How to bake puffy planets

Coupling radius inflation with high eccentricity migration

Jiapeng Gao

Advisor: Gongjie Li

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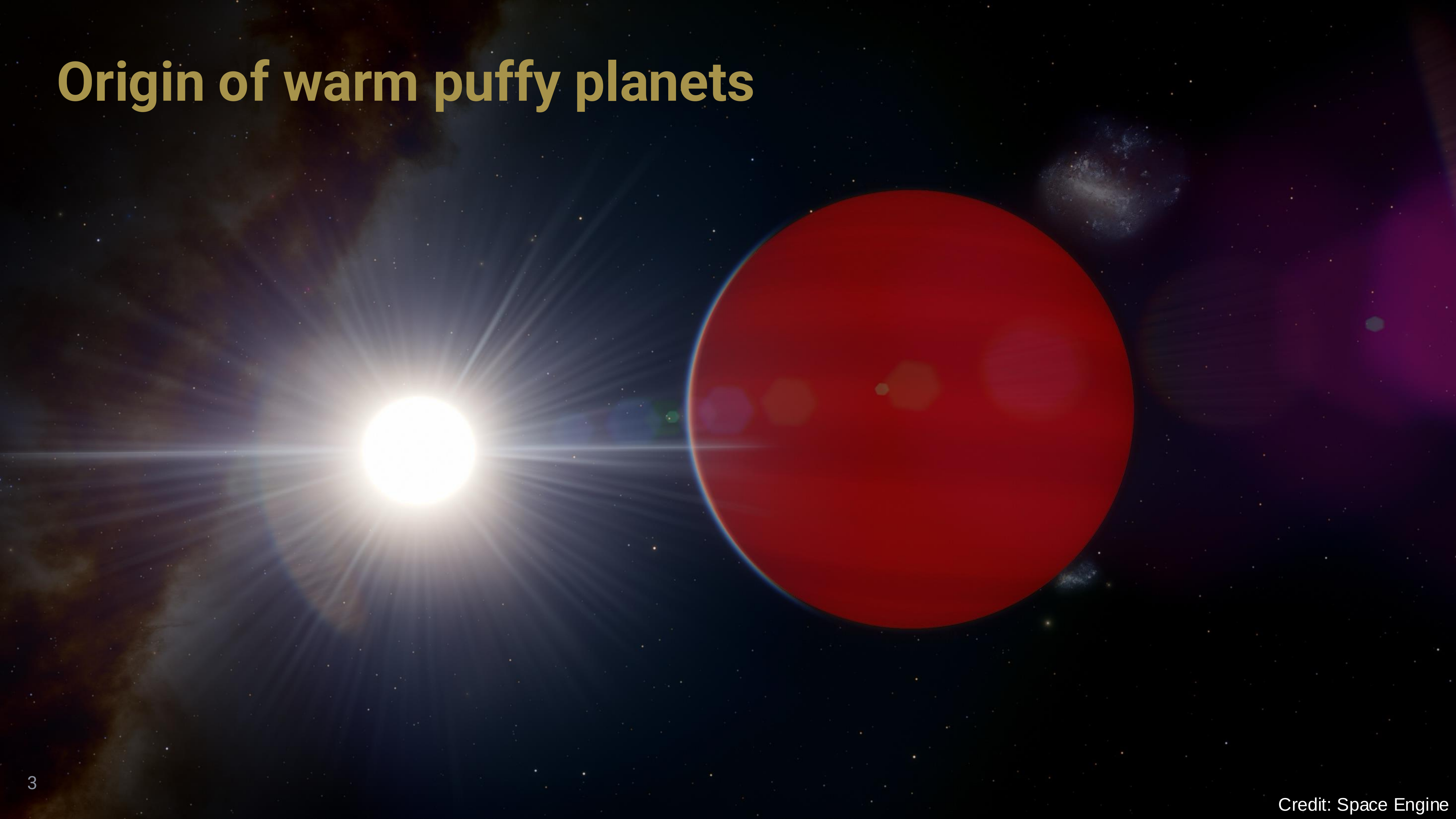
ExoPAG 31 Early Career Talk

 Jan 11, 2025

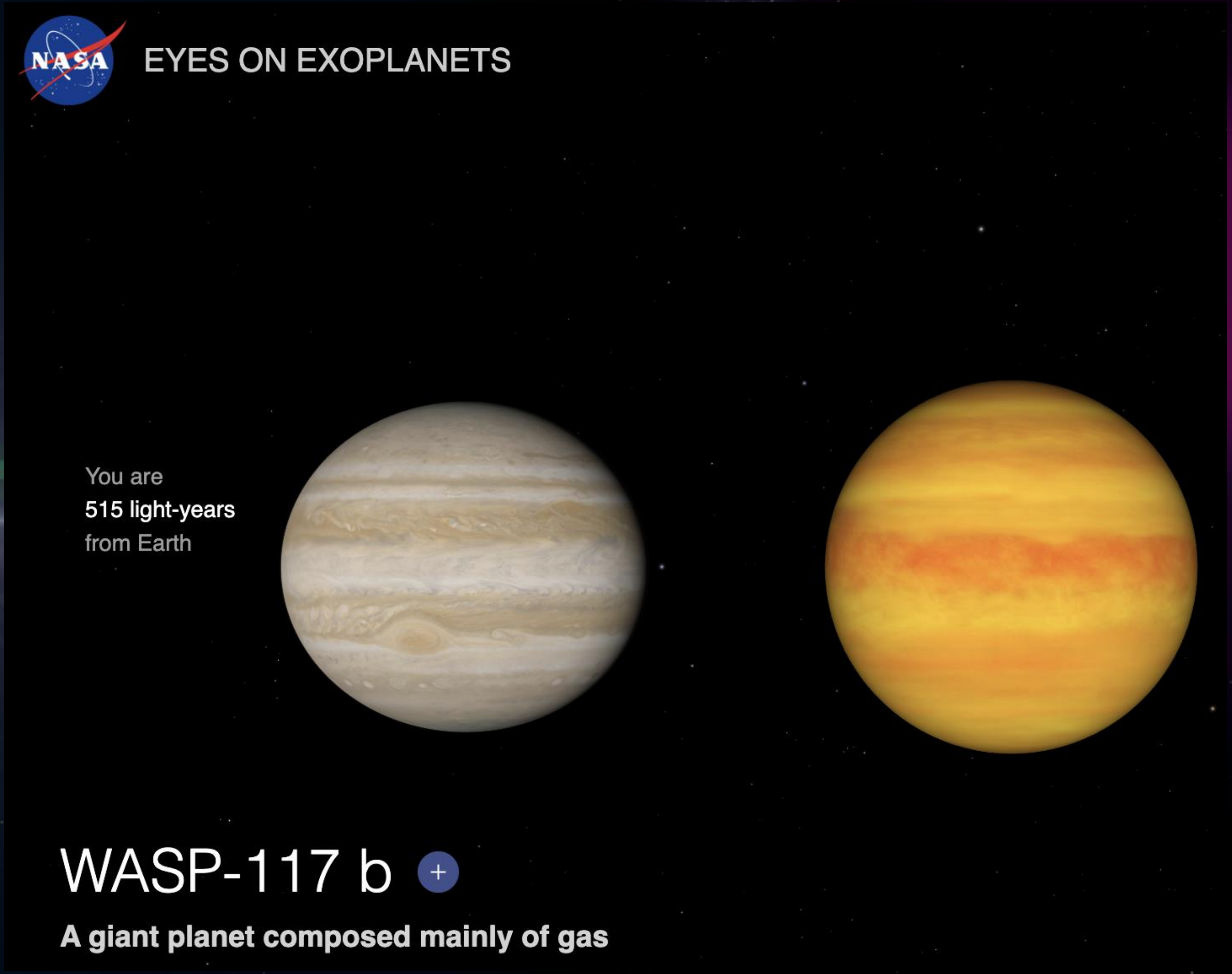
Origin of warm puffy planets



Credit: Space Engine

Origin of warm puffy planets

- WASP-117b -- Saturn mass planet with Jupiter radius
- WASP-117b has only a density of 0.345 g/cm3, while Saturn has 0.687 g/cm3 (Lendl et al. 2014)



Credit: NASA/Lunar and Planetary Institute

Credit: Space Engine

Puffy planets

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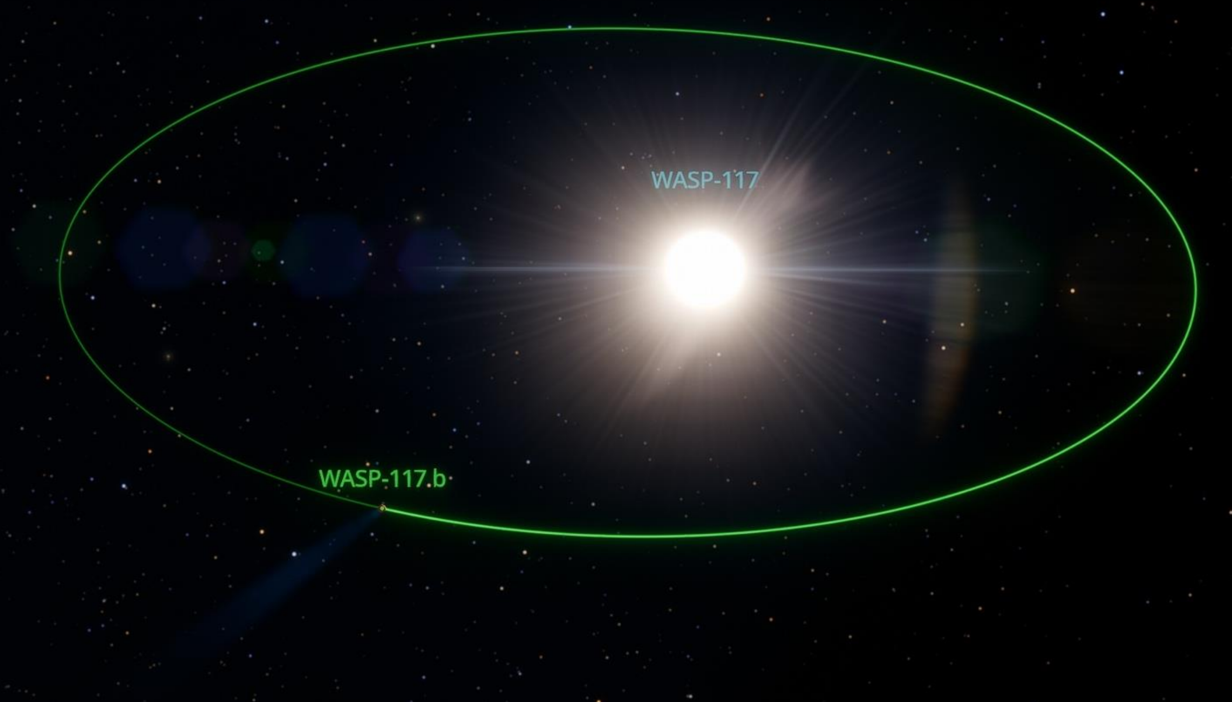
Parameter	Value
Orbital period (days)	10.02165 ± 0.00055
Eccentricity e	0.302 ± 0.023
True obliquity ψ (deg)	$69.6^{+4.7}_{-4.1}$
Semi-major axis a (au)	$0.09459^{+0.00084}_{-0.00079}$

Table 1: WASP-117b Orbital Parameters

Lendl et al. 2014



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Puffy planets

- WASP-117b -- Saturn mass planet with Jupiter radius
- WASP-117b has only a density of 0.345 g/cm3, while Saturn has 0.687 g/c

How does tidal heating affect the structure of the planet, which in turn influence the dynamical evolution?

