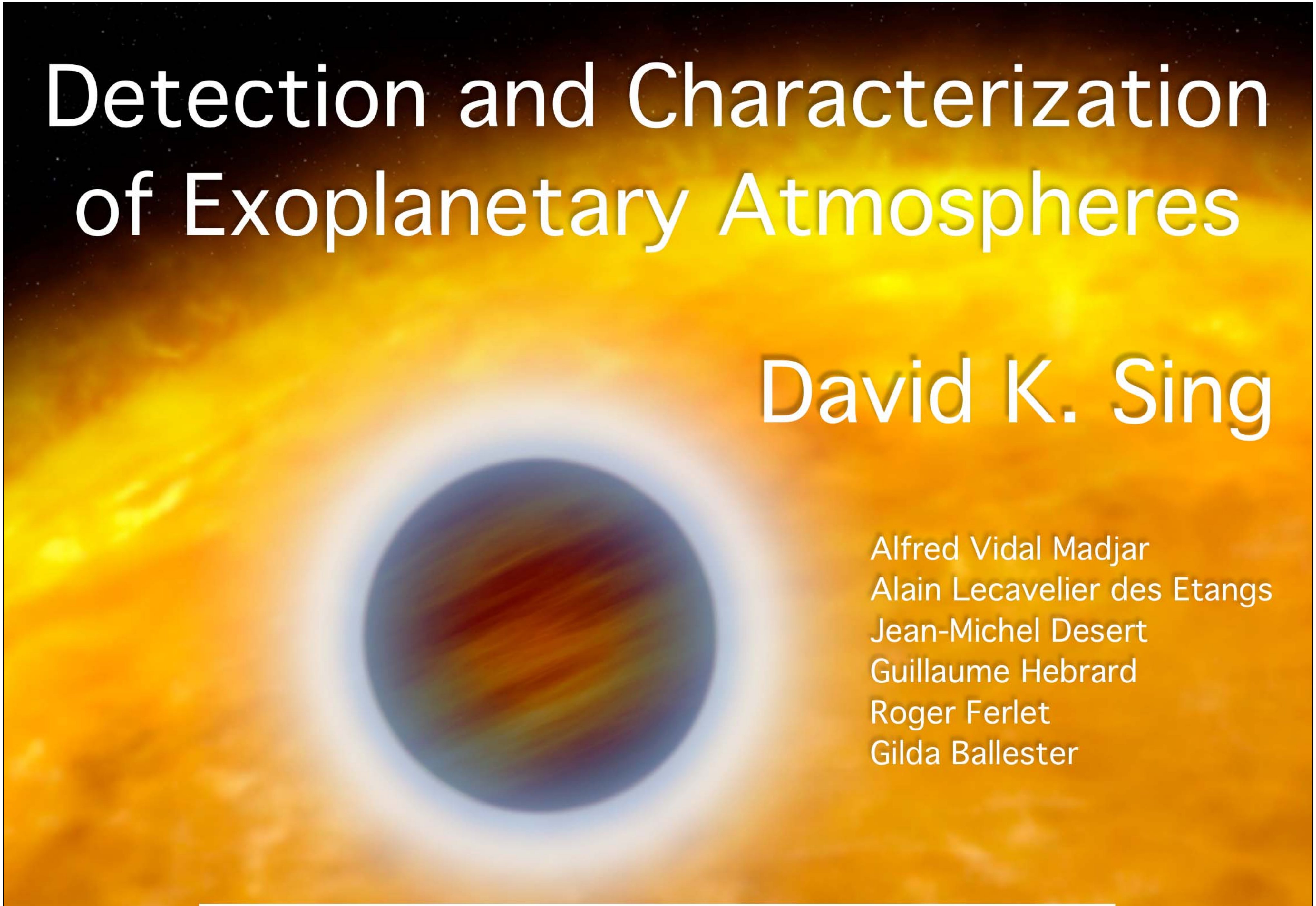

Detection and Characterization of Exoplanetary Atmospheres

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Overview

- Introduction

  exoplanet detection techniques

- Theory

  what can we learn from transits?

- Results

  Part 1: HD209458b: HST transit results

  HD189733b

  Part 2: Ground-based Secondary eclipse detetion

- Conclusions
- Future

Introduction

5 current planet discovery techniques

- Timing Techniques
- Radial Velocity
- Transits
- Microlensing Events
- Direct Imaging

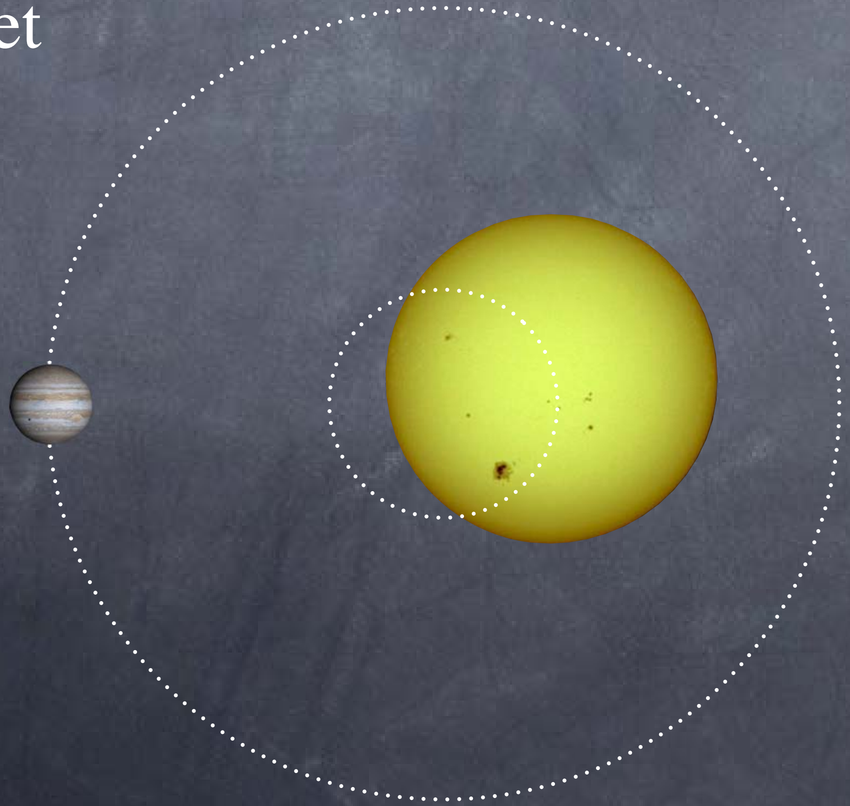
Detection Techniques

5 current planet discovery techniques

- Timing Techniques

  - Measure accurate pulses/oscillations from the star

  - Light travel time of pulse changes with orbit of planet



Wolszczan & Frail 1992

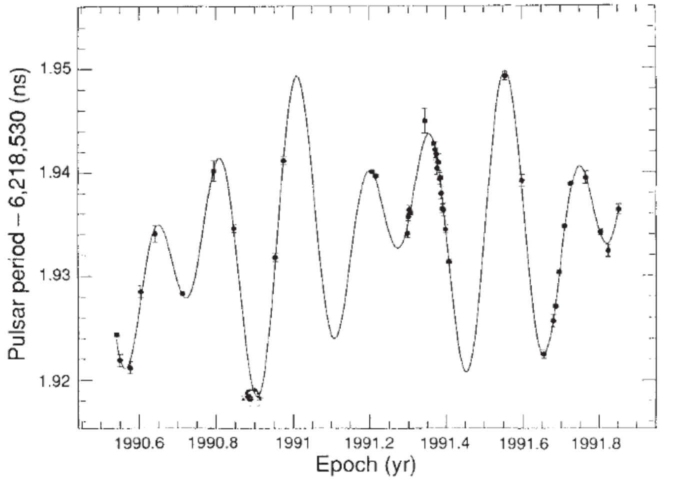
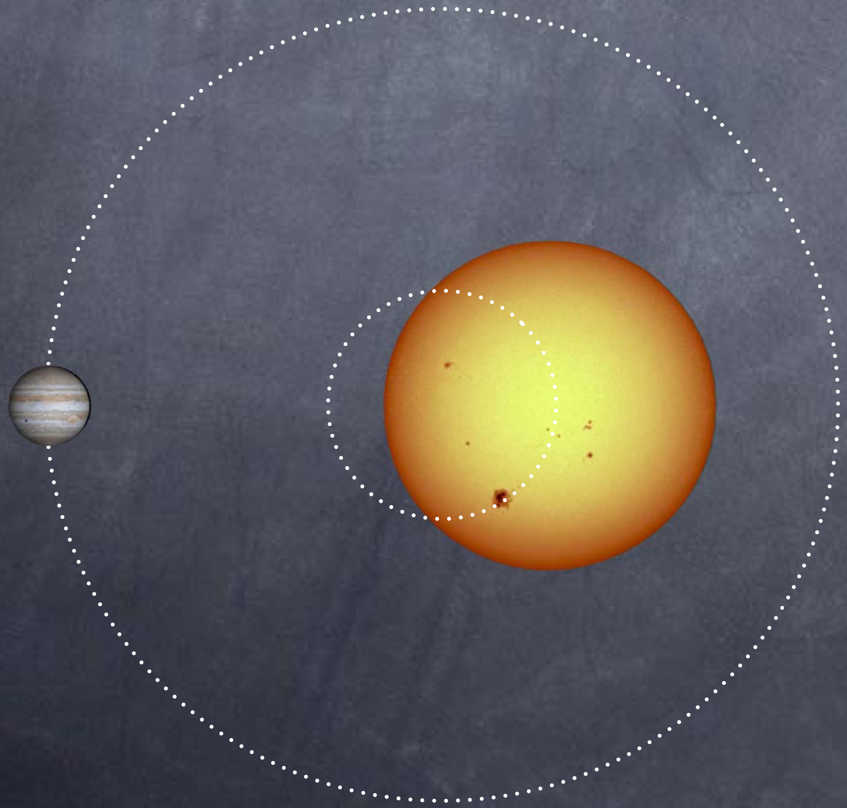


FIG. 3 Period variations of PSR1257+12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257+12 system.

Detection Techniques

- Radial Velocity
  - Reflex motion of planet-star system
    precise radial velocity measurements of the star



Mayor & Queloz 1995

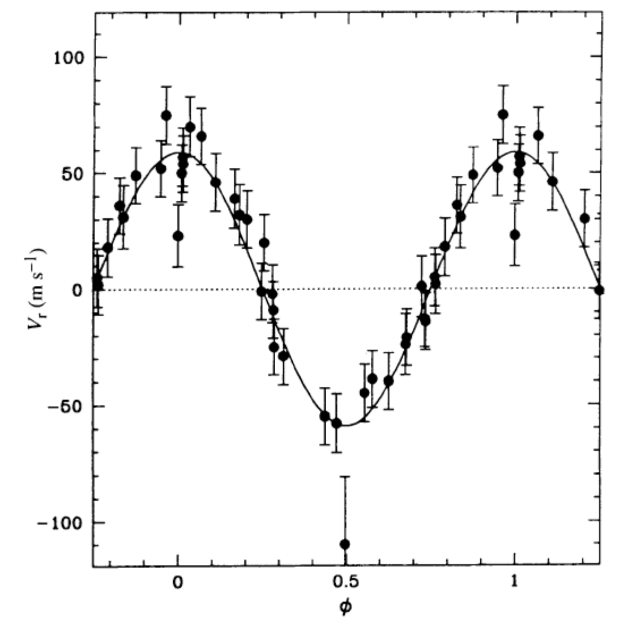


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed

Detection Techniques

- Transits

  By chance, the planet can be viewed passing in front of the star. Photometric light curve shows drop in flux.

Carbonneau et al. 2000

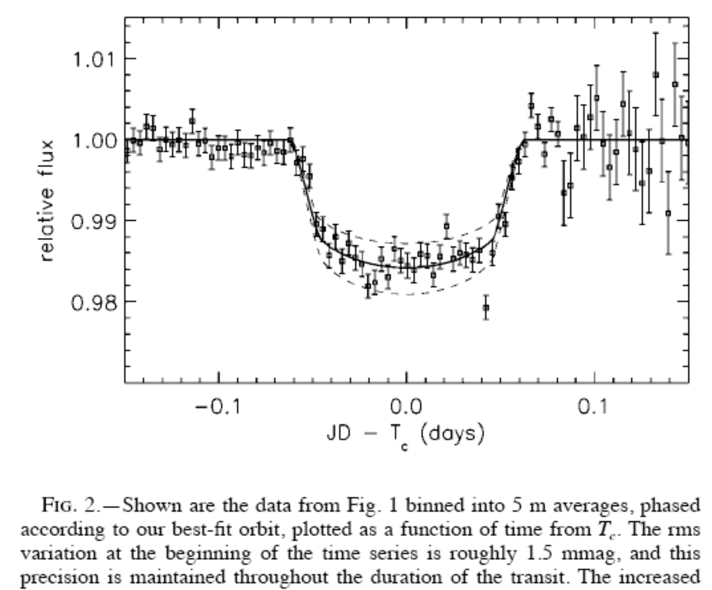


FIG. 2.—Shown are the data from Fig. 1 binned into 5 m averages, phased according to our best-fit orbit, plotted as a function of time from T_c. The rms variation at the beginning of the time series is roughly 1.5 mmag, and this precision is maintained throughout the duration of the transit. The increased

Detection Techniques

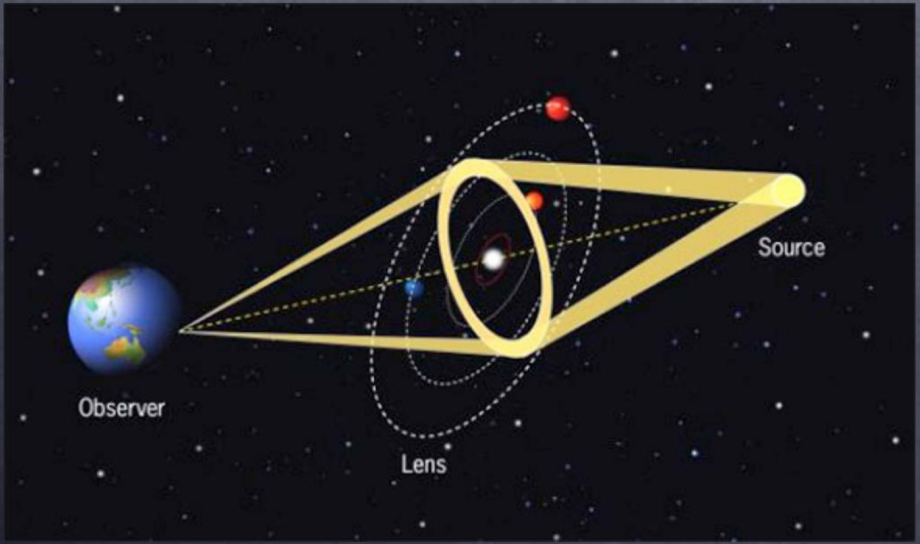
- Microlensing events

  - By chance, two stars line up.

  - The source star brightening through the gravitational lens of the intervening star.

  - A planetary companion (in the right spot) can then further magnify the event.

Bond et al. 2004



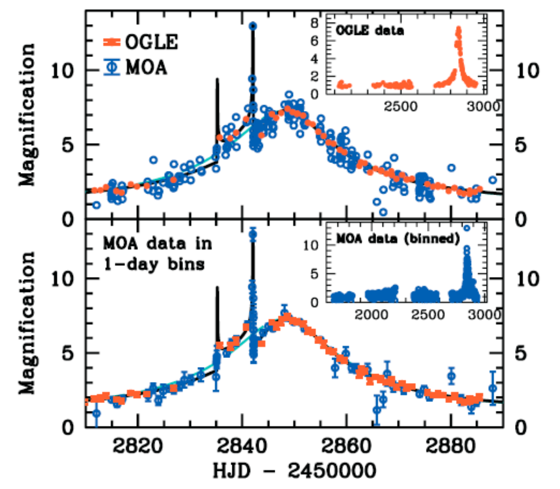
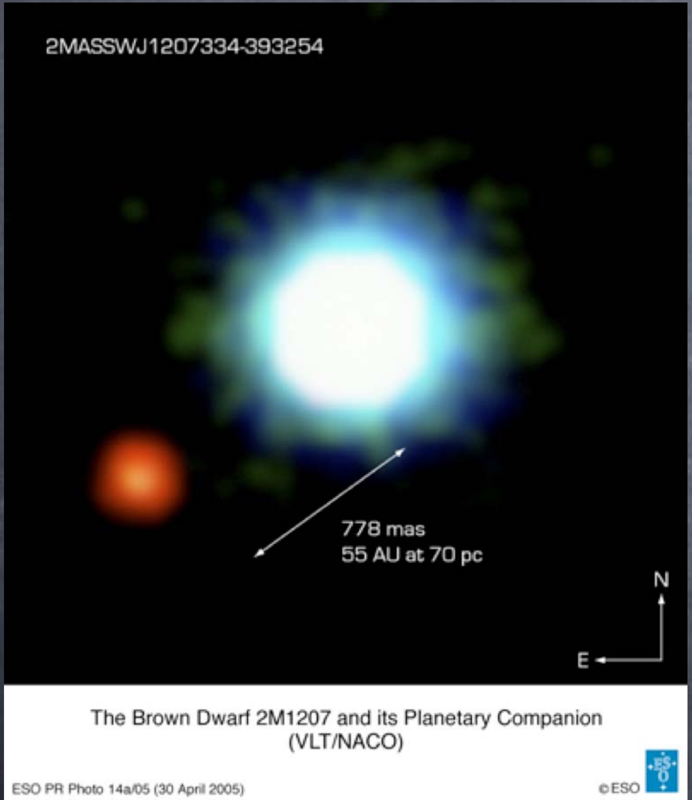


FIG. 1.—Light curve with best-fitting and single-lens models of O235/M53. The OGLE and MOA measurements are shown as red filled circles and open blue circles, respectively. The top panel presents the complete data set during

Detection Techniques

- Direct Imaging

Chauvin et al. 2004

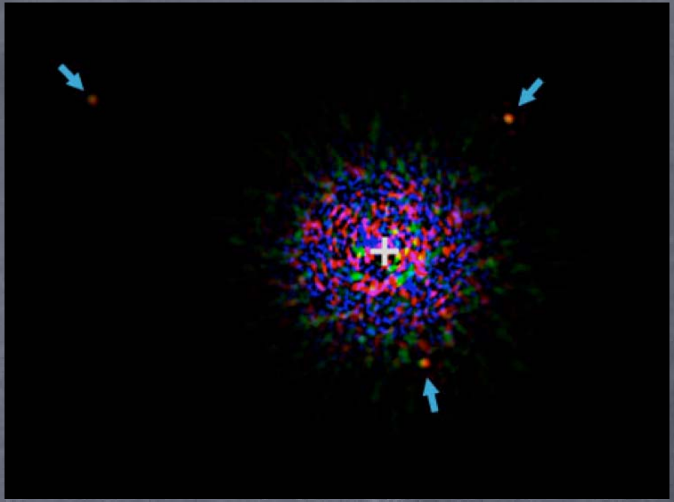


The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

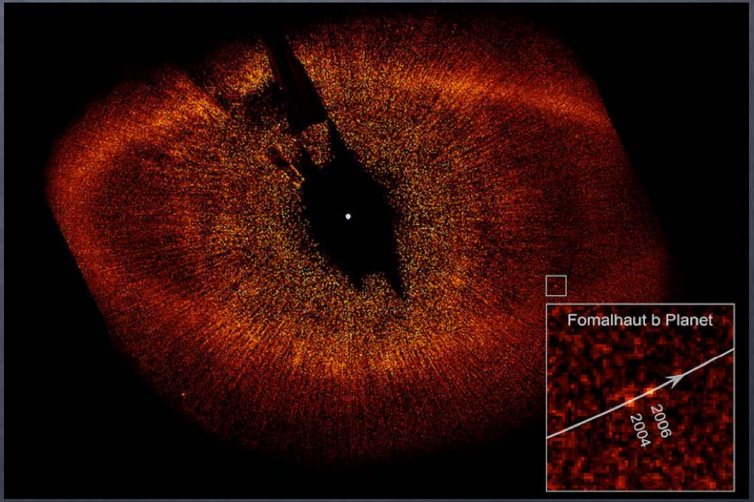
ESO PR Photo 14a/05 (30 April 2005)

