Star-planet coalescence

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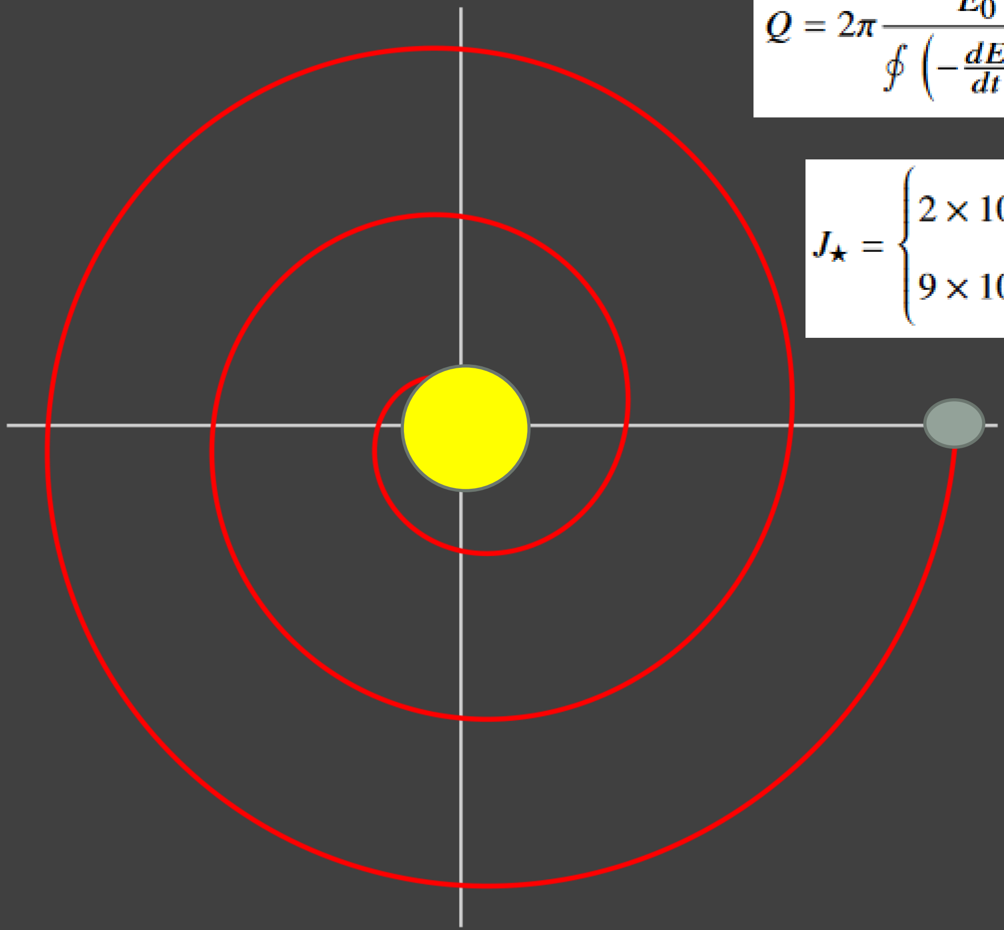
Tidal interaction



$$Q = 2\pi \frac{E_0}{\oint \left(-\frac{dE}{dt}\right) dt}.$$

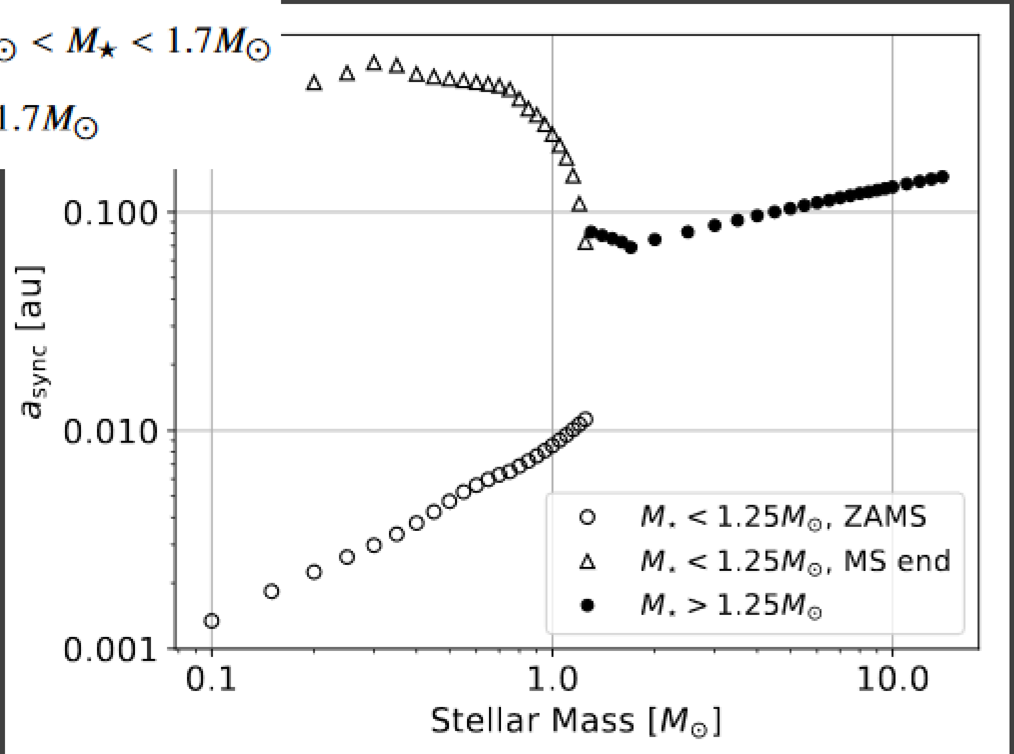
$$Q' = \frac{3Q}{2k},$$

$$\frac{1}{a}\frac{da}{dt} = -\frac{9}{2}\left(\frac{n}{Q'_\star}\right)\left(\frac{M_\mathrm{p}}{M_\star}\right)\left(\frac{R_\star}{a}\right)^5\left[1-\left(\frac{P_\mathrm{orb}}{P_\mathrm{rot}}\right)\right]$$

