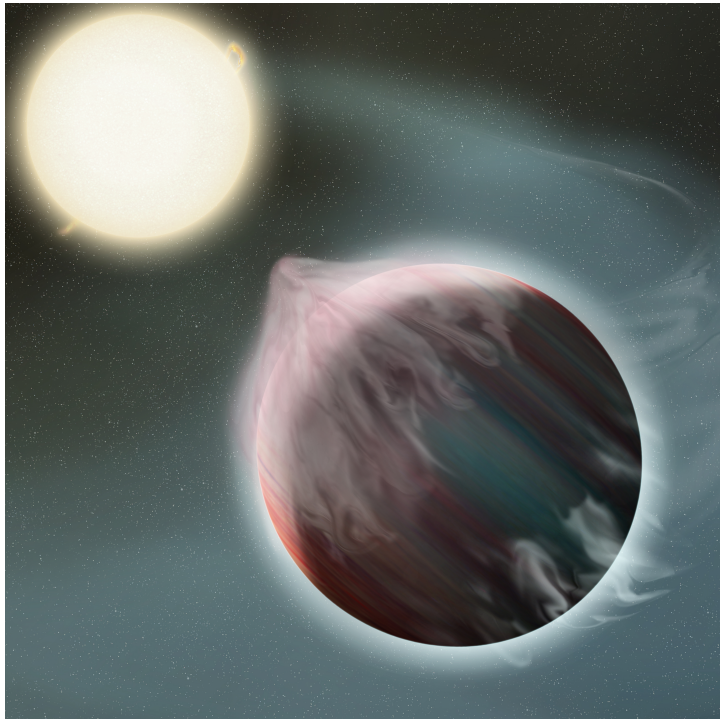
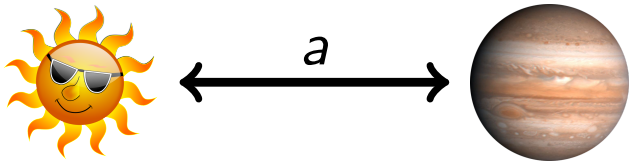
The Fate of Hot Jupiters

Sivan Ginzburg Re'em Sari

Racah Institute of Physics, The Hebrew University, Jerusalem, Israel



Tidal Inspiral



$M_\star \; R_\star \; Q \sim 10^6$ $\qquad$ $M_p \; R_p$

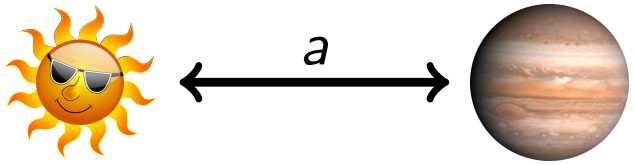
Orbital Decay Timescale

$$t_{\rm tide} = Q t^\star_{\rm dyn} \left(\frac{a}{R_\star}\right)^{13/2} \frac{M_\star}{M_p}$$

$$\approx 4 \text{ Gyr} \left(\frac{a/R_\star}{5}\right)^{13/2} \frac{M_{\rm J}}{M_p}$$

Goldreich & Soter 66

Tidal Inspiral



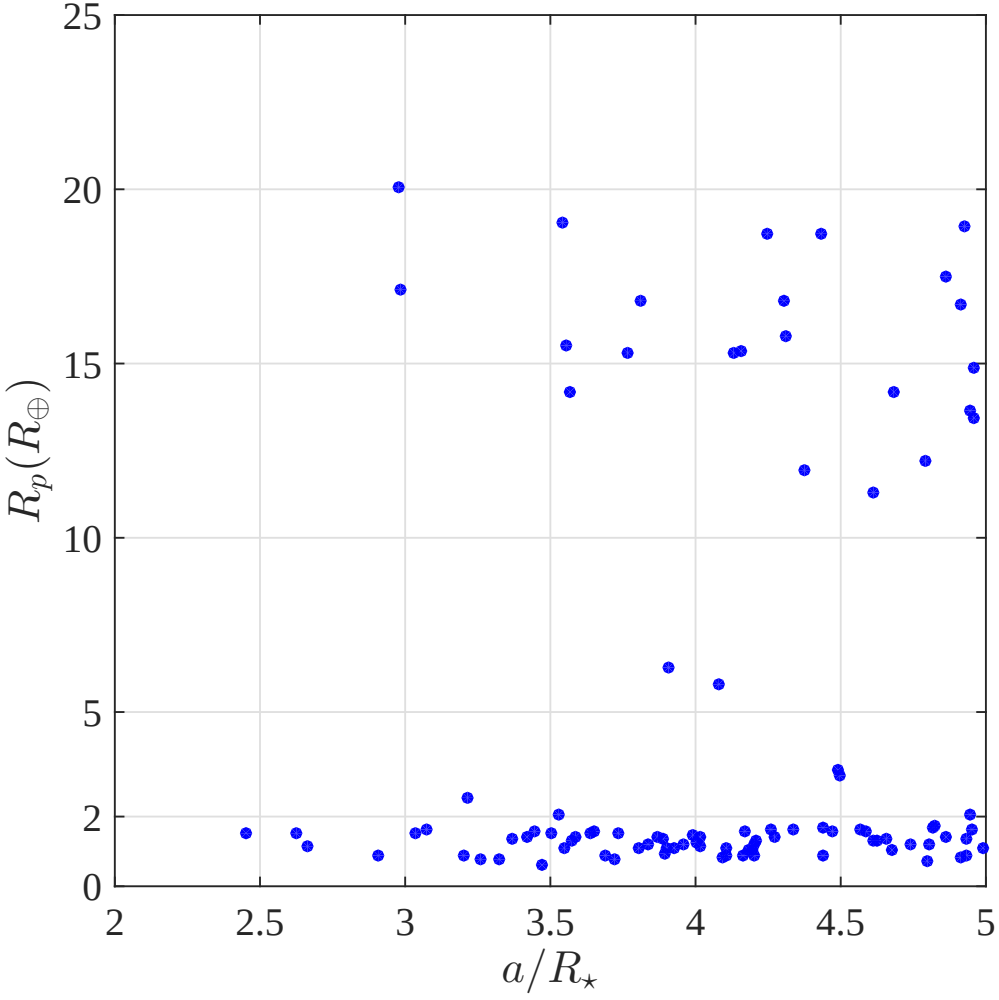
$M_\star \; R_\star \; Q \sim 10^6$ $\qquad$ $M_p \; R_p$

Orbital Decay Timescale

$$t_{\rm tide} = Q t^\star_{\rm dyn} \left(\frac{a}{R_\star}\right)^{13/2} \frac{M_\star}{M_p}$$

$$\approx 4 \text{ Gyr} \left(\frac{a/R_\star}{5}\right)^{13/2} \frac{M_{\rm J}}{M_p}$$

