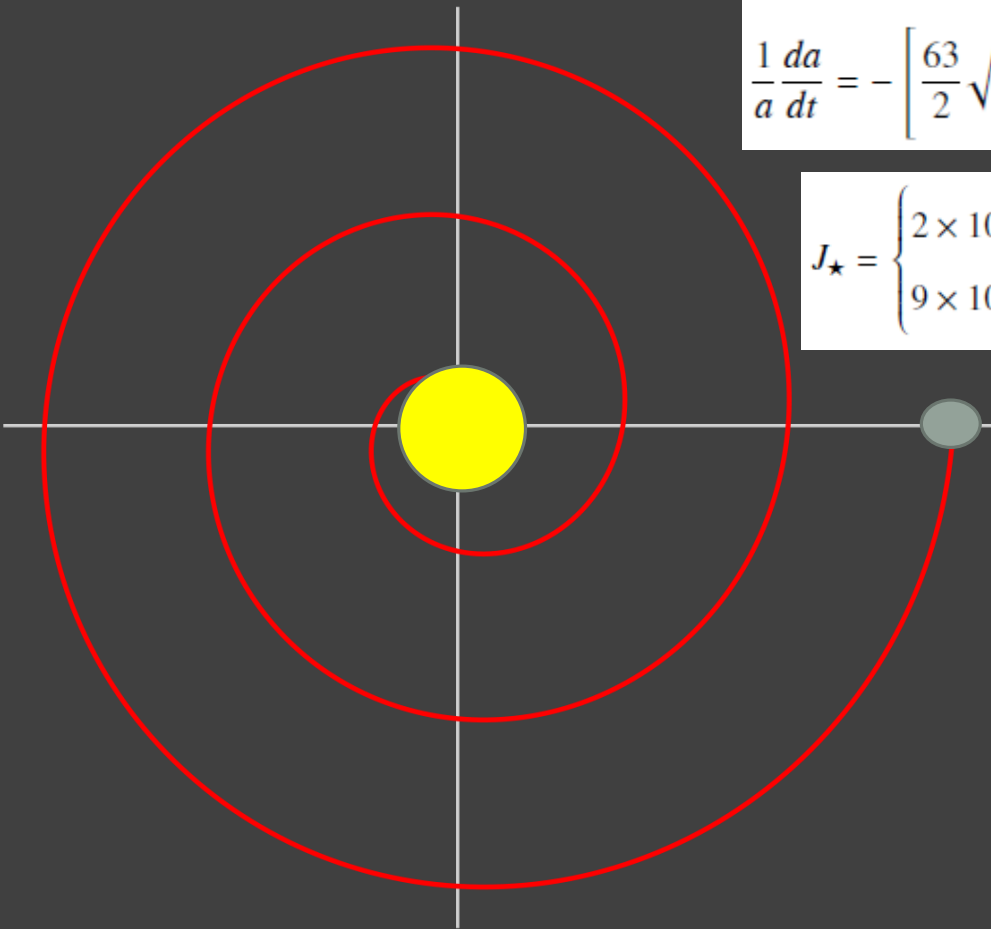


Star-planet coalescence

SERGEI POPOV, ALEKSANDR POPKOV

Tidal interaction



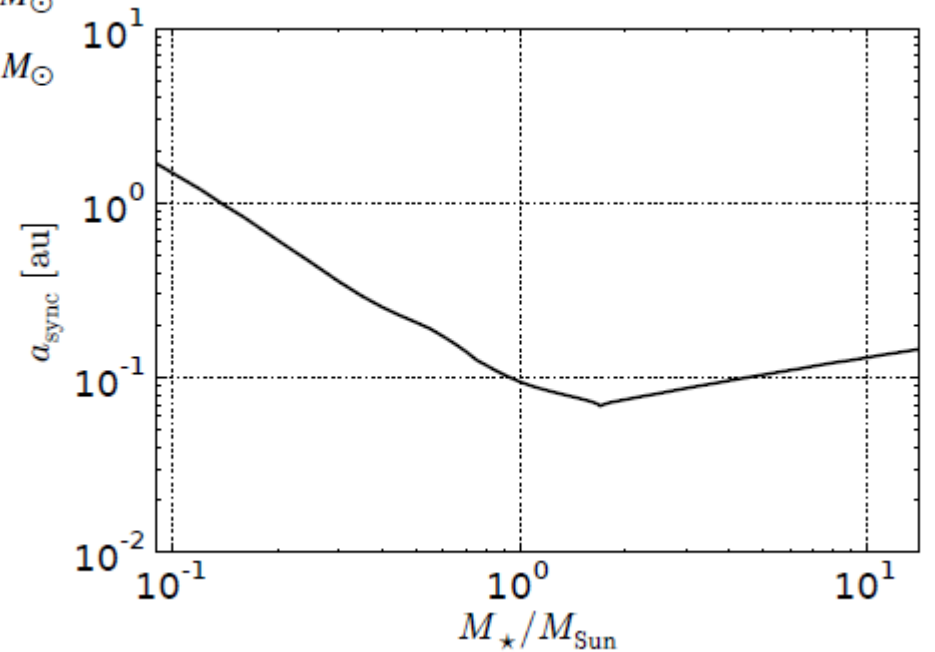
$$\frac{1}{a} \frac{da}{dt} = - \left[\frac{63}{2} \sqrt{GM_{\star}^3} \frac{R_p^5}{Q_p' M_p} e^2 + \frac{9}{2} \sqrt{\frac{G}{M_{\star}}} \frac{R_{\star}^5 M_p}{Q_{\star}'} \right] a^{-13/2},$$

$$\frac{1}{a} \frac{da}{dt} = - \frac{9}{2} \sqrt{\frac{G}{M_{\star}}} \frac{R_{\star}^5 M_p}{Q_{\star}'} a^{-13/2}, \quad a < a_{\text{sync}}.$$

$$J_{\star} = \begin{cases} 2 \times 10^{49} \text{ g cm}^2 \text{ s}^{-1} \left(\frac{M_{\star}}{M_{\odot}} \right)^{4.9}, & M_{\star} < 1.7 M_{\odot} \\ 9 \times 10^{49} \text{ g cm}^2 \text{ s}^{-1} \left(\frac{M_{\star}}{M_{\odot}} \right)^{2.1}, & M_{\star} \geq 1.7 M_{\odot} \end{cases}$$

$$\Omega_{\text{rot}} = \frac{J_{\star}}{I_{\star}} \approx \frac{J_{\star}}{\frac{2}{5} M_{\star} R_{\star}^2},$$

$$a_{\text{sync}} = \left(\frac{GM_{\star}}{\Omega_{\text{rot}}^2} \right)^{1/3},$$



