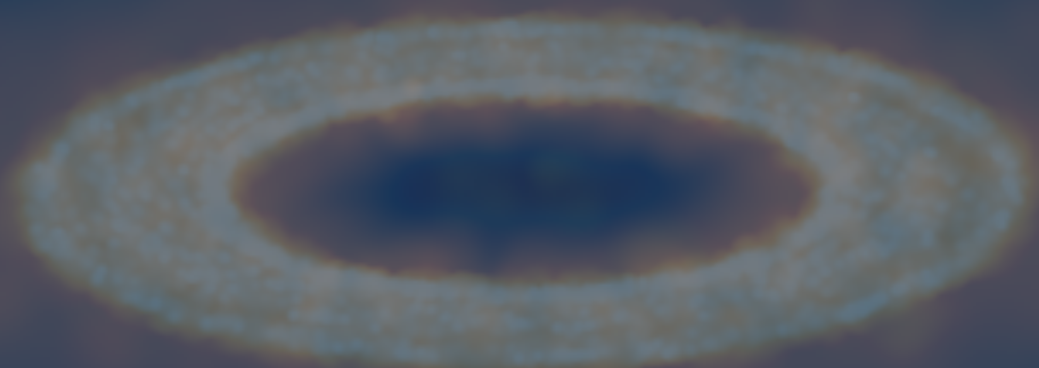


# Self-induced dust traps: overcoming planet formation barriers



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# Planet formation

- Core accretion paradigm

- Small dust grains → pebbles → planetesimals → planets

easy

bottleneck

easy

- The barriers of planet formation

- Radial drift

*Weidenschilling1977, Nakagawa+1986, Birnstiel+2010, Laibe+2012,2014*

- Fragmentation

*Dullemond+Dominik2005, Blum+Wurm2008*

- Bouncing

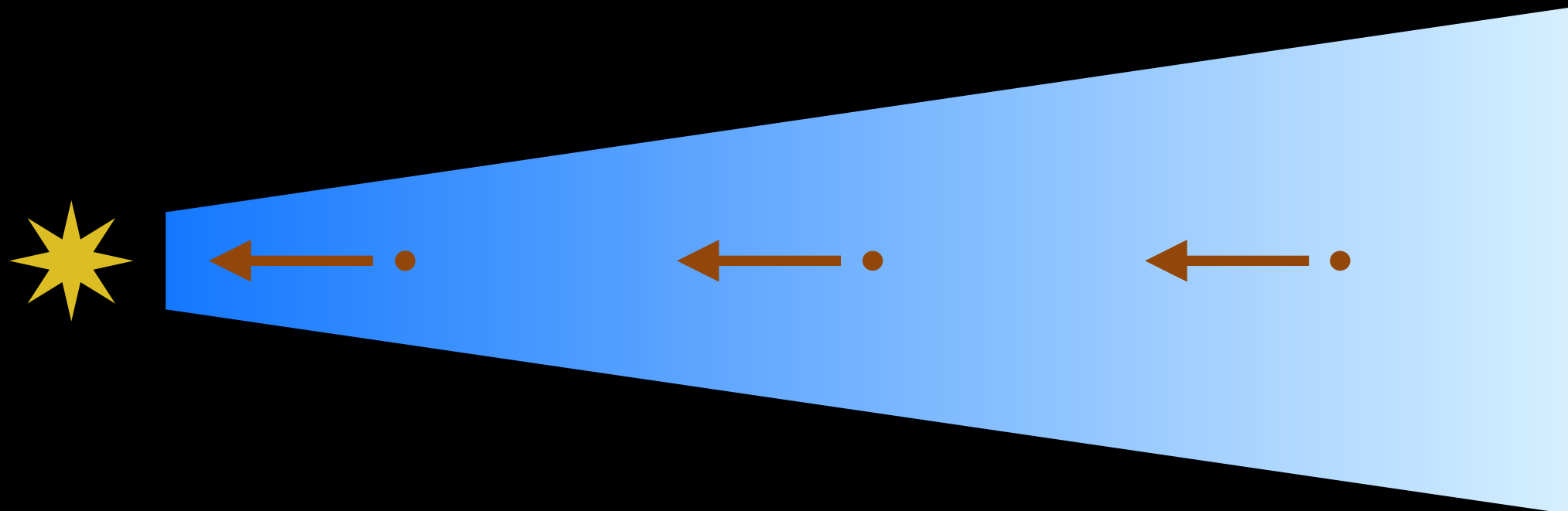
*Zsom+2010, Windmark+2012*

# The radial drift barrier

- Sub-Keplerian gas drags Keplerian dust  $\Rightarrow$  dust settling and drift
- Dust dynamics controlled by the Stokes number  $St$

$$St = \frac{\rho_s \Omega_K s}{\rho_g c_s} \quad St_{\text{mid}} = \frac{\sqrt{2\pi} \rho_s s}{\Sigma_g}$$

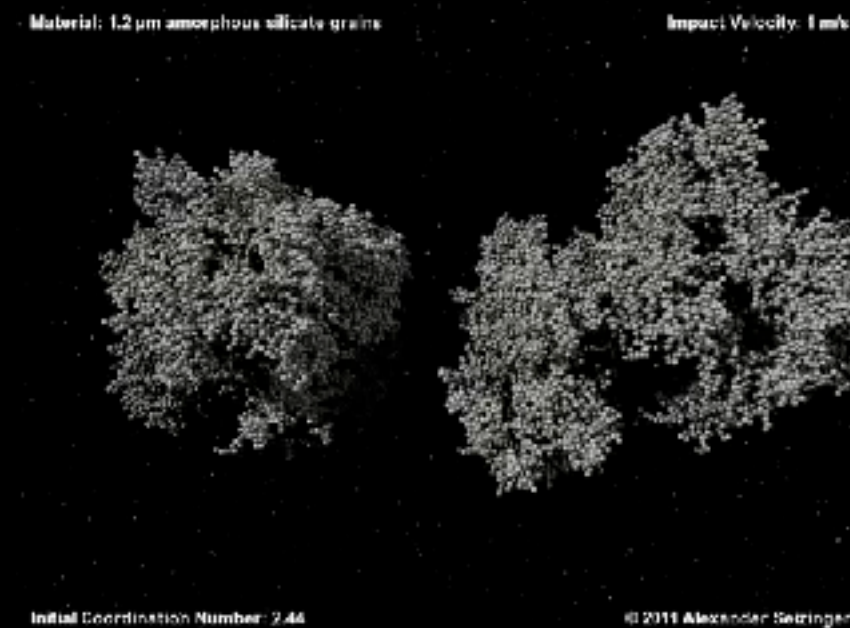
$$v_{d,r}(z=0) = \frac{St}{1 + St^2} \left( \frac{H}{r} \right)^2 \frac{d \ln P_g}{d \ln r} v_K$$



