The Dynamical Evolution of Exoplanet Systems

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First problem: is our solar system stable?

Must model the evolution of the planetary system for about 10^{10} orbits.

Planetary masses are much smaller than the mass of the sun.

Even very small perturbations can sometimes lead to significant outcomes via planet-planet interactions within planetary systems.

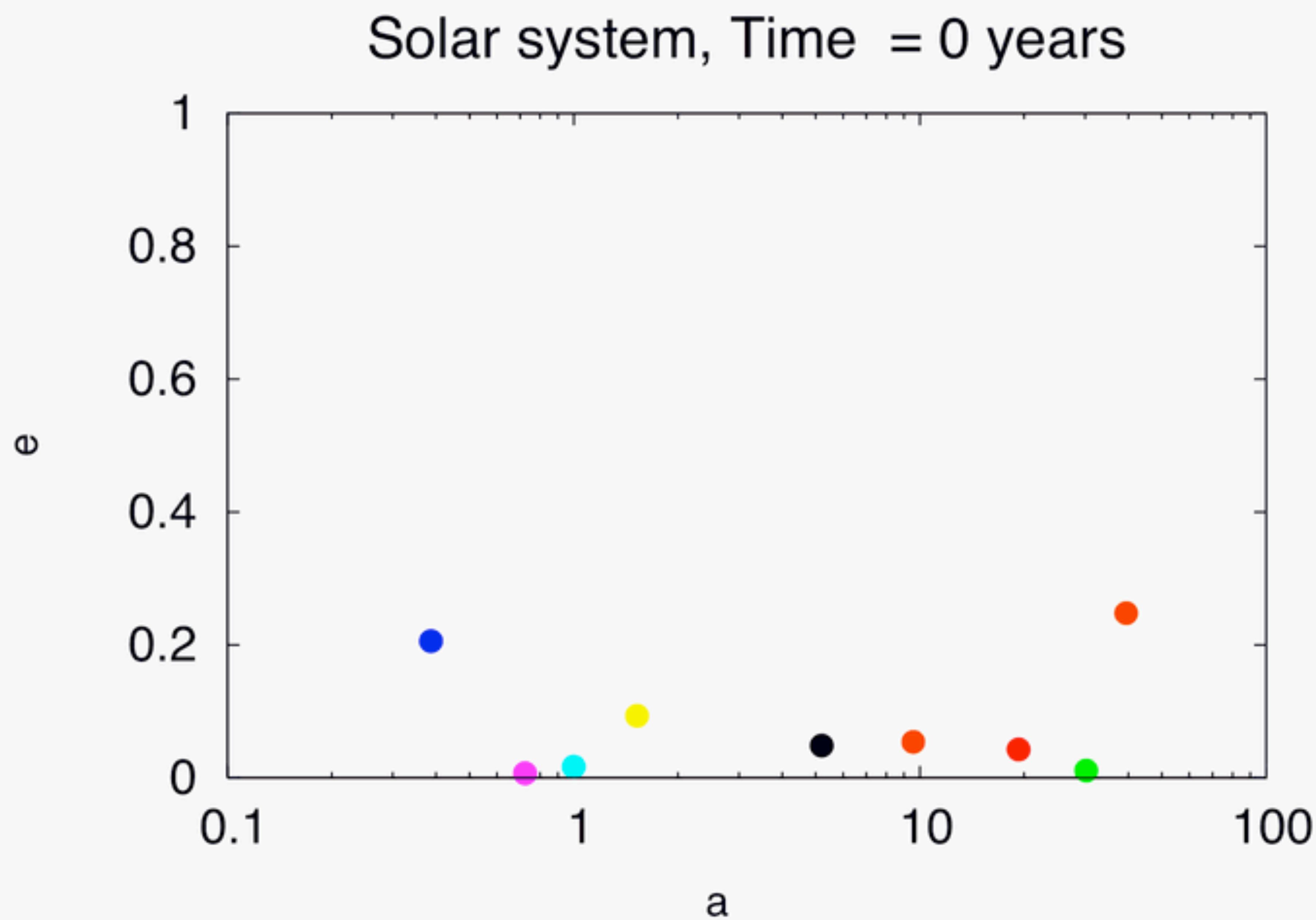
Two-body problem (Brahe, Kepler, Newton)

Planets orbit in ellipses around the sun.

$$E = -\frac{GM_1M_2}{2a}$$

$$e^2 = 1 + \frac{2EJ^2}{G^2\mu^3M^2}$$

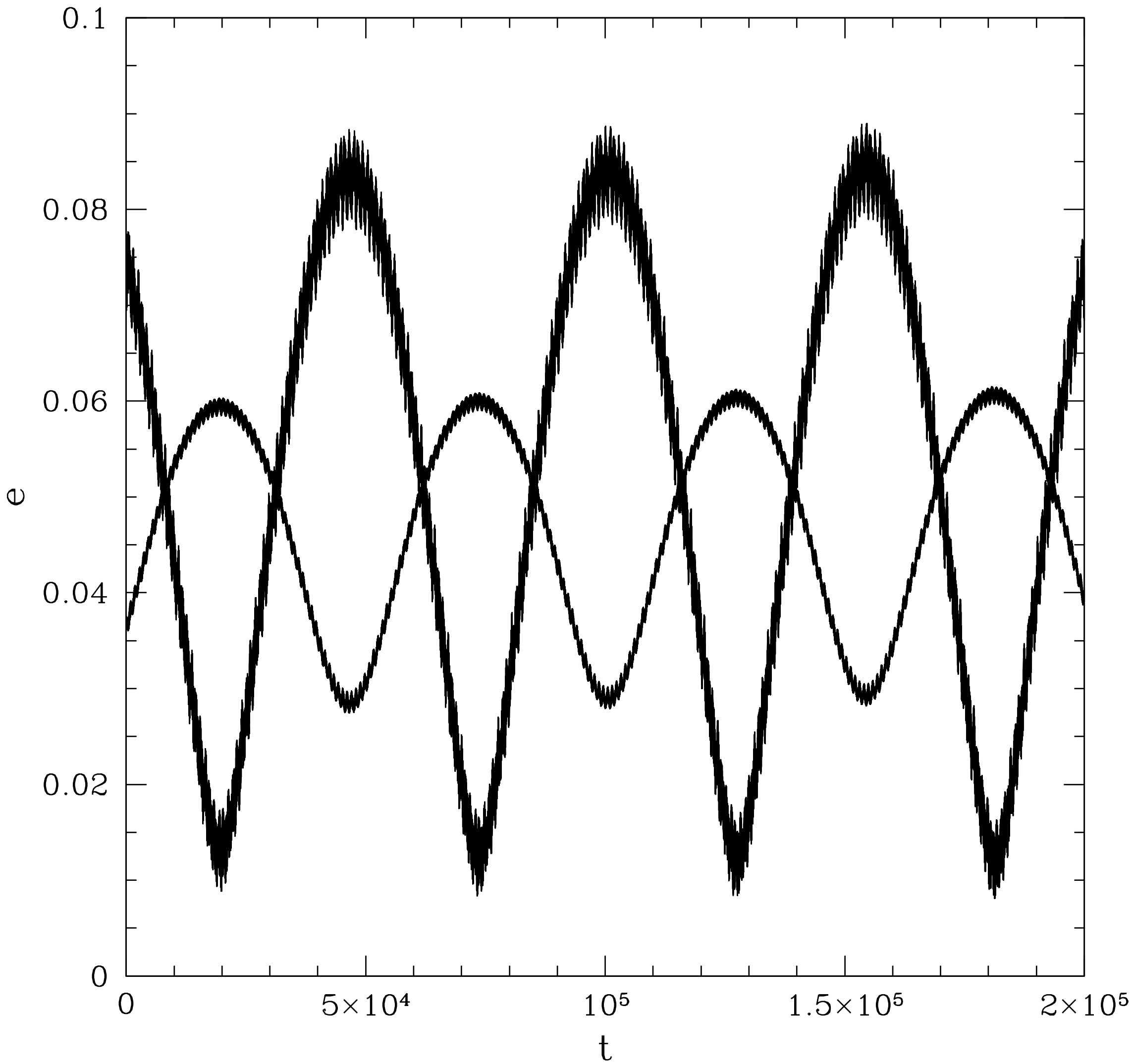
Planet's orbits are roughly circular and coplanar.


