Secular Evolution of Multiple Planet Systems & Implications for the Planet Scattering Model

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KITP program on Theory & Observation of Exoplanets

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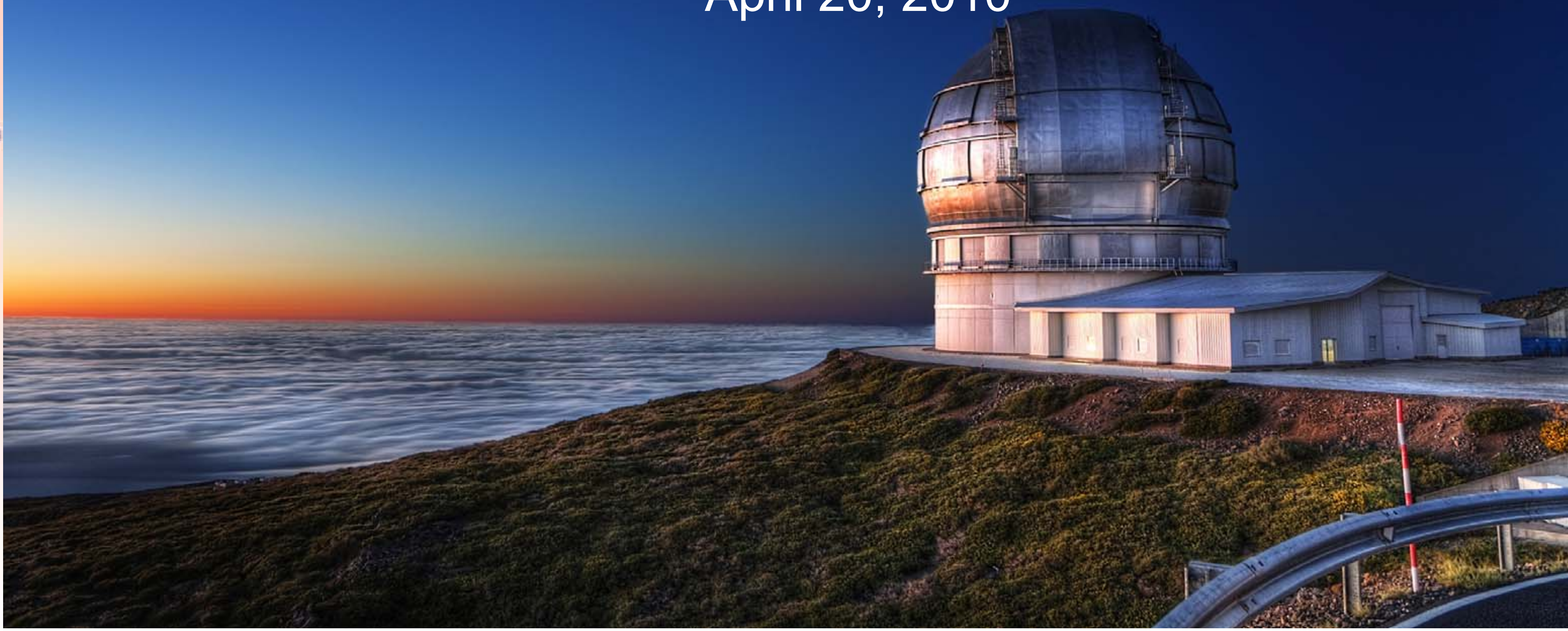

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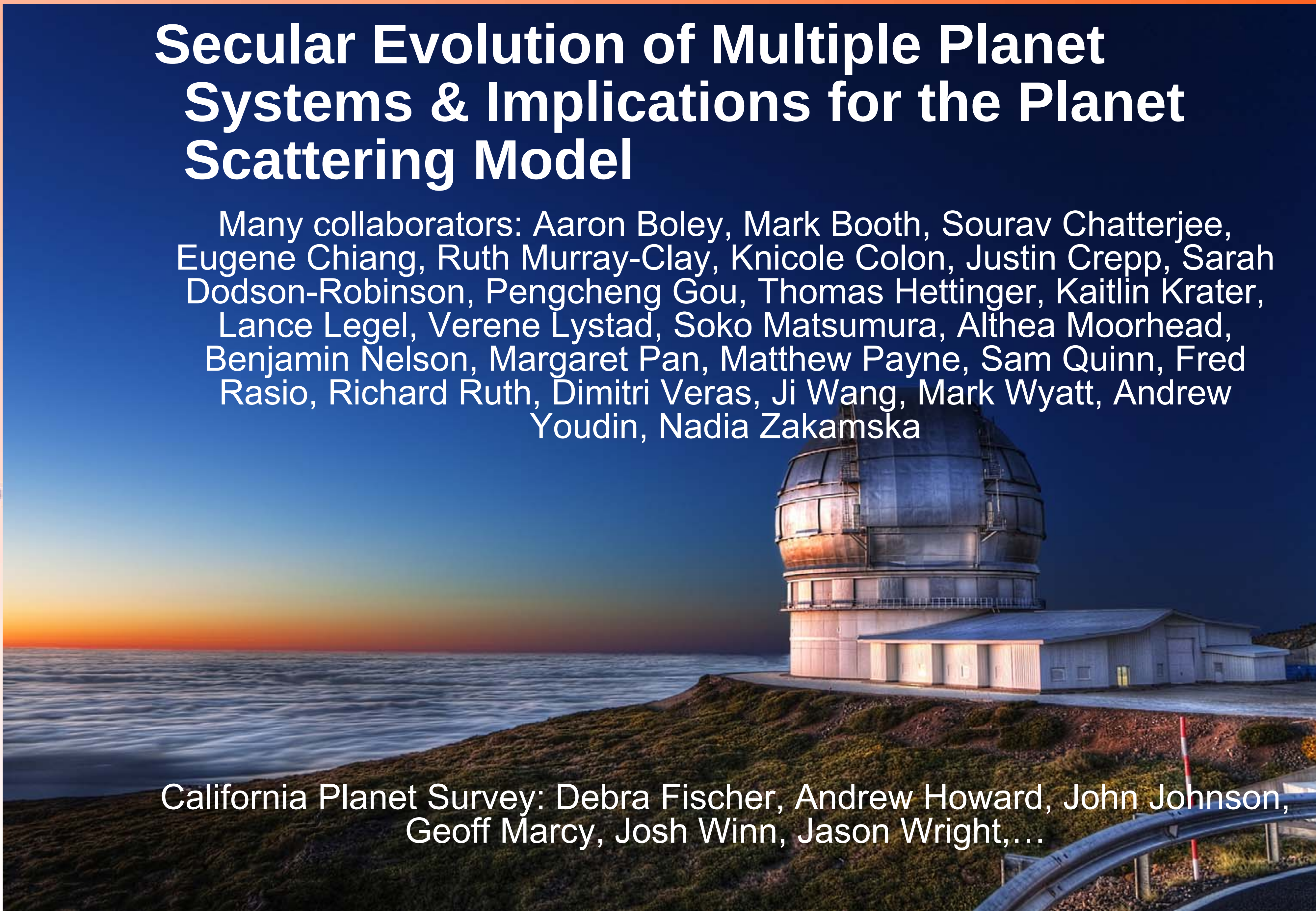
Secular Evolution of Multiple Planet Systems & Implications for the Planet Scattering Model

Many collaborators: Aaron Boley, Mark Booth, Sourav Chatterjee, Eugene Chiang, Ruth Murray-Clay, Knicole Colon, Justin Crepp, Sarah Dodson-Robinson, Pengcheng Gou, Thomas Hettinger, Kaitlin Krater, Lance Legel, Verene Lystad, Soko Matsumura, Althea Moorhead, Benjamin Nelson, Margaret Pan, Matthew Payne, Sam Quinn, Fred Rasio, Richard Ruth, Dimitri Veras, Ji Wang, Mark Wyatt, Andrew Youdin, Nadia Zakamska



California Planet Survey: Debra Fischer, Andrew Howard, John Johnson, Geoff Marcy, Josh Winn, Jason Wright,…

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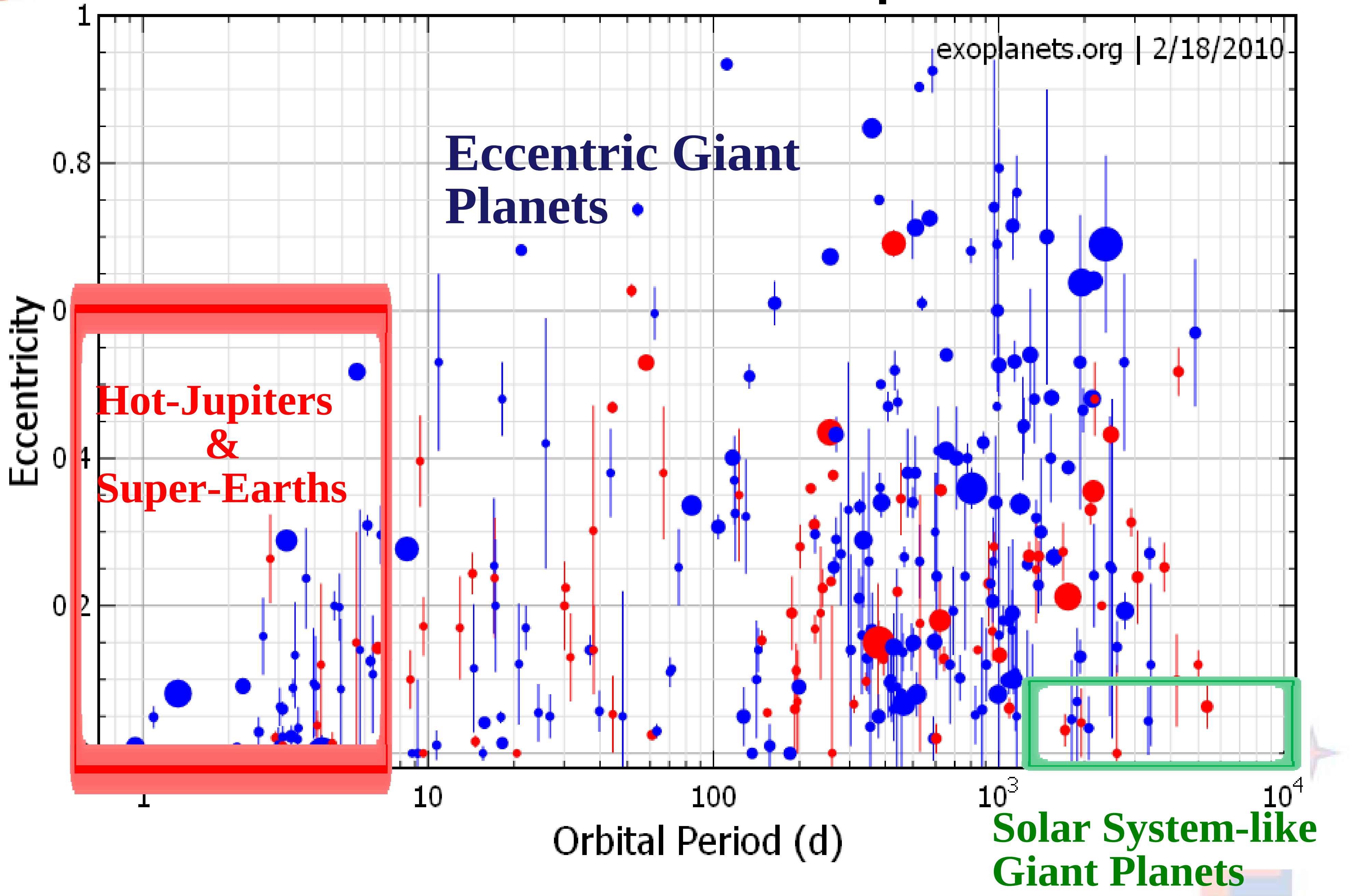
Particularly relevant papers:

- "Secular Orbital Dynamics of Hierarchical Two Planet Systems"
  Veras & Ford 2010 accepted to ApJ; arXiv:1004.1421)
- "Secular Evolution of HD 12661: A System Caught at an Unlikely Time"
  Veras & Ford 2009 ApJ 690, L1
- "Apsidal Behavior among Planetary Orbits: Testing the Planet Scattering Model"
  Barnes & Greenberg 2007 ApJ 659, L53
- "Extrasolar Planetary Systems Near a Secular Separatrix"
  Barnes & Greenberg 2006 ApJ 638, 478
- "Planet-planet scattering in the upsilon Andromedae system"
  Ford et al. 2005 Nature 434, 873.