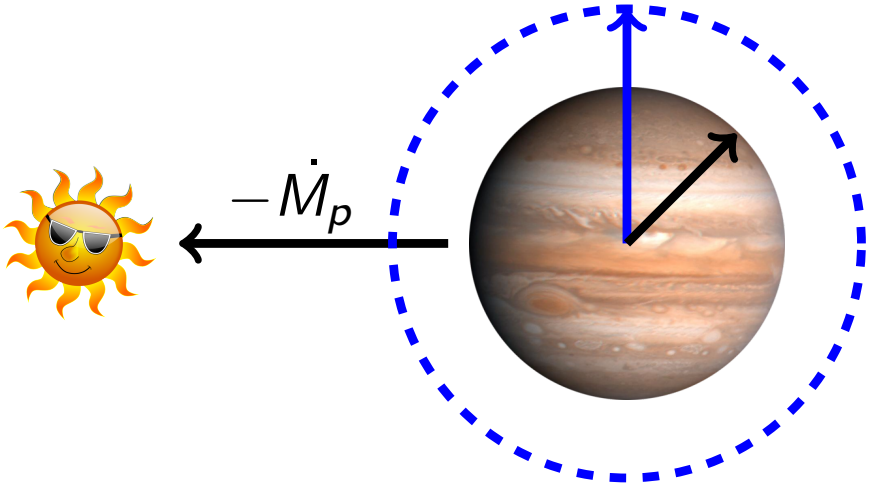
Goldreich & Soter 66



Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$



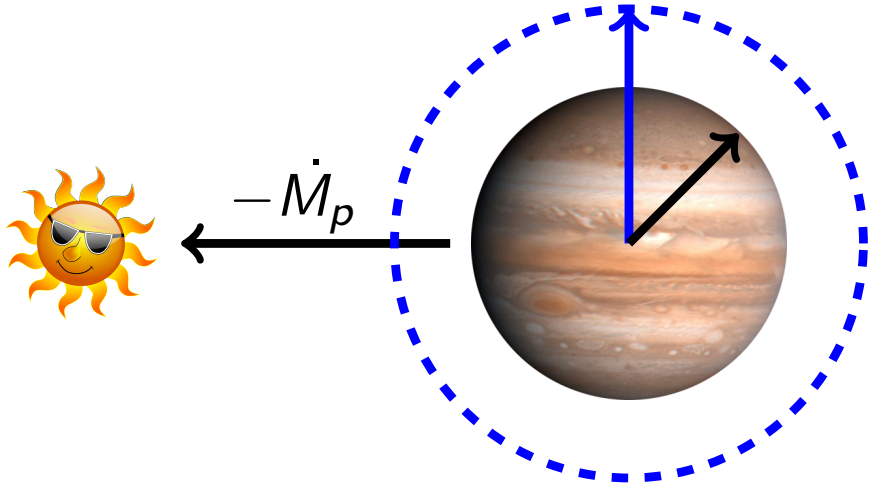
Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$

Stable Overflow (Rappaport+82)

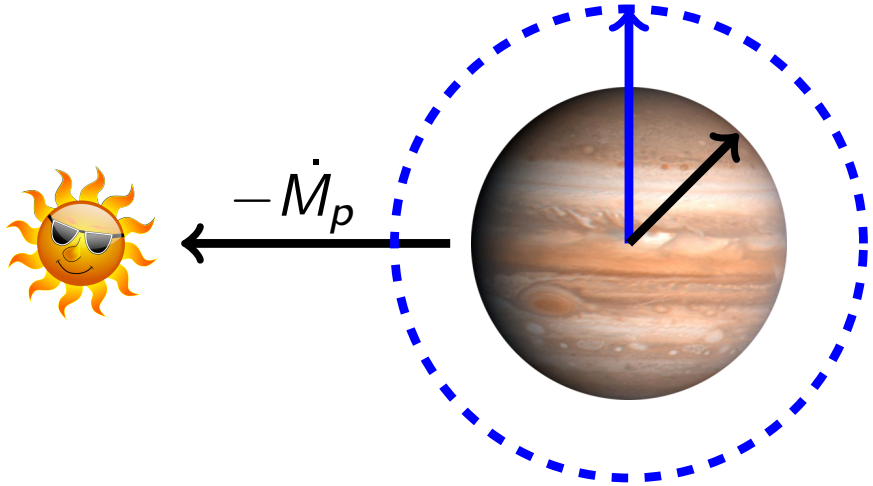
$$M_p/\dot{M}_p \sim t_{\rm tide} \qquad a \propto \rho_p^{-1/3}$$



Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$



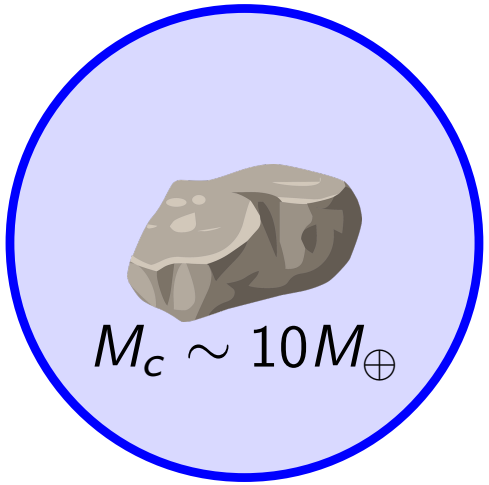
Stable Overflow (Rappaport+82)

$$M_p/\dot{M}_p \sim t_{\rm tide} \qquad a \propto \rho_p^{-1/3}$$

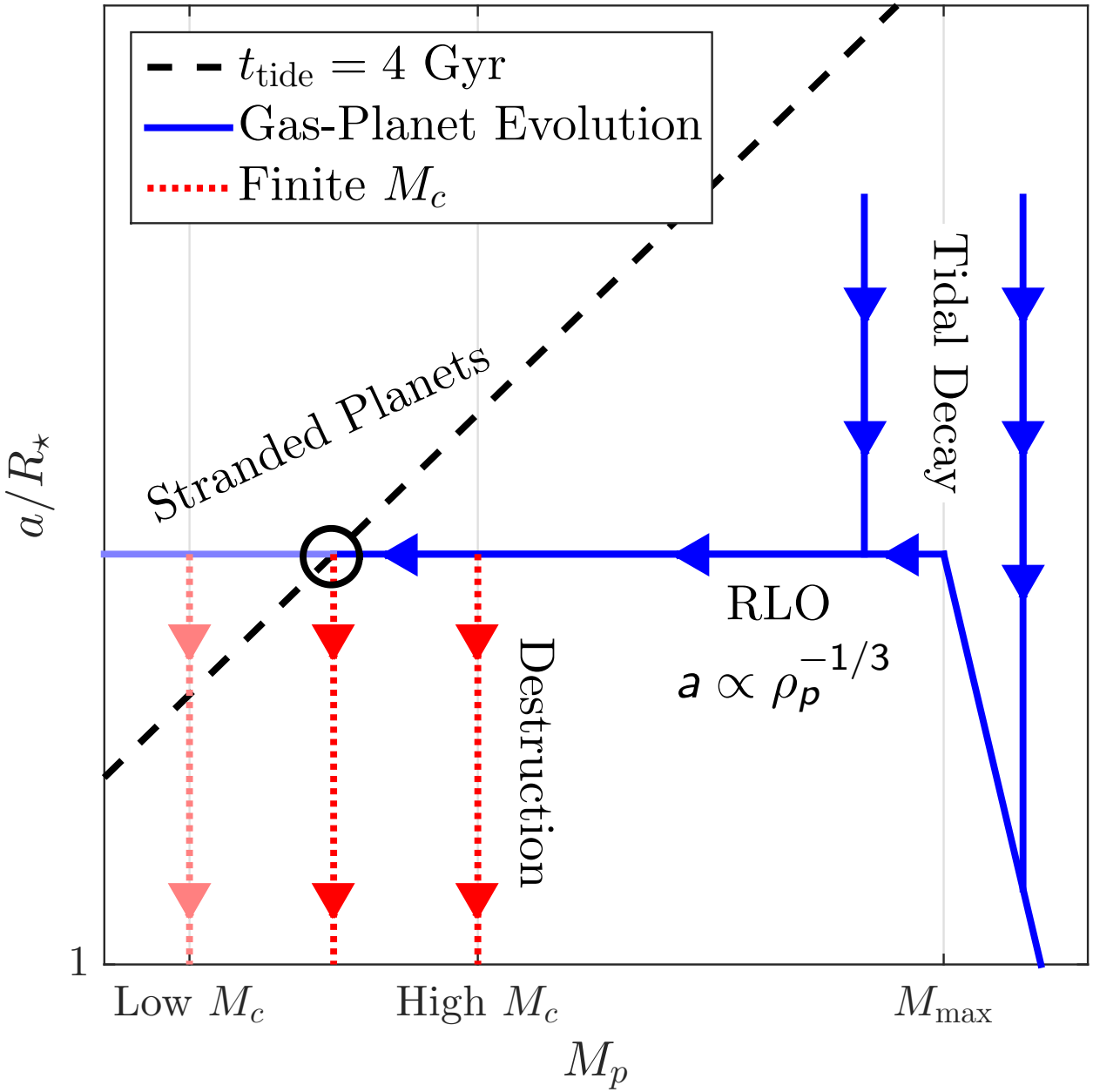
Mass-Density Relation $\rho_p(M_p)$

- $\rho_{\rm atm}^{1/3} \propto 1 + \left(\frac{M_{\rm atm}}{M_{\rm max}}\right)^{2/3}$
  Adiabatic[a]; $M_{\rm max} \simeq 3 M_J$
- Rocky core M_c

