2.5-MHD models of circumstellar discs around FS~CMa post-mergers

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Star-Disk Magnetospheric Interaction (SDMI)

Pioneering simulations:

-Kluzniak & Kita (2000)

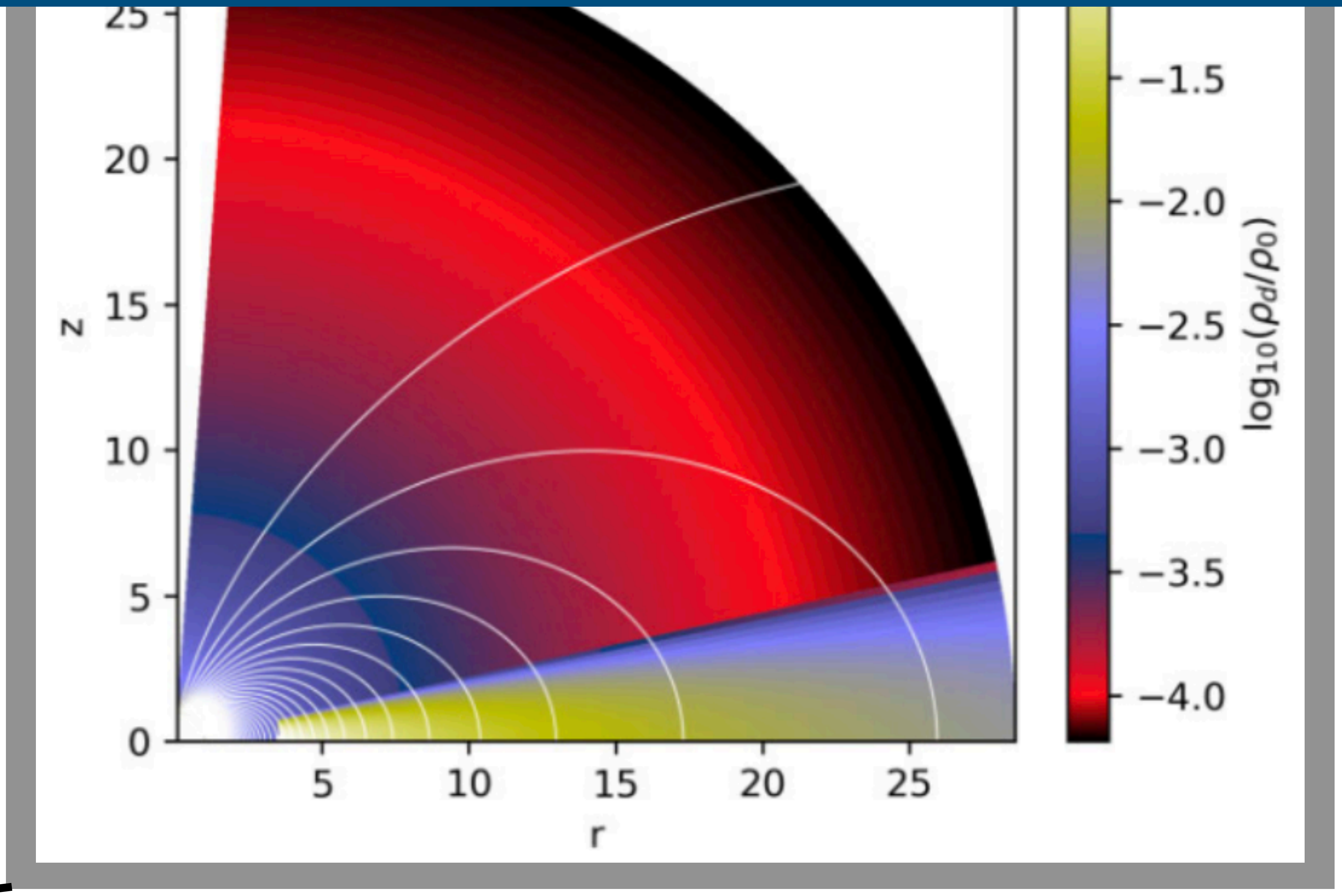
-Romanova et.al (2009, 2013)

-Zanni & Ferreira (2009)

-Čemeljić (2019, 2023)

Density evolution Disk+Column+Ejection
$B_\star = 500G, \alpha_m = 0.1, \Omega_\star/\Omega_{br} = 0.1$ (Čemeljić & Brun 2023)

