PLANETARY ENGULFMENT AS A TRIGGER FOR WHITE DWARF POLLUTION

Petrovich & Muñoz, ApJ 834, 2 (2017)

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e.g., Vanderburg et al (2015
asteroid around WD 1145+017, a white dwarf located 570 light-ye
Image Credit: CfA/Mark
25-50% polluted (Koester et al, 2014),
~1-5% dusty disks (Farihi et al 2009; Rocchetto et al2015)

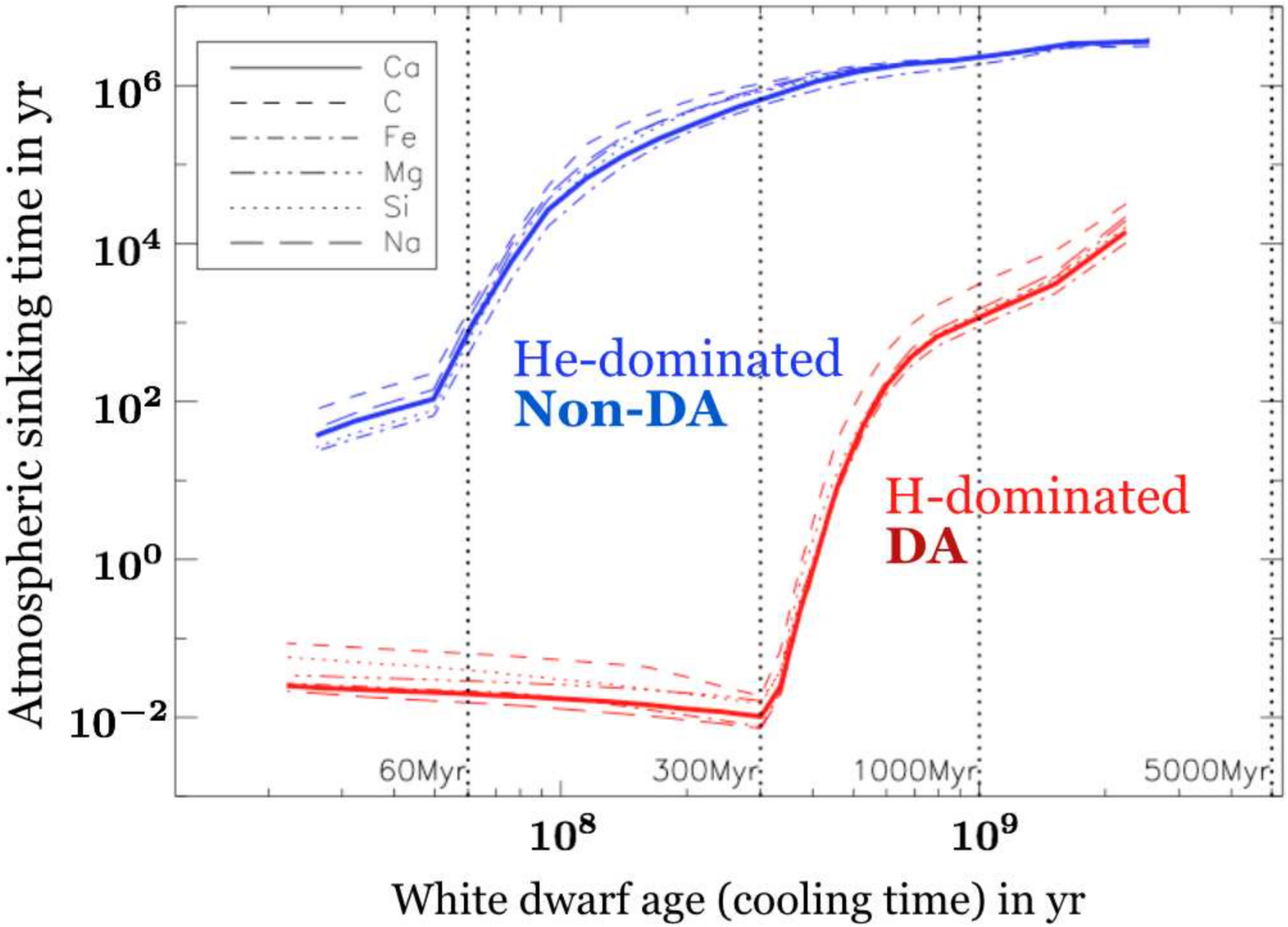
The **puzzles in WD pollution** include a **problem of timescales,** a problem of **delivery efficiency,** and problem of **composition**

1. **Sinking/settling** timescale

"You can only have a duty cycle of ~3"

— Andrew Shannon

Observations



(Review articl
Veras, D. 201

We should detect metals <<0.1% of the time, but pollution in DA WD's detected ~25% of the time —> accretion is **ongoing**!

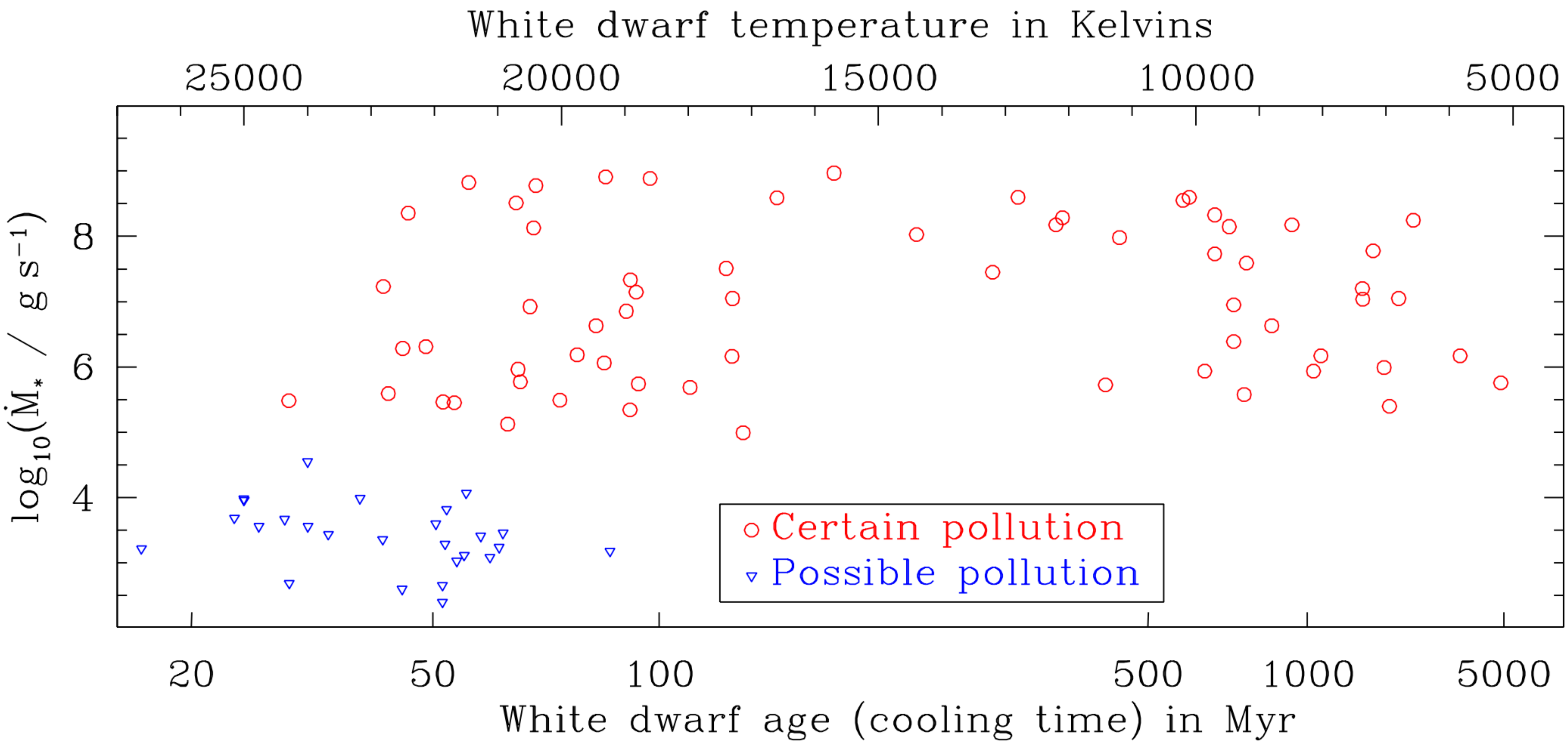
The **puzzles in WD pollution** include a **problem of timescales,** a problem of **delivery efficiency,** and problem of **composition**