Solar system, Time = 0 years
1
0.8
0.6
0.4
0.2
0
e
0.1
1
10
100
a

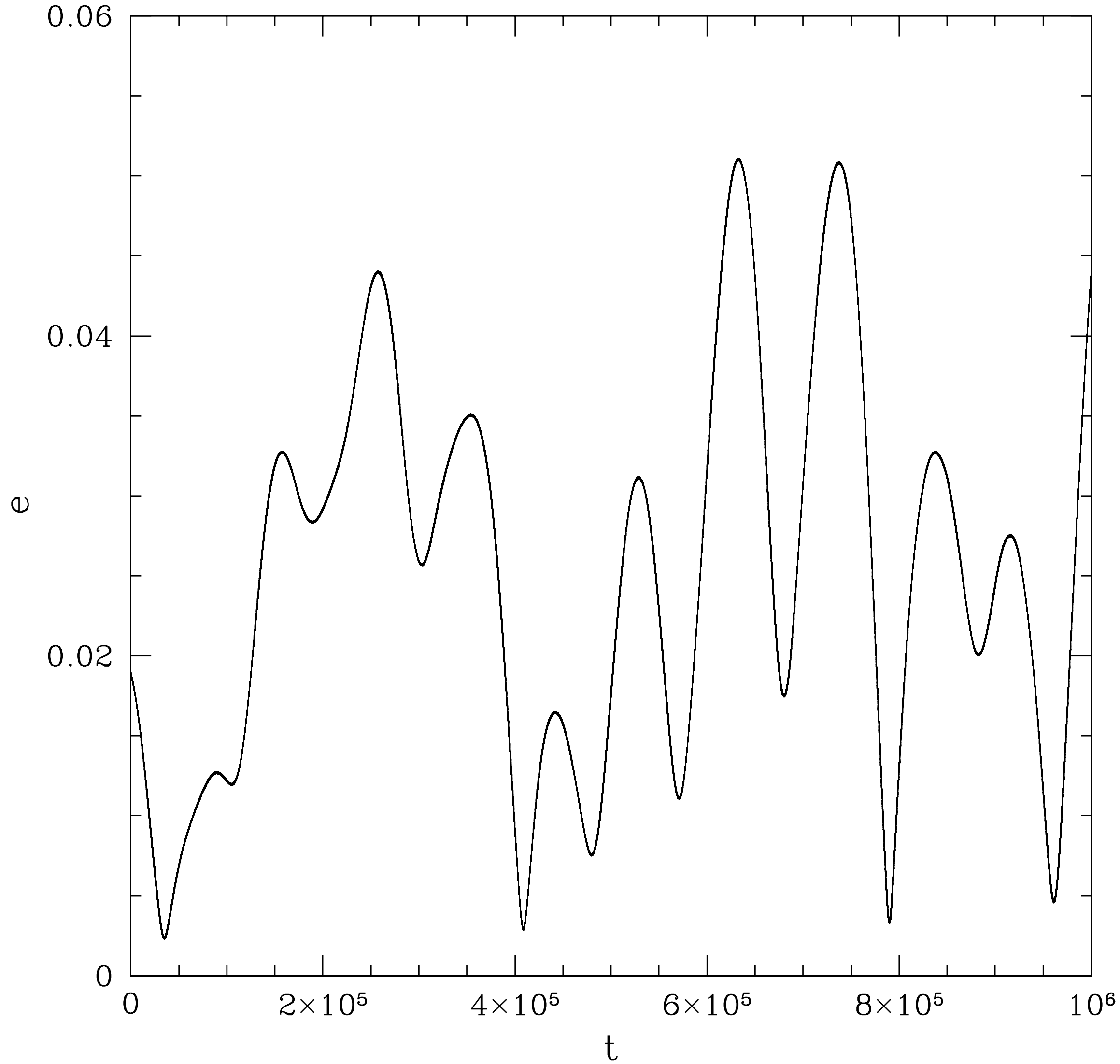
Laplace-Lagrange Secular Perturbations

To first order in eccentricity and inclination, perturbations from planets produce oscillations in eccentricity and inclination which do not grow over time.

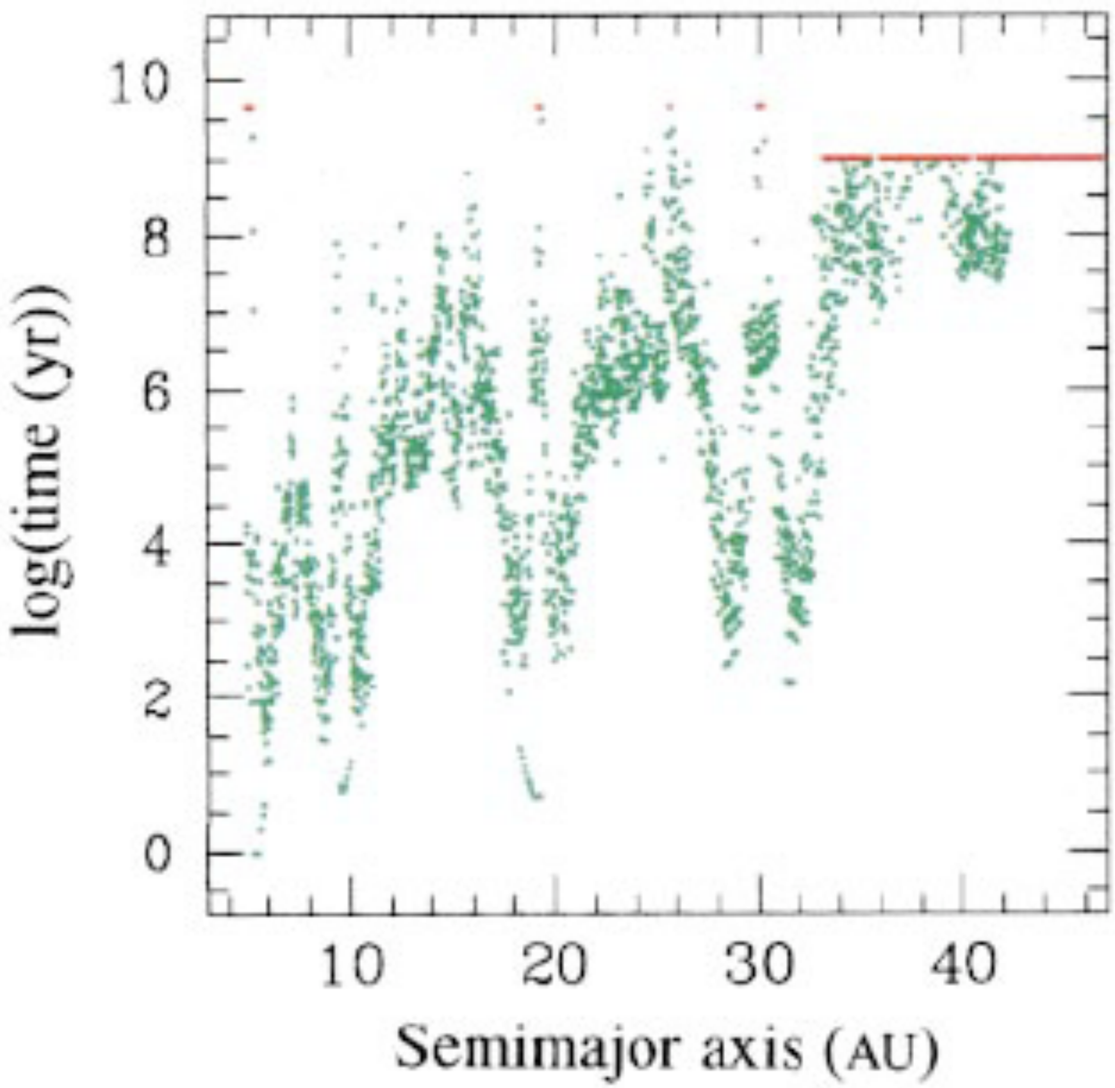
Eccentricity of Jupiter and Saturn



Earth's eccentricity as a function of time



Is the solar system full?



Holman (1997)

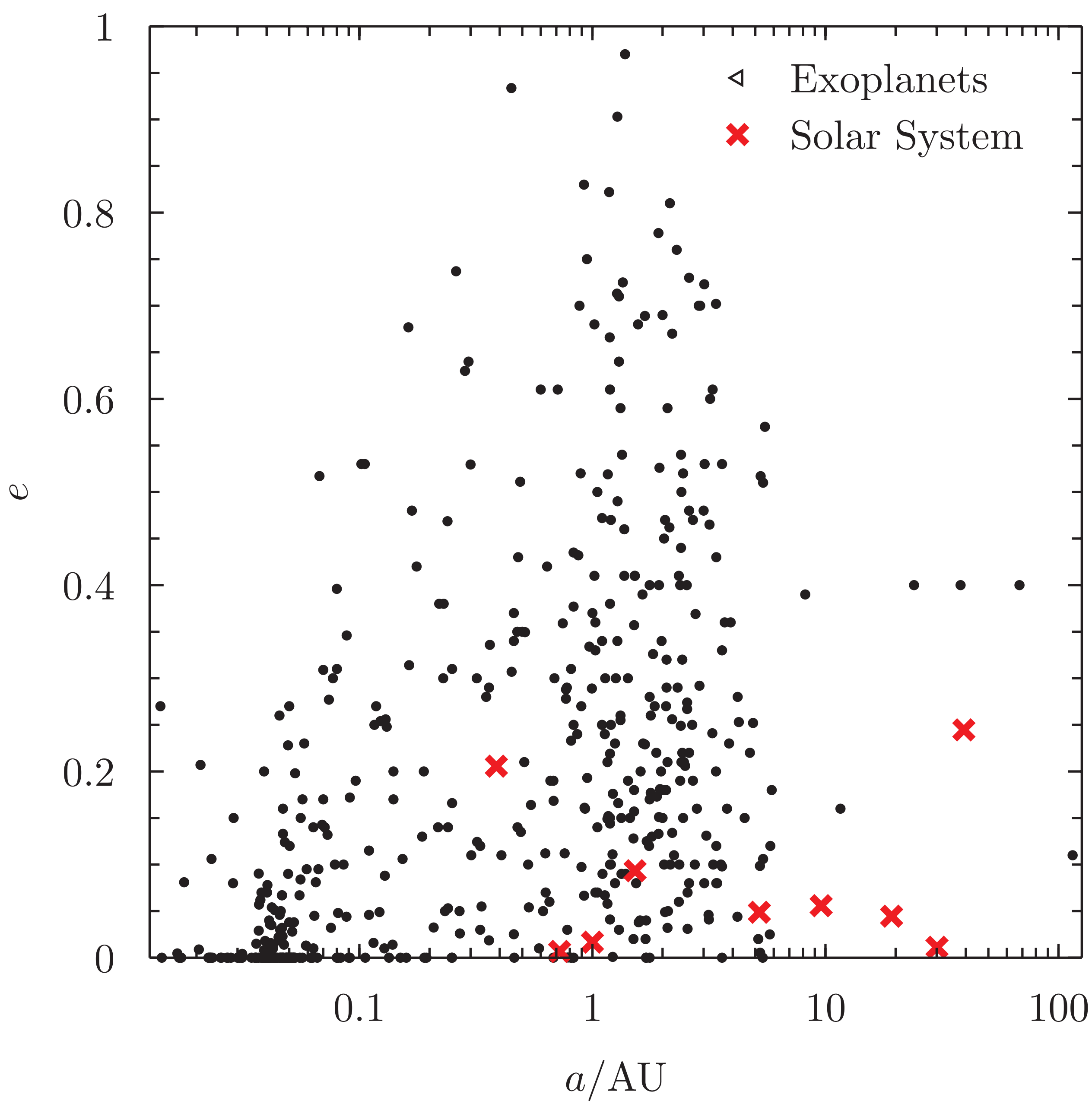
Solar System Summary

The solar system is chaotic on a timescale of 5-20 Myr.

