Influence of grain properties on dust evolution in protoplanetary discs

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DUST BUSTERS

European Commission

Dust dynamics

aerodynamic parameter

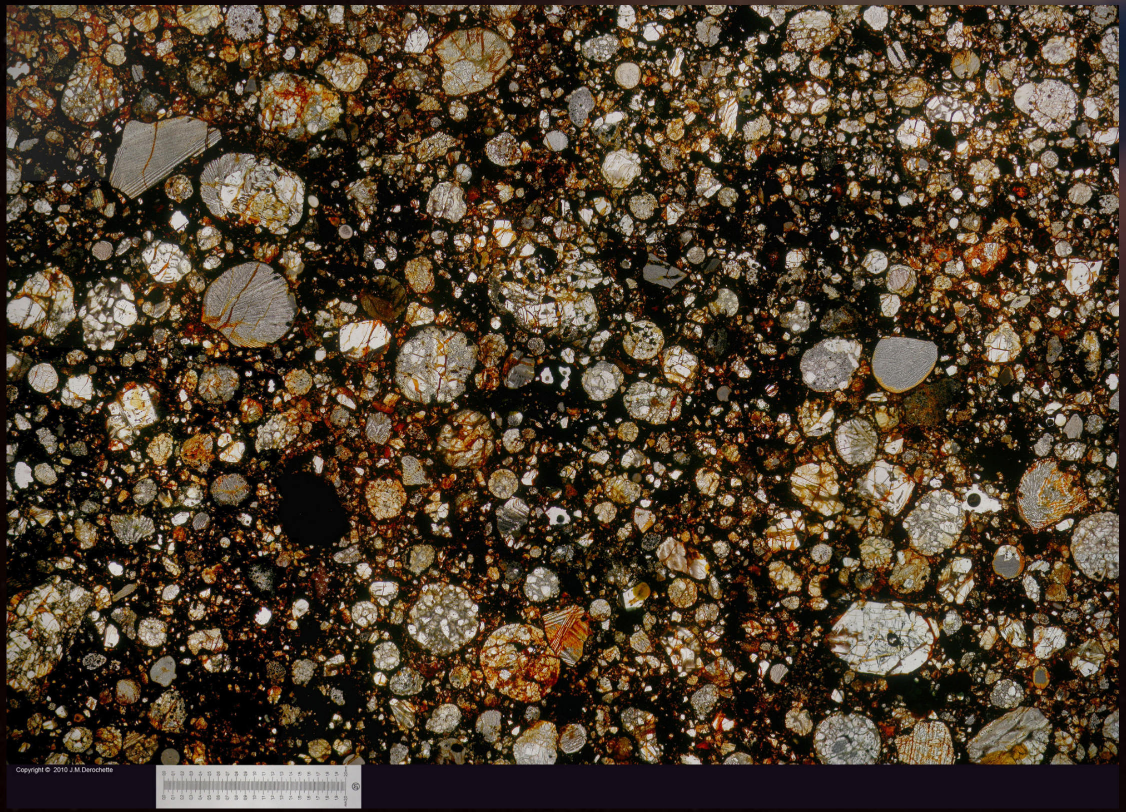
$$\mathrm{St} = \frac{\Omega_{\mathrm{K}} \rho_{\mathrm{s}} s}{\rho_{\mathrm{g}} c_{\mathrm{s}}}$$

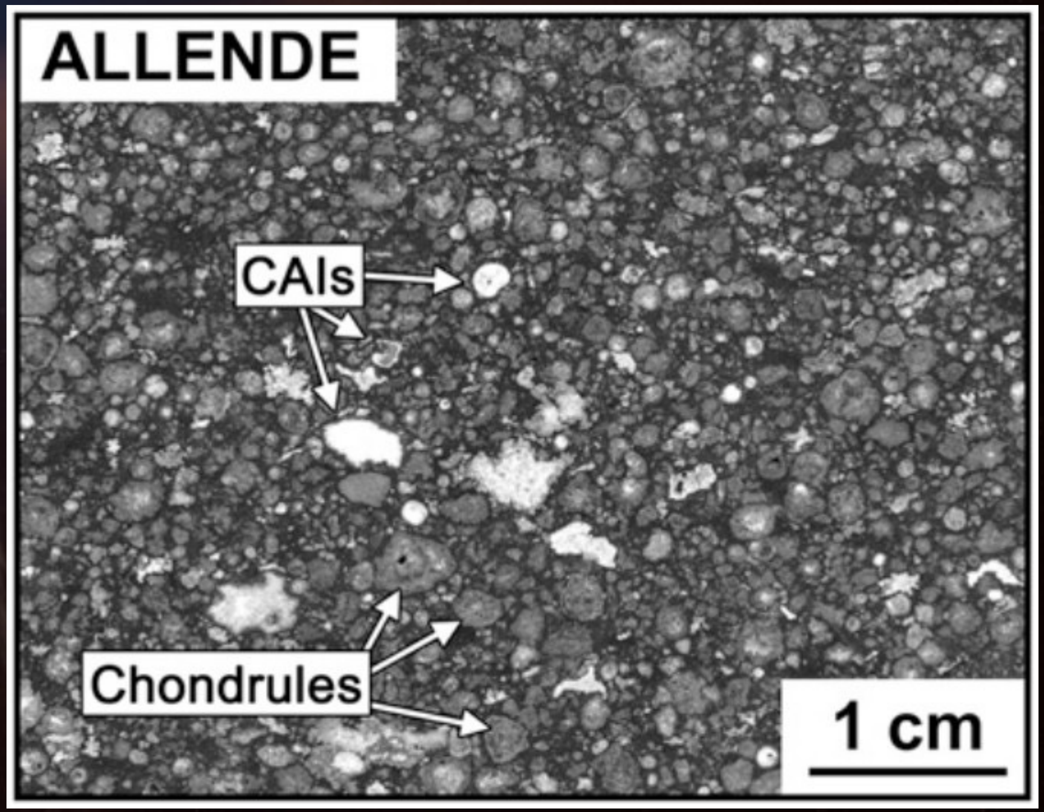
- Changing grain density
  - composition
  - porosity

Grain composition

Chondrites

- Undifferentiated meteorites
  - chondrules
  - calcium-aluminum rich inclusions (CAIs)
  - metallic grains (Fe+Ni)
  - matrix
- Formation
  - after CAIs (4567.2±0.6 Myr ago)
  - lasted 3 Myr



