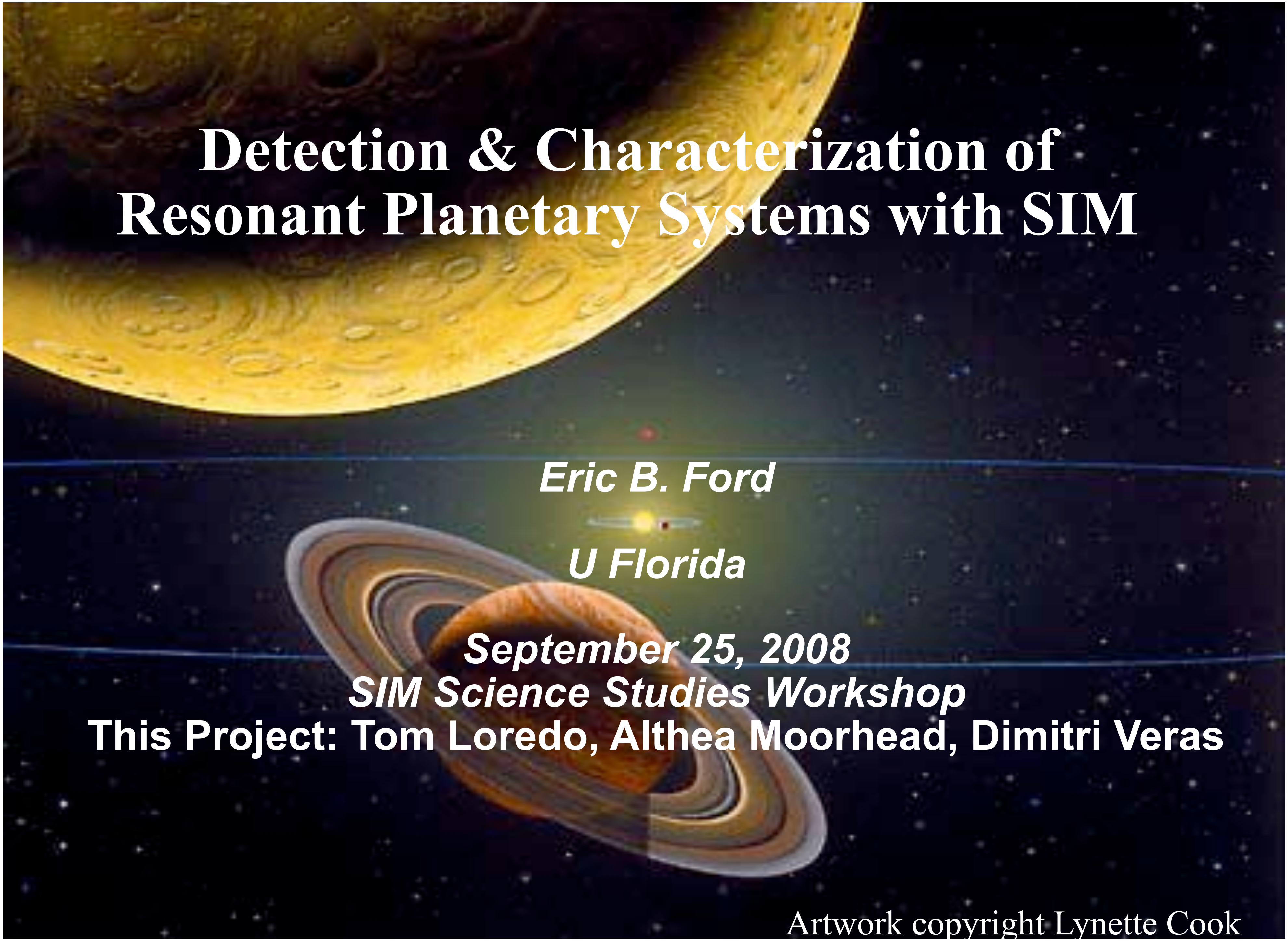


Detection & Characterization of Resonant Planetary Systems with SIM

Eric B. Ford

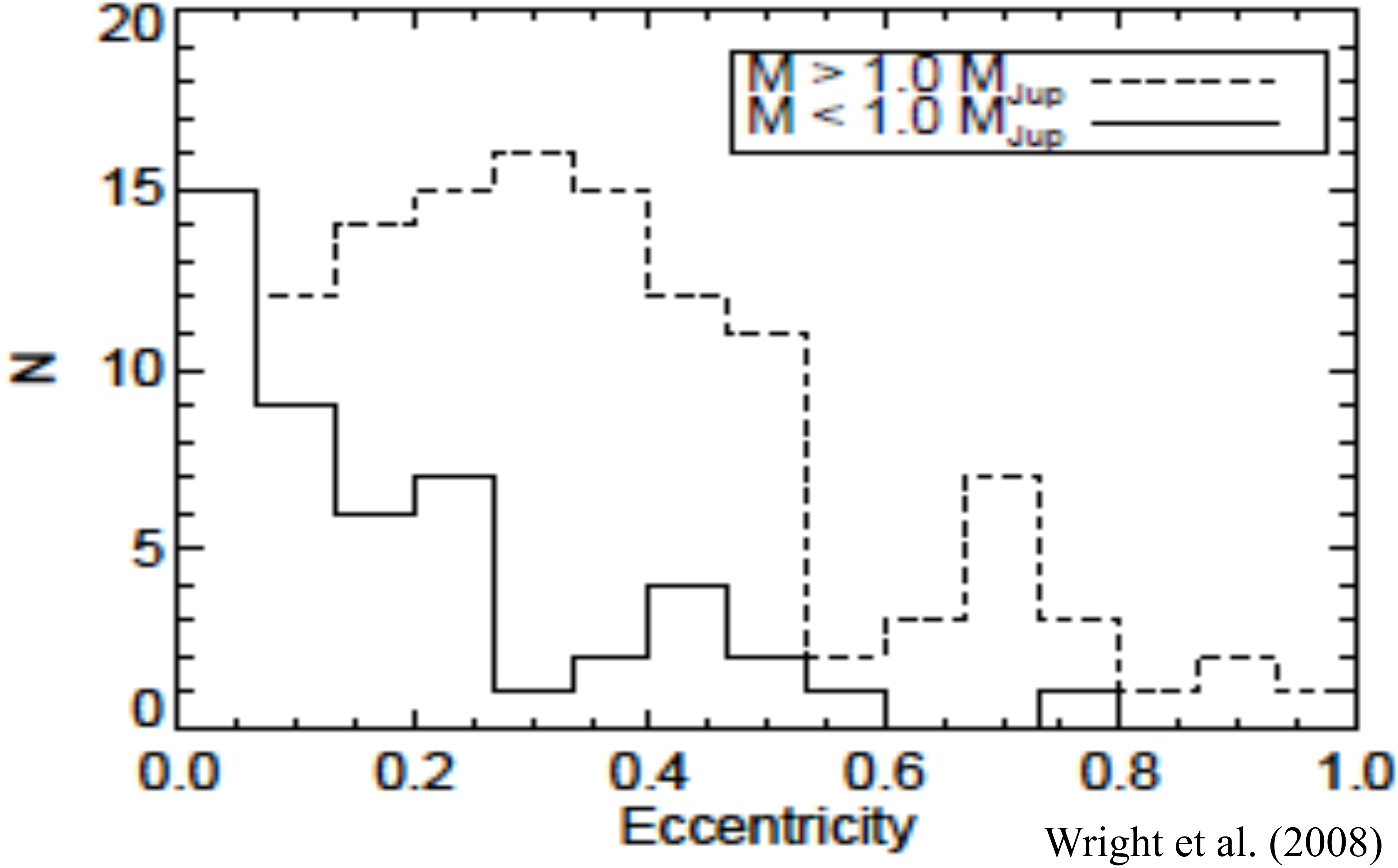
U Florida

September 25, 2008
SIM Science Studies Workshop
This Project: Tom Loredo, Althea Moorhead, Dimitri Veras

