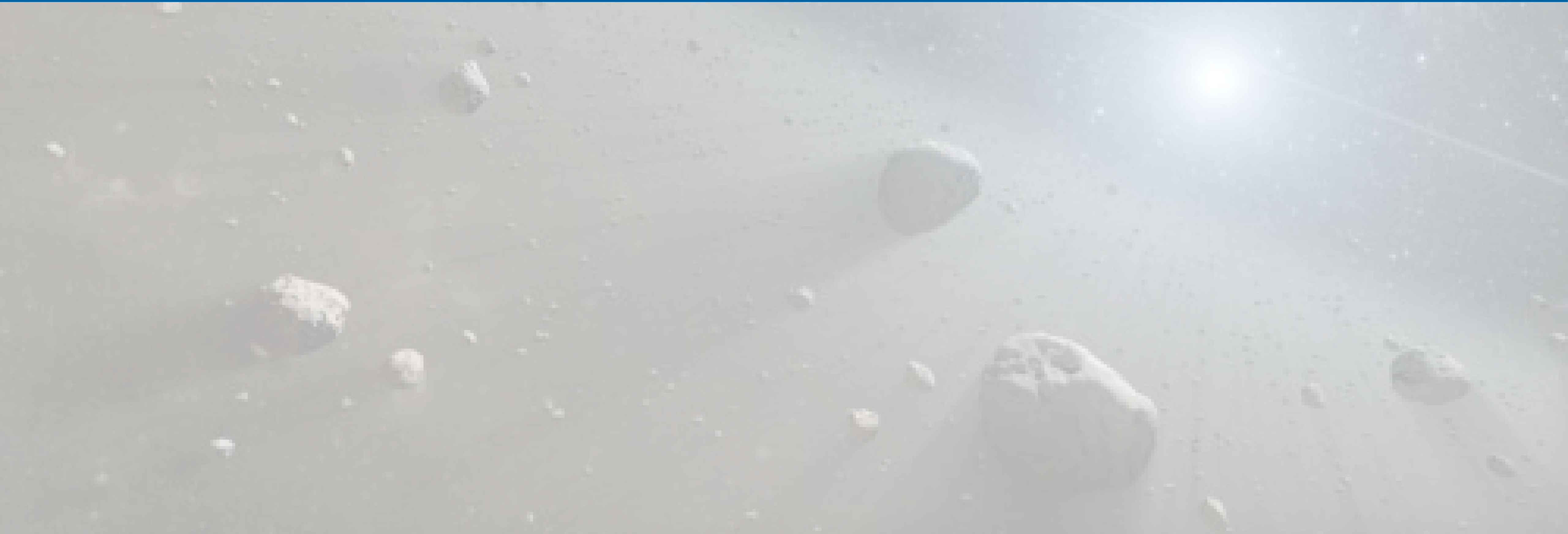
Terrestrial planet formation considering various binary star configurations

