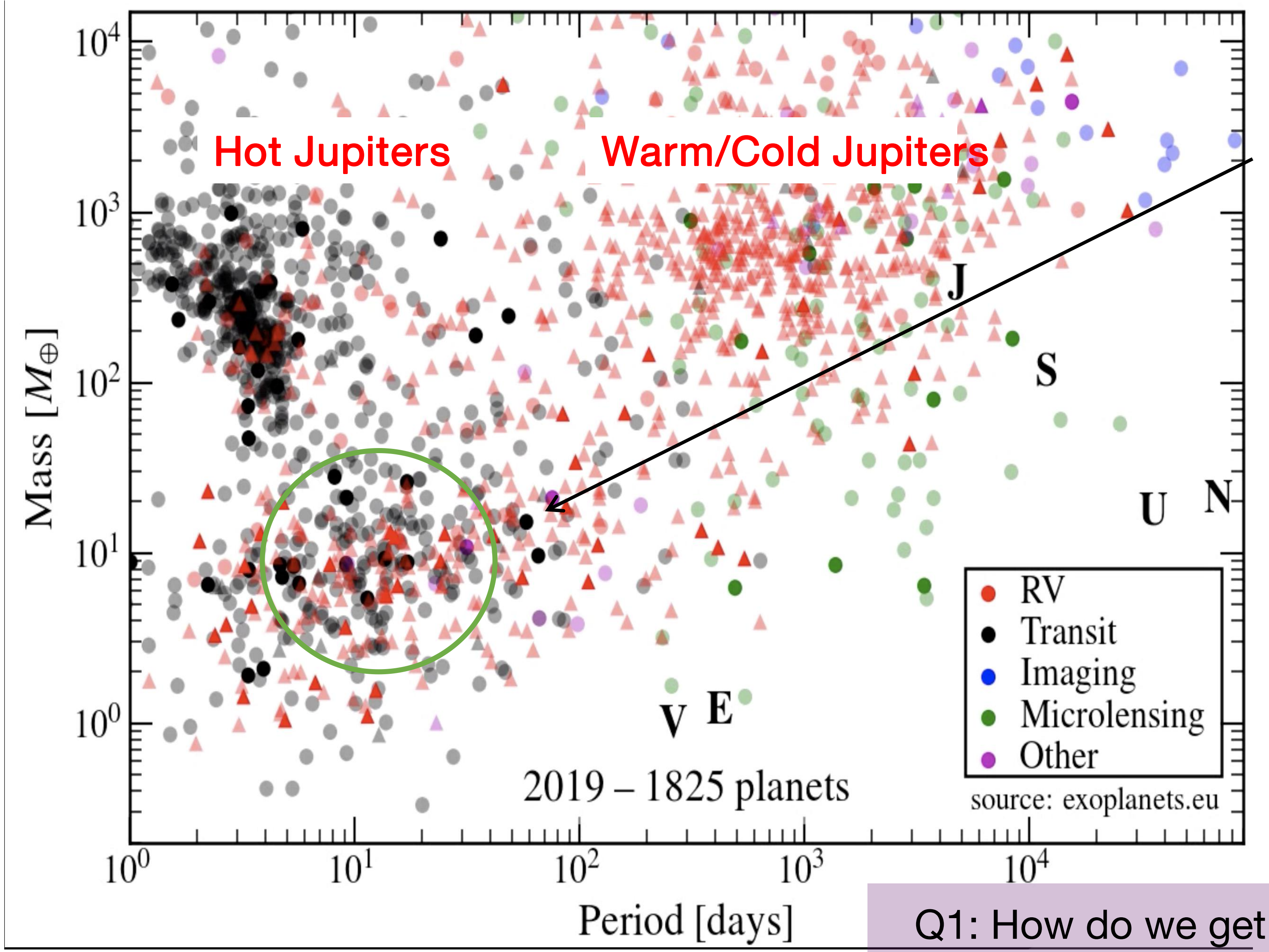
Formation of Close-in Planets (Super Earths, Sub-Neptunes)

Yixian Chen
Contact: Chris Ormel

Tsinghua University

A Population of Close-in Planets



Hot Jupiters

Warm/Cold Jupiters

2019 – 1825 planets

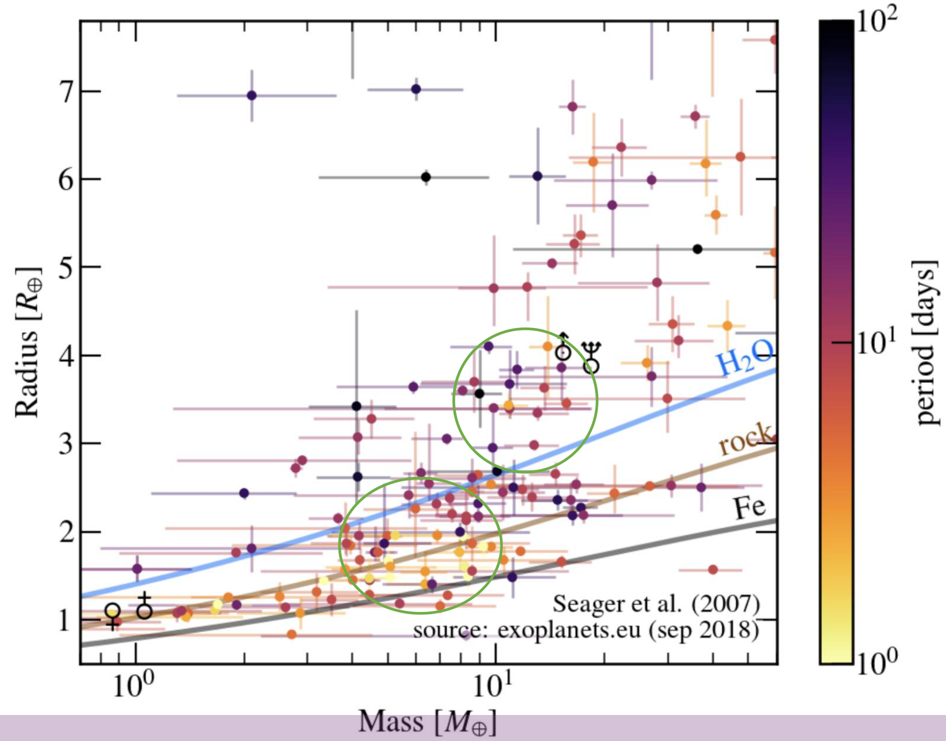
source: exoplanets.eu

Close-in planets in the narrow sense:

Super Earths / Sub-Neptunes

2-20 M_e; Rock core with 1-10% atmosphere (Earth: 1e-4%)

But 0.03-0.5 AU close in and very common (Howard et al. 2010)