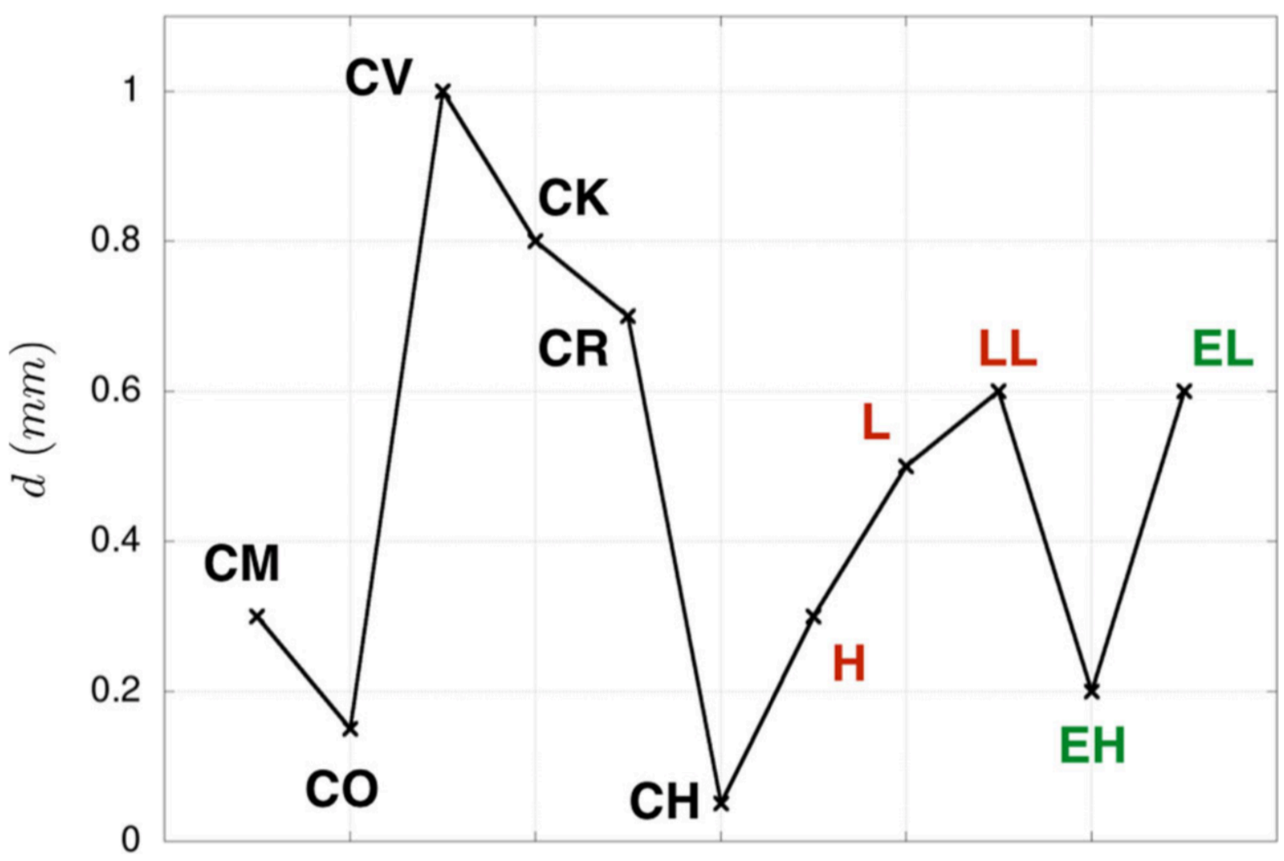


Derochette2010

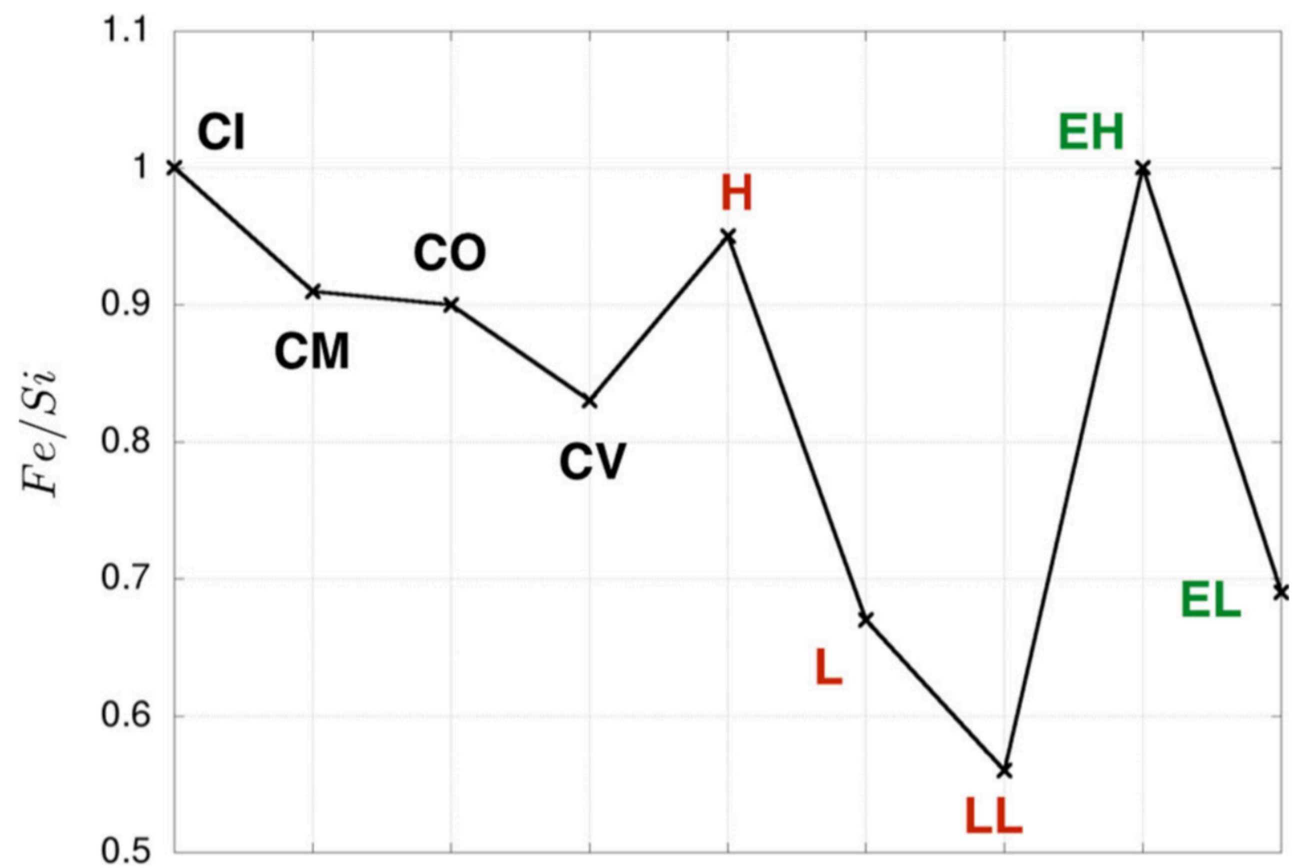
MacPherson+Boss2011

Properties of chondrites

Chondrule size



Chondrite composition



Palme+Jones2003

$$(\rho s)_{\mathrm{chondrules}} \sim (\rho s)_{\mathrm{metal}} \sim (\rho s)_{\mathrm{sulphides}}$$

Benoit+1998

⇒ size-density sorting by gas drag?

Simulations

- SPH 3D two-phase (gas+dust) global simulations
  Barrière-Fouchet+2005, Laibe+2008, Gonzalez+2015, Pignatale+2017, Garcia+2018
  - Aerodynamic drag
    - self-consistent, grain-size dependent dynamics
    - backreaction of dust on gas
  - Grain growth
    - Stepinski & Valageas (1997)
    - compact particles
    - perfect sticking
  - Fragmentation
    - when $V_{rel} > V_{frag}$
    - conservative model
  - Initial disk model
    - $\Sigma_g \propto r^{-p}$
    - $T \propto r^{-q}$

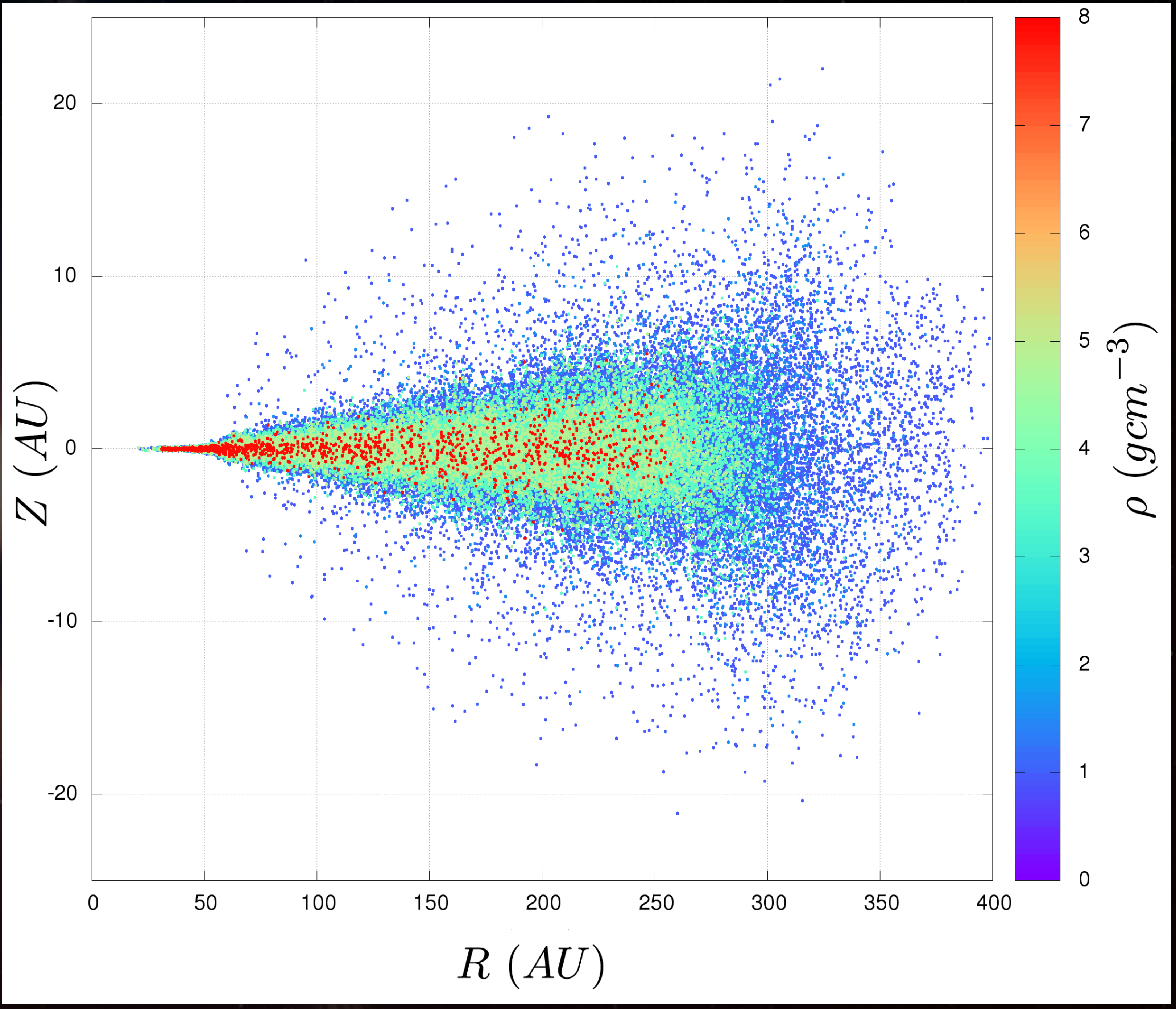
Simulations

- Setup
  - CTTS disk
    - $M_\star = 1\ M_\odot$, $M_{disk} = 0.01\ M_\odot$
    - $p = 3/2$, $q = 3/4$
    - $\alpha = 10^{-2}$
  - Initial dust/gas ratio
    - $\epsilon_0 = 1\%$, uniform
  - Initial grain size
    - $s_0 = 10\ \mu m$, uniform
  - Grain composition
    - ice, silicates, sulfides, iron
  - Grain density
    - $\rho_s = 1, 3.2, 4.6, 7.8\ g.cm^{-3}$
  - Size evolution
    - Growth only
    - Growth + fragmentation
      - $V_{frag} = 56, 36, 42, 35\ m.s^{-1}$