Max Zimmermann & Elke Pilat-Lohinger

submitted to A&A



Planets in binary star systems

- Considerable fraction of stars are member of a binary or multiple star system
- Small fraction of discovered exoplanet systems (778 out of 4522) are part of a binary star system
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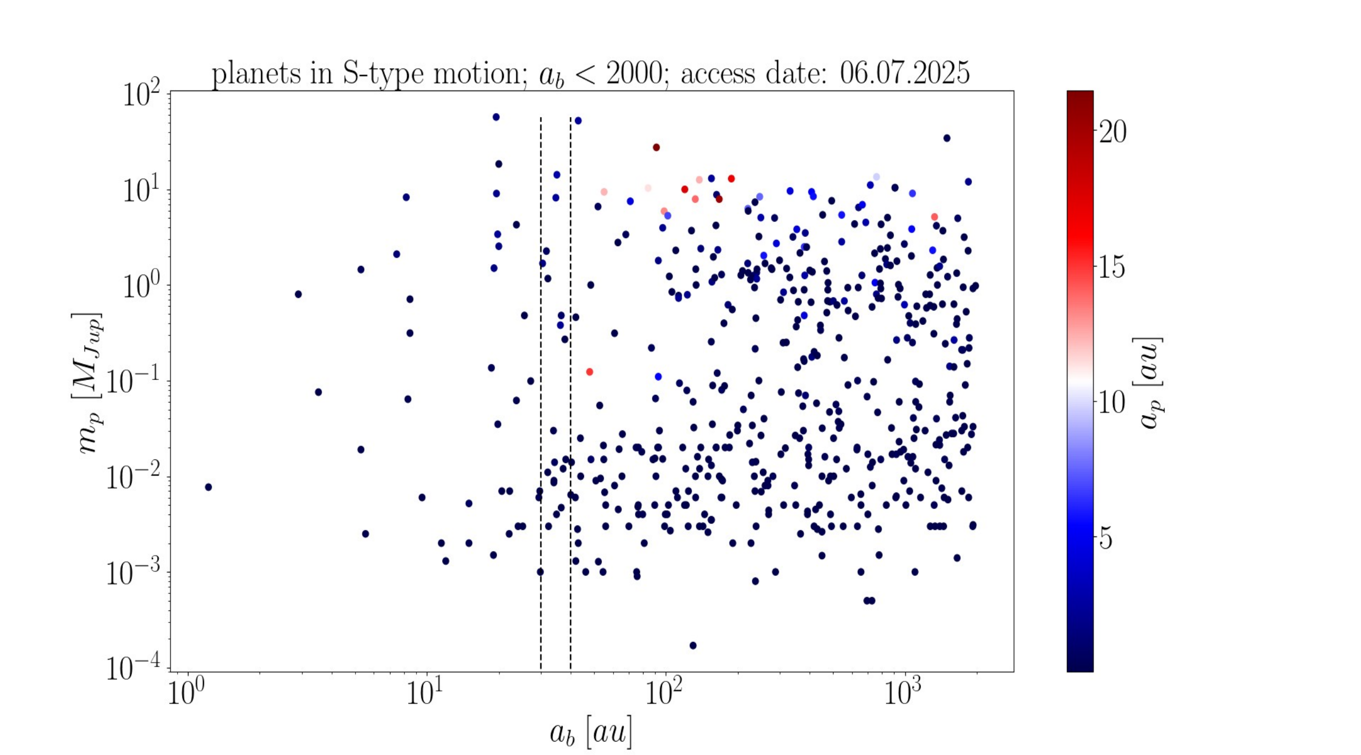
- Observational bias, or suppression by the secondary star?
- Hale (1994): a_b > 30 – 40 au: inclination between two stars randomly distributed



Data from: https://exoplanet.eu/planets_binary/

Methods and initial conditions

- Late stage of terrestrial planet formation
- GPU accelerated N-body code GANBISS (Zimmermann & Pilat-Lohinger 2023)
- Perfect merging
- Simulation time: 10 Myr
- Equal mass binary stars: 1 $M_\odot$

a_b [au]	e_b	i_b [°]
30	0.0	0
60	0.2	20
100	0.4	45

N-body problem:

$$\dot{\boldsymbol{r}}_\nu = \boldsymbol{v}_\nu, \qquad \nu = 0, \ldots, N$$

$$\dot{\boldsymbol{v}}_\nu = k^2 \sum_{\mu=0, \mu\neq\nu}^{N} m_\mu \frac{\boldsymbol{r}_\mu - \boldsymbol{r}_\nu}{|\boldsymbol{r}_\mu - \boldsymbol{r}_\nu|^3}$$

- Disk contains 2000 planetesimals and 25 planetary embryos
- Between 1 – 4 au around the primary star (S-type)
- Total disk mass: $M_{tot} \approx 4.8\ M_\oplus$
- Dynamically excited disk objects in the inclined configurations

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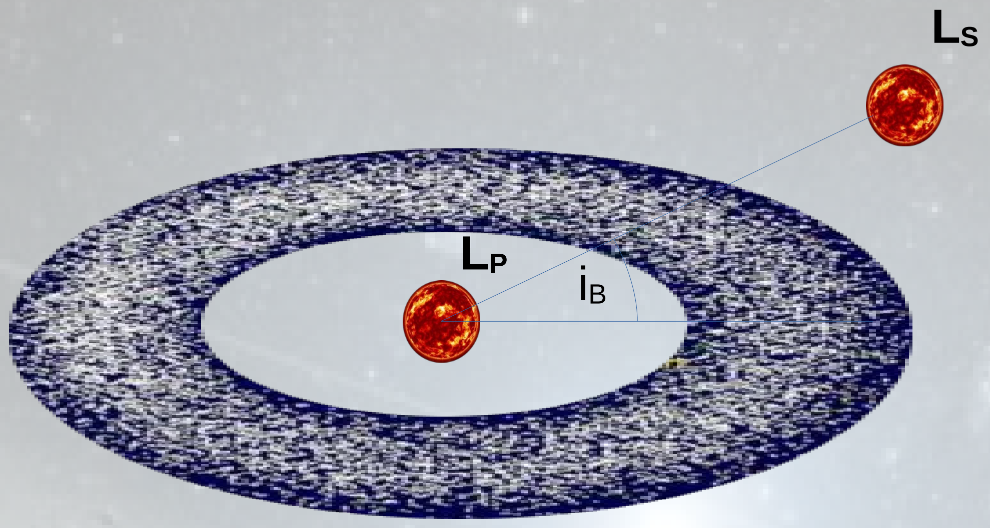