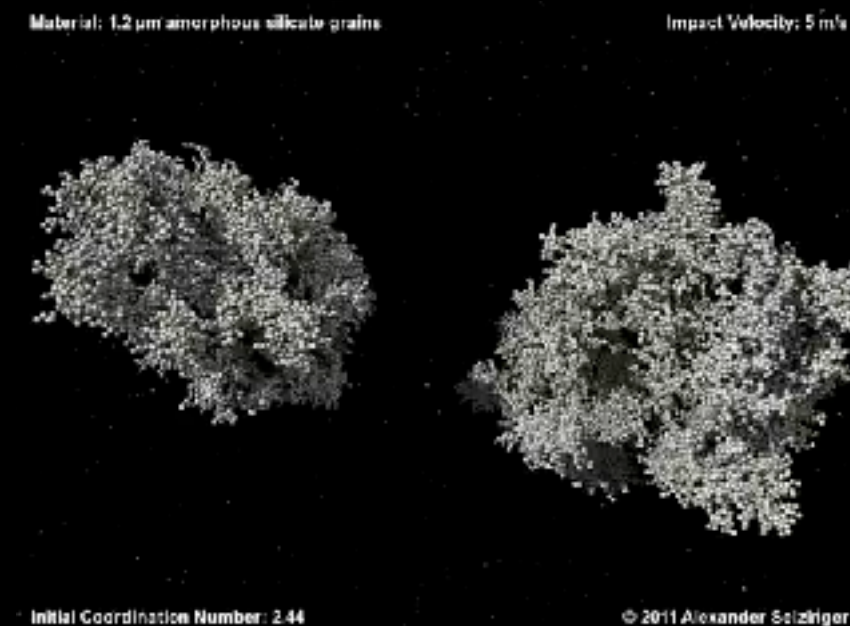
- $St \ll 1$ , small sizes (1-10  $\mu\text{m}$ ): dust coupled to gas
- $St \sim 1$ , median sizes (100  $\mu\text{m}$ -10 cm): strong influence of gas drag
- $St \gg 1$ , large sizes (1-10 m): dust insensitive to gas

# The fragmentation and bouncing barriers

- Grain collisional evolution: fragmentation threshold  $V_{\text{frag}}$
- Growth when  $V_{\text{rel}} < V_{\text{frag}}$



- Fragmentation when  $V_{\text{rel}} > V_{\text{frag}}$



- Bouncing when  $V_{\text{rel}} \approx V_{\text{frag}}$

# Possible solution: dust traps

- Pressure maxima in the disk

- Vortices

*Barge+Sommeria1995, Lyra+Mac Low2012, Regály+2012, Méheut+2013, Zhu+2014*

- Dead zone inner edge

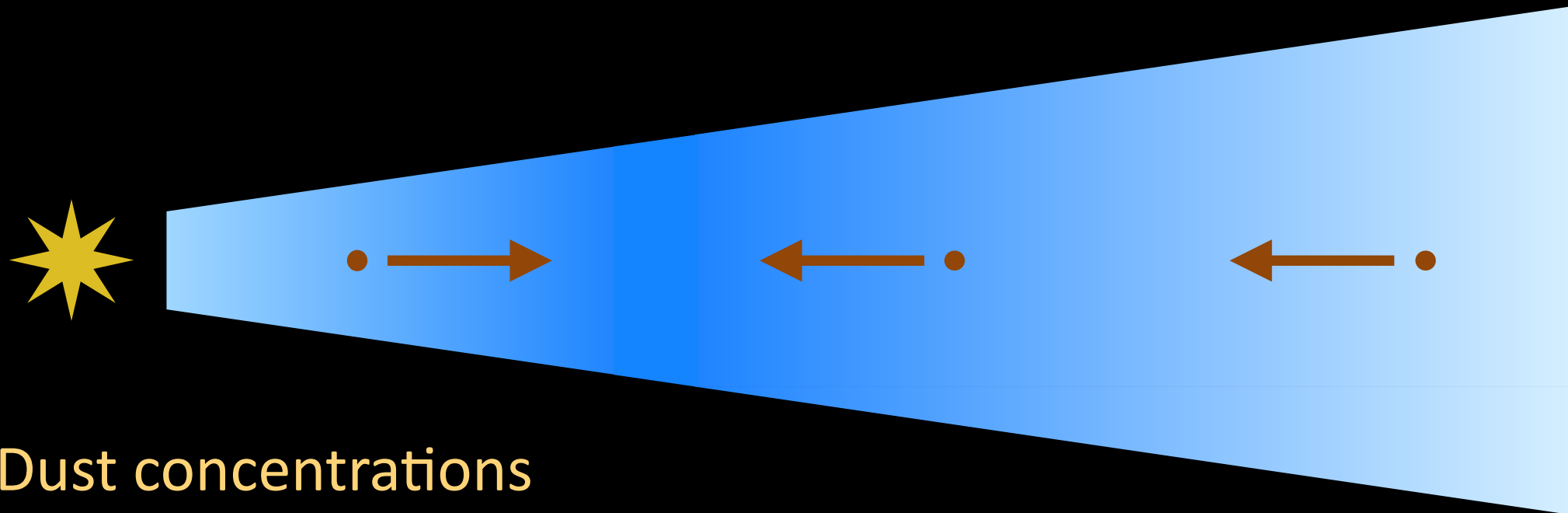
*Dzyurkevich+2010*

- Planet gap edges

*de Val-Borro+2007, Fouchet+2007,2010, Gonzalez+2012, Zhu2012,2014*

- “Bumpy” gas surface density

*Pinilla+2012, Bethune+2016*



## ➡ Dust concentrations

- $\epsilon = \rho_d / \rho_g \nearrow$ ,  $V_{\text{rel}} \searrow \Rightarrow$  solves planet formation barriers

- ...but need for special conditions

# Simulations

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

*Barrière-Fouchet+2005, Laibe+2008, Gonzalez+2015, Pignatale+2017*

- Aerodynamic drag

- self-consistent, grain-size dependent dynamics
- backreaction of dust on gas

- Grain growth

- Stepinski & Valageas (1997)
- compact particles
- perfect sticking

- Fragmentation

- when  $V_{\text{rel}} > V_{\text{frag}}$
- conservative model

- Initial disk model

- $\Sigma_g \propto r^{-p}$
- $T \propto r^{-q}$

$$\frac{ds}{dt} \propto \epsilon V_{\text{rel}}$$

$$\epsilon = \frac{\rho_d}{\rho_g}$$
$$V_{\text{rel}} \propto c_s \frac{\sqrt{\text{St}}}{1 + \text{St}}$$

$$\text{St}_{\text{mid}} \propto s r^p$$

$$c_s \propto r^{-q/2}$$

# Flat disk

- Setup

- CTTS disk

- $M_{\star} = 1 M_{\odot}, M_{\text{disk}} = 0.01 M_{\odot}$
- $p = 0, q = 1$
- $R_{\text{out}} = 160 \text{ AU}$
- $\alpha = 10^{-2}$

