How stellar encounters affect planetary systems

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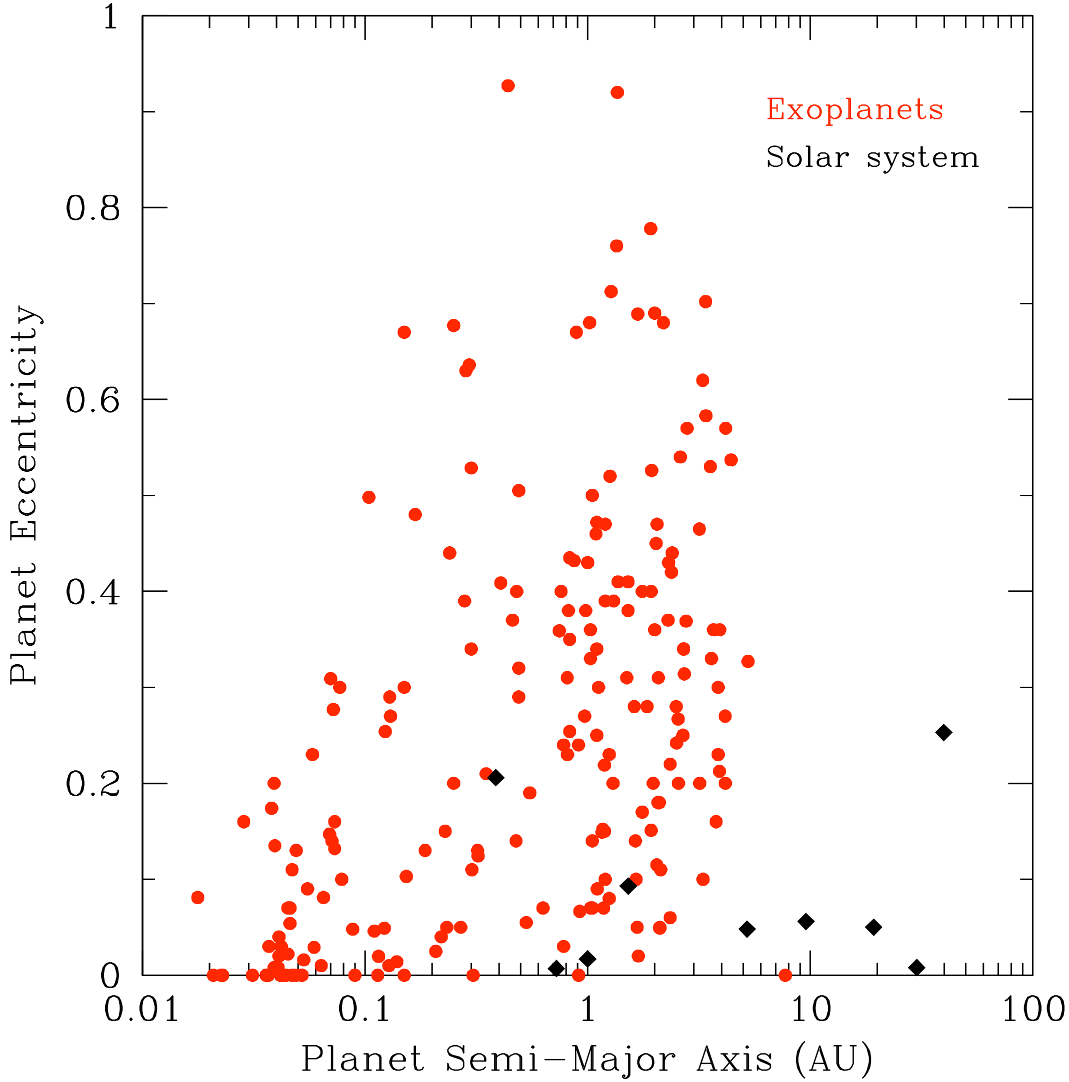
The solar system is not like the others.


Exoplanets
Solar system
Planet Eccentricity
Planet Semi−Major Axis (AU)
0
0.2
0.4
0.6
0.8
1
0.01
0.1
1
10
100

Three IDEAS:

1) Planets migrate within disk around star.

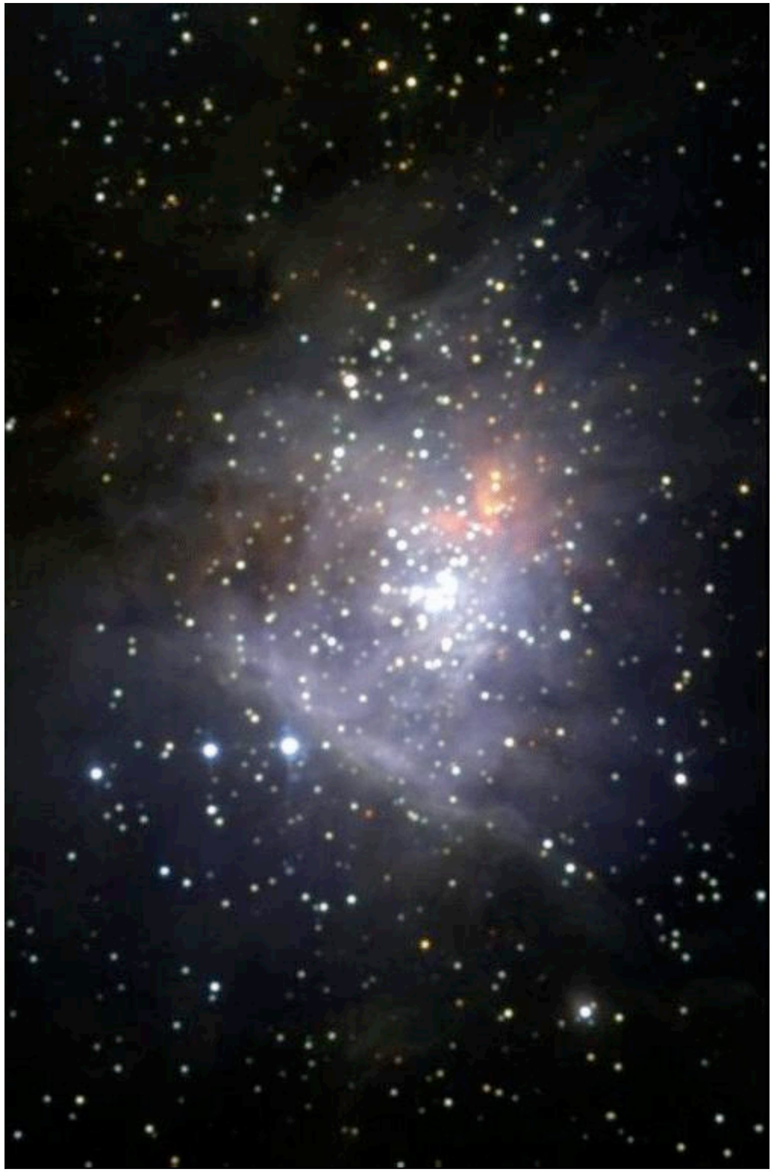
2) Planetary systems become unstable on their own *(self-unstable)*.

3) Something happens to (stable) planetary systems within young stellar clusters.

Explore third idea today:

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

Strong planet-planet interactions within planetary systems may follow.



Orion nebula and Trapezium cluster (2MASS image)

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

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

Simulate open cluster evolution

Evolve open clusters considering a range of sizes and masses.

Place some stars in binaries whilst others are initially single.

Trace stellar histories: count the number of stars which exchange into and out of binaries.

