Using Kepler systems to constrain the frequency and severity of dynamical effects on habitable planets

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Dynamical instability bad for habitability

- Excitation of eccentricity can shift HZ or cause extreme seasons (Spiegel+10, Dressing+10)
- Planets may be scattered out of HZ
- Planet-planet collisions may remove biospheres, atmospheres, water
- Earth-like planets may be eaten by Neptunes/Jupiters

Strong dynamical effects: scattering and Kozai

- Scattering: closely-spaced giant planets excite each others' eccentricities (Chatterjee+08)

- Kozai: inclined external perturber (e.g. binary) can cause very large eccentricity fluctuations (Kozai 62, Lidov 62, Naoz 16)

Relevance of inner systems to HZ

- If you can
  - form a hot Jupiter through high-eccentricity migration
  - damage a *Kepler* system at few tenths of an au
- you will damage the habitable zone too

Relevance of inner systems intrinsically

- Large number of single-candidate systems found by *Kepler* relative to multiples

- Is this left over from formation? Or do the multiples evolve into singles through dynamics? (Johansen+12)

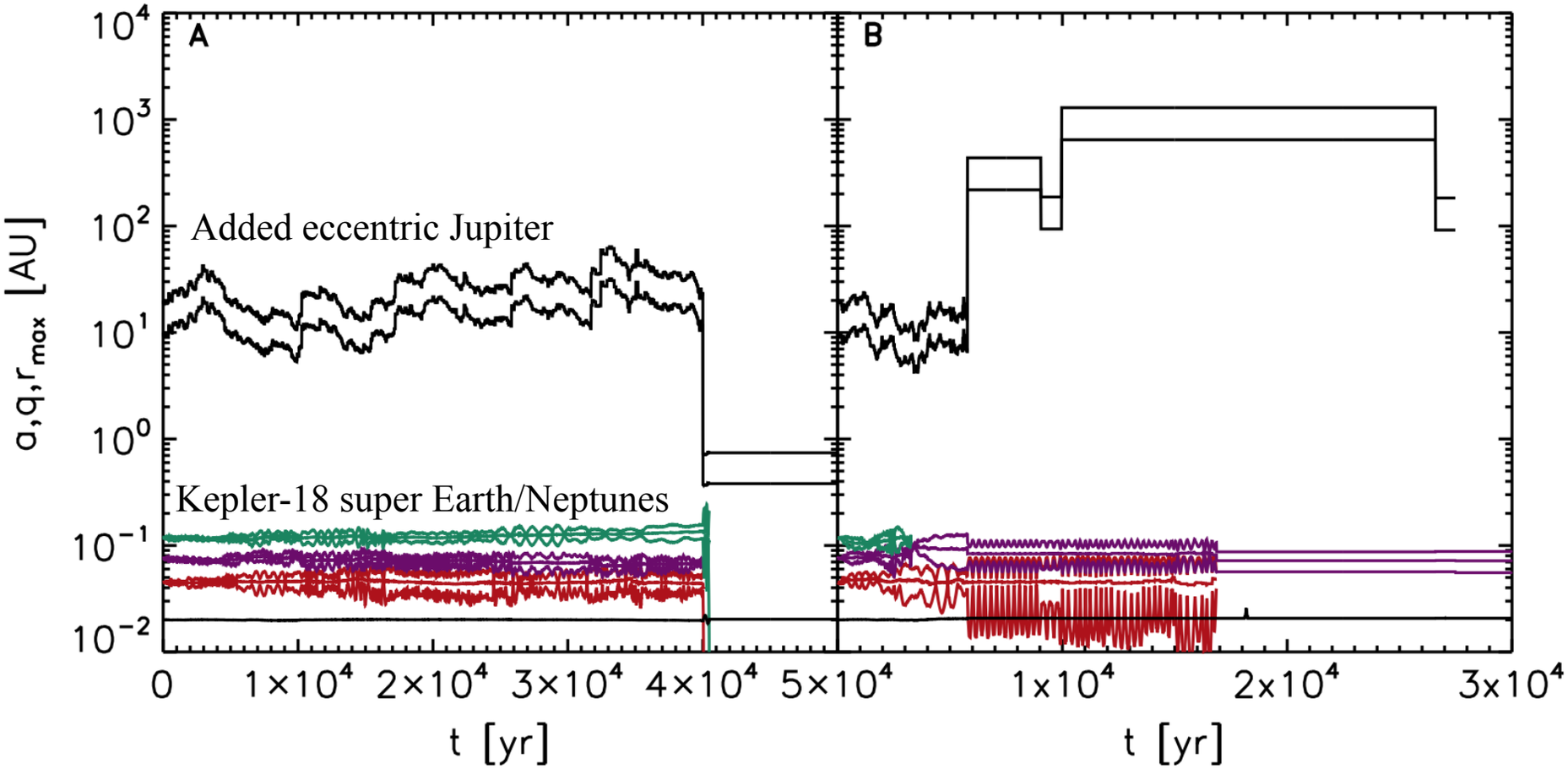
- Informs models of planet formation

  - all the *Kepler* systems are interestingly different to the Solar system, but do we have two interestingly different channels of planet formation or only one?

What do we know about the prevalence of strong dynamical effects?

- So far know little about planets in HZ
- What we do know:
  - Violent dynamical history strong contender for hot Jupiter migration
  - Many giants have high eccentricities
  - Many stars in binaries
  - Reasonable statistics on region closer to star than HZ from *Kepler* (few 1000 candidates)

Hot Jupiters: high-eccentricity migration effectively clears out inner planets



- Explains lack of close companions to hot Jupiters (Mustill, Davies & Johansen 15)

Hot Jupiters: high-eccentricity migration effectively clears out inner planets

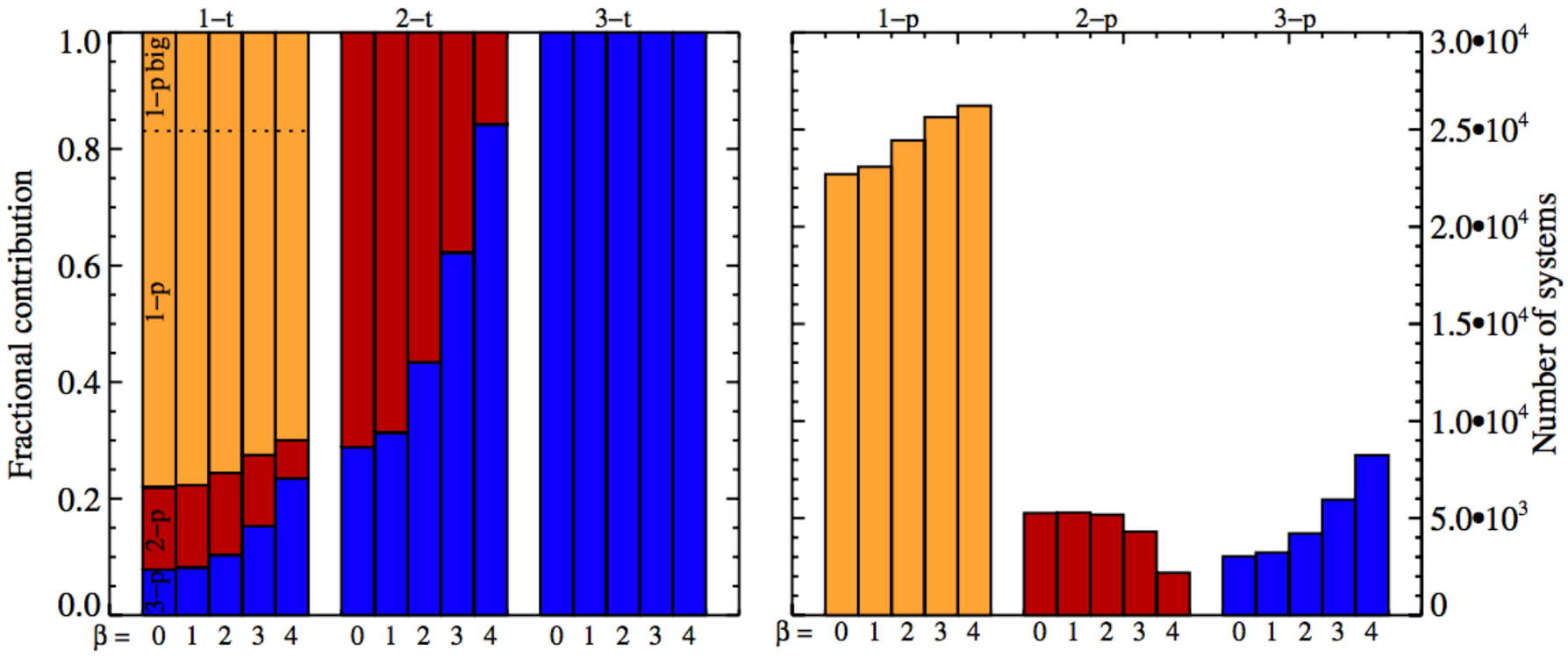
- giant migrating under high-eccentricity migration almost never ends up with a nearby super-Earth/ Neptune

- but many migrating Jupiters fail
  - hit star/get tidally shredded (Petrovich 15, Anderson+16)
  - ejected by inner planets (Mustill, Davies & Johansen 15)
  - prospect for more common damage to inner systems than 1% occurrence of hot Jupiters suggests

Single *Kepler* candidates: evidence of strong dynamical histories?

