Terrestrial Planet Formation in Binary Star Systems

Kavli Institute for Theoretical Physics, UCSB
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Outline

Brief overview of planet formation around single stars

Motivation for this study

Planet formation in the α Centauri AB binary system

Planet formation around very close binary stars

Current status

Solar Nebula Theory

(Kant 1755, LaPlace 1796)

The Planets Formed in a Disk in Orbit About the Sun

Explains near coplanarity and circularity of planetary orbits

Disks are believed to form around most young stars

Theory: Collapse of rotating molecular cloud cores

Observations: Proplyds, β Pic, IR spectra of young stars

Predicts planets to be common, at least about single stars

Planetesimal Hypothesis

(Chamberlain 1895, Safronov 1969)

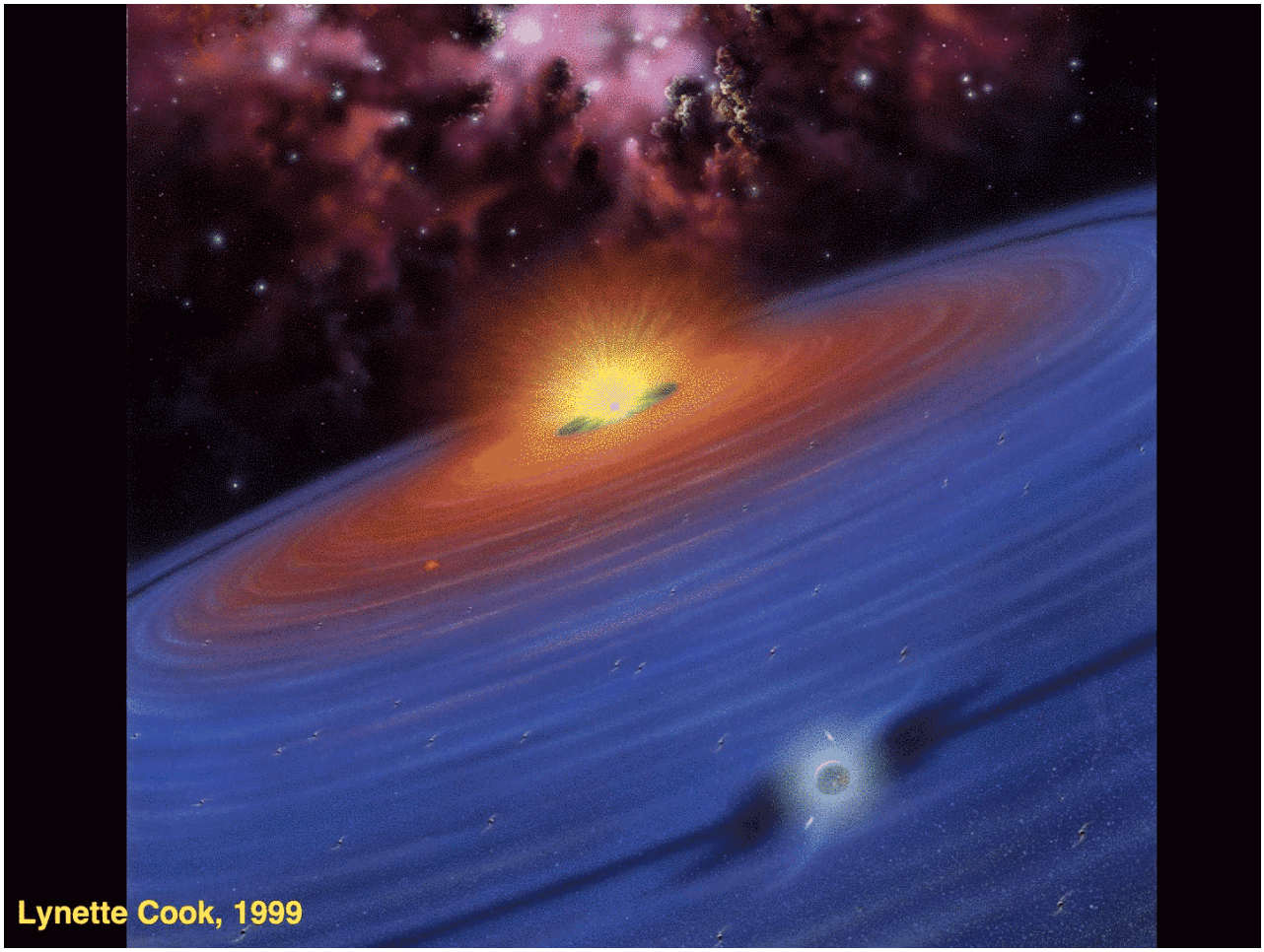
Planets Grow via Binary Accretion of Solid Bodies

Massive Giant Planets Gravitationally Trap H_2 + He Atmospheres

Explains planetary composition vs. mass

General; for planets, asteroids, comets, moons

Can account for Solar System; predicts diversity



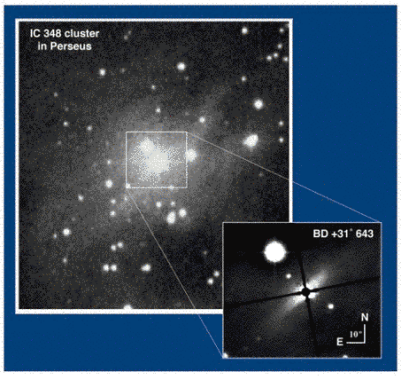
Motivation

> 50 % stars are in multiple star systems (Duquennoy & Mayor 1991)

19 planets known in multiple star systems (Eggenberger et al. 2004)

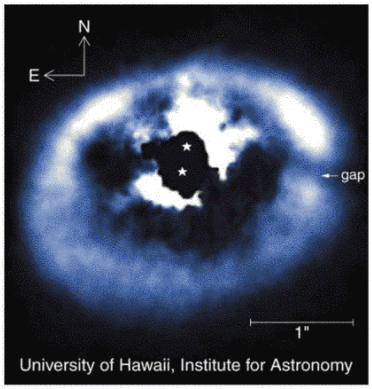
What is the effect of a **stellar companion** on the planet formation processes?

Dust Disks Around Young Binaries



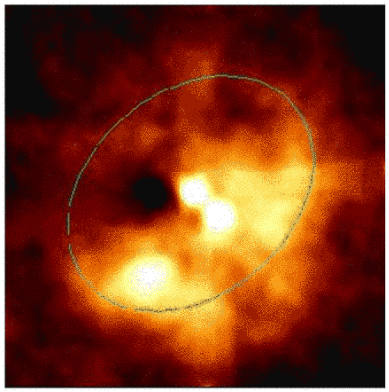
← BD +31 643

a_B (stellar semimajor axis) ~ 40 AU



UY Aur

↓ a_B ~ 130 AU



GG Tauri →

a_B ~ 35 AU

180 AU < r_{disk} < 260 AU

a_B < 1AU

GW Ori (disk mass m_D ~ 0.3 M_{sun})

DQ τ (m_D = 0.02 M_{sun})

UZ τ E (m_D = 0.06 M_{sun})

Planet Formation

Early stage

dust grains ⟶ planetesimals

~ μm ~1-10 km

Middle stage

planetesimals ⟶ planetary embryos

~10^3 km

Late stage

embryos ⟶ planets

Accretion in the Solar System

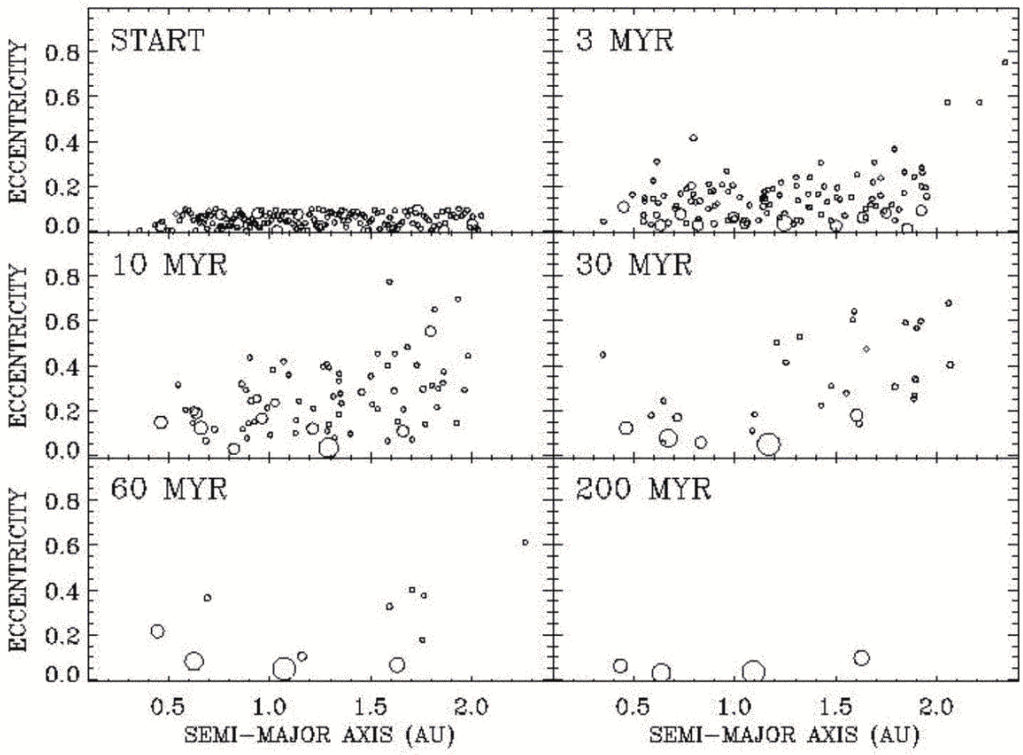
Chambers (2001) - Terrestrial planet accretion in the Solar System

- Bimodal mass distribution (0.3 - 2.0 AU):
  - 14 large embryos (0.0933 M_{Earth})
  - 140 smaller planetesimals (0.00933 M_{Earth})
  - Randomized e (0.0 - 0.01), i (0 - 0.5), ω, Ω, M
- Early formed Jupiter and Saturn
- *Mercury5* Hybrid-symplectic integrator (inelastic collisions)

~4 terrestrial planets formed within 200 Myr with above conditions

Terrestrial Planet Growth Sun-Jupiter-Saturn

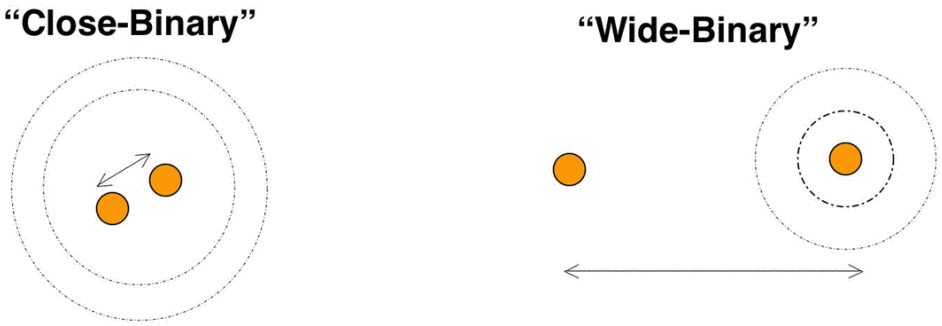
(Chambers 2001)



Methodology

Symplectic integrators: widely used algorithms to study long-term behavior of N-body systems with a dominant central mass

- Based on mapping method of Wisdom & Holman (1991)
  - order of magnitude faster than conventional integrators
  - no secular changes in energy of system
- Modified to include 2nd dominant mass (Chambers et al. 2002):



Tests of New Algorithms

1. Conservation of Jacobi constant

2. Massless particles orbiting α Cen A

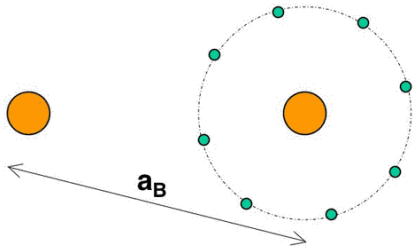
3. Integrations of Mercury through Jupiter with Saturn as 'binary companion'

4. Terrestrial planet accretion simulations with Jupiter as 'binary companion'

Test #1: Conservation of Jacobi Constant

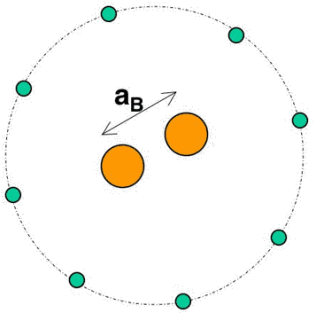
Wide-binary

a_B = 4 AU



Close-binary

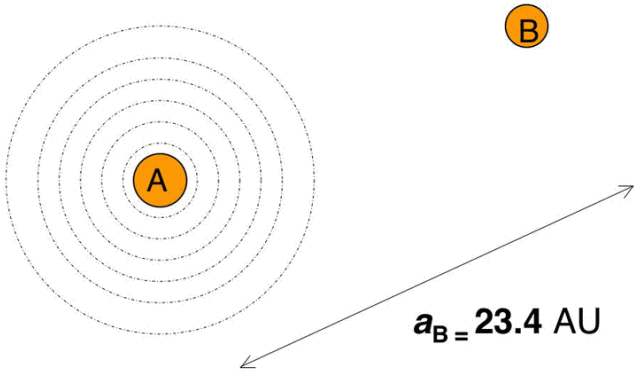
a_B = 0.25 AU



Test #2: Particles around α Centauri A

Reproduce the results of Weigert & Holman (1997)
(50 massless particles between 0.2 - 11.7 AU from α Cen A)

Compute a_c = critical semimajor axis using widebinary code



Test #3: Six Solar System Planets

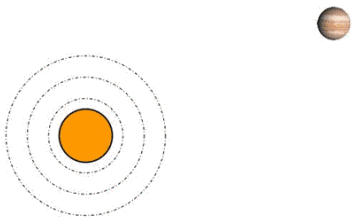
- Integration of Mercury ~~Jupiter~~ with Saturn = 'binary' for 1 Myr

Using 3 symplectic integrators:

'Wide-binary'
Standard code #1 ('Symba')
Standard code #2 ('Hybrid')

- Compare evolution of planets' eccentricities with very accurate (but slow) integrator (RADAU)

Test #4: Terrestrial Planet Accretion



- ~ 150 Embryos around Sun
  Jupiter = 'binary'

- 3 simulations:

  - Standard 'Hybrid' code

  - New binary code

  - New binary code with one embryo (near 1AU) shifted along its orbit by 1 meter (to test relative importance of chaos vs. different integrators)