(Malmberg et al 2007b)

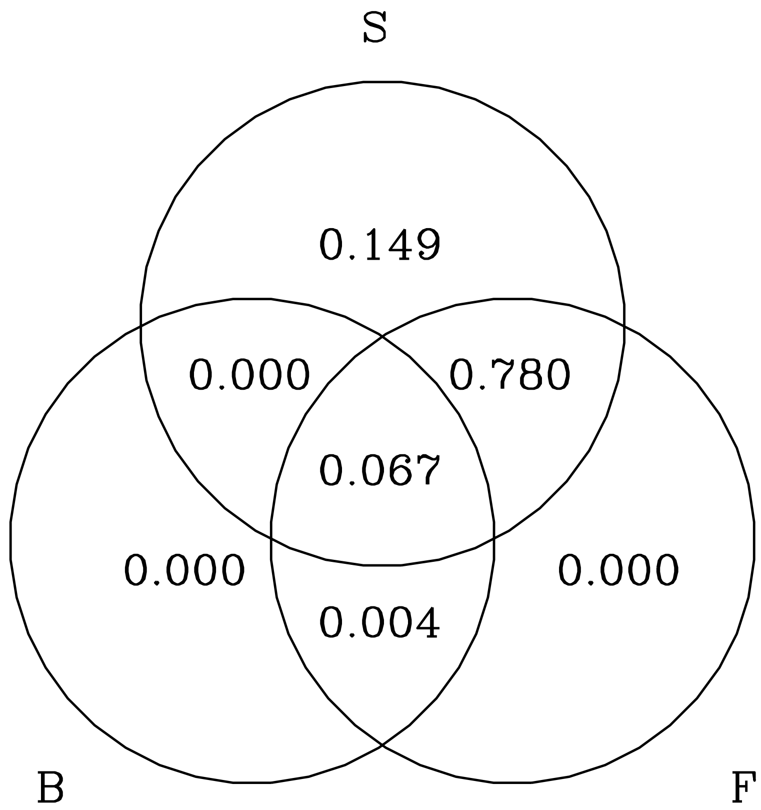
Singleton:

1) a star which has not formed in a binary,

2) a star which has not later spent time within a binary system,

3) a star which has not suffered close encounters with other stars.

How common are singletons?



N=700 stars, R=2-4 pc

(Malmberg et al 2007b)

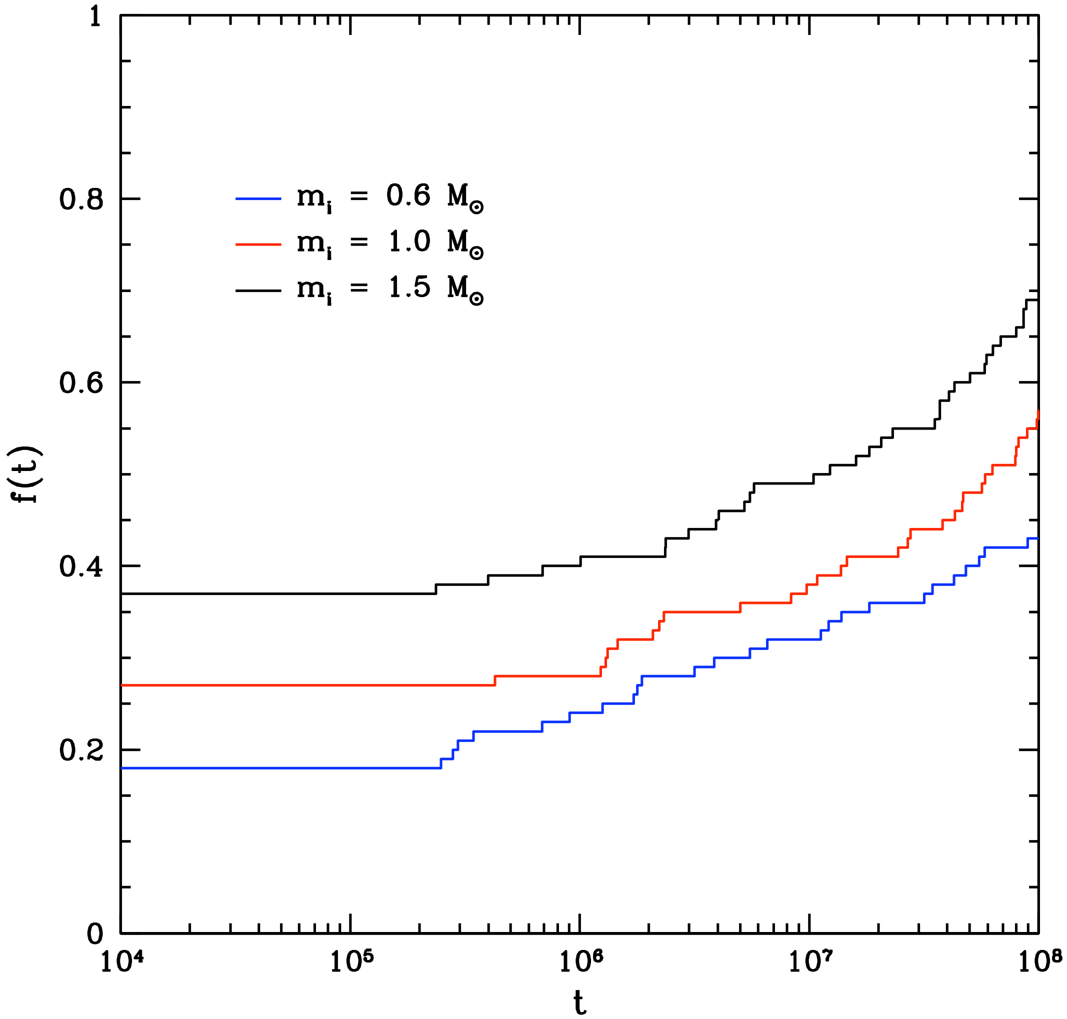
Effects of close encounters

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.

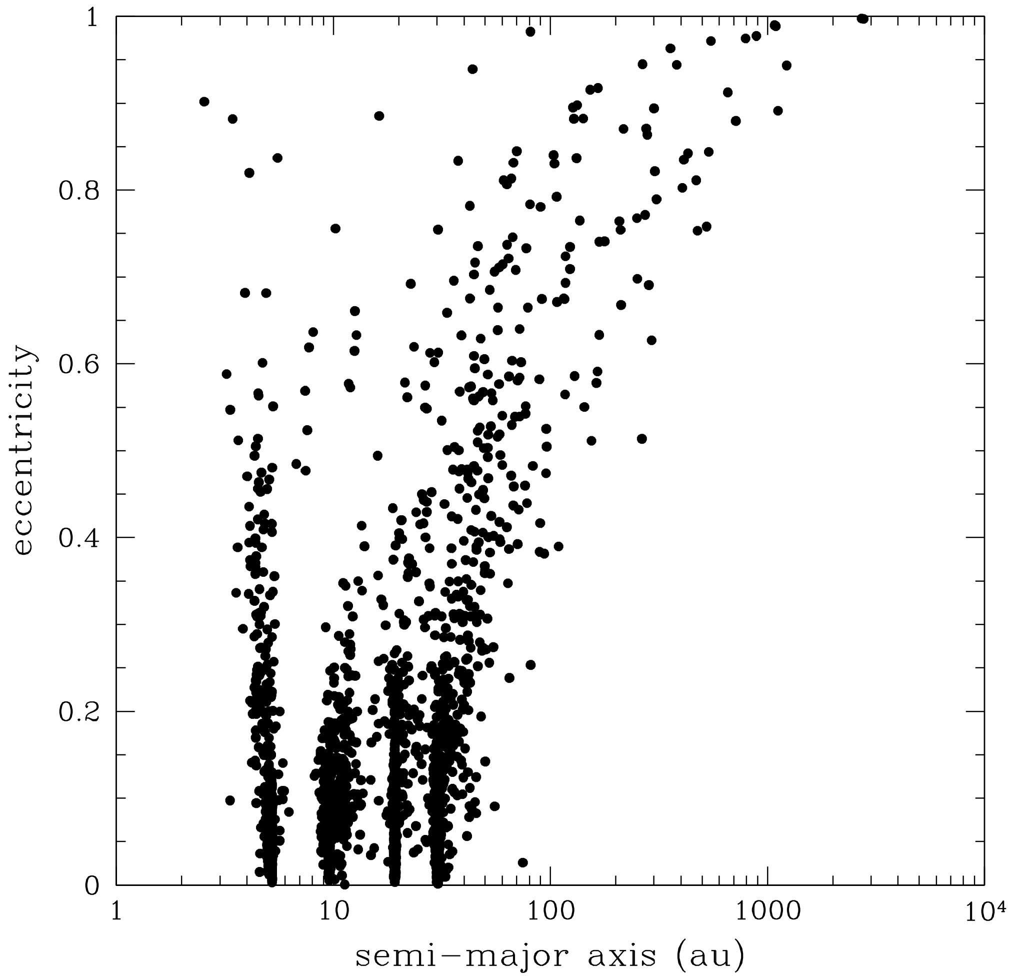
The long term effect of fly-bys (within 100 AU)



