Dynamical Evolution of Planetary Systems and Debris Disks

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Extrasolar Planets: detection, formation, evolution, and dynamics of planetary systems
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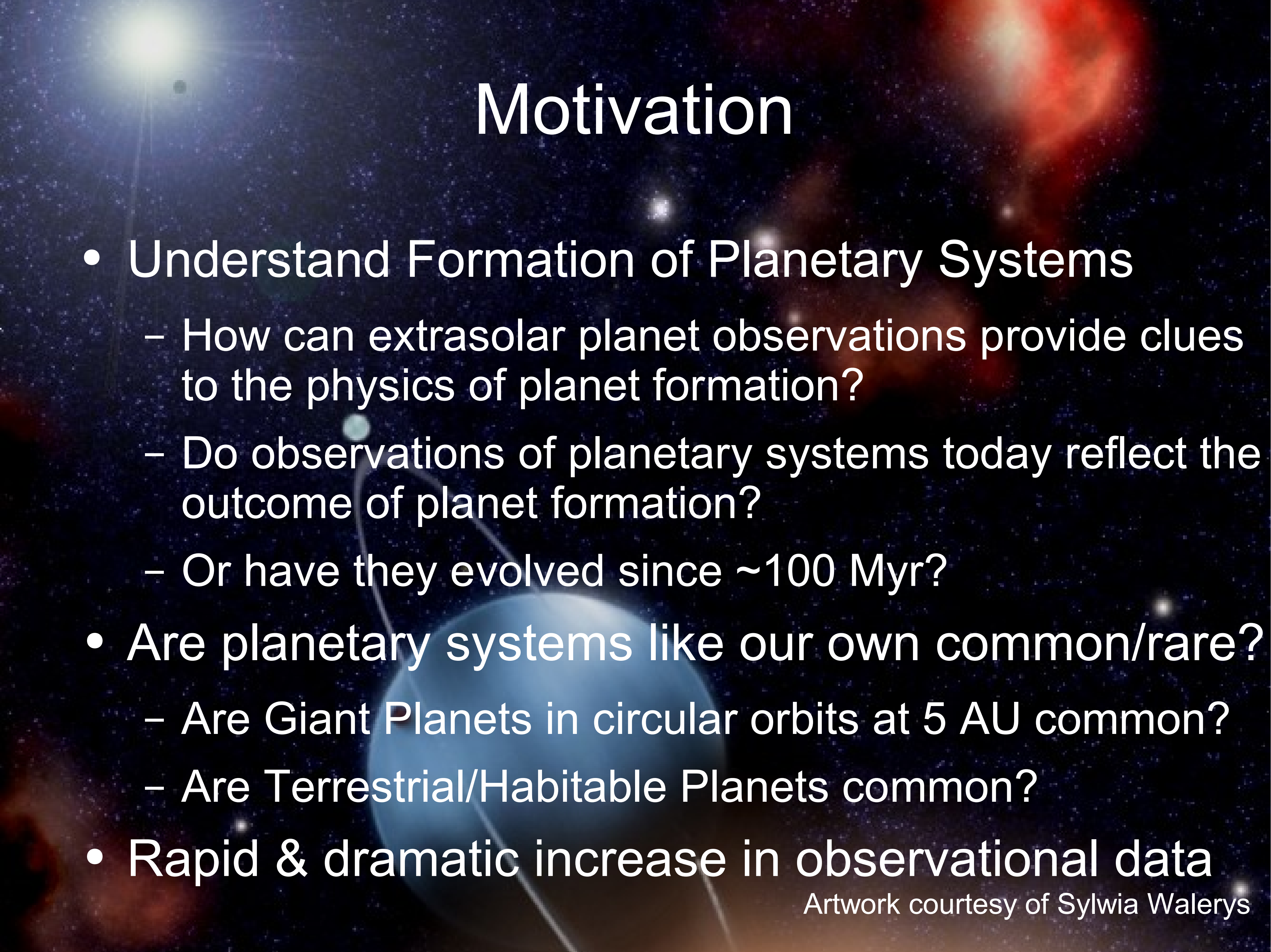
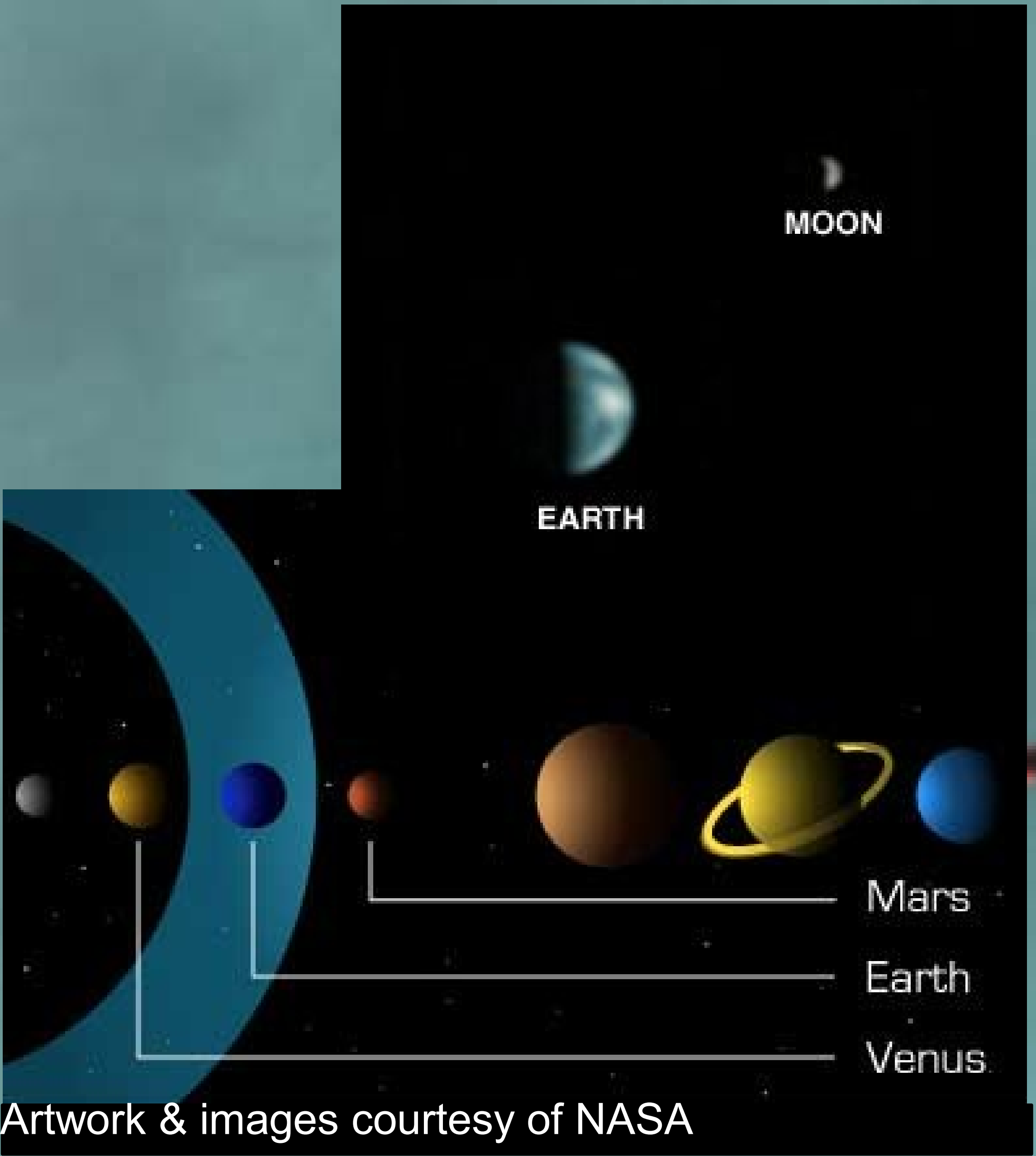
Motivation



- 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

Observed Planetary Systems



Artwork & images courtesy of NASA

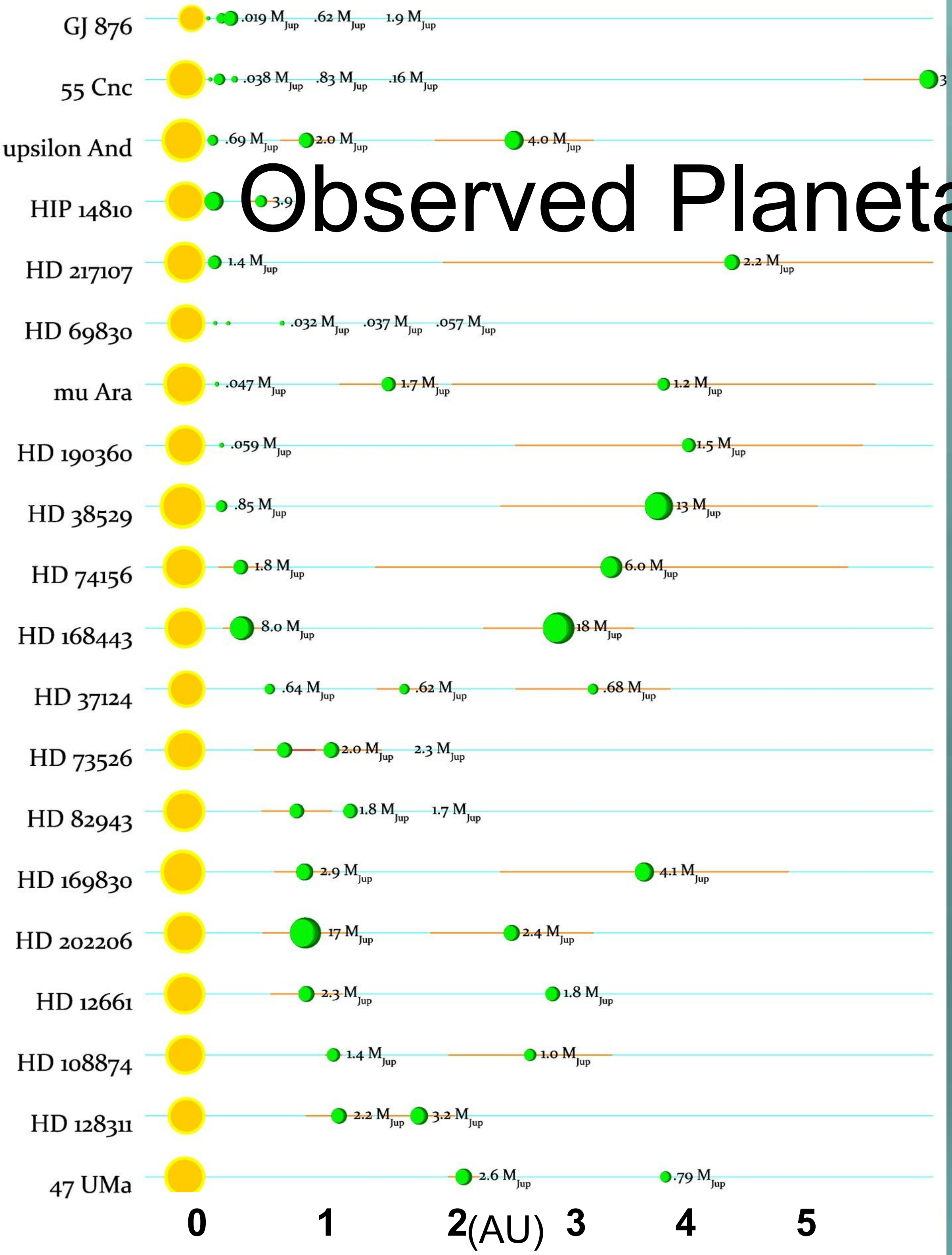
1543: Copernicus: *Revolutionibus*
1576: Digges: Universe infinite?
1600: Bruno burned
1604: Kepler's Supernova
1609: Galileo's telescope
1618: Kepler's 3rd law

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

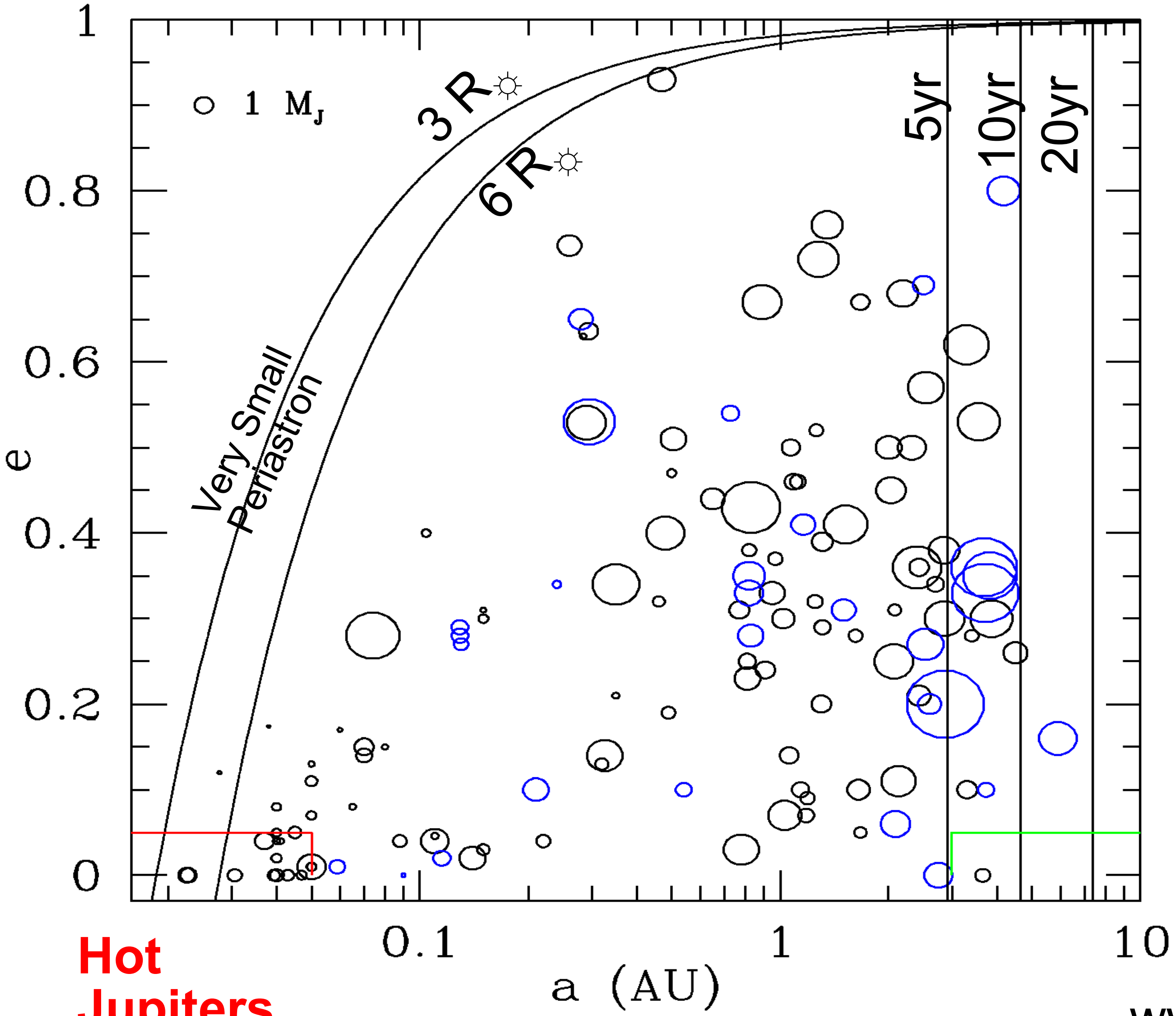
1995: 51 Pegasi

1999: Upsilon Andromedae
2000: ~50 Planetary Systems

2006: ~147 Planetary Systems
2007: ~200 Planetary Systems

www.exoplanets.org

Diversity of Extrasolar Planets



Eccentric Planets

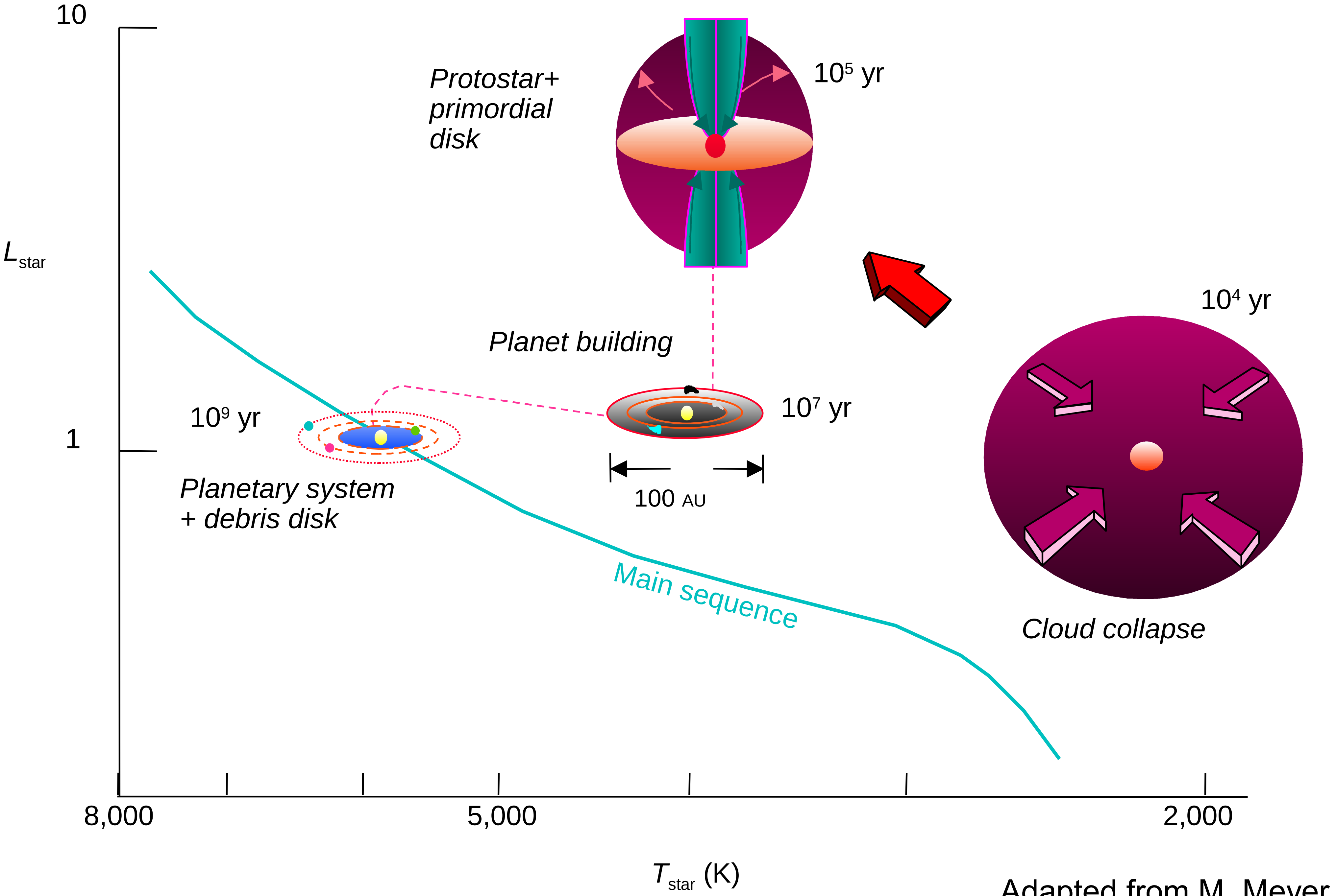
Multiple Planet Systems

Solar System-like Giant Planets

Hot Jupiters

www.exoplanets.org

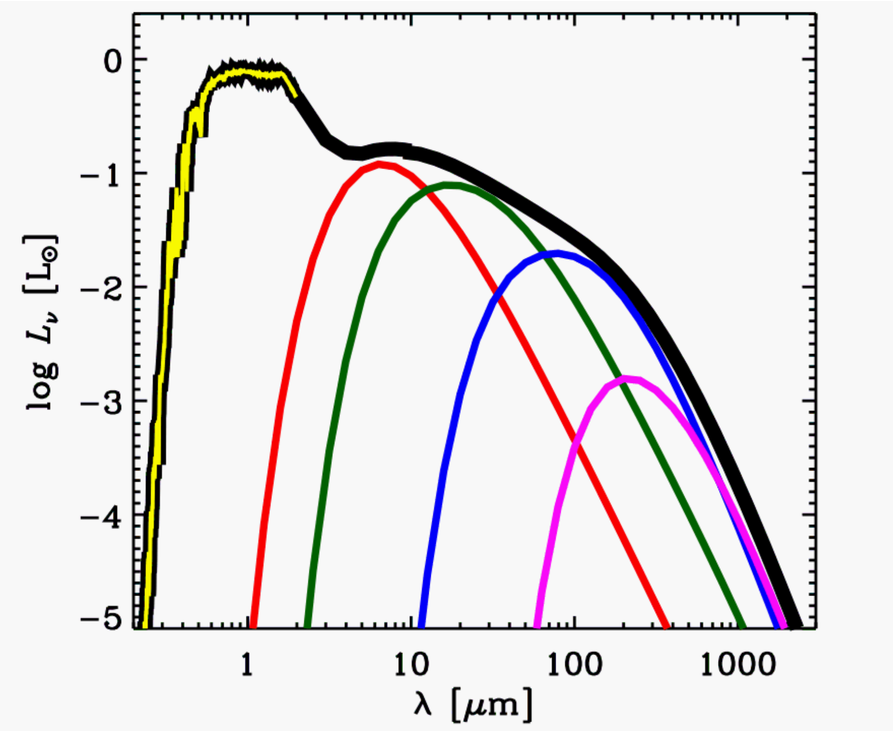
Pre-main Sequence Evolution

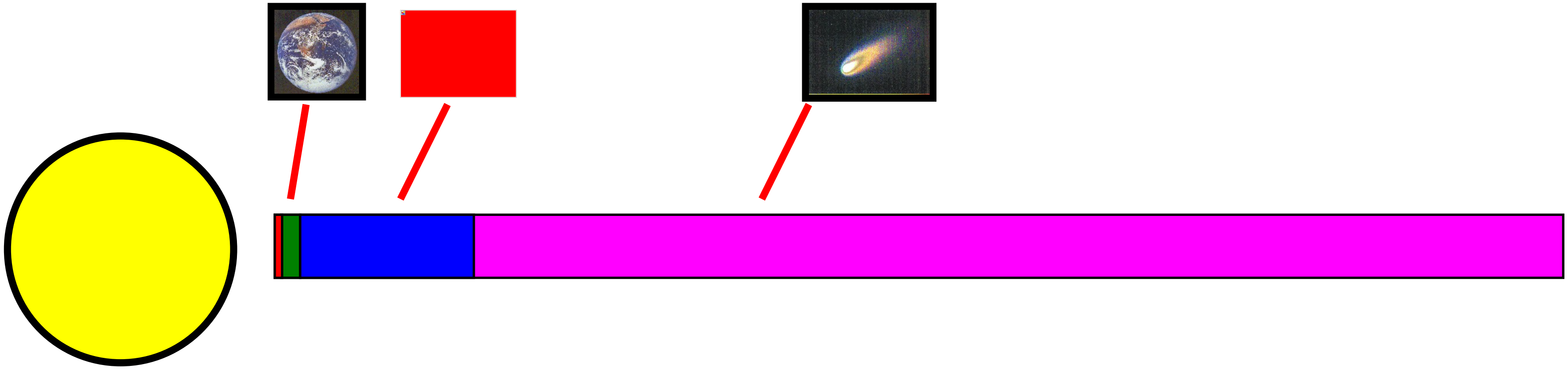


Adapted from M. Meyer

SED: thermal emission from irradiated thin dust disk

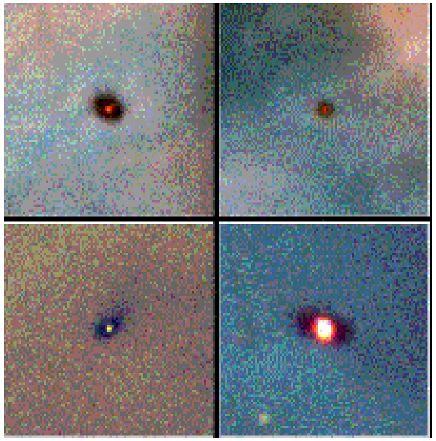
different disk regions contribute at different λ based on local temperature and density conditions

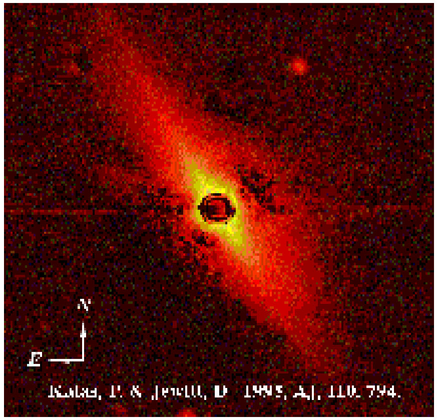




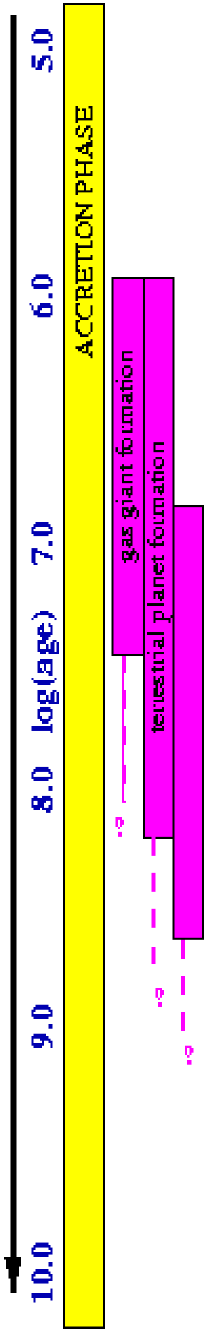
Adapted from S. Andrews

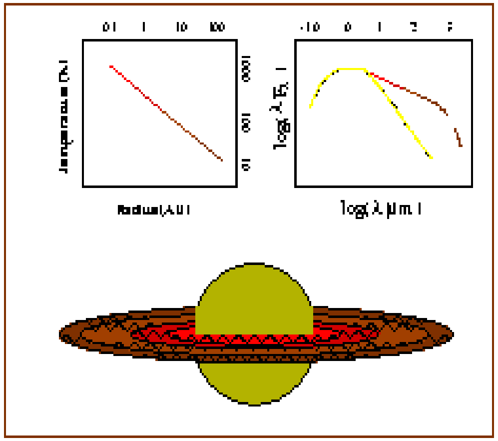
From Protostellar Disks to Mature Planetary Systems

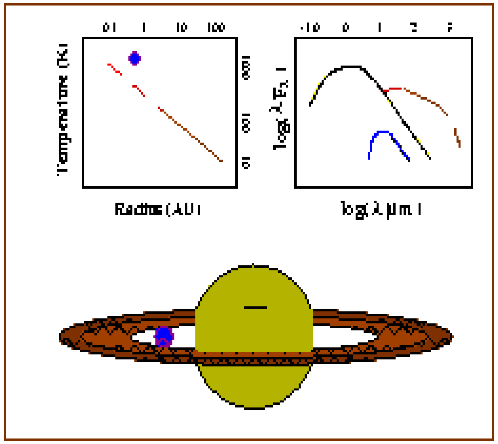


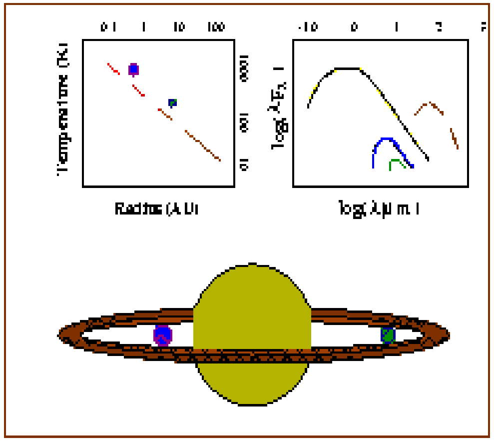


Kalas, P. & Jewitt, D. 1995, AJ, 110, 794.









Primordial Disks:

- gas rich
- opacity is dominated by primordial grains.

Transition Disks:

- very short time scale
- planetesimals grow

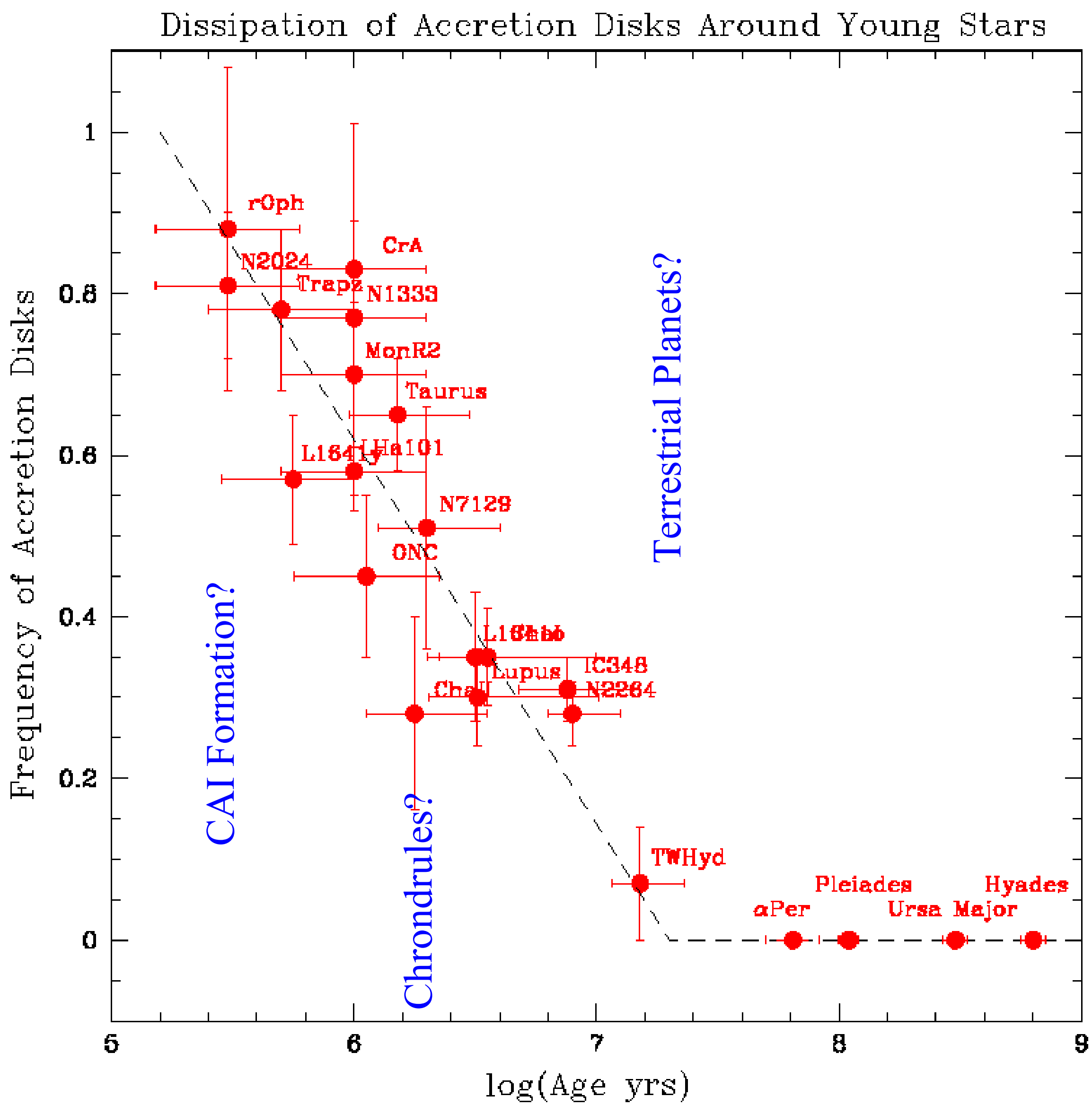
Debris disks:

- no detection of gas
- Poynting-Robertson (P-R) drag time scale is shorter than the age of system, therefore pristine grains in a disk had been spiraled into the star. Therefore, we expect no residual ISM dust left over from formation.
- opacity is dominated by 2nd generation grains produced by collisions of planetesimals.

See recent review by Meyer et al. (2006).

From Soderblom et al (FEPS team); http://feps.as.arizona.edu/

NIR Excess Fraction (< 0.1 AU) vs. Cluster Age

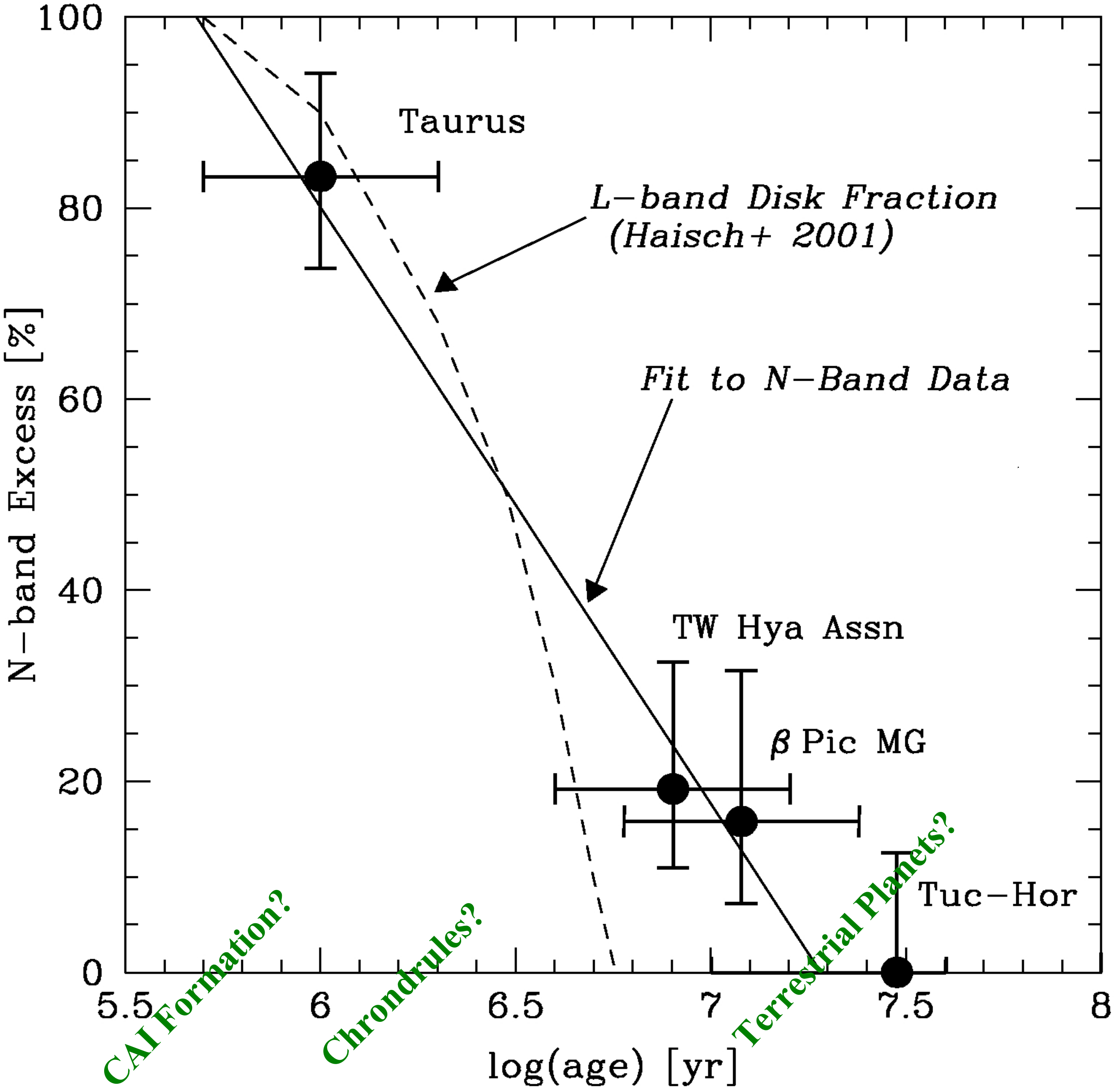


Haisch etal. 2001; see also Hillenbrand, Meyer, and Carpenter (2002).

Adapted from M. Meyer

MIR

MIR Excess (0.3-1.0 AU) vs. Cluster Age



Dust in terrestrial planet zone dissipates when accretion stops!

Mamajek et al 2004, ApJ.

Metchev, Hillenbrand, and Meyer, 2004, ApJ.

See also Low et al. (2005) as well as Chen et al. (2005).

Adapted from M. Meyer

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?

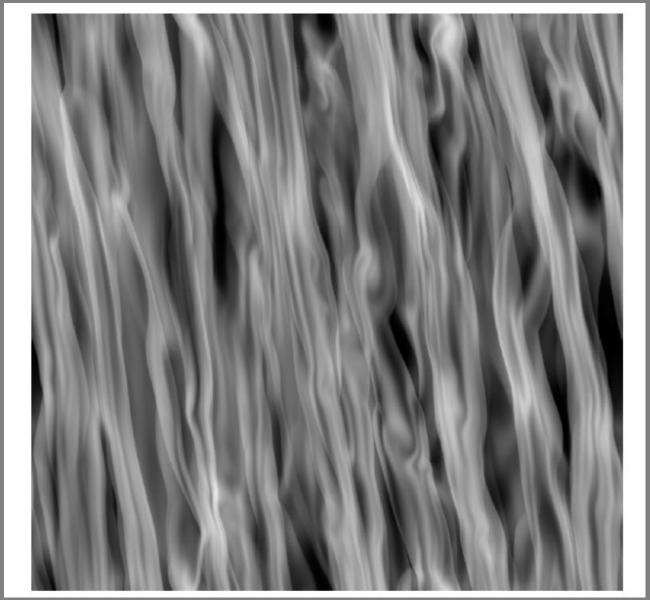
Adapted from S. Tremaine

Disk fragmentation

Gammie (2001) showed that for fragmentation to set in one needs

$$\Omega\, t_c < 3$$

$\Omega\, t_c = 50$ **No fragmentation**



Gammie '01

2D hydro

$\Omega\, t_c = 2$ **Fragmentation**

When $t_c \sim \Omega^{-1}$ fragments lose thermal support at the same rate at which they collapse. Isothermal gas effectively has $t_c = 0$

3D simulations confirm this general picture $(\Omega\, t_c < 3 - 5)$

Rice et al 2003

Adapted from R. Rafikov

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

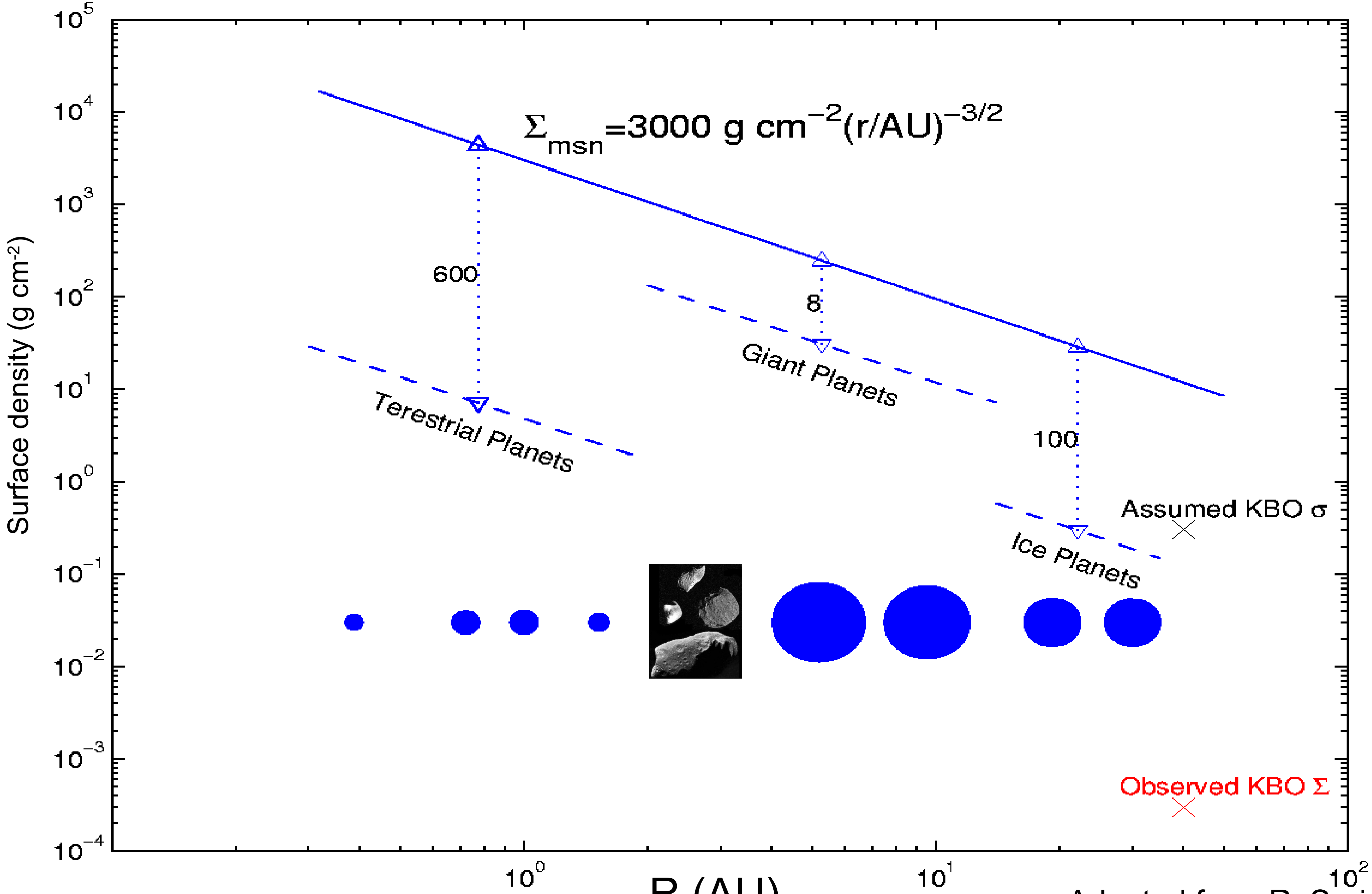
Challenges of Planet Formation

- 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

Processes in Planet Formation

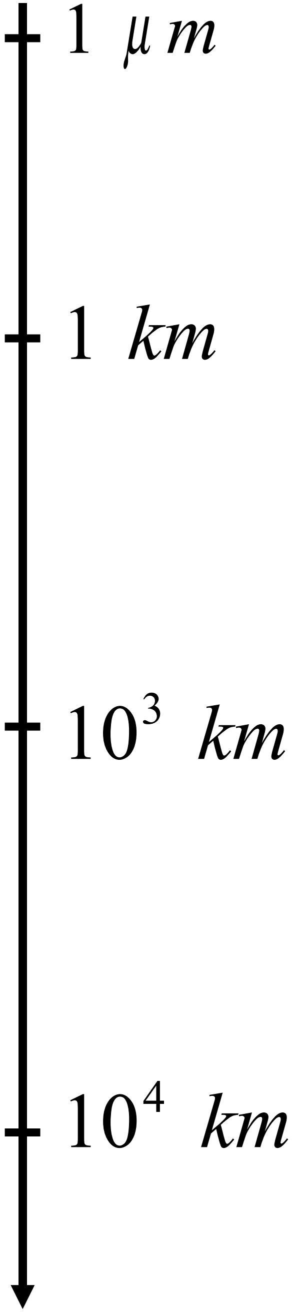
- Condensation of grains from Solar nebular (complicated physics & chemistry)
- Planetesimal Formation (highly uncertain)
- Migration (Type I, II, III)
- “Simple” Accretion
  - Chaotic Growth
  - Oligarchic Growth
  - Orderly Growth
  - Runaway Growth

Minimum Mass Solar Nebula



Adapted from R. Sari

Stages of Planet Formation by Core Accretion



- **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)**
  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
- **From embryos to terrestrial planet cores (part 1)**
  Gravitational interactions stir and reduce gravity focusing
  Oligarchic growth up to isolation mass (0.1-10M_{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.
- **Possible accretion of gas and transition to gas giants**

Adapted from R. Rafikov

From pebbles to boulders

Very poorly understood! Potential planetesimal formation mechanisms:

- **Gravitational instability** (Goldreich & Ward 1973; Youdin & Shu 2002)

  Dust sediments towards midplane, forms dense layer, becomes gravitationally unstable.
  1-10 km size bodies form on dynamical (about 100 yr) timescale.

  ??? Can dust really sediment? What is the role of turbulence in the disk?

- **Coagulation of dust particles** (Weidenschilling & Cuzzi 1993)

  Dust particles collide with each other and stick ensuring growth.
  1 m bodies grow in less than 10,000 yr **if** 100% sticking probability.

  ??? Sticking mechanism is **very** unclear. Collisions may occur at high velocities leading to dust fission rather than fusion.

- **“Exotic” mechanisms: vortices, turbulent concentration, etc.**

  ??? Do these work at all?

Adapted from R. Rafikov

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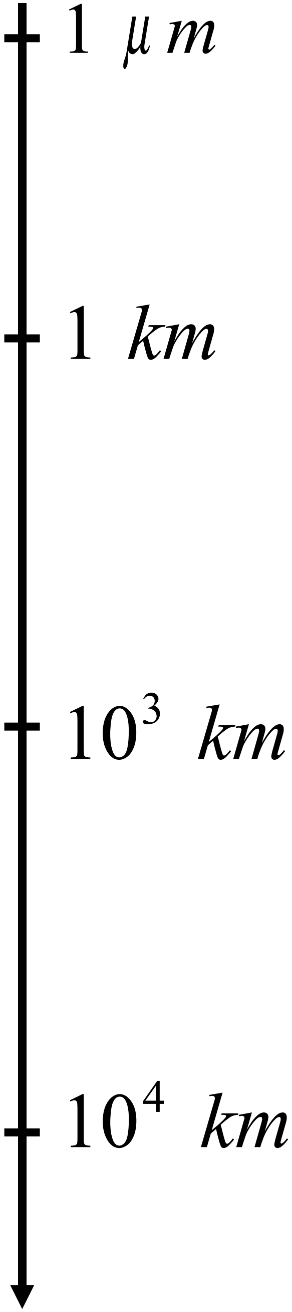

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From planetesimals to Moon-size “embryos”

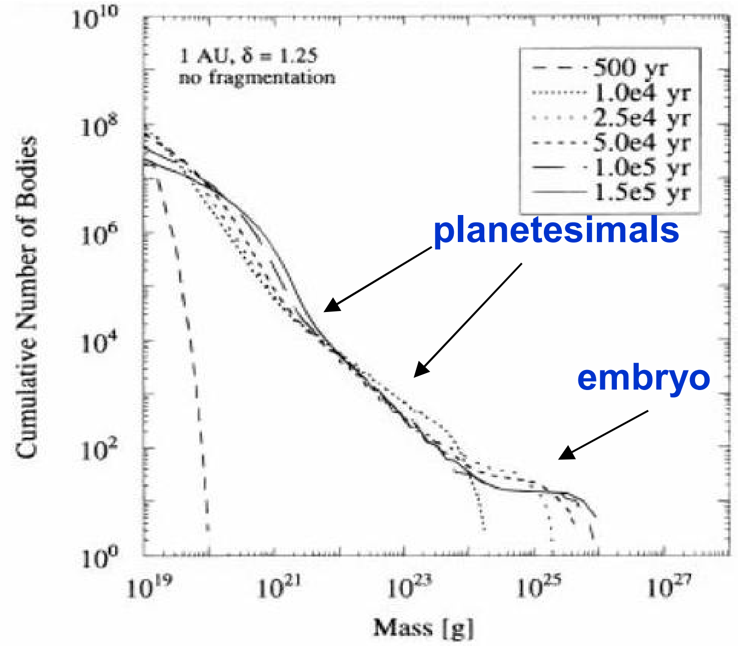
Features of this evolutionary stage:

- Many planetesimals ($\approx 10^{12}$ within 1 AU); orbits overlap.
- Mutual gravitational perturbations excite their eccentricities and inclinations -energy gets pumped from circular orbital motion into random motion.
- Low-velocity collisions lead to mergers and planetesimal grows, high velocity collisions cause erosion and fragmentation
- System evolves under simultaneous action of all these processes

Because of the huge number of bodies involved, kinetic theory should be employed to study planetesimal agglomeration, including both mass and velocity evolution.