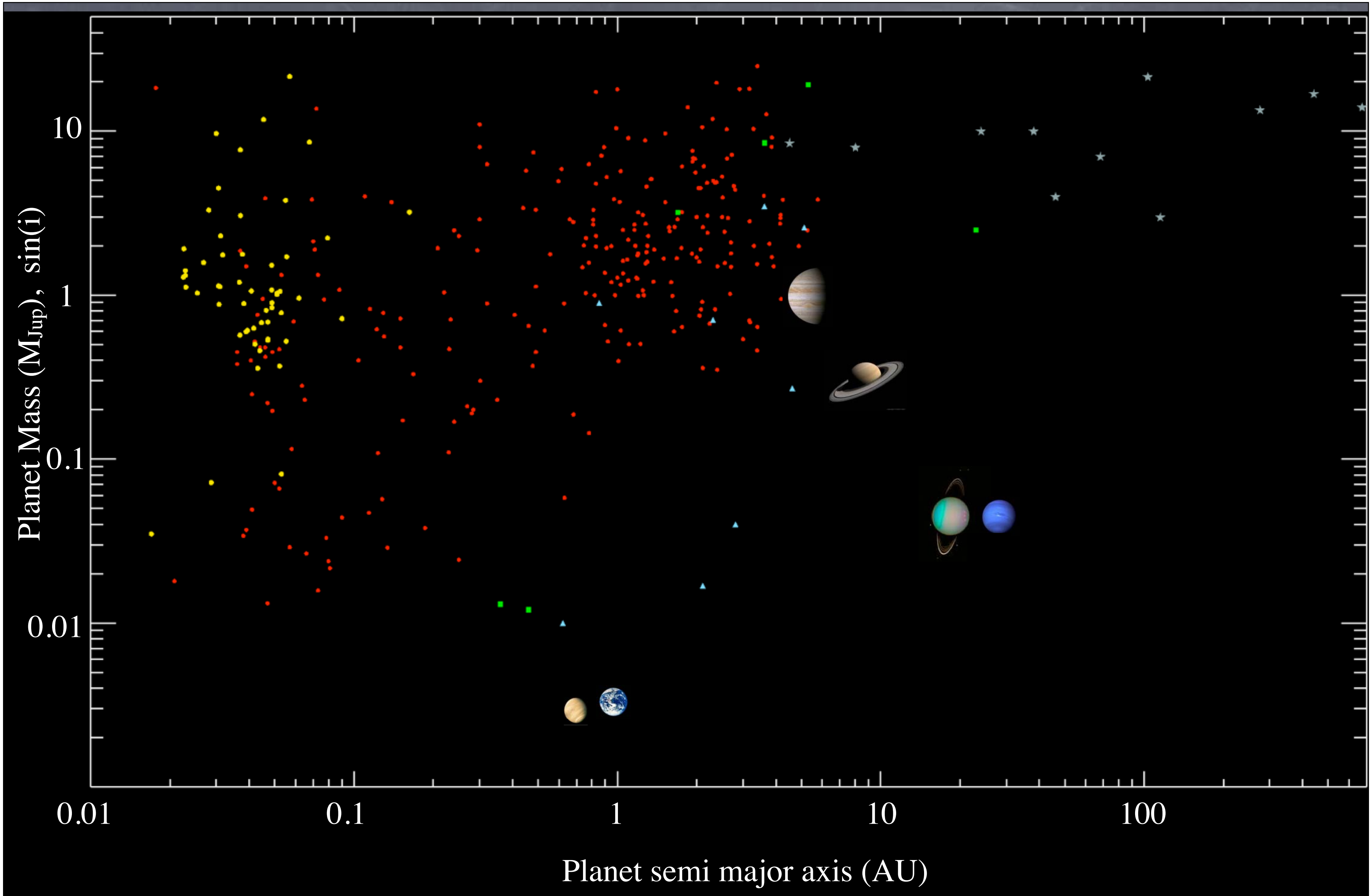
©ESO

Marois et al. 2008



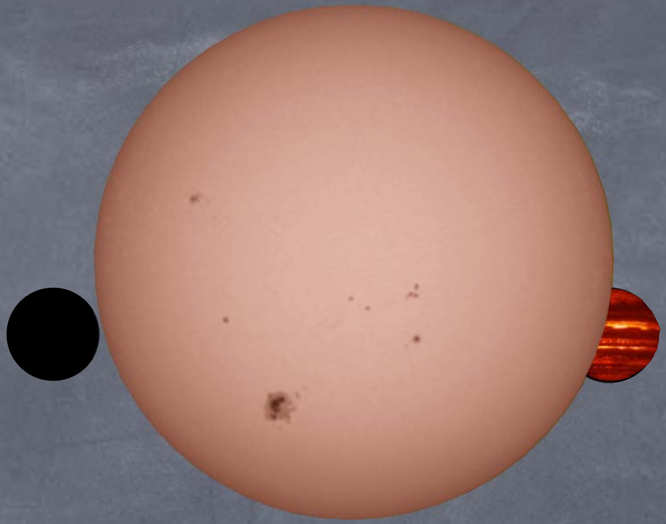
Kalas et al. 2008



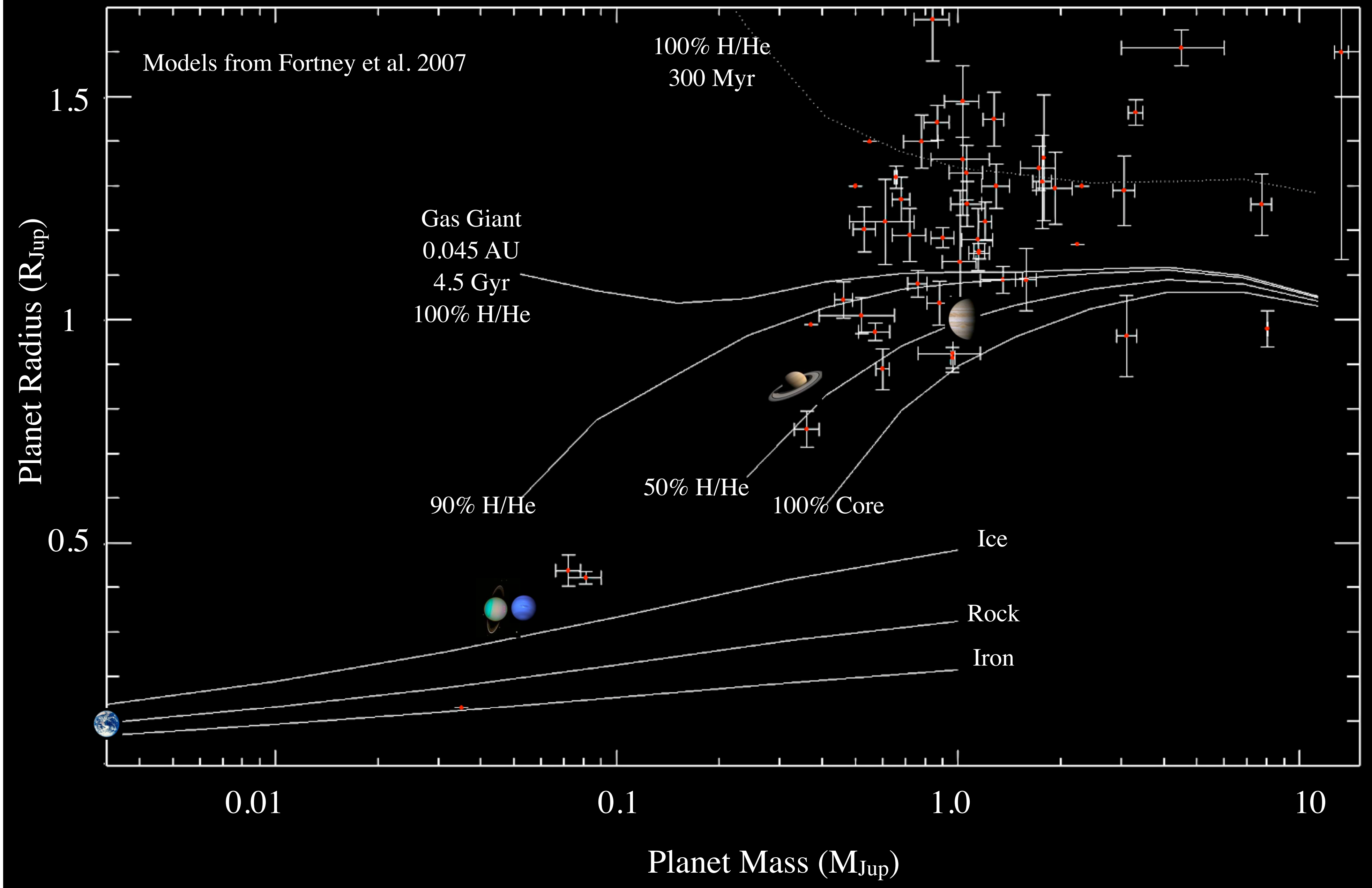


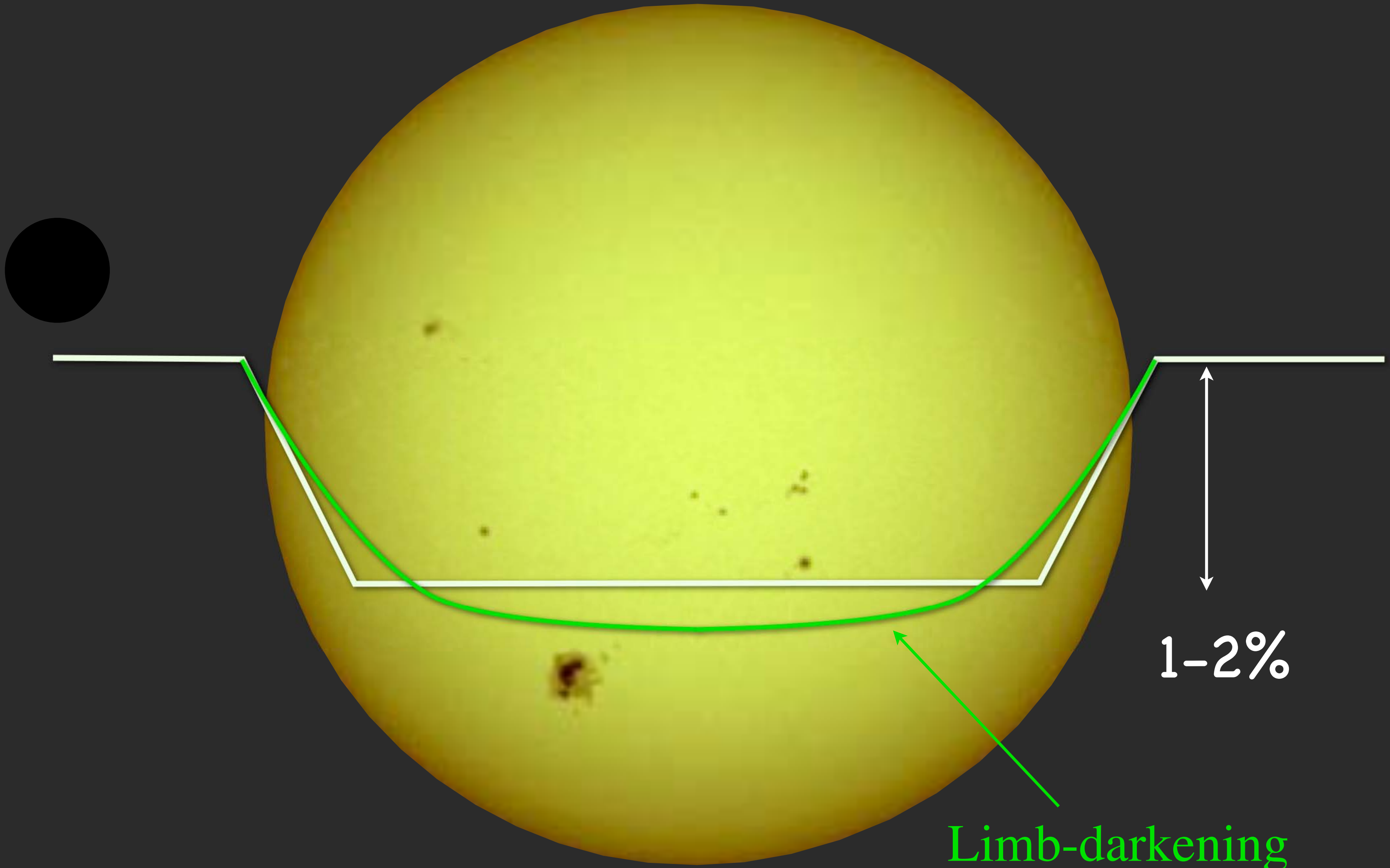
Planet Mass (M_{Jup}), sin(i)
10
1
0.1
0.01
0.01
0.1
1
10
100
Planet semi major axis (AU)

Transits



- Radius can be determined accurately & robustly along with inclination, Mass (M, R)
- Wavelength dependance of transit signature is sensitive to the atmosphere
- Anti-transit in the infrared can give planetary temperature info (Spitzer), IR emission spectra/photometry.


Models from Fortney et al. 2007
100% H/He
300 Myr
Gas Giant
0.045 AU
4.5 Gyr
100% H/He
90% H/He
50% H/He
100% Core
Ice
Rock
Iron
1.5
1
0.5
0.01
0.1
1.0
10
Planet Radius (R_{Jup})
Planet Mass (M_{Jup})


