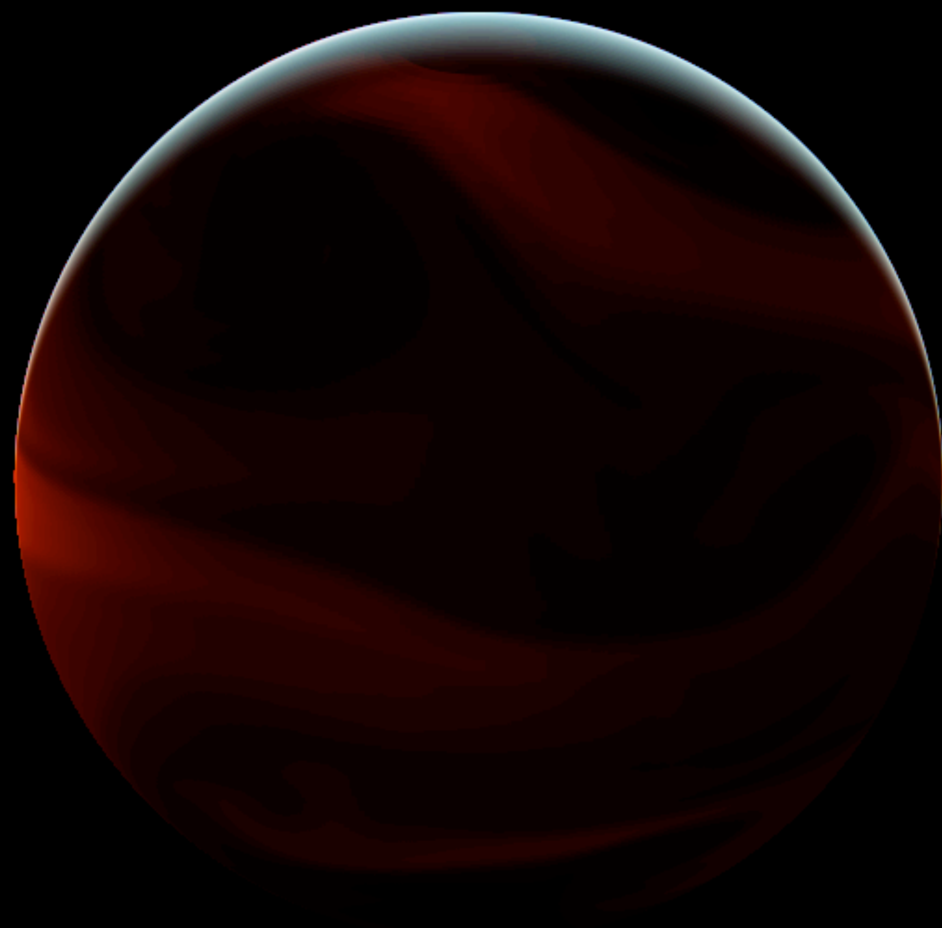
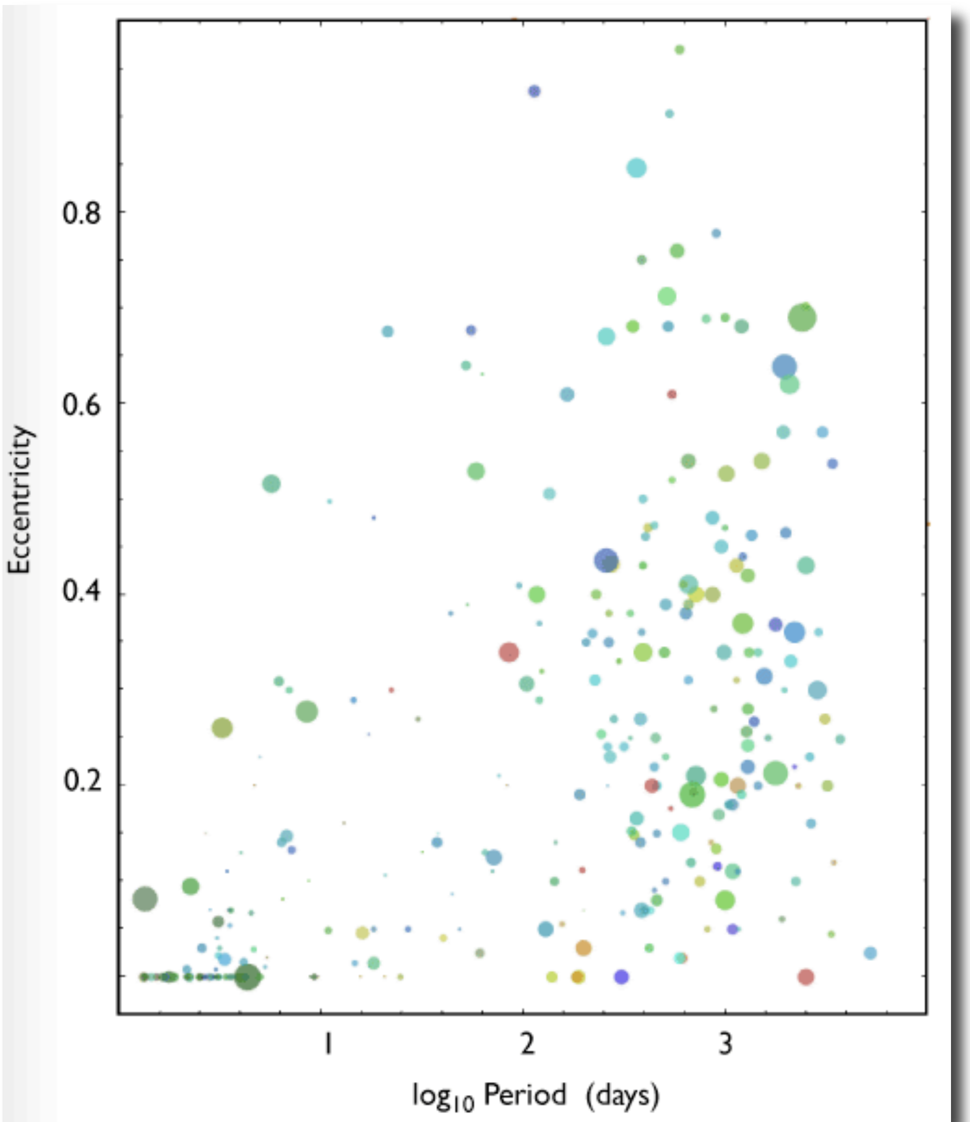
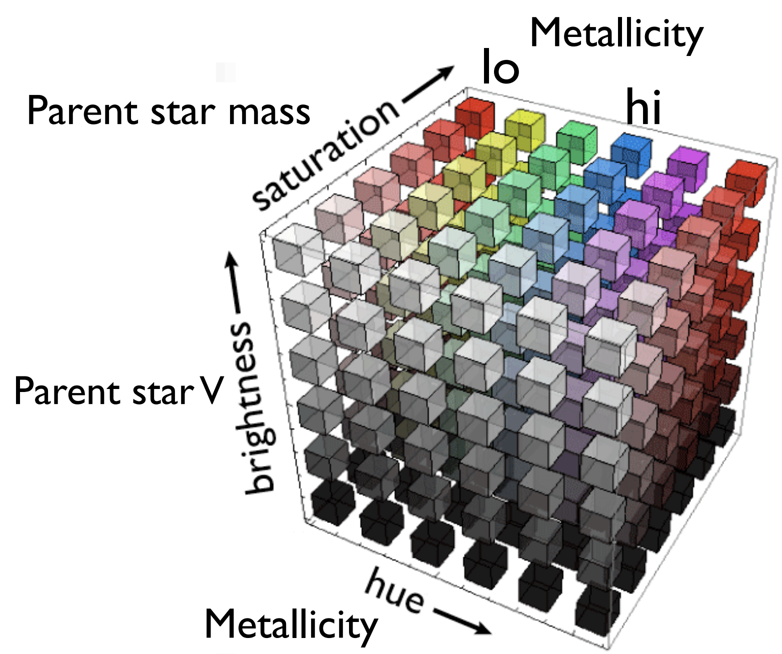
The Thermal and Dynamical Properties of





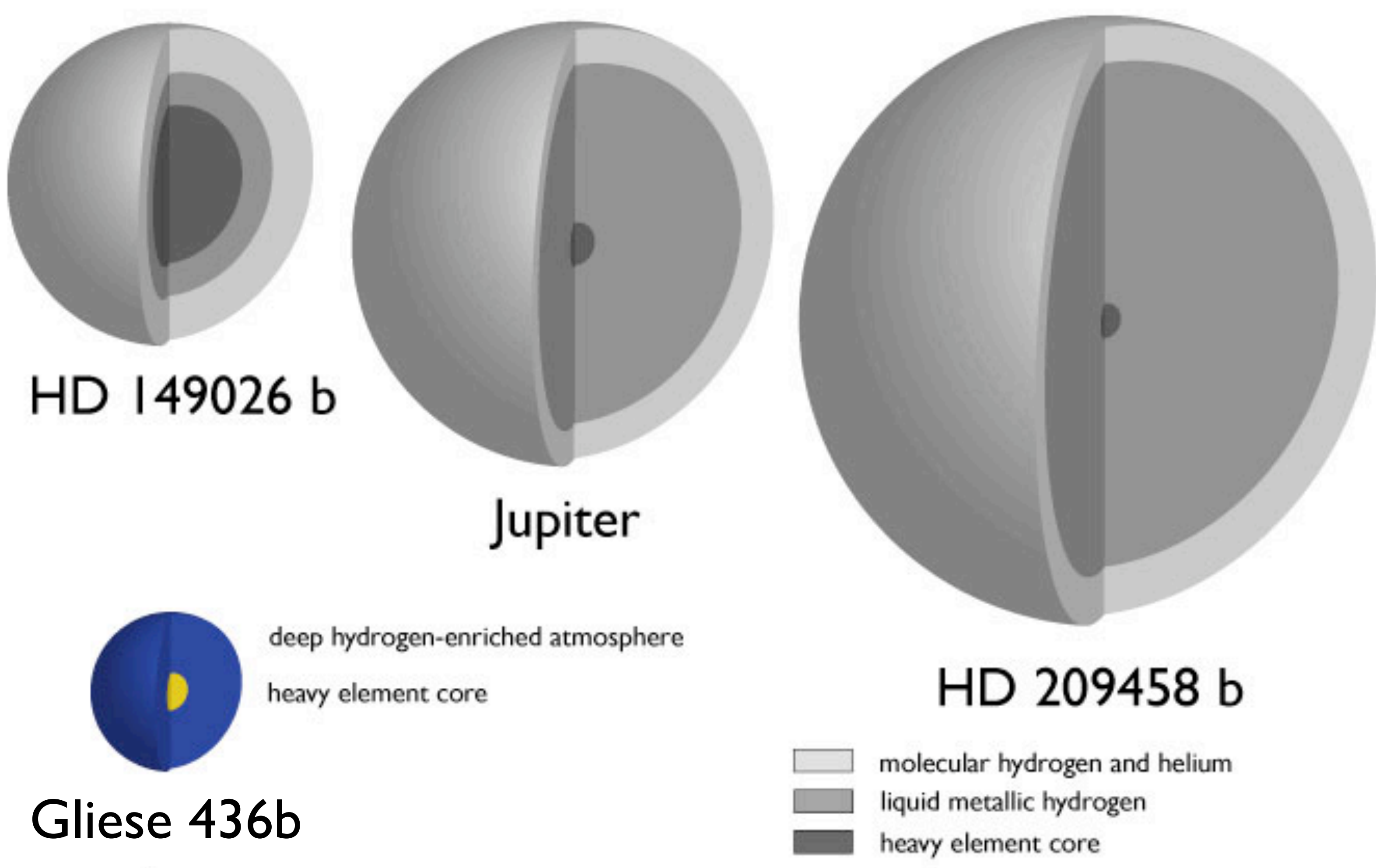
6D correlation diagram for extrasolar planets

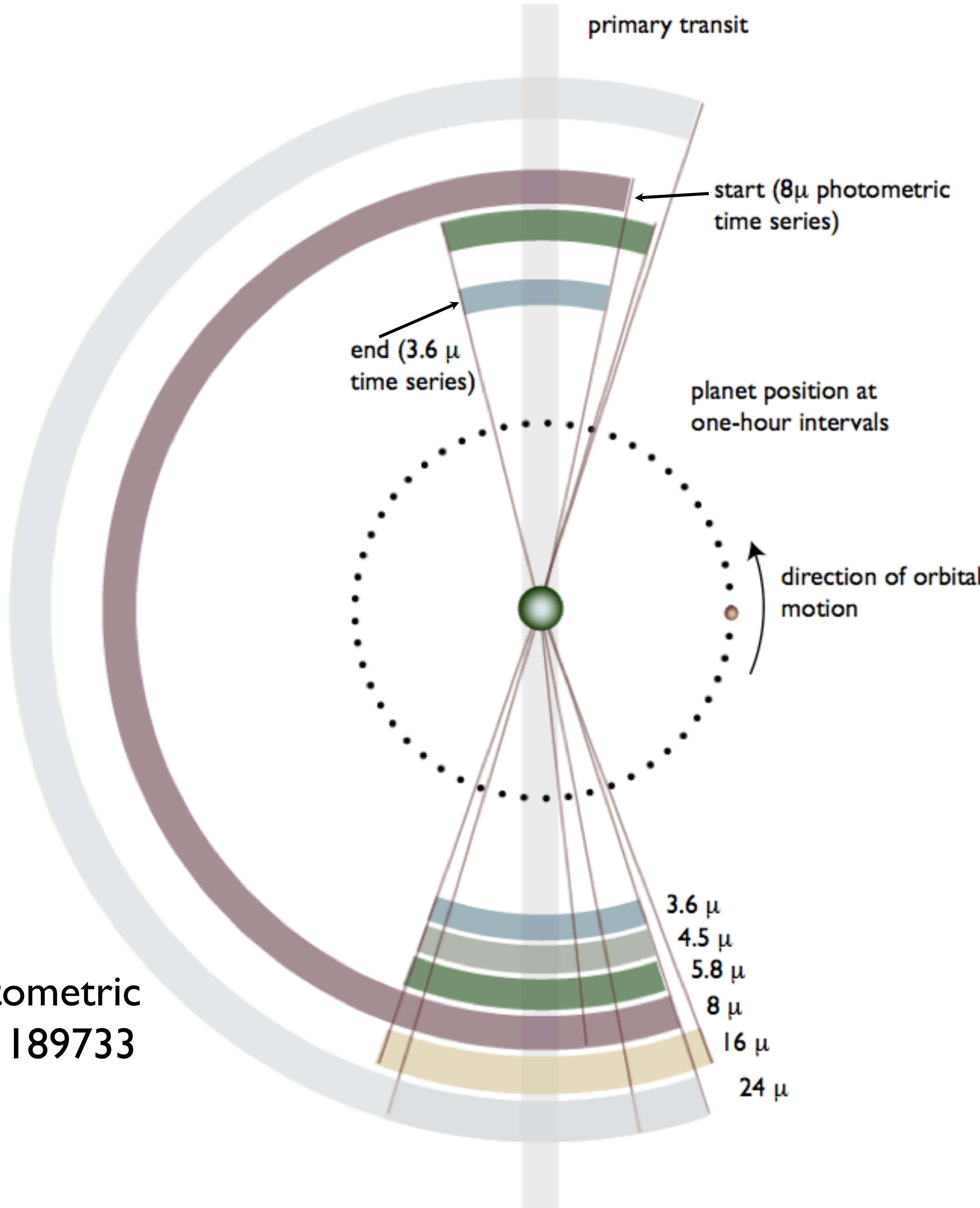


(*First of 33 slides*)

