On the multiphase nature of galactic magnetised outflows

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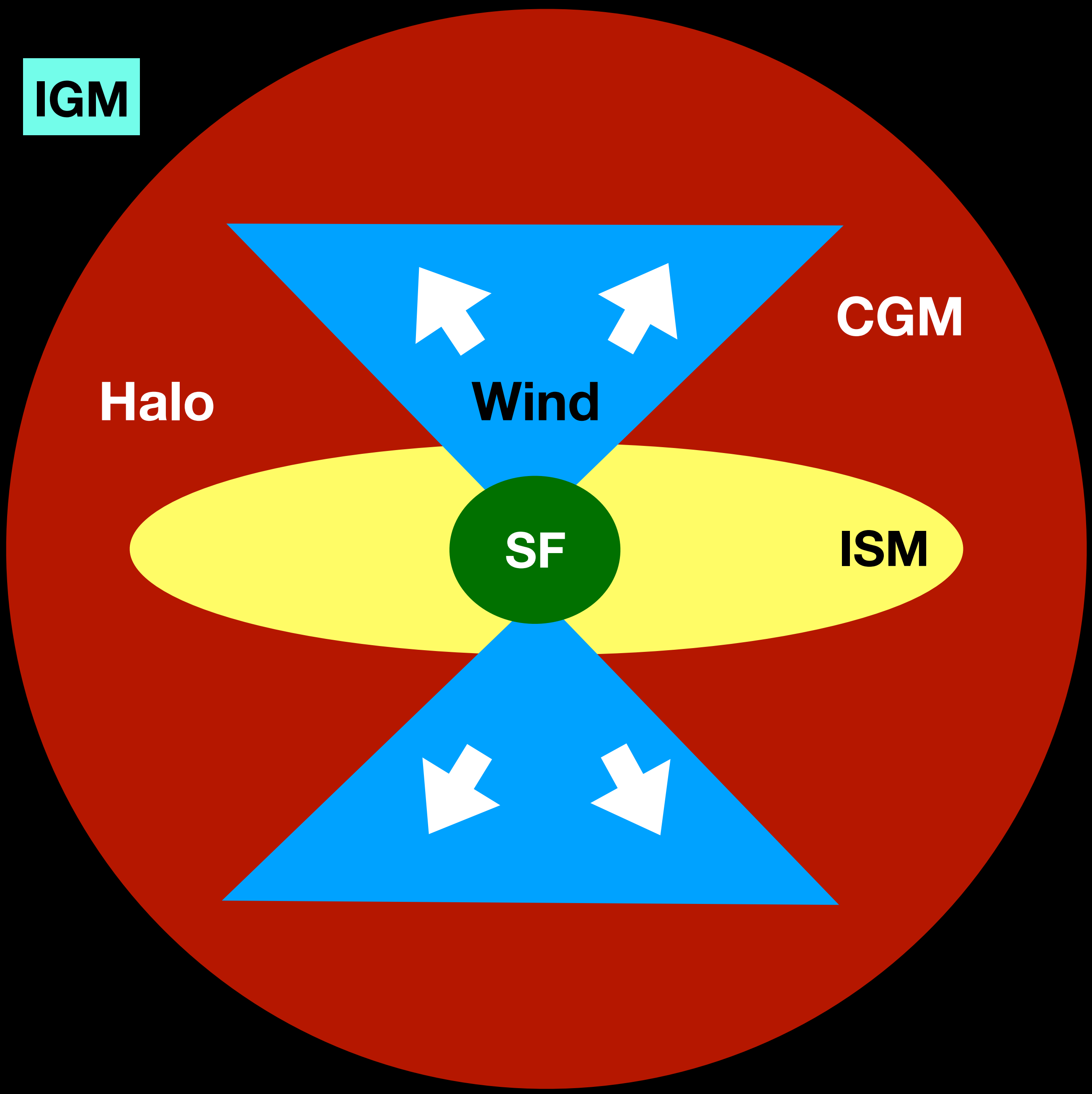
CHALLENGES AND INNOVATIONS IN COMPUTATIONAL ASTROPHYSICS - III

18 June 2021

Stellar-driven galactic winds

Large-scale energy and matter flows that remove material from galaxies.



SF = Star formation
ISM = interstellar medium
CGM = circumgalactic medium
IGM = intergalactic medium

How do stellar-driven winds form?

Supernovae (SNe) / massive stars power galactic winds.

Galactic winds can:

Exchange mass and energy with CGM.

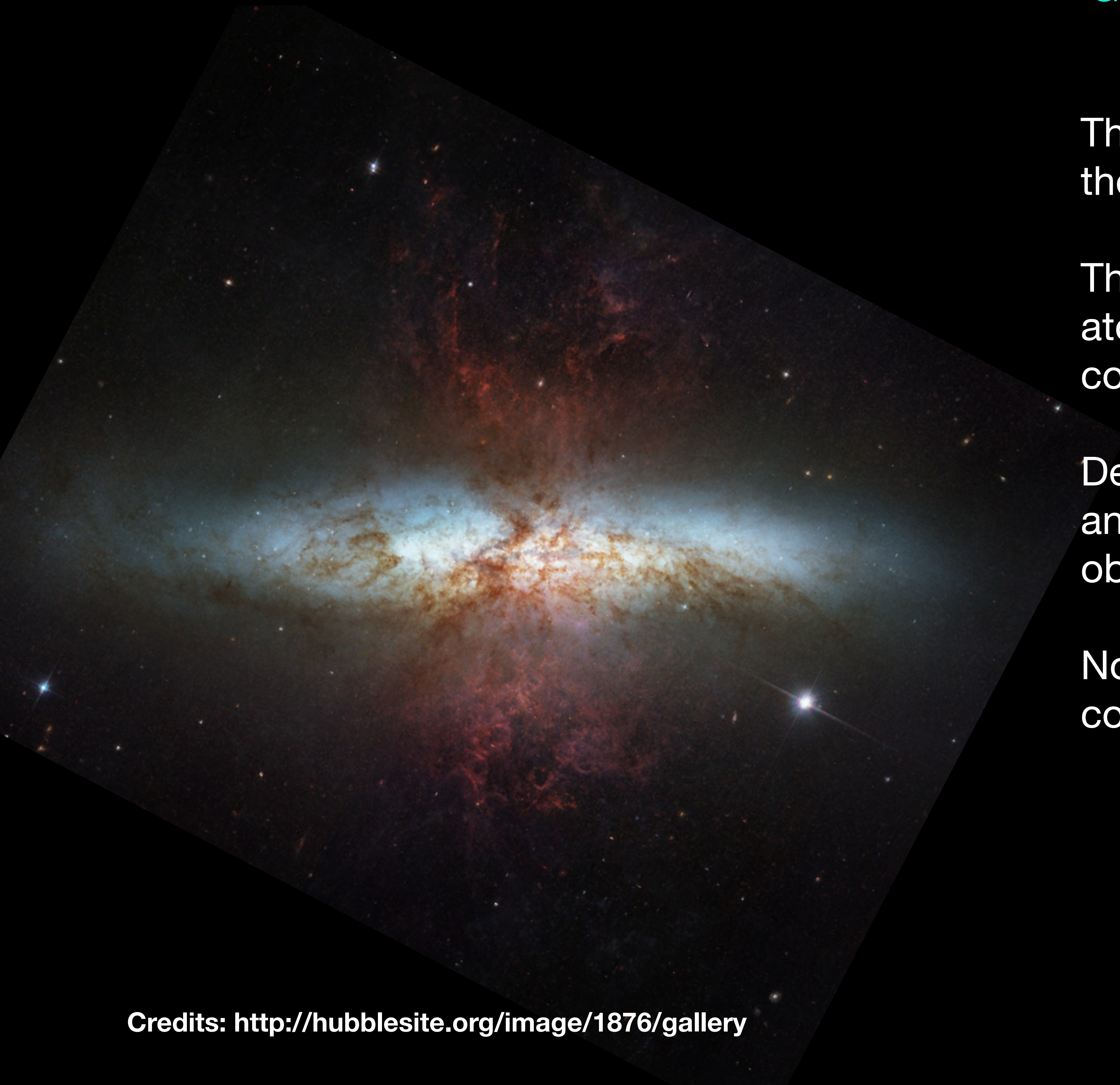
Enrich the CGM with metals.

Regulate star formation.

Influence galaxy evolution.