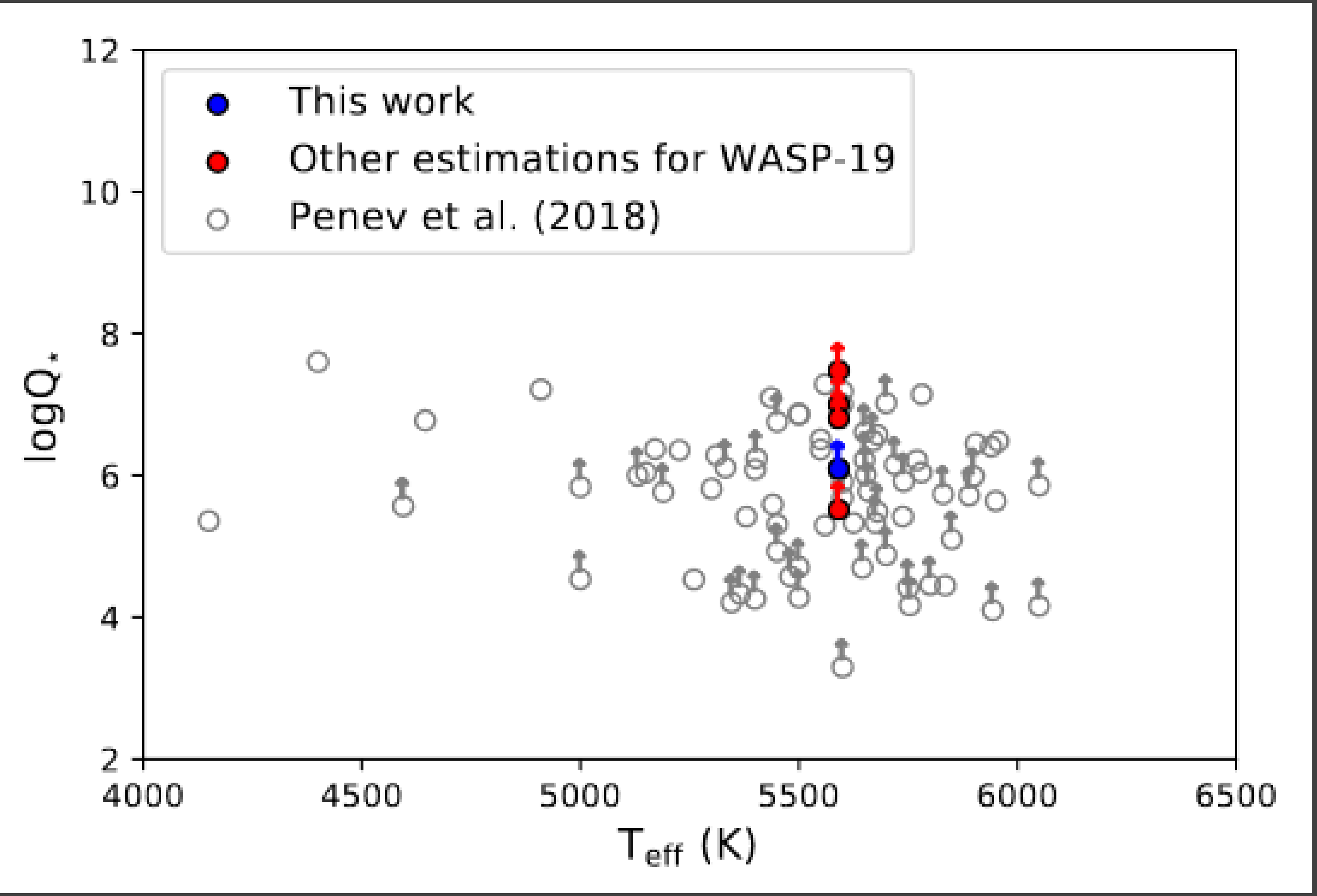
$$J_\star = \begin{cases} 2\times10^{49}\,\mathrm{g\,cm^2\,s^{-1}}\left(\frac{M_\star}{M_\odot}\right)^{4.9}, & 1.25M_\odot < M_\star < 1.7M_\odot \\ 9\times10^{49}\,\mathrm{g\,cm^2\,s^{-1}}\left(\frac{M_\star}{M_\odot}\right)^{2.1}, & M_\star \geq 1.7M_\odot \end{cases}$$

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

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

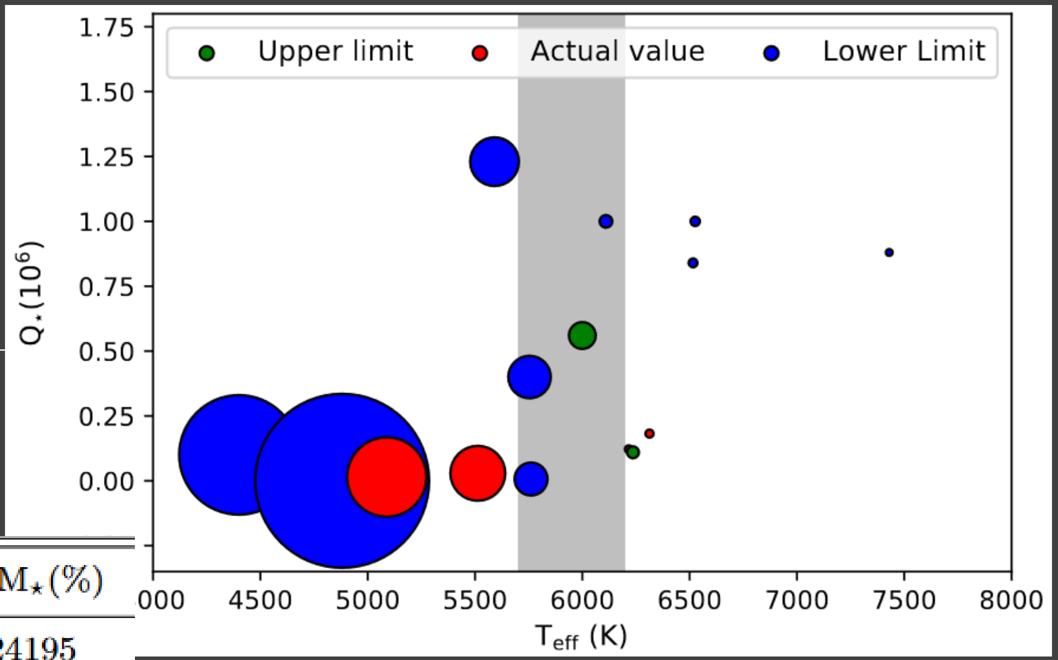


Estimates of parameter Q’$_*$



Parameter Q'$_*$

Stars with more massive convective zones
and lower temperatures tend to have smaller values of Q'$_*$



Size of a circle is proportional to the fraction of convective zone mass.

System	T_{eff}	$\log g$	P[days]	M_P [M_{Jup}]	$Q'_\star$	$M_{cz}/M_\star$(%)
Kepler-78	5089 ± 50	4.6 ± 0.1	0.3550074	0.025	14695^b	9.624195
WASP-19	5591 ± 62	4.46 ± 0.09	0.78884	1.114	1230000	3.609035
WASP-43	4400 ± 200	4.5 ± 0.2	0.813477	2.052	100000	21.734019
WASP-103	6110 ± 160	$4.22^{+0.12}_{-0.05}$	0.925542	1.49	1000000	0.245736
WASP-18	6526 ± 69	4.73 ± 0.08	0.941451	10.43	1000000	0.132701
KELT-16	6236 ± 54	$4.253^{+0.031}_{-0.036}$	0.968995	2.75	110000	0.215928
WASP-12	6313 ± 52	4.37 ± 0.12	1.0914203	1.47	182000	0.010152
HAT-P-23	6000 ± 125	4.5 ± 0.2	1.212884	2.09	560000	1.088569
KELT-1	6516 ± 49	$4.234^{+0.012}_{-0.018}$	1.217514	27.23	840000	0.021936
WASP-33	7430 ± 100	4.3 ± 0.2	1.219869	2.1	880000	0.000004
WASP-4	5513 ± 43	4.5 ± 0.1	1.338231	1.237	29000	4.580076
WASP-46	5761 ± 16	4.47 ± 0.06	1.43037	2.101	7000	1.654130
Kepler-1658	6216 ± 78	3.673 ± 0.026	3.8494	5.88	121900	0.000894
XO-1	5754 ± 42	4.61 ± 0.05	3.941512	0.9	400000	2.745198
K2-39	4881 ± 20	3.44 ± 0.07	4.60543	0.158	0.178^b	46

