“Particle traps” at planet gap edges in disks: effect of grain growth and fragmentation

Jean-François Gonzalez

Centre de Recherche Astrophysique de Lyon, France

CRA Lyon

Guillaume Laibe

University of St Andrews, Scotland, UK

Sarah Maddison

Swinburne University of Technology, Melbourne, Australia

Christophe Pinte, François Ménard

Institut de Planétologie et d’Astrophysique de Grenoble

& Laboratoire Franco-Chilien d’Astronomie

Particle traps

- The barriers of planet formation
  - Radial drift $\mathrm{St} = \Omega_{\mathrm{k}} \rho_{\mathrm{d}} s / \rho_{\mathrm{g}} c_{\mathrm{s}} = 1$

    Weidenschilling (1977), Nakagawa et al. (1986), Birnstiel et al. (2010), Laibe et al. (2012,2014)
  - Fragmentation

    Dullemond & Dominik (2005), Blum & Wurm (2008)
  - Bouncing

    Zsom et al. (2010), Windmark et al. (2012)

    ⇒ can be overcome with stochastic motion

    Garaud et al. (2013)
- Particle traps: possible solutions
  - Vortices

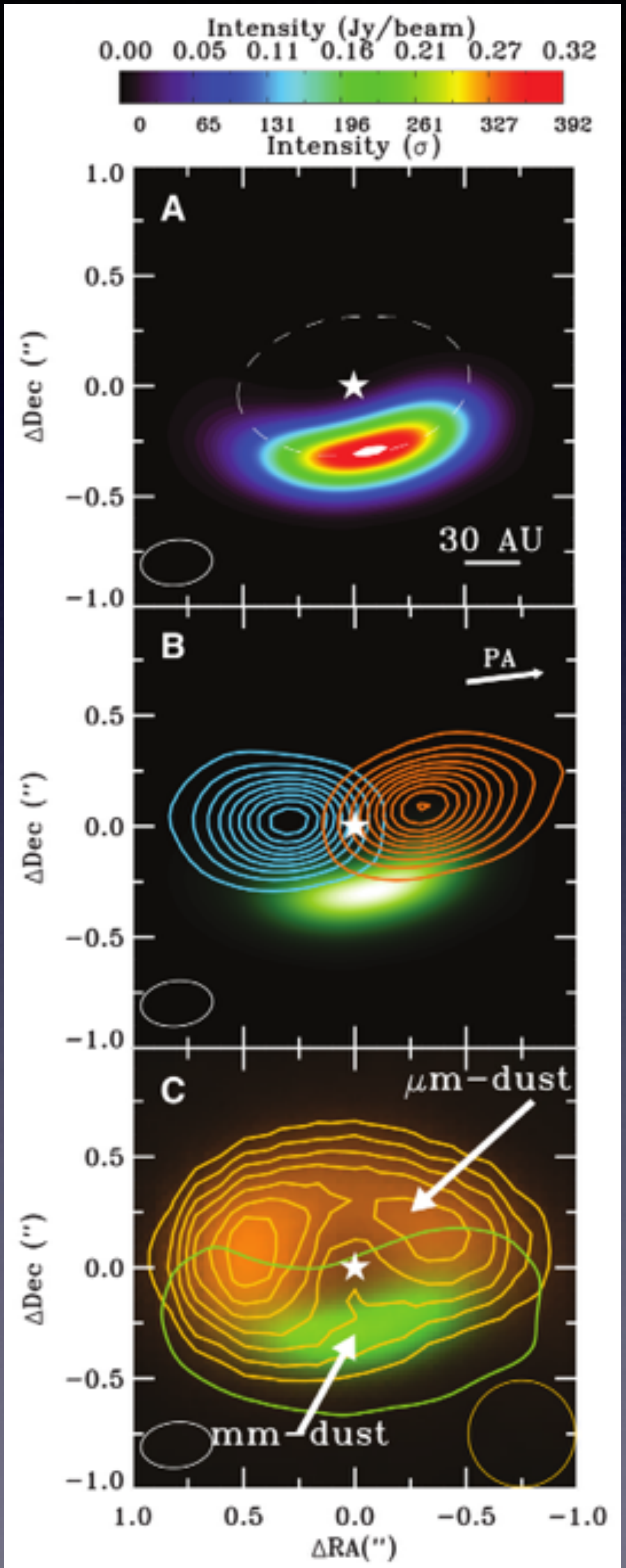
    Barge & Sommeria (1995), Regály et al. (2012), Méheut et al. (2013)
  - Snow line, dead zone inner edge

    Kretke & Lin (2007), Dzyurkevich et al. (2010), Flock et al. (this meeting)
  - Planet gap edges

    Paardekooper et al. (2004), de Val-Borro et al. (2007), Fouchet et al. (2007,2010), Gonzalez et al. (2012)
  - “Bumpy” gas surface density

    Pinilla et al. (2012)

