Planetary System Stability and Evolution

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(Lots of help from Eric Ford, Florida and Robert Vanderbei, Princeton)

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Motivation

- Understand Formation of Planetary Systems
  - How can extrasolar planet observations provide clues to the physics of planet formation?
  - Do observations of planetary systems today reflect the outcome of planet formation?
  - Or have they evolved since ~100 Myr?
- Are planetary systems like our own common/rare?
  - Are Giant Planets in circular orbits at 5 AU common?
  - Are Terrestrial/Habitable Planets common?
- Rapid & dramatic increase in observational data

Artwork courtesy of Sylwia Walerys

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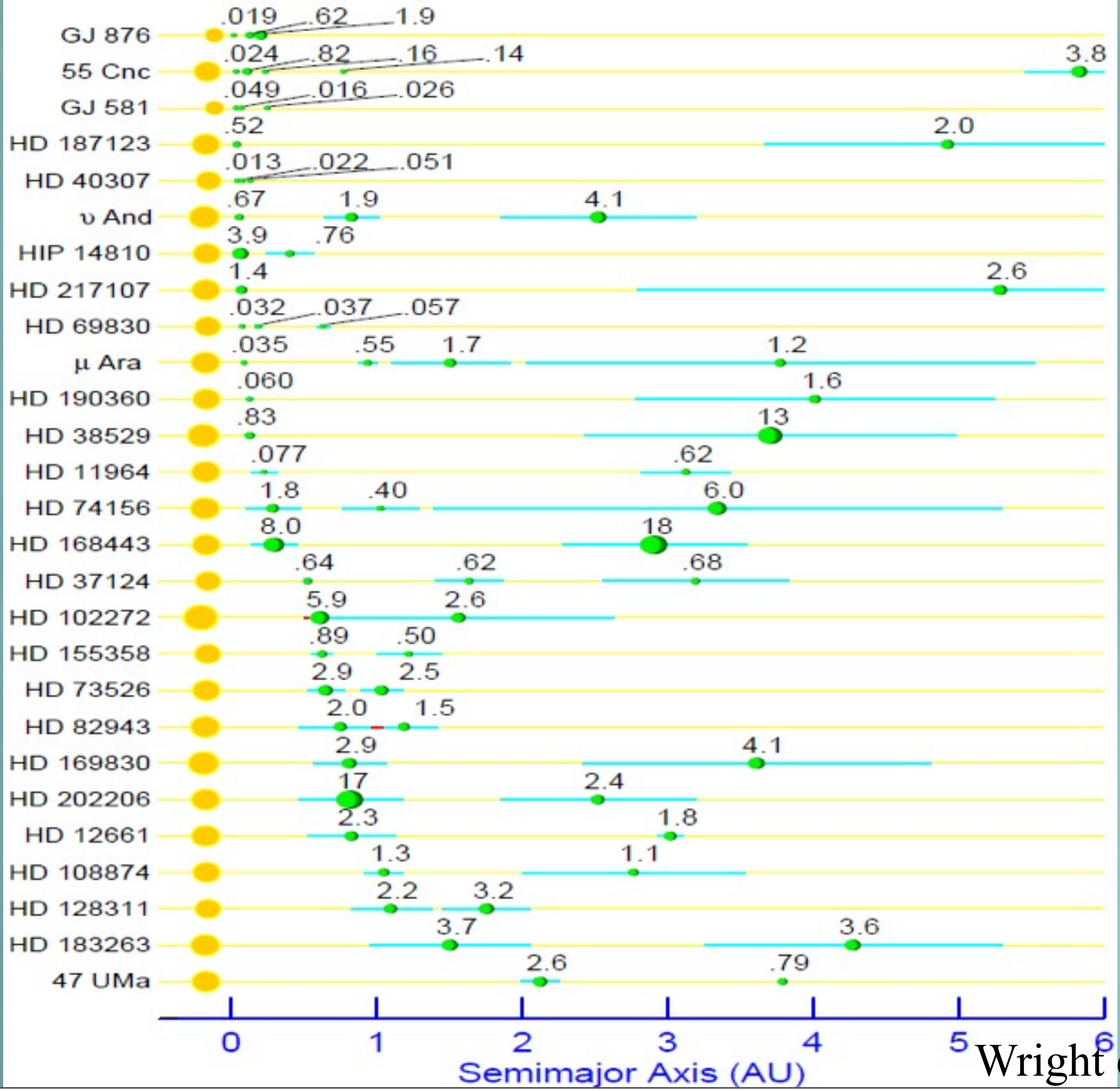
Multi-Planet Systems



Wright et al. (2008)