Outline

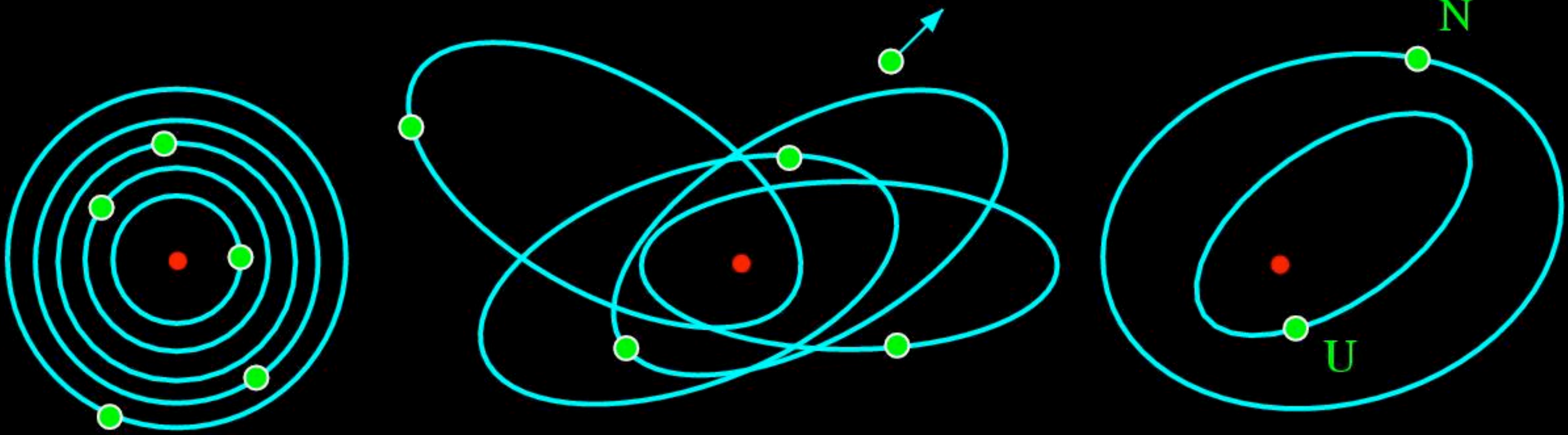
- Multiple planet systems are common
- Value of SIM for determining architecture of planetary systems and their orbital evolution
- Degeneracies if only RV data
- Theoretical predictions of resonant planets
- Role of SIM for breaking degeneracies
- Analysis Plan

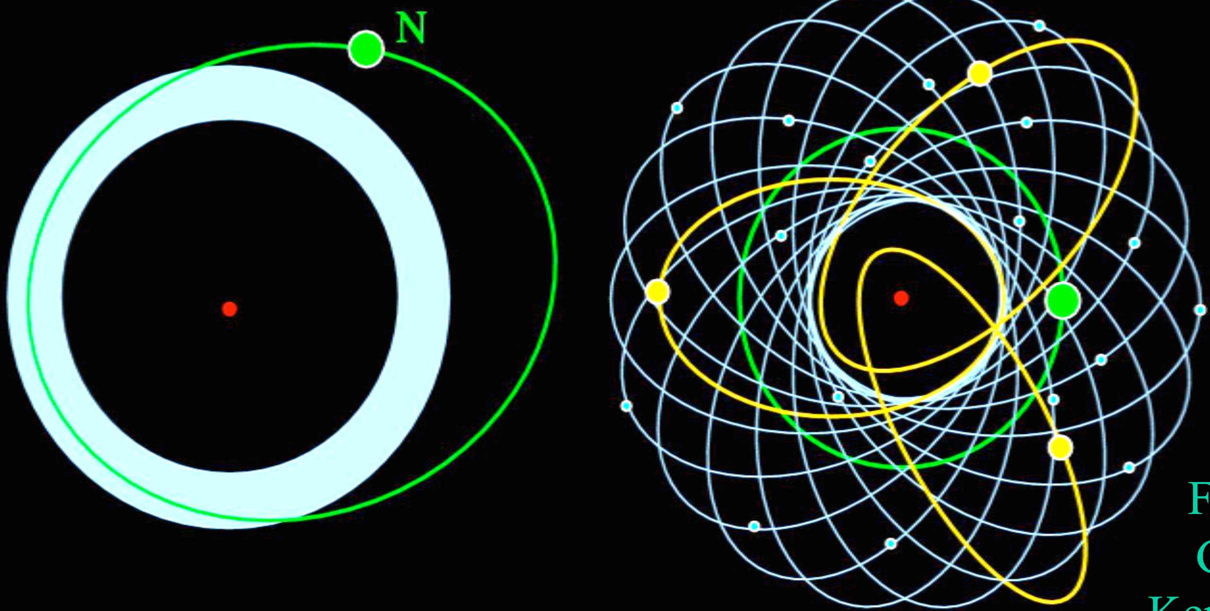
Eccentric Planets are Common



Wright et al. (2008)

What Determines Final Orbits?

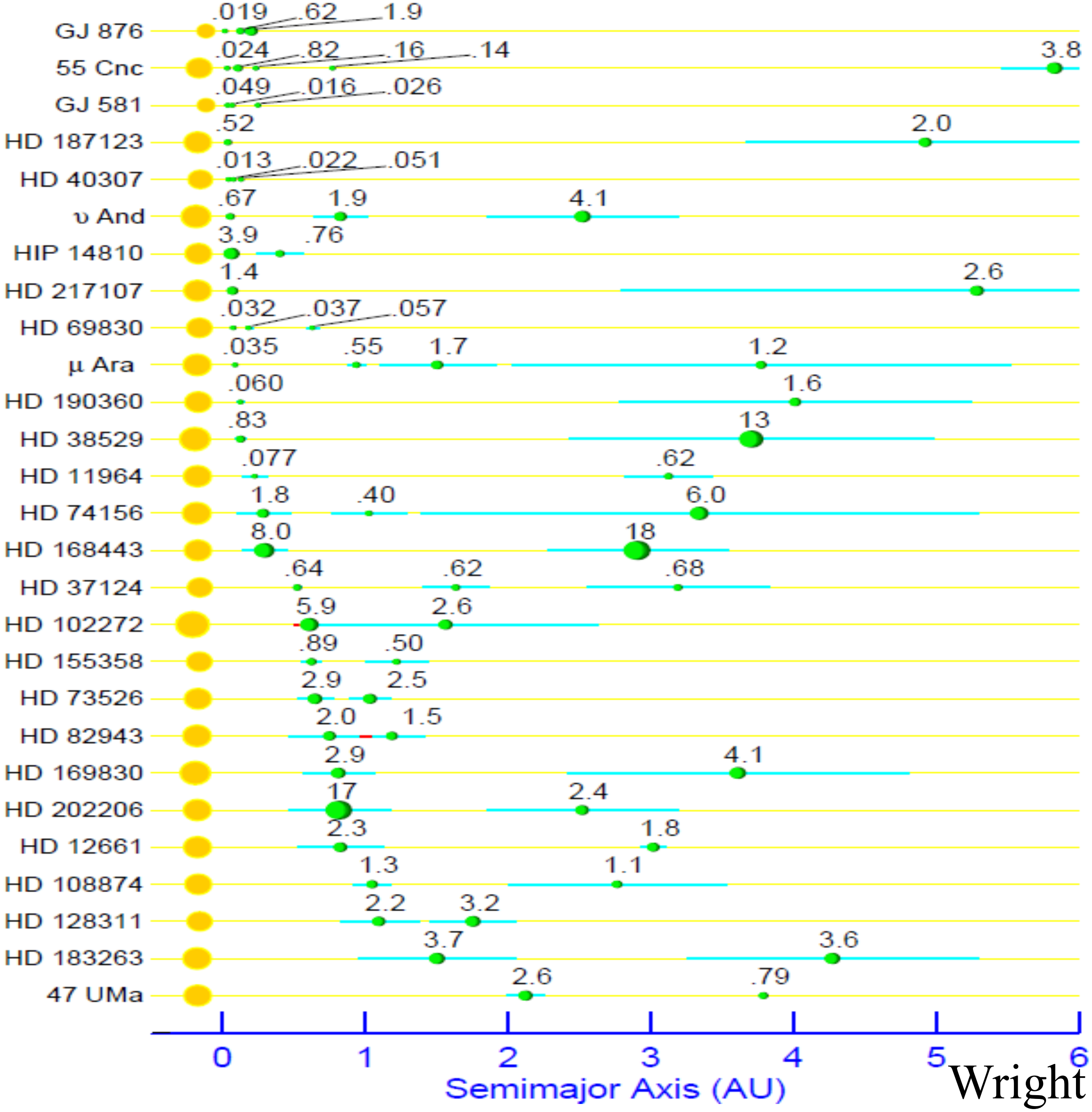




Ford & Chiang 2007
Goldreich et al 2004
Kenyon & Bromley 06
Thommes et al. 99, 02

Illustration by E. Chiang

Multi-Planet Systems are Common

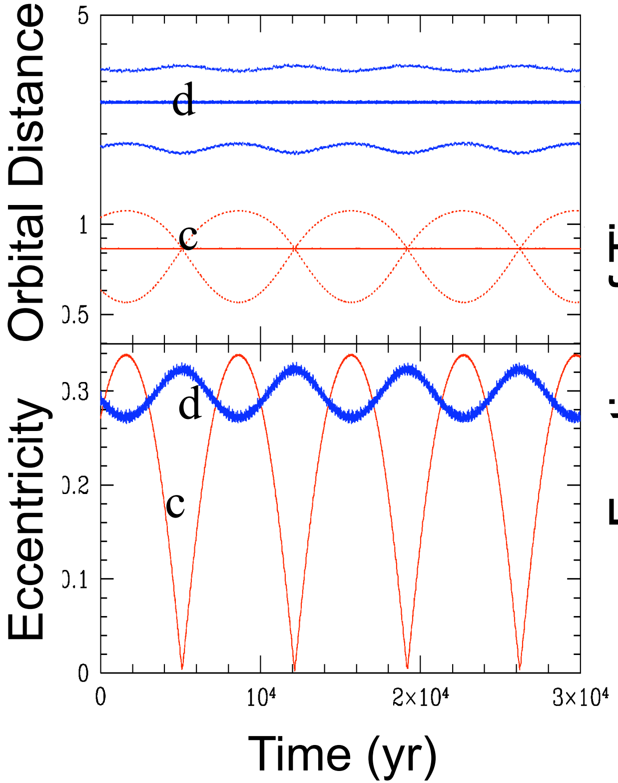


Wright et al. (2008)