Eccentricities of Exoplanets



Planet-Planet Scattering Model

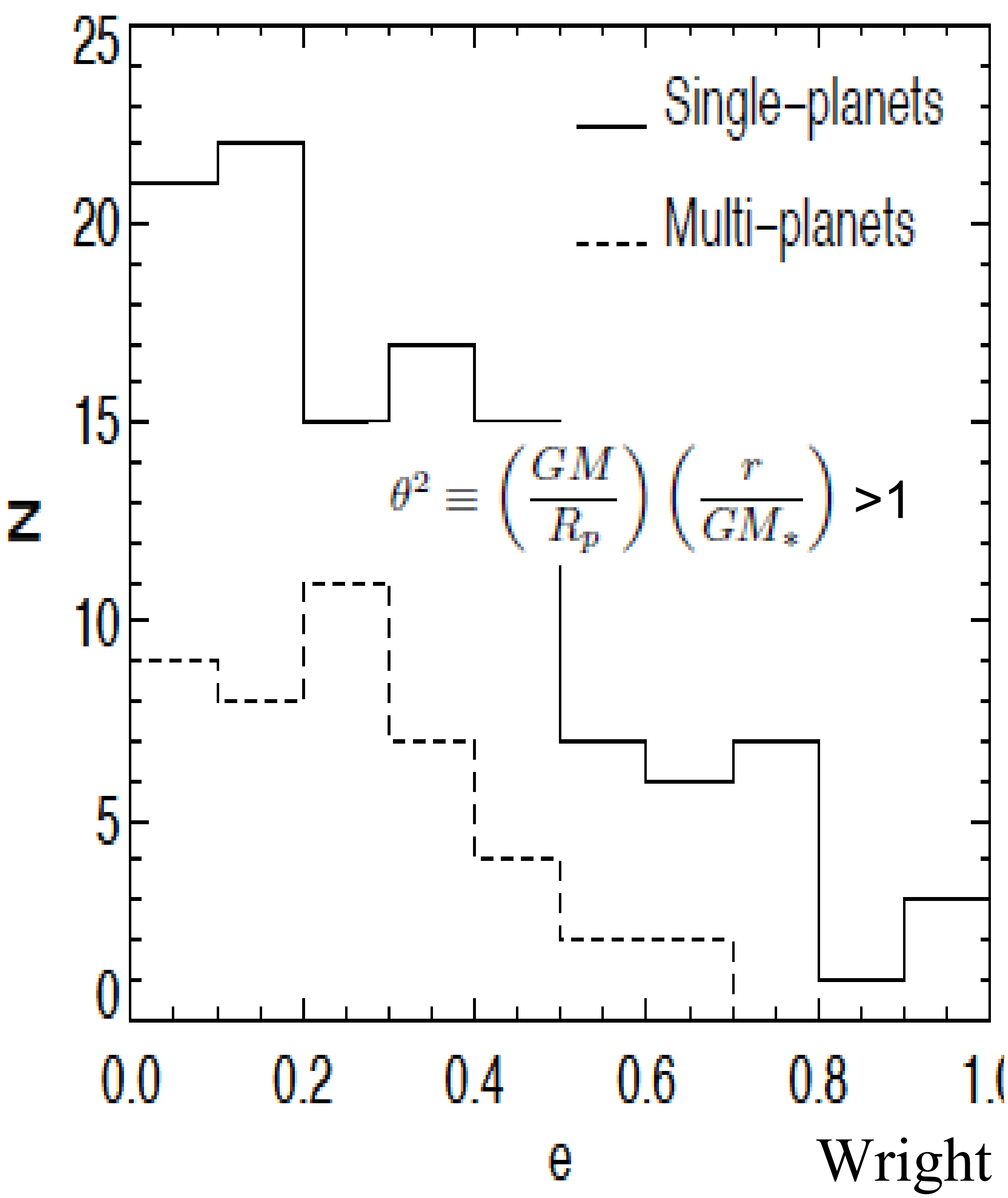
- Assumptions for individual eccentric systems:
  - Multiple massive planets formed around star
  - System formed with "dynamically active" planet masses and separations (e.g., Chatterjee et al. 2008; Juric & Tremaine 2008)
  - At least one planet capable of ejecting other bodies: $v_{esc,pl}/v_{esc,star}>1$ (e.g., Ford & Rasio 2008, Raymond et al. 2009)
  - Last planet scattering event occurs once gas disk has begun to dissipate (e.g., Matsumura et al. 2010)

Planet-Planet Scattering Model

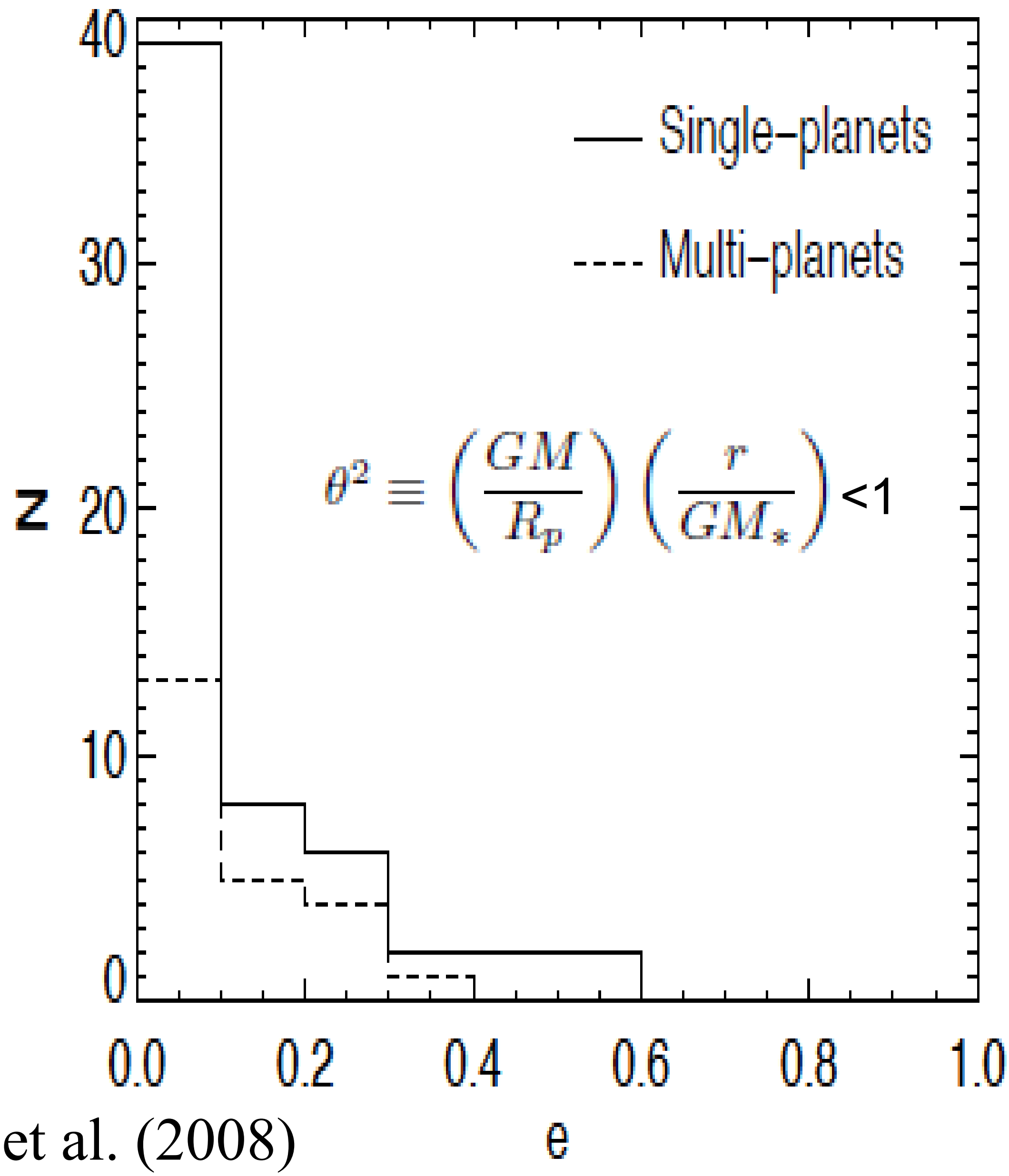
- Predictions for individual eccentric systems: (robust, many authors)
  - The most massive planet remains bound
  - Semi-major axis distribution depends on initial conditions
  - Eccentricity distribution is relatively insensitive to ICs
  - Inclinations are typically excited (but loose correlation w/ e)
  - Various correlations (often depend on detailed assumptions)
- Prediction if initially exactly 2 circular planets: (Ford & Rasio 2008)
  - Only massive planet in the system today
  - Eccentricity distribution is only sensitive to planet mass ratio
  - Maximum eccentricity of 0.8 (~358/362, 210/214 w/ e>0.1)

Eccentricity Distribution

Planets that Scatter Efficiently



Planets that Scatter Inefficiently



Wright et al. (2008)

What Determines Final Orbits?

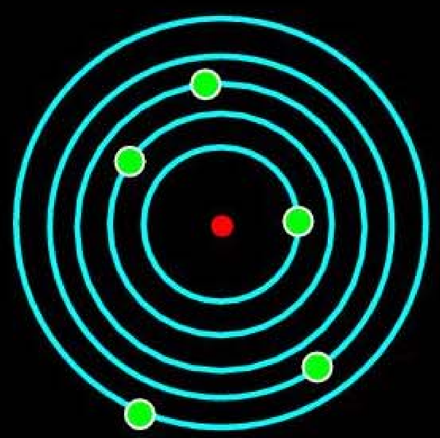


Illustration by E. Chiang

What Determines Final Orbits?

