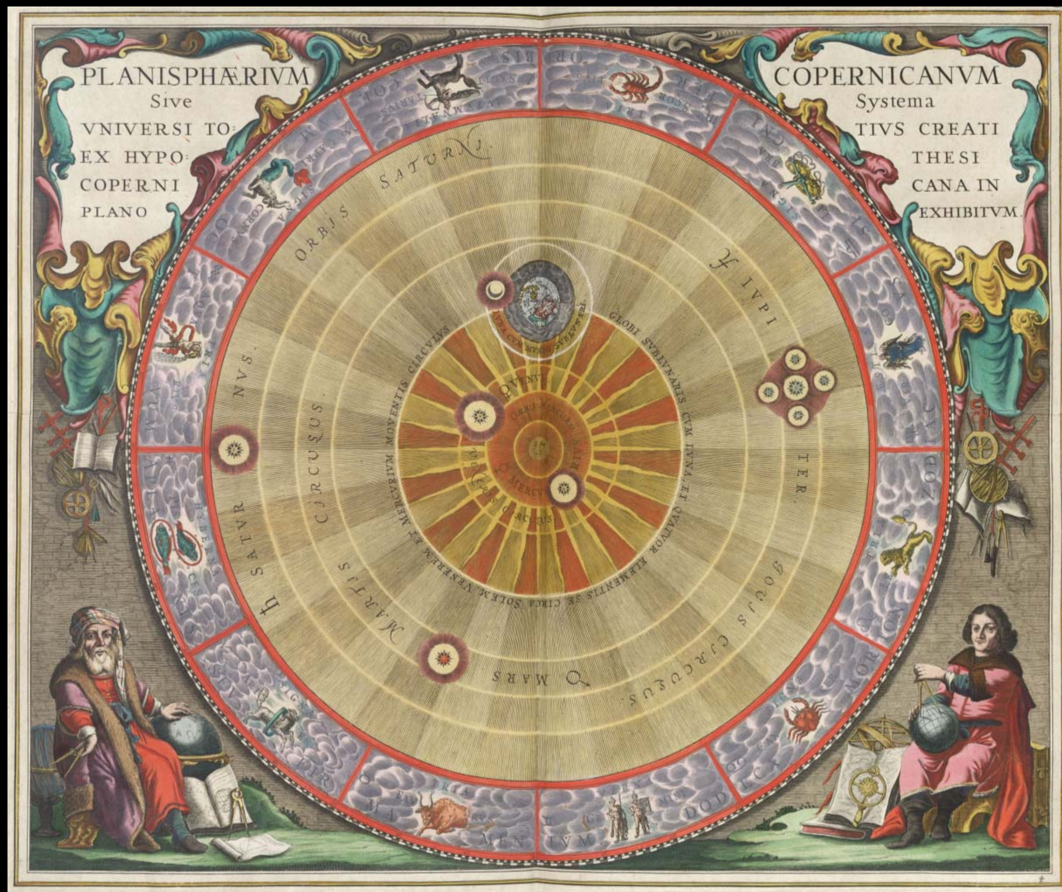
On the Origin of the Rocky Planets, Fugue in Venus Megacollision



Simon Porter

October 30, 2009

And art thou, then, a world like ours,
Flung from the orb that whirled our own
A molten pebble from its zone?
How must the burning sands absorb
The fire-waves of the blazing orb,
Thy chain so short, thy path so near
Thy flame-defying creatures hear
The maelstroms of the photosphere!

- Oliver Wendell Homes, Sr

Paper 1: Narrow Annulus Formation

- Basic premise:
  - Majority of terrestrial planet-forming mass was concentrated in an annulus from 0.7-1.0 AU
  - Computational simulations of accretion from this annulus can produce solar system-like results
  - Effects constraints on disk condensation, initial accretion, comsochemical signatures, and *collisional environment*

Background

- Prior planetary formation models tend to produce systems that are dynamically “too hot” – meaning too much eccentricity and inclination
- Prior solutions:
  - Include a small-bodies to damp out orbits
    - But how do the small bodies survive long enough?
  - Giants sweeping orbital resonances

Hypothesis

- Rather than invoking a way to later reduce angular momentum, simply have less to begin with
- Concentrate all planet-forming mass in ring between present Earth and Venus orbits
- Assume totally oligarchic accretion, removing small-body effects

