Formation theory of Earth

Shigeru Ida (ELSI, Tokyo Tech)

OUTLINE

- Overview and perspectives of theory of terrestrial planet formation
  - Evolving by observations of exoplanets
  - Getting able to predict "Early Earth" and ubiquity/diversity of "habitable" exoplanets

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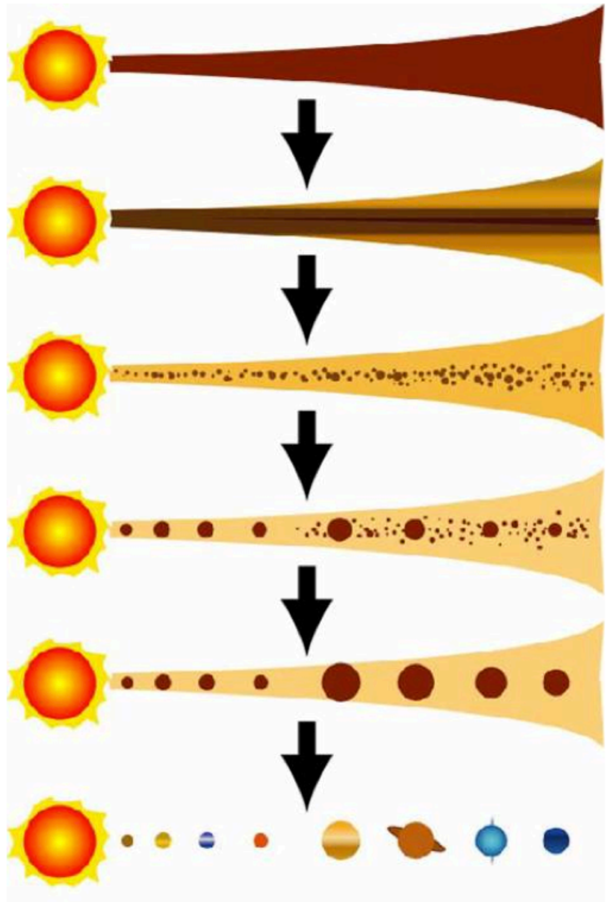
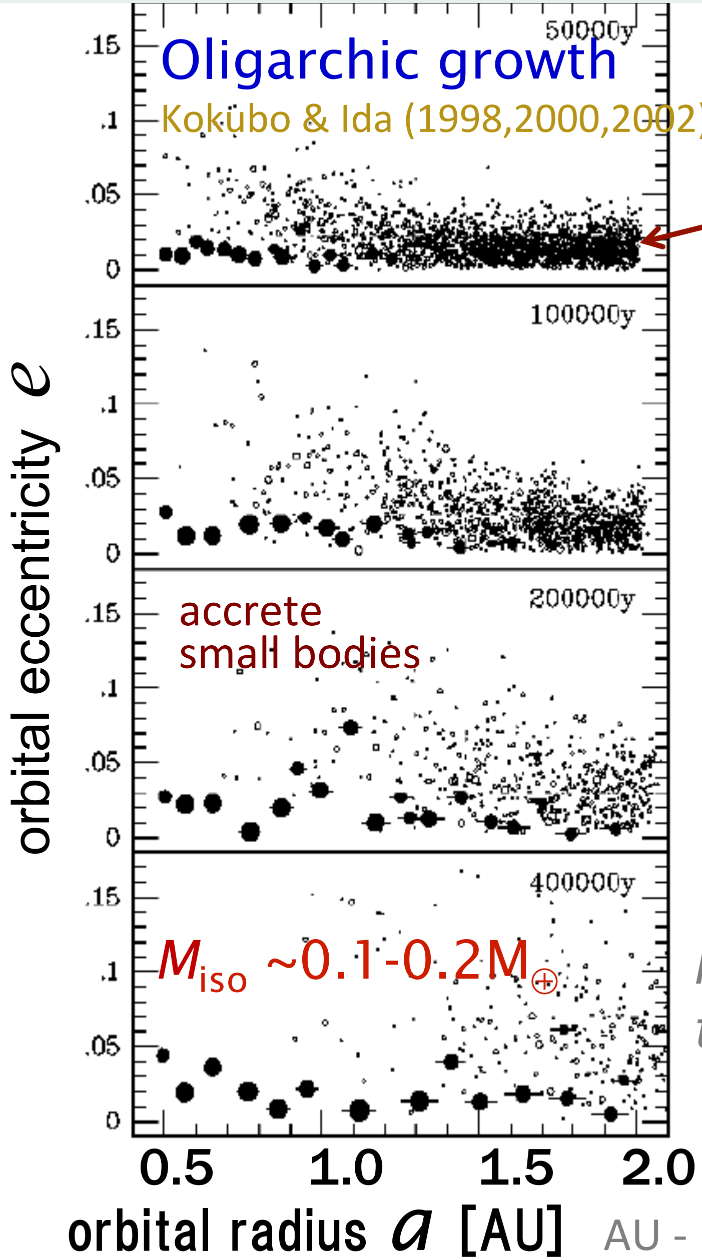
Plant Formation

- Early Earth: venue of birth of Life
- Formation processes of the Earth
  → atmosphere, H_2O ocean, magma ocean, ...
- Planet formation
  - ➢ in a circumstellar disk
    - disk: H/He gas + 1wt.% dust
    - dissipates in a few Myrs
      → planets: left behind
    - interaction with disk gas
      → dust, planet undergo orbital migration
  - ➢ multiple processes
    dust(μm) → planetesimals(~1-10km)
    → rocky & icy planets(~10^{3-4}km)
    → gas giant planets(~10^{4-5}km)



"Classical" model for formation of terrestrial planets



start from
equal masses

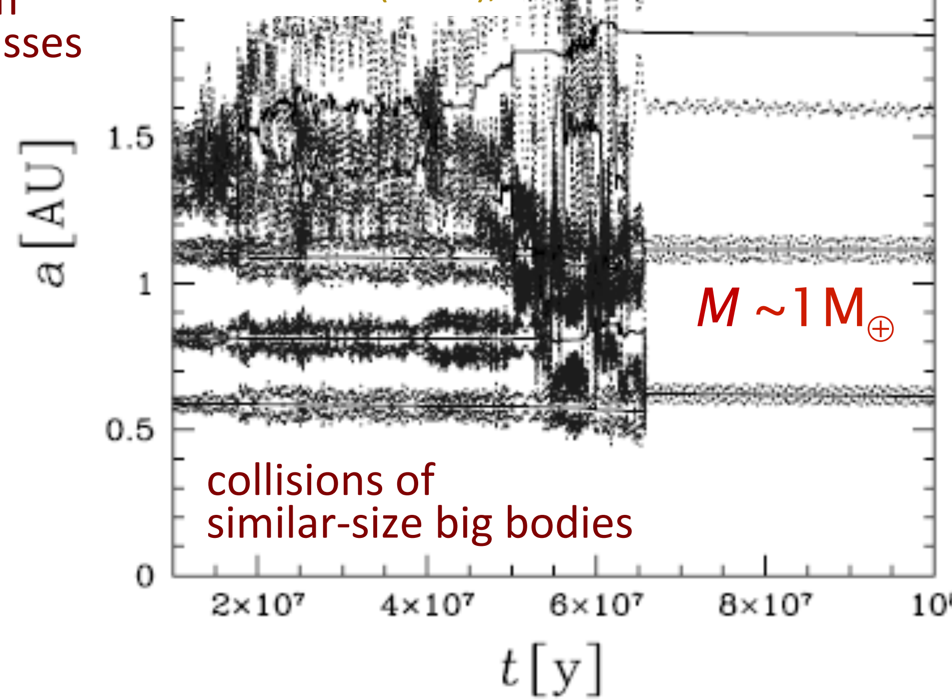
$M_{iso} \propto (M_{disk} \eta_{ice})^{3/2} a^{3/4}$