Stellar-driven galactic winds

The galactic wind in starburst galaxy M82



Credits: http://hubblesite.org/image/1876/gallery

Galactic winds are **multi-phase** and **magnetised:**

They have thermal and non-thermal components

Thermal gas has ionised, atomic, and molecular (+ dust) components.

Detected in both emission line and absorption line observational studies

Non-thermal component: cosmic rays

Stellar-driven galactic winds

The galactic wind in starburst galaxy M82

Clouds are far away from the Galactic plane.

Outflowing speeds of a few 100’s km/s.

Key questions

How can gas phases with different temperatures co-exist?

What is the origin of dense (atomic/molecular) clouds and filaments?

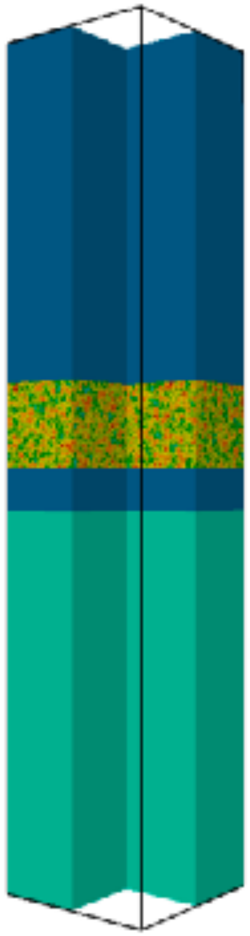
How does dense gas reach large distances and high velocities?

Issue

It is hard to accelerate dense gas owing to its large column densities and the emergence of instabilities.

Numerical MHD simulations

Medium-scale shock-cloud models



Banda-Barragán et. al 2020a,b

Part I:
No radiative processes

Part II:
+ radiative processes

Part III:
+ magnetic fields

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

Momentum conservation:

$$\frac{\partial [\rho \boldsymbol{v}]}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I}P] = 0,$$

Energy conservation:

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\,\boldsymbol{v} - \boldsymbol{B}\,(\boldsymbol{v} \cdot \boldsymbol{B})] = \Gamma - \Lambda,$$

Cooling & heating terms

Induction equation + solenoidal condition:

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0, \qquad \nabla \cdot \boldsymbol{B} = 0$$

Equation of state:

$$P_{\rm th} = P_{\rm th}(\rho, \epsilon) = (\gamma - 1)\,\rho\epsilon.$$

$$\gamma = \frac{5}{3}$$

$$P = P_{\rm th} + P_{\rm mag}$$

$$E = \rho\epsilon + \frac{1}{2}\rho \boldsymbol{v}^{2} + \frac{1}{2}|\boldsymbol{B}|^{2}$$

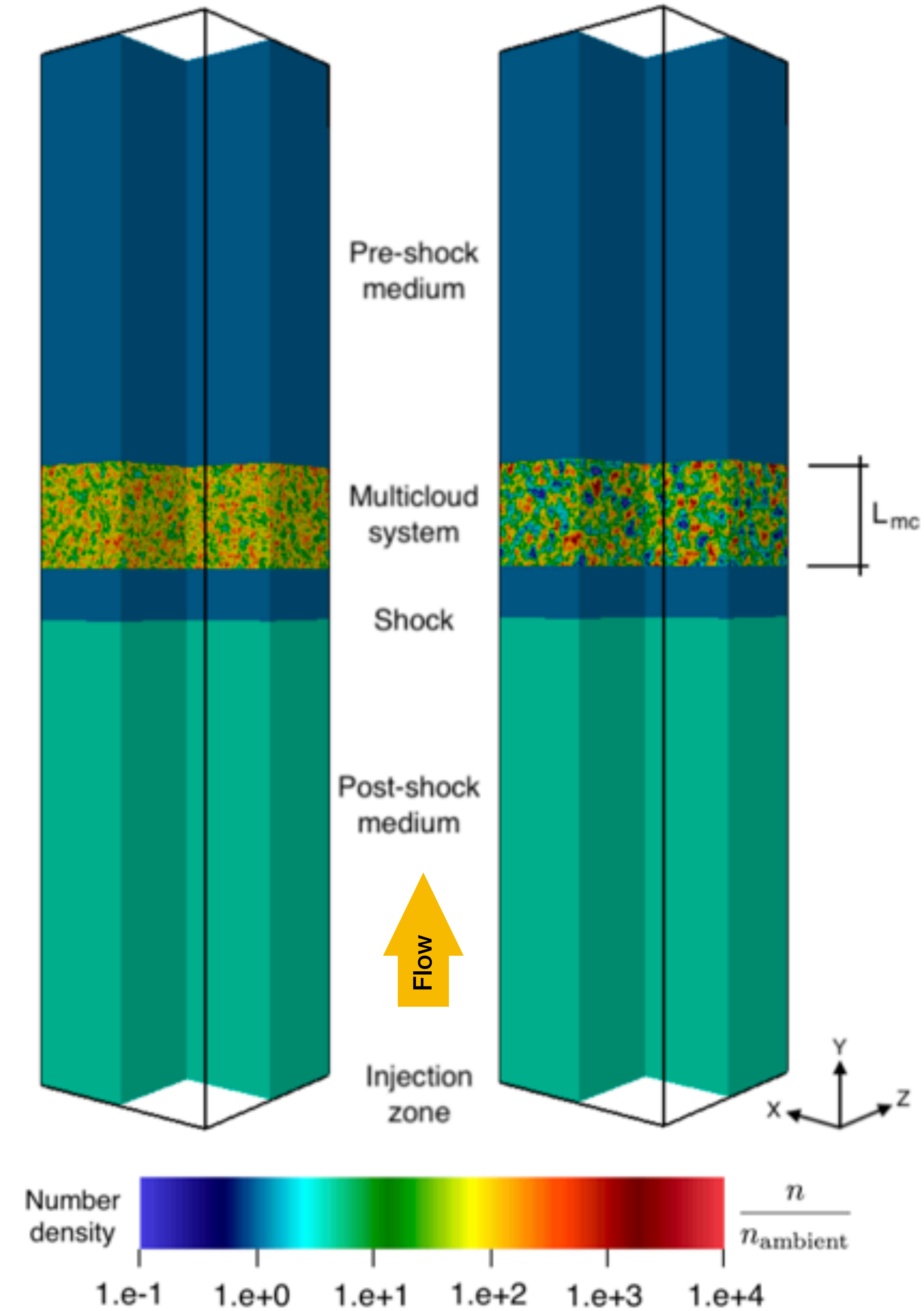
Codes:

Pluto v4.3
(Mignone et. al. 2007)

pyFC (Wagner, A.)

What is the role of the initial density distribution?

Compact layers | **Porous layers**



Banda-Barragán et. al 2020a (arXiv:2009.07718)

Shock Mach number:

$$\mathcal{M}_{\rm shock} = \frac{|\boldsymbol{v}_{\rm shock}|}{c_{\rm ambient}} = 10$$

Plasma beta (MHD):

$$\beta = \frac{P_{\rm th}}{P_{\rm mag}} = \frac{P_{\rm th}}{\frac{1}{2}|\boldsymbol{B}|^2}$$

Density contrast:

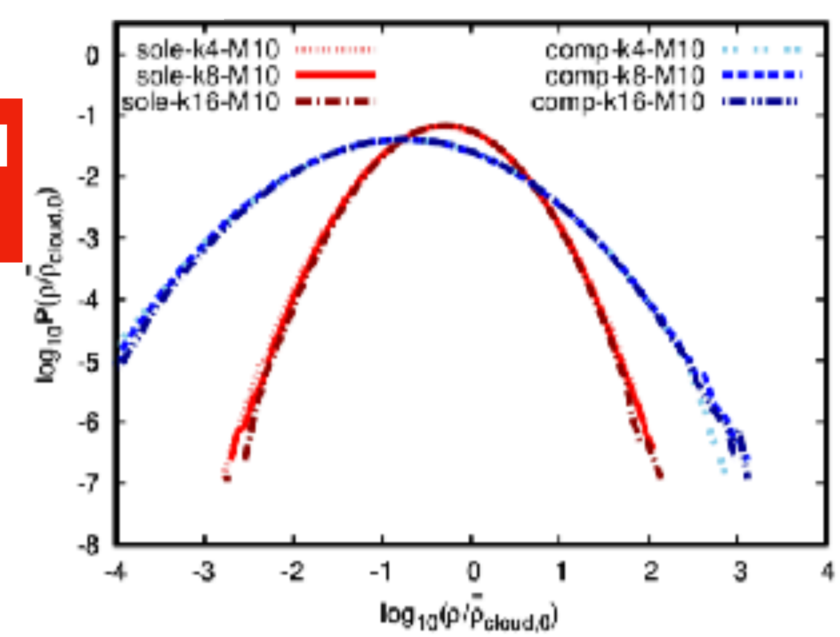
$$\chi = \frac{\bar{\rho}_{\rm cloud,0}}{\rho_{\rm ambient}} = \frac{\bar{n}_{\rm cloud,0}}{n_{\rm ambient}} = 10^2$$

