Collisional crafting of compact planetary systems

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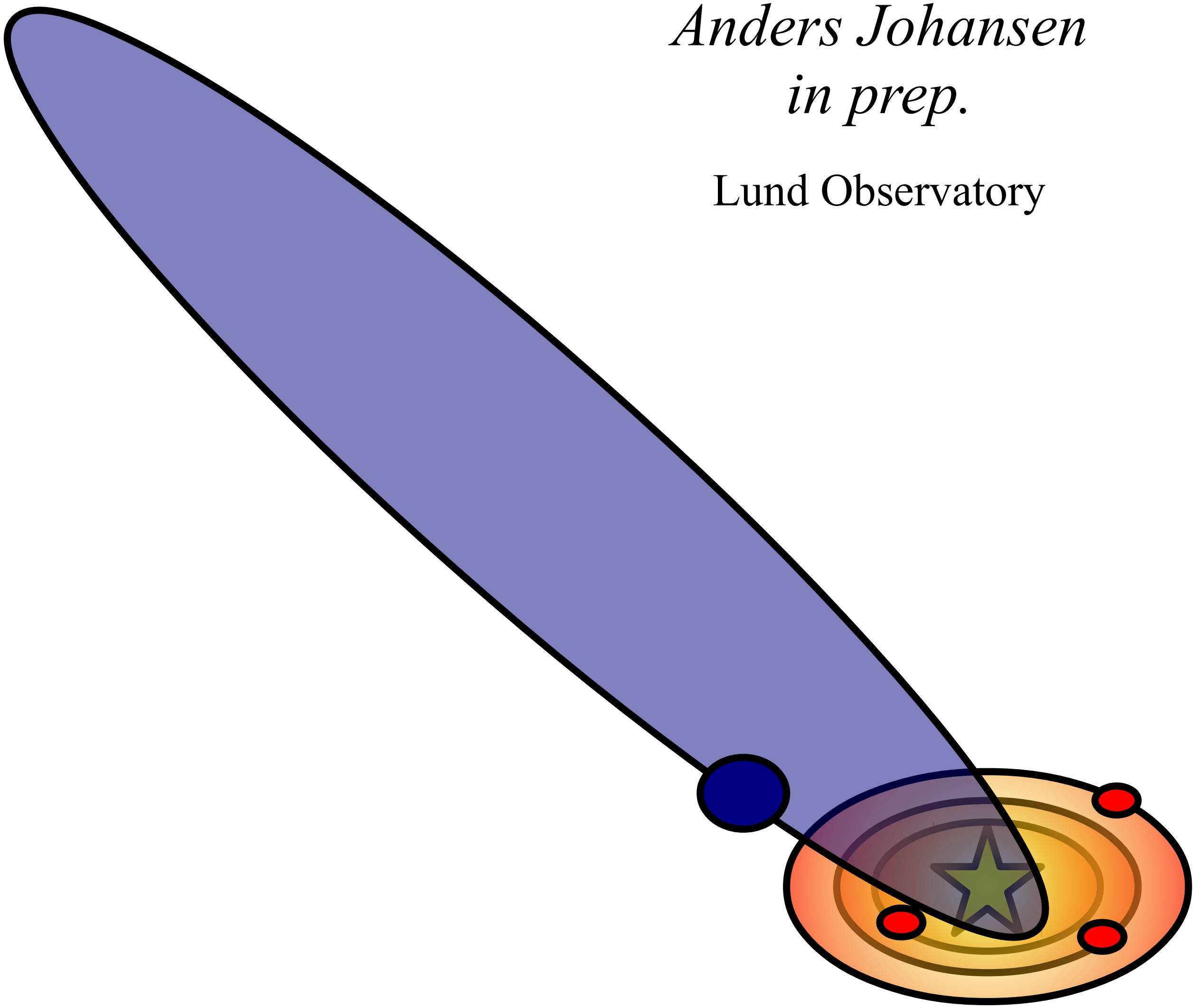
in prep.

Lund Observatory



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Single-planet systems are common in *Kepler* data

- **Can they derive from the population of triple-planet systems?**
- **No (Lissauer *et al.* 2011; Johansen *et al*. 2012):**
  - **Triple systems are *too flat* to create enough single-transits**
  - **Triple systems are *too stable* to reduce to single-planet systems through internal instabilities on astronomically interesting timescales**

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  - **Triple systems are *too flat* to create enough single-transits**
  - **Triple systems are *too stable* to reduce to single-planet systems through internal instabilities on astronomically interesting timescales**
- **Can we find some other way of dynamically reducing the multiplicity of multi-planet systems...?**

Preliminary work on dynamically decreasing system multiplicity

- *Exogenous dynamics:* **Inner planets are affected by dynamics of (mostly undetected) outer system**
  - **scattering between massive gas giants (*cf* Sean Raymond papers on effects on terrestrial planet formation)**
  - **Kozai cycles on outer planets driven by binary companion**

