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Title: Relativistic MHD simulations of collision-induced magnetic dissipation in Poynting-flux-dominated jets/outflows

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Relativistic MHD simulations of collision-induced magnetic dissipation in Poynting-flux-dominated jets/outflows

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ApJ, in press, arXiv:1501.07595

LA-UR-15-20564

What is the energy composition of the jets/outflows in high energy astrophysical systems, e.g. GRBs, AGNs ?

Matter-flux-dominated (MFD) $\sigma < 1$

and/or

Poynting-flux-dominated (PFD) $\sigma > 1$

Affect the following:

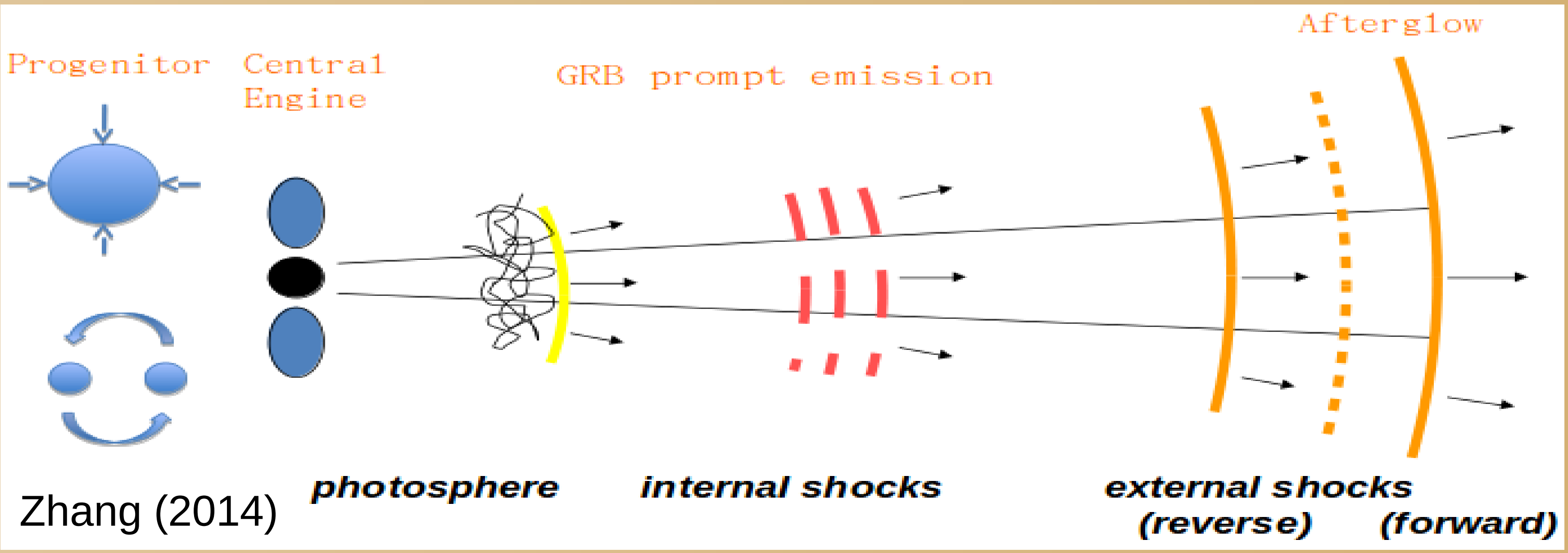
- Energy dissipation mechanism;
- Particle acceleration mechanism;
- Radiation mechanism.

Several models have been proposed:

MFD -- Standard fireball IS model

(Rees & Mészáros 1994, Paczýnski & Xu 1994)

- Merits: relative easy to interpret the fast variability of the light curve; shocks widely exist in many astrophysical systems.
- Criticisms: synchrotron fast cooling problem, low energy dissipation efficiency problem, electron number excess problem, missing bright photosphere, and so on.



Zhang (2014)

MFD – Dissipative photosphere model

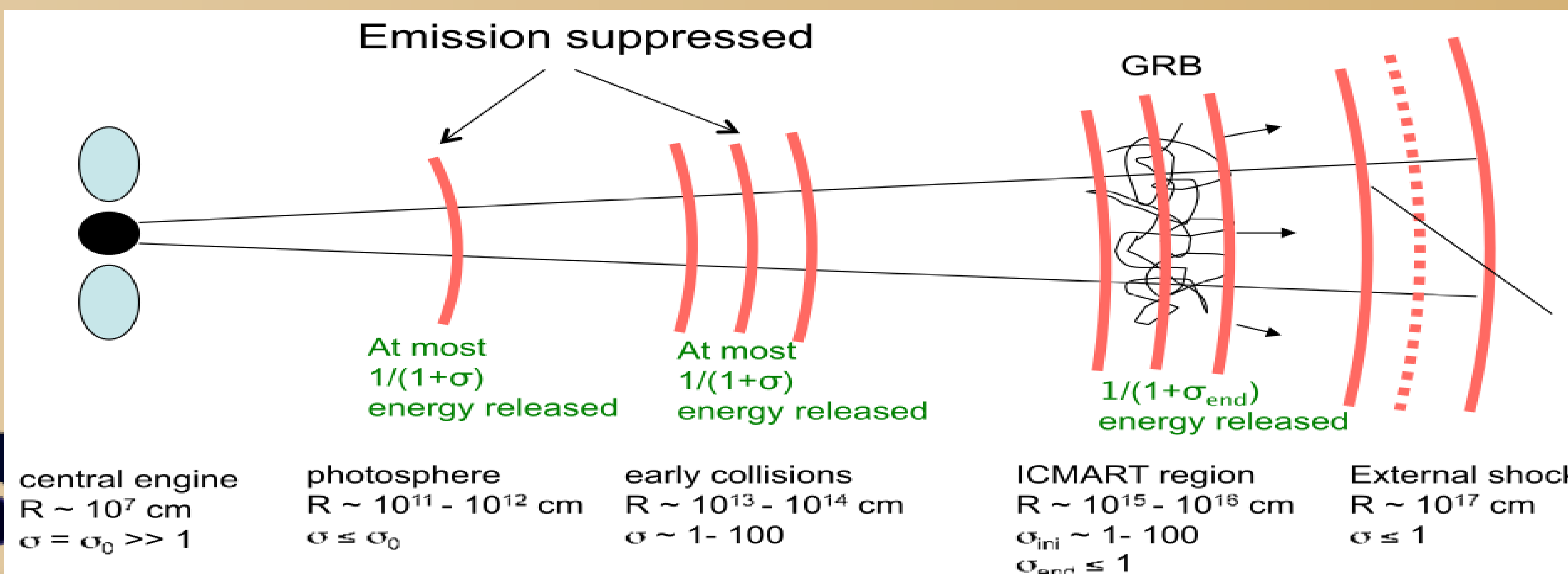
(Beloborodov, 2010; Lazzati & Begelman, 2010)