- Initial dust/gas ratio

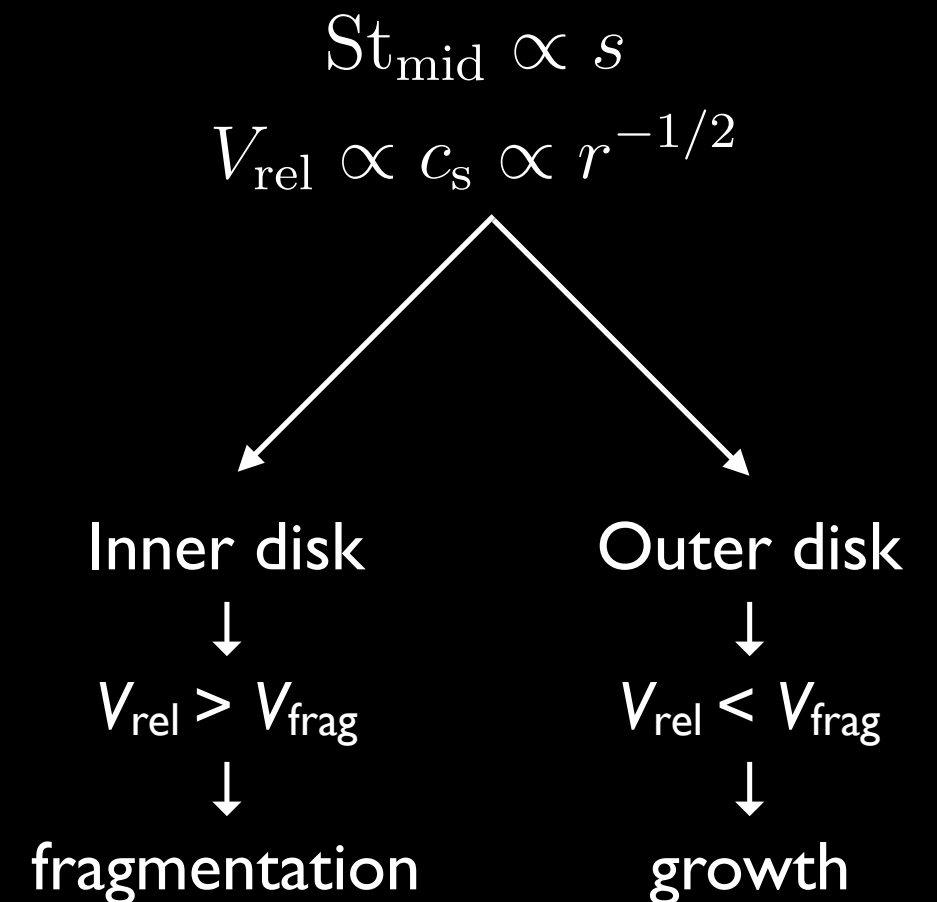
- $\epsilon_0 = 1\%$ , uniform

- Initial grain size

- $s_0 = 10 \mu\text{m}$ , uniform

- Fragmentation threshold

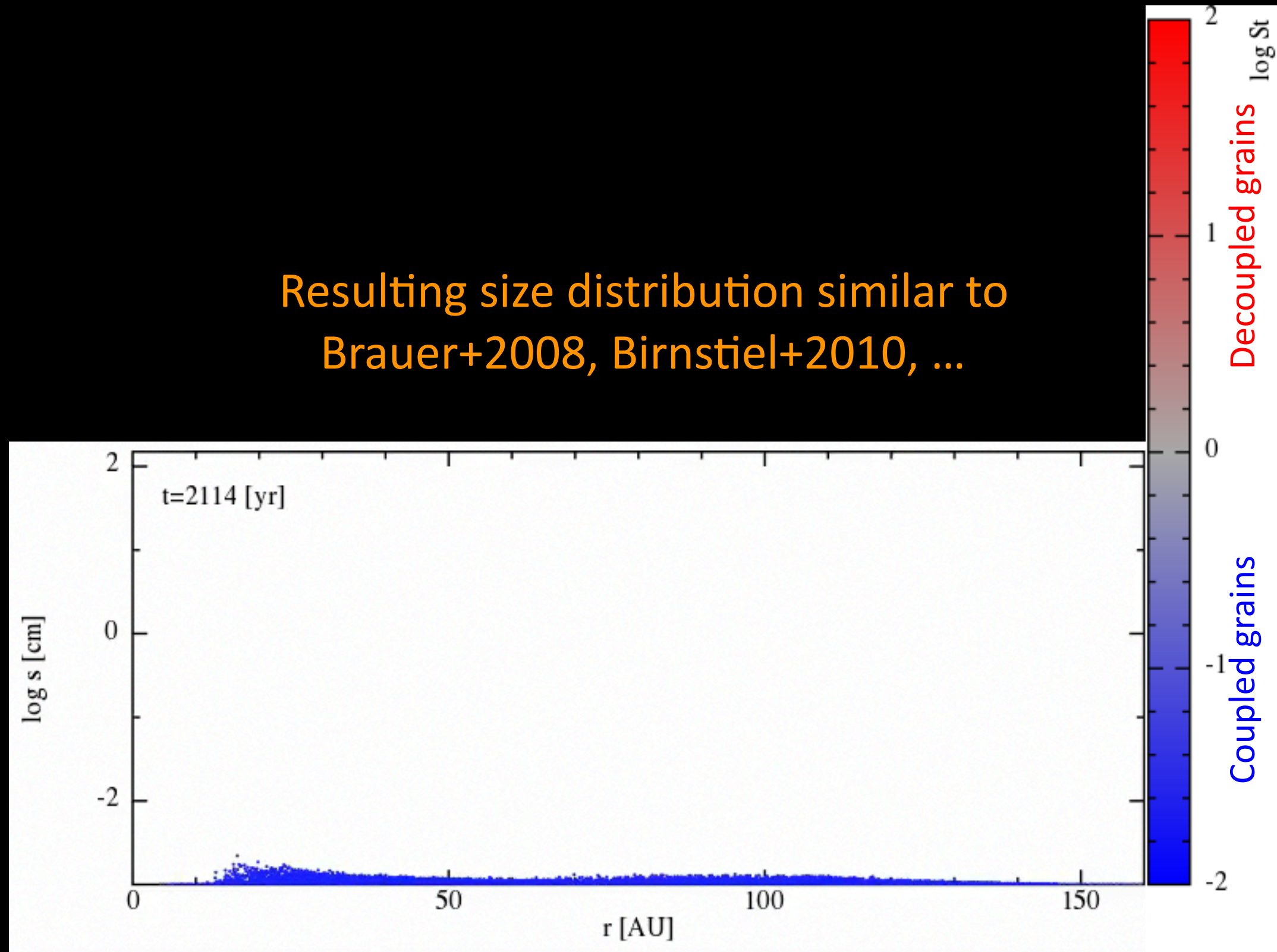
- $V_{\text{frag}} = 10, 15, 20, 25 \text{ m.s}^{-1}$





# Flat disk, $V_{\text{frag}} = 15 \text{ m.s}^{-1}$

Resulting size distribution similar to  
Brauer+2008, Birnstiel+2010, ...



