Formation of gas giant planets and its interior structure

Shigeru Ida

(ELSI, Tokyo Tech)

Interior structure of Jupiter should constrain its formation processes

- accretion of the core
- runaway gas accretion
- gap opening in the gas disk

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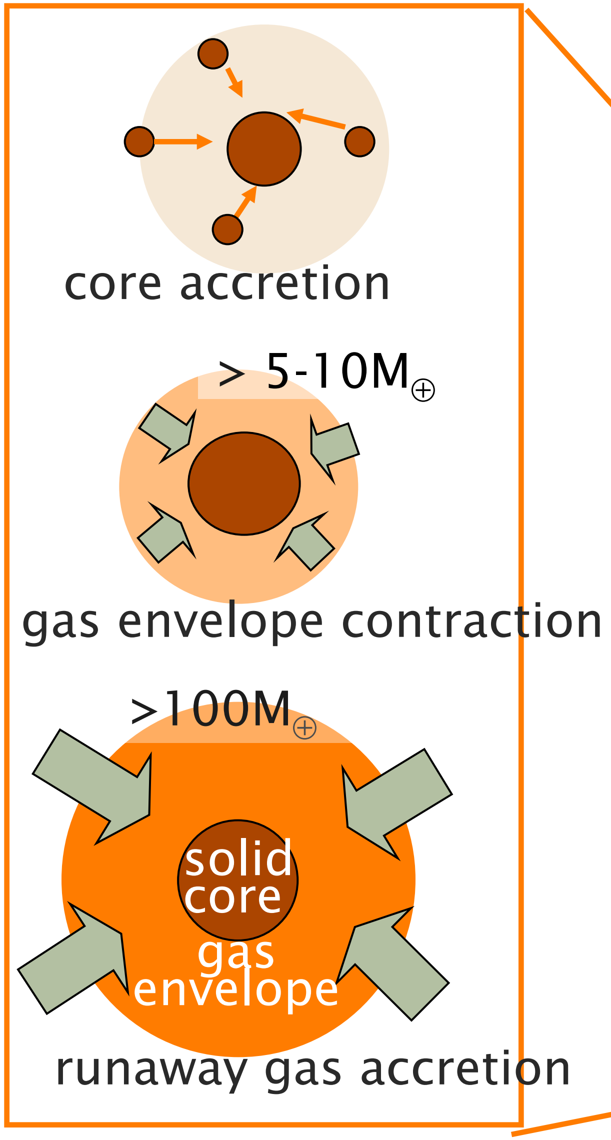
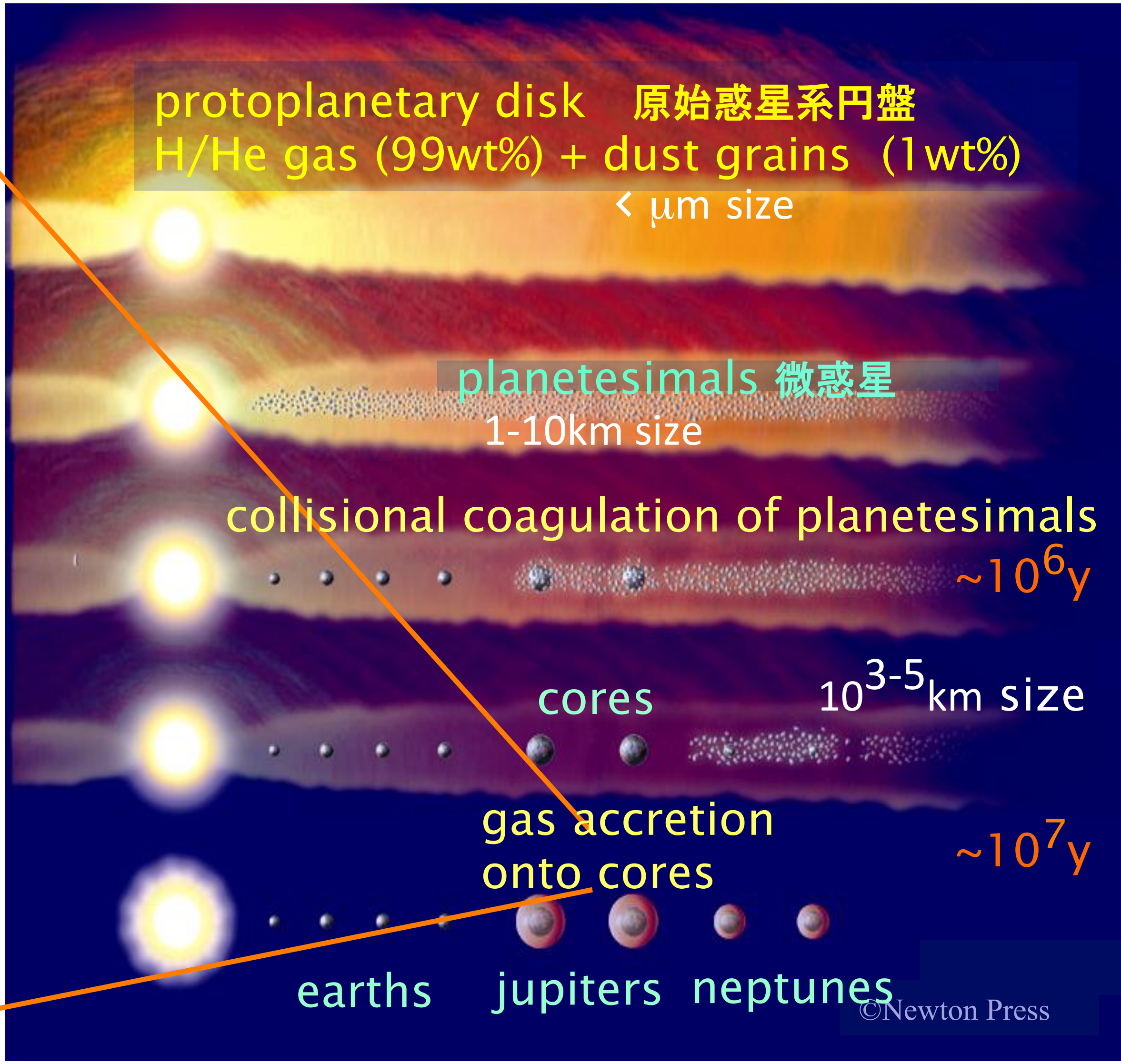
“Classical” planet formation model

