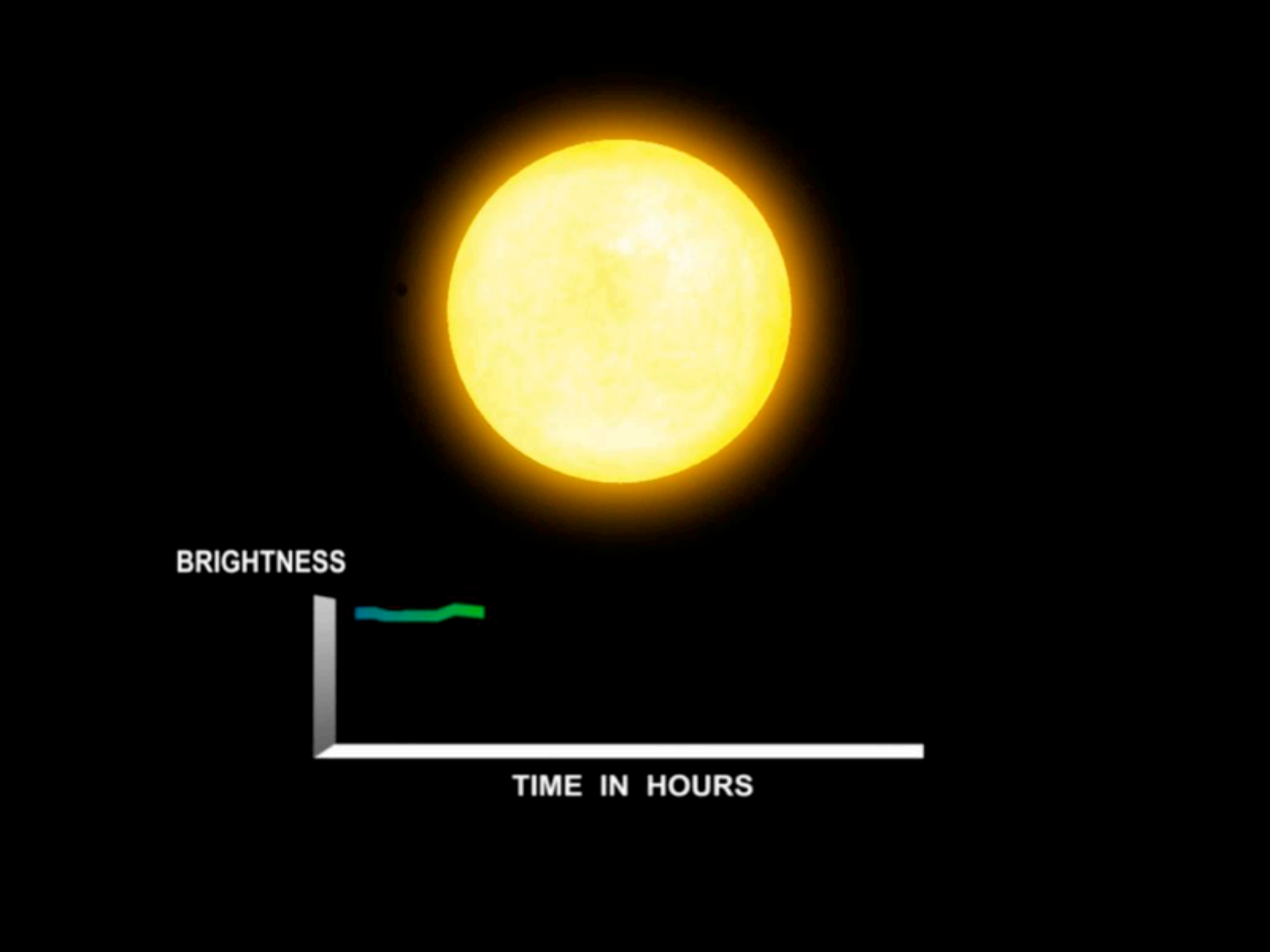
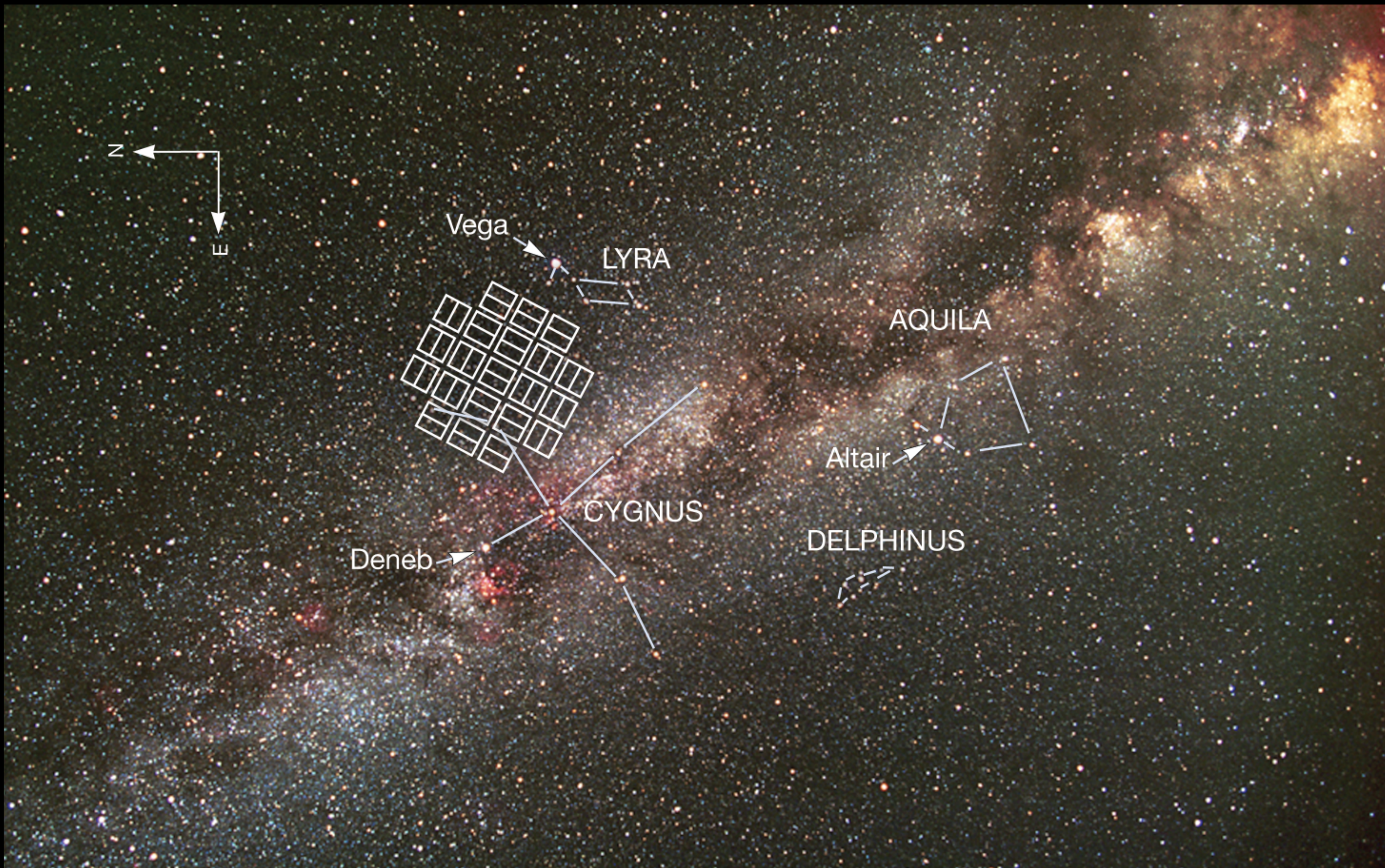
Observations of Extrasolar Planets

I. Kepler transits
II. Doppler velocity
III. Microlensing
IV. Imaging
V. Disks


BRIGHTNESS
TIME IN HOURS

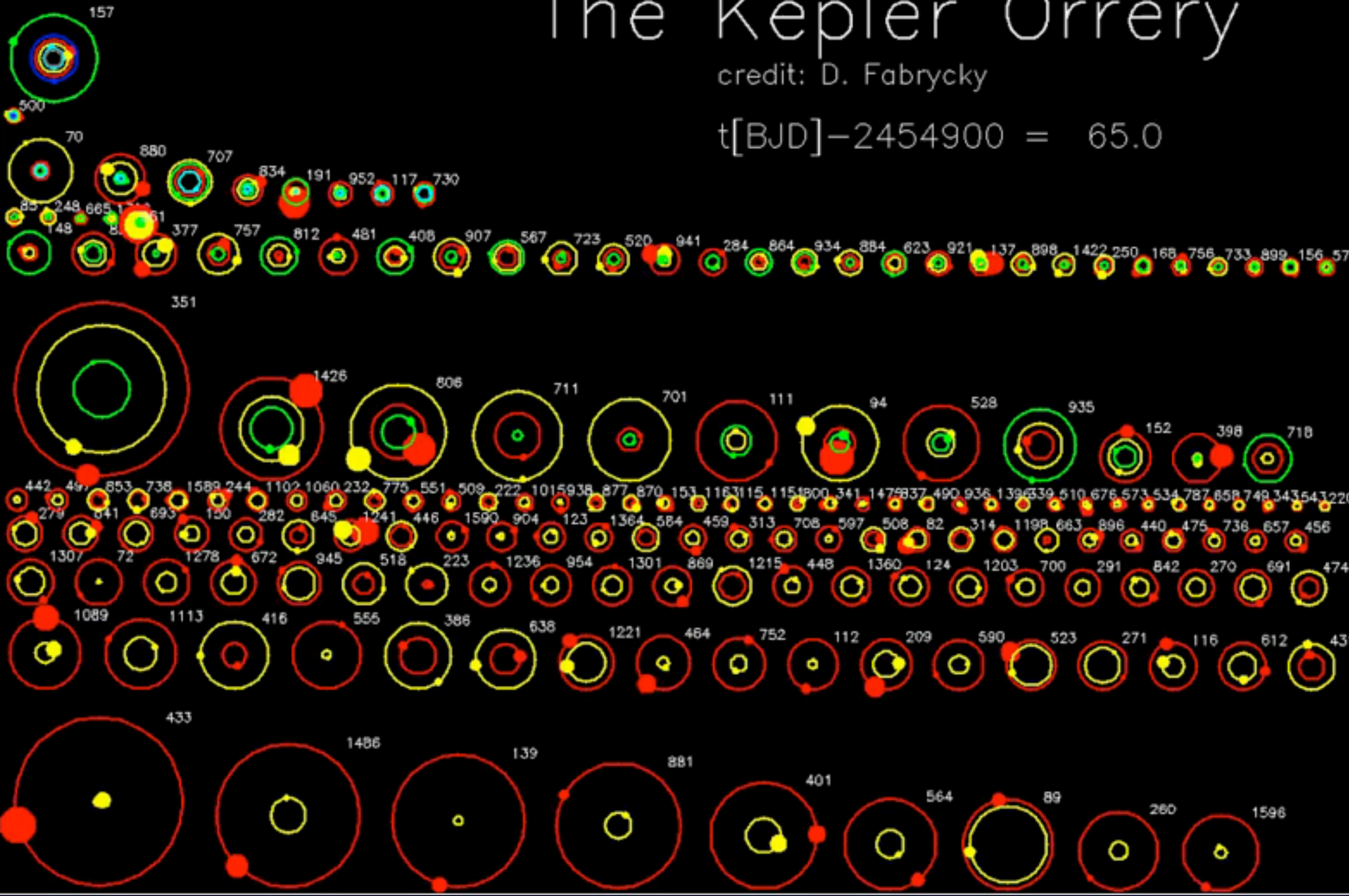
NASA's Kepler Mission



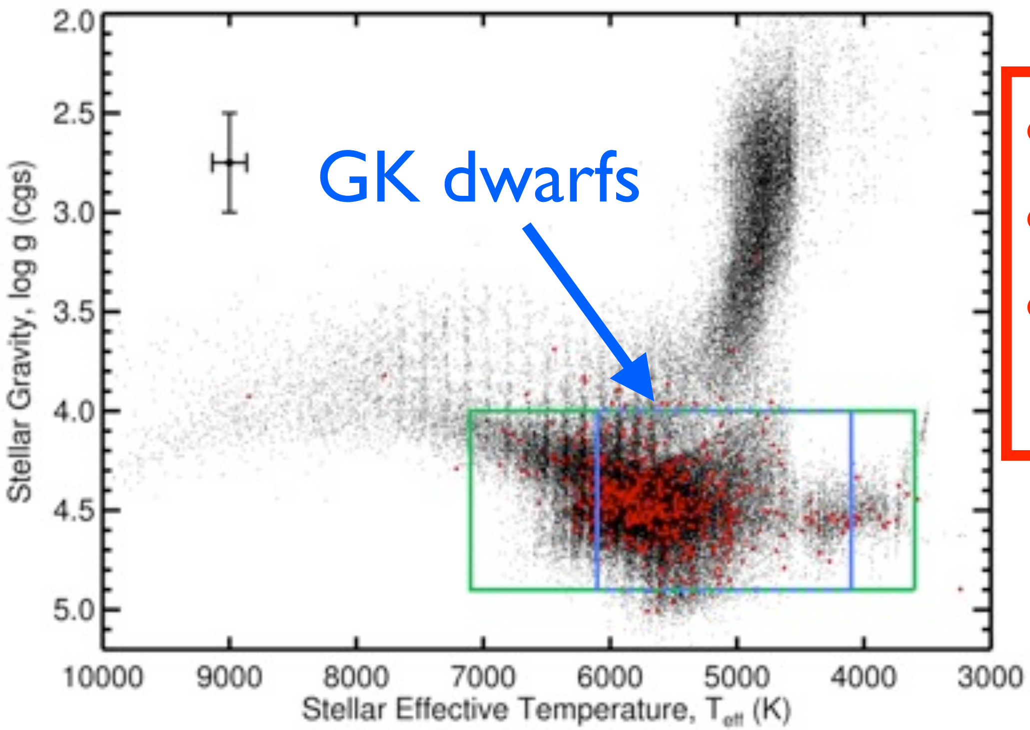
The Kepler Orrery

credit: D. Fabrycky

t[BJD]−2454900 = 65.0

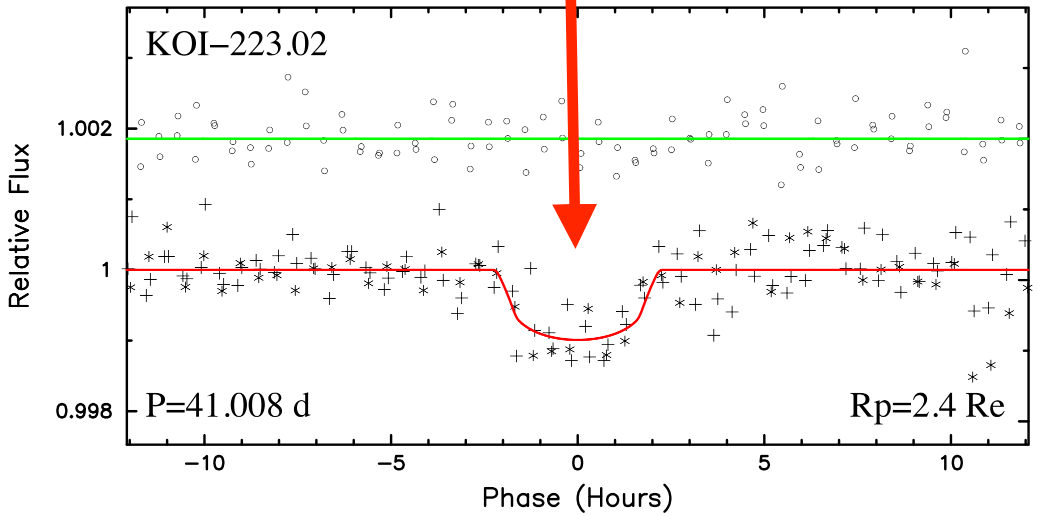


Choose Subset of Planets/Stars for High Detectability



- Only GK dwarfs (T_{eff}/log g)
- Only bright stars (Kp < 15)
- Only high SNR transits (SNR > 10 in 90 days)

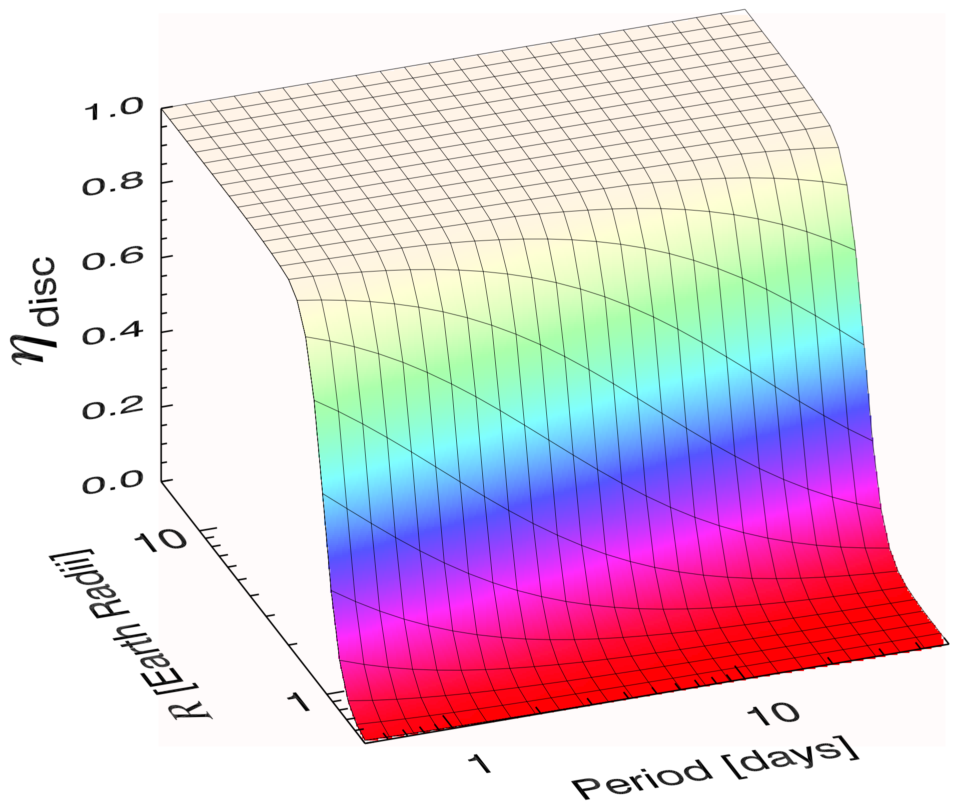
SNR ≈ 10

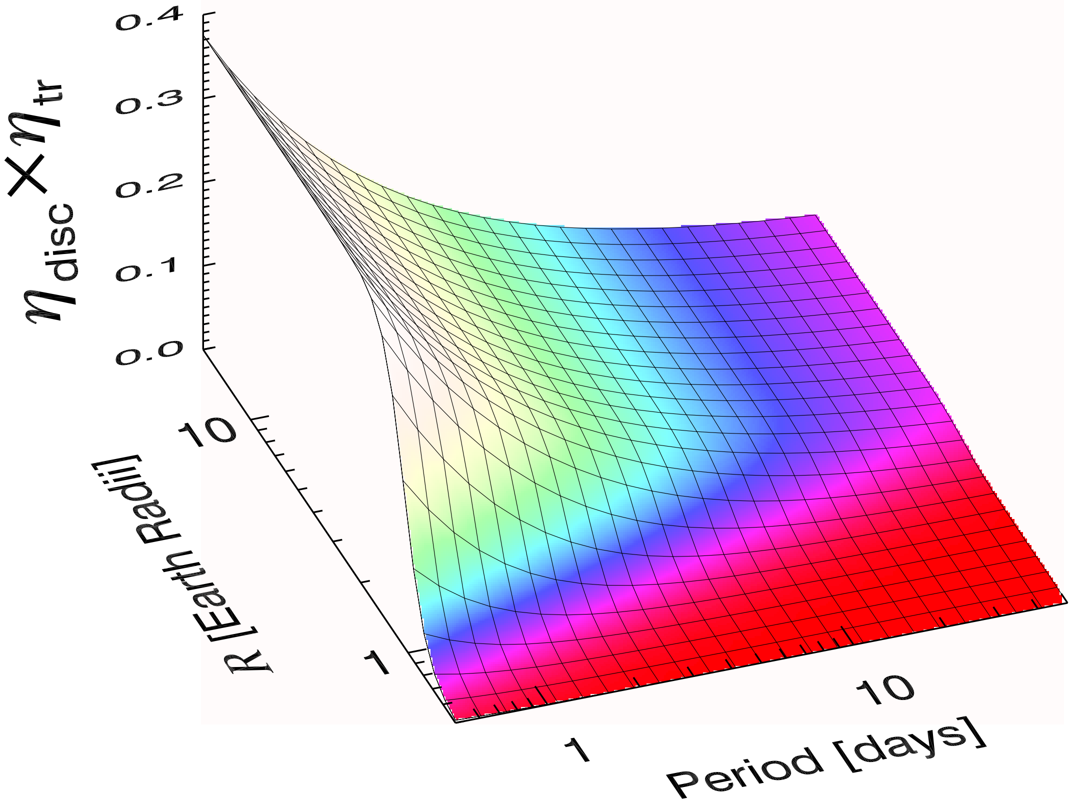


<u>Full sample</u>
~156,000 stars
1,230 planets

→

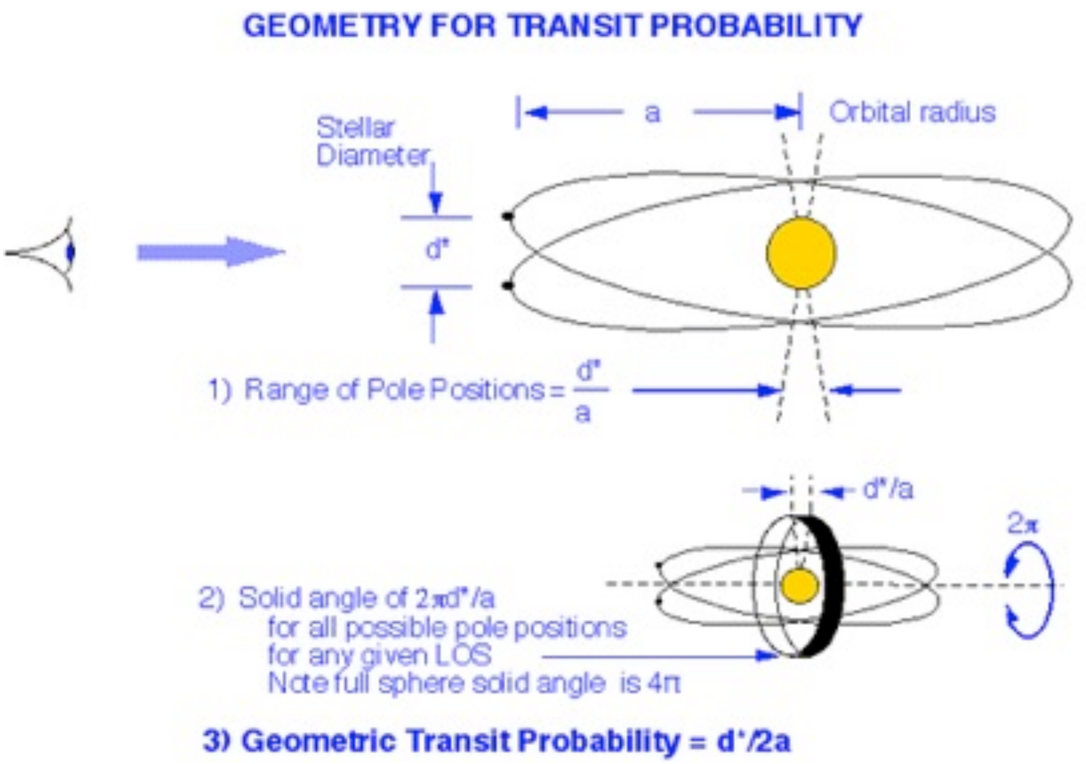
<u>Restricted sample</u>
~58,000 stars
438 planets





