Back-reaction of dust on gas in protoplanetary discs: crucial, yet often overlooked

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Gas and dust dynamics

- Sub-Keplerian gas drags Keplerian dust ⇒ dust settling and drift

$$v_{\mathrm{g},r} = v_{\mathrm{visc}}$$

$$v_{\mathrm{d},r} = \underbrace{\frac{\mathrm{St}}{1+\mathrm{St}^2}\, v_{\mathrm{drift}}}_{\text{dominates for } \mathrm{St} \gg \alpha} + \underbrace{\frac{1}{1+\mathrm{St}^2}\, v_{\mathrm{visc}}}_{\text{dominates for } \mathrm{St} \ll \alpha}$$

where $v_{\mathrm{drift}} = \frac{1}{\rho_{\mathrm{g}}\Omega_{\mathrm{K}}}\frac{\partial P_{\mathrm{g}}}{\partial r} = \left(\frac{H}{r}\right)^2 \frac{\partial \log P_{\mathrm{g}}}{\partial \log r} v_{\mathrm{K}} < 0$ *Nakagawa+1986*

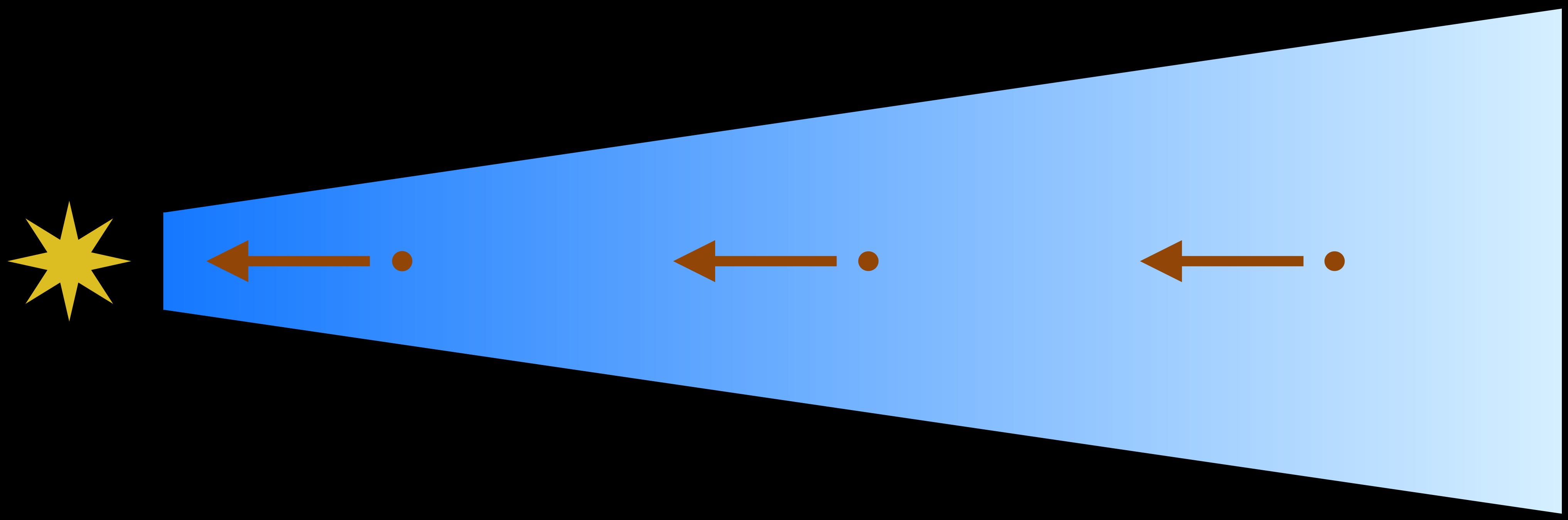
and $v_{\mathrm{visc}} = \frac{\frac{\partial}{\partial r}\left(\rho_{\mathrm{g}}\nu r^3 \frac{\partial \Omega_{\mathrm{K}}}{\partial r}\right)}{r\rho_{\mathrm{g}}\frac{\partial}{\partial r}\left(r^2\Omega_{\mathrm{K}}\right)} < 0$ *Lynden-Bell+Pringle1974*

with $\frac{v_{\mathrm{drift}}}{v_{\mathrm{visc}}} \sim \frac{1}{\alpha}$

- Dust dynamics controlled by the Stokes number $\mathrm{St} = \frac{\Omega_{\mathrm{K}}\rho_{\mathrm{s}} s}{\rho_{\mathrm{g}} c_{\mathrm{s}}}$

The radial drift barrier

$$\mathrm{St} \gg \alpha \Rightarrow v_{\mathrm{d},r} = \frac{\mathrm{St}}{1+\mathrm{St}^2}\left(\frac{H}{r}\right)^2 \frac{\partial \log P_{\mathrm{g}}}{\partial \log r} v_{\mathrm{K}}$$



- St≪1, small sizes (1-10 μm): dust coupled to gas
- St~1, median sizes (100 μm-10 cm): strong influence of gas drag
- St≫1, large sizes (1-10 m): dust insensitive to gas