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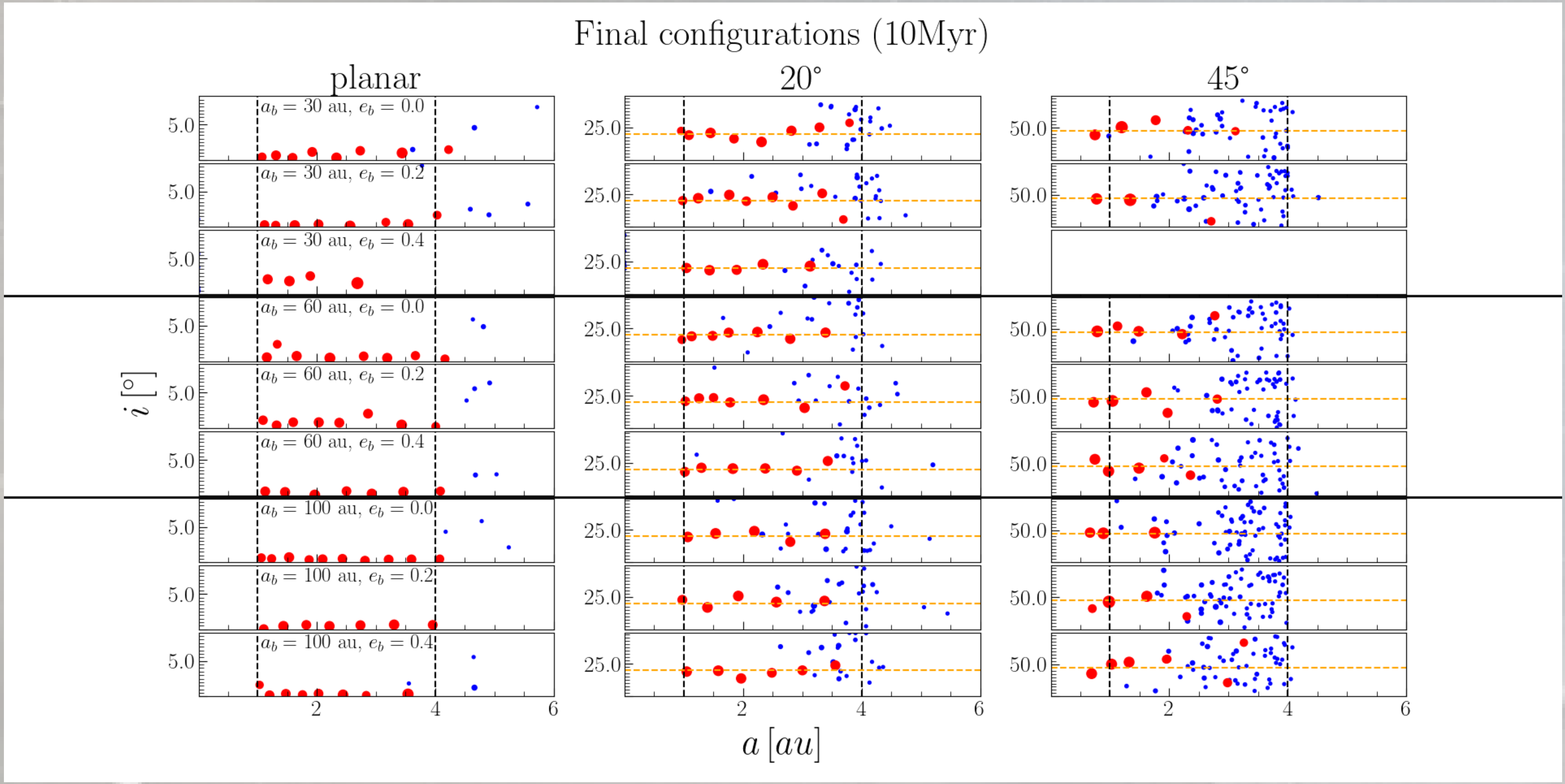