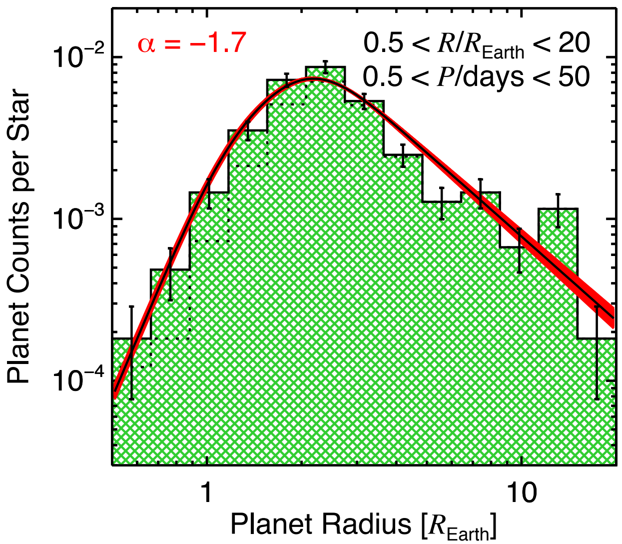
η_{disc} = Kepler discovery efficiency

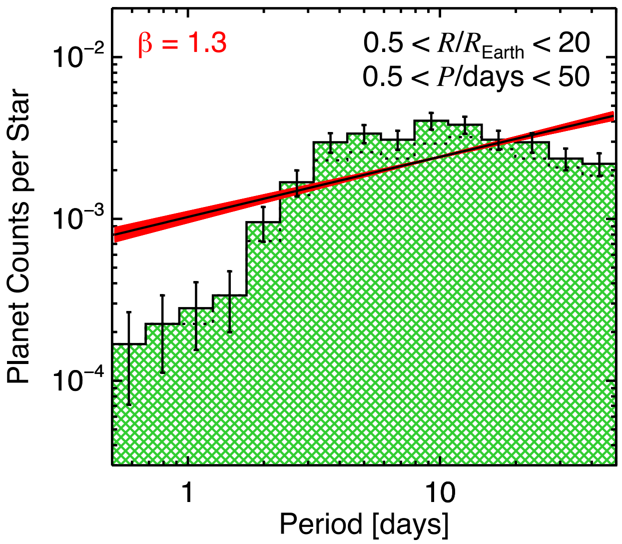
η_{tr} = planet transit probability



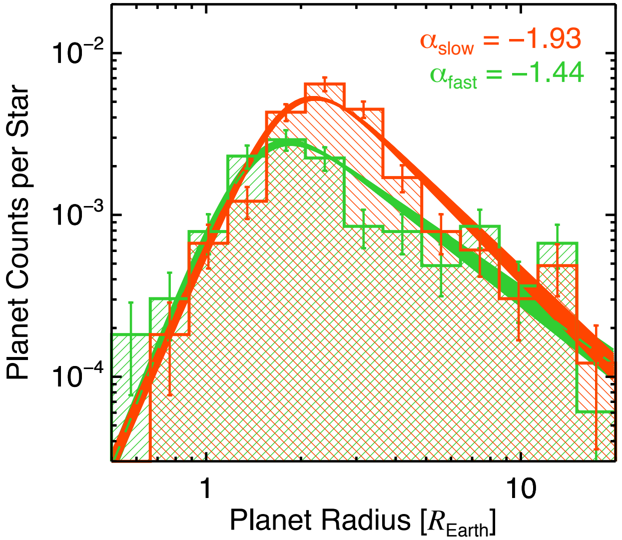
$$n \equiv \text{number of planets per star}$$

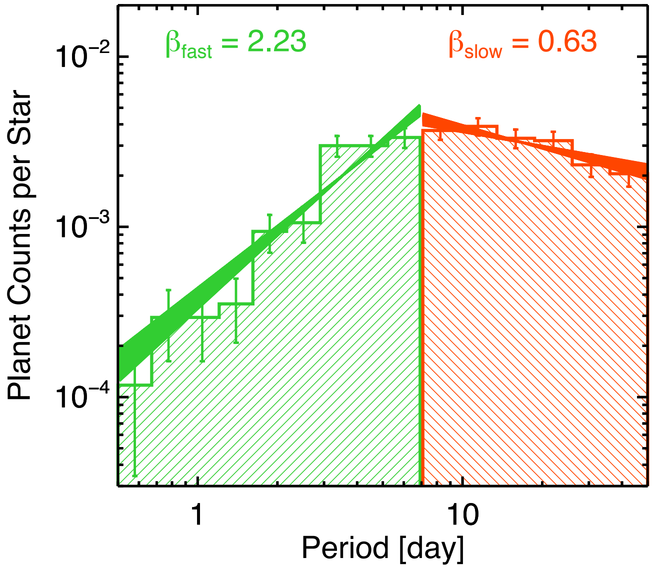
$$\frac{\partial^2 n}{\partial \ln R \, \partial \ln P} \propto R^{\alpha} P^{\beta} \text{ (say)}$$





period distribution not well fitted by single power law





divide into fast and slow populations and fit separately

P < 7 days

$$\frac{\partial^2 n}{\partial \ln R \, \partial \ln P} \propto R^{-1.4} P^{2.2}$$

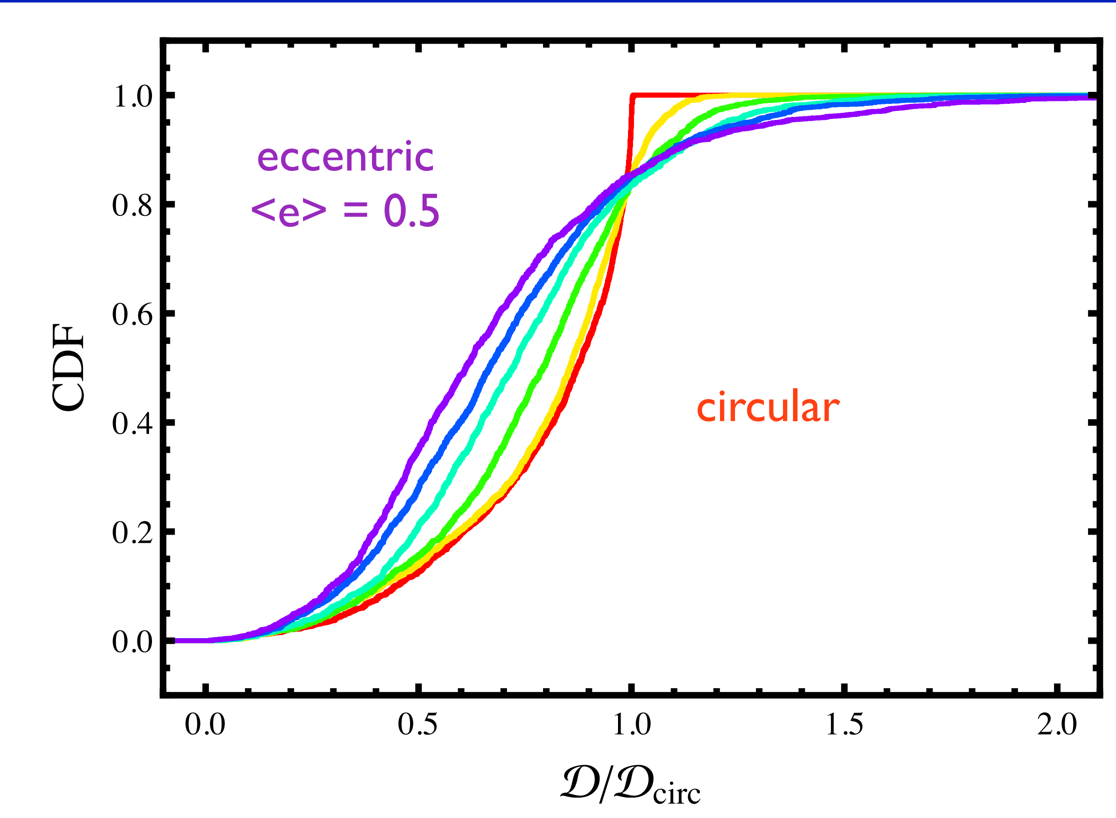
P > 7 days

$$\frac{\partial^2 n}{\partial \ln R \, \partial \ln P} \propto R^{-1.9} P^{0.6}$$

$n\ (R > 2\ R_\oplus, P < 50$ days$) \sim 0.2$ planet per star

Trust detection efficiency down to $1 R_\oplus$,
and extrapolate to 365 days :

$n\ (R > 1\ R_\oplus, P < 365$ days$) \sim 2$ planets per star

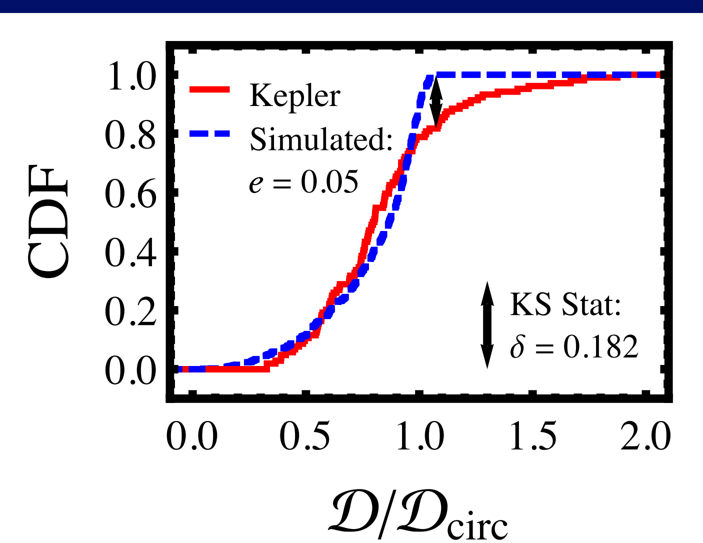


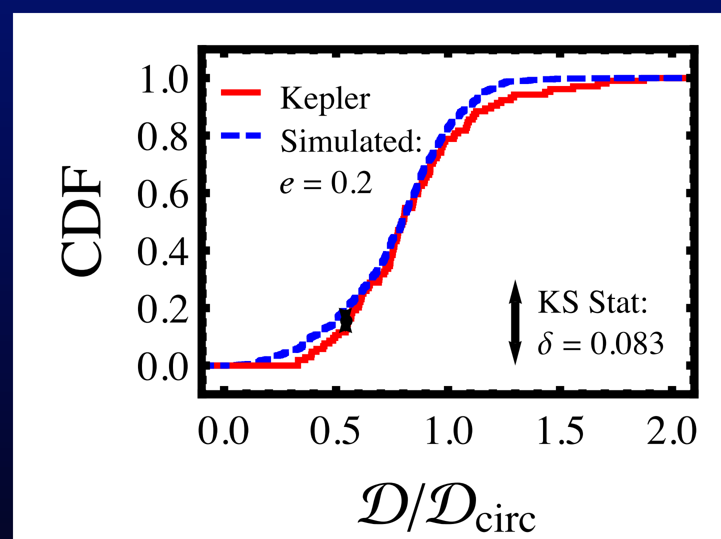
Eccentricity alters transit duration

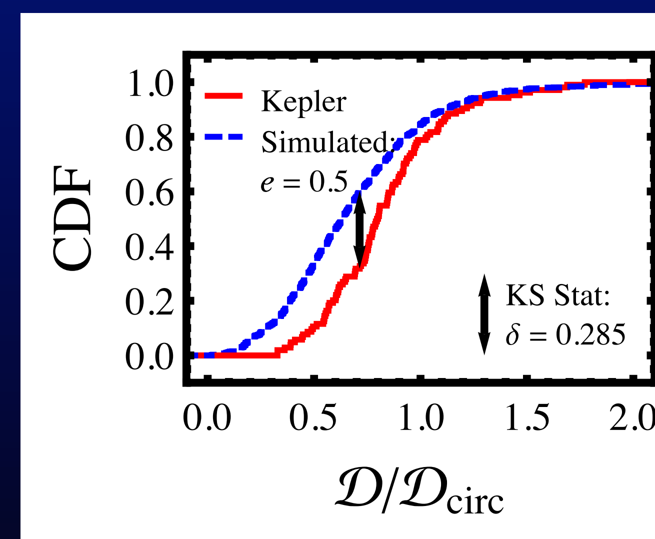
$$\mathcal{D}_{\rm circ} \equiv P \times \frac{2R_\star}{2\pi a}$$

Actual $\mathcal{D}$ lower if inclined, near periapse

Actual $\mathcal{D}$ higher if near apoapse







Mean <e> ~ 0.2 but beware uncertainty in $R_\star$

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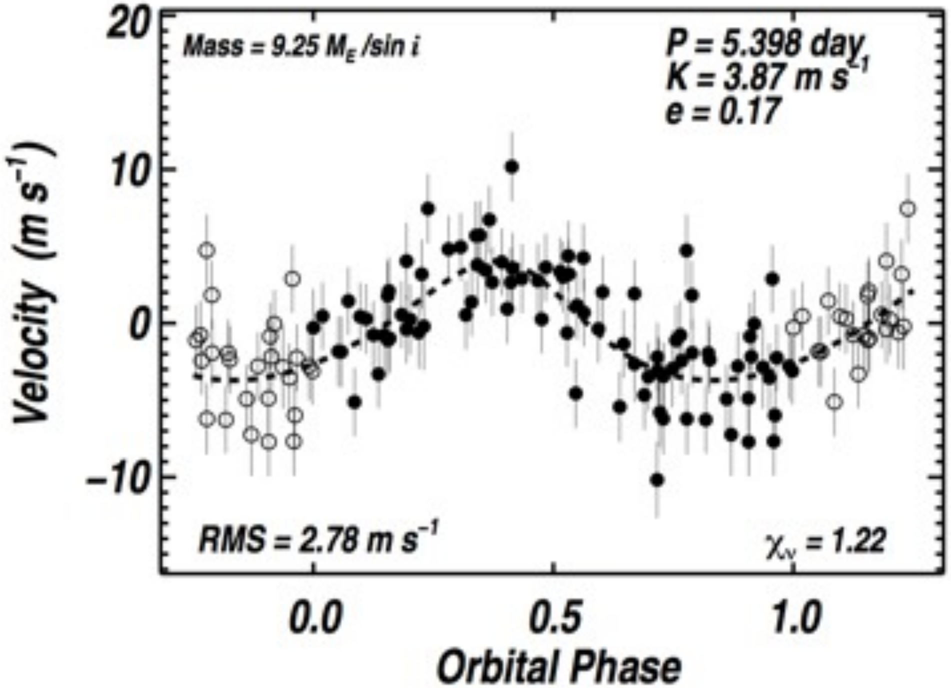
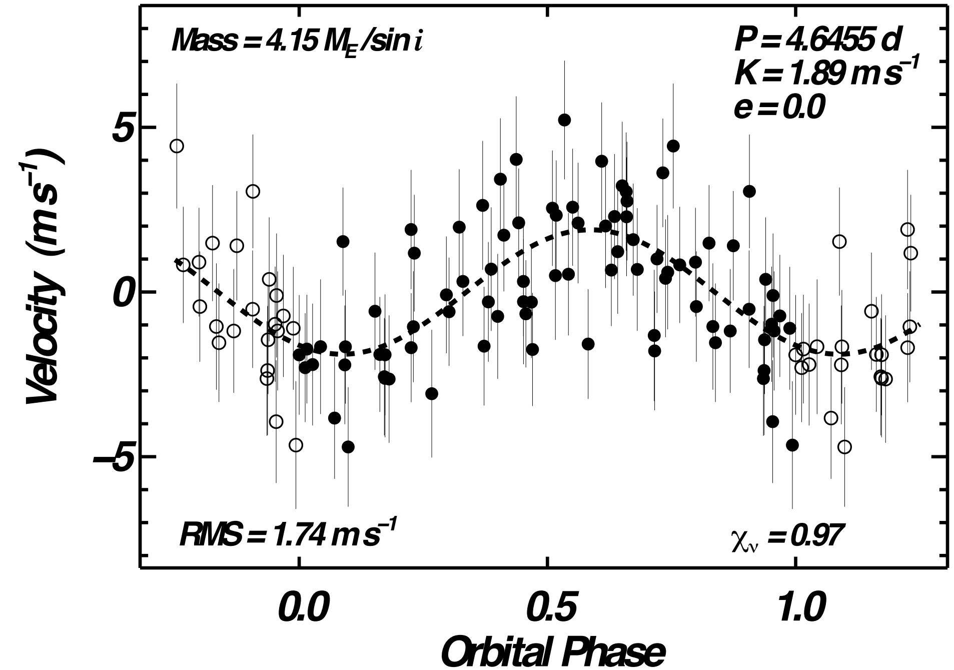
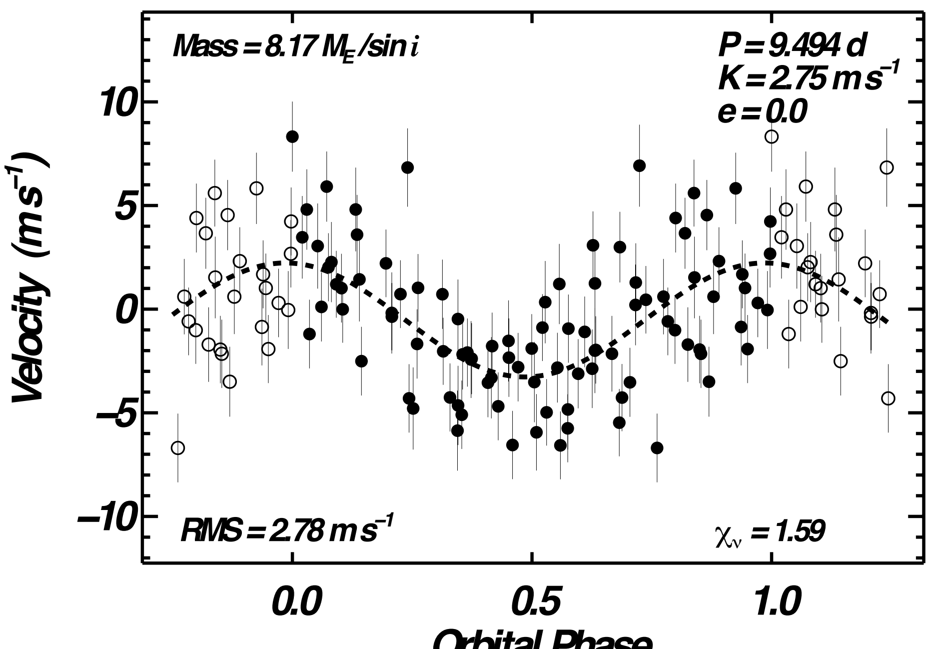
HD 7924 b