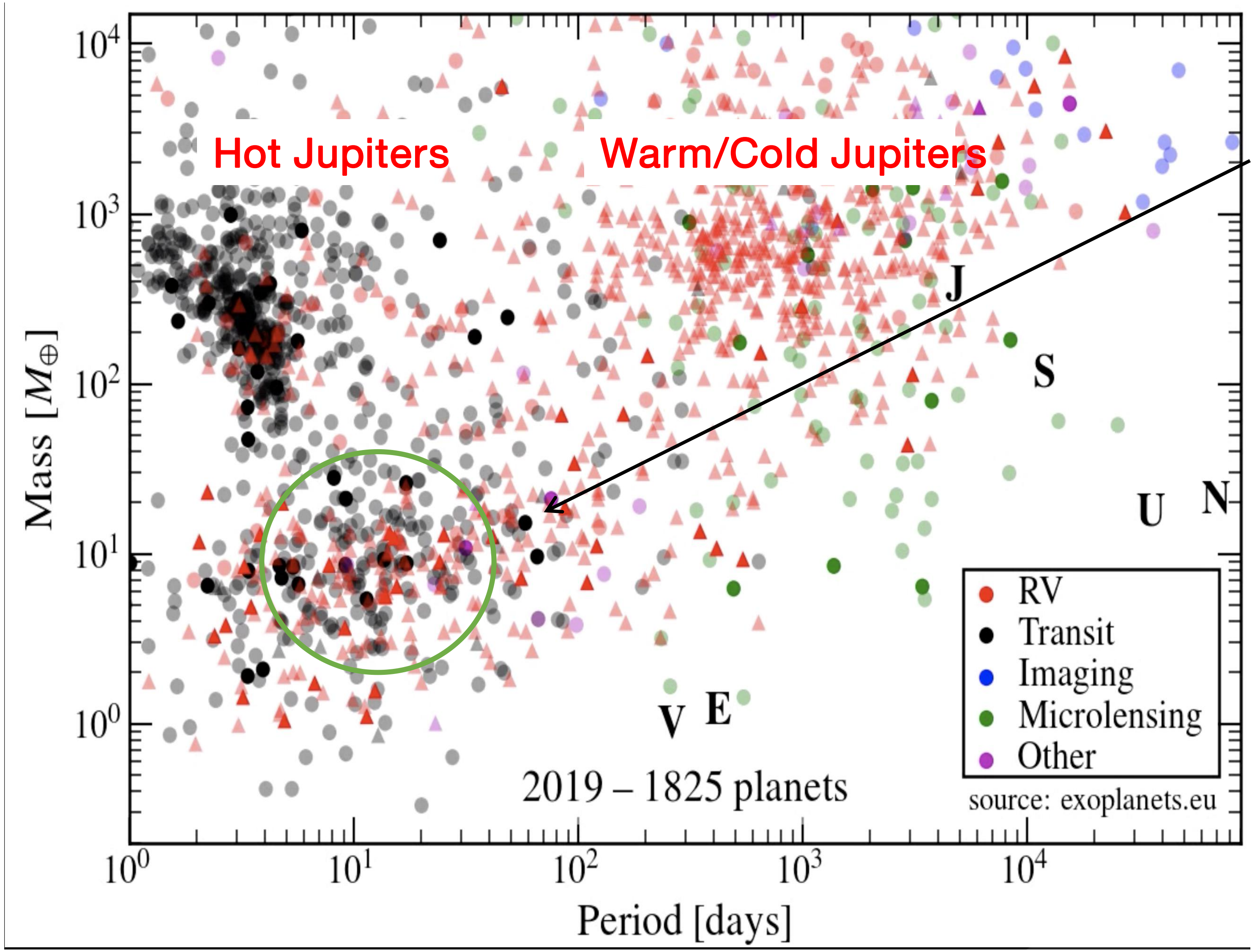


Seager et al. (2007)

source: exoplanets.eu (sep 2018)

Q1: How do we get the mass and the radius of close-in planets?

A Population of Close-in Planets



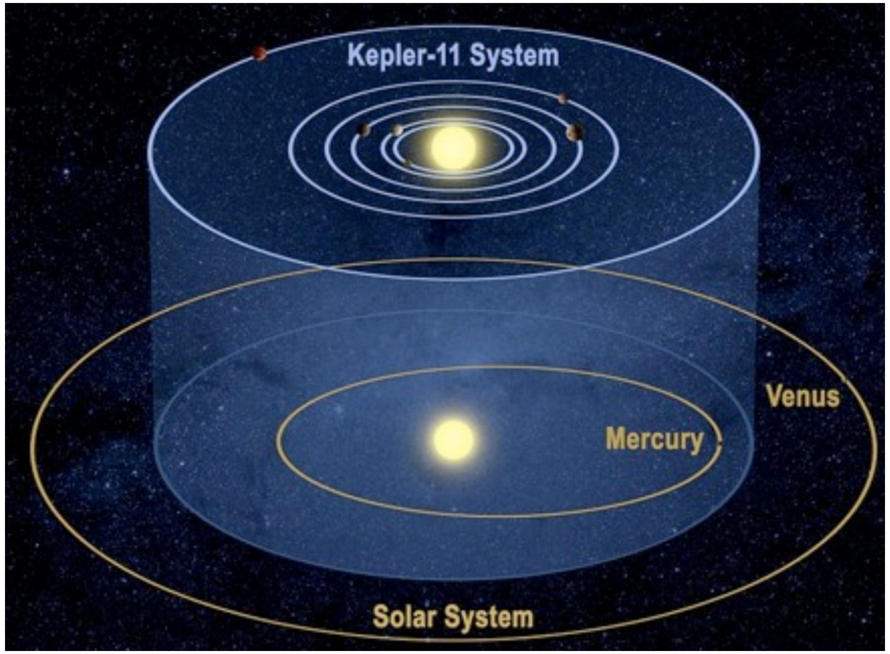
source: exoplanets.eu

Close-in planets in the narrow sense:

Super Earths / Sub-Neptunes

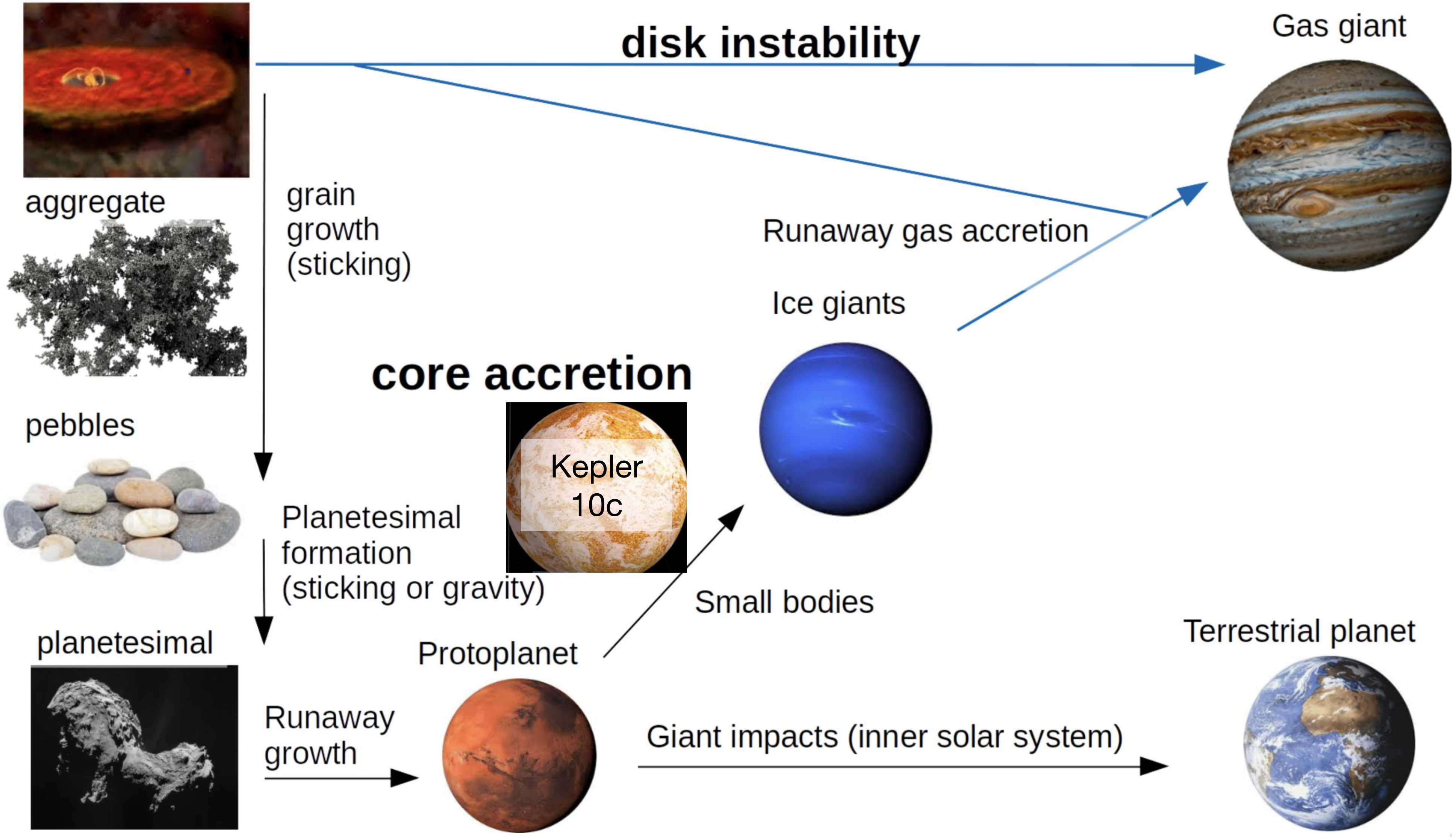
2-20 M_e; Rock core with 1-10% atmosphere (Earth: 1e-4%)

But 0.03-0.5 AU close in and very common (Howard et al. 2010)



E.g. Kepler 11 System

Formation Channel



Outline

Formation of Solid Cores

- Local formation by coagulation of planetesimals - the MMEN
- “Inside-out” formation by pebble drift and accretion
- Embryo Migration and Breaking of Resonance Chains

Accretion of Gas

- Dilemma: May accrete too efficiently - how do they avoid exploding into Jupiters?