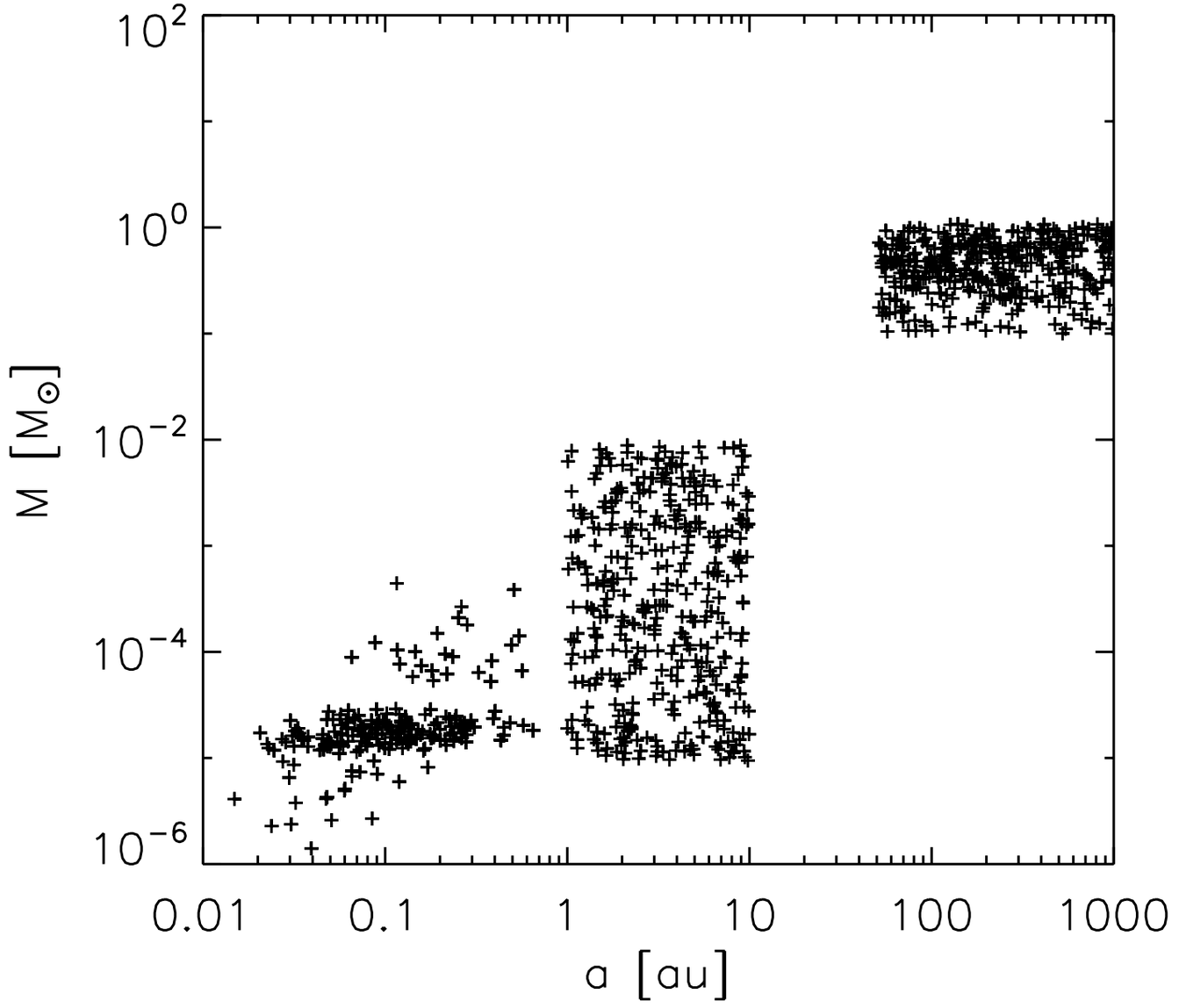
- Cannot simultaneously match statistics of single-, double- and triple-transit systems by inclining multiples

- Large population of singles required



Johansen, Davies, Church & Holmelin 2012

Consistent scattering and Kozai simulations



Mustill, Davies & Johansen in prep

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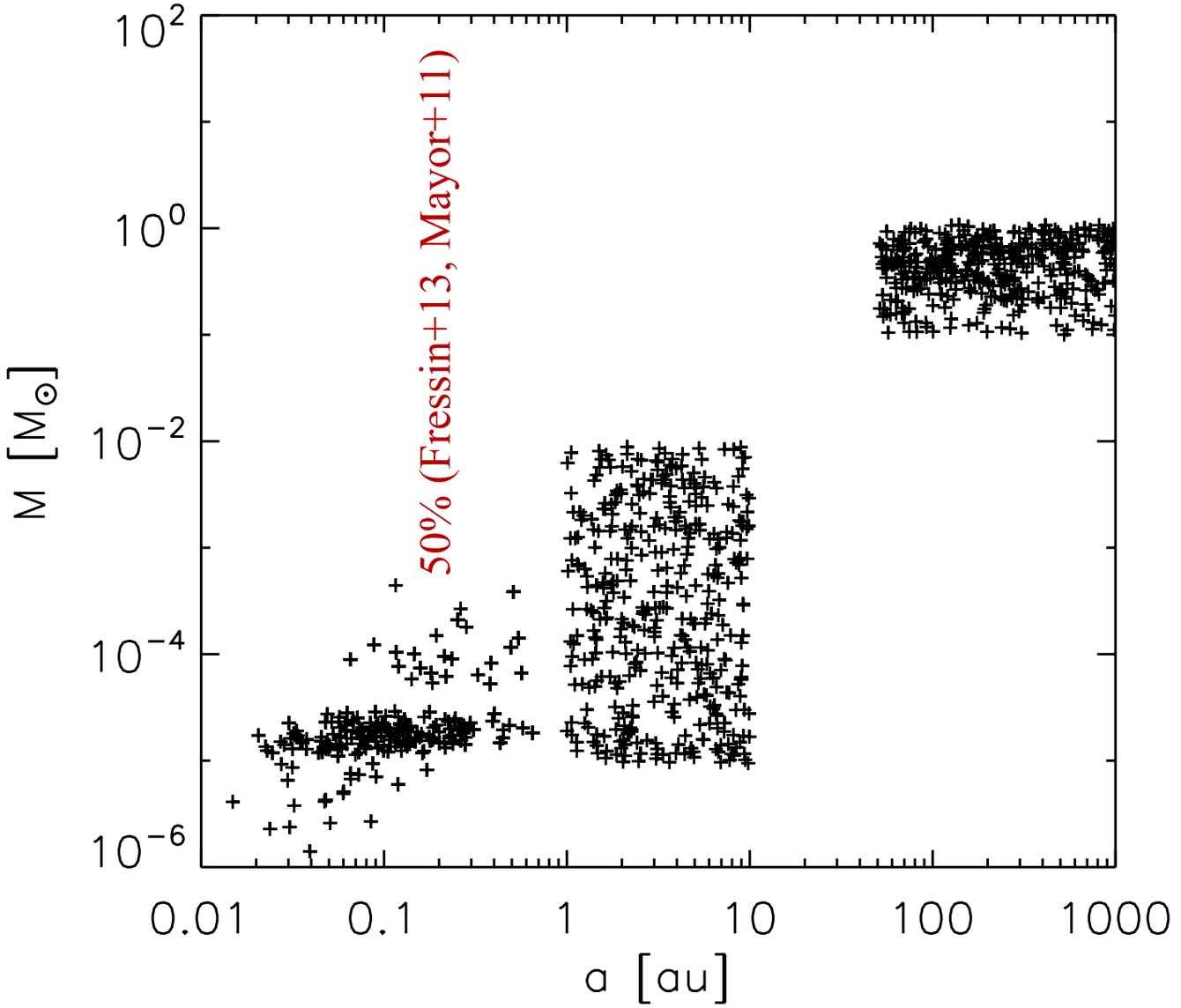

