Relativistic MHD Simulations of Magnetic Fields in Jets of GRBs

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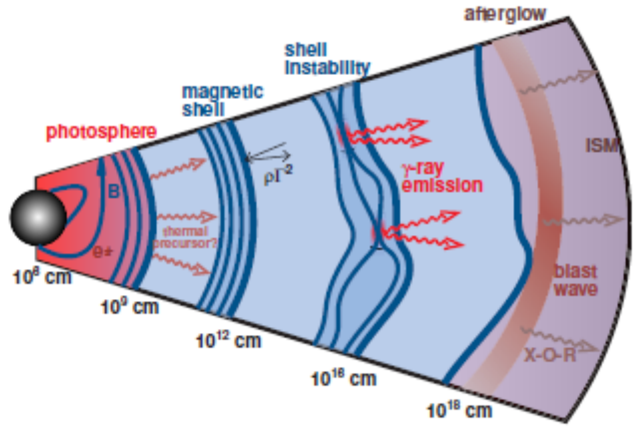
Summary of the Theoretical Efforts

- As posed by Asaf Pe'er(2011):
  - Understanding the nature of the progenitor
  - Understand jet launching mechanism, and the role played by photons and magnetic fields in the processes.
  - Jet Composition: what is the role played by leptons, hadrons and magnetic fields (e.g., Ferrari et al.)?
  - Understand the nature of dissipation mechanism that leads to the emission of gamma-rays
  - Radiative processes, and physical explanation to the broad band spectrum observed.
  - Connections between GRBs and others object of interest

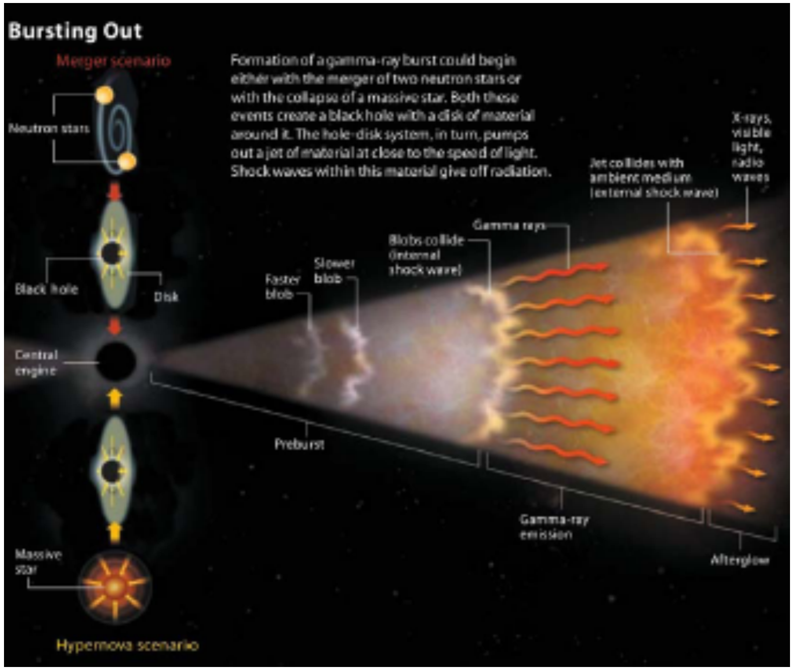
Numerical Simulations can address almost all of them!!!

Models of GRB's

- We have at least 2 classes of models
  - Standard fireball
  - MHD, Eletromagnetic Model



Lyutikov,M. arXiv 0310040



Gehrels, Piro, & Leonard 2007

Diference between Models

Composition of the emission ?

Answer remains in the ratio between Poynting Flux and (baryonic) matter flux :

$$\sigma = \frac{F_{\mathrm{Poynting}}}{F_{\mathrm{p}}} = \frac{B^2}{4\pi\Gamma\rho c^2} = \frac{b'^2}{8\pi\rho' c^2}$$

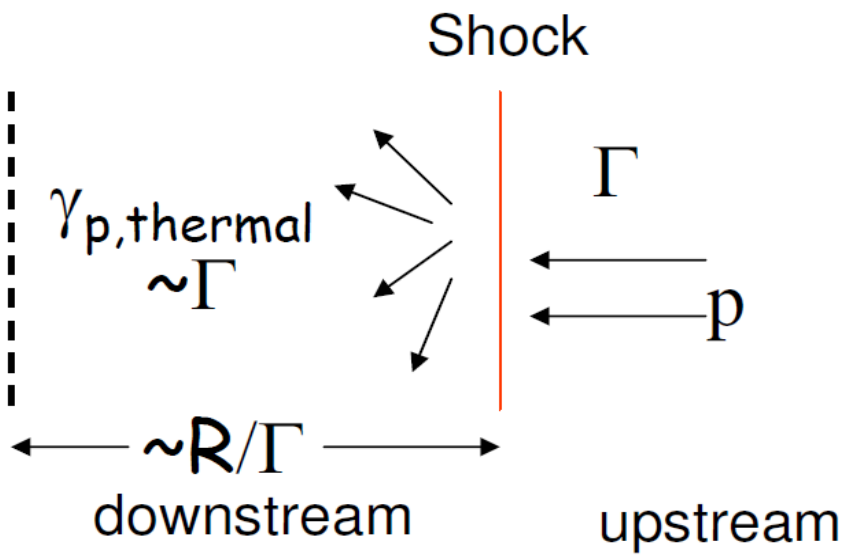
In the FBM σ << 1, MHD models work in the regime σ ~ 1,

EMM model assumes σ >> 1.

The question of the GRB model is then reduced to the question how large is σ in the ejecta?

