MHD simulations of ram pressure stripping of a disk galaxy

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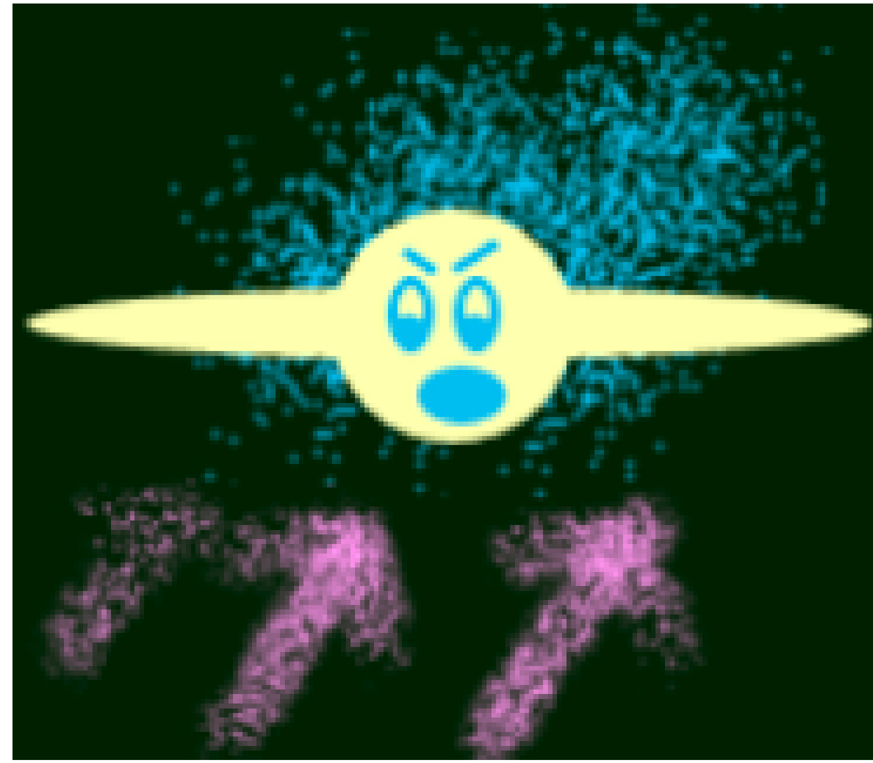
Ram Pressure Stripping (RPS)

- It has been exhaustively studied through a variety of models and simulations:

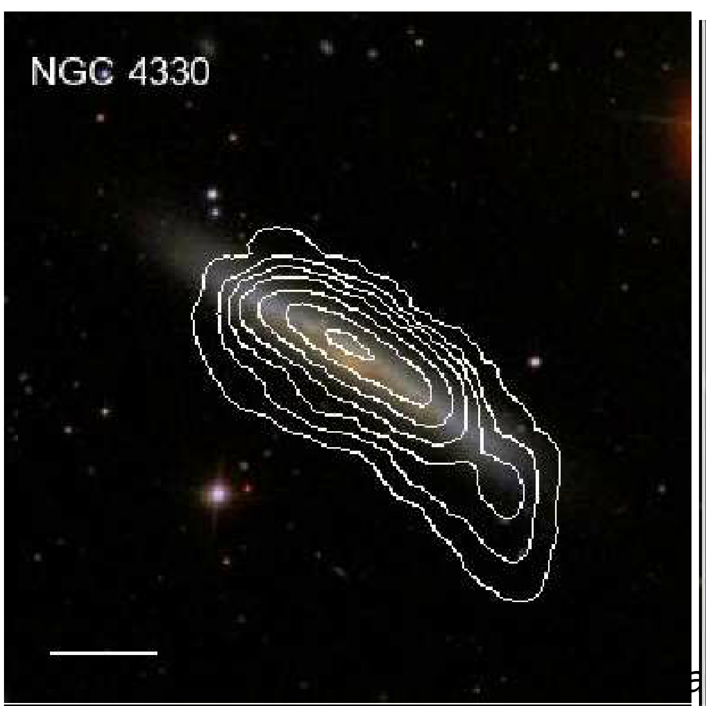


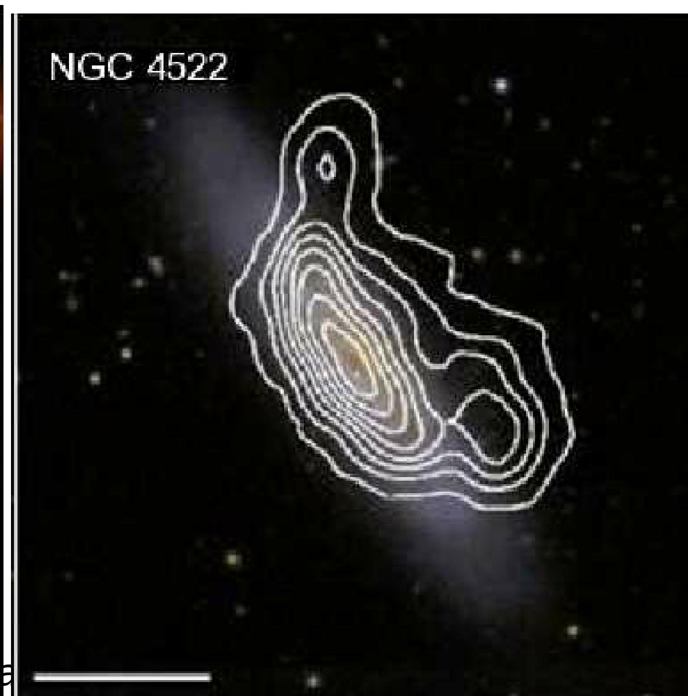
Abadi et al. 1999; Quilis et al. 2000; Roediger & Hensler 2005; Roediger & Brüggen 2006; Vollmer et al. 2006; Kronberger et al. 2008; Tonnesen & Bryan 2009...

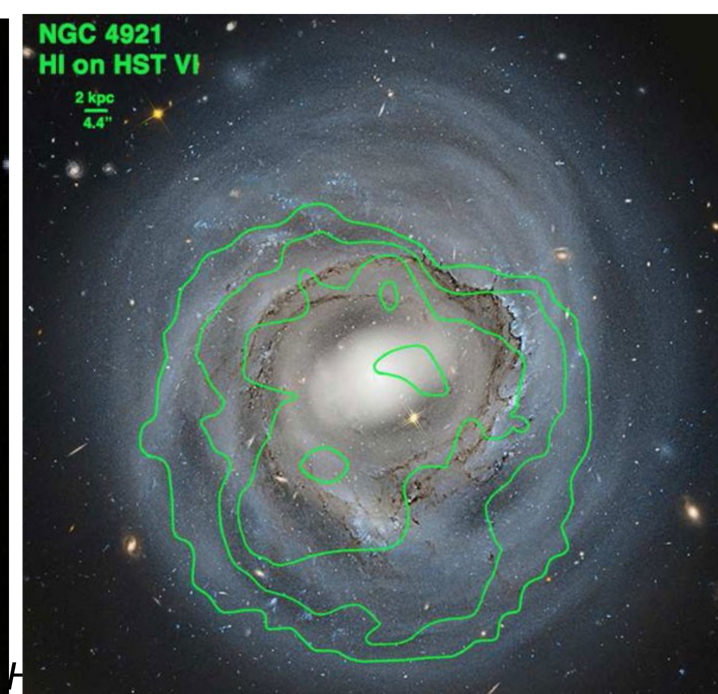
RPS

- Multiwavelength observations have shown galaxies undergoing RPS:

Cayatte et al. 1990; Kenney & Koopman 1999; Bravo-Alfaro et al. 2000; Kenney et al. 2004, 2015; Sun et al. 2006, 2010; Zhang et al. 2013; Jáchym et al. 2014; Poggianti et al. 2016...







