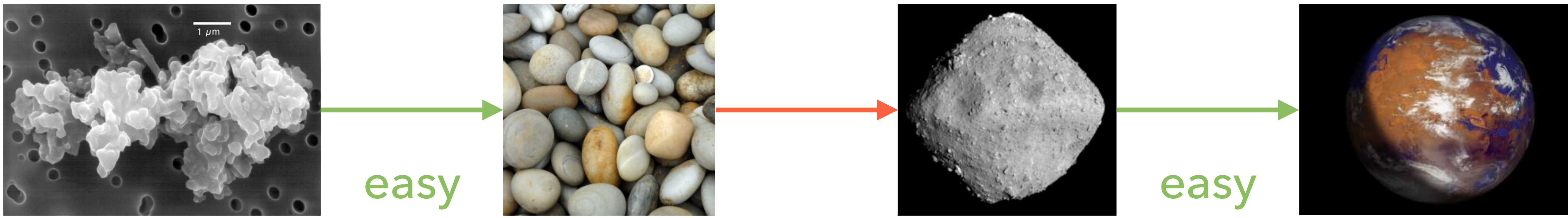
DUST GRAIN EVOLUTION IN PROTOPLANETARY DISKS

Jean-François Gonzalez

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

HOW DO PLANETS FORM?

- Core-accretion paradigm



- Planet formation barriers: radial drift, fragmentation
- Proposed solutions: thin, dense mid-plane layer of pebbles
  - Streaming instability
  - Self-induced dust traps
- No quantitative observational constraint!

DUST DYNAMICS

aerodynamic parameter

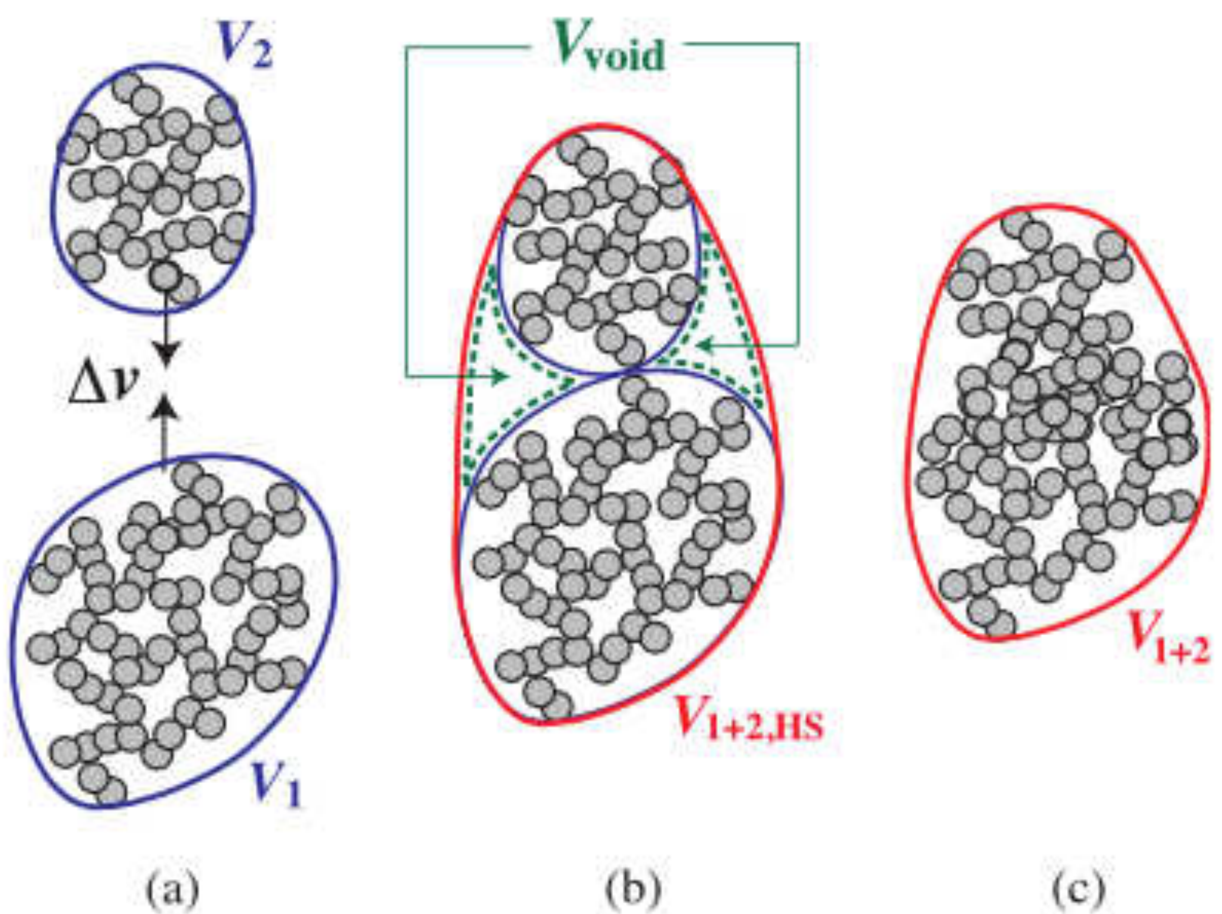
$$\mathrm{St}_{\mathrm{Epstein}} = \frac{\Omega_{\mathrm{K}} \rho_{\mathrm{s}} s}{\rho_{\mathrm{g}} c_{\mathrm{s}}}$$

- Changing grain density
  - Composition
  - Porosity

Collisional evolution

Filling factor:

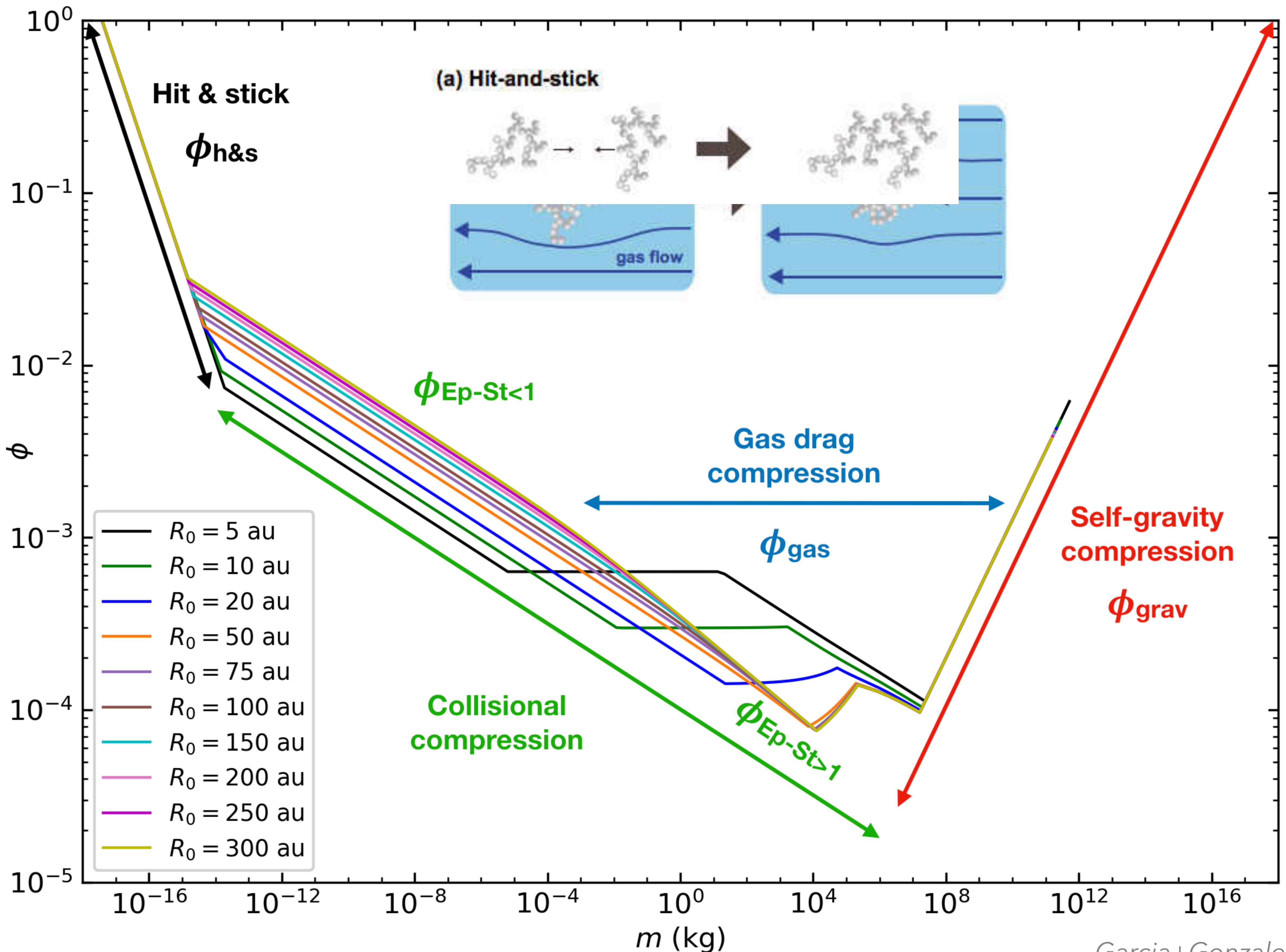
$$\phi = \frac{V_{\mathrm{mat}}}{V} = \frac{\rho}{\rho_{\mathrm{s}}}$$