I. **Sinking/settling** timescale

II. **Age-of-polluted-targets** timescale

Observations

Independent of age…



(Review article: Veras, D. 2016)

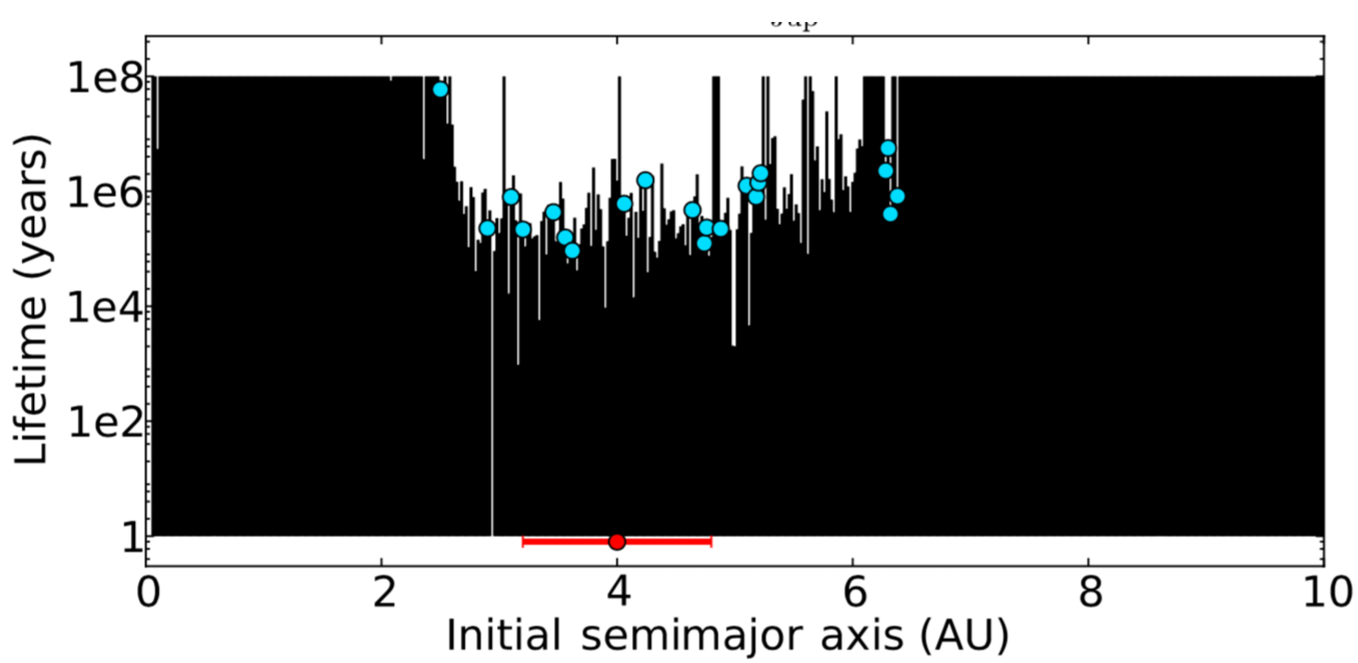
We need a **steady supply of material**; and we also need a

and we need a **sustained supply/long-lasting of material**

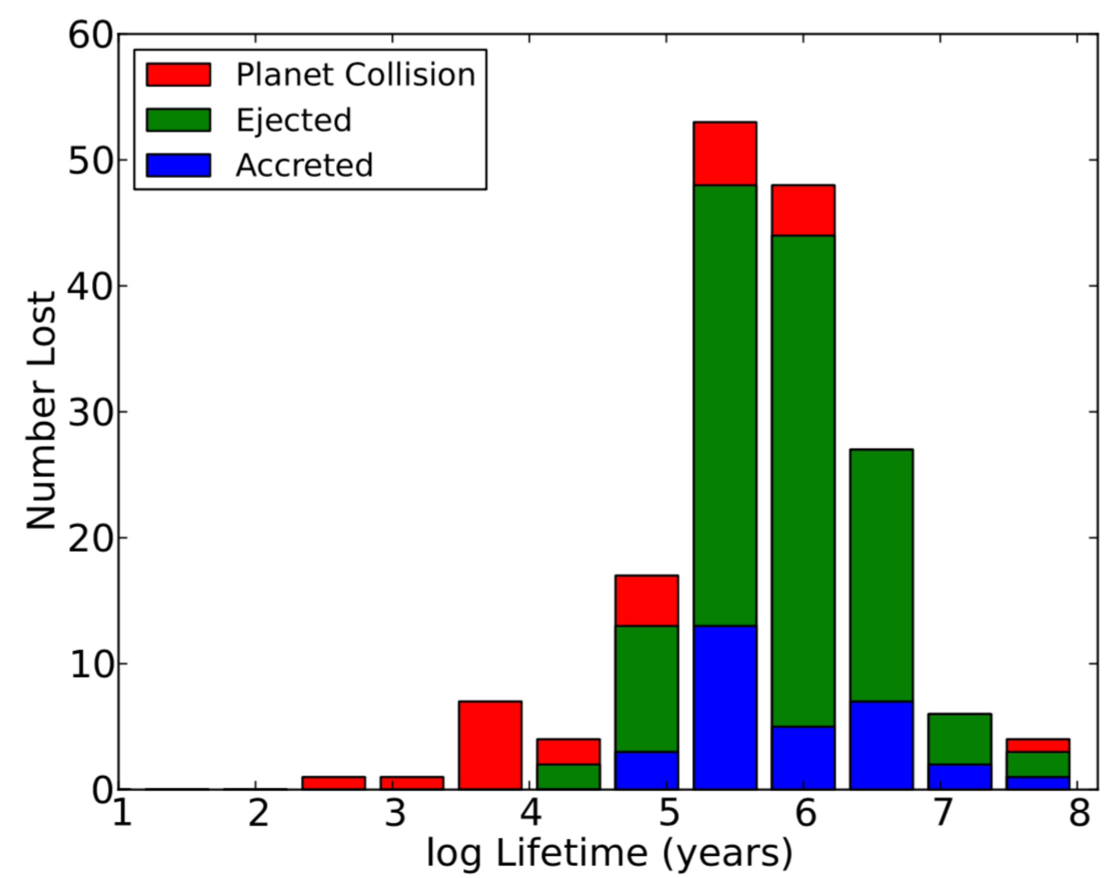
This is a **difficult to achieve via N-body/ dynamical processes**

Debes & Sigurdsson 2002: *planetary instabilities triggered by mass loss (MS to WD)*

$$\text{Unstable if: } \frac{\Delta a}{a} <\sim 3\left(\frac{m_{planet}}{M_{star}}\right)^{1/3}$$



Frewen & Hansen 2014



Hard to pollute old systems…

This is a **difficult to achieve via N-body/ dynamical processes**

"It has been difficult to explore the dynamics beyond 1Gyr!"

