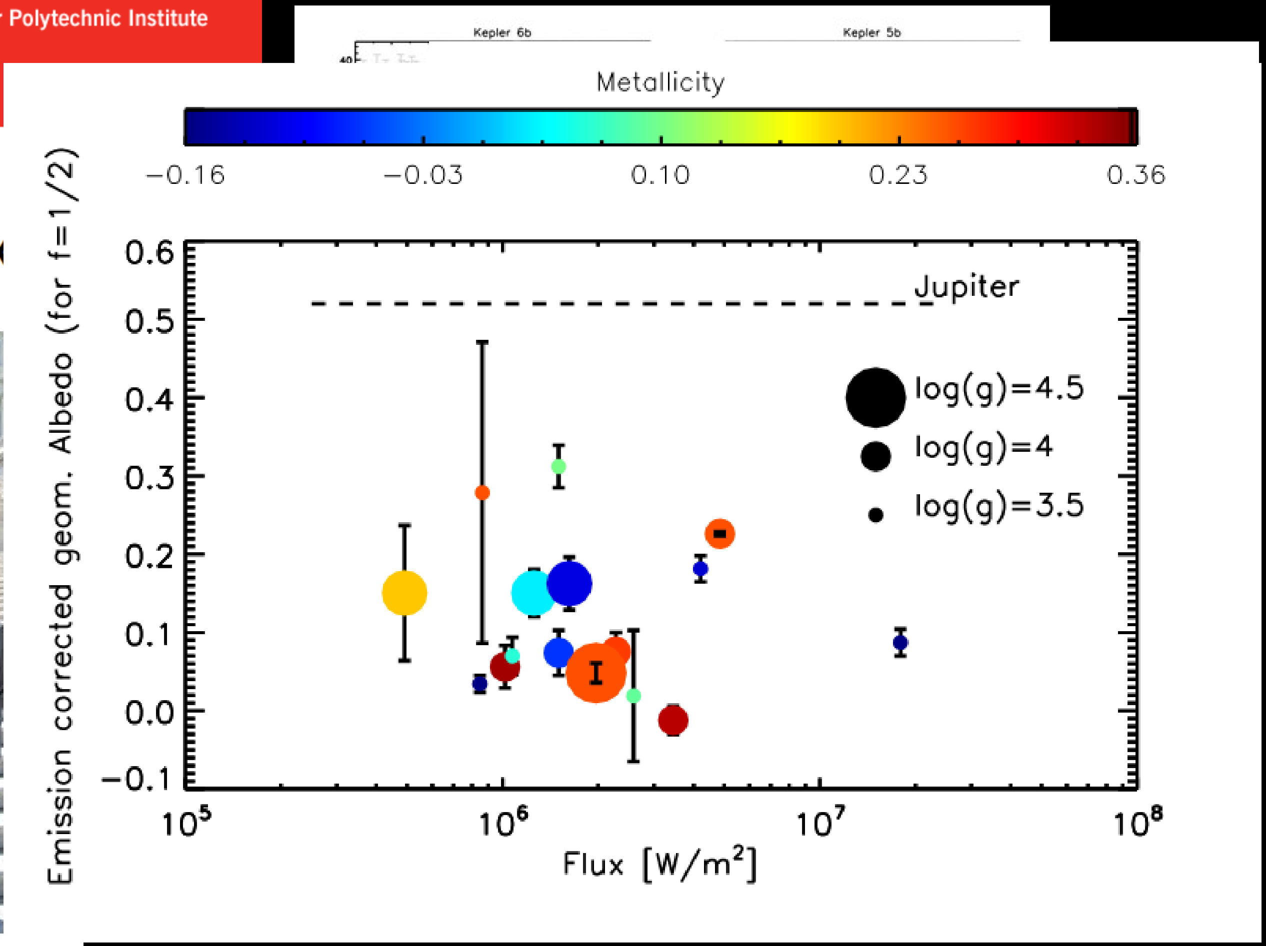
Empfehlen 7

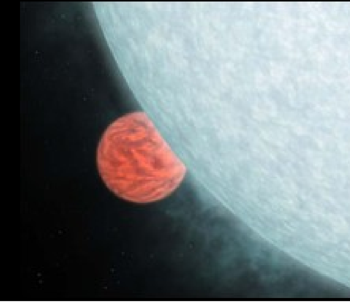
Undergraduate Research Ex
Capitol Hill

(l-r) Professor Jon Morse, Senator Bob Casey (D-PA), Emily DeLarme, and Daniel Angerhausen, a Rensselaer post-doc.



(Angerhausen, DeLarme & Morse, PASP, 2015)

Space-based: *Kepler*



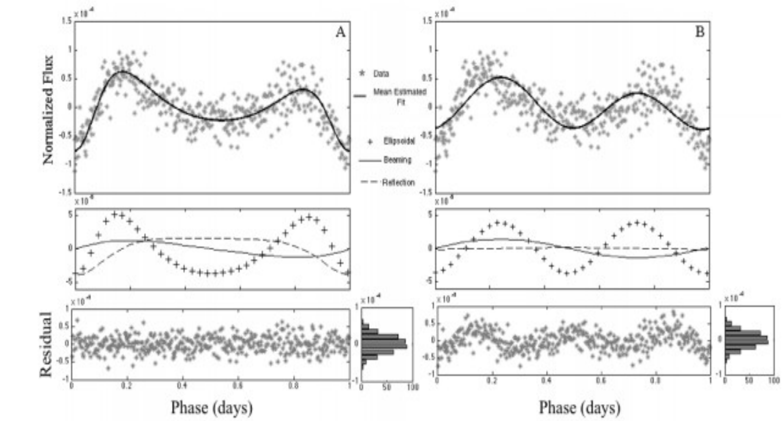


Fig. 2.— Phase folded synthetic eccentric data with fits for eccentric (A) and circular (B) models including reflected light, Doppler beaming, and ellipsoidal variations. The circular model clearly leaves un-modeled structure in the residuals.

The Astrophysical Journal, 795:112 (15pp), 2014 November 10 doi:10.1088/0004-637X/795/2/112

EXONEST: BAYESIAN MODEL SELECTION APPLIED TO THE DETECTION AND CHARACTERIZATION OF EXOPLANETS VIA PHOTOMETRIC VARIATIONS

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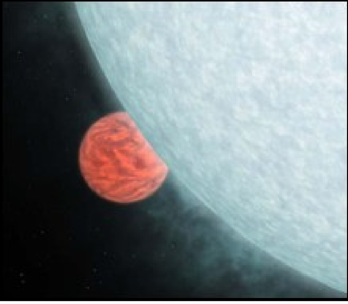
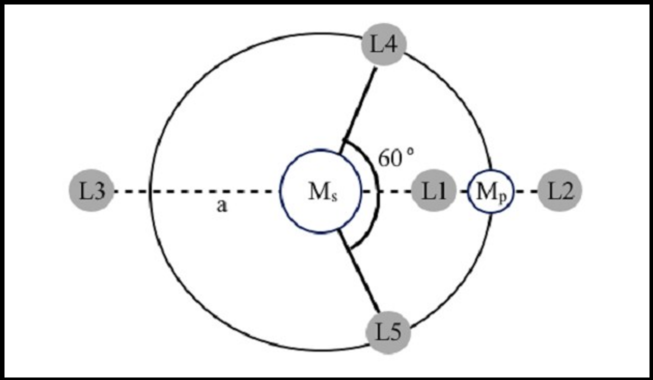
Statistical evidence for 'Exo-Trojans'