Okuzumi+2012

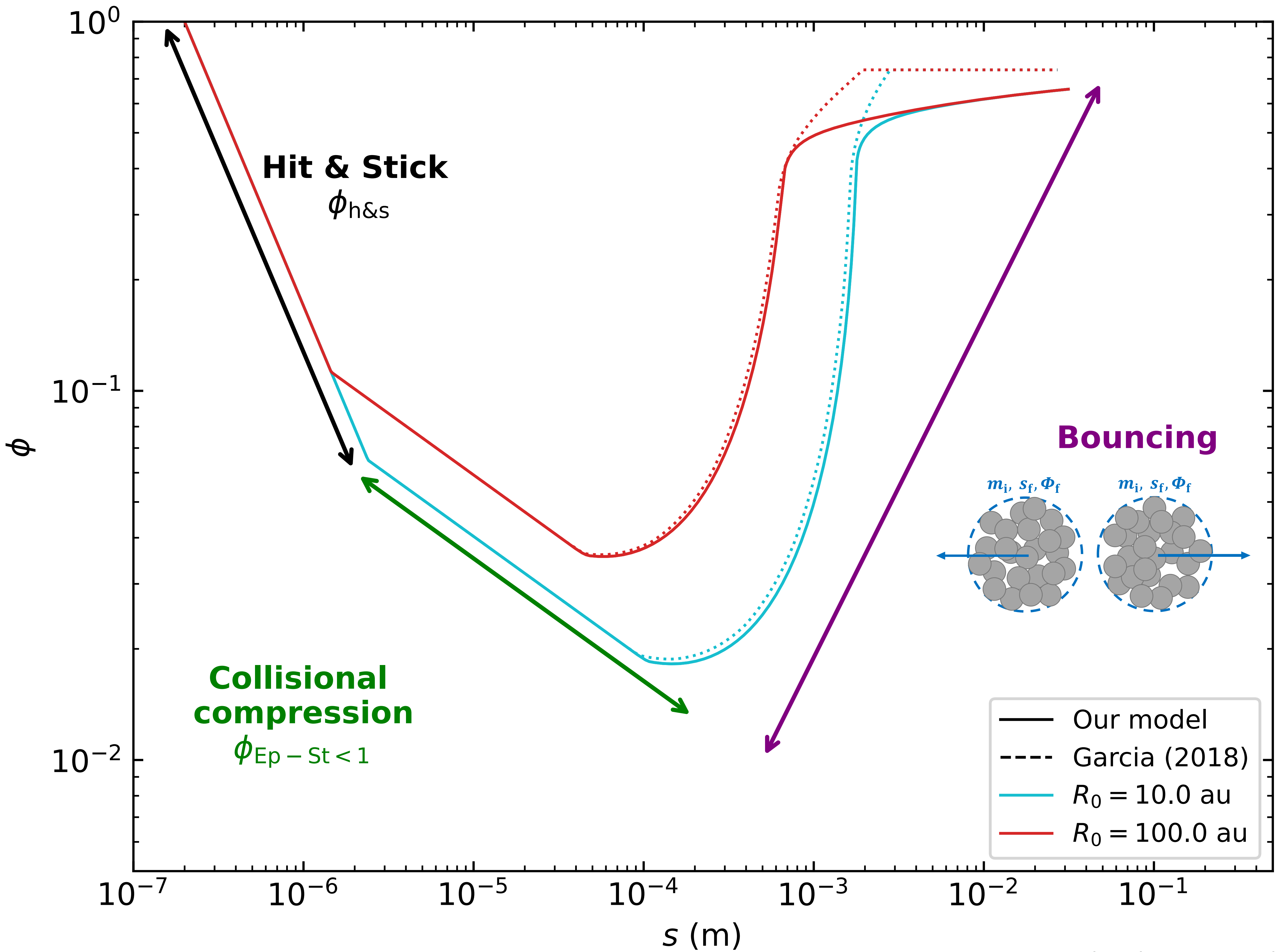
- Porous grains are larger ⇒ faster growth
- Stokes number
    - Epstein regime: $\mathrm{St}_{\mathrm{Epstein}} = \dfrac{\Omega_{\mathrm{K}} \rho_{\mathrm{s}} \phi s}{\rho_{\mathrm{g}} c_{\mathrm{s}}}$
    - Stokes regime: $\mathrm{St}_{\mathrm{Epstein}} = \dfrac{4\Omega_{\mathrm{K}} \rho_{\mathrm{s}} \phi s^2}{9 \rho_{\mathrm{g}} c_{\mathrm{s}} \lambda_{\mathrm{g}}}$