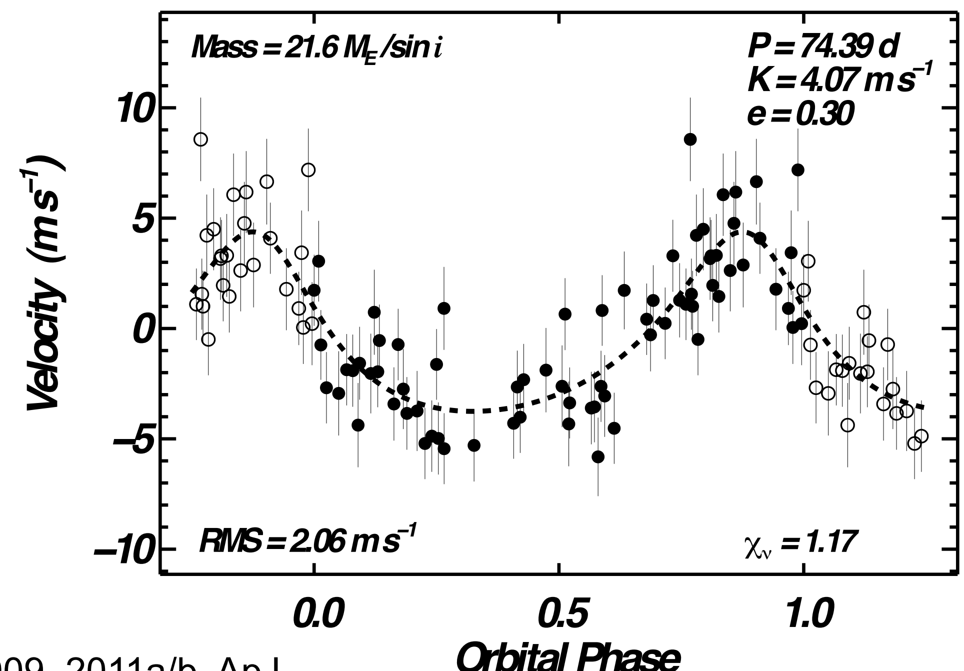
HD 156668 b



HD 97658 b



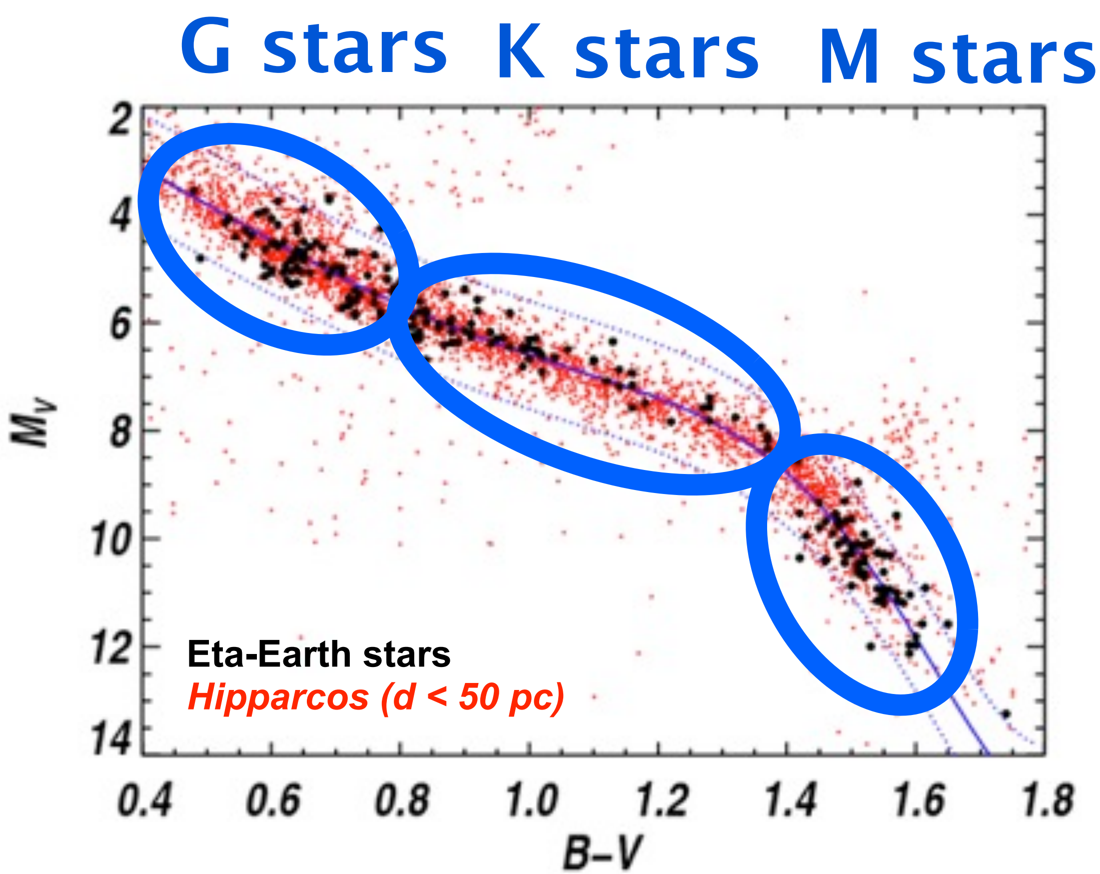
Gl 785 b



Howard et al. 2009, 2011a/b, ApJ

NASA-UC Eta-Earth Survey

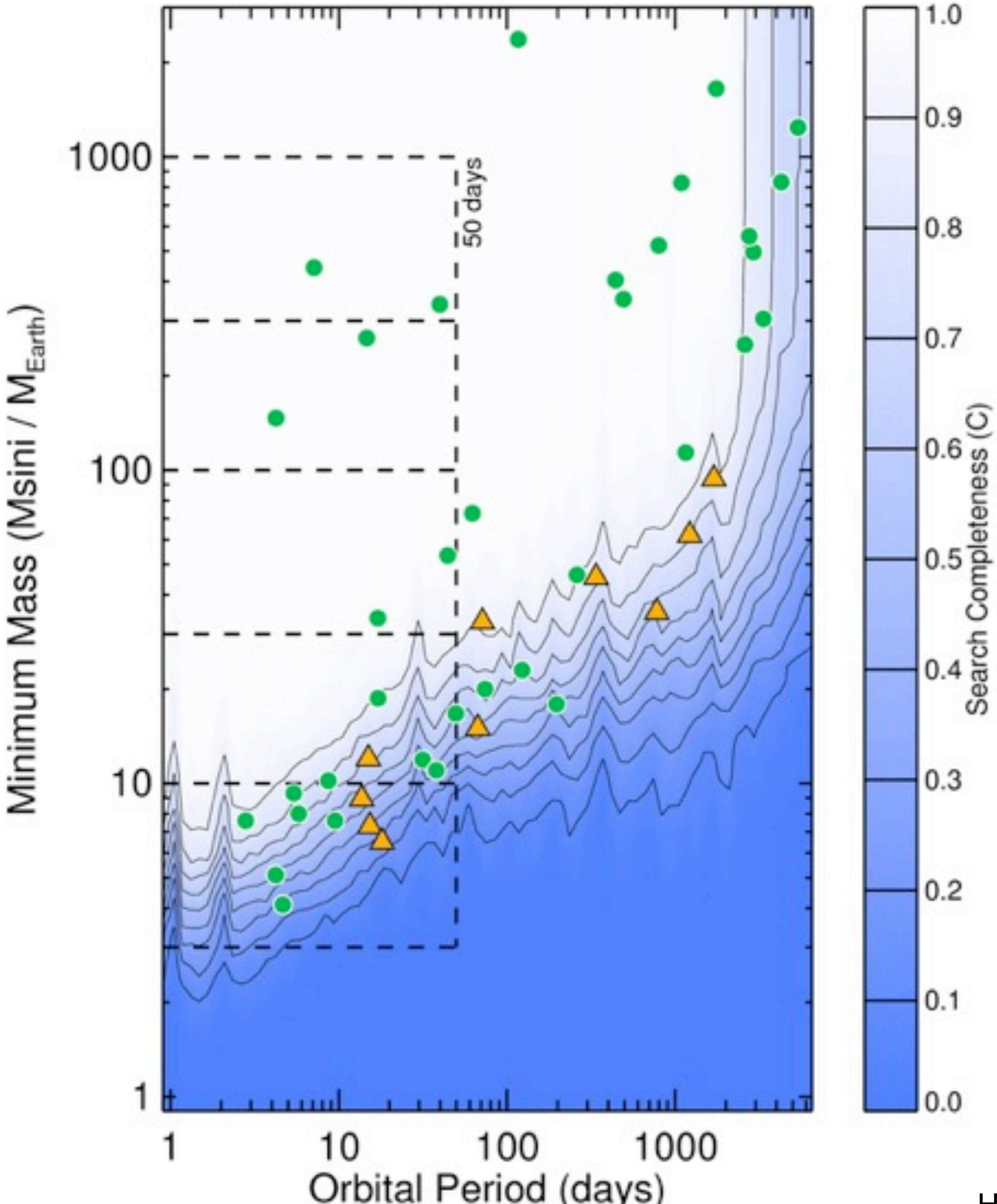
RV survey of 238 nearby GKM dwarfs
Search for low-mass planets (Msini > 3 M_{Earth})
Constrain population of low-mass planets



39% G stars
33% K stars
28% M stars

Statistically unbiased (nearly) stellar population:

- V < 11
- distance < 25 pc
- log R'HK < −4.7 (inactive)

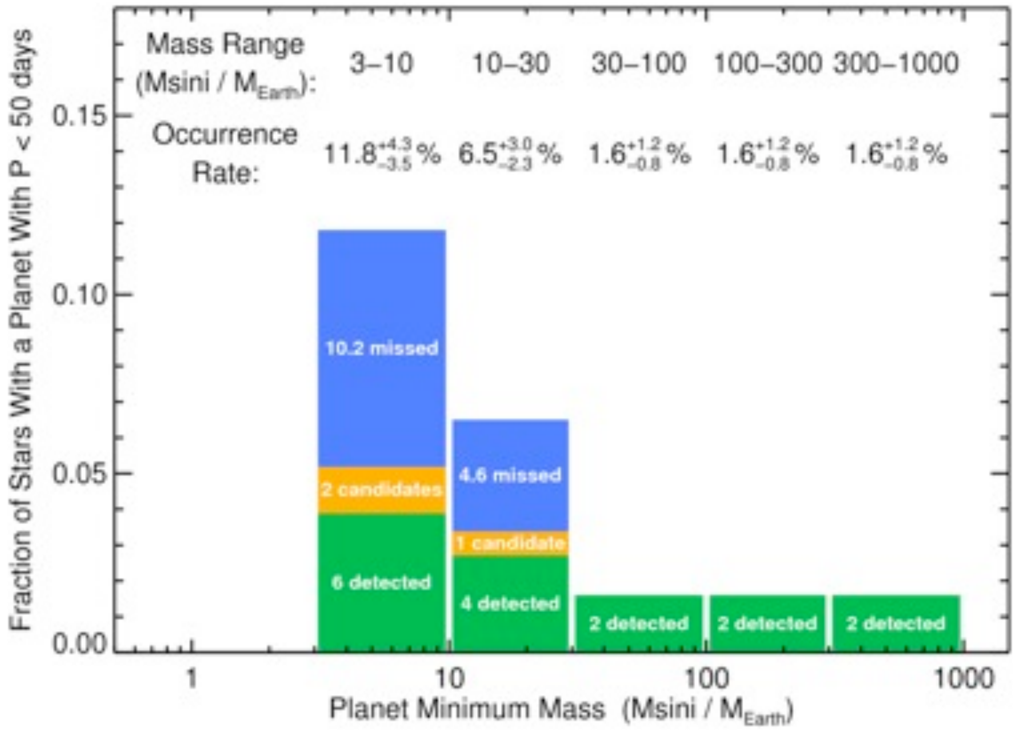


- Detected planets
- Candidate planets (FAPs ~ 1-5%)

Candidate planets included in counting planets.

Howard et al. 2010, Science, 330, 653

Key Result: Power-law Mass Distribution



$df/d\log M = kM^{\alpha}$

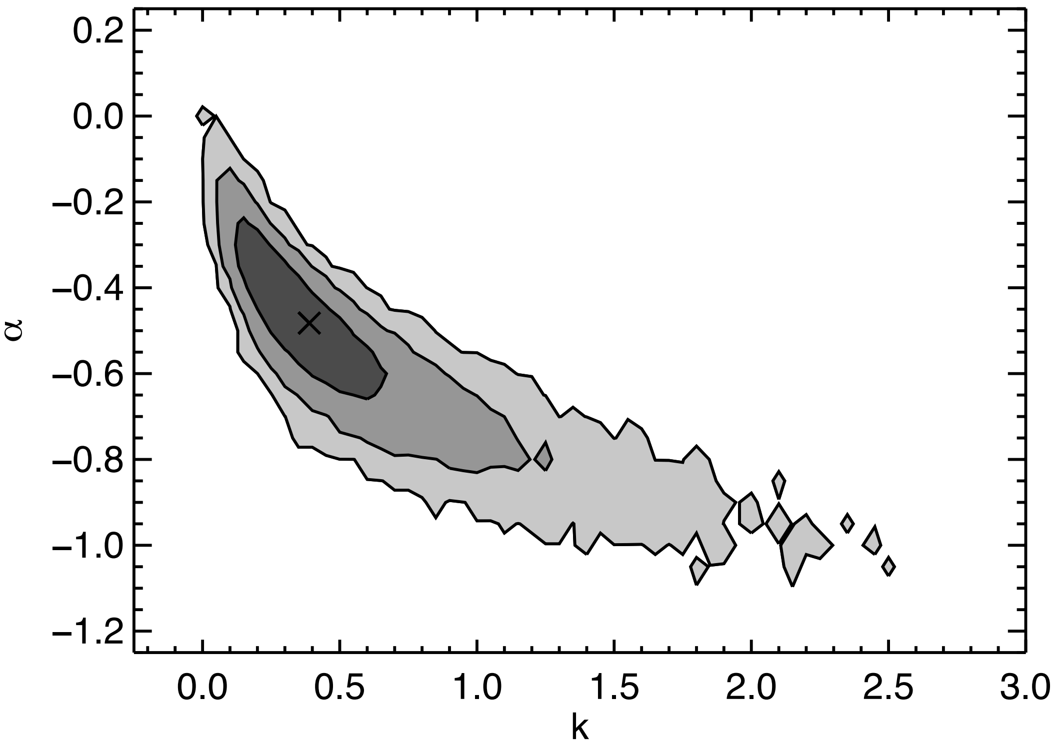
$k = 0.39^{+0.27}_{-0.16}$

$\alpha = -0.48^{+0.12}_{-0.14}$

<u>Compute Errors</u>

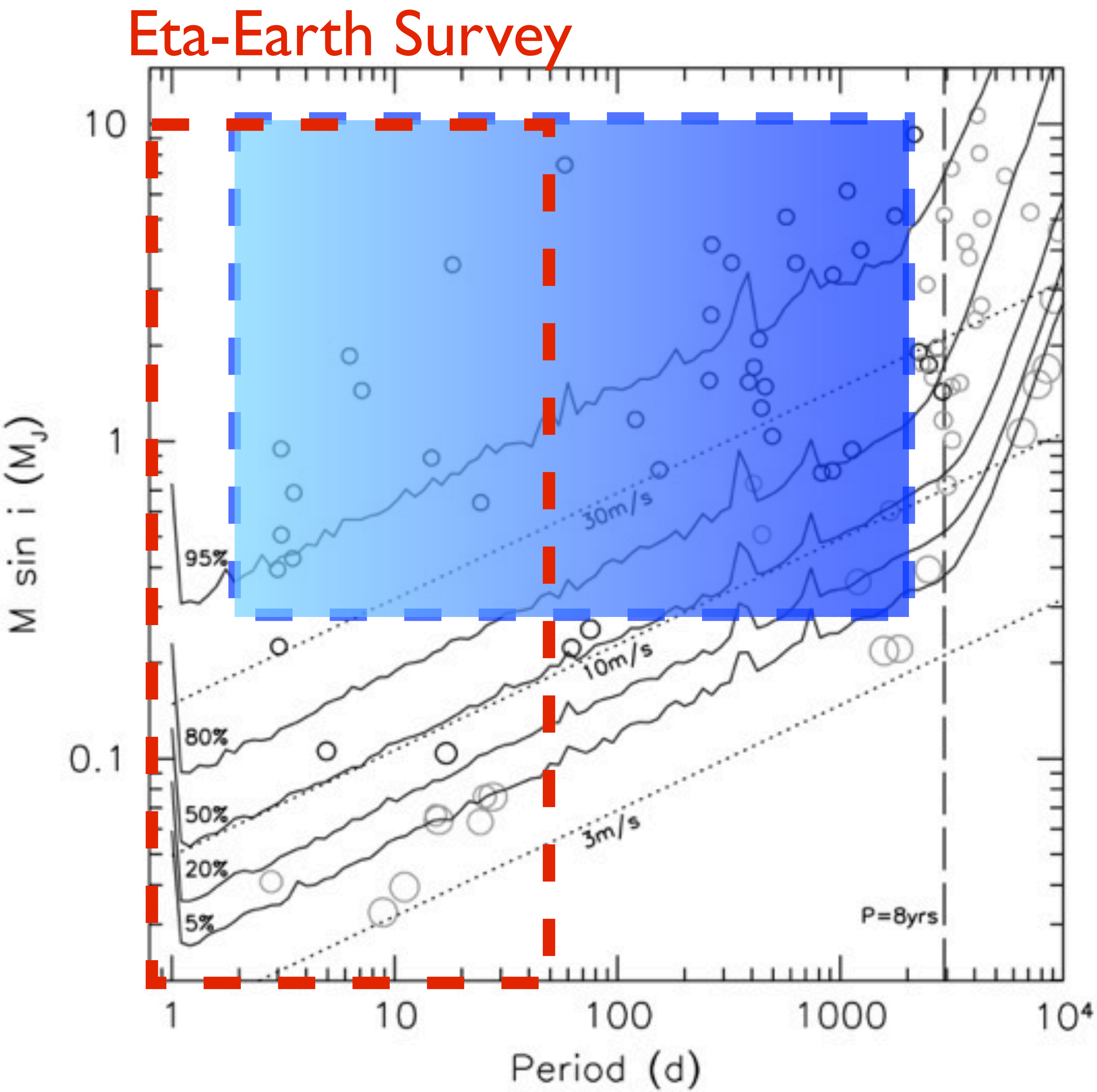
assume binomial statistics

scale missed planets w/det + cand



Howard et al. 2010, Science, 330, 653

Giant Planet Occurrence Rates



Cumming et al. (2008)

475 FGK dwarfs
Giant Planet Occurrence:

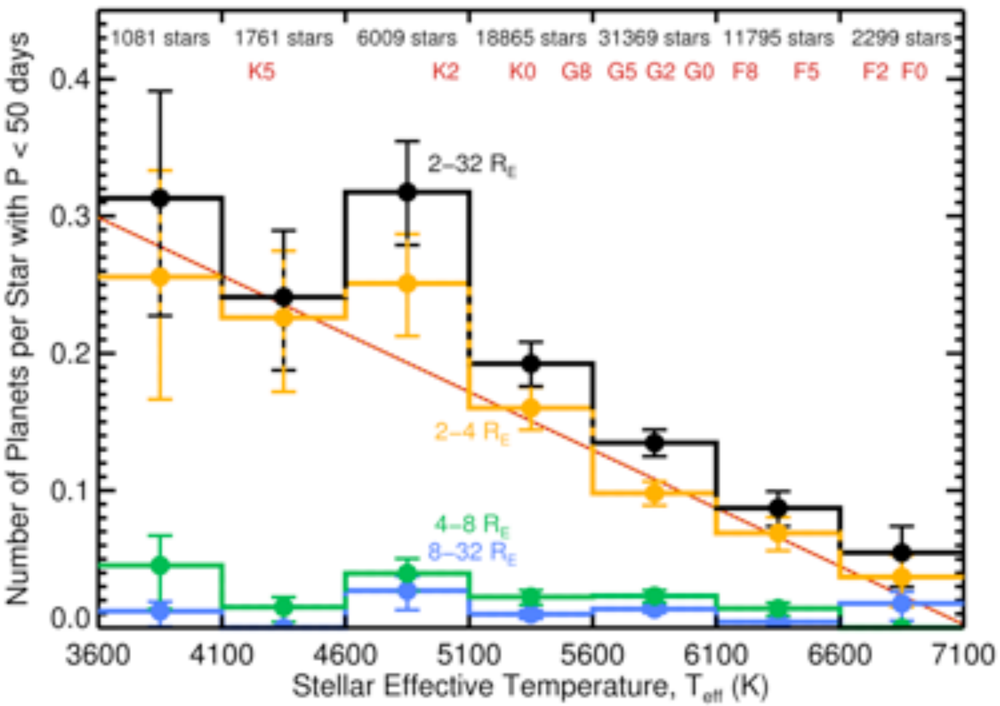
$$\frac{dN}{d\ln P\ d\ln M} = CM^{\alpha}P^{\beta}$$

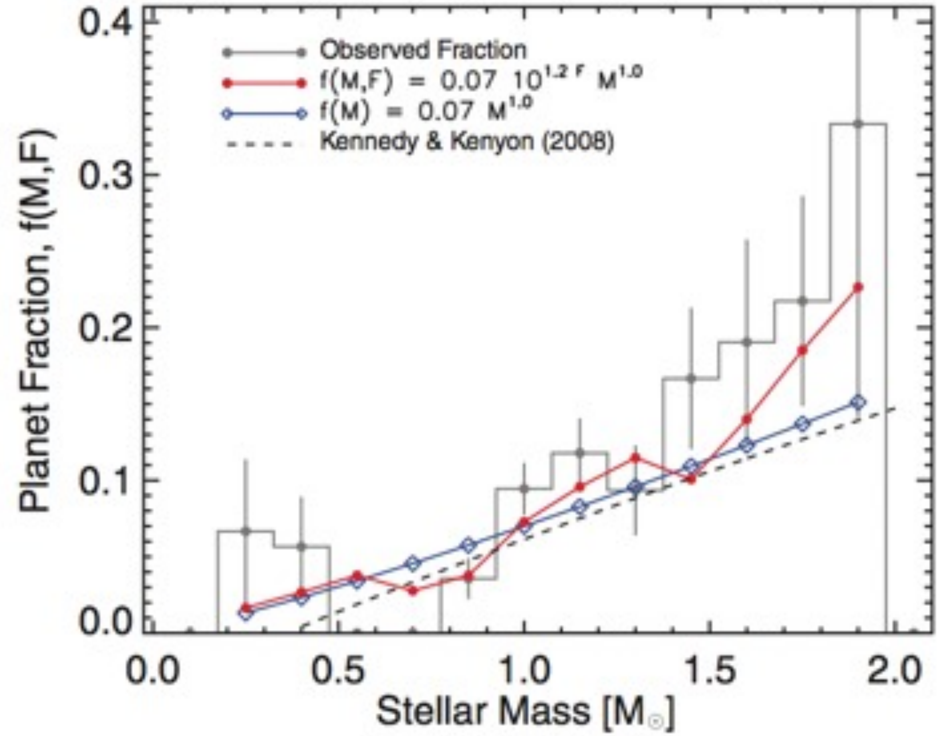
α = –0.31 ± 0.2
β = +0.26 ± 0.1

10.5% occurrence for
Msini = 0.3–10 M_J
P = 2–2000 days

See also, e.g., Udry et al. (2003)

Planet Occurrence vs. M★





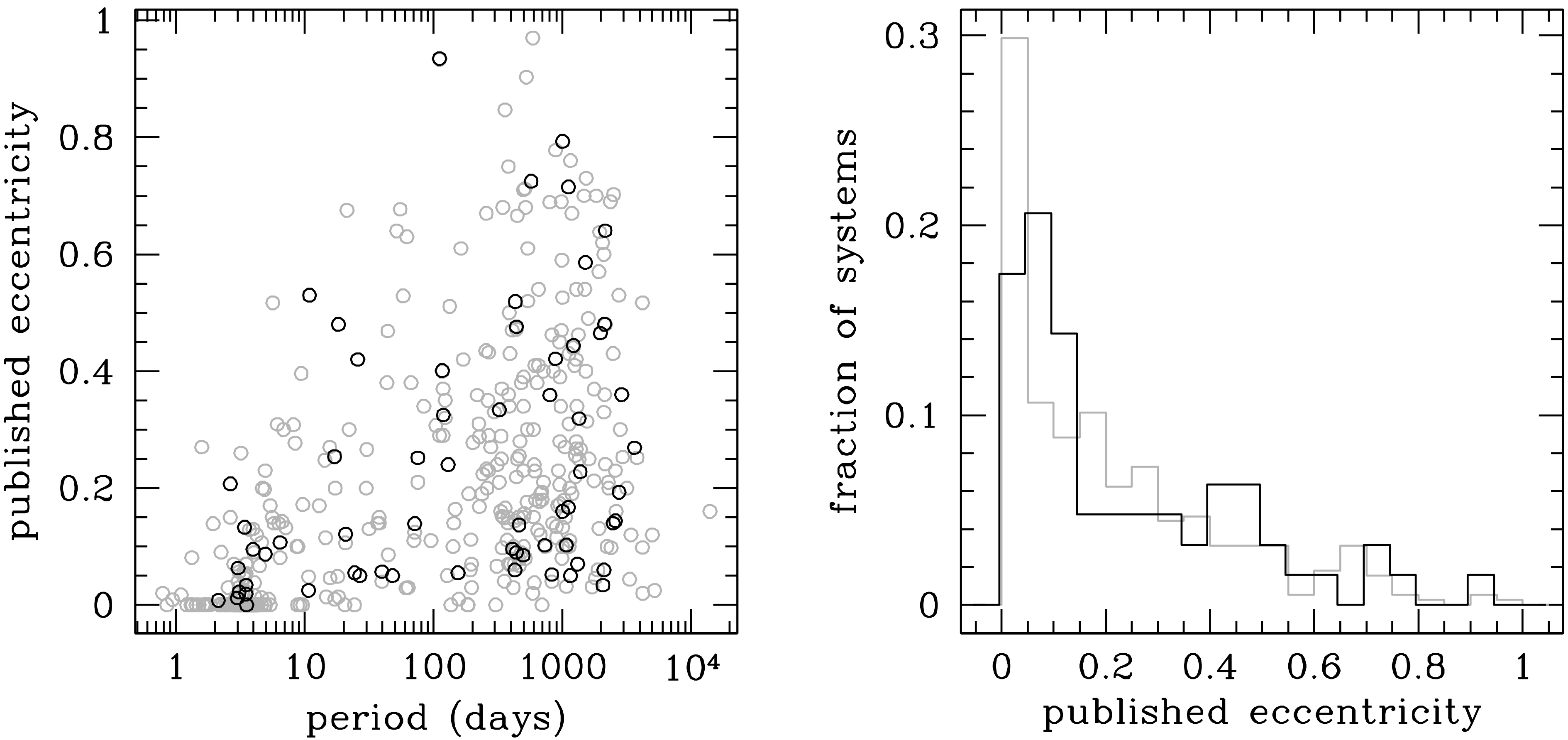
Occurrence within 0.25 AU
of small planets
decreases with M★

Occurrence within 2.5 AU
of giant planets
increases with M★

Howard et al. (2011c)

Johnson et al. (2010)