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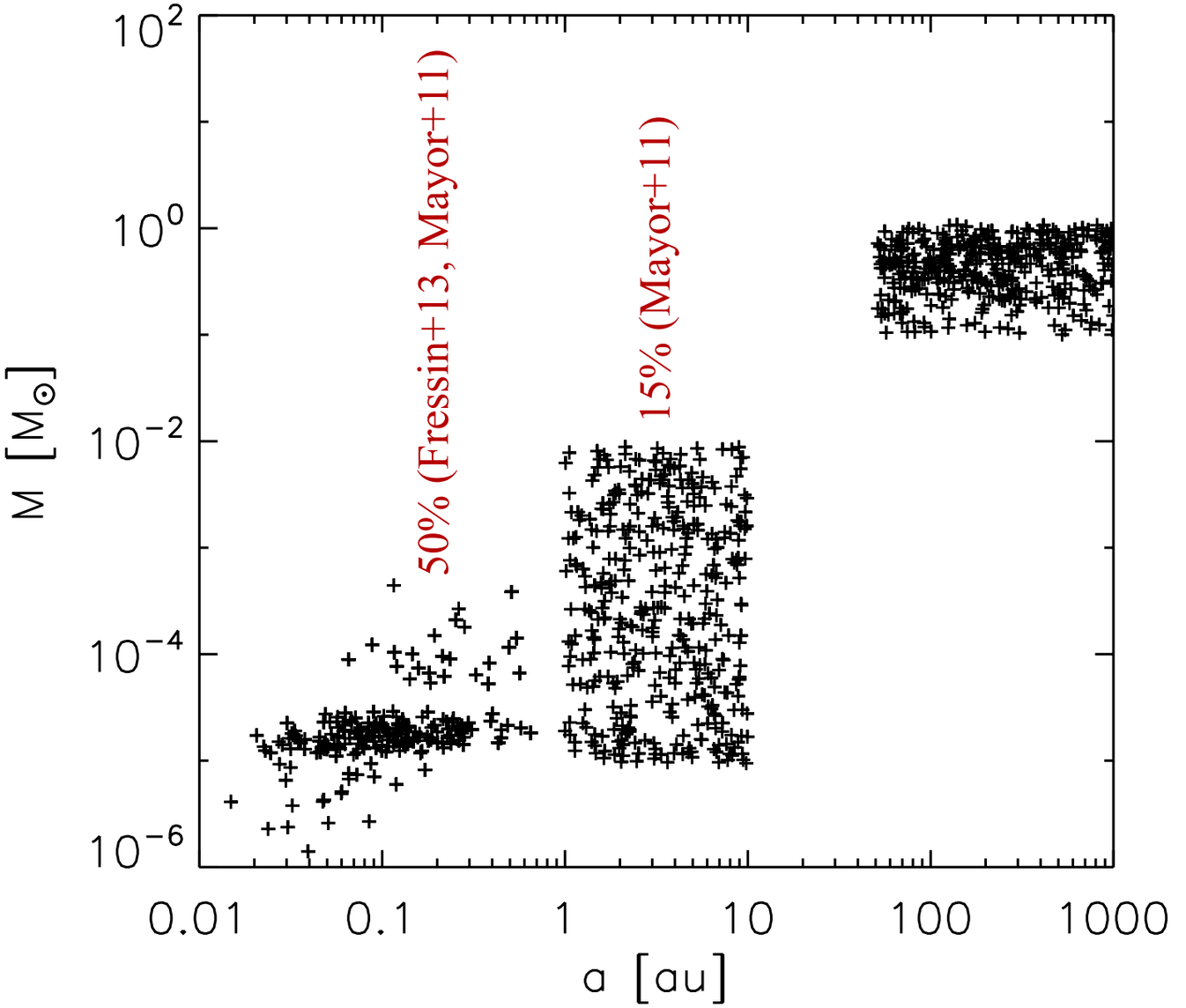

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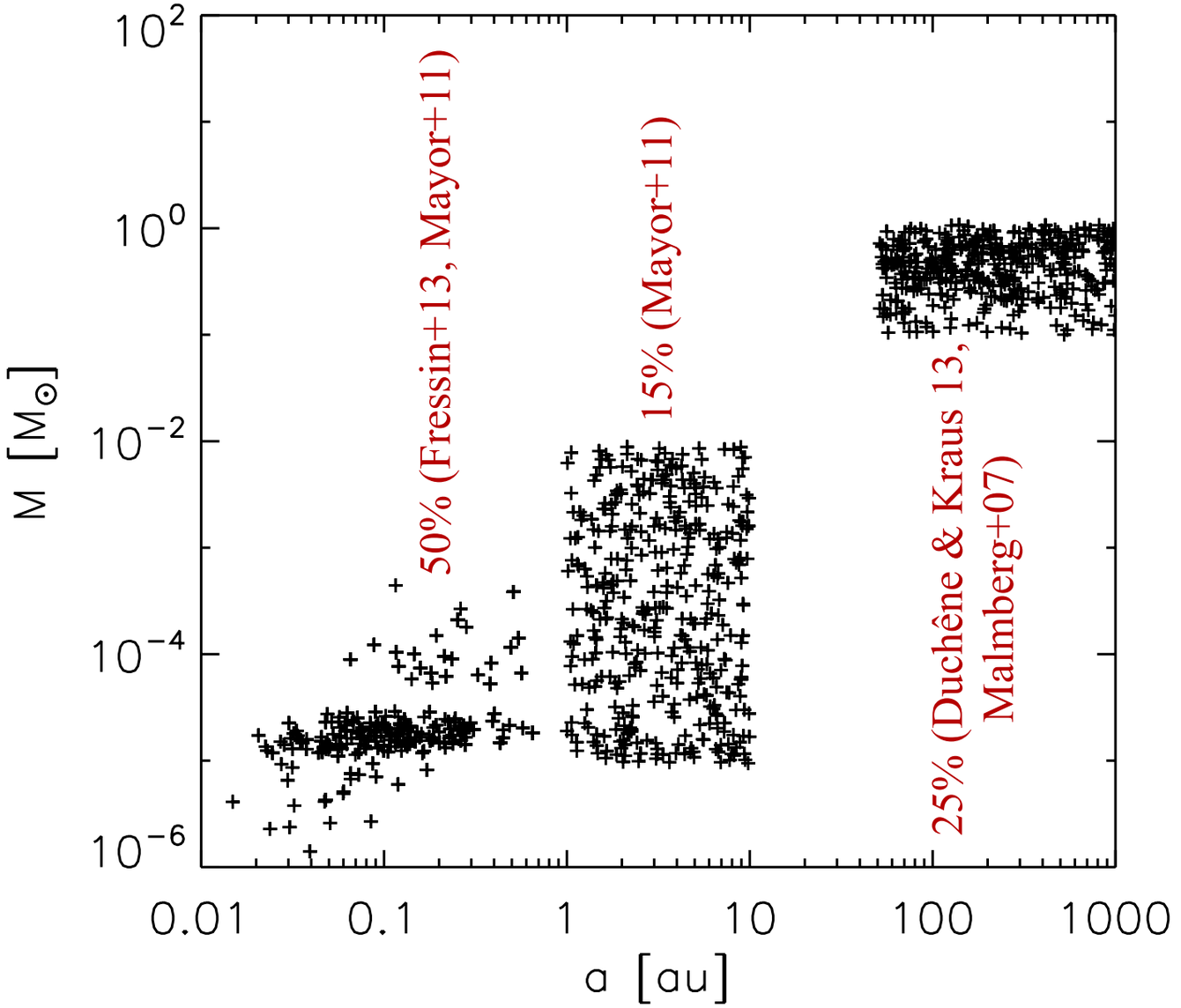

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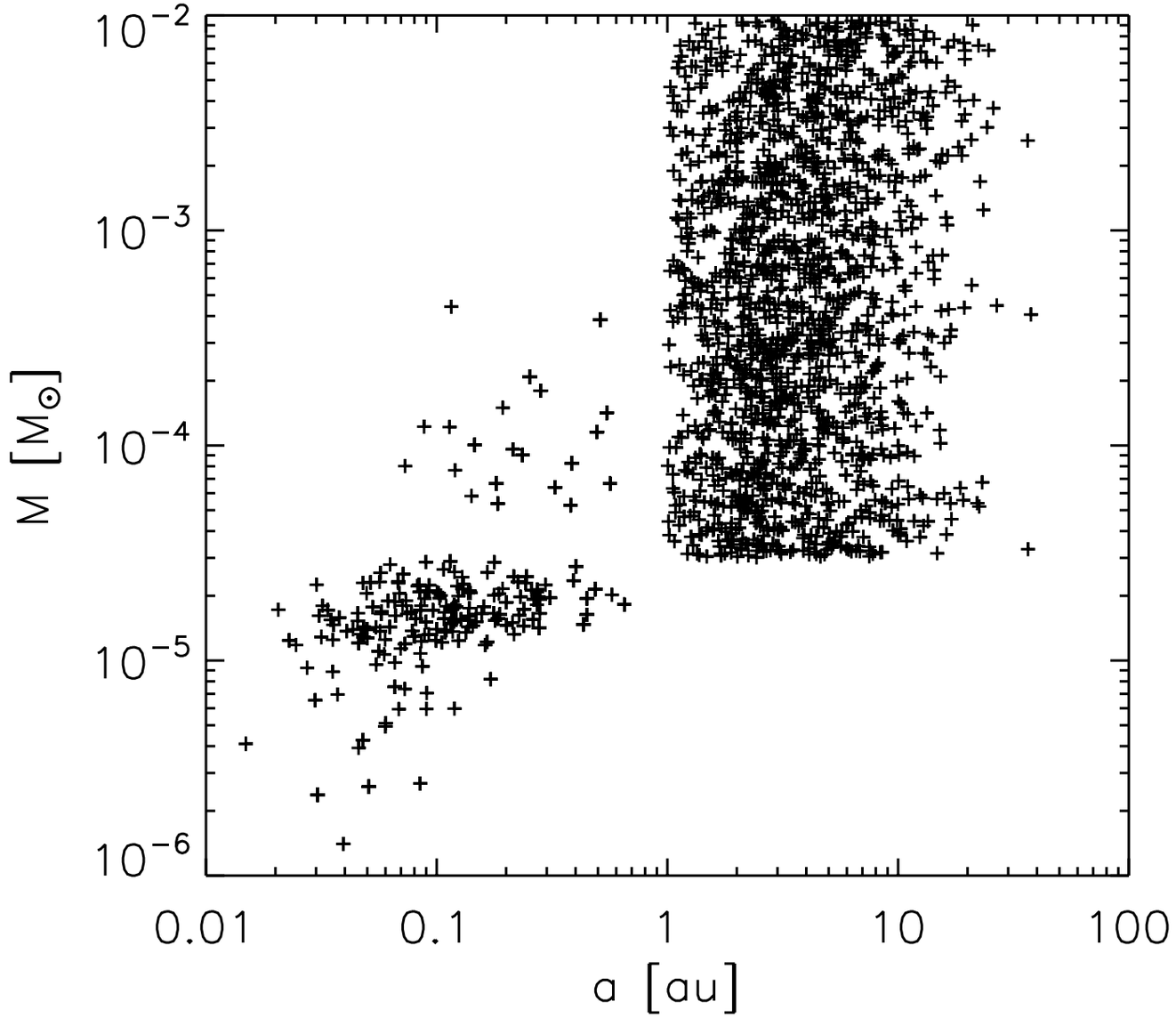

