Overview of Planetesimal Accretion

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with

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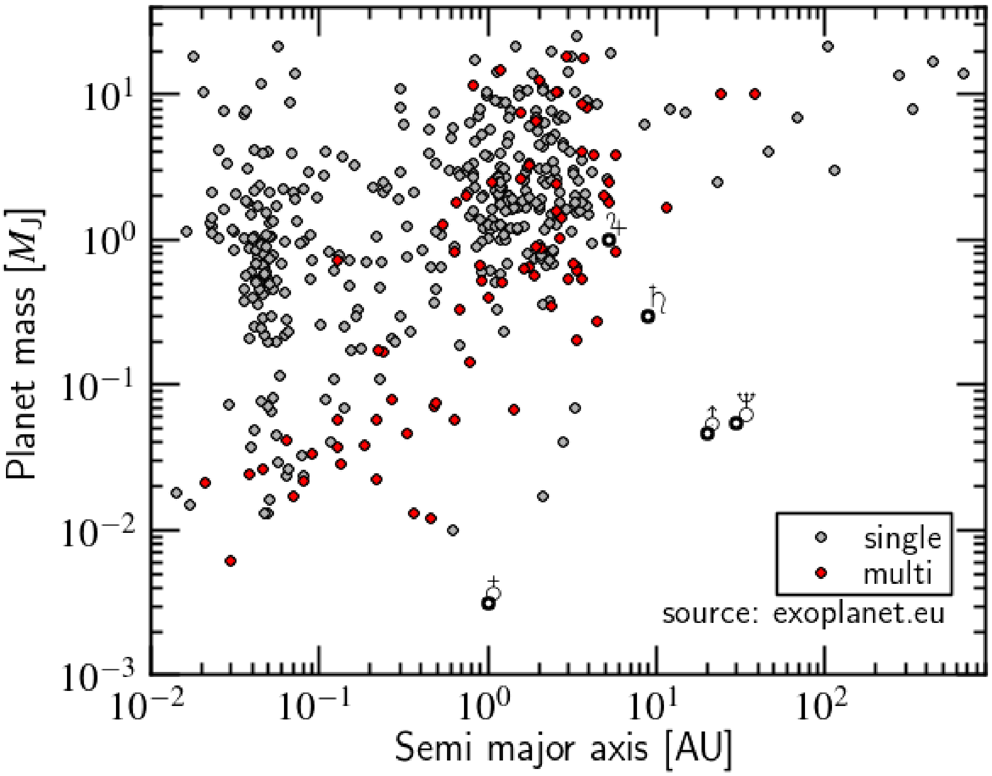
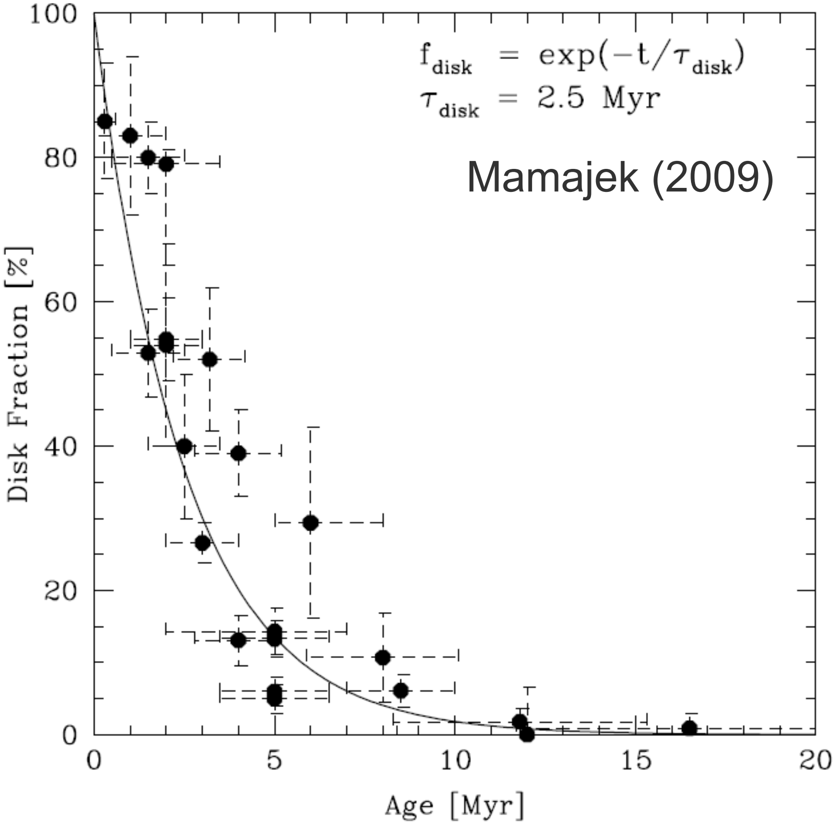
Contents

- Planet formation in context
- Gravitational focusing
- Runaway & oligarchy growth
- Timescales
- Role of debris

Observational constraints, context



source: exoplanet.eu



Mamajek (2009)