  Effects of High Opacity/Metallicity

  Entropy Advection - constant flow between atmosphere and disk environment

- Photoevaporation - the Fulton Gap

PART I Assembly of Solids

How do Super-Earths obtain 5~10 M_e Solid Mass?

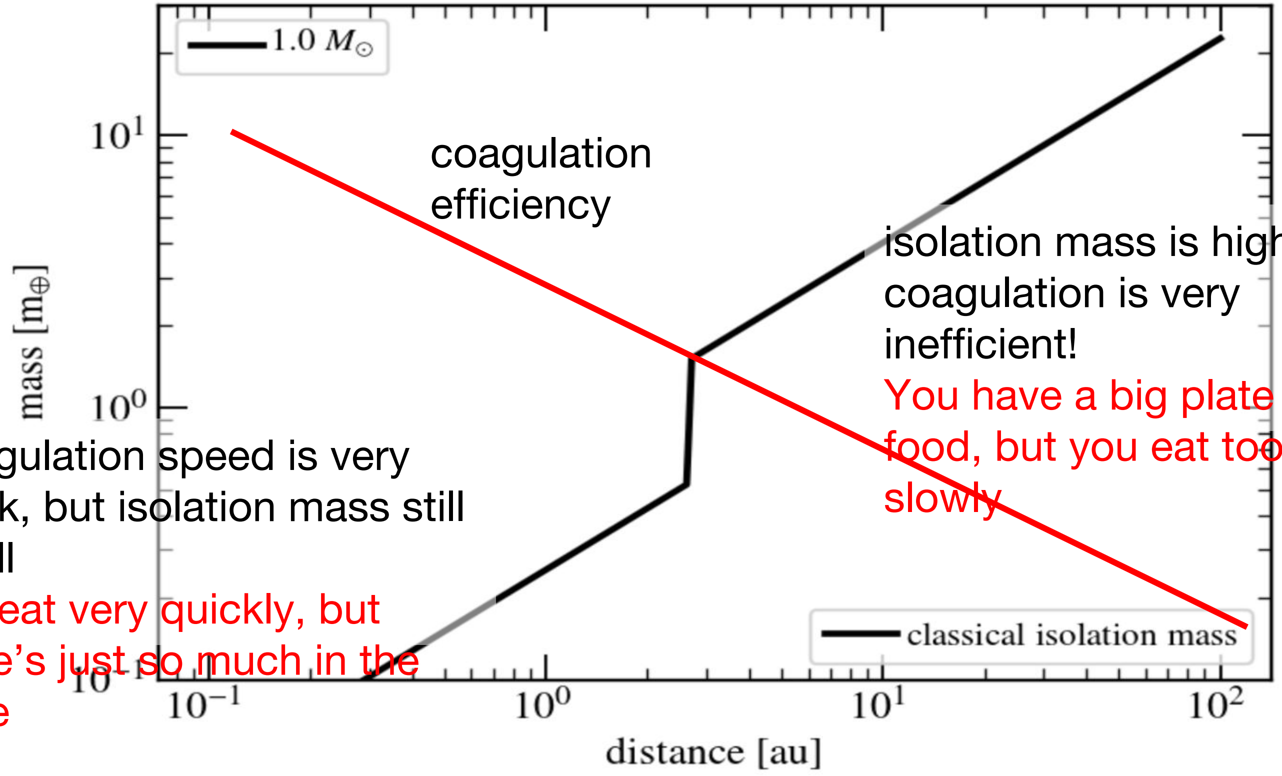
ISOLATION MASS

- the planet **isolation mass** is reached when

  $$M_{\text{iso,pl}} = 2\pi r \cdot \Sigma \cdot \Delta(M_{\text{iso,pl}})$$

  with:
  - –Δ the spacing between embryos
  - –Σ the surface density (solids)
- the mutual spacing is usually expressed in terms of Hill radii:

  $\Delta = bR_{\text{Hill}}$ where $b \approx 10$.



coagulation efficiency

isolation mass is high, the coagulation is very inefficient!

You have a big plate of food, but you eat too slowly

Coagulation speed is very quick, but isolation mass still small

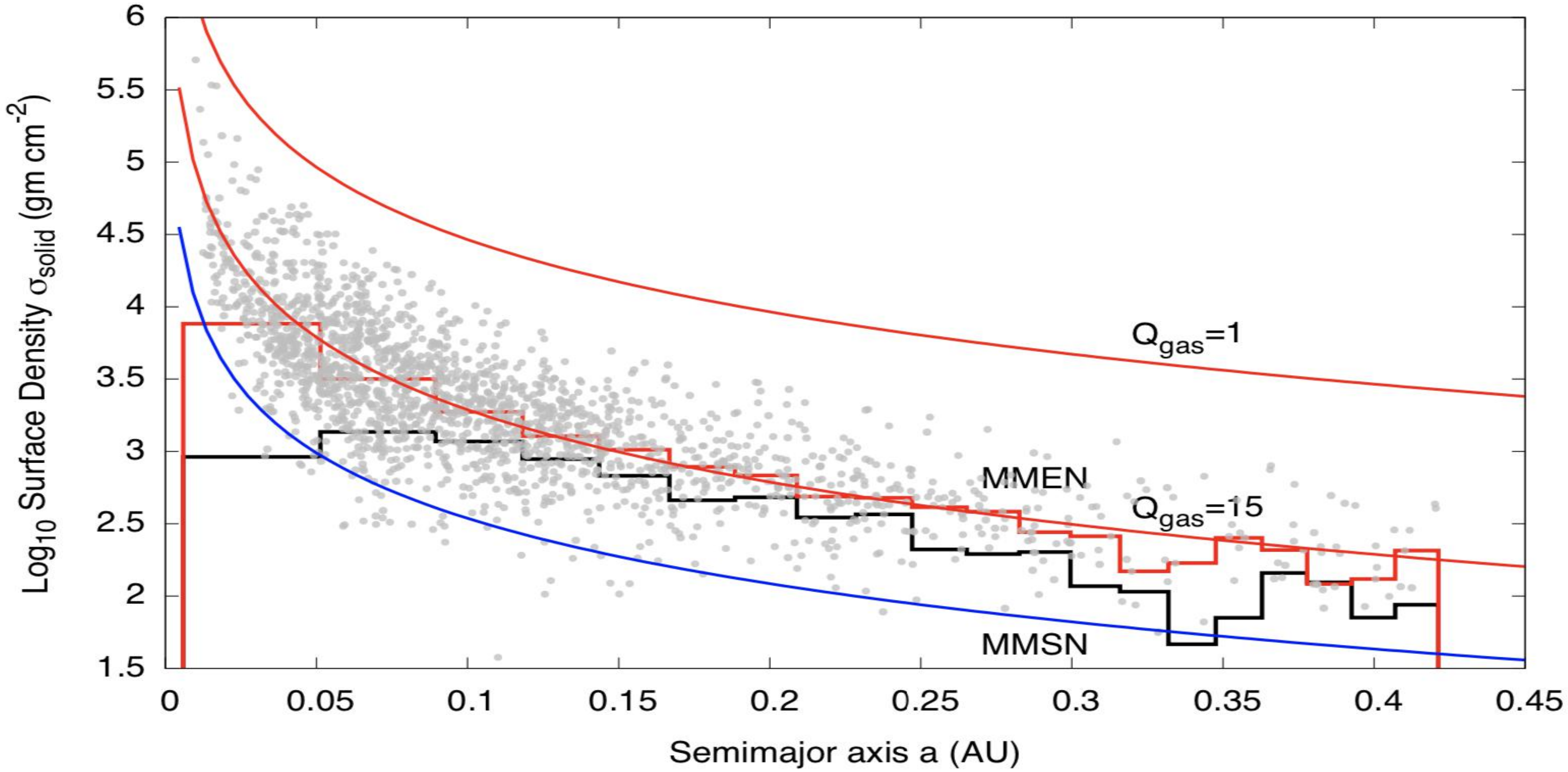
you eat very quickly, but there’s just so much in the plate

Classical isolation mass with b=10 and MMSN Σ (2x enhancement outside iceline)

$$t_{\text{coagulate}} = \frac{M_{\text{core}}}{\dot{M}_{\text{core}}} \sim \frac{1}{\mathcal{F}_{\text{grav}}} \frac{\rho_{\text{core}} R_{\text{core}}}{\sigma_{\text{solid}} \Omega}$$

t_0.2AU=0.2Myrs;
t_20AU=200Myrs

1. In-situ Formation: the MMEN



$$\sigma_{\text{solid},i} \equiv \frac{M_i}{2\pi a_i \Delta a_i} \equiv \frac{M_i}{2\pi a_i^2}$$