Long-Term Orbital Evolution

- Secular evolution uniquely determined for few very-well observed systems
- Often measurement errors & unknown masses/inclinations leave ambiguities in secular evolution

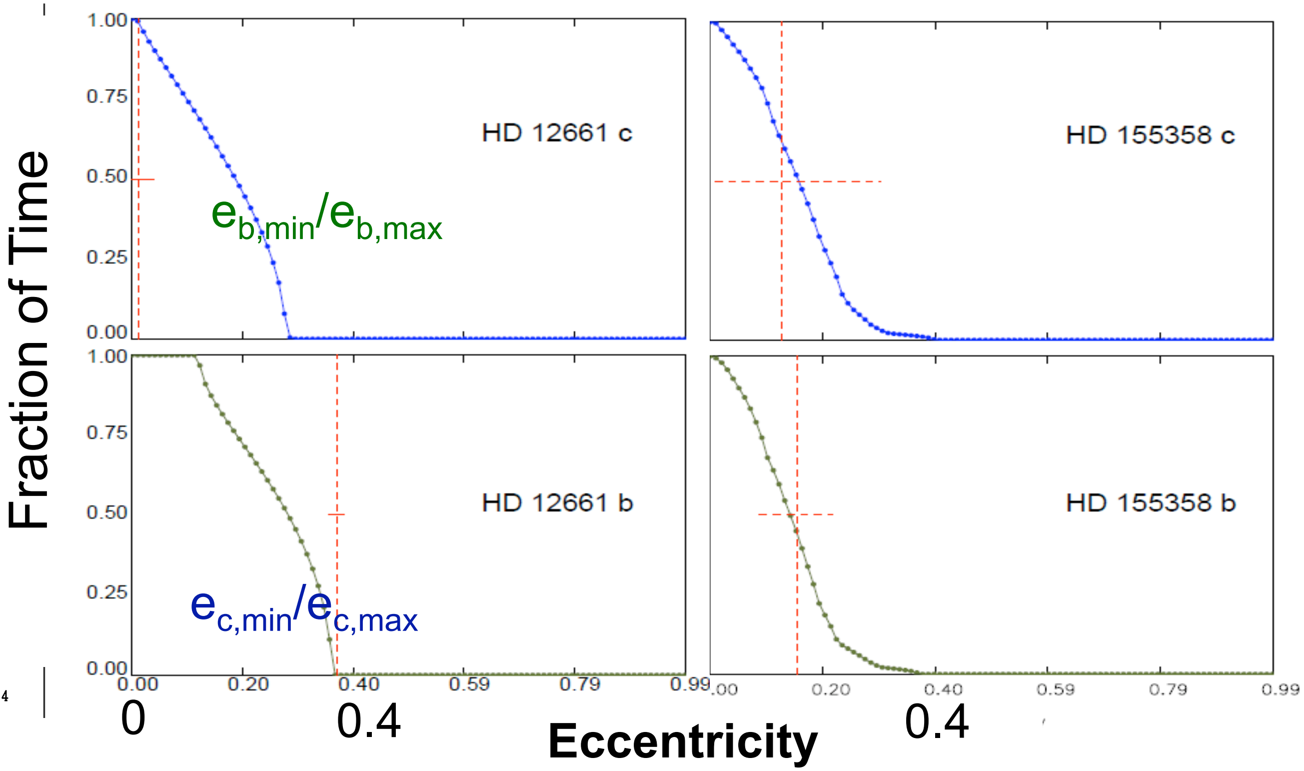
Upsilon Andromedae c & d



Ford, Lystad, Rasio 2005

HD 12661 b & c

HD 155358 b & c



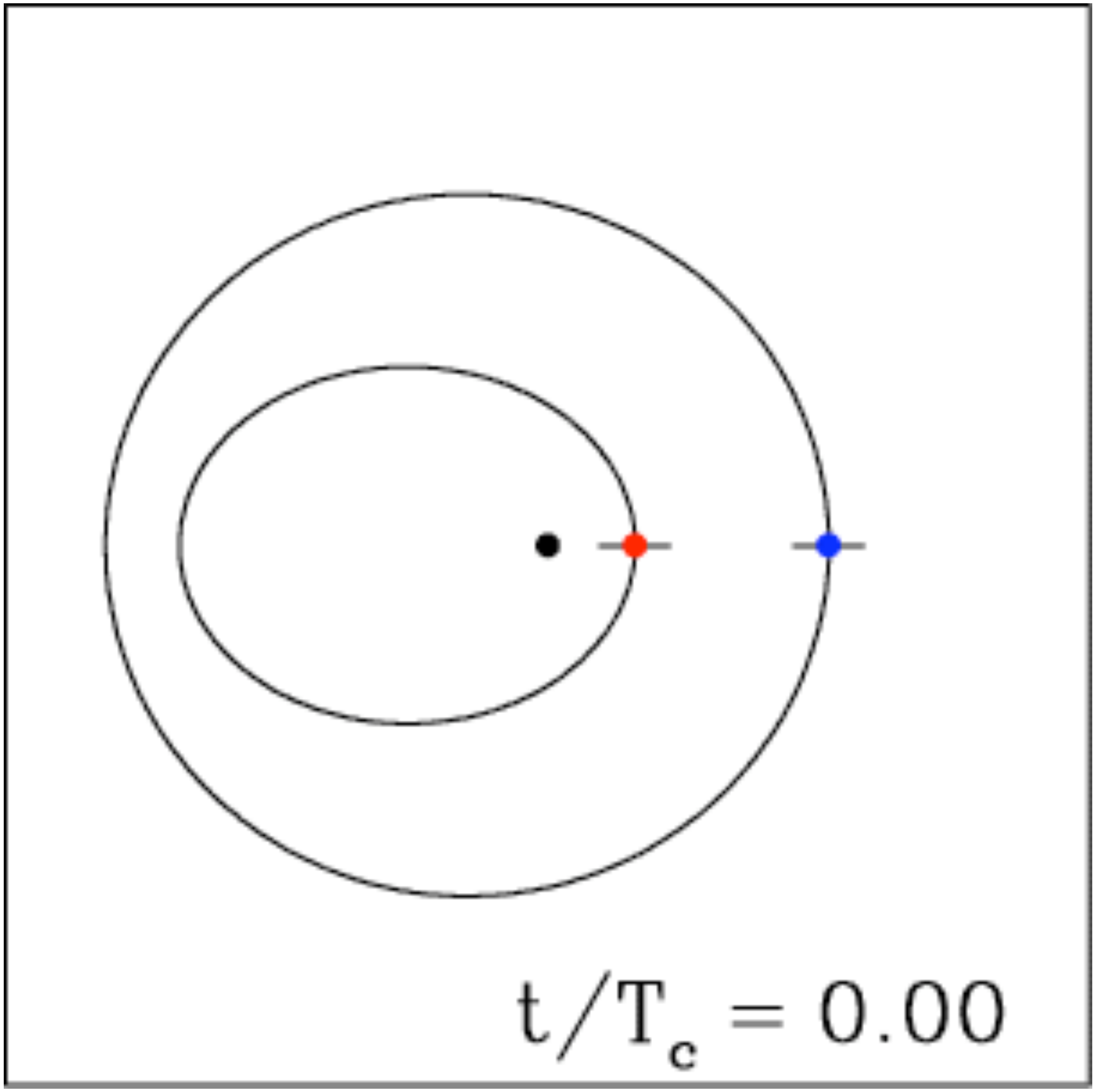
Veras & Ford 2008

Veras & Ford in prep

SIM & Planetary Dynamics

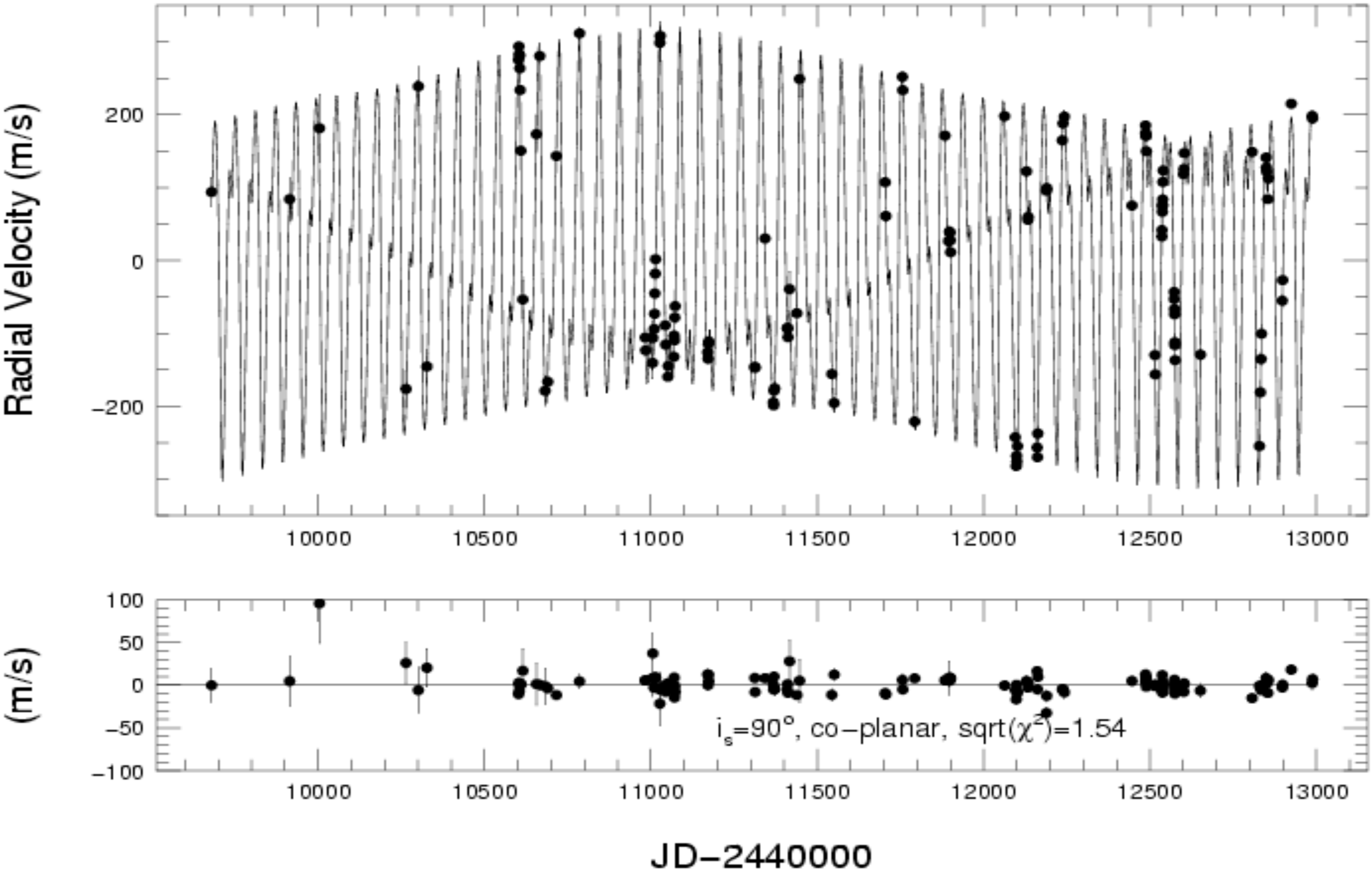
- Planet Masses & full 3-d Orbits
- Planetary system architectures
- Secular Orbital Evolution
  (eccentricity and inclination oscillations)
- Search for low-mass planets in/near mean motion resonances (MMRs)
- Characterize dynamical properties
  (e.g., libration amplitudes)?