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, *in preparation*)

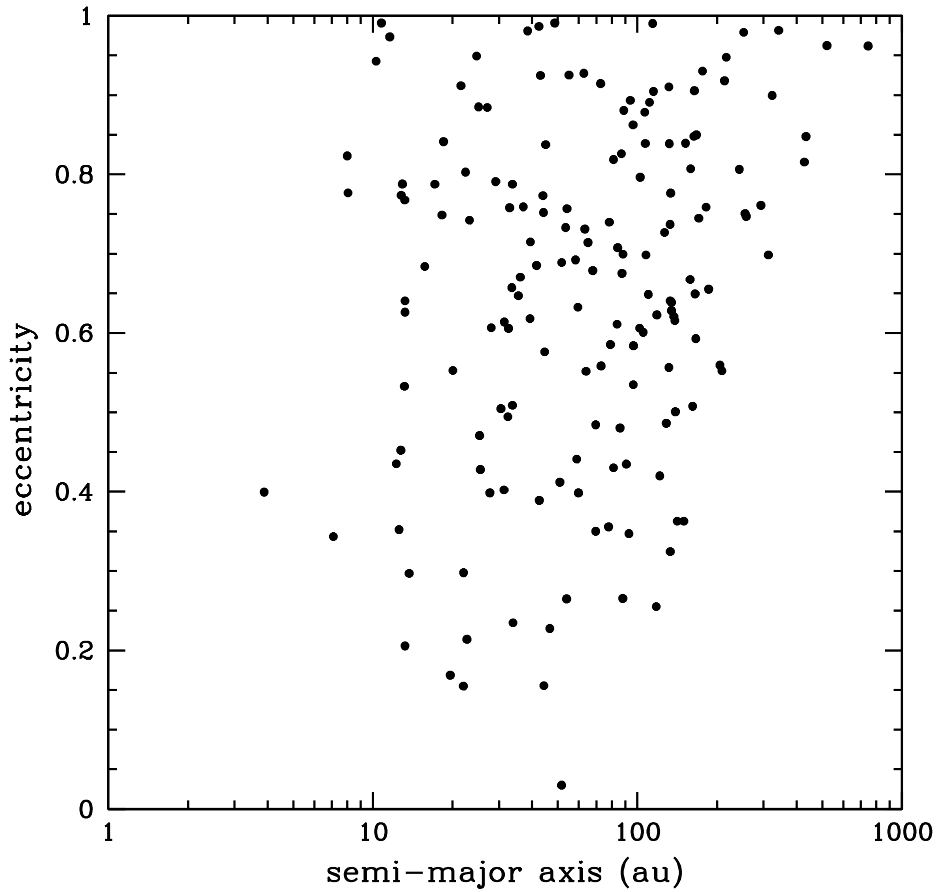
The four gas giants 10^8 years after fly-by (r_{Min} < 100 AU)



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, *in preparation*)

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



(Malmberg, Davies & Heggie, *in preparation*)

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.

Important point

Stars with planetary systems which exchange into binaries may later be single again.

For example binary may be broken up in an encounter with another (harder) binary.

The Kozai Mechanism

For low inclinations, see small oscillations in eccentricity only.

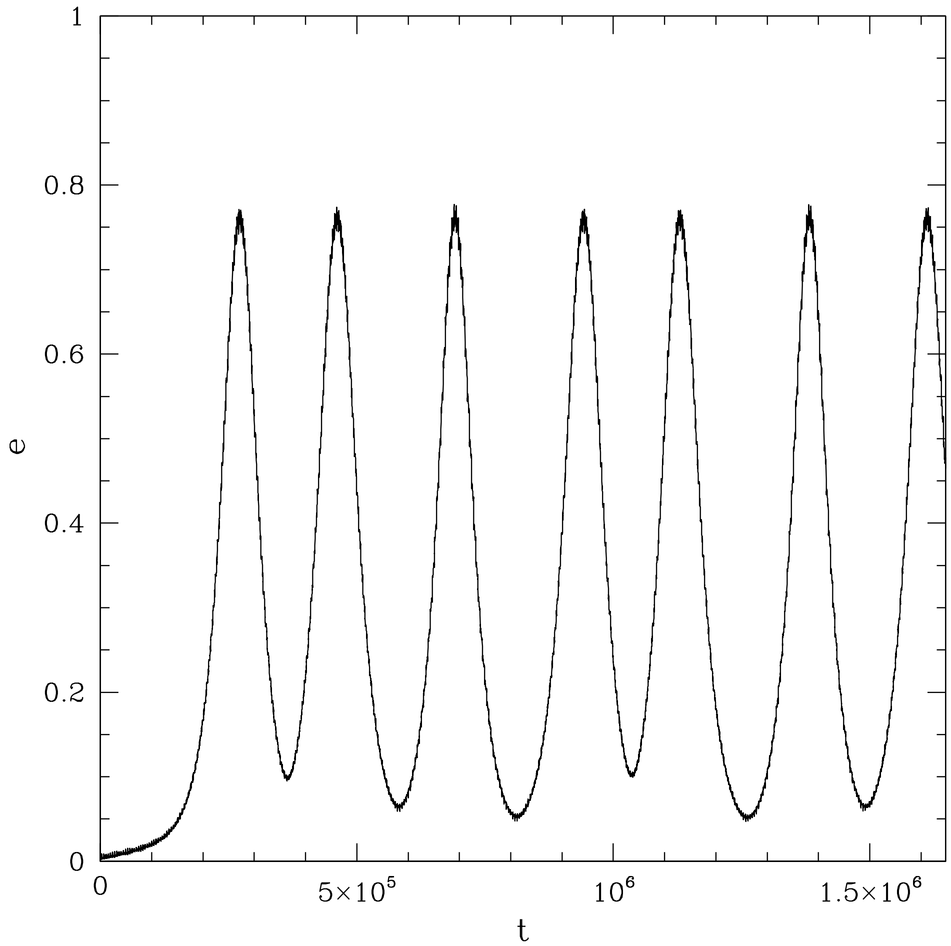
If $i_0 > i_c$ where $sin(i_c) = \sqrt{2/5}$

