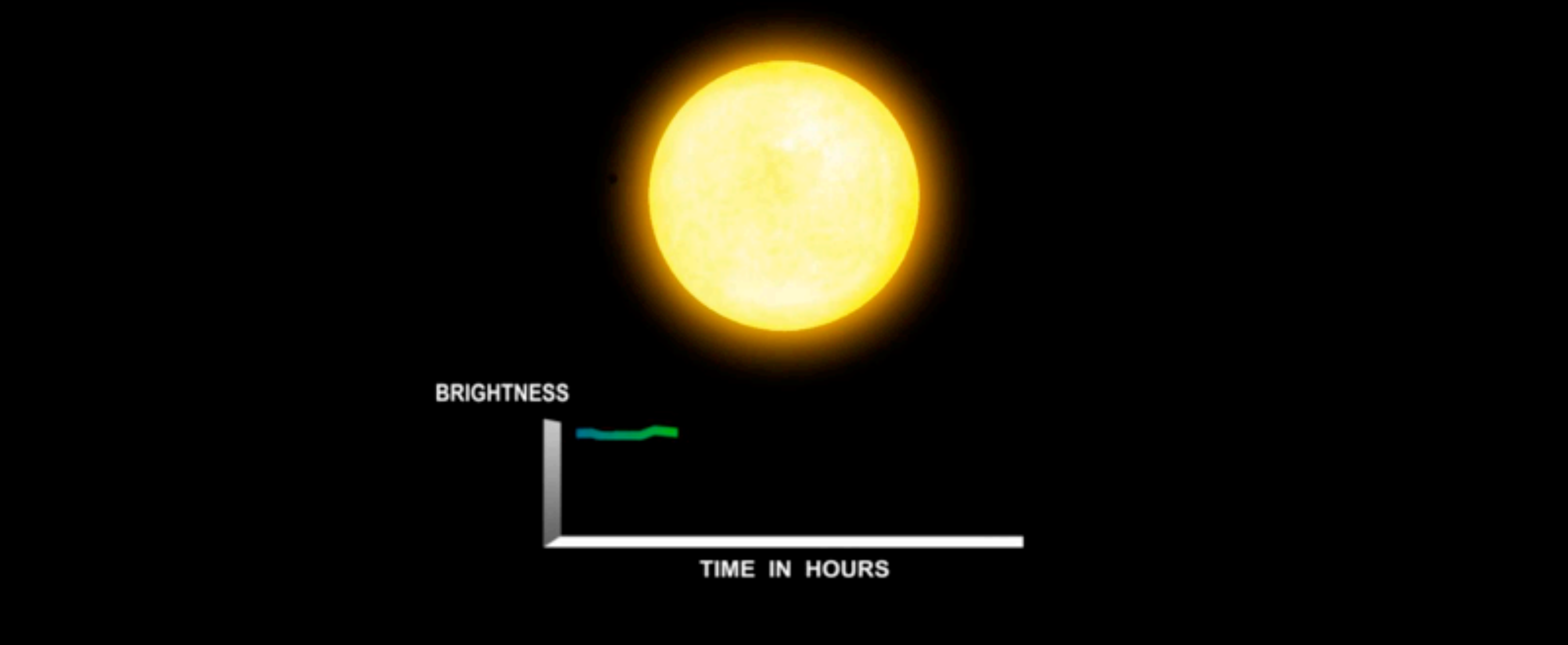
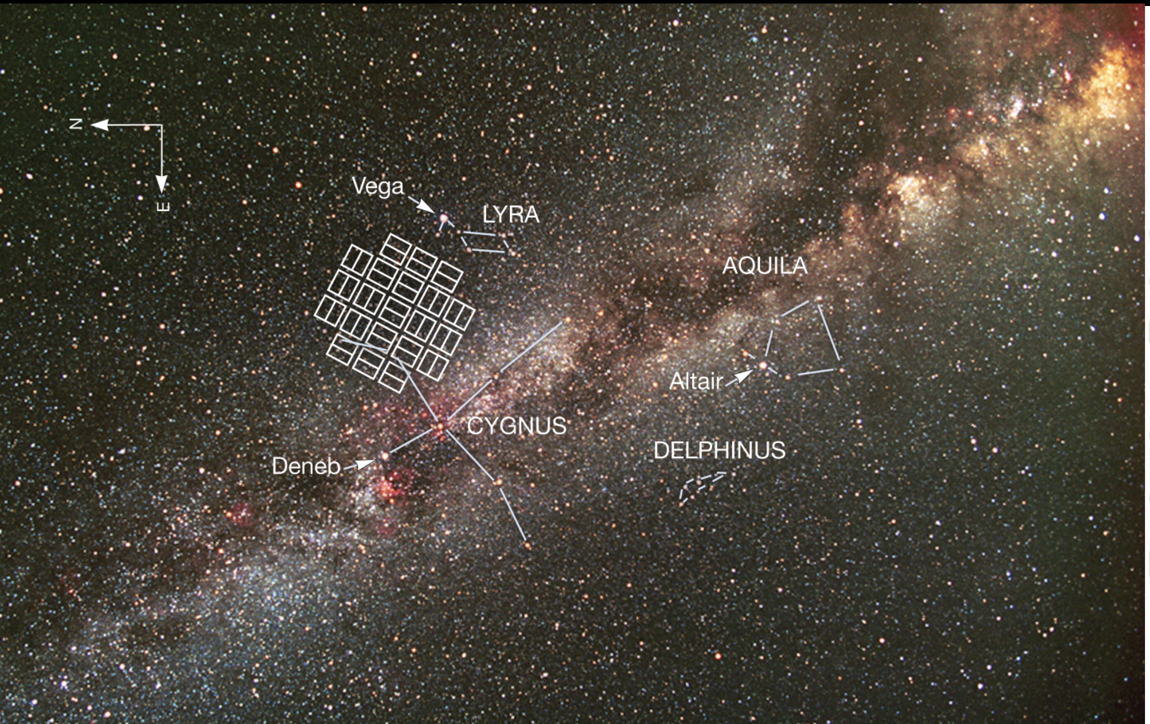
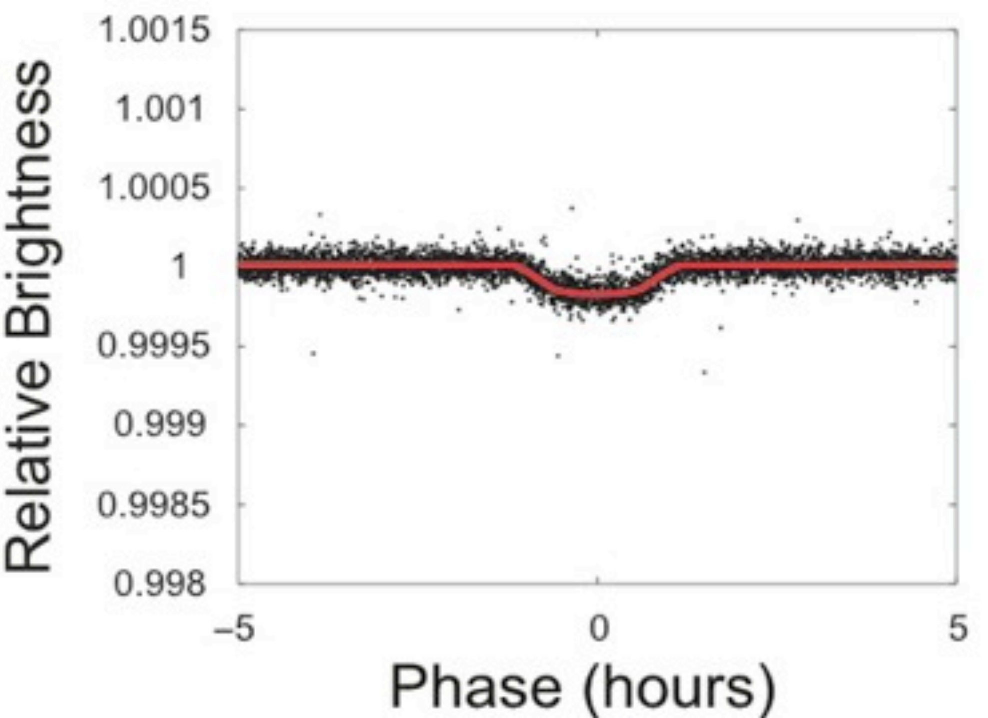
Close-in Planets:
From Hot Jupiters to Super-Mercuries

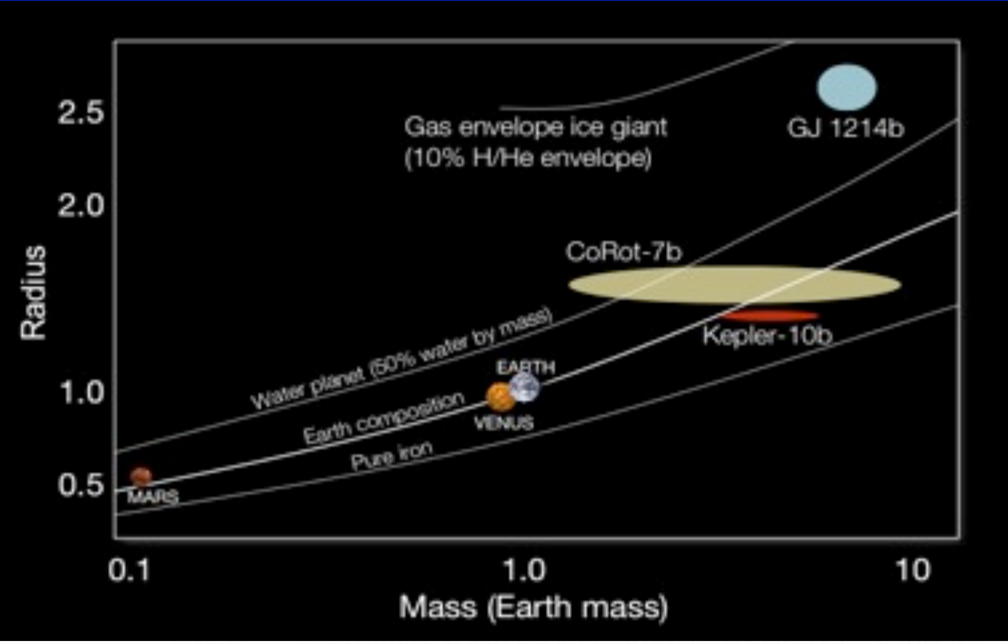
E. Chiang (UC Berkeley)

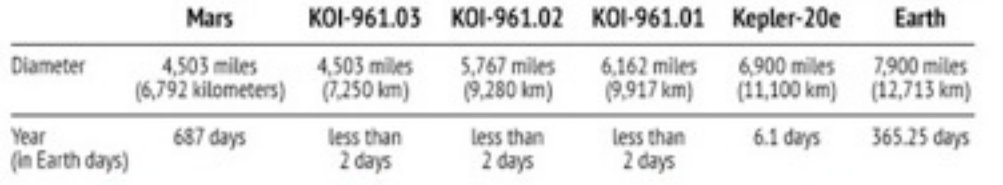

BRIGHTNESS
TIME IN HOURS


N
E
Vega
LYRA
AQUILA
Altair
CYGNUS
Deneb
DELPHINUS

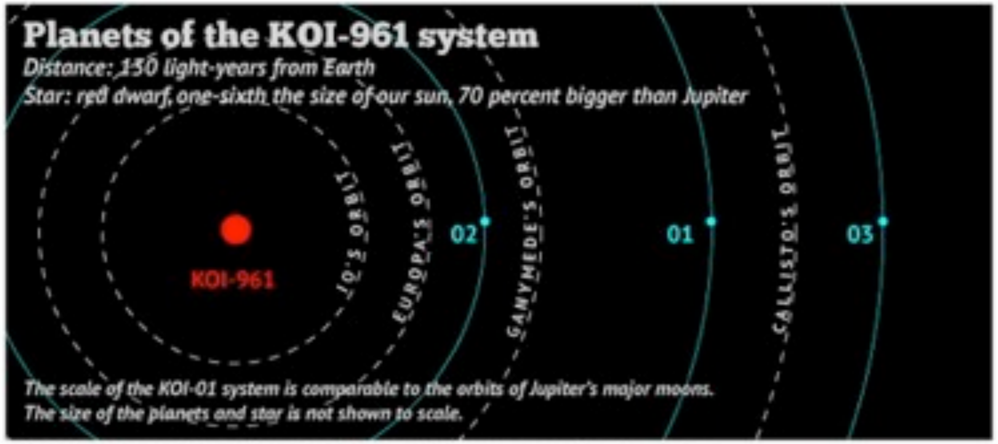

Relative Brightness
1.0015
1.001
1.0005
1
0.9995
0.999
0.9985
0.998
–5
0
5
Phase (hours)

From exo-Jupiters to exo-Mars





	Mars	KOI-961.03	KOI-961.02	KOI-961.01	Kepler-20e	Earth
Diameter	4,503 miles (6,792 kilometers)	4,503 miles (7,250 km)	5,767 miles (9,280 km)	6,162 miles (9,917 km)	6,900 miles (11,100 km)	7,900 miles (12,713 km)
Year (in Earth days)	687 days	less than 2 days	less than 2 days	less than 2 days	6.1 days	365.25 days



Planets of the KOI-961 system

Distance: 150 light-years from Earth

Star: red dwarf, one-sixth the size of our sun, 70 percent bigger than Jupiter

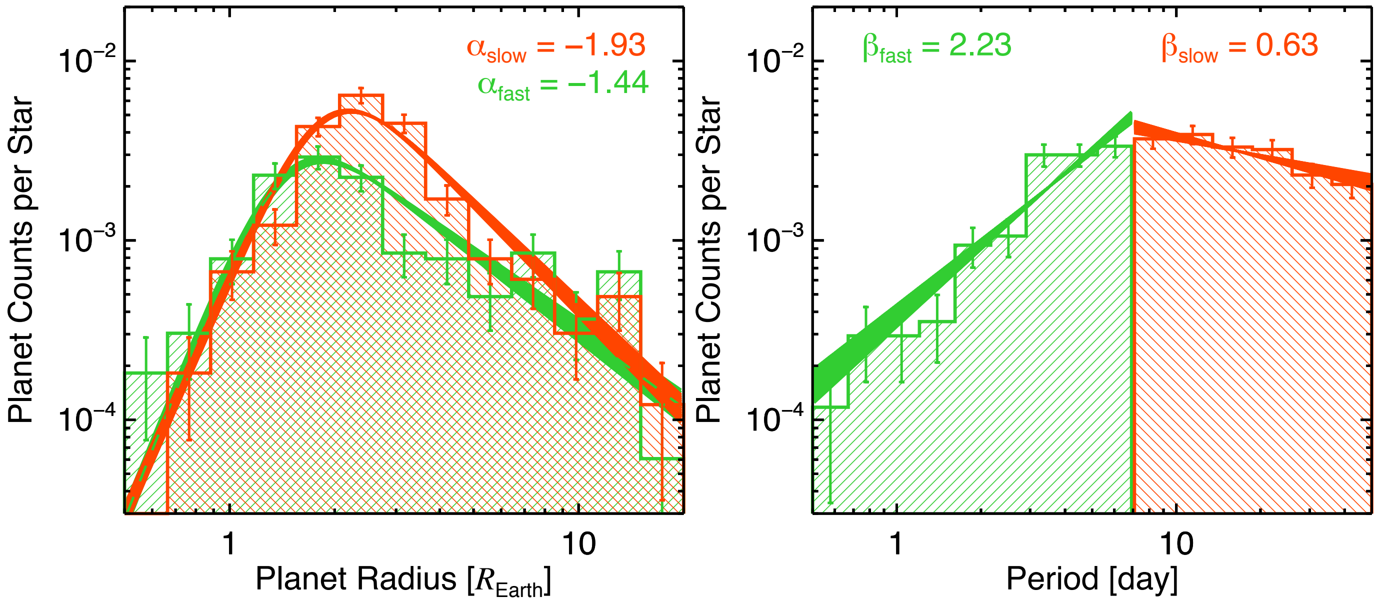
The scale of the KOI-01 system is comparable to the orbits of Jupiter's major moons.
The size of the planets and star is not shown to scale.