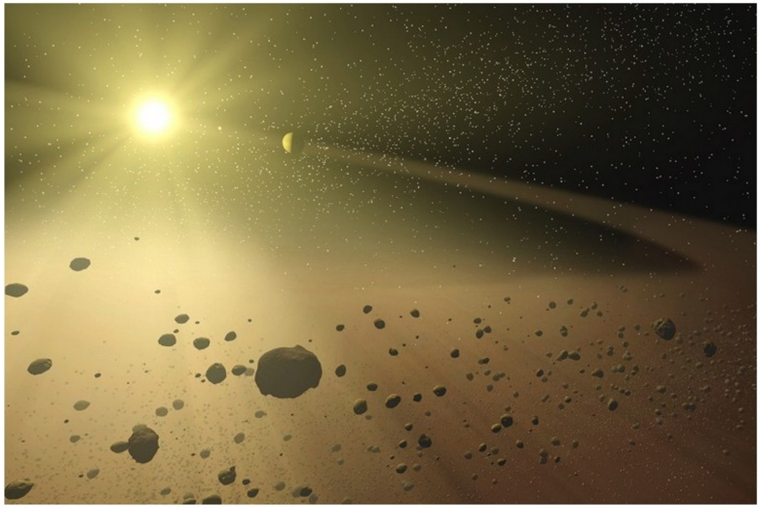




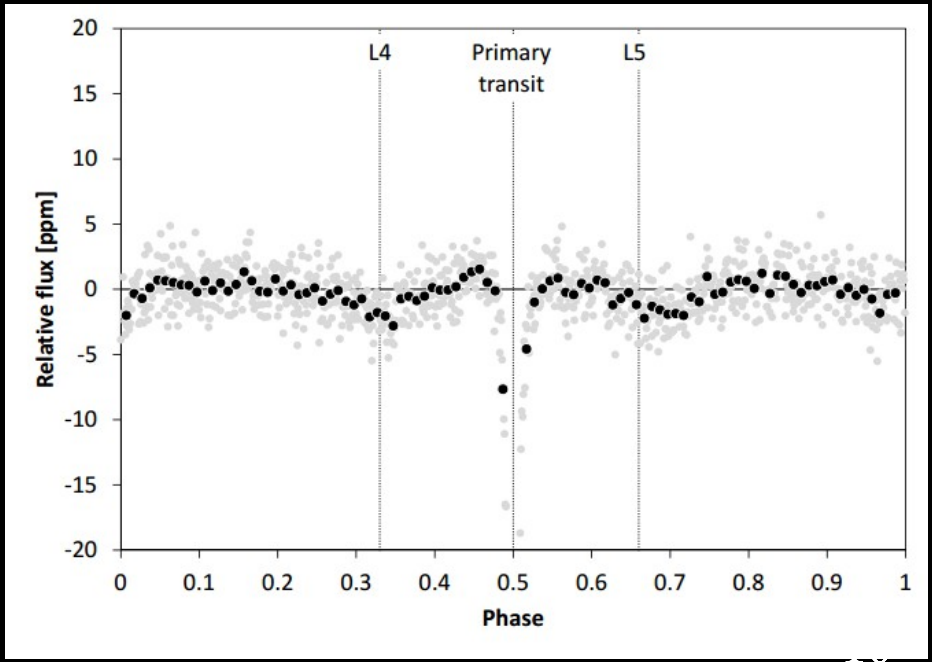
Hippke & Angerhausen, ApJ, 2015:

-star/planet systems have gravitational stable points
-asteroids collect there (e.g. Jupiter Trojans)
-combined ~90.000 lightcurves of ~4000 planets from *Kepler*
-found extra dimming at the phases of the Lagrange points
-corresponding to an occulting area of one body with R~970km

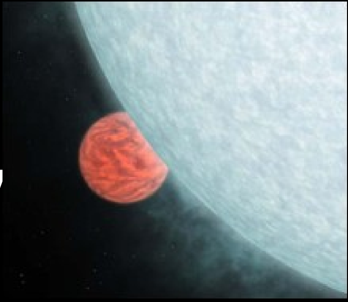
Kepler sees hints of asteroids pursuing planets near other stars

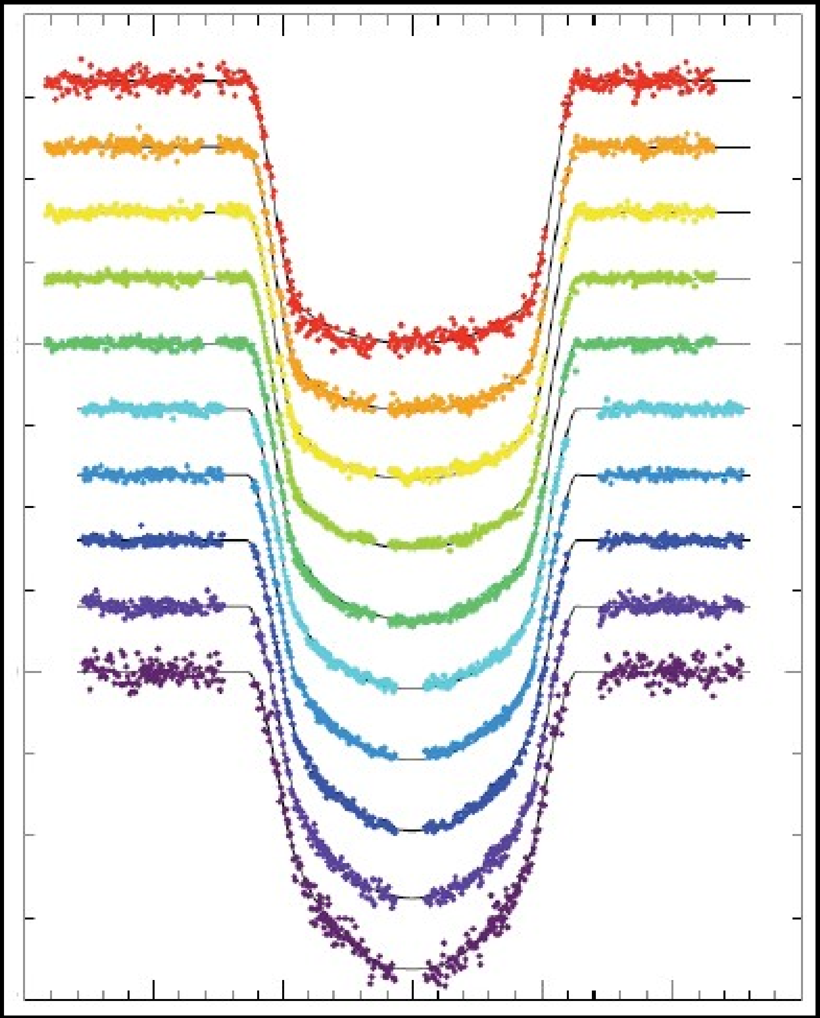


(Image: NASA/JPL-Caltech/T. Pyle (SSC)) New Scientist

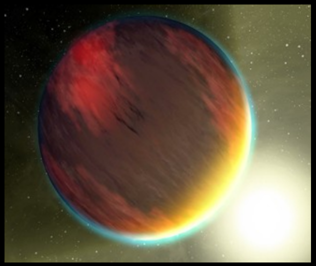


(NIR-) Spectrophotometry





(Knutson 2008)



Credit: T. Pyle (SSC)

Primary transit:

Probing terminator, high in the atmosphere

Broadband depth: ~ < 3 %

Spectral features: ~ few 10^{-4}

Credit: D. A. Aguilar (CfA)

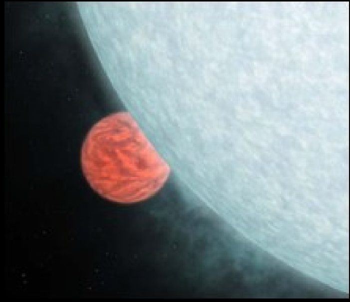
Secondary eclipse:

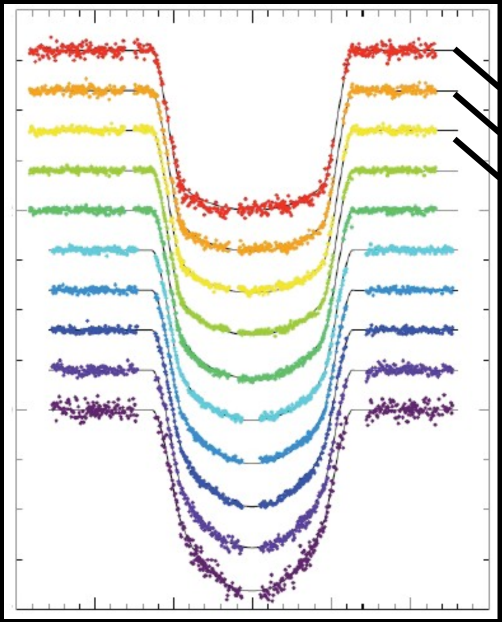
Probing dayside, emitting photosphere deep in the atmosphere

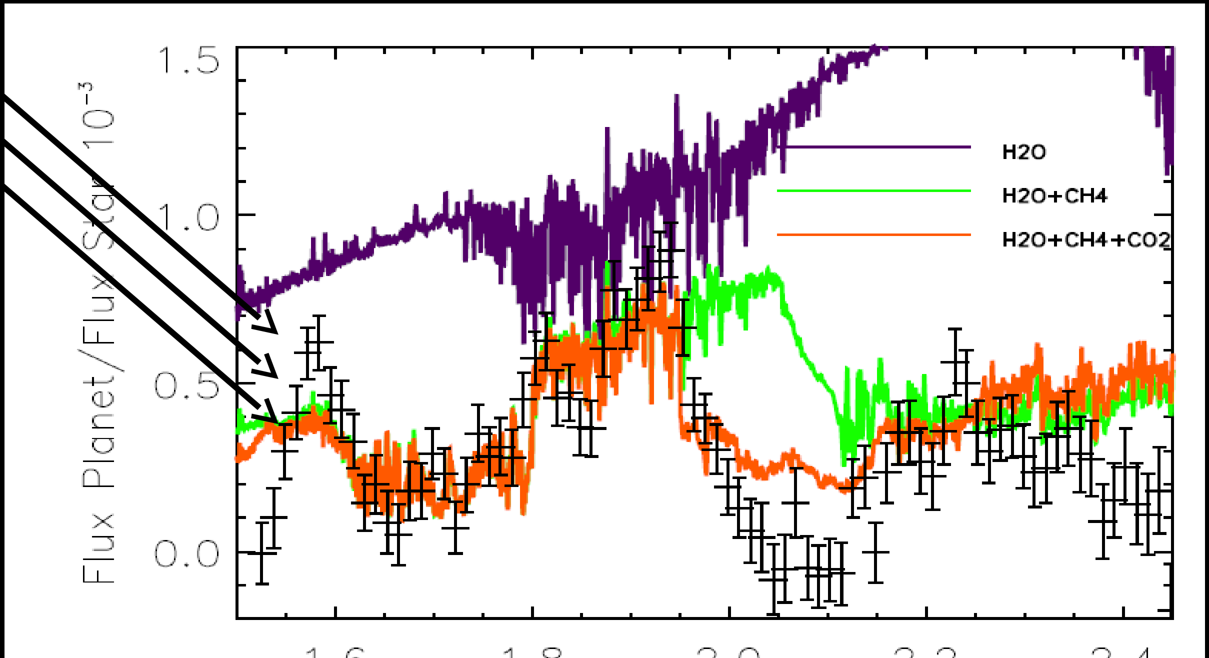
Broadband depth: ~ < 0.3 %

Spectral features: ~ few 10^{-4}

(NIR-) Spectrophotometry



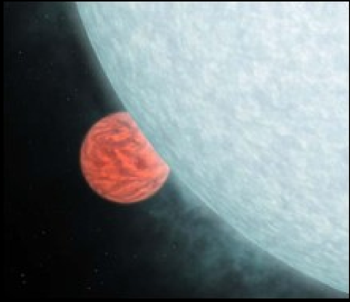




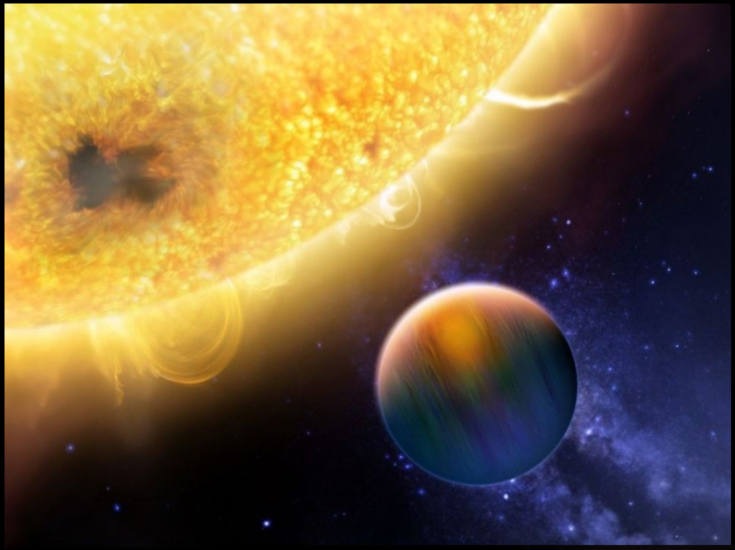
(Swain et al. 2009,
Hubble-NICMOS dayside HD209)

-every lightcurve represents the spectral value at its particular wavelength,
putting them together reveals the spectrum

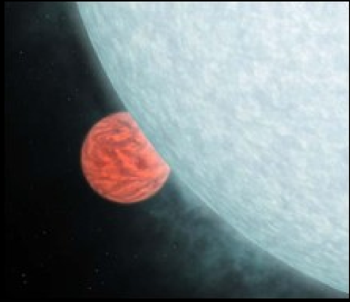
-“comparison“ with models show molecule abundances and T-P profile of the planet