Types of mergers

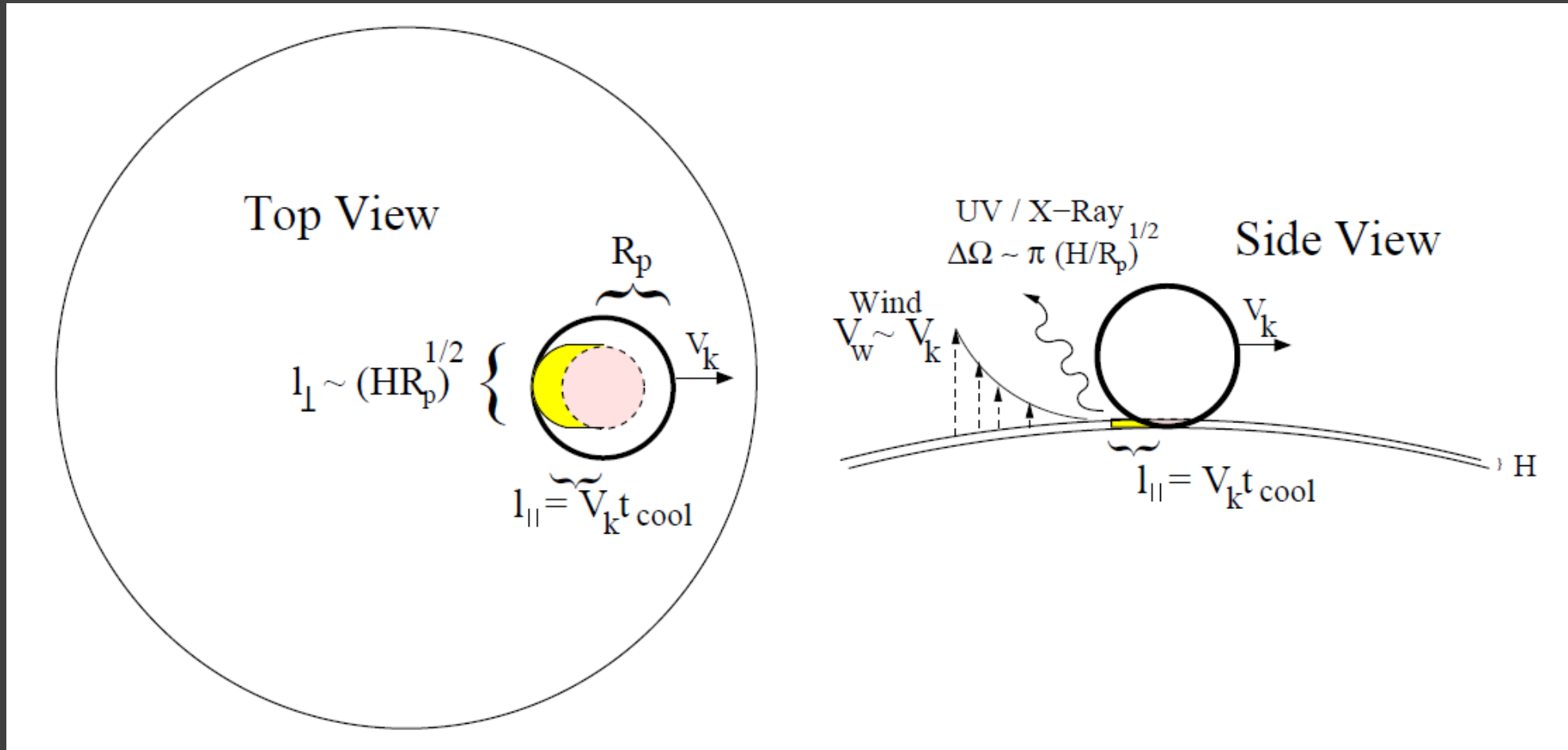
- Stable accretion $\rho_{pl} < \rho_*$
- Tidal disruption $1 < \rho_{pl} / \rho_* < 5$
- Direct impact $\rho_{pl} > 5\rho_*$

$$L_{\text{peak,td}} \approx 3 \times 10^{34} \text{ erg s}^{-1} \frac{M_p}{M_\oplus}$$

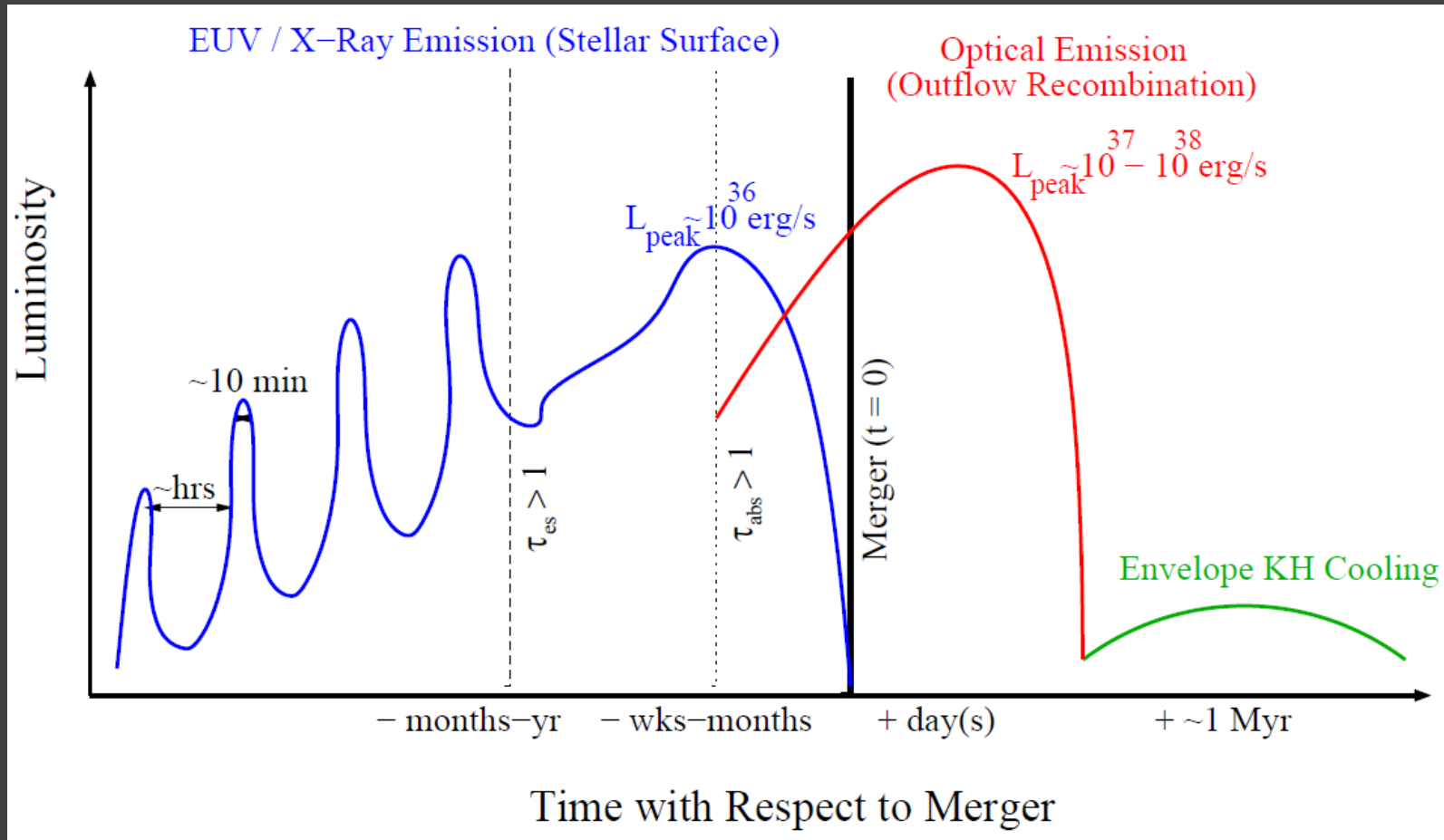
$$L_{\text{peak,di}} \approx (4\pi\sigma)^{1/3} T_{\text{rec}}^{4/3} \left(\frac{GM_\star}{R_\star} \right)^{1/3} \left(\frac{0.1M_p}{m_p} \text{Ry} \right)^{2/3}$$