POROSITY EVOLUTION MODEL: PURE GROWTH



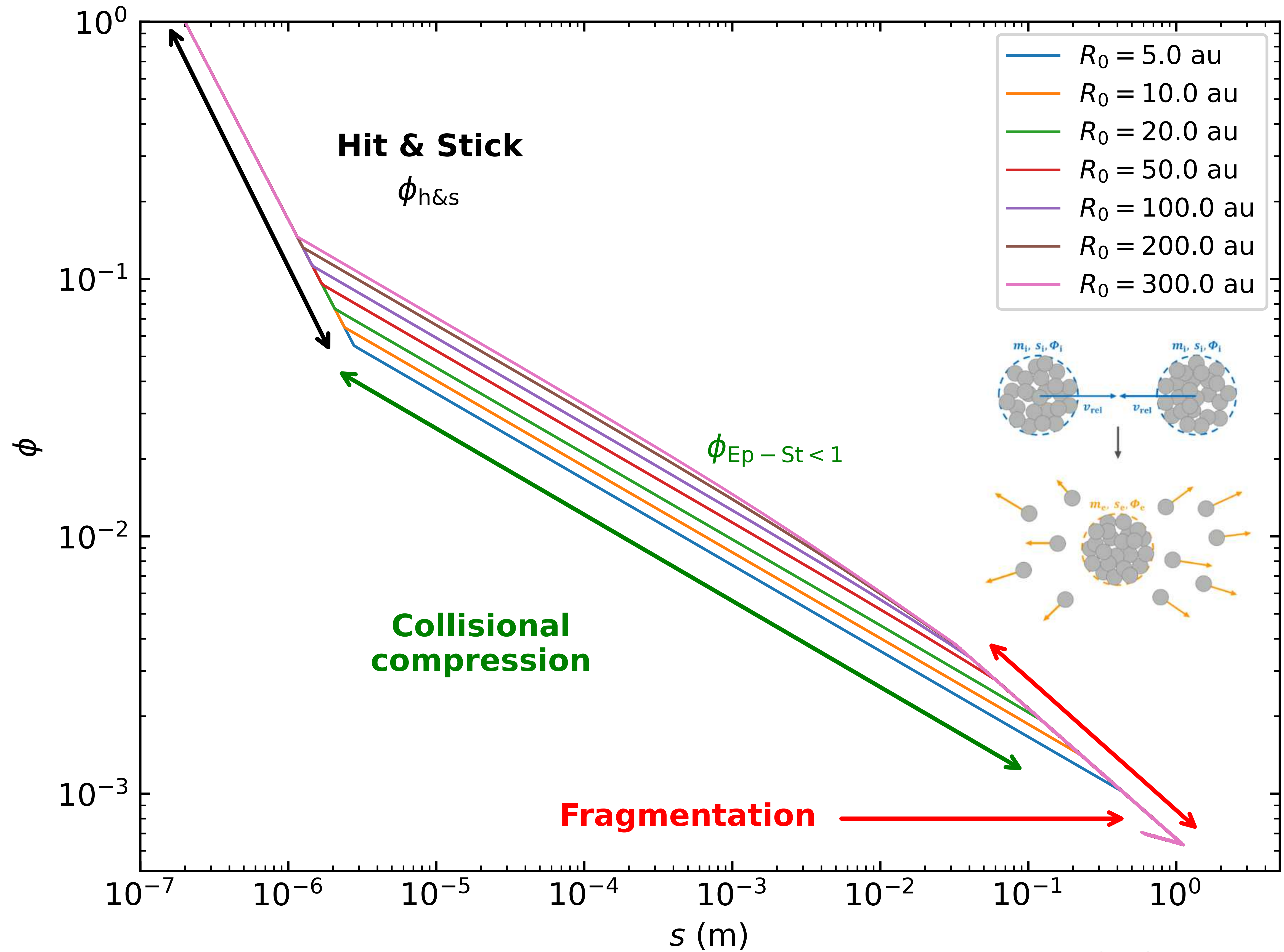
Garcia+Gonzalez2020

POROSITY EVOLUTION MODEL: BOUNCING



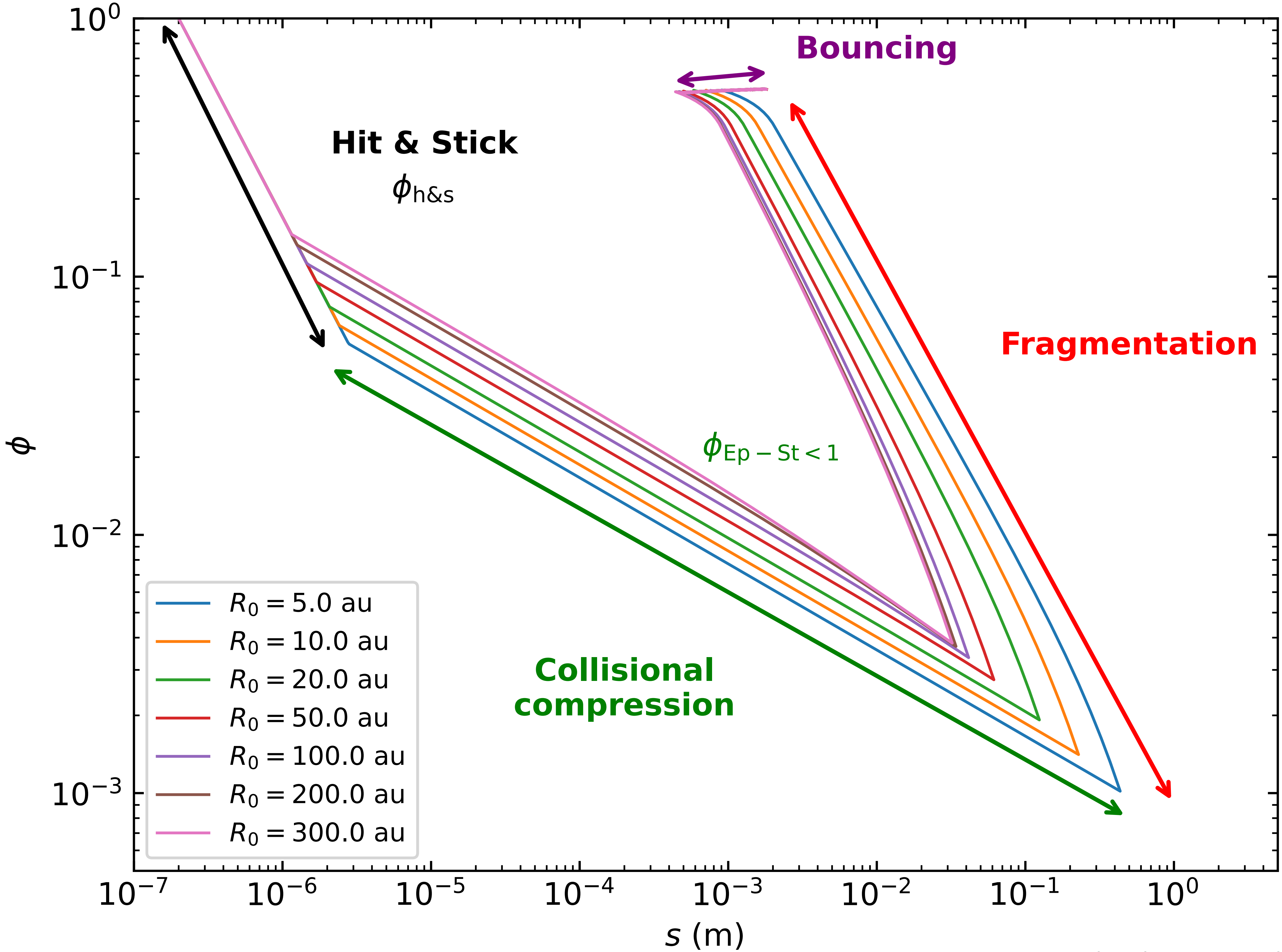
Michoulier+Gonzalez2024

POROSITY EVOLUTION MODEL: FRAGMENTATION



Michoulier+Gonzalez2024

POROSITY EVOLUTION MODEL: COMPACTION



Michoulier+Gonzalez2024

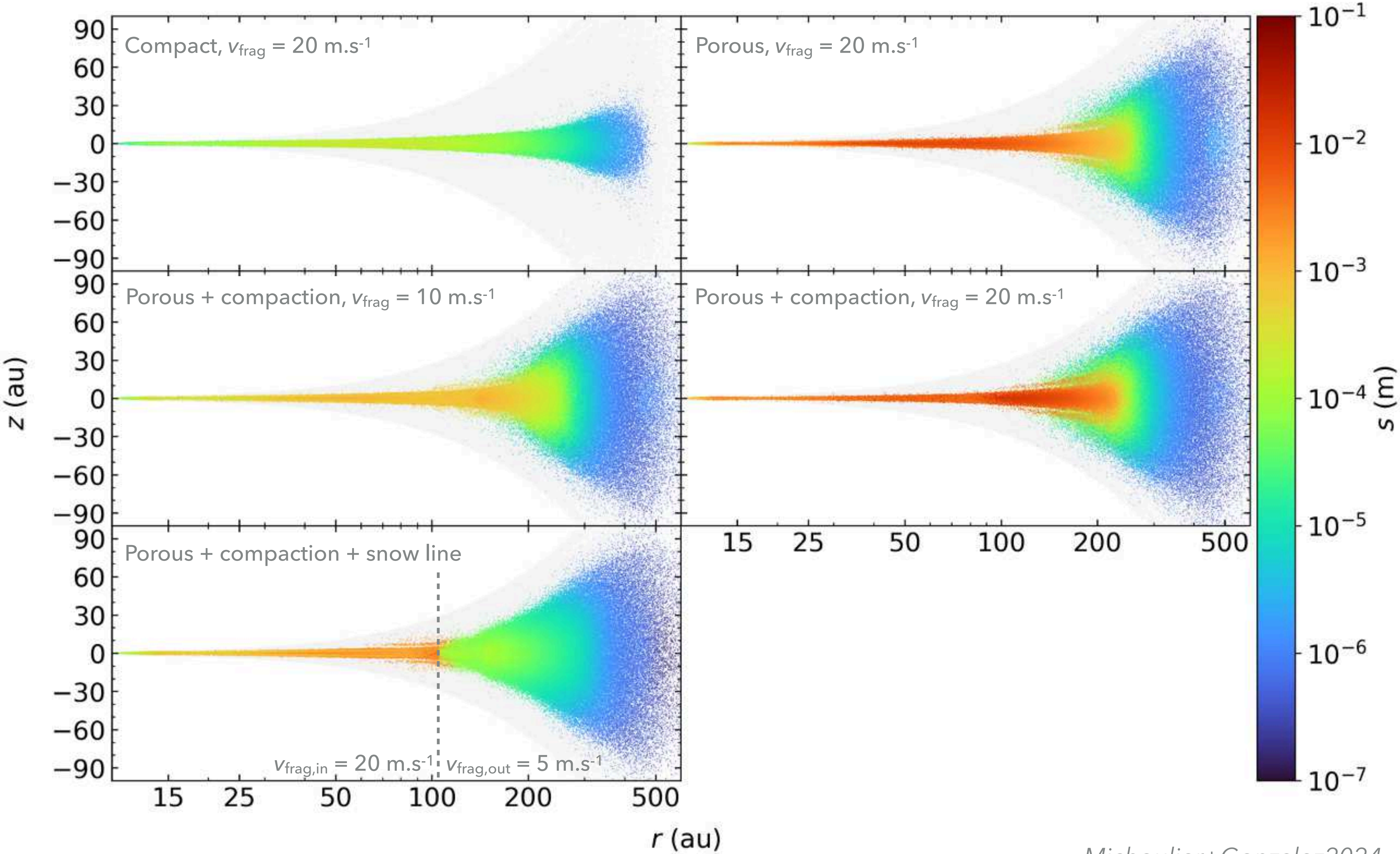
SIMULATIONS

- CTTS disk
  - $M_\star = 1\ M_\odot$
  - $M_\mathrm{disk} = 0.01\ M_\odot$
  - $p = 3/4$
  - $q = 1/2$
  - $\alpha = 5\mathrm{x}10^{-3}$
- Material
  - Silicates, $v_\mathrm{frag} = 10, 20, 40\ \mathrm{m.s^{-1}}$
  - Water ice, $v_\mathrm{frag} = 15\ \mathrm{m.s^{-1}}$
- Dust
  - Initial dust/gas ratio
    - $\varepsilon_0 = 1\%$, uniform
  - Monomer size
    - $a_0 = 0.2\ \mu\mathrm{m}$
  - Size evolution
    - Growth + fragmentation
    - w/o or w/ compaction
  - Porosity evolution
    - Compact only
    - Porous, $\phi_0 = 1$

