The dynamical evolution of transiting planetary systems including a realistic collision prescription

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MNRAS submitted, arxiv.org/abs/1708.08939

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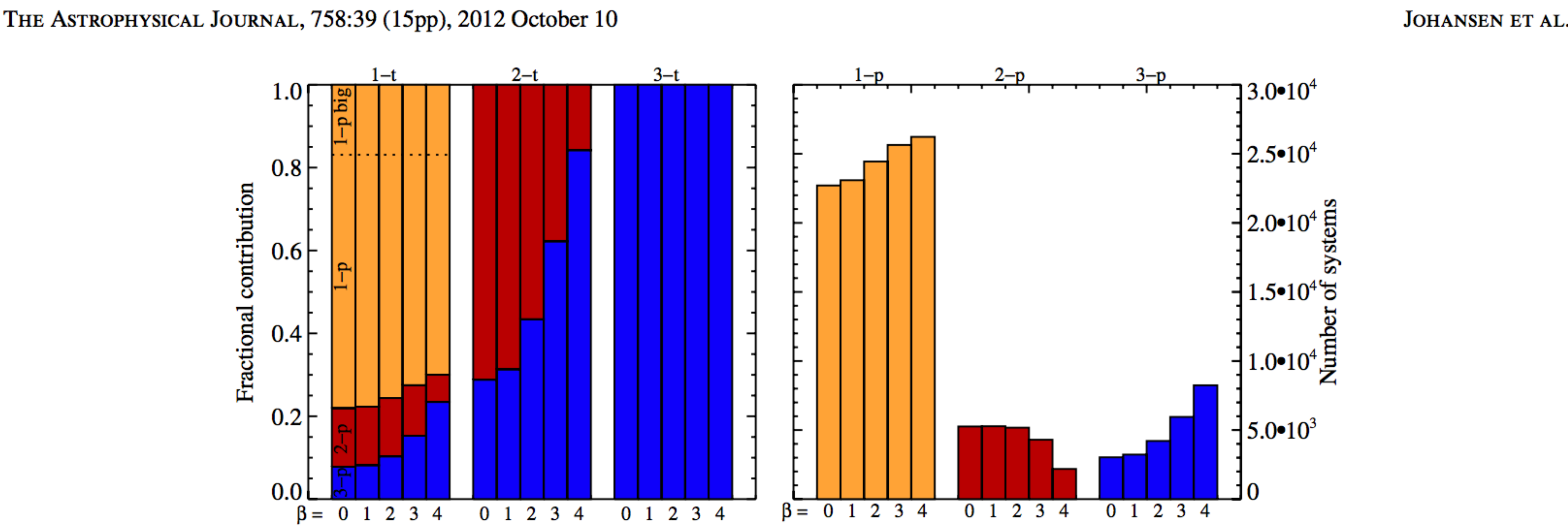
The *Kepler* Dichotomy: an excess of systems with a single transiting candidate



Contribution to single-, double- and triple-candidate systems

Reconstructed intrinsic multiplicities at different mutual inclinations

Johansen *et al* 2012; see also Fang & Margot 2012, Ballard & Johnson 2016

The *Kepler* Dichotomy: explanations

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- Unstable non-resonant systems (Pu & Wu 2015, Volk & Gladman 2015)
- Unstable resonant systems (Izidoro *et al*. 2017)
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- Destabilisation by outer systems (Mustill *et al* 2017, Huang *et al* 2017)

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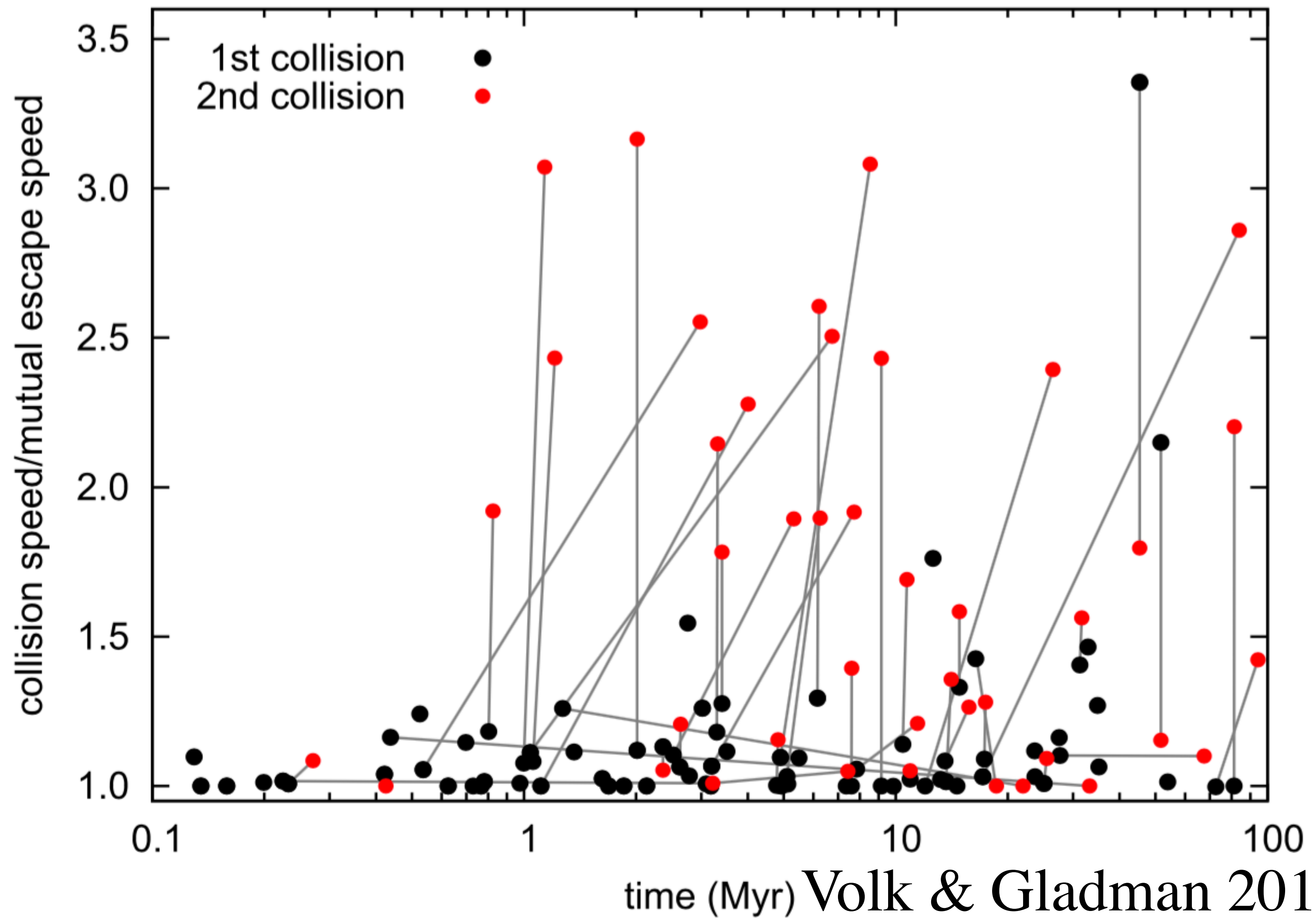

Volk & Gladman 2015

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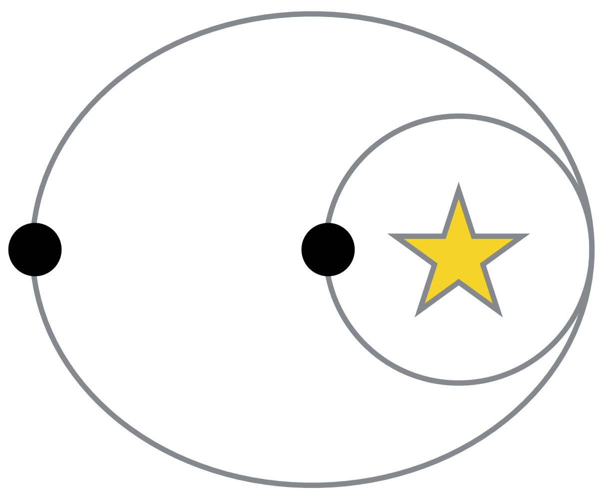
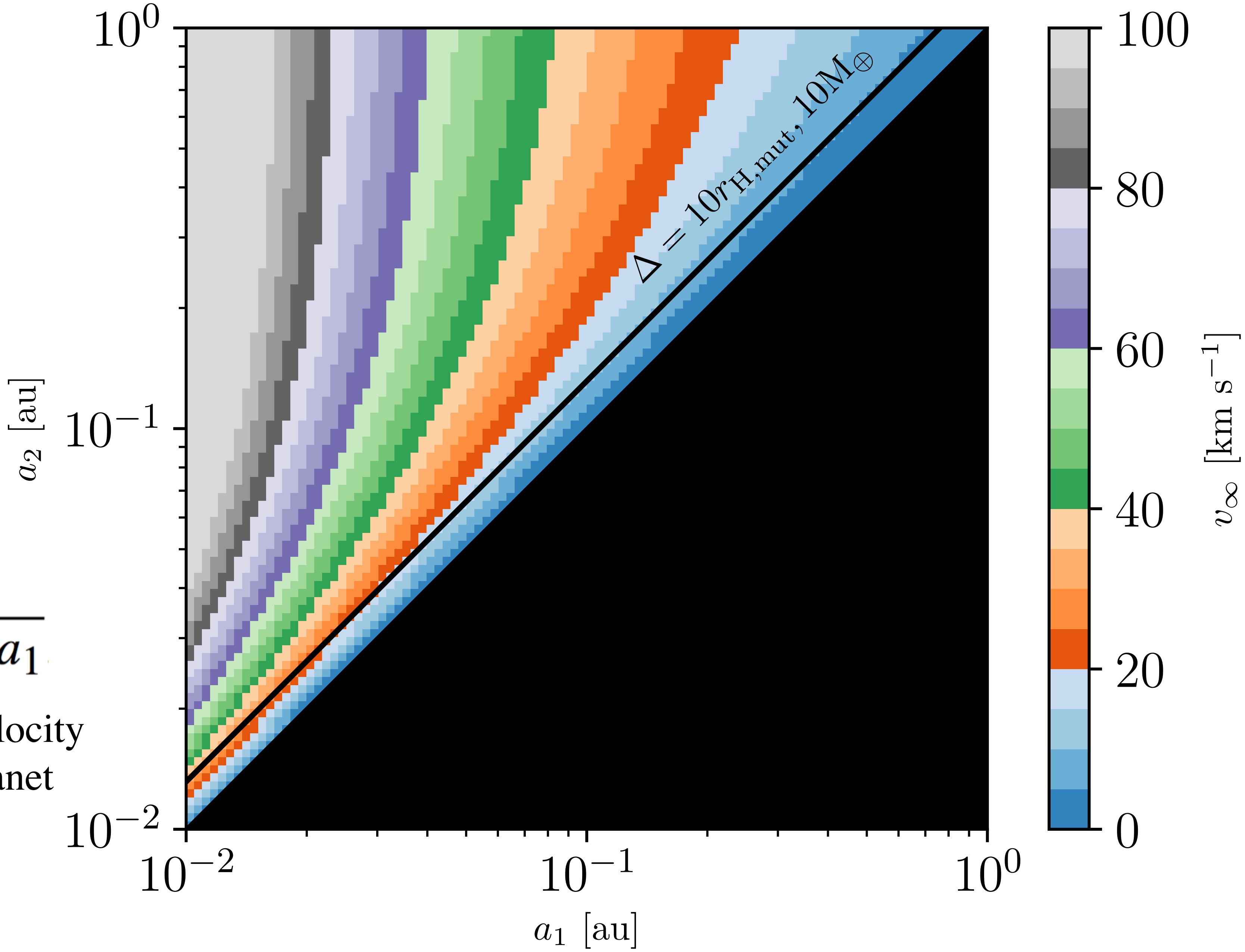
What are the encounter velocities in unstable planetary systems?