Direct N-body simulations can also probe spatial evolution but they are very limited.

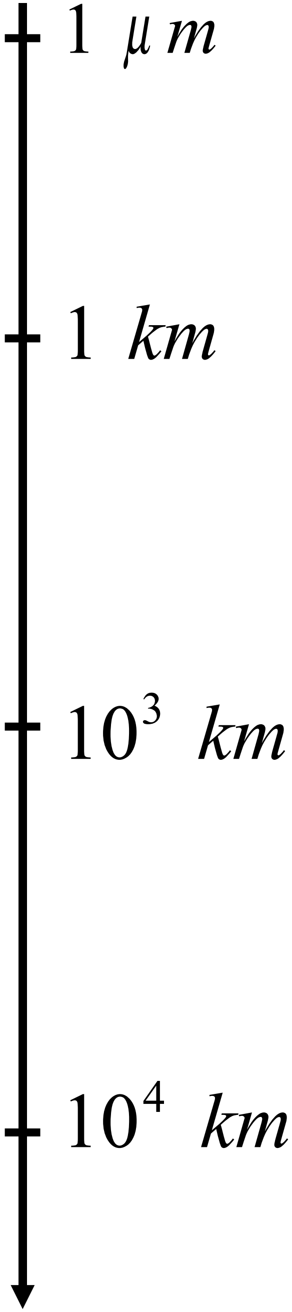
Particle-in-a-box simulations (modeling disk as a “gas” of gravitating particles) demonstrate growth up to 10^{26} g in 10^5 yr at 1 AU – Moon-size embryos in the terrestrial region.



(Kenyon & Luu 1998)

Adapted from R. Rafikov

Stages of Planet Formation by Core Accretion



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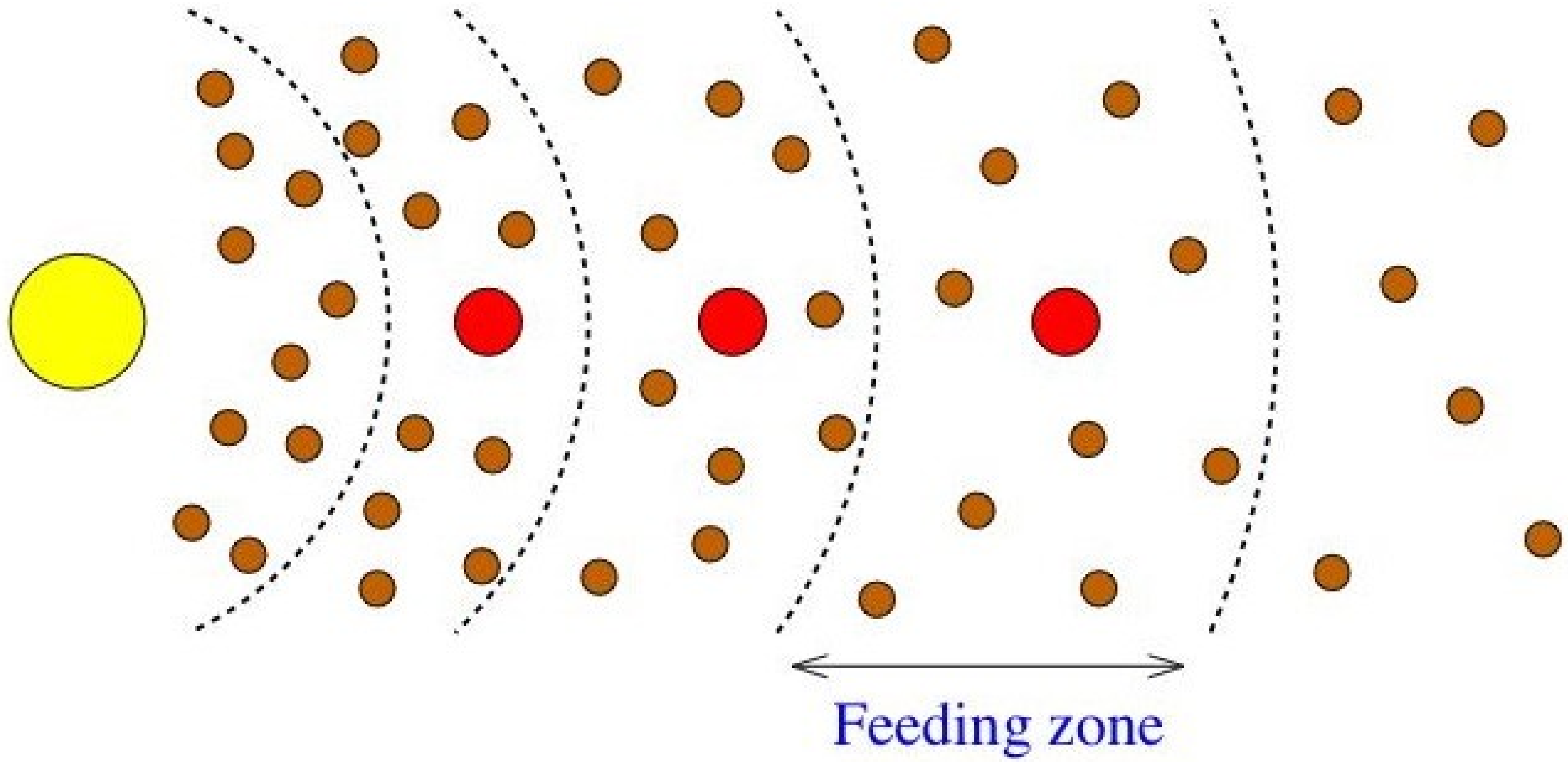
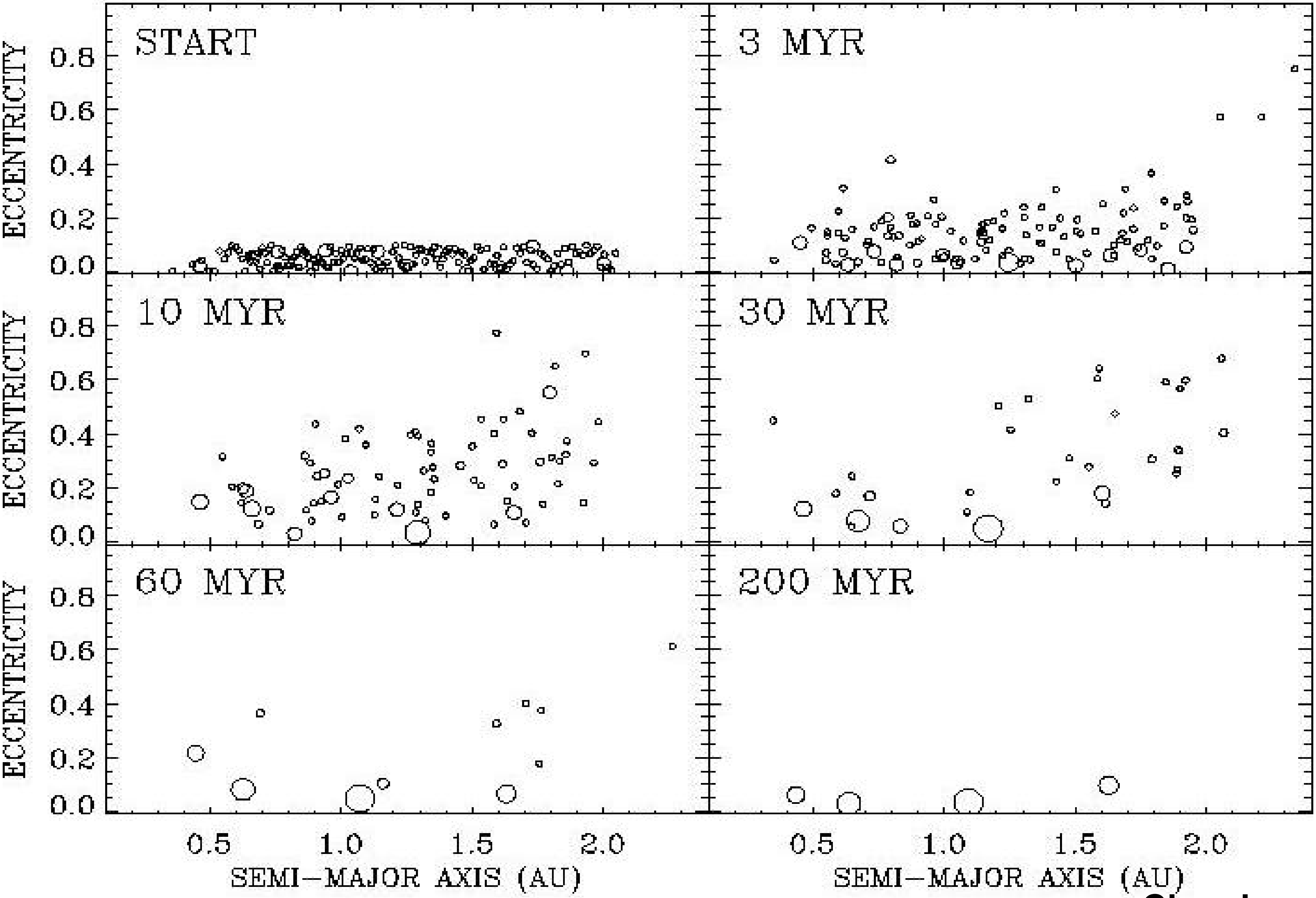
Adapted from R. Rafikov

Oligarchic Growth



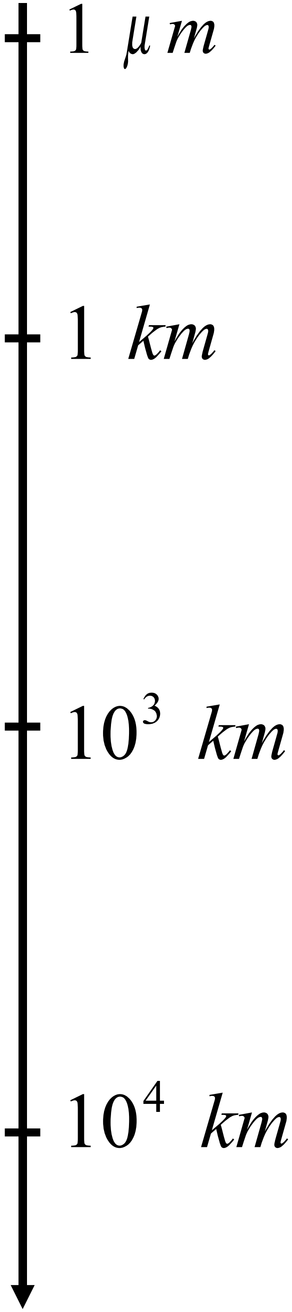
Adapted from J. Chambers

Embryos to Terrestrial Planets (Sun-Jupiter-Saturn)



Chambers 2001

Stages of Planet Formation by Core Accretion



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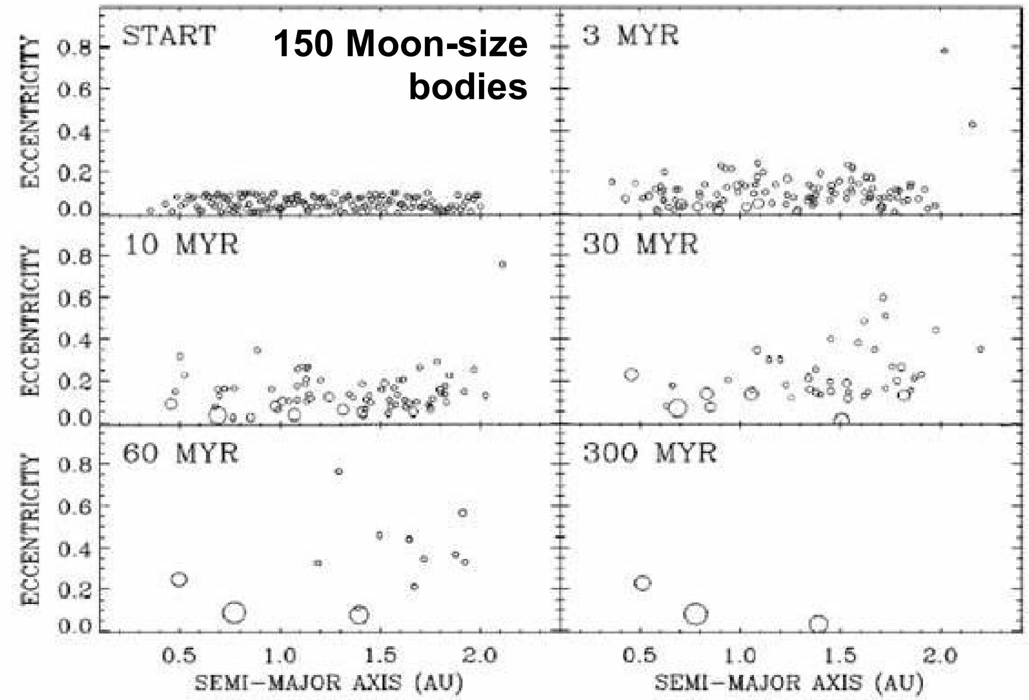
Adapted from R. Rafikov

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

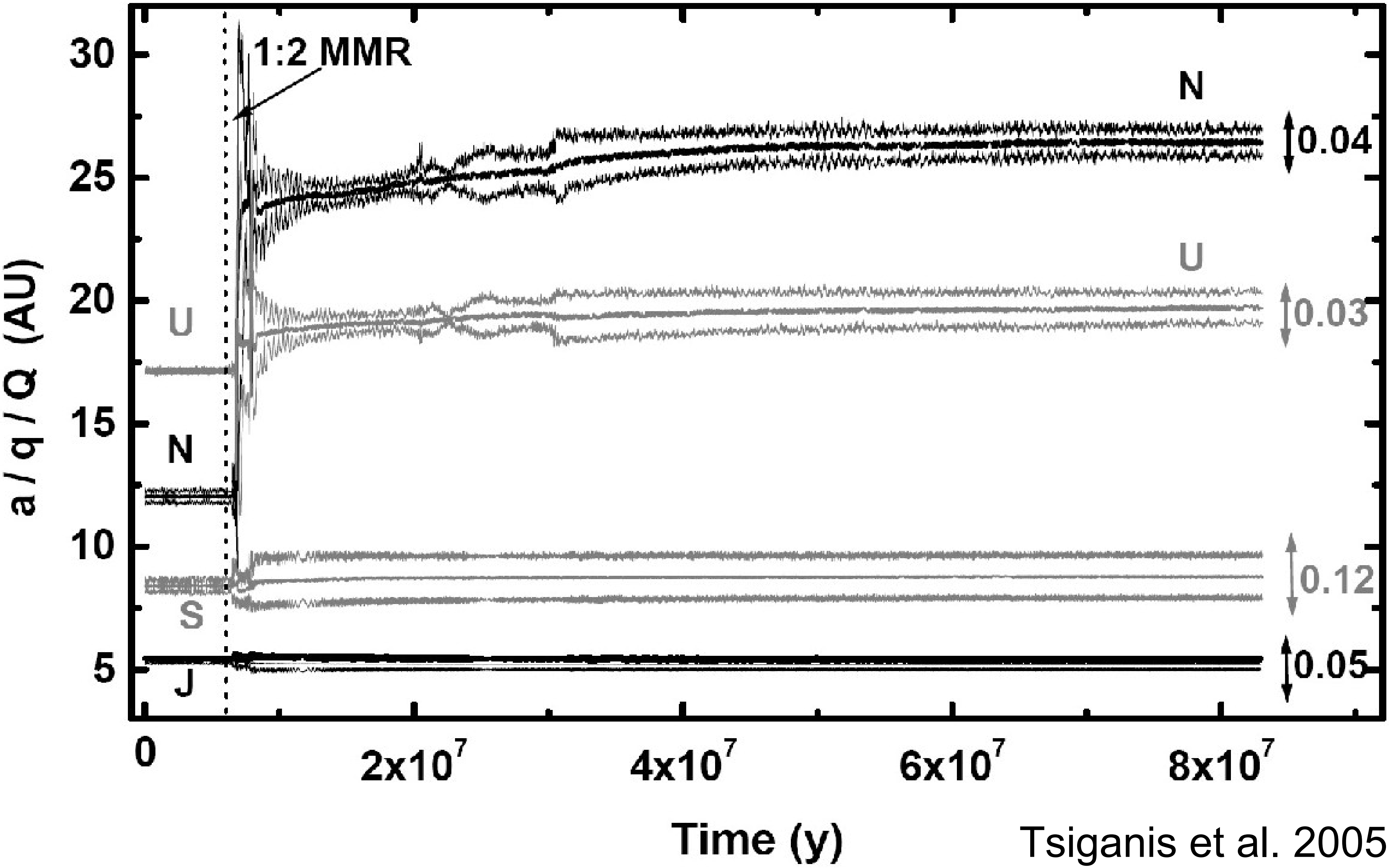
Violence in the Solar System

- 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

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)

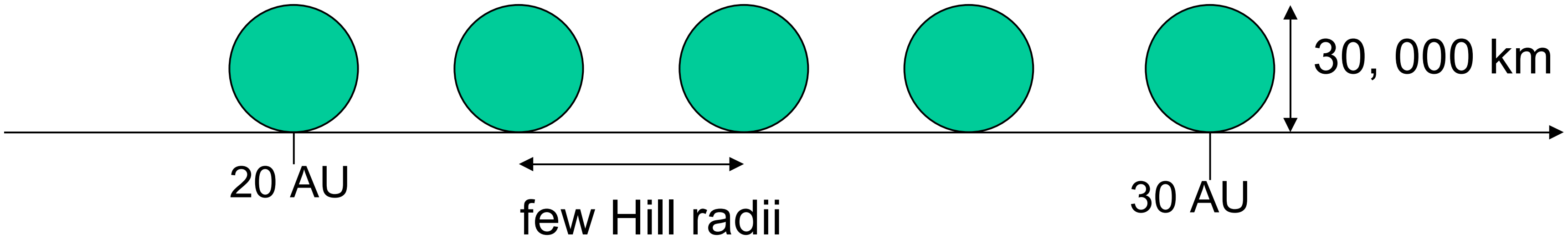
Jupiter, Saturn, 2 Ice Giants + small bodies



Tsiganis et al. 2005

Uranus & Neptune = End of Oligarchy?

- Formation time of Uranus & Neptune fast enough (10 Myr) if small bodies are very small (< 1 m) and very cold (e<0.05)
- In cold (sub Hill) accretion, might expect:



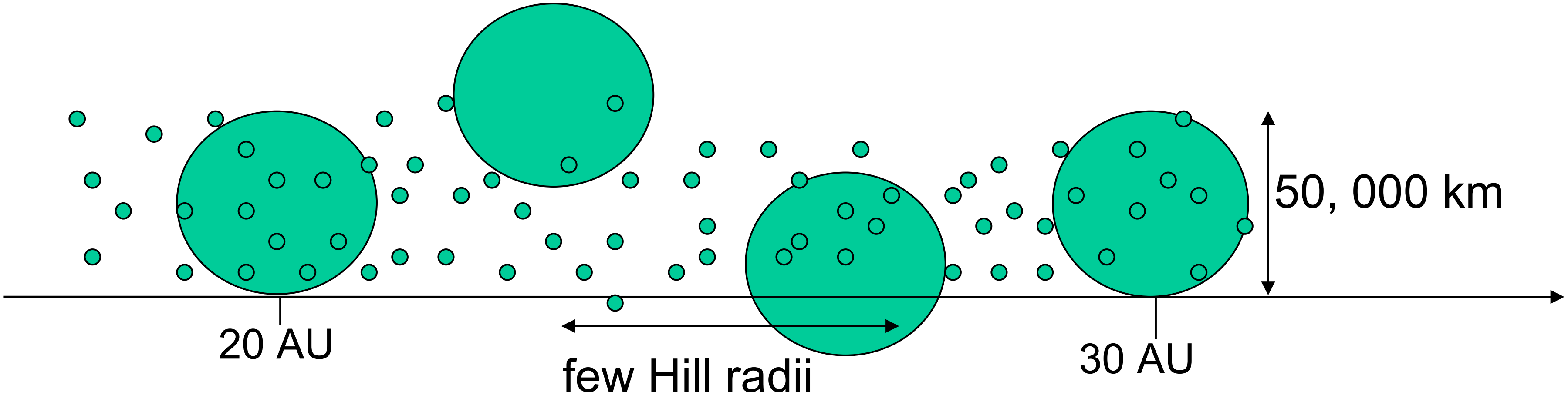
Observe:

Adapted from R. Sari

Uranus & Neptune: Beyond Isolation

- Isolation when $\Sigma \sim \sigma$.
- we assume $u \sim v_H$

$$T_{\rm isolation} \sim \Omega^{-1} \frac{\alpha \rho R}{\sigma} \sim 10 \text{ million years}$$

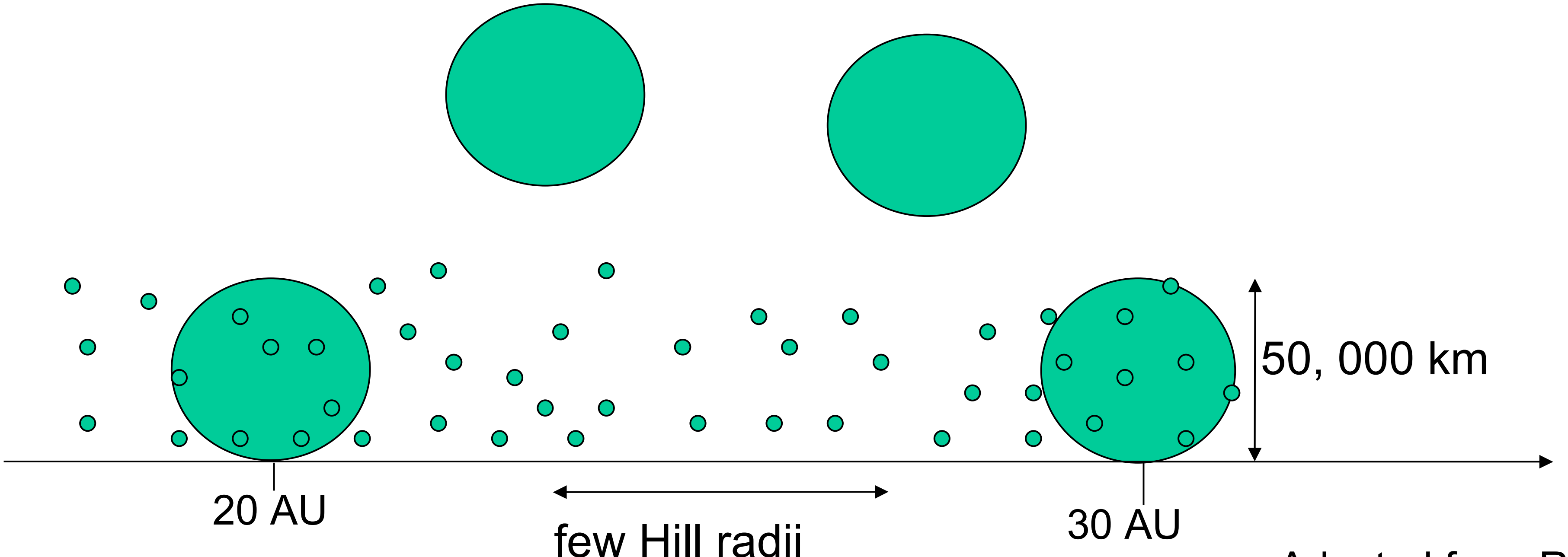


Adapted from R. Sari

Uranus & Neptune: Ejection

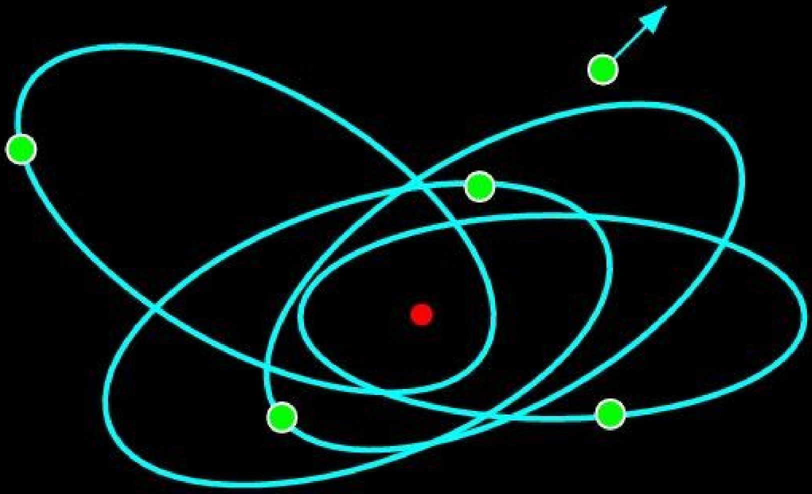
- After 10 million years, $\Sigma > \sigma$
- Heating > Cooling ⇒ **runaway heating**
- Planets are ejected in time

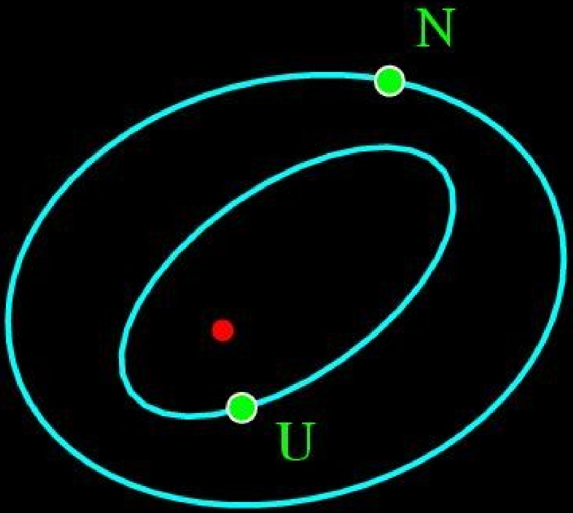
$$T_{\mathrm{eject}} \sim \frac{1}{10}\Omega^{-1}\left(\frac{M_\odot}{M_{\mathrm{Neptune}}}\right)^2 \sim \text{billion years}$$

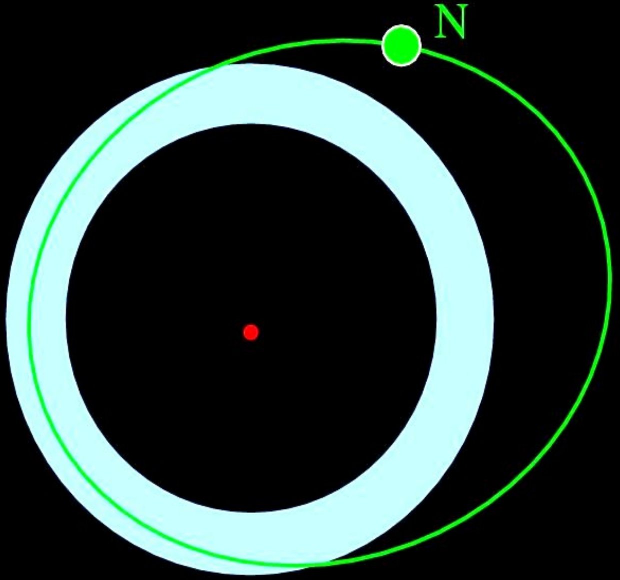


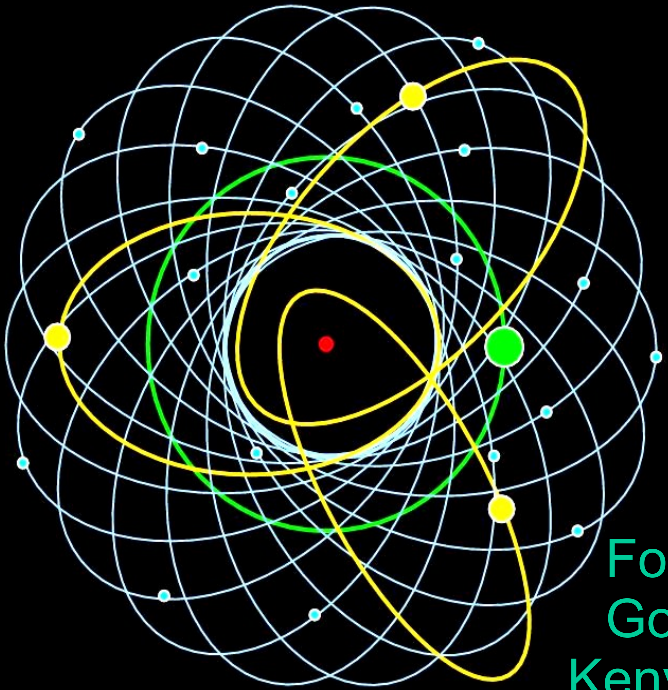
Adapted from R. Sari

Very Late Stages of Planet Formation?









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

Sculpting of the Kuiper Belt

- Problem 2: How to excite Scattered Disk?
- Possible Solutions:

a) Migration & sweeping resonances (secular, Kozai & high-order mean-motion; Gomes et al. 2003ab)… But has very low efficiency, ~10^{-3}

b) Stirring of scattered disk by oligarchs during chaotic stage (Chiang et al. 2006)…
We will test this with simulations (Ford & Chiang 2007)

Goals

Test analytic predictions of GLS & C06 with numerical simulations. Will outcomes resembling our Solar System be common?

- Can 3 of 5 oligarchs be ejected?
- Where will remaining oligarchs be?
- Can their eccentricity/inclination be damped to observed values?
- Can scattered disk be created in the process?

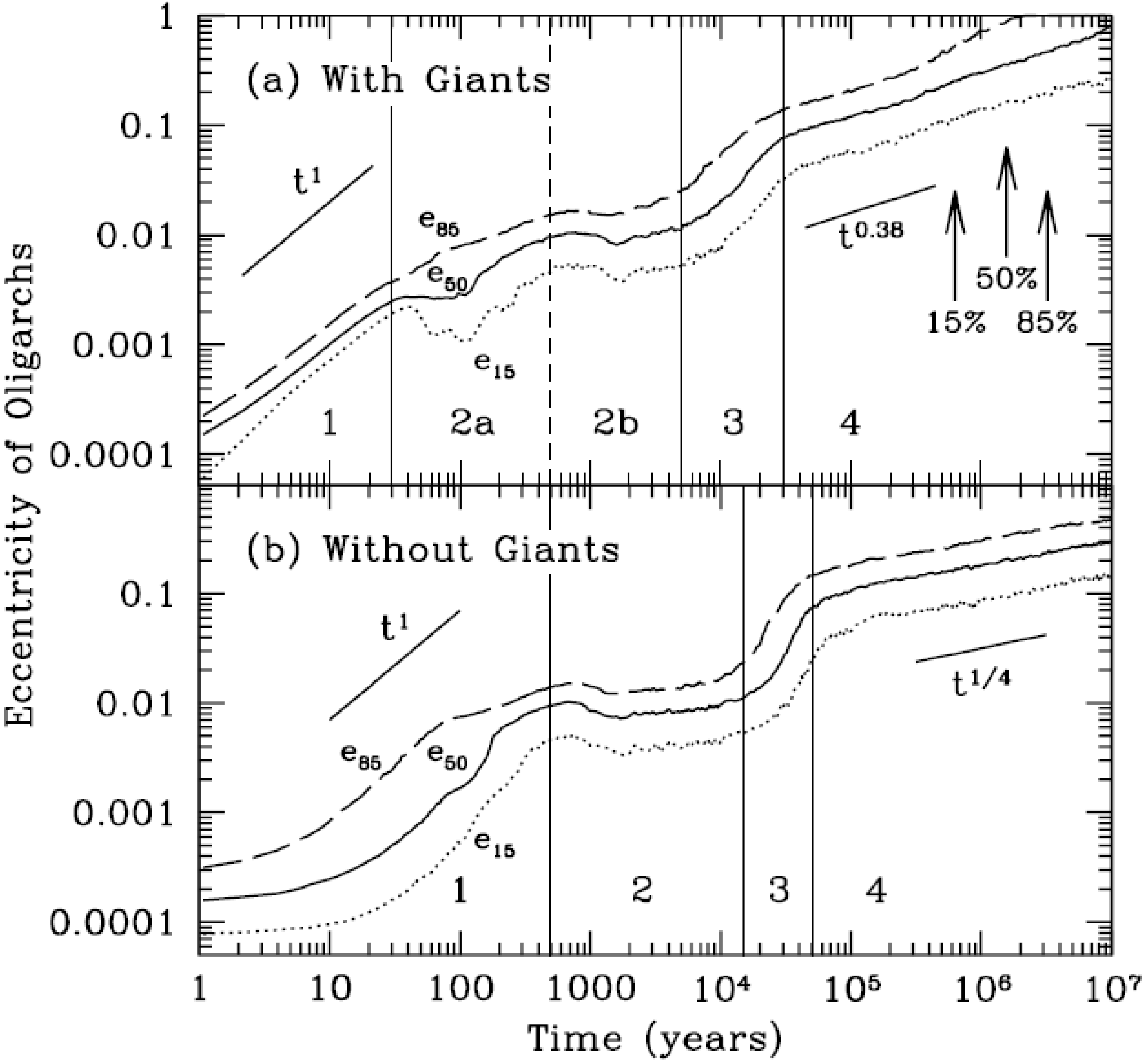
Ford & Chiang (2007) see also Levison & Morbidelli (2007)

Our Model: Initial Conditions

- Jupiter & Saturn on current orbits: a_{init} = 5.18, 9.54 AU
- 5 Neptune-mass Oligarchs:
  - a_{init} = 15, 20, 25, 30, 35 AU
  - $e_{init} = \sin(i_{init}) = 0.0001$

Ford & Chiang (2007)

Eccentricity Growth w/o Dissipation



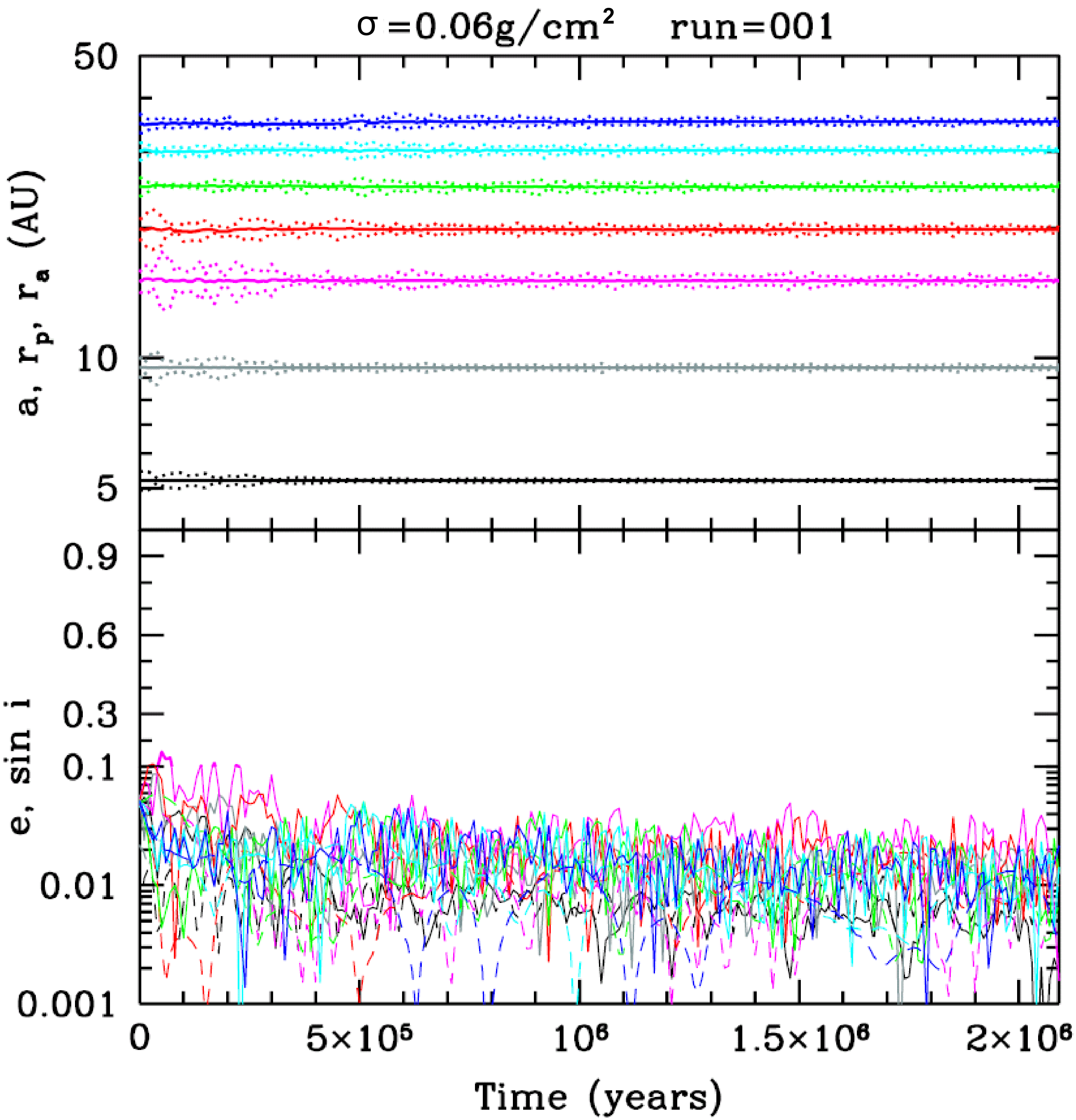
Ford & Chiang (2007)

Our Model: Initial Conditions

- Jupiter & Saturn on current orbits: a_{init} = 5.18, 9.54 AU
- 5 Neptune-mass Oligarchs:
  - a_{init} = 15, 20, 25, 30, 35 AU
  - $e_{init} = \sin(i_{init}) = 0.05$
- Small bodies (static, constant σ disk):
  - 12.5 AU < a < 45 AU
  - Interact with oligarchs only via dynamical friction
- Large (~100km) Kuiper Belt Objects
  - 400 test particles
  - a_{init} = 40-45 AU
  - $e_{init} = \sin(i_{init}) = 0.01$

Ford & Chiang (2007)

Full Simulations: $\sigma > 0.06\ \mathrm{g/cm^2}$

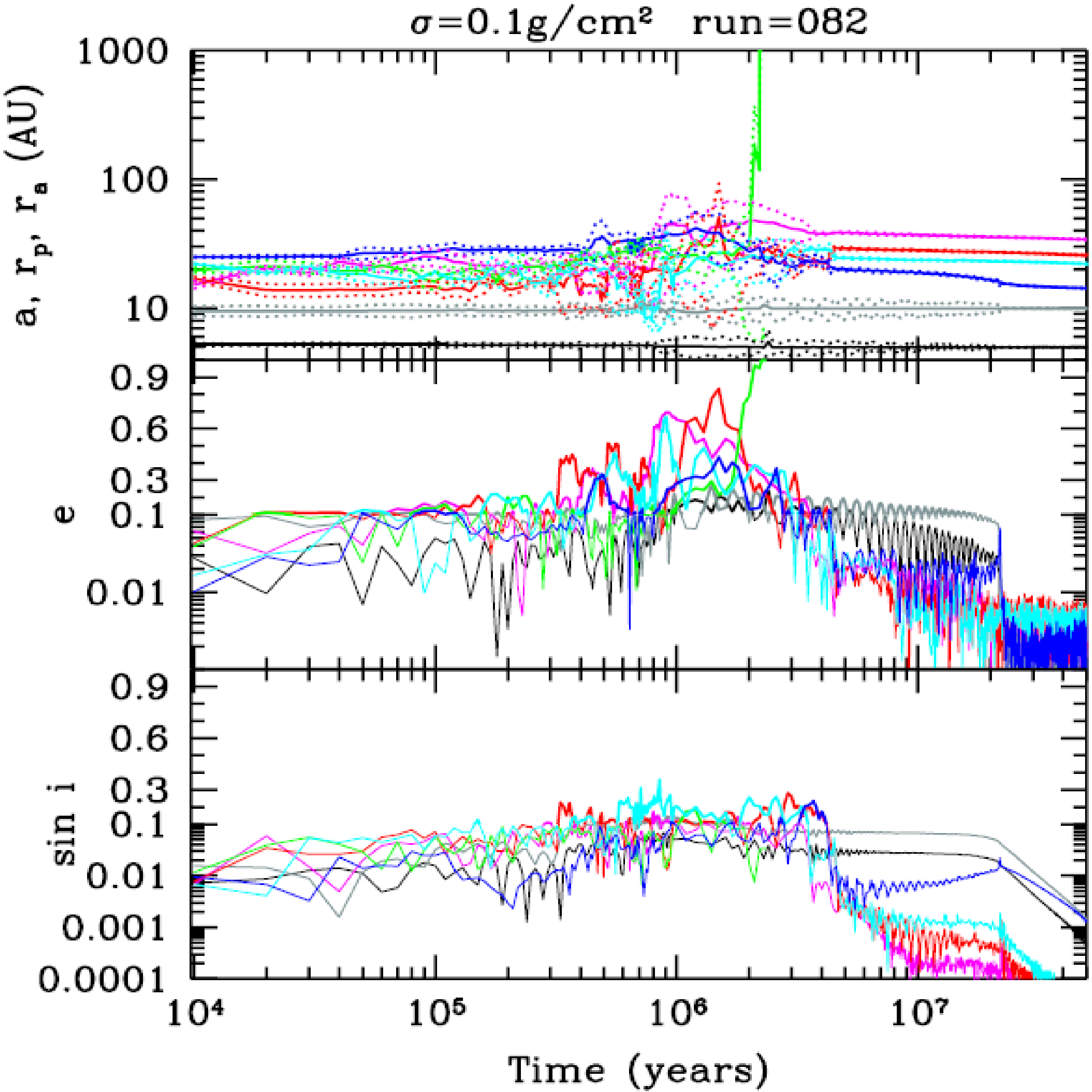


vs $\Sigma \sim 0.7\ \mathrm{g/cm^2}$

- Dynamical friction prevents close encounters
- Systems retain 5 oligarchs

Ford & Chiang (2007)

Full Simulations: $\sigma \sim 0.1\ g/cm^2$

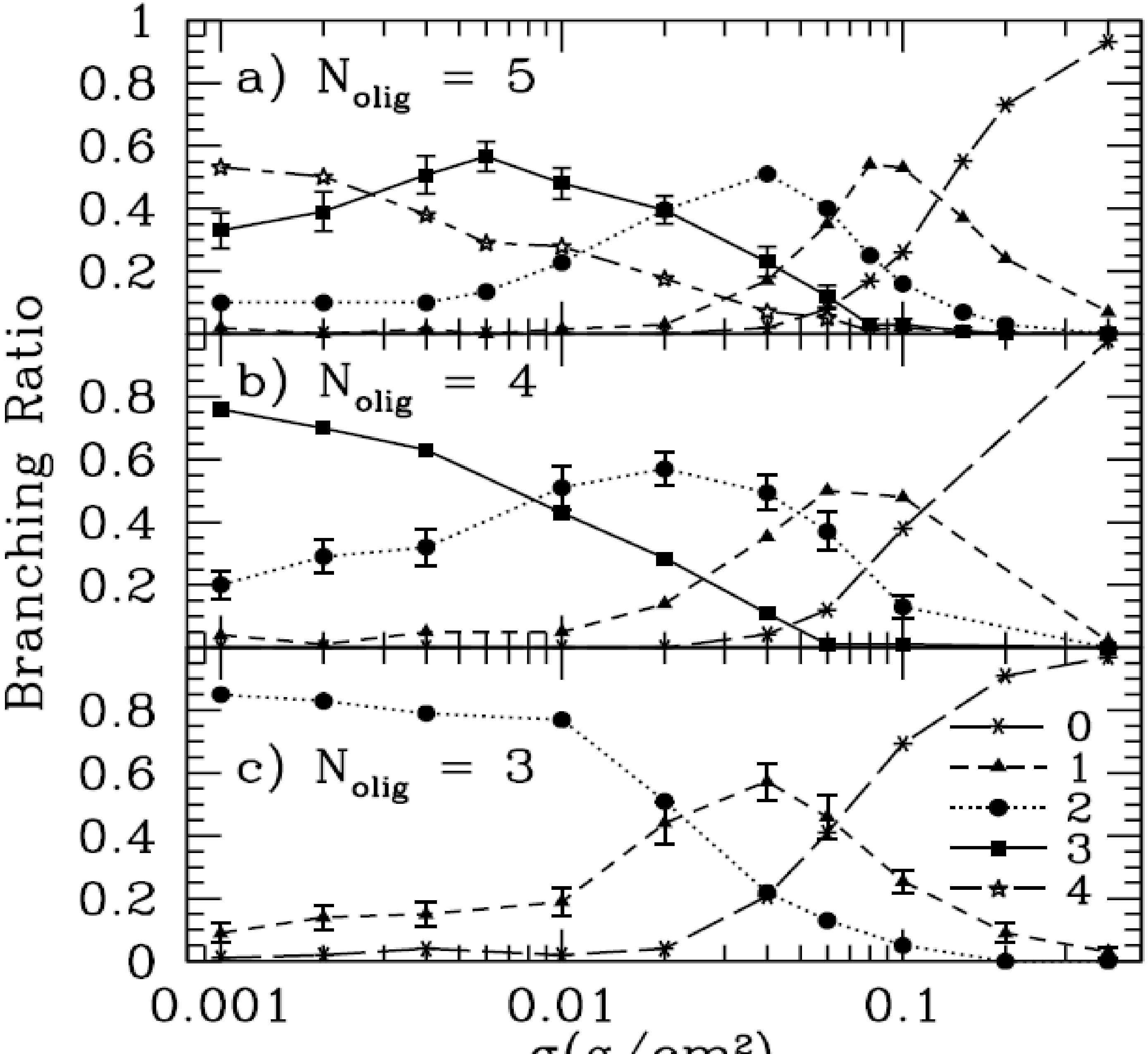


vs $\Sigma \sim 0.7\ g/cm^2$

- Near threshold of instability
- One oligarch ejected
- Remaining planets recircularize
- Results in outward migration

Ford & Chiang (2007)