ALMA observations of Oph IRS 48

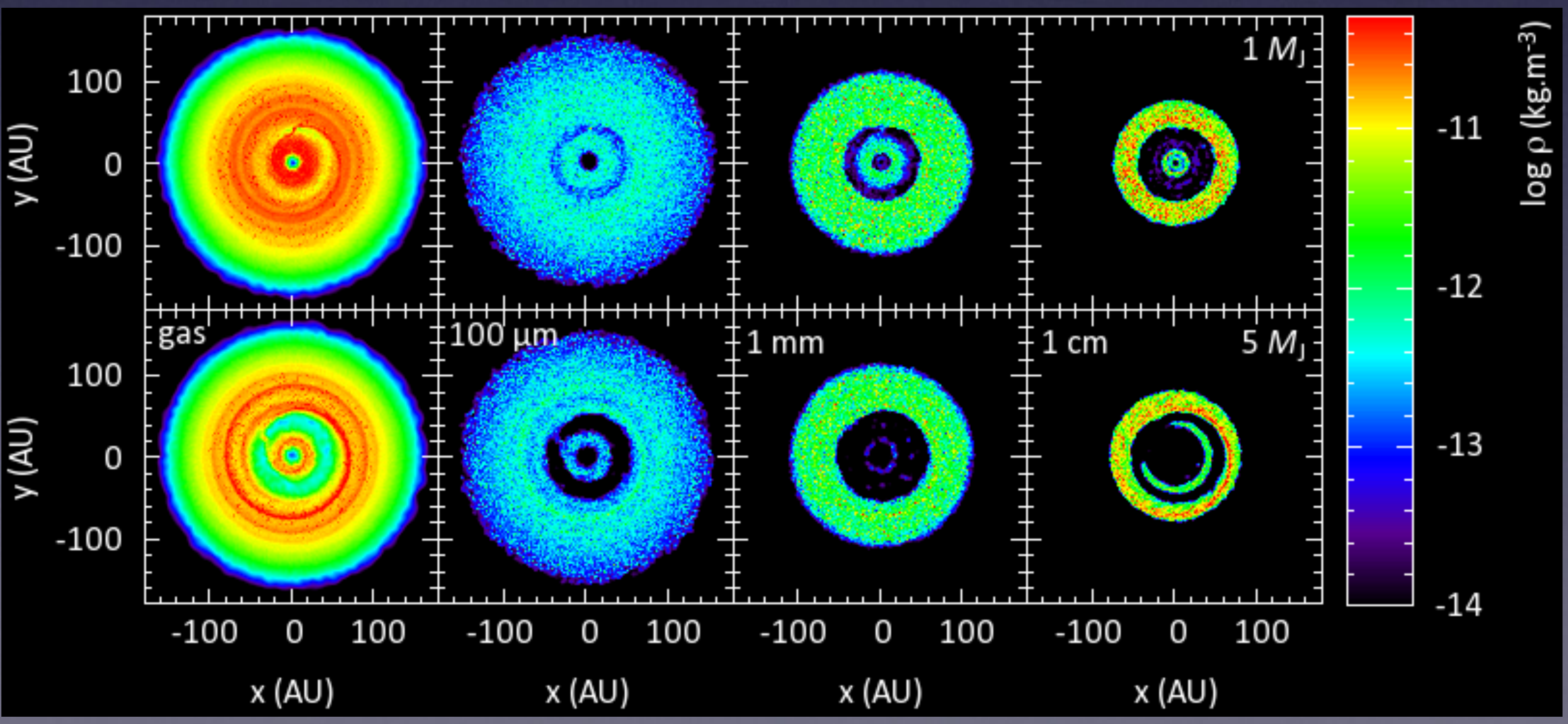


van der Marel et al. (2013)

Grains of constant size

SPH 3D two-phase (gas+dust) simulations

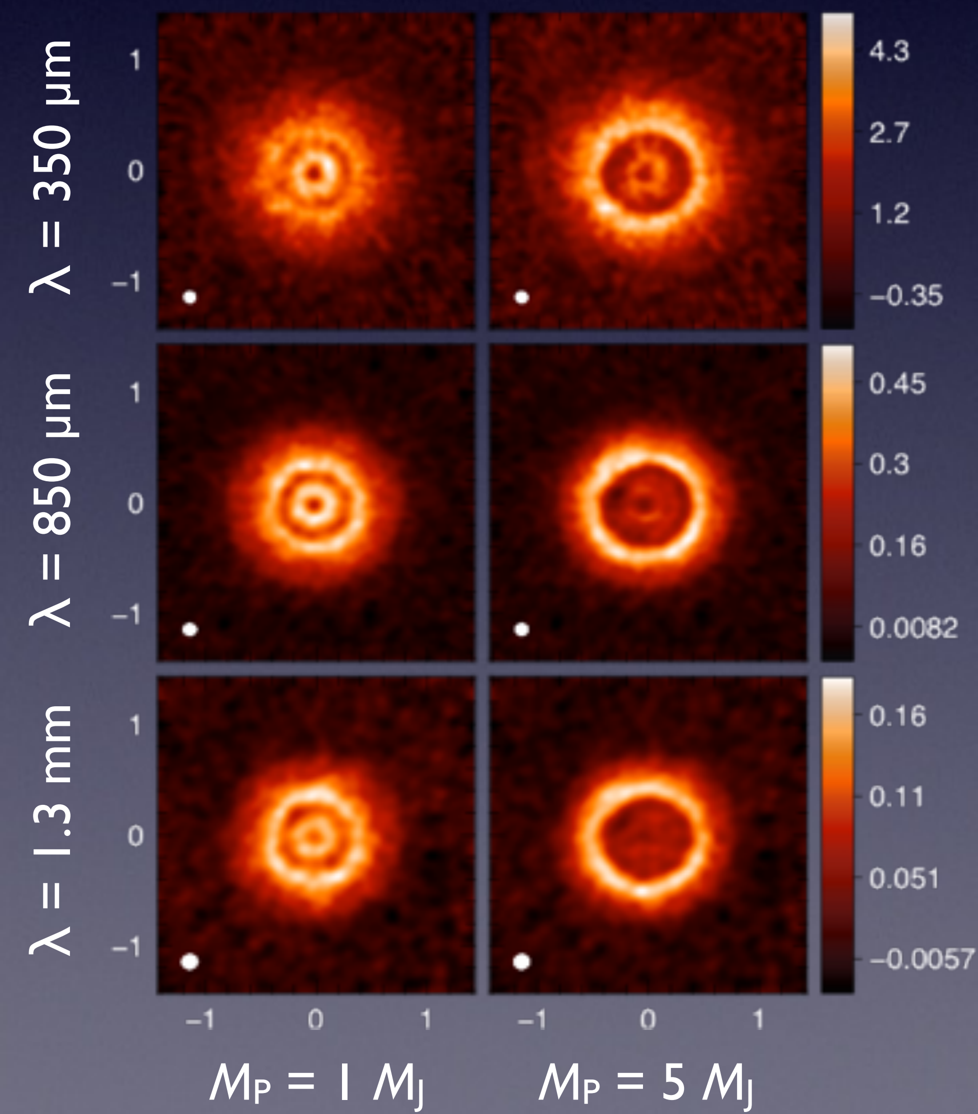
- CTTS disk: $M_{☆} = 1\ M_{\odot}$, $M_{disk} = 0.02\ M_{\odot}$
- Planet: $M_P = 1$ and $5\ M_J$, $a = 40$ UA
- Initial dust/gas ratio: 10^{-2}
- Grain sizes: 100 µm, 1 mm, 1 cm