— Dimitri Veras

"Getting it down to the star is the difficult part"

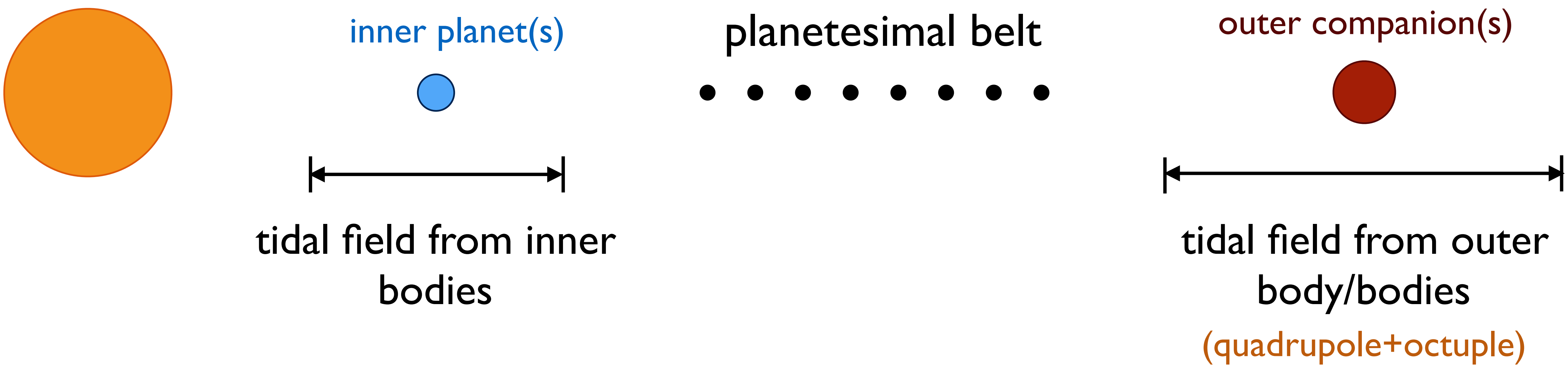
— Andrew Shannon

Secular instabilities...

- act **very slowly** (compared to dynamical time),
- span a **wide range of timescales**,
- can produce **eccentricities of 0.9999**
- can be easily stabilized by additional bodies

Commonly associated to **distant companions**: i.e., Lidov-Kozai oscillations (Lidov, 1962; Kozai, 1962)

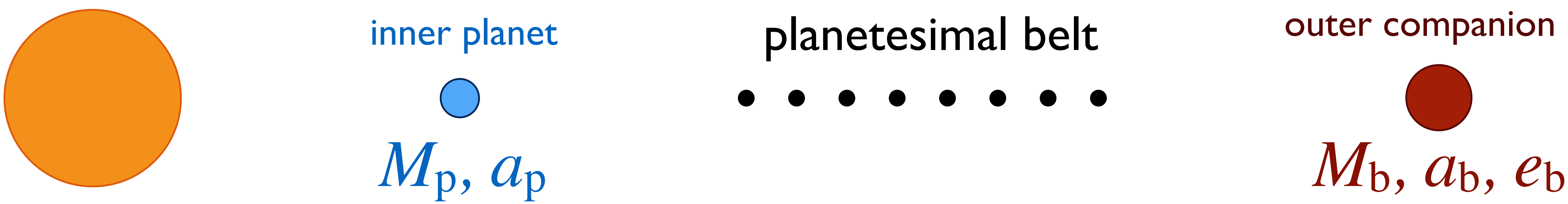
The tidal field of an **inner planetary** system can **shield planetesimals** against external perturbations: **engulfment is a trigger**



The tidal field of an **inner planetary** system can **shield planetesimals** against external perturbations: **engulfment is a trigger**

$$\dot{\varpi}_{\mathrm{in}} \simeq \frac{1}{2} n \left(\frac{M_{\mathrm{p}}}{M_{\mathrm{s}}}\right)\left(\frac{a_{\mathrm{p}}}{a}\right)^2$$

$$\dot{\varpi}_{\mathrm{out}} \simeq n \left(\frac{M_{\mathrm{b}}}{M_{\mathrm{s}}}\right)\left(\frac{a}{a_{\mathrm{b}}}\right)^3$$