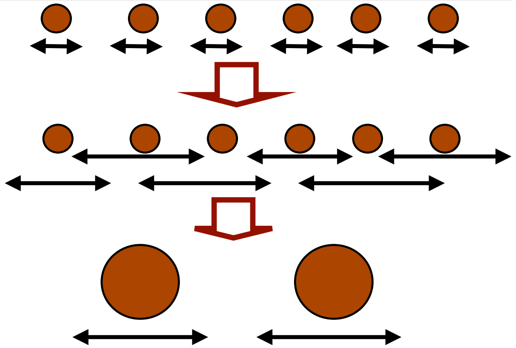
$t_{grow} \propto (M_{disk} \eta_{ice})^{-1} a^{3}$

AU - Earth's orbital radius

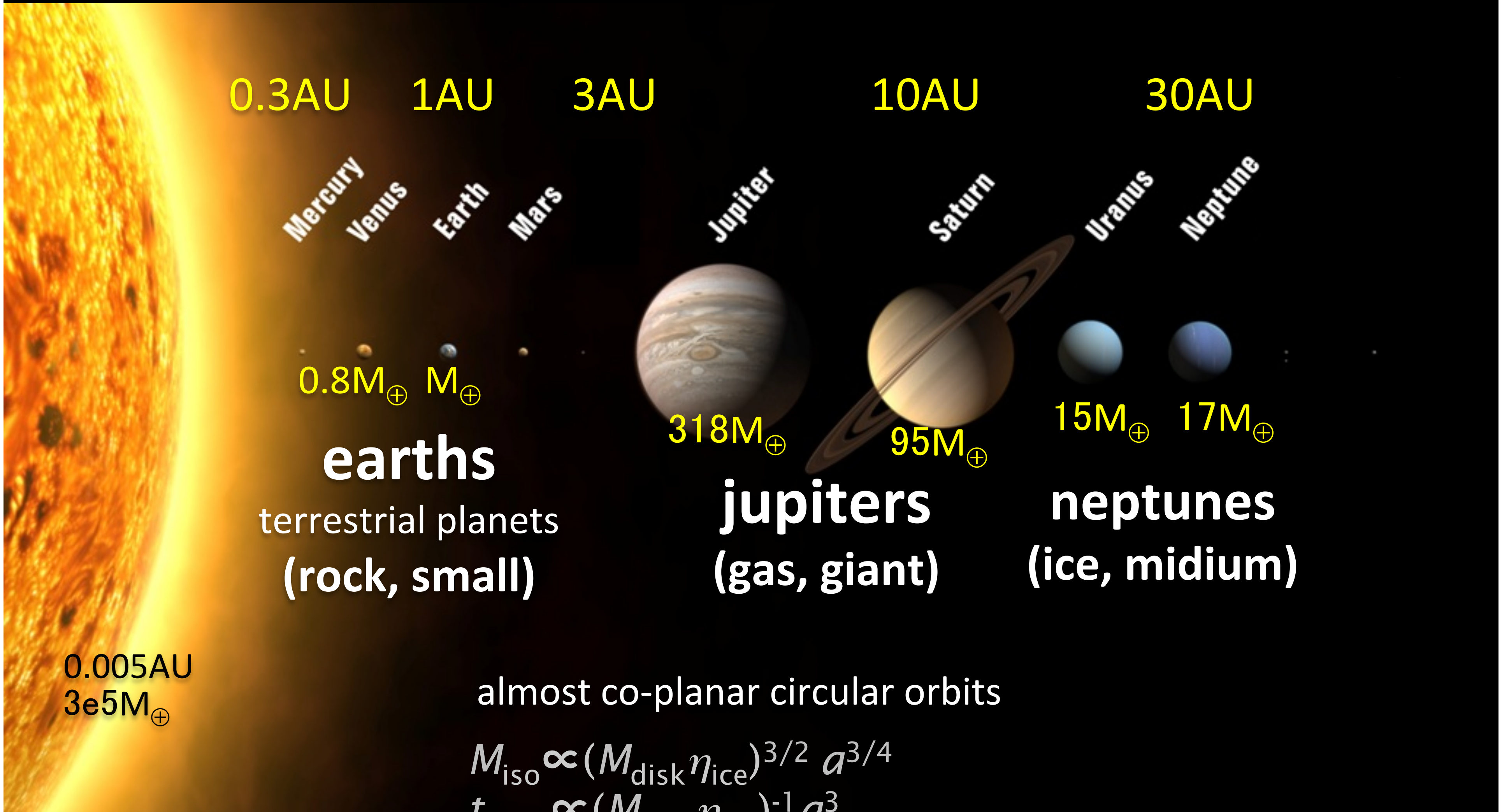
Post-oligarchic giant impacts

Lissauer (1986), Chambers & Wetherill (1998), Agnor et la. (1999), Raymond et al. (2003), Kokubo et al. (2006), ...