Garcia+Gonzalez2020

SIMULATION RESULTS

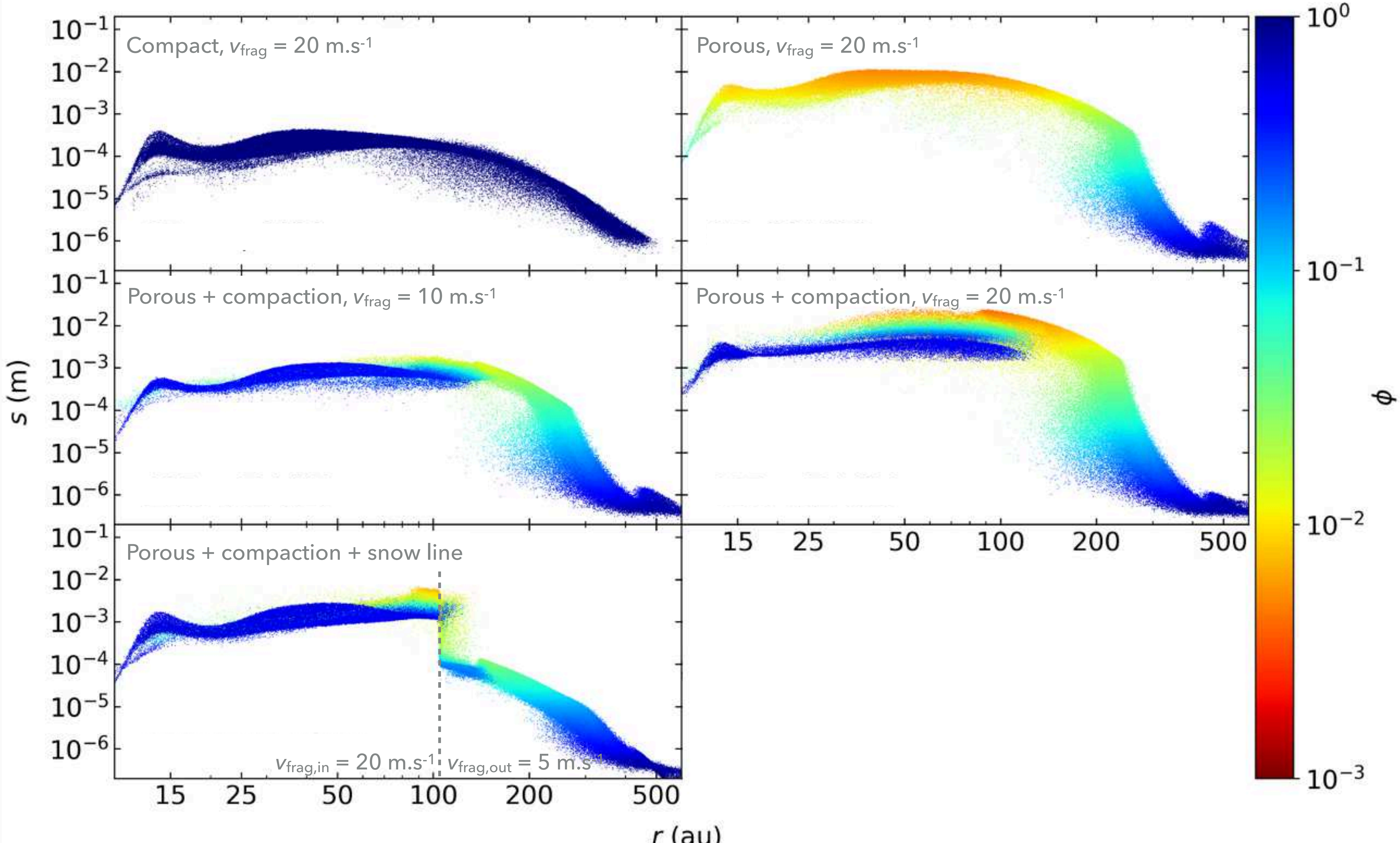
Silicates with growth+fragmentation, t = 100,000 yr



Michoulier+Gonzalez2024

SIMULATION RESULTS

Silicates with growth+fragmentation, t = 100,000 yr



Michoulier+Gonzalez2024

EFFECTIVENESS OF THE STREAMING INSTABILITY

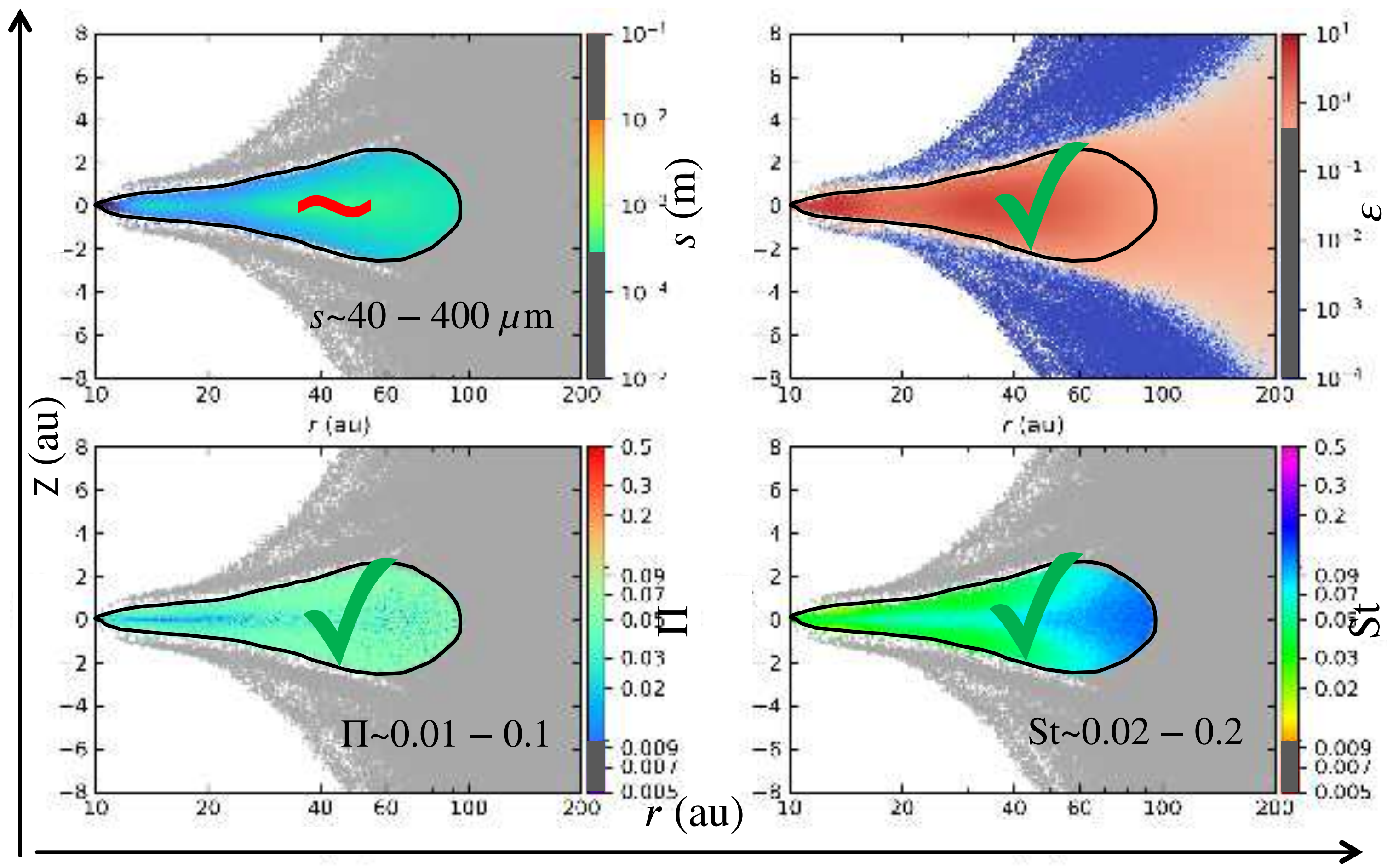
- Triggering criterion for the SI expressed in terms of St
  - what size do grains with St ~ 1 have?
- Global simulations provide size and porosity at each location
  - verify the viability of the SI
  - study robustness of SIDTS