The two tidal fields are of equal magnitude when

$$\boxed{\dot{\varpi}_{\mathrm{in}} = \dot{\varpi}_{\mathrm{out}}}$$

or

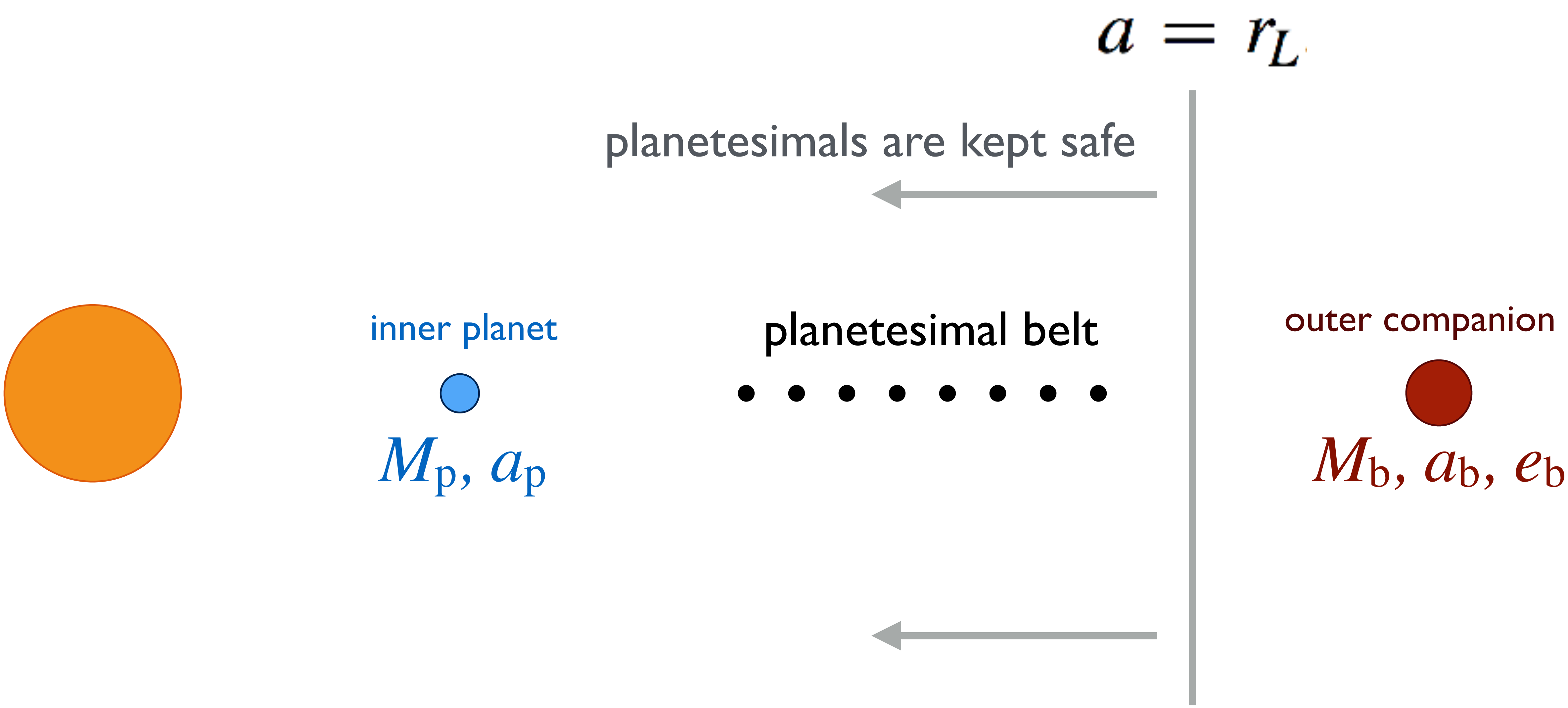
$$\boxed{a = r_L}$$

where

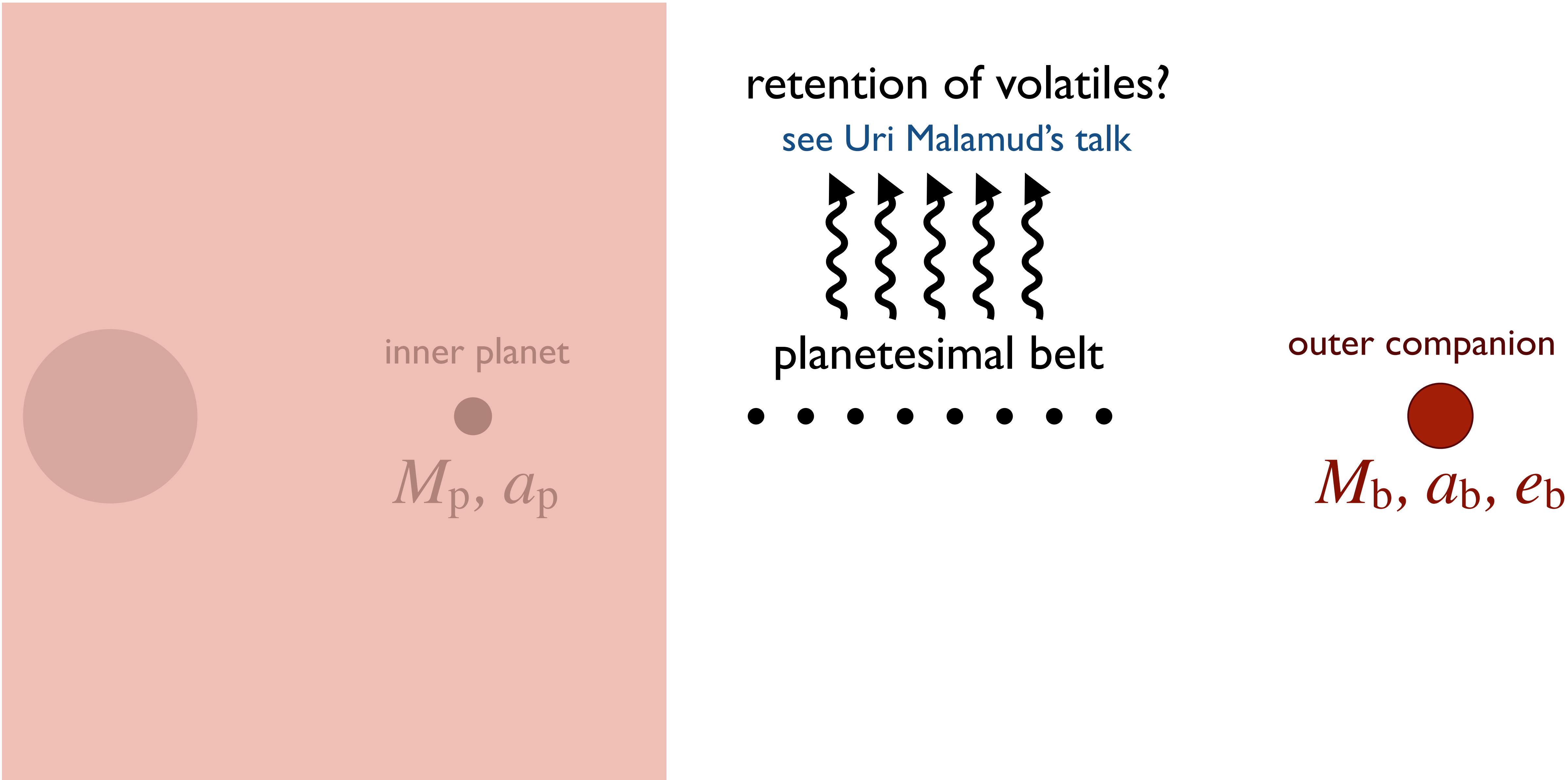
$$r_{\mathrm{L}} \equiv \left(\frac{M_{\mathrm{p}}}{2M_{\mathrm{b}}} a_{\mathrm{p}}^2 a_{\mathrm{b}}^3 [1 - e_{\mathrm{b}}^2]^{3/2}\right)^{1/5}$$

the so-called *Laplace radius*

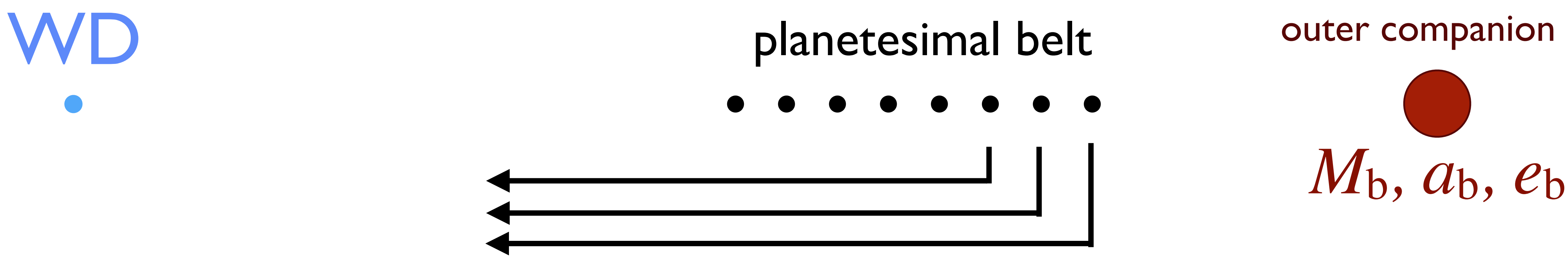
The tidal field of an **inner planetary** system can **shield planetesimals** against external perturbations



The tidal field of an **inner planetary** system can **shield planetesimals** against external perturbations: **engulfment is a trigger**