The relevant aspect of microphysics: *Magnetic Fields*

- In the standard fireball model: afterglow shocks are highly non-magnetized



Upstream

$$U_{B,up}/nm_pc^2 \sim 10^{-10} \text{ (Waxman, 2006)}$$

$$B_{up} \sim 3\mu G$$

Ratio of magnetic energy density: $U_{B,upstream}/U_{B,downstream} = 10^{-8}$

Question:

If we have synchroton emission:

Magnetic fields + relativistic electrons

How do we explain the fact that observations require high magnetic field (even up to ~1Gauss see Yost, S. A.; Harrison, F. A.; Sari, R.; Frail, D. A., ApJ,597,497) **in downstream and high efficient acceleration ?**

Possible Answers:

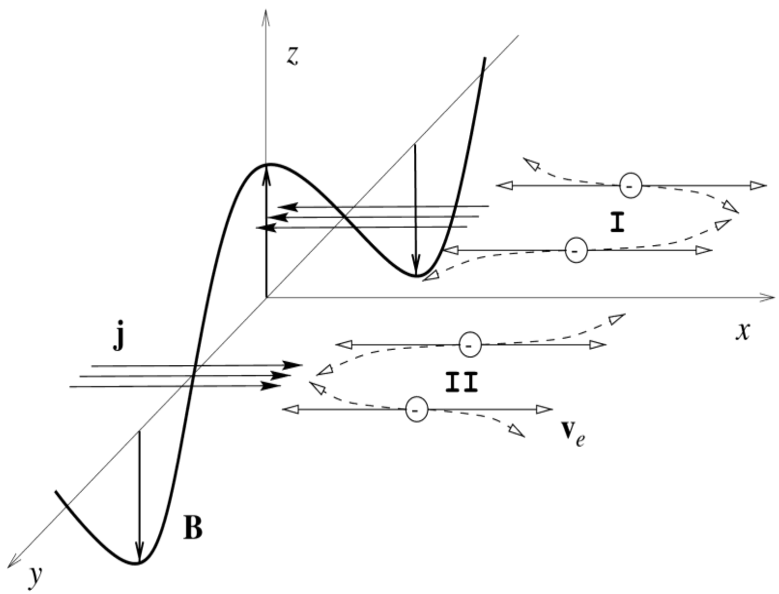
~~- Reduced Data is wrong !~~
- Standard fireball model is wrong !
- Strong amplification of magnetic field

Amplification Mechanisms

Possible mechanisms:

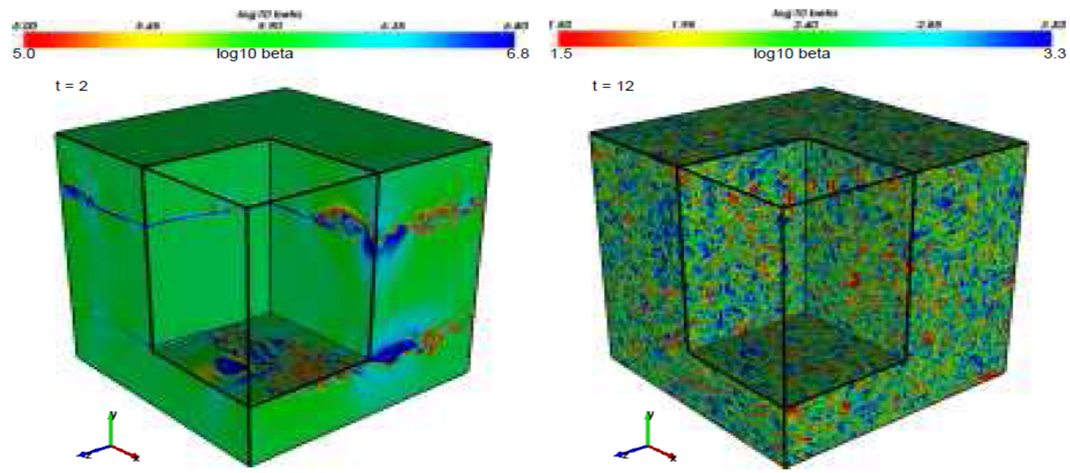
- Instabilities and Shock Compression

- Weibel (Two-Stream)



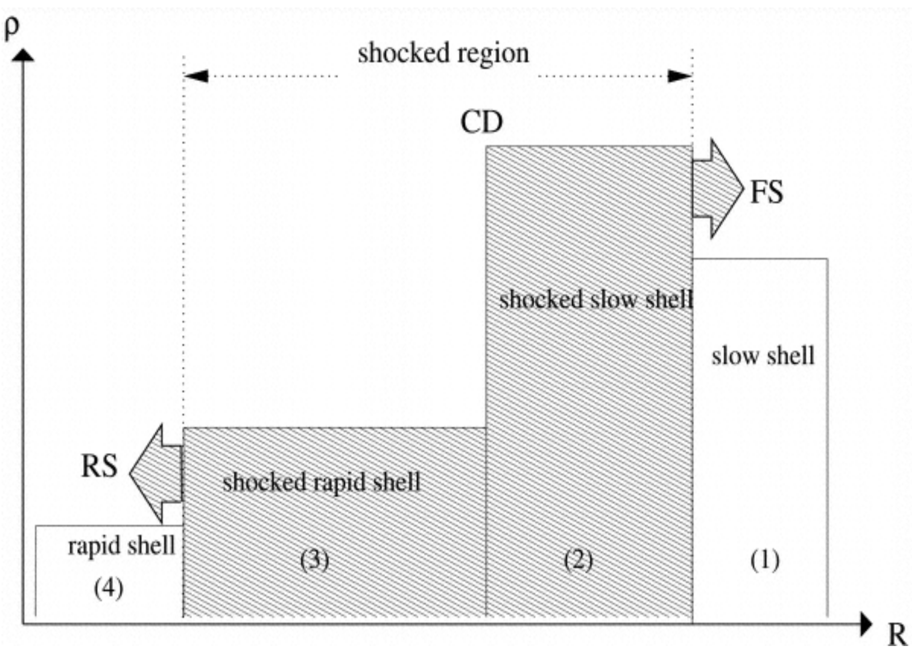
Medvedev e Loeb (1999)