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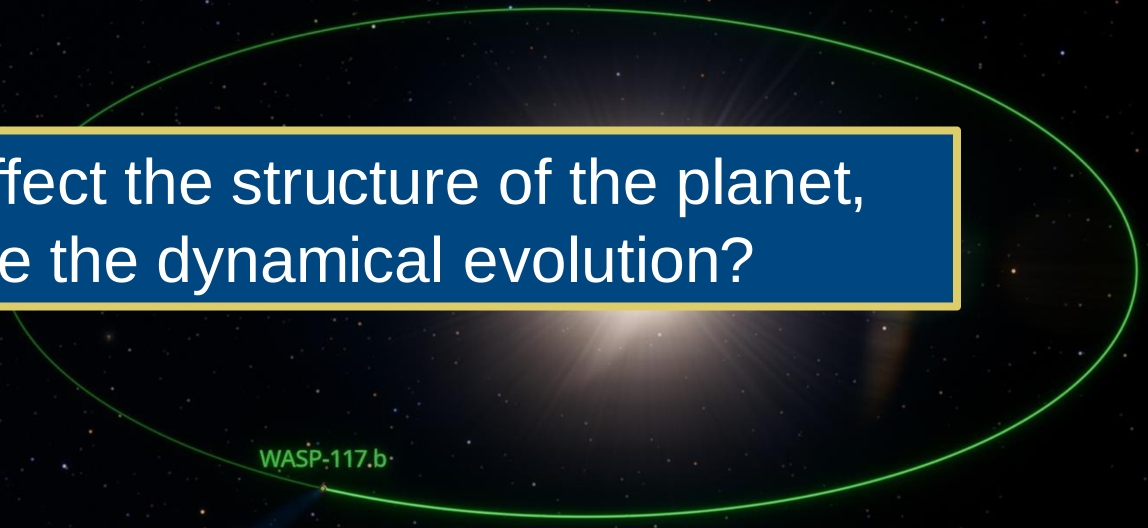

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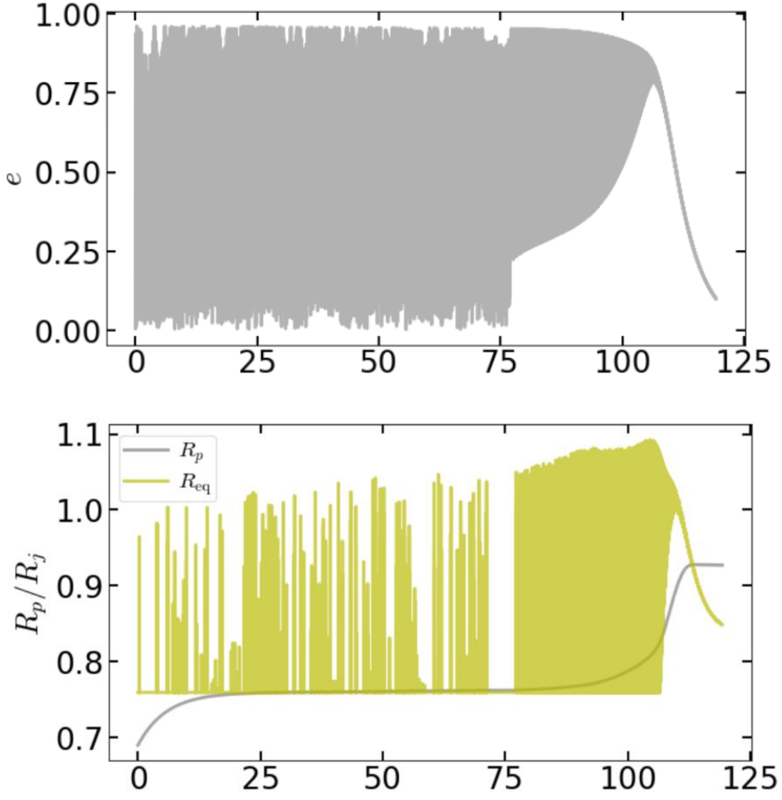
Previous works on coupling radius inflation with tidal migration

- Yu & Dai, 2024:
  - Formation of WASP-107b with high-e migration and radius inflation.



- Lu et al., 2024:
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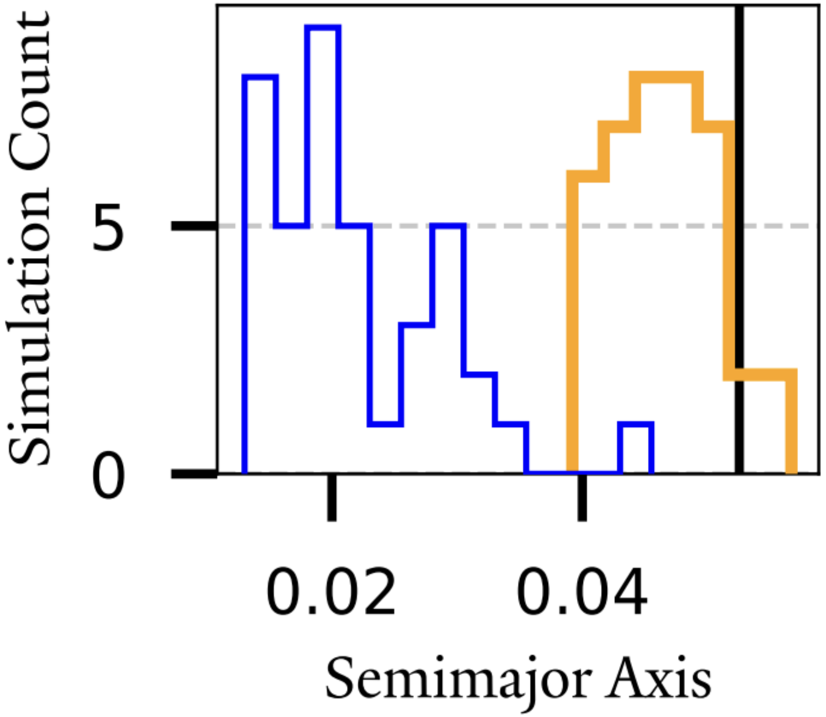

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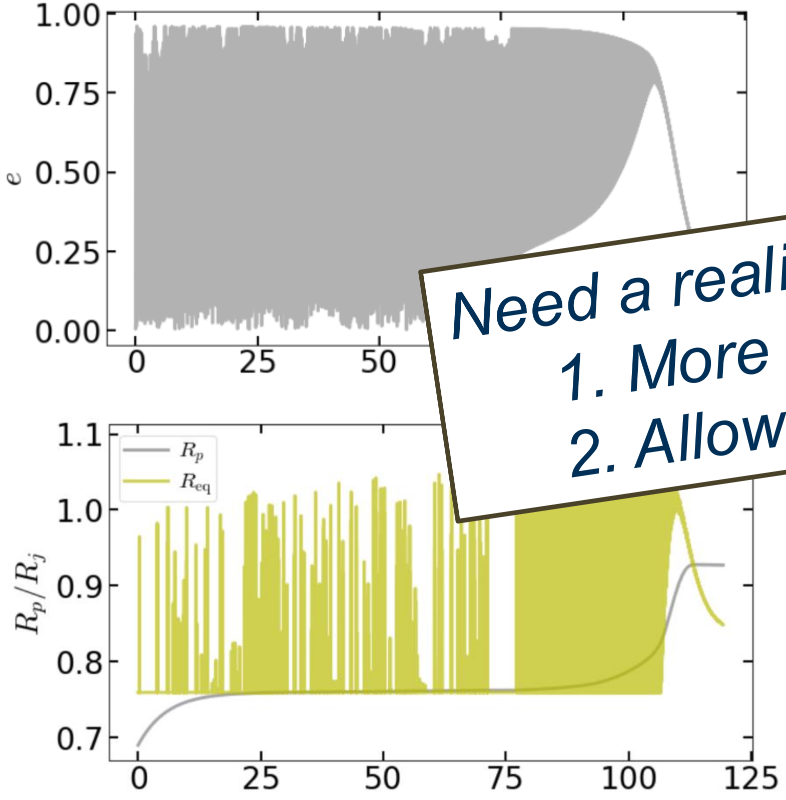

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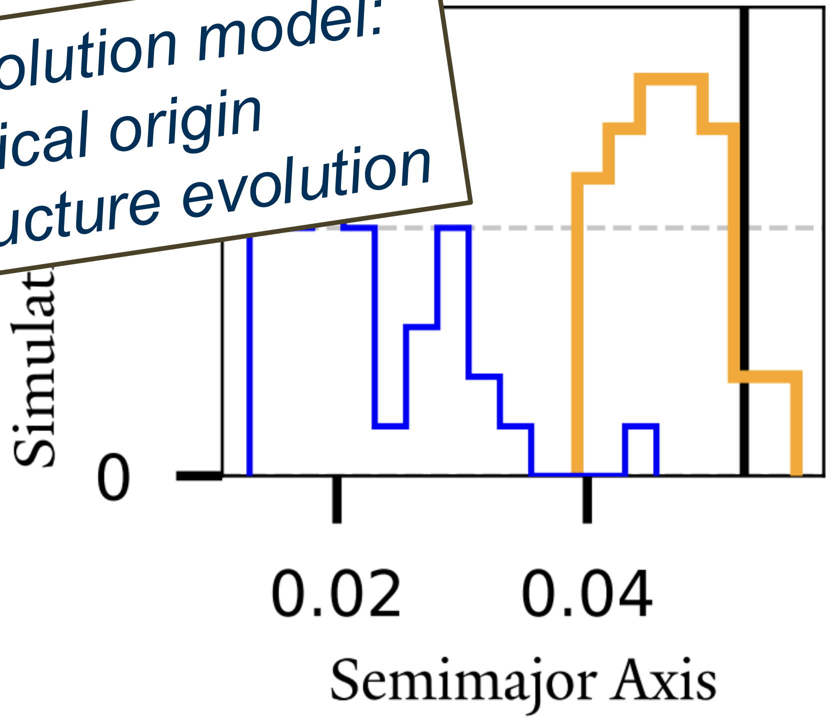
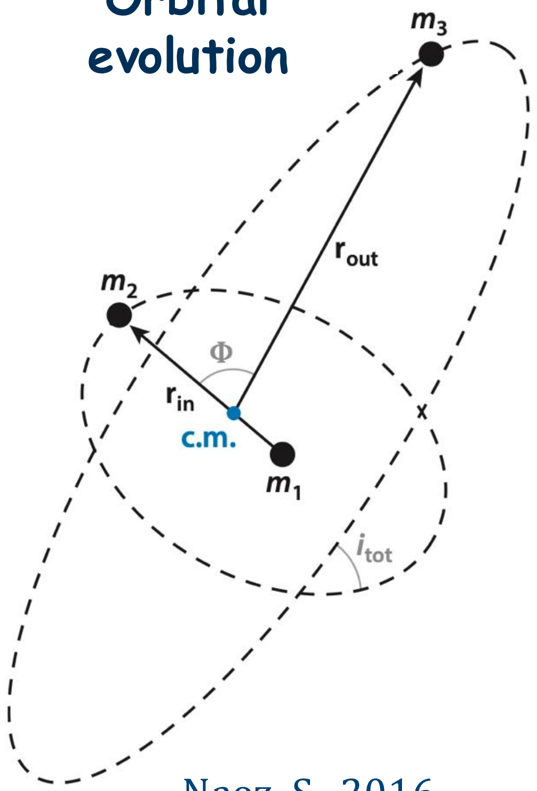
Need a realistic structure evolution model:
1. More accurate dynamical origin
2. Allows a probe for structure evolution



How are puffy planets formed?