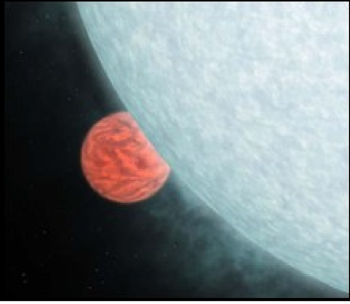
Hot Jupiters

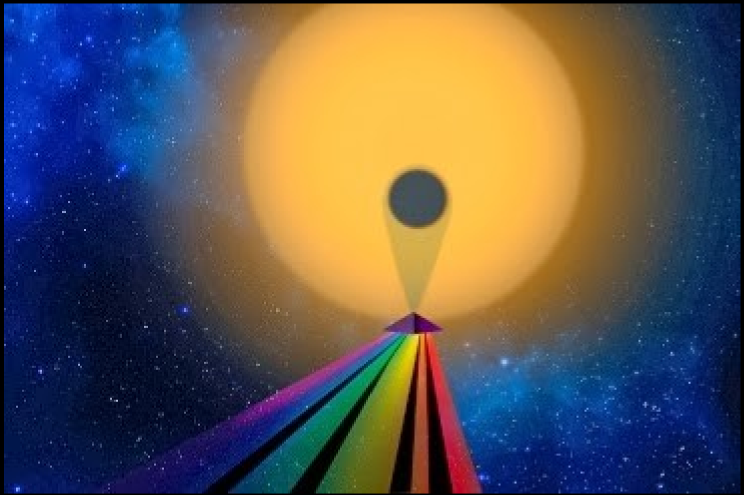


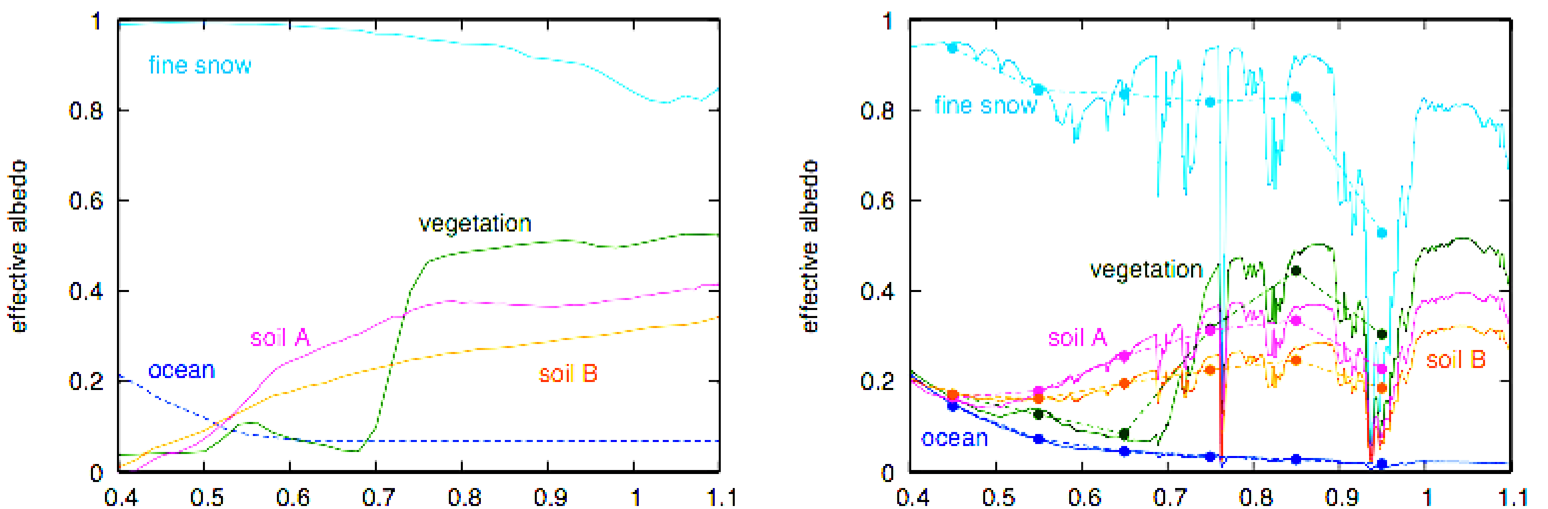

Super Earth vs Mini Neptun



Future: Biomarkers

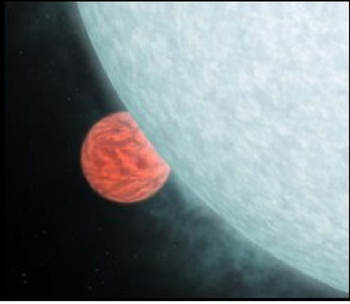






(Fujii et al. 2011)

Ground-Based

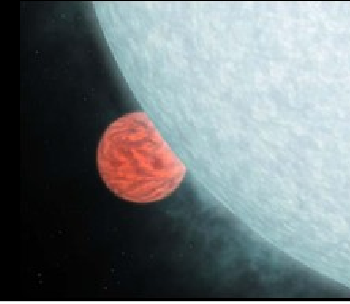


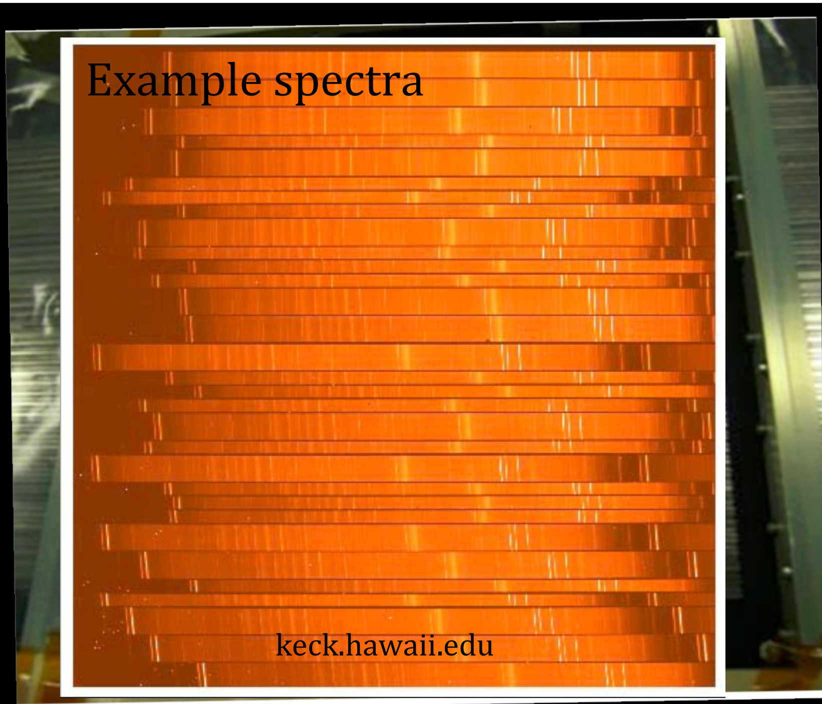
- (~2005) Early tests e.g. with IFU (SINFONI@VLT, OSIRIS@Keck) -- limited by atmospheric variations

-some (promising) results , but no breakthrough

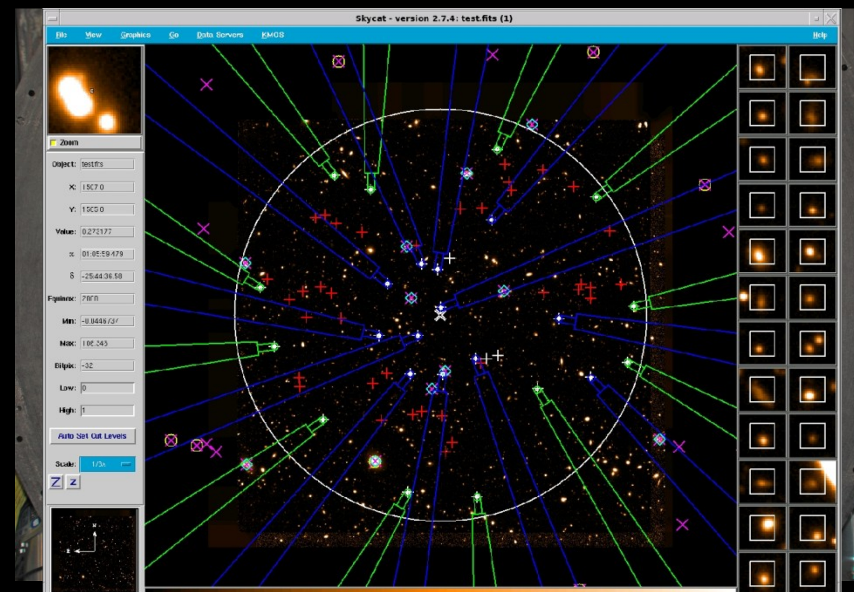
-new opportunities with multi-object spectroscopy: (recent observations with MOSFIRE at Keck, KMOS at VLT)

Ground-Based



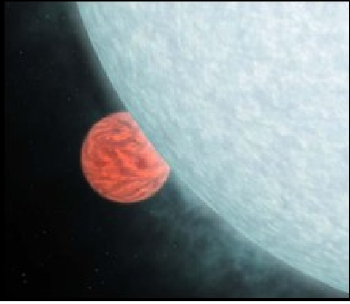


MOSFIRE @ Keck
-comparison stars to correct for telluric variation
-variable slit-width to control slit-losses (we use a wide-slit setup)