$$v_\infty = \sqrt{\mathcal{G}M_\star\left(1+e_2\right)/a_1} - \sqrt{\mathcal{G}M_\star/a_1}$$

Pericentre velocity of outer planet

Keplerian velocity of inner planet



This is a minimum: will be higher including z-components of velocity and gravitational focusing

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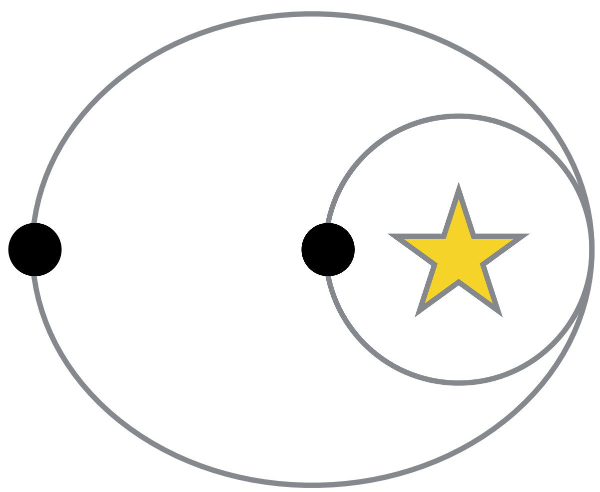

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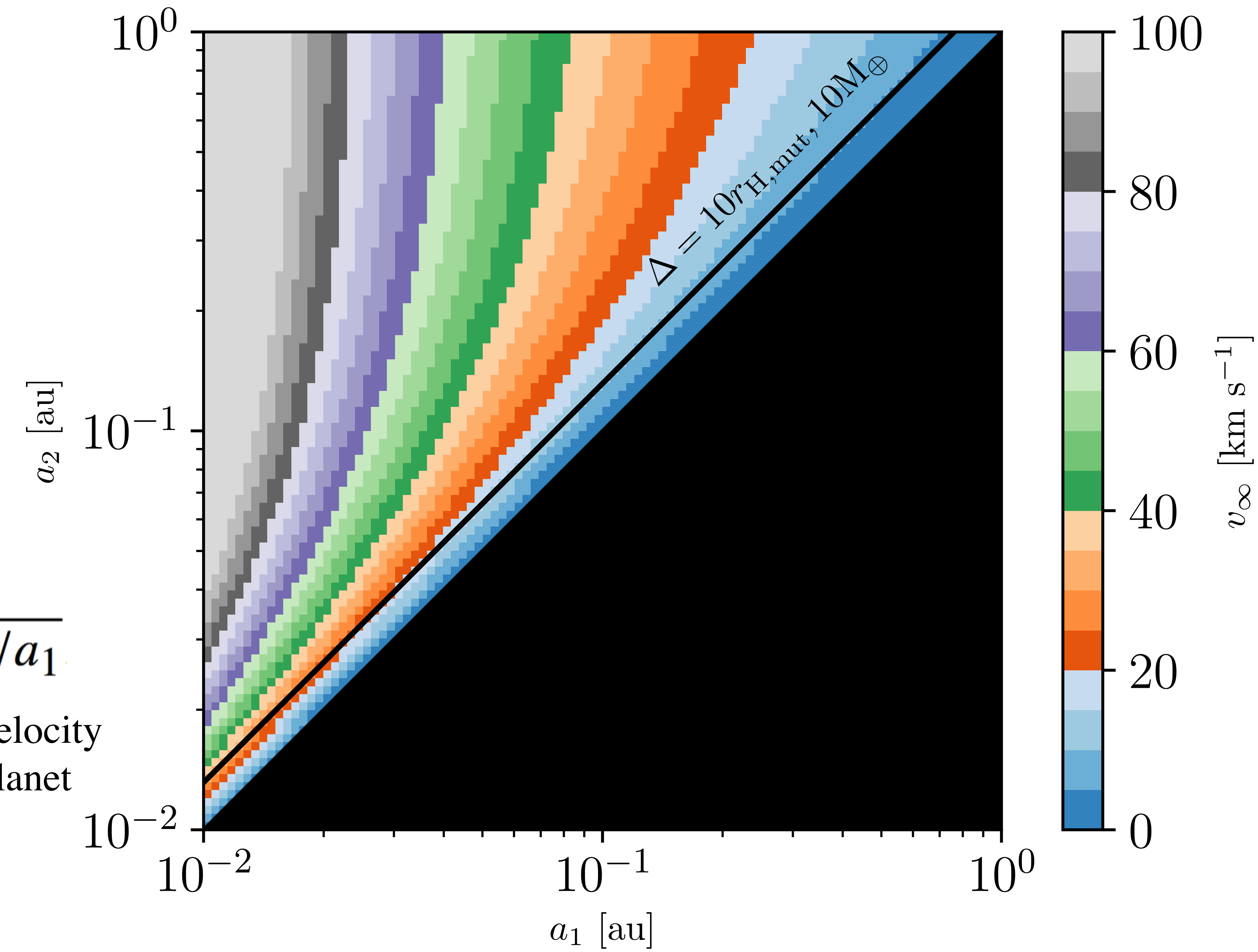

$v_{\text{coll}}/v_{\text{esc}}$ sets how destructive the collision is

Improving the collision treatment in the MERCURY N-body integrator

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- Treatment of collision fragments: two approximations:
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Use this as most extreme case

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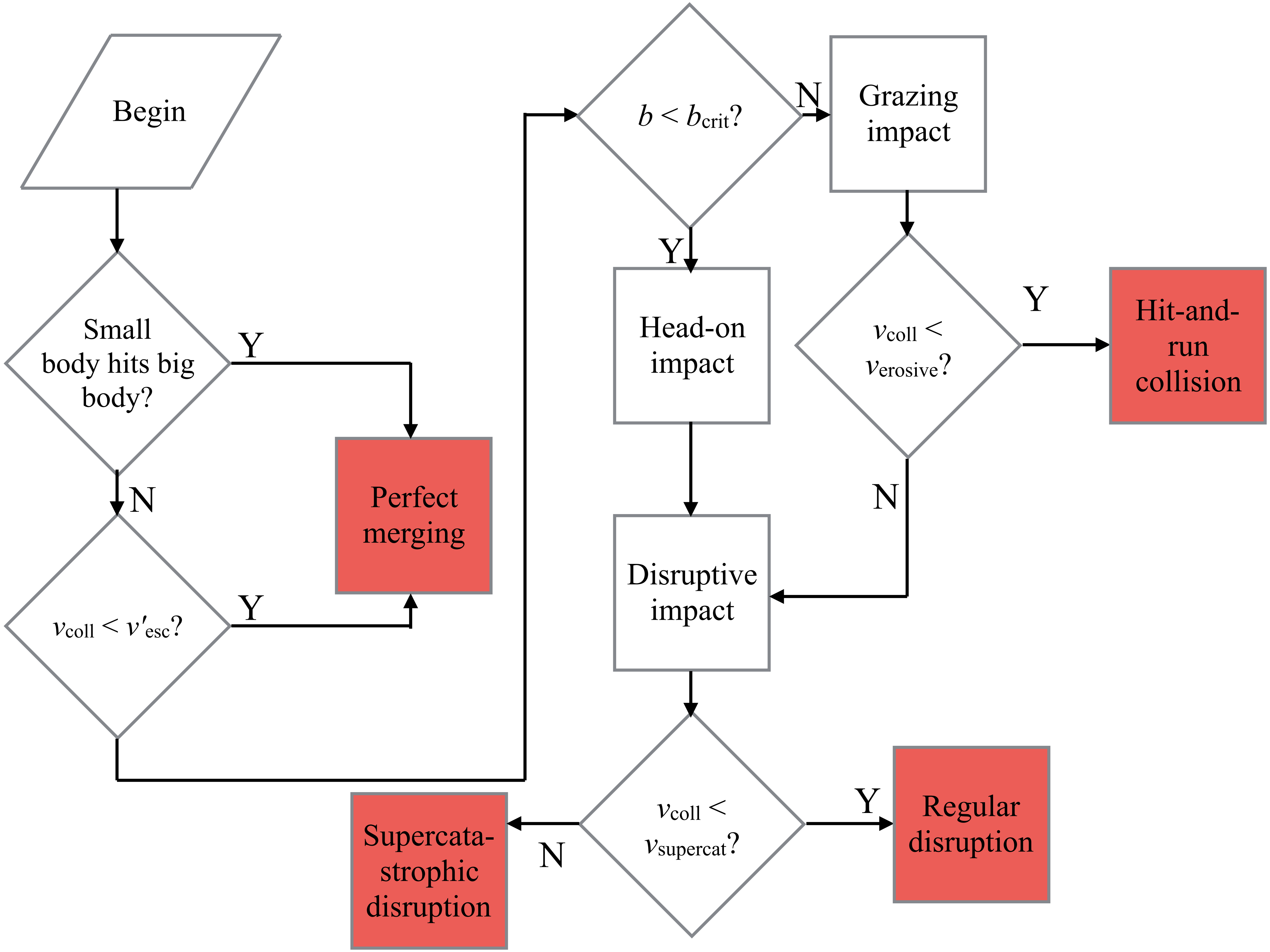
Begin
Small body hits big body?
Y
N
Perfect merging
$v_{coll} < v'_{esc}$?
Y
$b < b_{crit}$?
N
Y
Grazing impact
Head-on impact
$v_{coll} < v_{erosive}$?
Y
Hit-and-run collision
N
Disruptive impact
$v_{coll} < v_{supercat}$?
Y
Regular disruption
N
Supercata-strophic disruption