- First combination of realistic interior structure evolution with high-e migration.

Orbital evolution

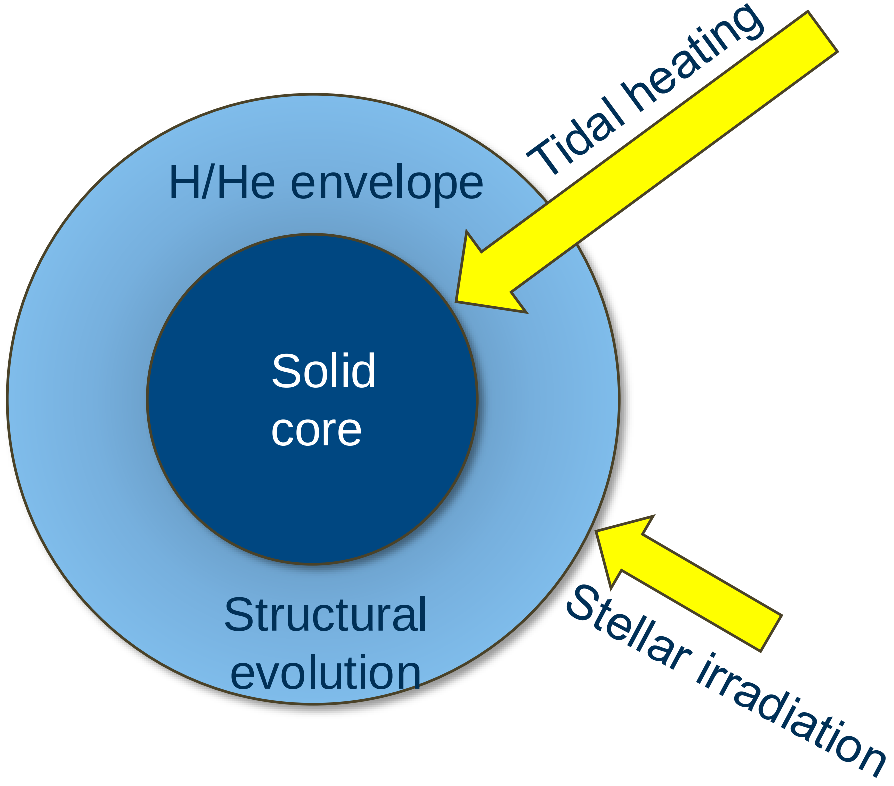


Naoz, S., 2016.

Octupole L-K+ Short range forces

Tidal heating rate & Surface heating rate

Radius inflation



MESA
(Paxton et al., 2011)

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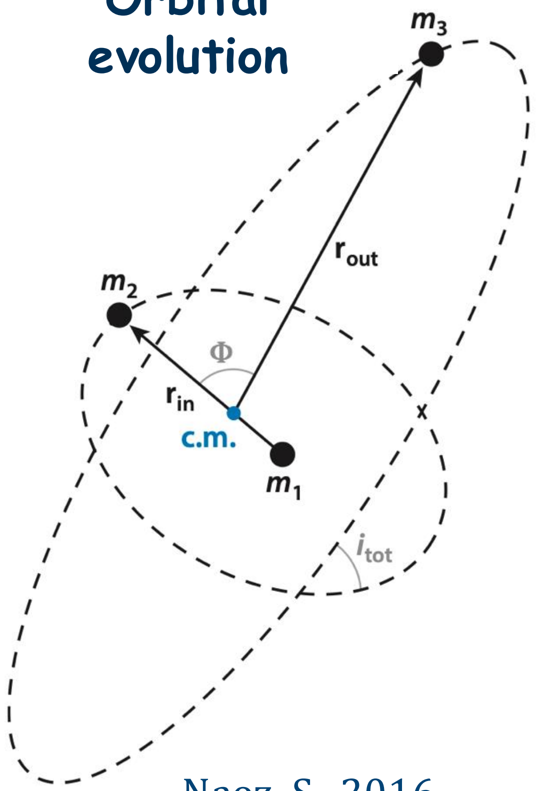

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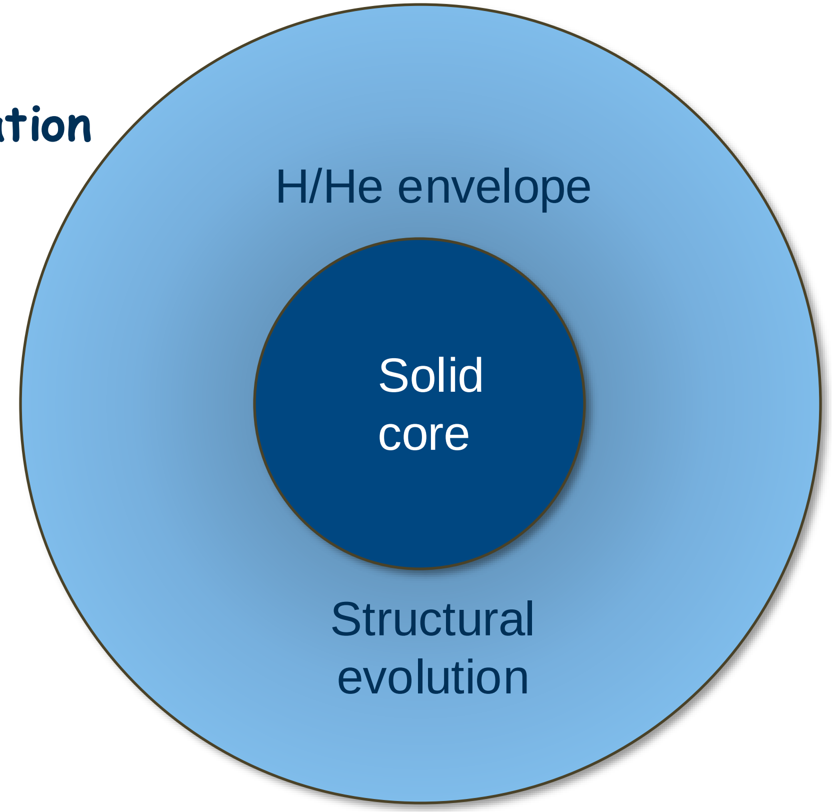
Tidal heating rate & Surface heating rate

Planet radius and love number

Radius inflation



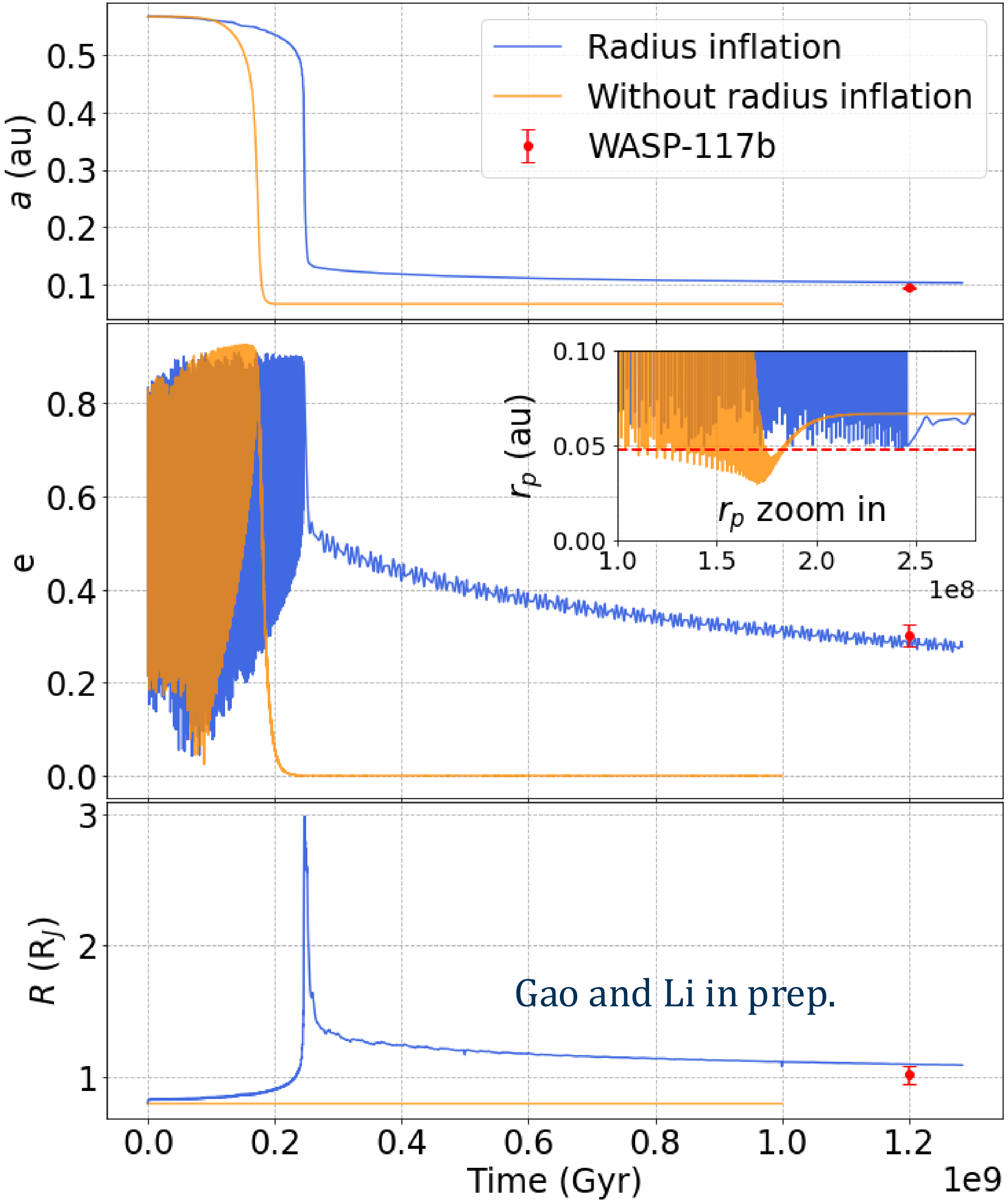
MESA

(Paxton et al., 2011)

Radius inflation

- Eccentricity excitation increases tidal heating rate
- Tidal heating inflate the planet, triple the radius.
- L-K suppressed, semi-major axis decrease sharply with residual eccentricity
- Planet quickly cools down, orbit slowly circularize.