see oscillations in inclination between i_0 and i_c

$\sqrt{a(1-e^2)}cos(i)$ is constant

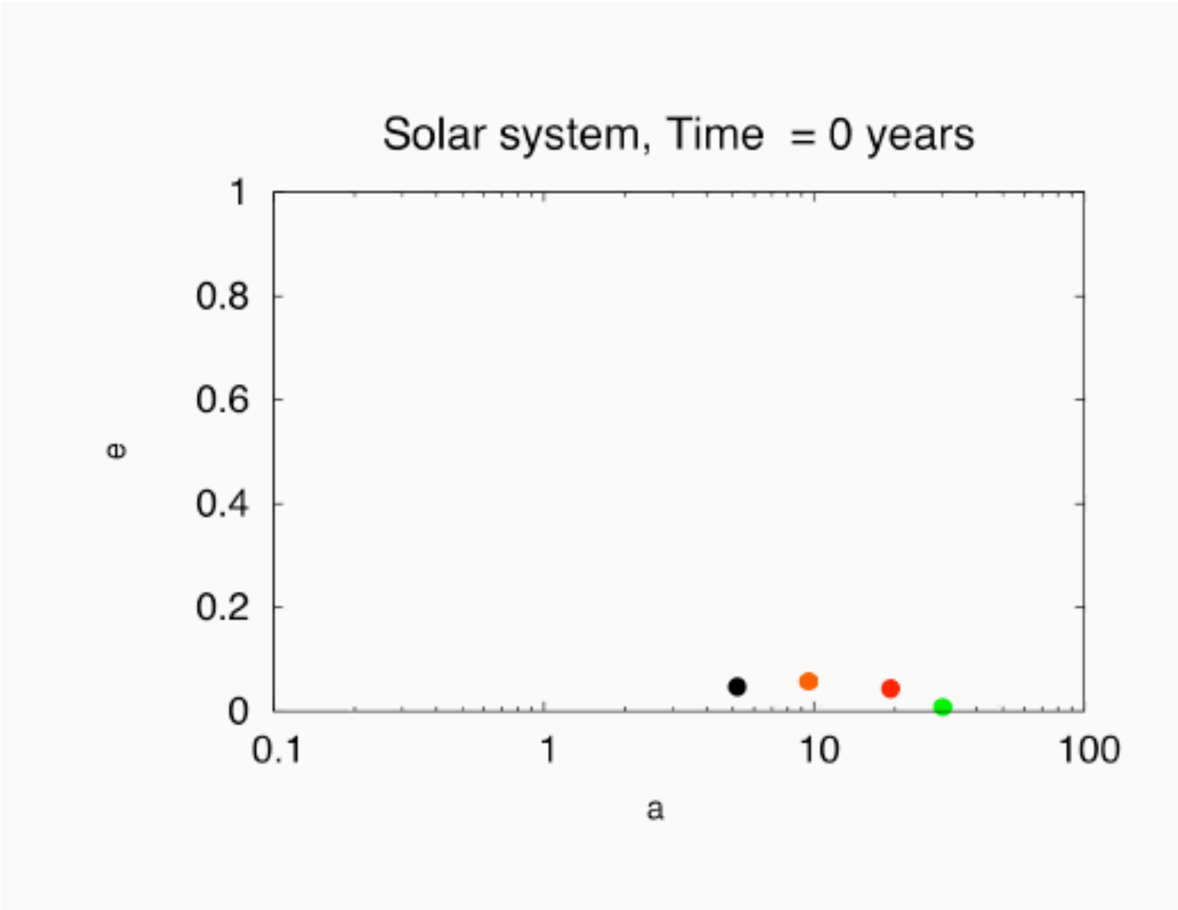
$$e_{max} = \sqrt{1 - 5/3cos^2(i_0)}$$

Evolution of a planet within a stellar binary



i=60 degrees

Evolution of our solar system in a binary



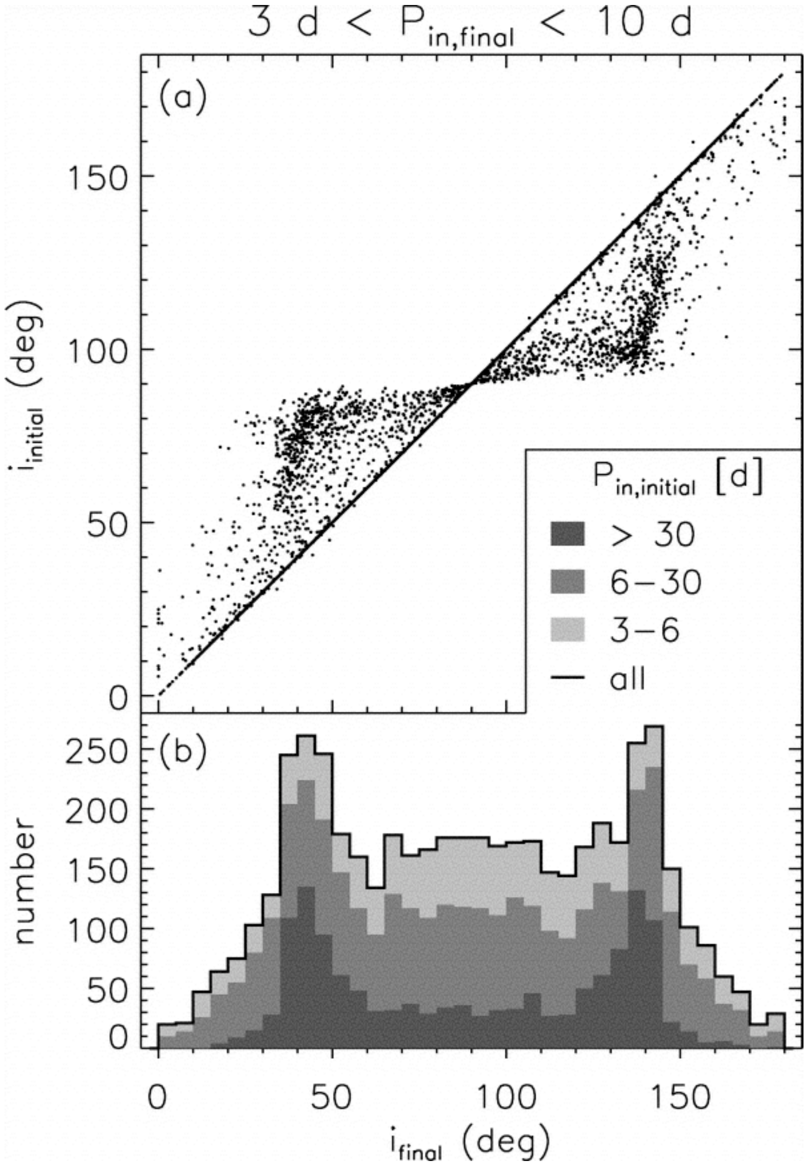
(Malmberg, Davies & Chambers, 2007;
Malmberg & Davies 2009)

Could the Kozai Mechanism produce hot jupiters?

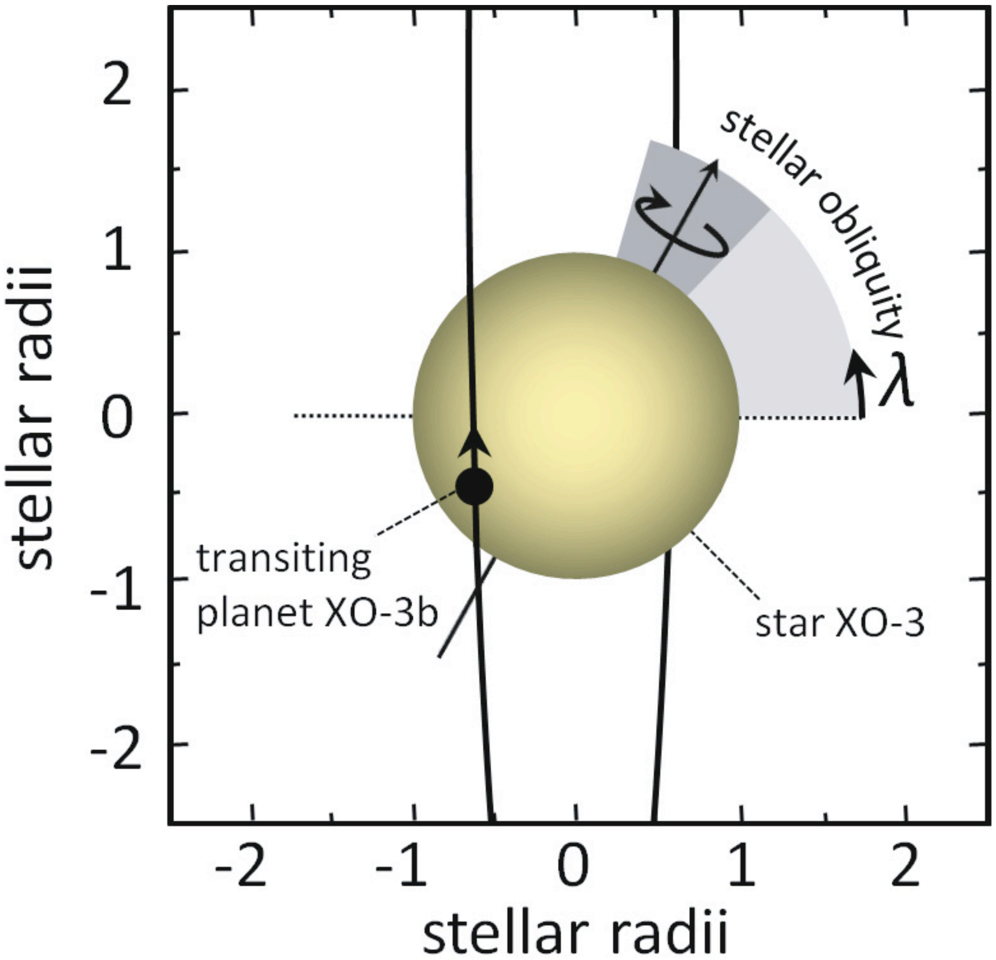
The idea is that Kozai produces extremely eccentric systems, which could undergo tidal interactions with the star, leaving the planet on a much tighter orbit.