Smash a planet into pieces to obtain a typical surface density data point at its orbital radius, then scale gas with solid

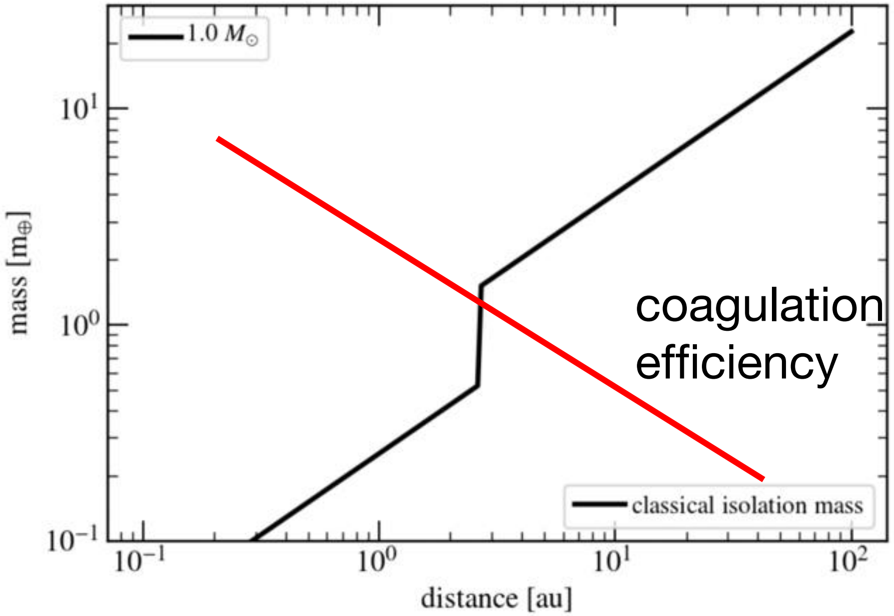
Chiang & Laughlin 2013 (earlier attempt by Kushner 2004):

1. Raise the solid surface density from MMSN to match the observed EXOSOLAR planetary systems, A.K.A Minimum Mass Extrasolar Nebular (MMEN) (more food on the plate)
2. Assume that orbit is rather chaotic, s.t. a core could accrete more than the isolation mass:

(Δ ~ a) (loosen the limit on plate size)

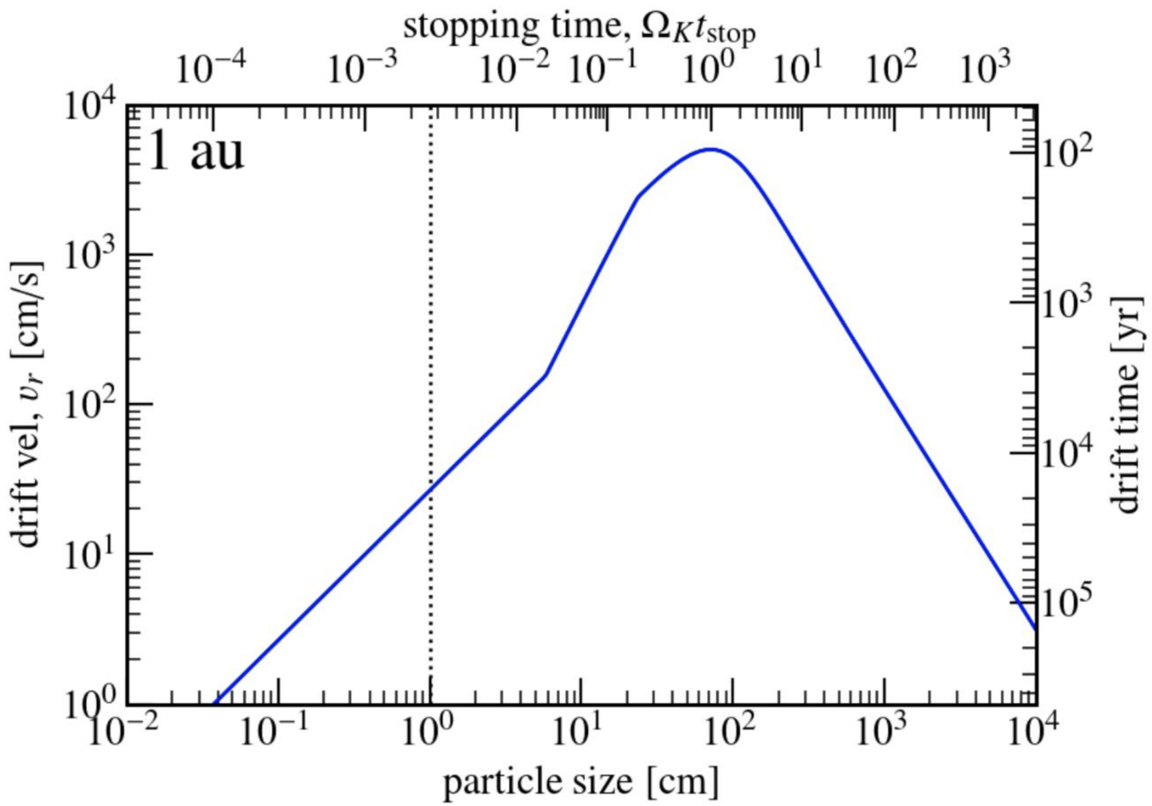
Pebble Accretion

Bypassing the Limit of Isolation Mass!



coagulation efficiency

Classical isolation mass with b=10 and MMSN Σ (2x enhancement outside iceline)

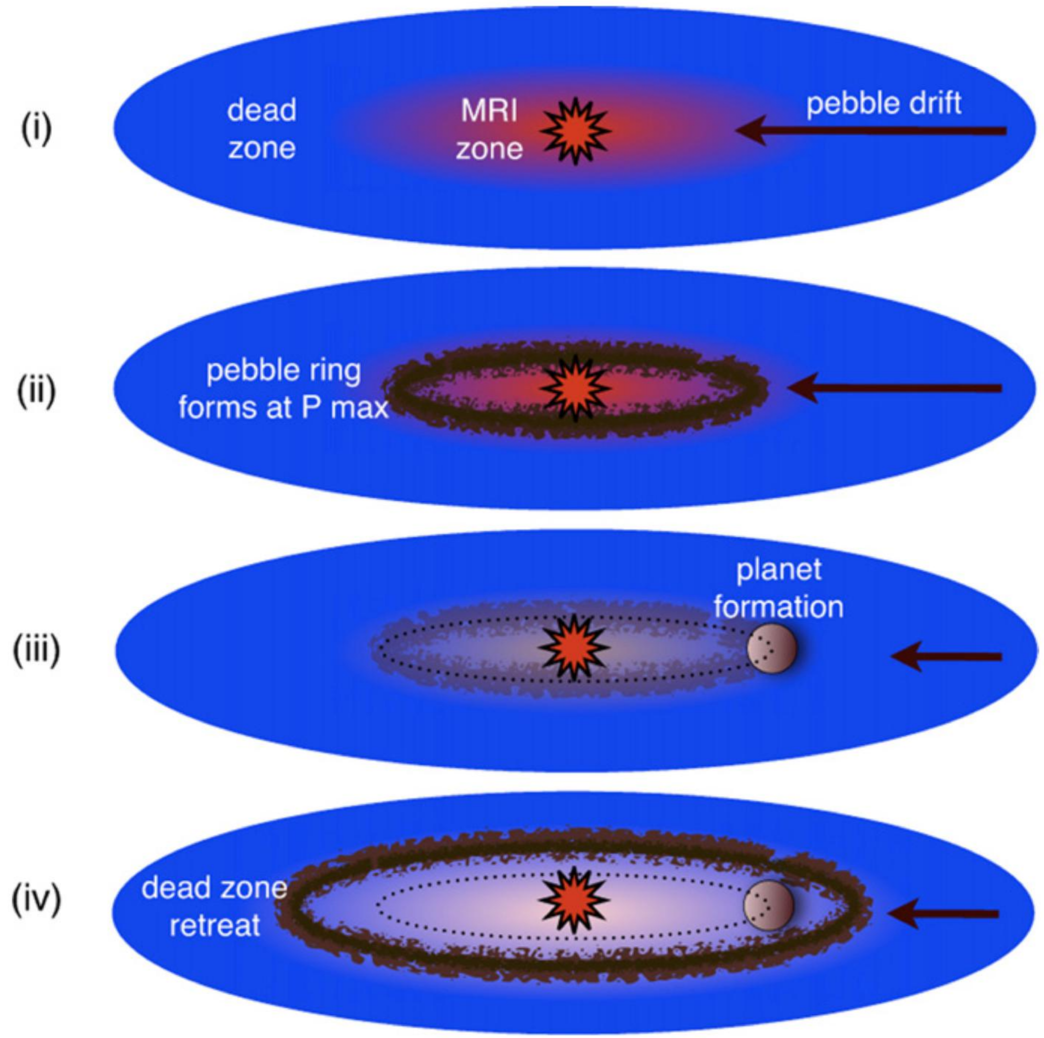


Ormel & Klahr 2010: Pebbles coupled with gas could be easily slowed down from original trajectory and then get focused

These pebbles drift together with gas from outer disk and passes the planet orbit, offering continuous feeding

Should provide most of bulk mass where planetesimal coagulation is less efficient (relax requirements on the accretion realm)

2. Inside-out Formation



Chatterjee & Tan 2014
A typical trapping radius (pressure/density maxima):

- Inner edge of the disk (connects to magnetosphere)
- transition radius of MRI region (fast-accreting) - dead zone (slow accreting)
- ...

