The KELT Transit Survey:

Hot, Planets around Hot, Bright Stars*

The KELT North and South Collaborations

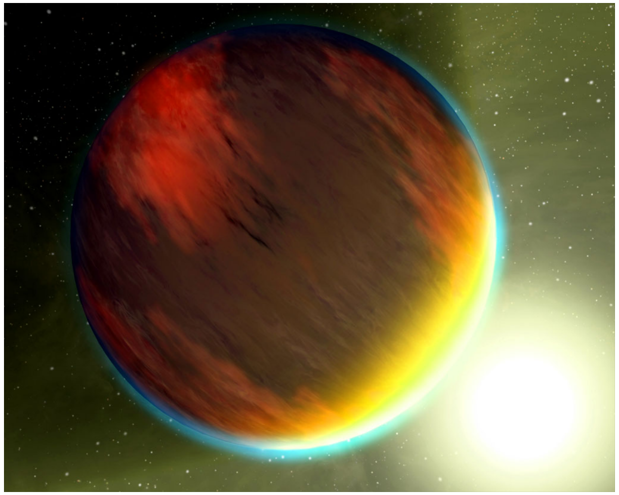
The KELT-FUN

"the race to the bottom"

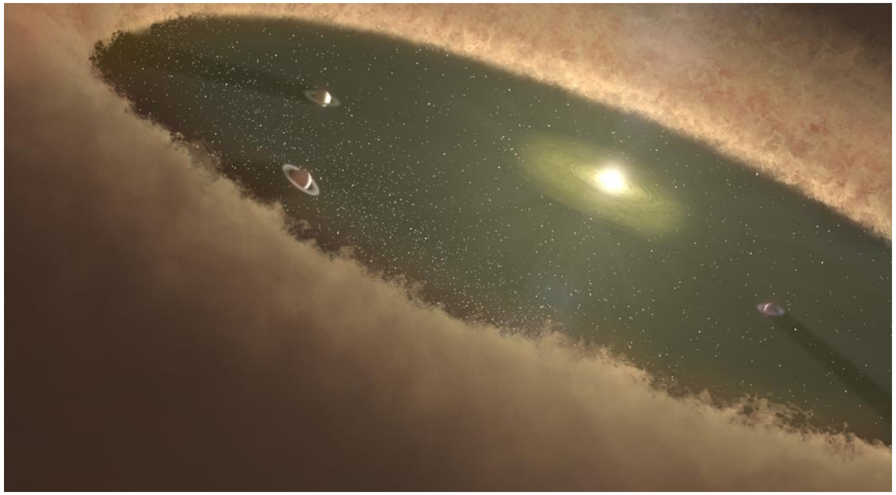
*i.e., refusing to participate in the ~~"small star opportunity."~~

Aren’t we done with hot Jupiters?

- Atmospheres.



- Origins.



The KELT Collaboration (mostly)

- Lehigh University
  - Josh Pepper (Co-PI)
  - Jonathan Labadie-Bartz
- OSU
  - Scott Gaudi (Co-PI)
  - Dan Stevens
  - Marshall Johnson
  - Matthew Penny
  - Rick Pogge
  - Andy Could
- Vanderbilt (Co-PI)
  - Keivan Stassun
  - Mike Lund
  - Karen Collins
  - Ryan Oelkers
- CfA
  - Dave Latham
  - Joey Rodriguez
  - George Zhou
  - Allyson Bieryla
  - Jason Eastman
- Other institutions
  - Rob Siverd
  - Thomas Beatty
  - Eric Jensen
  - Mark Trueblook
  - Patricia Trueblood
  - Darren DePoy
  - Jennifer Marshall
  - Lars Buchave
  - Knicole Colon
  - Rudy Kuhn

+the KELT-FUN Network

What is KELT?

The Kilodegree Extremely Little Telescope

KELT Hardware

The Kilodegree Extremely Little Telescope(s).

KELT-North is located at Winer Observatory in Arizona.

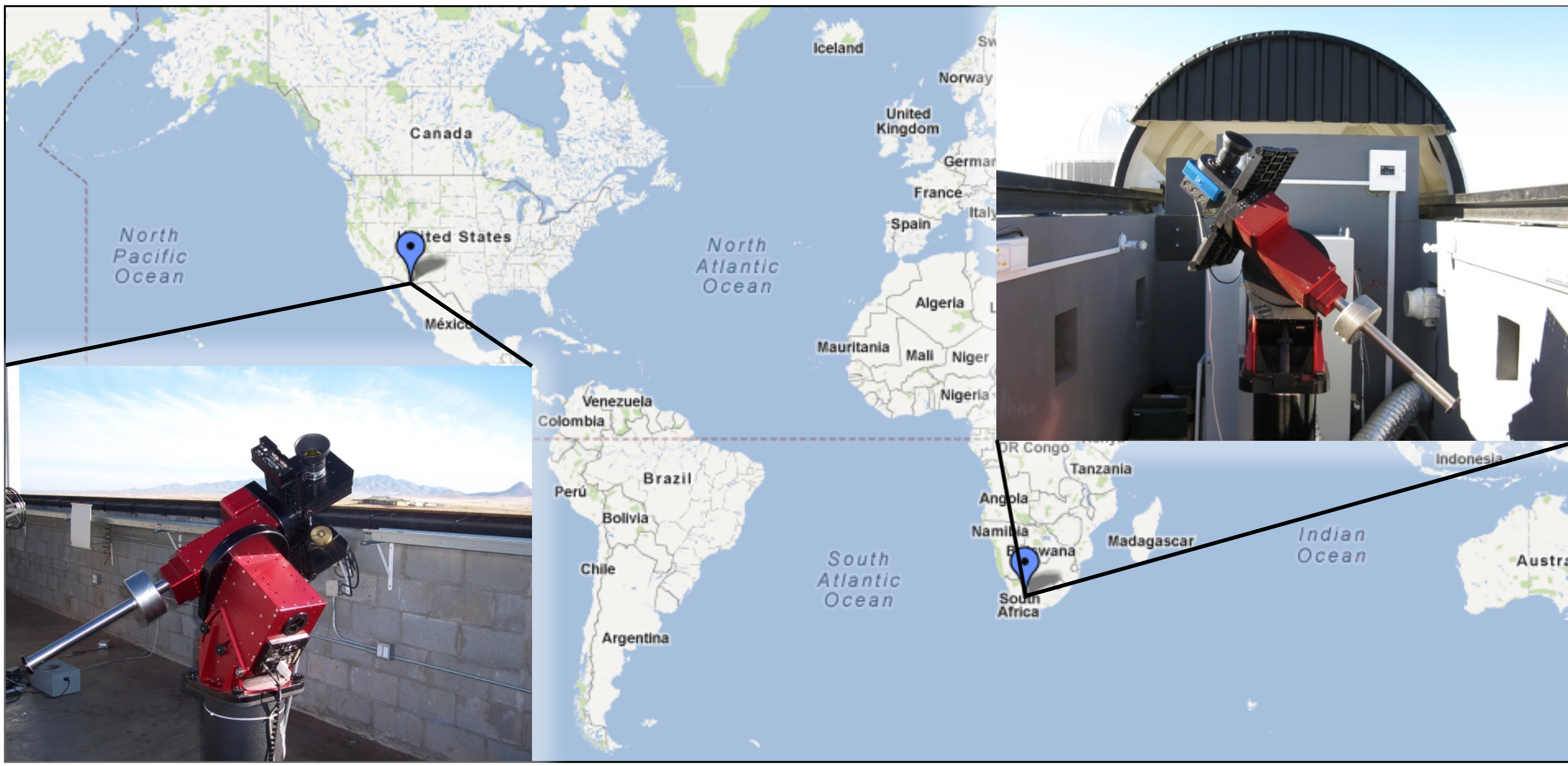
Science observations began in 2006

"Better late than never"

- 42mm aperture
- 4K x 4K Apogee AP16E
- 26.0 x 26.0 degrees FOV
- 23.0 arcsec/pixel

KELT Hardware

The Kilodegree Extremely Little Telescope(s).



KELT-North

Deployed 2005 to Winer Observatory, AZ

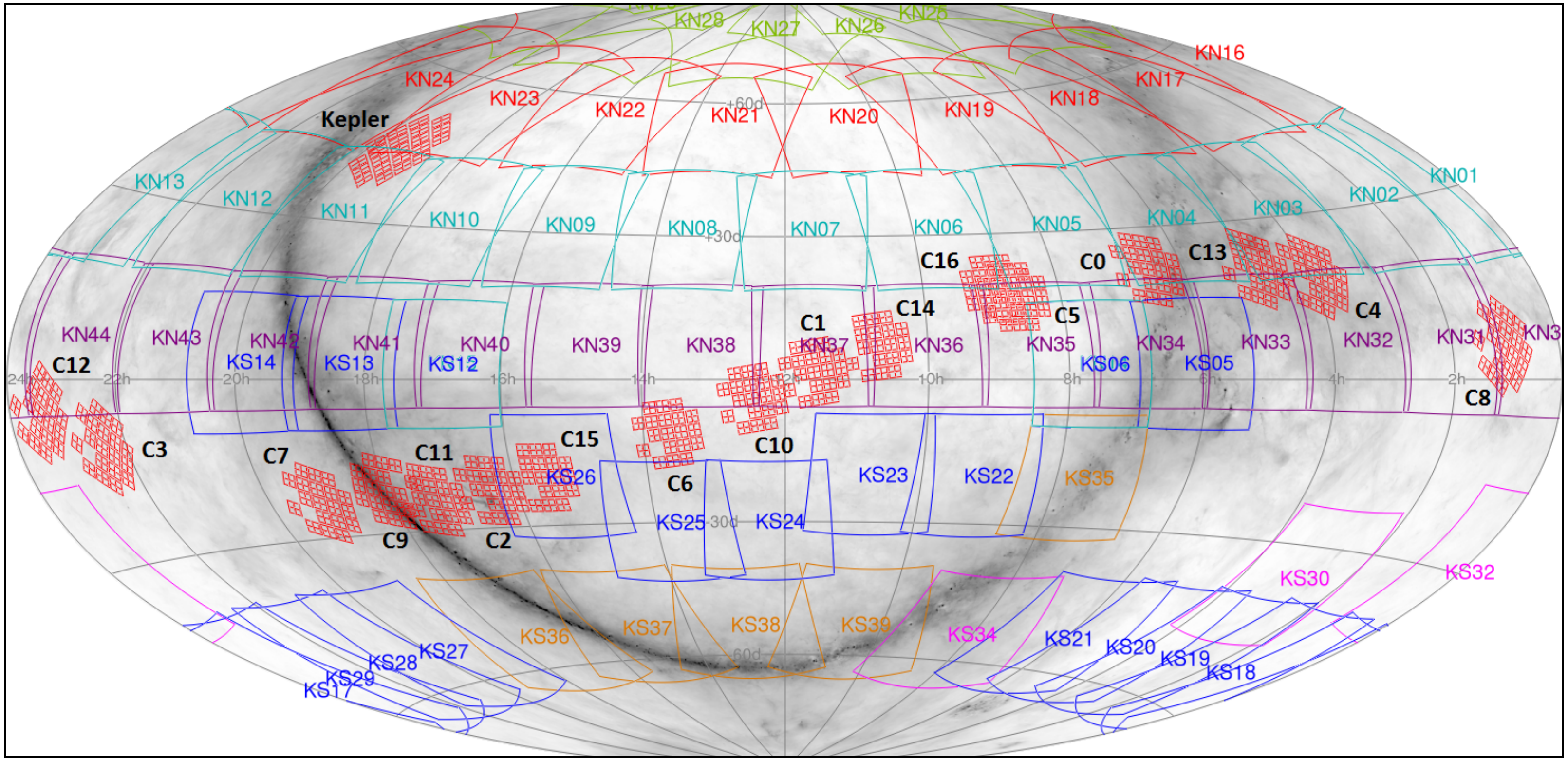
Operated by Lehigh, Ohio State, and Vanderbilt

KELT-South

Deployed 2009 to Sutherland, South Africa

Operated by Lehigh, Vanderbilt, Fisk, and the University of Cape Town

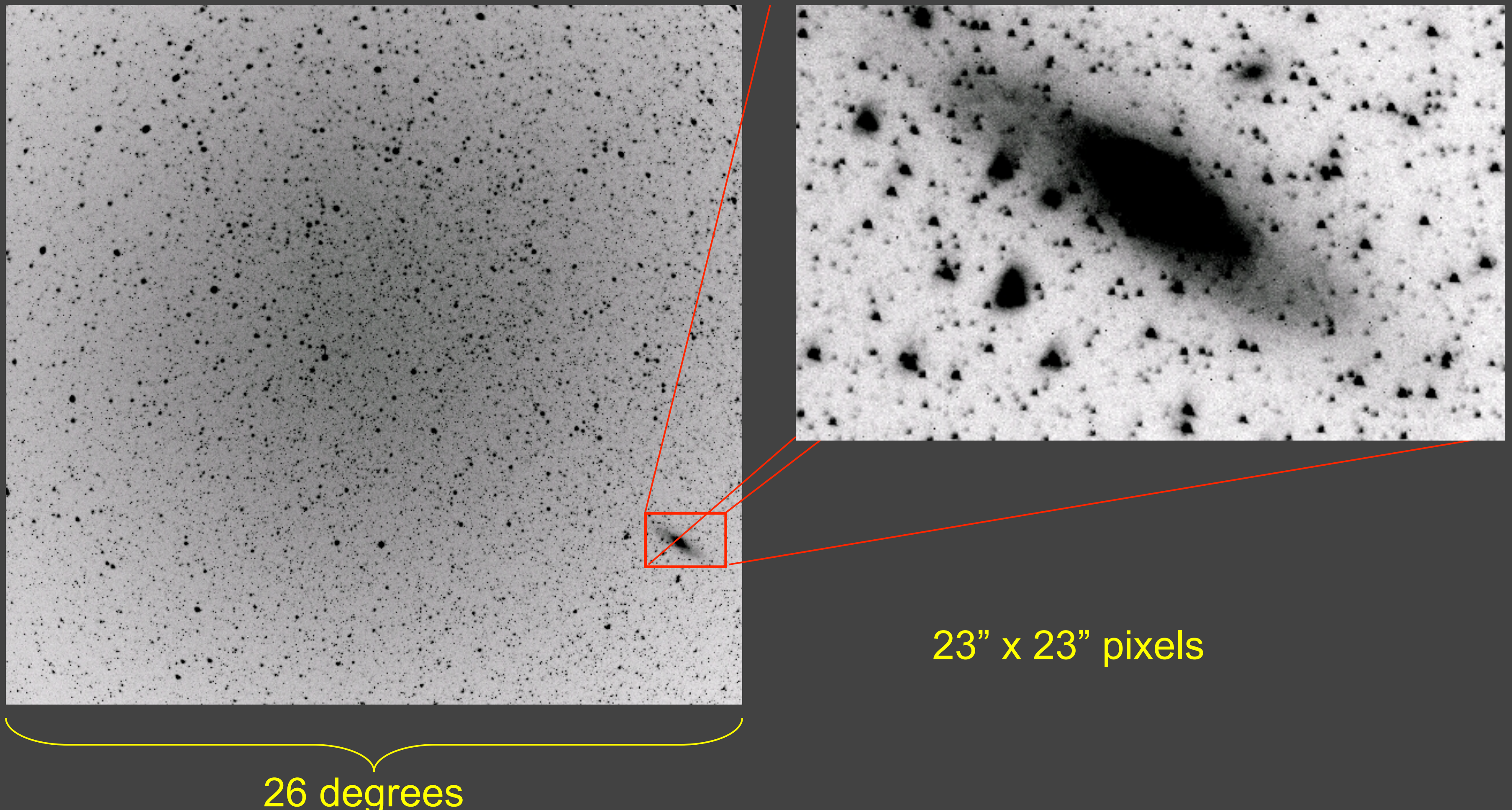
Nearly all sky.