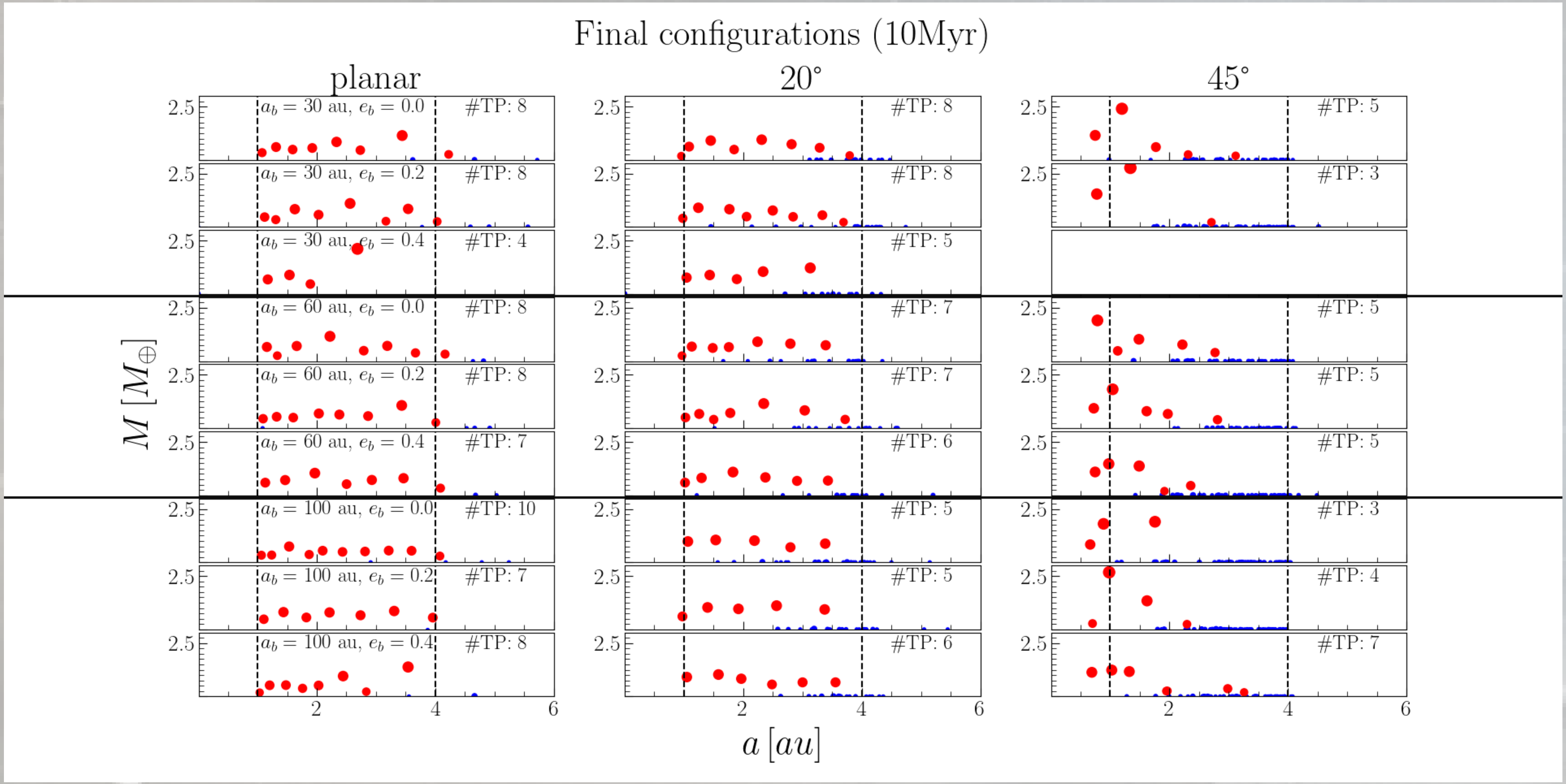
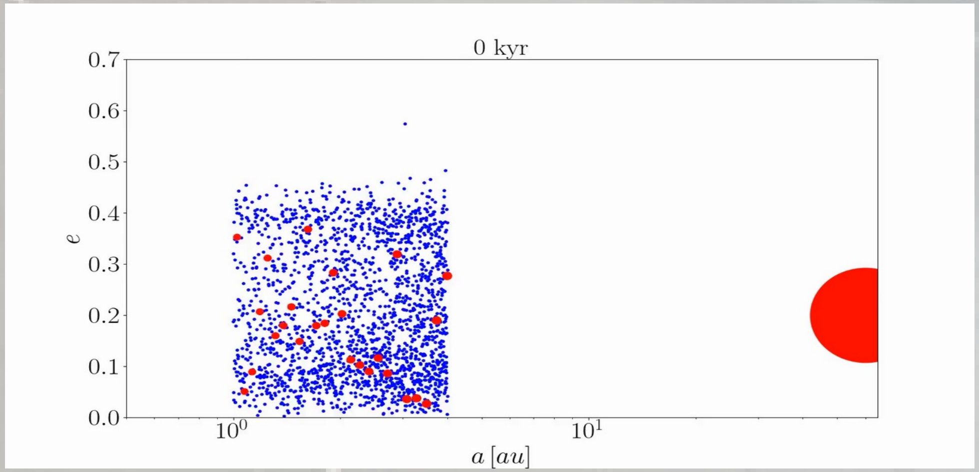
Final configurations: Inclination