Collision outcomes in unstable super-Earth systems

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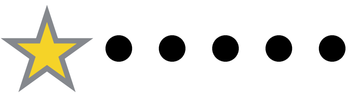

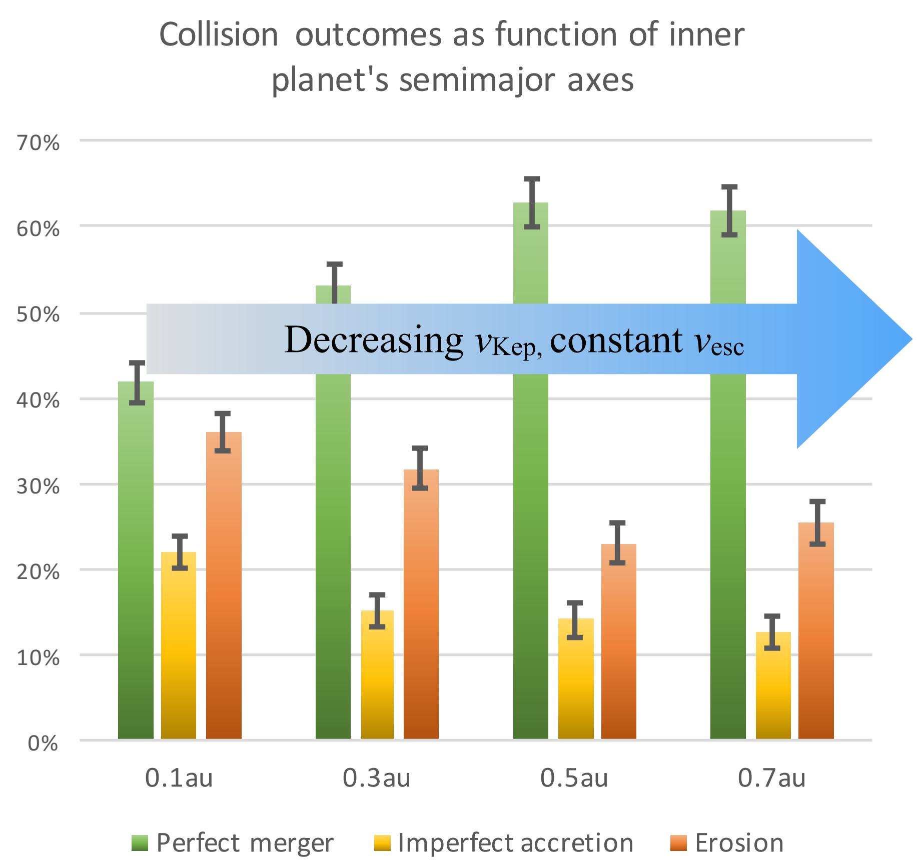

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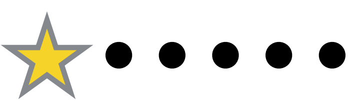

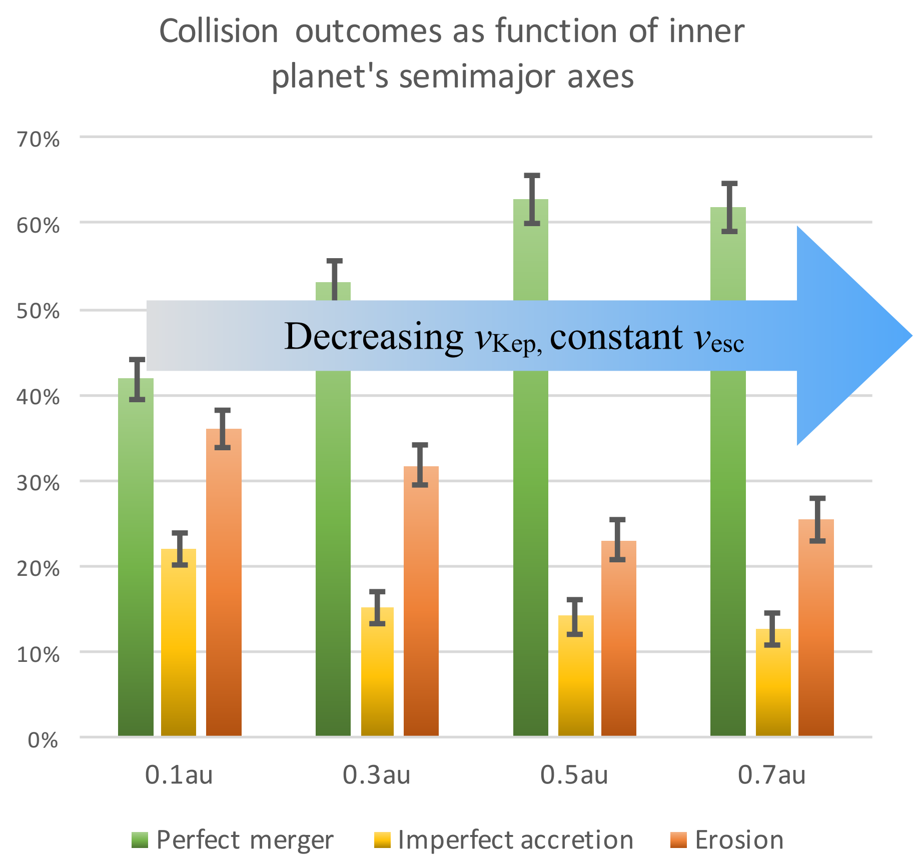

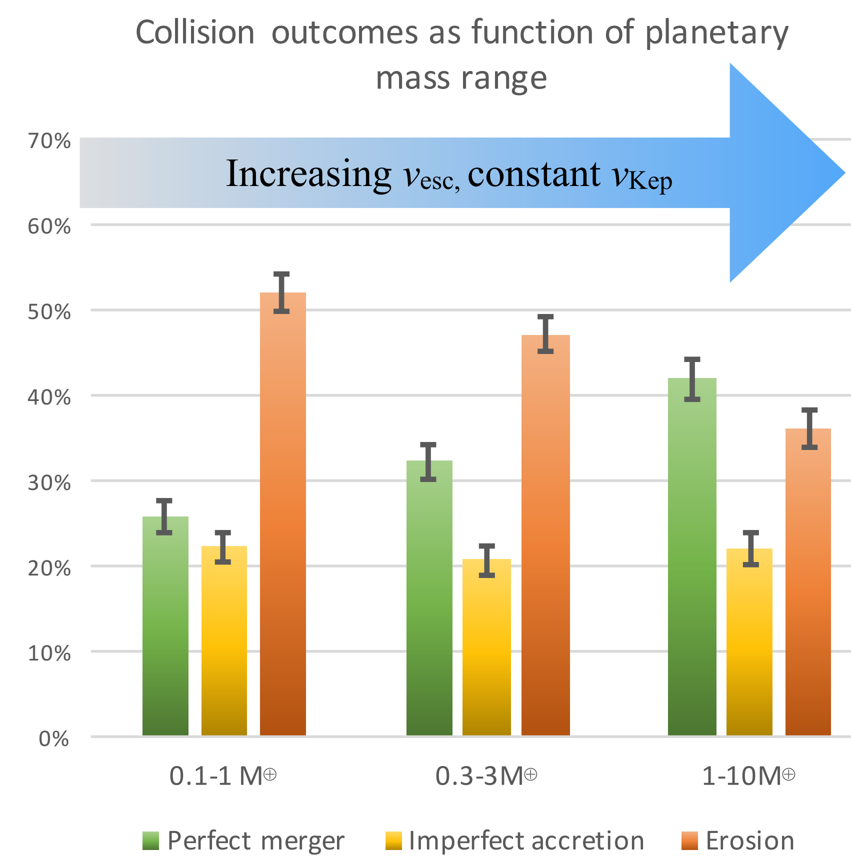

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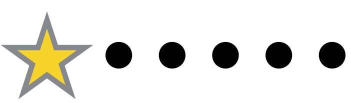

