Exoplanet and Host Star Overview

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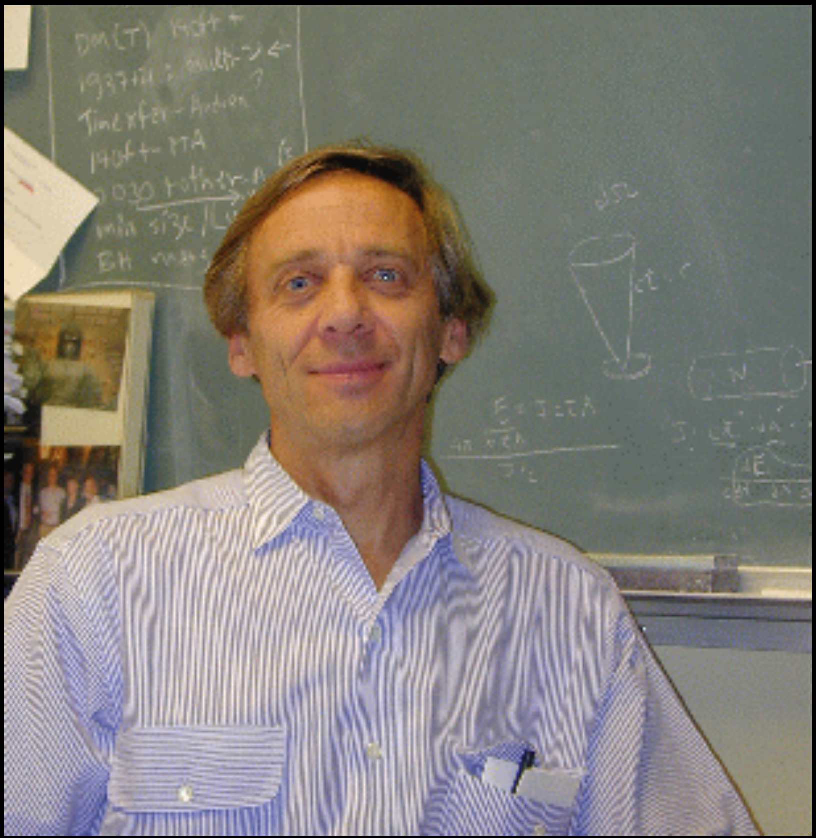
UC Berkeley

2010 Sagan Exoplanet Summer Workshop: July 26-30, 2010

In memory of Don Backer (1943-2010)



Outline

- A Brief History of Exoplanet Science, a Personal View
  - What we know and how we know it
- Recent Examples of Host Star Physics Playing a Key Role in Exoplanet Science
  - How did hot Jupiters migrate from beyond the ice line?
  - Why do some hot Jupiters have inverted atmospheres?

Do planets exist around other stars?

The first hints (1984): Kuiper Belt-like dust emission

IR excess of Vega:

85K blackbody,

solid angle

of emitting region

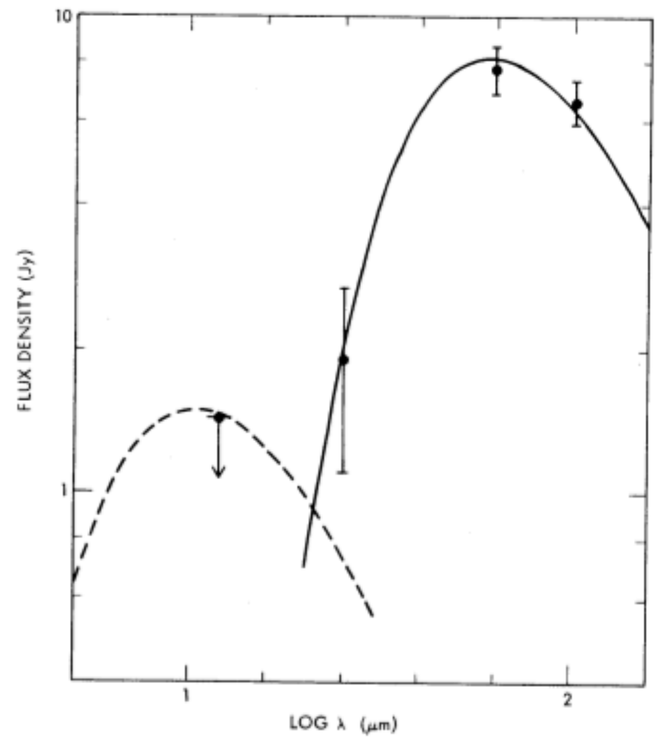


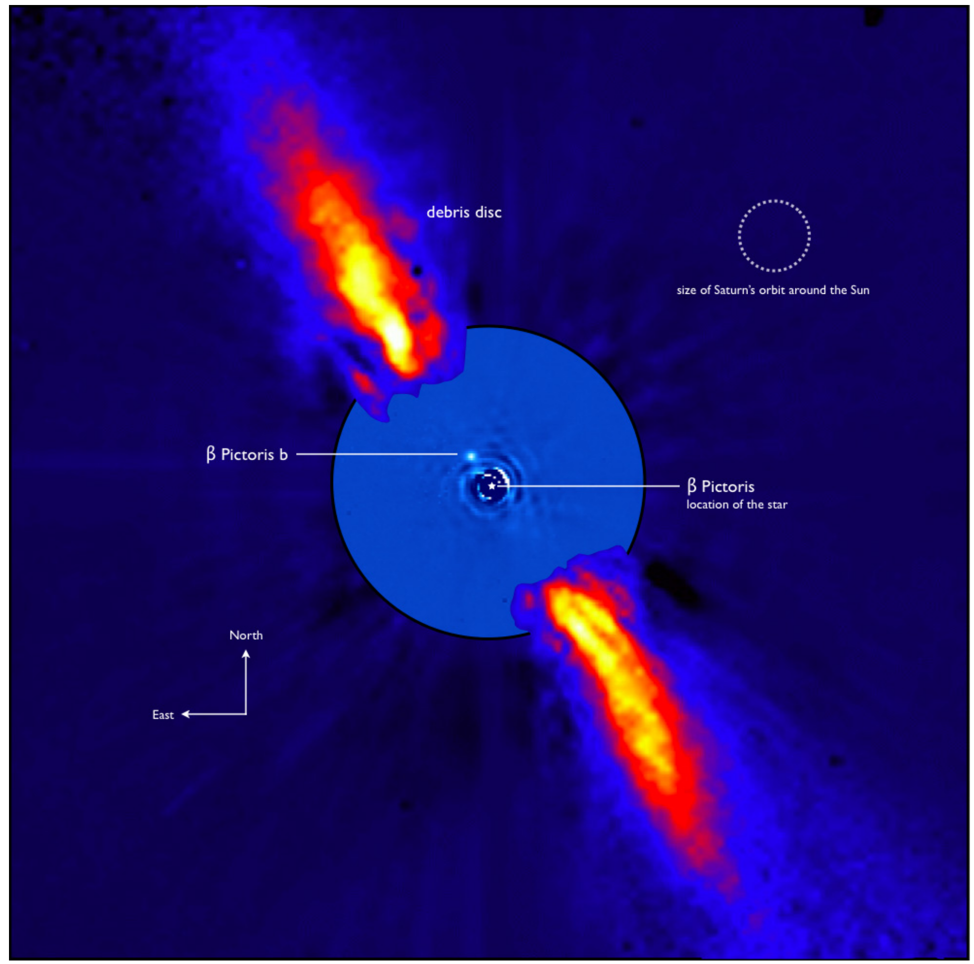
FIG. 1.—Energy distribution of the infrared excess from α Lyr. The error bars represent the 10% calibration uncertainty. The 12 μm upper limit indicates the effect of the 5% uncertainty in the absolute calibration at 12 μm. The solid line represents a 85 K blackbody spectrum with a solid angle of 7×10^{-13} sr fitted to the excess. The dashed line represents a 500 K blackbody spectrum with a solid angle of 6.3×10^{-16} sr arbitrarily fitted to the 12 μm upper limit.

Aumann et al. 1984

The first hints (1984): Kuiper Belt-like dust emission - β Pictoris

IR excess (Aumann et al. 1984)

First images of warm, dusty disk by Smith & Terrile 1984



The first hints (1989): RV detection of "sub-stellar objects"

Latham et al. (1989) in Nature –

"The unseen companion of HD 114762 – a probable brown dwarf"

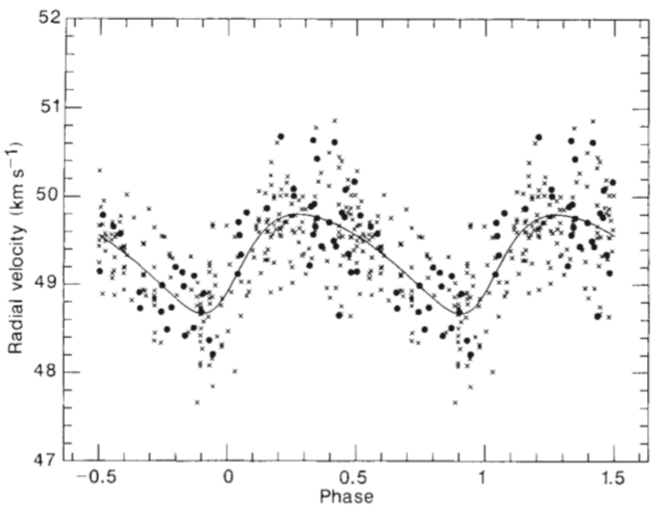
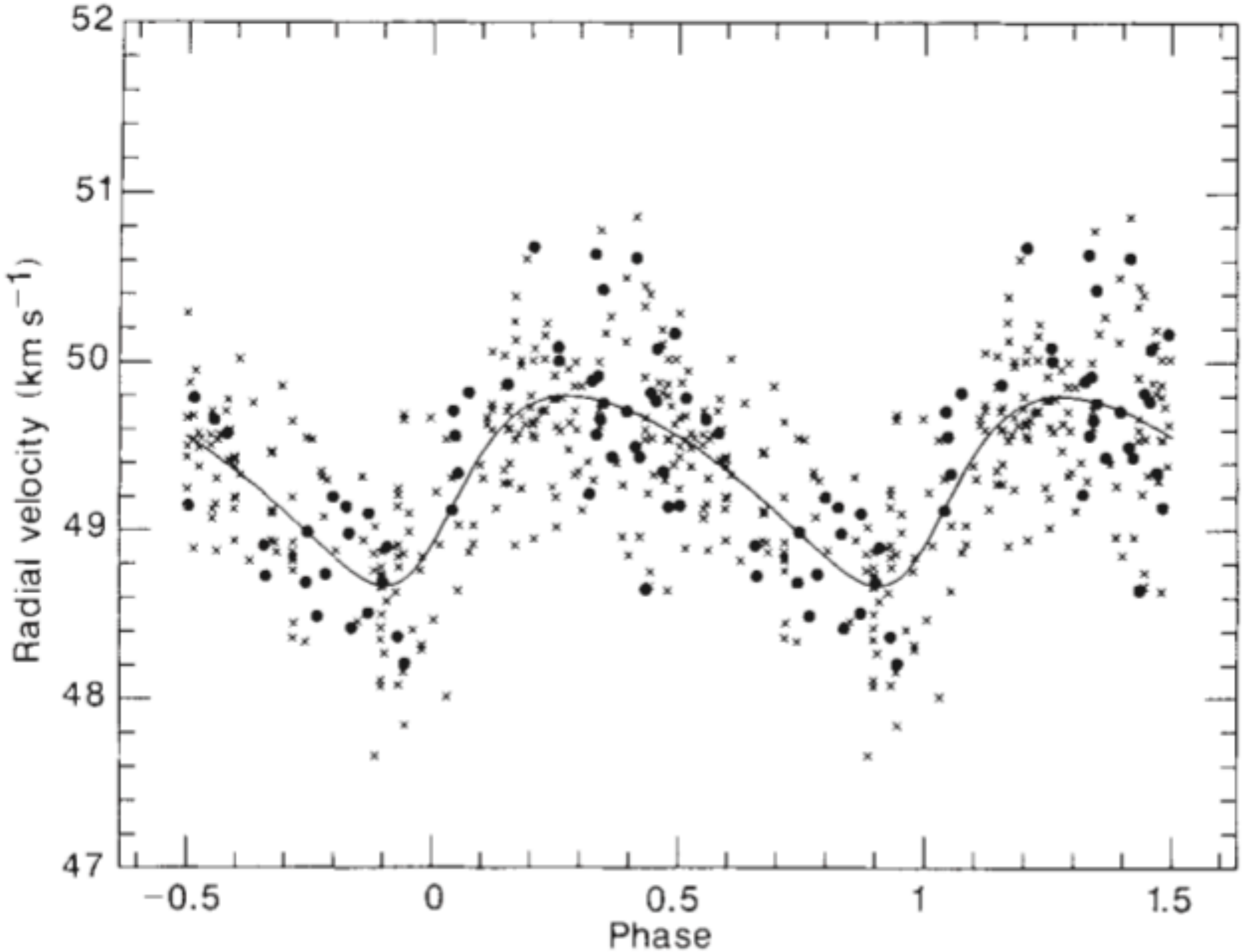


FIG. 2 The orbital solution for the combined data set. The continuous line is the orbital solution with the parameters of Table 1. The CfA velocities are denoted by crosses, the CORAVEL velocities by filled circles.

TABLE 1 Orbital solutions

	CfA	CORAVEL	Combined
Period (days)	84.03 ± 0.14	83.91 ± 0.09	84.05 ± 0.08
System velocity, γ (km s^{-1})	49.31 ± 0.03	49.39 ± 0.06	49.35 ± 0.04
Orbital half-amplitude, K (km s^{-1})	0.55 ± 0.04	0.75 ± 0.12	0.57 ± 0.04
Eccentricity, e	0.26 ± 0.07	0.30 ± 0.15	0.25 ± 0.06
Longitude of periastron, ω (°)	237 ± 11	280 ± 16	235 ± 10
Epoch, T (Julian date − 2440000)	5,029 ± 5	5,033 ± 4	5,027 ± 4
Mass function (10^{-6} $M_{\odot}$)	1.3 ± 0.3	3.1 ± 1.5	1.4 ± 0.3
Number of observations	230	50	280
r.m.s. residuals (km s^{-1})	0.42	0.39	0.42



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The first hints (1992): Pulsar Planets

Wolszczan & Frail (1992)

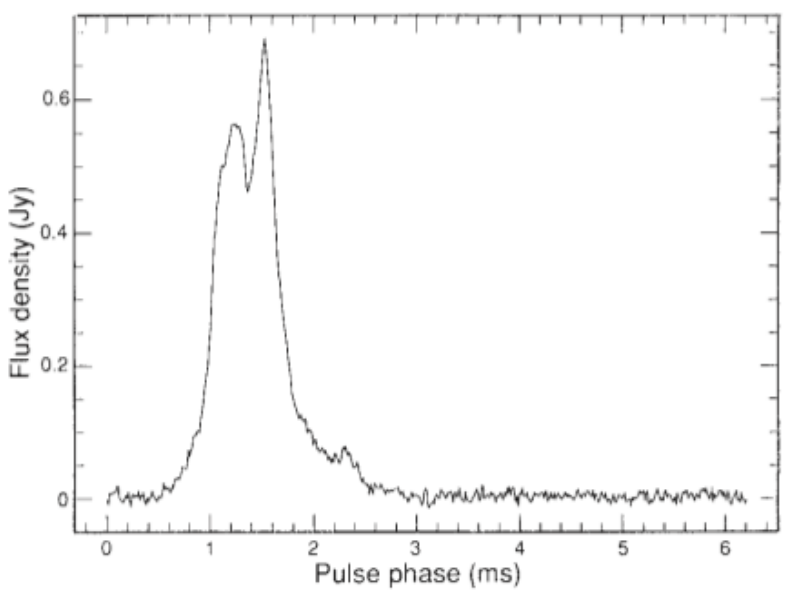


FIG. 1. The average pulse profile of PSR1257 +12 at 430 MHz. The effective time resolution is ~12 μs.

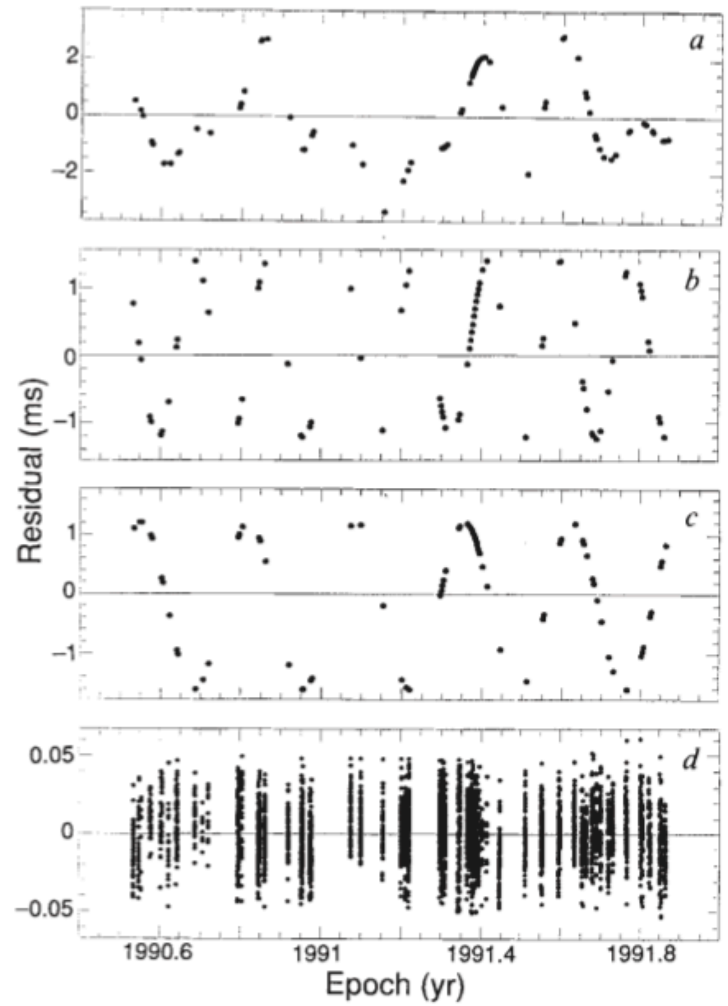


FIG. 2 The post-fit residuals of pulse arrival times from PSR1257 +12. *a*, Fit for rotational parameters only (VLA position of the pulsar fixed); *b*, fit for a 98.2-day keplerian orbit (leaves a 66.6-day periodicity as residual); *c*, fit for a 66.6-day keplerian orbit (leaves a 98.2-day periodicity as residual); *d*, fit for all parameters of *a*–*c*.

The first hints (1992): Pulsar Planets

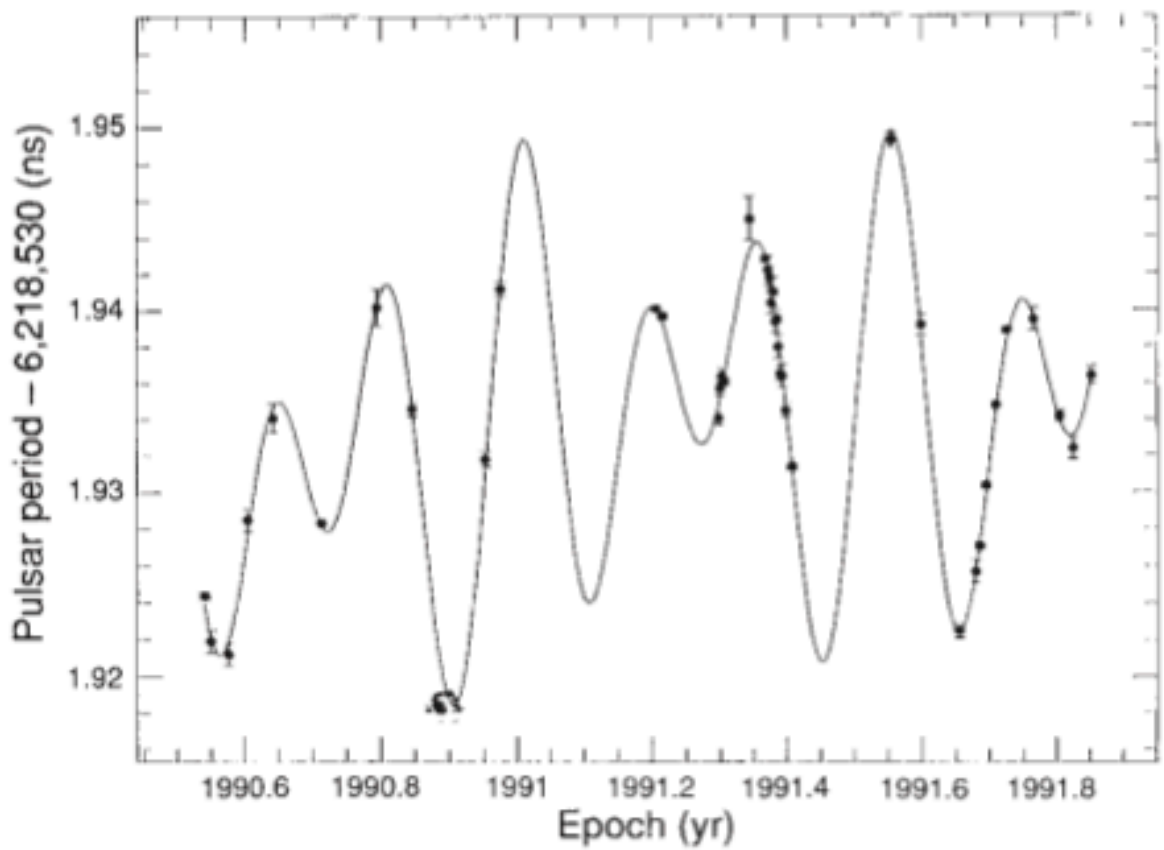
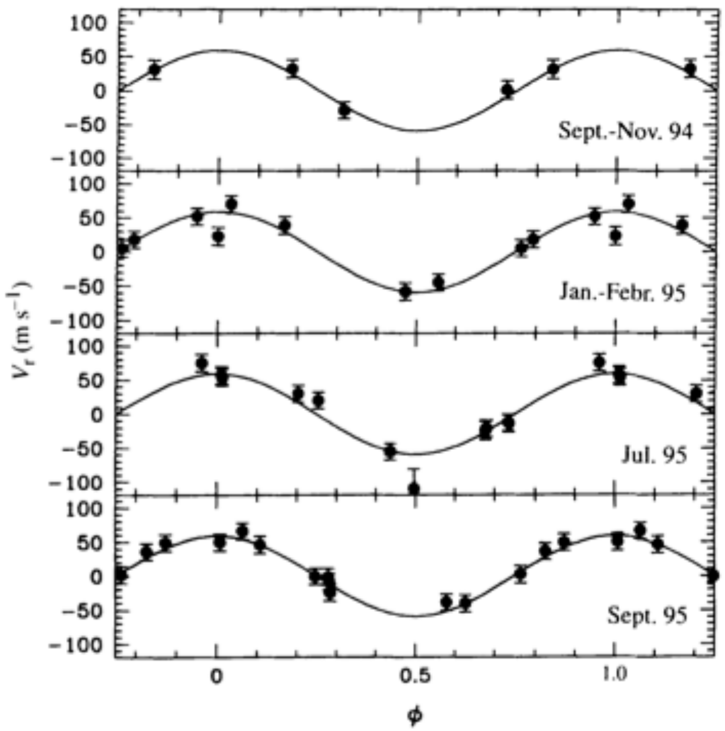
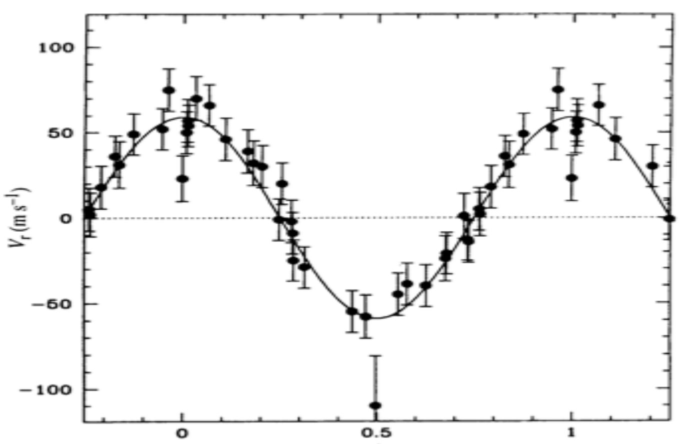


FIG. 3 Period variations of PSR1257+12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257+12 system.

51 Peg: The first “real” planet





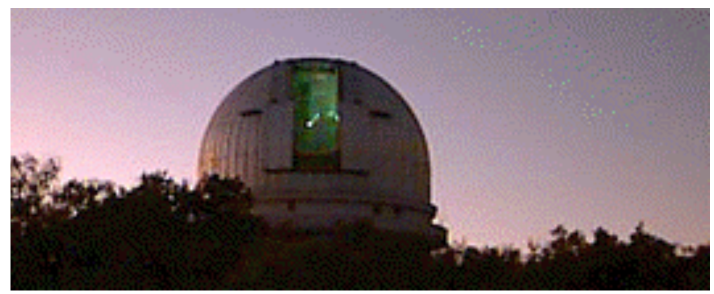


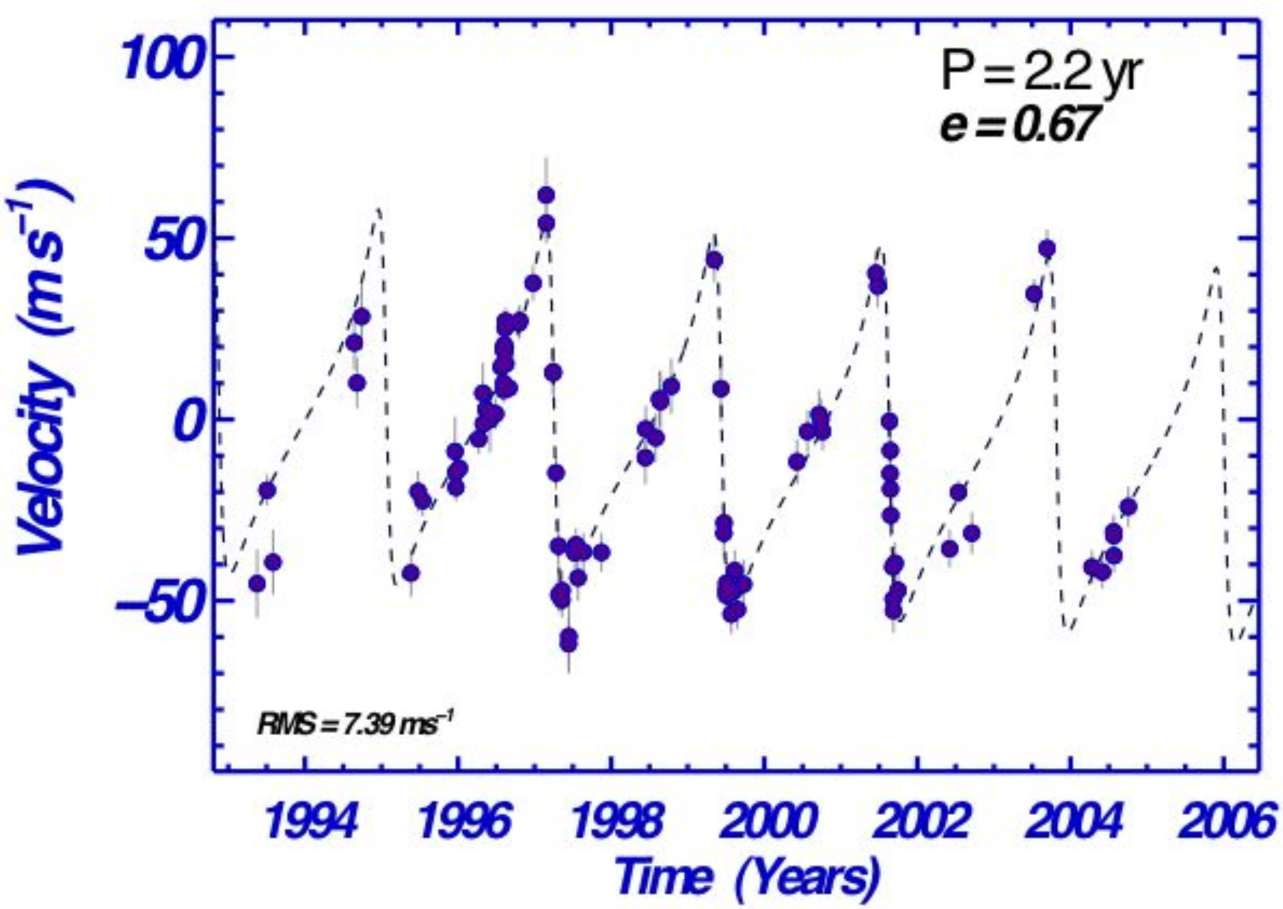
TABLE 1 Orbital parameters of 51 Peg

P	4.2293 ± 0.0011 d
T	$2{,}449{,}797.773 \pm 0.036$
e	0 (fixed)
K_1	0.059 ± 0.003 km s^{-1}
$a_1 \sin i$	$(34 \pm 2)\ 10^5$ m
$f_1(m)$	$(0.91 \pm 0.15)\ 10^{-10}\ M_\odot$
N	35 measurements
$(O-C)$	13 m s^{-1}

P, period; T, epoch of the maximum velocity; e, eccentricity; K_1, half-amplitude of the velocity variation; $a_1 \sin i$, where a_1 is the orbital radius; $f_1(m)$, mass function; N, number of observations; $(O-C)$, r.m.s. residual.

Another surprise: eccentricity!