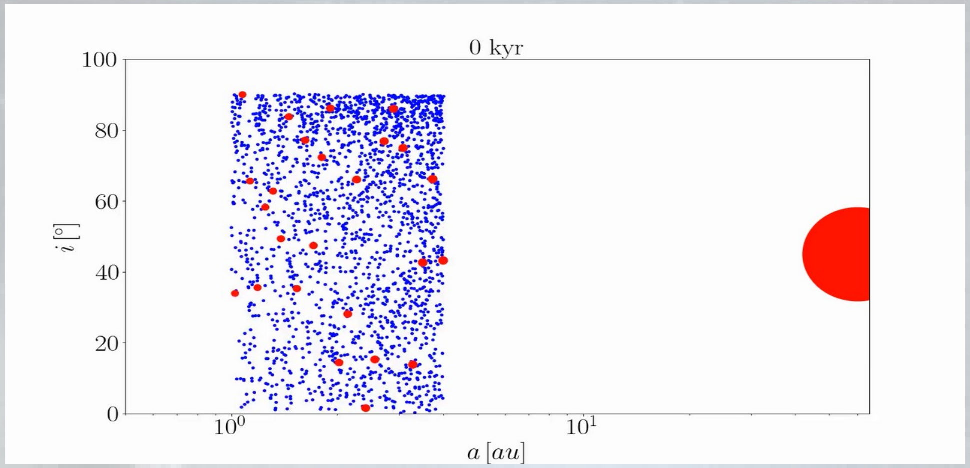


Final configurations: Mass



Evolution of e and i



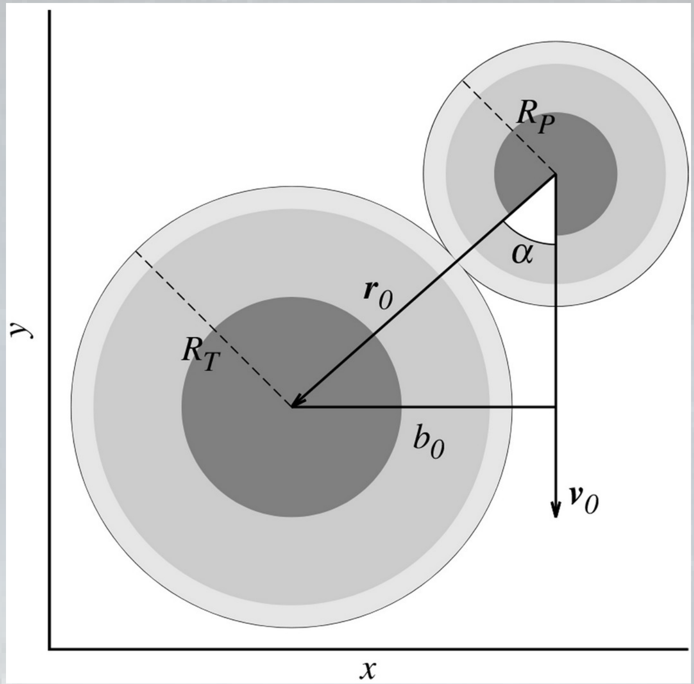


A_b = 60 au, e_b=0.2, i_b=45°

Two-body collisions

- Apply collision model from Leinhardt and Stewart 2012 in a post-process
- Predicts the collision outcome based on impact velocity, impact angle, and mass ratio

- 6 different collision outcomes:
  - Perfect merging: hit and stick
  - Graze and merge: hit, separate, but grav. bound and merge
  - Partial accretion: target gains mass
  - Partial erosion: target loses mass
  - Super catastrophic: both objects destroyed
  - Hit-and-run: hit, separate, not bound