Log-normal density fields (PDFs):

$$\sigma_{\rm cloud} = \frac{\sigma_{\rho_{\rm cloud,0}}}{\bar{\rho}_{\rm cloud,0}} = 1.9 \text{ or } 5.9$$

Compressive Porous

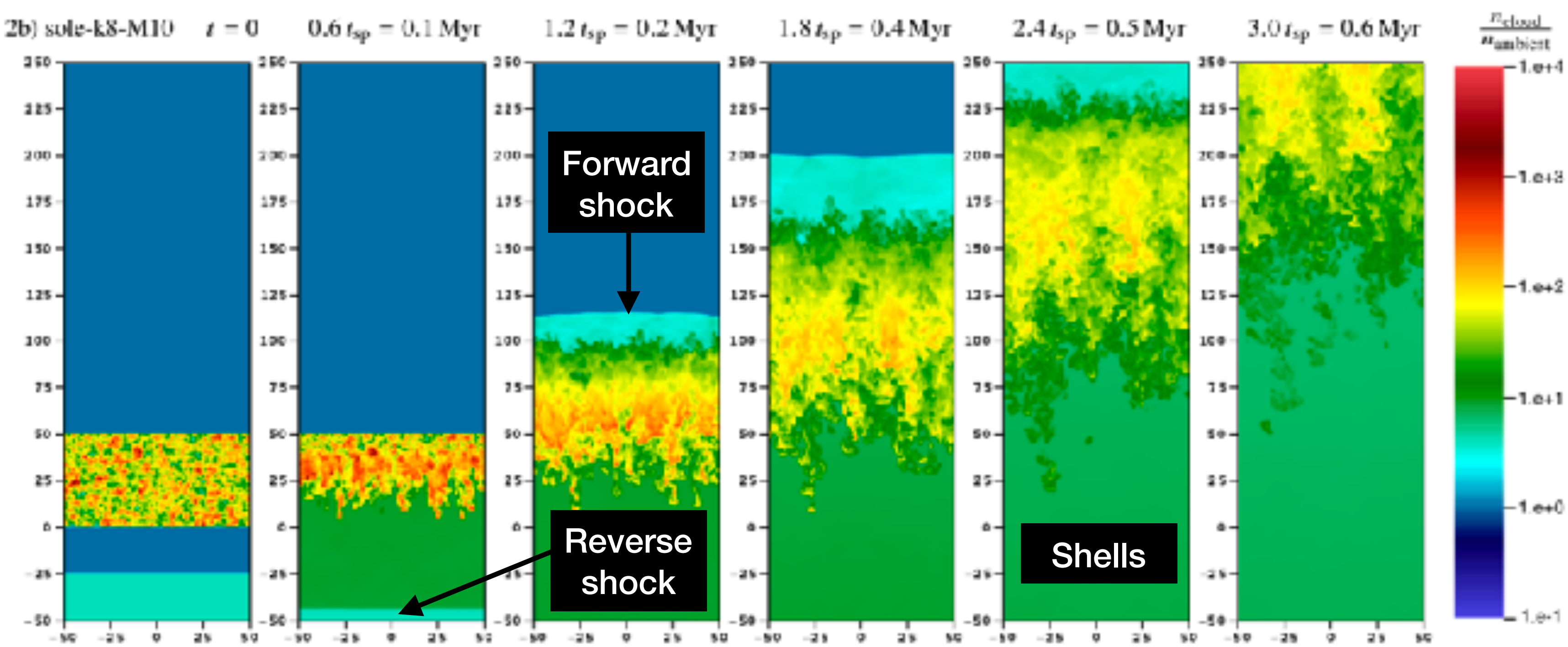
Solenoidal Compact



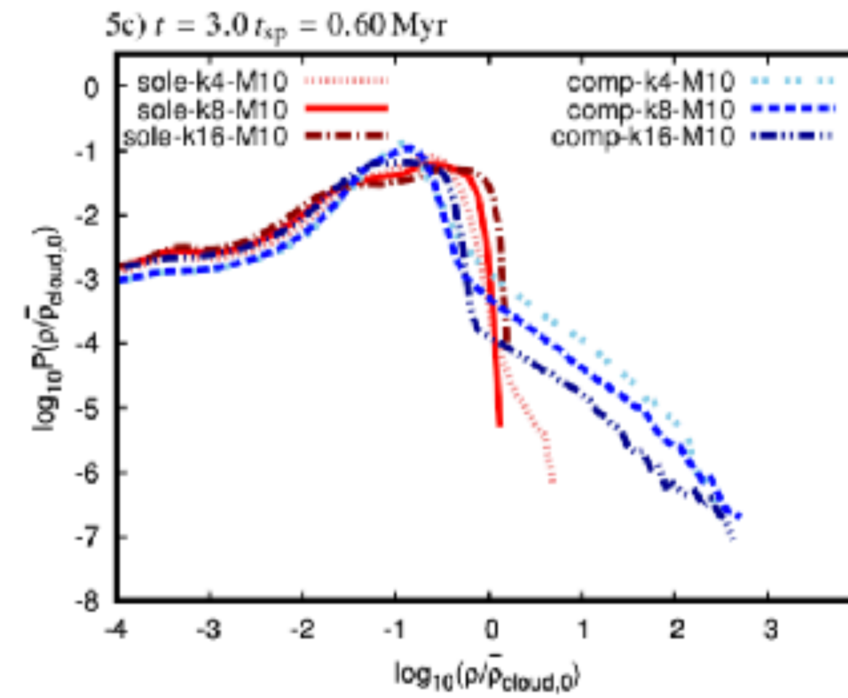
Part I: Models without radiative heating/cooling