Fouchet et al. (2010)

ALMA simulated images

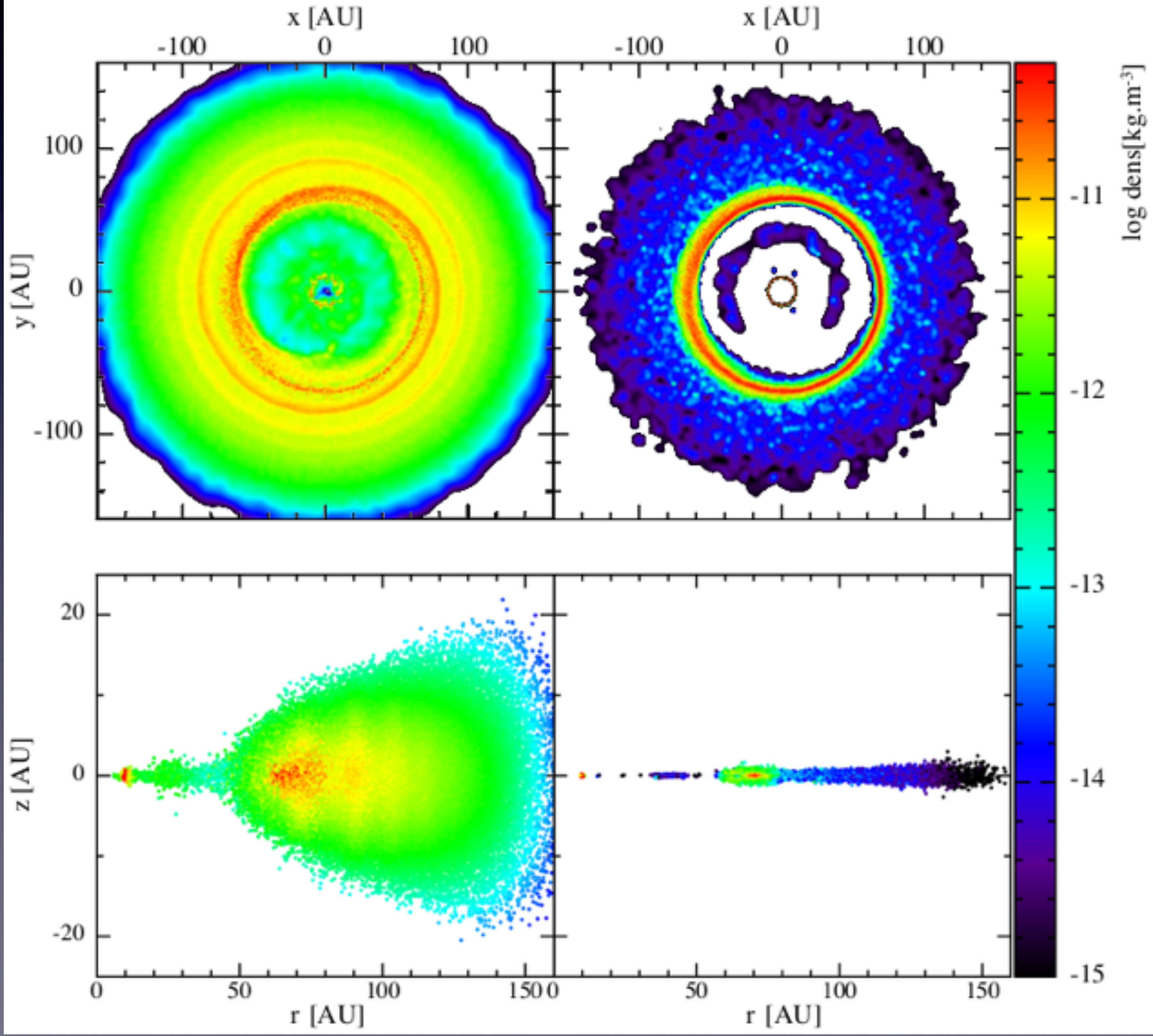
$t = 1$ h $\theta = 0.10$"
$d = 140$ pc $\delta = -23°$