Event Type	Photon Energy	Peak Luminosity (erg s ⁻¹)	Peak Duration
Direct-Impact (§4, Figs. 3, 6, 7):			
Stellar Surface Emission (§4.4.1)	EUV/Soft X-ray	10 ³⁶ ($\epsilon_{\text{rad}}/0.1$)	months–year
Inspiral-Driven Outflow (§4.4.2)	Optical	10 ³⁷ – 10 ³⁸ (eq. 17)	days (eq. 16)
Tidal-Disruption (§5, Figs. 9, 10, 11):			
Super-Eddington Disk Wind (§5.1)	Optical	10 ³⁶ – 10 ³⁷ (M_p/M_J)	day–week
Accretion Disk (§5.2)	Optical(UV)	10 ³⁶ (10 ³⁷)	months–year
Classical Novae ^(a)	Optical	10 ³⁷ – 10 ³⁹	days–months

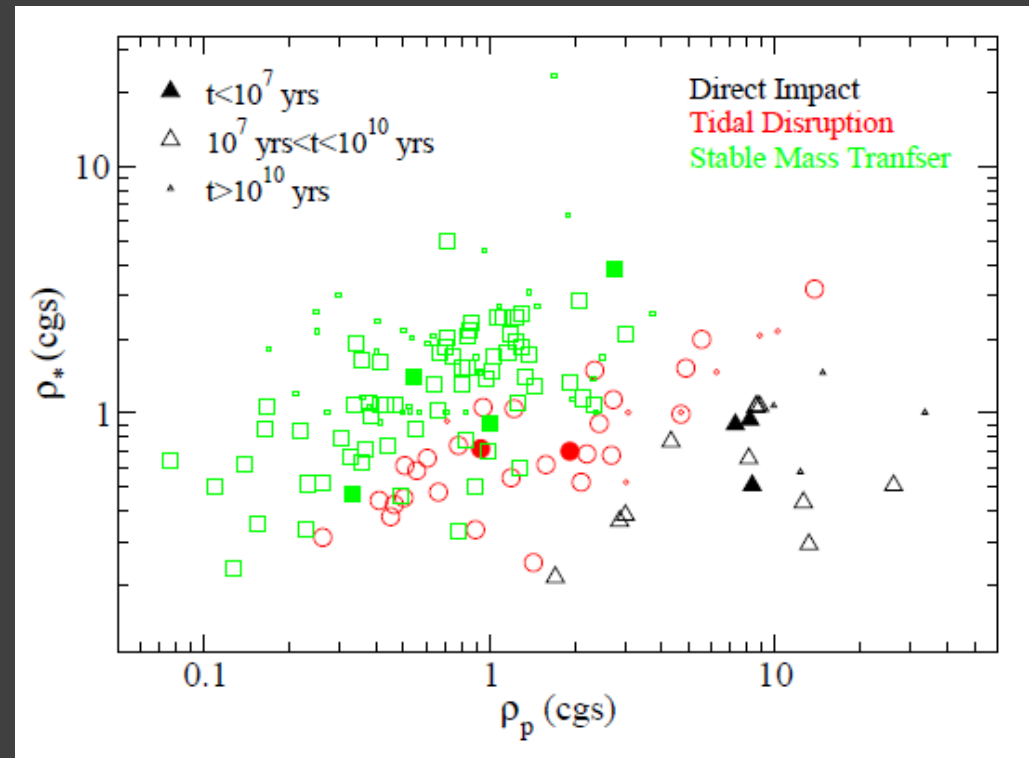
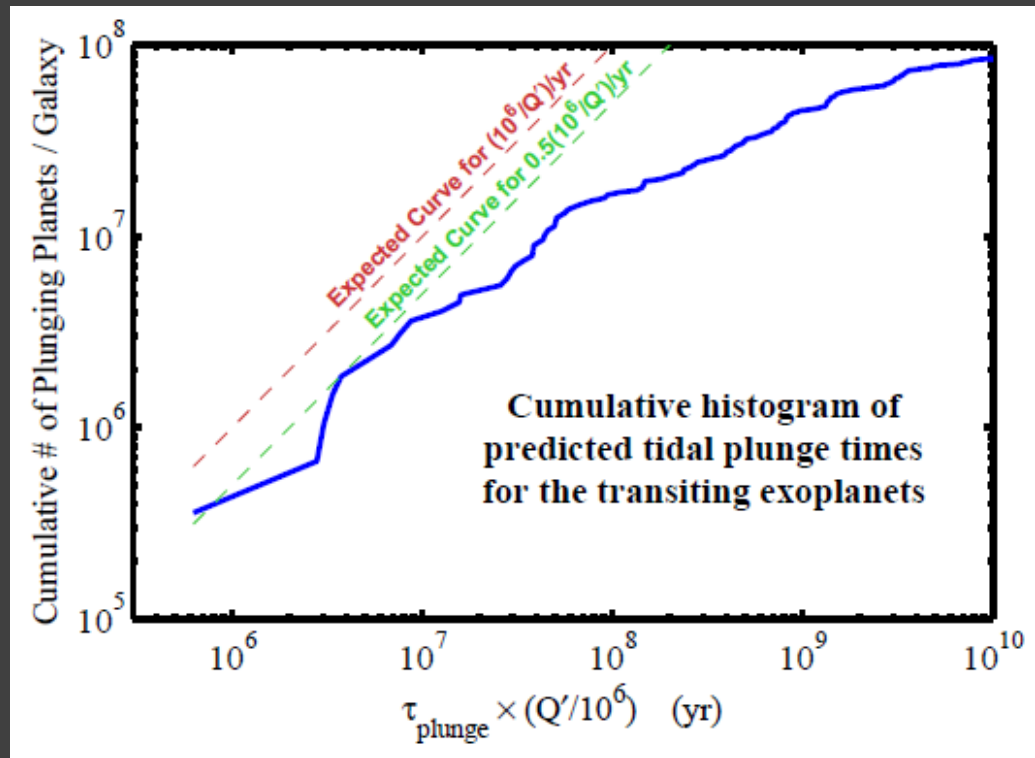
Direct impact dynamics