Eccentricities from Doppler Surveys

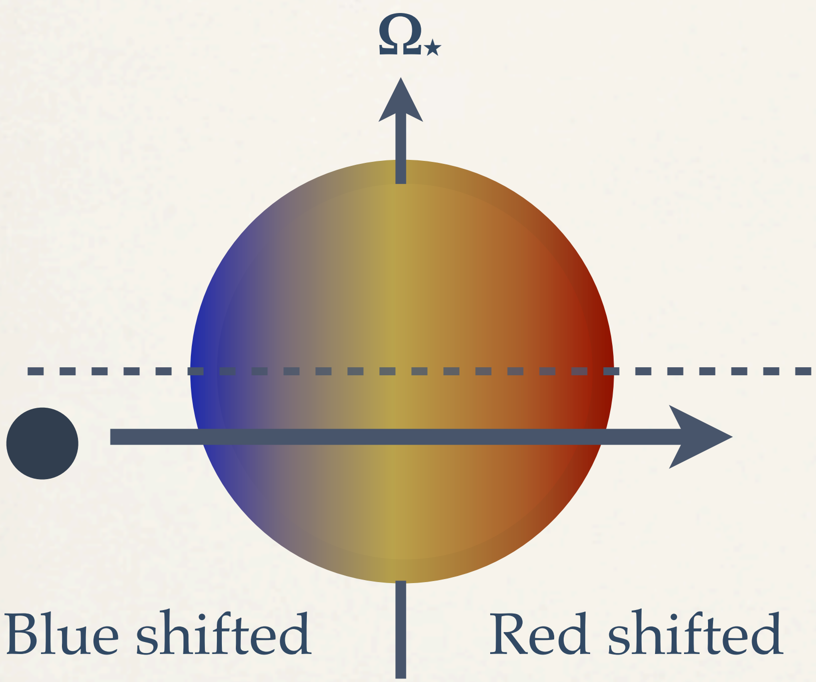


P > 10 days: At face value, 10% of systems have e < 0.05

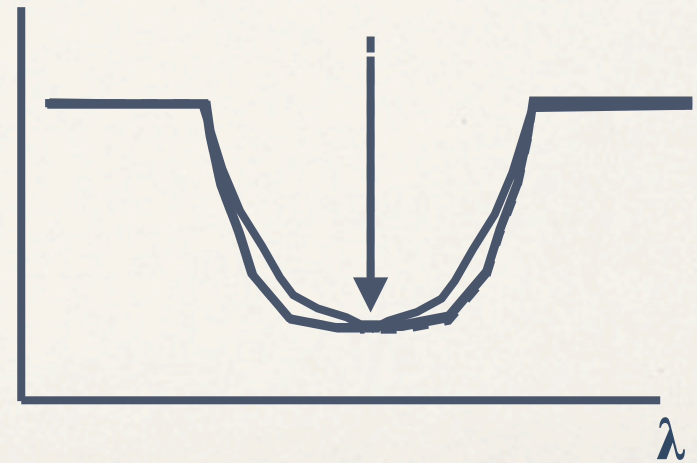
But corrected for eccentricity bias: 28+/-8%

Transits with stellar rotation

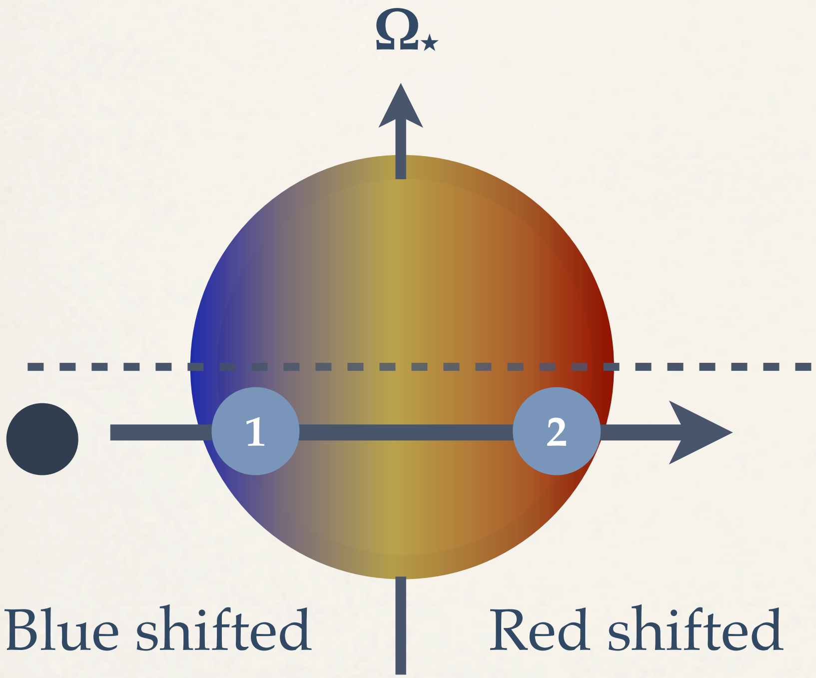
- Intensity of the star is Doppler shifted.



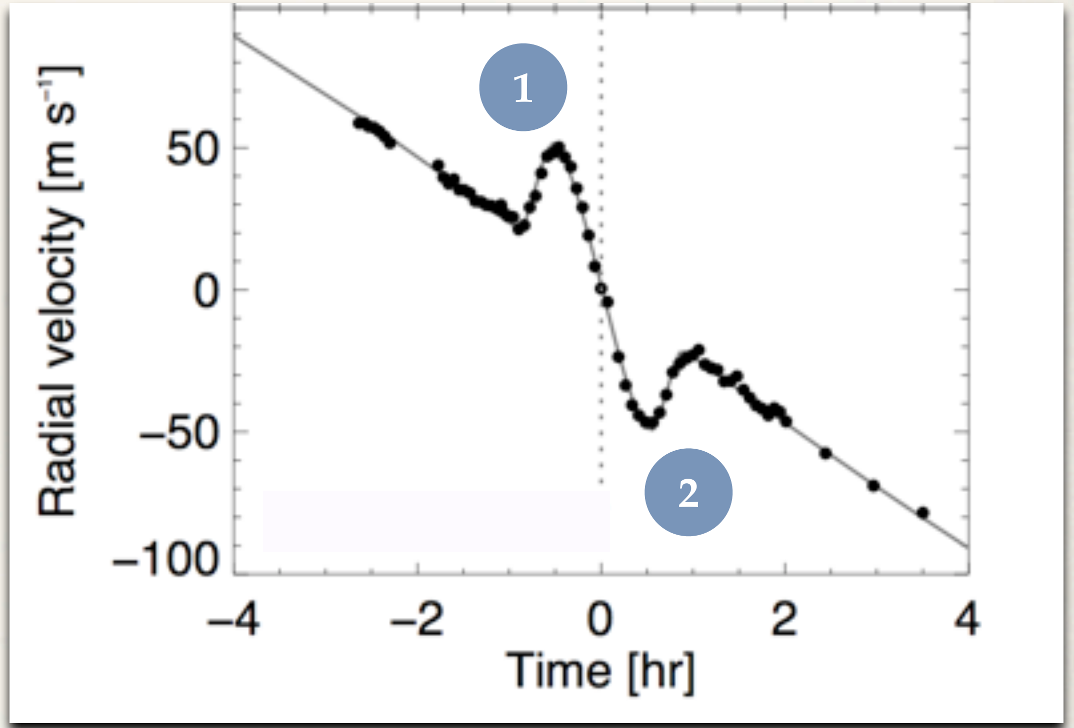
- Planet blocks blue shifted and red shifted side at different times.
- Results in an "anomalous" Doppler shift of line centers.



Transits with stellar rotation



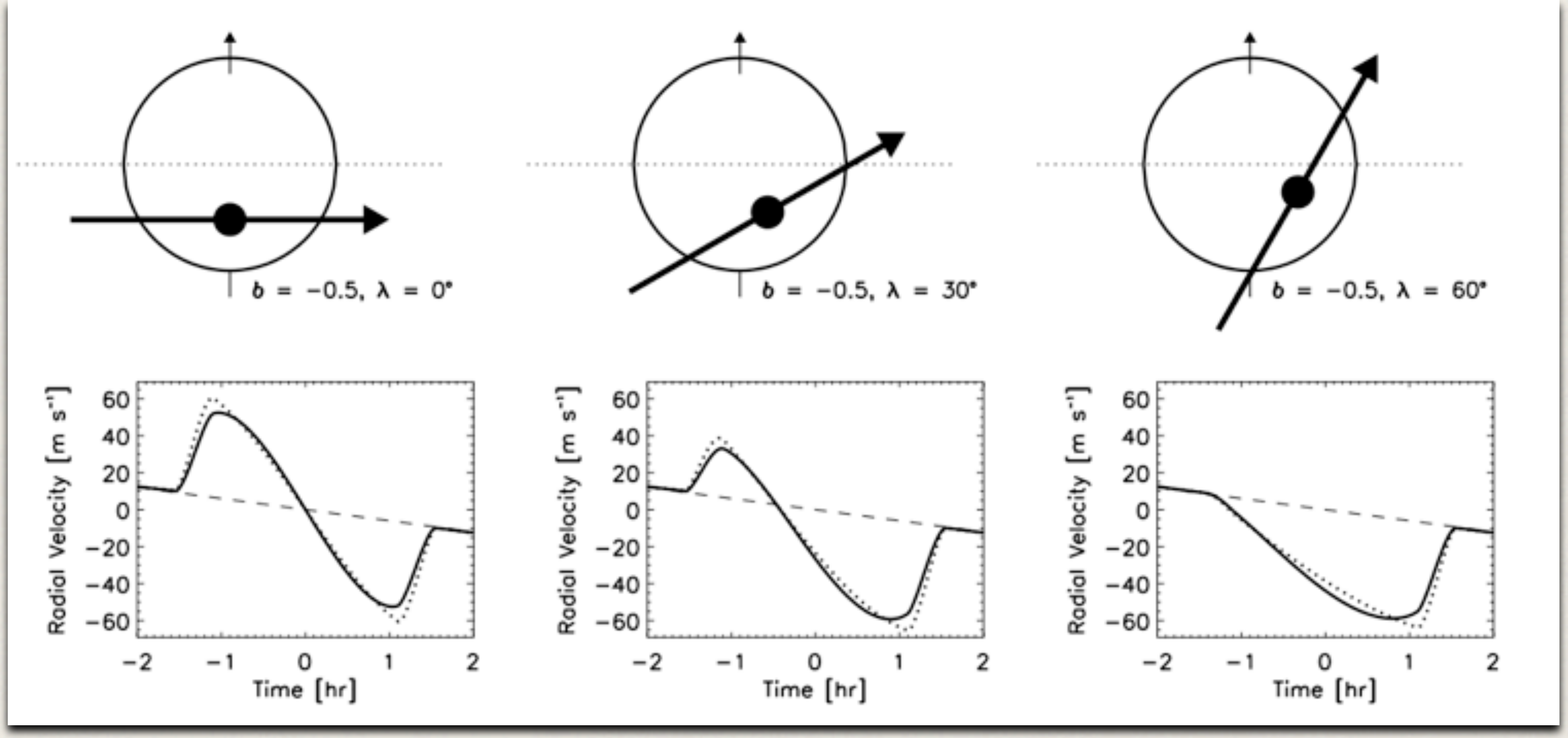
HD 189733



1. Blocks blue --> Appears red
2. Blocks red --> Appears blue

Winn et al. 2006 ; Winn 2011

Three examples

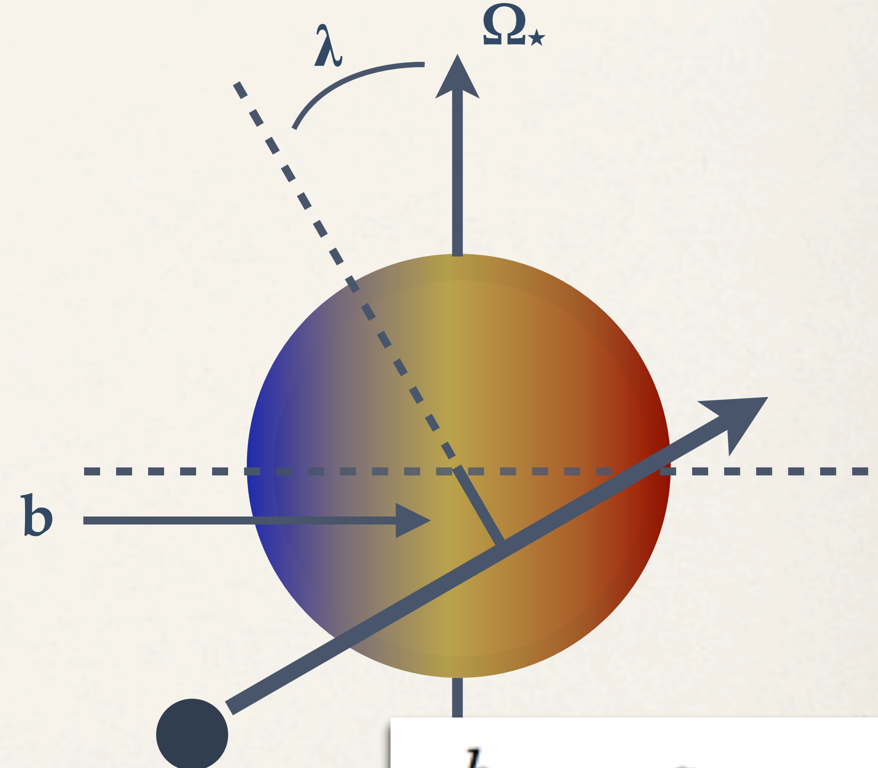


Gaudi & Winn 2007

Projected obliquity

- Orbits with the same photometry (same b) can have different obliquities.
- The RM effect depends on λ, b and $\Omega_\star \sin i_\star$.
- The angle λ relates to the true stellar obliquity ψ.

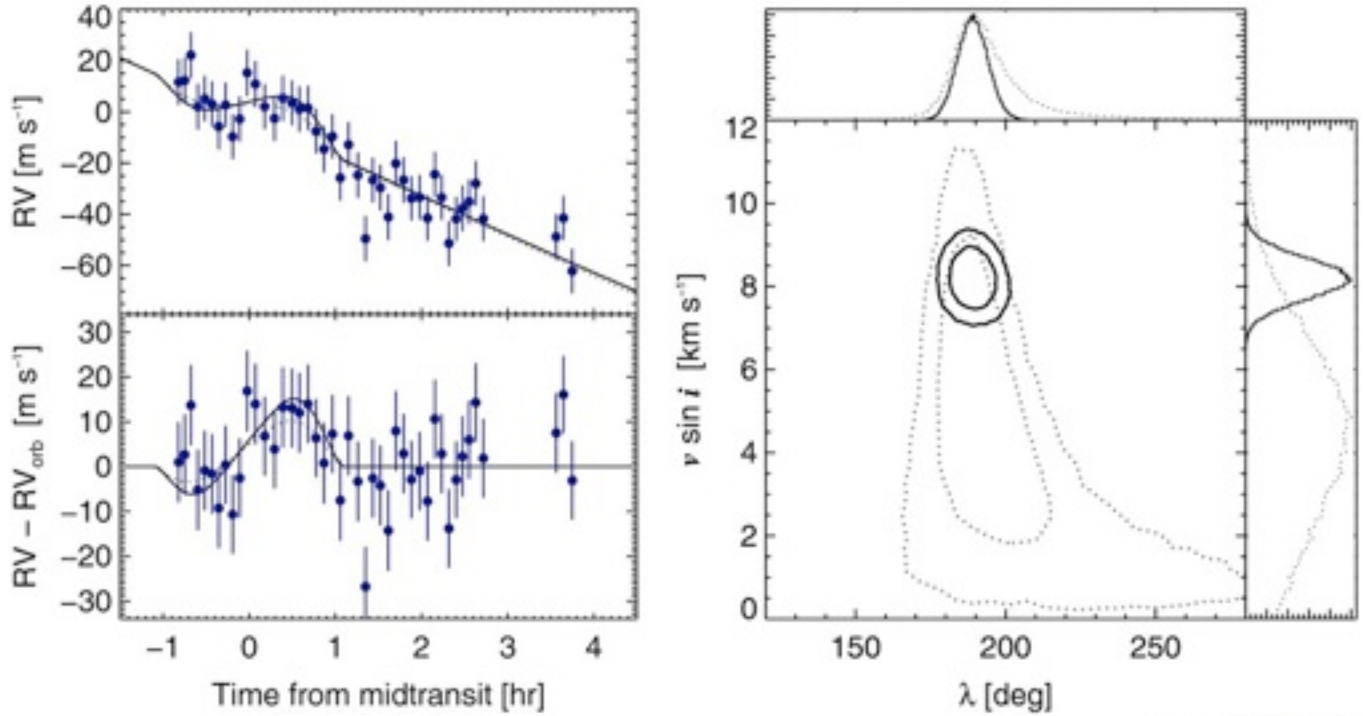
λ = (sky projected) stellar obliquity



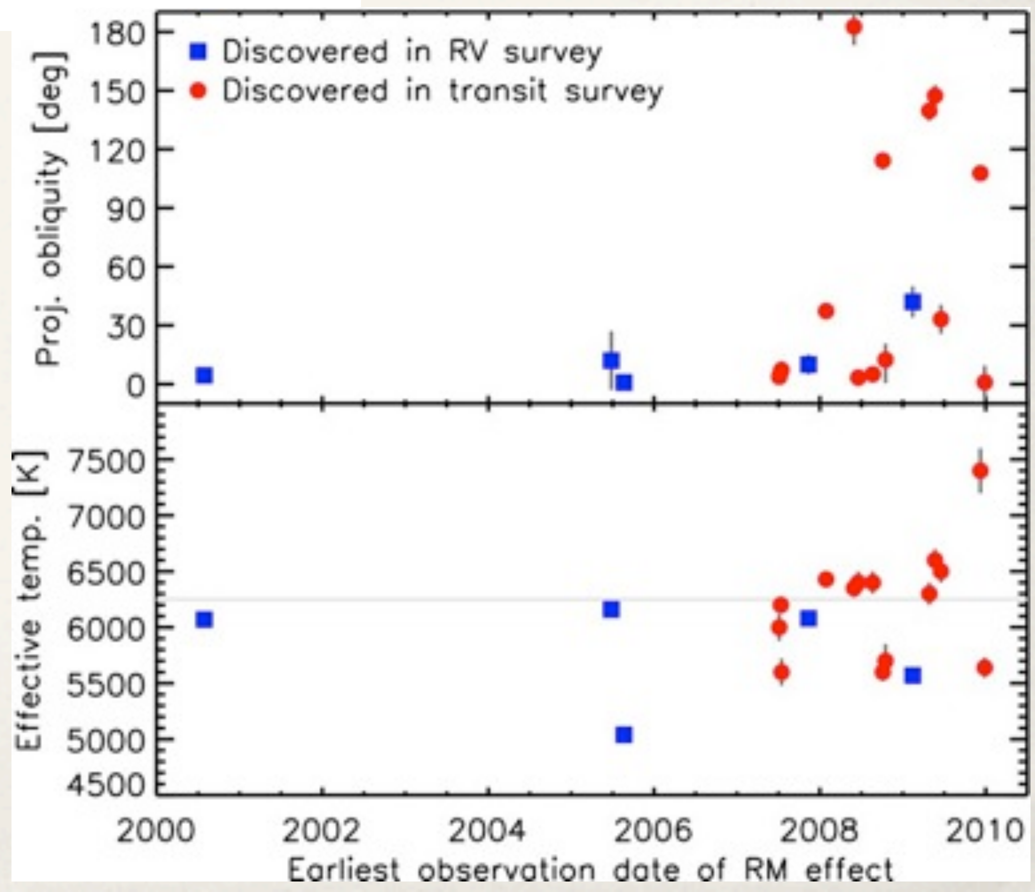
$$\frac{b}{R_\star} = \frac{a}{R_\star} \cos i_p$$

$$\cos\psi = \sin i_\star \cos\lambda \sin i_p + \cos i_\star \cos i_p$$

Even retrograde! (HAT-P-14)



Large spin-orbit misalignments



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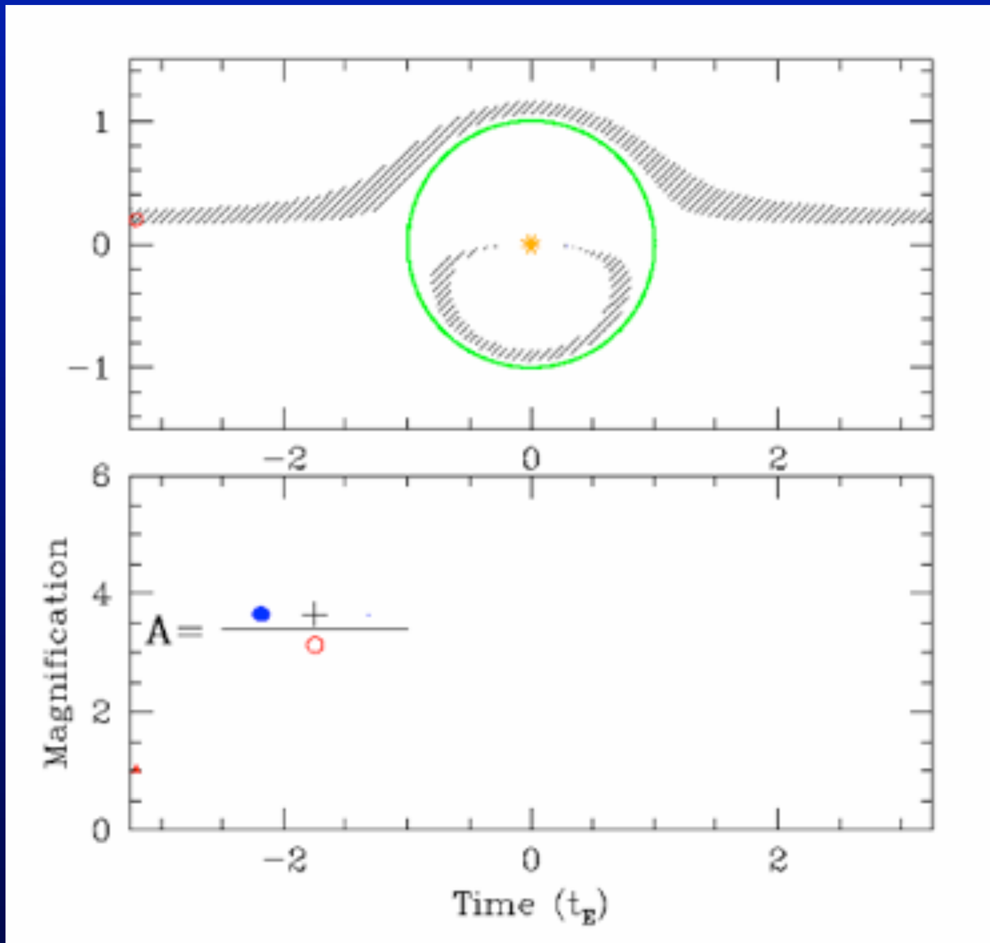
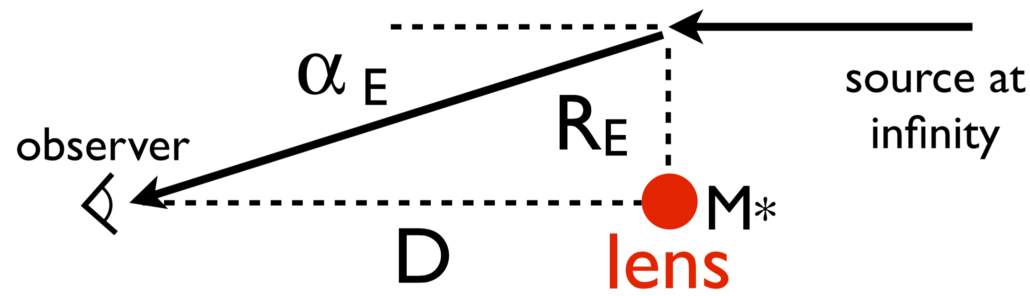
Gravitational Microlensing