1-2%
Limb-darkening

Anatomy of Transit

Transit light curve depends on

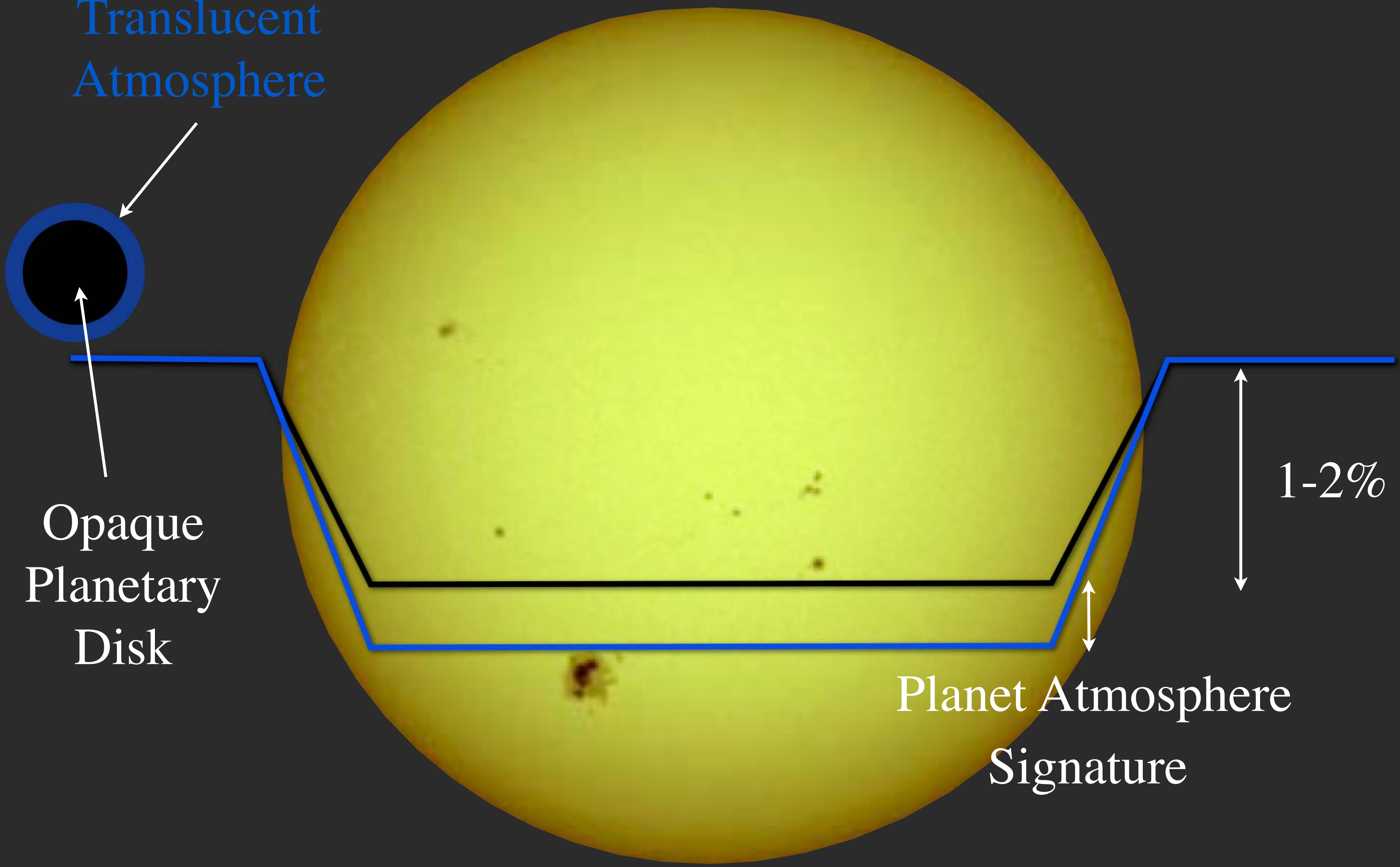
1) Limb-darkening C_1, C_2, C_3, C_4

2) Planet/Star radius contrast $R_{pl}/R_{\star}$

3) Impact parameter $M_{\star}^{\frac{1}{3}} R_{\star}, M_{pl}, P, i$

Transit is very sensitive to radius ratio $R_{pl}/R_{\star}$

Planet parameters ultimately limited by Star



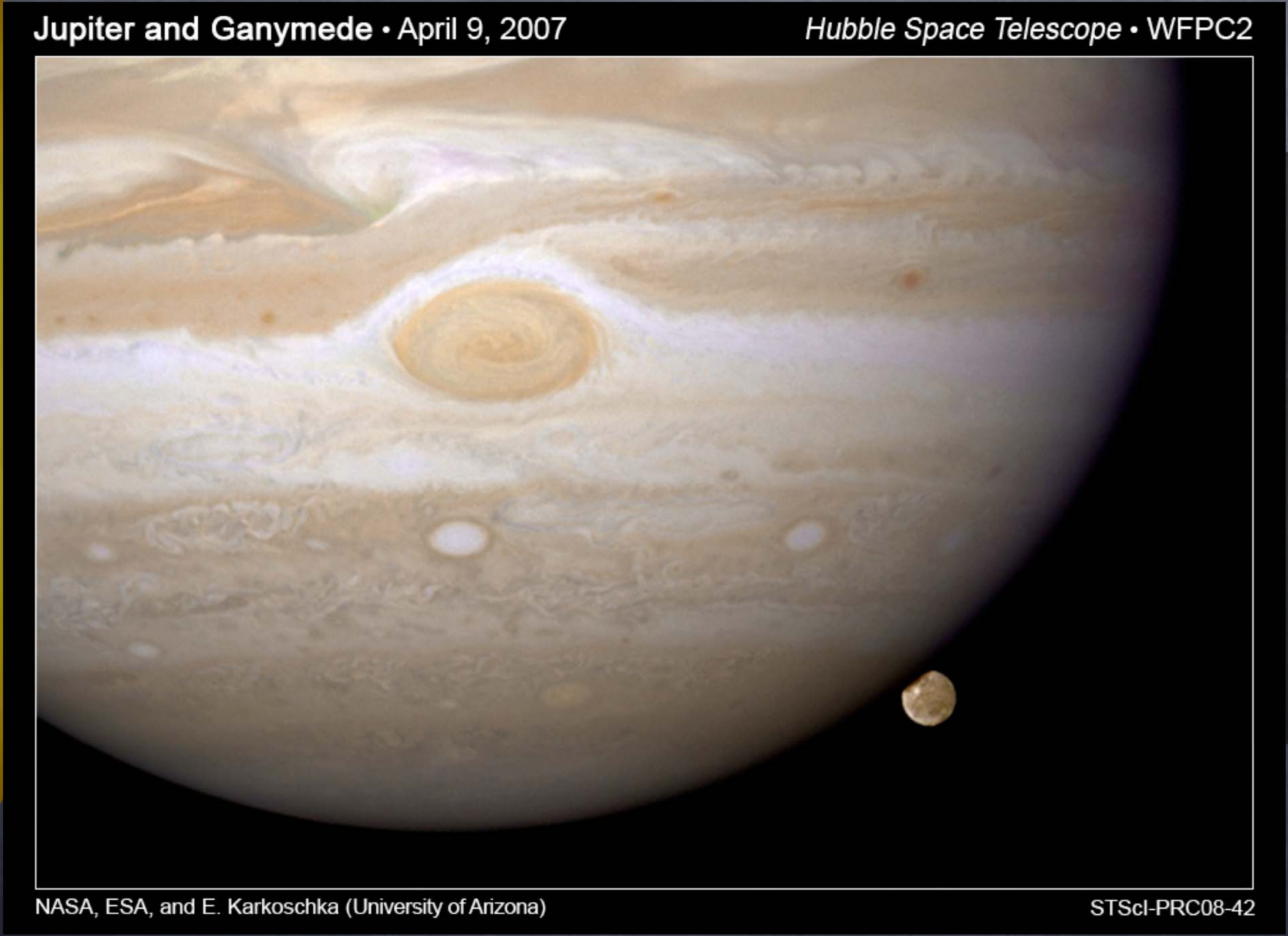
Translucent Atmosphere

Opaque Planetary Disk

1-2%

Planet Atmosphere Signature

Atmosphere has λ dependance



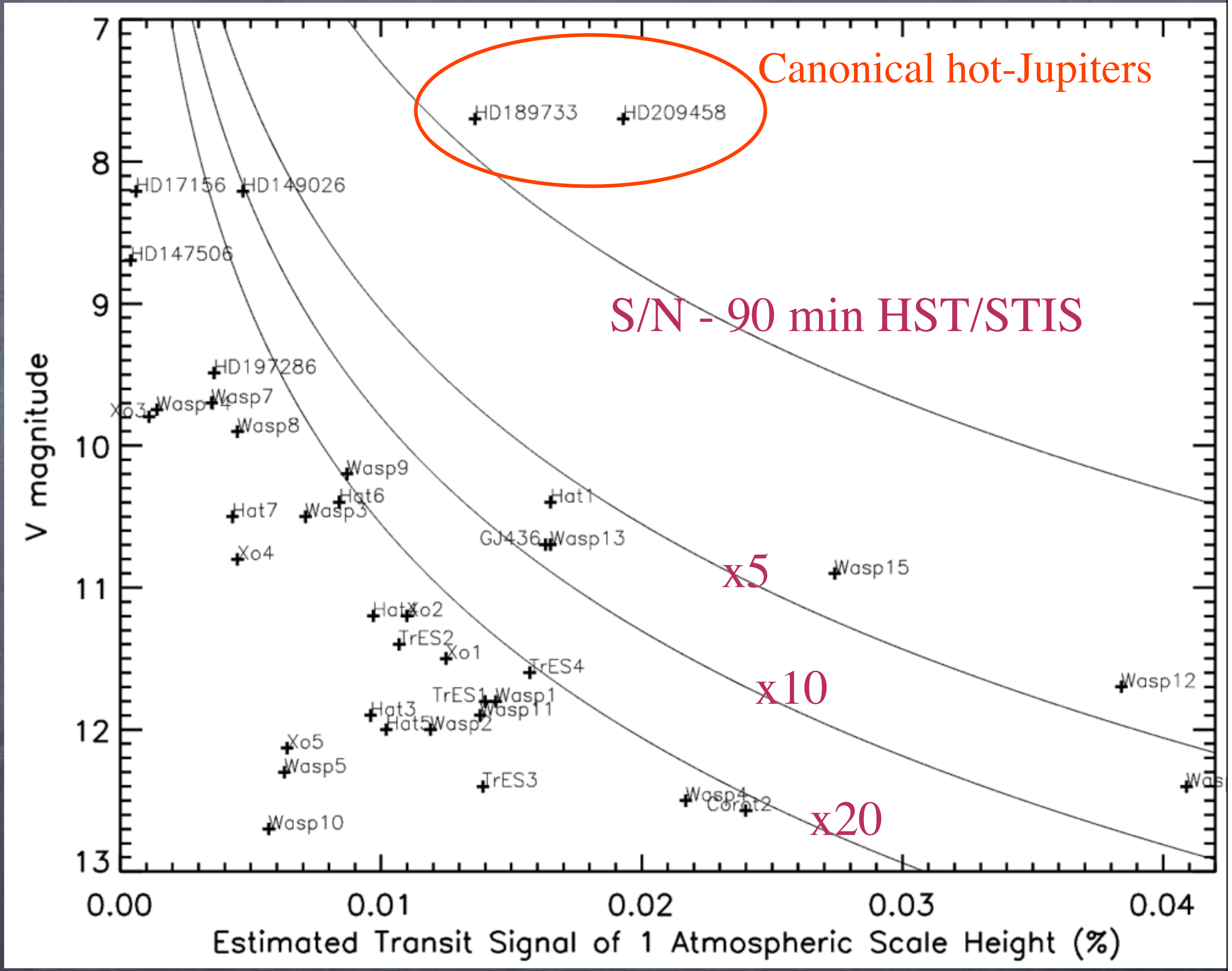
Exoplanetary Atmospheres

- Very accurate+fast photometry needed
    - Typical hot-Jupiter signatures (0.02-0.05%) in 1 hour
    - 1 mmag phot. accuracy = 0.1%
- Techniques to high precision (key: relative measurement)
    - Stable pointing/no dithering (reduces flatfield errors)
    - Minimize duty cycle (defocusing to increase exp. time)
    - Characterize systematics from out-of-transit data

Transit Atmosphere Signals

Signal is easier to detect if:

- Bright
- Large contrast (deep transit)
- Large atmosphere (lower surface g, higher Teff)



Transmission Spectra

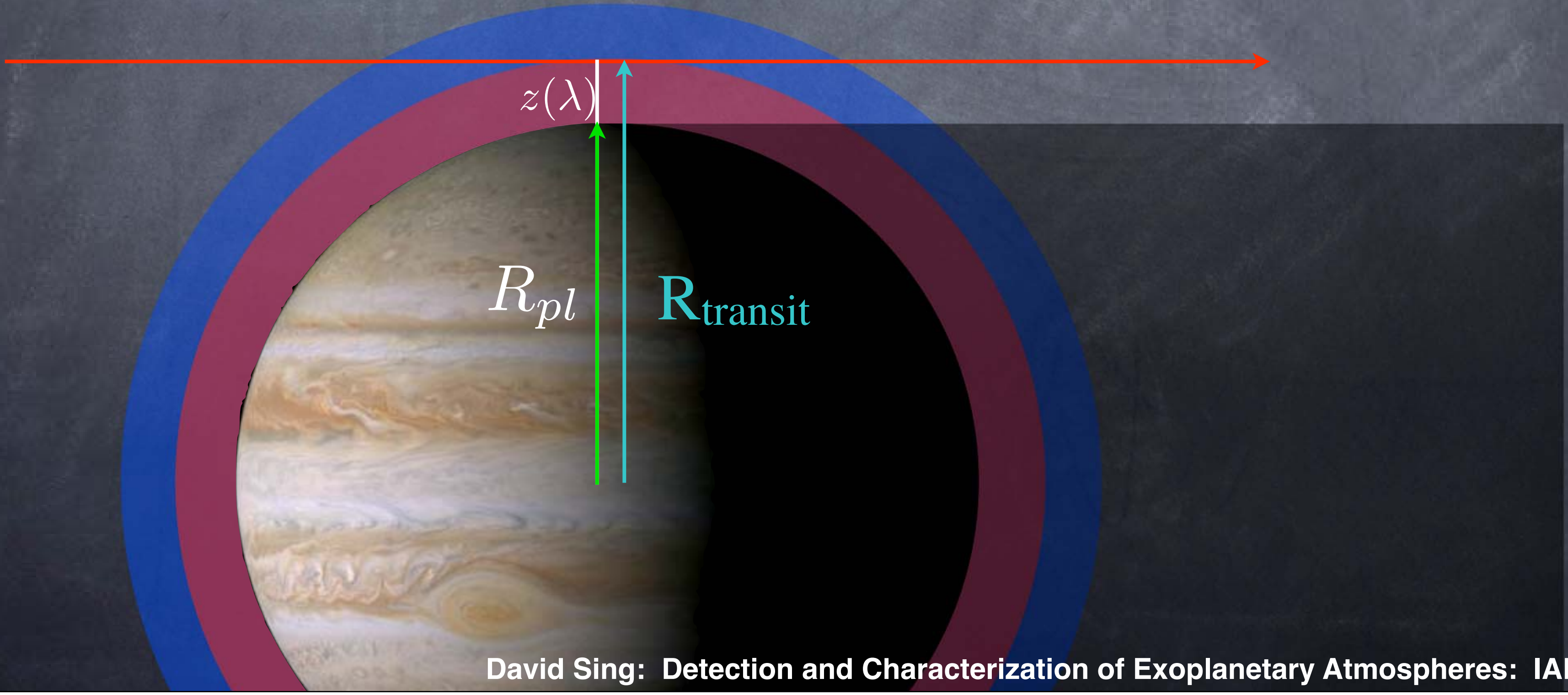
- For bright targets, HST can produce FULL planetary transmission spectra from the UV-Opt-NIR
- Push transit precision to better than 0.01% (S/N 10,000)

Atmospheres by Transit

- Transit opacity, Lecavelier et al. (2008)

$$\tau(\lambda, z) = \sigma(\lambda) n(z) \sqrt{2\pi R_{pl} H} \qquad n(z) = n(_{z=0}) e^{-z/H} \qquad H = kT/\mu g$$

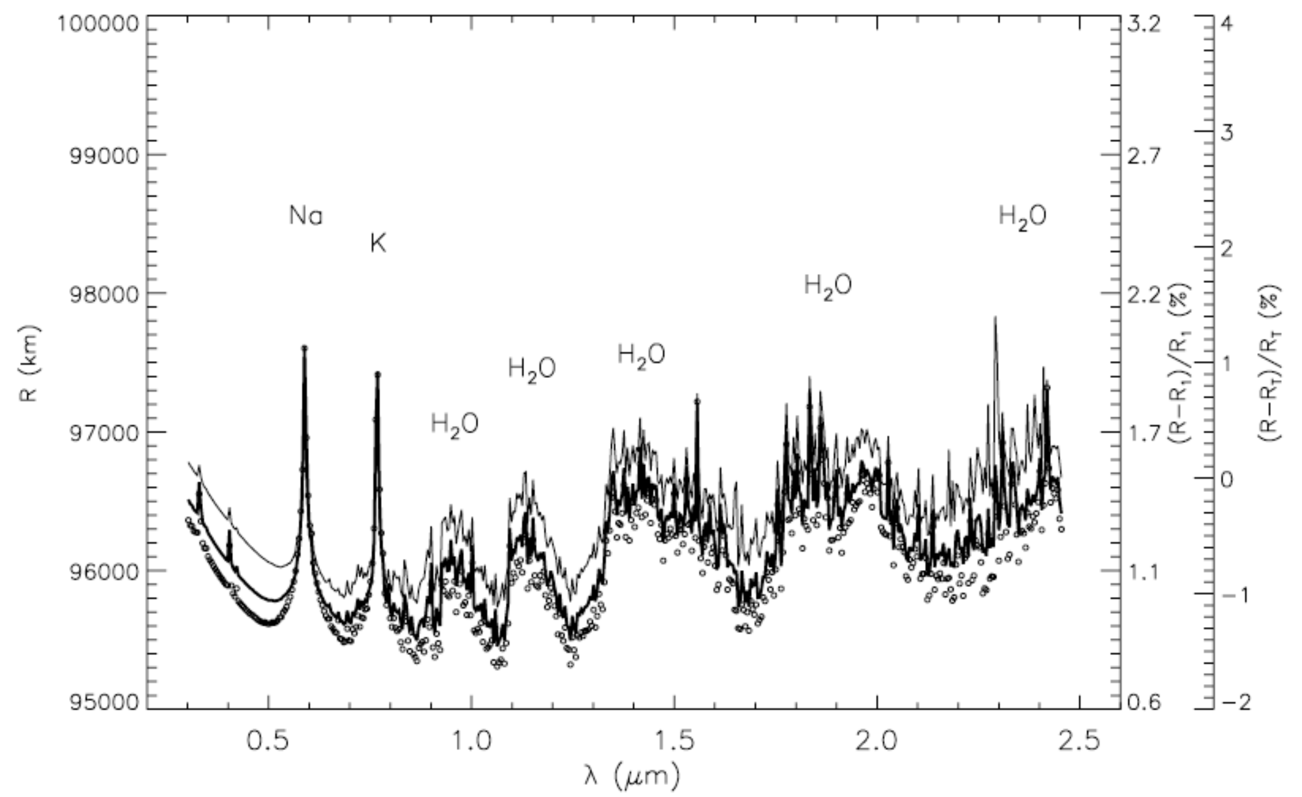
$$z(\lambda) = H\ ln \left(\frac{\xi_{abs} P_{z=0} \sigma(\lambda)}{\tau \mu g} \sqrt{\frac{2\pi R_{pl}}{H}} \right)$$



Atmospheres by Transit

$$z(\lambda) = H\ ln\left(\frac{\xi_{abs}P_{z=0}\sigma(\lambda)}{\tau\mu g}\sqrt{\frac{2\pi R_{pl}}{H}}\right)$$

- Altitude - Composition - Press - Temp very important in shaping transit spectra



HD209458b
Hubbard et al. 2001

A Few Programs to date:

HD209458b

- T. Brown et al. 2001 high S/N transit “proved” existence of exoplanets
- D. Charboneau et al.2002 , Na detection 0.02% in 12 Å band
- Mystery: smaller Na signal than expected (clouds? Na depletion?)

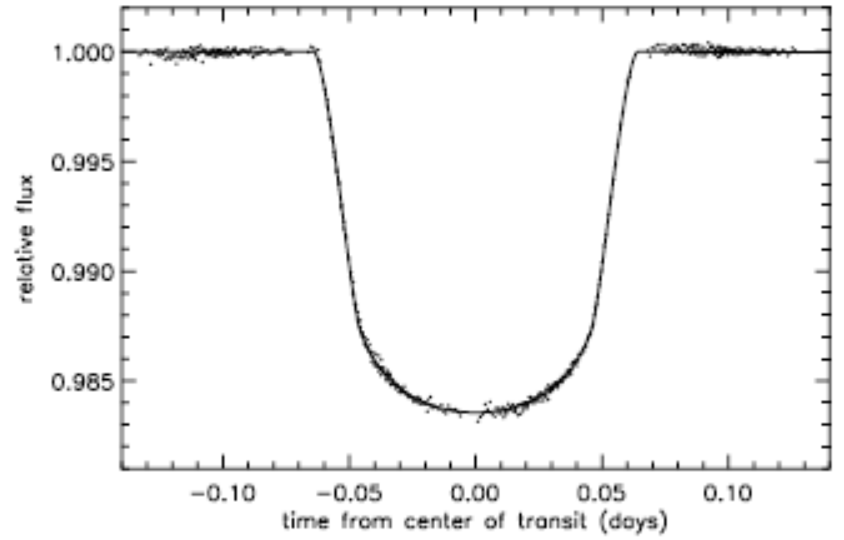
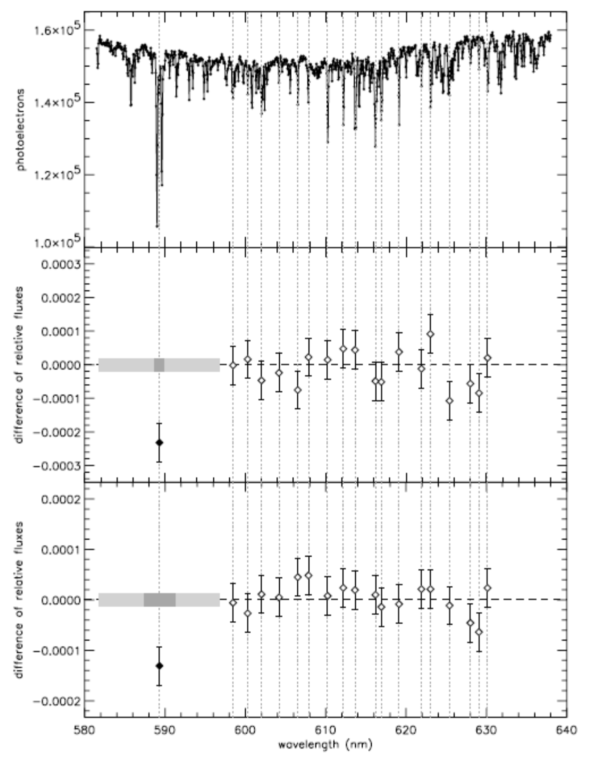
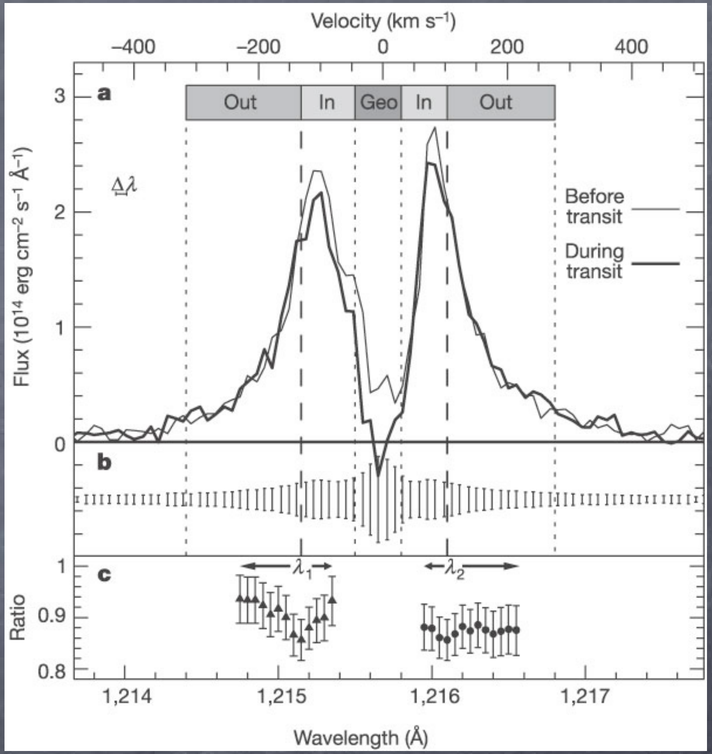


FIG. 3.—Phased light curve for all four transits, assuming a planetary orbital period of 3.52474 days. The time series for each transit has been scaled to have the same average intensity over the second and fifth (out-of-transit) orbits.