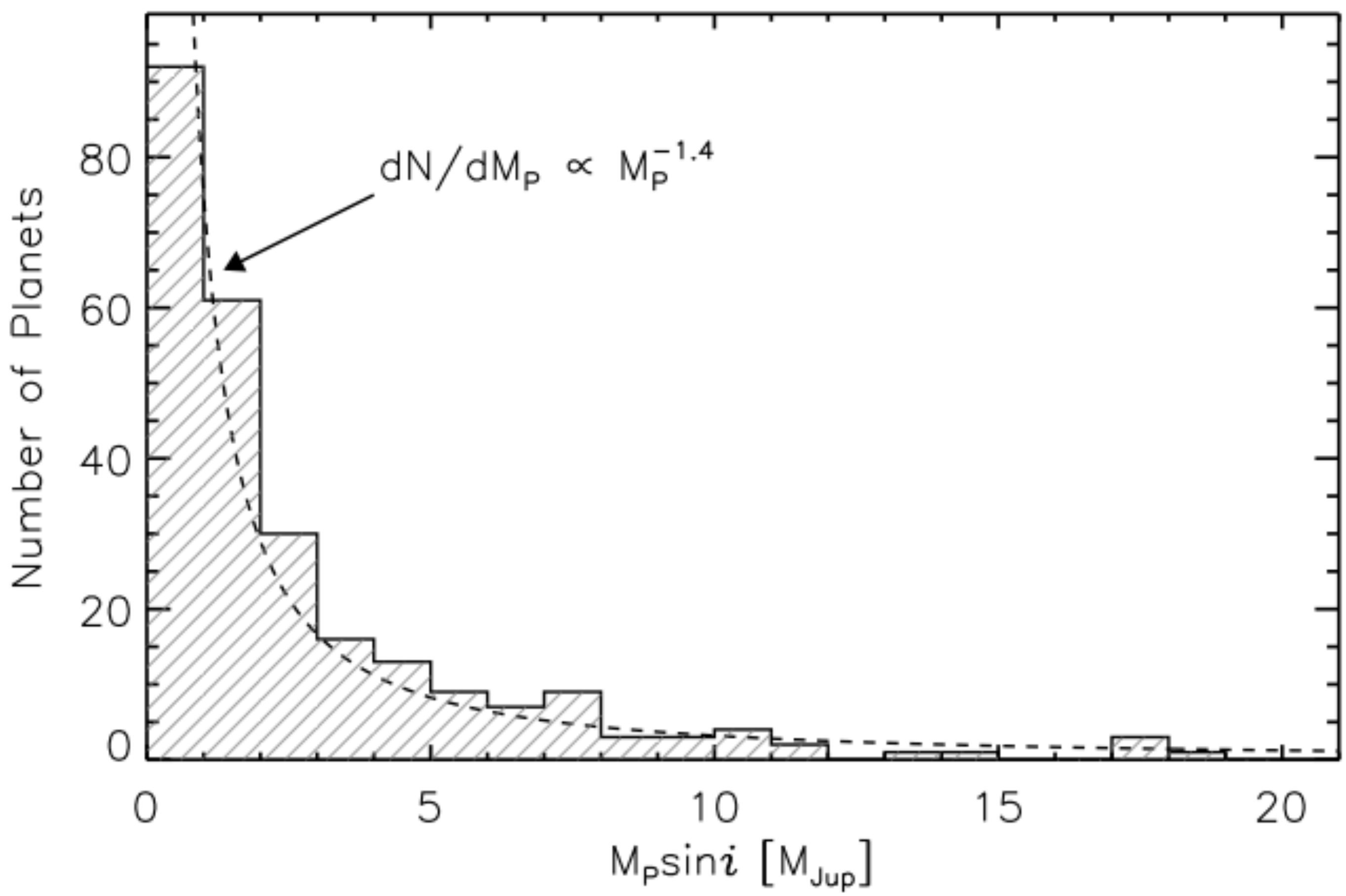
16 Cyg A



The Golden age of Doppler Planet Discovery (1995-)

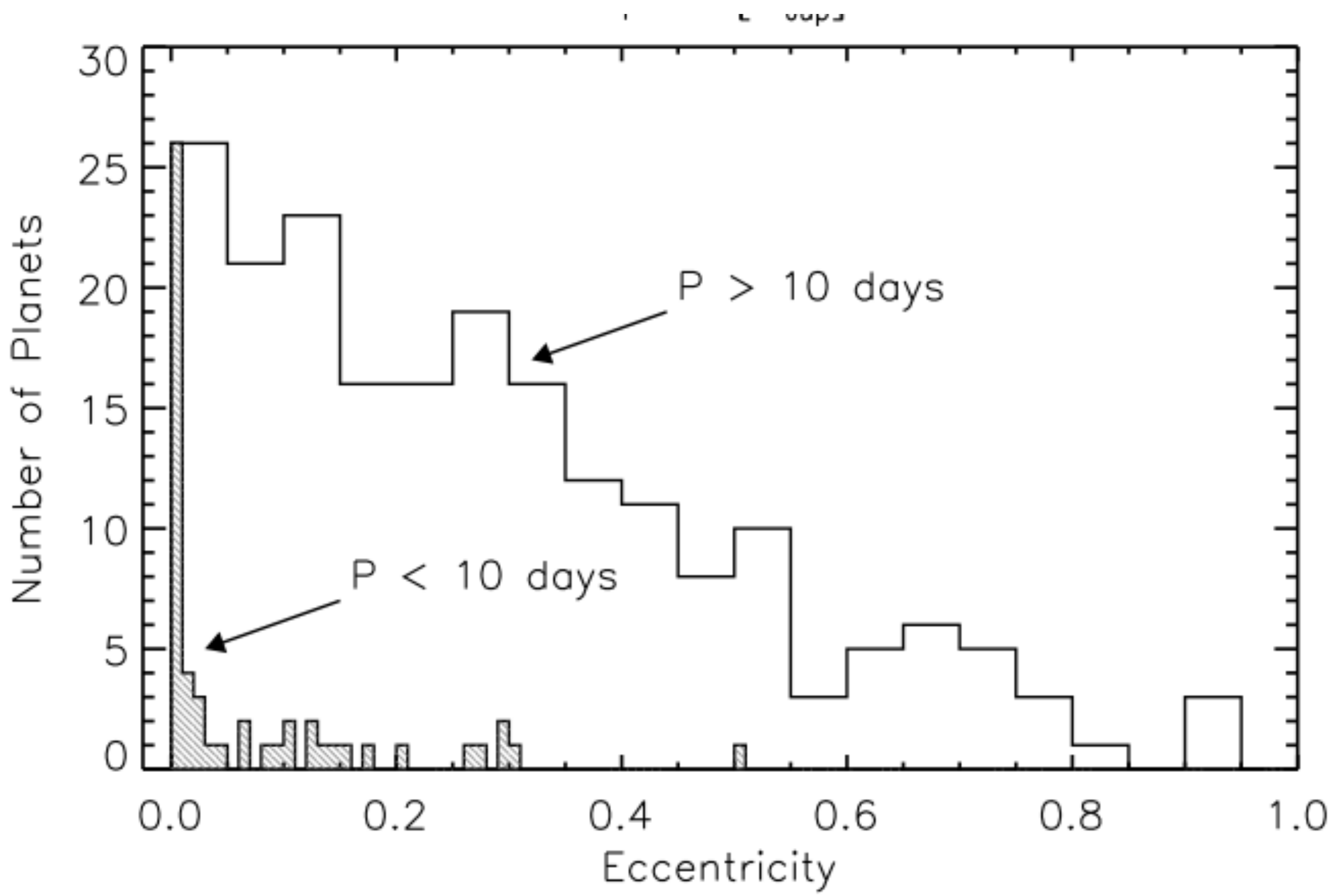
- RVs provides key planetary properties: orbits and masses
- Measure distributions of planet properties
- Probe multi-planet systems, including interactions
- Tests planet formation theory – core accretion theory over disk instability theory

Mass Distribution

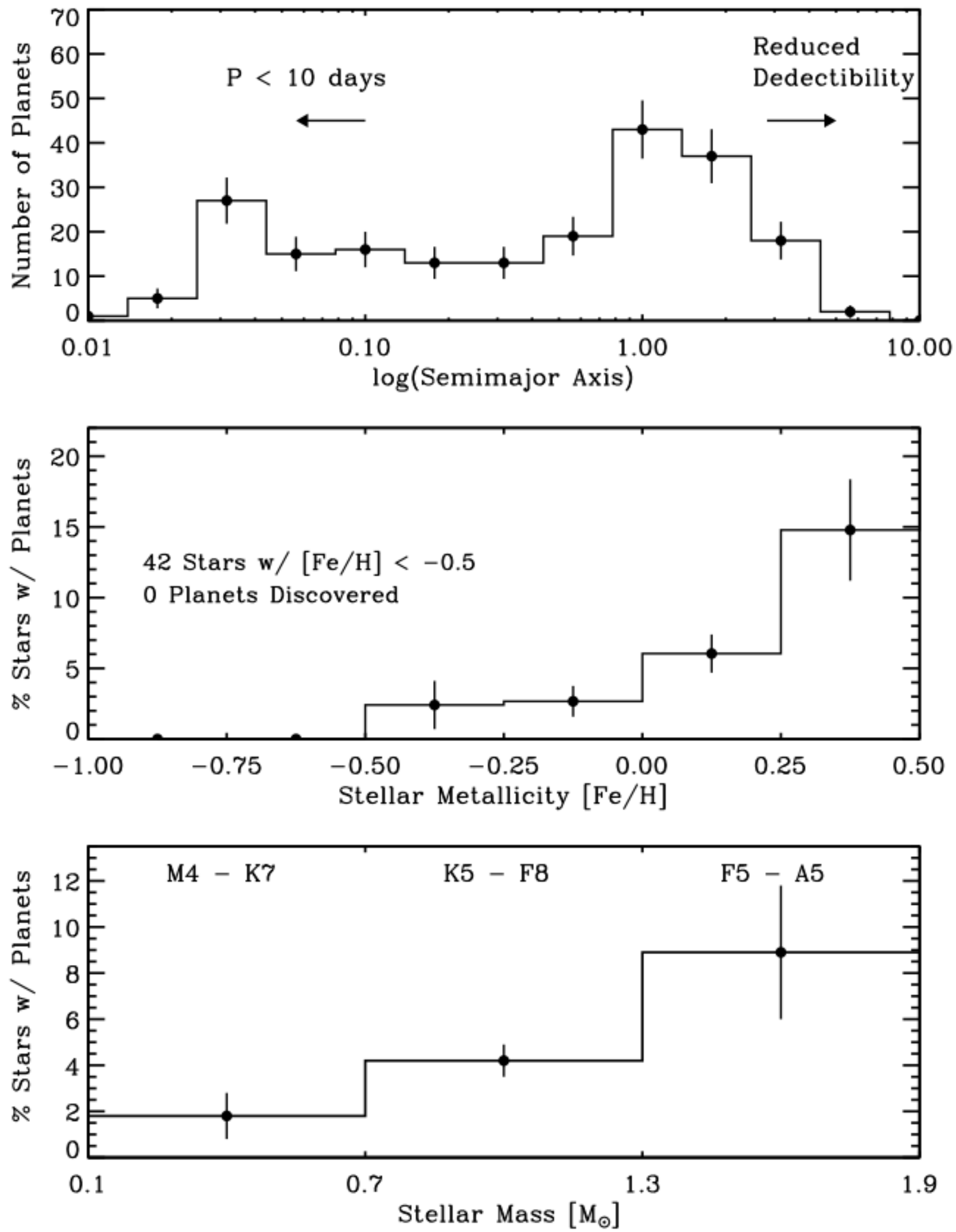


Johnson (2009)

Eccentricity Distribution



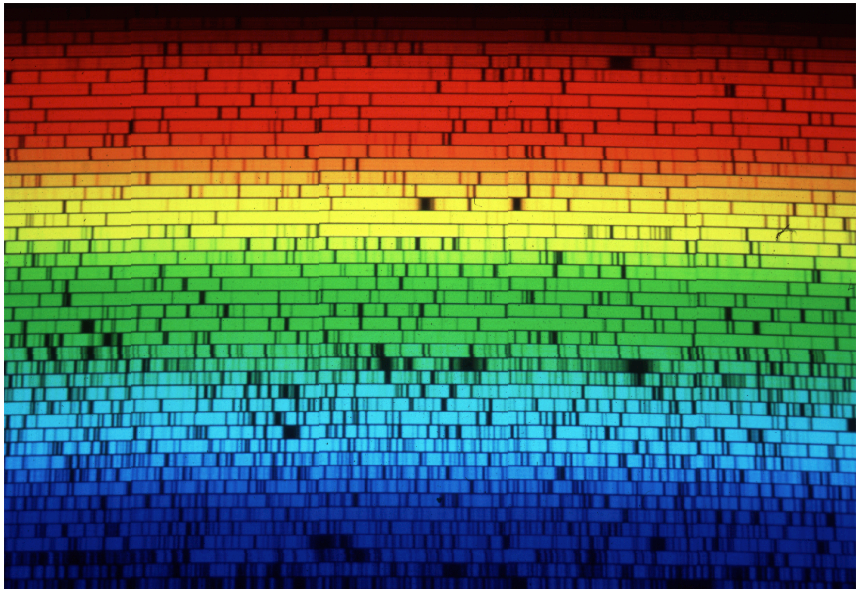
Johnson (2009)



Johnson (2009)

Spectroscopic parameters

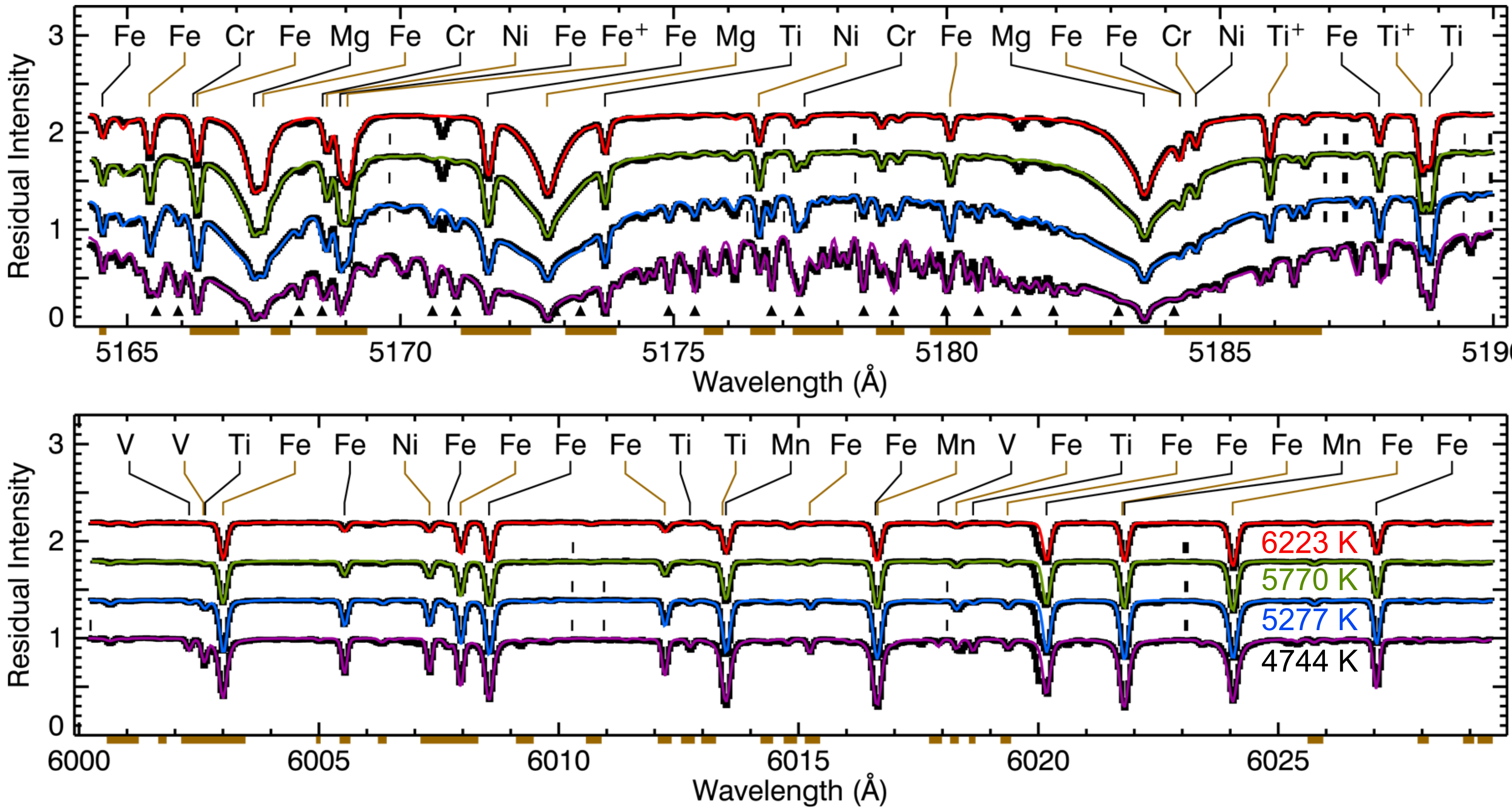
- Stellar parameters that affect spectrum
  - **Effective temperature** (via ionization and excitation)
  - **Gravity** (high gravity broadens line wings due to collisions)
  - **Abundances** or a global metallicity (affects opacity in lines)
  - **Magnetic fields** (changes opacity versus wavelength)
  - **Microturbulence** and **Macroturbulence** (Doppler smearing)
  - **Rotation** (more Doppler smearing)
  - **Radial velocity** (Doppler shift)



- Spectroscopy Made Easy (SME)
  - Fit observations or just synthesize a spectrum
  - Atomic data still a challenge
  - Valenti & Piskunov (1996, A&AS, 118, 595)

Slide courtesy of Jeff Valenti

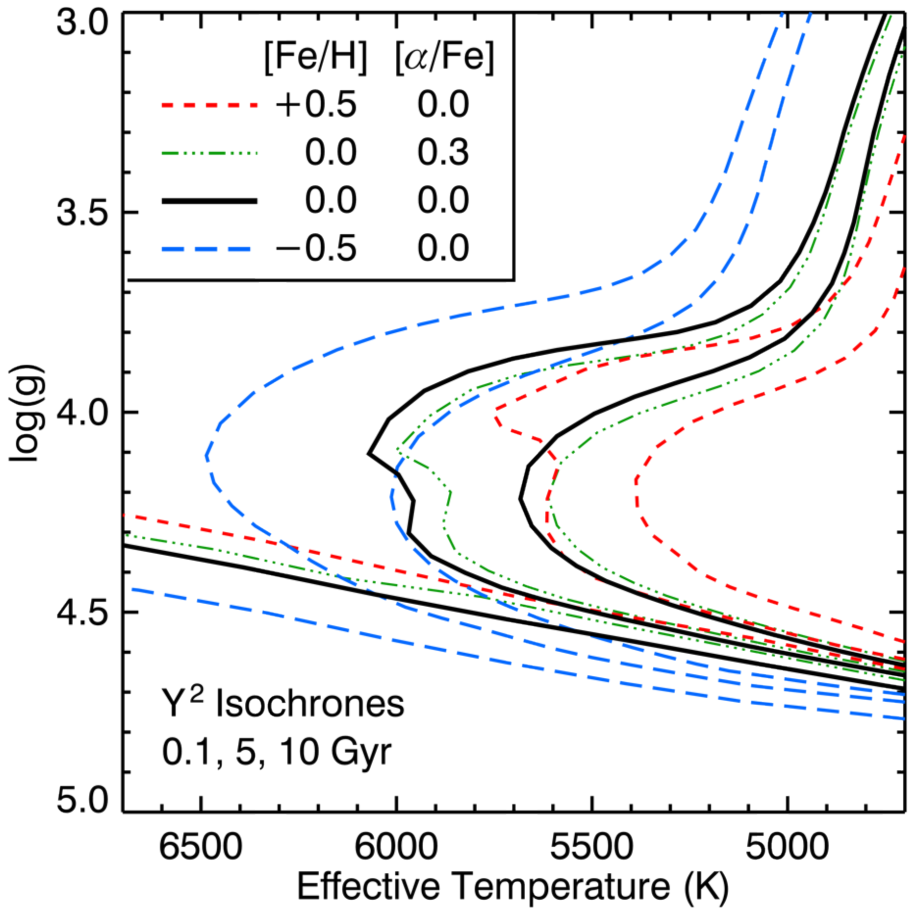
Spectroscopy Made Easy (SME)

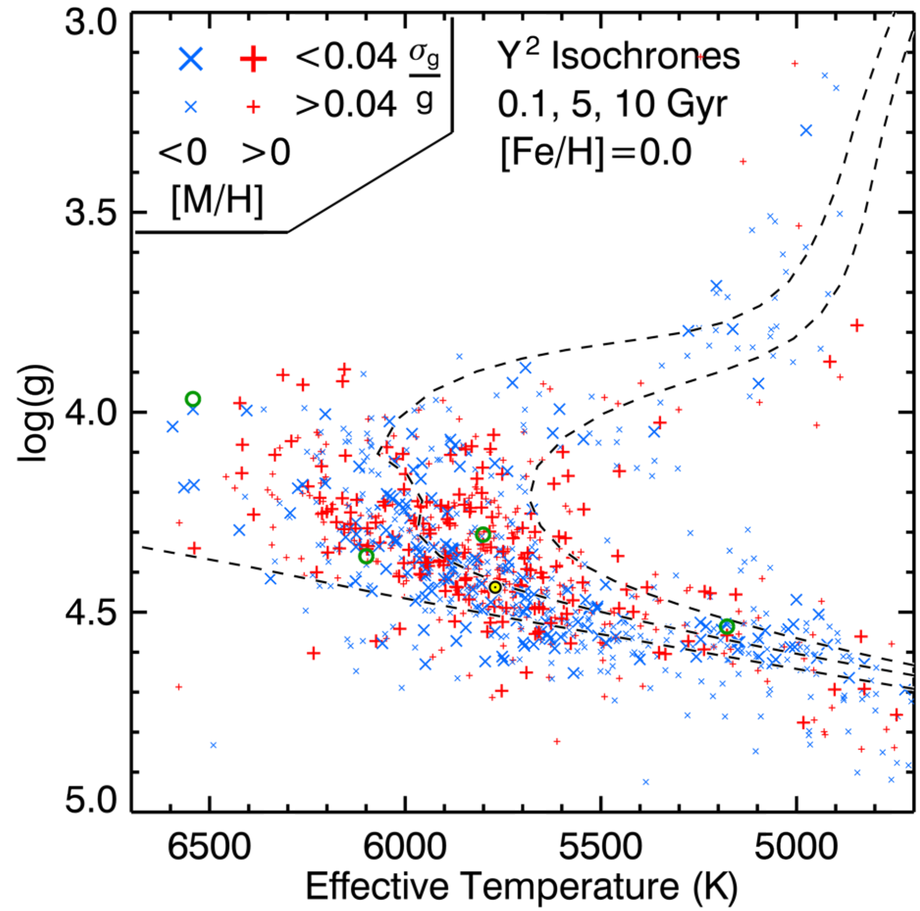


Valenti & Fischer (2005, ApJ, 159, 141)

Slide courtesy of Jeff Valenti

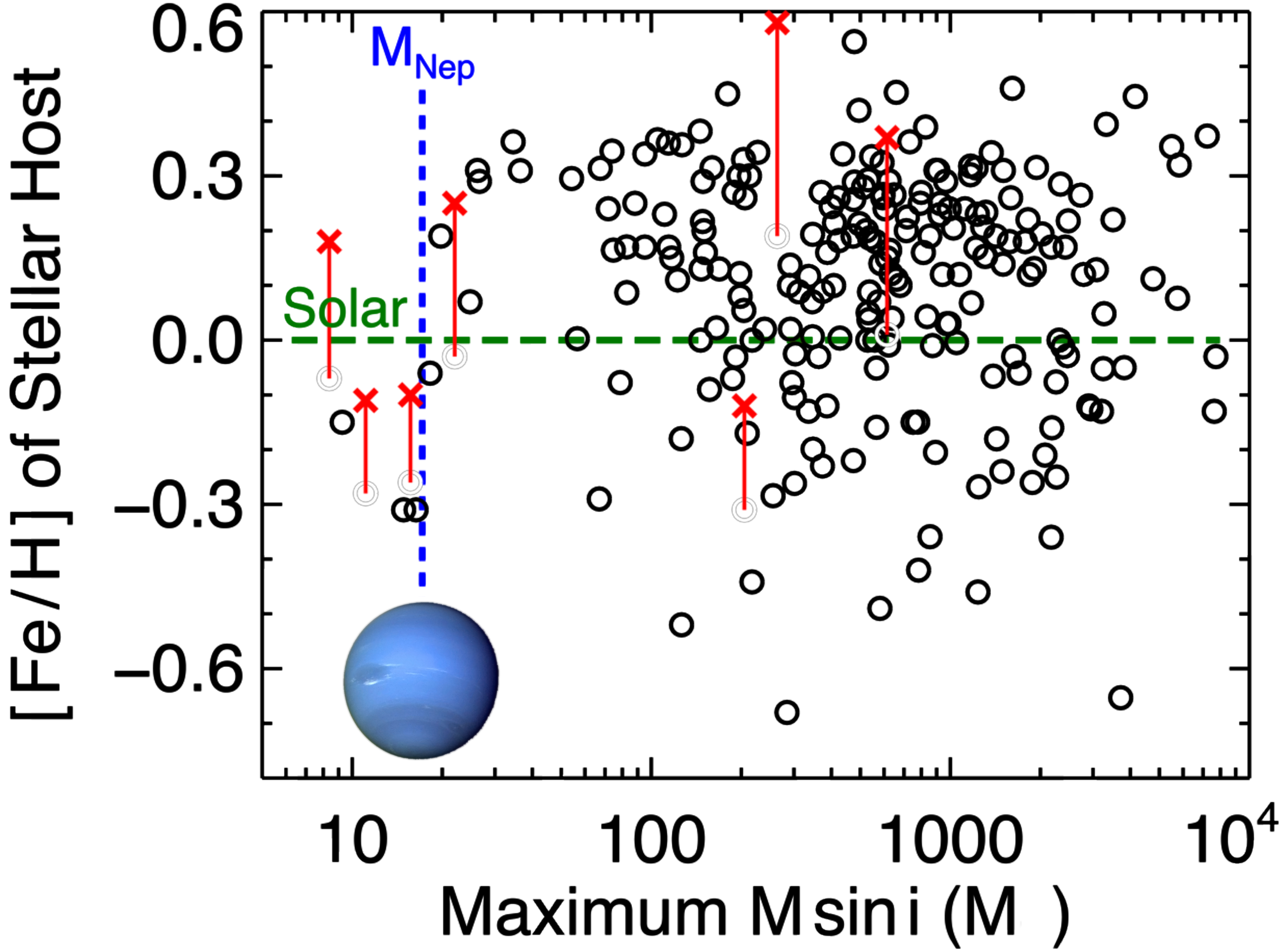
Stellar structure parameters using gravity





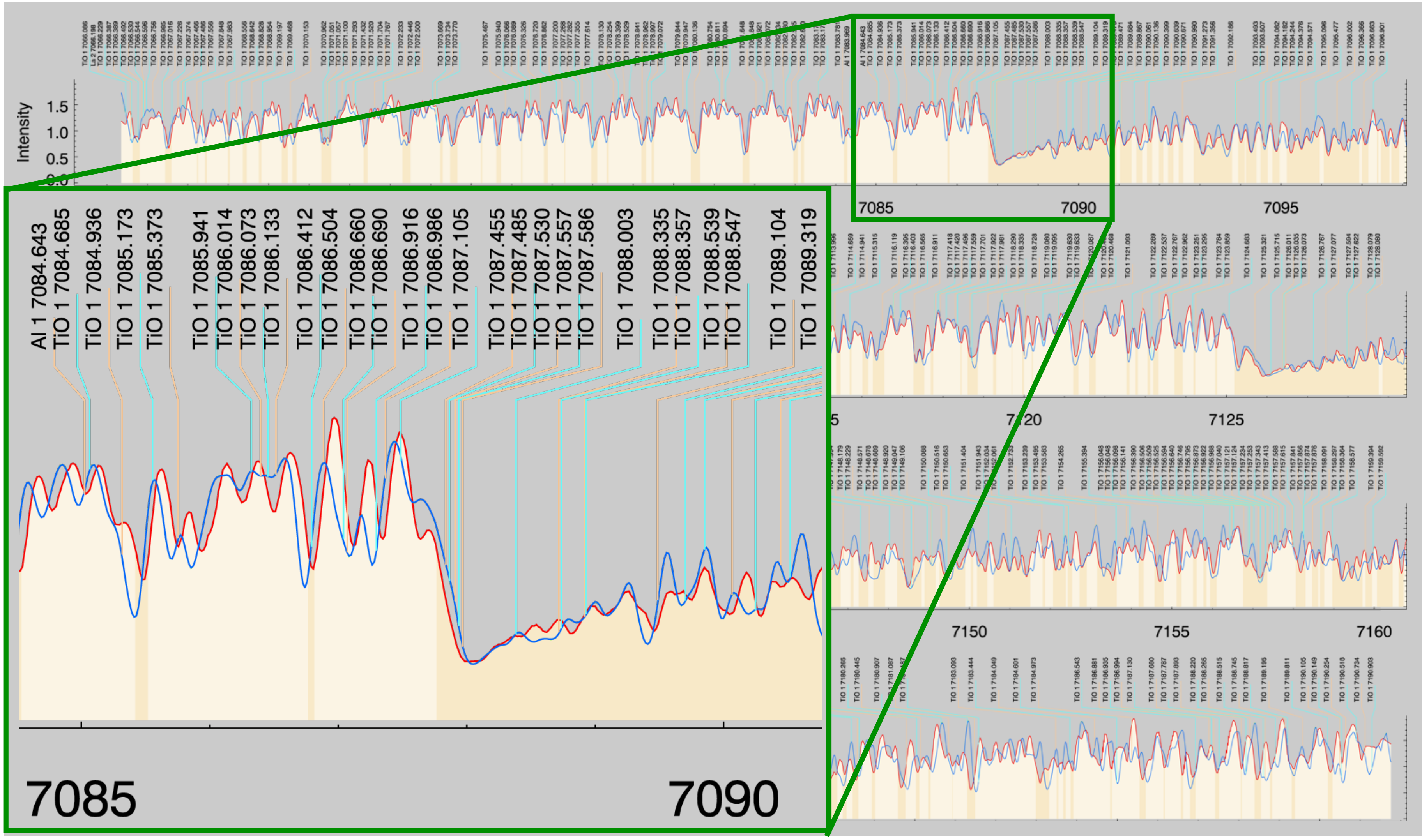
Slide courtesy of Jeff Valenti

Planet-Metallicity Correlation



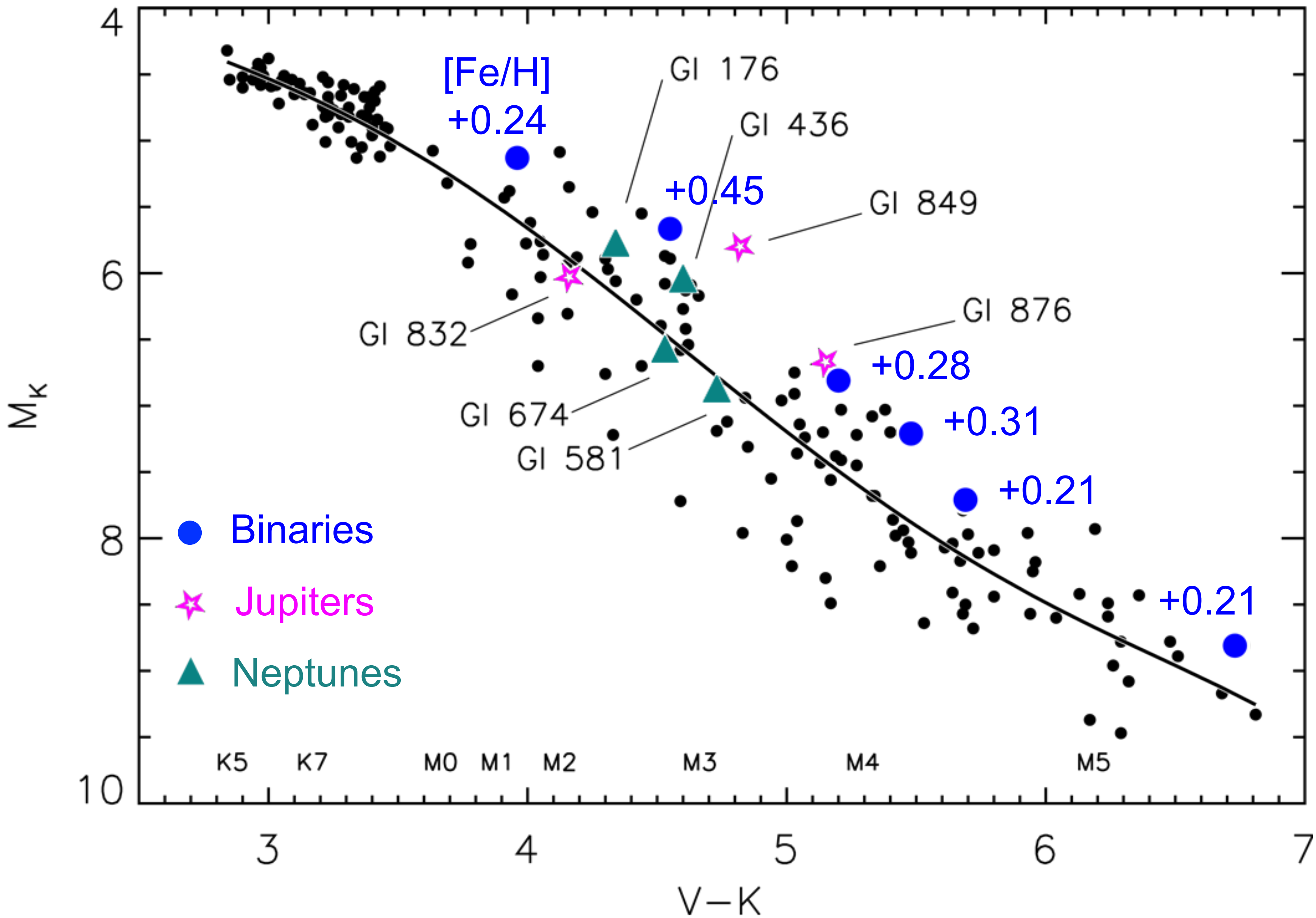
Slide courtesy of Jeff Valenti

TiO line data are inadequate for abundance work



Courtesy of Prof. Nikolai Piskunov (Uppsala)

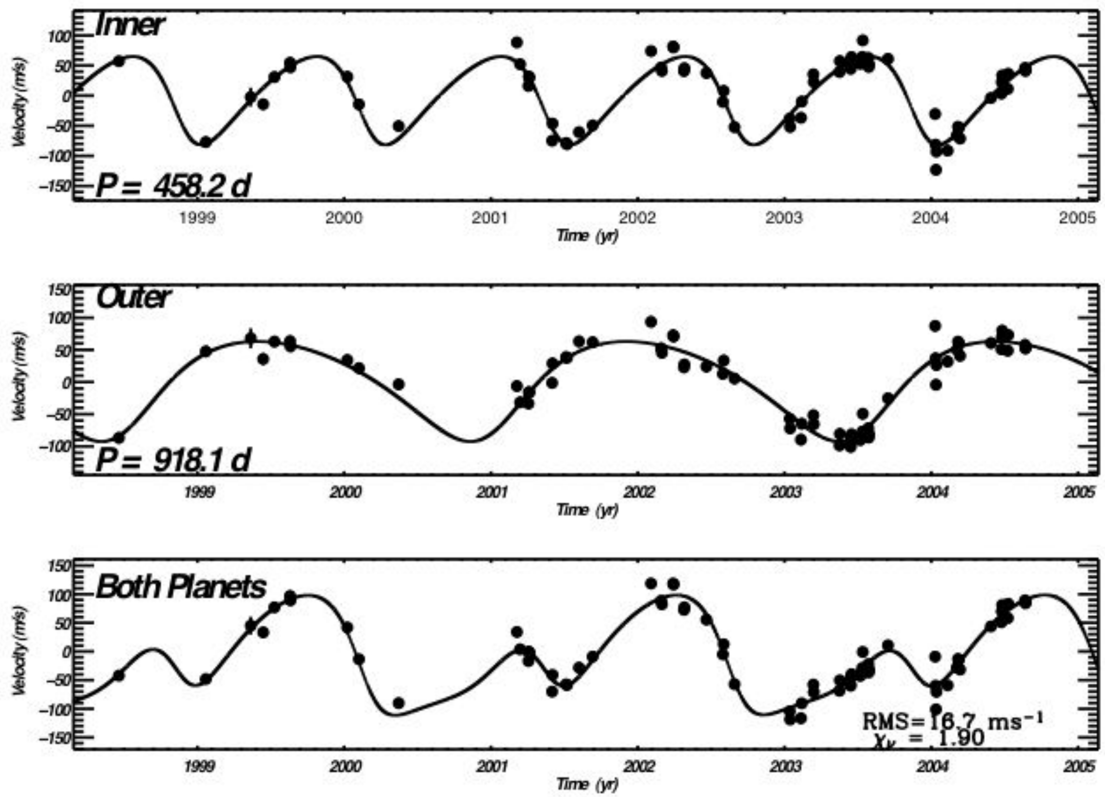
Photometric [Fe/H] for M dwarfs



Johnson & Apps (2009, ApJ, 699, 933)