Outcome of Instability

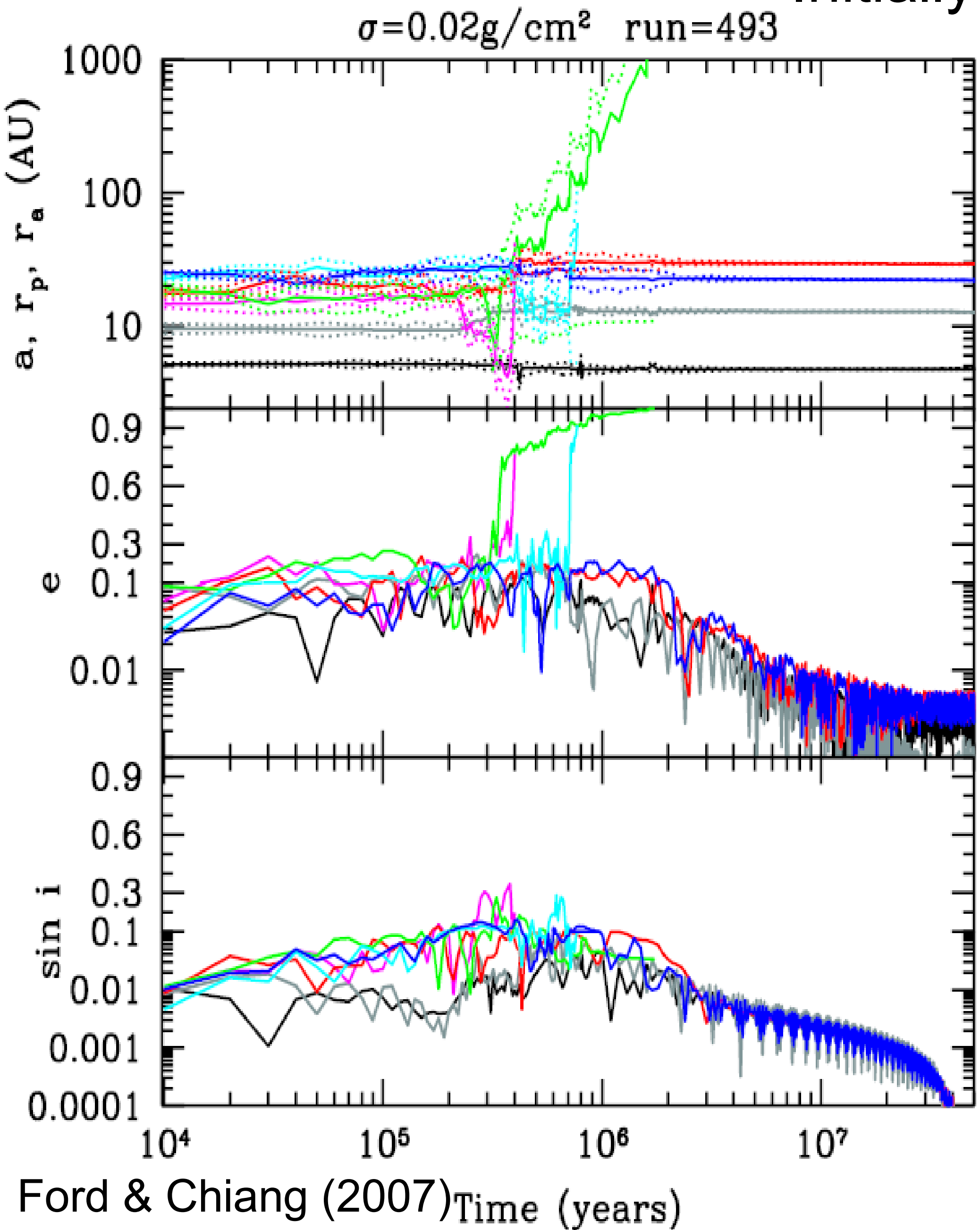


Ford & Chiang (2007)

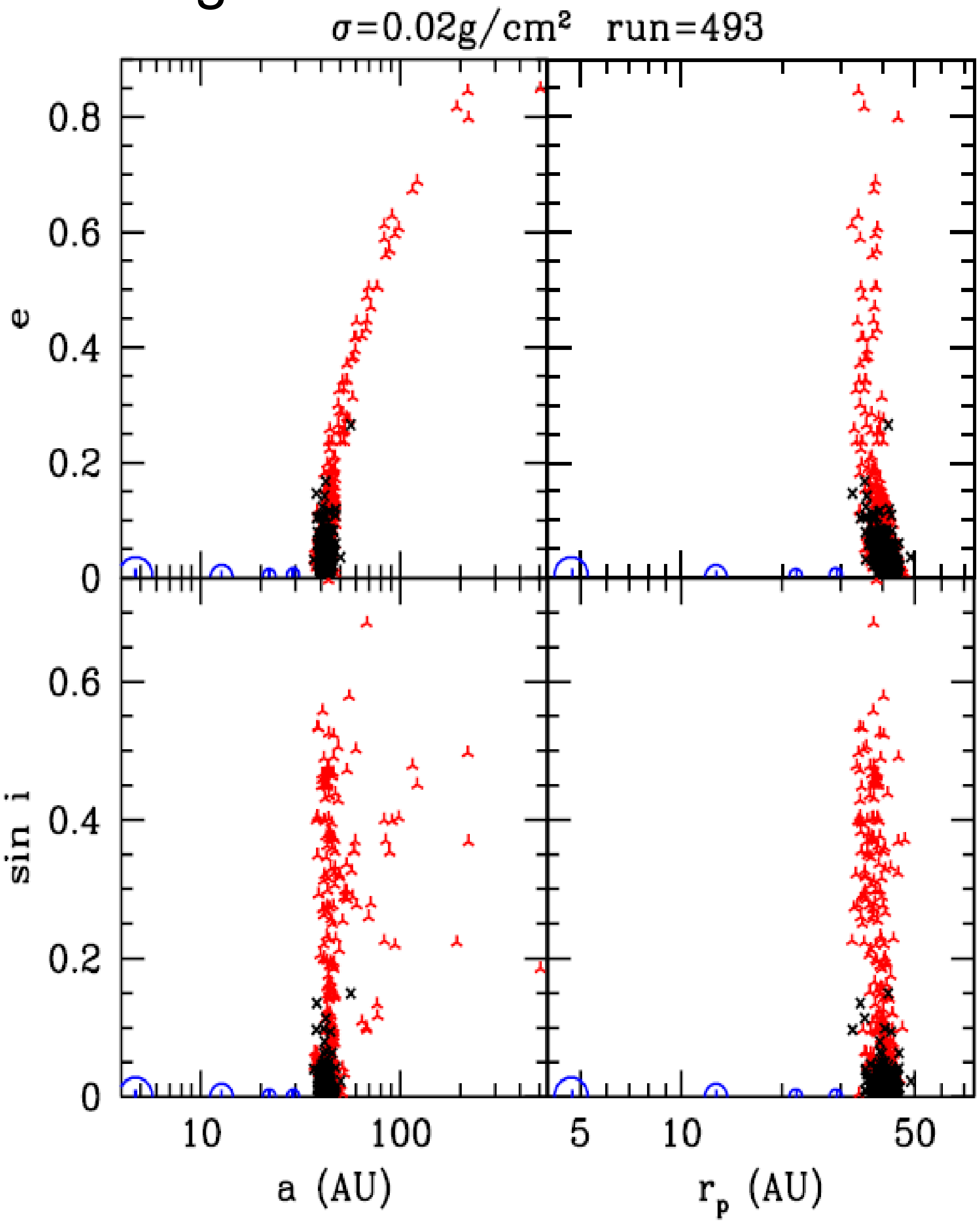
Full Simulations: $\sigma \sim 0.02$ g/cm^2

vs $\Sigma \sim 0.7$ g/cm^2

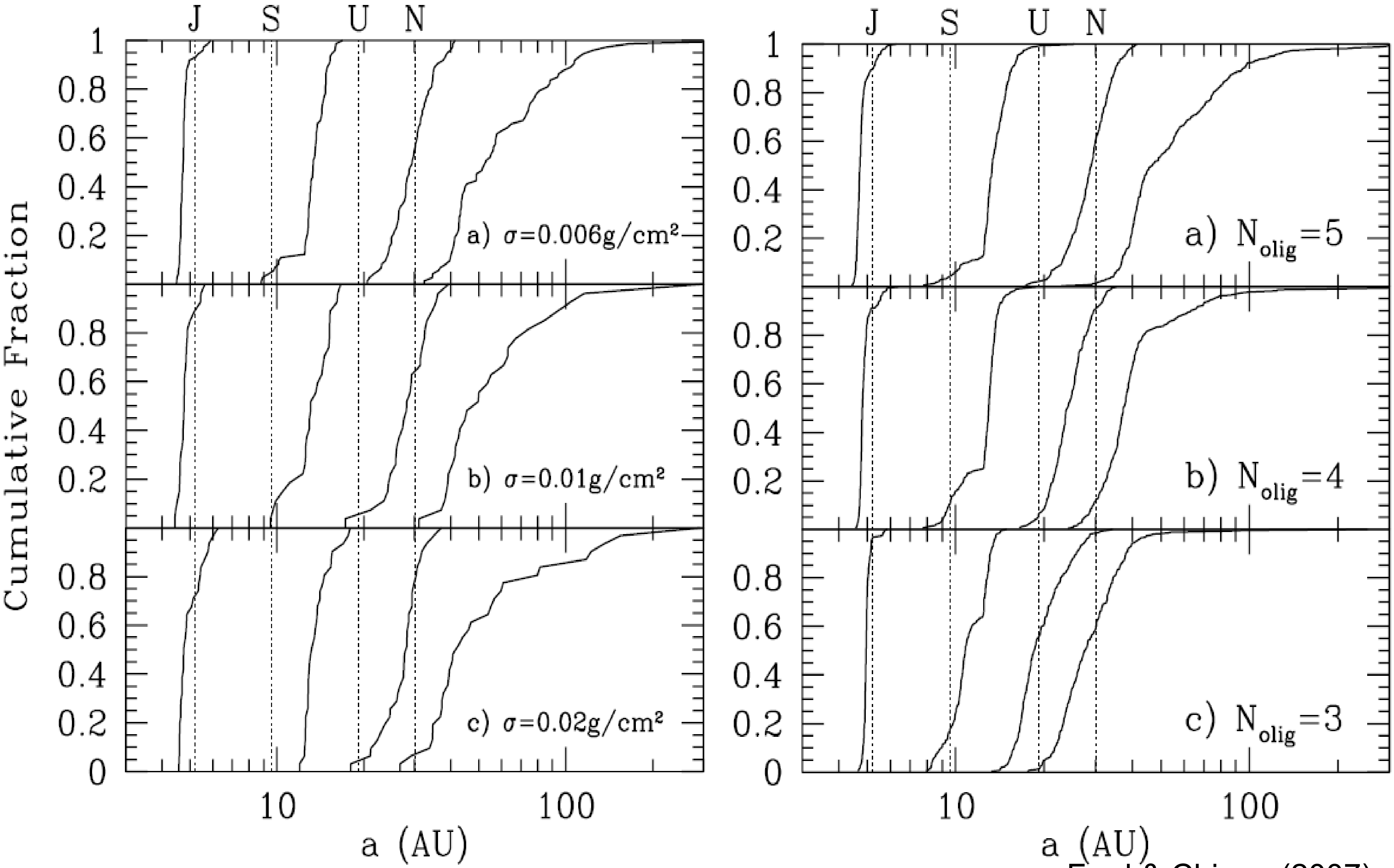
Initially Five Oligarchs



Ford & Chiang (2007)



Outward Spreading of Oligarchs

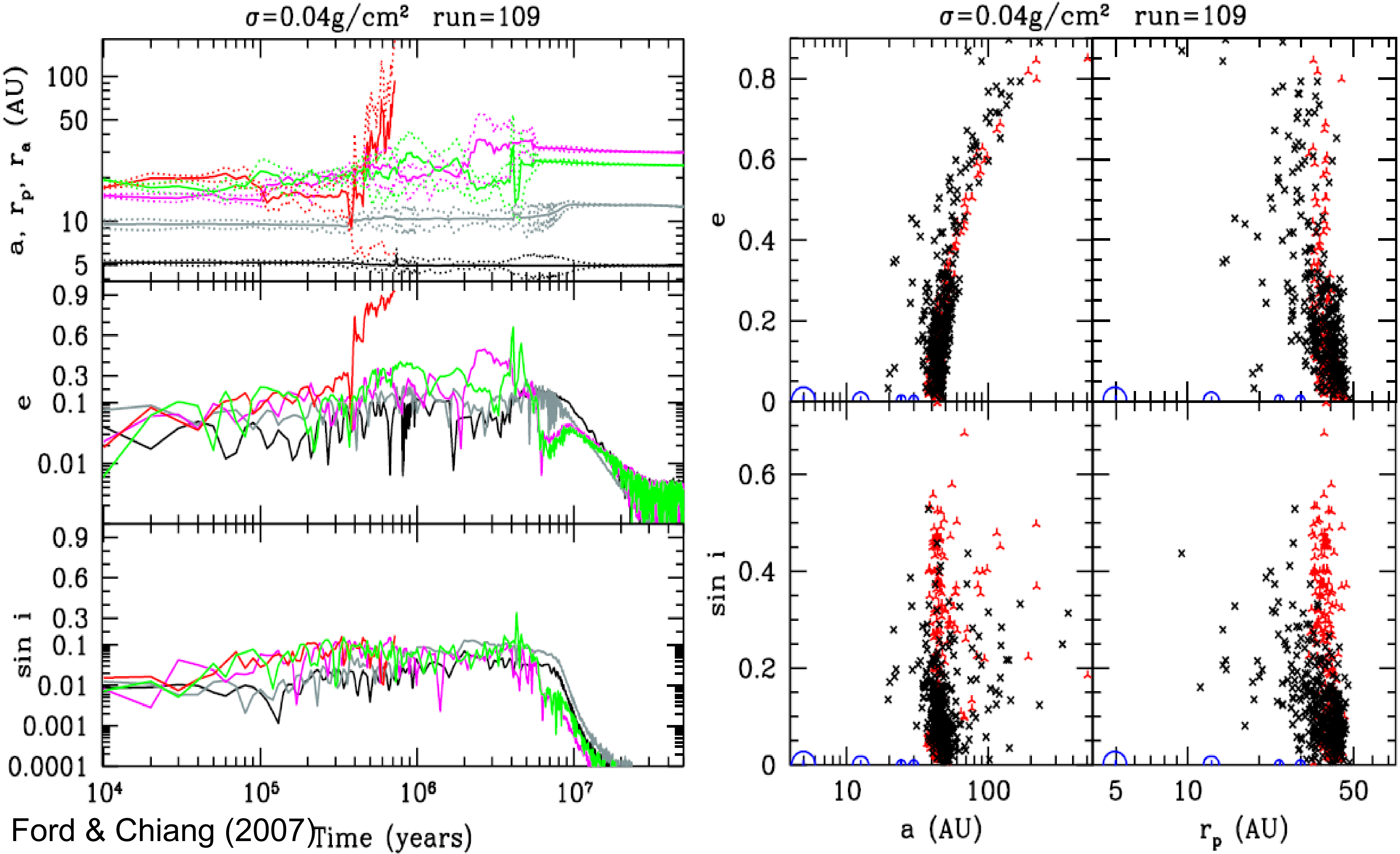


Ford & Chiang (2007)

Full Simulations: σ ~ 0.04 g/cm^2

vs Σ ~ 0.7 g/cm^2

Initially Three Oligarchs



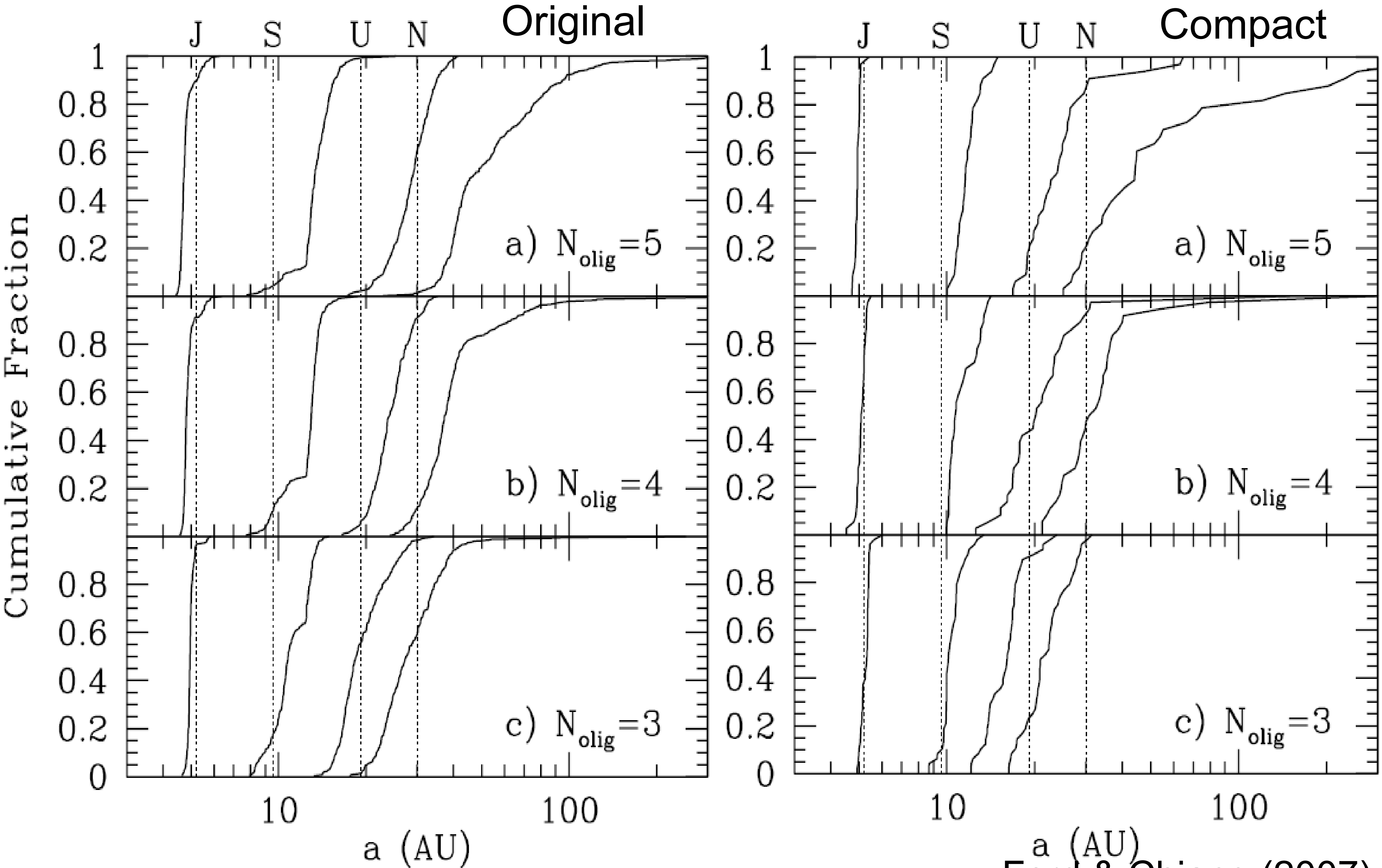
Ford & Chiang (2007)

Our Model: Initial Conditions

- Consider more compact initial conditions
- Jupiter & Saturn: a_{init} = 5.7, 8 AU
- 5 Neptune-mass Oligarchs:
  - a_{init} = 13.17, 15.5, 17.7, 20.1AU
  - $e_{init} = \sin(i_{init}) = 0.05$
- Small bodies (static, constant σ disk):
  - 10 AU < a < 45 AU
  - Interact with oligarchs only via dynamical friction
- Large (~100km) Kuiper Belt Objects
  - 400 test particles
  - a_{init} = 40-45 AU
  - $e_{init} = \sin(i_{init}) = 0.01$

Ford & Chiang (2007)

Outward Spreading of Oligarchs



Original

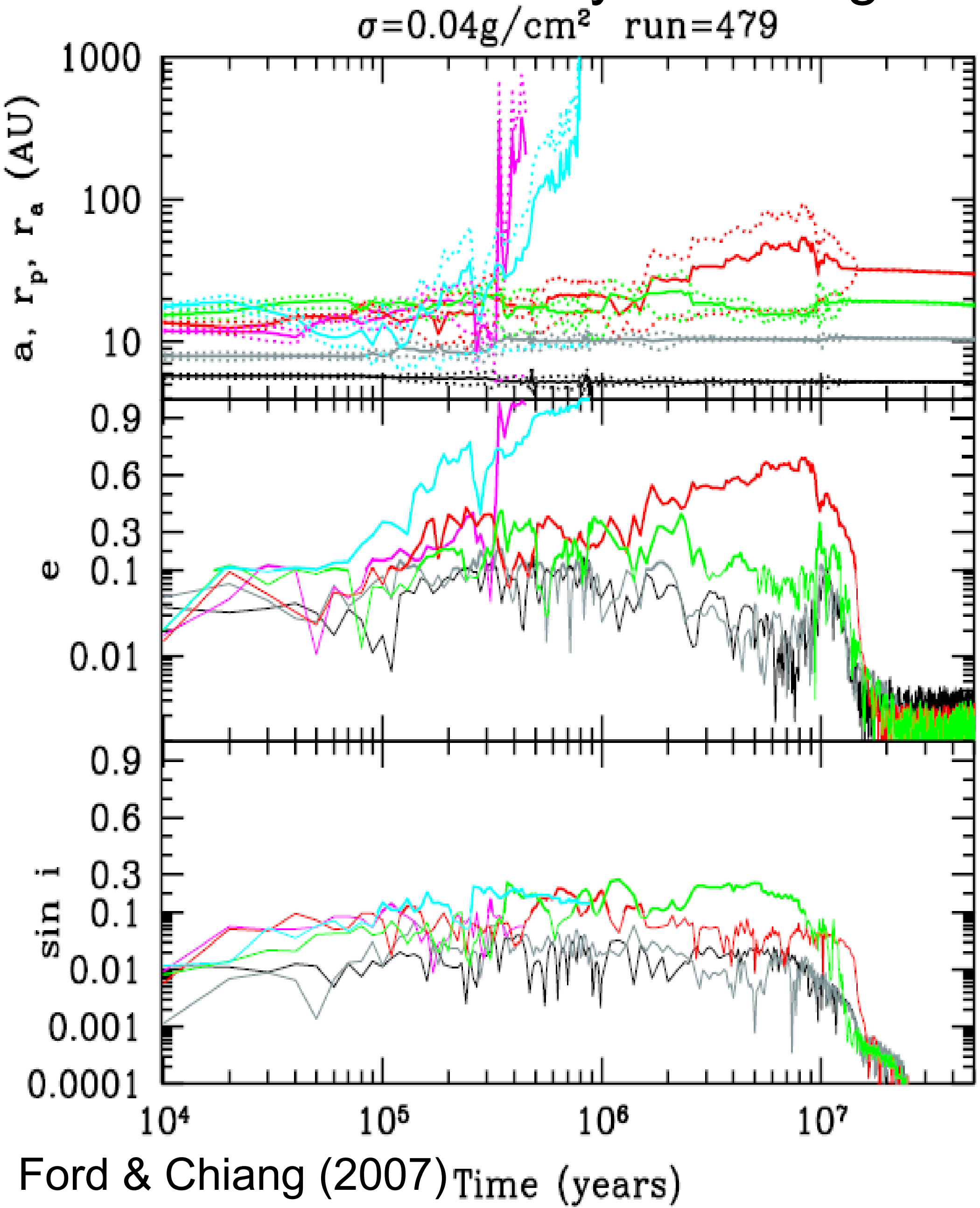
Compact

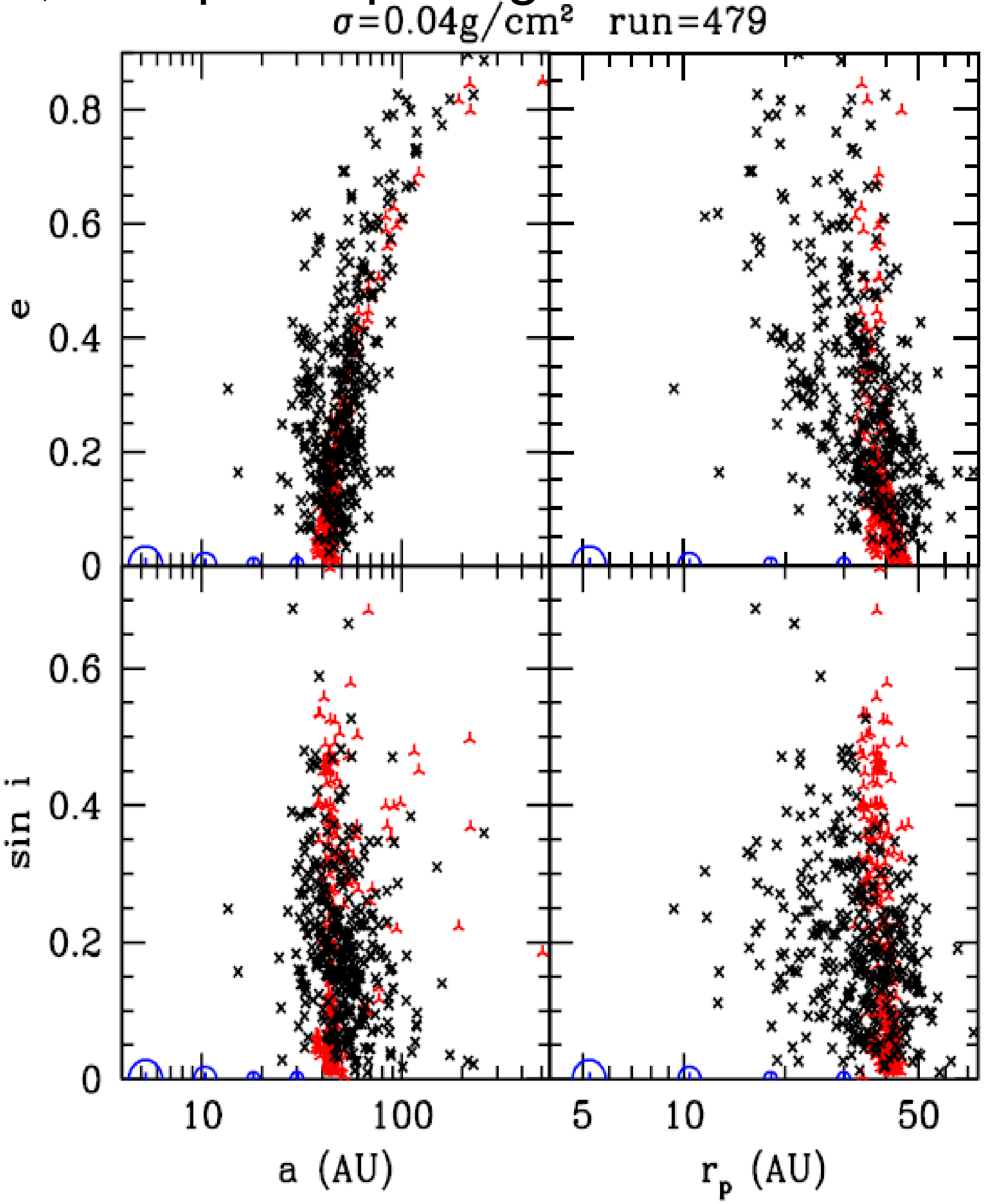
Ford & Chiang (2007)

Full Simulations: $\sigma \sim 0.04$ g/cm^2

vs $\Sigma \sim 1.8$ g/cm^2

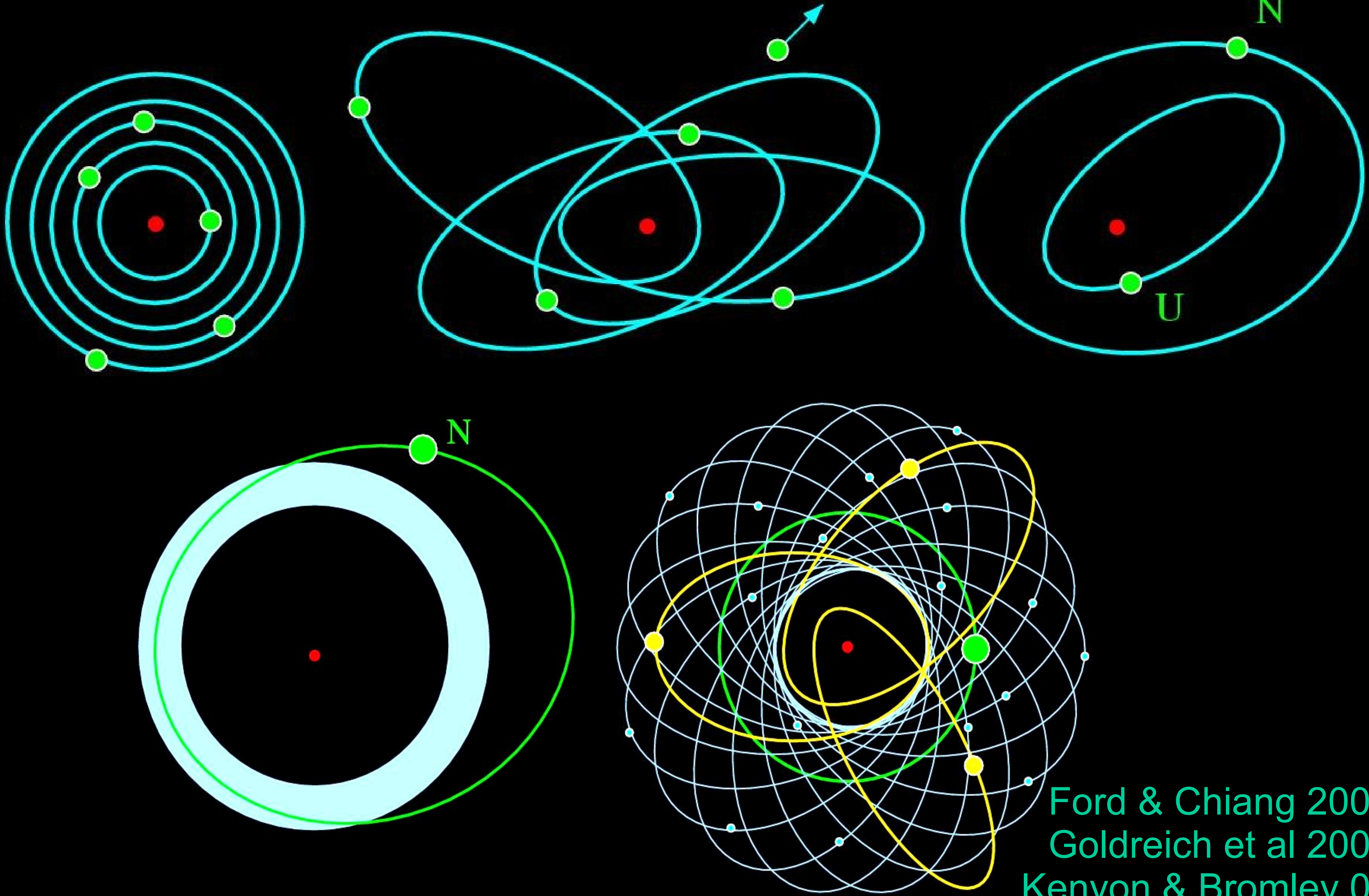
Initially Four Oligarchs, Compact Spacing





Ford & Chiang (2007)

Very Late Stages of Planet Formation?



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

Conclusions

- 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

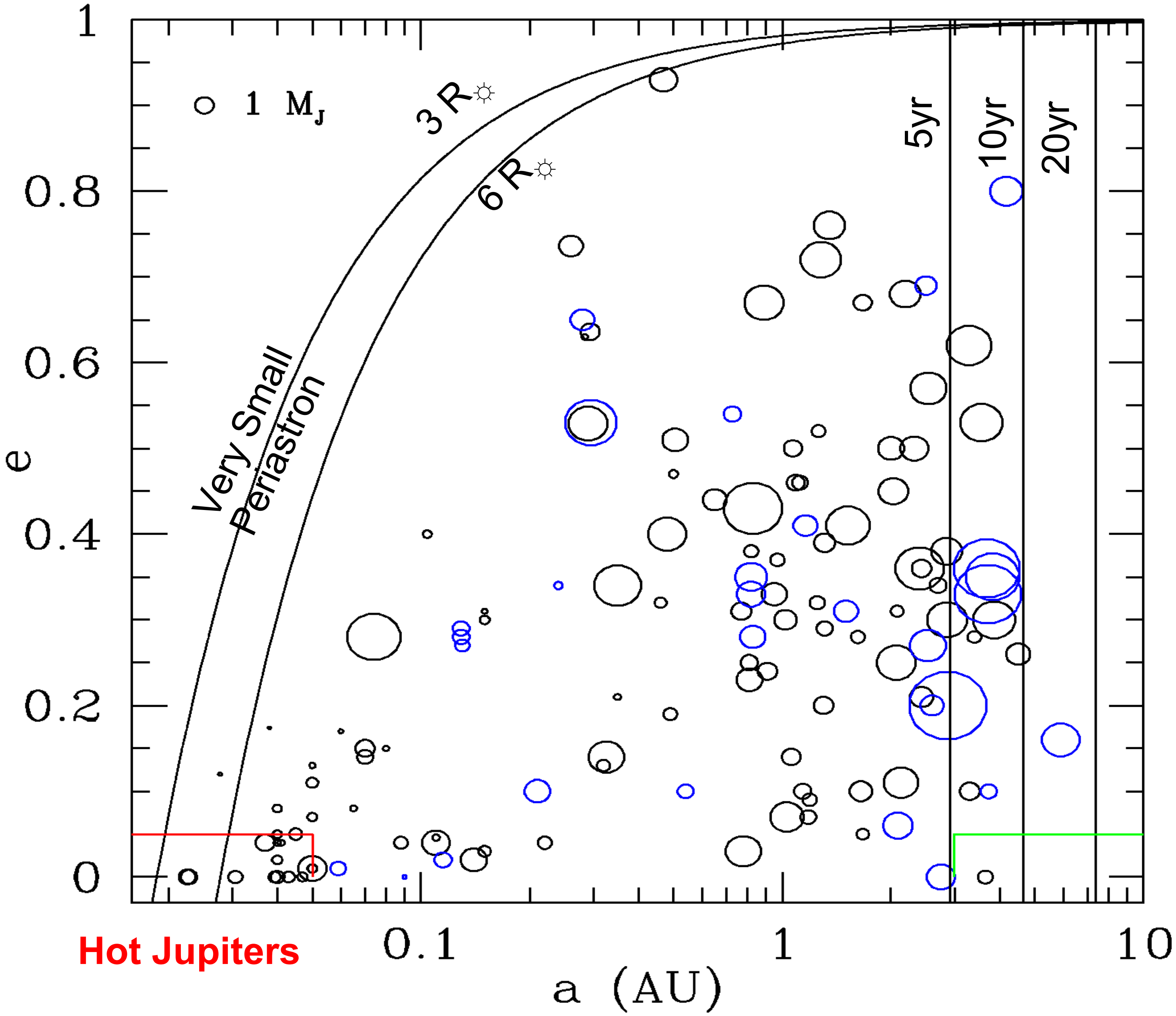
Dynamical Evolution of Planetary Systems and Debris Disks

Eric B. Ford
Harvard-Smithsonian Center for Astrophysics
University of Florida (starting in August, 2007)

May 30, 2007
Extrasolar Planets: detection, formation, evolution, and dynamics of planetary systems
Sabhal Mor Ostaig, Isle of Skye, United Kingdom

Collaborators: Sourav Chatterjee[G], Eugene Chiang, Scott Gaudi, Matt Holman, Kris Joshi[G], Mario Juric, Boris Kozinsky[U], Verene Lystad[U], Fred Rasio, Boris Zbarsky[U]

Diversity of Extrasolar Planets



Eccentric Planets

Multiple Planet Systems

Solar System-like Giant Planets

Hot Jupiters

Ford

How to Excite Eccentricities?

- Gas Disk (Artymowicz 1992, Chiang & Murray 2002, Goldreich & Sari 2003, Papalouizou et al. 2001, Ogilvie & Lubow 2003)
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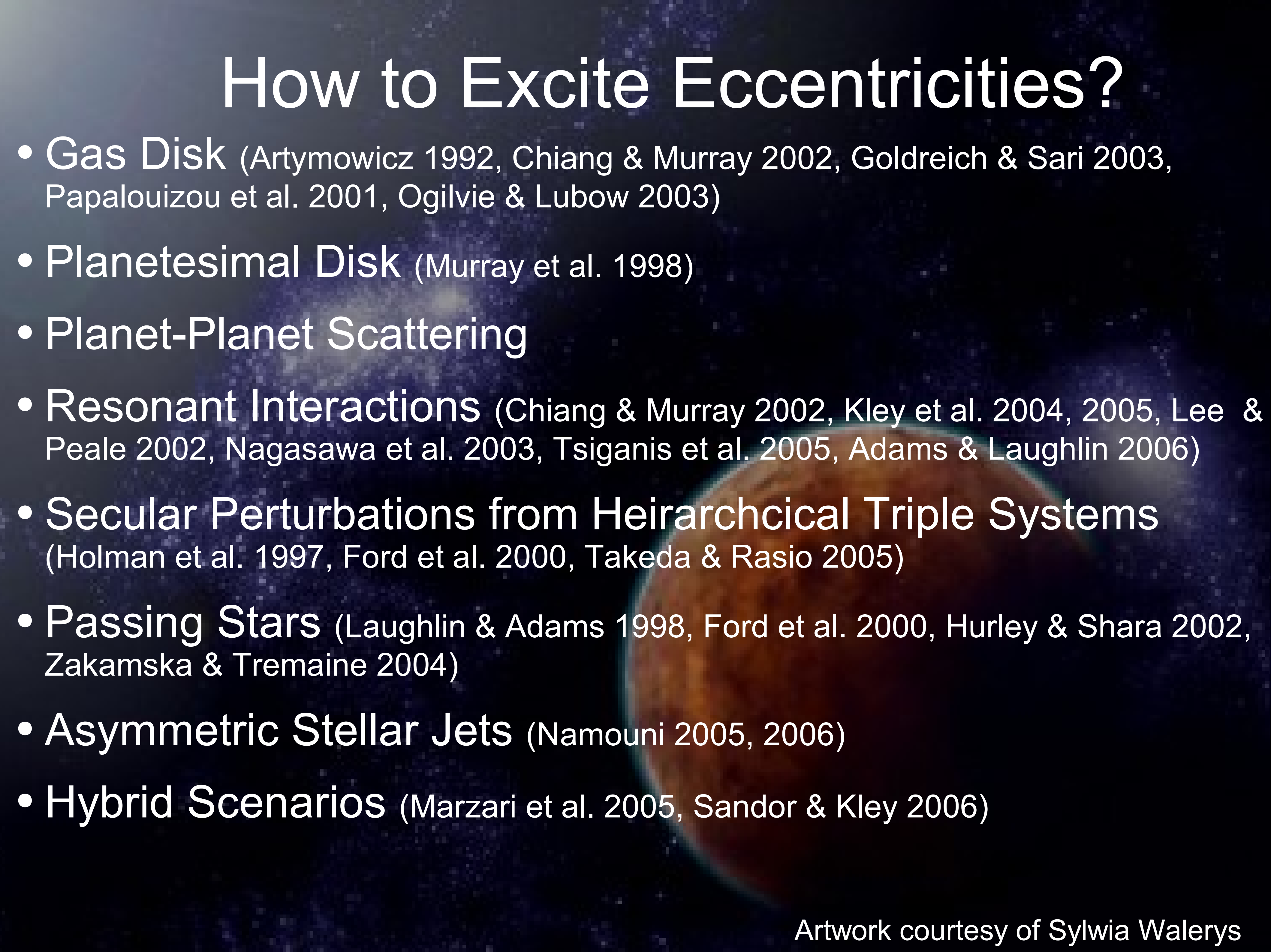

Artwork courtesy of Sylwia Walerys

How to Excite Eccentricities?

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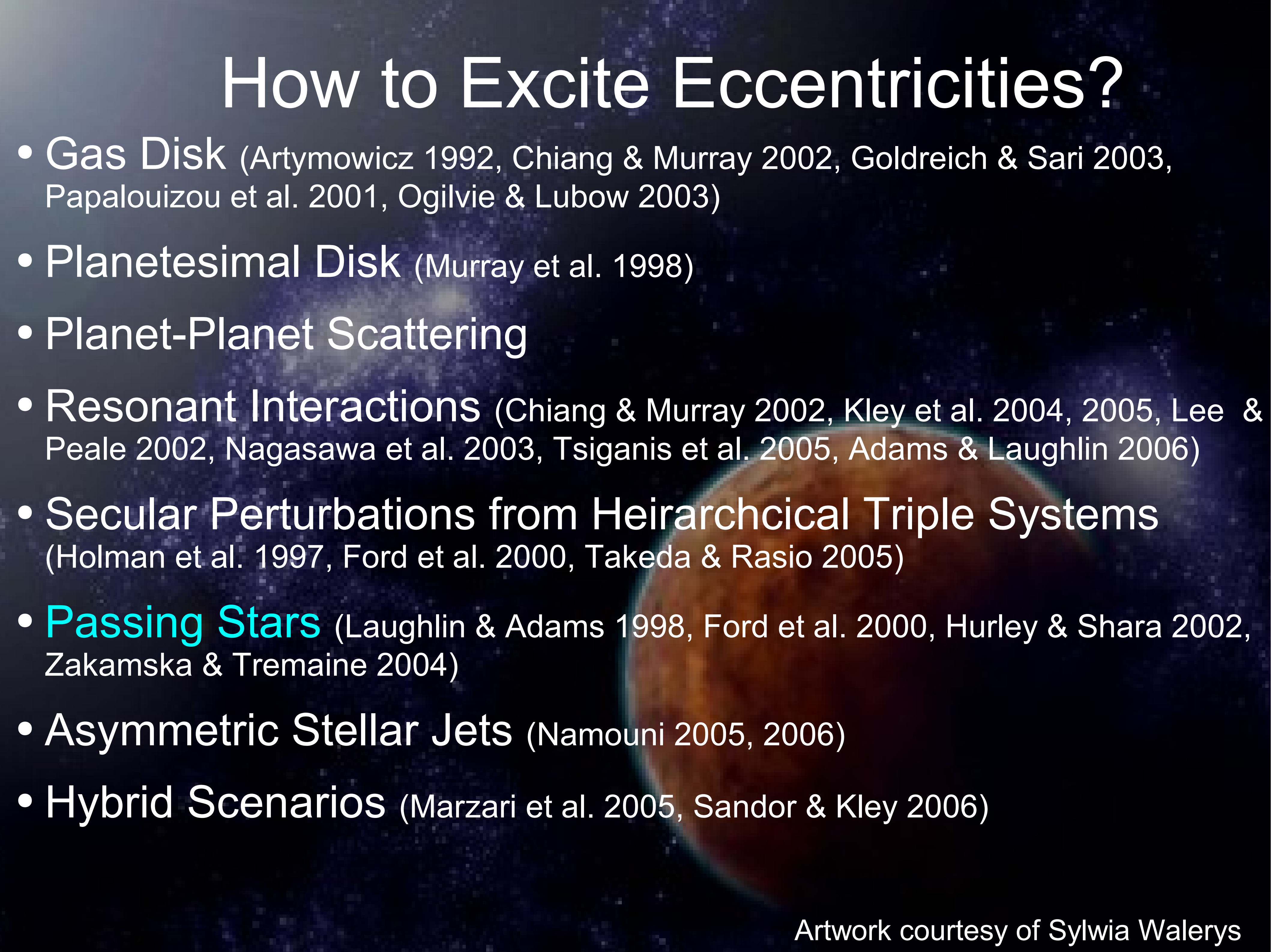
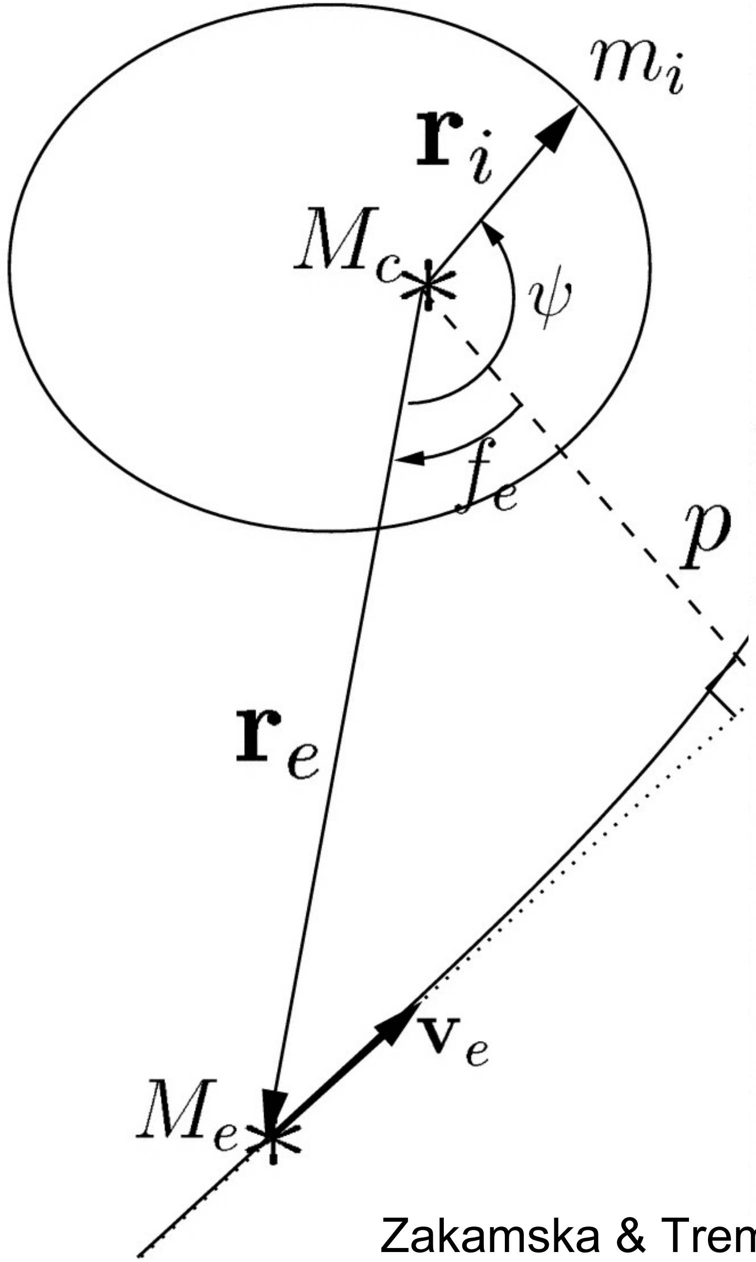
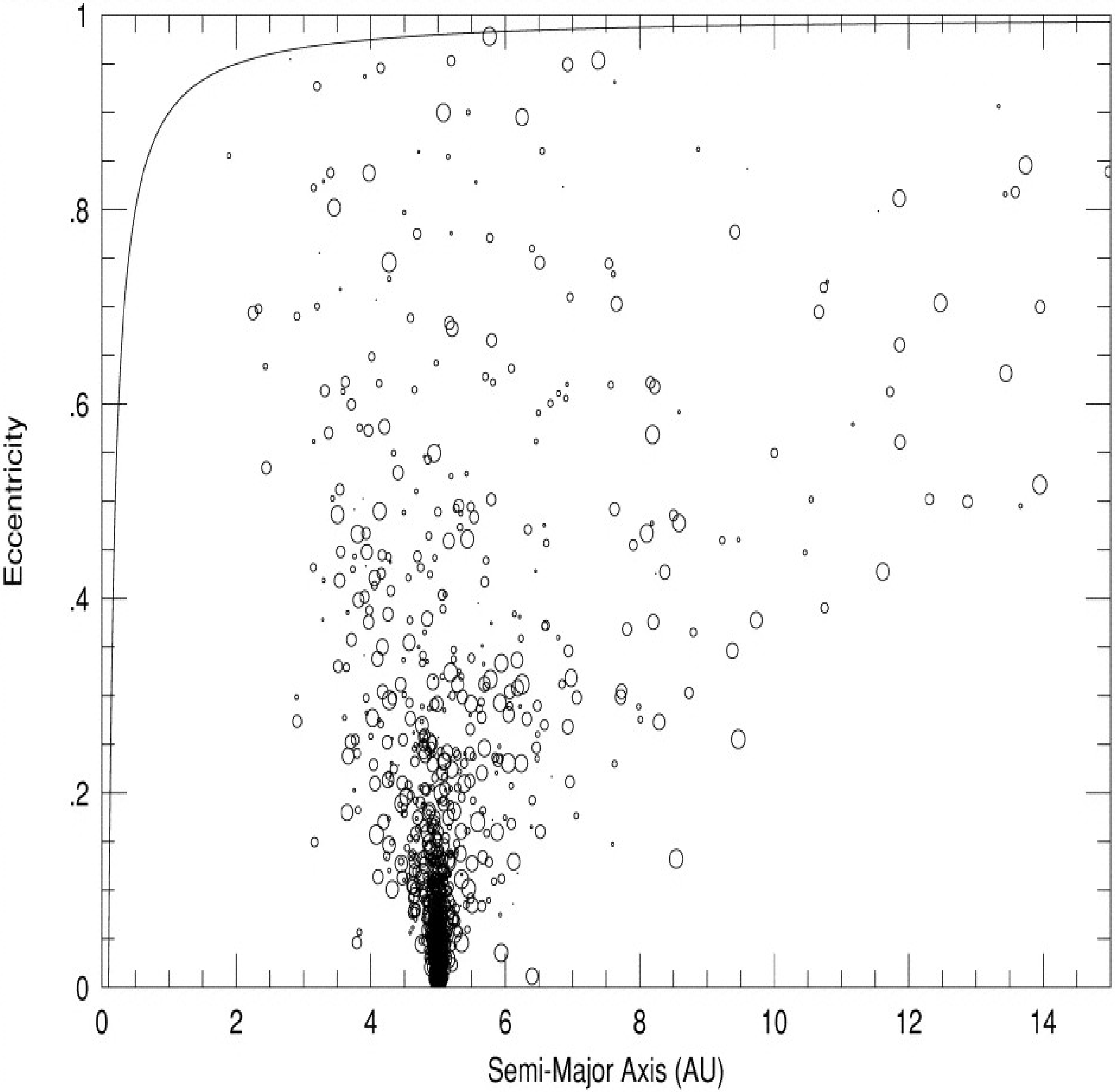