Solar System



almost co-planar circular orbits

$$M_{iso} \propto (M_{disk}\eta_{ice})^{3/2}\, a^{3/4}$$

$$t_{grow} \propto (M_{disk}\eta_{ice})^{-1}\, a^{3}$$

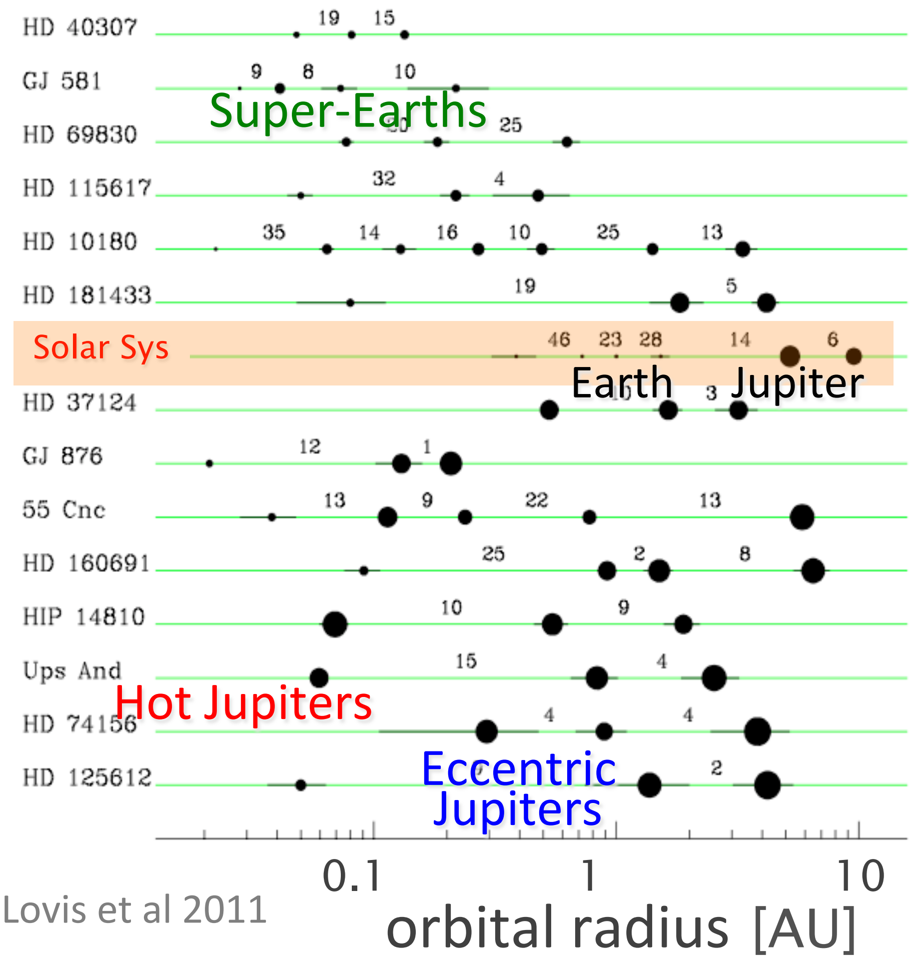
$M_\oplus = 6\text{x}10^{24}$ kg

AU = $1.5\text{x}10^{8}$ km

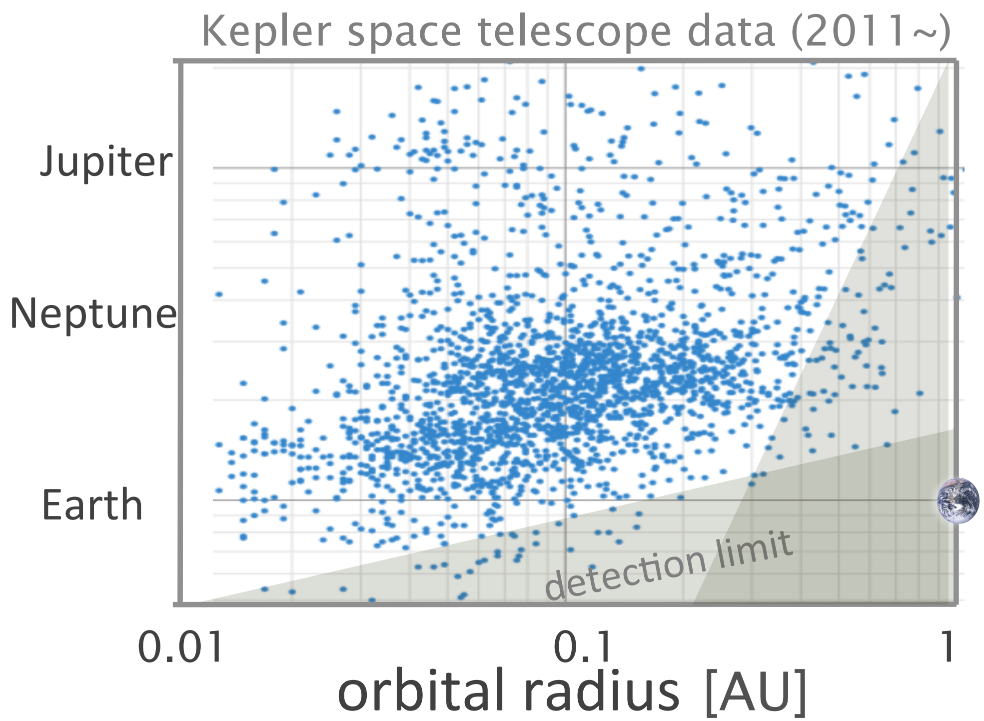
Discovery of Exo-planets

- Before 1995 sample: ONLY Solar system
- After 1995 many samples: 670 systems, 3000 candidates
  - ➢diversity of planetary systems
  - ➢ubiquity of terrestrial planets (> 50% of solar-type stars)

→formation model change
e.g., orbital migration



Lovis et al 2011



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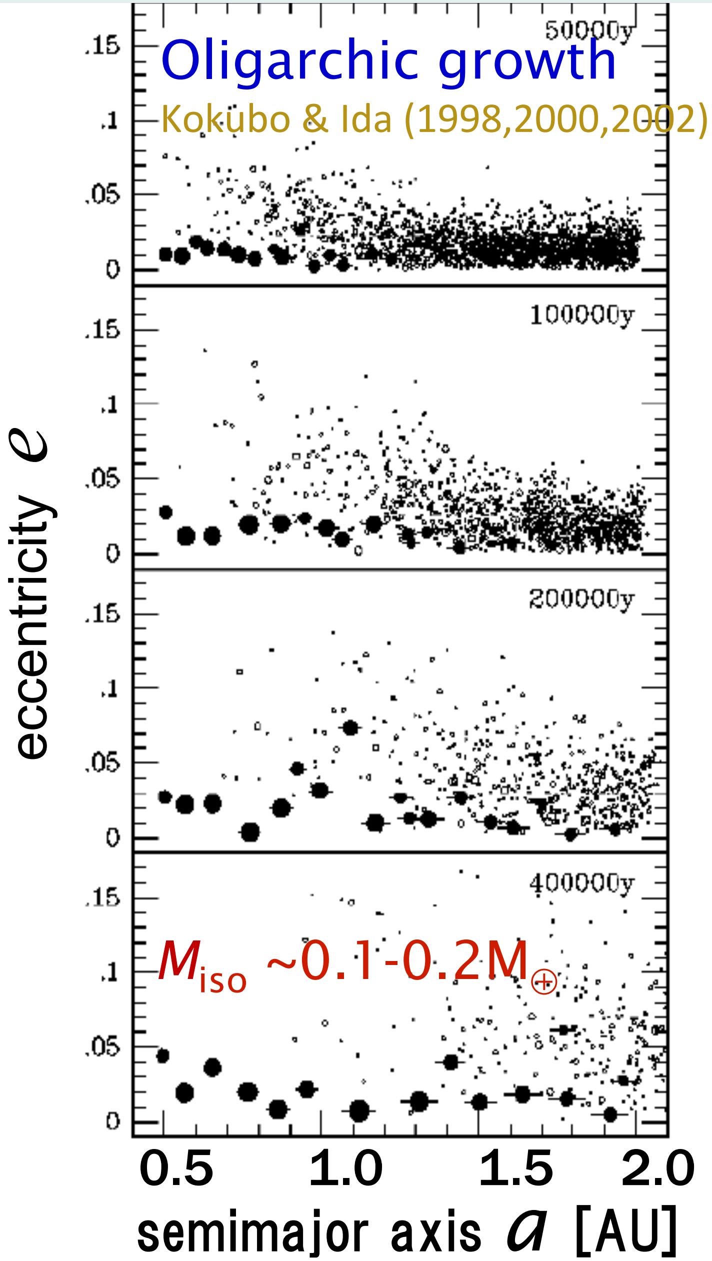
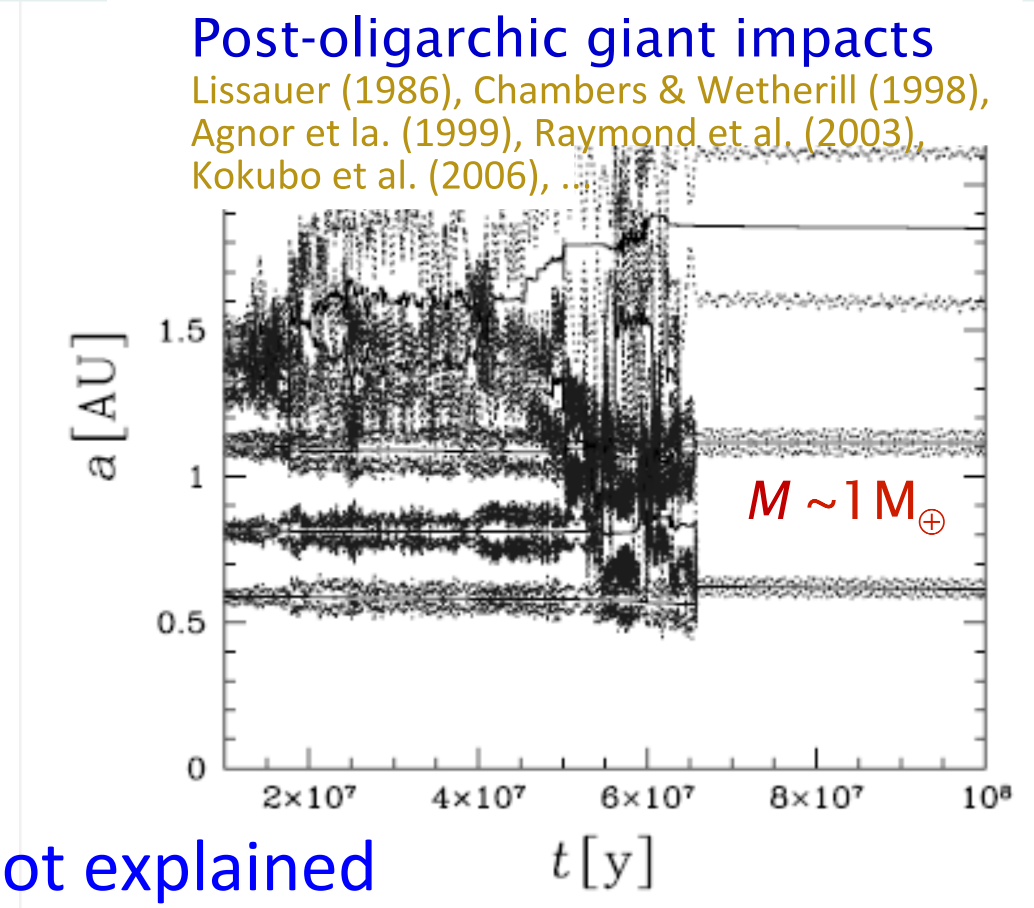
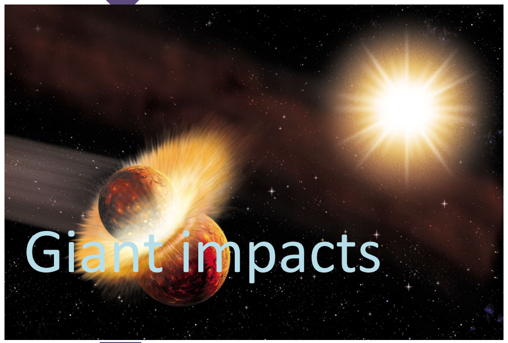