e.g., Hayashi et al. (1985)





New model: Pebble accretion
- how jupiter formation changes? -

- **“radial drift barrier”**
  serious difficulty for
  μm-grains → km-planetesimals
  too rapid migration of pebbles by gas drag (< 100 yrs)

- **Pebble accretion?** (pebbles: 1-100cm)
  (←→ classical km-size planetesimal accretion)
  very rapid migration of pebbles is fine!

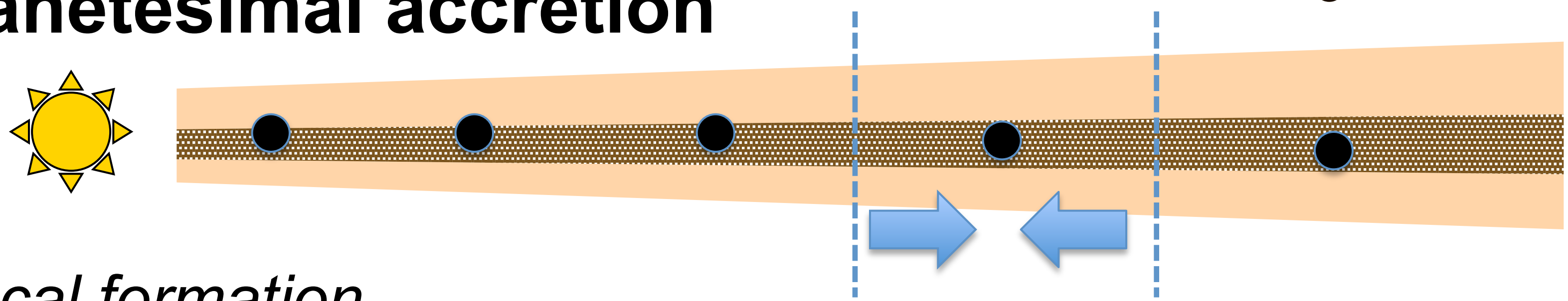
  ✓ “traffic jam” → formation of > 100km-sized bodies (seeds)
  ✓ the seeds catch migrating pebbles