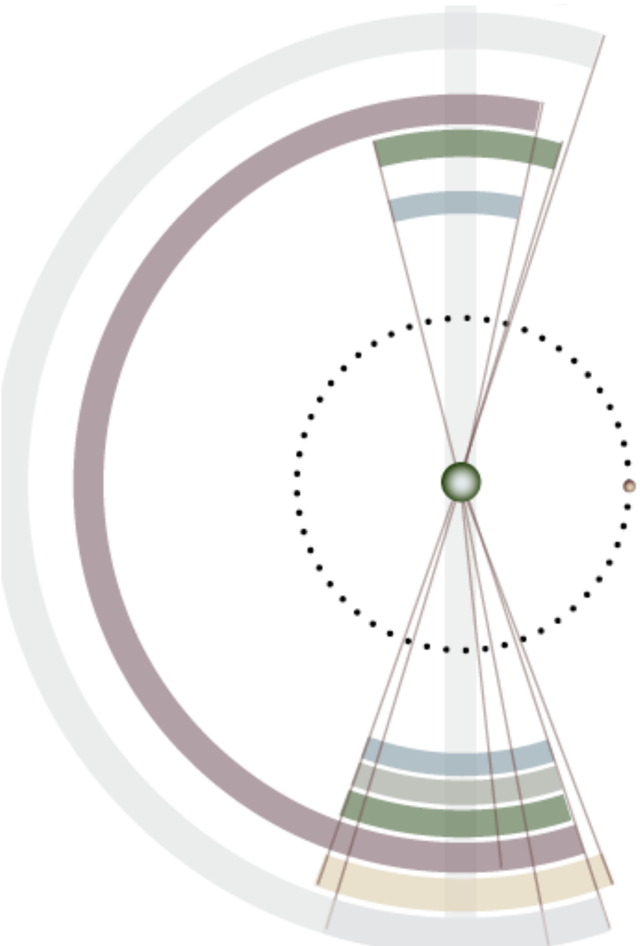
Parent star mass

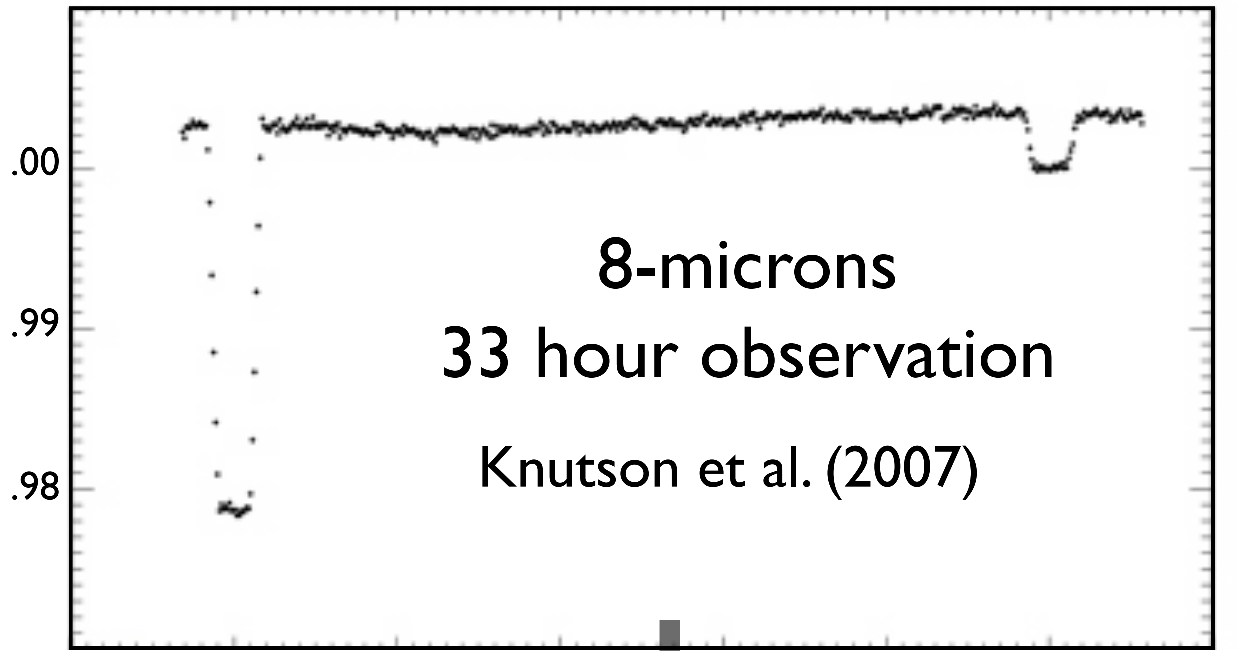
Planetary mass and insolation are *not* fully correlated with observed planetary radii.

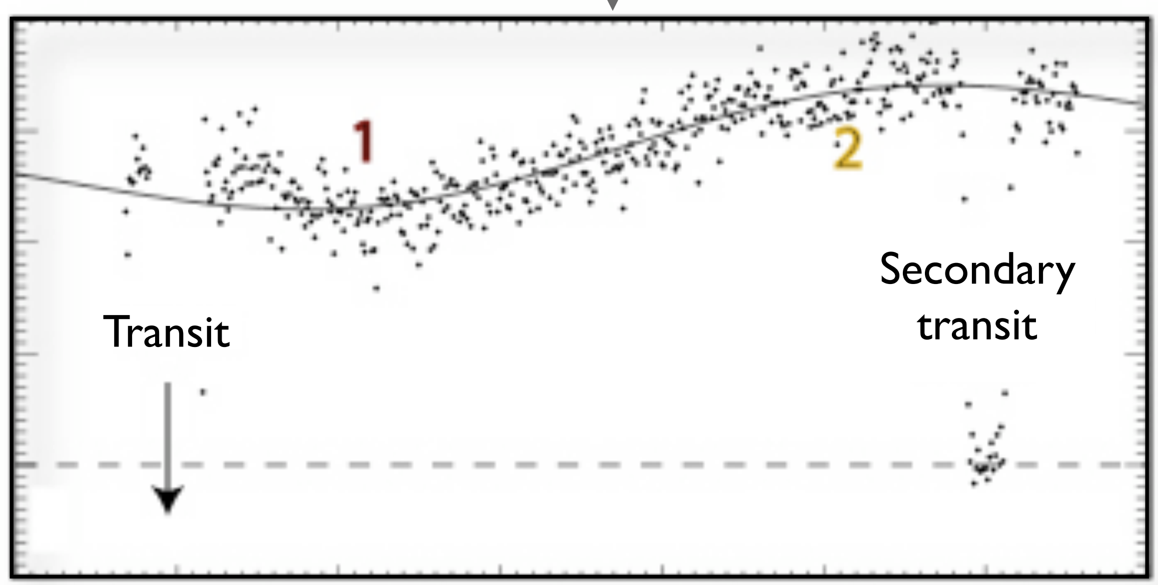


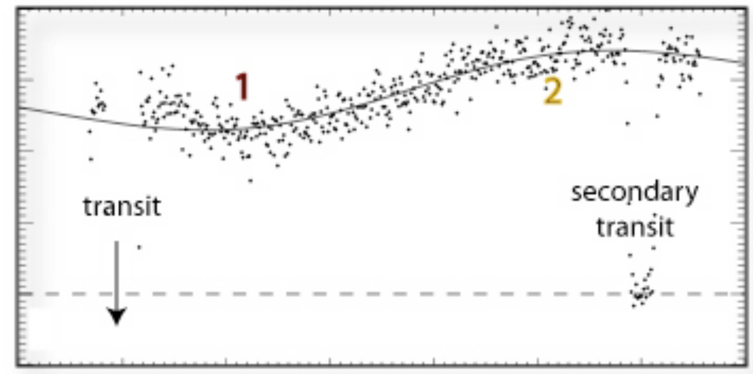


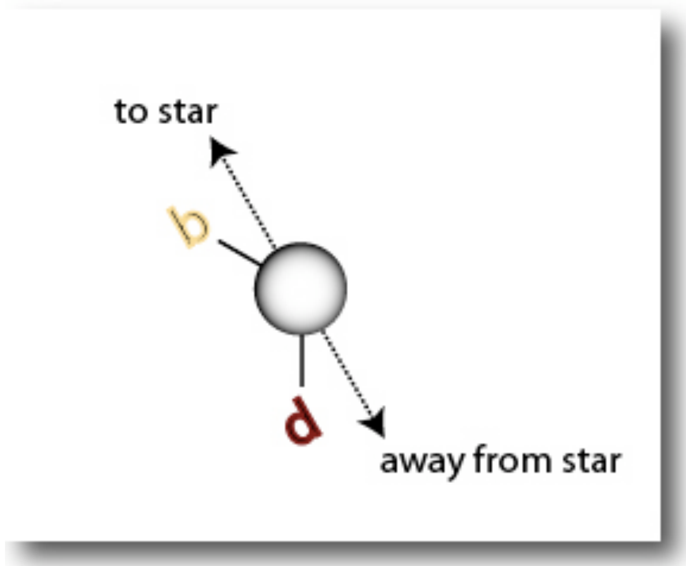
Cold Spitzer's Photometric Campaigns on HD 189733

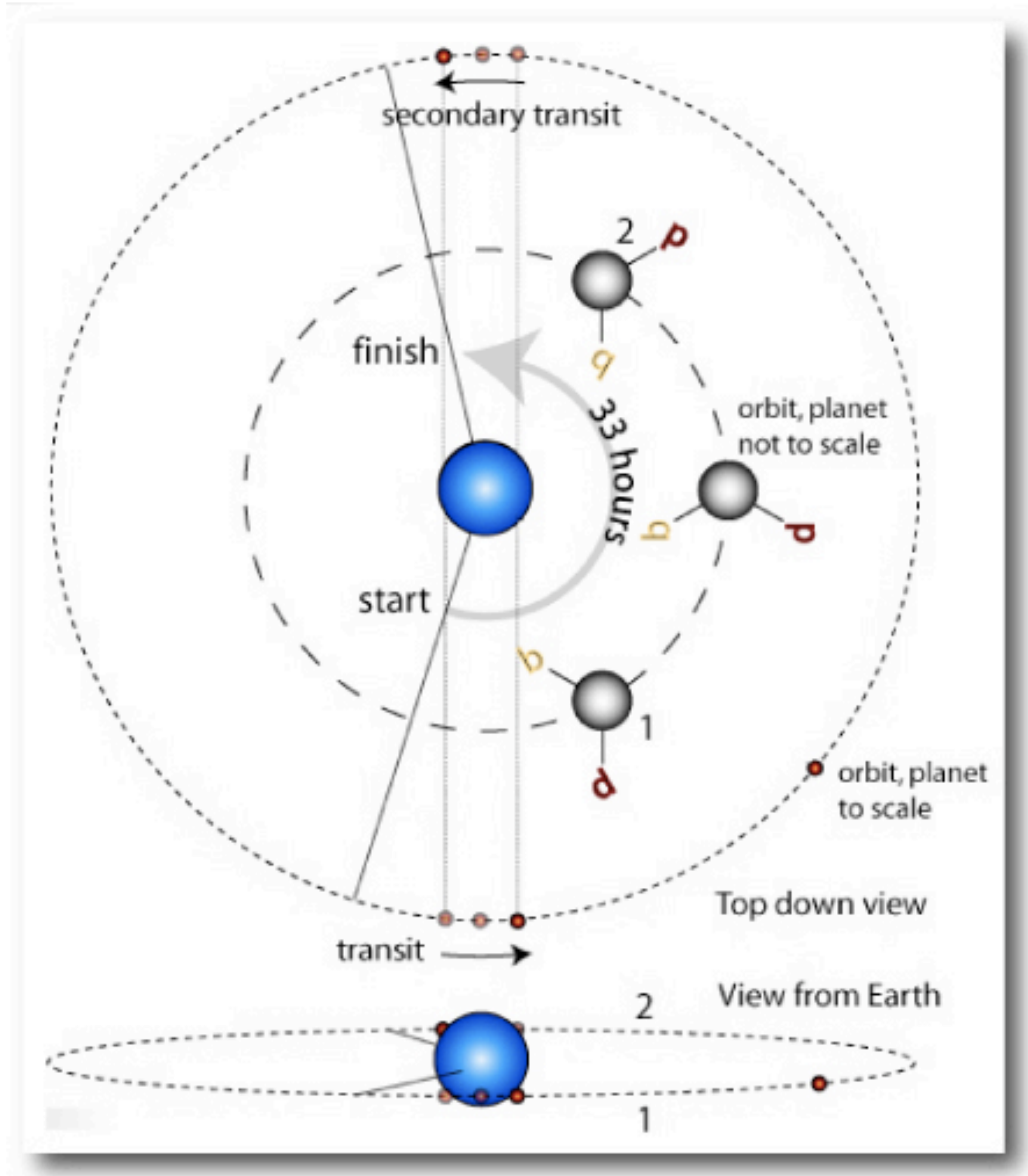



.00
.99
.98
8-microns
33 hour observation
Knutson et al. (2007)

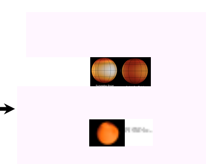

1
2
Transit
Secondary
transit







Interpretation of the result: Hottest and coldest spots are on the same side of the planet. First resolved "image" of an extrasolar planet. →



Strategy: Adopt a "back-of-the-envelope" computational model to interpret the one-pixel satellite weather videos.

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla \mathbf{v} - \left(\frac{\alpha_2 (1 - \alpha_2/2)}{(1 - \alpha_2)^2} \right) \mathbf{v} \nabla \cdot \mathbf{v} - R \alpha_1 \nabla T - 2 \Omega_{\rm rot} \sin\theta (\hat{n} \times \mathbf{v})$$

$$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T - k \left(\frac{1 - \alpha_2/2}{1 - \alpha_2} \right) T \nabla \cdot \mathbf{v} + f_{\rm rad}.$$

$$\alpha_1 \equiv \ln(p_b/p)$$

$$\alpha_2 \equiv 1/(1 + \alpha_1)$$

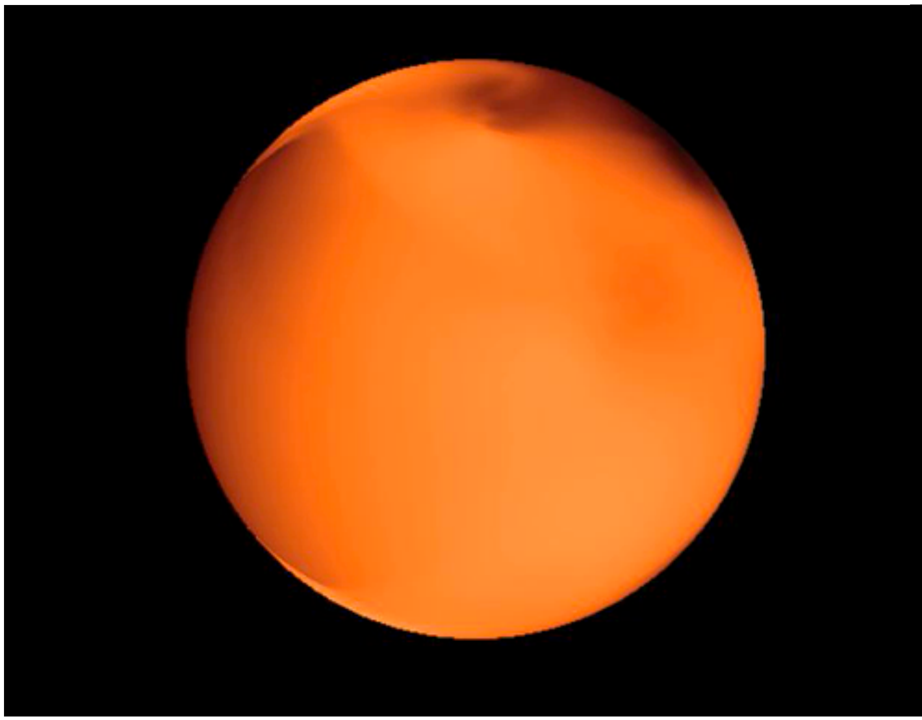
$$F_{\rm pen} = (1 - A)(1 - X) \left(\frac{L_*}{16 \pi a^2 \sqrt{1 - e^2}} \right)$$

$$T_{\rm n} = \left(\frac{F_{\rm pen}}{\sigma} + T_{\rm int}^4 \right)^{1/4}$$

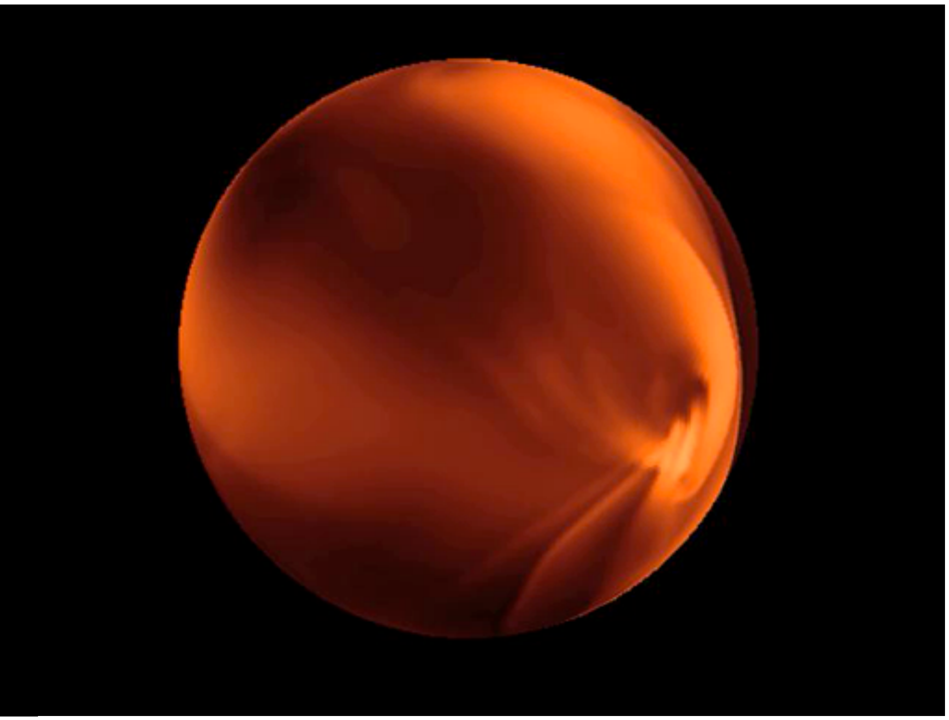
$$f_{\rm rad} = \left(\frac{\sigma g}{p c_p} \right) \left(X (1 - A) \left(\frac{L_*}{4 \pi \sigma a^2} \right) \cos\alpha + T_{\rm n}^4 - T^4 \right).$$

X = fraction of incoming flux absorbed at or above the IR photosphere.