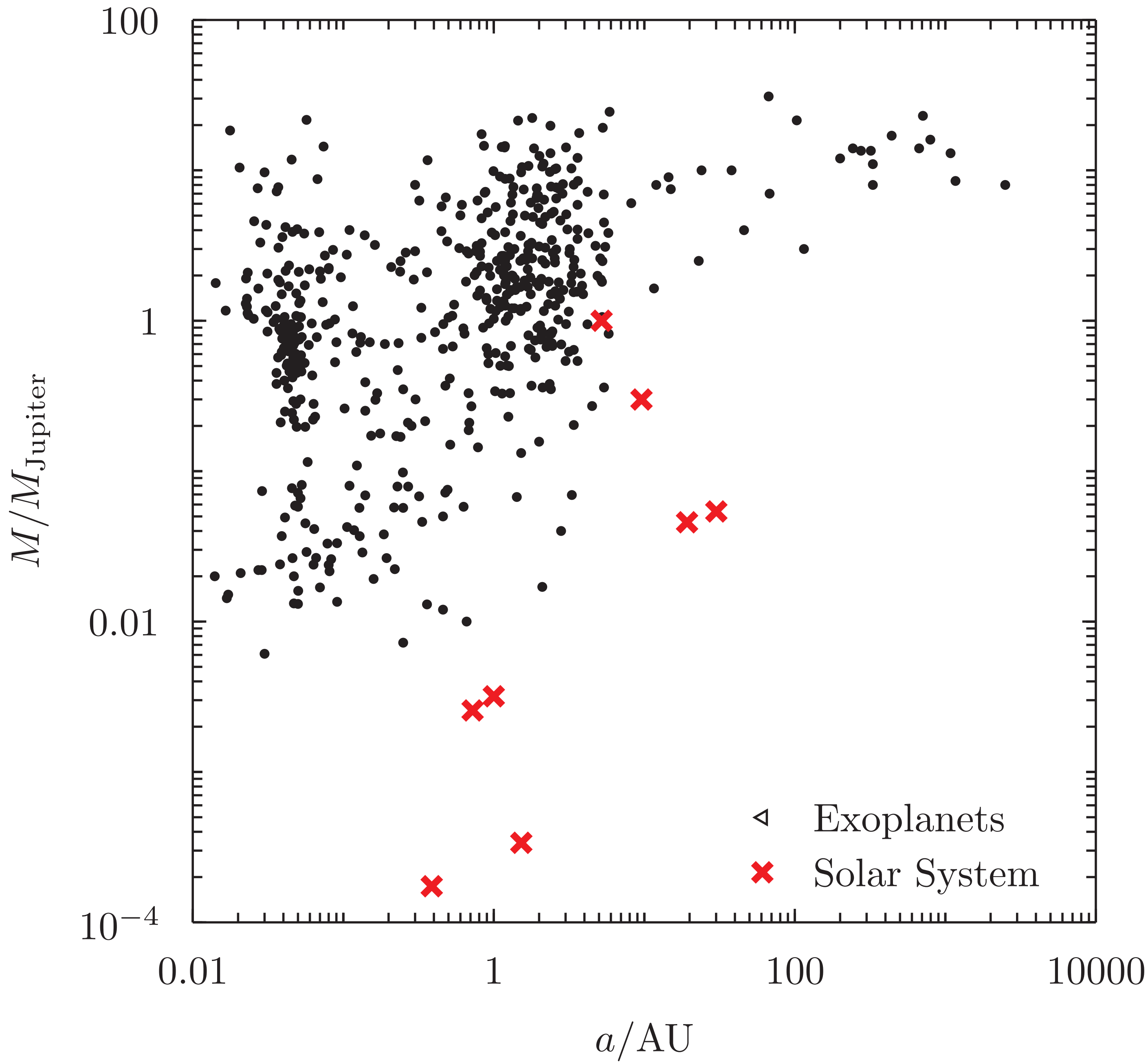
It is unlikely that any planet will be ejected or collide before the sun becomes a red giant.

Most of the solar system is full. Planets may have been ejected in the past.

The current catalogue of known exoplanets

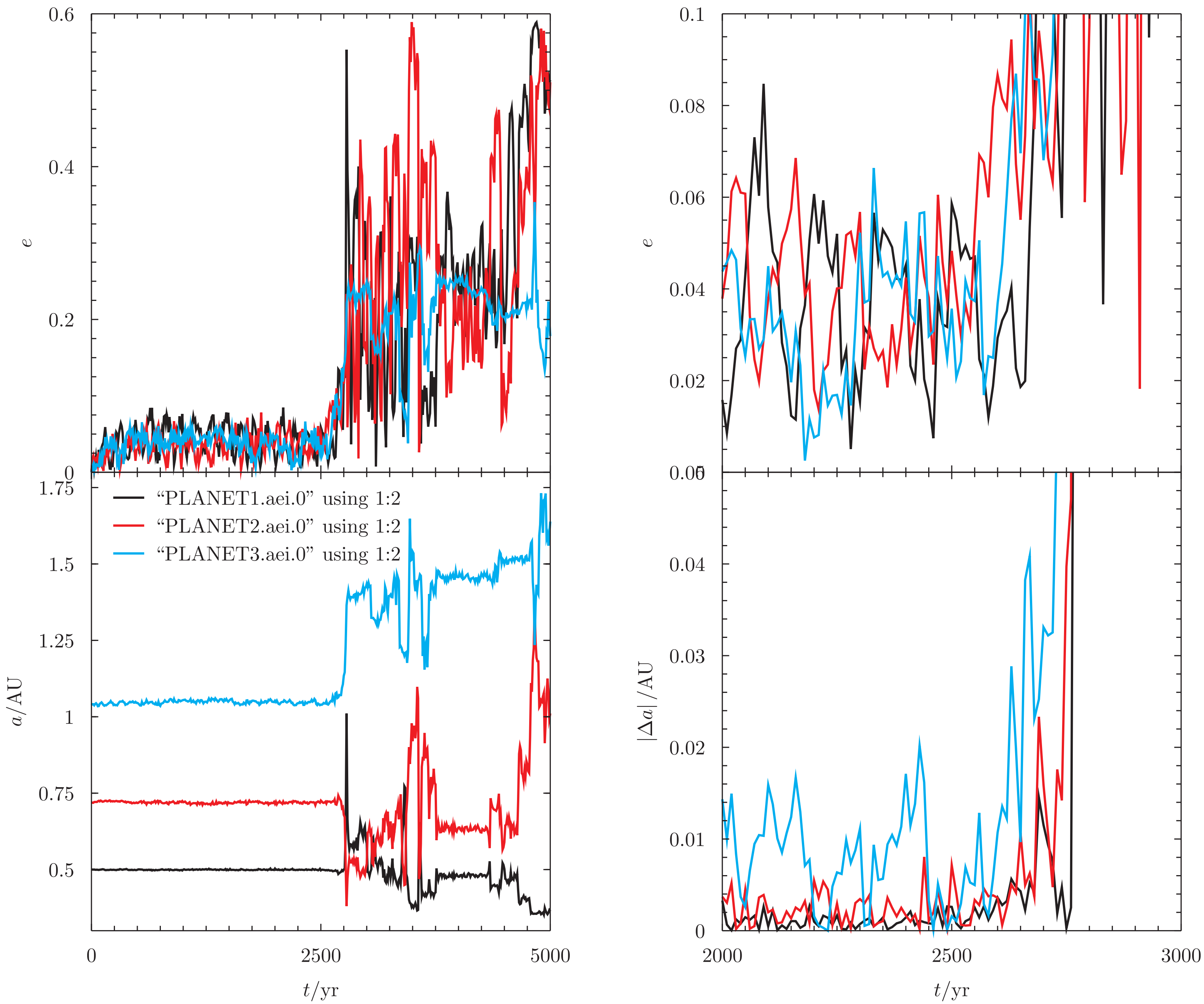


Sunday January 29, 2012



Sunday January 29, 2012

An unstable system containing three Jupiters



A CLAIM:

Think of a planetary system containing a number of gas giants. Either:

1) Planetary system is self-unstable, leading to the ejection of giant planets, leaving others on eccentric orbits,