HD 128311

2:1 Resonance



	Inner	Outer
Per (d)	458	918
Msini	2.3	3.1
ecc	0.23	0.22
ω	119	212

K0V, 1Gy, 16 pc

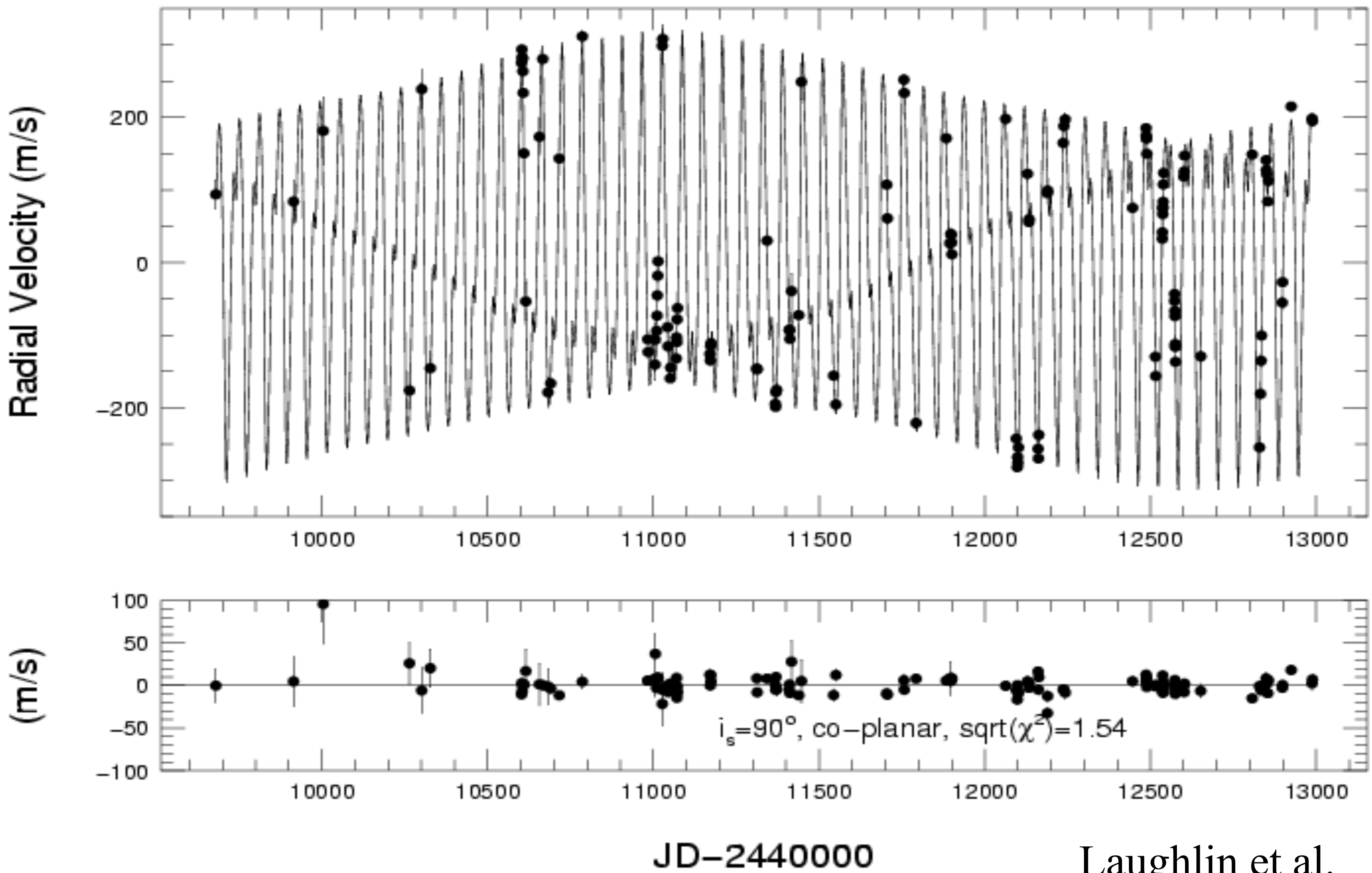
$P_c / P_b = 2.004$

Dynamical Resonance

(Laughlin)

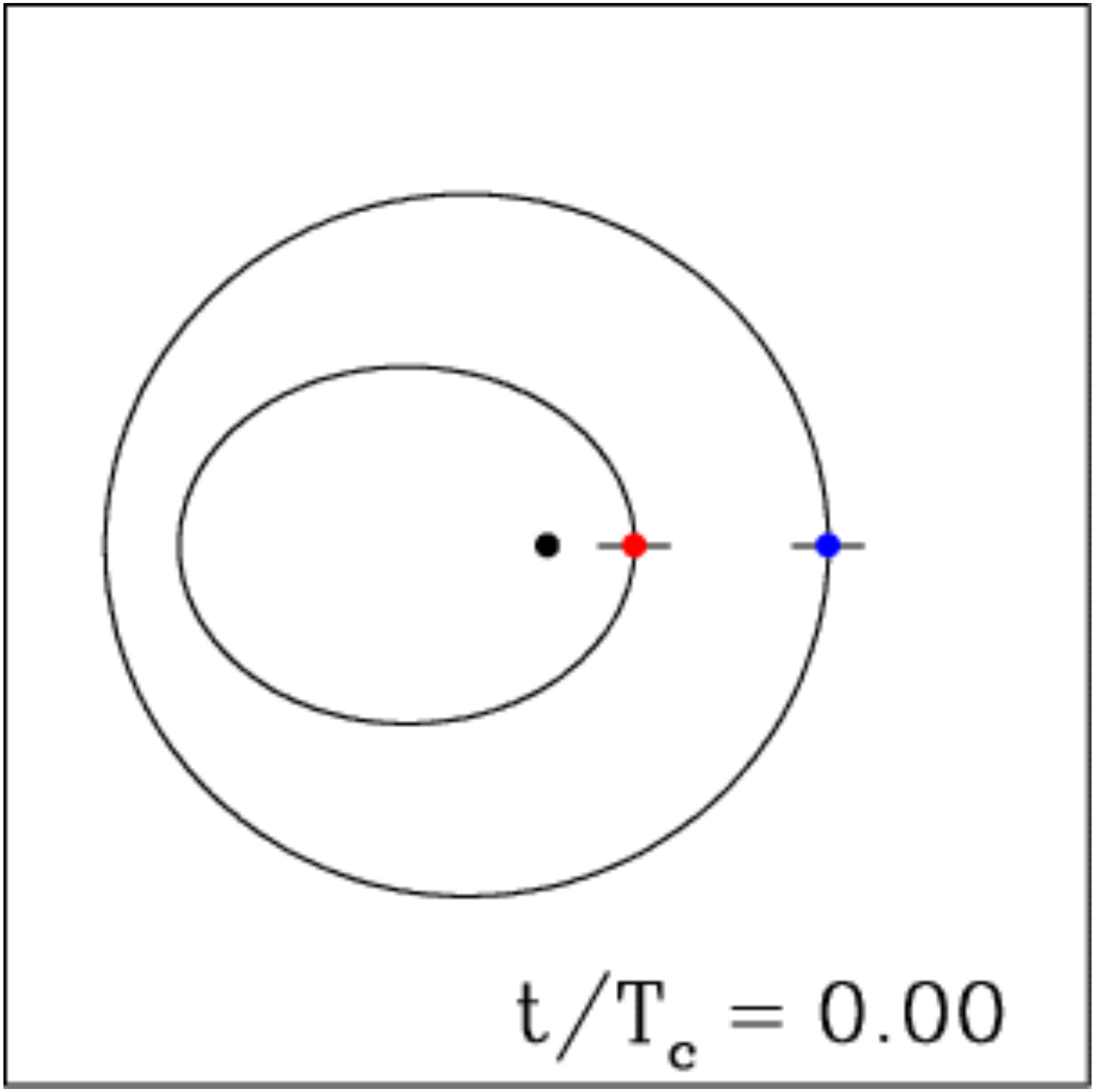
GJ 876: Velocities

Two-Planet Model



Laughlin et al. 2004

Gliese 876



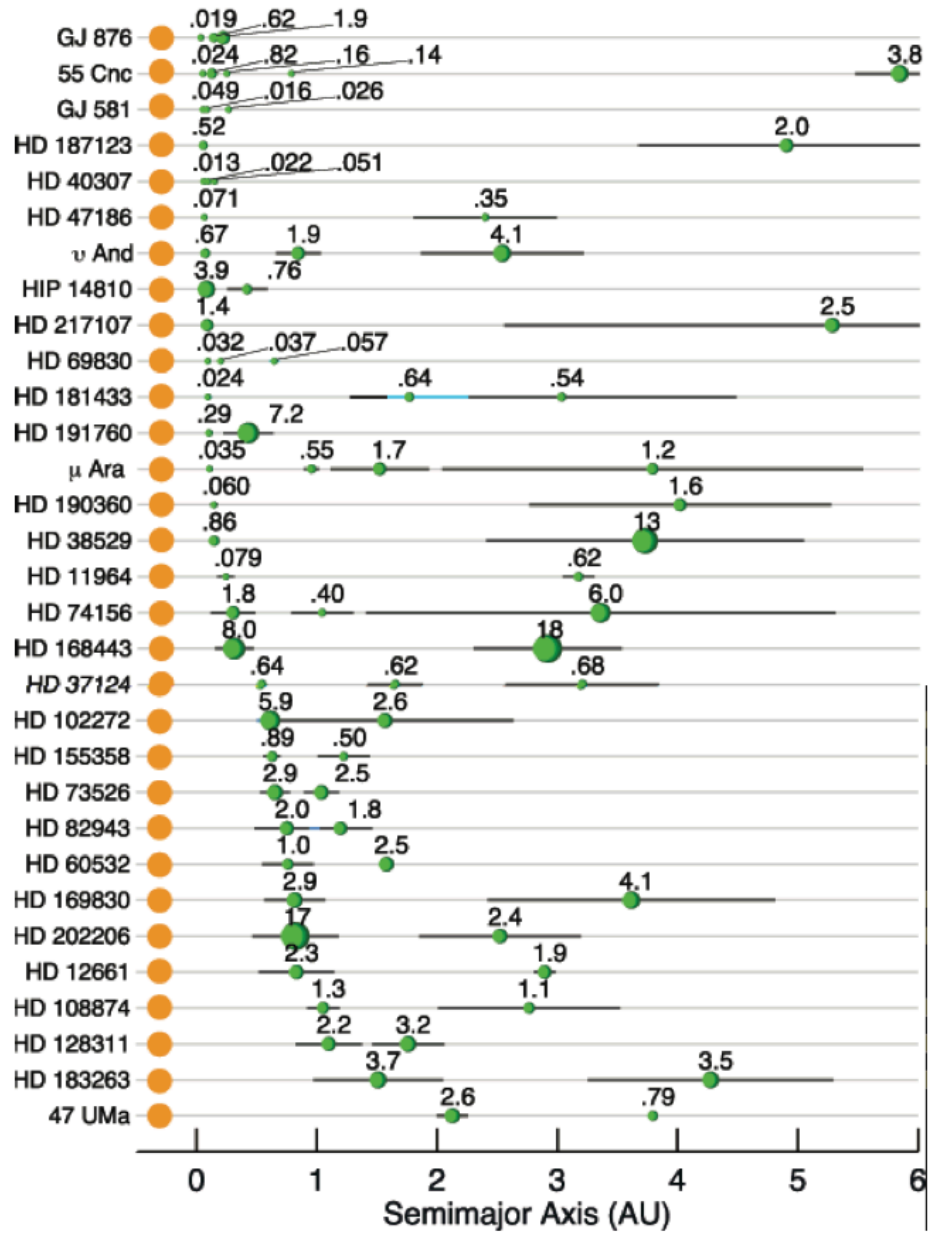
- 2:1

Mean Motion Resonance

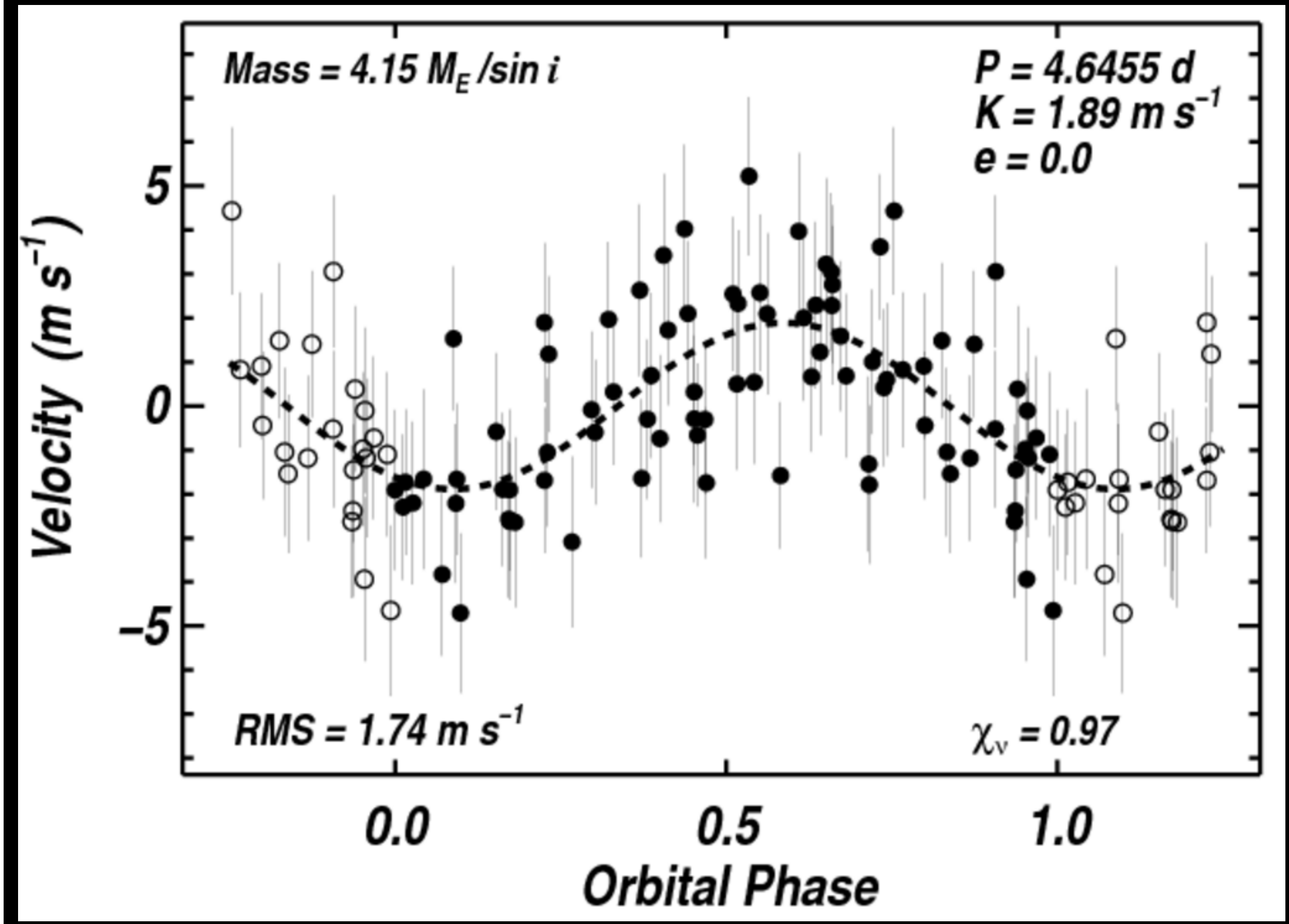
Precession Period: 9 yr

Man Hoi Lee

30+ Multi-planet Systems



HD 156668b - Super-Earth



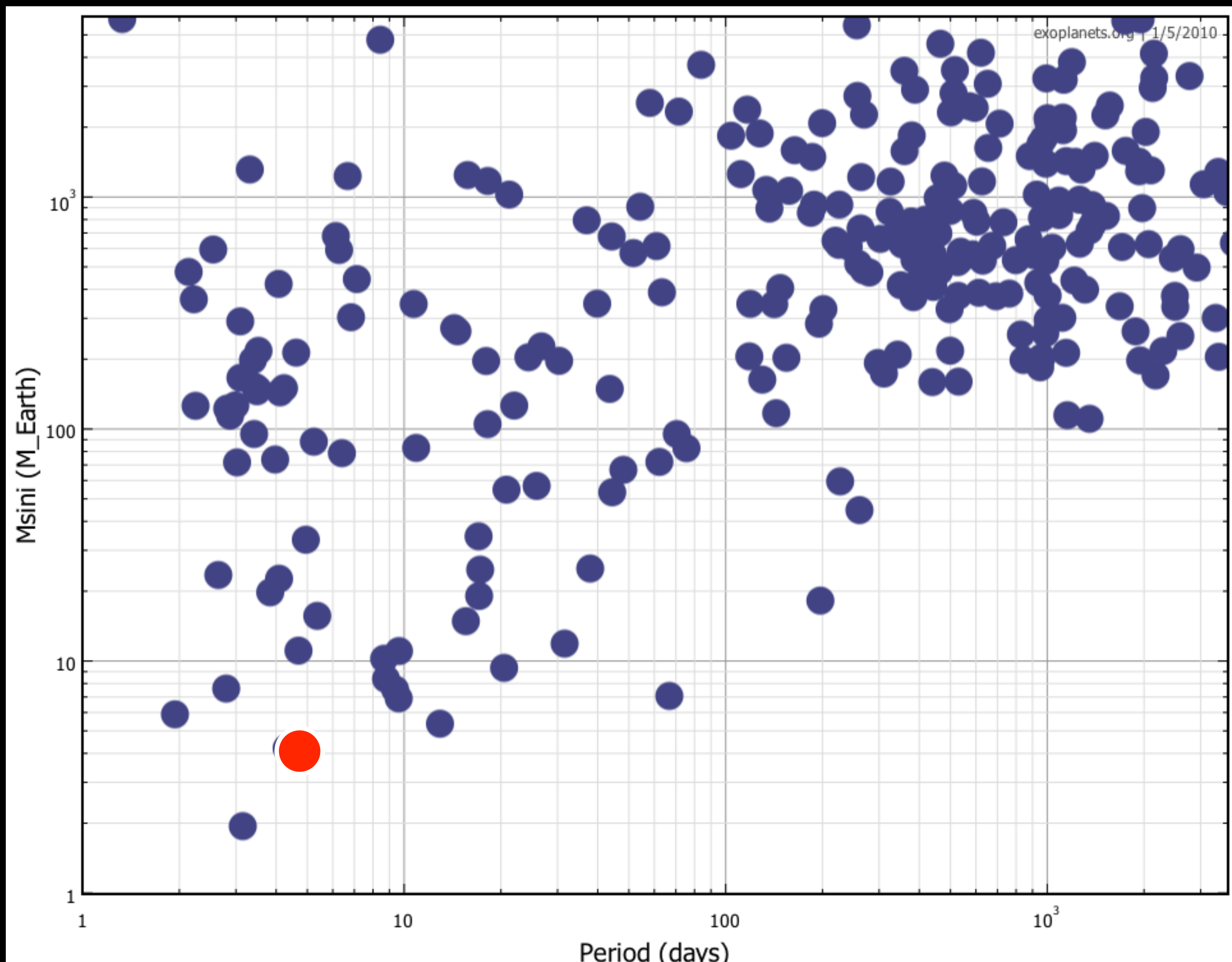
Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = 0.05
quiet

Planet:
M sin i = 4.15 M_E
P = 4.6455 d
e = 0 (fixed)

Howard et al. 2010, ApJ, submitted

Among Lowest Msin$i$

Msin$i$ (M_{Earth}) vs. P (days)



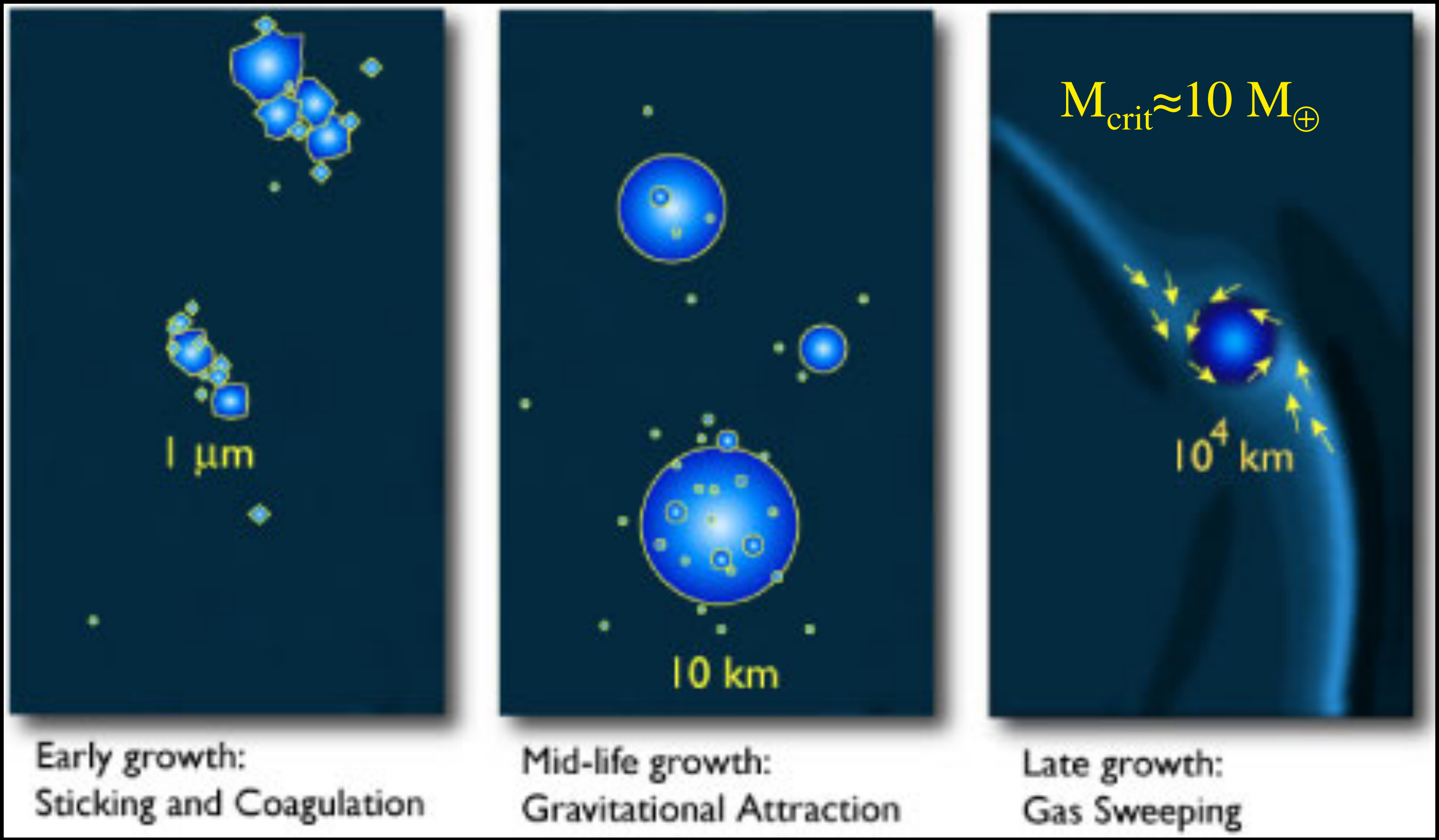
Msin$i$ = 4.15 M_{Earth}

2nd smallest
Msini ever!
(GJ 581e has
Msini = 1.9 M_{Earth})

Pushing down
to the RV limit
to the lowest masses

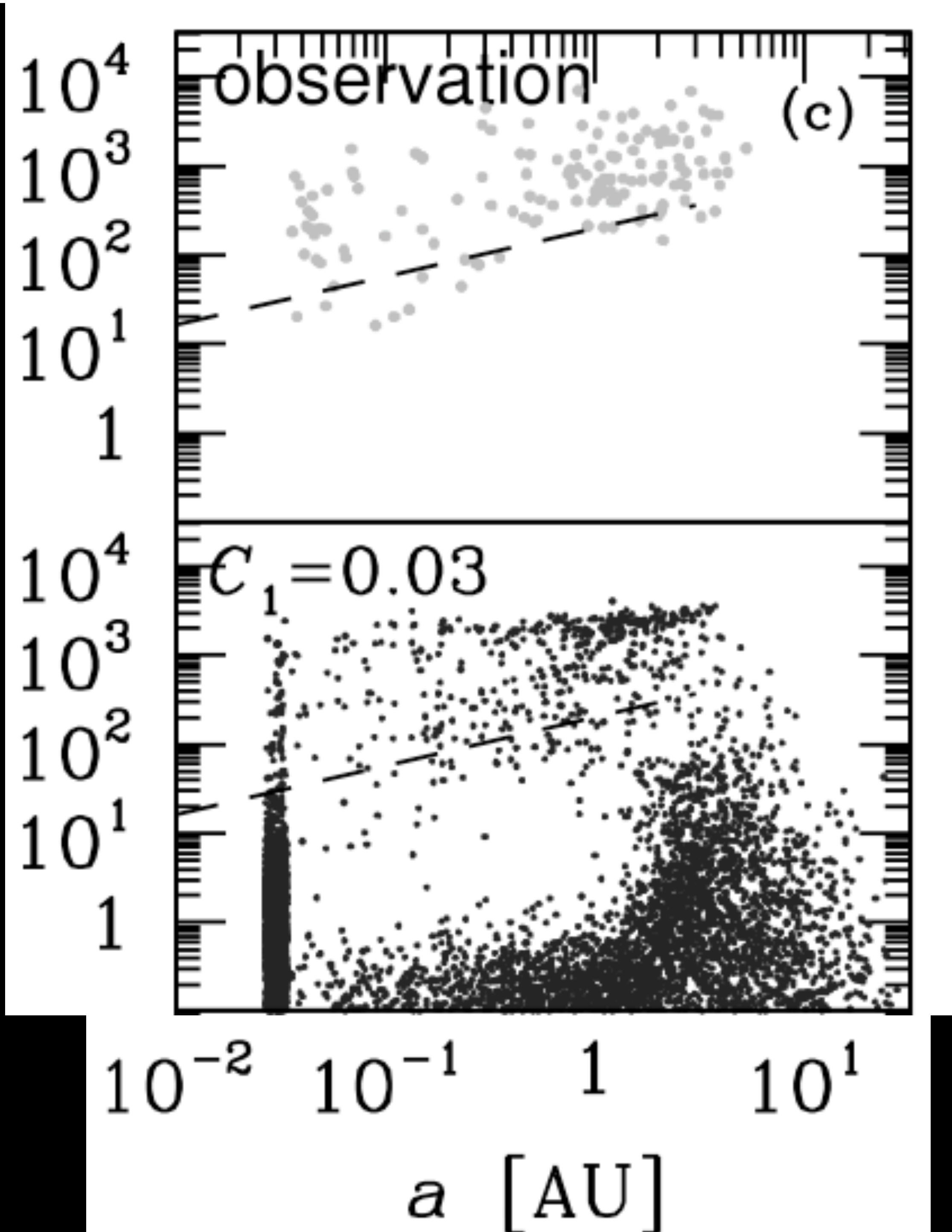
To make plots like this: exoplanets.org

Core Accretion Model



Ida-Lin Planet Formation Theory

- Simulate core-accretion process
- Start with rocky planetesimals and gas
- All them to grow, migrate, and accrete gas
- Include effects such as gas-planetesimal interactions and ice condensation
- Artistry: tune migration efficiency (Type 1 & 2) and condensation points
- Compare final planet distribution with observations

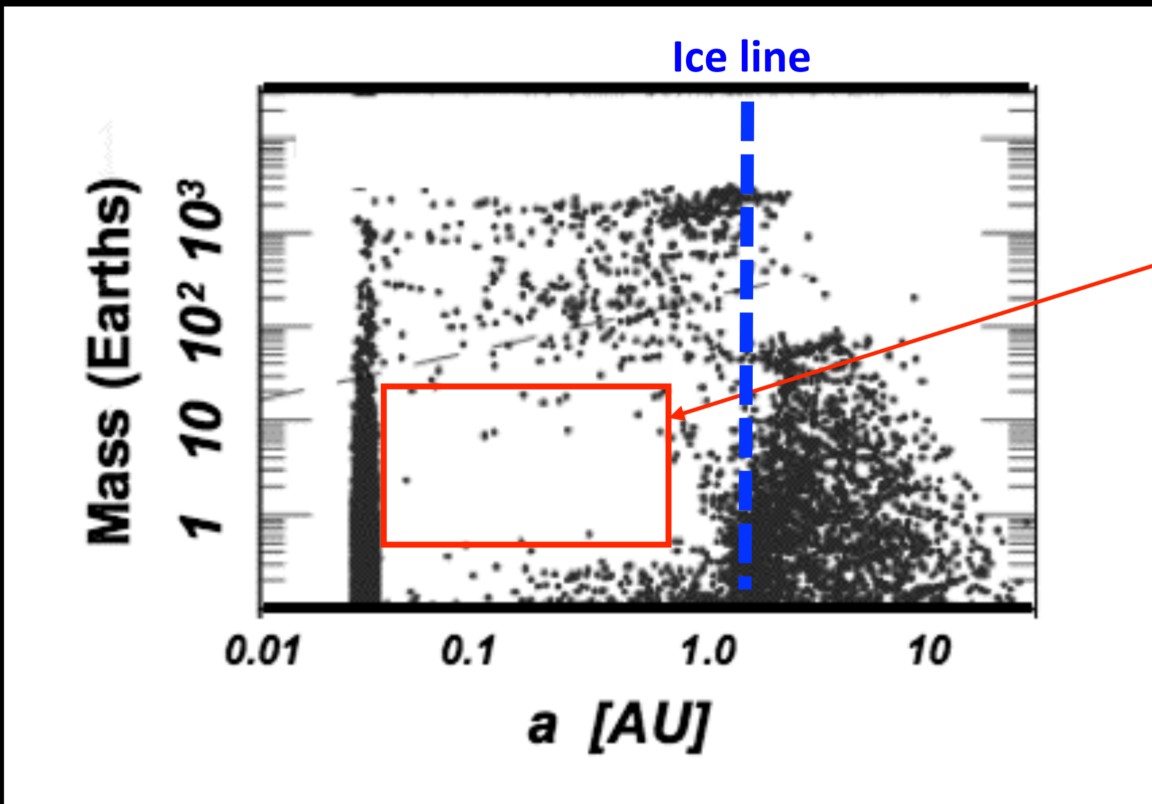


RV Observations

Ida/Lin Theory

Ida & Lin 2009, ApJ, 685, 584

Predicted
Mass vs. Orbital Distance
(Ida & Lin 2008)



Planet Desert:
a = 0.05 - 1.0 AU
M = 1 - 30 M_{Earth}

Desert: Type 1 Migration Off
Type 2 Migration Tuned down

How Common are Low-mass Planets?

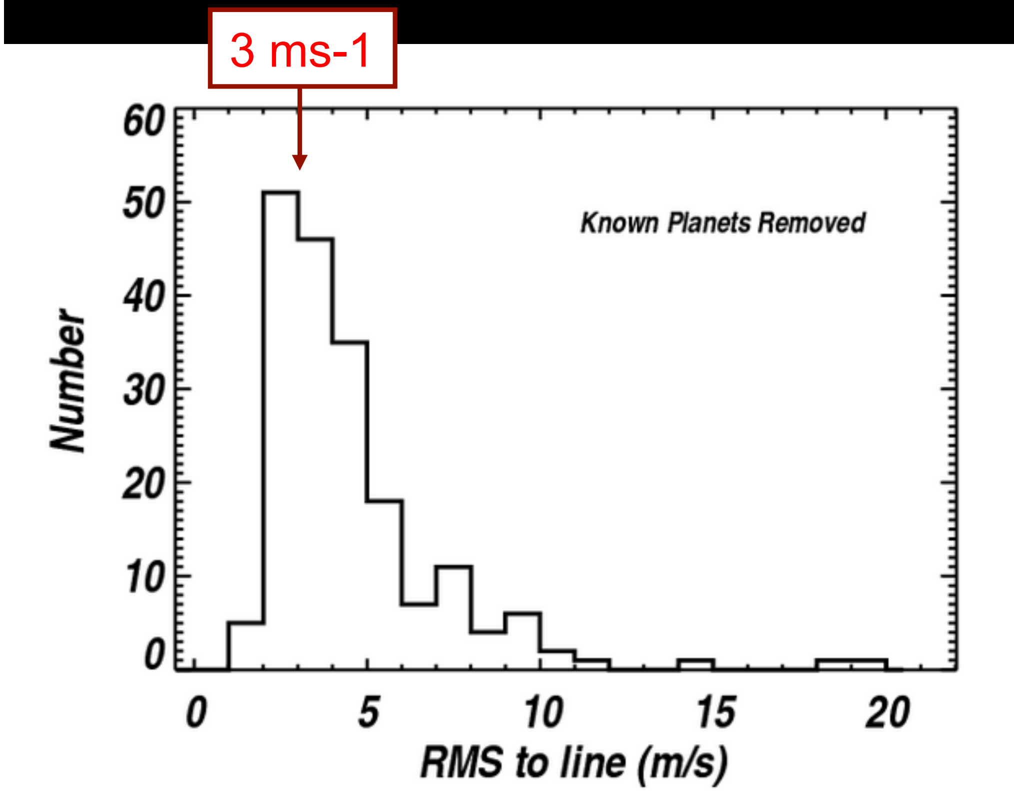
Burning Debate!

38% - 58% !!