The importance of back-reaction

- Drag of dust on gas

$$v_{\mathrm{g},r} = -\frac{\epsilon \mathrm{St}}{(1+\epsilon)^2 + \mathrm{St}^2} v_{\mathrm{drift}} + \frac{1+\epsilon+\mathrm{St}^2}{(1+\epsilon)^2 + \mathrm{St}^2} v_{\mathrm{visc}}$$

$$v_{\mathrm{d},r} = \frac{\mathrm{St}}{(1+\epsilon)^2 + \mathrm{St}^2} v_{\mathrm{drift}} + \frac{1+\epsilon}{(1+\epsilon)^2 + \mathrm{St}^2} v_{\mathrm{visc}}$$

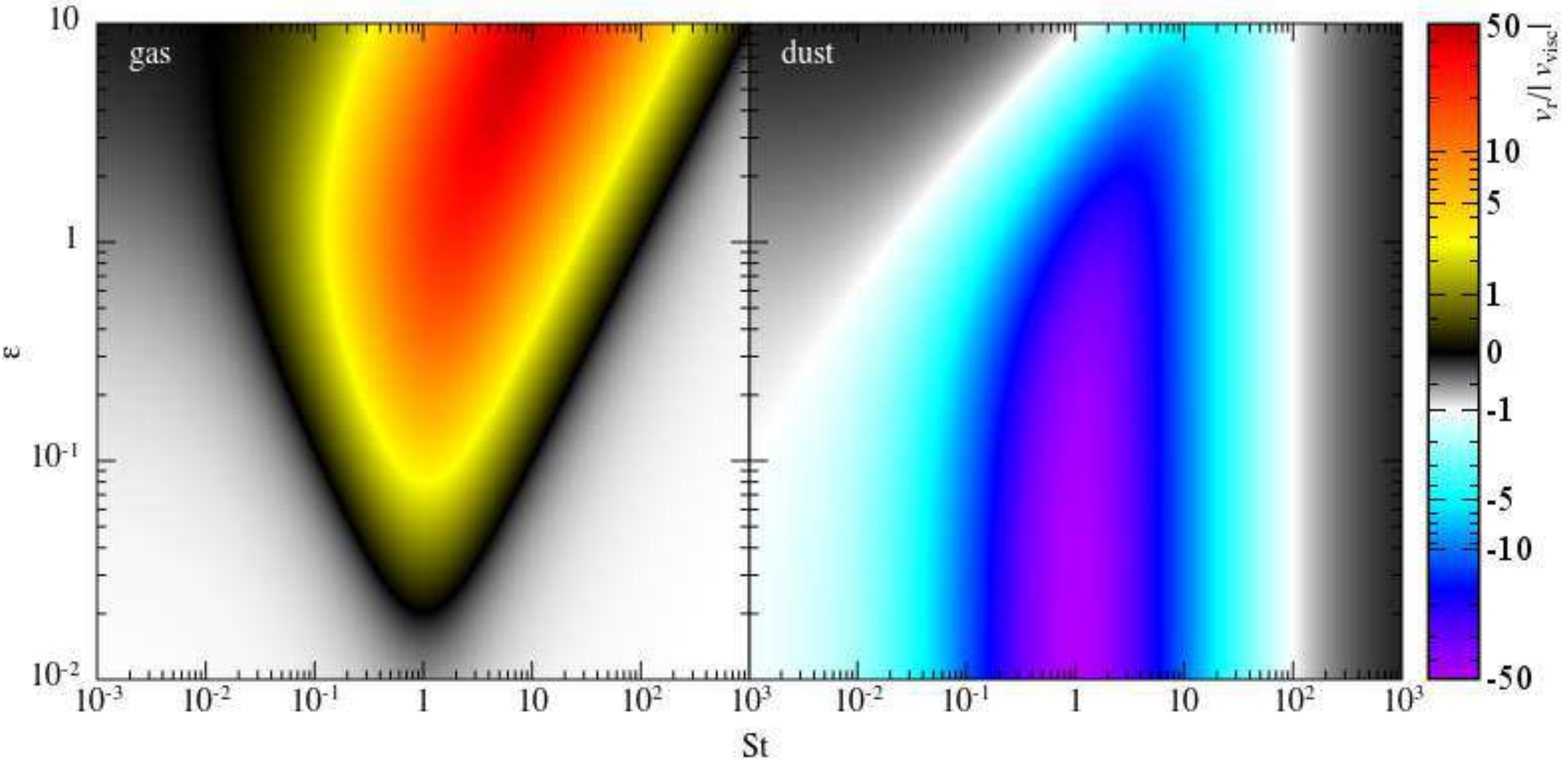
Kanagawa+2017, Dipierro+Laibe2017

  - slows down dust radial drift
  - modifies the gas motion

- Consequences
  - Streaming instability — *Youdin+Goodman2005, Johansen+2007, Bai+Stone2010, Yang+Johansen2014, Drążkowska+Dullemond2014*
  - Self-induced dust traps — *Gonzalez+2017a,b*
  - …