■ not explained

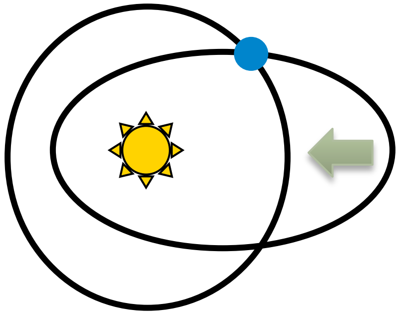
- Close-in exoplanets
- Circular orbits of Earth & Venus
- Orbital distr. of Mercury, Venus, Earth, Mars and asteroid belt

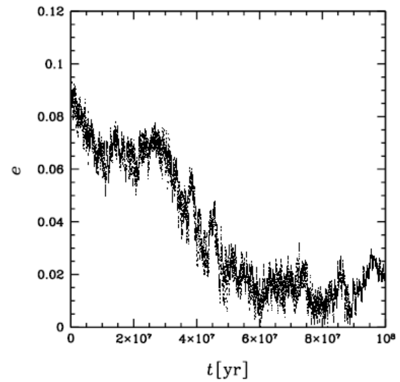
Circularization of the Earth orbit due to collision debris – H. Genda



Ejection of impact debris (rock and iron)

Circularization by dynamical friction

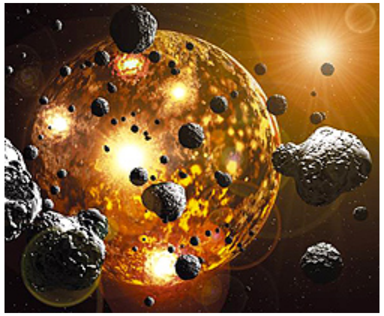


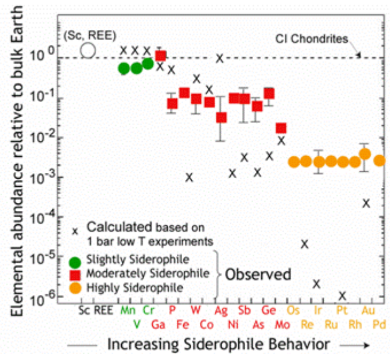


Effects on geochemistry

Late veneer, Primordial Ocean, Early Atmosphere

→ Next talk by H. Genda





Atmosphere of Early Earth

- 1950-60 reducing (CH_4, NH_3, H_2, H_2O)
  → Urey & Miller experiment
- 1980' planetesimal accretion → impact degassing
  oxidizing (CO_2, H_2O) Matsui & Abe (1986)
- 1990-2010 giant impacts still oxidizing

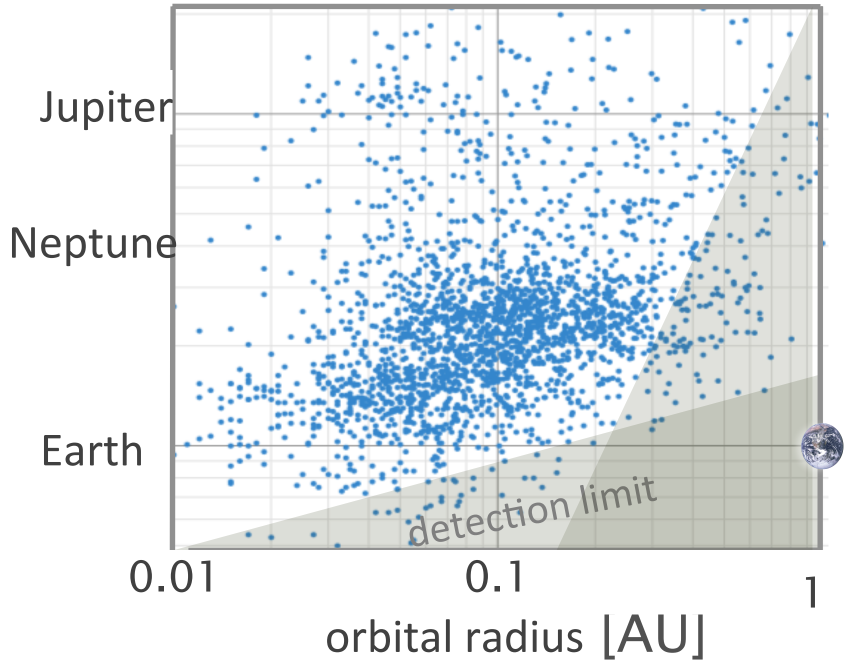
- 2010- giant impacts + debris accretion (late veneer)
  reducing (H_2-rich)?
  Genda, Sasaki, Ueno... (ELSI team)

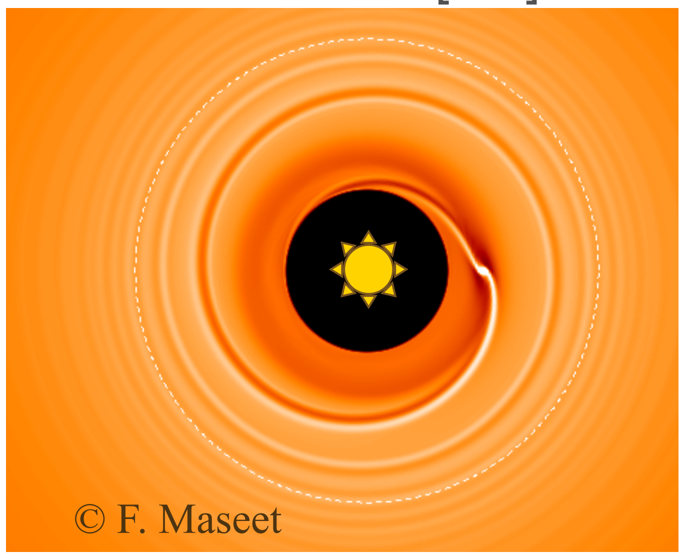
- 2005- ice grain condensation < 1AU
  Davies (2005), Garaud & Lin (2007), Oka et al. (2012)
  need to keep Earth materials "dry"

Close-in planets: Orbital migration?