Motivation



Scheme view of FS~CMa stars

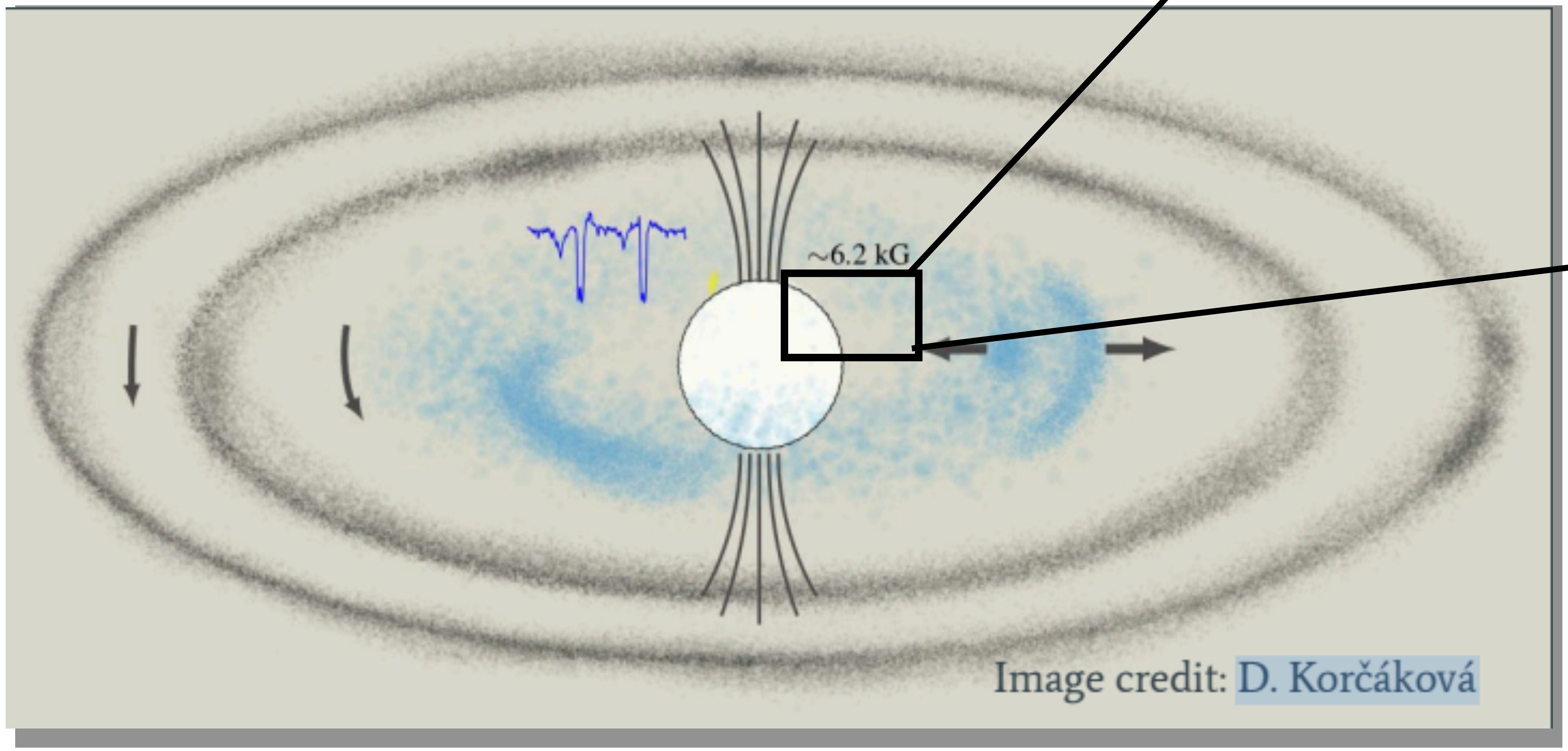


Image credit: D. Korčáková

Observational characteristics of FS~CMa stars:

- Strong magnetic field $B_* = 6.2kG$ Korčáková et al. 2022
- Slow stellar rotation
- Low Densities

MHD equations- PLUTO CODE (Mignone, 2009)

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

Conservation of momentum

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{\mathrm{B} \cdot \mathrm{B}}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} - \tau \right] = -\rho \nabla \Phi,$$

Energy equation

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\mathbf{v} \left(E + P + \frac{\mathbf{B} \cdot \mathbf{B}}{8\pi} \right) - \frac{1}{4\pi} (\mathbf{v} \cdot \mathbf{B}) \mathbf{B} \right] + \nabla \cdot \left(\eta_m \mathrm{J} \times \frac{\mathbf{B}}{4\pi} - \mathbf{v} \cdot \tau \right) = -\rho (\nabla \Phi) \cdot \mathbf{v} - \Lambda_{cool},$$

Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B} - \eta_m \mathrm{J}) = 0,$$

the viscous stress tensor $\tau = \eta_v \left[(\nabla \mathbf{v}) + (\nabla \mathbf{v})^T - \frac{2}{3} (\nabla \cdot \mathbf{v}) I \right]$

To explore different descriptions of resistivity $\eta_m = 4\pi \nu_m$, we considering that the magnetic diffusivity ν_m is given by:

- Classical description (Zanni & Ferreira 2009, Cemeljic 2019 :

$$\nu_m = \frac{\alpha_m C_s^2}{\Omega_K}$$

- Modified first version

$$\nu_m = \frac{\alpha_m C_s^2}{\Omega_K} \sqrt{1 + \beta_\phi}$$

- Radial and vertical dependence as given in Bessolaz et al. 2007:

$$\nu_m = \nu_m = \alpha_m \Omega_K H^2 \exp \left[-\left(\frac{z}{H} \right)^4 \right]$$

***NOTE :** The added terms in the equations indicated in blue color are the modifications that were carried out to develop the simulations considering the case of the quasi-stationary accretion stage.

Physical model description

Accretion disc

The density ρ_d and pressure P_d of the gas in the accretion disc is set following the three-dimensional models of Keplerian accretion discs considering spherical coordinates (R, θ, ϕ) used in Zanni et al. 2009

$$\rho_d(R, r) = \rho_{d0} \left\{ \frac{2}{5h^2} \left[\frac{R_0}{R} - \left(1 - \frac{5h^2}{2} \right) \frac{R_0}{r} \right] \right\}^{3/2},$$

$$P_d = h^2 \rho_{d0} v_{K0}^2 \left(\frac{\rho_d}{\rho_{d0}} \right)^{5/3}$$

where $h = C_s / v_K$ is the aspect ratio, with C_s and $v_K = \sqrt{GM_* / R}$ the sound speed and the Keplerian velocity, respectively. Note that we define $r = R \sin \theta$ as the cylindrical radius.

The velocity components $(u_{Rd}, u_{\theta d}, u_{\phi d})$ of the accretion disc are:

$$u_{Rd} = -\alpha_\nu h^2 \left[10 - \frac{32}{3} \Lambda \alpha_\nu^2 - \Lambda \left(5 - \frac{1}{h^2 \tan^2 \theta} \right) \right] \sqrt{\frac{GM_\star}{R \sin^3 \theta}},$$

$$u_{\phi d} = \left[\sqrt{1 - \frac{5h^2}{2}} + \frac{2}{3} h^2 \alpha_\nu^2 \Lambda \left(1 - \frac{6}{5h^2 \tan^2 \theta} \right) \right] \sqrt{\frac{GM_*}{r}},$$

$$u_{\theta d} = 0.$$

Disc Atmosphere

We included a non-rotating polytropic hydrostatic atmosphere with a density

$$\rho_{\mathrm{atm}}(R) = \rho_{\mathrm{atm}}^0 \left(\frac{R_*}{R} \right)^{\frac{1}{\gamma - 1}}$$

and pressure

$$P_{\mathrm{atm}}(R) = \rho_{\mathrm{atm}}^0 \frac{\gamma - 1}{\gamma} \frac{GM_\star}{R_*} \left(\frac{R_*}{R} \right)^{\frac{\gamma}{\gamma - 1}}$$

with $\gamma = 5/3$. The density contrast between the disc and the atmosphere is $\rho_{\mathrm{atm}}^0 / \rho_{d0} = 0.01$, which is kept fixed in all our models.