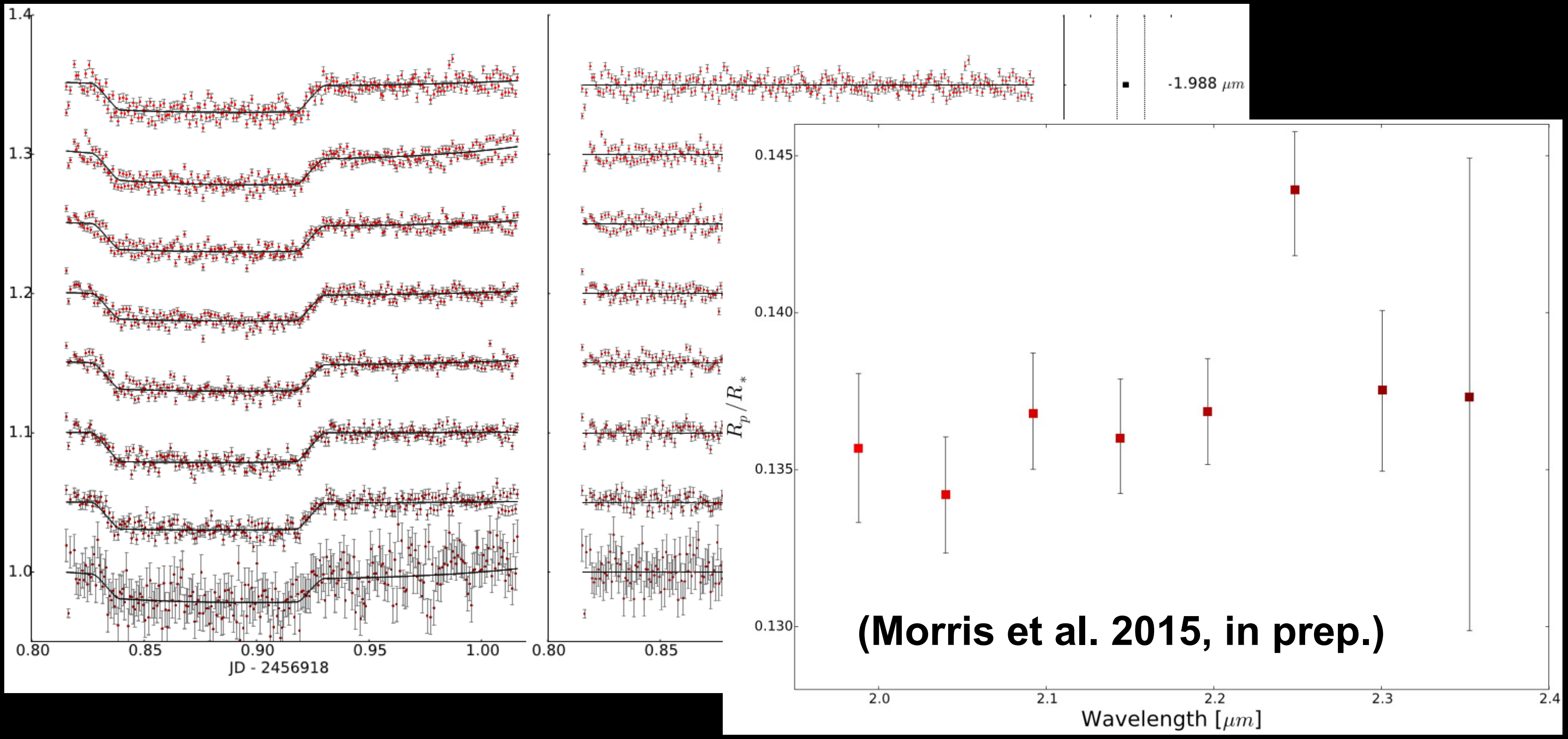


KMOS @ VLT
-multiple integral field units (3x3 arcsec)
-ESO science verification proposal 2013 (GJ 1214 b transit, but technical issues),
2 nights 2014 (but bad weather),
2 nights in Jun 2015 (but power failure)

Ground-Based

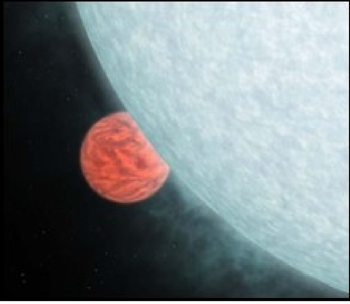


Example: WASP-6b transit with Keck-MOSFIRE (PI: Brett Morris, UW):

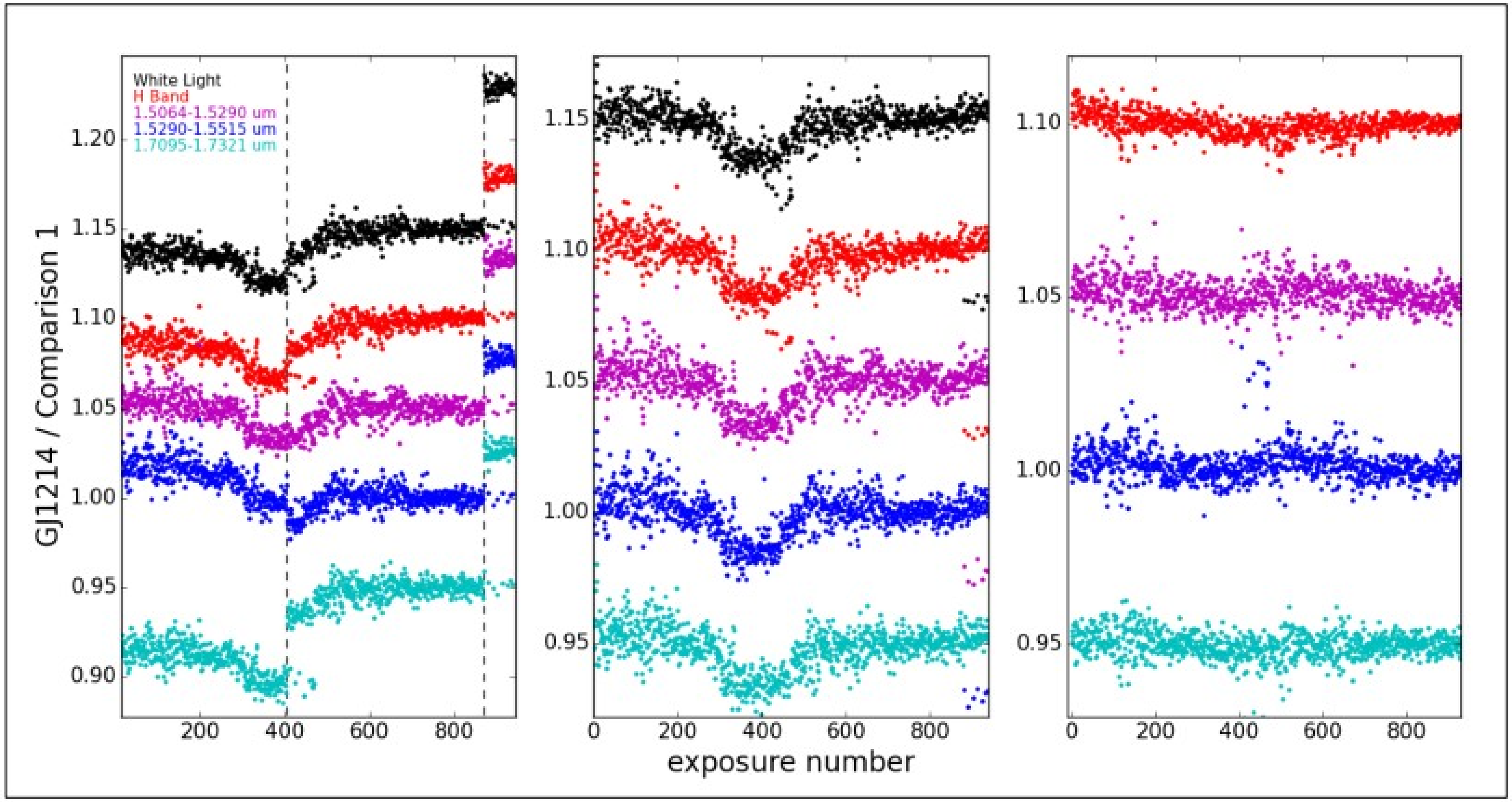


(Morris et al. 2015, in prep.)