Pignatale+2017

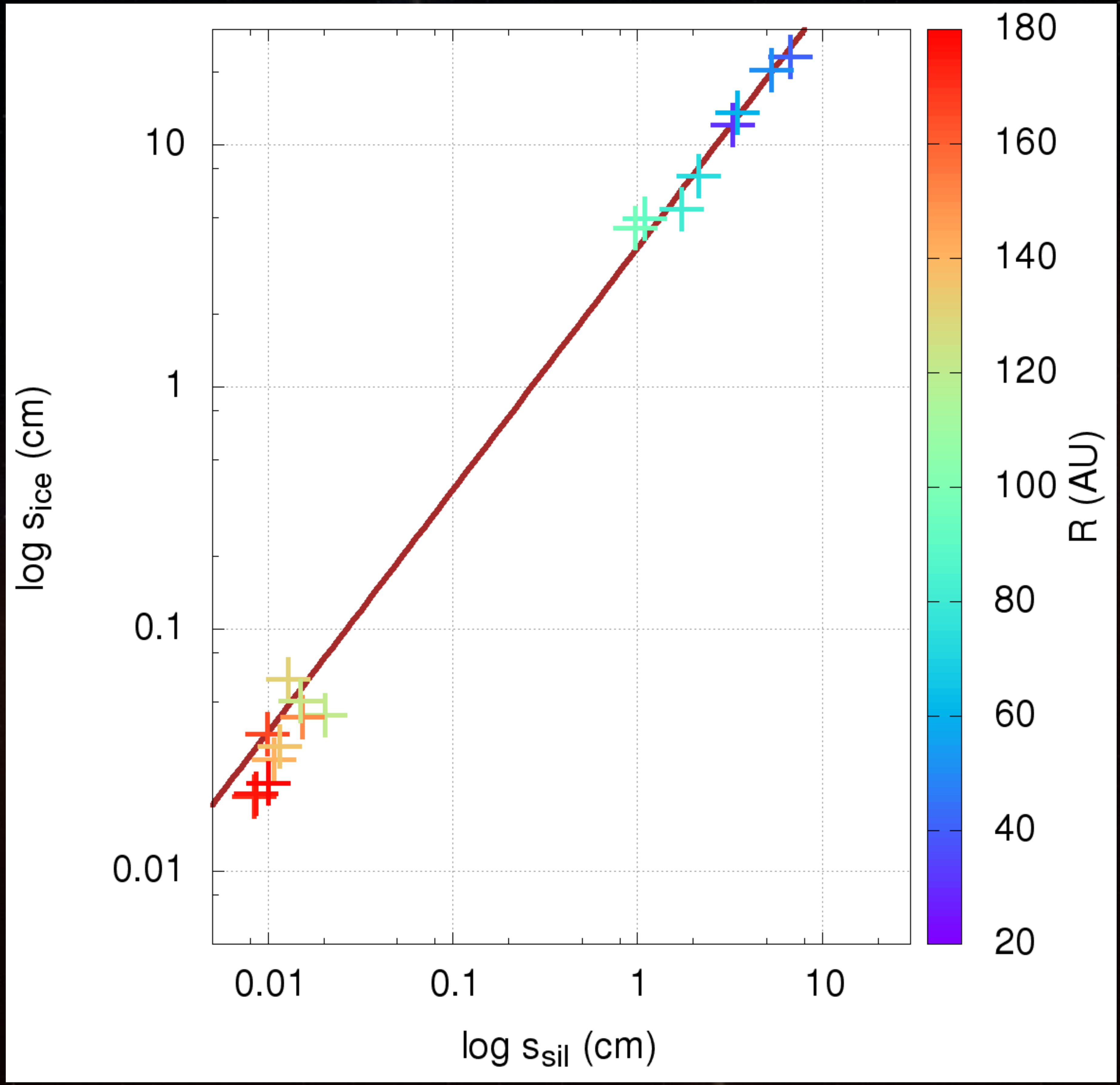
Spatial distributions

- Vertical settling
  - first density-driven
  - then size-driven
- Radial drift
  - efficient chemical sorting



Pignatale+2017

Size-density sorting



Pignatale+2017

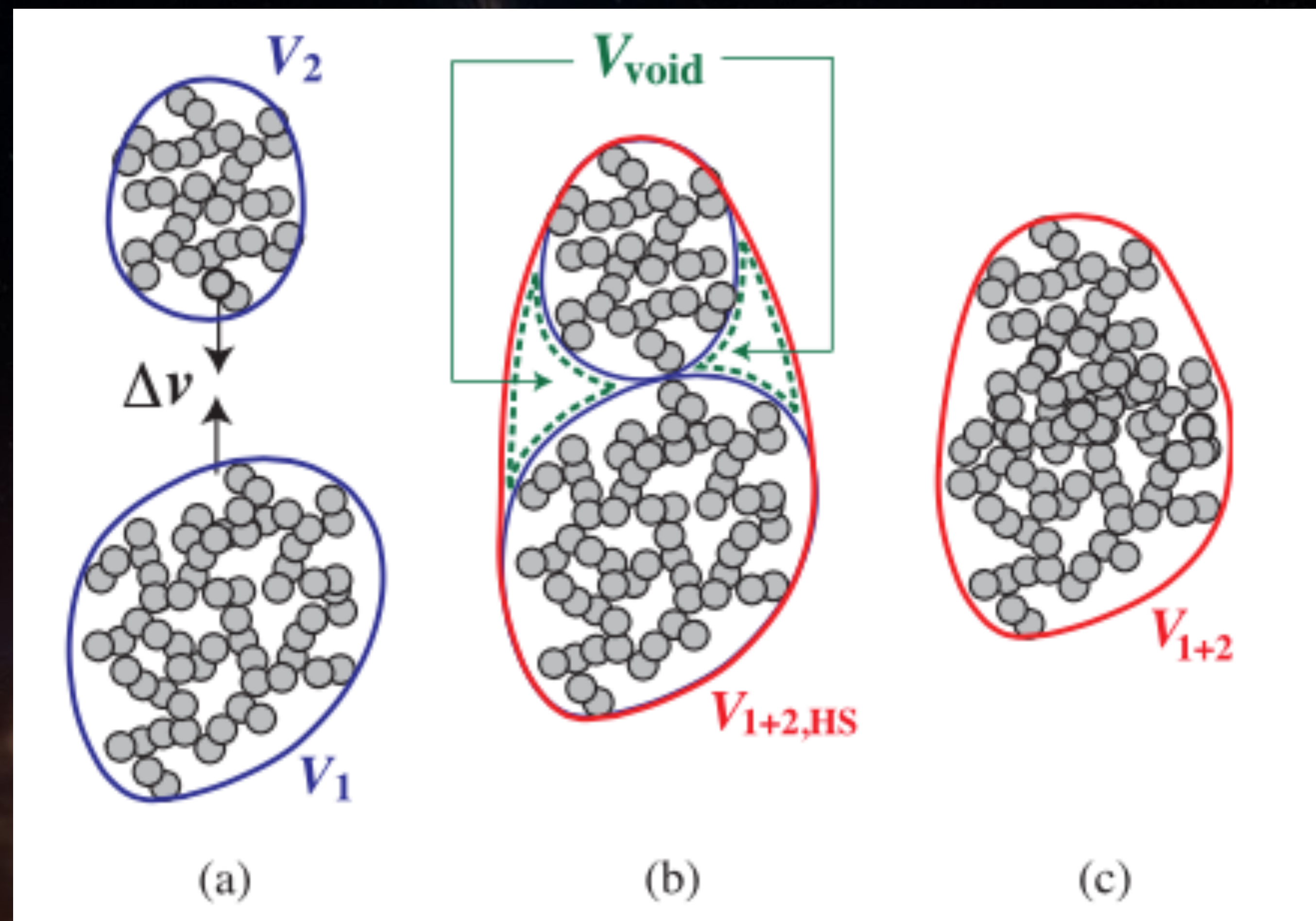

Grain porosity

Porosity

Collisional evolution

Filling factor:

$$\phi = \frac{V_{\rm mat}}{V} = \frac{\rho}{\rho_{\rm s}}$$

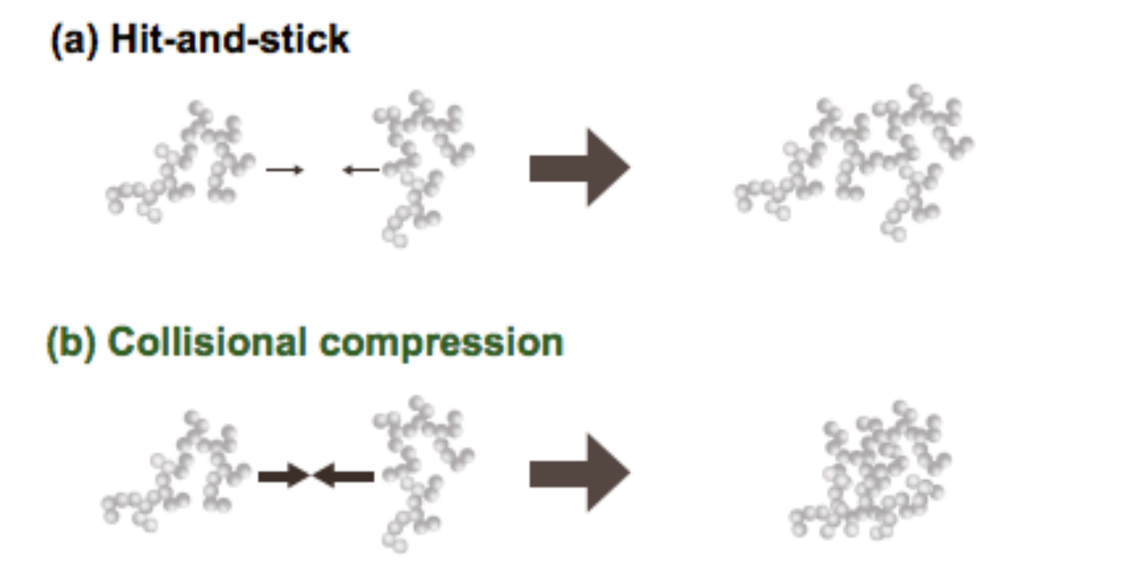


Okuzumi+2012

- Porous grains are larger ⇒ faster growth
- Stokes number
  - Epstein regime: $\mathrm{St} = \dfrac{\Omega_{\rm K} \rho_{\rm s} \phi s}{\rho_{\rm g} c_{\rm s}}$
  - Stokes regime: $\mathrm{St} = \dfrac{2\Omega_{\rm K} \rho_{\rm s} \phi s^2}{9\mu_{\rm g}}$