$t_{sp} \equiv$ shock passage time

Compact 'solenoidal' layers

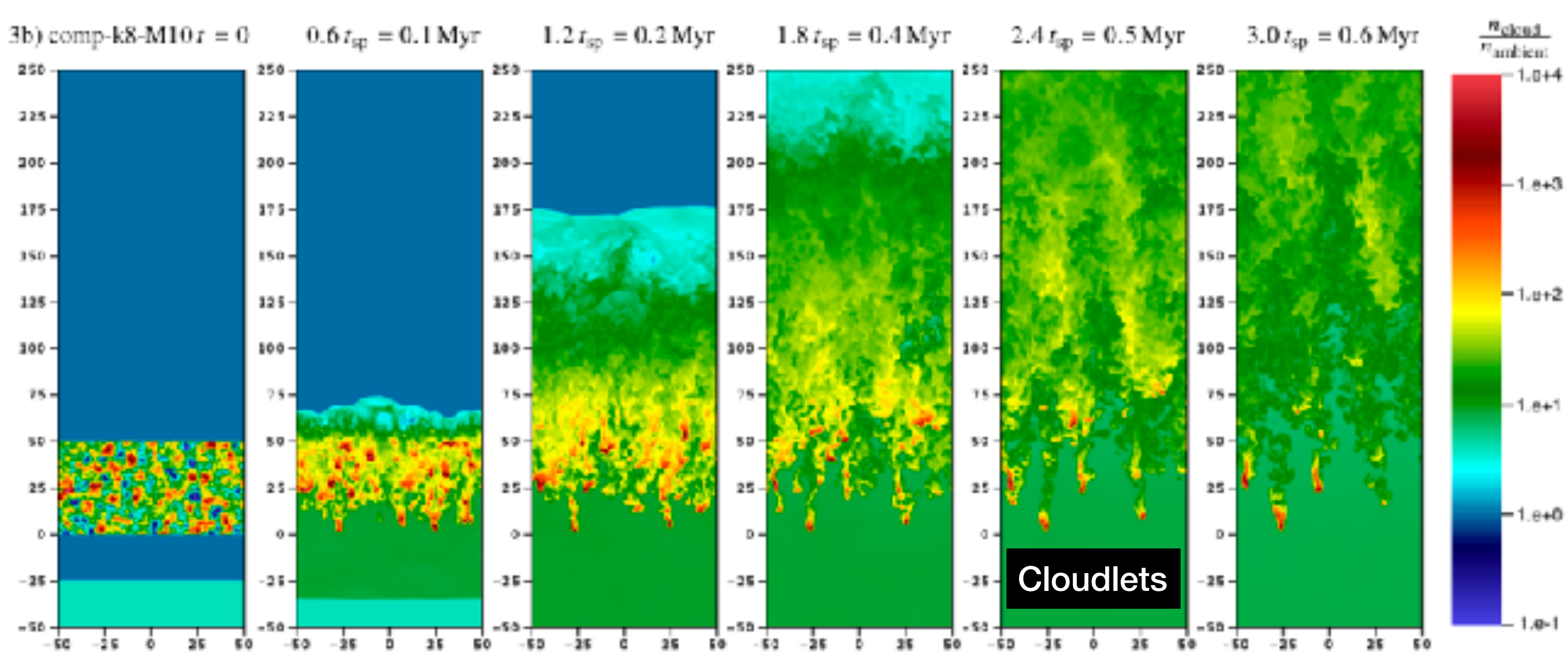


PDF evolution

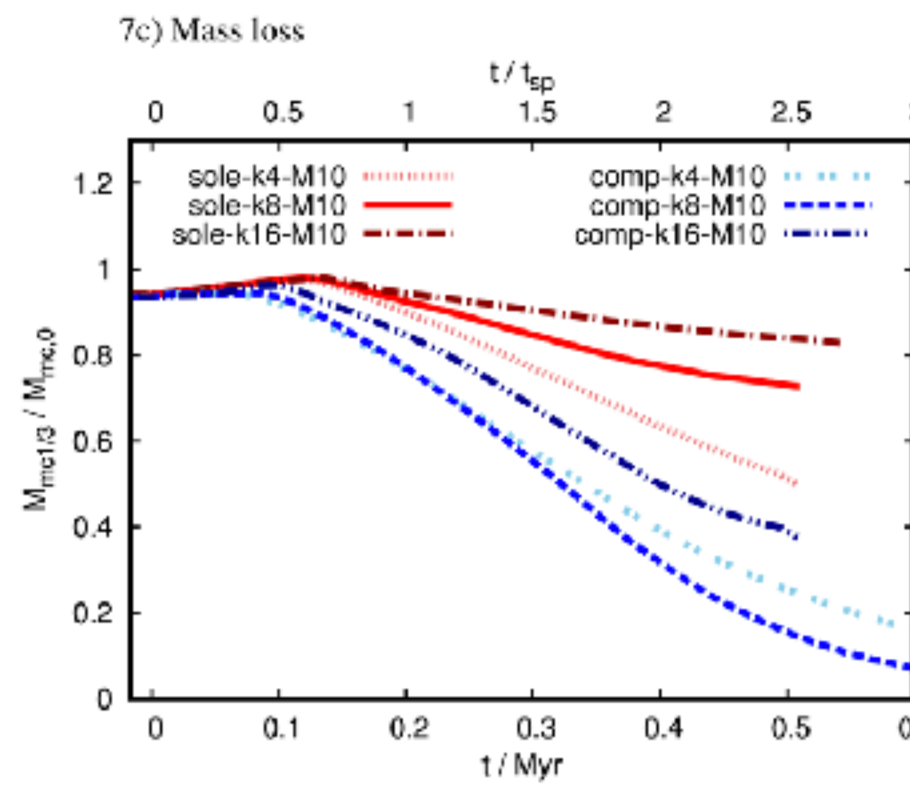


Porous 'compressive' layers

Vertical extent



Dense gas mass fraction



Banda-Barragán et. al 2020a (arXiv:2009.07718)

Question

What are the effects of changing the initial density PDF?

Conclusions

1. Shock-multicloud systems evolve in **4 stages**.

2. Porous layers retain some dense cores while compact layers develop shells.

3. The **morphology and vertical extent** are functions of the initial **density PDFs** and **number of cloudlets** (see https://arxiv.org/abs/2009.07718).

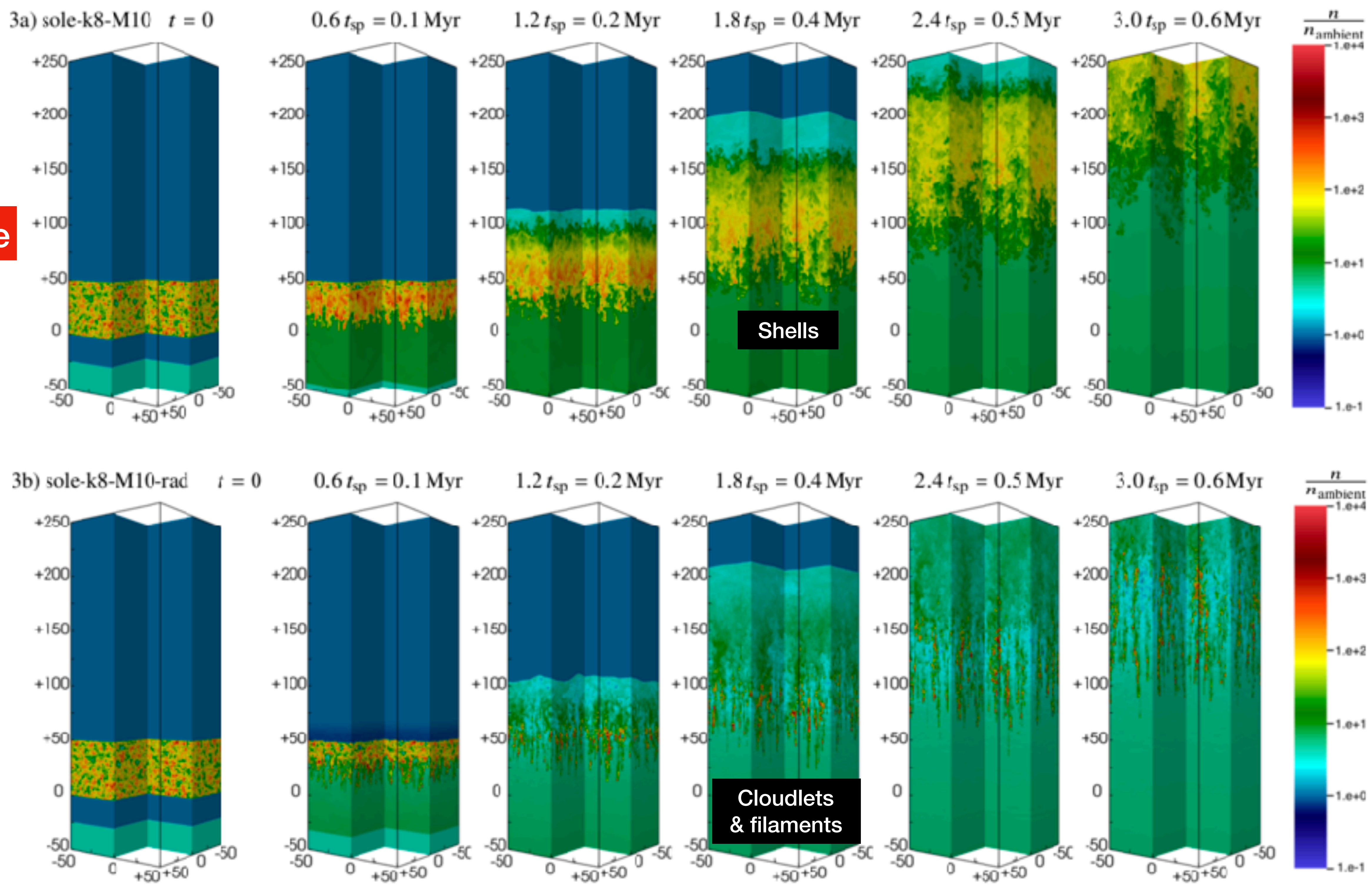
4. Dense gas entrainment is **inefficient** in all models, but mixed gas is efficiently mass loaded.

Part II: What are the effects of radiative processes?