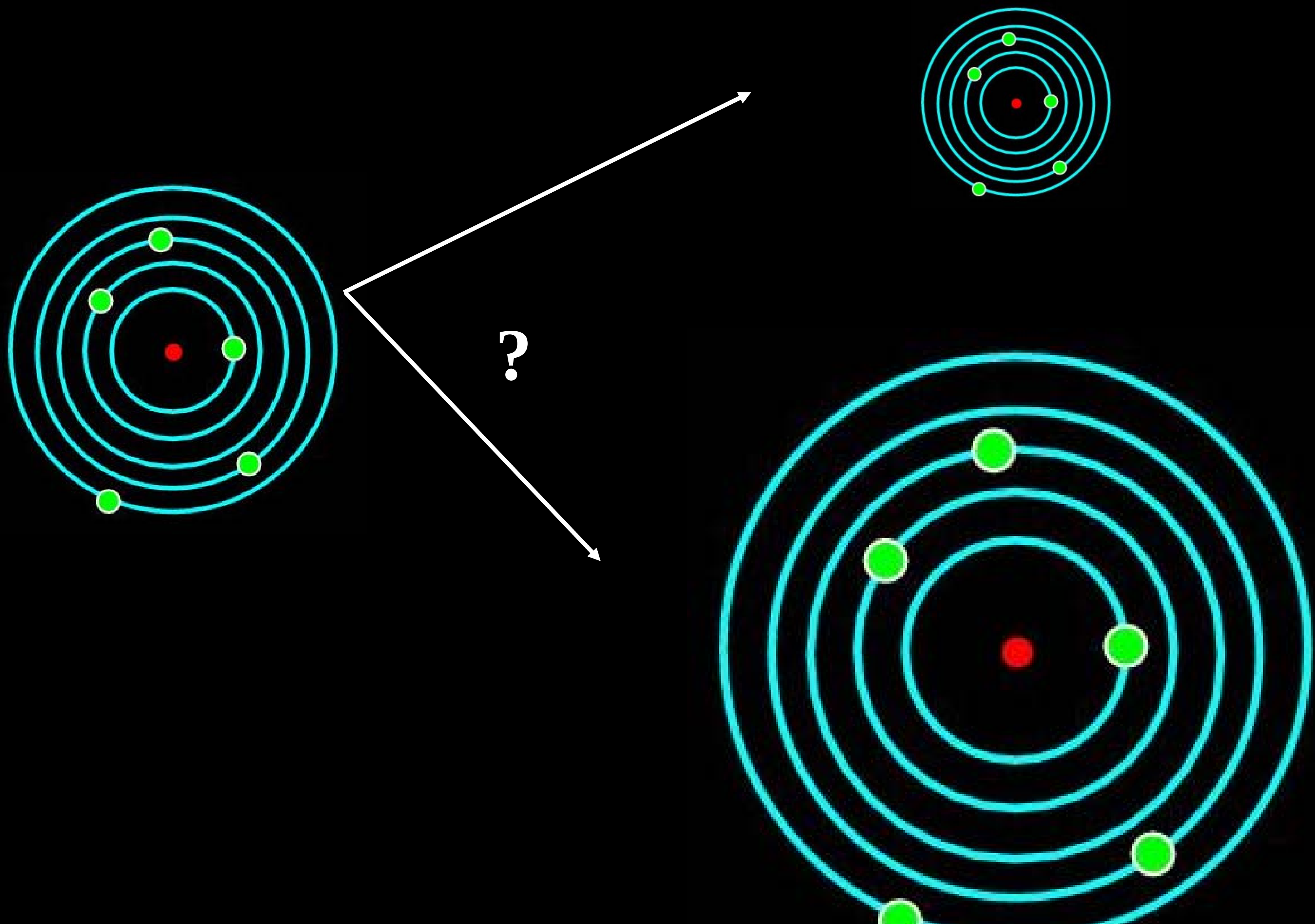


Illustration by E. Chiang

Late Stages of Planet Formation

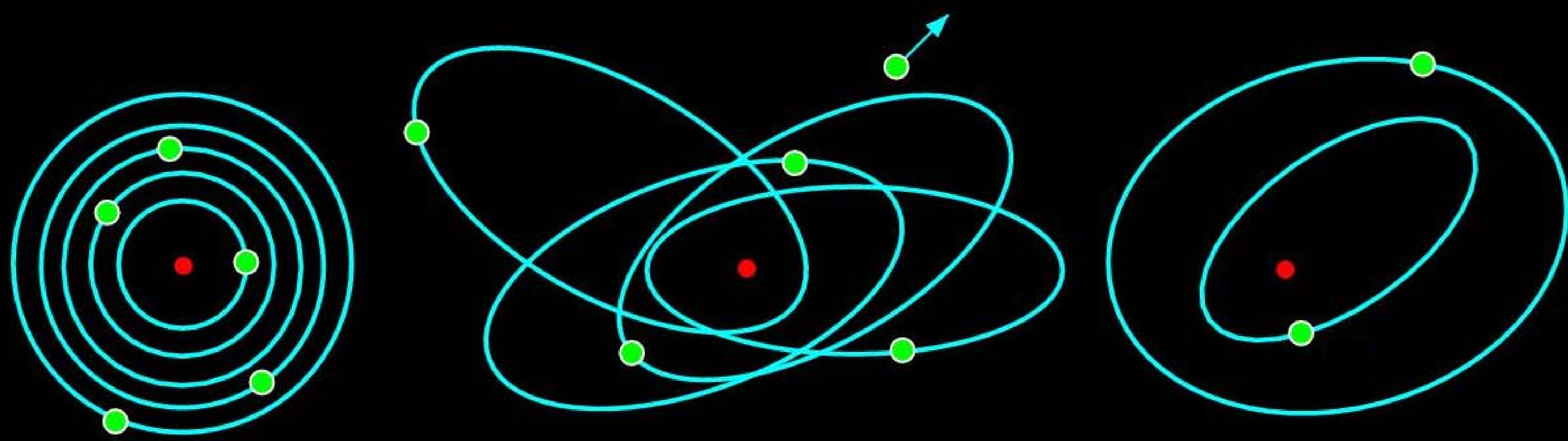
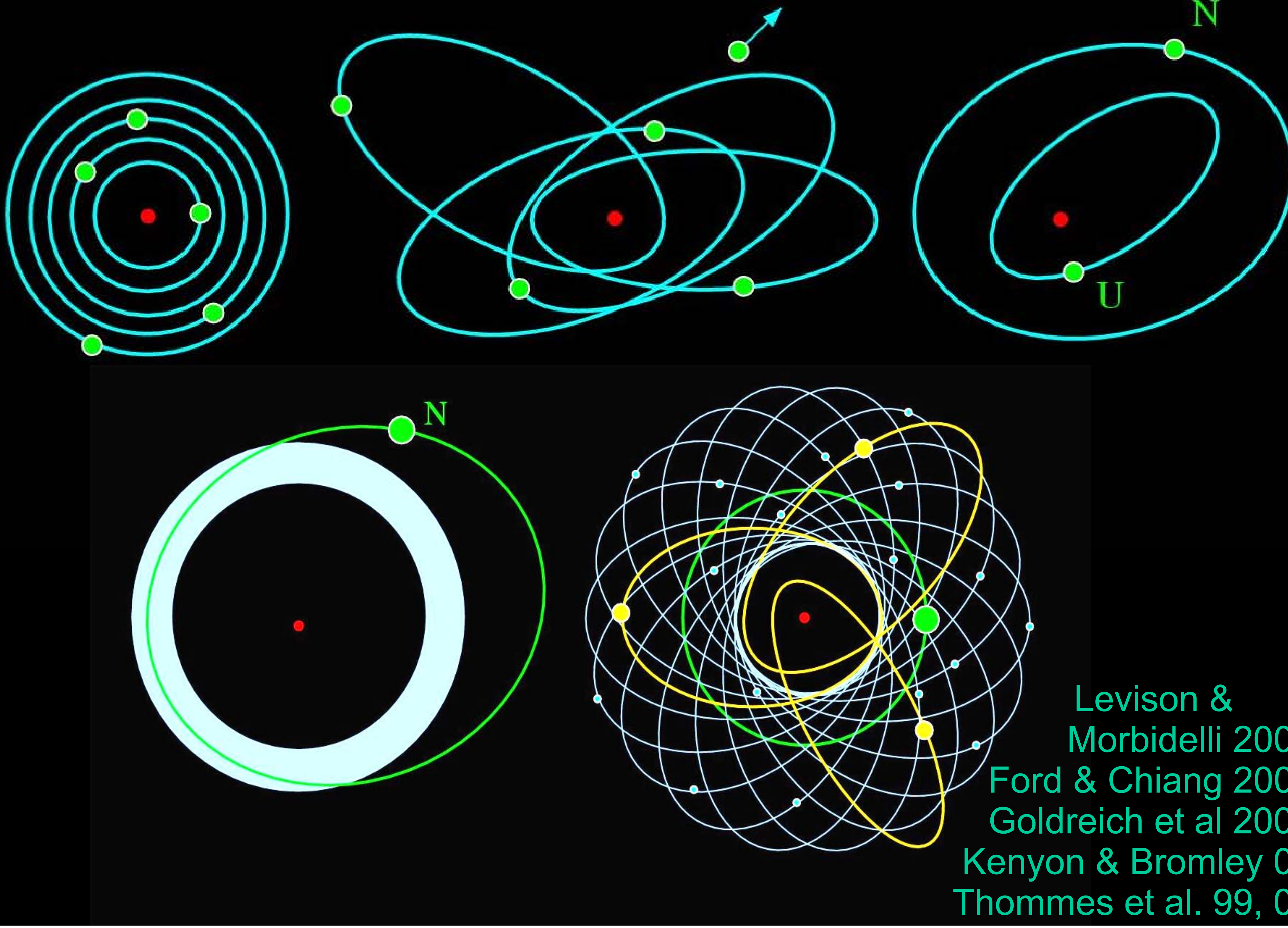