RPS with magnetic fields

- The role of magnetic fields (MFs) on the gas dynamics in this process has hardly been explored, although the large-scale magnetic structure of the disk is well established (Beck 2005; Beck & Wielebinski 2013 and references therein).

RPS with magnetic fields

For magnetized ICM only:

- Ruszkowski et al. (2014), the MFs affect the gas tail morphology, clumpier hydro tail and smoothed and filamentary-like for the MHD tail.

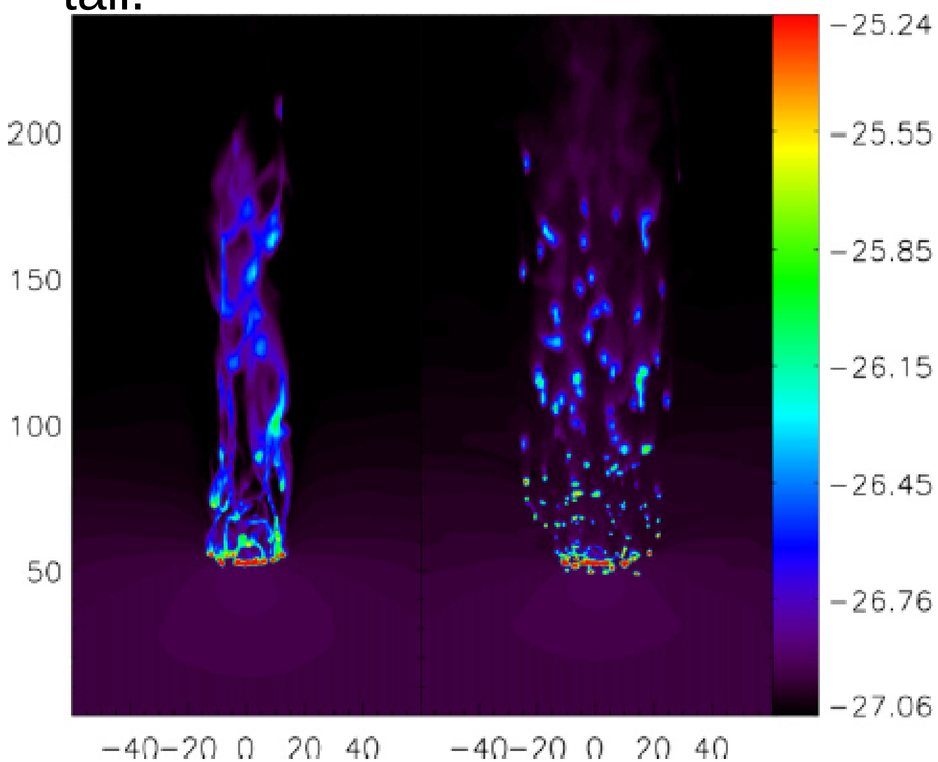
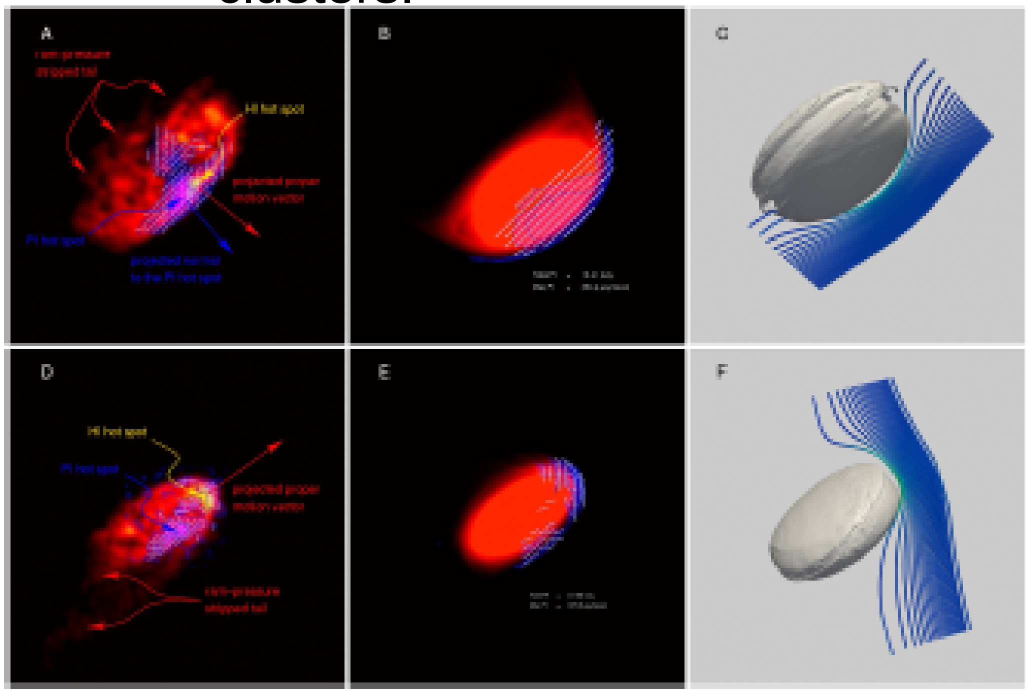


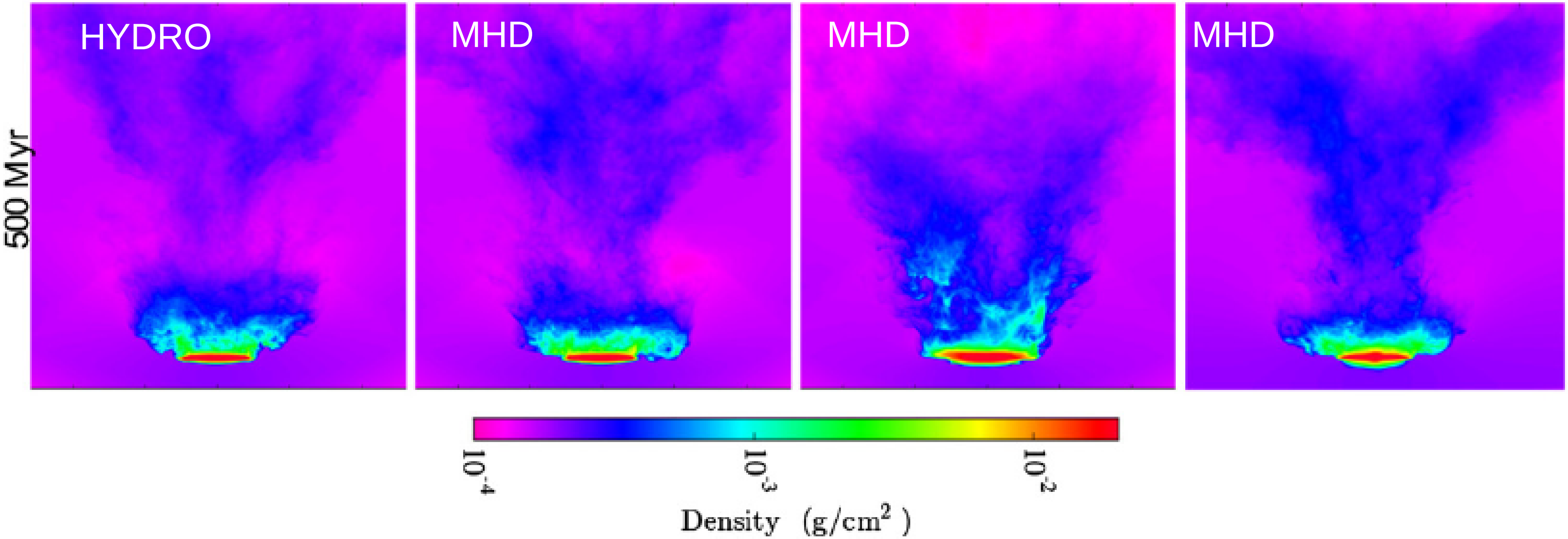
Figure 1. Gas density projected along the line of sight (in log space). Left: MHD case. Right: non-magnetic case. Both cases are for $t = 0.7$ Gyr. The difference between tail morphologies in these two cases is striking.