- Try to interpret the Band-function spectrum using the photosphere facilitated process.
- Merits: high efficiency of the photosphere emission; avoids the “missing bright photosphere” problem; can produce high energy spectrum segment by introducing up-scattering.
- Criticisms: Ep too narrow, GeV emission, Low energy spectrum problem, confliction with thermal+Band spectrum and so on.

PFD-- ICMART model

Internal-Collision-induced MAgnetic Reconnection and Turbulence (*Zhang & Yan 2011*)

- Early collisions → Distort the ordered magnetic field → Fast and turbulent cascaded reconnection
- Great potential to keep the merits of IS model and solve the criticisms of the IS model, but lack detailed simulation studies.

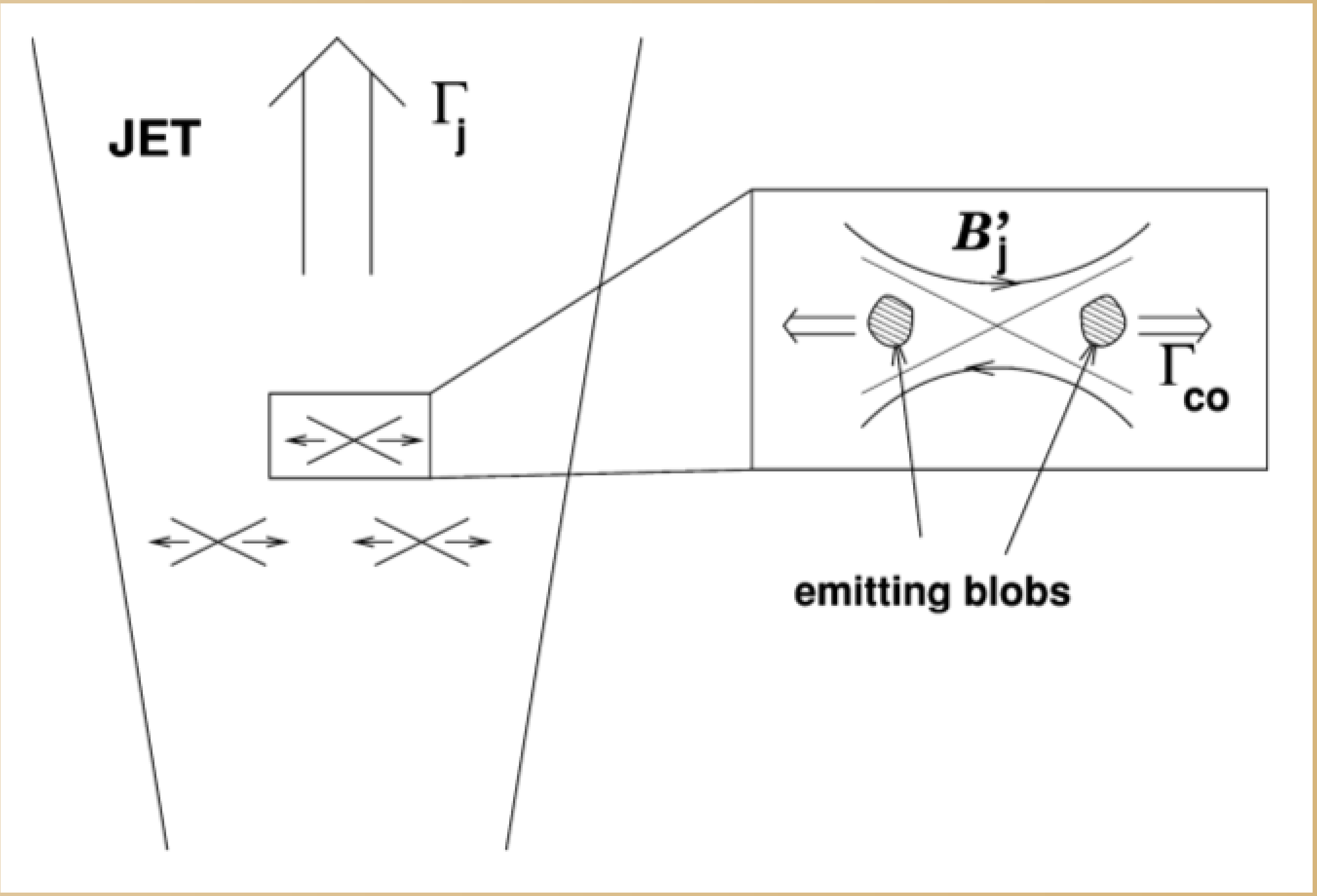


Zhang & Yan (2011, ApJ, 726, 90)

“Jets in a jet” model of AGN/Blazar-PFD

Giannios et al. (MNRAS 2009)

- Mini-jets due to local reconnection; double Lorentz boost; interpret fast TeV variability of some blazars.