Initial Conditions:

$B_* = 6.2kG,\ M = 6M_\odot,\ R = 3R_\odot$ (Korčáková et al. 2022, Kříček et al. 2017)

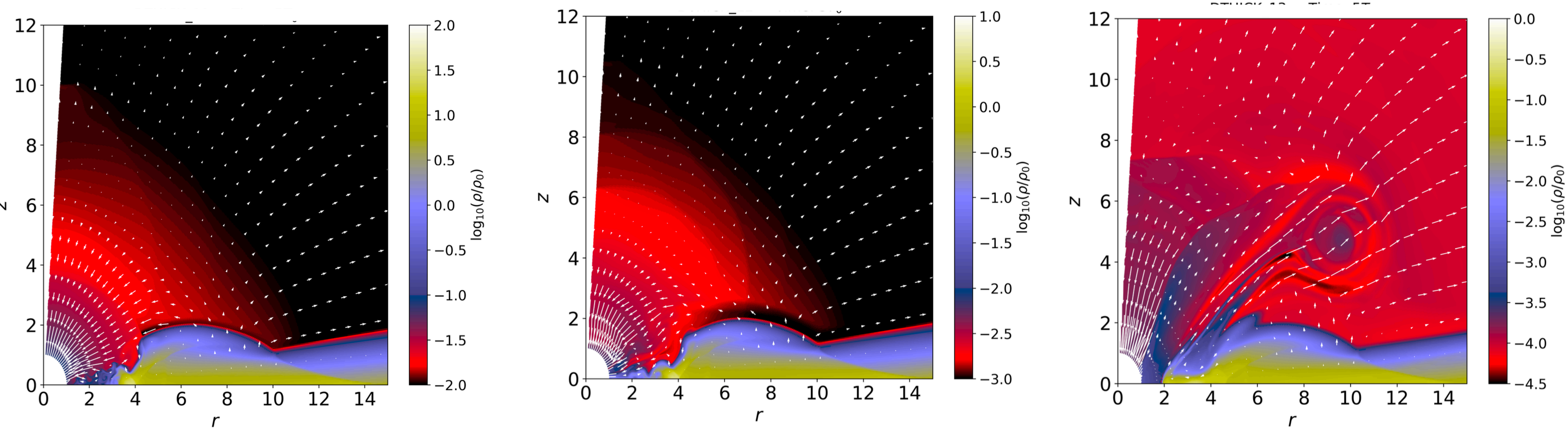
I. Non stationary accretion stage:

- Magnetized **Non-rotating** star with dipolar configuration
- Sub-Keplerian disc rotating around the star.
- Resistivity within the disc.
- Initial density:
  - $1 \times 10^{-13} gcm^{-3}$,
  - $1 \times 10^{-12} gcm^{-3}$,
  - $1 \times 10^{-11} gcm^{-3}$

II. Quasi-Stationary accretion stage:

- Magnetized **rotating** star with dipolar configuration
- Sub-Keplerian disc rotating around the star
- Viscosity ($\alpha_\nu = 1.0\ ,0.1$)and resistivity ($\alpha_m = 1.0\ ,0.1$)within the disc
- Initial density: $1 \times 10^{-13} gcm^{-3}$

Results : I. Non stationary accretion stage



A) h=1.0 & $\rho_{d0} = 1 \times 10^{-11} gcm^{-3}$

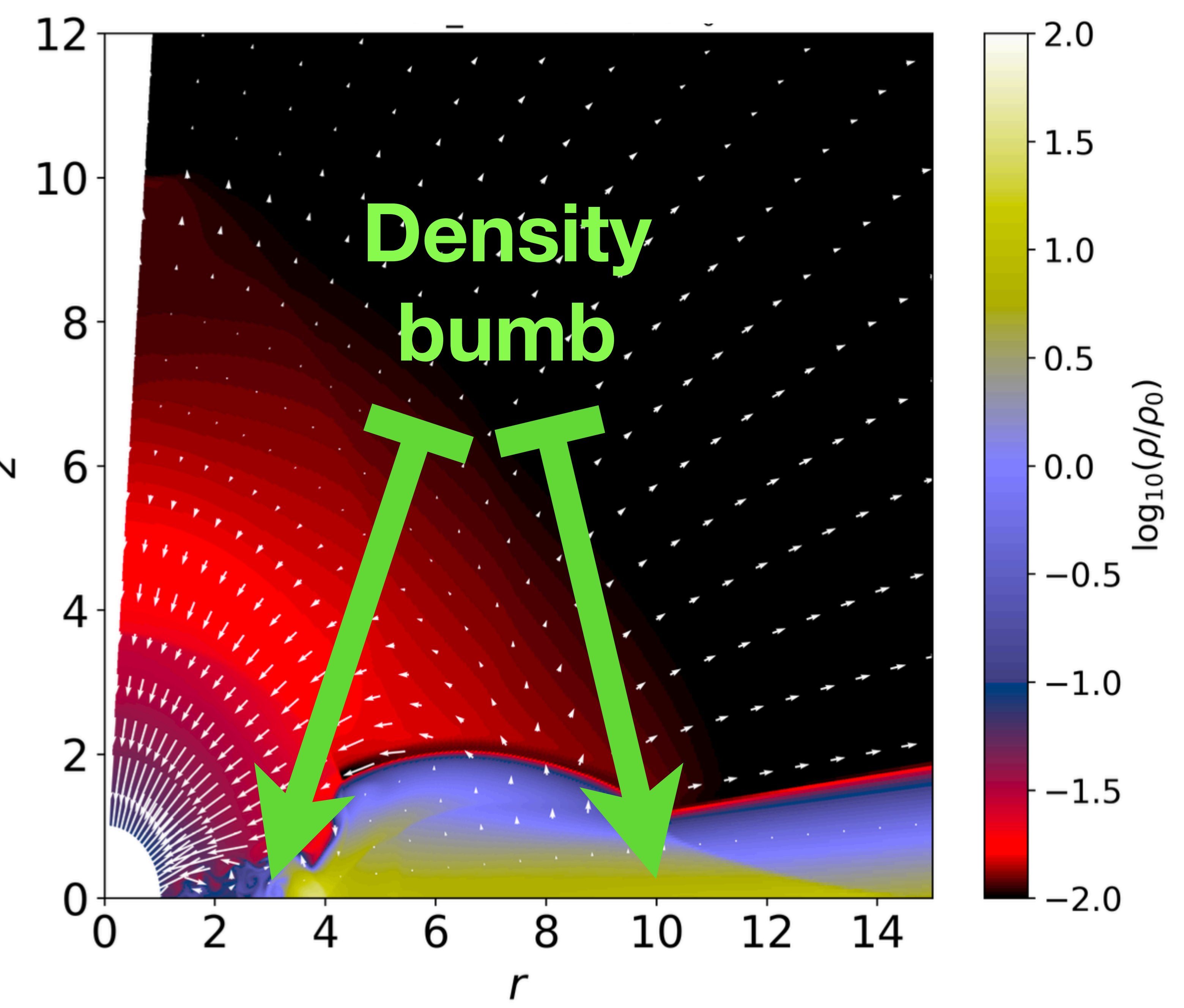
B) h=1.0 & $\rho_{d0} = 1 \times 10^{-12} gcm^{-3}$

