Planet Formation and Evolution

Eve J. Lee
(UC San Diego)

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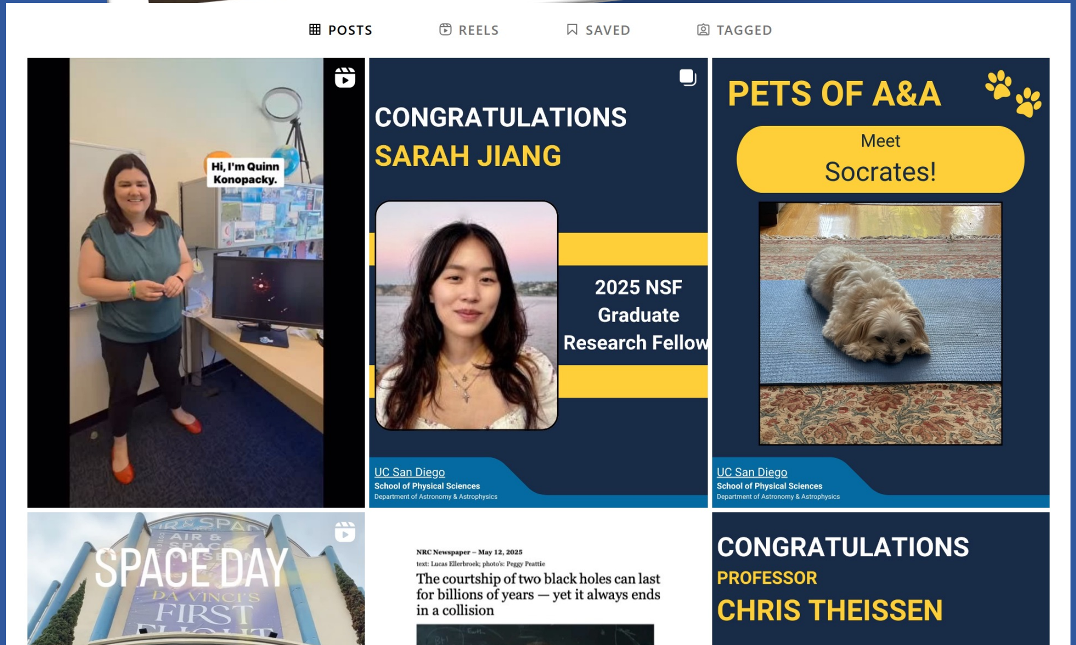
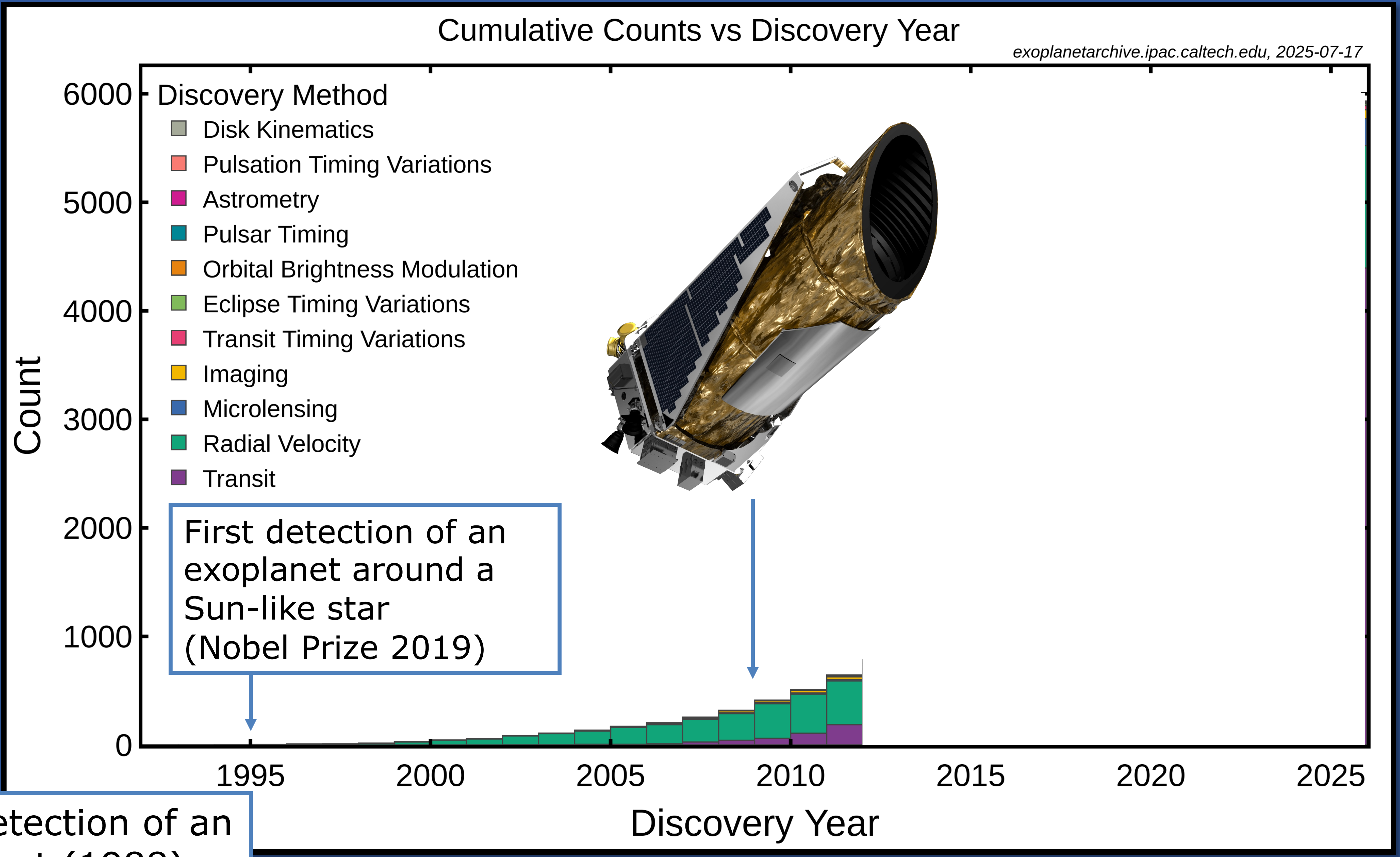
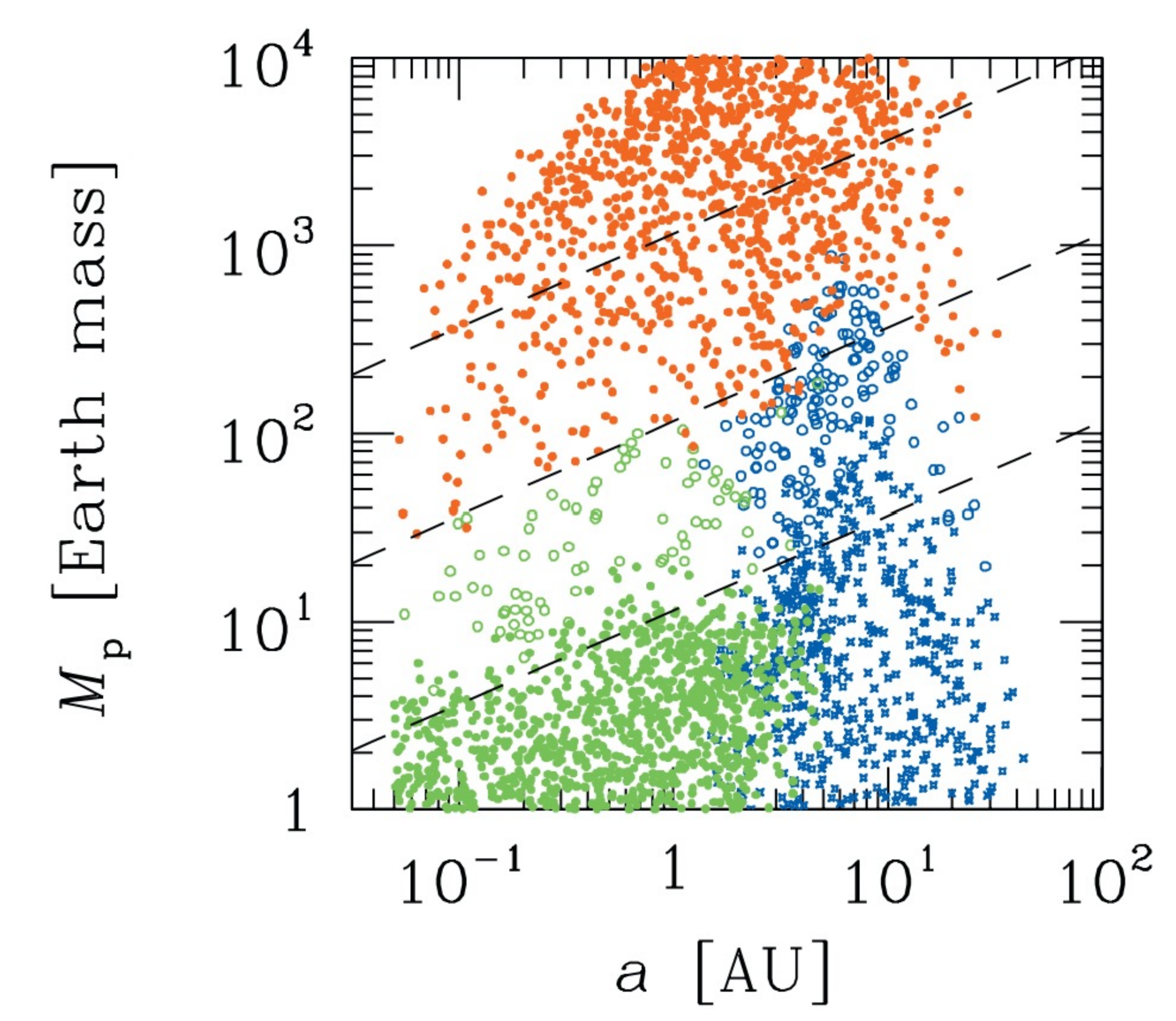




First detection of an exoplanet (1988)

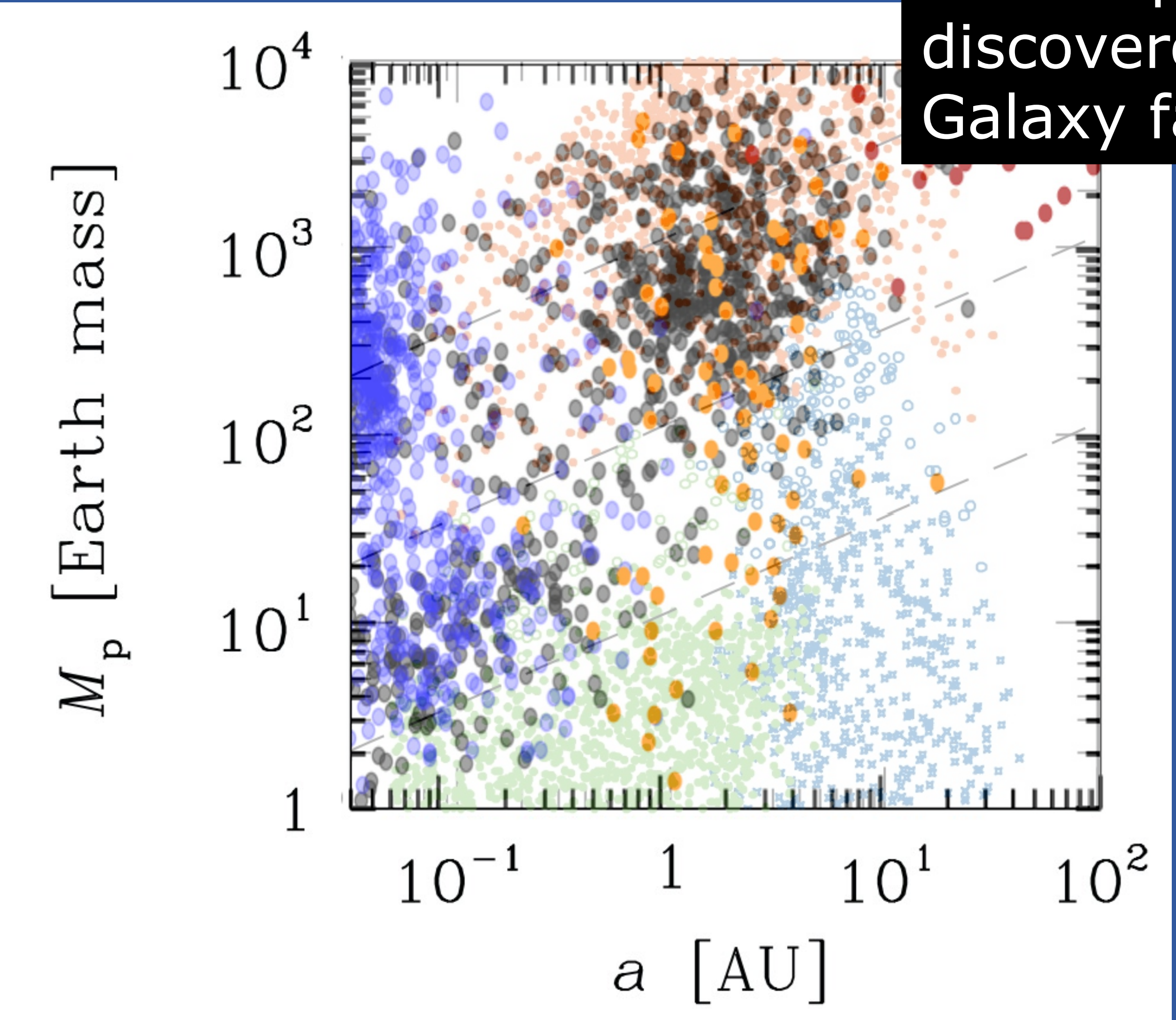
Pre-Kepler, theorists thought we should see rocky planets and gas giants and very few in between



Ida & Lin (2004)