Giannios et al. (MNRAS 2009)

Numerical simulations

- Motivated by ICMART model and other relevant problems, such as “jets in a jet” model of AGNs.
- Investigate the models from the EMF energy dissipation efficiency, relativistic outflow generation, and σ evolution points of view.
- Simulate collisions between high-σ blobs to mimic the situation of the interactions inside the PFD jets/outflows.

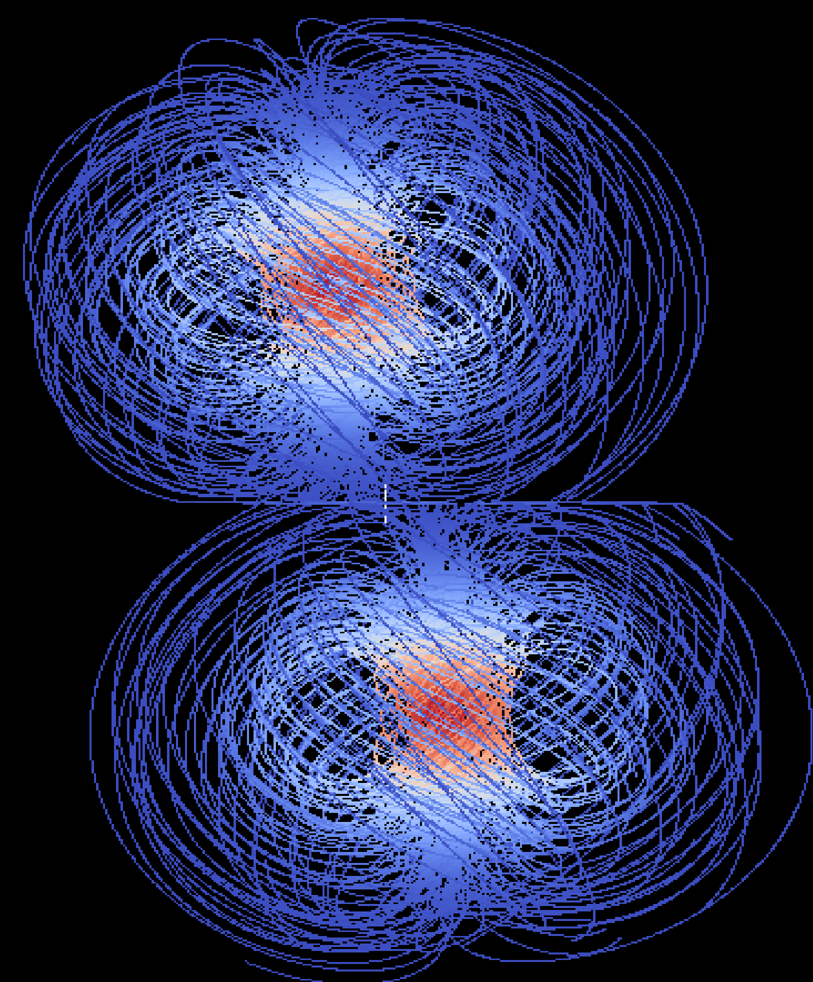
Problem setup

- We use a 3D SRMHD code which solves the conservative form of the ideal MHD equations. This code is a development version of the "LA-COMPASS" MHD code which was firstly developed by Li & Li (2003) at LANL.
- Field configuration: model (mag. tower) from Li et al. (2006), considering the ``dynamo'' of the central engine, contains both poloidal and toroidal components.

$$B_r = -\frac{1}{r}\frac{\partial \Phi}{\partial z} = 2B_{\mathrm{b},0}\frac{zr}{r_0^2}\exp\left(-\frac{r^2+z^2}{r_0^2}\right)$$

$$B_z = \frac{1}{r}\frac{\partial \Phi}{\partial r} = 2B_{\mathrm{b},0}\left(1-\frac{r^2}{r_0^2}\right)\exp\left(-\frac{r^2+z^2}{r_0^2}\right)$$

$$B_\phi = \frac{\alpha\Phi}{r} = B_{\mathrm{b},0}\alpha r\exp\left(-\frac{r^2+z^2}{r_0^2}\right)$$



$$B_r = -\frac{1}{r}\frac{\partial \Phi}{\partial z} = 2B_{\mathrm{b},0}\frac{zr}{r_0^2}\exp(-\frac{r^2+z^2}{r_0^2})$$