Gas and dust radial velocities

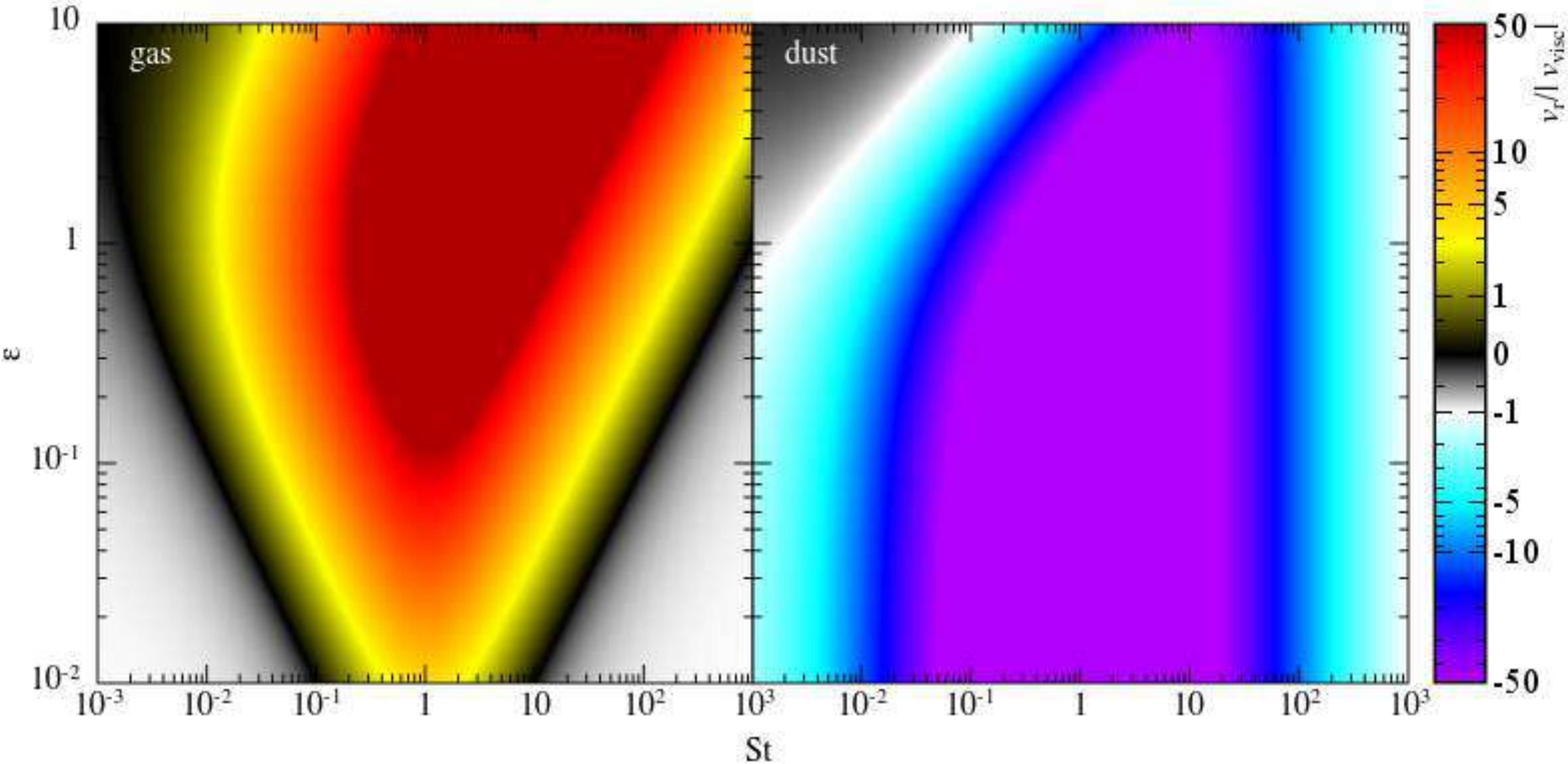
Maps of $\frac{v_r}{|v_{\mathrm{visc}}|}$



α = 10^{-2}

Gas and dust radial velocities

Maps of $\frac{v_r}{|v_{\rm visc}|}$



$\alpha = 10^{-3}$

Power-law disk

$$\Sigma_{\rm g} = \Sigma_0 \left(\frac{r}{r_0}\right)^{-p} \qquad\qquad T = T_0 \left(\frac{r}{r_0}\right)^{-q}$$