Artwork courtesy of Sylwia Walerys

Eccentricity from Stellar Encounters

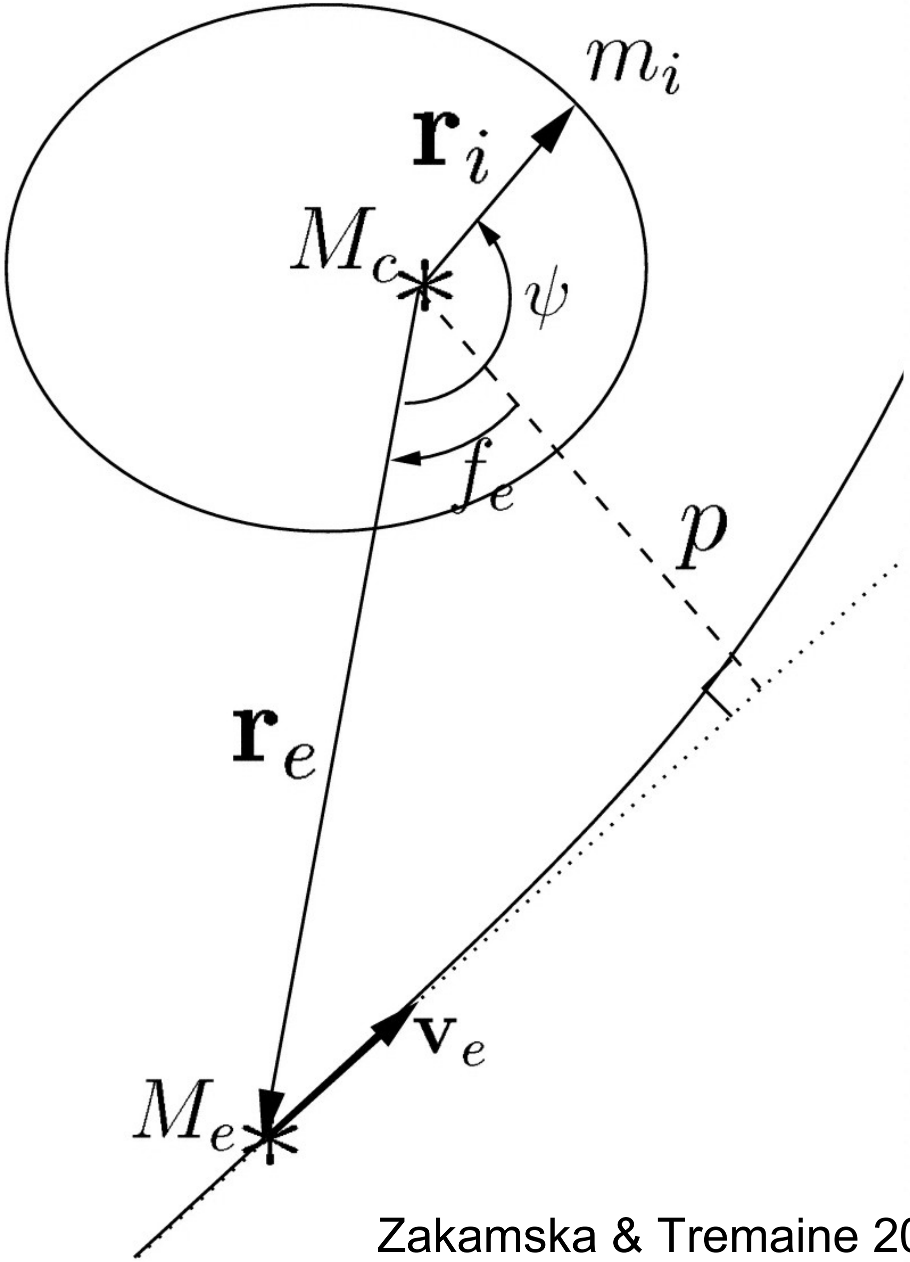


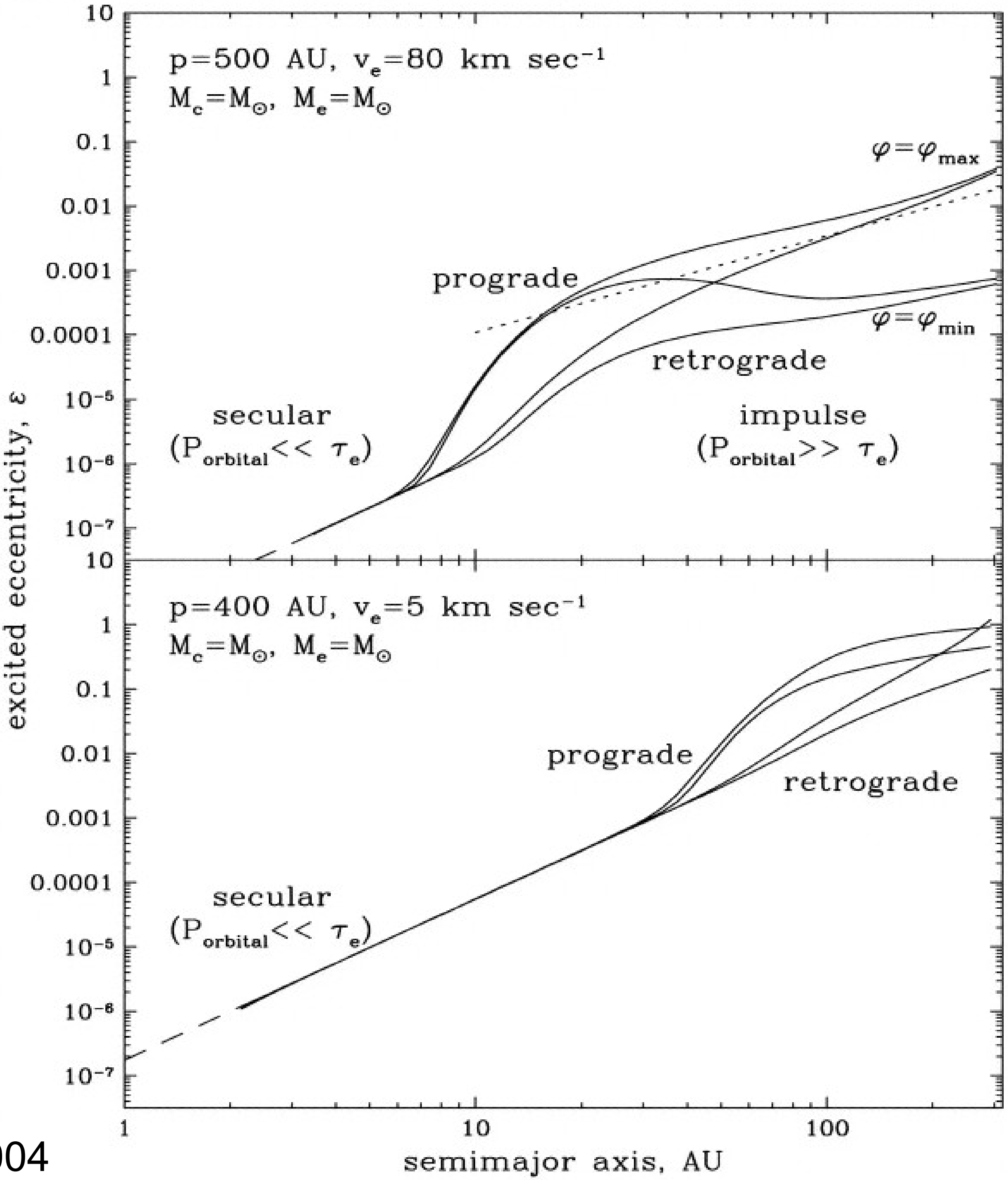
Zakamska & Tremaine 2004



Laughlin & Adams 1998

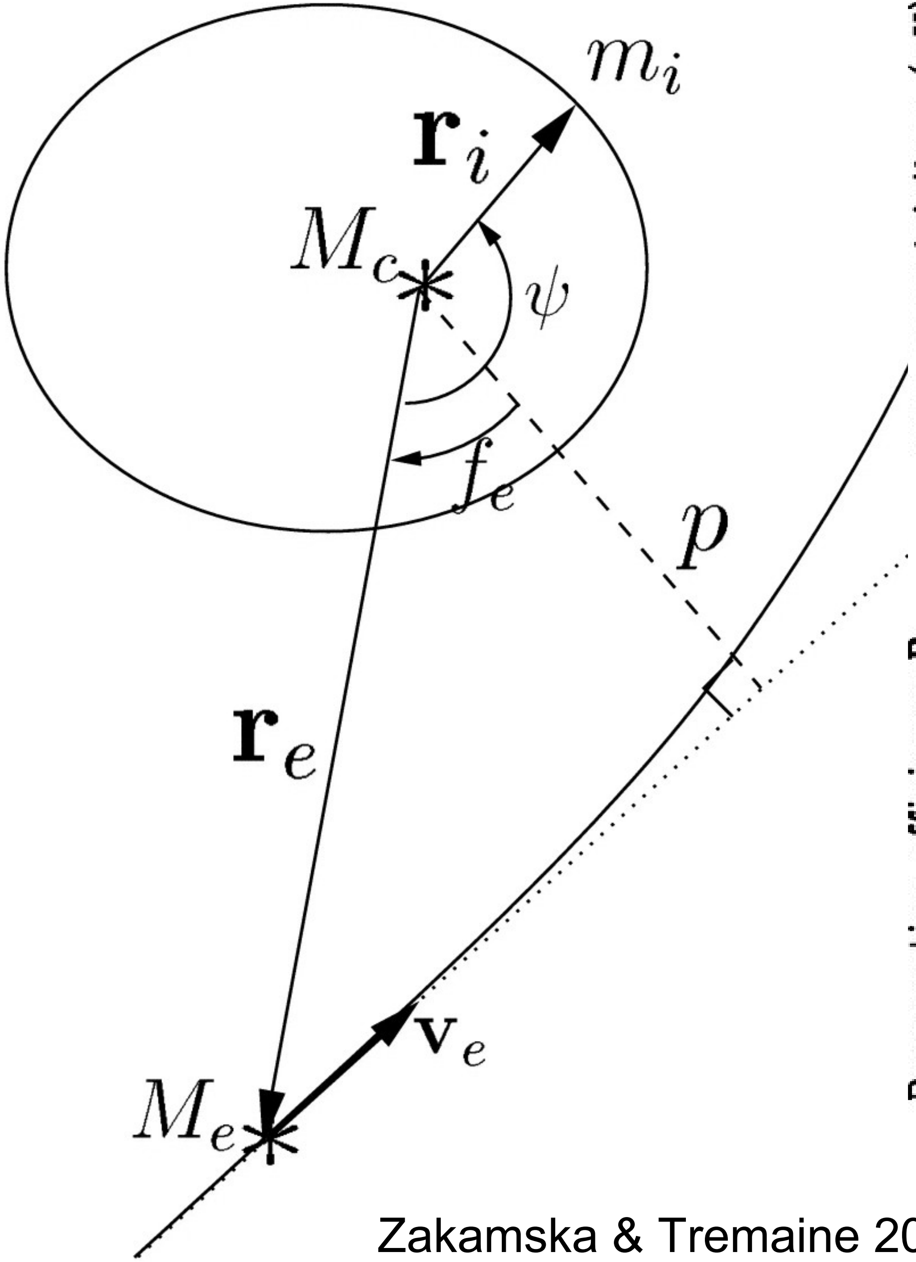
Eccentricity from Stellar Encounters

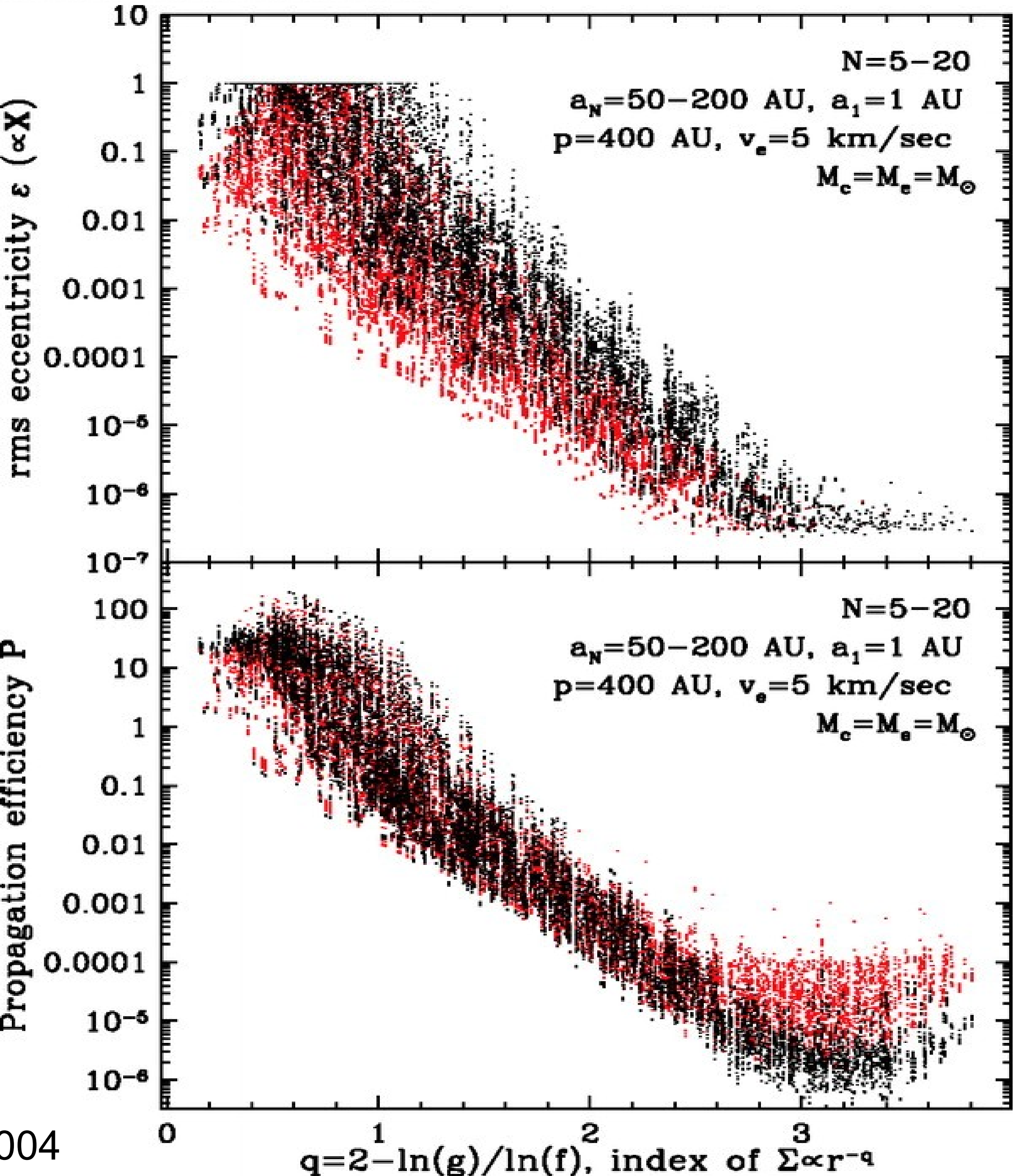




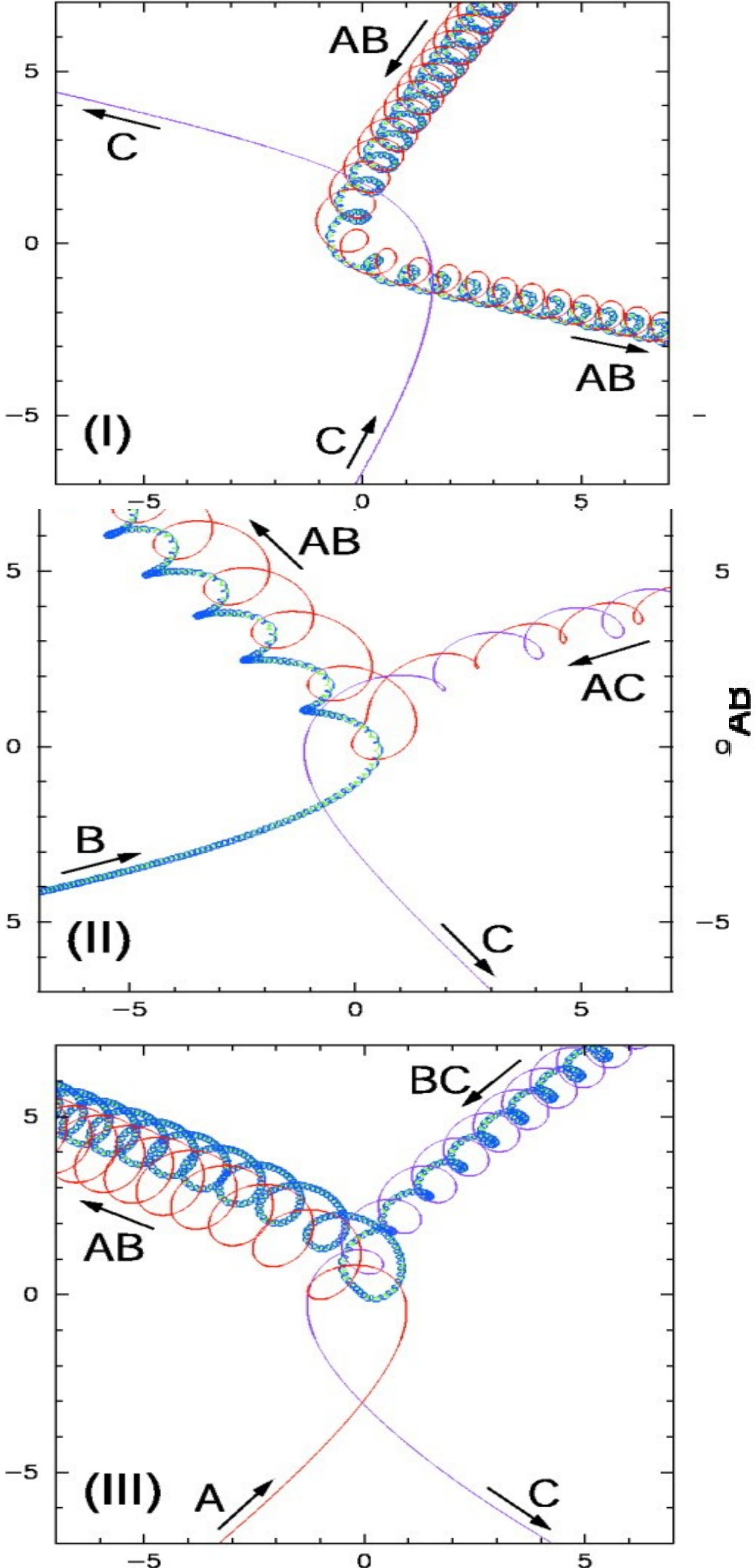
Zakamska & Tremaine 2004

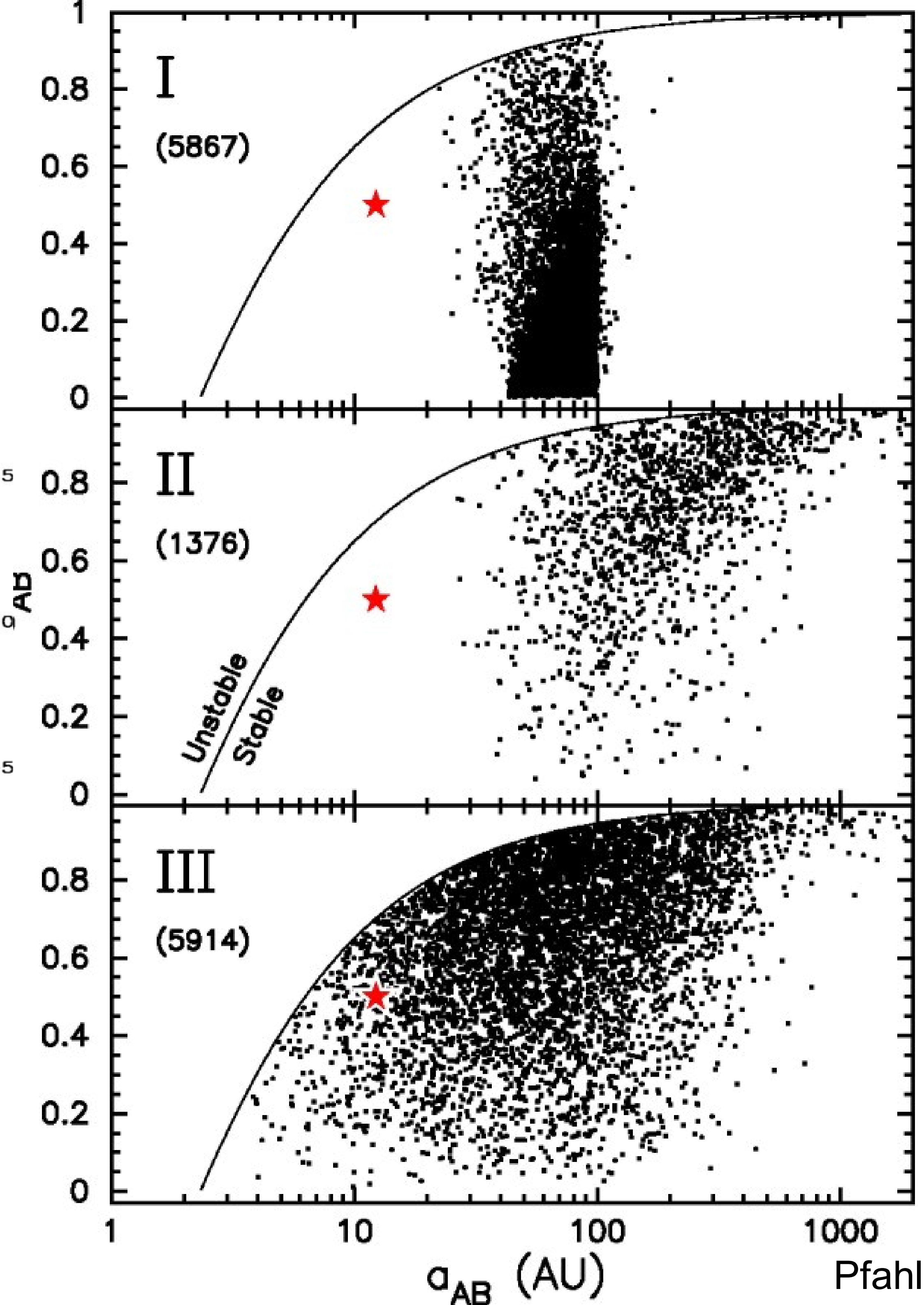
Eccentricity from Stellar Encounters





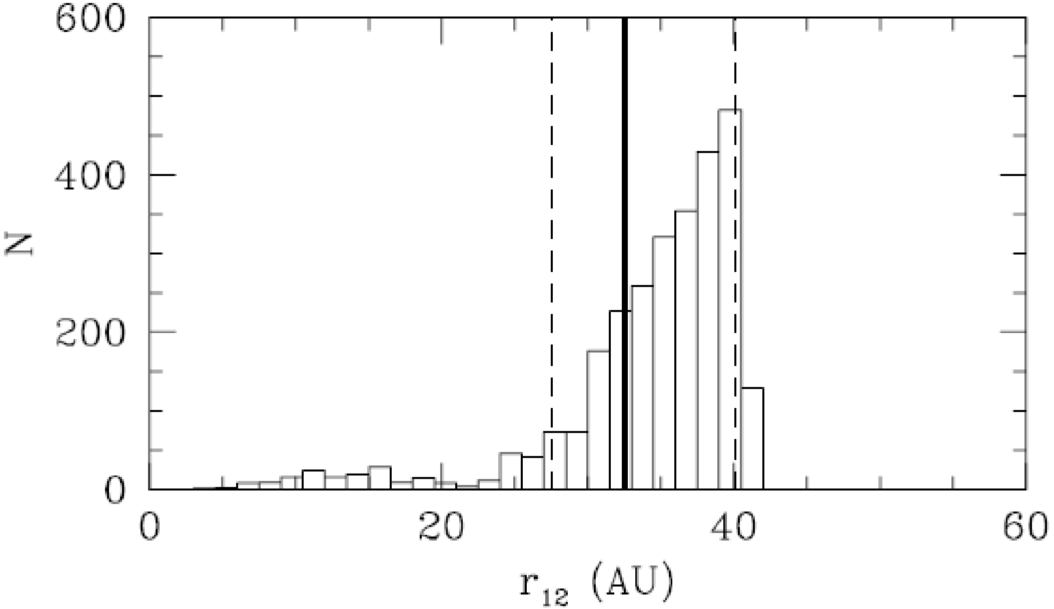
Zakamska & Tremaine 2004

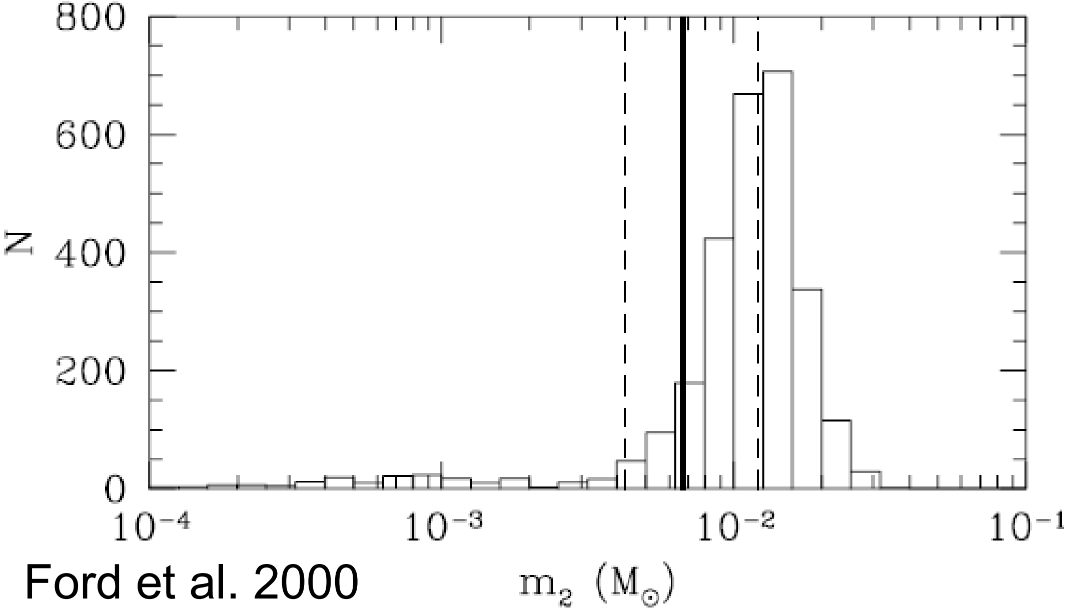

AB
C
AB
C
(I)
AB
AC
B
C
(II)
BC
AB
A
C
(III)
5
0
−5
−5
0
5


I
(5867)
II
(1376)
Unstable
Stable
III
(5914)
e_AB
a_AB (AU)
0
0.2
0.4
0.6
0.8
1
1
10
100
1000

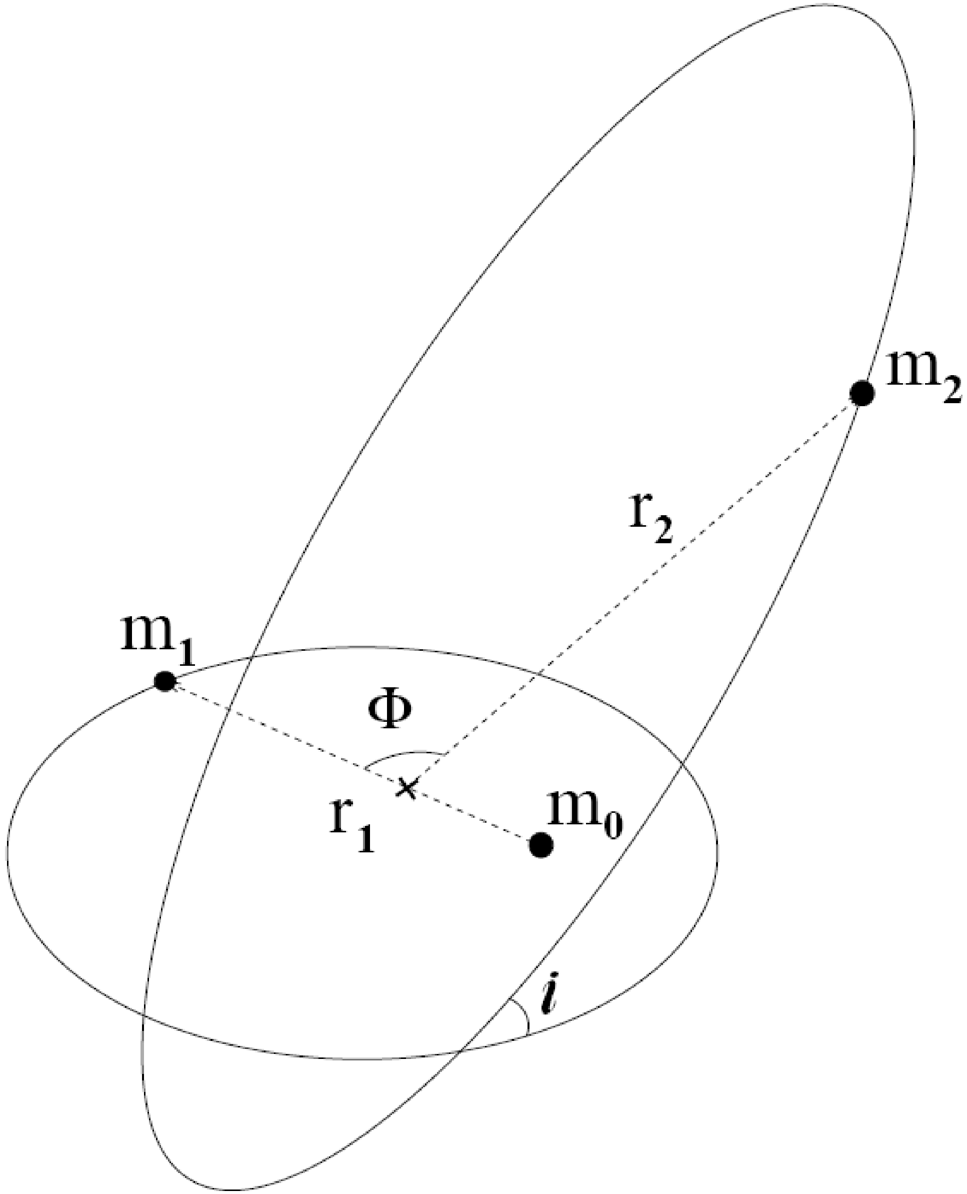
Pfahl 2005

A Captured Planet in PSR 1620+26?





Ford et al. 2000



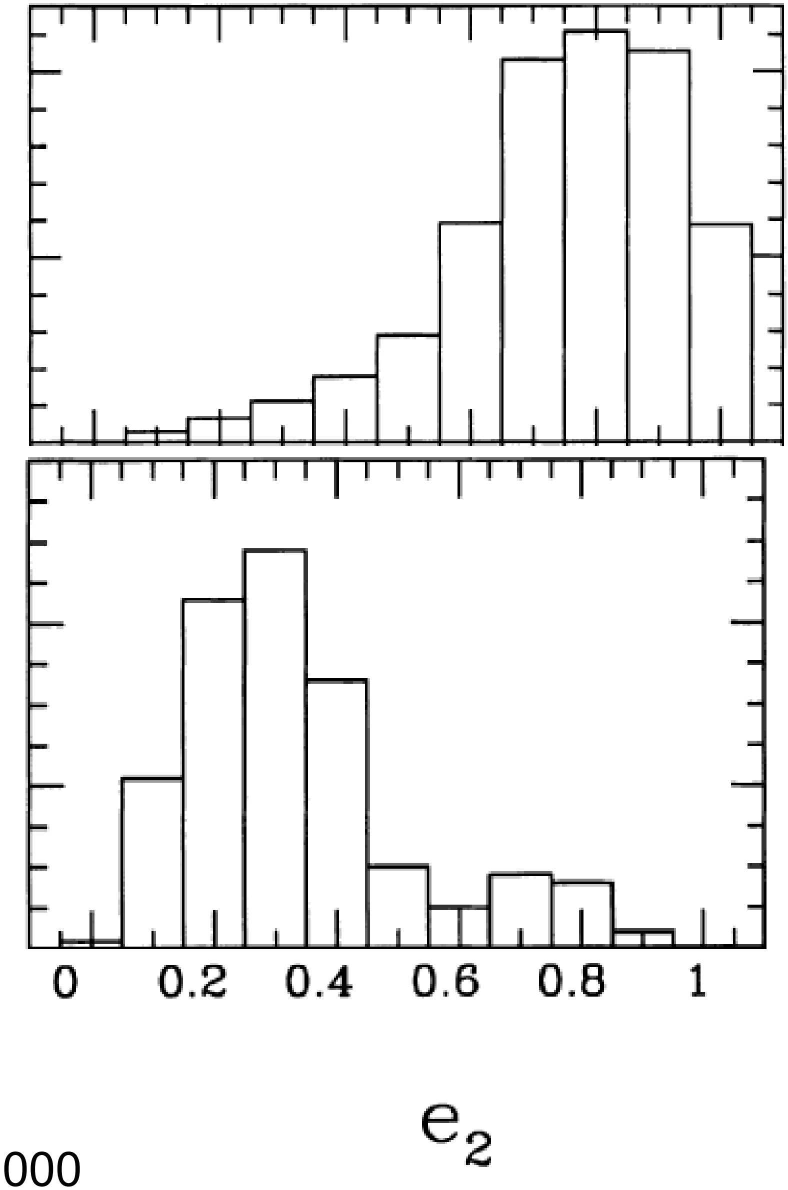
A Captured Planet in PSR 1620+26?

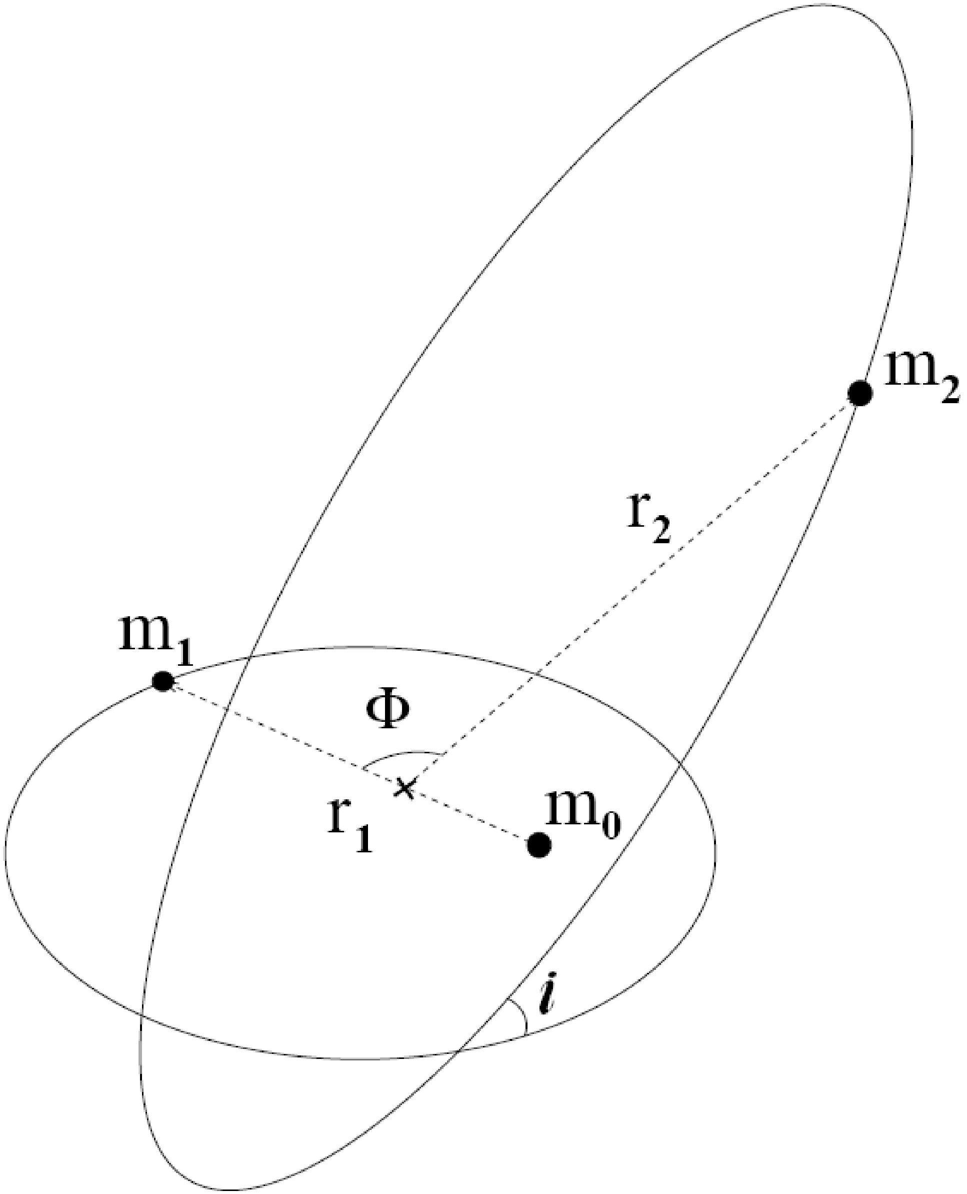
Without

With

Constraint on max e_1

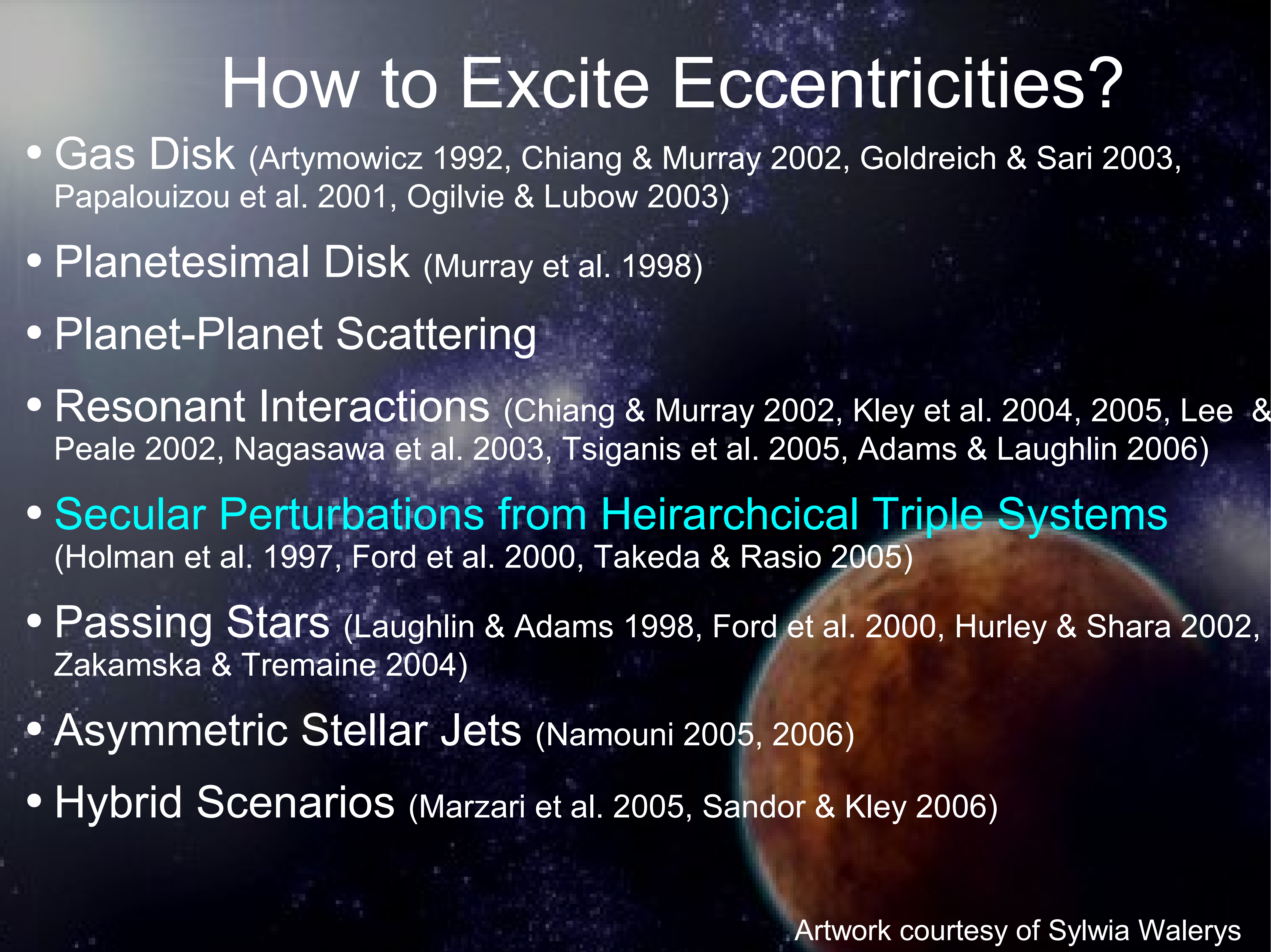
Histograms





Ford et al. 2000

How to Excite Eccentricities?