EFFECTIVENESS OF THE STREAMING INSTABILITY

Compact silicates with growth+fragmentation

v_{frag} = 20 m.s^{-1}

- Triggering criteria
  - $\varepsilon \gtrsim 0.5$
  - St ~ 0.01–1
  - $\Pi = \Delta v/c_s > 0.01$
- Sizes and porosities compatible w/ obs.
  - s > 0.3–1 mm
  - ϕ ~ 0.1–1



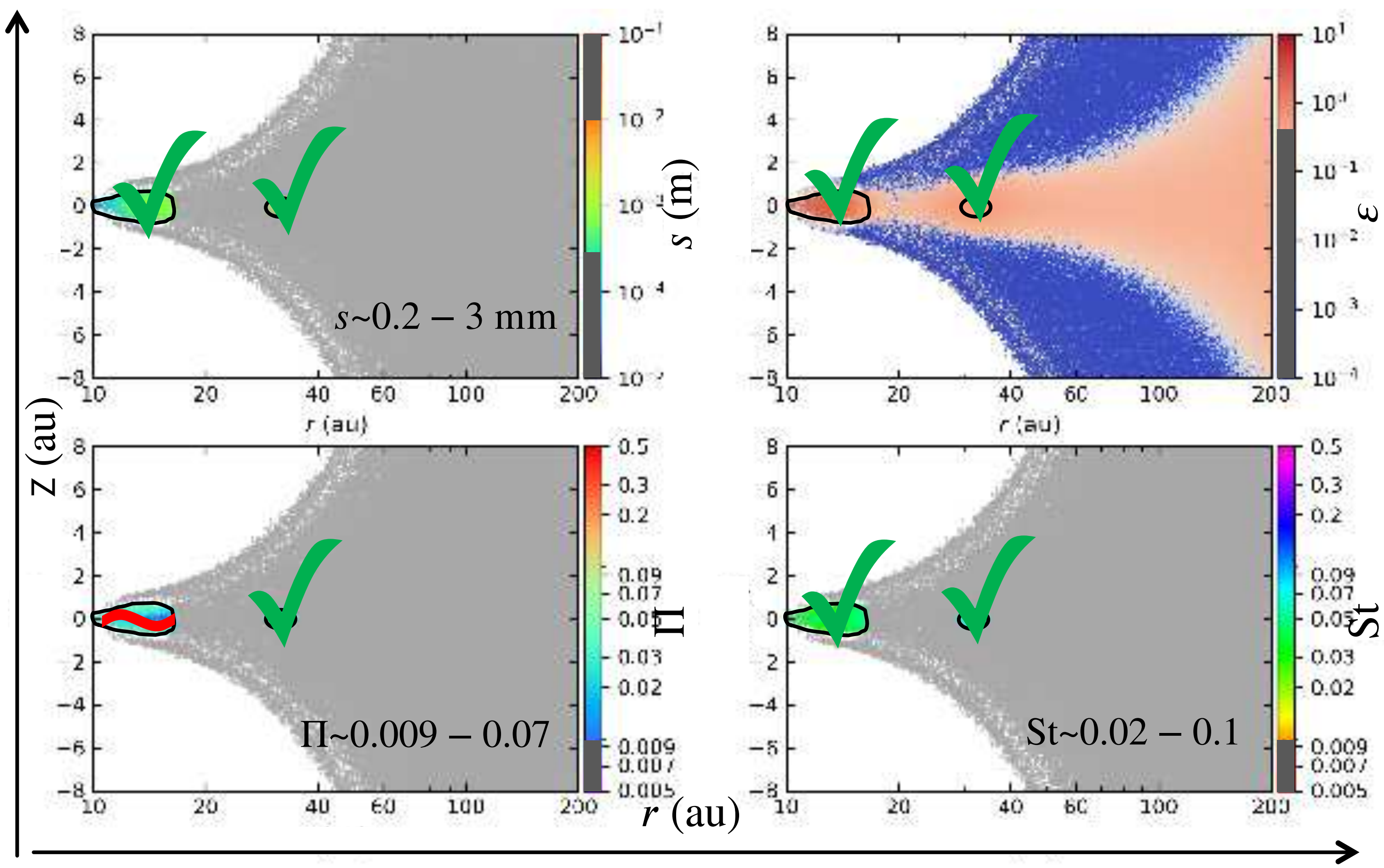
Michoulier+Gonzalez2024

EFFECTIVENESS OF THE STREAMING INSTABILITY

Porous silicates with growth+fragmentation+compaction

$v_{\mathrm{frag}} = 20$ m.s^{-1}

- Triggering criteria
  - $\varepsilon \gtrsim 0.5$
  - St ~ 0.01–1
  - $\Pi = \Delta v/c_s > 0.01$
- Sizes and porosities compatible w/ obs.
  - s > 0.3–1 mm
  - ϕ ~ 0.1–1