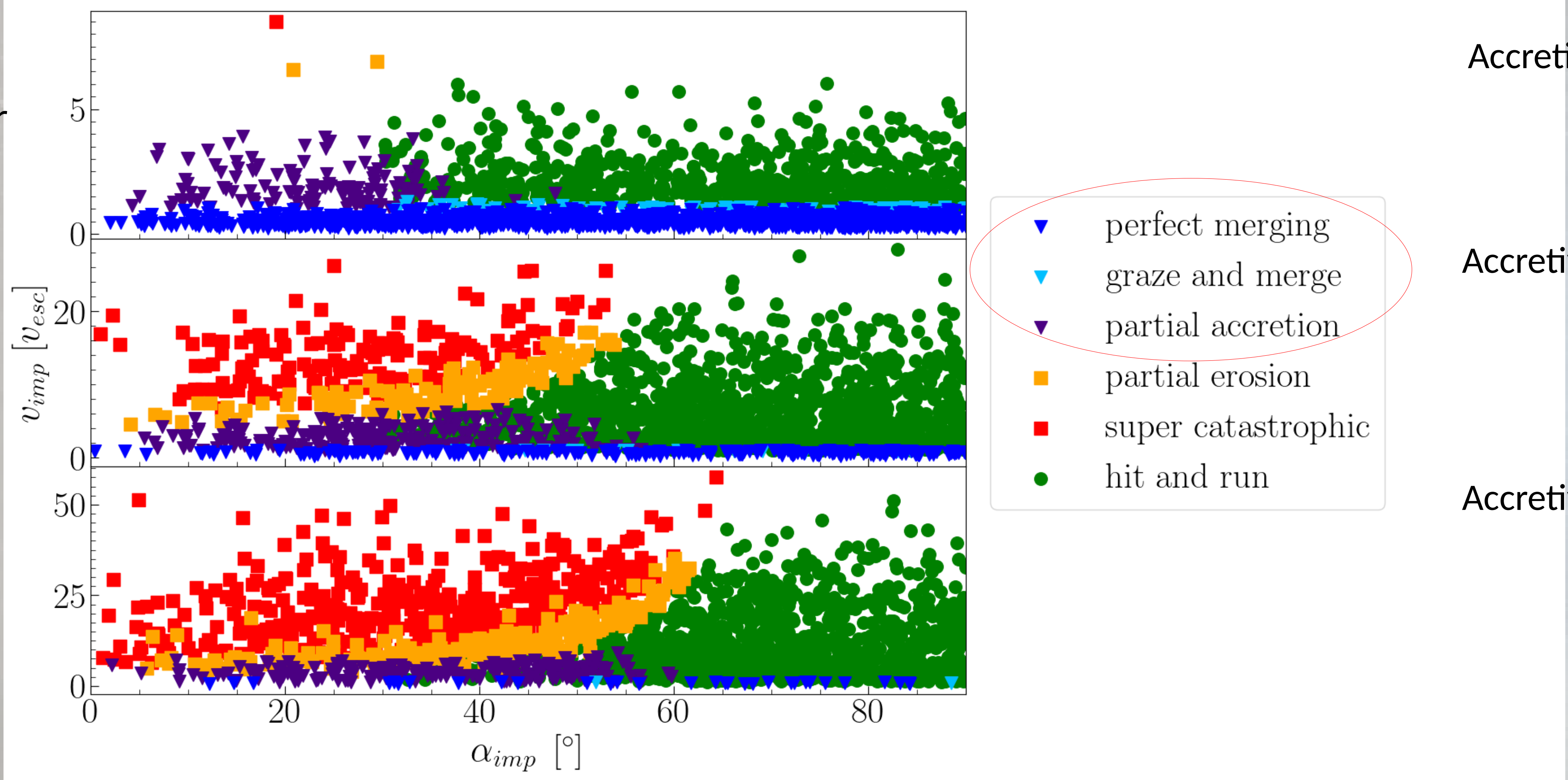
Burger et al., 2020

Collision outcome maps

planar

20°

45°



Accretive: 65,52%

Accretive: 21,83%

Accretive: 11,71%