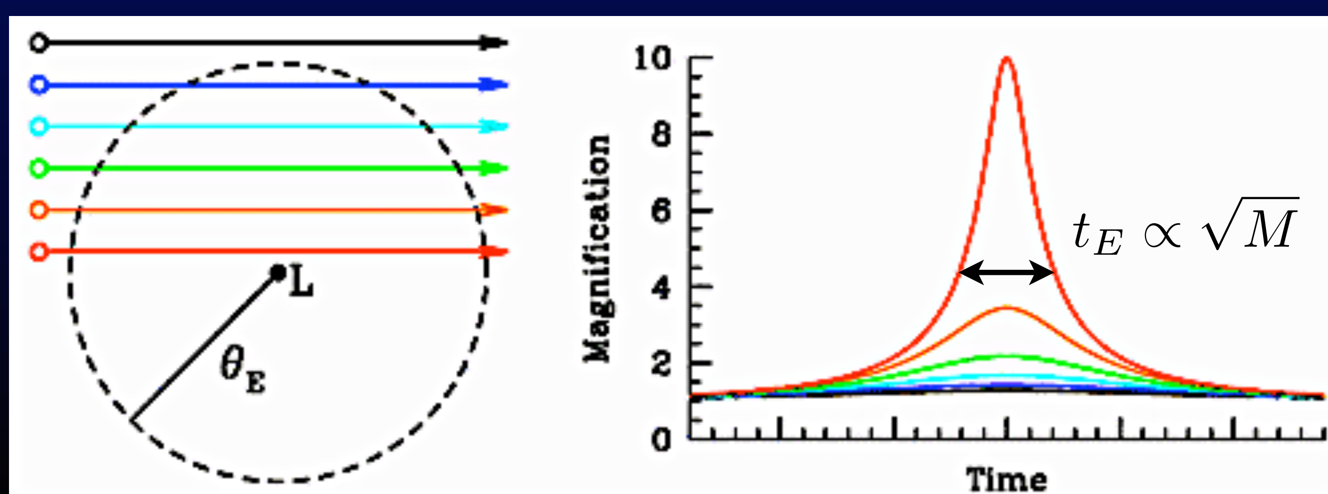


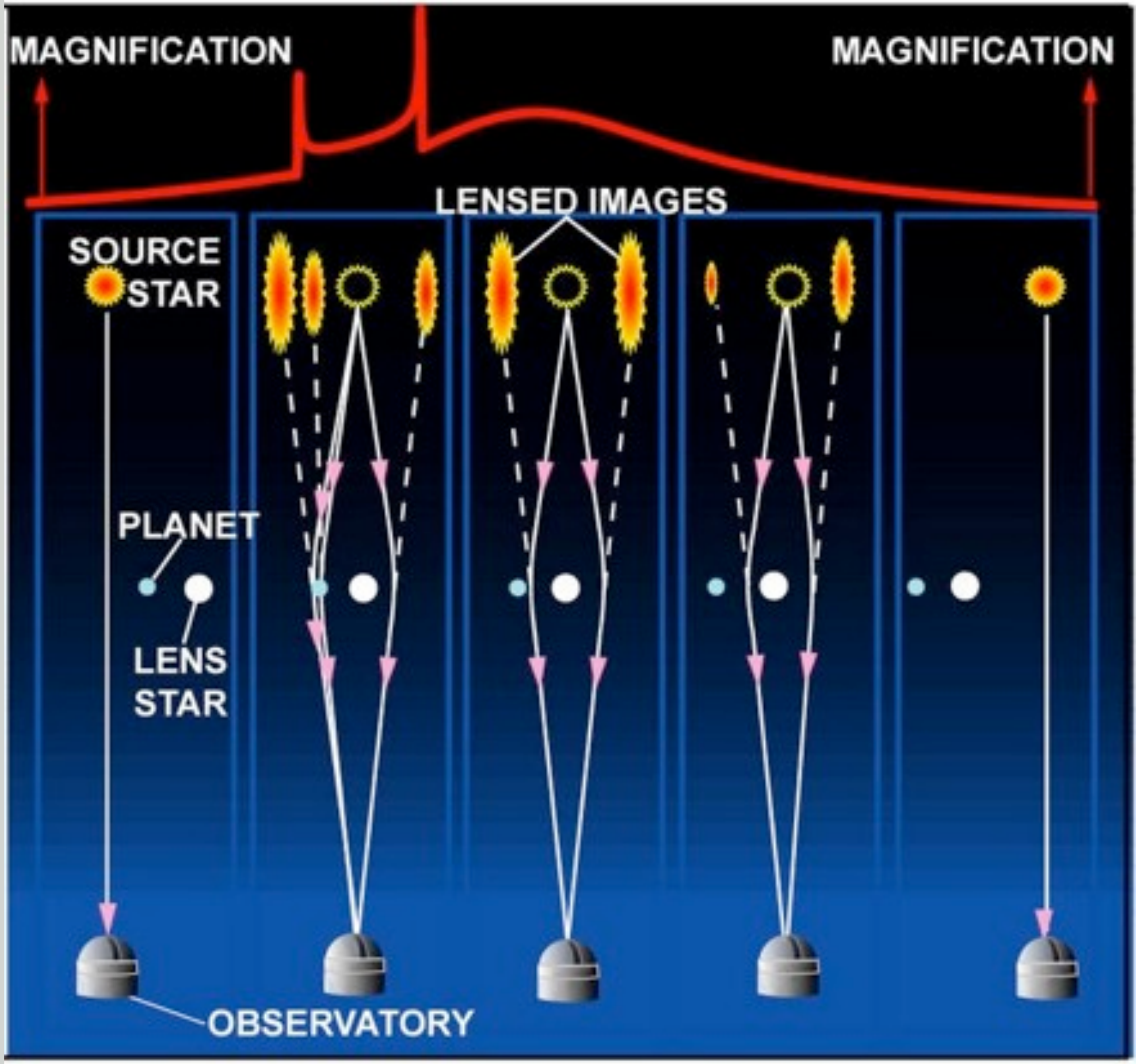
$$\Delta v \sim \frac{GM_*}{R_E^2} \times \frac{2R_E}{c} \qquad \alpha_E \sim \frac{\Delta v}{c} \sim \frac{R_E}{D}$$

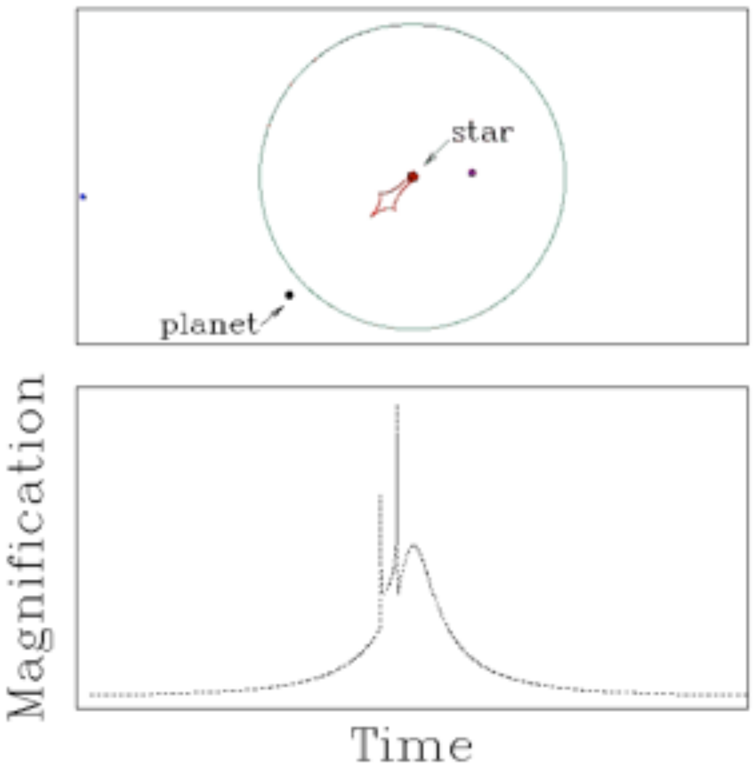
$$\alpha_E \sim 1\,\mathrm{mas} \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{\mathrm{kpc}}{D}\right)^{1/2}$$

$$R_E \sim 1\,\mathrm{AU} \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{D}{\mathrm{kpc}}\right)^{1/2}$$

$$t_E \sim \frac{R_E}{v_{\mathrm{rel}}} \sim 1\,\mathrm{month} \left(\frac{R_E}{\mathrm{AU}}\right) \left(\frac{30\,\mathrm{km/s}}{v_{\mathrm{rel}}}\right)$$





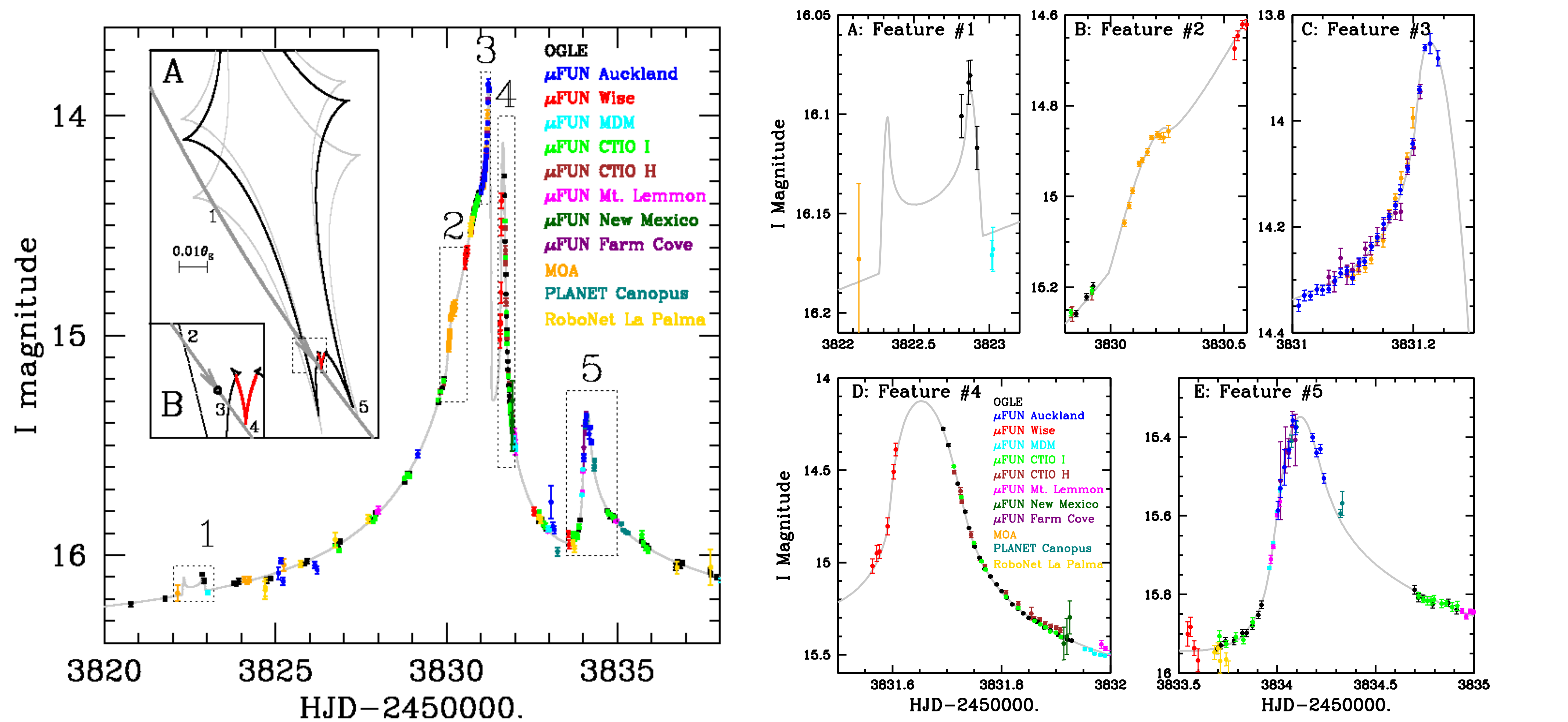


$$t_P \sim t_E \sqrt{\frac{M}{M_*}}$$

Planetary Microlensing (Binary lens)

$D \approx 5.2^{+0.2}_{-2.9}\,\mathrm{kpc}$ $\qquad$ $a \approx 3.0^{+0.1}_{-1.7}\,\mathrm{AU}$

$M_* \approx 0.36^{+0.03}_{-0.28}\,M_\odot$ $\qquad$ $M \approx 1.5^{+0.1}_{-1.2}\,M_J$



$M_* \approx 0.5 M_\odot$ $\quad D \approx 1.5\,\mathrm{kpc}$

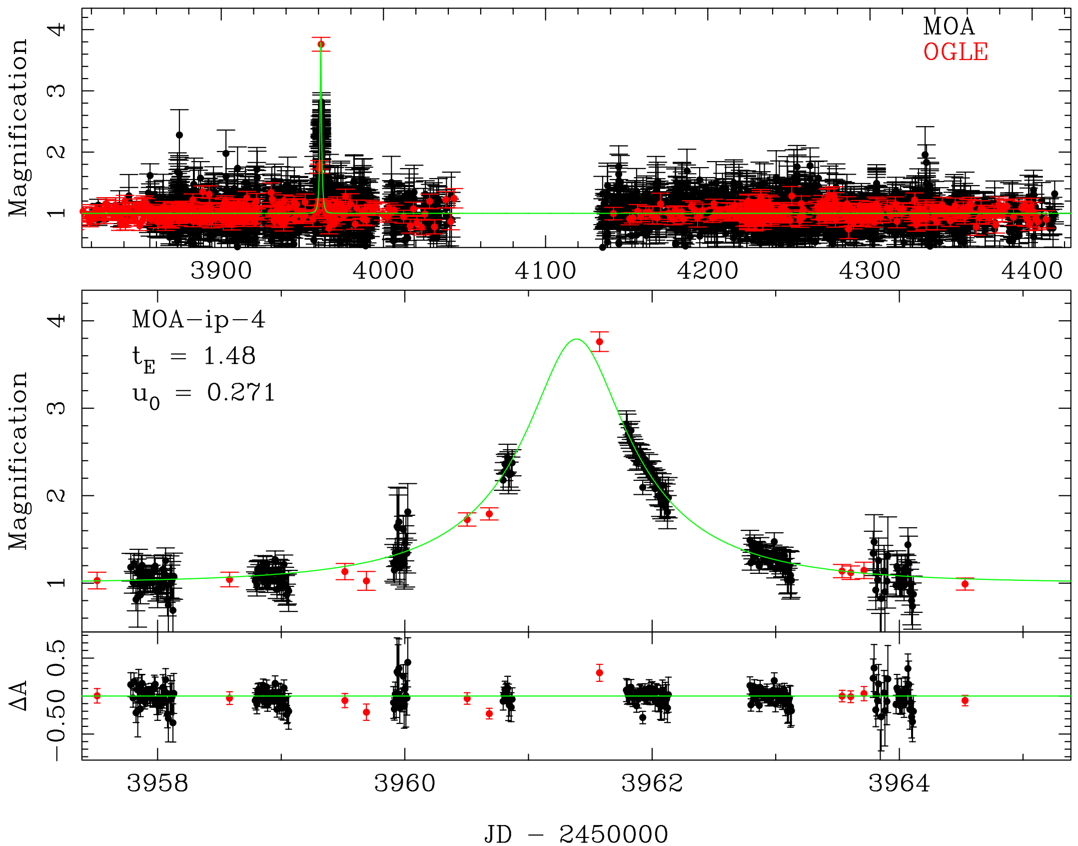
$M_1 \approx 0.71 M_J$ $\quad a_1 \approx 2.3\,\mathrm{AU}$

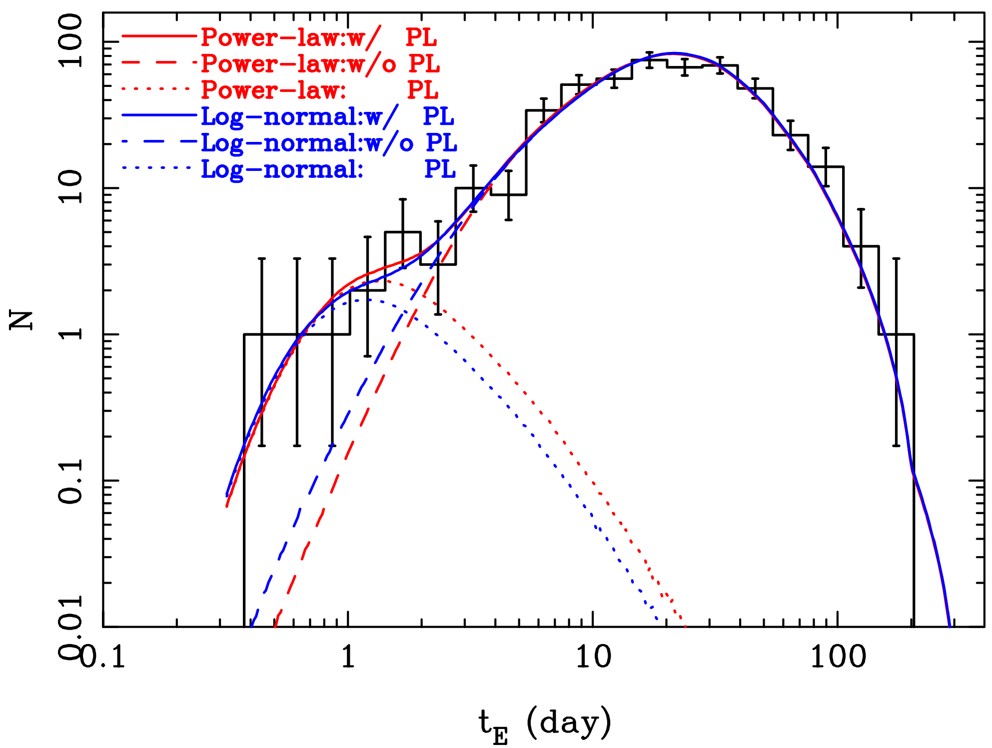
$M_2 \approx 0.27 M_J$ $\quad a_2 \approx 4.6\,\mathrm{AU}$ $\quad e_2 \approx 0.15^{+0.17}_{-0.10}$

from orbital motion!

Statistics from microlensing

1. At fixed $M_\star$, $dN/dM \propto M^{-1.7}$
2. 20 +/- 10% of stars have 5-15 $M_\oplus$ at a ~ 1.6-4.3 AU
3. For every star $0.08\ M_\odot < M_\star < 1\ M_\odot$,
   there are ~2 *free-floating* Jupiter-mass objects!





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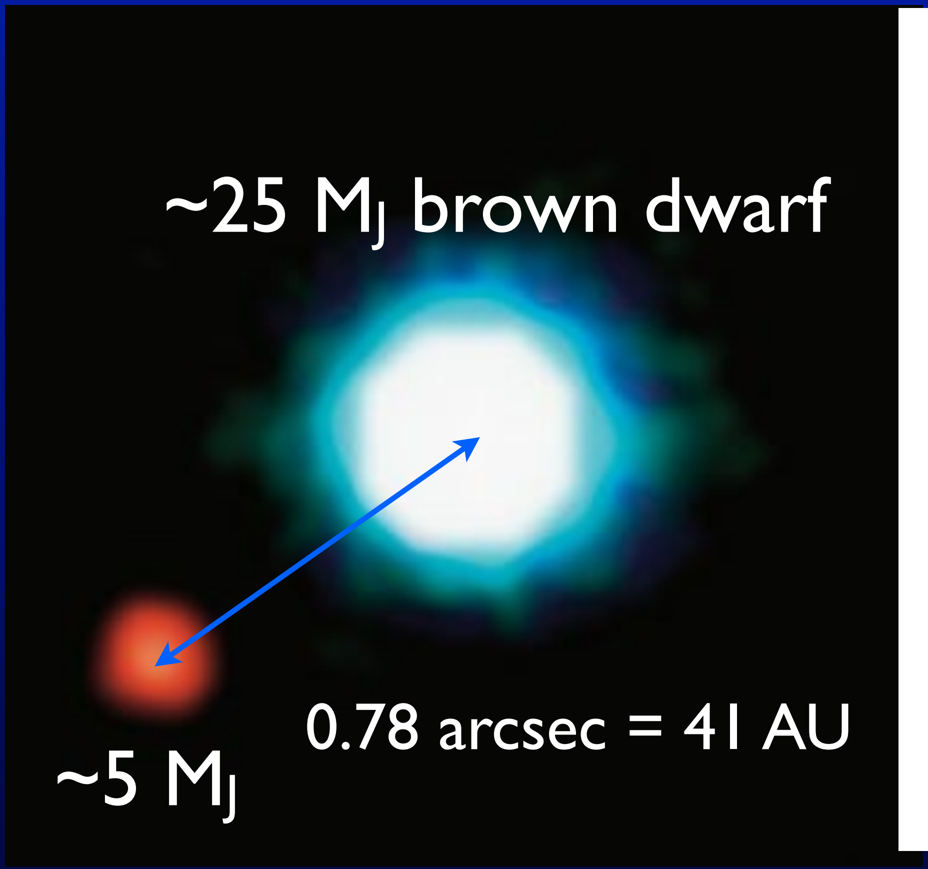
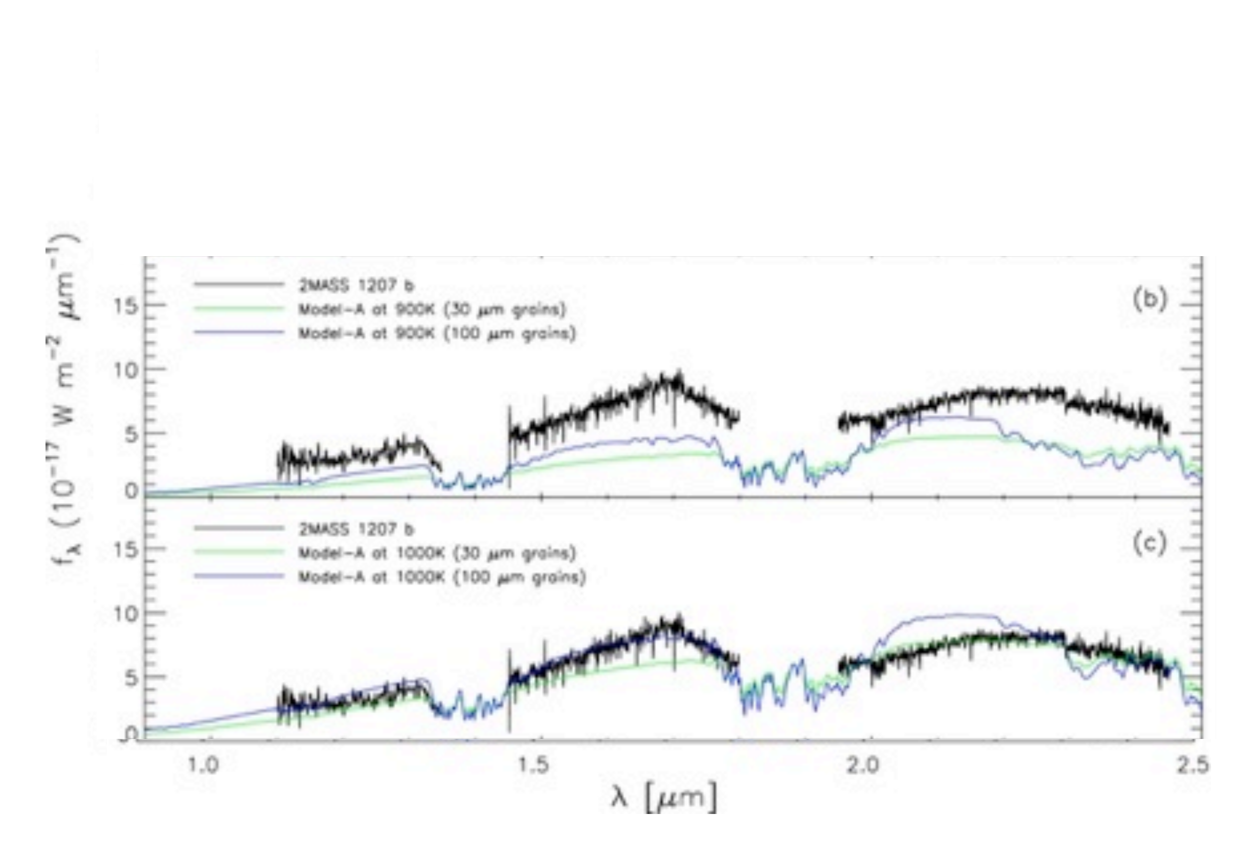
2MASS 1207 b