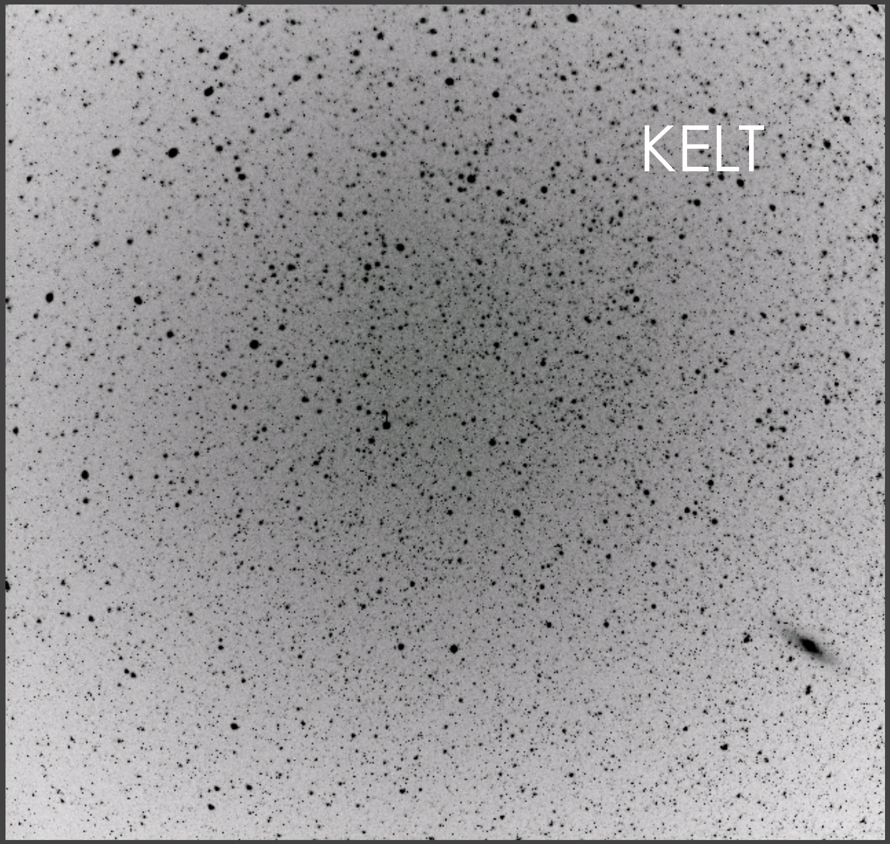
3-11 years of data, 60-70% of the sky

KELT Follow-up Network

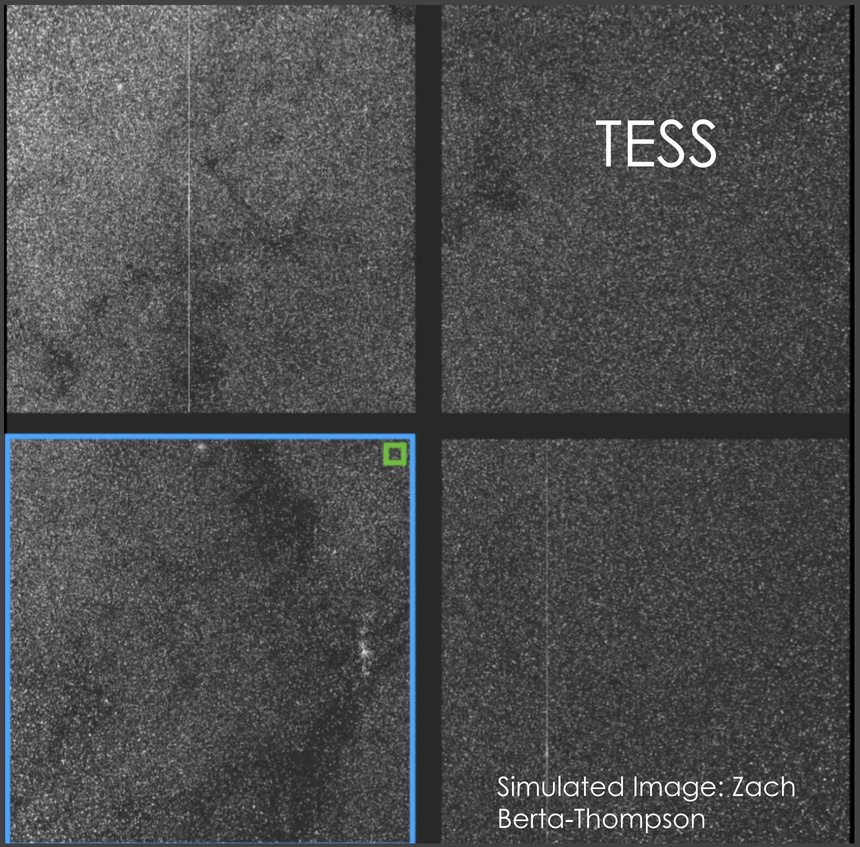
How large is 26 degrees?



KELT compared to TESS



26 degrees

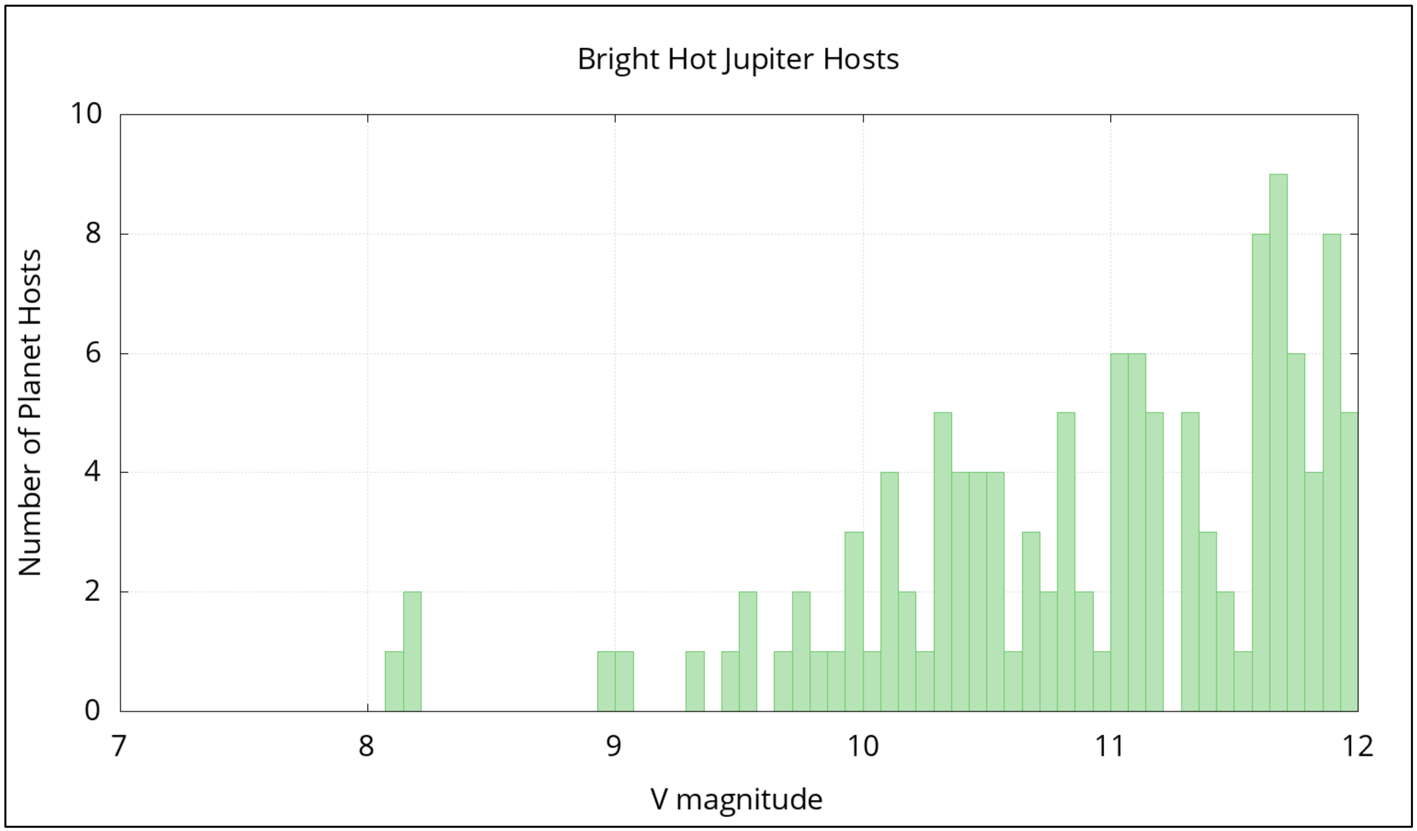


24 degrees

Who cares?

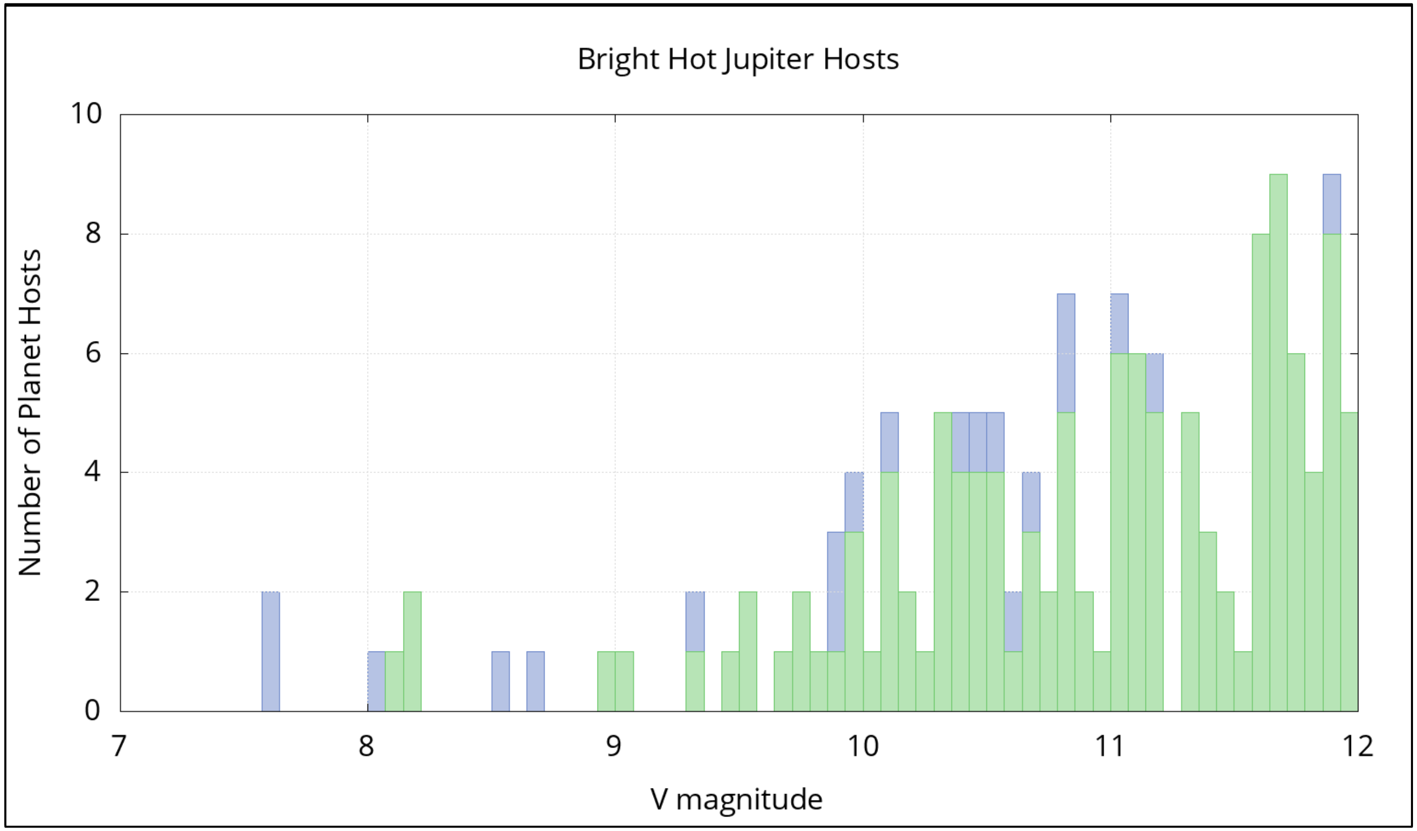
Why KELT is different than other transit surveys.