SOURCES: NASA, JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

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

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

Youdin 11



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

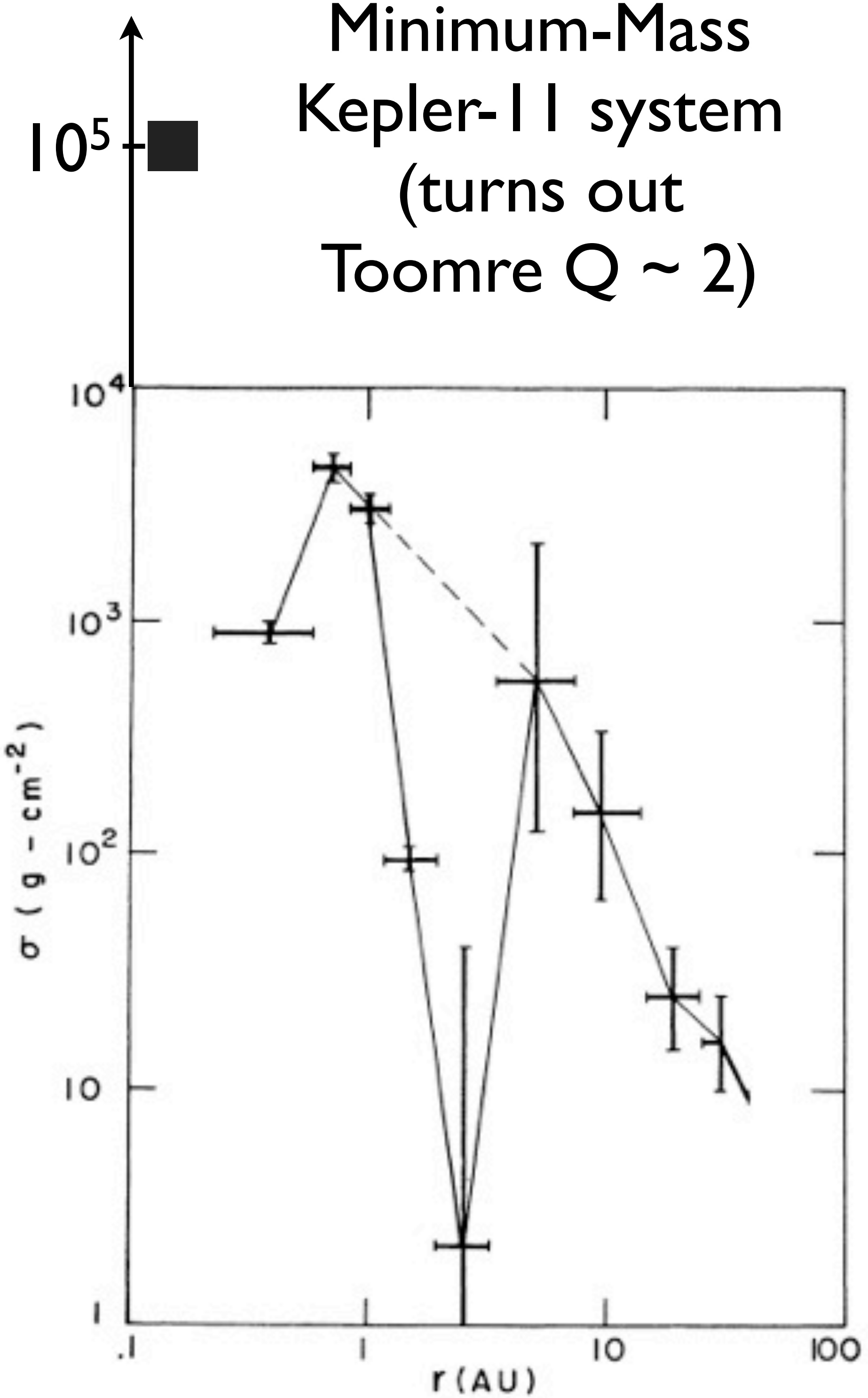
$$\frac{\partial^2 n}{\partial \ln R \, \partial \ln P} \propto R^{-1.9} P^{0.6}$$

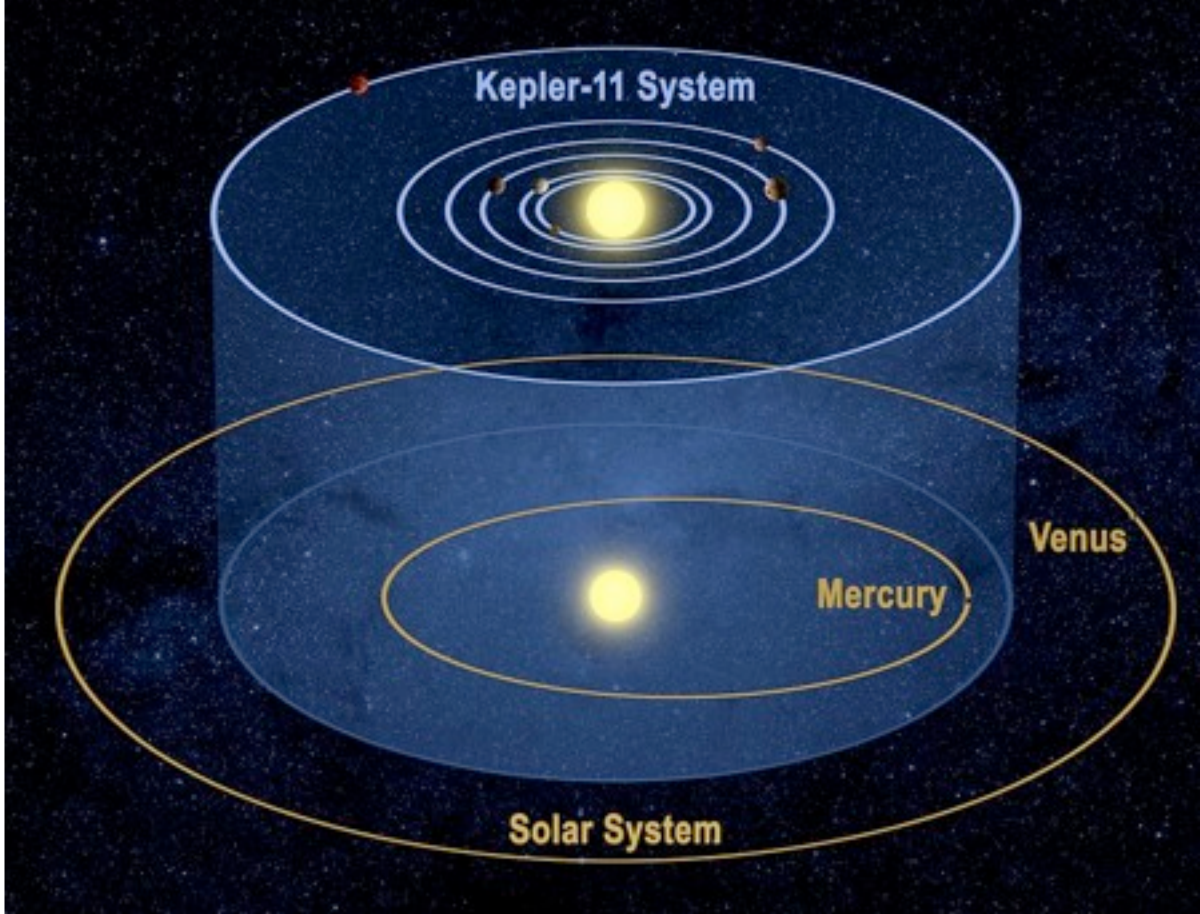
n ($R > 2\ R_\oplus$, $P < 50$ days) ~ 0.2 planet per star

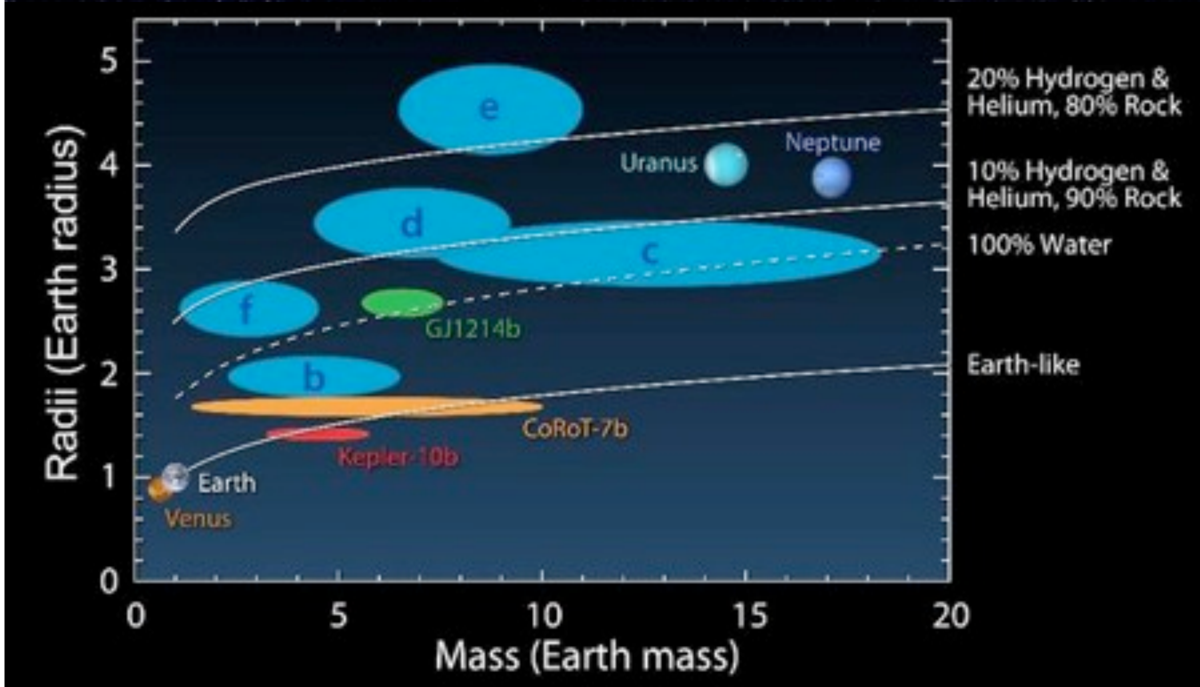
Trust detection efficiency down to $1 R_\oplus$,
and extrapolate to 365 days :

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

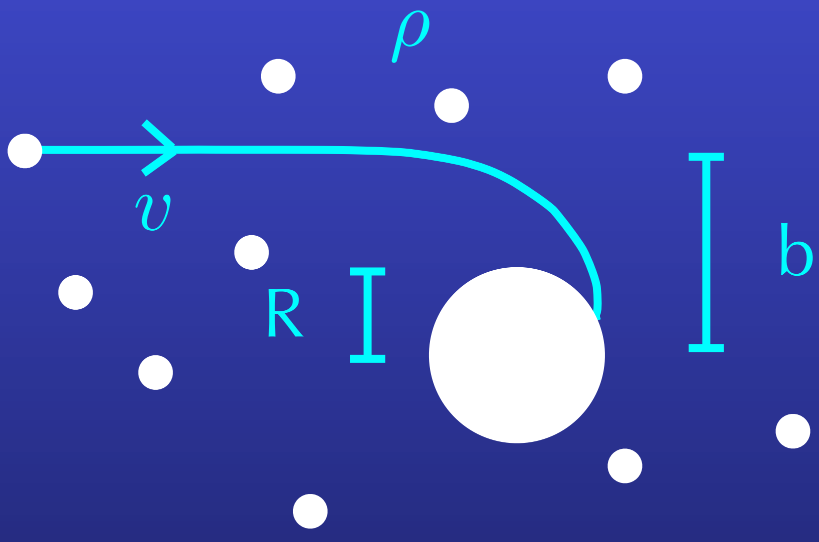
Minimum-Mass Kepler-11 system (turns out Toomre Q ~ 2)







In situ formation of rocky planets



Mass accretion rate

$$\dot{M} \sim \rho\, v\, R^2\, F_{\rm grav}$$

$$\rho \sim \begin{array}{l}\;\;\sigma\\ \hline \enclose{circle}{h} \sim \dfrac{v}{\Omega}\end{array}$$

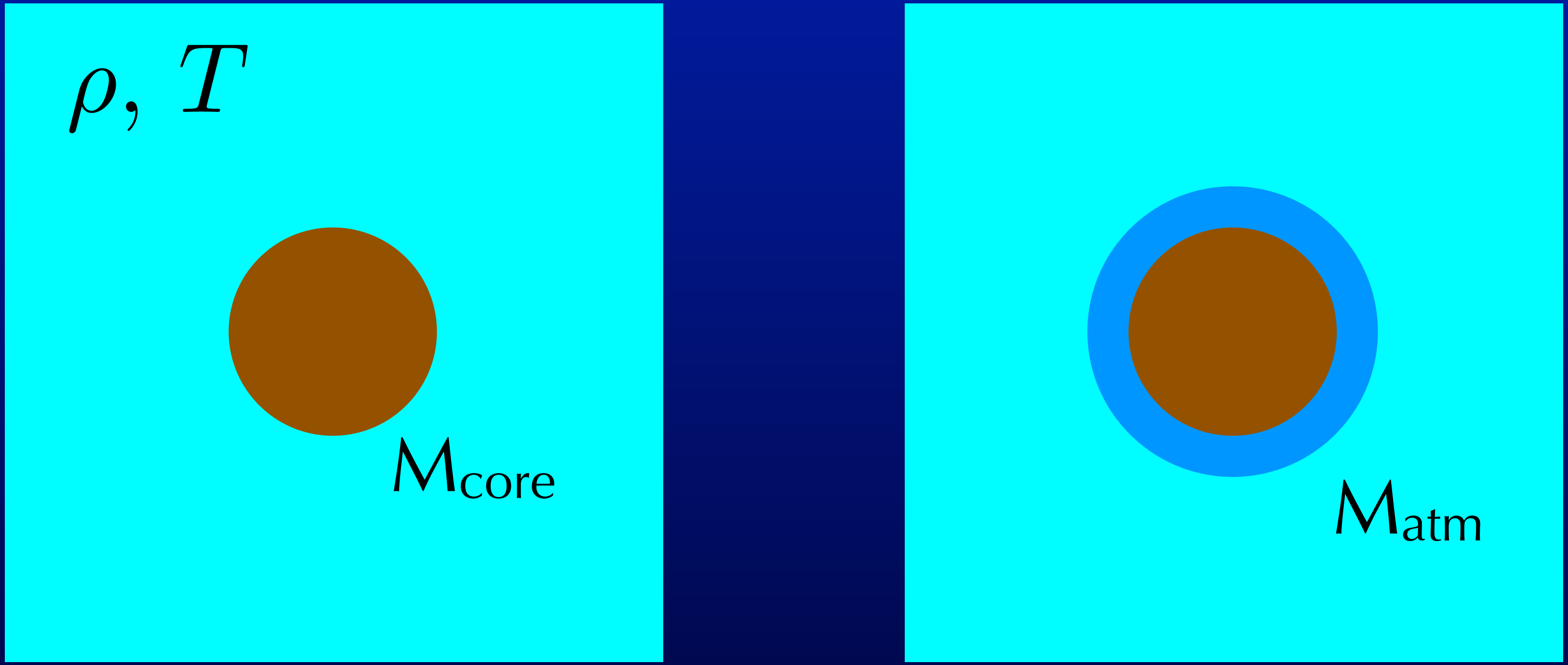
$$\longrightarrow \quad \dot{M} \sim \sigma\, \Omega\, R^2\, F_{\rm grav}$$

$$t_{\rm form} \sim \frac{M}{\dot{M}} \sim \frac{\rho_{\rm b} R}{\sigma\, \Omega}\, \frac{1}{F_{\rm grav}}$$

$\sim 10^4$ yr for Kepler-11

In situ formation of hot Jupiters?

Core accretion



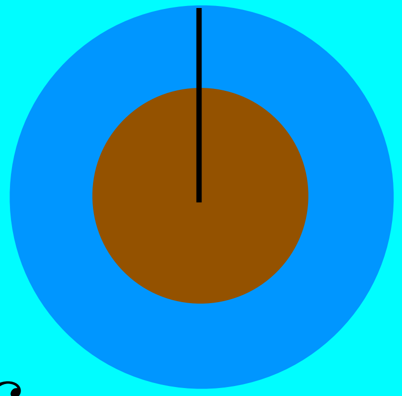
$$M_{\mathrm{atm}}(M_{\mathrm{core}}, \rho, T, \kappa, \dot{M}_{\mathrm{planetesimal}})$$

if $M_{\mathrm{atm}} \sim M_{\mathrm{core}}$ $\longrightarrow$ instability

(runaway envelope accretion)