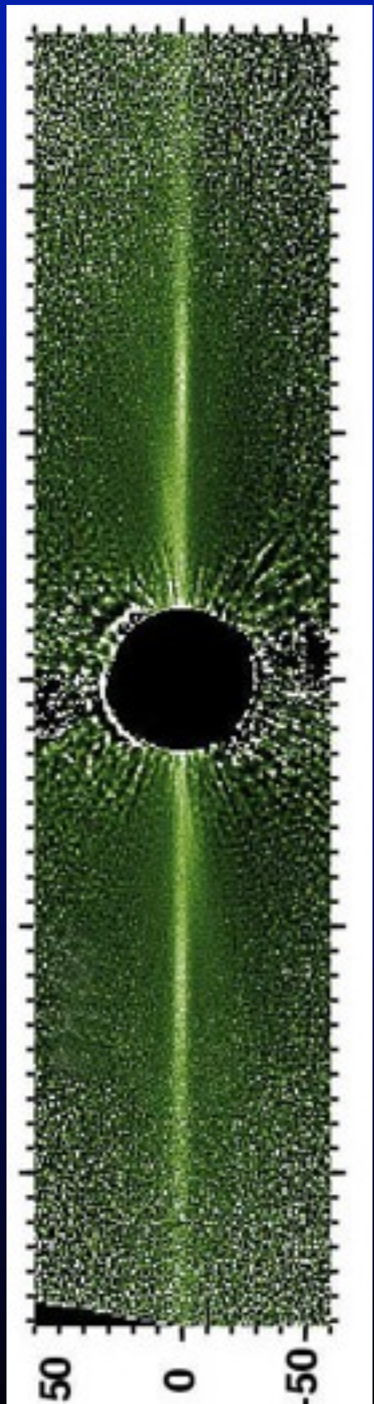


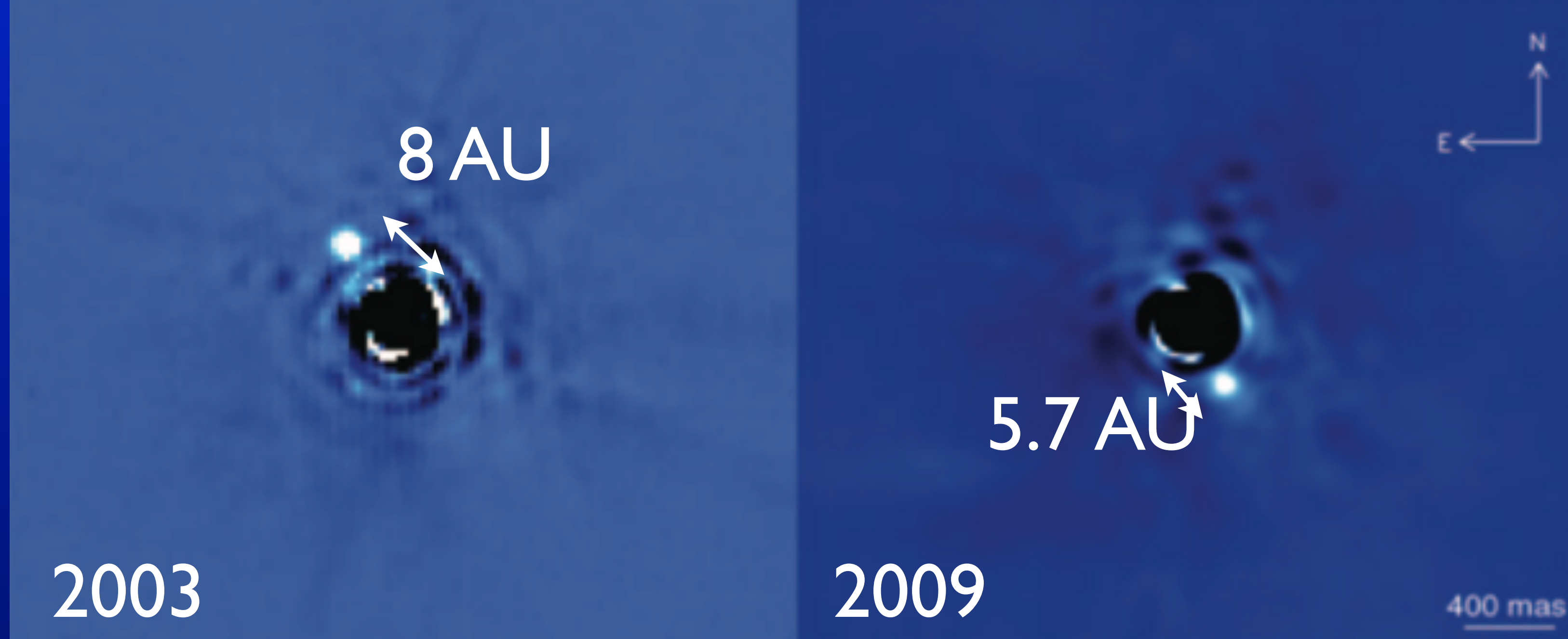
VLT 8-m with Infrared Adaptive Optics

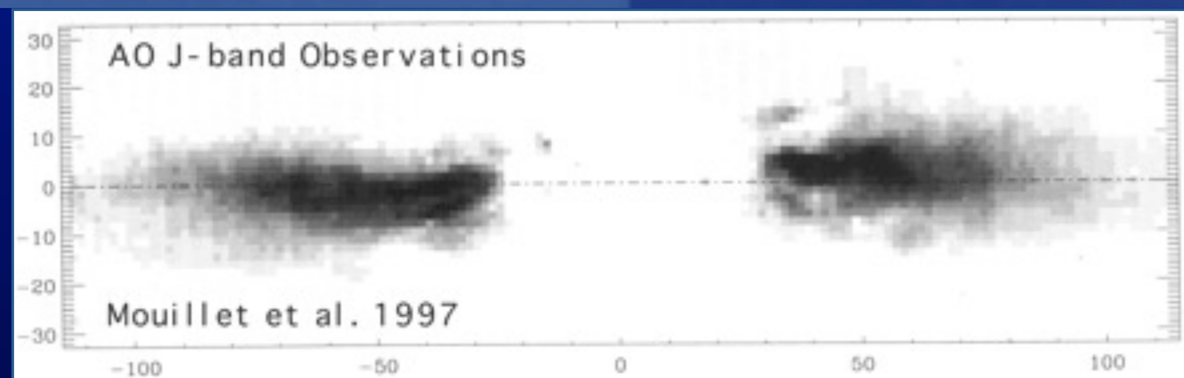
common proper motion

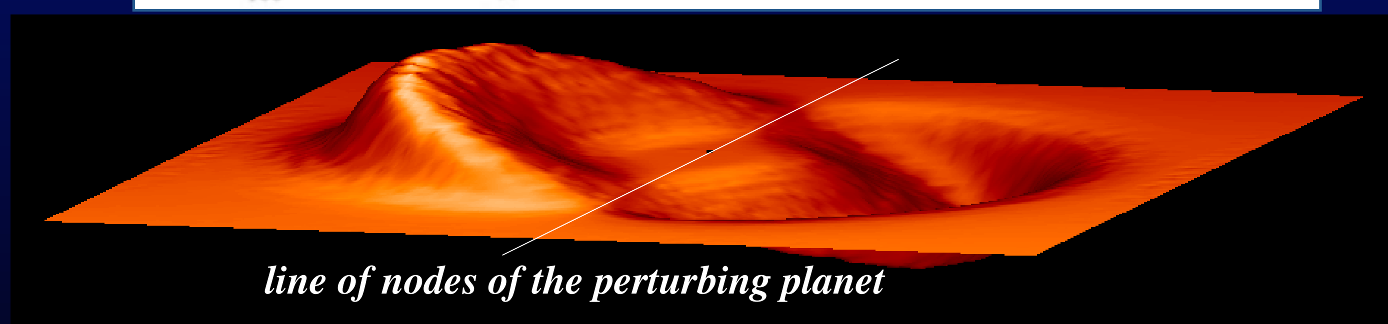
$L \sim 10^{-4.7} L_\odot$, $t \sim 8$ Myr → $M \sim 5 M_J$

beta Pic b







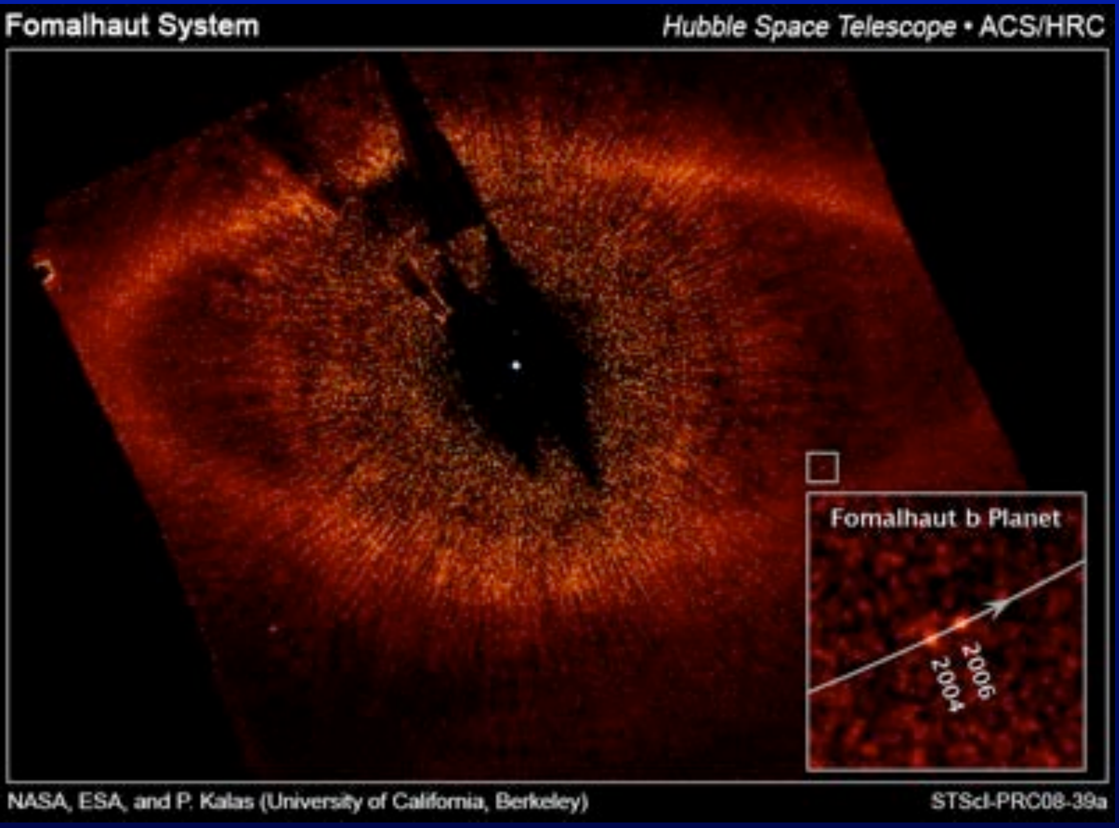


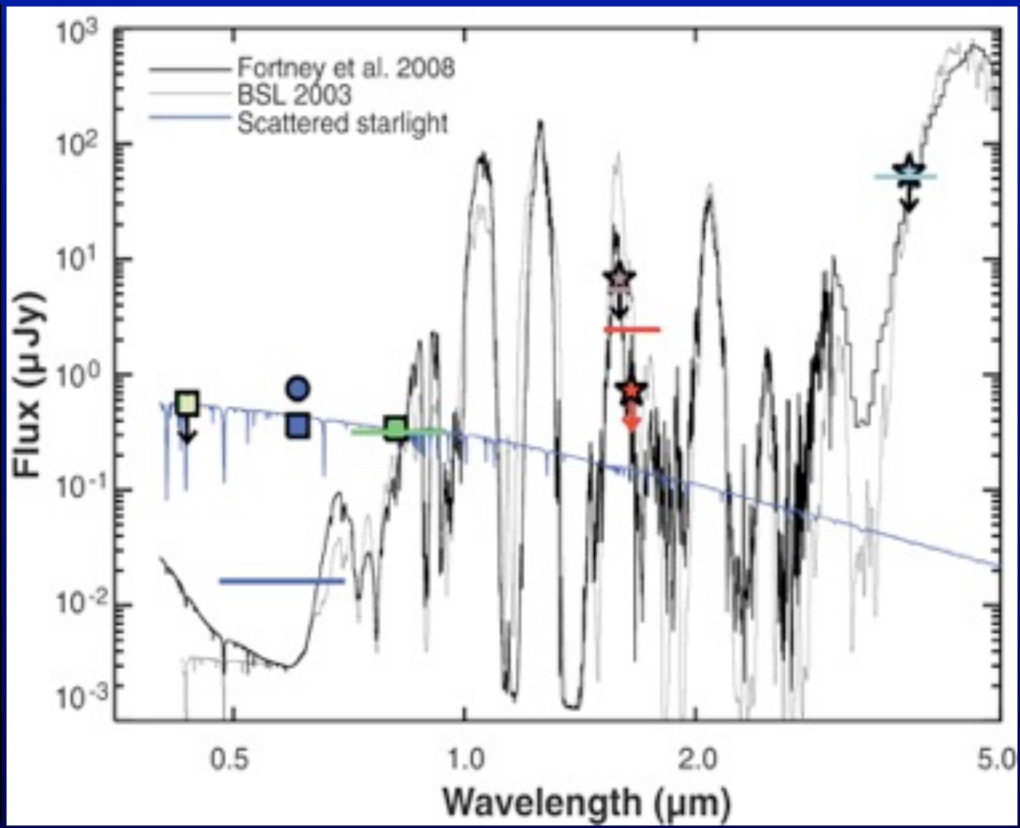
VLT 8-m with L' Adaptive Optics

$L \sim 10^{-3.7} L_{\odot}$, $t \sim 12$ Myr $\rightarrow$ $M \sim 9 M_J$

semimajor axis 8-15 AU; consistent with evolving vertical warp

Fomalhaut b ($L \sim 2 \times 10^{-7} L_\odot$)





if $\omega_{\rm planet} = \omega_{\rm belt}$ (nested ellipses)

then
$$a_{\rm planet} = 115\ {\rm AU}$$
$$e_{\rm planet} = 0.12$$
$$M_{\rm planet} = 0.5 M_{\rm J}$$

not thermal emission from planetary atmosphere

40 R_J reflective dust disk?

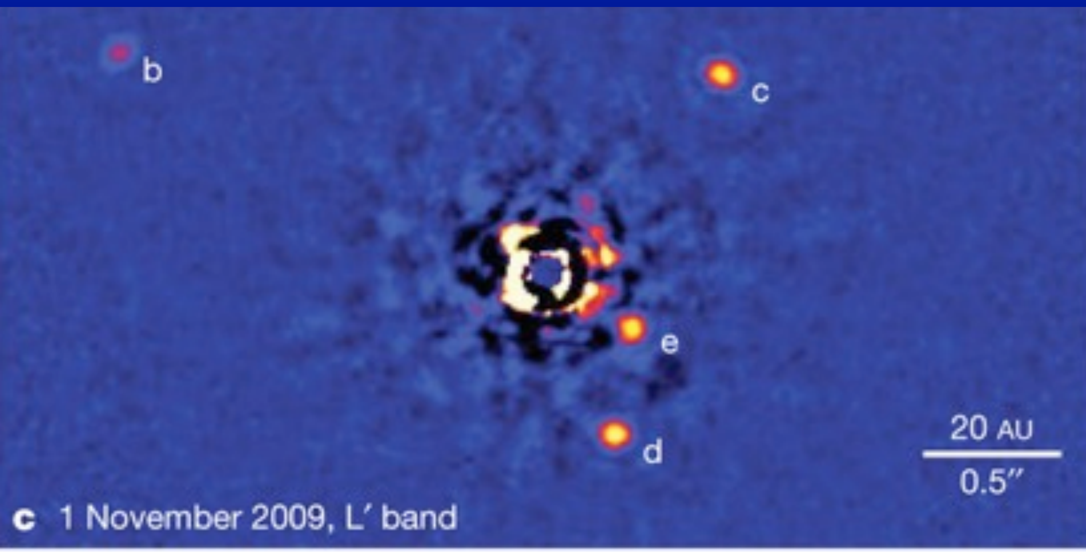
Variable Hα emission?

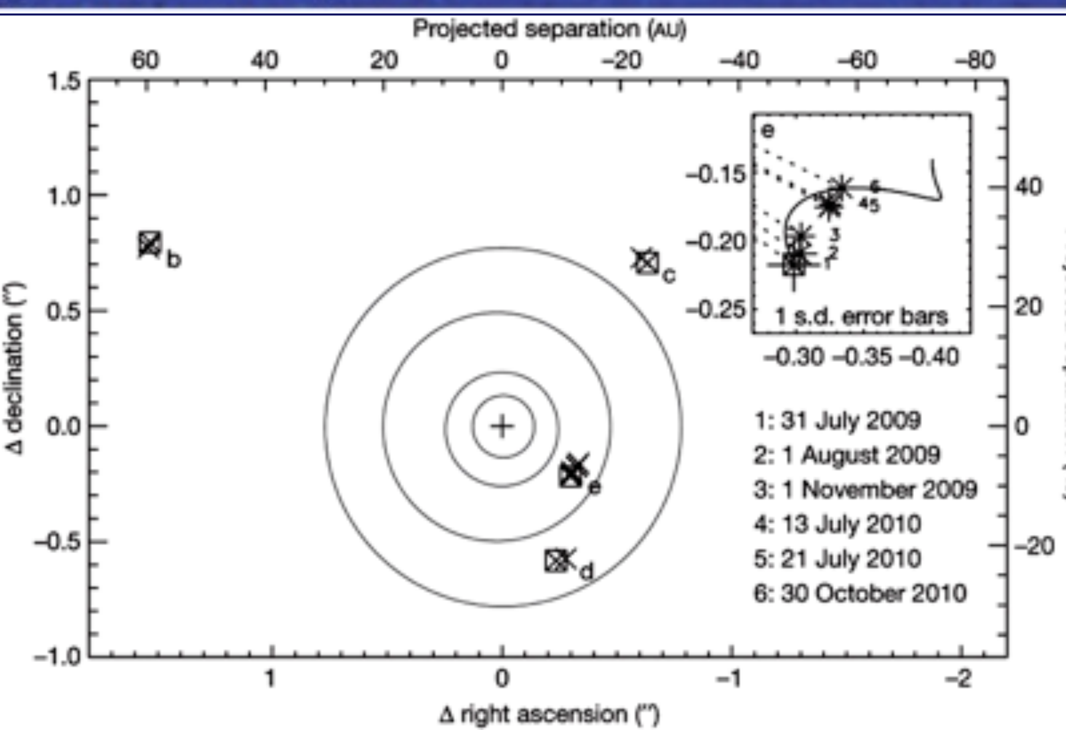
HR 8799
A-type star 30-60 Myr old
with 4 Super-Jupiters

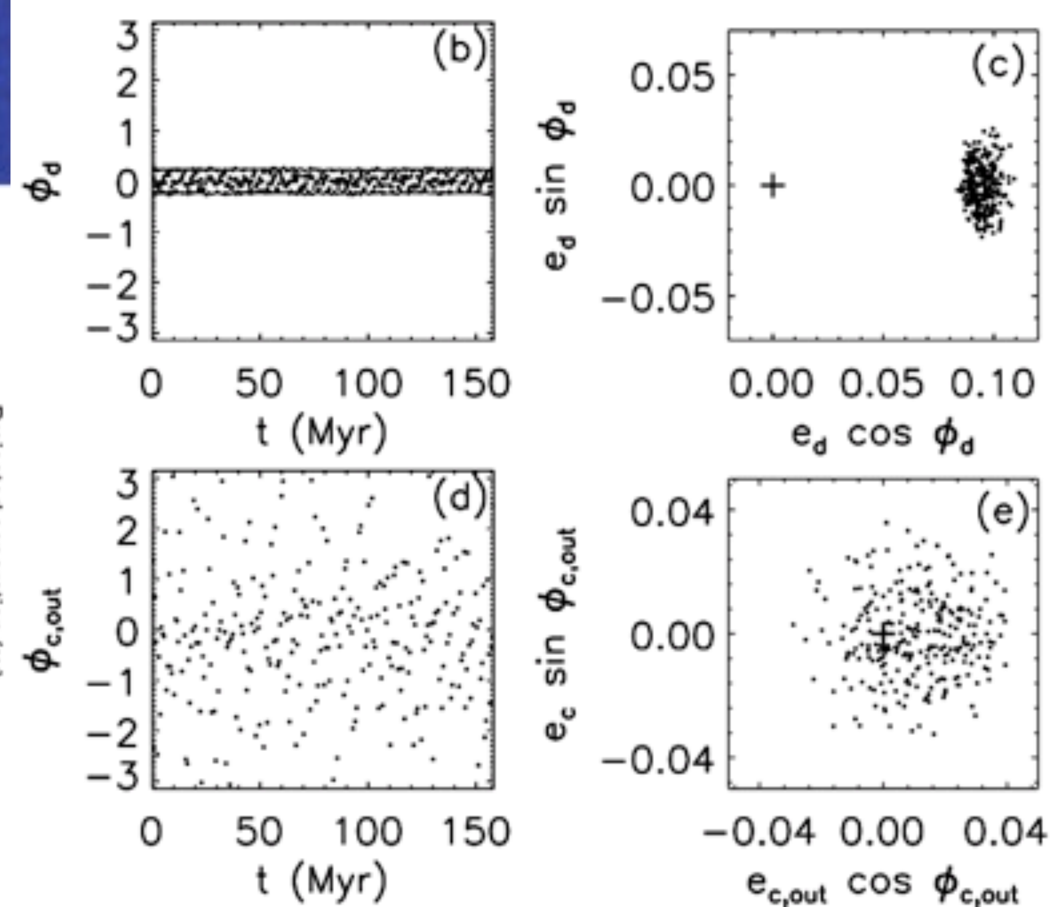
Orbital resonances afford stability
d:c = 2:1 resonance

Other possibilities include
d:c:b = 4:2:1
e:d:c = 4:2:1

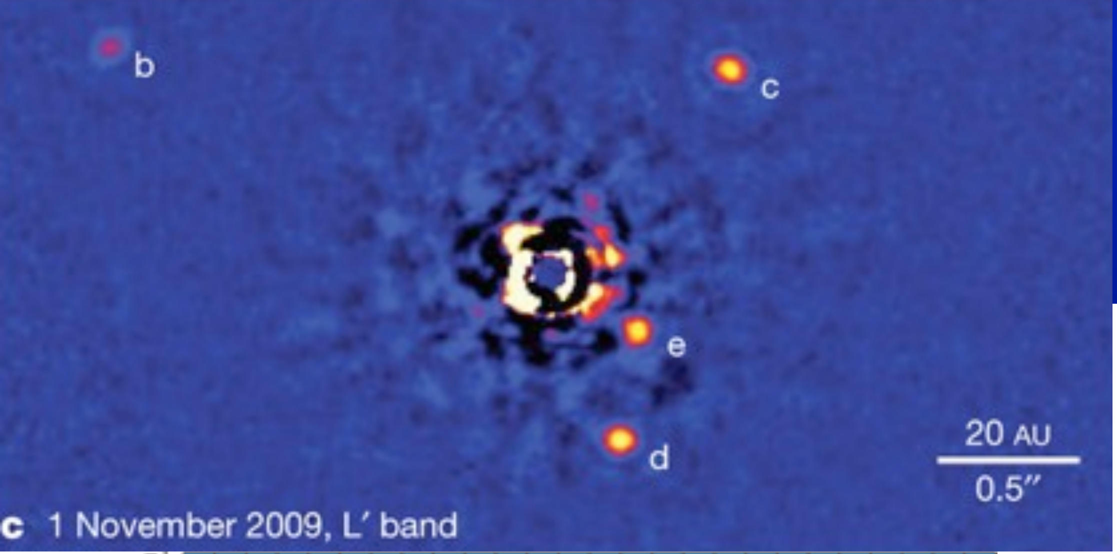
dynamical masses < 20 Jupiter masses each