Fabrycky & Tremaine (2007)

Wu, Murray & Ramsahi (2007)

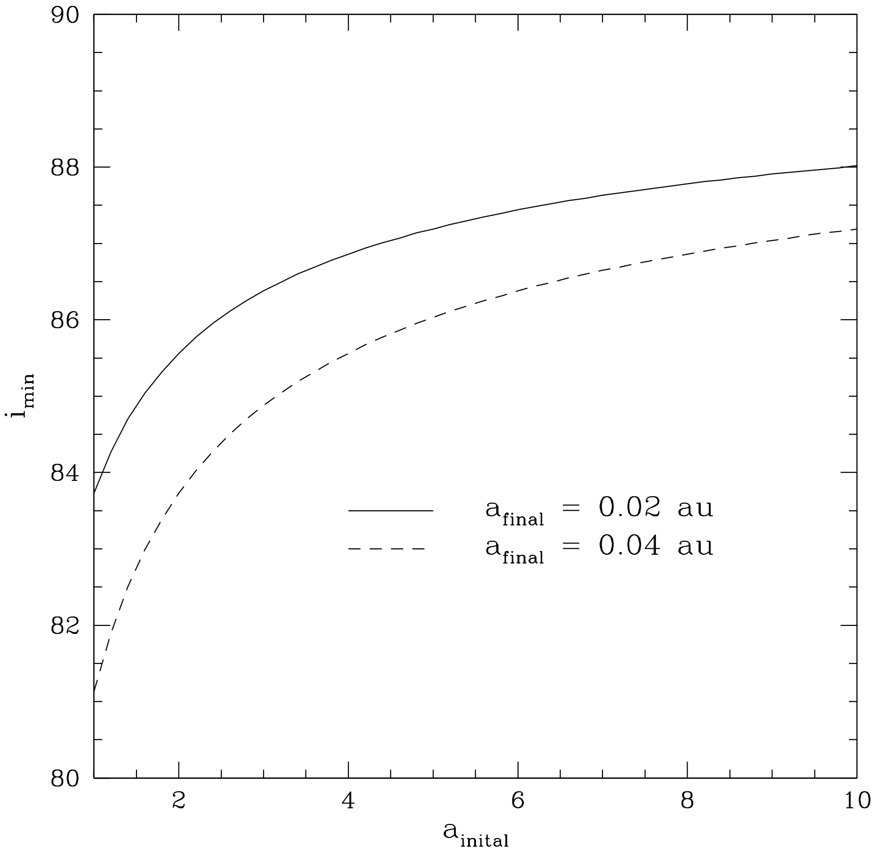


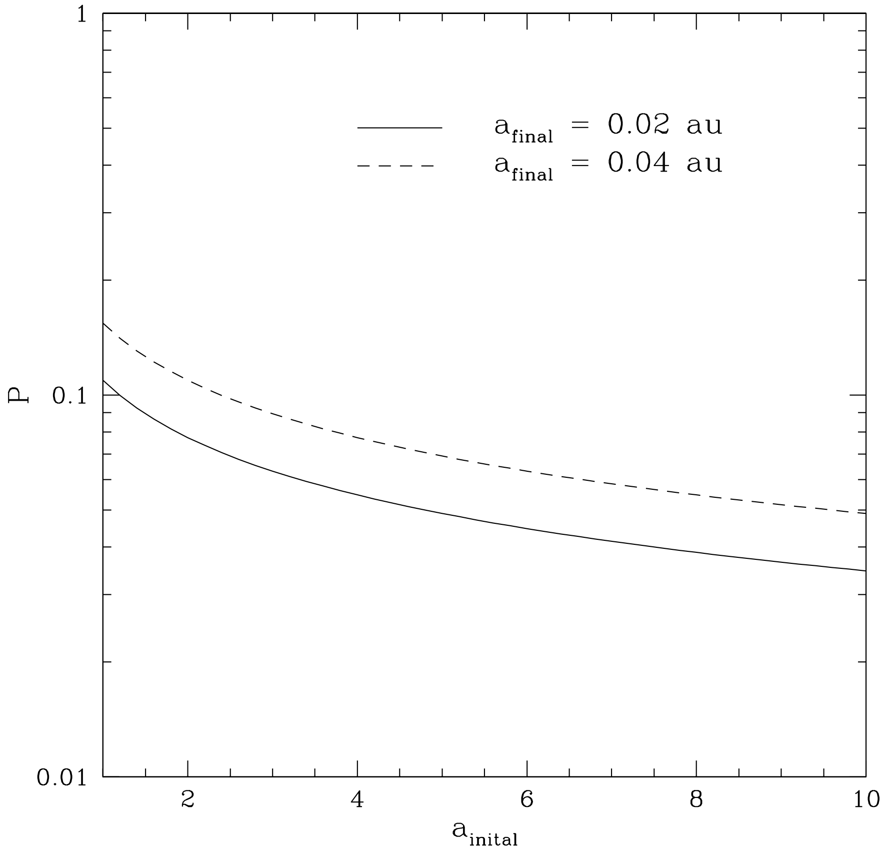
Fabrycky & Tremaine (2007)



(eg Hébrard et al 2008, Triaud et al 2010)

Inclination required and its probability





(Malmberg, Davies et al, in prep)

How common is Kozai-induced tidal capture?

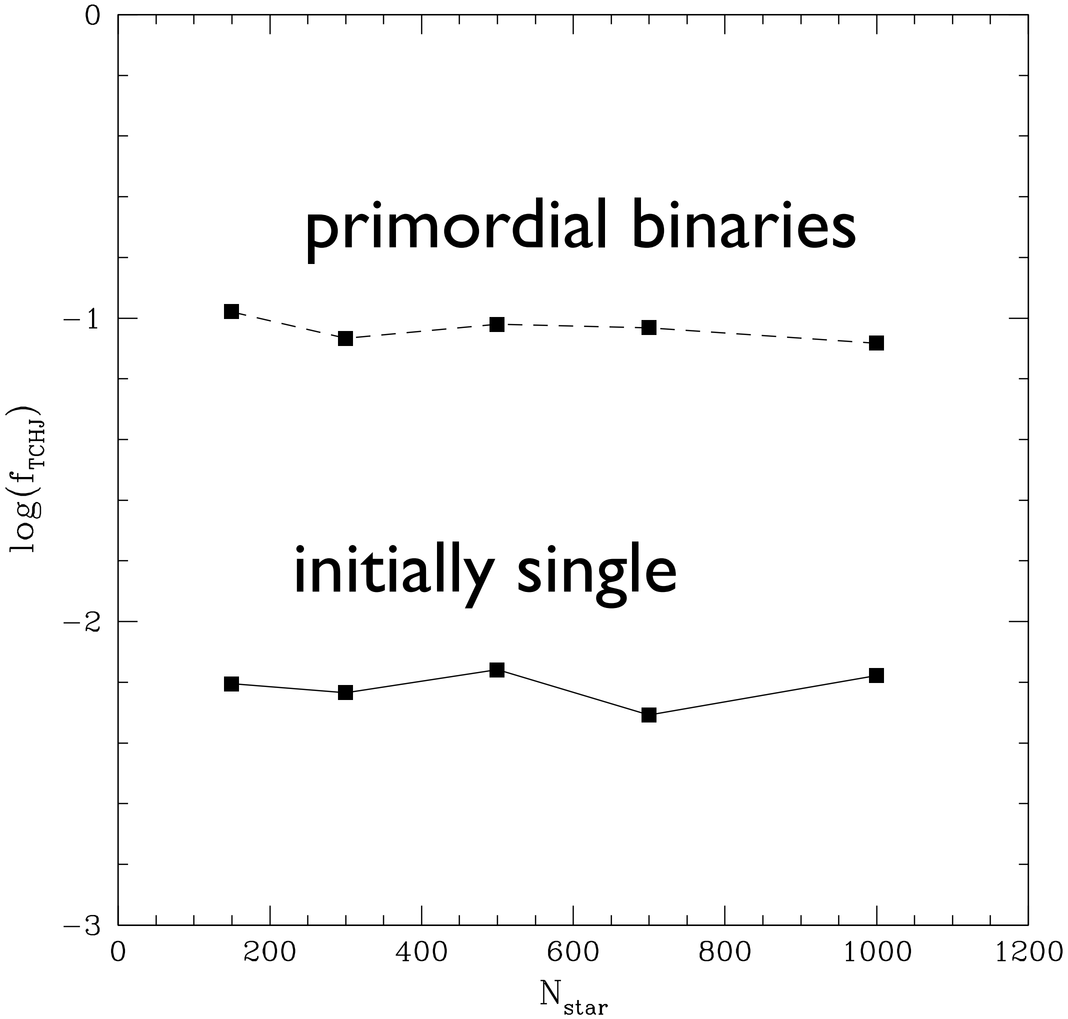
Want to produce hot jupiters in ~0.005 solar-like stars

Fraction of random binary orientations which lead to tidal capture for planet at 5 AU ~0.05

But some stars in many binaries/orientations

Probably need to consider primordial binaries as well as initially-single stars to get reasonable rates

Potential fraction of stars with hot jupiters



(Malmberg, Davies et al, in prep)

What are the effects of encounters?