Results agree well
with observation ☺



Radius inflation

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- Tidal heating inflate the planet, triple the radius.
- L-K suppressed, semi-major axis decrease sharply with residual eccentricity
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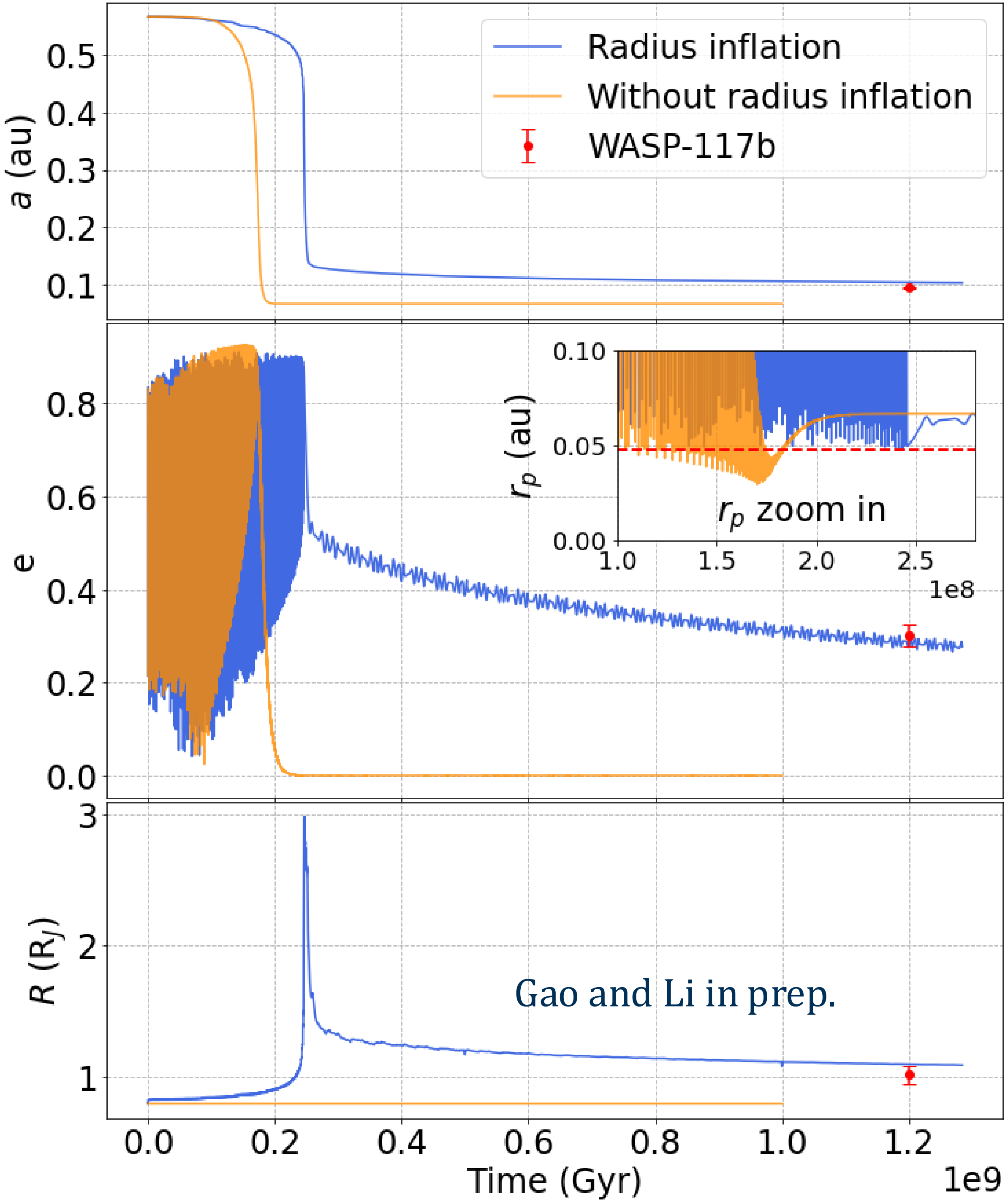
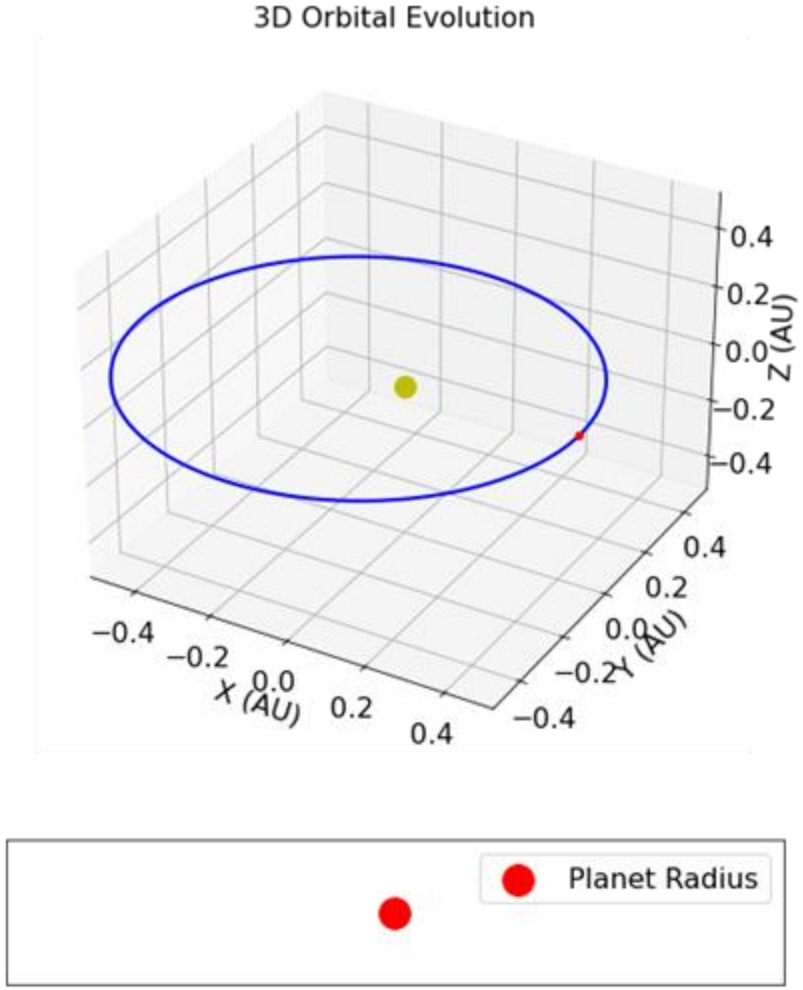
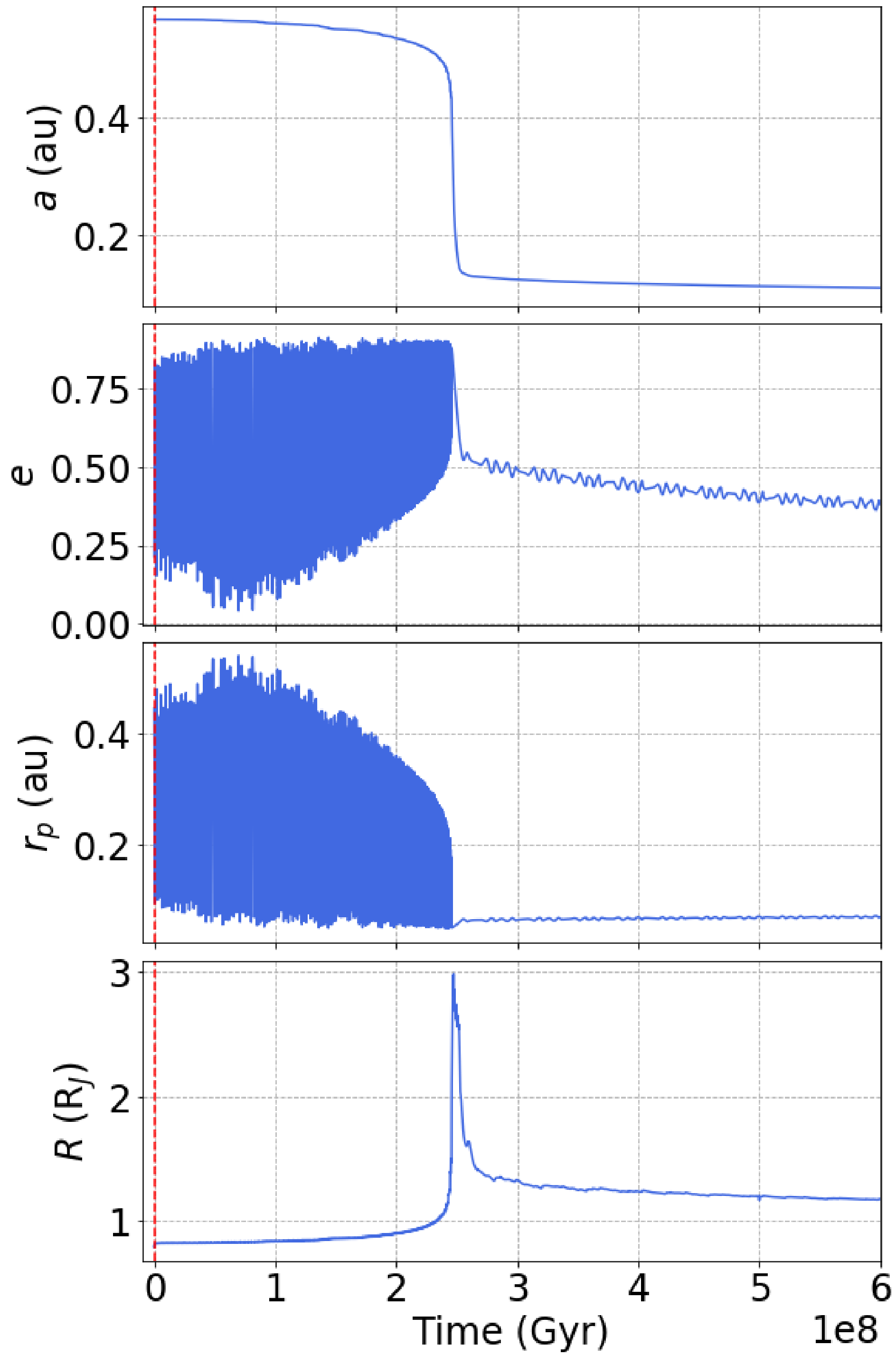
In short, we will have larger final a, e and radius with radius inflation.

