Extrasolar Planets:
Testing Models of Planet Formation

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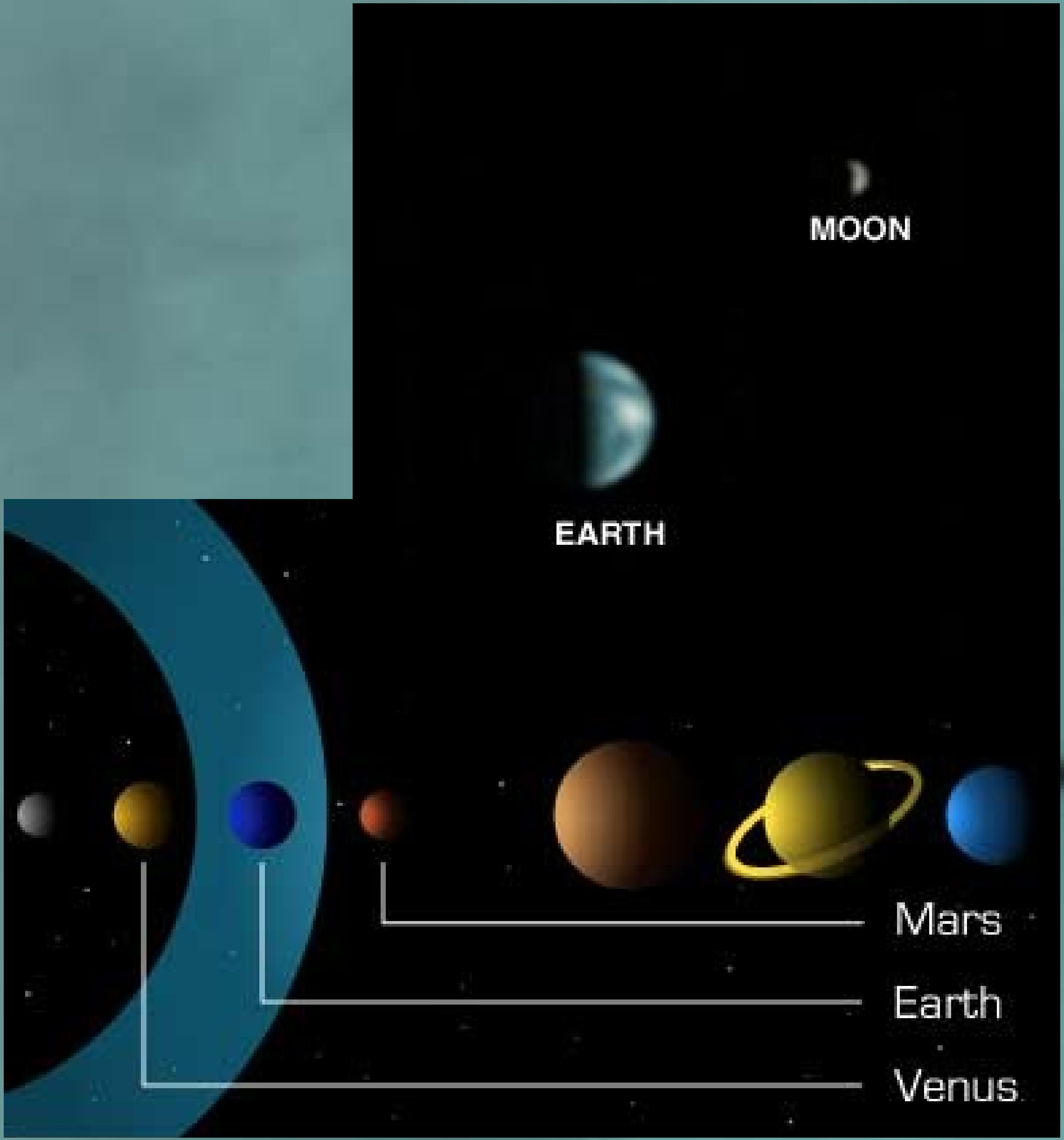
Observed Planetary Systems



Artwork & images courtesy of NASA

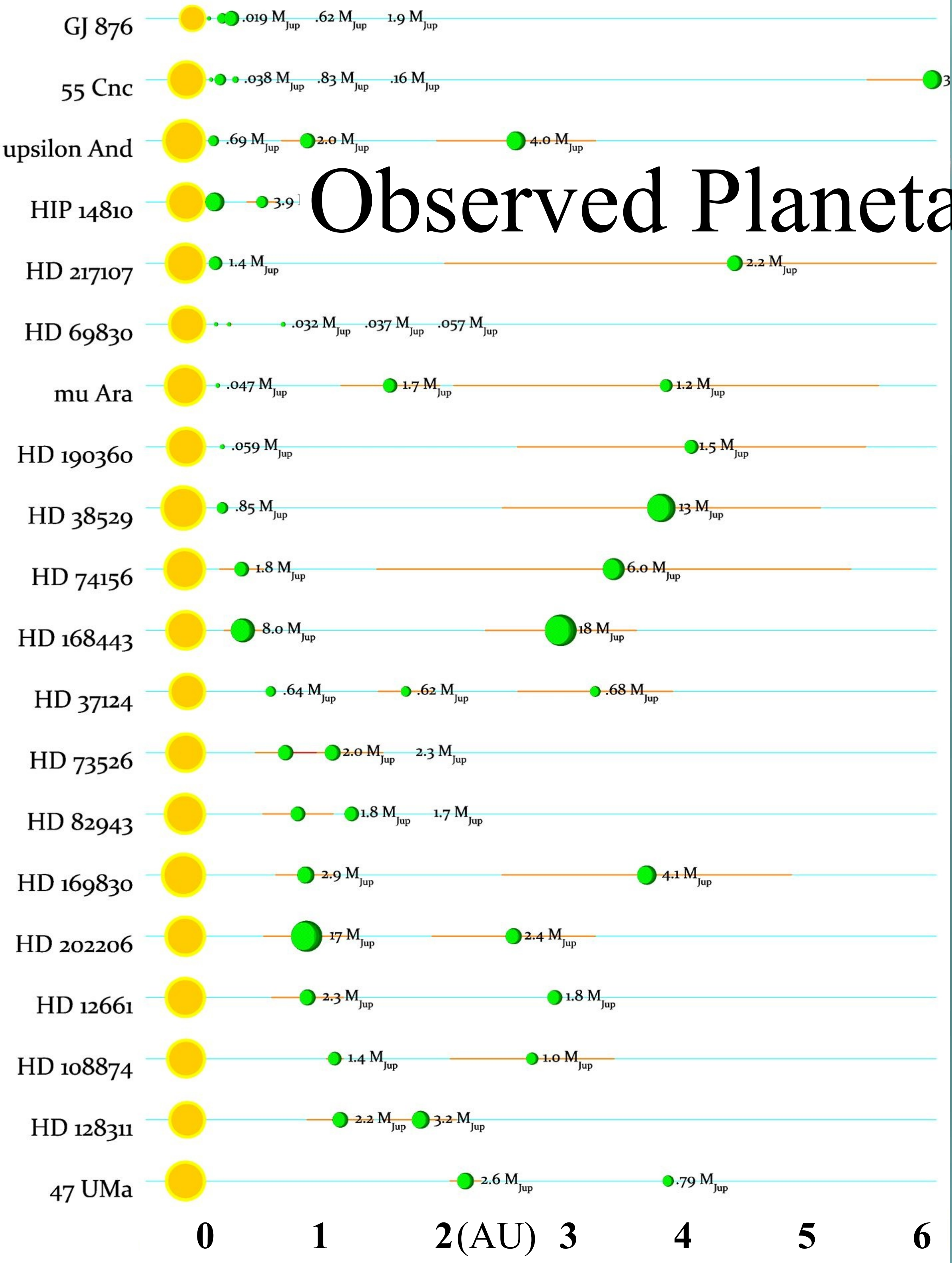
1543: Copernicus: *Revolutionibus*
1576: Digges: Universe infinite?
1600: Bruno burned
1604: Kepler's Supernova
1609: Galileo's telescope
1618: Kepler's 3rd law

1687: Newton: *Principia*
1698: Huygens: Distance to Sirius
1755: Kant on planet formation
1781: Herschel: Uranus
1796: Laplace on planet formation

1838: Parallax measured
1846: Adams & Le Verrier: Neptune

1925: Hubble: Cepheids in “nebulae”
1926: Eddington: Sun's energy
1930: Tombaugh: Pluto