Gonzalez et al. (2012)

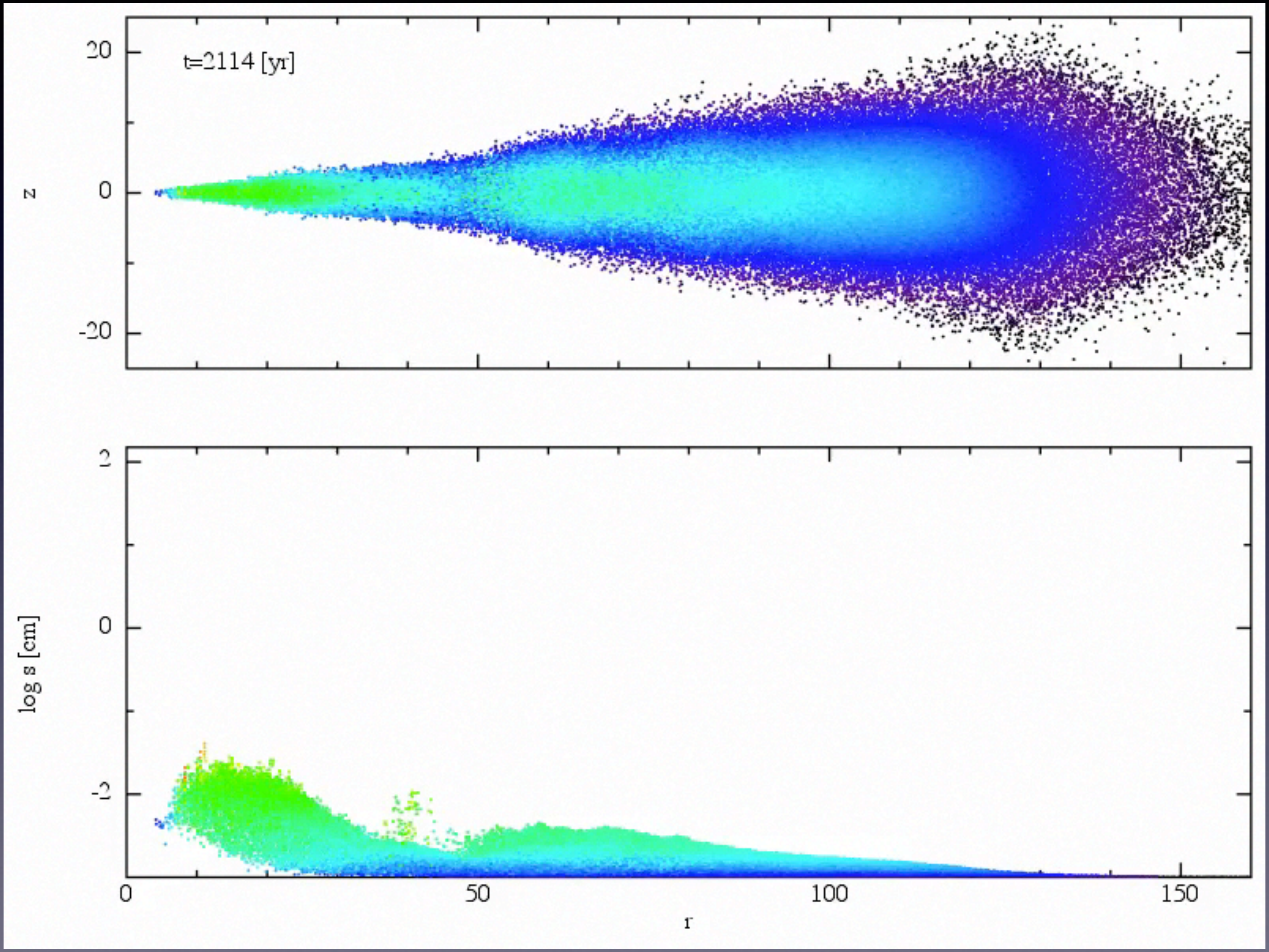
Growth and fragmentation

- Growth model of Stepinski & Valageas (1997)
  - Compact icy particles
  - Perfect sticking
- Fragmentation threshold
  - $V_{rel} < V_{frag}$: growth
  - $V_{rel} > V_{frag}$: shattering
- Initial grain size
  - 10 µm, uniform
- Same setup
  - CTTS disk
  - 5 M_J planet



Gonzalez et al. (2014)