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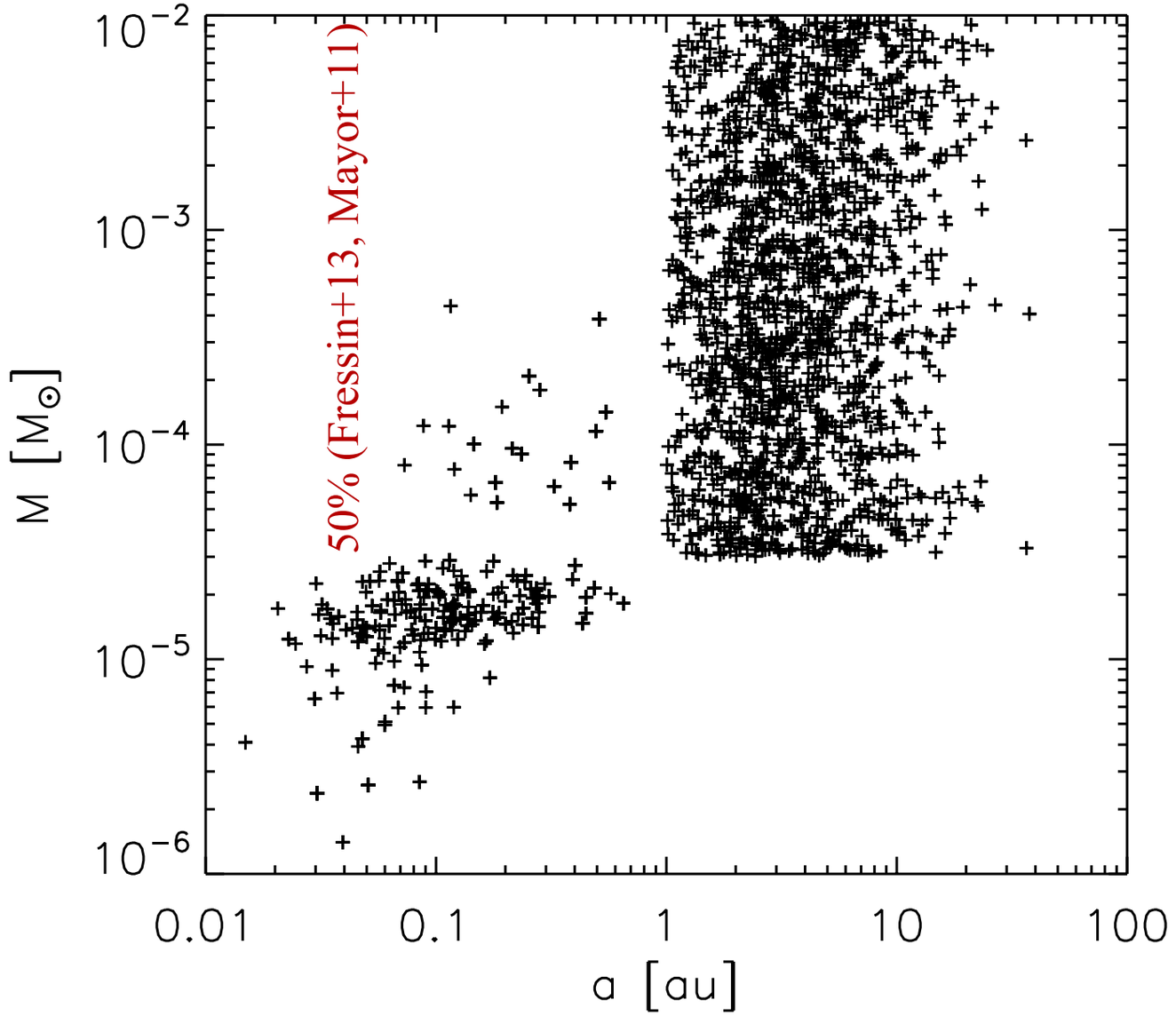