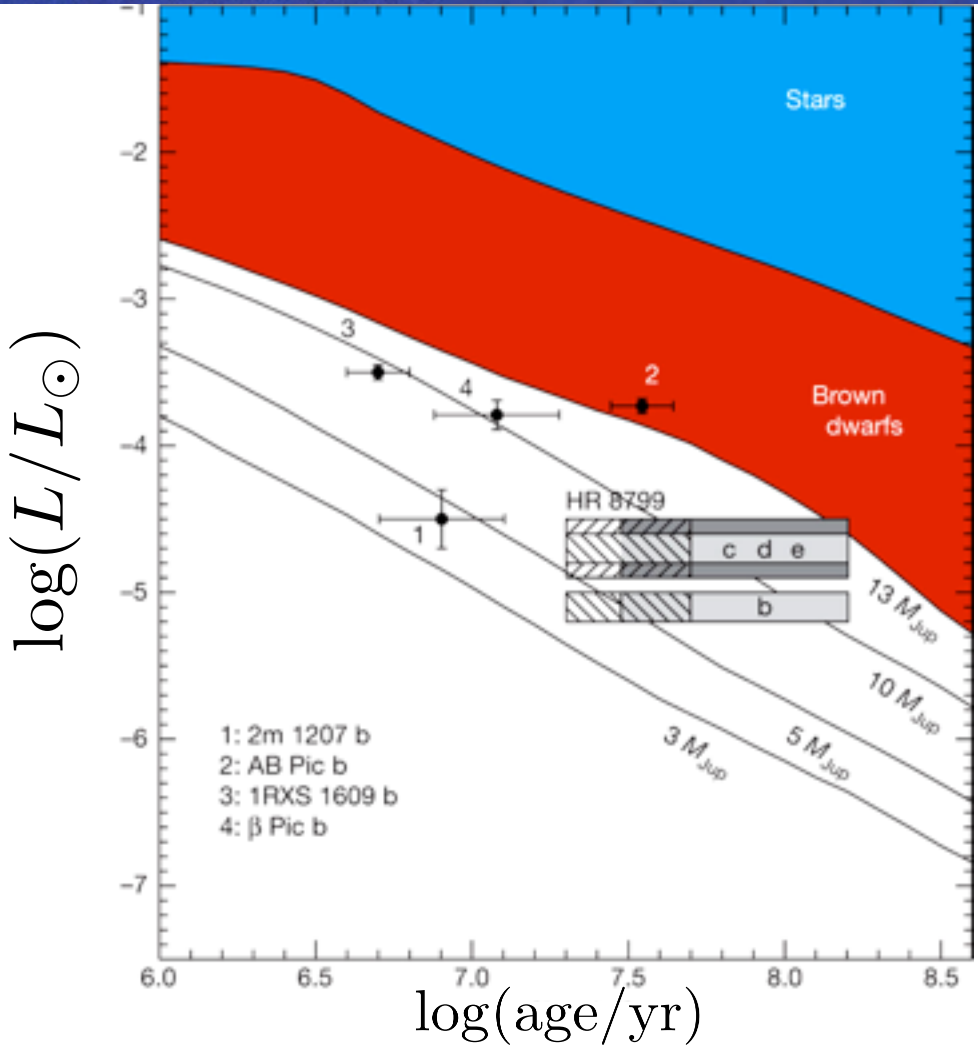


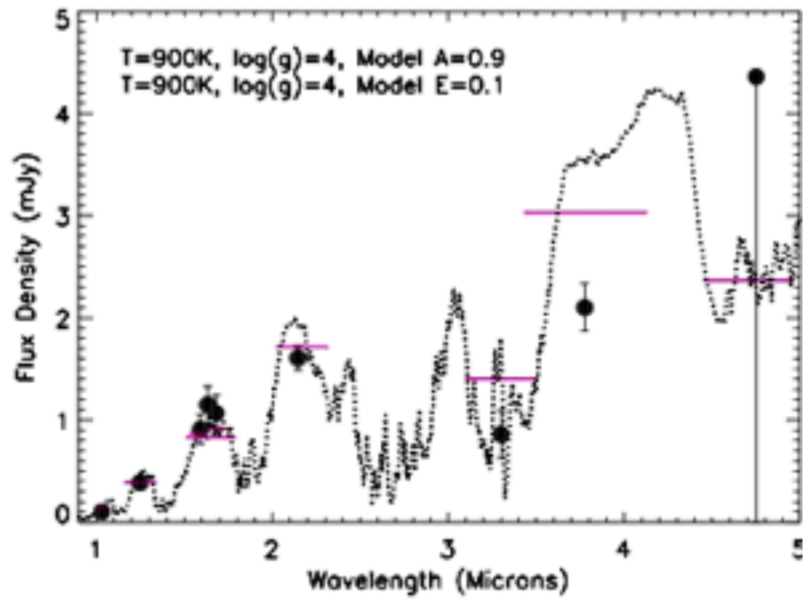




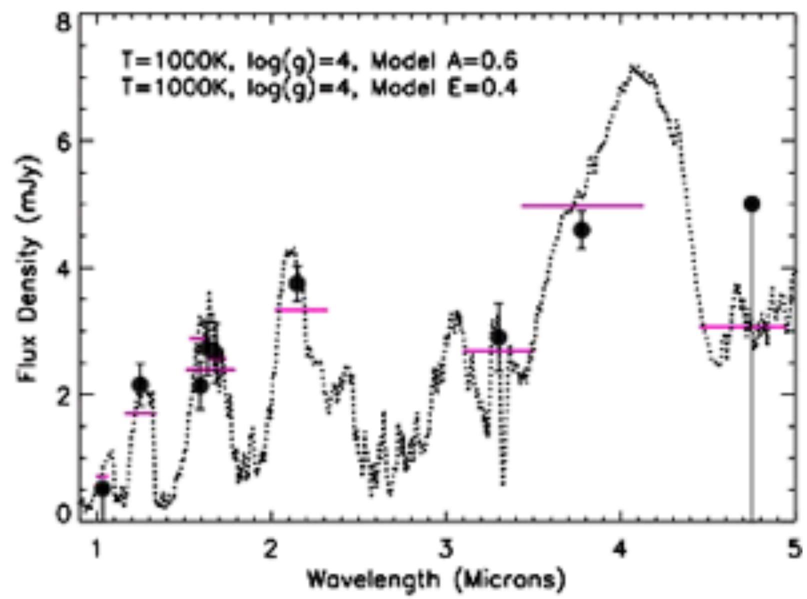
Cloudy spectra unlike brown dwarfs







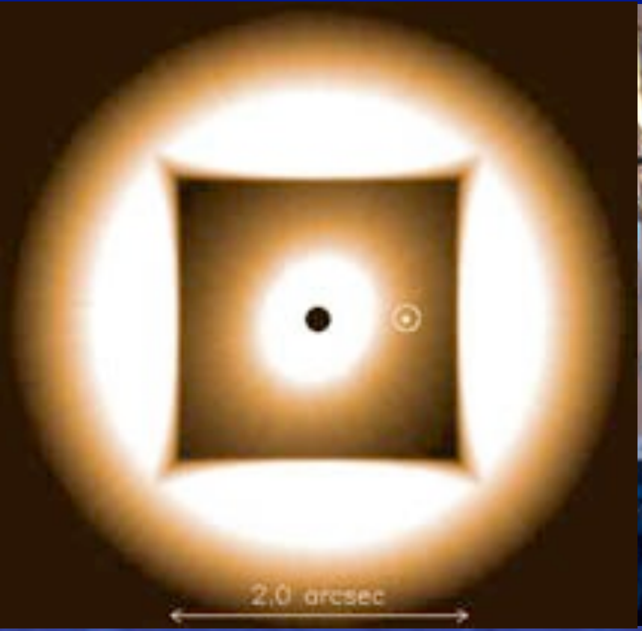
6-7 M_J

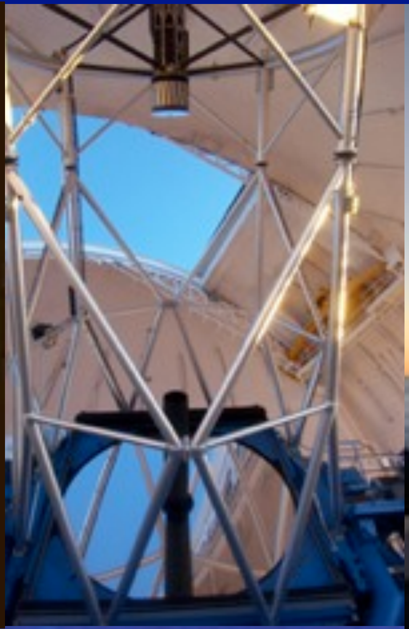


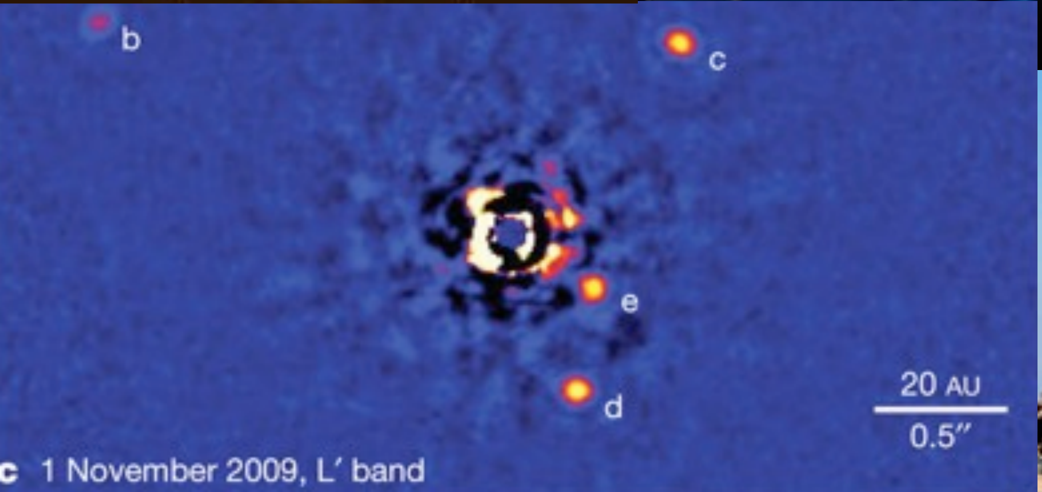
7-10 M_J

Gemini Planet Imager (GPI) 2012

Pan-STARRS (once a week, mag 24) and LSST (once every few days, mag 24.5)





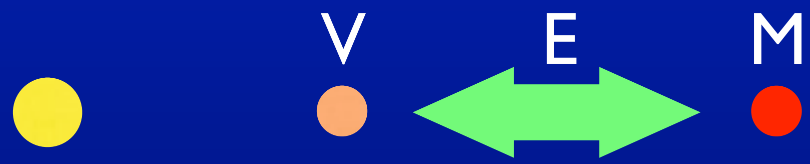


Observations of Extrasolar Planets

I. Kepler transits
II. Doppler velocity
III. Microlensing
IV. Imaging
V. Disks

Reconstructing protoplanetary disks: "Minimum-Mass Solar Nebula"

solar composition by mass (Lodders 2003)
gas (H,He) : ice (O, C, ...) : rock (Mg, Si, ...)
1 : 0.015 : 0.005



156 S. J. WEIDENSCHILLING

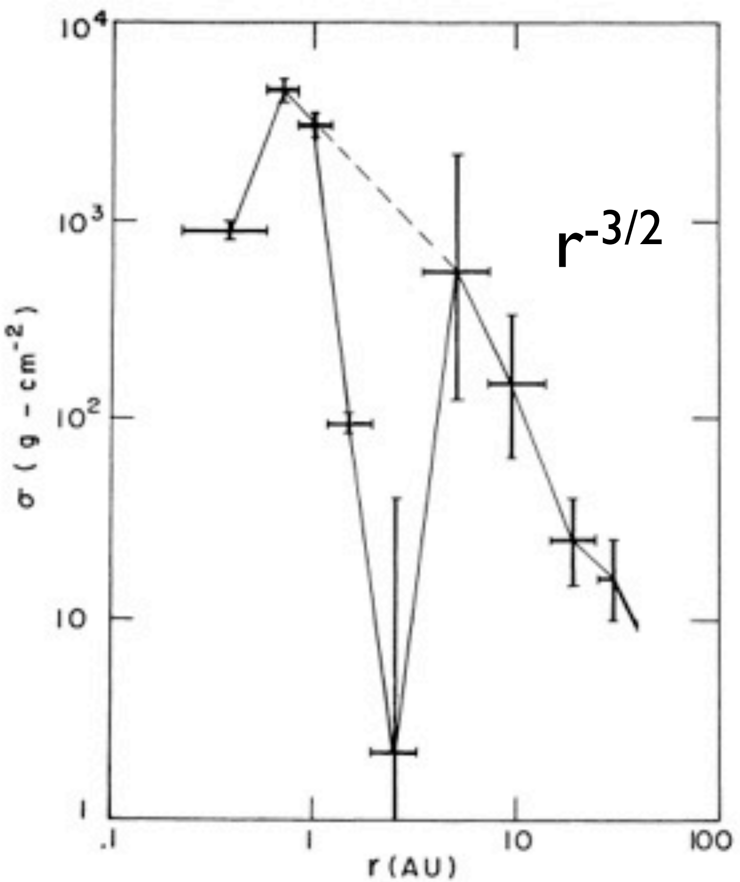


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

At r ~ 1 AU:

$$\Sigma_d \sim \frac{1\,M_\oplus}{\pi\,\mathrm{AU}^2} \sim 10\,\mathrm{g/cm^2}$$

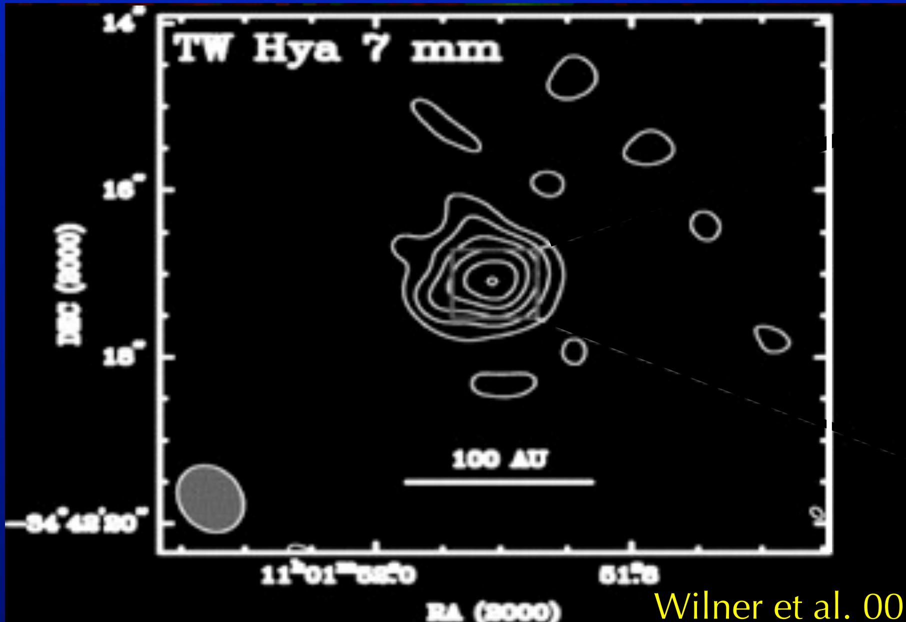
if just rock (too hot for ice):

