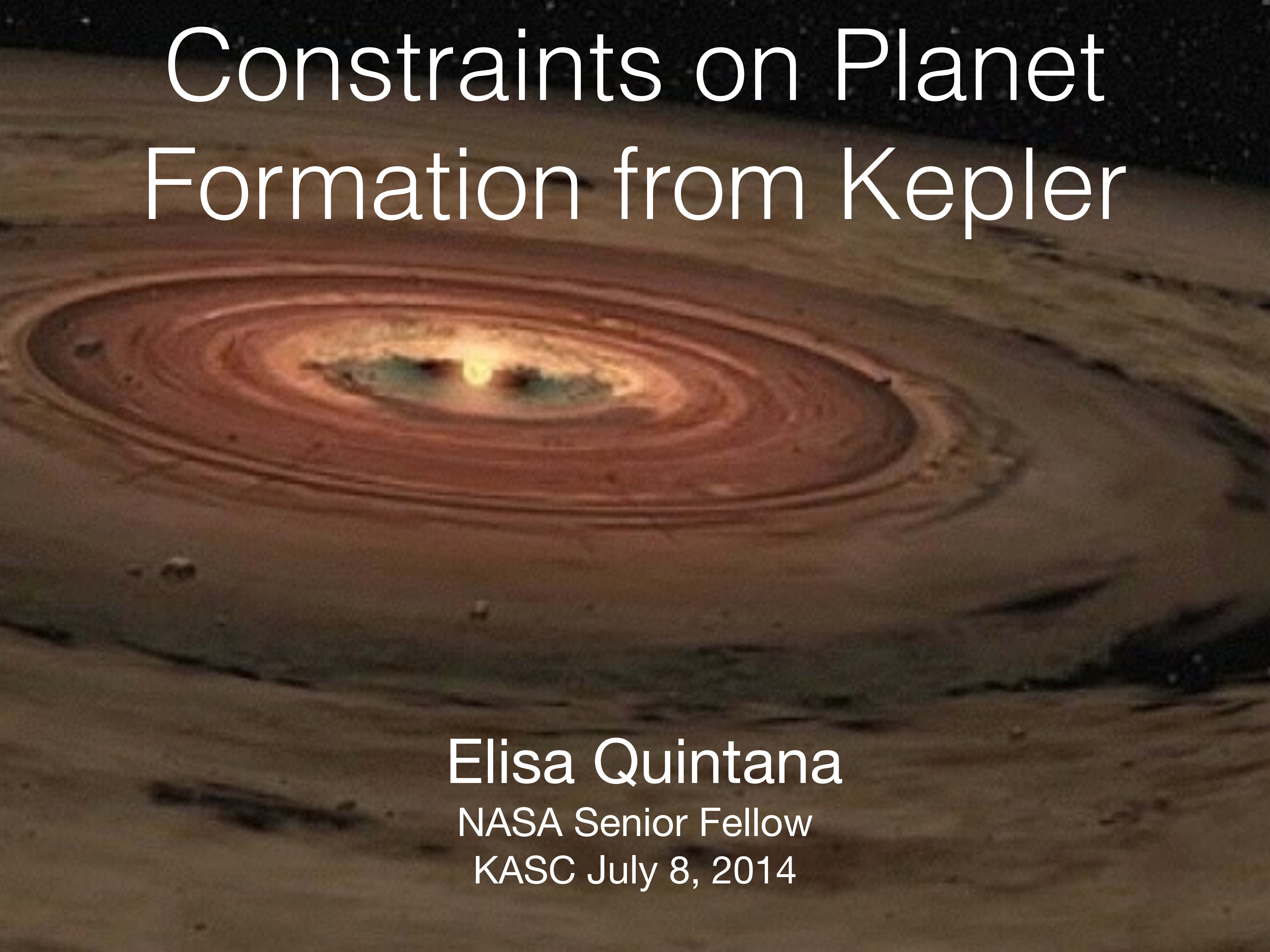

Constraints on Planet Formation from Kepler

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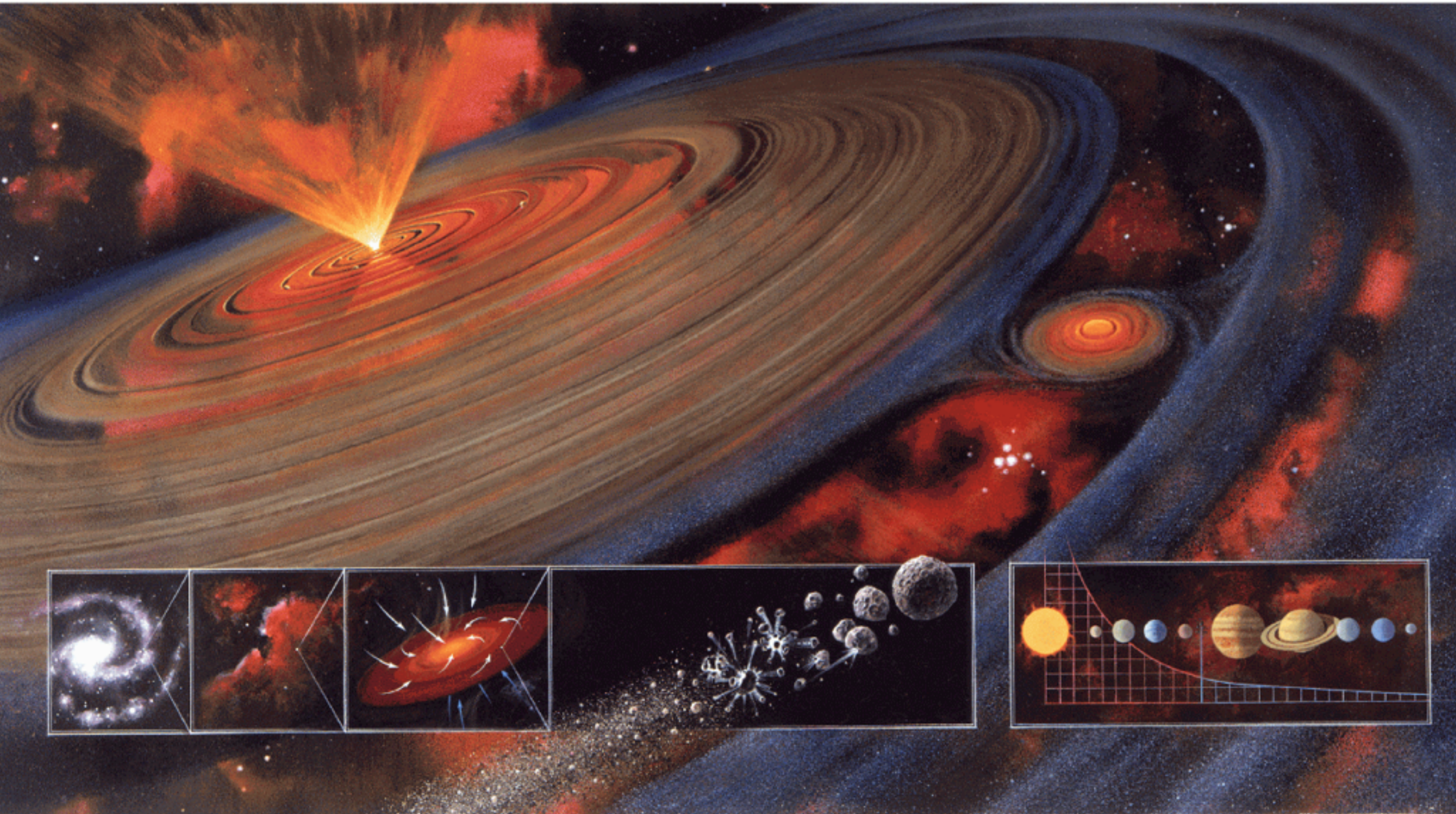
KASC July 8, 2014