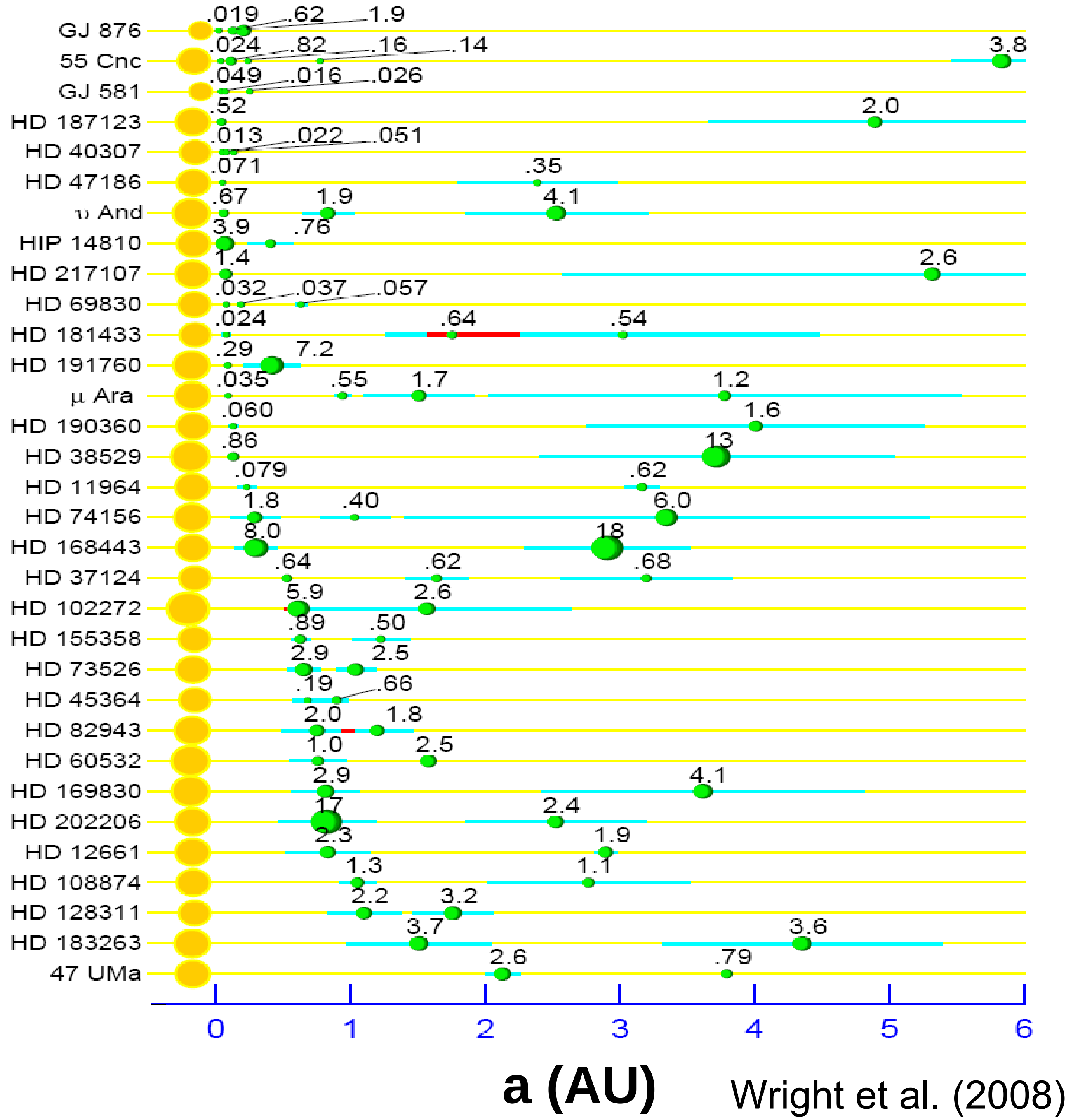
Illustration by E. Chiang

Late Stages of Planet Formation



Levison &
Morbidelli 2007
Ford & Chiang 2007
Goldreich et al 2004
Kenyon & Bromley 06
Thommes et al. 99, 02

Multiple Planet Systems

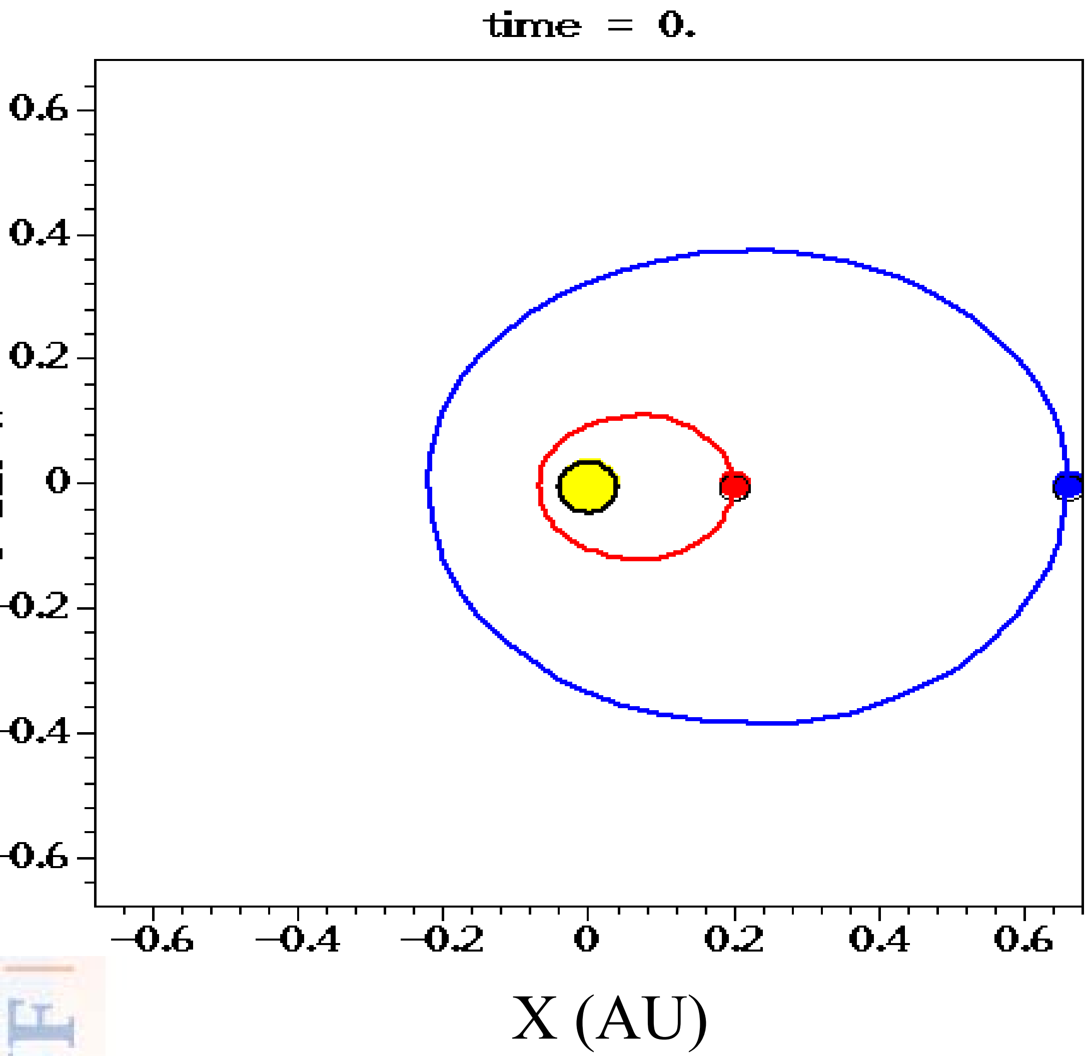


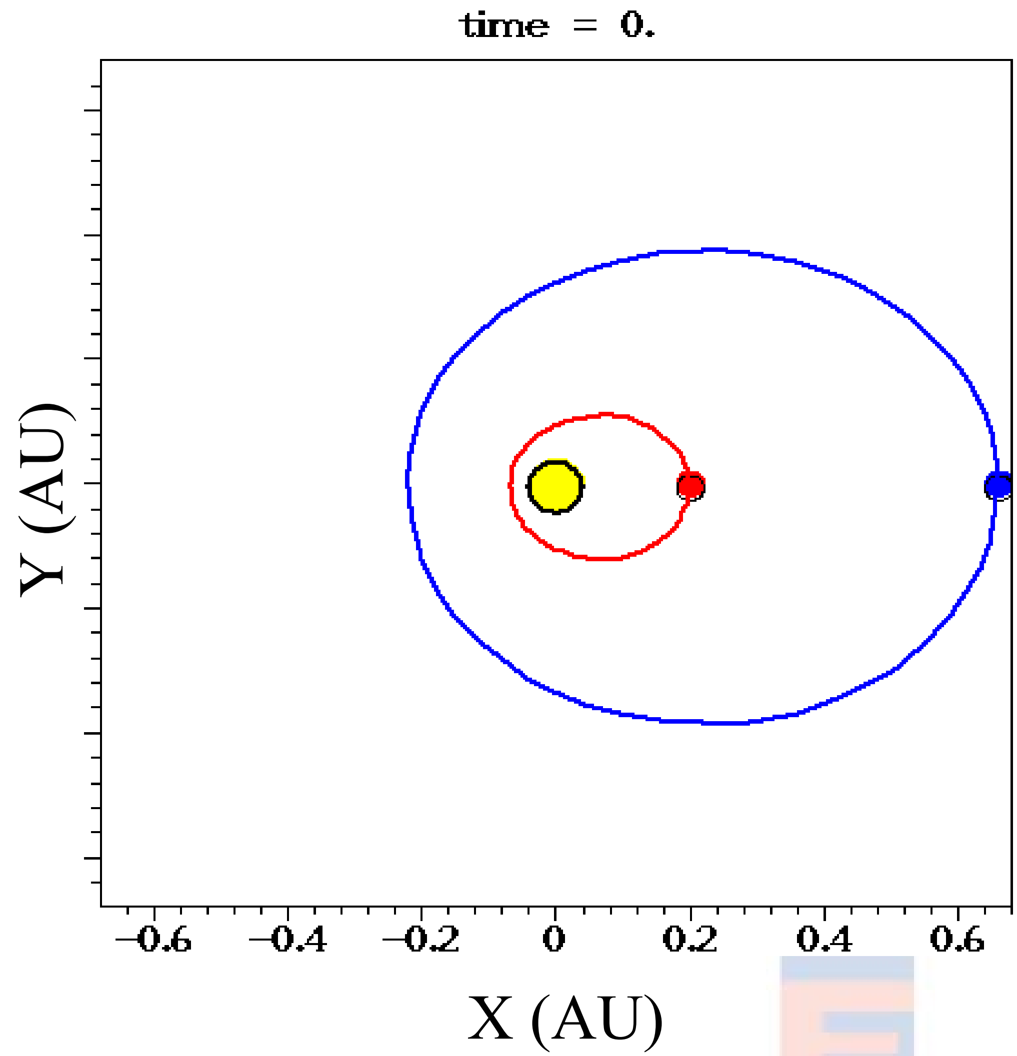
Architecture of Multi-Planet Systems

- Multiple Planet Systems: ~41
- Hierarchical (No Significant Interactions, assuming low-inclination)
- Secular Evolution (Insignificant short-term interactions)
  - History of eccentricity & inclination excitation
  - If one is tidal evolving, can probe planet structure
- Mean Motion Resonances (short & long-term interactions)
  - Evidence for convergent migration
  - Relative frequency of different MMRs can probe:
    - Migration rates
    - Eccentricity at time of migration
    - Significance of turbulence
    - Relative importance of migration via gas disk versus planetessimal disk