- Theory predicts few super-Earths and Neptunes in short-period orbits
- Swiss group claims that 30% ± 10% of GK dwarfs have rocky or Neptune planets inward of 50-day orbits
- Initial results from the Eta-Earth Survey show fewer Super-Earths and Neptunes

Doppler Noise

Keck/HIRES



Eta-Earth GKM stars:
Chromospherically quiet
20-100 observations each

HARPS

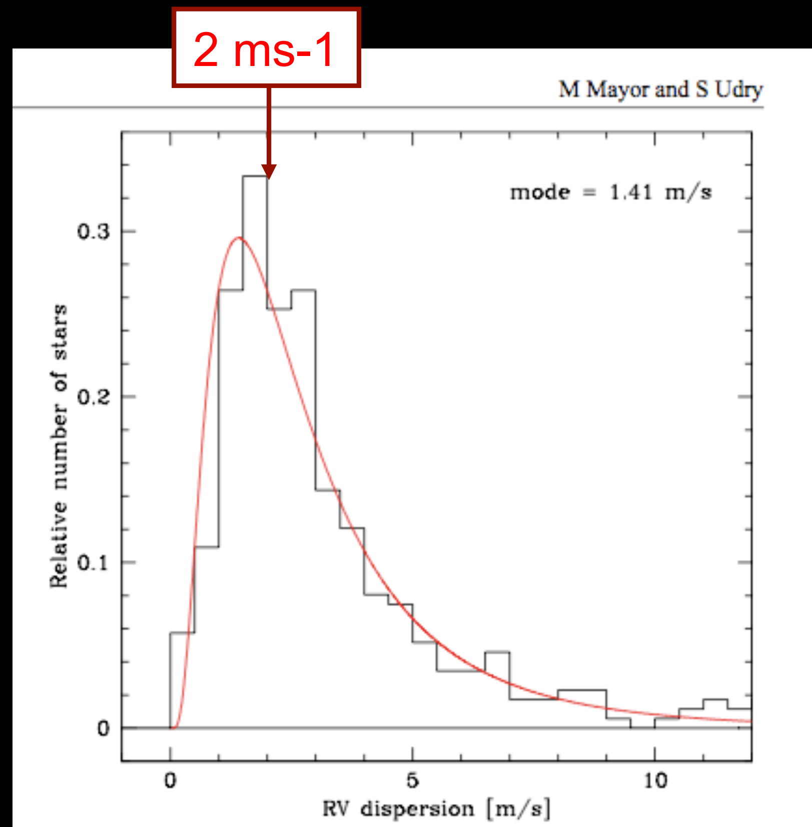
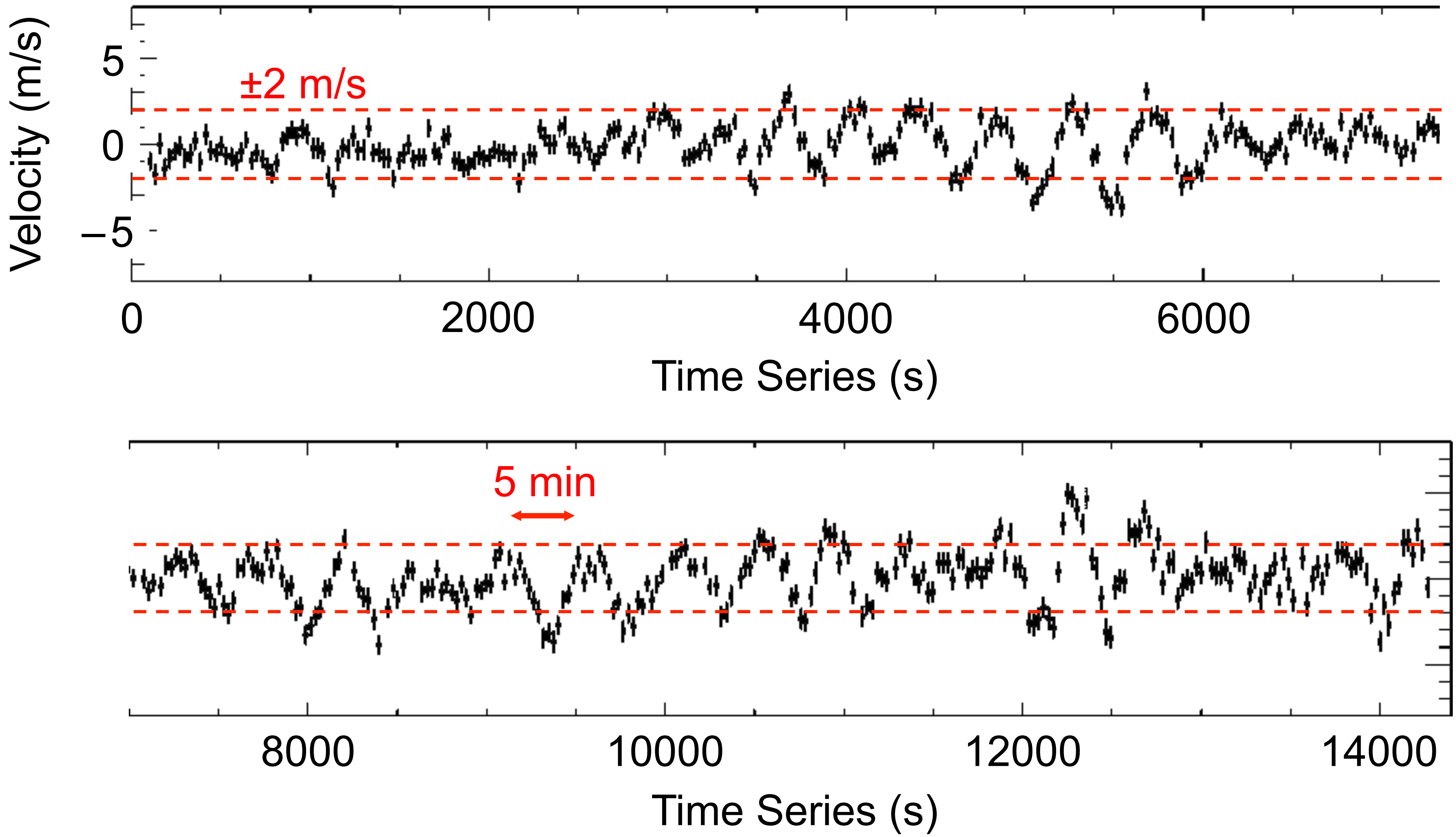


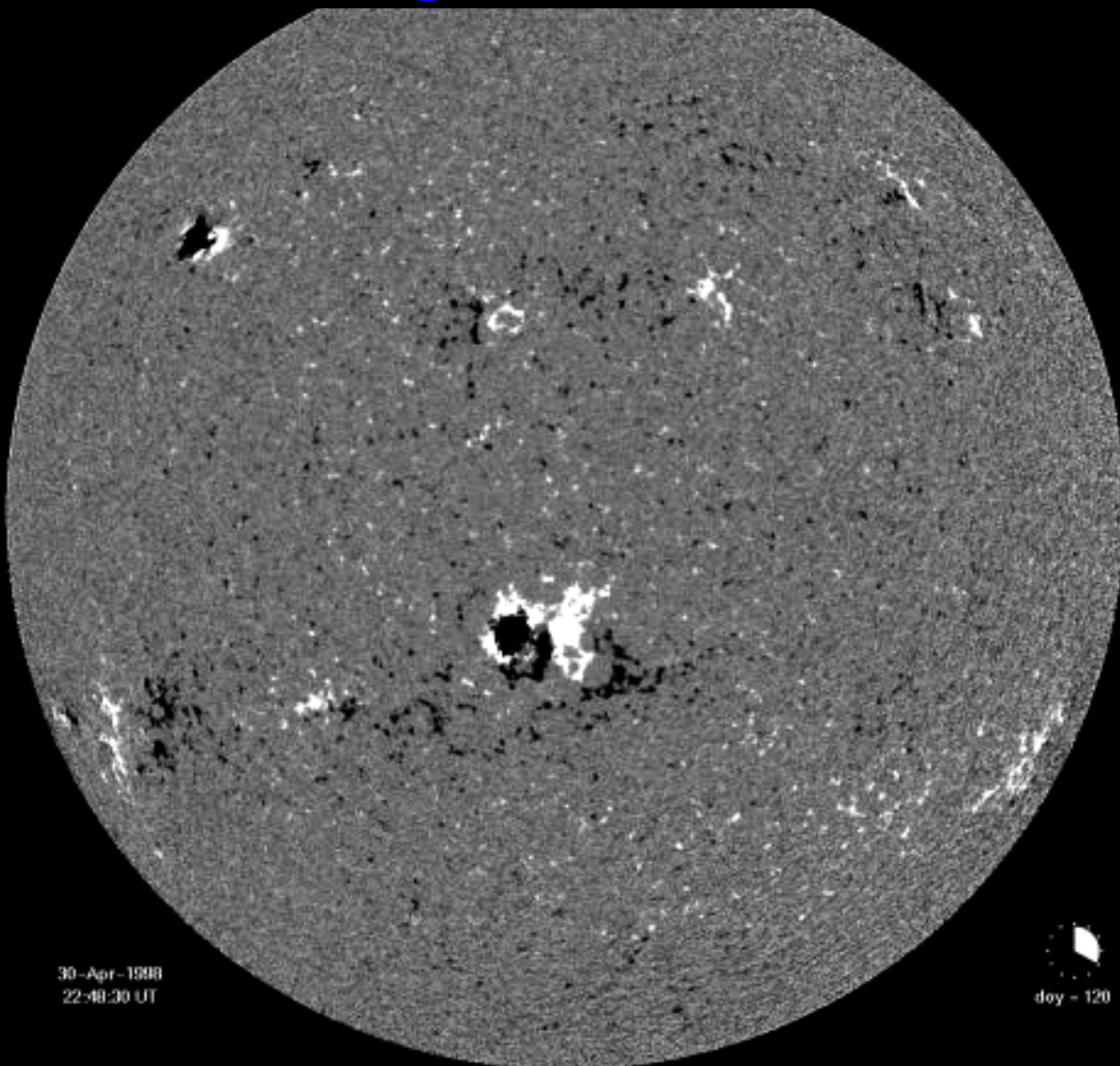
Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

Significant velocities due to p-modes

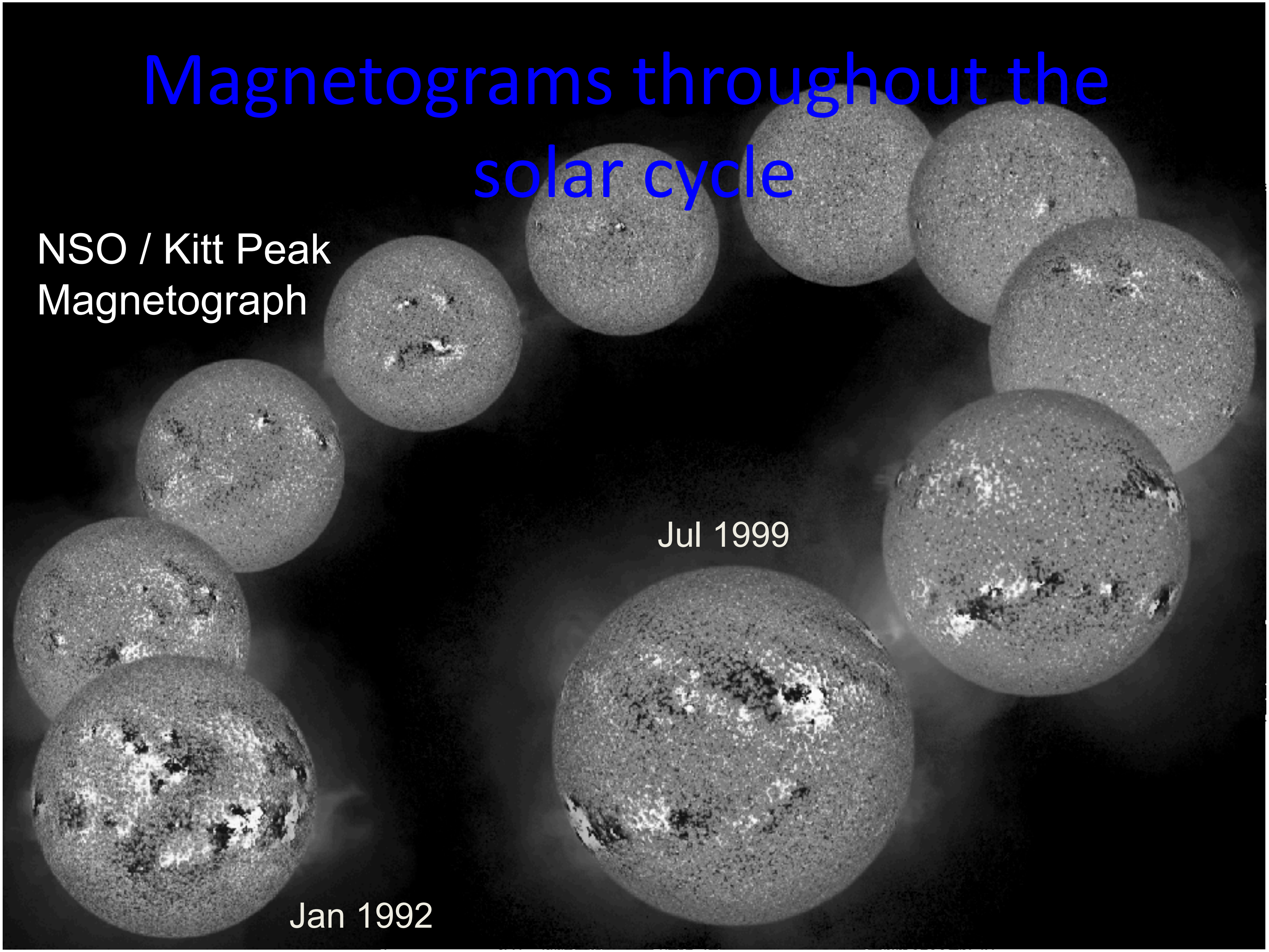


Butler et al. (2004, ApJ, 600, L75)

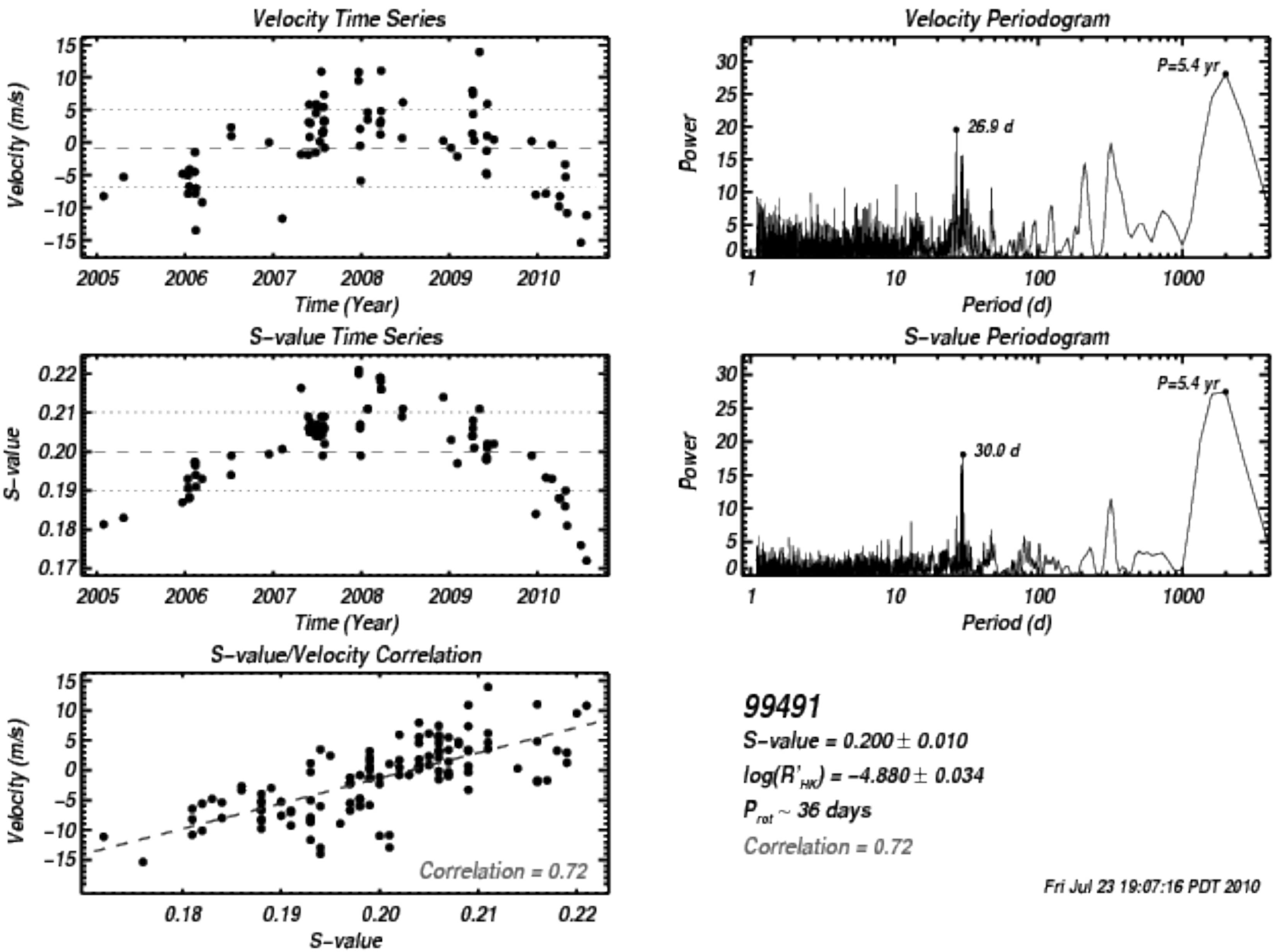
Rotational modulation of photospheric magnetic fields



Magnetograms throughout the solar cycle



Stellar Activity

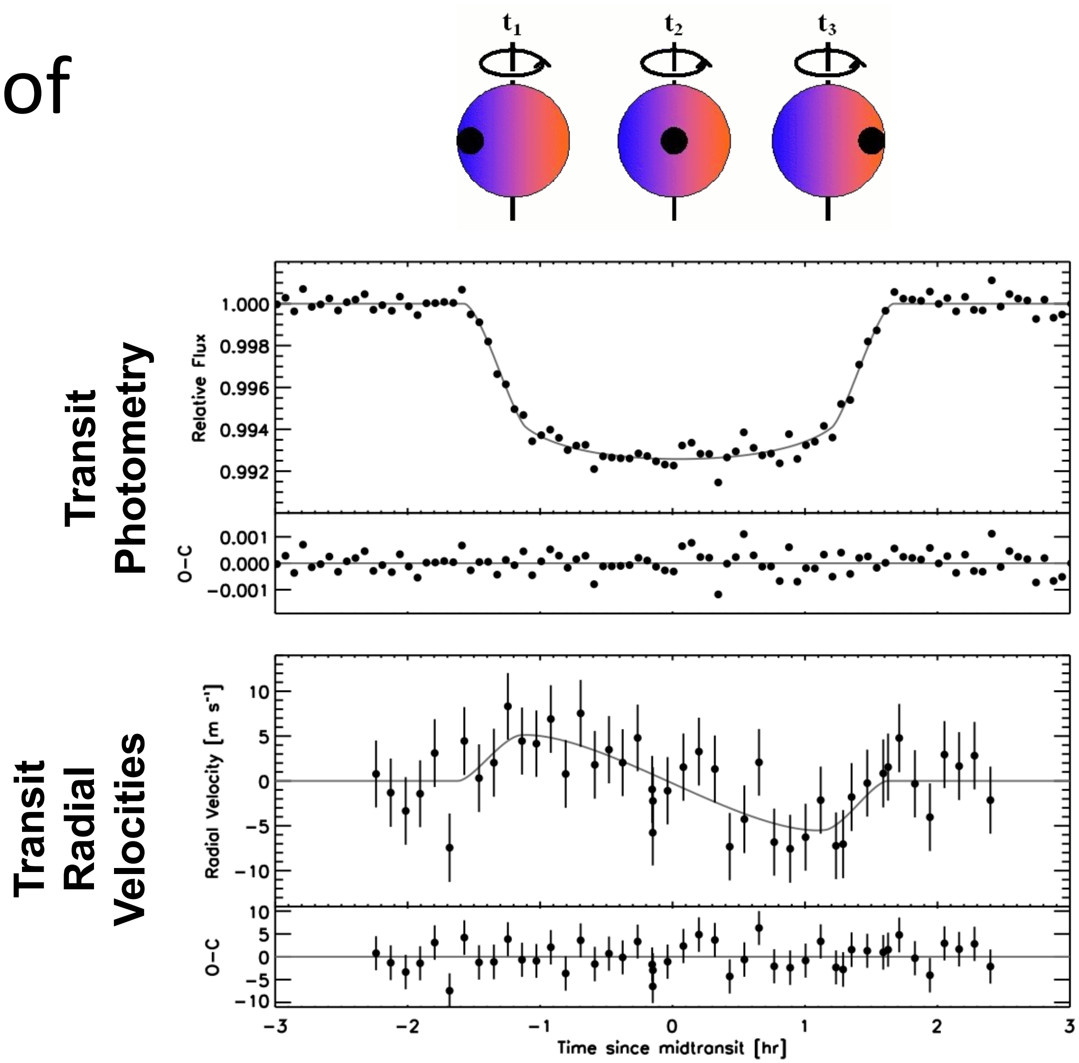


Ideal Spectral Types for RV?

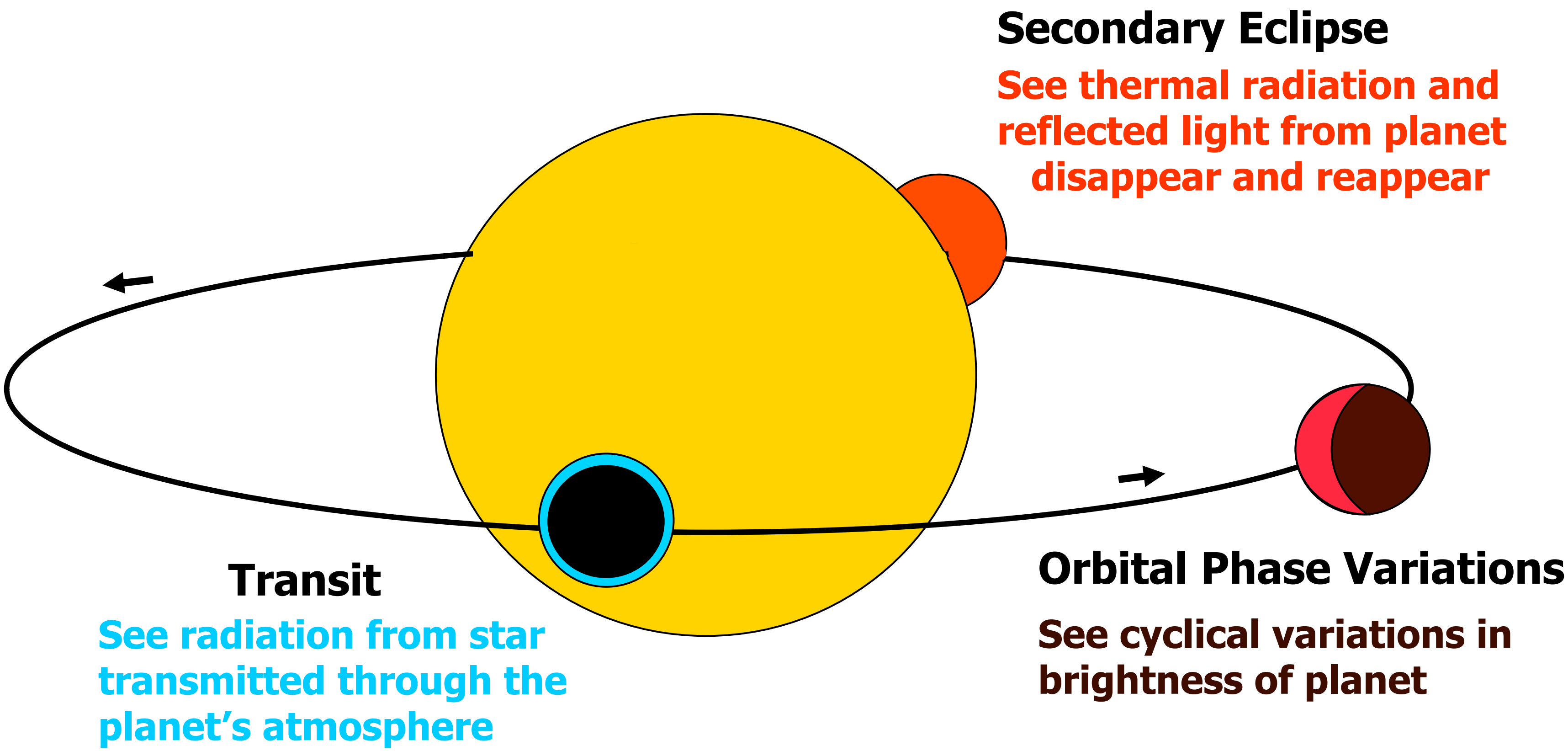
- Iodine/ThAr Doppler surveys cover F8 – M3
  - Earlier spectral types: broadened, sparse lines
  - Later spectral types: too faint
  - Sweet spot: late G/early K –
    minimum of activity and acoustic modes
- EDI & IR Doppler survey mid M-dwarfs

Rossiter-McLaughlin Measurements

Probe alignment of stellar spin and planetary orbital plane

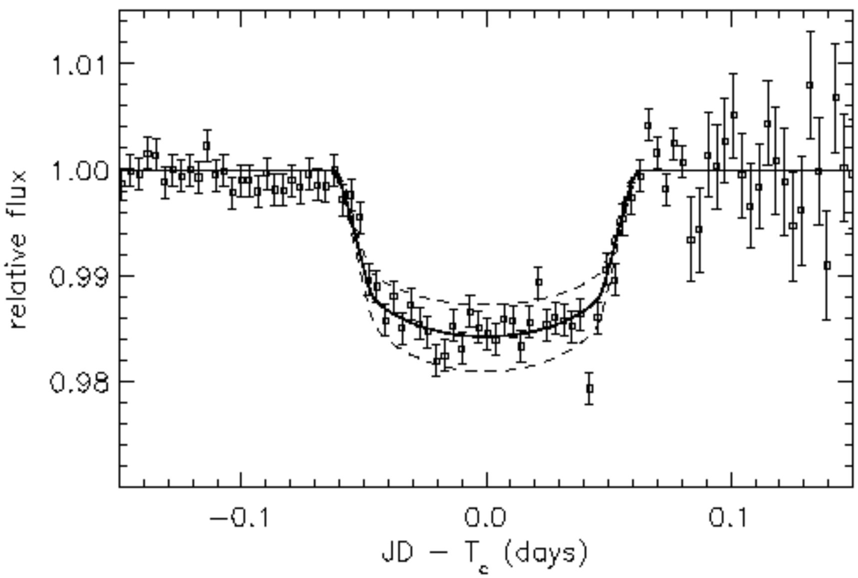


Transiting Extrasolar Planets

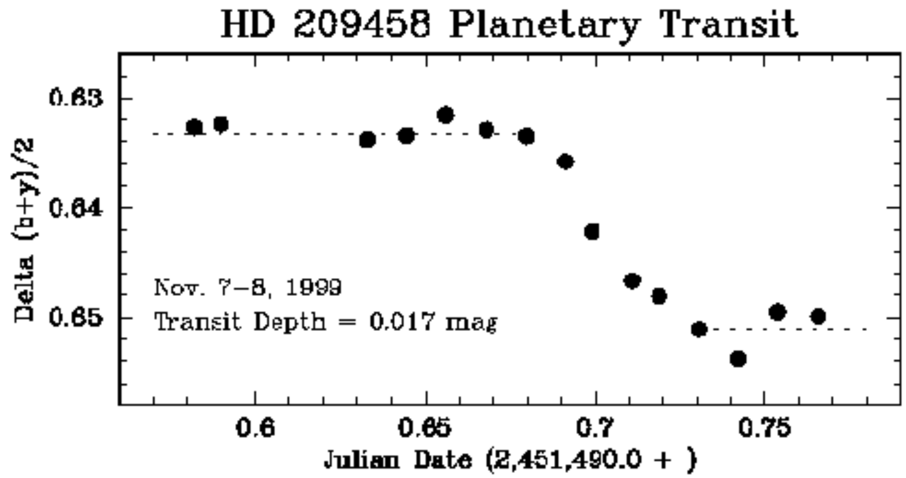


Slide courtesy H. Knutson

HD 209458 (1999) – the first transiting planet



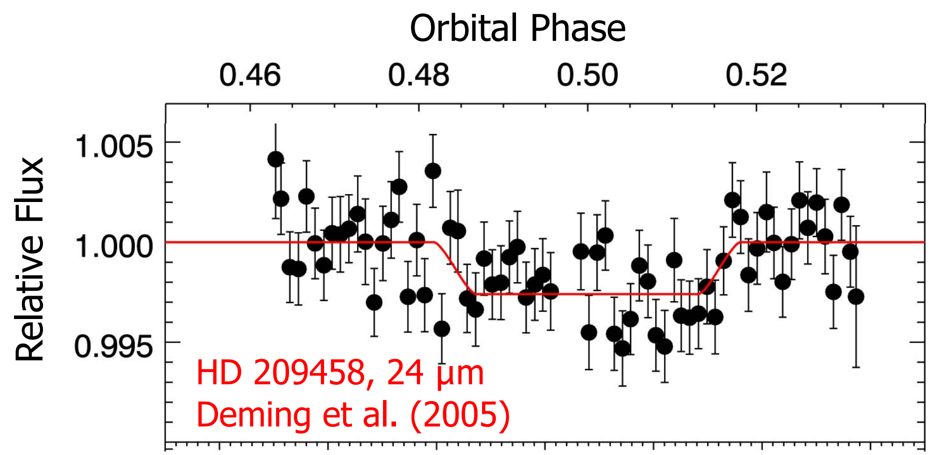
Charbonneau et al. (1999)



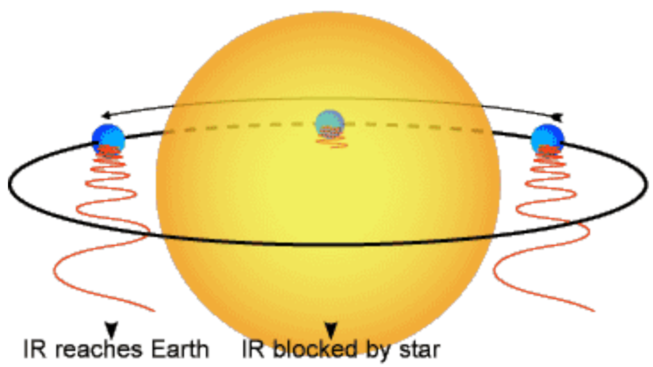
Henry et al. (1999)

Mass (Doppler) / Radius^3 (Transit) -> Density!

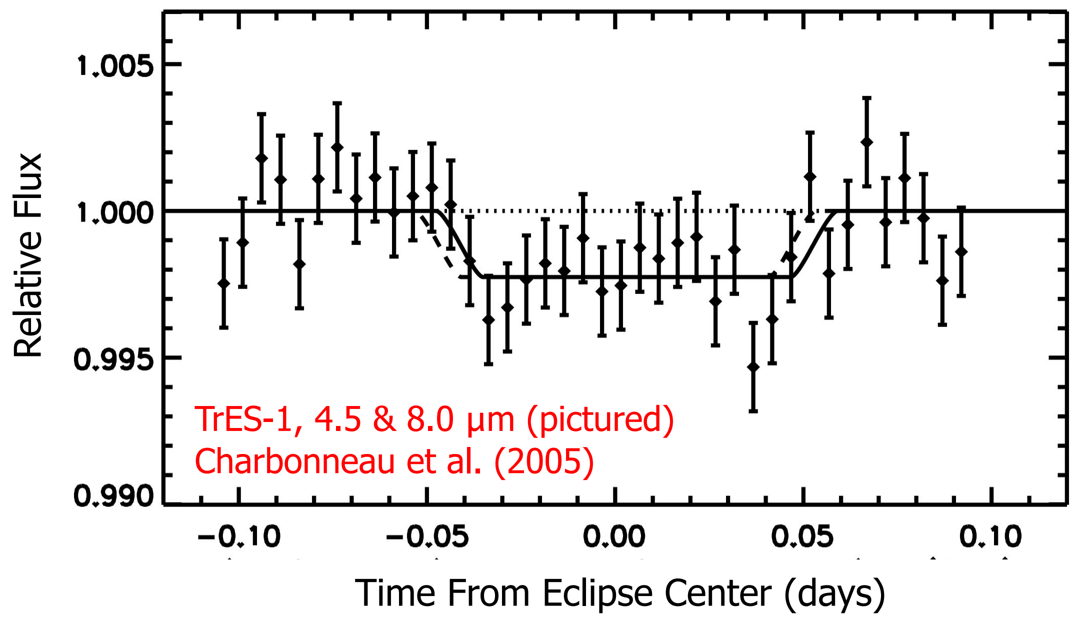
2005: First Detection of Light From An Extrasolar Planet



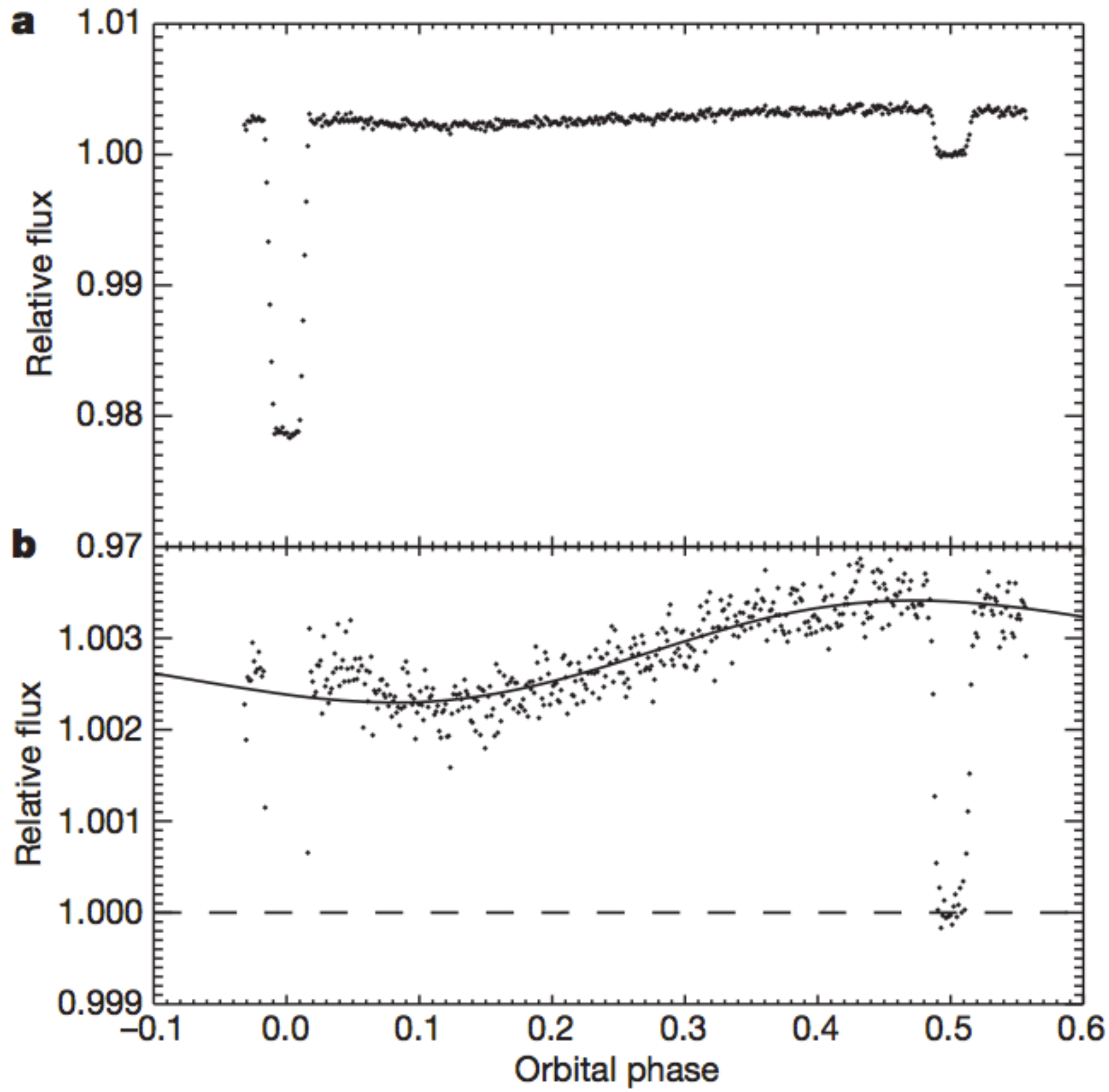
Can measure the planet's emitted flux without the need to spatially resolve the planet's light separate from that of the star.