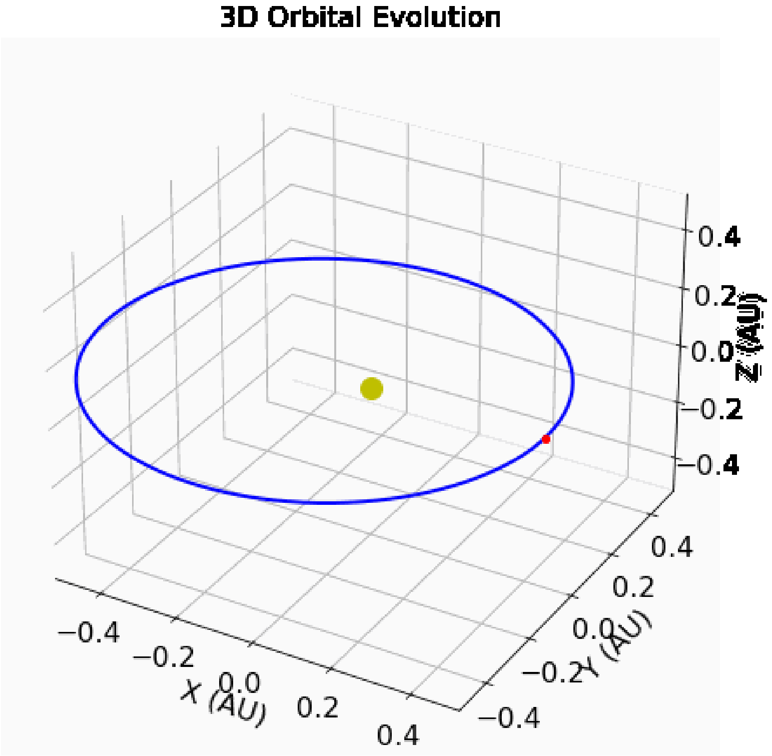


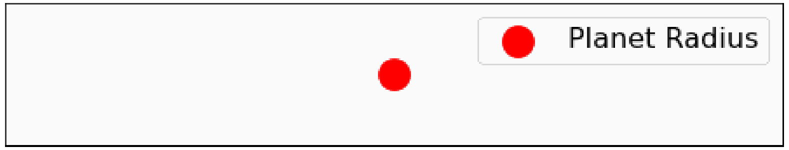
Radius inflation

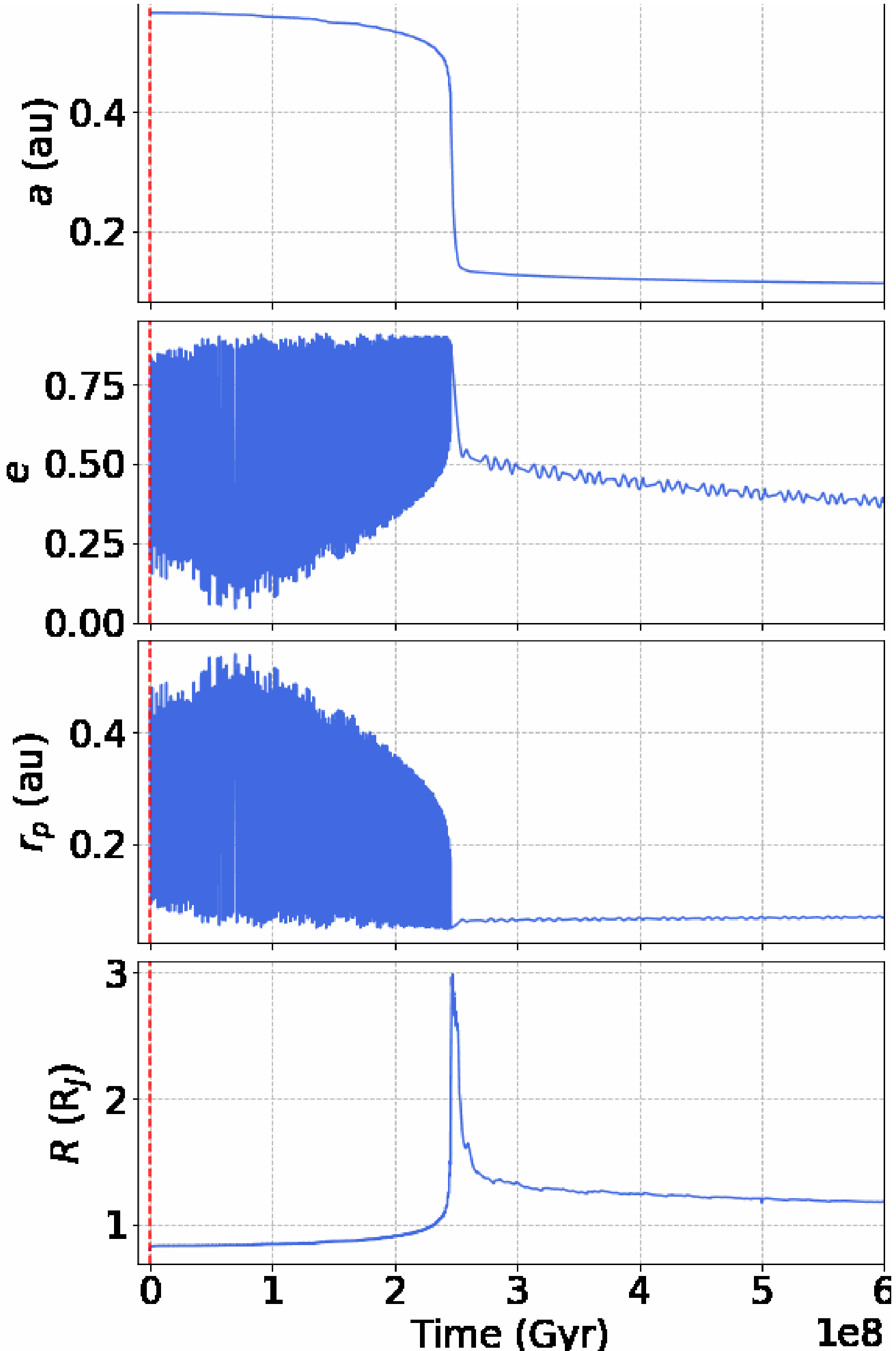




Radius inflation

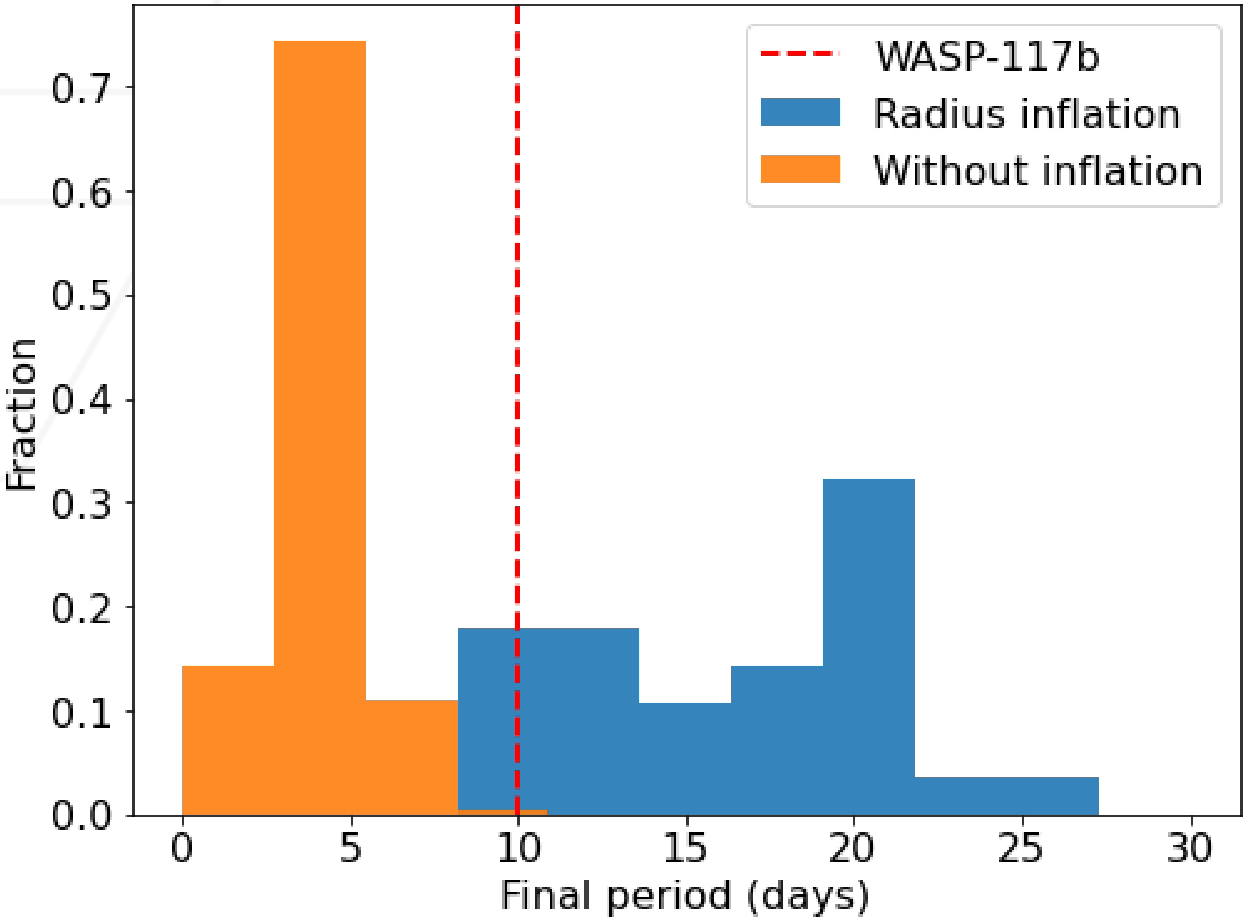






Parameter dependencies

- Final orbital period distribution

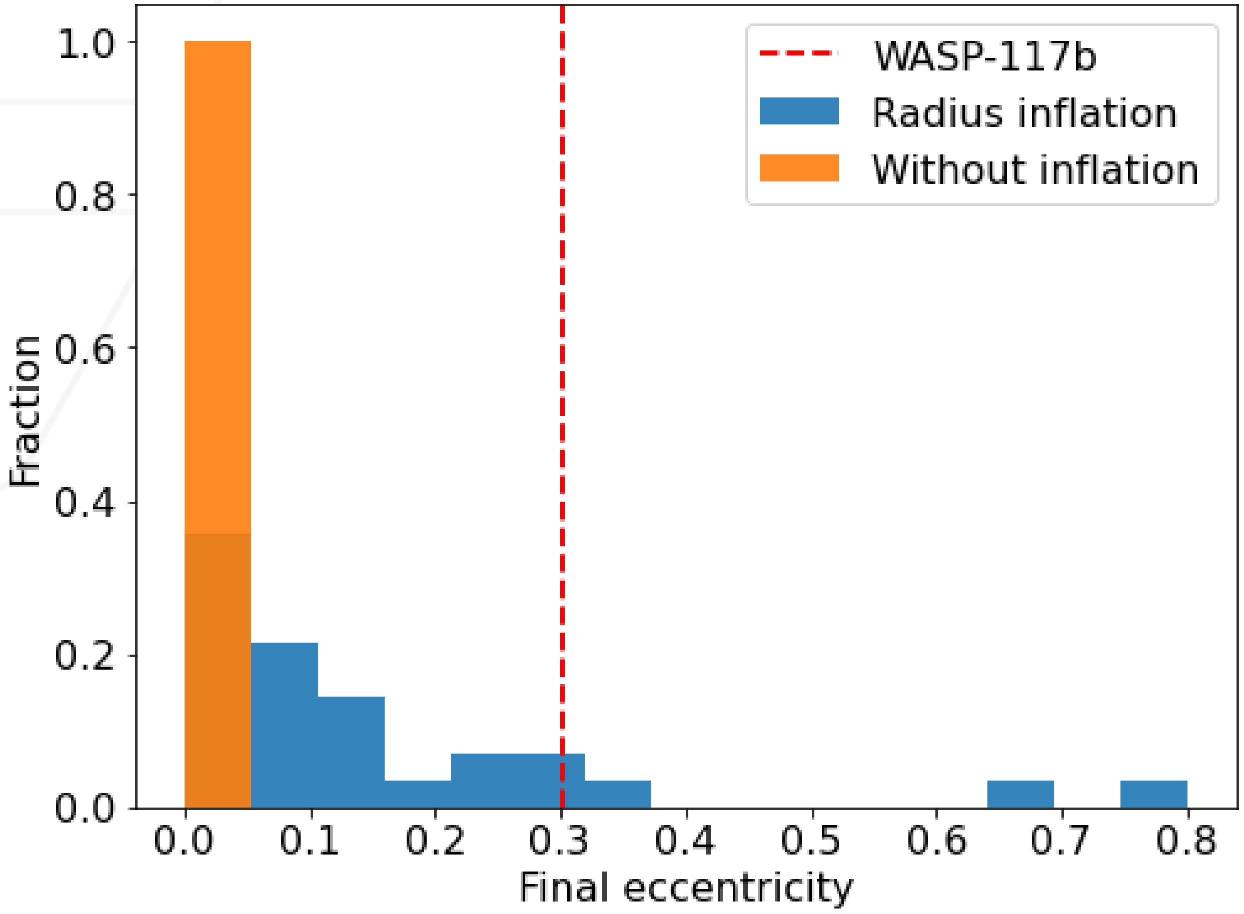


- Radius inflation increases the final orbital period to ~ 10 days.
- ~10 days is exactly what we need for warm Saturn WASP-117b.