- Timescales for (gas) disk disappearance

  Several Myr

- Abundance of gas-giants in exo-systems

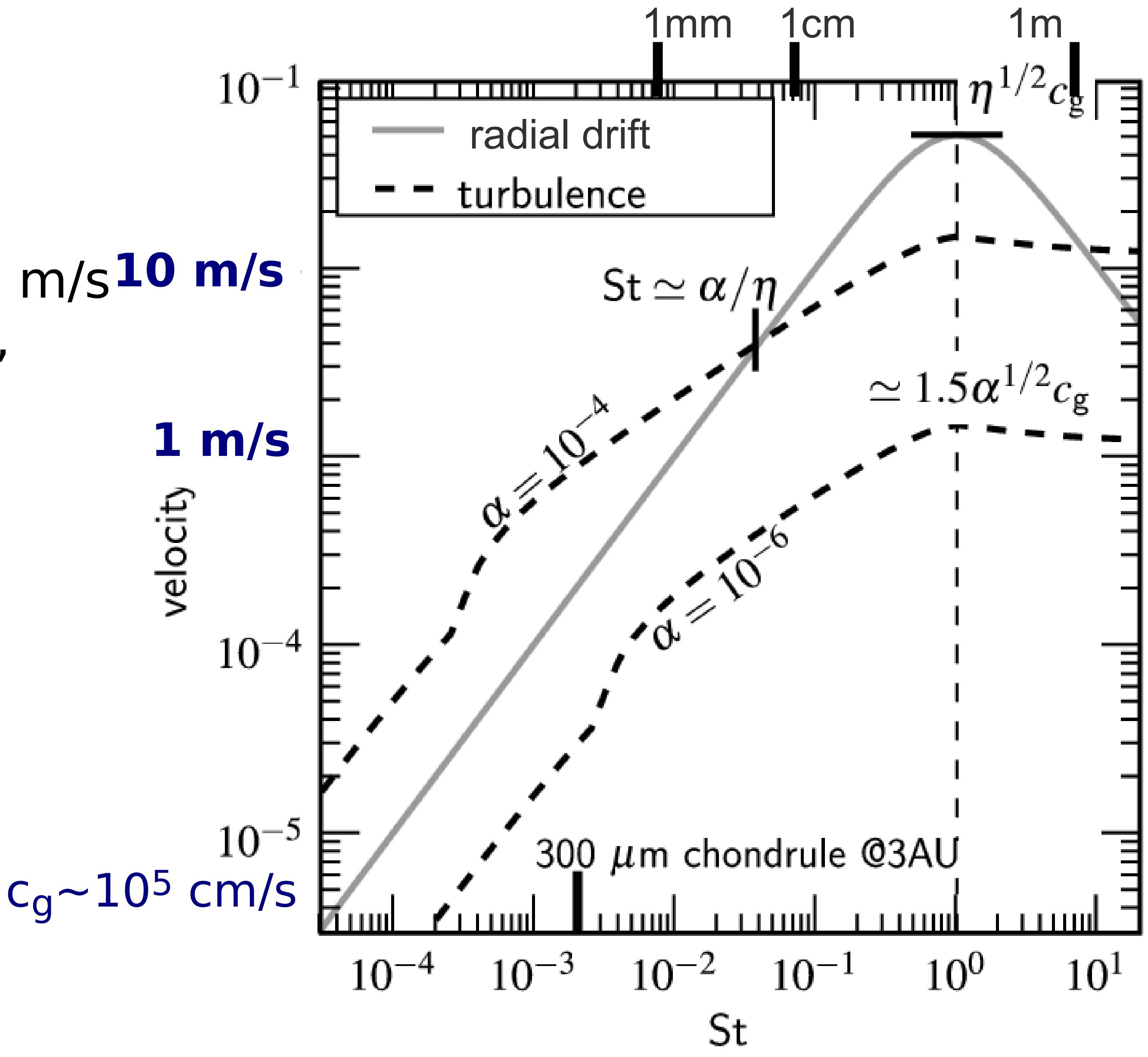
Solar system

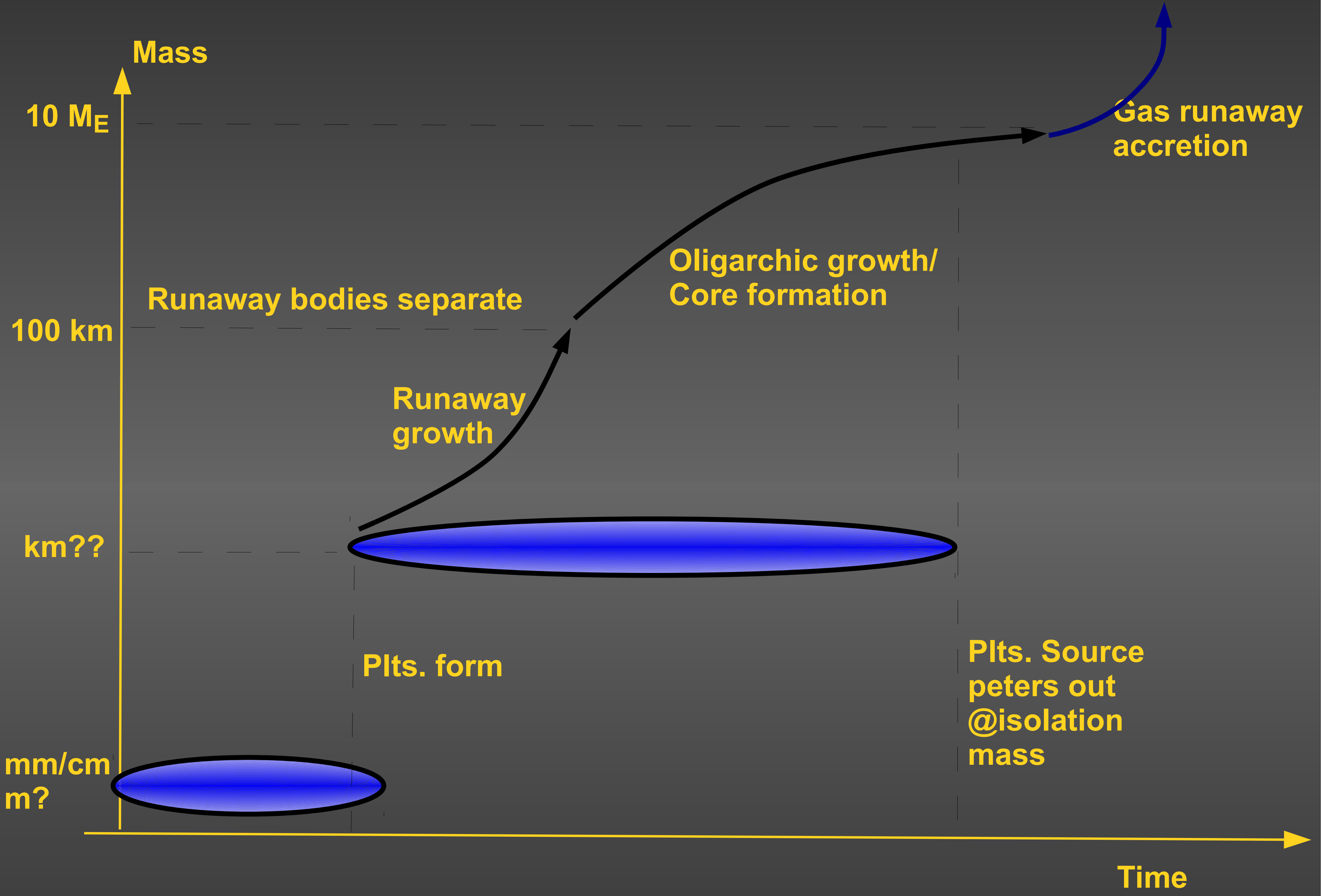
Eros © NASA

Allende, ©Carsten Münker

Particle motions

- Gas moves **subkeplerian**
- Radial drift ~10 m/s
- “m-size barrier”





Mass

$10\ M_E$

100 km

km??

mm/cm

m?

Runaway bodies separate

Runaway growth

Oligarchic growth/
Core formation

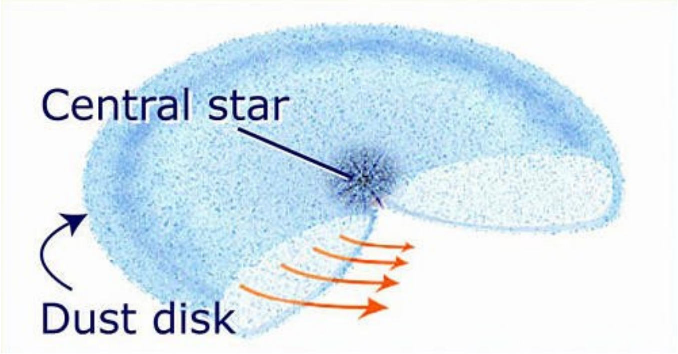
Gas runaway
accretion

Plts. form

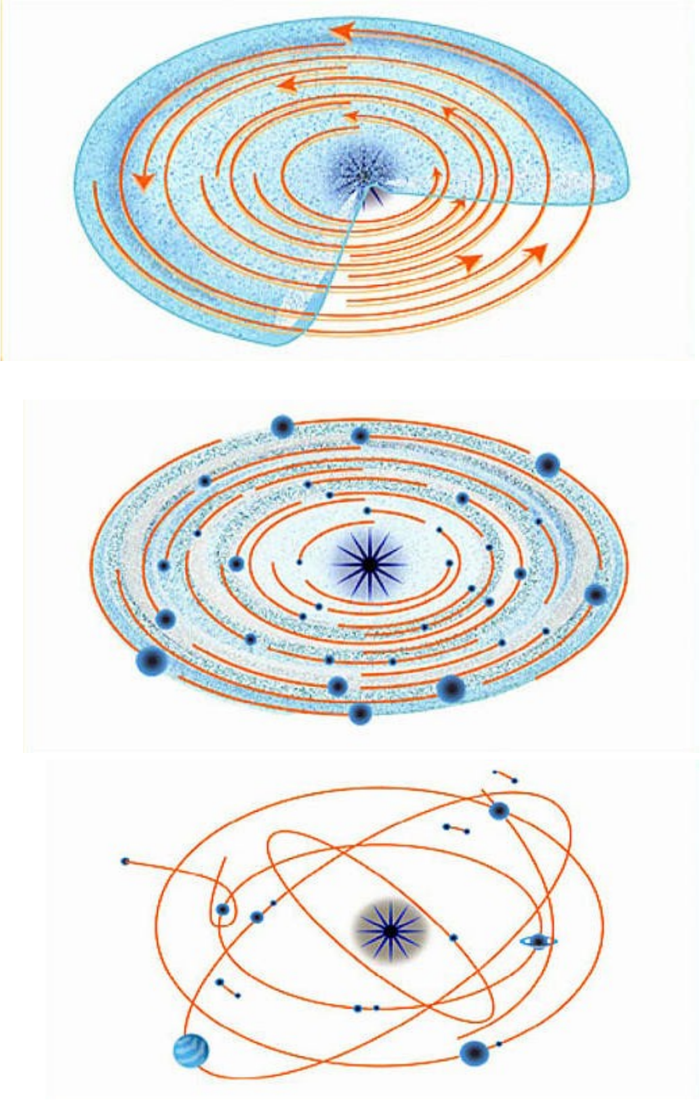
Plts. Source
peters out
@isolation
mass

Time

Planet formation



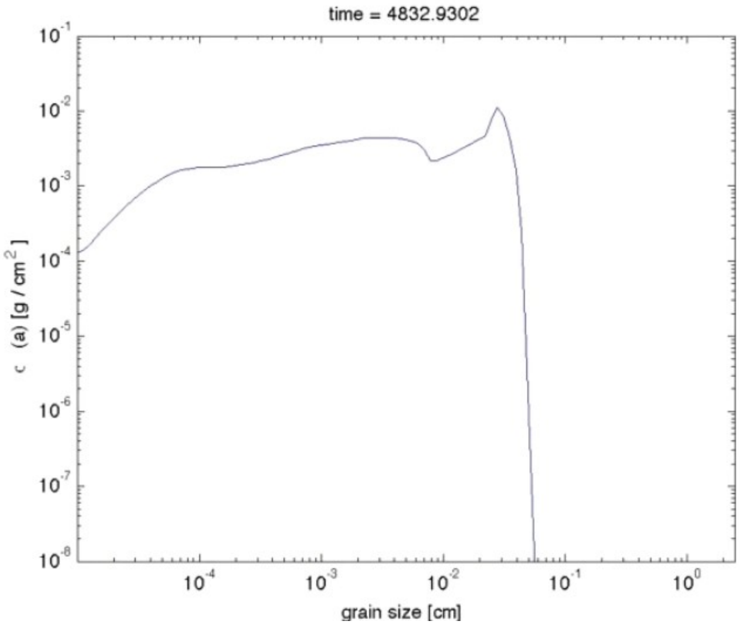
- Disk Instability
  - Gas in the disk collapses
    e.g. Boss papers