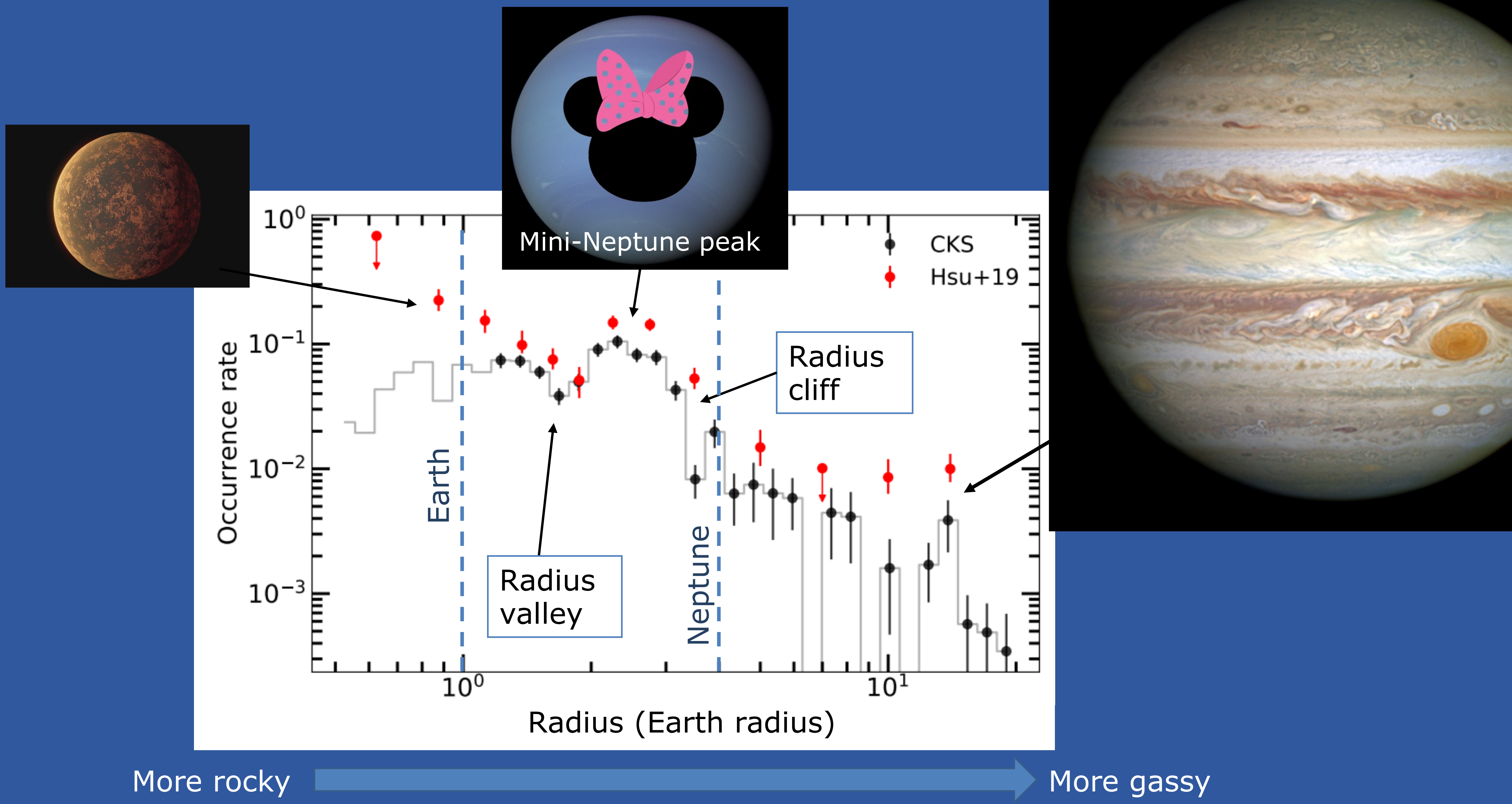
Pre-Kepler, theorists thought we should see rocky planets and gas giants and very few in between

Post-Kepler, most (of the discovered) planets in our Galaxy fall right in-between!

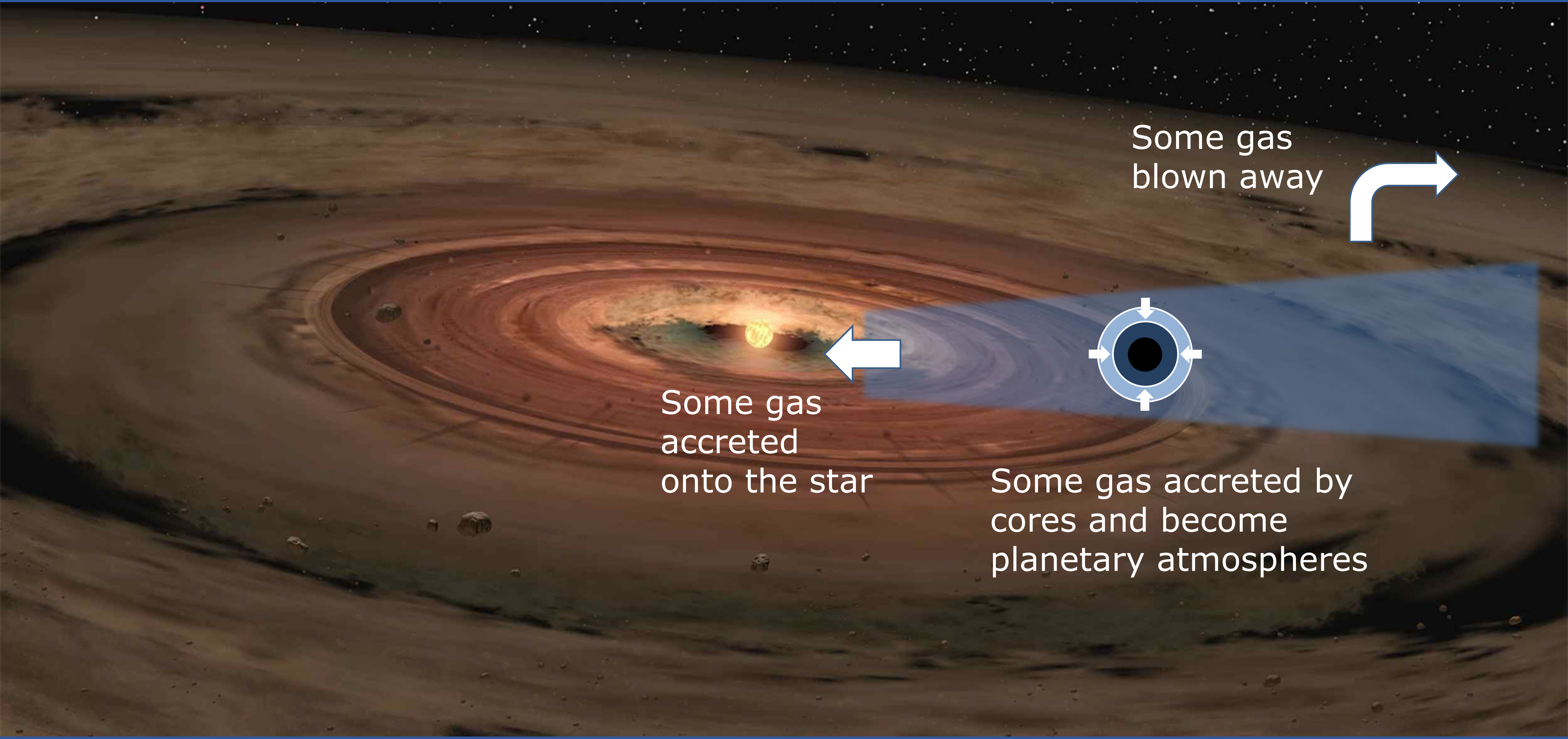


NASA Exoplanet Archive

Ida & Lin (2004)

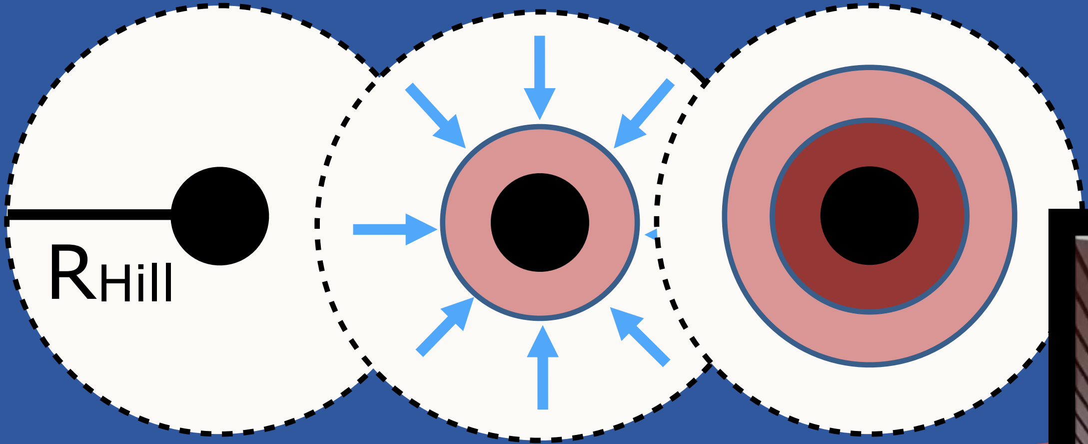


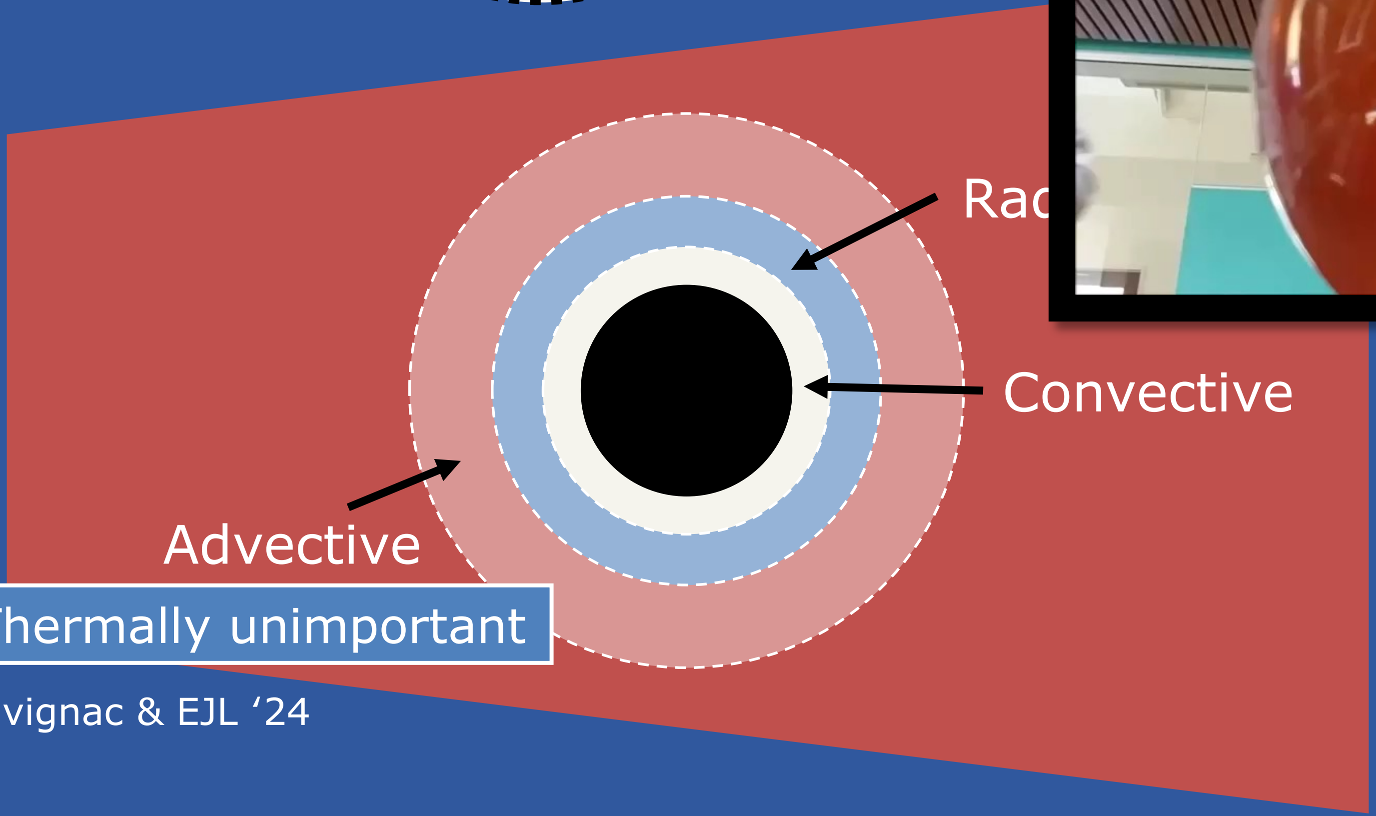
Mini-Neptune peak
CKS
Hsu+19
Radius cliff
Radius valley
Earth
Neptune
Occurrence rate
Radius (Earth radius)
More rocky
More gassy



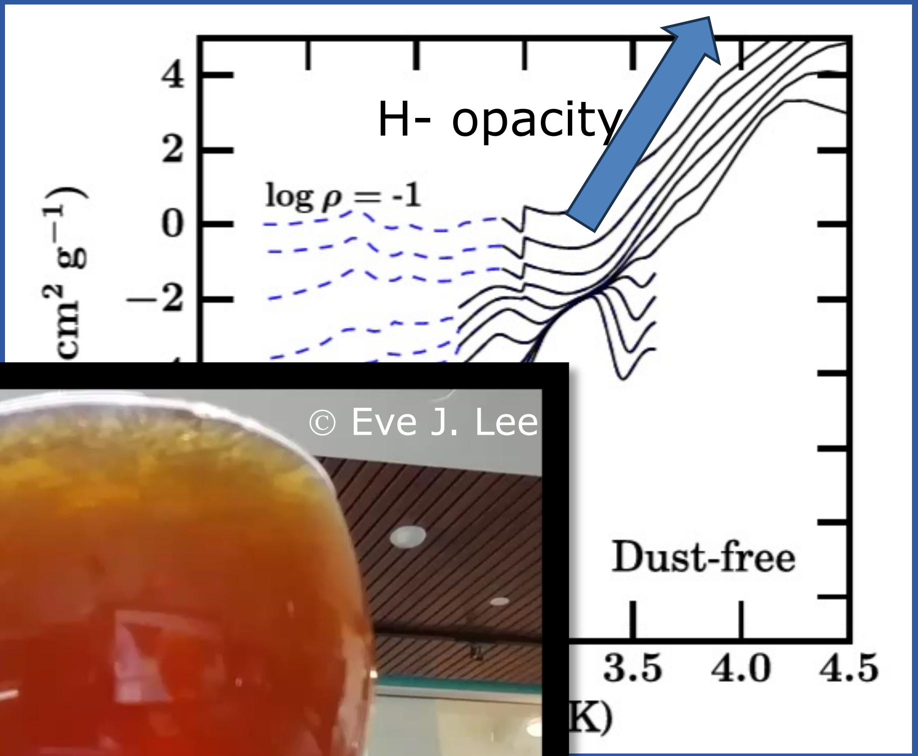
NASA/JPL-Caltech/T. Pyle (SSC)