Observed Planetary Systems

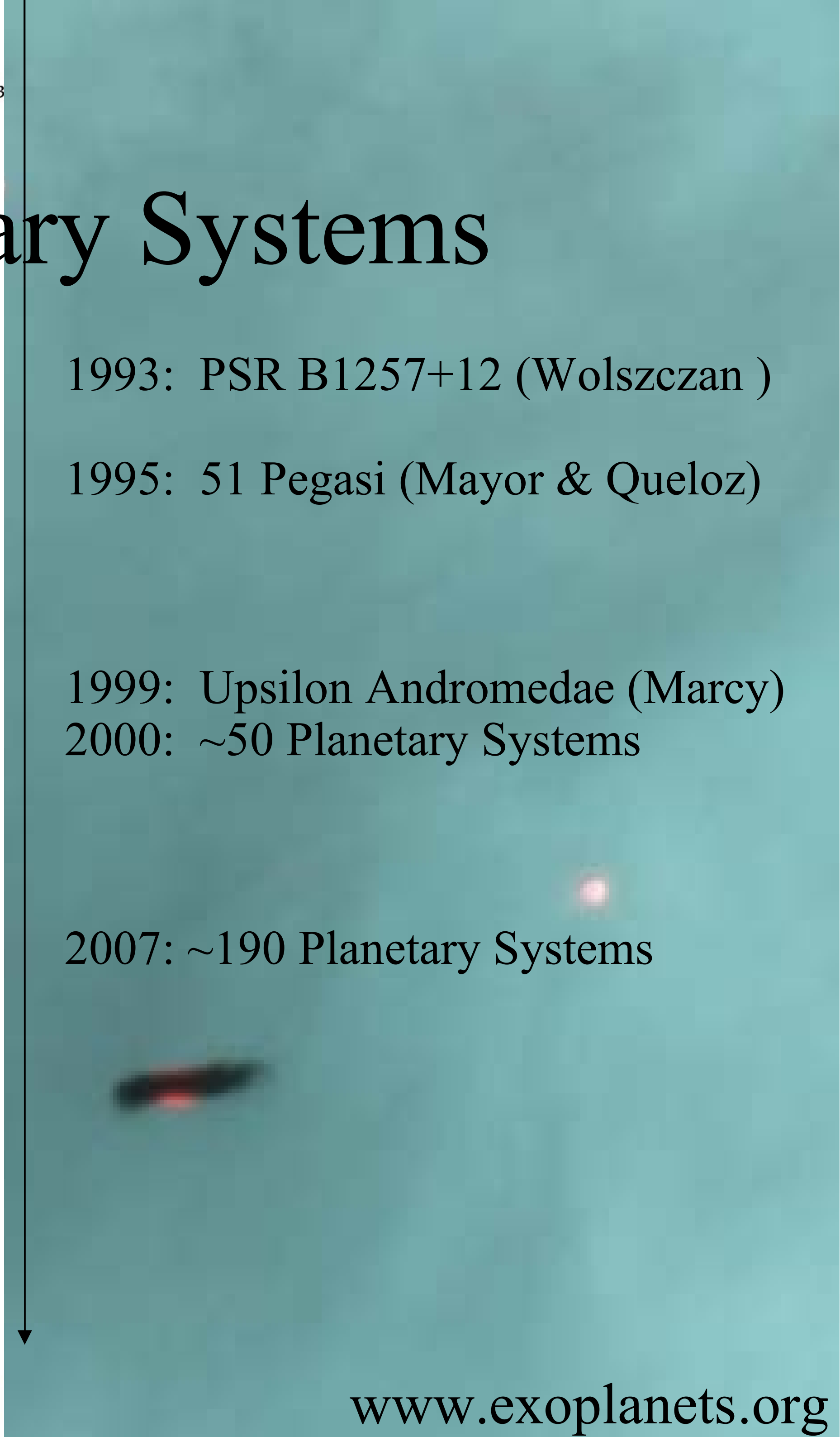


1993: PSR B1257+12 (Wolszczan)

1995: 51 Pegasi (Mayor & Queloz)

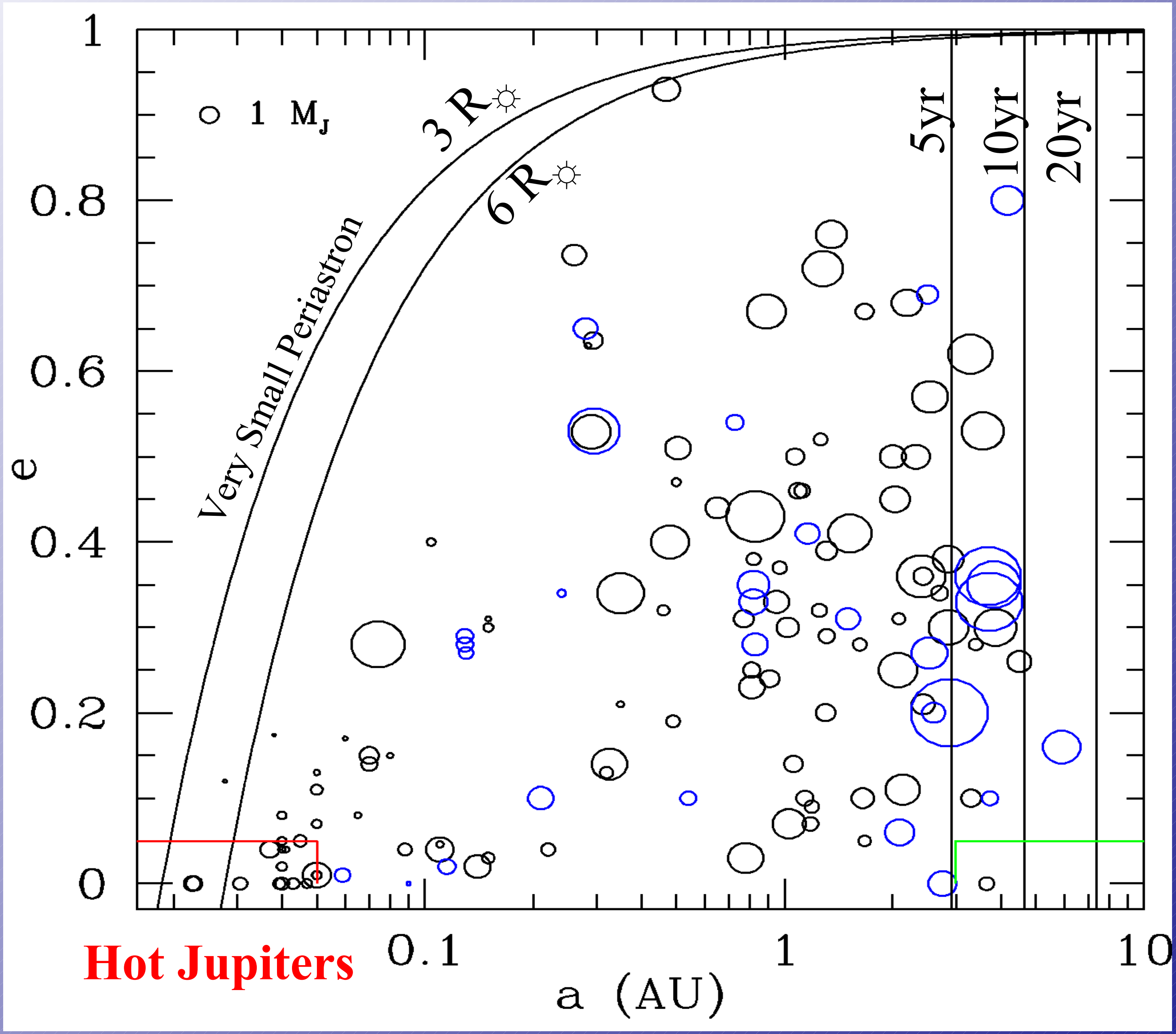
1999: Upsilon Andromedae (Marcy)
2000: ~50 Planetary Systems

2007: ~190 Planetary Systems



www.exoplanets.org

Diversity of Extrasolar Planets



Eccentric Planets

Multiple Planet Systems

Solar System-like Giant Planets

www.exoplanets.org

New Questions

Do most giant planets…

- Migrate?
- Have eccentric orbits?

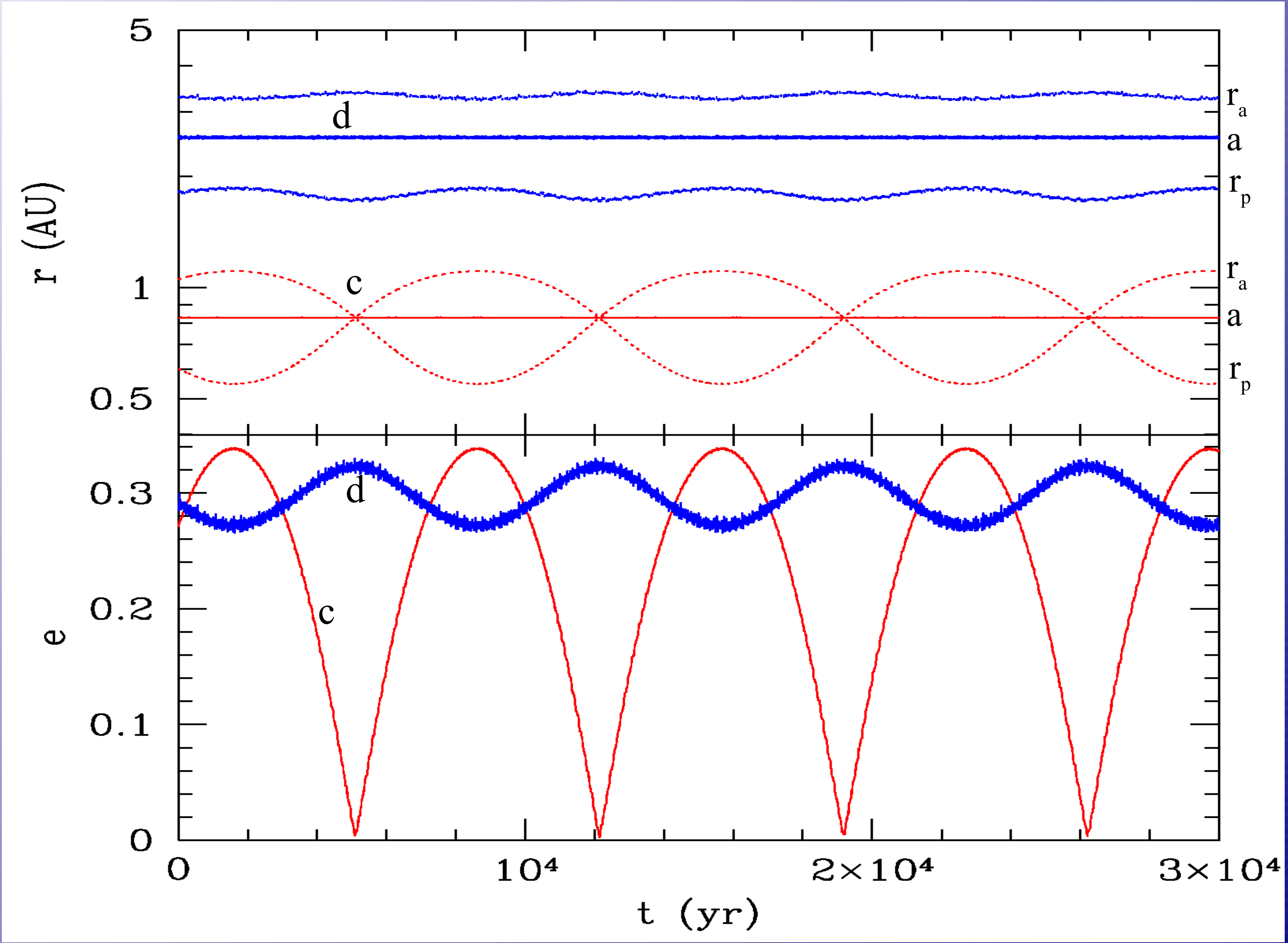
What limits…

- Migration?
- Eccentricities?