Pure growth



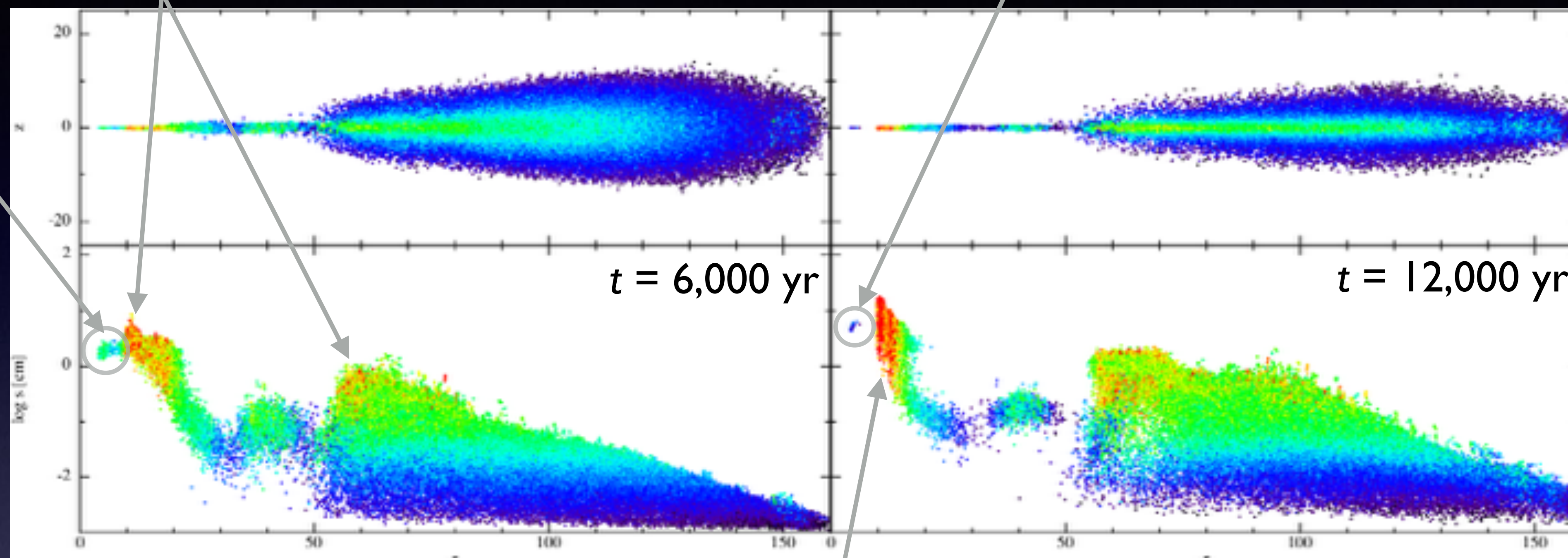
Gonzalez et al. (2014)

Pure growth

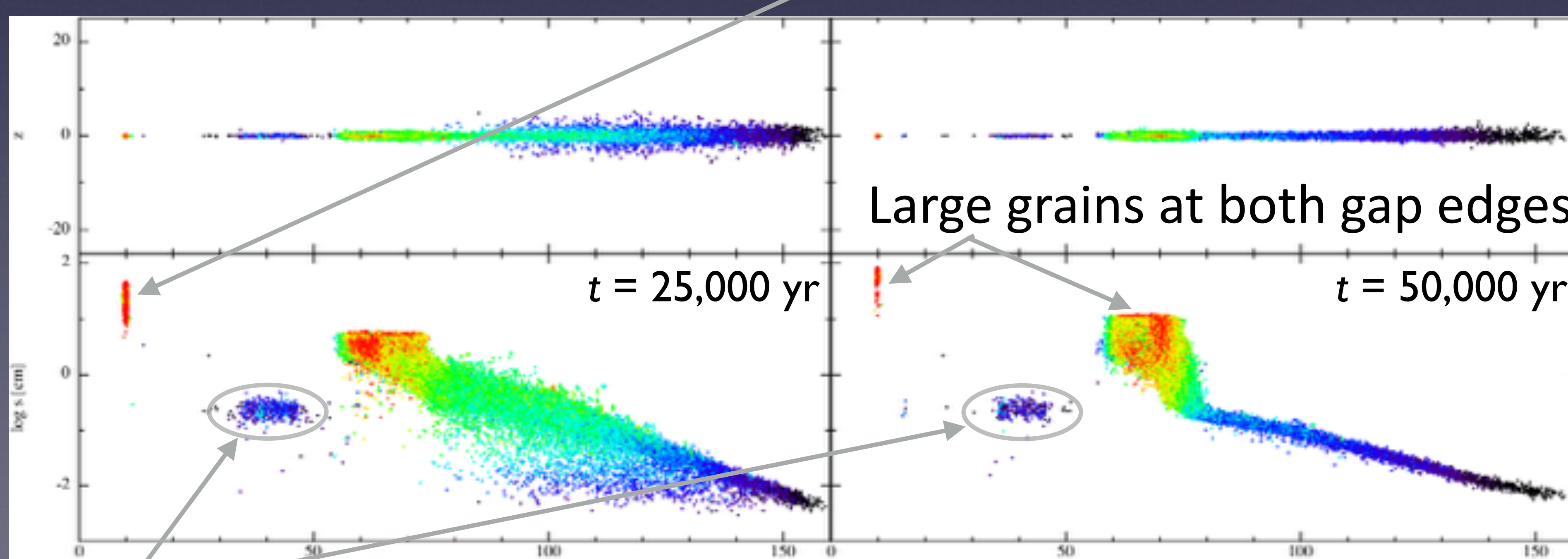
Grains having reached St=1 migrate rapidly towards the star