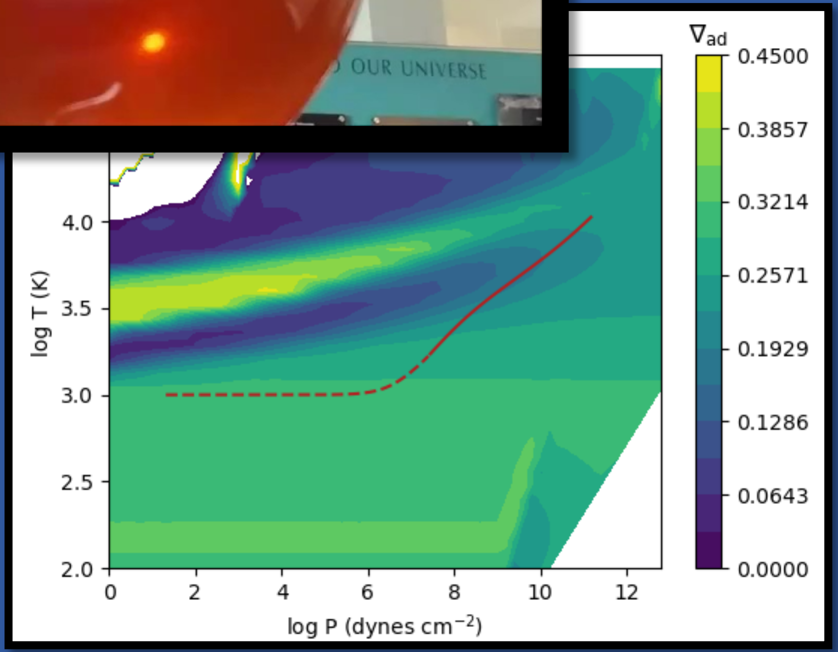
Physics of gas accretion





Savignac & EJL '24





EJL & Chiang '15; opacity from J. Ferguson

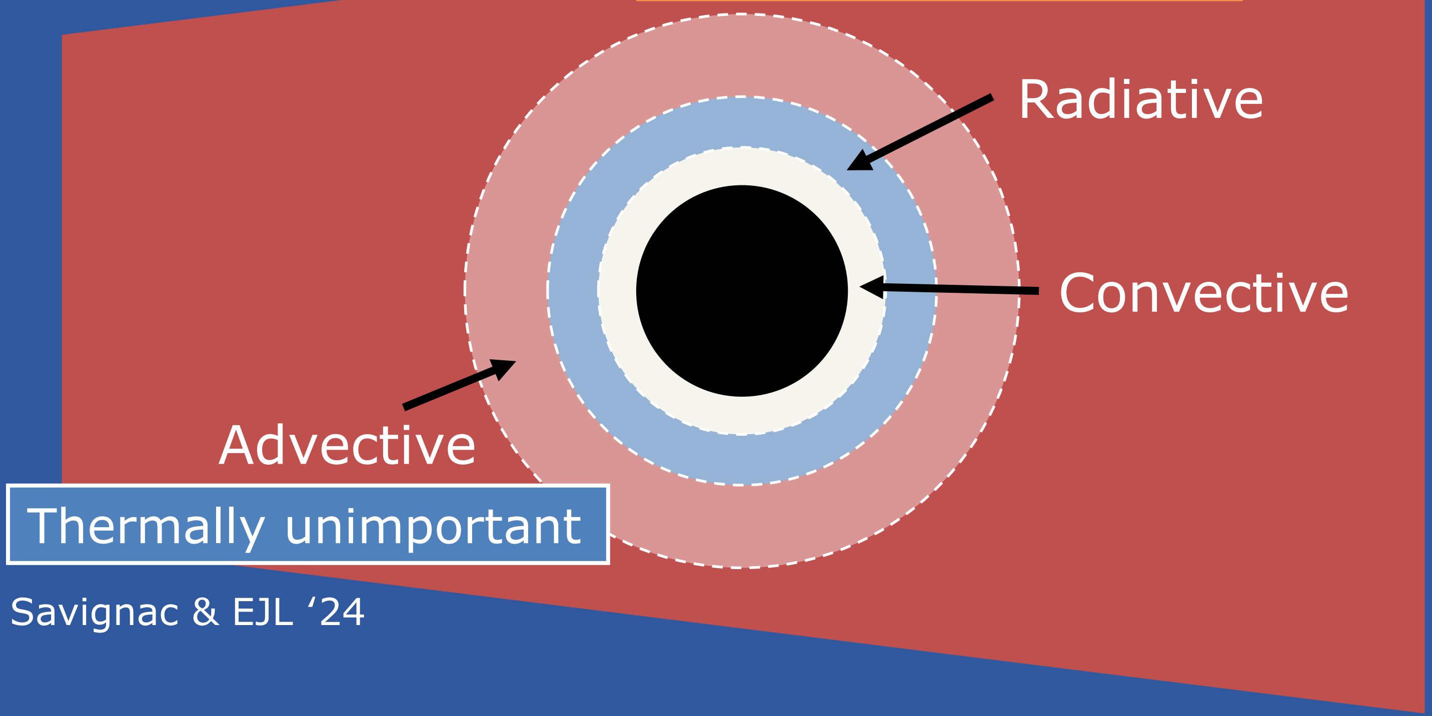
Mass inwardly concentrated

Physics of gas accretion

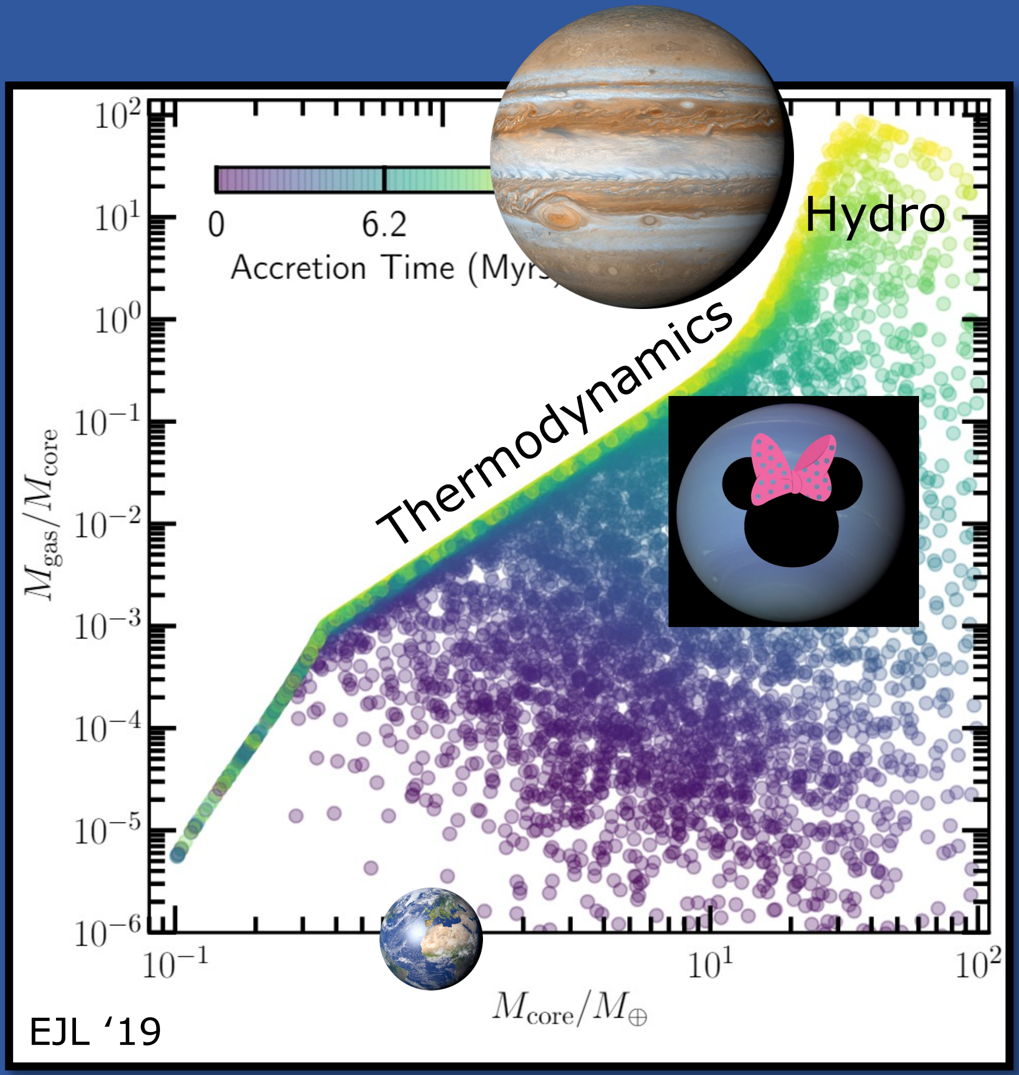
EJL & Chiang ‘15

$$\frac{M_{gas}}{M_{core}} \sim 0.06 \left(\frac{t}{1\ Myr}\right)^{0.4} \left(\frac{M_{core}}{5M_{\oplus}}\right)^{1.7} \left(\frac{0.02}{Z}\right)^{0.4}$$

Strong dependence from central mass concentration



Savignac & EJL ‘24



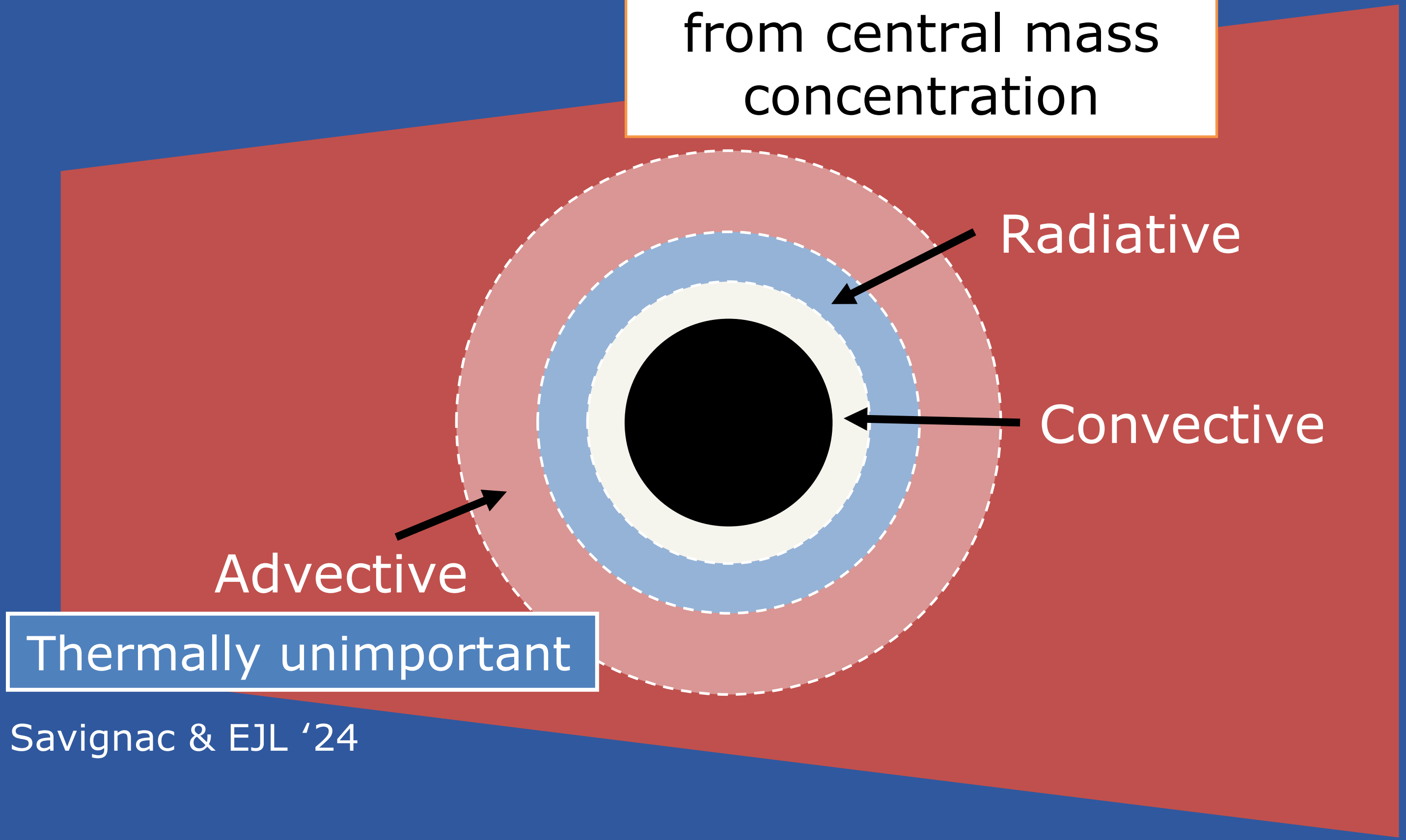
EJL ‘19

Physics of gas accretion

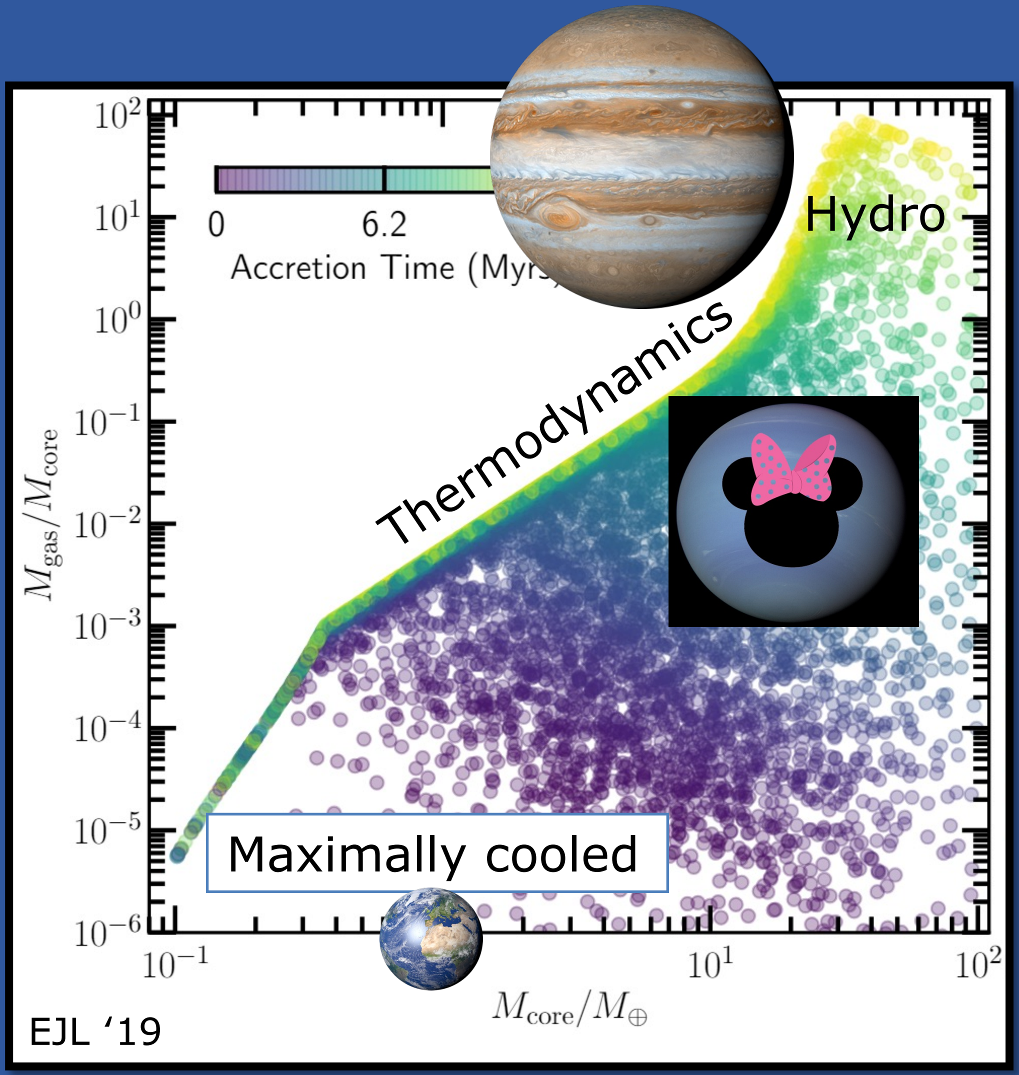
EJL & Chiang '15

$$\frac{M_{gas}}{M_{core}} \sim 0.06 \left(\frac{t}{1\,Myr}\right)^{0.4} \left(\frac{M_{core}}{5M_\oplus}\right)^{1.7} \left(\frac{0.02}{Z}\right)^{0.4}$$