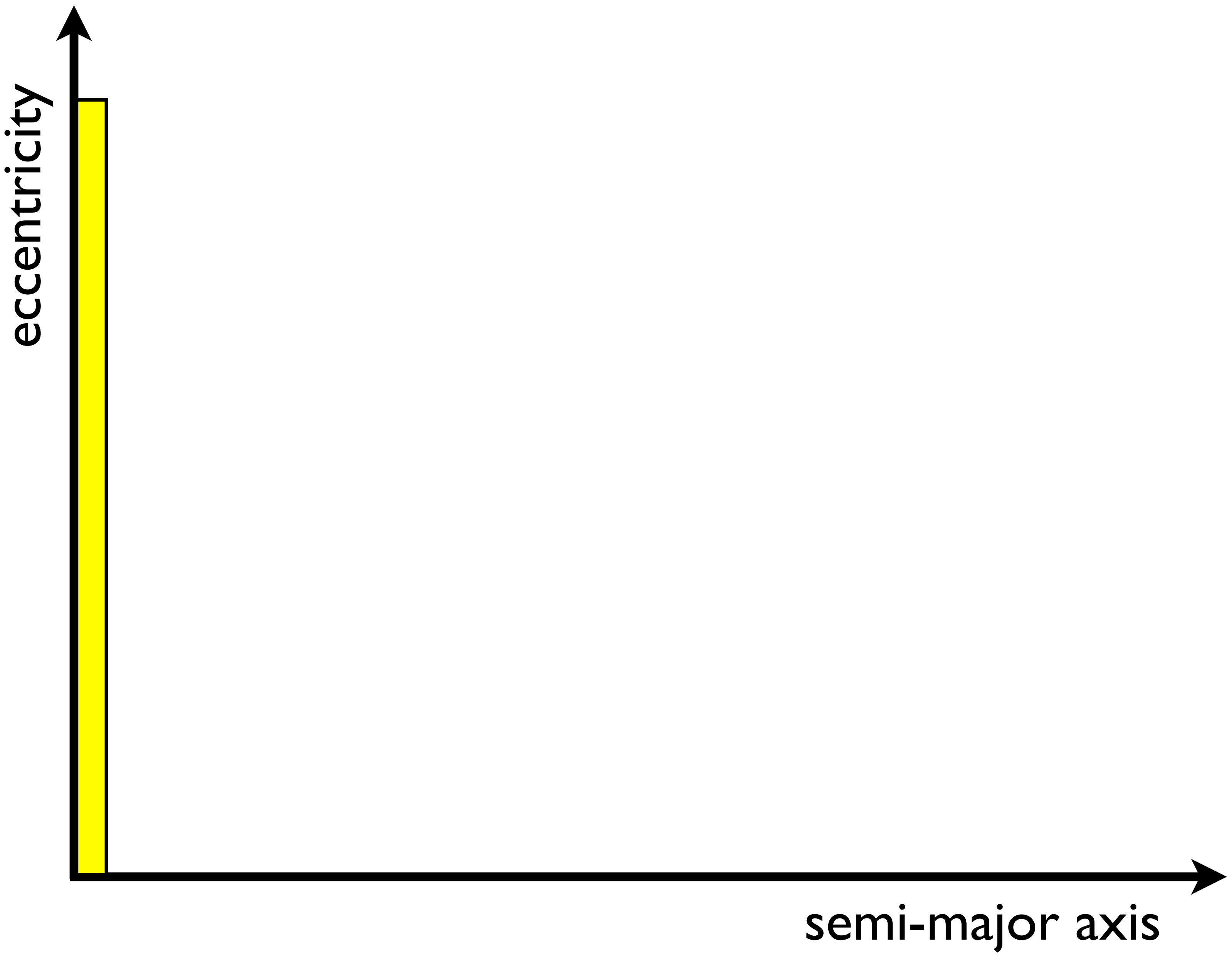
Considering single, solar-mass stars with four gas giants in a cluster of 700 stars:

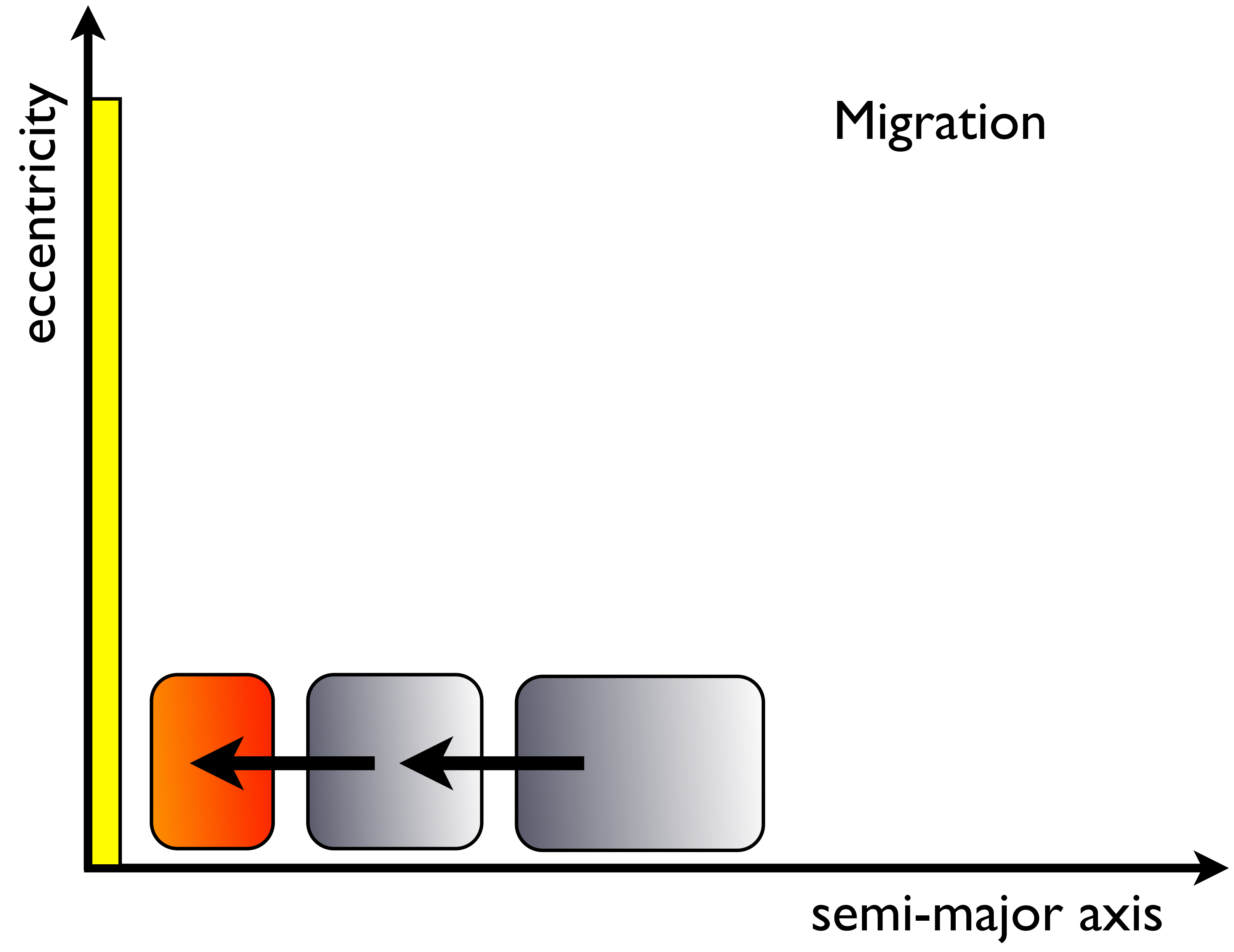
Fraction of stars losing at least one planet due to stellar binary companions ~0.05