Efficient growth at the gap edges

Last grains lost to the star



After outgrowing St=1, grains are decoupled and grow without migrating



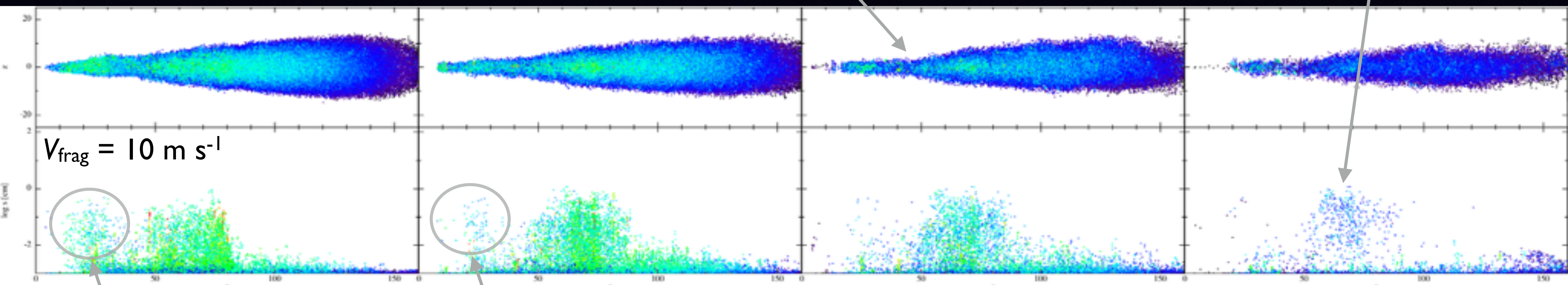
Grains in corotation with the planet, on horseshoe orbits

Gonzalez et al. (2014)