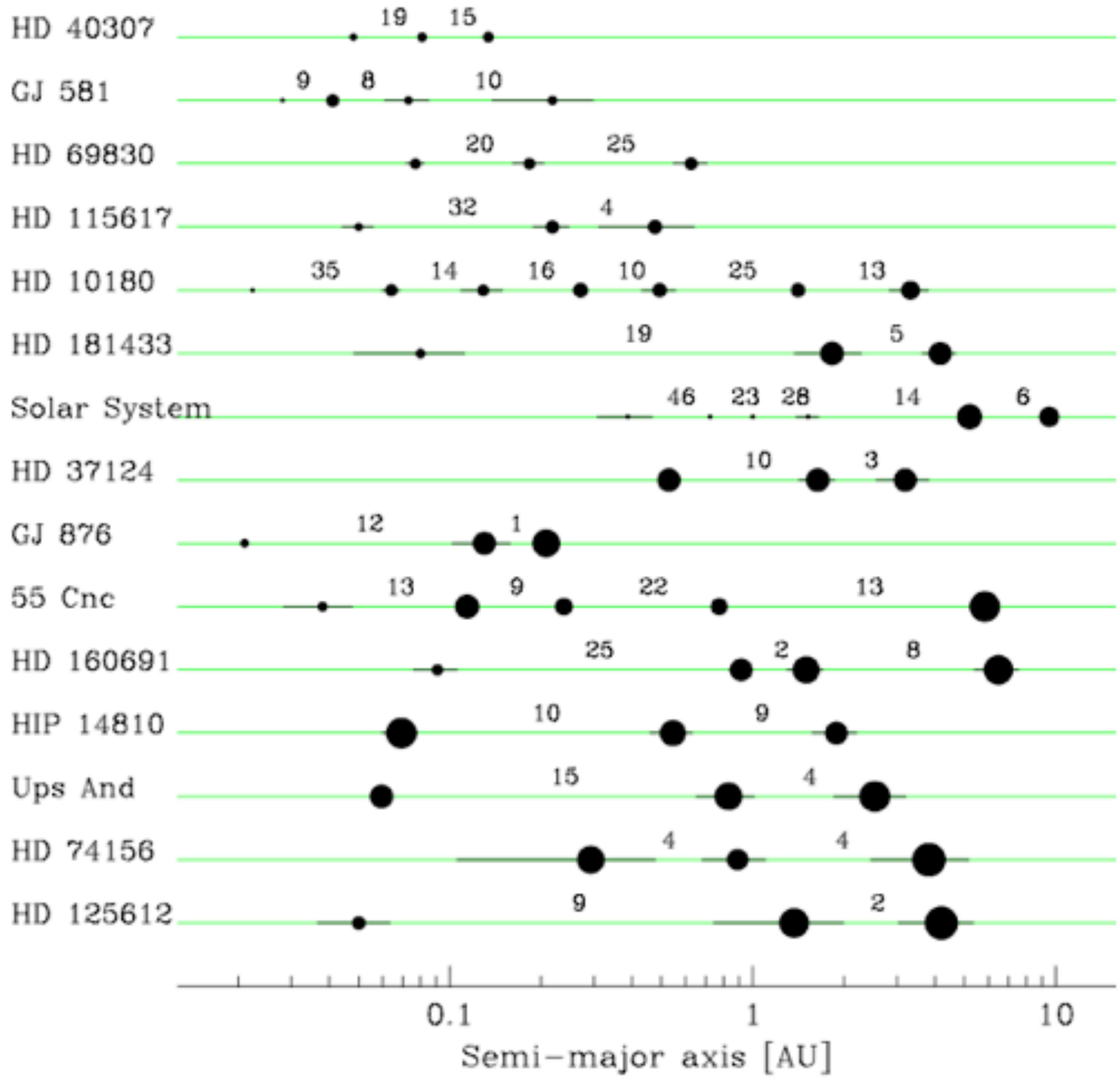
(eg. Rasio & Ford 1996; Juric & Tremaine 2008)

OR

2) Planetary system is not self-unstable (rather like our own solar system).

(see also Lovis et al 2010)

Known multiple-planet systems



(Lovis et al 2010)

Stable Systems

Something Happens

Unstable Systems

What is the something?

The something is either i) close encounters within young stellar groupings or ii) exchange encounters which leave planetary systems in binaries.

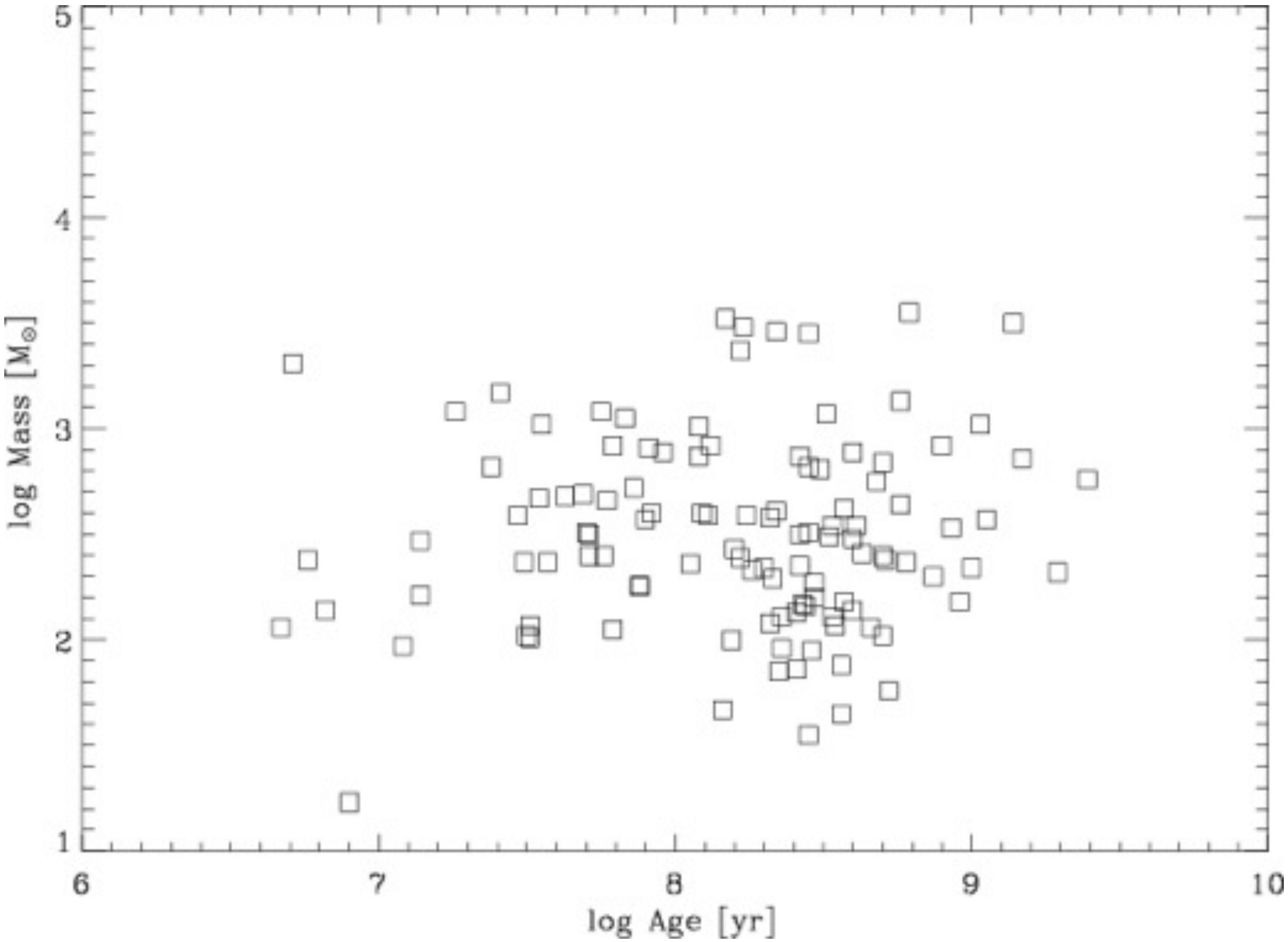
Strong planet-planet interactions within planetary systems may follow.

Singletons are stars born single which don't have close encounters or exchange in to binaries.

Orion nebula and Trapezium cluster (2MASS image)

All stars are formed in some sort of grouping.

Open cluster properties



(Lamers et al 2005, Kharchenko et al 2005)

Simulate cluster evolution

Evolve clusters considering a range of sizes and masses.

Place some stars in binaries whilst others are initially single.

Trace stellar histories: log all the close encounters between two stars and binary/single encounters.

Consider effects of gas and initial stellar kinetic energy (system can form "cold").

(Malmberg et al 2007b, Bonnerot et al, in prep.)

Stellar encounter timescales

Cross section is given by

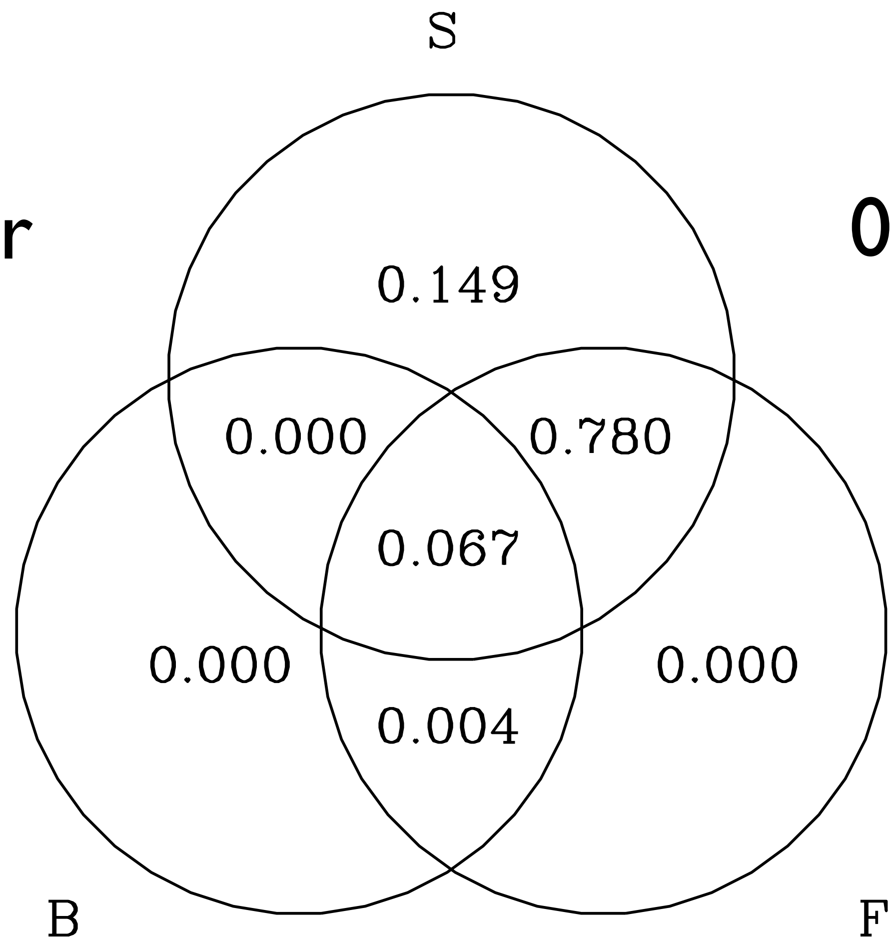
$$\sigma = \pi R_{min}^2 \left(1 + \frac{2G(M_1 + M_2)}{R_{min} V_\infty^2}\right)$$