Without backreaction

Gonzalez+2017



# The importance of back-reaction

- Drag of dust on gas

- often neglected when  $\epsilon = \rho_d/\rho_g$  is small
- becomes important when dust **concentrates**
- **slows down** dust radial drift

$$v_{d,r}(z=0) = \frac{\text{St}}{(1+\epsilon)^2 + \text{St}^2} \left(\frac{H}{r}\right)^2 \frac{d \ln P_g}{d \ln r} v_K$$

- **modifies** the gas motion

$$v_{g,r}(z=0) = v_{g,r}^{\text{visc}} - \frac{\epsilon \text{St}}{(1+\epsilon)^2 + \text{St}^2} \left(\frac{H}{r}\right)^2 \frac{d \ln P_g}{d \ln r} v_K$$

- Consequences

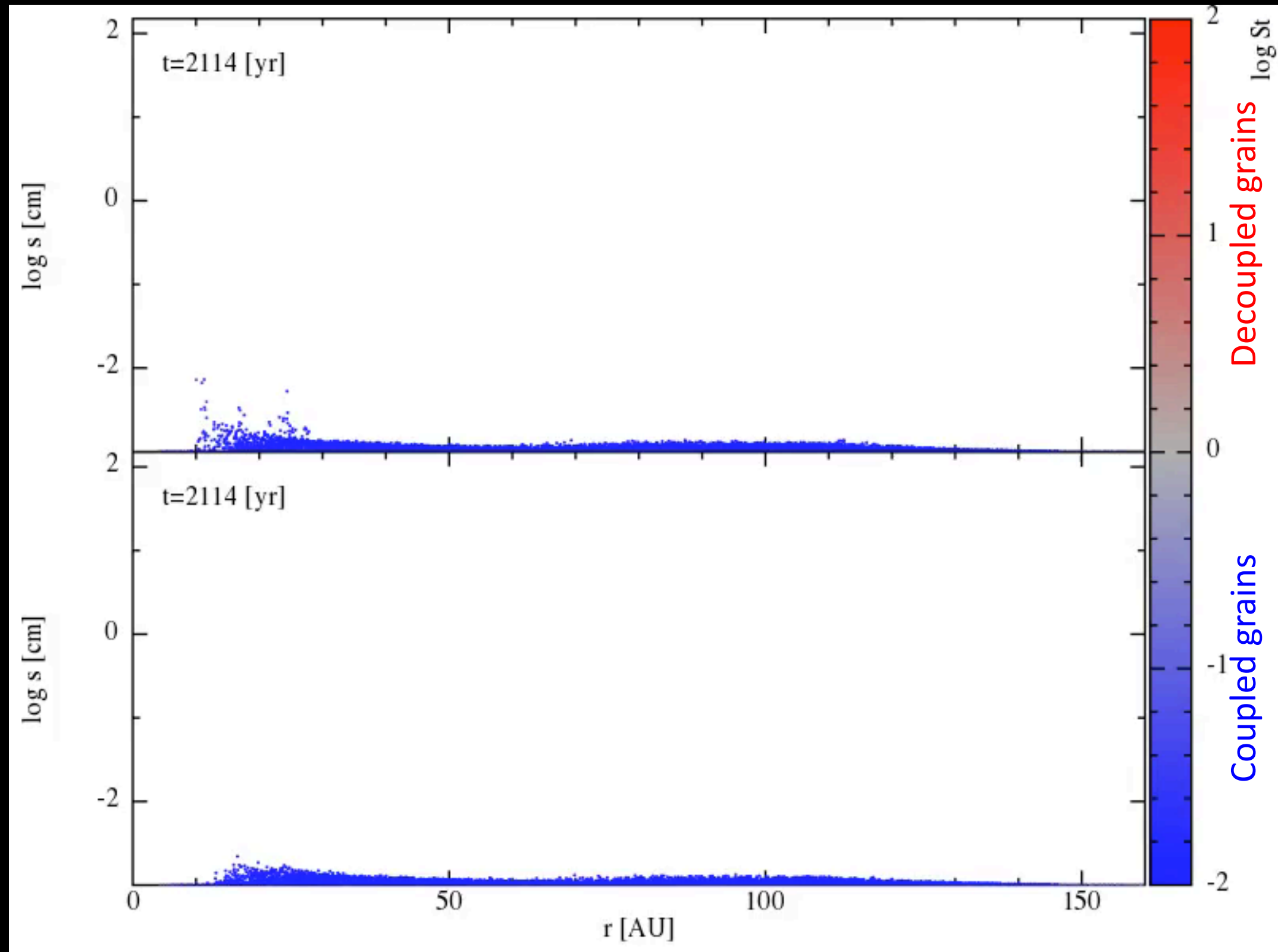
- **Streaming instability**

*Youdin+Goodman2005, Johansen+2007, Bai+Stone2010,  
Yang+Johansen2014, Drążkowska+Dullemond2014*

- **Self-induced dust traps**

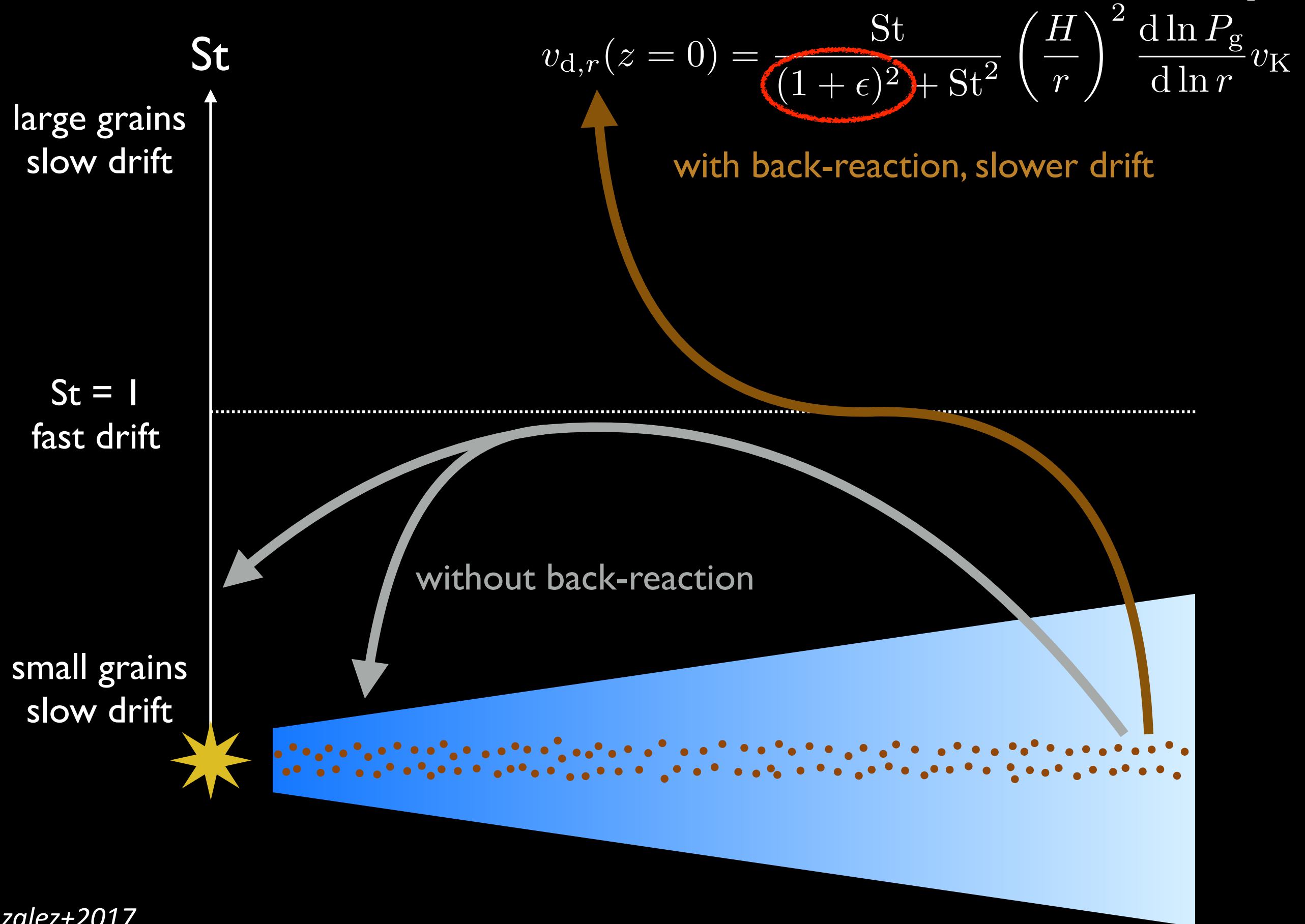
# Flat disk, $V_{\text{frag}} = 15 \text{ m.s}^{-1}$