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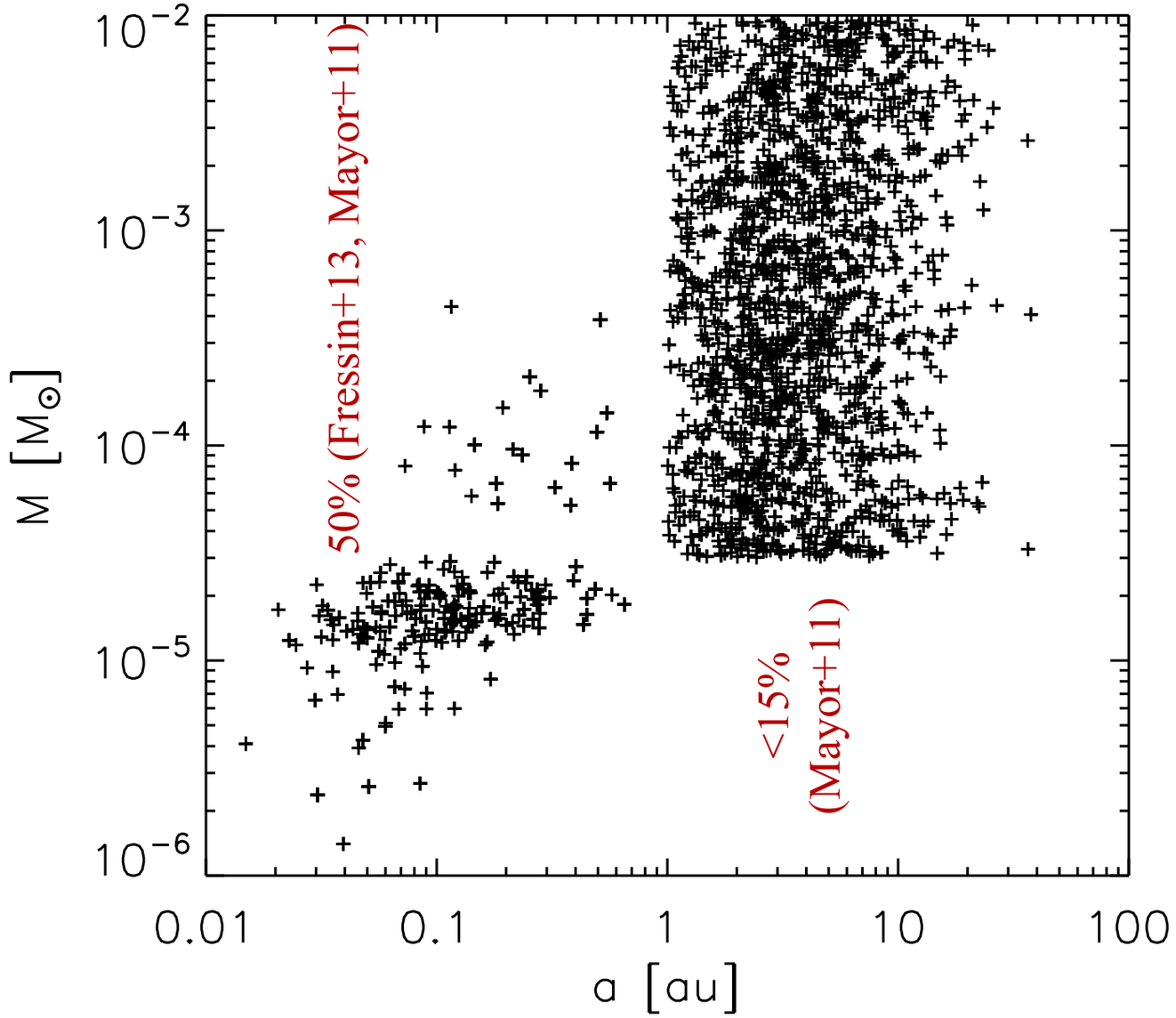
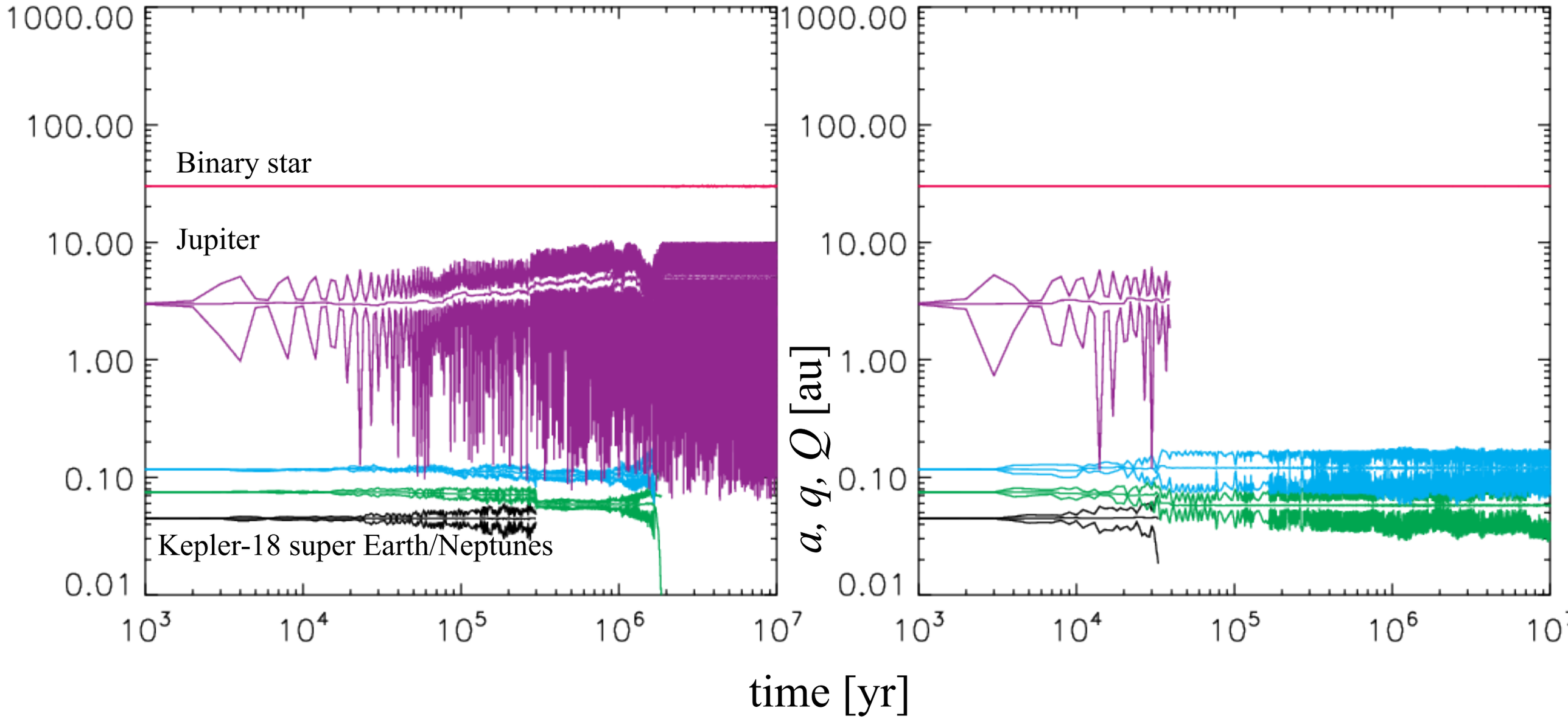


Mustill, Davies & Johansen in prep

Example of Kozai



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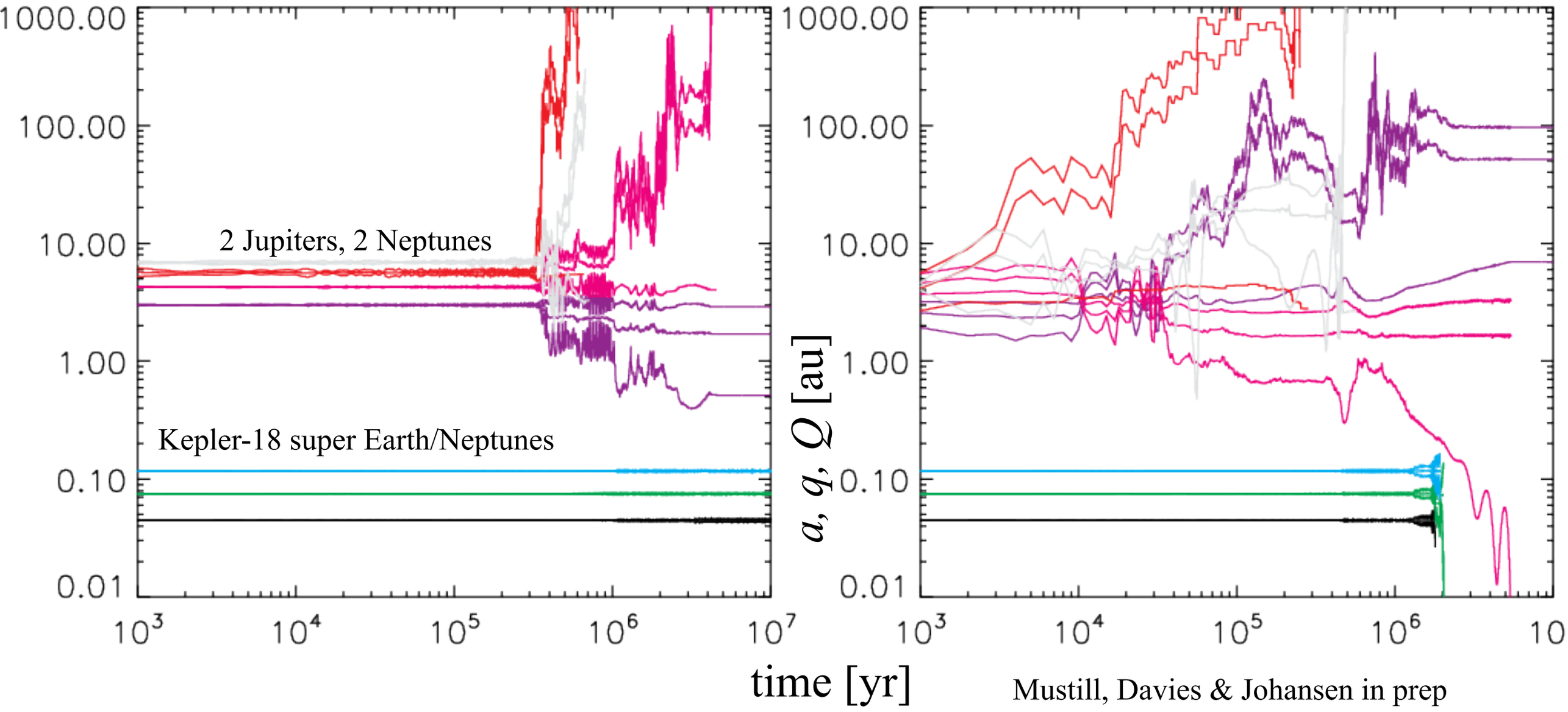
Example of scattering