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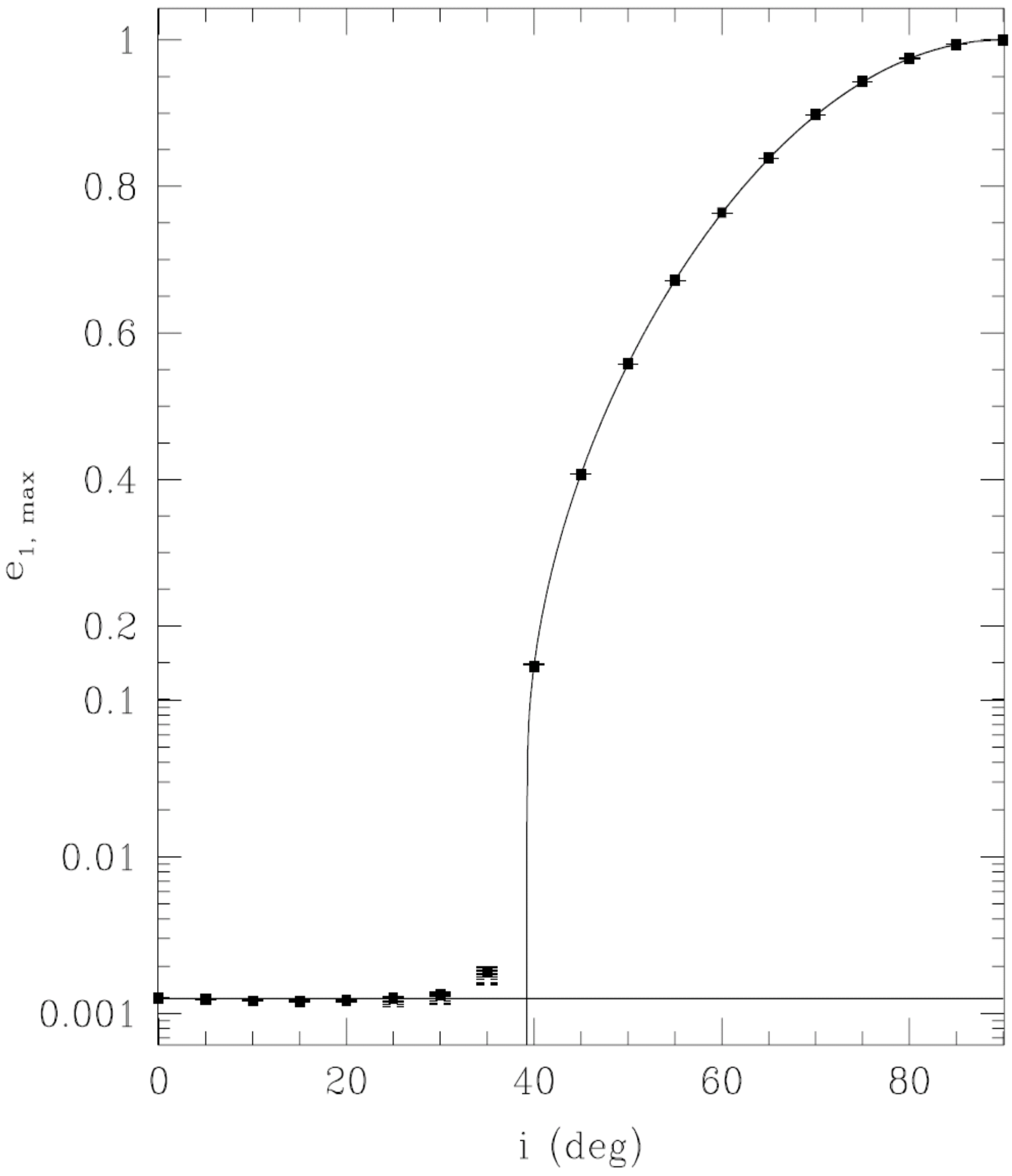
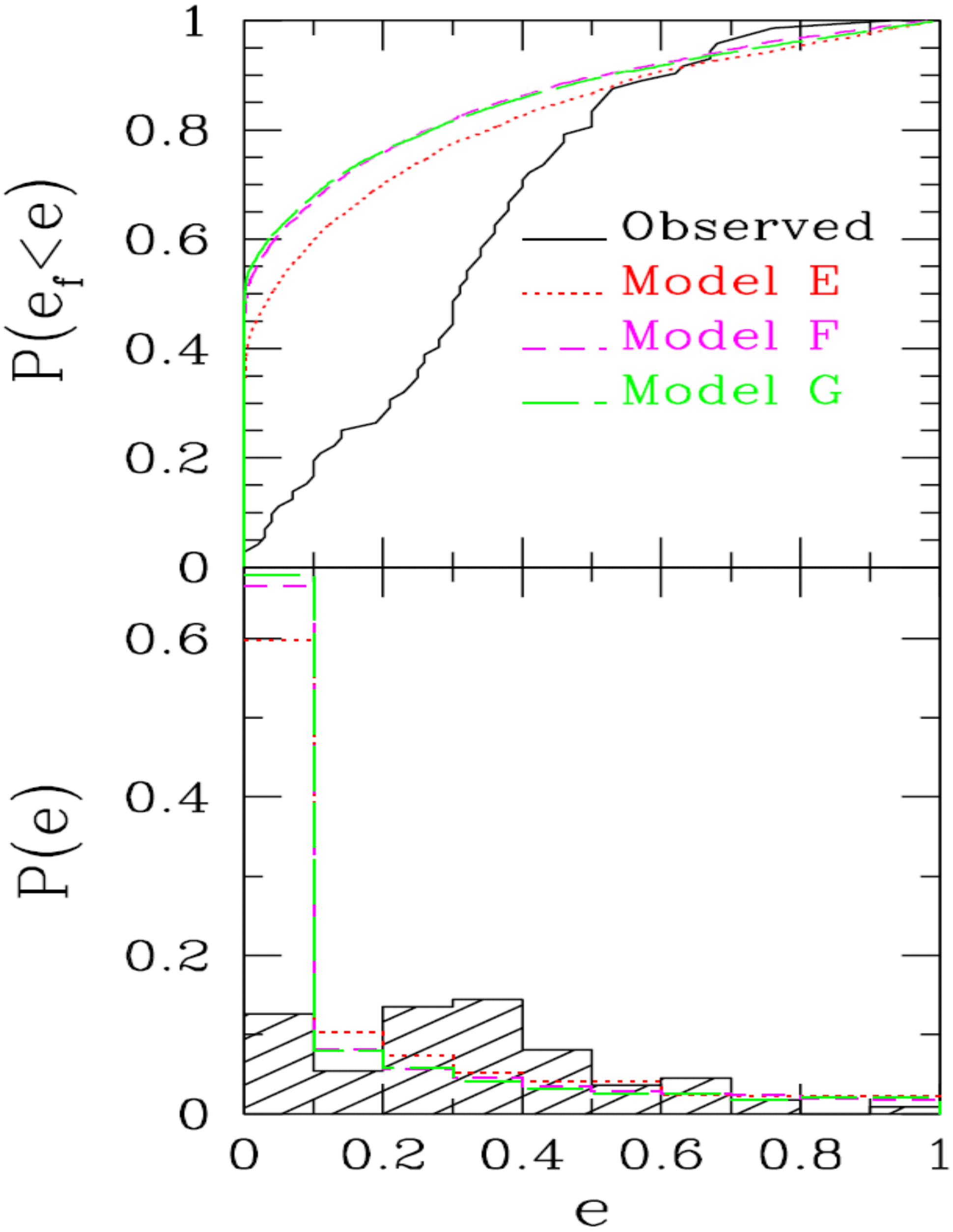
Artwork courtesy of Sylwia Walerys

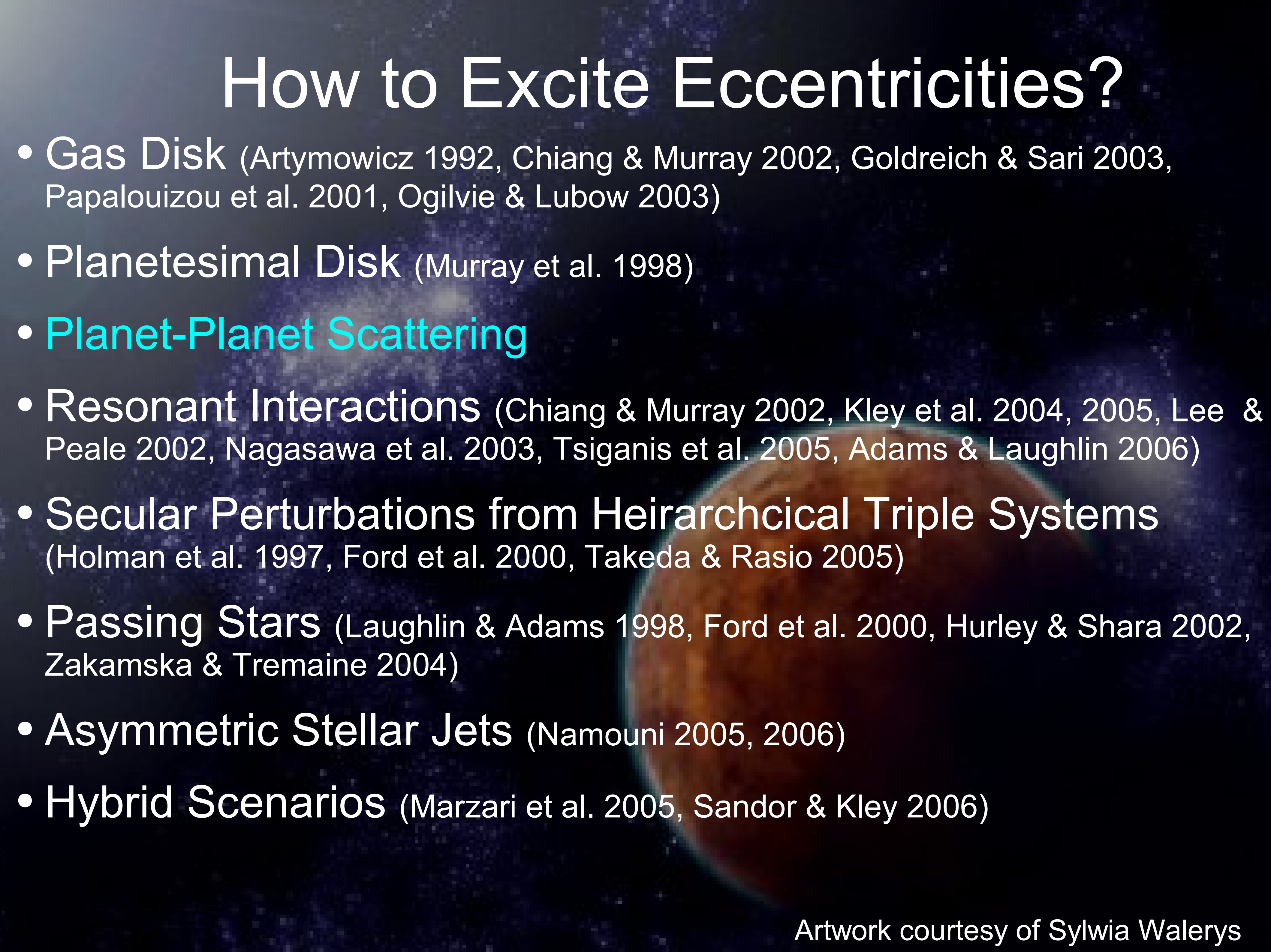
Binaries Exciting Eccentricities



Ford et al. 2000



Takeda & Rasio 2005



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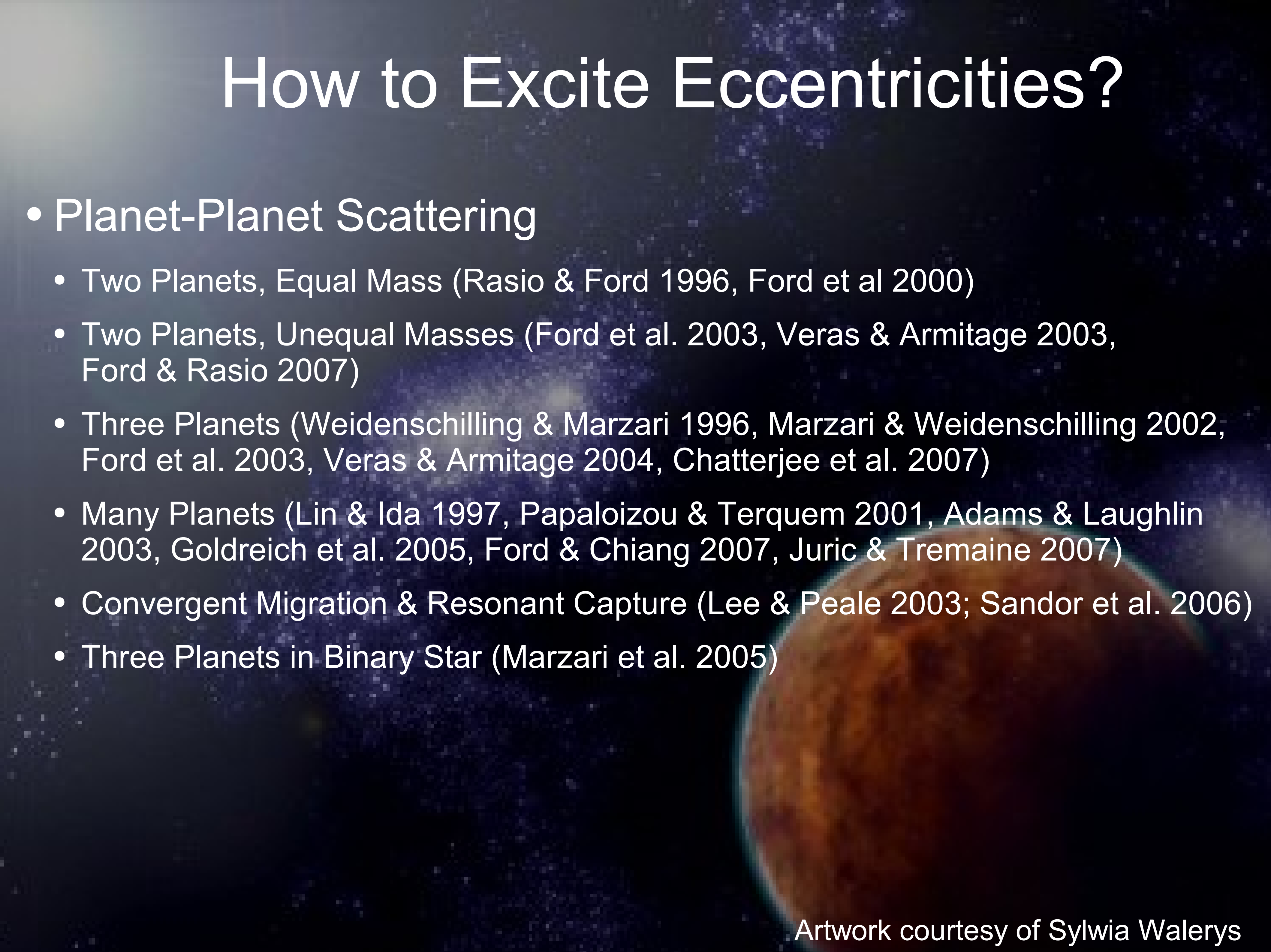
Artwork courtesy of Sylwia Walerys

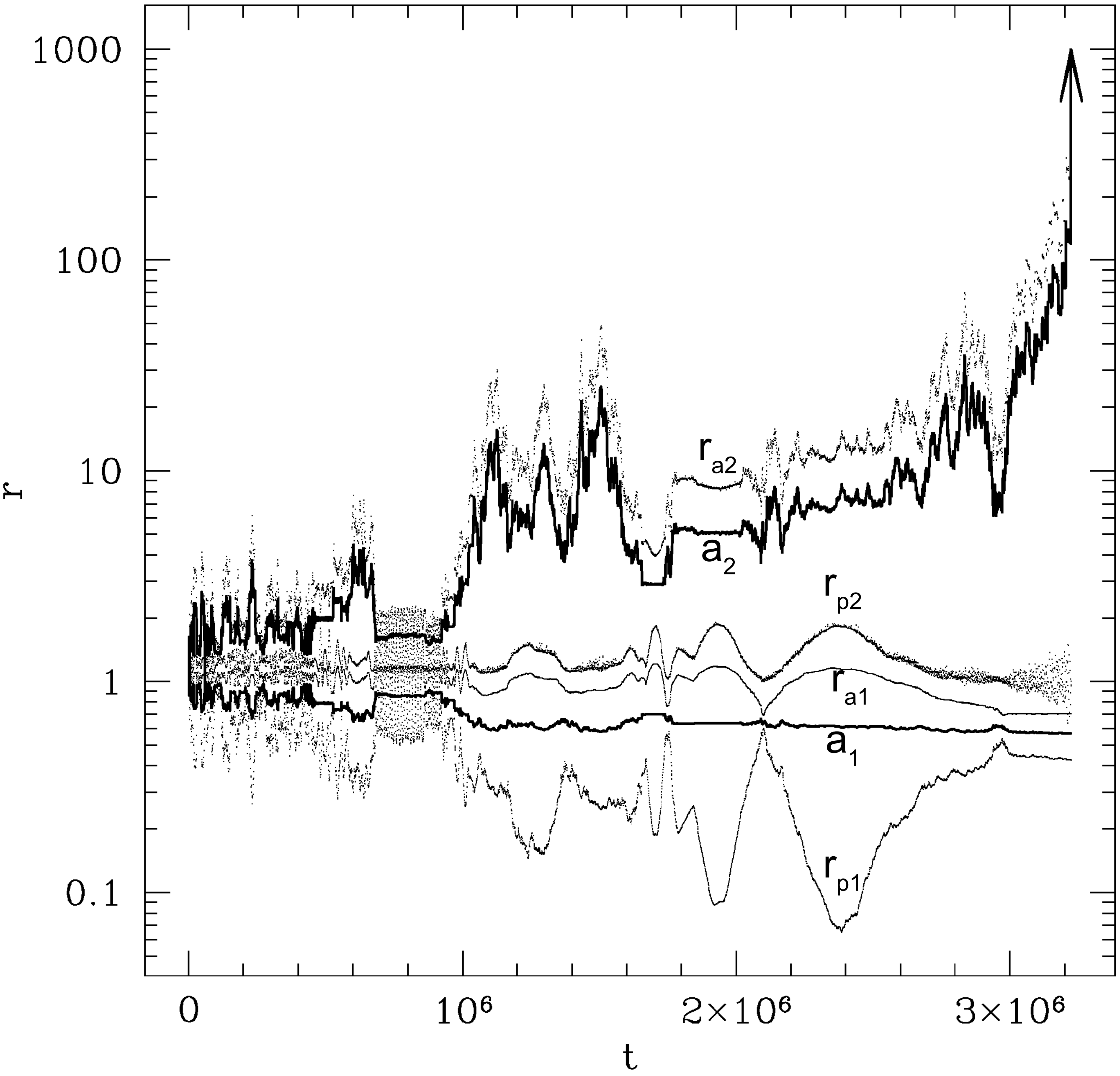
How to Excite Eccentricities?

- Planet-Planet Scattering
  - Two Planets, Equal Mass (Rasio & Ford 1996, Ford et al 2000)
  - Two Planets, Unequal Masses (Ford et al. 2003, Veras & Armitage 2003, Ford & Rasio 2007)
  - Three Planets (Weidenschilling & Marzari 1996, Marzari & Weidenschilling 2002, Ford et al. 2003, Veras & Armitage 2004, Chatterjee et al. 2007)
  - Many Planets (Lin & Ida 1997, Papaloizou & Terquem 2001, Adams & Laughlin 2003, Goldreich et al. 2005, Ford & Chiang 2007, Juric & Tremaine 2007)
  - Convergent Migration & Resonant Capture (Lee & Peale 2003; Sandor et al. 2006)
  - Three Planets in Binary Star (Marzari et al. 2005)



Artwork courtesy of Sylwia Walerys

Planet-Planet Scattering

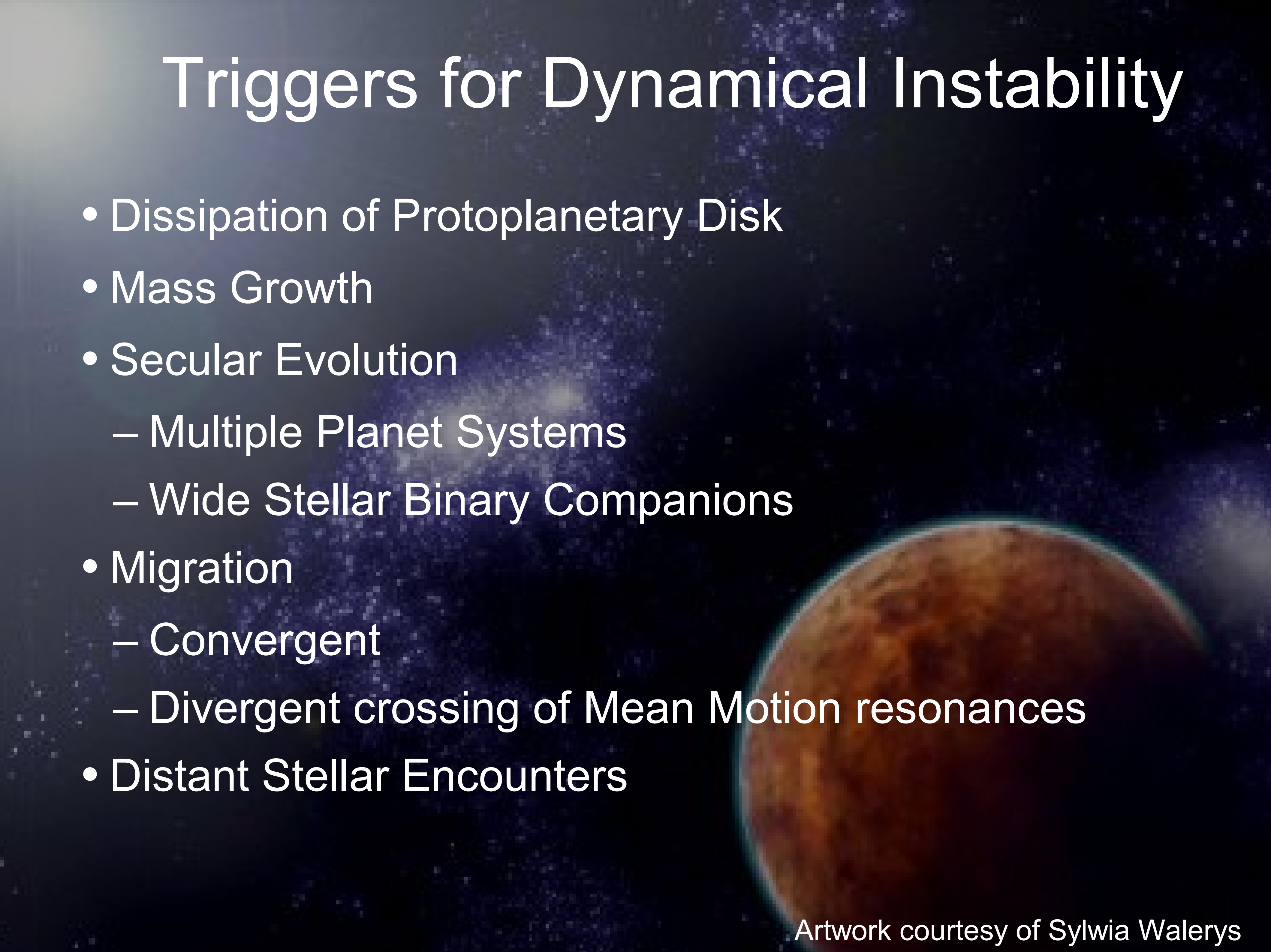


- Two giant planets initially on nearly circular orbits
- Dynamical instability leads to close encounters
- Typically results in planets colliding or one being ejected
- Sometimes planet acquires small pericenter distance

Rasio & Ford 1996

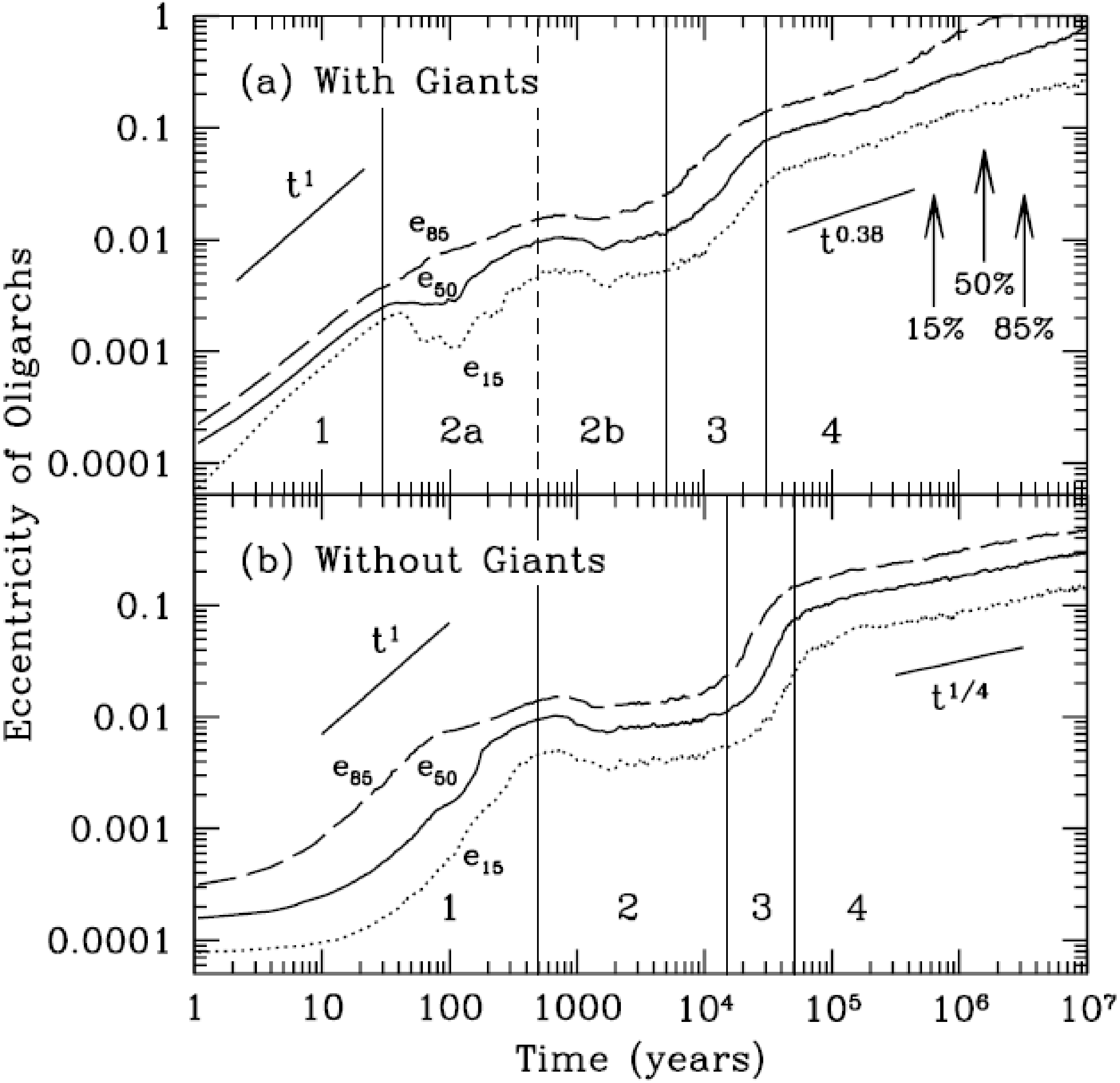
Triggers for Dynamical Instability

- Dissipation of Protoplanetary Disk
- Mass Growth
- Secular Evolution
  - Multiple Planet Systems
  - Wide Stellar Binary Companions
- Migration
  - Convergent
  - Divergent crossing of Mean Motion resonances
- Distant Stellar Encounters



Artwork courtesy of Sylwia Walerys

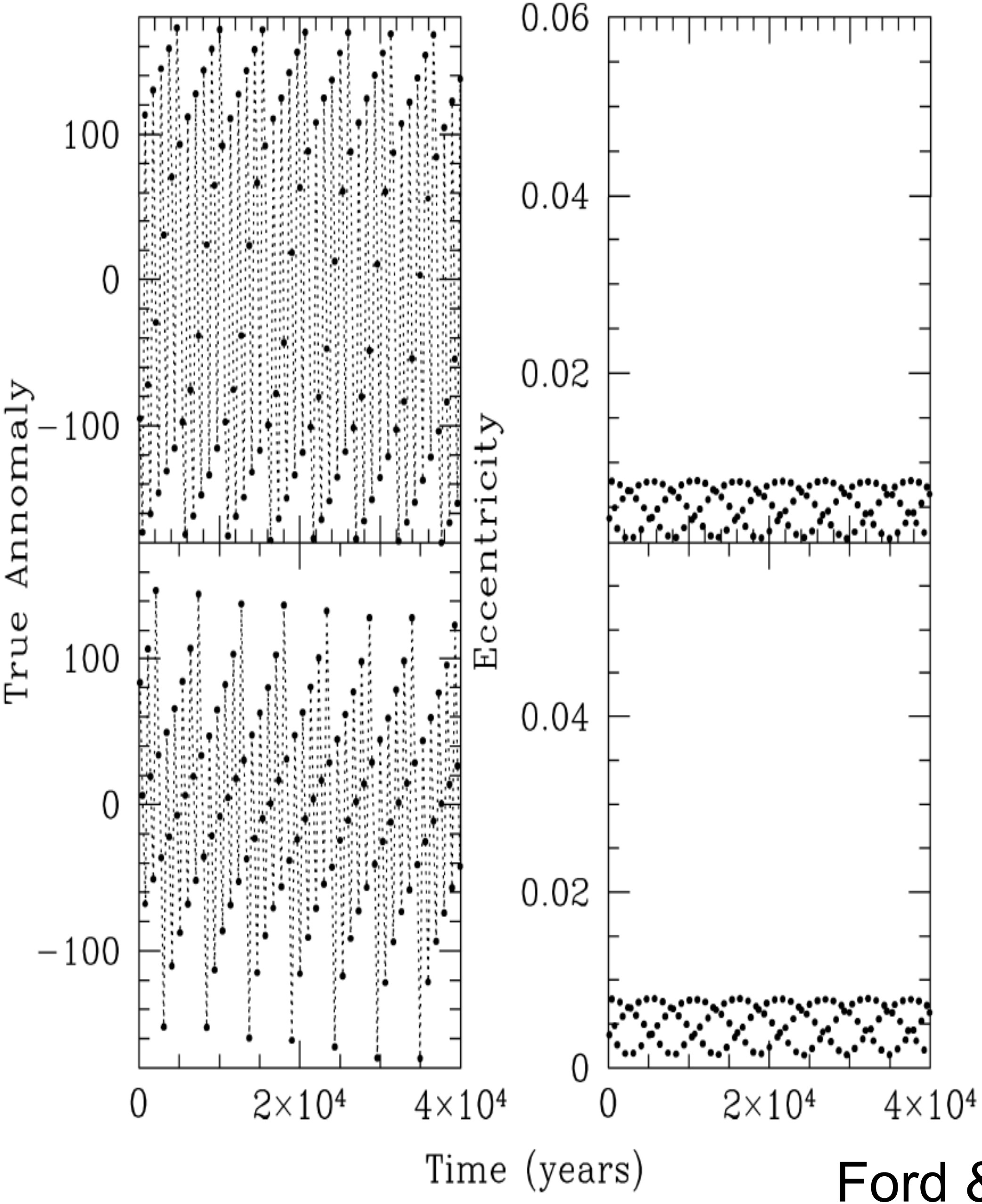
Eccentricity Growth



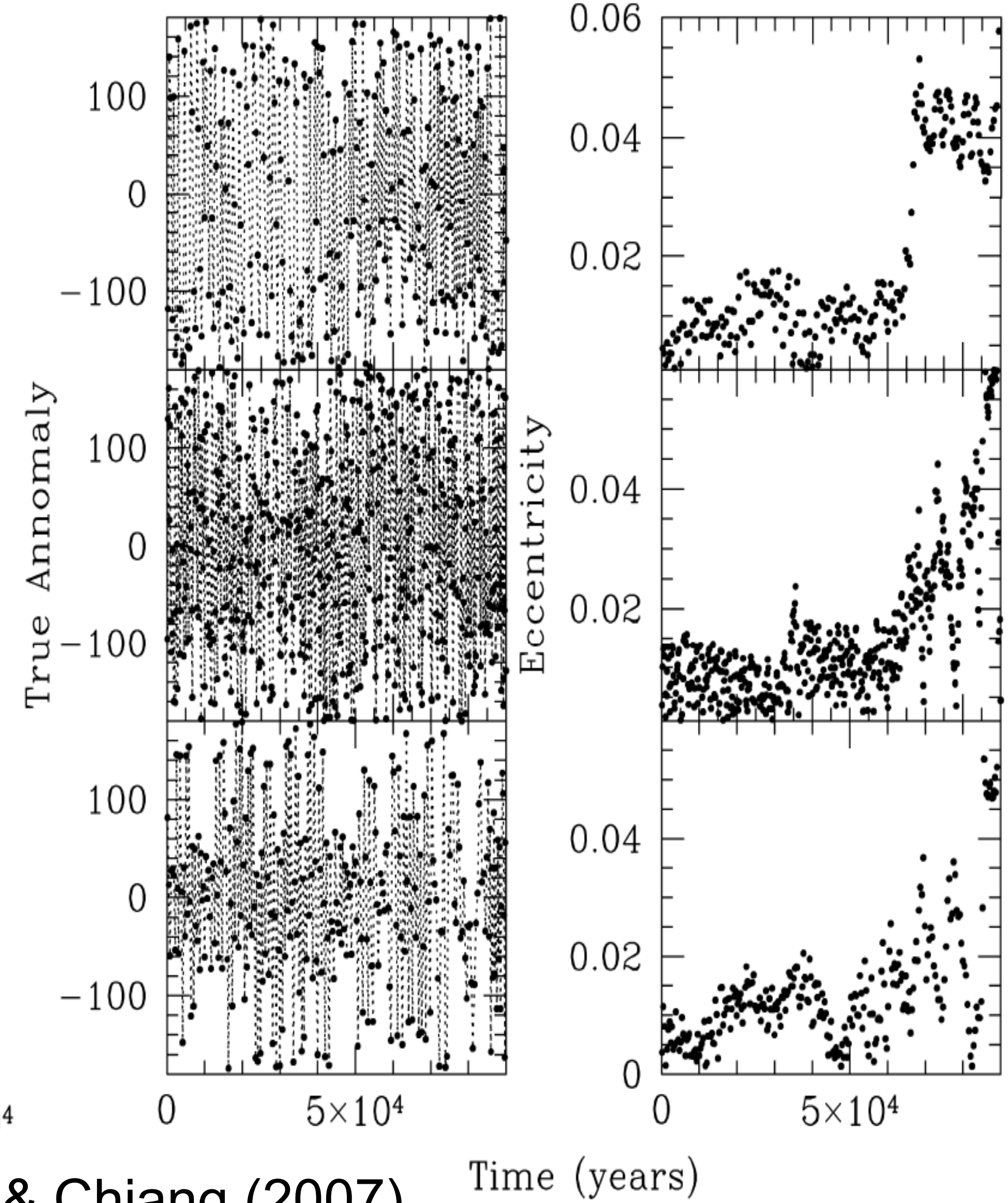
Ford & Chiang (2007)

Route to Chaos

Two Planets

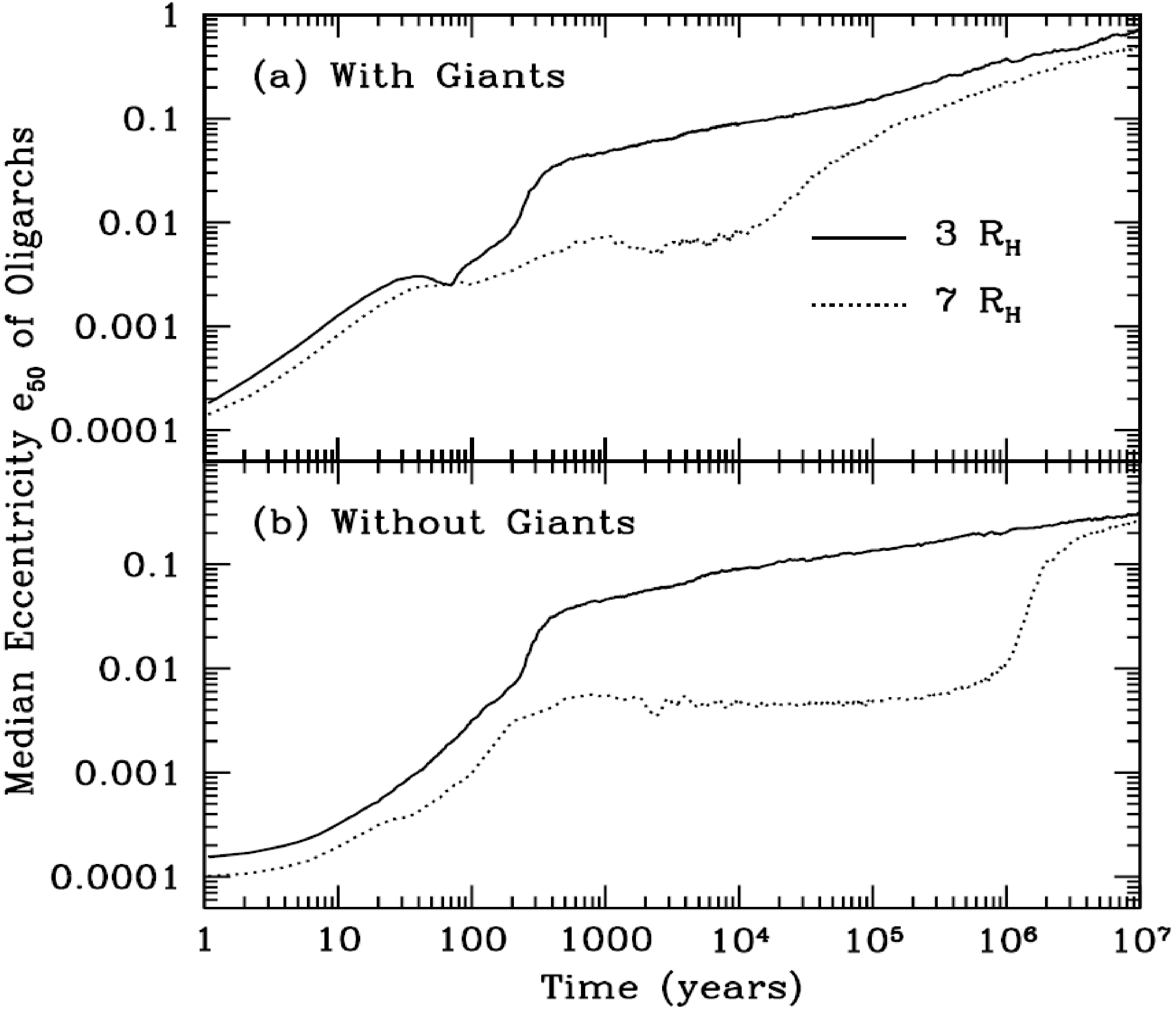


Three Planets



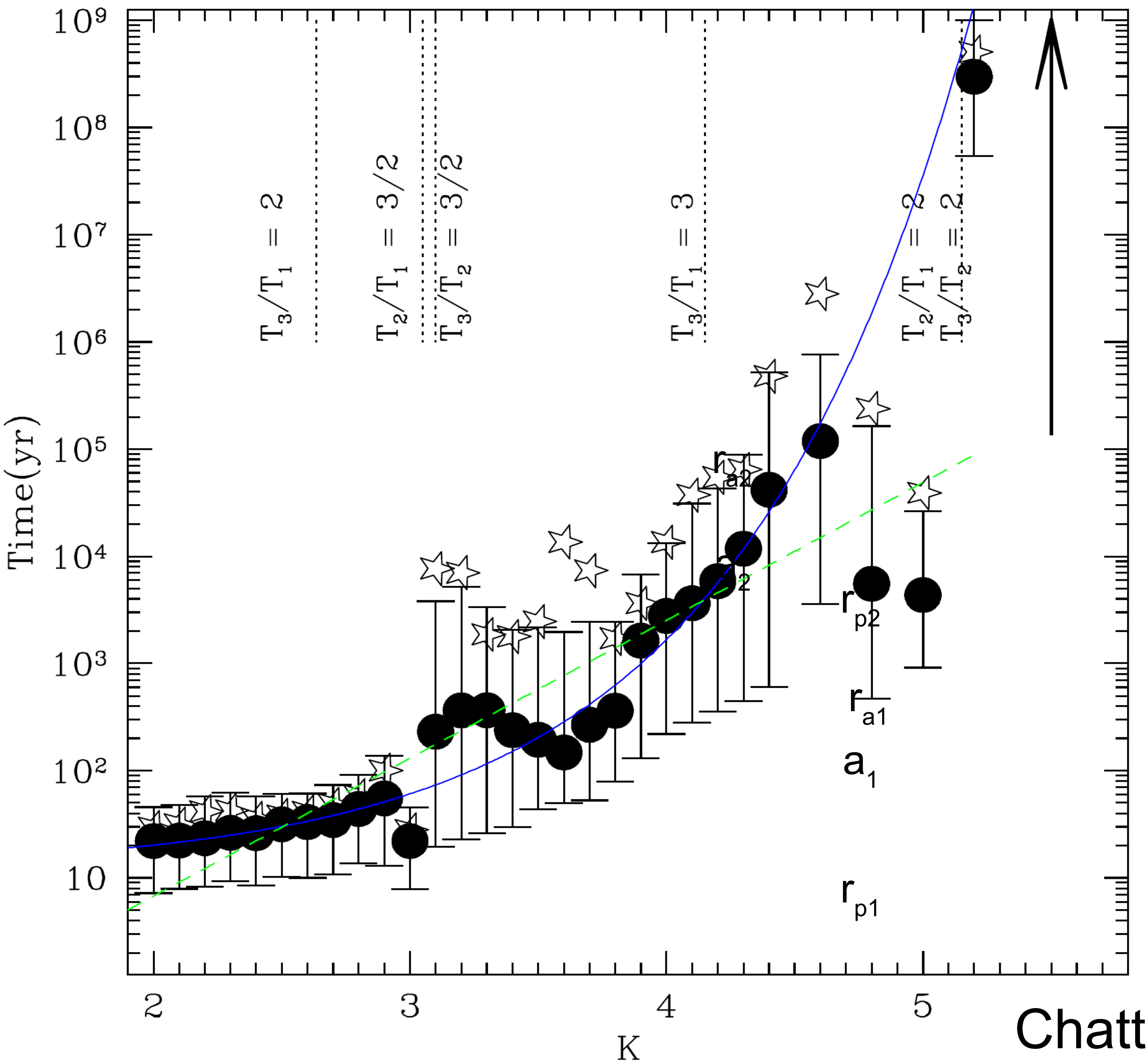
Ford & Chiang (2007)

Eccentricity Growth of Five Neptune Mass Planets



Ford & Chiang (2007)

Timescale Until Instability for Three Giant Planets



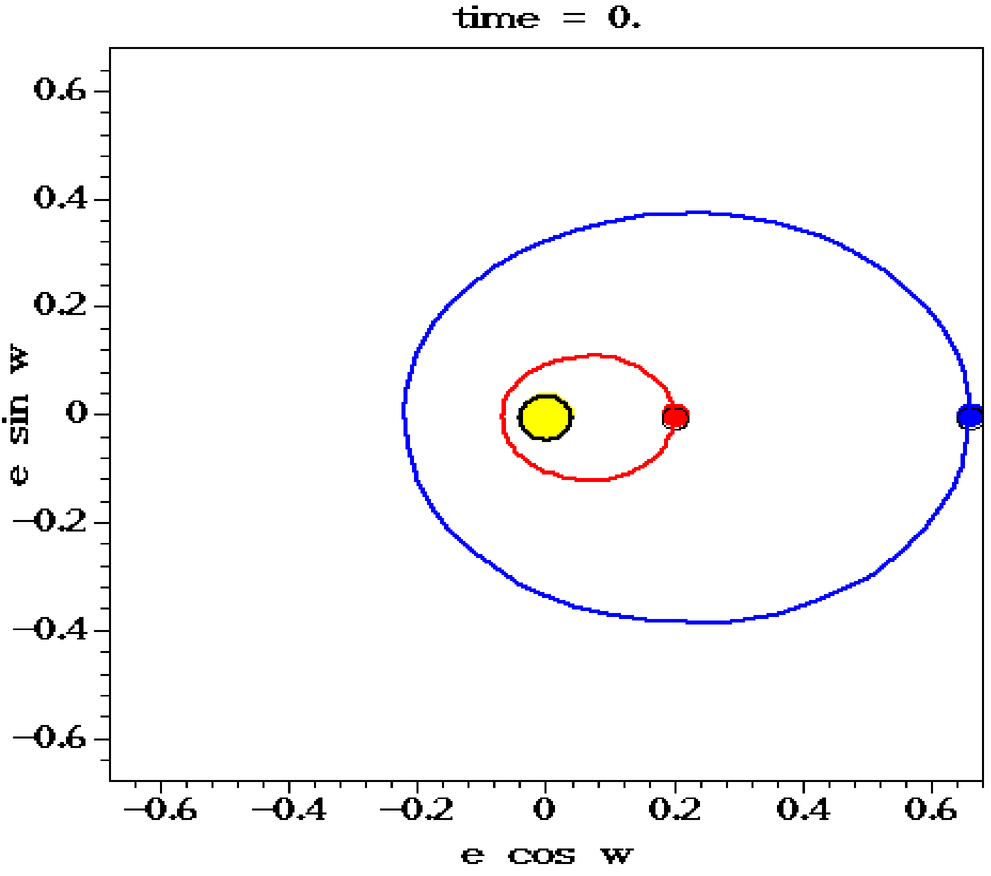
- Three giant planets initially on *well-separated* nearly circular orbits
- Timescale until dynamical instability depends on the masses and spacing
- Timescale until a dynamical instability is manifest can be arbitrarily long

Chatterjee et al. 2007 see also Marzari & Weidenschilling 2003

υ Andromedae

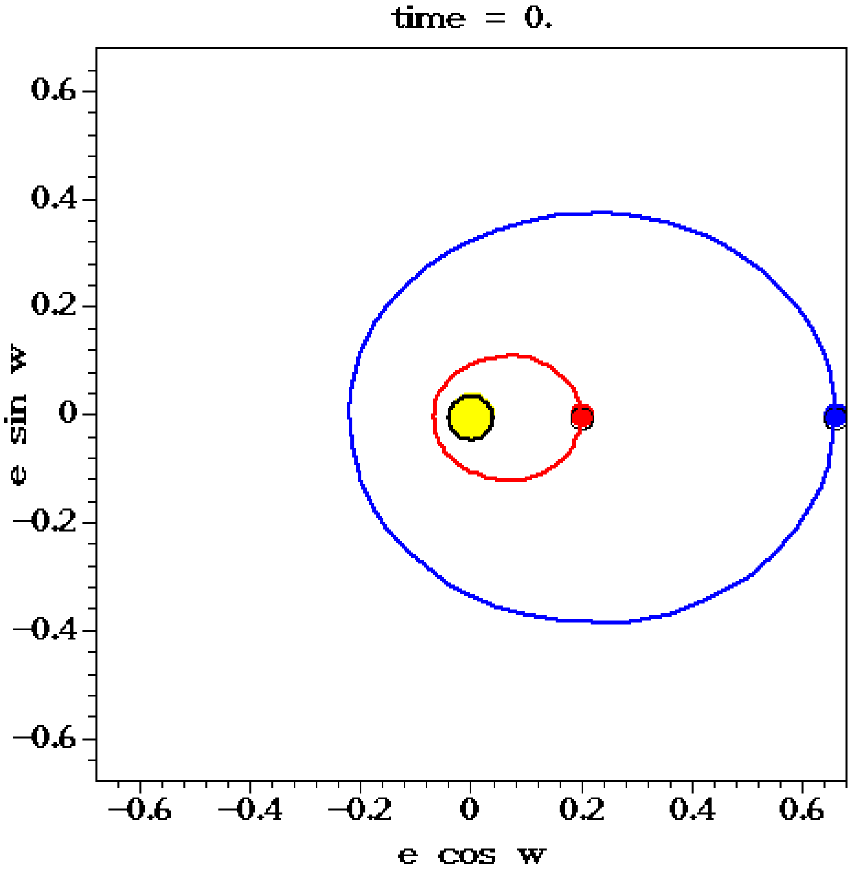
- First multiple planet system discovered around main sequence (F8V, 1.3 $M_{\odot}$, 3Gyr) star in 1999.
- Now have ~ 450 radial velocity observations with precision limited by stellar jitter of ~ 7.5m/s
- υ And c & d have significant eccentricities (~0.26 & 0.28 ±0.02)
- Significant secular eccentricity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

Circulation vs Libration



X (AU)

Y (AU)



X (AU)

Ford

How to Excite Eccentricities?

- Adiabatic Torque on u And d
- Impulsive Perturbation to u And d

How to Excite Eccentricities?

- Adiabatic Torque on υ And d
  - Gas disk beyond υ And d
  - Excites Eccentricity of υ And d
  - Drives System from Circulating to Librating Regime
  - Damps Libration Amplitude about Aligned Configuration
  - Predicts: Small Libration Amplitude &
    Small Eccentricity Oscillations

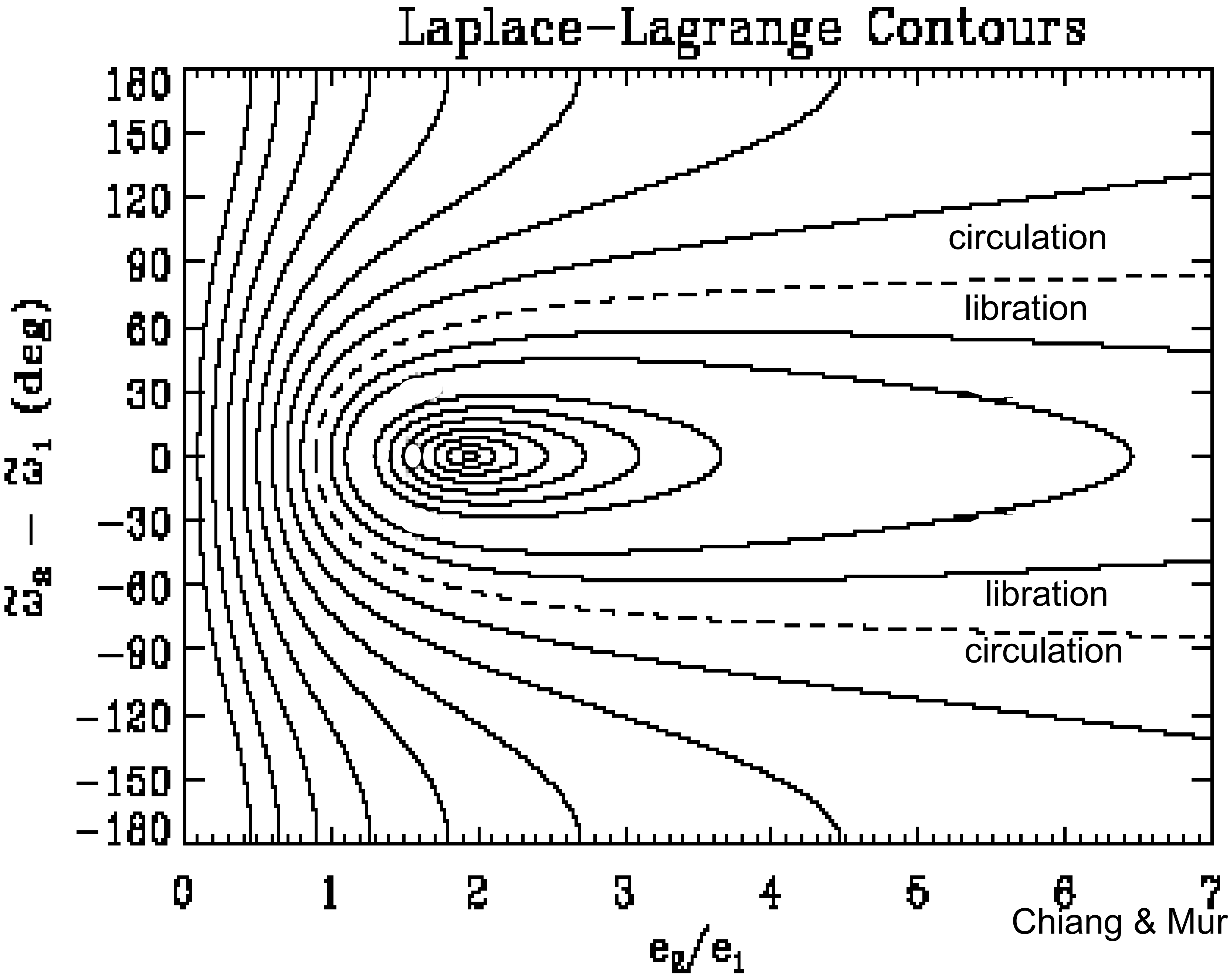
Chiang & Murray 2002

How to Excite Eccentricities?