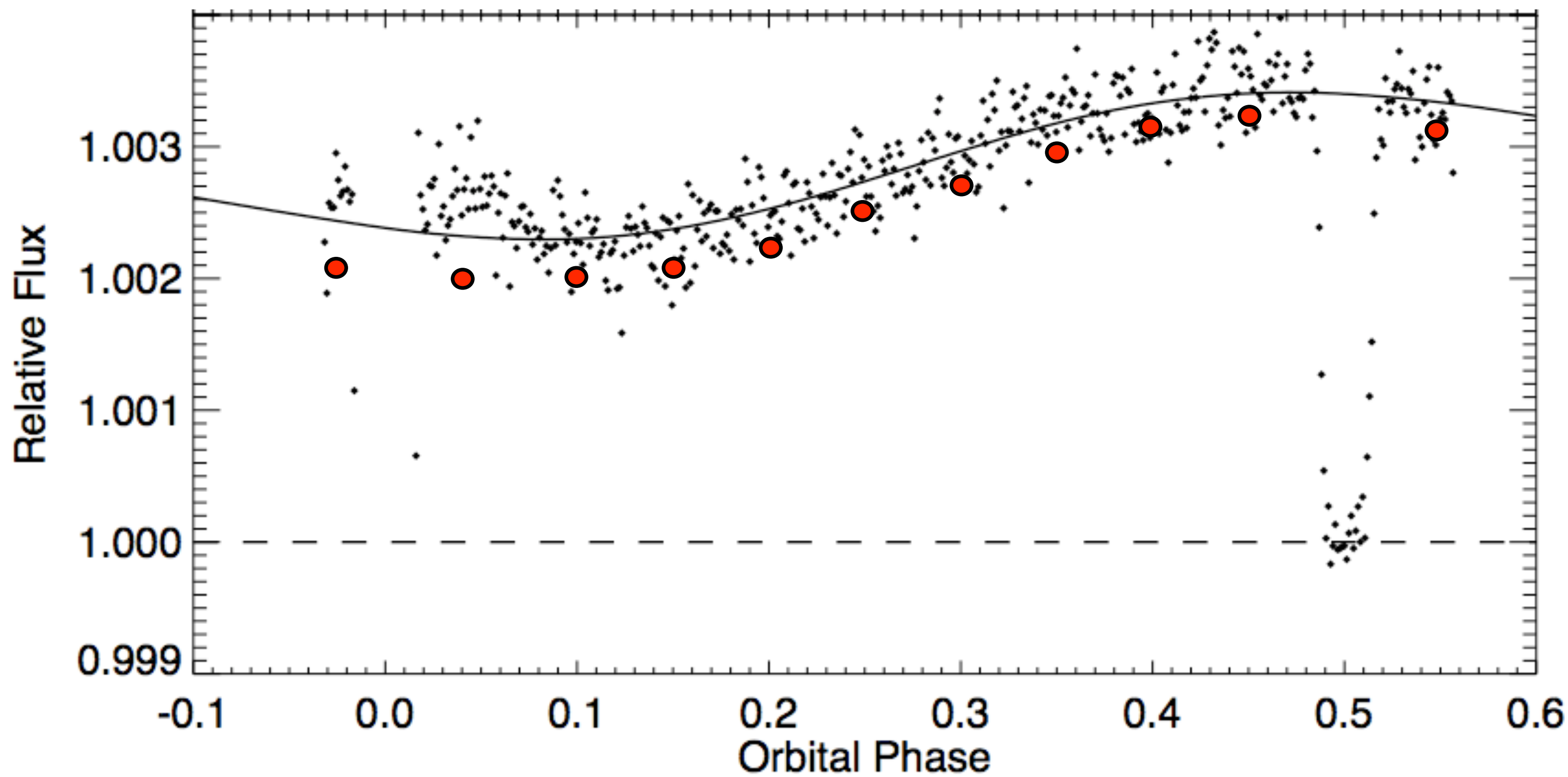
p = atmospheric pressure at the IR photosphere



Day Side



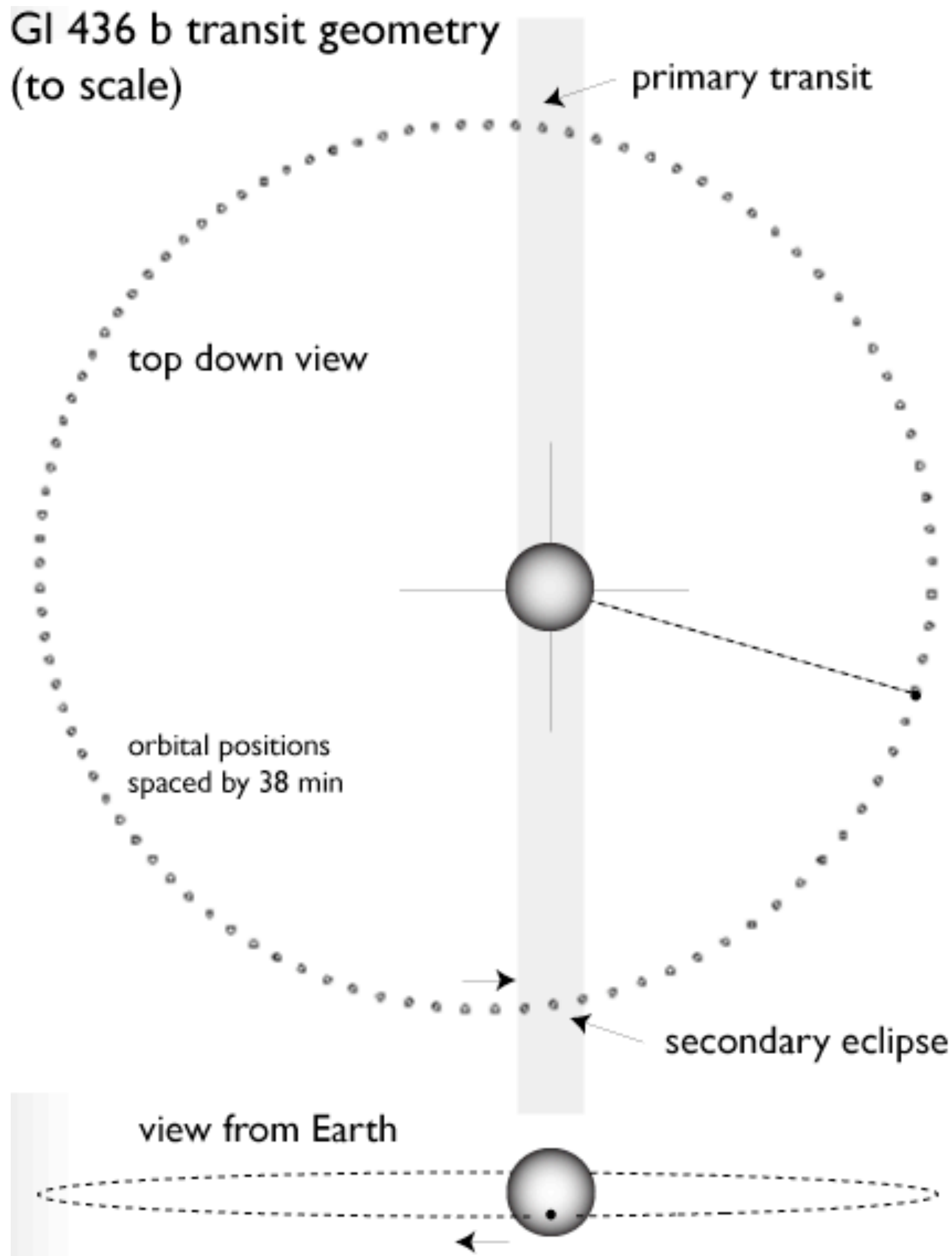
Night Side

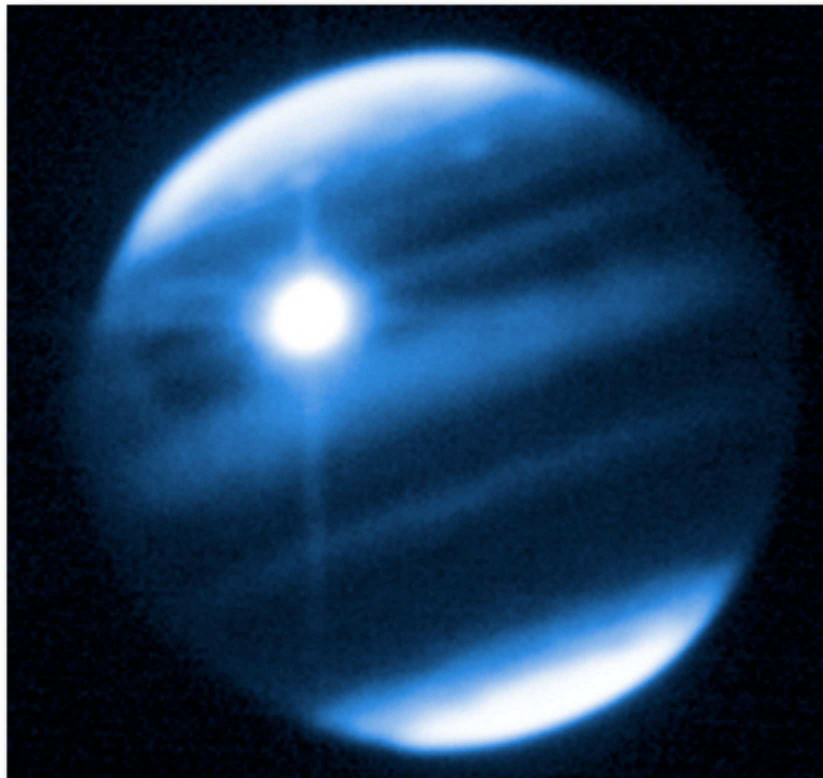


The simple model, plotted in red, gives a reasonable fit to the HD 189733 8-micron photometry if the 8-micron photosphere lies at 150 mbar, and 1/2 of the incident starlight has been absorbed at this pressure depth. (Also a good fit to 24-micron photometry.)

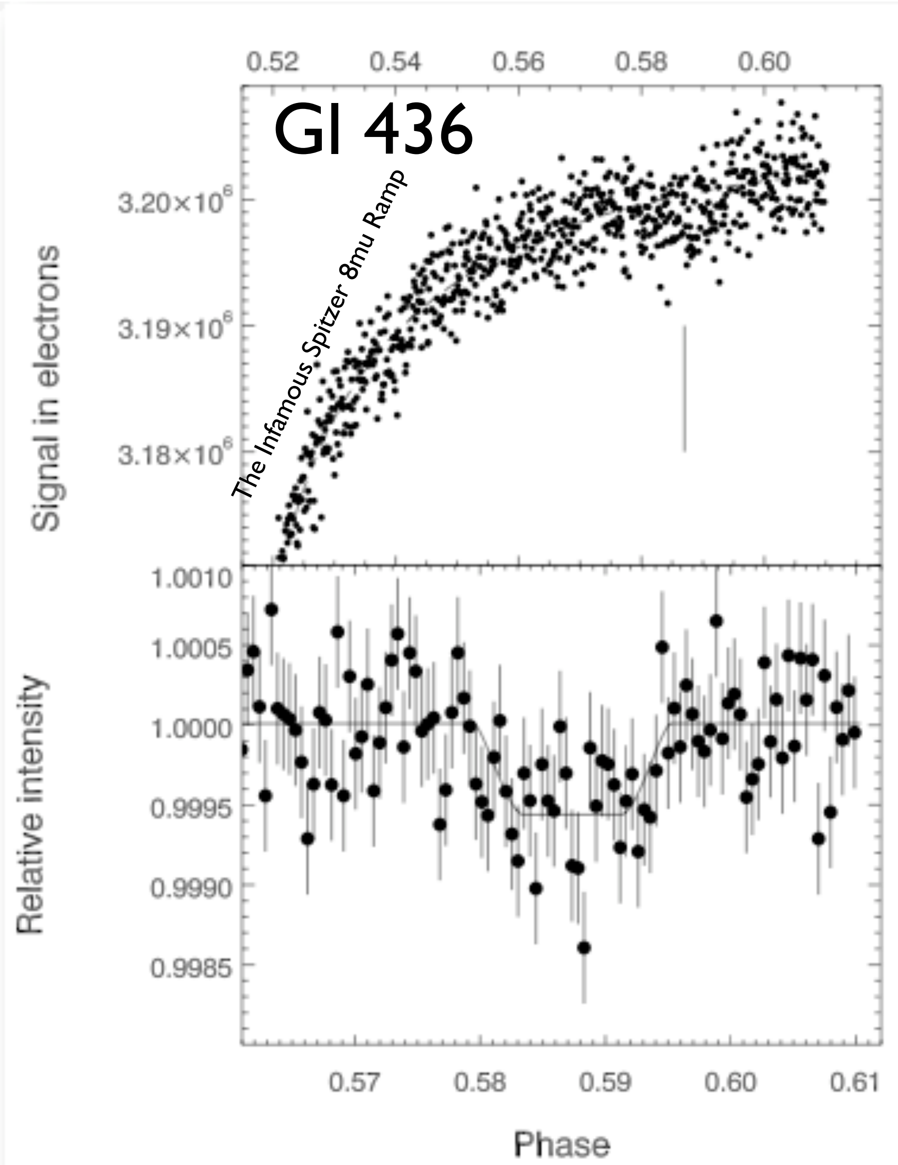
It would be interesting to test radiation-hydrodynamical models on planets that are *not* in steady state.

This would allow a clear distinction to be made between the effects of advection (wind) and the radiative time constant in the atmosphere.


Gl 436 b transit geometry
(to scale)
primary transit
top down view
orbital positions
spaced by 38 min
secondary eclipse
view from Earth

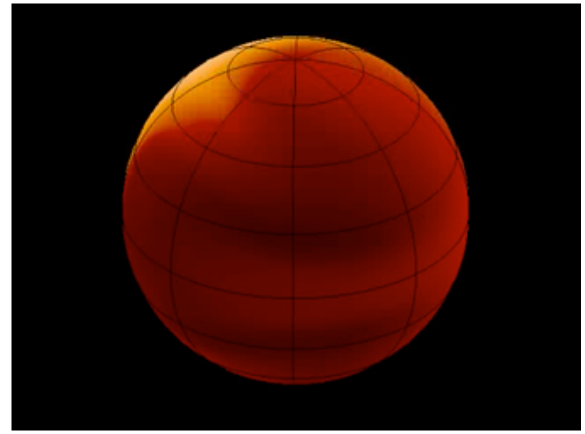


Jupiter and Io in the K-band

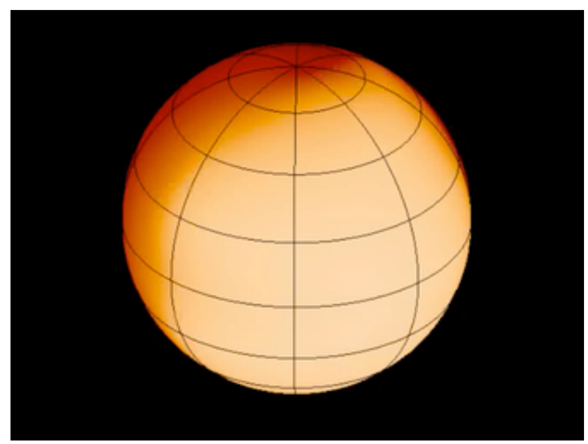


(Seemingly) hotter than expected.