Circumstellar Disk

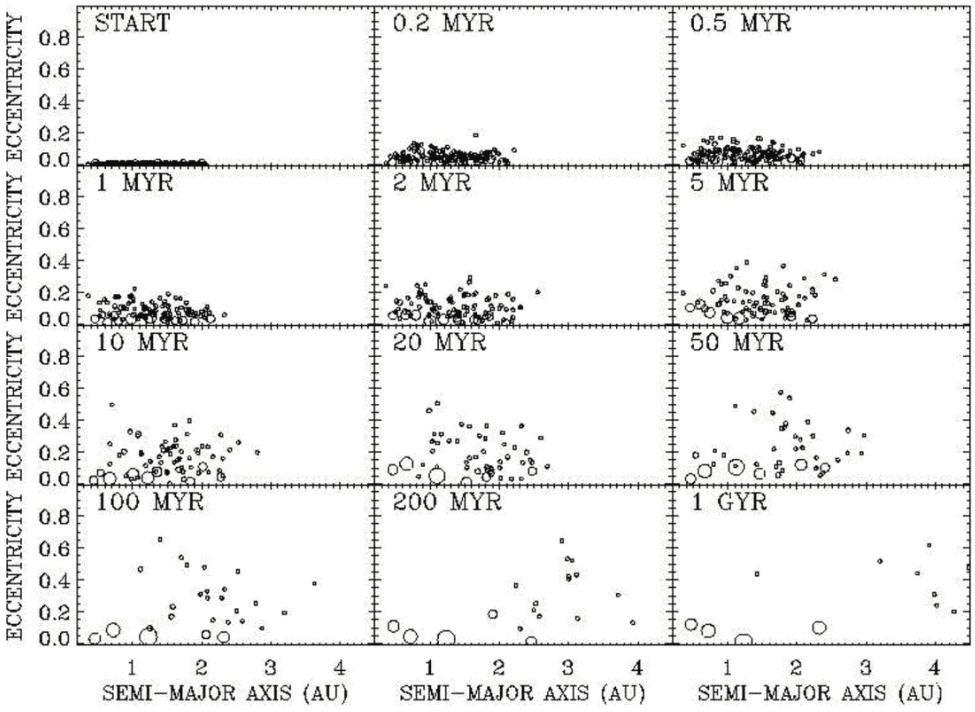
Disk mass distribution adopted from Chambers (2001) accretion simulations in the Sun-Jupiter-Saturn system

#1 - Bimodal mass distribution
- 14 large embryos (0.0933 M_{Earth})
- 140 smaller planetesimals (0.00933 M_{Earth})
- a = 0.3 - 2.0 AU
- Random e (0.0 - 0.01), i (0 - 0.5°), ω, Ω, M

To examine effects of chaos, each simulation was performed 2 - 4 times with:

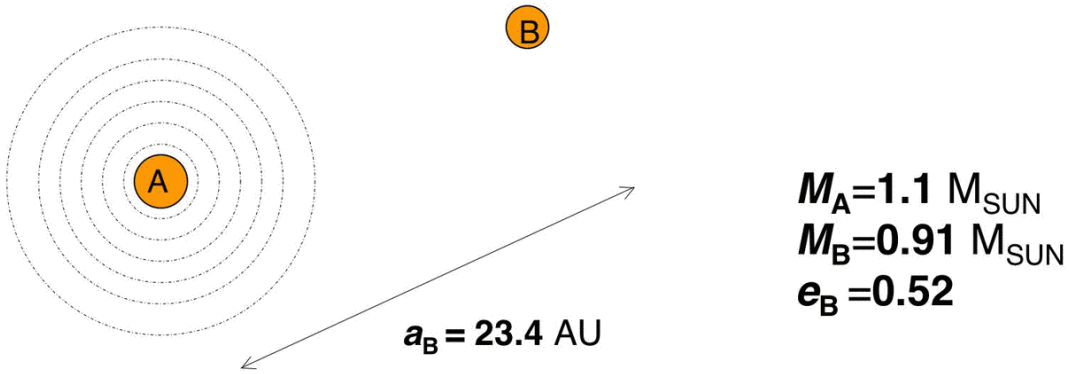
#2 - Bimodal mass distribution (as above)
- 1, 2 or 3 meter shift in mean anomaly of one planetesimal

RUN 1 ($i = 0°$) Single Star, no giant planets



Stable Orbits in the α Cen System

Weigert & Holman (1997) showed that massless particles placed on circular orbits in the binary midplane within 3 AU of α Cen A remain on bound orbits for at least 2.5 Myr.



Planetesimal Accretion in α Cen

Marzari & Scholl (2000) - Planetesimal accretion in α Cen

• ~ 5000 planetesimals (0.8 - 3.0 AU) coplanar with binary orbital plane (bidimensional)

• inelastic collisions and gas drag forces, no gravitational interactions among planetesimals

• 4th-order Runge-Kutta integrator

Planetesimal accretion possible within 2 AU of α Cen A

α Cen - Initial Conditions

- Bimodal mass distribution around α Cen A
- Binary star inclined at $i = 0,\ 15,\ 30,\ \text{or } 60^\circ$
  argument of periastron $\omega = 0 \text{ or } 90^\circ$
- Identical systems with one planetesimal ~1 AU shifted by 1 m
- Widebinary symplectic integrator (inelastic collisions)
- 200 Myr - 1 Gyr integrations

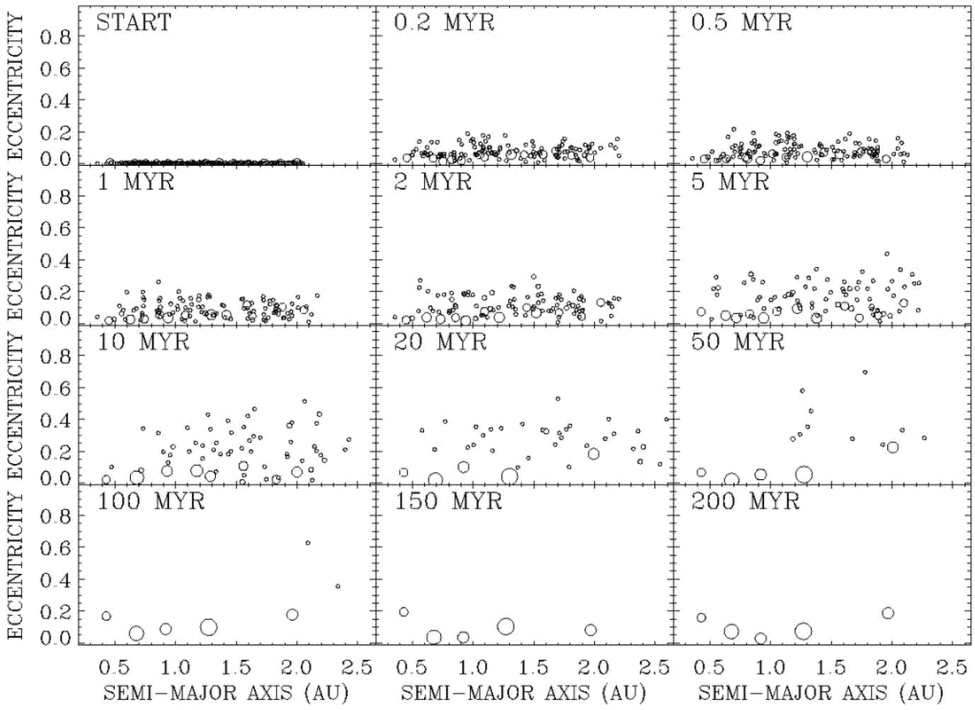
α Centauri System

G2 star
M = **1.1** Msun

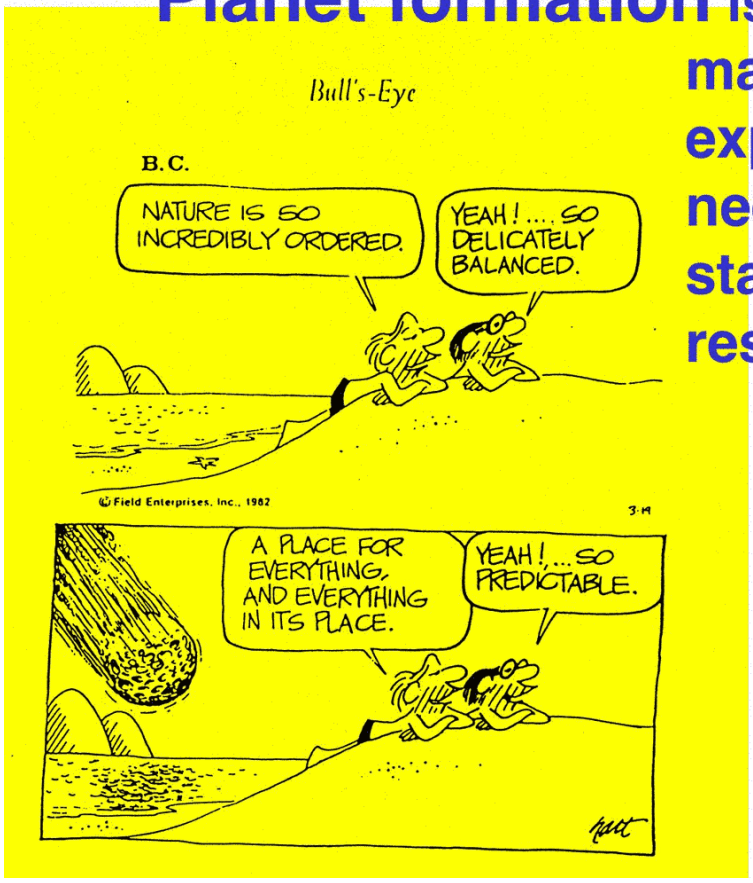
K1 star
M = **0.91** Msun

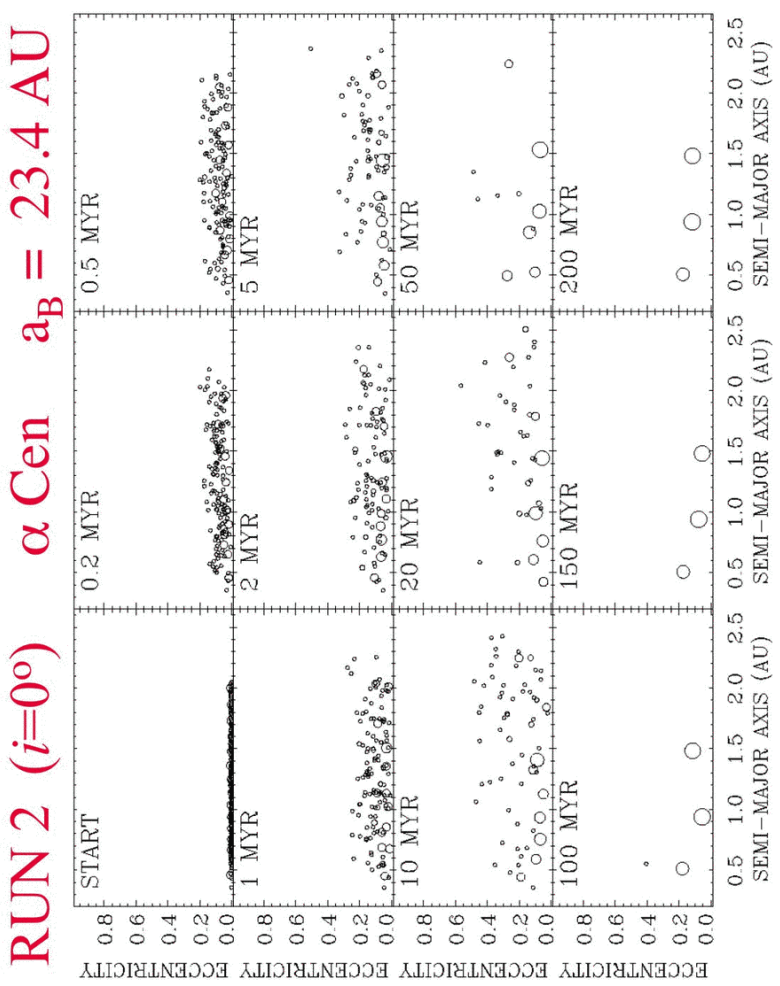
- Disk inclined to binary orbit:
  $i = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 180^\circ$
- Integration time = 200 Myr - 1 Gyr
- Time-step = 1 - 7 days