Gao and Li in prep.

Parameter dependencies

- Final eccentricity distribution

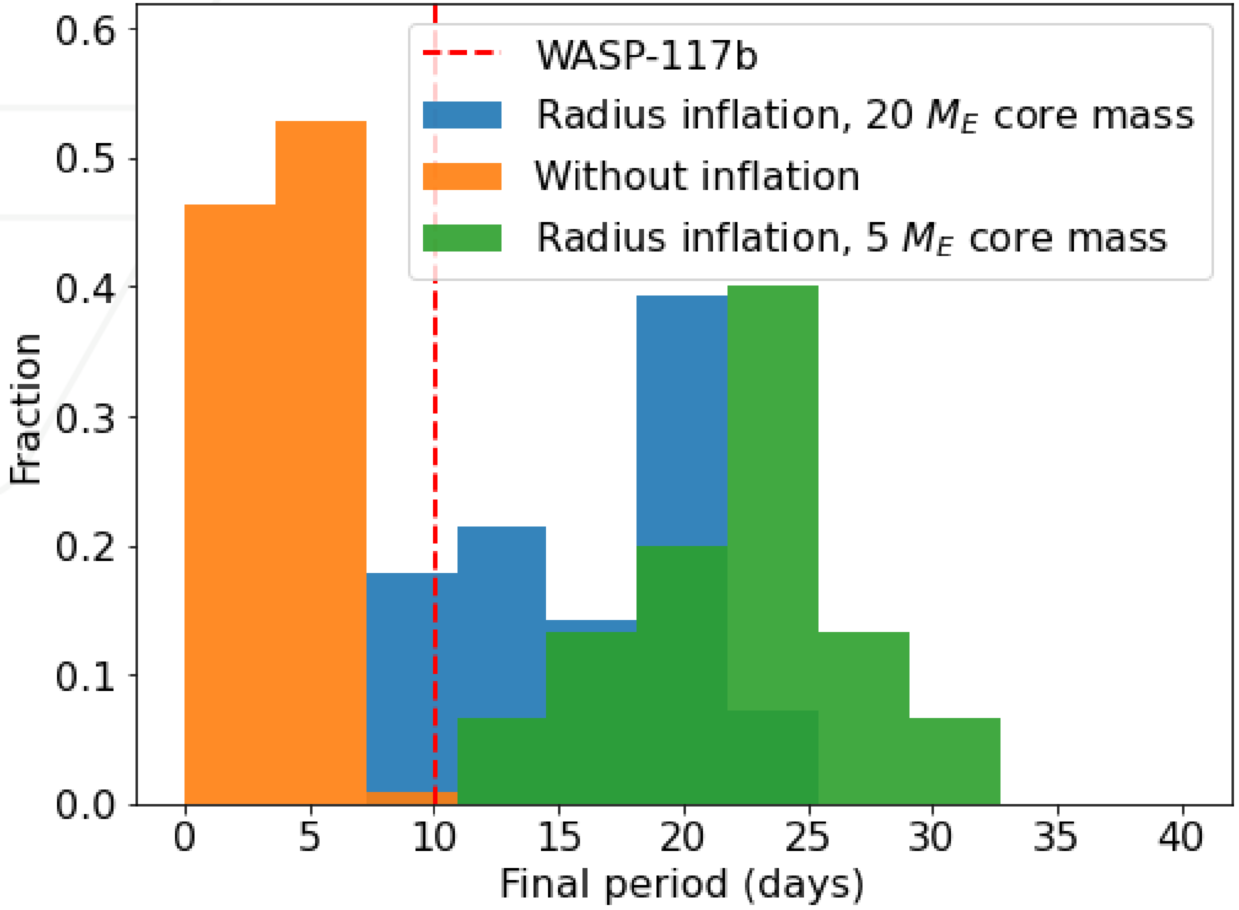


- Radius inflation induces larger final eccentricity, due to larger pericenter distance when Kozai suppressed
- Explains the observed residual eccentricity.

Gao and Li in prep.

5 M_E core mass simulation

- Final orbital period distribution



- Lager final period than 20 M_E core mass case.
- Lower core mass leads to higher radius inflation, thus suppresses L-K effect at even larger pericenter distance.

Gao and Li in prep.

Conclusion

- Tidal heating is capable of explaining the radius inflation of ***warm*** puffy planets.
- Radius inflation suppressed L-K during migration of puffy planets, leading to residual eccentricity and larger orbital periods compared with fixed radius.
- Smaller core mass generates larger final radius, larger final orbital periods.

- More transit (eg. ***TESS***) and RV observation for precise determination of the radii and masses of inner planets.
- Long term RV measurements or astrometric measurements, (eg. ***Gaia)*** for characterizing the outer planets.
- Atmosphere chemical abundance observation (eg. ***JWST***) also helps us determine the interior structure and core mass. (Sing et al., 2024)

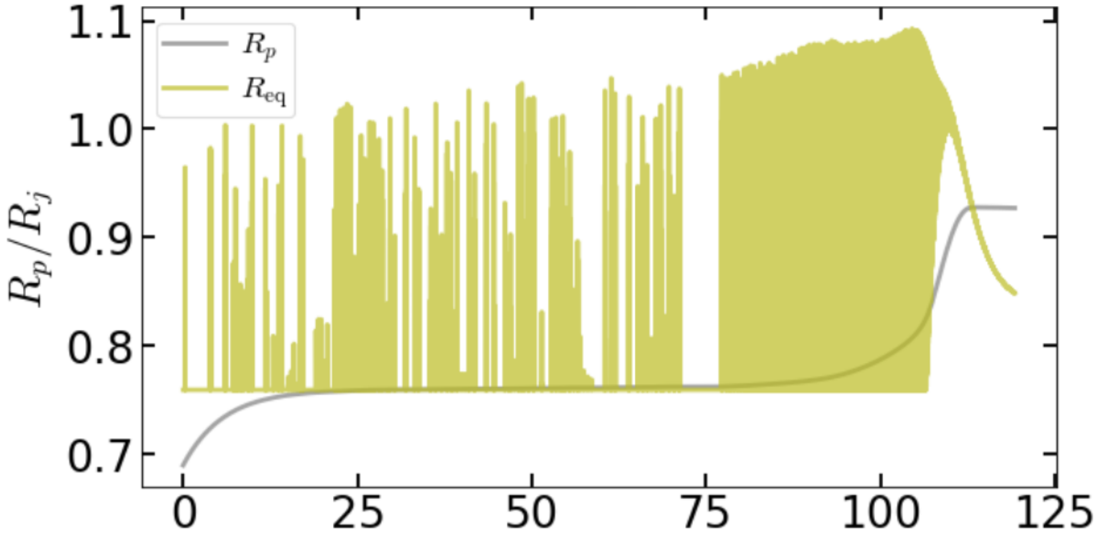
Thank you

Caveats of previous works

- Yu & Dai, 2024:
  - The radius inflation model is an analytical evolution between equilibrium radii

$$\frac{dR}{dt} = \frac{R_{\rm eq} - R}{\tau},$$
$$\tau = \begin{cases} \tau_{\rm def}, & R > R_{\rm eq}, \\ \tau_{\rm inf}, & R < R_{\rm eq}. \end{cases}$$

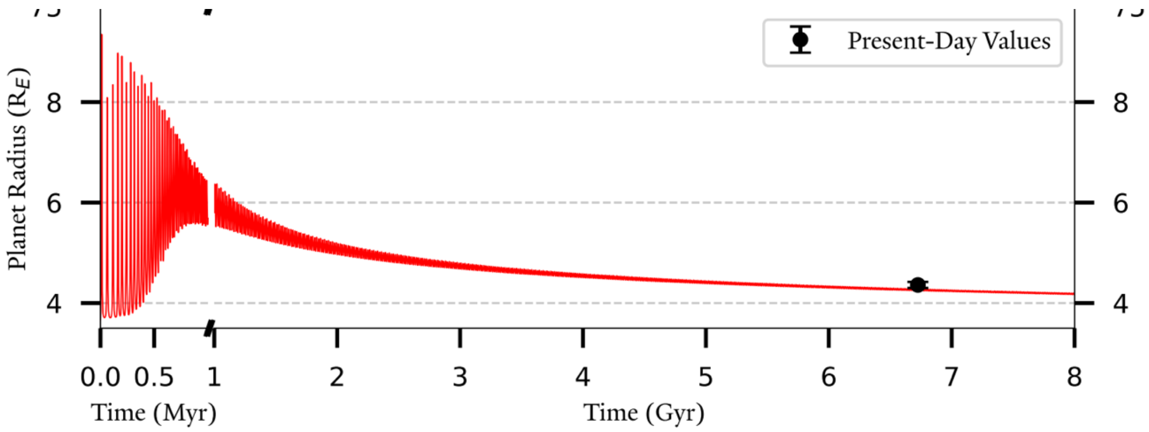
  - Constant timescale should depend on tidal inflation.



- Lu et al., 2024:
  - Used a fitted radius model

$$\frac{R}{R_{\rm E}} = A\left[\log_{10}\left(\frac{\mathcal{L}}{\mathcal{L}_\odot}\right)\right]^4 + B\left[\log_{10}\left(\frac{\mathcal{L}}{\mathcal{L}_\odot}\right)\right]^3 + C\left[\log_{10}\left(\frac{\mathcal{L}}{\mathcal{L}_\odot}\right)\right]^2 + D\left[\log_{10}\left(\frac{\mathcal{L}}{\mathcal{L}_\odot}\right)\right] + E$$