C) h=1.0 & $\rho_{d0} = 1 \times 10^{-13} gcm^{-3}$

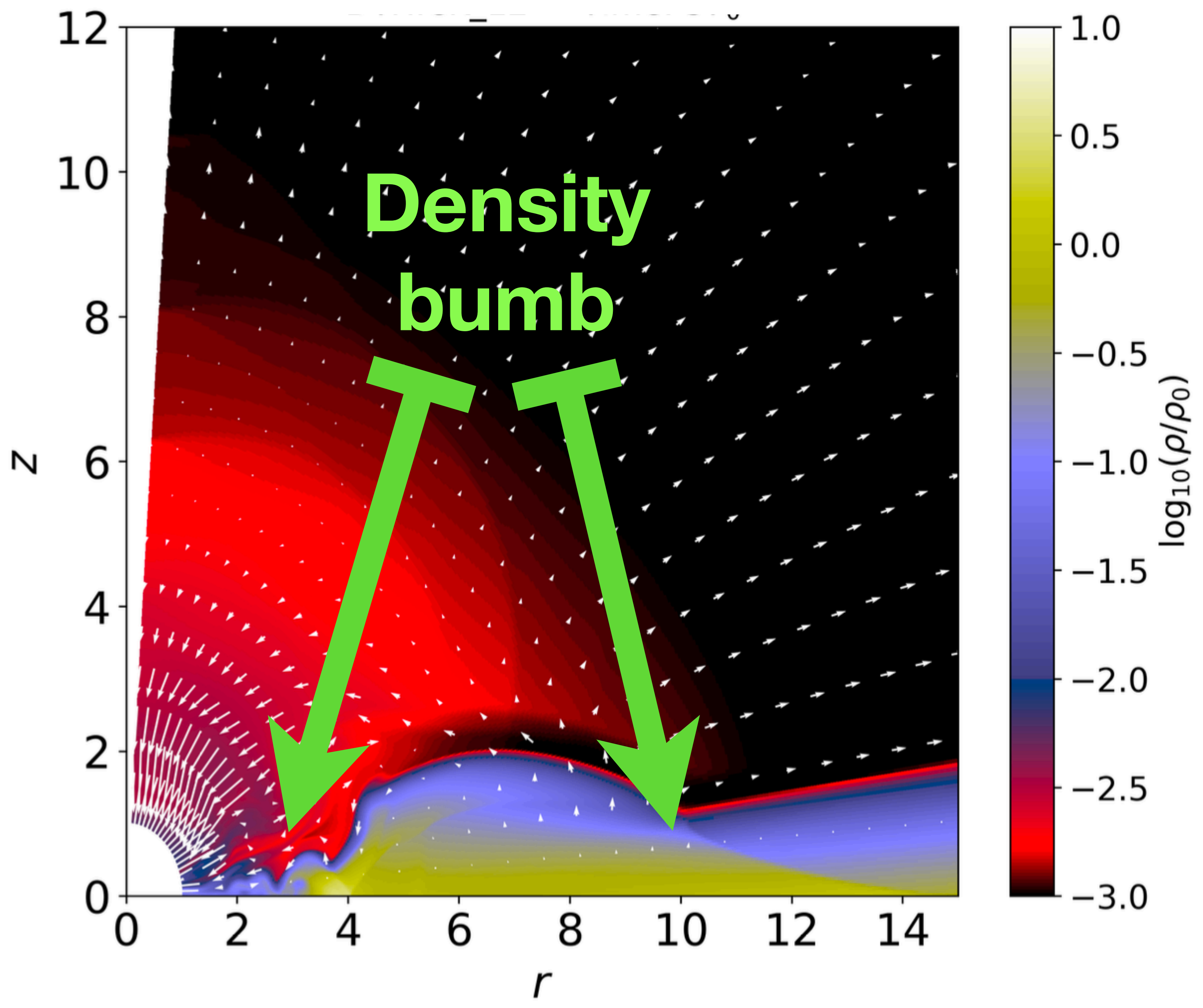
Disc and corona density for three different models at $t = 5T_0$. White arrows depict velocity vectors in the $R - z$ plane. Note, the color scale is different from panel to panel in order to see the structures in the corona region, since it is where the "optical-jet" or "hot-plasmoid" can be form. (Moranchel-Basurto et al. 2023)