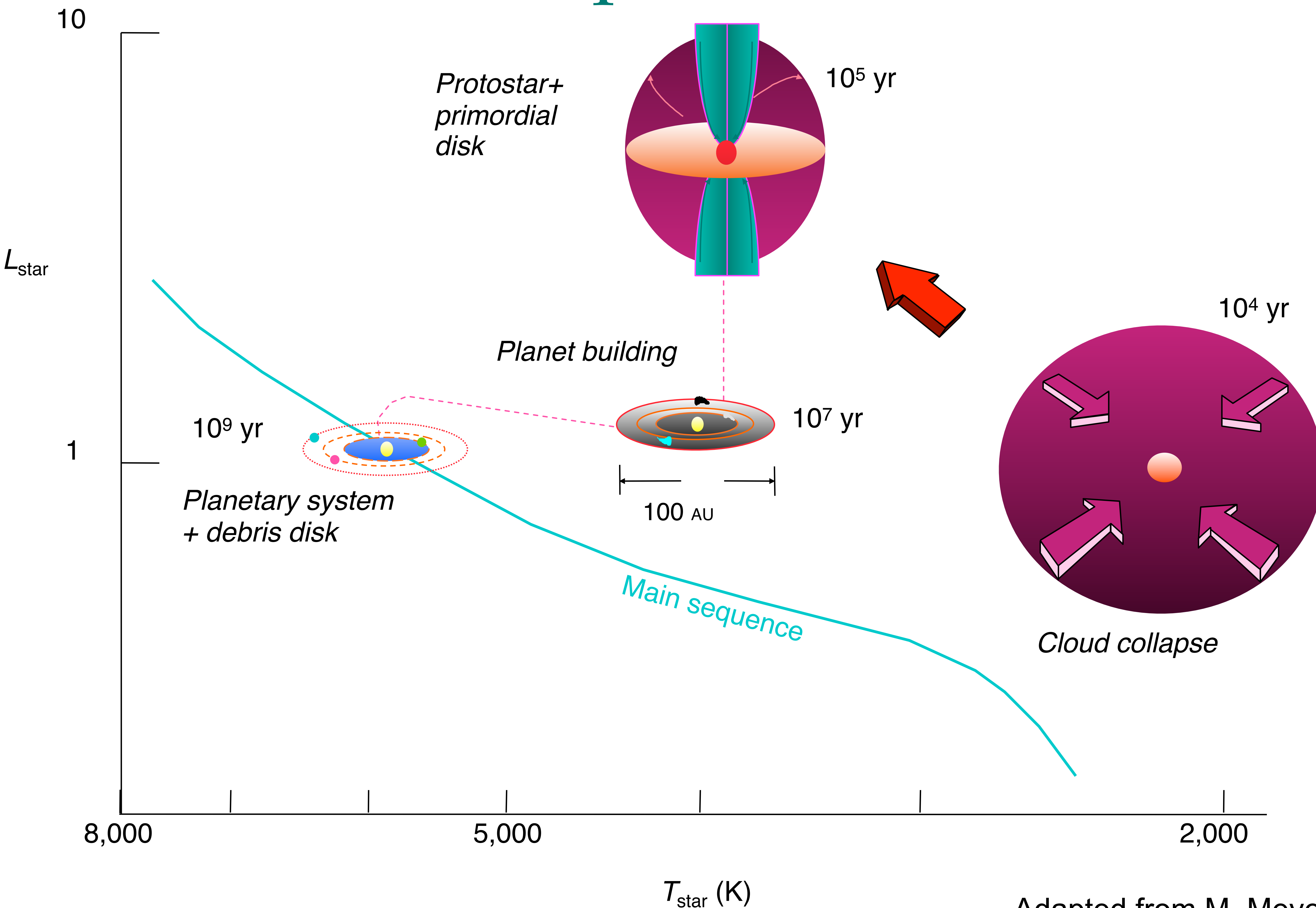
Chas told you about Early Stage evolution (disks and planetesimals).

This discussion focuses on Late Stage evolution.

Def.: The *Late Stage* of a planetary system is defined as the time after which it becomes *Hamiltonian*. The dynamical evolution is determined entirely by gravity.

Bottom Line: We can and should expect to see complex non-Keplerian motion of multi-planet systems. Even our solar system has measurable deviations!

Pre-main Sequence Evolution



Adapted from M. Meyer

Three Hypotheses for System Formation

- Brown Dwarf Hypothesis
- The Nebular Hypothesis (gravitational instability)
- Core Accretion Hypothesis

Stages of Planet Formation by Core Accretion

$1\ \mu m$

- **From dust (~μm-cm) to pebbles (~cm)**

Myriads of microscopic dust particles merging together
Motion of solid objects is strongly coupled to gas

- **From pebbles to boulders (~10m)**

$1\ km$

Many bodies, rapid growth (<100yr), but how?
Motion of solid objects is weakly coupled to gas

- **From boulders to planetesimals (>10km)**

Orderly growth through collisions, mergers, & fragmentation

- **From planetesimals to embryos (~1000km, Moon-sized)**

Runaway growth of a small number of separated embryos

$10^3\ km$

- **From embryos to terrestrial planet cores (part 1)**

Gravitational interactions stir and reduce gravity focusing
Oligarchic growth up to isolation mass ($0.1\text{-}10M_{Earth}$)

- **From embryos to terrestrial planet cores (part 2)**

Weak gravitational perturbations cause their orbits to cross leading to chaotic growth via giant impacts or ejections.