With backreaction

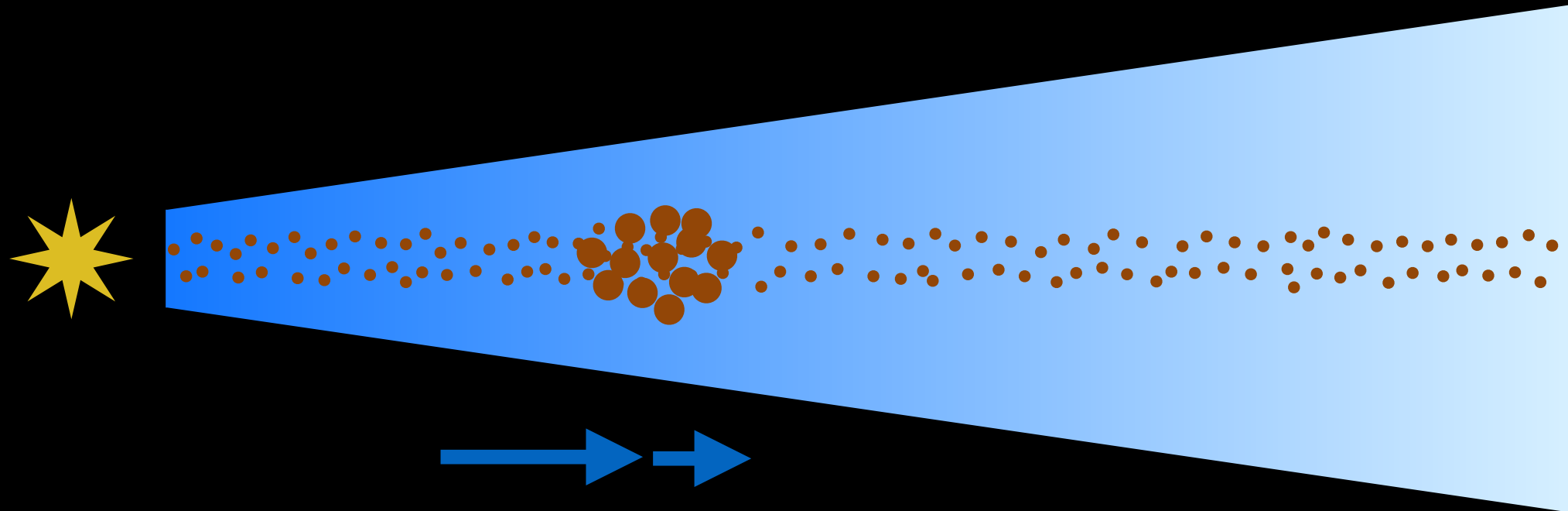


Without backreaction

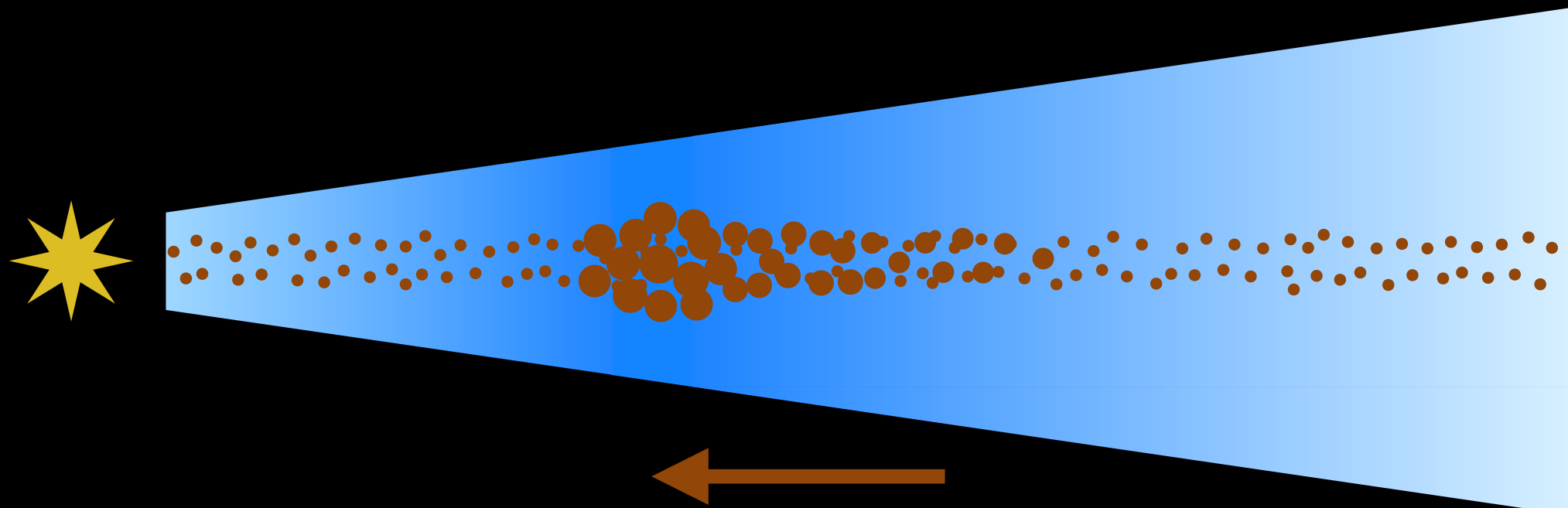
# Formation of the self-induced dust trap