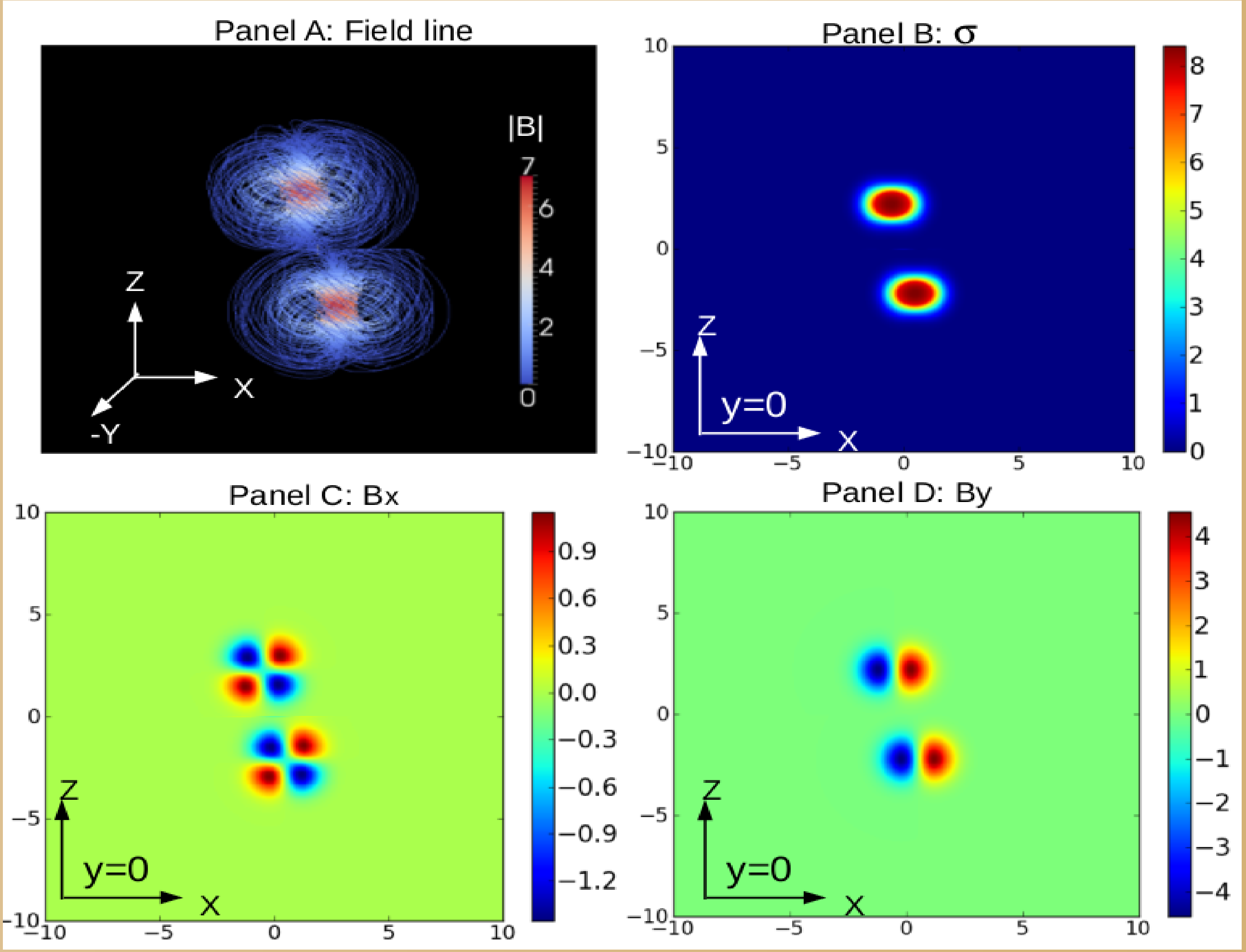
$$B_z = \frac{1}{r}\frac{\partial \Phi}{\partial r} = 2B_{\mathrm{b},0}(1-\frac{r^2}{r_0^2})\exp(-\frac{r^2+z^2}{r_0^2})$$

$$B_\phi = \frac{\alpha\Phi}{r} = B_{\mathrm{b},0}\alpha r\exp(-\frac{r^2+z^2}{r_0^2})$$

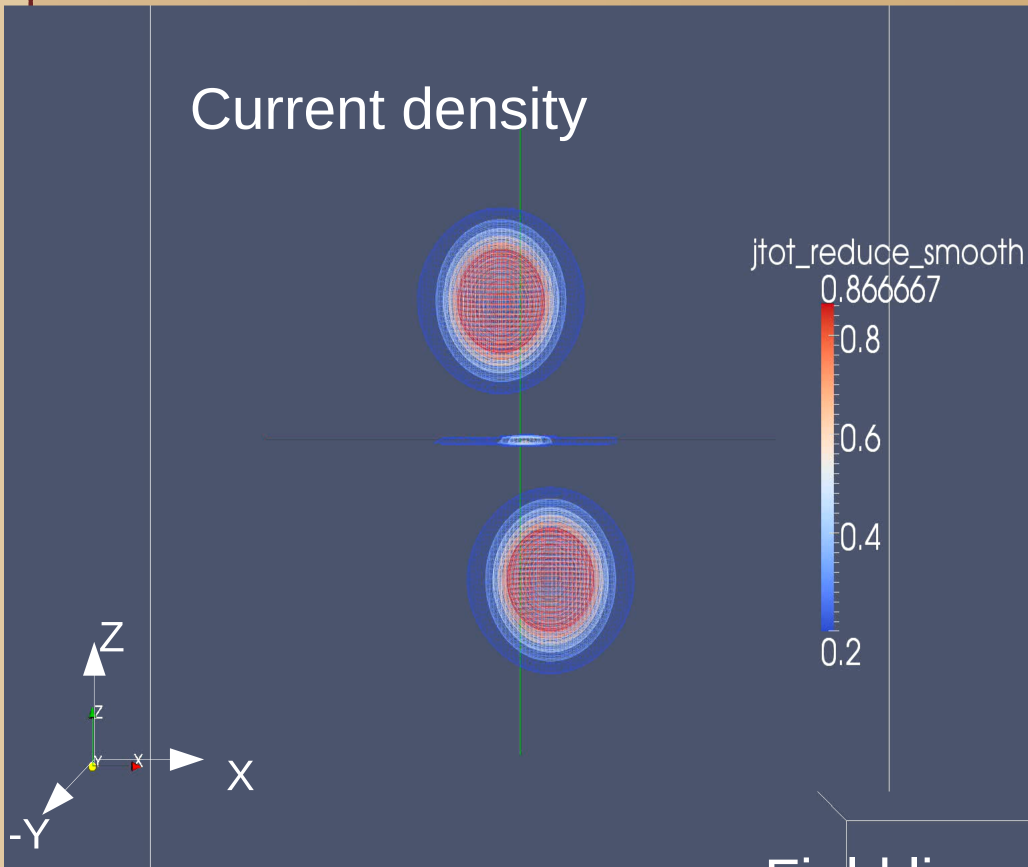
An example case:
Initial parameters and cuts