- Core accretion
  - Dust to planetesimals
  - Planetesimals to protoplanets
  - Protoplanet growth/migration
  - (protoplanet interactions)

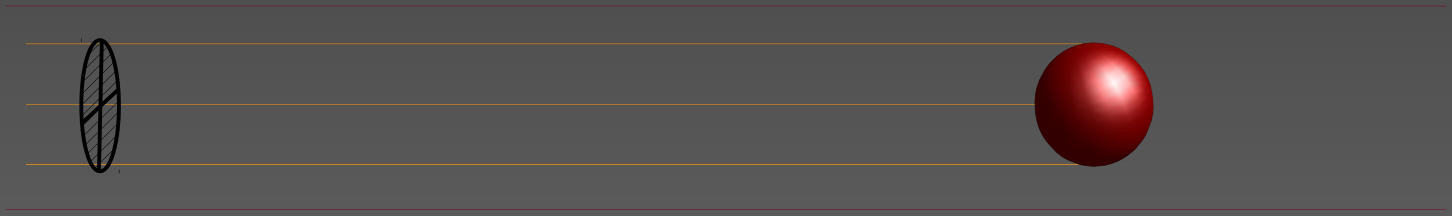
Accretion unknowns

- How are planetesimal bodies formed?
  - Several barriers: bouncing, radial drift, fragmentation, charge
    (Güttler/Zsom et al. 2010; Brauer et al 2007; Birnstiel et al. 2009; Okuzumi 2009)
  - Particle concentration through turbulence
    Johansen et al. 2007, 2009; Cuzzi et al 2008, 2010
  - Initial size, formation timescale



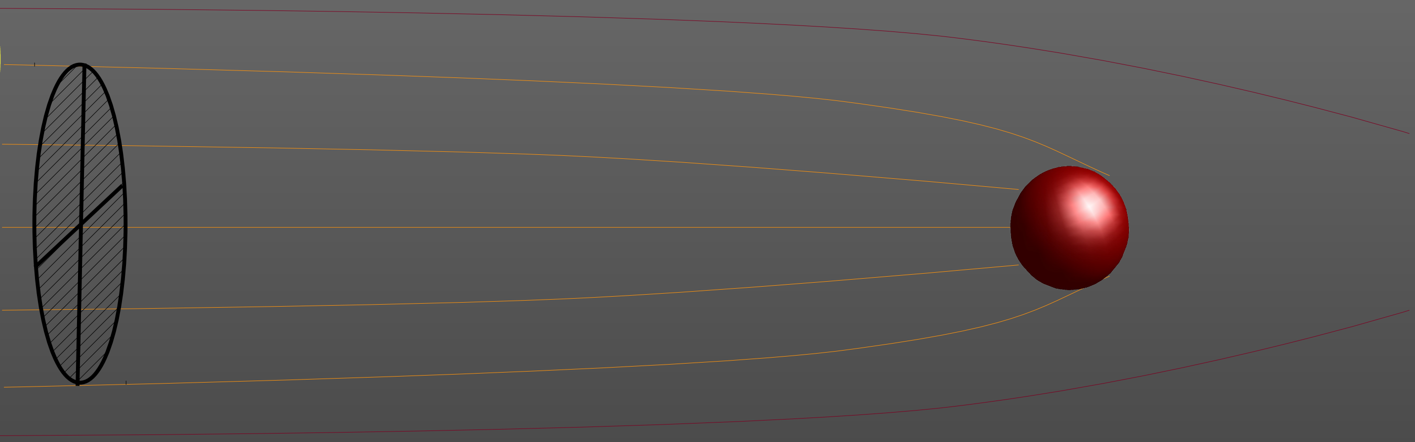
Gravitational focusing

$$\sigma_{\mathrm{col}} = \pi R^2$$



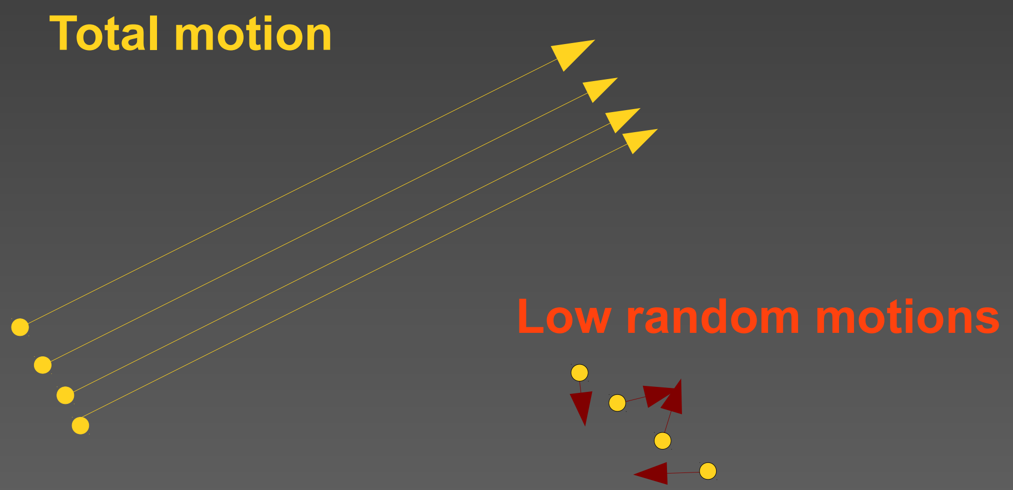
$$\sigma_{\mathrm{col}} = \pi R^2 \left(1 + \frac{v_{esc}^2}{v_a^2}\right)$$

$$v_{esc} = \sqrt{\frac{GM}{2R}} \propto R$$



Viscous stirring (VS)

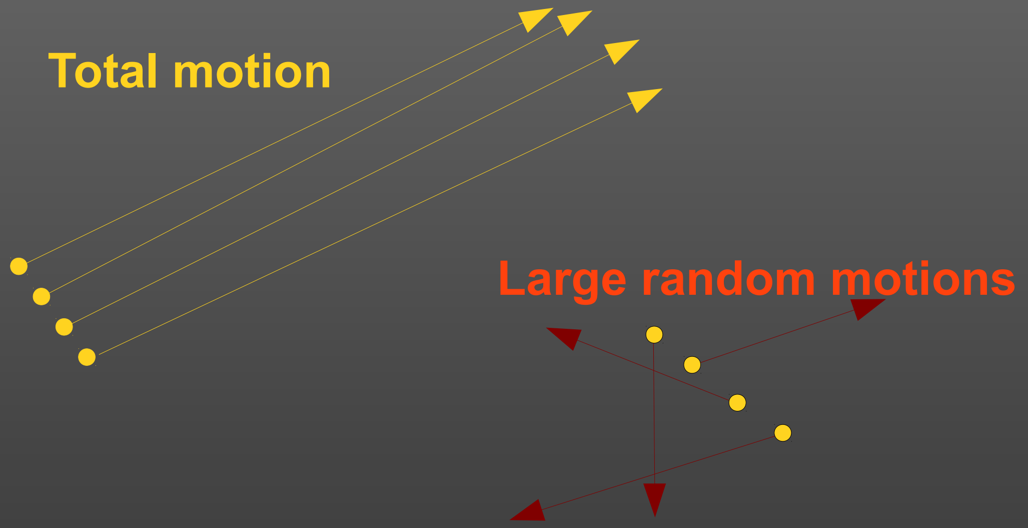
- Feedback effects growth
  - Increase v_{esc}
  - Increase VS



Total motion

Low random motions

$\mathbf{v}_{tot} = \mathbf{v}_{kepl} + \mathbf{v}_{ran}$; $v_{ran} \sim e v_{kepl}$