# Formation of the self-induced dust trap

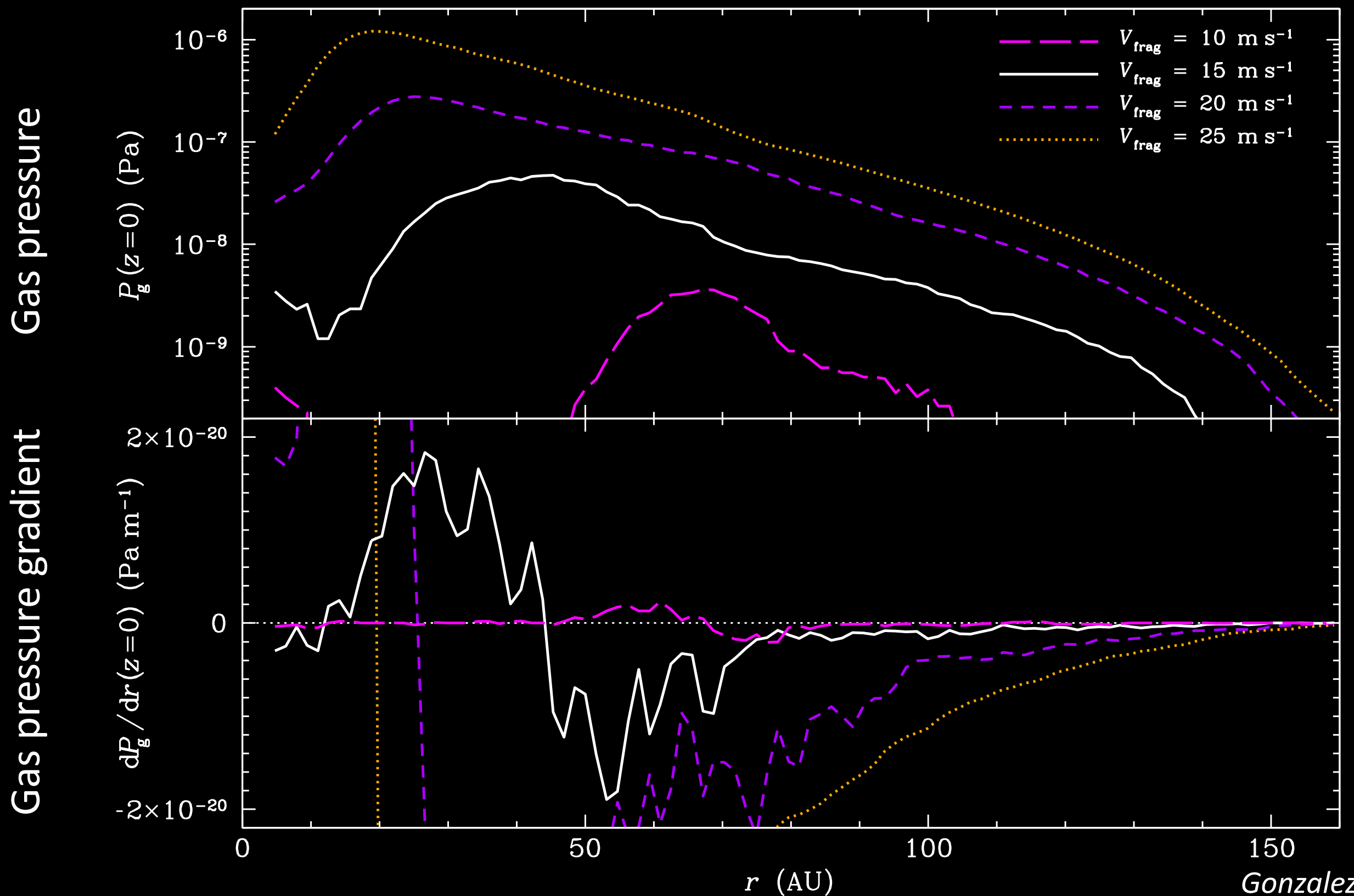


$$v_{g,r}(z=0) = v_{g,r}^{\text{visc}} - \frac{\epsilon \text{St}}{(1+\epsilon)^2 + \text{St}^2} \left(\frac{H}{r}\right)^2 \frac{d \ln P_g}{d \ln r} v_K$$



# Influence of $V_{\text{frag}}$

Pile-up location: largest grains have  $\text{St} \sim 1$  and  $V_{\text{rel}} \sim V_{\text{frag}} \Rightarrow r_{\text{pu}} \propto V_{\text{frag}}^{-2/q}$