$$v_{\rm drift} = -(p+q)\frac{\nu_0}{r_0}\left(\frac{r}{r_0}\right)^{1/2-q}$$

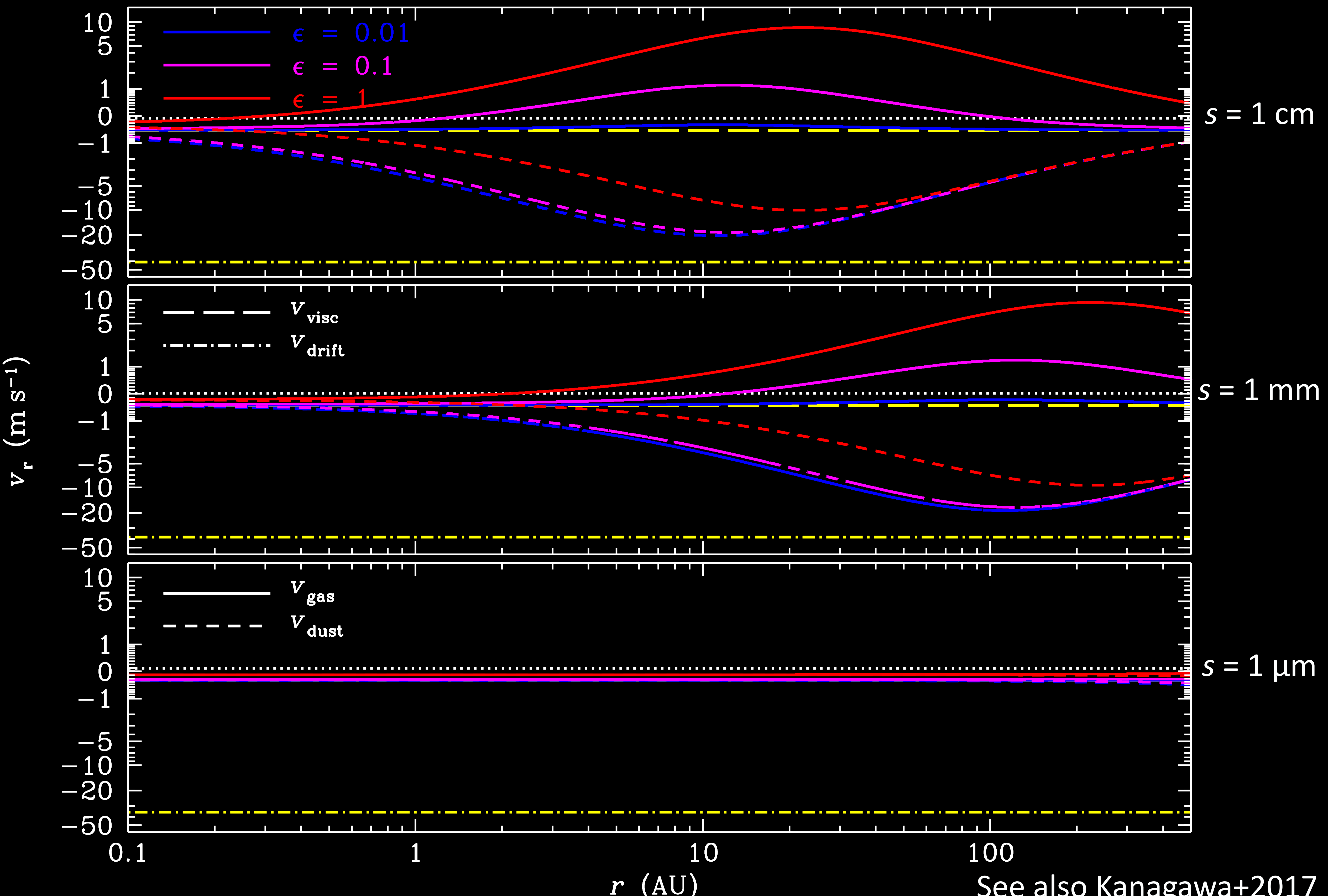
$$\frac{v_{\rm drift}}{v_{\rm visc}} = \frac{p+q}{3(2-p-q)}\frac{1}{\alpha}$$

$$v_{\rm visc} = -3(2-p-q)\frac{\nu_0}{r_0}\,\alpha\left(\frac{r}{r_0}\right)^{1/2-q}$$

$$p=1,\ q=1/2 \ \Rightarrow\ v_{\rm drift},\, v_{\rm visc} = \mathrm{cst};\ \ \frac{v_{\rm drift}}{v_{\rm visc}} = \frac{1}{\alpha}$$