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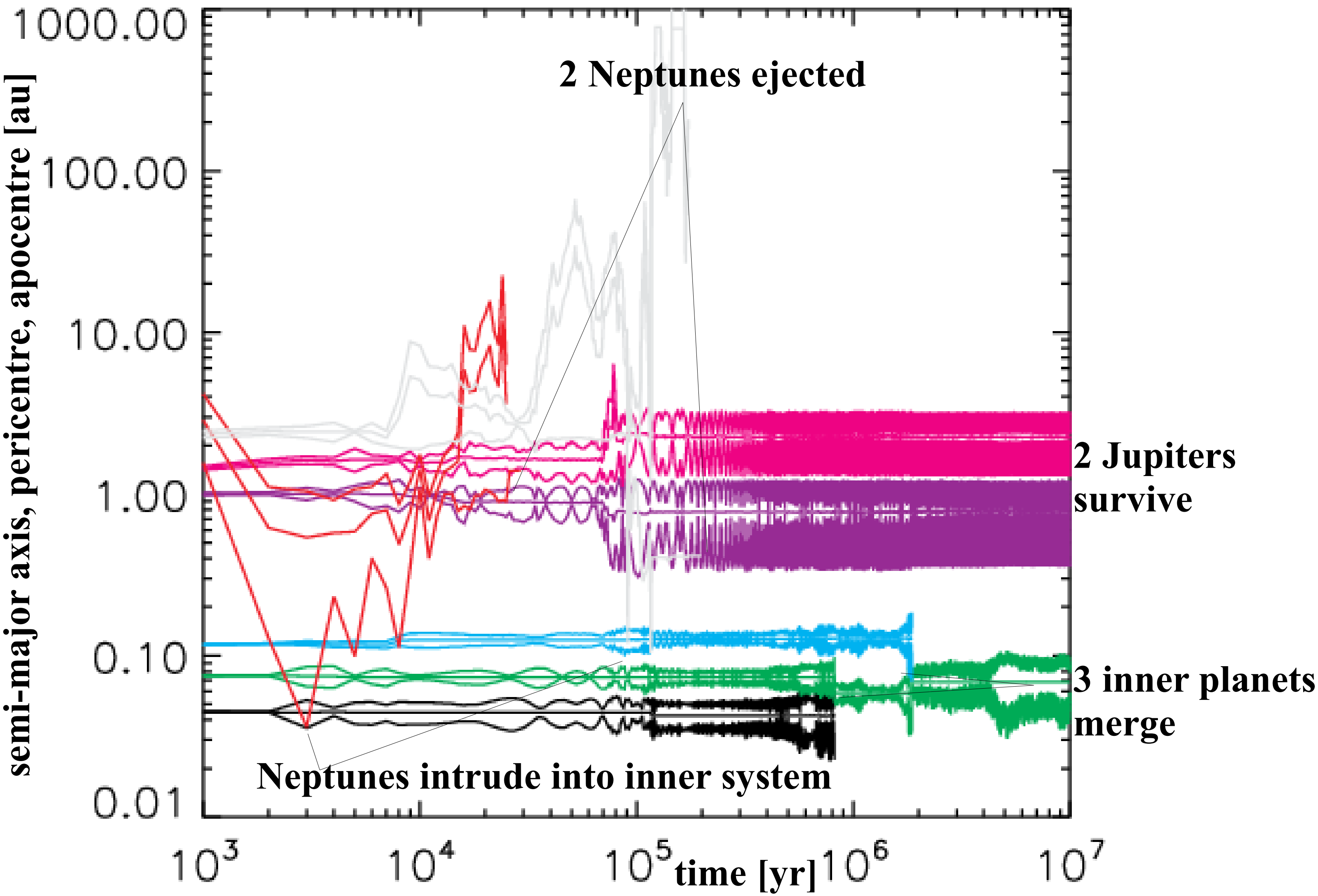
  - Kozai cycles on outer planets driven by binary companion
- *Endogenous dynamics:* Inner planets are unstable by themselves
  - triples are stable (Johansen *et al.* 2012)
  - what about higher multiplicities (Pu & Wu 2015)
  - collision velocities are high close to star, so collisions may be destructive (Volk & Gladman 2015)

Exogenous dynamics: the scattering scenario

- **Add an unstable outer system to a *Kepler* close-in triple**
- **Not implausible scenario:**
  - **Scaled-down Solar System**
  - **Kepler-48 (Marcy *et al.* 2014): $2M_J$ planet at 980 days**
  - **Kepler-90 (Rowe *et al.* 2014; Cabrera *et al.* 2014): 0.7, 1.0 R_J at 211, 332 days**

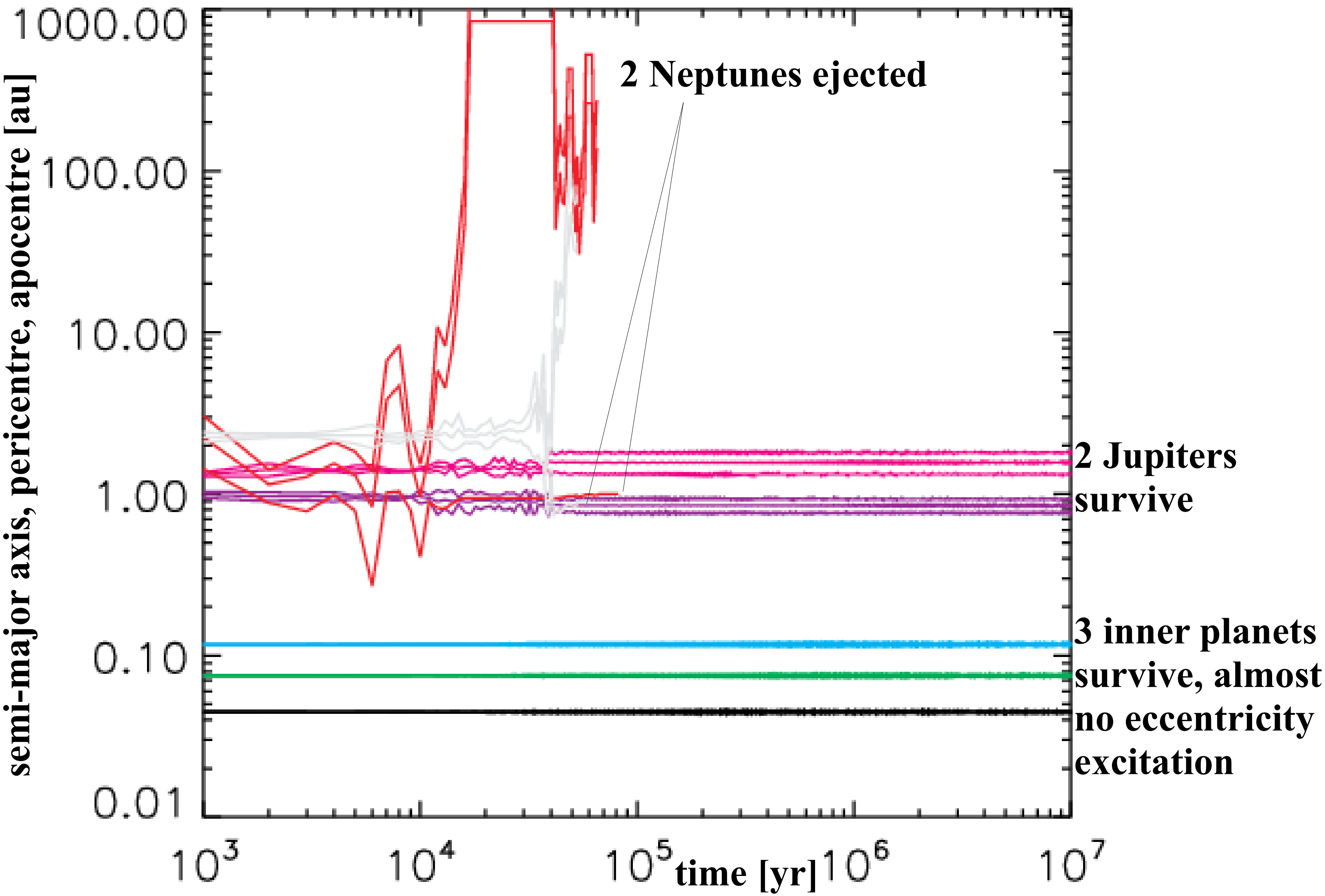
Exogenous dynamics: the scattering scenario