Strong dependence from central mass concentration

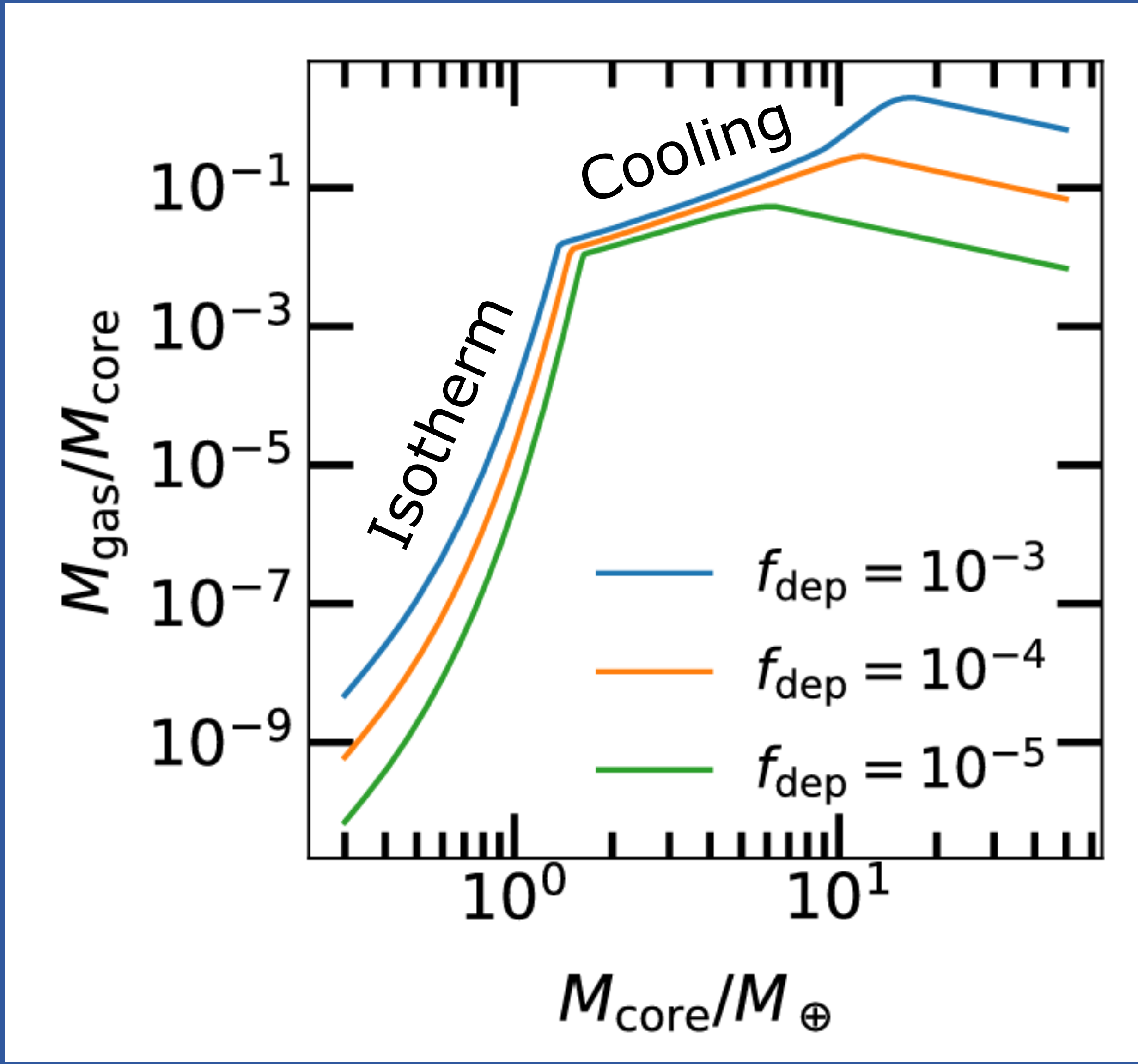


Savignac & EJL '24



$$M_{iso} = 4\pi\rho_{disk}\int_{R_{core}}^{R_{out}} r^2\,\mathrm{Exp}\left[\frac{GM_{core}}{c_{s,disk}^2}\left(\frac{1}{r}-\frac{1}{R_{out}}\right)\right]dr,$$

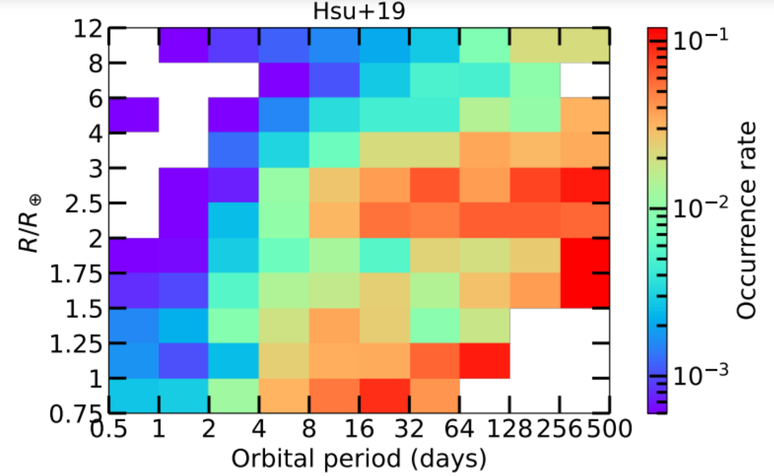
EJL & Connors '21



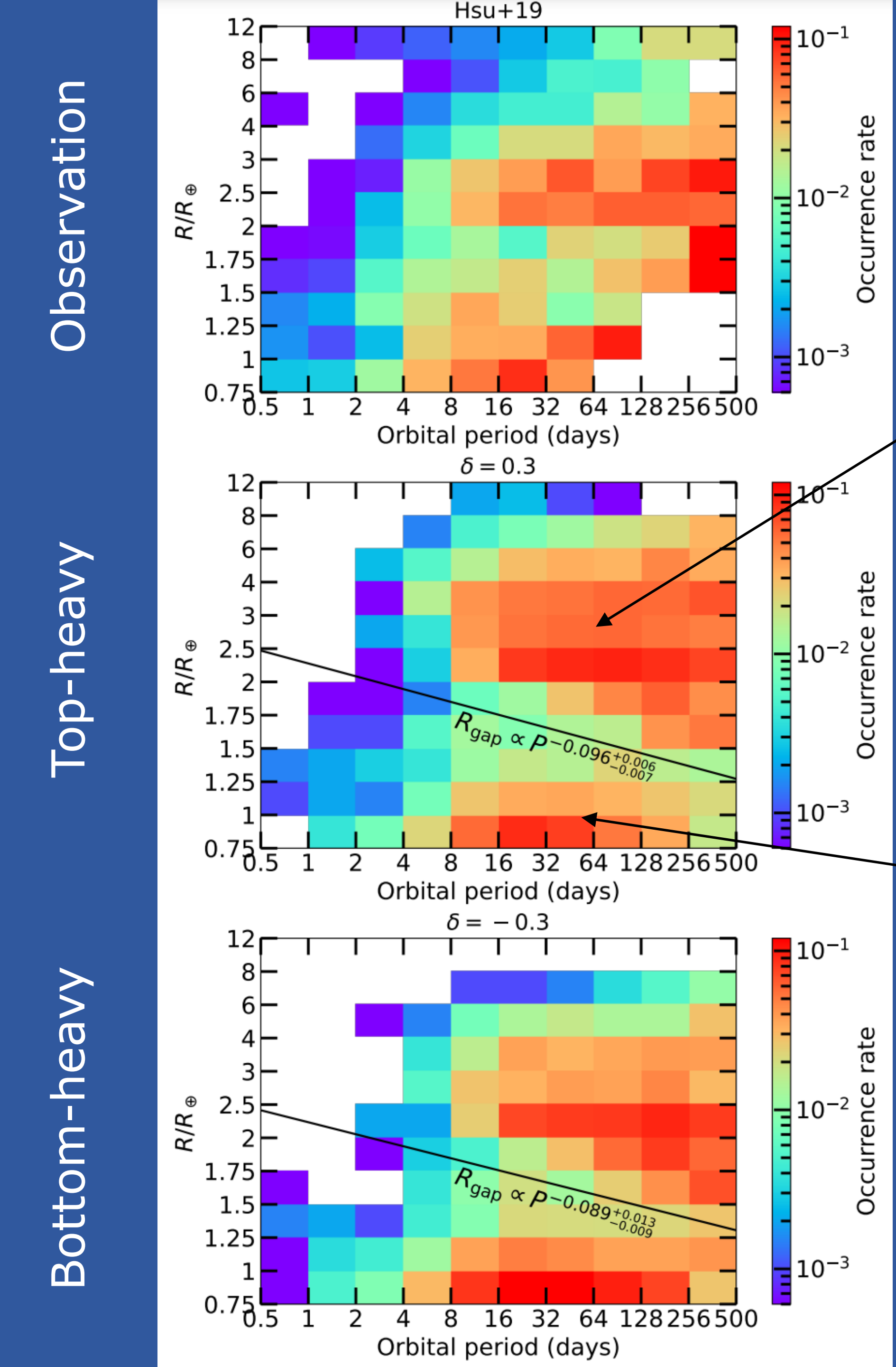
EJL & Connors '21
EJL, Karalis, & Thorngren '22

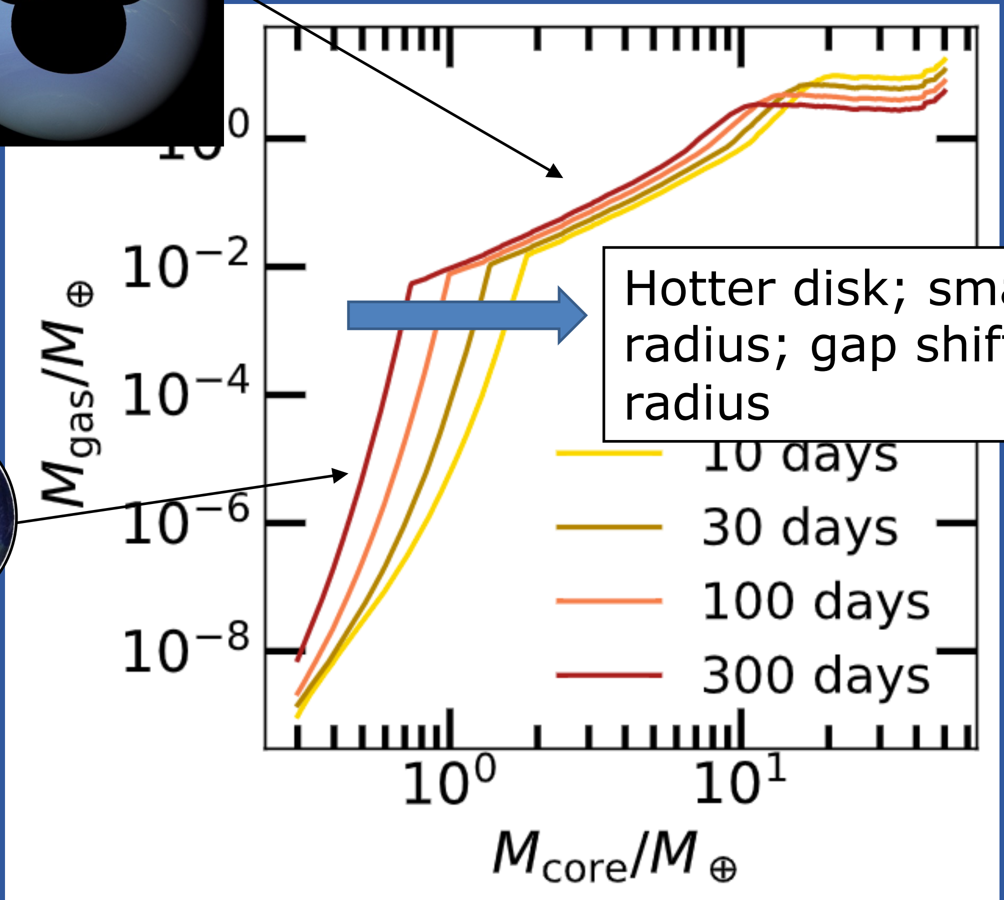
Formation alone can carve out the radius gap