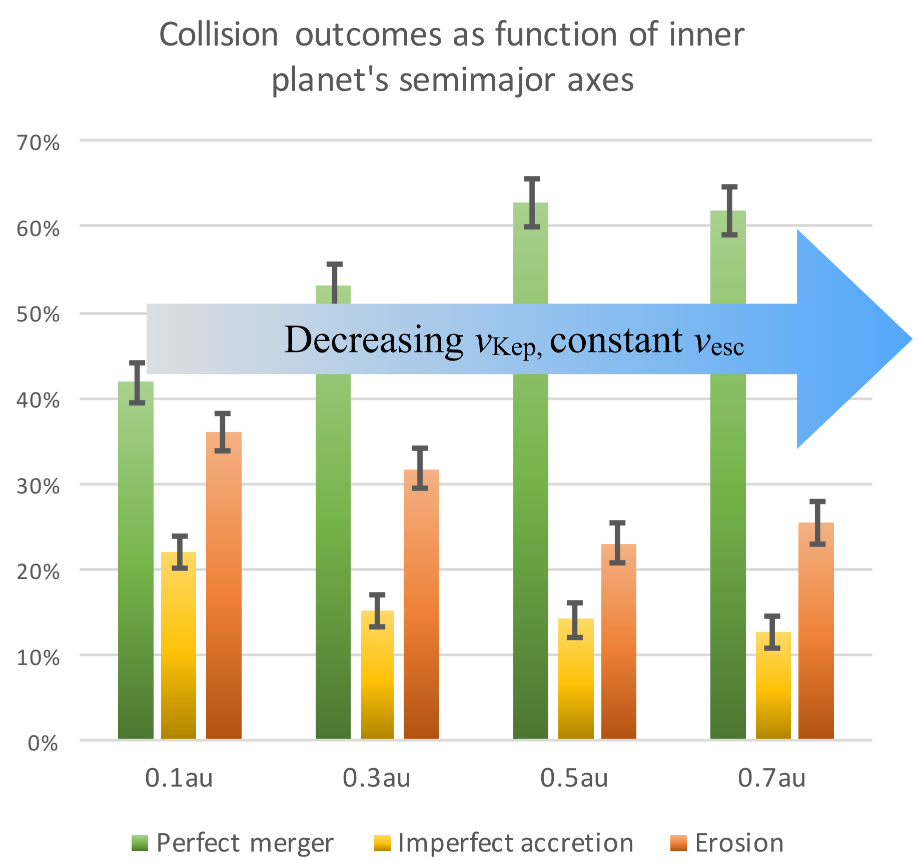

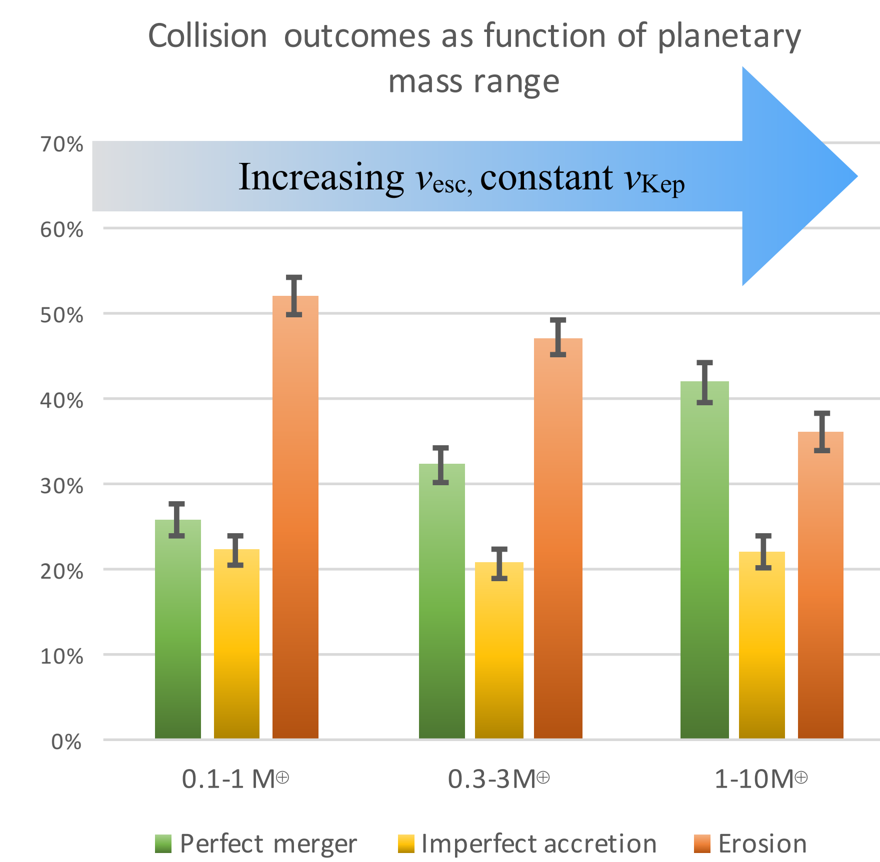

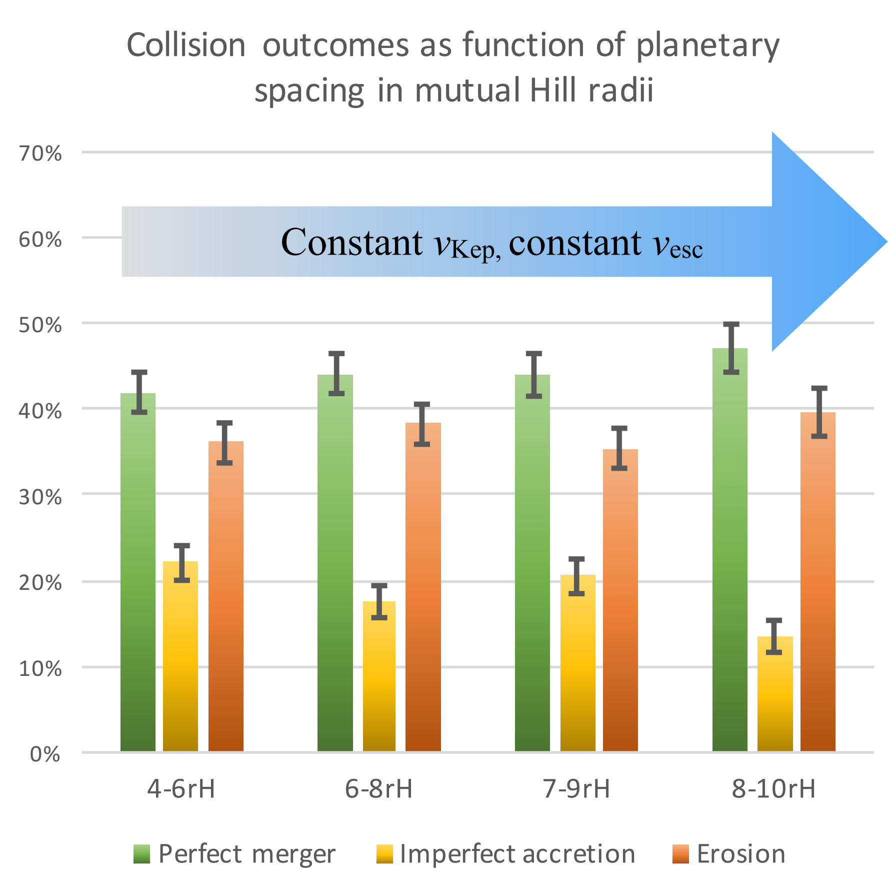

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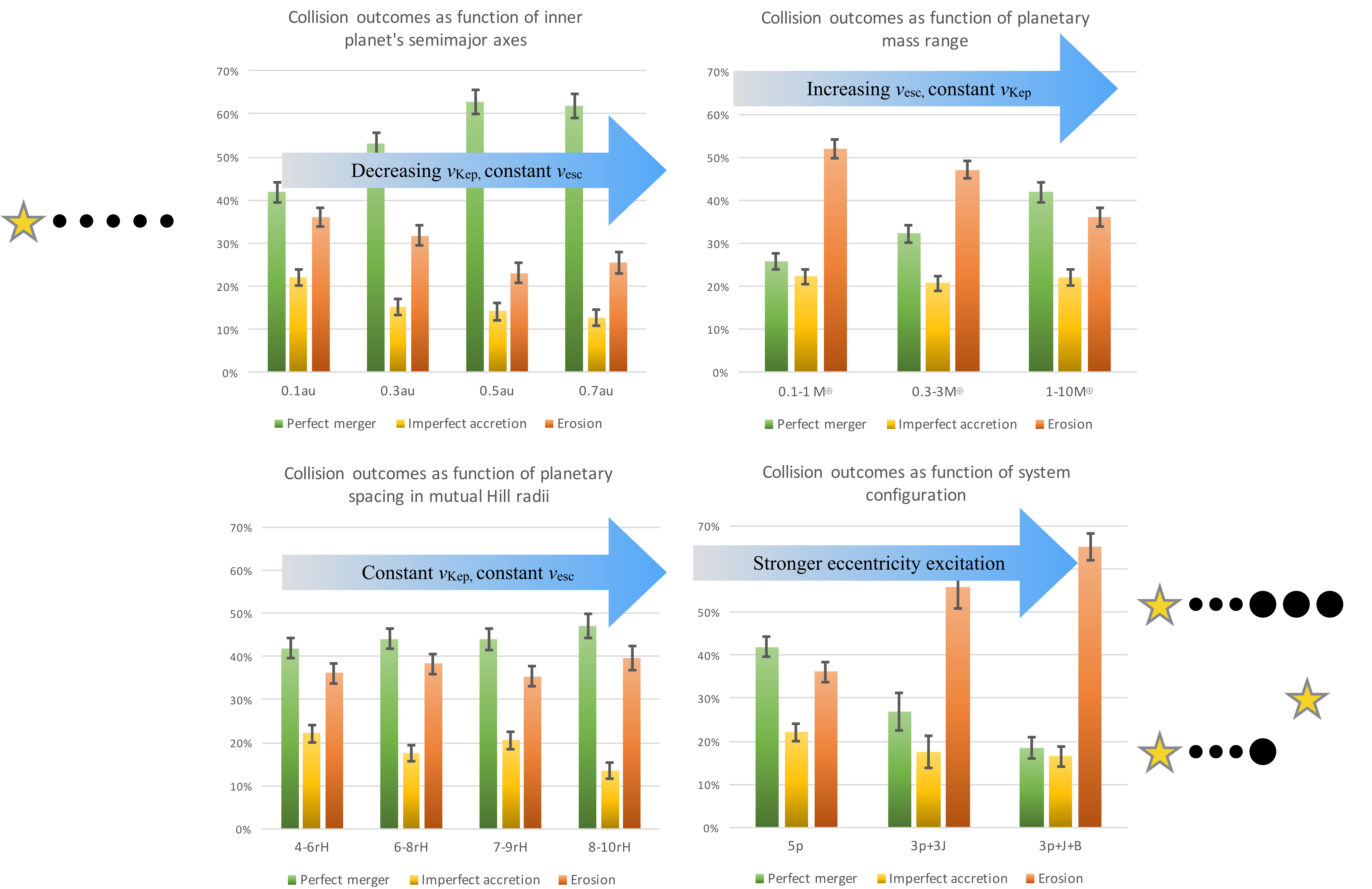