Initial Conditions

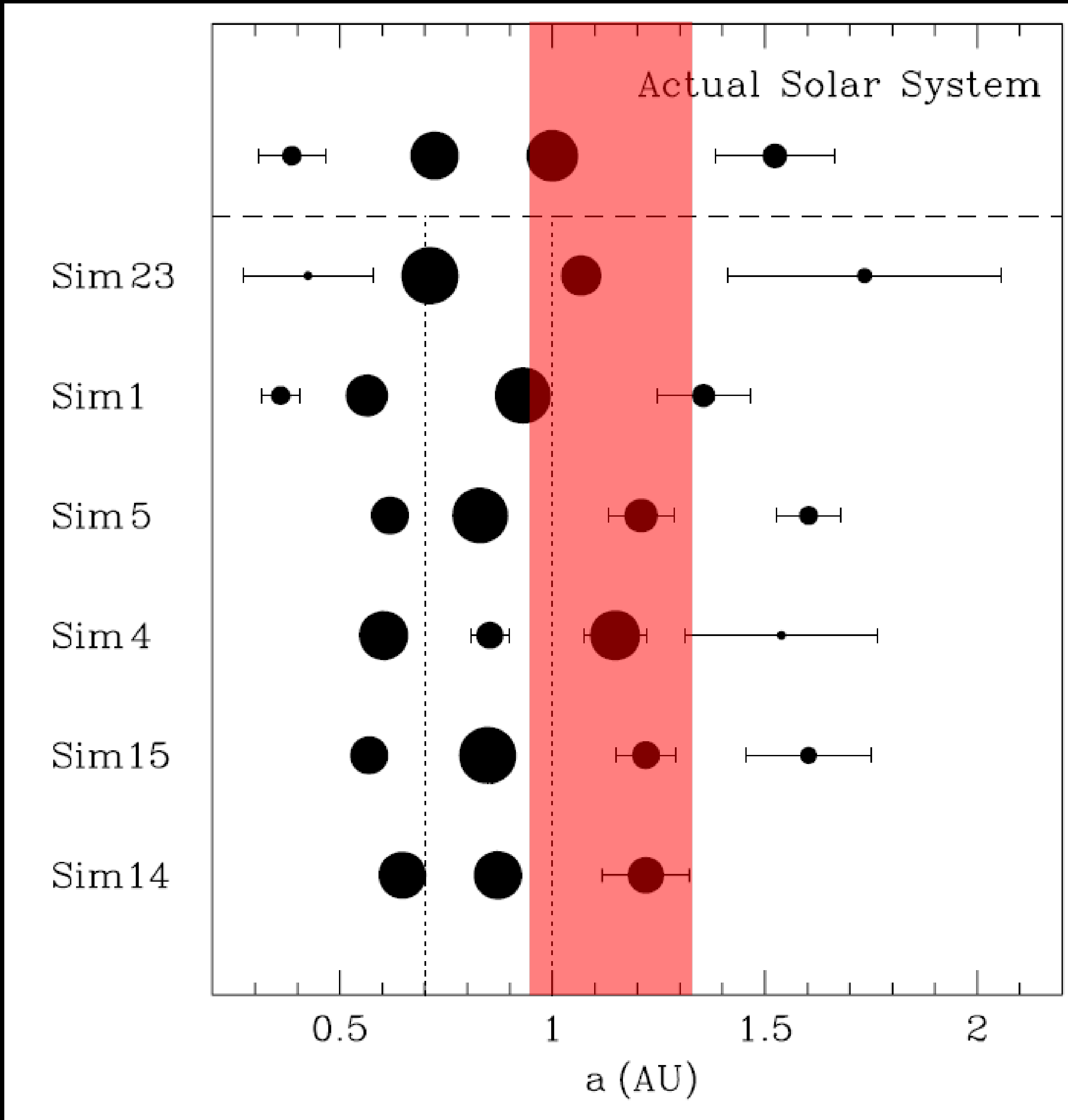
- Total of 2 $M_\oplus$ of mass spread over 0.7 and 1.0 AU, in 400 equal mass bodies
  - Surface density of 333 kg/m^2
- Currently 1.98 $M_\oplus$ of mass between 0.4 and 1.5 AU, density of 80 kg/m^2
- Each object 0.005 $M_\oplus$ ≈ Europa Mass