- Kelvin-Helmholtz



Evolution of plasma beta. Ratio of gas pressure to the magnetic pressure.
Zhang, MacFadyen & Wang (2009)

Shock Compression



Kino,Mizuta & Yamada 2003

We find that the magnetic field required in the external forward shock for the observed high and low energy emissions for these three bursts is consistent with shock-compressed magnetic field in the CSM; the magnetic field in the CSM – before shock compression – should be on the order of a few tens of micro-Gauss (see figs. 1, 3 and 5). For these three bursts, at least, no magnetic dynamo is needed to operate behind the shock front to amplify the magnetic field.

The data for the short burst (GRB 090510) are consistent with the [illegible]dium in the vicinity of the burst (within $\sim$1 pc) being [illegible]form and wi[illegible]ensity less than 0.1 cm^{-3}; the data r[illegible]out a CSM where $n \propto R^{-2}$. On the [illegible] the data for one of the two long *Fermi* bursts (GRB 080916C) prefers a wind like medium and the other (GRB 090902B) a uniform density medium; these con-

Kumar & Barniol Duran, 2010
Analysis of Fermi results for GRBs: 080916C,090510,090902B

Shock compression maybe is working fine !
Limitations: Amplification is not that large!

Relativistic Rankine-Hugoniot Conditions

Ideal MHD:

$$n_1 u_1 = n_2 u_2 \,,$$

$$E = \frac{u_1 B_1}{\gamma_1} = \frac{u_2 B_2}{\gamma_2} \,,$$

$$\gamma_1 \mu_1 + \frac{E B_1}{4\pi n_1 u_1} = \gamma_2 \mu_2 + \frac{E B_2}{4\pi n_1 u_1} \,,$$

$$\mu_1 u_1 + \frac{P_1}{n_1 u_1} + \frac{B_1^2}{8\pi n_1 u_1} = \mu_2 u_2 + \frac{P_2}{n_1 u_1} + \frac{B_2^2}{8\pi n_1 u_1} \,.$$

$$\mu = mc^2 + \frac{\Gamma}{\Gamma - 1}\left(\frac{P}{n}\right);$$

Ideal RMHD: Magnetic Field Amplification

$$Y \equiv \frac{B_2}{B_1} = \frac{N_2}{N_1} = \frac{\gamma_2 u_1}{\gamma_1 u_2} \,.$$

$$Y^2 - Y\left[\frac{2}{\gamma_2 u_2}\left(u_2^2 + \frac{1}{4}\right)\frac{u_1}{\gamma_1}\right] + \left[\frac{2}{\gamma_2 u_2}\left(u_2^2 + \frac{1}{4}\right)\left(\frac{4\pi n_1 \mu_1 \gamma_1^2}{B_1^2} + \frac{u_1}{\gamma_1}\right)\right] - \frac{2\pi n_1 mc^2}{B_1^2}\frac{u_2}{u_1} - \left(1 + \frac{8\pi n_1 \mu_1 u_1^2 + P_1}{B_1^2}\right) = 0 \,.$$

Set of Equations solved for the Shock

If we have RRH equations why Numerical Simulations?

- Shock is not the only important phenomena associated with the jet propagation!

- What about the combined effect of amplification, in the bow shock region, and Kelvin-Helmholtz instability?

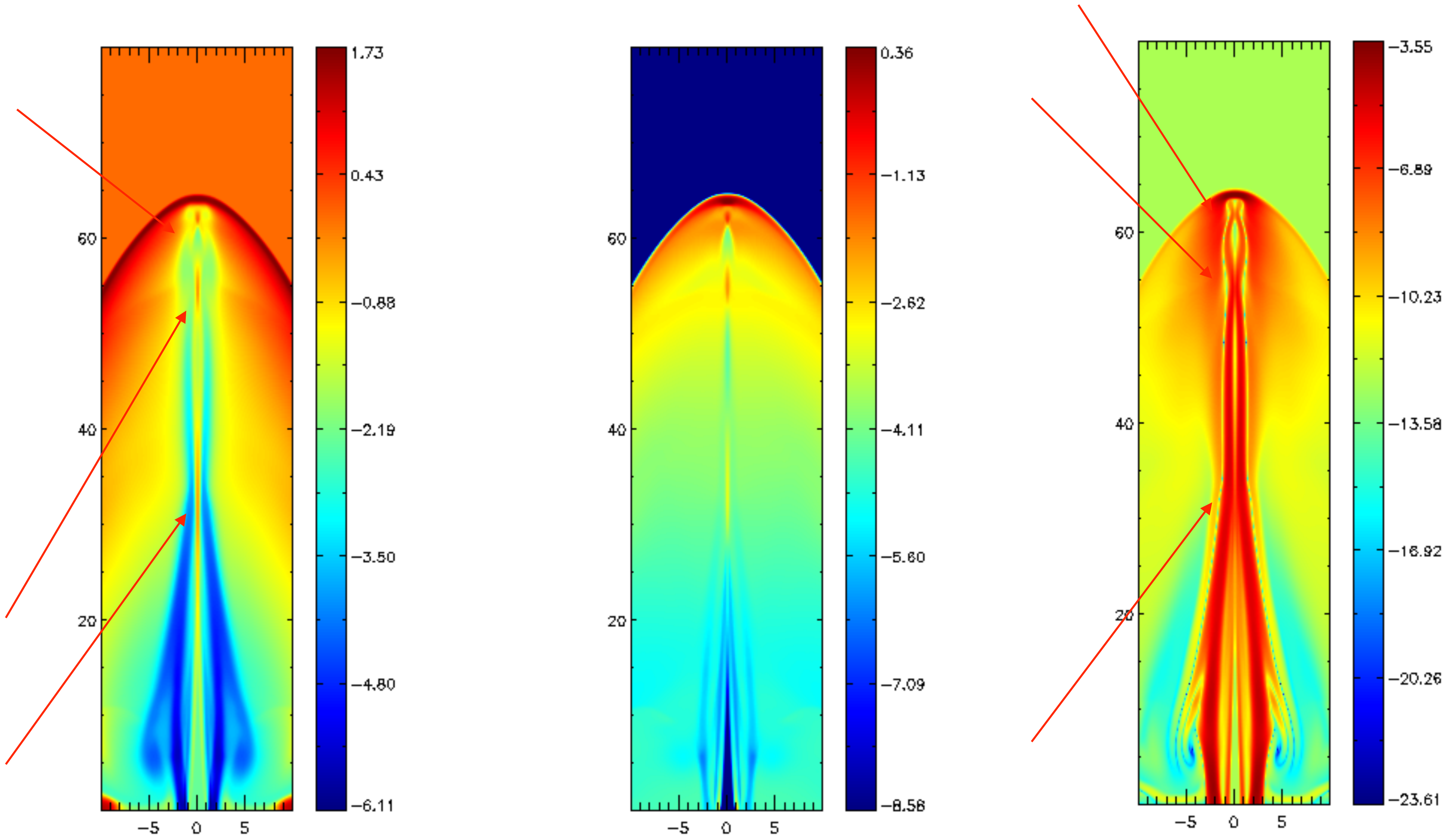
- What about cooling effects ? Can we emulate this without knowing in detail the dominant radiative processes ?