A Few Programs to date:



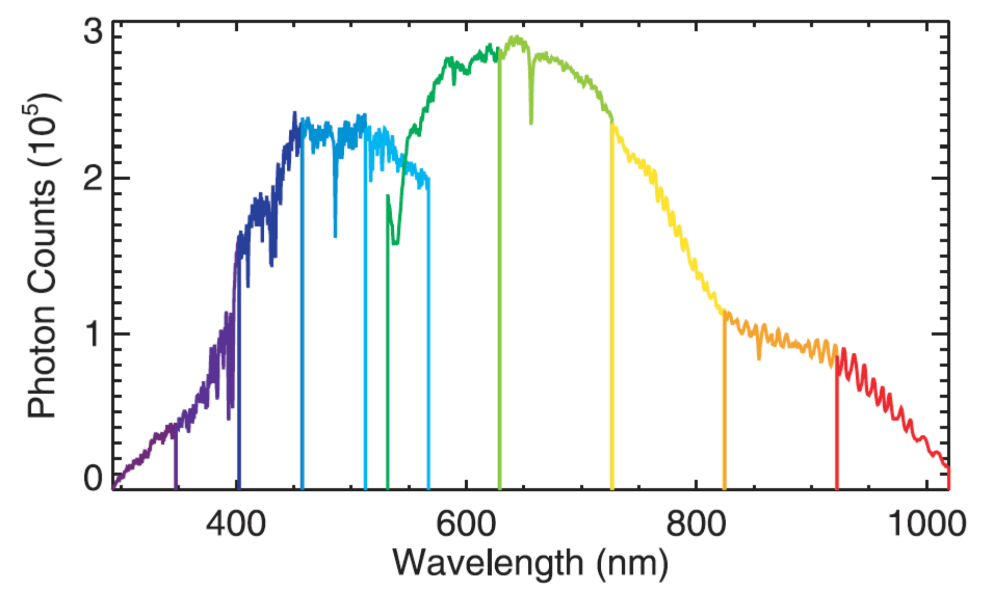
HD209458b

- A. Vidal-Madjar et al. 2003 escaping atmosphere

A Few Programs to date:

HD209458b

- Knutson et al. 2007 used optical HST/STIS low resolution to derive accurate planetary parameters, study limb-darkening



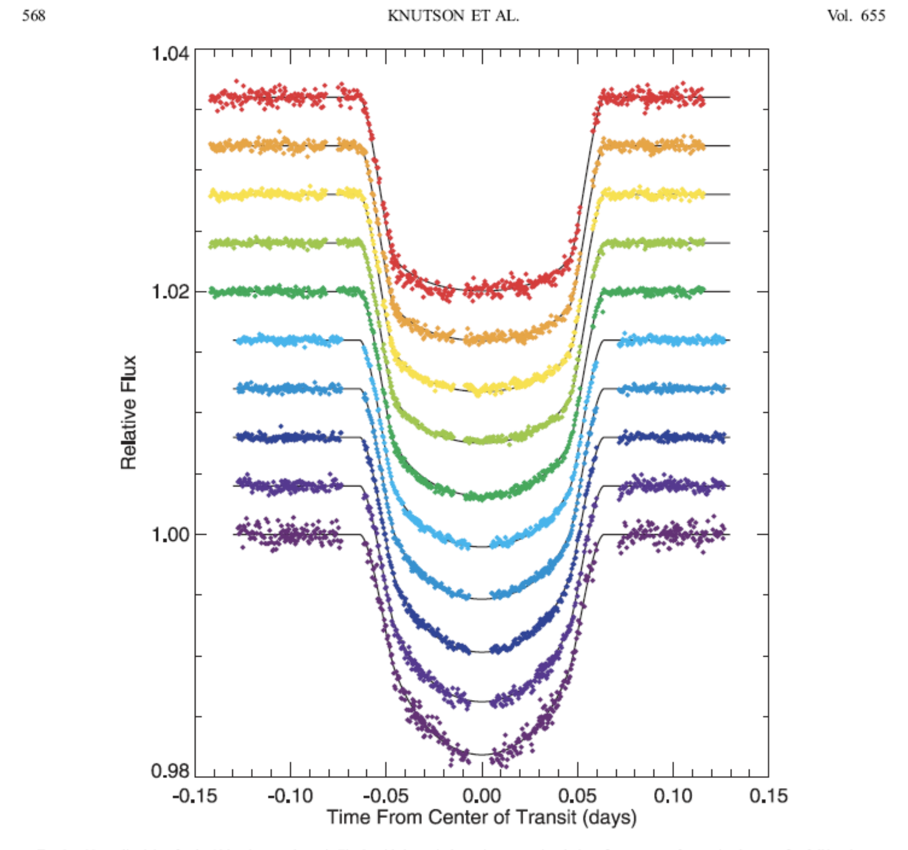
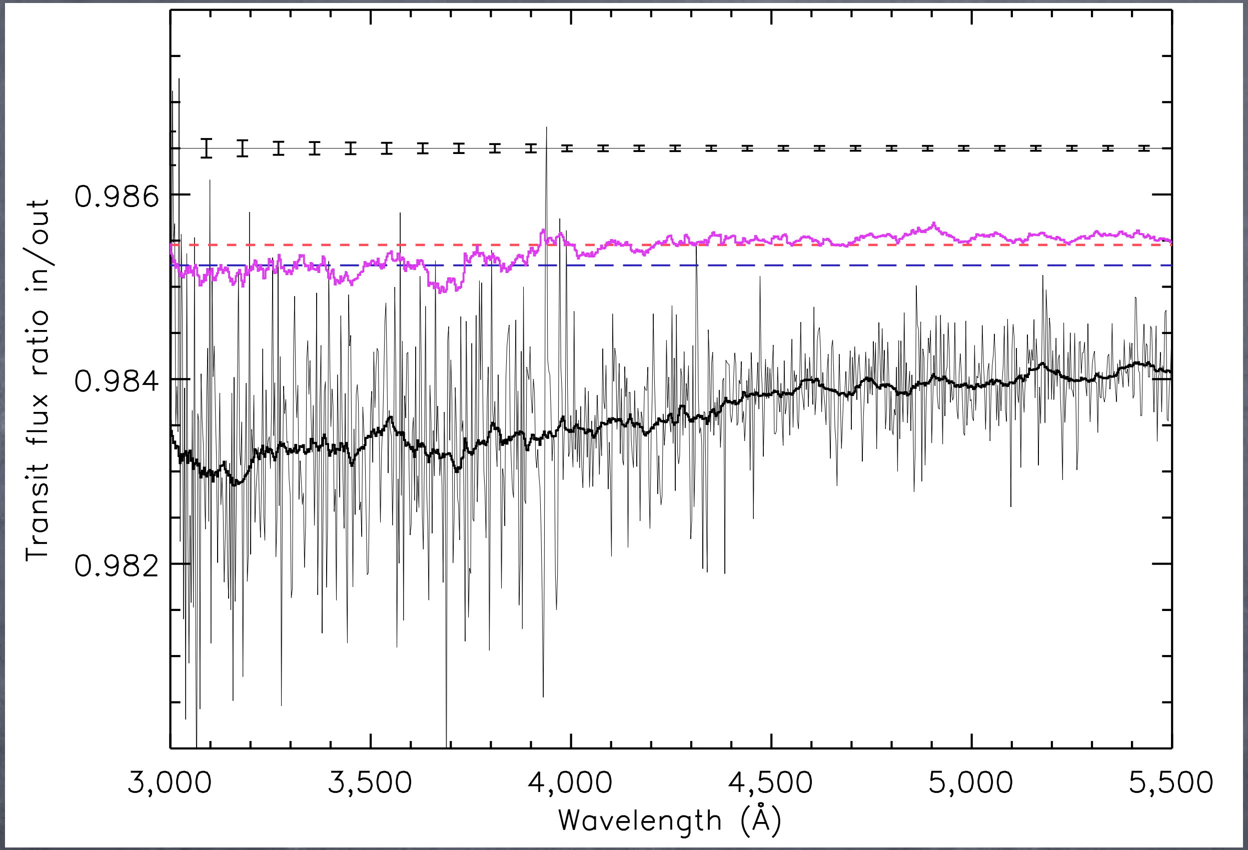

568 KNUTSON ET AL. Vol. 655

Fig. 3.—Normalized data for the 10 bandpasses shown in Fig. 2, with theoretical transit curves using the best-fit parameters from a simultaneous fit of all bandpasses (Tables 4 and 6) and model four-parameter nonlinear limb-darkening coefficients overplotted. Note that each bandpass contains data from two separate visits, consisting of

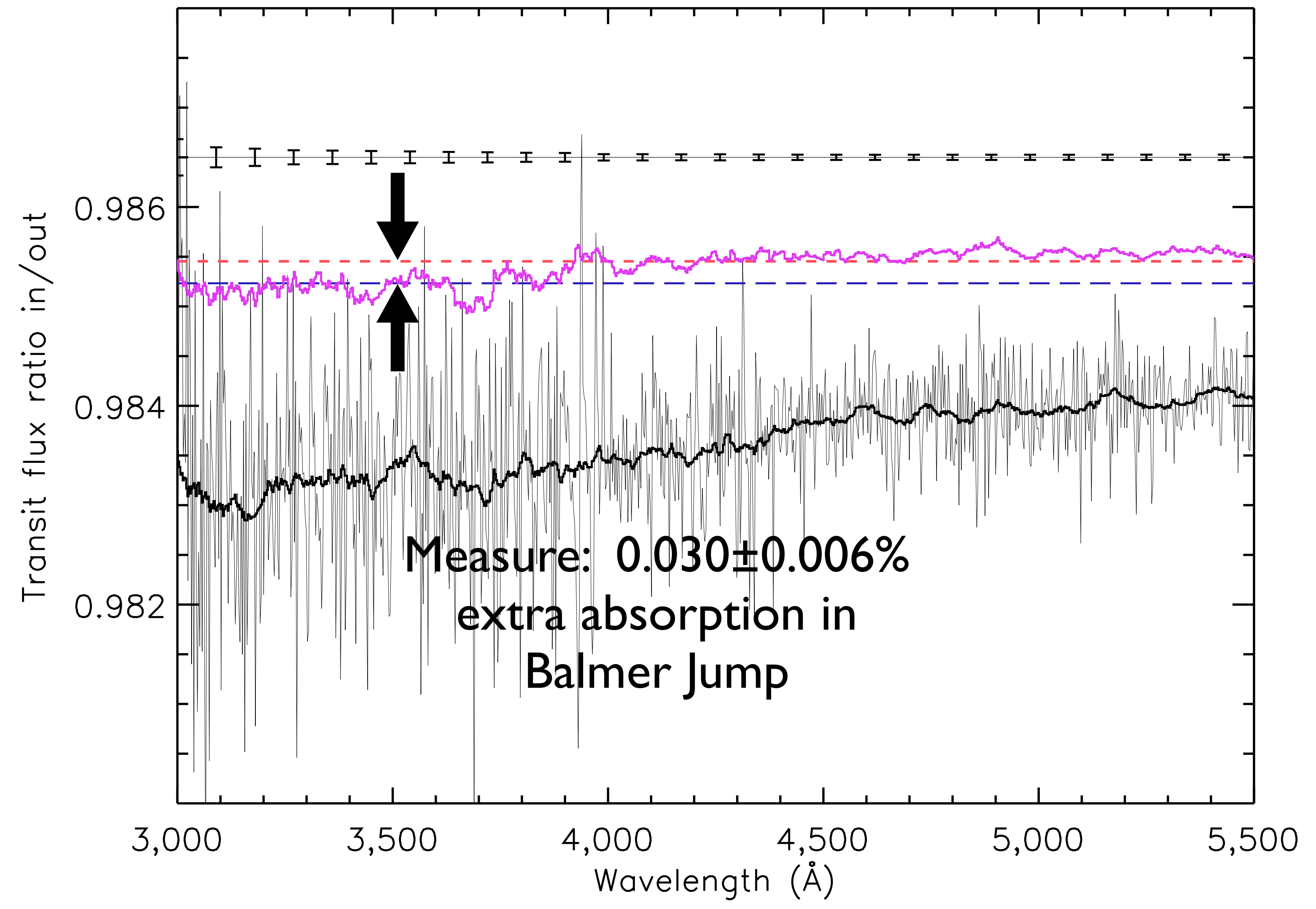
Hot Hydrogen Discovery



Ballester, Sing & Herbet 2007

- Full pixel-by-pixel limb-darkening correction
- Full spectroscopic information

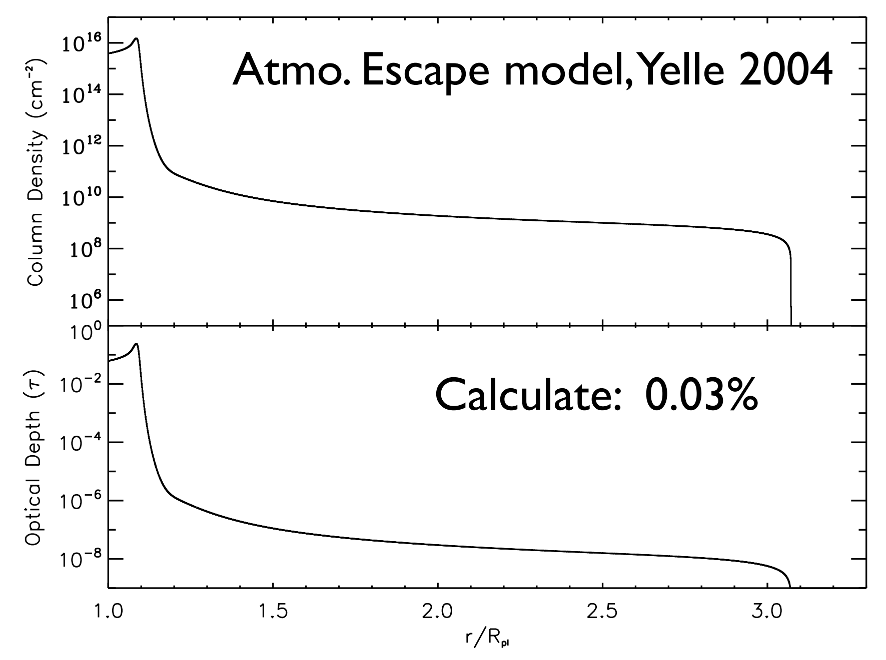
Hot Hydrogen Discovery



Measure: 0.030±0.006%
extra absorption in
Balmer Jump

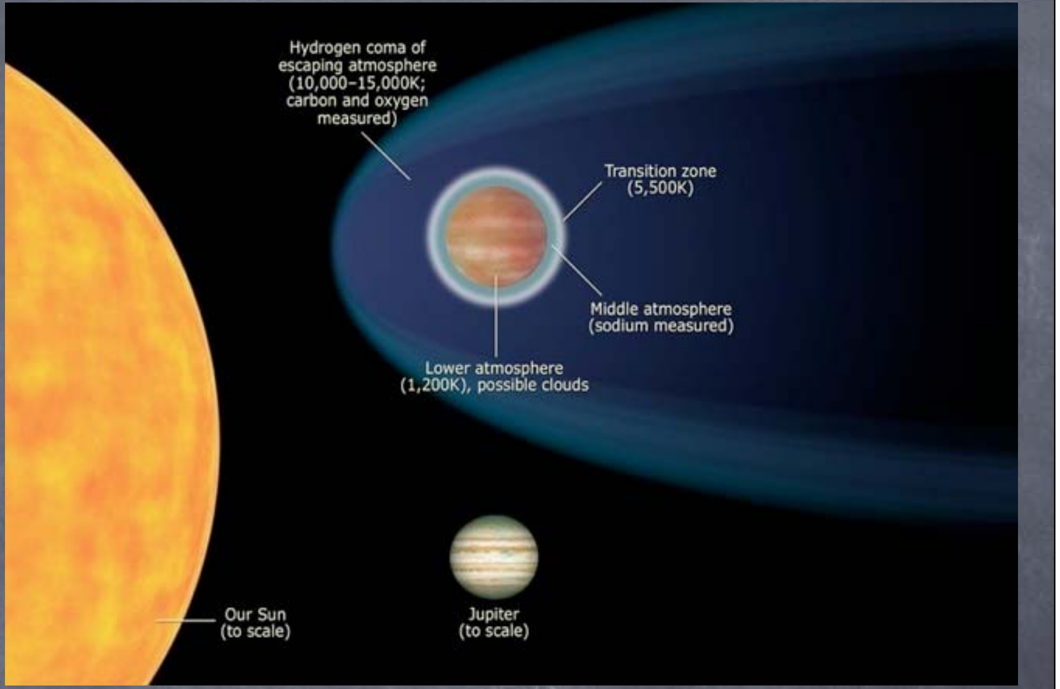
Ballester, Sing & Herbet 2007 Nature

Hot Hydrogen Discovery



Atmo. Escape model, Yelle 2004

Calculate: 0.03%



STScI press release image
Ballester, Sing & Herbet 2007

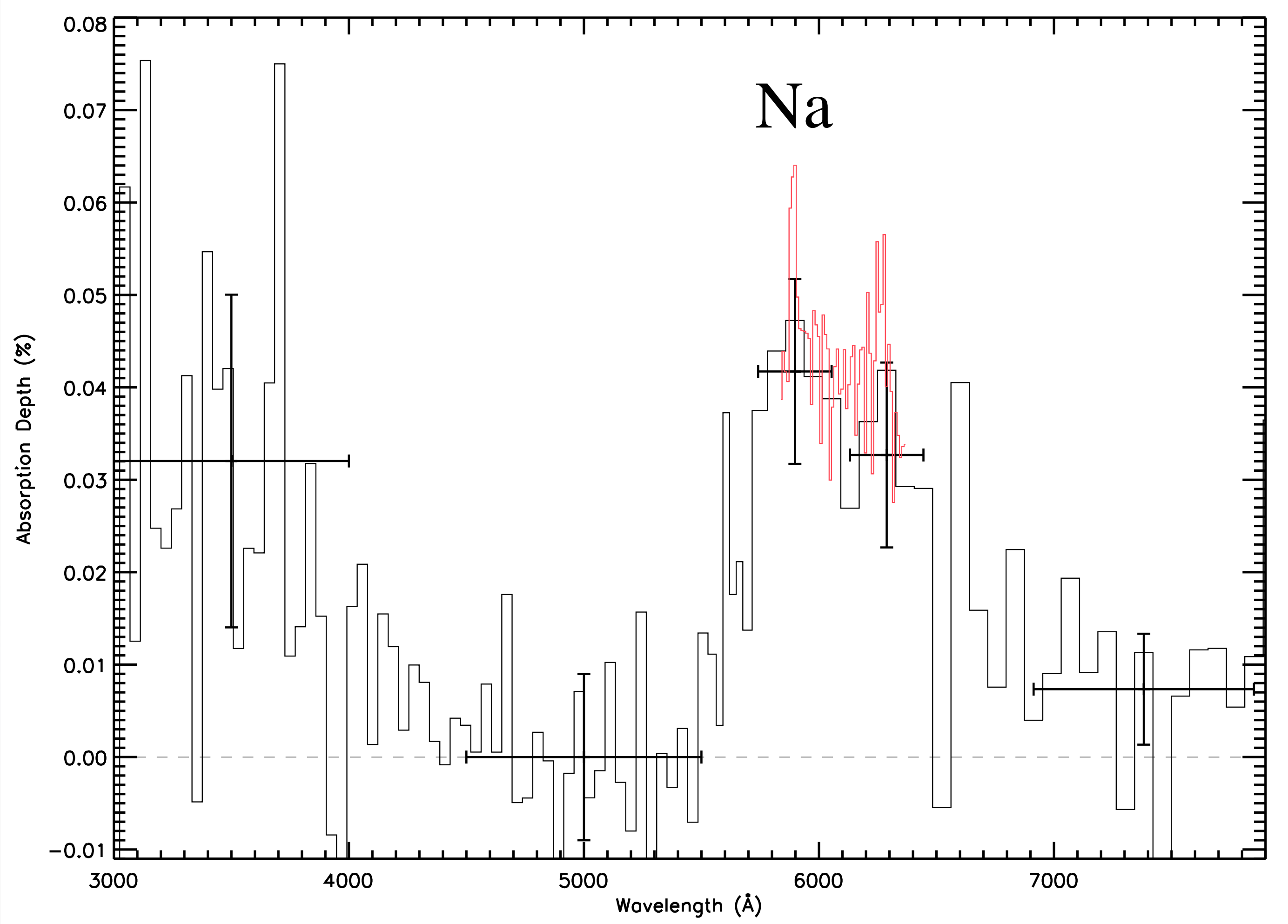
- Stellar UV heats upper atmosphere (10,000+ Kelvin) resulting in hydrodynamic escape
- Transition region of detectable hot H (H I in 1st exited state n=2), between lower colder H_2 atmosphere and escaping exosphere
- Potential new method of probing escaping hot-Jupiter atmospheres