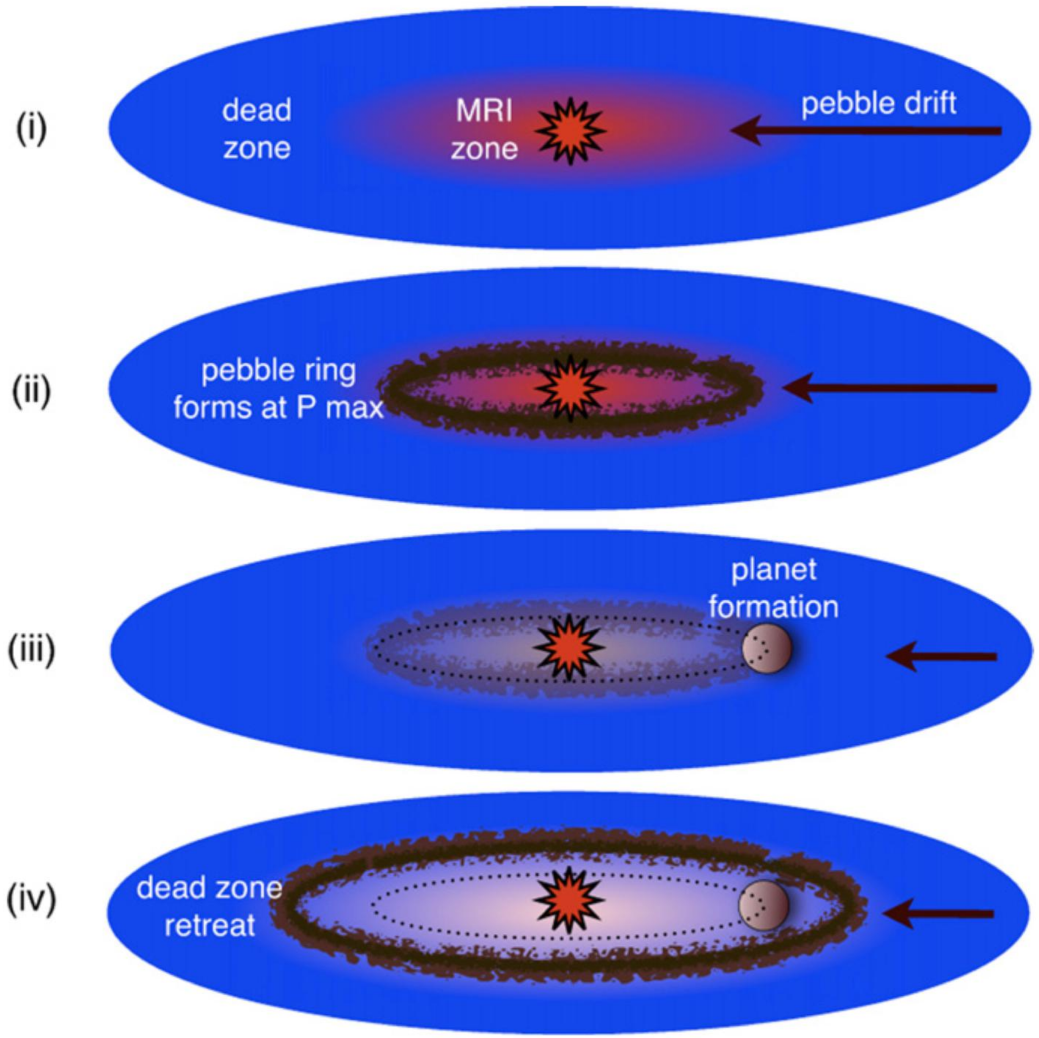
i) Pebble with high radial drift velocities quickly reach the trapping radius

ii) Accumulation of pebbles

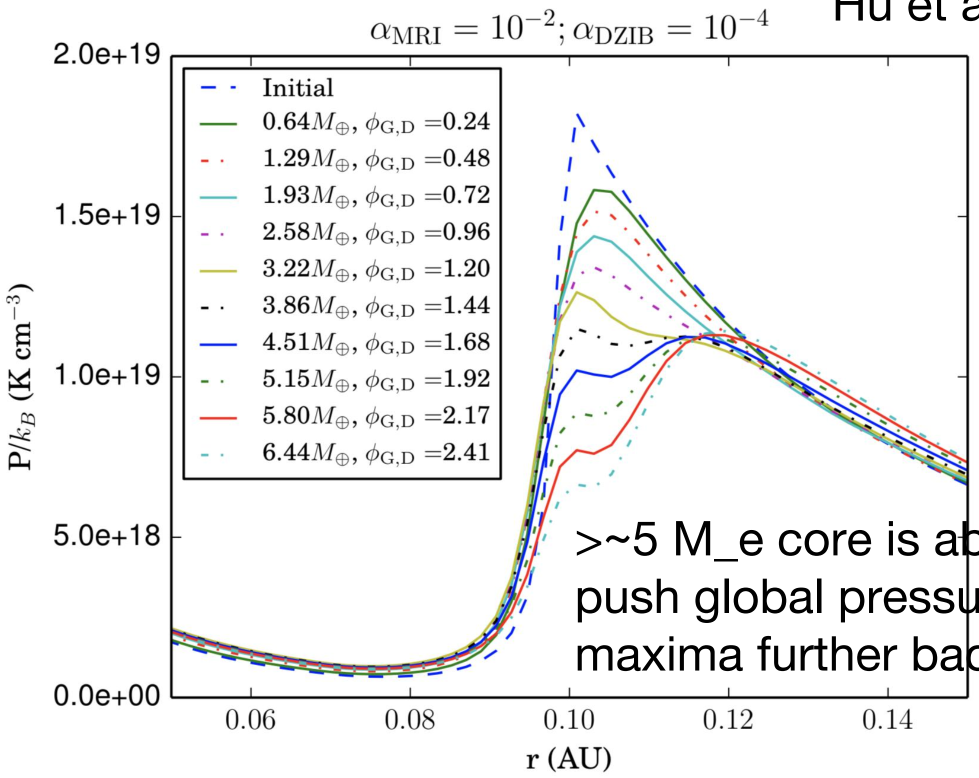
iii) Streaming instability -> small embryos
-> accretion of inward pebble
GI -> gap-opening embryos } new trapping radius (pressure maxima pushed back)

iv) New pebble accumulation at the outer pressure maxima

Inside-out Formation



Hu et al. 2017



>~5 M_e core is able to push global pressure maxima further back

To form typical close-in system, viscosity cannot be too high in the outer zone, or the pebbles drain out too quickly

3. Formation Through Migration and Pebble Accretion

- Assume some embryos are formed around the snow line (from SI, coagulation, “traffic”, etc…)