$10^4\ km$

- **Possible accretion of gas and transition to gas giants**

Adapted from R. Rafikov

Two Questions (its only 15 minutes):

How do planetary systems evolve in the Late Stage?

Don’t know ??

Are planetary systems stable?

What do you mean?

Planetary System Stability

Two types: True dynamic instability (ejection) and chaos.
Depends upon initial conditions, *which we don't know!*

Since systems are Hamiltonian, if they are in bounded orbits, they must be long term stable and can be regular or chaotic. However, chaotic trajectories can seem bounded for long periods and still be dynamically unstable.

Best we can do is ask whether a quasi-periodic planetary system stays quasi-periodic (i.e., stays close to its initial conditions) over lifetimes of the solar system.

Answer: It depends. (There is no general solution!)

Need lots of numerical integrations and observations!
Must be symplectic!

Most formation models require ejection of large planets at start of Late Stage, so systems are likely to be dynamically unstable, but not necessarily so.

One or more chaotic phases are likely for migration of gas giants, otherwise, for instance, Neptune and Uranus couldn't form.

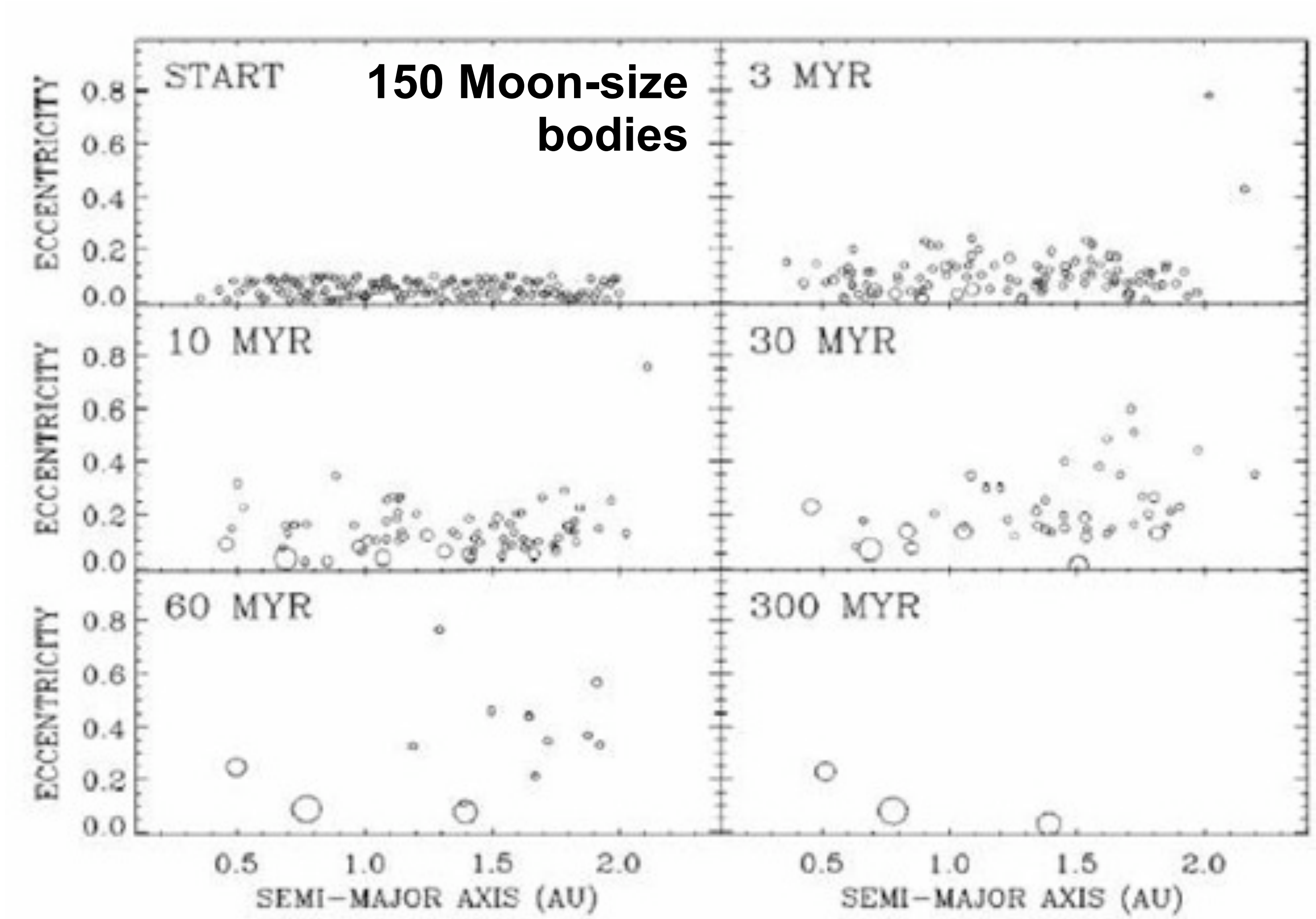
Scattering is needed to form Kuiper belt. Perhaps due to many mean motion resonances.