υ Andromedae

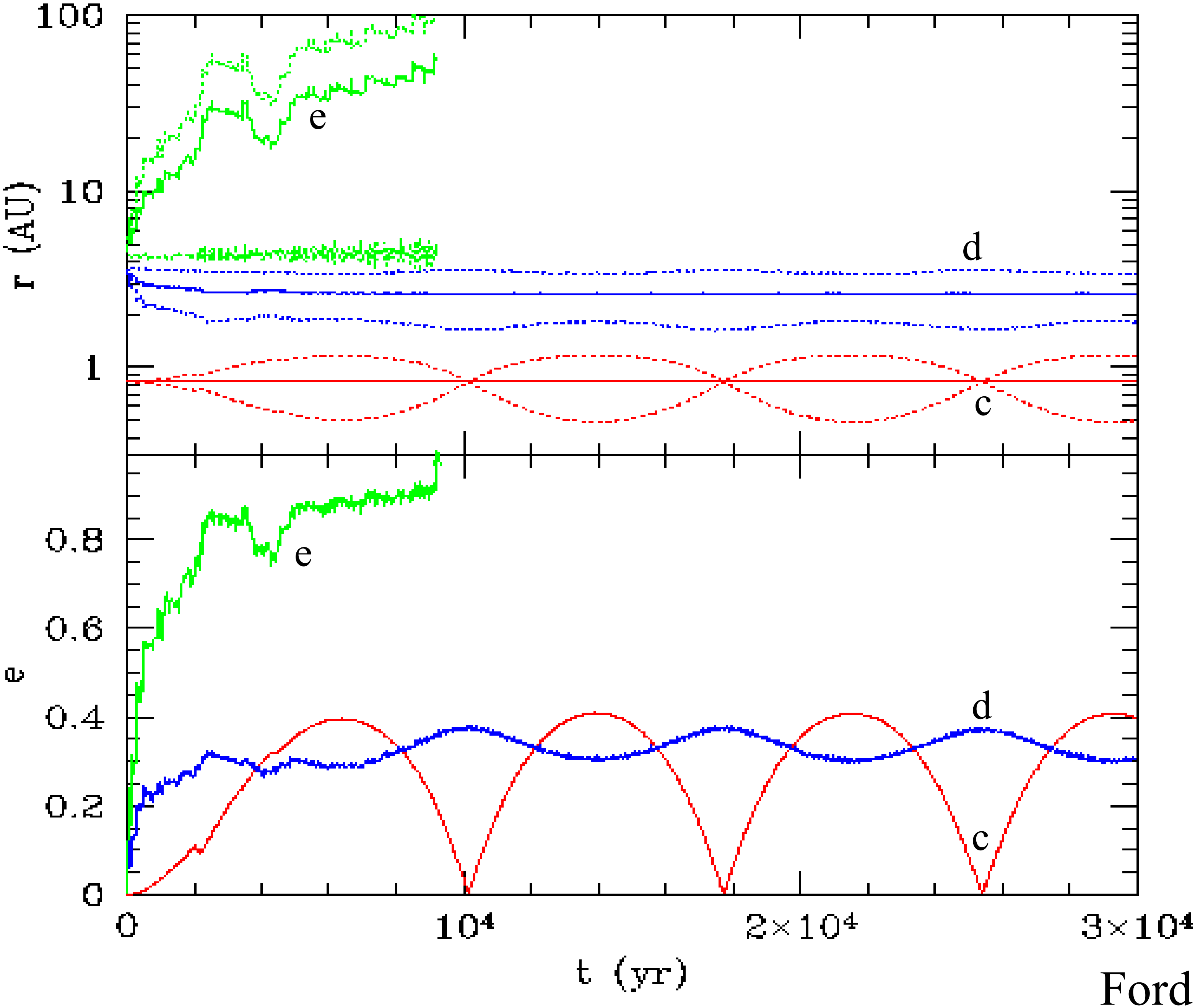
- First multiple planet system discovered around main sequence (F8V, 1.3 $M_{\odot}$, 3Gyr) star in 1999.
- Now have ~ 450 radial velocity observations with precision limited by stellar jitter of ~ 7.5m/s
- υ And c & d have significant eccentricities (~0.26 & 0.28 ±0.02)
- Significant secular eccentricity evolution
- What is the origin of these eccentricities?
  - Orbital Migration (Chiang & Murray 2002)
  - Planet Scattering (Malhotra 2002)

Ups And: Secular Evolution



Ford, Lystad, Rasio 2005

Impulsive Formation Scenario



Initial:

$P_d = 5.8$ yr

$m_d = 3.8\ M_{Jup}$

$e_d = 0.003$

$P_e = 8.7$ yr

$m_e = 1.9\ M_{Jup}$

$e_e = 0.004$

Final:

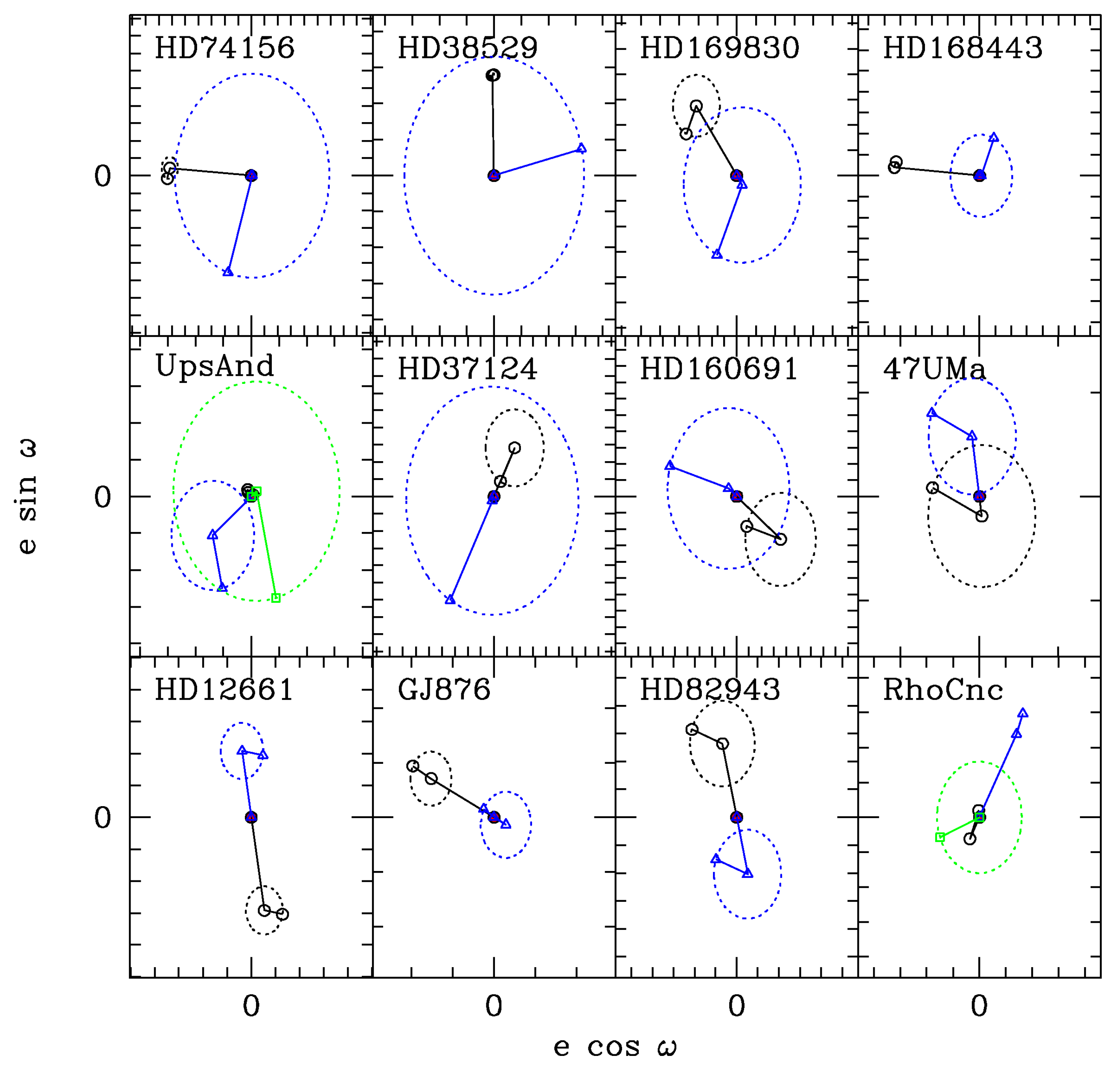
$P_d = 3.7$ yr

$e_d = 0.29$

Ford, Lystad, Rasio 2005

Simulation: Ford, Lystad, Rasio 2005
Animation: Trent Schindler (NSF)