Johansen et al. 2007
Lambrechts & Johansen 2012

Planetesimal vs. Pebble Accretion

$M_{\rm iso} \sim 5\,(a/5\ {\rm au})^{3/4}\,{\rm M}_\oplus$

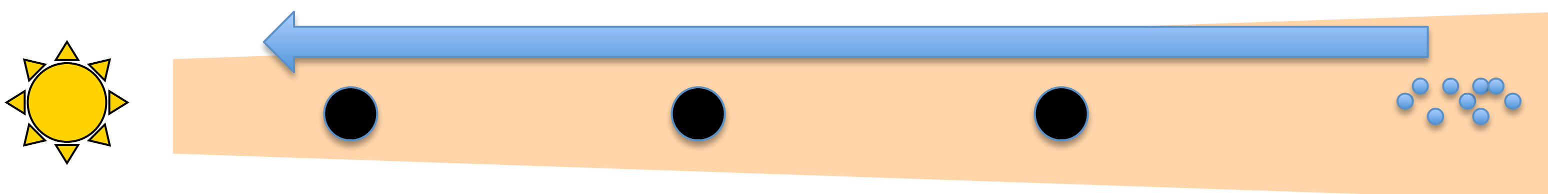
Planetesimal accretion



- *local formation*
- *slow in outer region*

Wetherill & Stewart (1989,93)
Kokubo & Ida (1996,98,00,02)

Pebble accretion



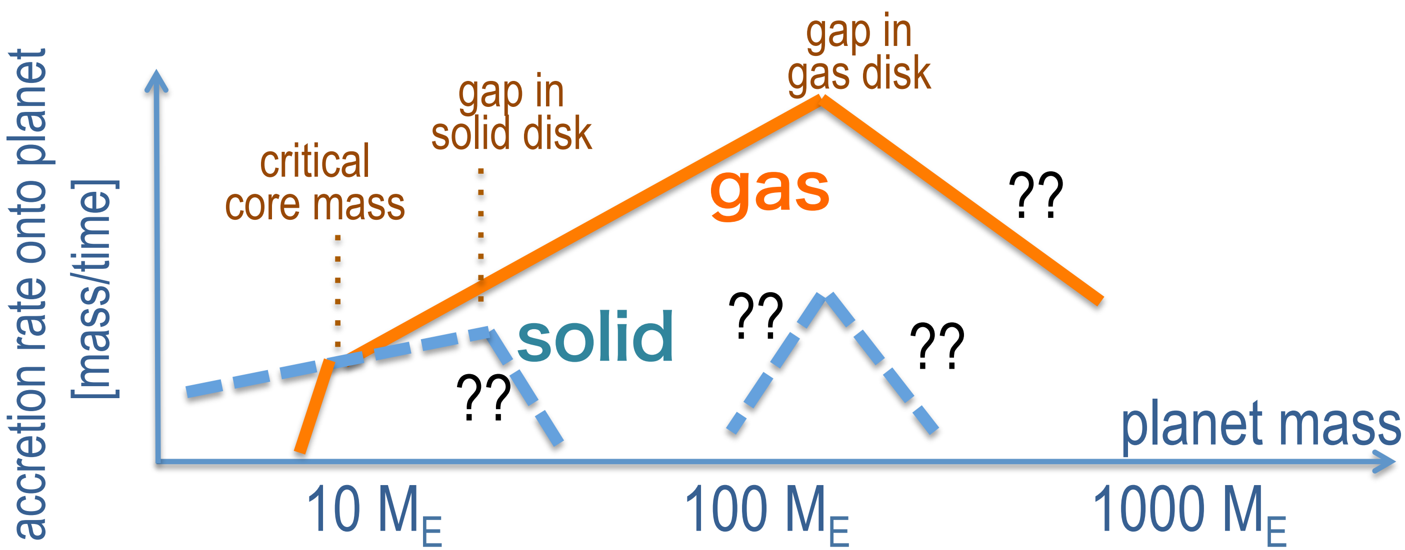
- *global*
- *fast once >100km bodies are formed*