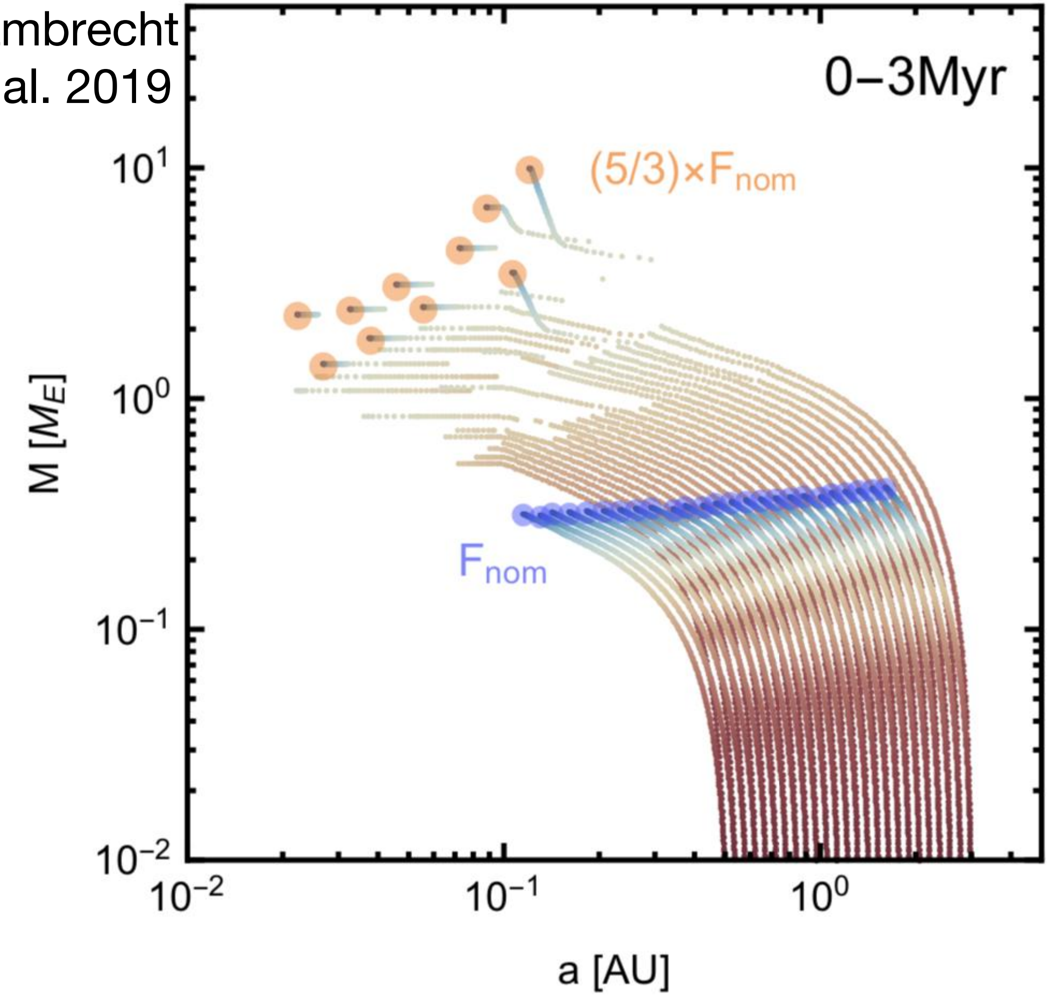
- Grows by pebble accretion, migrates inwards (more massive cores move faster), artificially stops at a trapping radius

- Result: bunch of ~5 M_e planets locked up in resonance chains
- (less pebble -> bunch of Mars size cores as in solar system)

(order-of-magnitude description of inward migration timescale)

$$\frac{M_\odot}{M_\mathrm{p}}\frac{M_\odot}{\Sigma_\mathrm{g} a_\mathrm{p}^2}\left(\frac{H}{r}\right)^2\Omega_\mathrm{p}^{-1}$$

Lambrecht et al. 2019



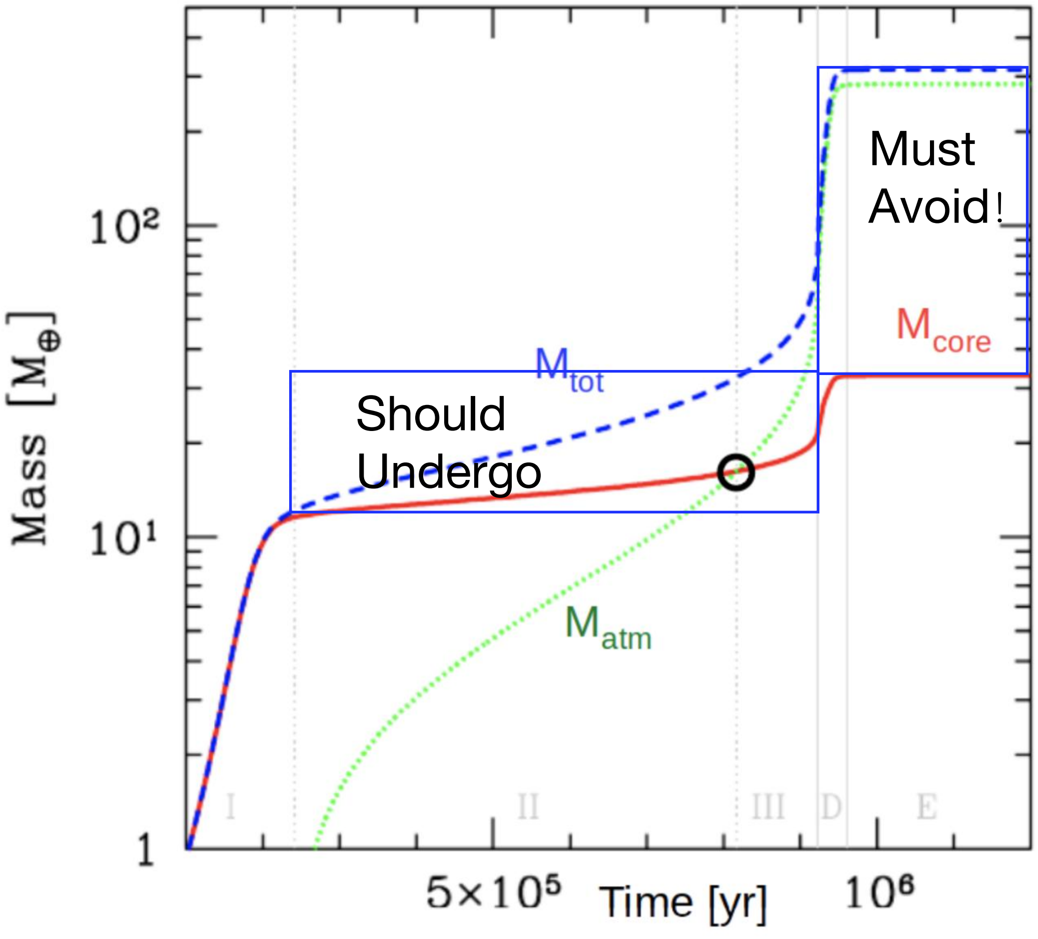
F: normalized pebble flux

Izidoro et al. 2019: could merge again after the gas depletes, 95% breaks the resonance chain and experience the last oligarch growth to ~10M_e (exception: TRAPPIST-1)

PART II Accretion of Gas

How do Super-Earths Avoid Runaway

Recall the core-accretion model: After formation of core, a ~10 M_e planet core undergoes slow accretion till Gas to Core mass ratio ~1 then explode into a gas giant



Mordasini et al. (2012)

Typical Disk Lifetime ~10 Myrs

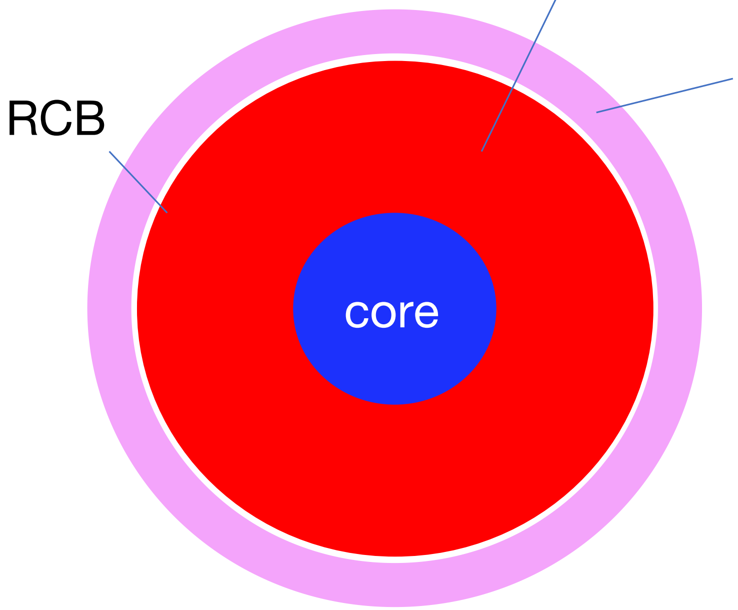
The retention problem: if the accretion of solids completed rather early, cores might accrete massive envelopes and explode into gas giants