Future Observational Tests



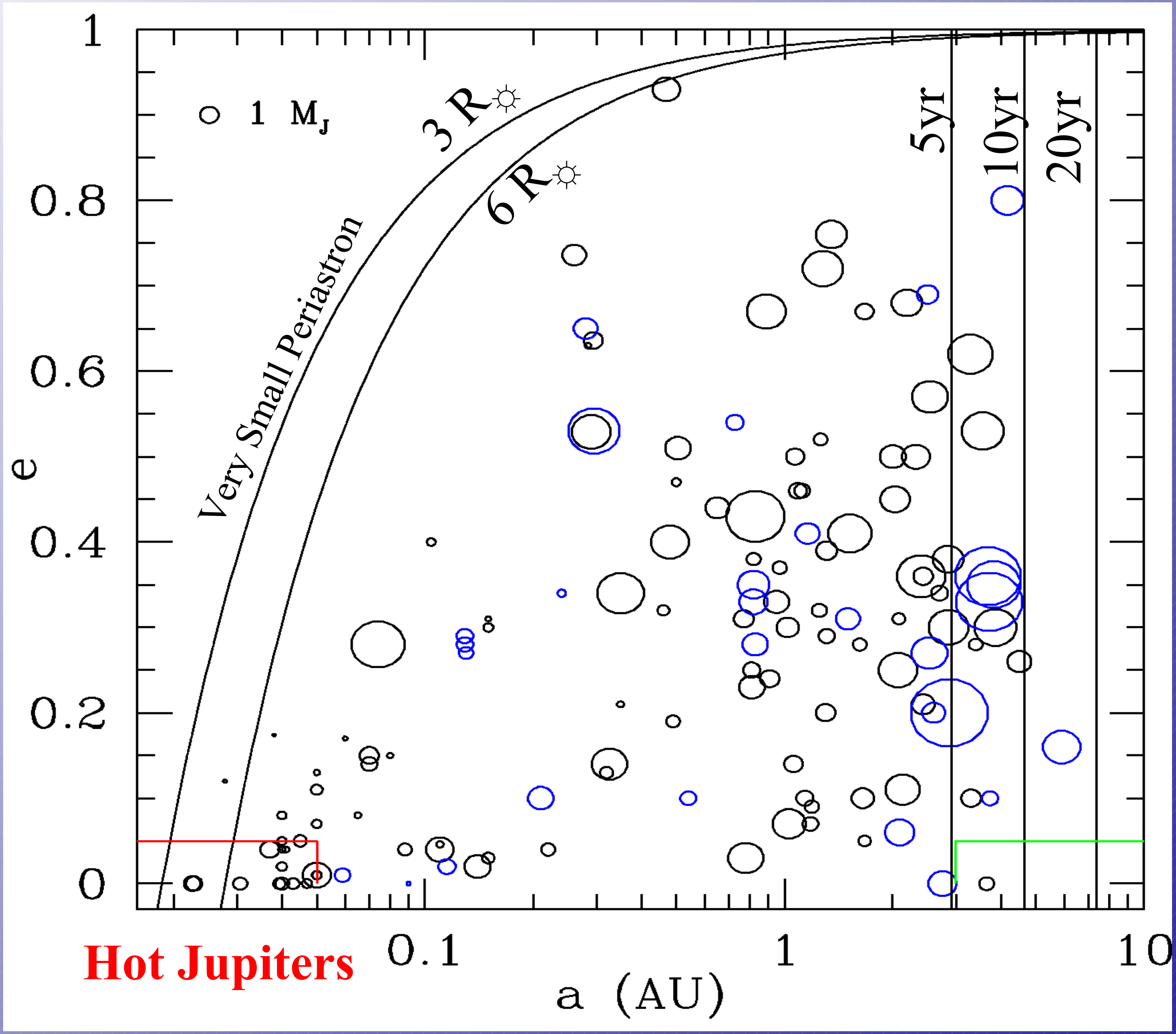
Hierarchical: 9

Significant Secular Evolution: 6

Near Mean Motion Resonances: 5

Ford in prep

Diversity of Extrasolar Planets



Hot Jupiters

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www.exoplanets.org

Orbital Migration

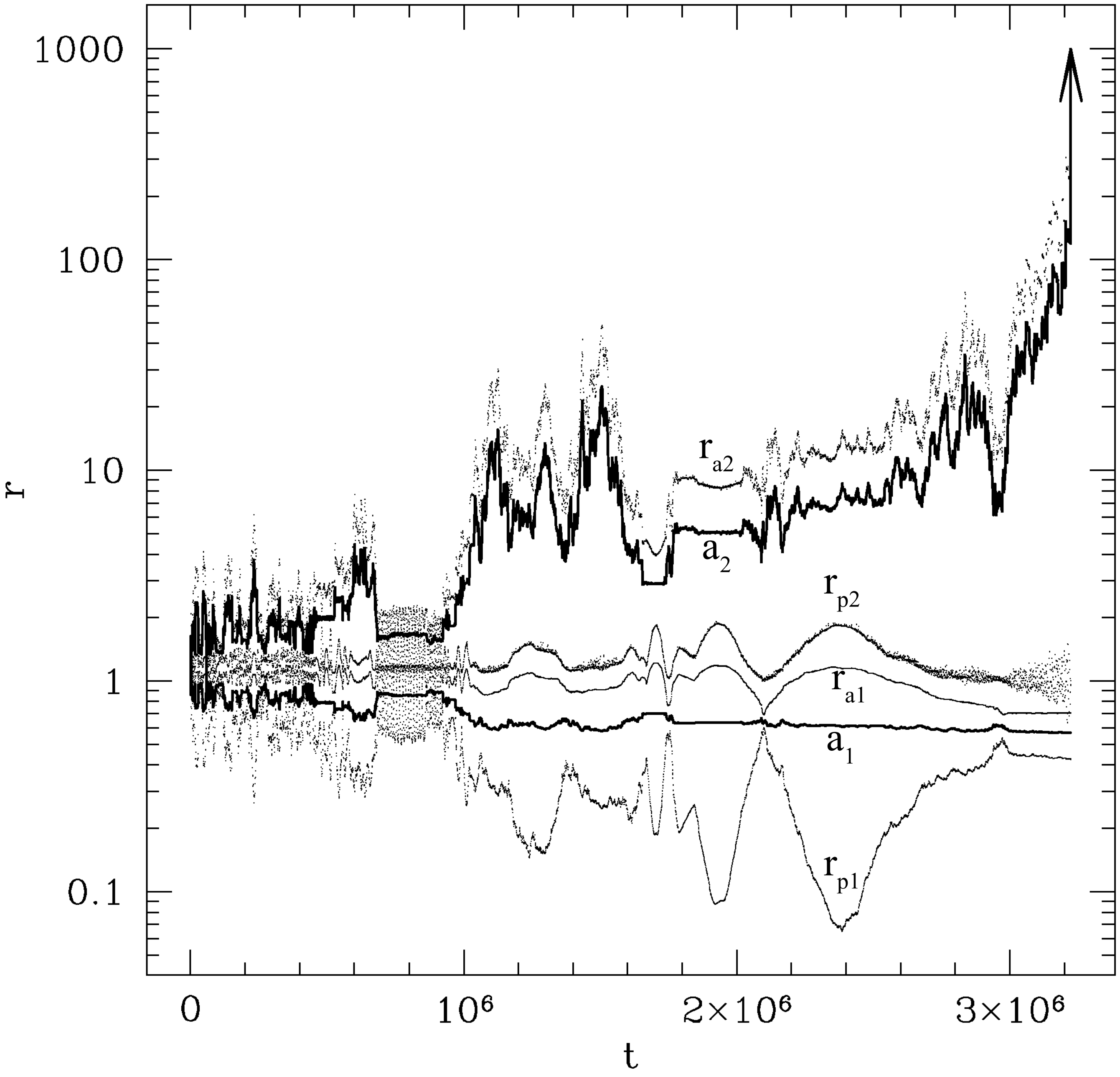
- What causes hot-Jupiters to migrate?
- What halts migration? Survival?
- Clues from observed distribution of Hot Jupiters?
- Early pile-up of Hot Jupiters at P = 3d
- Recent detections of lower mass planets with P < 3d, suggesting cutoff is a function of mass
- What is the theoretical limit for survival?

Roche Limit & Migration

- Roche Limit (a_R): $R_P = 0.462 a_R \left(\frac{M_P}{M_*} \right)^{1/3}$
- Theoretical limits on orbital migration:
  - Slow inspiral: Predicts edge at the Roche limit
    - Gaseous disk
    - Planetesimal scattering
  - Circularization of highly eccentric orbits with small pericenter distances: Predicts edge at *twice* the Roche limit
    - Planet-planet scattering
    - Tidal-capture of free-floating planets
    - Secular perturbations from highly inclined binary star