GJ 876: Geometry



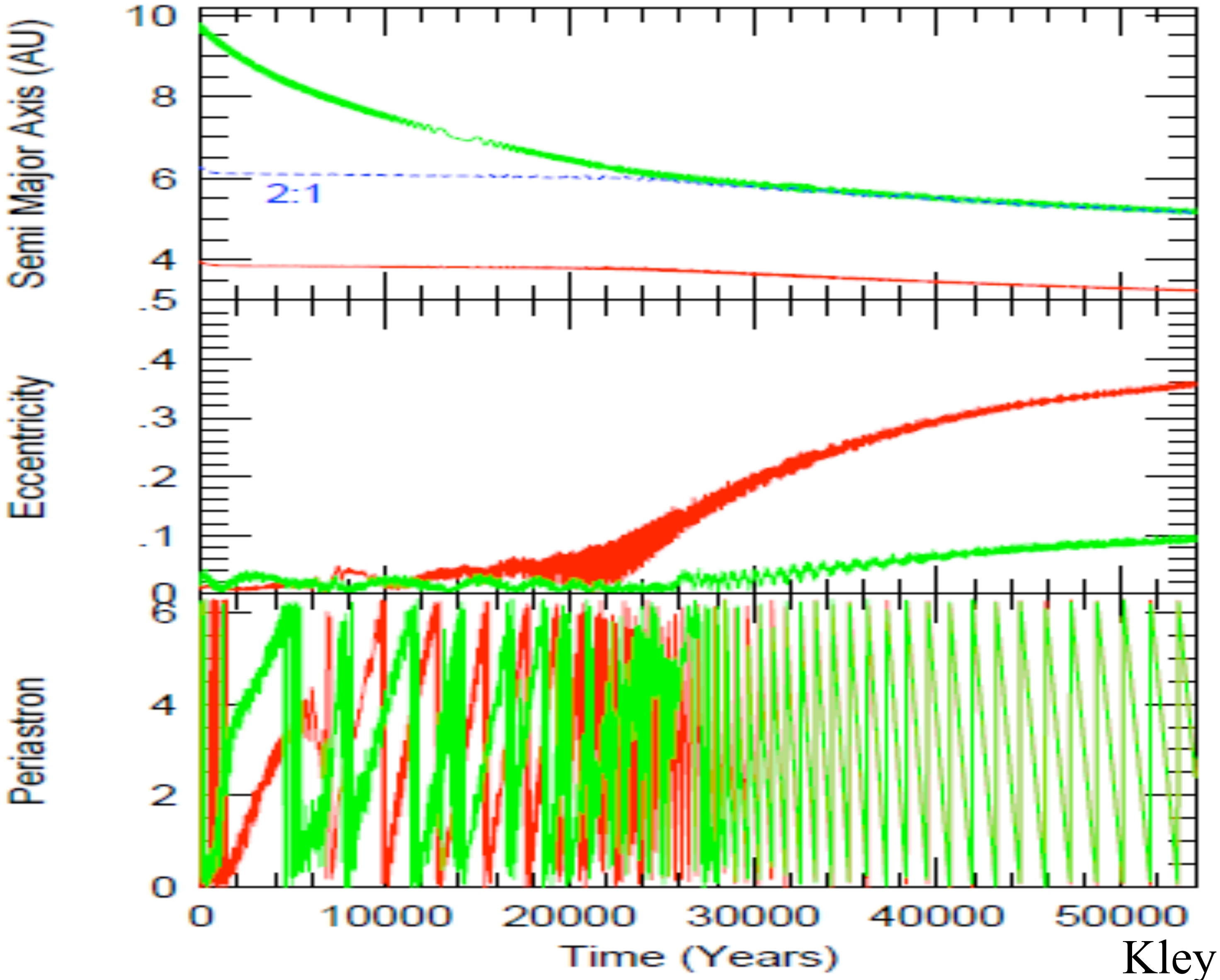
Lee

GJ 876: Radial Velocities



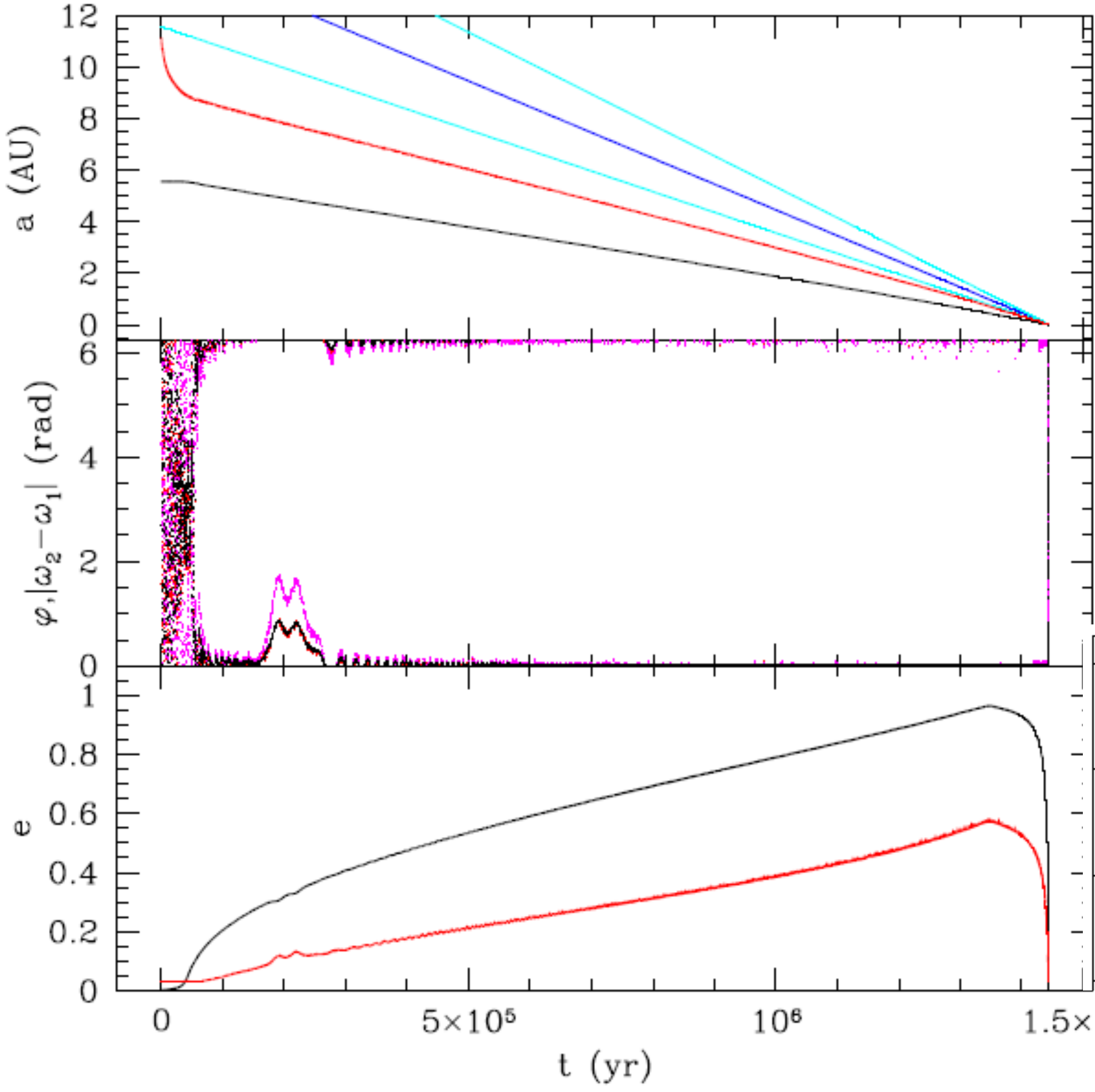
Laughlin et al. 2004

Migration & Resonance Trapping

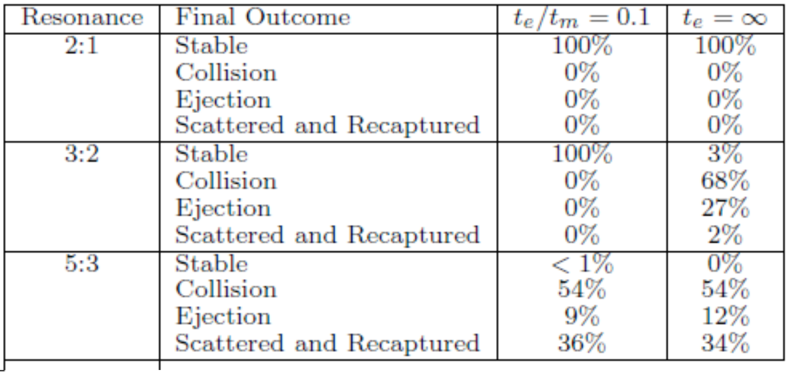


Kley et al. 2004

Migration Into & Out of Resonance



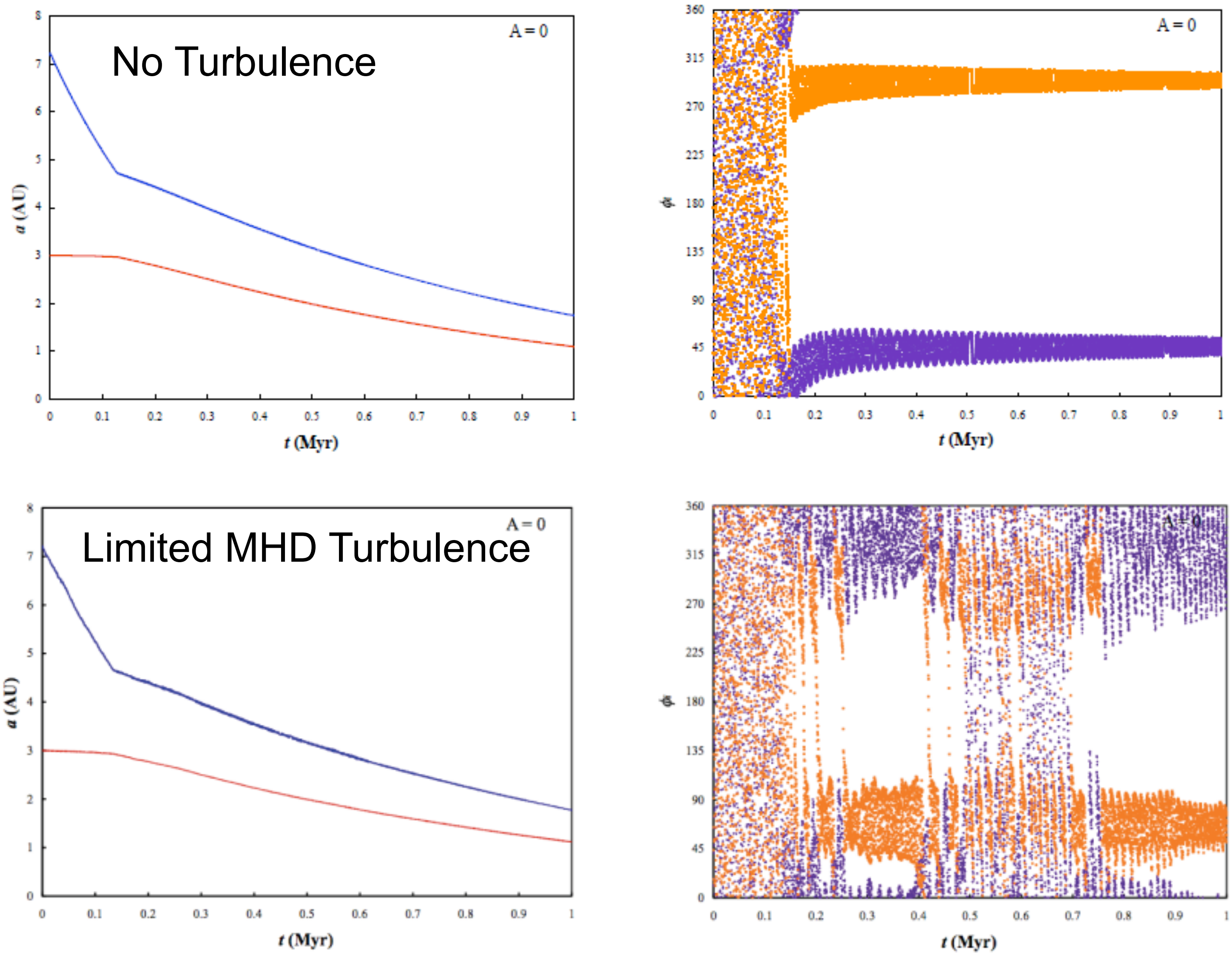
- Two giant planets trapped into 2:1 MMR
- Tidal forces break resonance