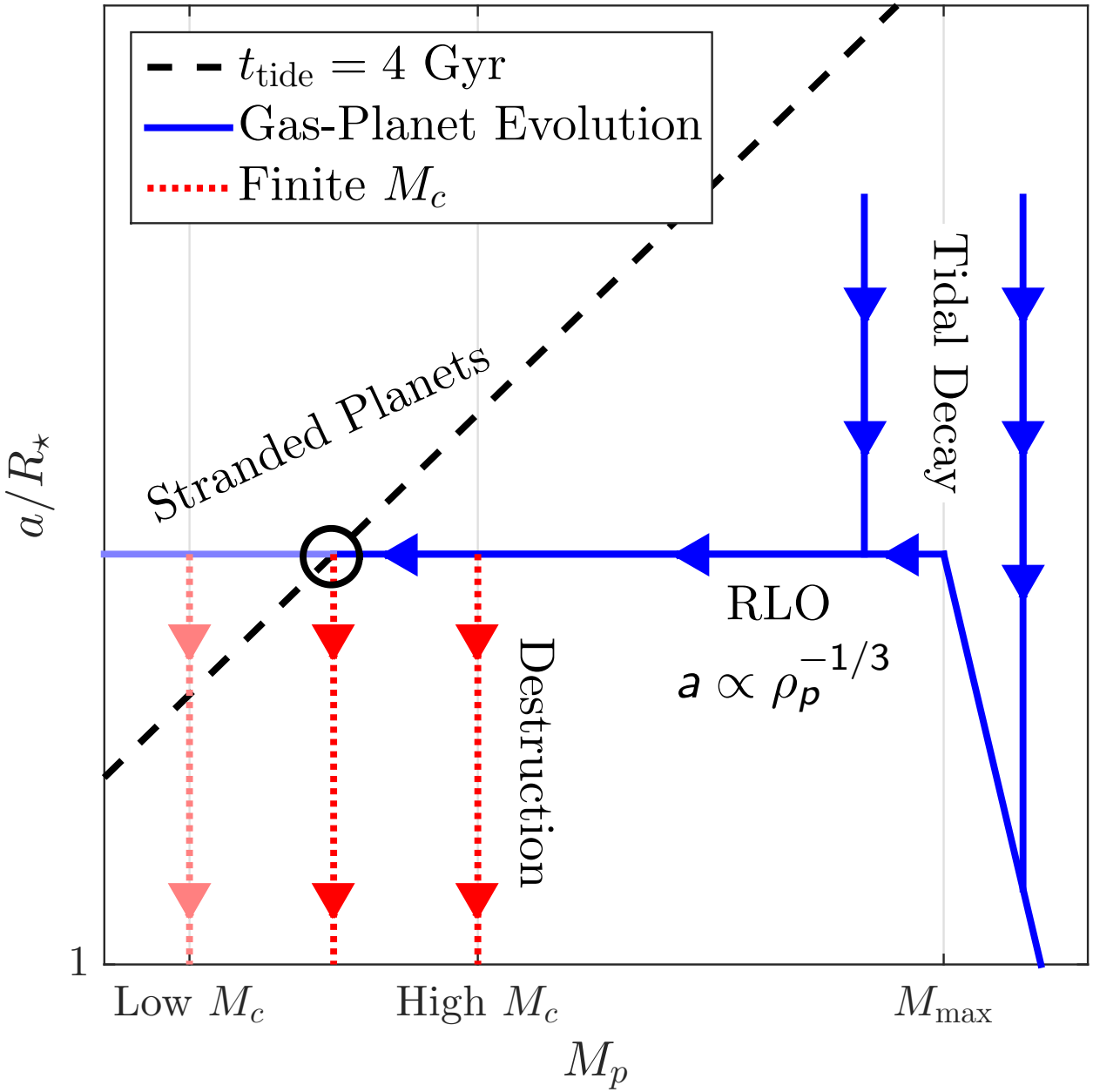
[a] Wu&Lithwick13, Ginzburg&Sari16



Asymptotic Trajectories



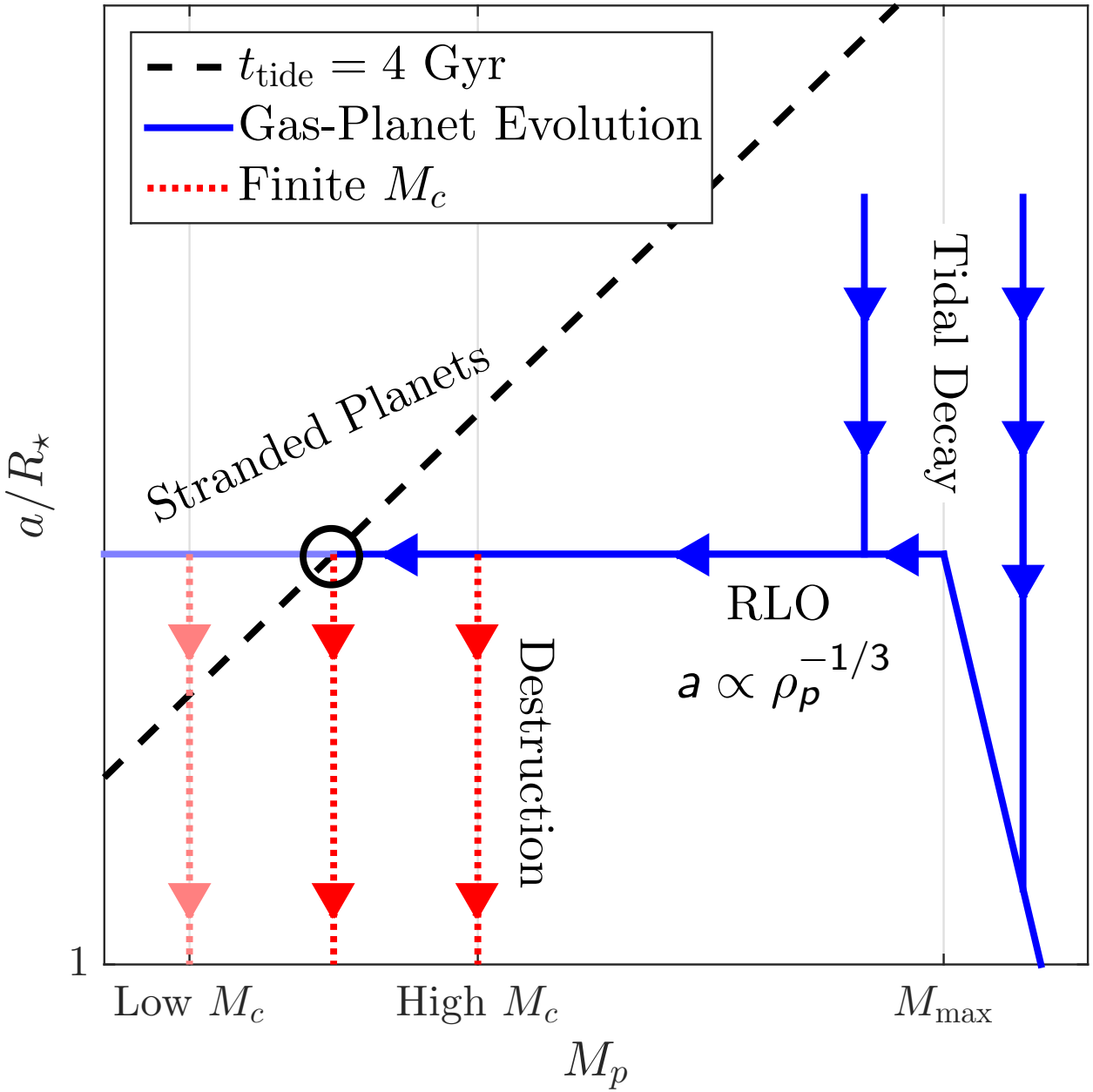
Asymptotic Trajectories



Planet's Fate

- High M_c: Destroyed
- Low M_c: Stranded

Asymptotic Trajectories