Some Questions: How are eccentricities excited? What is migration mechanism? How are eccentricities later damped? Do <u>mean motion resonances</u> provide an answer?

From Moon-size embryos to fully-grown planets

- **Spatially widely separated embryos gravitationally excite each other into crossing orbits**

- **Bigger bodies form in catastrophic collisions in about 10^8 years in the inner Solar System**



Chambers 2001

Evidence:

- Earth-Moon system: giant impact about 30 million yrs after Earth formed.

- Planetary obliquities

??? Final dynamical state?

Adapted from R. Rafikov

Violence in the Solar System

- Mercury large density
- Mars-sized Earth-impactor created the Moon
- Giant planet's irregular satellites
- Saturn's large ring system
- Uranus's obliquity
- Neptune's retrograde moon Triton
- Excitation of Kuiper Belt

Diversity of Possible Planetary Systems

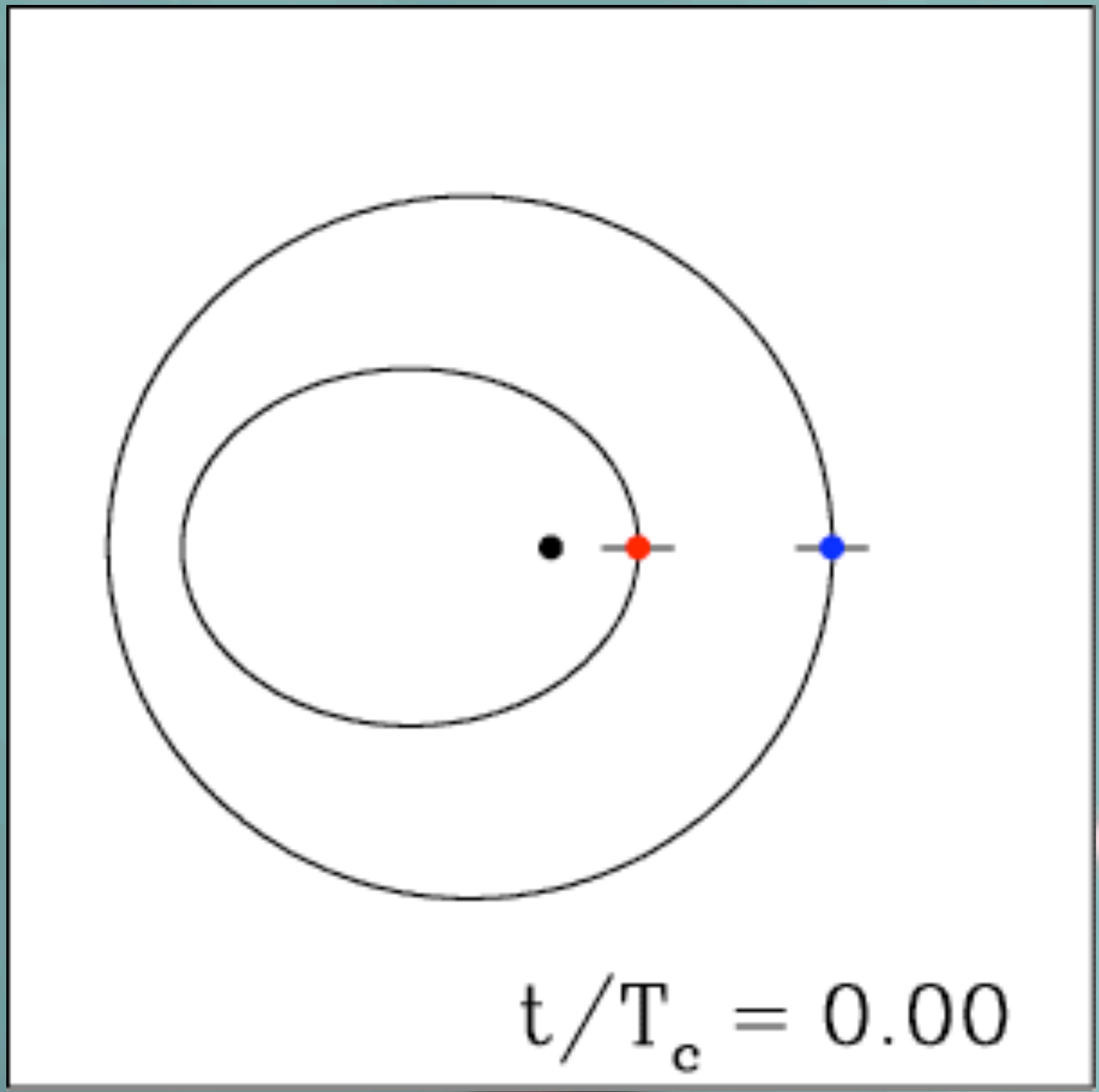
Secular evolution may or may not be chaotic.