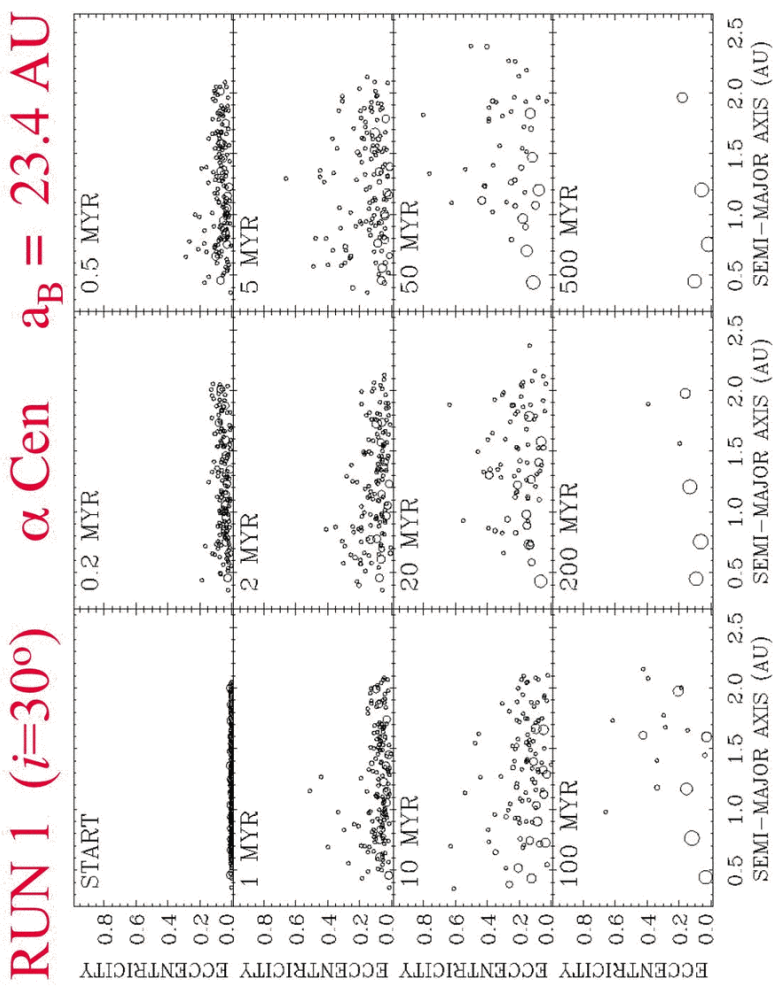
RUN 1 (i=0°) α Cen a_B = 23.4 AU

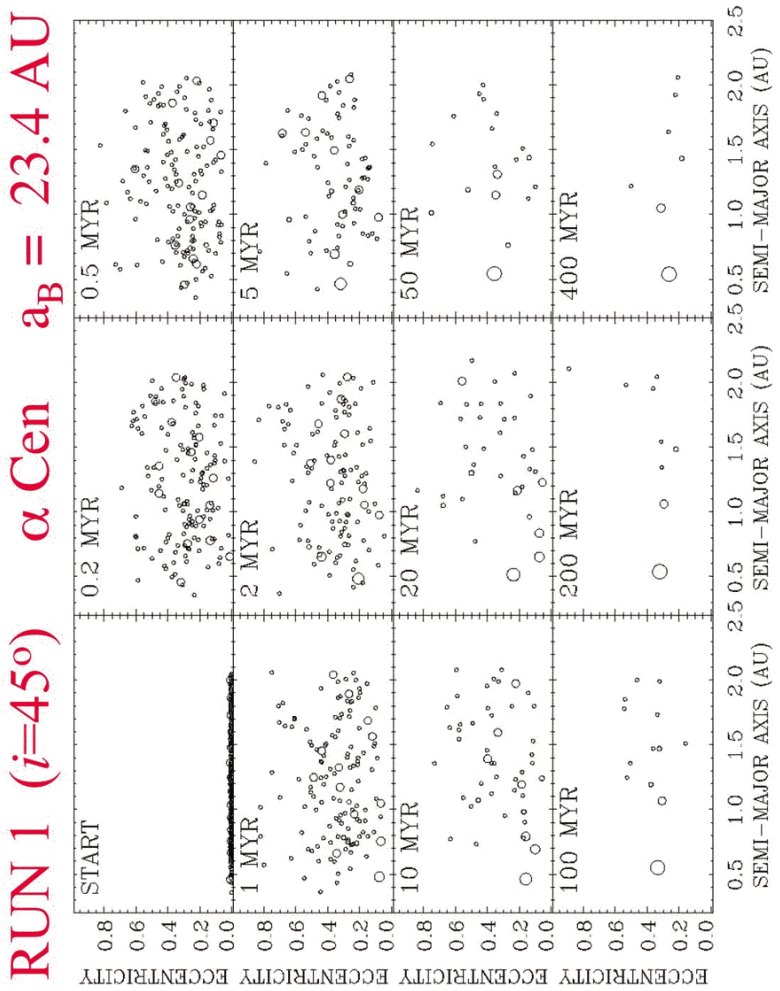


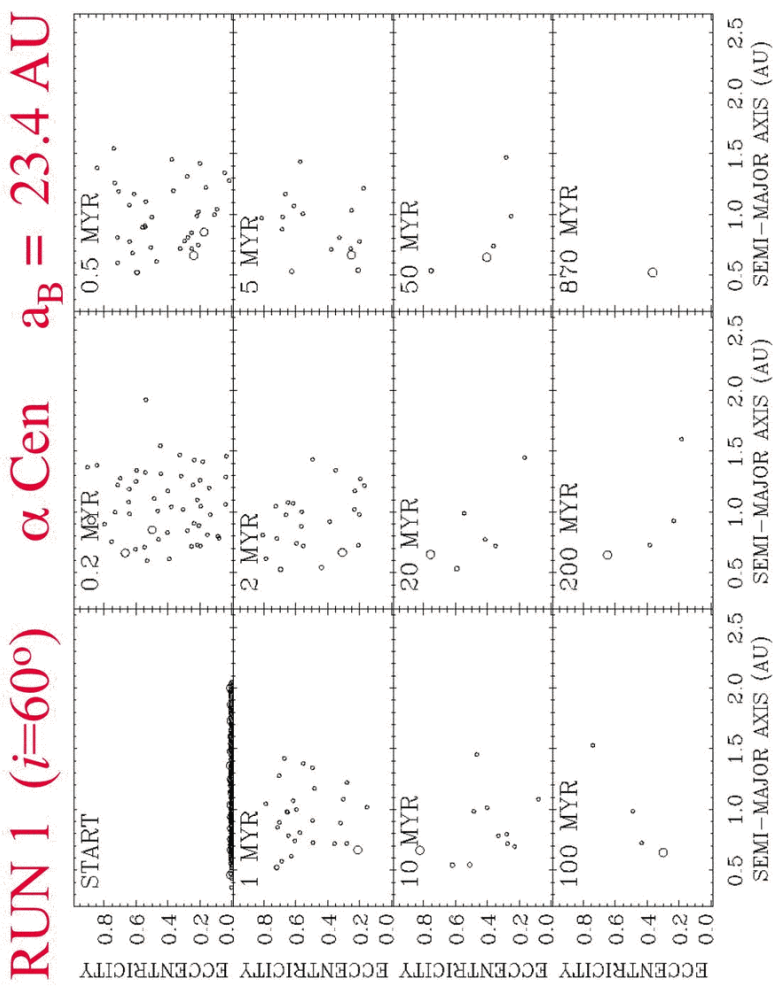
Planet formation is $c^h a_{ot}{}^i c$, so many numerical experiments are needed to get statistically valid results.



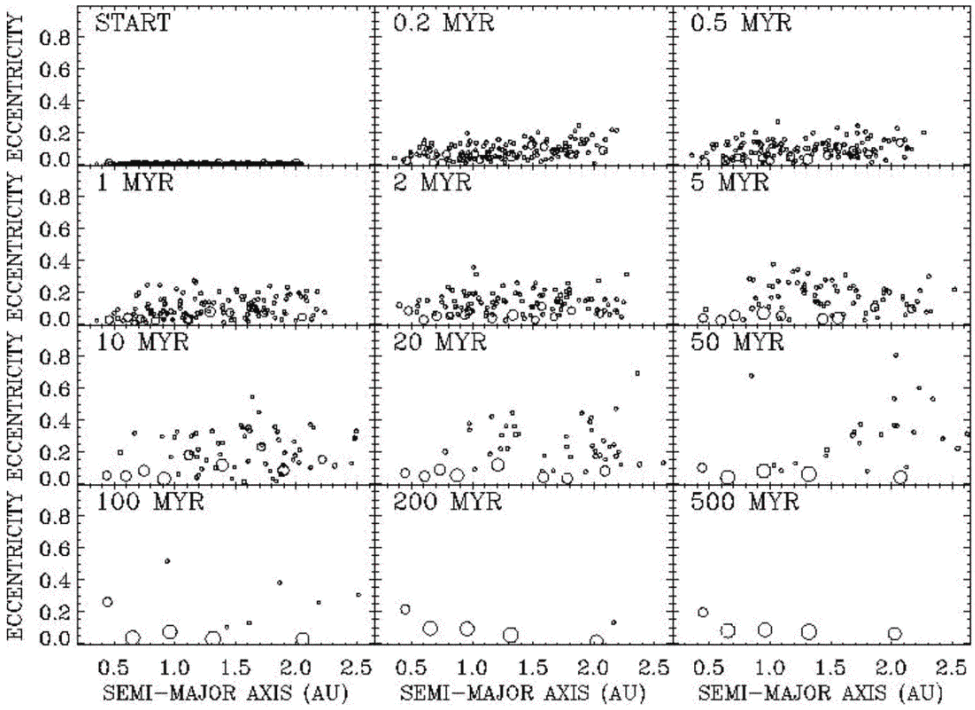

RUN 2 (i=0°) α Cen a_B = 23.4 AU
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMI−MAJOR AXIS (AU)


RUN 1 (i=30°) α Cen a_B = 23.4 AU
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
500 MYR
ECCENTRICITY
SEMI−MAJOR AXIS (AU)

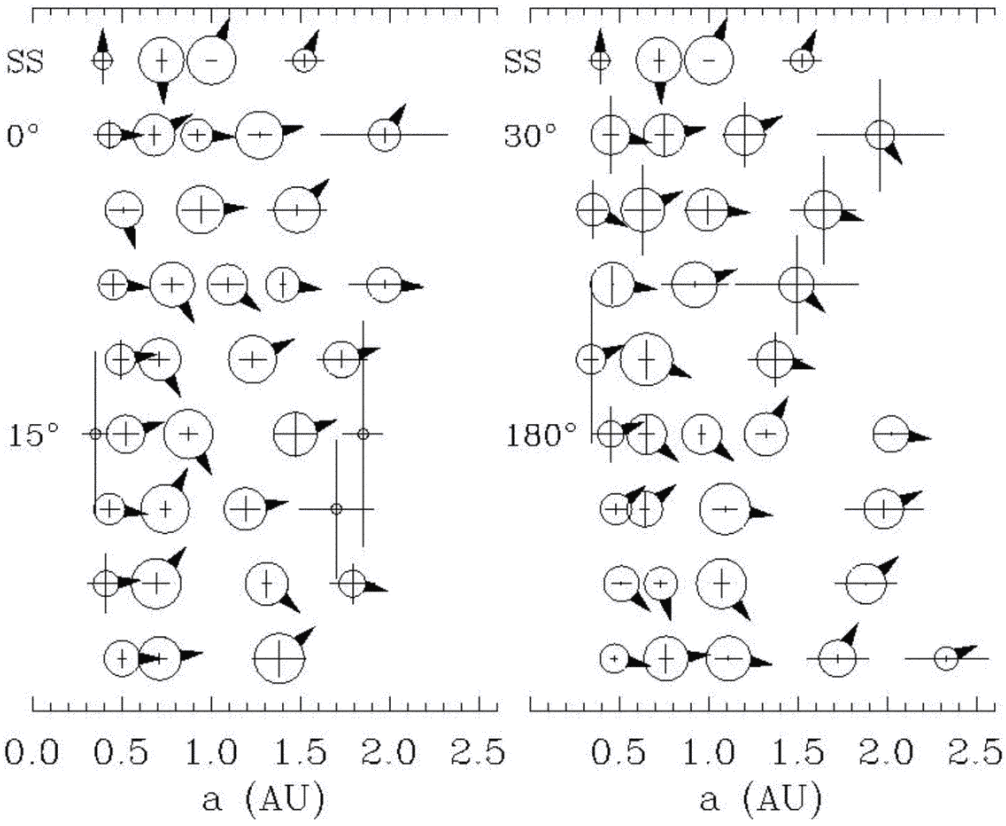

RUN 1 (i=45°) α Cen a_B = 23.4 AU
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
400 MYR
ECCENTRICITY
SEMI-MAJOR AXIS (AU)


RUN 1 (i=60°) α Cen a_B = 23.4 AU
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
870 MYR
ECCENTRICITY
SEMI-MAJOR AXIS (AU)

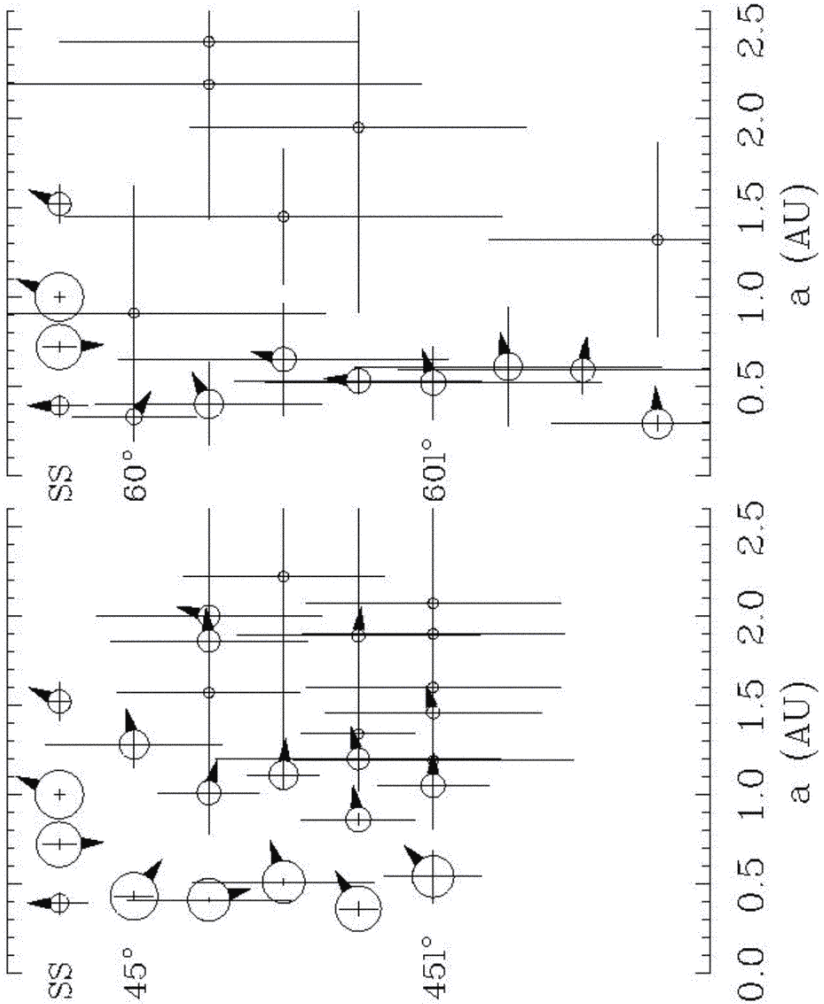
RUN 1 (i=180°) α Cen a_B = 23.4 AU



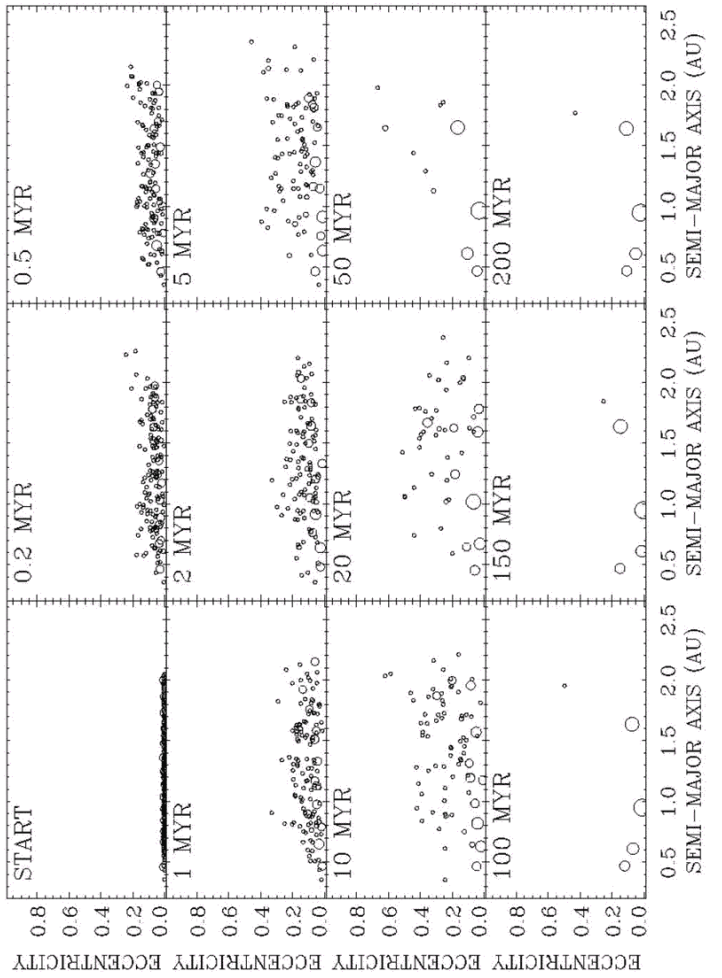
Final Terrestrial Planets Orbiting α Cen A



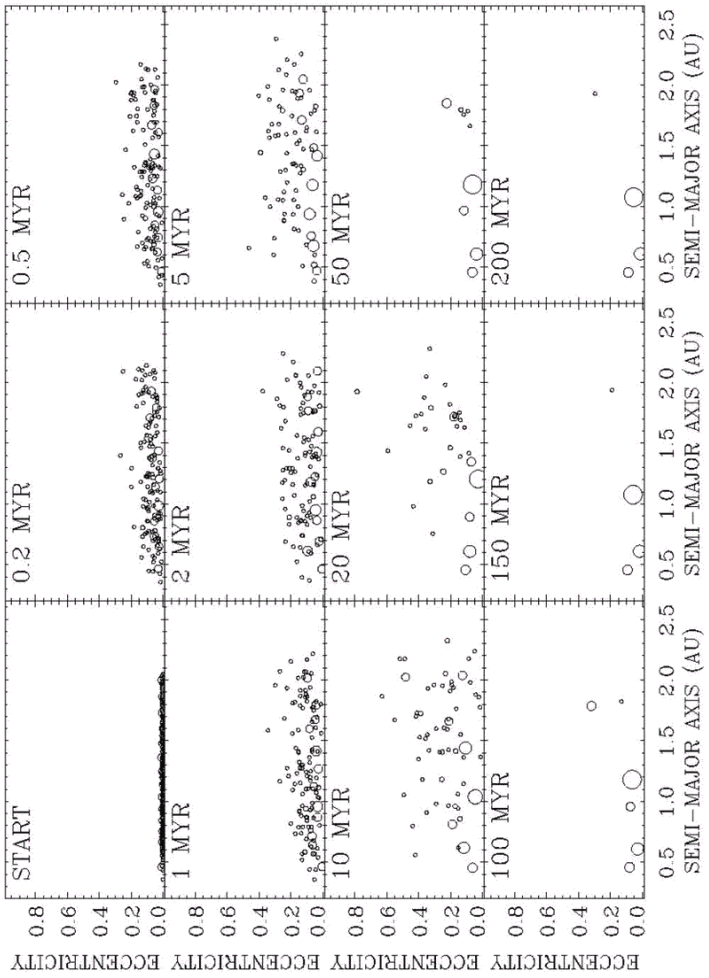
Final Planets Orbiting α Cen A (high *i* disks)