Lambrechts & Johansen (2012,14a,b);
Chatejee & Tan (2014a,b), Levison+(2015)
Guillot, Ida, Ormel (2014)
Ida, Guillot, Morbidelli (2016)

Interior structure constraints formation

interior structure:
reflect solid vs. gas accretion onto Jupiter

- discriminate planetesimals vs. pebbles
- constrain gap opening process
  in the planetesimal/pebble disk & gas disk
  ←→ planet/satellite formation



Critical core mass

- Dependence of solid accretion rate (e.g., Ikoma+ 2000)

$$M_{c,\mathrm{crit}} \simeq 10 \left(\frac{\dot{M}_c}{10^{-6}\ M_\oplus\ \mathrm{yr}^{-1}} \right)^{0.2-0.3} \left(\frac{\kappa}{1\ \mathrm{cm}^2\ \mathrm{g}^{-1}} \right)^{0.2-0.3} M_\oplus$$

✓ planetesimal accretion (5au) (e.g., Ida & Lin 2004)

$dM_c/dt \sim 10^{-7} (M_c/5M_\oplus)^{-1/3}\ M_\oplus/\mathrm{yr}$

→ $M_{c,\mathrm{crit}} \sim 5\ M_\oplus$ ←→ planetesimal isolation mass Kokubo & Ida 1998

✓ pebble accretion (e.g., Ida, Guillot & Morbidelli 2016)

$dM_c/dt \sim 10^{-4} (M_c/5M_\oplus)^{-1/3}\ M_\oplus/\mathrm{yr}$

→ $M_{c,\mathrm{crit}} \sim 25\ M_\oplus$ ←→ pebble isolation mass Lambrechts + 2014

→ **Core mass may be larger for pebble accretion**

- Total gas accretion timescale $\sim 10^7 (M_{c,\mathrm{crit}}/5M_\oplus)^{-3.5}$ yr

Ikoma & Genda 200)