- Solar system like (low eccentricity)
- High-eccentricity orbits
- Mean Motion Resonances
- Choreographies
- Horseshoe orbits
- Chaotic systems
- Others?

Many questions: How stable is solar system? What causes large eccentricity? How frequent is resonant trapping?

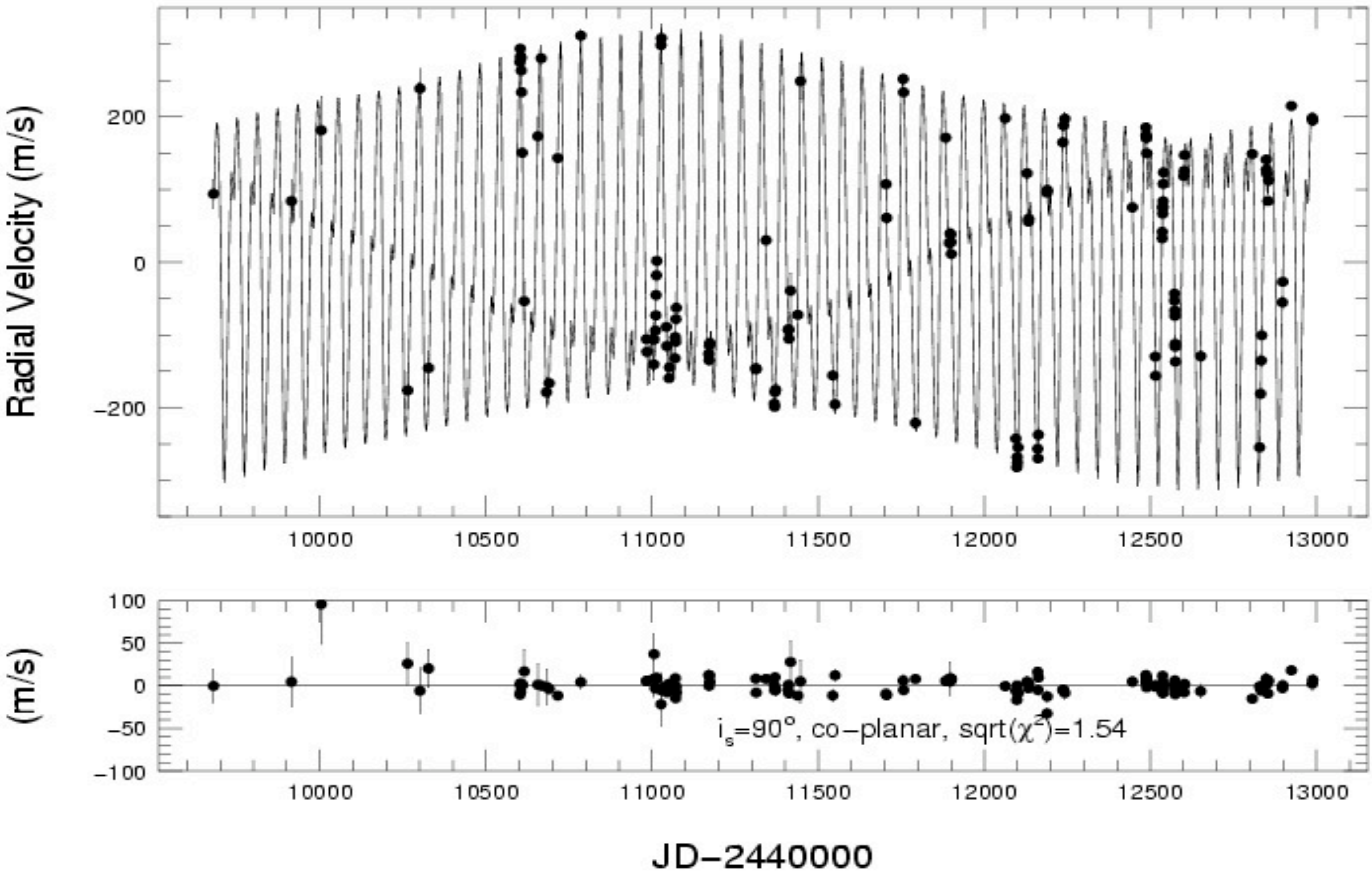
Two resonant systems have been observed!