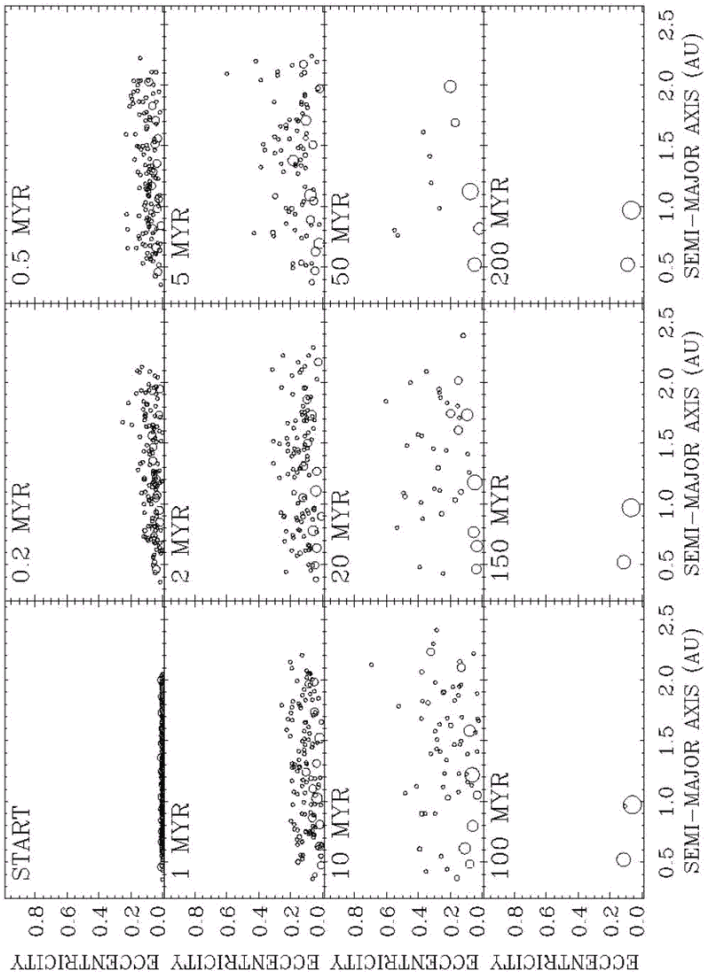
α Centauri B, Run 1 ($i = 0$)



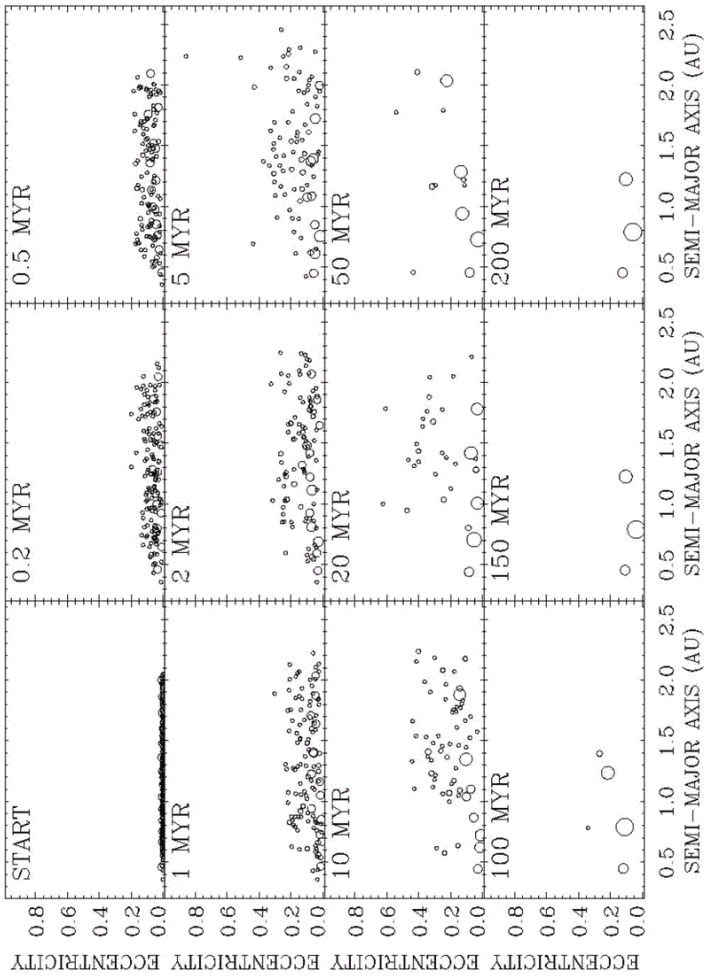
α Centauri B, Run 2



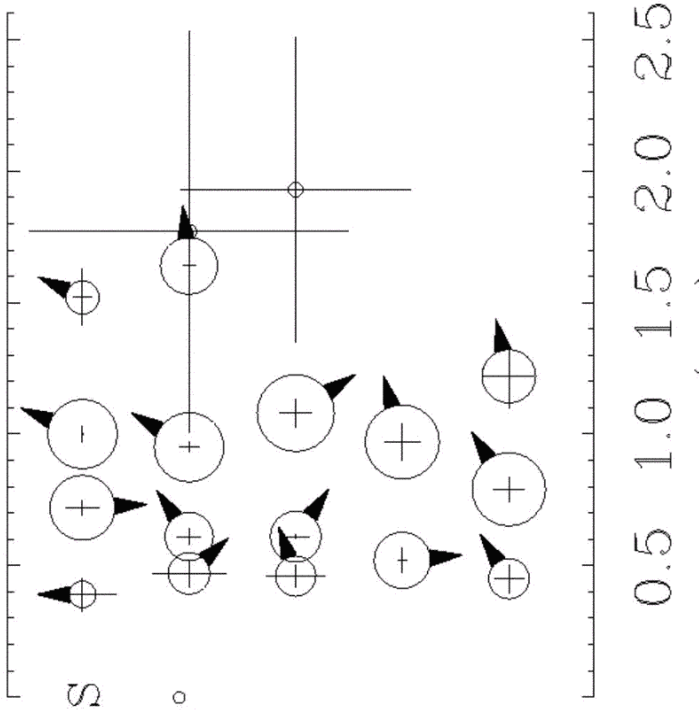
α Centauri B, Run 3



α Centauri B, Run 4



Final Planets Orbiting α Cen B



Results: α Centauri System

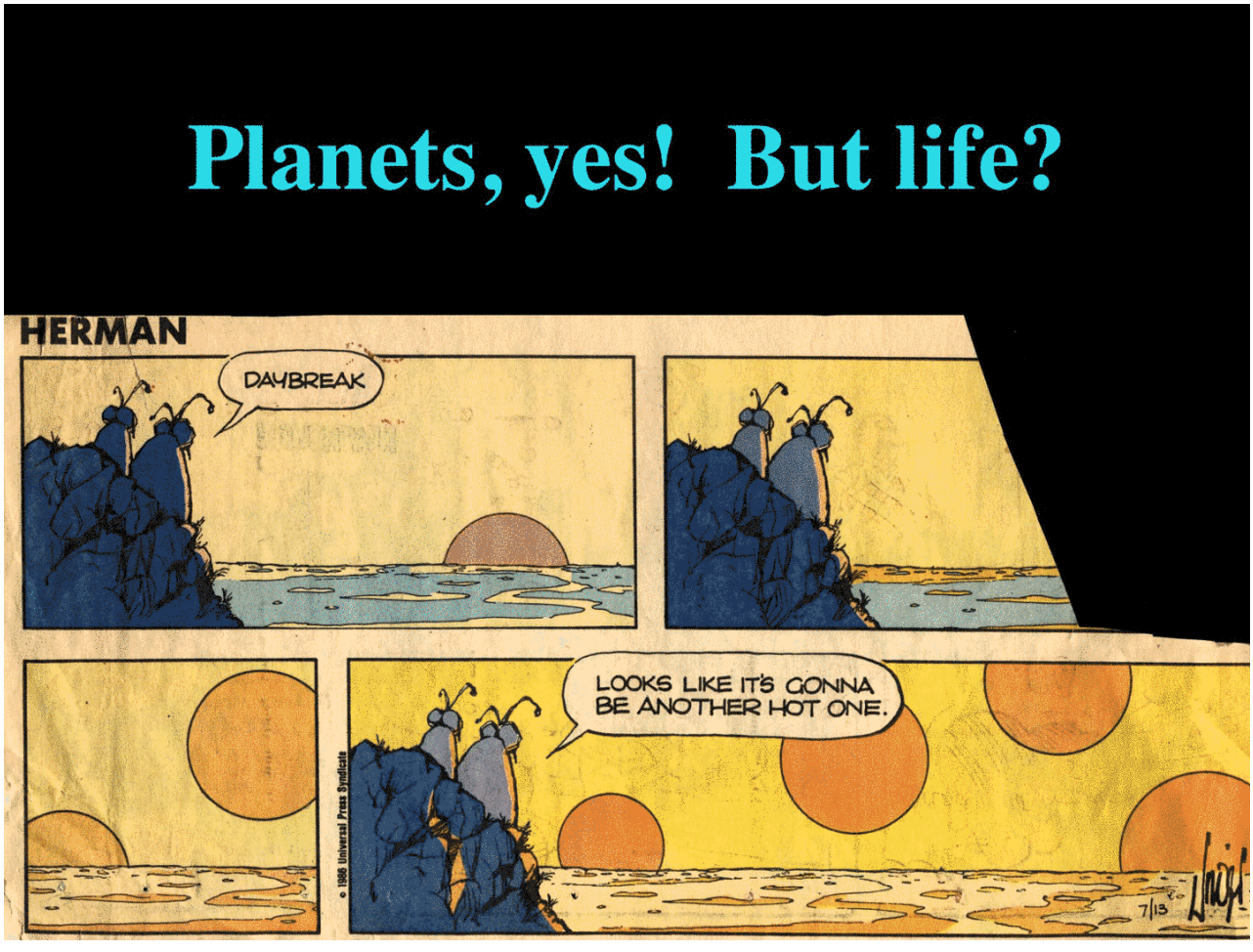
Planetesimal disk near plane of binary orbit: $i_{disk} \leq 30°$

- 3 - 5 terrestrial planets formed
- < 25% of initial disk mass lost
- similar to our Solar System

Accretion much less efficient as i_{disk} increased:

$i_{disk} = 45°$: ~ 60% of initial disk mass lost
$i_{disk} = 60°$: ~ 98% of initial disk mass lost

Terrestrial planets may have formed around α Cen A and/or around α Cen B, despite the proximity of these two stars.

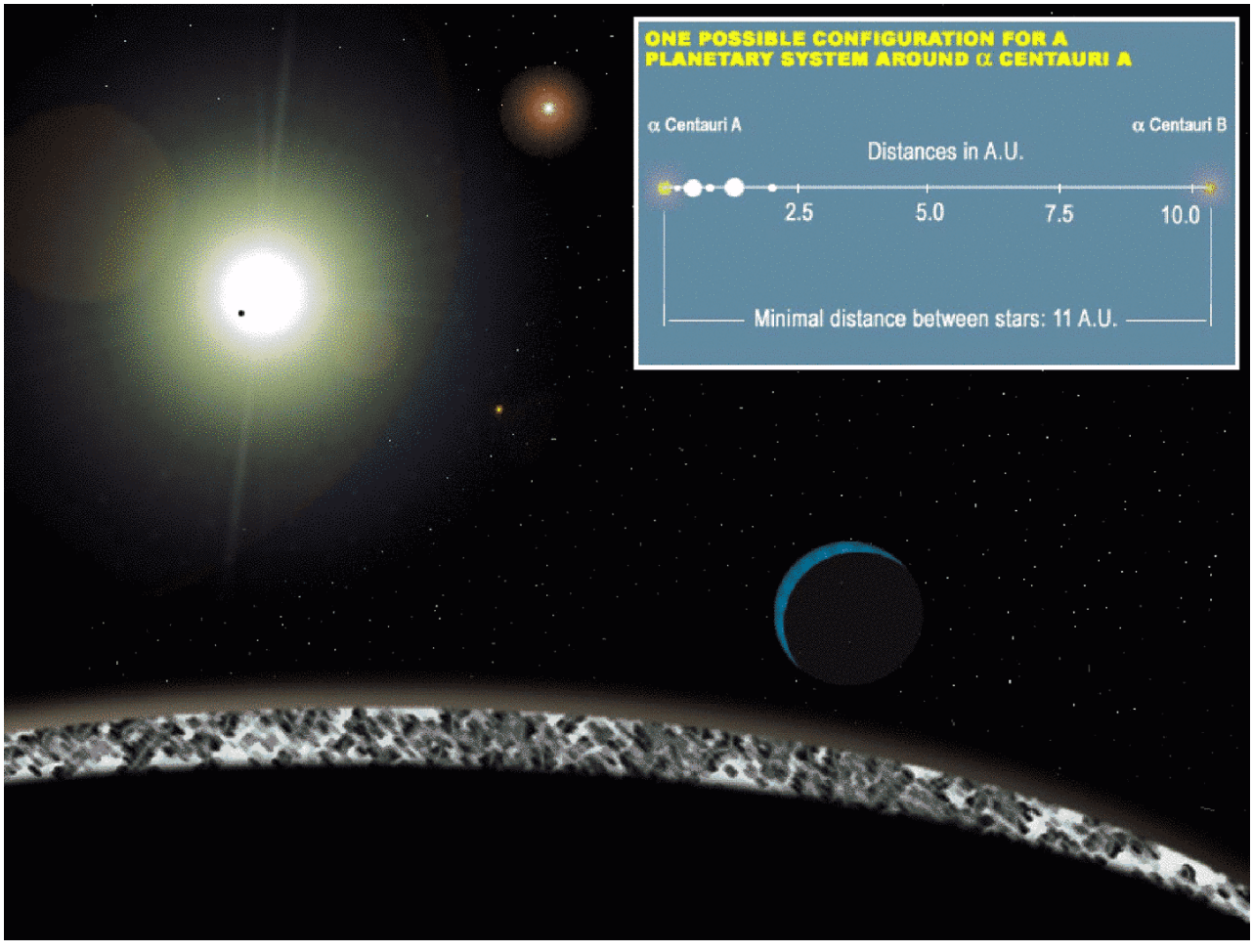


Volatiles and Habitability

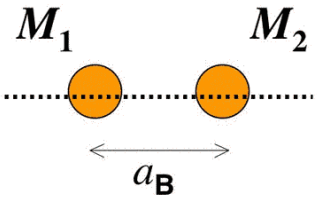
If planets formed around α Centauri A and/or α Cen B, would such planets be habitable?

Probably not. Models for delivery of volatiles (Morbidelli et al. 2000) suggest terrestrial planets receive volatiles primary from the asteroid belt and beyond. In the α Cen system, orbits > 3 AU from α Cen A or B are very unstable, and material would not form planetesimals in these regions.

α Centauri may thus have **dry terrestrial planets**, devoid of the C/H_2O-based life which thrives on Earth.