Planetary engulfment (if "fast" enough) **removes** this tidal **shielding**, suddenly **exposing planetesimals to secular instabilities**



if unstable, eccentricity ~1 over an (octupole) timescale

$$\boxed{\sim \epsilon_{\rm oct}^{-1/2} \tau_{\rm KL} \propto a^{-2}}$$ ~0.1 -10 Gyr

$$\tau_{\rm KL} \sim 8 \text{ Myr}$$

e-growth **timescale increases inward**

Secular Dynamics

Secular 4-body problem (Hamers 2015, Muñoz & Lai 2015)

$$\boxed{\Phi = \langle \Phi_{\rm in,quad} \rangle + \langle \Phi_{\rm in,Oct} \rangle + \langle \Phi_{\rm out,quad} \rangle + \langle \Phi_{\rm out,Oct} \rangle}$$

$$\langle \Phi_{\rm in,quad} \rangle (\mathbf{e},\mathbf{j}) = -\frac{1}{8}\frac{\mathcal{G}M_{\rm in}}{a} \epsilon_{\rm in} (1-e^2)^{-5/2} \left[(1-6e_{\rm in}^2)(1-e^2) - 3(\hat{\mathbf{j}}_{\rm in}\cdot\mathbf{j})^2 + 15 e_{\rm in}^2 (\hat{\mathbf{e}}_{\rm in}\cdot\mathbf{j})^2 \right]$$

$$\langle \Phi_{\rm out,quad} \rangle (\mathbf{e},\mathbf{j}) = -\frac{1}{8}\frac{\mathcal{G}M_{\rm in}}{a} \epsilon_{\rm out} (1-e_{\rm out}^2)^{-3/2} \left[1-6e^2 - 3(\hat{\mathbf{j}}_{\rm out}\cdot\mathbf{j})^2 + 15 (\hat{\mathbf{j}}_{\rm out}\cdot\mathbf{e})^2 \right],$$

Strength of the tidal potentials

$$\boxed{\epsilon_{\rm in} \equiv \left(\frac{\mu_{\rm in}}{M_{\rm in}}\right)\left(\frac{a_{\rm in}}{a}\right)^2} \xrightarrow{\text{long time}} 0$$

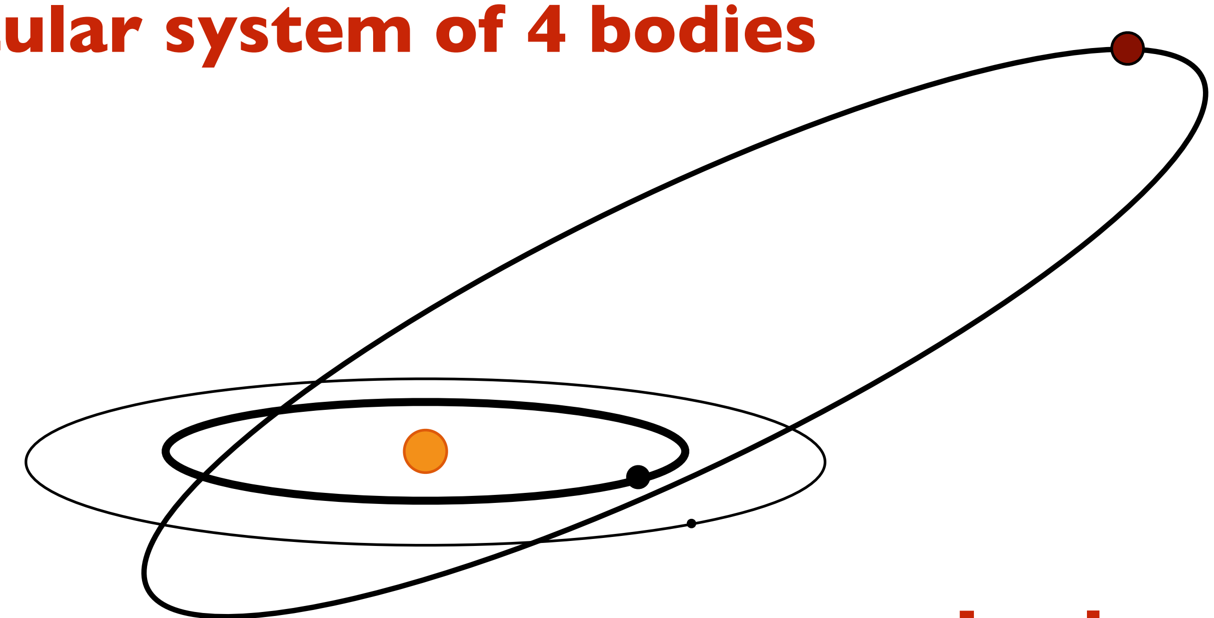
$$\boxed{\epsilon_{\rm out} \equiv \frac{1}{(1-e_{\rm out}^2)^{3/2}}\left(\frac{M_{\rm out}}{M_{\rm in}}\right)\left(\frac{a}{a_{\rm out}}\right)^3}$$

Same set of eqs. Muñoz & Lai 2015

As an example: WD **pollution induced by a binary**

see also Bonsor & Veras (2015), Kratter & Perets (2012)

secular system of 4 bodies



$$M_s = 2M_\odot$$
$$M_p = 1M_J$$
$$M_b = 0.5M_\odot$$
$$a_p = 2 \text{ au}$$
$$a_b = 600 \text{ au}$$
$$e_b = 0.5$$
$$i_b = 80^\circ$$