Types of mergers

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

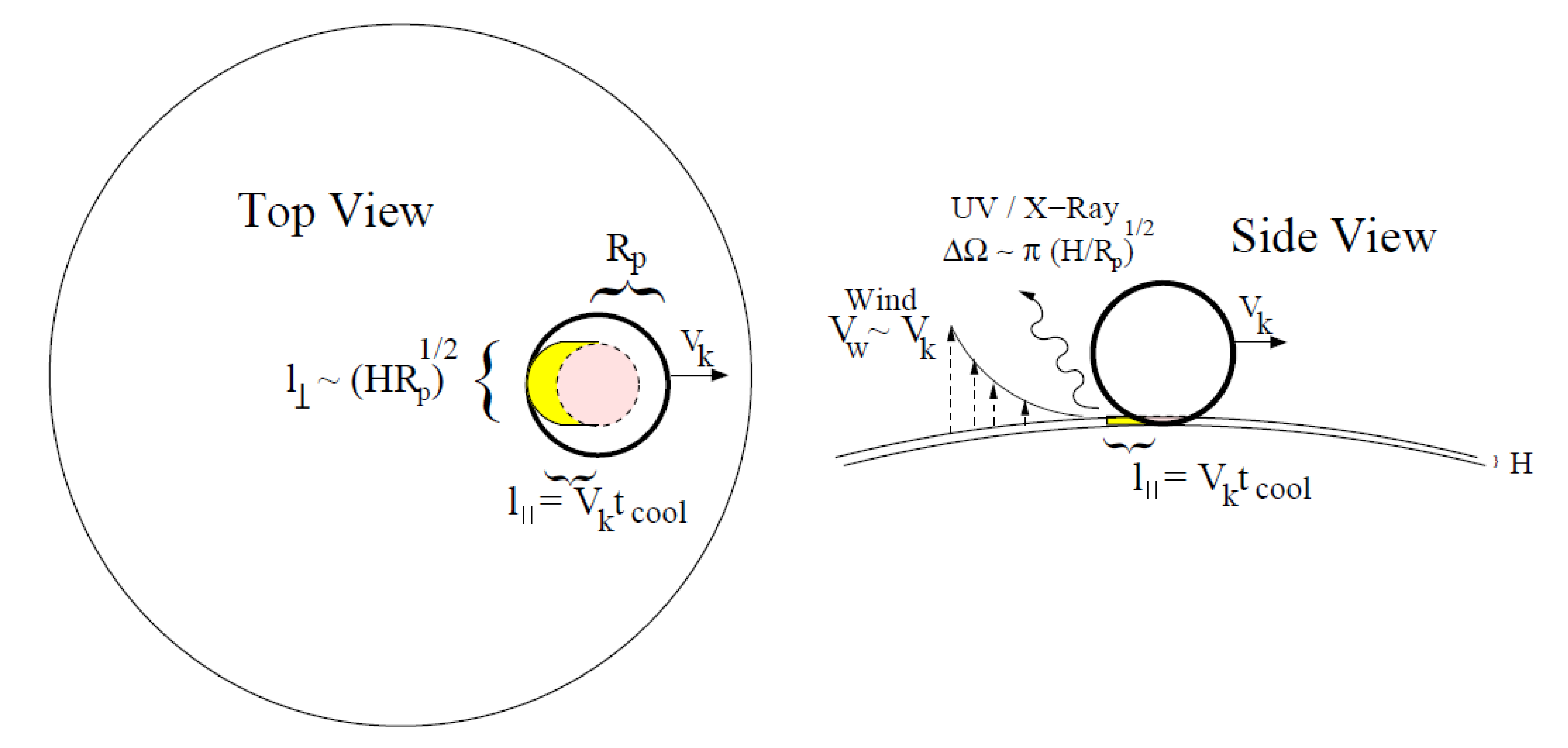
$$L_{\rm peak,td} \approx 3\times 10^{34}\,{\rm erg\ s^{-1}}\,\frac{M_{\rm p}}{M_\oplus}$$

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

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	$10^{36}(\epsilon_{\rm rad}/0.1)$	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	$10^{36}-10^{37}(M_{\rm p}/M_{\rm J})$	day–week
Accretion Disk (§5.2)	Optical(UV)	$10^{36}(10^{37})$	months–year
Classical Novae[(a)]	Optical	$10^{37}-10^{39}$	days–months