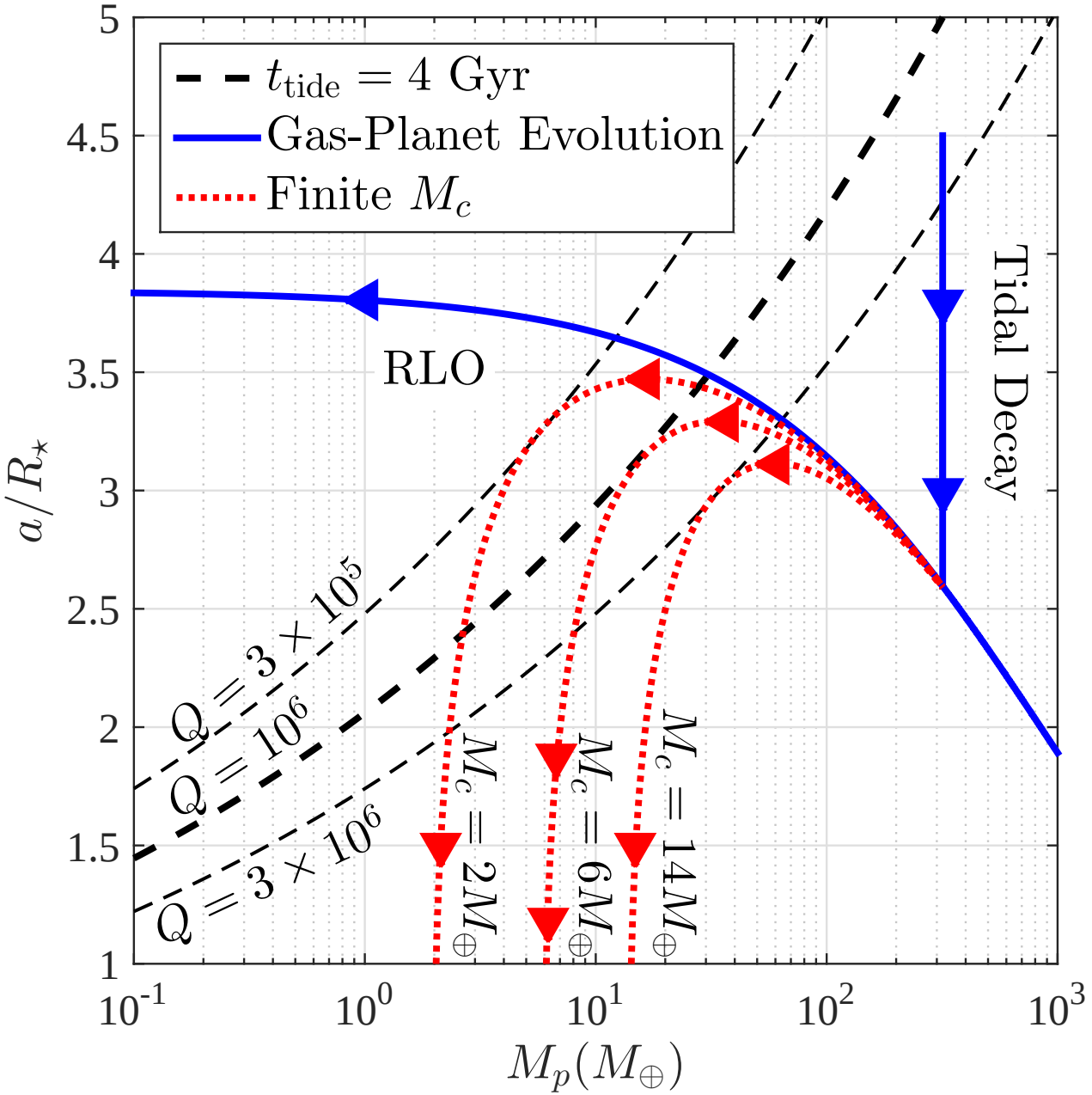
Planet's Fate

- High M_c: Destroyed
- Low M_c: Stranded

Remnant Planets

- Low mass
- Gas rich

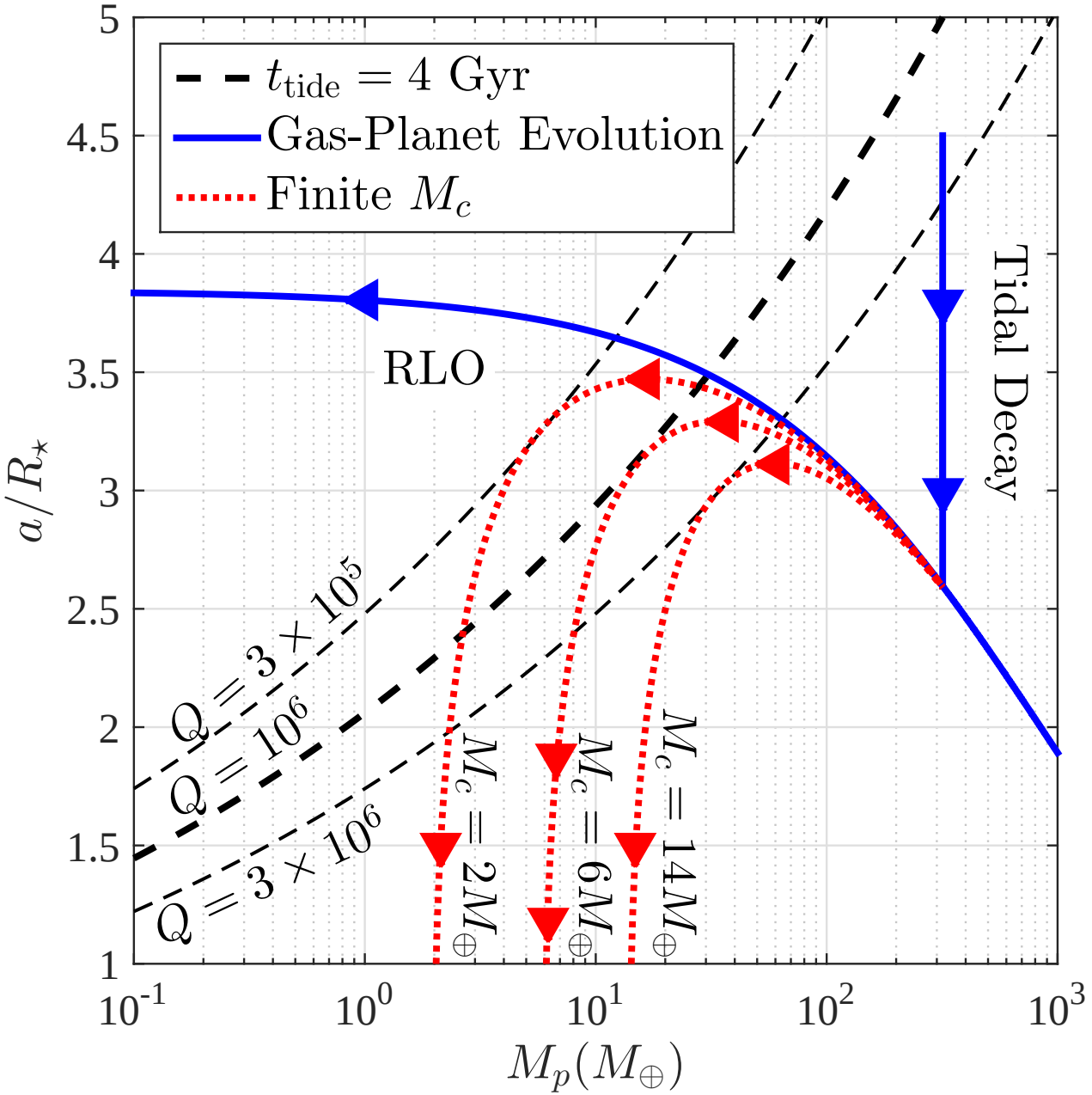
Critical Core Mass



Critical Core Mass

- $M_c = 6M_\oplus$
- $M_c \propto Q$

Critical Core Mass