Solar Nebular Theory



Formation of Solar System Planets

Early stage

dust grains → planetesimals
~ μm ~1-10 km

- non-gravitational sticking process remains poorly understood

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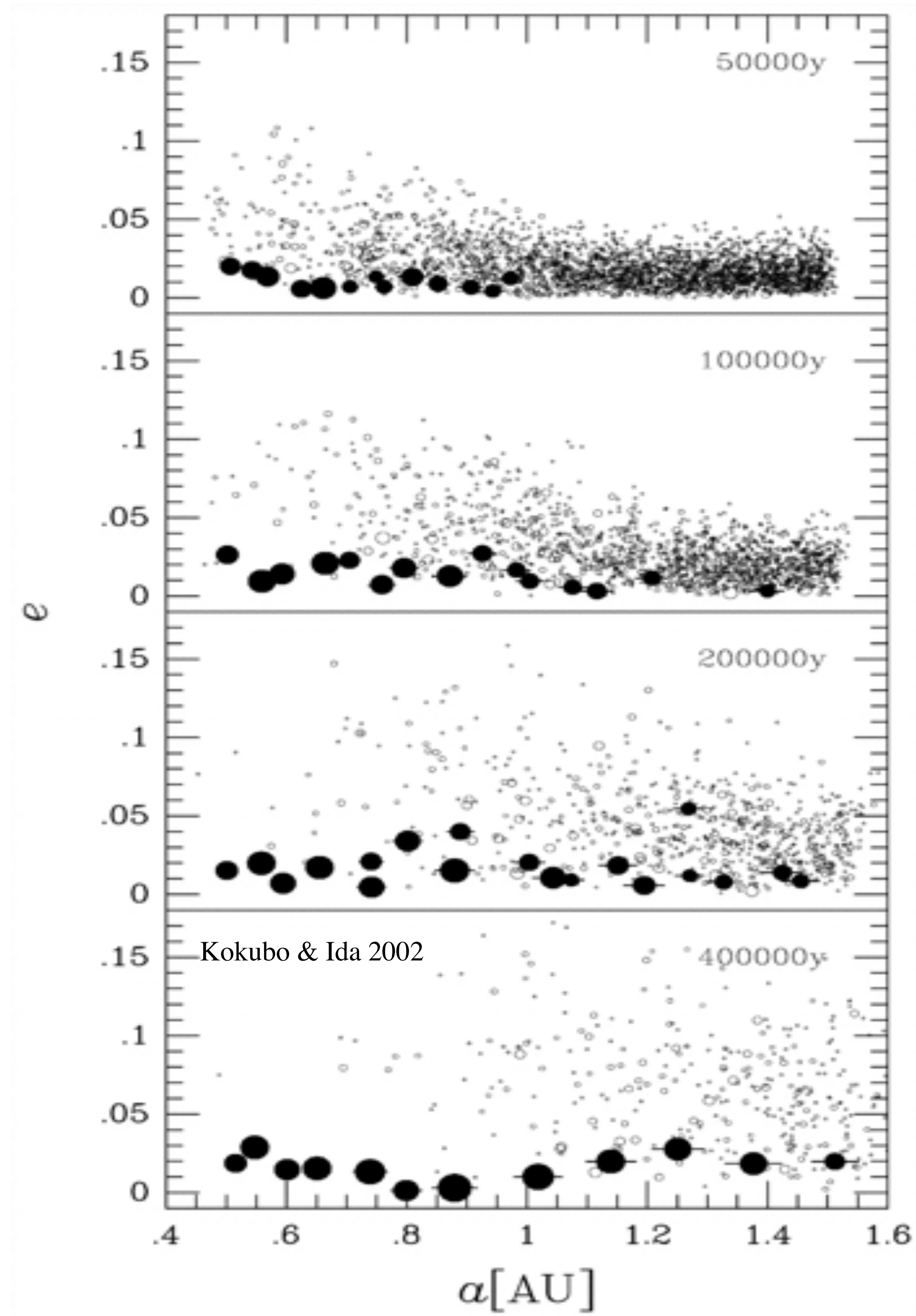
Middle stage

planetesimals ⟶ planetary embryos
~10^3 km



Formation of Solar System Planets

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Late stage

embryos → planets

Formation of Solar System Planets

Early stage