Direct impact luminosity



Estimates by Metzger et al. (2012)

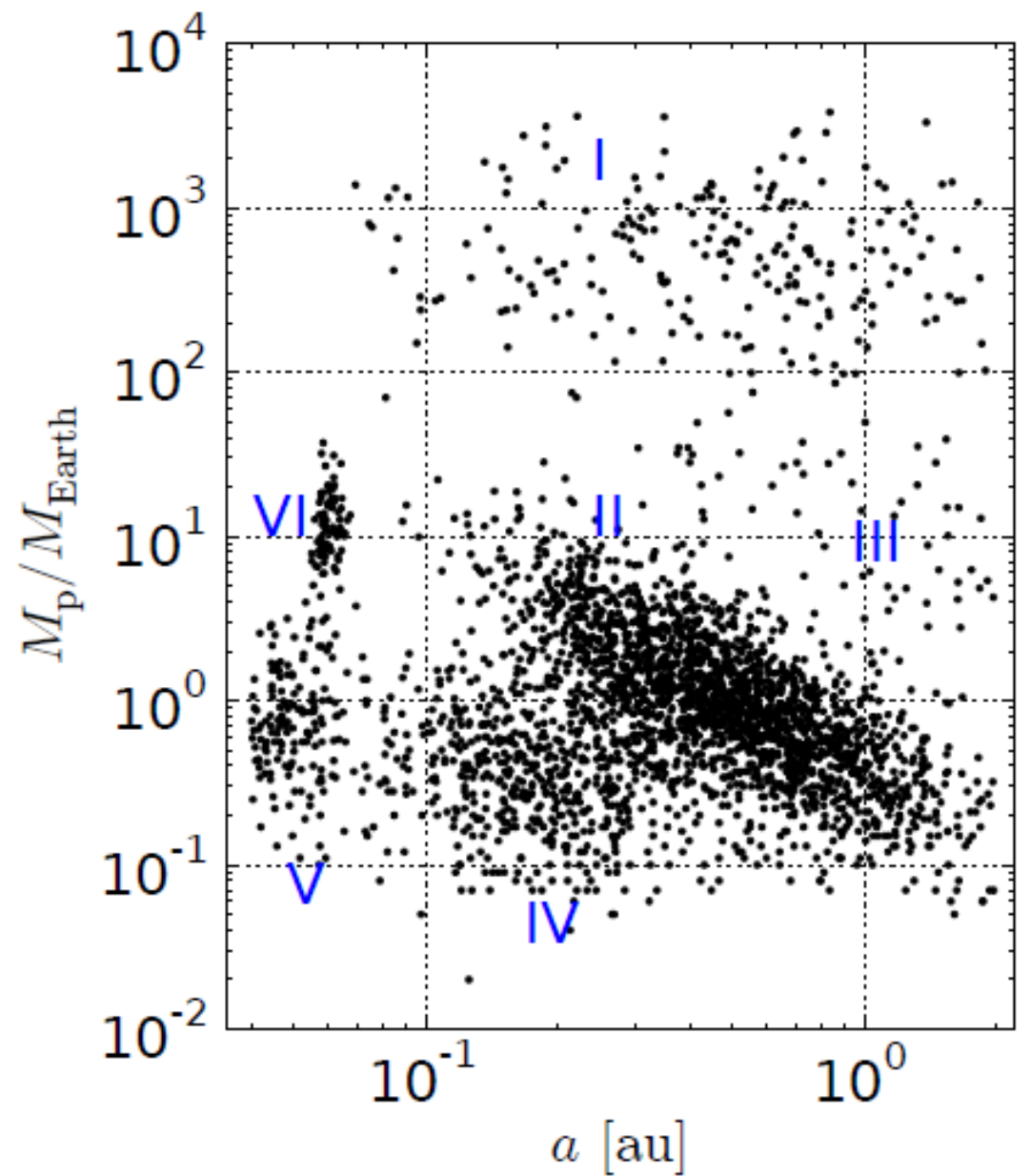


Numbers can reach 0.1-1 mergers per year!