Observation



Formation alone can carve out the radius gap

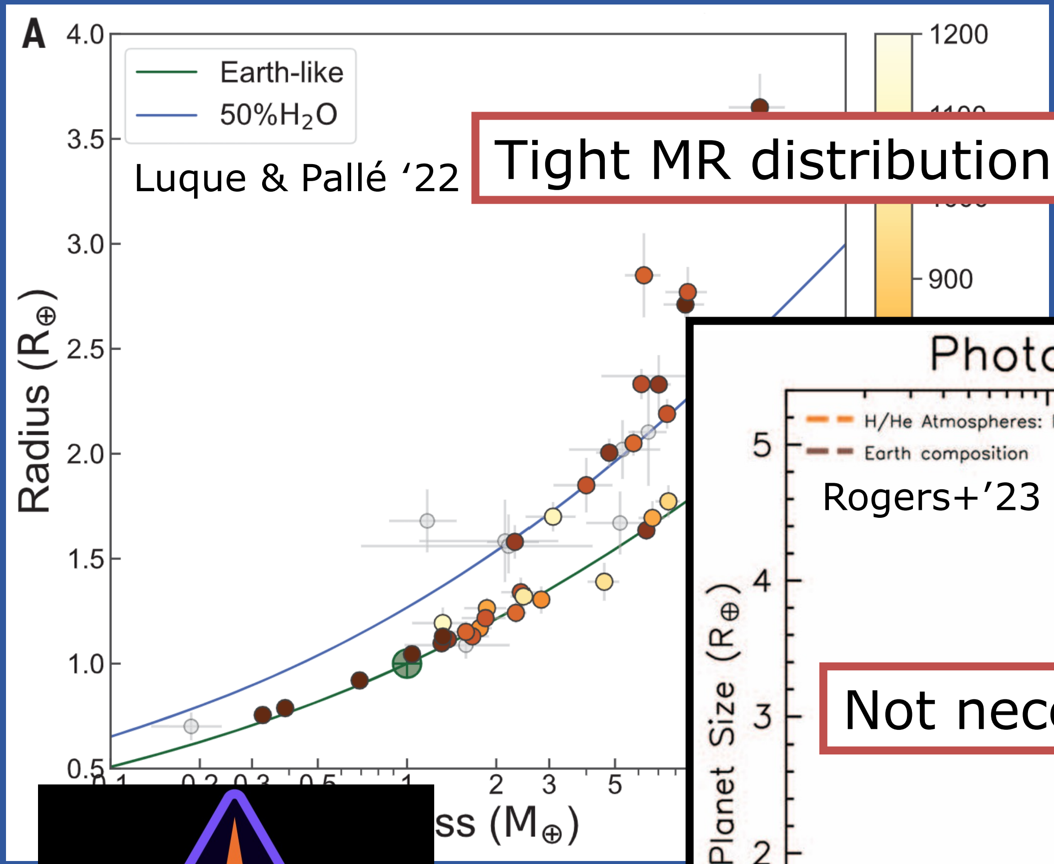




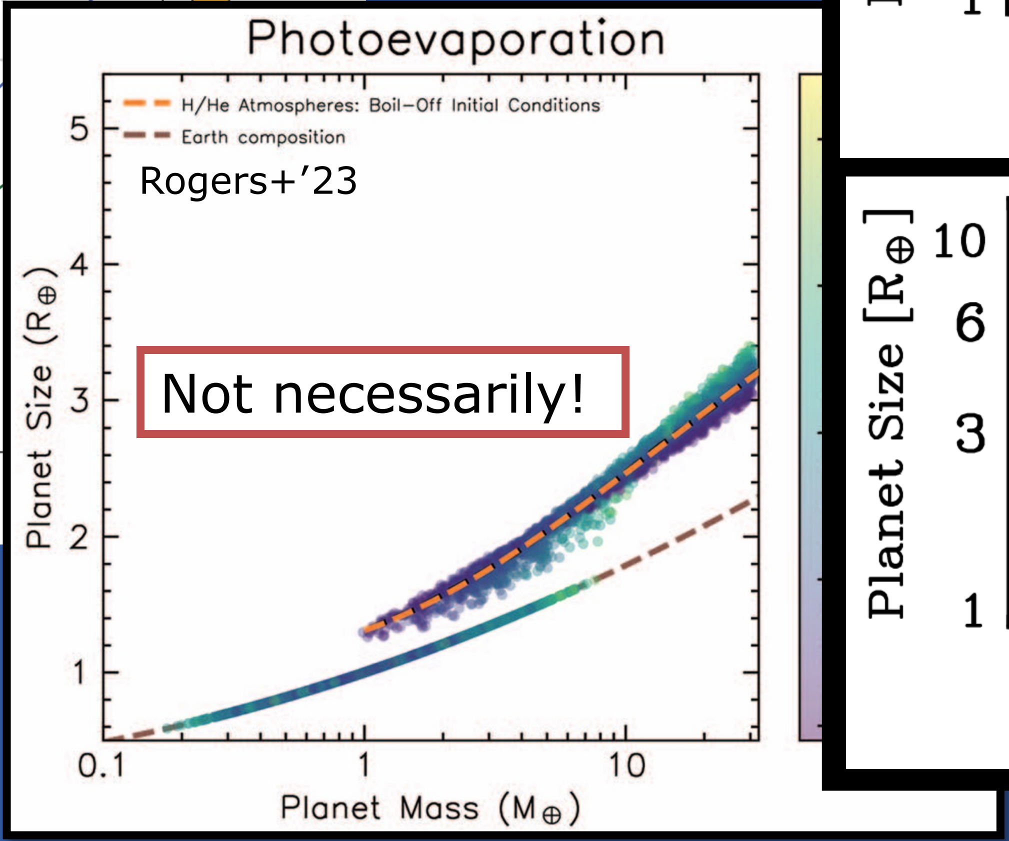
Hotter disk; smaller Bondi radius; gap shifts to larger radius

EJL, Karalis & Thorngren (2022)

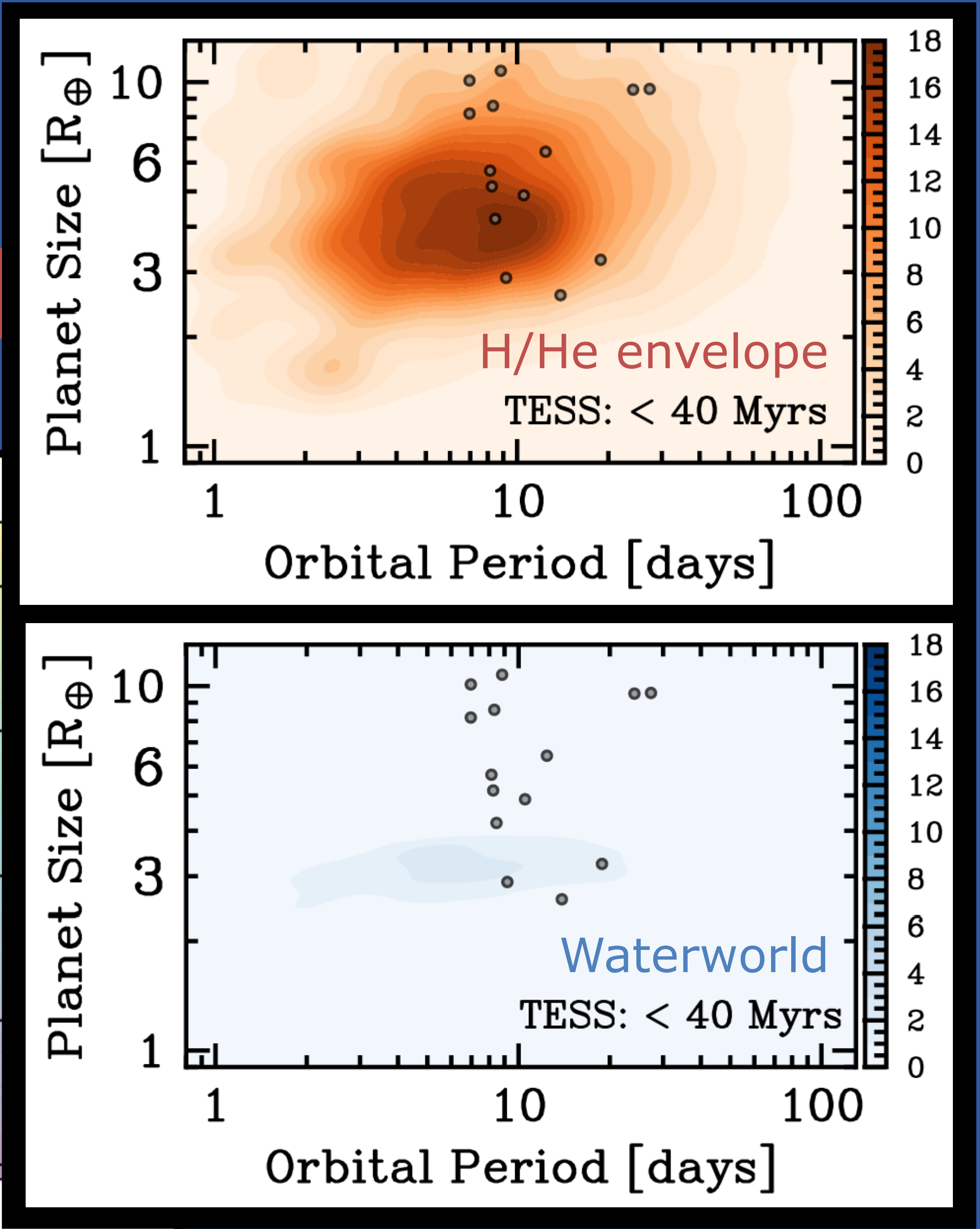
H/He envelope vs. waterworld



Tight MR distribution = waterworld?



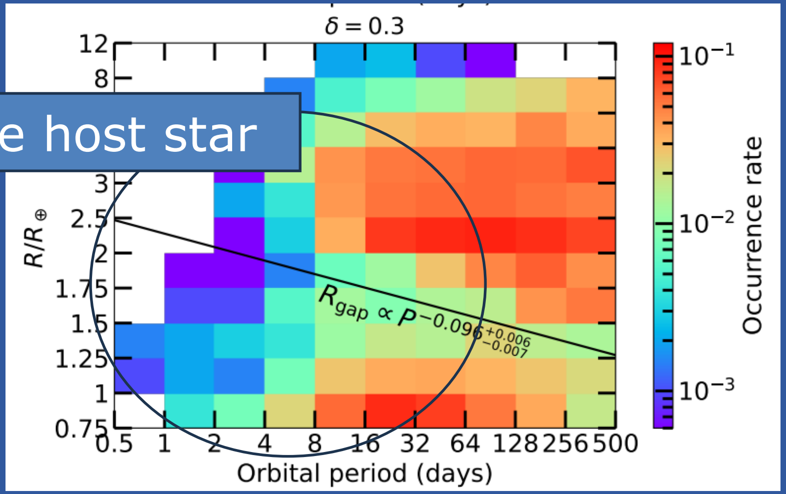
Not necessarily!