Resonance	Final Outcome	$t_e/t_m = 0.1$	$t_e = \infty$
2:1	Stable	100%	100%
	Collision	0%	0%
	Ejection	0%	0%
	Scattered and Recaptured	0%	0%
3:2	Stable	100%	3%
	Collision	0%	68%
	Ejection	0%	27%
	Scattered and Recaptured	0%	2%
5:3	Stable	< 1%	0%
	Collision	54%	54%
	Ejection	9%	12%
	Scattered and Recaptured	36%	34%

Lee et al. 2008

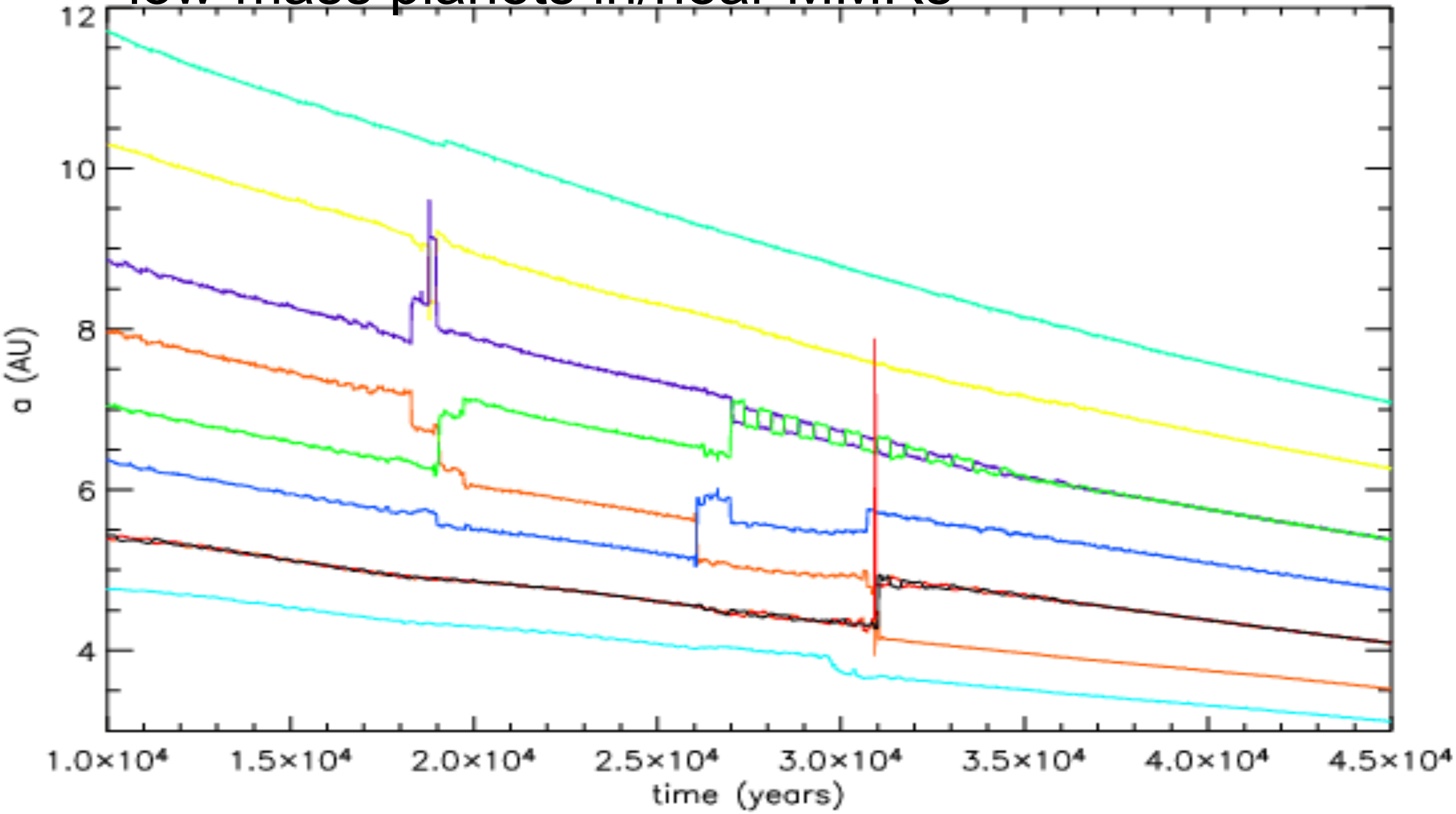
Tides & Turbulence Affect Resonant Trapping & Survival of Resonant Planets