- Pfrommer & Dursi (2010), the MHD models help to determine the orientation of the MFs in clusters.

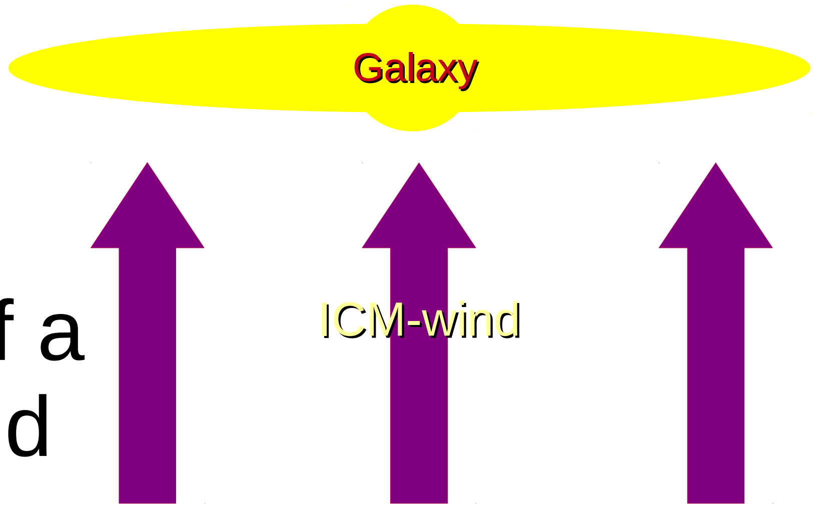


RPS with magnetic fields

- Galactic magnetic fields: Tonnesen & Stone (2014), the MFs don't alter dramatically the stripping rate of ISM but the MFs inhibit the mixing of gas in the tail.



The model



- 3D MHD and HD simulations of a disk galaxy under RPS in a wind tunnel, with the RAMSES code (Teyssier 2002).

- The gas of the galaxy is set up in rotational equilibrium with the gravitational potential, the centrifugal force, the thermal and magnetic pressure gradients and the magnetic tension (for the MHD case).

$$\frac{v_\phi^2(r,z)}{r} = \frac{\partial \Phi}{\partial r} + \frac{1}{\rho(r,z)}\left[\frac{\partial P}{\partial r} + \frac{2P_B(r,z)}{r}\right]$$

The model

- In the disk, we define the density profile in the midplane ρ(r,z=0) and then we assume hydrostatic equilibrium to solve the density distribution at any z (Gómez & Cox 2002).

$$\frac{\partial P}{\partial z} = -\rho \frac{\partial \Phi}{\partial z}$$

The model

- For the MHD model, the MF is random in the bulge region:

$$\mathbf{B}_{inner} = \nabla \times \mathbf{A}$$

- and azimuthal in the disk:

$$\begin{aligned} B_x &= B \sin \phi \\ B_y &= B \cos \phi \\ B_z &= 0 \end{aligned}$$

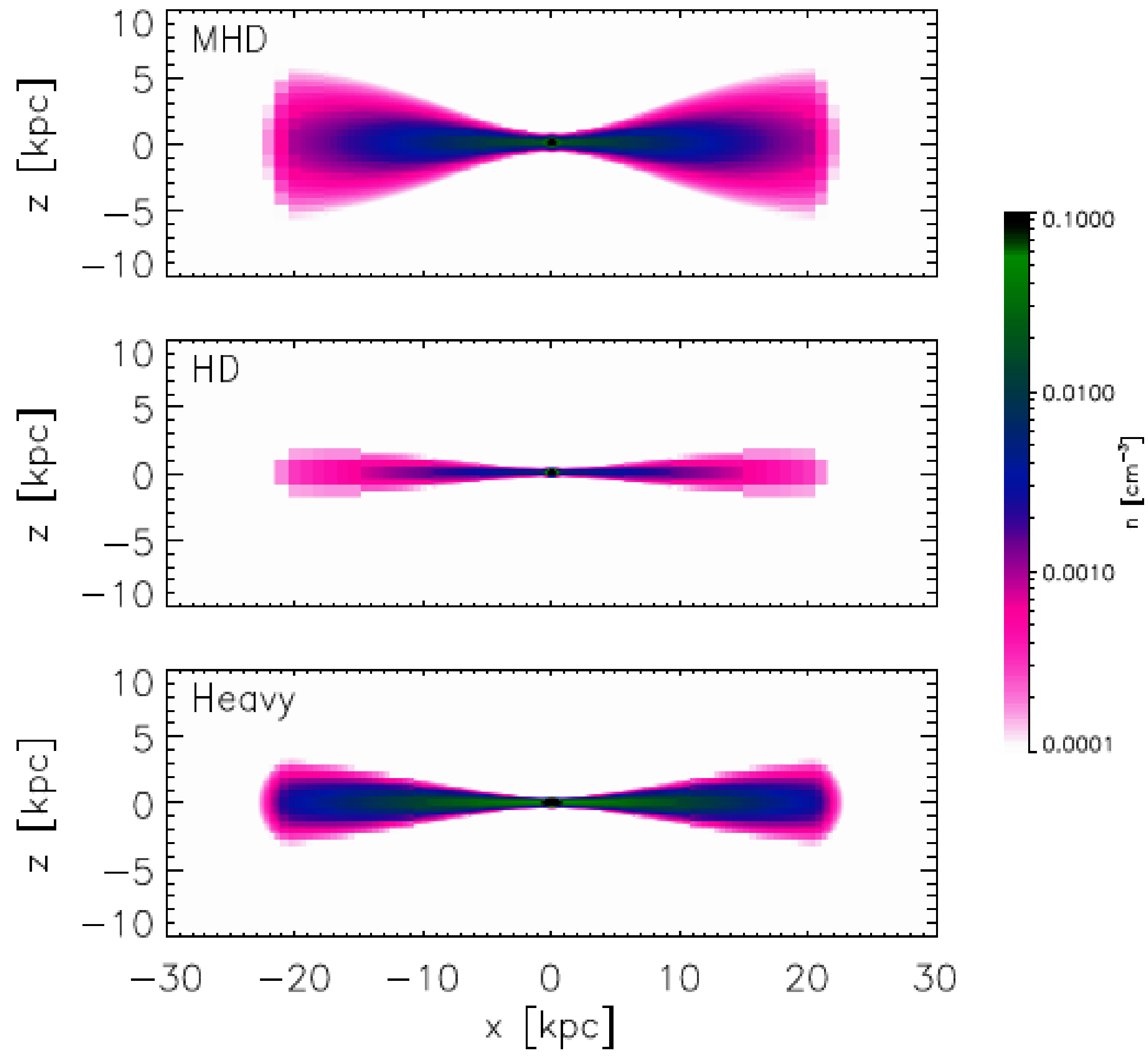
- The MF magnitude depends of the gas density.

$$P_B = \frac{P_{B0}\, n}{(n + n_c)}$$

The model

- A similar recipe is used to construct the hydro model but with **B** = 0.