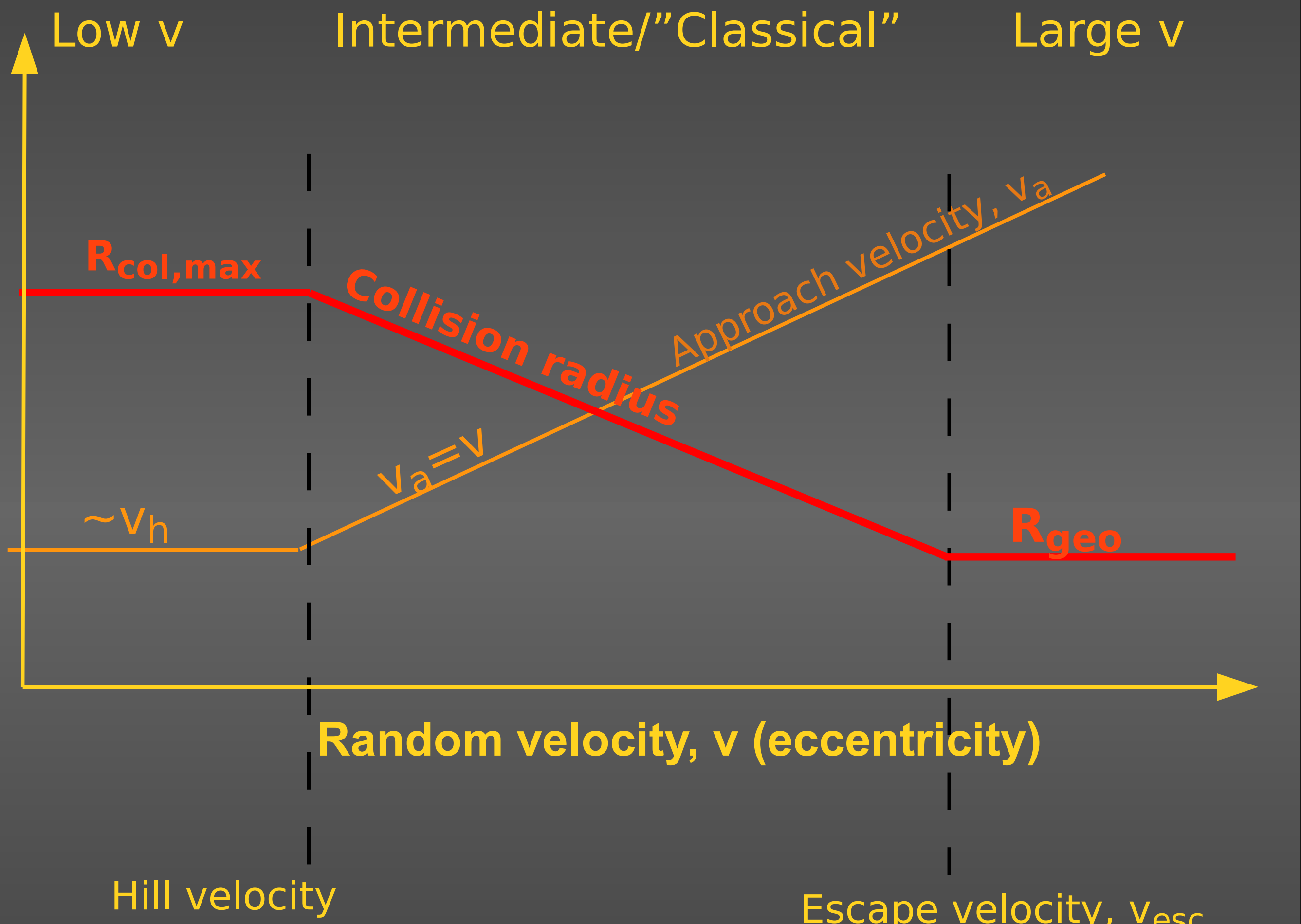
Total motion

Large random motions

GF – velocity regimes

$$\sigma_{\mathrm{col,max}} \sim \pi R^2 \left(\frac{v_{esc}}{v_h}\right)^2$$

$$\sim 10^3 \pi R^2$$



$$v_h = v_k \left(\frac{M}{3M_\odot}\right)^{1/3} \propto R$$

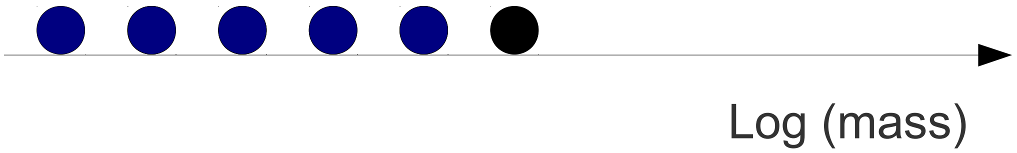
$$v_{esc} = \sqrt{\frac{GM}{2R}} \propto R$$

Runaway and oligarchic growth

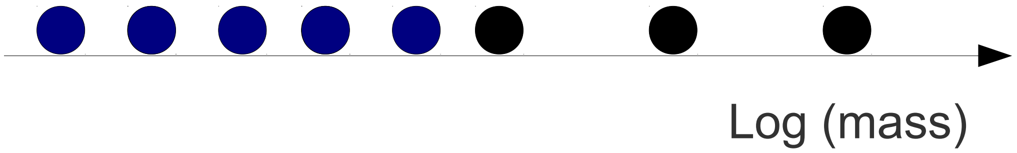
$$\frac{dM}{dt} \propto \pi R^2 \left(\frac{v_{esc}}{v_{ran}}\right)^2 \propto M^{4/3}$$

$$T_{\rm growth} = \frac{M}{dM/dt} \propto M^{-1/3}$$

Normal growth



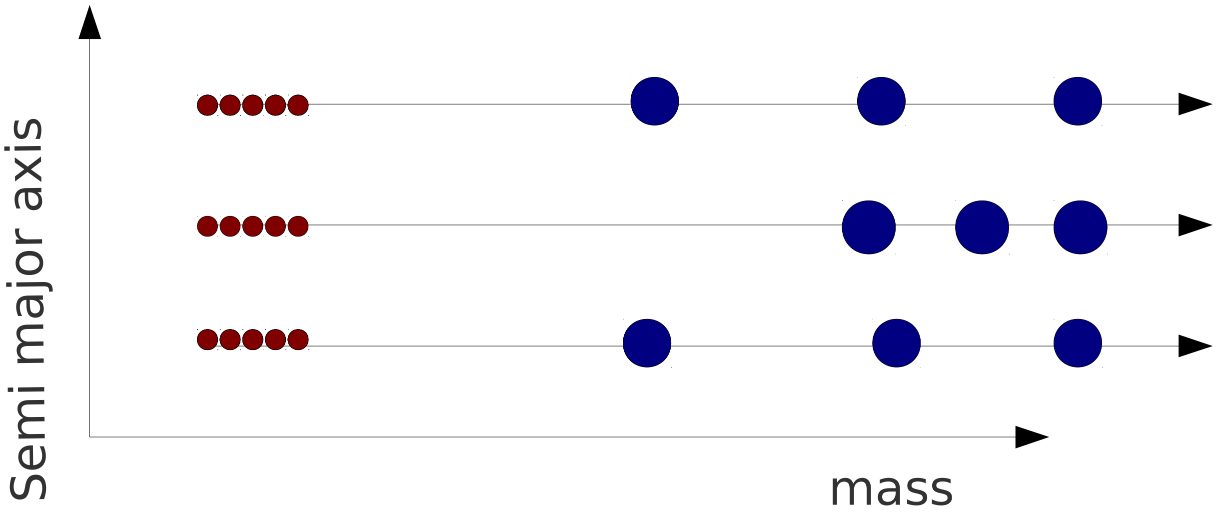
Runaway growth



2 component distribution of oligarchs & Planetesimals

(Kokubo & Ida 1998)

Oligarchic growth



(Color indicates eccentricity/random motion)