- **Kepler-18 plus 2 Jupiters and 2 Neptunes at 1au and beyond**



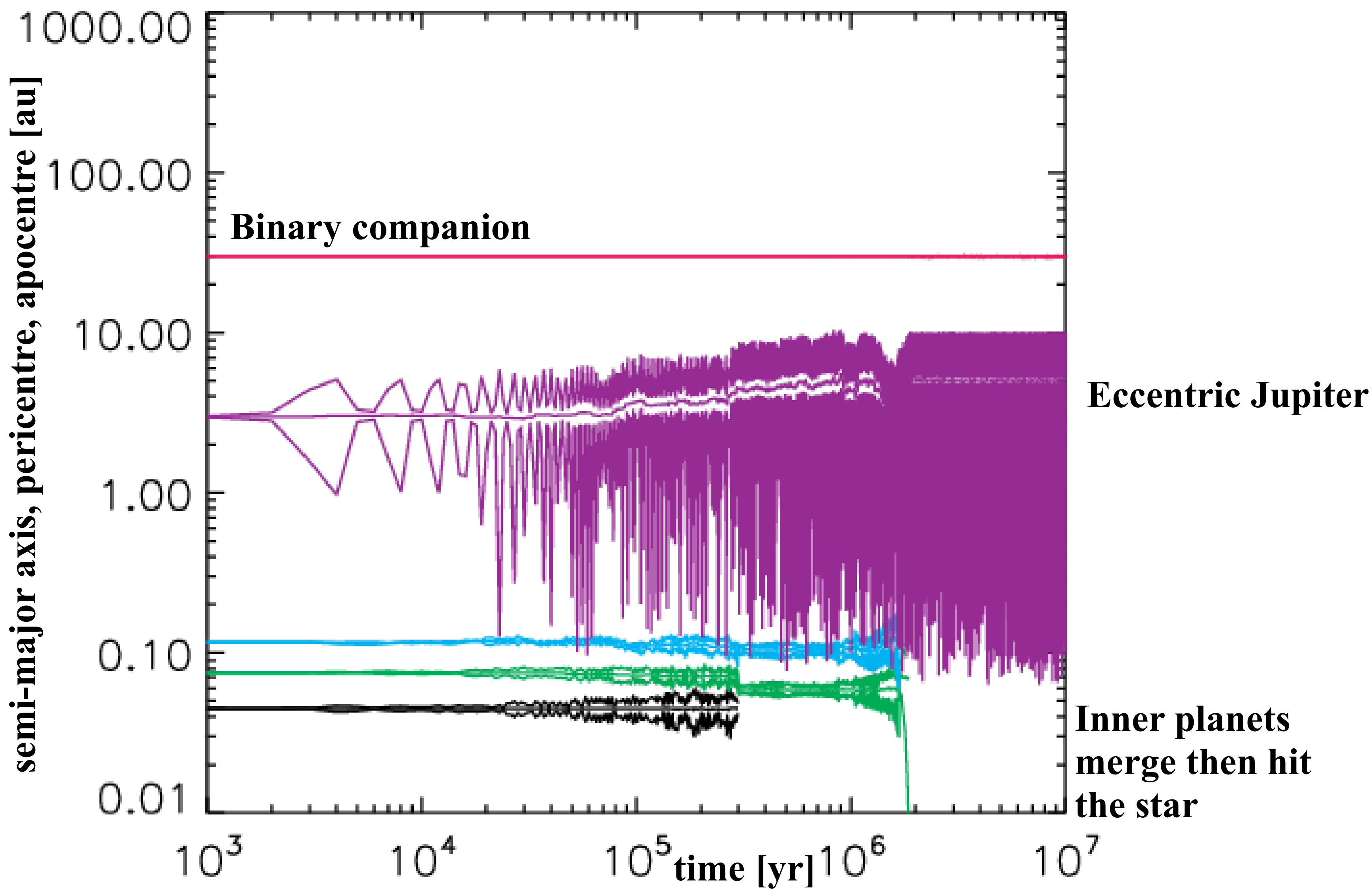
Exogenous dynamics: the scattering scenario