Results : I. Non stationary accretion stage

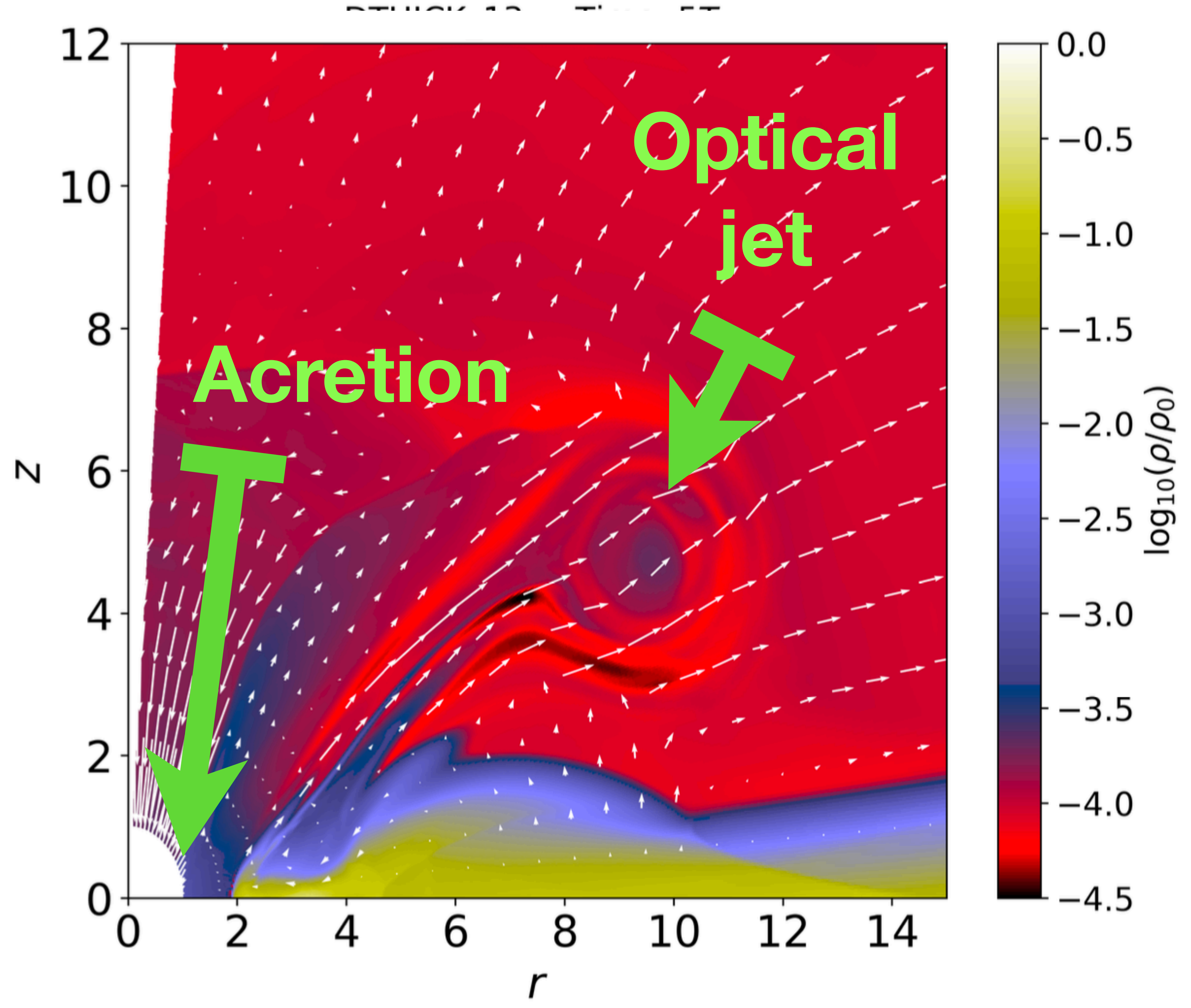
A) h=1.0 & $\rho_{d0} = 1 \times 10^{-11} gcm^{-3}$



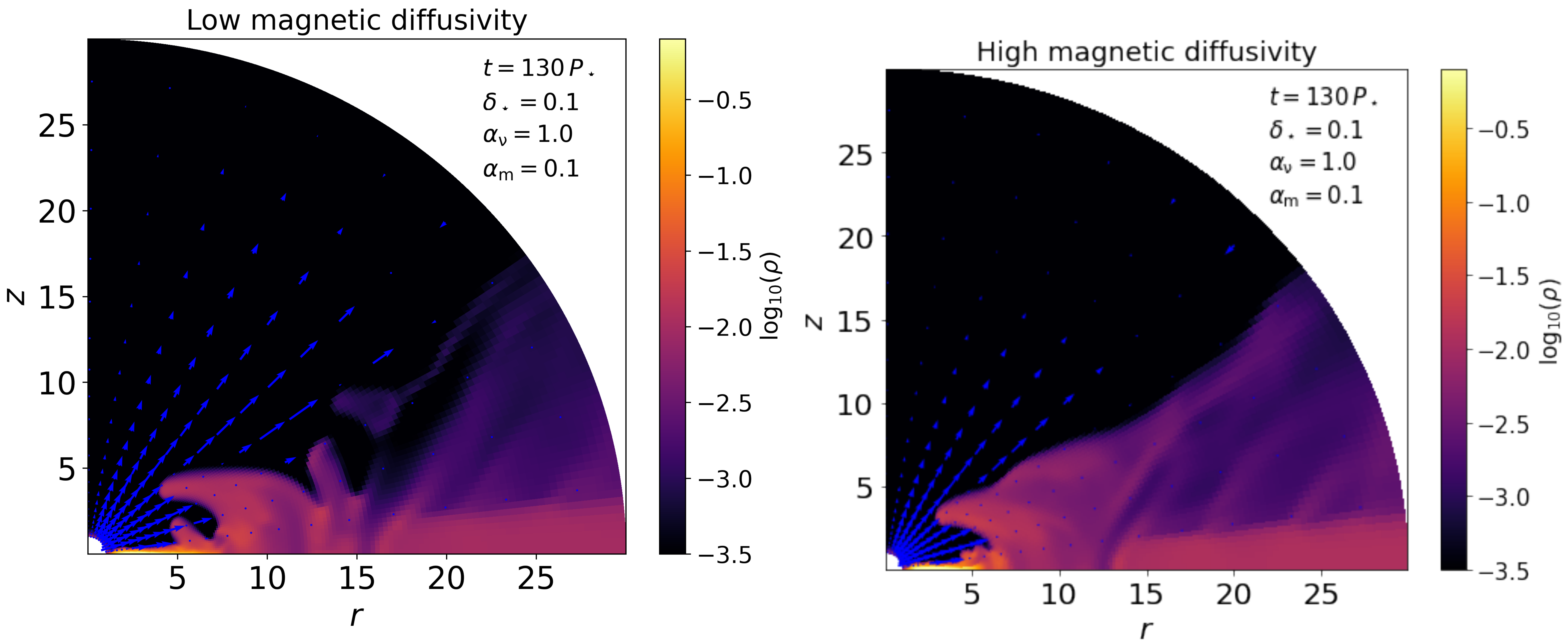
B) h=1.0 & $\rho_{d0} = 1 \times 10^{-12} gcm^{-3}$



