系外惑星形成の最前線

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OUTLINE – review current status of planet formation studies

- **Observations of exoplanets**
  - diversity & ubiquity
- **Many ideas: proposed to account for the observations**
  - interaction of pebbles/planets with a protoplanetary gas disk
- **Current status of planet formation model**
  - many ideas, many clues: diverged, not converged yet

宇宙生命計算科学連携拠点
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Tokyo Tech
wpi
EARTH-LIFE SCIENCE INSTITUTE
TOKYO INSTITUTE OF TECHNOLOGY

系外惑星の観測

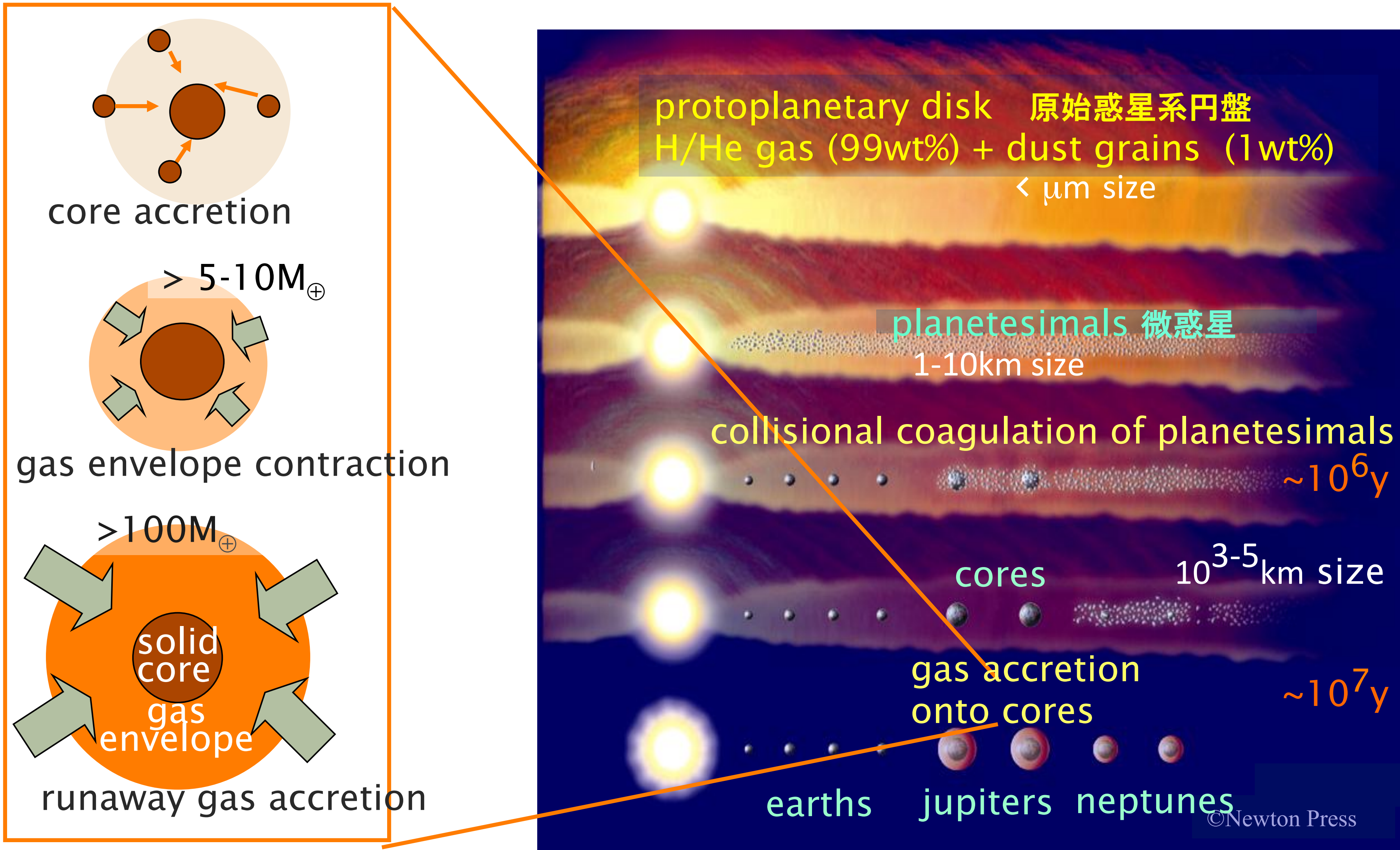
- 系外惑星系の多様性
- Super-Earths/Earths の遍在性

- TESS (2018~) までは一段落？
- Microlensing は発展？

Planet formation theory

Classical planet formation model

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



Newly proposed physical processes

To explain diversity,

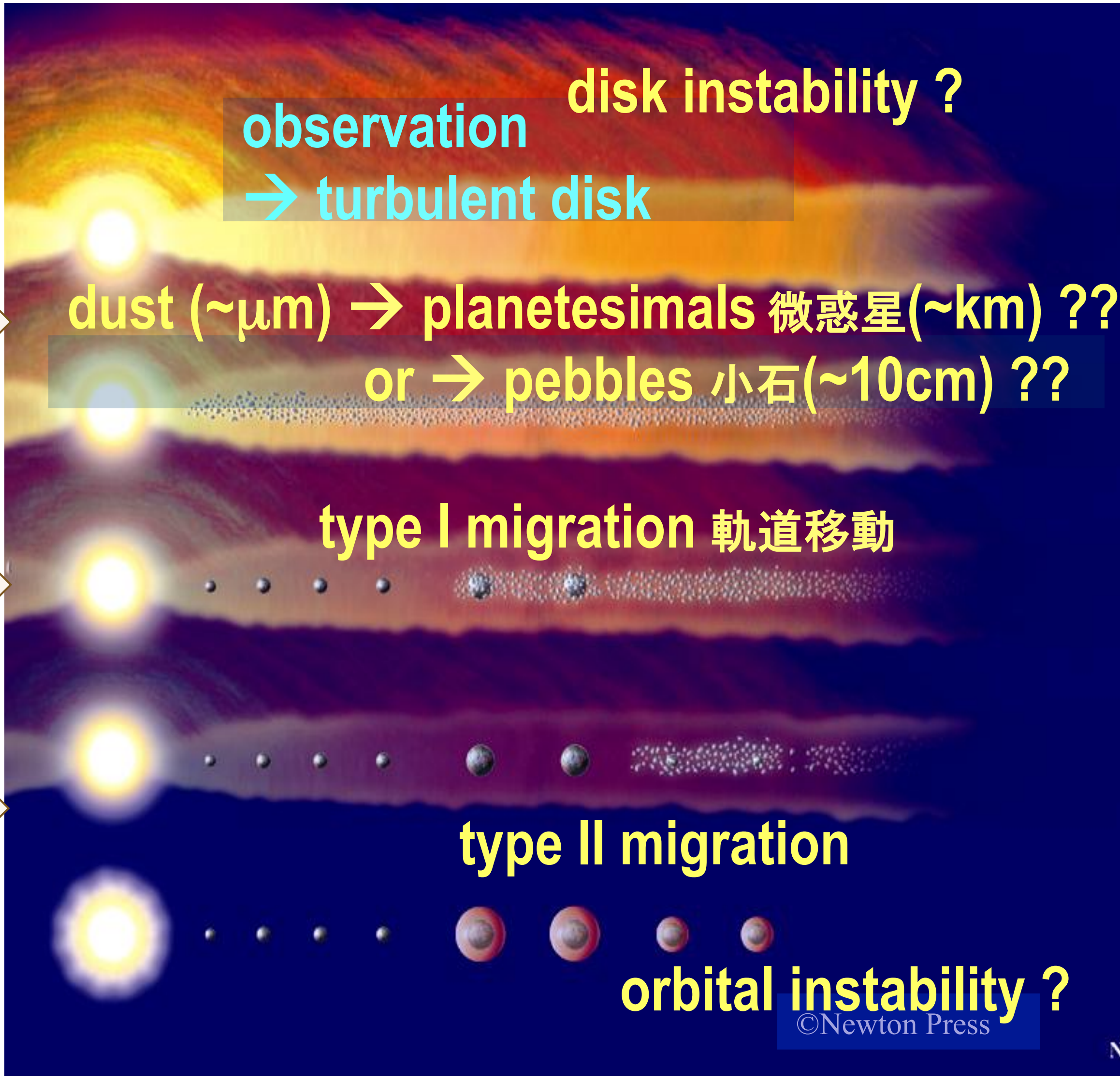
turbulent disk

→ inhibit planetesimal formation

→building blocks: pebbles?

close-in exoplanets

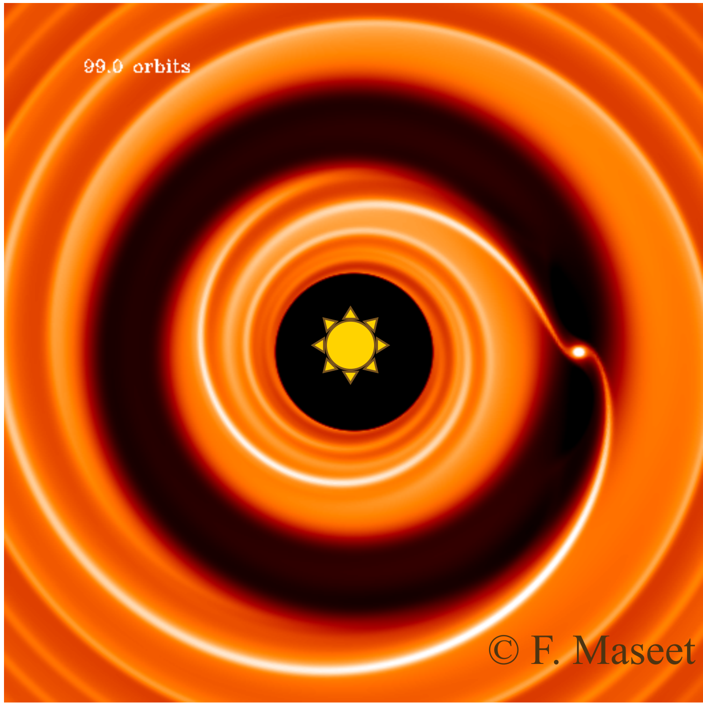
→ orbital migration due to disk-planet int.