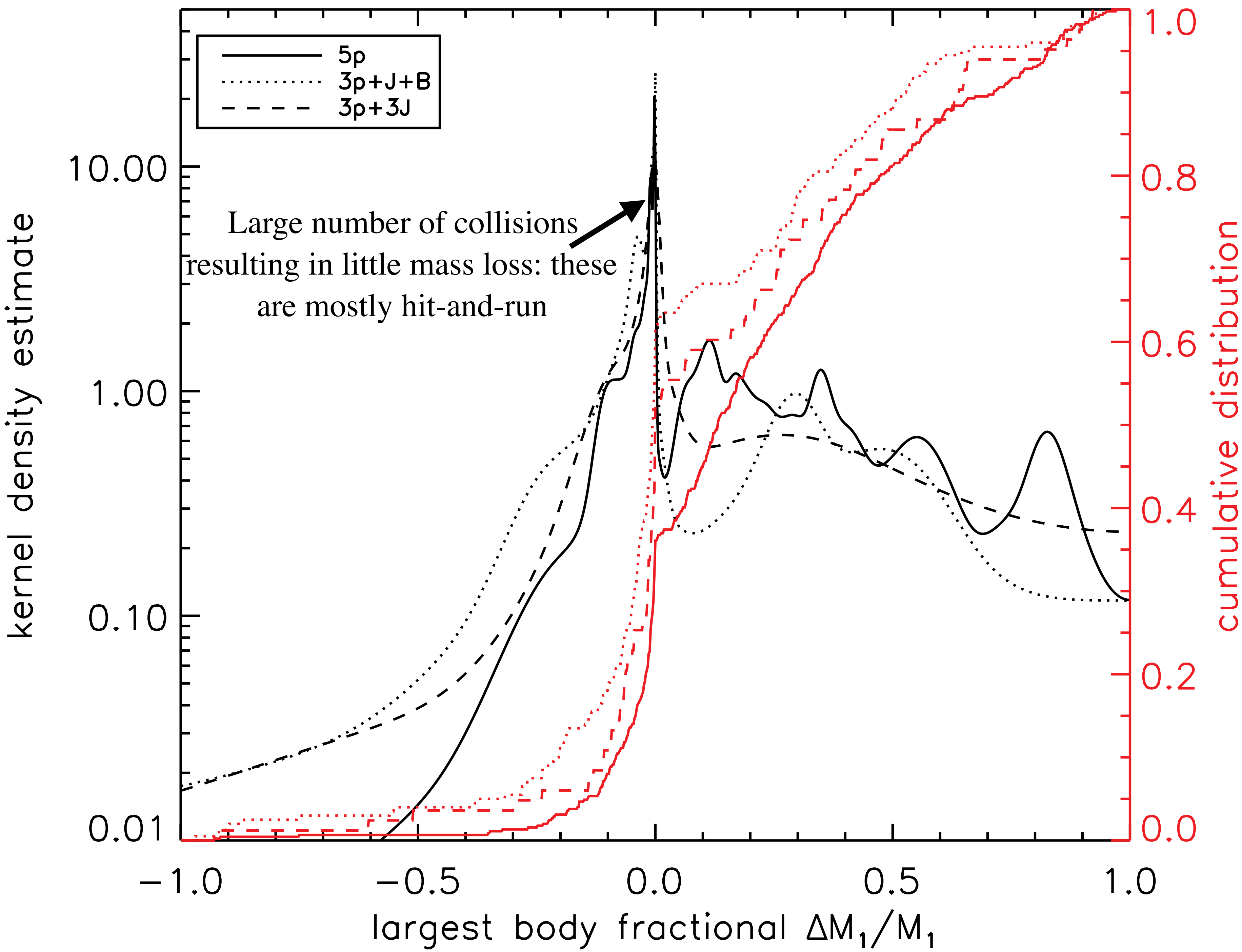
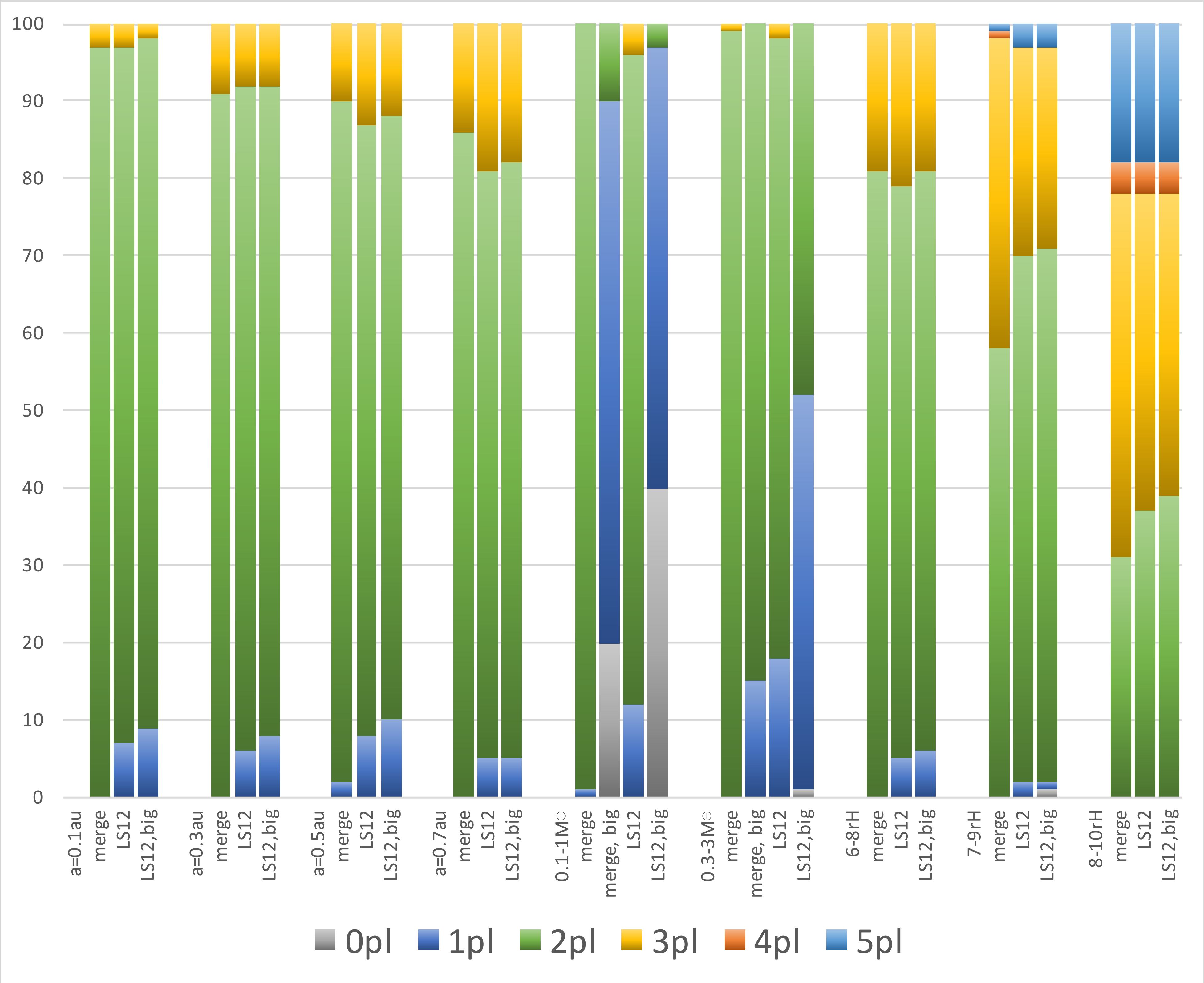


At 0.1 au most collisions are not perfect mergers. But erosive collisions do not result in much mass loss