Timescale for a given star to undergo an encounter is

$$\tau_{enc} \simeq 3.3 \times 10^7 yr \left(\frac{100\ pc^{-3}}{n}\right) \left(\frac{V_\infty}{1\ km/s}\right) \left(\frac{10^3\, AU}{R_{min}}\right) \left(\frac{M_\odot}{M_t}\right)$$

How common are singletons?

Entire cluster lifetime

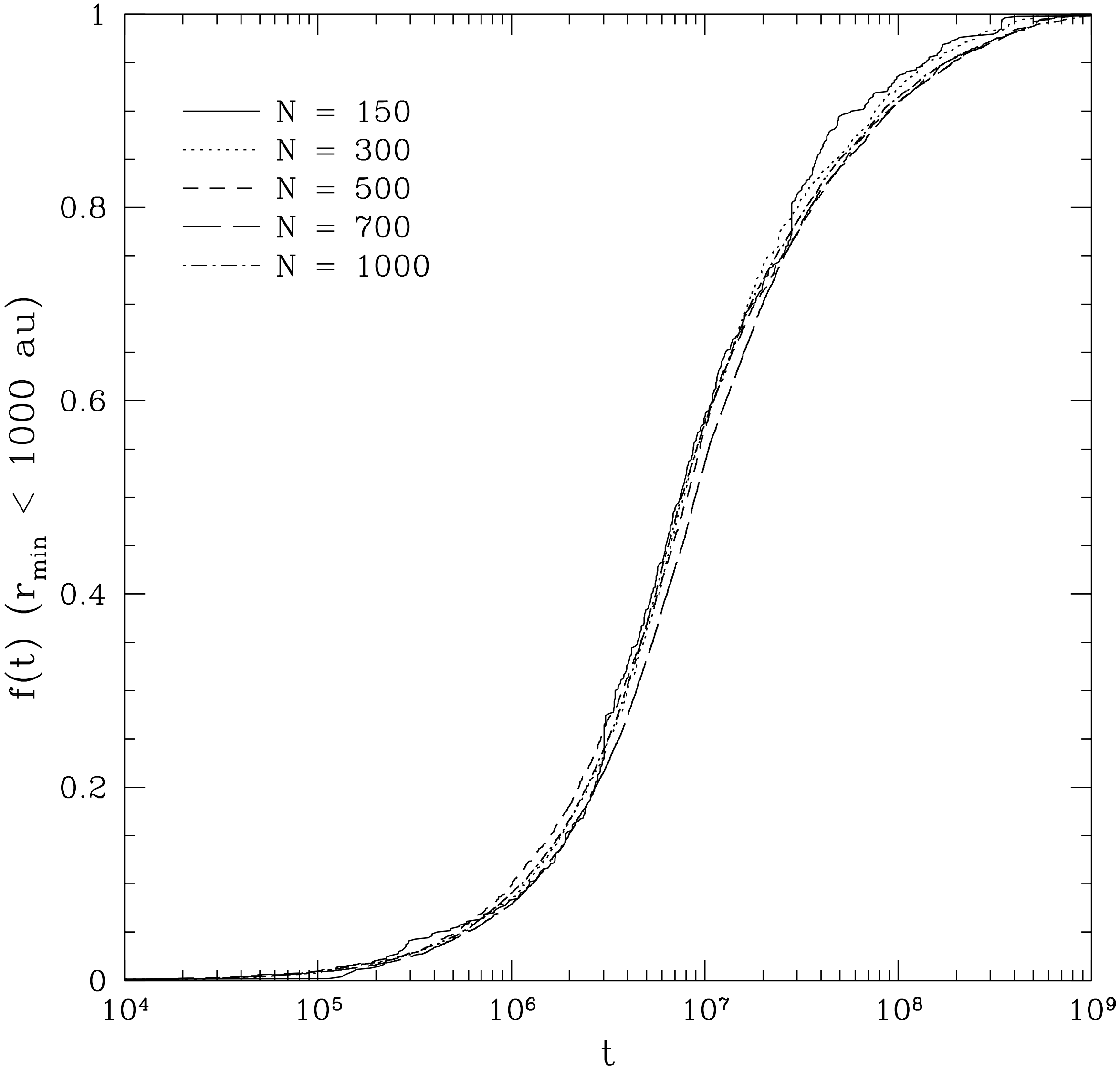


0.8-1.2 msol

N=700 stars, R=2-4 pc

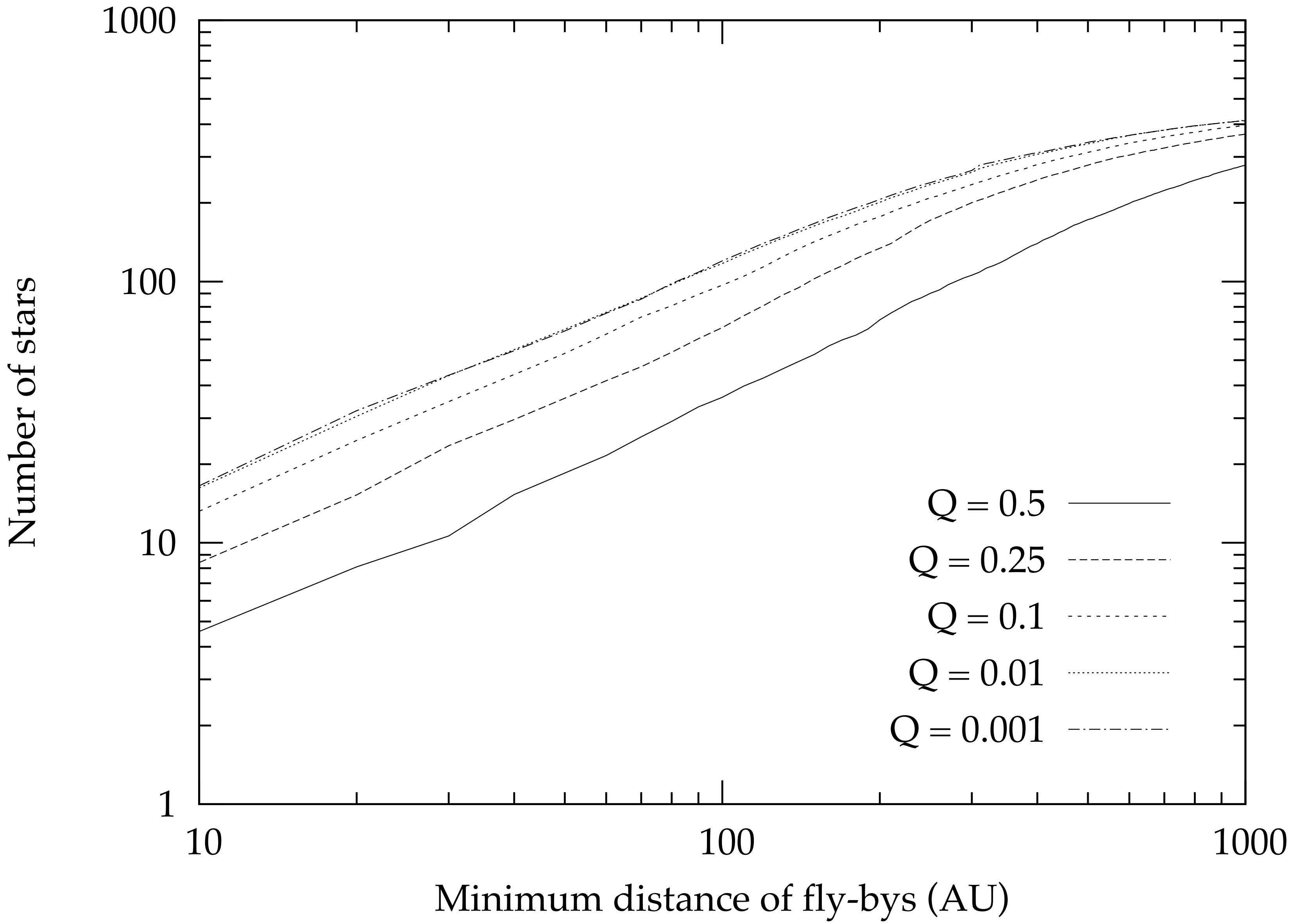
(Malmberg et al 2007b)

Distribution of encounters over time



(Malmberg et al 2007b)

Distribution of close encounters (first 10 Myr)