- **But not always effective...**



Exogenous dynamics: the Kozai case

- **Kepler-18 plus Jupiter at 3au plus inclined binary at 30 au**



Exogenous dynamics: early-stage statistics

	0 planets	1 planet	2 planets	3 planets
Kepler-18 + scattering planets at 3 au	**14** ***11%***	**8** ***6%***	**4** ***3%***	**102** ***80%***
Kepler-18 + scattering planets at 1 au	**9** ***28%***	**6** ***19%***	**1** ***3%***	**16** ***50%***
Kepler-18 + Kozaied Jupiter	**22** ***69%***	**1** ***3%***	**7** ***22%***	**2** ***6%***
Kepler-18 + Kozaied Neptune	**2** ***6%***	**4** ***13%***	**3** ***9%***	**23** ***72%***
Kepler-58 + scattering planets at 3 au	**5** ***16%***	**2** ***6%***	**2** ***6%***	**23** ***72%***

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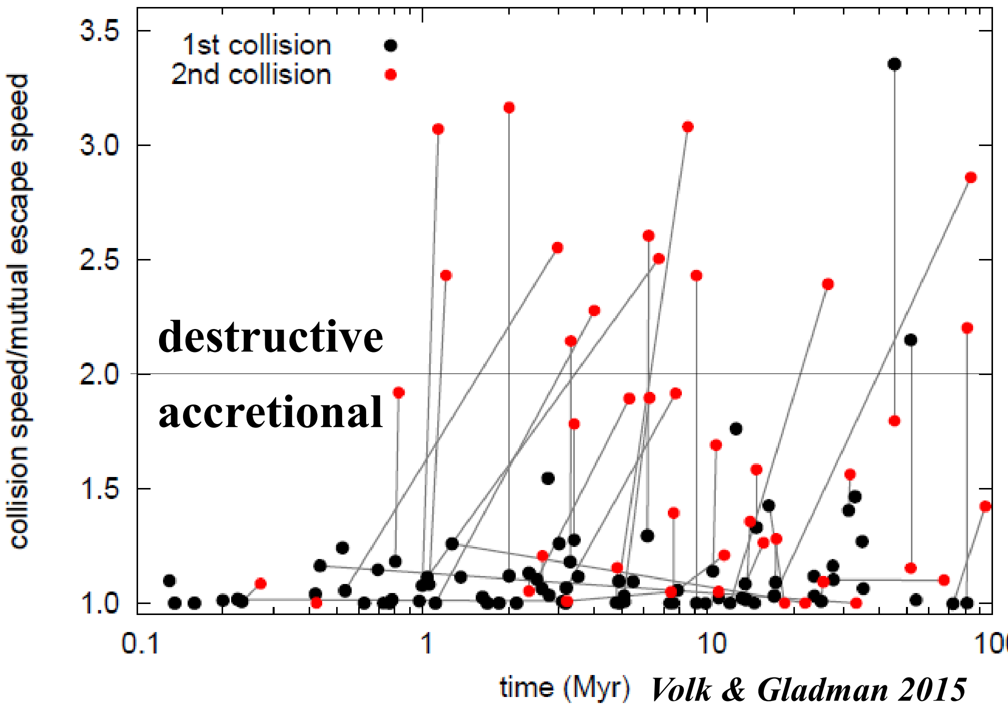
Best at making singles

Endogenous dynamics: more multiplicity

- ***Kepler* triples are very stable (Johansen *et al.* 2012)**
- **But higher-multiplicity systems are much closer to the edge of stability (Pu & Wu 2015; Volk & Gladman 2015)**
- **Volk & Gladman note that collision velocity**
  - $v_{\mathrm{coll}} \sim e\, v_{\mathrm{kep}}$

  is greater than planets' escape speed, so collisions will be highly destructive

- **However, study of systems' dynamical evolution under destructive collision prescriptions is yet to be performed...**