M-a distribution

Group	Distribution	Parameters	% of total
I	2D Log-normal	$\zeta_a = \ln 0.5$ $\zeta_M = \ln 500$ $\sigma_a = 0.9$ $\sigma_M = 1.0$	7.9
II	Bivariate Gaussian in log	$\zeta_a = \lg 0.5$ $\zeta_M = 0$ $\sigma_a = 0.25$ $\sigma_M = 0.45$ $\rho = -0.8$	55.0
III	Uniform in log	$\lg a_{\min} = -0.7$ $\lg a_{\max} = 0.4$ $\lg M_{\min} = -1$ $\lg M_{\max} = 1.6$	6.1
IV	2D Log-normal	$\zeta_a = \ln 0.2$ $\zeta_M = \ln 0.4$ $\sigma_a = 0.5$ $\sigma_M = 0.8$	20.7
V	2D Log-normal	$\zeta_a = \ln 0.045$ $\zeta_M = \ln 0.7$ $\sigma_a = 0.2$ $\sigma_M = 0.8$	7.1
VI	2D Log-normal	$\zeta_a = \ln 0.06$ $\zeta_M = \ln 12$ $\sigma_a = 0.05$ $\sigma_M = 0.5$	3.2

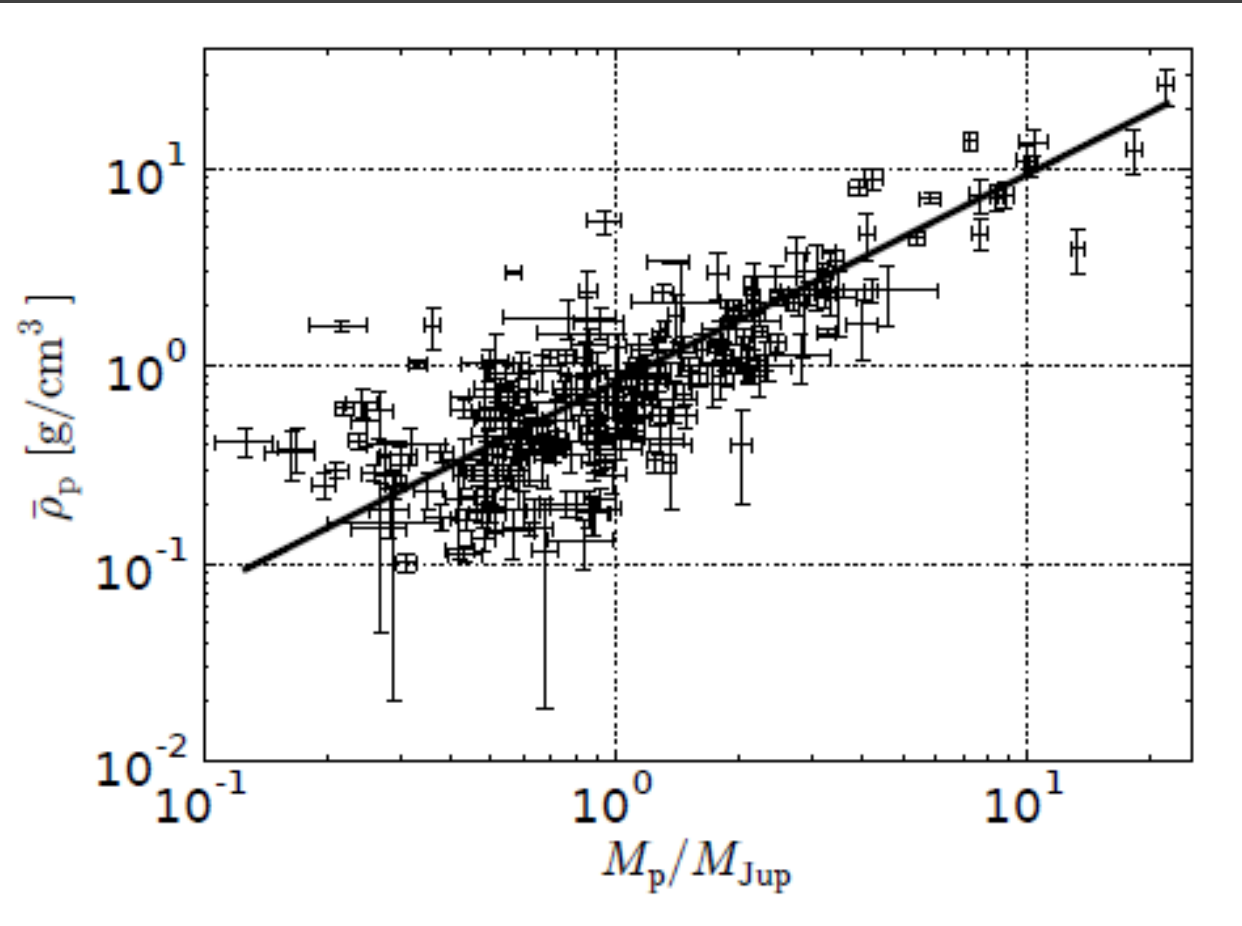
Initial distribution
in a-M plane
is taken from
population synthesis.



Planetary parameters

$$n_{\text{pl}}(M_{\star}) = \begin{cases} \left(\frac{M_{\star}}{M_{\odot}}\right)^{1.2} n_{\text{pl}}(M_{\odot}), & M_{\star} < 1.5M_{\odot} \\ 6.5, & M_{\star} \geq 1.5M_{\odot}, \end{cases}$$

$$\bar{\rho}_{\text{p}} = \begin{cases} \bar{\rho}_{\oplus}, & M_{\text{p}} \leq M_{\oplus} \\ \bar{\rho}_{\oplus} \left(\frac{M_{\text{p}}}{M_{\oplus}}\right)^{-0.46}, & M_{\oplus} < M_{\text{p}} \leq 200M_{\oplus} \\ 1.9 \times 10^{-3} \left(\frac{M_{\text{p}}}{M_{\oplus}}\right)^{1.05} \text{ g cm}^{-3}, & M_{\text{p}} > 200M_{\oplus} \end{cases}$$



Other parameters

$$t_{\text{disk}} = \begin{cases} 10^7 \text{ yr}, & M_{\star} < 1.5M_{\odot} \\ 10^7 \left(\frac{M_{\star}}{1.5M_{\odot}}\right)^{-1/2} \text{ yr}, & M_{\star} \geq 1.5M_{\odot}. \end{cases}$$