Western Hemisphere

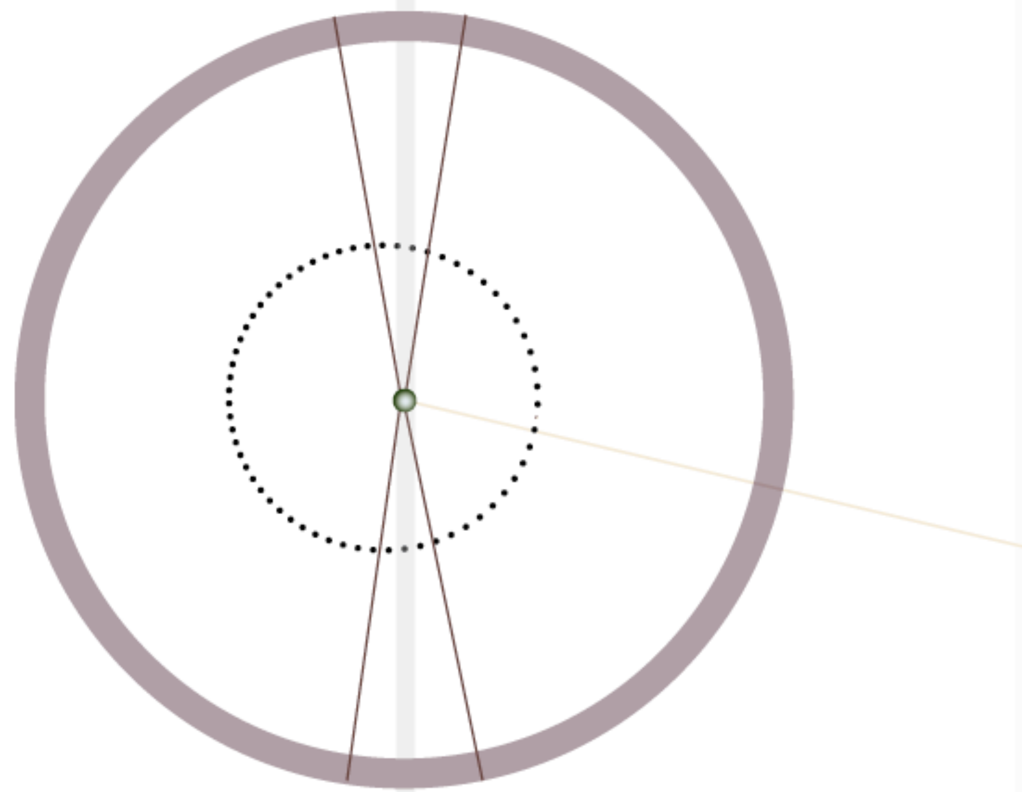


Eastern Hemisphere



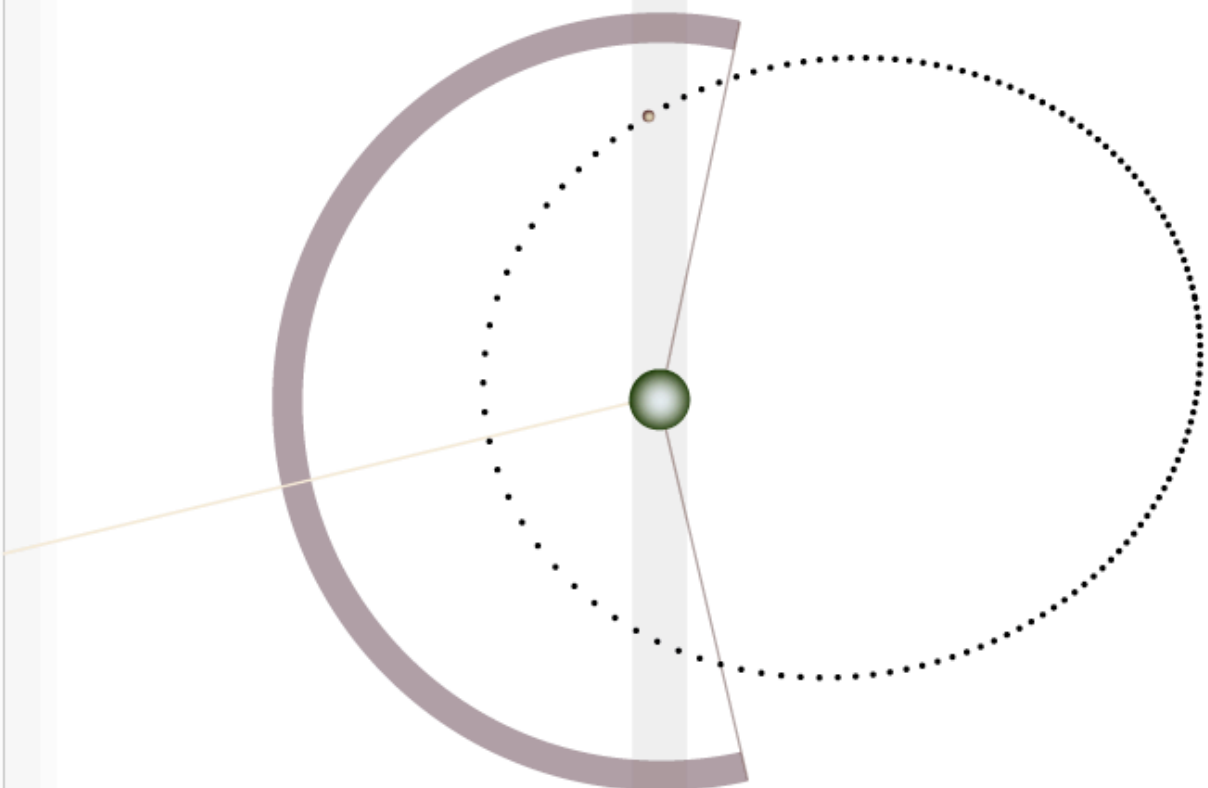
Hydrodynamic model: Langton & Laughlin 2008, using Hut 1981 pseudosynchronous spin frequency.