Orbital Simulation

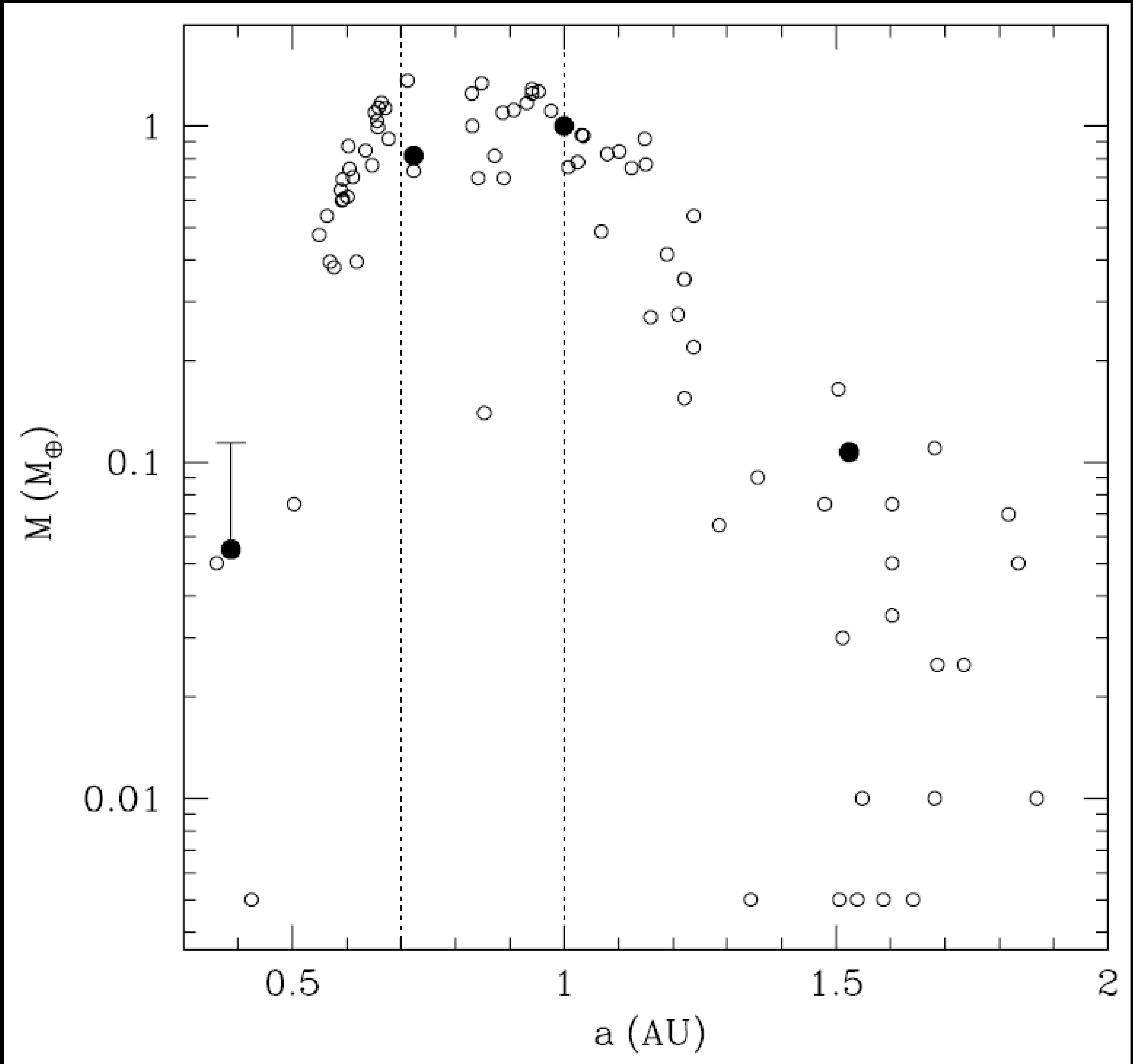
- Orbits circular, low inclination, and spread randomly across annulus
- Four-day timestep for 1 billion years
- Jupiter at perturbing at 5.2 AU

- Mercury6 open-source orbital integrator (Chambers et al. 1999)