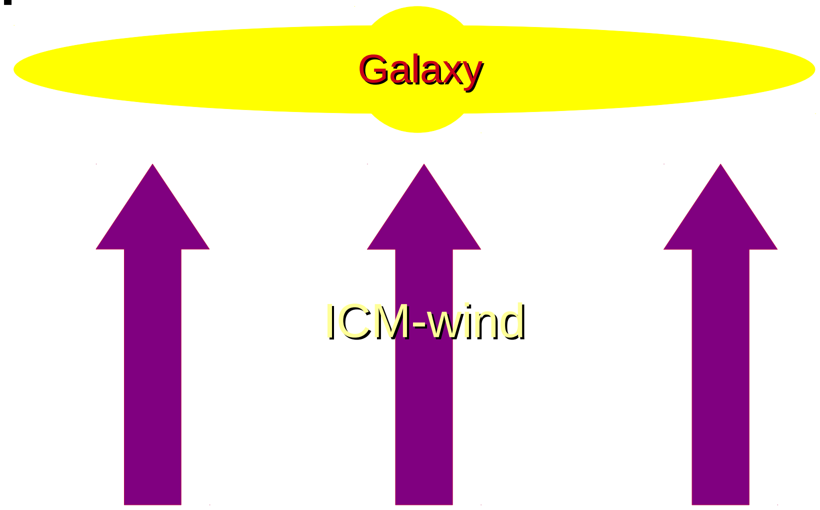
- Also a heavy hydro model with a higher $\rho(r,z=0)$, which yields to $\Sigma \sim \Sigma_{MHD}$.

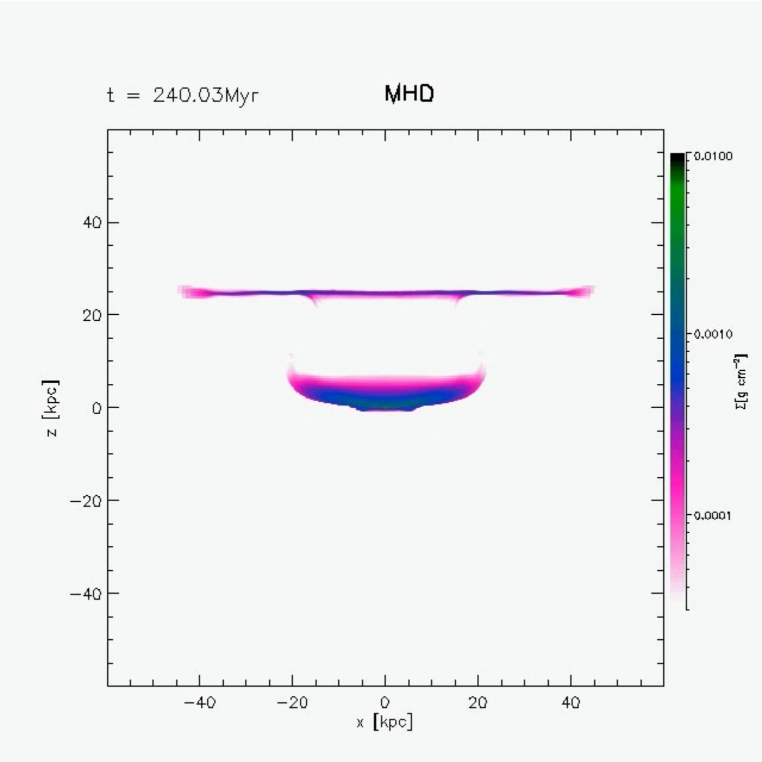


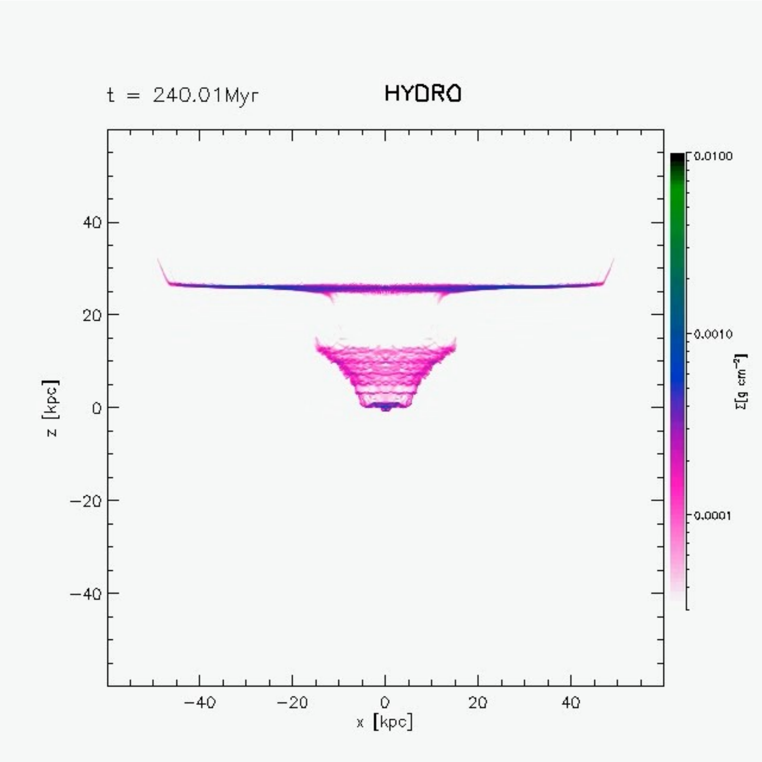
The model

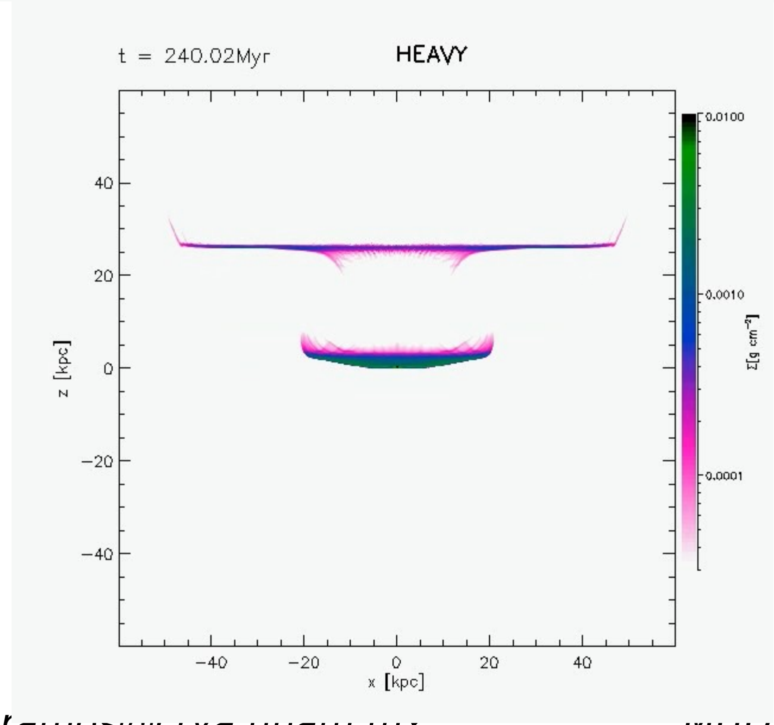
Initial conditions for the ICM:

- Density $n = 10^{-5}$ cm^{-3}.
- The velocity grows linearly in time, from 300 km s^{-1} at t = 0 to 1000 km s^{-1} in 700 Myr.
- The wind flows up from the bottom of the box.



