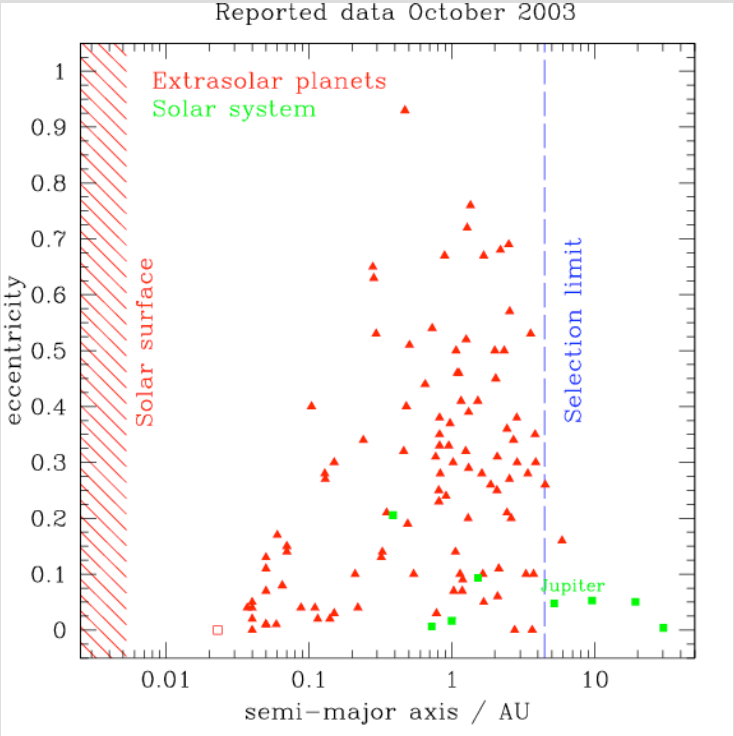
Properties of extrasolar planets

Two aspects of the orbital properties of extrasolar planets differ from those of Solar System planets and are unexpected based on simple theory of planet formation:



Existence of hot Jupiters

Expected giant planets to form outside the snow line where there was a larger density of rock / ice to allow rapid planet formation.

Frequently non-circular orbits

Expected close to circular orbits since planets form out of disks that have circular orbits.

Migration

Most popular explanation for the existence of hot Jupiters is **orbital migration**:

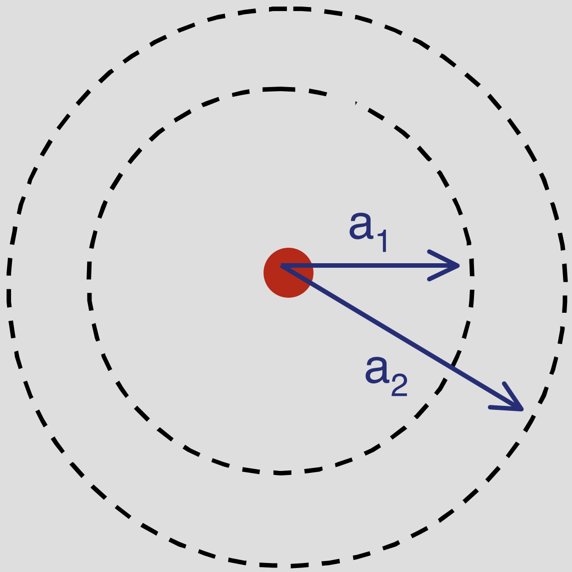
- Giant planets **form** at large radii within the protoplanetary disk (several au)
- Lose energy and angular momentum
- **Migrate** to present orbits closer to the star

Suggested mechanisms for orbital migration:

Gravitational scattering of other planets or planetesimals in an initially unstable planetary system

Gravitational interactions of a single planet with the protoplanetary disk soon after planet formation

How might gravitational scattering work in practice



Form two or more planets in orbits that are too close to be stable over long time scales.