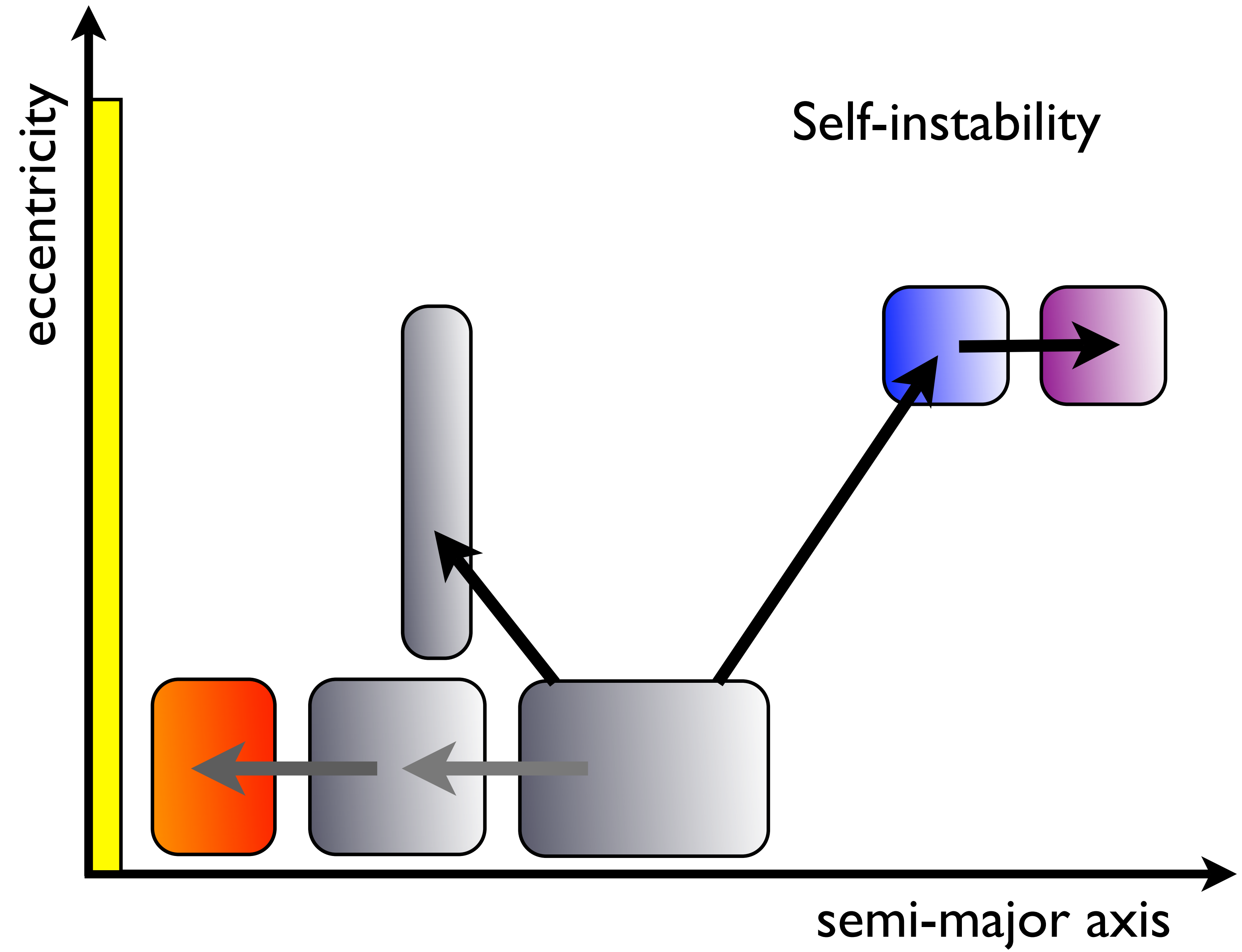
Fraction of stars losing at least one planet in 100 million years due to fly-bys ~0.15

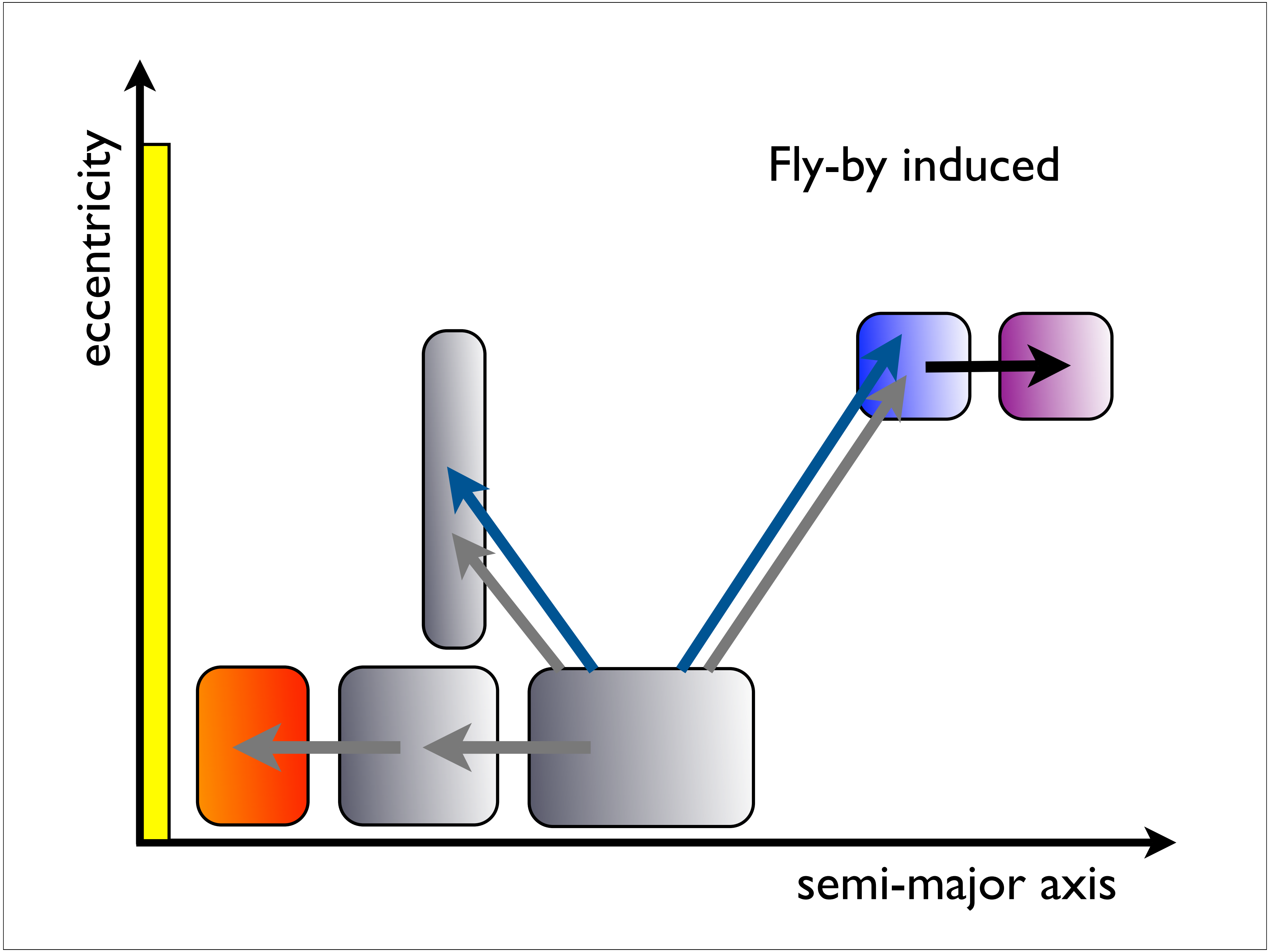
In other words: fly-bys and binary companions can make stable planetary systems unstable