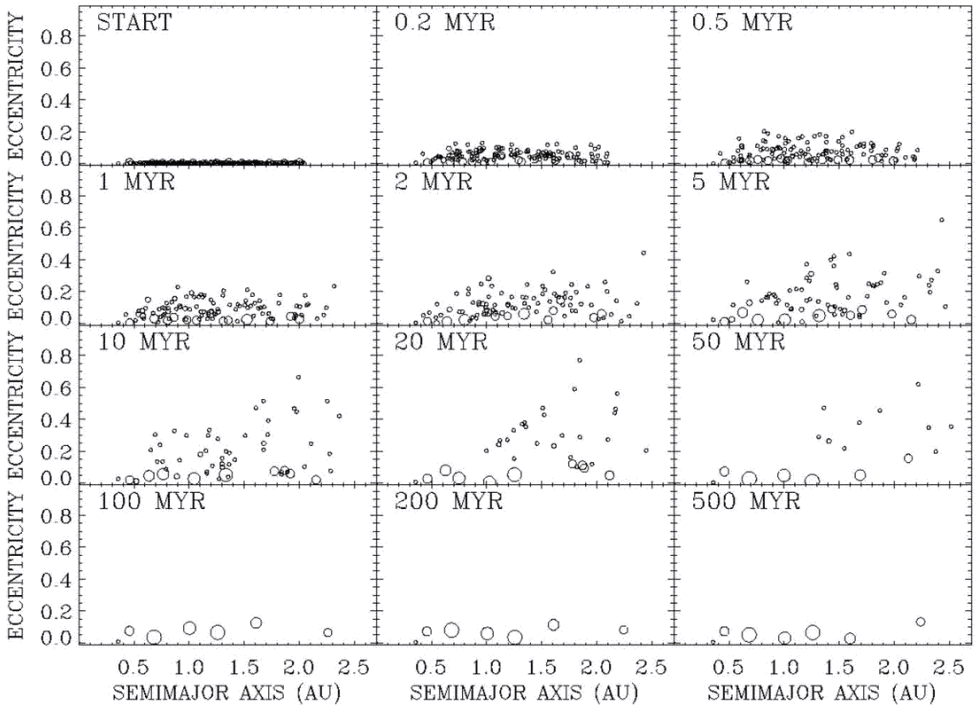


Close Binary Systems

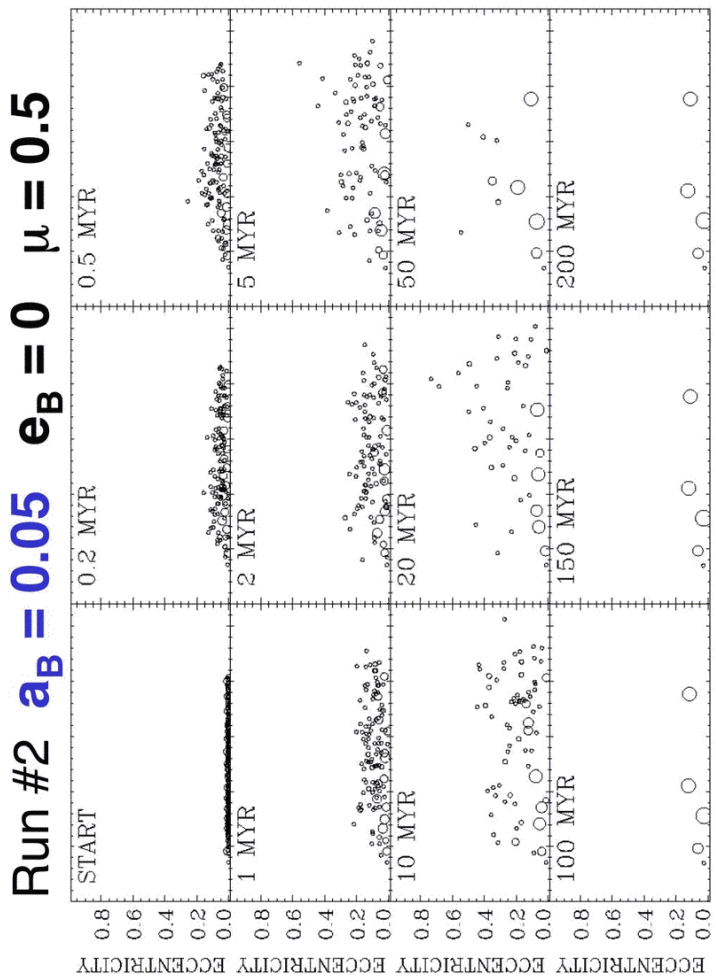


- $a_B = 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.4$ AU
- $e_B = 0.0, 0.33, 0.5, 0.8$
- $i_B = 0°, 30°$
- Mass Ratio $\mu = M_2 / (M_1 + M_2) = 0.5$ or 0.2
- Integration time = 200 Myr - 1 Gyr

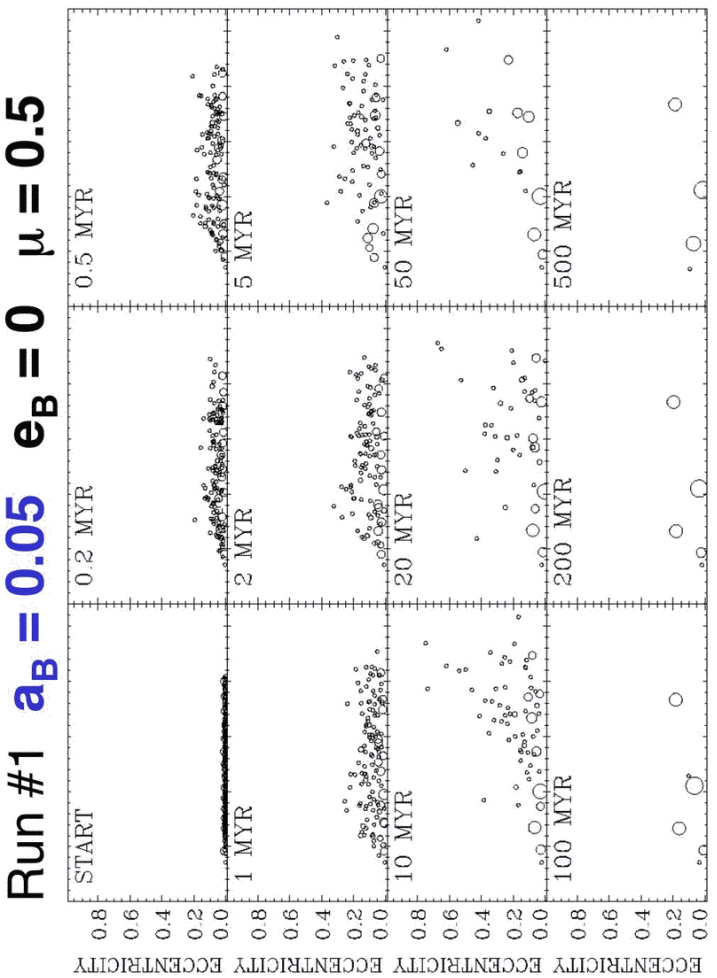
Run #1 $a_B = 0.05$ $e_B = 0$ $\mu = 0.5$



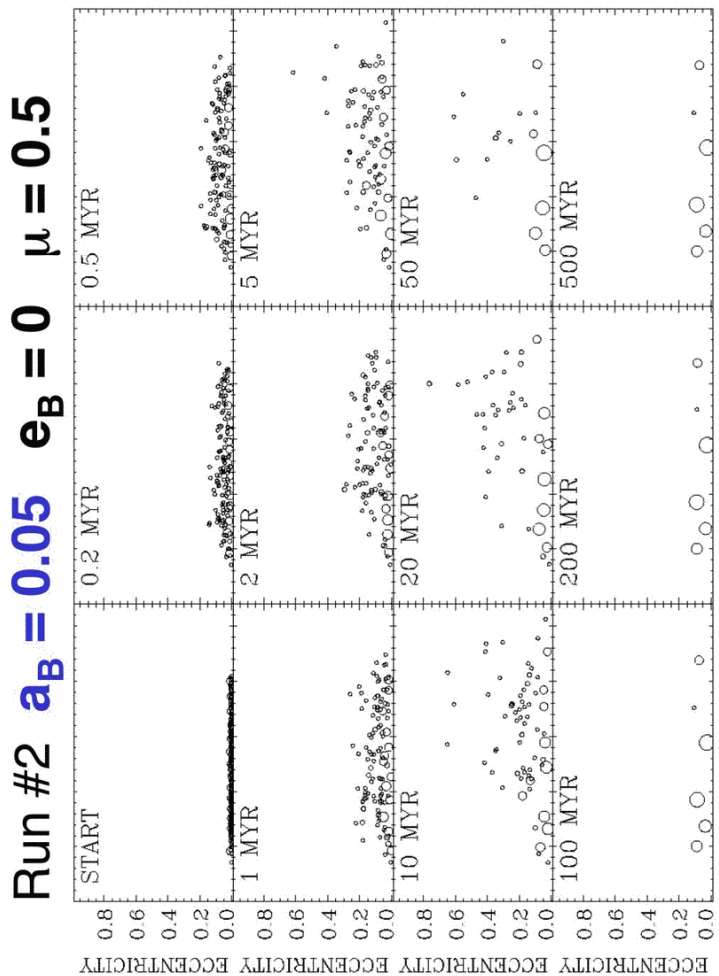
Includes 'Jupiter'

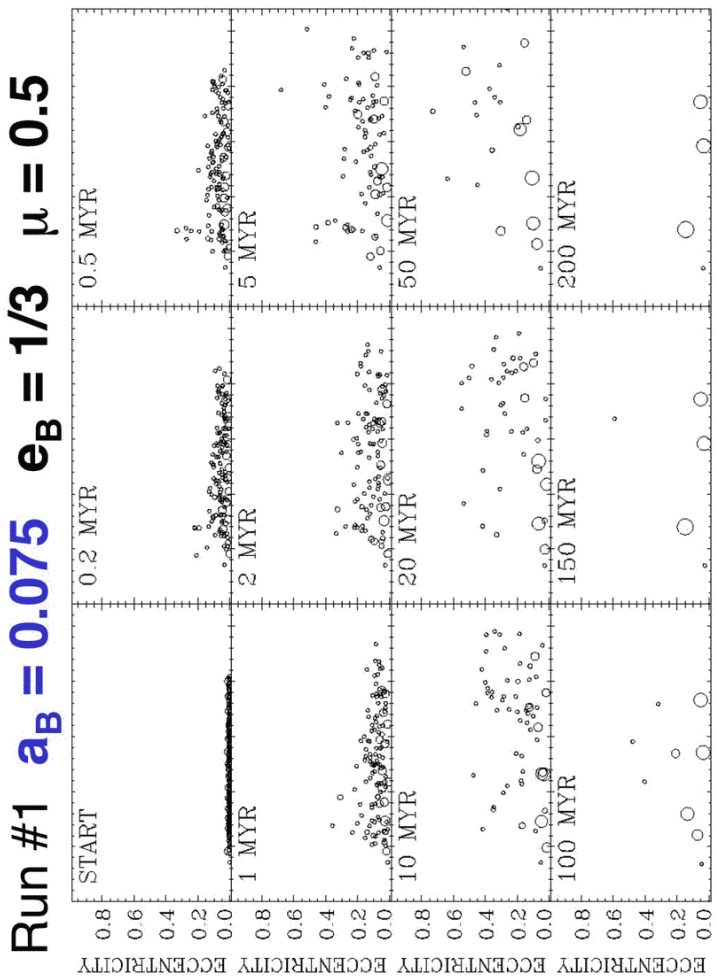


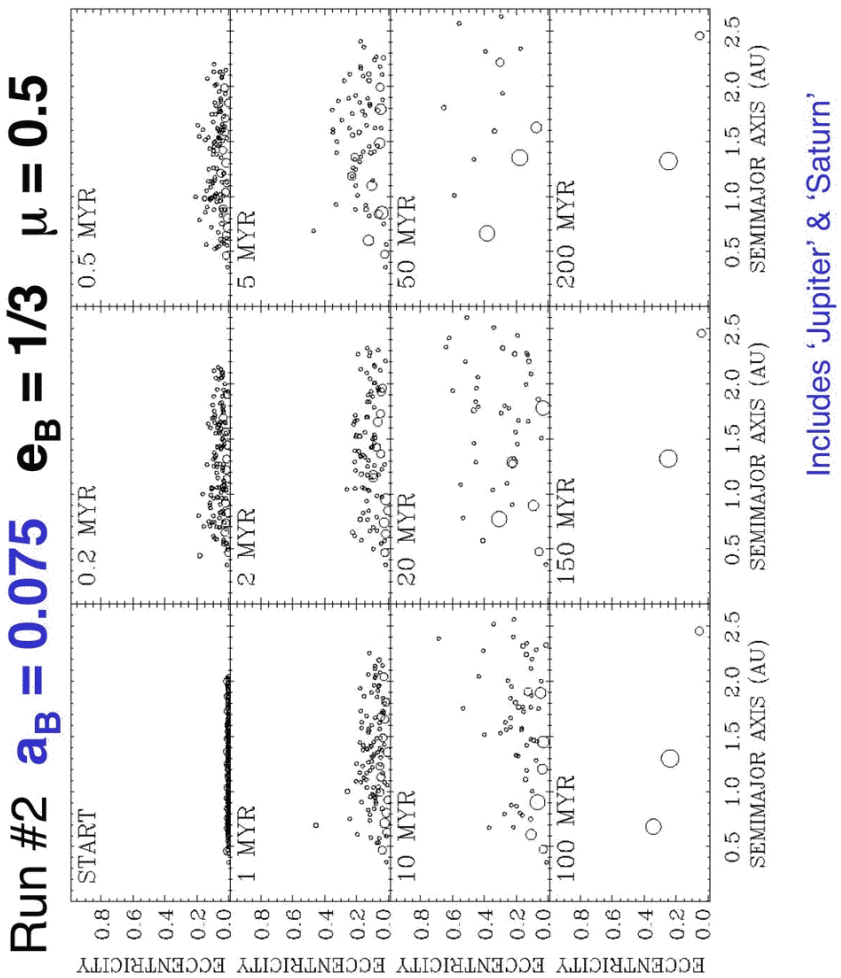
Includes 'Jupiter'