→ 多様性もいいが、
太陽系も統一的に
説明する必要

Key: Interactions with disk gas

- pebbles (~10cm): aerodynamic gas drag
- Earth-mass planets: grav. interaction (type I migration)
- Jupiter-mass planets: grav. interaction (type II migration)

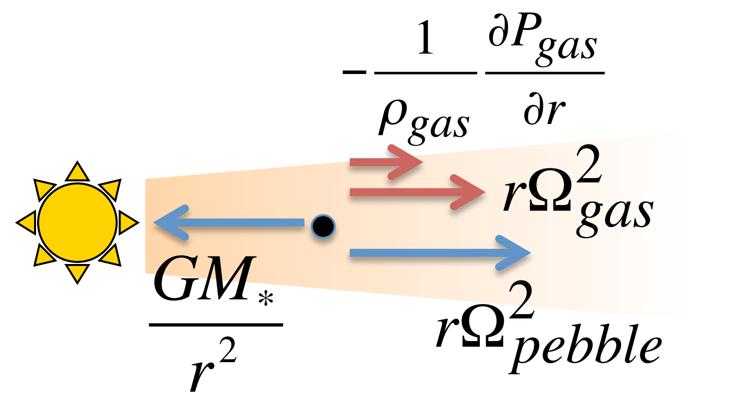


Planet formation theory: Pebble accretion

Pebbles
– Building blocks? Not km-planetesimals? -

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

- **New accretion model: Pebble accretion?**
  (←→ classical planetesimal accretion)
  ✓ formation of 1000km-sized bodies (seeds) by jams during pebble fast migration Johansen et al (2007)
  ✓ the seeds catch migrating pebbles Lambrechts & Johansen (2012)



Gas rotation velocity:
slower by $\eta \sim 10^{-3}$-10^{-2}
→ Bodies suffer “head wind” from gas
→ inward drift (migration)
$v_r \sim St/(1+St^2) \times \eta\, v_K$

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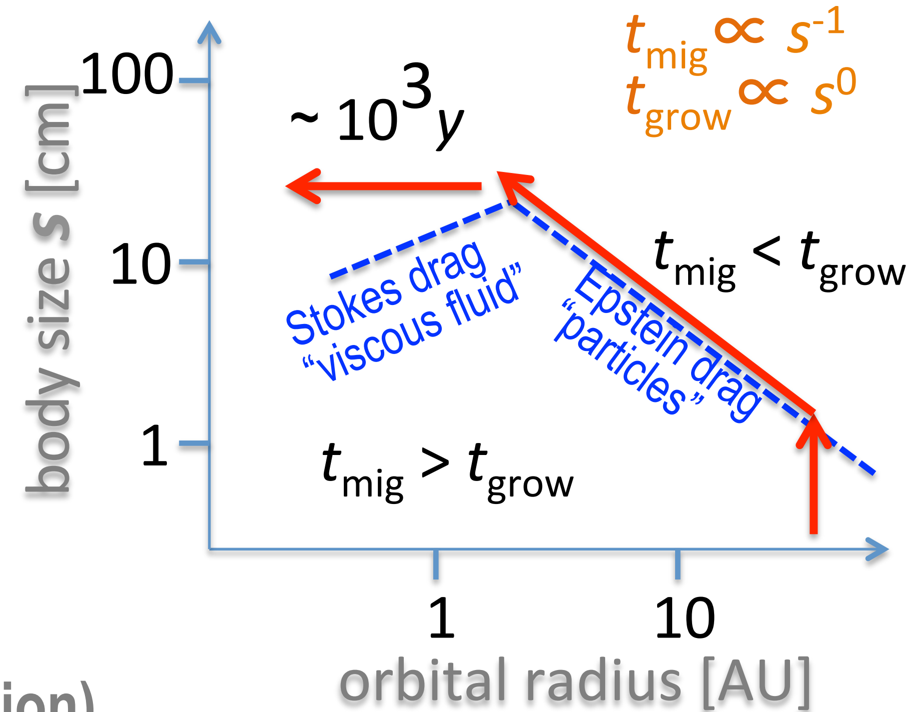

- **New accretion model:**
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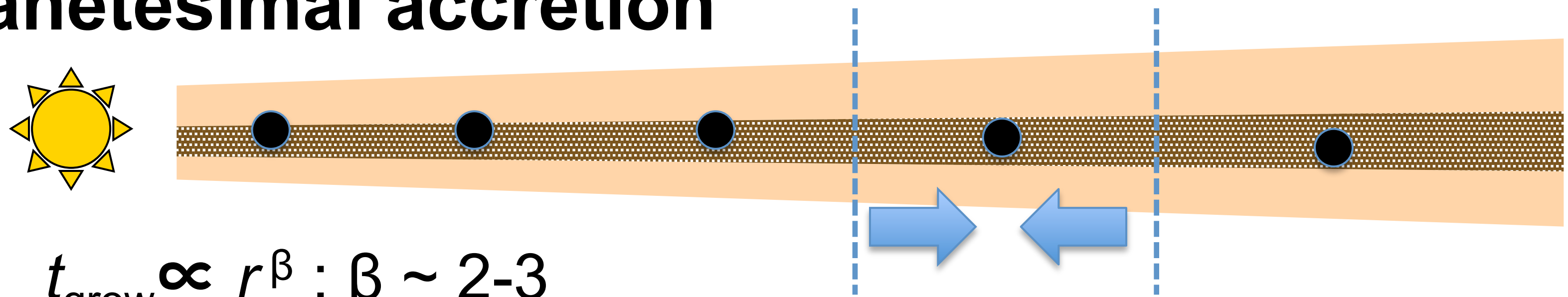
(←→ classical planetesimal accretion)