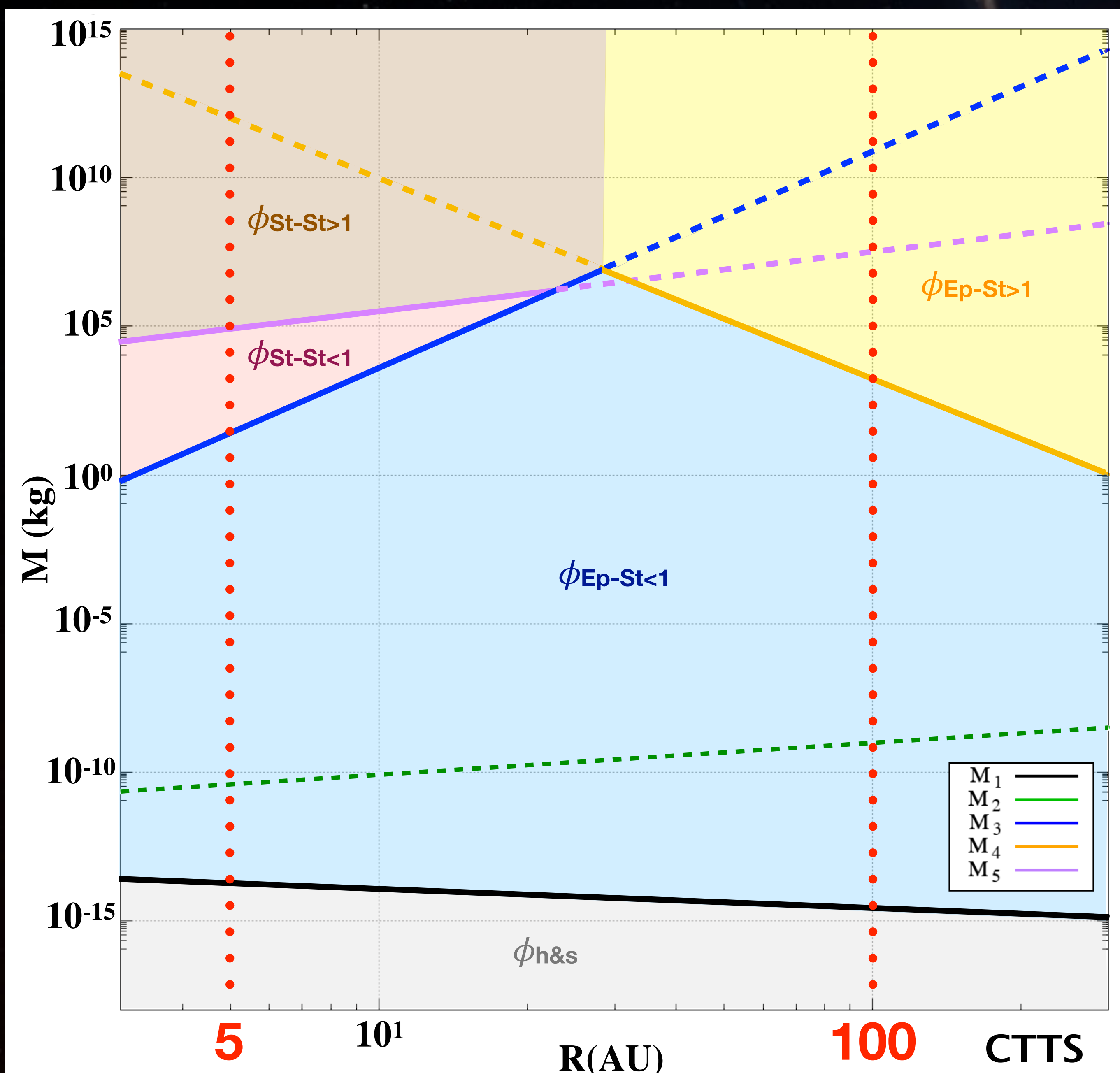
Porosity evolution model

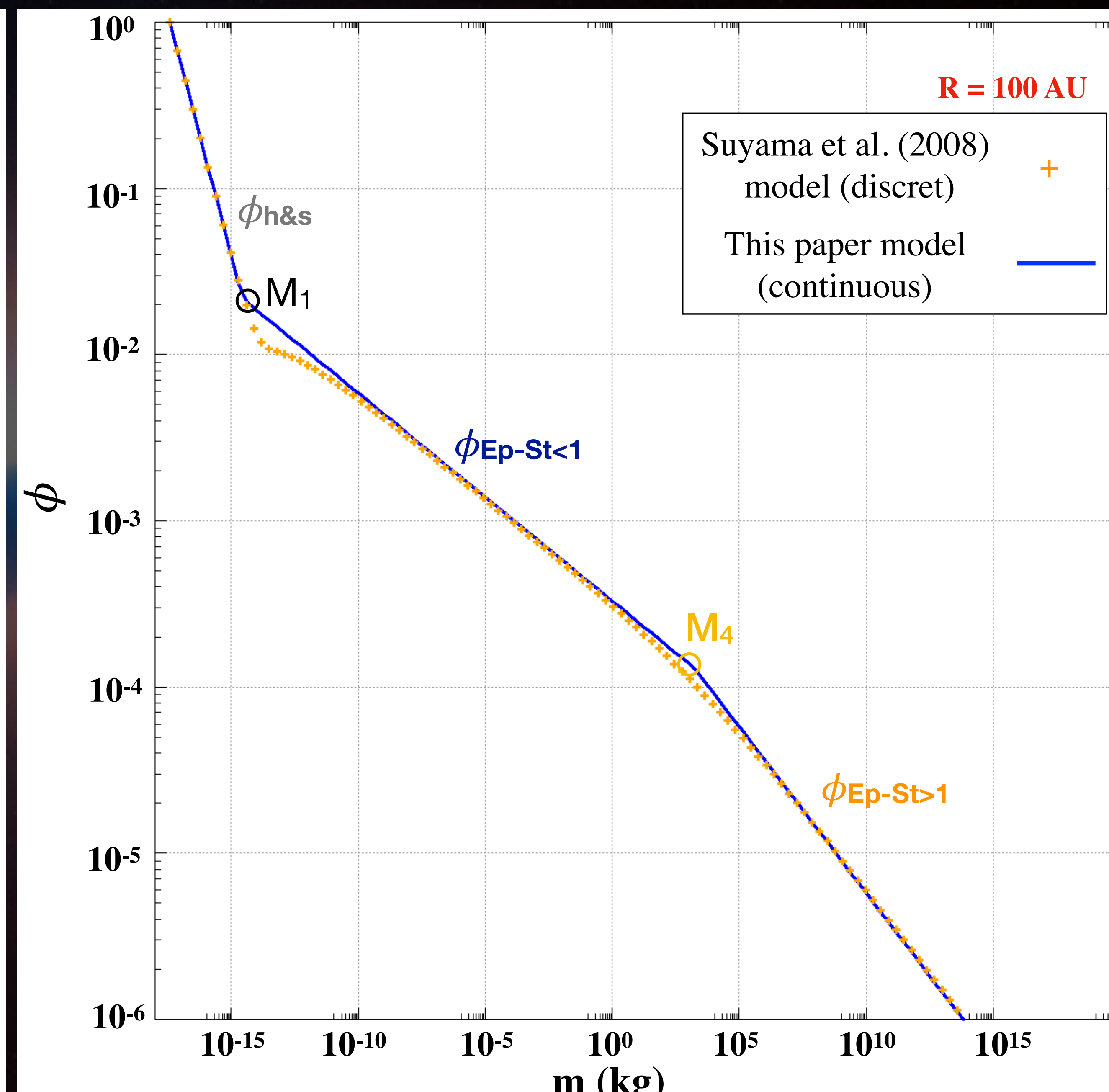
Collisional evolution



Porosity evolution model

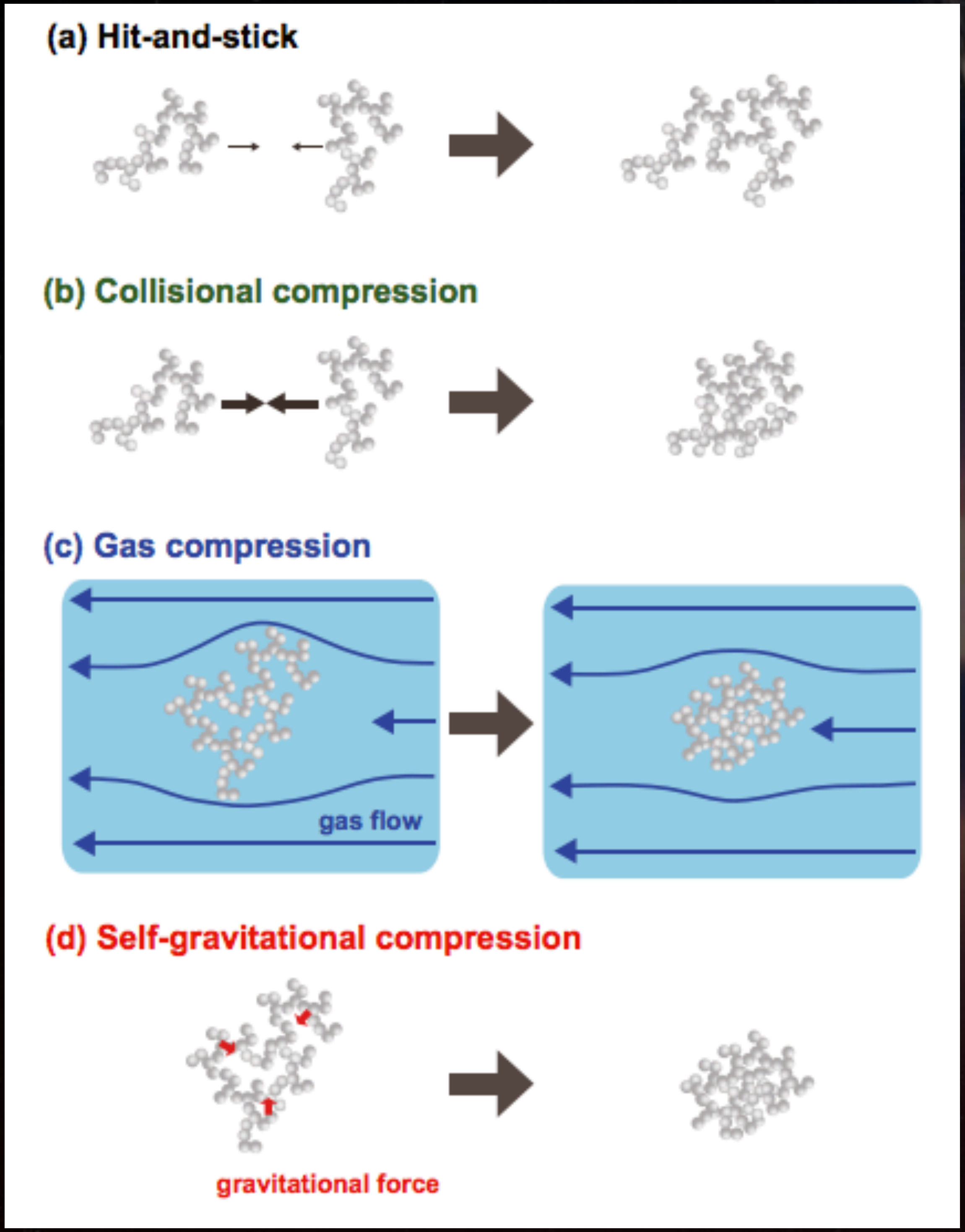
Collisional evolution

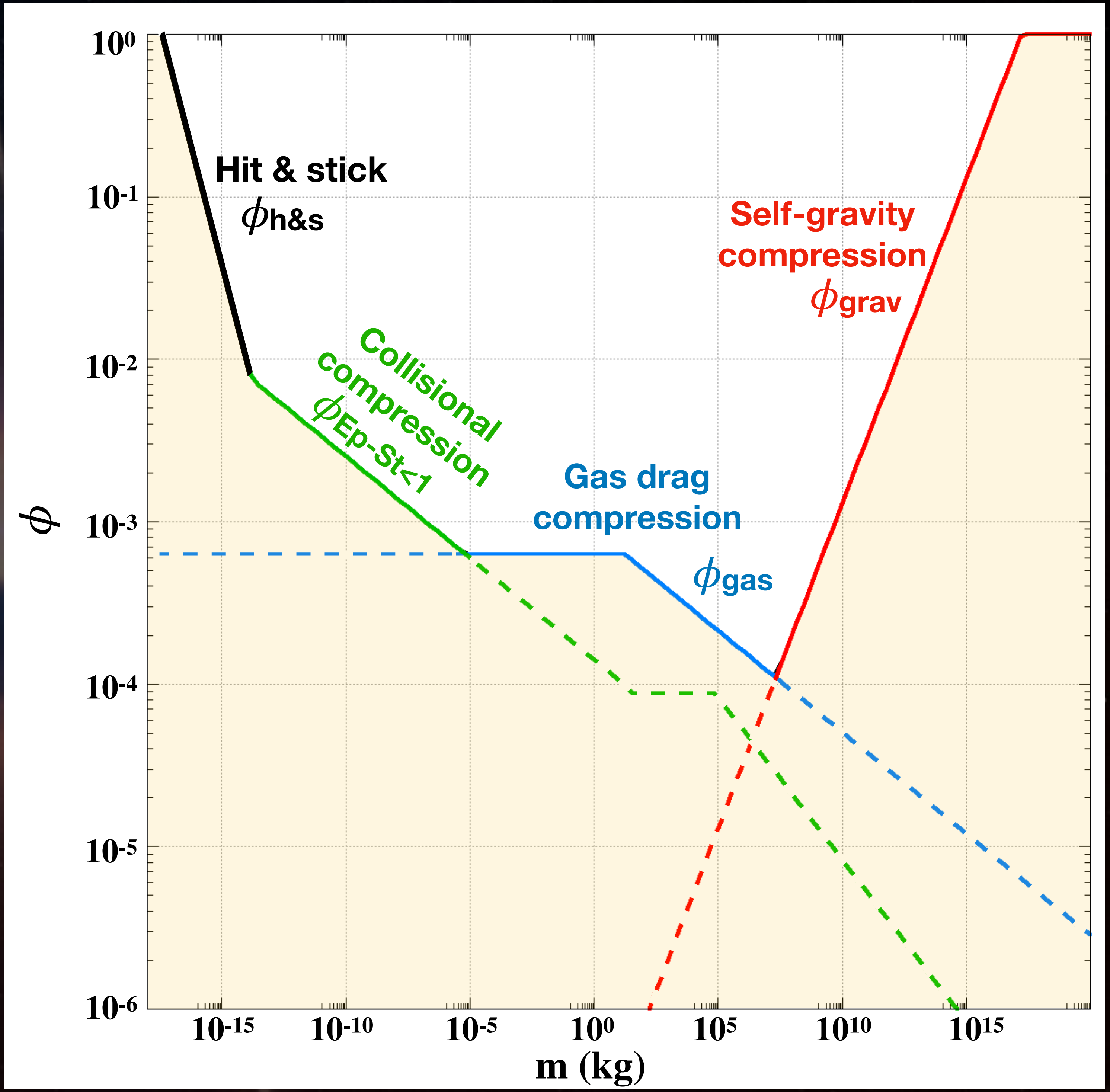




Garcia+Gonzalez2019

Porosity evolution model





Kataoka+2013

Garcia+Gonzalez2019

Simulations

- 1D code
  - CTTS disk
    - $M_{\star} = 1\ M_{\odot}$, $M_{\rm disk} = 0.01\ M_{\odot}$
    - $p = 3/2$, $q = 3/4$
    - $\alpha = 10^{-2}$
  - One grain at a time
    - static gas background
  - Initial grain size
    - $s_0 = 0.1\ \mu$m
  - Size evolution
    - Growth only
  - Prescriptions
    - vertical settling
    - radial drift

- SPH code
  - CTTS disk
    - $M_{\star} = 1\ M_{\odot}$, $M_{\rm disk} = 0.01\ M_{\odot}$
    - $p = 3/2$, $q = 3/4$
    - $\alpha = 10^{-2}$
  - Initial dust/gas ratio
    - $\epsilon_0 = 1\%$, uniform
  - Initial grain size
    - $s_0 = 10\ \mu$m, uniform
  - Size evolution
    - Growth only
    - Growth + fragmentation