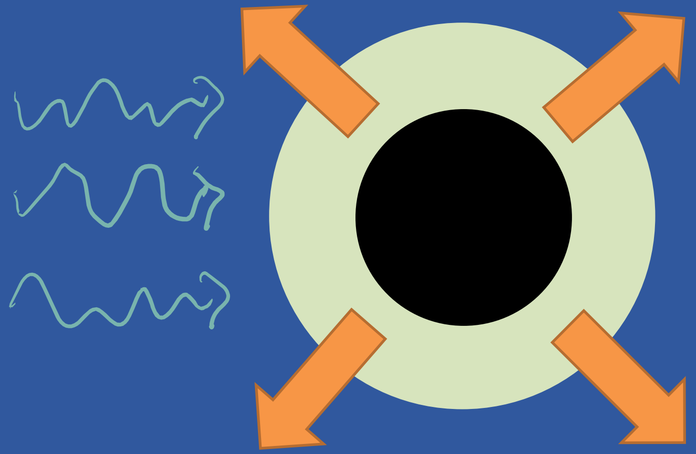
Rogers '25

PI: M. McGregor

Post-formation evolution

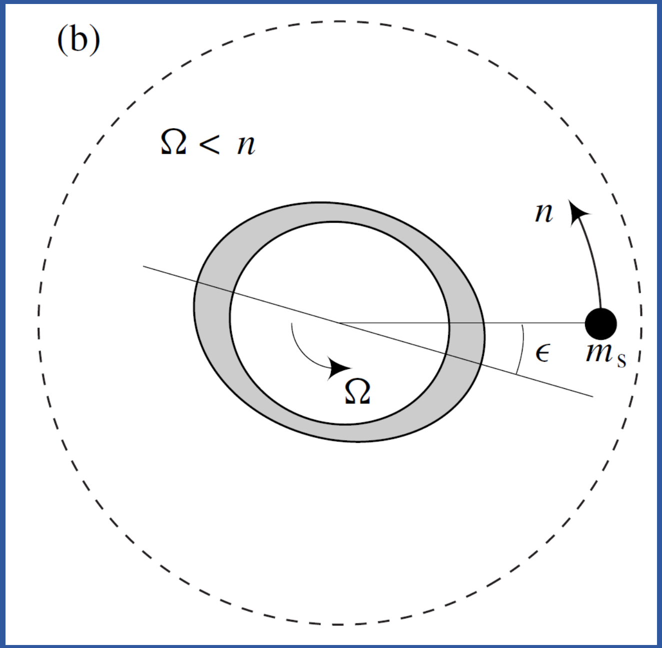


Affected by the host star



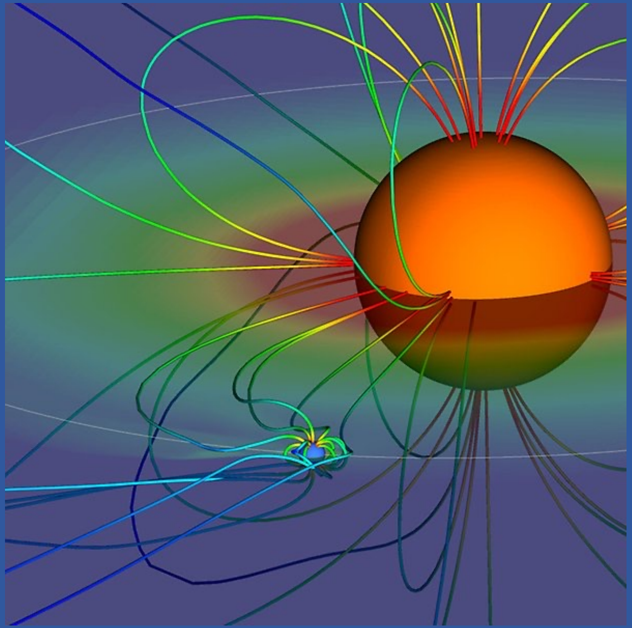
Photoevaporative mass loss

<30-50 days



Tidal orbital decay

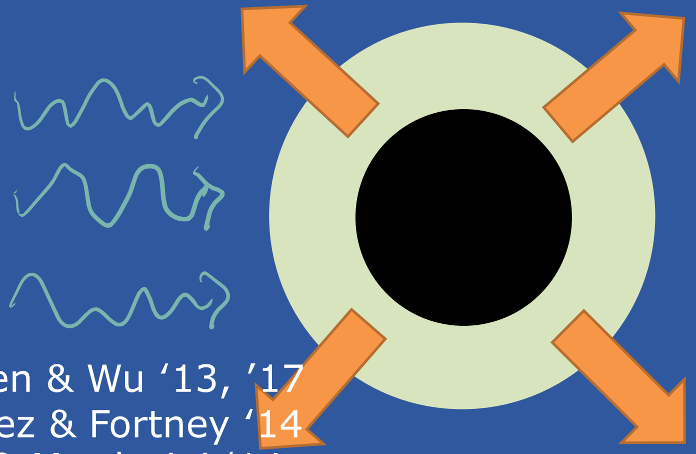
<1-3 days



Magnetic decay & heating

<1 days

Post-formation evolution

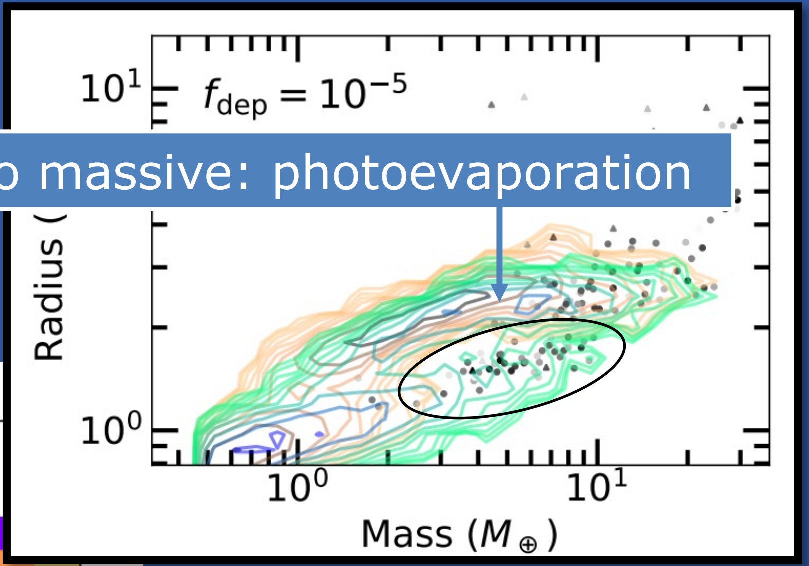


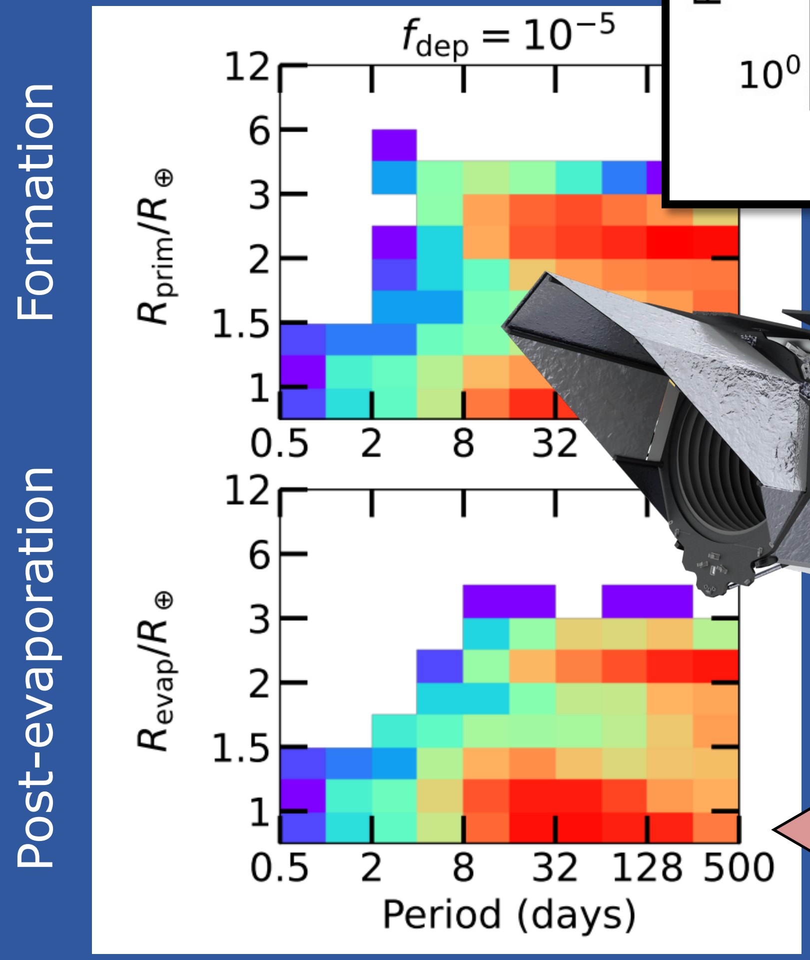
Owen & Wu ‘13, ’17
Lopez & Fortney ‘14
Jin & Mordasini ‘14

Photoevaporative mass loss

<30-50 days

Short-period super-Earths too massive: photoevaporation

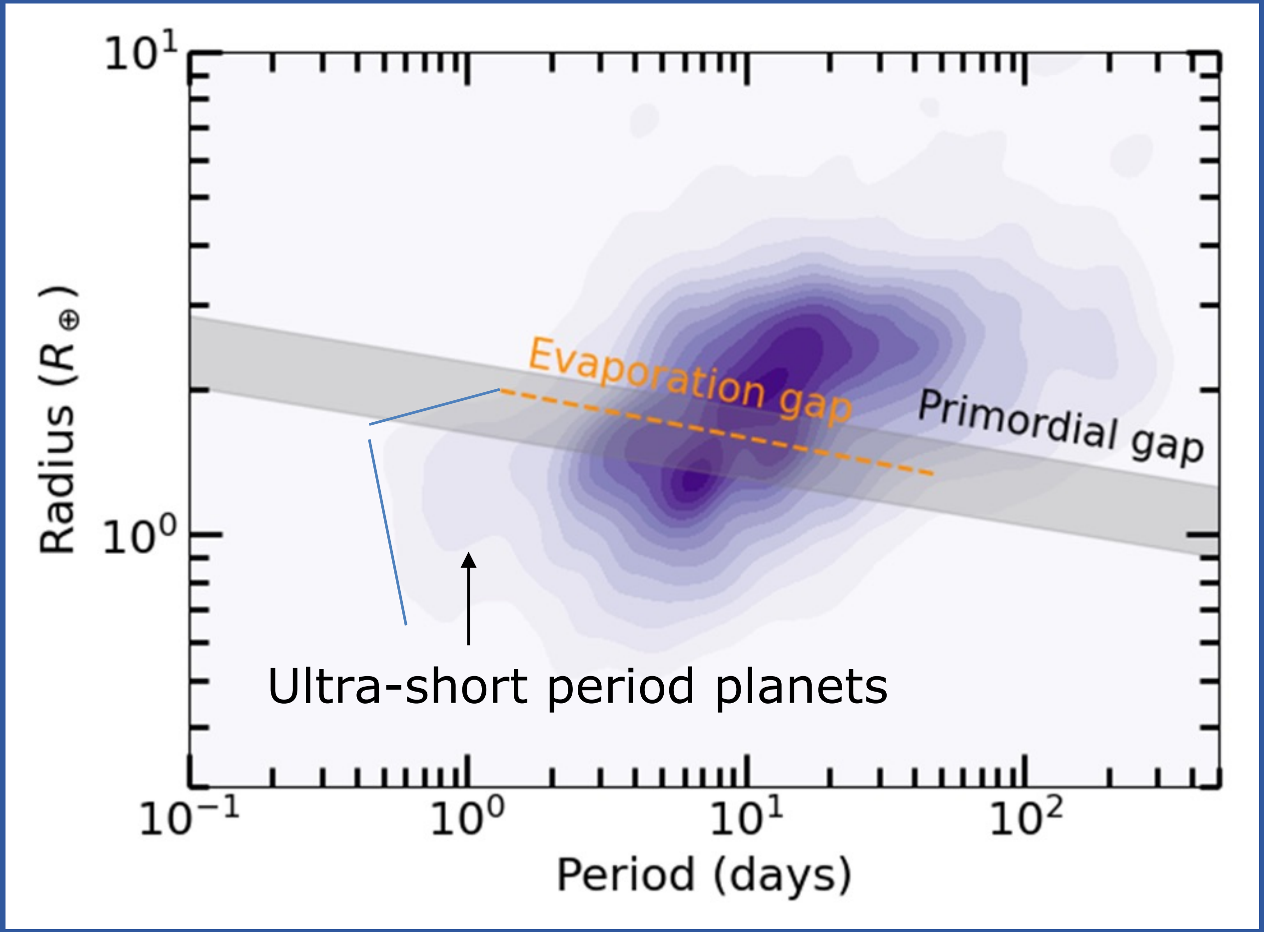




Long-period rocky planets: primordial

EJL, Karalis & Thorngren ‘22

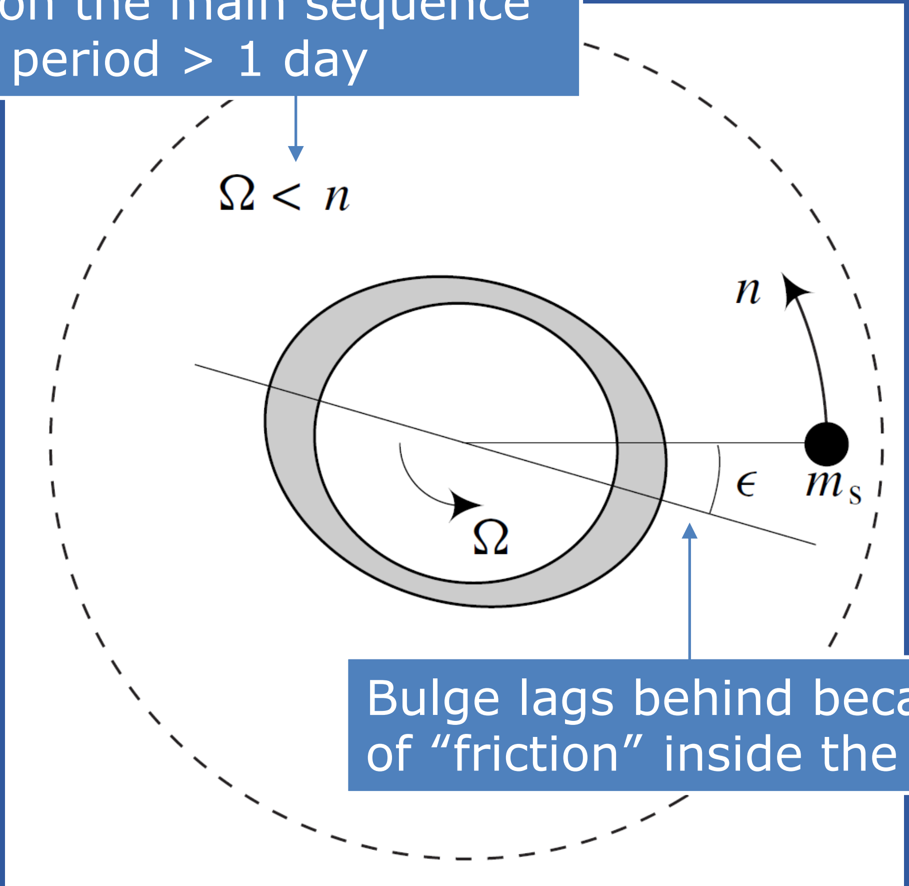
Short-period small planet population



Raw data from NASA Exoplanet Archive

Short-period physics: tides

Star is on the main sequence so spin period > 1 day



Bulge lags behind because of “friction” inside the star

Murray & Dermott

For stellar spin and orbital motion to become synchronous:

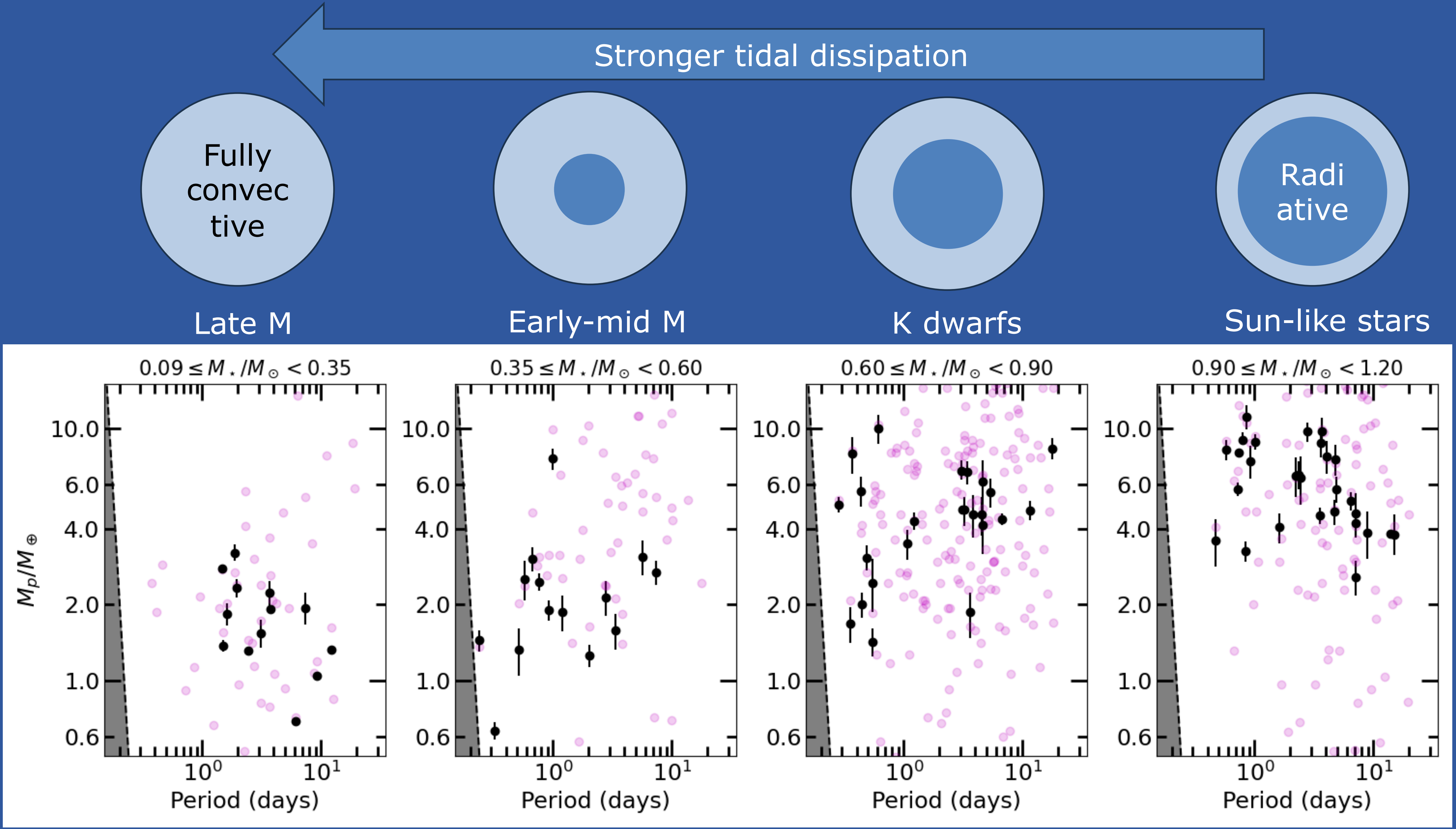
$$L_{spin} < L_{orb}/3$$

For a $5M_\oplus$ planet orbiting a solar mass star:

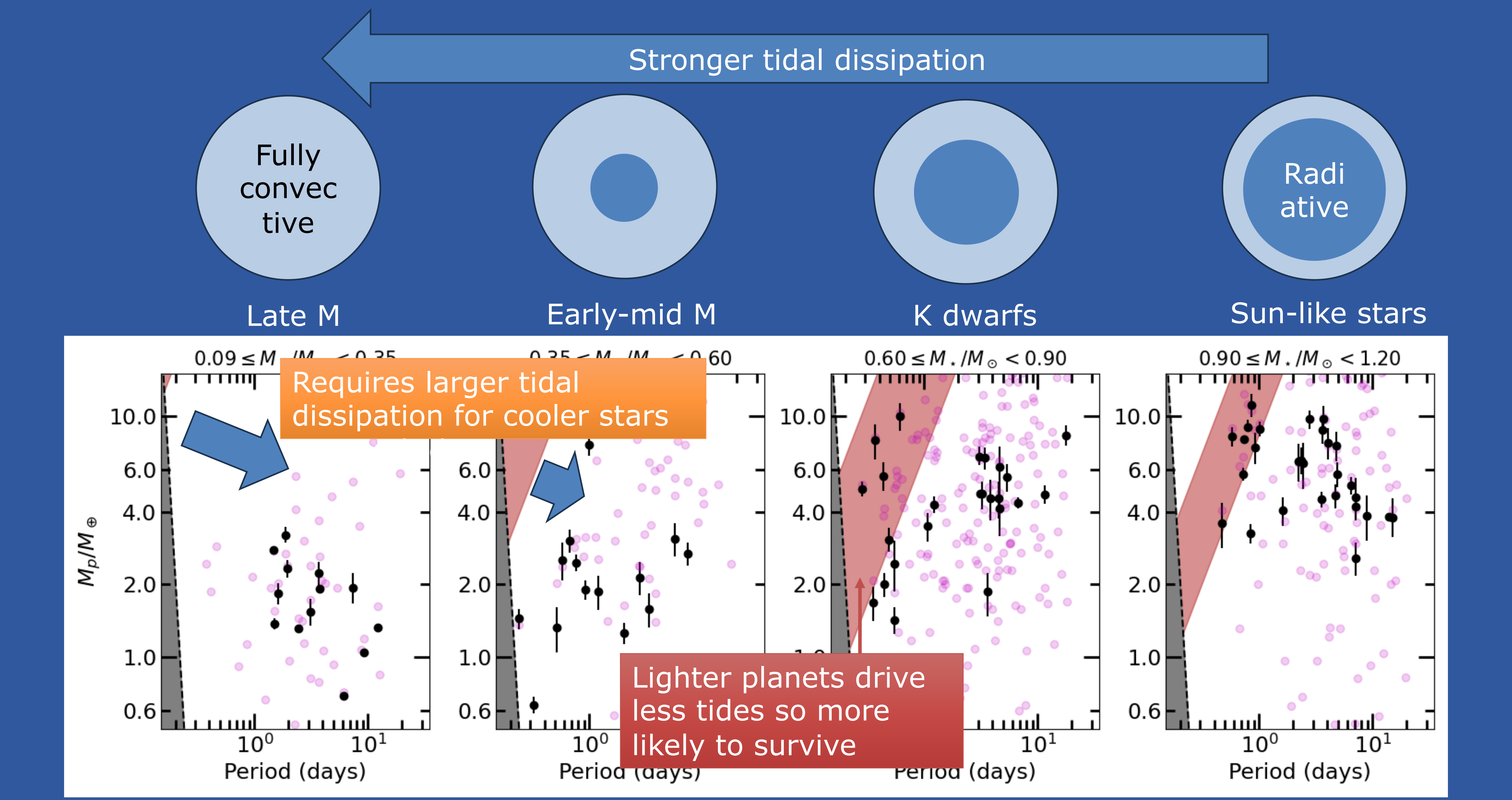
$$L_{spin} \sim 100 L_{orb}$$

$$\dot{a} \propto -a^{-11/2} \frac{M_p}{M_*^{1/2}} \frac{R_*^5}{Q'_*}$$

Tidal quality factor: hiding all the uncertain physics of dissipation



EJL & Owen '25 data from NASA Exoplanet Archive; <2 Rearth; precise mass measurement



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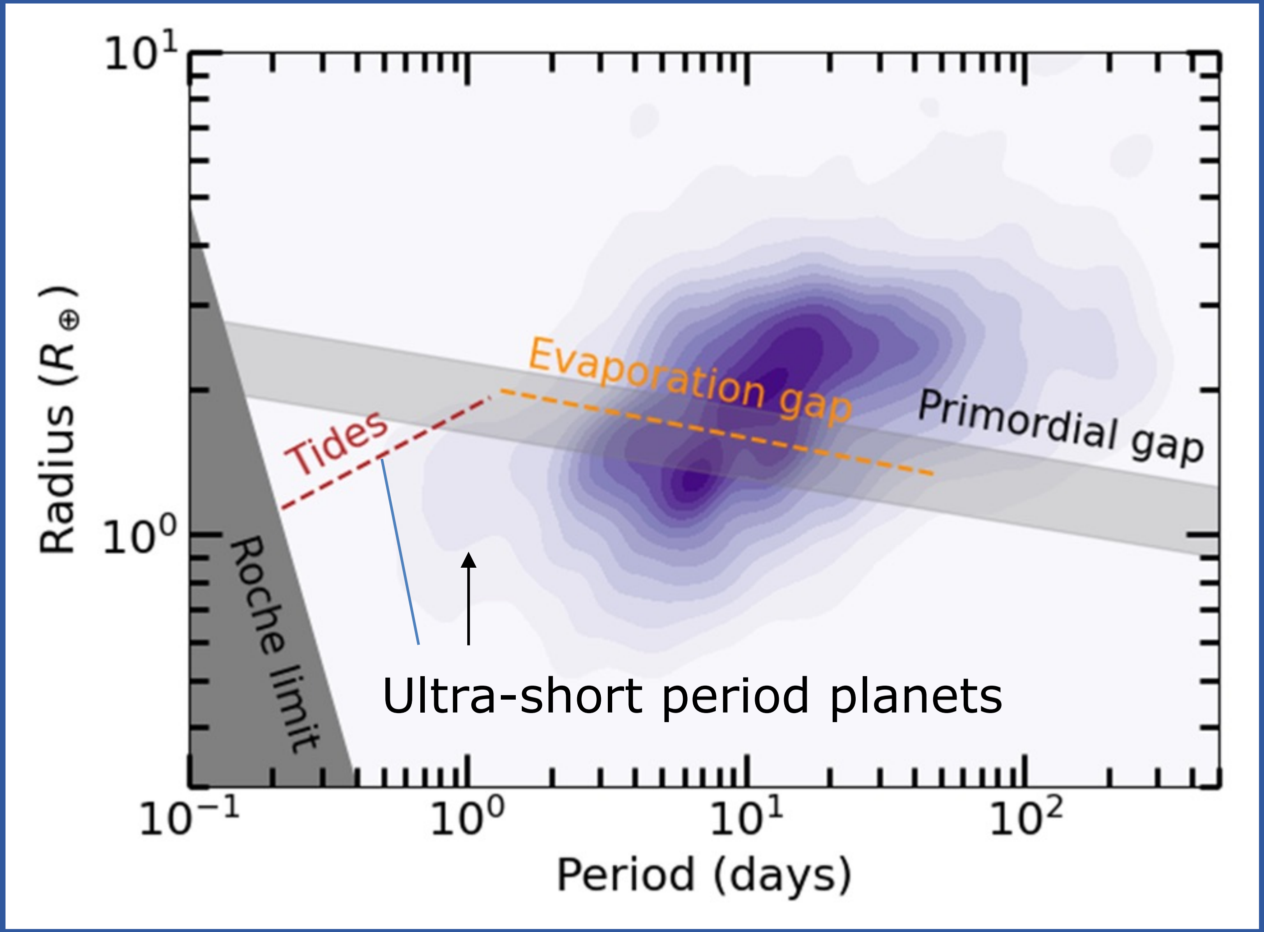
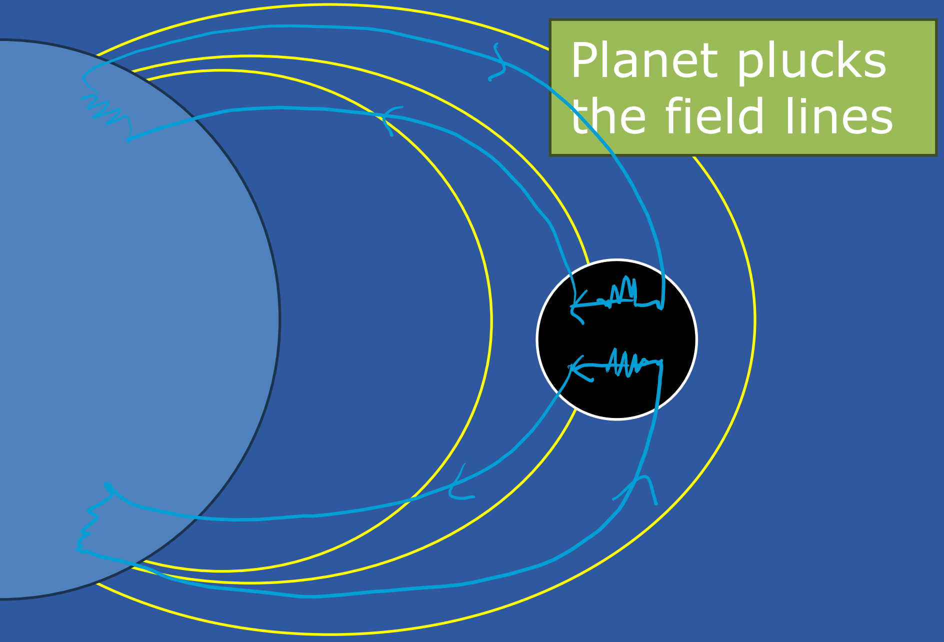


Raw data from NASA Exoplanet Archive

Short-period physics: electromagnetism



Alfven velocity > orbital velocity: causal connection and minimal twist in field

Planet is losing orbital angular momentum to stellar spin

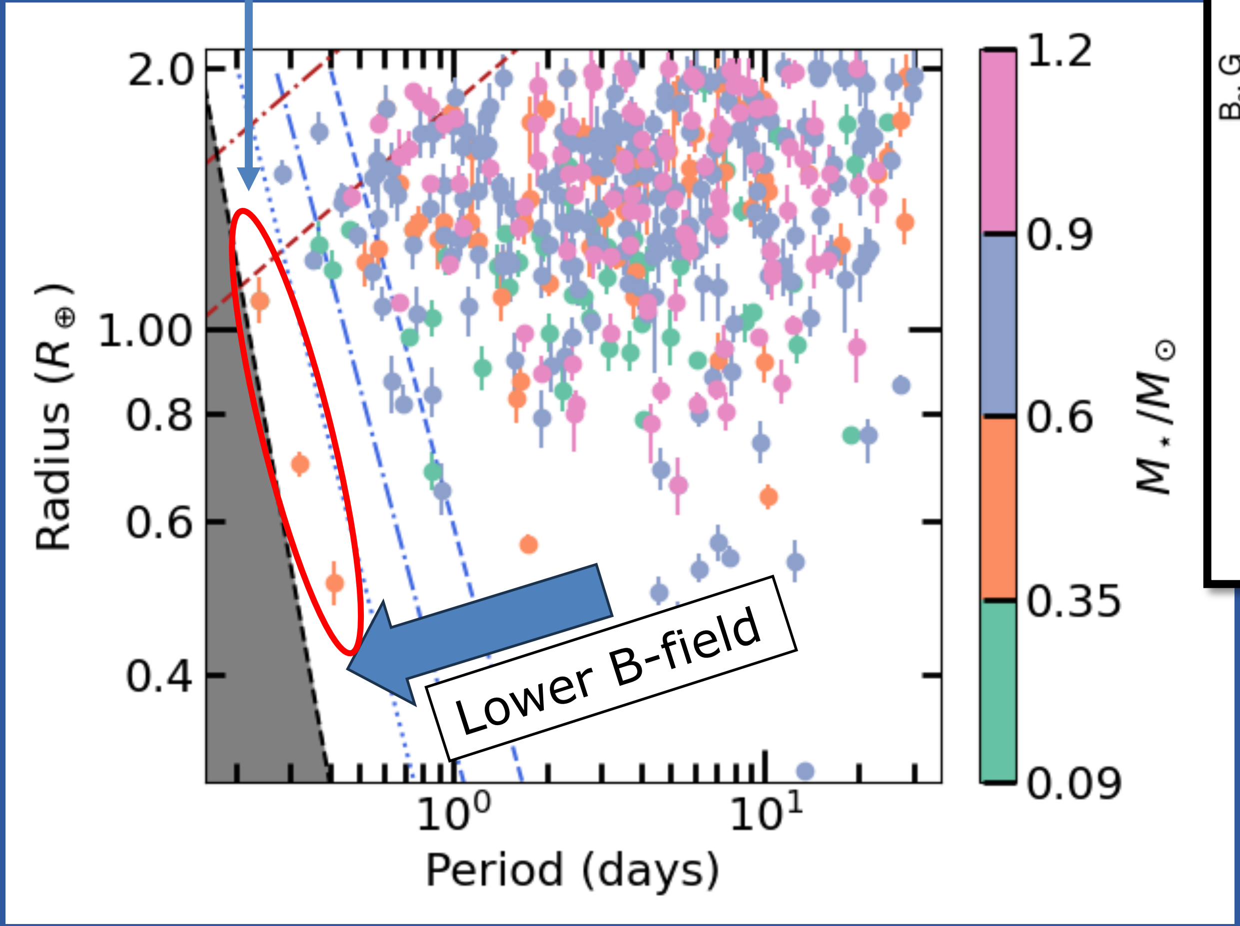
The entire system is losing energy through Joule heating