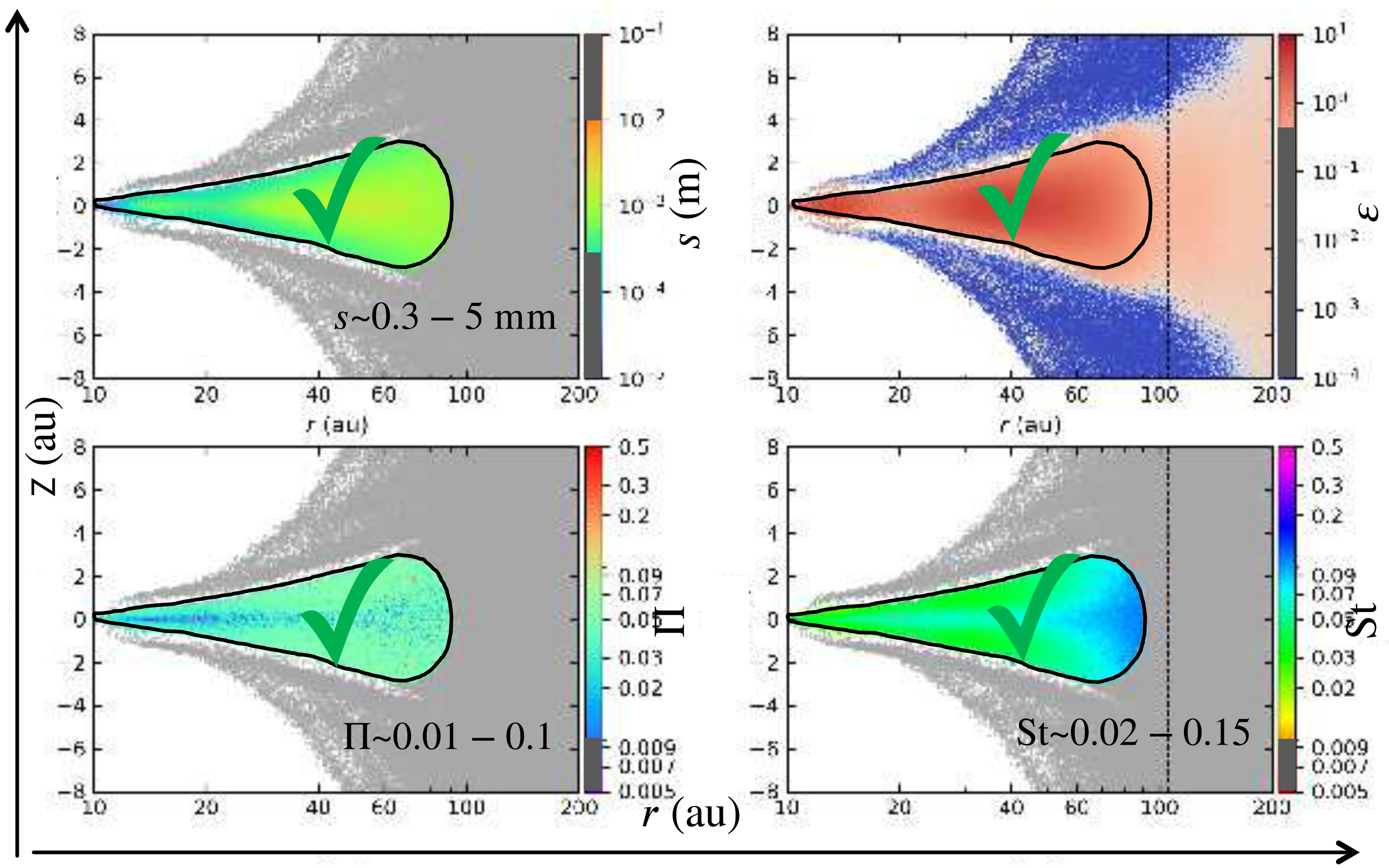


Michoulier+Gonzalez2024

Porous silicates with growth+fragmentation+compaction+snow line

$v_{\mathrm{frag,in}}$ = 20 m.s^{-1}, $v_{\mathrm{frag,out}}$ = 5 m.s^{-1}

- Triggering criteria
  - $\varepsilon \gtrsim 0.5$
  - St ~ 0.01–1
  - $\Pi = \Delta v / c_s > 0.01$
- Sizes and porosities compatible w/ obs.
  - s > 0.3–1 mm
  - ϕ ~ 0.1–1



Michoulier+Gonzalez2024

TAKE-HOME MESSAGE

Conclusions w/ PHANTOM

- Porosity needed: compact grains too small, porous grains observed
- Compaction needed: observed porosities only moderate
- CO snow line: retains more grains, helps SI triggering conditions

Perspectives w/ MCFOST

- Global simulations of spatial, size and porosity evolution
  - more realistic settling profiles
  - better multi-λ fitting with MCFOST
- Porosity as a space-varying property in MCFOST
  - search for porosity variations in observed discs