Growth and fragmentation

Grains never decouple and follow the gas through the gap

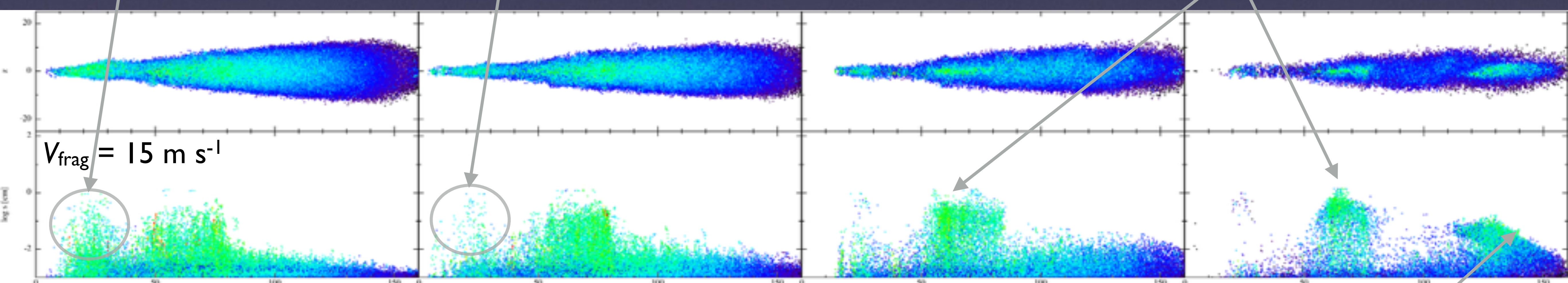
The dust disk slowly drains out



Grains can't overcome the radial-drift barrier

The inner disk is lost to the star

Grains overcome St=1 at the outer gap edge and grow slowly



Lower V_{rel} lead to slow growth

t = 6,000 yr

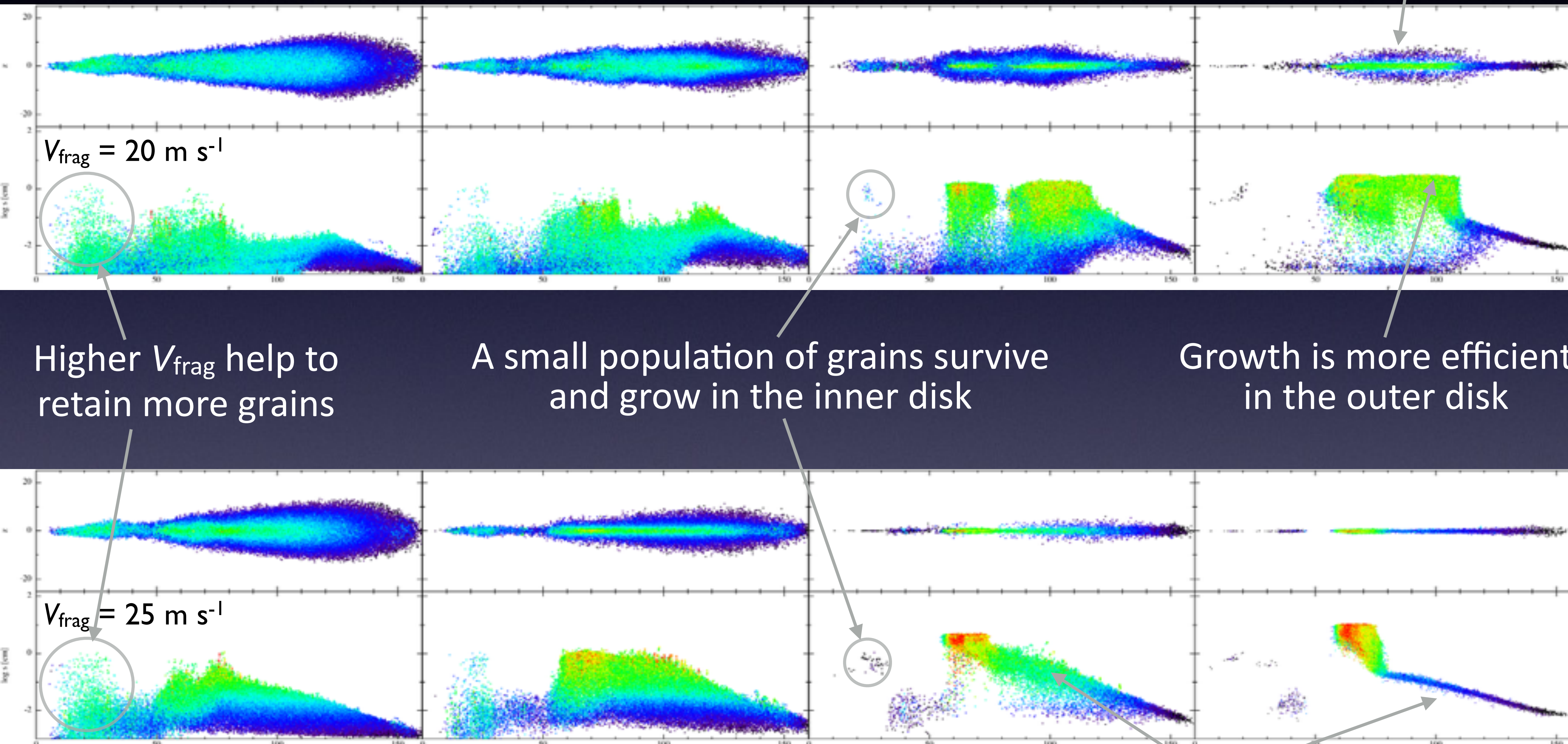
t = 12,000 yr

t = 25,000 yr

t = 50,000 yr

Growth and fragmentation

Larger grains are more settled



Higher V_{frag} help to retain more grains

A small population of grains survive and grow in the inner disk

Growth is more efficient in the outer disk

The outer disk is almost not affected by fragmentation

t = 6,000 yr | *t* = 12,000 yr | *t* = 25,000 yr | *t* = 50,000 yr

Summary

- Pure growth
  - Very efficient growth at both gap edges
  - Sizes > 10 cm
  - Gap edges: potential sites for the formation of additional planets

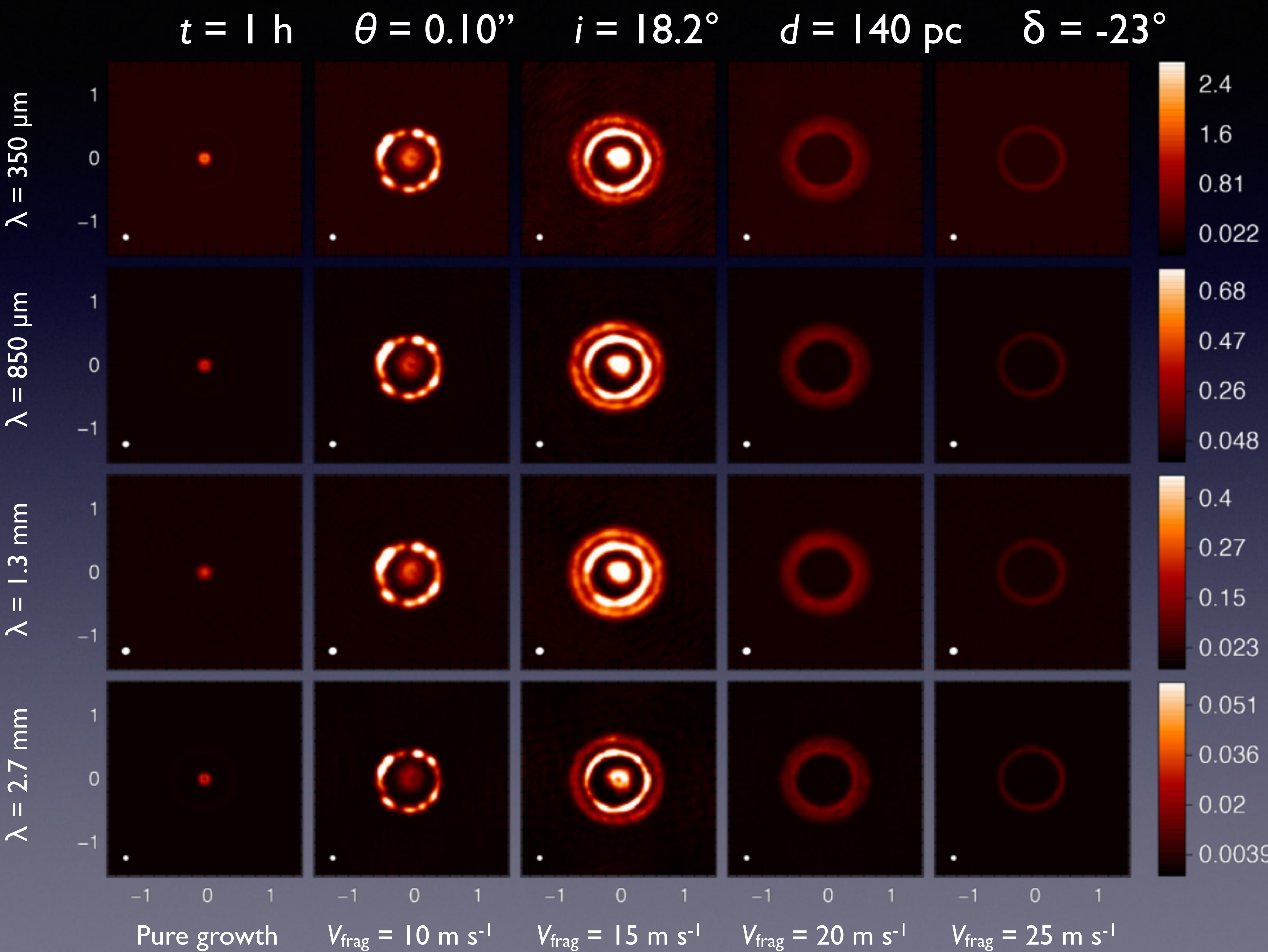
- Growth and fragmentation
  - Different growth behavior depending on radial location
  - Easier growth for larger V_{frag}
  - Low V_{frag} (considered in most studies)