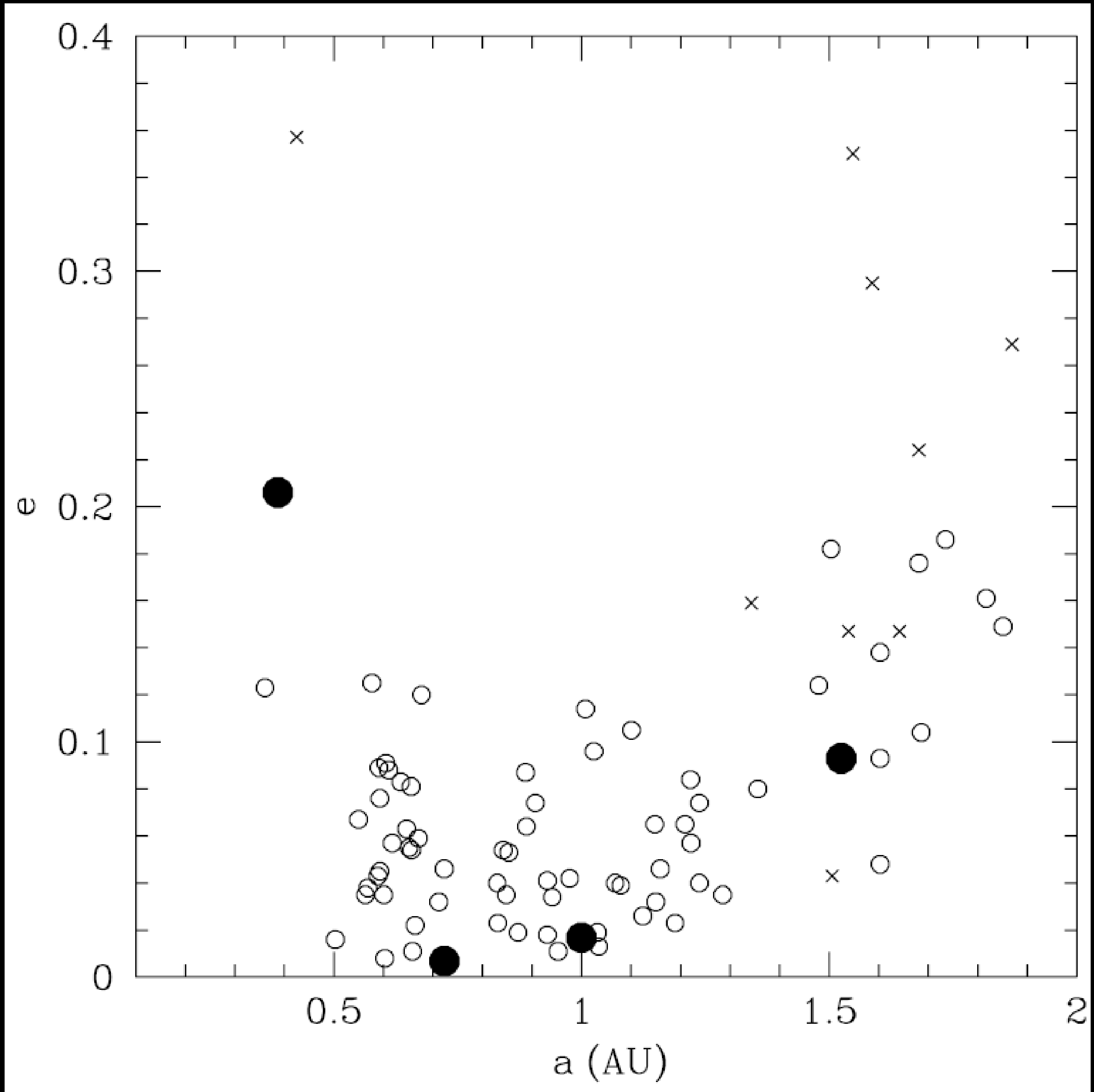
Example Results



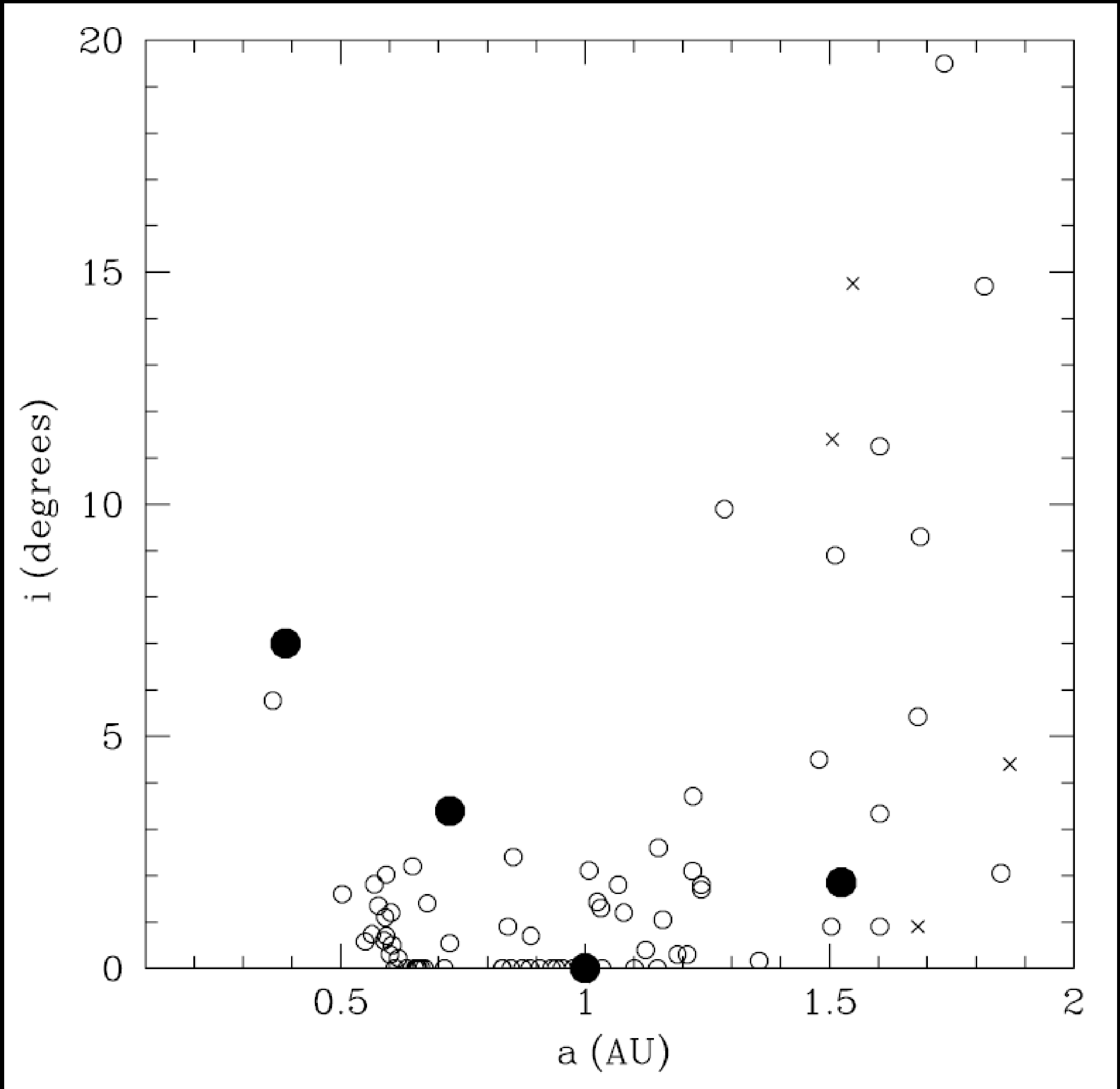
Survivors 1

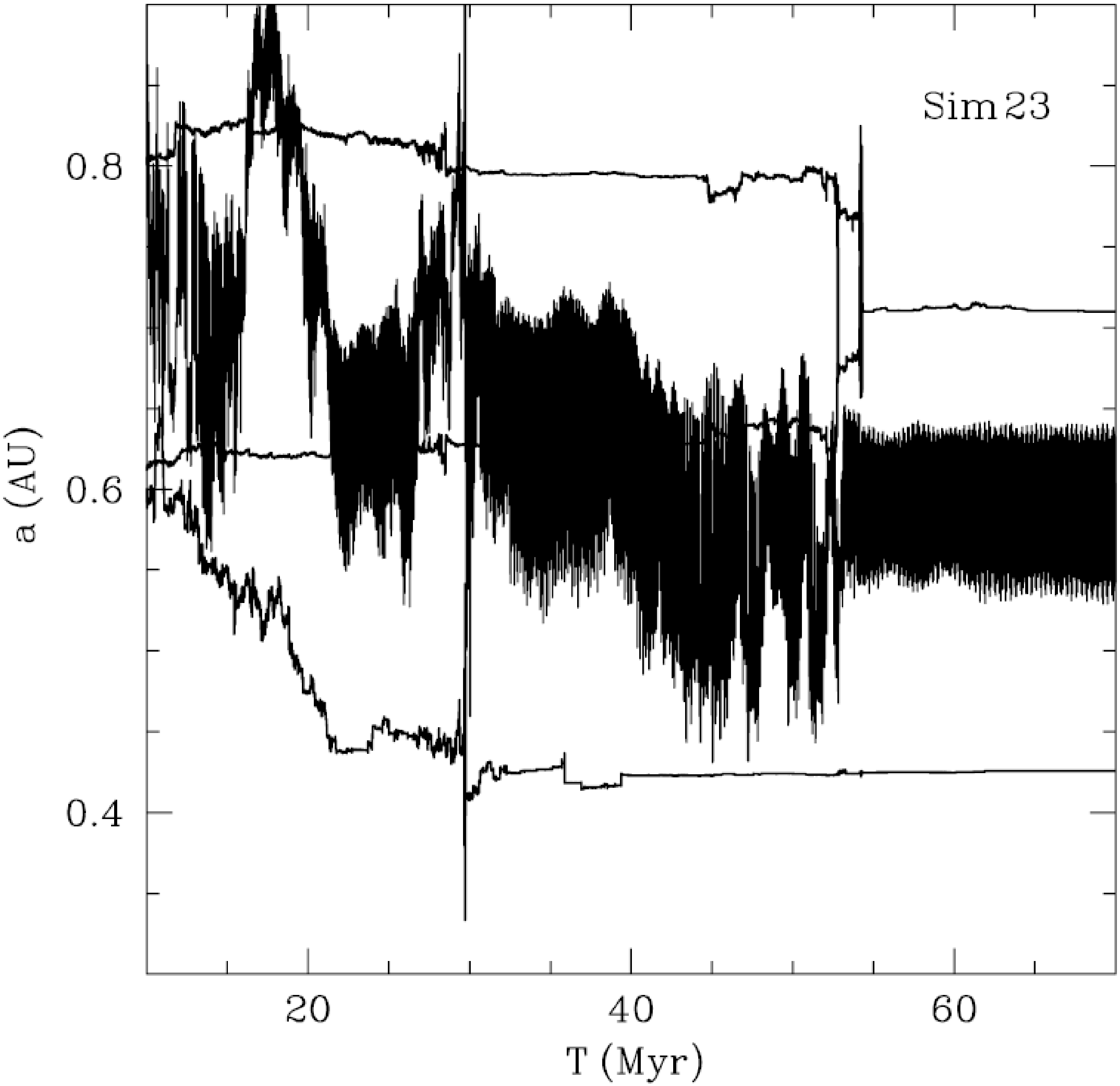


Survivors 2



Survivors 3





Sim 23
0.8
0.6
0.4
a (AU)
20
40
60
T (Myr)

Discussion: Collisions

- Tend to form multiple large planets in 0.7-1.0 AU zone, which then collide in giant impacts

- Higher probability of planet-disrupting impactors hitting Earth and Venus

- On Earth => Moon-forming impact
- On Venus => ???

Discussion: Mars Formation

- Mars-analog forms in most cases
  - Low-mass, scatted out from main annulus

1. Mars accretes in Earth-region
2. Is then scattered out and remains coupled to the proto-Earth
3. Until the intermediary embryos are removed, finally isolating Mars