→ **300 times shorter for pebble accretion**

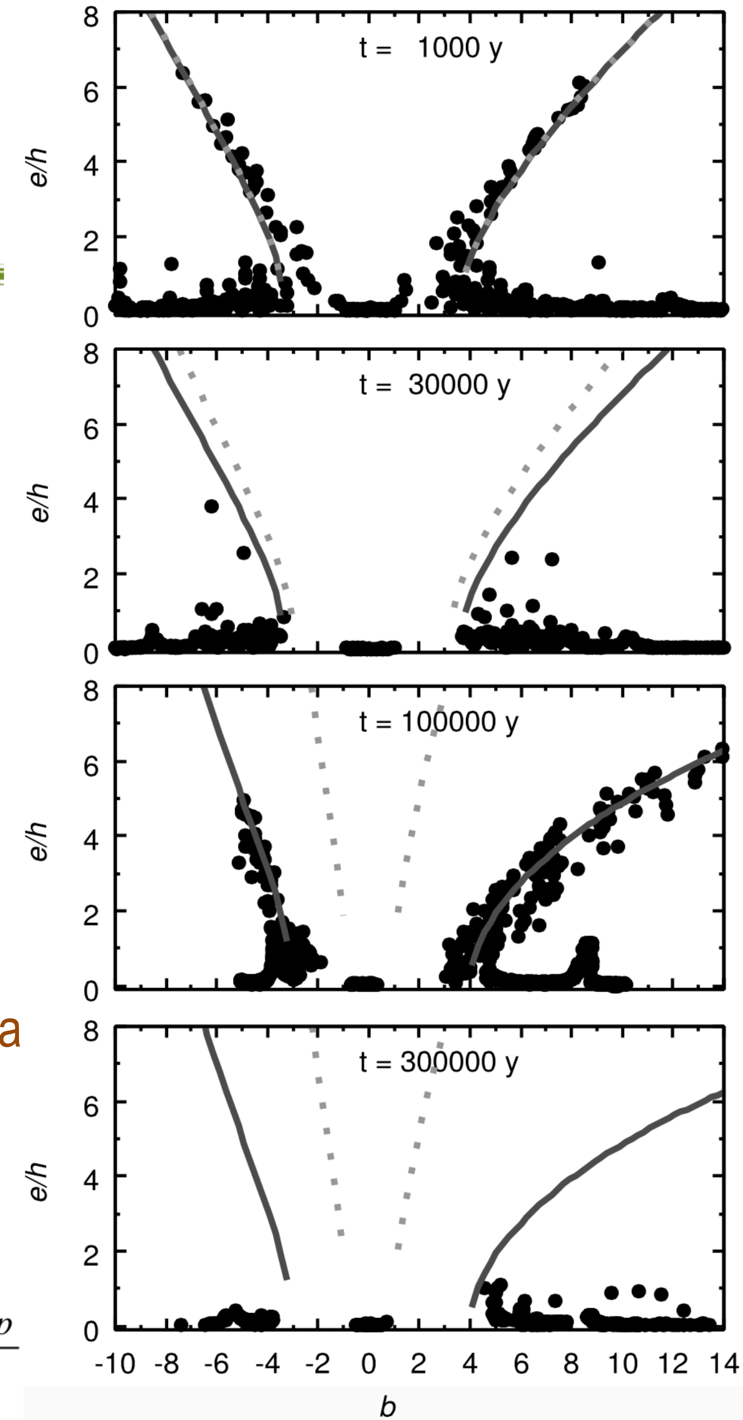
Gap formation in a planetesimal disk

scattering + *e*-damping

- planetesimals: very weakly coupled to gas
- gap opening: $M > 1\text{-}10\ M_\oplus$