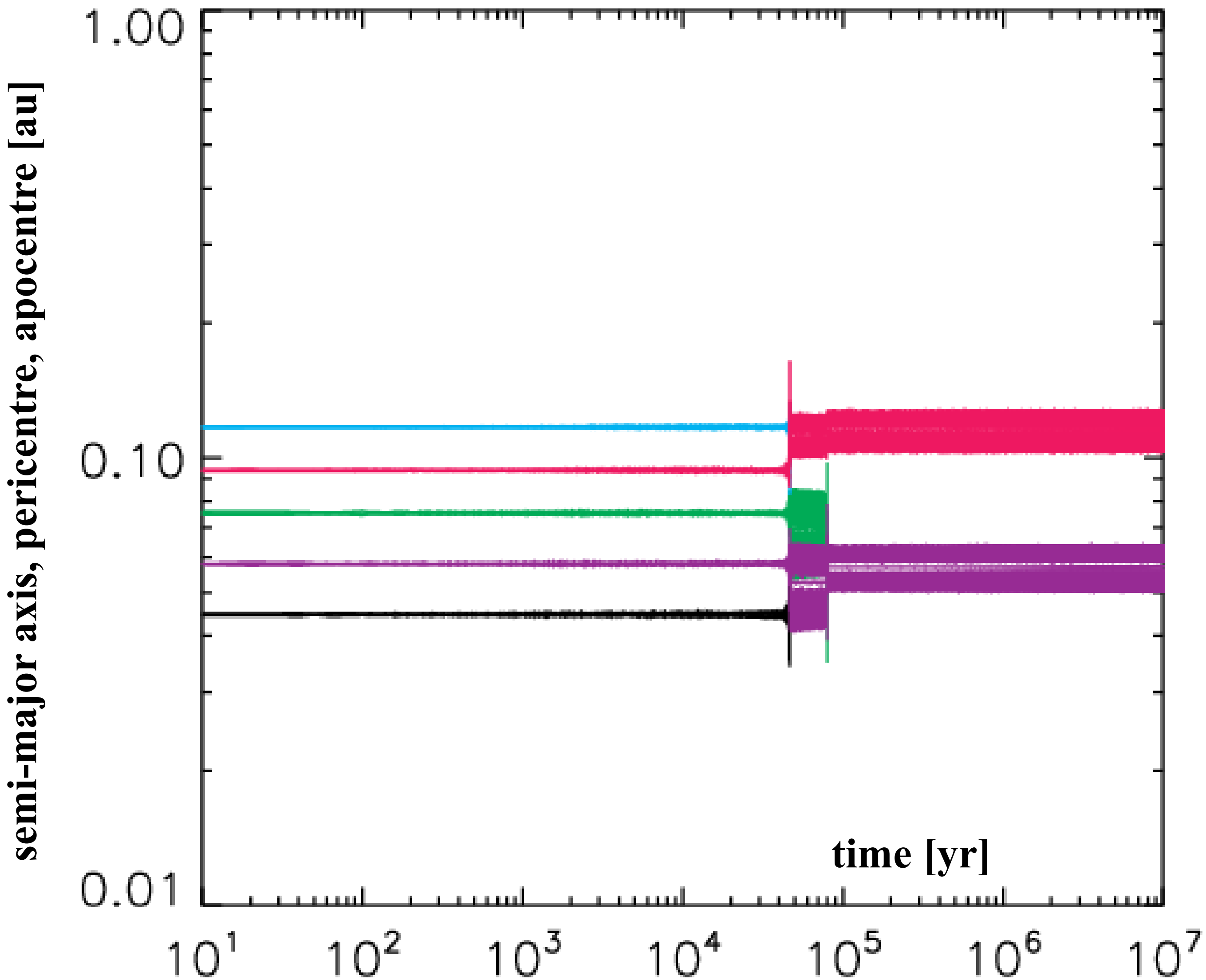
Volk & Gladman 2015

Endogenous dynamics: more multiplicity

- **Take Kepler-18 and add extra planets *in between* the extant ones—quick instability guaranteed**
- **Explore how outcome depends on collision prescription**
  - **perfect merging**
  - **perfect destruction**
  - **semi-realistic: remove half of mass of colliding bodies**
  - **(future): realistic collision outcomes and remnant masses (*e.g* Leinhardt & Stewart 2012)**