Adams et al. 2008
Lee et al. 2008
Moorhead & Adams 2008

Could MMRs be Very Common?

- Smooth migration can trap planets in MMRs
- If slow, smooth migration is common, expect many low-mass planets in/near MMRs



Cresswell & Nelson 2006

Challenge of Detecting 2:1 MMRs

- RV signature of one planet (epicycle approximation)

$$RV = -K \sin\left(n(t-\tau) - \varpi\right) - eK \sin\left(2(t-\tau) - \varpi\right) + \mathcal{O}(e^2)$$

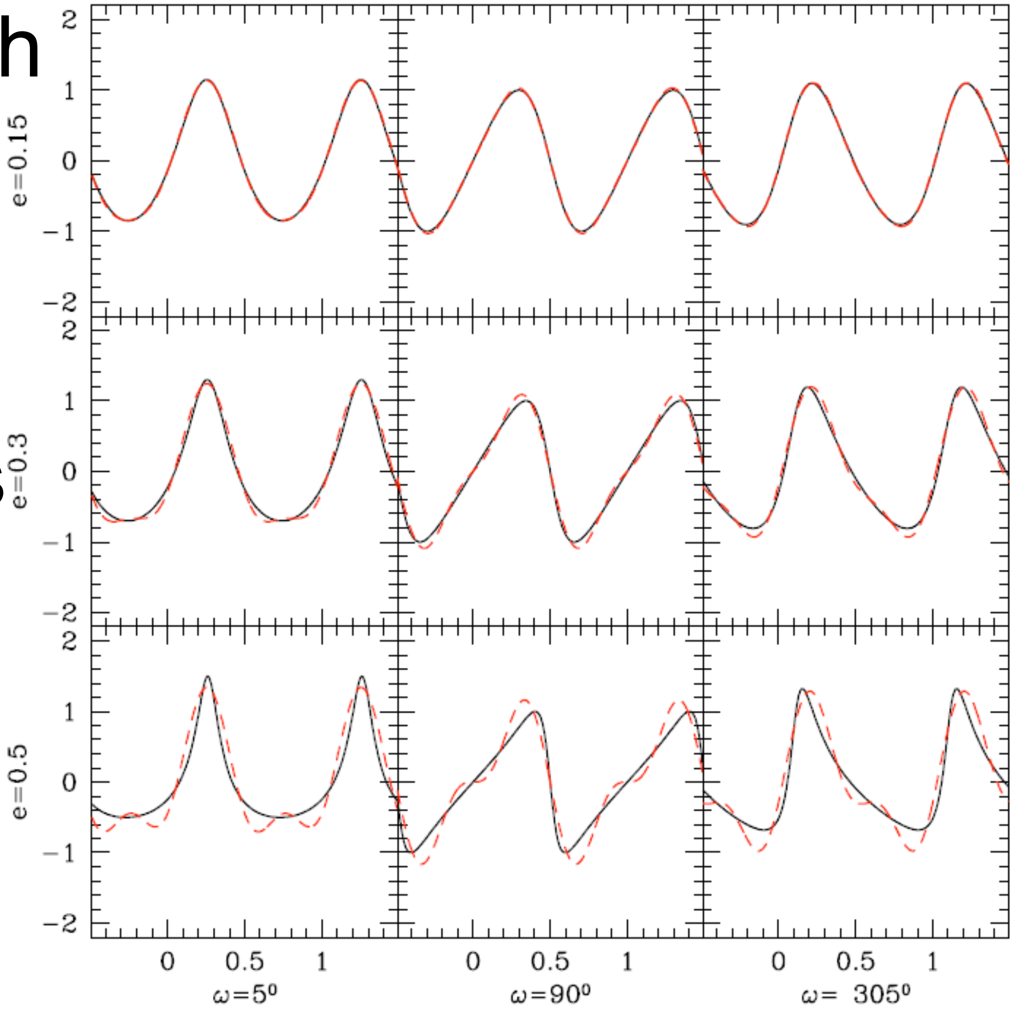
- RV signature of two planets at exact 2:1 MMR (epicycle approx. for outer planet & circular inner planet)

$$\begin{aligned} RV \;=\; & -K_1 \sin\left(nt - n\tau_1 - \varpi_1\right) - e_1 K_1 \sin\left(2(nt - n\tau_1) - \varpi_1\right) + \mathcal{O}(e_1^2) \\ & -K_2 \sin\left(2nt - 2n\tau_2 - \varpi_2\right) + \mathcal{O}(e_2) \end{aligned}$$

Konacki & Maciejewski 1999
Ford 2006; Ford & Rasio 2008
Anglada-Escude et al. 2008
Moorhead & Ford, in prep

RVs for One Eccentric Planet vs Pair of Planets in 2:1 MMR

- Difficult to distinguish between models from RVs alone
- Selected high eccentricity systems being targeted for extra RVs at Keck