Bright (V<12) transiting planets.



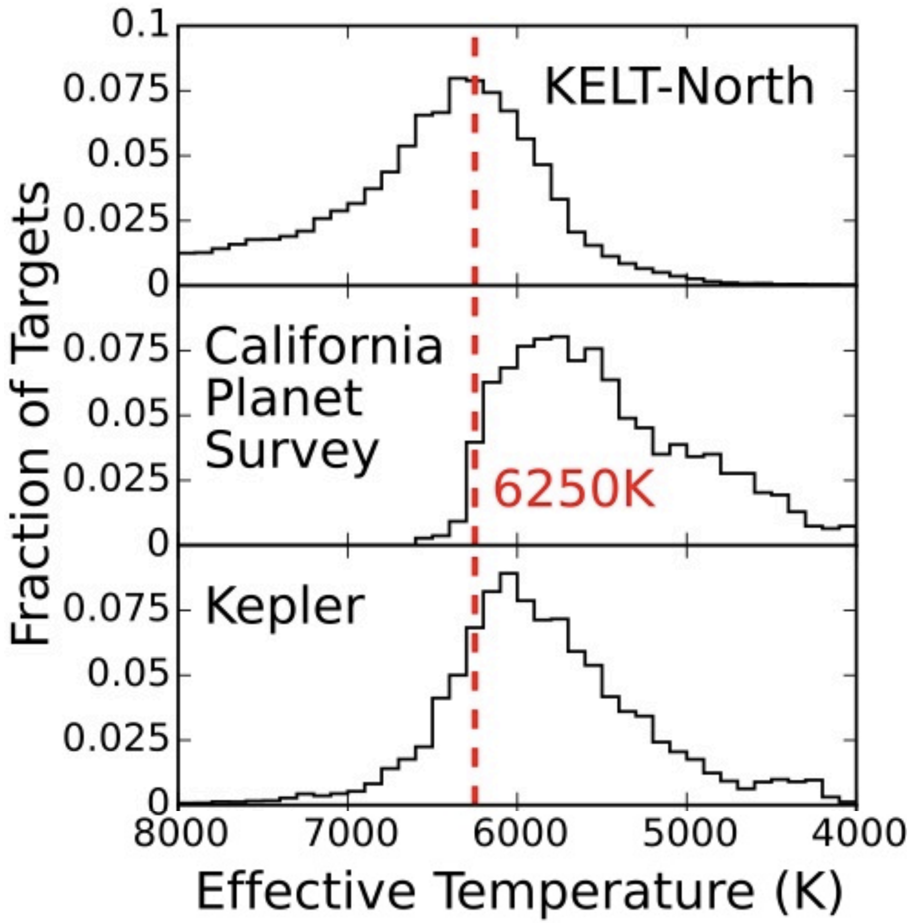
$R_p > 0.5\ R_J$ and $V < 12$

Bright (V<12) transiting planets.



$R_p > 0.5\ R_J$ and $V < 12$

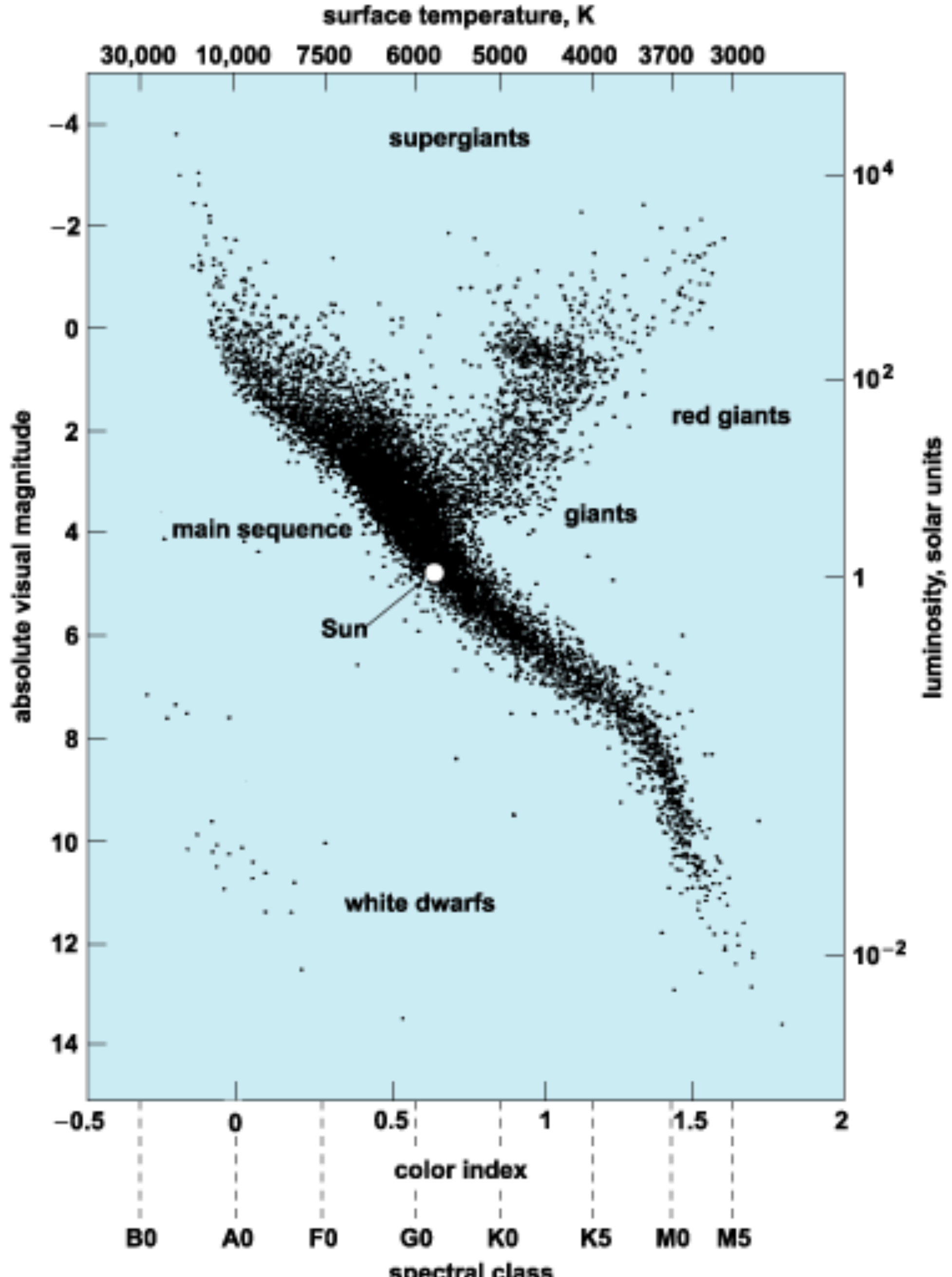
Hot (T_{eff}>6250K) Stars



42K/80K ~ 53%

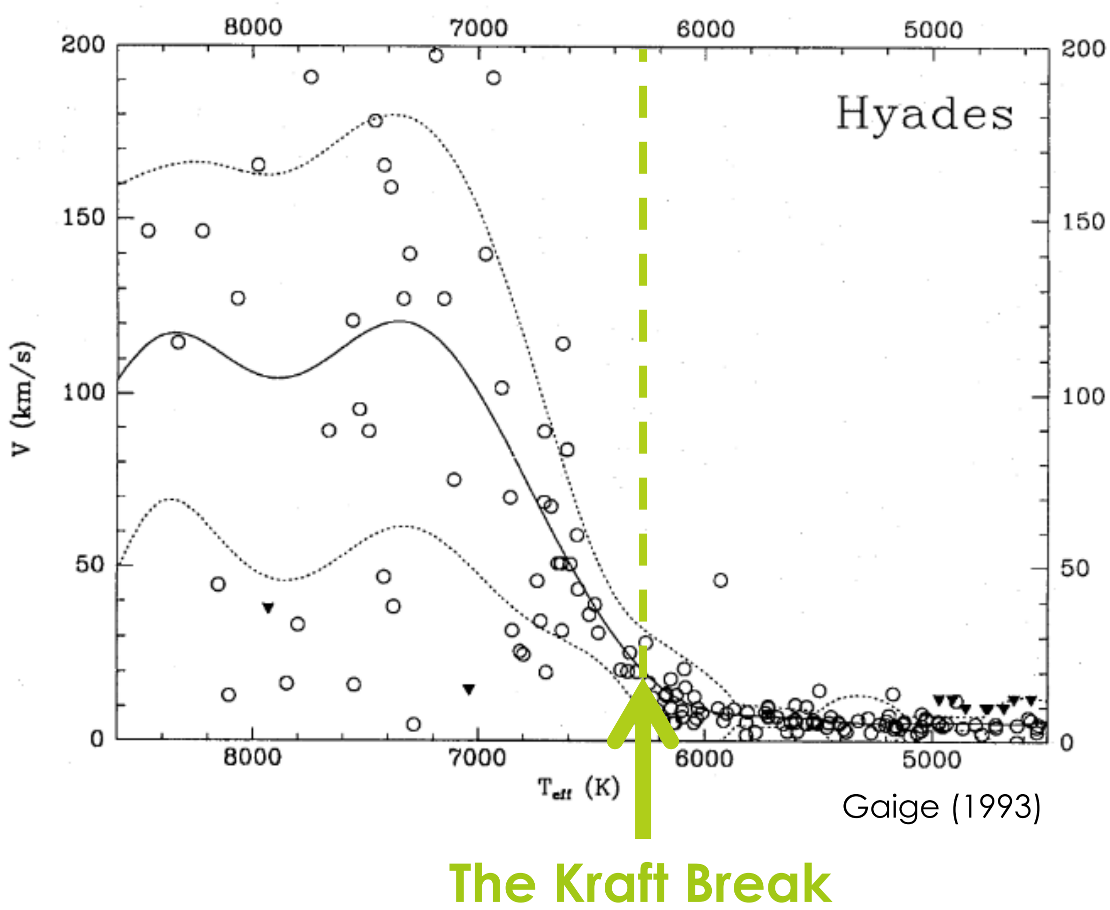
28/1196 ~ 2%

14K/150K ~ 9%



surface temperature, K
30,000
10,000
7500
6000
5000
4000
3700
3000
supergiants
red giants
giants
main sequence
Sun
white dwarfs
absolute visual magnitude
−4
−2
0
2
4
6
8
10
12
14
luminosity, solar units
10^4
10^2
1
10^{-2}
−0.5
0
0.5
1
1.5
2
color index
B0
A0
F0
G0
K0
K5
M0
M5
spectral class