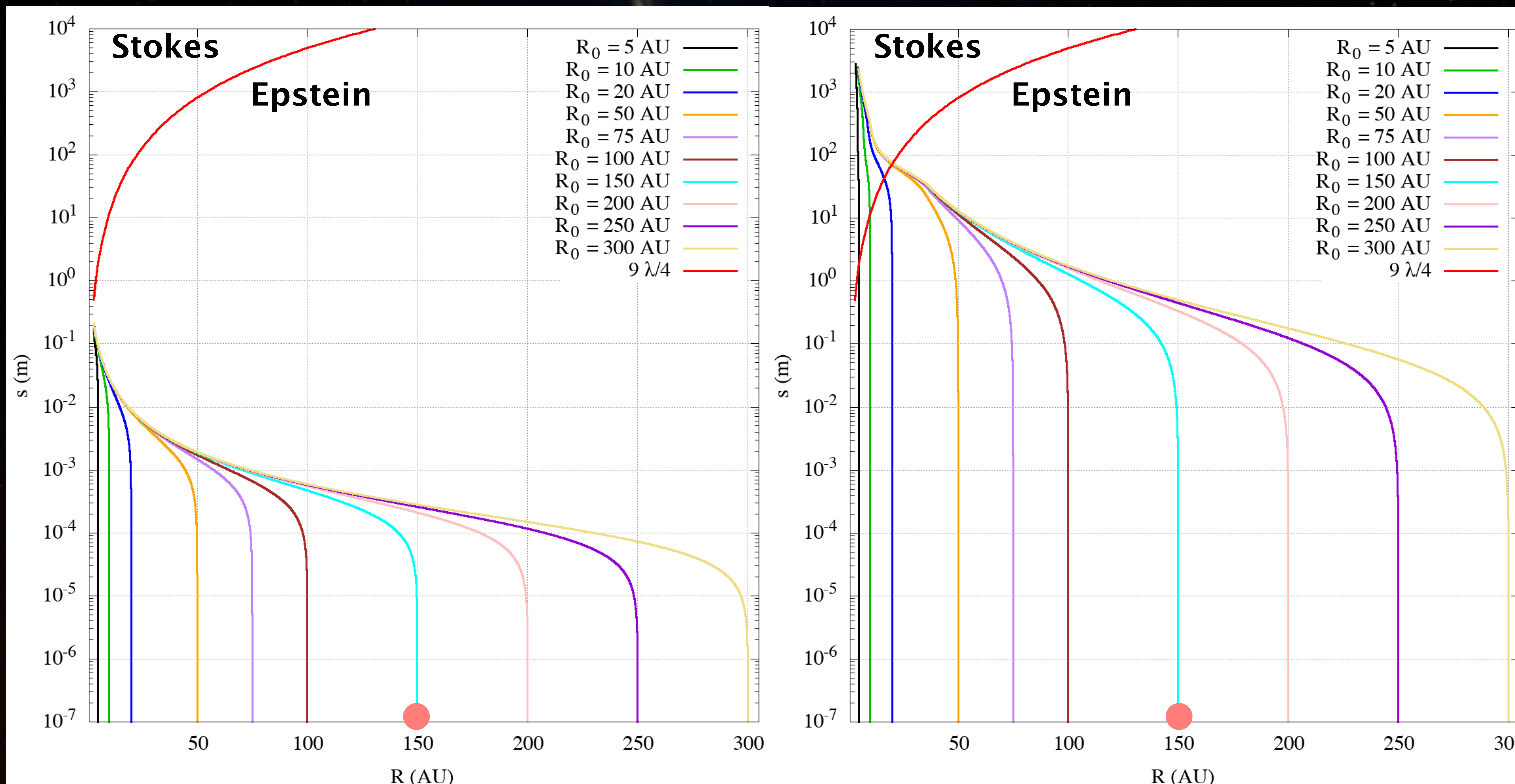
- Porosity evolution
  - Compact only
  - Porous, $\phi_0 = 1$