RG/Oligarchy: physical processes

- Dynamical
  - Viscous stirring;
  - Dynamical friction;
  - Gas drag;
  - Scattering;
- Physical
  - Accretion
  - Fragmentation

$$\text{GF factor} = \left(\frac{v_{esc}}{v_{ran}}\right)^2$$

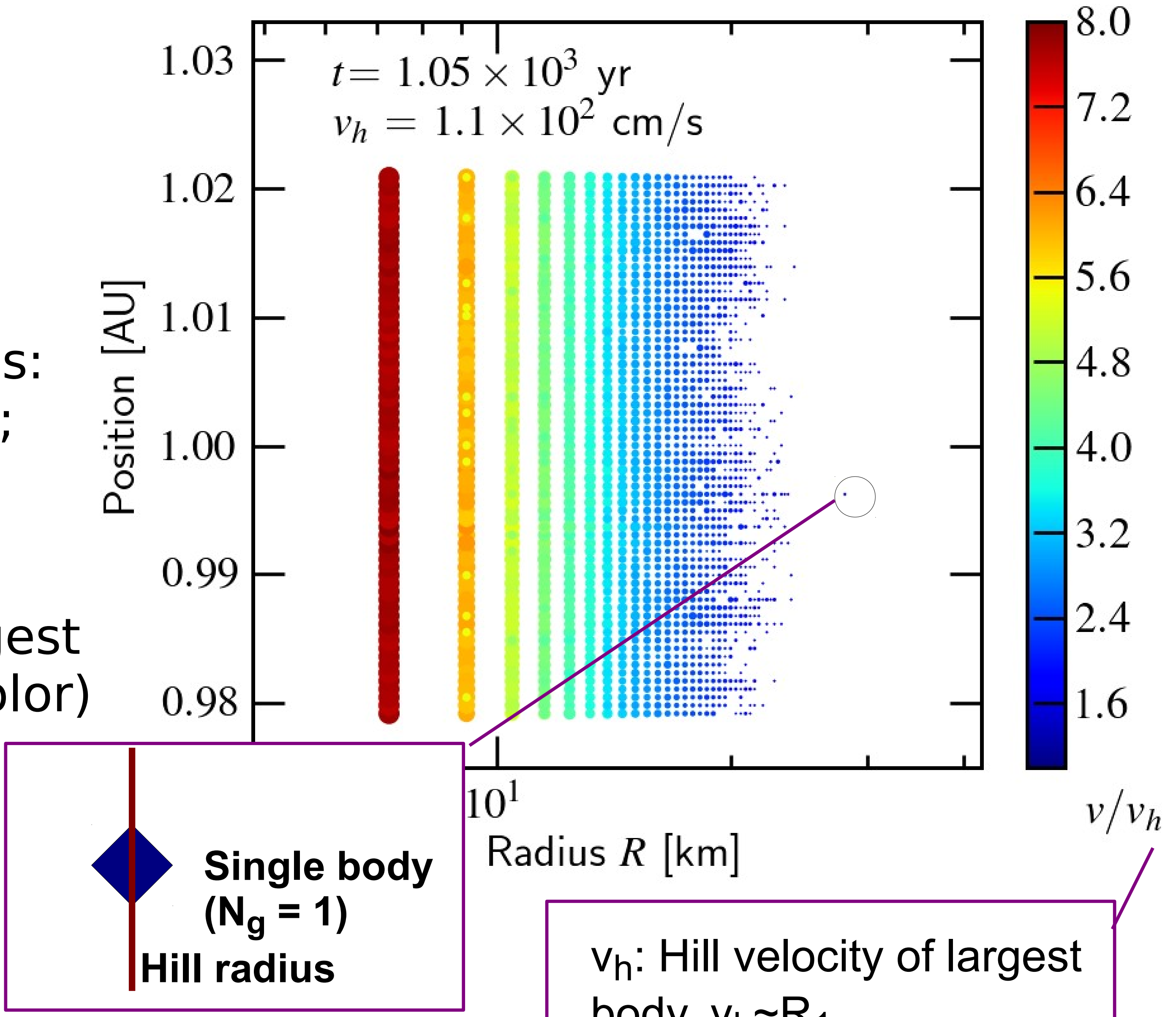
- Growth: increases v_{esc}
- Stirring: increases v_{ran}

Ormel et al. (2010a):

- Runaway growth: GFF increase
- Oligarchy: GFF decrease/stabilize

1 AU simulation (Ormel et al 2010b)

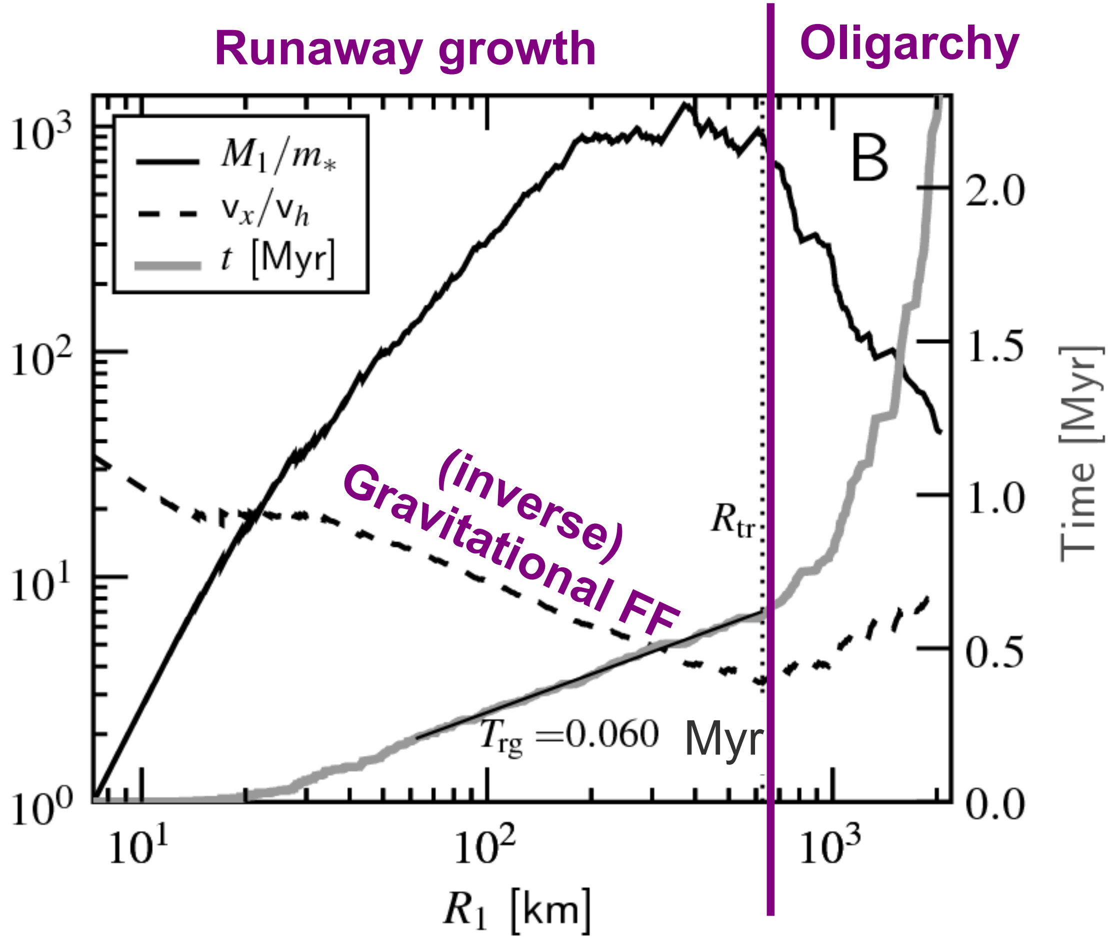
- Indicated are:
  - Radius plts. (X)
  - Position plts. (Y)
  - Group total mass: Area dot~$m^{1/3}_{tot}$; $m_{tot} = N_g\, m_{idv}$
  - Grav. focusing factor w.r.t. biggest particle (v/v_h, color)