If they only form very late after gas dissipates, then it might be hard for them to get 1-10% atmosphere

Need for some robust mechanism to avoid runaway

Gas Accretion of Super-Earths

Convective zone, instability between layers of gas creates turbulence, lets them flow freely and keep an adiabatic gradient



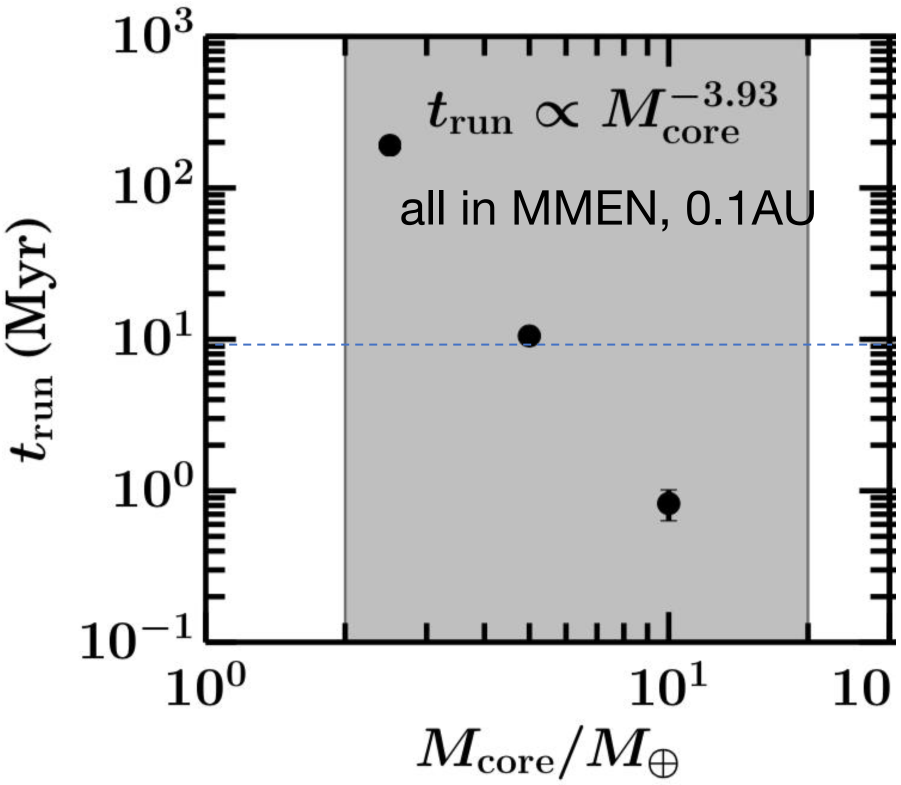
Radiative Zone:
Relatively stable, temperature gradient determined by radiative diffusion

Quasi-steady Accretion:
heat is dissipated in form of luminosity, allows for atmosphere to contract and more gas flows in

“To Cool is to Accrete!”
——Lee & Chiang 2015

t=E/L (cooling luminosity)

Lee et al (2014):
1-D model, accretes everything within Hill/Bondi Radius



>5M_e are relatively easy to trigger runaway growth within disk lifetime!

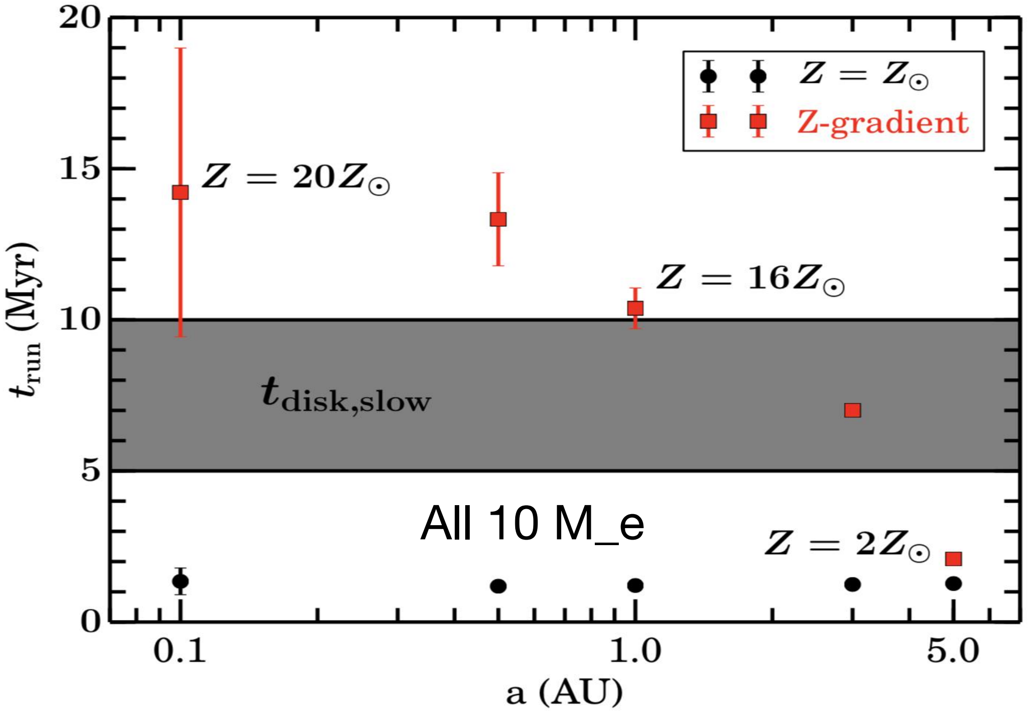
1. Effect of High Opacity/Metallicity

radiative zone gradient

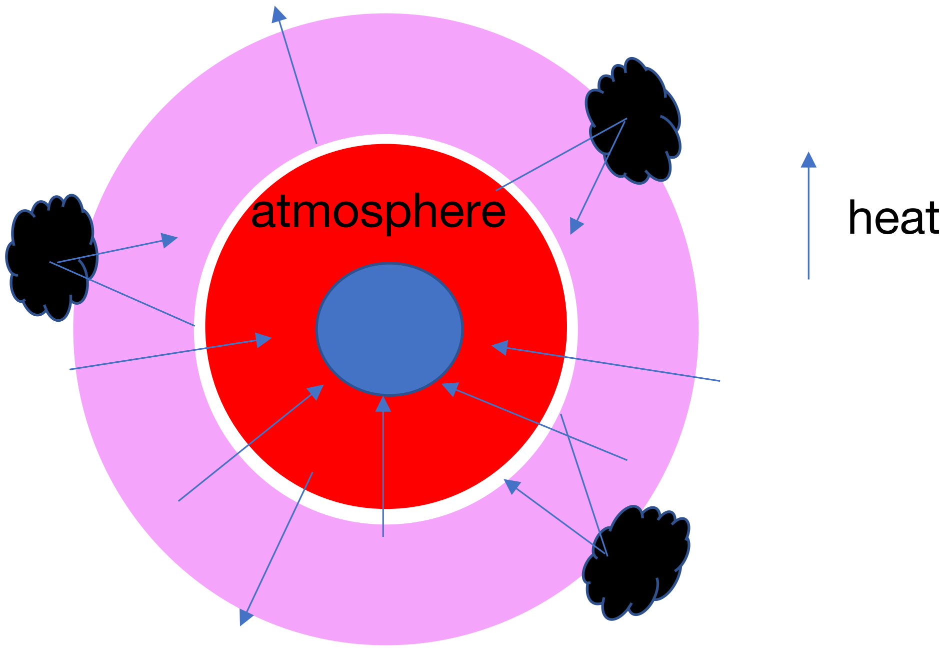
$$\nabla_{rad} = \frac{3\kappa P}{64\pi G M \sigma T^4} L.$$

Contributed by dust grains <2000 K (usually since radiative zone is near outer boundary)
or gas >2000K