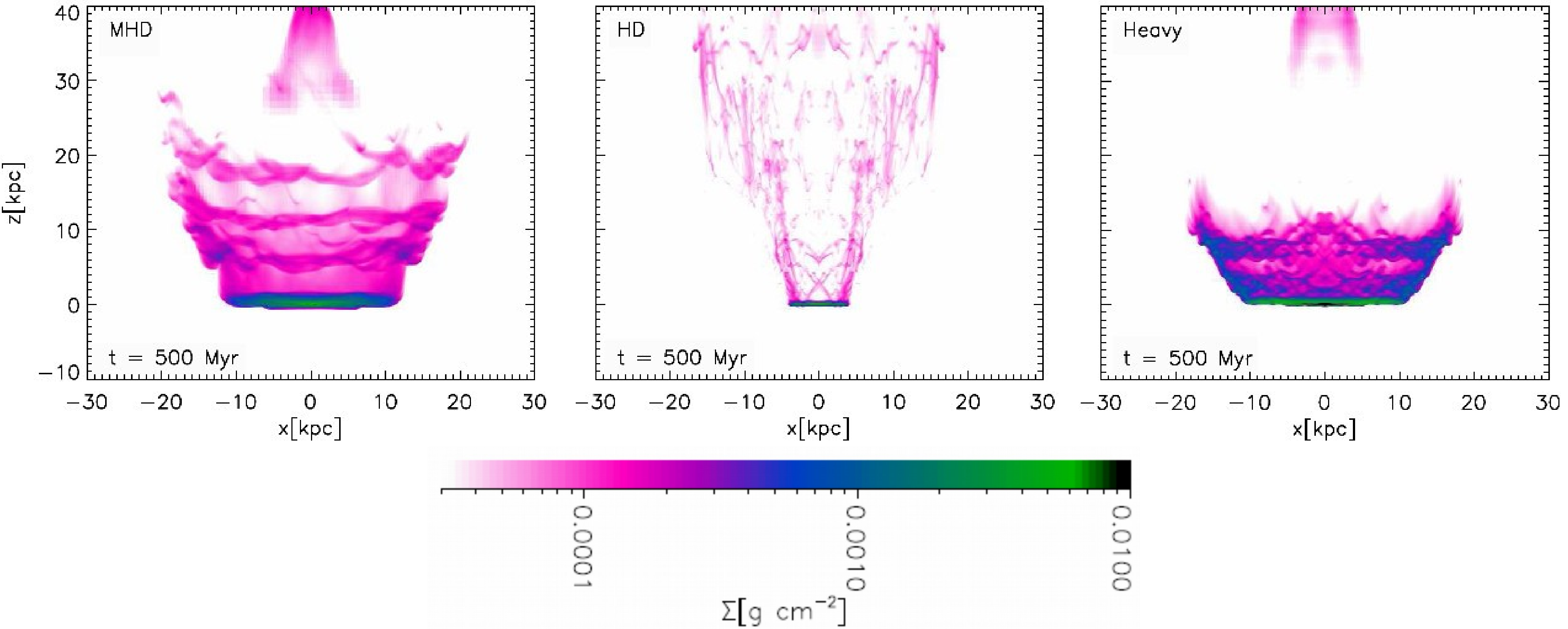

t = 240.03Myr
MHD
z [kpc]
x [kpc]
Σ[g cm^-2]
0.0100
0.0010
0.0001


t = 240.01Myr
HYDRO
z [kpc]
x [kpc]
Σ[g cm^-2]
0.0100
0.0010
0.0001


t = 240.02Myr
HEAVY
z [kpc]
x [kpc]
Σ[g cm^-2]
0.0100
0.0010
0.0001

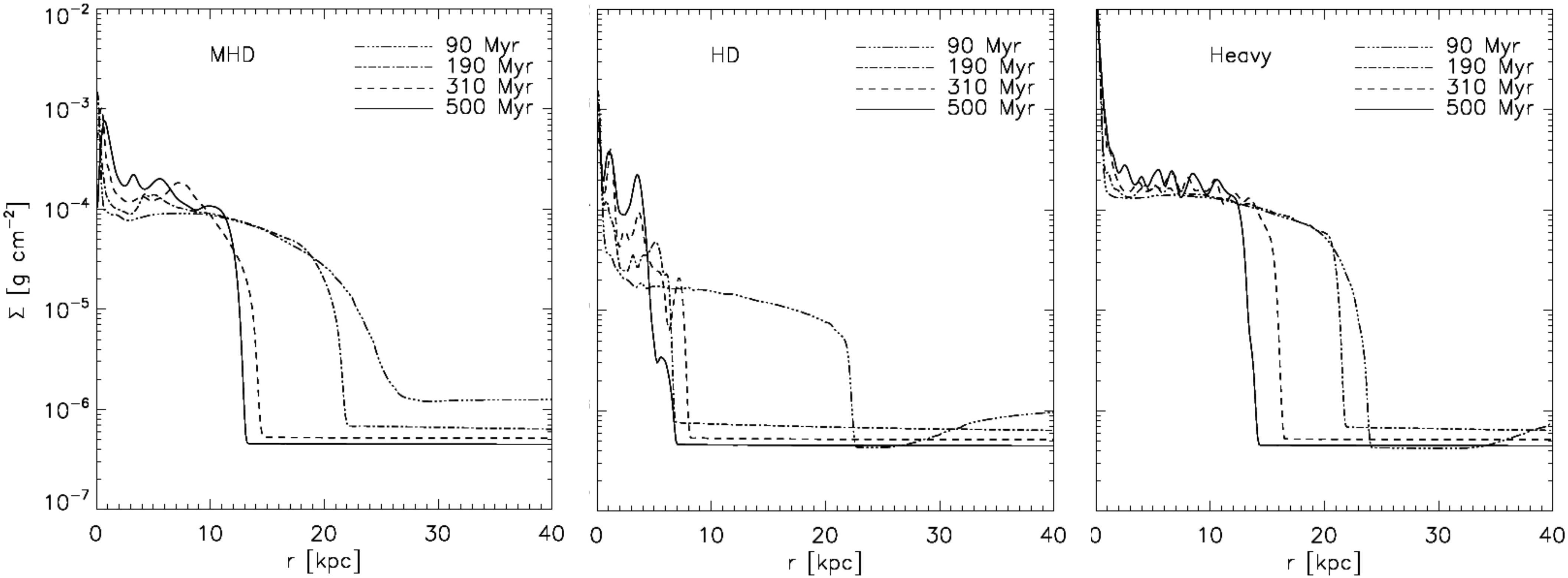
Evolution of the models

- MHD, hydro and heavy models at t = 500 Myr.