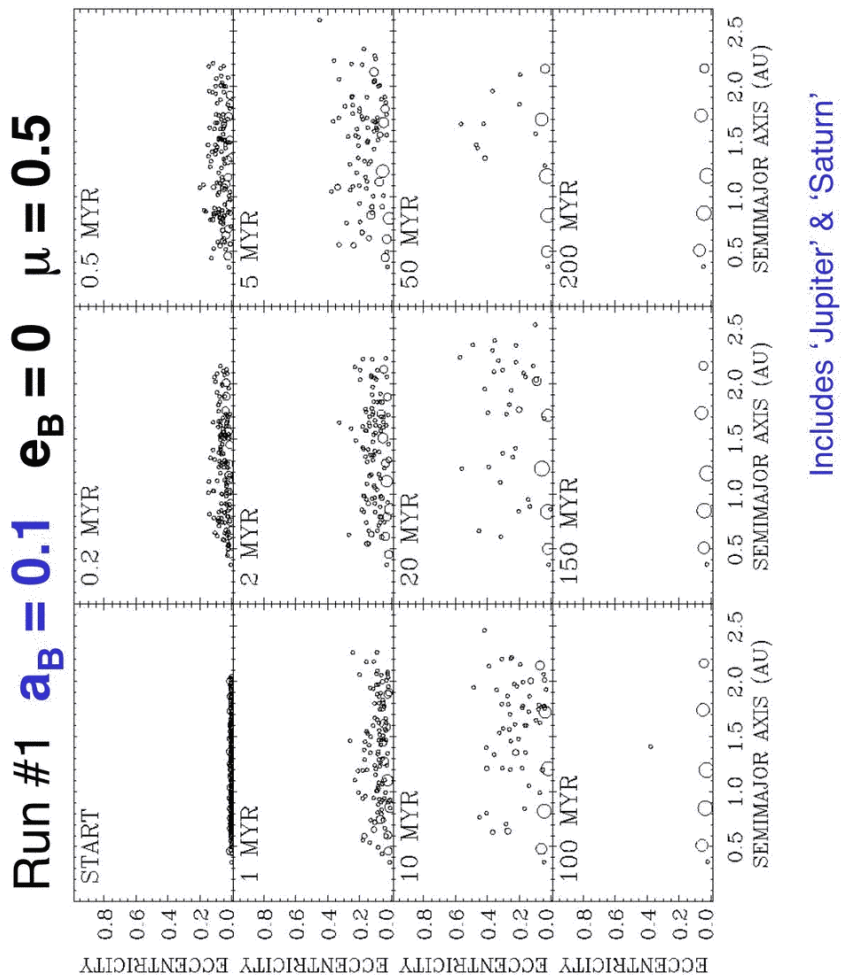


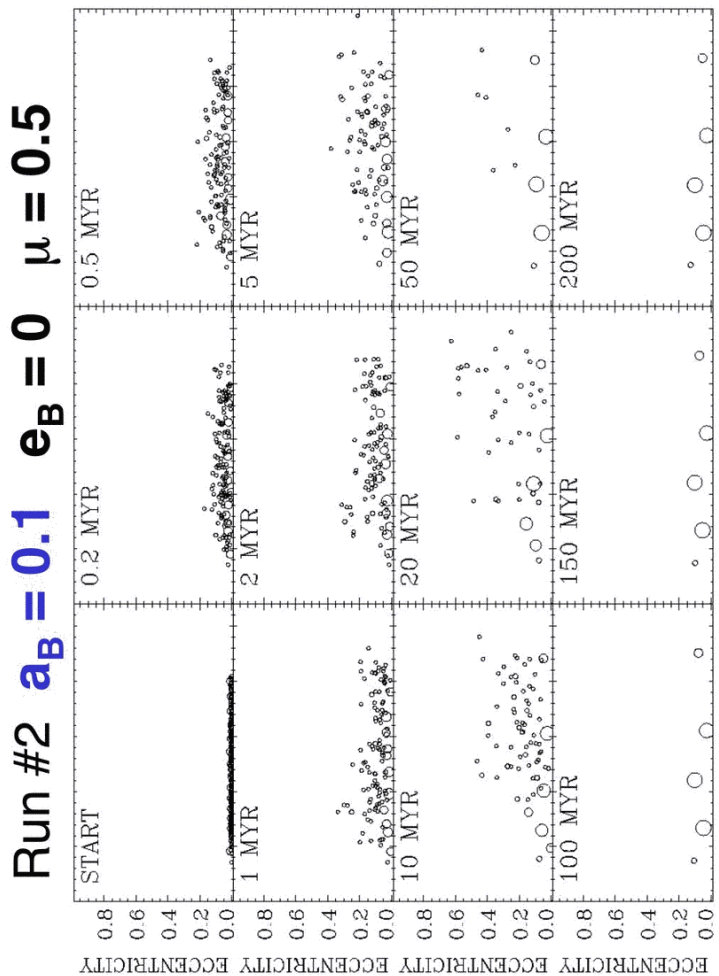
Includes 'Jupiter' & 'Saturn'

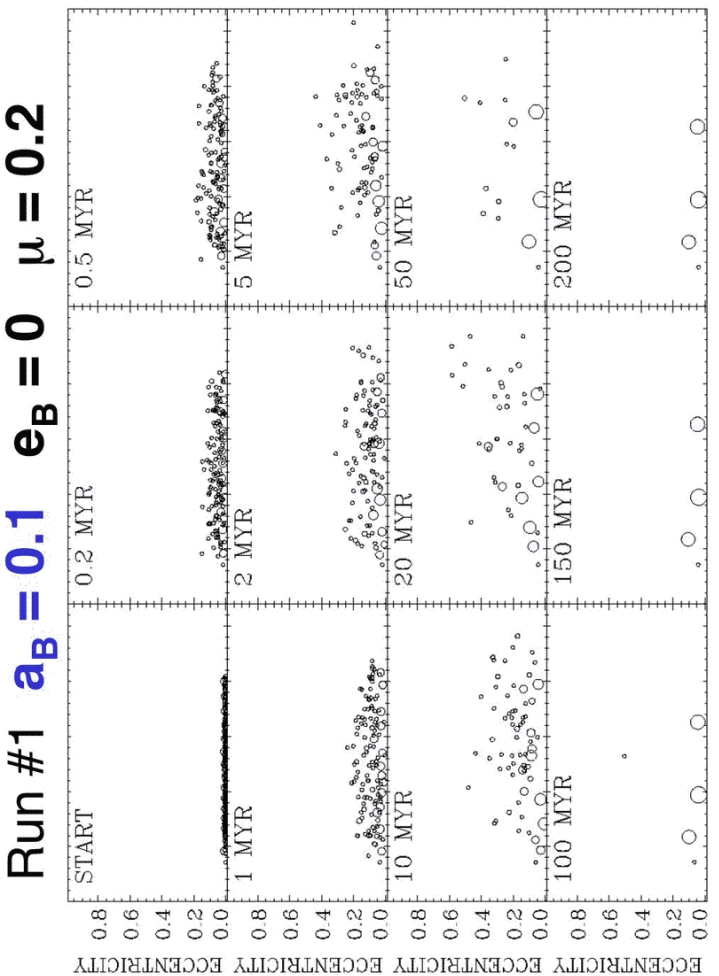

Run #2 $a_B = 0.05$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
500 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

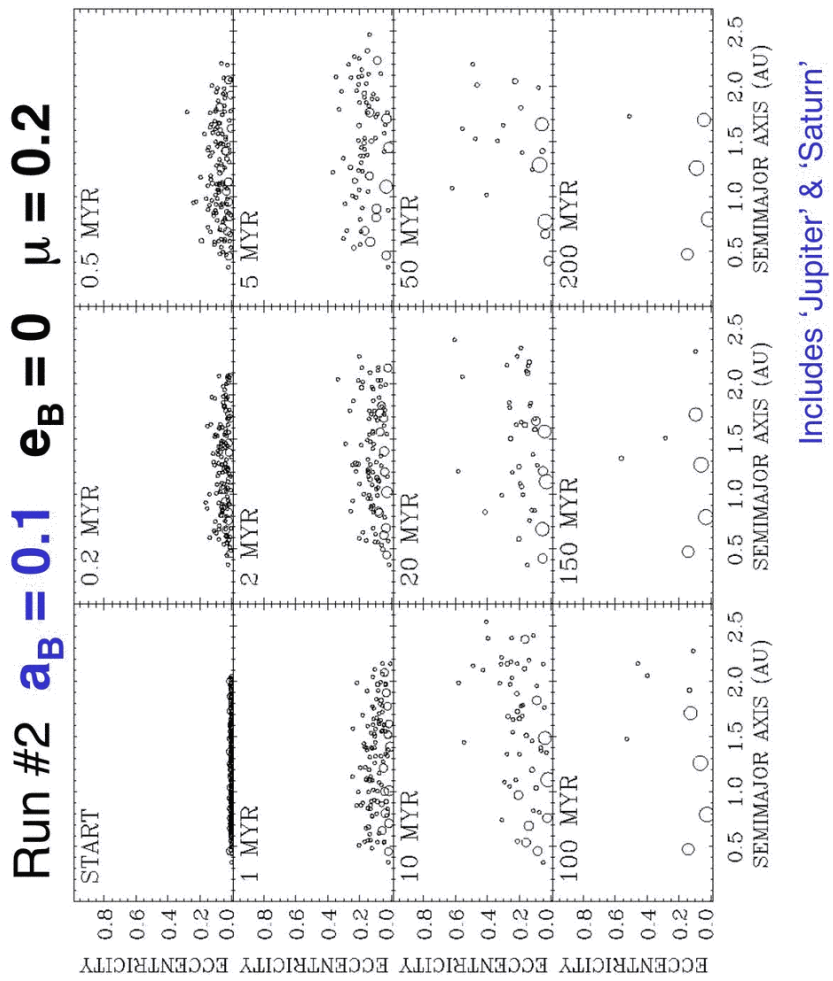

Run #1 $a_B = 0.075$ $e_B = 1/3$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

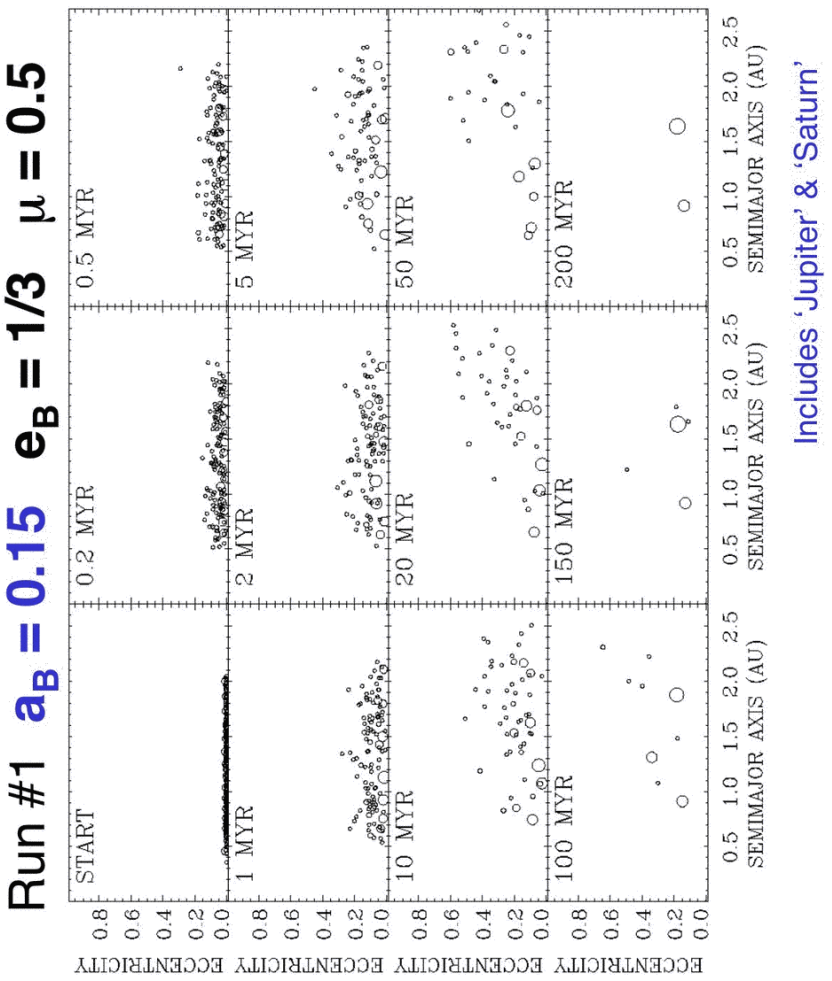

Run #2 a_B = 0.075 e_B = 1/3 μ = 0.5
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

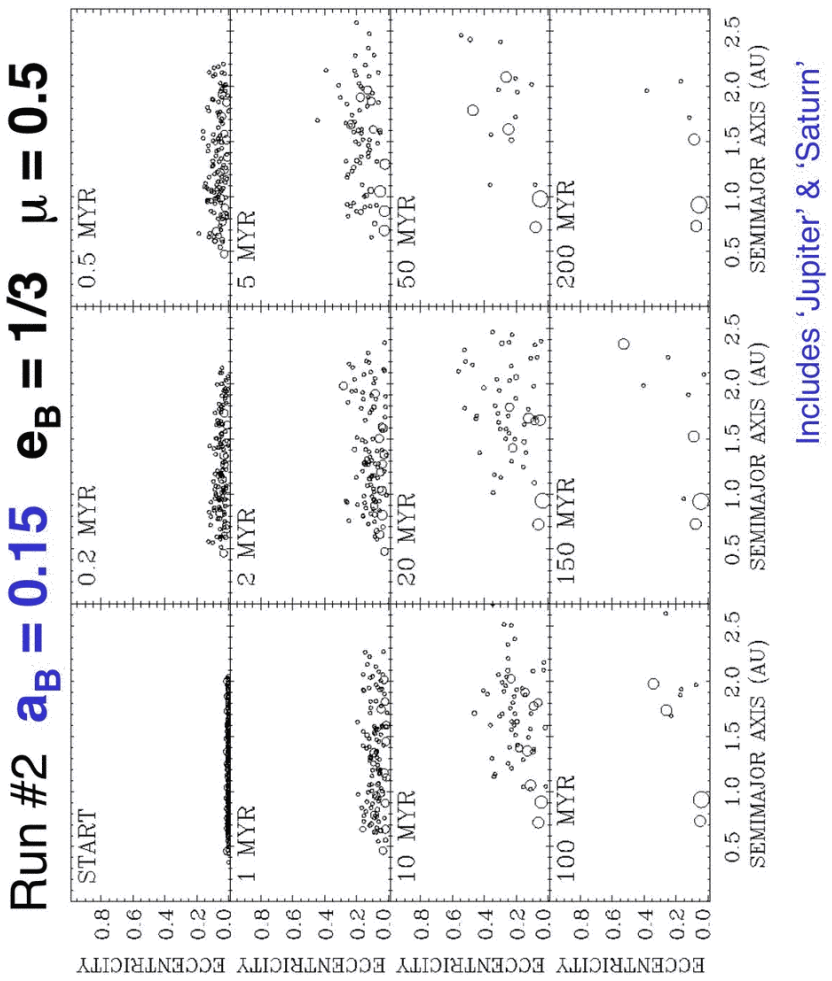

Run #1 a_B = 0.1 e_B = 0 μ = 0.5
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