How close is too close? Define quantity Δ:

$$\Delta = 2.4\left(\frac{m_1}{M_*} + \frac{m_2}{M_*}\right)^{1/3}$$

If: $a_2 > a_1(1+\Delta)$ …the system will be stable

Otherwise, the system will often be unstable. Note: for two Jupiter mass planets Δ = 0.3, so planets have to be close together for instability.

No known results for 3 or more planets…

When instability occurs:

- Planets evolve until orbits cross
- Close encounters lead to:

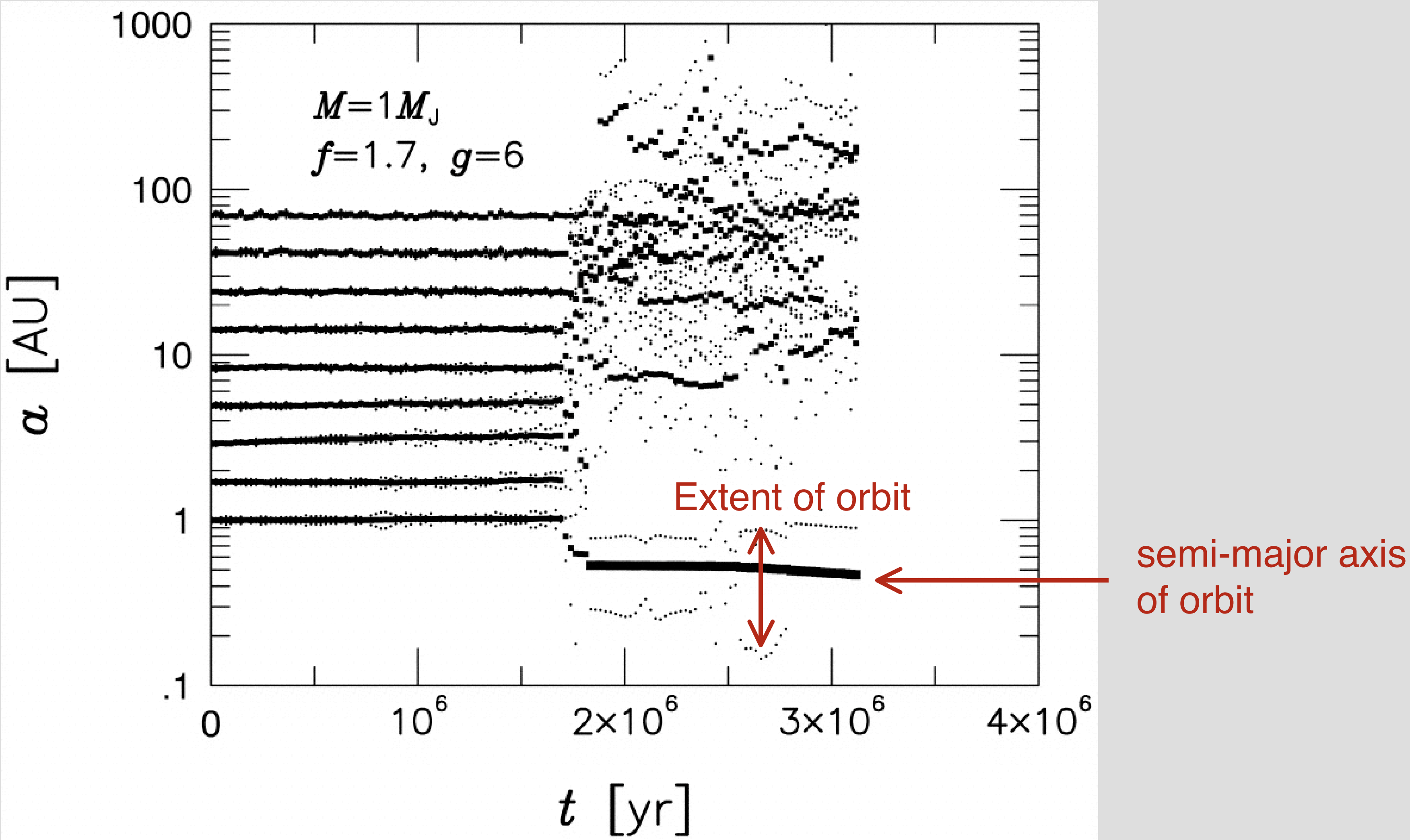
  (i) Migration of some planets to larger radii, or ejection from whole system