Modes of Secular Evolution

Circulation vs Libration



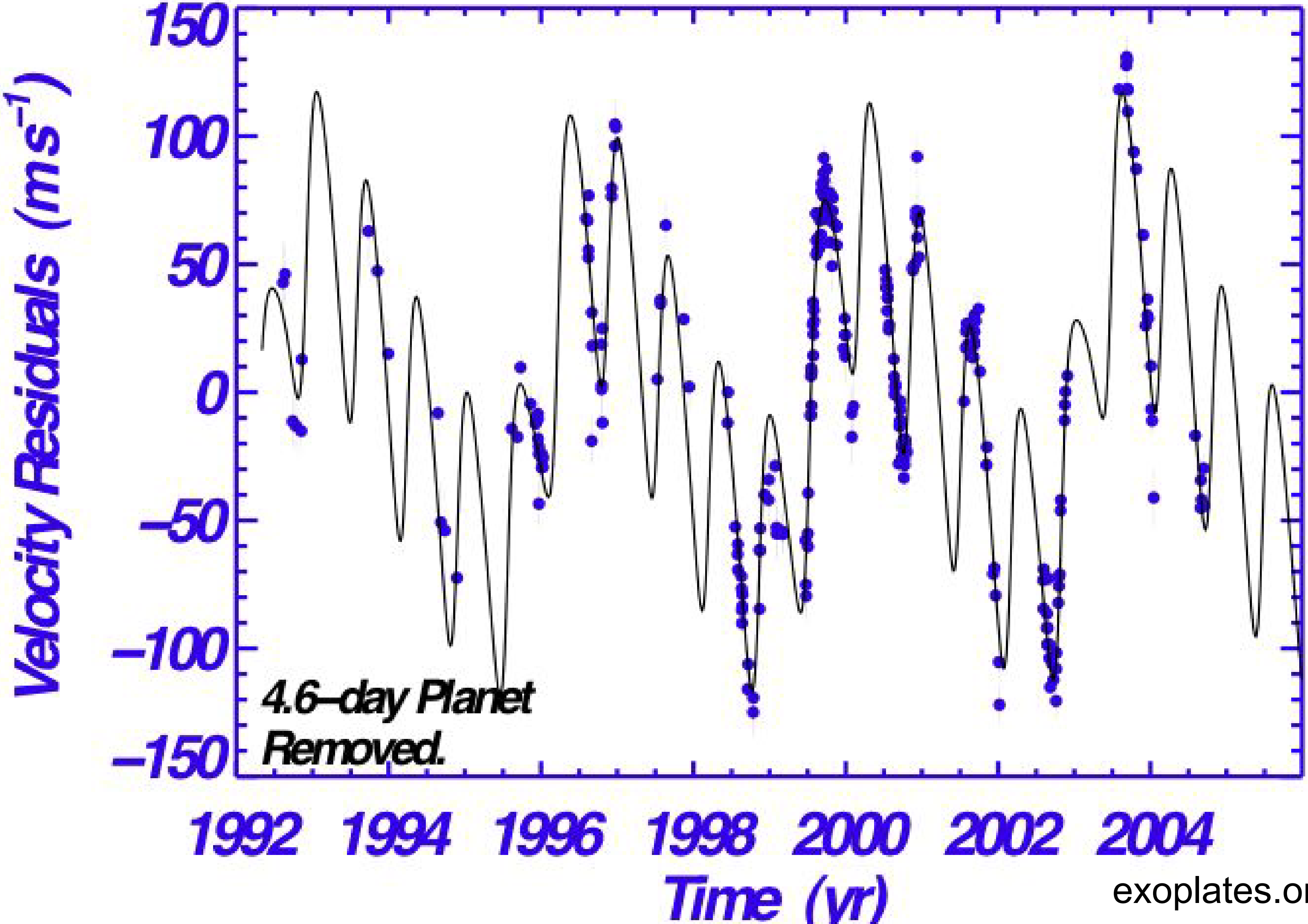


Ford

υ Andromedae

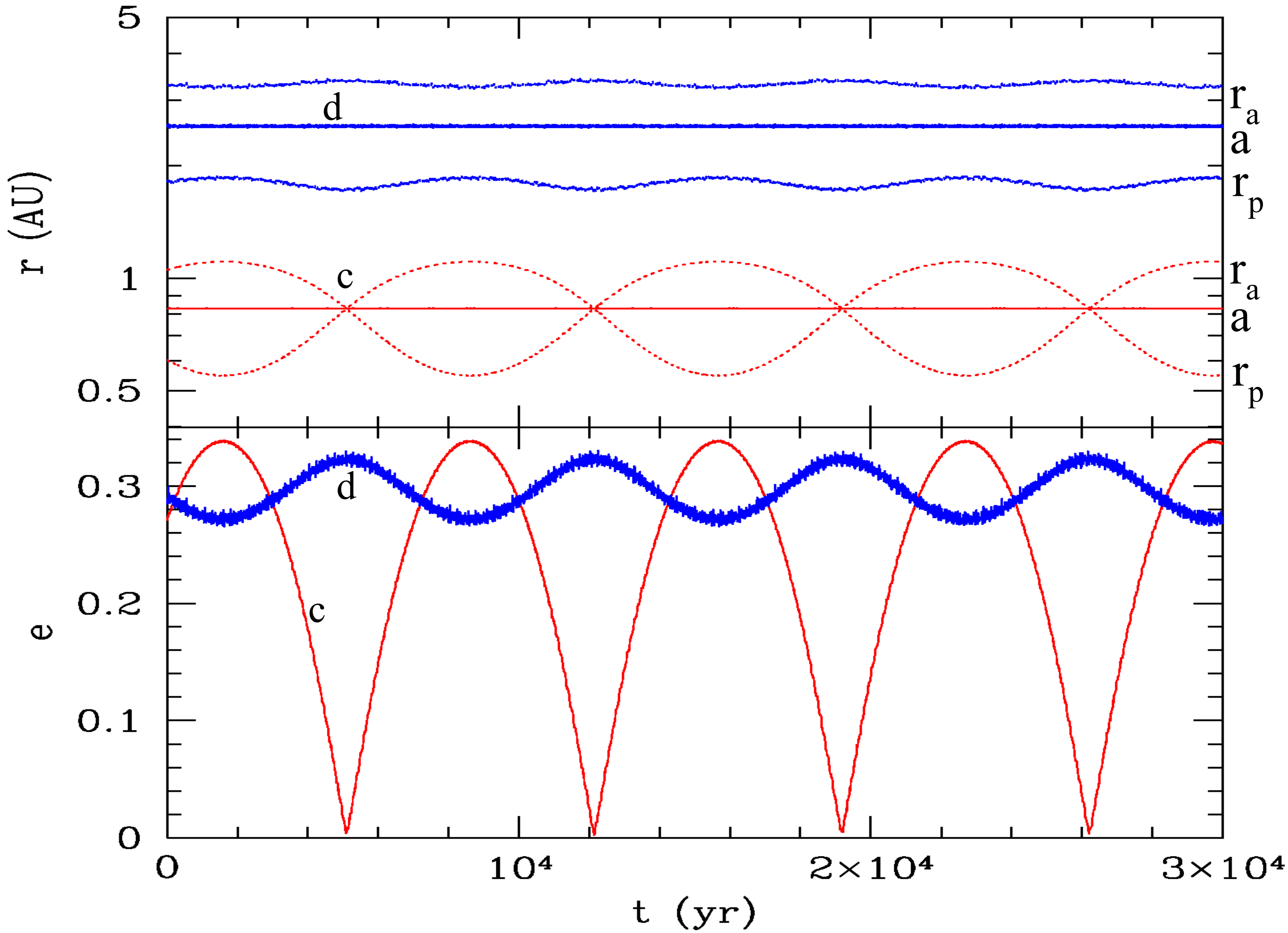
- First multiple planet system discovered around main sequence (F8V, 1.3 $M_{\odot}$, 3Gyr) star in 1999.
- Hundreds of radial velocity observations
- υ And c & d have significant eccentricities (~0.26 & 0.28 ±0.02)
- Significant secular eccentricity evolution
- What is the origin of these eccentricities?