✓ formation of 1000km-sized bodies (seeds) by jams during pebble fast migration   Johansen et al (2007)

✓ the seeds catch migrating pebbles
Lambrechts & Johansen (2012)

Planetesimal vs. Pebble Accretion

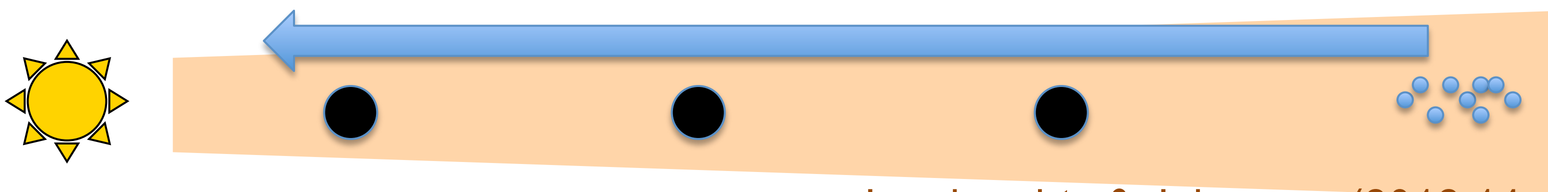
Planetesimal accretion



$t_{grow} \propto r^{\beta}$; $\beta \sim 2\text{-}3$

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

Pebble accretion



$t_{grow} \propto r^{\beta}$; $\beta \sim 0$

Lambrechts & Johansen (2012,14a,b);
Chatejee & Tan (2014a,b), Levison+(2015)

→ easy to make diversity of planetary systems?
depends sensitively on disk parameters

Ida, Guillot, Morbidelli (2016), Chambers (2016)

ガス惑星の形成も違う

- Dependence of critical core mass on 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
    [effect of pollution?]

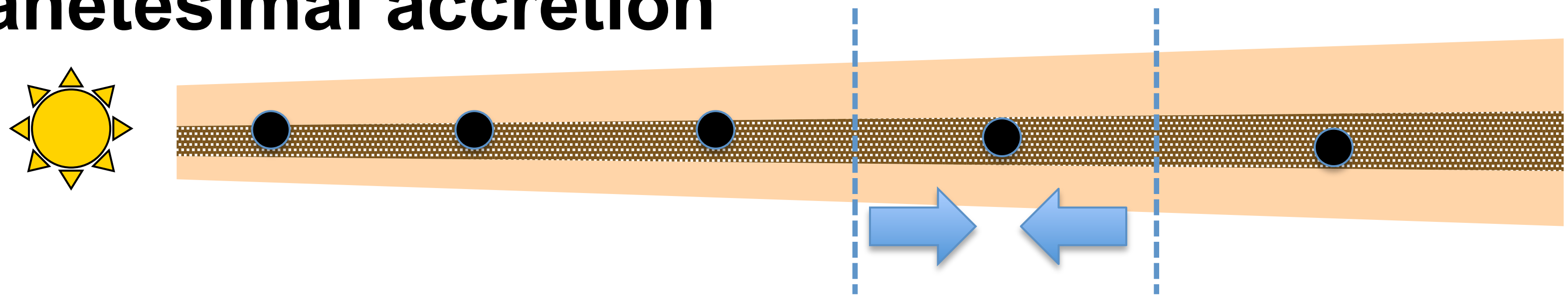
→ **Core mass may be larger for pebble accretion**

- 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**

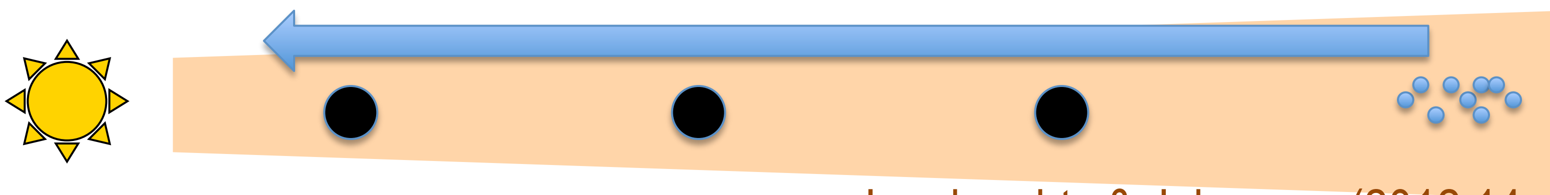
Planetesimal vs. Pebble Accretion

Planetesimal accretion



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

Pebble accretion



Lambrechts & Johansen (2012,14a,b);
Chatejee & Tan (2014a,b), Levison+(2015)

- R << 100km embryos: slow & inefficient:
- R > 100km embryos: fast & moderately efficient