In situ hot Jupiter

$$R_{\rm B} = GM/c_s^2 \quad (v_{\rm esc} \sim c_s)$$



$\rho,\ c_s$

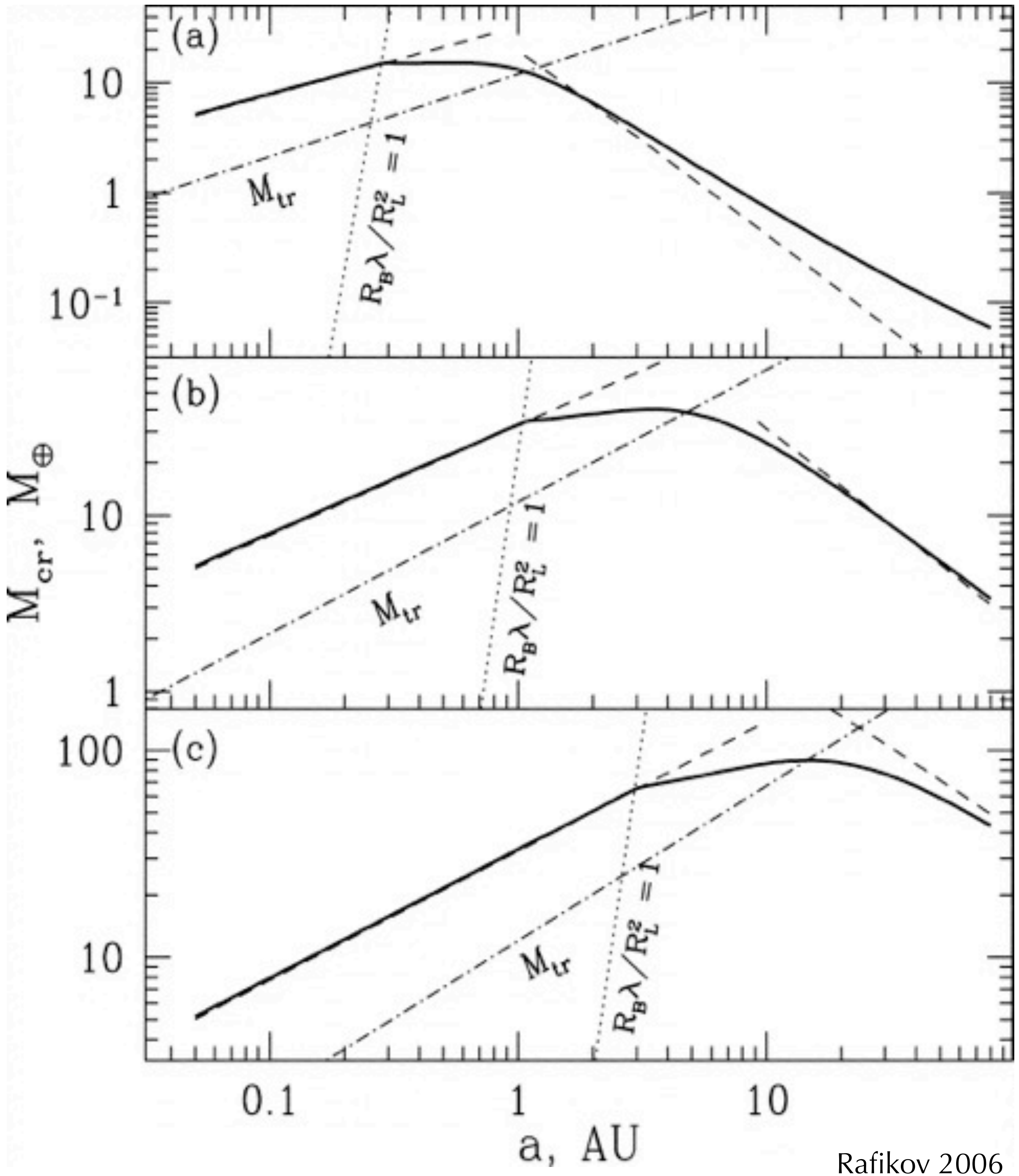
$$M_{\rm atm} \sim 4\pi\rho R_B^3$$

$$\sim M_{\rm core}$$

↑

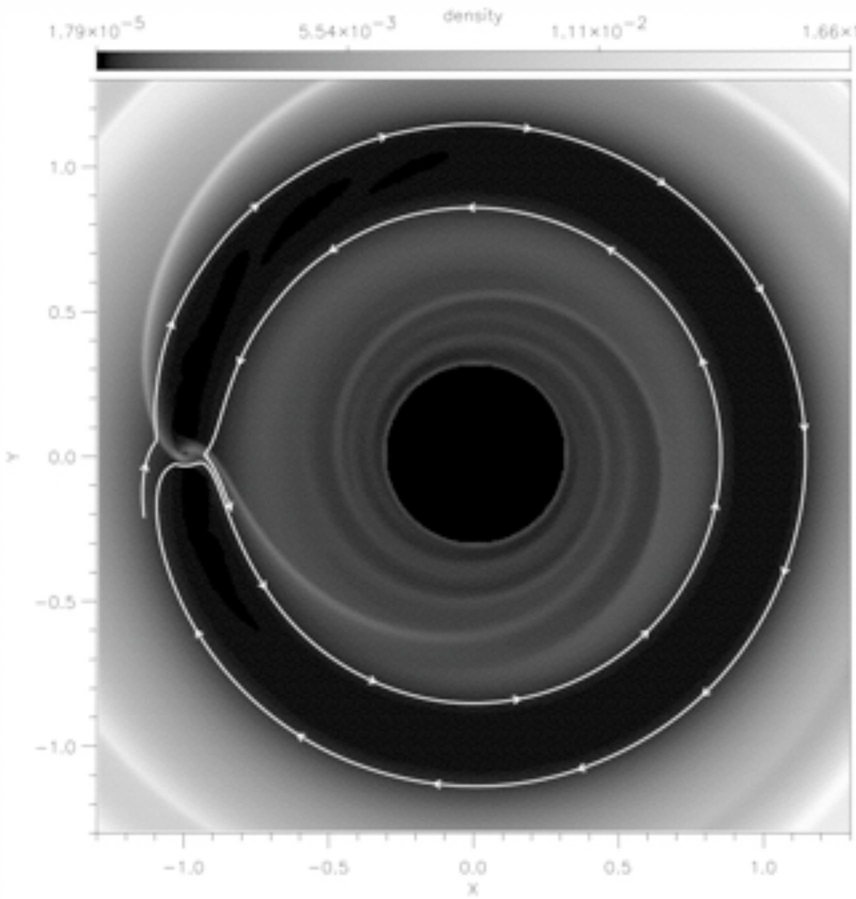
instability

$$M_{\rm core,crit} \sim \frac{c_s^3}{\sqrt{4\pi G^3\rho}}$$



Rafikov 2006

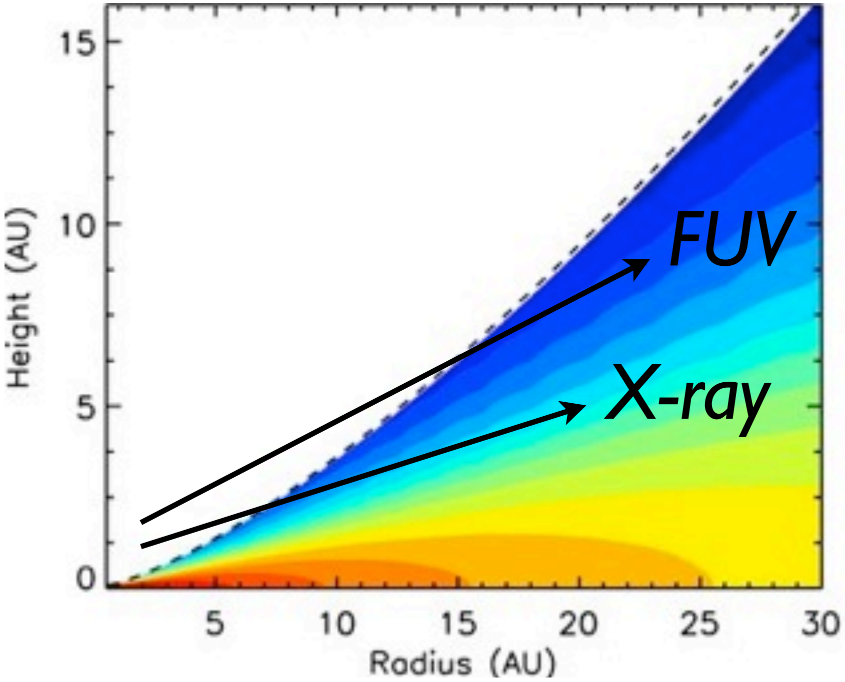
Formation of hot Jupiters by disk-driven migration

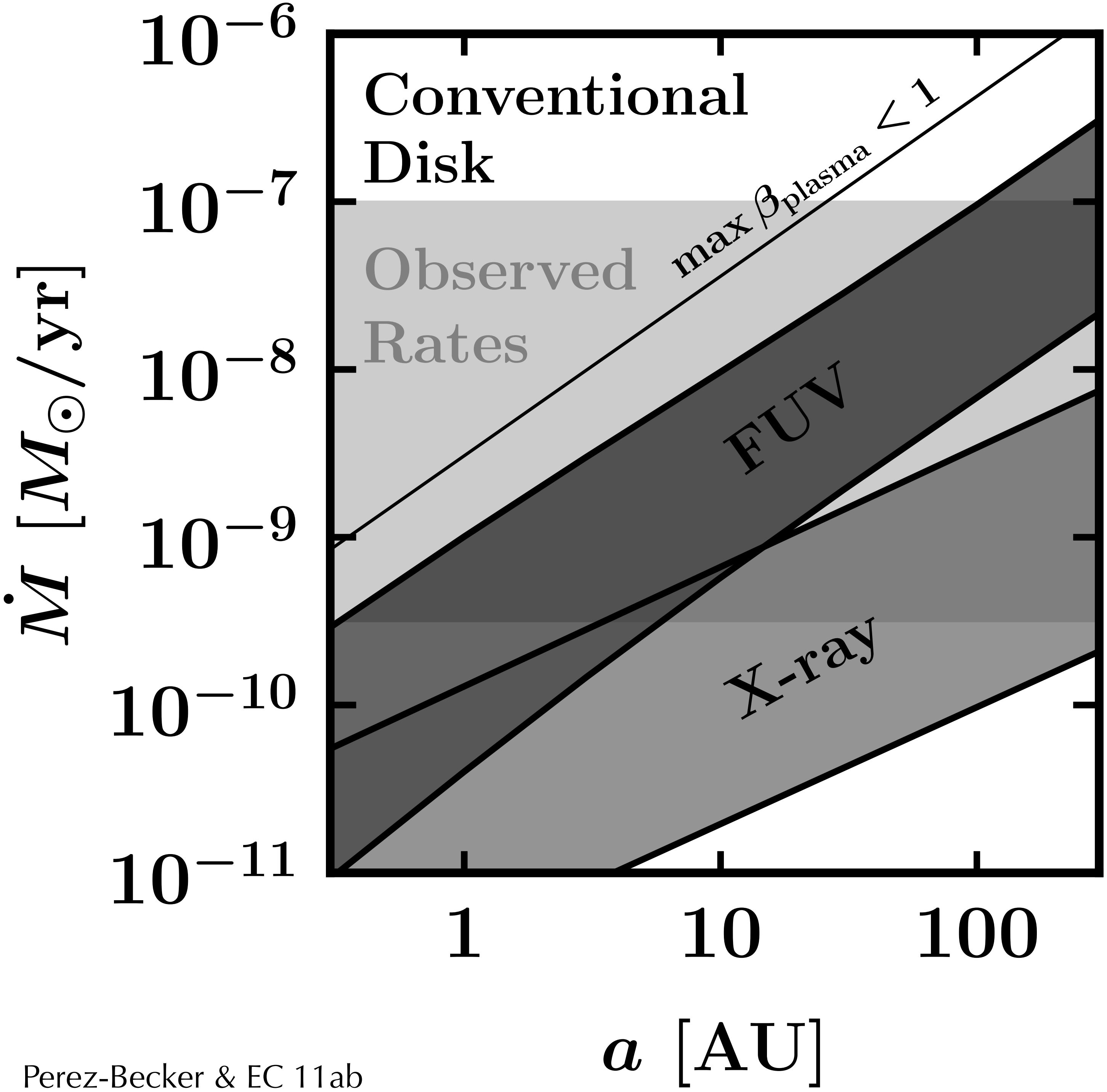


Lubow et al. 99

What is the source of disk viscosity?

MRI activity in surface layers only





Perez-Becker & EC 11ab
Bai & Stone 11, Bai 11

$$\dot{M} \sim 2 \times 3\pi\Sigma^*\nu \sim 6\pi\Sigma^*\alpha\frac{kT}{\mu\Omega}$$

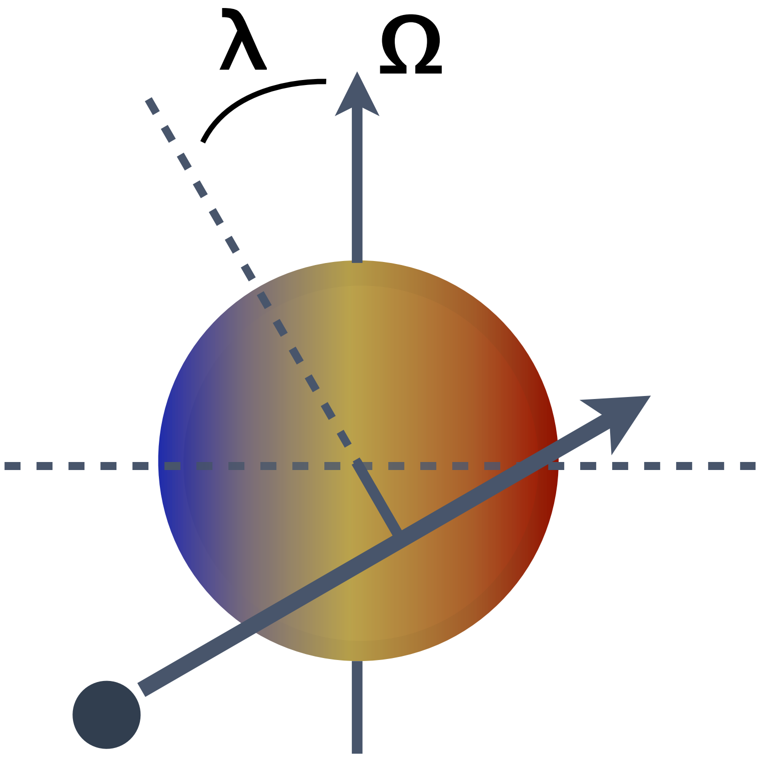
MRI accretion rates too low

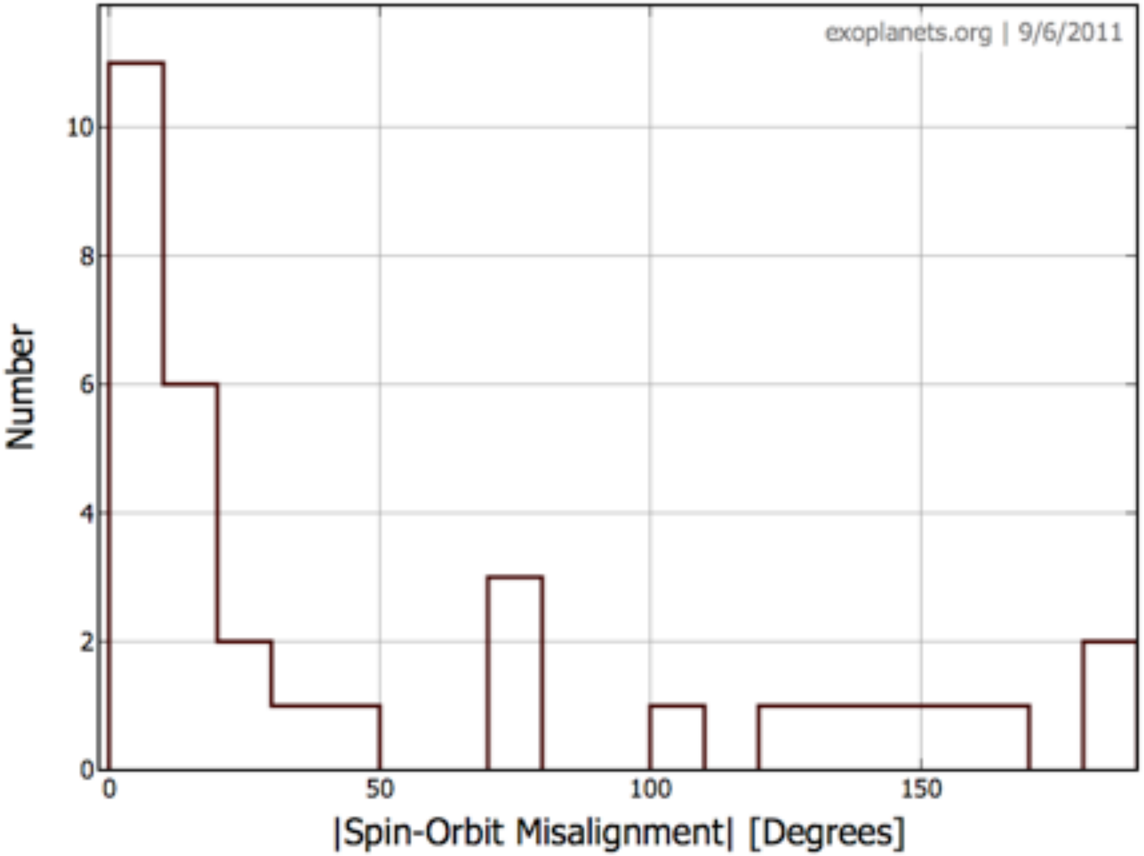
FUV-ionized layer too thin

X-ray-ionized layer weakened by PAHs and ambipolar diffusion

Spin-orbit alignment of hot Jupiters

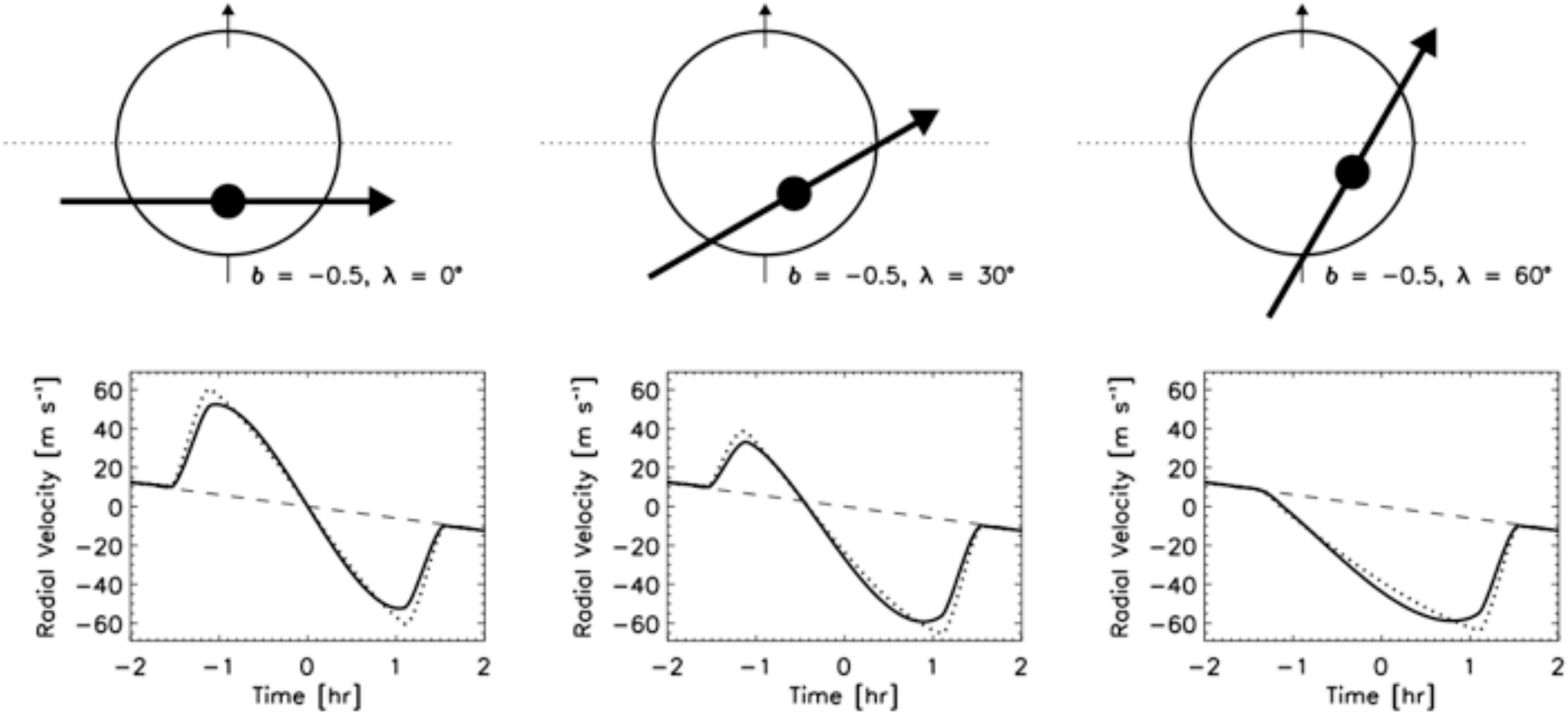
λ = stellar obliquity
(sky projected)