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Timescales/composition support *In Situ* formation for Solar System

Middle stage

planetesimals → planetary embryos

~10^3 km

Late stage

embryos → planets

Formation of Solar System Planets

***N*-body integrators widely used algorithms to study planetary accretion**

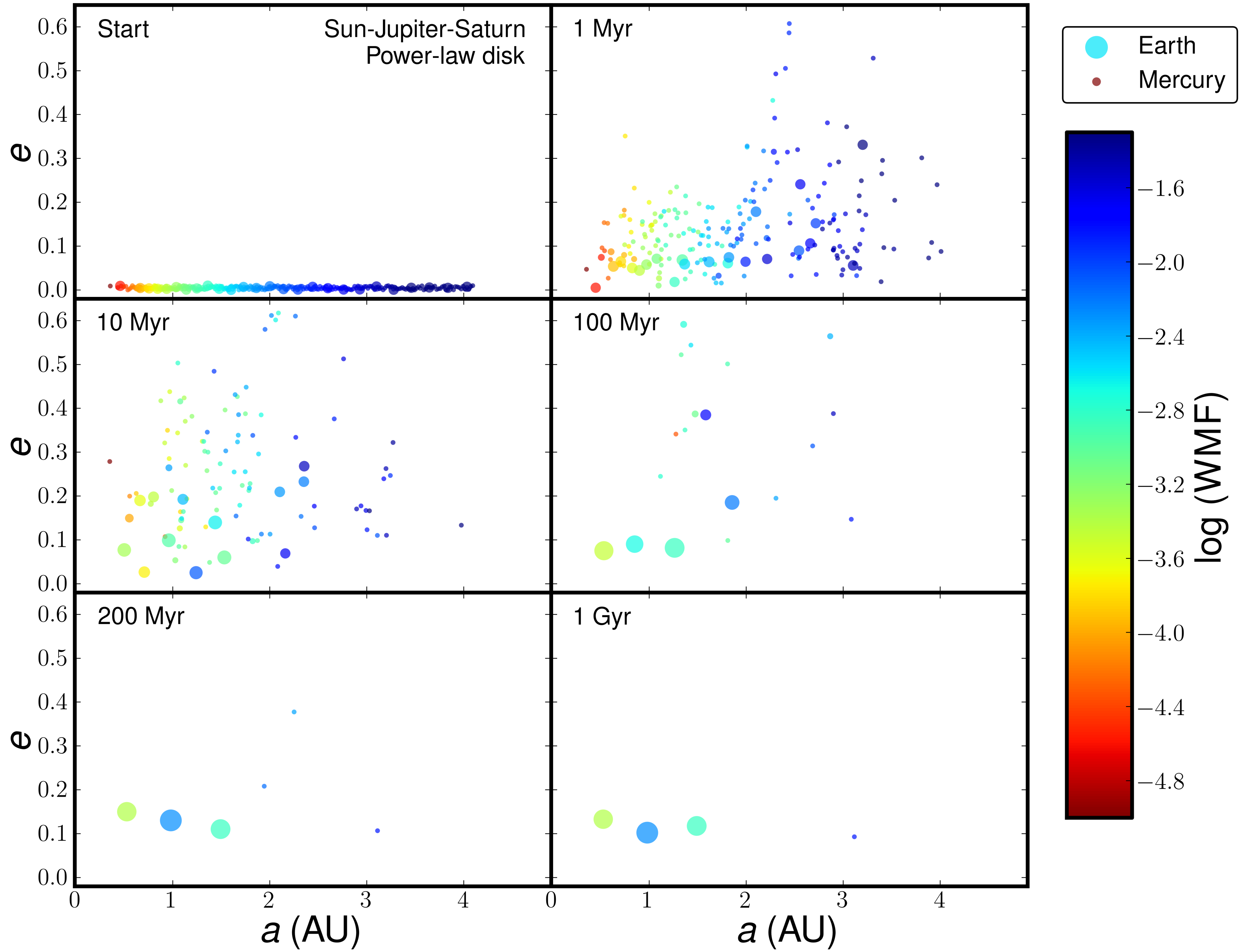
- close encounters are integrated with high accuracy (Bulirsch-Stoer)
- gravitational perturbations and inelastic collisions
- late stage accretion N = 10^2 - 10^3