Tanaka & Ida 1997

Shiraishi & Ida 2008



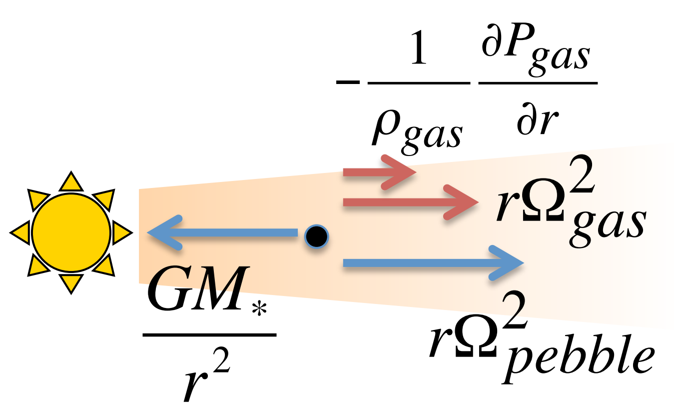
$$b = \frac{a - a_p}{h a_p}$$

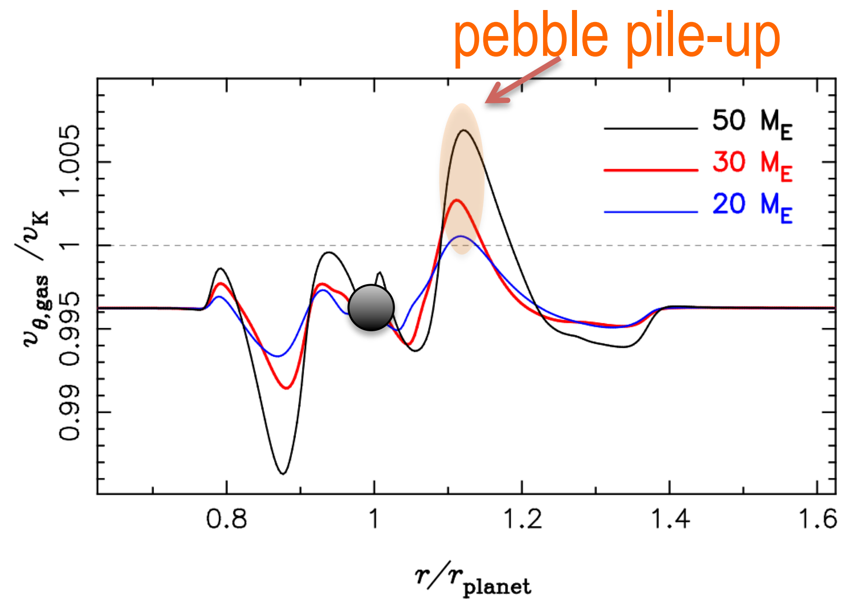
Gap formation in a pebble disk

- pebbles: marginally coupled to gas
- migration ← deviation of gas motion from Kepler
  - ✓ uniform gas → inward migration
- when $M > M_{iso}$

$$M_{iso} \approx 20 \left(\frac{a}{5\,\mathrm{AU}}\right)^{3/4} \mathrm{M_E},$$ Lambrechts + 2014

  - ✓ gap opening in ***gas*** disk → disk outer edge: super-Kepler
    → migration of pebbles: halted
    → gap opening in a ***pebble*** disk