a_b=60 au, e_b=0.2, i_b=0/20/45°

Collision outcome maps

planar

20°

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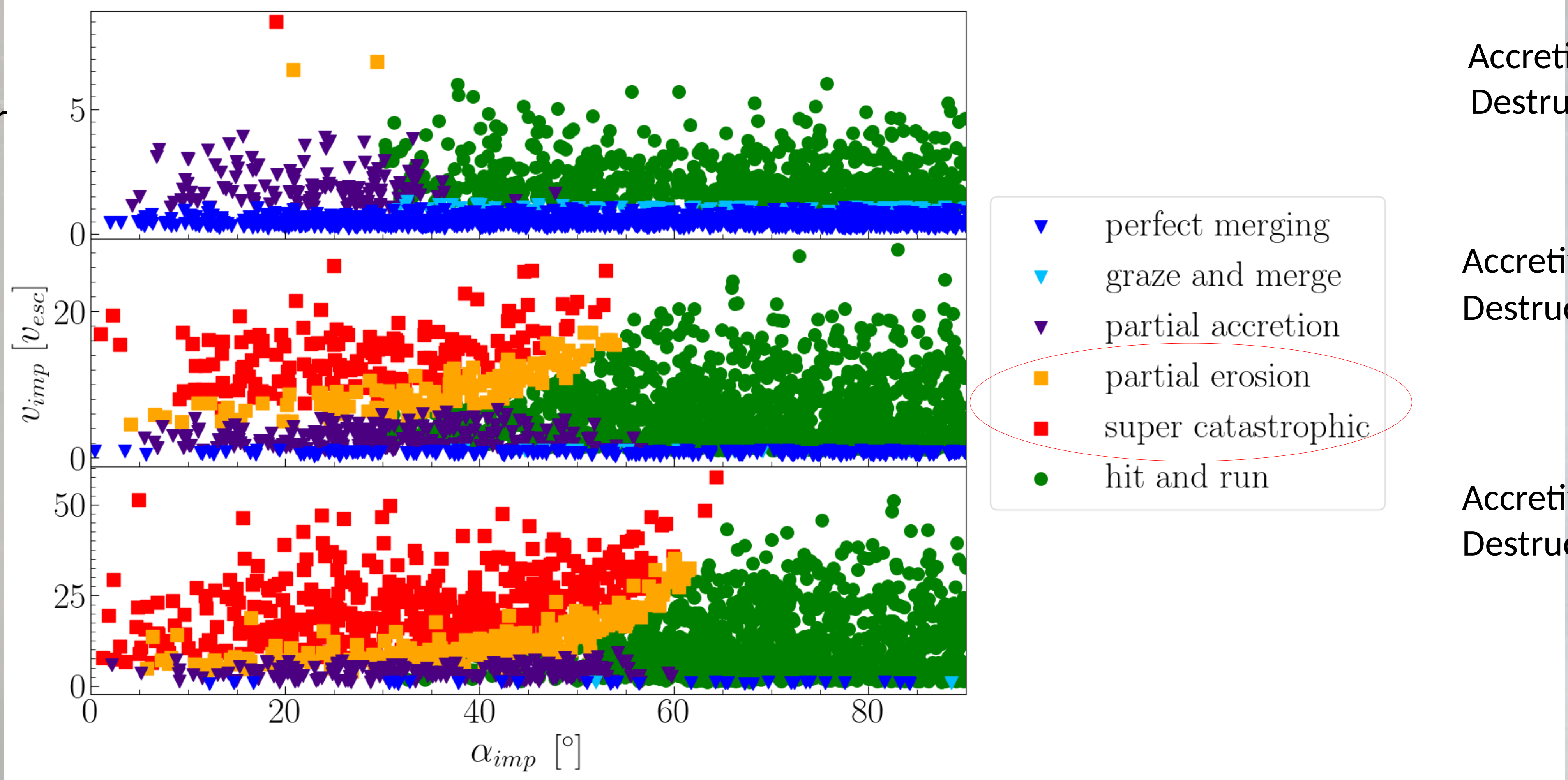