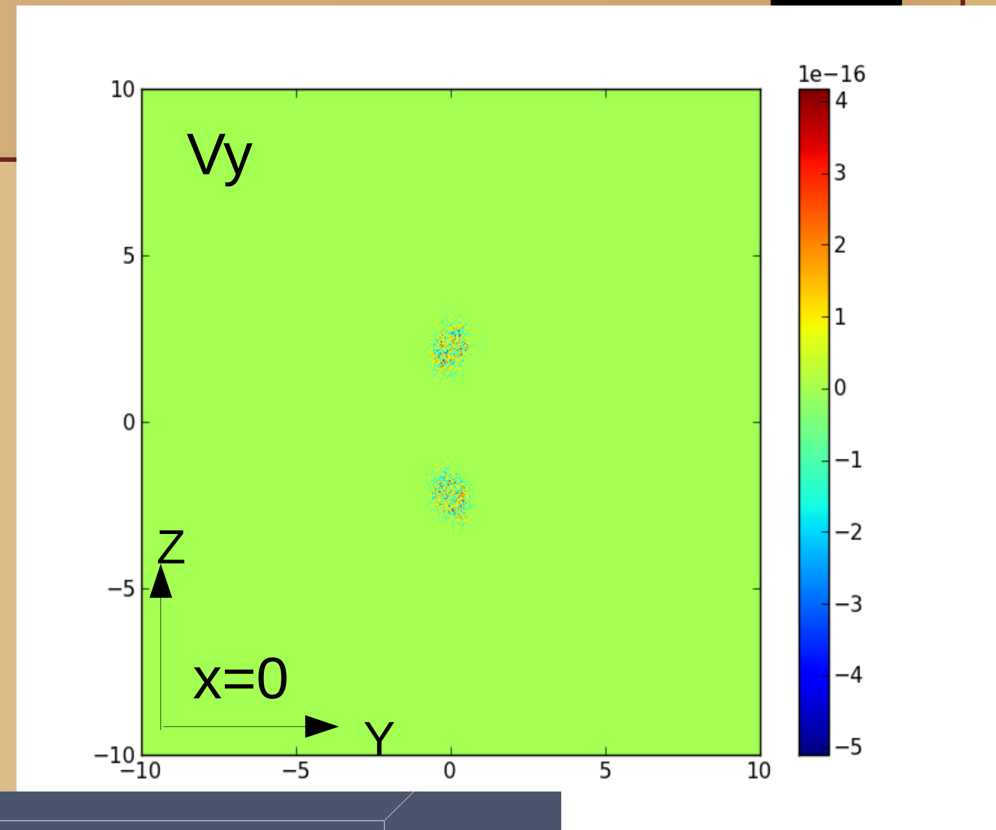
- Initial typical radius of blobs $r_0=1$
- Collision along Z direction
- Misalignment in X direction (x_s)
- Box size: 20^3 ; Resolution: 1024^3

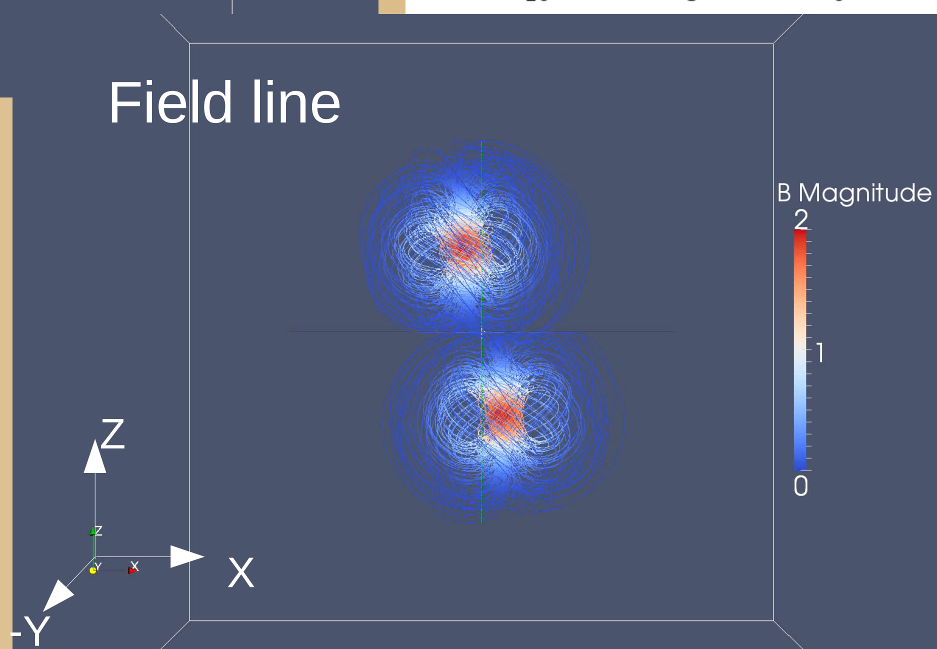
$\sigma_{\mathrm{b,i}}$	$B_{\mathrm{b,0}}$	$V_{\mathrm{b,z}}$	P	ρ_{bkg}	z_d	x_s
8	$\sqrt{4\pi}$	0.3c	10^{-2}	10^{-1}	4.4	1.0