    ⇒ no significant growth past the radial-drift barrier

Conclusion

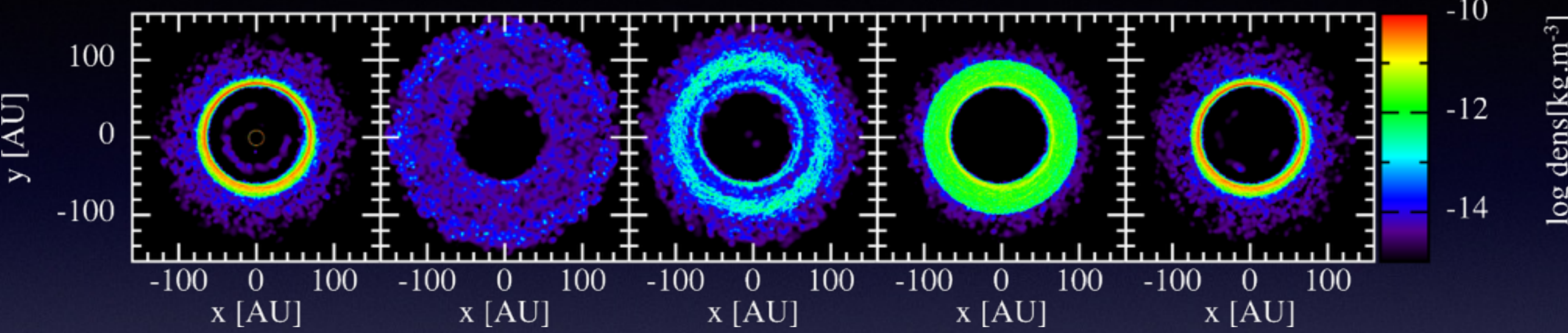
- Can grains really grow at V_{rel} above 20 m s^{-1}?
  ⇒ Yes!
  - Porous material
    - V_{frag} ~ 60 m s^{-1} for icy aggregates but ~ 6 m s^{-1} for silicates
      Wada et al. (2009)
    - V_{frag} >~ 27 m s^{-1} for cm-sized silicate aggregates
      Meru et al. (2013)
  - Mass transfer in high-mass-ratio collisions
    - V_{frag} ~ 60 m s^{-1} for silicate aggregates
      Teiser & Wurm (2009)
    - V_{frag} ~ 80 m s^{-1} for icy aggregates but ~ 8 m s^{-1} for silicates
      Wada et al. (2013)
  - Updated values of the surface energies
    - V_{frag} ~ 30-40 m s^{-1} for silicate aggregates
      Yamamoto et al. (2014)

ALMA simulated images

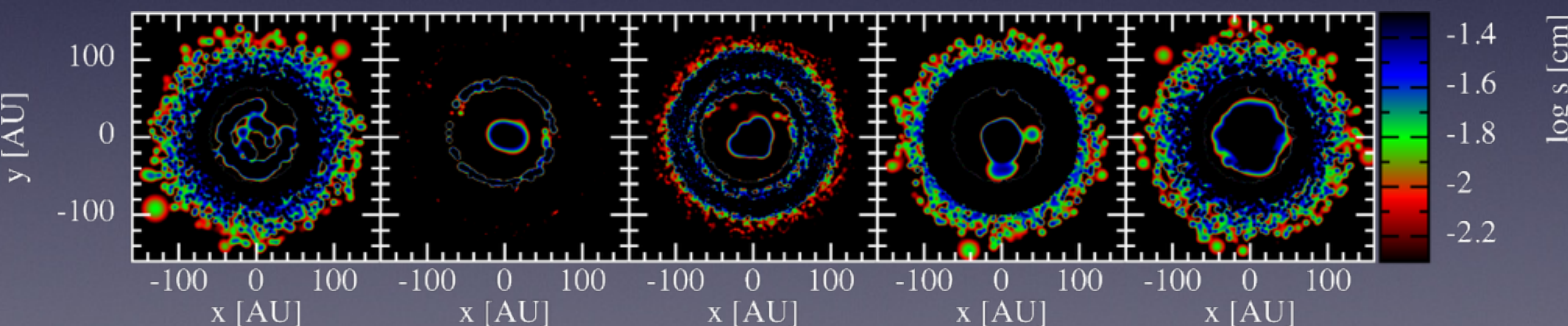


Contributions to images

Density



Grain size



Pure growth — V_{frag} = 10 m s^{-1} — V_{frag} = 15 m s^{-1} — V_{frag} = 20 m s^{-1} — V_{frag} = 25 m s^{-1}