Laplace radius

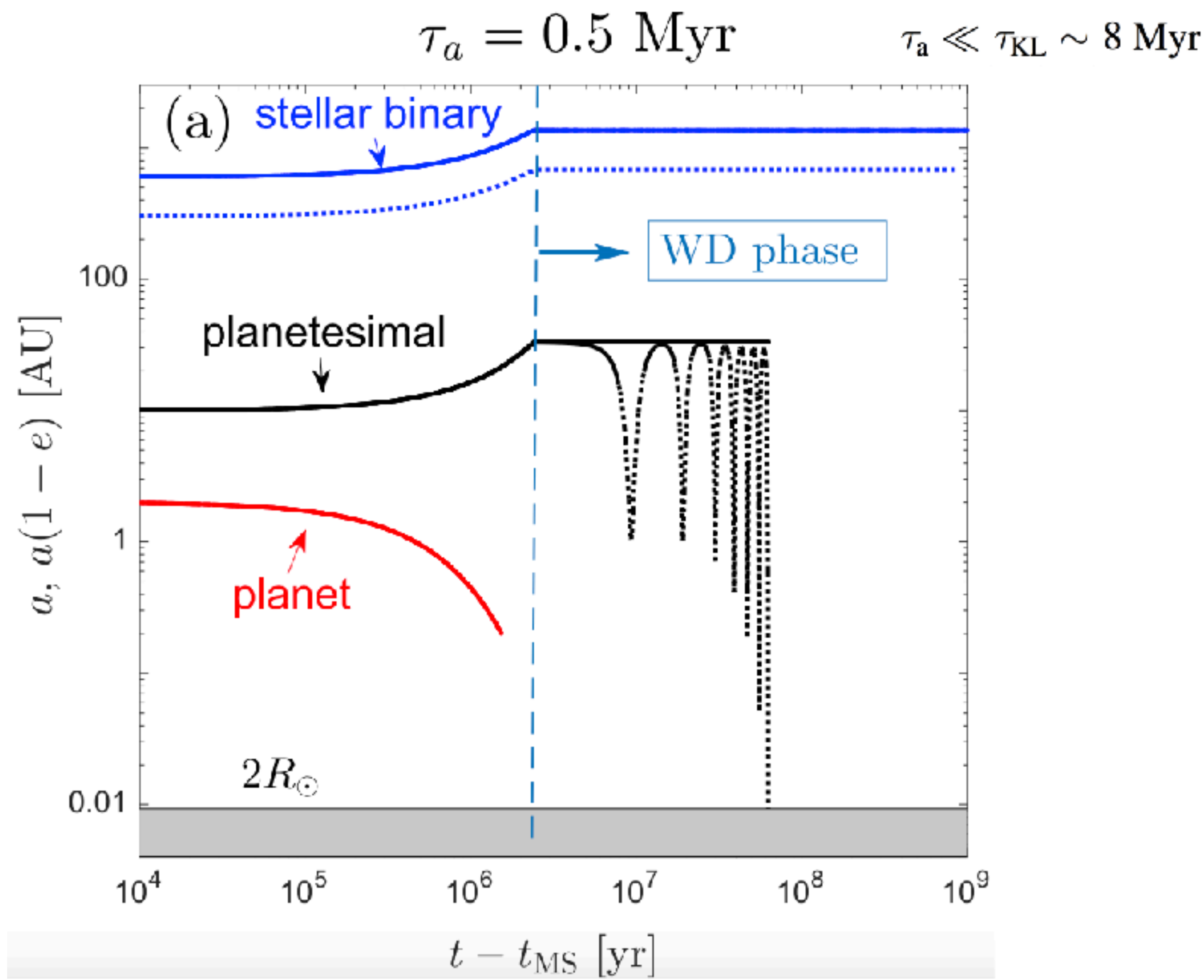
$$\boxed{r_L \approx 16 \text{ au}}$$

and we place a test particle at

$$a = 10 \text{ au}$$

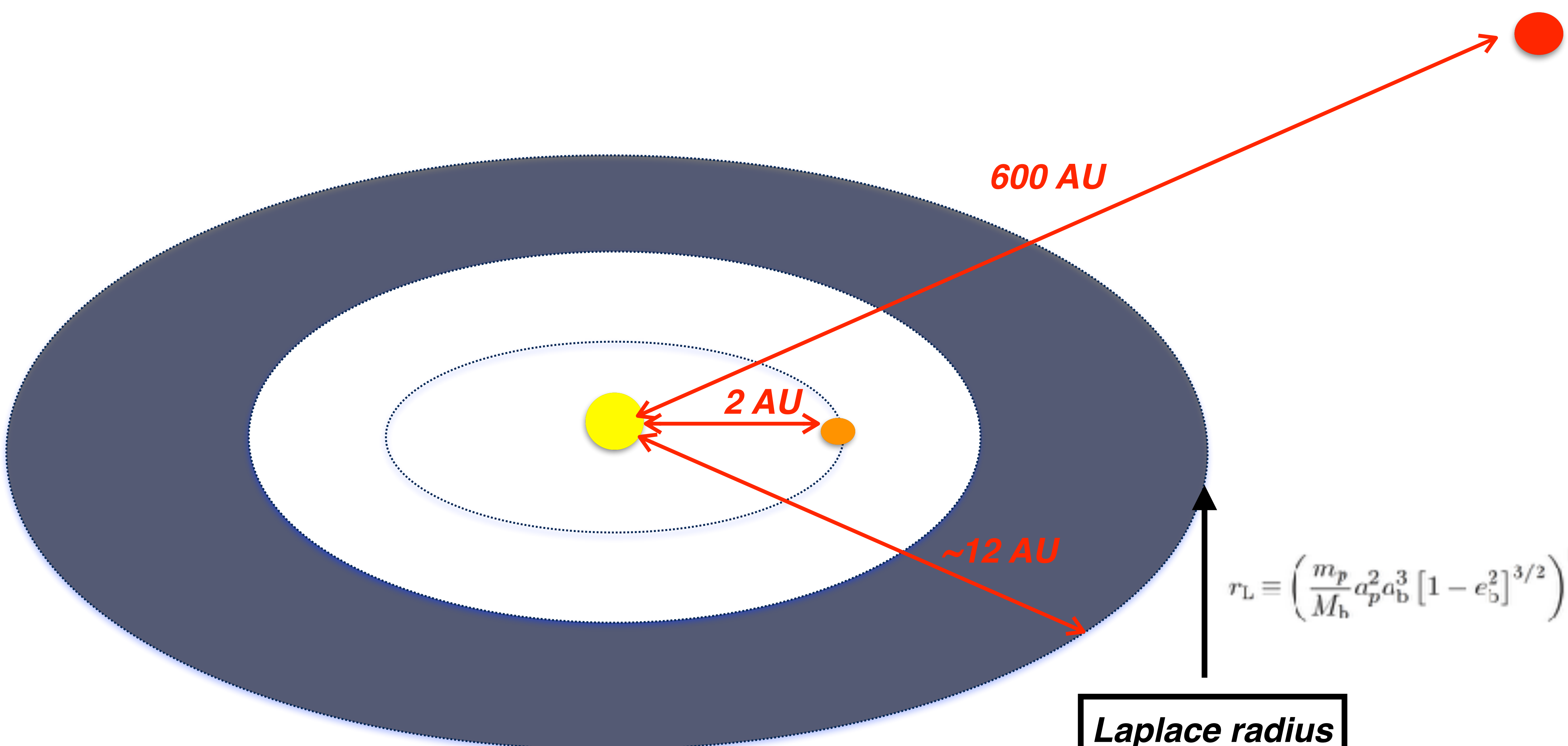
planetesimals in a belt of $a_p < a < r_L$ will be **safe** for as long as the is a planet

As an example: WD **pollution induced by a binary**



As an example: WD **pollution from a belt of planetesimals**

$$\Sigma(a) = \frac{M_{\rm disk}}{2\pi(a_{\rm out} - a_{\rm in})} \cdot \frac{1}{a},$$