Compact ‘solenoidal’ layers

Non-radiative

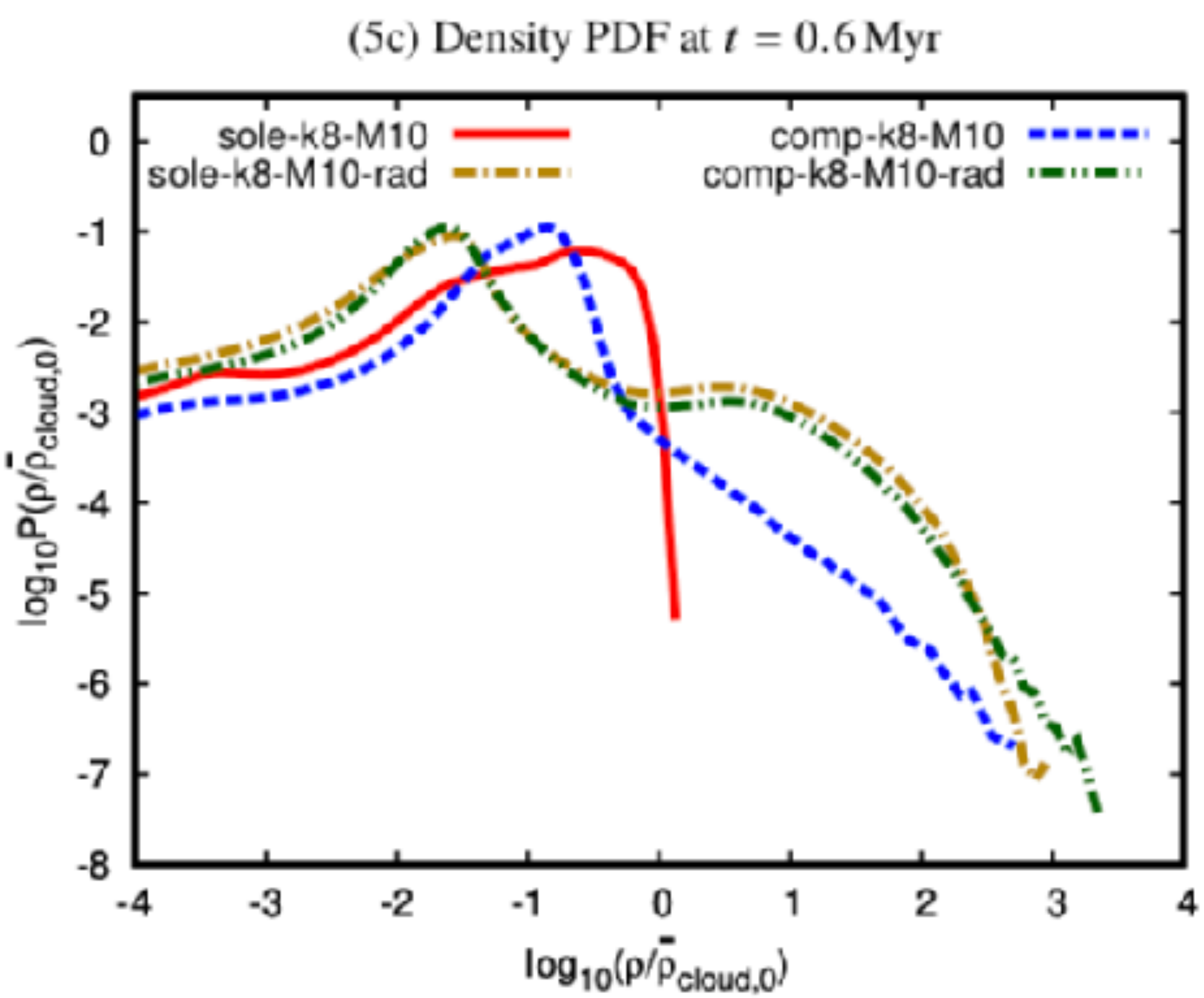
Radiative



There are no shells and the flow acquires a rain-like morphology.
Dense cloudlets can be seen along the flow even at late times.

Part II: What are the effects of radiative processes?

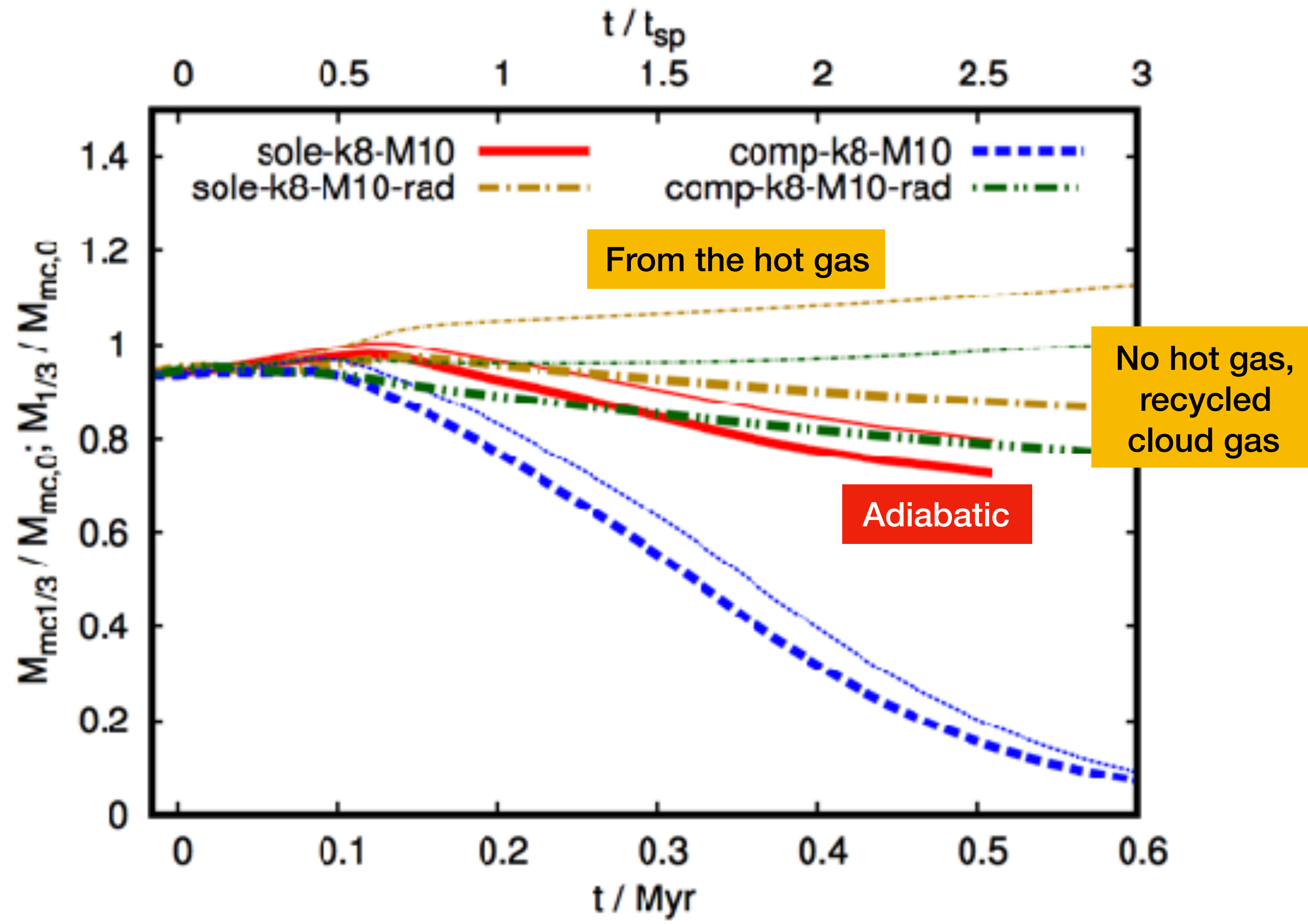
PDF evolution



PDFs become bi-modal distributions.

Diffuse and dense gas co-exist in the outflow.