- Grain Contaminant ↑
- Opacity ↑
- Cooling ↓ (blocked!)
- Accretion Rate↓



All 10 M_e

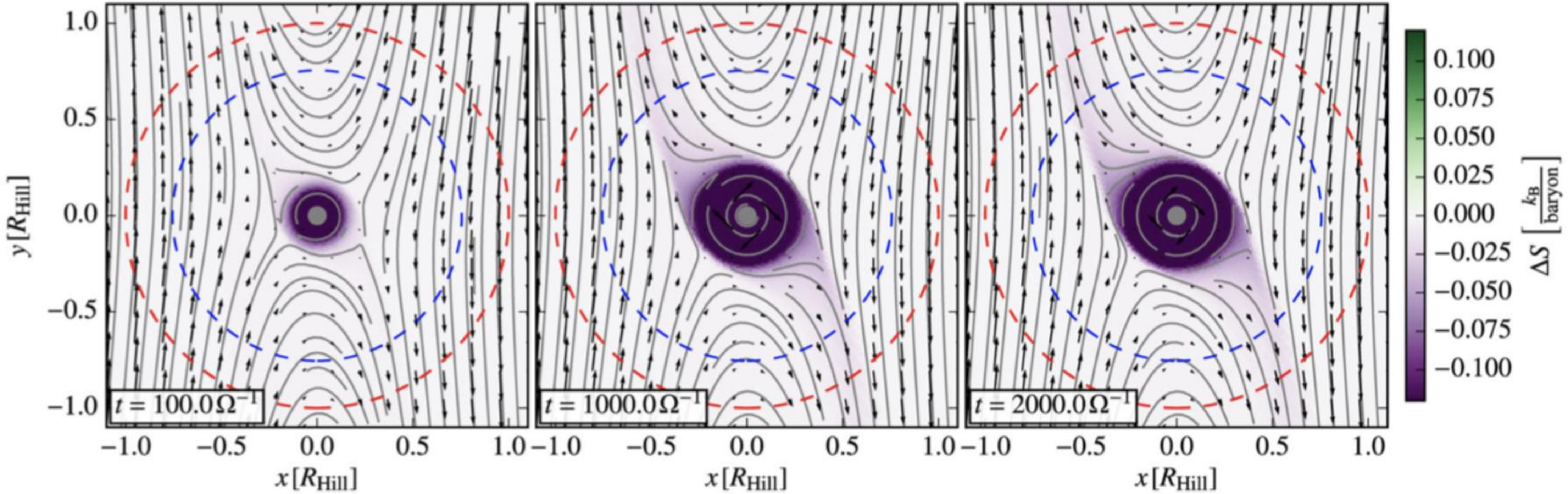


2. Entropy Advection

atmospheres of low-mass cores cannot be considered isolated from the protoplanetary disc

Ormel et al 2015, Cimerman et al 2017

Time

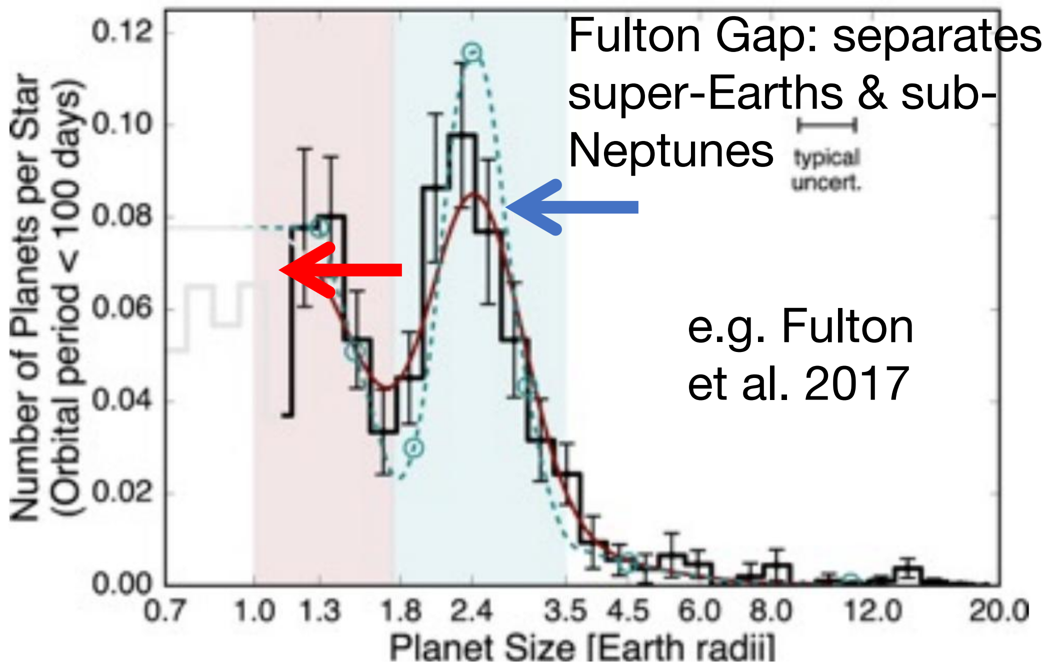


In 3D simulations, gas continually RECYCLES between the cores atmosphere and the back-ground disk

A considerable part of the Hill/Bondi radius maintains same ENTROPY with disk environment and is not bounded to the core. <~0.3 R_H we finally see trace of entropy transition (radiative zone), and an inner equi-entropy zone (real bounded convective zone)

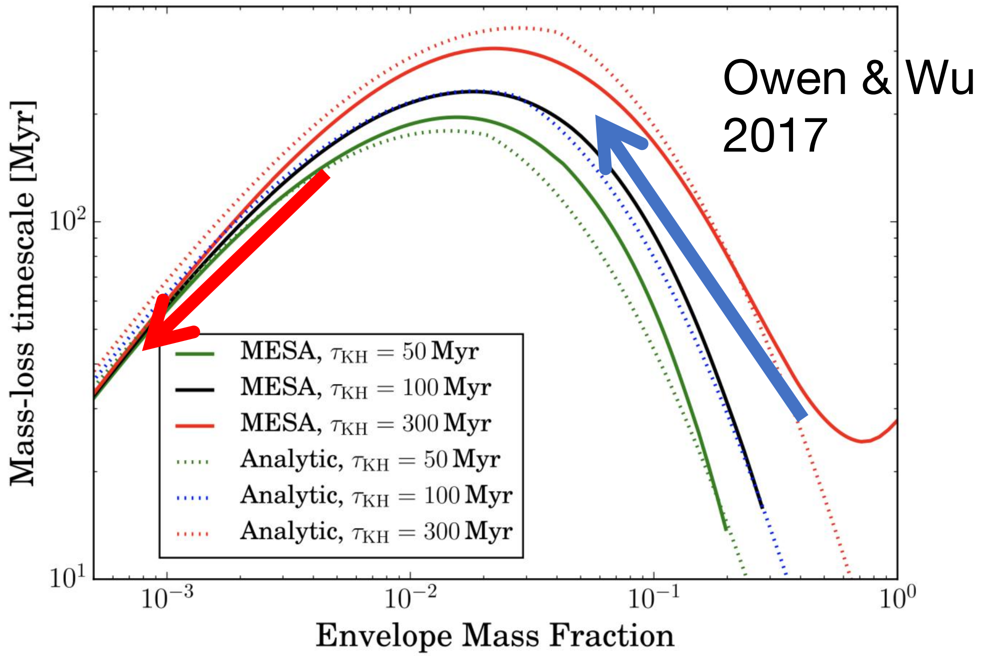
Cooling is confined to a smaller and hotter surface, prolongs accretion timescale

Photo-evaporation - Atmospheric loss post-formation



Fulton Gap: separates super-Earths & sub-Neptunes

e.g. Fulton et al. 2017



Owen & Wu 2017

$$\dot{M}_{\mathrm{env}} = \eta \frac{\pi R_p^3 L_{\mathrm{HE}}}{4\pi a^2 G M_p}$$

(Photon energy per unit time)/
(binding energy of unit mass)

- the mass-loss timescale peaks at around where the envelope mass is of order a few percent
- The timescale drops below this value: while the envelope becomes more tenuous, the planet radii remain largely constant and so do the photoevaporating fluxes they receive
- The timescale also drops above this value: planet swells up faster than the losing of envelope mass.

Q2: can you describe how the mass-loss time distribution helps explain Fulton gap?

Summary

Formation of Solid Cores

Channel	In-situ Formation	Inside out formation	Migration
Advantages	Derived directly from observational properties	Address the formation of the first core	Late formation avoids runaway; Avoid dust sublimation at close-in radii
Disadvantages	Must have feeding zone comparable to a; Neglect realistic migration	Pebble drift is very lossy; Formation too close-in that dust sublimates	Form resonance chains, not found in most observation

Accretion of Gas May accrete too efficiently - how do they avoid exploding into Jupiters?

Channel	High opacity	Entropy Advection
Advantages	Very effectively reduces cooling	Follows directly from 3D
Disadvantages	Might quench gas giant formation too	Long-term evolution not well-known

Photoevaporation - the Fulton Gap

After the accretion, when planet is exposed to the star