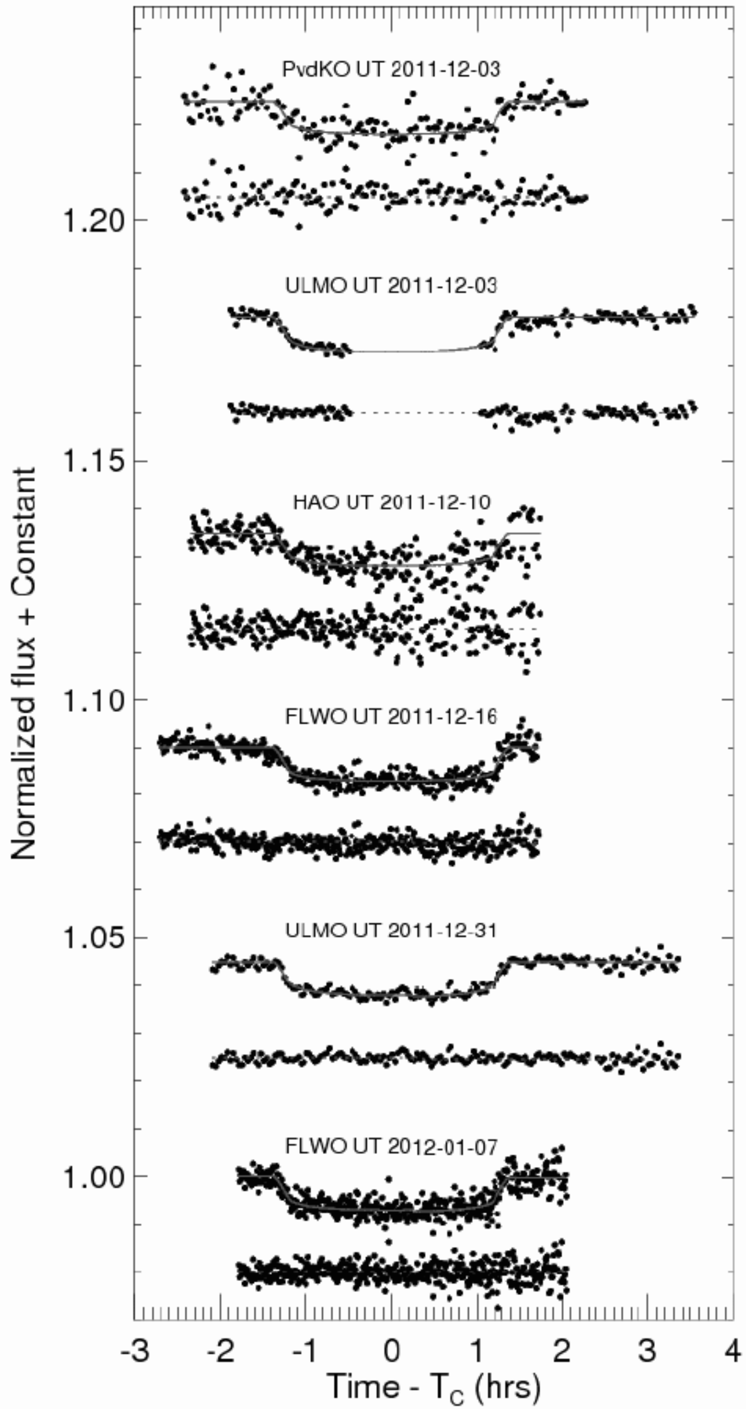
The Challenge of Hot Stars

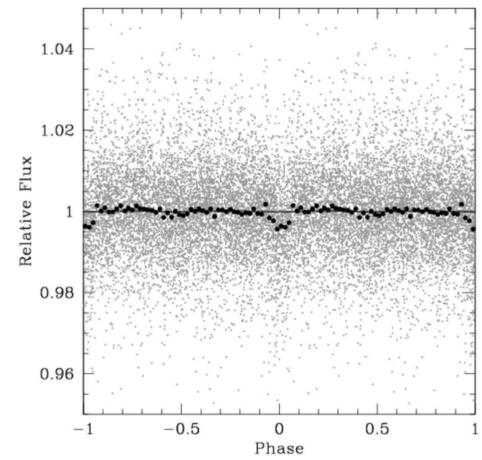


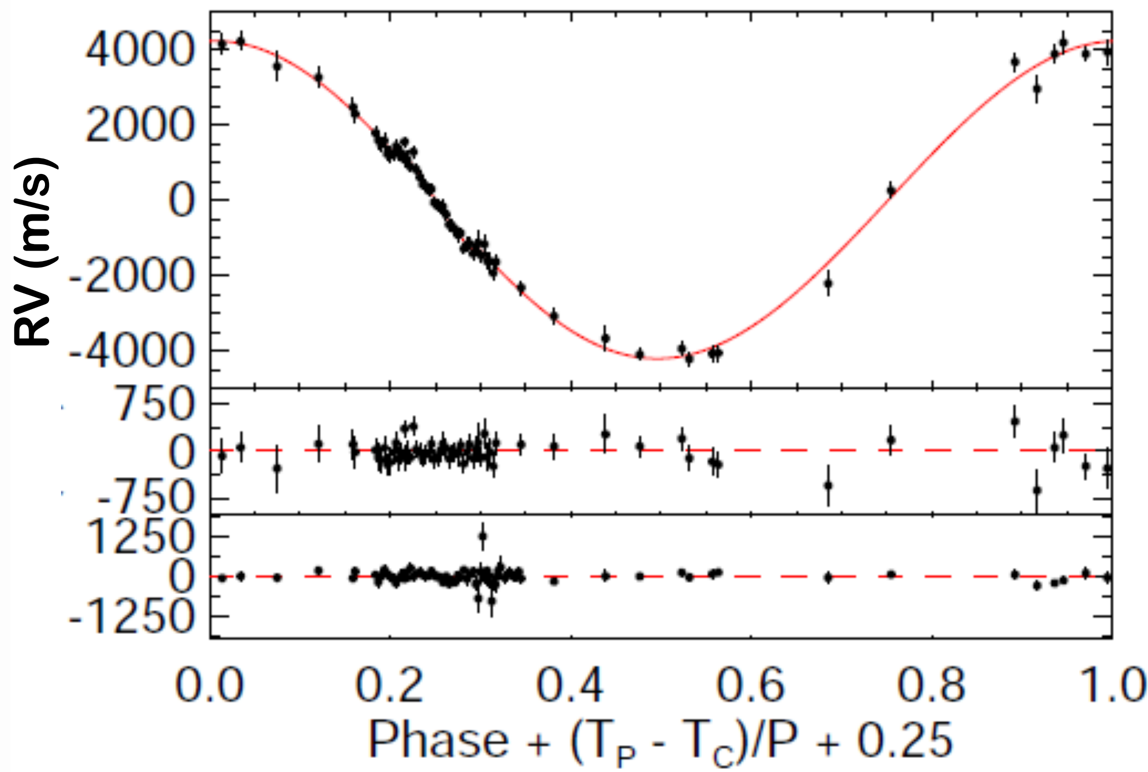
Discoveries

KELT-1b through KELT-21b*

***not all published.**


PvdKO UT 2011-12-03
ULMO UT 2011-12-03
HAO UT 2011-12-10
FLWO UT 2011-12-16
ULMO UT 2011-12-31
FLWO UT 2012-01-07
Normalized flux + Constant
1.20
1.15
1.10
1.05
1.00
-3
-2
-1
0
1
2
3
4
Time - T_C (hrs)

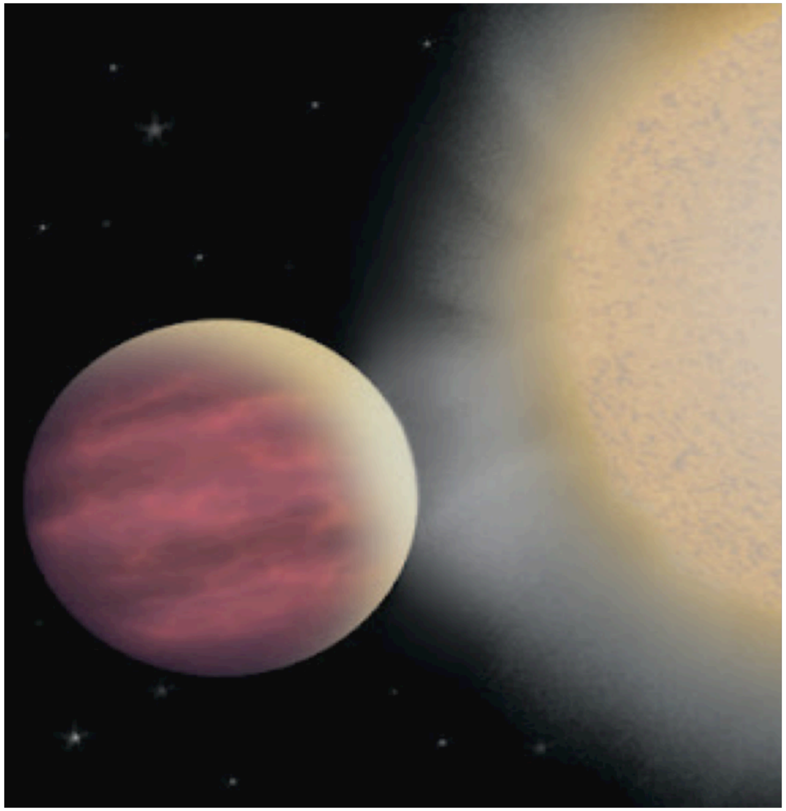

Relative Flux
1.04
1.02
1
0.98
0.96
−1
−0.5
0
0.5
1
Phase


RV (m/s)
4000
2000
0
-2000
-4000
750
0
-750
1250
0
-1250
0.0
0.2
0.4
0.6
0.8
1.0
Phase + $(T_P - T_C)/P$ + 0.25

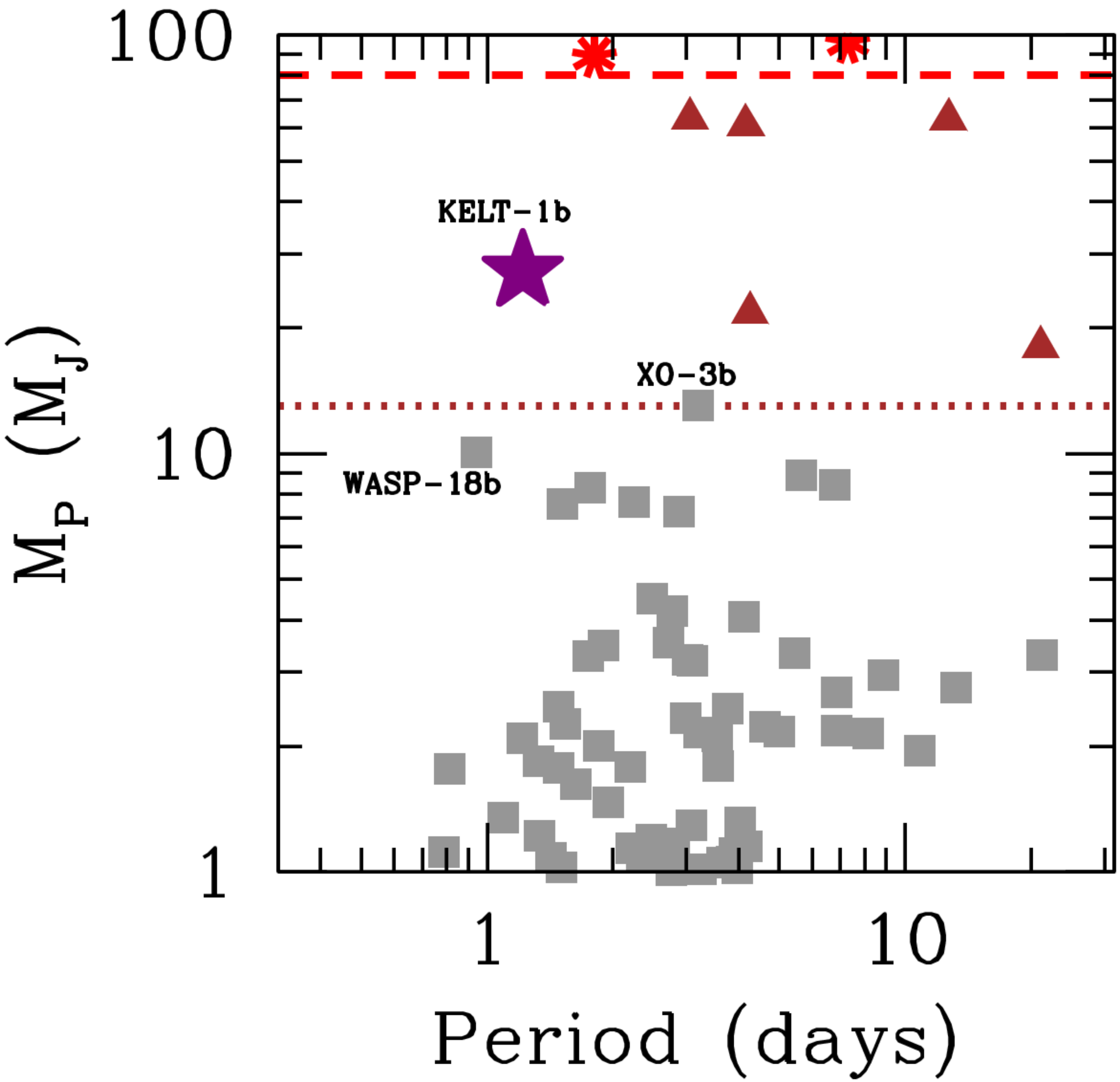
KELT-1b

A Benchmark Transiting Brown Dwarf

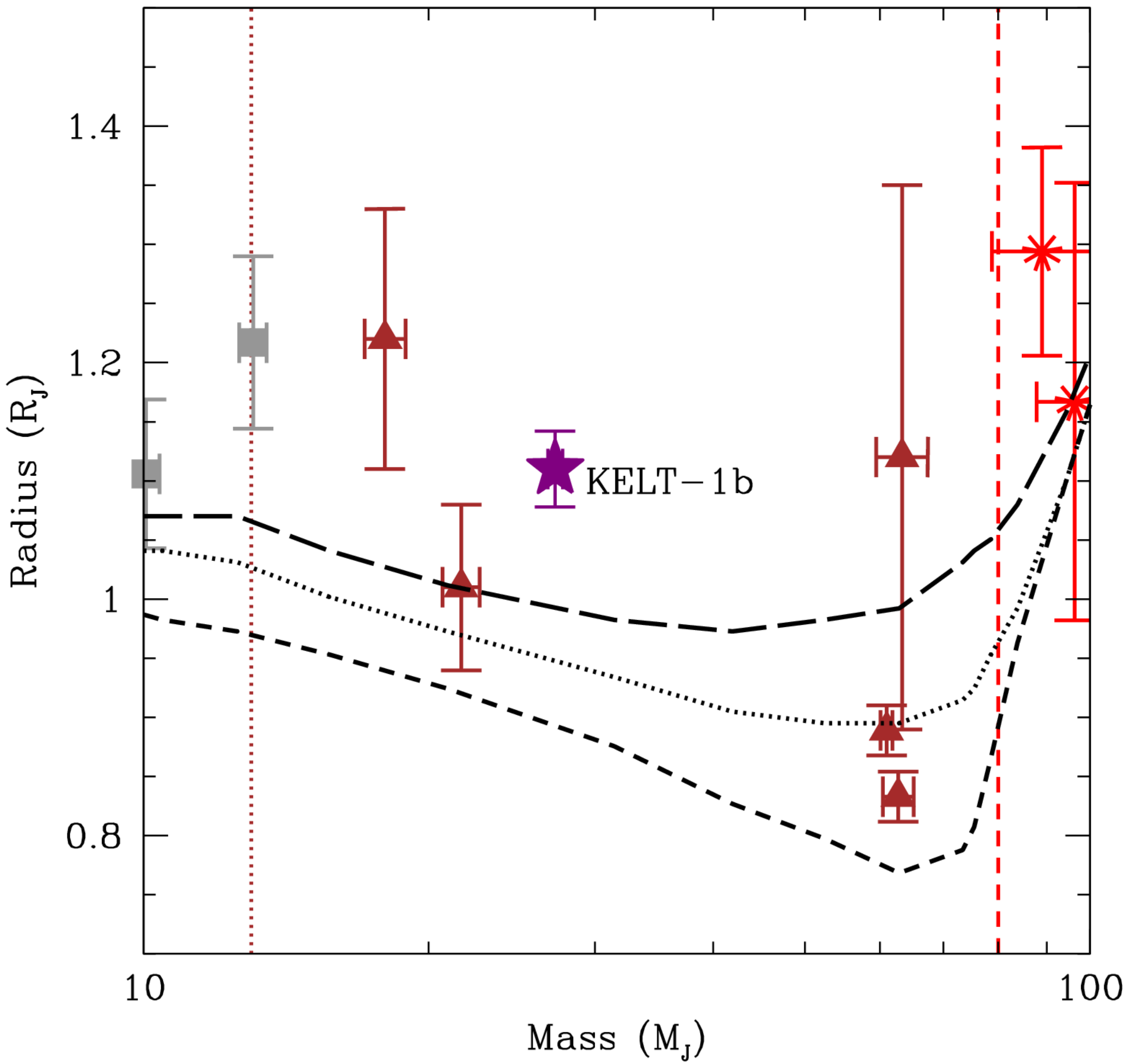
- Planet (KELT-1b)
  - Mass: 27.38 M_J
  - Radius: 1.116 R_j
  - Period: 1.2175 days
  - T_{eq}: 2423K
  - $\mathrm{Log}(g_p)$: 4.744
  - λ : 2±16
- Star (KELT-1)
  - V=10.7
  - Mass: 1.335 $M_\odot$
  - Radius: 1.471 $R_\odot$
  - T_{eff}: 6516K
  - v sini: 56 km/s