Ups And: Radial Velocities



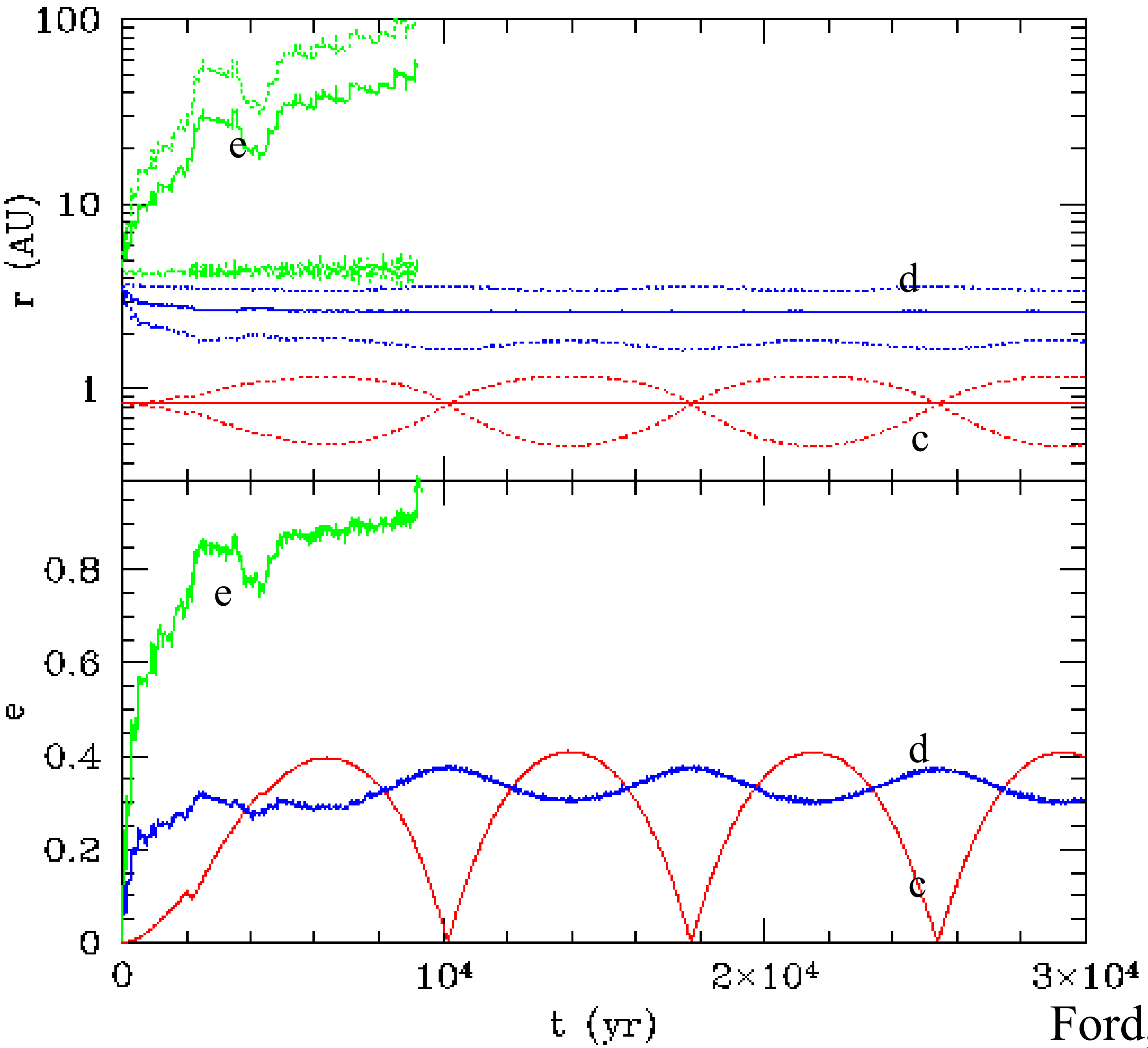
exoplates.org

Secular Evolution of Upsilon Andromedae



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

$e_d = 0.29$

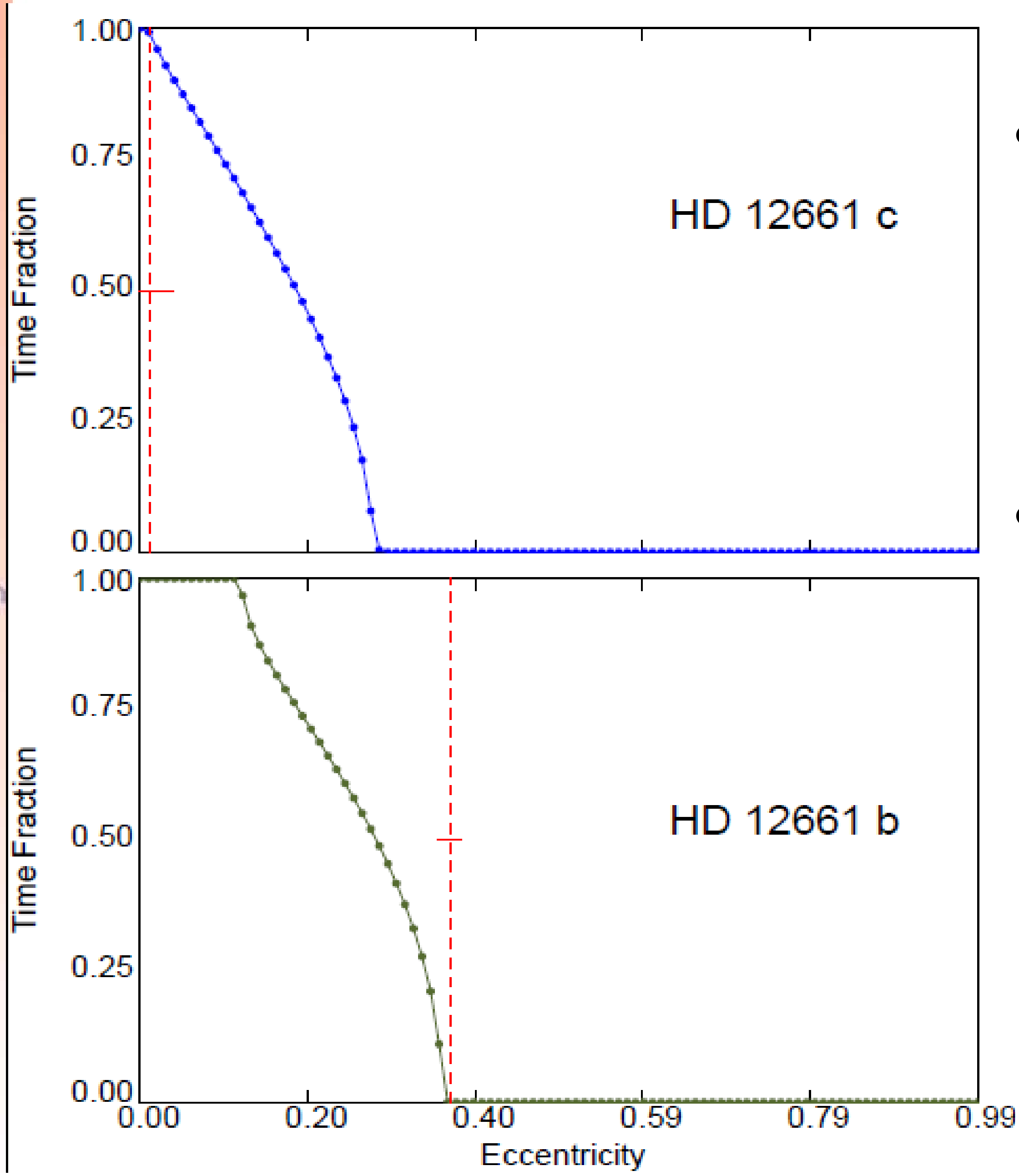
Malhotra 2002

Ford, Lystad, Rasio 2005

Conclusions for υ And c & d

- Very near boundary of libration & circulation
- If librating, large amplitude
- υ And c periodically returns to $e_c \sim 0.01$
- Implies υ And c & d initially on circular orbits when υ And d received impulsive perturbation
- Secular evolution transfer eccentricity to υ And c
- Impulsive perturbation naturally provided by Planet-Planet scattering of ~1.9 M_{Jup} planet
- Multiple planet systems can provide valuable information about history of planet formation

Secular Evolution of HD 12661



- Planet c nearly circular now, but periodically acquires large eccentricity
- Planet b typically has smaller eccentricity (but does not return to circular orbit)

Veras & Ford 2008

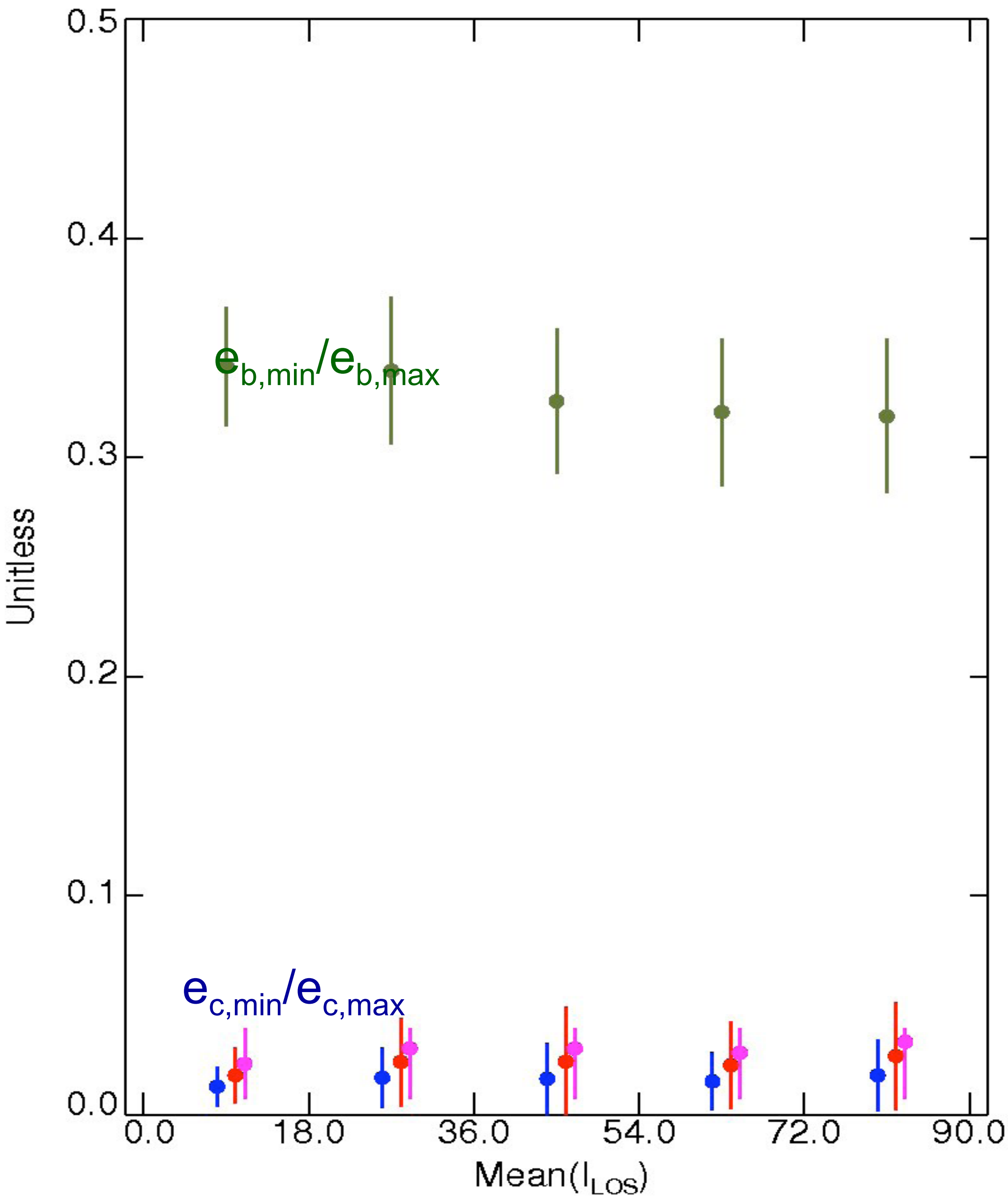
Secular Evolution of HD 12661

Depends on Relative Inclination

Relative Inclination (degrees)	Libration About 0 degrees	Libration About 180 degrees	Stable	Isotropic
0	0%	100%	100%	No data
0-30	8.3%	91.8%	99.3%	6.7%
30-60	35.6%	64.4%	92.9%	18.3%
60-90	47.0%	53.0%	66.8%	25.0%
90-120	No data	No data	0.2%	25.0%
120-150	49.1%	50.9%	22.8%	18.3%
150-180	59.5%	40.5%	94.8%	6.7%
Isotropic	40.8%	59.2%	55.9%	No data
Prograde	25.8%	64.2%	80.7%	No data