Observe the decrease in light as the planet disappears behind the star and then reappears.

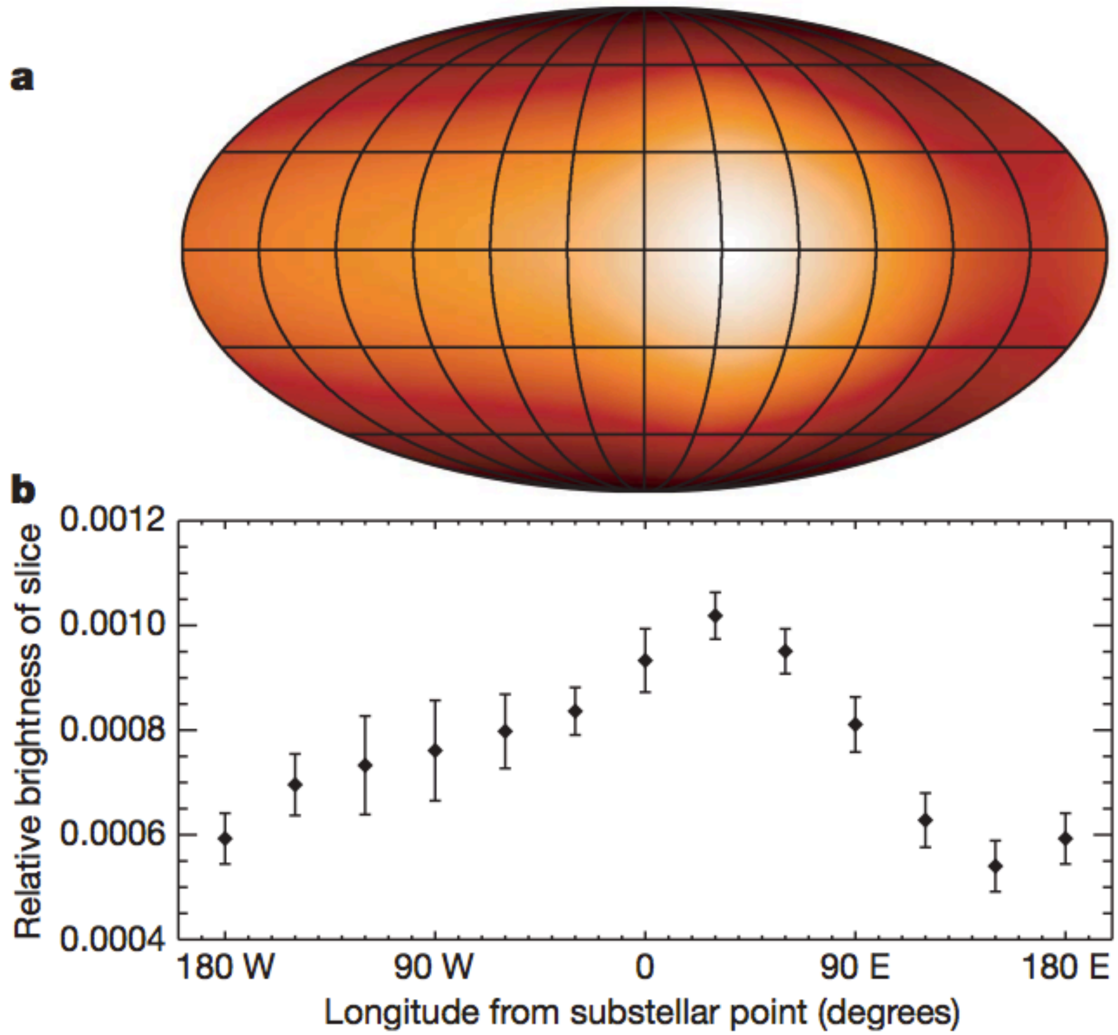


Transiting planets – phase curves



Knutson et al. (2007)

Transiting planets – phase curves



Knutson et al. (2007)

Secondary Eclipse Observations of HD 189733b Constrain Atmospheric Structure, Composition

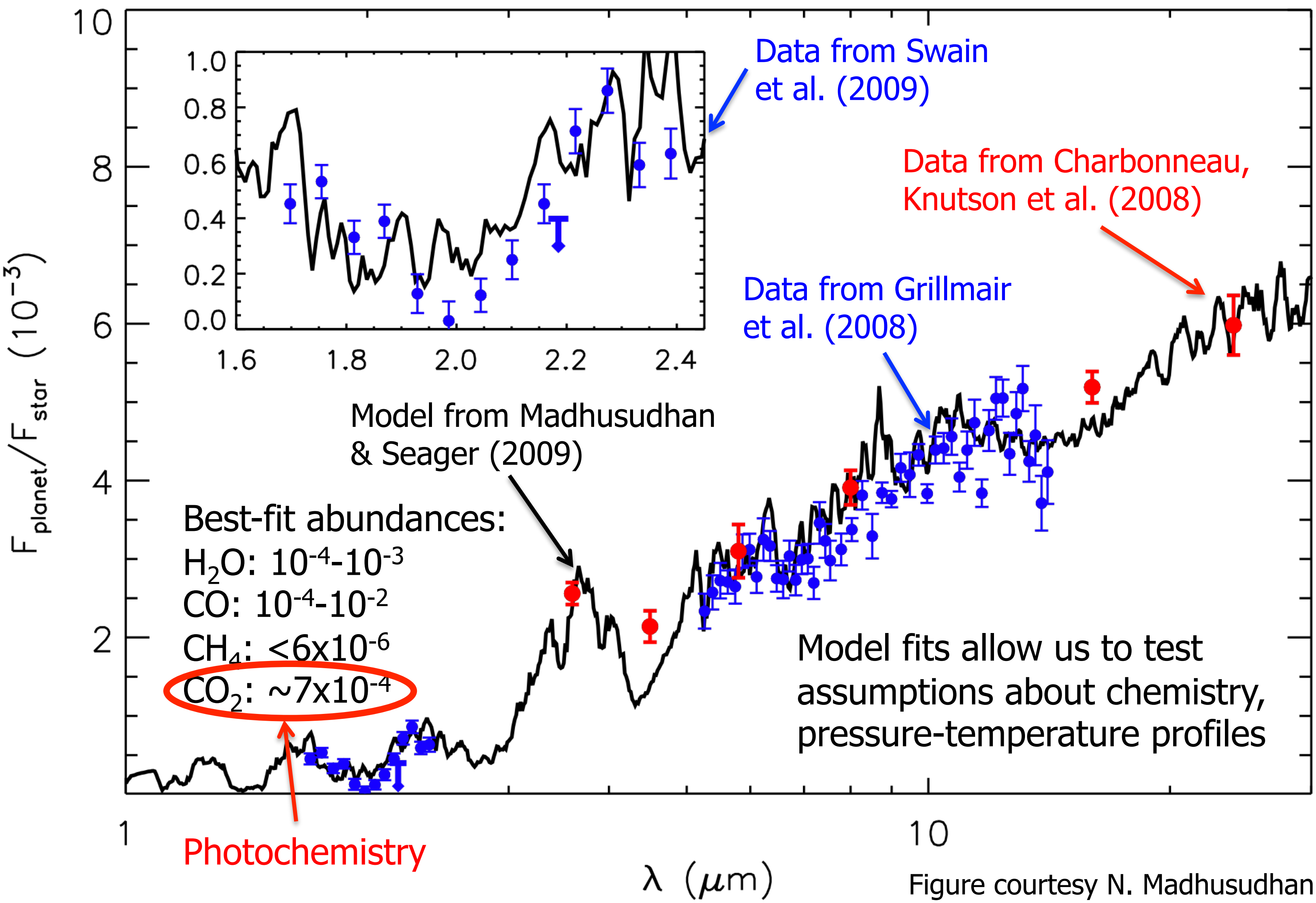
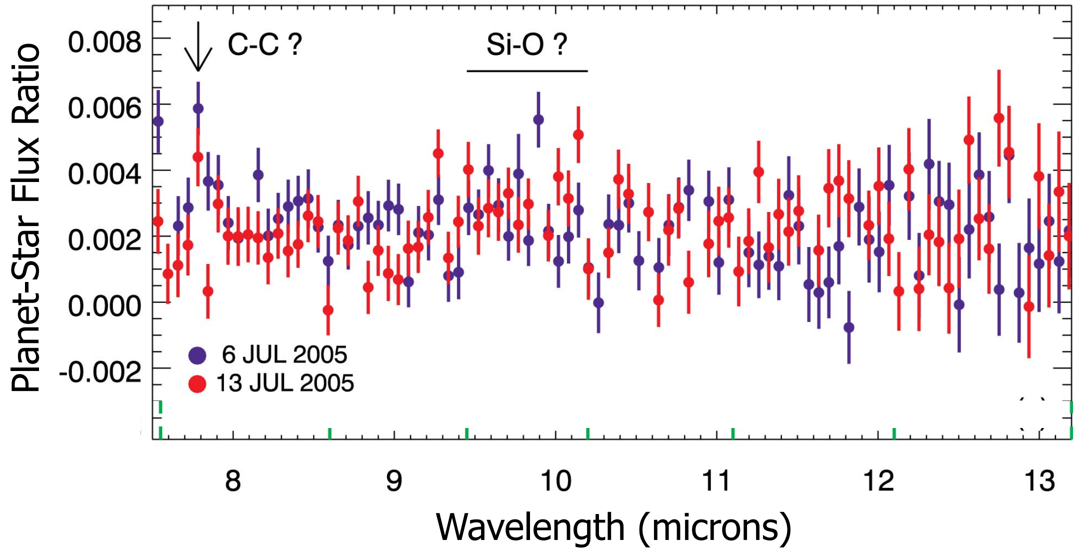


Figure courtesy N. Madhusudhan

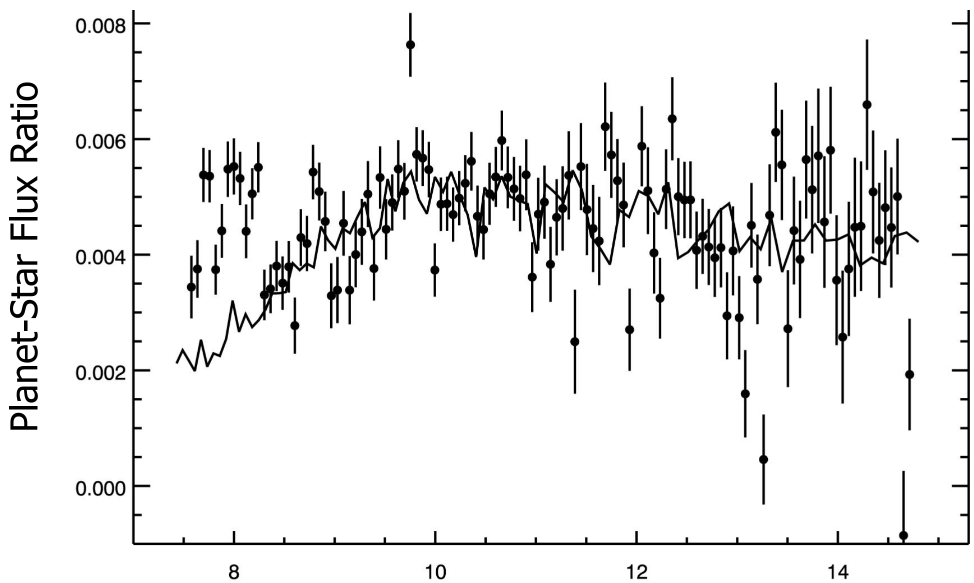
2007: First Spectrum for an Extrasolar Planet

IRS observations of two planets during secondary eclipse:

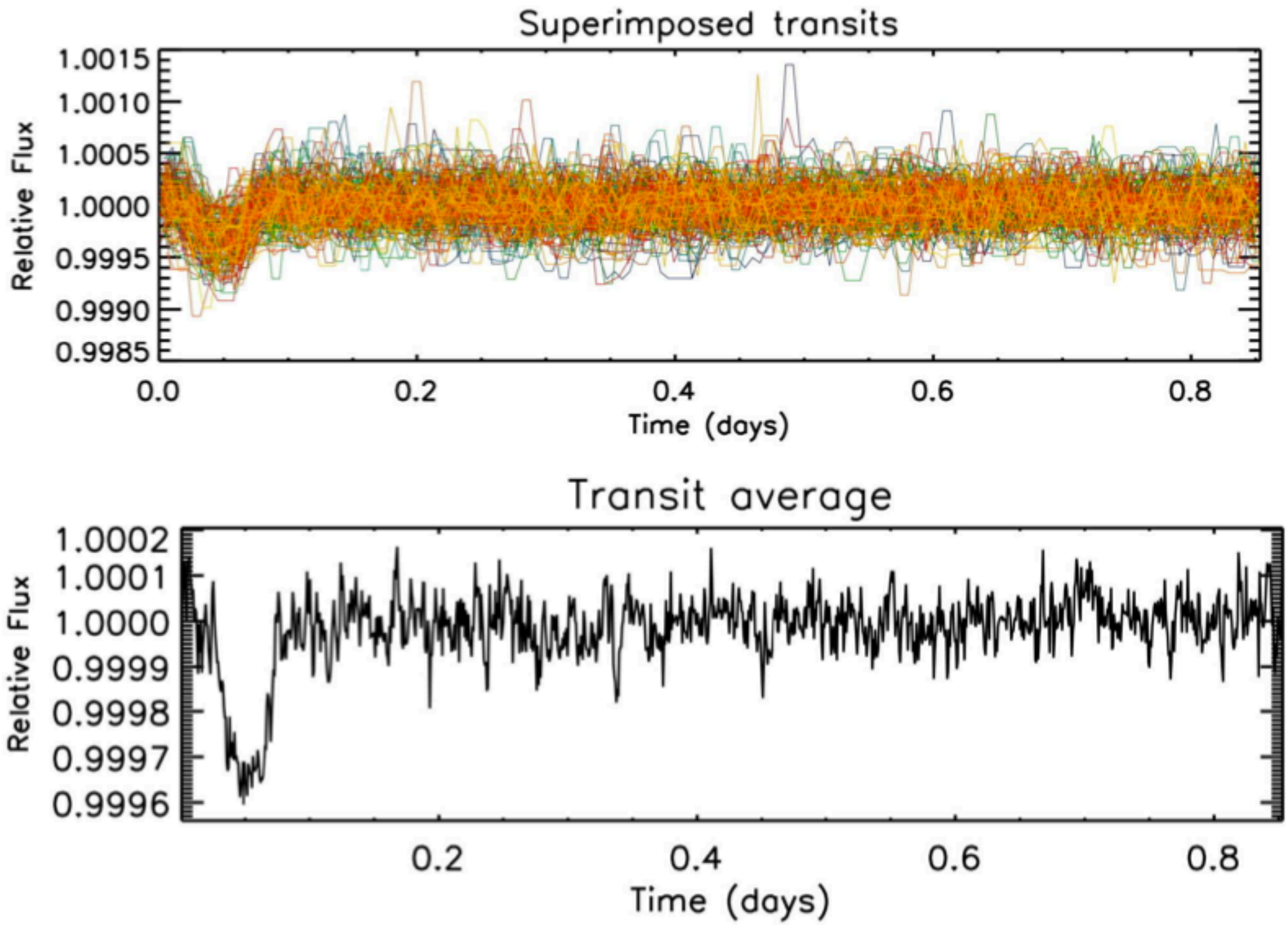
HD 209458b
Richardson et al. (2007)



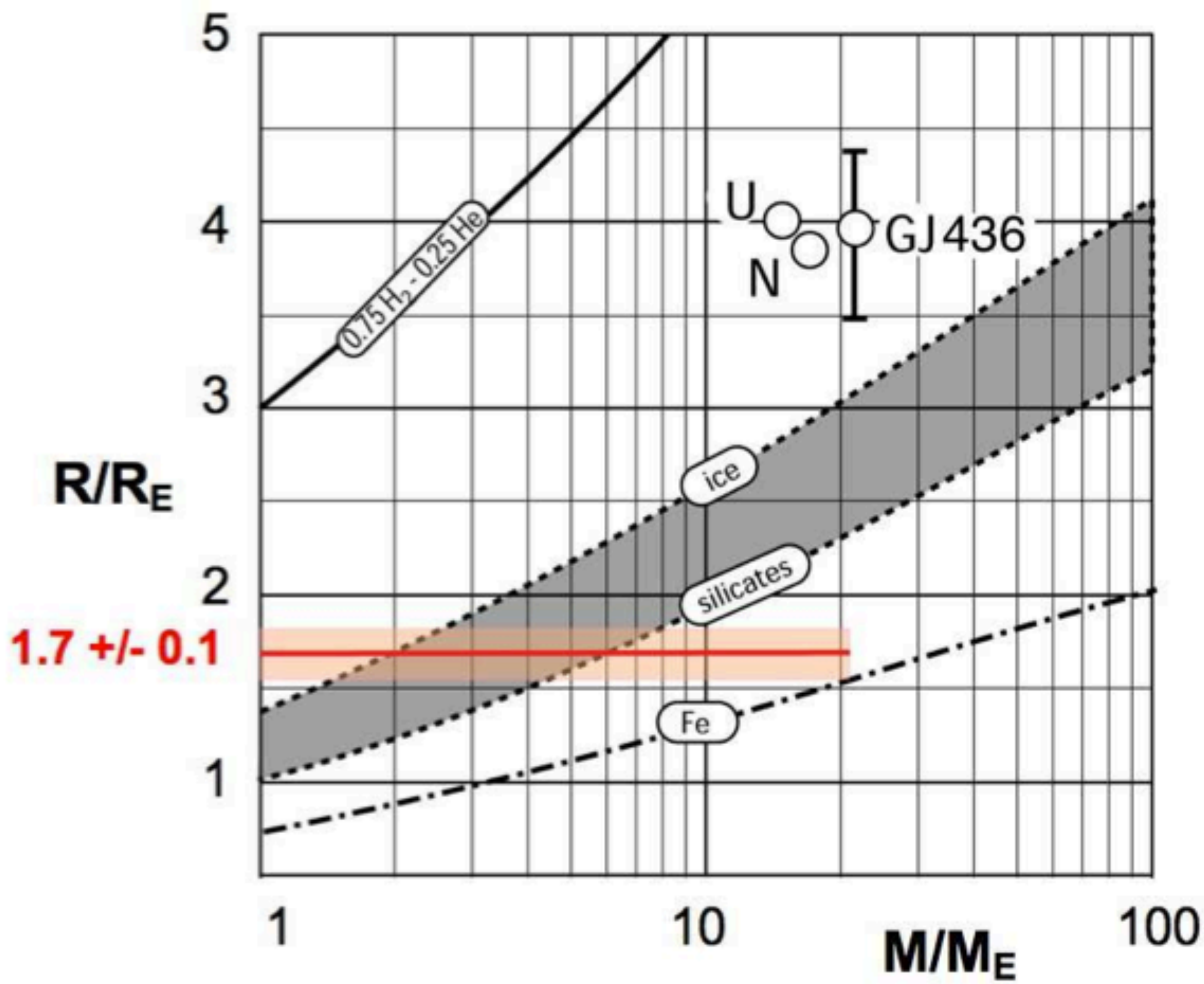
HD 189733b
Grillmair et al. (2007)



Neptunes and Super-Earths – Corot-7b

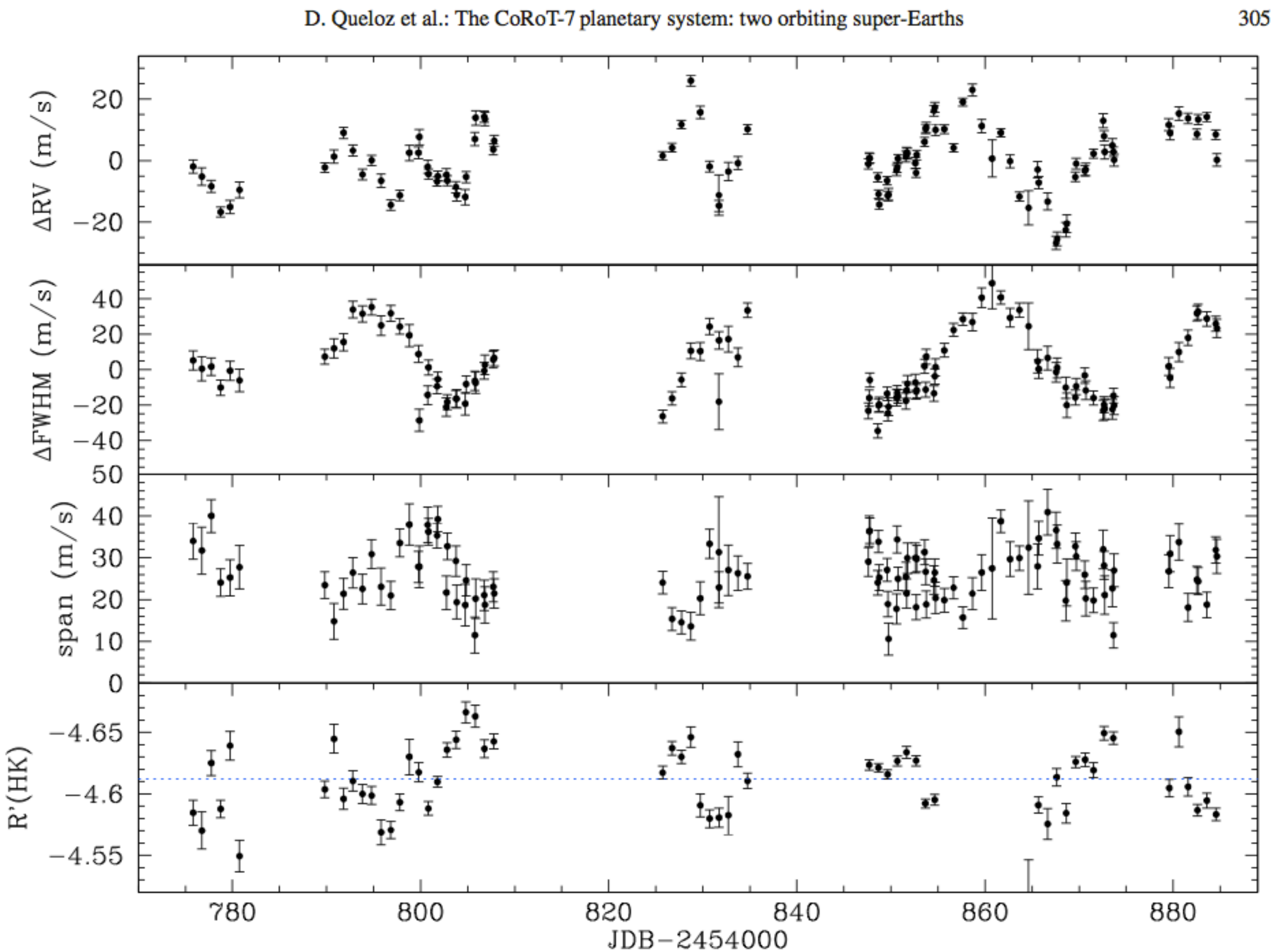


Corot-7b

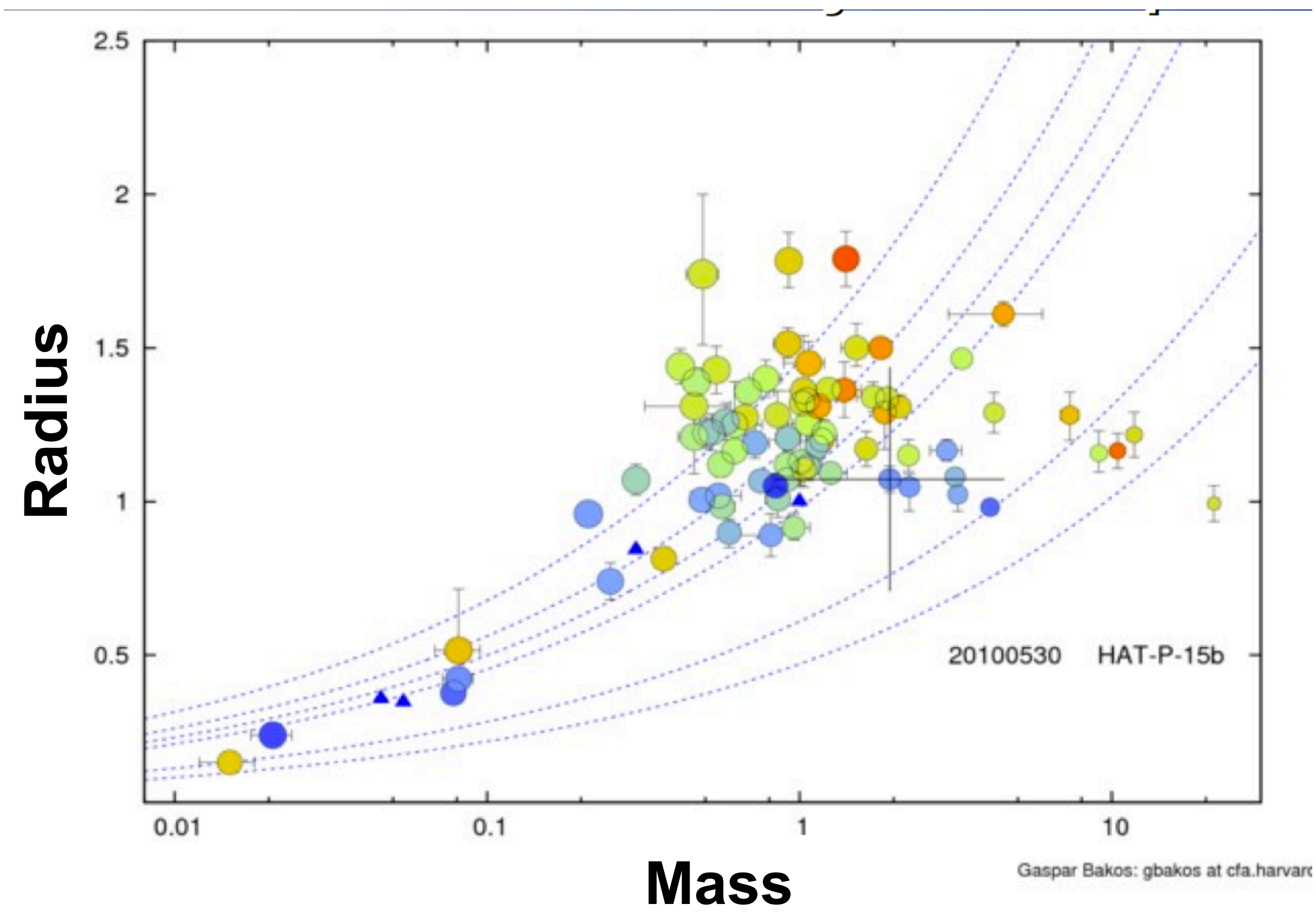


5
4
3
2
1
1.7 +/- 0.1
R/R_E
1
10
100
M/M_E
0.75 H2 - 0.25 He
U
N
GJ 436
ice
silicates
Fe