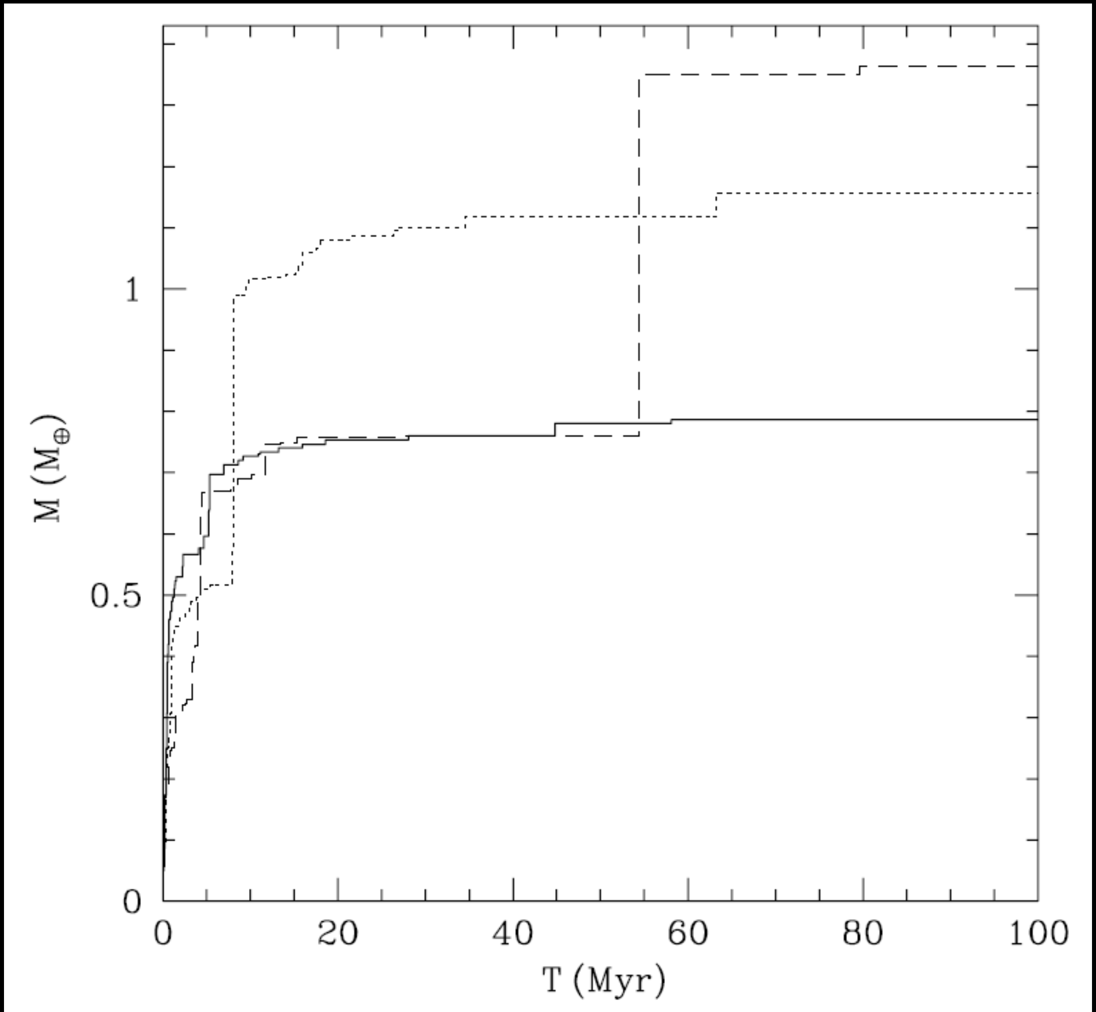
Discussion: Mercury Formation

- Much harder to form Mercury-analog
- Generally requires both scattering and large collisions
- Could explain Mercury's huge density / apparently large core (Urey 1951)

- Not really helped by additional matter interior of main annulus

Discussion: Timescale

- Compact annulus allows for fast planetary accretion to near-final mass



Broader Implications

- If a narrow annulus is a natural effect, then would be a function of disk structure
- The disk structure is a function of stellar mass
- Thus, the locations of the largest terrestrial planets may be some function of stellar type

Paper 2: Venus MEGA-COLLISION!

- Venus has several striking differences from the Earth, both physically and chemically

- A giant impact can influence both simultaneously
- A nearly head-on collision appears to have enough energy to dry Venus
  - And is more likely than previous anticipated

Venus Background

- Earth-like mass
- Slow, retrograde rotation rate
- Atmosphere very dry
- Interior inferred to also be very dry

- Why and How?

Water and Venus

- Solar losses can explain atmosphere, not interior
- Gravity strongly matches topography, limited lithospheric relaxation in craters
- Implies stronger rheology than Earth

- Only possible in Venusian temperatures if interior has an order of magnitude less water than Earth

Why so dry?

- Three previously proposed possibilities:

1. Venus formed from dry embryos from interior to its present orbit
2. Earth just as dry, water delivered later
3. Venus just never recycled, because no subduction

Mega-Collision

- Basis of Moon-forming impact theory was the dryness of returned Moon rocks
- A planet-disrupting impact could have a similar effect on Venus
- Would require two similar-mass proto-Venuses, impacting head-on
  - Totally disrupts, but combines as a single body