Gliese 436

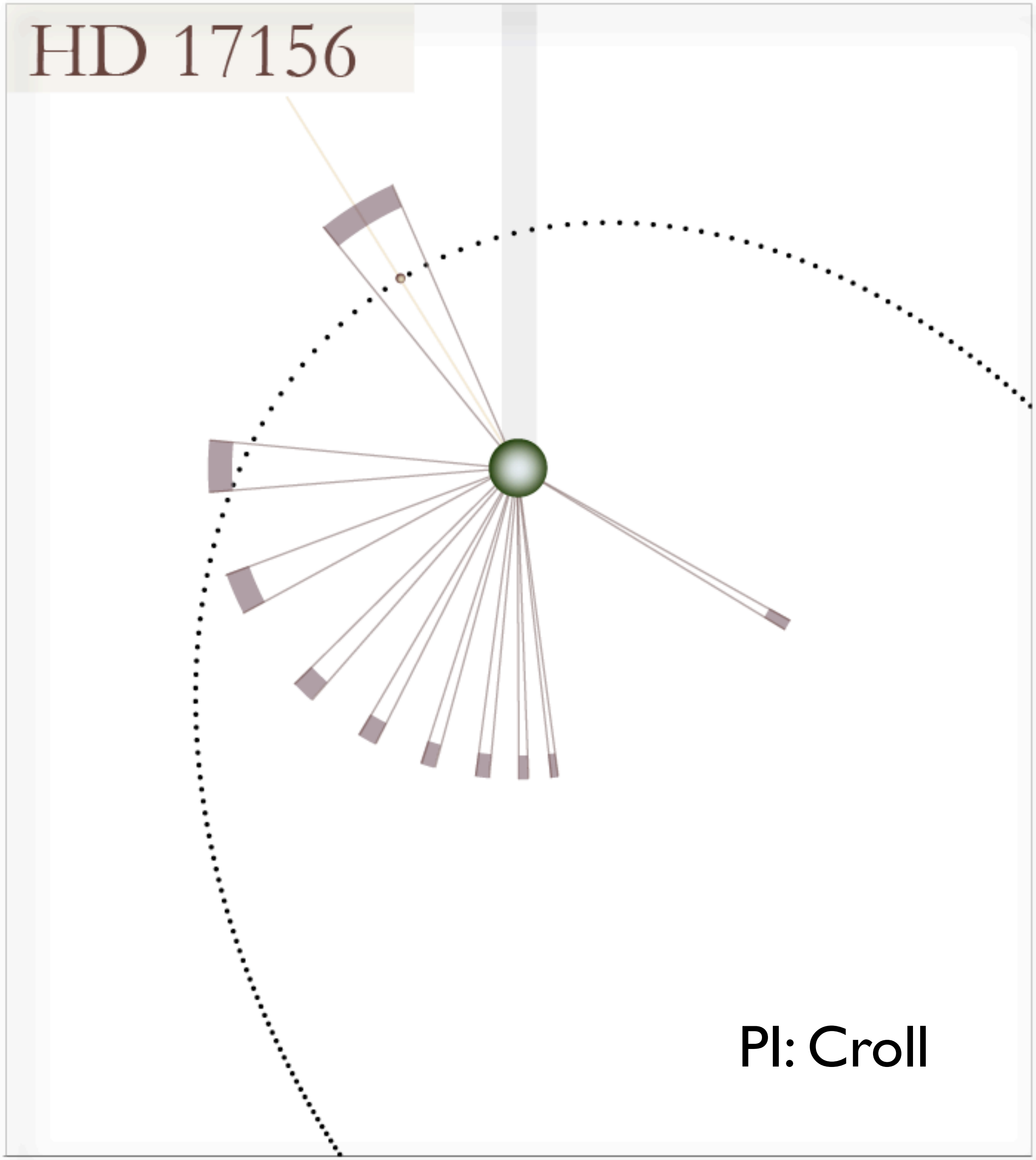


PI: Knutson

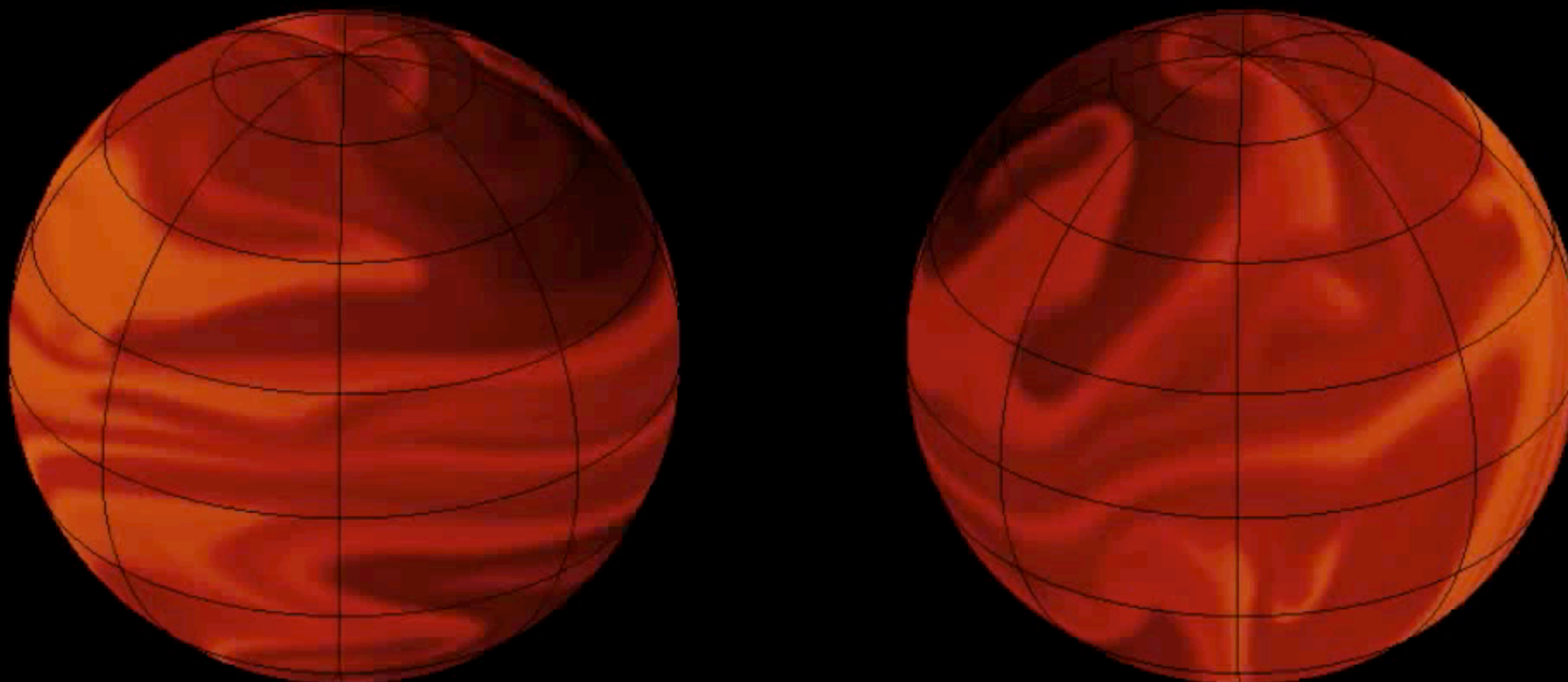
HAT-P-2



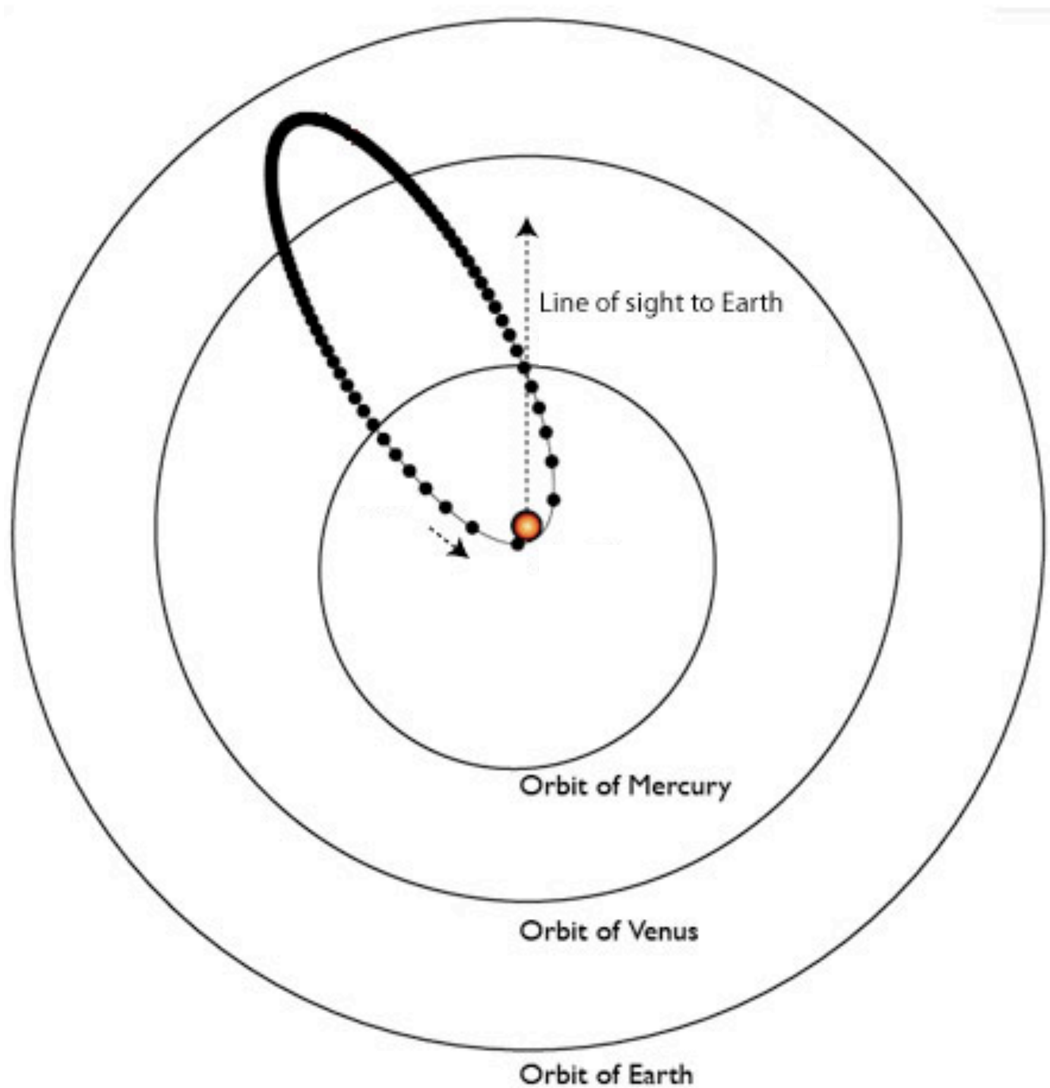
PI: Bakos


HD 17156
PI: Croll

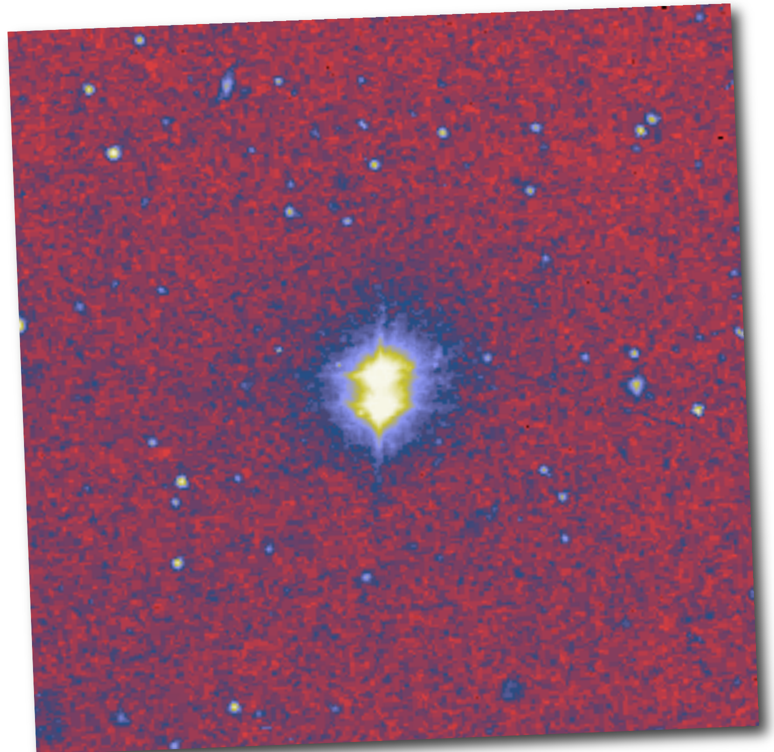
HD 17156 b



Temperature Range: 620K to 1430K

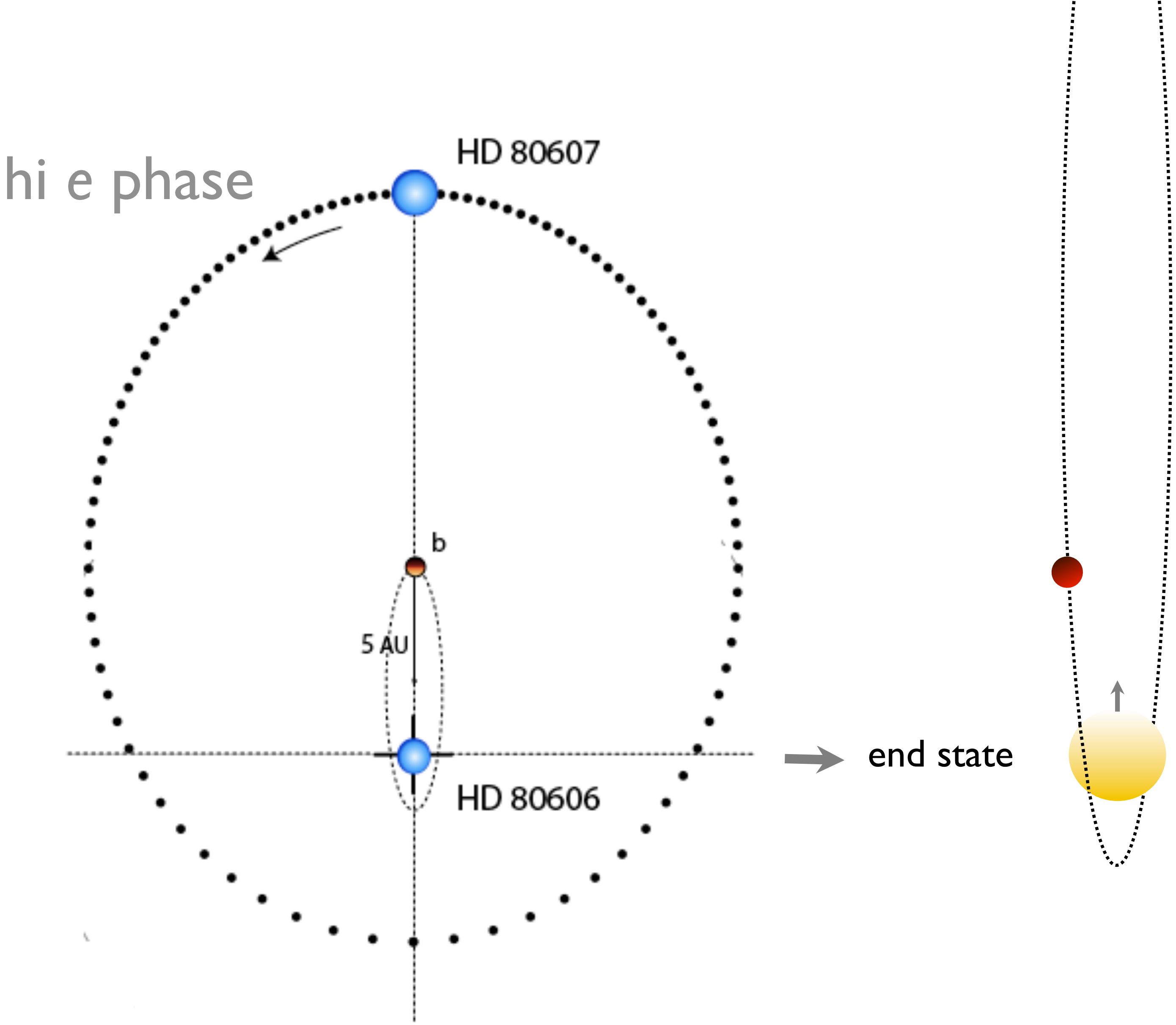


HD 80606b has a P=111.4 day orbital period, a semi-major axis, a=0.45 AU, e=0.9327, $M\sin(i)$=4 Mjup, and a periastron distance, $a(1-e)$~7 stellar radii.



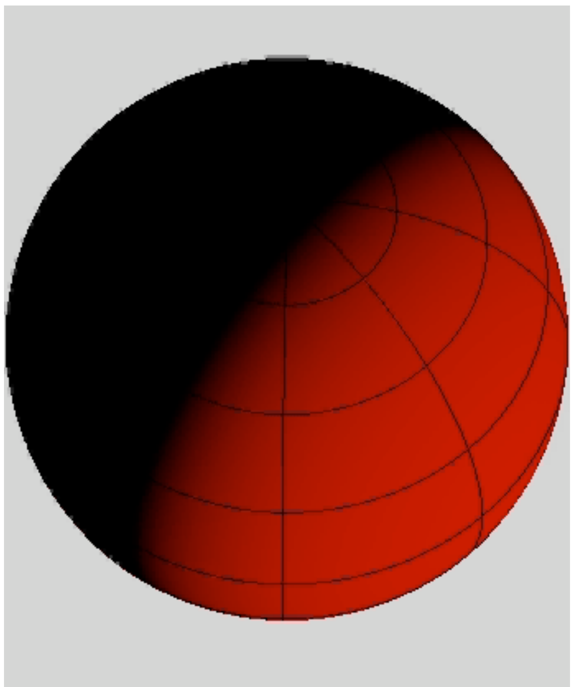
HD 80606 & HD 80607

~1000 AU Separation

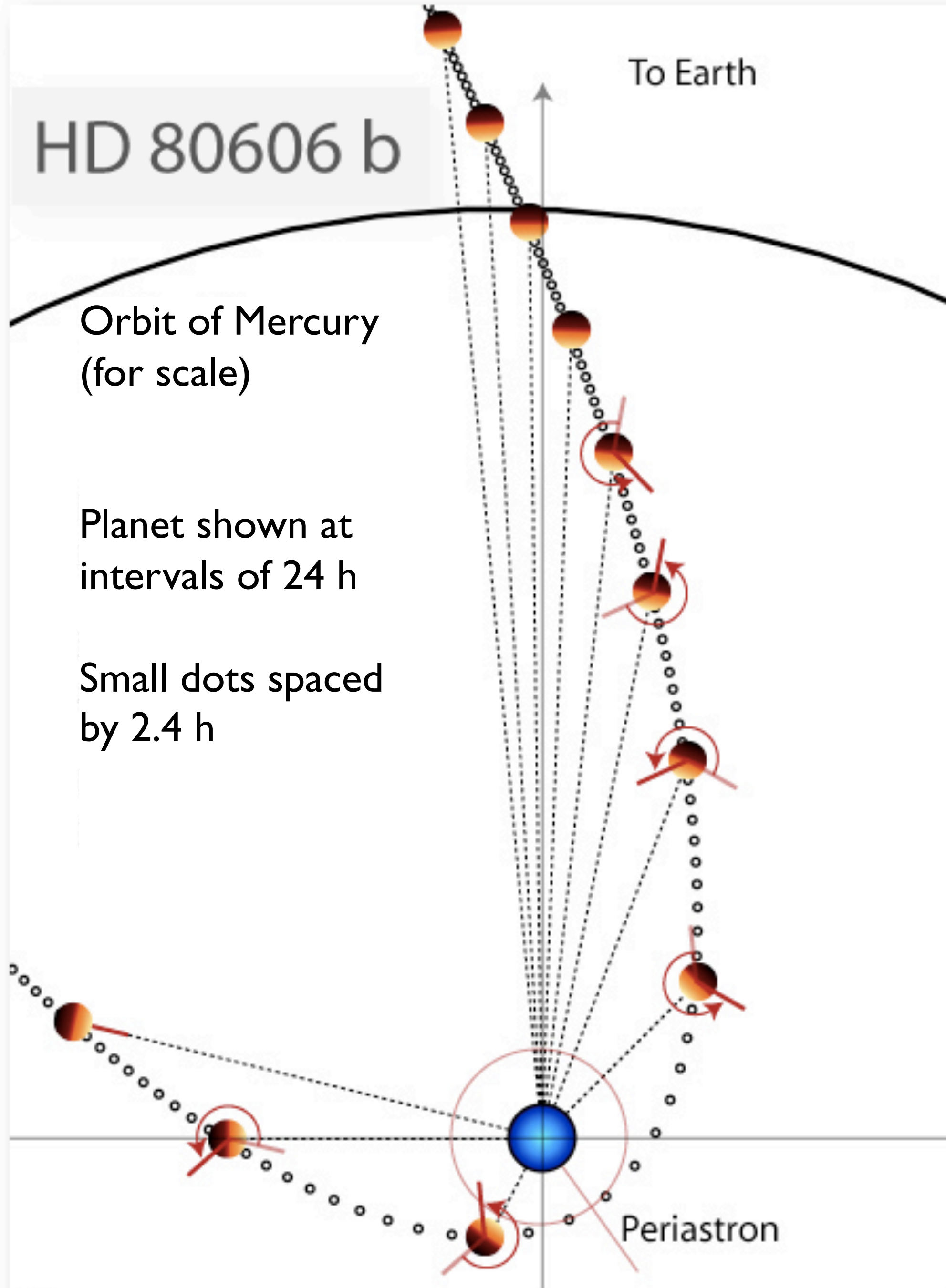


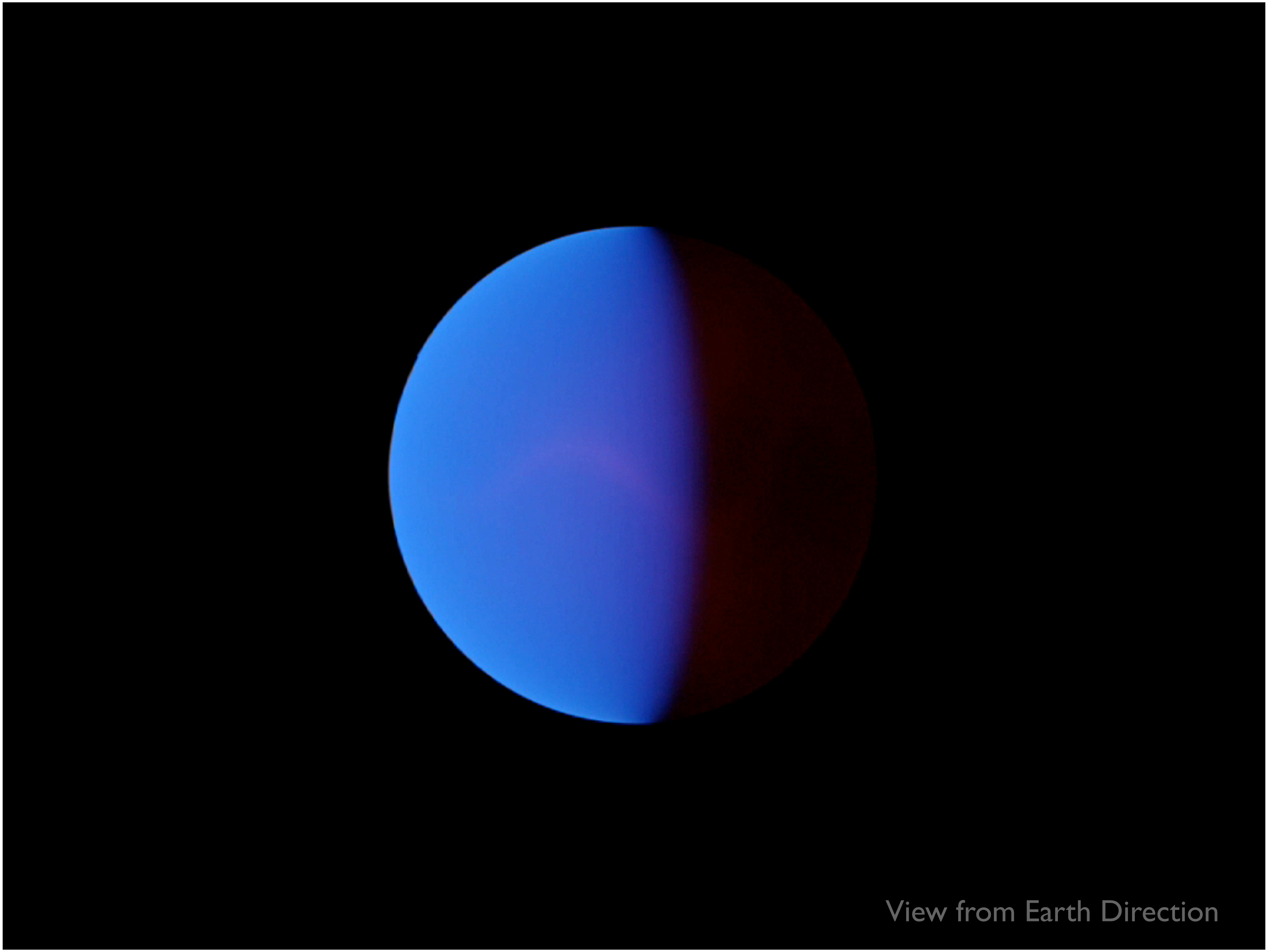
As the orbit shrinks, GR precession eventually destroys the Kozai oscillations, leaving the planet marooned in its high-e state.