Accretive: 65,52%
Destructive: 0,15%

Accretive: 21,83%
Destructive: 15,6%

Accretive: 11,71%
Destructive: 31,99%

a_b=60 au, e_b=0.2, i_b=0/20/45°

Collision outcome maps

planar

20°

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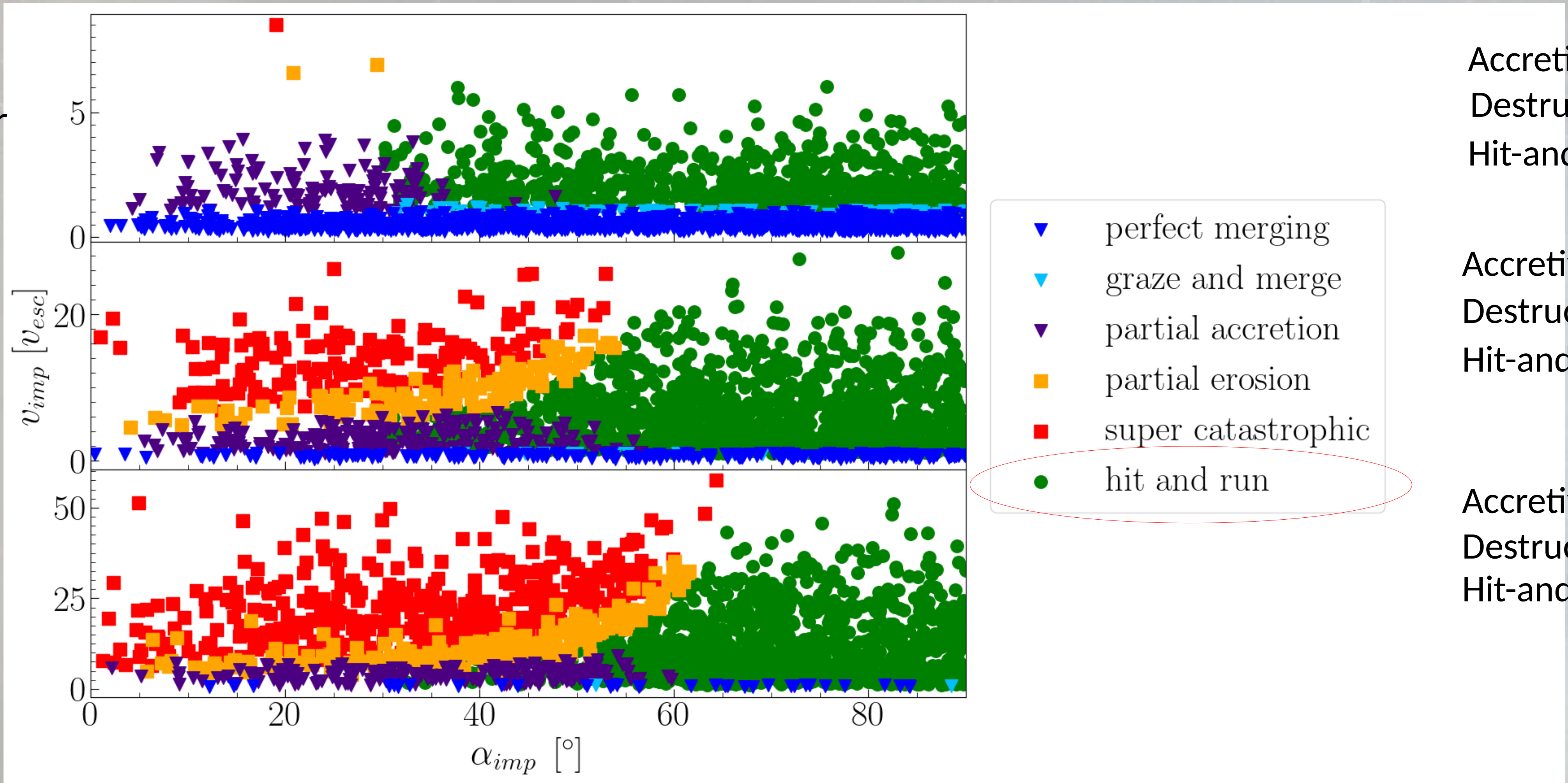

Accretive: 65,52%
Destructive: 0,15%
Hit-and-run: 34,33%

Accretive: 21,83%
Destructive: 15,6%
Hit-and-run: 62,56%

Accretive: 11,71%
Destructive: 31,99%
Hit-and-run: 56,3%

a_b=60 au, e_b=0.2, i_b=0/20/45°

Conclusion

- Application of the GPU N-body code GANBISS – planar vs. Inclined binary system
  - Study of the late stage of terrestrial planet formation
  - Full N-body simulation (up to 10000 objects) in this study: 2027 objects
  - Post-processing analysis of 2-body collisions (Leinhardt and Stewart 2012)
- Inclined binary system:
  - Inward migration of protoplanets (due to interaction with planetesimal disk)
  - Oscillation of the disk objects' inclination around i_{binary}
  - Damping of the amplitude (due to interaction with planetesimal disk)
- Collision outcomes:
  - Planar systems: mainly accretive events and barley destructive events
  - Inclined systems: mainly hit-and-run events, more destructive events, less accretive events