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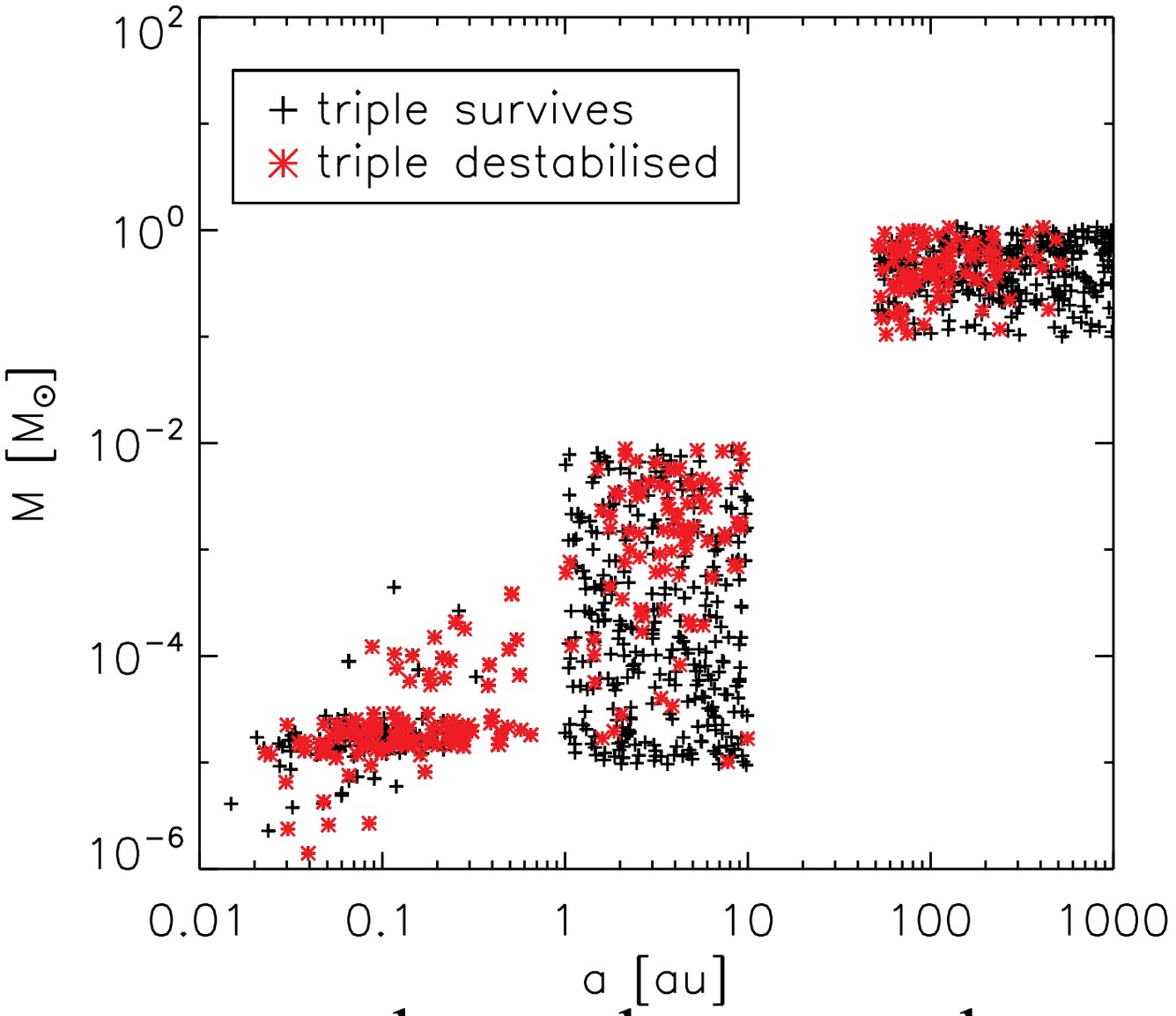
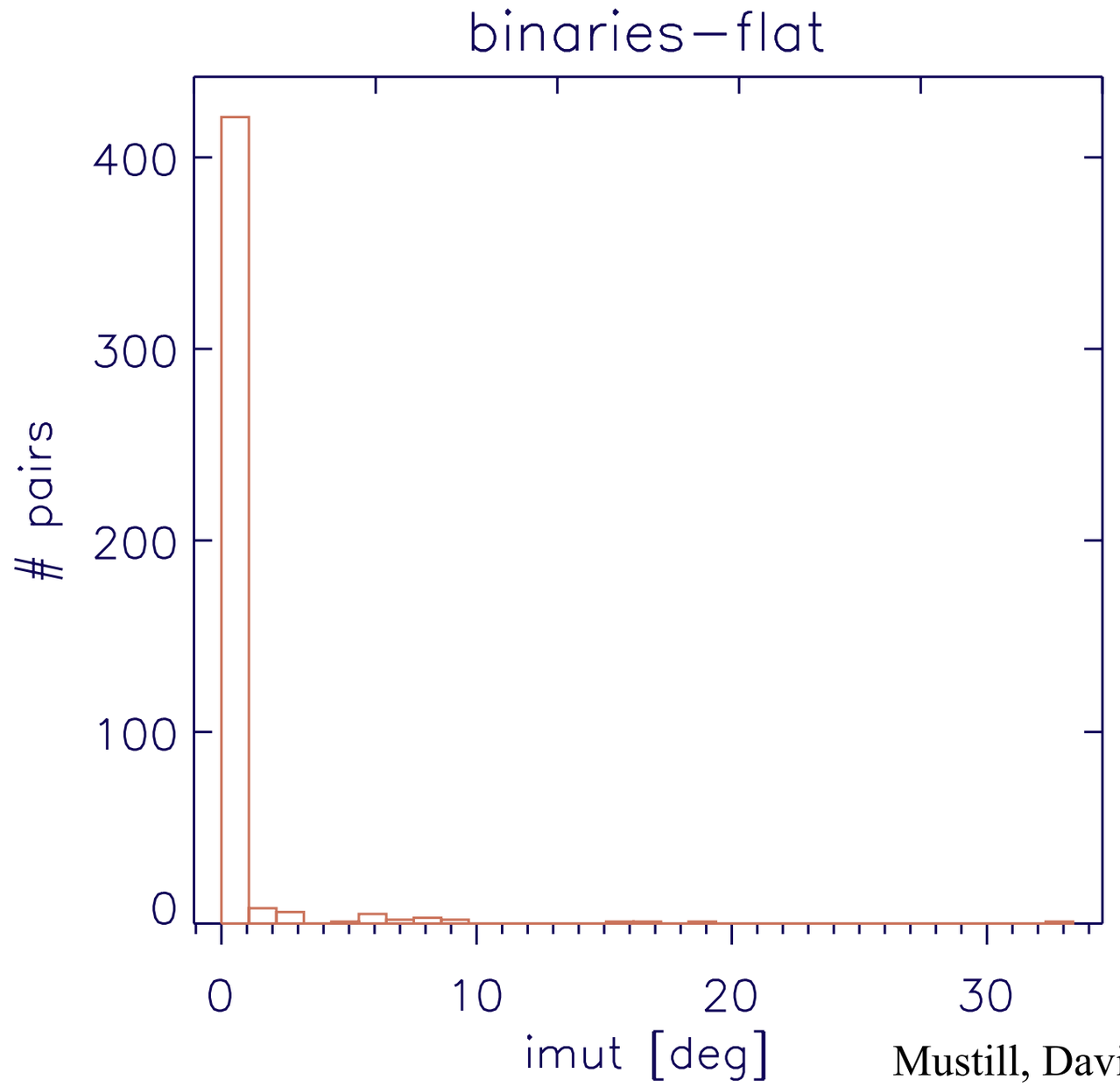
Results of Kozai



- 88/400 inner systems lose at least one planet

Mustill, Davies & Johansen in prep

Mutual inclinations of inner planets very unexcited



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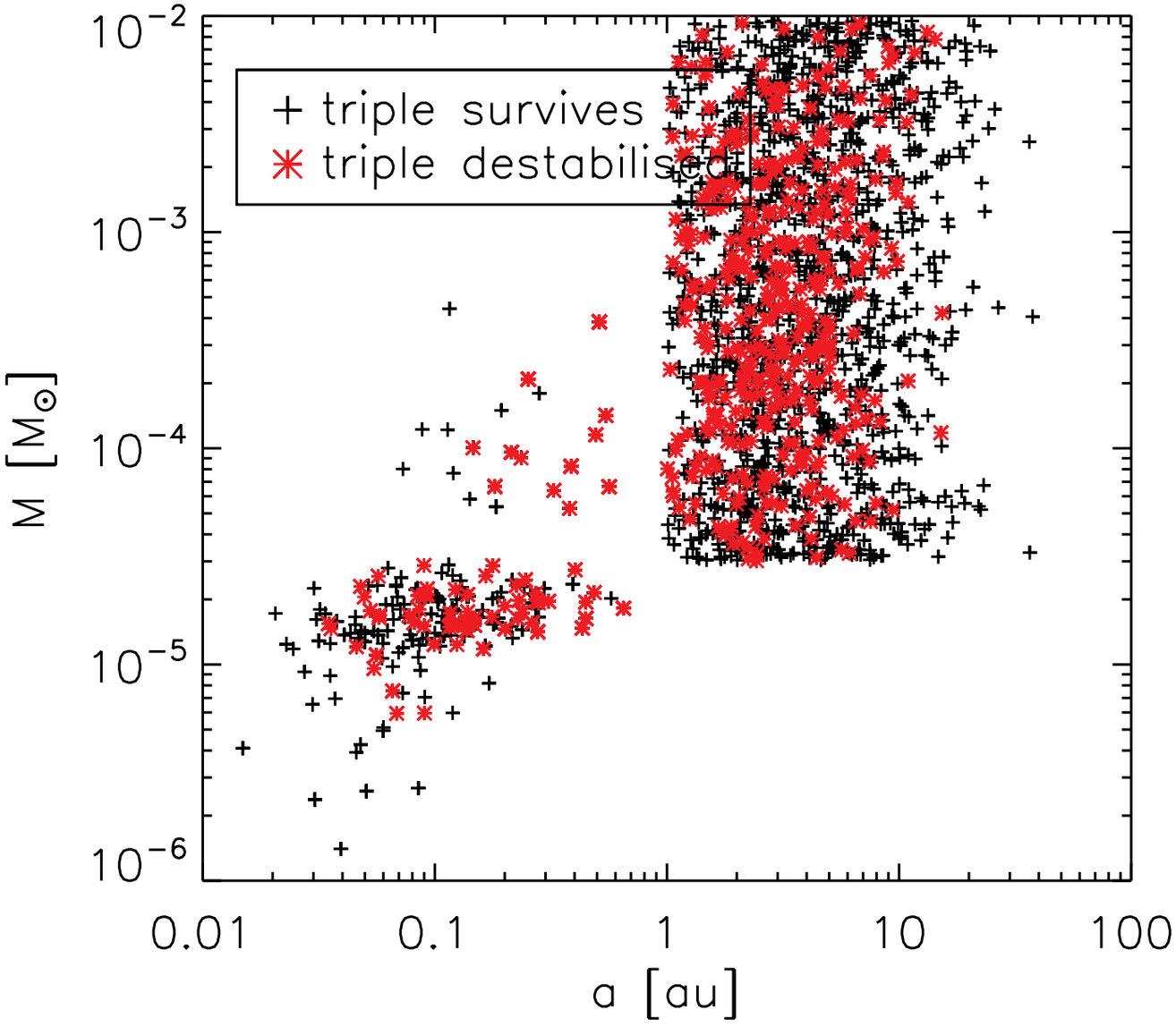