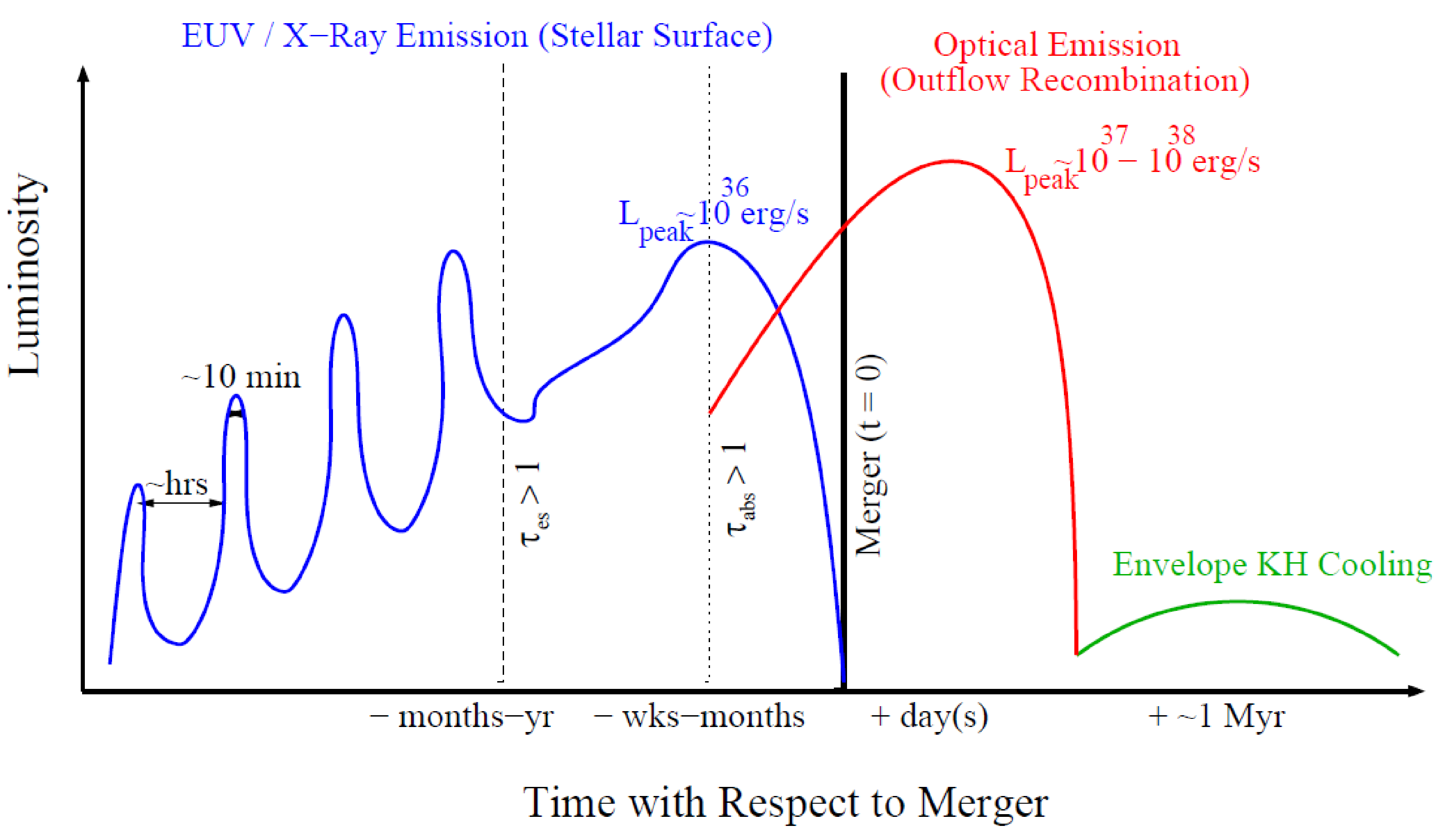
Metzger et al. 2012

Direct impact dynamics



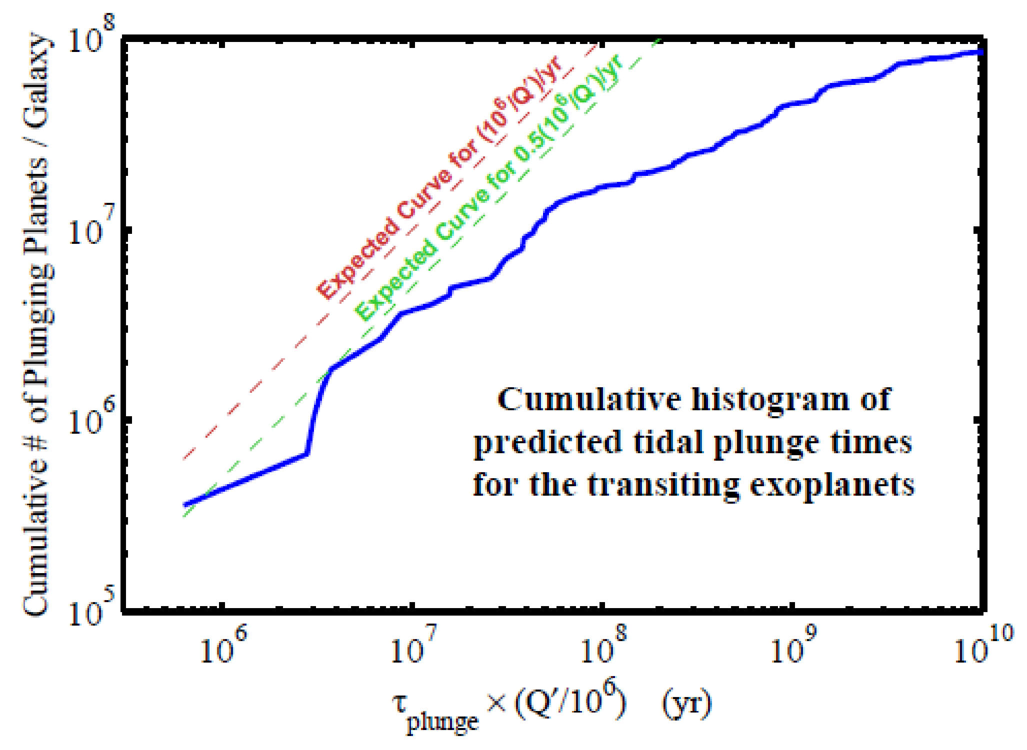
Metzger et al. 2012

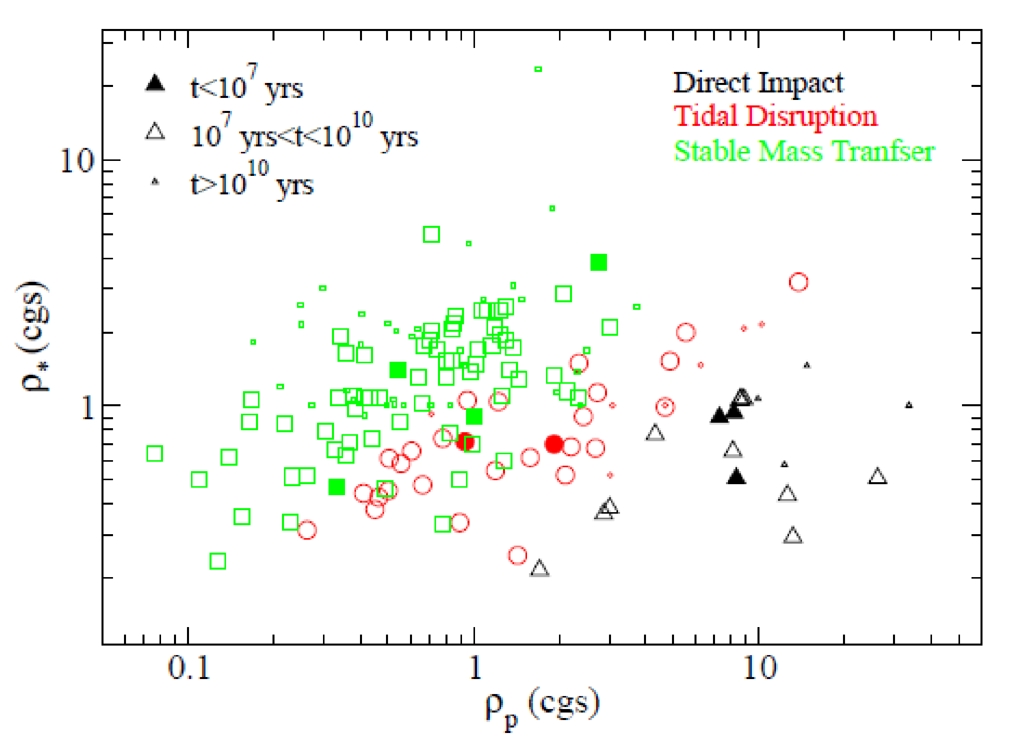
Direct impact luminosity



Metzger et al. 2012

Estimates by Metzger et al. (2012)



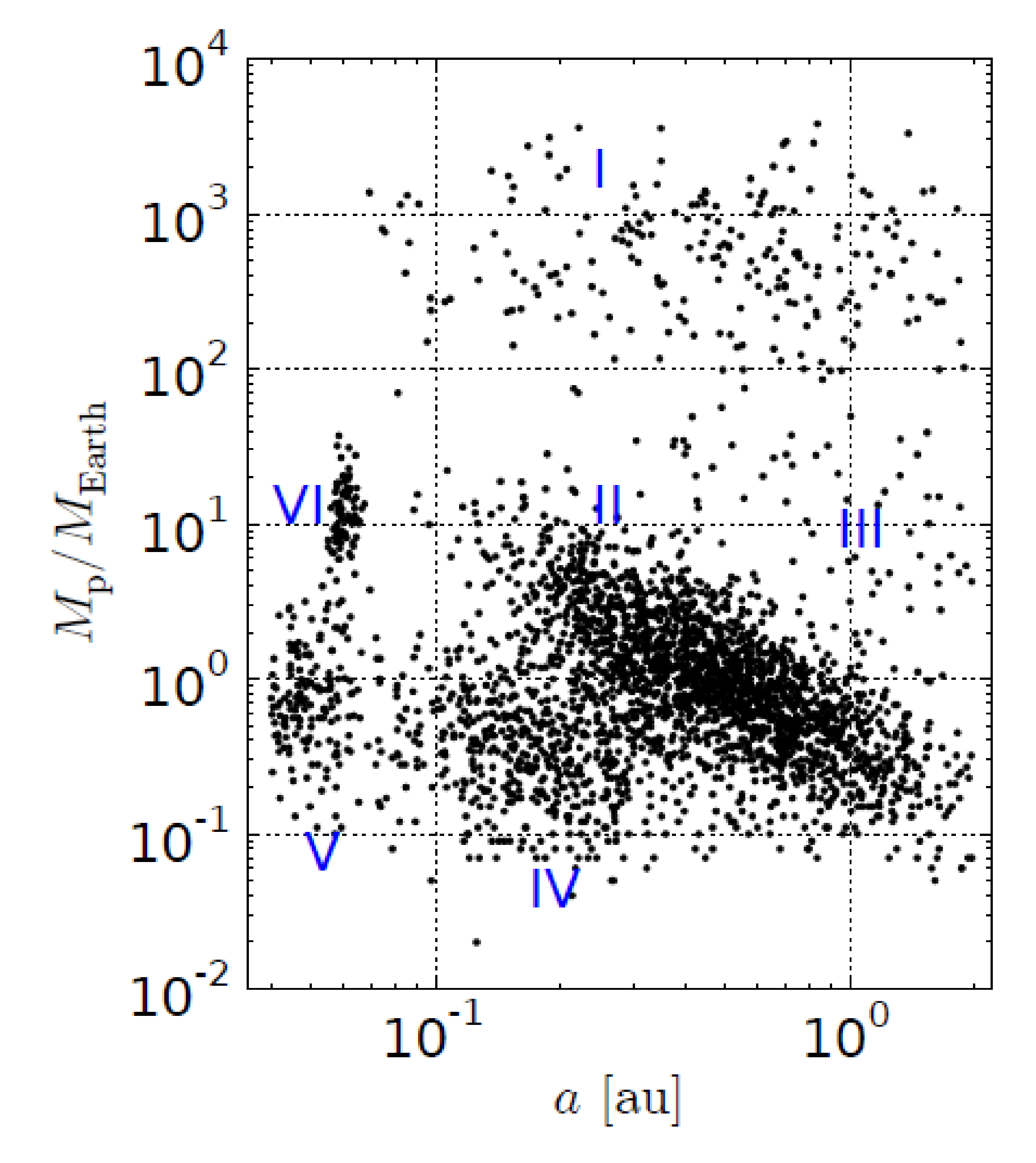


Numbers can reach 0.1-1 mergers per year!