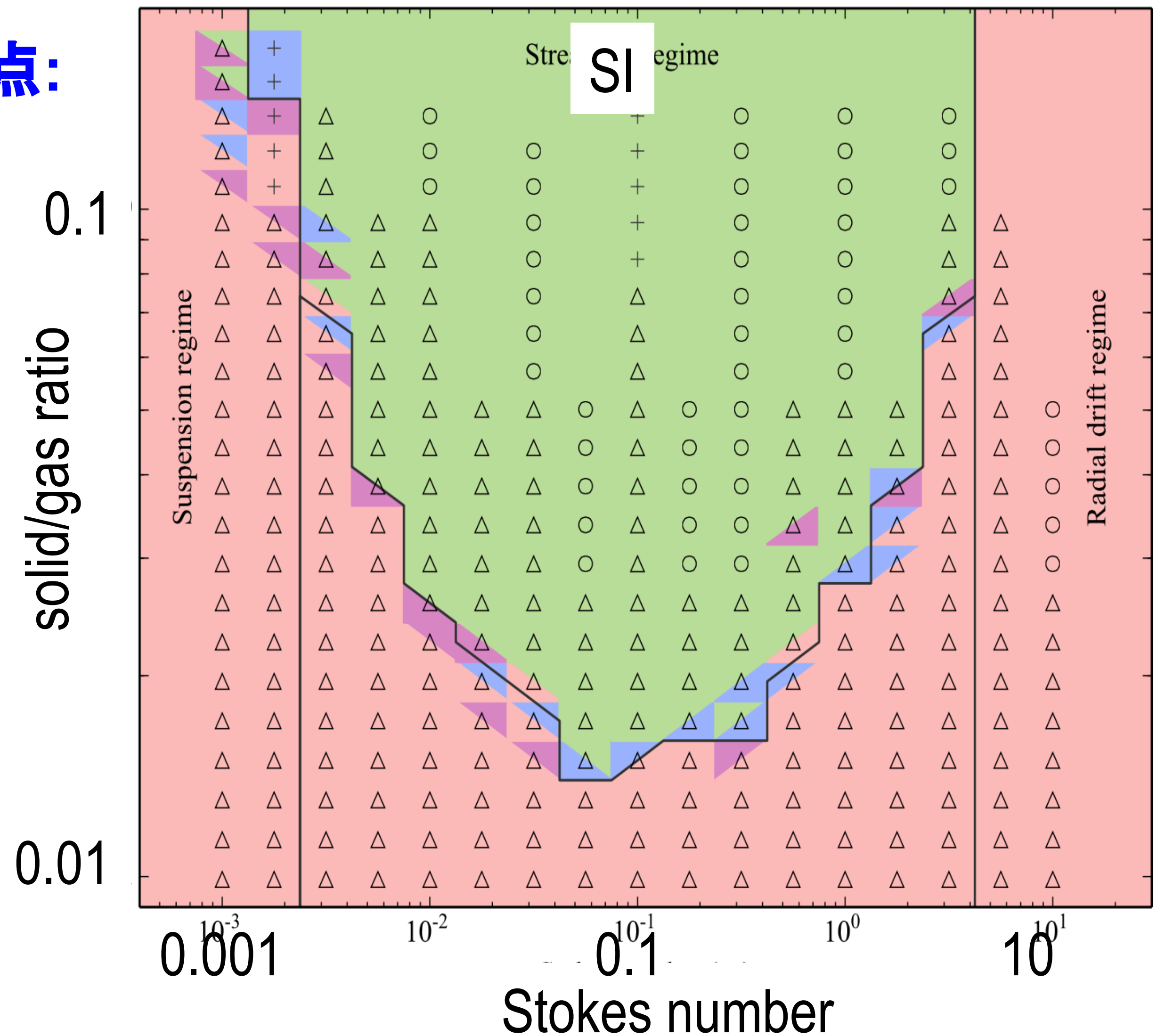
gravitational focusing & gas drag:
capture all pebbles within R_{Bondi} or R_{Hill}

Difficulty of Streaming Instability

pebble accretion の問題点:
>100kmの種の形成
– streaming 不安定?