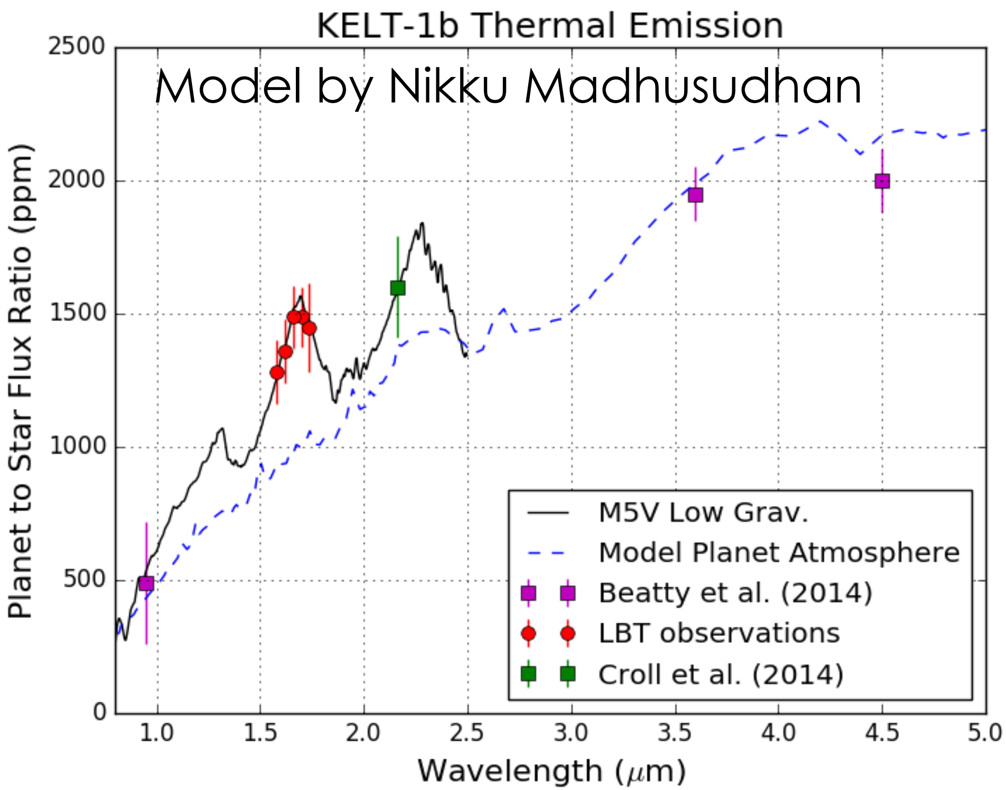
Siverd et al. 2012



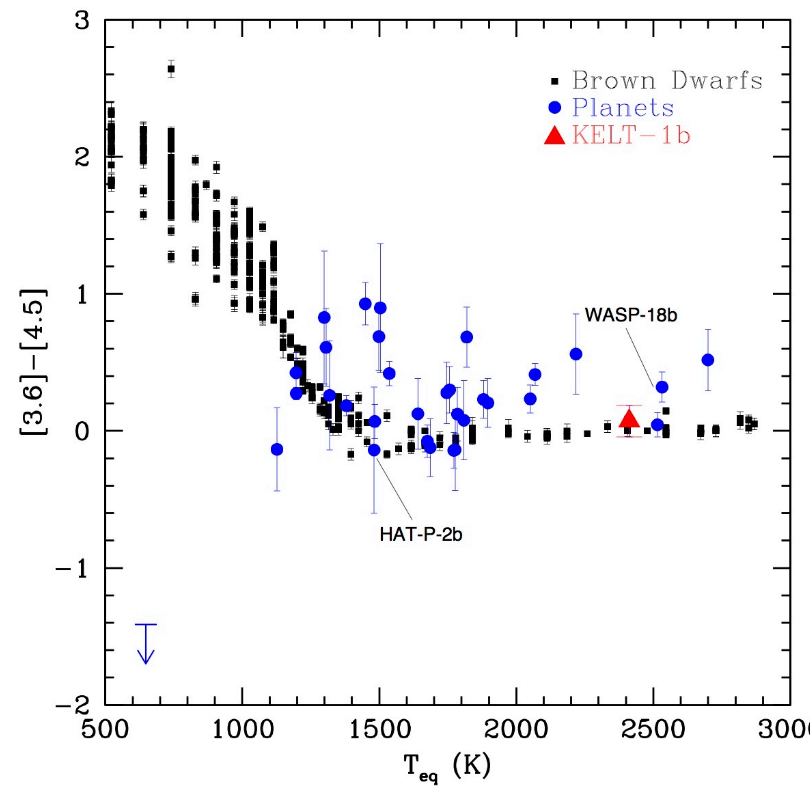
Siverd et al. 2012



Siverd et al. 2012



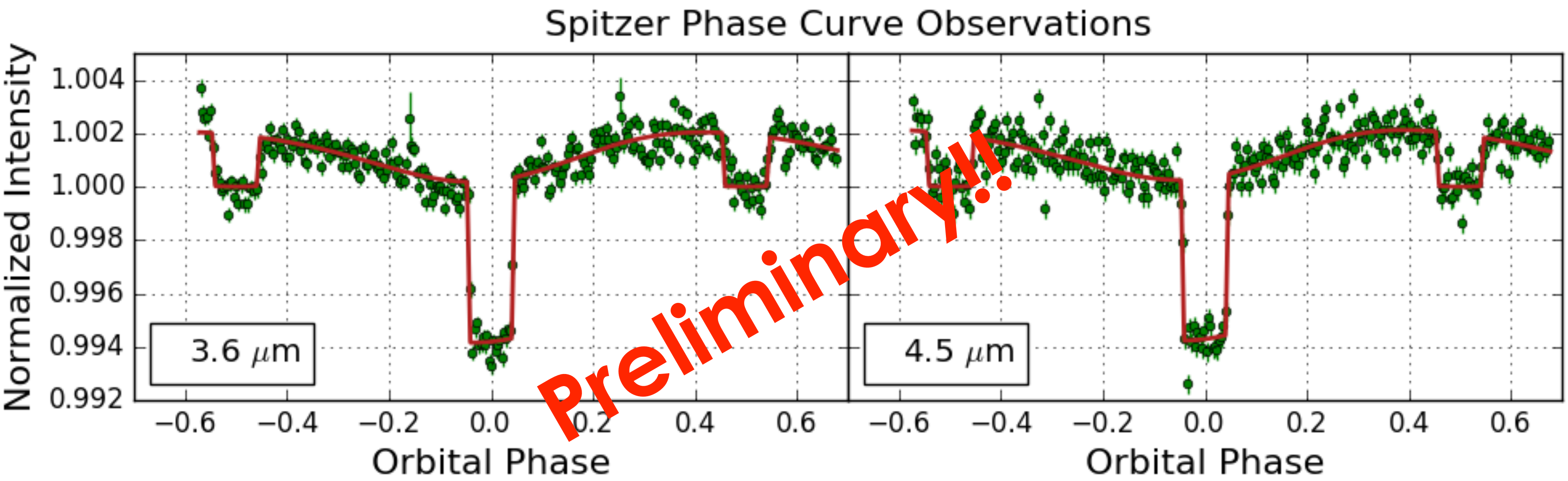
Beatty et al. 2017



Beatty et al. 2014

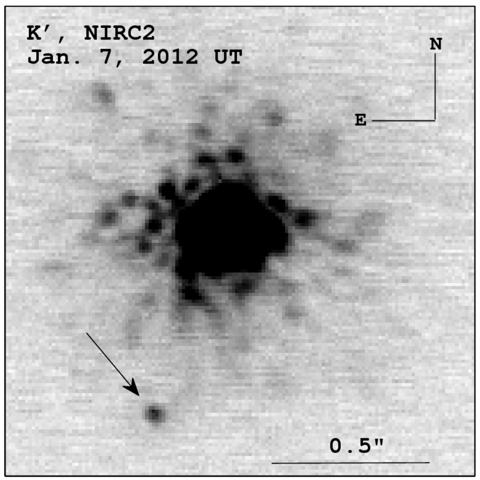
z' band and Spitzer 3.6μm + 4.5μm secondaries (Beatty et al. 2014); K band measurement from (Croll et al. 2014); H band from LBT (Beatty et al. 2017); Just acquired full 3.6μm and 4.5μm phase curves.

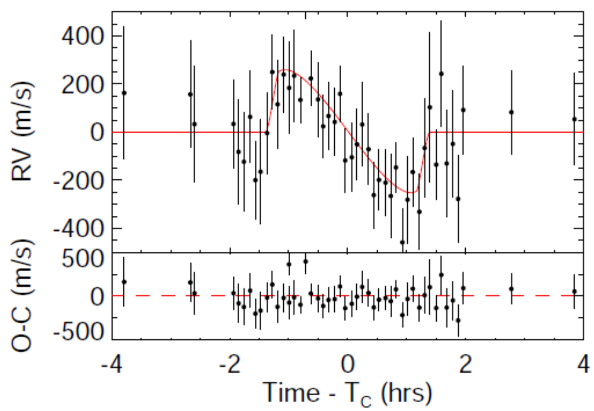
Spitzer phase curve.

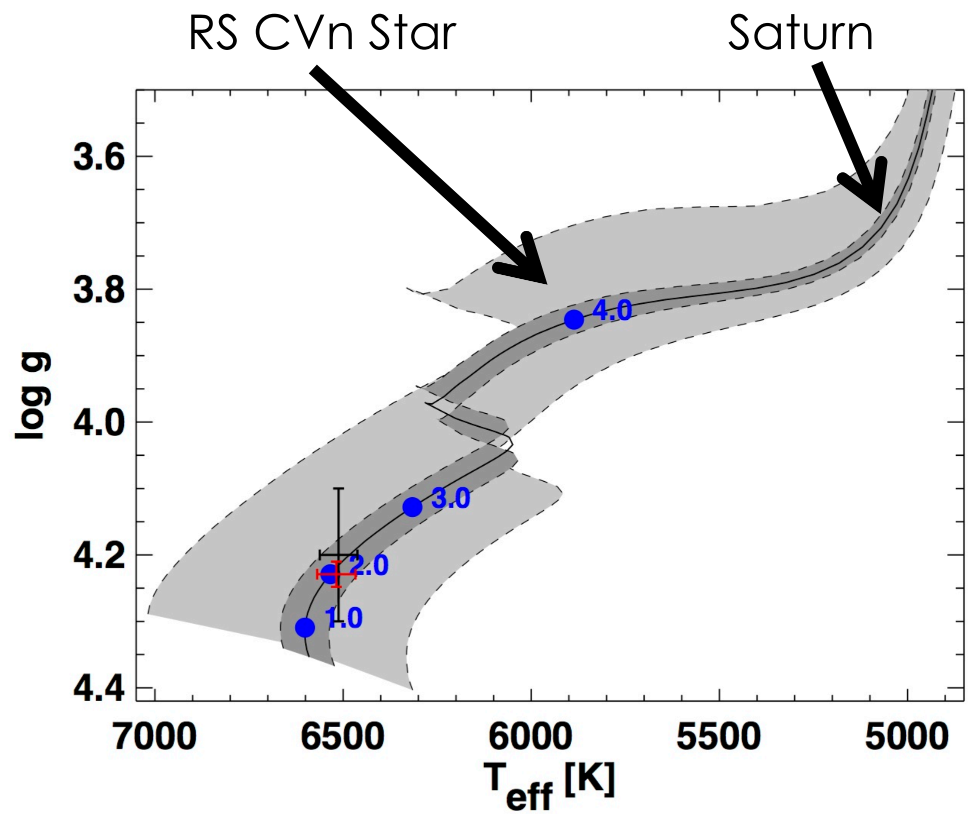


Beatty et al. in prep

Past and future evolution of KELT systems: KELT-1 as an example.