- Impulsive Perturbation to υ And d
  - Additional Massive Planet (υ And e, ~1.9 M_{Jup})
  - Chaotic Evolution (~1,000 yrs)
    - υ And e *Ejected*
    - υ And d remains on *Eccentric Orbit*
    - υ And c remains on orbit which may be circular *or* eccentric
    - Secular Interactions between c & d lead to current orbits
  - Predicts either Circulation or Large Amplitude Libration
    and Significant Eccentricity Evolution

Malhotra 2002

Secular Eccentricity Evolution

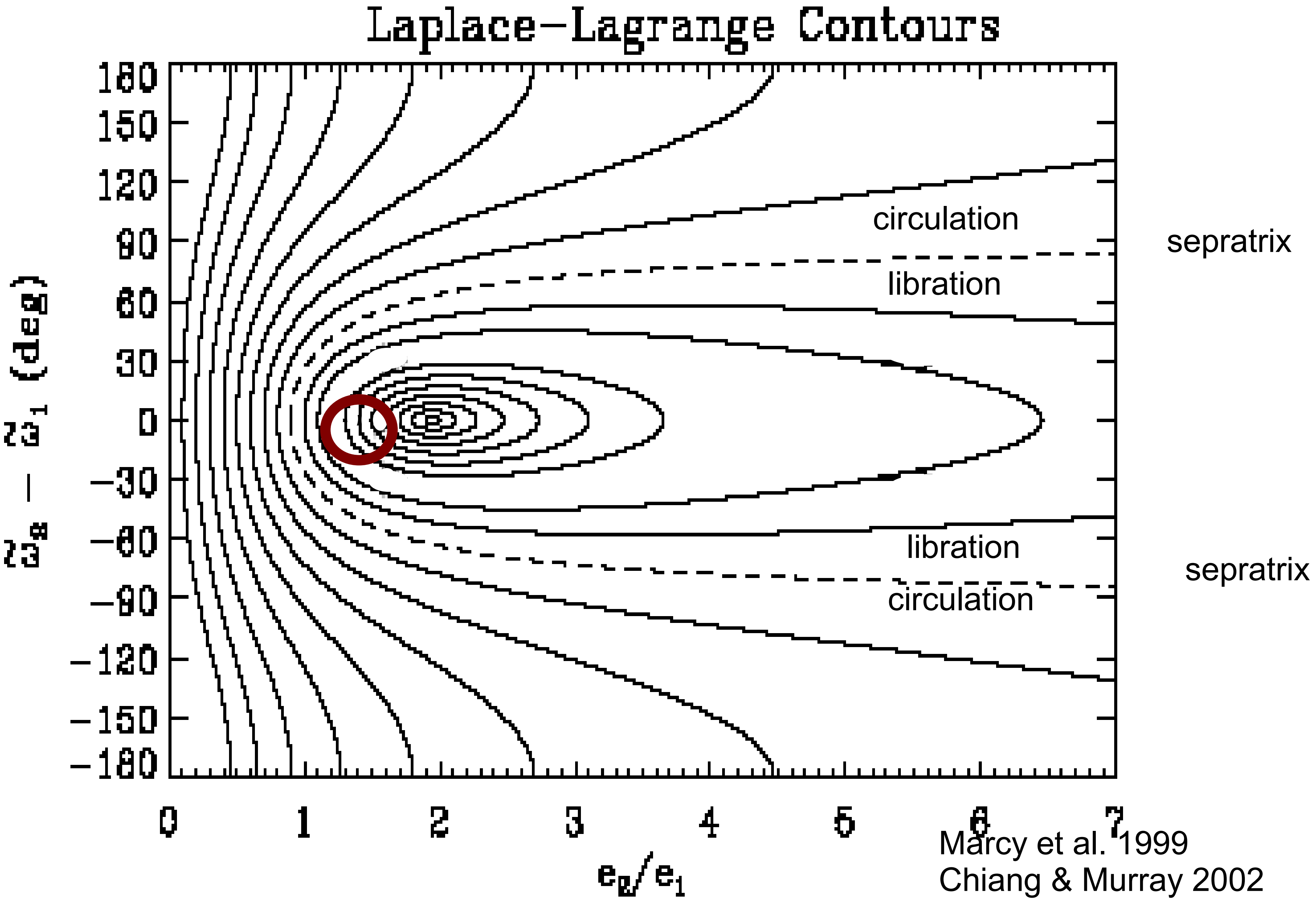


sepratrix

sepratrix

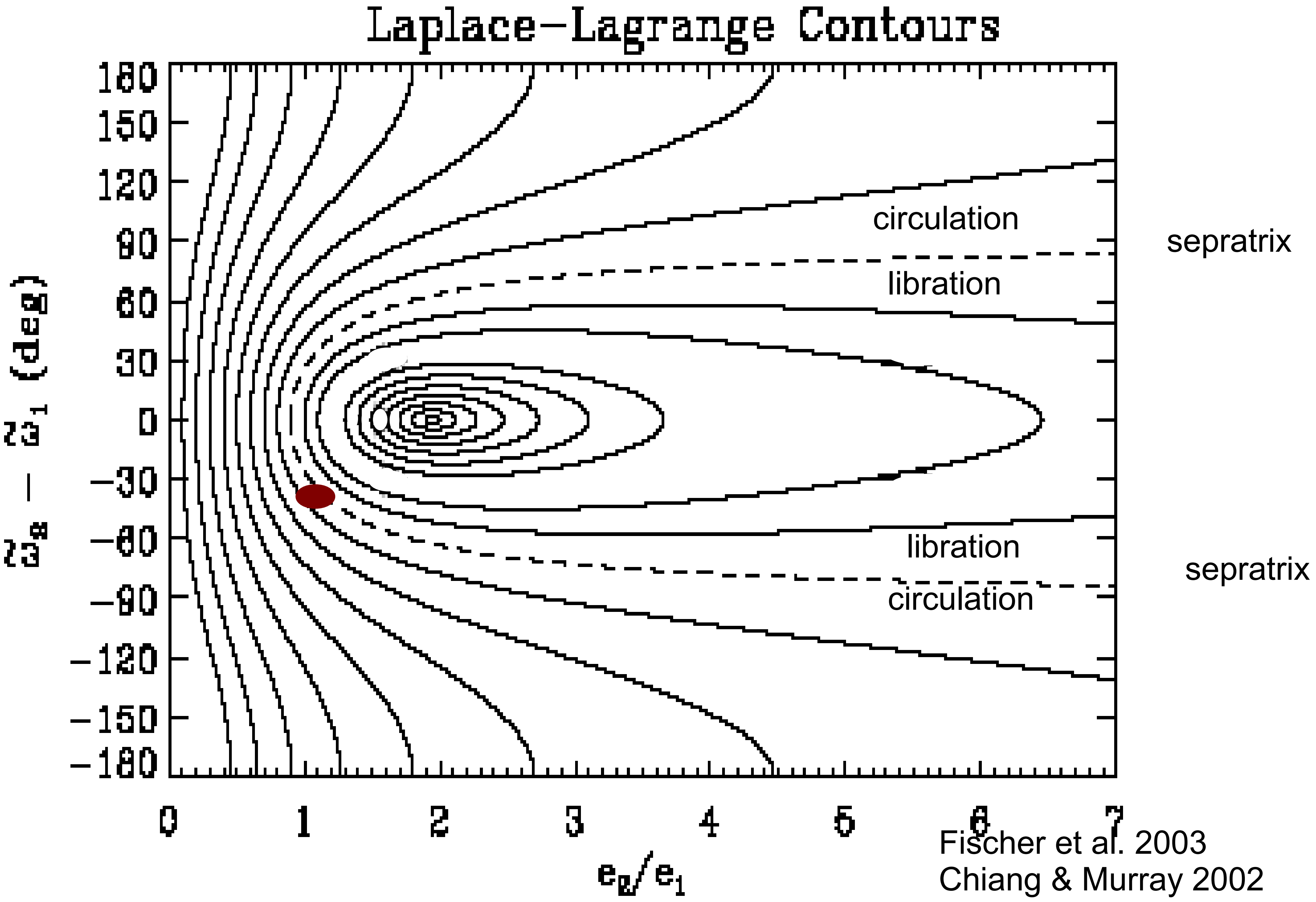
Chiang & Murray 2002

Secular Eccentricity Evolution



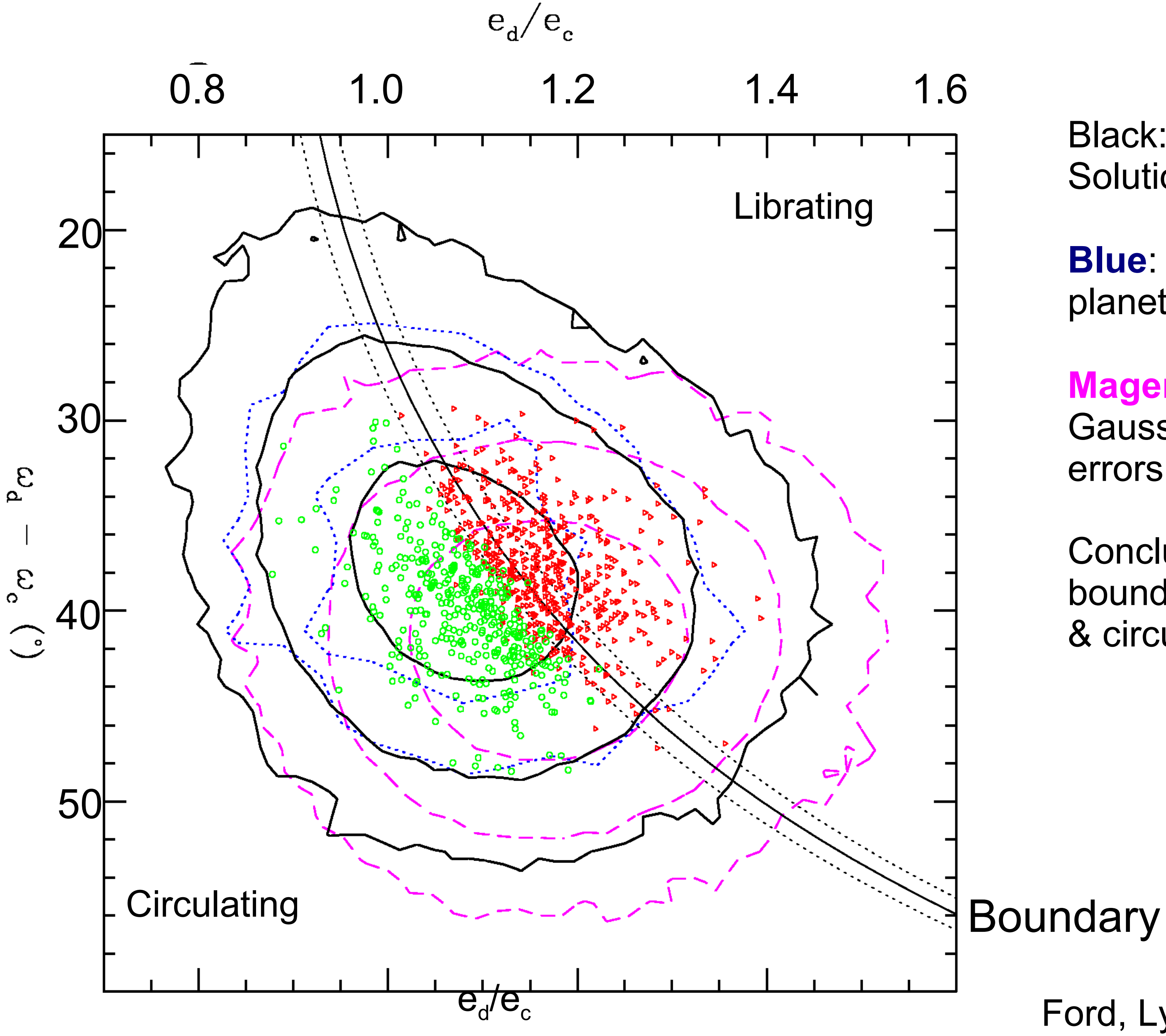
Marcy et al. 1999
Chiang & Murray 2002

Secular Eccentricity Evolution



Fischer et al. 2003
Chiang & Murray 2002

Current Location in Phase Space



Contours:

Black: Standard Orbital Solution

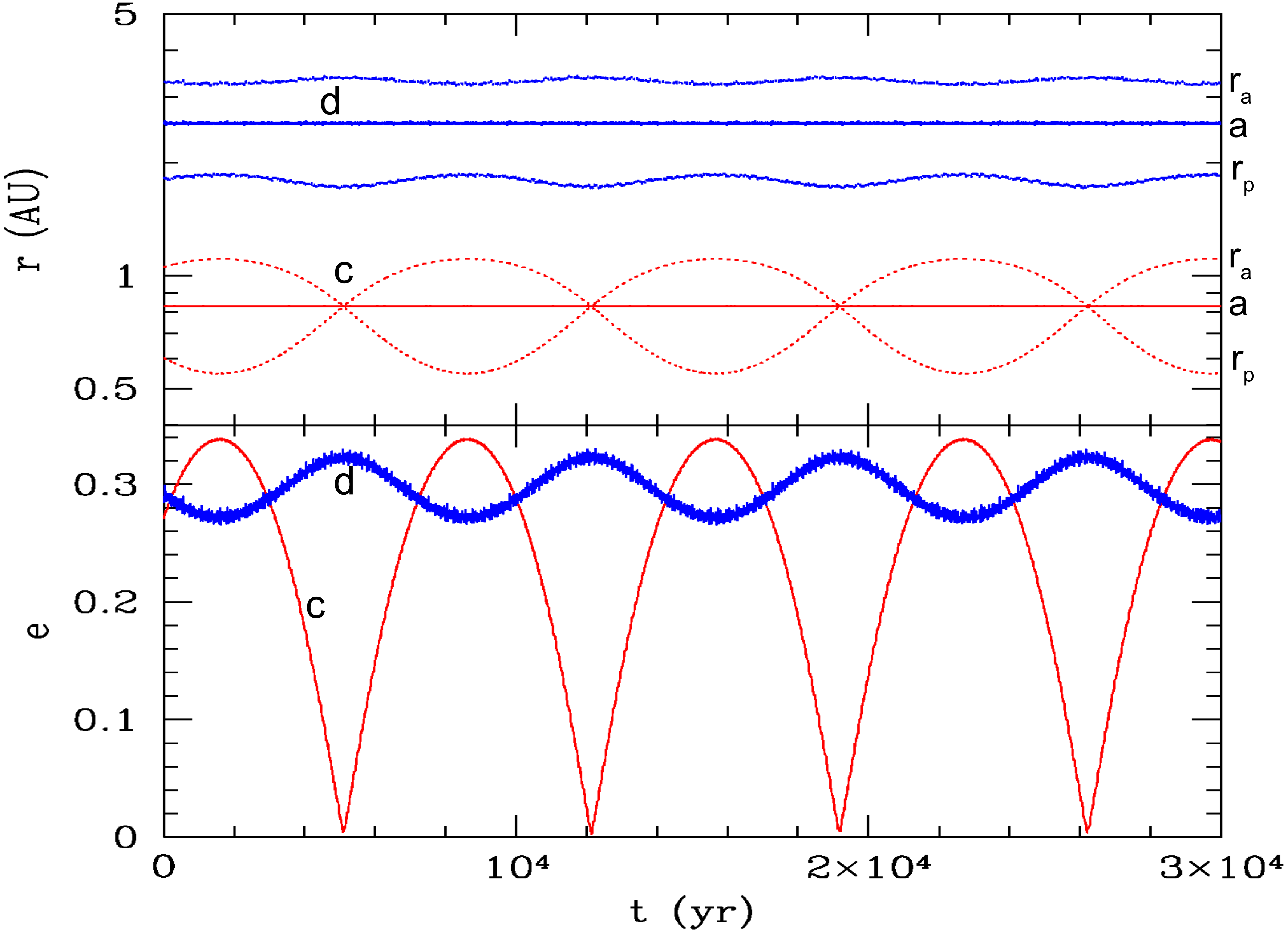
Blue: Includes planet-planet interactions

Magenta: Allows for non-Gaussian observational errors

Conclusion: System near boundary dividing libration & circulation

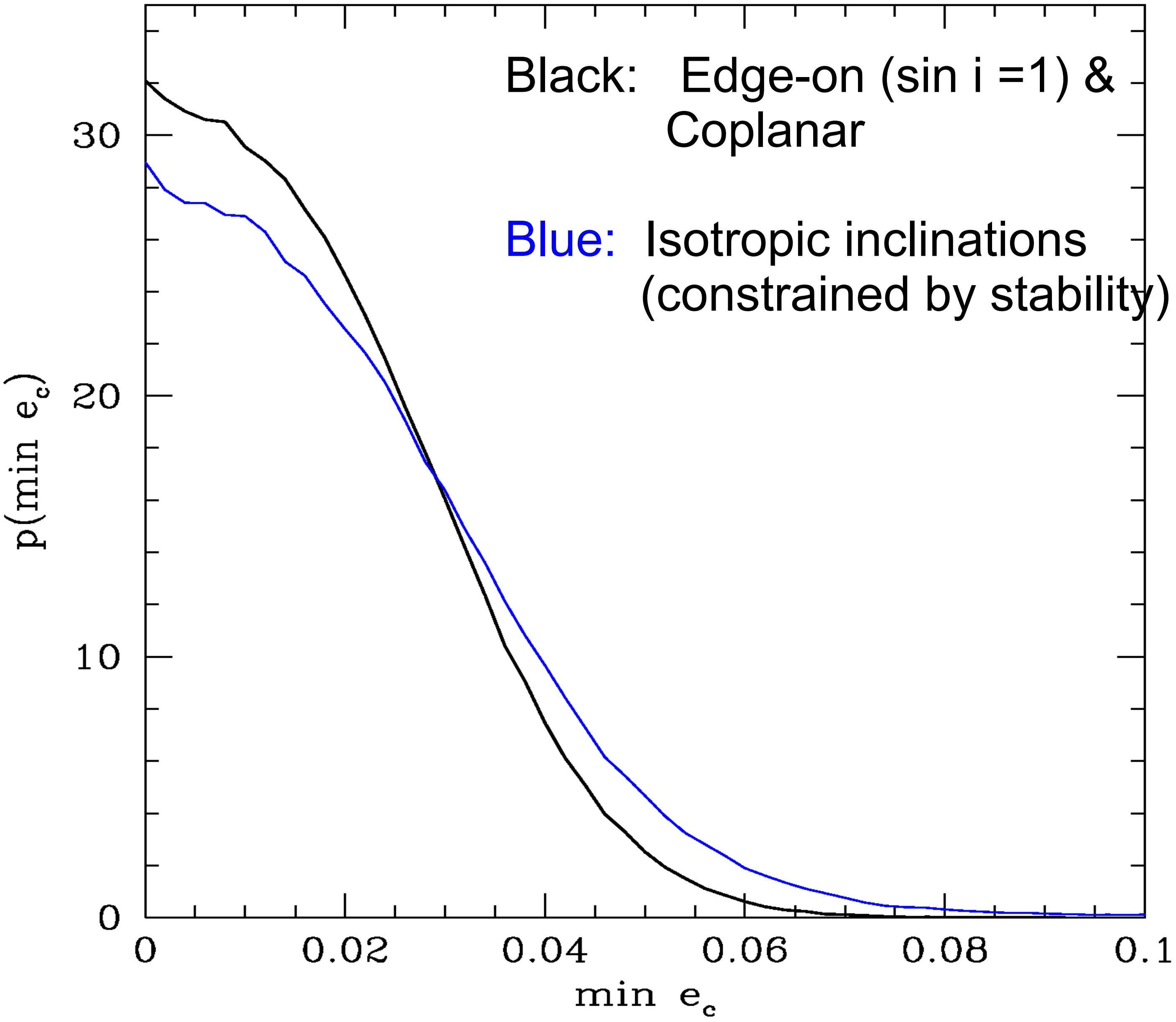
Ford, Lystad, Rasio 2005

Secular Evolution



Ford, Lystad, Rasio 2005

Minimum Eccentricity of Ups And c

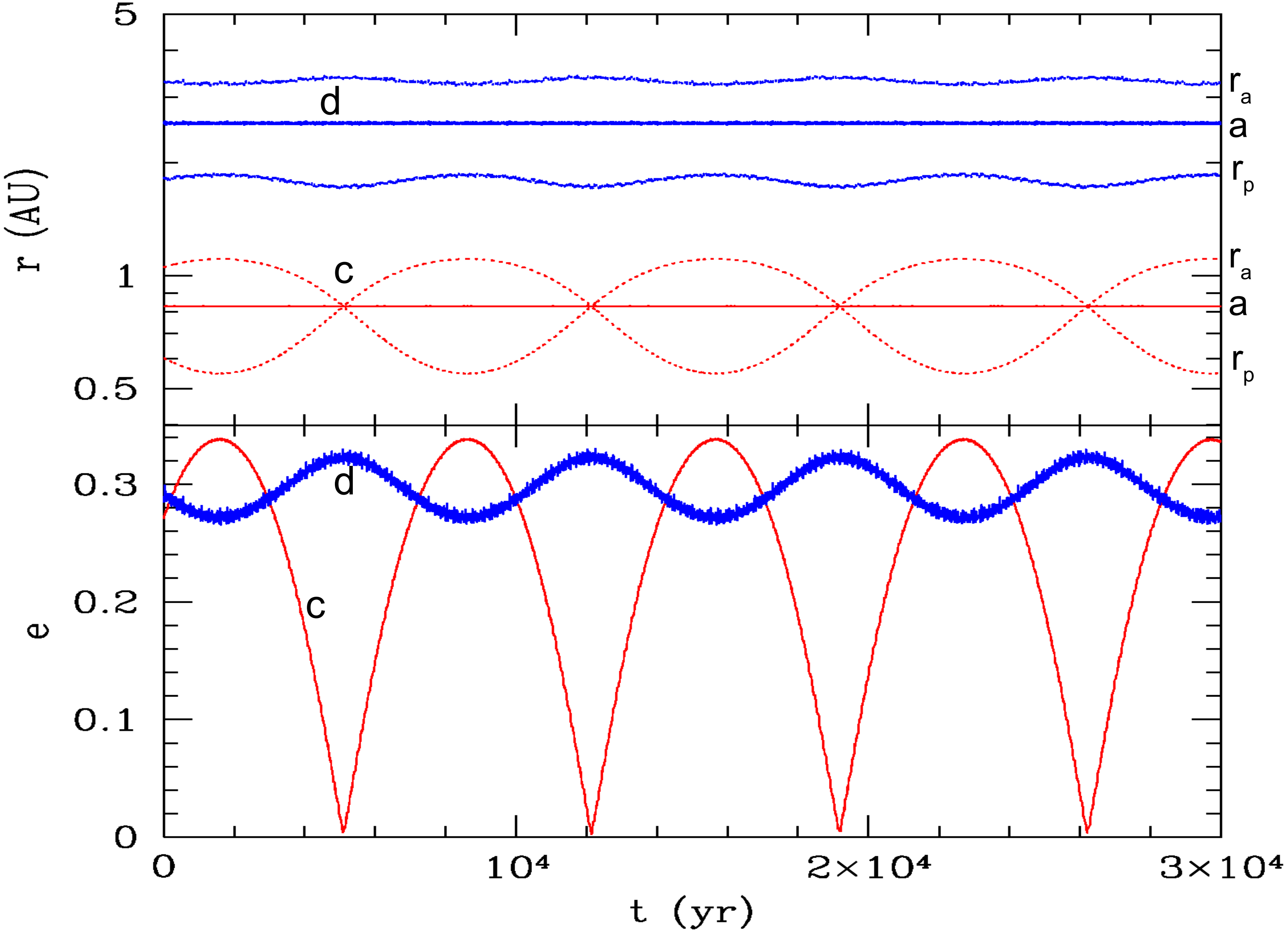


Black: Edge-on (sin i =1) &
Coplanar

Blue: Isotropic inclinations
(constrained by stability)

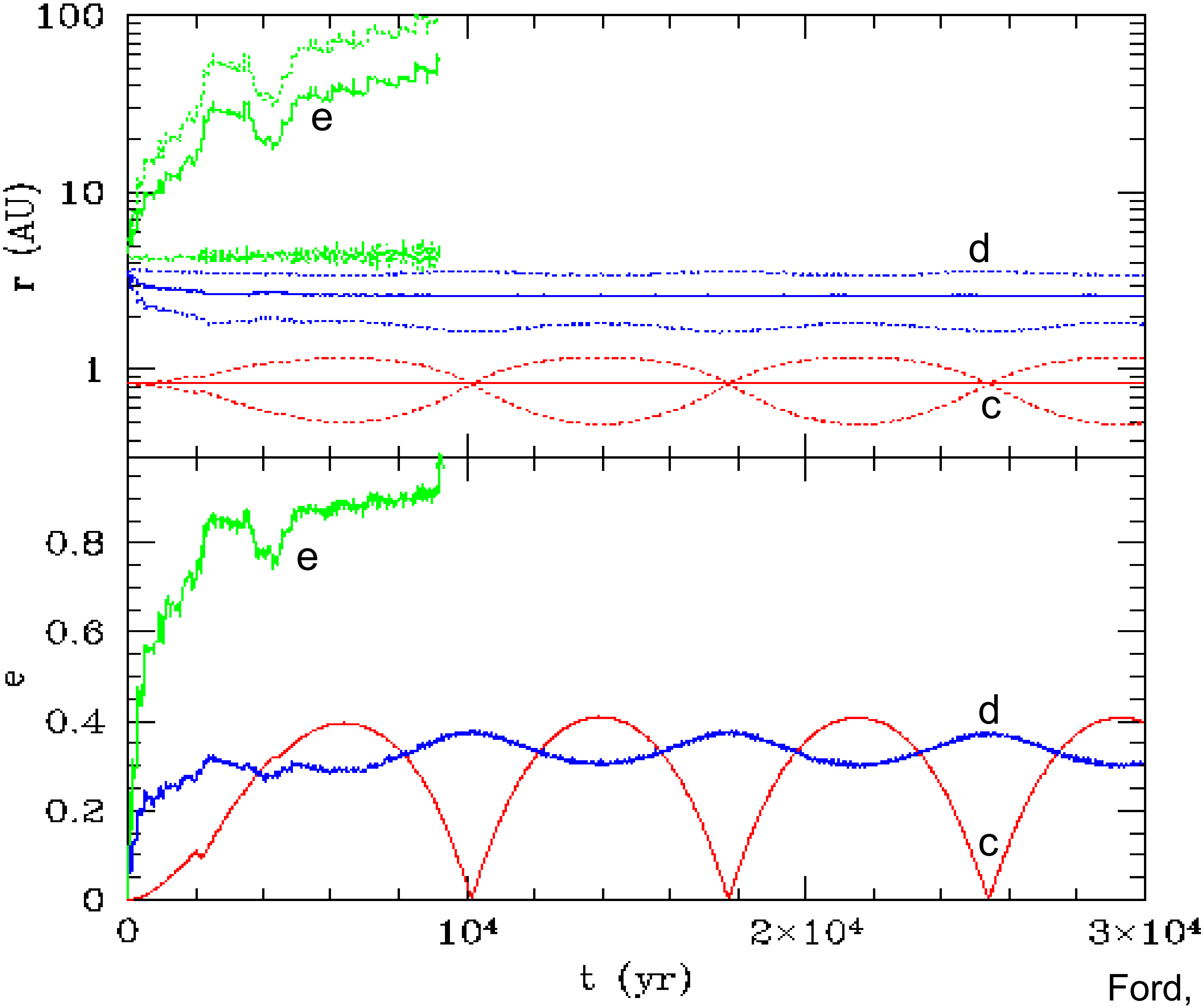
Ford, Lystad, Rasio 2005

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

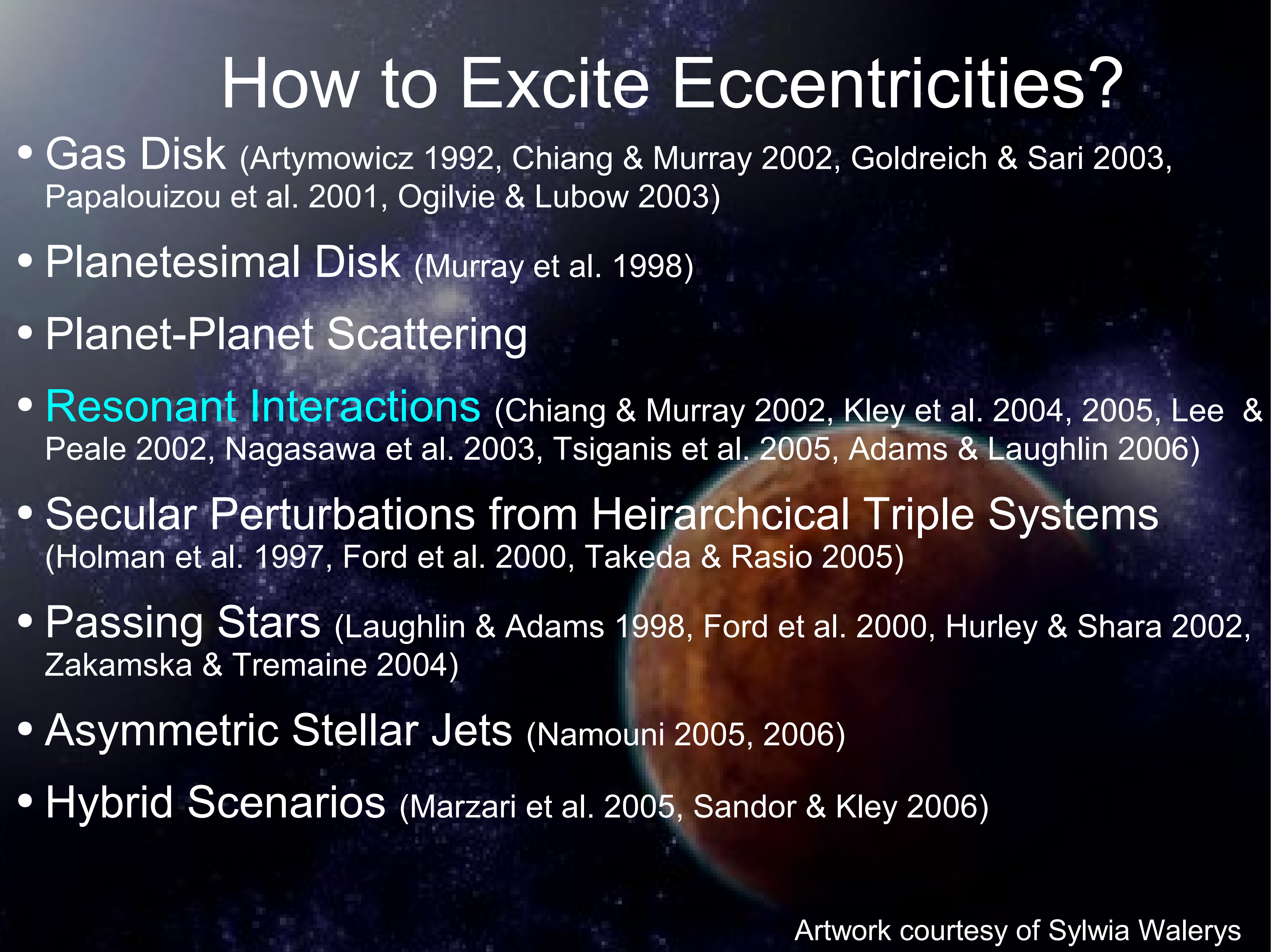
Final:
P_d = 3.7 yr
e_d = 0.29

Ford, Lystad, Rasio 2005

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

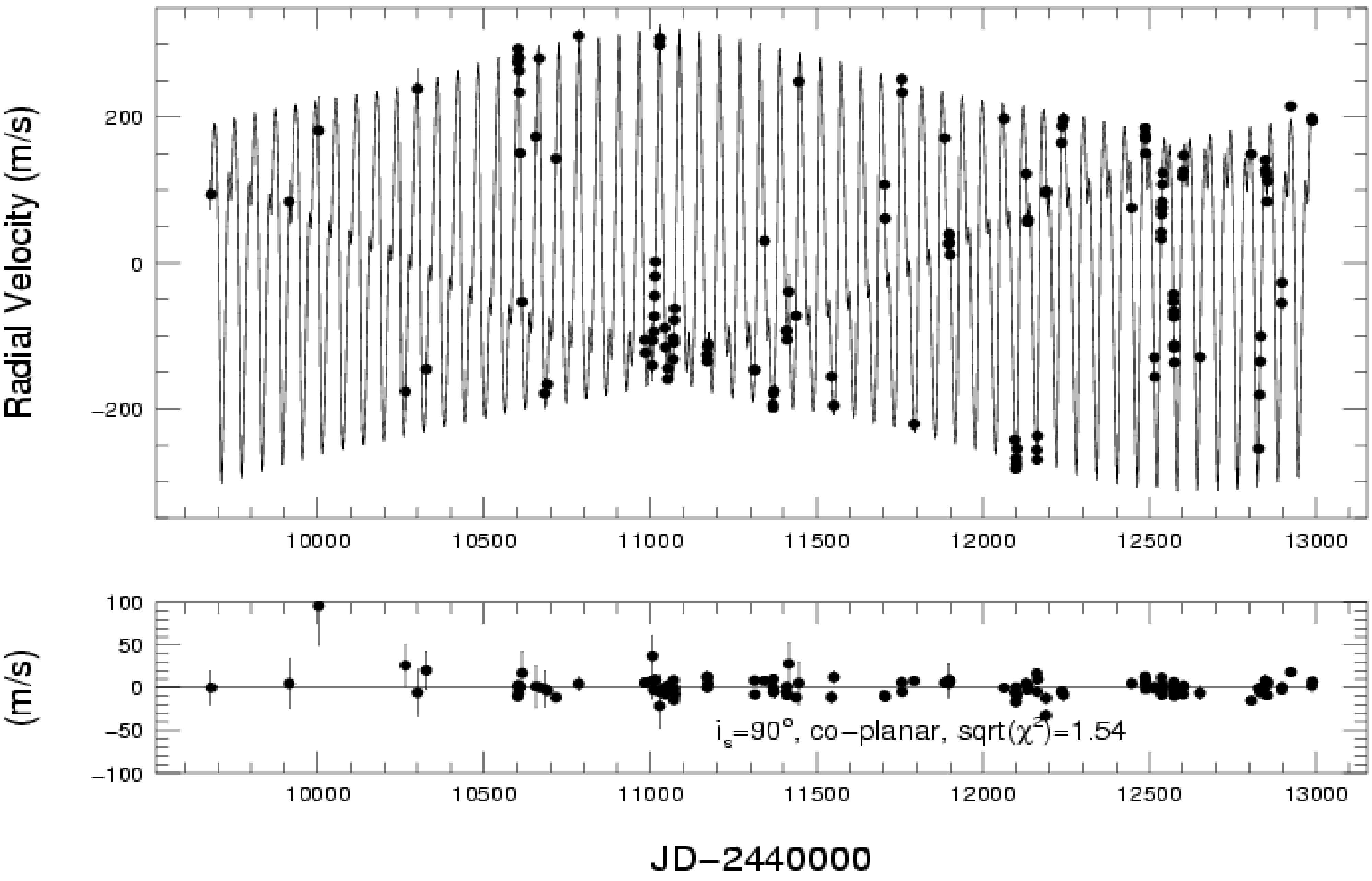
How to Excite Eccentricities?



- 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)