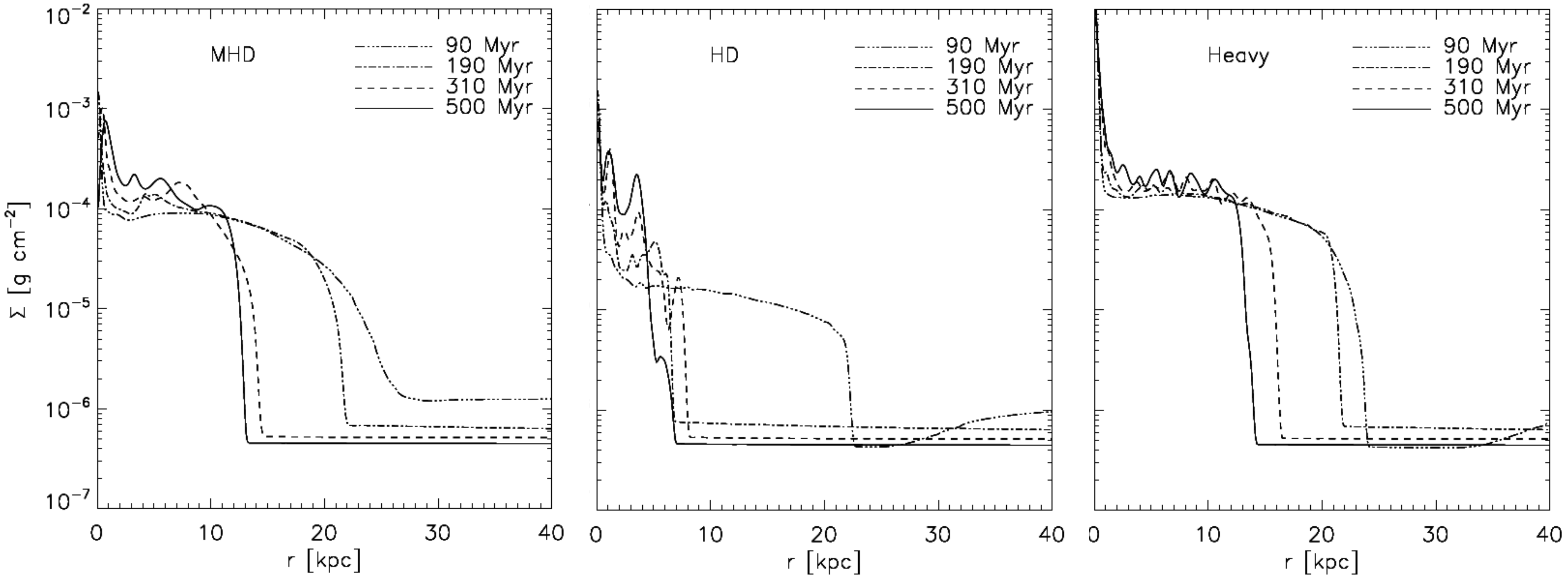
Disk truncation

- The disk truncation is measured through the surface density Σ perpendicular to the galactic disk.



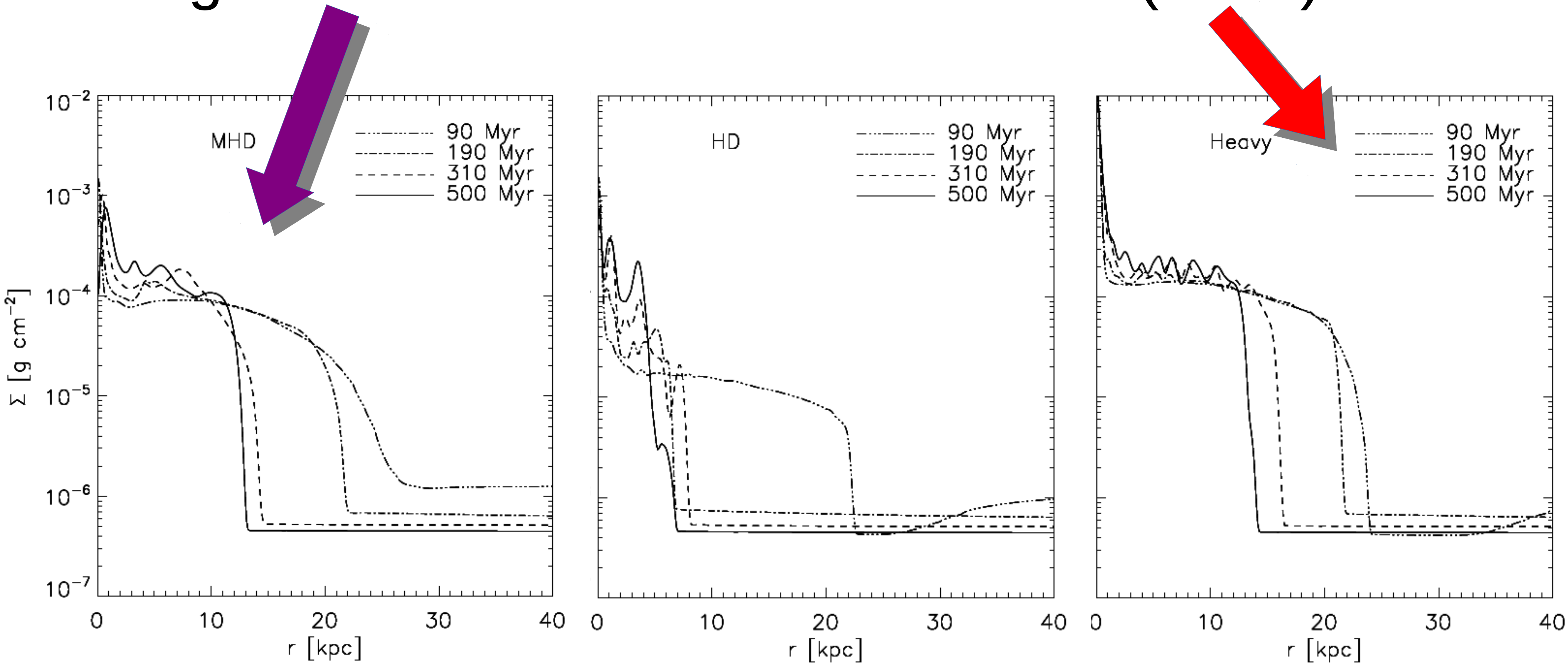
Disk truncation

- The HD disk is eroded more efficiently, showing a truncated disk with r ~ 4 kpc, than the MHD and the heavy ones, with a disk of r = 10-12 kpc.