Impact Conditions

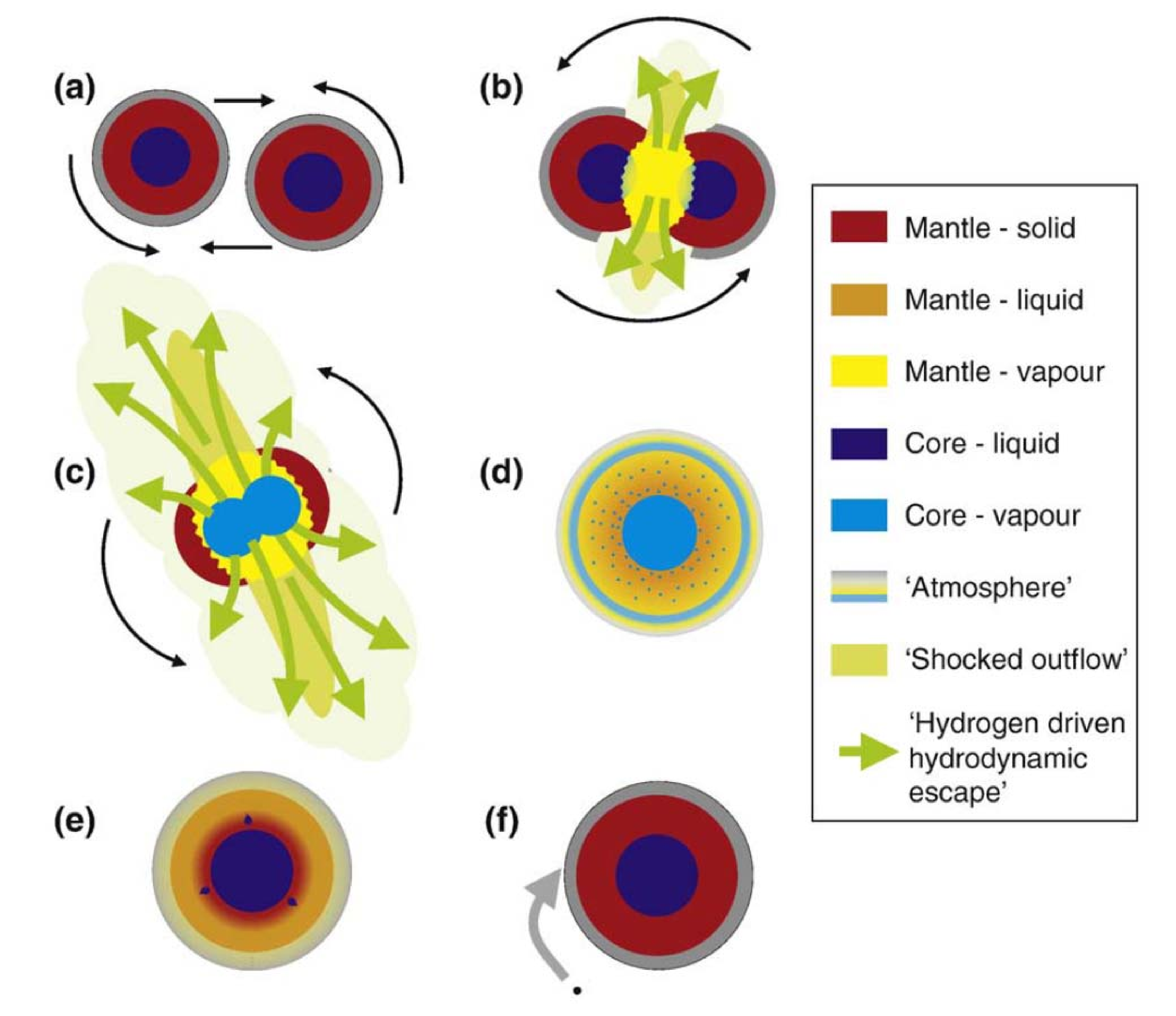
- Requires >10 Gpa across most of mantle(s) to totally dehydrate
- Scaling off Canup et al.'s Moon-forming impact simulations, two similar-sized impactors
- Also, low impact angle (<30°) more probable than Earth-Moon glancing impact

Atmospheric Effects

- After impact, the CO_2 should survive longer than H_2O due to lower UV photolysis and solar wind loss
- Also, the impact would devolatilize any carbonates, further increasing the CO_2 in the atmosphere

Compositional Effects

- Impact would initially produce large amounts of rock and iron vapor, insulated by CO_2 layer
- Most available water vapor oxidizes iron
- Mantle forms as a magma ocean, exclusive of water and CO_2
- Remaining water in atmosphere is gradually stripped away


(a)
(b)
(c)
(d)
(e)
(f)
Mantle - solid
Mantle - liquid
Mantle - vapour
Core - liquid
Core - vapour
'Atmosphere'
'Shocked outflow'
'Hydrogen driven hydrodynamic escape'

Spin Effects

- Final angular momentum is controlled by last few impacts (Agnor et al, 1999)

- Low angular momentum, retrograde spin consistent with near head-on collision (Canup and Ward, 2001)
  - Also consistent with no satellite formation

Venus Summary

- Single, very large impact could explain Venus's
  - Apparently dry atmosphere
  - Thick CO_2 atmosphere
  - Slow retrograde rotation

- However, needs proper simulations for verification


MEGA-COLLISION
VENUS
Firestone