Power-law disk

p = 1, q = 1/2, α = 10^{-2}

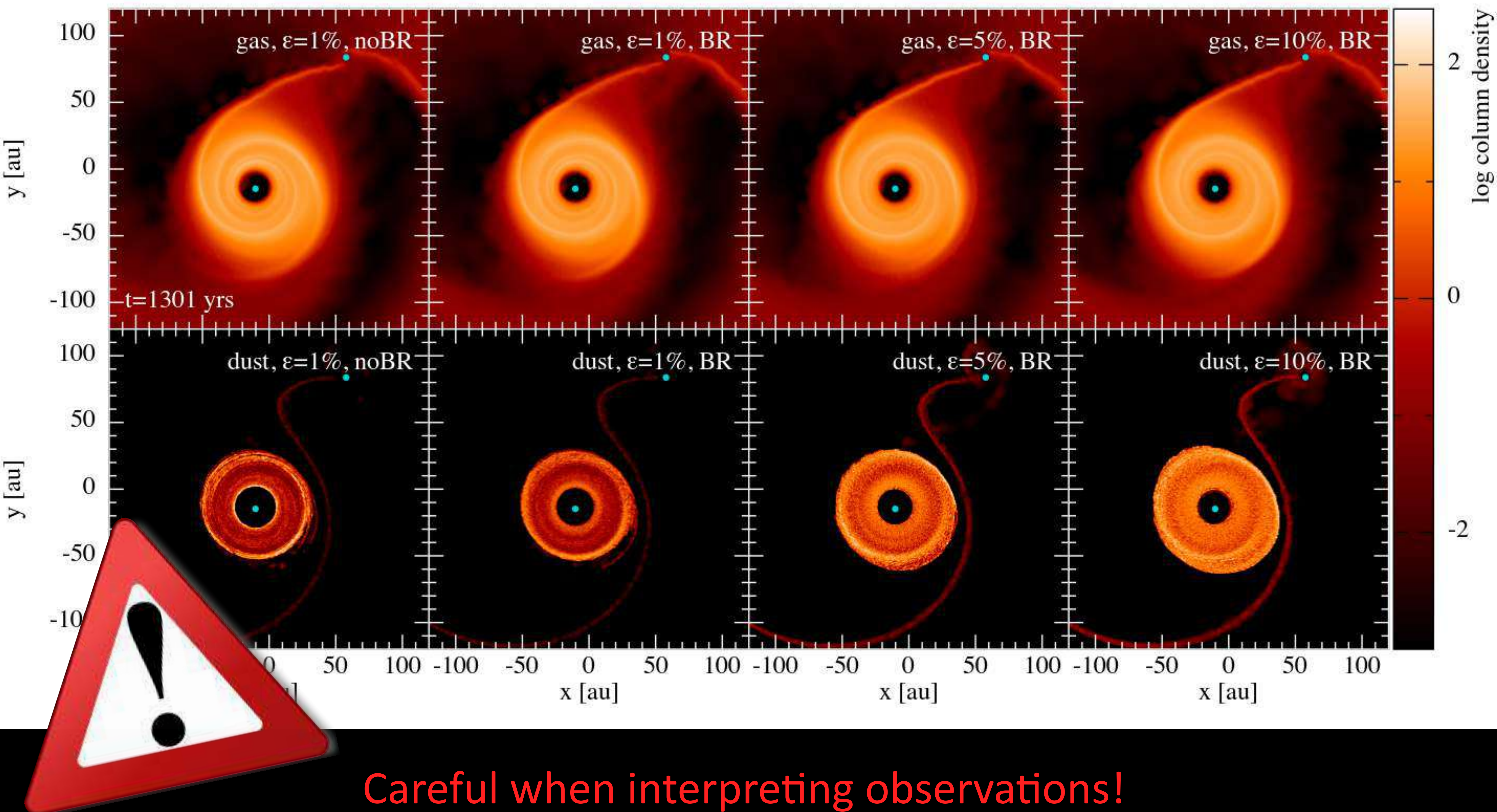


See also Kanagawa+2017

Practical case: a circumprimary disc in a binary star system

v1.1

gas + 1 mm grains, two-fluid

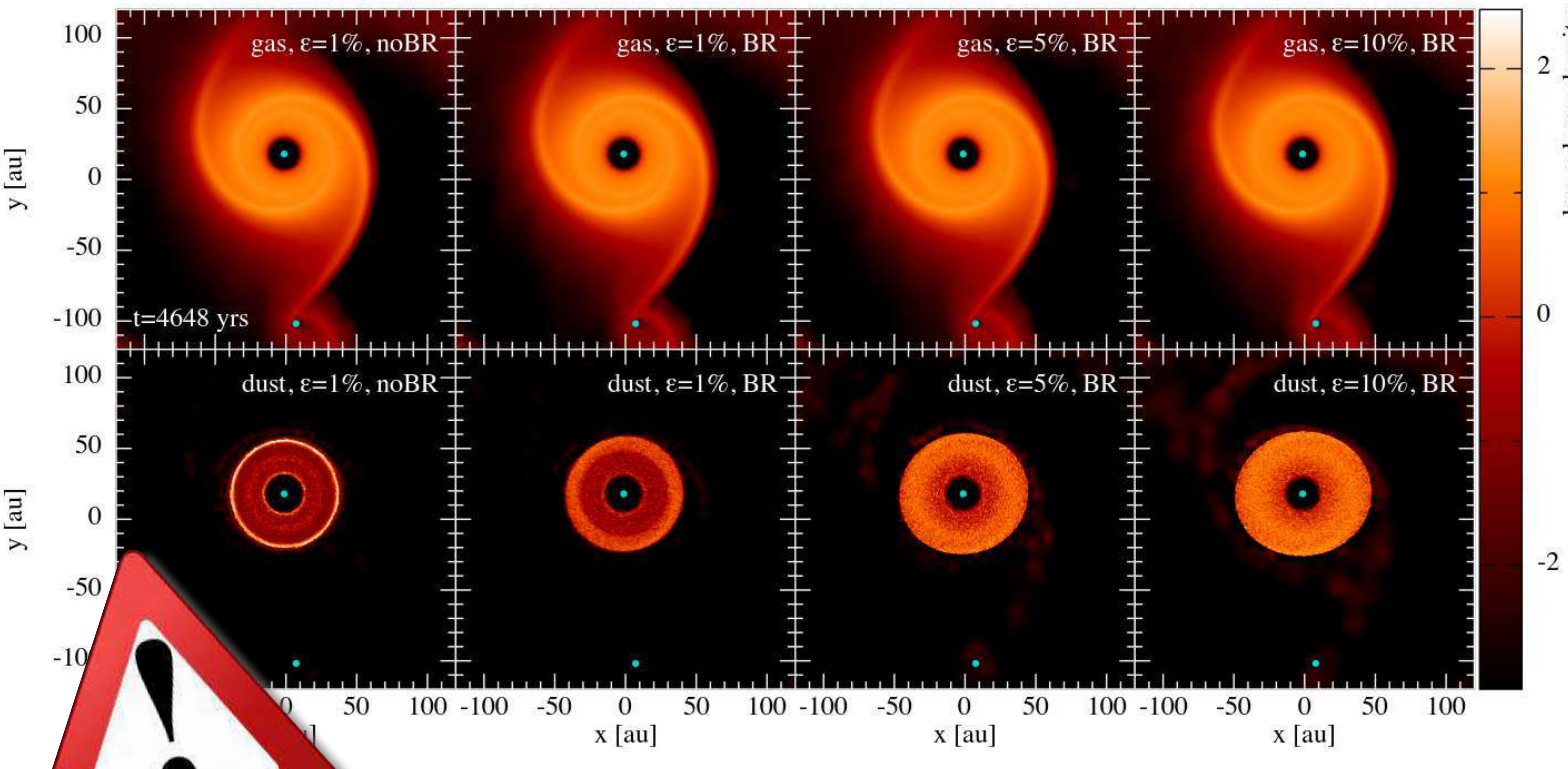


Careful when interpreting observations!