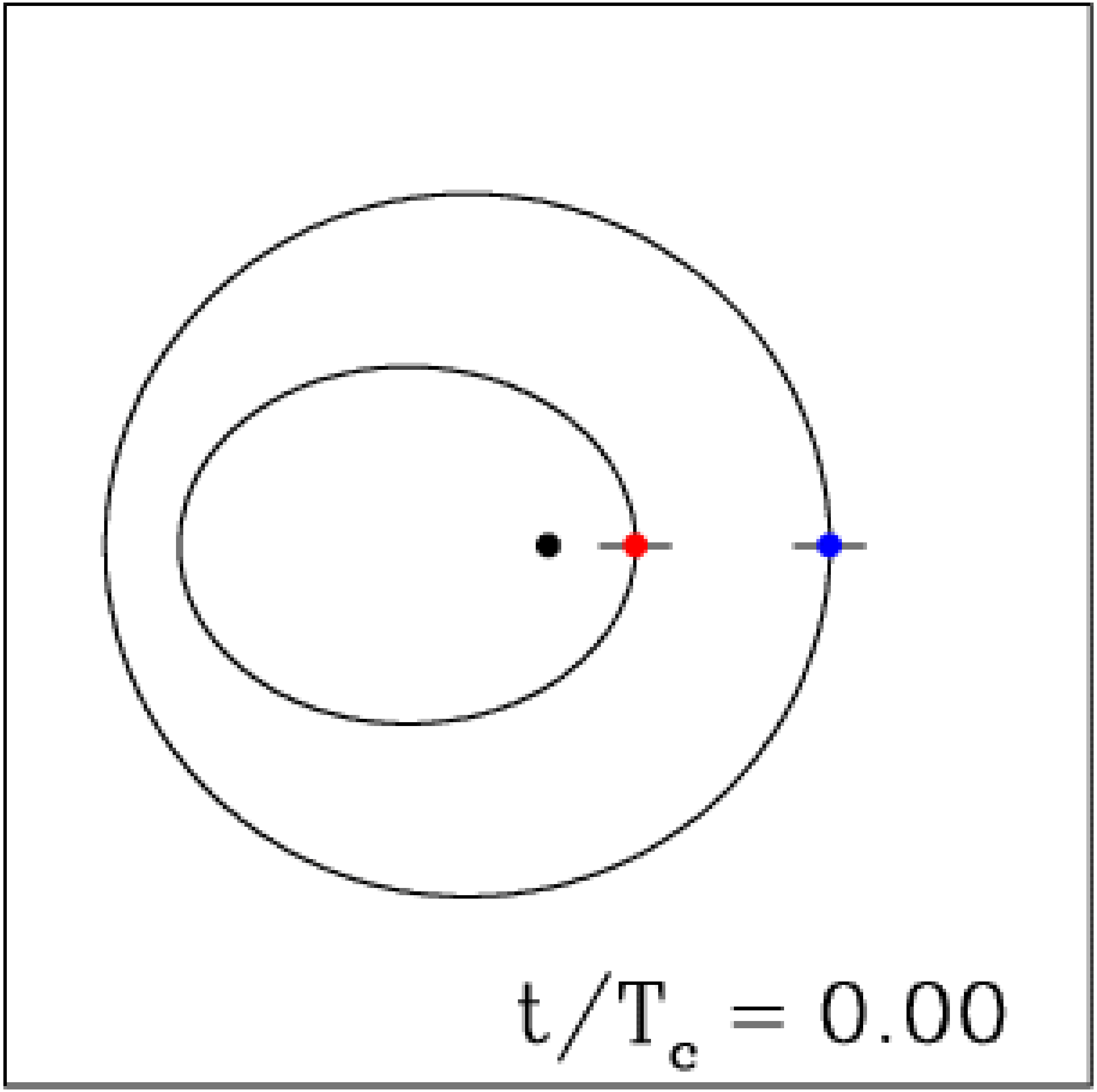
Artwork courtesy of Sylwia Walerys

GJ 876: Radial Velocities



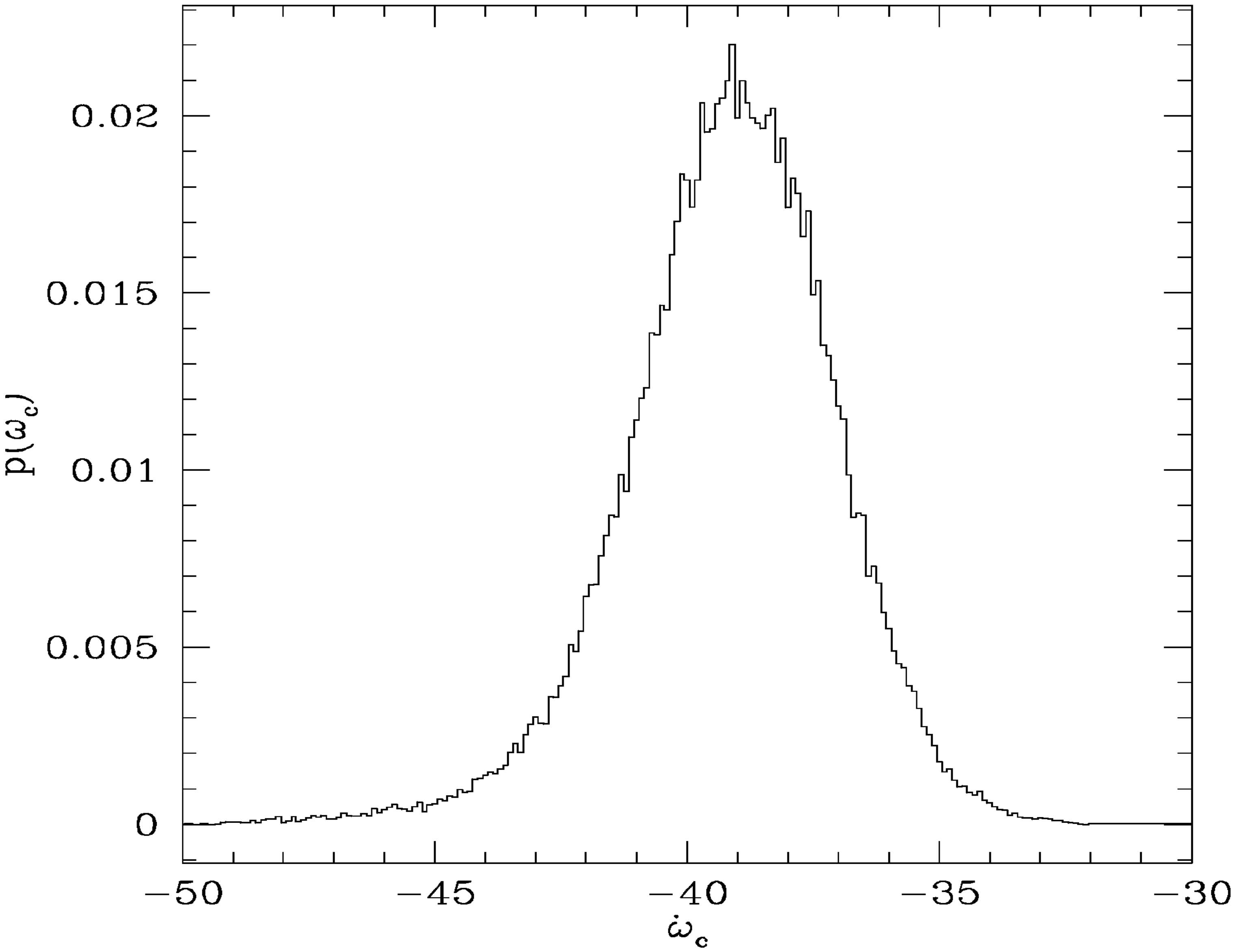
Laughlin et al. 2004

GJ 876: Geometry



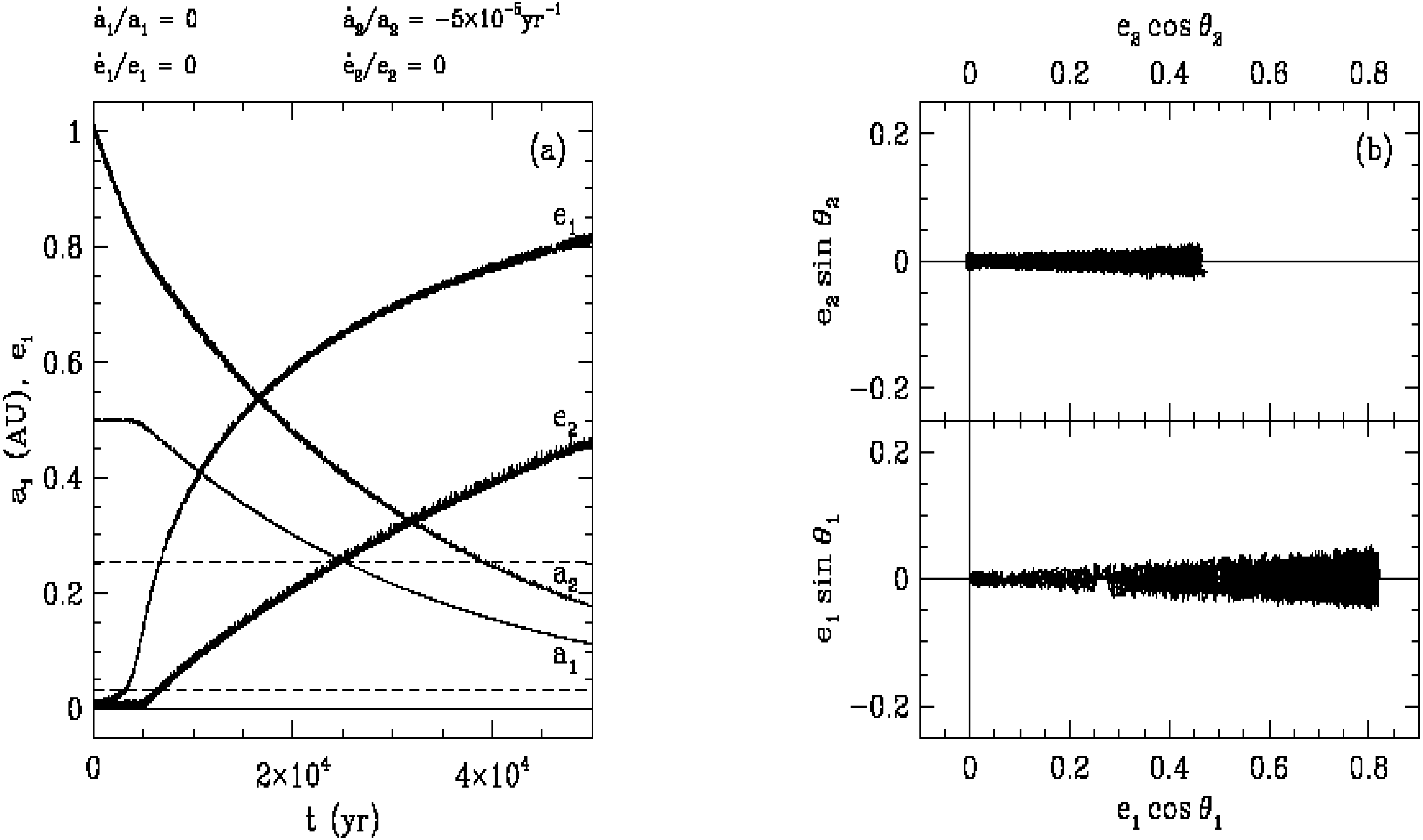
Lee

GJ 876: Precession Rate



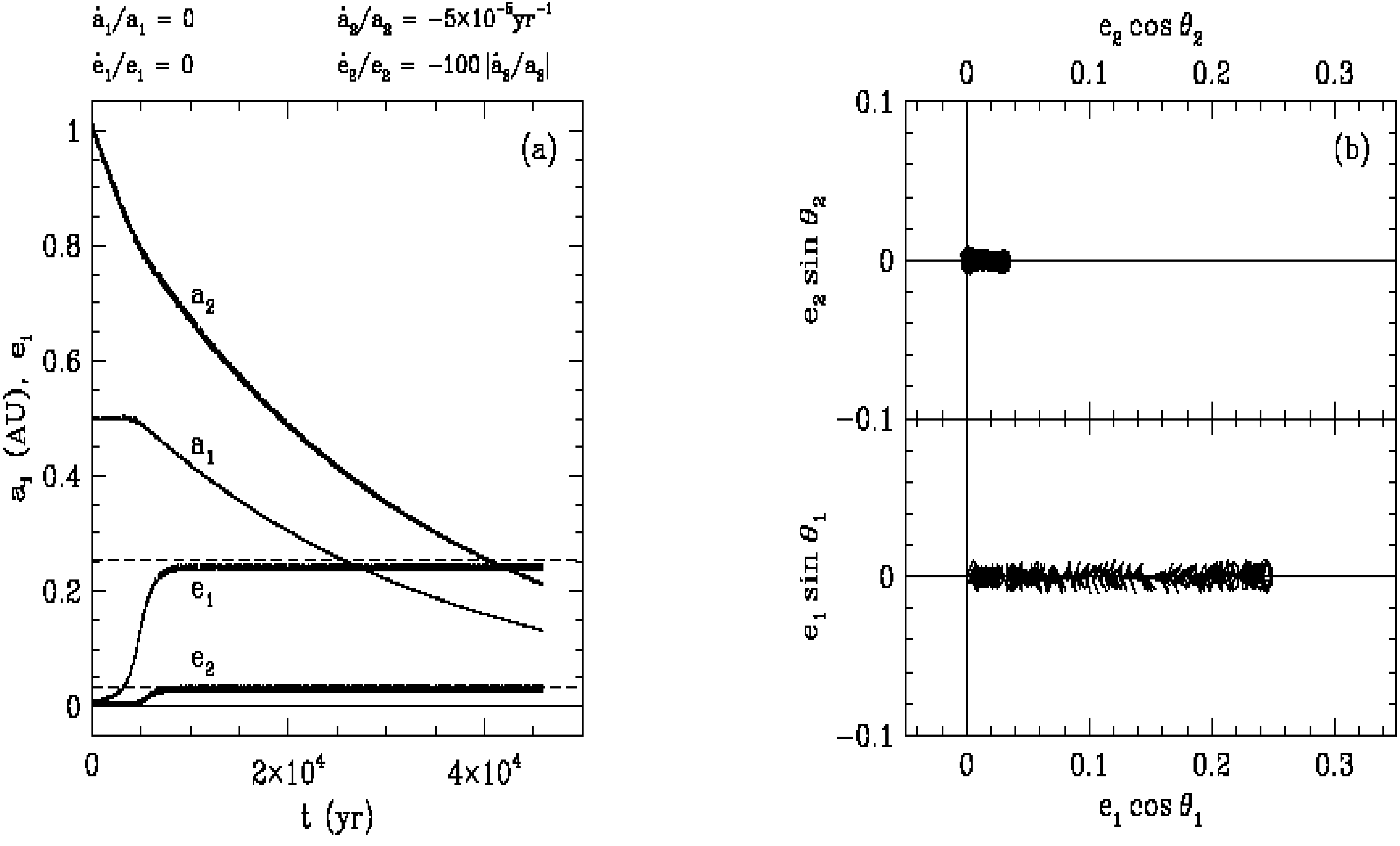
Ford 2004

GJ 876: Basic Migration



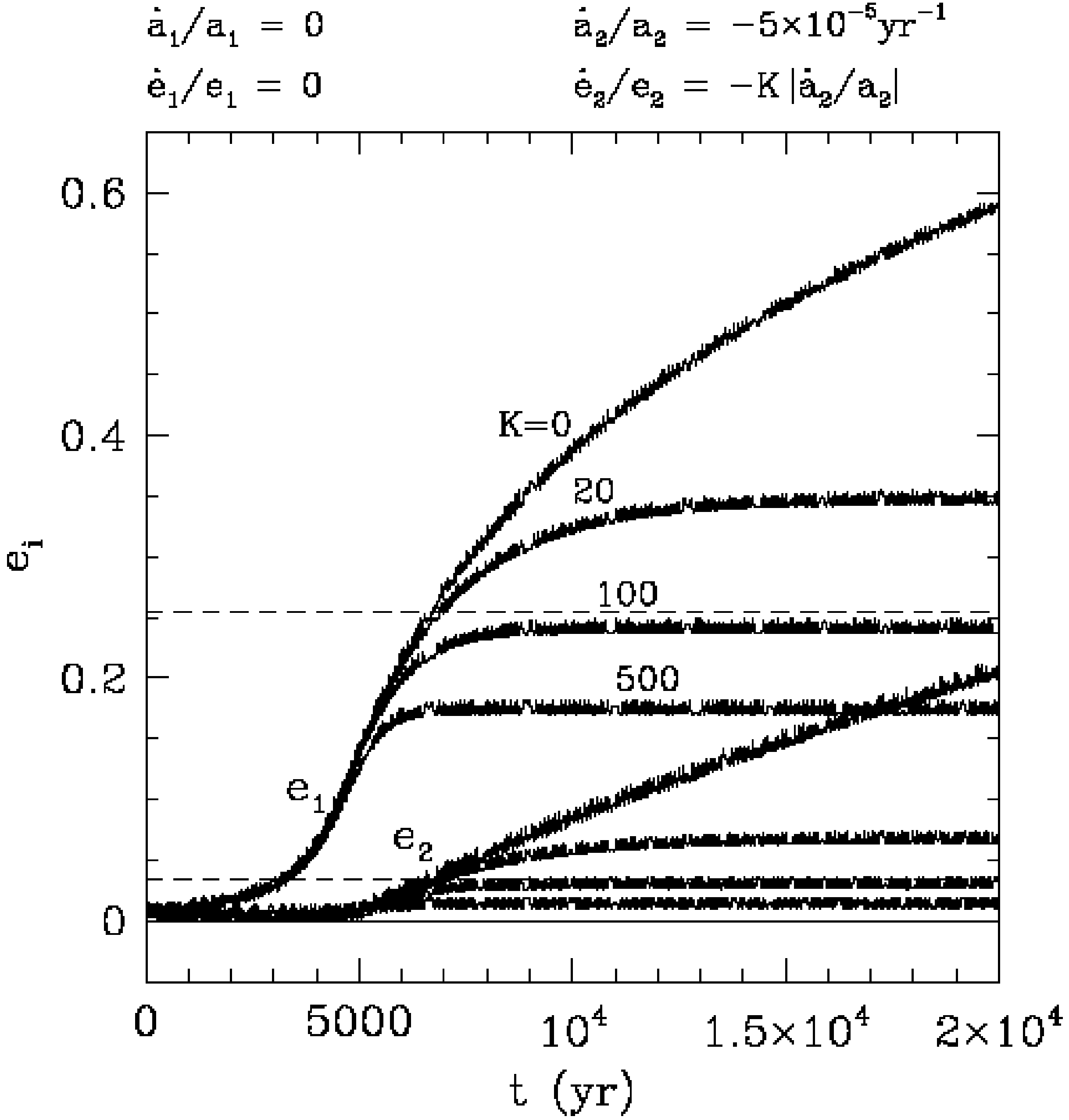
Lee & Peale 2003

GJ 876: Add Eccentricity Damping



Lee & Peale 2003

GJ 876: Final Eccentricity vs Damping



Lee & Peale 2003

Conclusions for GJ 876

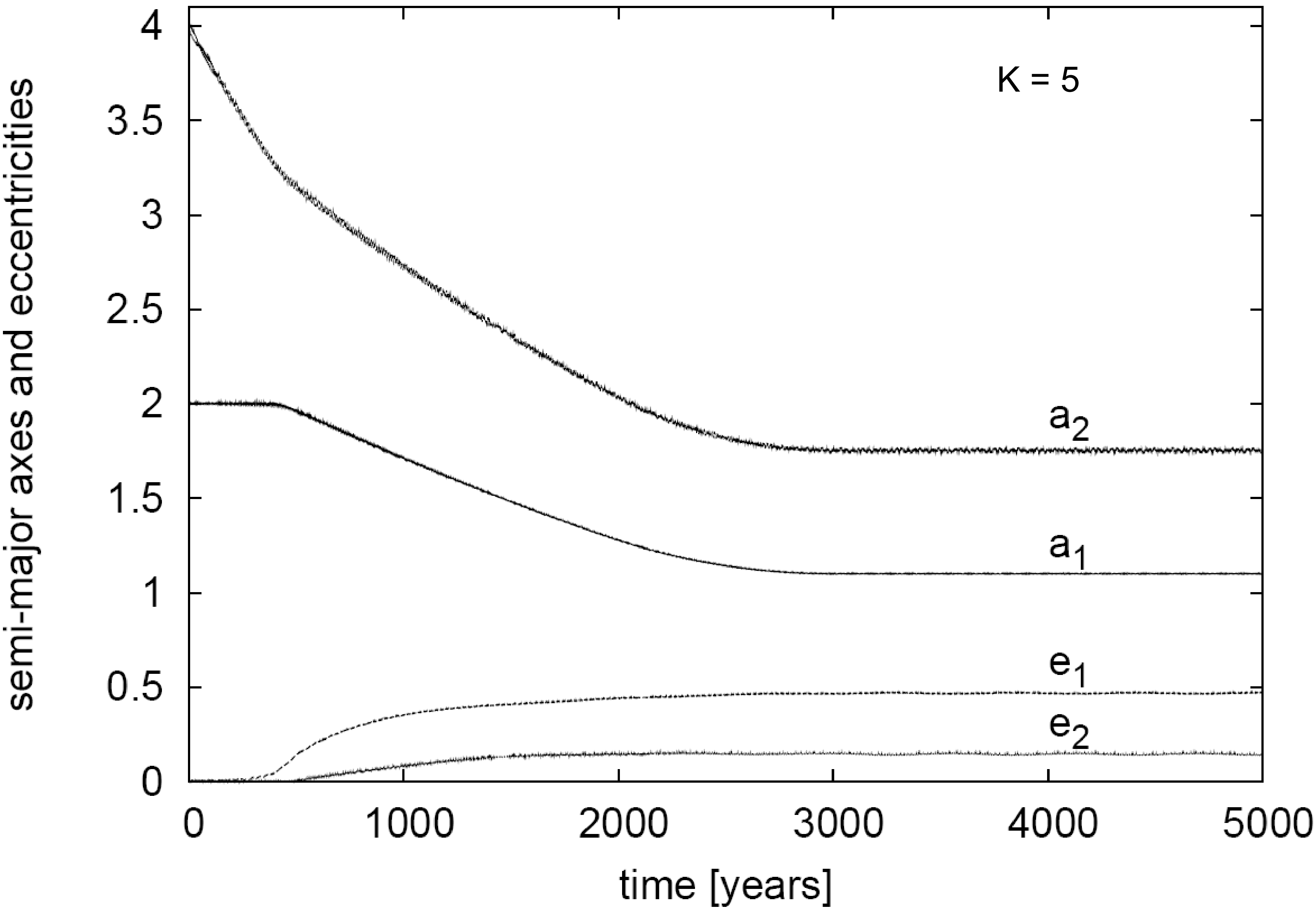
- Planet-Planet interaction leads to rapid precession
- Precession rate constrains masses & orbits
- Differential migration naturally led to resonant capture into 2:1 mean motion resonance
- Measured eccentricities demand either:
  - Migration halt shortly after resonant capture
  - Strong eccentricity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

Triggers for Dynamical Instability

- Dissipation of Protoplanetary Disk
- Mass Growth
- Secular Evolution
  - Multiple Planet Systems
  - Wide Stellar Binary Companions
- Migration
  - Convergent
  - Divergent crossing of Mean Motion resonances
- Distant Stellar Encounters

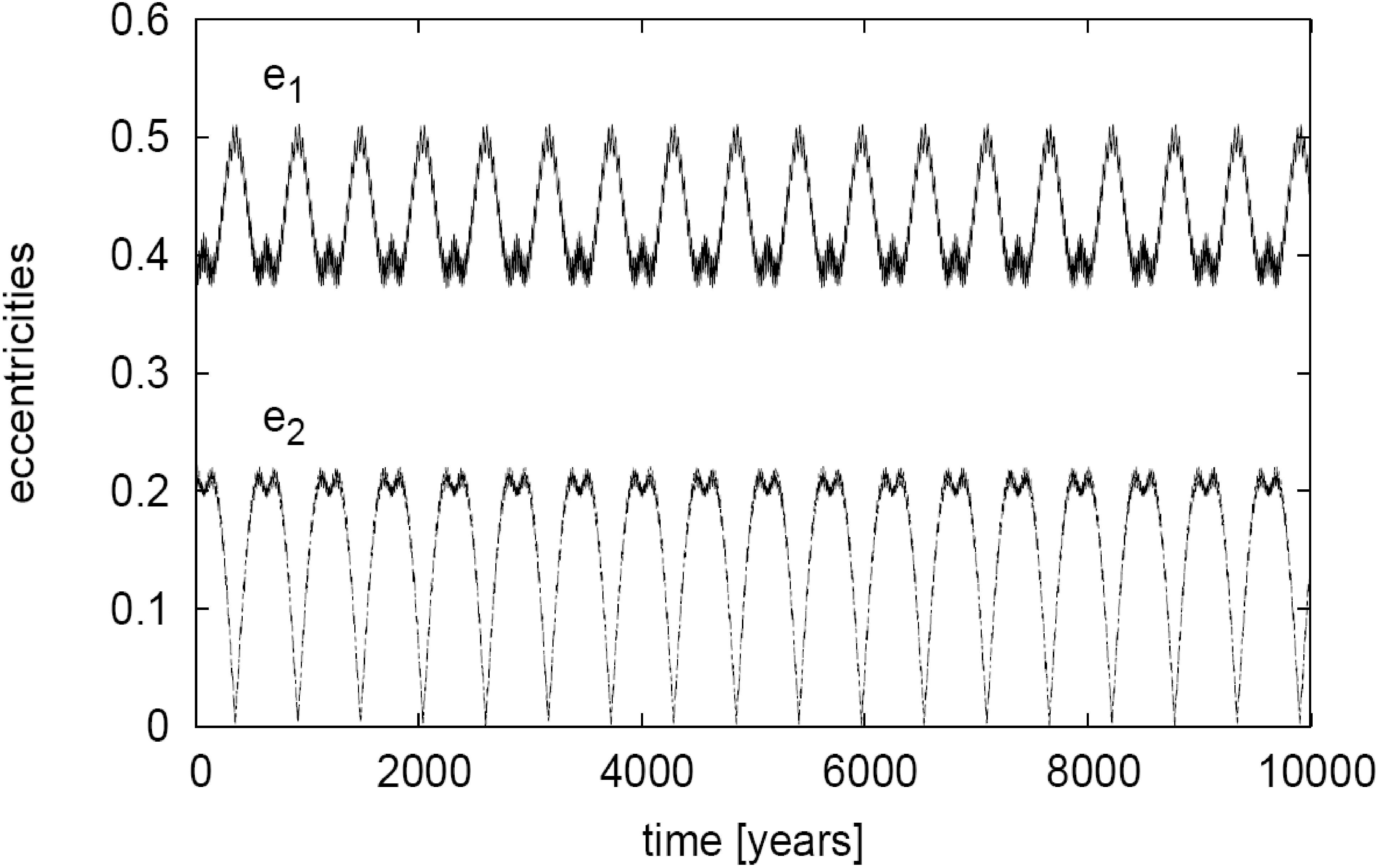
Artwork courtesy of Sylwia Walerys

HD 128311: Resonant Capture



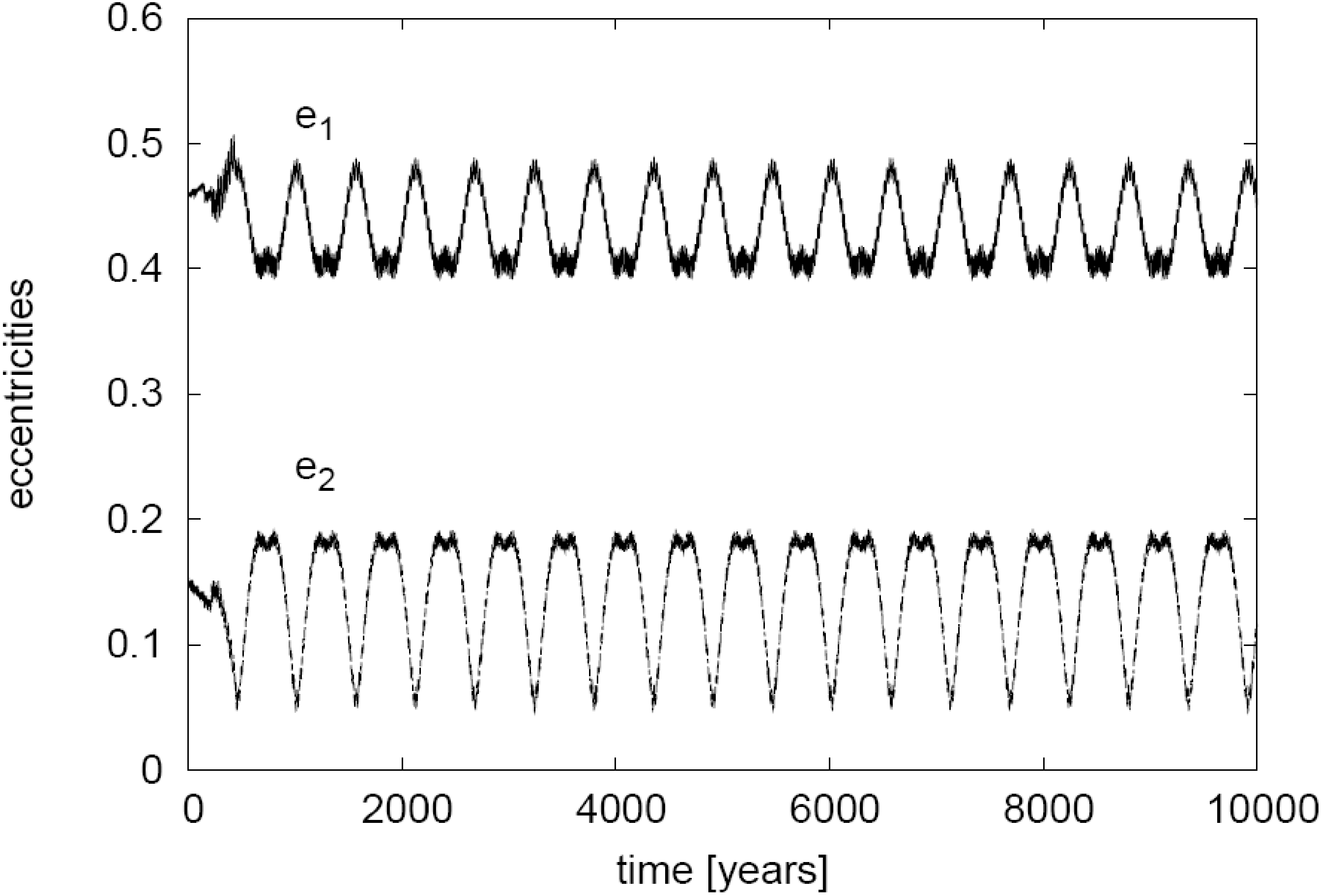
Sandor & Kley 2006

HD 128311: Secular Evolution



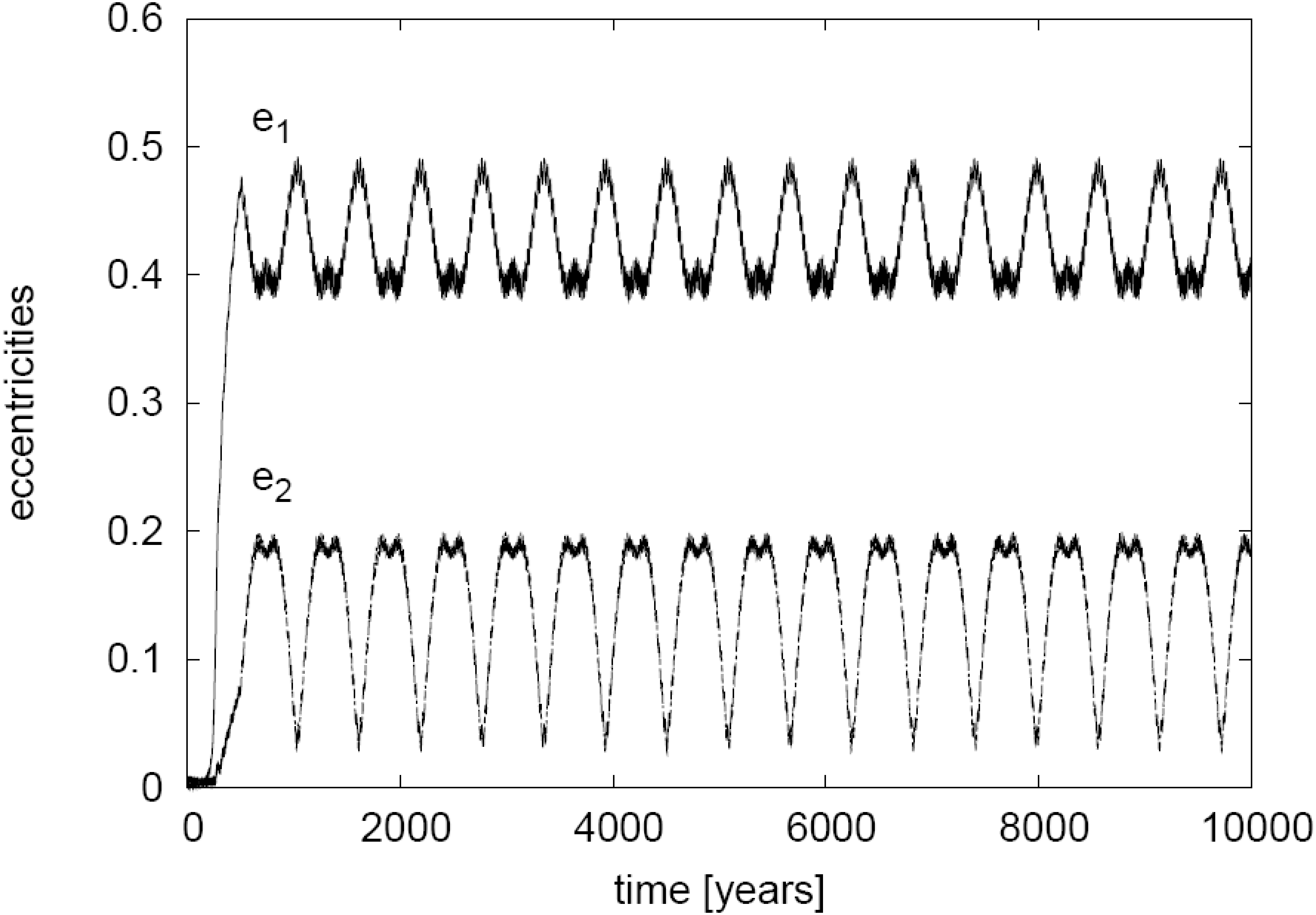
Sandor & Kley 2006

Resonant Capture + Planet Scattering



Sandor & Kley 2006

HD 128311: Sudden Halt to Migration



Sandor & Kley 2006

Conclusions for HD 128311

- 2:1 Mean motion resonance suggests differential migration and resonant capture
- Measured eccentricities again suggest limited eccentricity growth after resonant capture:
  - Strong eccentricity damping during migration, or
  - Migration halting shortly after resonant capture
- Secular evolution suggests an impulsive perturbation, e.g.,
  - Sudden halting of migration, or
  - Planet-Planet scattering after resonant capture
- Multiple planet systems are providing valuable information about history of planet formation

Triggers for Dynamical Instability

- Dissipation of Protoplanetary Disk
- Mass Growth
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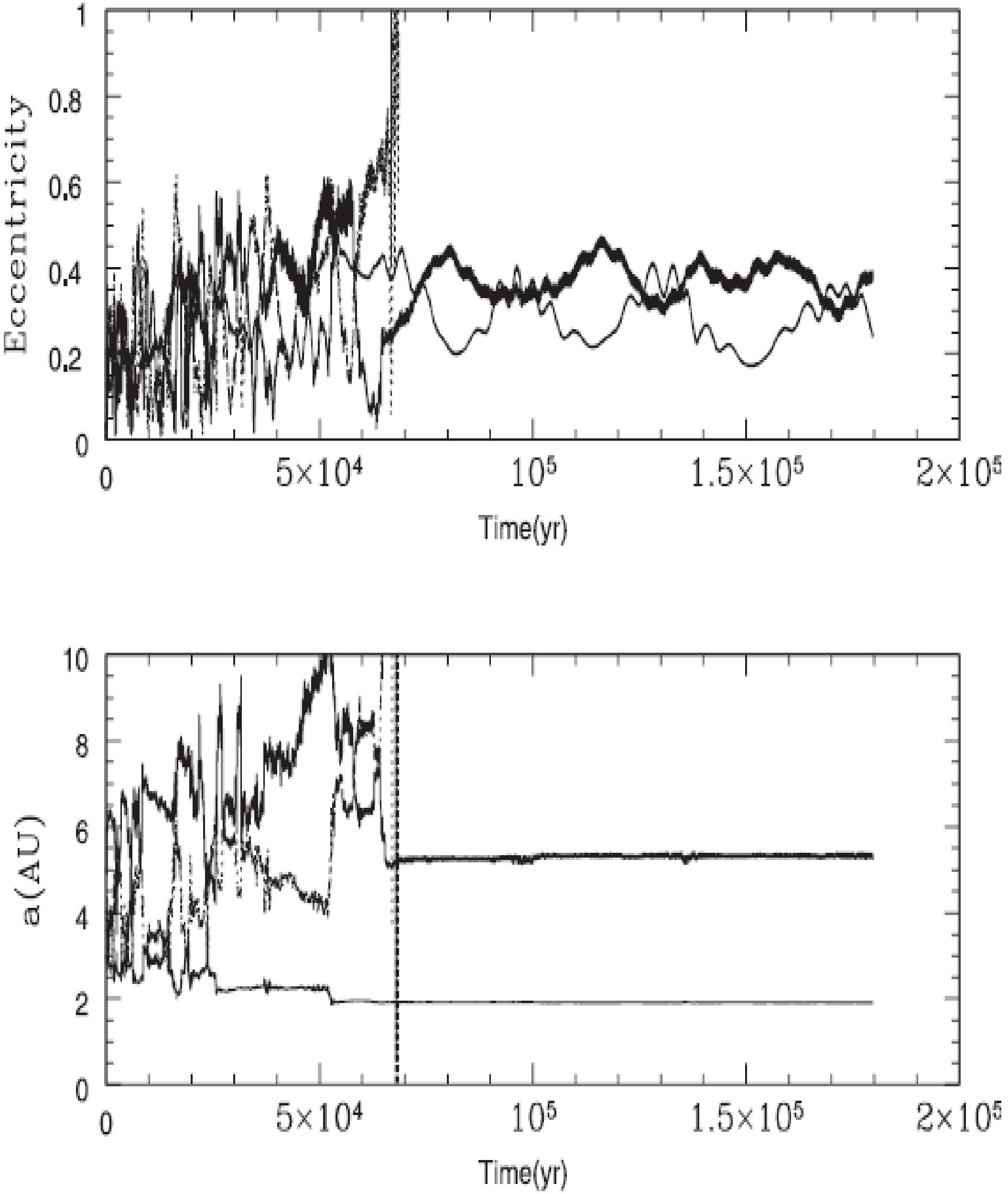
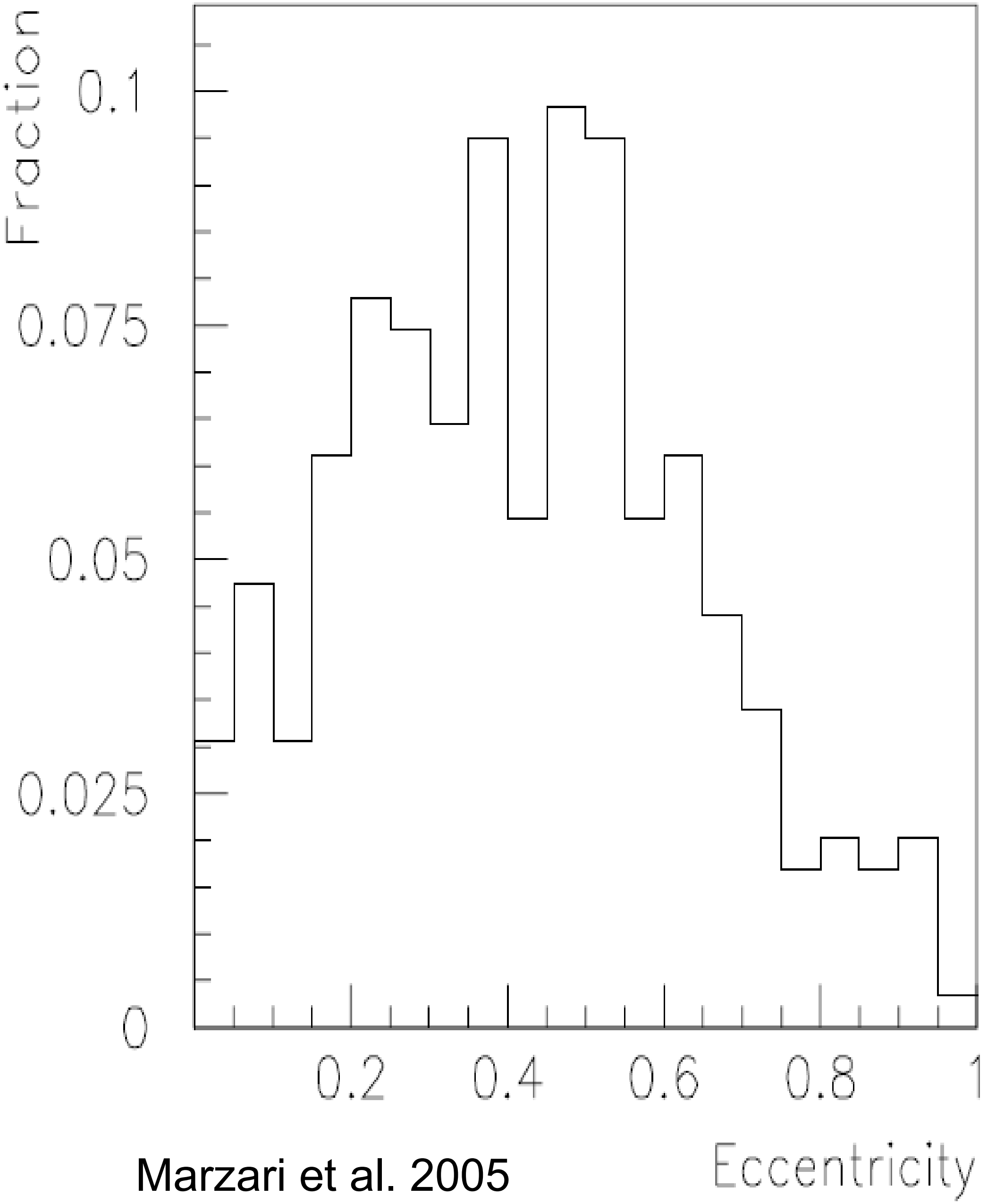
  - Multiple Planet Systems
  - Wide Stellar Binary Companions
- Migration
  - Convergent
  - Divergent crossing of Mean Motion resonances
- Distant Stellar Encounters

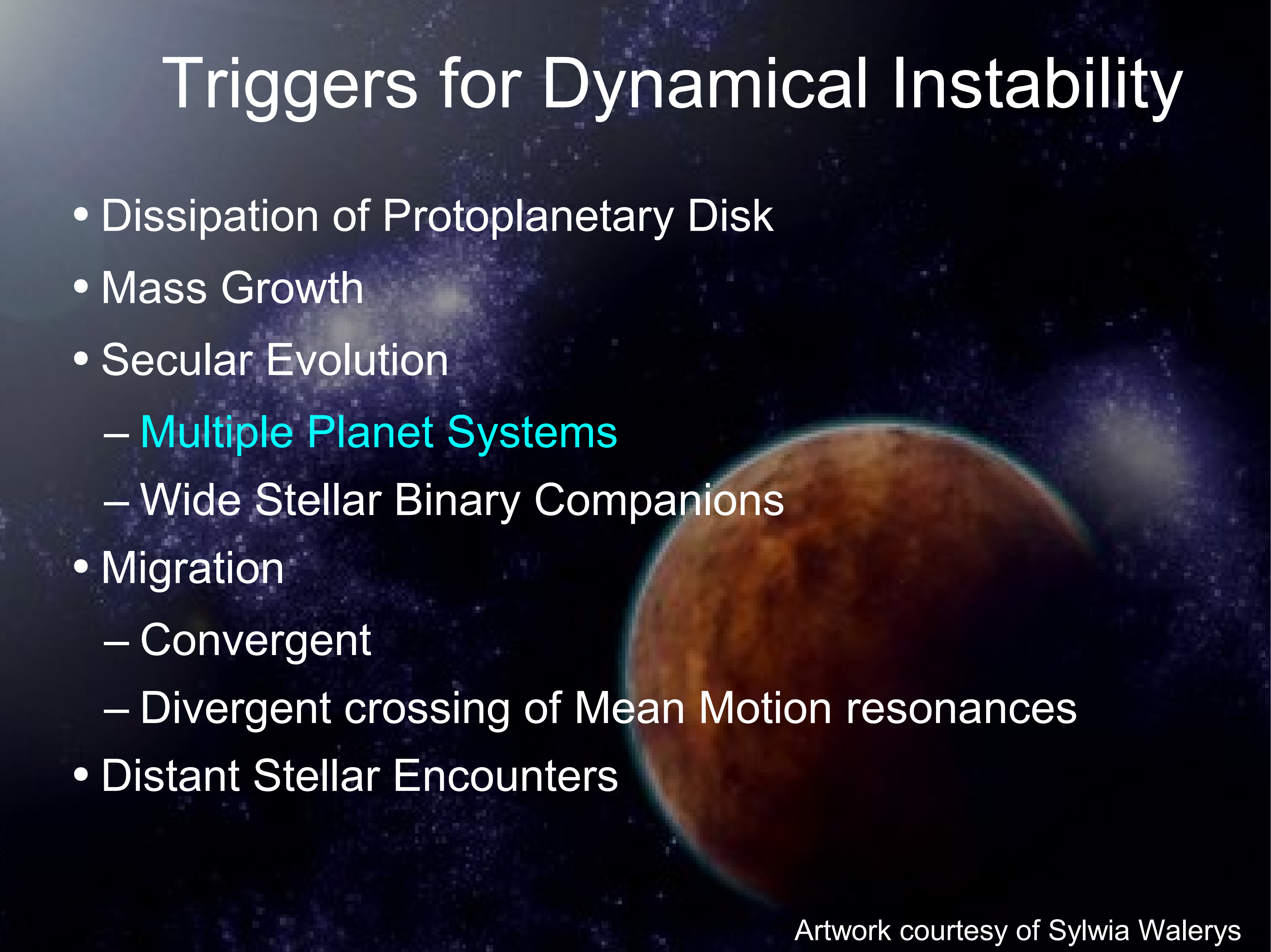
Artwork courtesy of Sylwia Walerys

Planet-Planet Scattering in a Binary





Marzari et al. 2005



Triggers for Dynamical Instability

- Dissipation of Protoplanetary Disk
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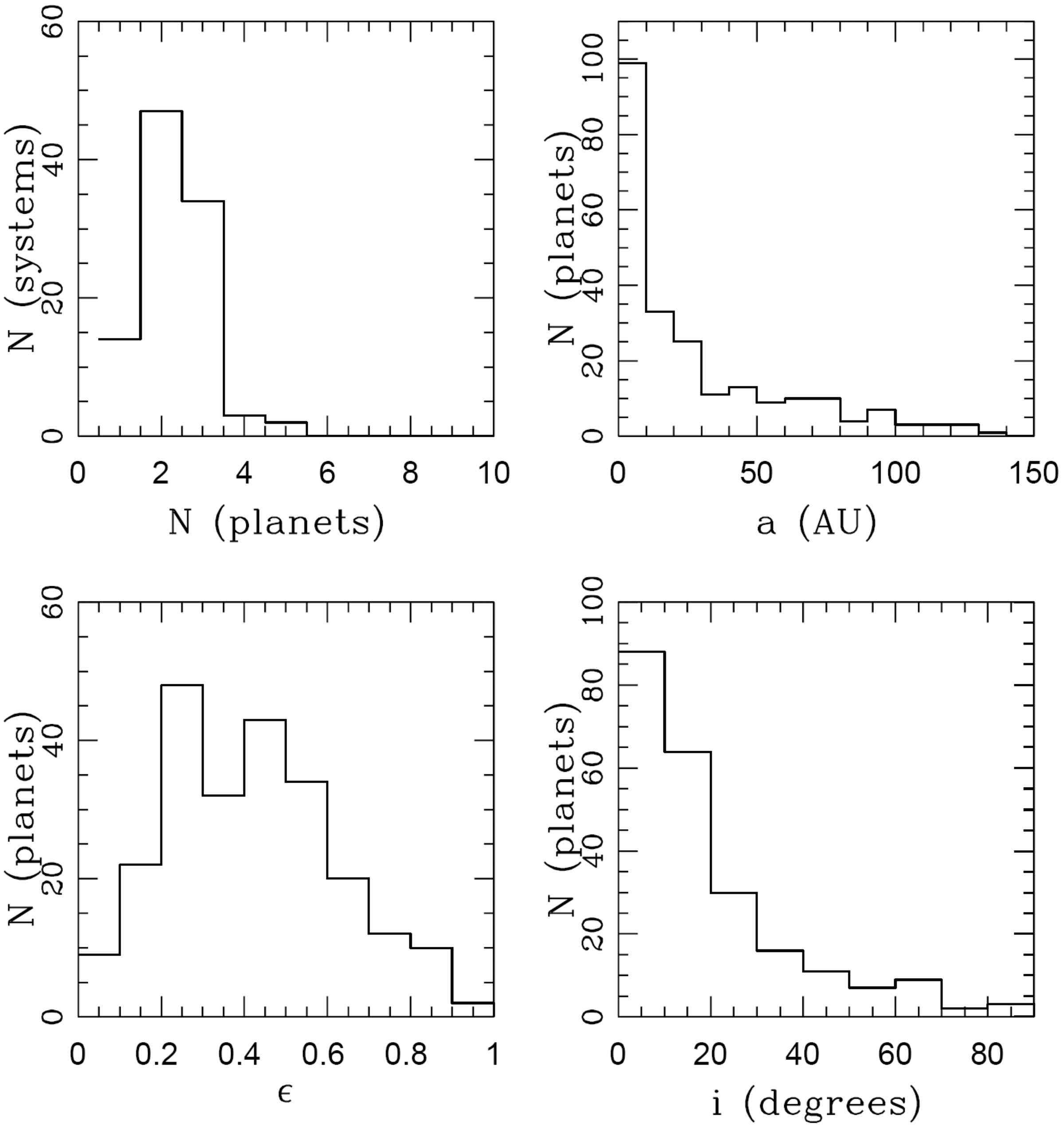
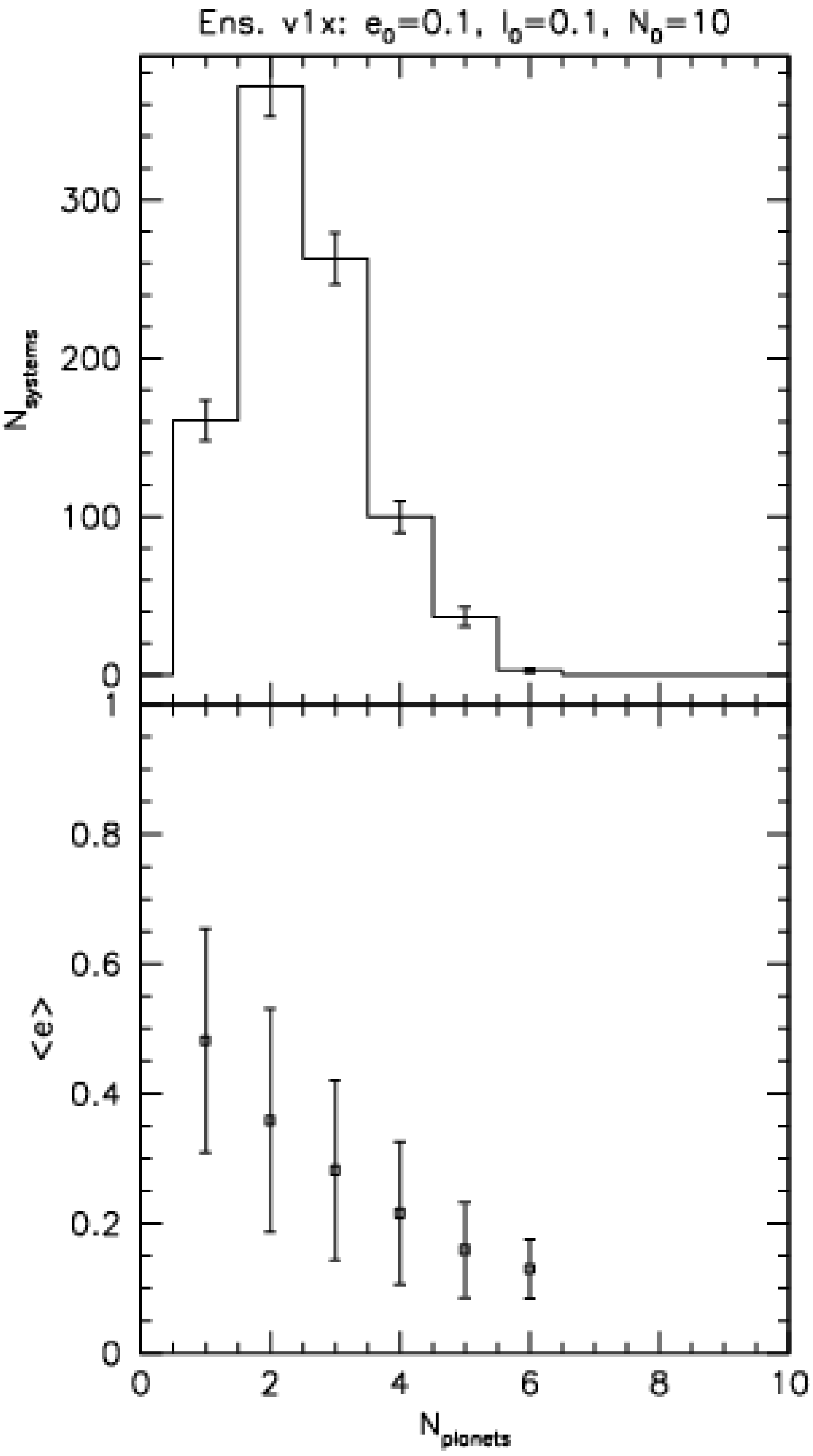
Artwork courtesy of Sylwia Walerys

Dynamical Relaxation



- Many giant planets initially on nearly circular orbits
- Many planets removed from system
- Typically 2 or 3 giant planets remain on eccentric orbits
- Often one giant planet in a very wide orbit

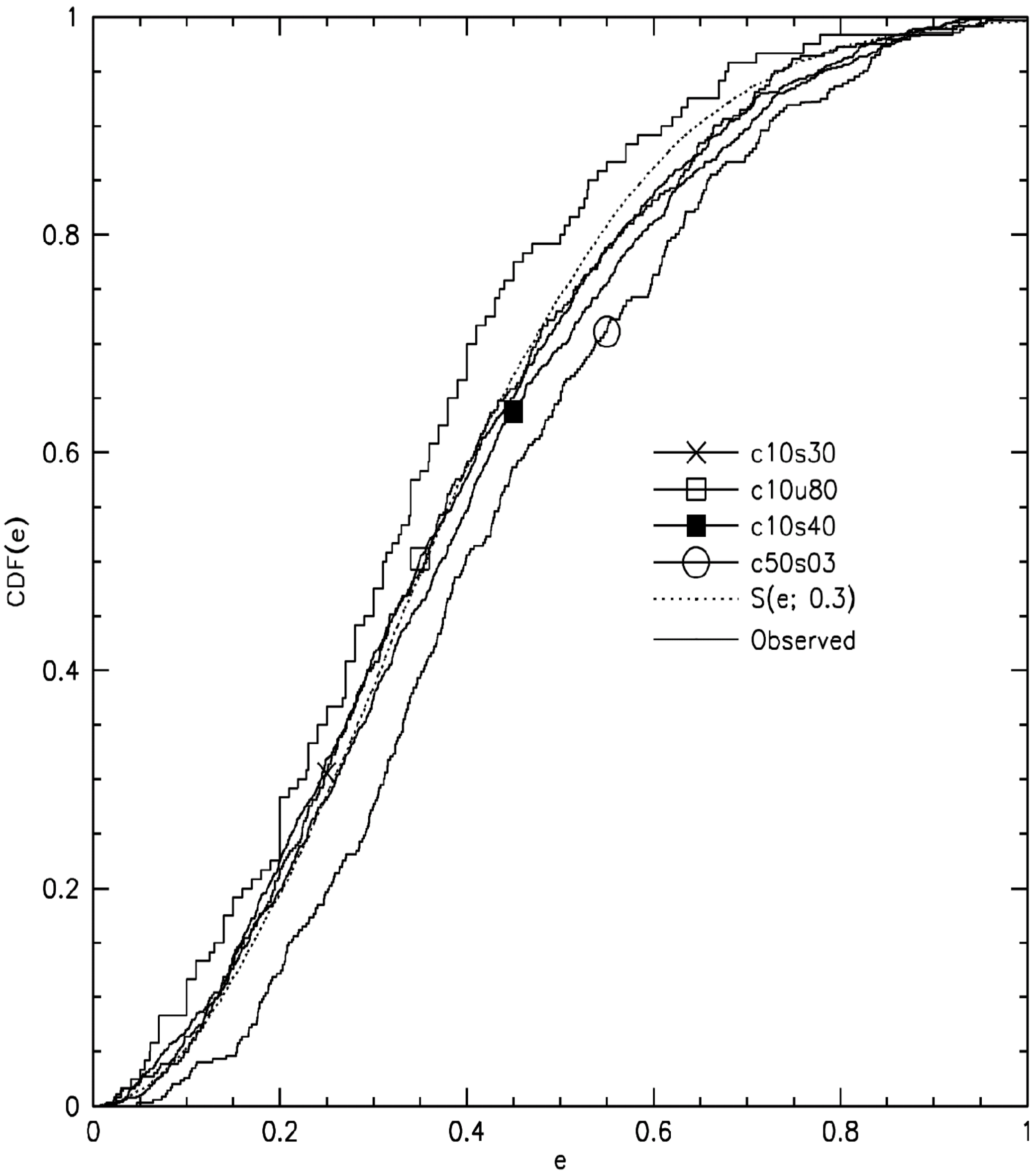
Adams & Laughlin 2003



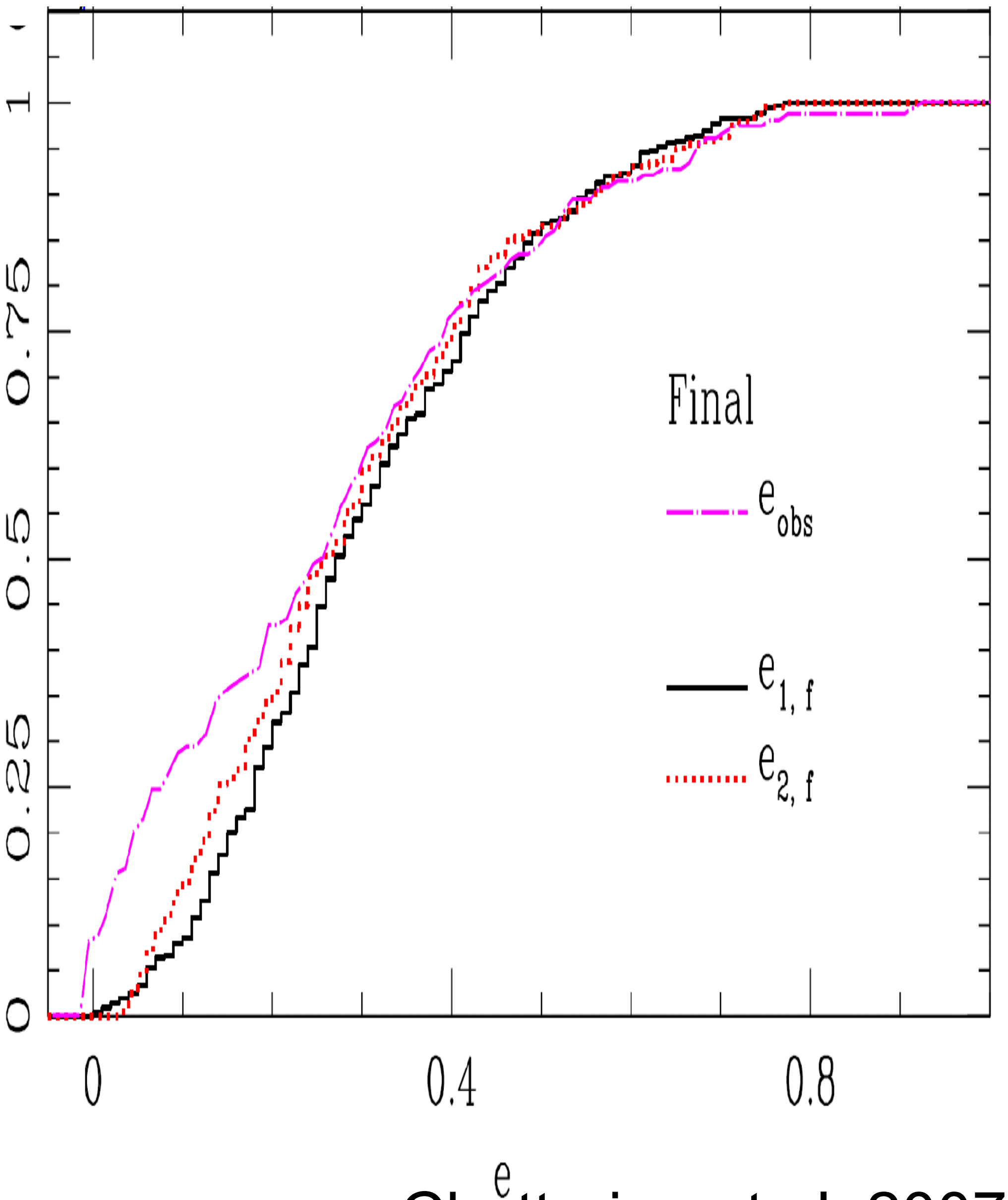
- mean eccentricity of surviving planets is correlated with number of surviving planets
- there are many high-eccentricity systems with 1 or 2 planets (the extrasolar planets?) and rare low-eccentricity systems with more planets (the solar system?)