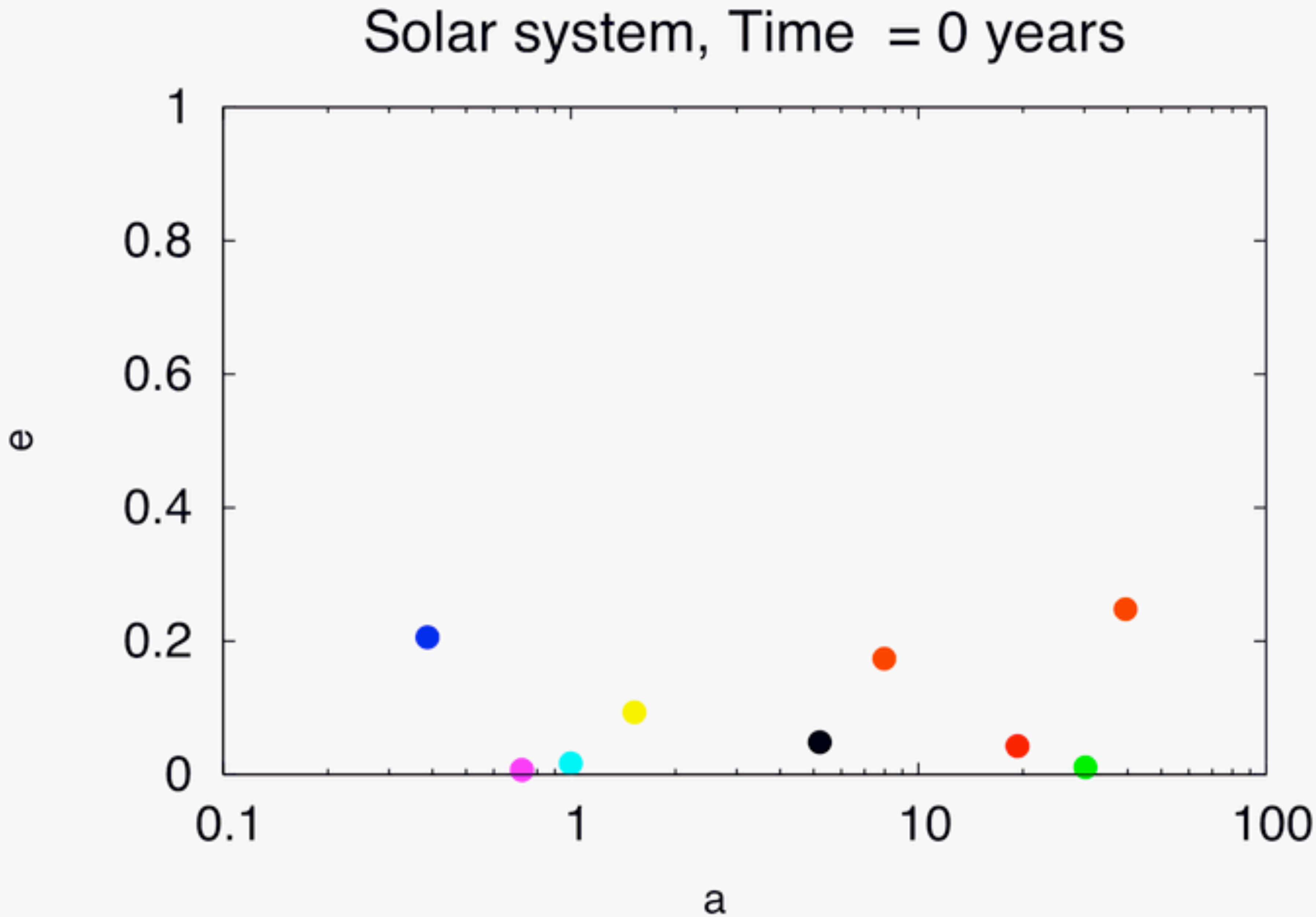
Out of 466 stars (Bonnerot et al, in prep.)

Effects of close encounters

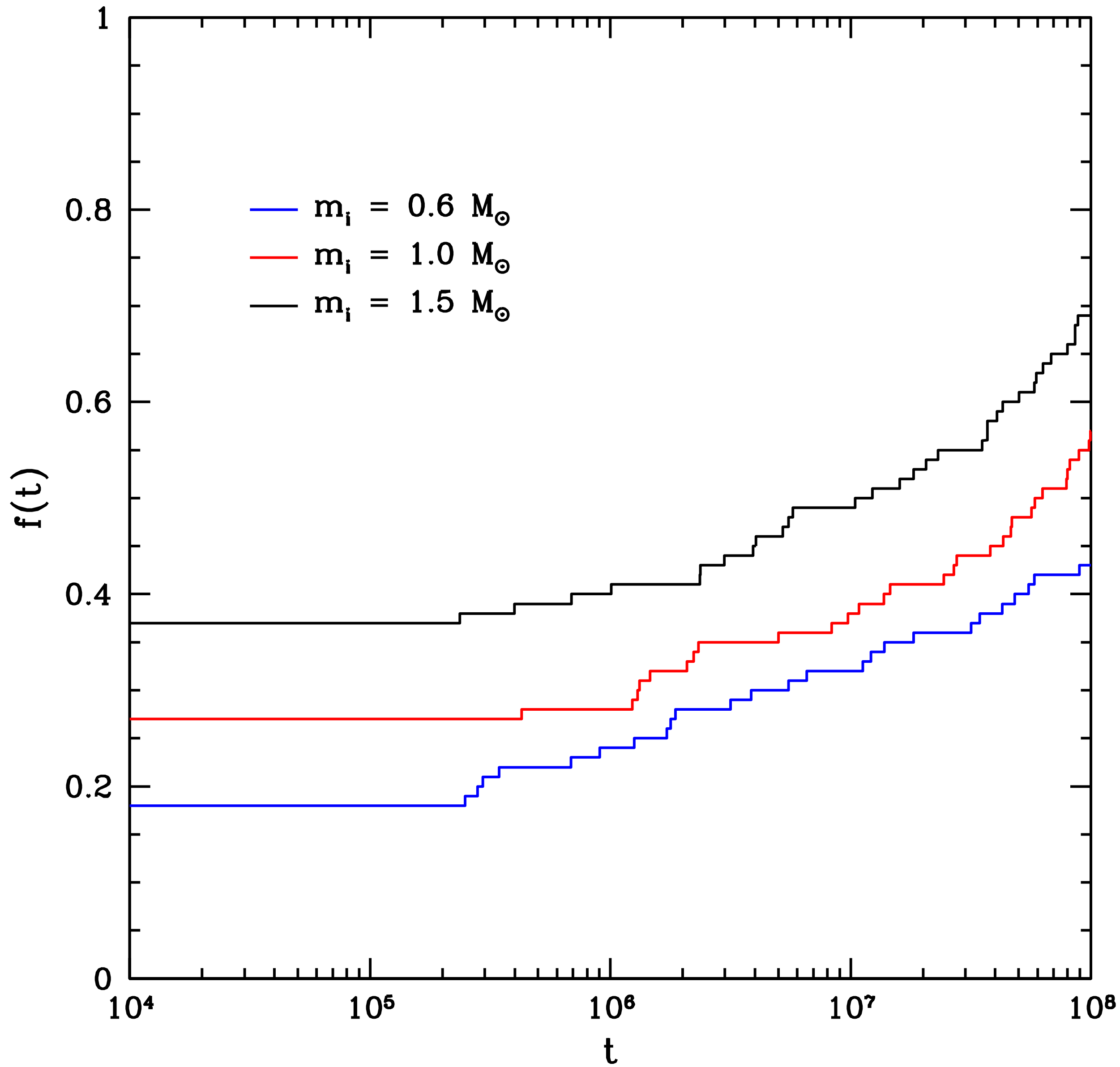
Extremely close fly-by encounters may result in the direct ejection of planets.

Other planets may remain bound but on tighter and more eccentric orbits.

Even very small perturbations can sometimes lead to significant outcomes via planet-planet interactions within planetary systems.