Siverd et al. 2012

KELT-7b KELT-17b

Two Hot Jupiters Orbiting Rapidly Rotating Stars

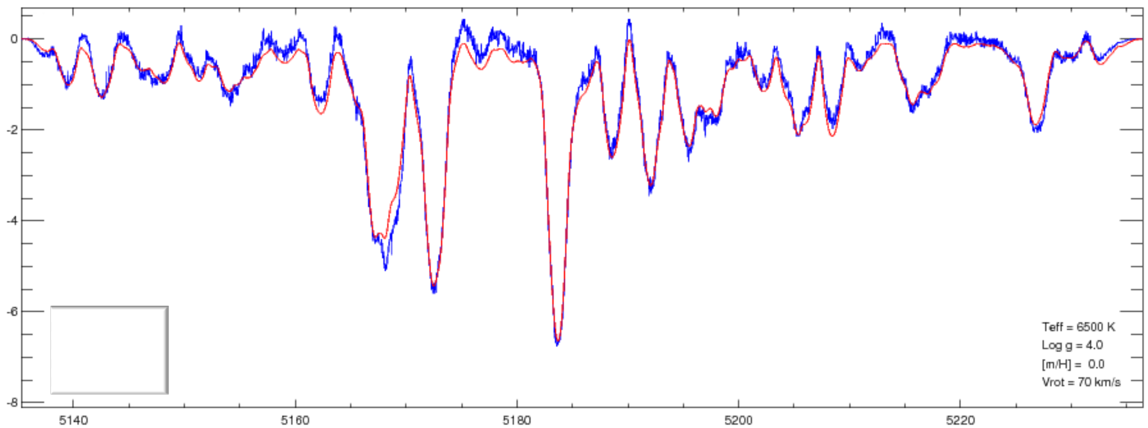
- Planet (KELT-7b)
  - Radius ~ 1.53 R_J
  - Mass ~ 1.28 M_j
  - Period = 2.73 d
  - λ =3^o
- Star (KELT-7)
  - V = 8.5 (HD 33643)
  - Mass = 1.53 $M_\odot$
  - Radius = 1.73 $R_\odot$
  - T_{eff} ~ 6790 K
  - v sin(i) = 65 km/s

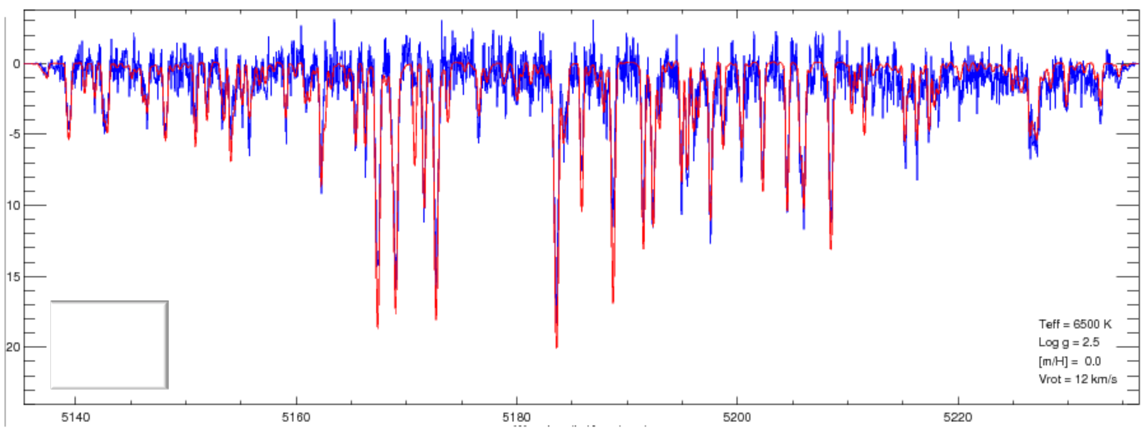
Bieryla et al., 2015

- Planet (KELT-17b)
  - Radius ~ 1.5 R_J
  - Mass ~ 1.3M_j
  - Period ~ 3 d
  - λ =-116^o
- Star (KELT-5)
  - V =9.29
  - Mass: 1.6 $M_\odot$
  - Radius: 2.2 $R_\odot$
  - T_{eff} = 7450K (A star)
  - v sin(i) = 44 km/s

Zhou et al., 2016

The challenge of rapid rotation

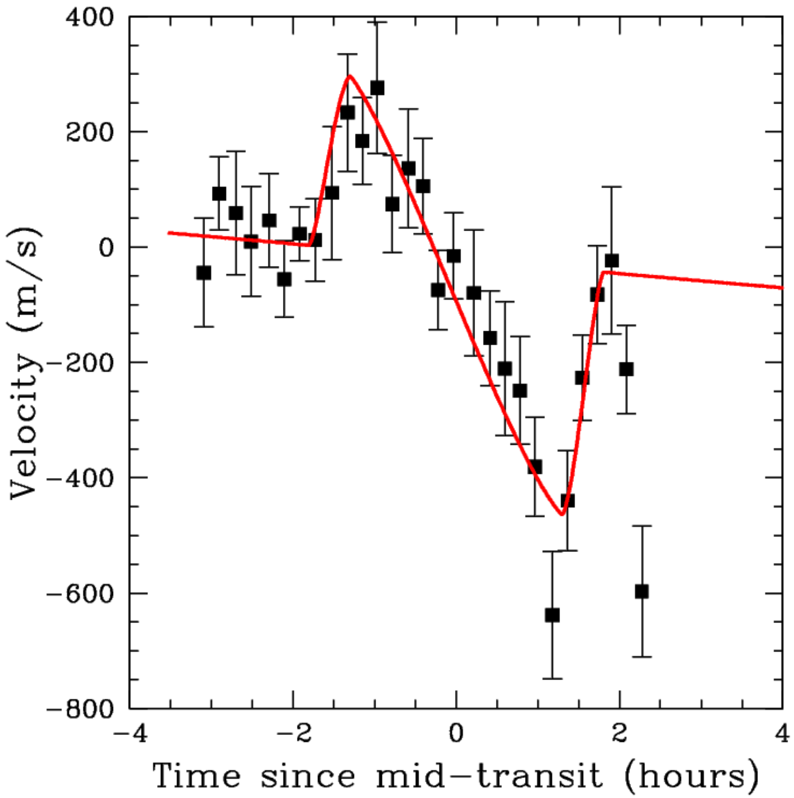




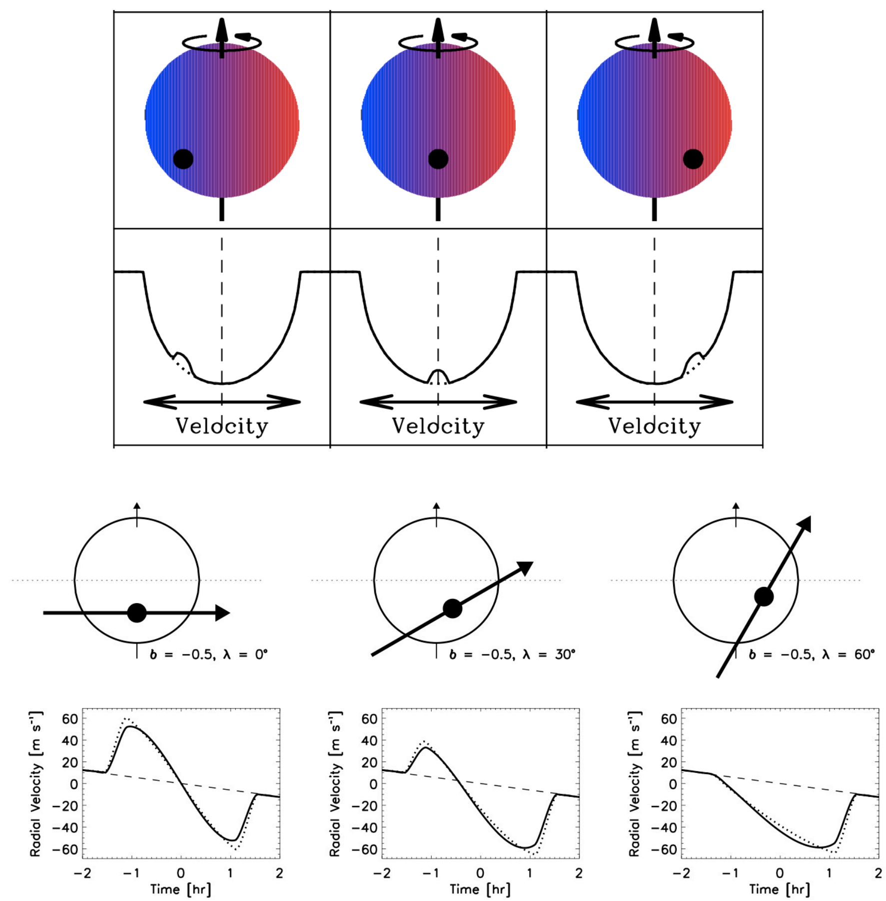
1. Better spectral cross-correlation techniques by Latham, Buchave & Co.

2. Rossiter-McLaughlin verification

KELT-7b: verified by RM measurements



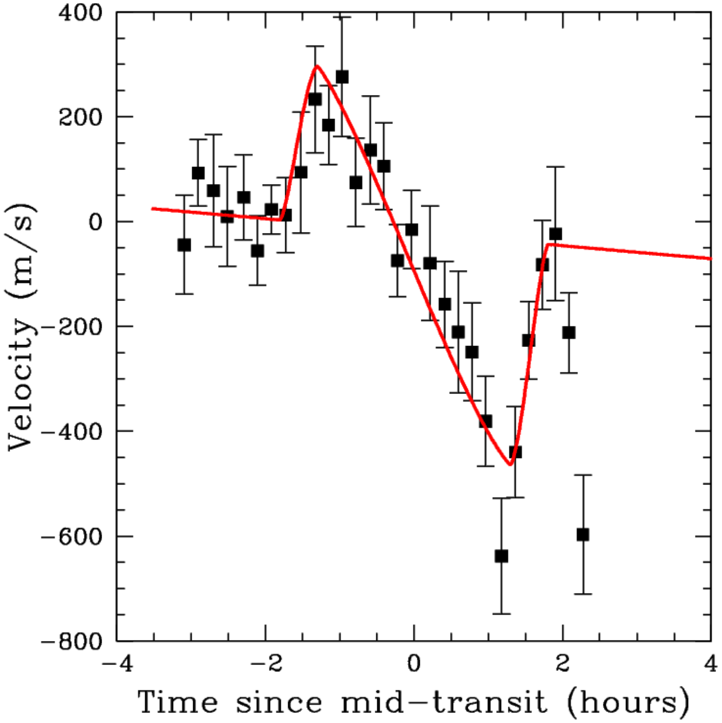
Bieryla et al., 2015



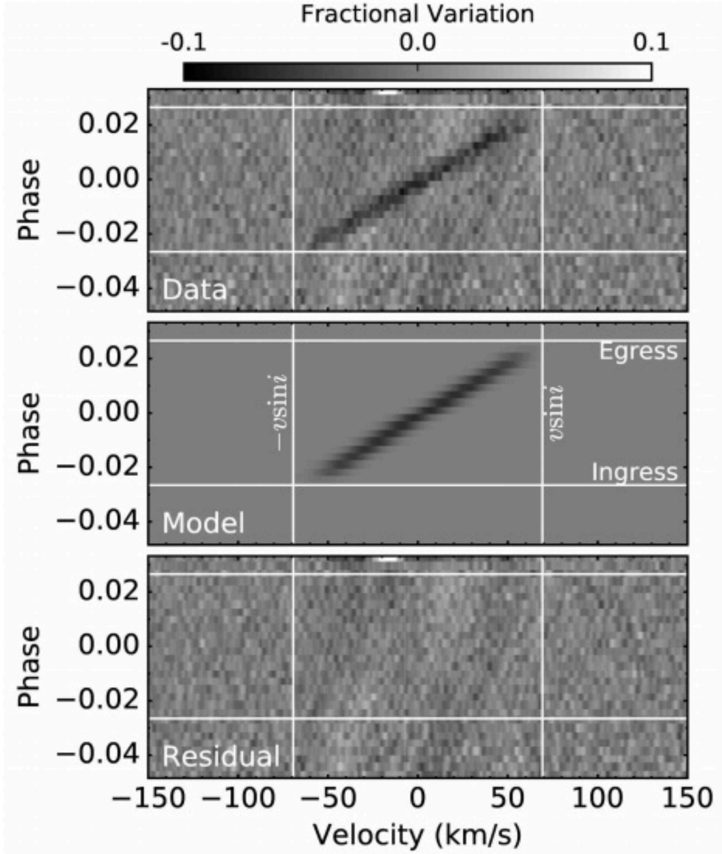
Gaudi & Winn 2007

KELT-7b: verified by RM and DT measurements

(see Collier-Cameron 2010b)