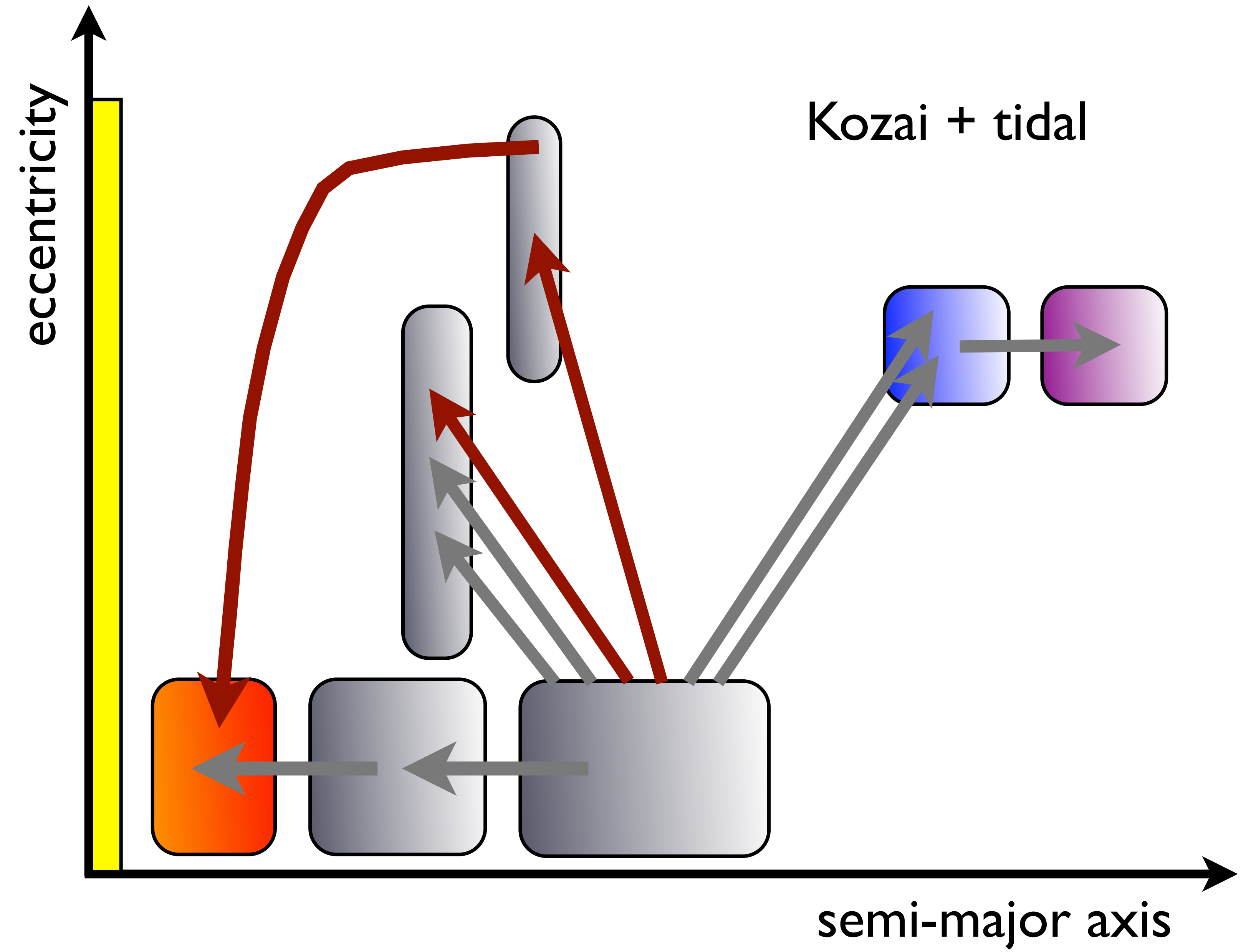
The Big Picture

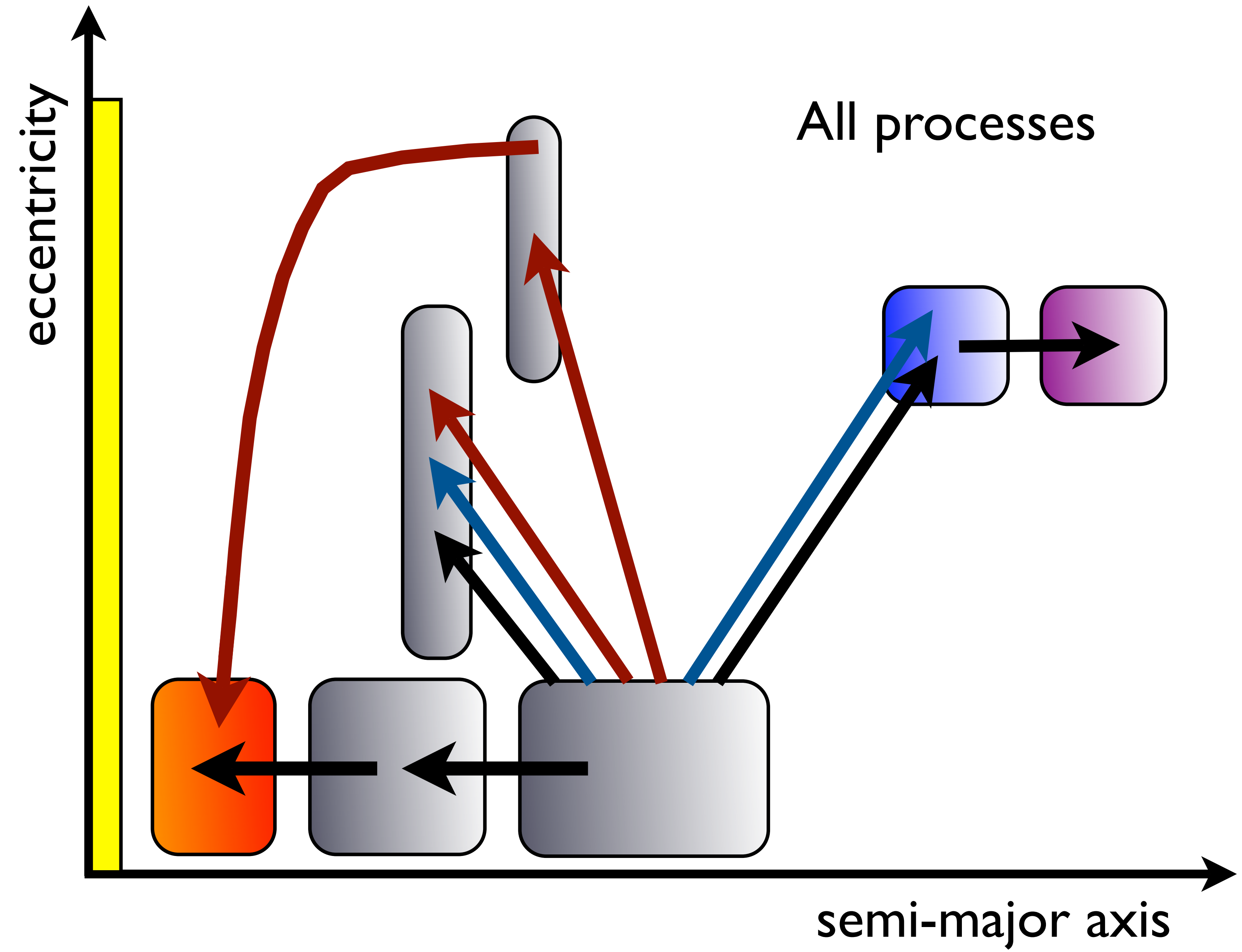

eccentricity
semi-major axis


Migration
eccentricity
semi-major axis


Self-instability
eccentricity
semi-major axis


Fly-by induced
eccentricity
semi-major axis


Kozai + tidal
eccentricity
semi-major axis


All processes
eccentricity
semi-major axis