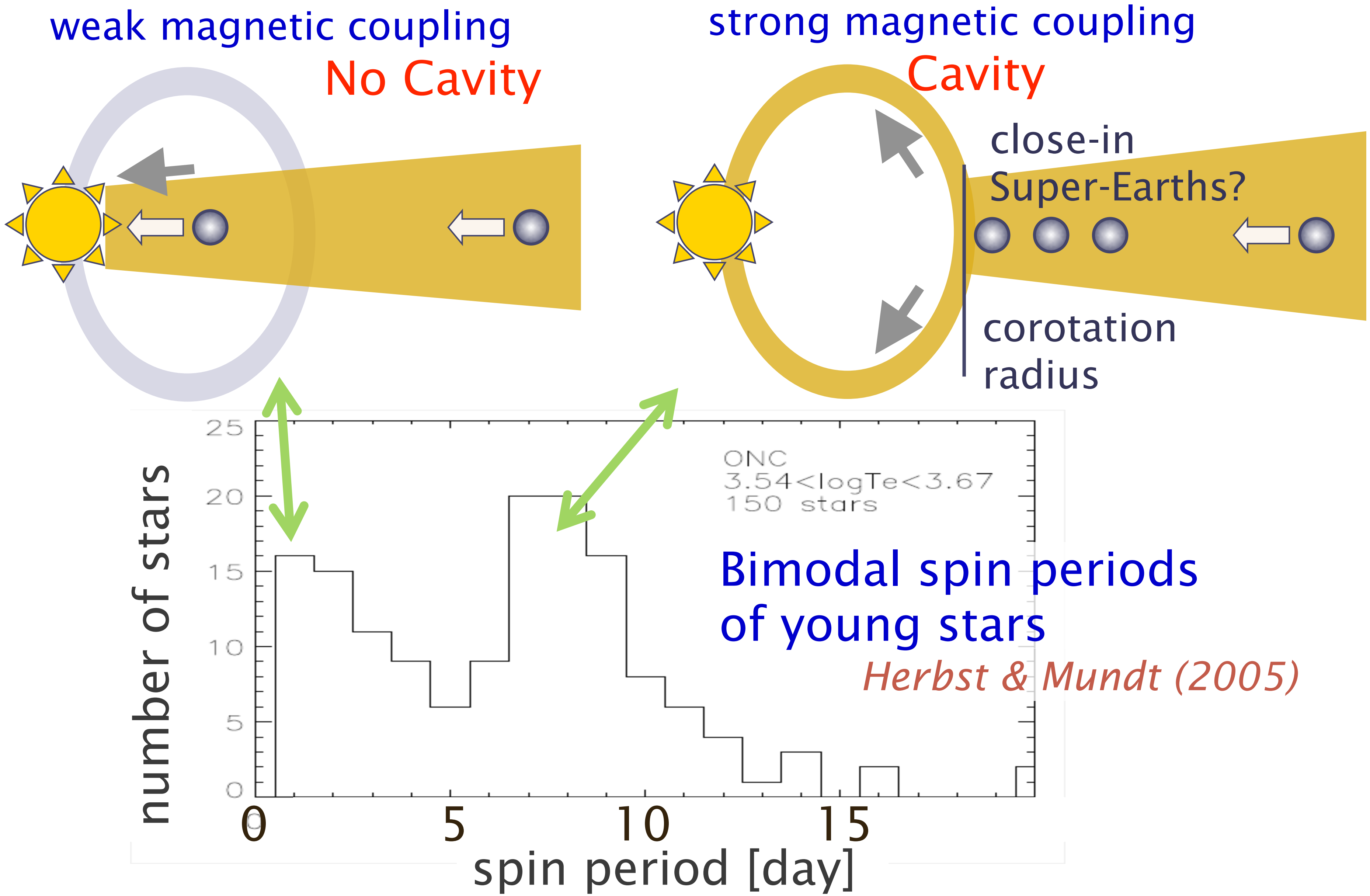
- Exoplanets: many close-in planets
  → form in outer regions
  + migrate inward ?
- Planet-disk grav. interaction
  - **rapid inward migration**
    Tanaka, Takeuchi, Ward (2002)
    → $1M_\oplus$ @1AU & $10M_\oplus$ @5AU
    fall onto a host star on < 10^5yr
    [←→ disk lifetime ~ a few 10^6yr]

- Migration is halted at disk inner edge?
  Ogihara & Ida (2009), Ida & Lin (2010)
  But, no close-in planet in Solar system





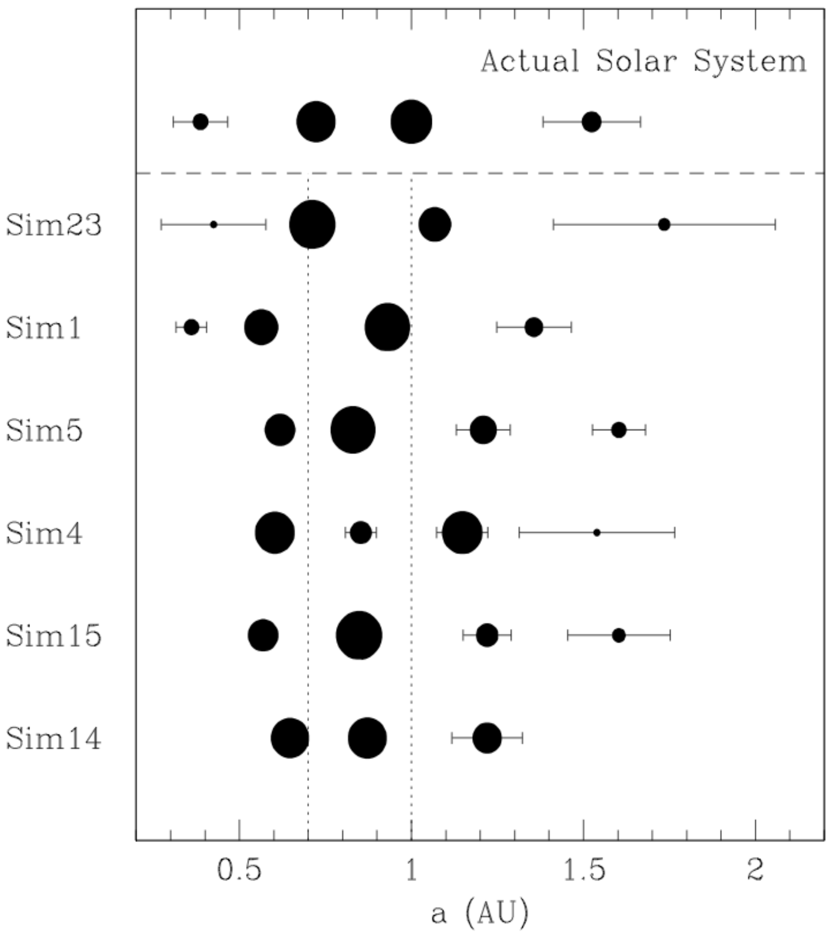
Migration trap at disk inner edge
-- evidence and diversity --