C) h=1.0 & $\rho_{d0} = 1 \times 10^{-13} gcm^{-3}$

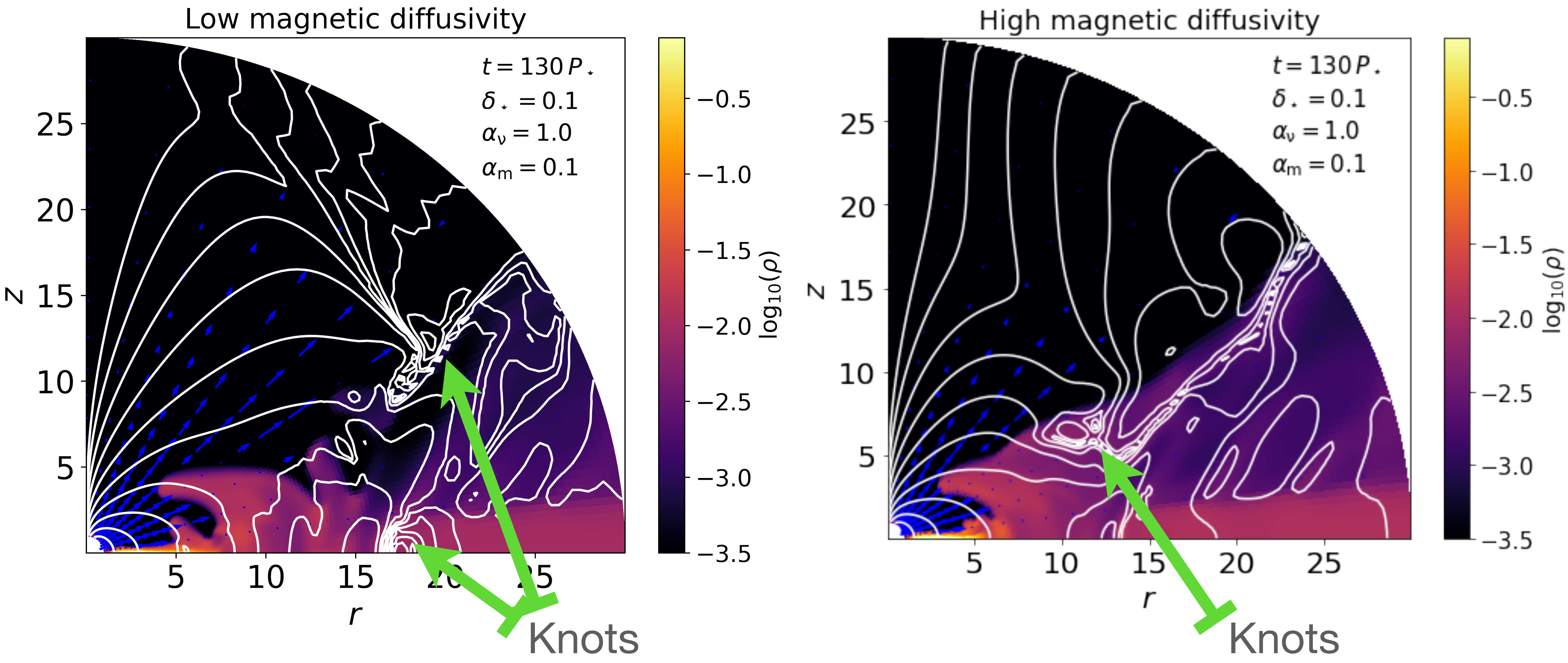


Results : II. Stationary accretion stage



Logarithmic gas density.