Disk Model based on *Minimum Mass Solar Nebula*: protoplanetary disk that contains the minimum amount of solids necessary to build the planets of the Solar System.

Surface density $\sigma = \sigma_0 \, (a \,/\, 1\ \mathrm{AU})^{-3/2}$

$\sigma_0 \sim 6$ g/cm^2 at 1 AU

Solar System Terrestrial Planets



This model has worked well to model the Solar System terrestrial planets

Kepler's Multiplanet Systems

Observations

> 600 Kepler multiple planet candidate systems

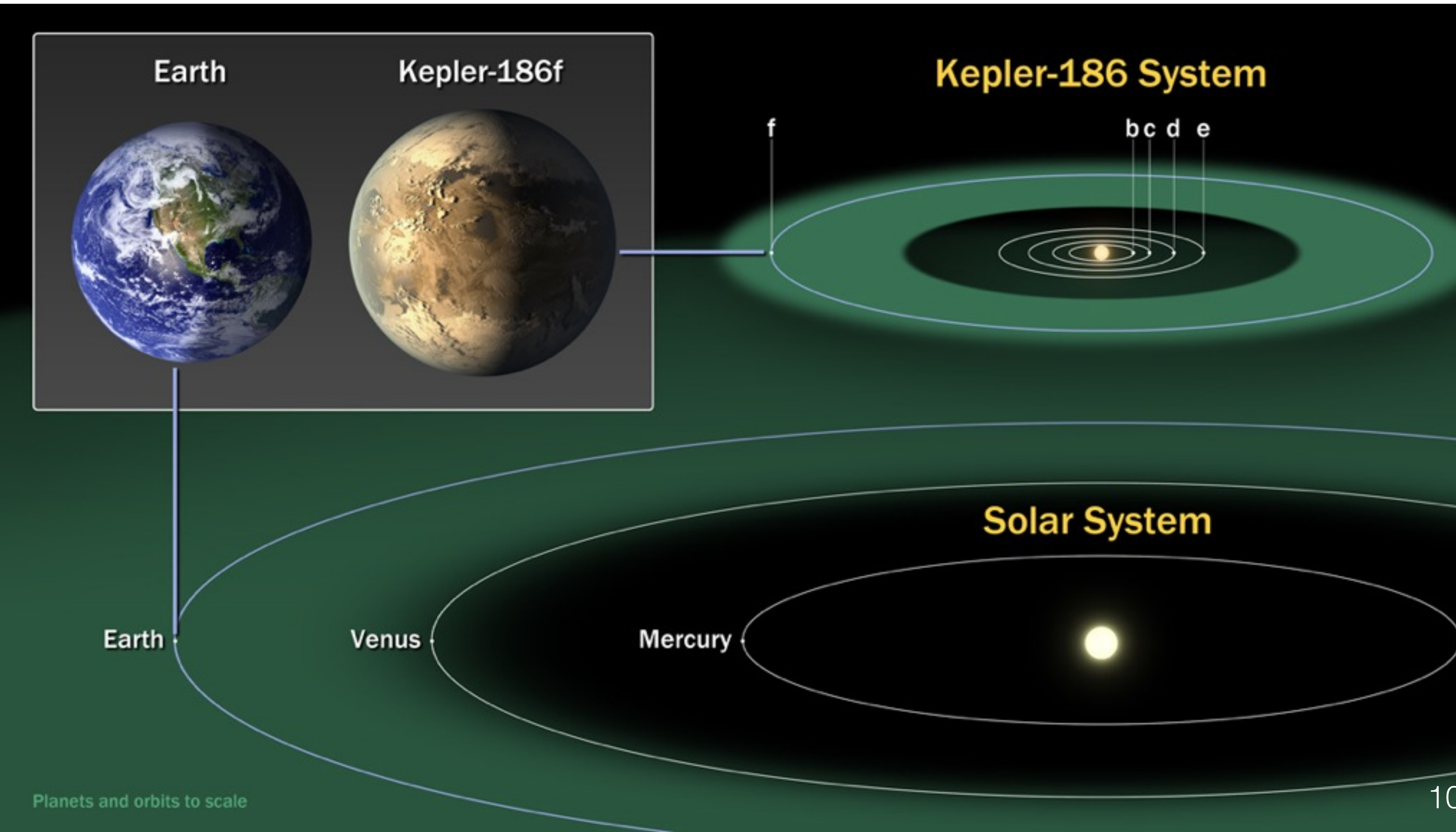
- many are compact systems of super-Earth and sub-Neptune
- giant planets appear to be rare