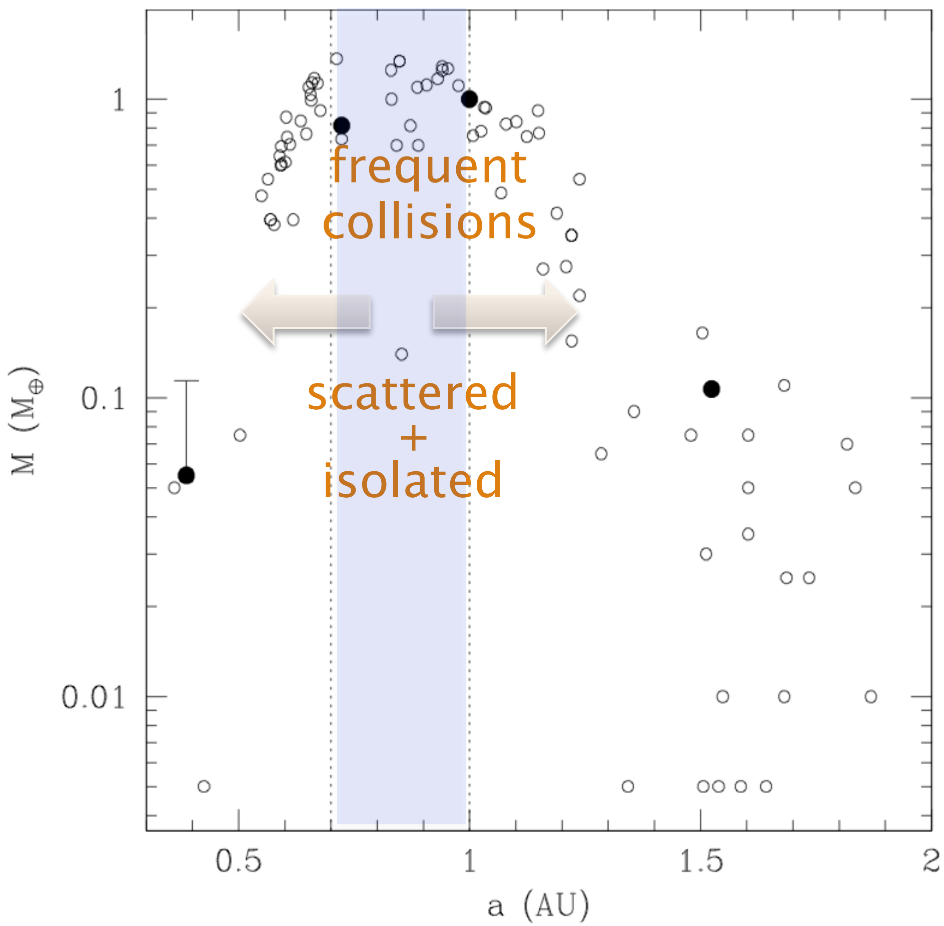


Migration trap at 0.7-1AU too?

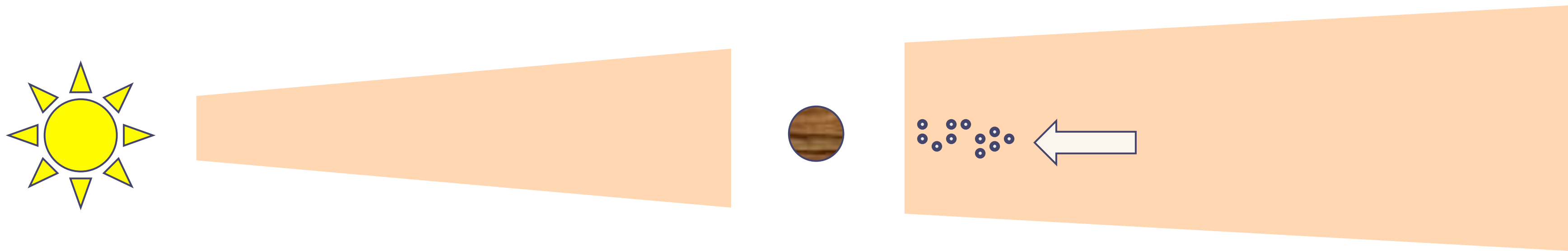
- If planetesimals are initially concentrated at 0.7-1AU, distr. of Mecury, Venus, Earth, Mars is reproduced
  [They consist of same materials?]

23 runs of N-body simulation
Hansen (2009)





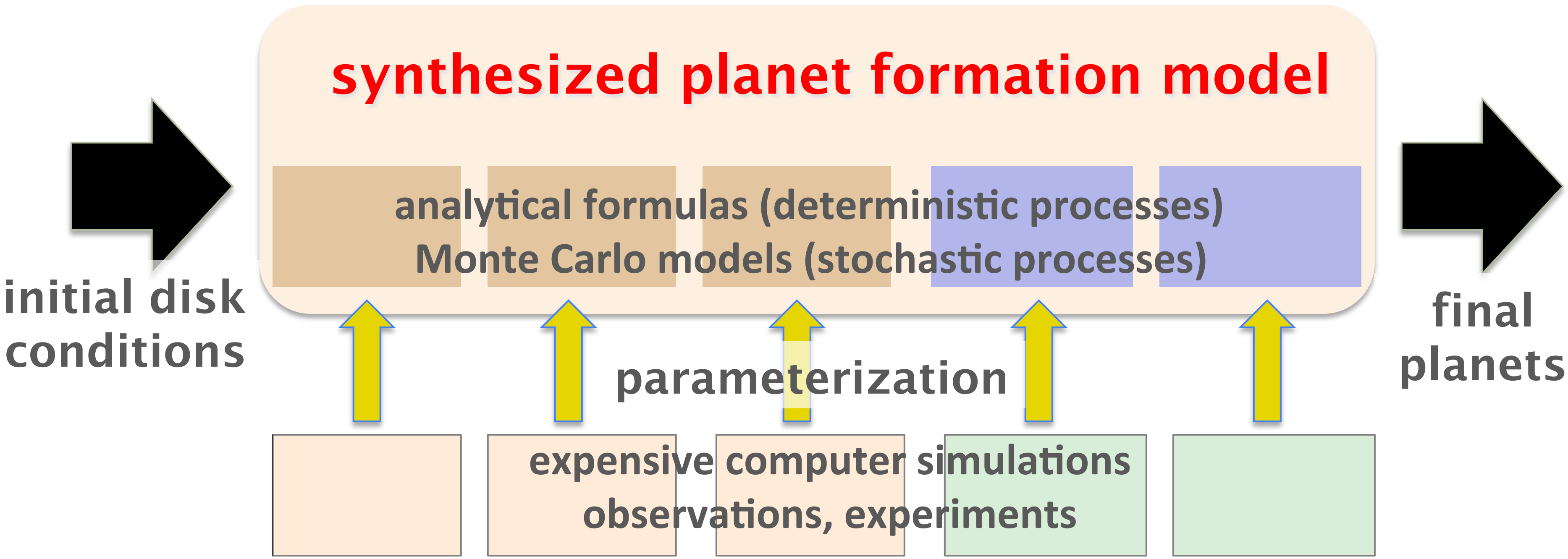
Saturn formation induced by Jupiter?