Solar system, Time = 0 years
1
0.8
0.6
0.4
0.2
0
e
0.1
1
10
100
a

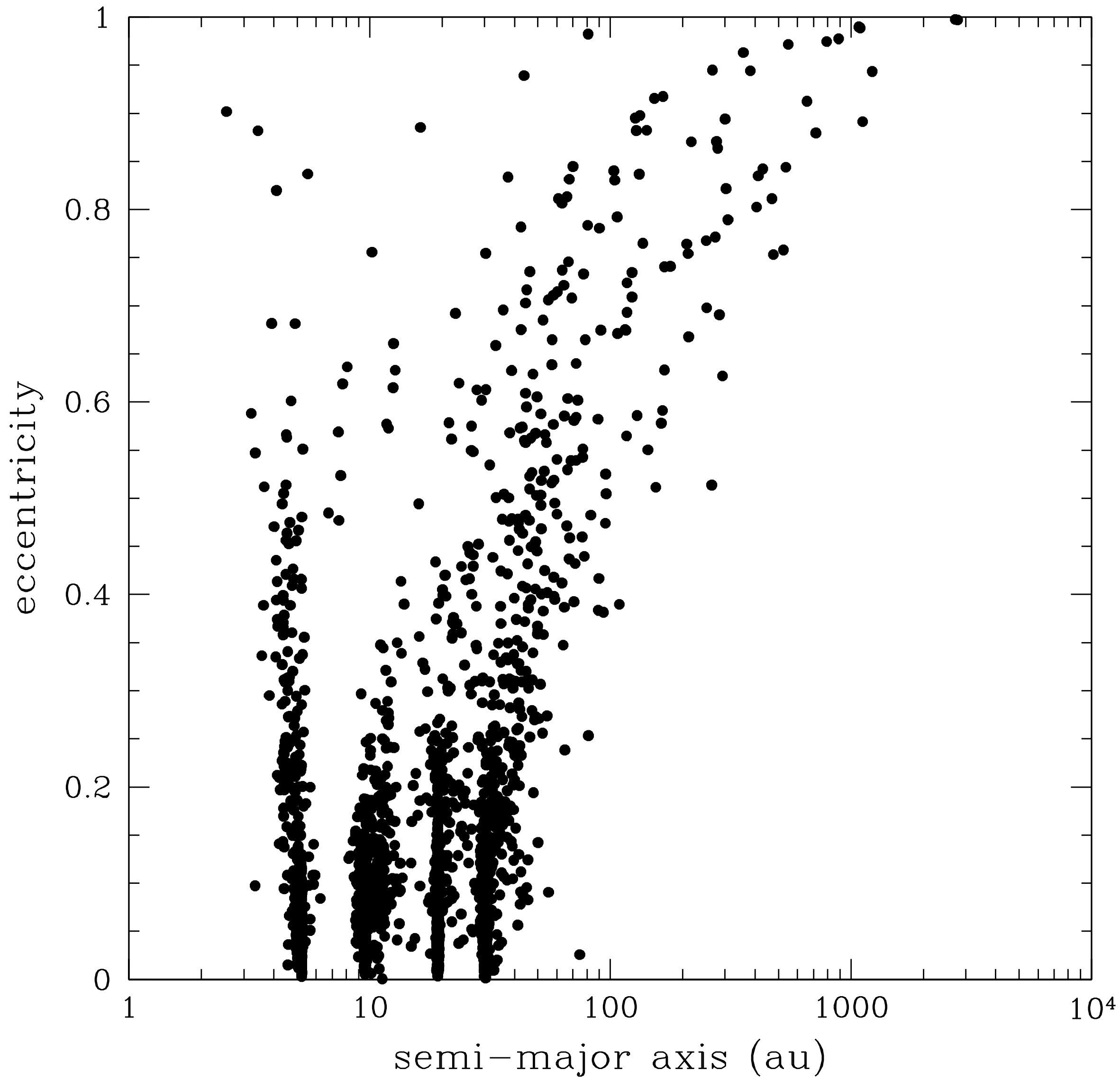
The long term effect of fly-bys (within 100 AU)



The fraction of solar-mass stars with four gas giants in a cluster of 700 stars that lose at least one planet within 100 million years of a close fly-by: 0.15

(Malmberg, Davies & Heggie, 2011)

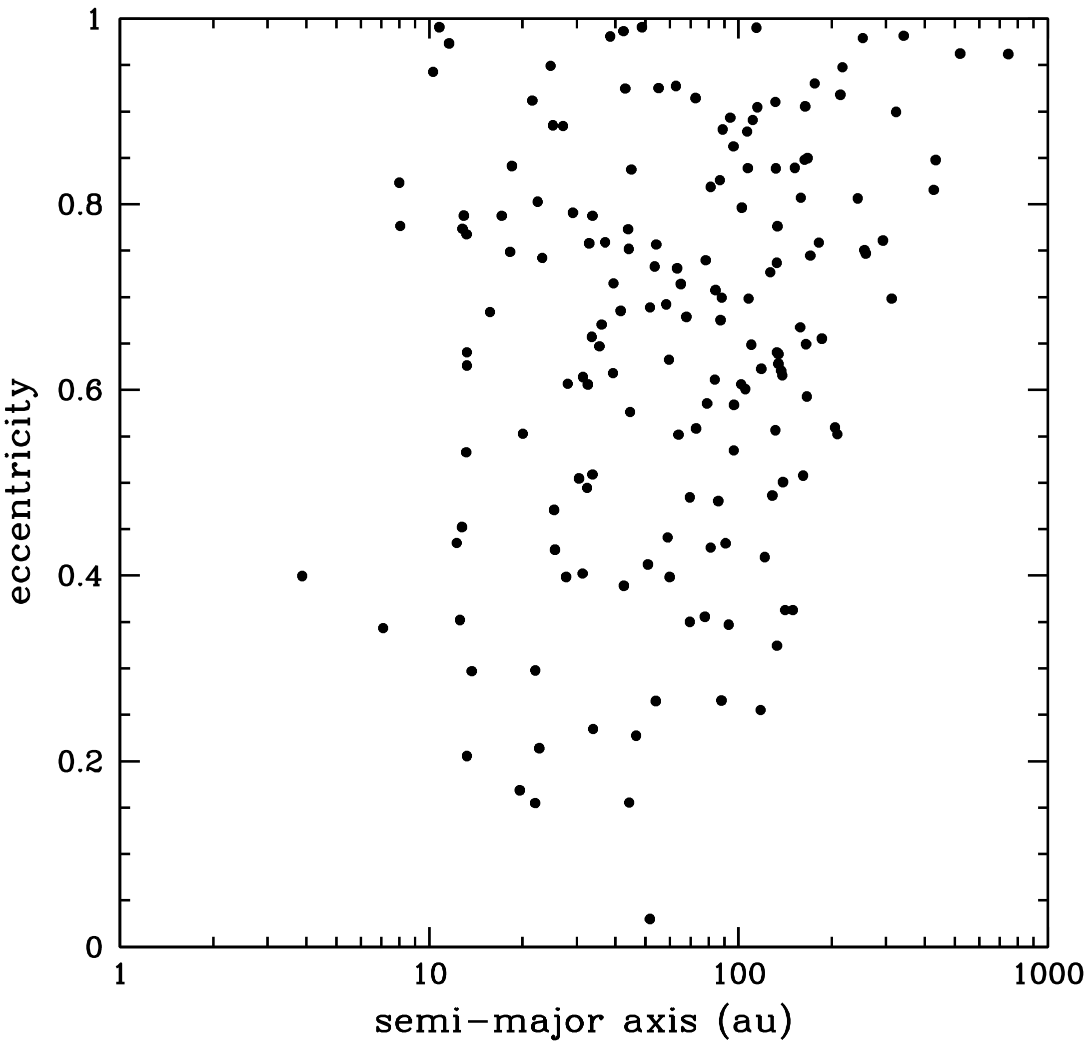
The four gas giants 10^8 years after fly-by (r_{Min} < 100 AU)



Fraction of solar-mass stars with initially four gas giants in a cluster of 700 stars having a planet with a>100 au 100 million years after fly-by: 0.02

(Malmberg, Davies & Heggie, 2011)

Post fly-by systems consisting of a single planet bound to the intruder star immediately after the fly-by



(Malmberg, Davies & Heggie, 2011)

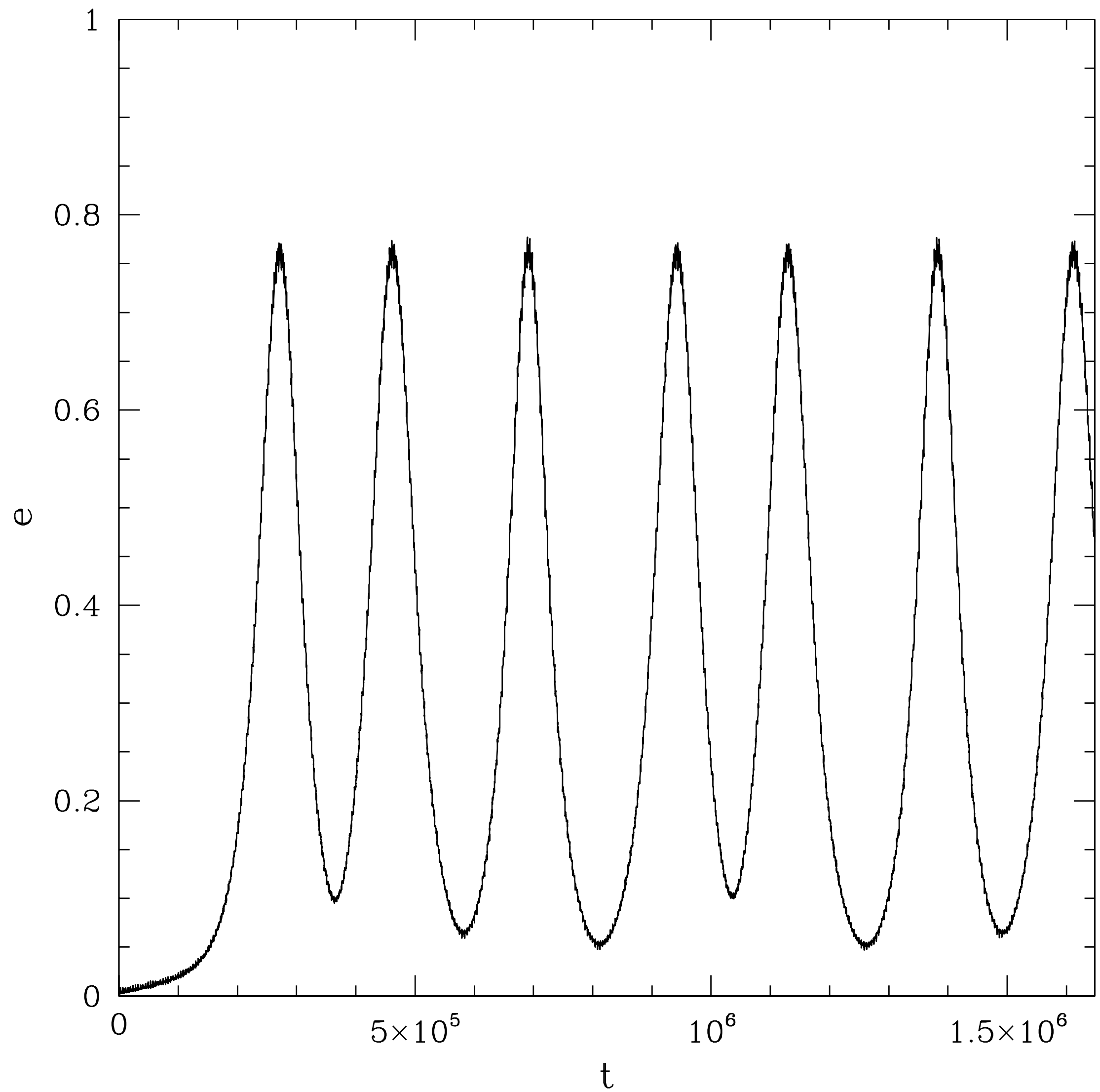
Effects of being in a binary

If the planetary system and stellar binary are highly inclined, the Kozai Mechanism will make the planetary orbits highly eccentric.