Disc lifetime

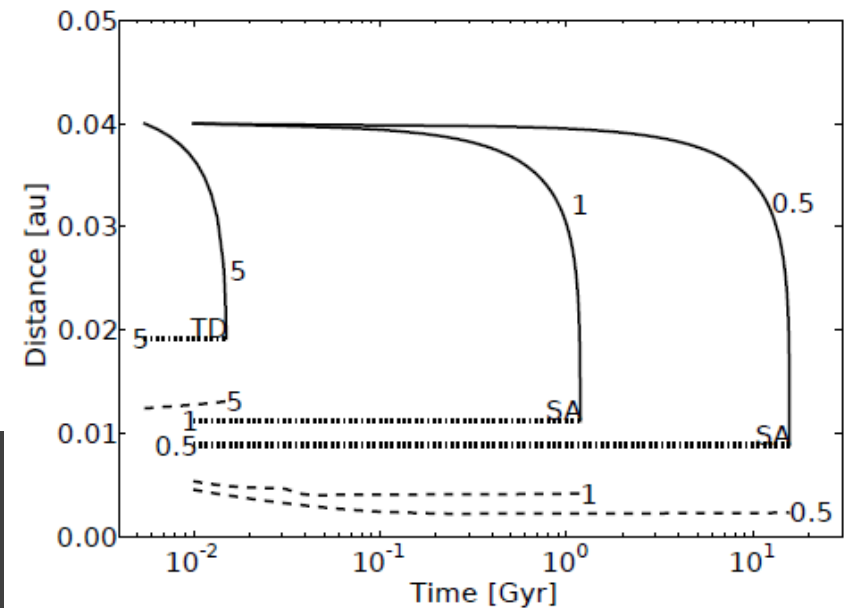
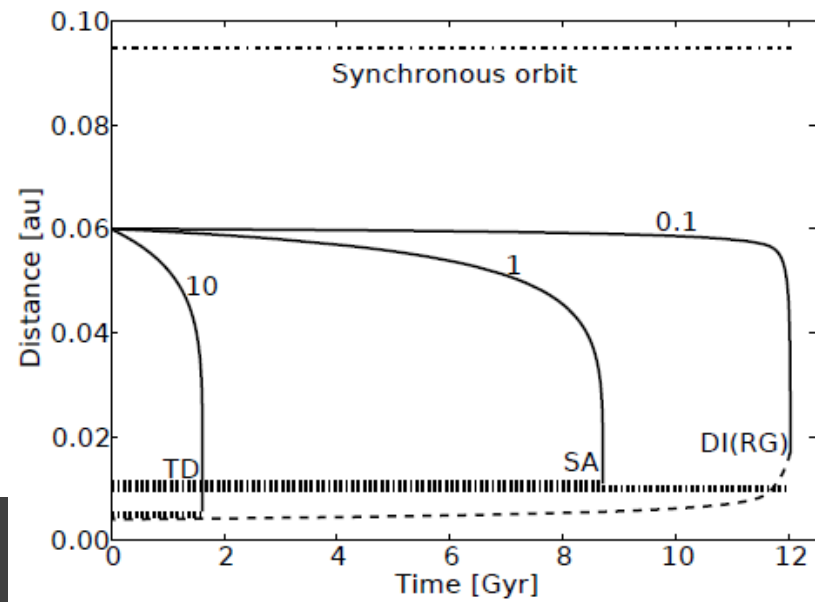
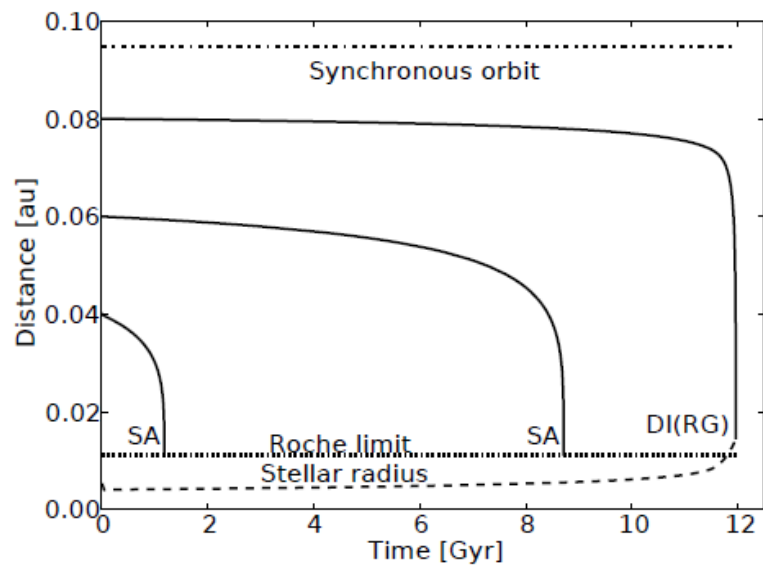
$$P(M < M_{\star} < M + dM) \propto \begin{cases} M^{-1.3}, & M < 0.5M_{\odot} \\ M^{-2.3}, & M \geq 0.5M_{\odot} \end{cases}$$

Stellar IMF

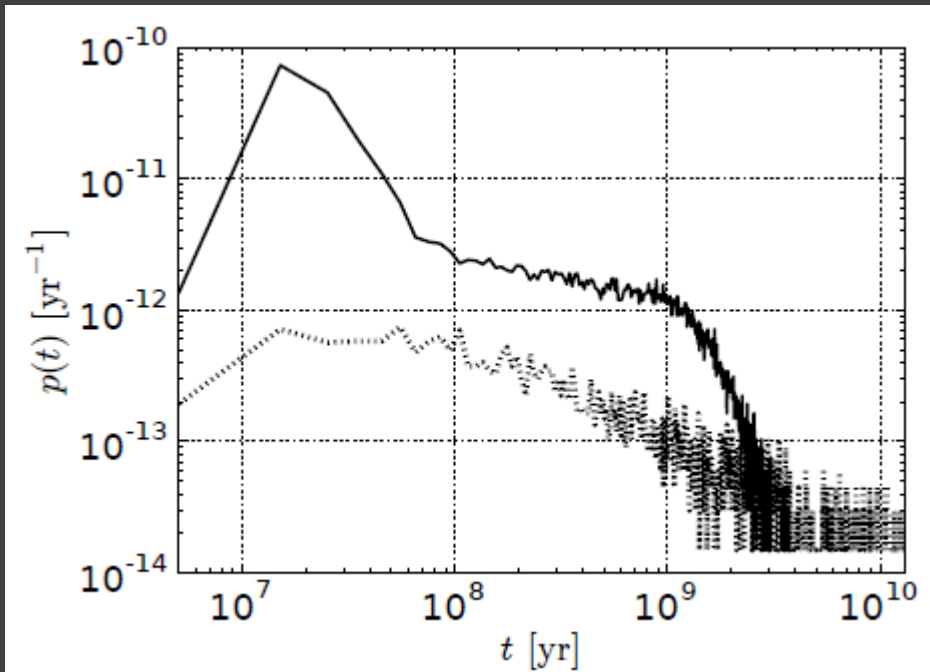
Galactic star formation rate

$$\text{SFR}(\tau) = \begin{cases} 3 M_{\odot}/\text{yr}, & \tau \leq 7 \times 10^9 \text{ yr} \\ 0, & 7 \times 10^9 \text{ yr} < \tau \leq 9.5 \times 10^9 \text{ yr} \\ 10 M_{\odot}/\text{yr}, & 9.5 \times 10^9 \text{ yr} < \tau \leq 12.5 \times 10^9 \text{ yr} \end{cases}$$