Garcia+Gonzalez2019

Grain size evolution

Growth only

Compact | Porous

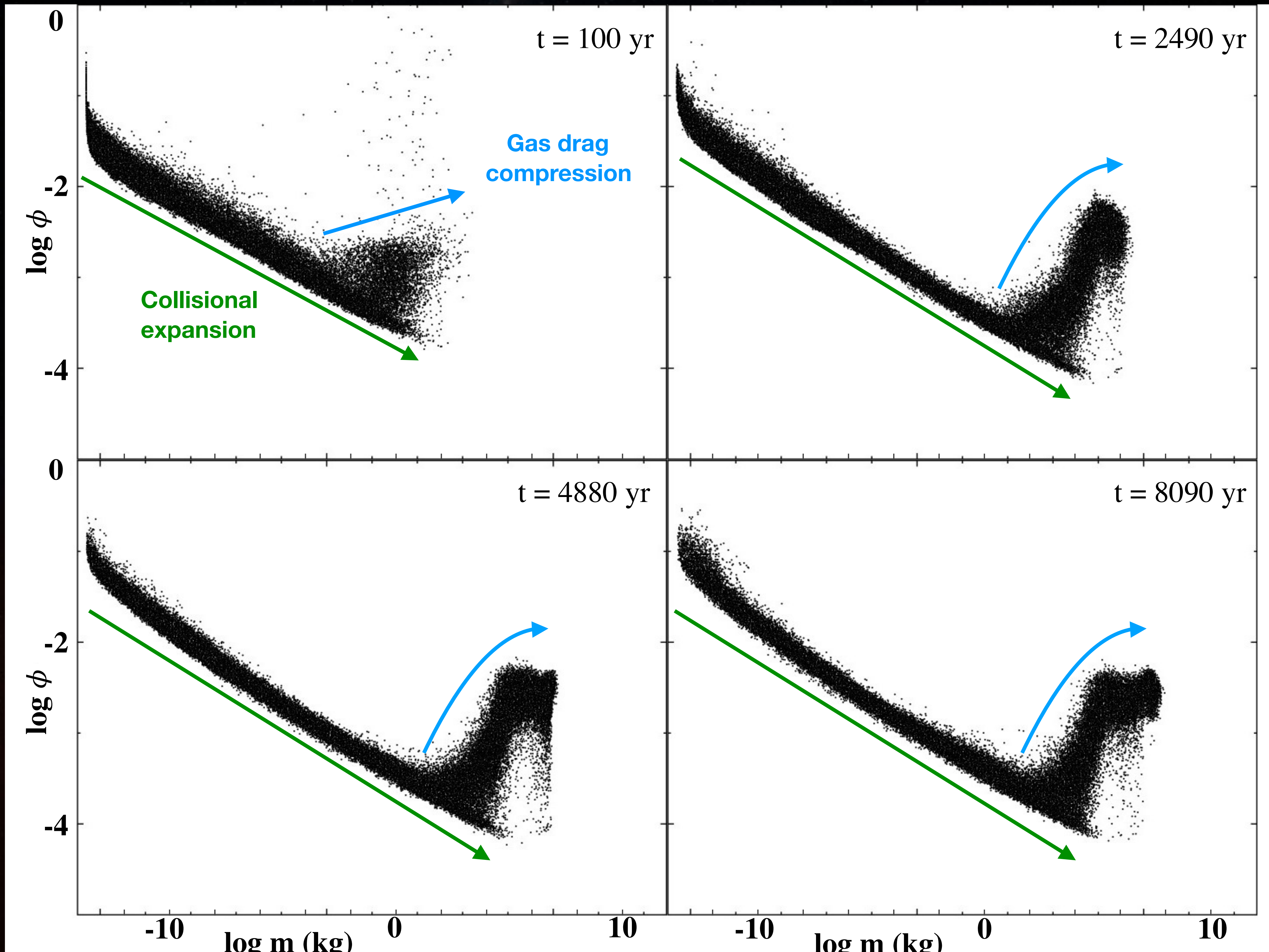


⚠ No collective effects

Garcia+Gonzalez2019

Porosity evolution

Growth only



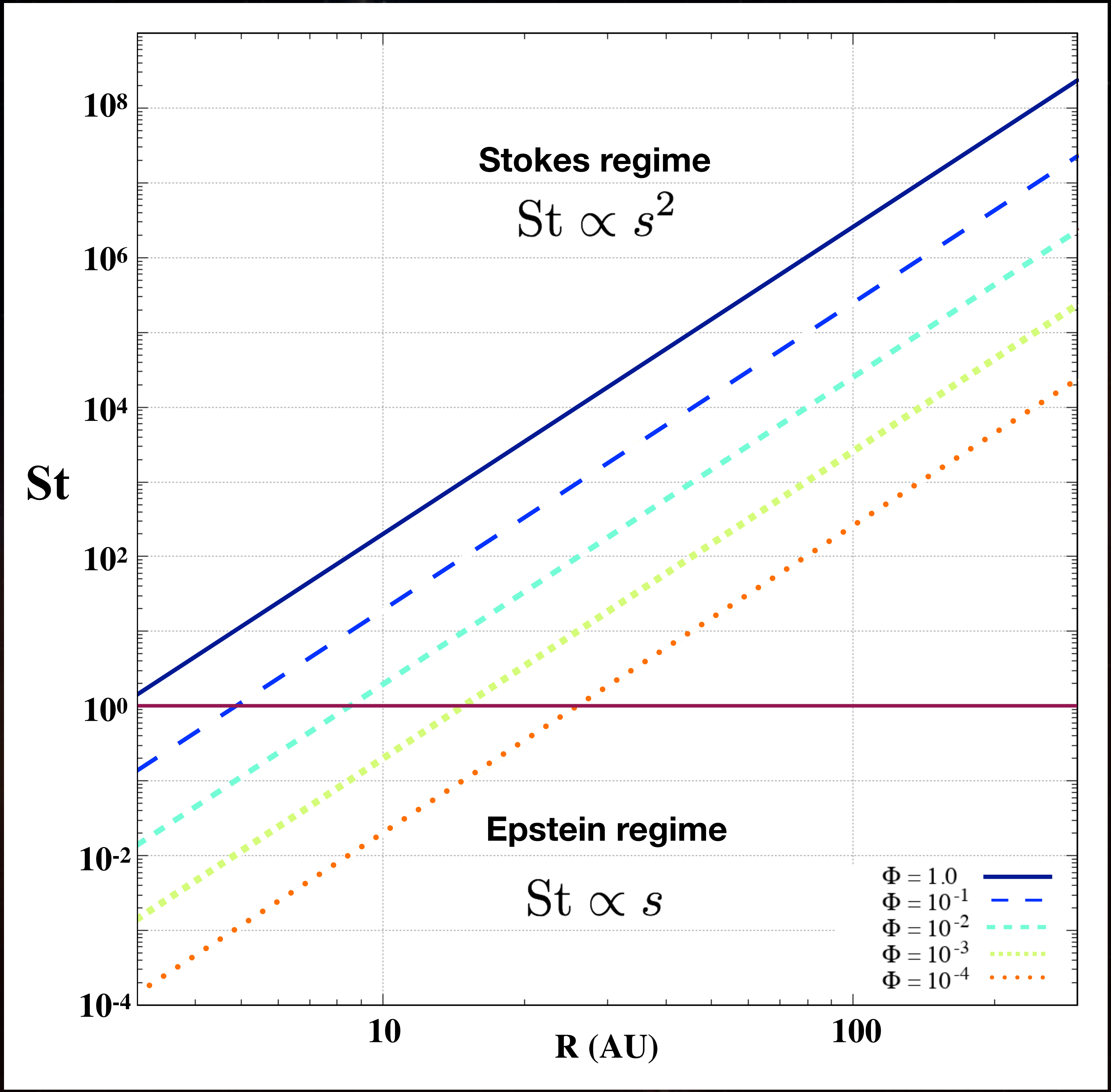
Garcia+Gonzalez2019

Importance of the Stokes regime

St ≫ 1
slow drift

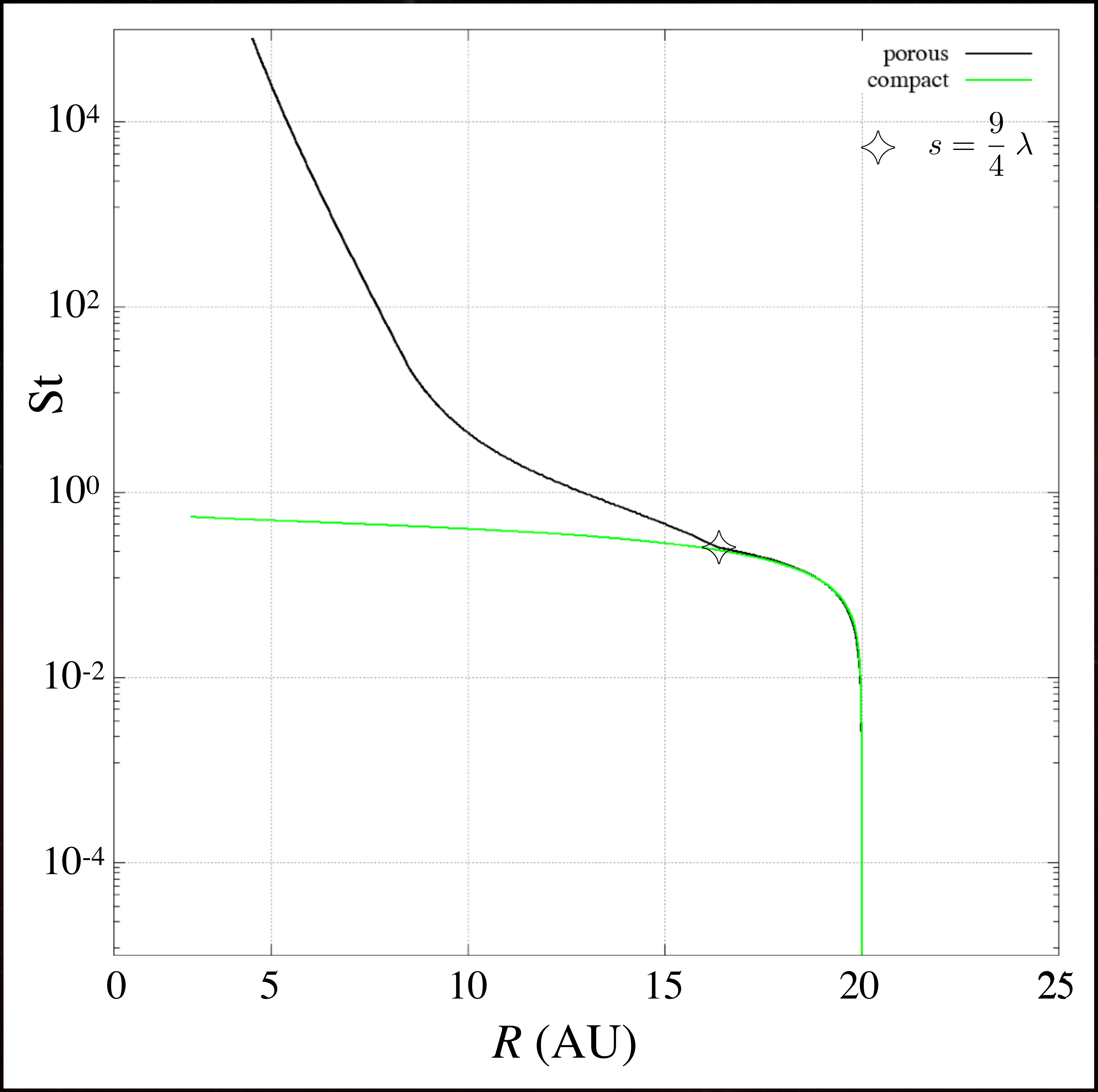
St ~ 1
fast drift

St ≪ 1
slow drift



Garcia+Gonzalez2019

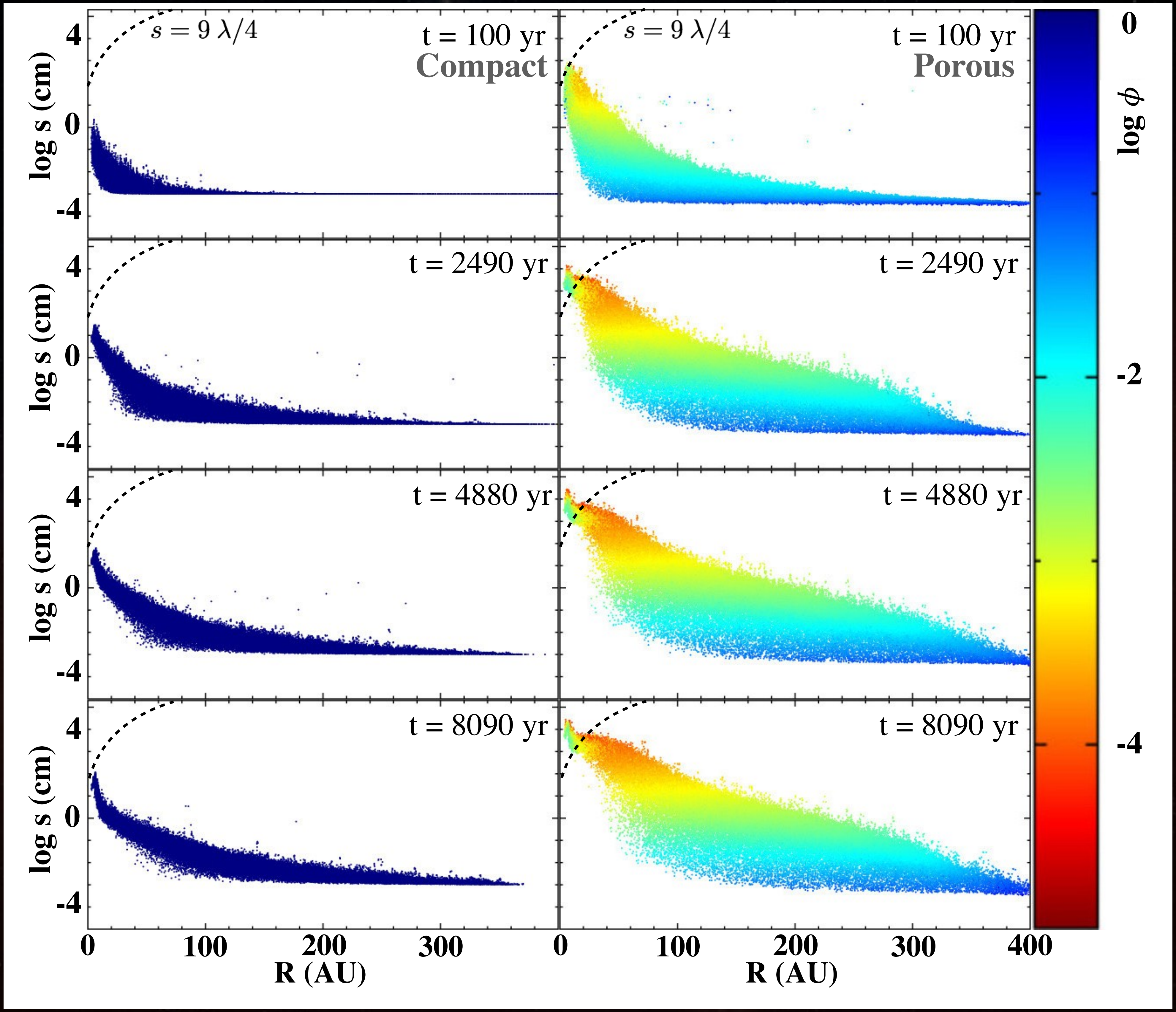
Importance of the Stokes regime



Garcia+Gonzalez2019

Spatial, size and porosity evolution

Growth only



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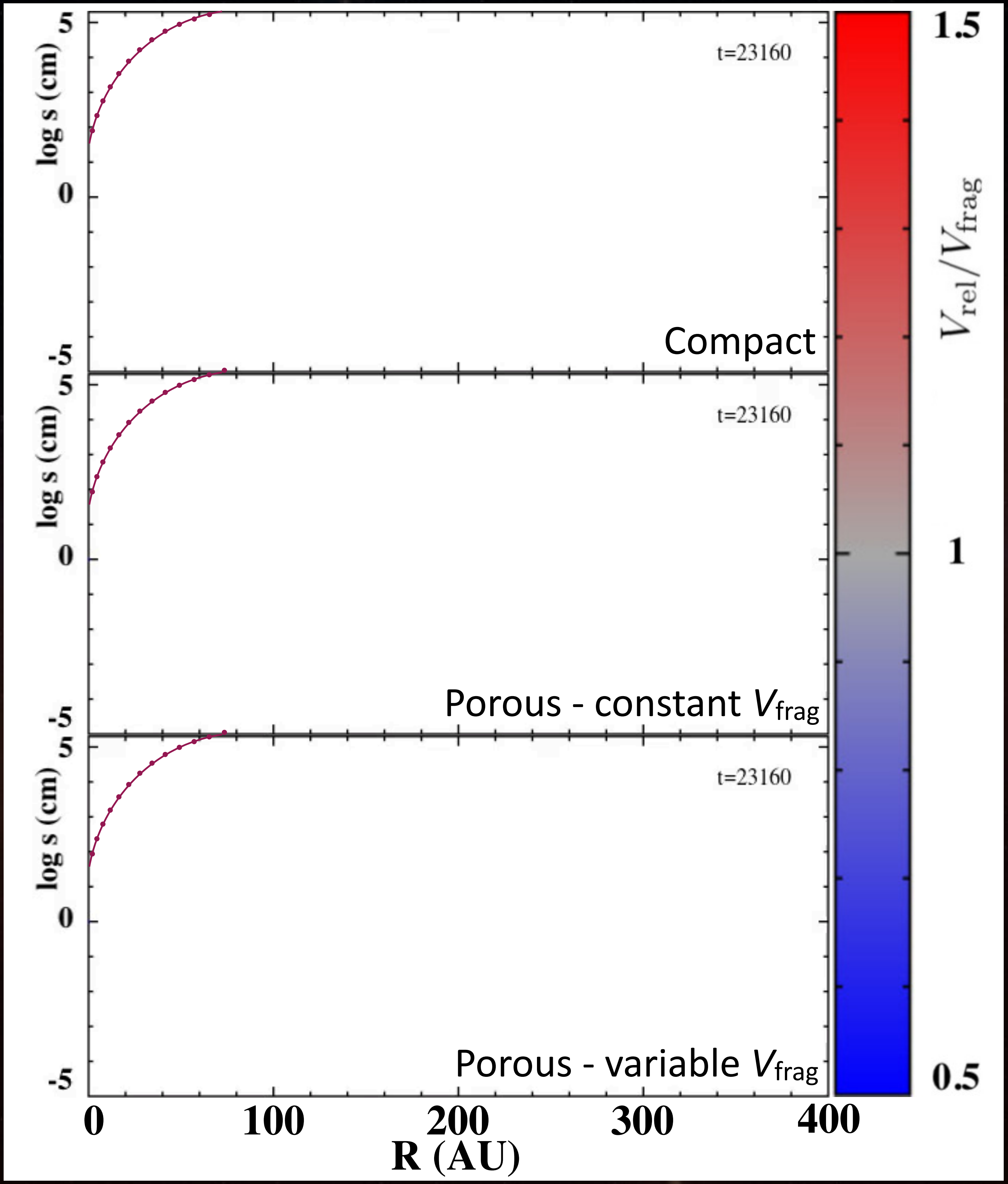