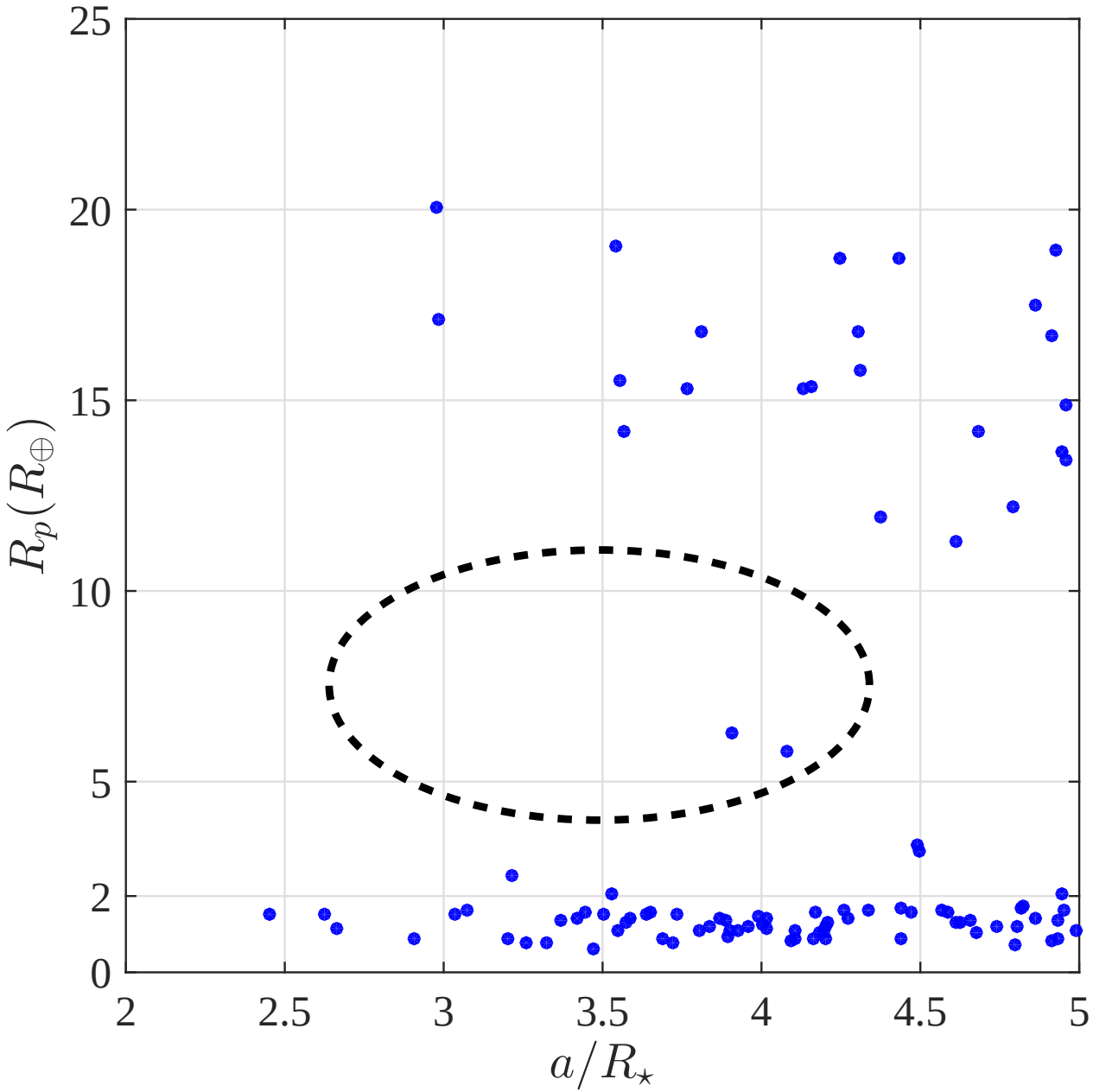
Critical Core Mass

- $M_c = 6M_\oplus$
- $M_c \propto Q$

Remnant Plantes ($M_c < 6M_\oplus$)

- $M_p : 15 - 30M_\oplus$
- $M_{\rm atm}/M_p > 60\%$ atm. survives
- $R_p : 5 - 10R_\oplus$
- $a/R_\star \approx 3.5$