Practical case: a circumprimary disc in a binary star system

v0.9

gas + 1 mm grains, two-fluid



Careful when interpreting observations!

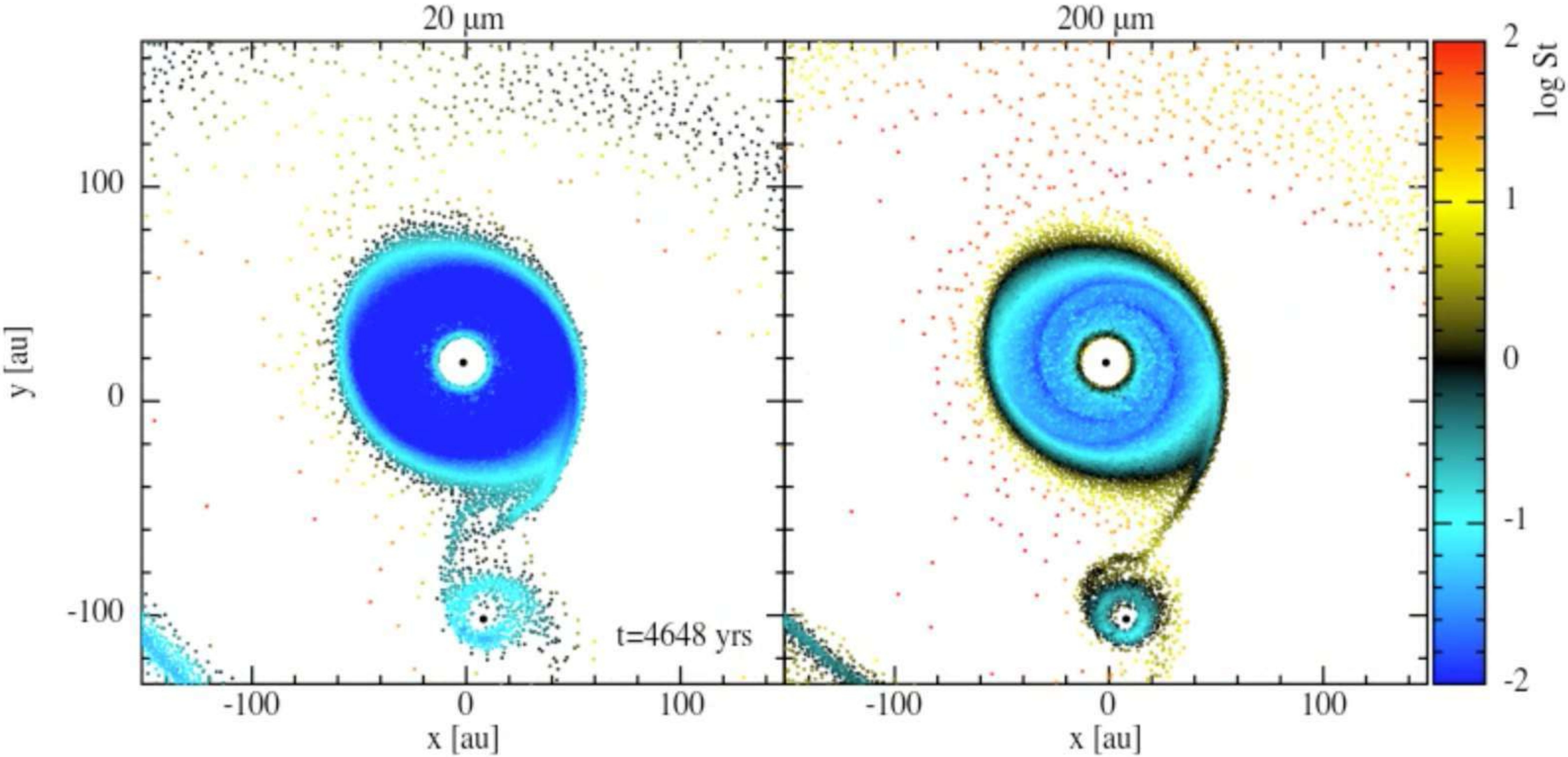
Conclusion

Back-reaction should
NOT
be neglected!

Bonus:

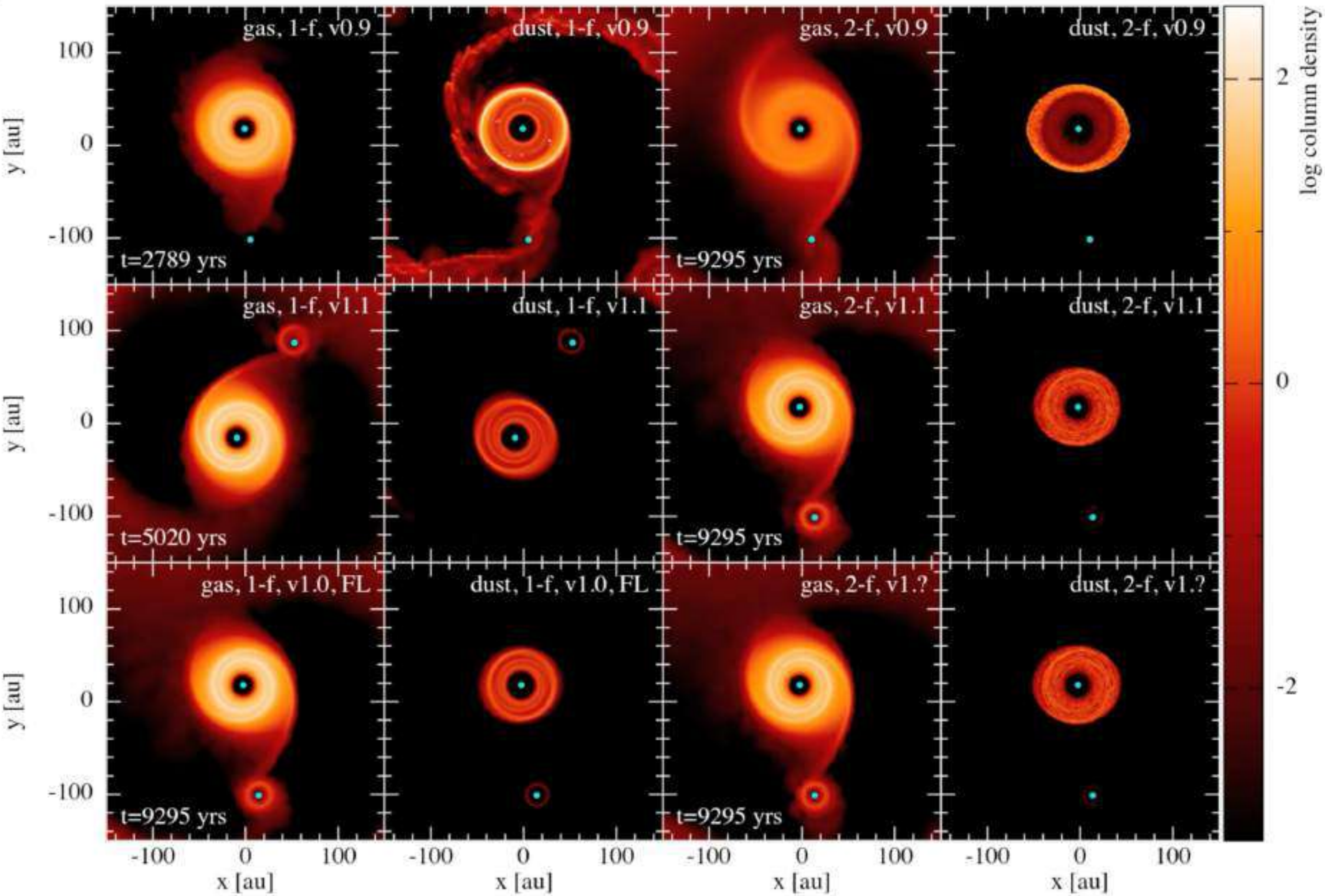
comparing Phantom versions

one-fluid vs. two-fluid



one-fluid vs. two-fluid

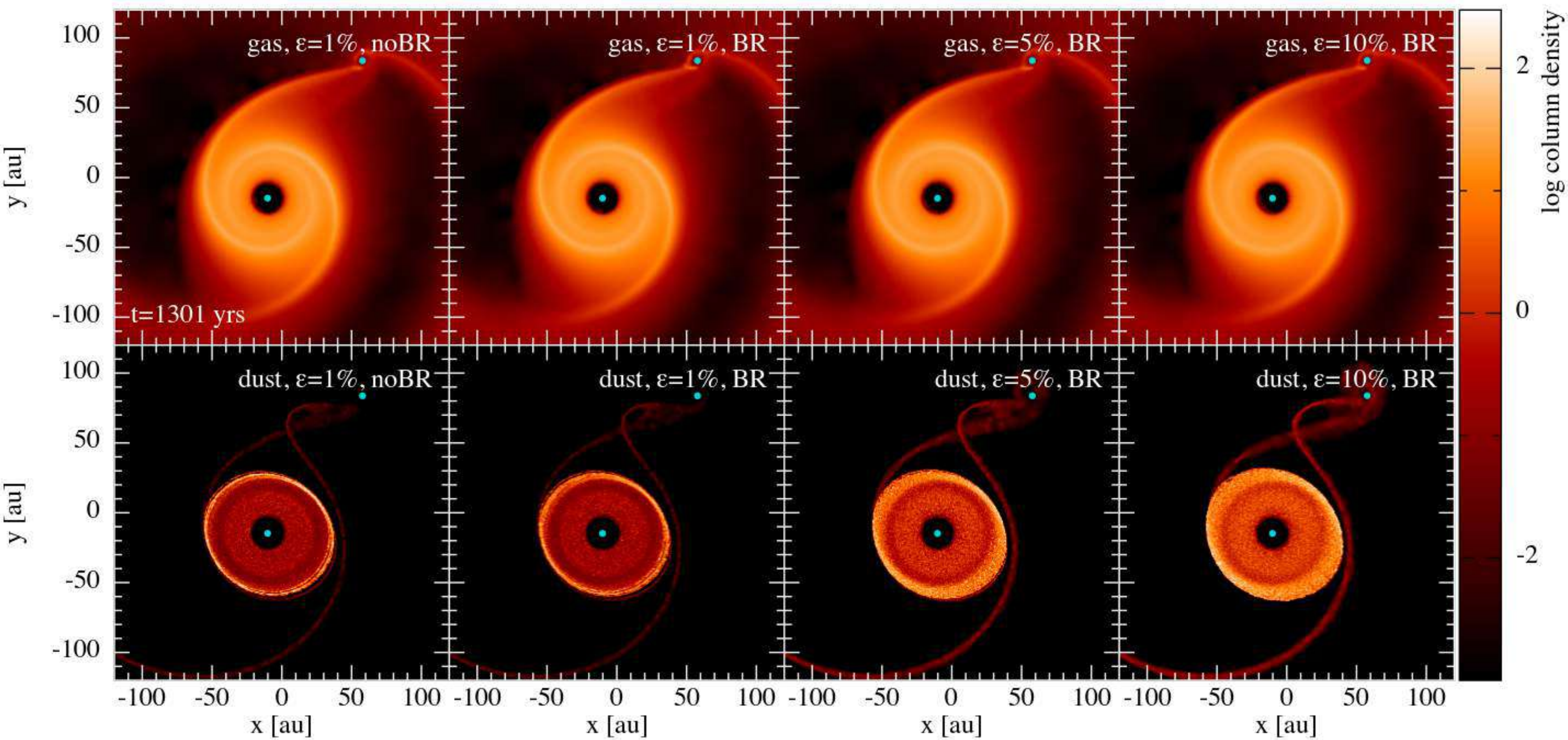
gas + 200 μm grains



v0.9 - pre bug correction