Dense gas mass fraction



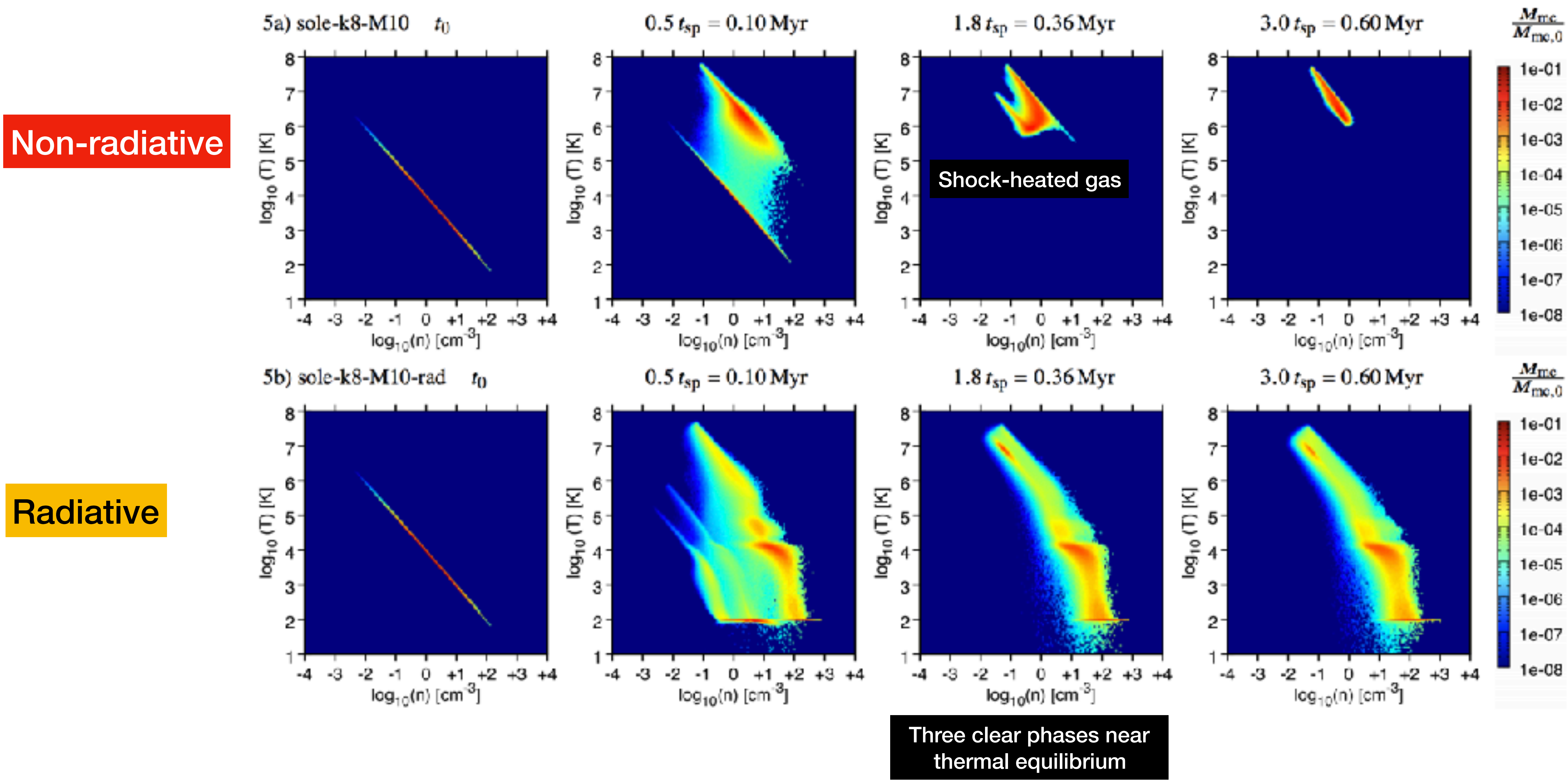
Dense gas is still present at late stages.

Some of it comes from the hot wind.

Banda-Barragán et. al 2020b (arXiv:2011.05240)

Temperature-density phase diagrams

Compact solenoidal layers



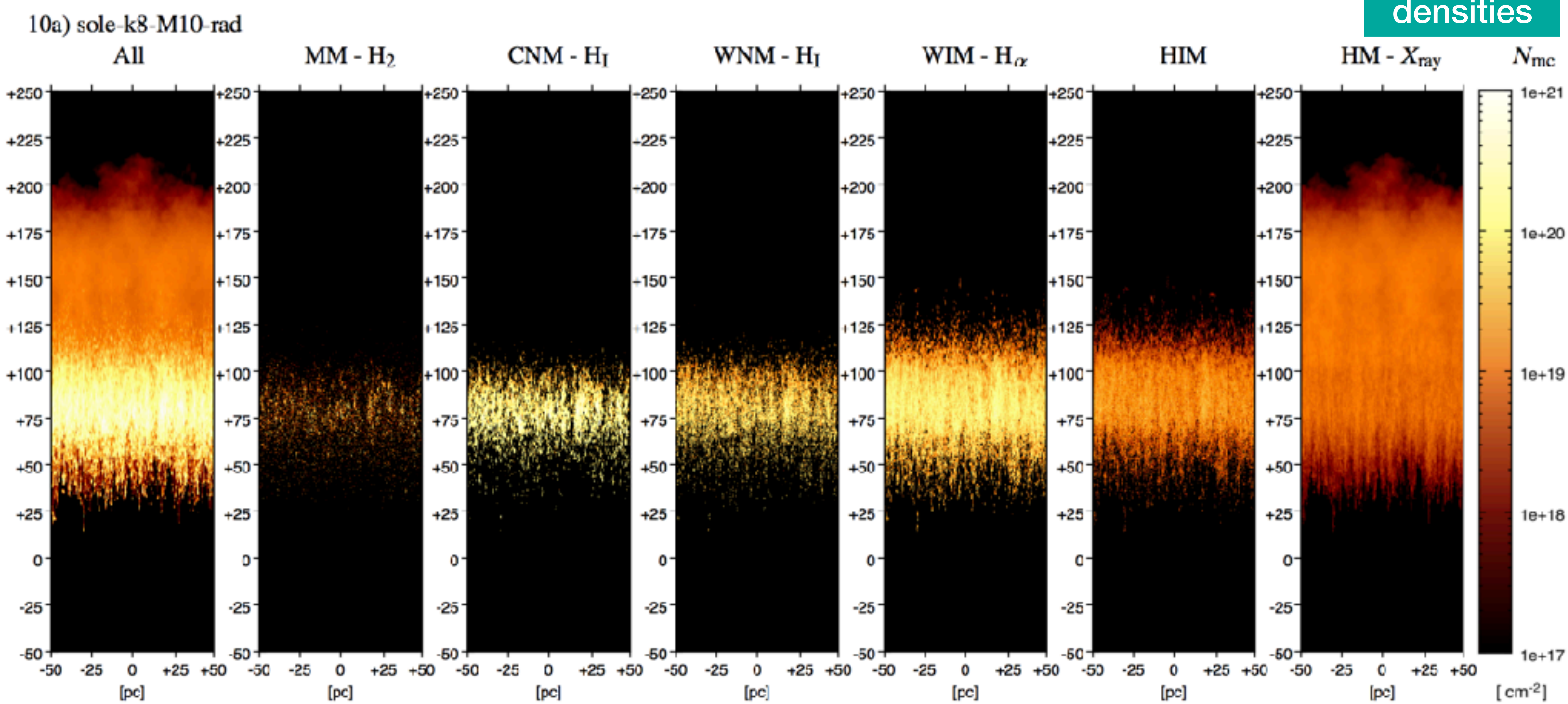
The interplay between heating & cooling creates a multi-phase flow.

Banda-Barragán et. al 2020b (arXiv:2011.05240)

A view of multi-phase outflows in different temperature bins

Compact layers

Column number densities



Hot gas has the largest volume filling factor (f>0.9)

Warm and cold gas contain most of the mass.

Banda-Barragán et. al 2020b (arXiv:2011.05240)

Issue

It is hard to accelerate dense gas owing to its large column densities.

Conclusions

1. Yes, **direct dense gas entrainment** is **inefficient** in all models.

2. However, **mass loading** of warm, mixed gas is **efficient**.

3. **Re-condensation** of mass loaded warm gas + **entrained gas** from the hot wind can **explain the presence of dense gas** in hot outflows.