Strong planet-planet scattering will then occur for multiple-planet systems.

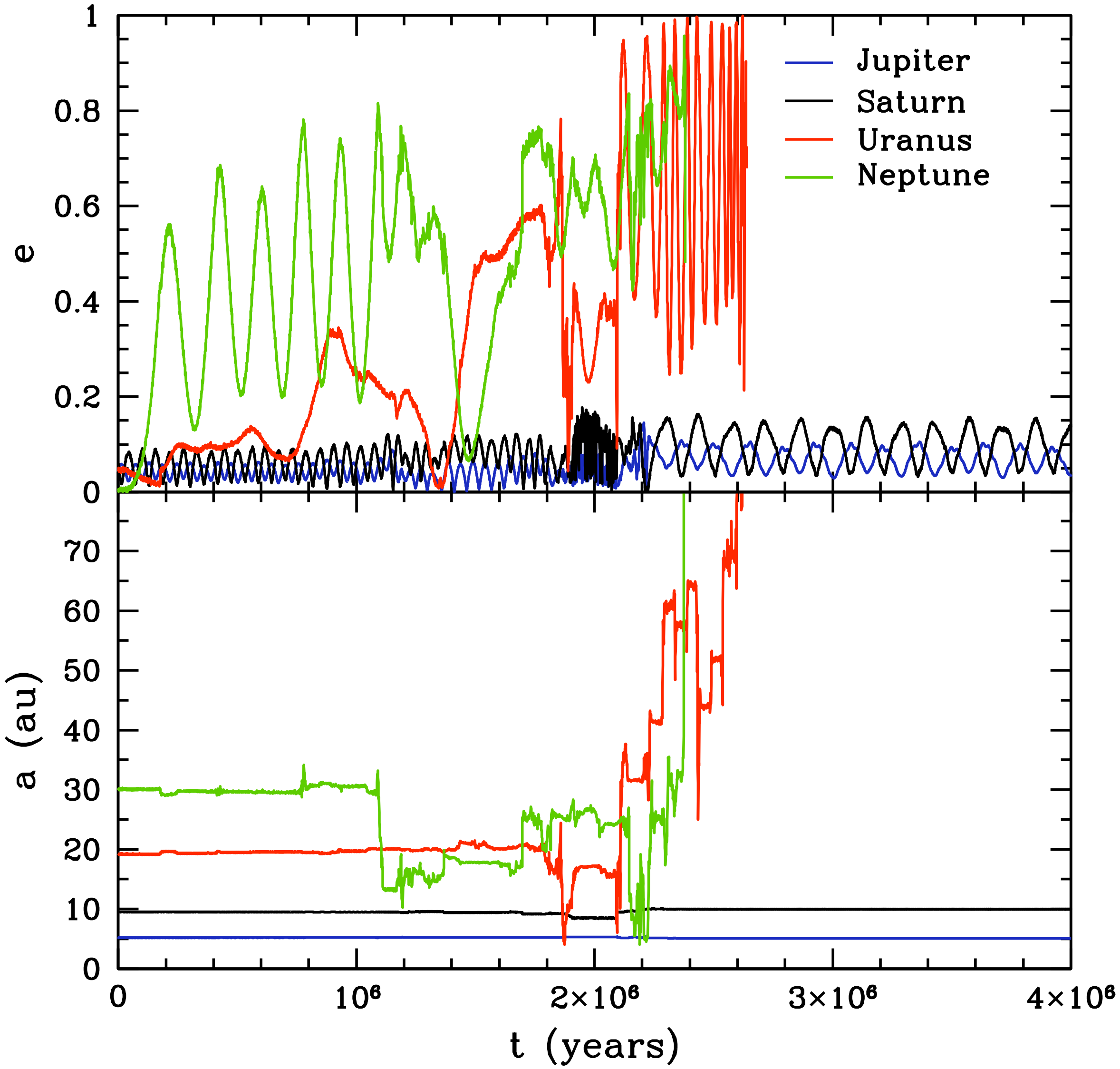
For high inclinations planets´ orbits may become extremely eccentric leading to tidal circularisation.

Evolution of a planet within a stellar binary



i=60 degrees

The four gas giants in a binary

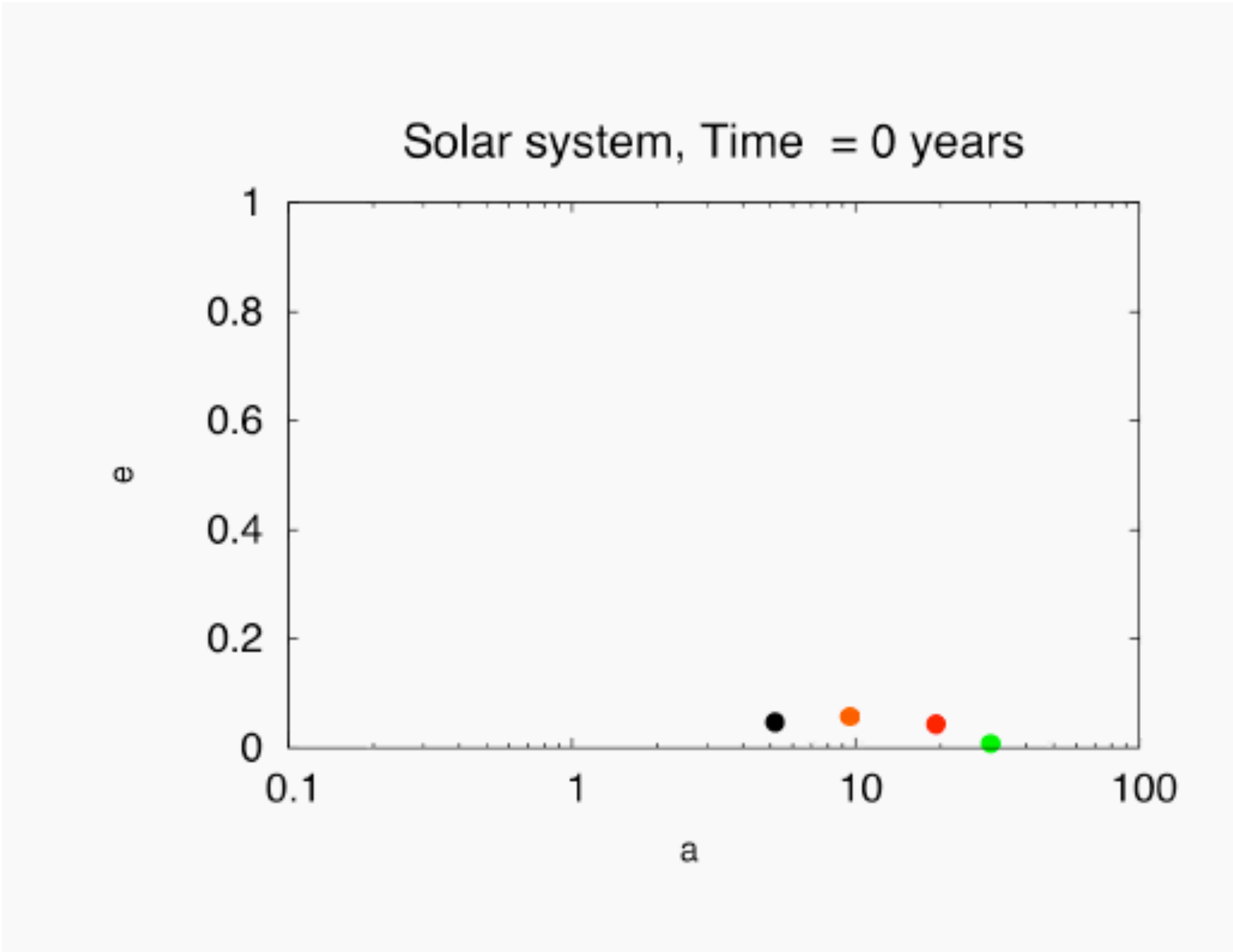


(Malmberg, Davies & Chambers, 2007; Malmberg & Davies 2009)

Evolution of our solar system in a binary

(Malmberg, Davies & Chambers, 2007;
Malmberg & Davies 2009)

Evolution of our solar system in a binary



(Malmberg, Davies & Chambers, 2007; Malmberg & Davies 2009)

The bottom line

Considering single, solar-mass stars with four gas giants in a cluster of 700 stars:

Fraction of stars losing at least one planet due to stellar binary companions ~0.05-0.20

Fraction of stars losing at least one planet in 100 million years due to fly-bys ~0.15-0.25

Numbers change only slowly with N, but depend on binary fraction, presence of gas, and speed of stars (see MDH2010, Bonnerot et al, in prep)

In other words: fly-bys and binary companions can make stable planetary systems unstable interestingly often.

Outstanding problems

Are planetary systems self-unstable?

Outcome of Kozai-ed planetary systems?

Does tidal capture via Kozai work?

What does solar-system-like mean?

Contribution to exoplanet population?

Conclusions

The solar system is chaotic but seemingly stable.

Other planetary systems can be born unstable to planet-planet interactions.

Planetary systems can be made unstable by close encounters with other stars or by exchanging into binaries.

Singletons are stars which are formed single and are never within binaries or have close encounters.