Results : II. Stationary accretion stage


Low magnetic diffusivity

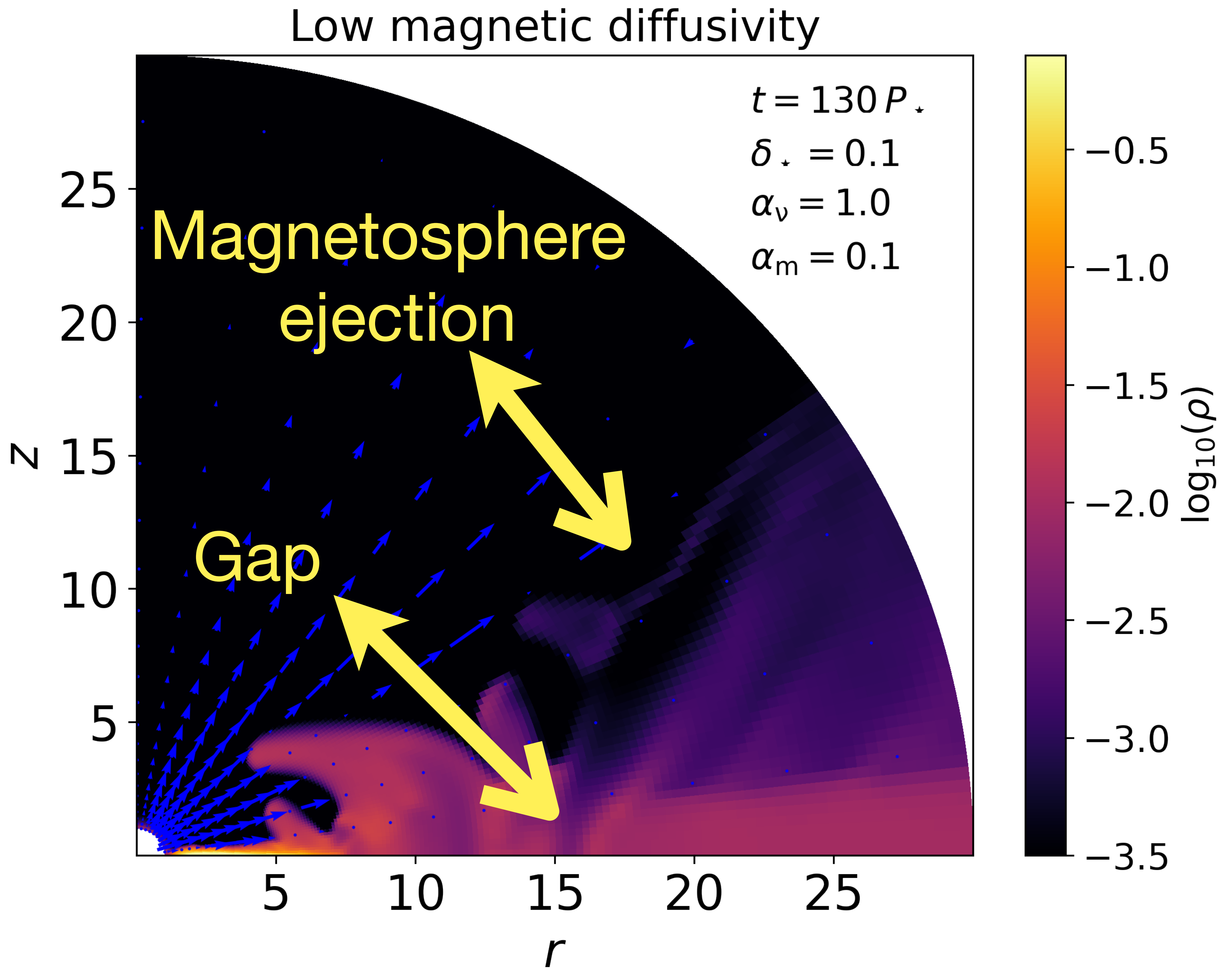
High magnetic diffusivity

Knots

Knots

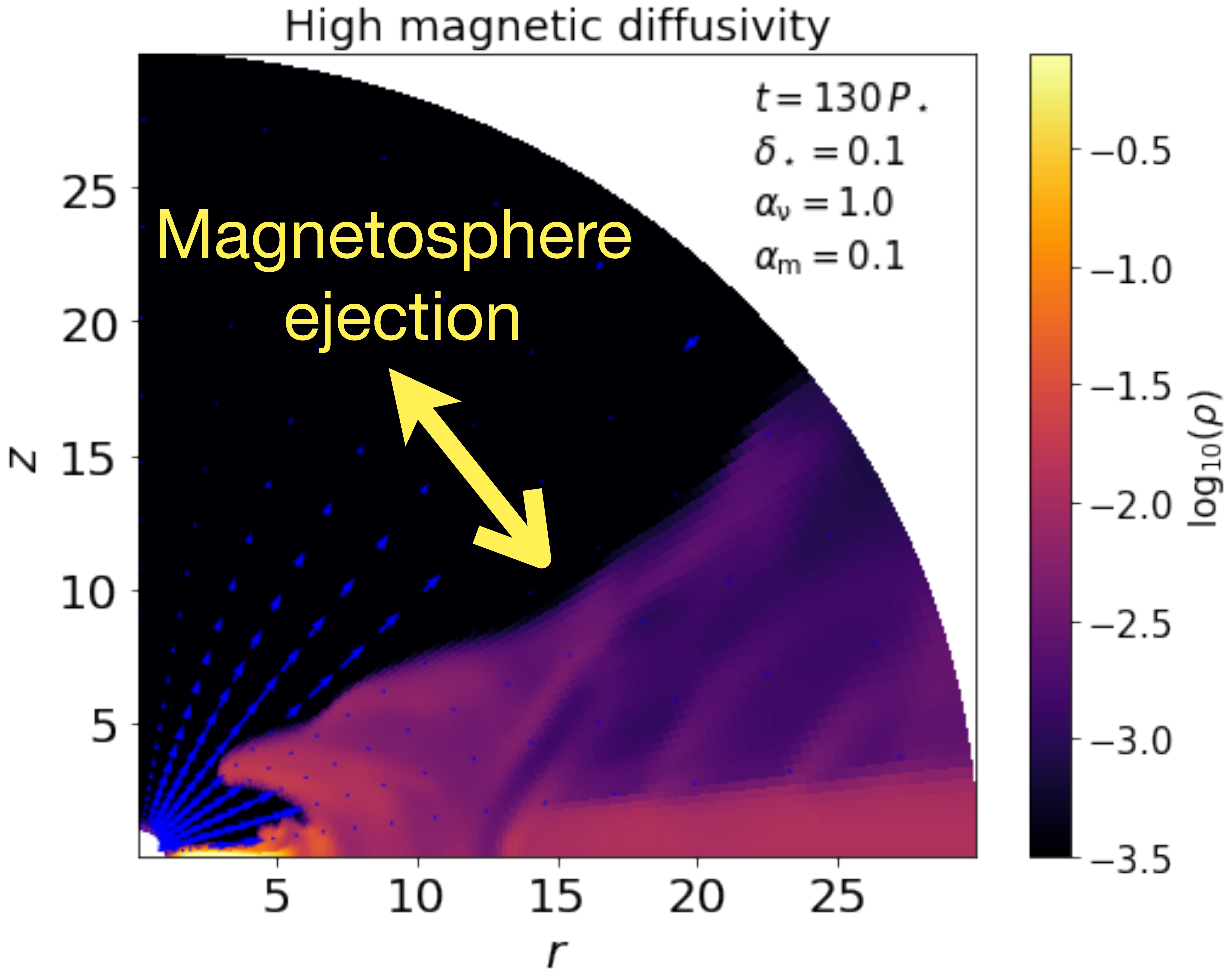
The white lines show the poloidal magnetic field lines.