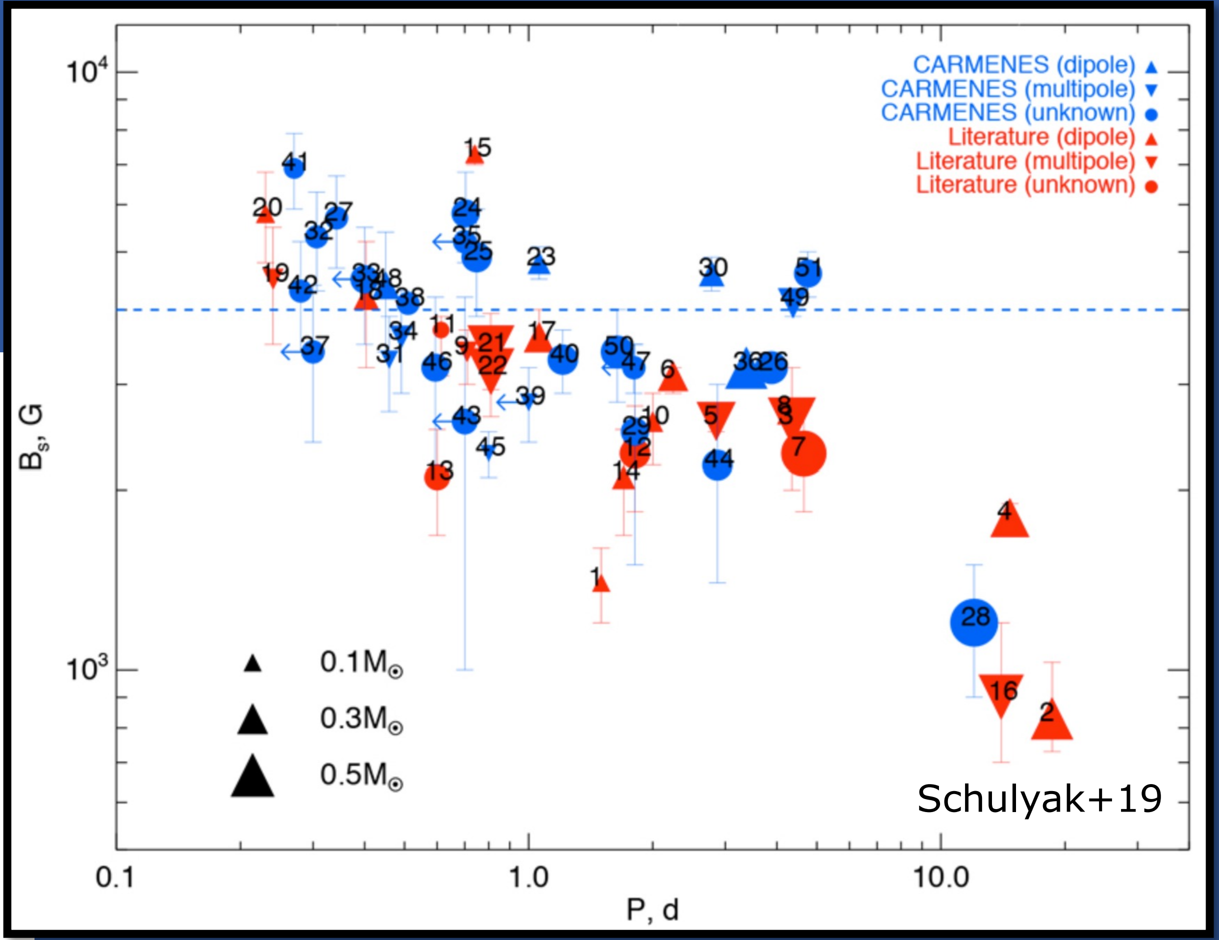
$$P = UI \qquad U \sim -E_{ind} R_p \sim \left(\frac{v_k}{c}\right) B R_p$$

$$\left.\begin{aligned} \nabla\times E &= -\frac{1}{c}\frac{\partial B}{\partial t} \\ \nabla\times B &= \frac{4\pi}{c} J \end{aligned}\right\} \quad I \sim \frac{c}{4\pi} R_p B \frac{v_k}{v_A}$$

$$P \sim \frac{32}{3\pi} \pi R_p^2 v_A \left(\frac{v_k}{v_A}\right)^2 \frac{B^2(a)}{8\pi} s$$

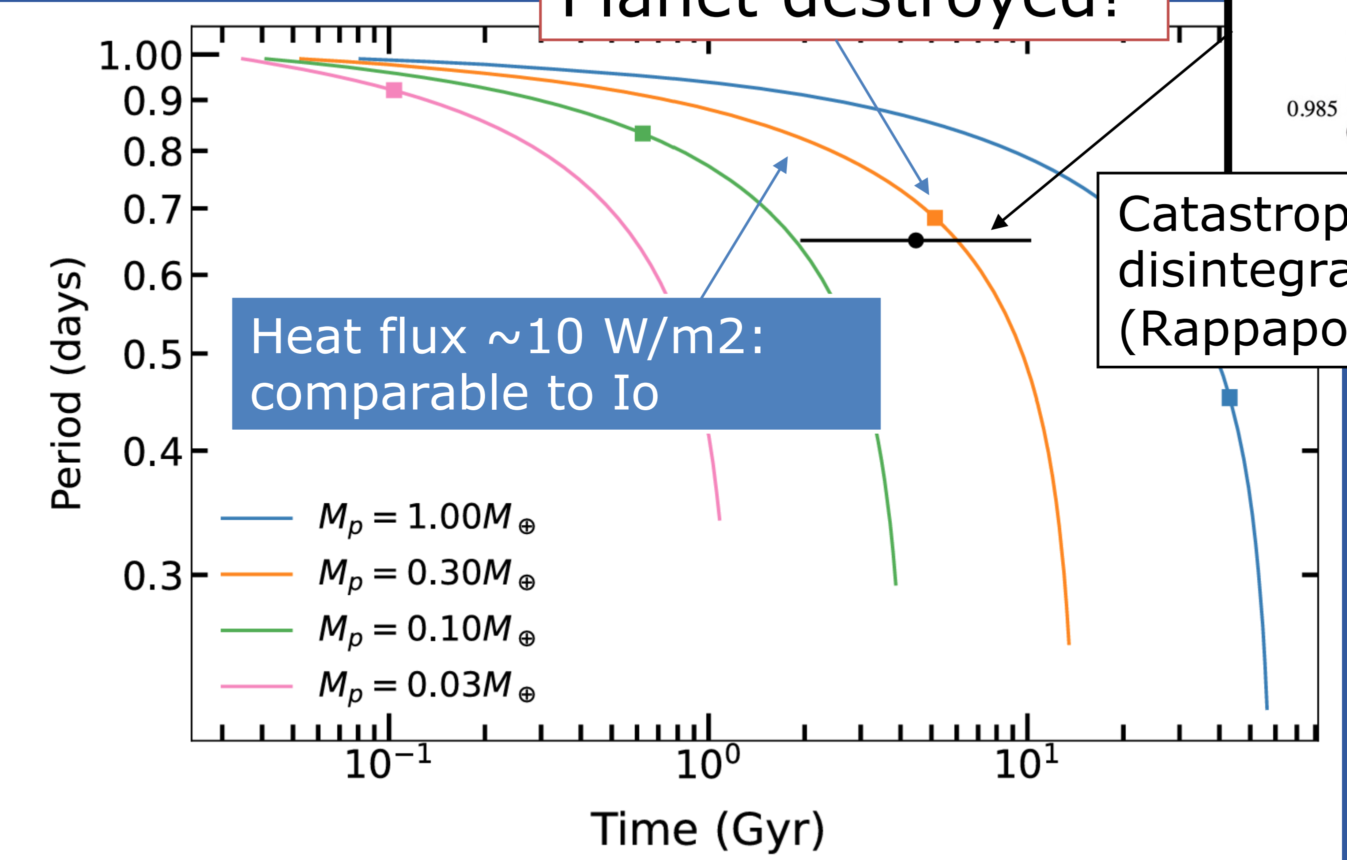
Slow rotators >~ 30-40 days

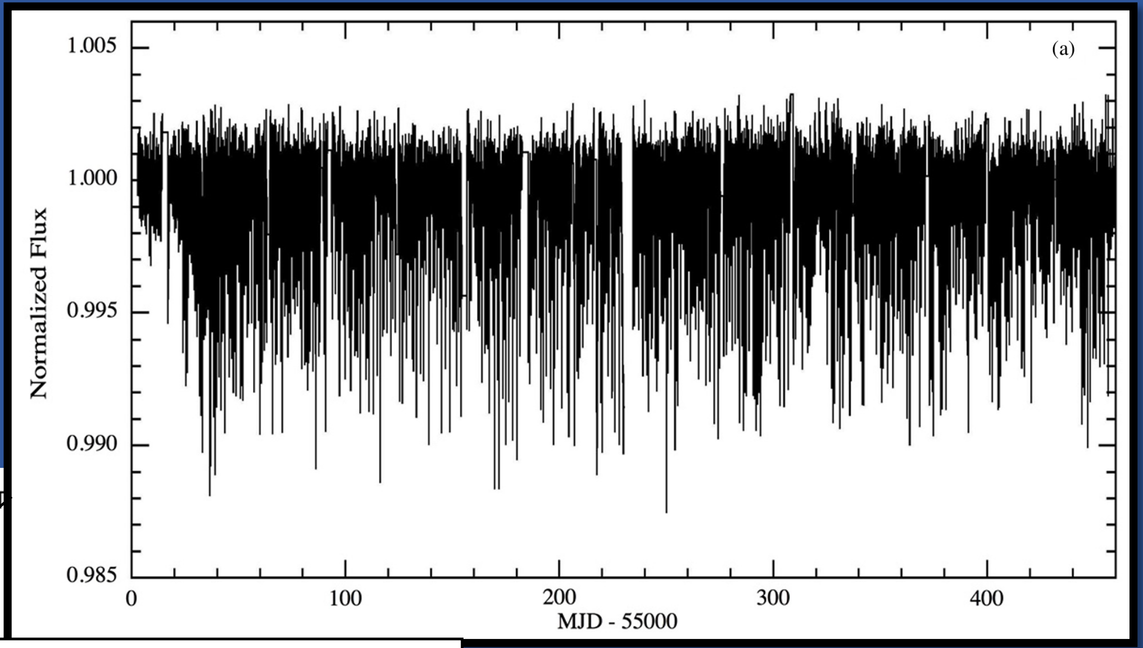


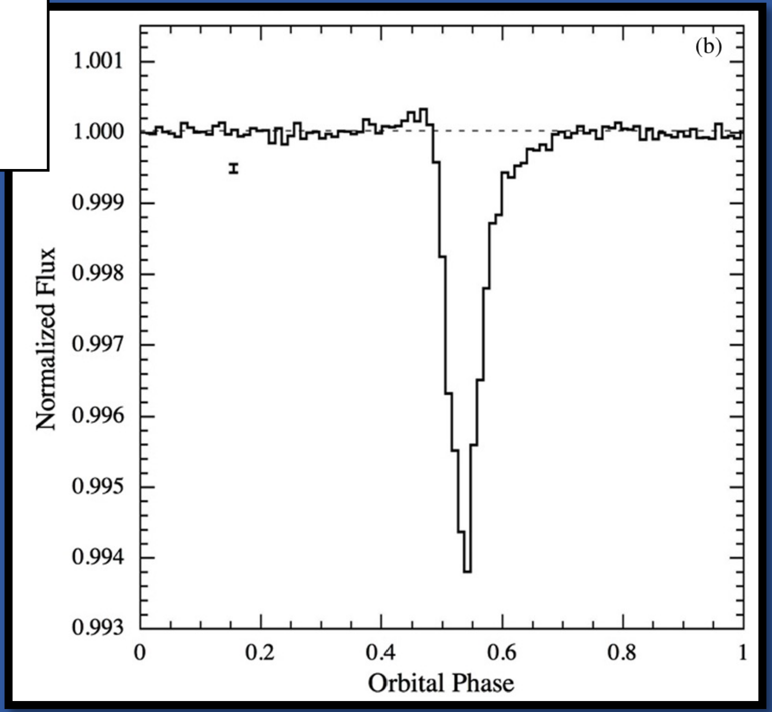


EJL & Owen ‘25

Consequence of magnetic drag







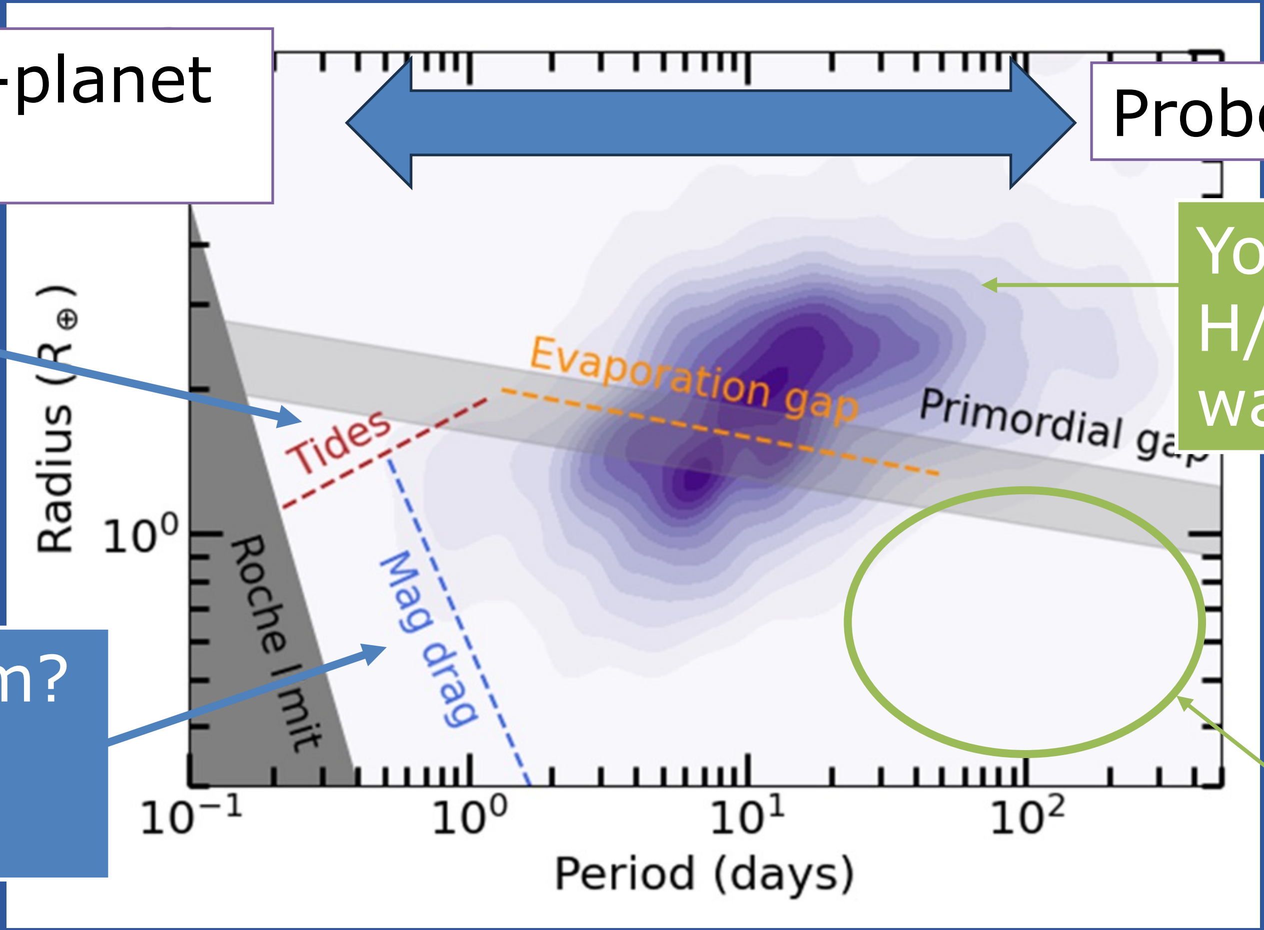
EJL & Owen '25

Probe star-planet interaction

Probe formation history

More mass measurement: tidal physics

Magnetic volcanism? Spectra for optical refractory species



Younger systems: H/He vs. waterworld

Rocky planets beyond ~100 days: initial conditions

EJL & Owen '25; Raw data from NASA Exoplanet Archive