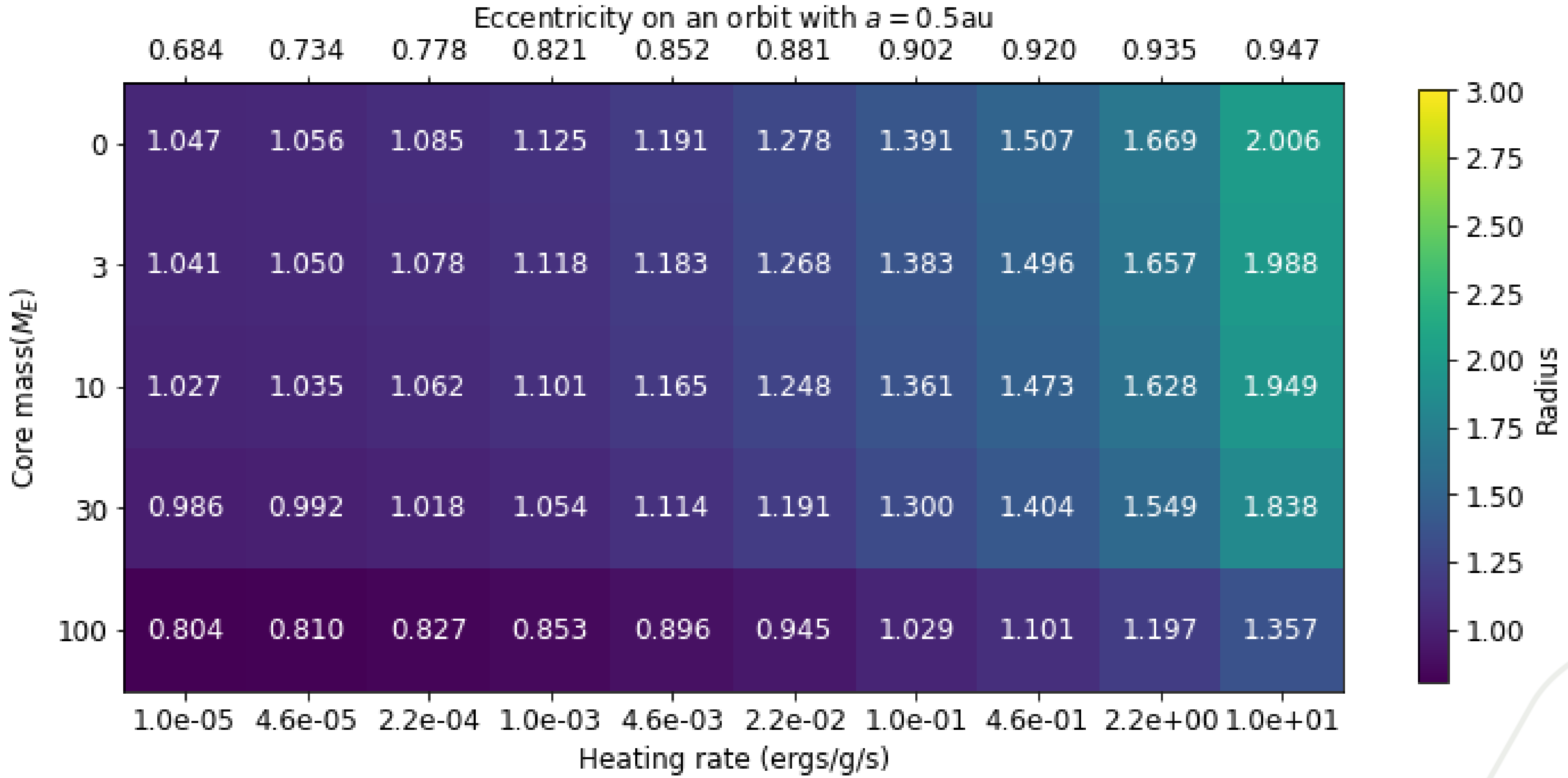
  - Inflation response is instantaneous



Dependence on core mass

- Constant heating on a Jupiter mass planet
  1. Smaller core mass ---> larger radius
  2. a=0.5 au, e=0.95 ---> 2 R_J

Note: We use 20 M_E core mass for our case



Georgia Tech

Couple MESA with secular Kozai effect

Stellar radiation

H/He envelope

Solid core

20 M_E

Tidal heating

MESA

Create planet

Planet model

Evolve

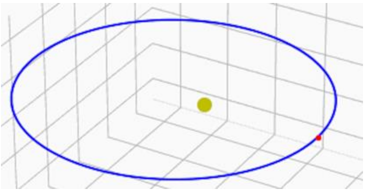
Planet model

Radius

Tidal heating rate

Surface heating rate

....