- Problem of Jupiter-Saturn system
  - Jupiter: did NOT migrate
    → formed in a decaying disk Ida & Lin (2008)
  - Saturn's core accretion: x 10 of Jovian core
    → no time to accrete disk gas
- Kobayashi, Ormel & Ida (2012)
  Jupiter formation → new migration trap at ~ 9AU
  → rapid Saturn formation

Population synthesis model

Ida+Lin (2004-), Alibert+Mordasini+Benz (2009-) → Y. Alibert's talk



Combine individual processes to *predict distributions of exoplanets*

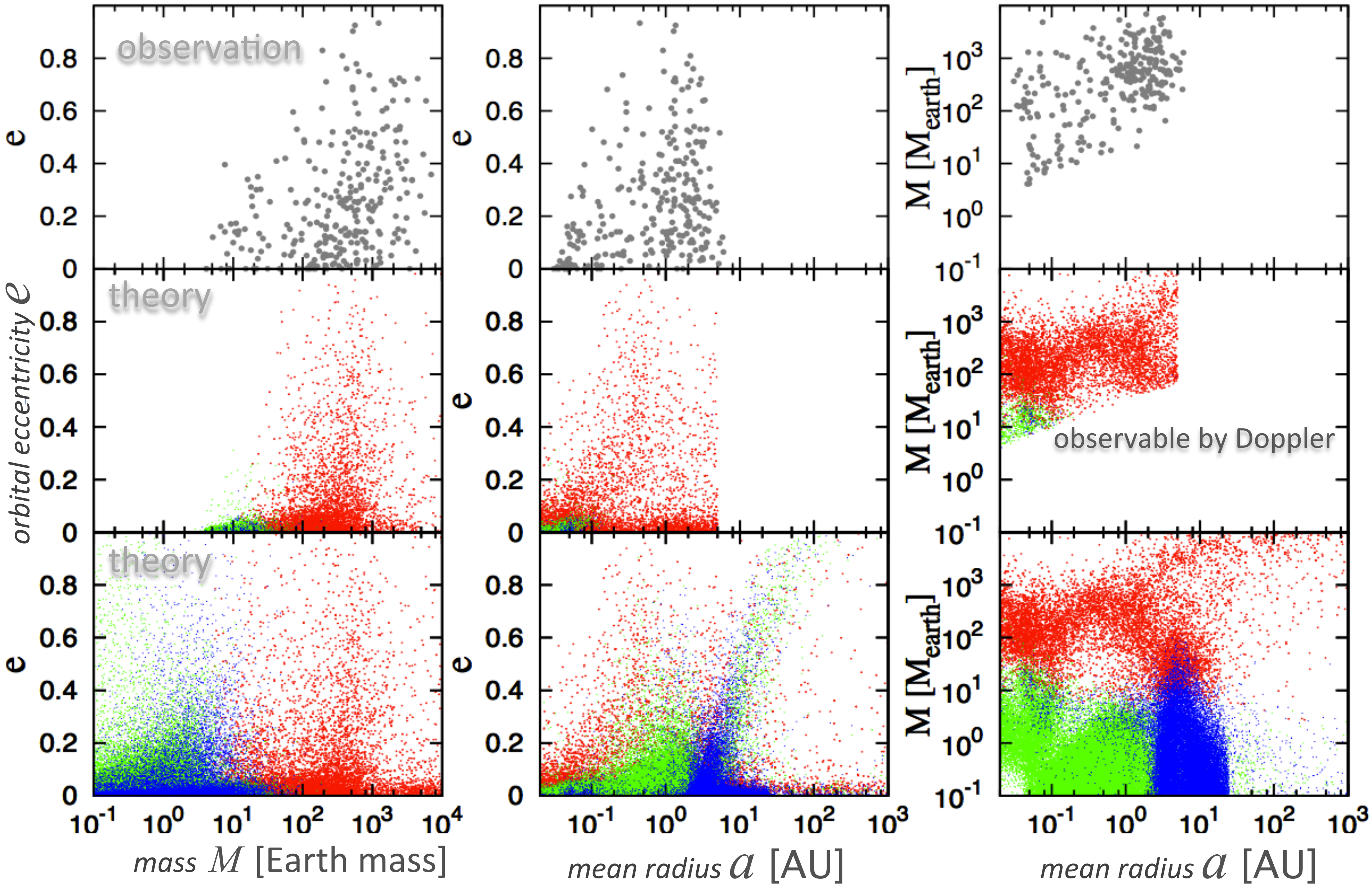
(similar to Grand Circulation Model for climate simulation)

& Constrain processes that are still uncertain

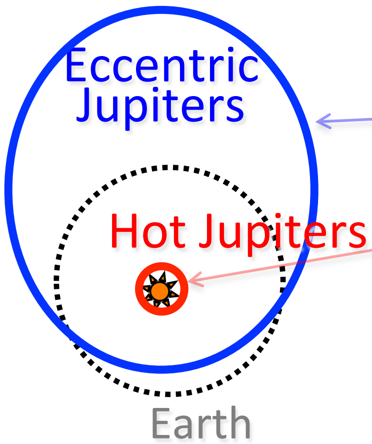
Population Synthesis

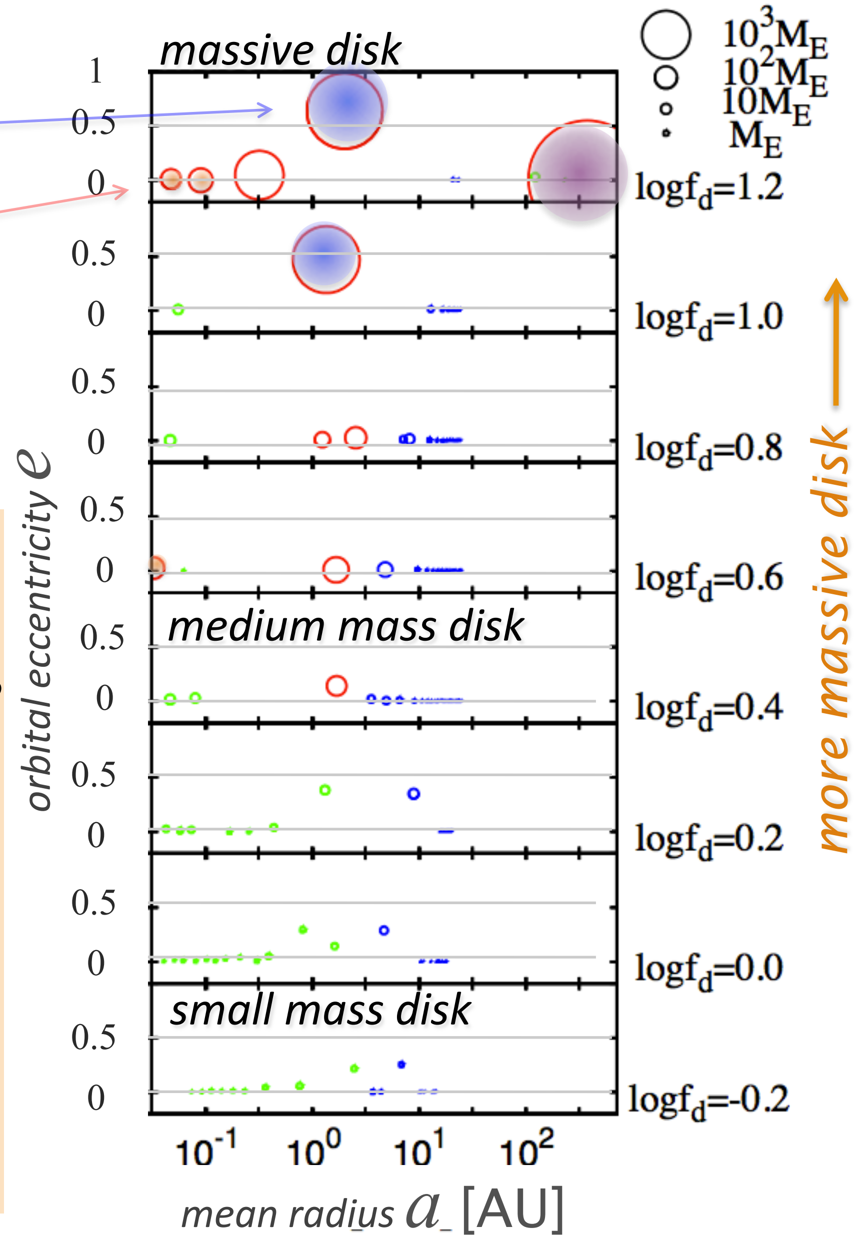
10^4 systems

Uniform disk + slowed migration



Systems from different mass disks





massive disks:
migration or perturbations
of jupiters remove terrestrial planets

medium-mass disks:
impacts from small bodies
controlled by jupiters
(obliquity too)