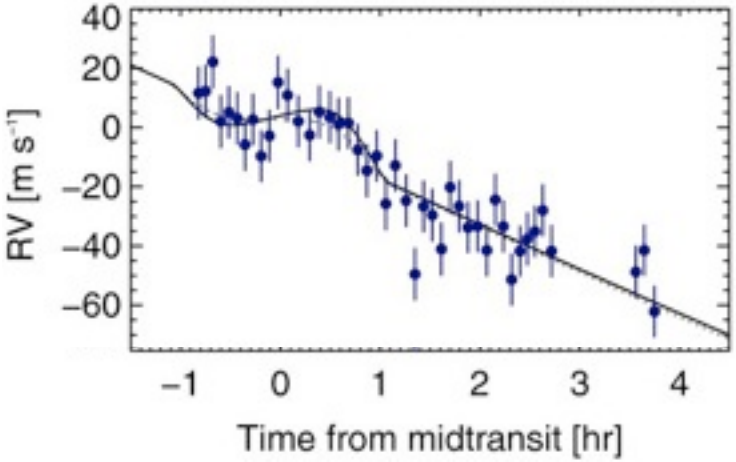




~50% are misaligned,
including retrograde

Measuring spin-orbit angles by Rossiter-McLaughlin

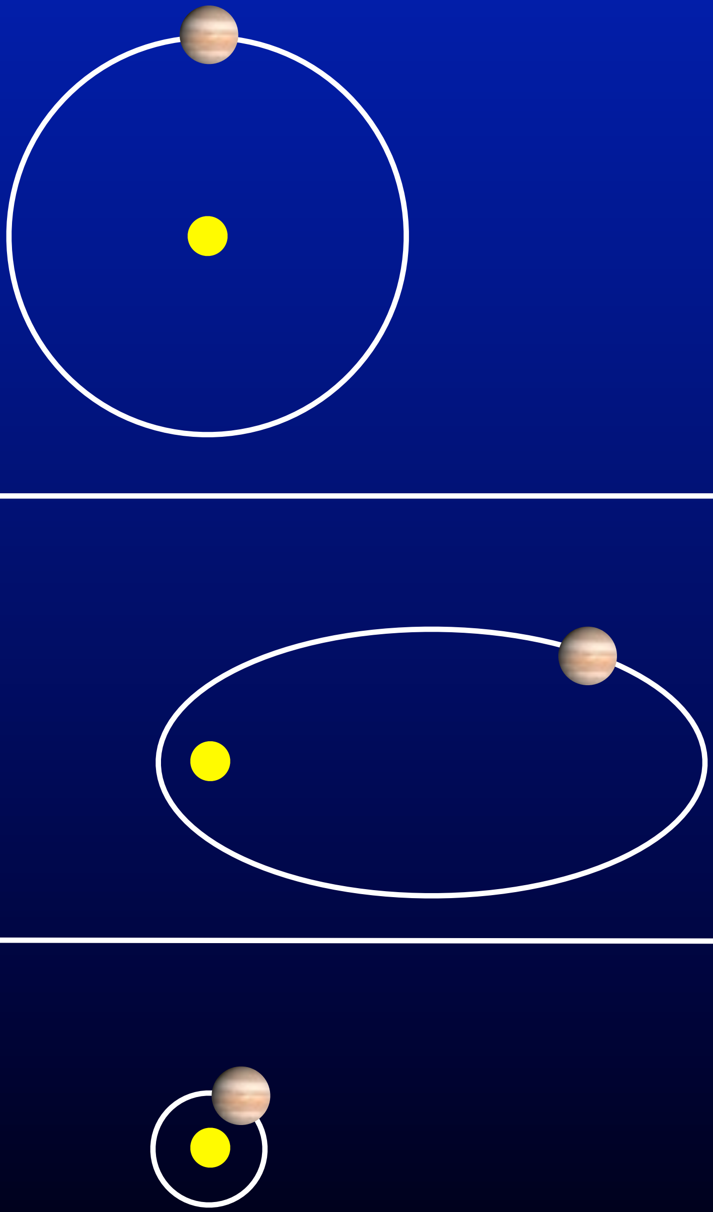




HAT-P-14

Winn+ 11
Gaudi & Winn 08

Migration by eccentricity excitation and tidal decay



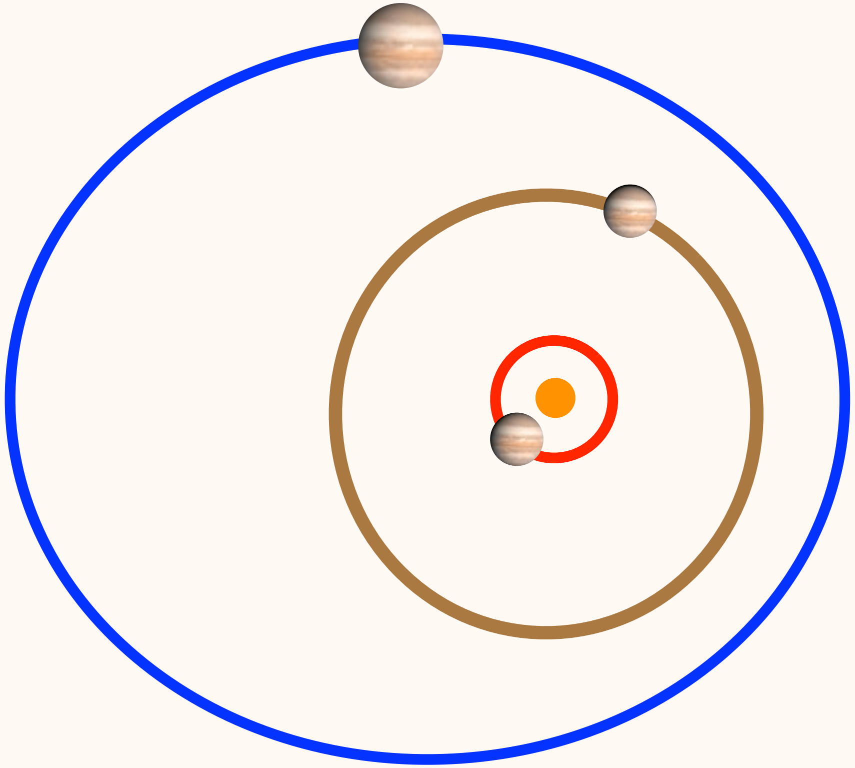
- Planet forms far from star
- Eccentricity is excited (somehow)
- When planet comes close enough to star, strong tides are raised on planet, circularizing its orbit

Y. Lithwick

Secular Chaos

- Start with 3 widely spaced, mildly eccentric & inclined planets:

a(AU)	*ecc.*	*inc. (deg)*	*mass (Mj)*
1	0.066	4.5	0.5
6	0.188	19.9	1.0
16	0.334	7.9	1.5

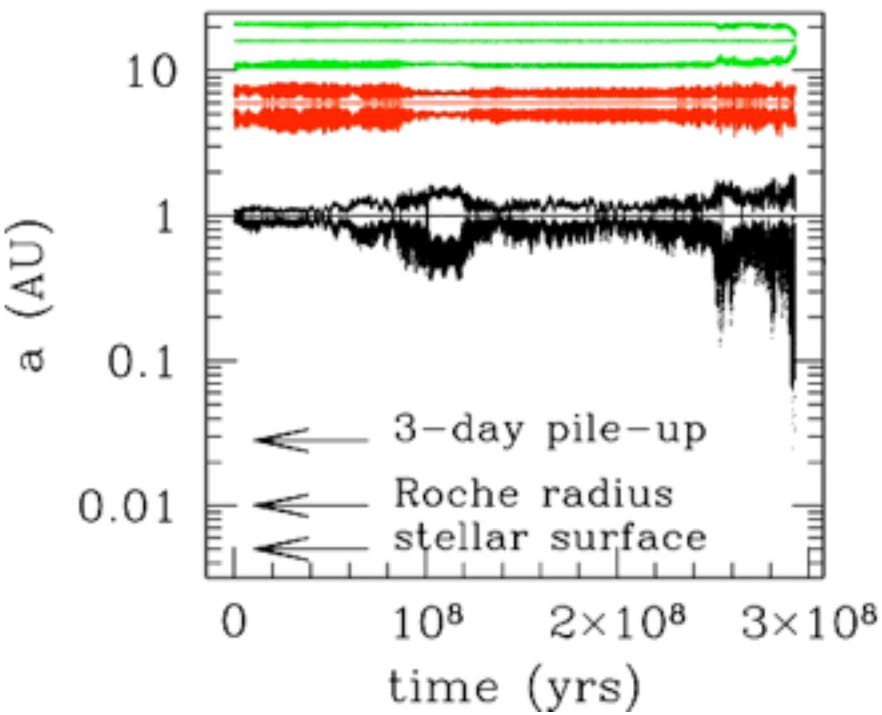


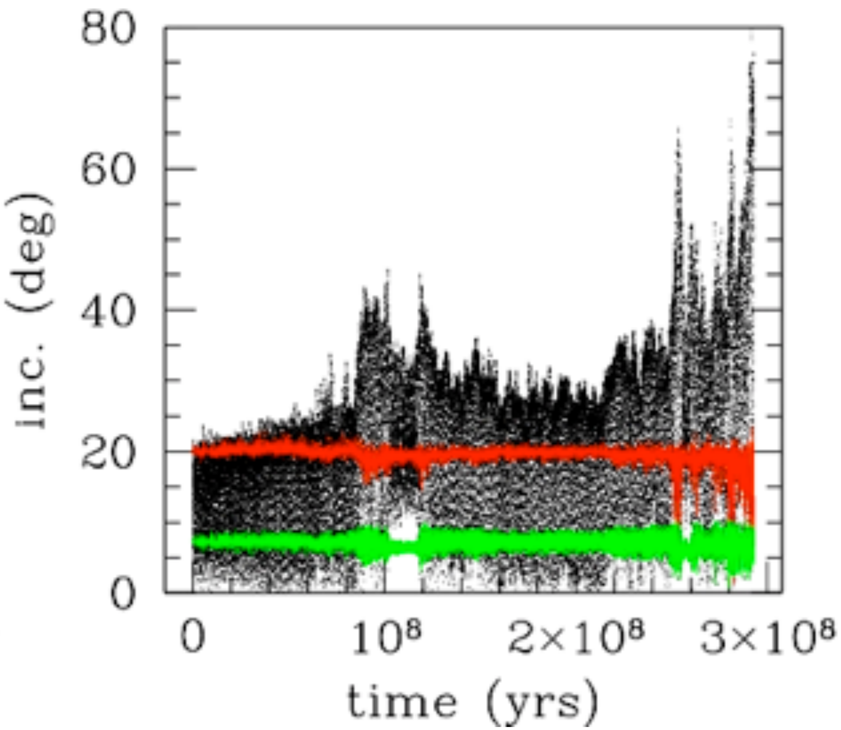
- no close encounters or strong resonances