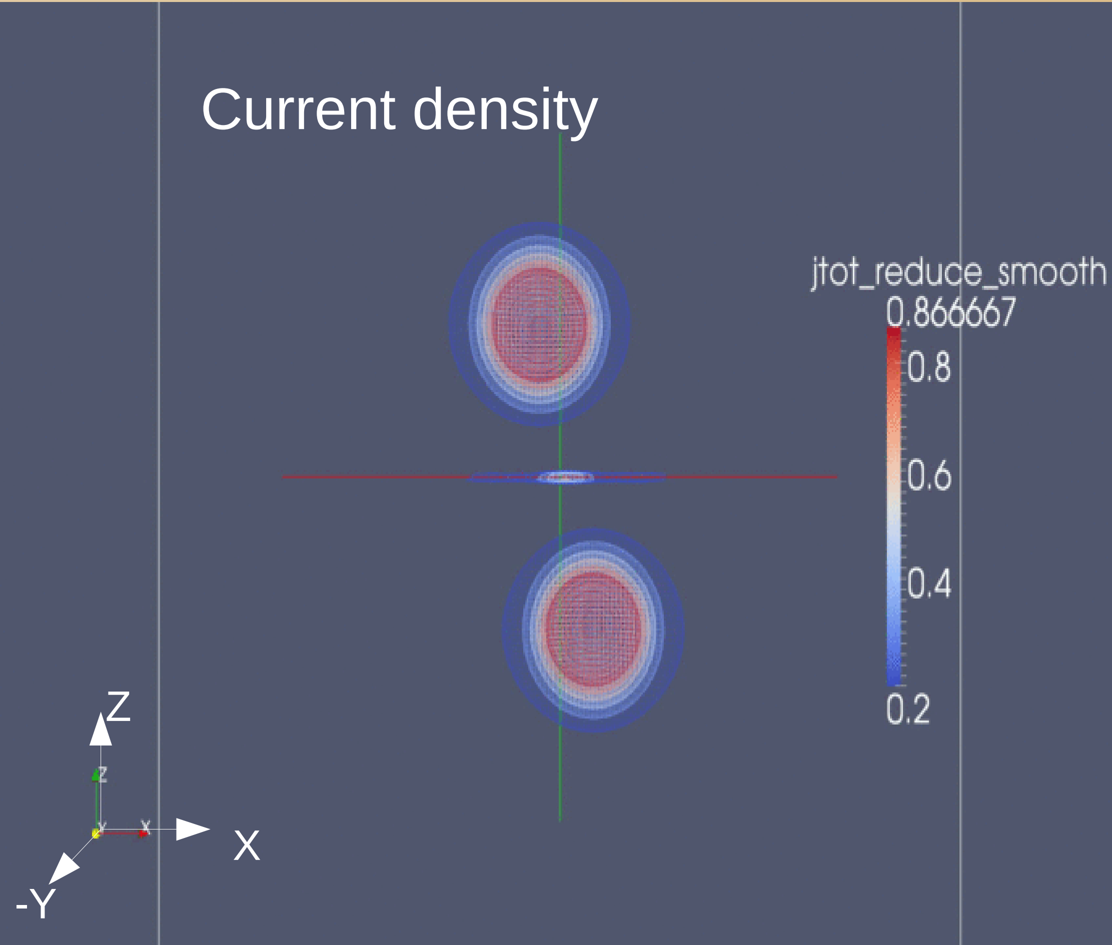


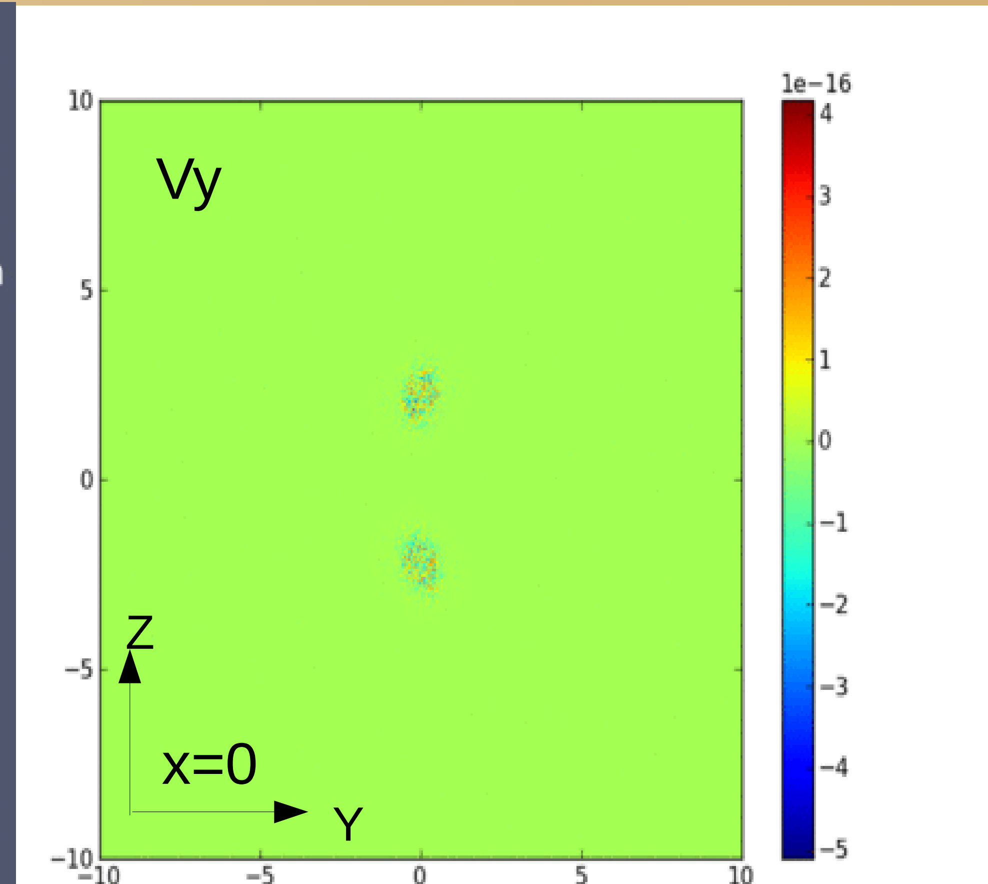
Movies for current and outflows

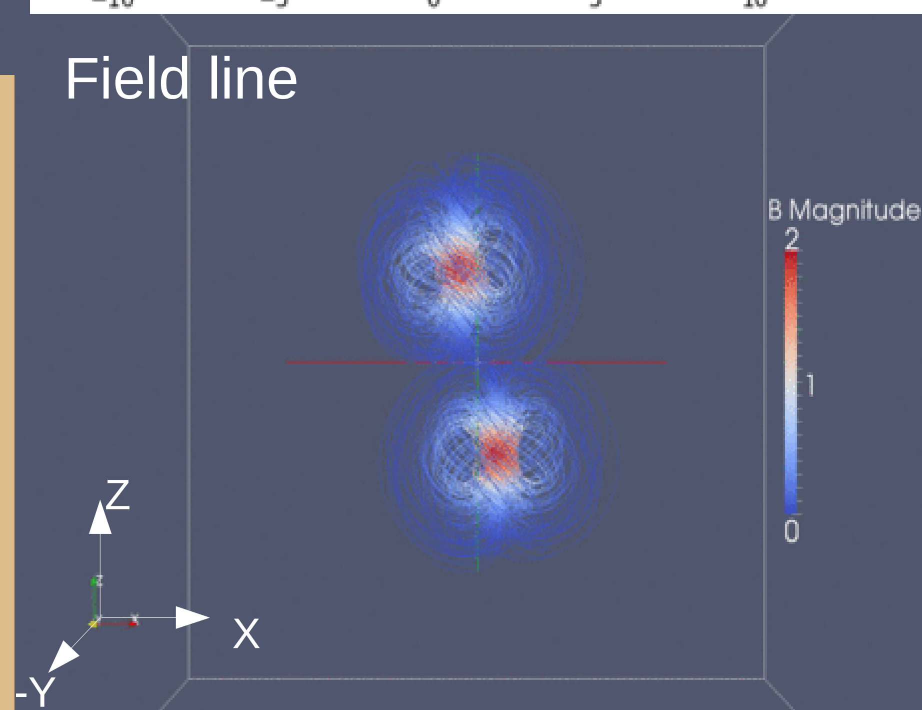