- What about the amplification of the magnetic field in an already magnetized jet for EMM models ?

Relativistic Magnetized Jets

RMHD Simulations: Adiabatic Jet

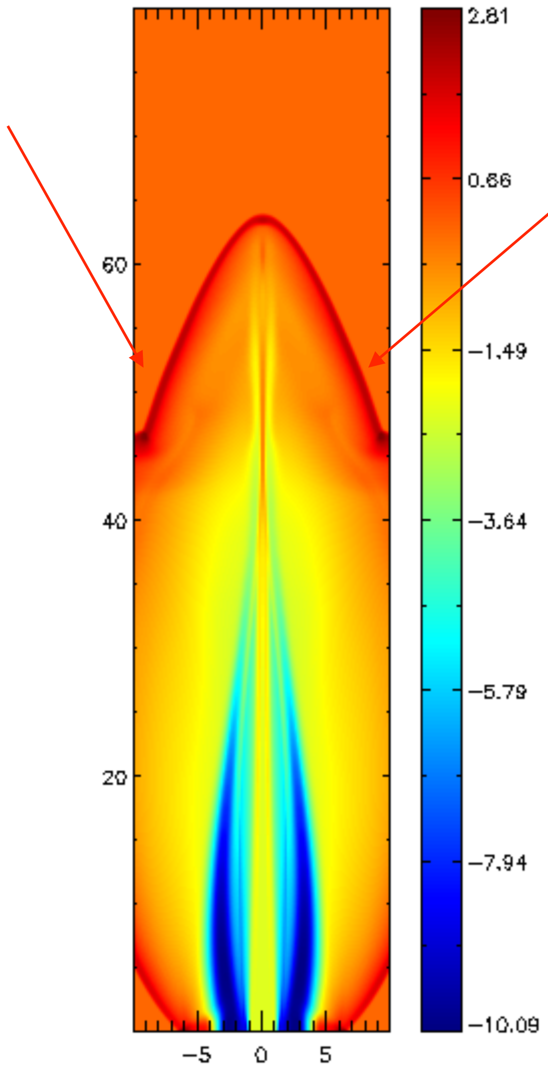
Important Parameters
Lorentz:10
Mach:20
rhoj/rhoa = 0.1
Gamma=4/3