Endogenous dynamics: collisional crafting

- **Perfect merging: 5 planets reduce to 2 or 3:**



Endogenous dynamics: collisional crafting

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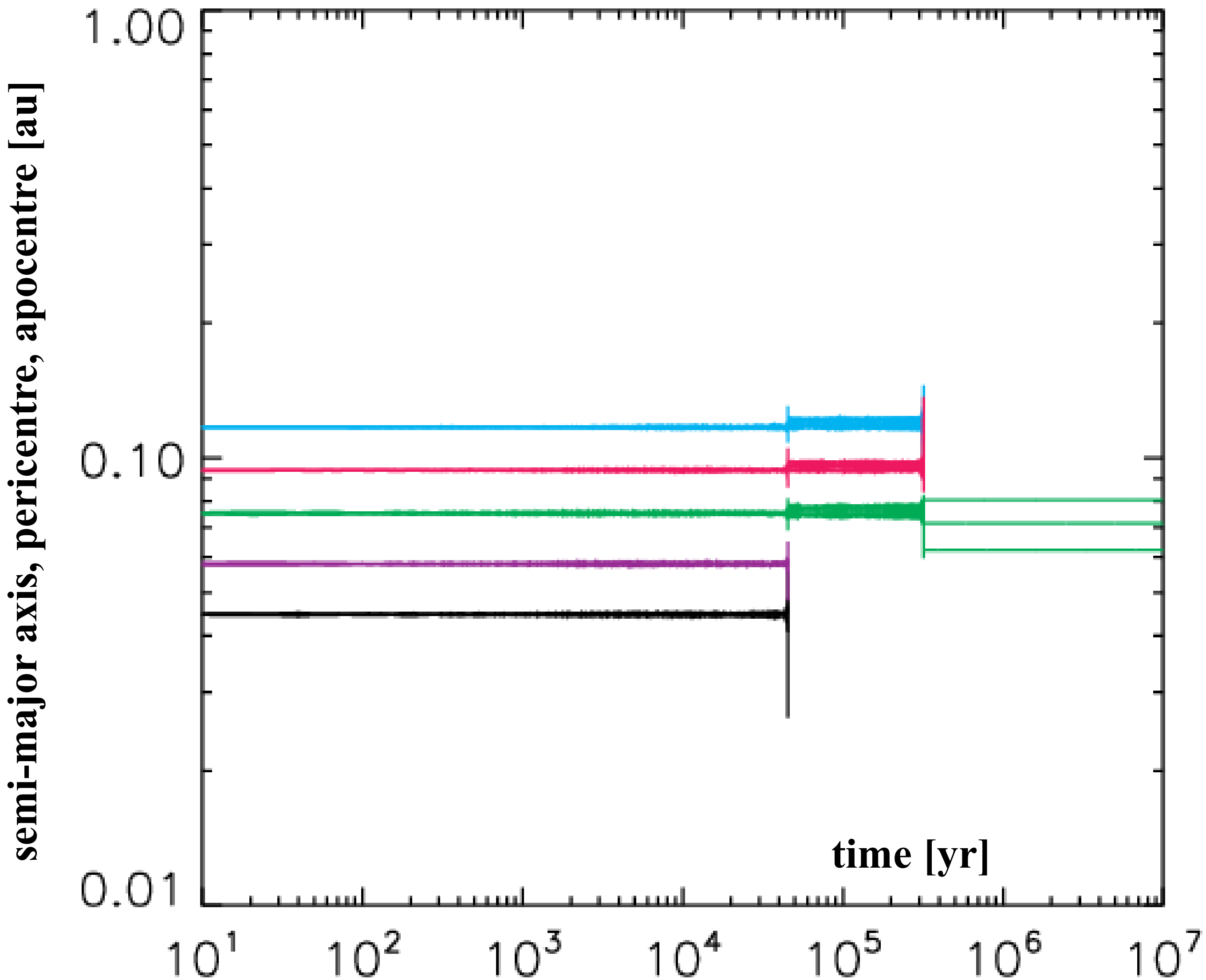
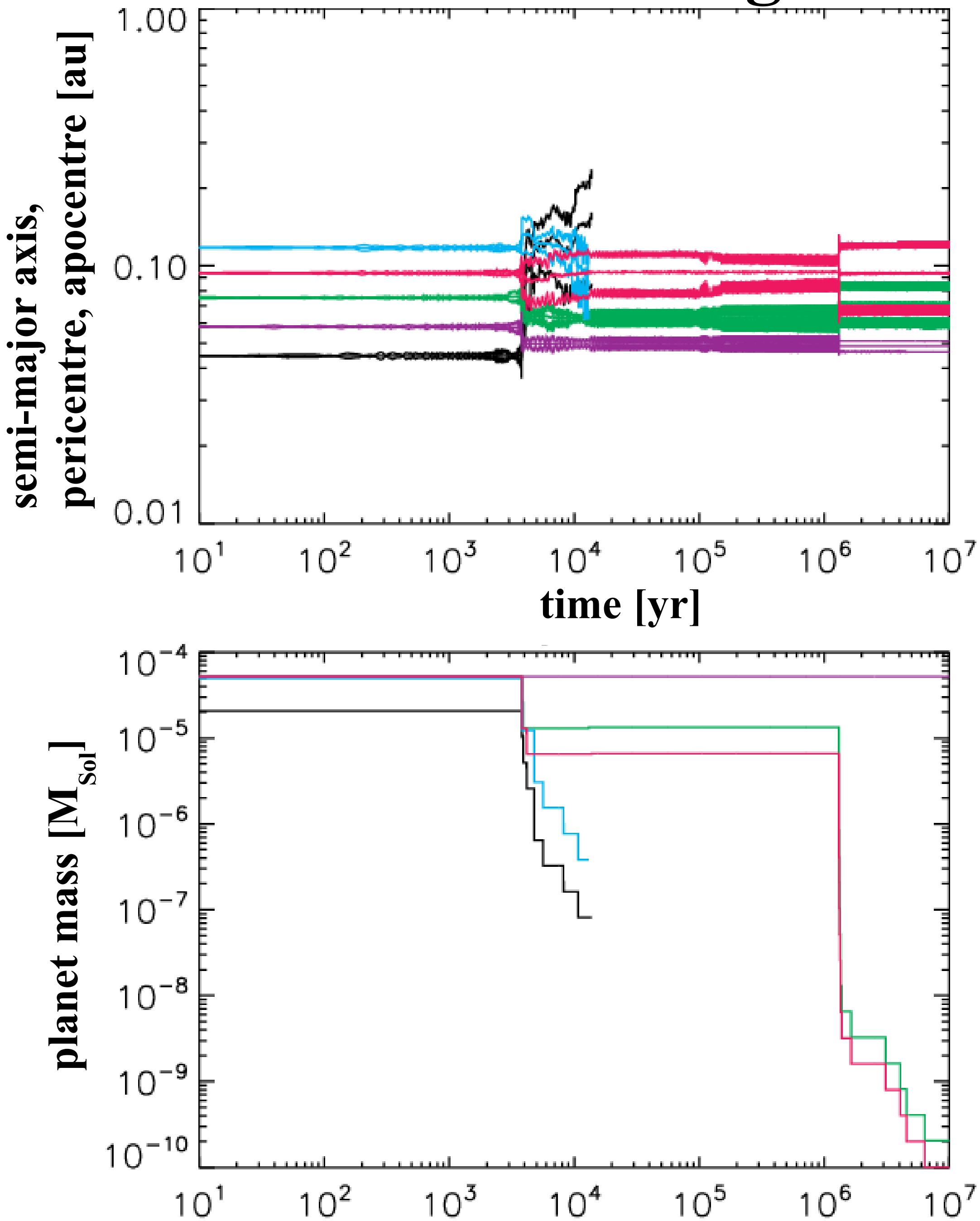


Endogenous dynamics: collisional crafting

- Semi-realistic prescription: remove half of mass on collision
- extreme mass ratios still merge
- efficient at making single detectable planets



Endogenous dynamics: collisional crafting

- **Preliminary statistics (all based on padded Kepler-18):**

	0 planets	1 planet	2 planets	3 planets	4 planets	5 planets
Perfect merging	**0**	**0**	**8** ***25%***	**24** ***75%***	**0**	**0**
Perfect destruction	**0**	**14** ***88%***	**0**	**2** ***13%***	**0**	**0**
Semi-realistic	**6** ***14%***	**24** **55%**	**9** ***20%***	**4** ***9%***	**0**	**1** ***2%***