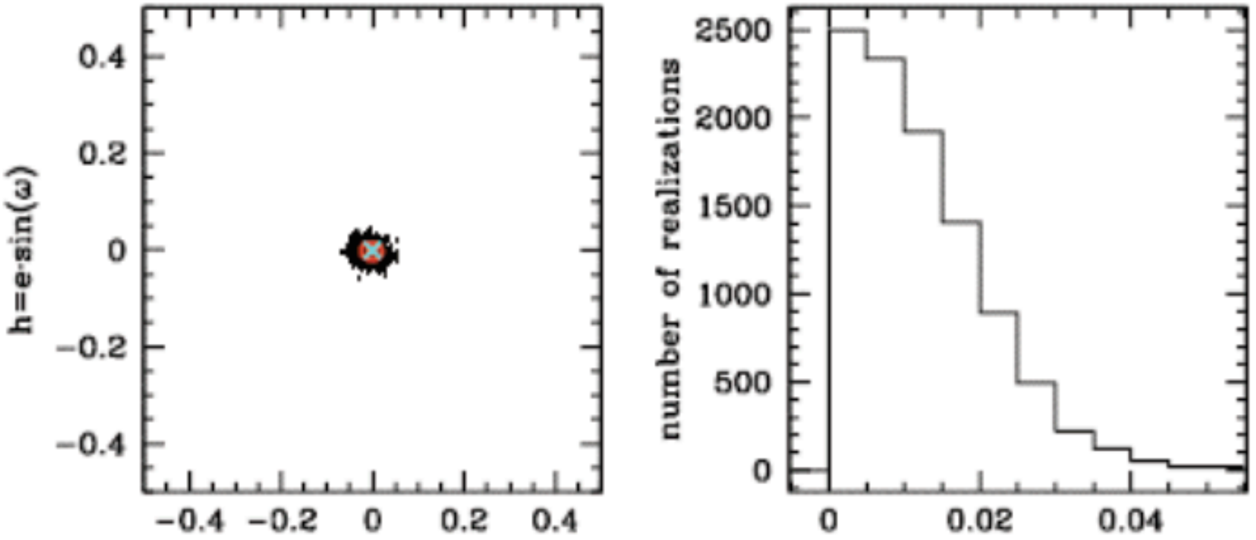
Anglada-Escude et al. 2008

Methods to Recognize Planets in 2:1 MMR

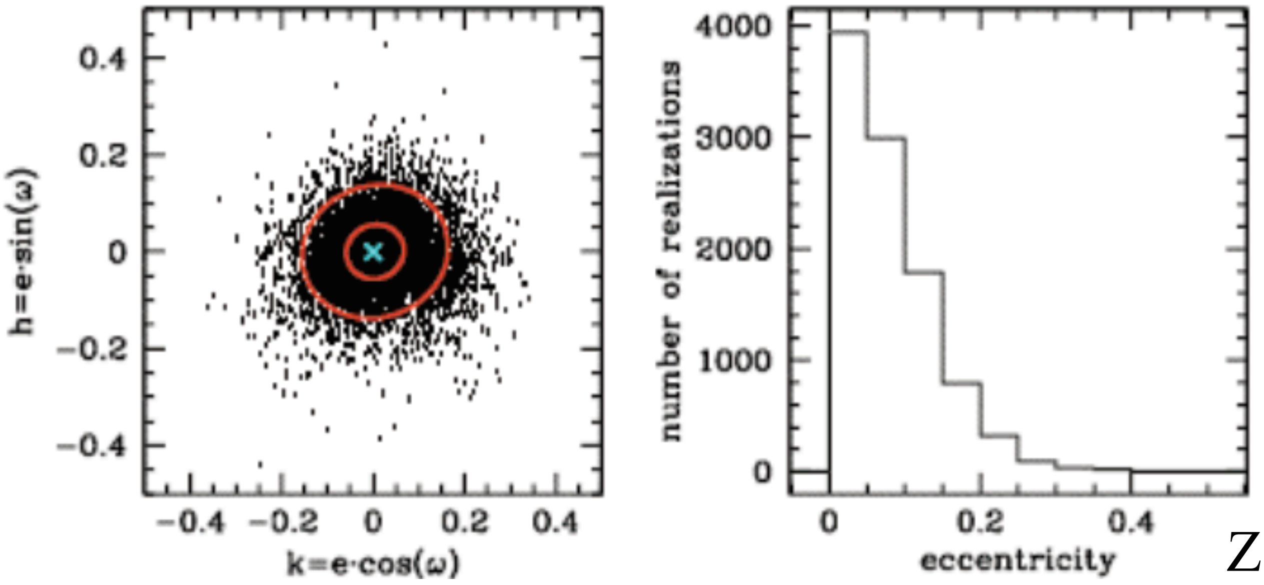
- Measure amplitude/phase of RV's 2^{nd} harmonic: $K_2 \sim e^2 K_0$ (practical for highly eccentric, giant planets in MMRs)
- Add transit observations (requires planet transits, so limited sample size, except at short orbital periods)
  - Time of primary transit + RV (becomes *very* expensive for e<0.05 or Neptune-mass planets)
  - Time of primary & secondary transit (Neptune-sized planets with warm Spitzer; smaller planets possible with JWST?)
  - Transit Timing Variations (need *many* transits, so unique solutions limited to short periods)
- Add astrometric observations

Biases for Small Eccentricities

Analysis of simulated RV data sets w/ circular orbits



Real RV data is clearly inconsistent with single circular orbit

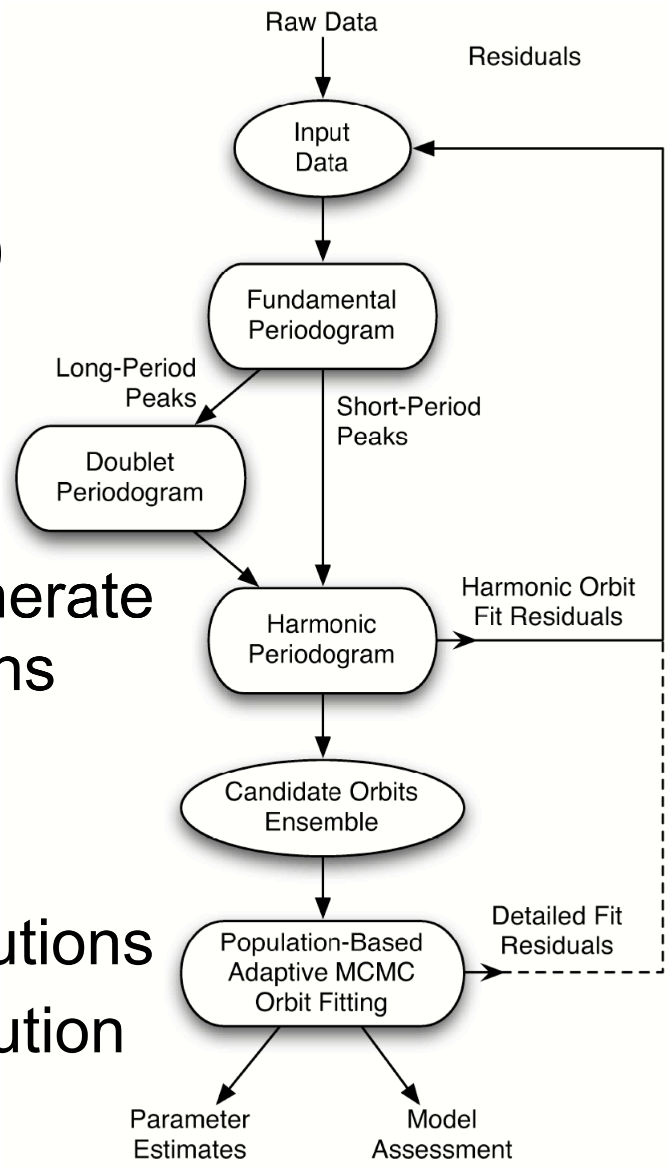


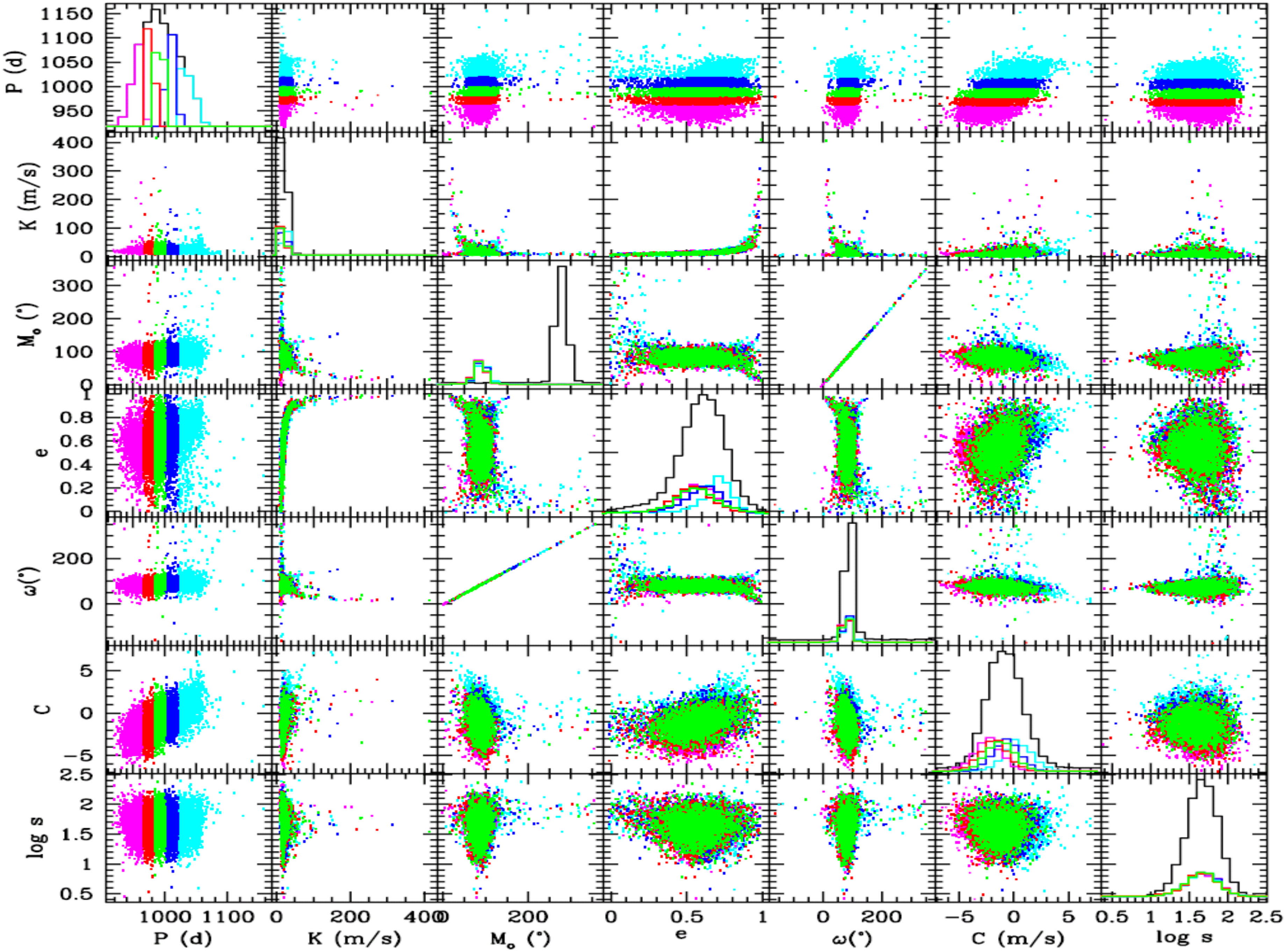
Real RV data is consistent with single circular orbit