Jupiters: key to "habitability" of
terrestrial planets

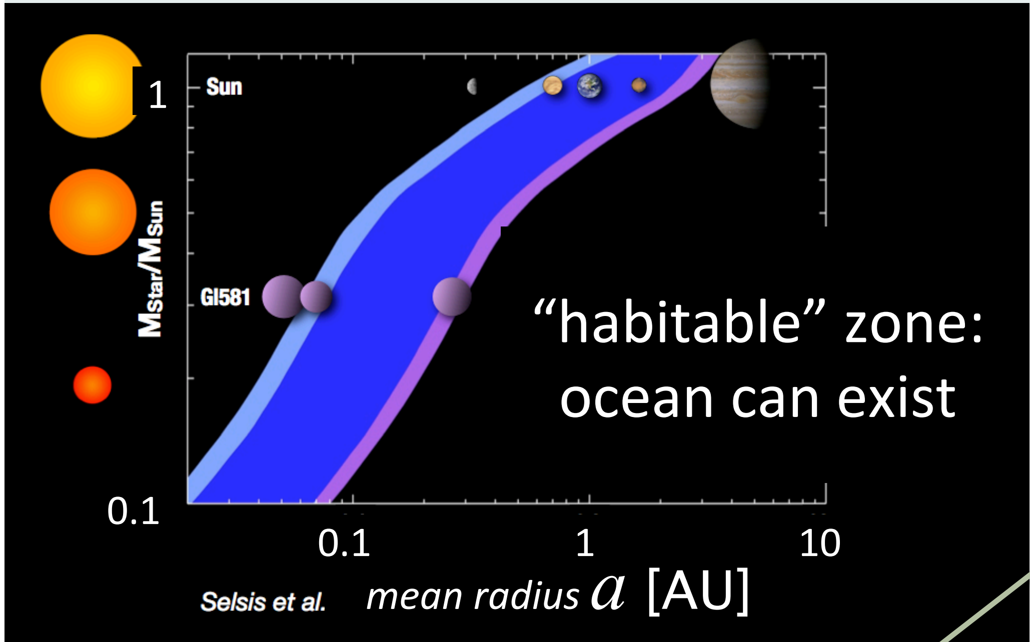
Summary

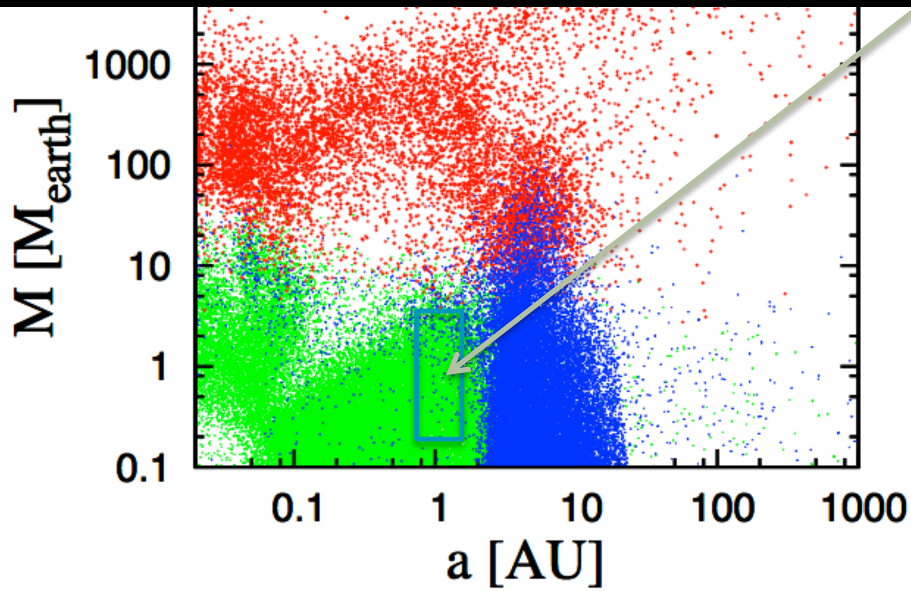
- **Theory of formation of the Earth**
  - Changing due to discovery of exoplanets
  - Getting able to predict "Early Earth"
    (H. Genda's talk) and
    ubiquity/diversity of "habitable" exoplanets

→ one approach to "origin of life"

  - Not established yet
  - High performance computer simulations
    + comparison with observations of exoplanets
    (Y. Alibert's talk), disk & host stars (T. Guillot's talk)

Prediction for “habitable” planets





predicted fraction of solar-mass stars having “habitable” planets

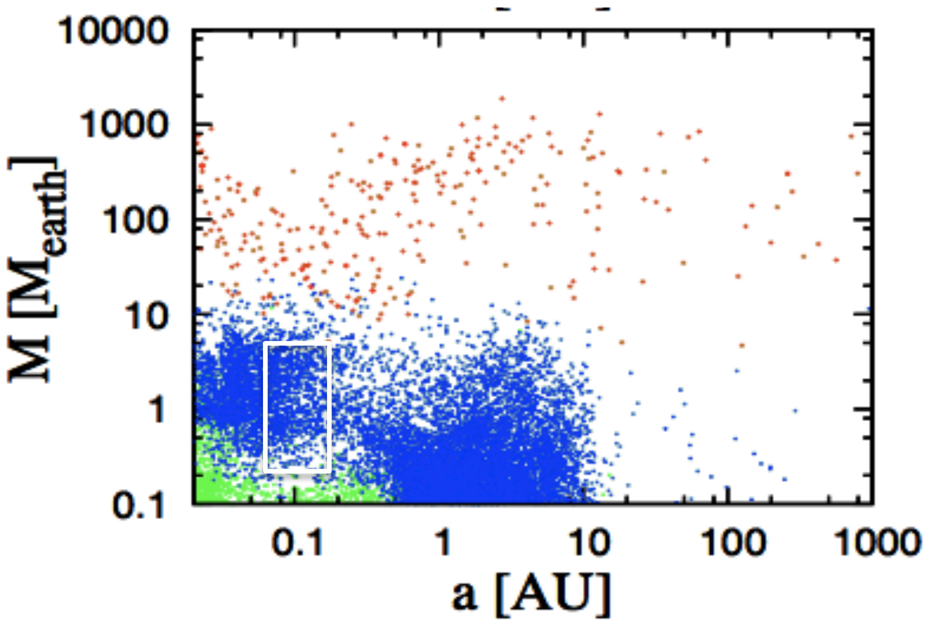
$$\eta_{\oplus} \sim 35\% \ (!)$$

yet to be observed;
many uncertain factors,
but very high

"Exotic" habitable planets around red dwarf stars (M dwarfs)

- M dwarfs – most abundant in our galaxy
- faint → cold disk → habitable zone: close to a star
  - ➢ habitable planets: currently observable
  - ➢ mostly of H_2O? → ocean: > 1000km
  - ➢ spin-orbit locking
  - ➢ strong XUV flux & stellar flare on the day-side

-- severe environmental conditions?



- On the Earths, life rapidly evolved when environment was very severe
  - 1st snowball Earth (2Gy ago)
    prokaryote → eukaryote
    原核生物　　　真核生物
  - 2nd snowball Earth (0.5Gy ago)
    Cambrian explosion
    カンブリア紀の生命大進化