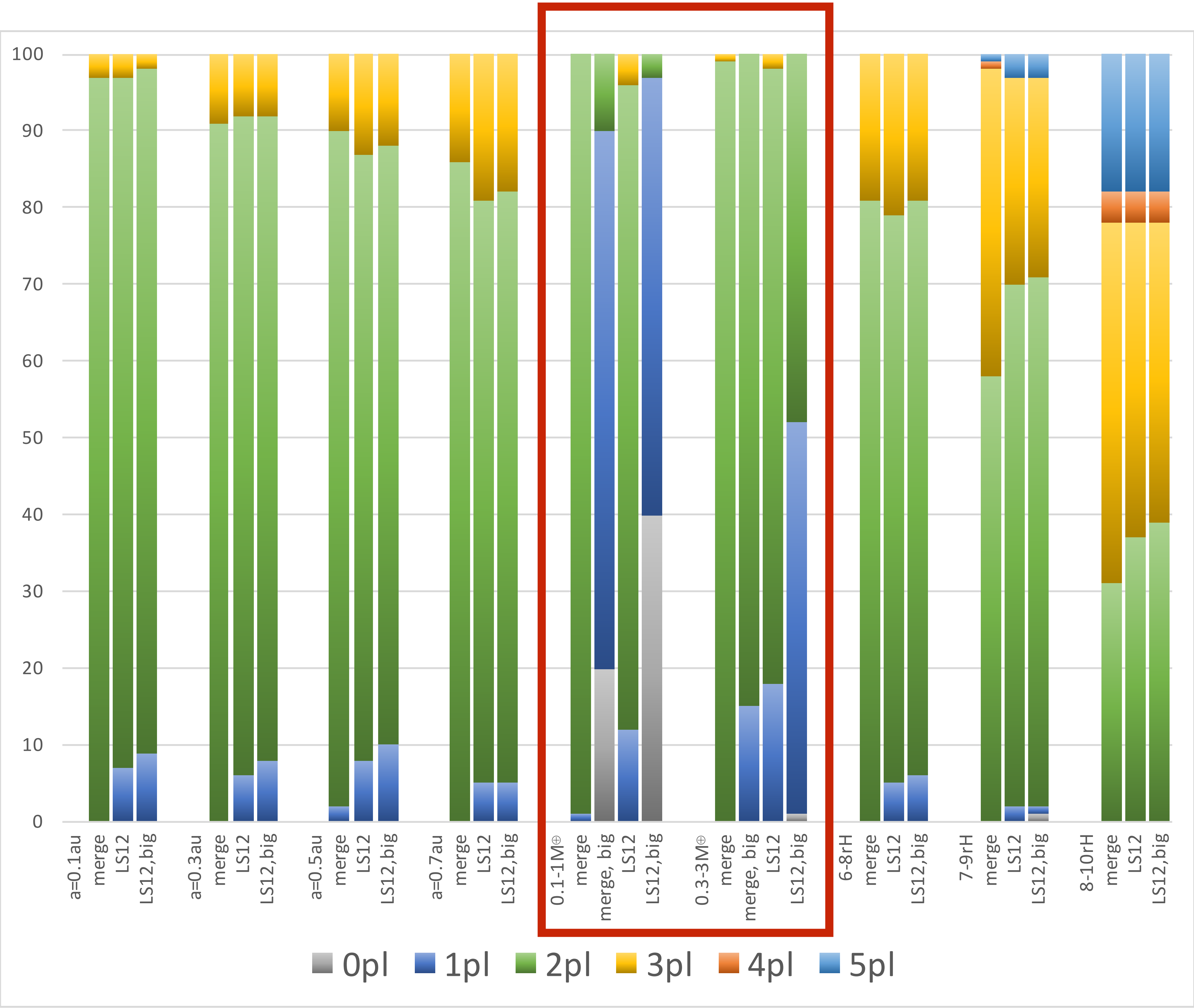


Little impact on final multiplicity after instability

Hard to grind a system down to one or zero detectable planets

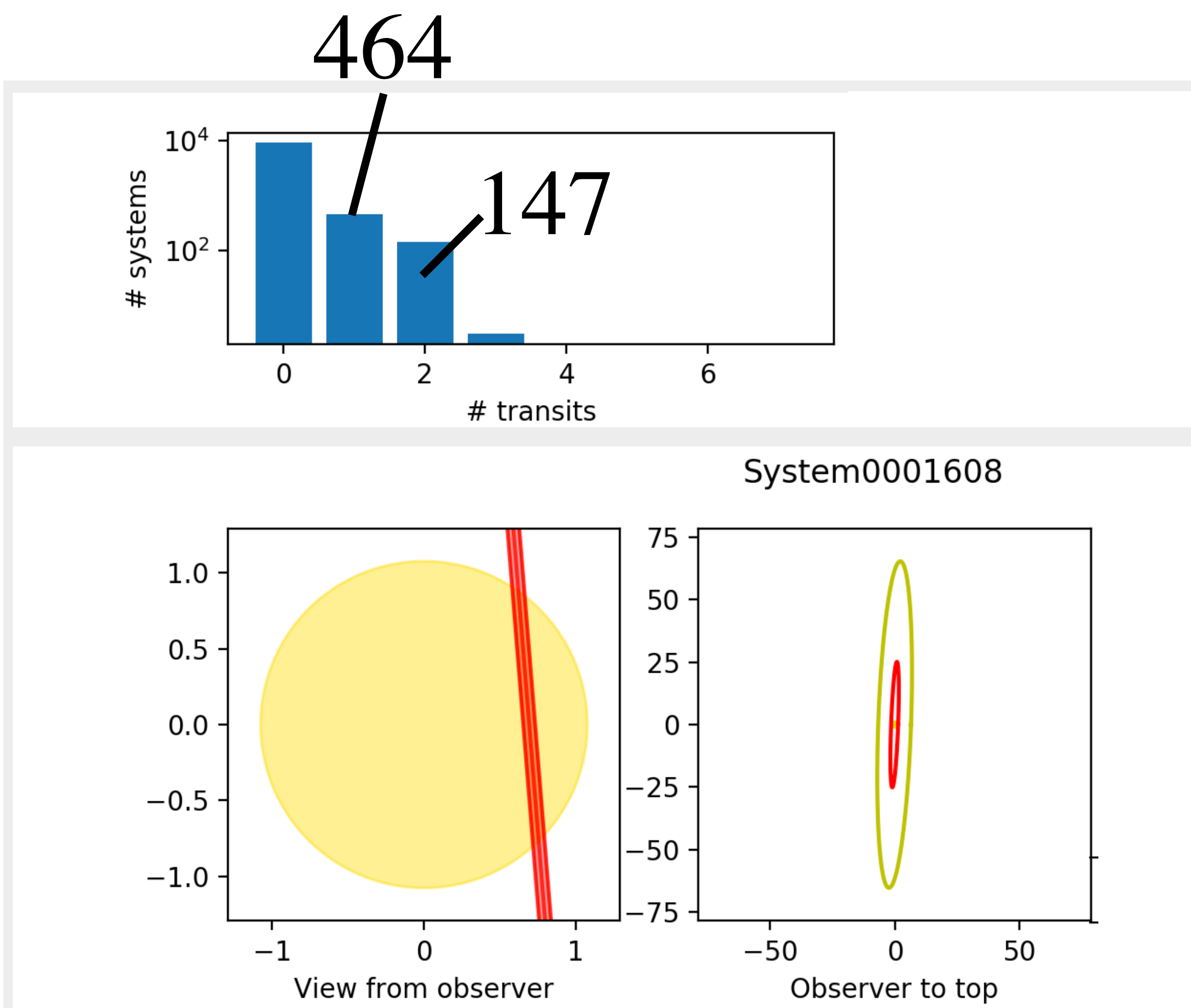


Exception: when starting from smaller planets



Observed multiplicities: still not enough singles

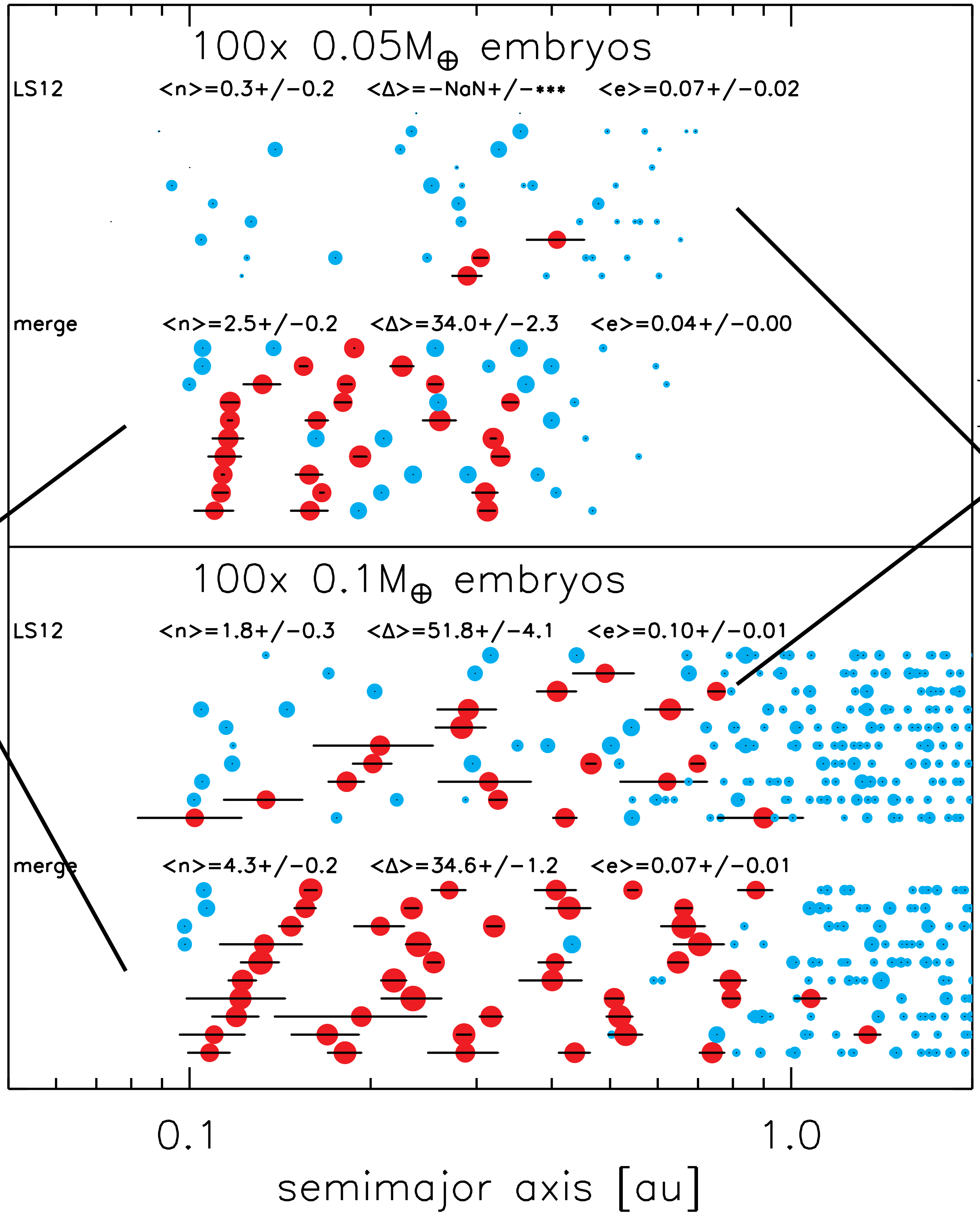
- Observed multiplicities: around 6 singles for every 1 double (depending slightly on selection criteria), *e.g*. Johansen *et al* (2012), Lissauer *et al* (2014)
- Our unstable multiples reduce to ~3:1 observed singles:doubles
- Still need extra source of singles (see also Izidoro *et al* 2017 for initially resonant systems, perfect merging assumed)



	Planet Name	a [R⊙]	i [˚]	Omega [˚]	r [R⊙]	B [R⊙]
1	00	25.15700	87.87747	273.19193	0.03882	0.93173
2	01	65.40640	87.99937	275.76462	0.01331	2.28337