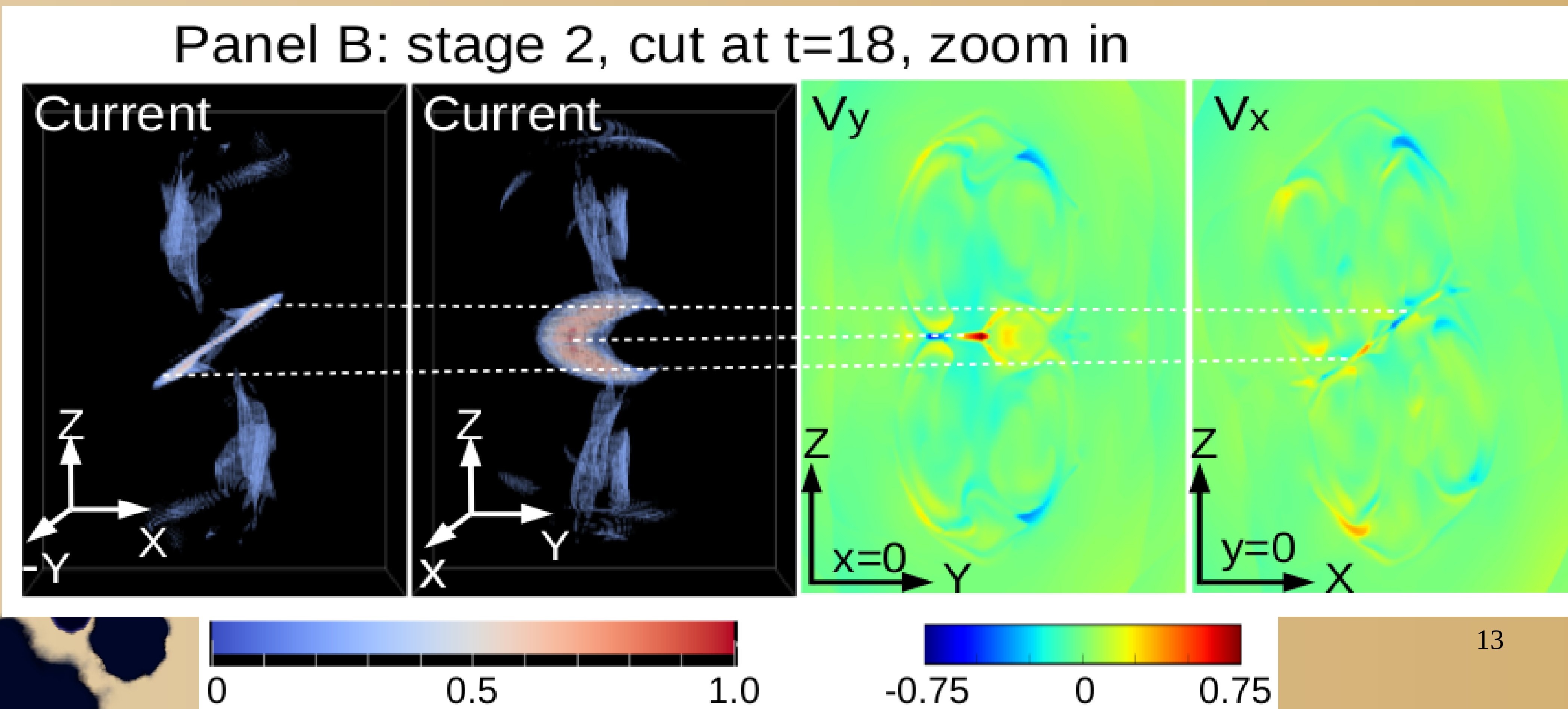




- Observe clear reconnection features.
- Kink-like instability is generated in the outflow.