Spatial and size evolution

Growth + fragmentation



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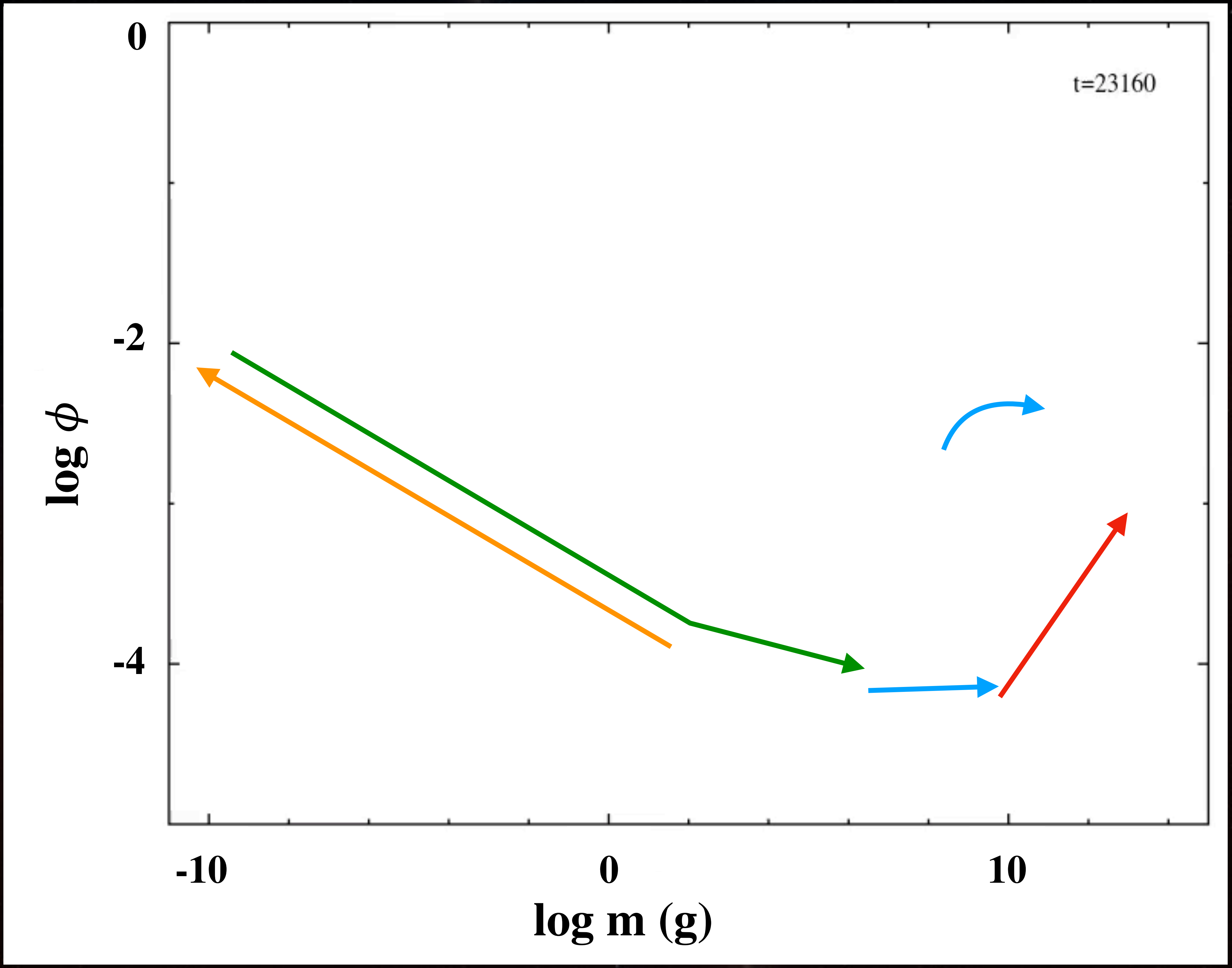
Porosity evolution

Growth + fragmentation



Similar values to pure growth

Garcia+Gonzalez2019

Conclusion

- Multicomponent dust
  - fractionation and aerodynamic sorting
  - aggregates mimic chondrite properties
  - differences in V_{frag} enhance Fe enrichment in inner disk
- Grain porosity accelerates grain growth
  - grains survive the radial-drift barrier
  - can form small planetesimals
  - fragmentation only delays planetesimal formation