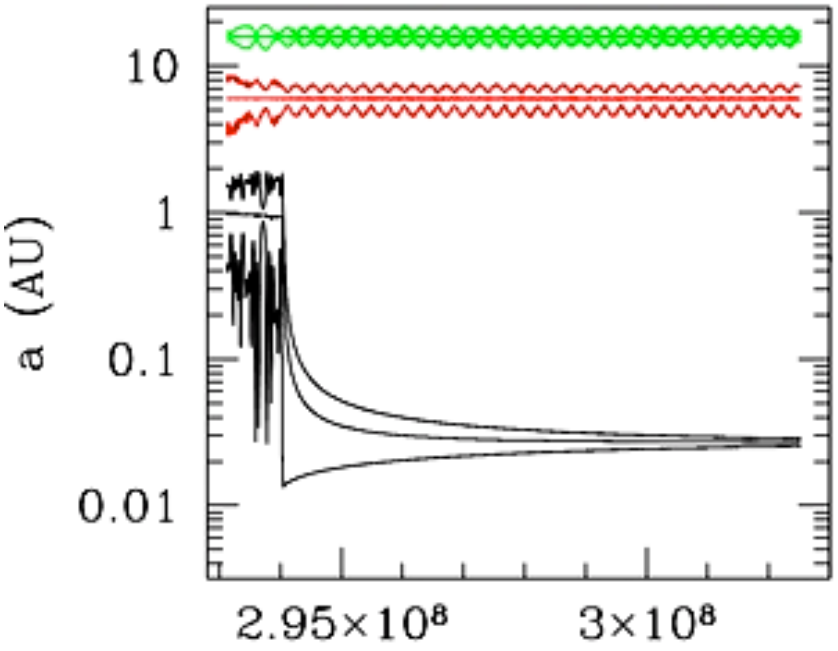
Wu & Lithwick 11

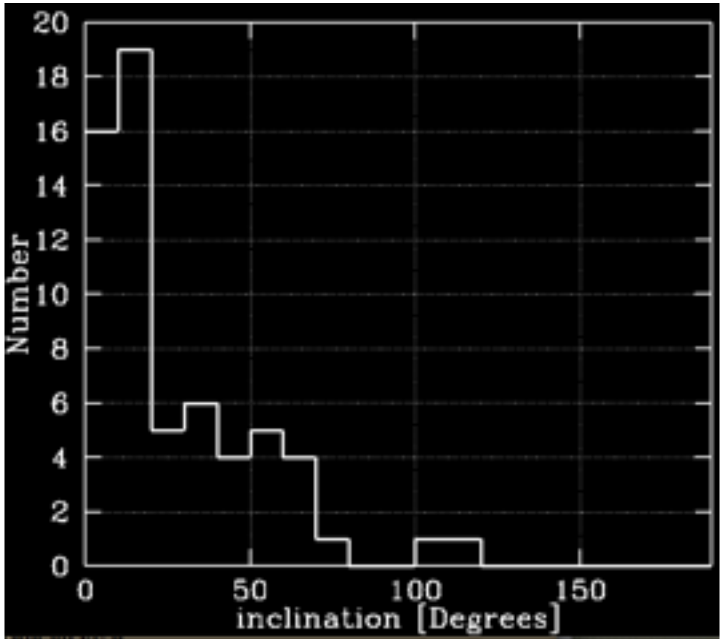
Secular Chaos and Migration

Wu & Lithwick 11

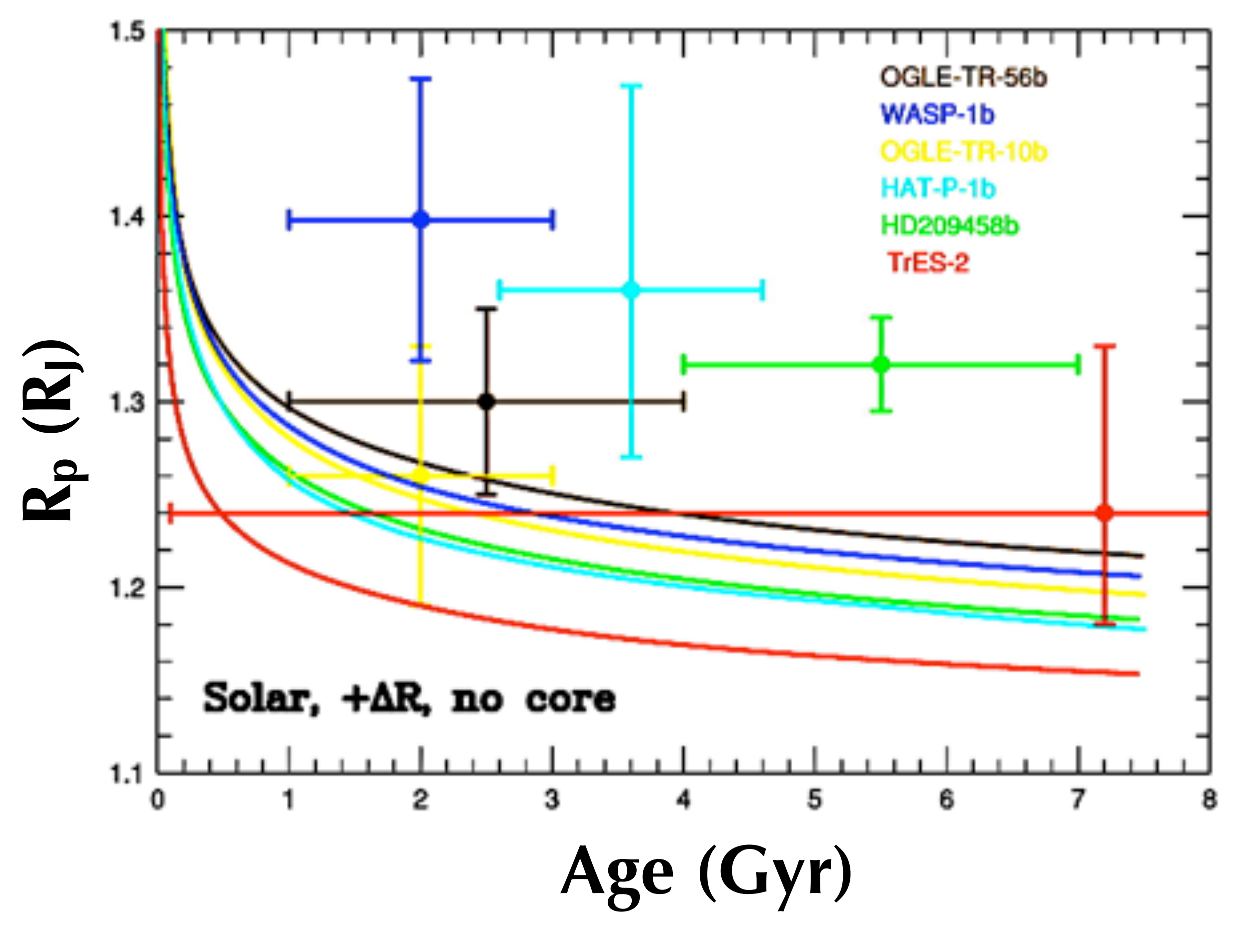








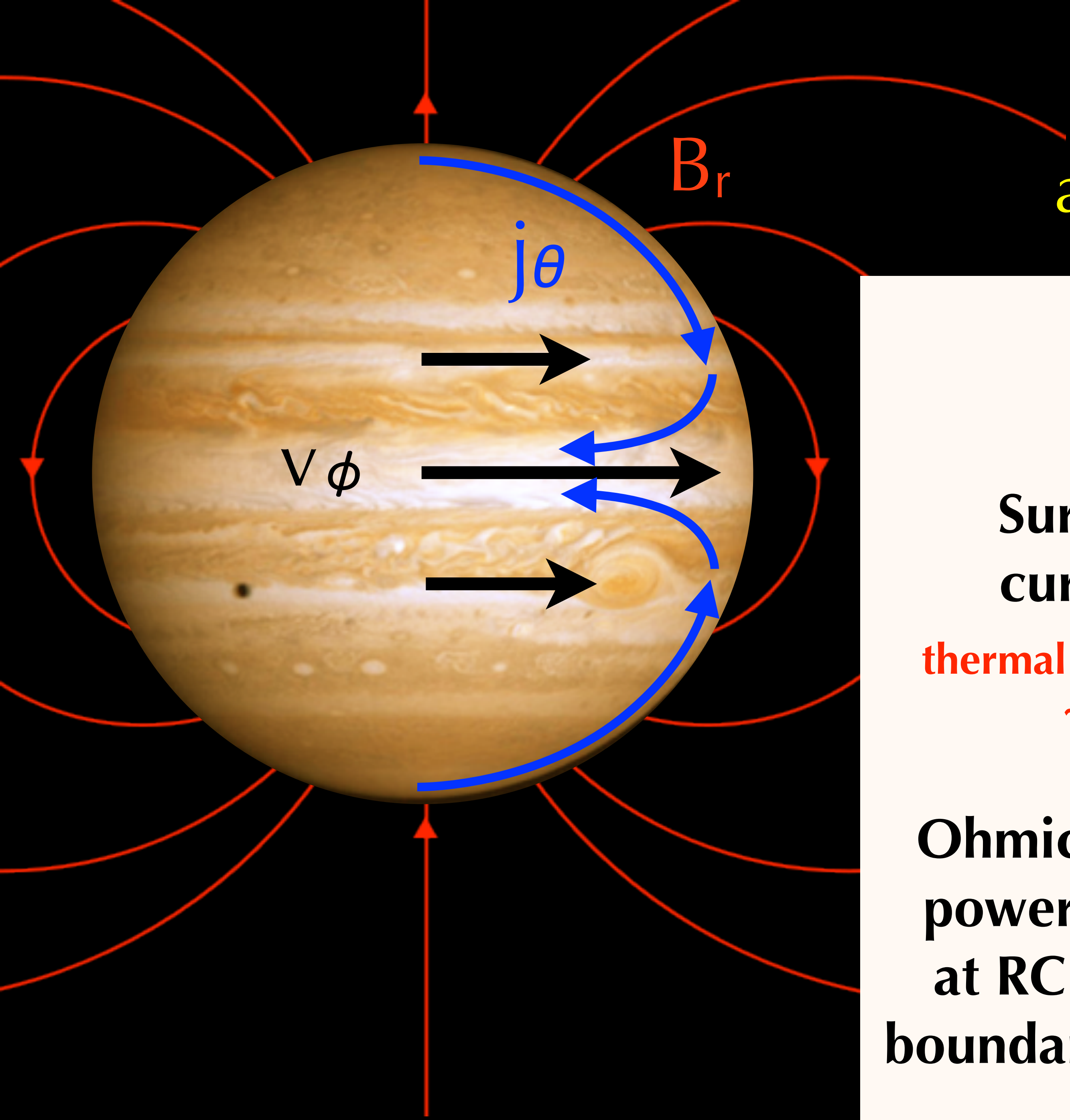
Hot Jupiters are inflated



Transit radii > Theoretical radii

Burrows et al. 2007

Wind Power and Ohmic Heating



Batygin & Stevenson 10

~1 km/s

Surface current

$$\mathbf{j} \sim \sigma \frac{\mathbf{v}}{c} \times B$$

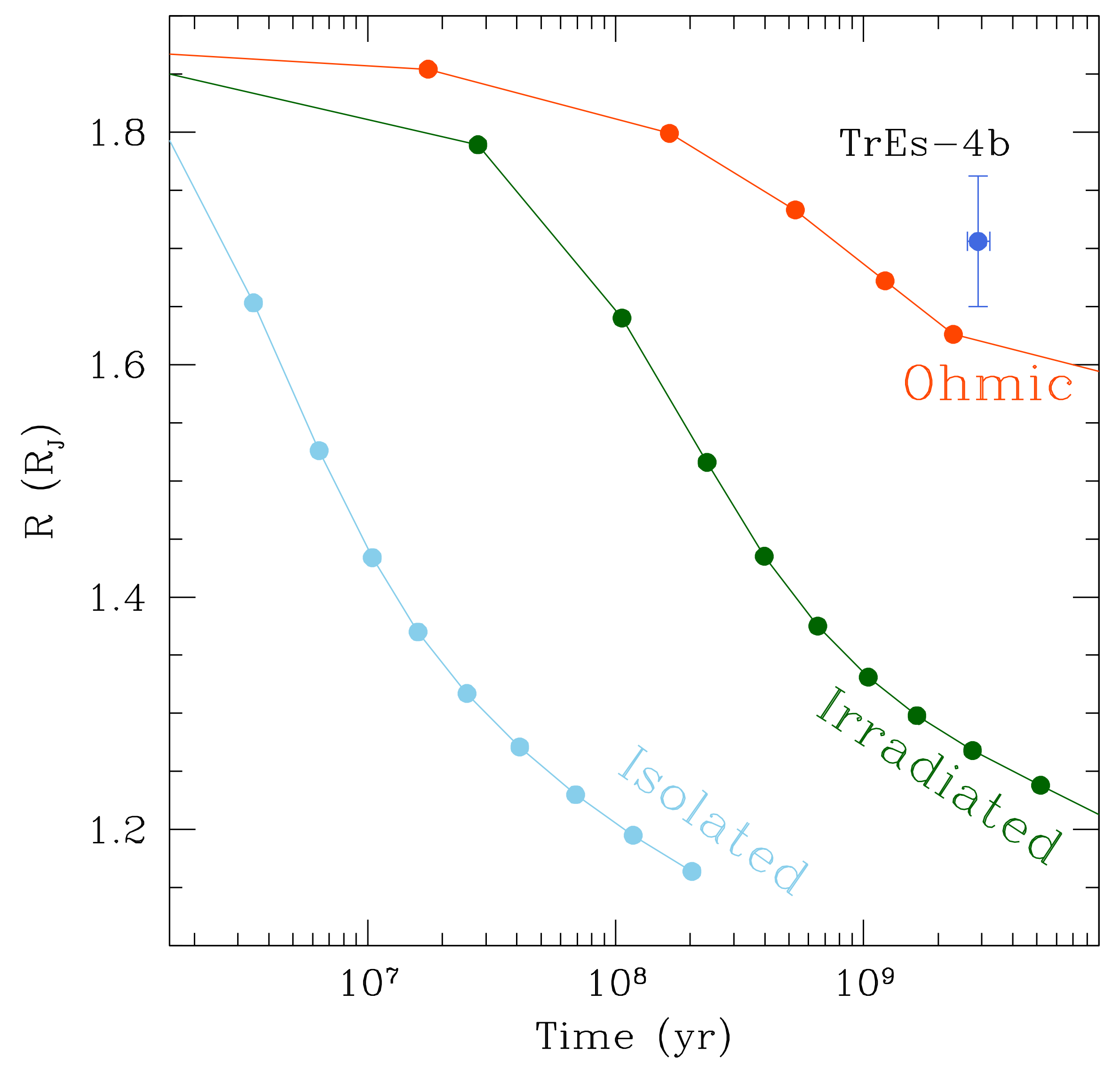
~1 G

thermal (Saha) ionization
~0.01 S/m

Ohmic power at RC boundary

$$P \sim \left.\frac{j^2}{\sigma}\right|_{RC} R^2 z_{RC}$$

Ohmic inflation (or suspension)



only works if hot Jupiter is parked early
(cf. secular migration which parks late)

Wu & Lithwick 12

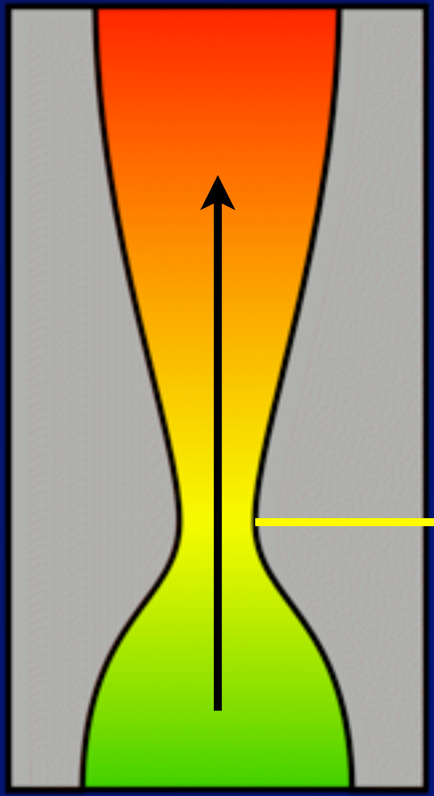
Thermally driven mass loss (Parker winds)

hot Jupiter → $T \geq 10^4\,\mathrm{K}$ → UV heating

$v_{\mathrm{esc}} \sim 40\,\mathrm{km/s}$

PdV work vs. radiative loss (e.g., Ly-α cooling)

Von Braun / Saturn V

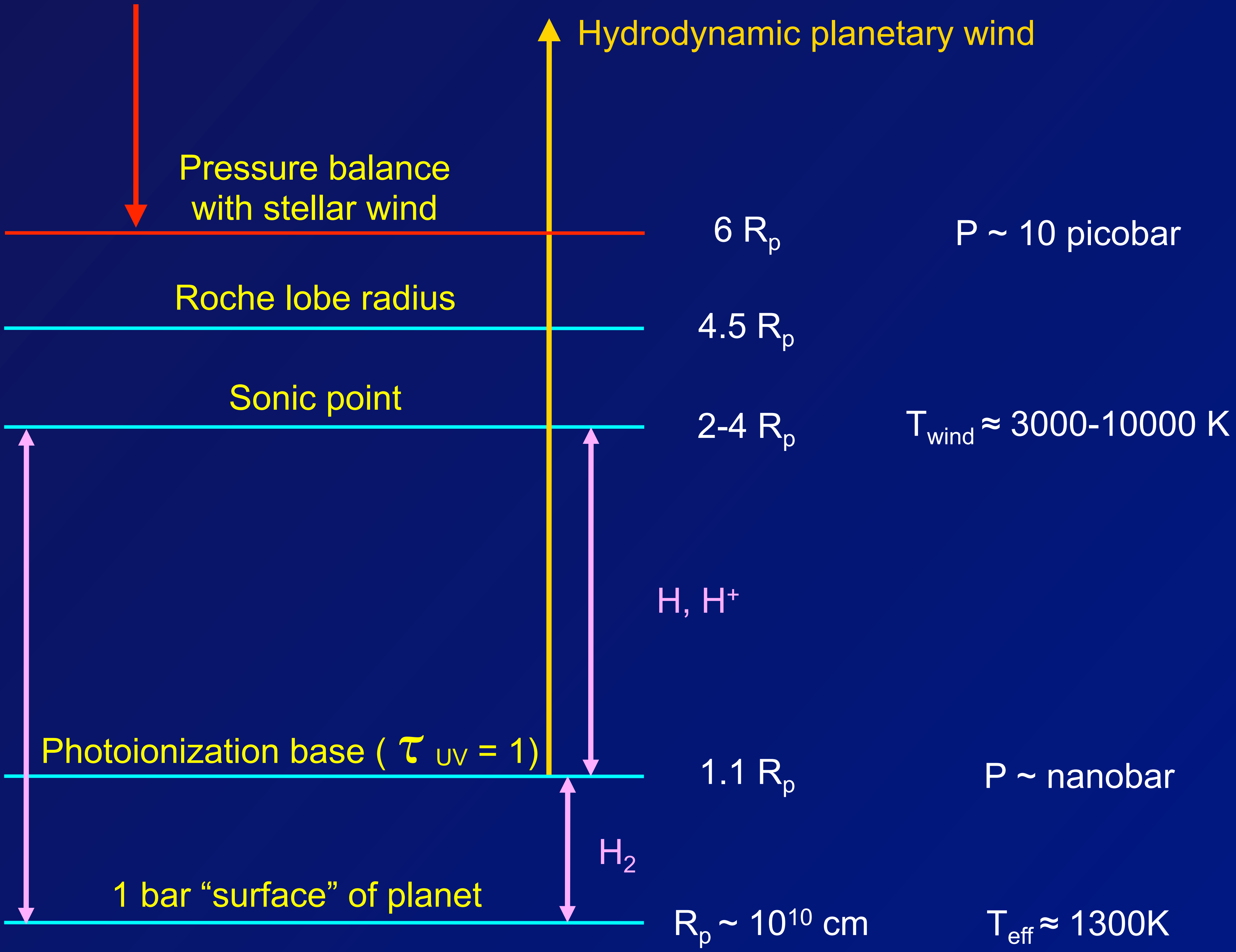


de Laval nozzle

transition from subsonic to supersonic occurs at sonic point

$$R_s = \frac{GM}{2c_s^2}$$

R. Murray-Clay



Hydrodynamic planetary wind

Pressure balance
with stellar wind

$6\ R_p$

$P \sim 10$ picobar

Roche lobe radius

$4.5\ R_p$

Sonic point

$2\text{-}4\ R_p$

$T_{wind} \approx 3000\text{-}10000$ K

H, H^+

Photoionization base ($\tau_{UV} = 1$)