- 100/400 inner systems lose at least one planet

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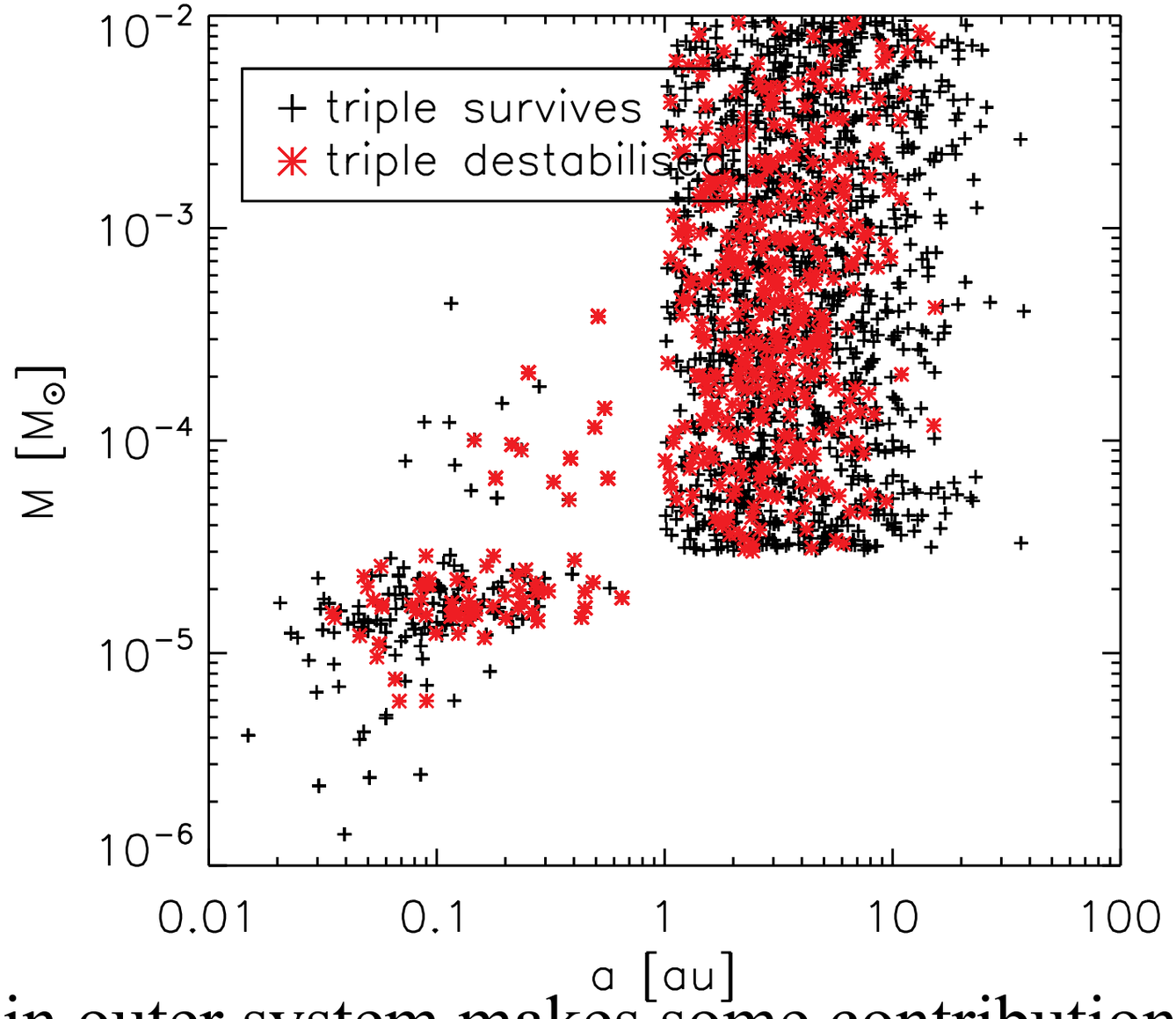
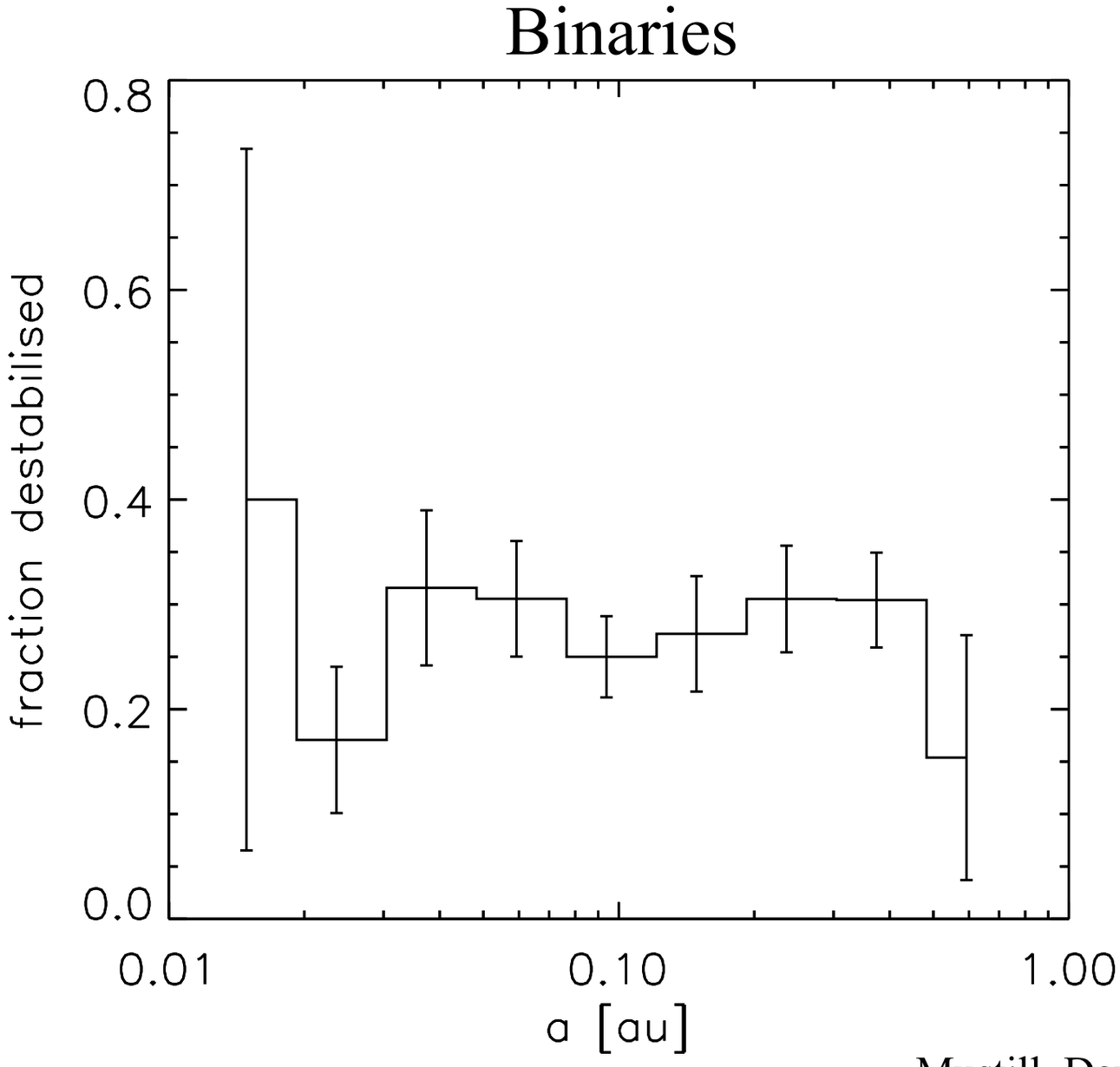
Results of scattering



- Dynamics in outer system makes some contribution to the excess of single *Kepler* candidates, but can't manage everything

Survivability as fn(a)