# Steep disk

- Setup

- CTTS disk

- $M_{\star} = 1 M_{\odot}, M_{\text{disk}} = 0.01 M_{\odot}$

- $p = 1, q = 1/2$

- $R_{\text{out}} = 400 \text{ AU}$

- $\alpha = 10^{-2}$

- Initial dust/gas ratio

- $\epsilon_0 = 1\%, 3\%, 5\%$ , uniform

- Initial grain size

- $s_0 = 10 \mu\text{m}$ , uniform

- Fragmentation threshold

- $V_{\text{frag}} = 10, 15, 20, 25 \text{ m.s}^{-1}$

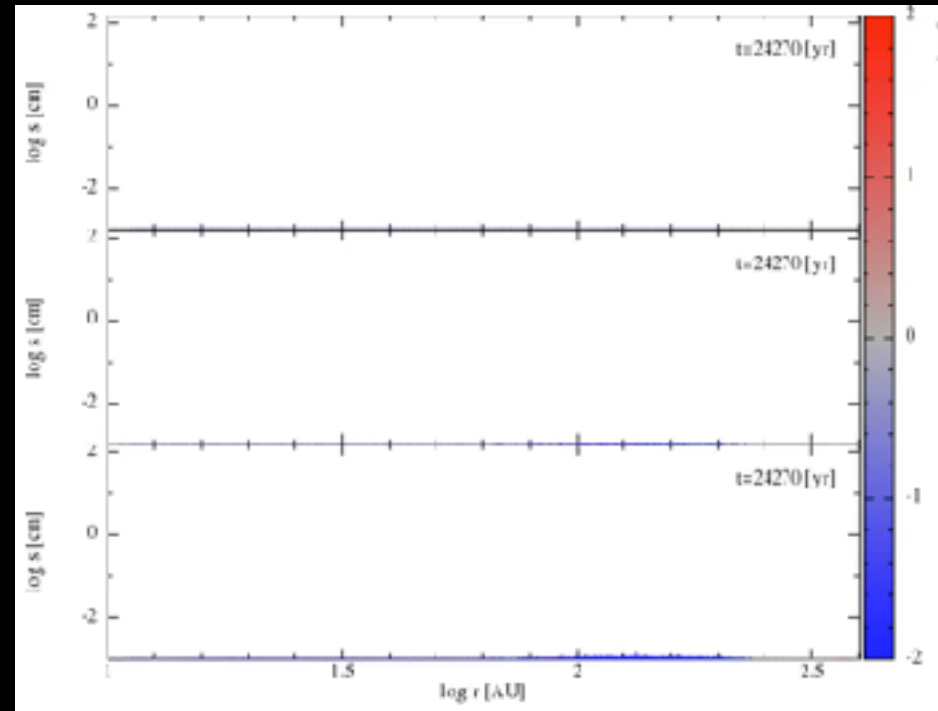
# Steep disk

## Influence of the dust-to-gas ratio

$\epsilon_0 = 1\%$

$\epsilon_0 = 3\%$

$\epsilon_0 = 5\%$



$V_{\text{frag}} = 10 \text{ m.s}^{-1}$

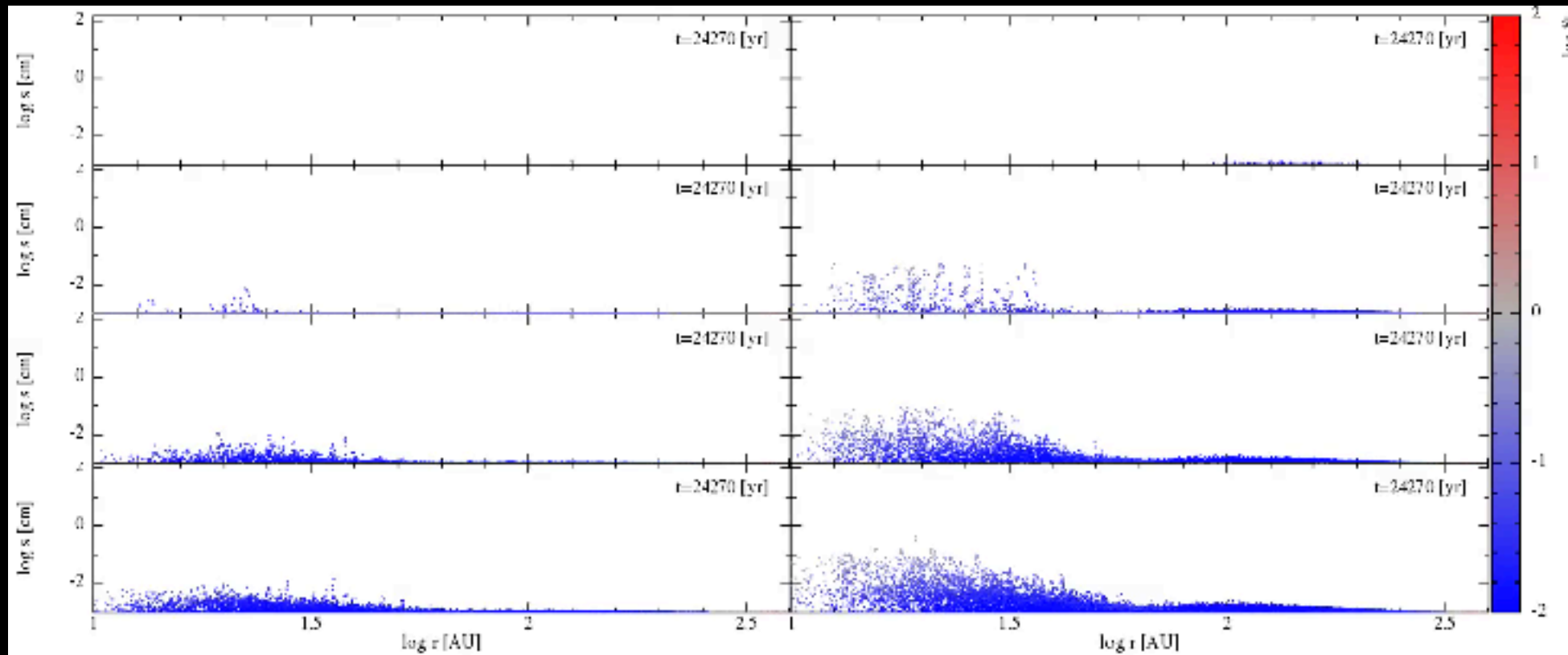
## Influence of the fragmentation threshold