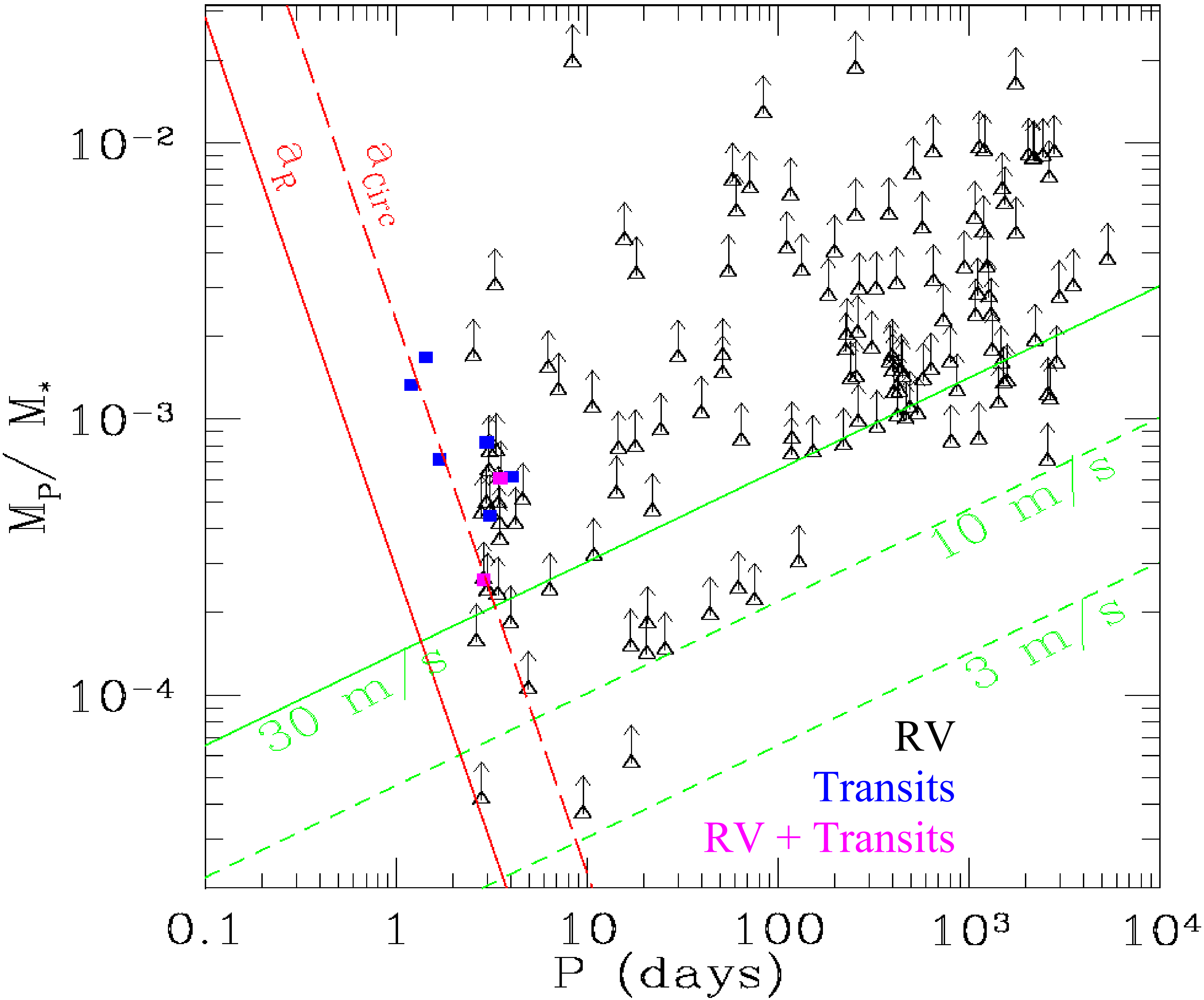
Ford & Rasio 2006

Planet-Planet Scattering



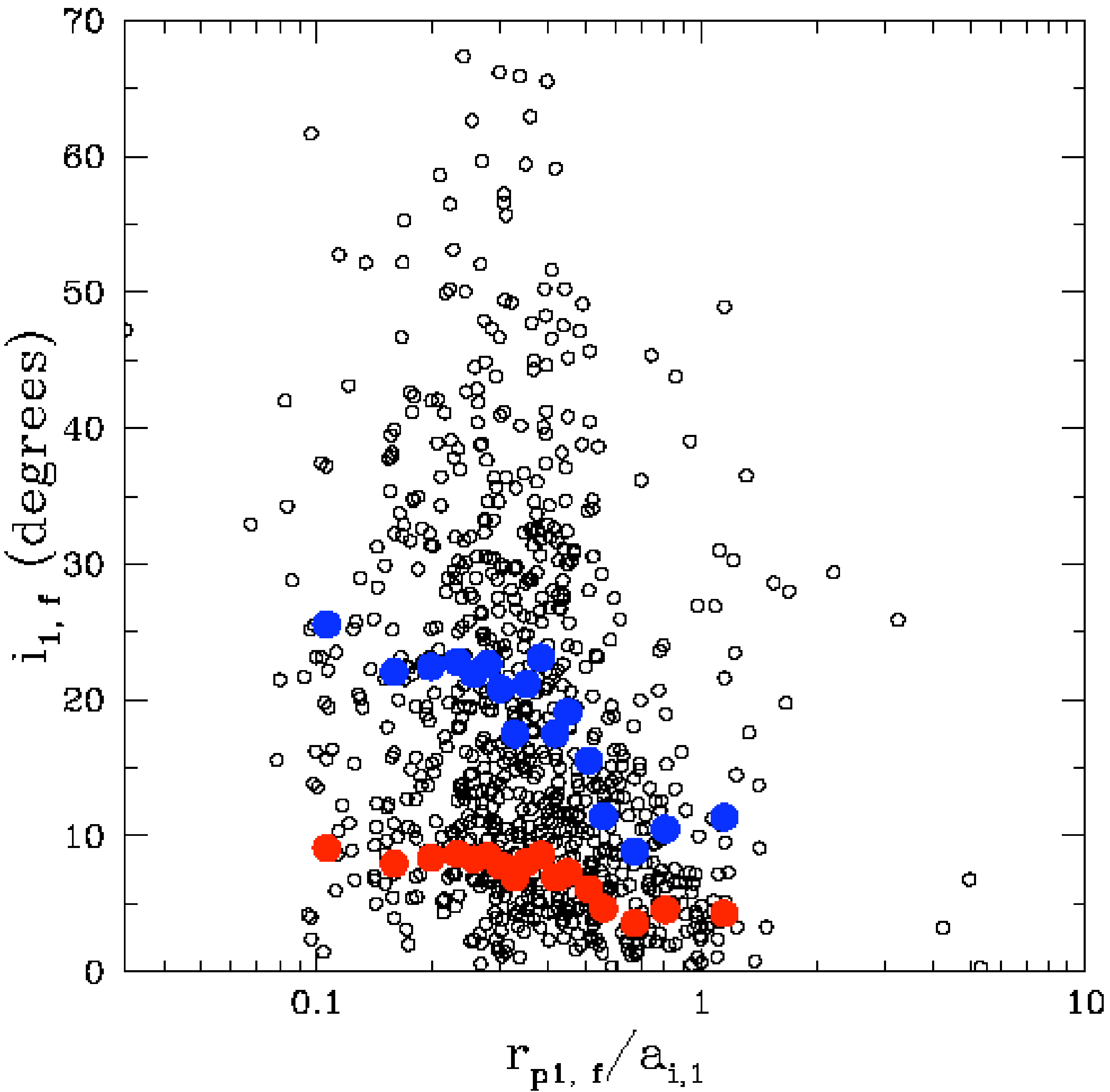
- Two giant planets initially on circular orbits
- Dynamical instability leads to close encounters
- Typically results in planets colliding or one being ejected
- Sometimes planet acquires small pericenter distance

Rasio & Ford 1996



Ford & Rasio 2006

Planet Scattering & Orbital Migration

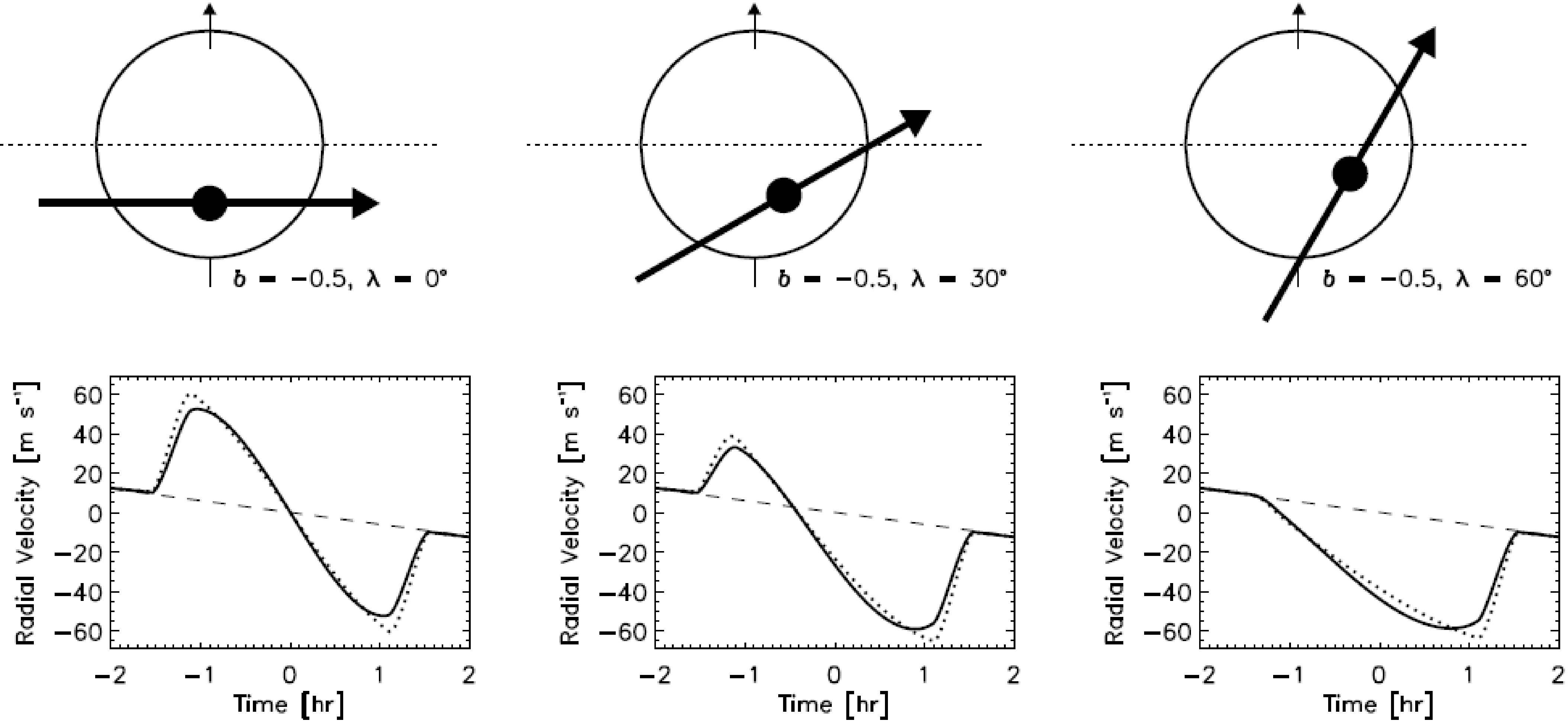


- Black: Final orbital elements from Individual simulations
- Blue: Mean final inner planet inclination
- Red: RMS final inner planet inclination

Chatterjee et al. 2007

Future Observational Tests

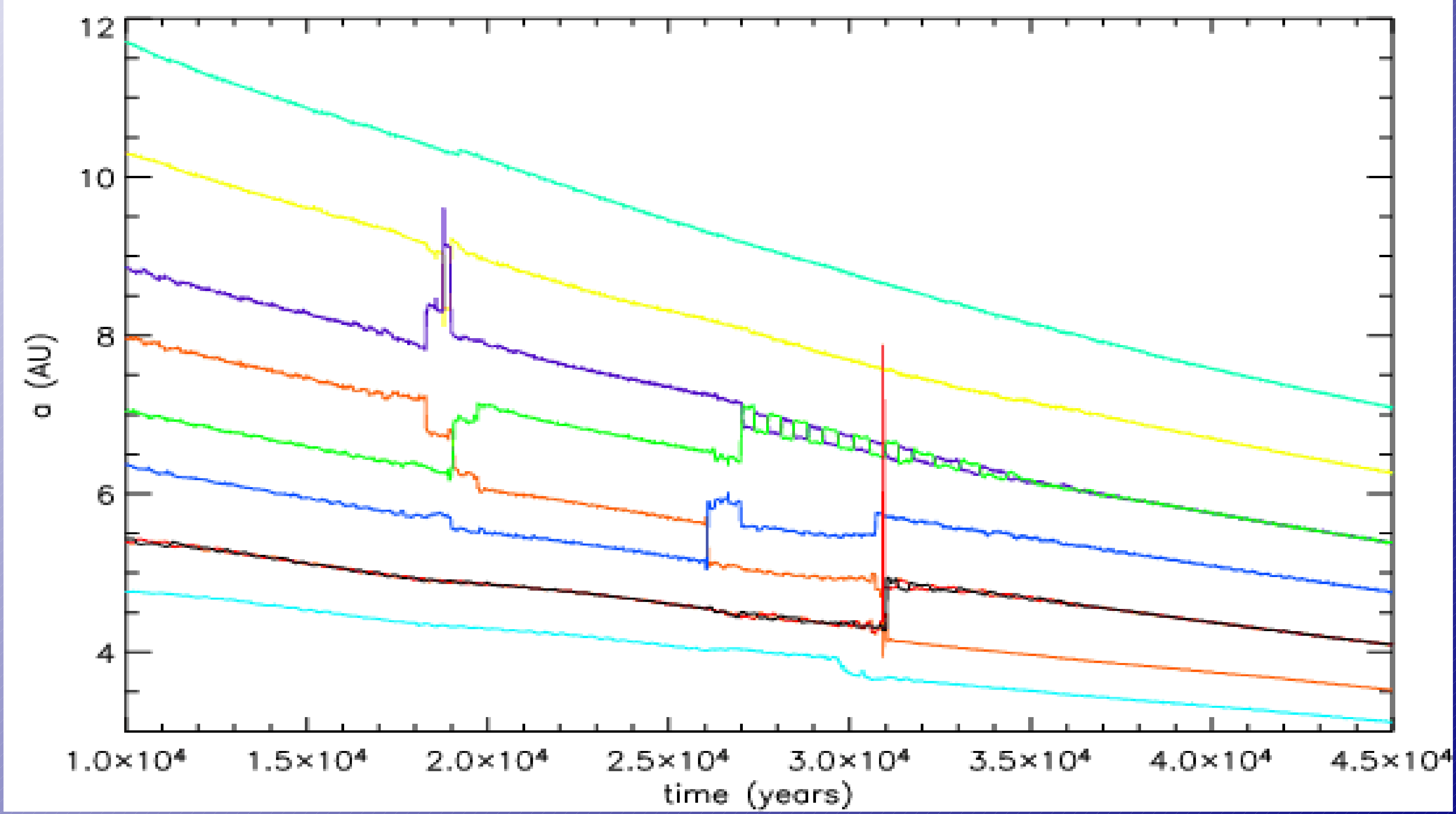
- Tidal dissipation in the planet rapidly damps eccentricity
- Search for planets with inclination excited by strong scattering