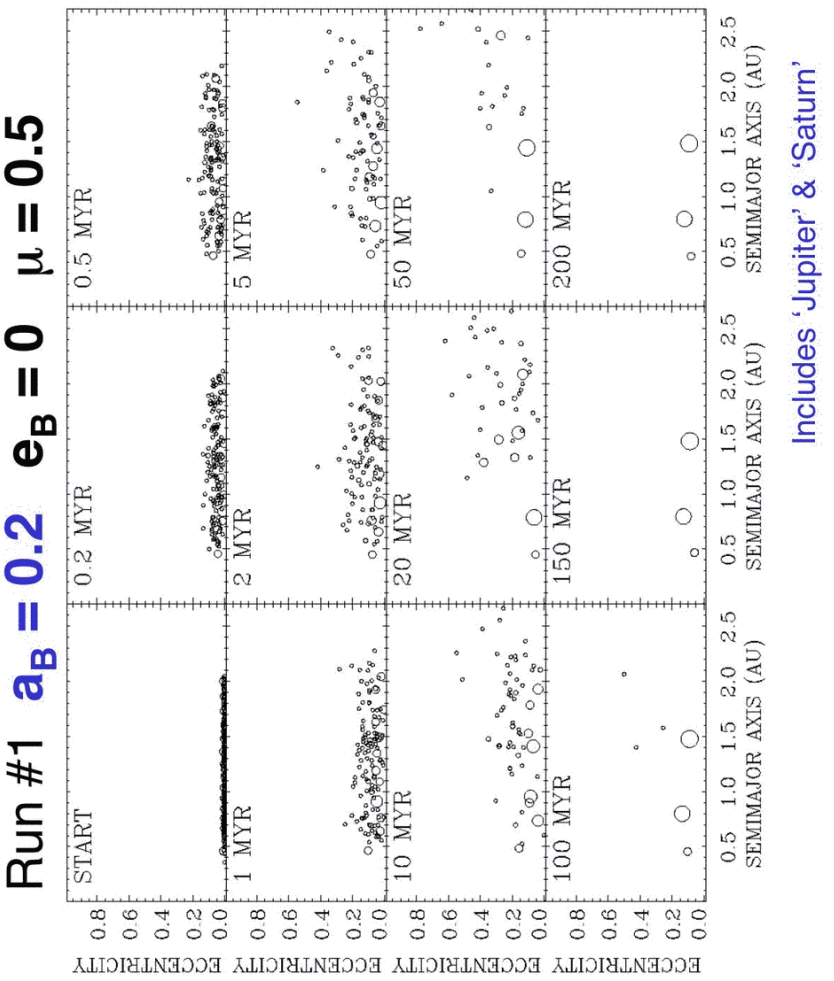

Run #2 $a_B = 0.1$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #1 $a_B = 0.1$ $e_B = 0$ $\mu = 0.2$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #2 $a_B = 0.1$ $e_B = 0$ $\mu = 0.2$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #1 $a_B = 0.15$ $e_B = 1/3$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #2 $a_B = 0.15$ $e_B = 1/3$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'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START
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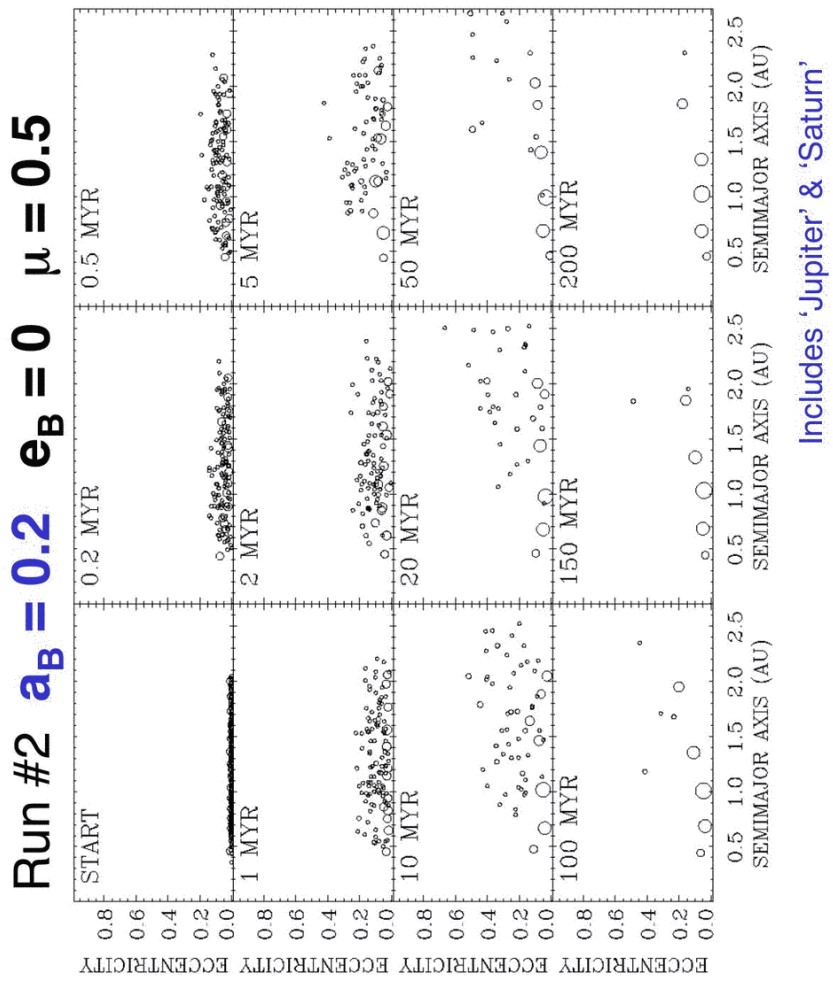
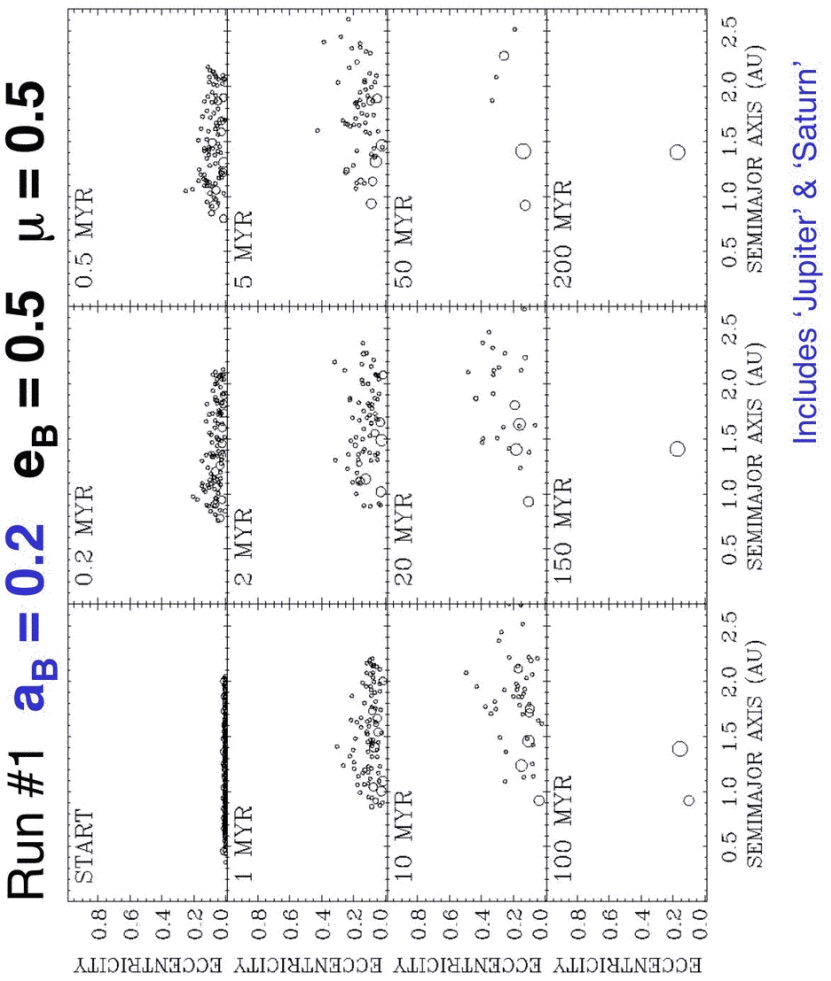
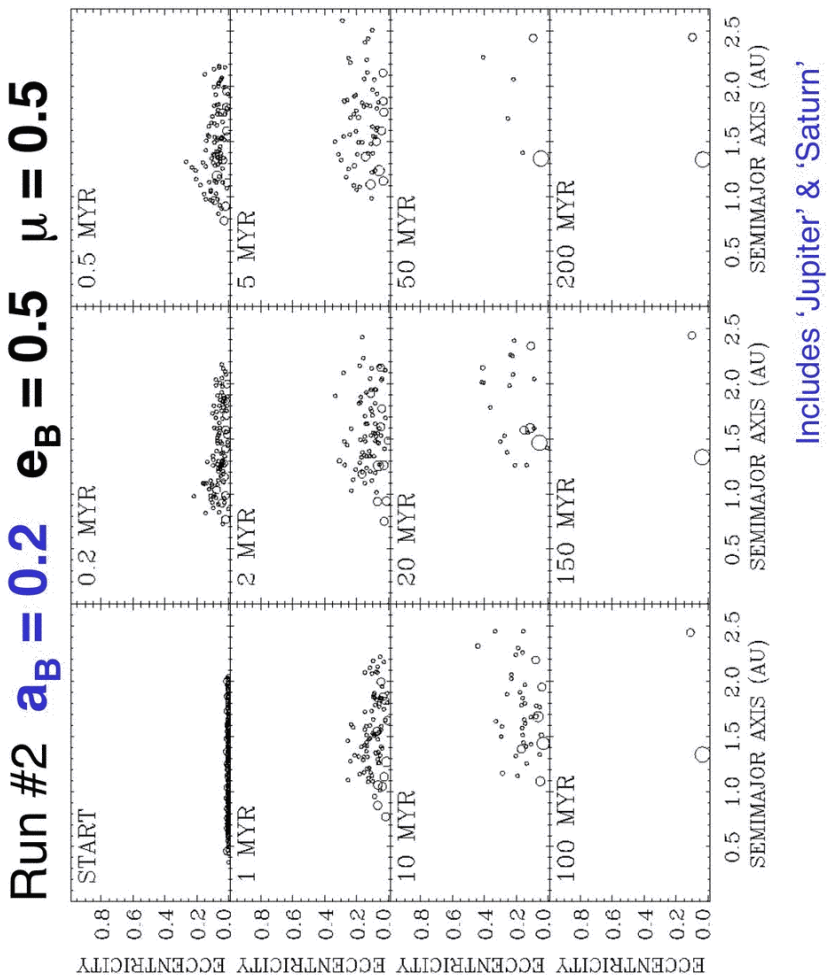
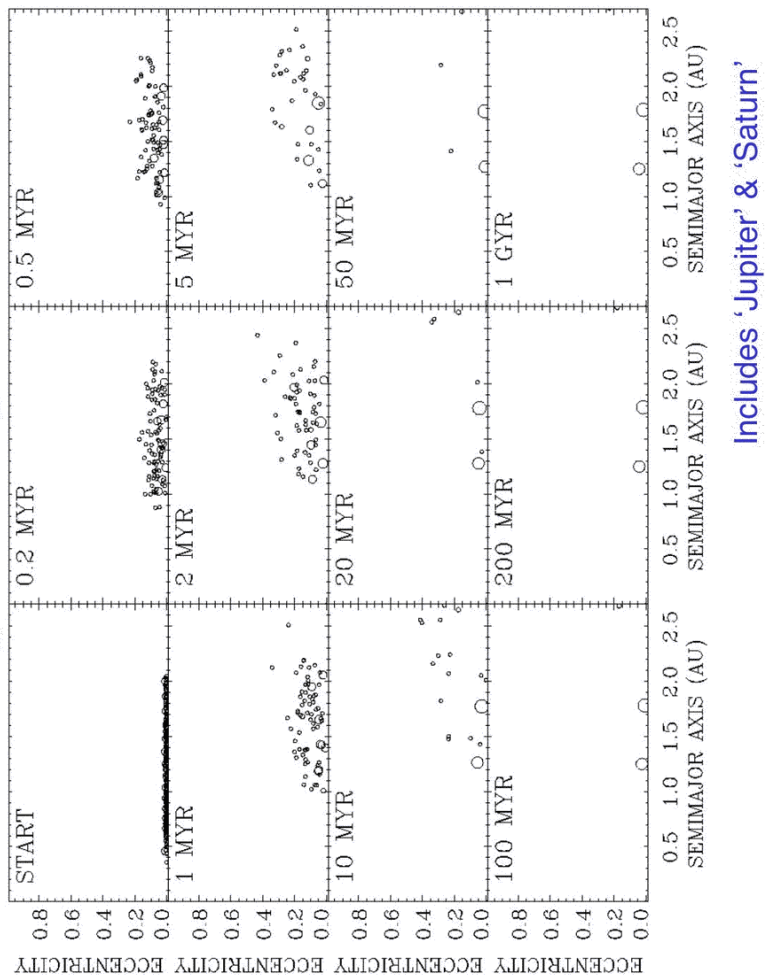
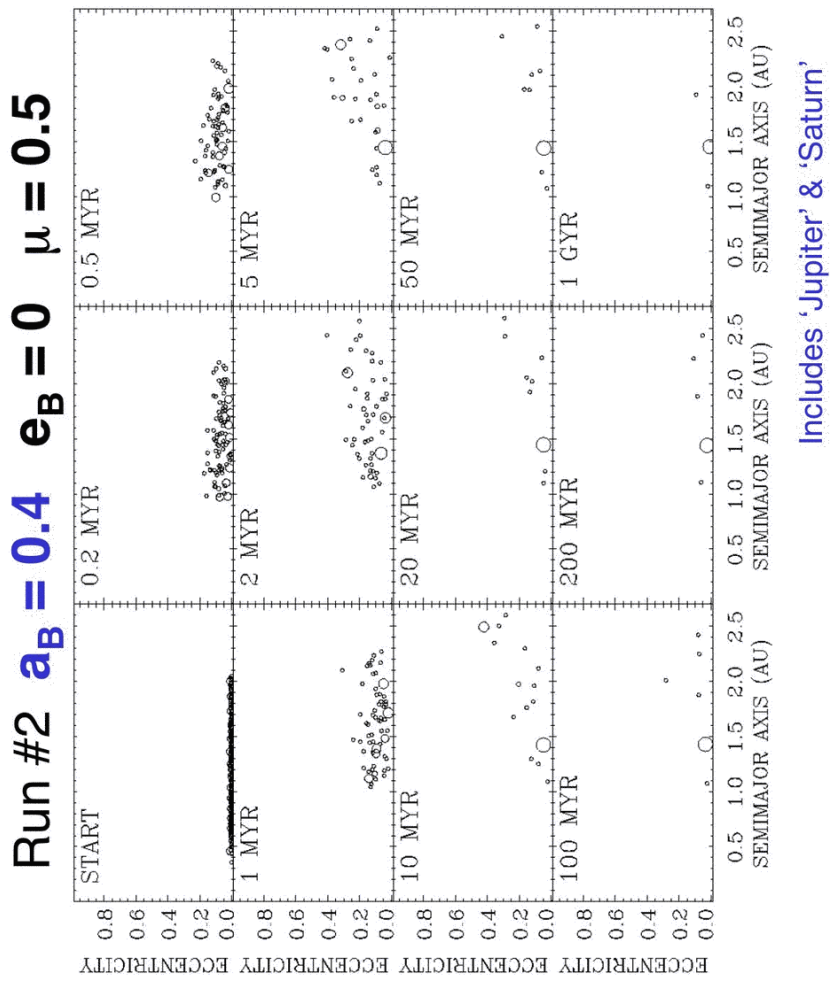
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

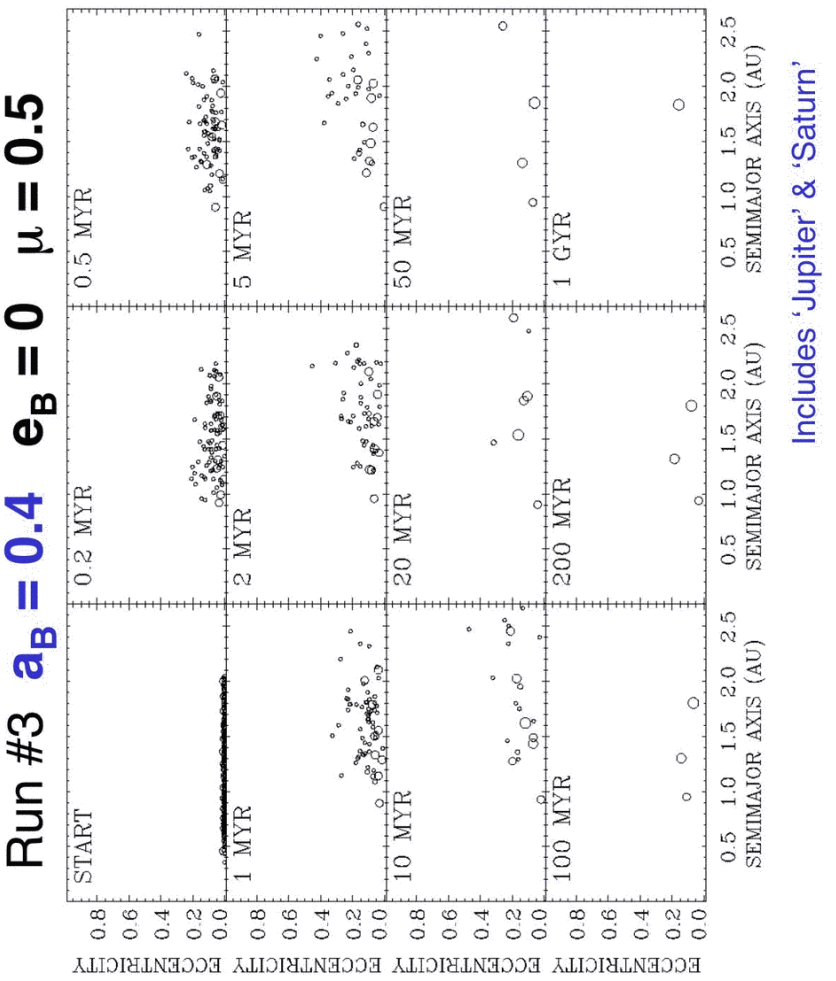

Run #2 $a_B = 0.2$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

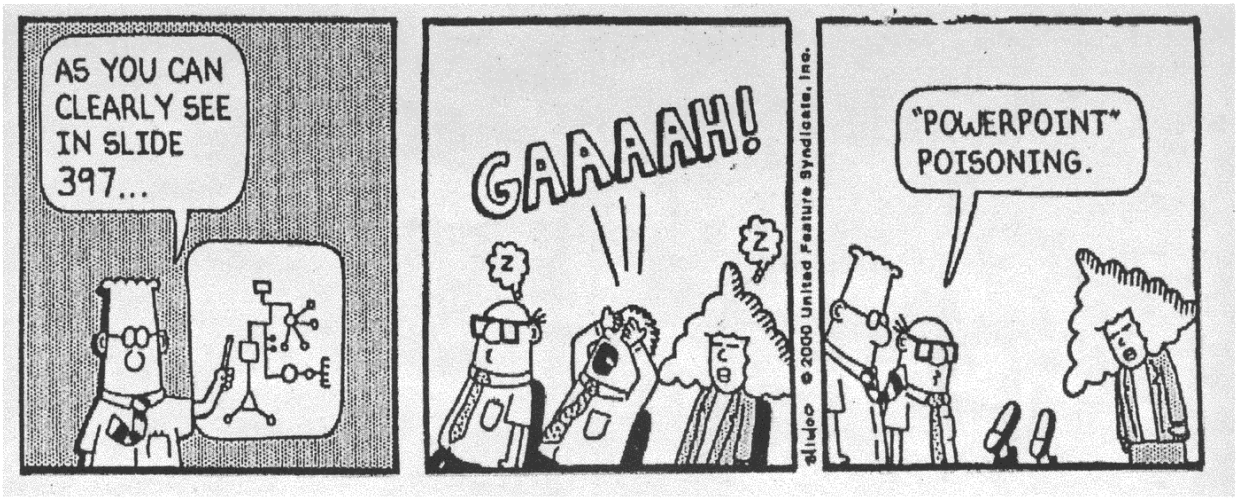

Run #1 $a_B = 0.2$ $e_B = 0.5$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #2 $a_B = 0.2$ $e_B = 0.5$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
150 MYR
200 MYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'