M-a distribution

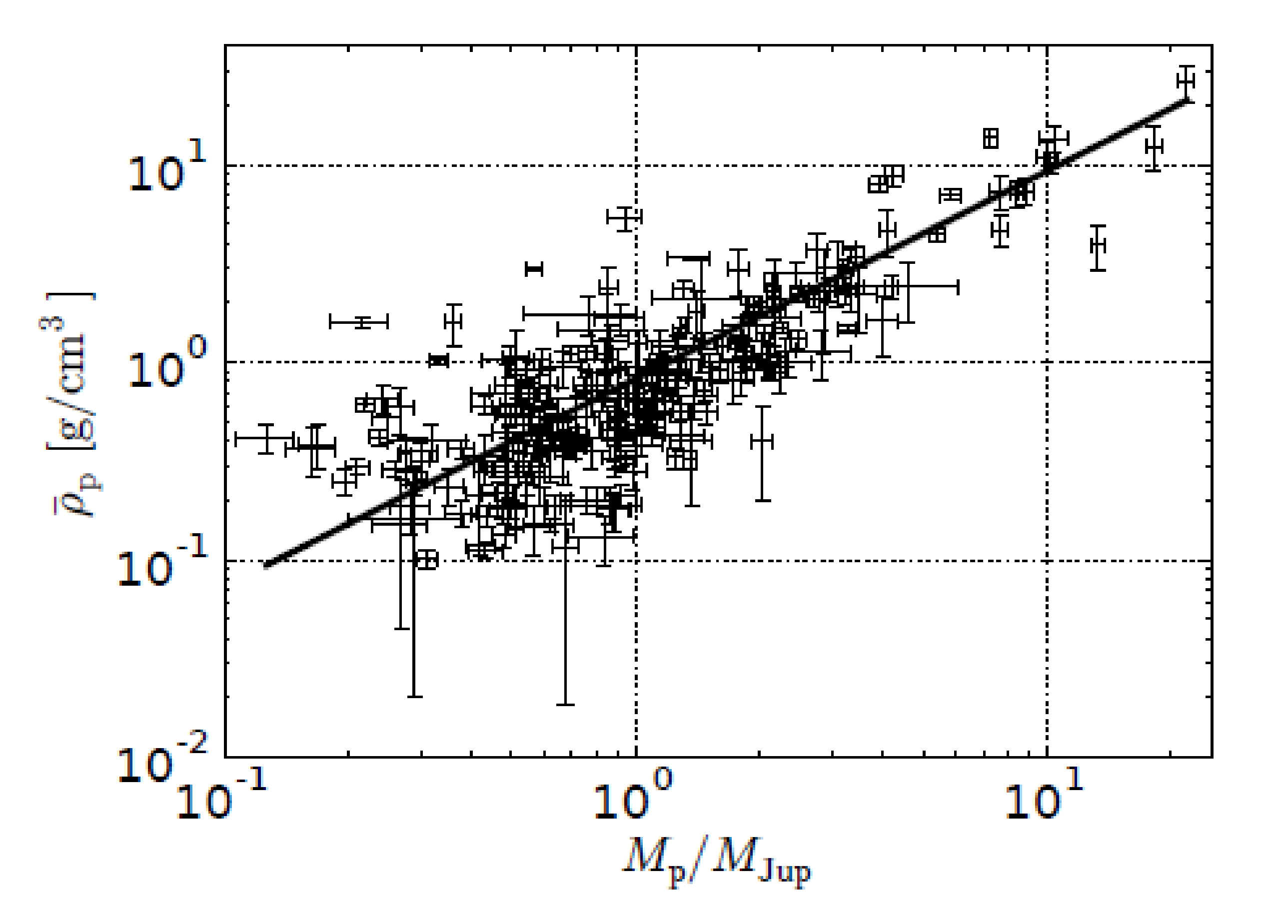
Group	Distribution	Parameters	% of total
I	2D Log-normal	$\zeta_a = \ln 0.5$ $\zeta_M = \ln 500$ $\sigma_a = 0.9$ $\sigma_M = 1.0$	7.9
II	Bivariate Gaussian in log	$\zeta_a = \lg 0.5$ $\zeta_M = 0$ $\sigma_a = 0.25$ $\sigma_M = 0.45$ $\rho = -0.8$	55.0
III	Uniform in log	$\lg a_{min} = -0.7$ $\lg a_{max}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

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



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

Other parameters

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

Disc lifetime

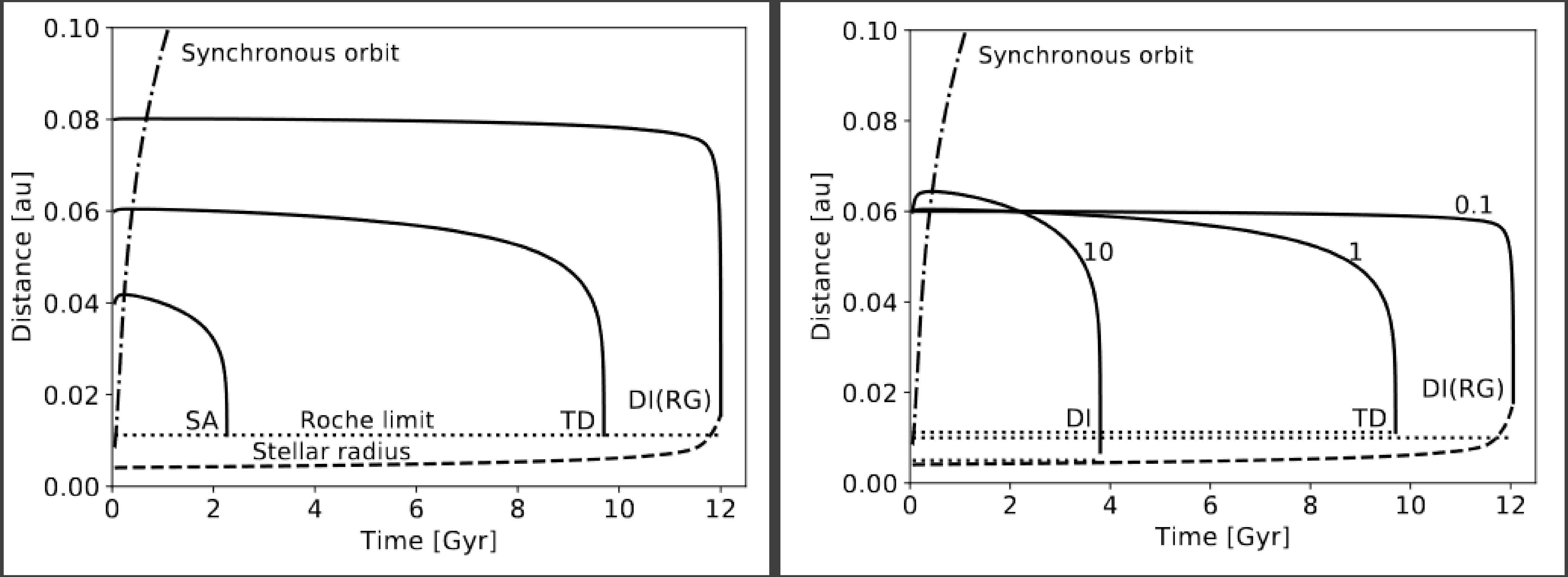
$$P(M < M_\star < M + dM) \propto \begin{cases} M^{-1.3}, & M < 0.5 M_\odot \\ M^{-2.3}, & M \geq 0.5 M_\odot \end{cases}$$