Effects on *in-situ* formation from embryos

Always perfect merging: high-multiplicity systems formed



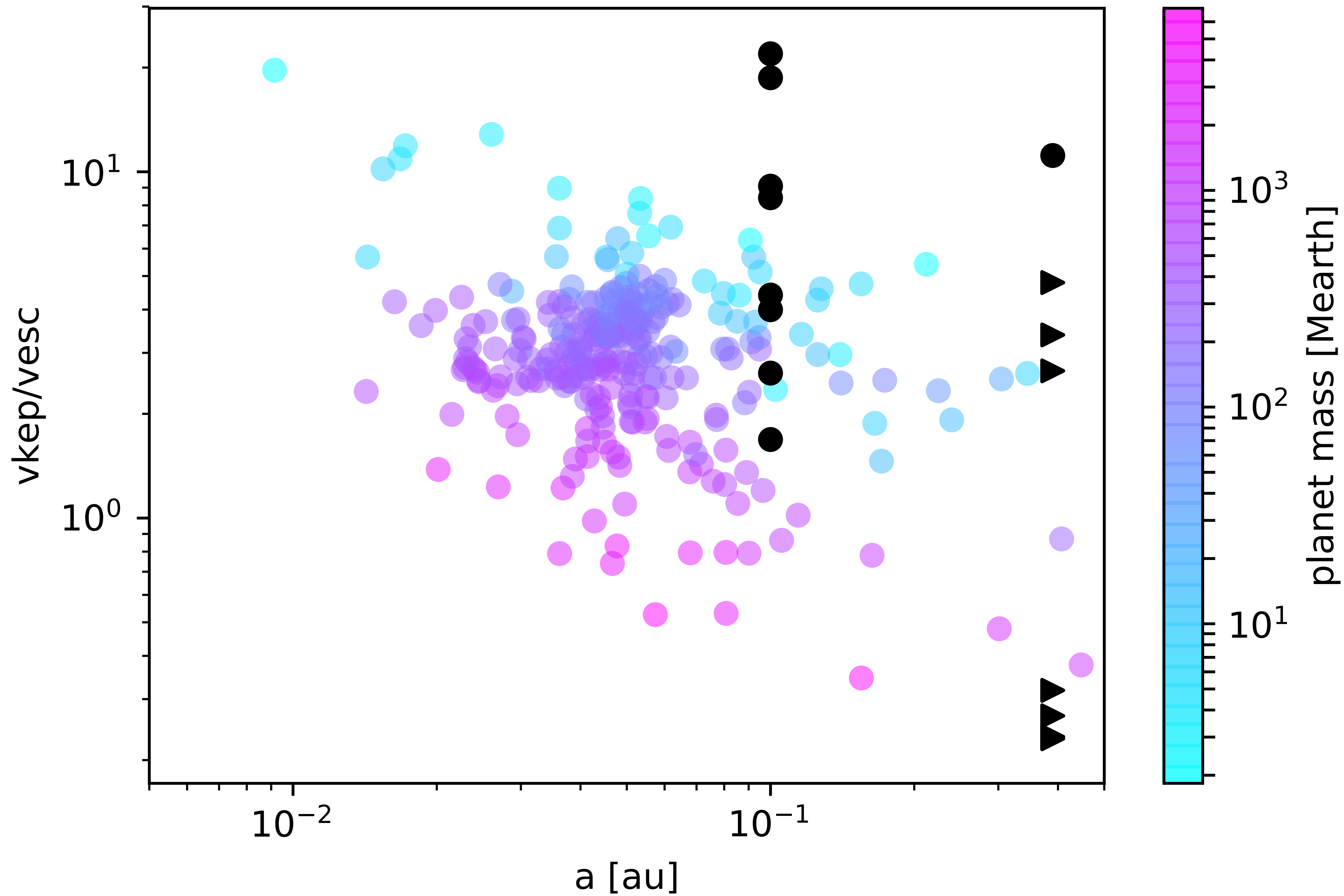
Realistic collision algorithm: few high multiplicity, many singles and zeros

Caveat: fragments removed (no reaccretion)

Conclusions

- Collisions between planets or embryos at ~0.1 au usually do **not** result in perfect mergers.
- **Fewer perfect mergers** when planets are smaller, or high eccentricities are excited by outer system dynamics.
- Many collisions are **grazing impacts** resulting in little mass loss.
- Little effect on final mass distribution or multiplicity when starting from large planets.
- ***In-situ formation from embryos*** is strongly affected by the collision prescription. If collision debris is efficiently removed, many single- or zero-planet systems form. **Contribution to the Kepler dichotomy** for rocky planets.
- See ***arxiv.org/abs/1708.08939*** for further details.

At small orbital distances, Keplerian velocity can significantly exceed surface escape velocity



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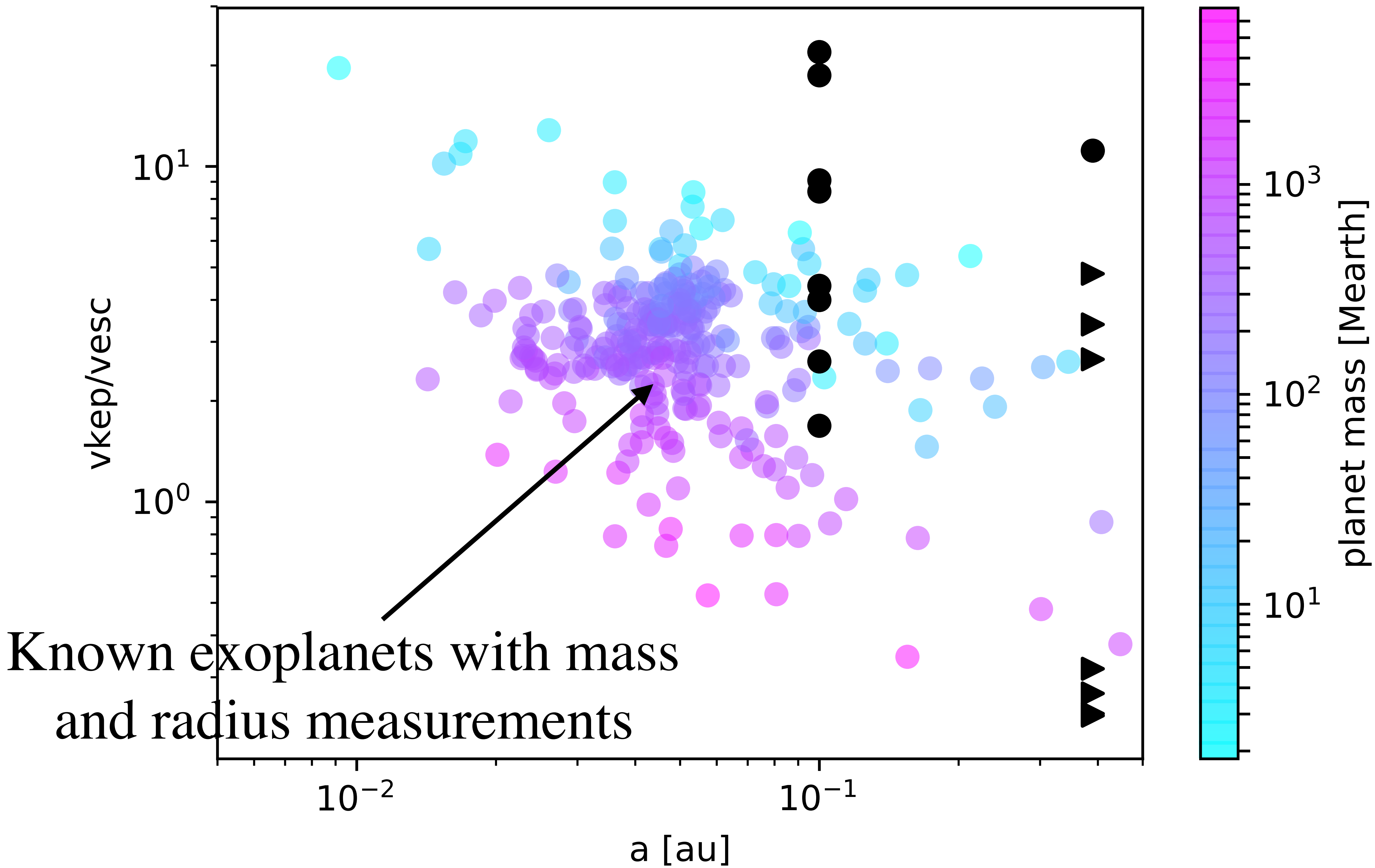

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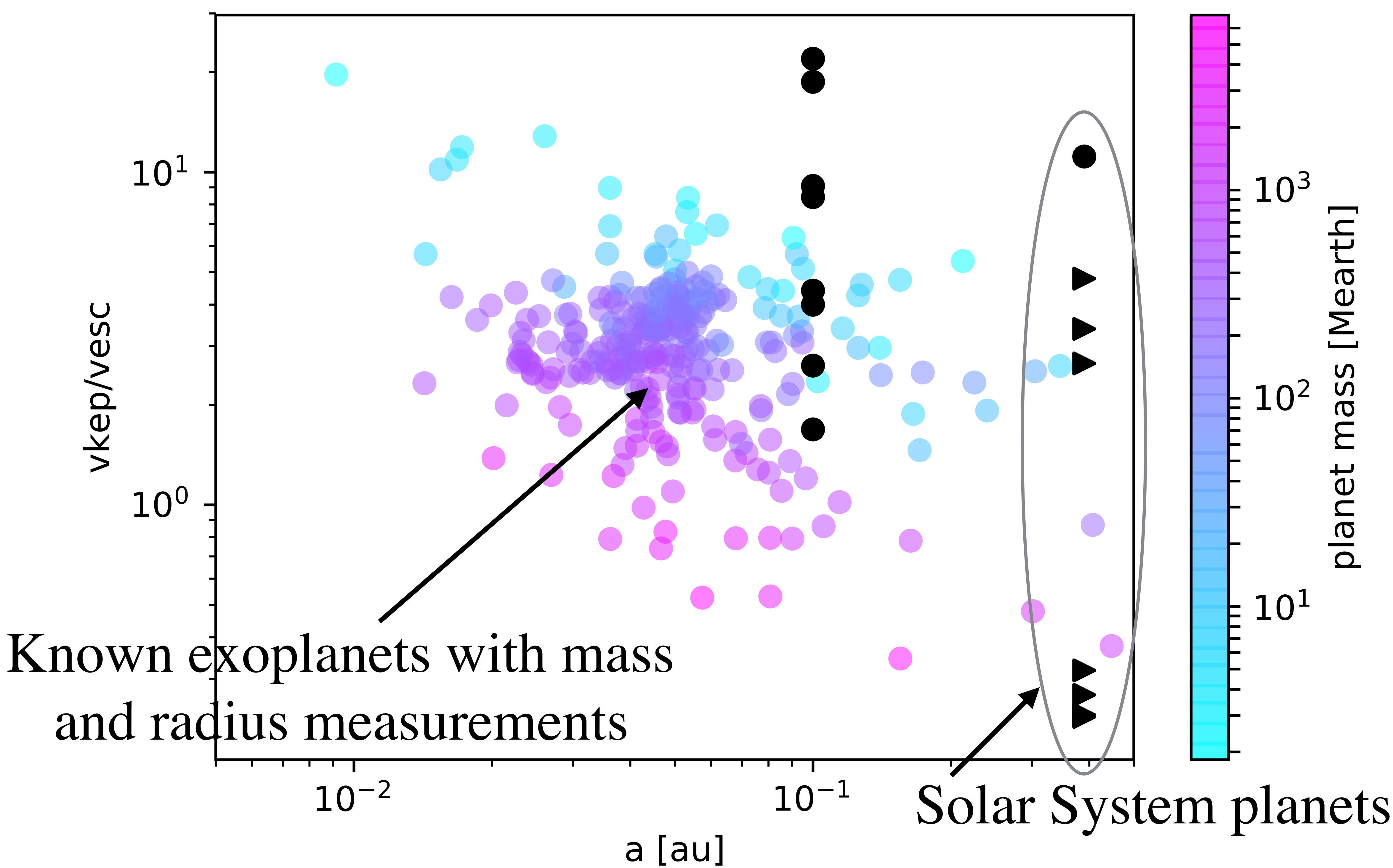