Gaudi & Winn 2006

Future Observational Tests

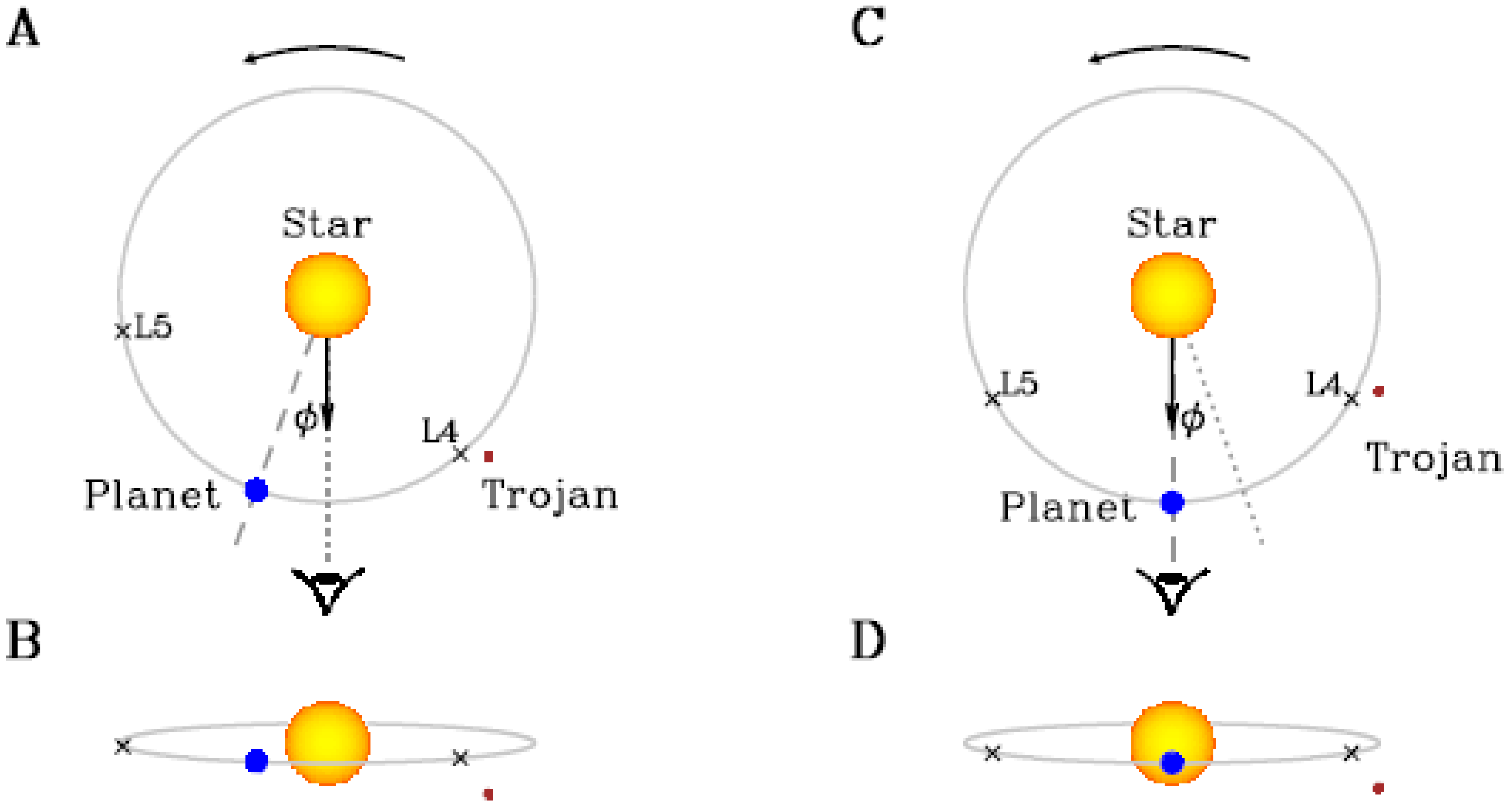
- Smooth migration can trap planets in resonances
- But planets in resonances can be hard to detect



Cresswell & Nelson 2006

Future Observational Tests

- Gravitational perturbations by another planet affect times of transit (Holman & Murray 2006; Agol et al. 2006)
- “Trojans” result in a constant time offset