Stellar IMF

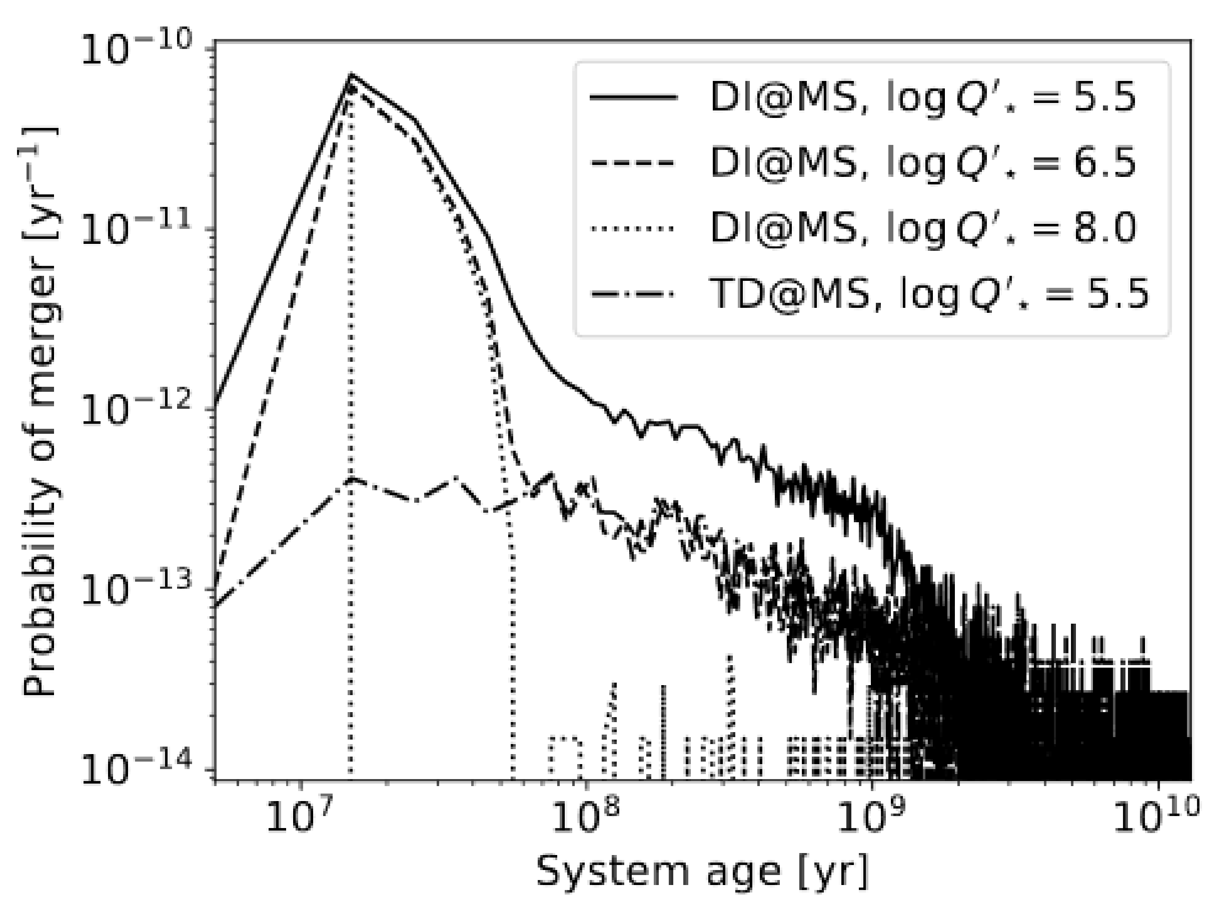
Galactic star formation rate

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

Tidal evolution. Q’=5.5



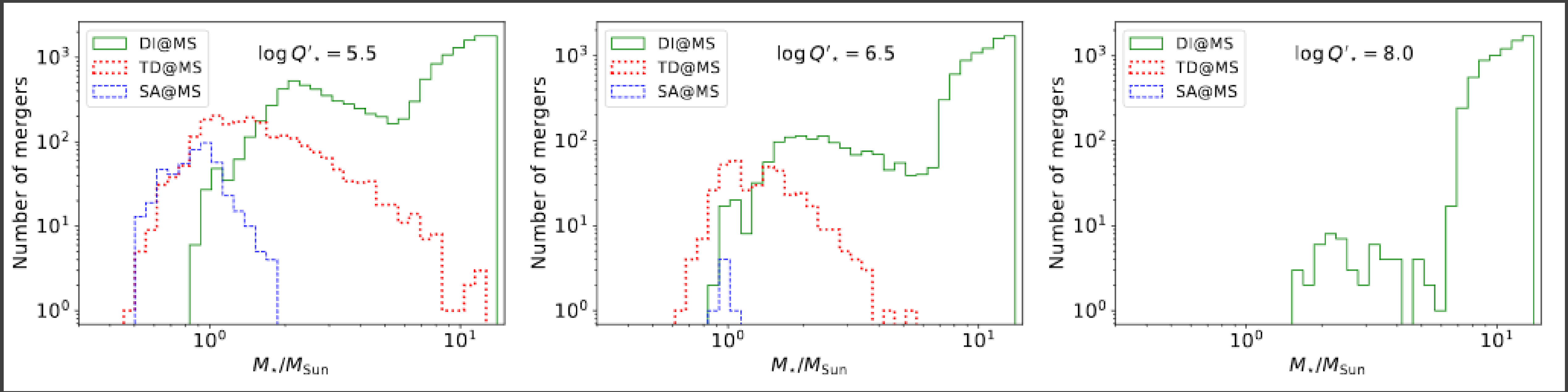
Results-1



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.

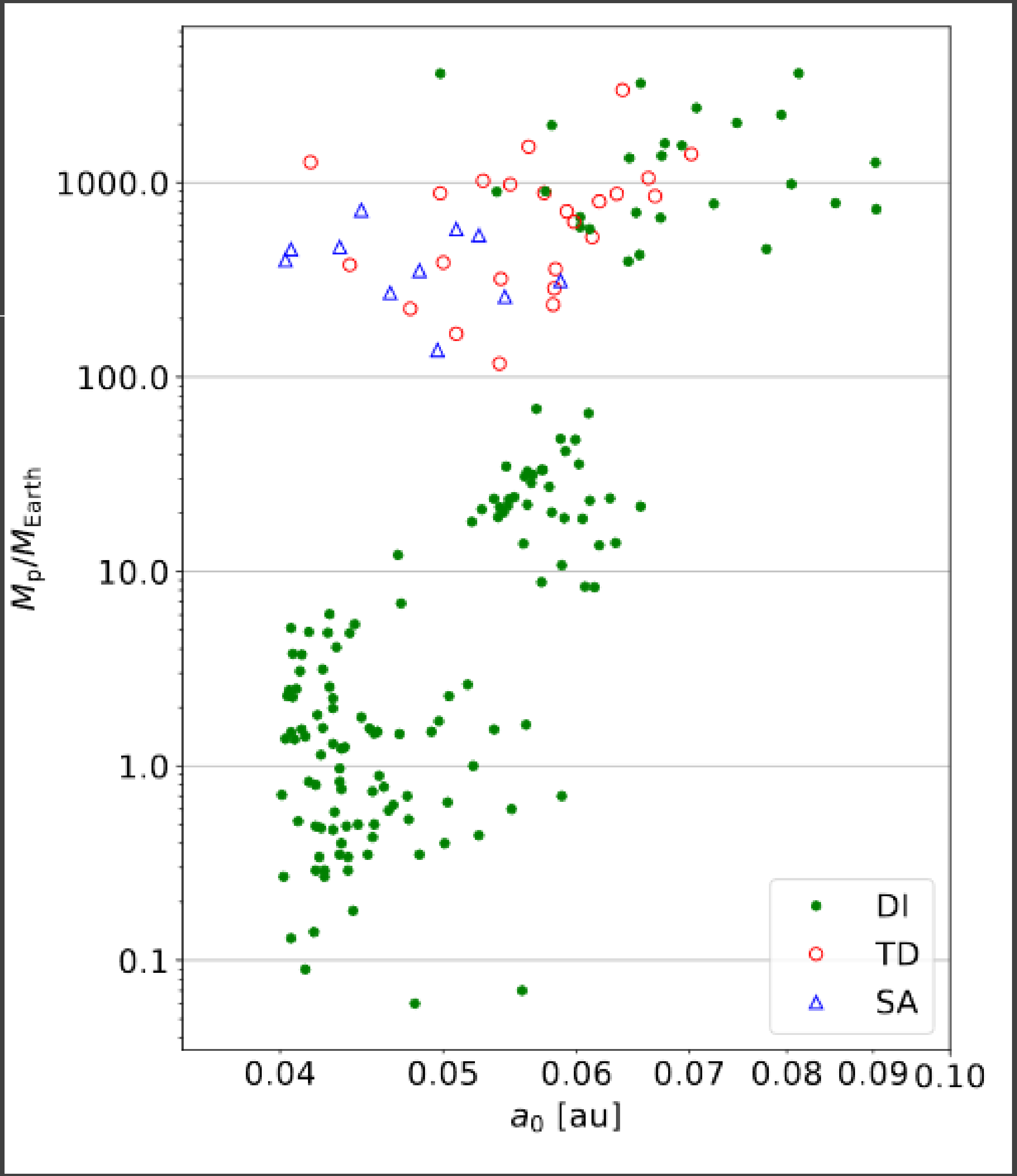
Which planets merge?