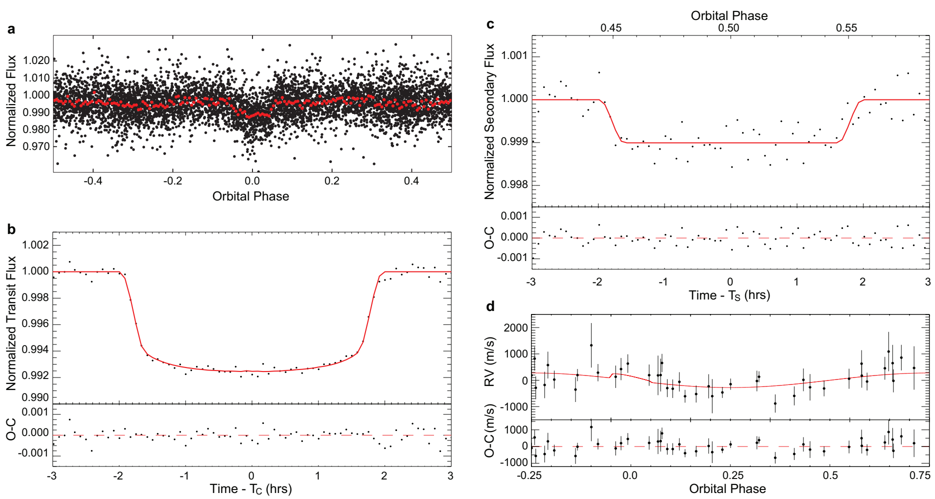


Bieryla et al., 2015



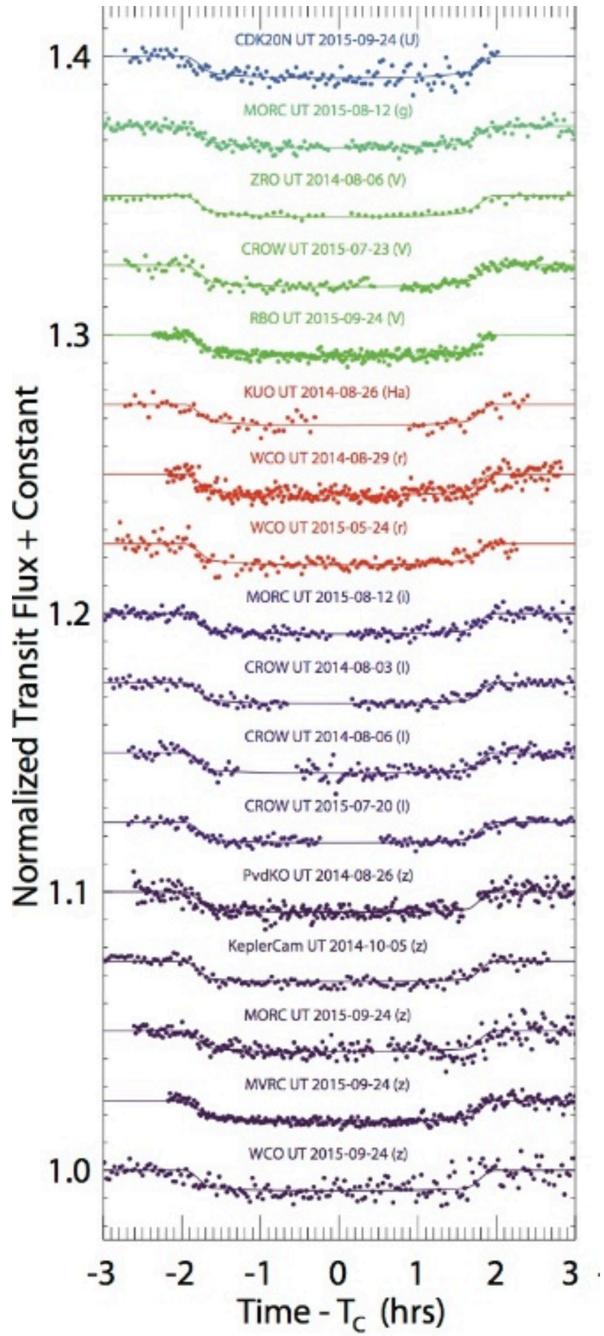
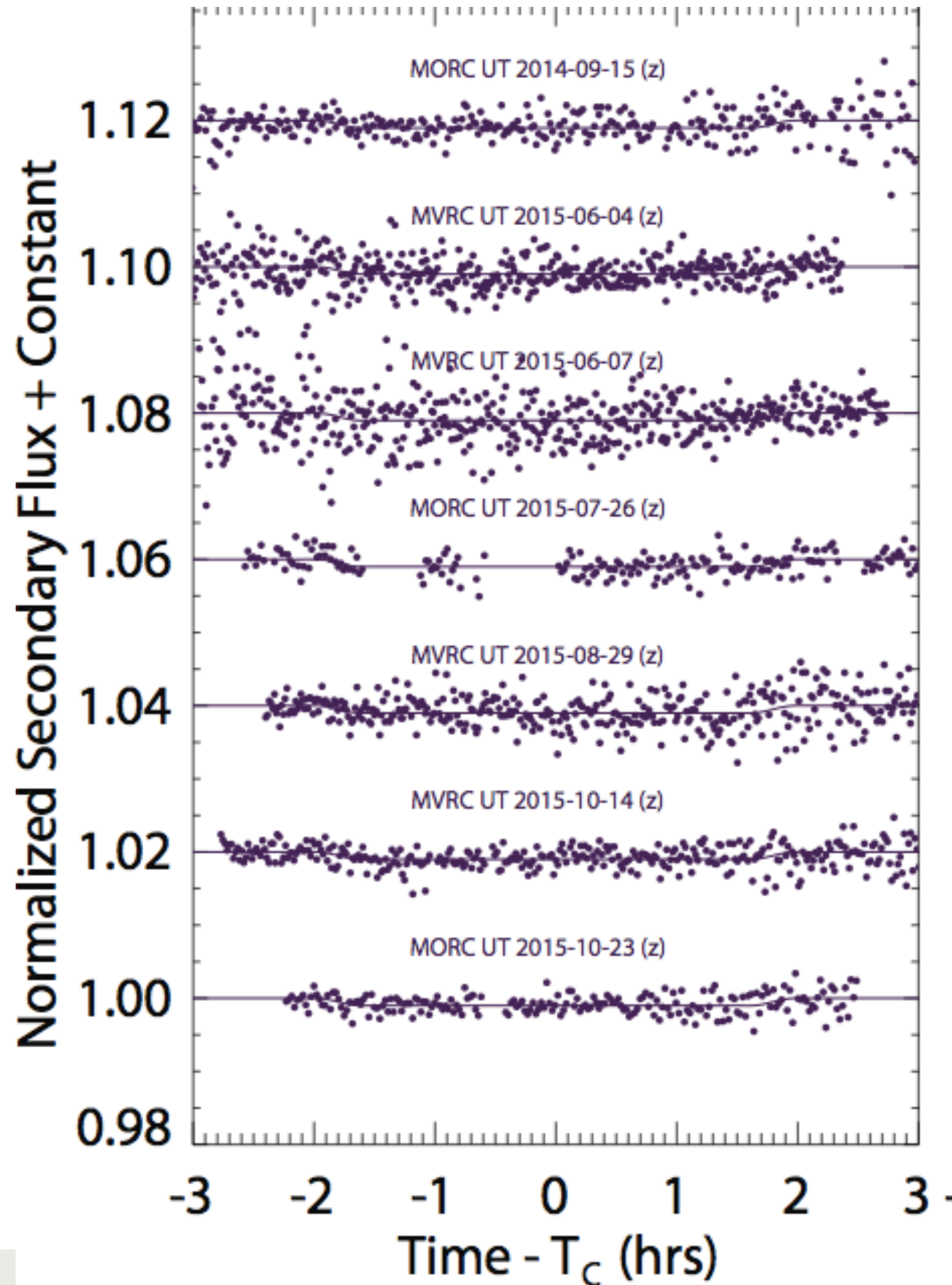
Zhou et al. 2016

KELT-9b: The most irradiated transiting Hot Jupiter.

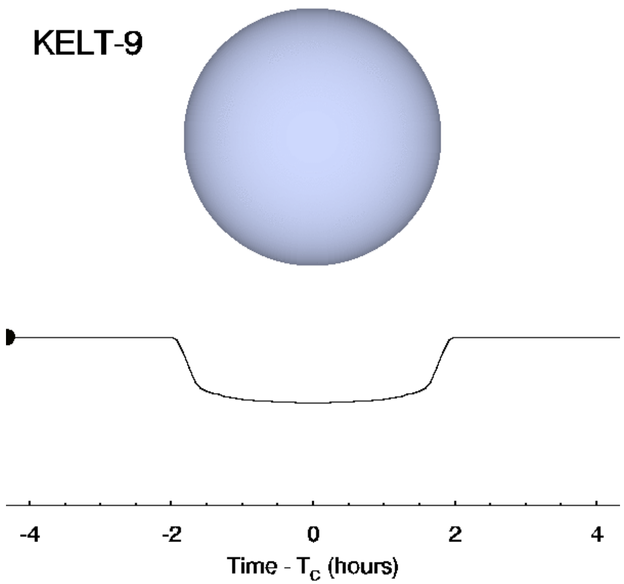


- Planet (KELT-9b)
  - Radius 1.9 R_J
  - Mass 2.9 M_j
  - Period ~ 1.5 d
  - λ =-84.8°
- Star (KELT-9, HD195689)
  - A0, V = 7.56 (!)
  - Mass: 2.5 $M_\odot$
  - Radius: 2.4 $R_\odot$
  - T_{eff} ~10,200K (A0 star)
  - v sin I_* = 100 km/s

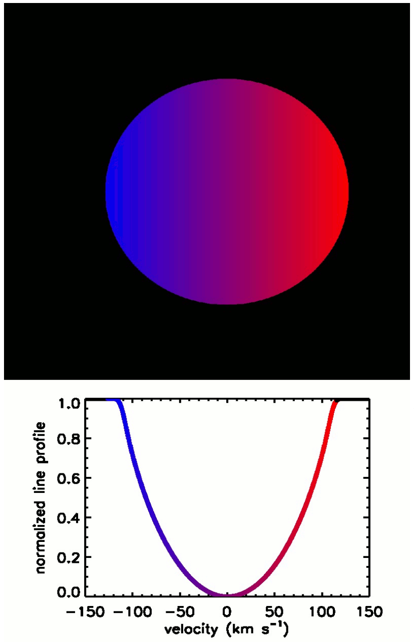
Gaudi, Stassun, Collins, et al., Nature, 2017


CDK20N UT 2015-09-24 (U)
MORC UT 2015-08-12 (g)
ZRO UT 2014-08-06 (V)
CROW UT 2015-07-23 (V)
RBO UT 2015-09-24 (V)
KUO UT 2014-08-26 (Ha)
WCO UT 2014-08-29 (r)
WCO UT 2015-05-24 (r)
MORC UT 2015-08-12 (i)
CROW UT 2014-08-03 (i)
CROW UT 2014-08-06 (i)
CROW UT 2015-07-20 (i)
PvdKO UT 2014-08-26 (z)
KeplerCam UT 2014-10-05 (z)
MORC UT 2015-09-24 (z)
MVRC UT 2015-09-24 (z)
WCO UT 2015-09-24 (z)
1.4
1.3
1.2
1.1
1.0
Normalized Transit Flux + Constant
-3
-2
-1
0
1
2
3
Time - T$_C$ (hrs)

MORC UT 2014-09-15 (z)
MVRC UT 2015-06-04 (z)
MVRC UT 2015-06-07 (z)
MORC UT 2015-07-26 (z)
MVRC UT 2015-08-29 (z)
MVRC UT 2015-10-14 (z)
MORC UT 2015-10-23 (z)
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
Normalized Secondary Flux + Constant
-3
-2
-1
0
1
2
3
Time - T$_C$ (hrs)

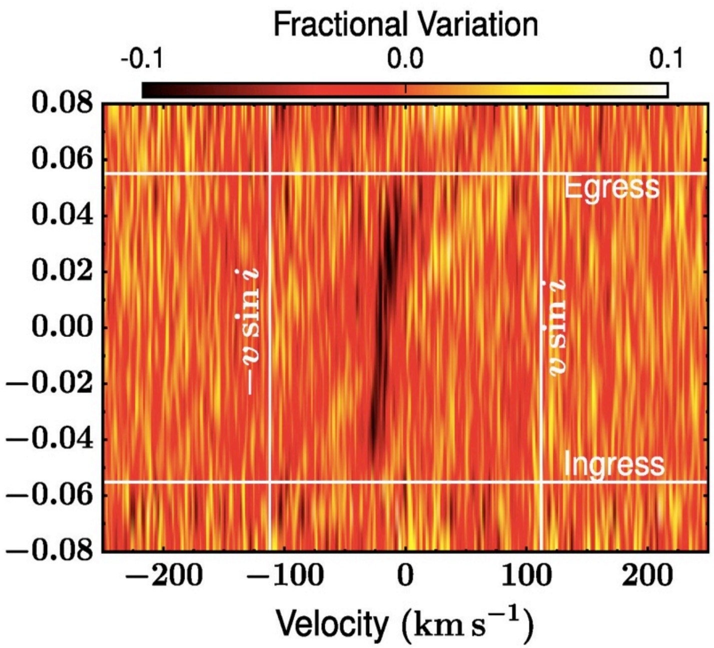
KELT-9b's Pathological R-M Signal.