The challenge – stellar activity



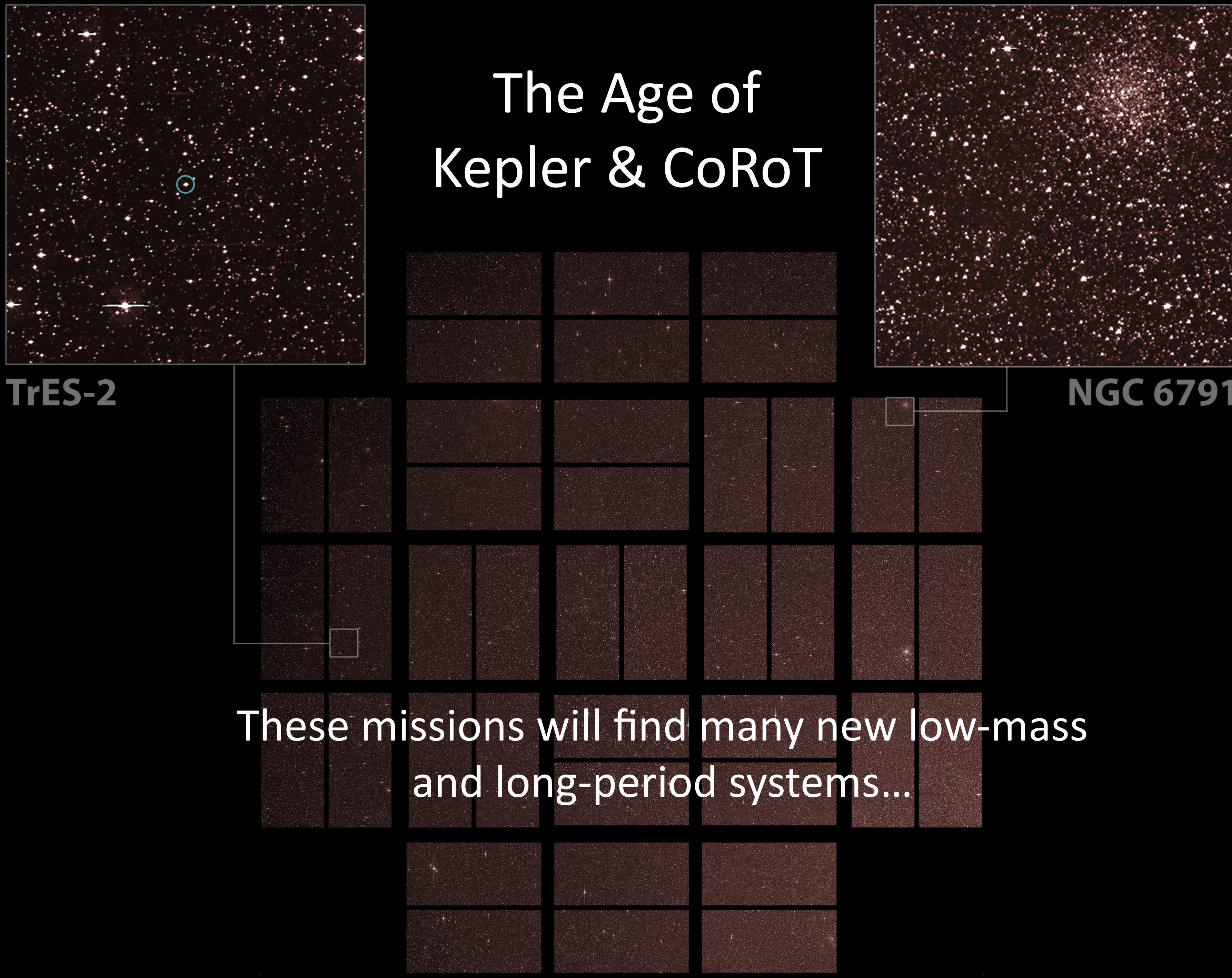
70+ Transiting Planets



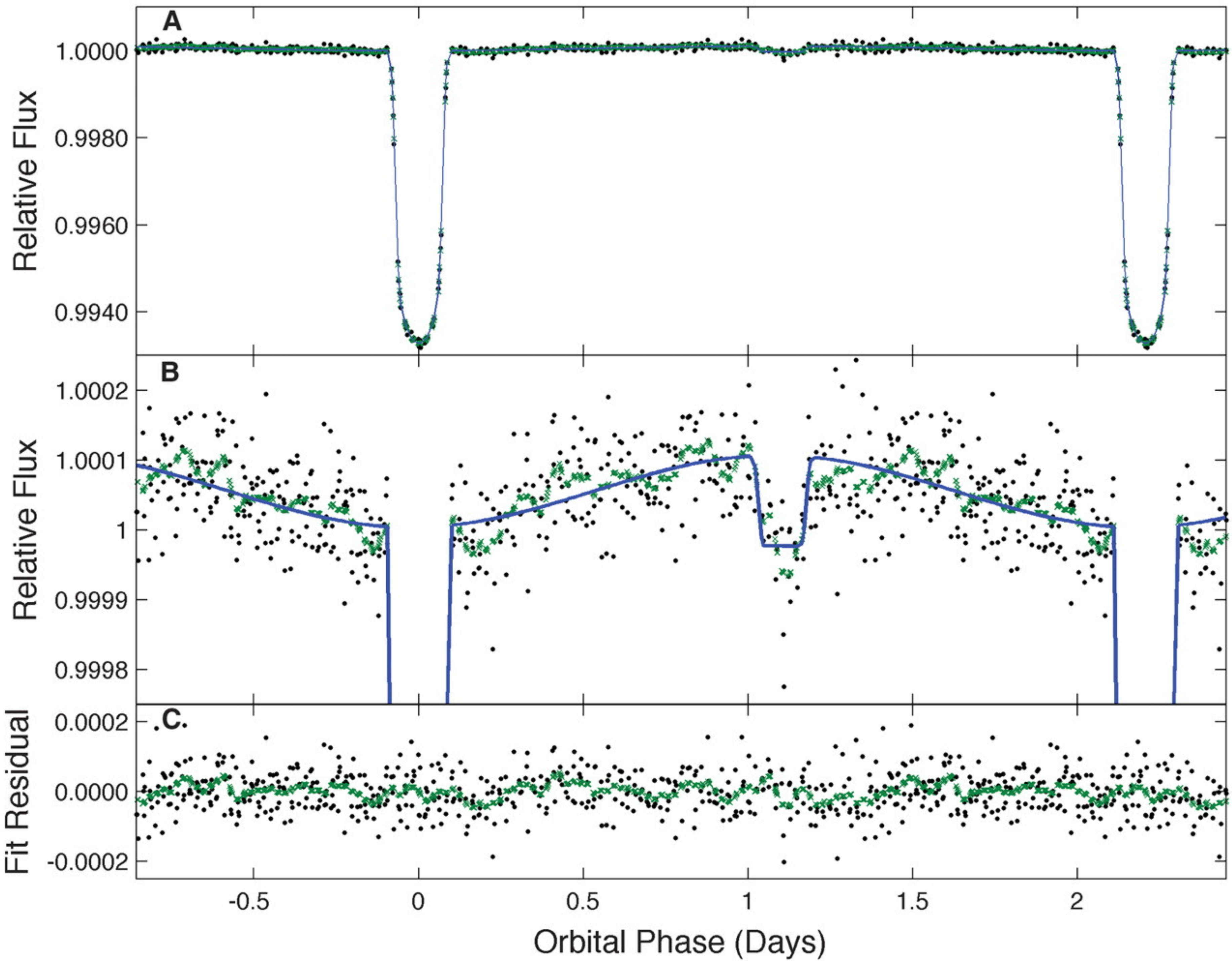
Transit surveys → statistical tests

Figure: Gaspar Bakos

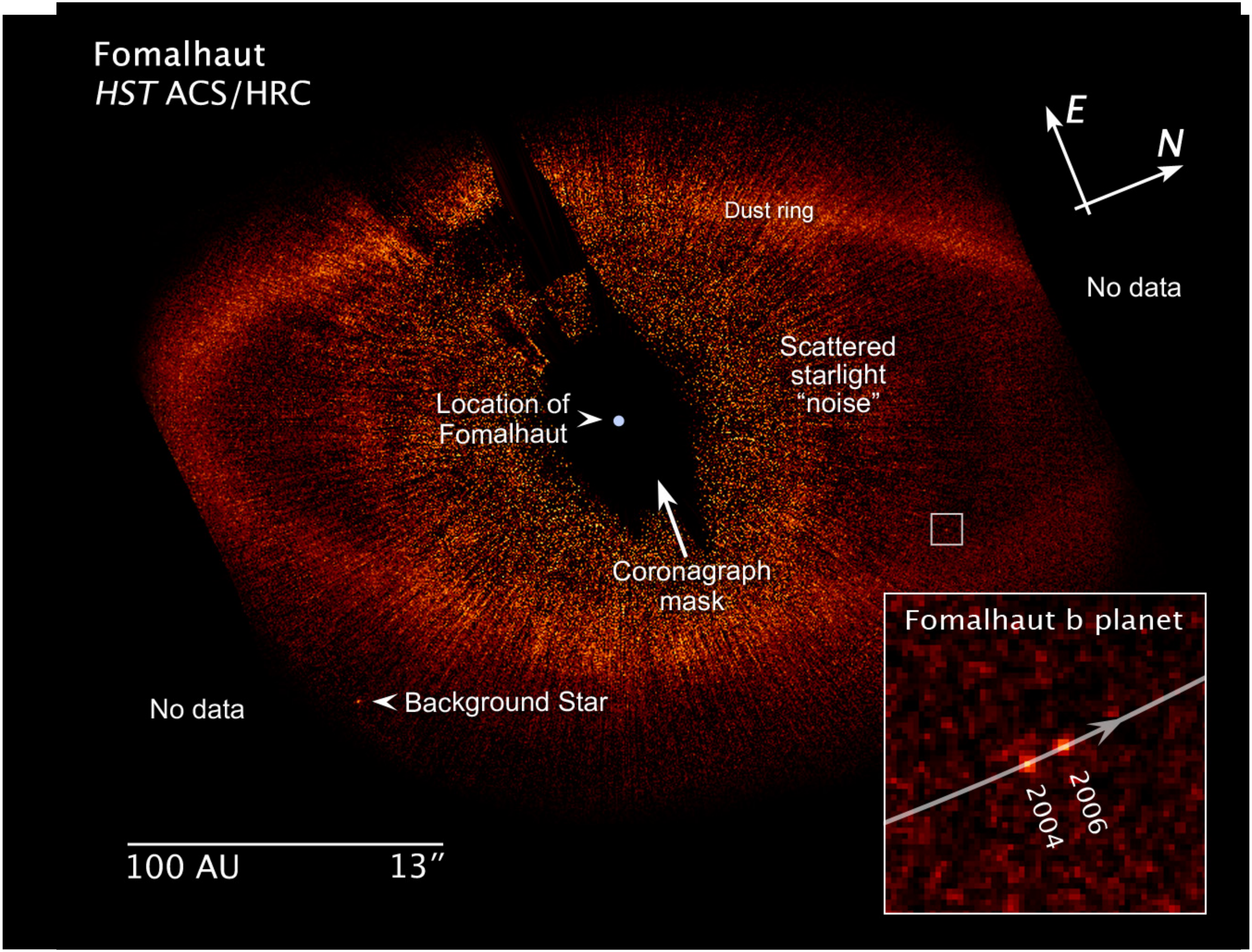
The Age of Kepler & CoRoT



These missions will find many new low-mass and long-period systems...



A
B
C
Relative Flux
Relative Flux
Fit Residual
1.0000
0.9980
0.9960
0.9940
1.0002
1.0001
1
0.9999
0.9998
0.0002
0.0000
-0.0002
-0.5
0
0.5
1
1.5
2
Orbital Phase (Days)


Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2004
2006
No data
Background Star
100 AU
13″

Gravitational Microlensing

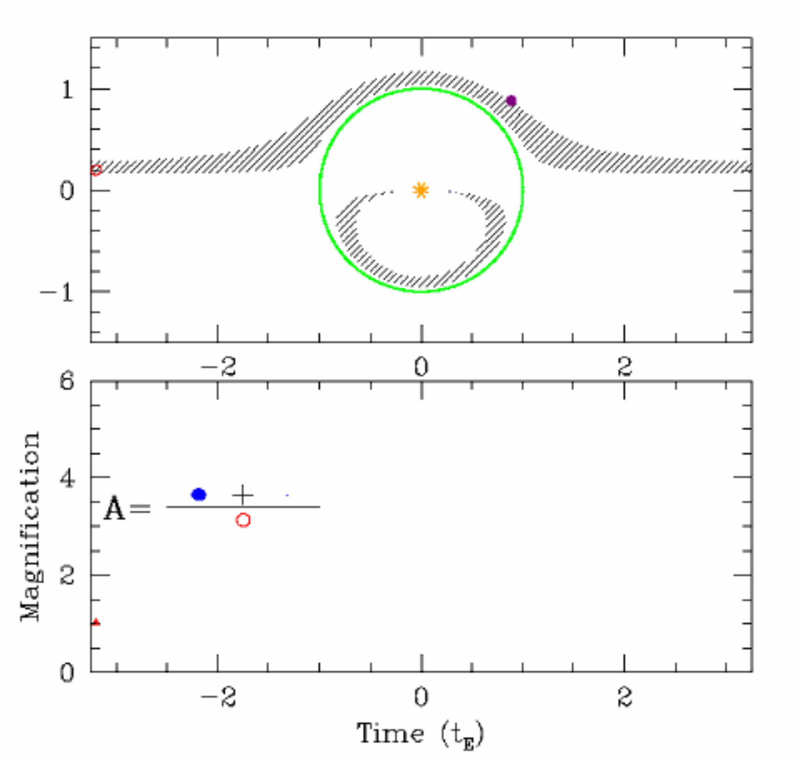
~10 planets detected

Advantages:

- probes low-mass near ice line
- Homogeneous occurrence statistics
- sensitivity down to (nearly) Earth mass

Disadvantages:

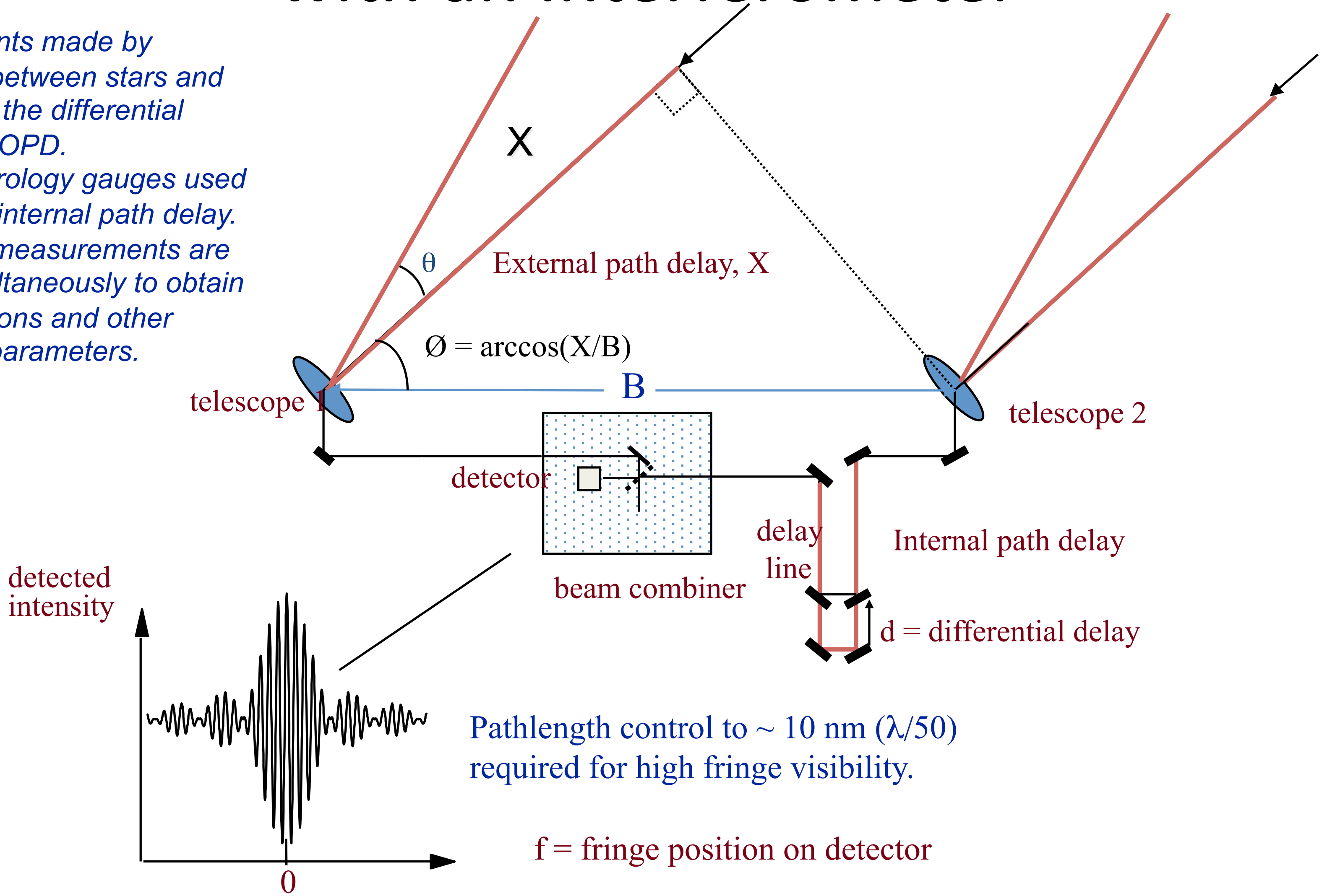
- only one event observed
- host star poorly characterized
- no meaningful follow-up
- enormous observing effort



Animation: Scott Gaudi

Astrometric measurements with an Interferometer

- *Measurements made by "chopping" between stars and determining the differential delay, d, in OPD.*
- *Internal metrology gauges used to measure internal path delay.*
- *Many such measurements are solved simultaneously to obtain stellar positions and other instrument parameters.*

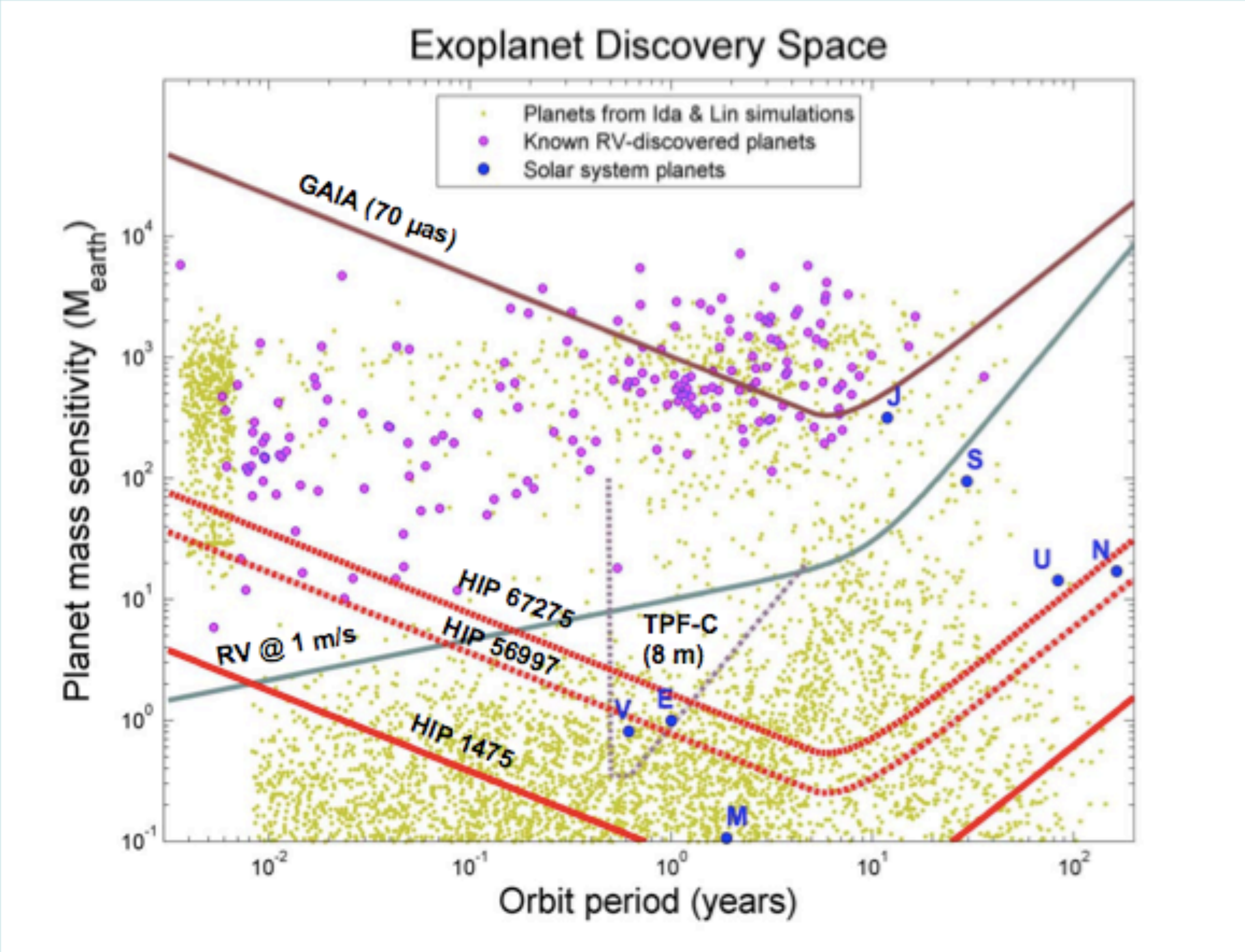


Pathlength control to ~ 10 nm (λ/50) required for high fringe visibility.

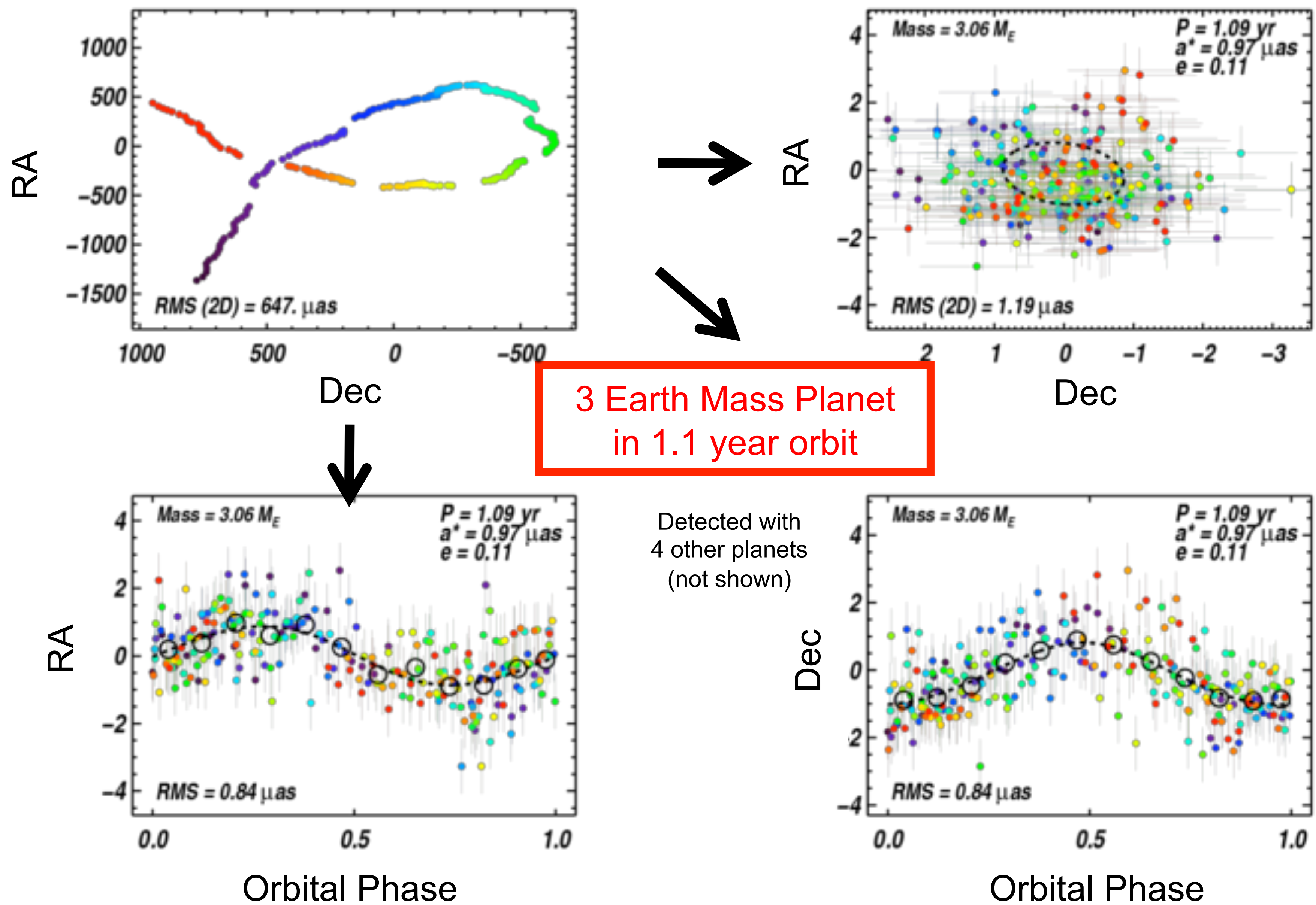
f = fringe position on detector

- The peak of the interference pattern occurs at zero OPD to star

Earth Analog Survey



Double Blind Example "Detection"



Outline

A Brief History of Exoplanet Science, a Personal View

- What we know and how we know it

Recent Examples of Host Star Physics Playing a Key Role in Exoplanet Science

- How did hot Jupiters migrate from beyond the ice line?
- Why do some hot Jupiters have inverted atmospheres?

How do hot Jupiters migrate from the Ice Line?

- Inspiral due to tidal interactions with protoplanetary disk?
- Planet-planet scattering?
- Kozai Mechanism with distant third body (star or planet)?

HOT STARS WITH HOT JUPITERS HAVE HIGH OBLIQUITIES

JOSHUA N. WINN[1], DANIEL FABRYCKY[2,3], SIMON ALBRECHT[1], JOHN ASHER JOHNSON[4]

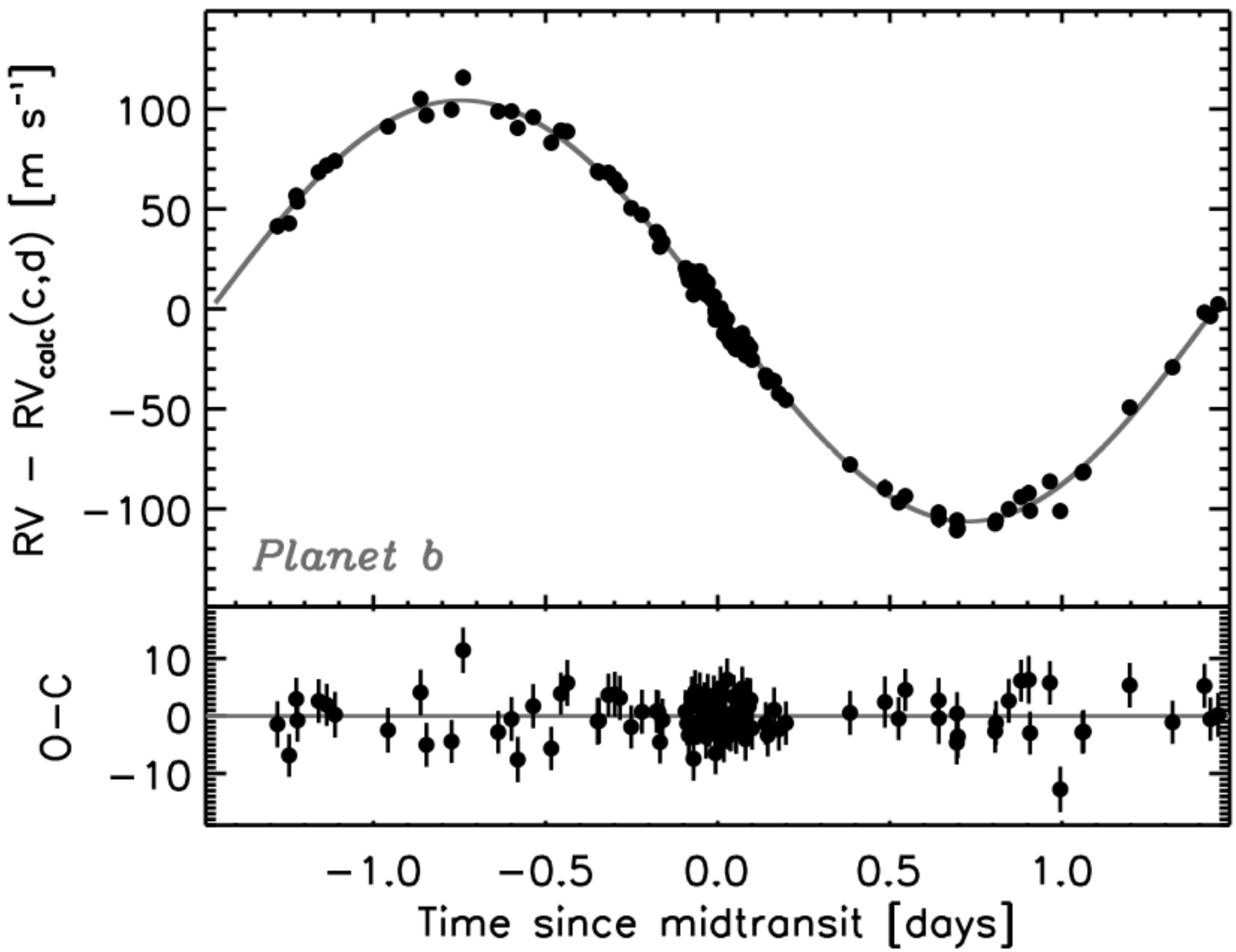
Submitted to ApJ Letters, May 3, 2010

ABSTRACT

We show that stars with transiting planets for which the stellar obliquity is large are preferentially hot ($T_{\rm eff} > 6250$ K). This could explain why small obliquities were observed in the earliest measurements, which focused on relatively cool stars drawn from Doppler surveys, as opposed to hotter stars that emerged later from transit surveys. The observed trend could be due to differences in planet formation and migration around stars of varying mass. Alternatively, we speculate that hot-Jupiter systems begin with a wide range of obliquities, but the photospheres of cool stars realign with the orbits due to tidal dissipation in their convective zones, while hot stars cannot realign because of their thinner convective zones. This in turn would suggest that hot Jupiters originate from few-body gravitational dynamics, and that disk migration plays at most a supporting role.

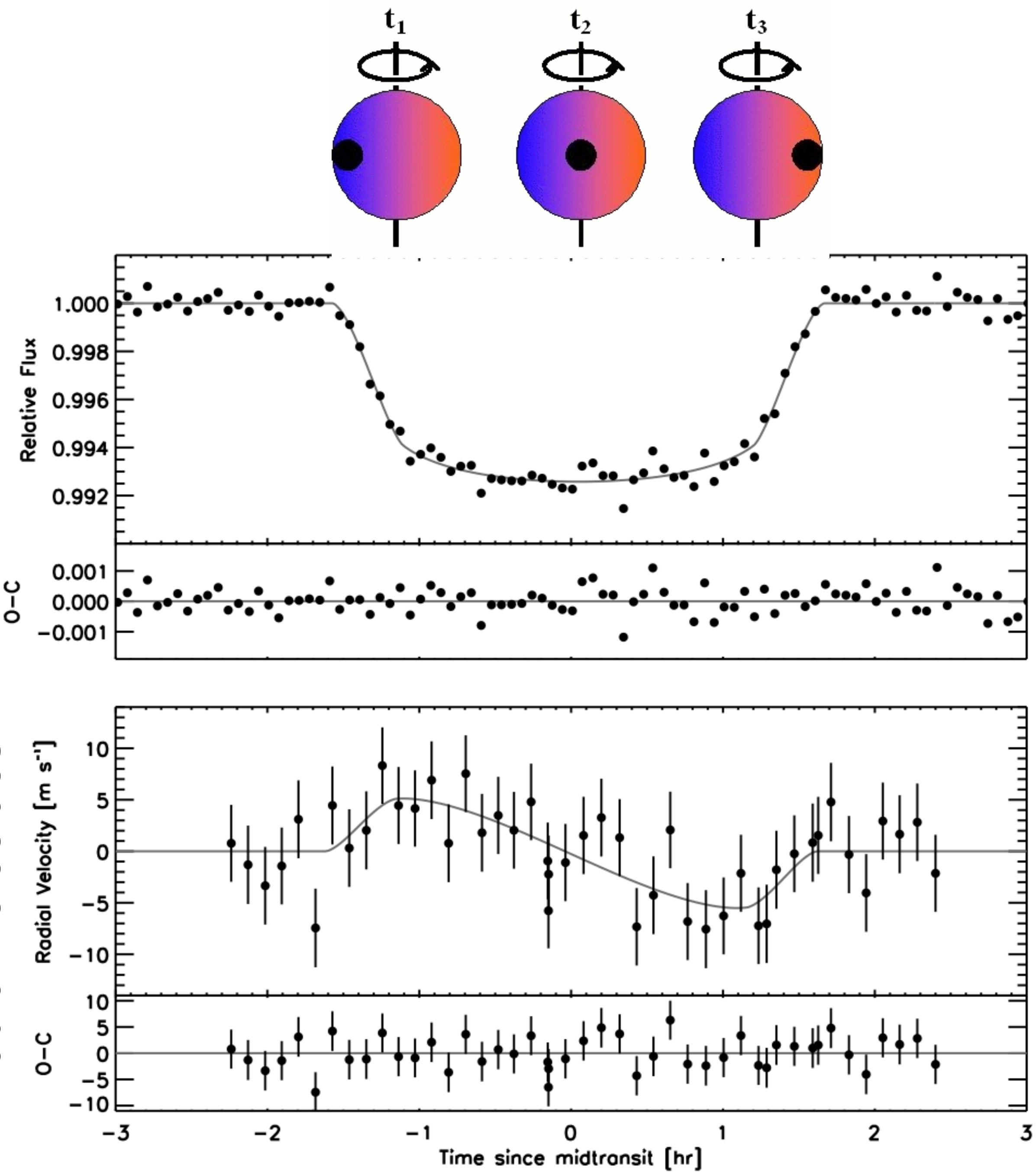
Subject headings: planetary systems — planets and satellites: formation — planet-star interactions — stars:

Rossiter-McLaughlin Measurements Probing Spin-Orbit Alignment



Transit Photometry

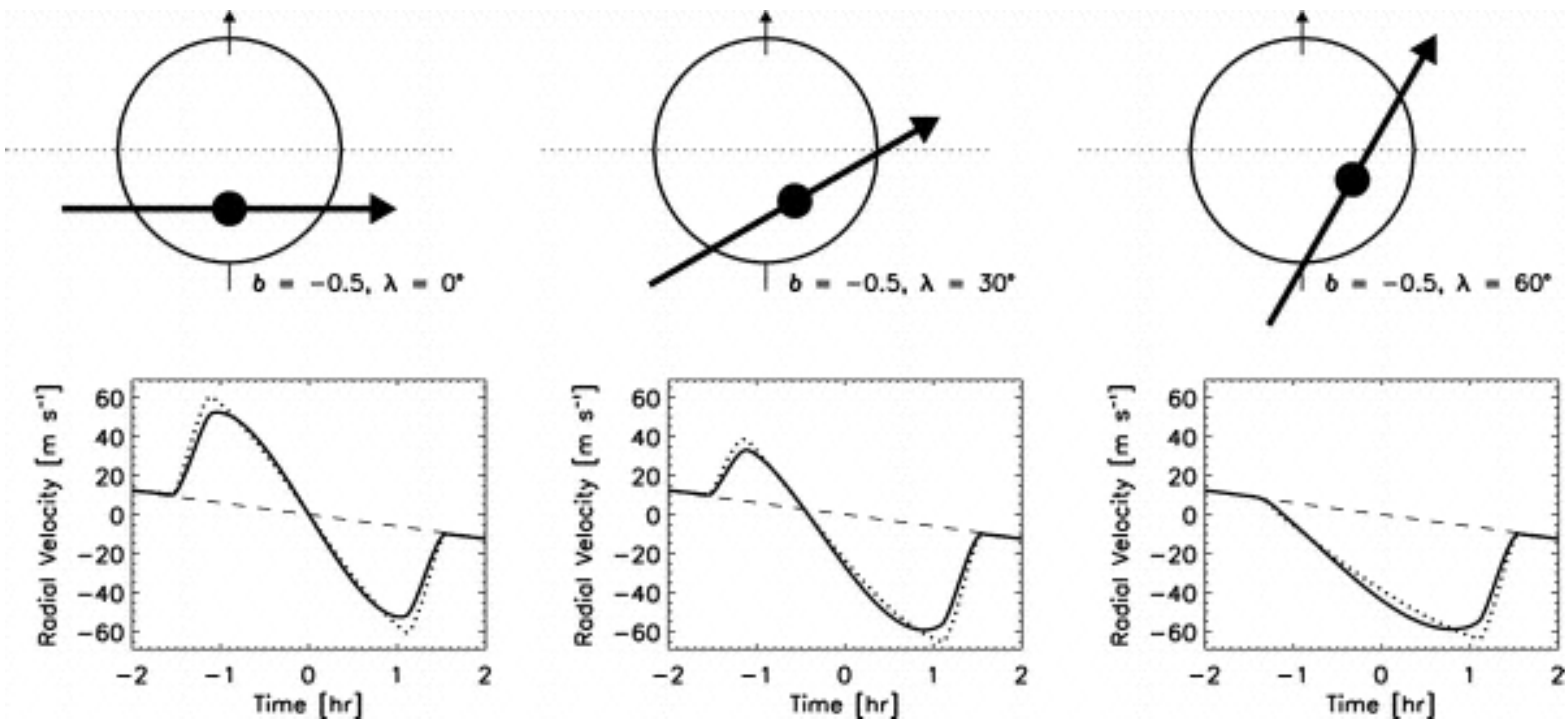
Transit Radial Velocities



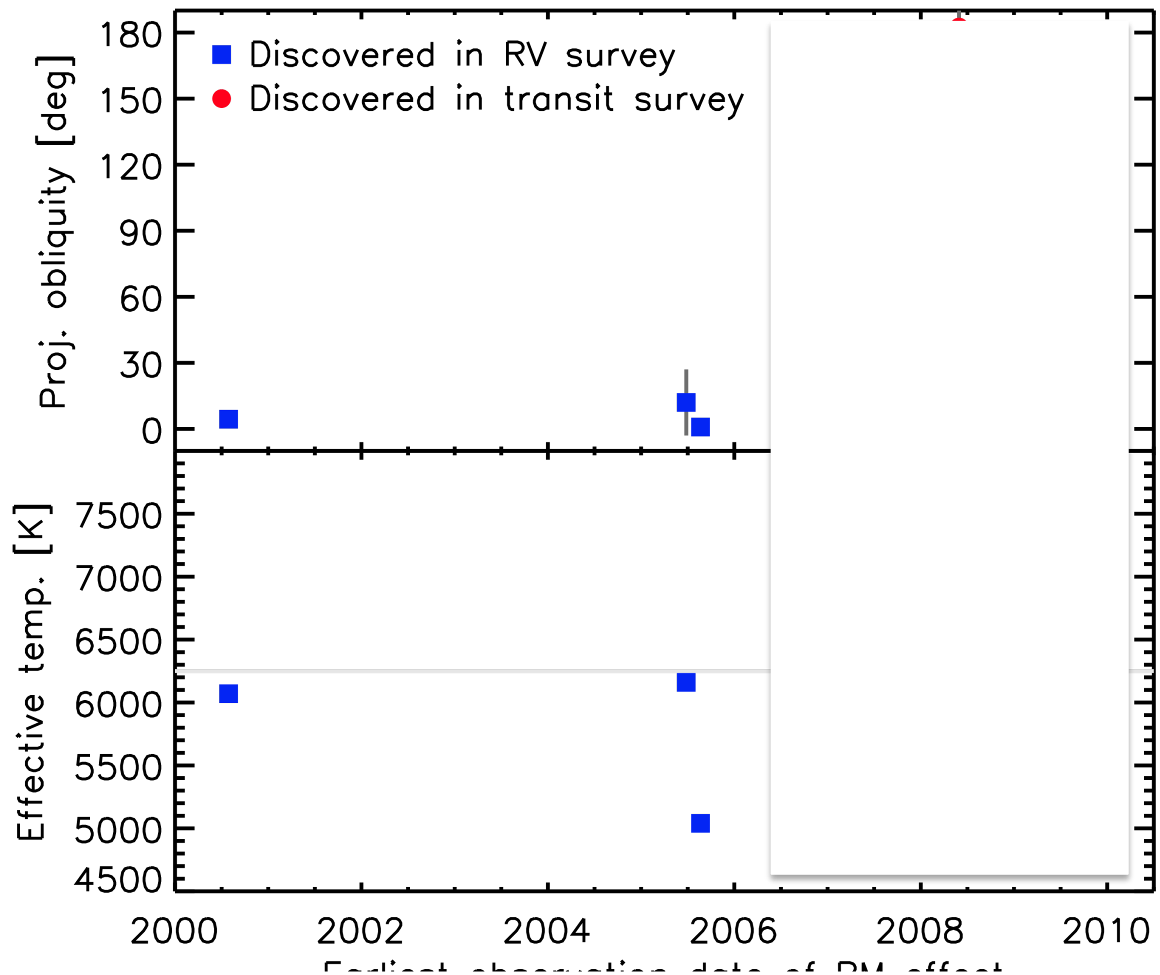
HAT-P-13b

Winn et al. (2010)

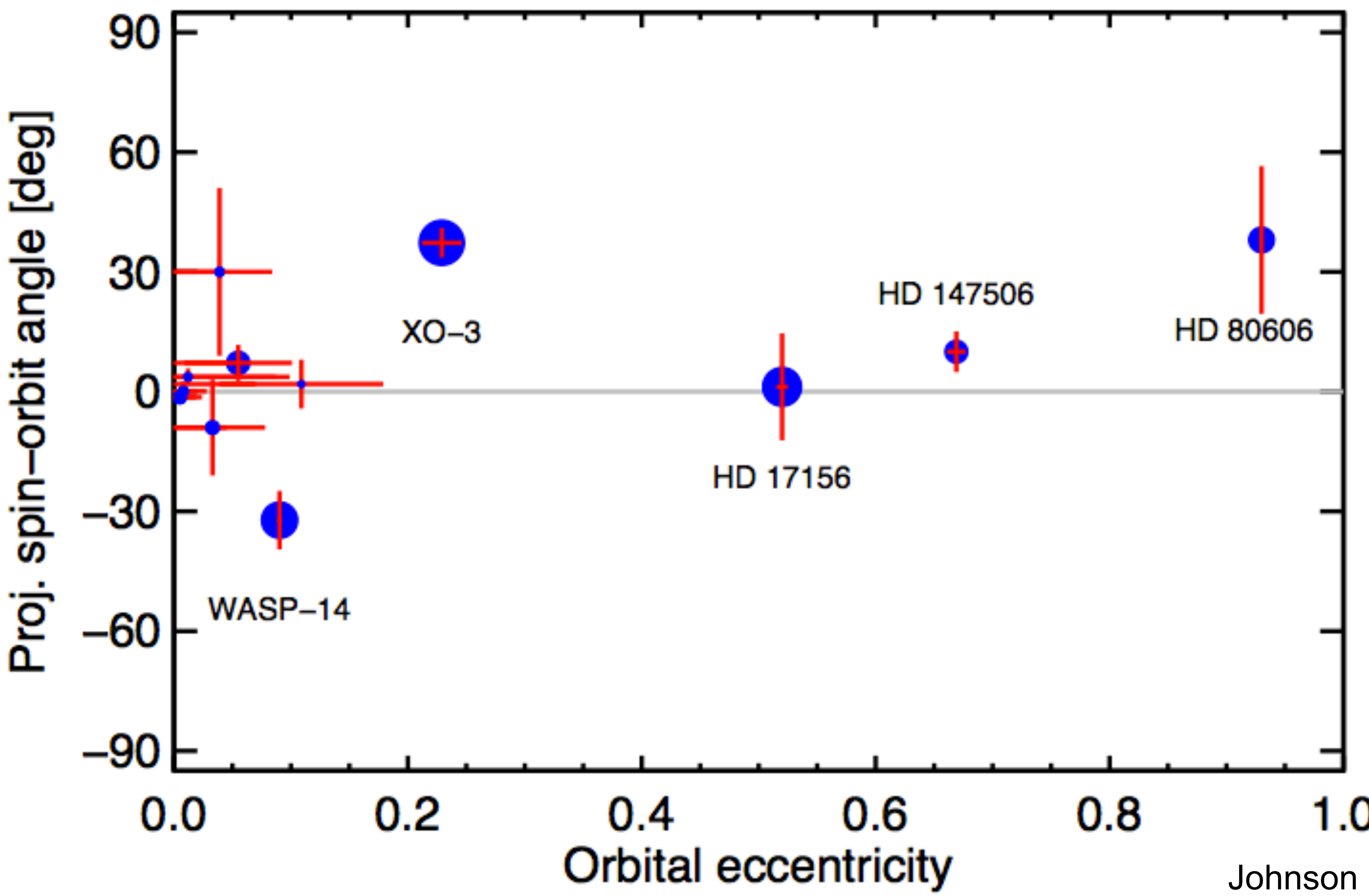
Projected Obliquity



Projected Obliquity Measurements

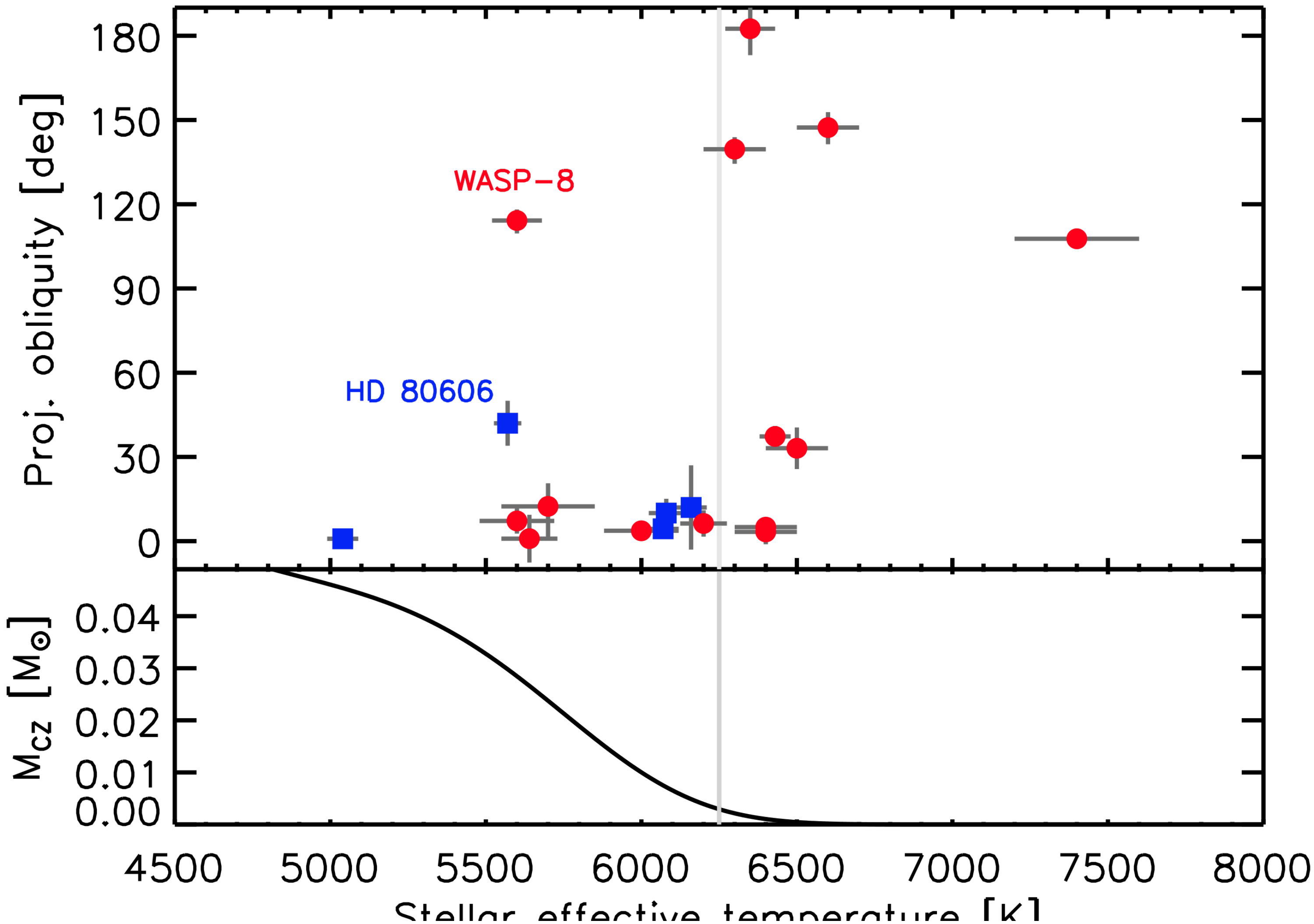


First Clues:
Misaligned planets are massive and eccentric



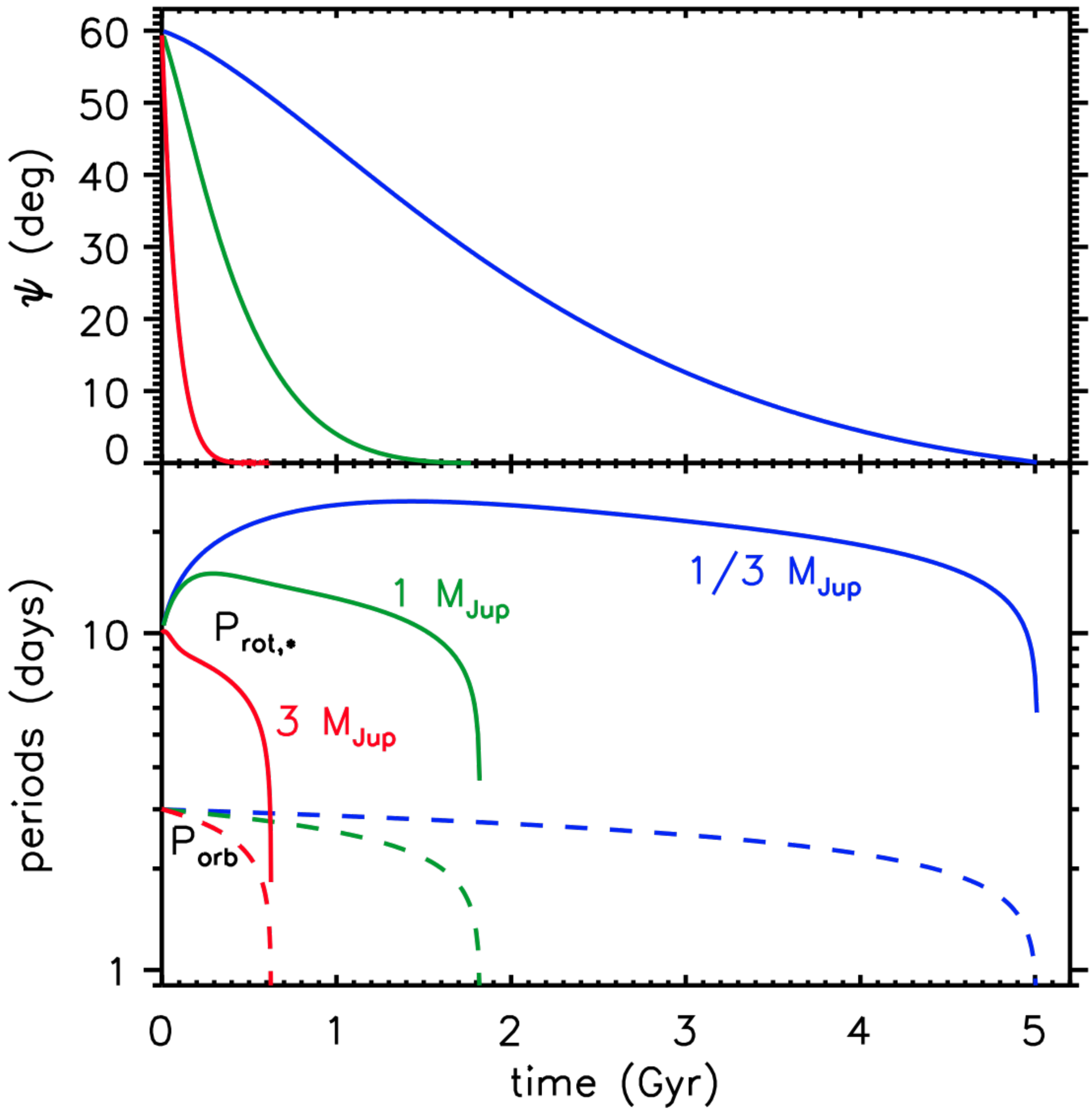
Johnson et al. (2008)

Projected Obliquity vs. Convective Zone Mass



Toy Model:

Orbital and obliquity evolution vs. time



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Why do some hot Jupiters have inverted atmospheres?

Active Stars Have Non-Inverted Planet Atmospheres

A CORRELATION BETWEEN STELLAR ACTIVITY AND HOT JUPITER EMISSION SPECTRA[1]

Heather A. Knutson[2,3], Andrew W. Howard[2,4], & Howard Isaacson[2]

Draft version July 12, 2010

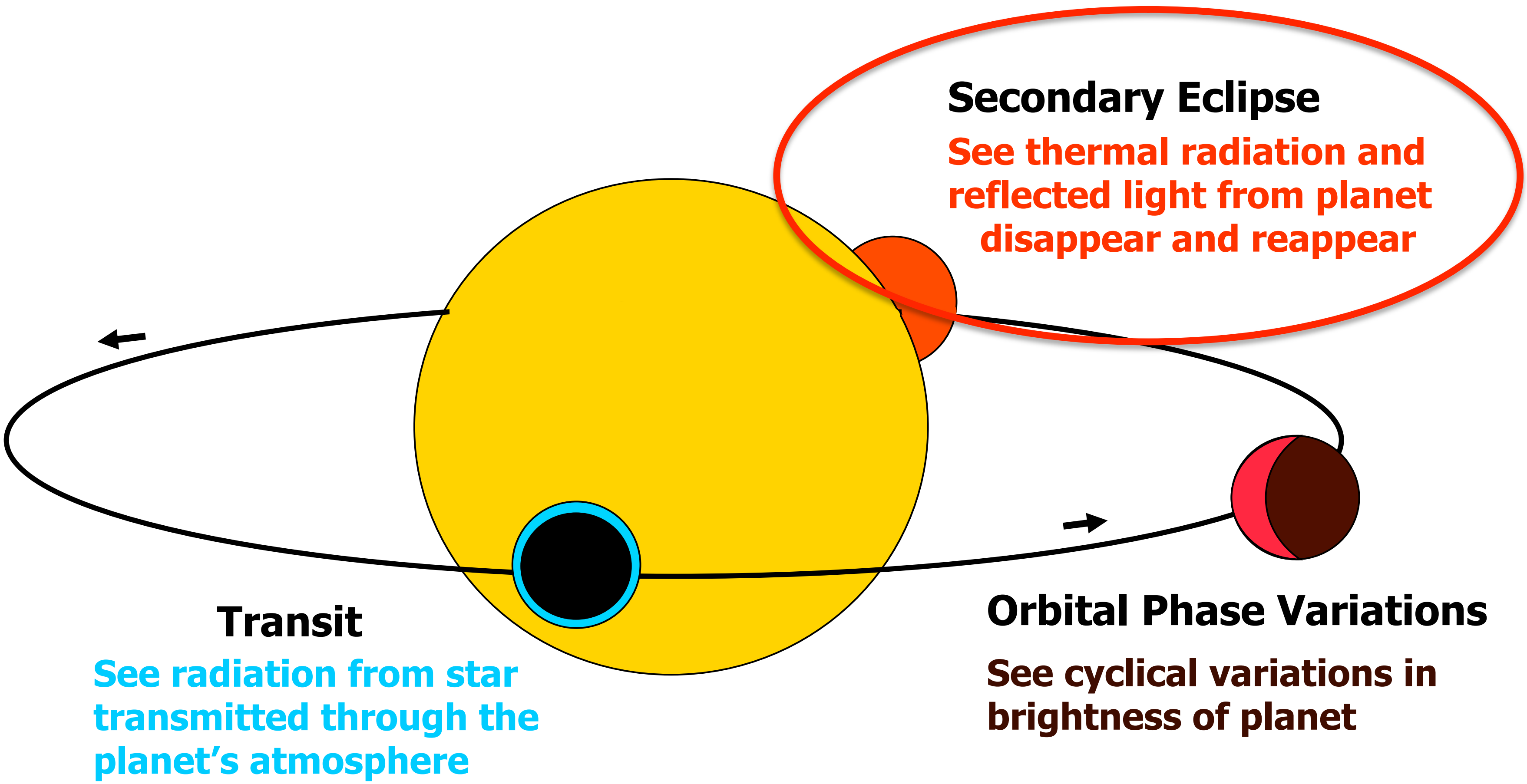
ABSTRACT

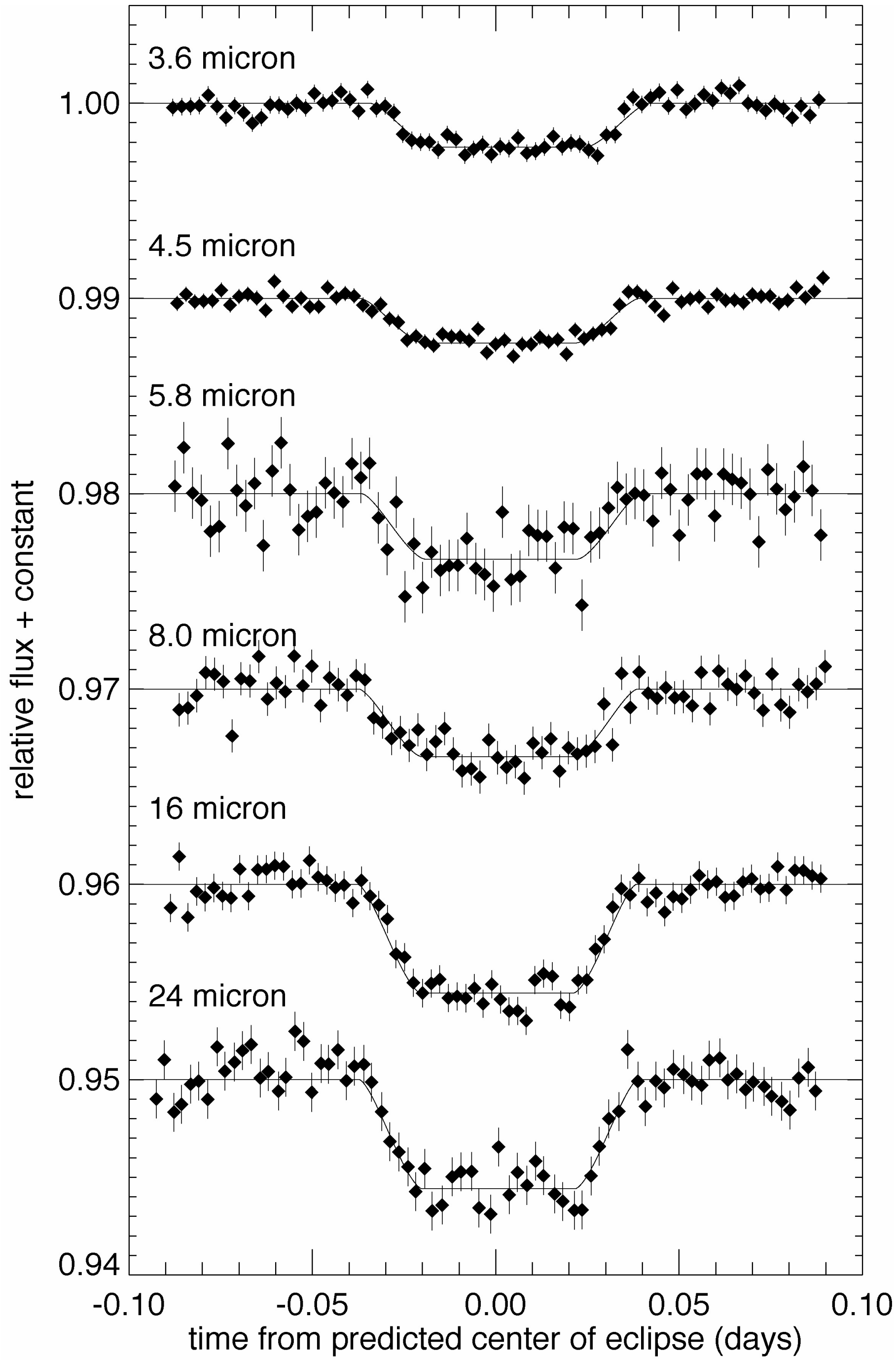
We present evidence for a correlation between the observed properties of hot Jupiter emission spectra and the activity levels of the host stars measured using Ca II H & K emission lines. We find that planets with dayside emission spectra that are well-described by standard 1D atmosphere models with water in absorption (HD 189733, TrES-1, TrES-3, WASP-4) orbit chromospherically active stars, while planets with emission spectra that are consistent with the presence of a strong high-altitude temperature inversion and water in emission orbit quieter stars. We estimate that active G and K stars have Lyman α fluxes that are typically a factor of $4-7$ times higher than quiet stars with analogous spectral types, and propose that the increased UV flux received by planets orbiting active stars destroys the compounds responsible for the formation of the observed temperature inversions. In this paper we also derive a model-independent method for differentiating between these two atmosphere types using the secondary eclipse depths measured in the 3.6 and 4.5 μm bands on the *Spitzer Space Telescope*, and argue that the observed correlation is independent of the inverted/non-inverted paradigm for classifying hot Jupiter atmospheres.

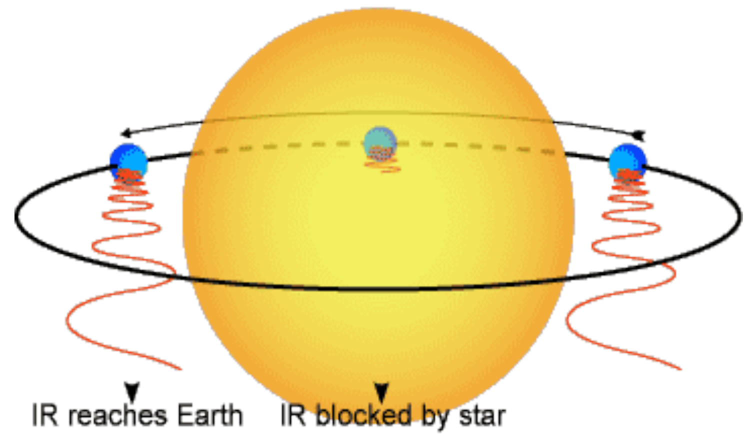
Subject headings: binaries: eclipsing — visible: stars — planetary systems — techniques: spectroscopic

Many following slides from Heather Knutson

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres





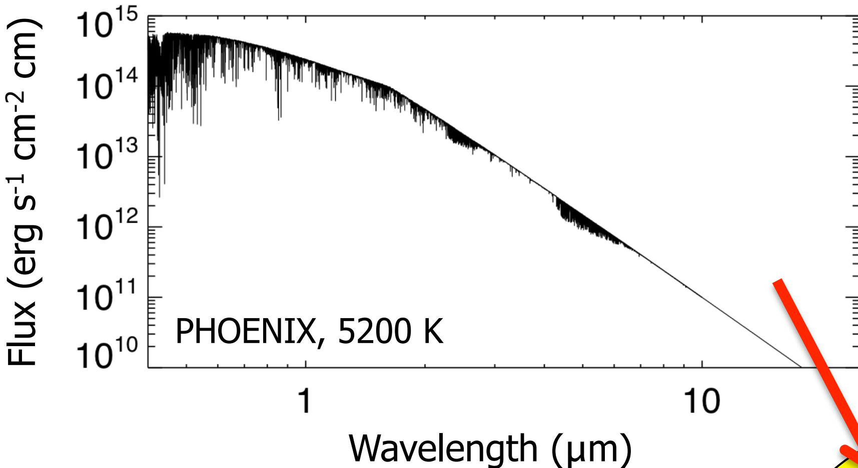


Observe the decrease in light as the planet disappears behind the star and then reappears.

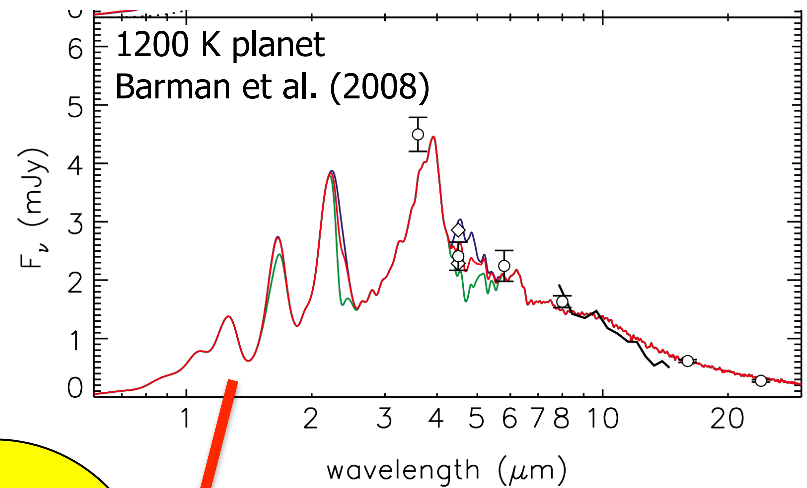
Spitzer observations of HD 189733b
(Charbonneau, Knutson et al. 2008)

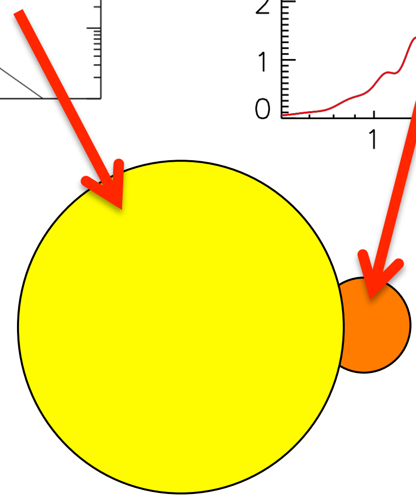
Comparison to Models

Stellar Atmosphere Model

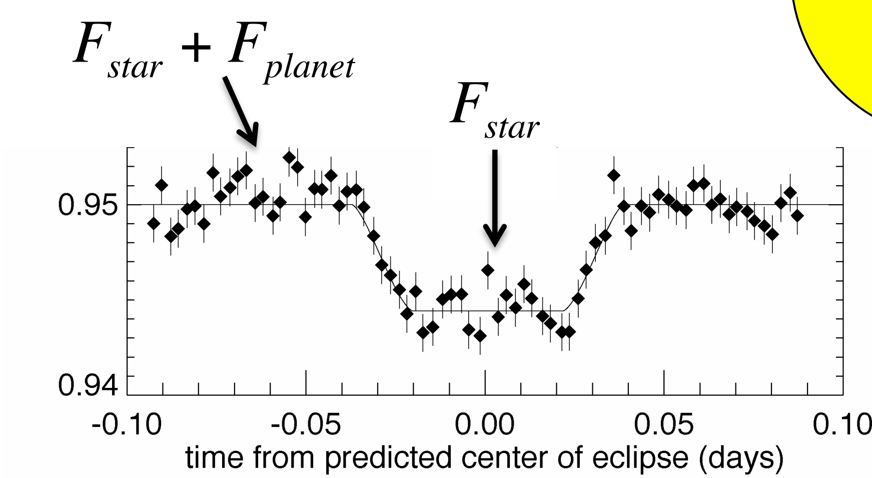


Planet Atmosphere Model





Model assumes solar composition atmosphere, chemistry in local thermal equilibrium.



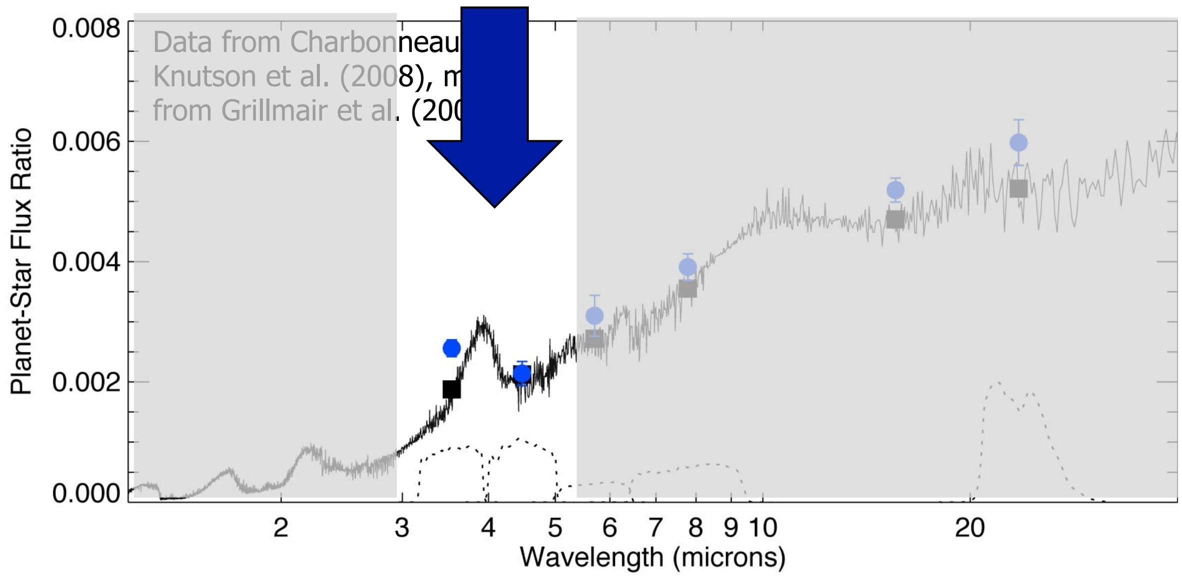
$$depth(\%) = \frac{F_{planet}}{F_{star} + F_{planet}} \approx \frac{F_{planet}}{F_{star}}$$

Two Classes of Hot Jupiter Atmospheres

Observations in the 3.6 and 4.5 μm channels can be used to determine whether or not a given planet has an inversion.