$1.1\ R_p$

$P \sim$ nanobar

H_2

1 bar “surface” of planet

$R_p \sim 10^{10}$ cm

$T_{eff} \approx 1300$K

Atmospheric escape from HD 209458b

$M_p = 0.7\ M_J$

$R_p = 1.4\ R_J$

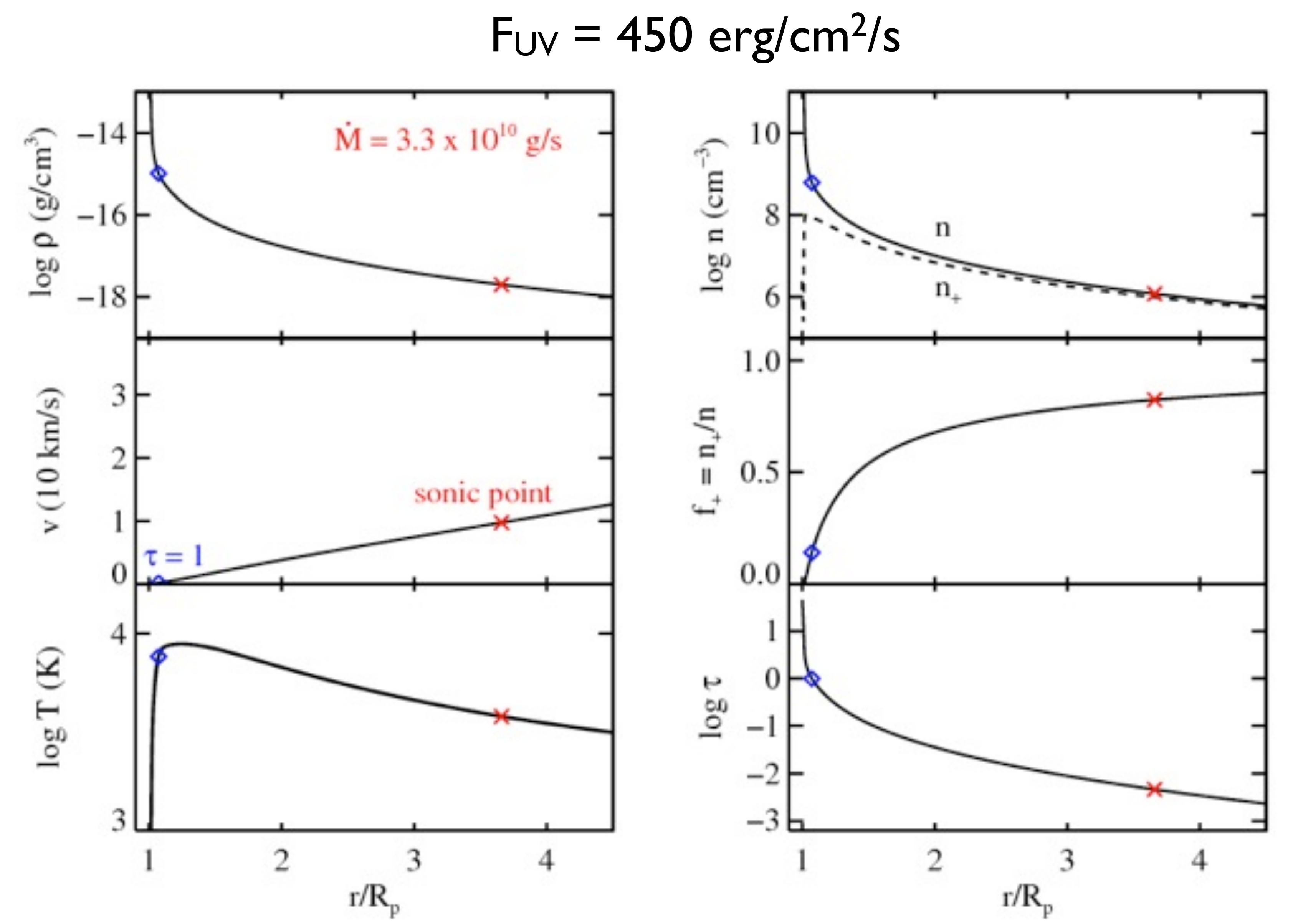
$h\nu_0 = 20$ eV

$\rho_{base} = 4\text{x}10^{-13}$ g

$T_{base} = 1000$ K

$f_{base} = 10^{-5}$

$\tau_{sp} = 0.0046$



$F_{UV} = 450\ \text{erg/cm}^2\text{/s}$

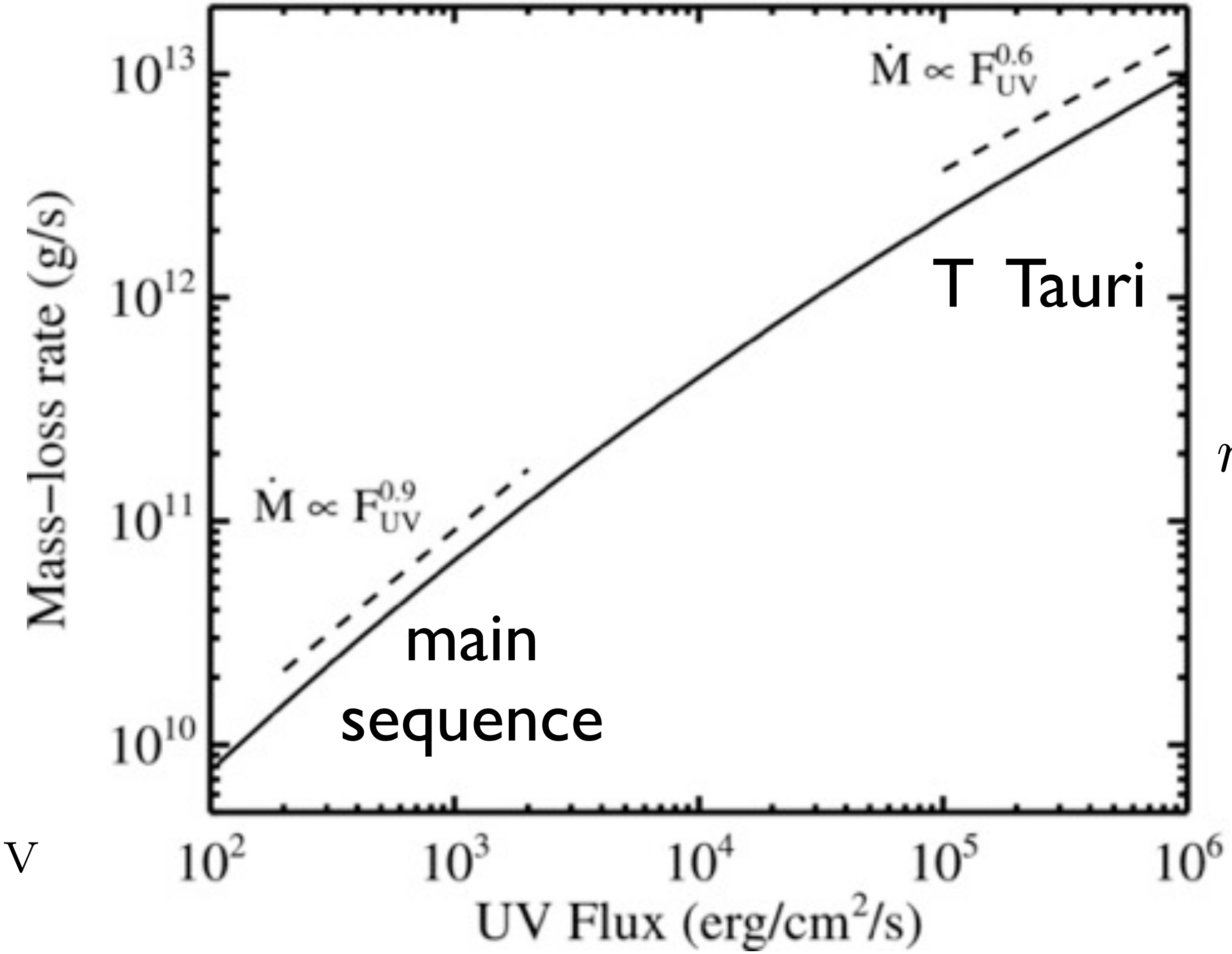
Murray-Clay, EC, & Murray 09

Mass-Loss Rates

At low
UV flux,
wind is
“energy-
limited”

$$\frac{GM\dot{M}}{R} \sim \varepsilon F_{\rm UV} \pi R^2$$

$$\Rightarrow \dot{M} \propto F_{\rm UV}$$



At high
UV flux,
wind is
“recombination-
limited”

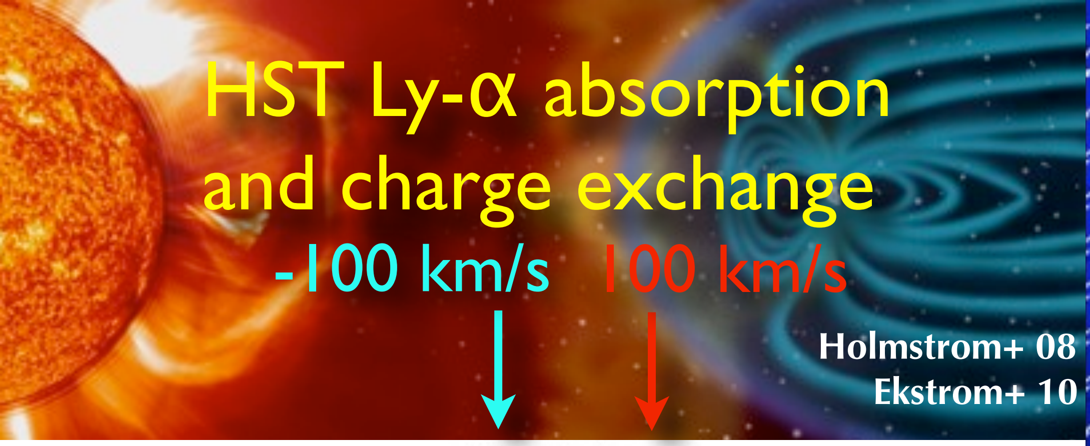
$$n_+^2 \alpha_{\rm rec} \sim \frac{F_{\rm UV}}{h\nu} \sigma_{\rm bf} n_0$$