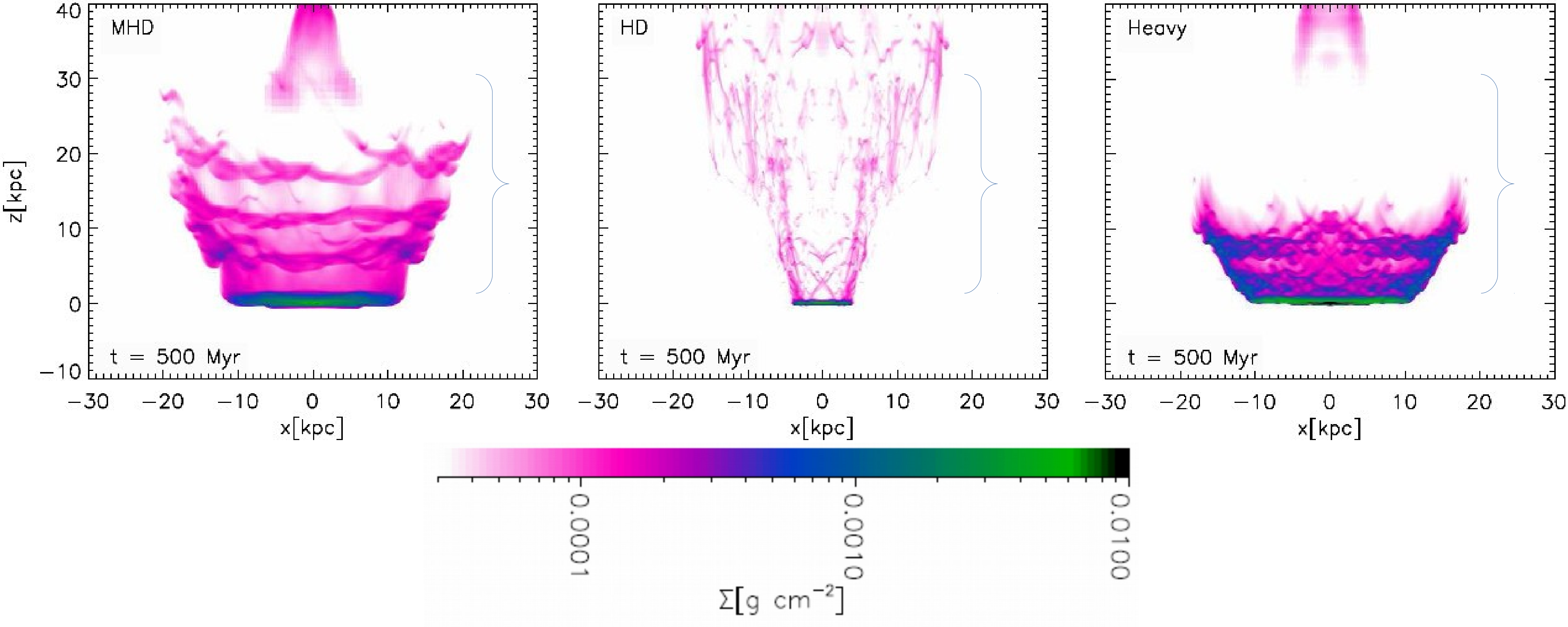
Disk truncation

- The hydro disk with $\Sigma \sim \Sigma_{MHD}$ (**heavy** disk) has nearly the same stripping rate as the MHD model, in agreement with Tonnesen & Stone (2014).



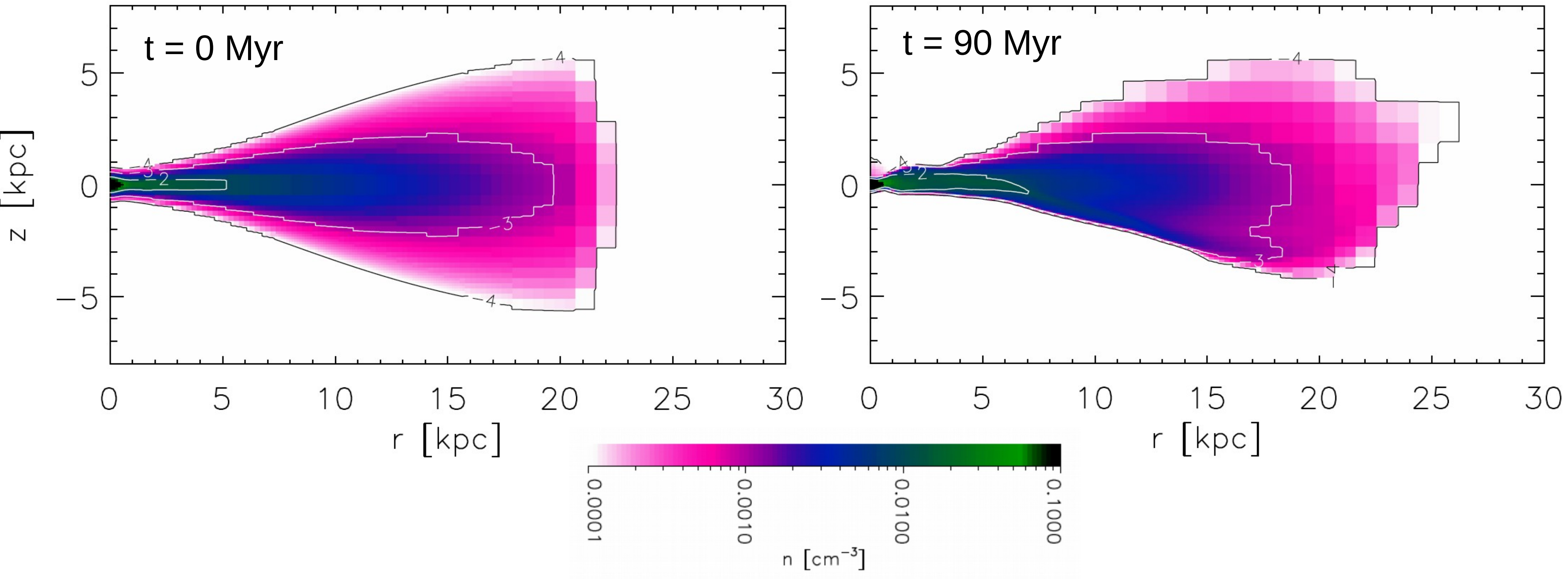
Disk truncation

- The difference of the heavy model with the magnetized case is the **morphology of the swept gas**!!



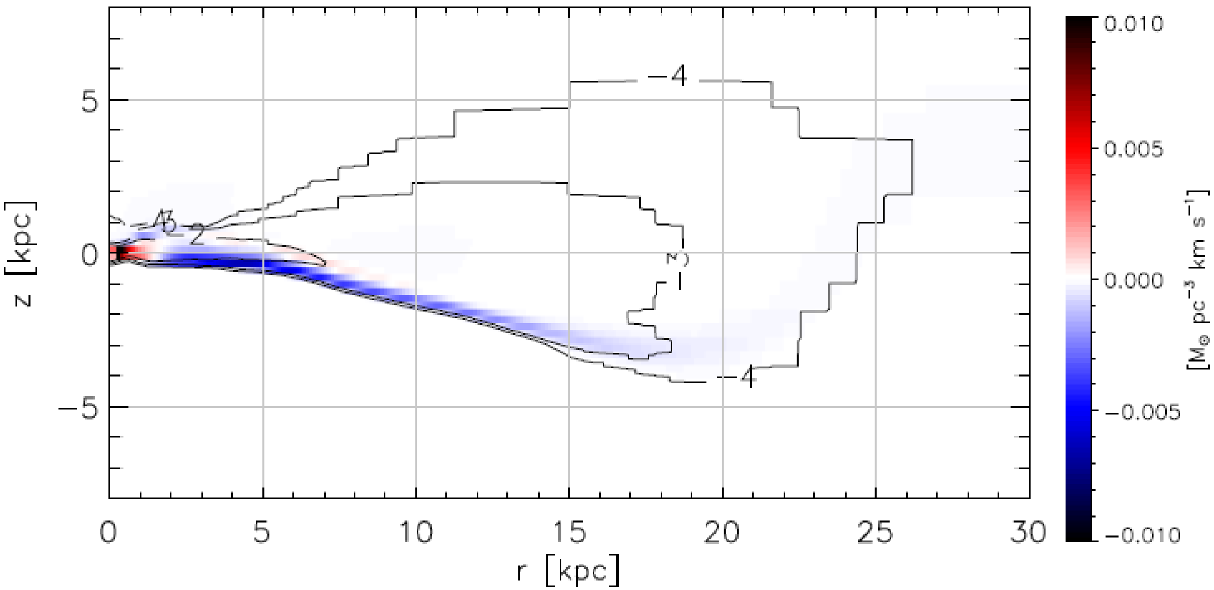
Oblique shocks

- The MF produces a flared disk.
- This yields to oblique shocks at the face of the ICM-ISM interaction.