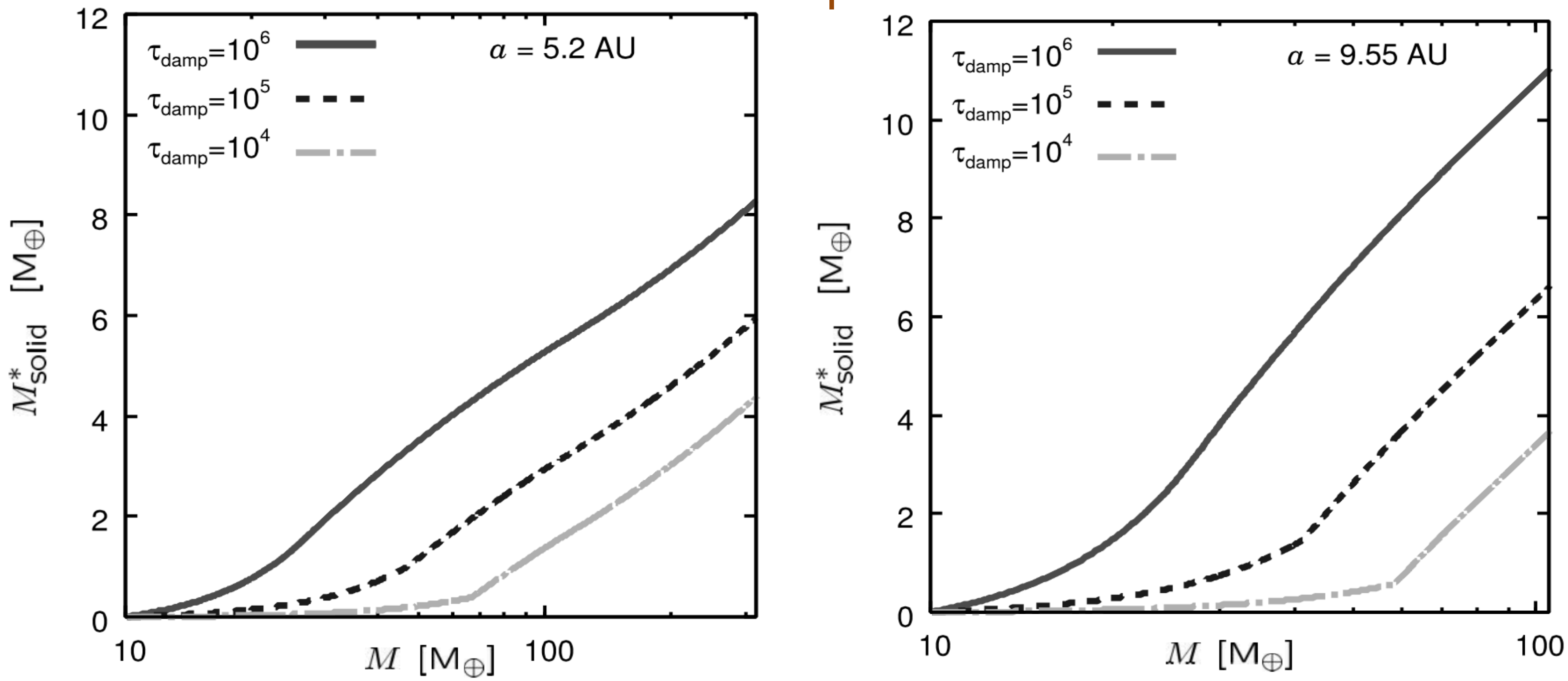




Re-accretion of solid

- gas accretion: runaway ($dM/dt \propto M^{4.5}$)
  → Expansion of Hill radius $(M/3M_*)^{1/3}a$
  becomes faster than gap expansion in late stage
  → solids are re-accreted

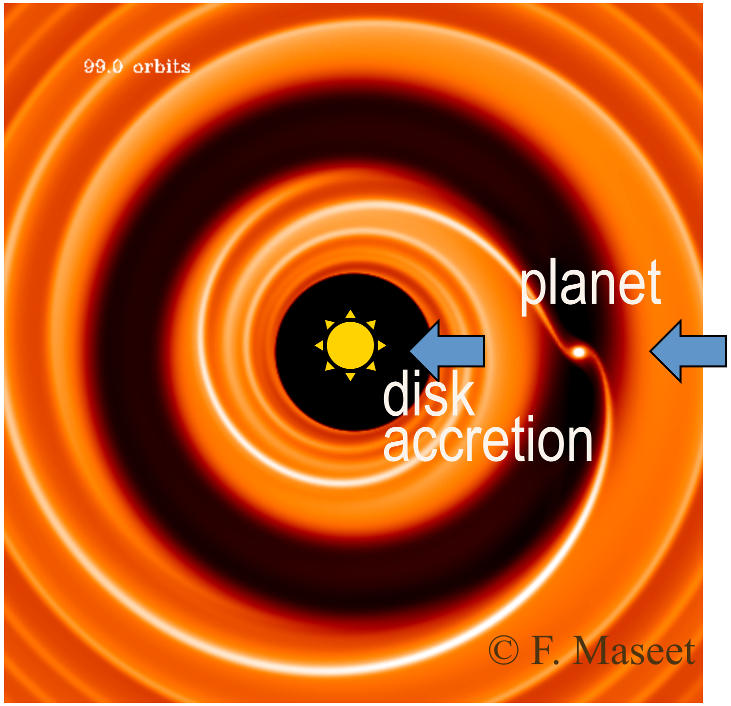
Shiraishi & Ida 2008: planetesimal accretion



pebble accretion case: no study so far

Re-accretion of solid

- How the re-accretion stops ?
- reduction of gas flow due to gap opening in the gas disk?
  - gap opening criteria *M* >~ Jupiter mass
    Lin & Papaloizou 1986, Crida+ 2006
  - recently questioned
    - ✓ gas flow is not terminated?
      Lubow & D'Angelo 2006
    - ✓ almost all gas flow cross the gap?
      Duffell+ (2014)



Summary

Interior structure of Jupiter constrains its formation

- ➢ **accretion of the core -- planetesimals vs. pebbles**
  - ✓ critical core mass, gas accretion
  - ✓ gap opening in the planetesimal/pebble disk
- ➢ **runaway gas accretion history**
  - ✓ re-accretion of solids -- penetration through envelope
    planetesimals vs. pebbles
- ➢ **gap opening in gas disk, gas flow across the gap**