streaming不安定条件
実現は一般に困難
Ida & Guillot, in prep

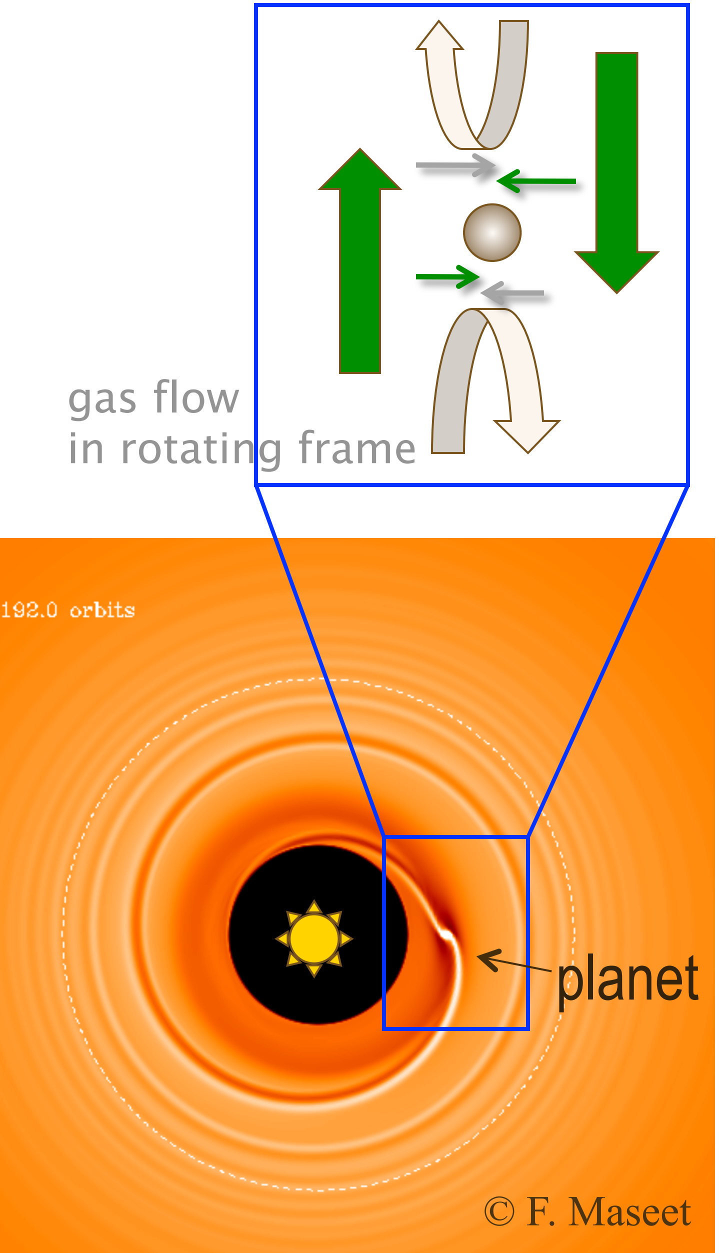
→ 現状では
pebble と planetesimal
のどちらが効くのか
不明



Carrera, Johansen & Davies (2015))

Planet formation theory: Planet orbital migration

type I migration 1-10$M_\oplus$ planets



- $M_{gas} \sim 100 M_{solid}$
  → planet orbital change
  by grav. interaction with disk gas
- **residual of 4 similar mag. torques**
- **isothermal disk**

linear calc: Tanaka, Takeuchi, Ward (2002)

hyrdo sims: many

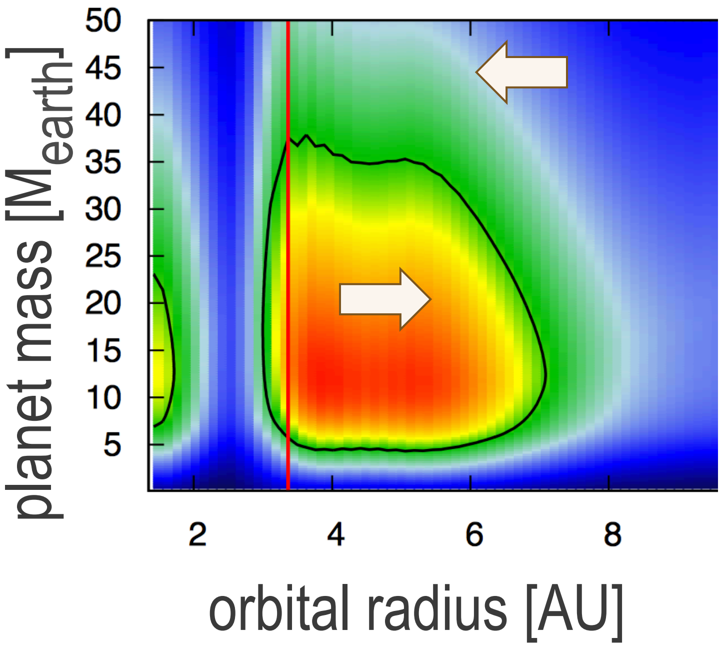
inward, very fast

→ 10^5y for 1M_{earth} @1AU
10M_{earth} @5AU
[←→ disk lieftime > 10^6yr]

serious problem;
but account for close-in super-Earths?

(a double-edged sword)

type I migration 1-10$M_\oplus$ planets



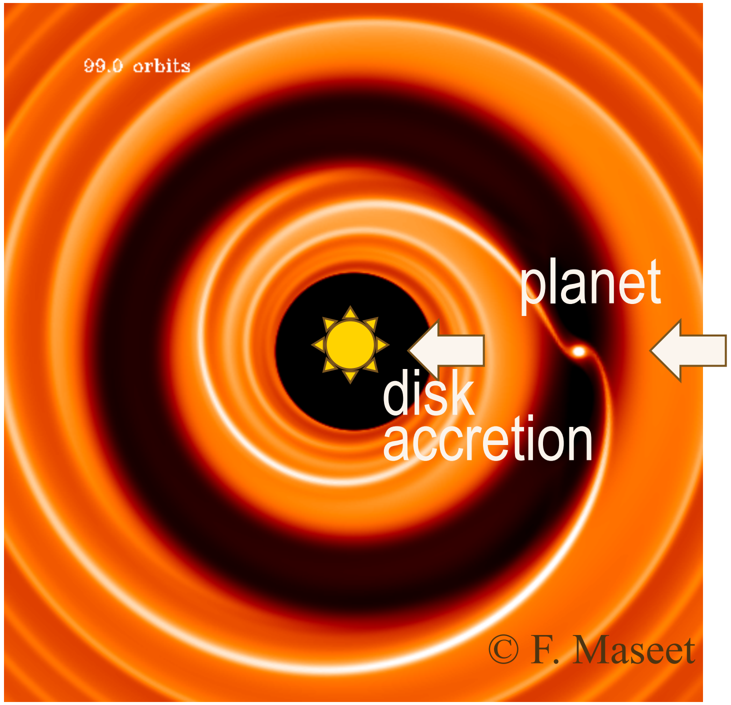
Bitsch+(2015)