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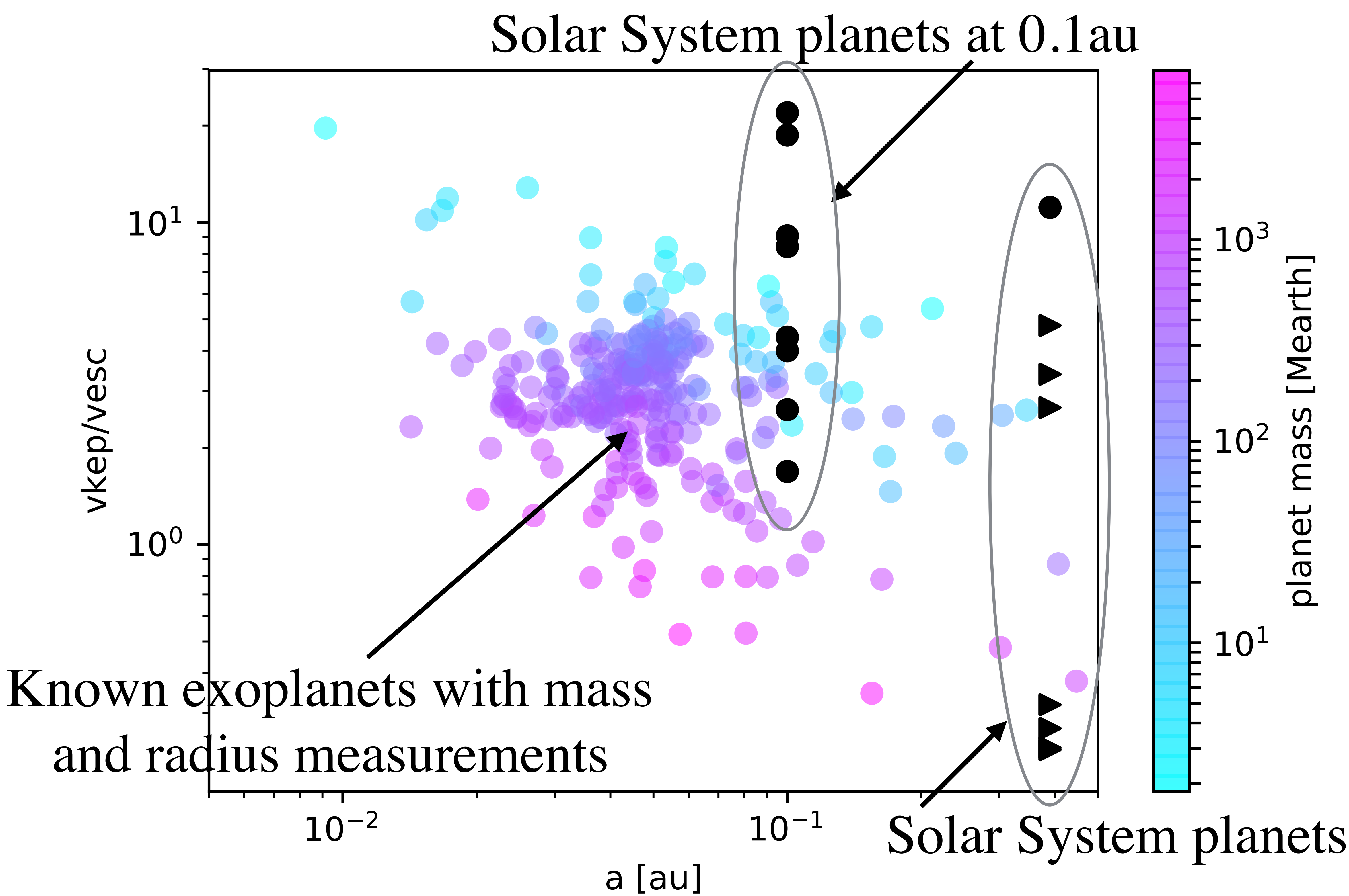
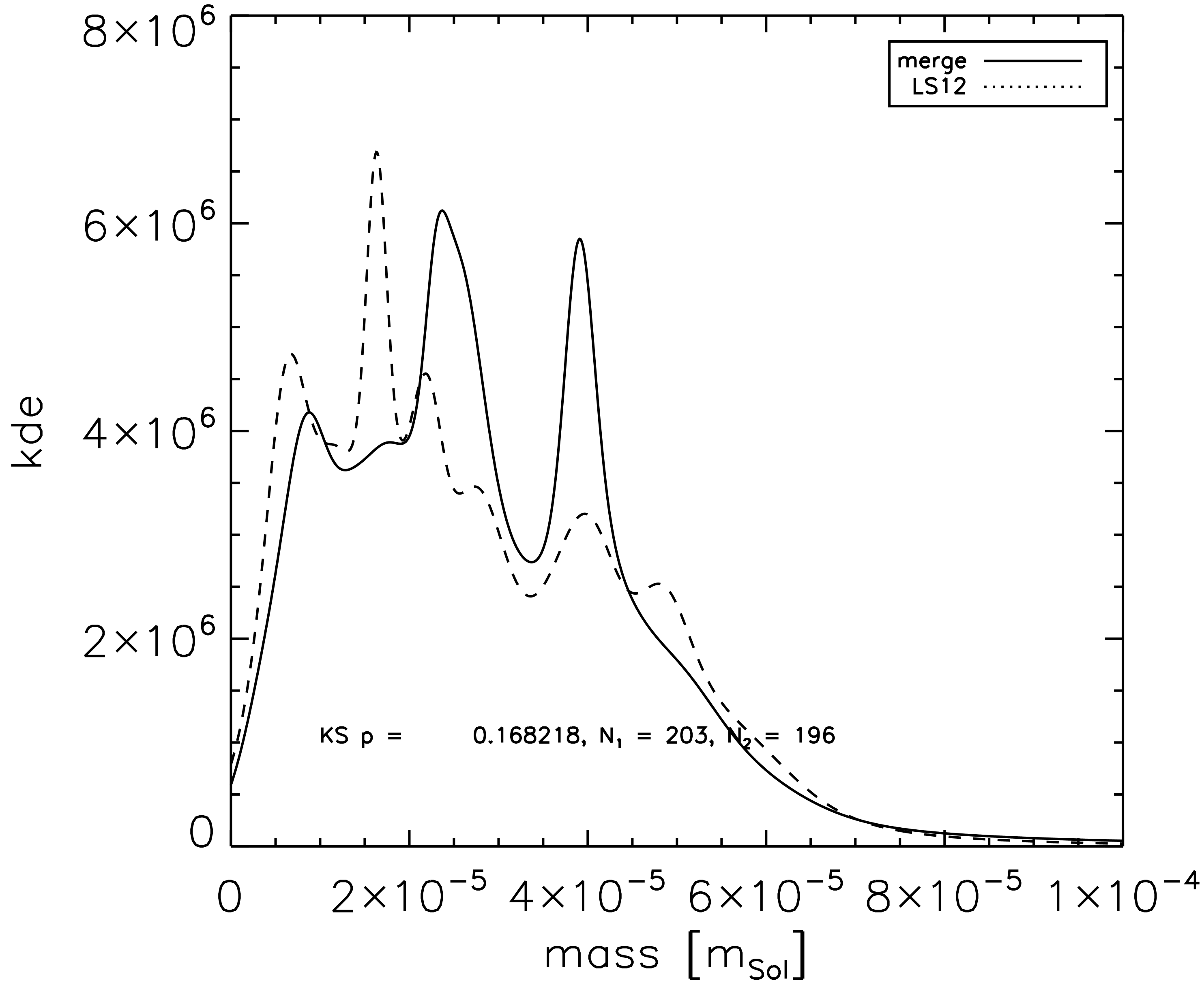
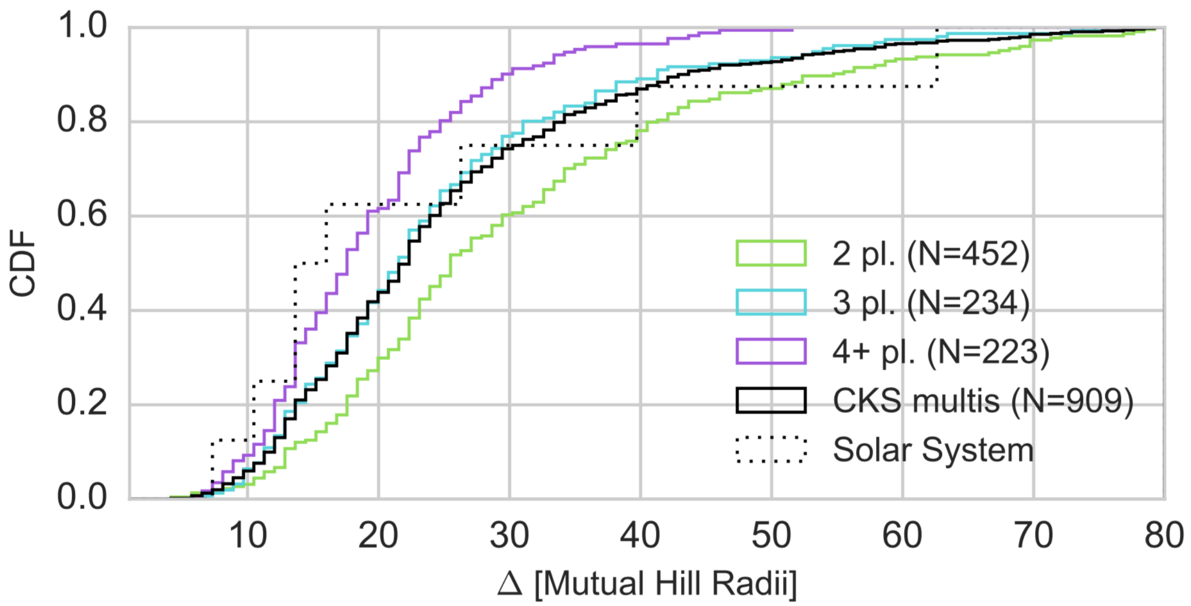


Final mass distributions in unstable super-Earth systems



Abandoning the perfect merging algorithm results in more widely-spaced systems



Empirical *Kepler* distribution
(Weiss *et al* 2017)