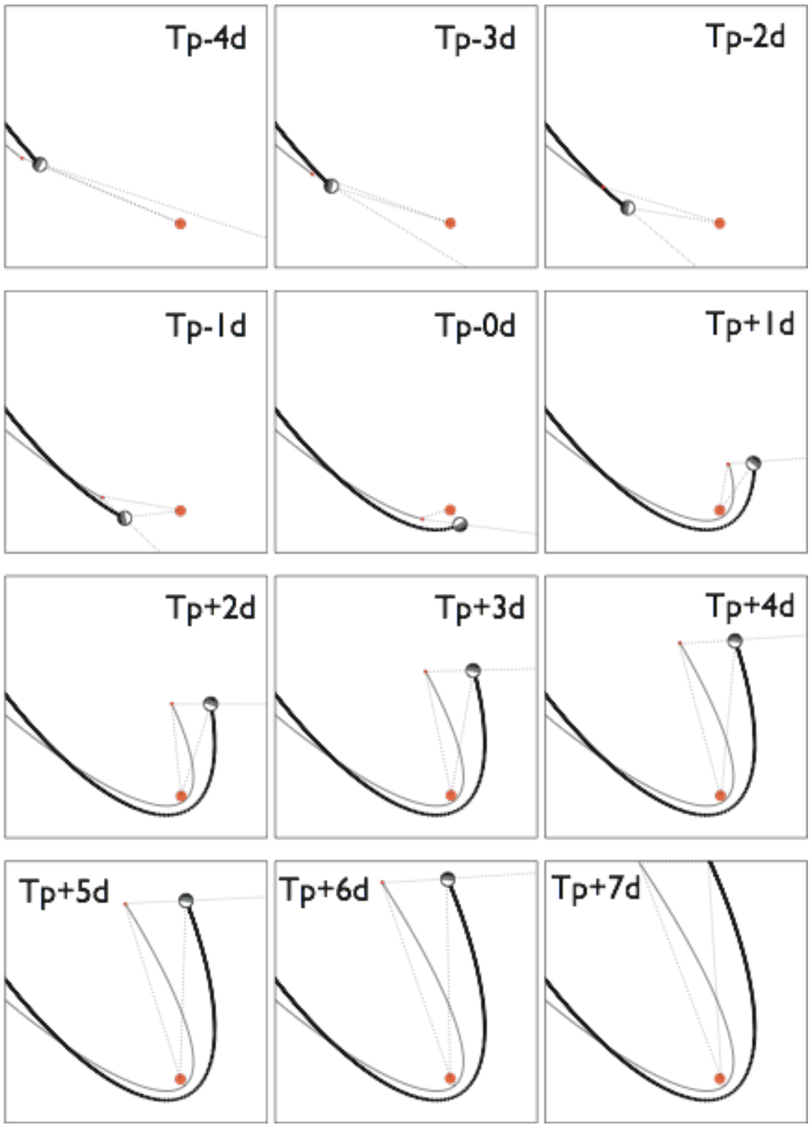
Expectation: pseudo-synchronization

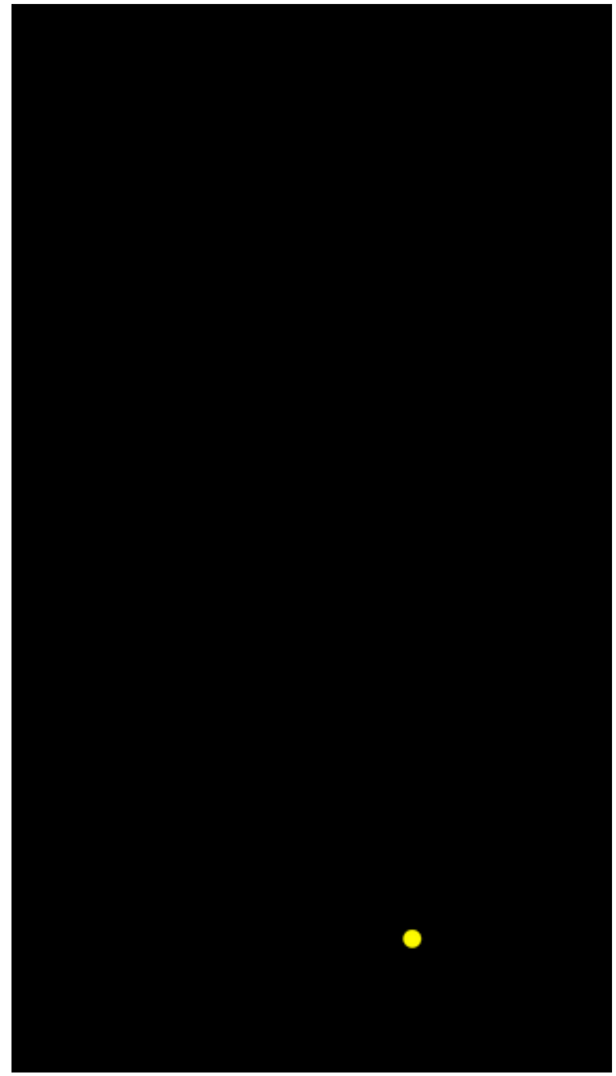


Irradiation thru Periastron: planet frame

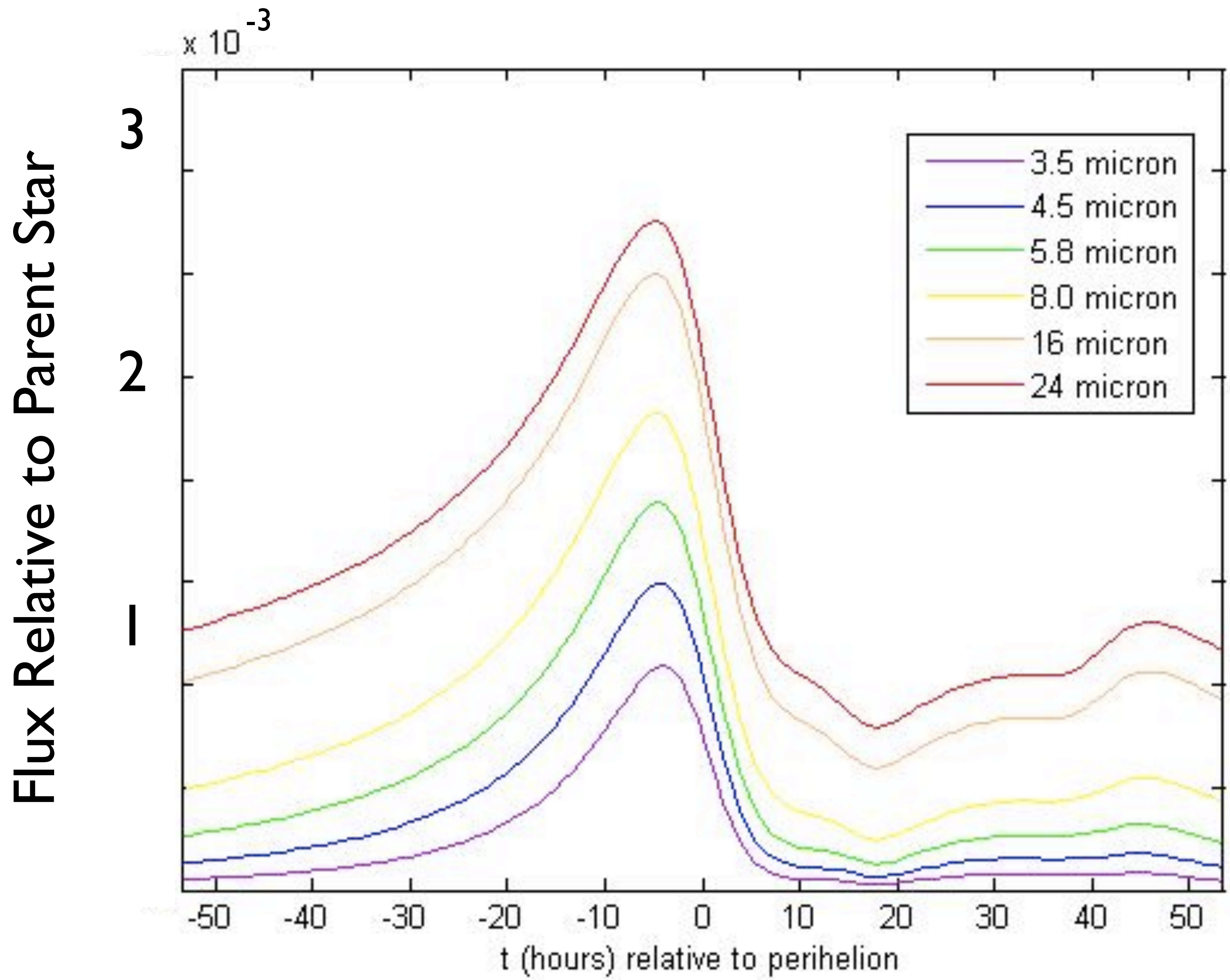



View from Earth Direction



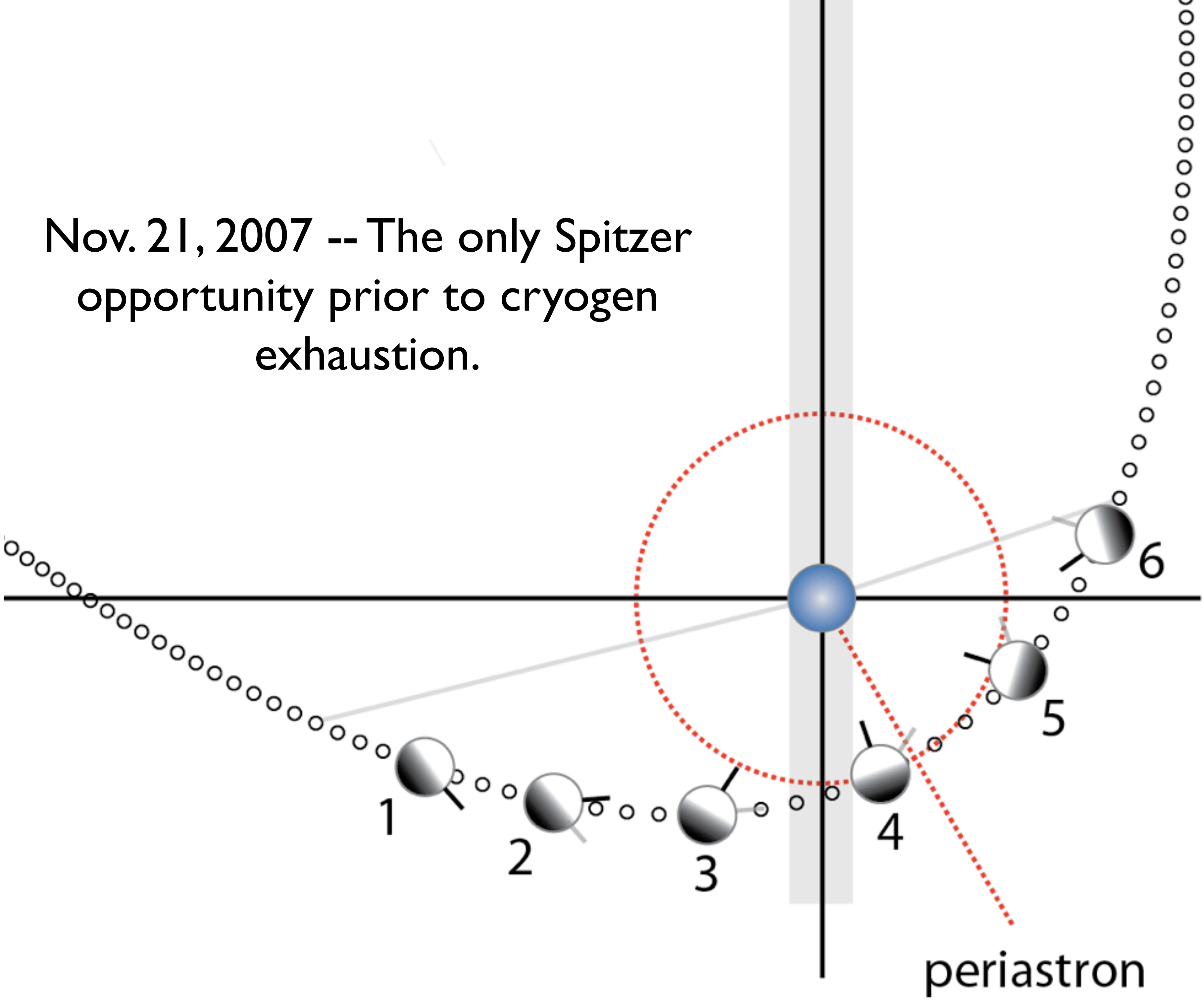


Synthetic “Missions” to HD 80606b

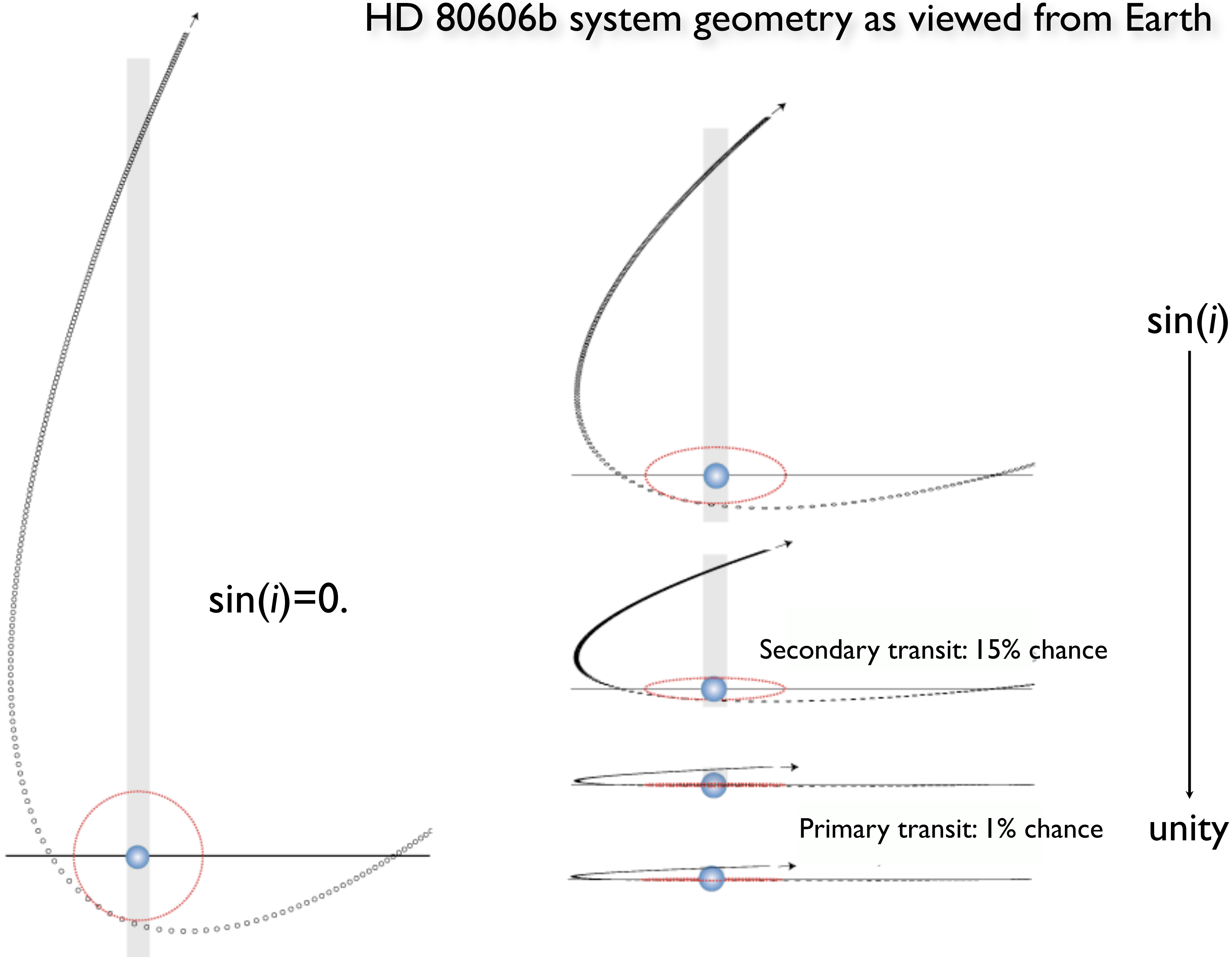


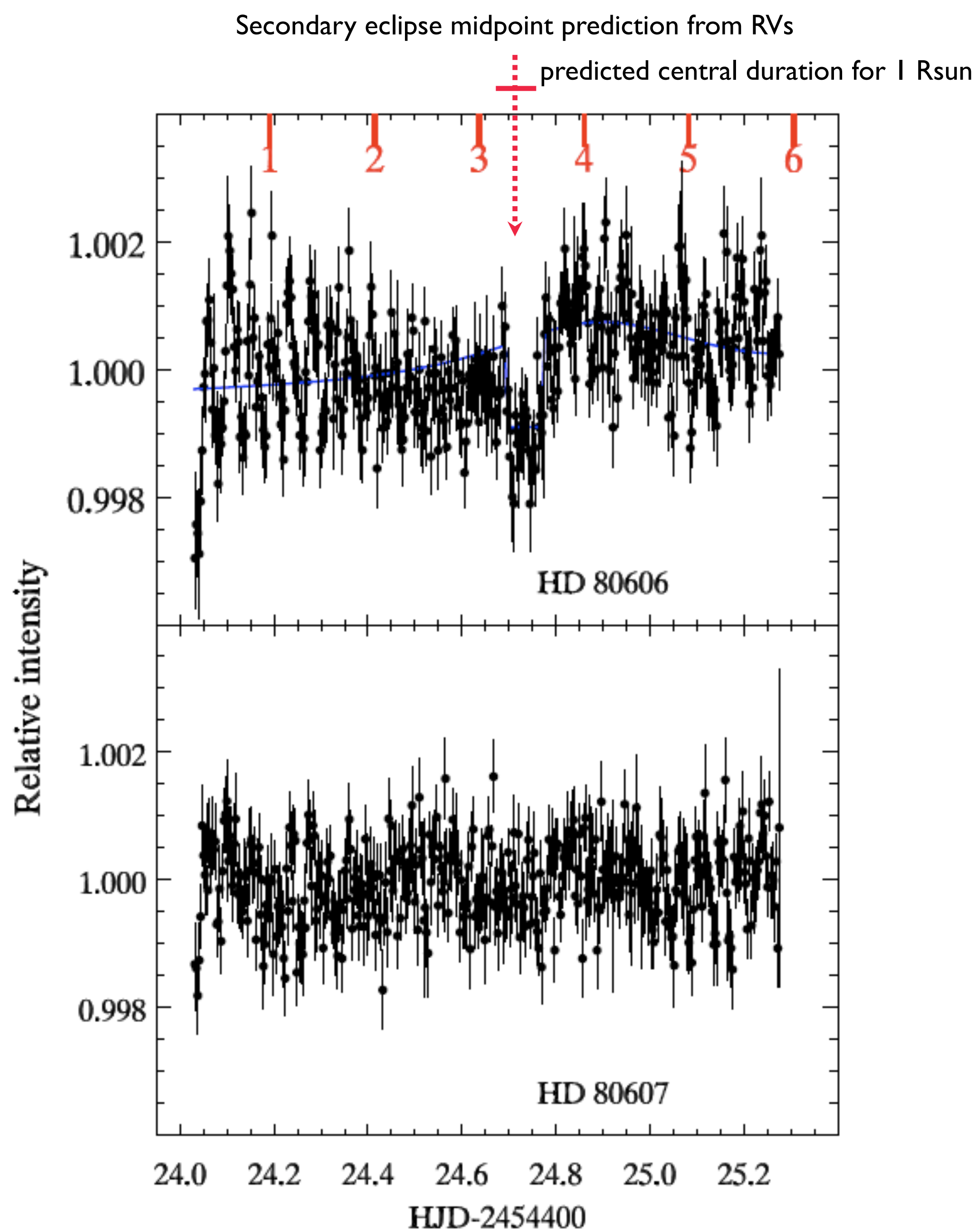
Predicted light curves in Spitzer bands for edge-on geomety

Nov. 21, 2007 -- The only Spitzer opportunity prior to cryogen exhaustion.