- **non-isothermal disk**
  linear calc: Paardekooper+(2010, 2011)
  balance of 4 torques changes:
  very fast but **either inward or outward**

  migration direction:
  sensitively depends on disk params.
- **perturbations from density fluctuation of disk turbulence → random walk**
  Ida+(2008), Okuzumi & Ormel (2012)
- **planetesimal-driven migration**
  Ida+(2000), Kirsh+ (2009)

Not well understood;
need detailed hydro, N-body

type II migration $>100M_\oplus$ planets



gap opening ← jupiter-mass planet

- **inward**
- **migrate with disk accretion onto a host star (relatively slow)**

Lin & Papaloizou (1986)

→ origin of hot jupiters ? Lin+(1996)

→ terminate growth of gas giants

← recently questioned

growth is not terminated?

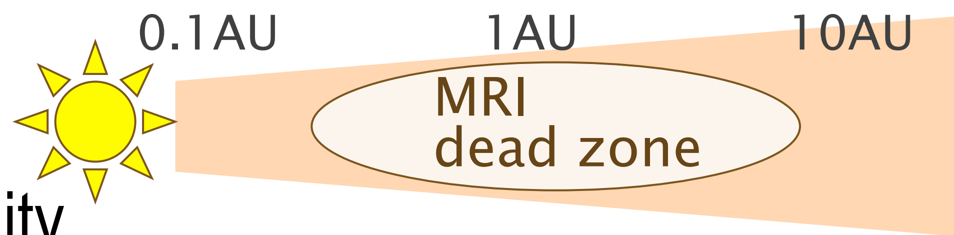
hydro: D'Angelo et al. (2002), Lubow & D'Angelo (2006)

gas mass flux $2\pi r\, v_r \Sigma$: conserved across gap?

hydro: Duffell+ (2014)

Dynamical/thermal evolution of disks

- **disk evolution**
  - **controls pebble accretion & type I, II migration**
  - viscous diffusion + photoevaporation by stellar UV radiation ? (+ disk wind??)
  - Neither viscosity nor young stellar UV flux is certain



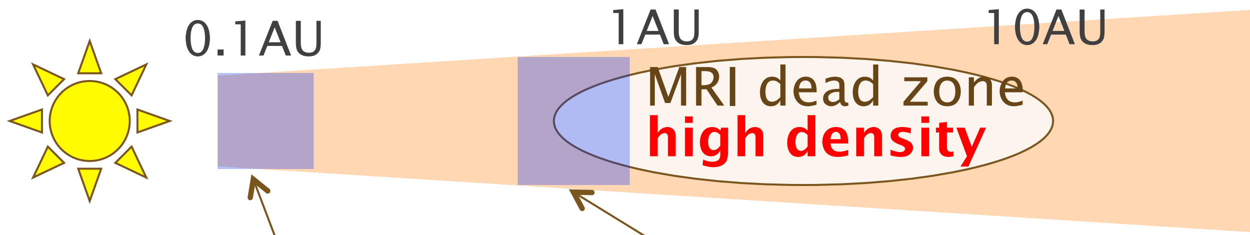
- **viscosity?**
  - Magneto-Rotational Instability 磁気回転流体不安定
    - ✓ “dead zone” 静穏領域 exists?
      MRI turbulence ← ionization degree ← dust growth ← turbulence
    - ✓ saturation level ← seed magnetic field ← star formation

No self-consistent global model exists

Migration trap?

inward migration ← gas: slower rotation (headwind)

- **MRI dead zone inner edge** -- gas: faster rotation (tail wind)
  → migration trap



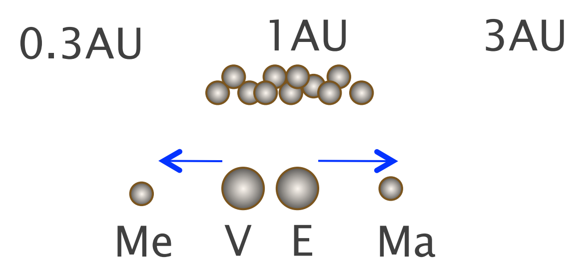
- **disk inner edge**
  - migration trap
  - stellar magnetic field
    vs. disk accretion onto star

dead zone inner edge

reproduce Solar system?

Hansen (2009)

Ebisuzaki & Imaeda (2015)



disk inner edge

close-in super-earths?