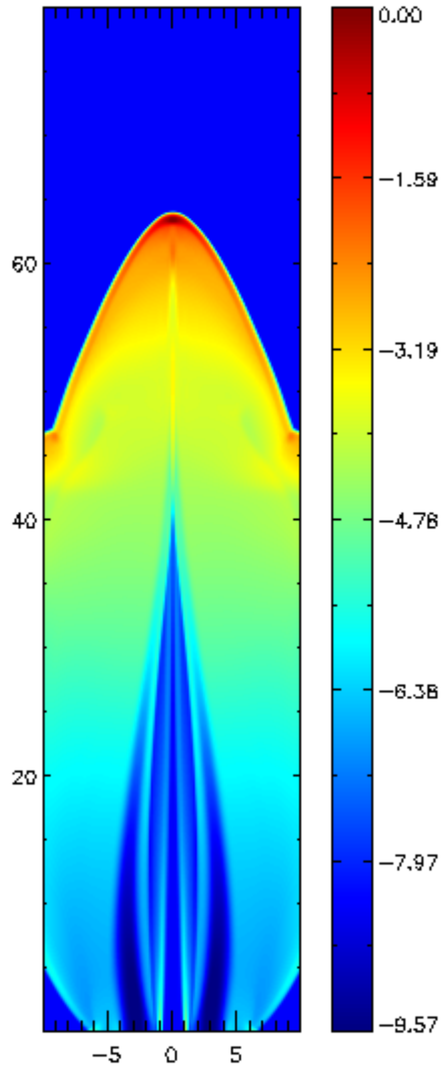
density pressure magnetic energy

RMHD Simulations: Non-adiabatic Jet

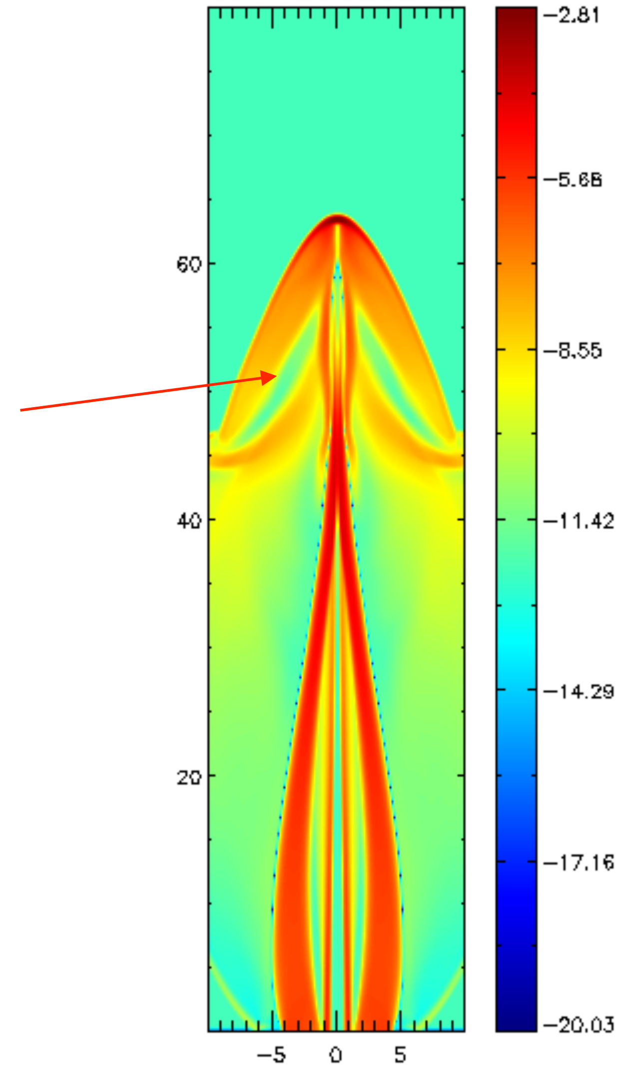
Important Parameters
Lorentz:10
Mach:20
rhoj/rhoa = 0.1
Gamma=1.1