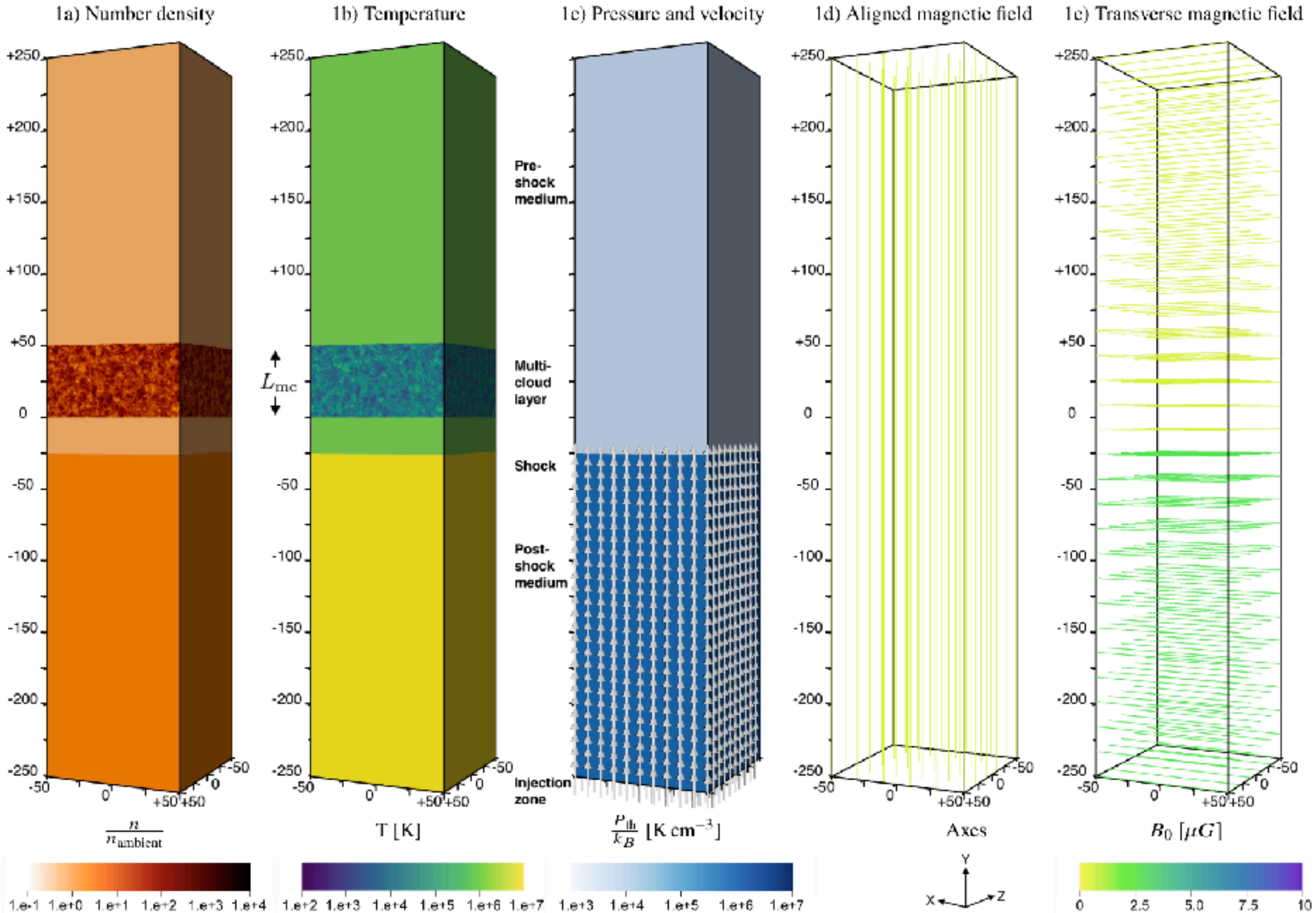
4. The **interplay between heating and cooling** naturally creates **a multi-phase flow.**

6. **Dense gas moves >100pc at speeds >100km/s** (see https://arxiv.org/abs/2011.05240)

Part III: What about magnetic fields?

Ongoing

Plasma beta = 100



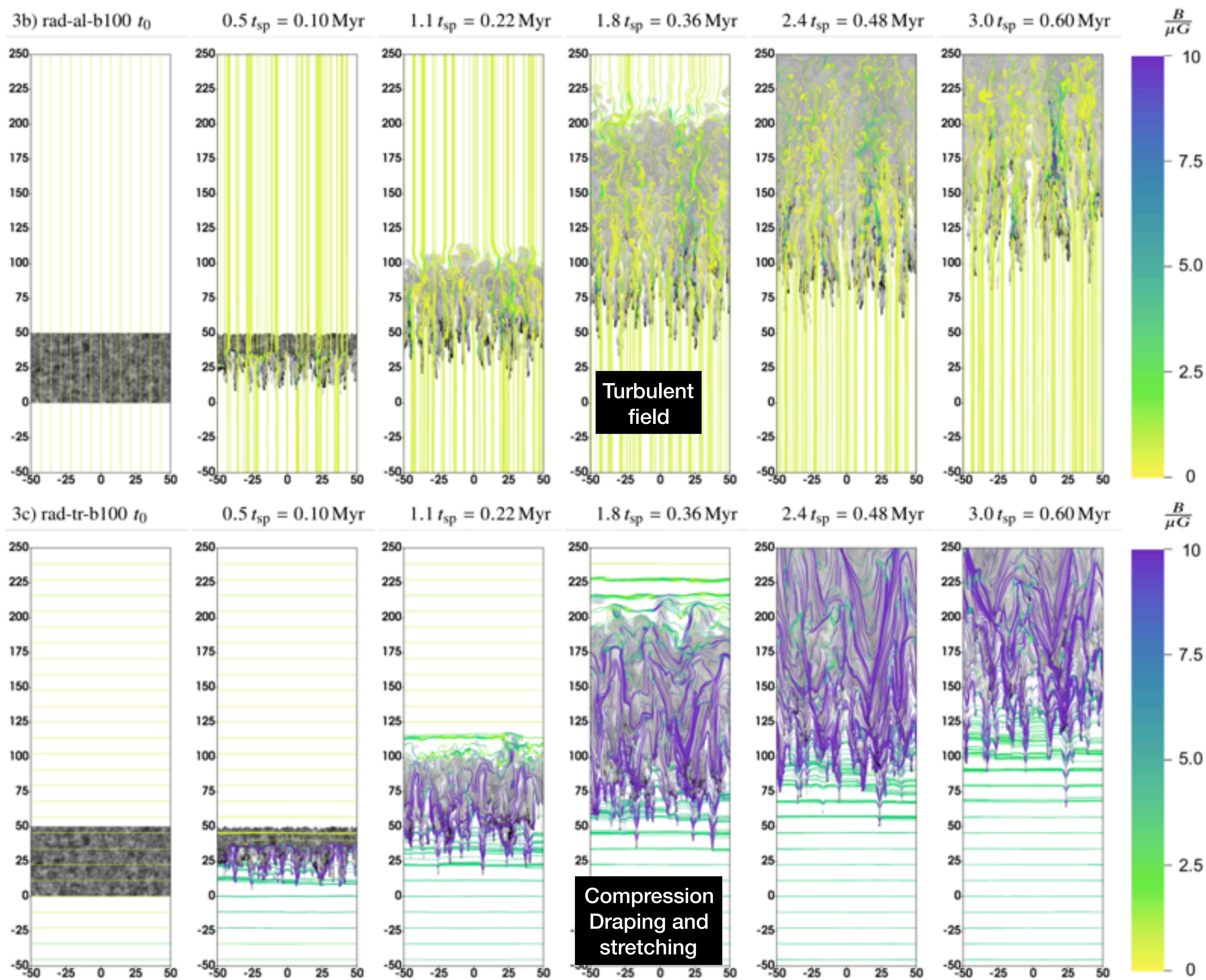
Part III: What about magnetic fields?