Ground-Based

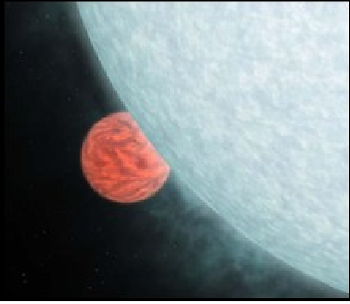


Preliminary Results:



(Work by NASA summer intern Brianna Lacy, UW)

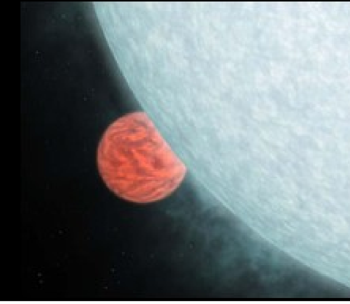
Airborne-based: SOFIA



-2.5 meter telescope carried aboard
Boeing 747-SP aircraft
-NASA (USA), DLR (Germany) 80%:20%
-observe at altitudes of >40000 ft
-1rst gen: 7 imagers/spectrographs
-Wavelength: 0.3 micron – 1.6 mm
-Operation: 20 years, 120 nights/y

<u>Advantages for transit-observations:</u>
-wavelength regime
-mobility
-less atmosphere
-dedicated instrumentation
(Angerhausen et al. 2011, McElwain et al. 2013)

-2007, April: First test flights of the Observatory
-2009, December: First open door flights.
-2010, May 26: First Light
-since 2011, science operations

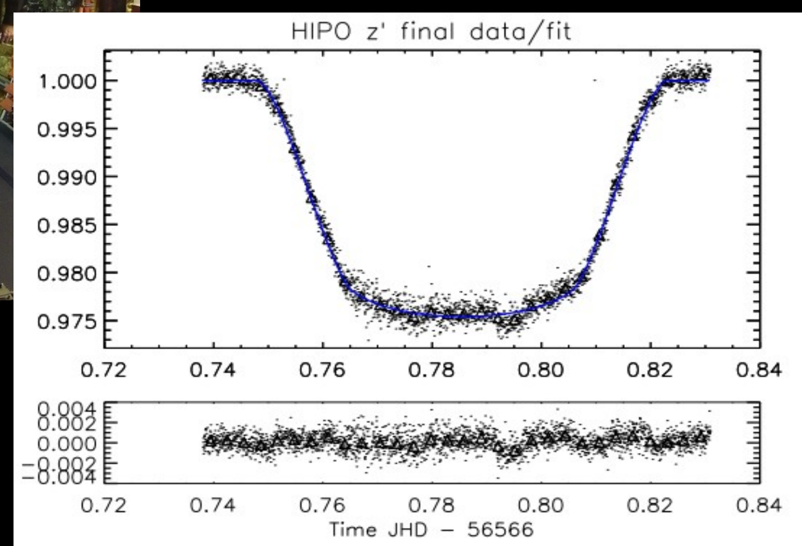


SOFIA – in practice

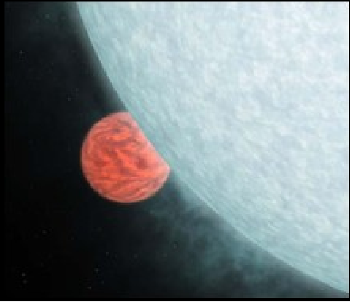
-First exoplanet observation: 1 October 2013 with FLIPO