Tidal evolution



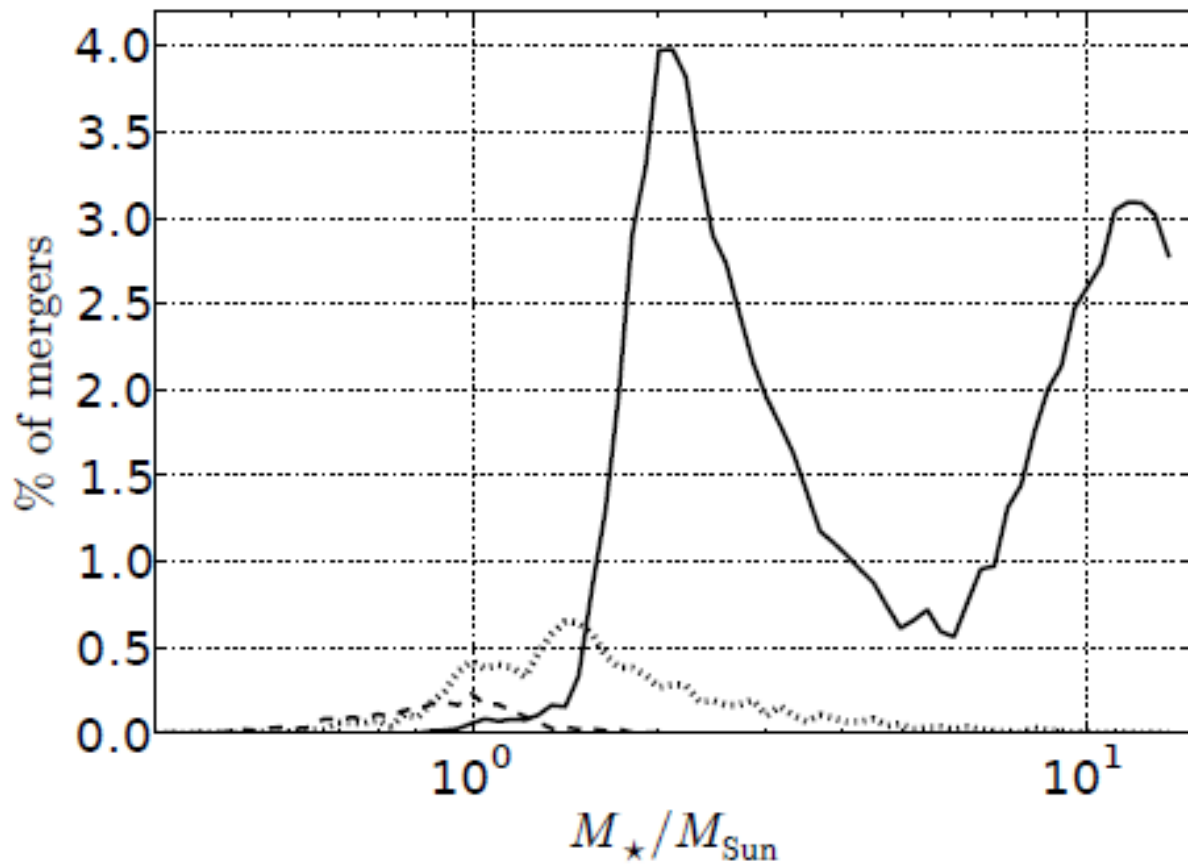
Results-1



Probability of a merger of a planet with a main sequence host star vs. system's age, $p(t)$.

Line style marks the type of merger:
solid curve - direct impact,
dotted curve - tidal disruption.

Distribution of stellar masses for mergers



Distribution of mergers with main sequence stars. Curves show fraction of merging planets depending on the host mass (given in solar units).

Only coalescences which happened at ages less than the age of the Galaxy are taken into account.

Solid line - direct impacts,
dotted line - tidal disruptions,
dashedline - stable accretion events.

Which planets merge?

Mass and initial orbital radius of planets which merge with their host stars during the main sequence phase in simultaneously formed population of planetary systems.

Symbol style marks the type of mergers:

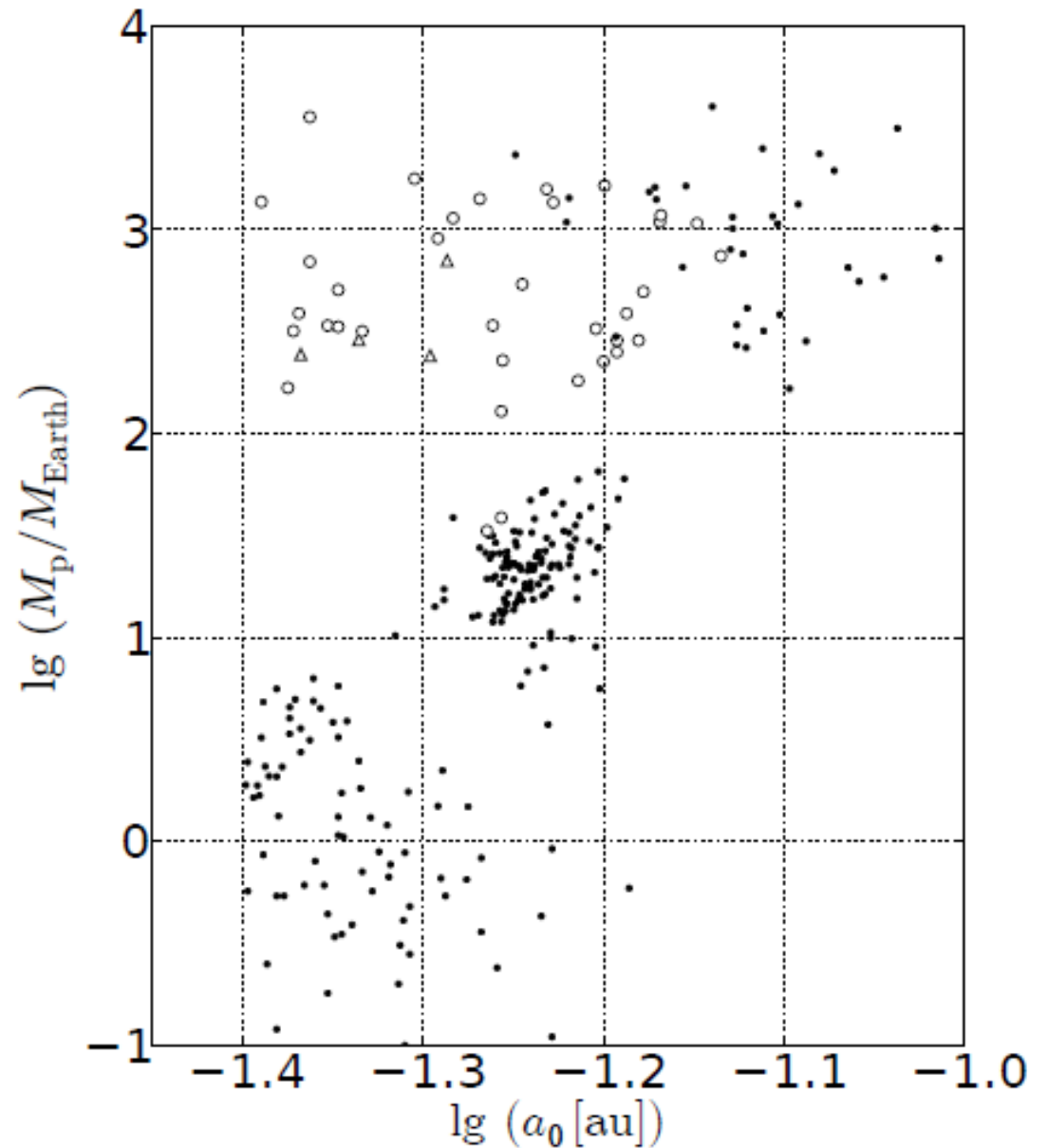
dots - direct impacts,

circles – tidal disruptions,

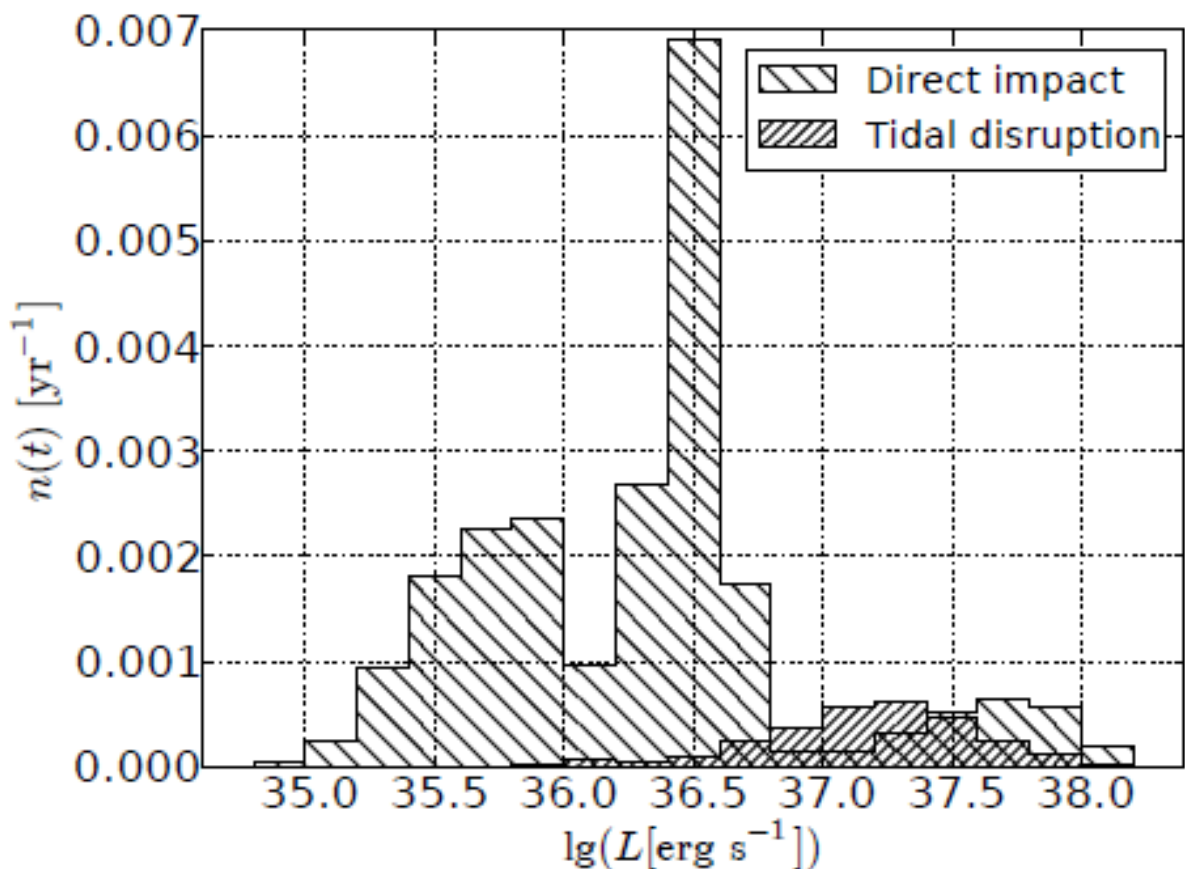
triangles - stable accretion events.

Only mergers happening at ages less than the age of the Galaxy are included.

Total number of planets in the population is 10^5 ,
the number of planets on this diagram is 269.



Luminosity distribution of mergers



Distribution in luminosity of planet-star mergers in a Milky Way-like galaxy.

Type of merger is marked by hatching.

The quantity on the ordinate is the rate of mergers per year per galaxy in a luminosity bin.

Stellar evolutionary stage	Direct impact	Tidal disruption	Stable accretion
Main sequence	2.2×10^{-2}	2.9×10^{-3}	8.0×10^{-4}
Post-main sequence	2.70	3.6×10^{-4}	1.7×10^{-6}
Total	2.72	3.2×10^{-3}	8.0×10^{-4}

Dependences

Illustration of the dependence of coalescence statistics on initial distribution in the a - M plane.

Symbols encode host star masses:

Circles: 0.09-1 Msolar; triangles: 1-1.5 Msolar; crosses: 1.5-4 Msolar; dots: 4-7 Msolar; stars: 7-14 Msolar.

Inclined lines mark the boundary of the “fall region” for stars of different masses (labeled in the legend in units of the Solar mass).

The solid line on the top corresponds to 1 Msolar.

Maximum radii of stars of 7 and 14 Msolar at the end of their evolution on the main sequence are plotted by vertical dashed lines and marked by the value of mass.