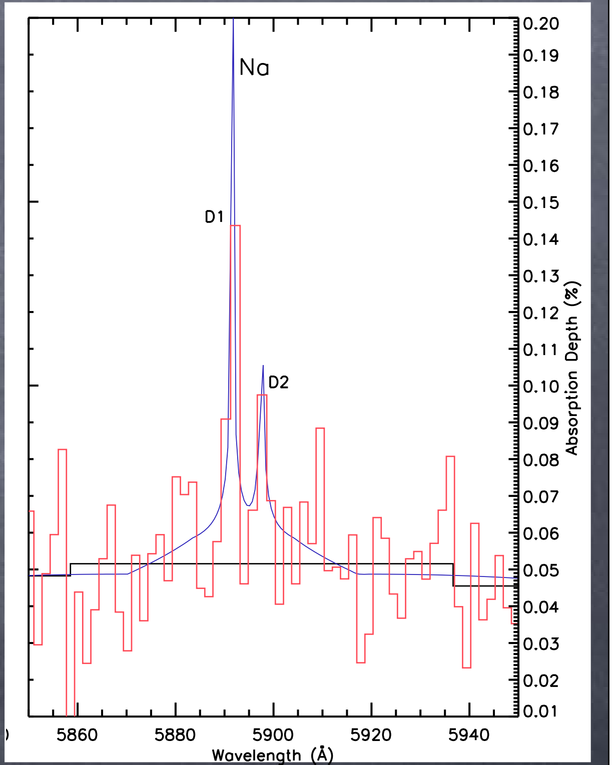
First Full Exoplanet Optical Transmission Spectrum

HD209458b

- Hot hydrogen discovery used only STIS/G430L grating
- Data from two other gratings available
- Combined all observations into a comprehensive atmospheric transmission spectra

First Full Exoplanet Optical Transmission Spectrum

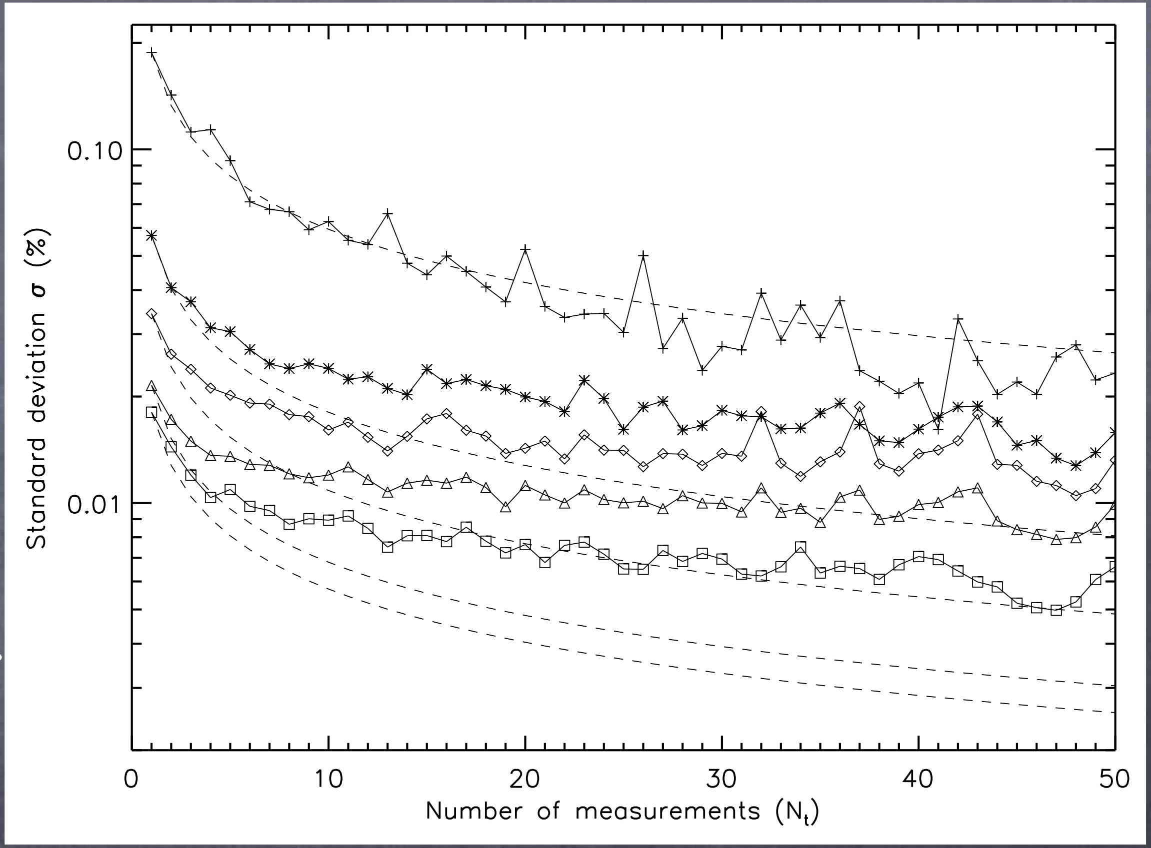




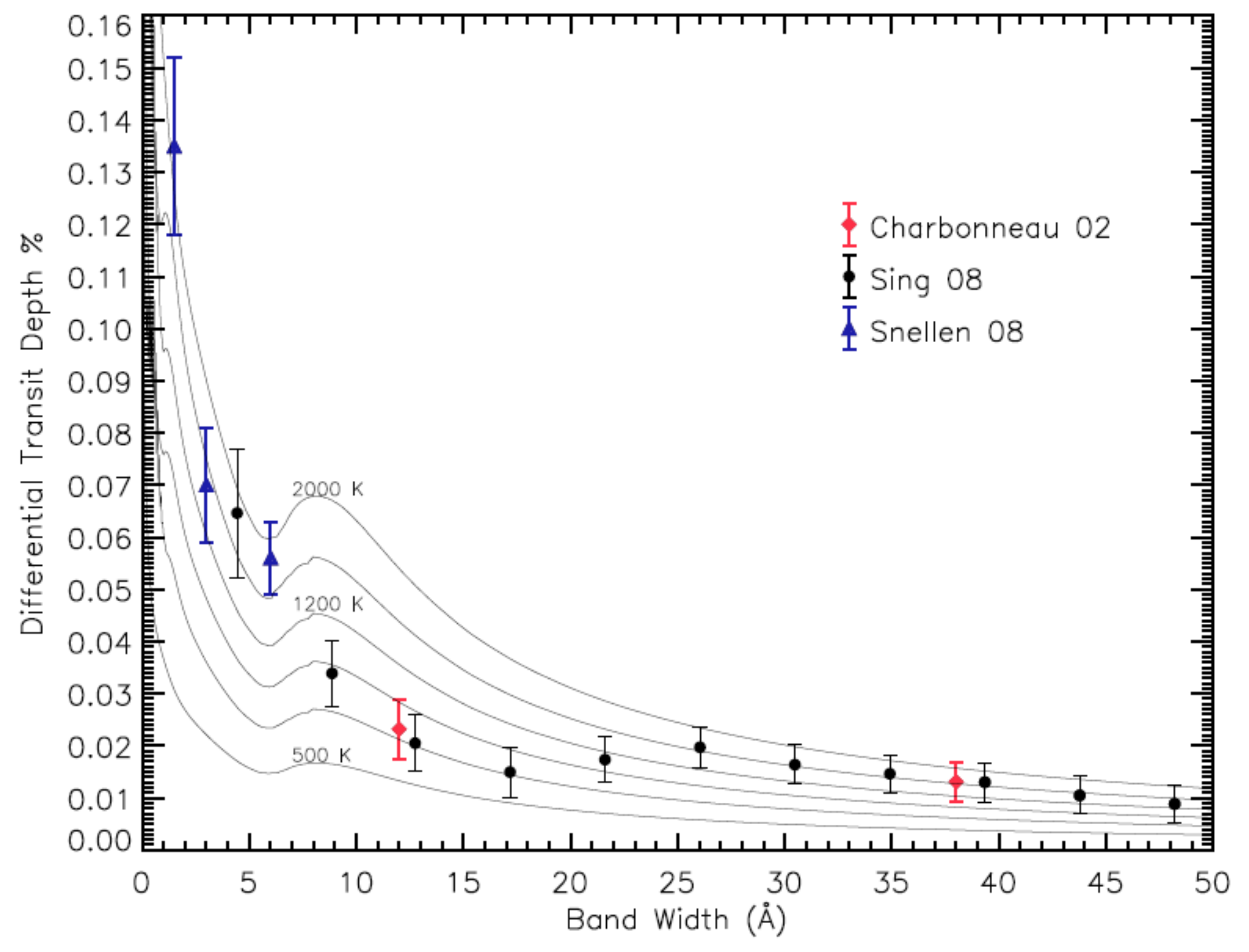
Sing et al. 2008

Red-Noise

- Systematic Errors Prevent co-adding multiple exposures from following $\frac{\sigma}{\sqrt{N_t}}$ relation
- Can reach precisions of $6x10^{-5}$ S/N=16,000

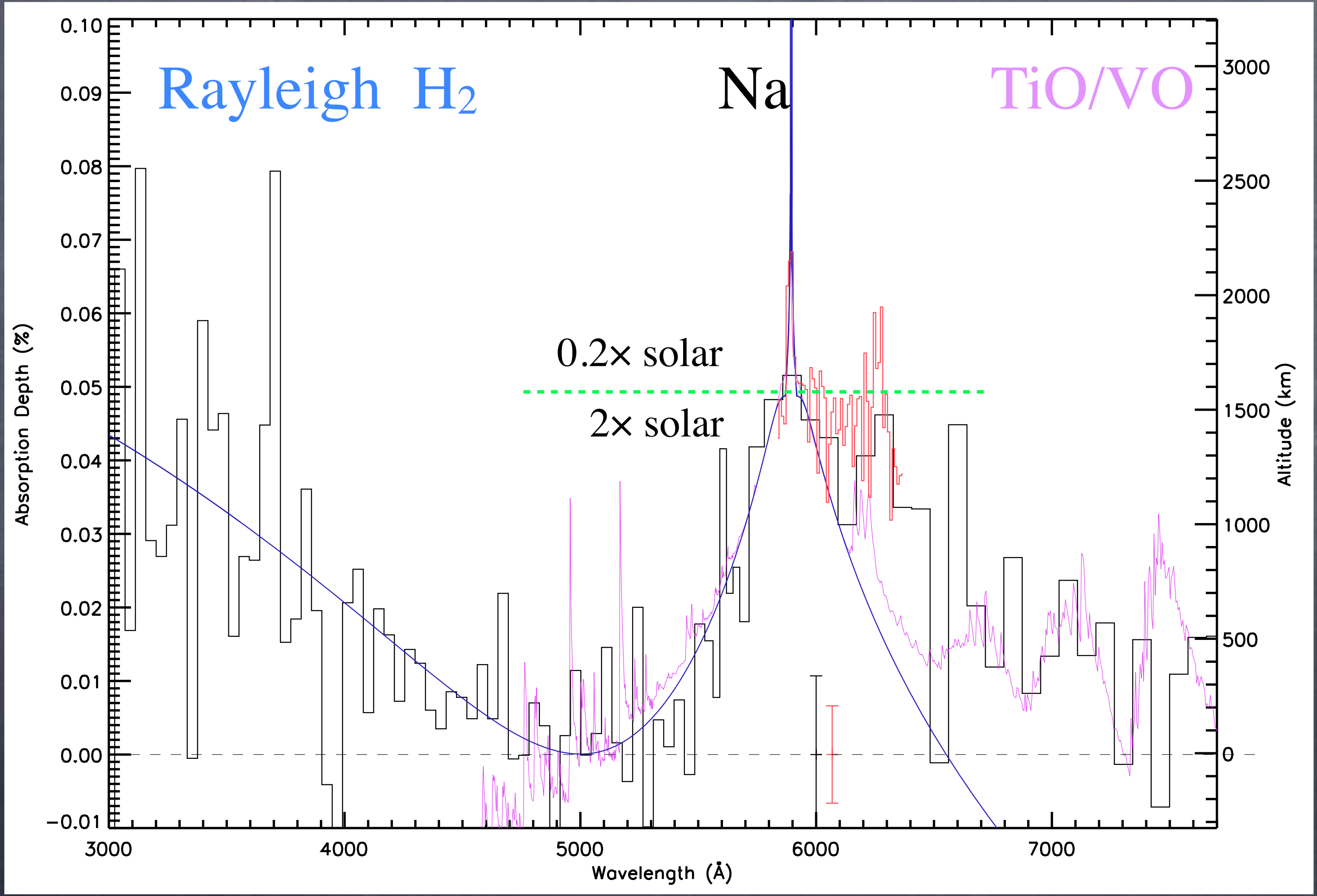


Atmospheric Na in HD209458b



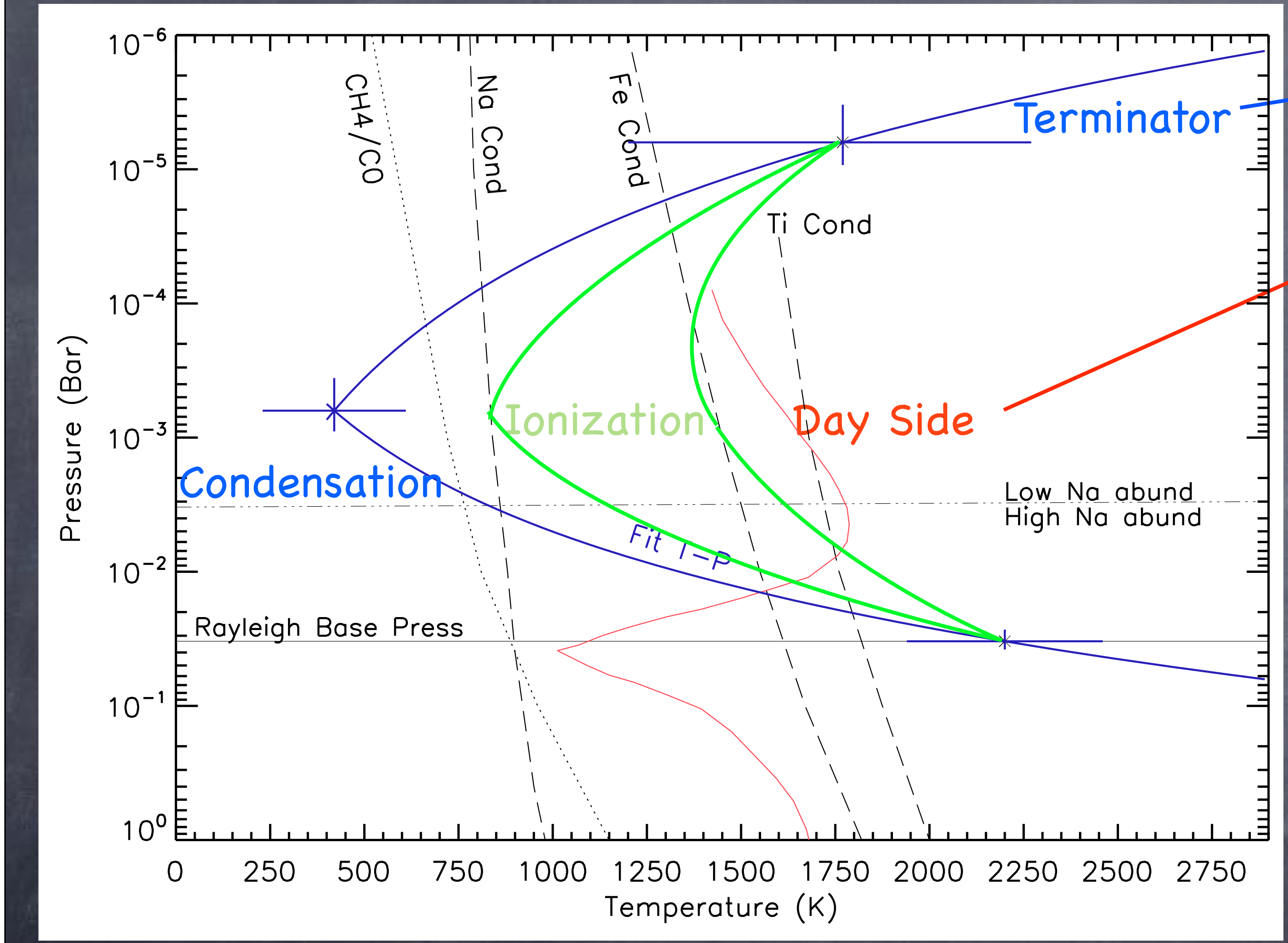
Comprehensive Atmospheric Model

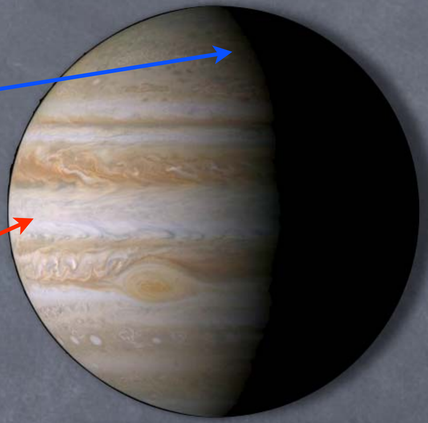
$$z(\lambda) = H\ ln\left(\frac{\xi_{abs}P_{z=0}\sigma(\lambda)}{\tau\mu g}\sqrt{\frac{2\pi R_{pl}}{H}}\right)$$



Sing et al. 2008

Temp-Pressure profile from Rayleigh + Na





Transit has determined:

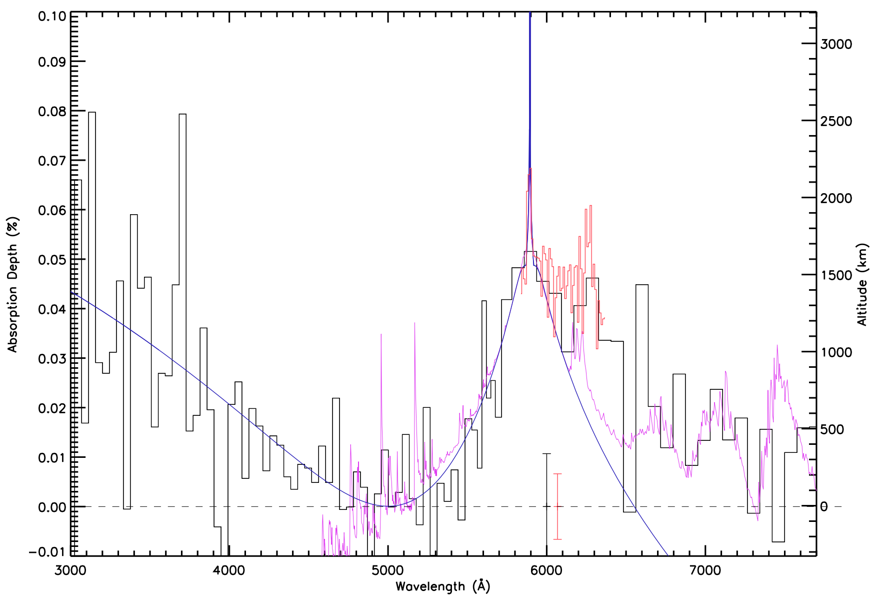
1) High Alt. Temp. inversion (thermosphere detection)
2) Global Na abundance
3) Two Na layers
4) Presence of TiO/VO which causes day-side inversion
5) Absolute T-P-z scale with presence of H_2

Sing et al. 2008a,b
Desert et al. 2008
Lecavelier de Etangs et al. 2008

Atmosphere of HD209458b

Just the start. More observations needed to distinguish between theories, understand absorption features, rule out systematic errors, g-b & space

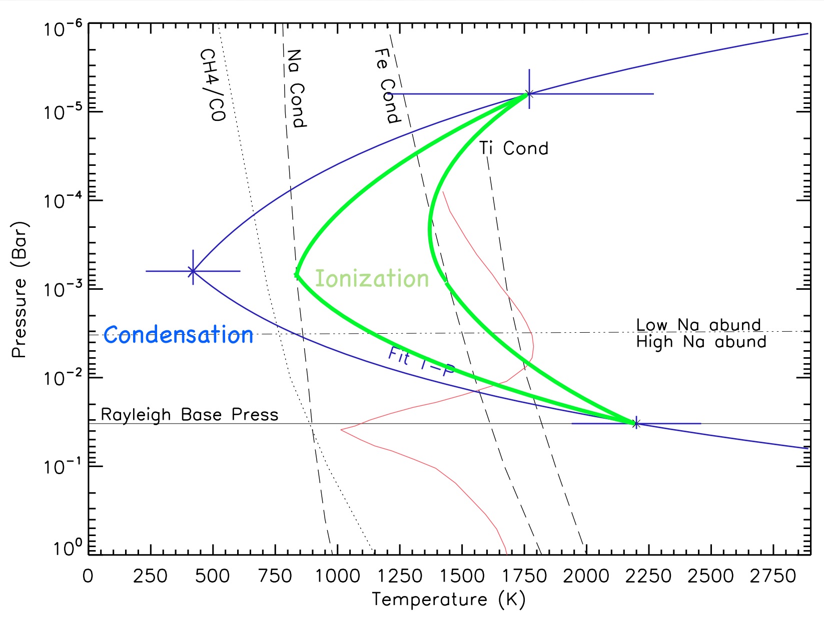
Proper identification



- Balmer Jump?
- Rayleigh Scattering?
- Atomic lines?