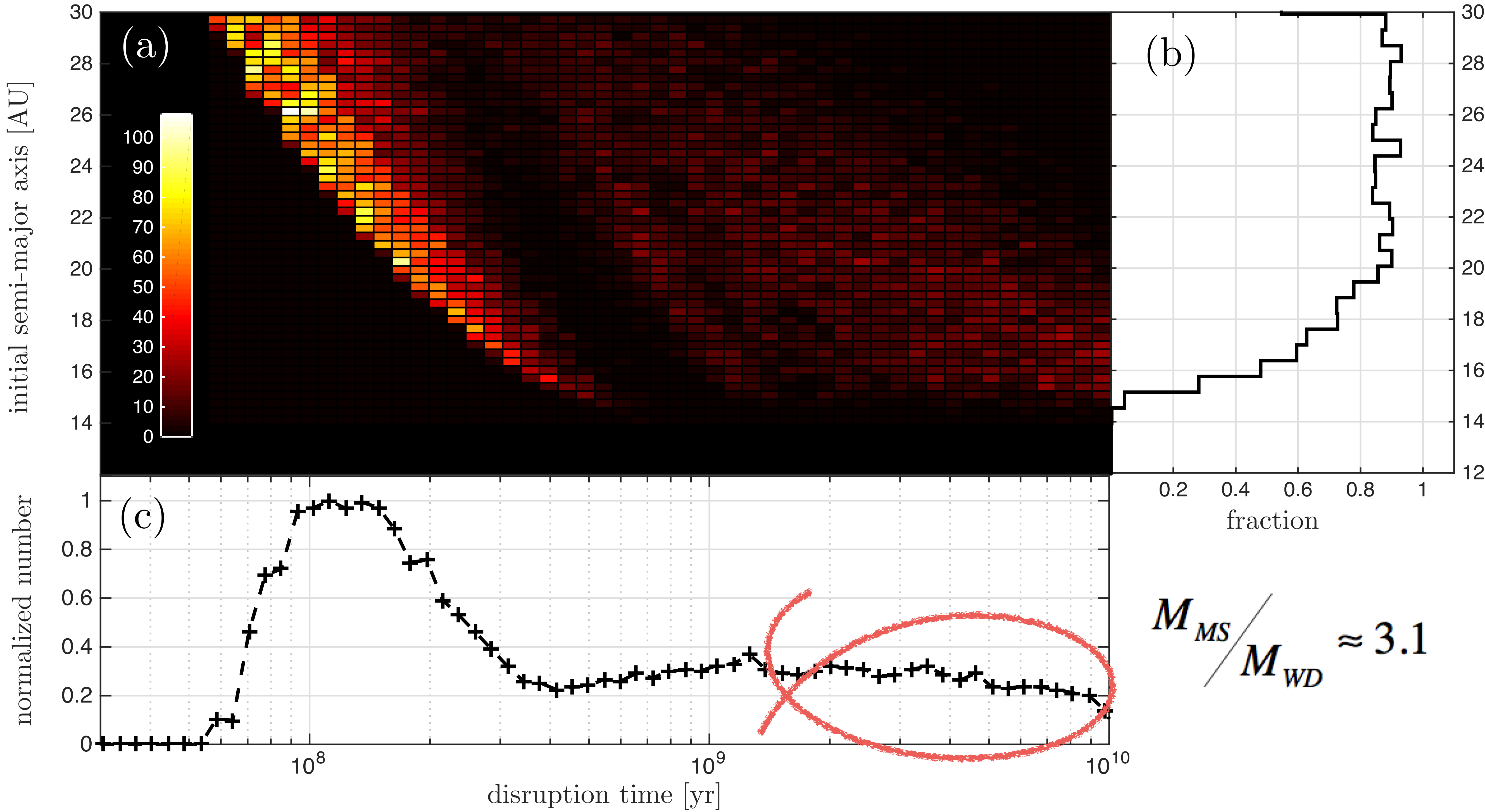
$$r_{\rm L} \equiv \left(\frac{m_p}{M_{\rm b}} a_p^2 a_{\rm b}^3 \left[1 - e_{\rm b}^2\right]^{3/2} \right)^{1/5}$$

Laplace radius

(Kozai-Lidov timescale=precession timescale due to the planet)

Disruption timescales

Evolve disk of 10^5 test particles for up to 10 Gyr



$$M_{MS} / M_{WD} \approx 3.1$$

$$dN / d \log(t) \sim \text{cst.}$$

We turn **body disruption rate** into **mass accretion rates**.

rate of arrival to Roche limit

disk mass

$$\boxed{\frac{dM_{\rm acc}}{dt} = \frac{df_{\rm td}}{dt} \cdot f_{\rm acc} \cdot M_{\rm disk}}$$

disrupted-to-accreted efficiency

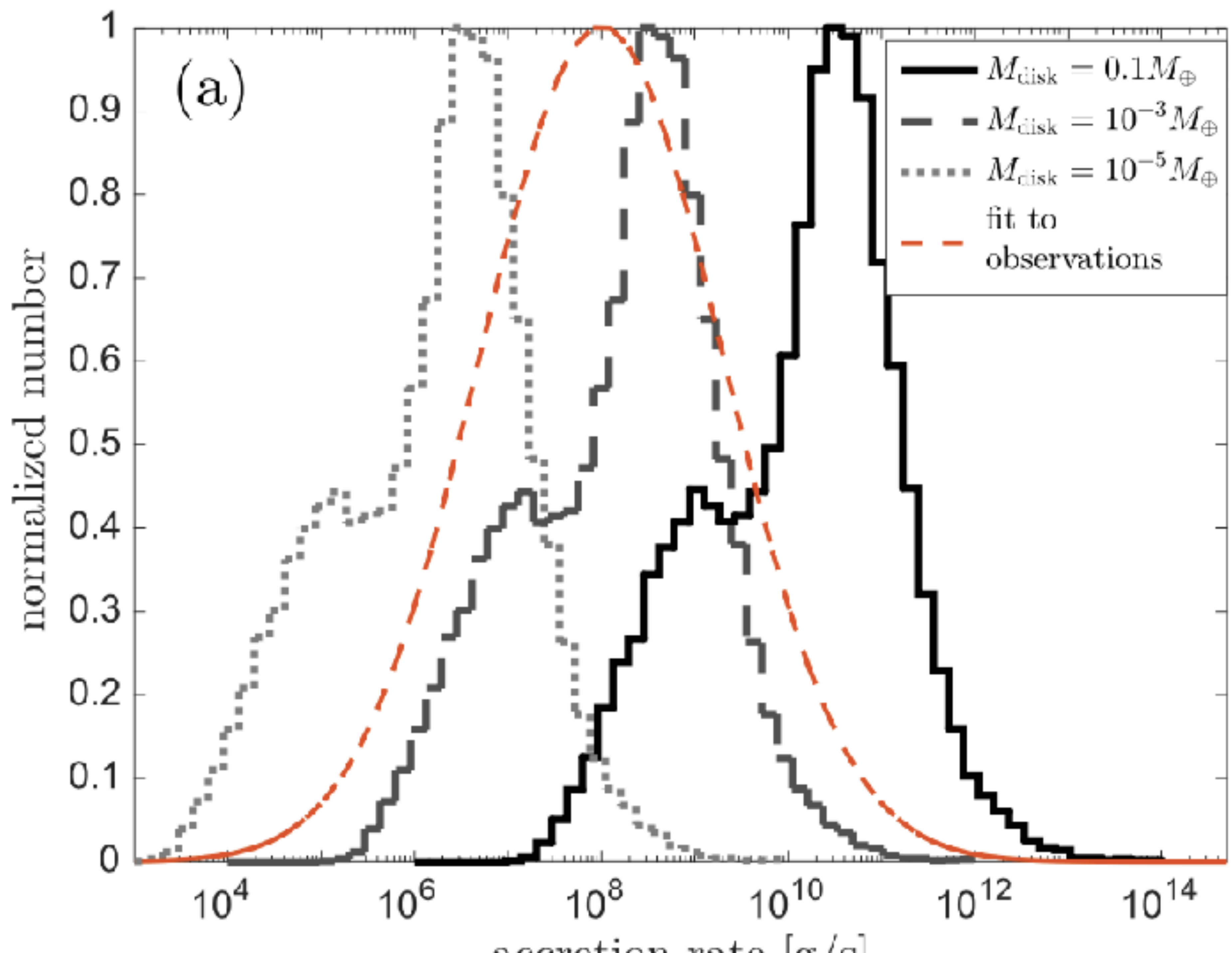
We want $M_{\rm disk}$ to be as large as possible **provided self-gravity is not important**, and **self-grinding is not important** (Heng & Tremaine, 2010)