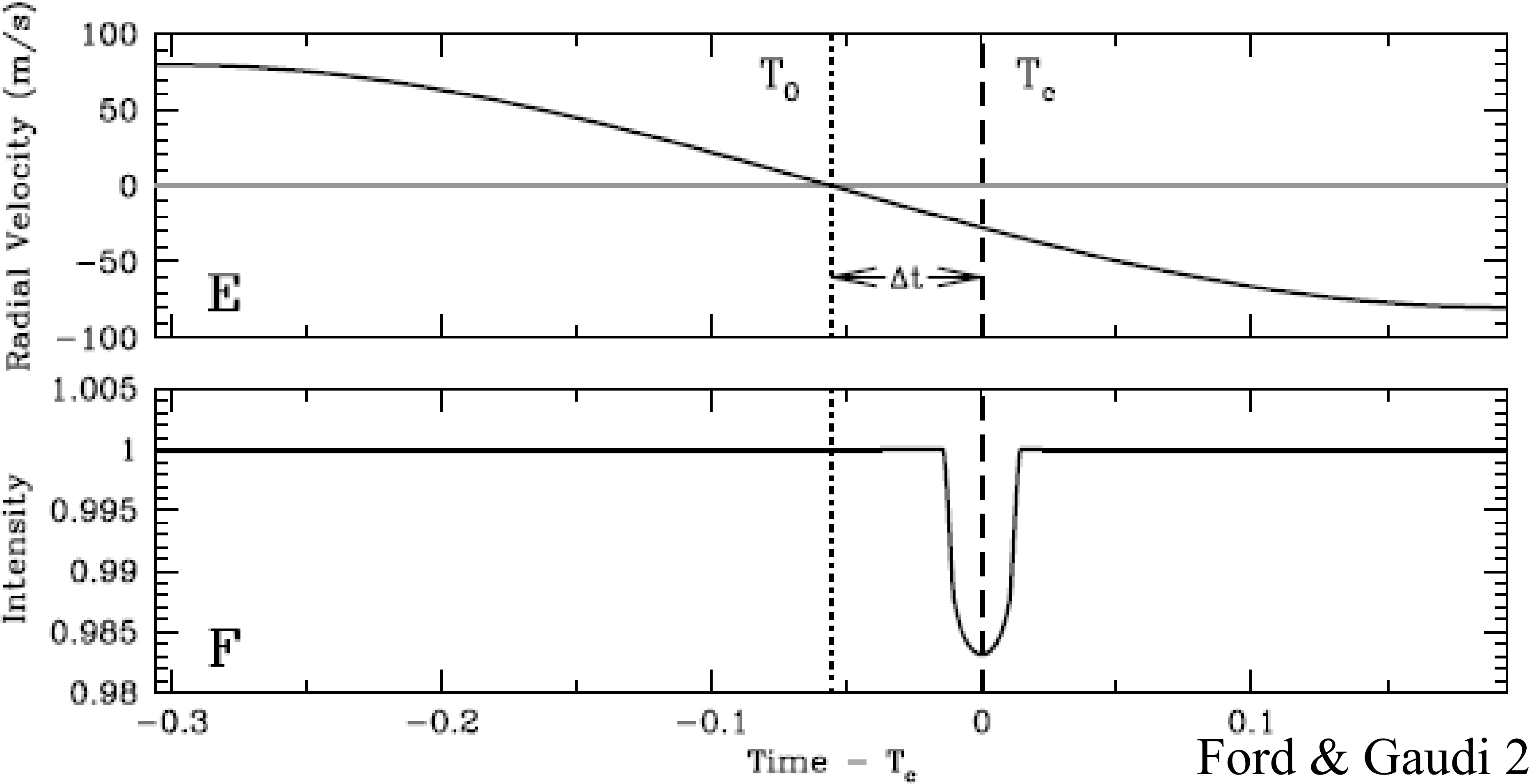


Ford & Gaudi 2006

Future Observational Tests

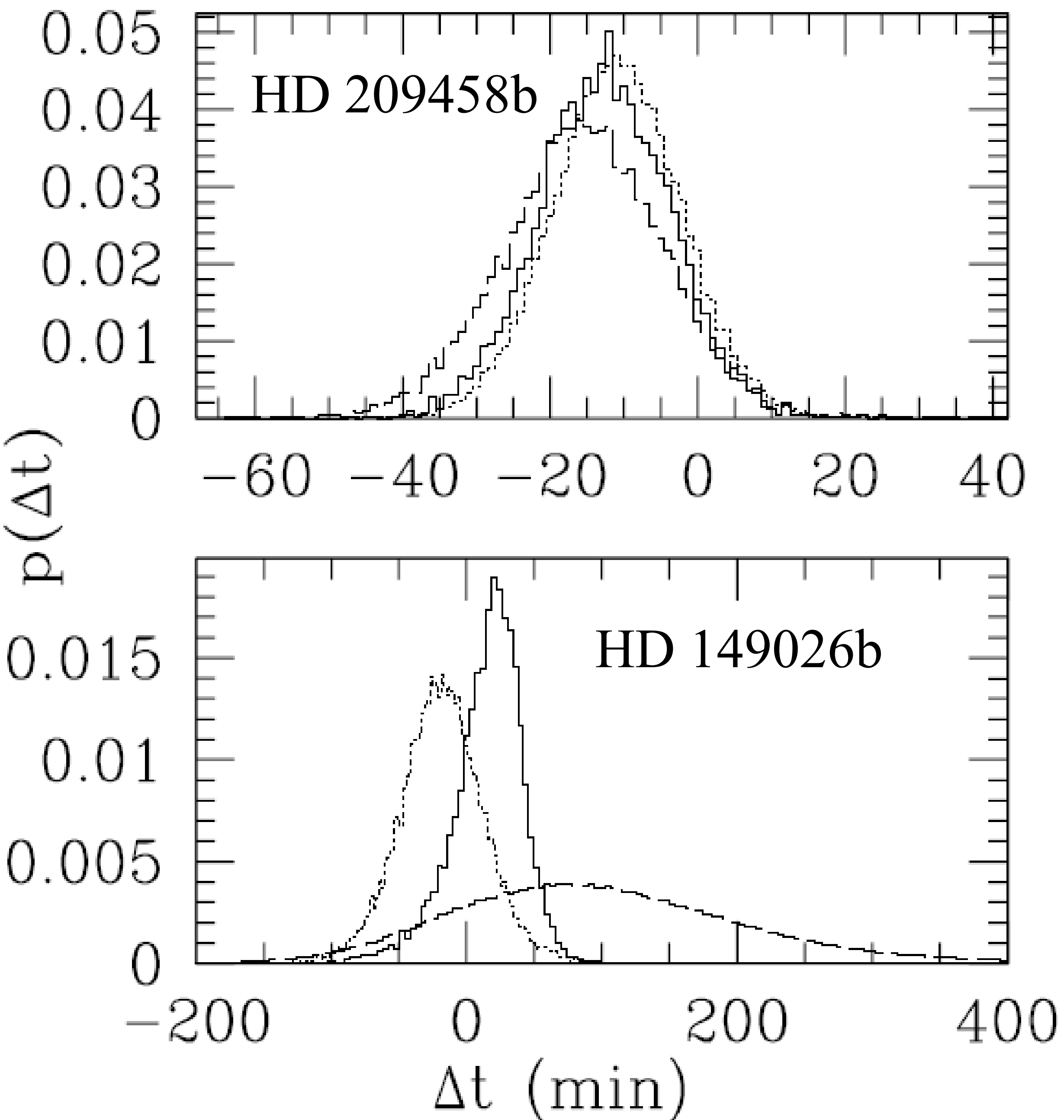
- Large constant offset between transit & RV null:

$$\Delta t \simeq 37.5 \left(\frac{P}{3\mathrm{d}}\right) \left(\frac{m_T}{10 m_\oplus}\right) \left(\frac{0.5 M_J}{m_p + m_T}\right) \mathrm{min}$$



Ford & Gaudi 2006

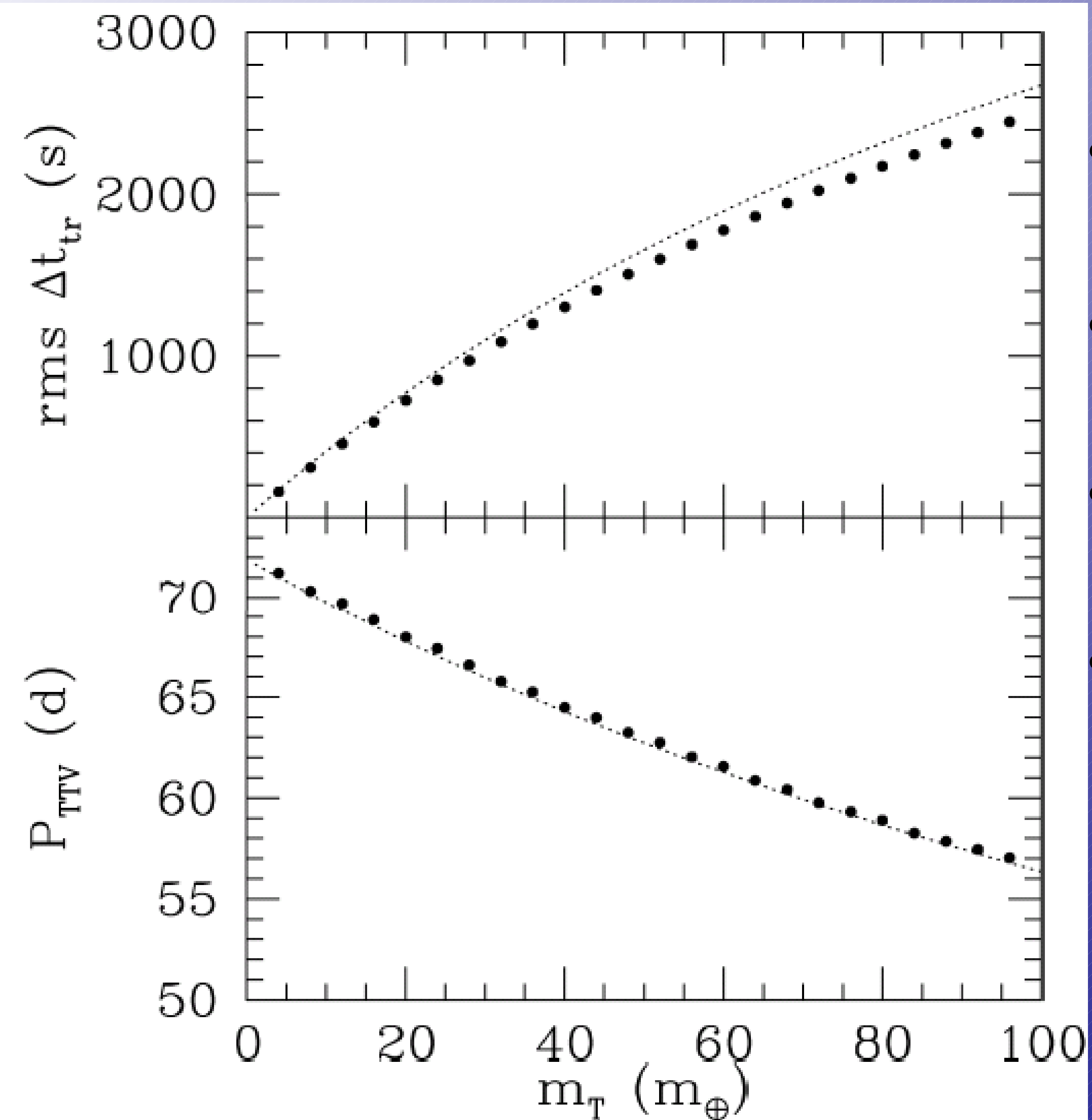
Existing Observational Constraints



- Already significant upper limits for spin-orbit inclinations & masses of “Hot-Trojans”:
- HD 209458b: $m_{Trojan} < 13\ M_{\oplus}$ (99.9%) $i = 4.4° \pm 1.4°$ (Winn et al. 2005)
- HD 149025b: $m_{Trojan} < 25\ M_{\oplus}$ (99.9%) $i = 11° \pm 14°$ (Wolf et al. 2006)

Ford & Gaudi 2006

Transit Timing of Trojan Planets



- Transiting Giant Planet:
  Semimajor axis: 0.05AU
  Planet Mass: 0.5 M_J
- Trojan Planet:
  Libration: 10º
- Earth-mass Trojan results in ~40s
- Precision of transit time measurements ~10s (Holman et al. 2006)

Ford & Holman in prep

What about our own Solar System?

Why did Jupiter stay…

- At 5 AU?
- In a circular orbit?

Implications for terrestrial planets...

- Formation?
- Habitability?

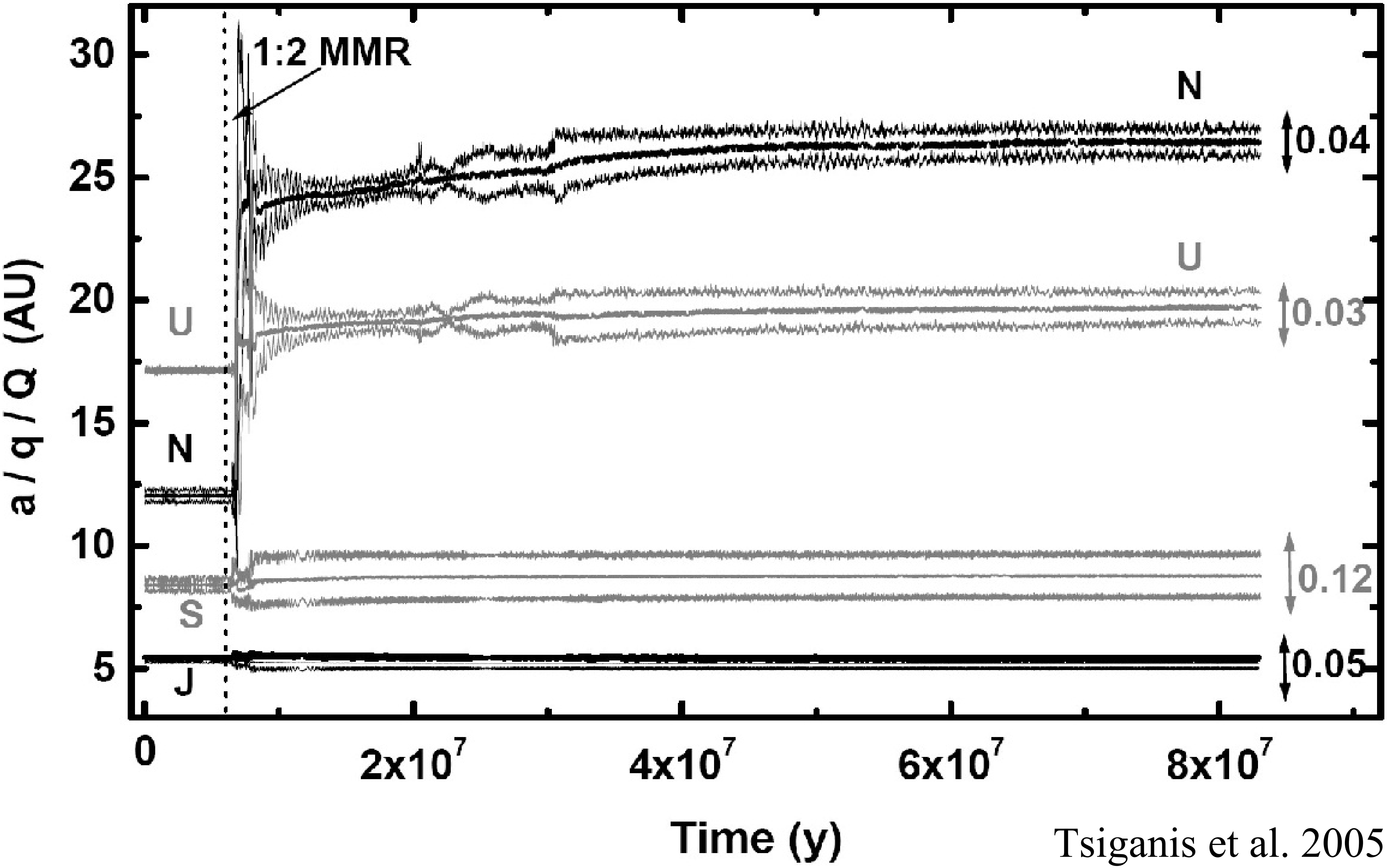
Violence in the Solar System

- Mercury large density
- Mars-sized Earth-impactor created the Moon
- Giant planet’s irregular satellites & rings
- Uranus’s obliquity
- Neptune’s retrograde moon Triton
- Excitation of Kuiper Belt