Secular code

Set initial orbital paras

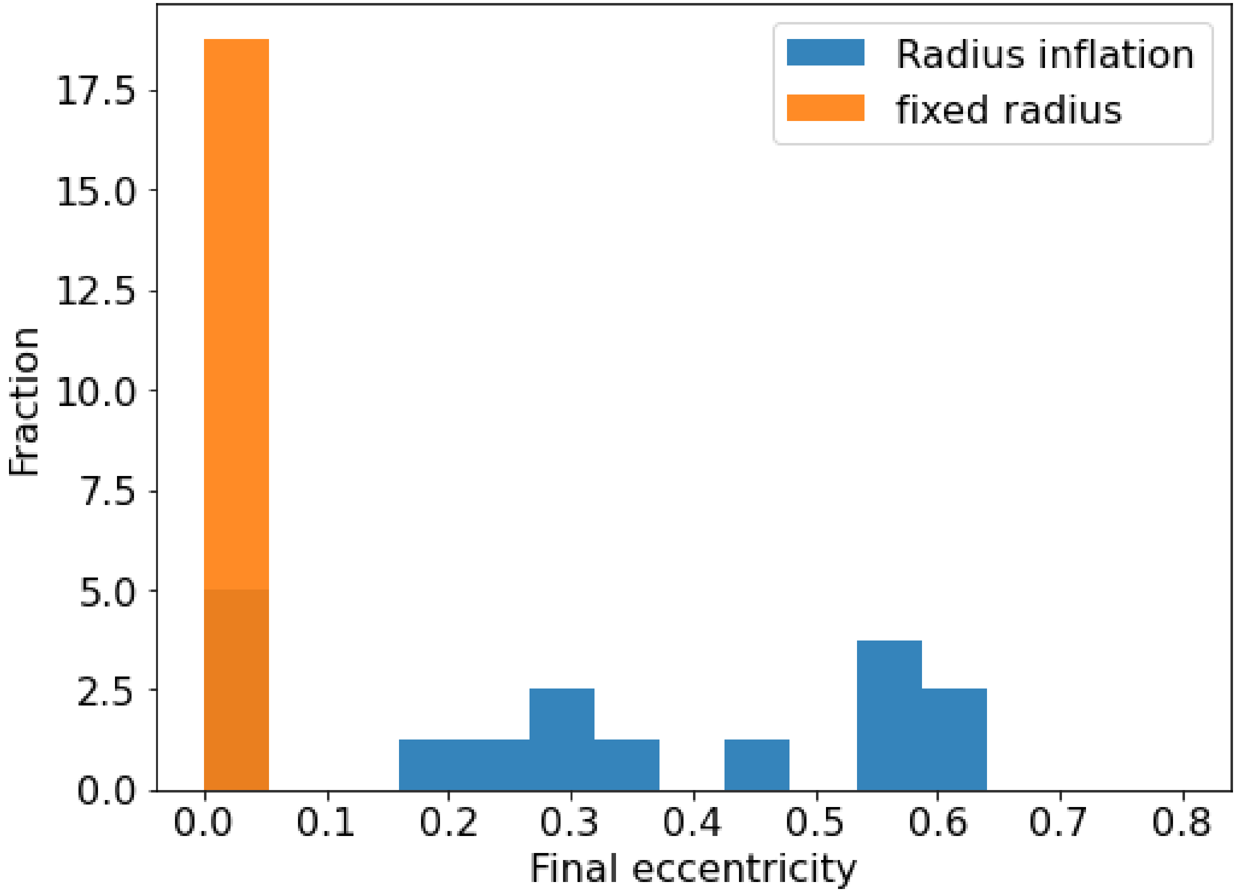
Secular code

Evolve

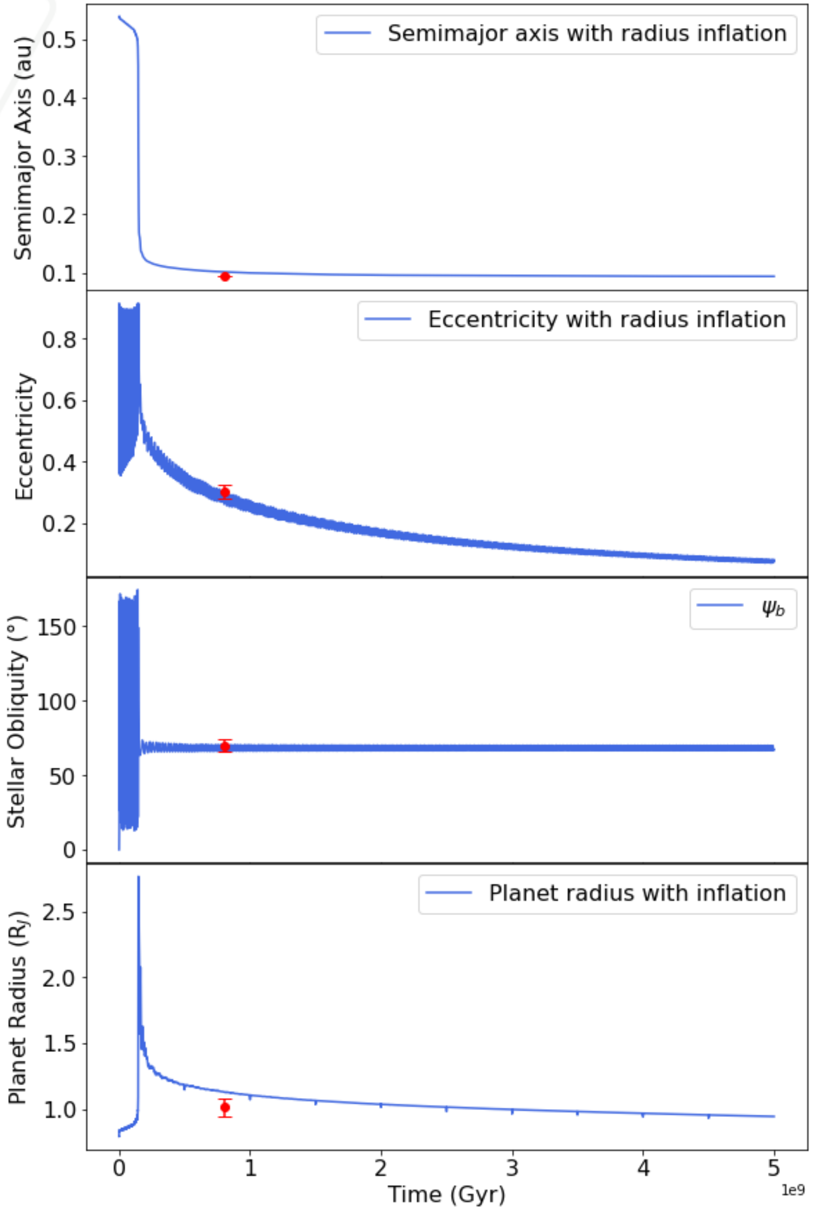
Secular code

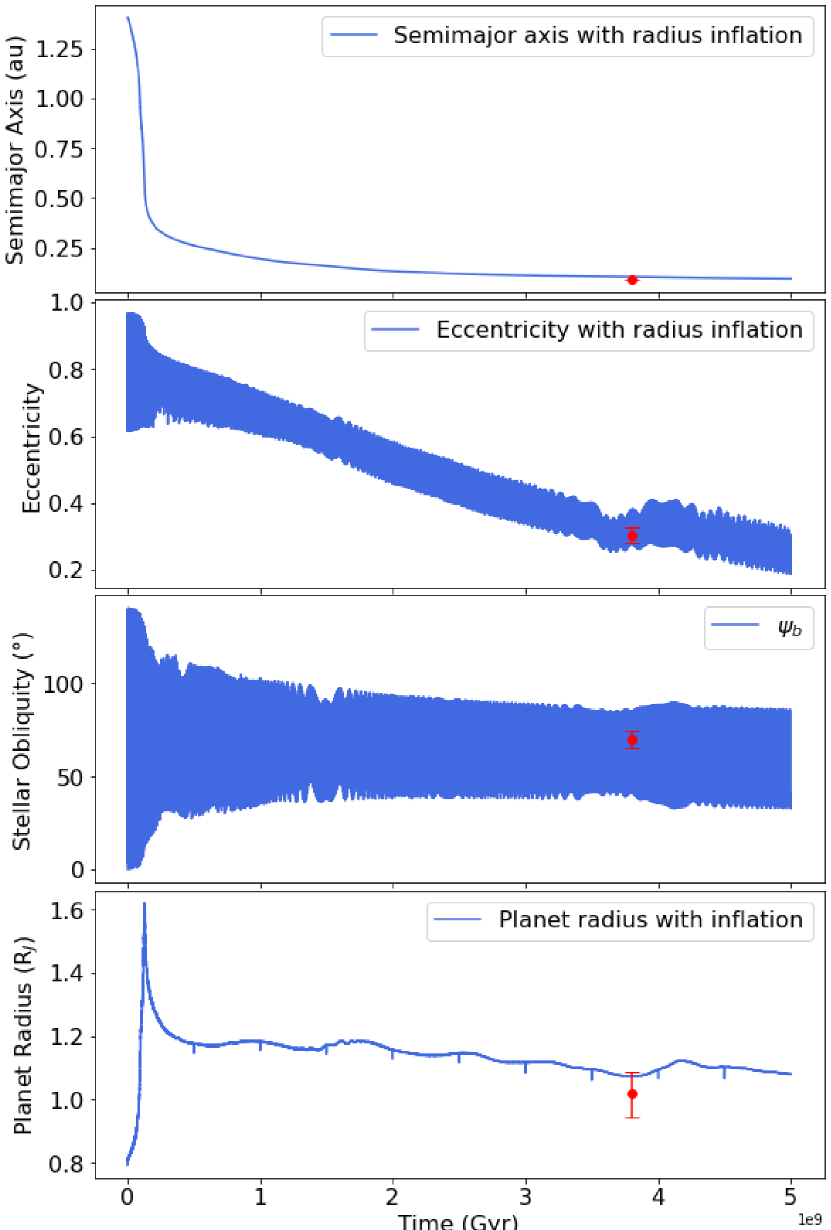
5 M_E core mass simulation

- Final eccentricity



More examples



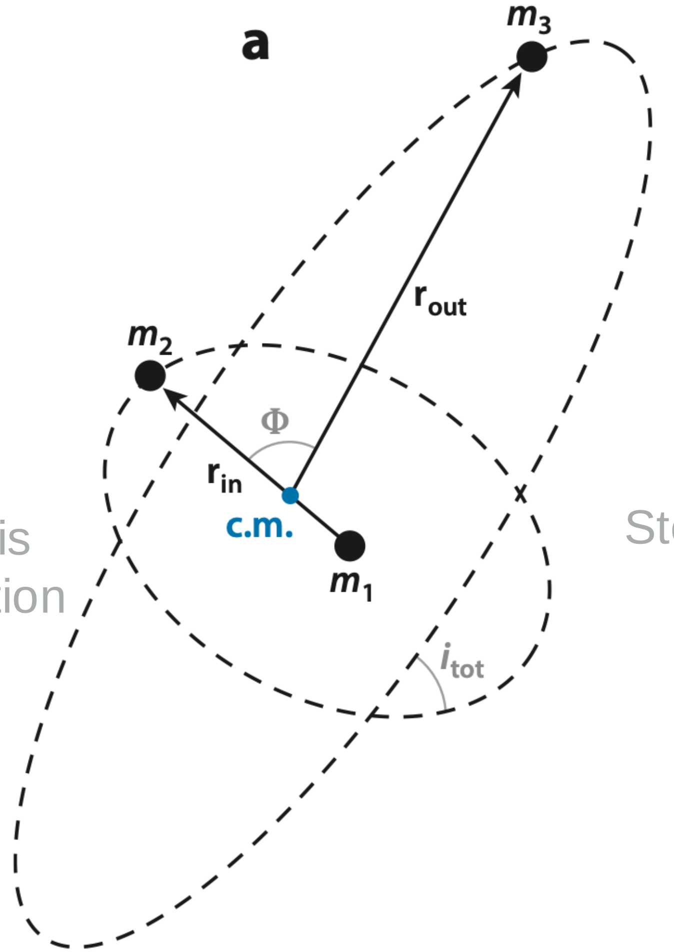


Constrain parameters of a specific system (Such as WASP 117b)

- Large parameter space

Outer planet

Mass
Initial semi-major axis

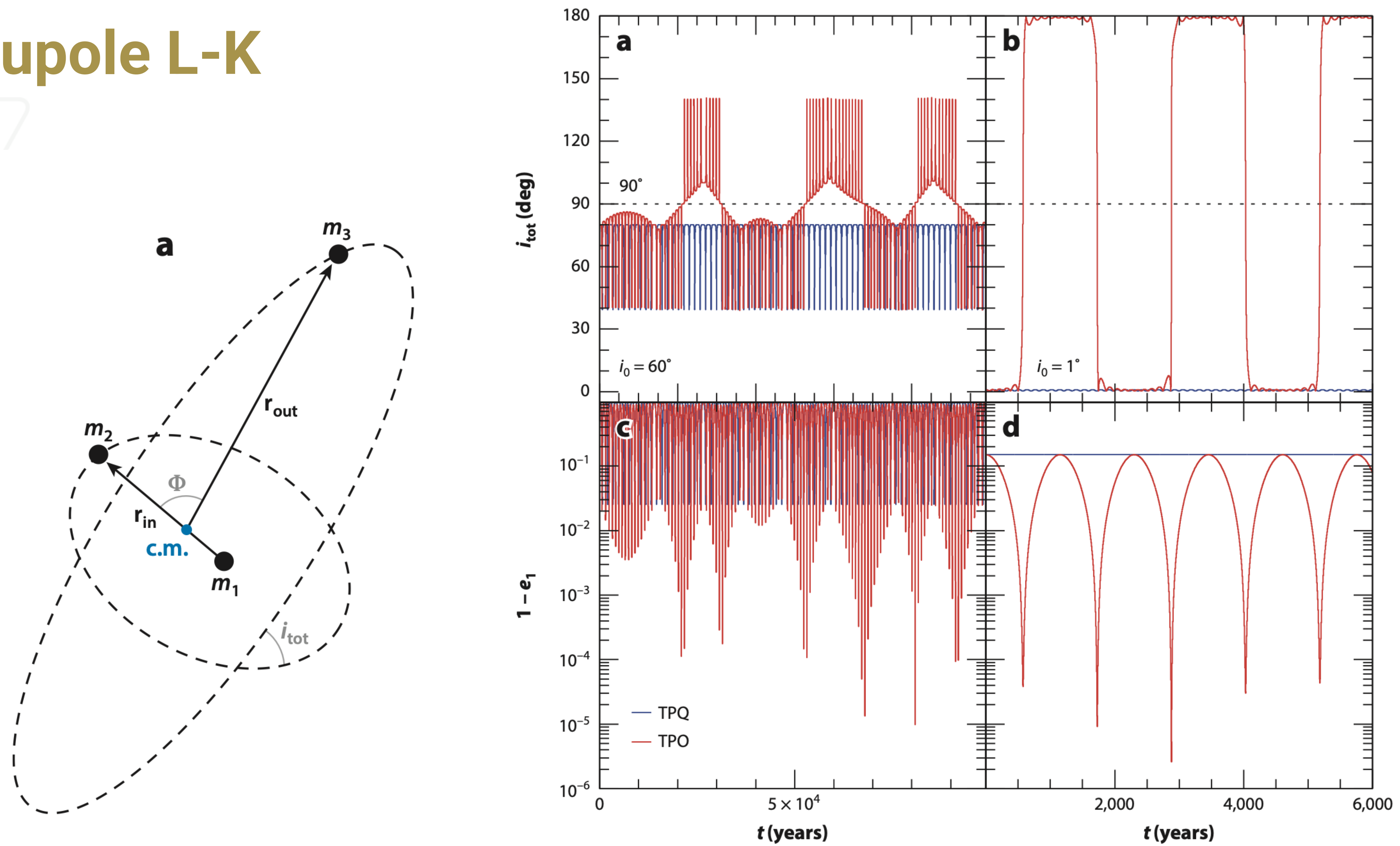


Inner planet

Mass
Core mass
Tidal Q value
Initial semi-major axis
Initial mutual inclination

Stellar age

Octupole L-K

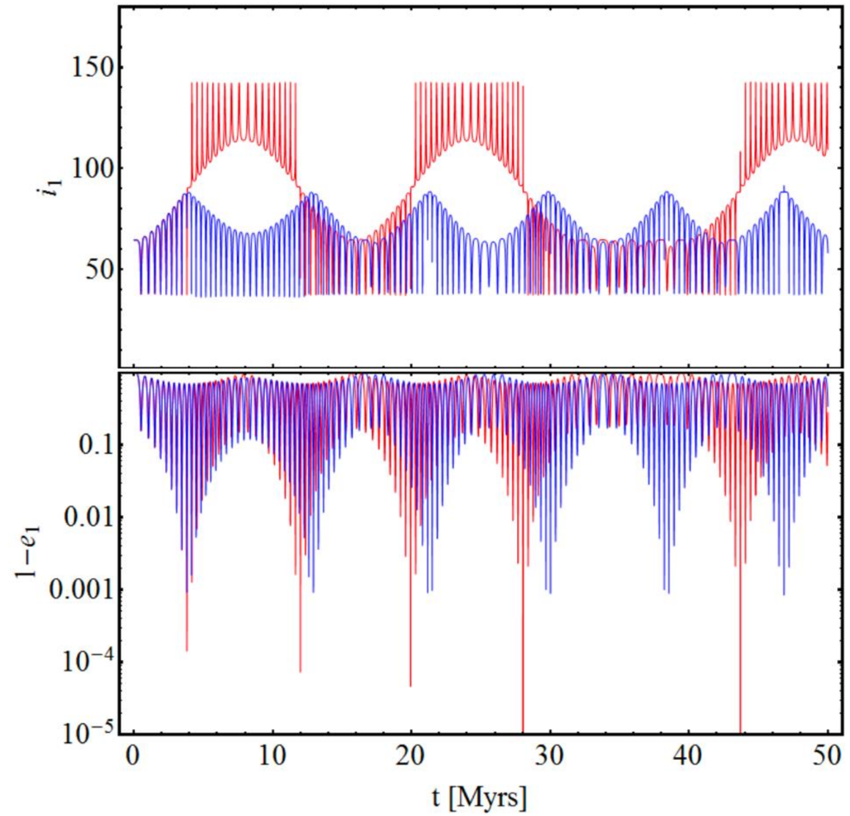

a
m_3
r_{out}
m_2
Φ
r_{in}
c.m.
m_1
i_{tot}
a
b
c
d
90°
$i_0 = 60°$
$i_0 = 1°$
i_{tot} (deg)
$1 - e_1$
TPQ
TPO
t (years)
5×10^4
2,000
4,000
6,000

Short range forces

- Stop planet from plunge into the star

$$\varepsilon_{\rm GR} \equiv \frac{3G(m_0+m_1)^2 a_2^3 (1-e_2^2)^{3/2}}{a_1^4 c^2 m_2}$$

$$\varepsilon_{\rm Tide} \equiv \frac{15 m_0 (m_0+m_1) a_2^3 (1-e_2^2)^{3/2} k_{2,1} \boxed{R_1^5}}{a_1^8 m_1 m_2}$$



Tidal dissipation

- Tidal dissipation rate:

$$L_{\mathrm{tide}}(e,\ \epsilon) = \frac{2K}{1 + \cos^2 \epsilon}[\sin^2 \epsilon + \boxed{e^2}(7 + 16 \sin^2 \epsilon)].$$

$$K = \frac{3n}{2} \frac{k_2}{\boxed{Q}} \left(\frac{GM_\star{}^2}{R_p}\right)\left(\frac{R_p}{a}\right)^6,$$

- High eccentricity will introduce super high heating rate, make the planet explode.