v_h: Hill velocity of largest body, $v_h \sim R_1$

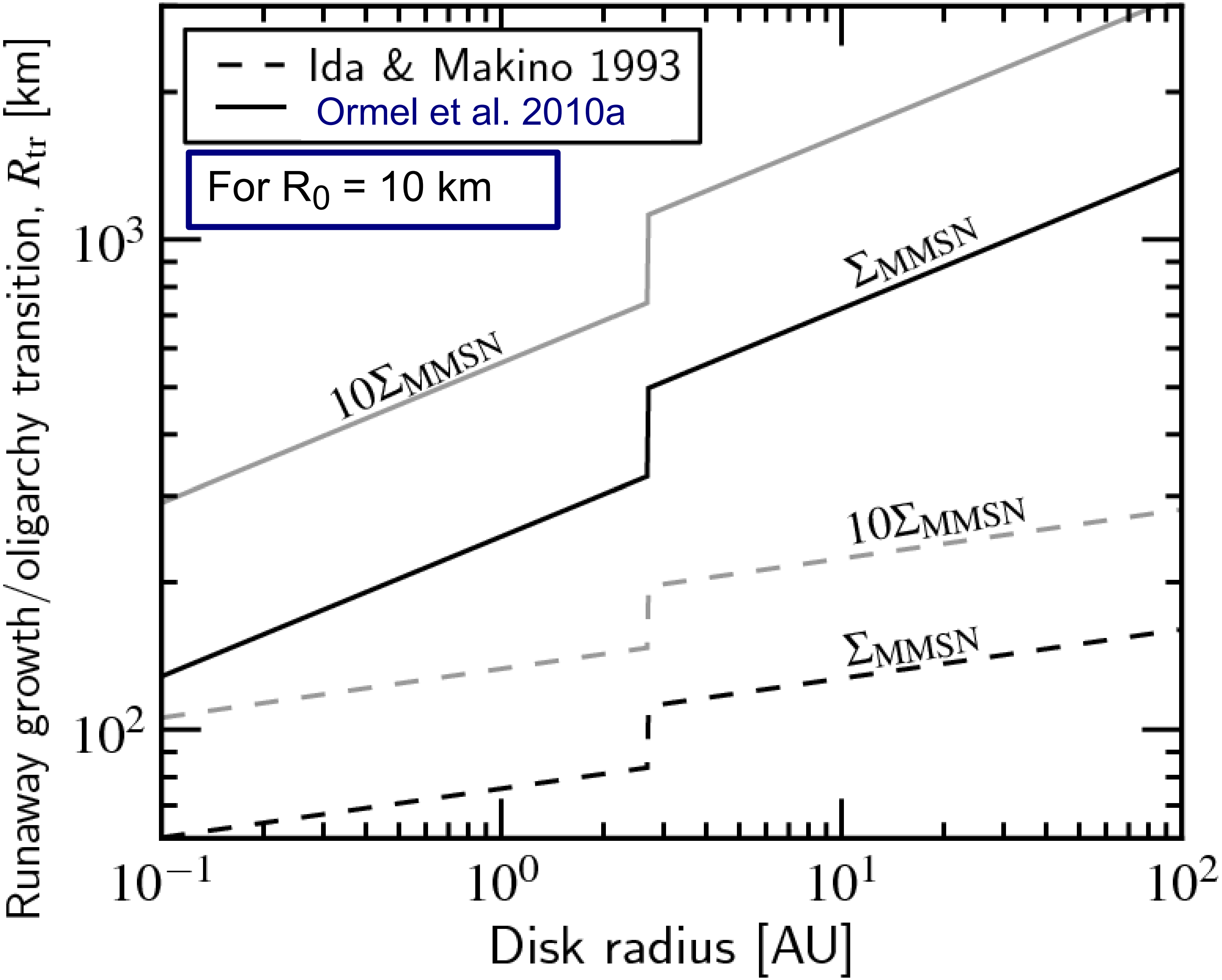
Analysis

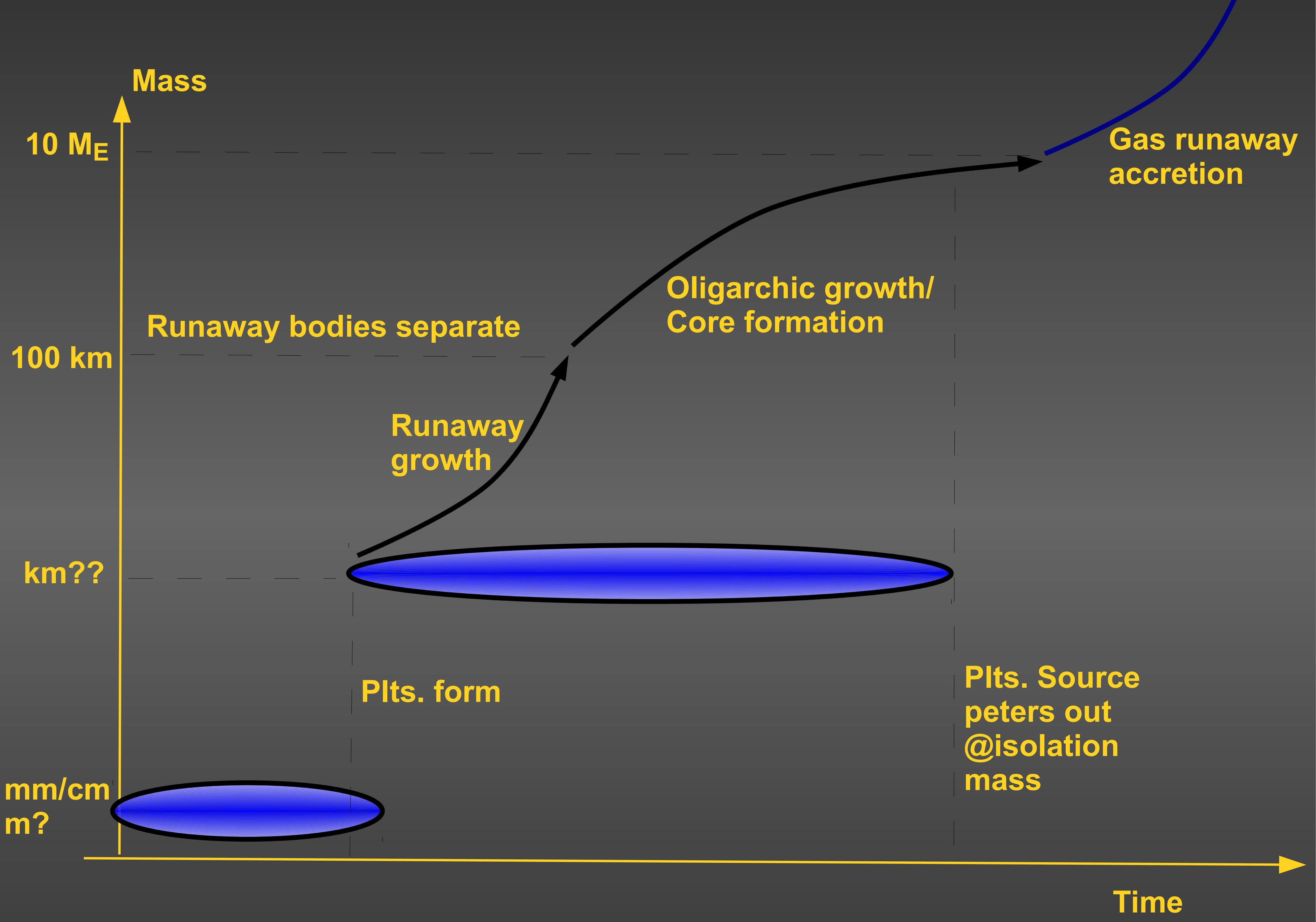
- Preconditions
  - Dynamically cold disk
  - All mass in planetesimals
- Runaway Growth
  - GFF increases
  - Growth timescales ~ same (fast!)
  - Size distribution
- Oligarchy
  - GFF increases (levels off)
  - Slower growth
  - 2 component



Radius of **biggest** body
(evolutionary parameter)

**Equate timescales to solve R_{tr}
(Ormel et al 2010a)...**


Ida & Makino 1993
Ormel et al. 2010a
For R_0 = 10 km
$10\Sigma_{\rm MMSN}$
$\Sigma_{\rm MMSN}$
$10\Sigma_{\rm MMSN}$
$\Sigma_{\rm MMSN}$
Runaway growth/oligarchy transition, $R_{\rm tr}$ [km]
10^3
10^2
10^{-1}
10^0
10^1
10^2
Disk radius [AU]



Mass

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100 km

km??

mm/cm
m?

Time

Runaway bodies separate

Runaway
growth

Oligarchic growth/
Core formation

Gas runaway
accretion

Plts. form

Plts. Source
peters out
@isolation
mass

Growth timescales in oligarchic reg.