Solution: 2000-3000 Å HST data
Planned after SM4!

Better constrained T-P



- Identify other species (K, Fe, H_2O, ect.)

- Constrain fit chemical equil. & line shape/intensity

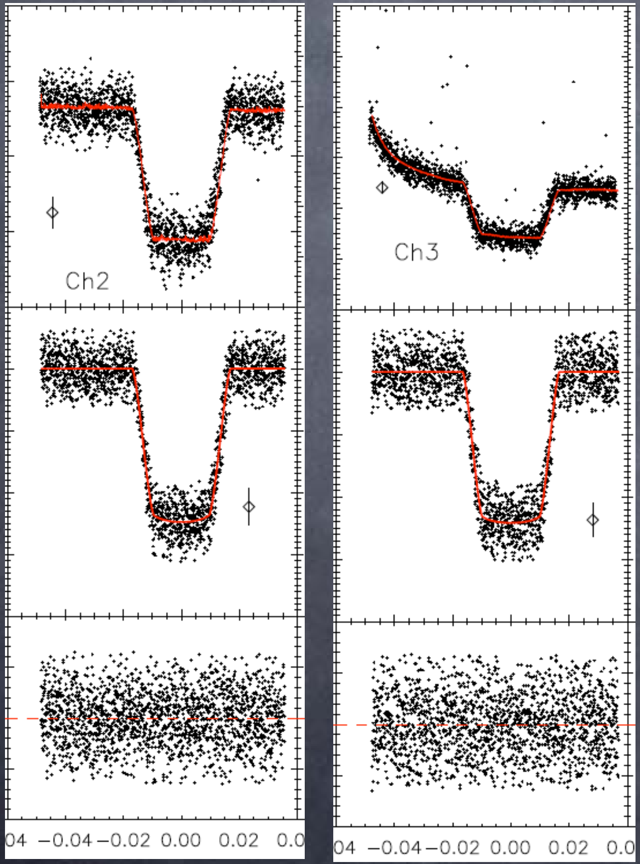
“Sunset” of HD209458b

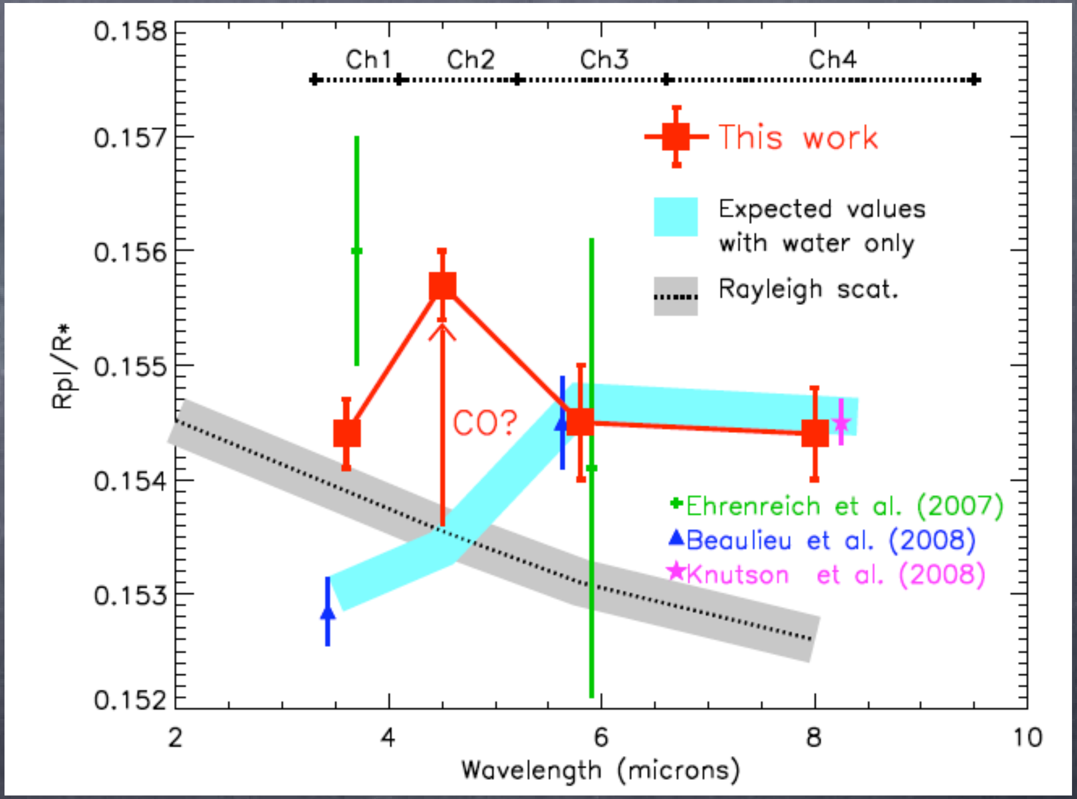
Monte Carlo simulation from optical transmission spectra

Atmosphere of HD189733b

Similar transmission spectra can be obtained, results from HST and Nicmos

- New Spitzer results (Desert et al. 2009)
- Atmospheric CO detected

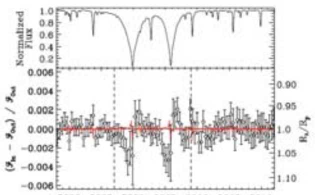




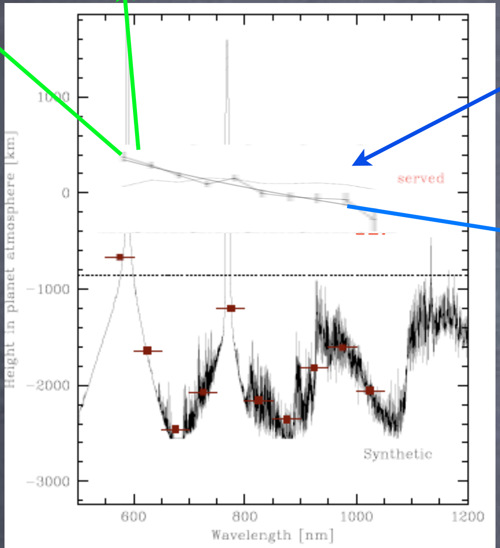
Other canonical hot-Jupiter

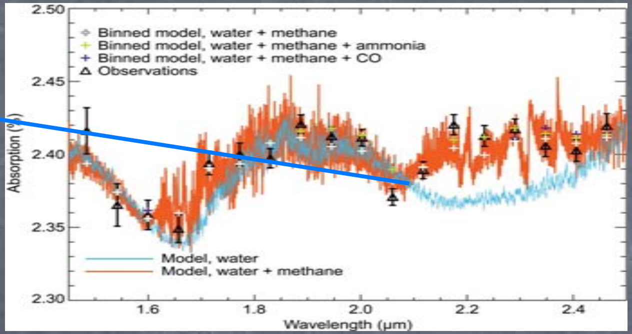
HD189733b, Not easy to fit pieces of different observations
- Full Optical/NIR Transmission Spectra Needed

Na - Redfield (2007)

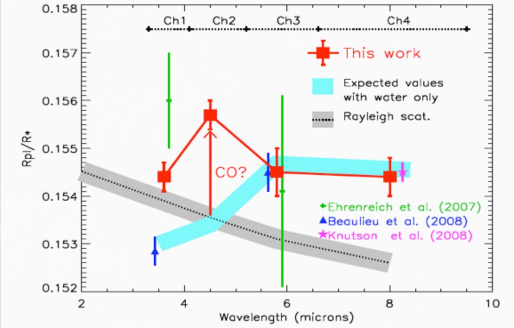


Rayleigh scattering $MgSiO_3$ - Lecavelier et al. (2008)





H$_2$O Methane - Swain et al. (2008)

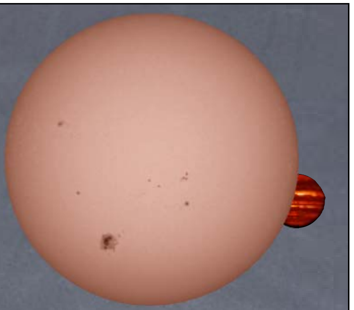


CO - Desert et al. (2009)

Haze - Pont et al. (2008)

- Haze, Na, and Rayleigh scattering are difficult to put together (problem with theory or observations?)
- Solution: HST cycle 17, multiple STIS/Nicmos programs will address these issues
  - Sing - Na/STIS
  - Lecavelier - Escaping atmosphere
  - Pont - STIS/Nicmos Full Optical transmission spectra

Ground Secondary Eclipse

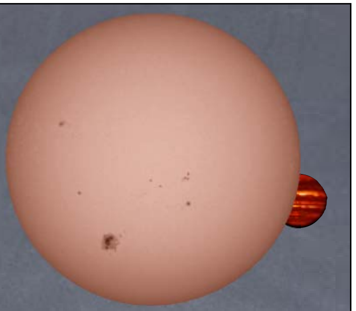


- Revolution with Spitzer anti-transit measurements
  (Deming 05; Charbonneau 05; Knutson 07, ect.)

- Past ground-based attempts
  (Knutson 07; Deming 07; Snellen 05; Snellen & Corvino 07, ect.)
  - Near-IR, difficult to do precision photometry

- Lopez-Morales & Seager (2007)
  - Significant optical flux for very-hot Jupiters Teff ~ 2500 - 3000 K
  - Precision optical photometry easier than in near-IR

Prediction



- Lopez-Morales & Seager (2007) ; z’ band
  - Thermal Emission or Reflected light

f = re-radiation factor

A_B = Bond albedo

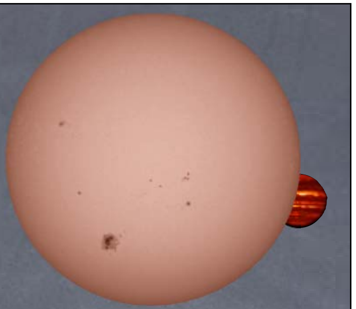
$$T_p = T_* \left(\frac{R_*}{a}\right)^{1/2} [f(1 - A_B)]^{1/4}$$

$$F_{p_{\rm th}} = \frac{2h\nu^3}{c^2} \frac{\pi R_p^2}{e^{h\nu/kT_p} - 1} \frac{1}{D^2}$$

$$F_{p_{\rm ref}} = F_* \tfrac{2}{3} A_B \frac{R_p^2}{a^2}$$

$$|\, \Delta{\rm mag}\, | = 2.5 \log\left(1 + \frac{F_p}{F_*}\right)$$

Prediction



- Lopez-Morales & Seager (2007)

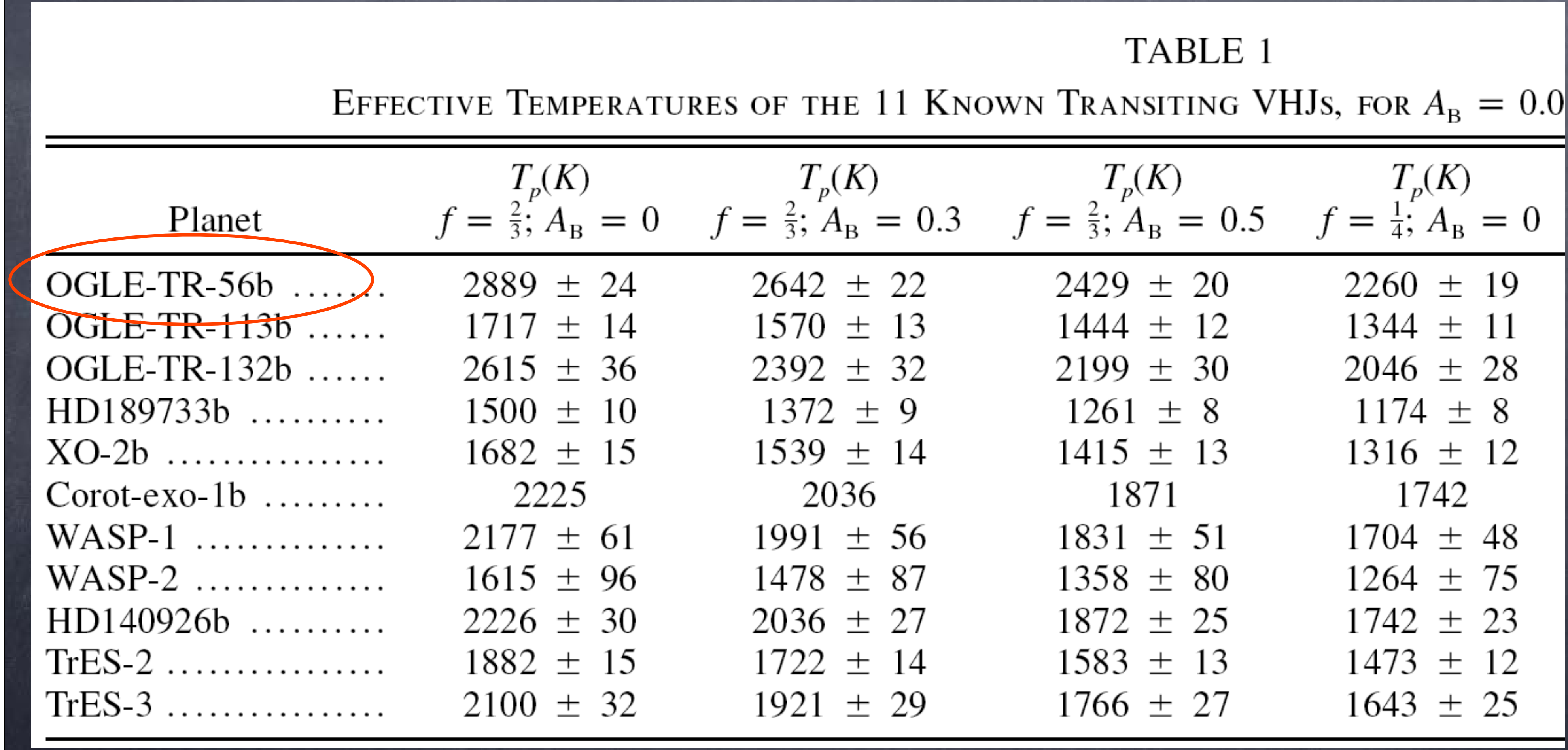
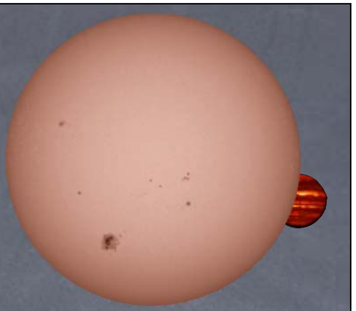


TABLE 1

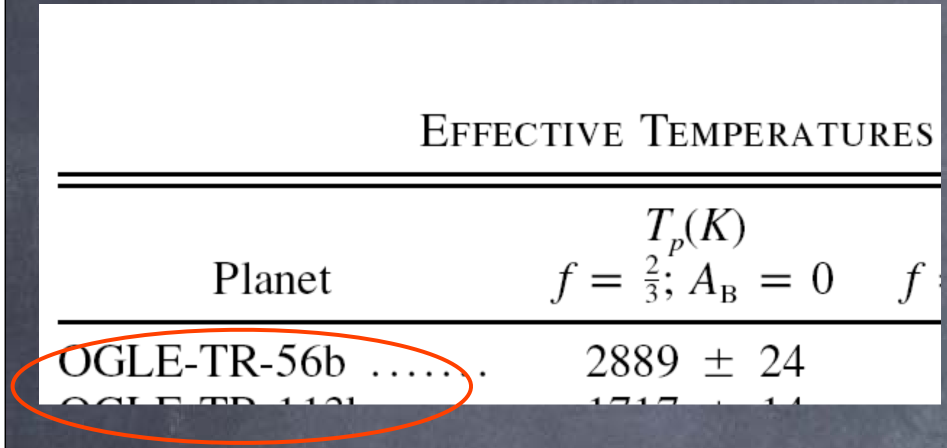
Effective Temperatures of the 11 Known Transiting VHJs, for $A_B = 0.0$

Planet	$T_p(K)$ $f = \frac{2}{3}; A_B = 0$	$T_p(K)$ $f = \frac{2}{3}; A_B = 0.3$	$T_p(K)$ $f = \frac{2}{3}; A_B = 0.5$	$T_p(K)$ $f = \frac{1}{4}; A_B = 0$
OGLE-TR-56b	2889 ± 24	2642 ± 22	2429 ± 20	2260 ± 19
OGLE-TR-113b	1717 ± 14	1570 ± 13	1444 ± 12	1344 ± 11
OGLE-TR-132b	2615 ± 36	2392 ± 32	2199 ± 30	2046 ± 28
HD189733b	1500 ± 10	1372 ± 9	1261 ± 8	1174 ± 8
XO-2b	1682 ± 15	1539 ± 14	1415 ± 13	1316 ± 12
Corot-exo-1b	2225	2036	1871	1742
WASP-1	2177 ± 61	1991 ± 56	1831 ± 51	1704 ± 48
WASP-2	1615 ± 96	1478 ± 87	1358 ± 80	1264 ± 75
HD140926b	2226 ± 30	2036 ± 27	1872 ± 25	1742 ± 23
TrES-2	1882 ± 15	1722 ± 14	1583 ± 13	1473 ± 12
TrES-3	2100 ± 32	1921 ± 29	1766 ± 27	1643 ± 25

Prediction



- Lopez-Morales & Seager (2007)



EFFECTIVE TEMPERATURES

Planet	$T_p(K)$ $f = \frac{2}{3}; A_B = 0$	f
OGLE-TR-56b	2889 ± 24	

< 0.5 mmag for Ogle-Tr-56

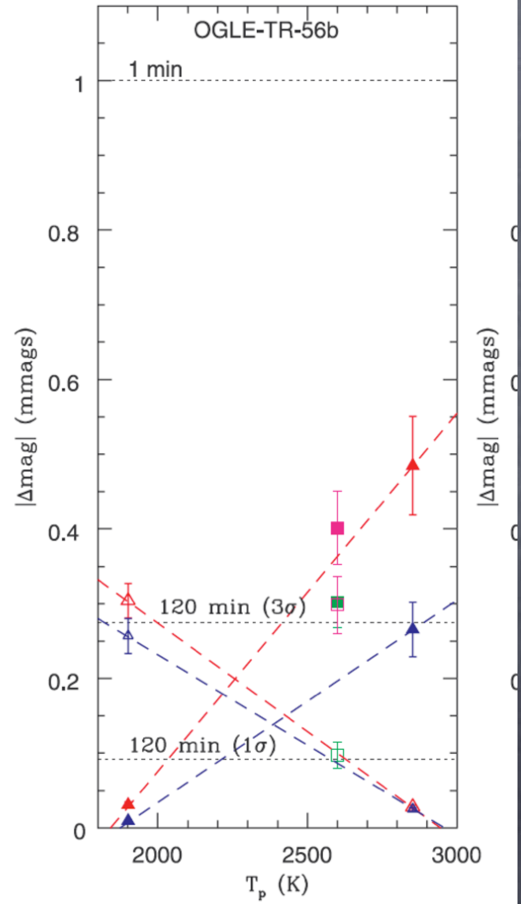
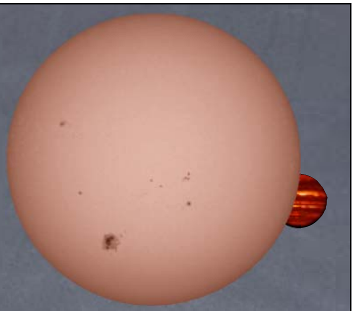