Observed Remnants



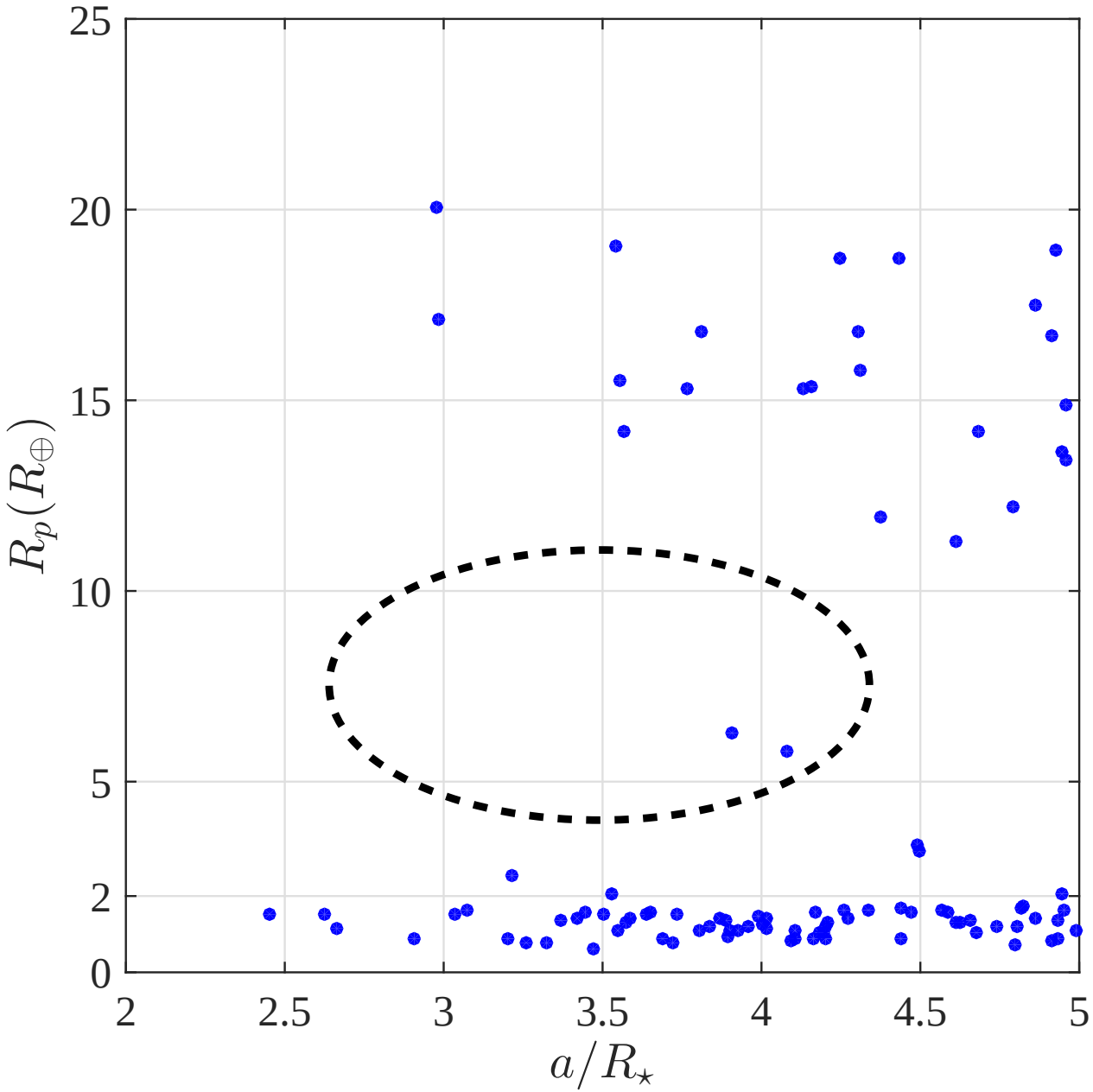
No Remnant Planets

- $\frac{M_c}{6M_\oplus} \gtrsim \frac{Q}{10^6}$

If Q is known

- $M_c \gtrsim 6M_\oplus$

Observed Remnants



No Remnant Planets

- $\frac{M_c}{6M_\oplus} \gtrsim \frac{Q}{10^6}$

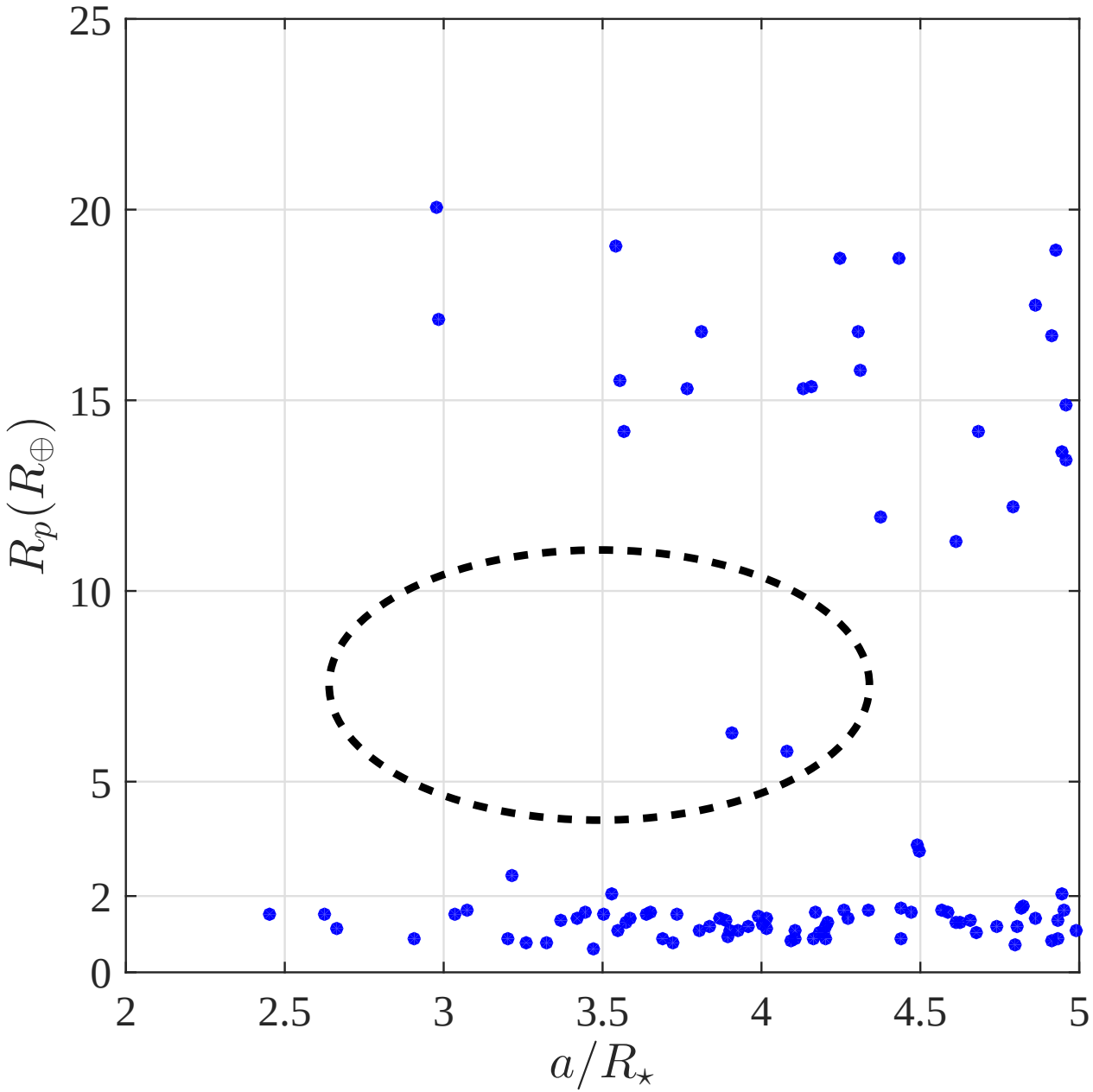
If Q is known

- $M_c \gtrsim 6M_\oplus$

If M_c is known

- $Q \lesssim 10^6$
  Core accretion
  Lee & Chiang 15
  Piso et al. 15

Observed Remnants



No Remnant Planets

- $\frac{M_c}{6M_\oplus} \gtrsim \frac{Q}{10^6}$

If Q is known

- $M_c \gtrsim 6M_\oplus$

If M_c is known

- $Q \lesssim 10^6$
  Core accretion
  Lee & Chiang 15
  Piso et al. 15
- or $Q \gtrsim 10^7$

Summary

Inspiralling Hot Jupiters

- ≈ 20 with $t_{\rm tide} < 4$ Gyr
- Stable Roche-lobe overflow: $a \propto \rho_p^{-1/3}$

Summary

Inspiralling Hot Jupiters

- ≈ 20 with $t_{\rm tide} < 4$ Gyr
- Stable Roche-lobe overflow: $a \propto \rho_p^{-1/3}$

Analytical Calibrated $\rho_p(M_p)$

- $\rho_p(M_c, M_{\rm atm}, \text{inflation})$
- Complex trajectories
- Fate determined by M_c
  Valsecchi+14,15 Jackson+16

Summary

Inspiralling Hot Jupiters

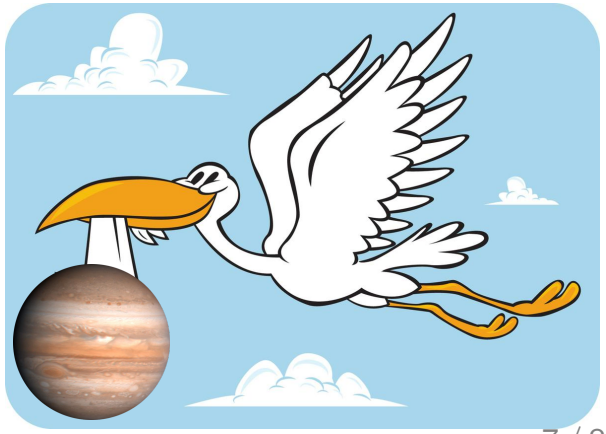
- ≈ 20 with $t_{\rm tide} < 4$ Gyr
- Stable Roche-lobe overflow: $a \propto \rho_p^{-1/3}$