$$\Rightarrow \dot{M} \propto F_{\rm UV}^{1/2}$$

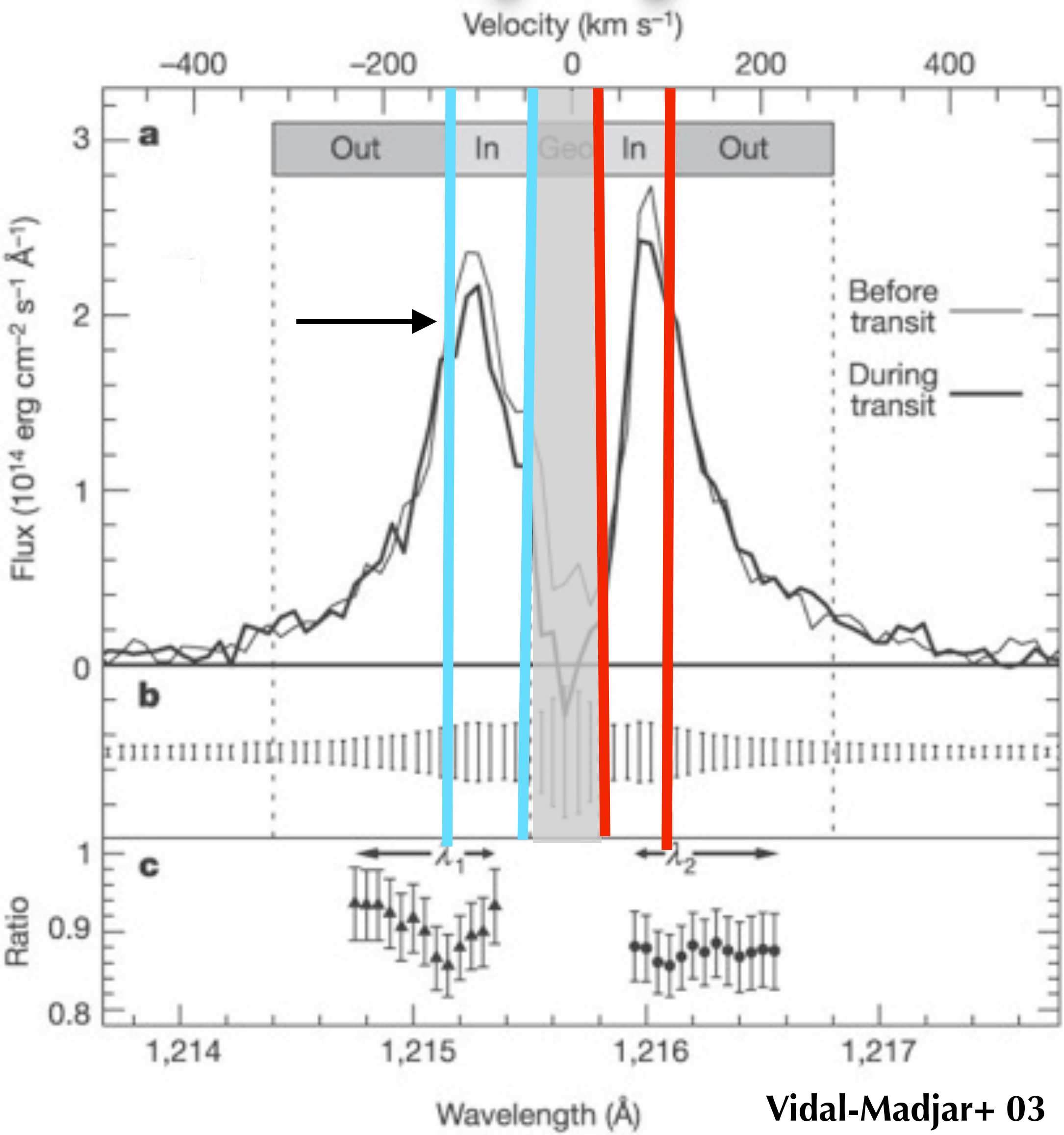
Planet loses ~1% of mass over lifetime

Murray-Clay, EC, & Murray 09

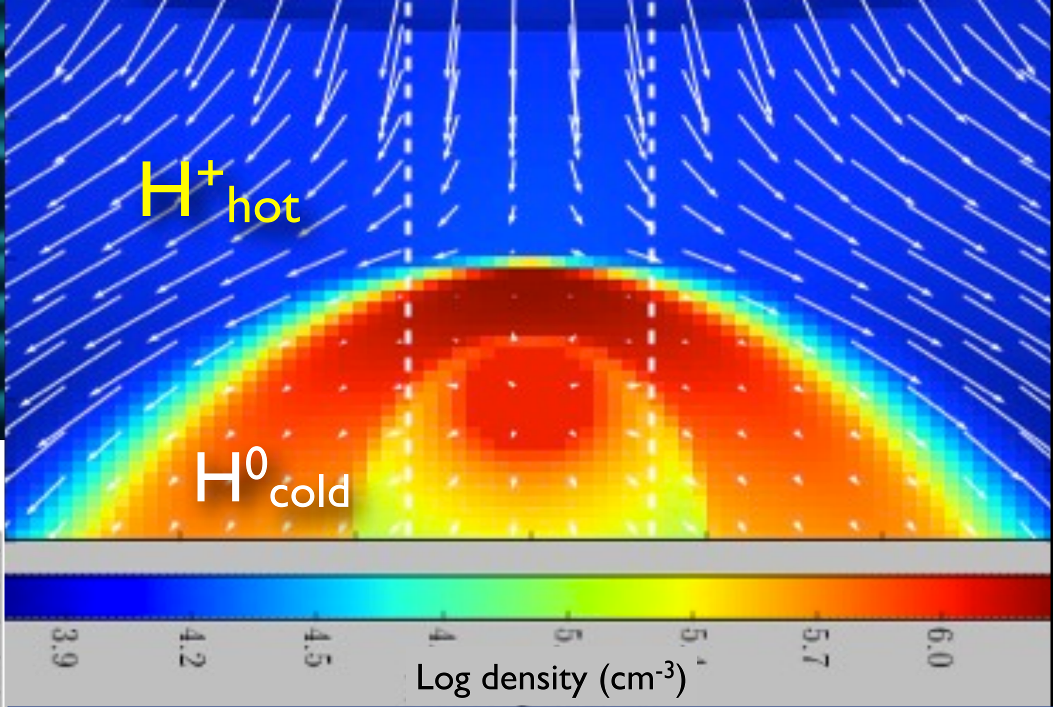
HST Ly-α absorption and charge exchange

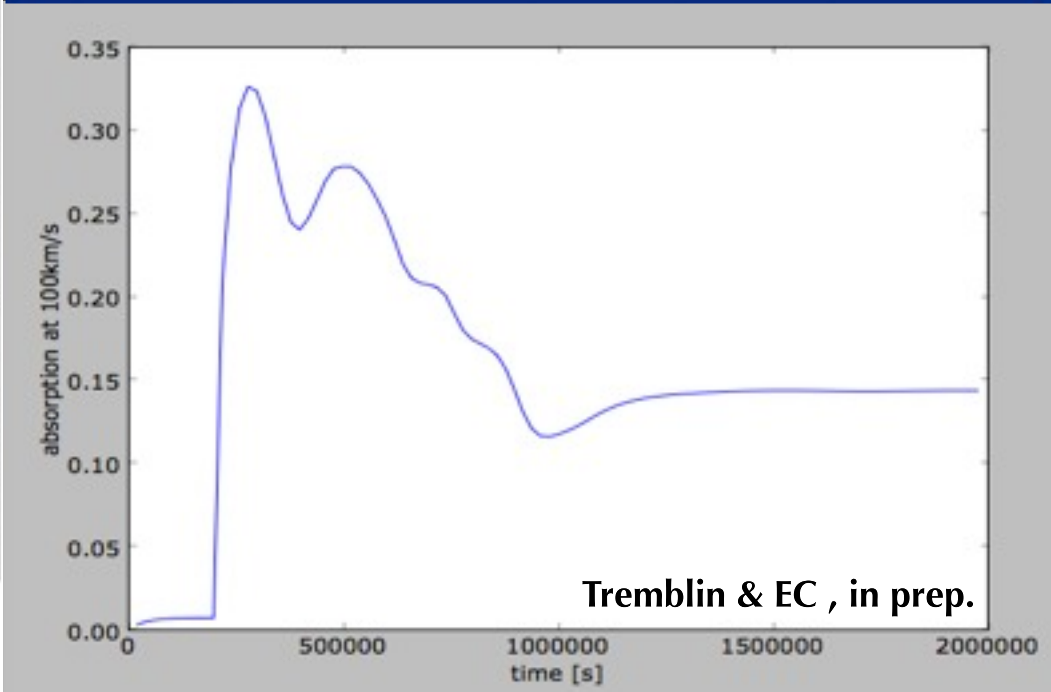


Holmstrom+ 08
Ekstrom+ 10



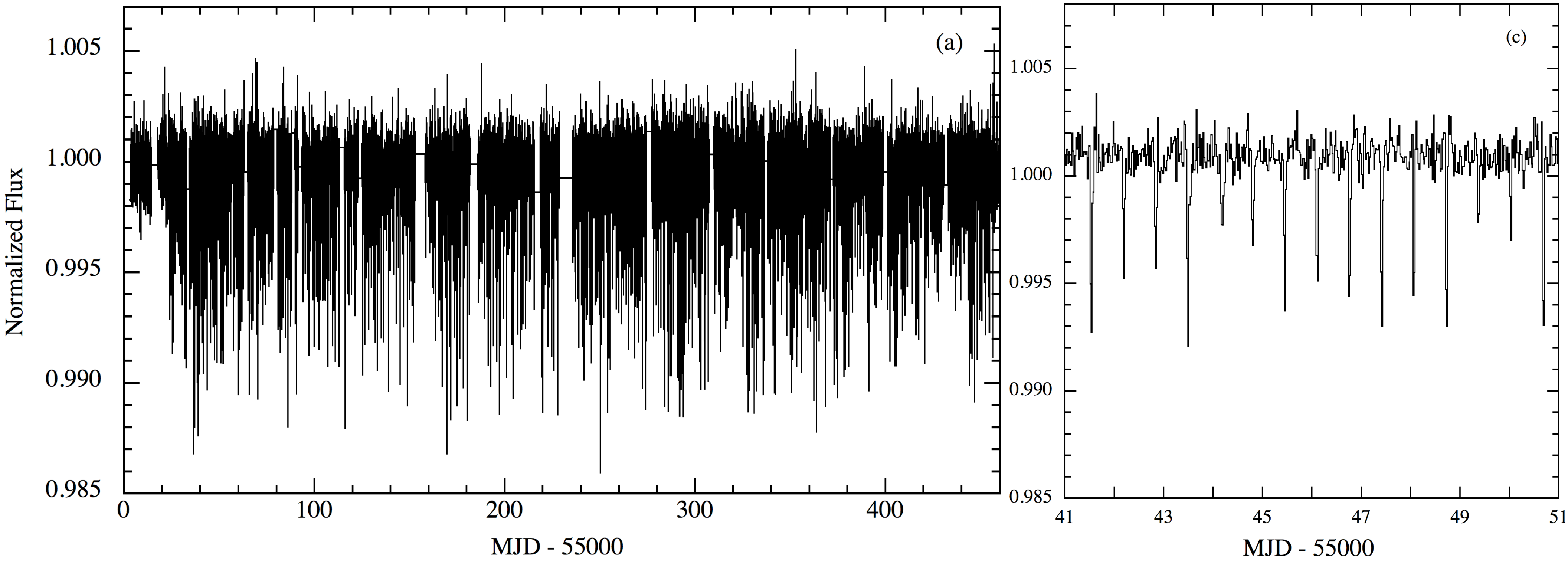
Vidal-Madjar+ 03





Tremblin & EC , in prep.

Kepler Input Catalog (KIC) 12557548



eclipse depth varies from orbit to orbit

K-type star

$M_* = 0.7\ M_\odot$

$R_* = 0.7\ R_\odot$

$T_* = 4400$ K

Companion

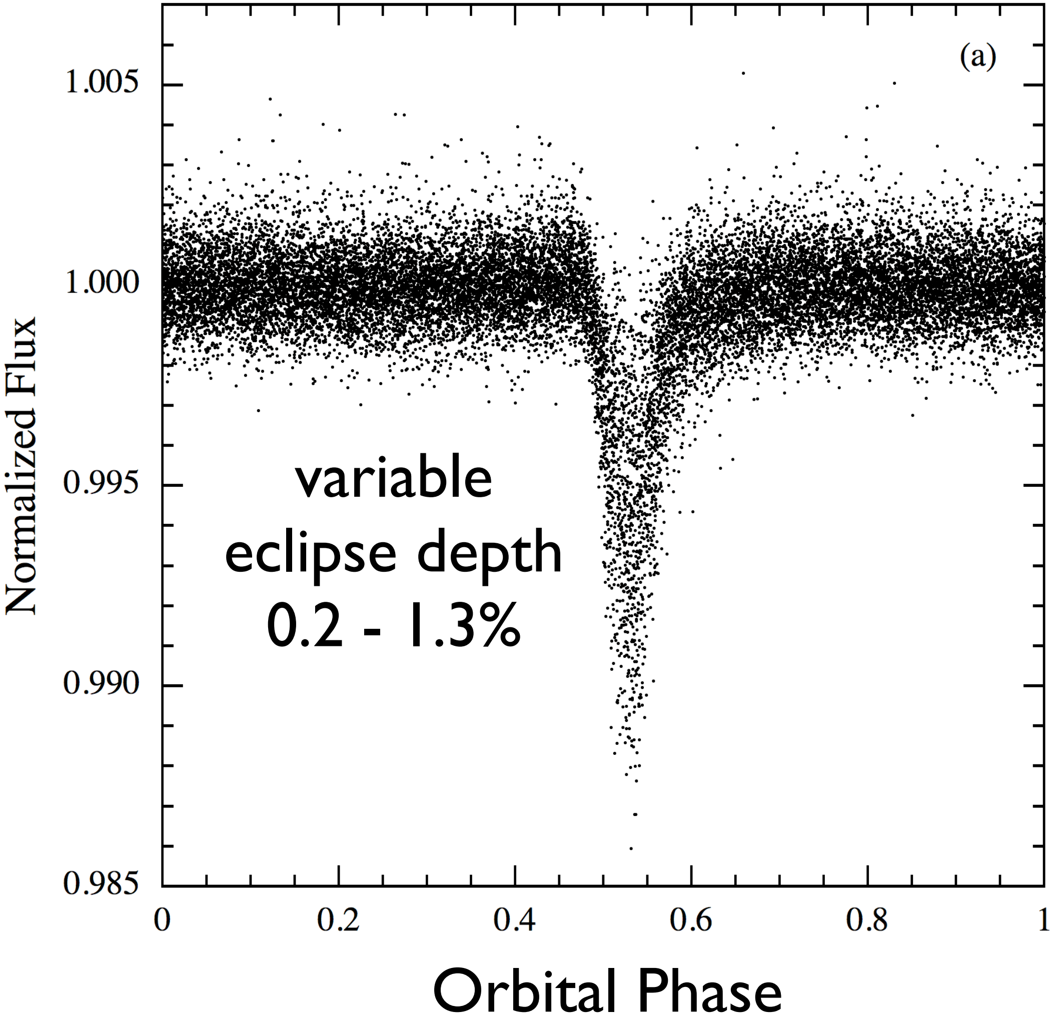
$P_{orb} = 15.685$ hr

$a = 0.013$ AU ($4\ R_*$)

$T_{eff} = 2100$ K

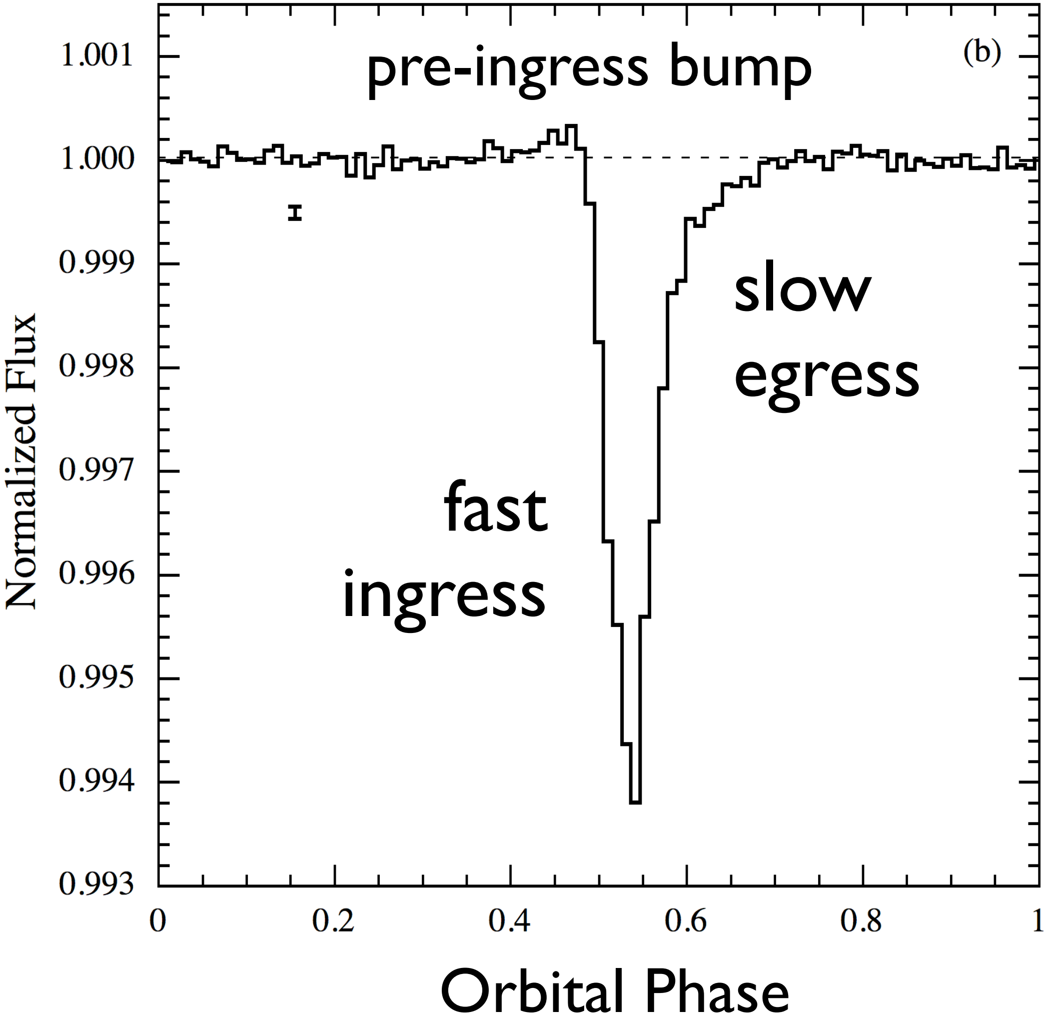
Rappaport, Levine, EC+ 12

folded about 15.685 hr



variable
eclipse depth
0.2 - 1.3%

folded, binned, averaged



pre-ingress bump

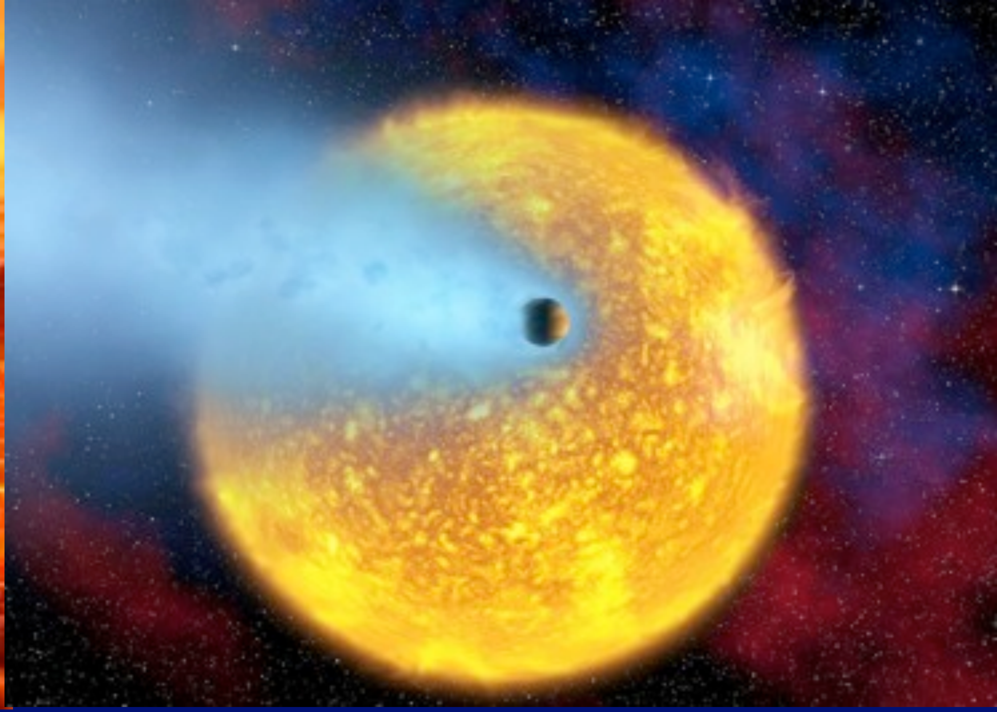
slow
egress

fast
ingress

out-of-eclipse variation < 5e-5

⇒ $M < 3\ M_J$ (no ellipsoidal light variation)

What it could be



A disintegrating super-Mercury

$R \sim 0.5\ R_\oplus \quad M \sim 0.1\ M_\oplus$

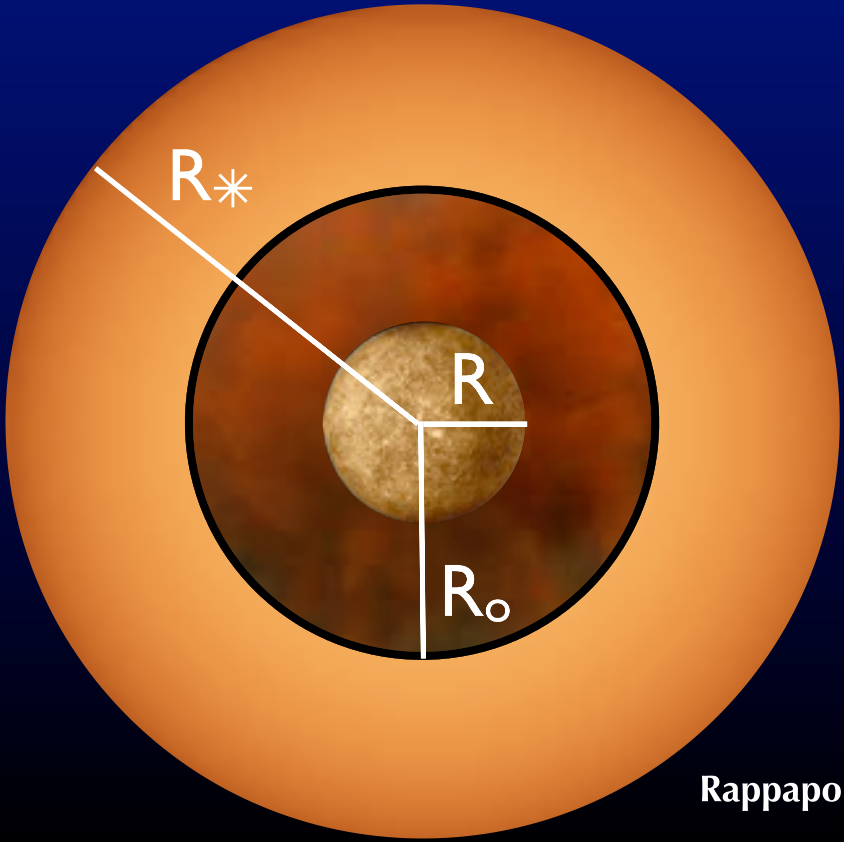
occulting size $R_o \lesssim 0.1\ R_*$

$\lesssim 15\ R$

$T_{\mathrm{eff}} \sim 2100$ K

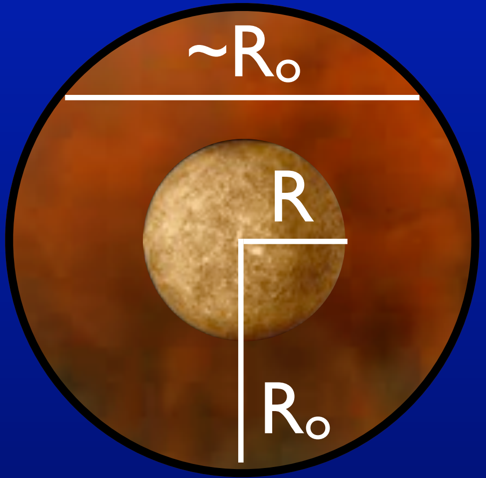
$\Rightarrow c_s \sim 0.7$ km/s

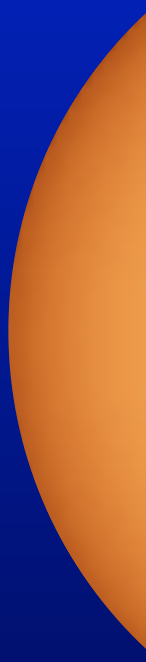
$\Rightarrow v_{\mathrm{esc}} \lesssim$ a few km/s (sub-Earth)