Formation of Uranus & Neptune

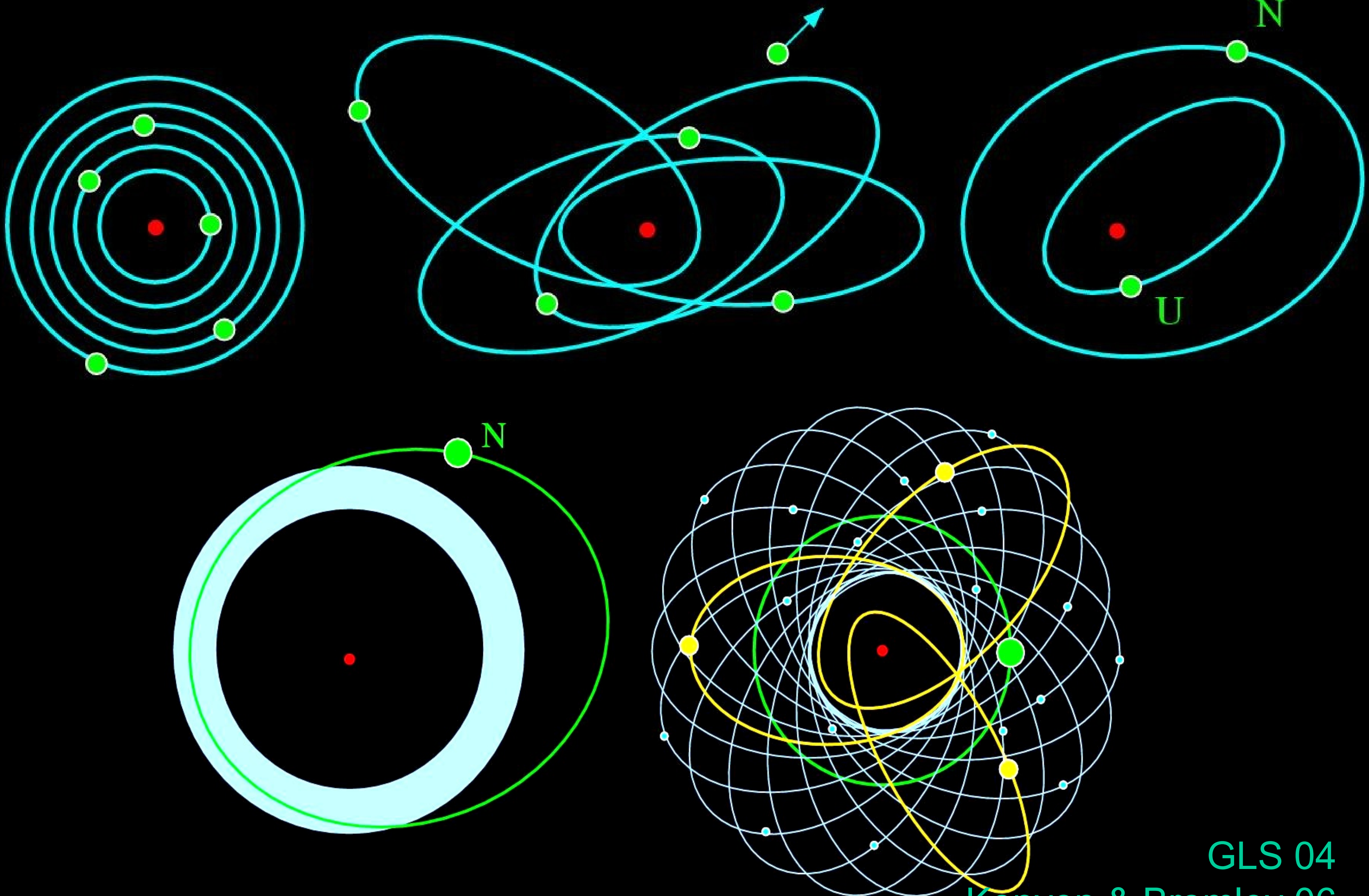
- Problem: Standard timescale to accrete Neptune *in situ* at ~30 AU exceeds 4 Gyr
- Possible Solutions:
  a) Form Uranus and Neptune closer to Sun (Thommes et al. 1999; Tsiganis et al. 2005)
  b) Majority of disk mass in small bodies, leading to more effective gravitational focusing and increased accretion rates (GLS = Goldreich et al. 2004)

Jupiter, Saturn, 2 Ice Giants + small bodies



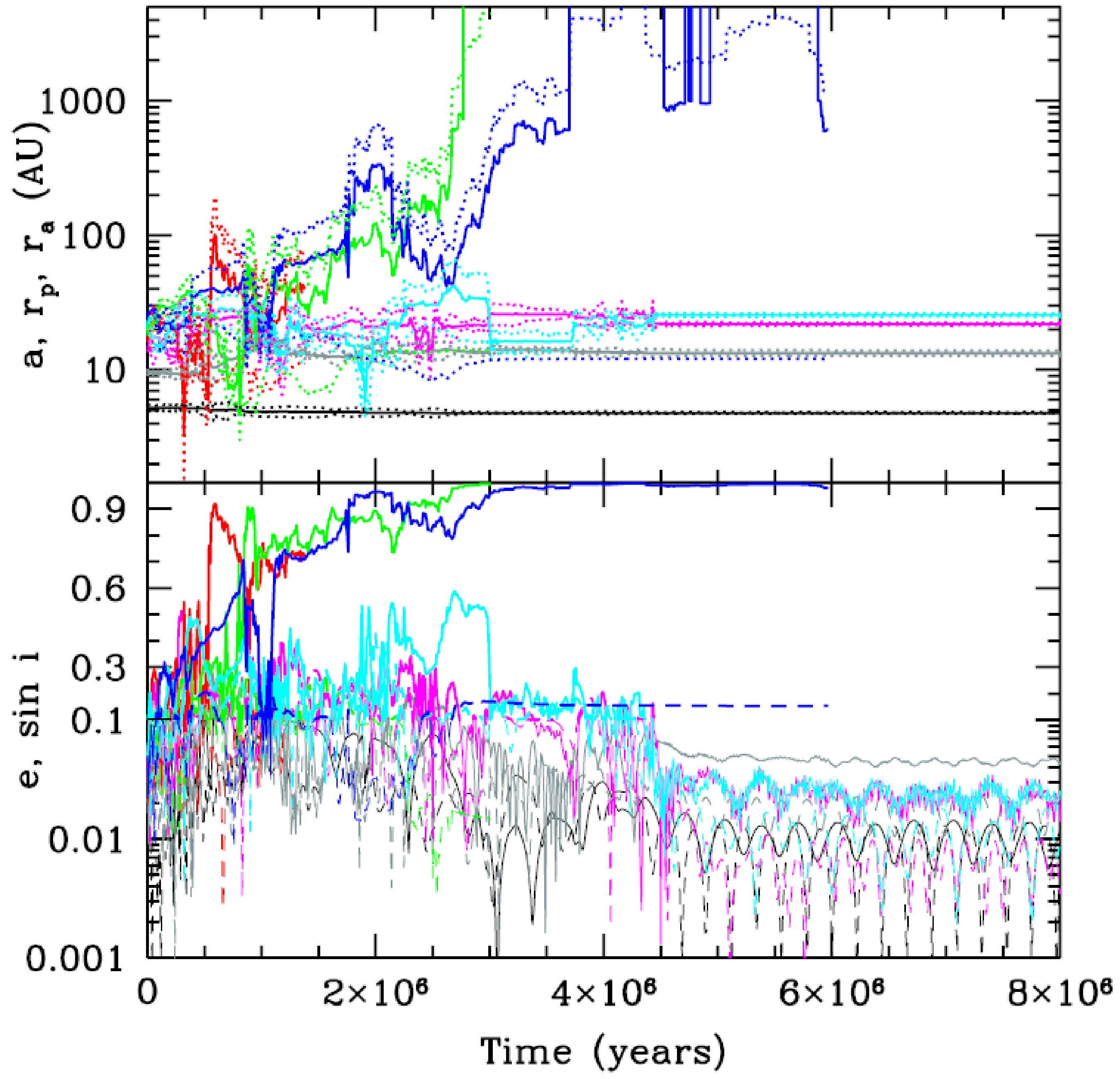
Tsiganis et al. 2005

Outline of GLS Scenario



GLS 04
Kenyon & Bromley 06
Thommes et al. 99, 02

Jupiter, Saturn, 5 Ice Giants + small bodies



- Near threshold of instability: (σ~0.06 g/cm^2 vs Σ ~1.8 g/cm^2)
- Three of five ice giants ejected
- Dynamical friction damps e & i
- Outermost oligarch ends at 25.6AU

Ford & Chiang, 2007

Conclusions

- Many giant extrasolar planetary systems very different from our solar system
- Interactions of multiple planet systems can contain information about their orbital history
- Statistical analyses of exoplanet population can be compared to predictions of planet formation
- Follow-up observations can search for additional planets and test orbital migration models
- Our own solar system may have once contained giant planets on eccentric orbits

Questions?