density

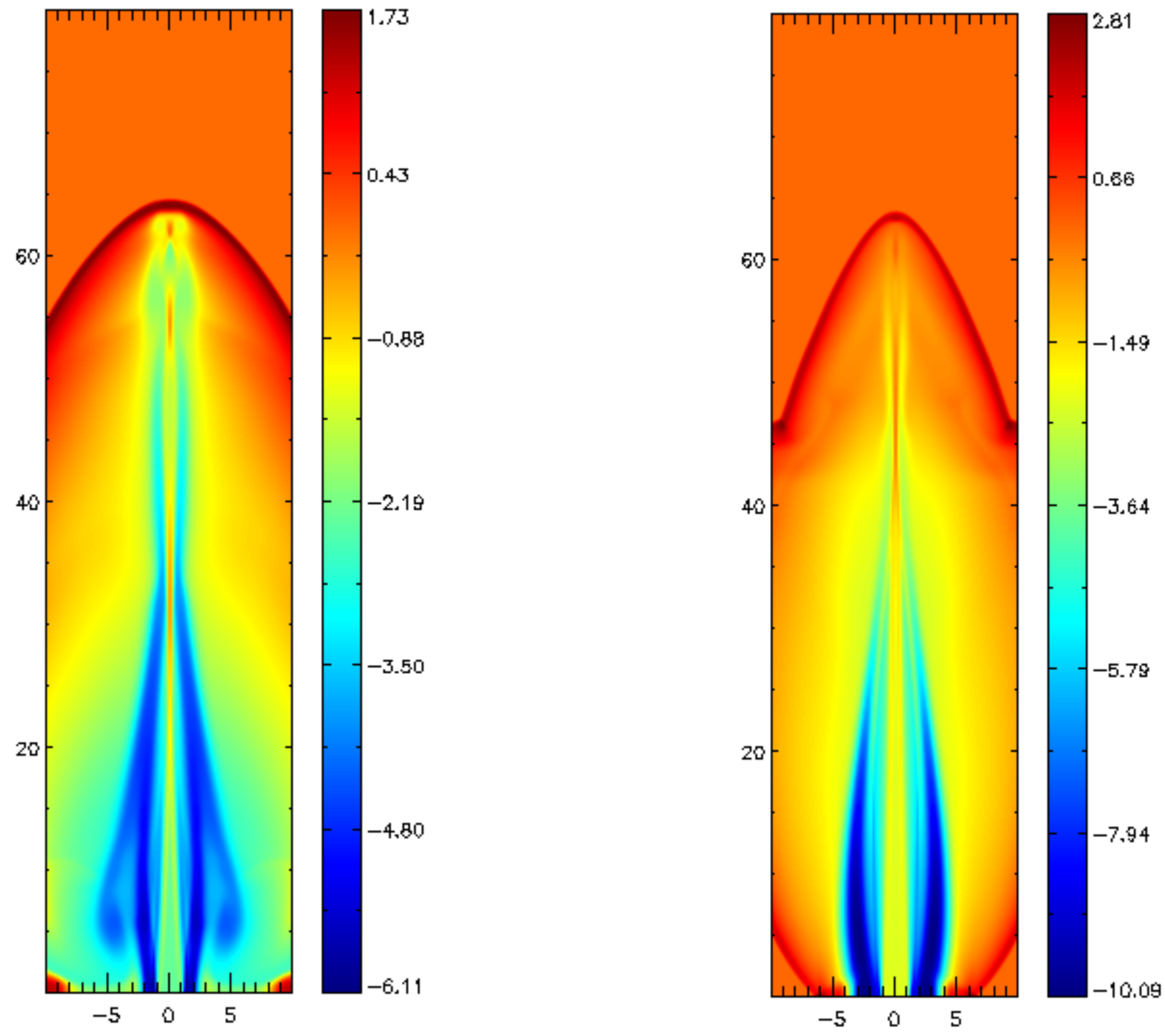


pressure

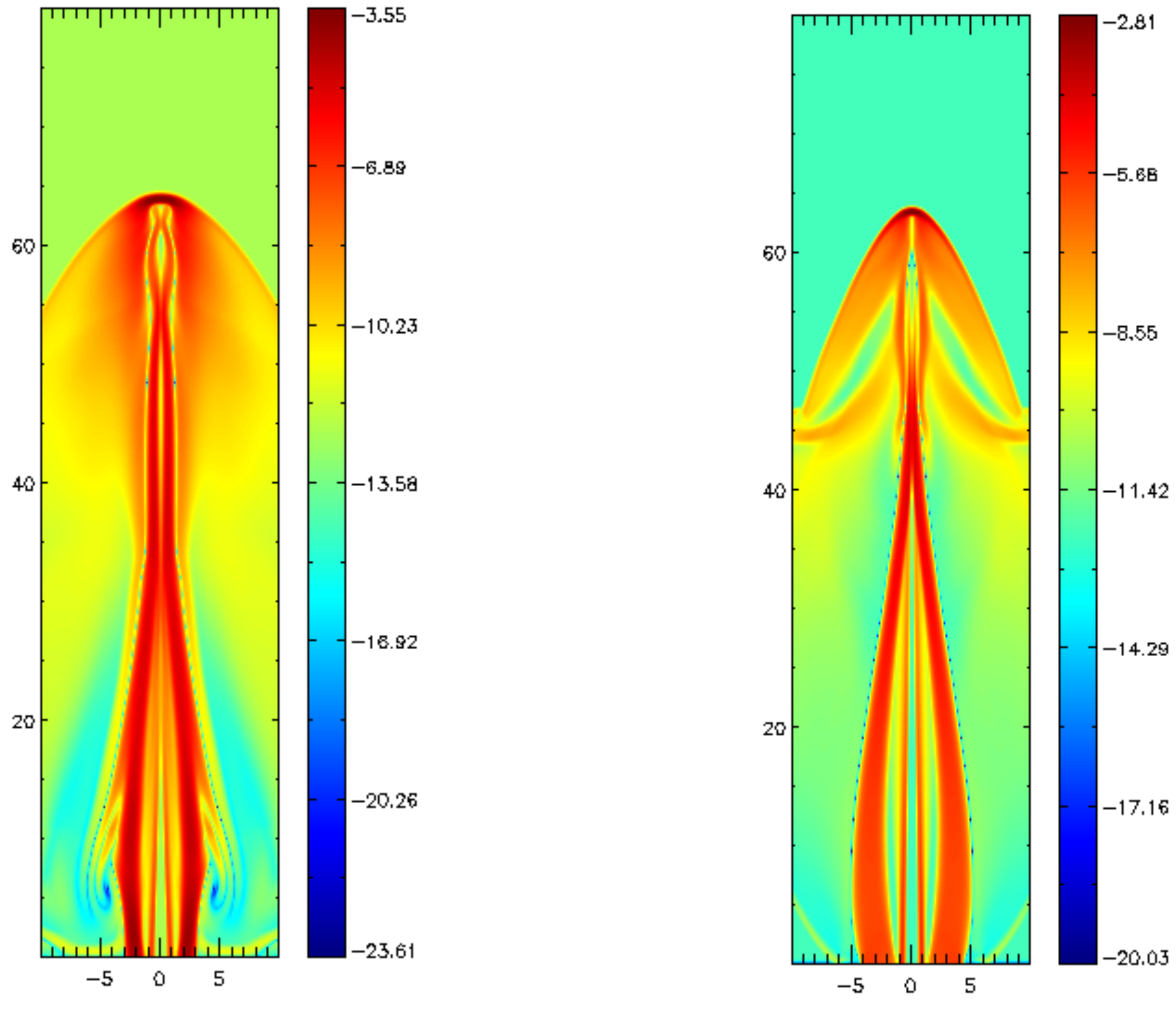


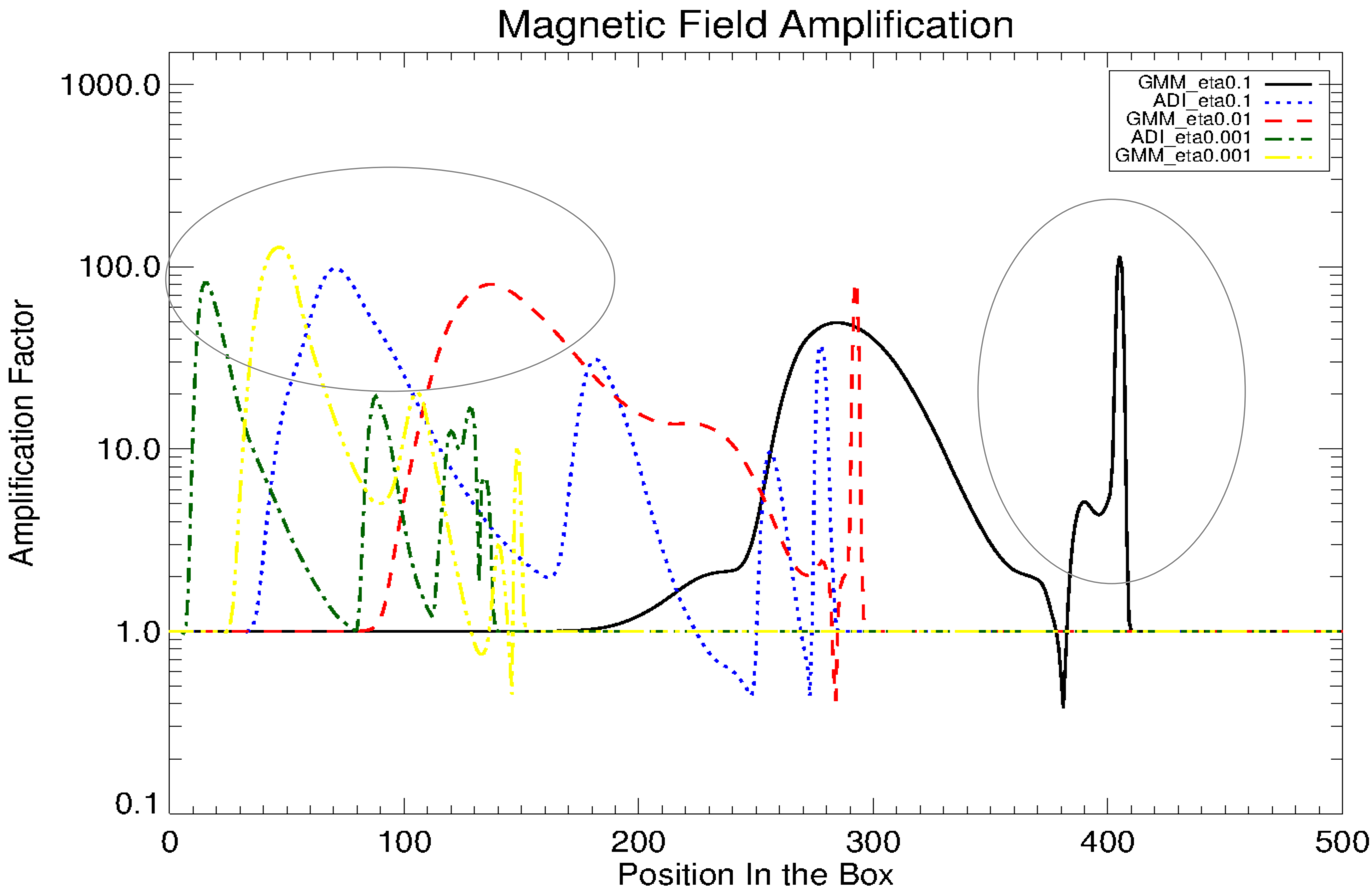
magnetic energy

Adiabatic X Non-adiabatic : Density

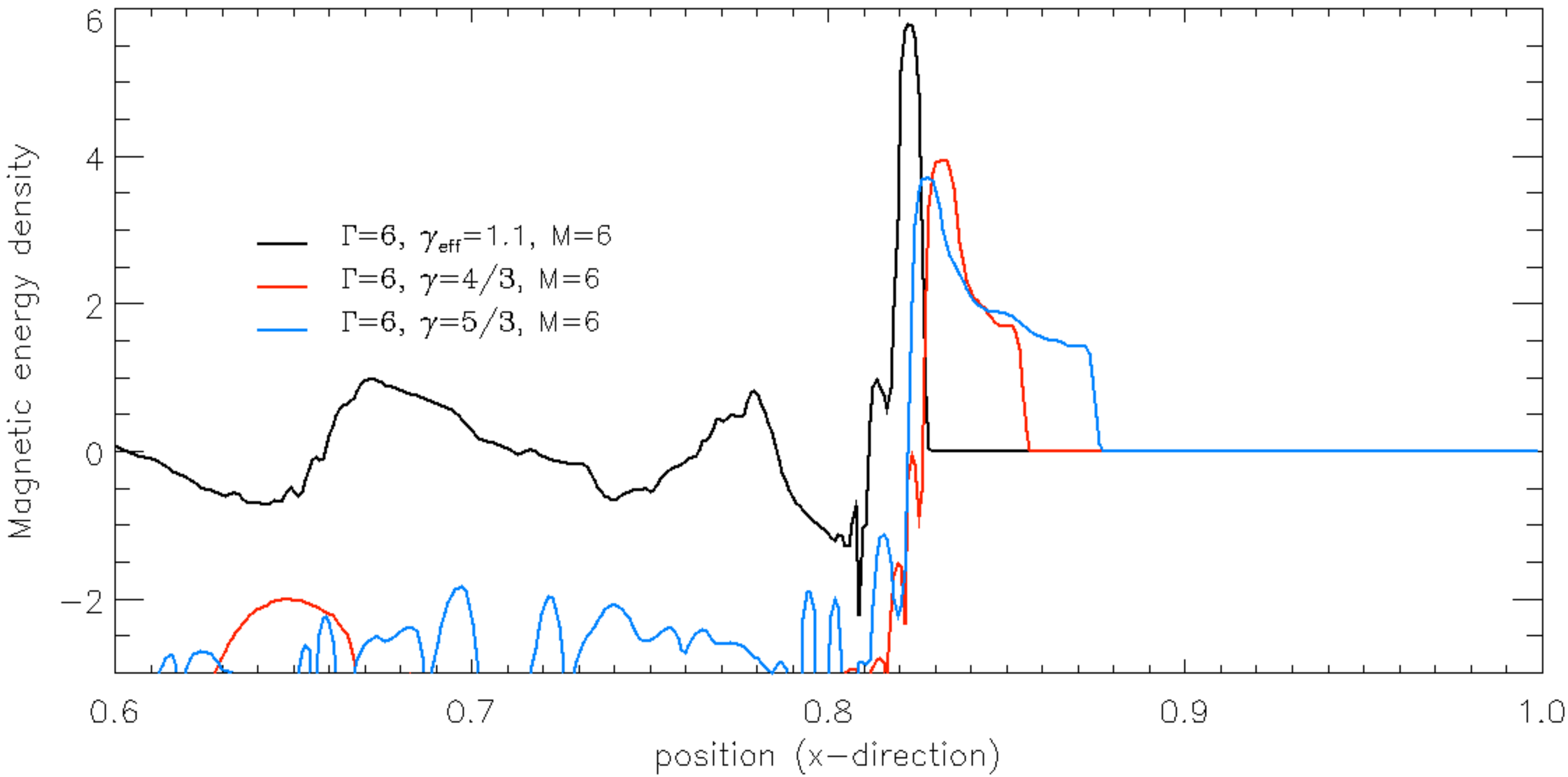


Adiabatic X Non-adiabatic : Magnetic Energy



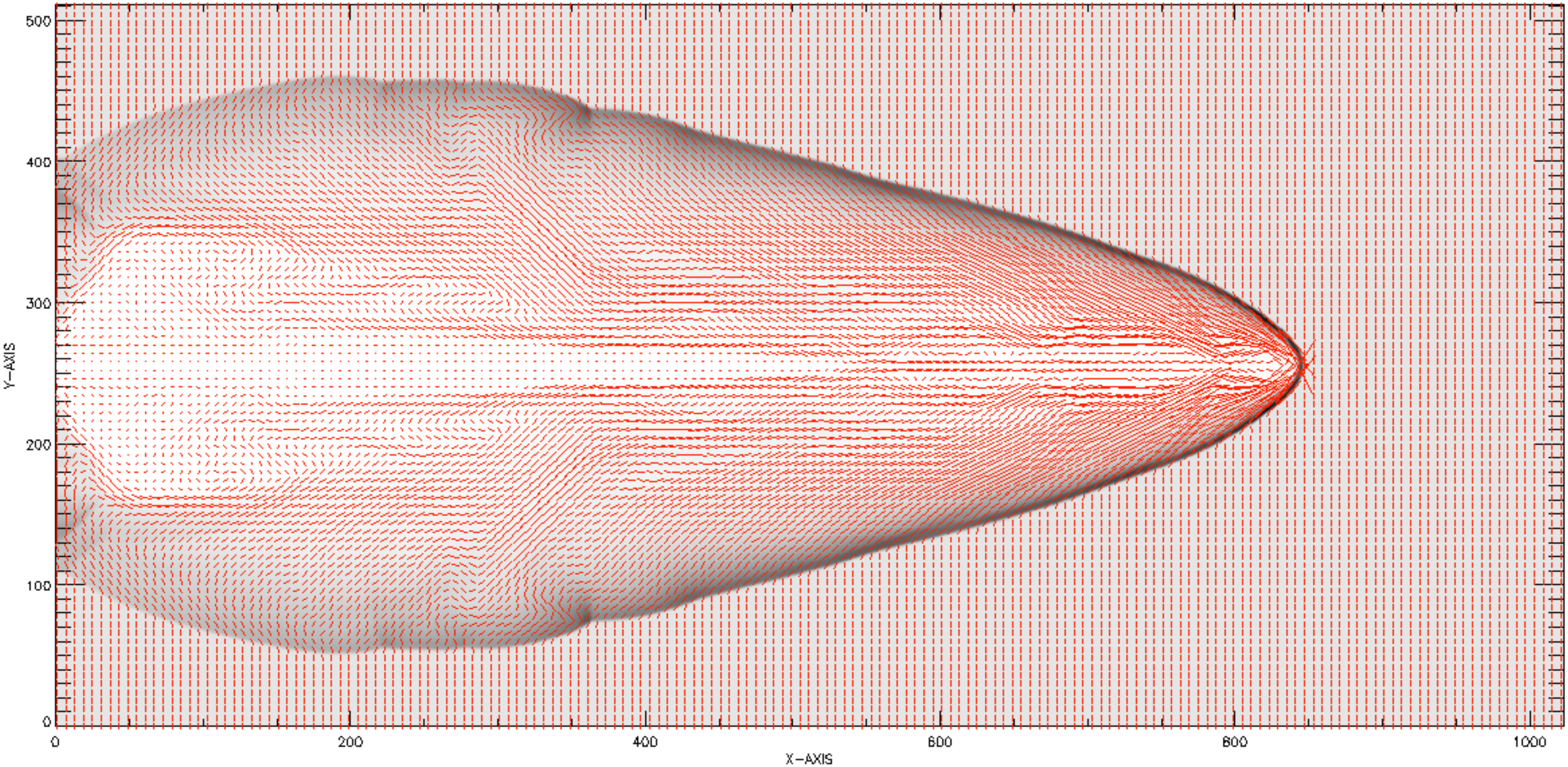


Magnetic Field Amplification
GMM_eta0.1
ADI_eta0.1
GMM_eta0.01
ADI_eta0.001
GMM_eta0.001
1000.0
100.0
10.0
1.0
0.1
0
100
200
300
400
500
Amplification Factor
Position In the Box



Non-Magnetized Jet
Diego Falceta-Gonçalves
AMUN Code - http://www.amuncode.org/
Now with an amazing Relativistic module !!!

Kowal, G., de Gouveia Dal Pino, E. M., and Lazarian, A., 2011, ApJ



500
400
300
200
100
0
Y–AXIS
0
200
400
600
800
1000
X–AXIS

Conclusions

- Cooling Effects are important not only because of jet morphology but because of the amplification factors of the magnetic field.

- Effects of plasma instabilities must be studied in order to verify their role on the emission (possible insights about magnetic fields and particle acceleration).

- Equipartition is a too simplistic approach and should not be considered.

- Magnetic field amplification in a cooling plasma is even more important in the case of a non-magnetized jet.

- The same approach can be used to study the validity of the internal shocks model, and not only for the afterglow emission.

- Pulsing Jets should be studied in order to study the effect on the magnetic field amplification.