- Oligarchic growth is slow
  - Eccentricities (random motions) strongly increase

    “Protoplanets heat food, before eating” (Goldreich ea 2004)
  - Gas damping → equilibrium (large) GFF

    e.g., Kokubo & Ida (2002)

$$\frac{dM}{dt} \simeq \pi R_p^2 \Sigma \Omega \left(\frac{v_{\rm esc}}{v} \right)^2$$

Depends slightly on planetesimal size

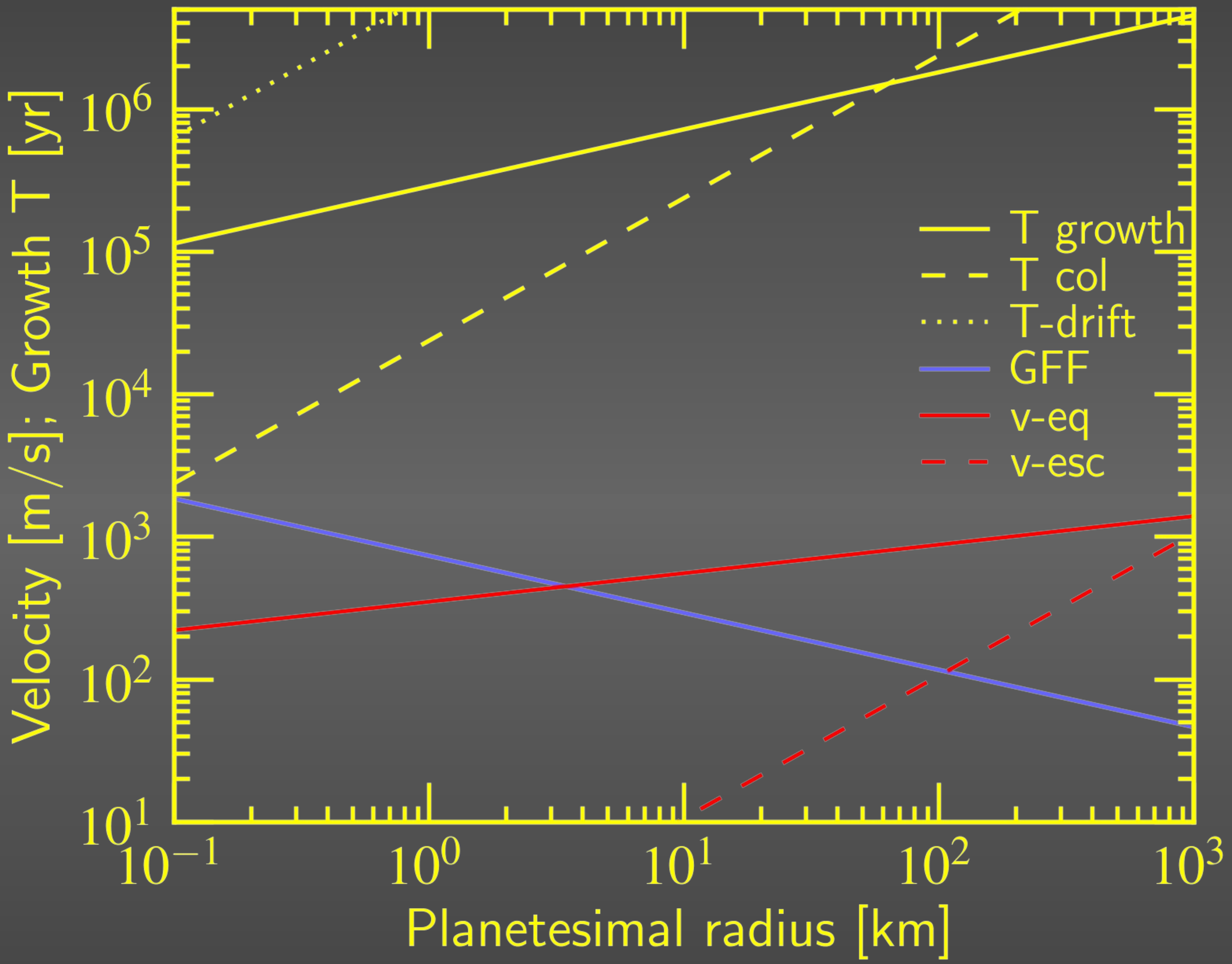
Core formation

$\Sigma \sim 10$ g/cm^2
(surface density plts)

1 M_{earth}

5 AU

V_{eq}, T_{growth} from
Kokubo & Ida (2002)



Growth timescales in oligarchic reg.

- Oligarchic growth is slow
  - Eccentricities (random motions) strongly increase
    "Protoplanets heat food first, before eating"
  - Gas damping → equilibrium (large) GFF
    e.g., Kokubo & Ida 2001
  - Scattering, gap formation
    Levison et al. (2010)
  - Expect planetesimals to fragment

→ Study accretion behavior of (small) fragments

Paardekooper (2007); Johansen & Lacerda (2010); Kobayashi et al. (2010);
Ormel & Klahr (2010)

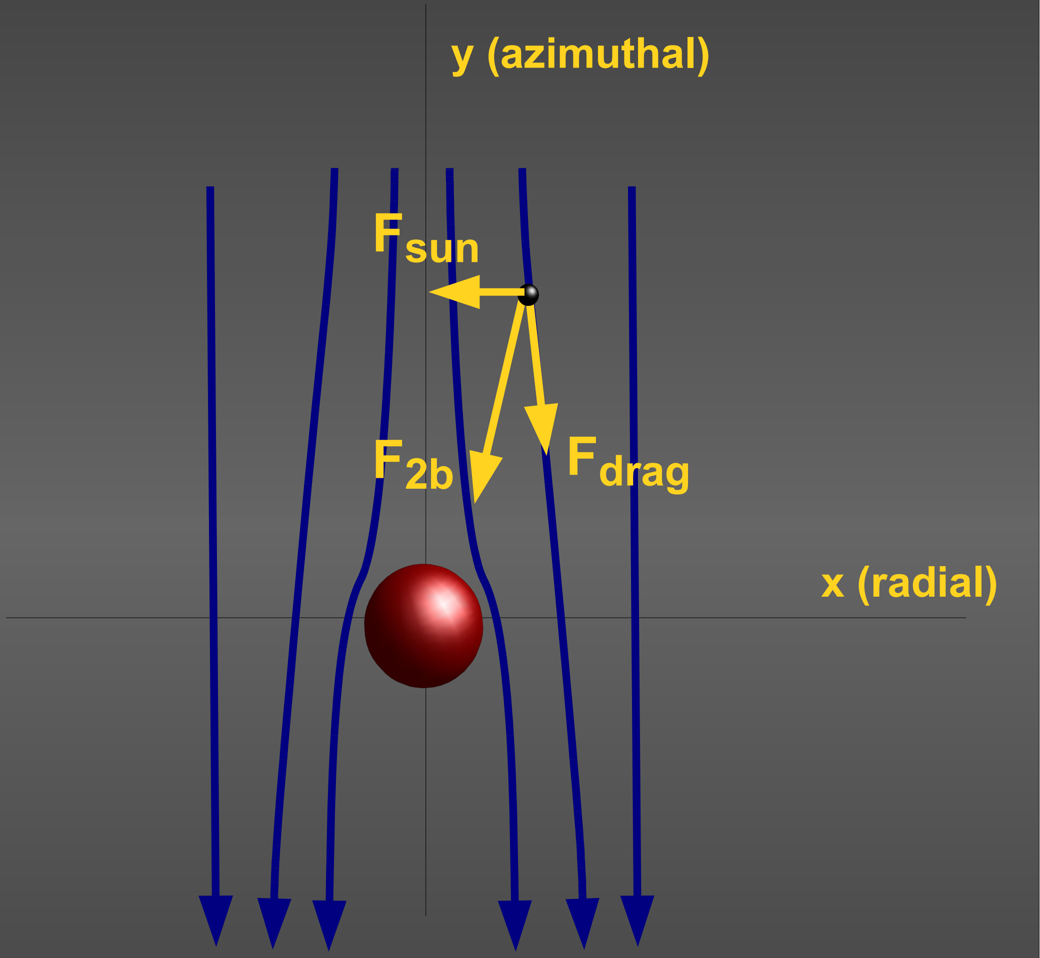
Accretion of debris/fragments

Factors:

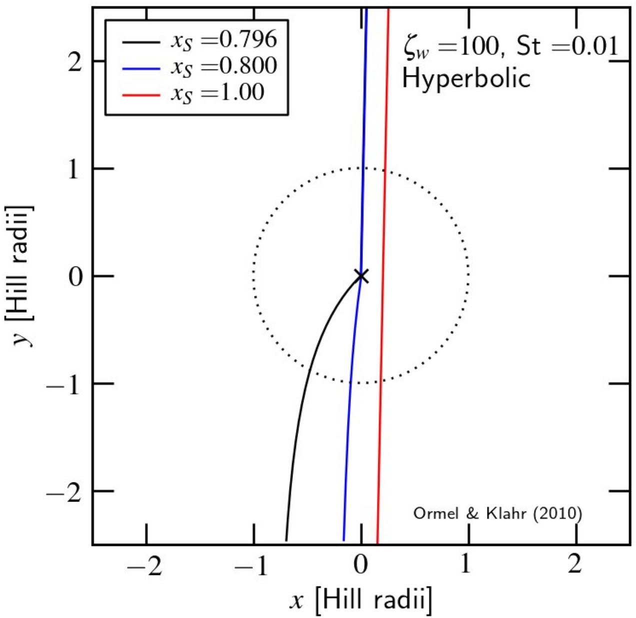
- Pre-planetesimal population is small
- Fragments settle in thin plane
  May speed up growth (Kenyon & Bromley 2009)
- Radial drift
  Removes fragments
- Large gravitational focusing factors (???)
  Not necessarily