Ogihara & Ida (2009)

Chatejee & Tan (2014)

Summary

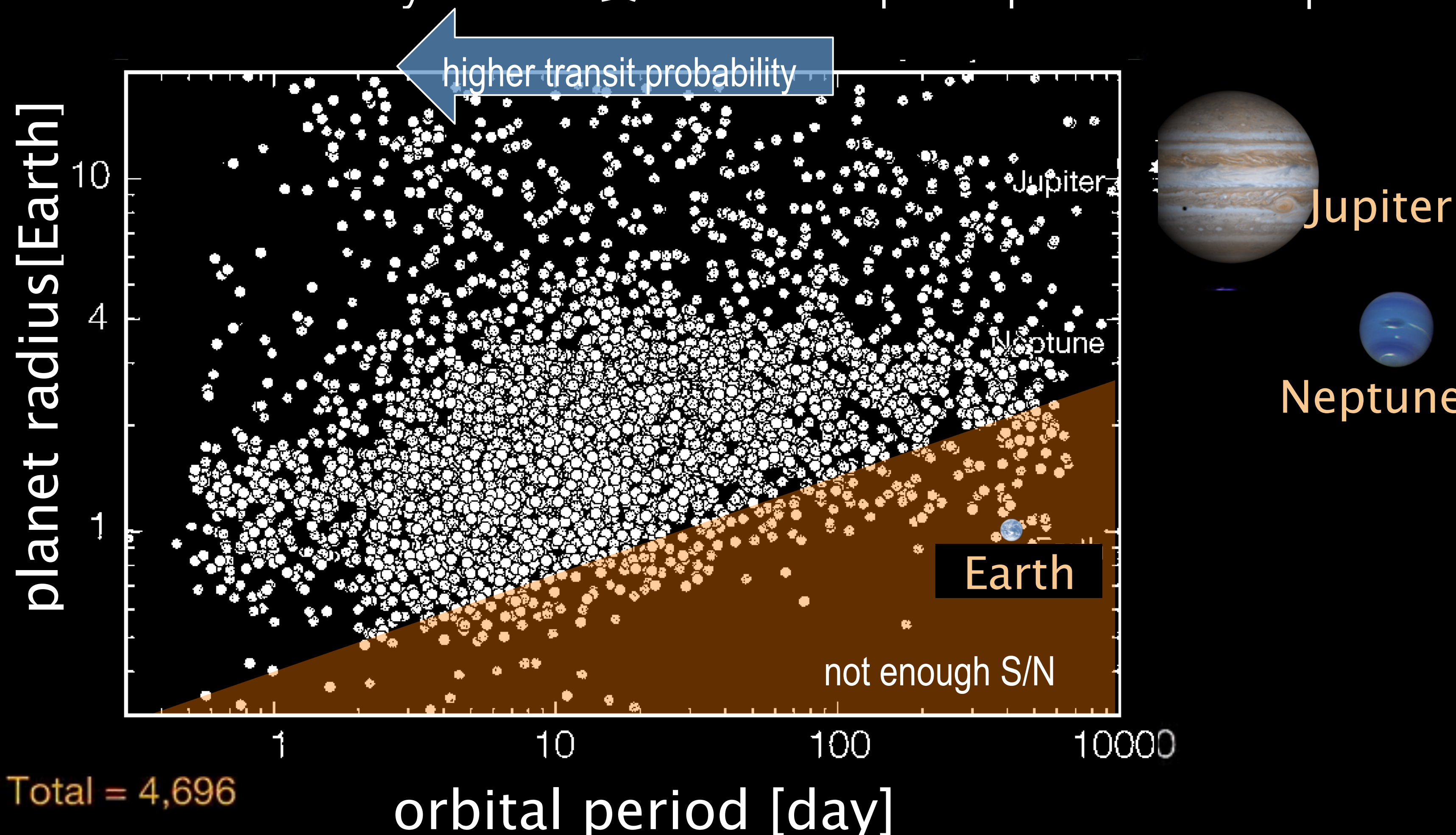
- **Observations of exoplanets**
  - diversity of exoplanetary systems
  - ubiquity of super-earths/earths
- **Many ideas: proposed to account for the observations**
  - interactions with gas of a protoplanetary disk
  - pebble accretion
  - type I & II migration
  - disk evolution, migration trap
- **Current status of planet formation model**
  - many ideas, many clues: diverged, not converged

Observations will constrain the chaotic status of theory!

Young people: many things to do! many topics to write papers!

Ubiquity of "super-Earths/Earths"

Planet Candidates by transit 食 obs of Kepler space telescope



$$\eta_{\text{superEarth/Earth}} \sim 20-50\% \ (!)$$

Gap formation in a pebble disk

- pebbles: marginally coupled to gas
- migration ← deviation of gas motion from Kepler
  - ✓ uniform gas → inward migration
- when $M > M_{\mathrm{iso}}$ $$M_{\mathrm{iso}} \approx 20\left(\frac{a}{5\,\mathrm{AU}}\right)^{3/4} \mathrm{M_E},$$ Lambrechts + 2014
  - ✓ gap opening in ***gas*** disk → disk outer edge: super-Kepler
    → migration of pebbles: halted
    → gap opening in a ***pebble*** disk