GJ 876: Geometry



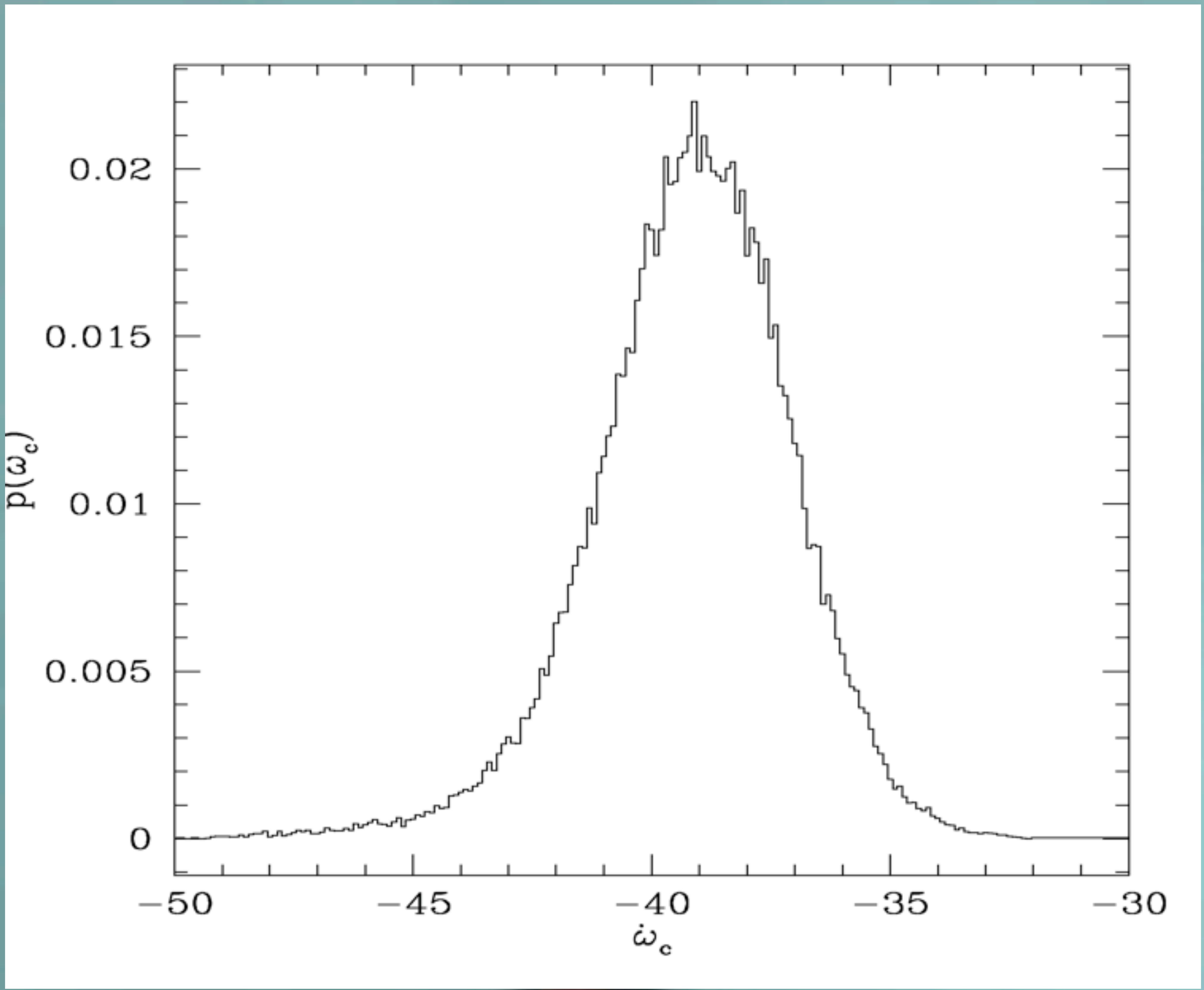
Lee

GJ 876: Radial Velocities



Laughlin et al. 2004

GJ 876: Precession Rate

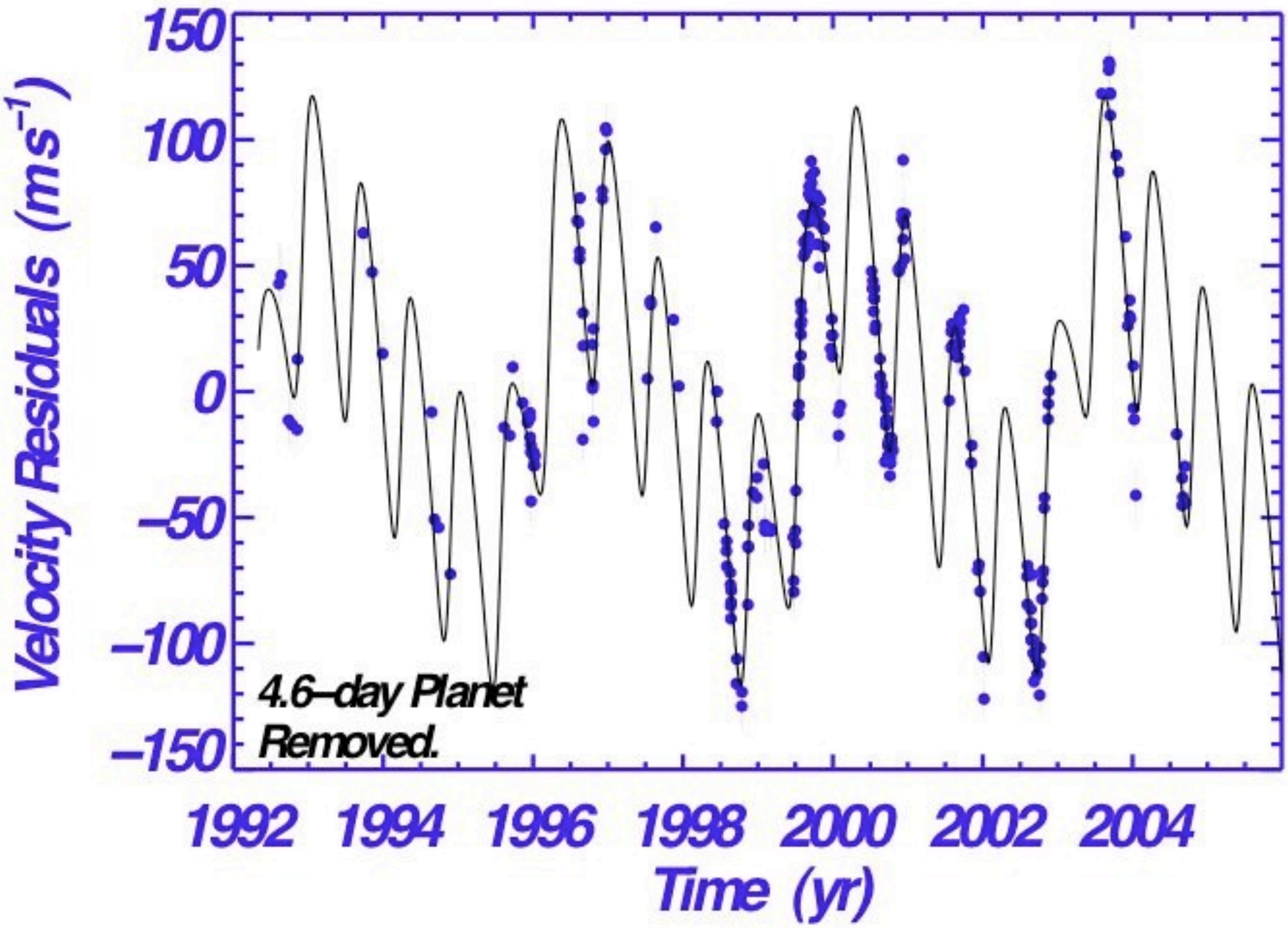


Ford 2004

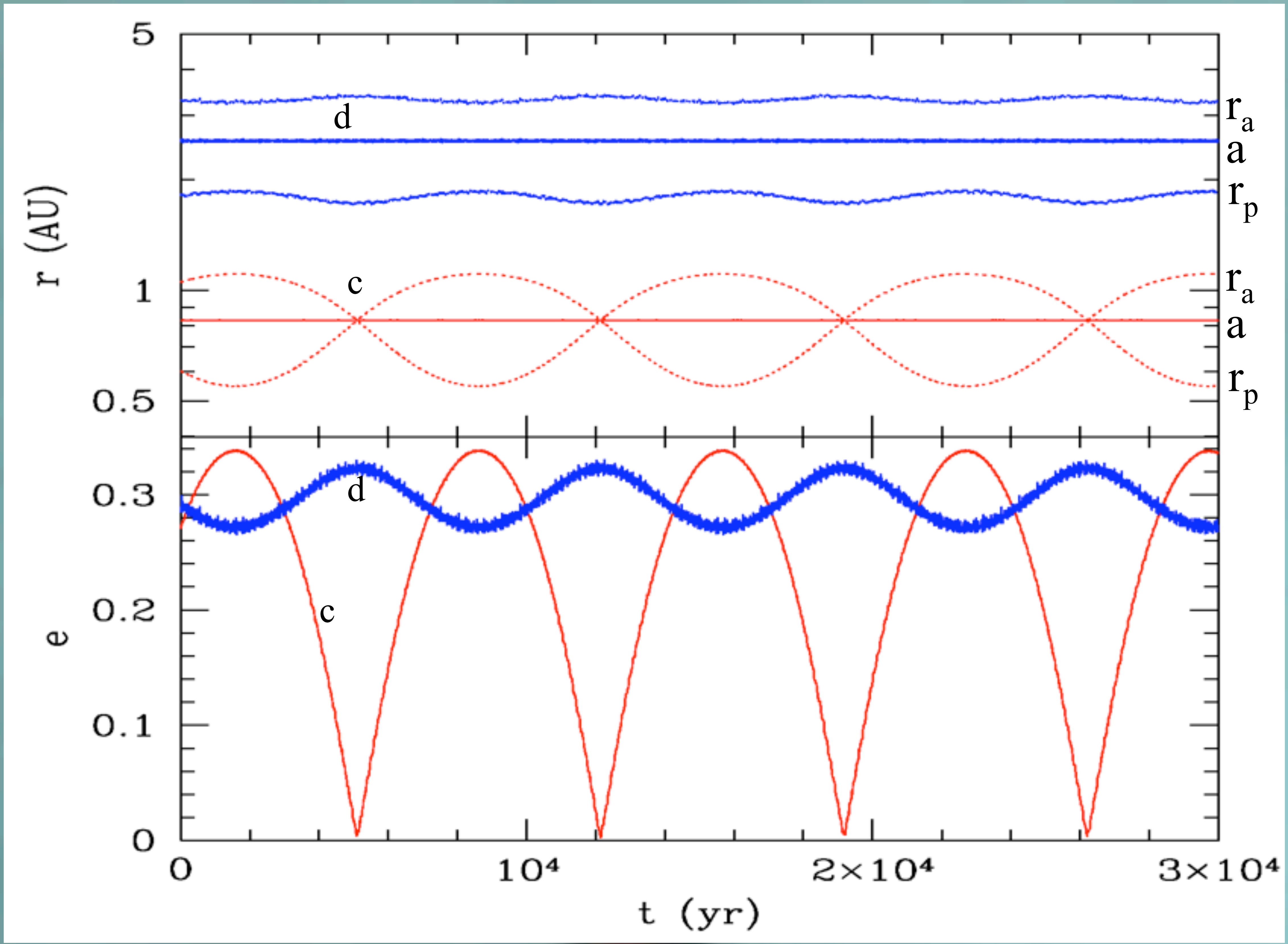
Conclusions for GJ 876

- Planet-Planet interaction leads to rapid precession
- Precession rate constrains masses & orbits
- Differential migration naturally led to resonant capture into 2:1 mean motion resonance
- Measured eccentricities demand either:
  - Migration halts shortly after resonant capture
  - Strong eccentricity damping during migration
- Multiple planet systems provide valuable information about history of planet formation, especially when interactions are observed.

Ups And: Radial Velocities



Secular Evolution of Ups And



Ford, Lystad, Rasio 2005 see also Malhotra (2002), Chiang et al. (2002)

Some Simulations

Conclusions (Eric Ford)

- Early stages of planet formation are highly uncertain due to complicated physics
- Oligarchic growth may regulate growth, enforcing a similar intermediate state
- Late stages of planet formation have simple physics, but can produce a wide variety of outcomes due to chaotic evolution
- Final state of planetary systems is determined by long-term chaotic orbital evolution

The brown dwarf hypothesis