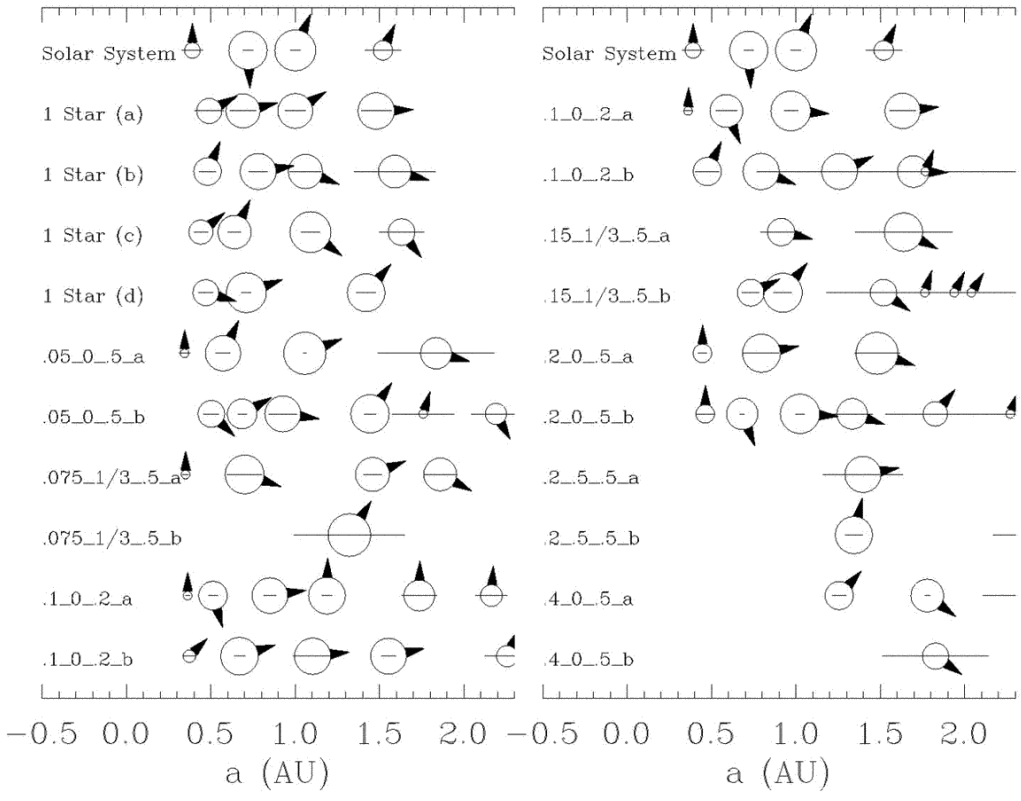

Run #1 $a_B = 0.4$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
1 GYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #2 $a_B = 0.4$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
1 GYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'


Run #3 $a_B = 0.4$ $e_B = 0$ $\mu = 0.5$
START
0.2 MYR
0.5 MYR
1 MYR
2 MYR
5 MYR
10 MYR
20 MYR
50 MYR
100 MYR
200 MYR
1 GYR
ECCENTRICITY
SEMIMAJOR AXIS (AU)
Includes 'Jupiter' & 'Saturn'



Final Planetary Systems



Planetary Statistics

Derived to quantify characteristics of planetary systems formed

N_p = # planets at least as massive as Mercury ($\sim 0.06\ M_\oplus$)

N_m = # planets less massive than Mercury

S_m = Fraction of the total (final) mass in the largest planet

For the Solar System terrestrial planets (MVEM) , $S_m = 0.51$ (more than half of the mass resides in Earth)

Orbital Spacing Statistic

$$S_s = \frac{6}{N_p - 1}\left(\frac{a_{max} - a_{min}}{a_{max} + a_{min}}\right)\left(\frac{3\,M_*}{2\,\overline{m}}\right)^{1/4}$$

$\overline{m}$ = mean mass of the final planets

M_* = total mass of the binary stars

a_{max} , a_{min} = max and min semimajor axes

Angular Momentum Deficit

$$S_d = \frac{\sum_j m_j \sqrt{a_j} \left[1 - \sqrt{(1-e_j^2)} \cos i_j\right]}{\sum_j m_j \sqrt{a_j}}$$

For *j* planets

• a measure of the fractional difference between the planets' actual orbital angular momenta and the angular momenta that they would have on circular uninclined orbits with the same semimajor axis

Mass Concentration Statistic

$$S_c = \max \left\{ \frac{\sum_j m_j}{\sum_j m_j \left[\log_{10} (a_i a_j)\right]^2} \right\}$$

For *j* planets

• a measure of the degree to which mass is concentrated in one part of the planetary system

Radial Mixing Statistic

$$S_r = \left(\sum_j \frac{m_j \; |a_{init,j} - a_{fin,j}|}{a_{fin,j}} \right) \Big/ \sum_j m_j$$

For *j* planets

$\mathbf{a_{init,j}}$ and **m** are the initial semimajor axis and mass of each embryo that becomes incorporated into a final planet
$\mathbf{a_{fin,j}}$ is the semimajor axis of the final planet

- a sum of the radial migrations of the bodies that form a planet

Simulation	N	Sm	Ss	Sd	Sc	Sr
CB_0.05_0_0.5_a	3	0.5	45.3	0.0069	30.8	0.379
CB_0.05_0_0.5_b	5	0.355	30.3	0.0026	31.4	0.309
CB_0.075_1/3_0.5_a	3	0.436	40.2	0.0166	27.7	0.363
CB_0.075_1/3_0.5_b	2	0.91	54.1	0.031	167.7	0.29
CB_0.1_0_0.5_a	5	0.313	29.8	0.0017	29.7	...
CB_0.1_0_0.5_b	4	0.335	33.2	0.004	32.9	0.253
CB_0.1_0_0.2_a	3	0.44	41.4	0.0039	35.6	0.314
CB_0.1_0_0.2_b	4	0.322	34.9	0.0053	29.7	0.422
CB_0.15_1/3_0.5_a	2	0.736	52.4	0.0203	79.5	0.174
CB_0.15_1/3_0.5_a	3	0.6	33.6	0.007	83.7	0.313
CB_0.2_0_0.5_a	3	0.545	47.6	0.0064	40	0.182
CB_0.2_0_0.5_a	5	0.429	29.6	0.0058	45.8	0.248
CB_0.2_0.5_0.5_a	1	1	...	0.0243	...	0.148
CB_0.2_0.5_0.5_b	2	0.89	57.2	0.0021	152.2	0.169
CB_0.4_0_0.5_a	2	0.598	34.1	0.0011	153.3	0.206
CB_0.4_0_0.5_b	1	0.971	...	0.0006	2183.7	0.141
Solar System	4	0.509	37.7	0.0018	89.9	...
One Star (ave)	3.5	0.482	39.5	0.0056	37.1	0.273

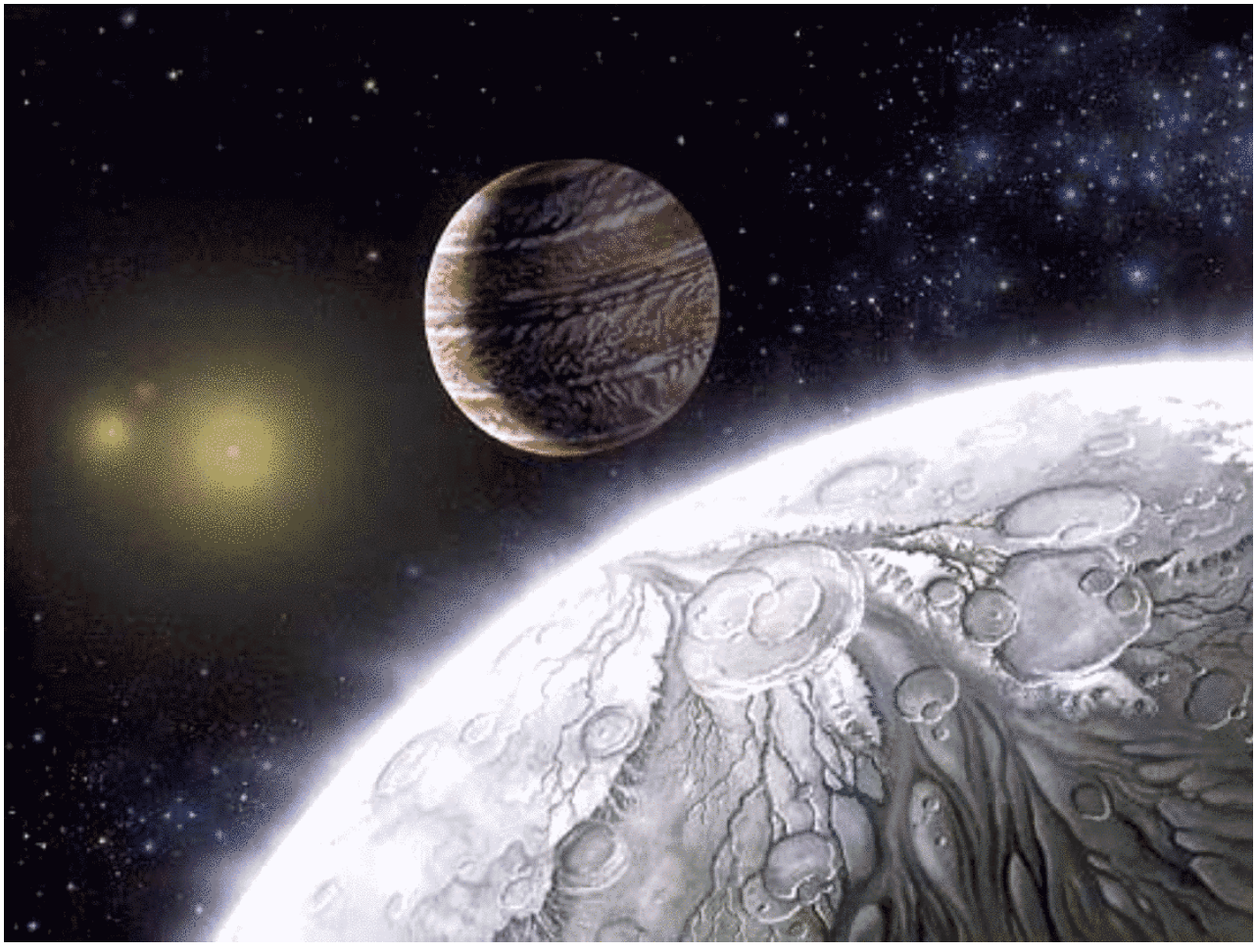
Table 1. A summary of the planetary statistics for our close-binary (CB) simulations are shown in blue (in the form CB_a_B_e_B_m), followed by statistics for the (actual and simulated) Solar System.

Results

Close binary stars with low e_B and a_B = 0.05 or 0.1 AU produce planetary systems similar to simulations of the Solar System.

Binary stars with a moderately eccentric orbit tend to produce fewer (2 - 3) planets.

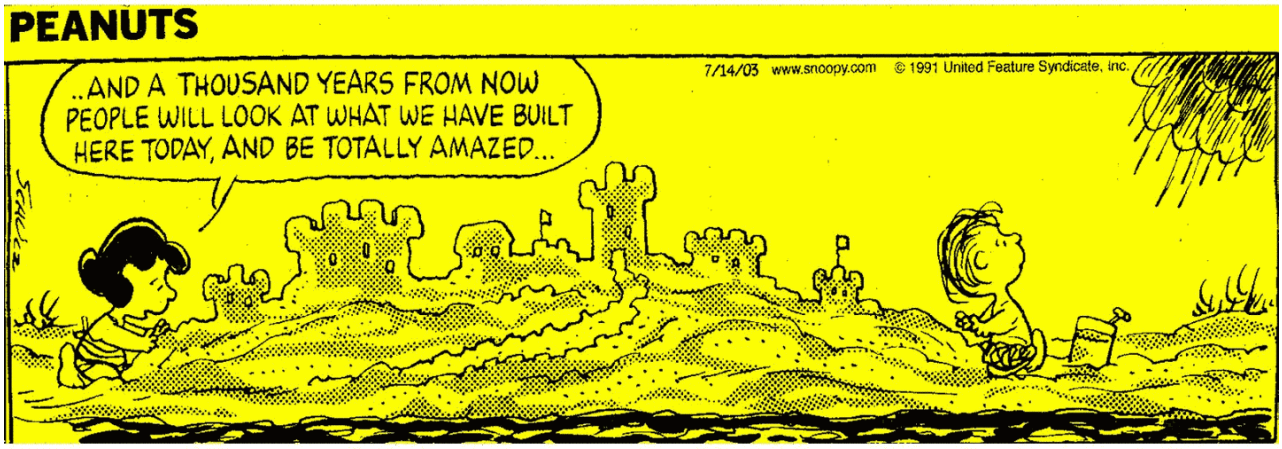
Planetary accretion is less effective around binary systems with $e_B > 0.2$ or $a_B > 0.2$ AU.



Status

Code Paper: Chambers, J.E., E.V. Quintana, M.J. Duncan, and J.J. Lissauer 2002. Symplectic Algorithms for Accretion in Binary Star Systems. *Astron. J.* **123**, 2884-2894.

Alpha Cen Simulations: Quintana, E.V., J.J. Lissauer, J.E. Chambers and M.J. Duncan 2002. Terrestrial Planet Formation in the α Centauri System. *Astrophys. J.* **576**, 982-996.

Close Binary Simulations: Mostly done

Wide Binary Simulations: Started