Ongoing

Aligned field

With cooling

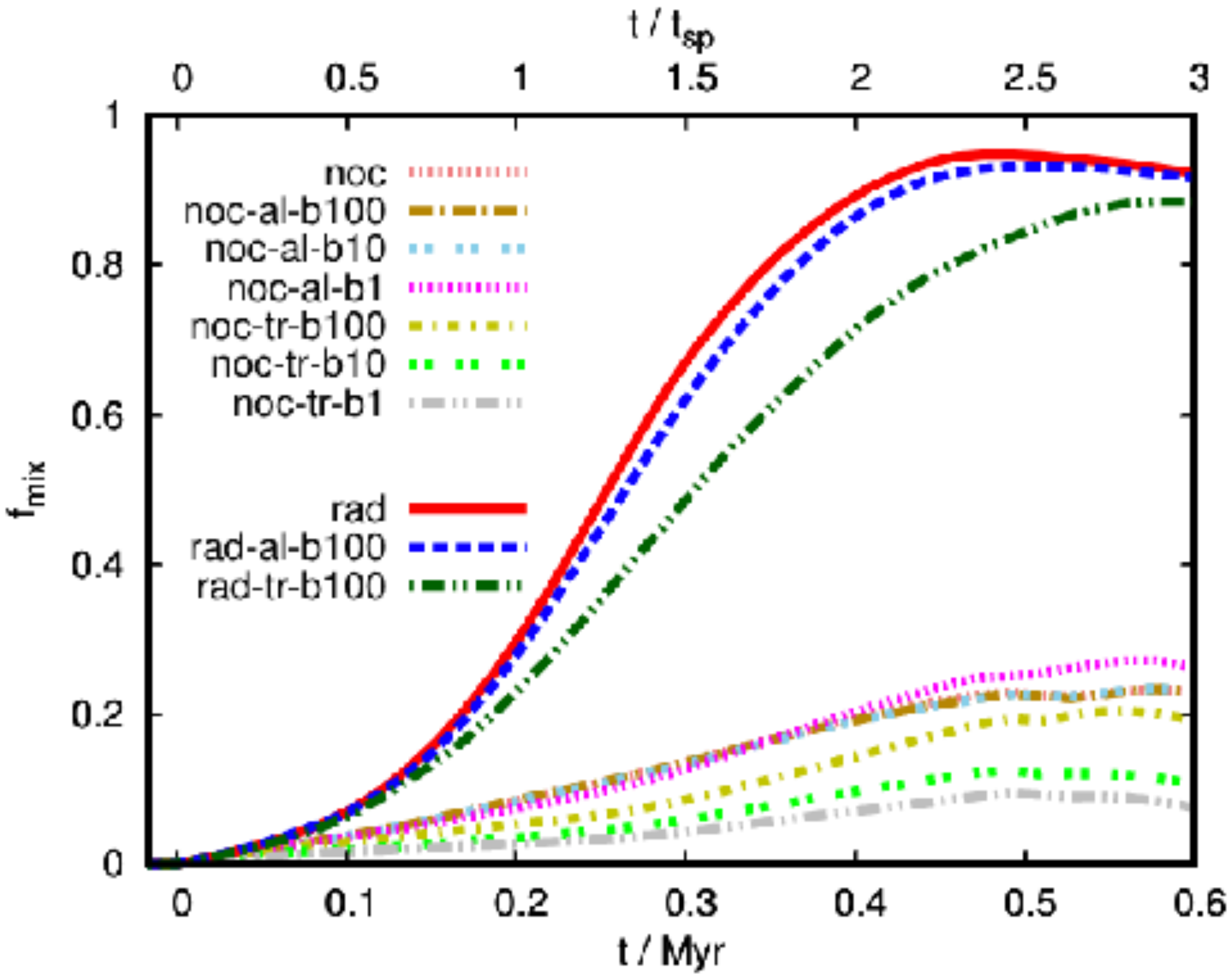
Transverse field



Part III: What about magnetic fields?

Ongoing

Mixing fractions

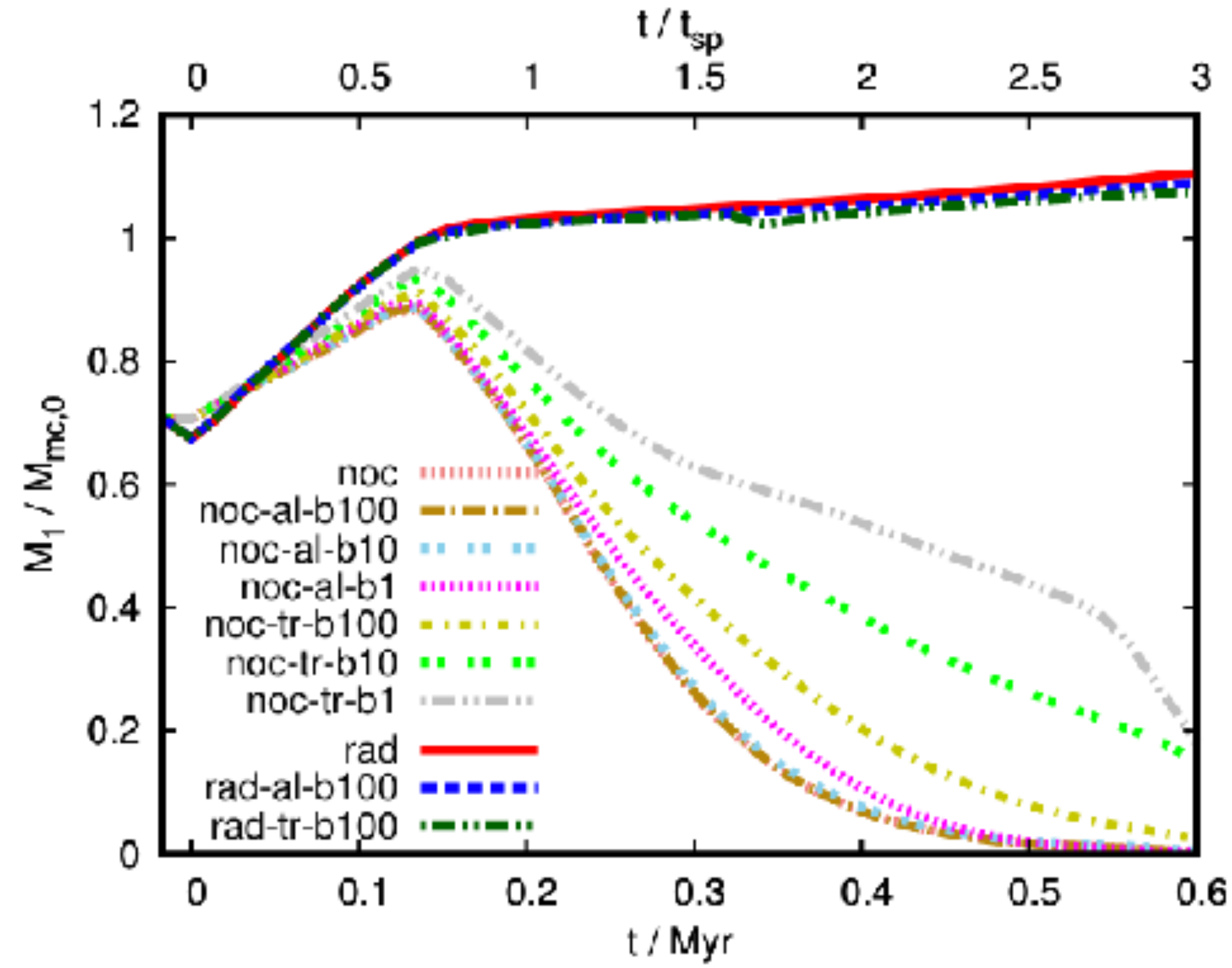


Cooling still induces mixing.

Cooling of mixed gas produces new dense gas.

Transverse magnetic fields reduce mixing.

Dense gas mass fraction



In radiative models, not much of a difference for plasma beta=100.

But non-radiative models show a different trend:

Transverse fields shield dense gas.

Question

Ongoing

What are the effects of magnetic fields?

Conclusions

Magnetic field becomes turbulent in aligned models.

Compression and stretching amplify transverse fields.

Transverse fields allow low plasma beta gas to survive, this gas is magnetically dominated (i.e. it has low plasma betas).

Shielding via a draping effect is more significant in models with transverse fields.

Increasing the field strength delays the emergence of KH instabilities.

Overall picture

Key questions & take-home messages

How can gas phases with different temperatures co-exist?

Heating and cooling naturally create a 3-phase outflow.

What is the origin of dense (atomic/molecular) clouds and filaments?

Entrainment is inefficient, but mass loaded gas can continuously condense back and feed the cool phases of an outflow.

Magnetic fields reduce mixing and the effects of KH instabilities.

How does dense gas reach large distances and high velocities?

Gas that precipitates from the fast-moving warm phase already has high velocities.