$$\boxed{M_{\rm disk} \lesssim M_{\oplus}}$$ is OK

over $\sim$10–40 au

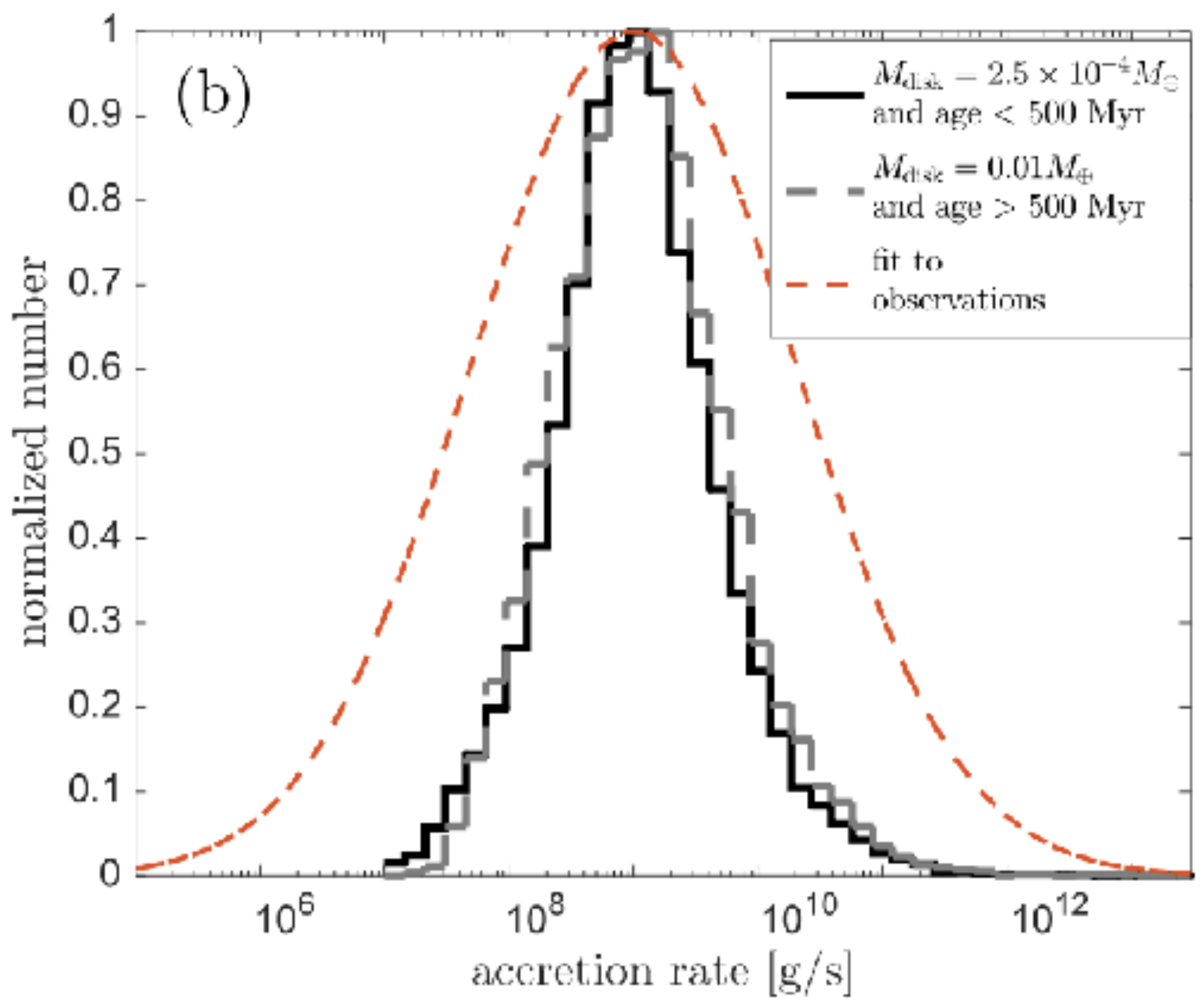
We turn **body disruption rate** into **mass accretion rates**.

$$\frac{dM_{\rm acc}}{dt} = \frac{df_{\rm td}}{dt} \cdot f_{\rm acc} \cdot M_{\rm disk}$$



fit to observations from Wyatt (2014)

Given a binary companion, an entire (approx) belt of planetesimals can be funneled into the WD



Requires of masses of ~0.01 Earth masses with substantial spread

Restrictions in disk mass (Heng & Tremaine 2010,Batygin et al 2011)

Given a binary companion, an entire (approx) belt of planetesimals can be funneled into the WD

but do we have **enough binaries?**

Can **late-onset Kozai-like mechanisms** explain the **pollution rates**?

$$f_{\mathrm{poll}} \equiv f_T \cdot f_{\mathrm{KL}} \cdot f_b \cdot f_p$$

similar to what one does for high-e migration
(e.g., Naoz et al. 2012; Petrovich 2015a; Anderson et al. 2016; Muñoz et al. 2016).

tidal disruption fraction

~1

Kozai-Lidov migration efficiency

~0.3

fraction of WDs in binaries

planet-bearing frequency

~0.3-1

f_b represents the frequency of **strong outer perturbers**… lacking a better constraint, it is the (wide) **binary fraction of A stars** (WD progenitors)

$$f_{b,\mathrm{A}} \sim 0.7 - 1.0$$

(e.g., Kouwenhoven et

only wide binaries

$$f_b \sim f_{b,\mathrm{A},>100\mathrm{au}} \sim 0.7 \times 0.7 \sim 0.5$$

$$f_{\mathrm{poll}} = f_T \cdot f_{\mathrm{KL}} \cdot f_b \cdot f_p$$

$$\sim 1 \times 0.3 \times 0.5 \times (0.3 - 1)$$

$$\boxed{\sim 0.05 - 0.15}$$

Pollution rate is 0.05-0.15… 10%-50% of what we need

<u>However…</u> the are **missing WD companions**

$$f_{b,\mathrm{WD}} \sim 0.3 \sim 0.5 f_{b,\mathrm{A}}$$ (Farihi et al. 2005; Holberg et

a) <u>hiding/dim</u>: M-dwarfs, WD-WD pairs

e.g., Ferrario (2012), De Rosa et al. (2014), Klein & Katz (2016)

b) <u>gone</u>: unbound due to mass loss, merged

e.g. Veras et al (2011,2012), Toonen et al (2017)

Can **late-onset Kozai-like mechanisms** explain the **pollution rates**?

Not quite …with **<u>just binaries</u>**

$$\boxed{f_{\rm poll,model} \sim 0.025 - 0.15}$$

$$\boxed{f_{\rm poll,obs} \sim 0.25 - 0.5}$$

Off by a **factor of a few**. As with hot Jupiters, **wide binaries do not suffice**

SUMMARY

- Puzzling timescales, delivery efficiency, composition
- Secular instabilities act very slowly, span a wide range of timescales,can produce eccentricities of 0.9999
- The tidal field of an inner planetary system can shield planetesimals agains external perturbations: engulfment is a trigger
- Planetary engulfment (if "fast" enough) removes this tidal shielding, sudde exposing planetesimals to secular instabilities
- As an example: WD pollution induced by a binary, acting on a belt of planetesimals can produce high pollution rates per star
- Pollution rate is 0.05-0.15… 10%-50% of what we need. However, the are missing WD companions
- As with hot Jupiters, wide binaries do not suffice. But binaries are only on kind of possible external perturbers