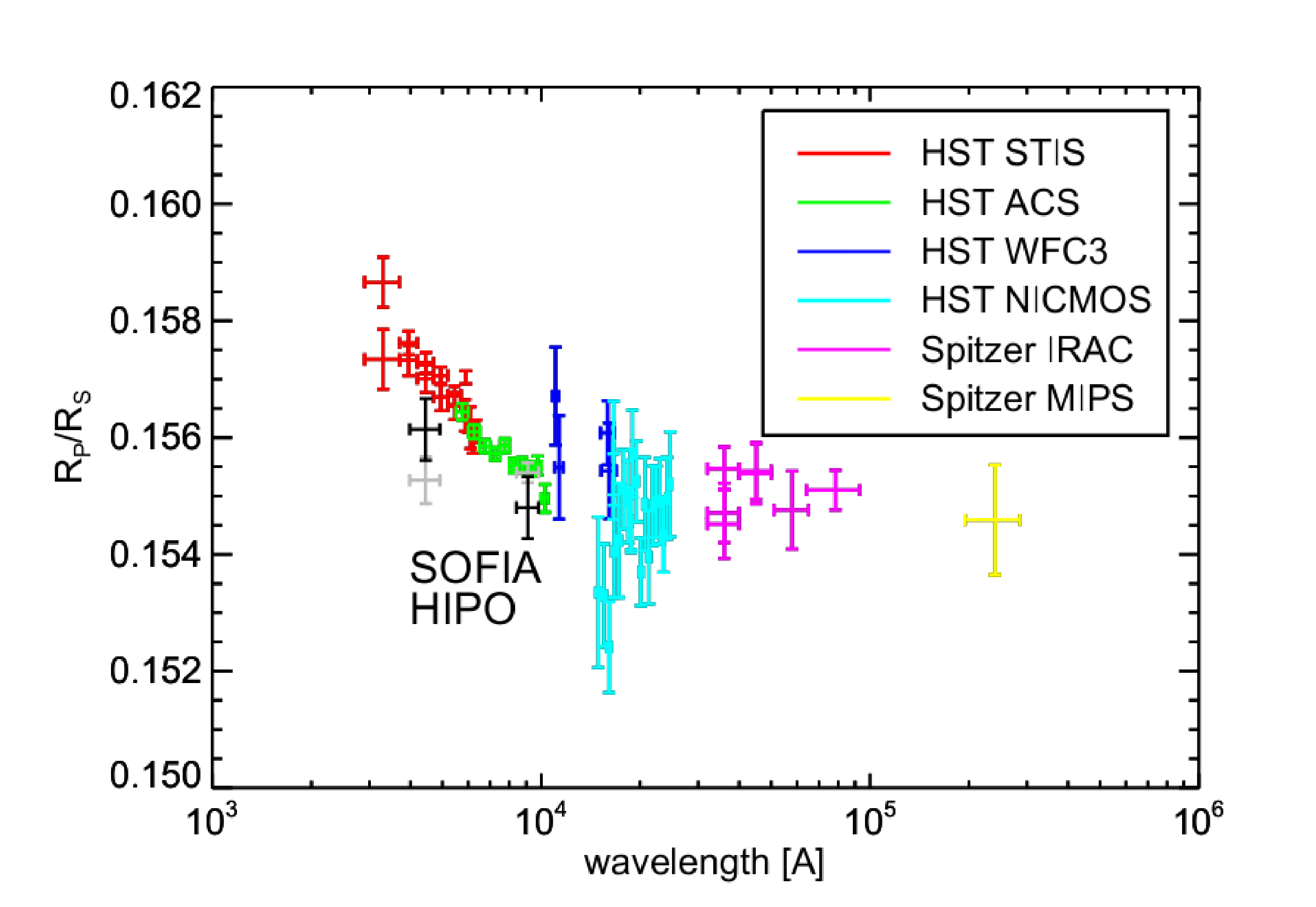
-transit of HD189733b

-”space based” quality



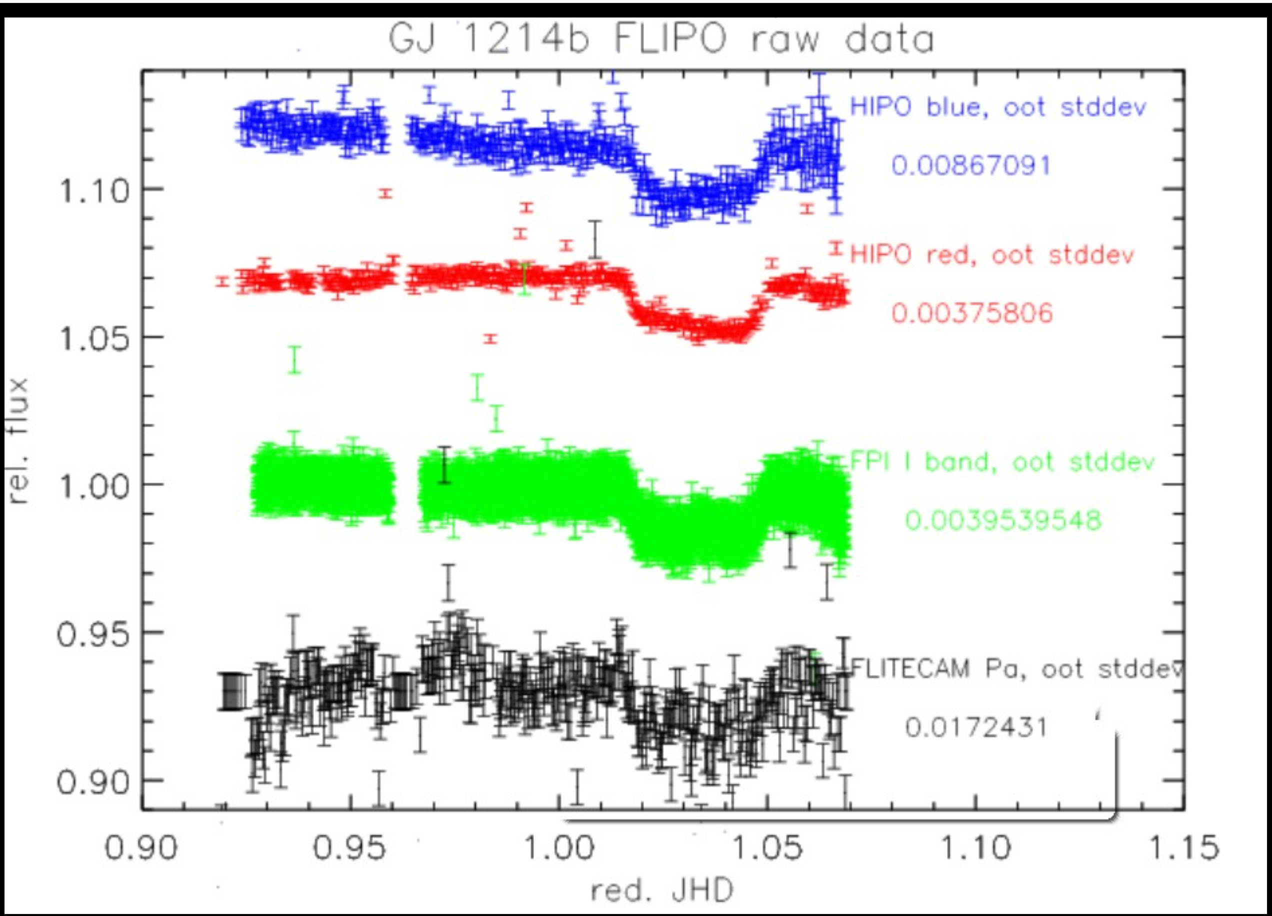
SOFIA – in practice



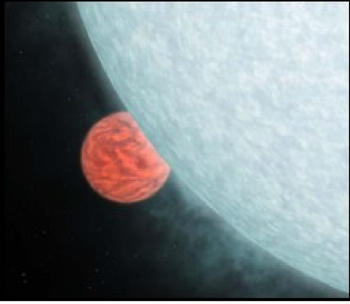


(~ 1.5 photon noise; 185/160 ppm: Angerhausen et al. JATIS, 2015)

SOFIA – in practice

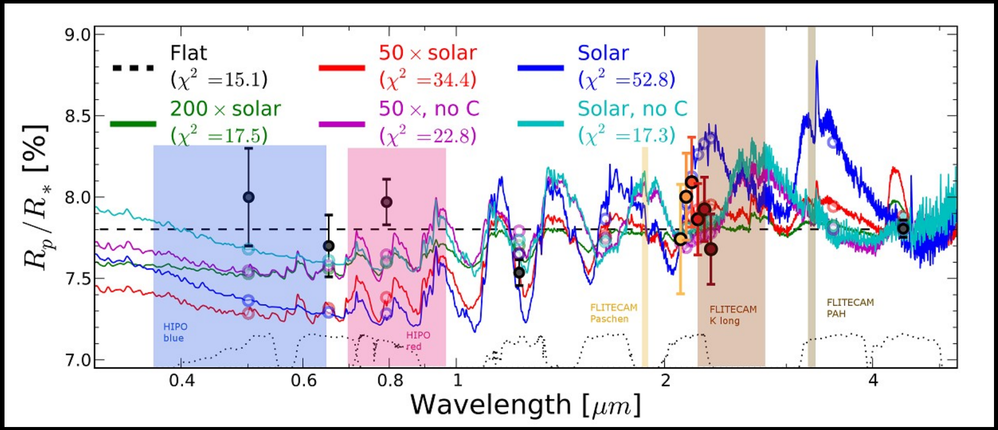


Feb 2014: transit of GJ1214b (2.7 R_e) in Paschen alpha
With FLITECAM imager/spectrograph, red/blue with HIPO, I band with FPI
Super earth or Mini Neptune?