- extrasolar "planets" are simply very low-mass stars that form from collapse of multiple condensations in protostellar clouds
- distribution of eccentricities and periods of extrasolar planets very similar to distributions for binary stars
- but:
  - why is there a brown-dwarf desert?
  - how did planets in solar system get onto circular, coplanar orbits?
  - how do you make planets with solid cores, or terrestrial planets?

Adapted from S. Tremaine

The nebular hypothesis

- the Sun and planets formed together out of a rotating cloud of gas (the "solar nebula")
- gravitational instabilities in the gas disk condense into planets (Kant 1755)
- Good points: variations might work to form Jupiter, Saturn, extrasolar gas giants
- Bad points: how do you make Uranus, Neptune, terrestrial planets?

Adapted from S. Tremaine

The core accretion hypothesis

- forming Sun is surrounded by a gas disk (like nebular hypothesis)
- planets form by multi-stage process:
  1. as the disk cools, rock and ice grains condense out and settle to the midplane of the disk – chemistry and gas drag are dominant processes
  2. small solid bodies grow from the thin dust layer to form km-sized bodies ("planetesimals") - gas drag, gravity and chemical bonding are dominant processes
  3. planetesimals collide and grow – gravitational scattering and solar gravity are dominant processes. "Molecular chaos" applies and evolution is described by statistical mechanics

requires growth by ~45 orders of magnitude in mass through ~6 different physical processes!

Adapted from S. Tremaine

Challenges of Planet Formation

- Planetesimals susceptible to very rapid in spiral.
- Collisions need to result in net accretion.
- Cores susceptible to rapid inward migration
- Giant planets must form before gas dissipates
- Uranus & Neptune must form in less than age of solar system

How to Excite Eccentricities?

- Gas Disk (Artymowicz 1992, Chiang & Murray 2002, Goldreich & Sari 2003, Papalouizou et al. 2001, Ogilvie & Lubow 2003)
- Planetesimal Disk (Murray et al. 1998)
- Planet-Planet Scattering
- Resonant Interactions (Chiang & Murray 2002, Kley et al. 2004, 2005, Lee & Peale 2002, Nagasawa et al. 2003, Tsiganis et al. 2005, Adams & Laughlin 2006)
- Secular Perturbations from Heirarchcical Triple Systems (Holman et al. 1997, Ford et al. 2000, Takeda & Rasio 2005)
- Passing Stars (Laughlin & Adams 1998, Ford et al. 2000, Hurley & Shara 2002, Zakamska & Tremaine 2004)
- Asymmetric Stellar Jets (Namouni 2005, 2006)
- Hybrid Scenarios (Marzari et al. 2005, Sandor & Kley 2006)

Artwork courtesy of Sylwia Walerys