Veras & Ford 2008

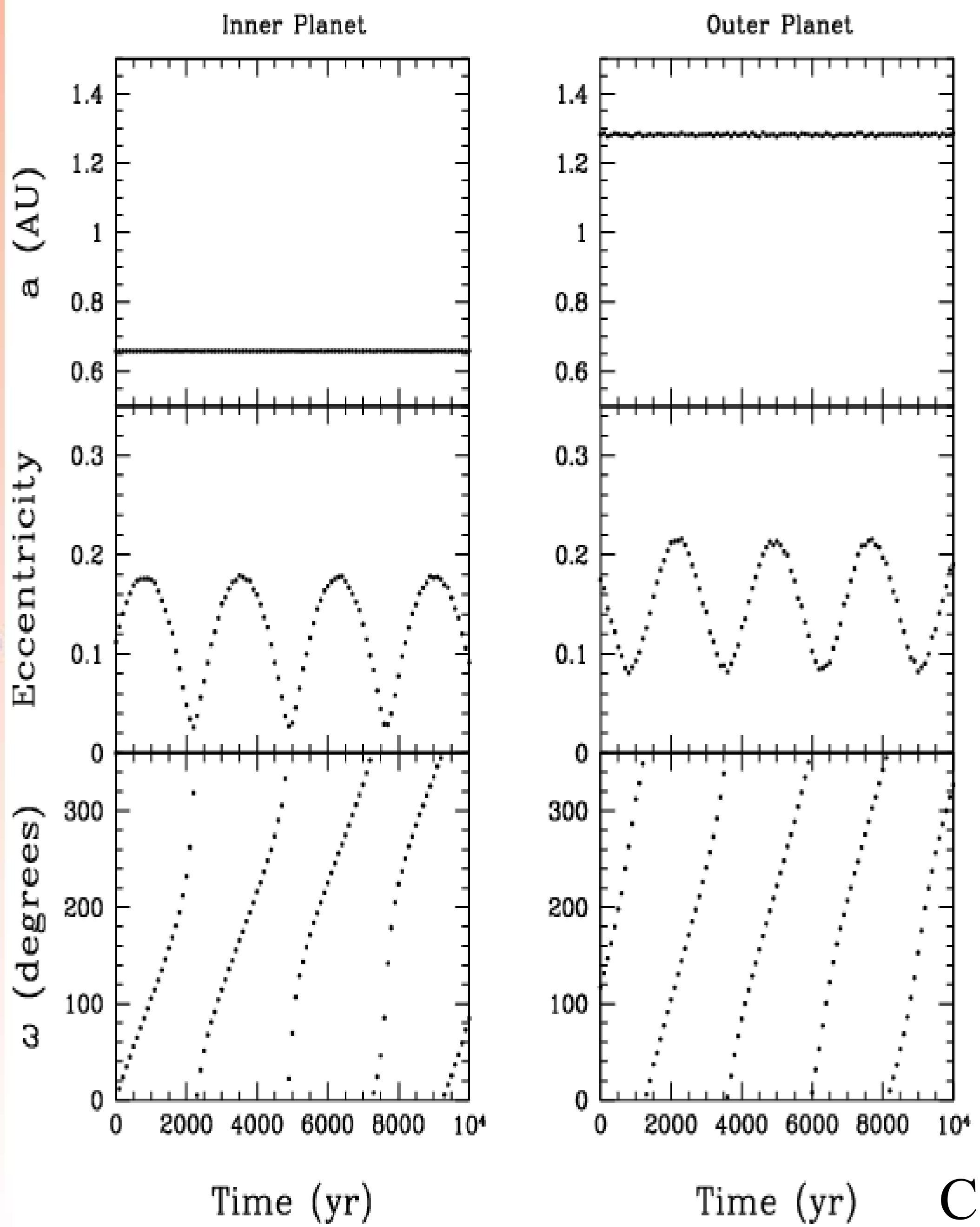
Secular Evolution of HD 12661



- Planet c nearly circular now, but periodically acquires large eccentricity
- Planet b typically has smaller eccentricity (but does not return to circular orbit)

Veras & Ford 2008

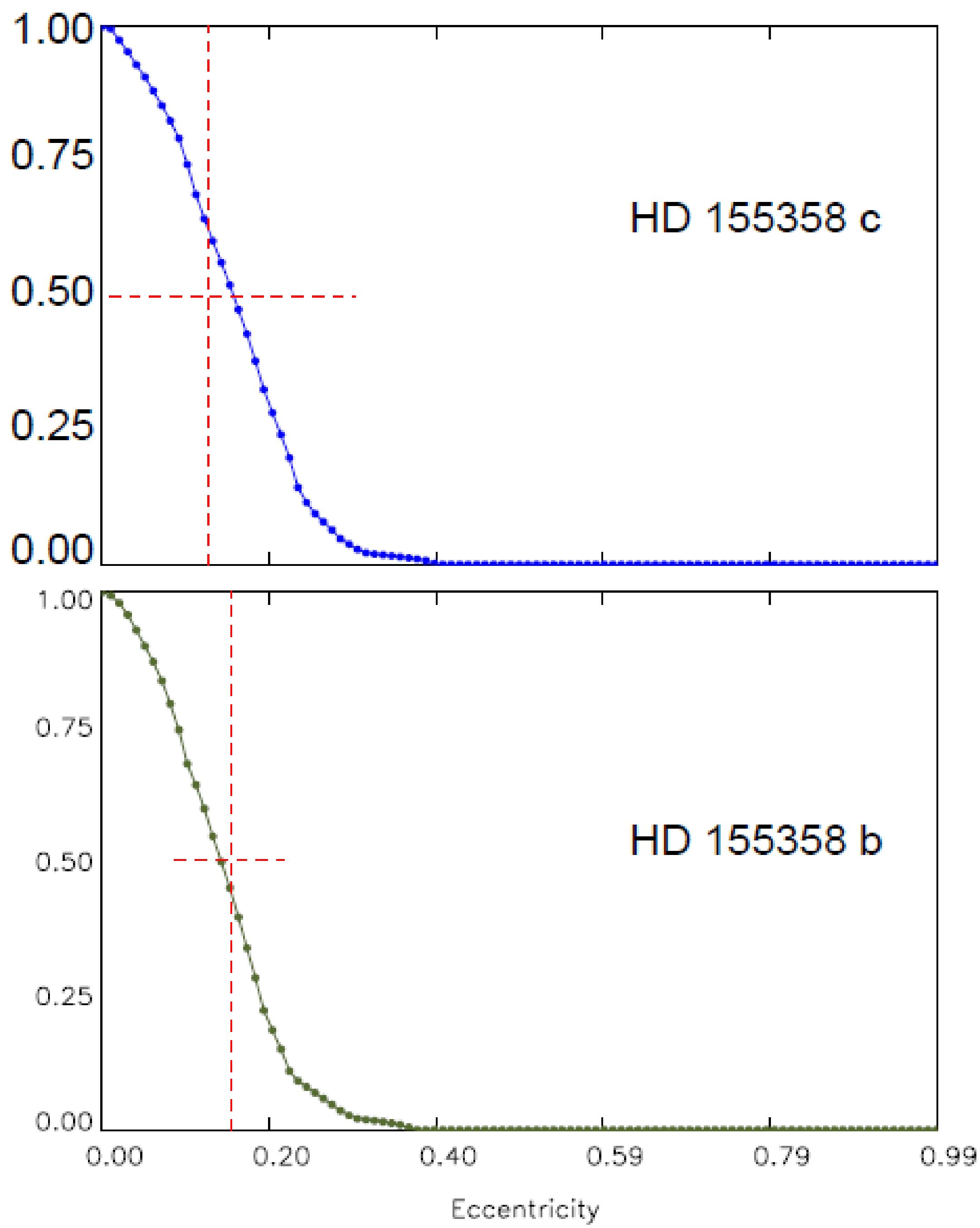
Secular Evolution of HD 155358



Cochran et al. 2007

- Best-Fit orbital solution lies near boundary of secular apsidal evolution
- Like Ups And & HD 12661?
- Perhaps too many systems like this? (Barnes & Greenberg 2006, 2007)

Secular Evolution of HD 155358



- Best-Fit orbital solution lies near boundary of secular apsidal evolution
- Like Ups And & HD 12661?
- Maybe, Maybe not
- Current orbit not known well enough