FIG. 2.—Expected depths of secondary

Observations



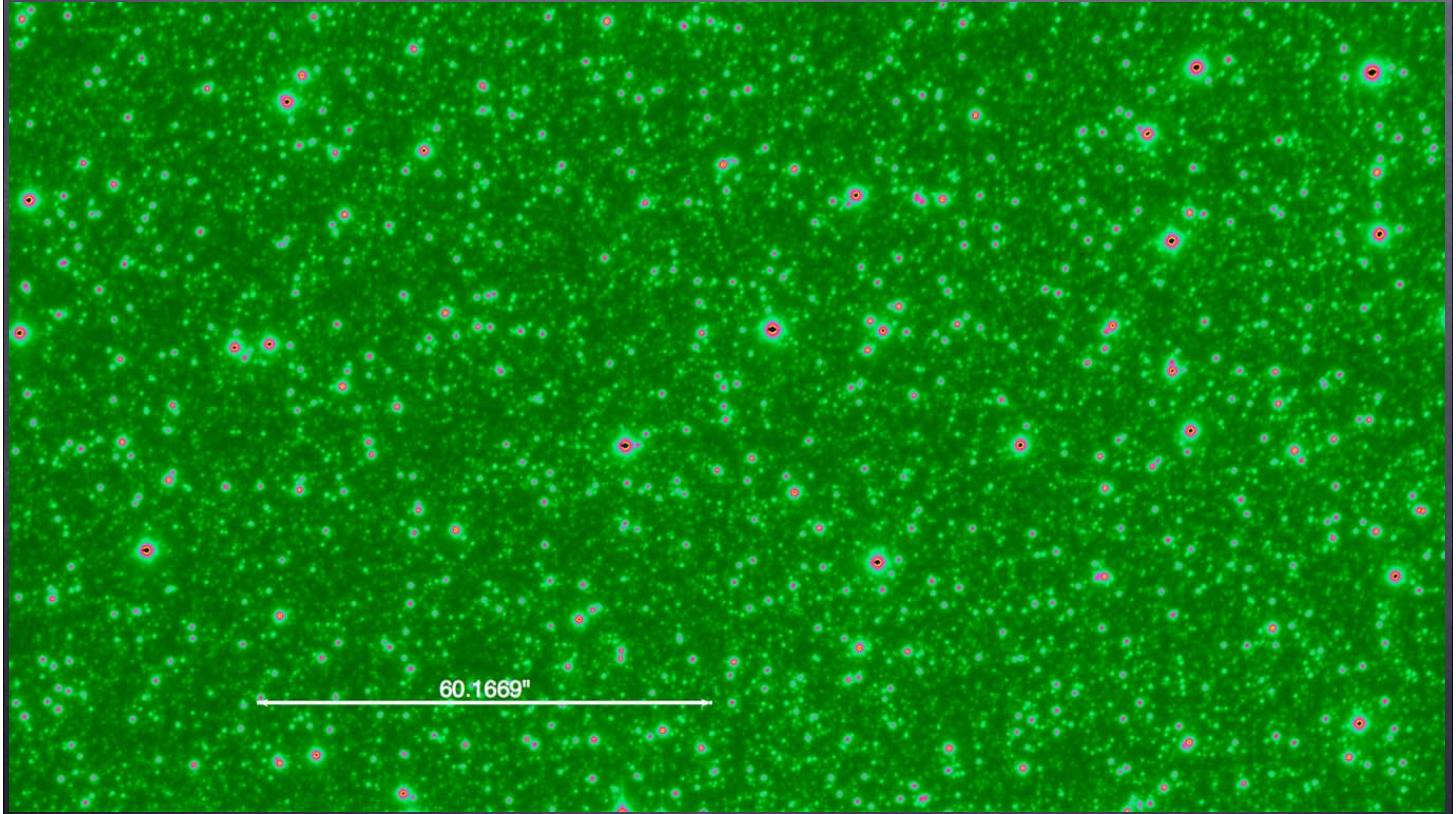
Challenges for Ogle-Tr-56

1) Faint (V=16.56); harder to reach necessary precision; 0.01% ⇨ 10^8 photons/1 hour

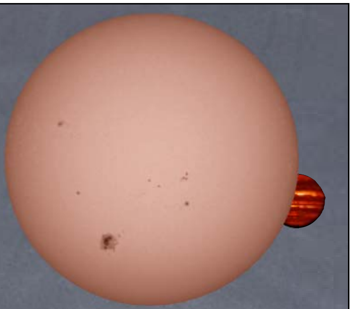
2) Small signal; secondary eclipse depth of < 0.05%

3) Crowded Field toward galactic center

Observations



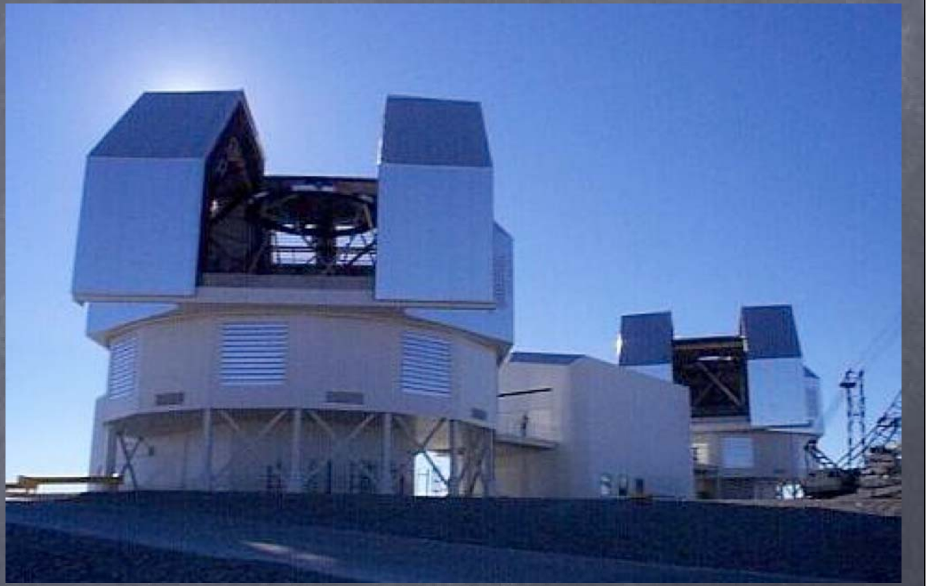
Observations



VLT 8.2 m

July 2, 2008
FORS2 camera

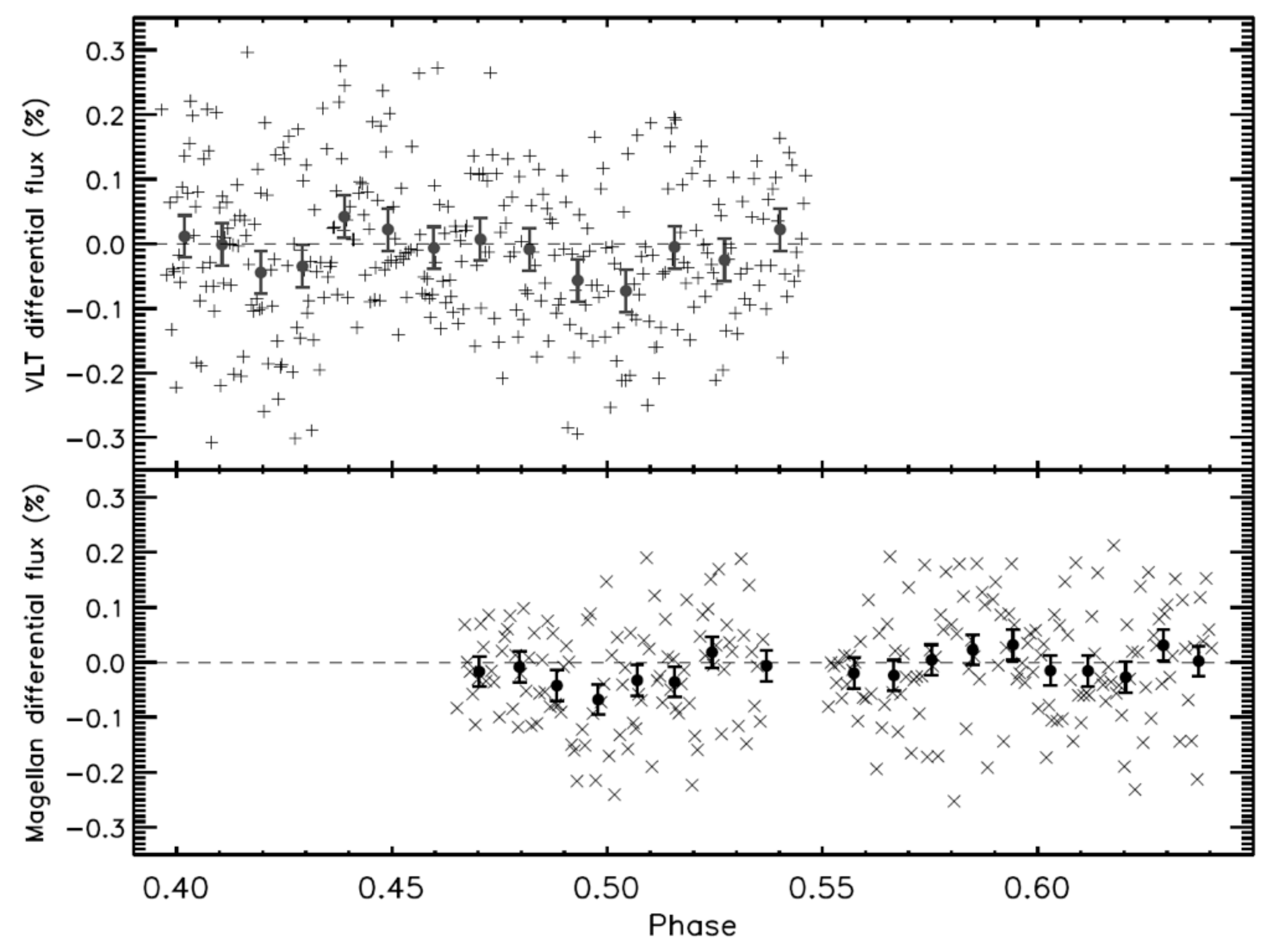
Magellan 6.5m



August 3, 2008
MagIC-E2V
frame transfer

Z band

Analysis

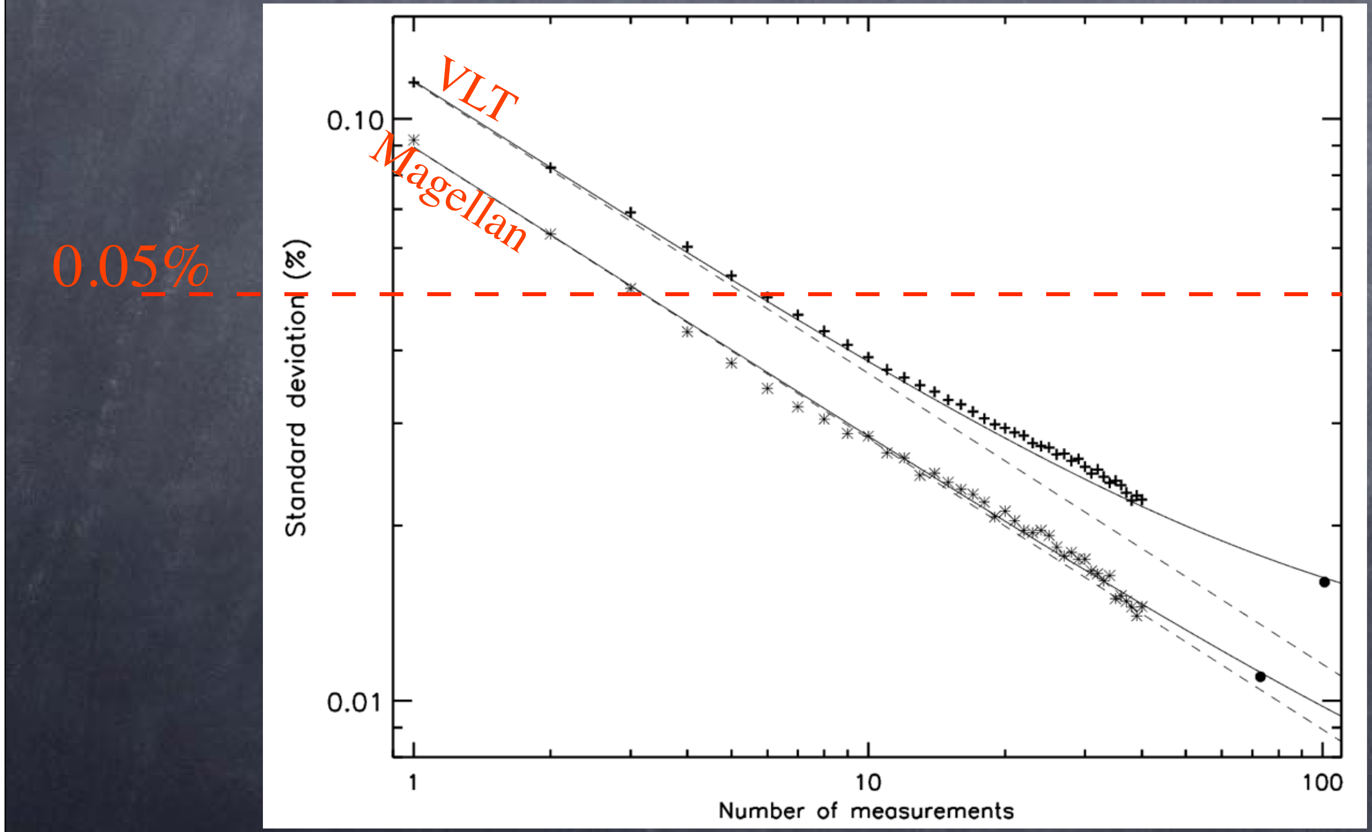


VLT differential flux (%)
Magellan differential flux (%)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.40
0.45
0.50
0.55
0.60
Phase

Analysis

- ~1 mmag/min
- Red-noise estimated with “prayer-bead” method

$$\sigma^2_{depth} = \sigma^2_w/N + \sigma^2_{red}$$



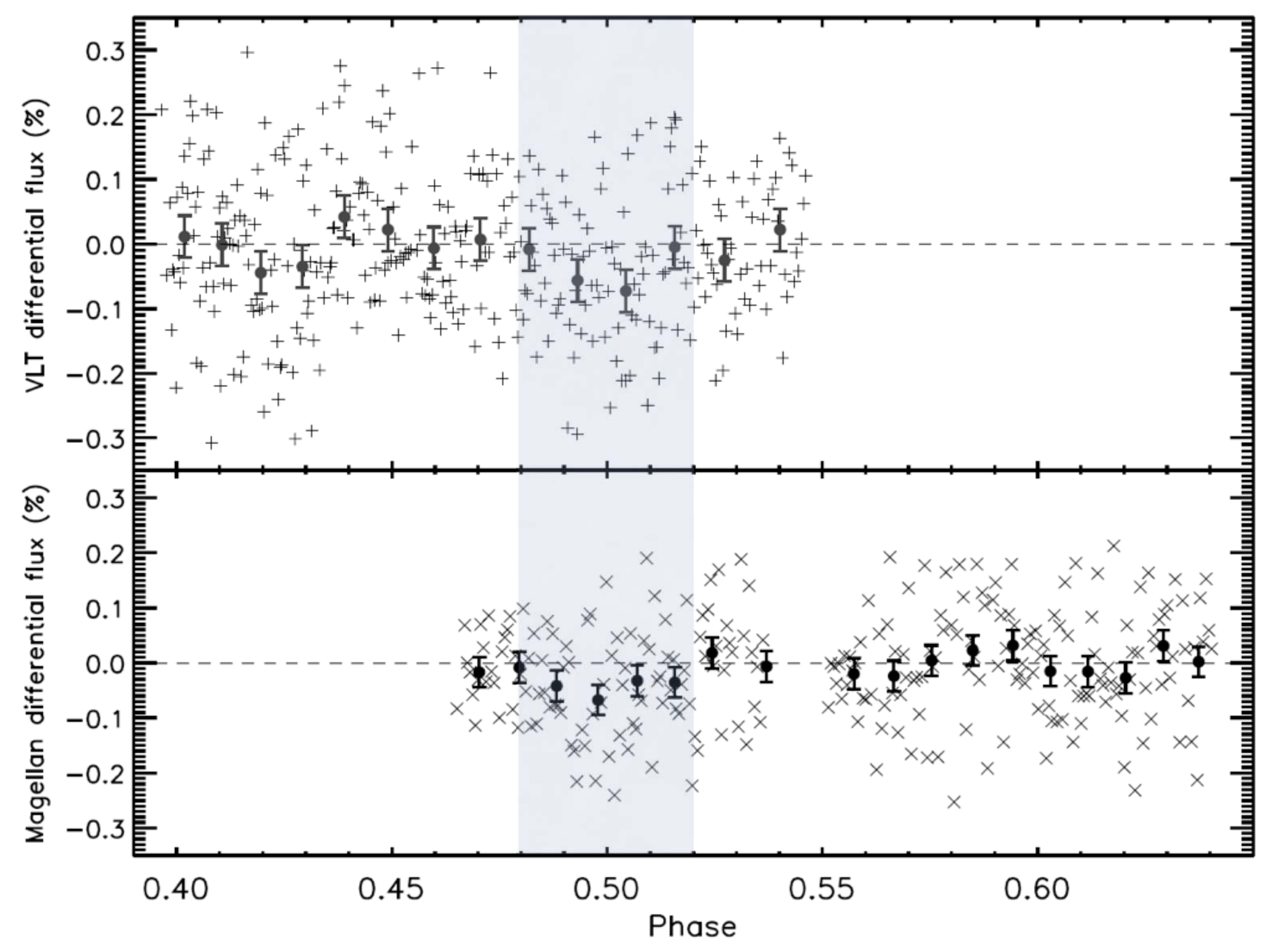
VLT

$\sigma_{red} = 1.1 \times 10^{-4}$

Magellan

$\sigma_{red} = 4 \times 10^{-5}$

Analysis


VLT differential flux (%)
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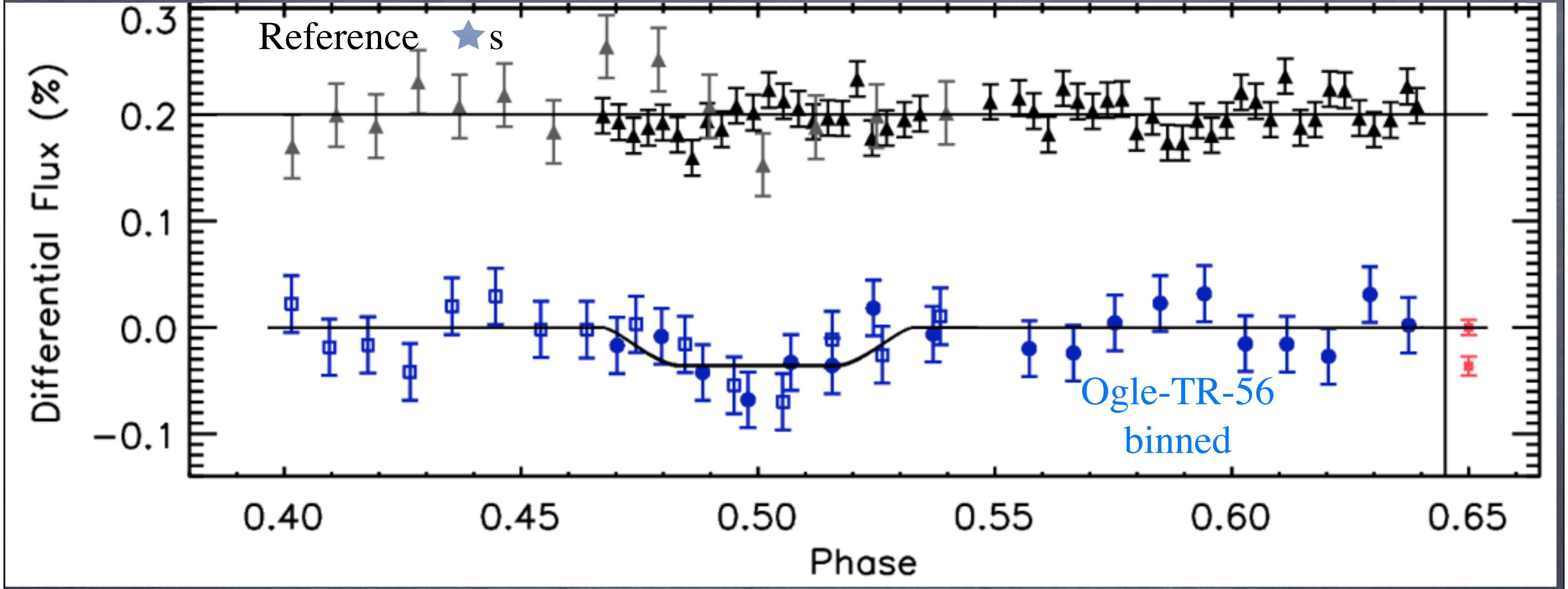
0.40
0.45
0.50
0.55
0.60
Phase