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.

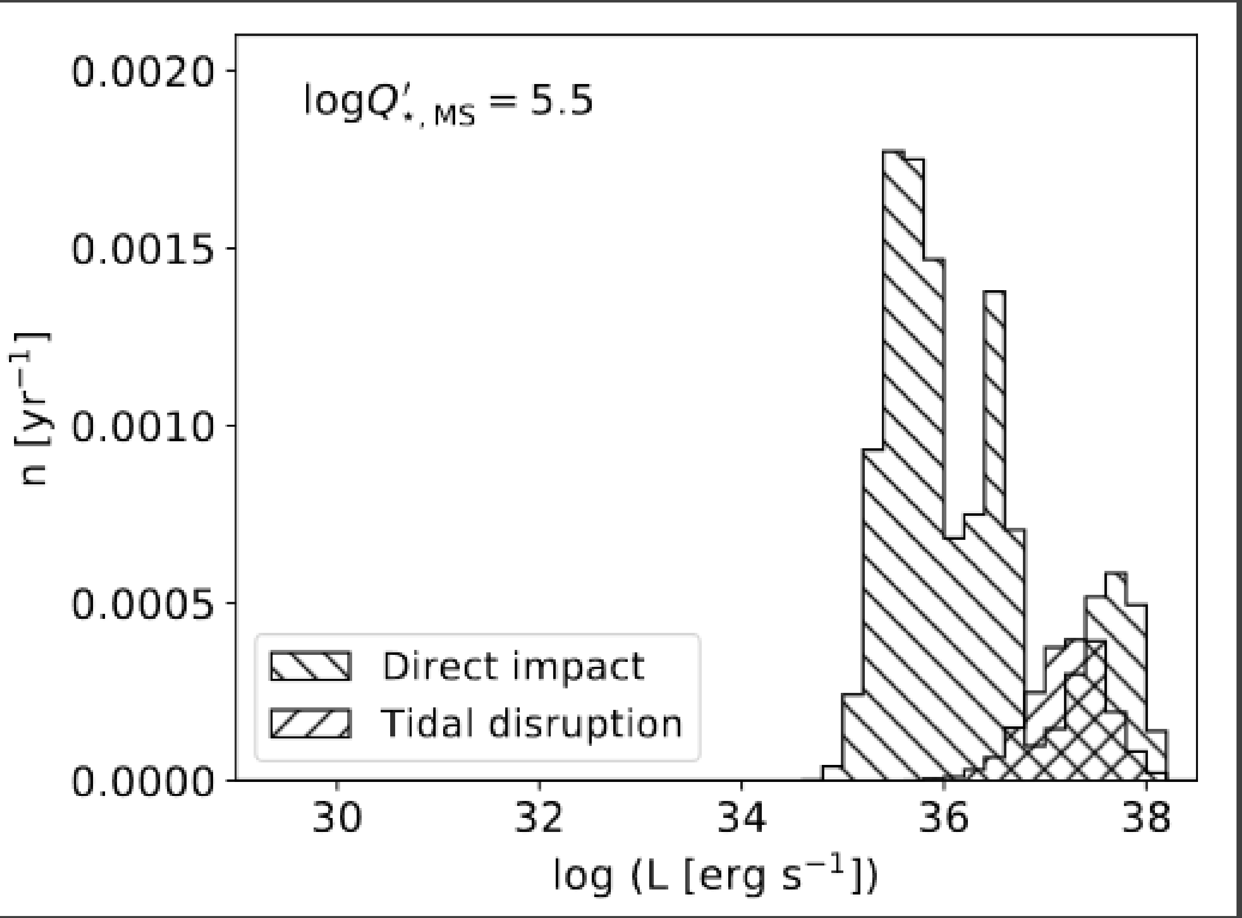
Symbol style marks the type of mergers:
dots - direct impacts,
circles – tidal disruptions,
triangles - stable accretion events.