(Juric & Tremaine 2007)

Distribution of Eccentricities



Juric & Tremaine 2007



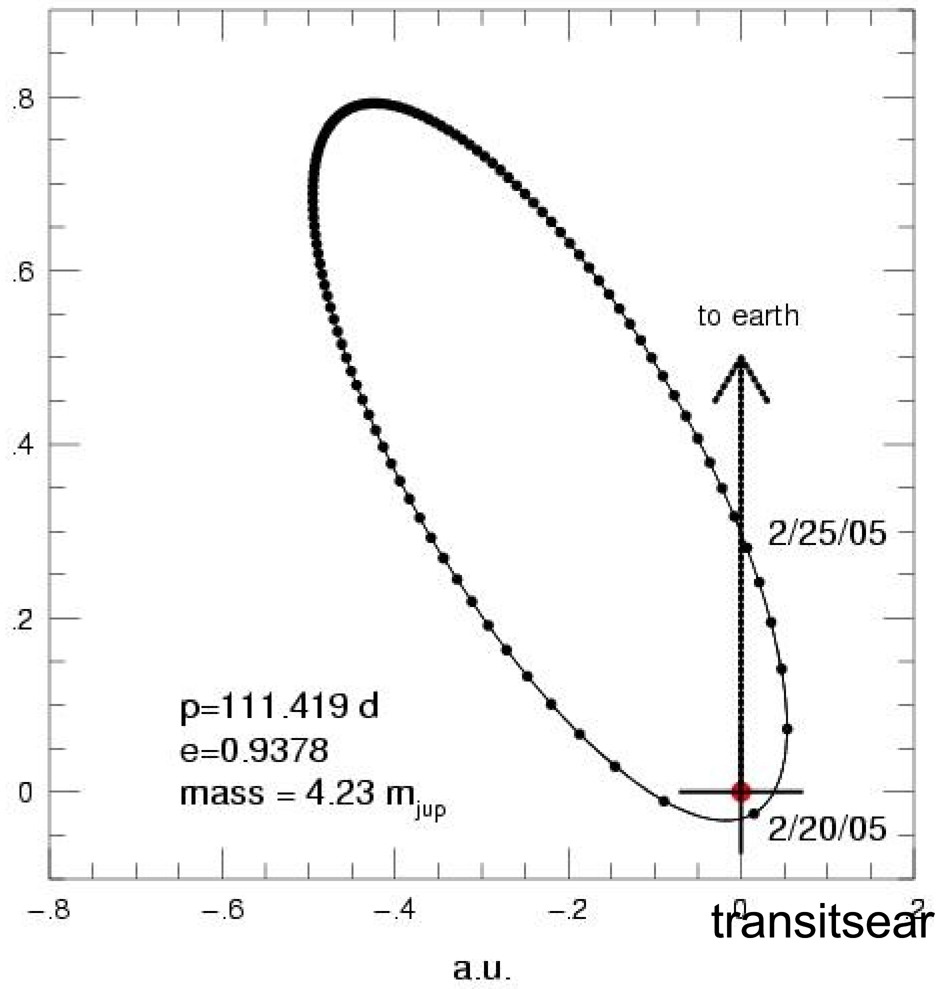
Chatterjee et al. 2007

Very Highly Eccentric Planets

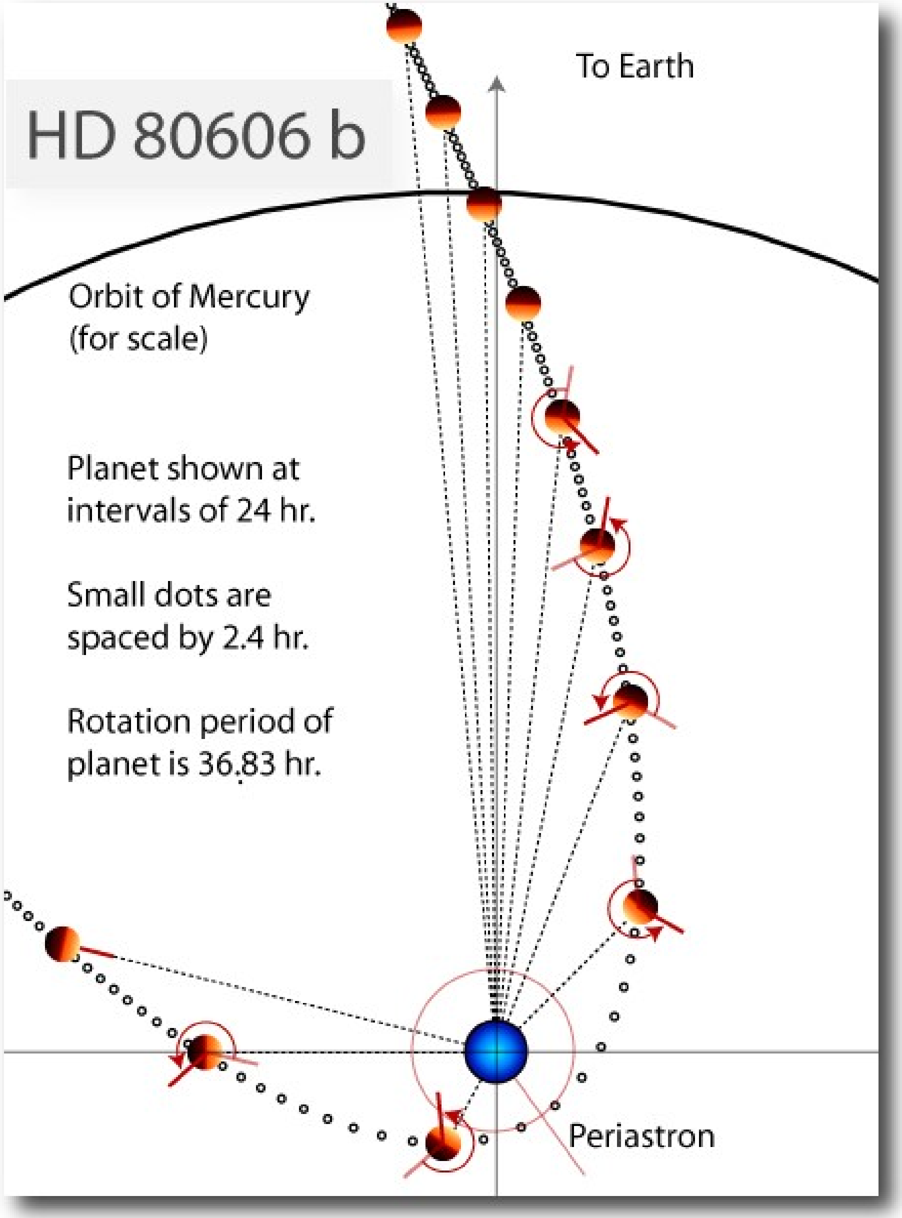
Highly Eccentric Planets

HD 80606b: $e=0.94$, $r_p= 0.03$ AU

HD 20782b: $e=0.92$, $r_p = 0.1$ AU



transitsearch.org



Laughlin; oklo.org

Constraining Orbital Migration

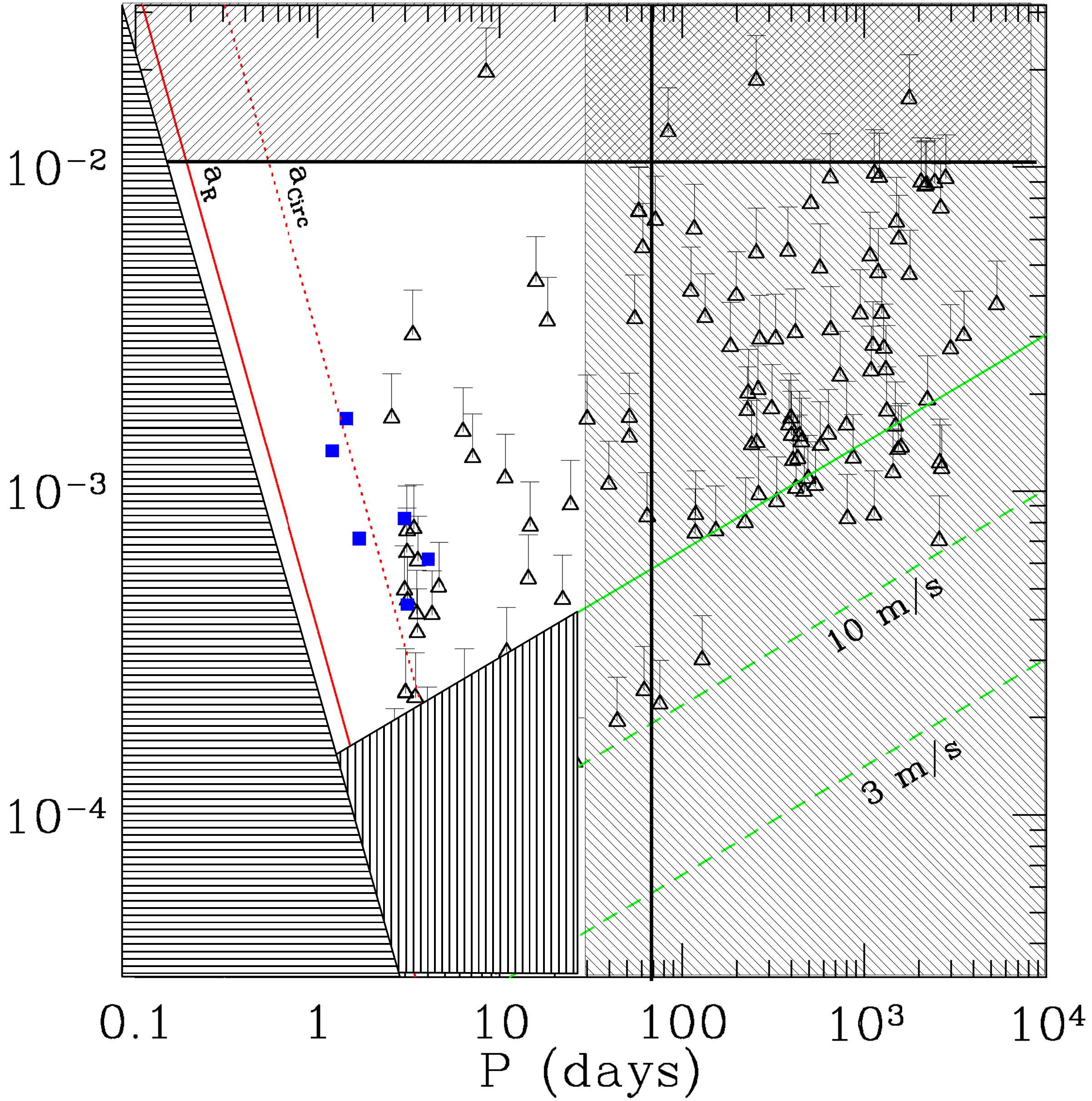
- What causes hot-Jupiters to migrate?
- What halts migration? Survival?
- Clues from observed distribution of Hot Jupiters?
- Early pile-up of Hot Jupiters at P = 3d
- Recent detections of planets with P < 3d
- What is the theoretical limit for survival?

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

Very Hot Jupiters

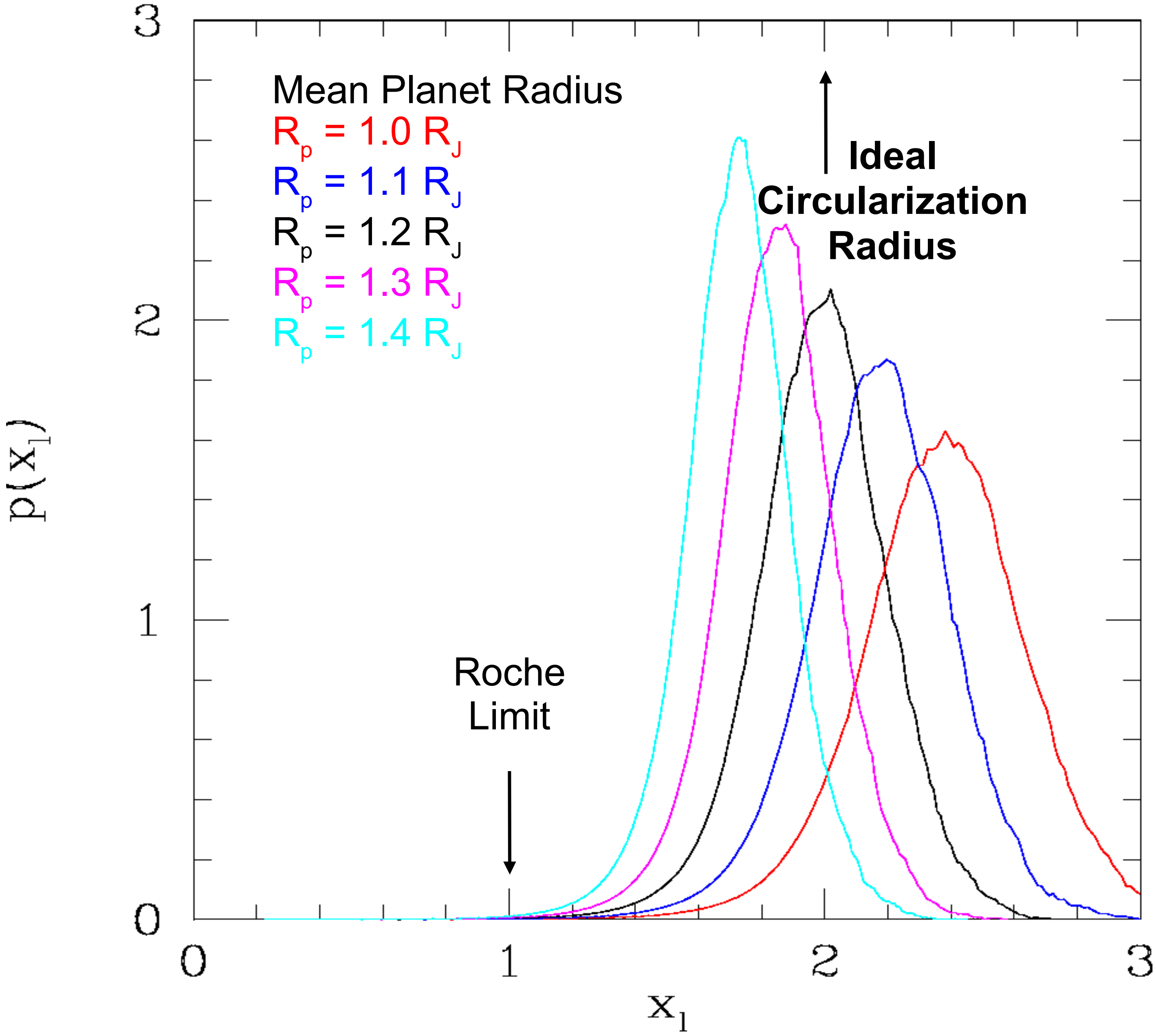


Assumptions:

- Inner edge proportional to Roche limit
- Power law mass-period distribution with upper limit of m =10 M_J
- Complete RV survey for K > 30 m/s & P < 30 d
- Transiting planets: Observed radii & inclinations
- Non-transiting planets Normal distribution for radii & isotropic orbits

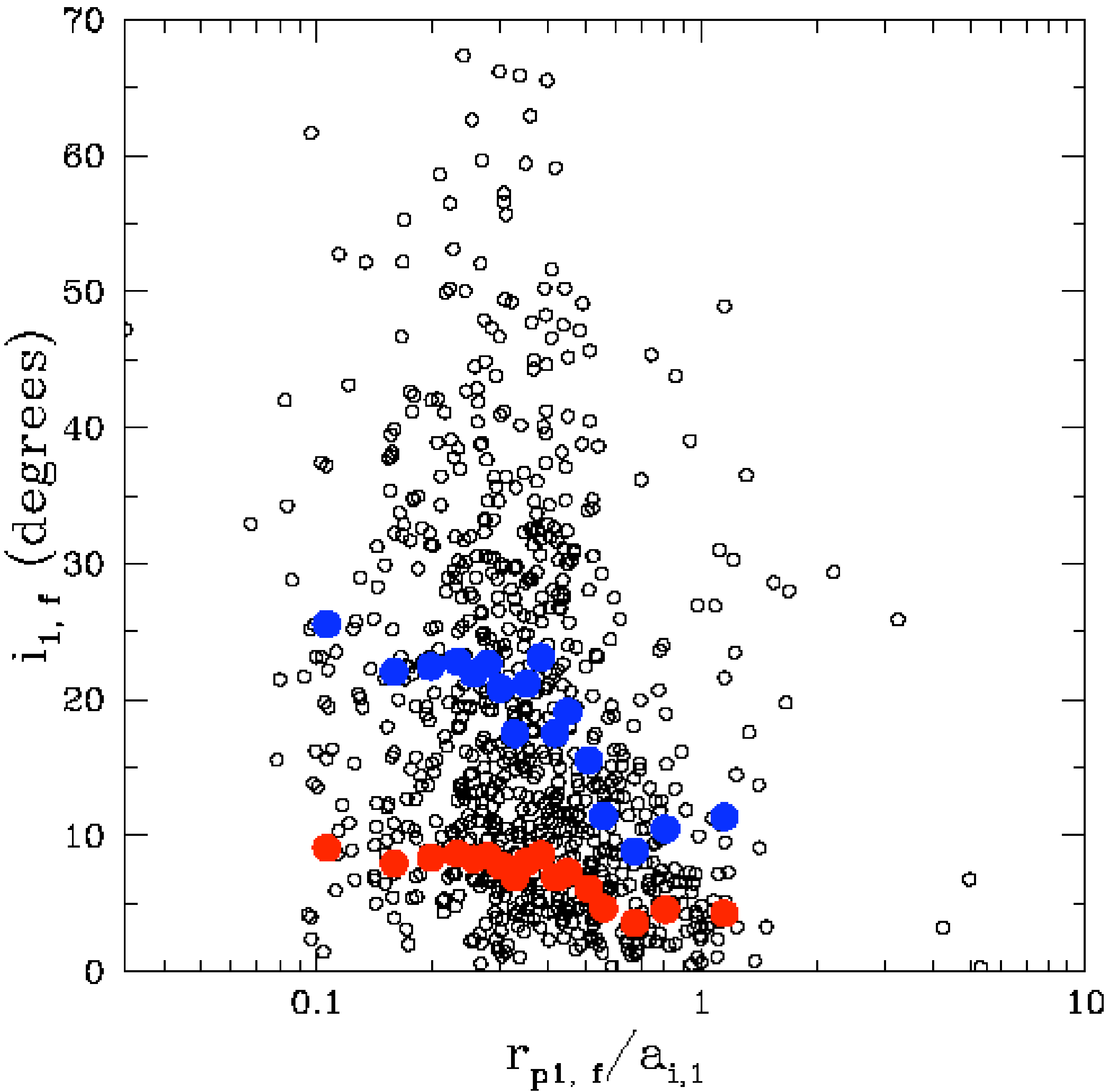
Ford & Rasio 2006

Location of Hot Jupiters' Inner Edge



Ford & Rasio 2006

Planet Scattering & Orbital Migration

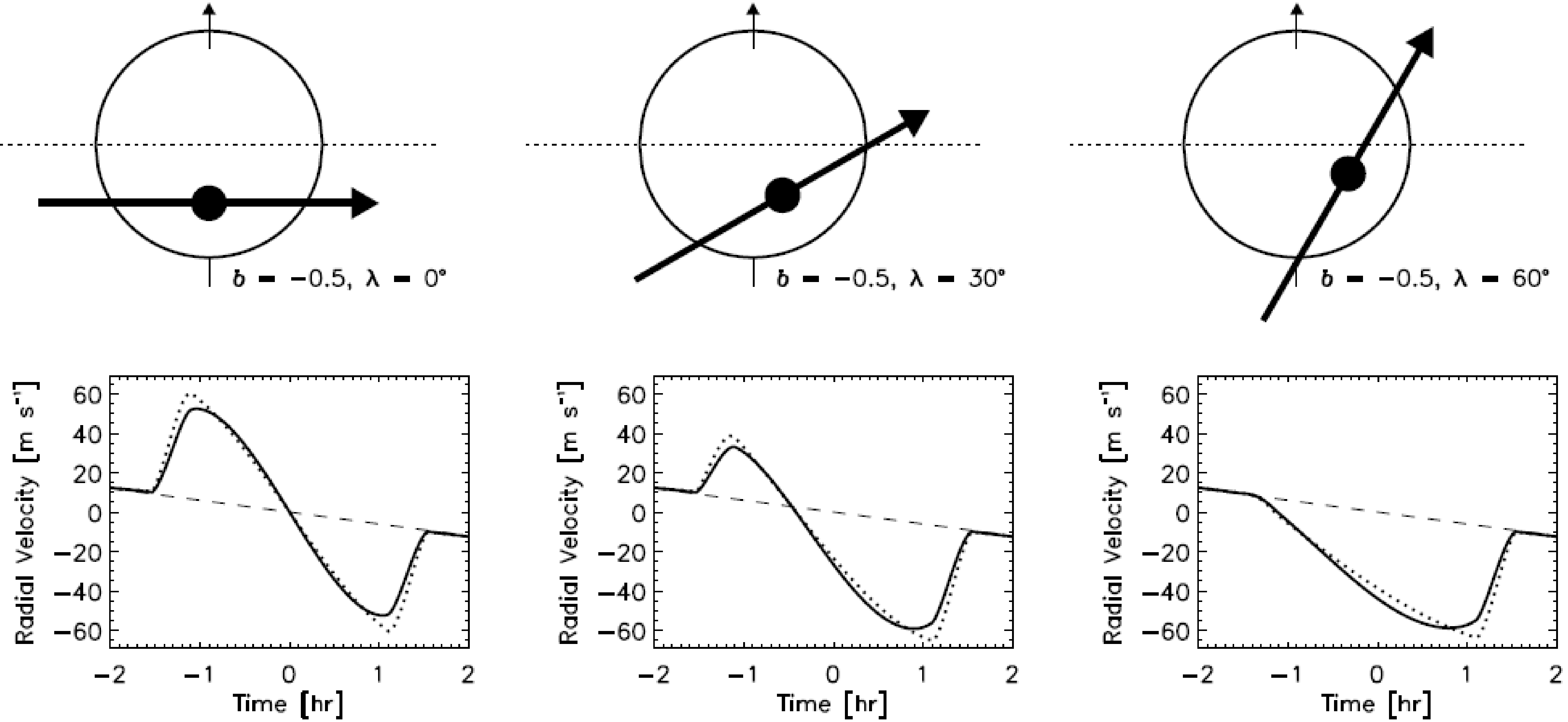


- Black: Final orbital elements from Individual simulations
- Blue: Mean final inner planet inclination
- Red: RMS final inner planet inclination

Chatterjee et al. 2007

Future Observational Tests

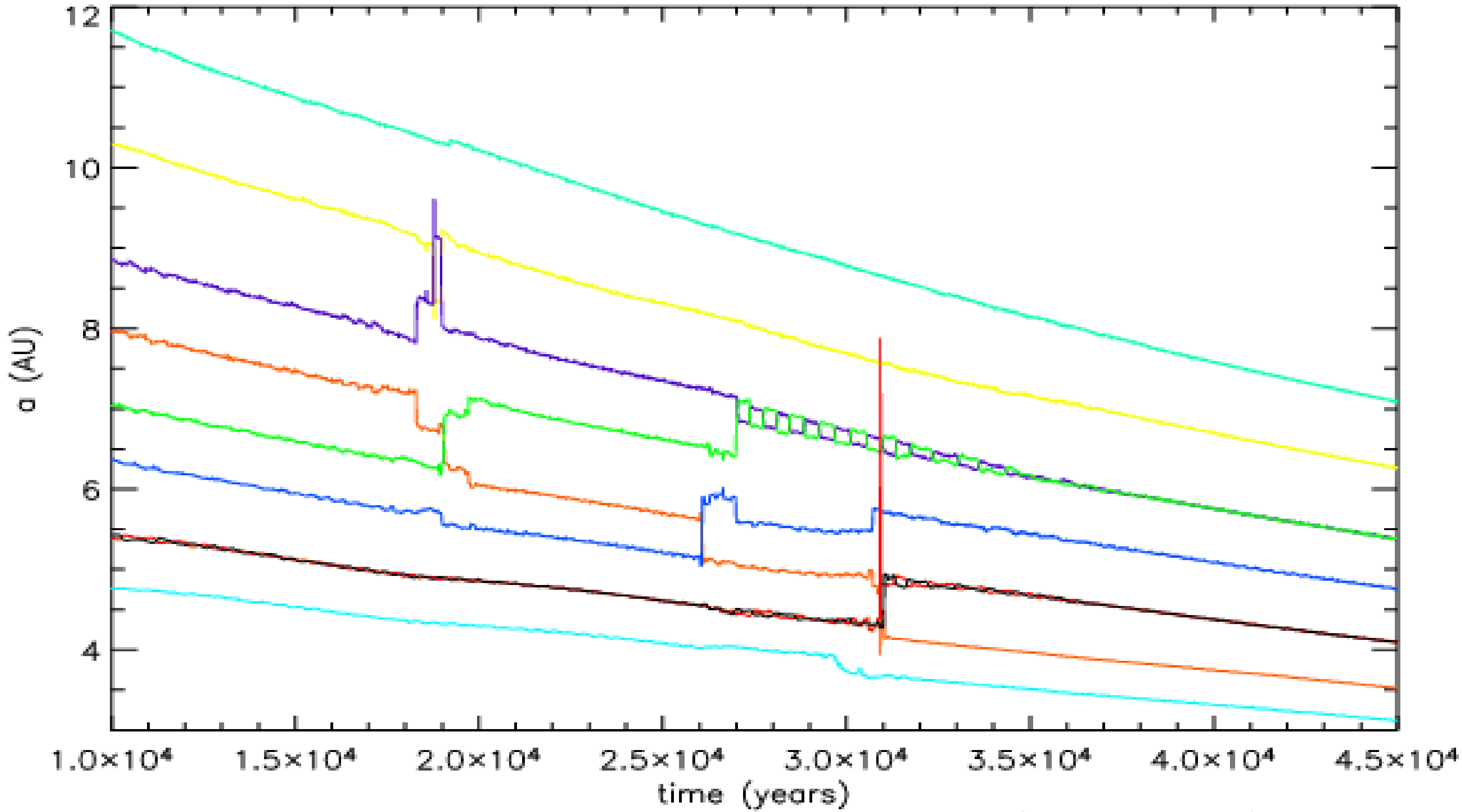
- Tidal dissipation in the planet rapidly damps eccentricity
- Search for planets with inclination excited by strong scattering



Gaudi & Winn 2006

Future Observational Tests

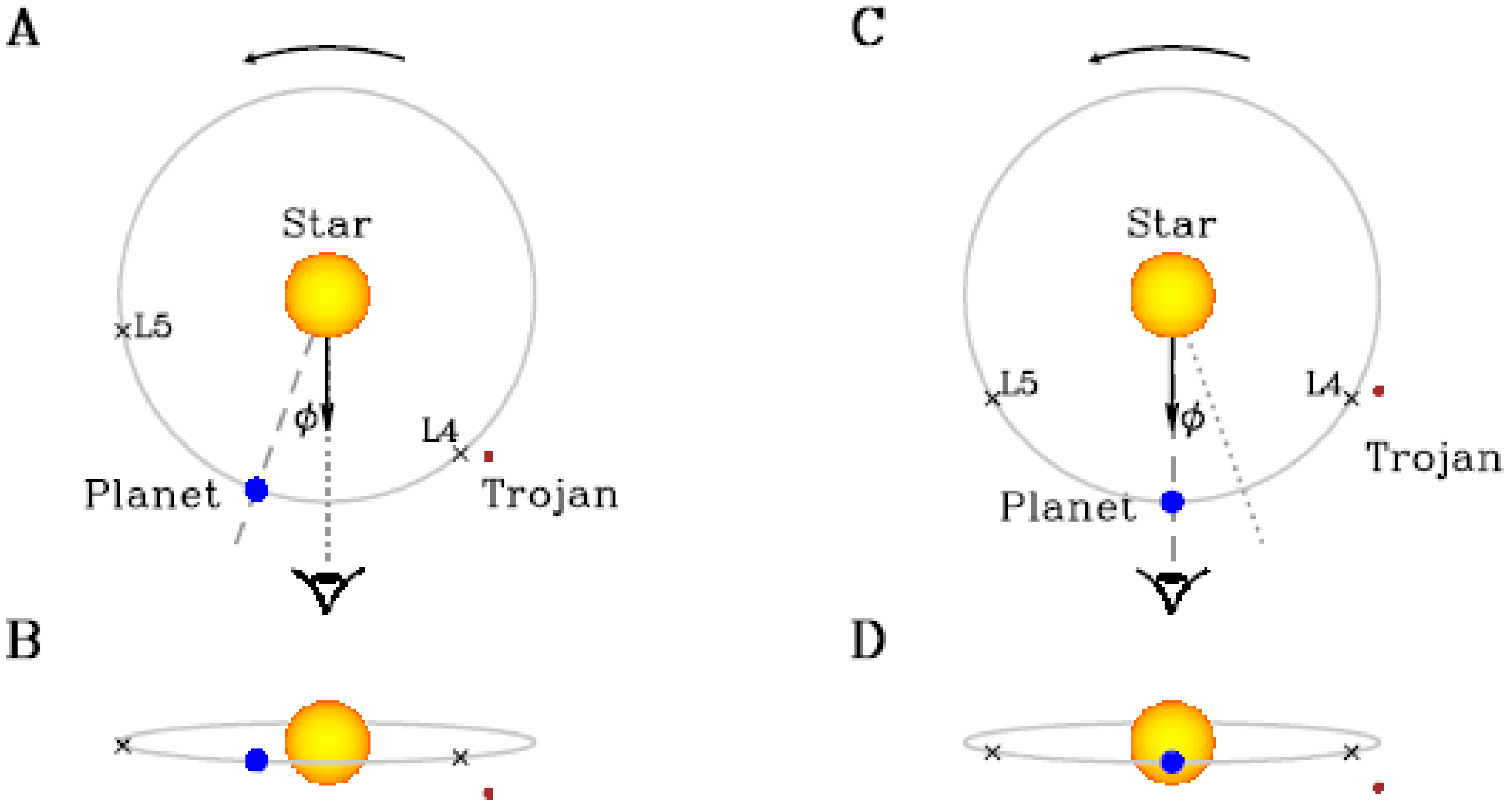
- Smooth migration can trap planets in resonances
- But planets in resonances can be hard to detect with RVs



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

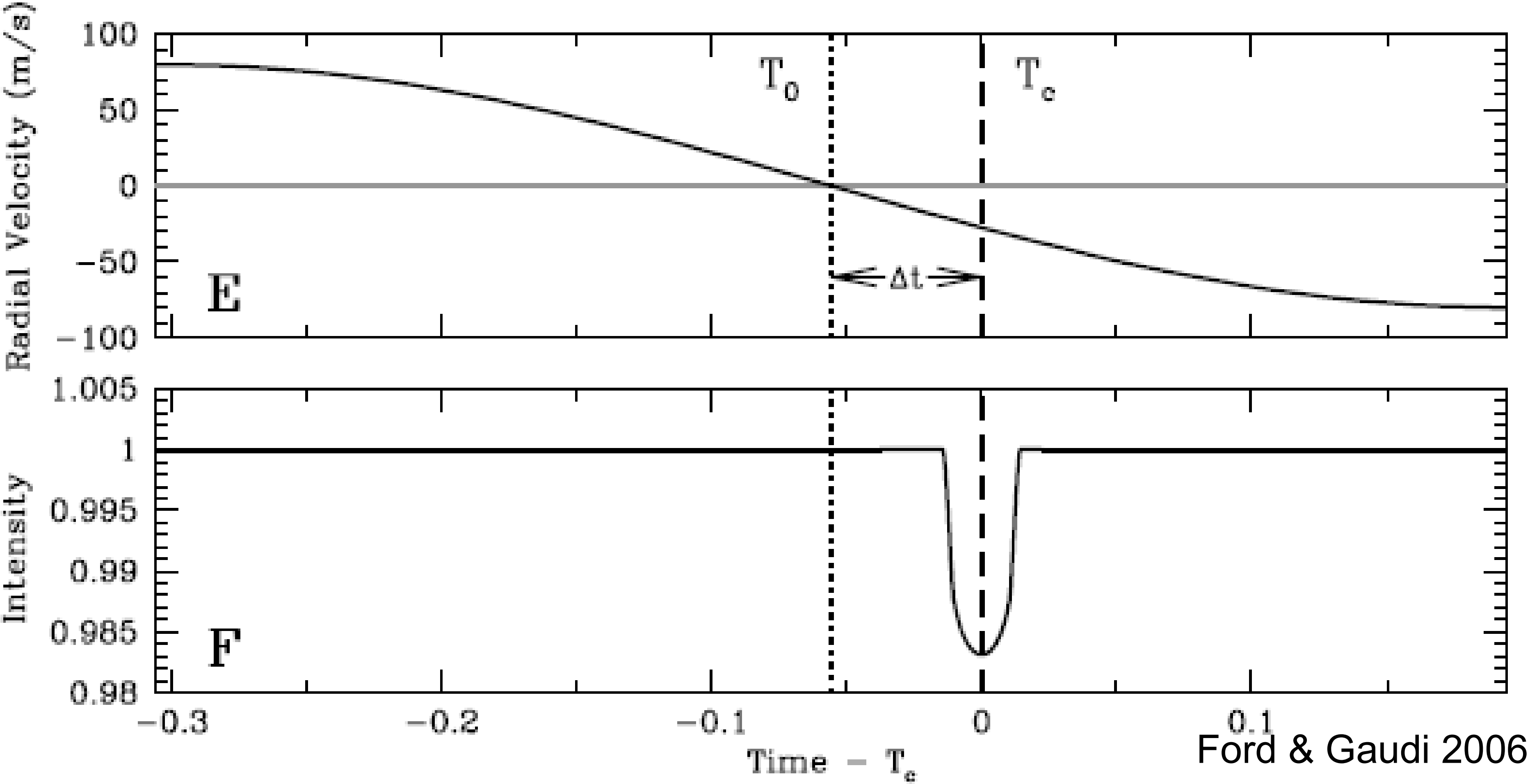


Ford & Gaudi 2006

Future Observational Tests

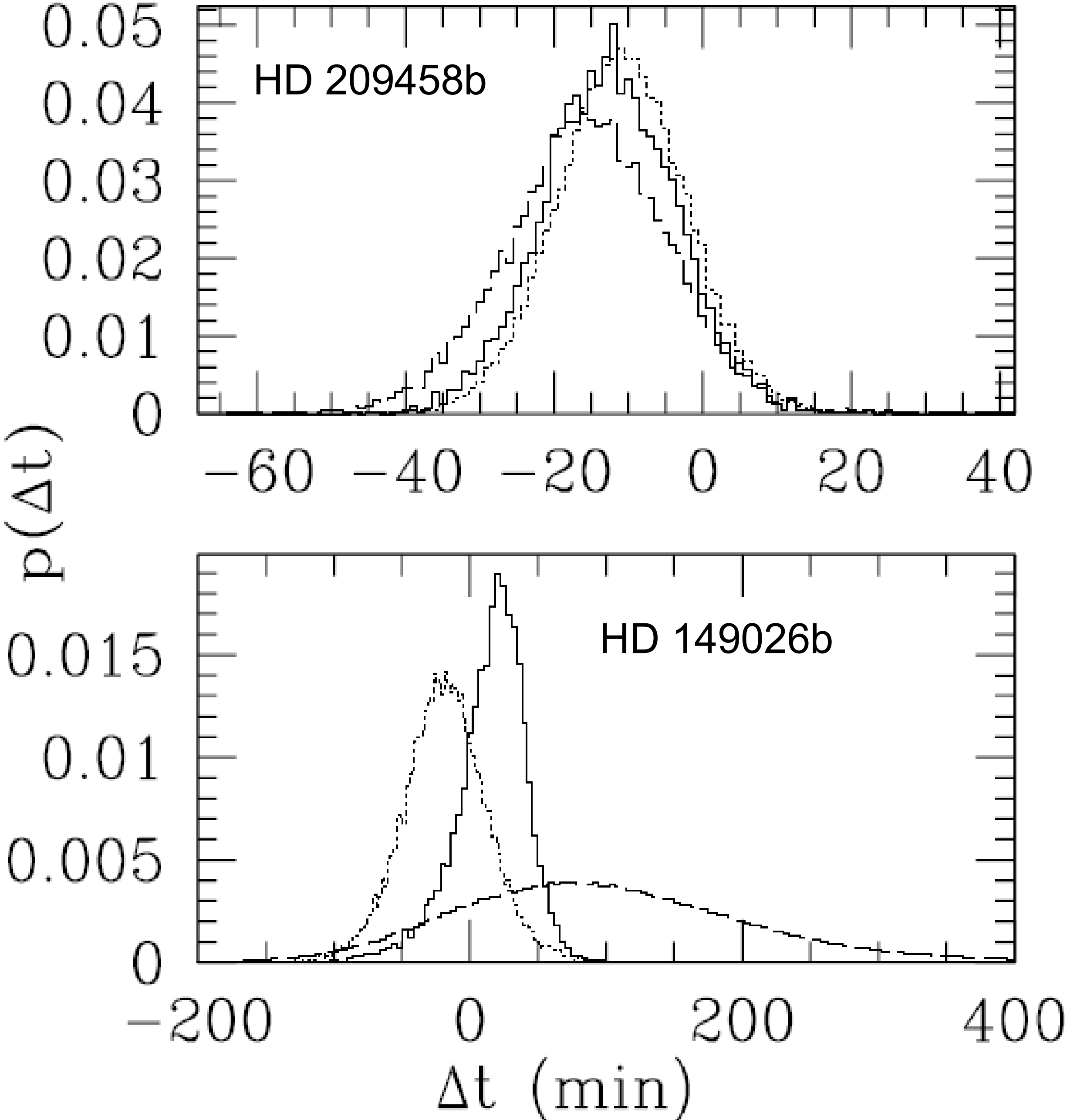
- Large constant offset between transit & RV null

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



Ford & Gaudi 2006

Existing Observational Constraints



Already significant upper limits for spin-orbit inclinations & masses of "Hot-Trojans":

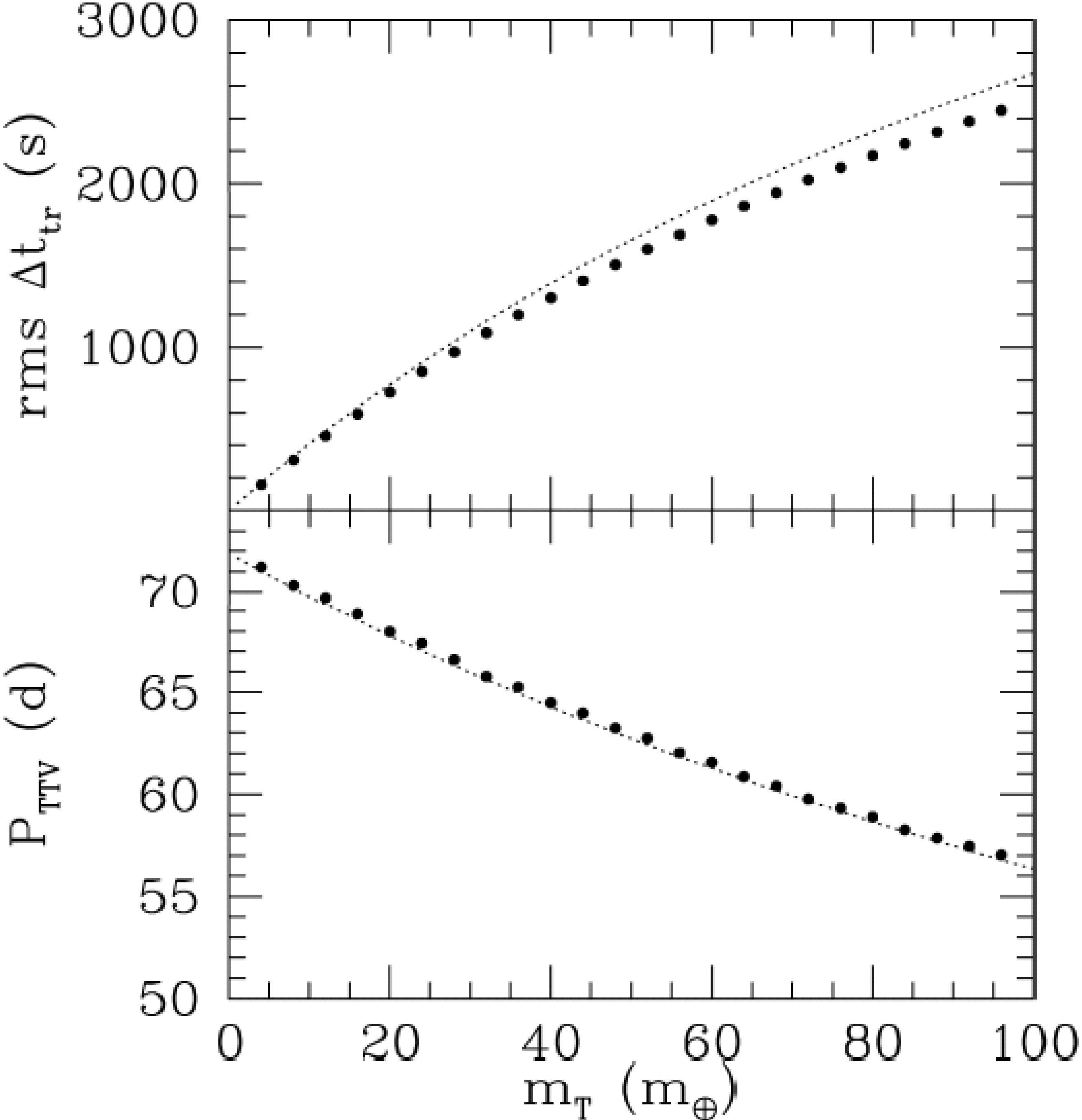
HD 209458b:
$m_{Trojan} < 13\ M_\oplus$ (99.9%)
i = 4.4°±1.4° (Winn et al. 2005)

HD 149025b:
$m_{Trojan} < 25\ M_\oplus$ (99.9%)

i = 11°±14° (Wolf et al. 2006)

Ford & Gaudi 2006

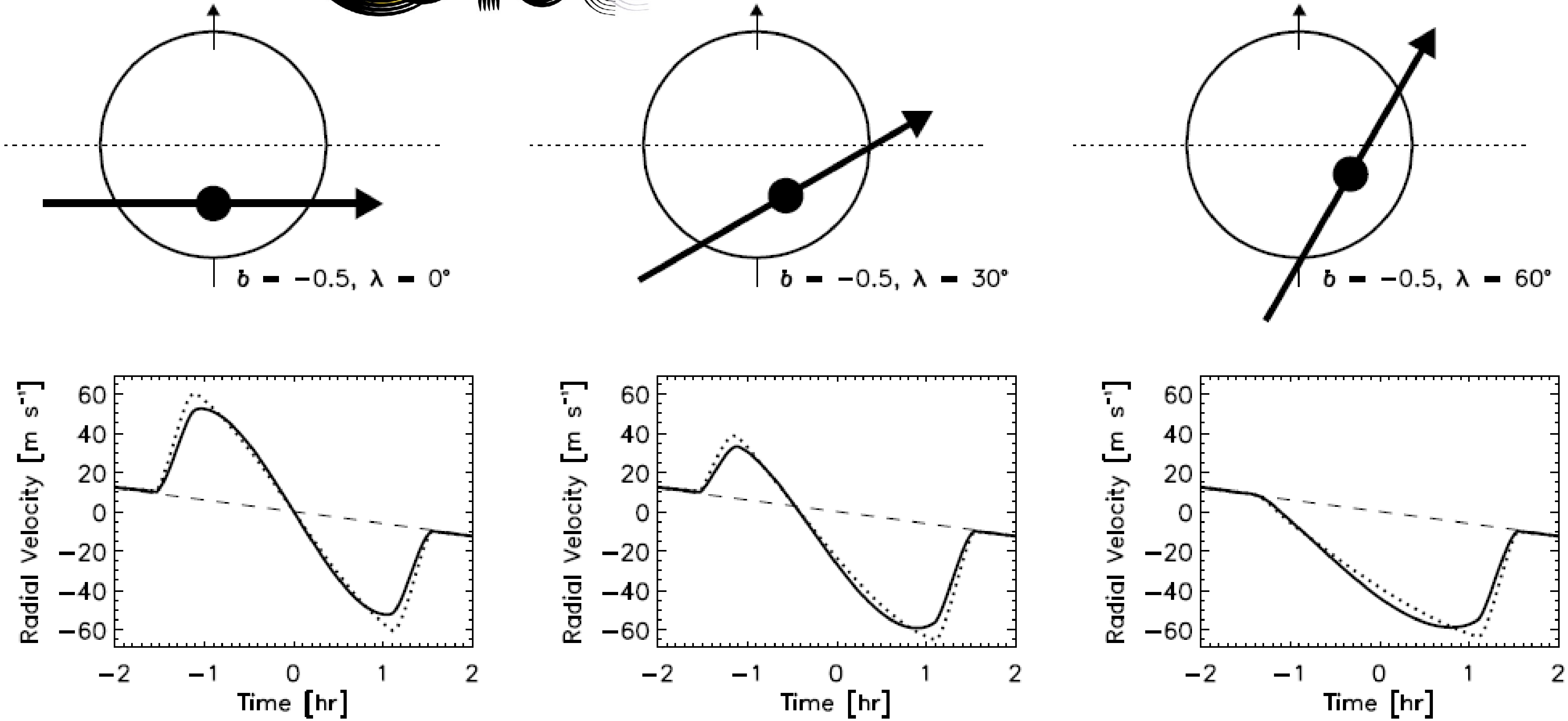
Transit Timing of Trojan Planets



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

Ford & Holman 2007

Transiting Planets



Gaudi & Winn 2006

Conclusions

- Many giant extrasolar planetary systems very different from our current solar system
- Our own solar system may have once contained giant planets on eccentric orbits
- Interactions of multiple planet systems can contain information about their orbital history
- Planet-planet scattering may frequent sculpt planetary systems
- Follow-up observations can search for additional planets and test orbital migration models