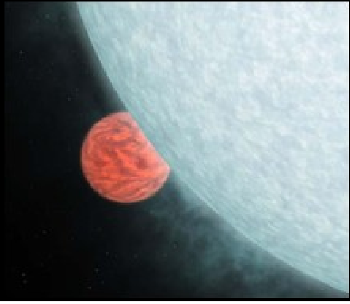


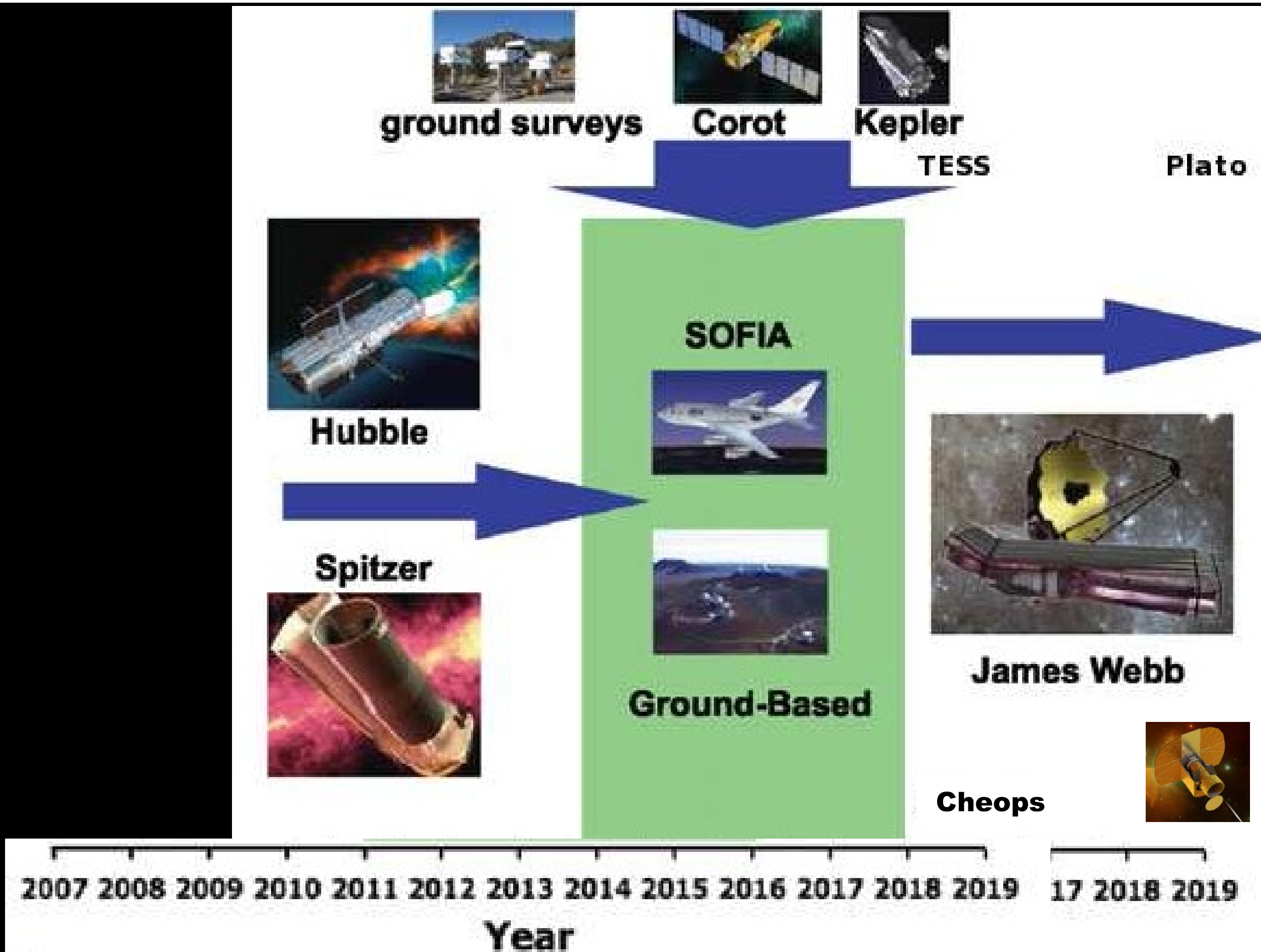
SOFIA – in practice

Sept 2015: transit of GJ3740b ('warm Uranus") in Paschen alphaWith FLITECAM imager and I band with FPI



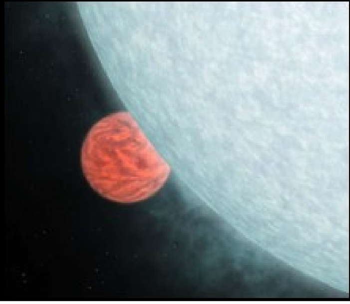
The next decade





From TESS to JWST

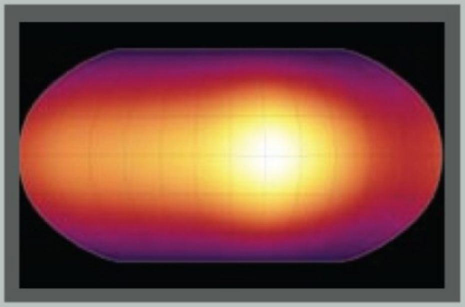
The TESS/JWST connection



WEATHER ON HOT JUPITERS

1000+ TESS-provided sample

- Compare hot (~0.05AU) and cooler (0.1-0.2AU) systems
- Determine radiation time scales
- Measure temperature with altitude



FORMATION AND MIGRATION OF NEPTUNES

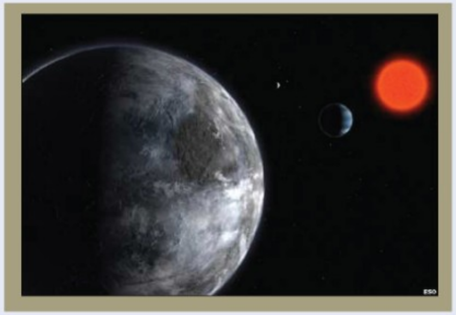
700+ TESS-provided sample

- Evaluate gas fraction vs. remnant core
- Differentiate atmospheric composition based on migration models

WET SUPER EARTHS

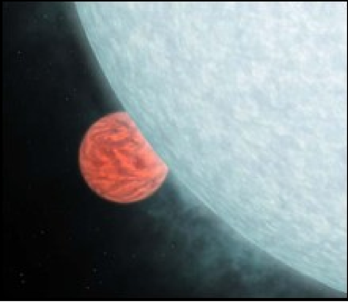
100+ TESS-provided sample

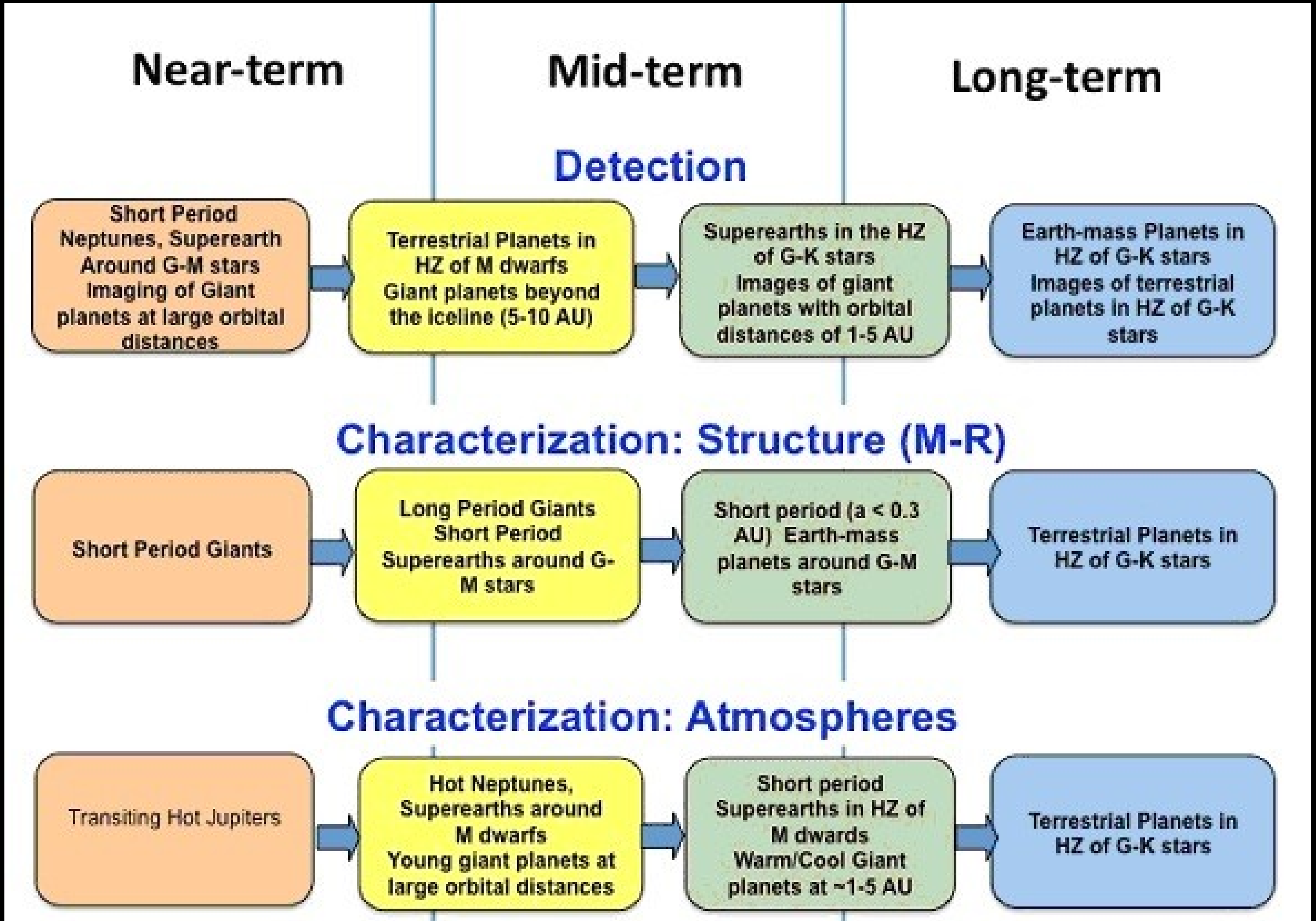
- Compare hot Super Earth's around the late type K stars and cooler Super Earths around mid-late M stars
- Investigate signs of habitability



(from Ricker et al.)

Future outlook/summary





Hatzes, 2011