Zakamska, Pan, Ford in prep

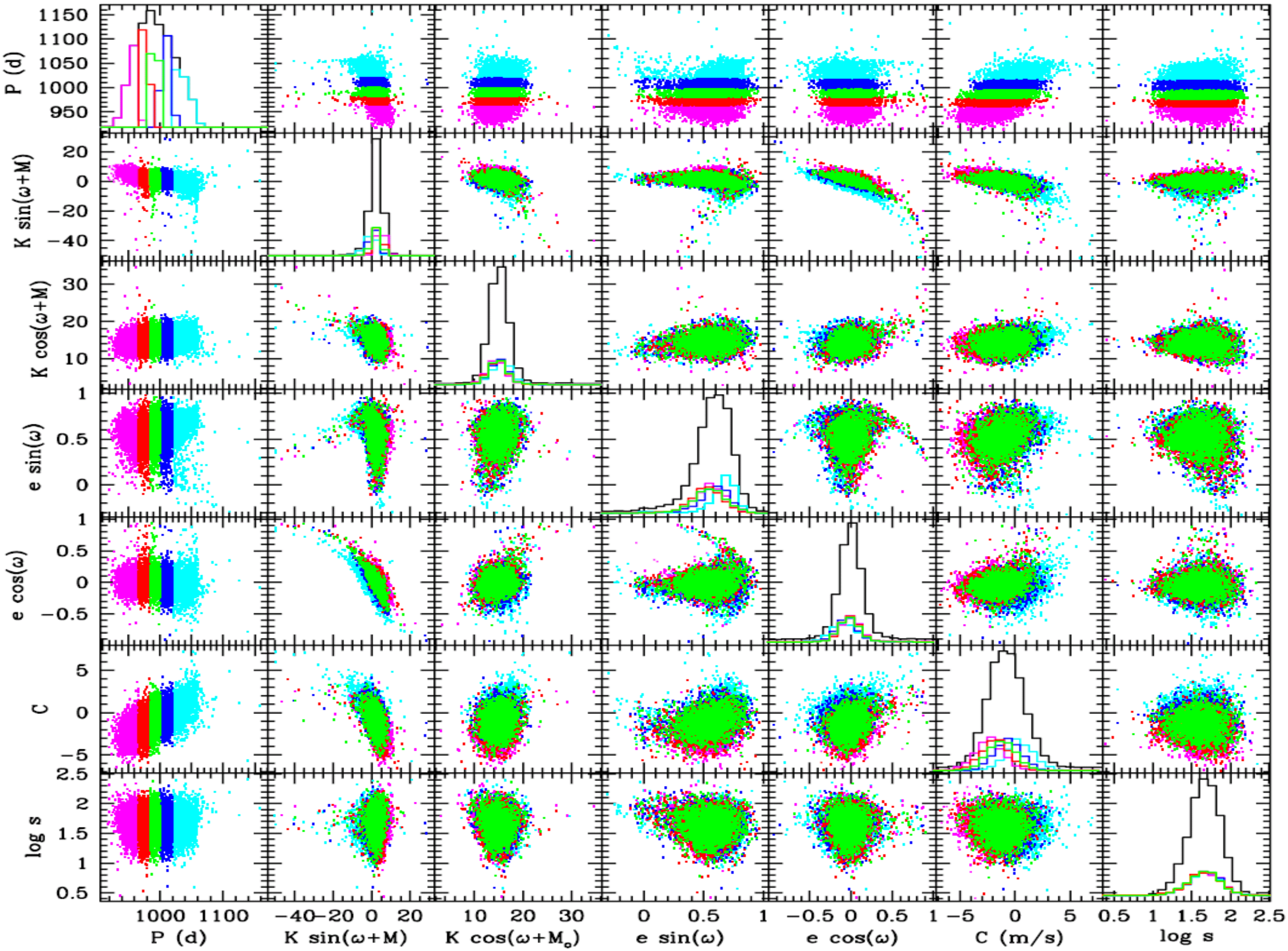
Data Analysis

- Building on procedure used in SIM double-blind test (team C-5)
- Iteratively
  - Global search for periodic signals (i.e., planets)
  - Bayesian posterior sampling to generate ensemble of allowed orbital solutions
  - Calculate residual distributions
- Long-term n-body integrations
  - Eliminate dynamically unstable solutions
  - Characterize long-term orbital evolution





Ford & Gregory 2008



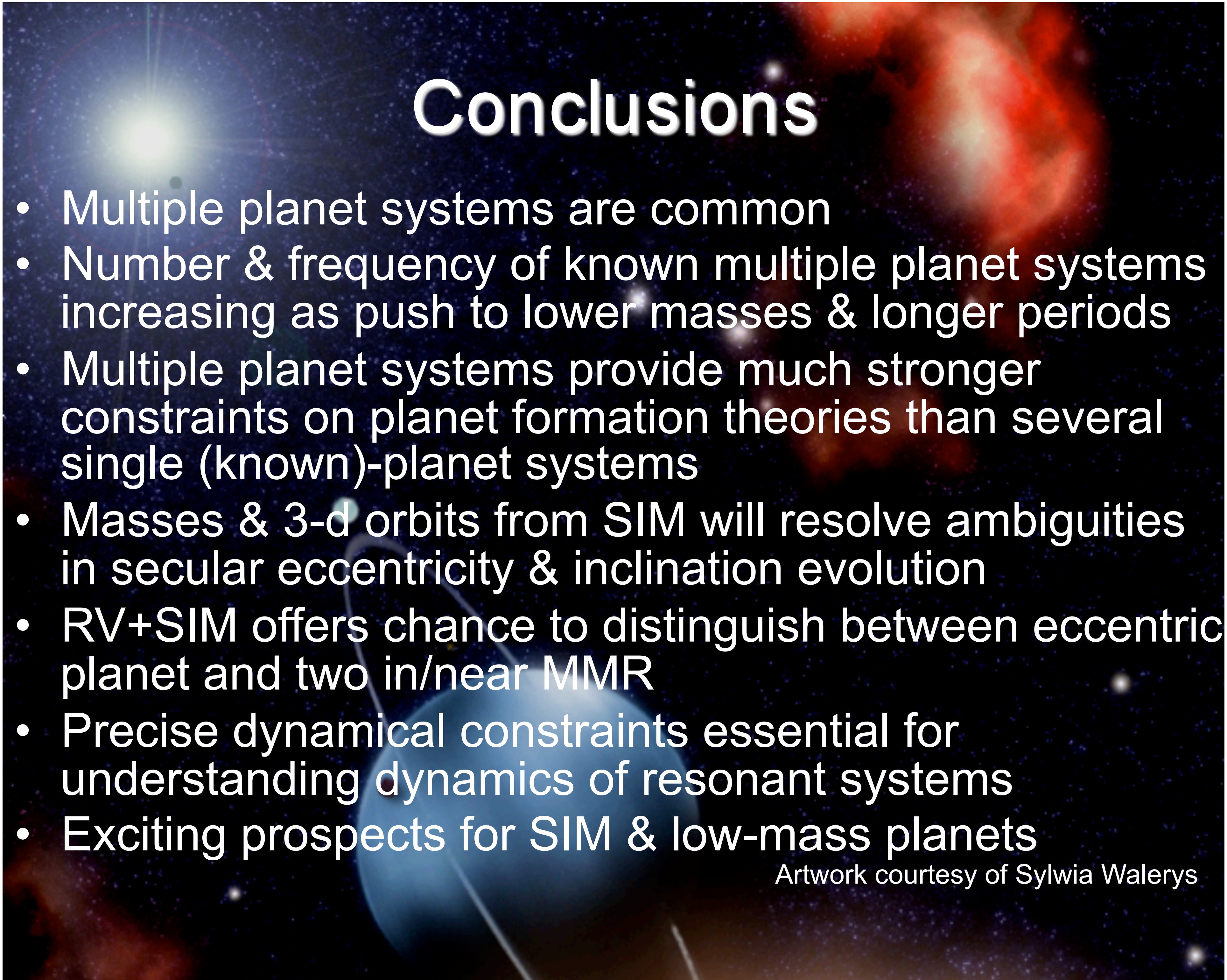
Transformations from Ford 2006

Ford & Gregory 2008

Open Questions for SIM

- How common is large scale planetary migration?
  - Search for low-mass planets in mean-motion resonances.
- Are there signs of previous violent phases of evolution, e.g., eccentric and/or highly inclined planets? In systems without short-period giants?
  - Search for planetary systems that will undergo significant long-term eccentricity/inclination evolution.
- What are the implications for the planet's formation, climate, the potential for liquid water, and the potential for Earth-like life?

Conclusions



- Multiple planet systems are common
- Number & frequency of known multiple planet systems increasing as push to lower masses & longer periods
- Multiple planet systems provide much stronger constraints on planet formation theories than several single (known)-planet systems
- Masses & 3-d orbits from SIM will resolve ambiguities in secular eccentricity & inclination evolution
- RV+SIM offers chance to distinguish between eccentric planet and two in/near MMR
- Precise dynamical constraints essential for understanding dynamics of resonant systems
- Exciting prospects for SIM & low-mass planets

Artwork courtesy of Sylwia Walerys

Questions?