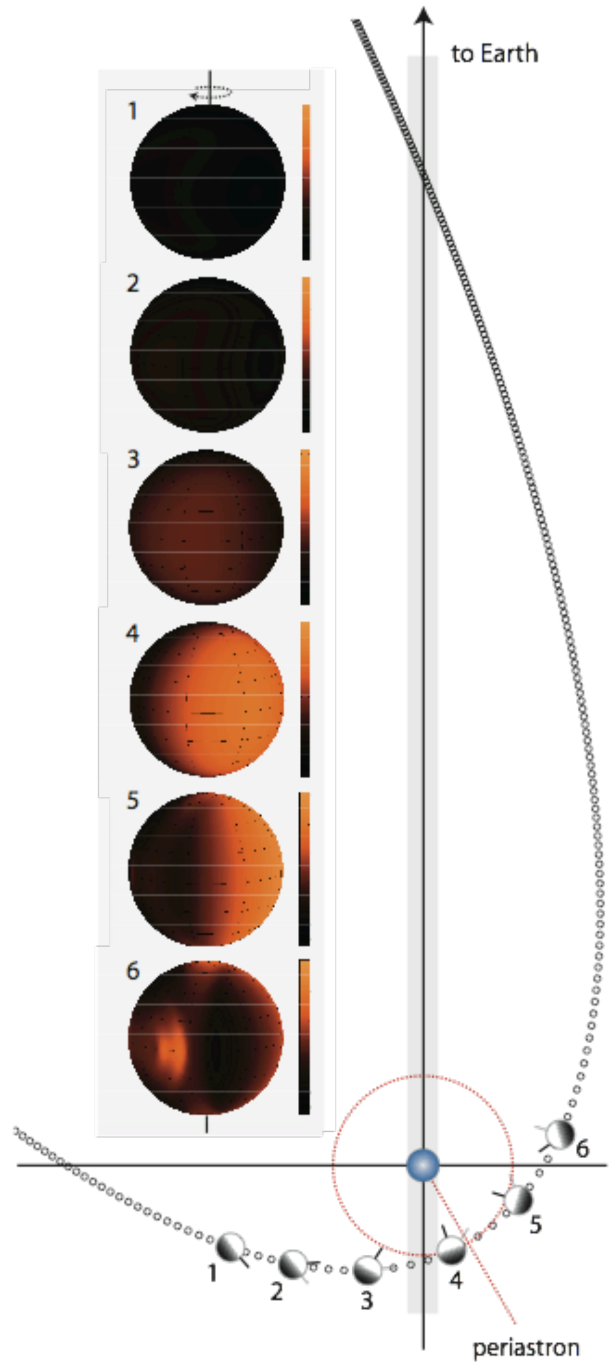


HD 80606b system geometry as viewed from Earth





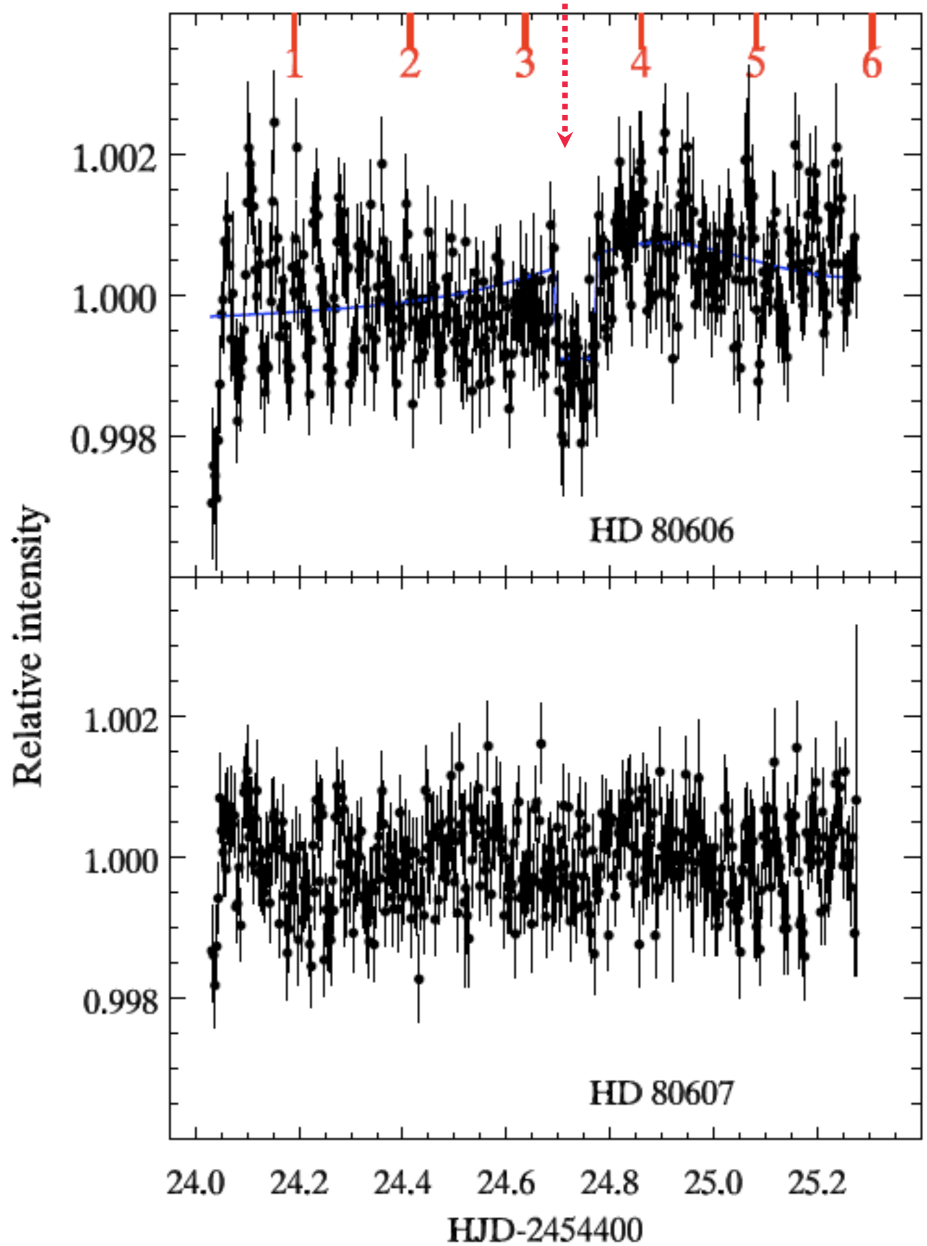
Secondary eclipse midpoint prediction from RVs
predicted central duration for 1 Rsun
1
2
3
4
5
6
1.002
1.000
0.998
HD 80606
HD 80607
Relative intensity
24.0
24.2
24.4
24.6
24.8
25.0
25.2
HJD-2454400



to Earth
1
2
3
4
5
6
periastron

Secondary eclipse midpoint prediction from RVs

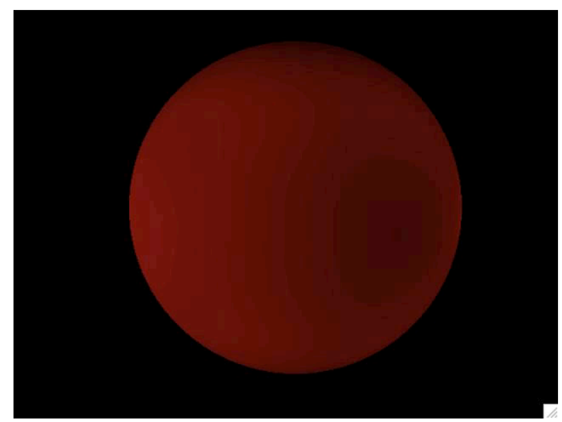
predicted central duration for 1 Rsun



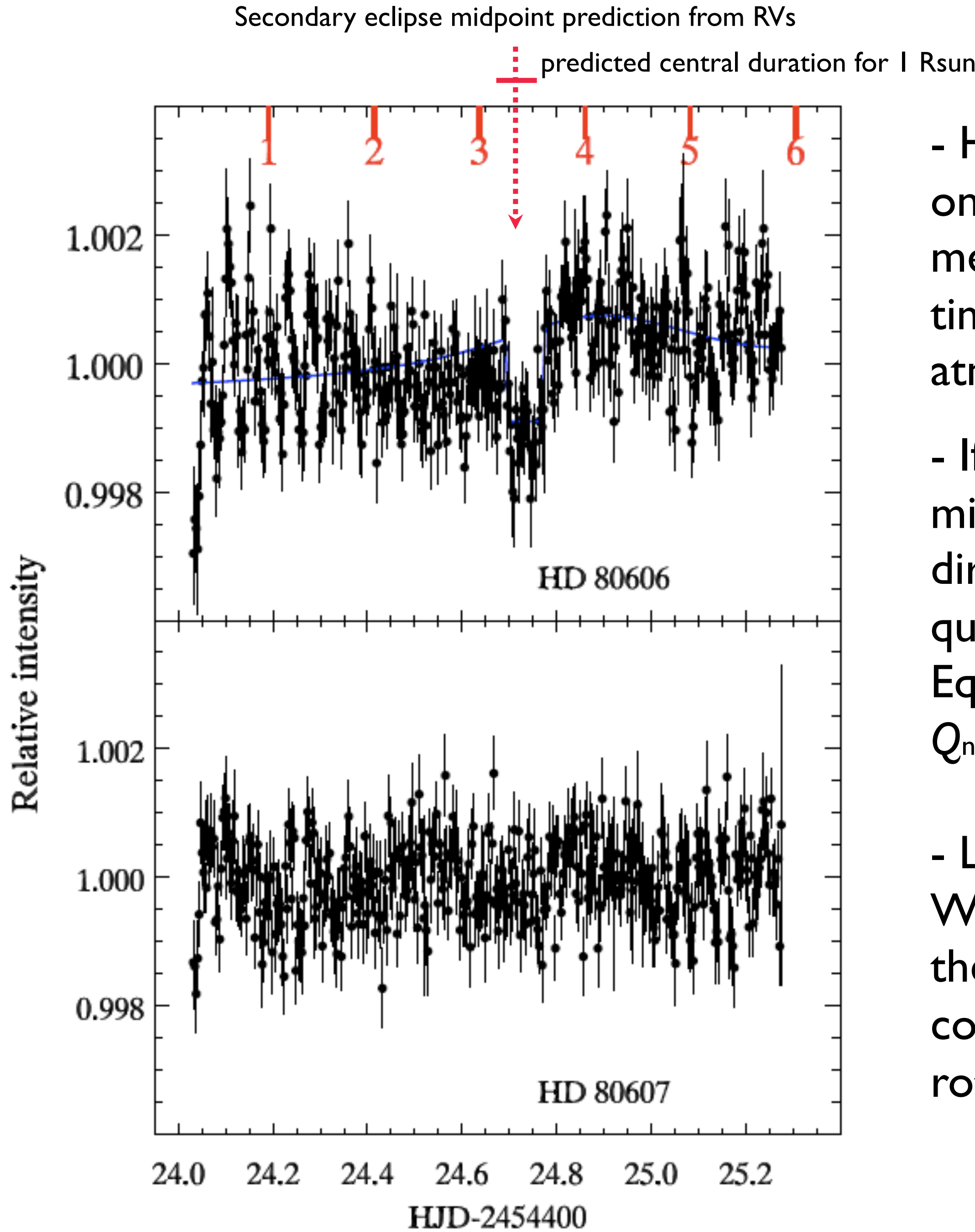
- Secondary Transit observed! Consistent with a central eclipse.

- Model calibrated to 189733 fits reasonably well. (Blue line).

- Heating from 800 to 1500K in only 6 hours.



Model (Earth view, 30h)
Tmin=750K, Tmax=1500K



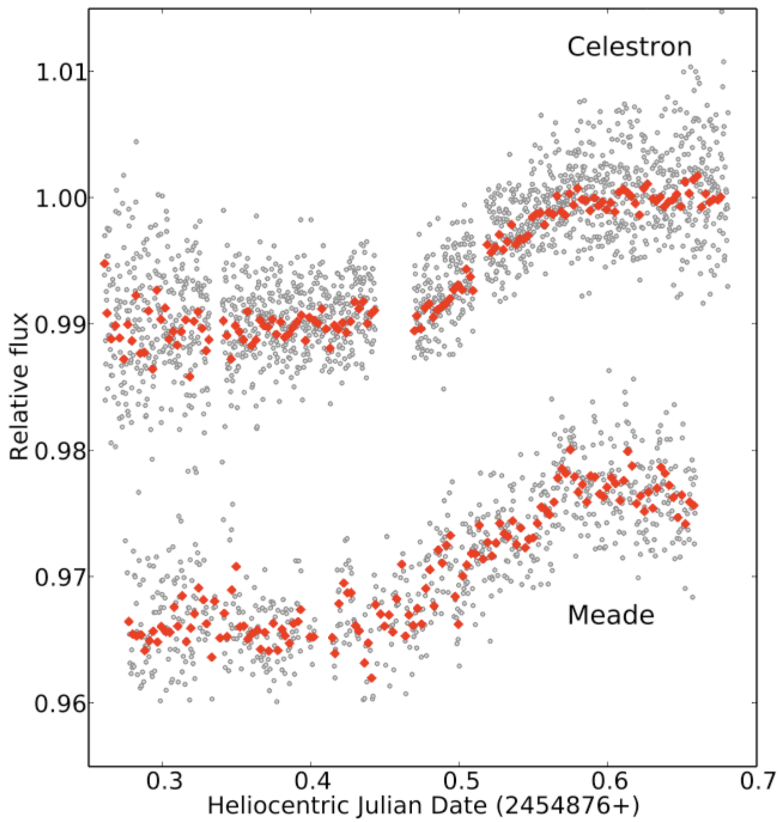
- Heating from 750 to 1500K in only 6 hours. Direct measurement of the radiative time constant in the atmosphere

- If we assume the Kozai migration history, we have a direct measurement of the tidal quality factor, *Q*, for the non-Equilibrium eccentricity tide: Q_{neq}~300,000

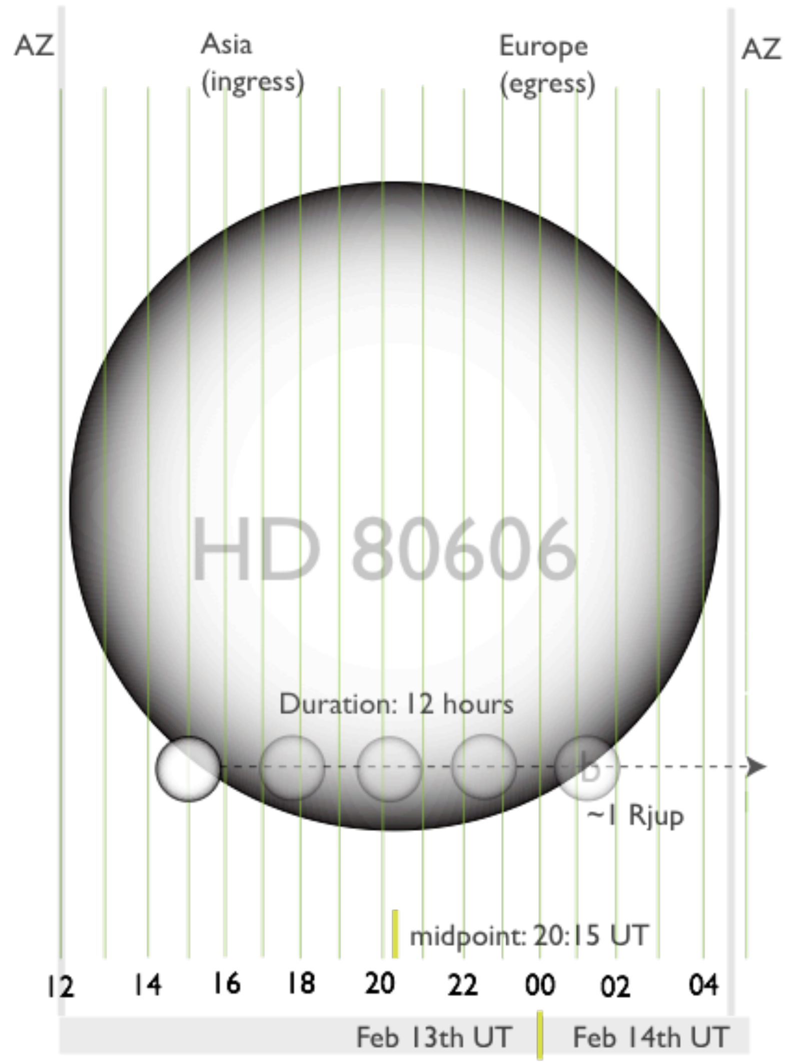
- Longer observations with Warm Spitzer can confirm these results, and can hopefully confirm pseudosynchronous rotation.