No universal minimum mass disk

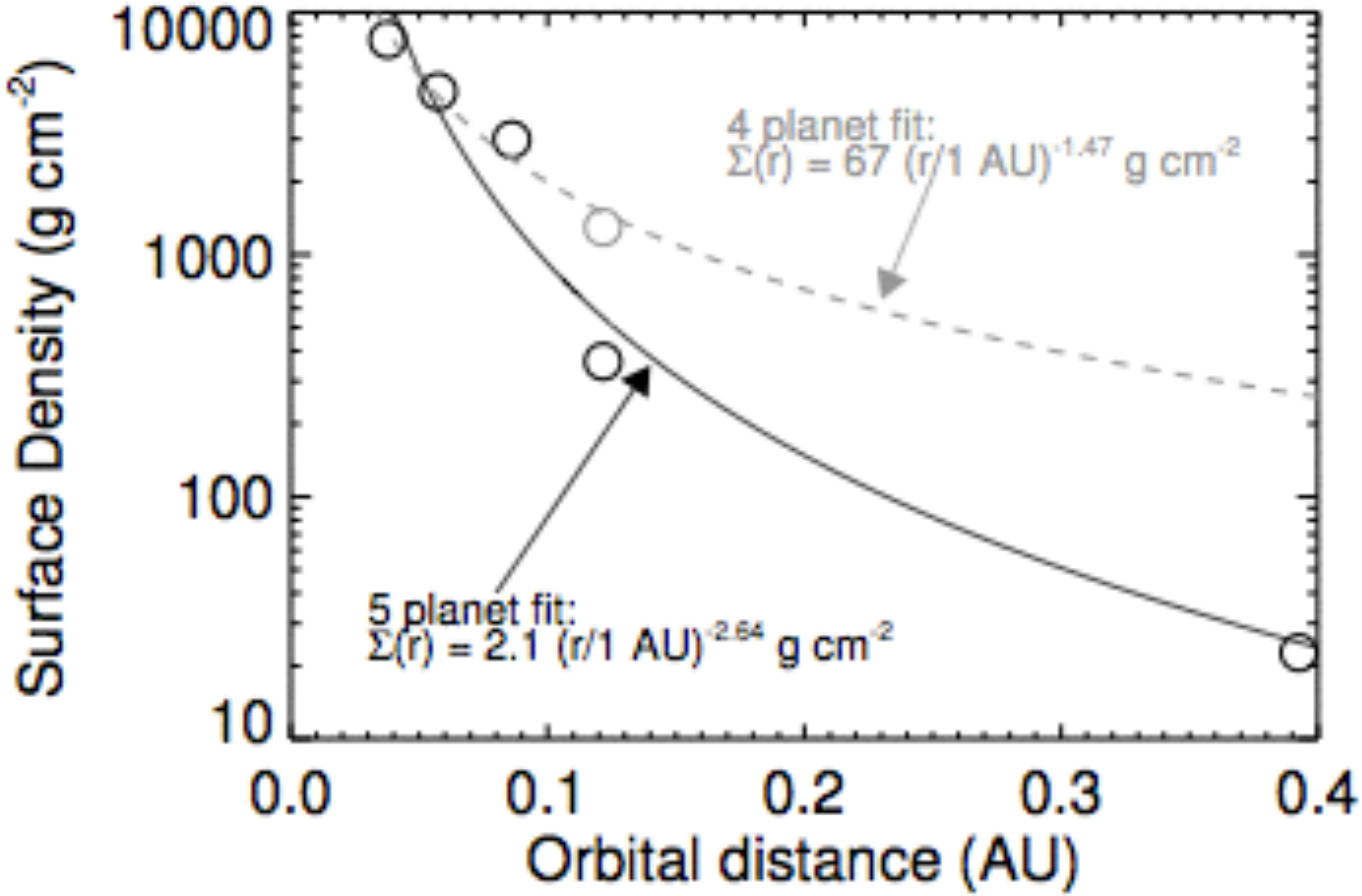
- "Minimum Mass Extrasolar Nebula" disks have wide range of surface density profiles $\Sigma \propto r^{-3.2}$ to $\Sigma \propto r^{0.5}$ (Raymond & Cossou 2014)