Oblique shocks

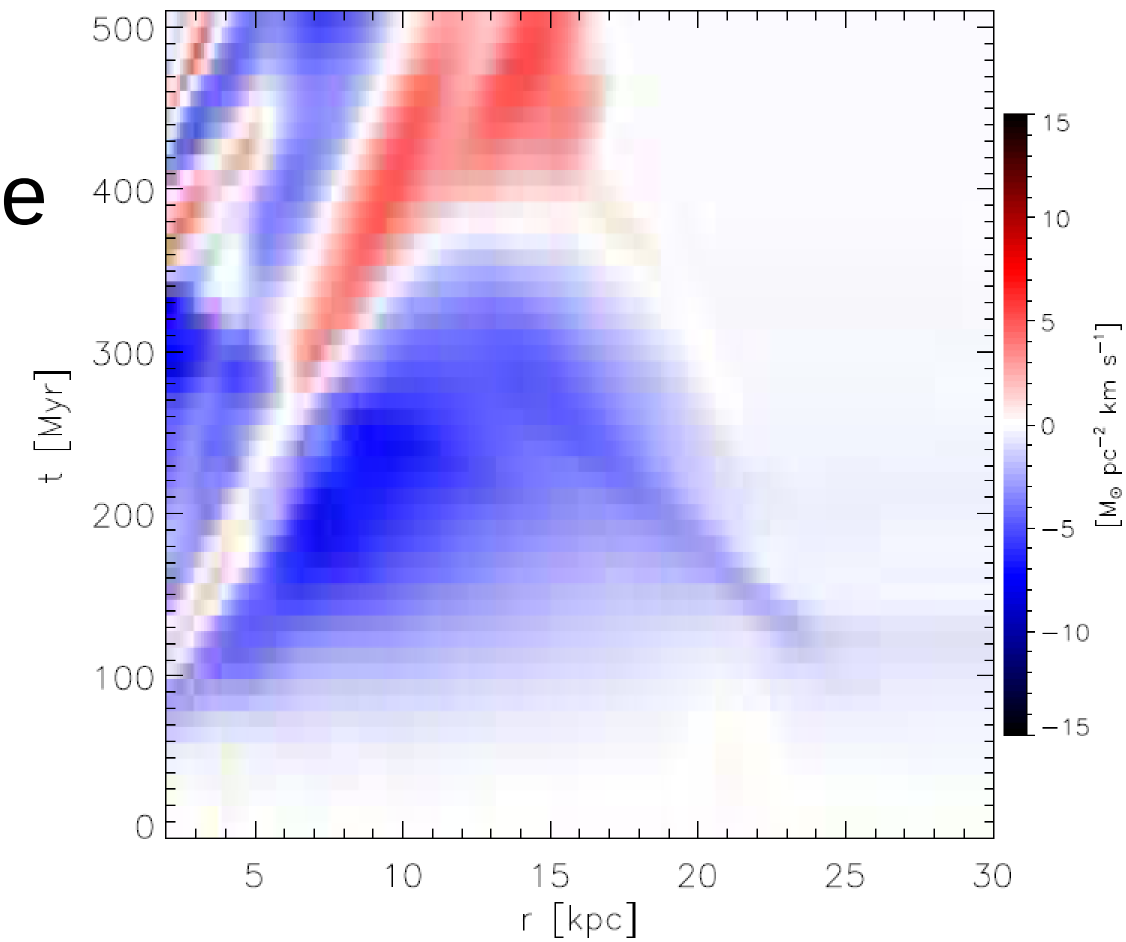
- Inflow of gas calculated at t = 90 Myr. Blue and red colours show radially inward and outward flux, respectively, with gas density contours overlaid.



- The oblique shocks move gas to smaller galactocentric radii.

Oblique shocks

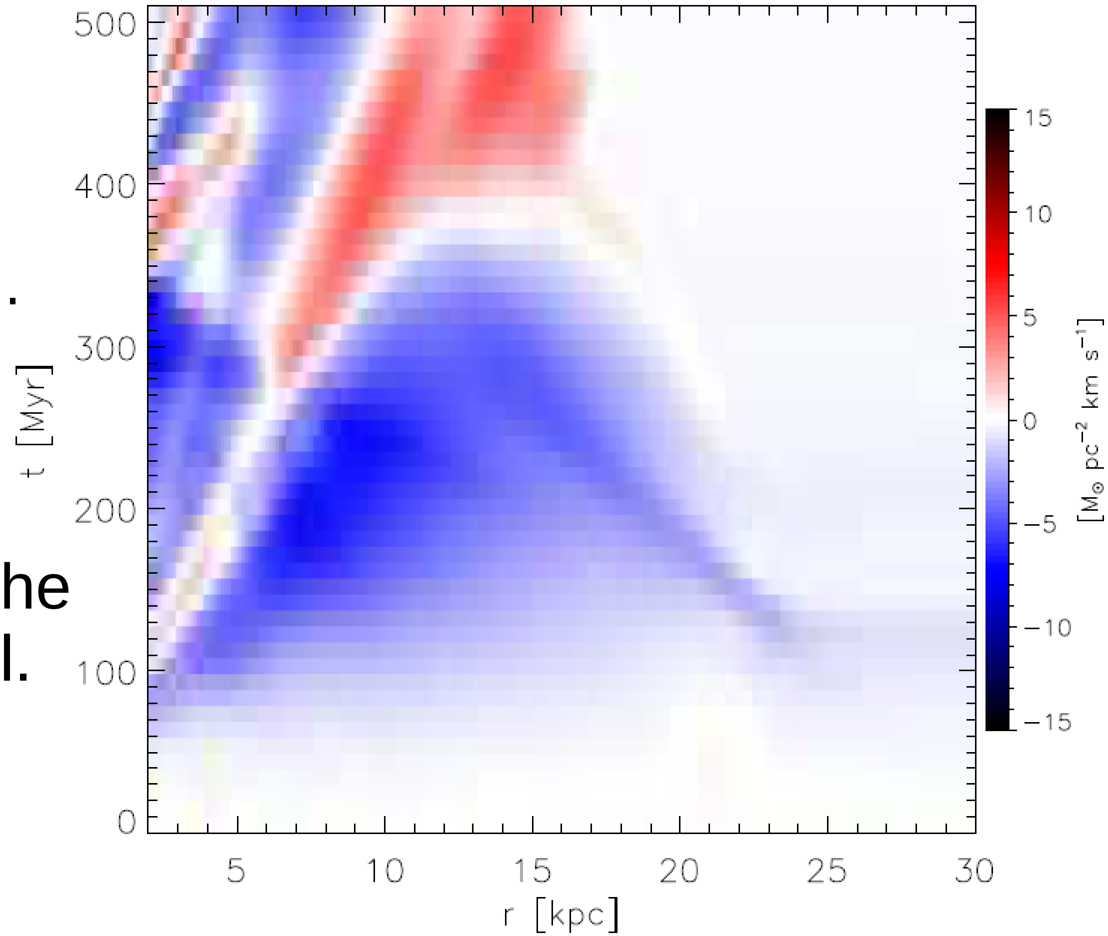
- Integrating the flux in the z-direction to obtain its evolution.



- The inflow appears at ~90Myr and last for ~250 Myr.

Oblique shocks

- This mechanism could provide a gas supply for star formation near the centre of the galaxy or ignite an AGN.
- Some studies of RPS galaxies have shown nuclear activity and also enhanced star formation in the compressed region (Cayatte et al. 1990; Poggianti et al. 2016).



- Poggianti et al. Nature (2017), found a very high incidence of AGN (Seifert 2) among jellyfish galaxies from MUSE data and they conclude that ram pressure triggers the AGN activity. See also Gullieuszik's talk.

Conclusions

- The magnetic field (MF) affects the stripping rate, in our simulations, only through the surface density Σ.
- The MF has an influence in the shape and structure of the swept gas, showing a smooth appearance, whilst in both of the hydro models the gas looks clumpier and filamentary-like.
- The MF produces a flared disk which yields to the emergence of oblique shocks when the ICM wind hits the disk.
- These shocks lead gas towards the central regions of the galaxy, that could have an impact in the star formation.