Credit: Steven Villanueva

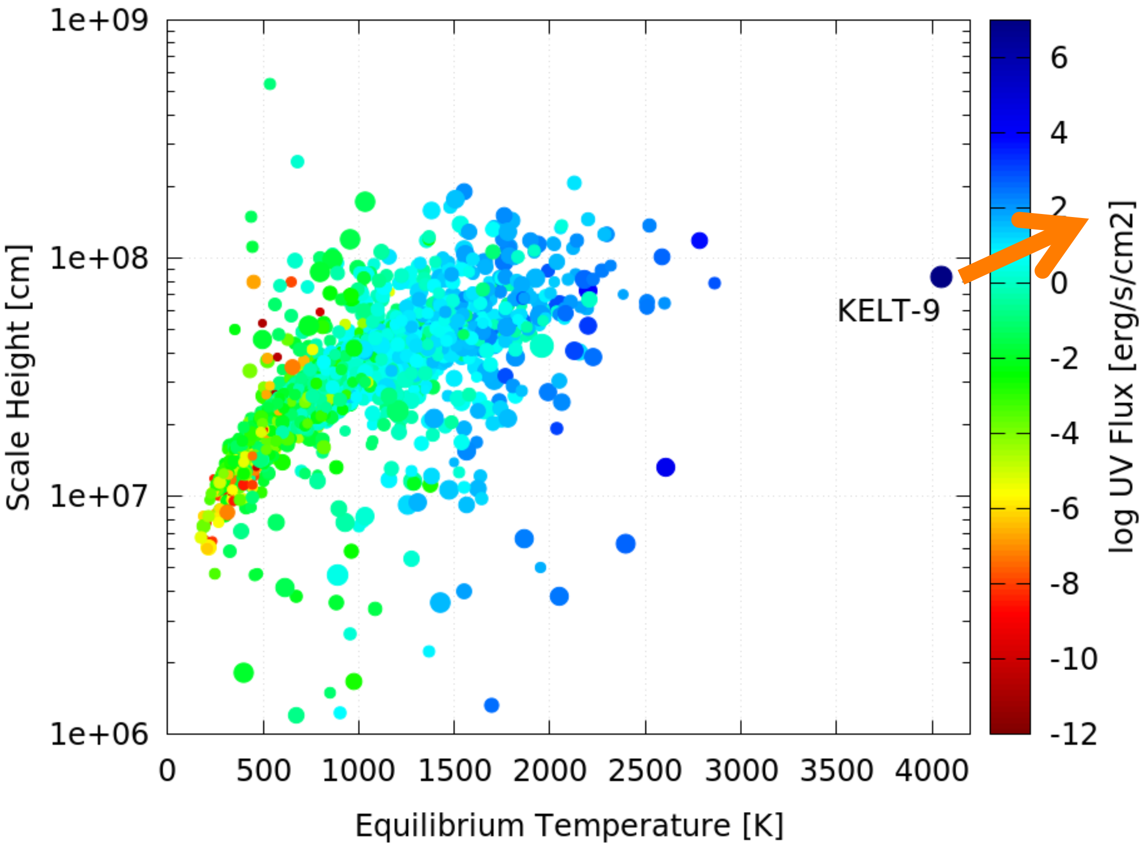


Credit: Marshall Johnson



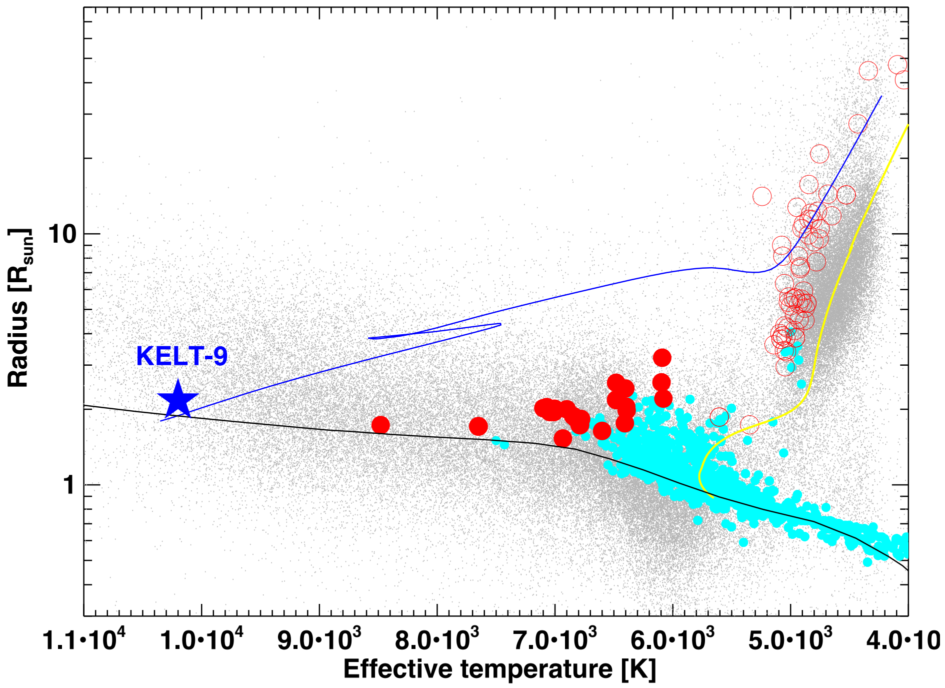
Credit: George Zhou

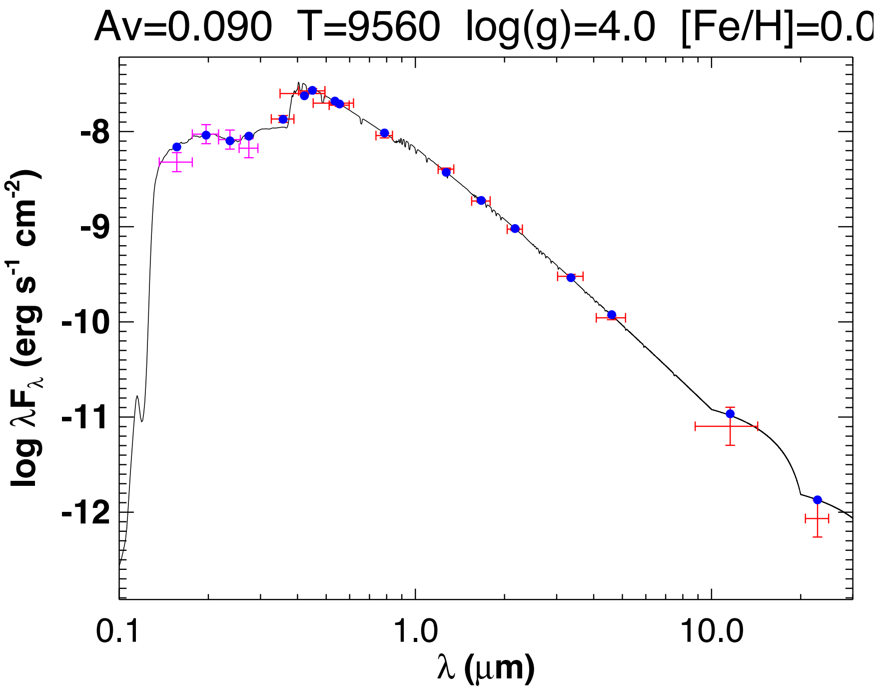
Highly Irradiated



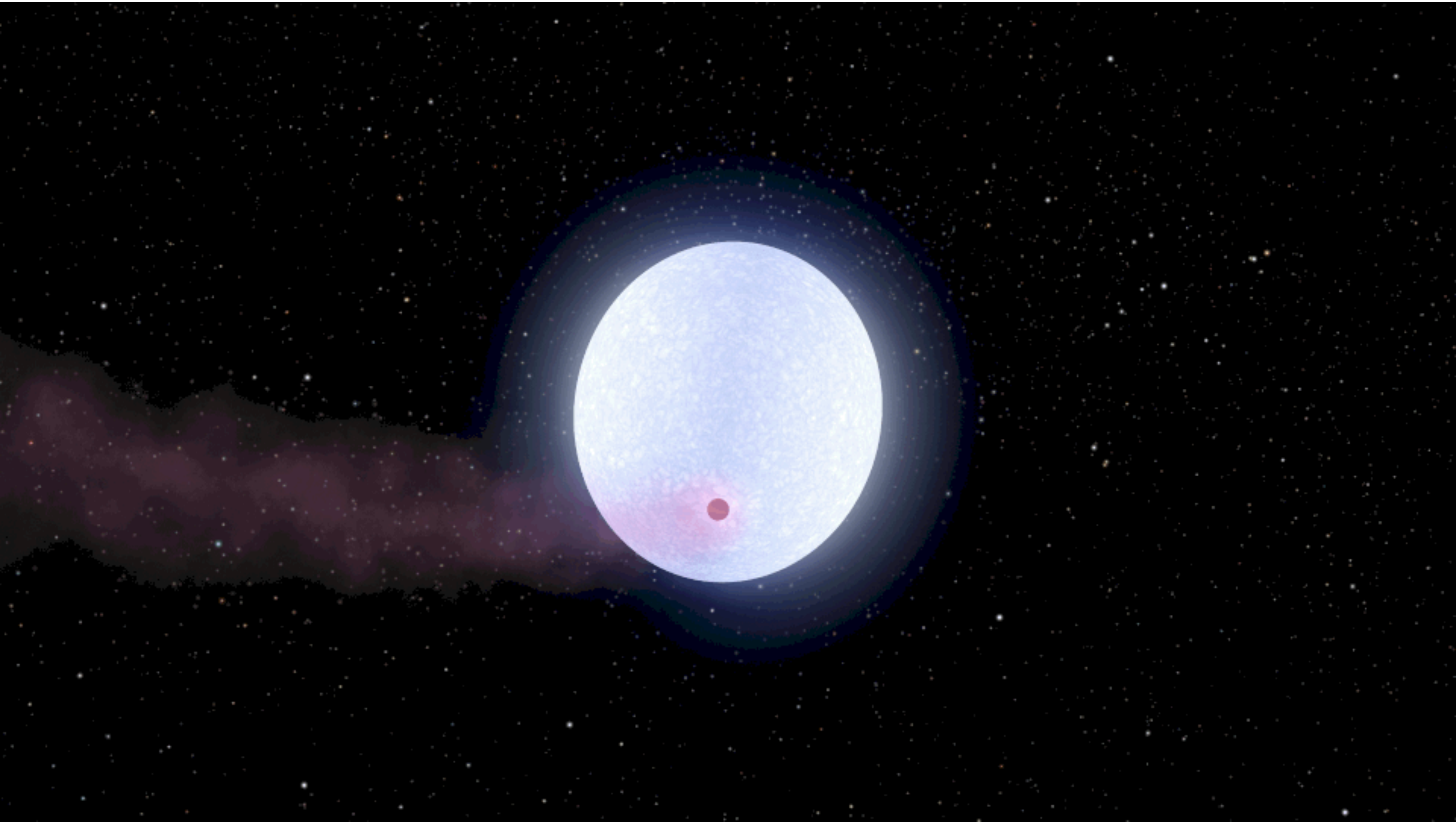
- **Detection of secondary eclipse likely implies poor redistribution**
- **Day-side temperature similar to a K spectral type**
- **Therefore most opacity sources are atomic metals (not molecules)**

Progenitor of a "Retired A Star"





Future fate uncertain!



KELT-9b: Gas giant planet hotter than most stars

- Brightest, hottest, most massive known transiting giant planet host.
- The hottest gas giant yet discovered.
- 1.5 day orbit ~perpendicular to equator of its host star.
- Dayside hotter than most stars.
- Planet receives 700x more ultraviolet radiation than any other giant planet.
- Planet is likely evaporating due to high-energy radiation.
- Prospects for follow-up with ground-based telescopes, HST, Spitzer, JWST are bright.

LETTER

doi:10.1038/nature22392

A giant planet undergoing extreme-ultraviolet irradiation by its hot massive-star host

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The amount of ultraviolet irradiation and ablation experienced by a planet depends strongly on the temperature of its host star. Of the thousands of extrasolar planets now known, only six have been found that transit hot, A-type stars (with temperatures of 7,300–10,000 kelvin), and no planets are known to transit the even hotter B-type stars. For example, WASP-33 is an A-type star with a temperature of about 7,430 kelvin, which hosts the hottest known transiting planet, WASP-33b (ref. 1); the planet is itself as hot as a red dwarf star of type M (ref. 2). WASP-33b displays a large heat differential between its dayside and nightside[2], and is highly inflated–traits that have been linked to high insolation[3,4]. However, even at the temperature of its dayside, its atmosphere probably resembles the molecule-dominated atmospheres of other planets and, given the level of ultraviolet irradiation it experiences, its atmosphere is unlikely to be substantially ablated over the lifetime of its star. Here we report observations of the bright star HD 195689 (also known as KELT-9), which reveal a close-in (orbital period of about 1.48 days) transiting giant planet, KELT-9b. At approximately 10,170 kelvin, the host star is at the dividing line between stars of type A and B, and we measure the dayside temperature of KELT-9b to be about 4,600 kelvin. This is as hot as stars of stellar type K4 (ref. 5). The molecules in K stars are entirely dissociated, and so the primary sources of opacity in the dayside atmosphere of KELT-9b are probably atomic metals. Furthermore, KELT-9b receives 700 times more extreme-ultraviolet radiation (that is, with wavelengths shorter than 91.2 nanometres) than WASP-33b, leading to a predicted range of mass-loss rates that could leave the planet largely stripped of its envelope during the main-sequence lifetime of the host star[6].

The first transiting planets were discovered around cool, solar-type stars[7,8], primarily because hot stars have few spectral lines and rotate rapidly, making Doppler confirmation of planets more difficult. Only in the past few years have transiting planets been confirmed around hot stars of types early-F and A[9,10], inspired by the discovery of WASP-33b[1]. That discovery demonstrated that it is possible to confirm transiting planets around rapidly rotating hot stars via a combination of relatively low-precision radial-velocity measurements and Doppler tomography. However, even the hottest of these few A-type transiting-planet host stars reach temperatures of only about 7,500 K. Thus, although transit surveys, in particular Kepler[11], have extended the census of planets around low-mass stars, our understanding of planets around massive, hot stars remains poor.

Massive stars cool and spin down as they evolve, enabling precise Doppler measurements. Thus the primary strategy to search for planets around high-mass stars has been surveys of 'retired A-stars'[12], high-mass stars that have already evolved into subgiant and giant stars. These stars have revealed a paucity of short-period giant planets relative to

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THE EYES HAVE IT

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Summary of Discoveries.

- Home Runs:
  - KELT-1b (Siverd et al. 2012)
    - M_p=27 M_J, P = 1.22d
  - KELT-9b (Gaudi et al., 2017)
    - M_p=2.8 M_J, P = 1.5d, T_{eff}~10,000K, T_{day}~4600 (K4 star), V=7.6
  - KELT-21b (Lund et al., submitted)
    - P=3.5d, T_{eff}~8700K, T_{day}~2250K, V=7.6,
  - KELT-11b (Pepper et al. 2017, Beatty et al. 2016)
    - V=8 subgiant, M_p=0.2 M_J, R_p=1.4R_J, Spitzer primary, Gaia parallax -> M_*~$_{2Sun}$
  - KELT-4Ab (Eastman et al. 2016)
    - R_p=1.7 R_J, in a hierarchical triple
  - KELT-6b (Collins et al. 2014)
    - P=7.9d hot Saturn with a metal-poor host
  - KELT-7b (Bieryla et al. 2015), KELT-17b (Zhou et al. 2016)
    - V=8.5, T_{eff}=6800K; V=9.2, T_{eff}=7500K
  - KELT-8b (Fulton et al. 2015) & KELT-12b (Stevens et al. 2017)
    - R_p=1.9R_J; R_p=1.8R_J
  - KELT-16b (Oberst et al. 2017)
    - P=0.97d (within 45 minutes within a sideral day)
  - KELT-17b (McLeod et al. 2017)
    - P=2.87d, V=10.1, F4V host, T_{eff}=6700K, M_p=1.2 M_J, R_p=1.5R_J, companion

KELT in the era of TESS.

- Transiting Exoplanet Survey Satellite.
  - 24° x 24° FOV (26° x 26°)
  - 100mm aperture (42mm KELT)
- FOV, aperture, and magnitude well-matched to KELT.
- KELT will provide an input list of eclipsing companions with radius > R_J.
- KELT “precovery” of single and two-transit events.
- Experience with hot, rapidly rotating stars will be useful.