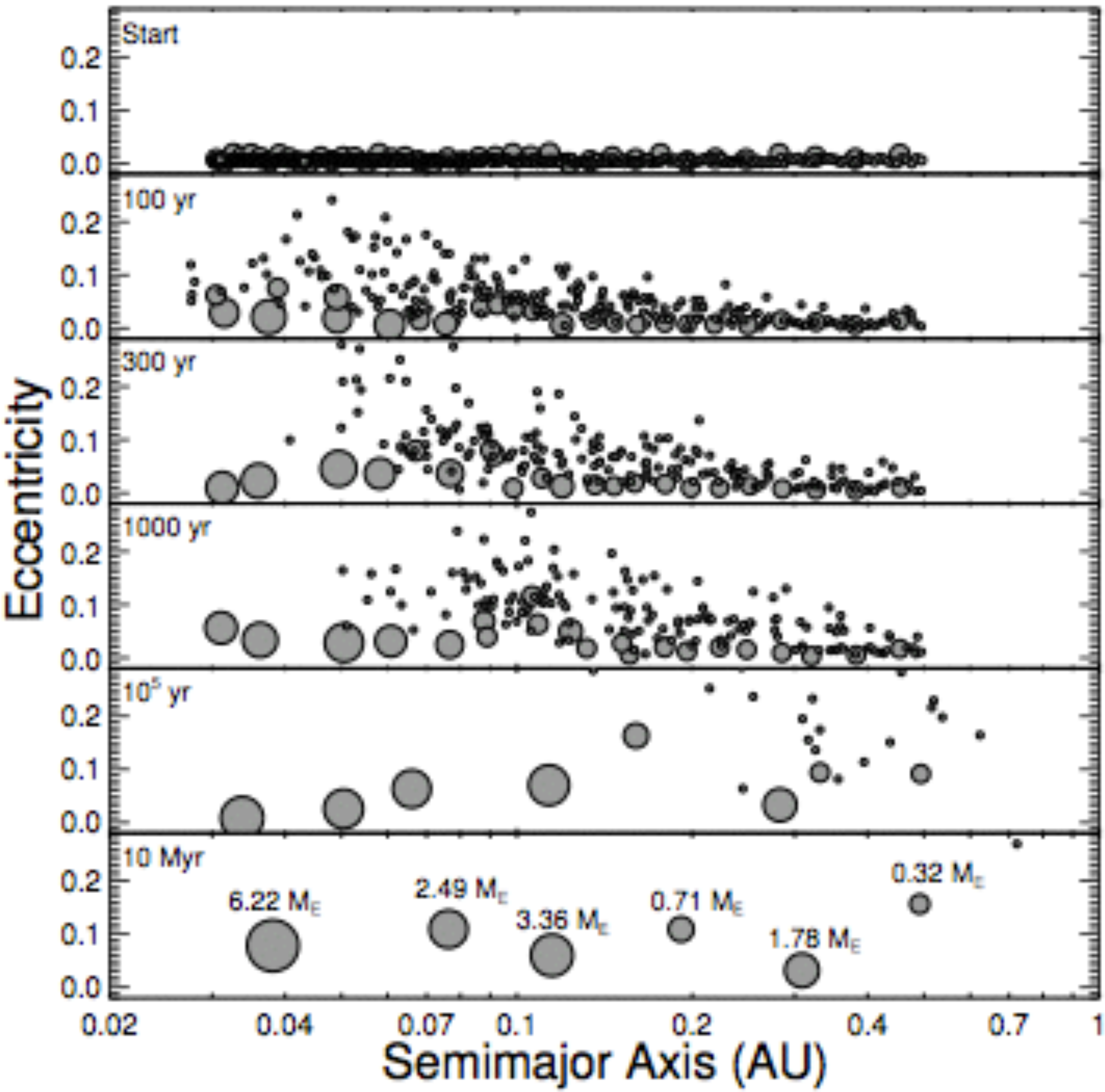
Is there a common formation mechanism for these systems?