Results : II. Stationary accretion stage


Low magnetic diffusivity

Magnetosphere ejection

Gap


High magnetic diffusivity

Magnetosphere ejection

Relationship between MHD-Simulations and observations

- Geometrically thick disc - Thick model with low density matches better

- Jets in low density model ->Discrete absorption components of resonance lines (material ejecta) observed in HD 50138 by Pogodin 1997; FS~CMa by Winter & van den Ancker 1997.

- Strong Magnetic field -> formation of a hot corona, observed in several FS~CMa's -> the Raman lines.

- Magnetospheric ejections (low & high resistivity) -> low stellar rotation

Conclusions

I. **Non stationary accretion stage:** the dynamics is driven mainly by the magnetic field of the central star. Especially relevant for the interpretation of the observed properties of FS CMa post-mergers are the results for low-density discs, in which we find a jet emerging from the inner edge of the disc, as well as the formation of the so-called 'hot plasmoid' in the coronal region.

II. **Quasi-Stationary accretion stage:** In all of our models, we find that the disc exhibits a thickening which is characteristic of FS CMa-type stellar objects. Additionally, we find that the poloidal magnetic field lines twist over short periods of time, leading to magnetic reconnection causing coronal heating that could explain the presence of the Raman lines found observationally in several FS CMa stars.

…. Thank you!

More details here

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2.5D magnetohydrodynamic models of circumstellar discs around FS CMa post-mergers – I. Non-stationary accretion stage

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2.5-MHD models of circumstellar discs around FS CMa post-mergers: II. Stationary accretion stage

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Magnetic field configuration

The magnetic field is defined by the flux function:

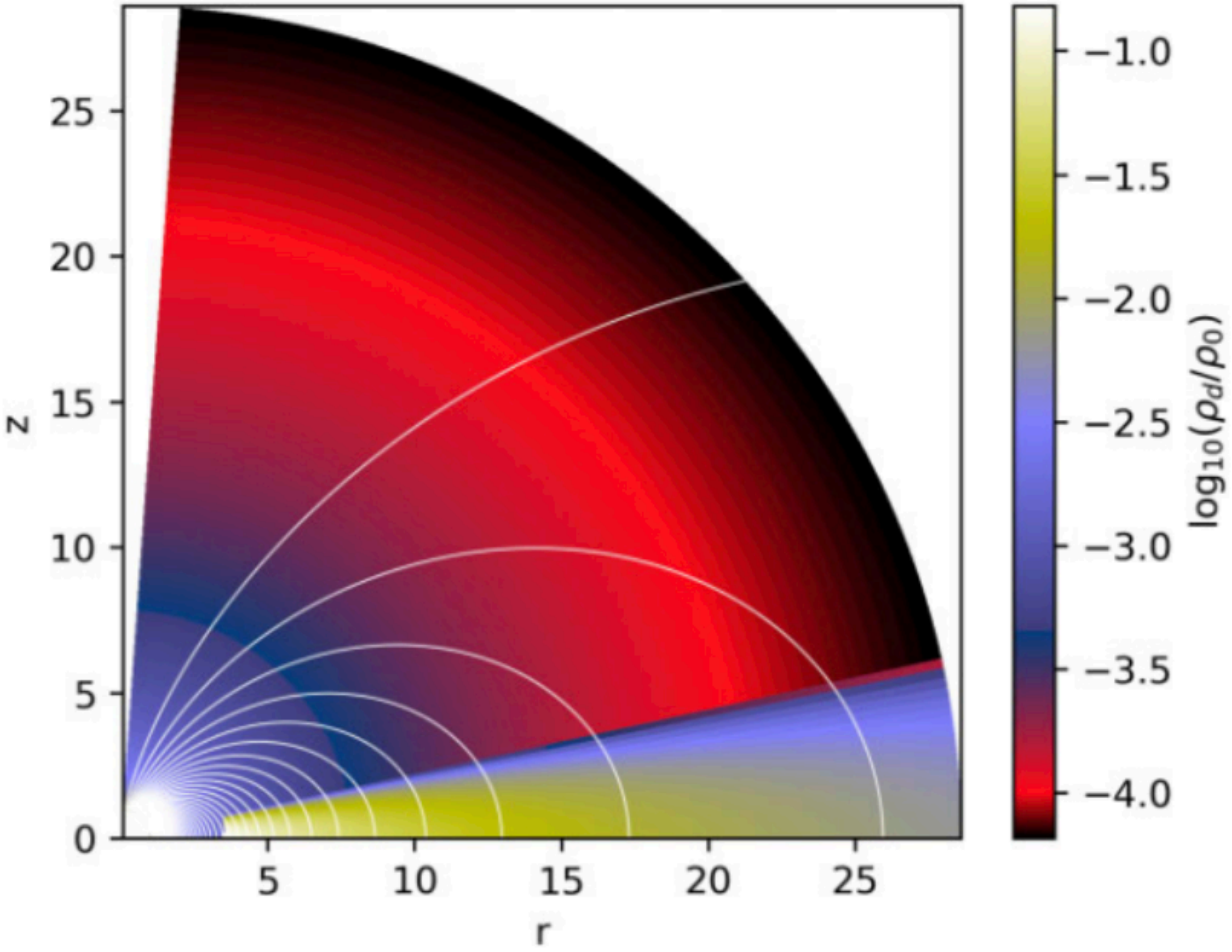
$$\Psi_*(R,\theta) = B_* R_*^3 \frac{\sin^2\theta}{R}$$

where B_* is the magnetic field at R_* and z=0. The radial and polar field components are therefore given respectively by:

$$B_R = \frac{1}{R^2\sin\theta}\frac{\partial\Psi_*}{\partial\theta} \quad ; \quad B_\theta = -\frac{1}{R\sin\theta}\frac{\partial\Psi_*}{\partial R}$$

The relation between flux function and potencial vector is given by: $\Psi_* = RA_\phi\sin\theta$. And then the components of potential vector in spherical coordinates are given by:

$$A_\phi(R,\theta) = \frac{B_* R_*^3\sin\theta}{R^2}, \quad A_R = 0,\ A_\theta = 0.$$



Initial density in the model with lower density in logarithmic scale in units of ρ_0 . Sample field lines of the initially dipolar magnetosphere are also shown (white lines). Moranchel-Basurto et al. 2023 (Paper 1).