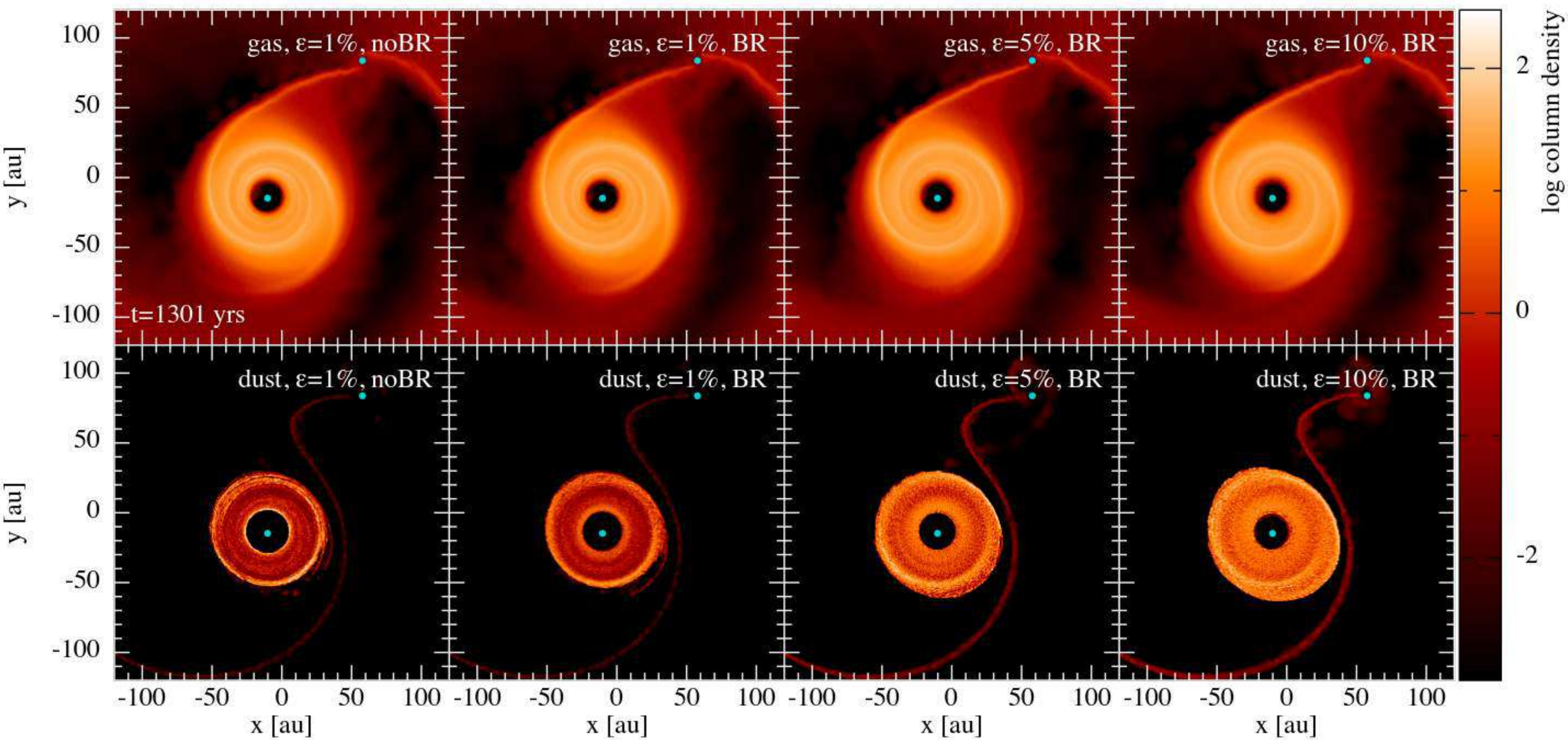
gas + 1 mm grains, two-fluid

v0.9



v1.1 - post bug correction

gas + 1 mm grains, two-fluid



v1.1

get_ts: rhogas instead of rhosum

gas + 1 mm grains, two-fluid

v1.1