Kepler-186 System

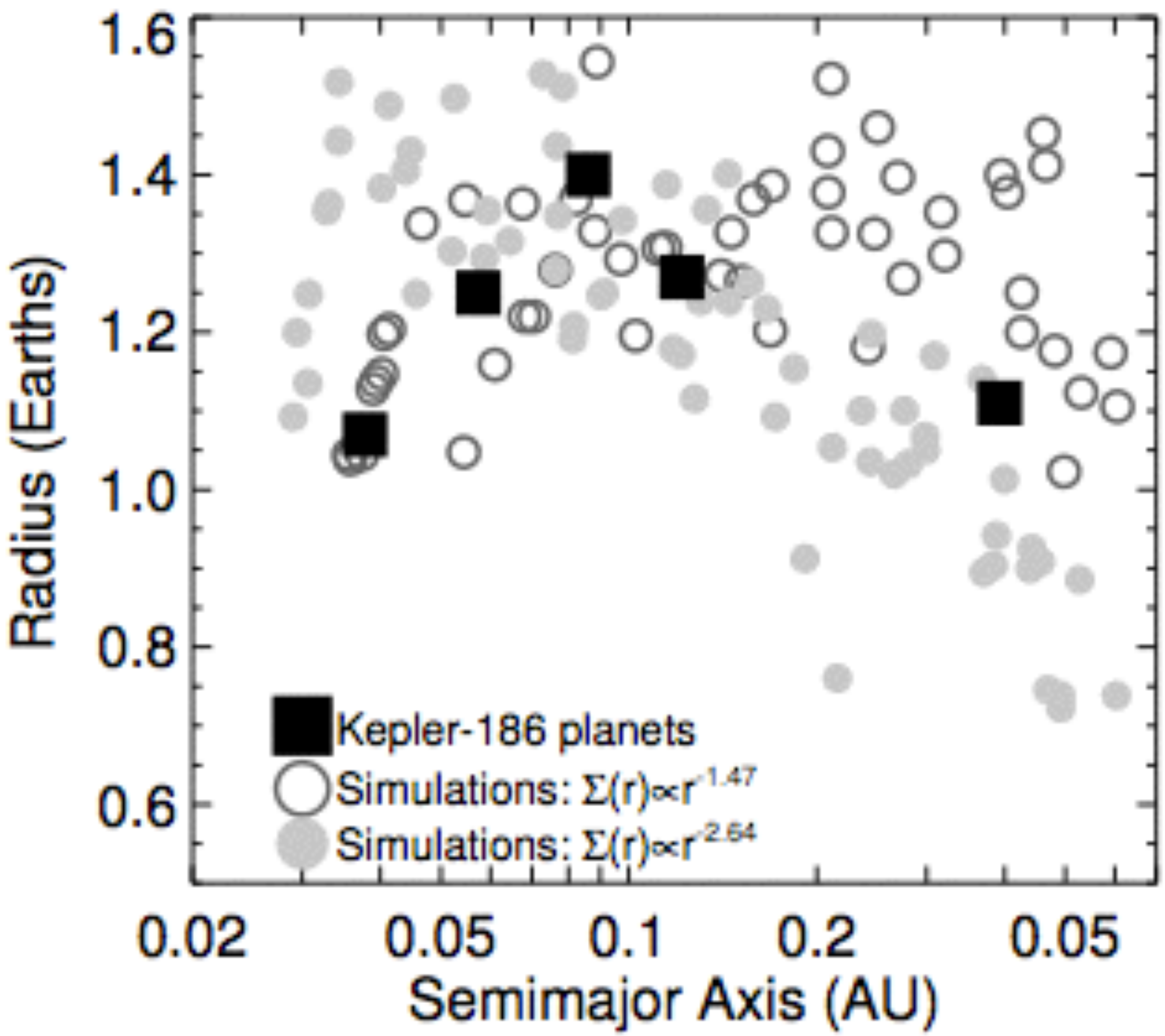


Minimum Mass Disk



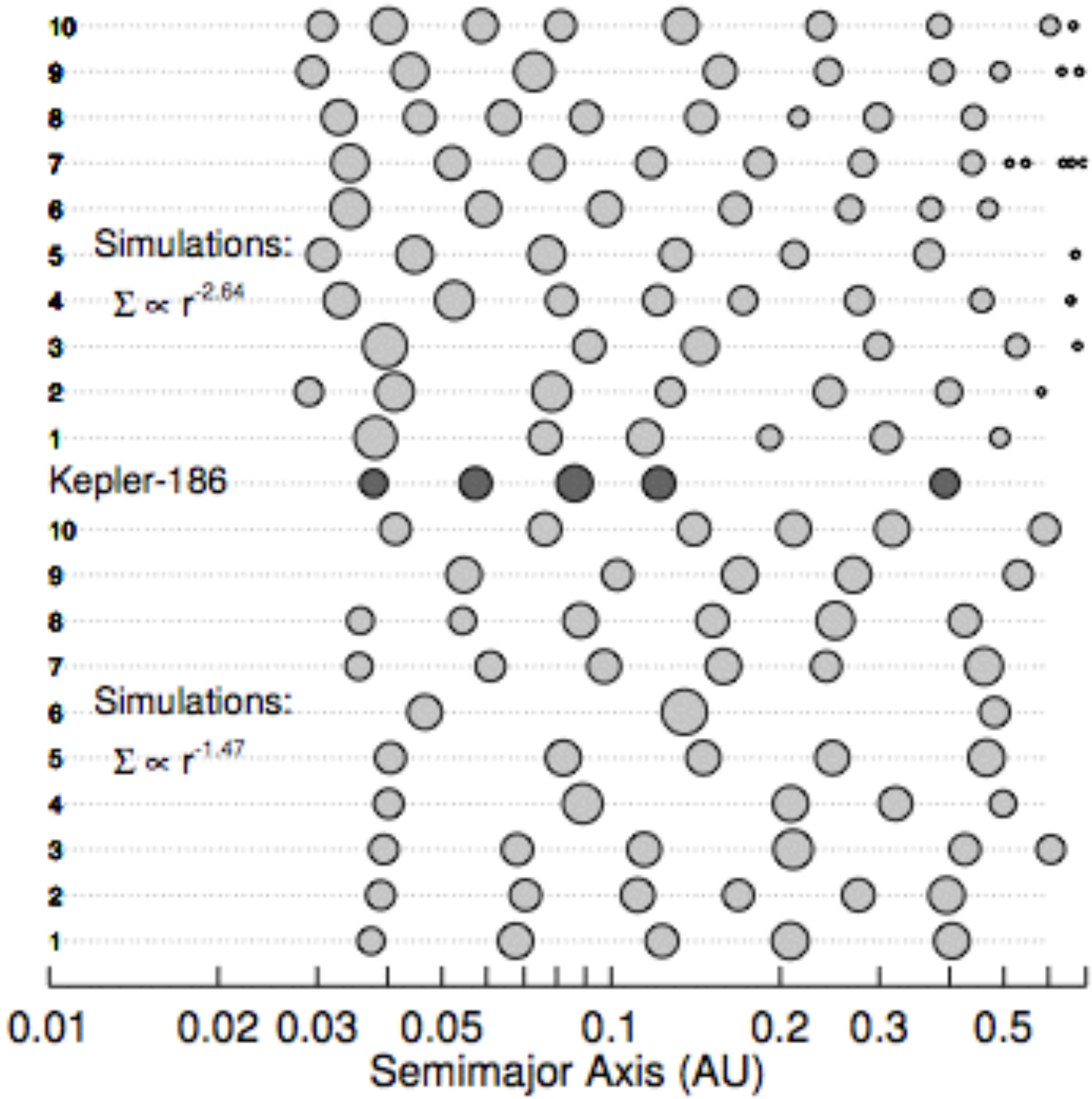


Start
100 yr
300 yr
1000 yr
10^5 yr
10 Myr
6.22 M_E
2.49 M_E
3.36 M_E
0.71 M_E
1.78 M_E
0.32 M_E
0.0
0.1
0.2
Eccentricity
0.02
0.04
0.07
0.1
0.2
0.4
0.7
1
Semimajor Axis (AU)



To form In Situ:

- steep profile
- >10 Mearth of disk mass


10
9
8
7
6
Simulations:
5
$\Sigma \propto r^{-2.64}$
4
3
2
1
Kepler-186
10
9
8
7
Simulations:
6
5
$\Sigma \propto r^{-1.47}$
4
3
2
1
0.01
0.02
0.03
0.05
0.1
0.2
0.3
0.5
Semimajor Axis (AU)

Conclusions (1/2)

For in situ accretion of most Kepler multis:

- need very massive disks that aren't commonly observed

- planet architecture should reflect initial radial distribution of disk material (solid and gas).

Models of gaseous disks can only explain a narrow range of surface density profiles ($\Sigma \propto r^0$ to $\Sigma \propto r^{-1.5}$)

Most known systems of hot super-Earths could not have formed predominantly *In Situ*

Conclusions (2/2)

Formation of Kepler-186 planets and other multis was most likely from a combination of:

(1) accretion during an inward migration of a population of planetary embryos to increase the solid surface density in the inner disk

(2) final phase of late-stage accretion

Currently modifying N-body algorithms to include aerodynamic gas drag (ecc/inc damping) and gravitational gas drag due to tidal interactions (to induce migration)