$V_{\text{frag}} = 10 \text{ m.s}^{-1}$

$V_{\text{frag}} = 15 \text{ m.s}^{-1}$

$V_{\text{frag}} = 20 \text{ m.s}^{-1}$

$V_{\text{frag}} = 25 \text{ m.s}^{-1}$

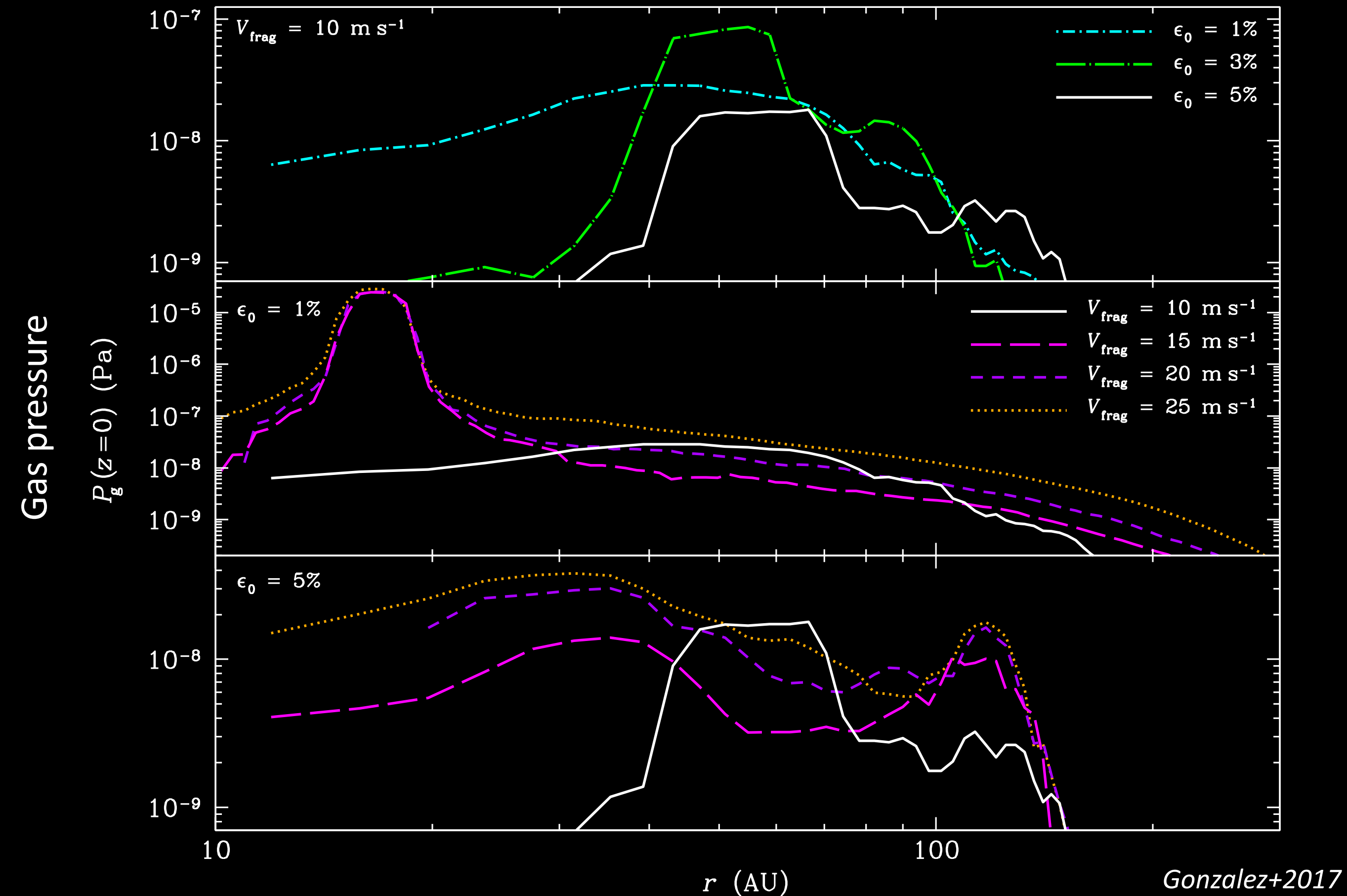


$\epsilon_0 = 1\%$

$\epsilon_0 = 5\%$

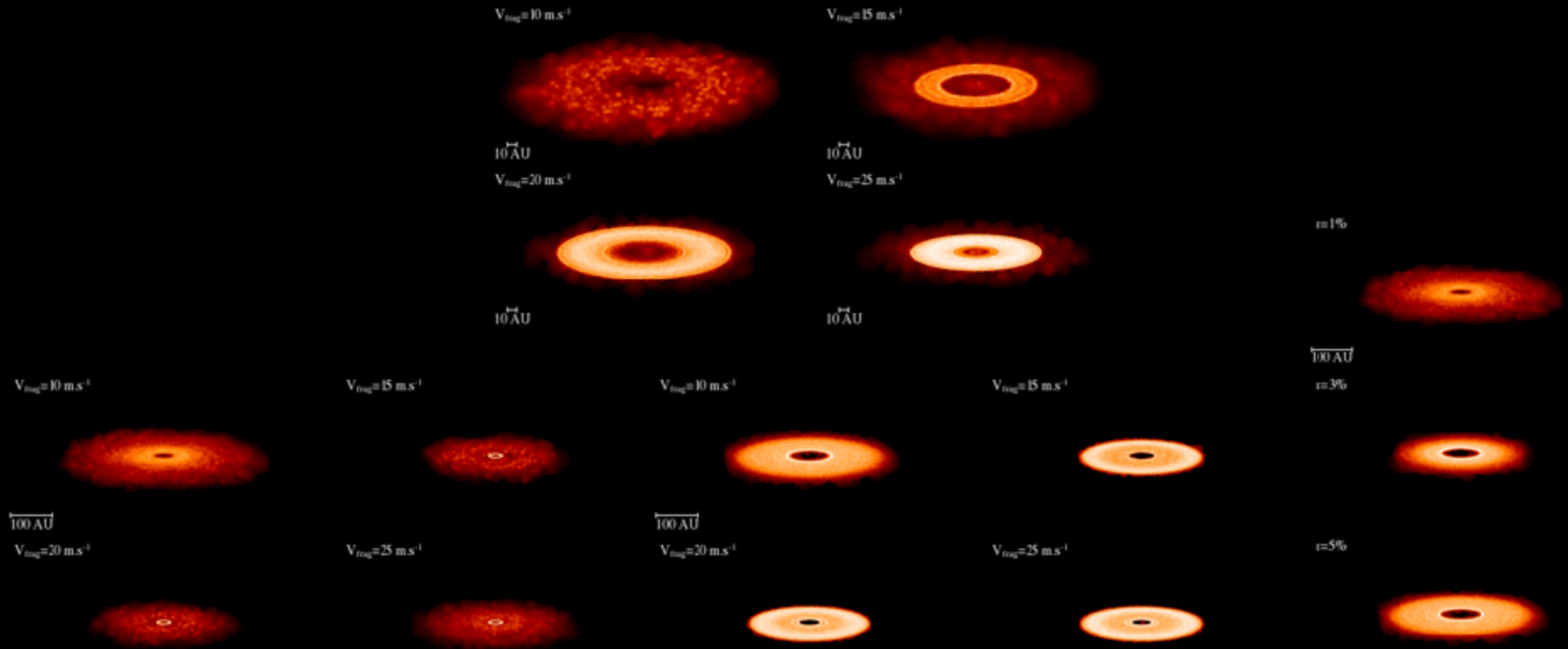


# Pressure maxima in the steep disk



# Conclusion

- Self-induced dust traps: **robust** mechanism
- Traps can cause **rings** and **gaps** in disk images



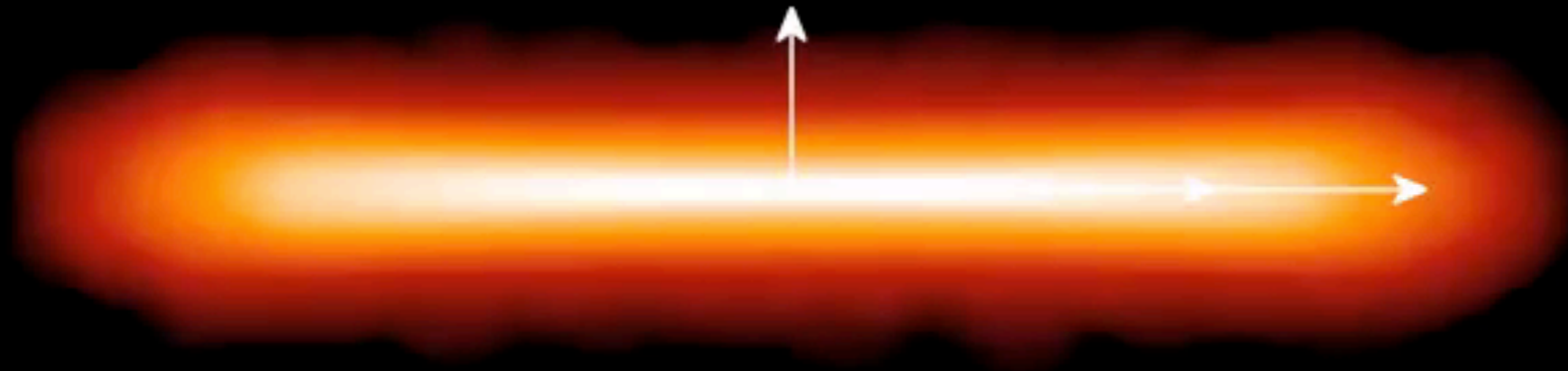
- **Easier** dust growth and planetesimal formation  
 $\Rightarrow$  solution to the **radial-drift** and **fragmentation barriers**
- Influence of **snow lines**  $\Rightarrow$  see **Arnaud's poster**

# Plans

- Switch to **PHANTOM** !
- Add dust **growth** and **fragmentation**
- 1st step: **Stepinski & Valageas formalism, two-fluid**
  - Arnaud's PhD project
- 2nd step: **Smoluchowski equation**
  - Maxime Lombart's PhD project (with Guillaume Laibe)
- Ultimate goal: unify with **multigrain**, in **one-fluid** and **multi-fluid**

$t=2114$  [yr]

# Thank you!



$10 \text{ AU}$