Veras & Ford

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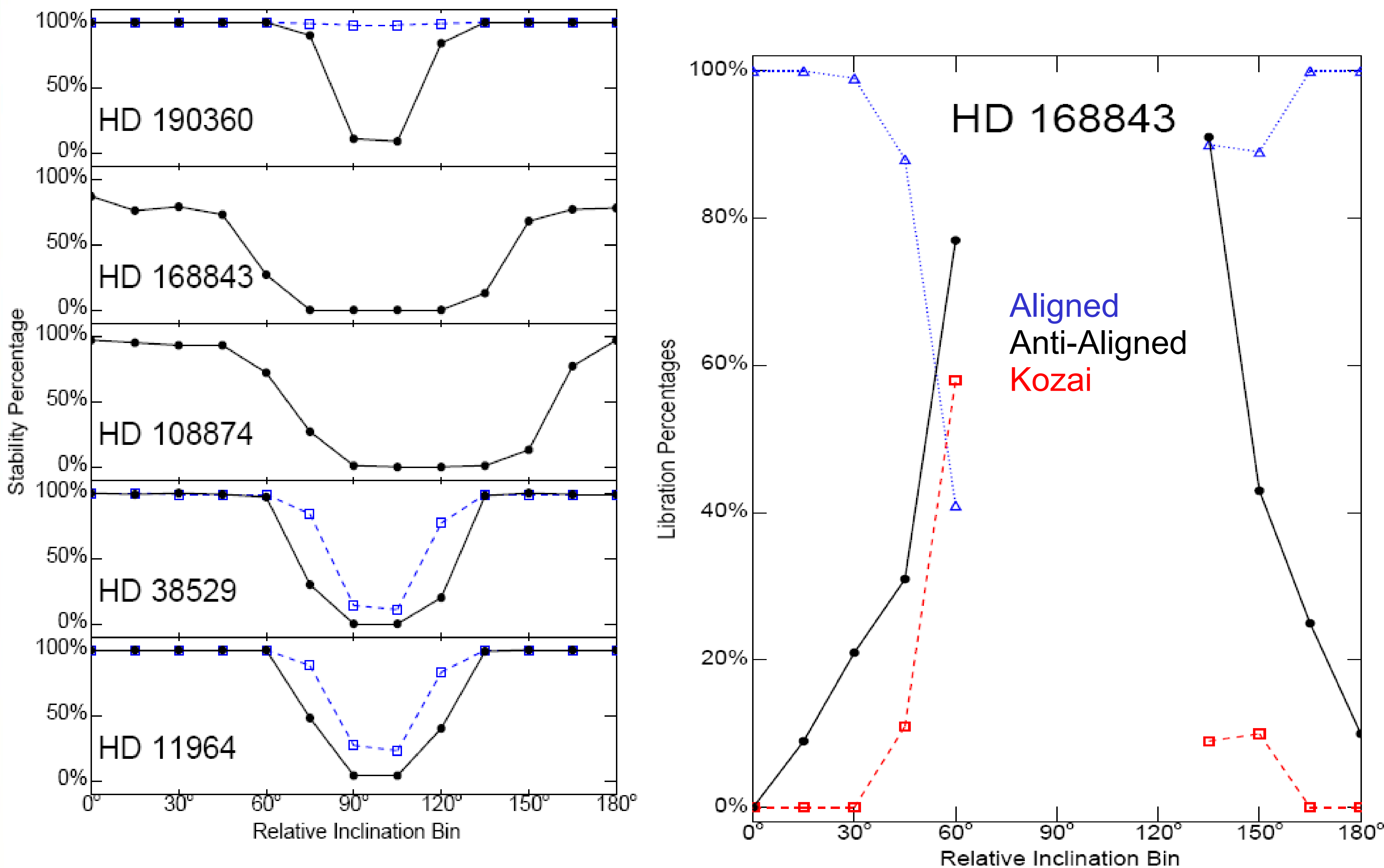
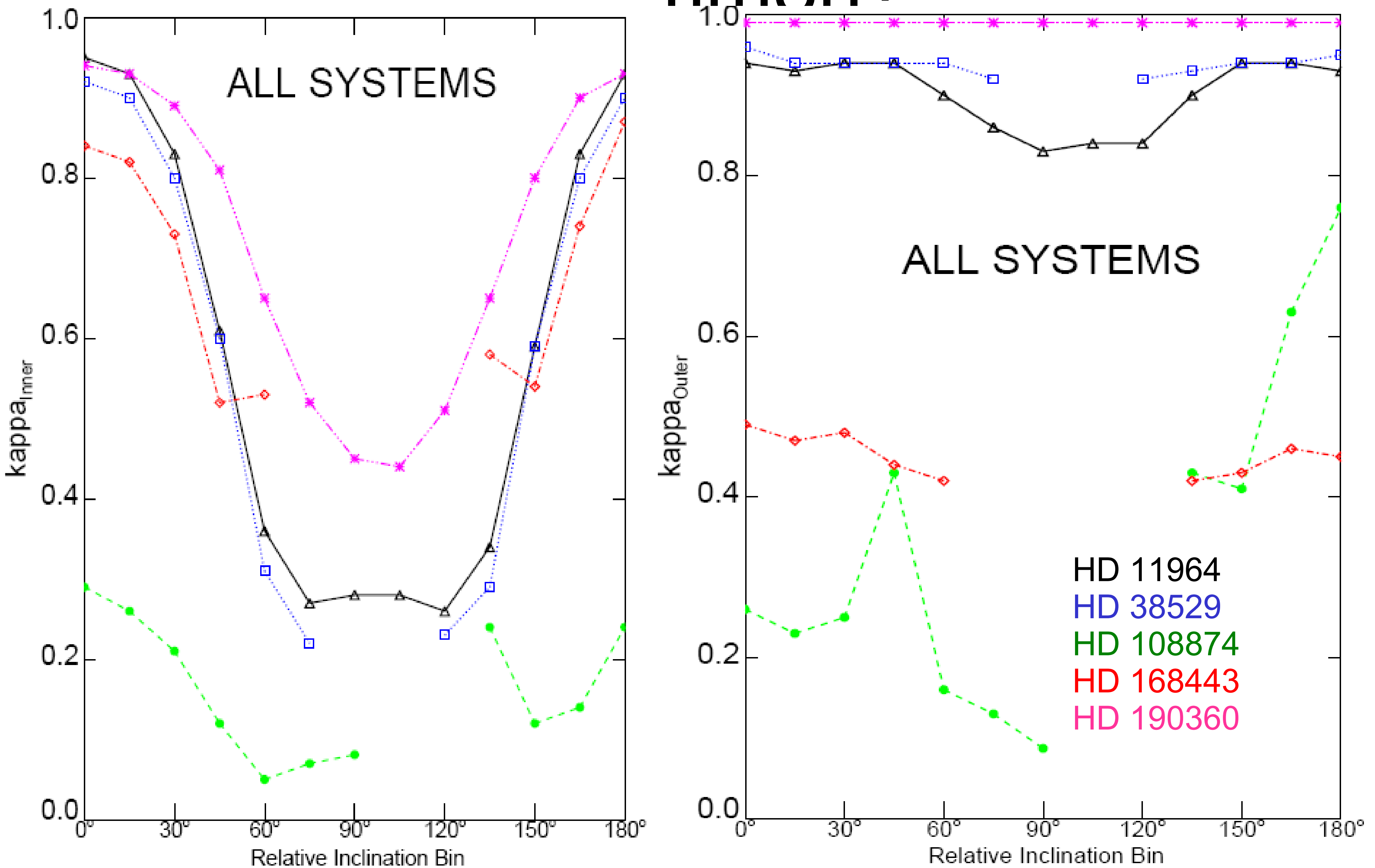
Stability & Secular Evolution depend on Relative Inclinations



Veras & Ford 2010

Is “Near-Sepratrix” behavior common?

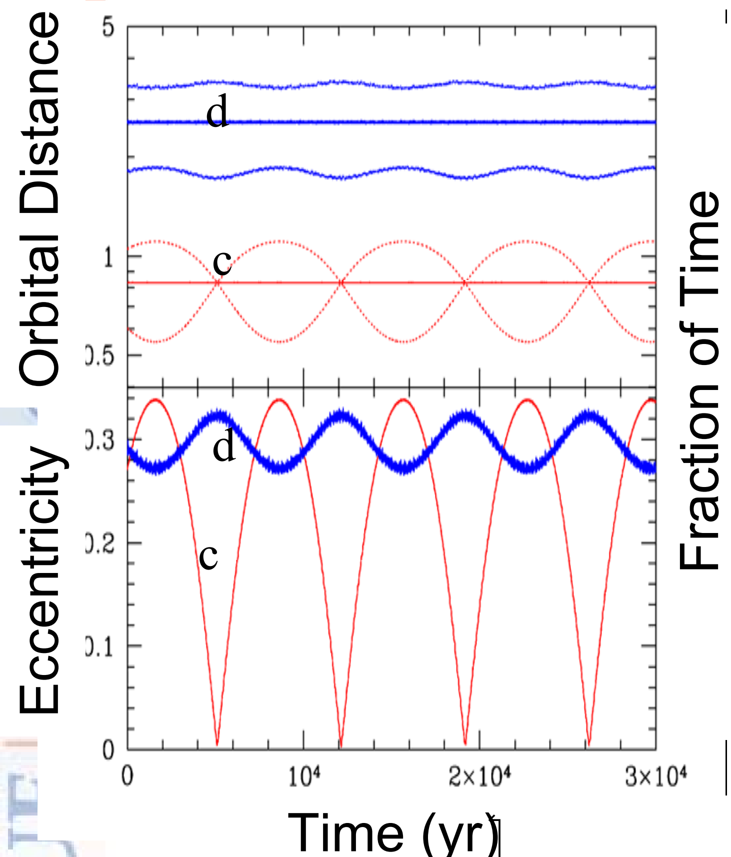


Veras & Ford 2010

Secular Orbital Evolution

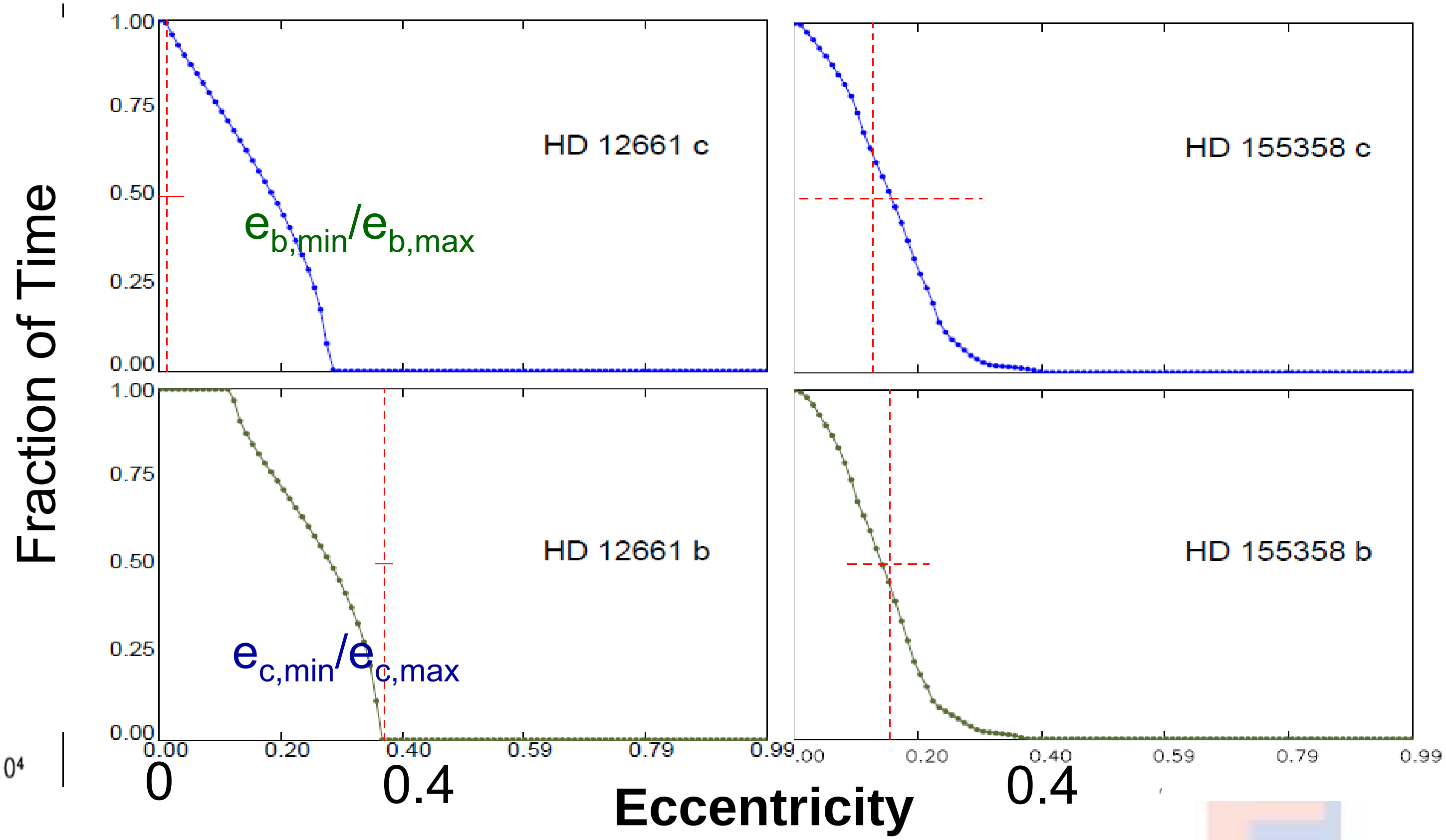
- Secular evolution uniquely determined for few very-well observed systems
- Upsilon And & HD 12661 show evidence for impulsive excitation
- More often measurement errors & unknown masses/inclinations leave ambiguities in secular evolution

Upsilon Andromedae c & d



Ford, Lystad, Rasio 2005

HD 12661 b & c **HD 155358 b & c**



Veras & Ford 2008

Veras & Ford 2010

Future Observational Tests

- Orbital Evolution of Multiple Planet Systems:
  (working to obtain many more high-precision RVs; SIM?)
- Architecture of Planetary Systems
  - Period, Mass, Eccentricity Correlations: now RV searches, soon Kepler, eventually SIM
  - Eccentricity & Inclination Evolution: Rossiter effect for transiting planets; planet-scattering predicts distribution
- Frequency of Resonant Planets:
  - Now: RV searches
  - Soon: space-based transit searches?
  - Transit timing variations observations gaining sensitivity