Analytical Calibrated $\rho_p(M_p)$

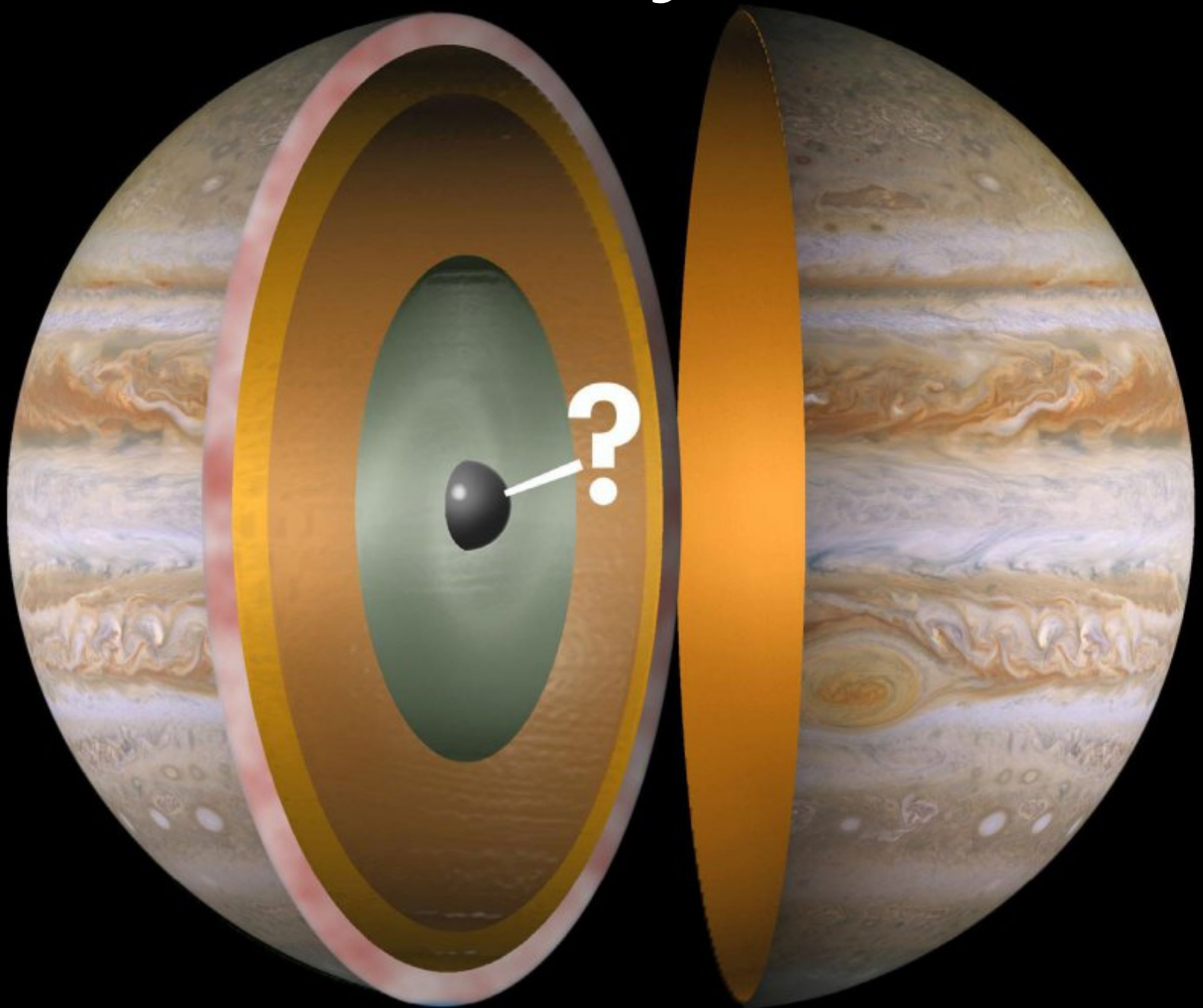
- $\rho_p(M_c, M_{\rm atm}, {\rm inflation})$
- Complex trajectories
- Fate determined by M_c
  Valsecchi+14,15 Jackson+16

No Remnants ("gas Neptunes")

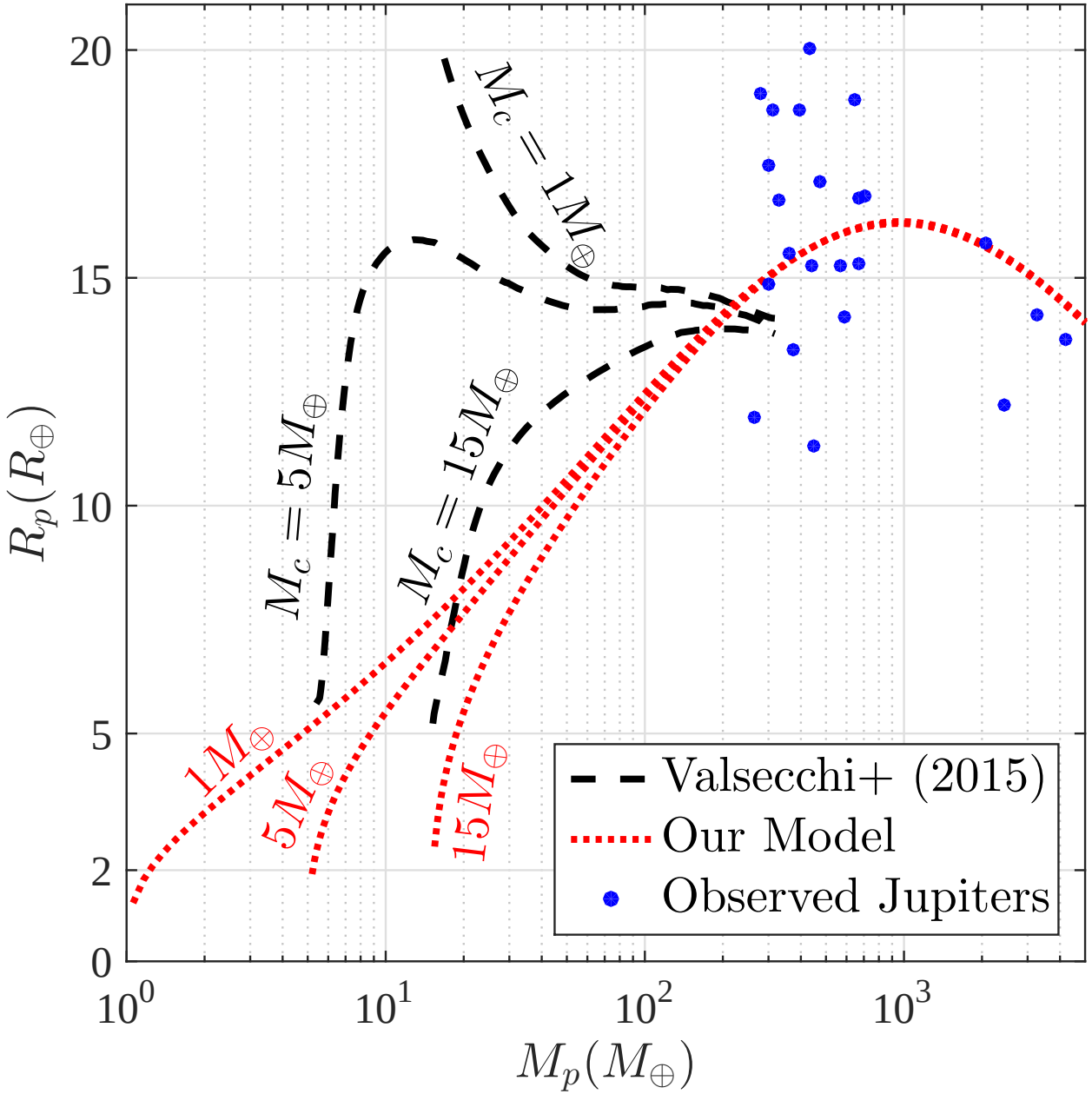
- Planet formation: $M_c \gtrsim 6 M_\oplus$
- Tidal evolution: $10^6 \lesssim Q \lesssim 10^7$ excluded
- Small "Keplers": only if Q is low



Thank you!



Mass-Radius Relation



Main Differences:

- Deep heating
- No re-inflation
  Wu&Lithwick 13,
  Ginzburg&Sari 16

Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$

Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$

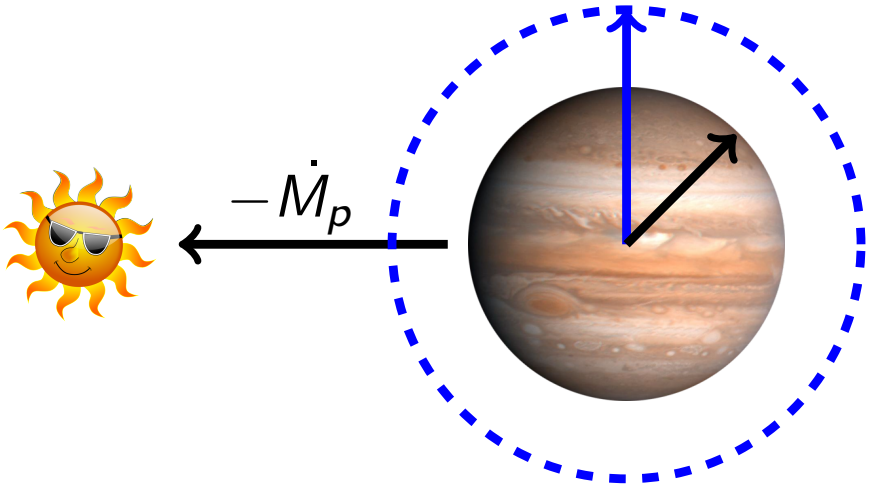
Stability & Rate

$$\frac{|\dot{M}_p|}{M_p} = \left(\frac{2}{5/3 + \xi - 2\alpha}\right) t_{\rm tide}^{-1}$$