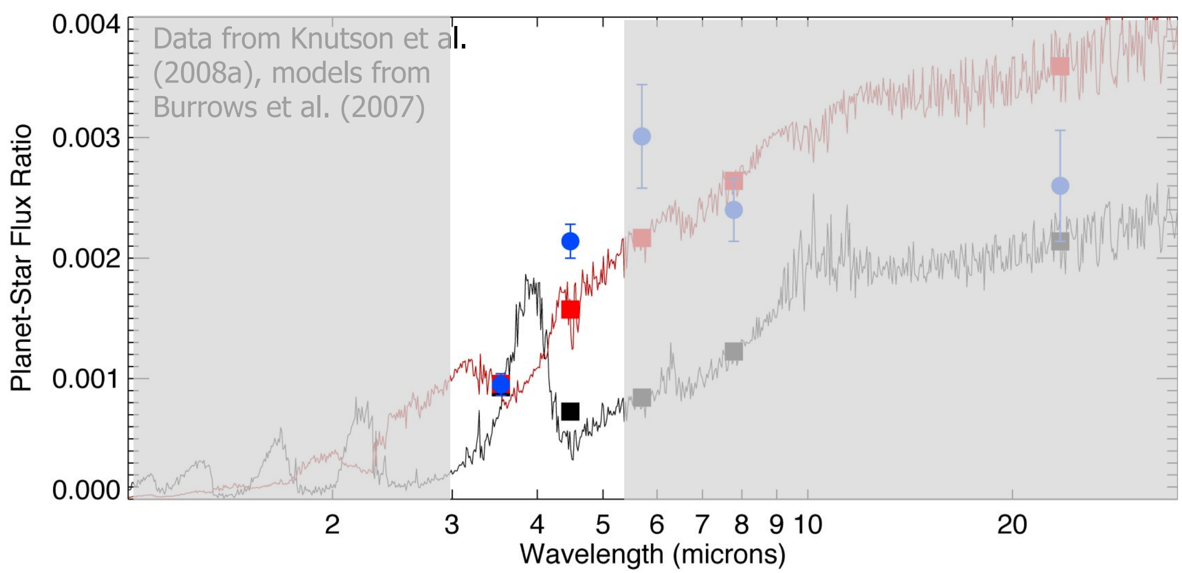
HD 189733b is well-described by a model with water and CO bands in absorption.

No stratosphere.

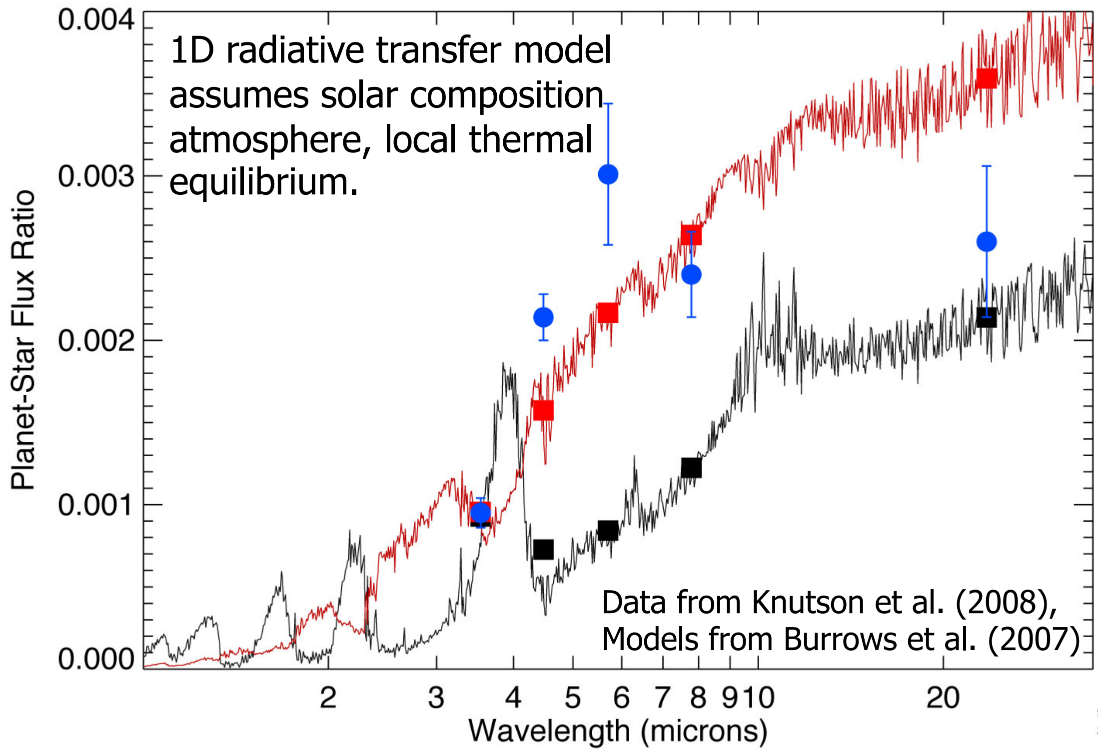


HD 209458b is NOT well-matched by this model, has water and CO *emission* features.

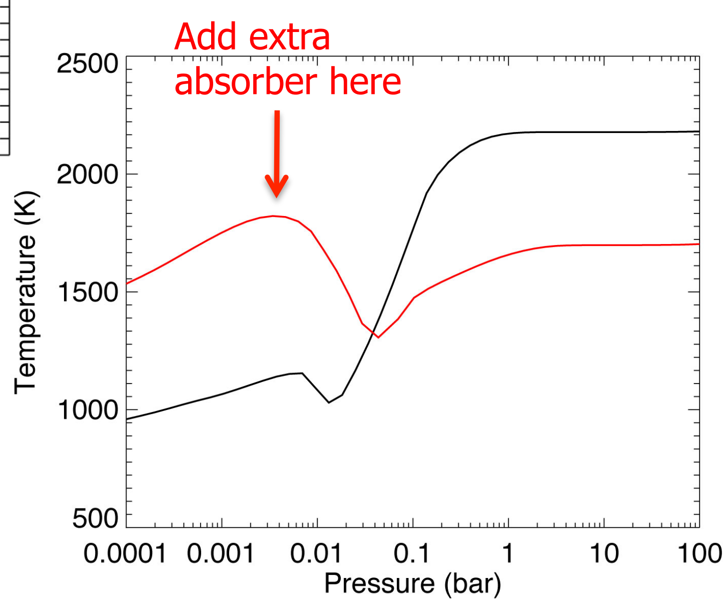
Stratosphere.



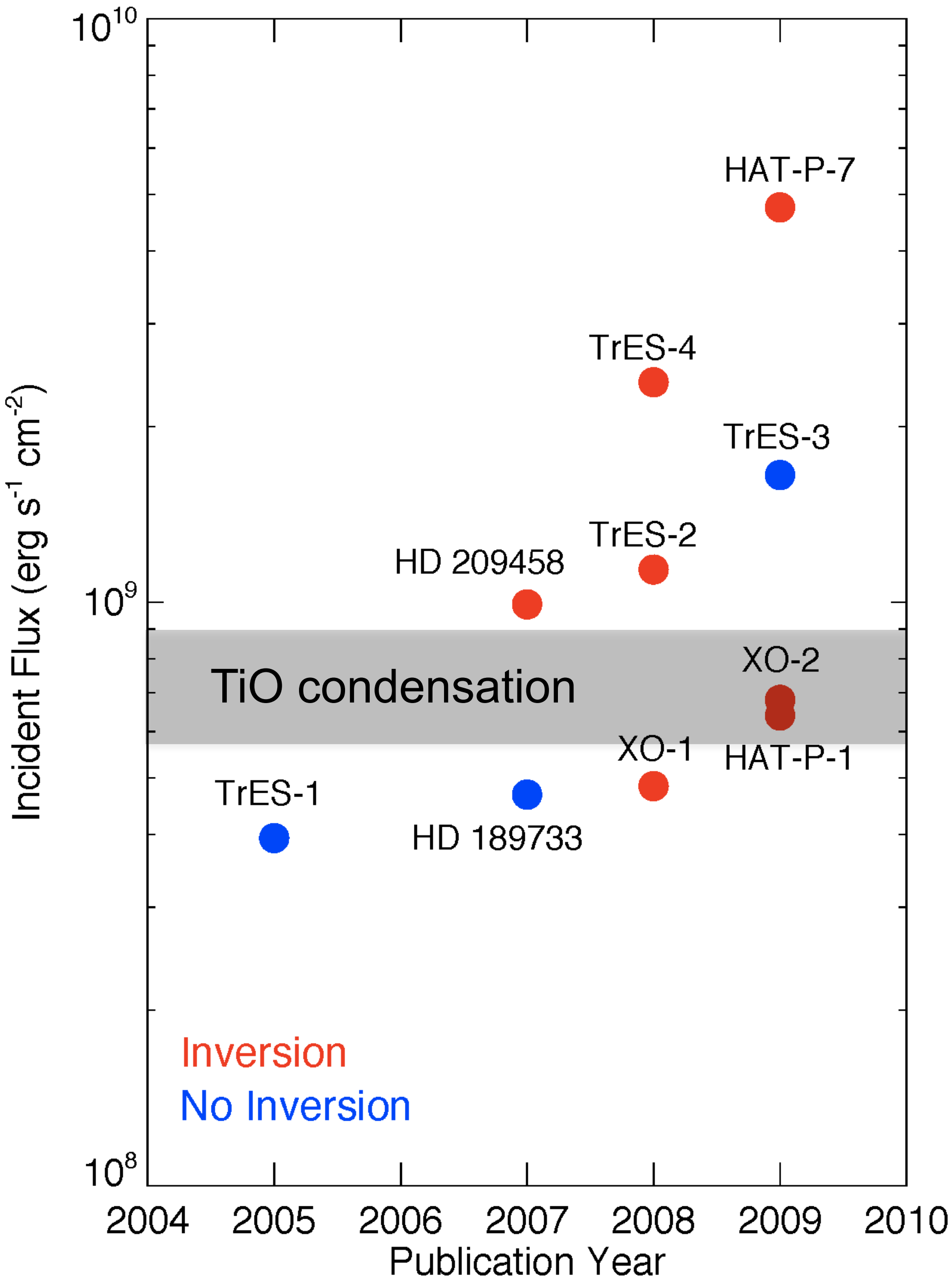
HD 209458b: Evidence for Two Classes of Hot Jupiter Atmospheres



Best described by a model with a temperature inversion and water features in emission instead of absorption.



Why would two hot Jupiters with similar masses, radii, compositions, and temperatures have such different emission spectra?



What causes temperature inversions in hot Jupiter atmospheres?

Gas phase TiO?

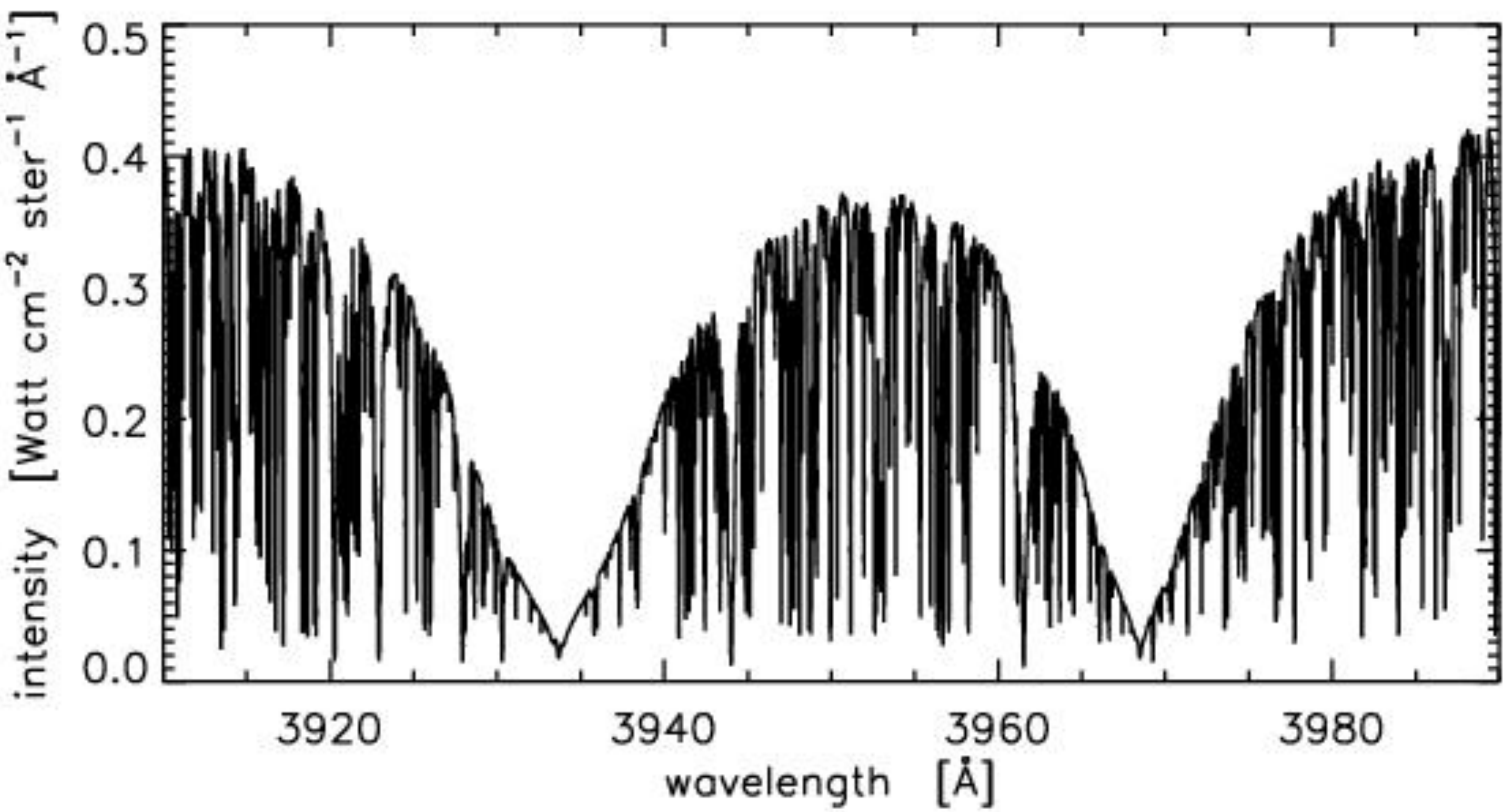
Problem: inversions do not appear to correlate with temperature

One alternative: sulfur compounds

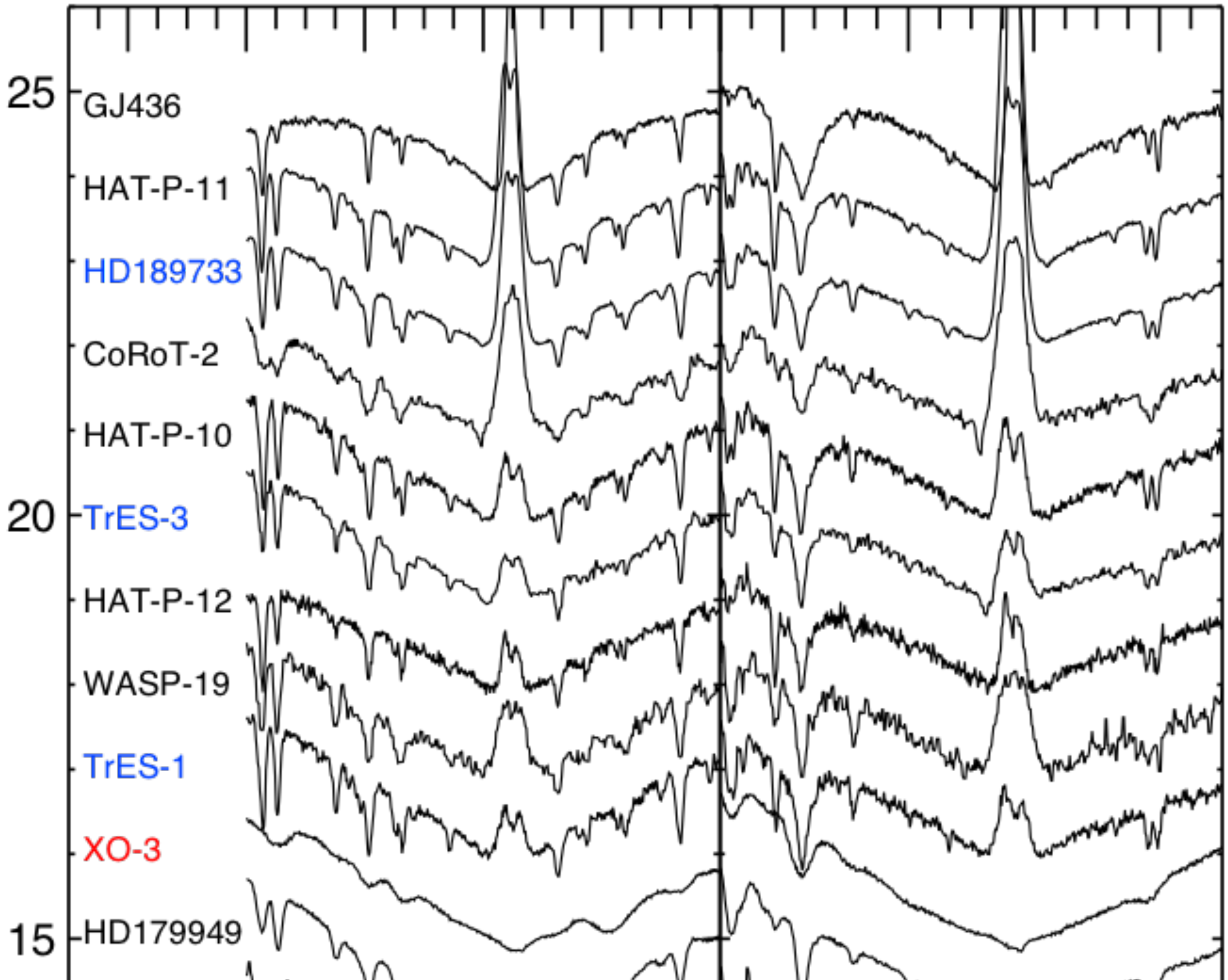
Nonequilibrium chemistry model, Zahnle et al. (2009)

As described in Hubeny et al. (2003), Burrows et al. (2007, 2008), and Fortney et al. (2008)

Stellar Activity – Ca II H & K Lines



Stellar Activity – Ca II H & K Lines



Active vs. Quiet Stars

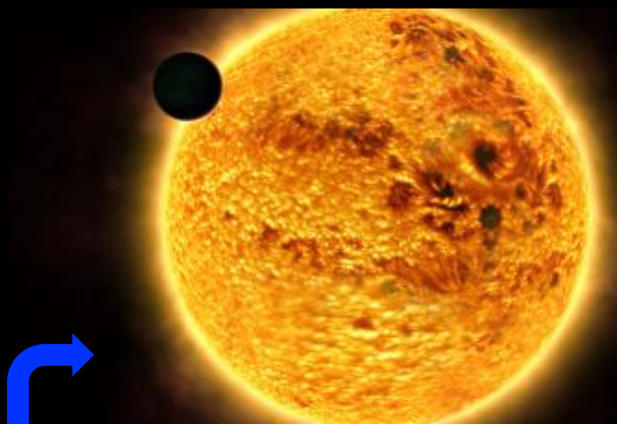
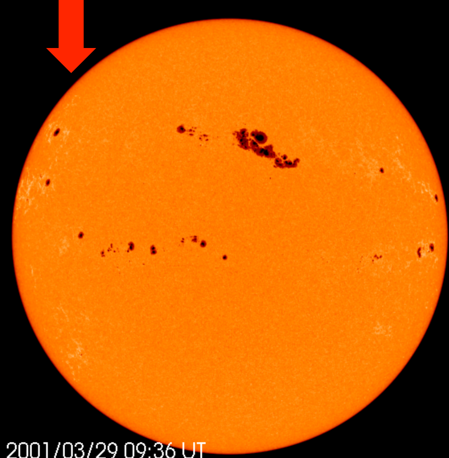


Image credit ESA/NASA, Frederic Pont

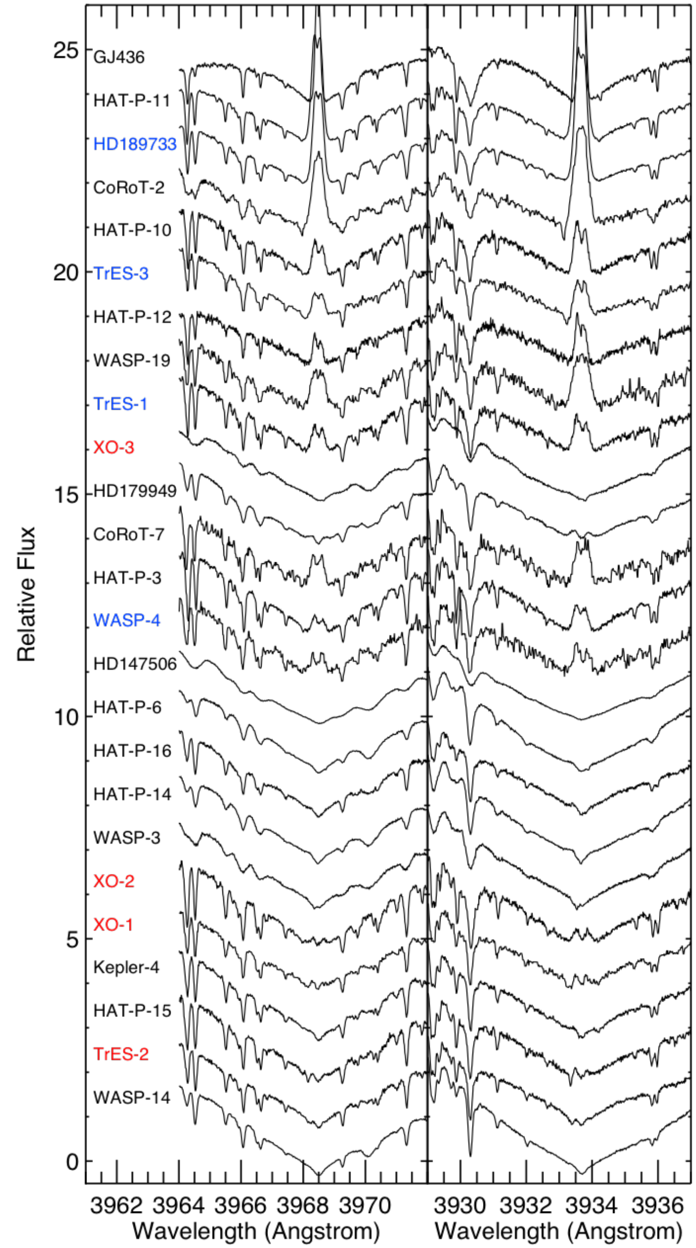
Active stars have enhanced magnetic fields, more spots, and increased UV/X-ray fluxes relative to quiet stars.

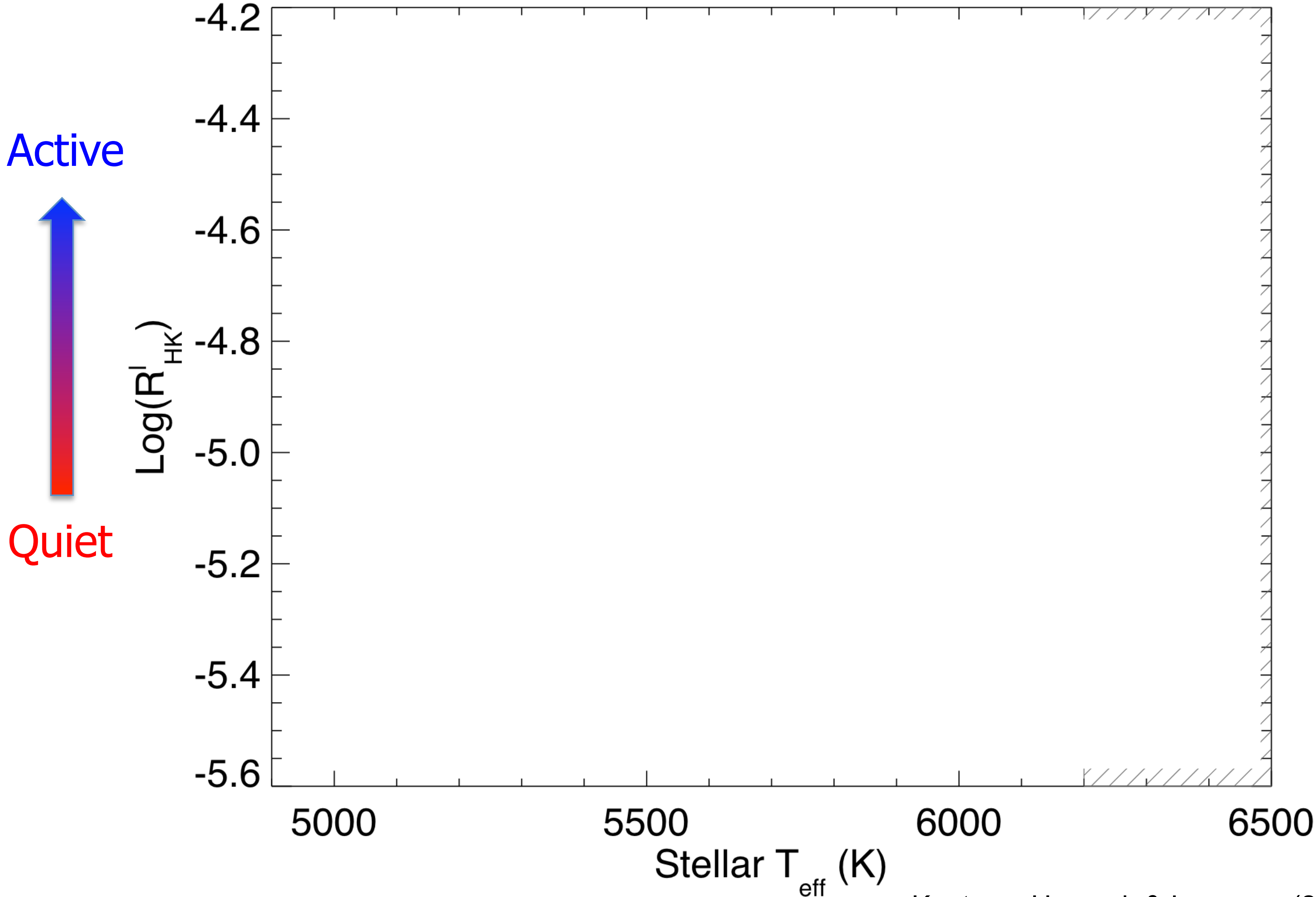


How do we measure activity?

Active

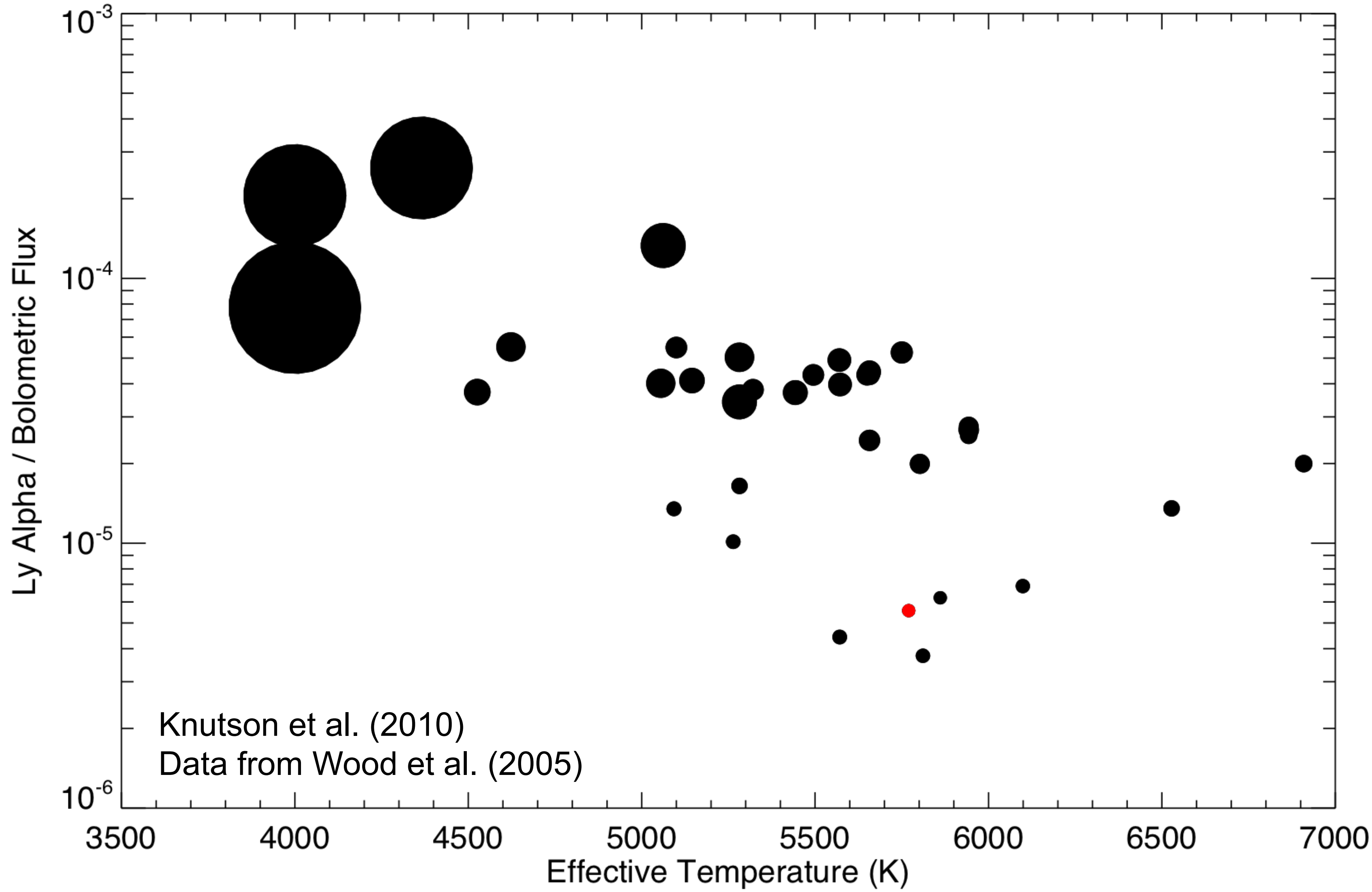
Quiet



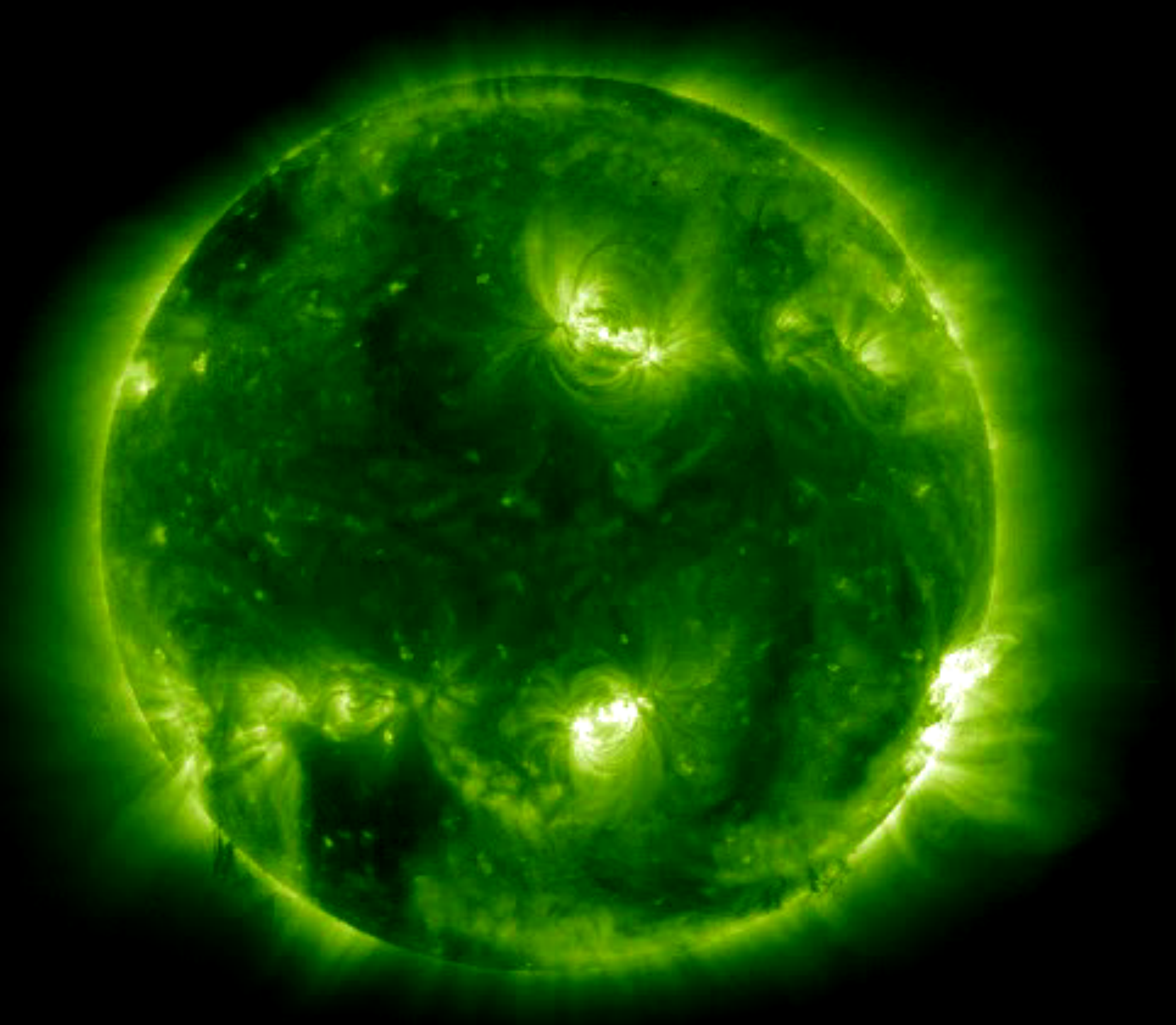


Knutson, Howard, & Isaacson (2010)

Lyman α Flux vs. Spectral Type



Rotational modulation of solar X-rays



Questions?