$$\Sigma_g \sim 10\,\mathrm{g/cm^2} \times \frac{1}{0.005}$$

$$\sim 2000\,\mathrm{g/cm^2}$$

$$M_g \sim \int^{100\,\mathrm{AU}} \Sigma_g 2\pi r\,dr$$

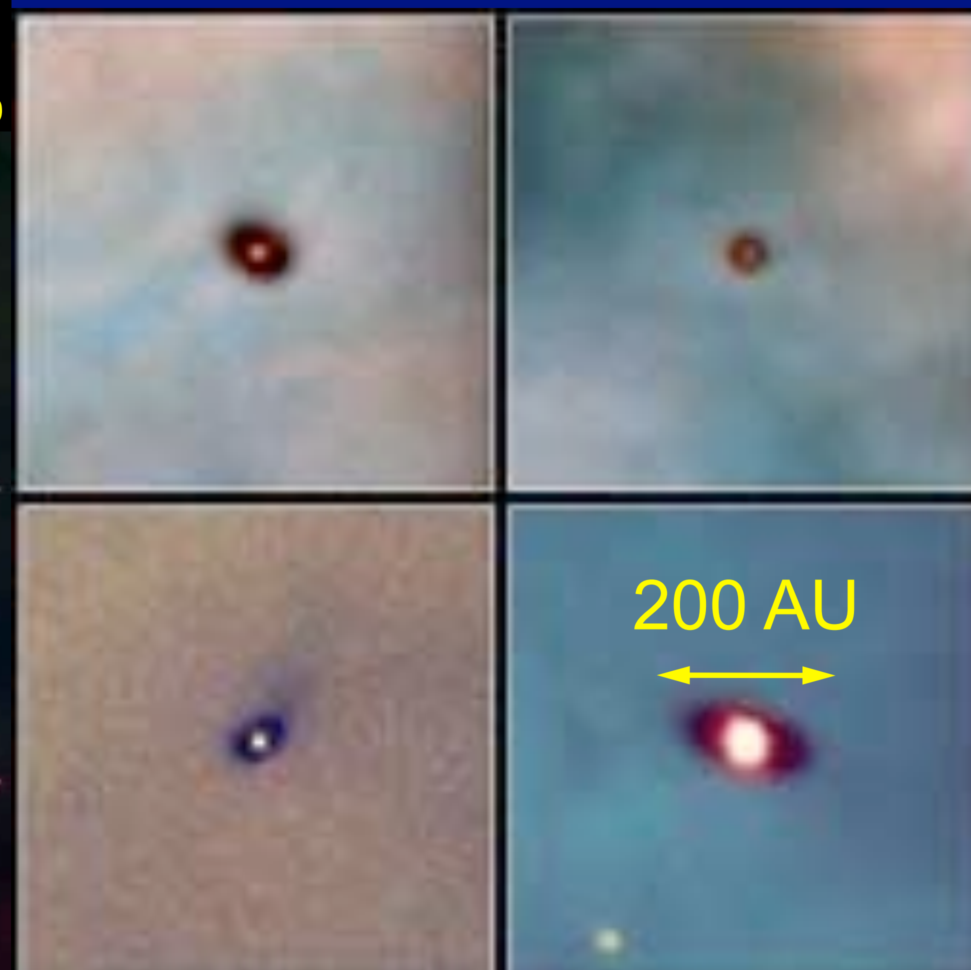
$$\sim 0.03 M_\odot$$



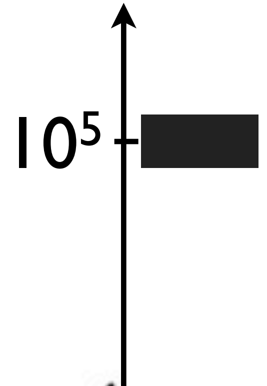
Wilner et al. 00

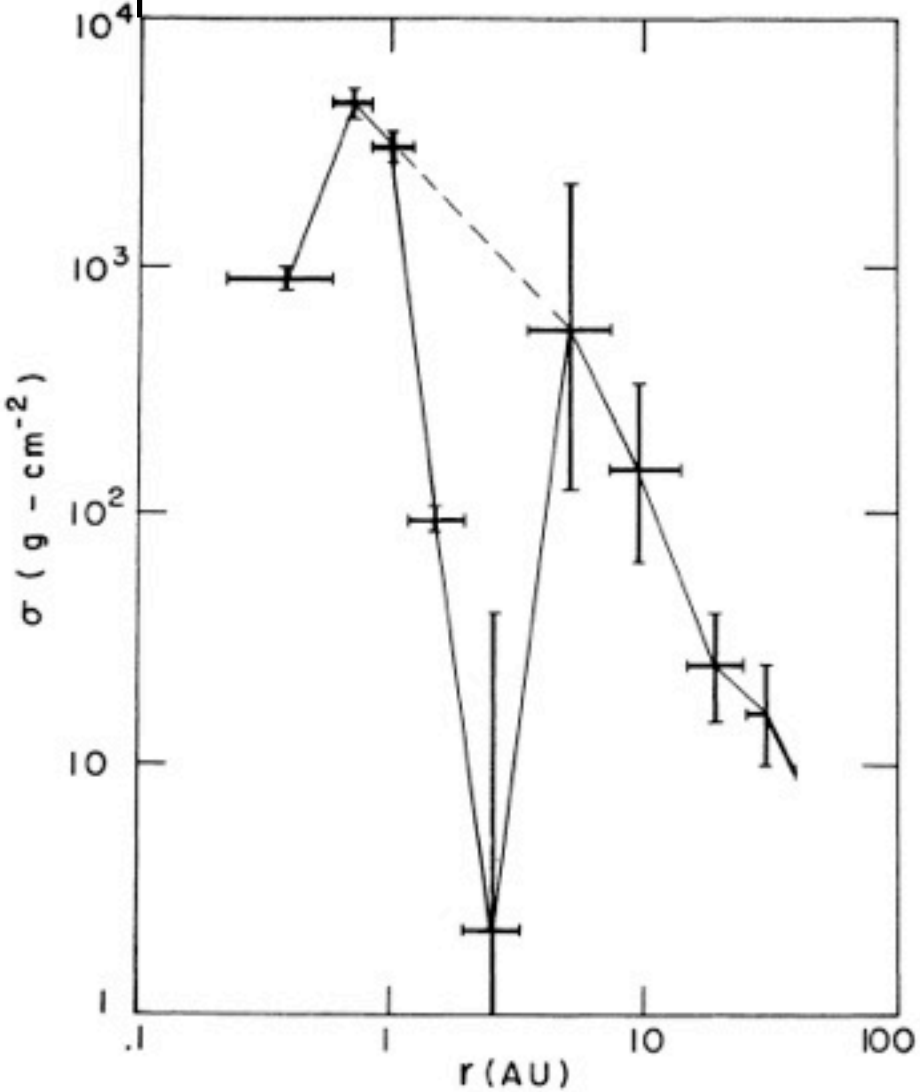
Protoplanetary Disks

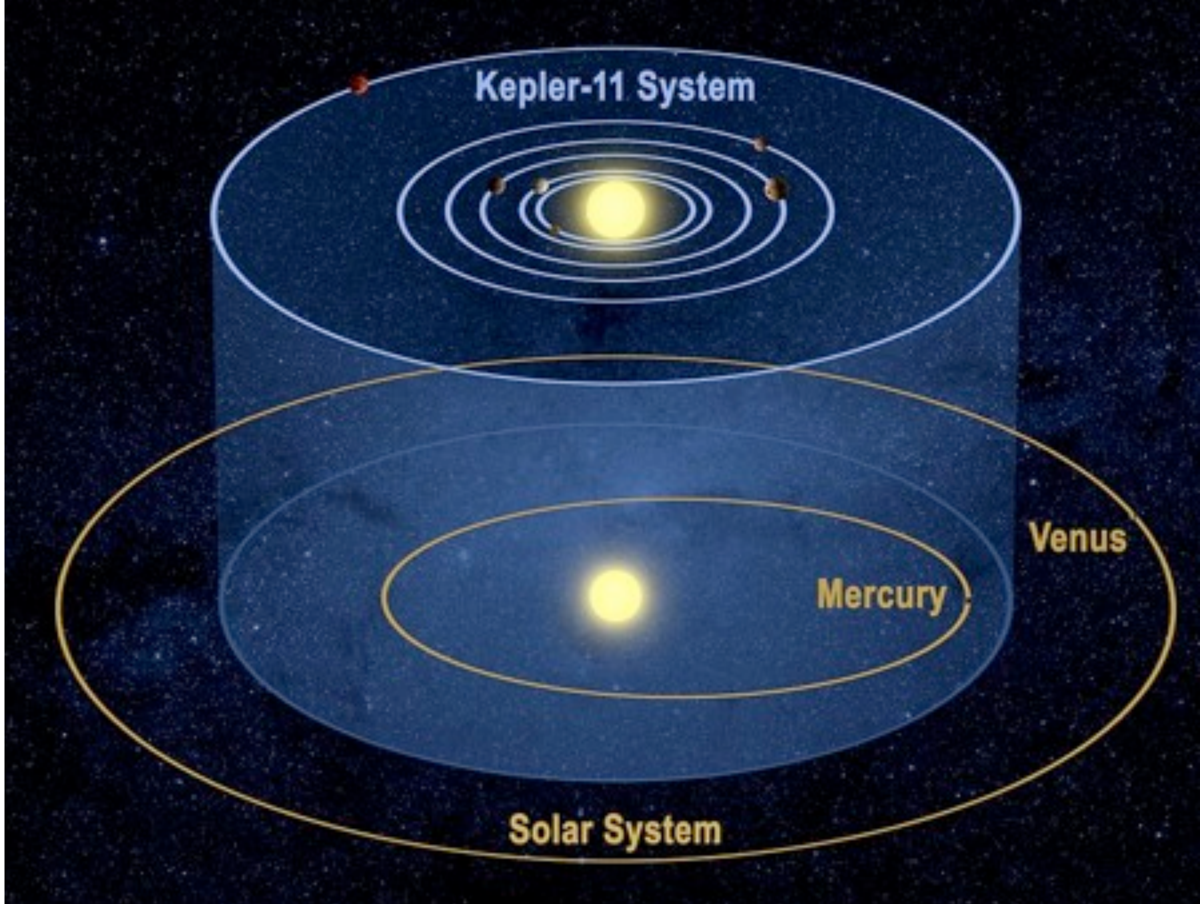
disk mass ~ 0.001-0.1 stellar mass

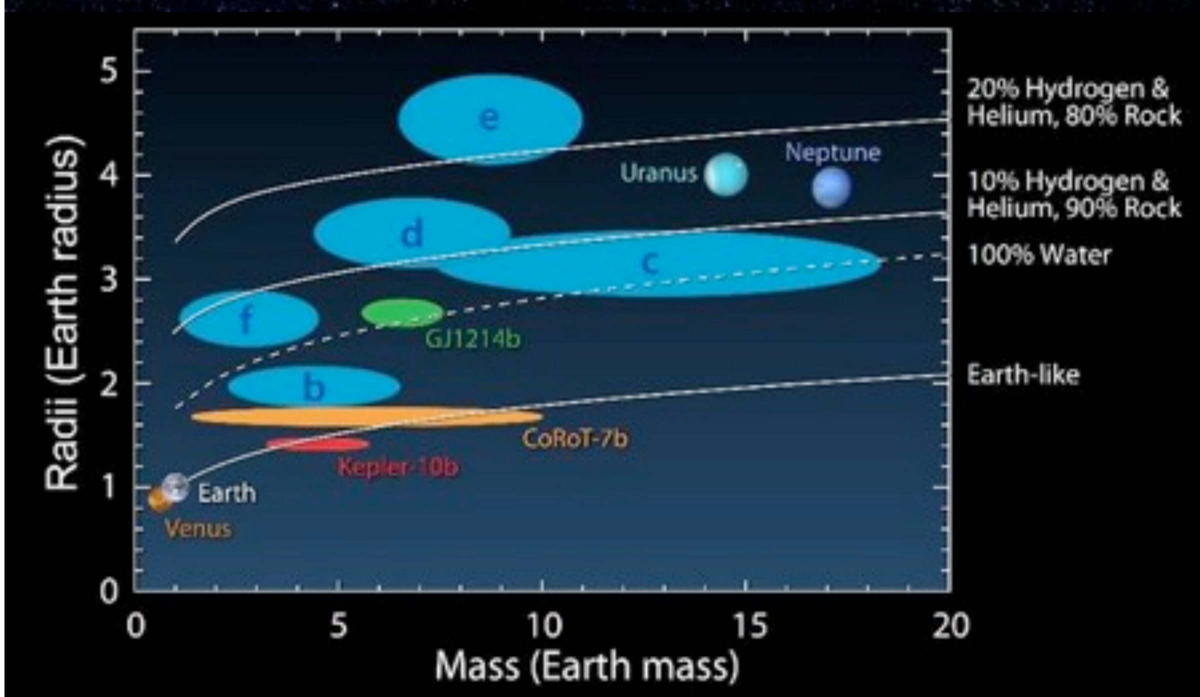


Minimum-Mass Kepler-11 system (turns out Toomre Q ~ 1)

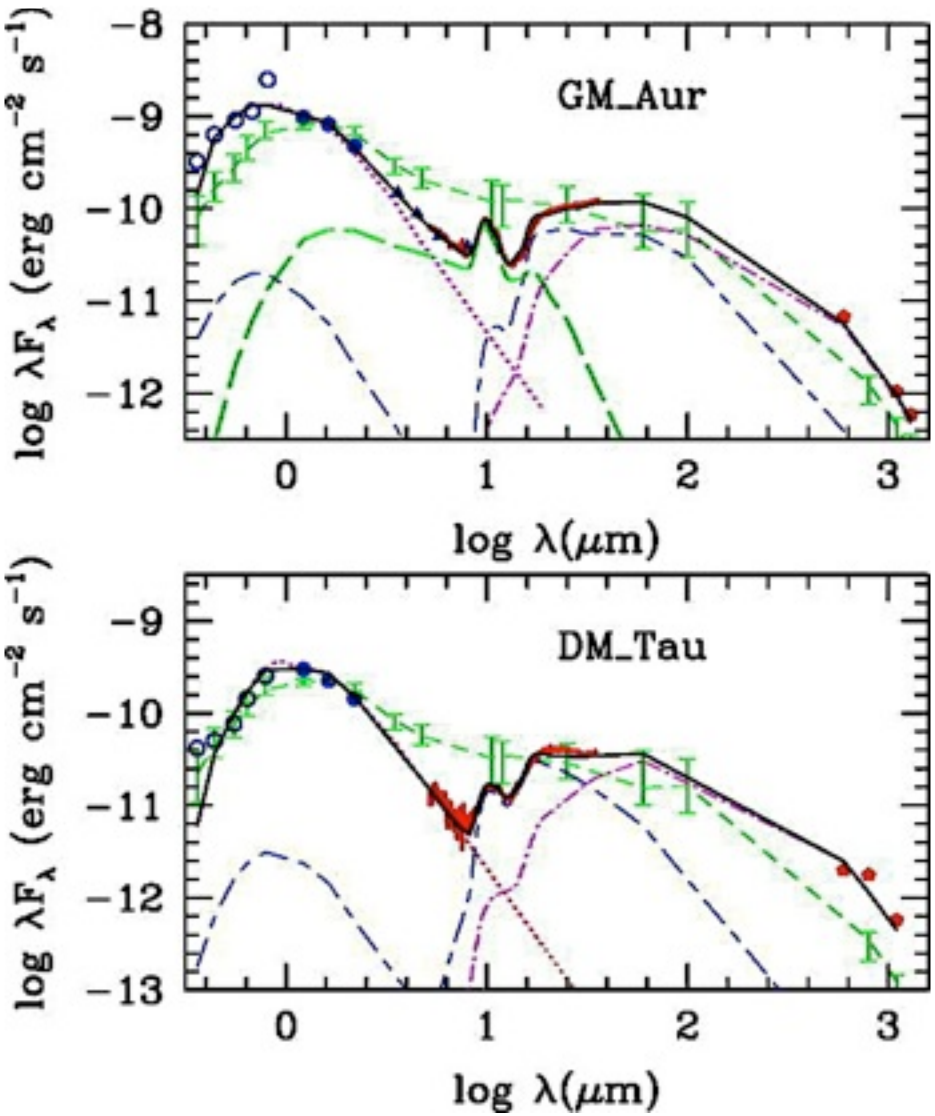




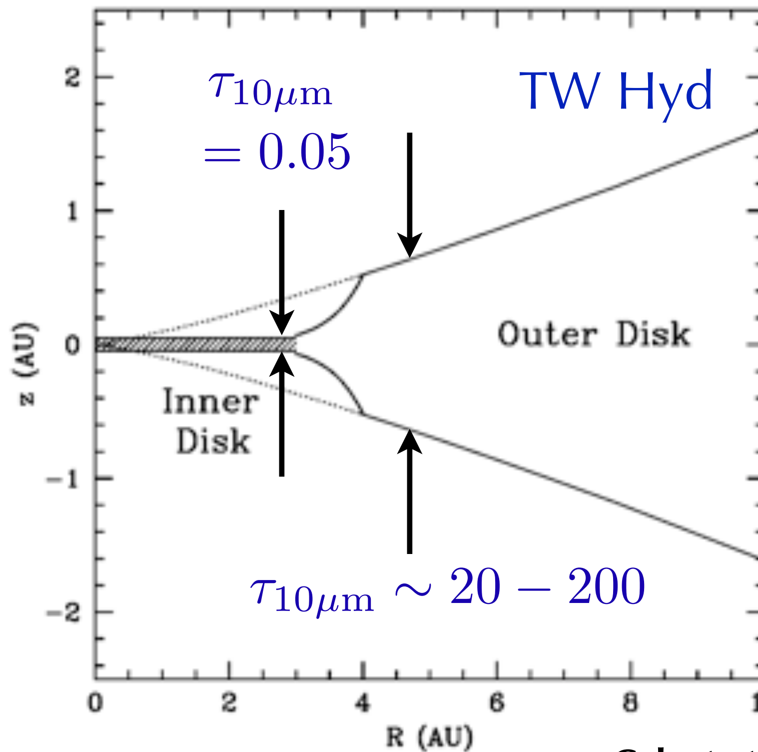




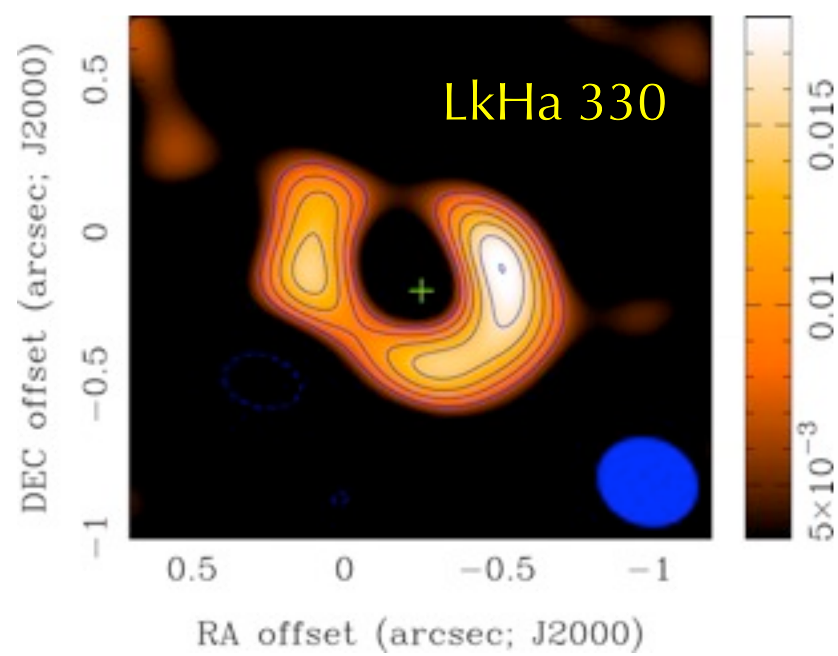
Transitional Disks



Calvet et al. 05

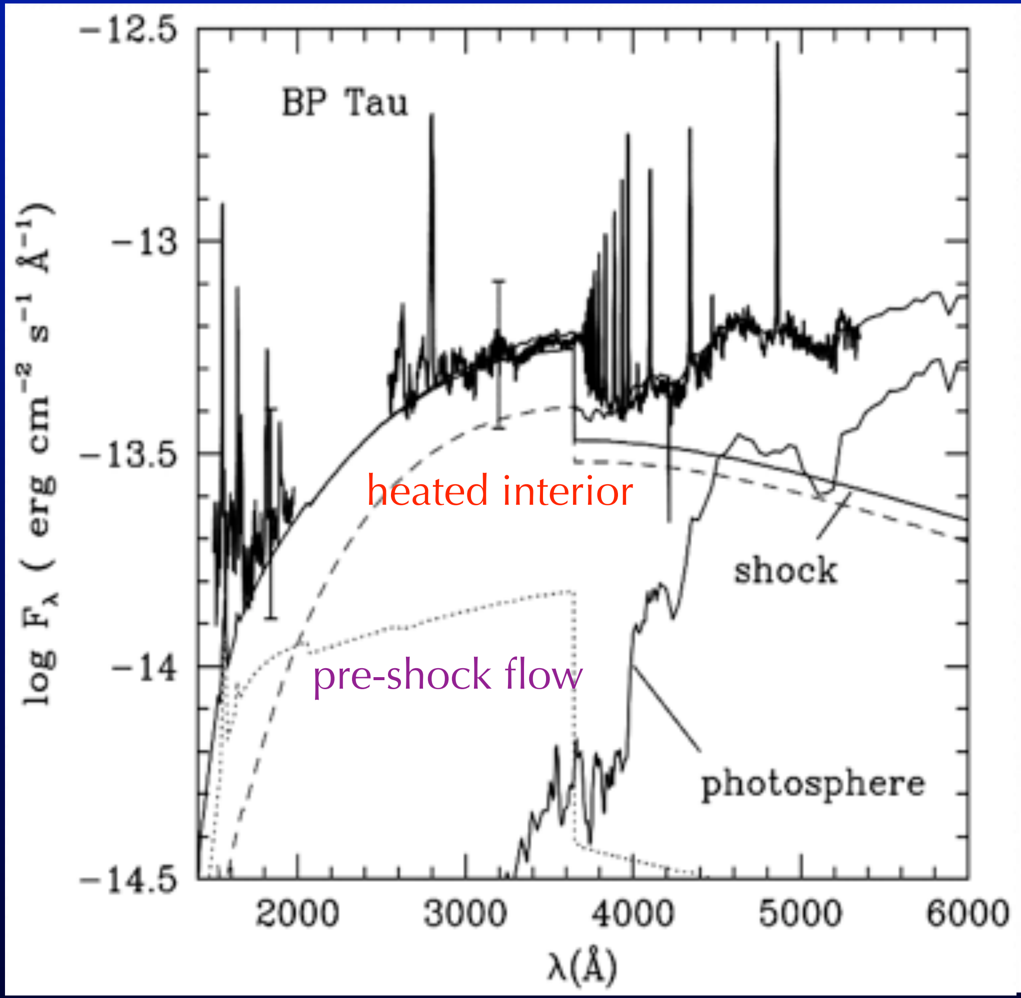


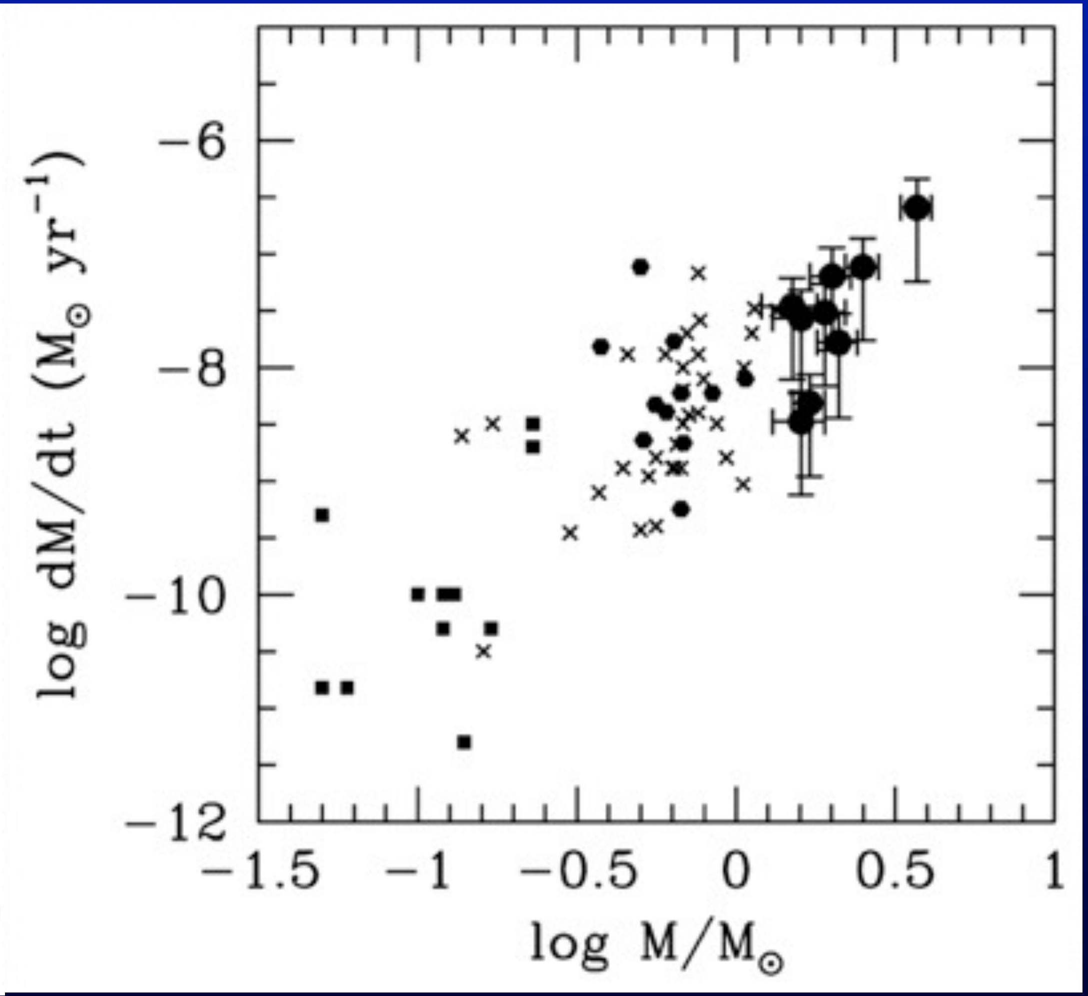
Calvet et al. 02



Brown et al. 08

Pre-main-sequence stars accrete





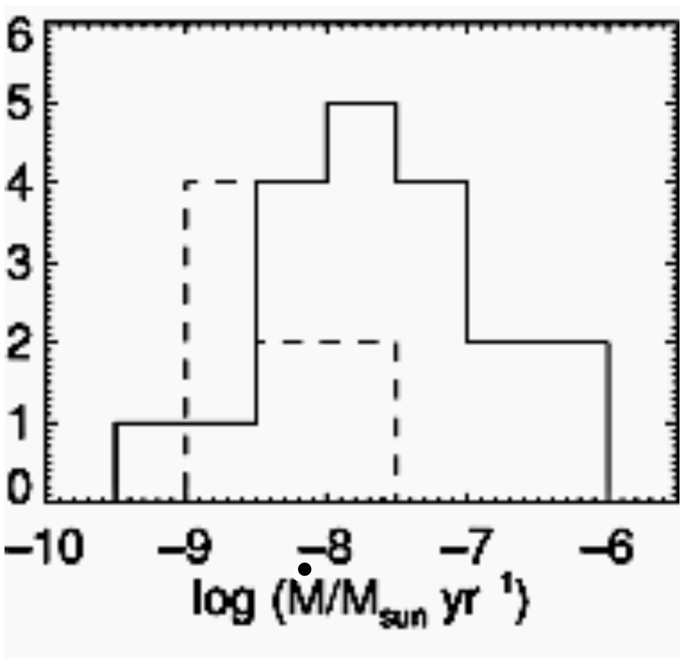
Blue excess powered by accretion

Calvet & Gullbring 98
Muzerolle et al. 05
Hartmann et al. 06
Herczeg & Hillenbrand 08

Holes are not empty

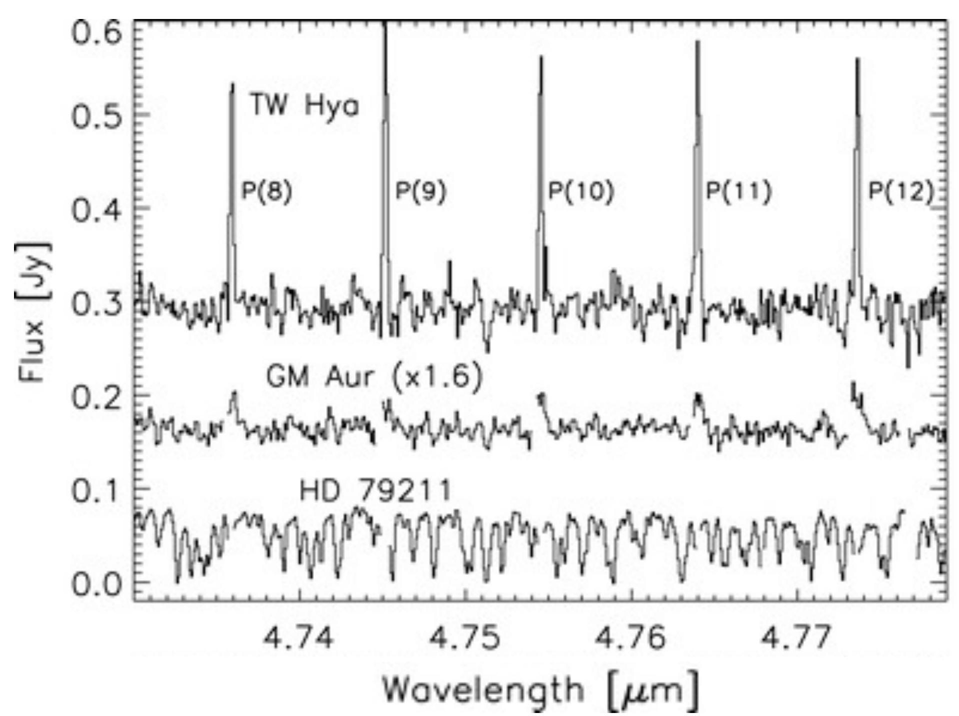
- Mild near-IR excesses in some sources
  $\tau_{10\mu m} \sim 0.002 - 0.05$

- Many accrete
  $\dot{M} \sim 0.1 \times \mathrm{median\,T\,Tauri}$



Najita et al. 07

- Inner molecular gas disks
  $\Sigma(H_2) > 0.1\,\mathrm{g\,cm^{-2}}$ at $\sim 0.2\mathrm{AU}$



Salyk et al. 07