$$\xi \equiv d\ln R_p / d\ln M_p$$

$$\alpha \leq \alpha_{\rm loss} + \sqrt{R_\star / a}$$

Rappaport et al. 82



Roche-lobe Overflow

The Roche Limit

$$\frac{a}{R_\star} \simeq 2.4 \left(\frac{\rho_\star}{\rho_p}\right)^{1/3}$$

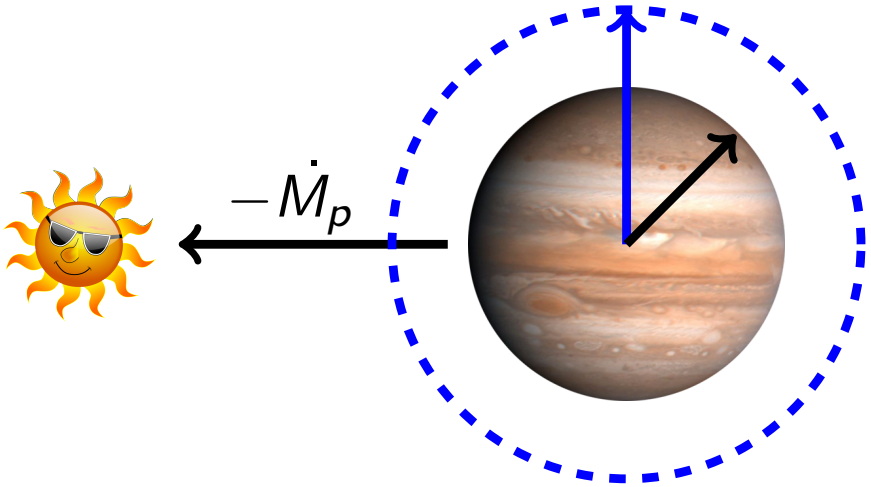
Stability & Rate

$$\frac{|\dot{M}_p|}{M_p} = \left(\frac{2}{5/3 + \xi - 2\alpha}\right) t_{\rm tide}^{-1}$$

$$\xi \equiv d\ln R_p / d\ln M_p$$

$$\alpha \leq \alpha_{\rm loss} + \sqrt{R_\star / a}$$

Rappaport et al. 82



Stable RLO:

$$a \propto \rho_p^{-1/3}$$

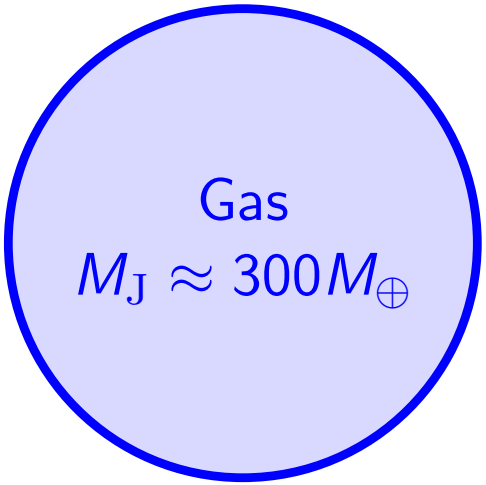
Mass-Density Relation $\rho_p(M_p)$

Cold Gas Balls

$$K\rho_p^{5/3}\left[1-\left(\frac{\rho_0}{\rho_p}\right)^{1/3}\right] \sim GM_p^{2/3}\rho_p^{4/3}$$

$$\left(\frac{\rho_p}{\rho_0}\right)^{1/3} = 1+\left(\frac{M_p}{M_{\max}}\right)^{2/3}$$

$$M_{\max} \simeq 3M_{\mathrm{J}}$$



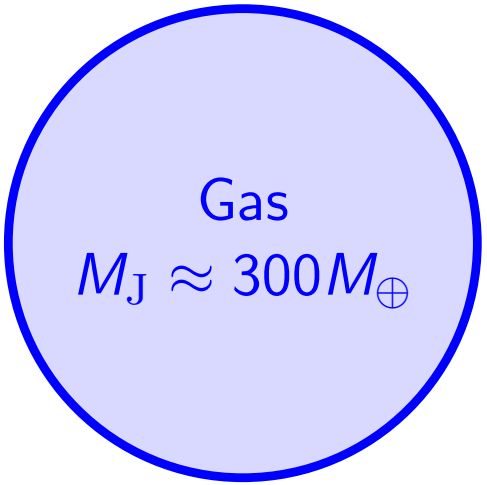
Mass-Density Relation $\rho_p(M_p)$

Cold Gas Balls

$$K\rho_p^{5/3}\left[1-\left(\frac{\rho_0}{\rho_p}\right)^{1/3}\right] \sim GM_p^{2/3}\rho_p^{4/3}$$

$$\left(\frac{\rho_p}{\rho_0}\right)^{1/3} = 1+\left(\frac{M_p}{M_{\max}}\right)^{2/3}$$

$$M_{\max} \simeq 3M_{\mathrm{J}}$$



Inflated Hot Jupiters

Adiabatic Mass-Loss:

$$\rho_p^{1/3} \propto 1+\left(\frac{M_p}{M_{\max}}\right)^{2/3}$$

Wu&Lithwick 13, Ginzburg&Sari 16

Mass-Density Relation $\rho_p(M_p)$

Cold Gas Balls

$$K\rho_p^{5/3}\left[1-\left(\frac{\rho_0}{\rho_p}\right)^{1/3}\right] \sim GM_p^{2/3}\rho_p^{4/3}$$

$$\left(\frac{\rho_p}{\rho_0}\right)^{1/3} = 1+\left(\frac{M_p}{M_{\max}}\right)^{2/3}$$

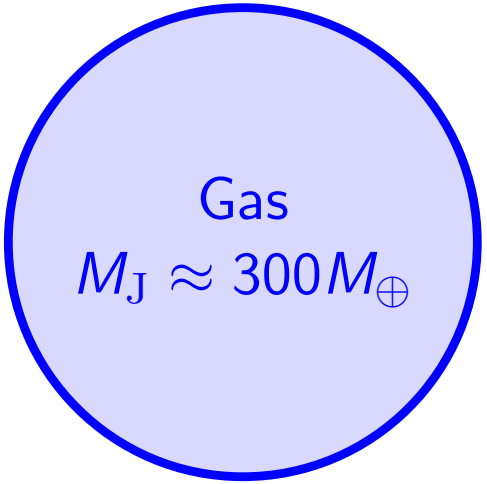
$$M_{\max} \simeq 3M_{\mathrm{J}}$$

Inflated Hot Jupiters

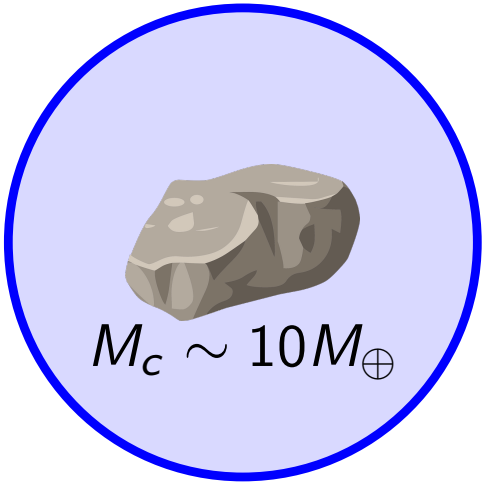
Adiabatic Mass-Loss:

$$\rho_p^{1/3} \propto 1+\left(\frac{M_p}{M_{\max}}\right)^{2/3}$$

Wu&Lithwick 13, Ginzburg&Sari 16



Gravitational Instability



Core Accretion