Gas flow around small protoplanet

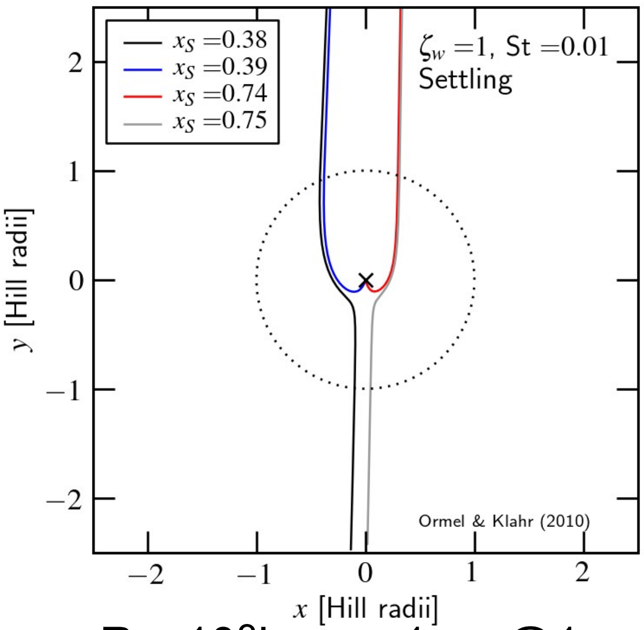
- Drag force large for small particles
- Small particles coupled to (head)wind
- $F_{drag} \sim F_{2b}$
- No energy conservation (orbital decay)



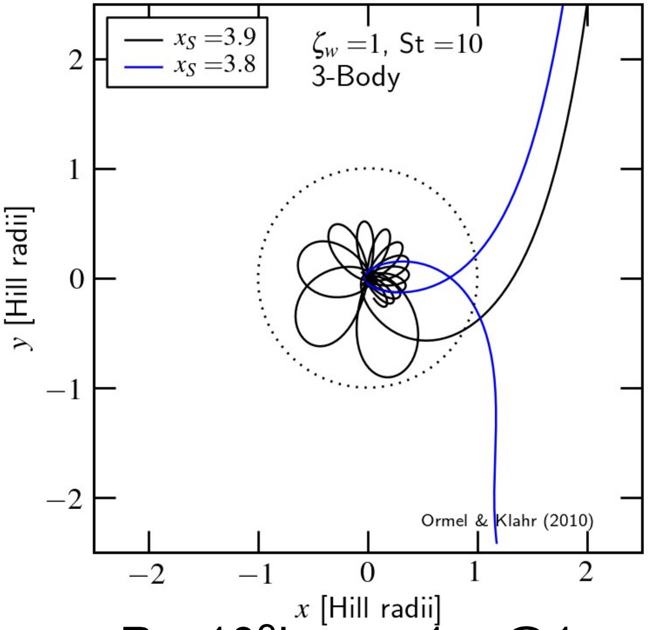
Interactions w/ gas friction



eg R_p=10km; s=1cm @1au

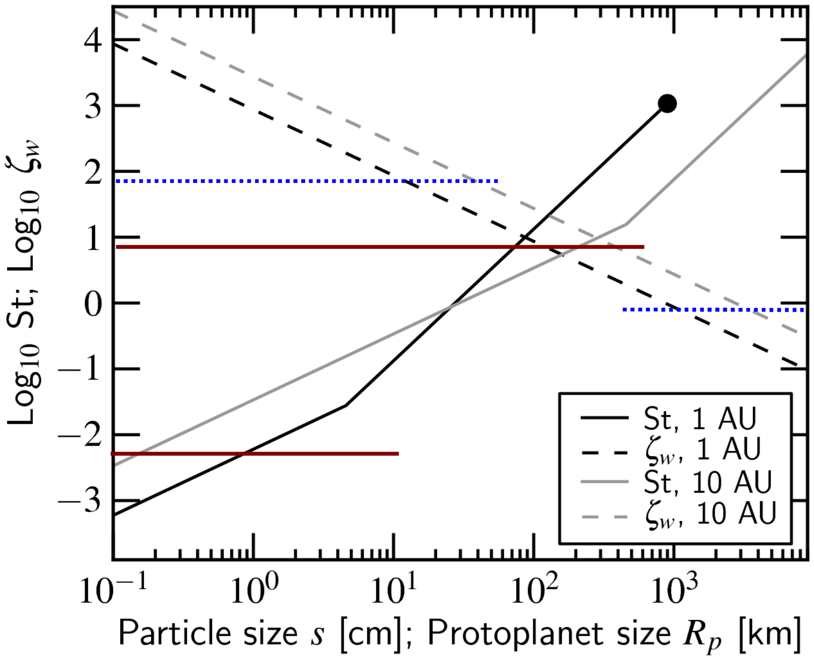


R_p=10^3km; s=1cm @1au



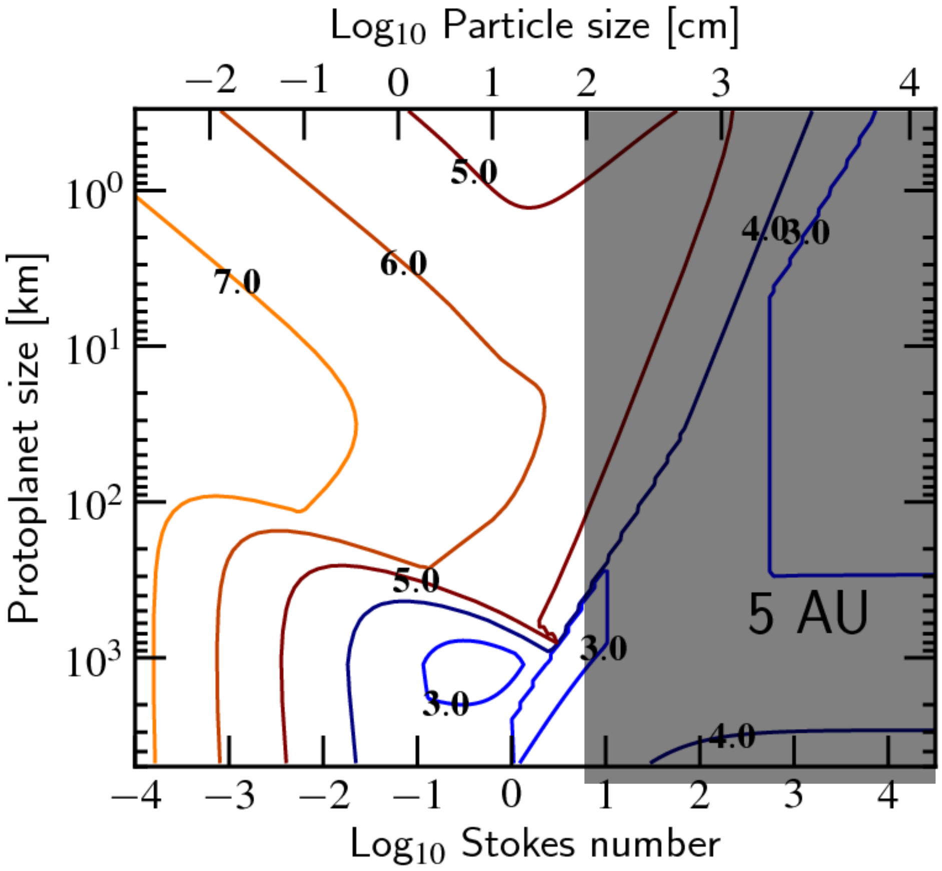
R_p=10^3km; s=1m @1au

St: size of test particles, s
ζ_w: size of planets, R_p



Fragment accretion timescales

- Accretion timescales
  - 5 AU, MMSN
  - "cold debris"
  - No depletion fragments
  - No trapping particles
  - No atmospheres
  - No turbulence (wake)



Summary/Neglected effects

- Identified the runaway growth & oligarchy stages
- Formation 10 M_{earth} core remains difficult
  - Fragmentation; gap formation/resonances; trapping
  - Planetary atmosphere; migration of solids/planet
- Gravitational focusing boost growth
  - Requires low random motions
- Role of the debris & gas-solid interaction