Rappaport, Levine, EC+ 12

Grain and Planet Lifetimes





Mass loss rate $\dot{M}_d \sim \rho_d v_o R_o^2$

optical depth $\tau \sim \rho_d\, R_o\, \underbrace{\kappa_d}_{s^2/(\rho_b s^3)} \sim \dfrac{\rho_d R_o}{\rho_b s}$

eclipse depth $f \sim \tau R_o^2/R_*^2$

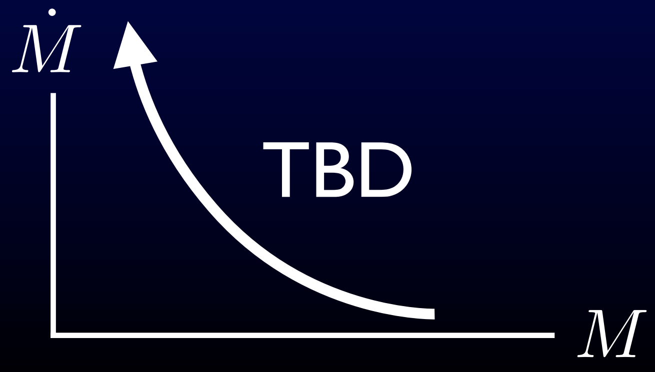
$$\Rightarrow \dot{M}_d \sim f s v_o \rho_b R_*^2/R_o$$

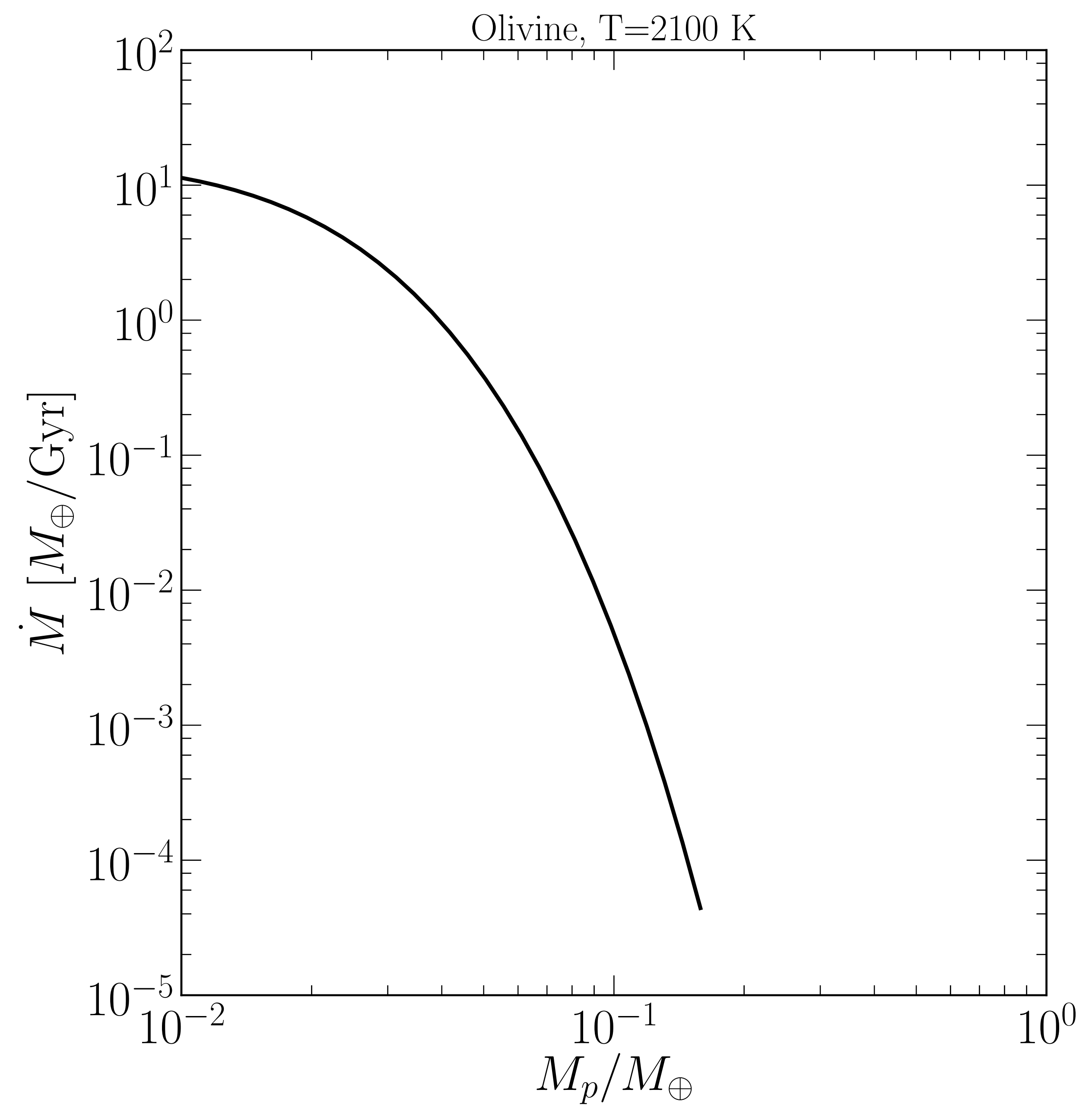
$$\sim 0.5\, M_\oplus \mathrm{Gyr}^{-1} \left(\frac{f}{0.01}\right)\left(\frac{s}{0.1\,\mu\mathrm{m}}\right)$$

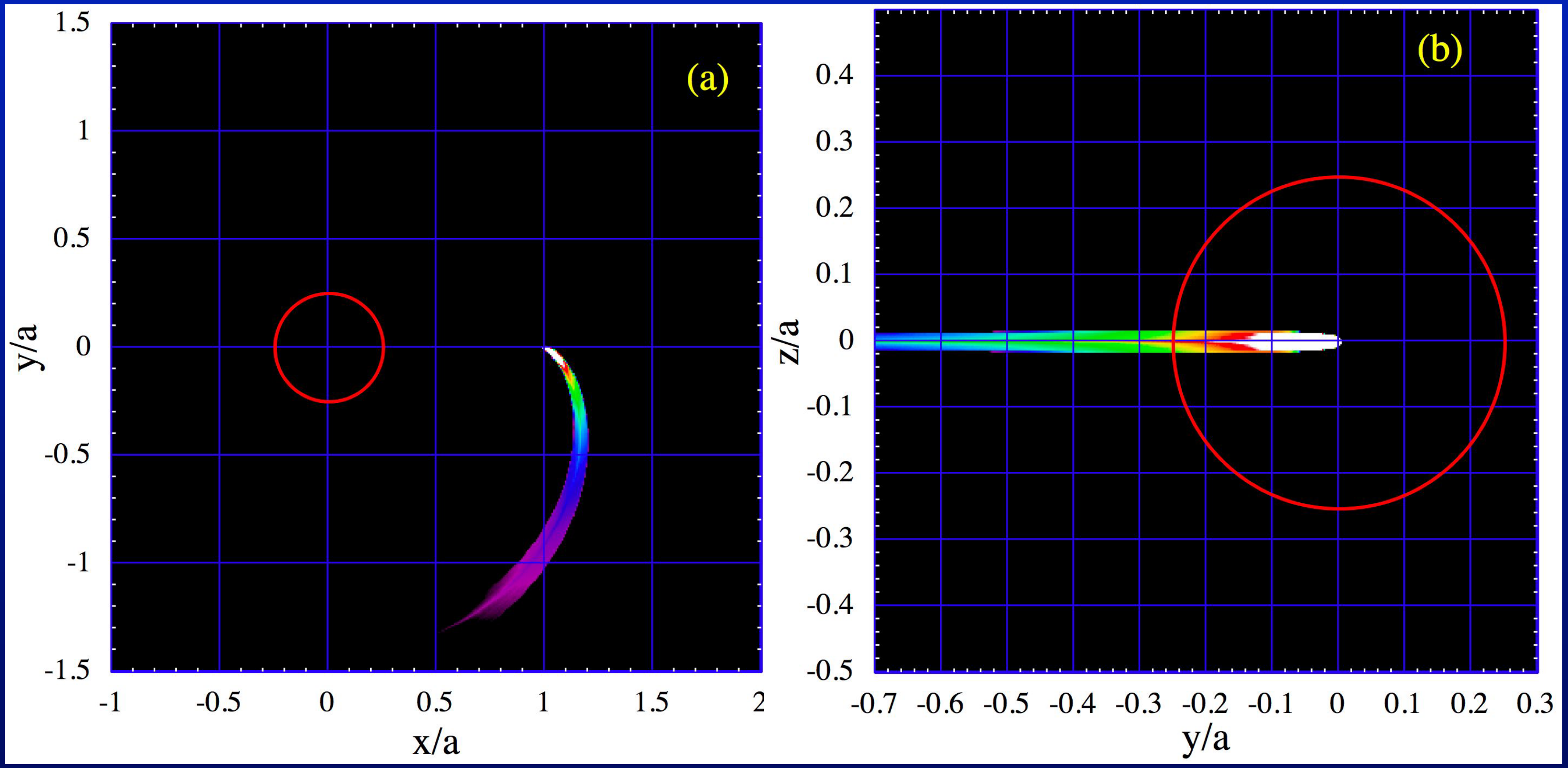
pyroxene grain sublimation lifetime ~ 10^4 s ~ travel time across R$_o$

planet lifetime

$$\frac{M}{\dot{M}} = \frac{M}{\dot{M}_d + \dot{M}_g} \sim 0.1\,\mathrm{Gyr}$$

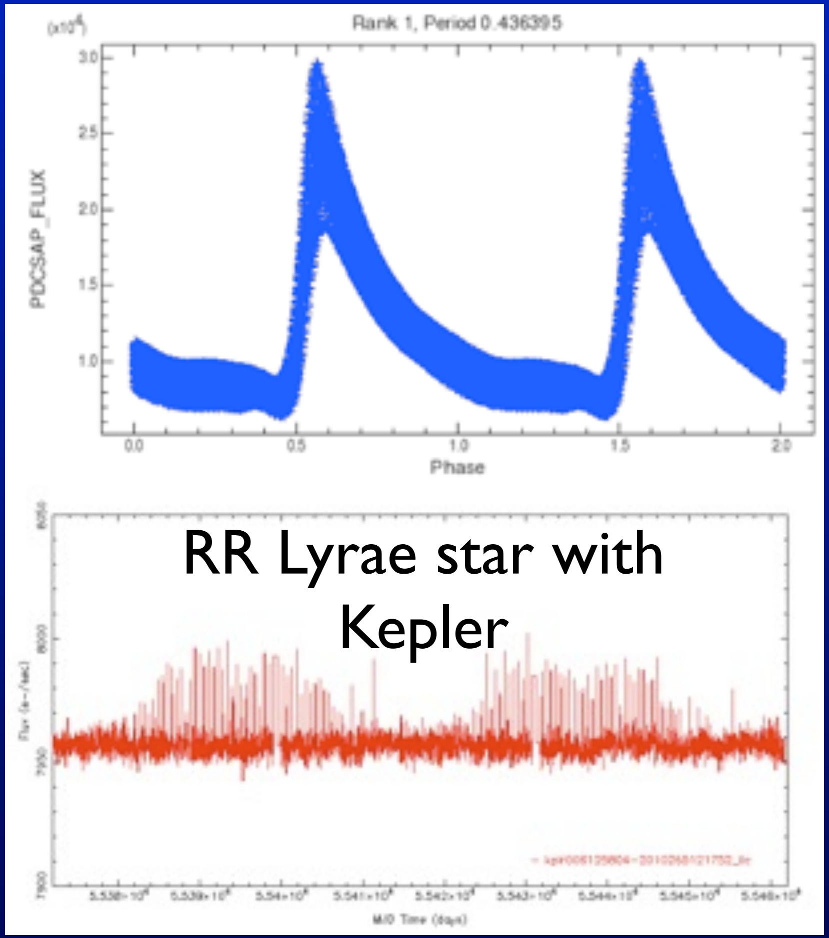



Olivine, T=2100 K
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\dot{M}\ [M_{\oplus}/\mathrm{Gyr}]$
10^{-2}
10^{-1}
10^{0}
$M_p/M_{\oplus}$



- Coriolis force + stellar radiation pressure on grains creates trailing tail
- Tail causes prolonged egress
- Scattered light off head of "comet" causes pre-ingress bump
- Predictions: (i) infrared eclipses shallower
  (ii) deeper eclipses in gas absorption lines

- Disk properties / Planet-disk interaction (Herschel, ALMA)
- Highly eccentric hot Jupiters (RV, Kepler)
- Hot Jupiter magnetospheres (LOFAR, SKA)
- Evaporating atmospheres (HST, JWST)



RR Lyrae star with Kepler

What it is not:

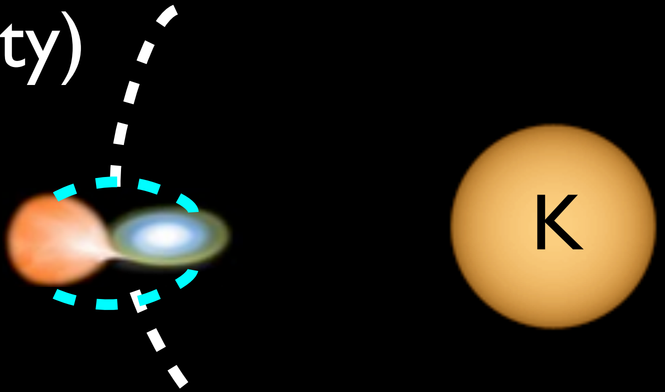
- gas giant (dynamically unstable)
- background blend with RR Lyrae variable star

  (background blends will be further checked with deep imaging)

What it is probably not:

- hierarchical triple containing accretion disk

  (no out-of-eclipse variability)

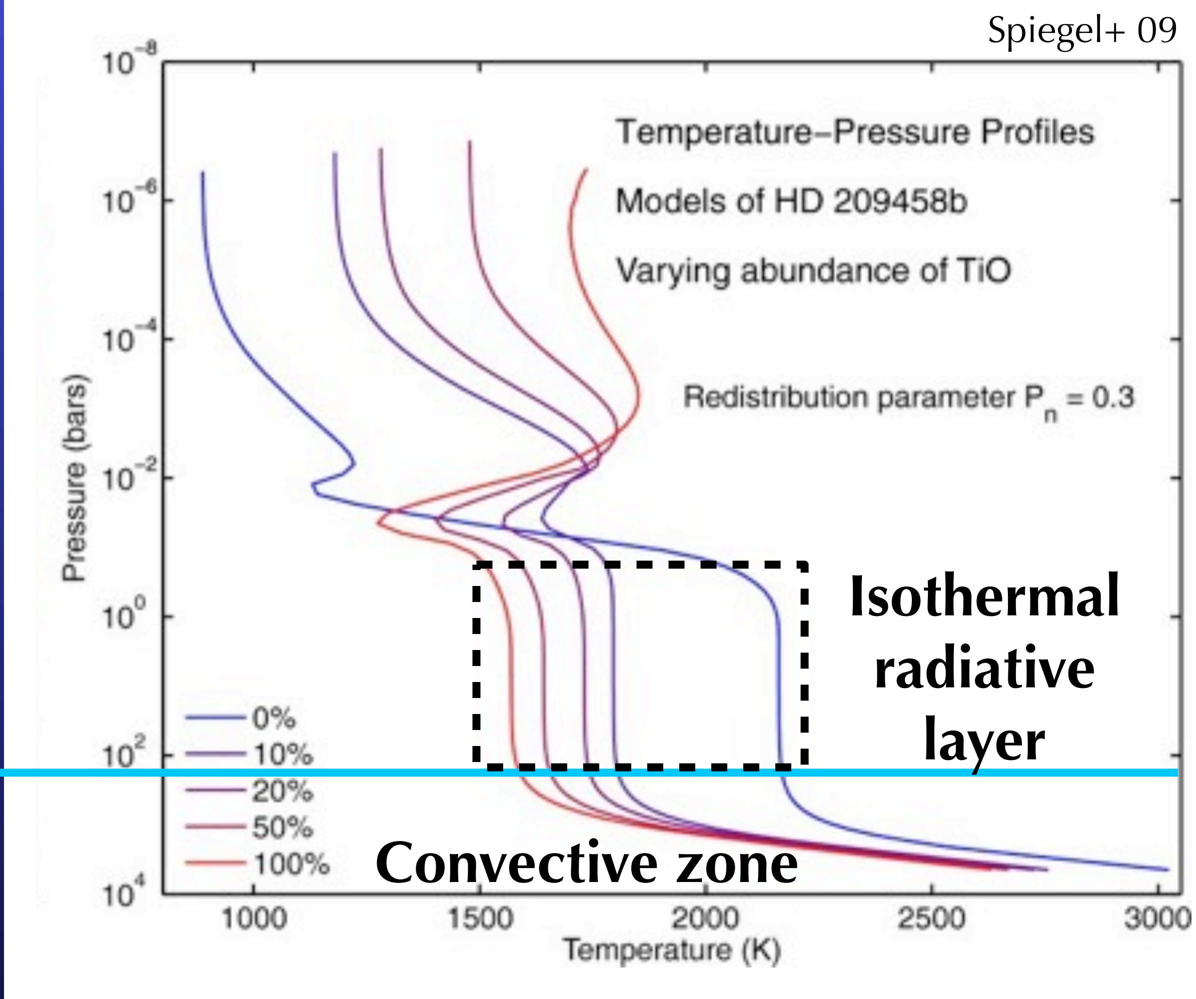


P_{orb} = 15.7 hr

How much extra power and where?

Where : convective interior

Radiative-convective (RC) boundary



Isothermal radiative layer

Convective zone

$$\frac{L_*}{4\pi a^2} \sim \sigma T_{\rm eq}^4$$

How much :

$$F_{\rm rad}\big|_{\rm RC} \sim \frac{\sigma T_{\rm eq}^4}{\tau_{\rm RC}} \qquad P \sim \frac{L_*}{4\pi a^2}\pi R^2 \times \tau_{\rm RC}^{-1}$$

The Kepler Orrery

credit: D. Fabrycky

t[BJD]−2454900 = 65.0