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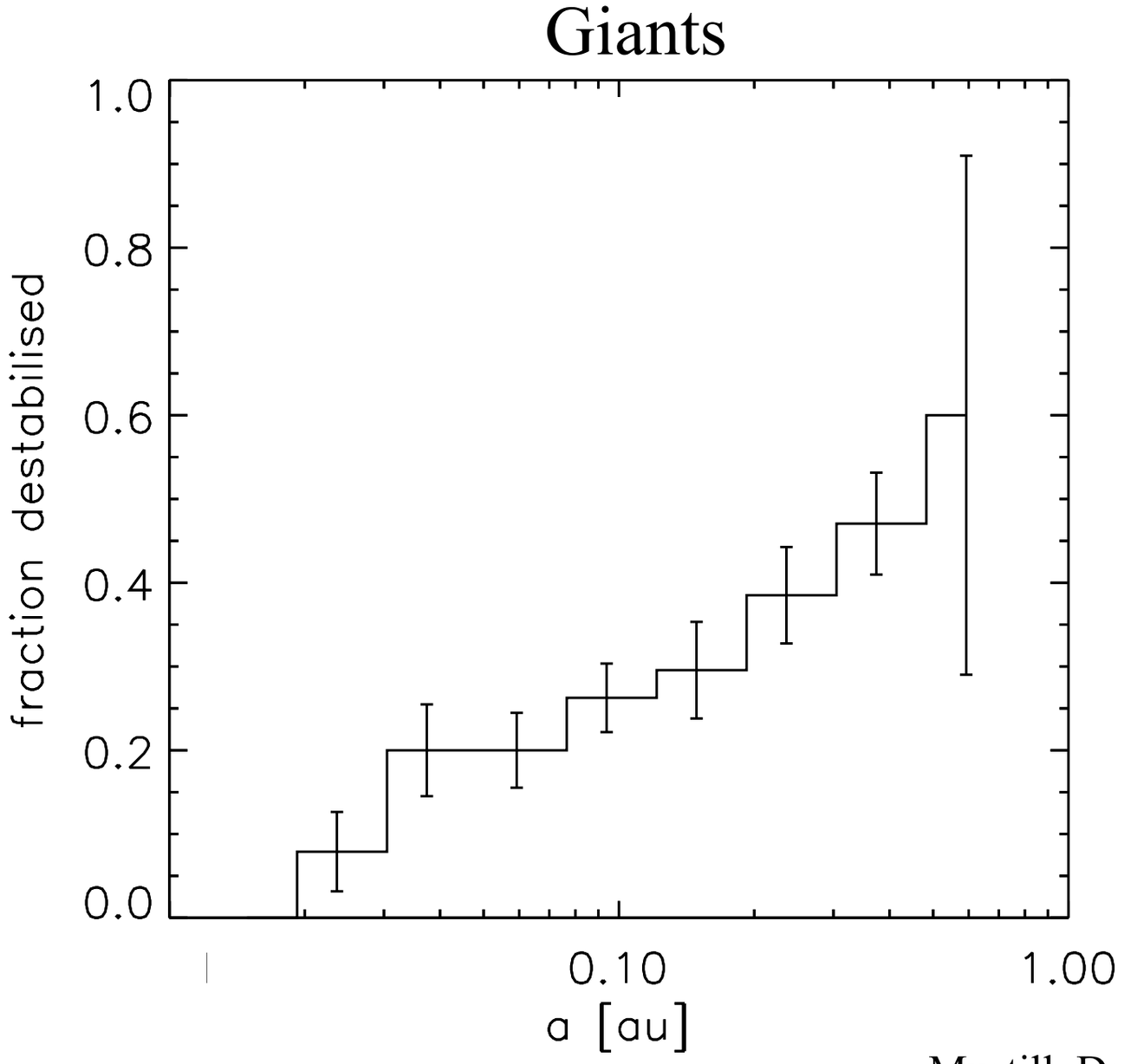


Mustill, Davies & Johansen in prep

Incidence estimate: Kozai

- Fraction of HZ planets in systems disrupted by Kozaied outer planets f_{disrupt}

  - $f_{\text{disrupt}} = f_{\text{wide binary}} \times f_{\text{outer planet}} \times f_{\text{disrupt in simulations}}$

  - $f_{\text{disrupt}} = 0.25 \times 0.15 \times 0.25 = \mathbf{1\%}$

Incidence estimate: scattering

- Fraction of HZ planets in systems disrupted by scattering outer planets f_{disrupt}
  - $f_{\text{disrupt}} = f_{\text{multiple outer planets}} \times f_{\text{disrupt in simulations}}$
  - $f_{\text{disrupt}} = <0.15 \times 0.60 <$ **10%**
- Dependent on the (uncertain) incidence of scattering in multi-planet outer systems

Conclusions

- Hot Jupiters being single is expected under high-eccentricity migration (Mustill, Davies & Johansen 15)

- Most *Kepler* systems are safe from serious damage by this kind of violent dynamics (Mustill, Davies & Johansen in prep)

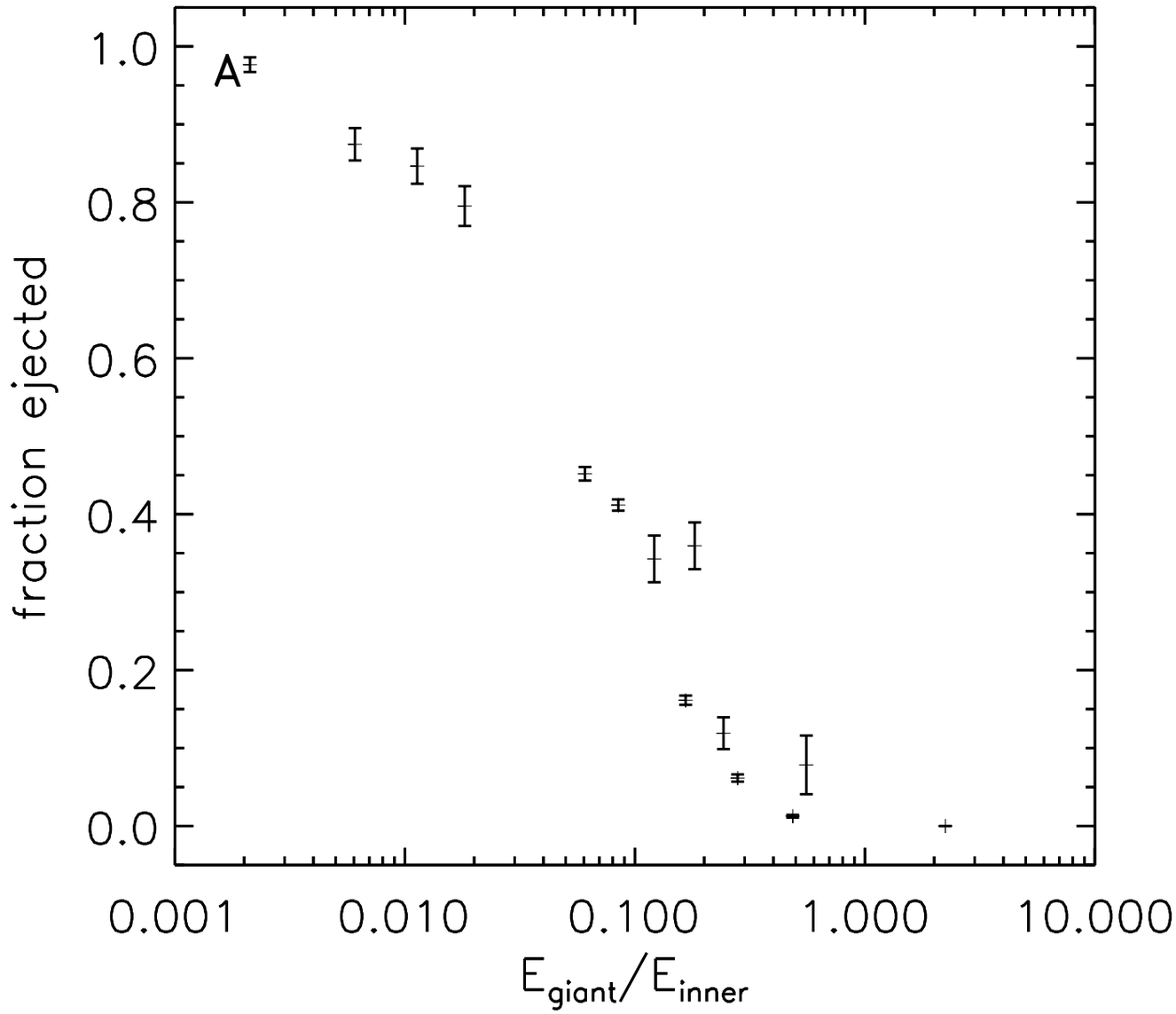
    - Violent outer system dynamics makes a small contribution to reducing *Kepler* multiples to singles

    - Survivability to an outer planet experiencing Kozai cycles is *insensitive* to inner planet's semi-major axis

    - Survivability to outer planets undergoing scattering decreases as the inner planet's semi-major axis increases

    - Estimate <~ 10% of HZ planets are strongly affected (collision, scattering into star) by outer system dynamics

Energy & ejection



Kepler mutual inclinations