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

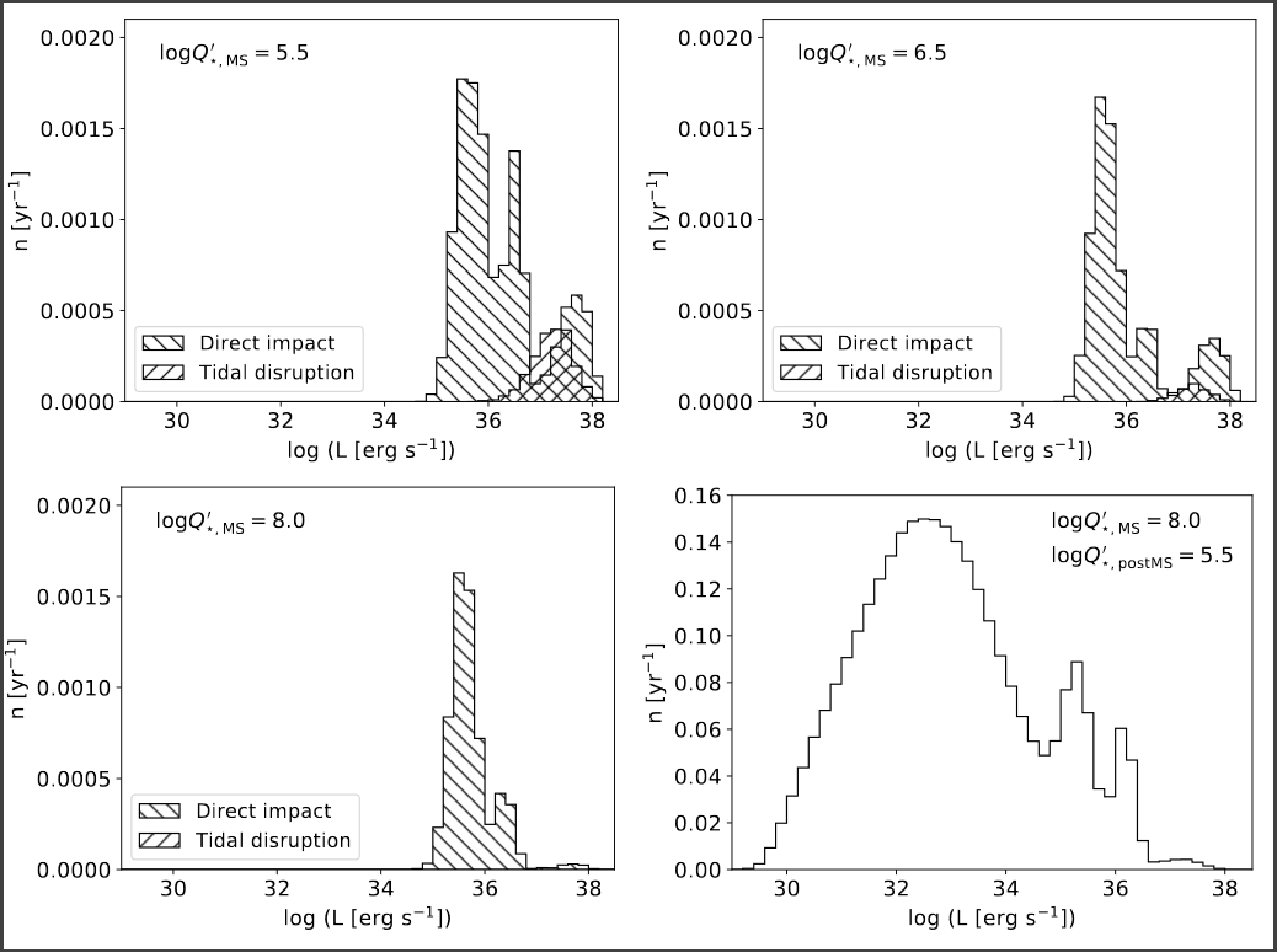


Distribution in luminosity of planet-star mergers in a Milky Way-like galaxy.

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.

$\log Q'_\star$	Stellar evolutionary stage	Direct impact	Tidal disruption	Stable accretion	Bright transients
5.5	Main sequence	1.2×10^{-2}	2.0×10^{-3}	5.1×10^{-4}	0.3×10^{-2}
	Post-main sequence	2.93	0.3×10^{-3}	$\lesssim10^{-6}$	0.9×10^{-2}
	Total	2.95	2.2×10^{-3}	5.1×10^{-4}	1.3×10^{-2}
6.0	Main sequence	8.3×10^{-3}	1.0×10^{-3}	1.6×10^{-4}	0.2×10^{-2}
	Post-main sequence	2.94	0.4×10^{-3}	2.9×10^{-6}	1.1×10^{-2}
	Total	2.95	1.4×10^{-3}	1.6×10^{-4}	1.3×10^{-2}
6.5	Main sequence	7.5×10^{-3}	0.4×10^{-3}	1.2×10^{-5}	0.2×10^{-2}
	Post-main sequence	2.94	0.5×10^{-3}	$\lesssim10^{-6}$	1.2×10^{-2}
	Total	2.95	0.9×10^{-3}	1.2×10^{-5}	1.4×10^{-2}
7.0	Main sequence	6.9×10^{-3}	0.05×10^{-3}	$\lesssim10^{-6}$	0.08×10^{-2}
	Post-main sequence	2.94	0.61×10^{-3}	$\lesssim10^{-6}$	1.3×10^{-2}
	Total	2.95	0.66×10^{-3}	$\lesssim10^{-6}$	1.4×10^{-2}
7.5	Main sequence	6.5×10^{-3}	$\lesssim10^{-6}$	$\lesssim10^{-6}$	0.03×10^{-2}
	Post-main sequence	2.95	0.6×10^{-3}	$\lesssim10^{-6}$	1.3×10^{-2}
	Total	2.95	0.6×10^{-3}	$\lesssim10^{-6}$	1.4×10^{-2}
8.0	Main sequence	6.2×10^{-3}	$\lesssim10^{-6}$	$\lesssim10^{-6}$	0.01×10^{-2}
	Post-main sequence	2.94	0.6×10^{-3}	$\lesssim10^{-6}$	1.4×10^{-2}
	Total	2.95	0.6×10^{-3}	$\lesssim10^{-6}$	1.4×10^{-2}



$\log Q'_{\star,\mathrm{MS}} = 5.5$
$\log Q'_{\star,\mathrm{MS}} = 6.5$
$\log Q'_{\star,\mathrm{MS}} = 8.0$
$\log Q'_{\star,\mathrm{MS}} = 8.0$
$\log Q'_{\star,\mathrm{postMS}} = 5.5$
Direct impact
Tidal disruption
n [yr^{-1}]
log (L [erg s^{-1}])

Dependences

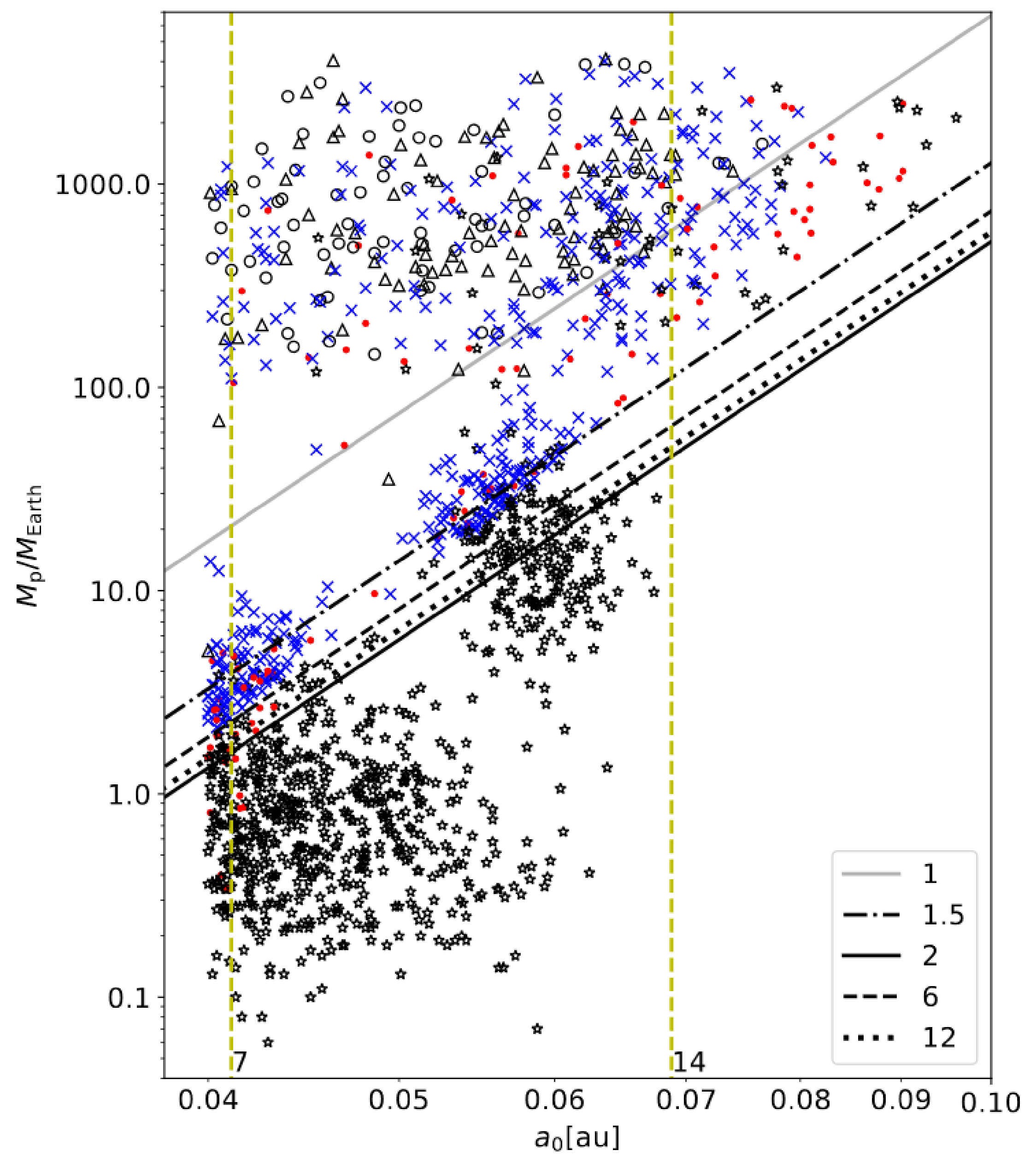
Illustration of the dependence of coalescence statistics on initial distribution in the a-M plane.

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.



Conclusions