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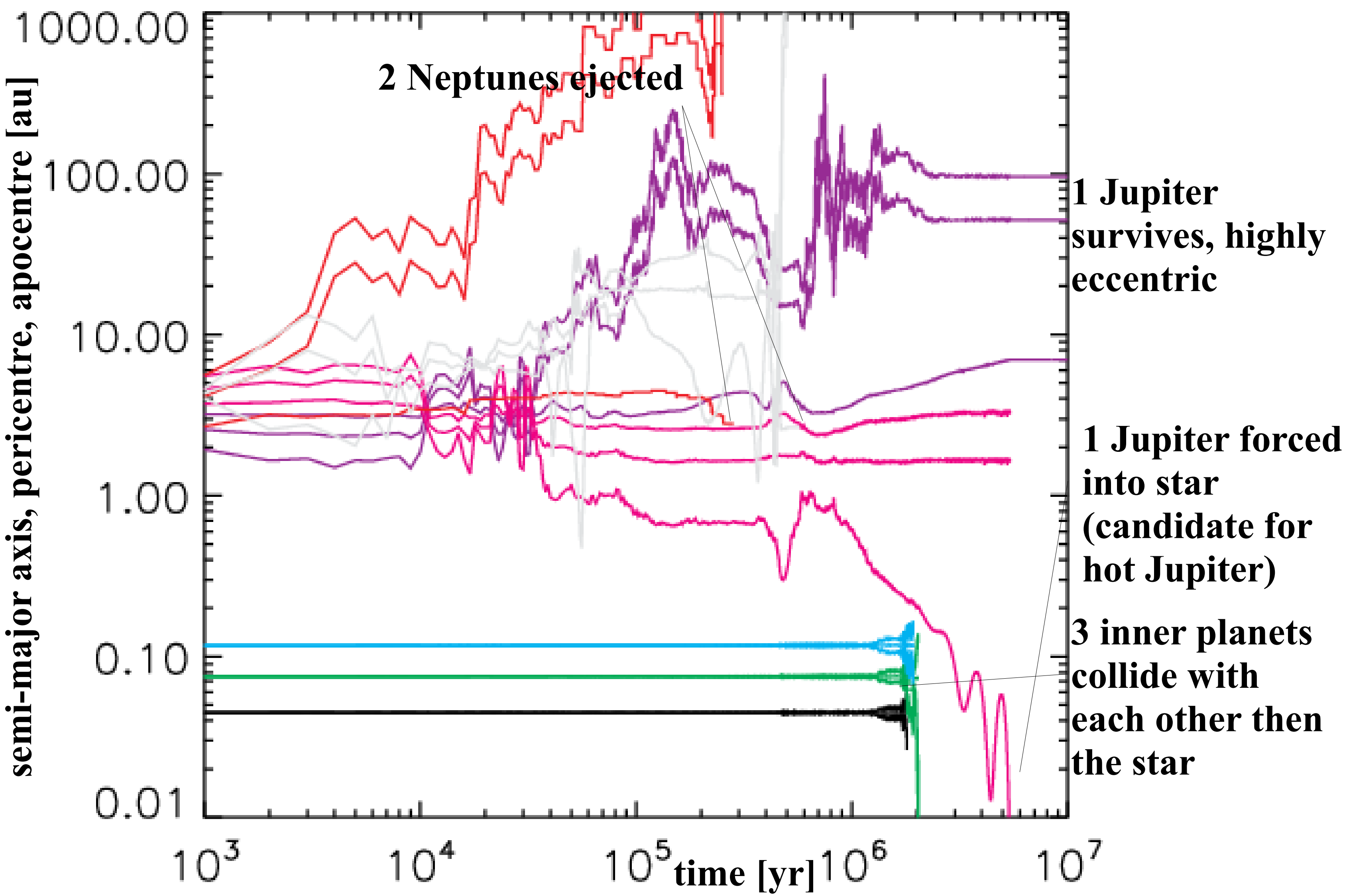
Many singles made!

Conclusions

- **Single planets are common**
- **Possible to dynamically reduce multiplicity through exogenous or endogenous means**
  - **scattering/Kozai in outer systems**
  - **collisions in packed inner systems**
- **Efficiency of each channel to be investigated...which one dominates?**
- **...formation effects could also play a role (*e.g.*, Izidoro *et al.* 2015)**