Analysis



VLT Eclipse Depth = $0.037\% \pm 0.016\%$ $\chi_\nu^2 = 0.90$

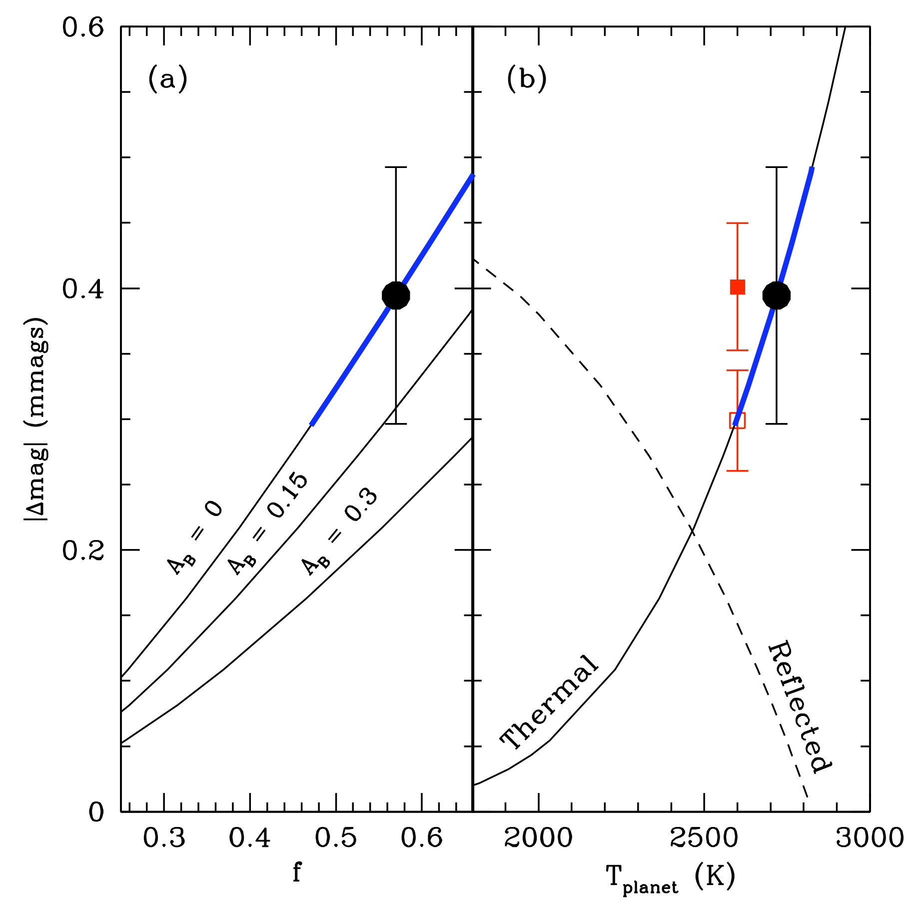
Magellan Eclipse Depth = $0.036\% \pm 0.011\%$ $\chi_\nu^2 = 0.93$

Total Eclipse Depth = $0.0363\% \pm 0.0091\%$

Analysis

Black Body

- $T_{eff} = 2718 \pm 117$ K
- Low albedo
- Instant re-radiation $f > 0.47$



Non-black body Models

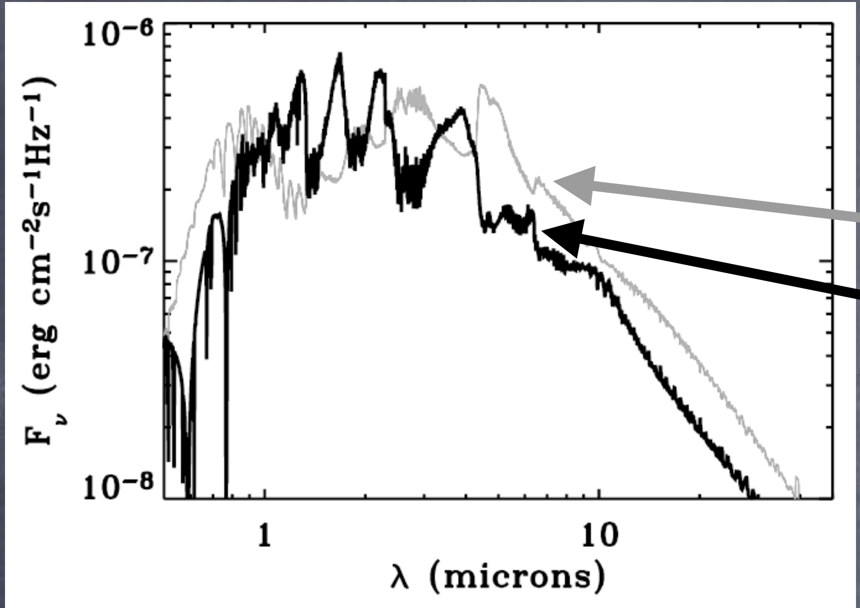
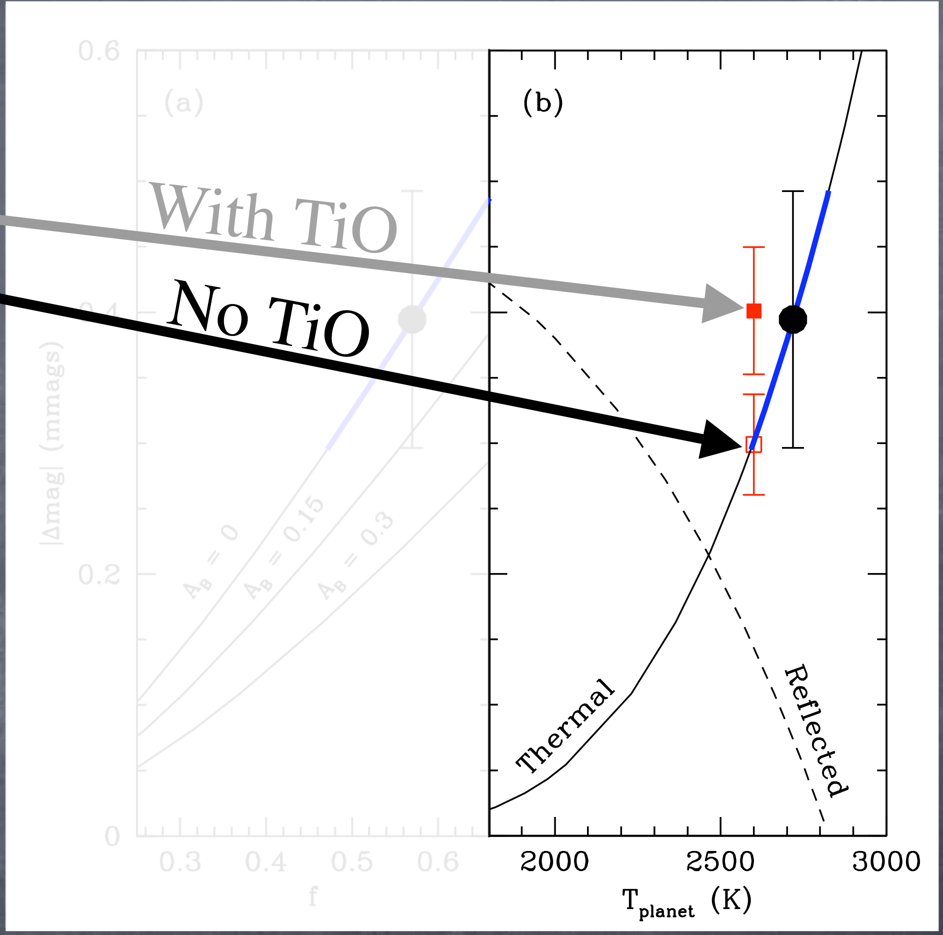


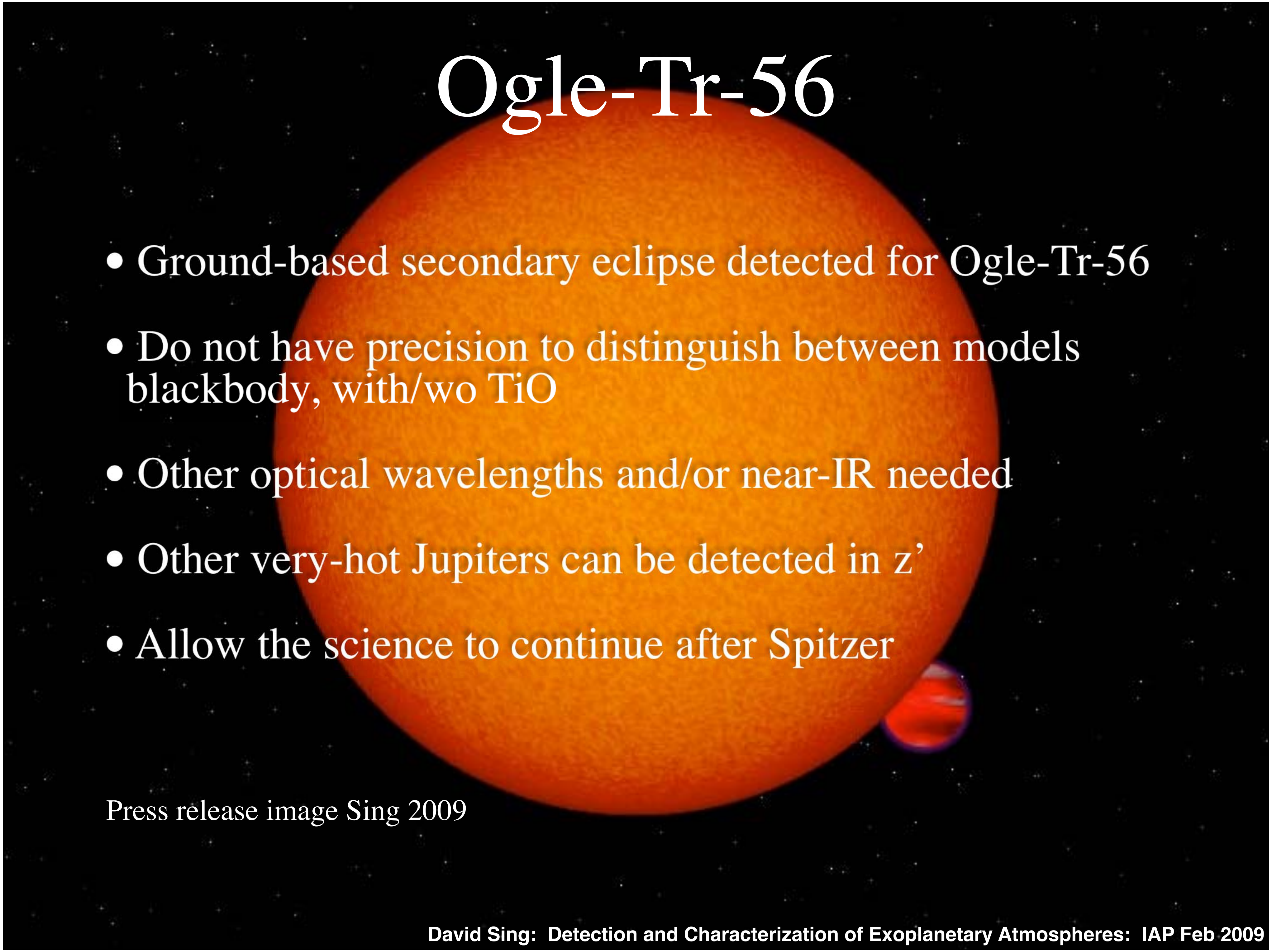
FIG. 14.—Two examples of theoretical flux spectra (F_ν, in ergs cm^{-2} s^{-1} Hz^{-1}) from the surface of the close-in EGP OGLE-TR-56b from the optical to 30 μm, with (*gray line*) and without (*black line*) TiO and VO in its upper

Model Planet flux Hubeny 2003



- Can not distinguish between models with and without TiO (upper atmo. Temp inversion)

Ogle-Tr-56



- Ground-based secondary eclipse detected for Ogle-Tr-56
- Do not have precision to distinguish between models blackbody, with/wo TiO
- Other optical wavelengths and/or near-IR needed
- Other very-hot Jupiters can be detected in z’
- Allow the science to continue after Spitzer

Press release image Sing 2009

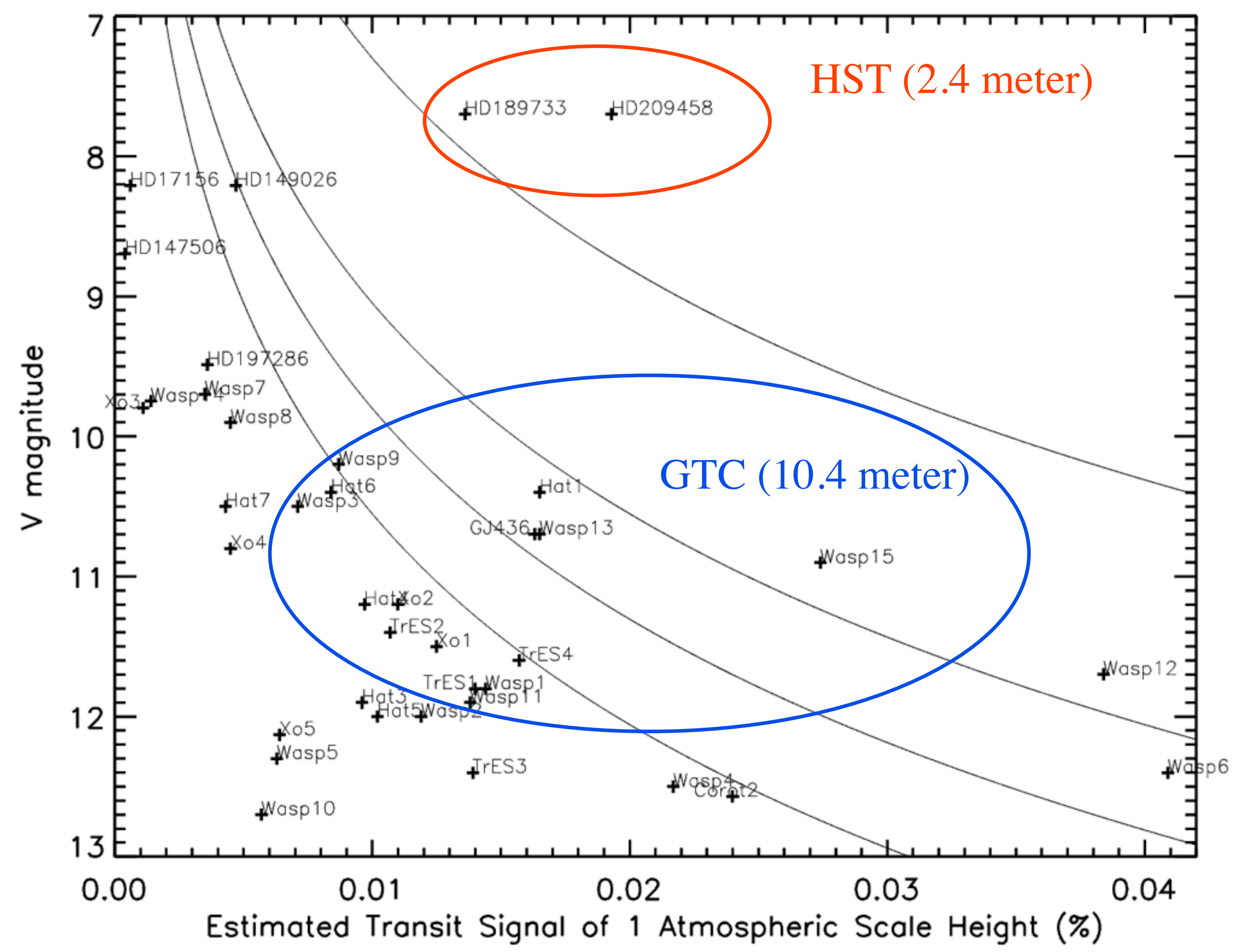
The Next Generation Transit Follow-up Project: Exoplanet Characterization and Detection Through Fast Photometry & Spectroscopy

1) 10.4 Meter Segmented Primary Mirror based on Keck design
2) Has adaptive optics shaping the primary mirror
3) First light - July 13, 2007
4) Science Observations start April 2009
5) Currently the "Largest Telescope in the World"

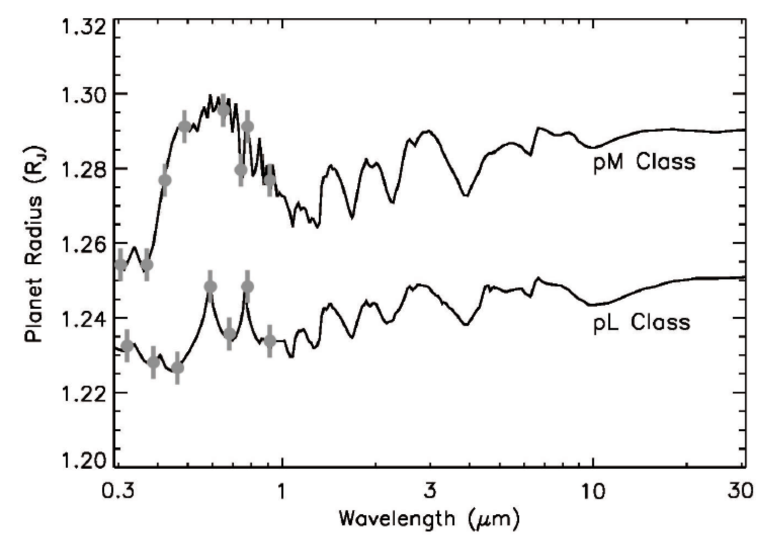
ESO granted time as part of Spain entry into ESO
- 122 total nights from (2009-2011) distributed in 40 clear nights/year
- ~6 total ESO projects granted over 4 proposal calls

Granted a total of 180 hours, service mode, 36 transits at 5h/event, 5.4% of total 1st year GTC time (Sing PI)

GTC gives full range of hot-Jupiters



GTC Transit Project



- Science Objectives:
  - Scrutinize the atmospheric composition of transiting planets with narrowband fast-photometry at multiple wavelengths (Na, K, TiO?, Rayleigh?)
  - Enable wide scale comparative exoplanetology, 6-7 hot-Jupiters
  - Detect other planets (sensitive to earth-mass planets with timing variations).

Conclusions

- Transits are the keystone to a strong foundation of comparative exoplanetology
- Ground-based programs will greatly enhance hot-Jupiter detections
- GTC- comprehensive hot-Jupiter atmospheric surveys