Transit opportunity: Valentines Day 2009

Transit!

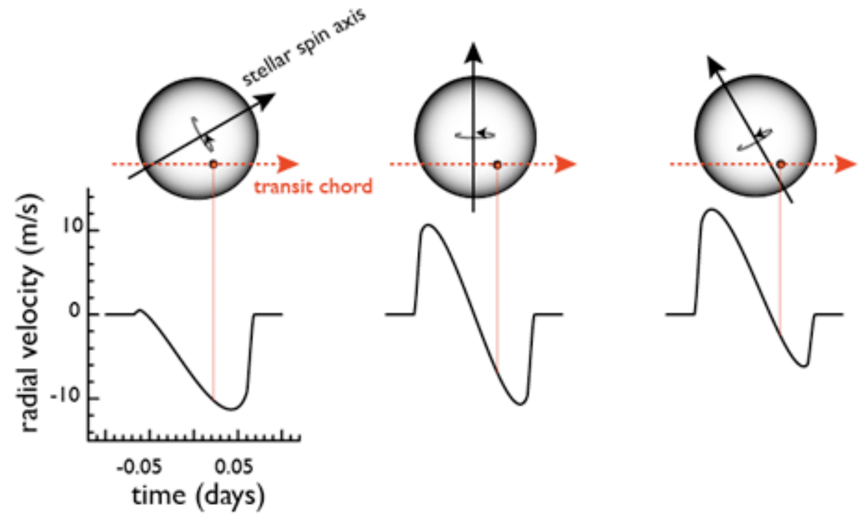


→



See oklo.org for details

The Rossiter-McLaughlin Effect



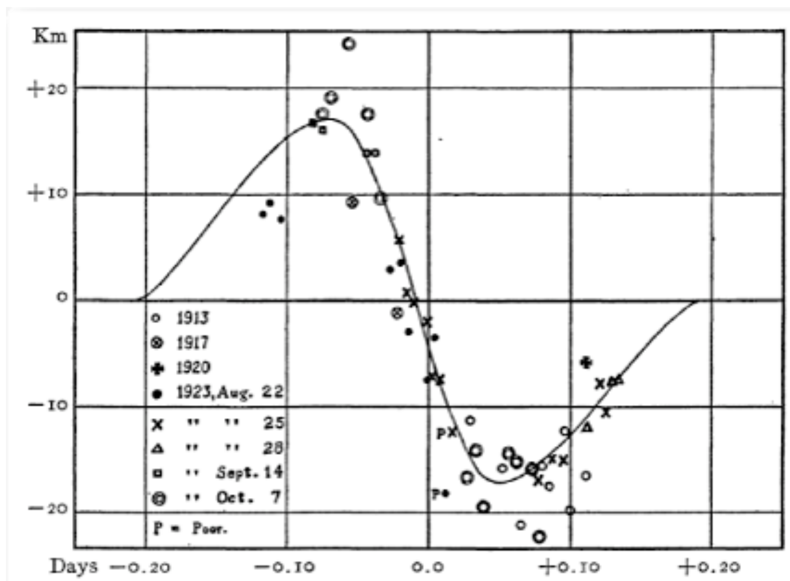
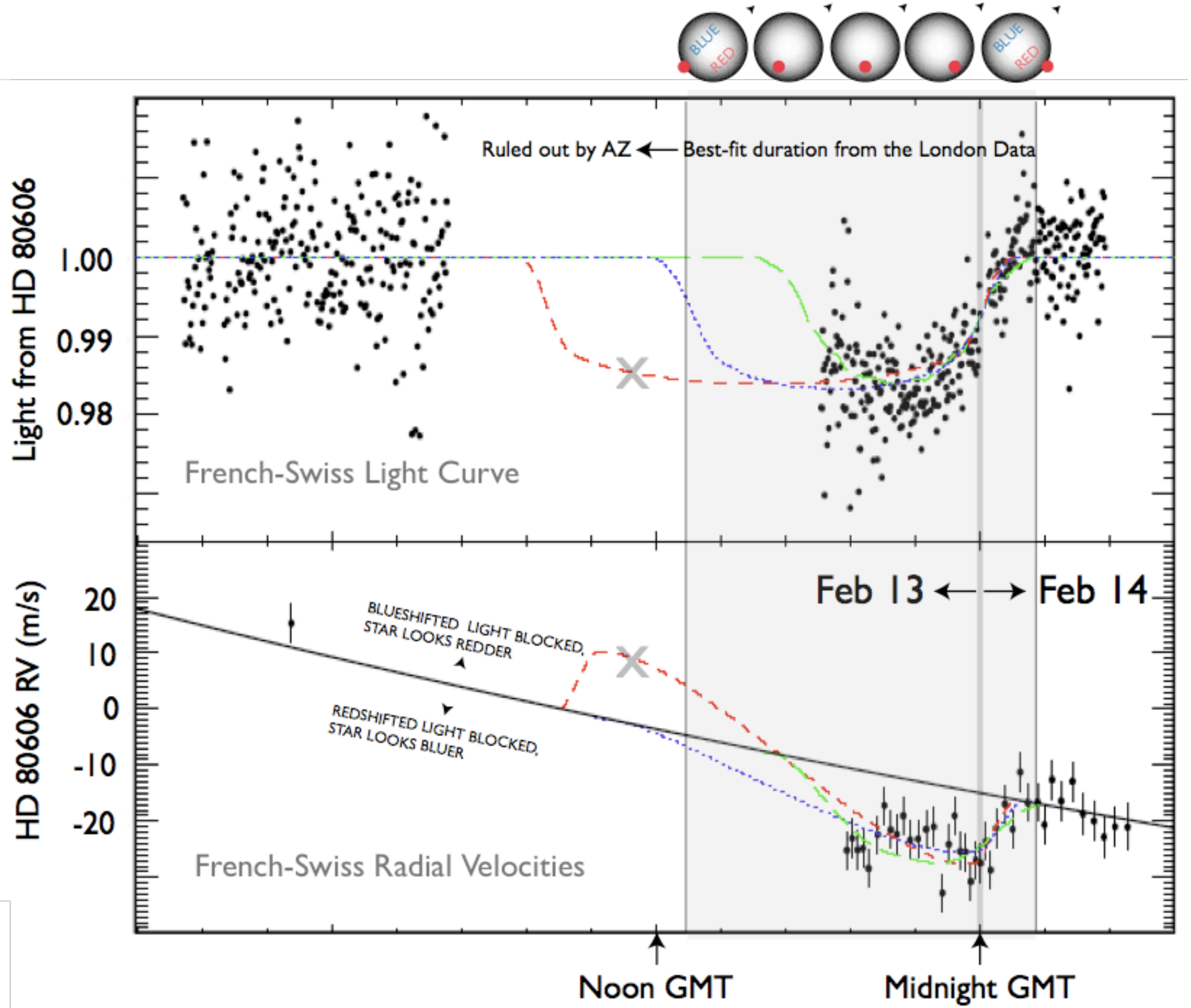


FIG. 1.—Curve of the rotational effect in Algol

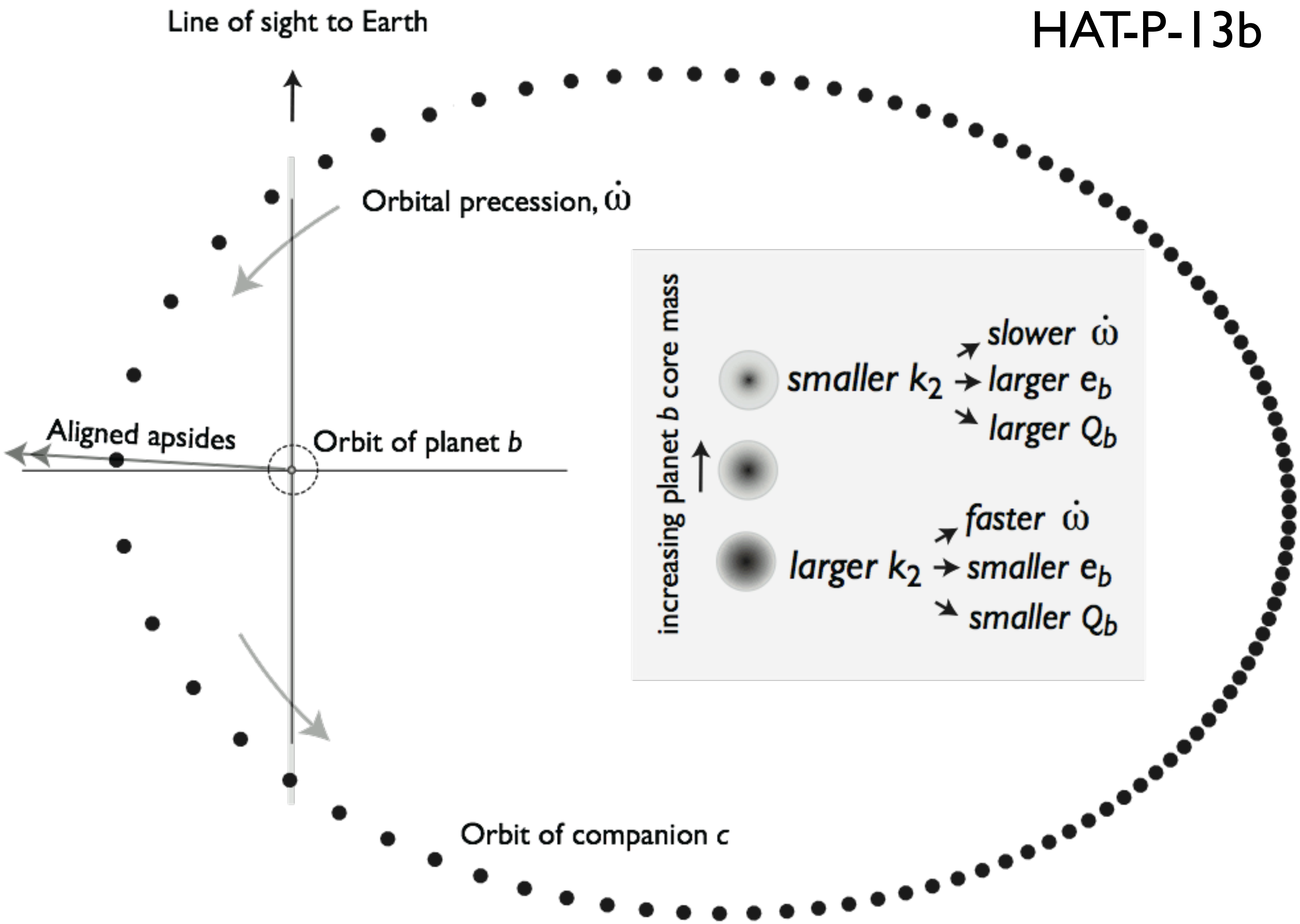
Rossiter 1924 (Algol)



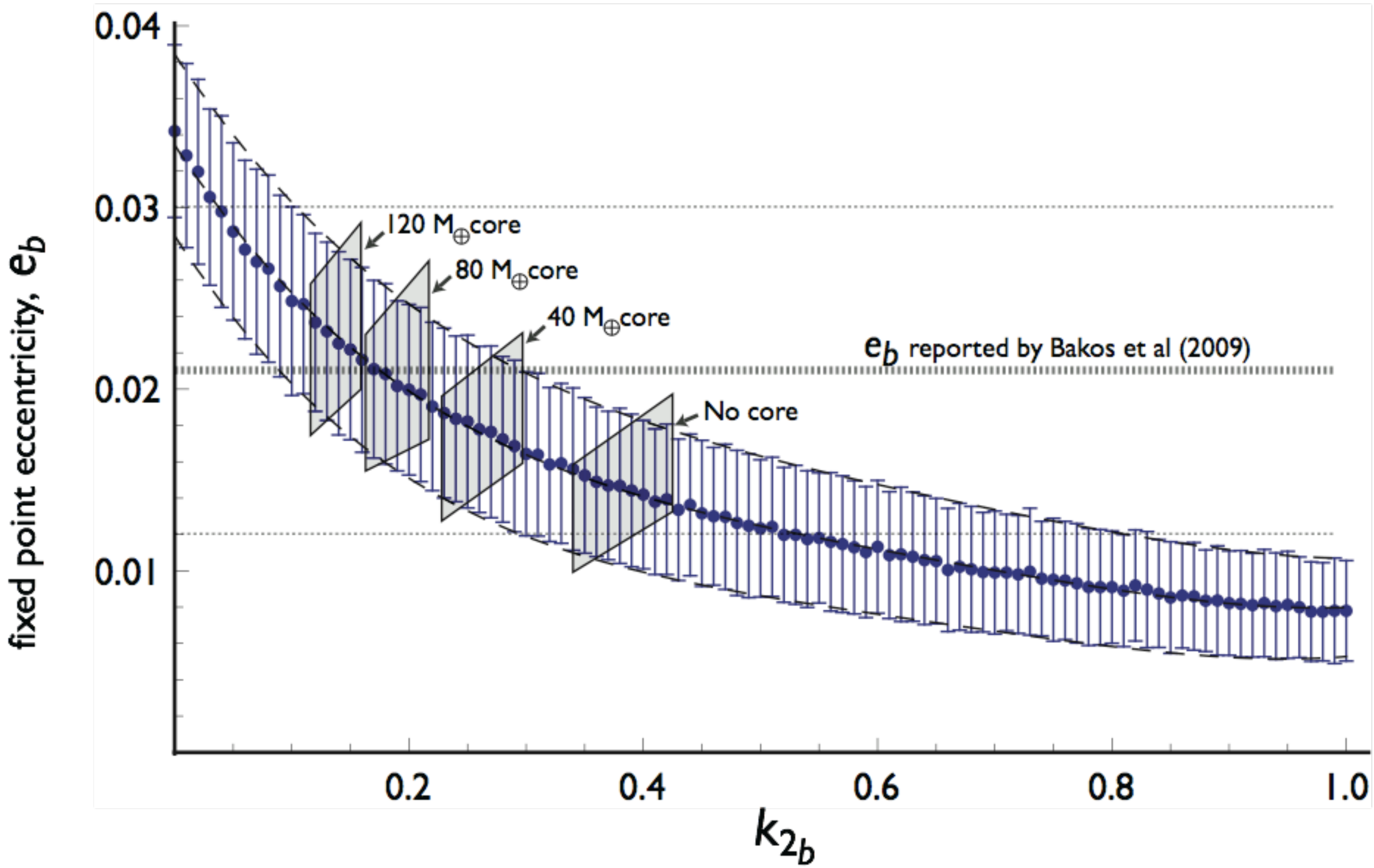
BLUE
RED
BLUE
RED
Ruled out by AZ
Best-fit duration from the London Data
Light from HD 80606
1.00
0.99
0.98
French-Swiss Light Curve
Feb 13
Feb 14
BLUESHIFTED LIGHT BLOCKED, STAR LOOKS REDDER
REDSHIFTED LIGHT BLOCKED, STAR LOOKS BLUER
HD 80606 RV (m/s)
20
10
0
-10
-20
French-Swiss Radial Velocities
Noon GMT
Midnight GMT

Warm Spitzer will be able to look *inside* certain extrasolar planets

HAT-P-13b



Line of sight to Earth
Orbital precession, $\dot{\omega}$
Aligned apsides
Orbit of planet *b*
Orbit of companion *c*
increasing planet *b* core mass
smaller k_2
slower $\dot{\omega}$
larger e_b
larger Q_b
larger k_2
faster $\dot{\omega}$
smaller e_b
smaller Q_b



0.04
0.03
0.02
0.01
fixed point eccentricity, e_b
120 $M_\oplus$ core
80 $M_\oplus$ core
40 $M_\oplus$ core
No core
e_b reported by Bakos et al (2009)
0.2
0.4
0.6
0.8
1.0
k_{2_b}