Exogenous dynamics: the scattering scenario

- **Vindication of the Mustill *et al.* 2015 set-up**



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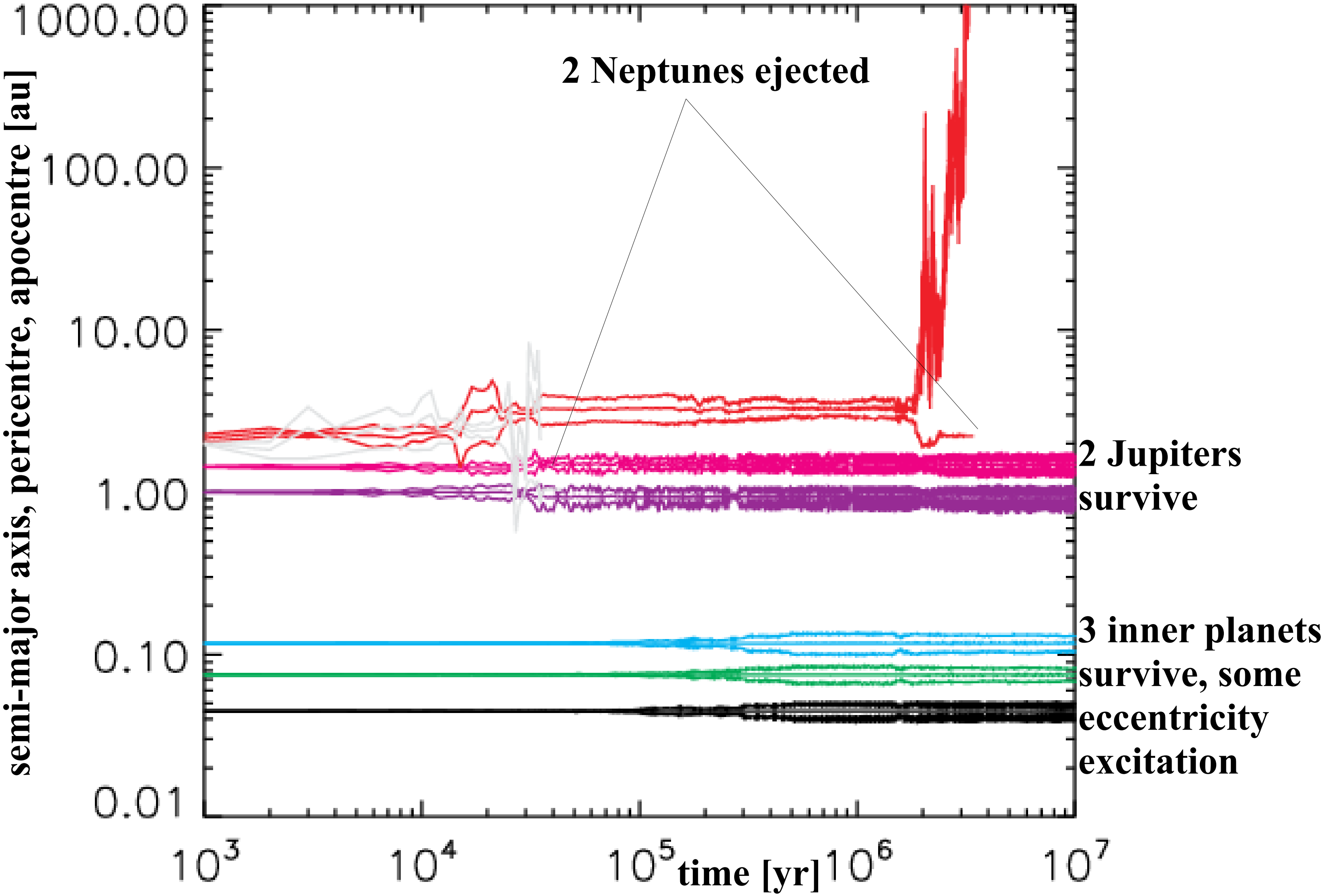
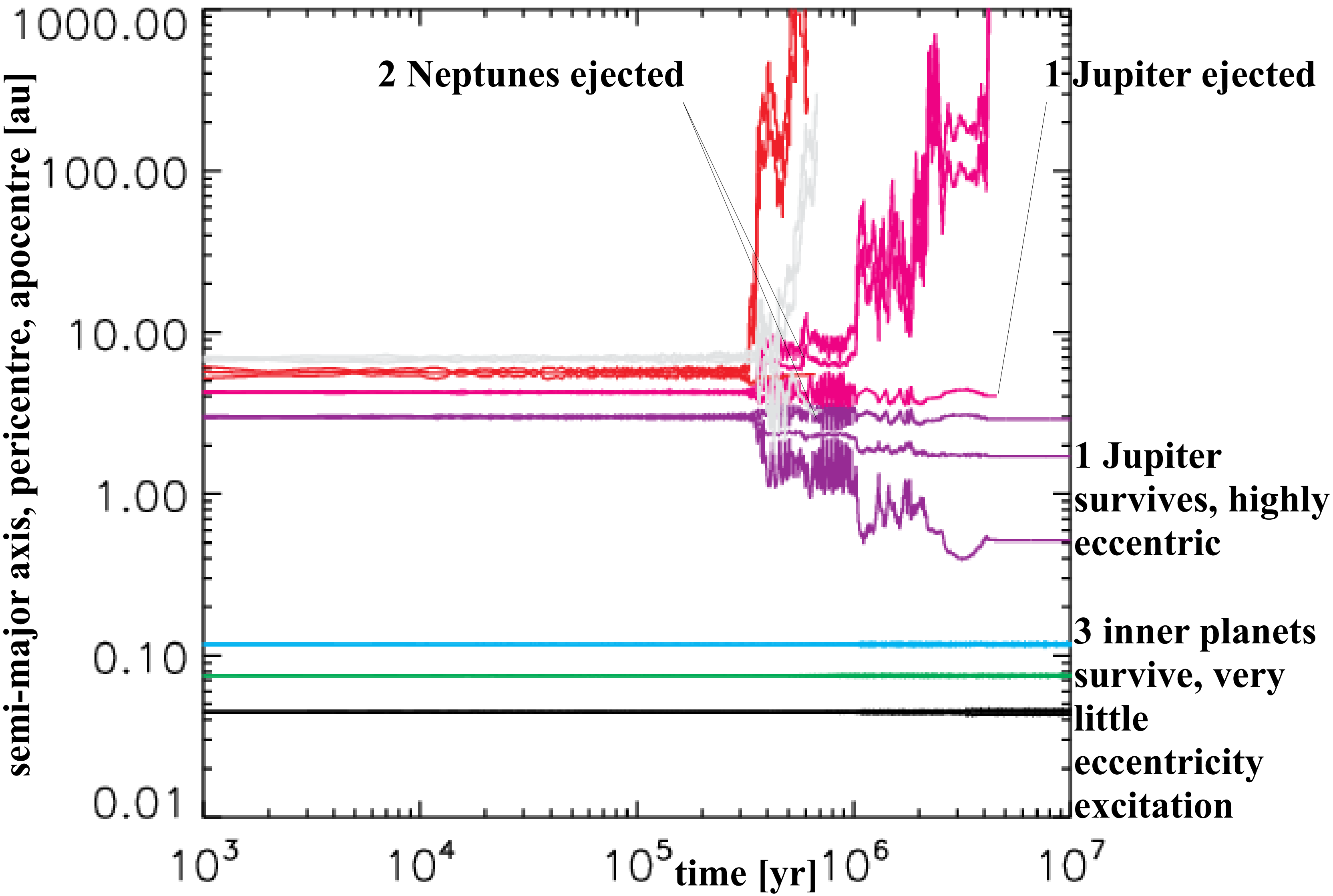


Exogenous dynamics: the scattering scenario

- **Less effective if outer planets more distant from star...**



Exogenous dynamics: the Kozai case

- **Multiplicity reduction still possible**