  (ii) Survivors move to closer orbits to conserve energy and angular momentum

  (iii) Develop significantly eccentric orbits

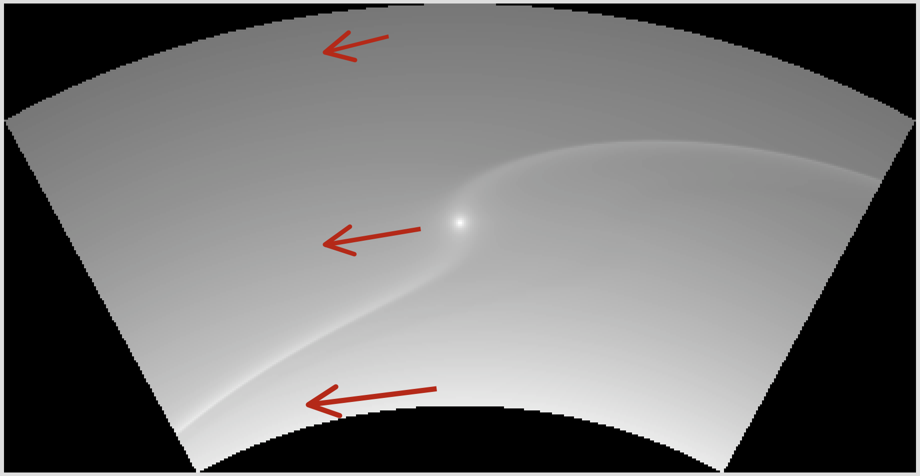
As a consequence of the interactions, system becomes more stable, eventually reaches a state that can survive for Gyr until observed epoch…

Mechanism yields eccentric planets, but only modest amount of inward radial migration toward the star



Lin & Ida (1997)

Planet - disk interactions



Planet embedded within the protoplanetary disk exerts a gravitational force on the gas: forms a spiral wave pattern in the gas

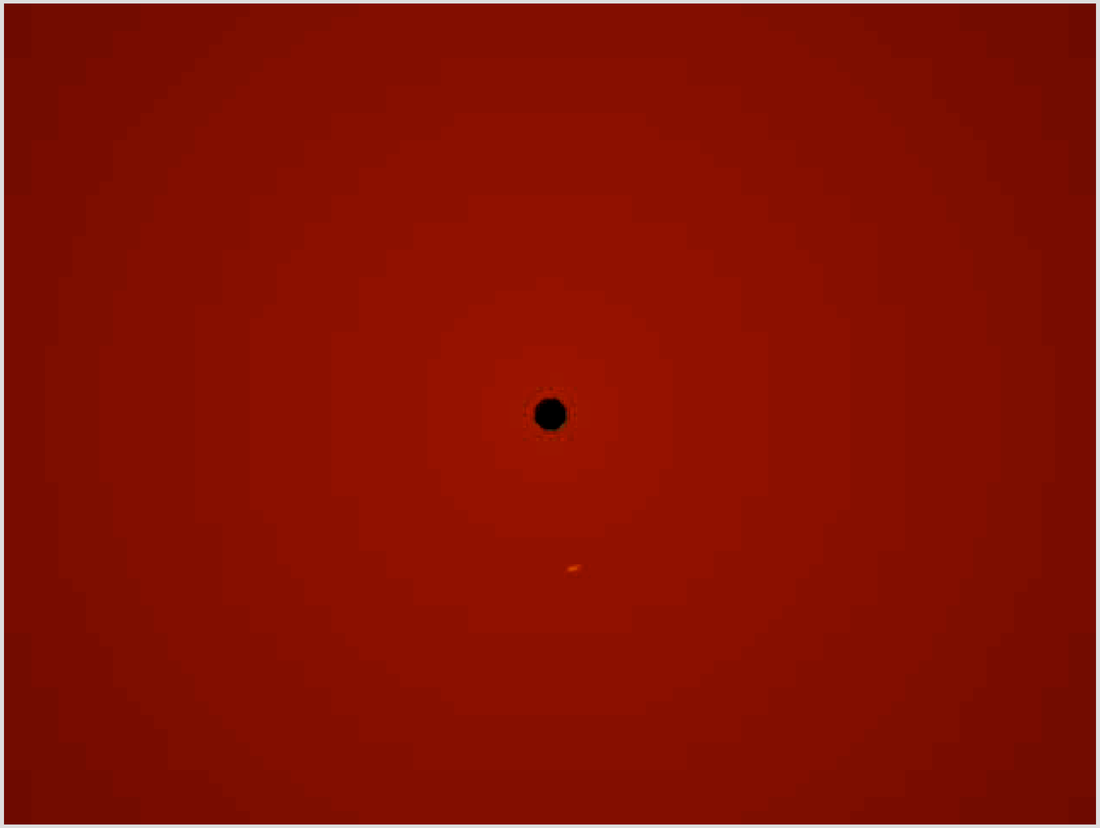
Interaction with gas inside location of planet:

- angular momentum is transferred to planet
- gas is decelerated - tends to `fall' to smaller radii

Interaction with gas outside orbit of planet:

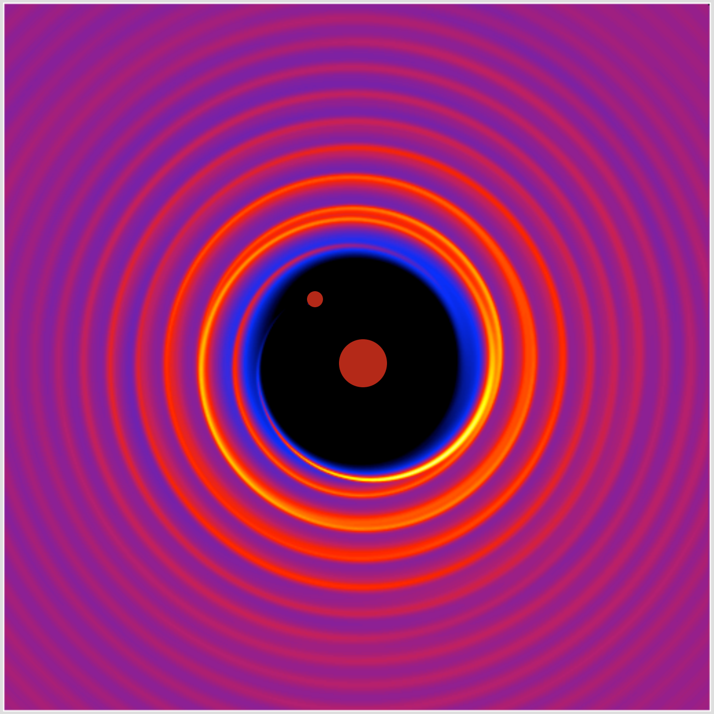
- planet loses angular momentum
- gas gains angular momentum, moves to larger radii

For a massive enough planet, interaction is strong enough to open a **gap** in the protoplanetary disk - annular region where the surface density of gas is very small:



Disk viewed from above, color indicates surface density of gas in the disk

How does this lead to orbital migration?



Once gap has been formed, planet acts as a dam in the disk, gas can only flow inward onto the star by first pushing the planet to smaller orbital radii.

Gravitational forces transfer the planet's angular momentum to the disk material at larger radii.

Ultimately, planet may end up being swallowed by the star, or may stop migrating when the disk is dispersed and survive at very small orbital radius as a hot Jupiter.