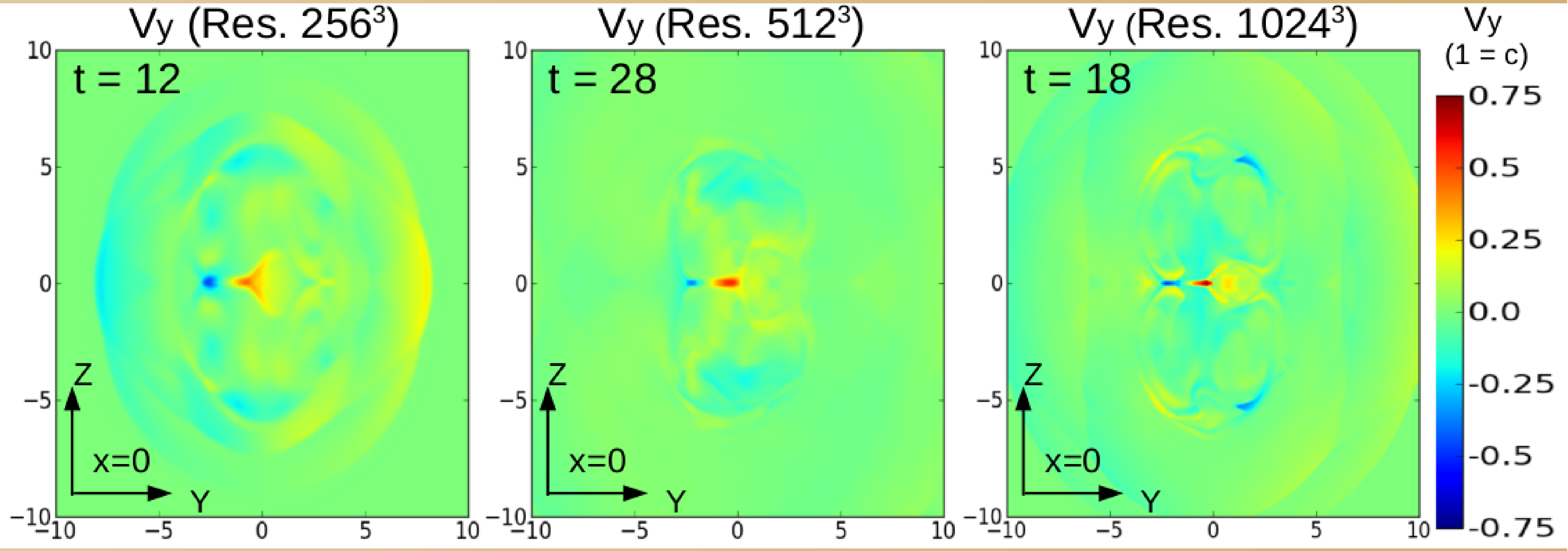
Qualitatively analyses — outflow study

- Fast multi-direction's outflows (0.75c, next slice shows that it can be higher for higher res.)



Qualitatively analyses — outflow study

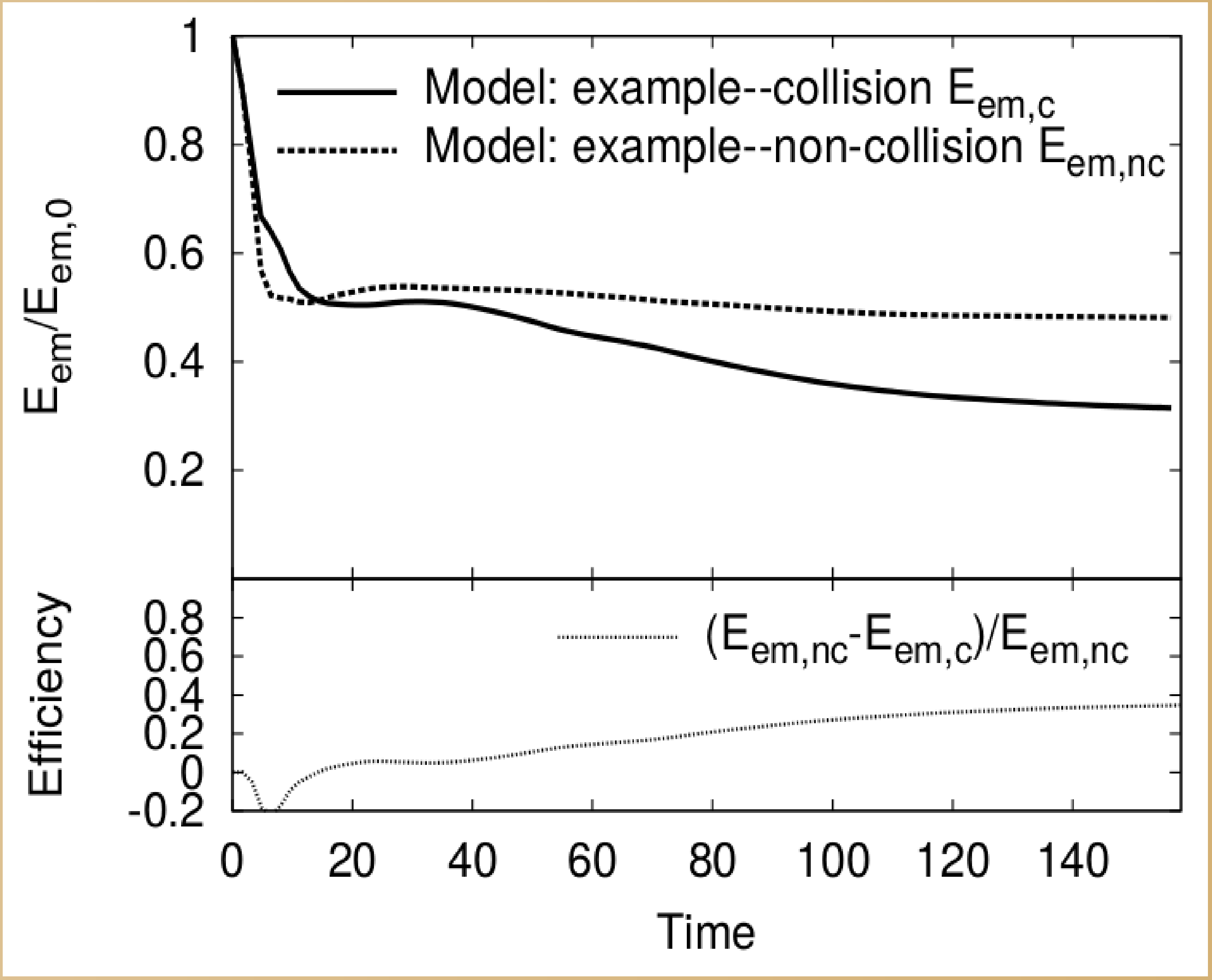
- Outflow speed can be higher for higher res (lower numerical resistivisity, more close to the real systems).)



- Great potential to generate multi-direction relativistic mini-jets (GRBs, AGNs...).

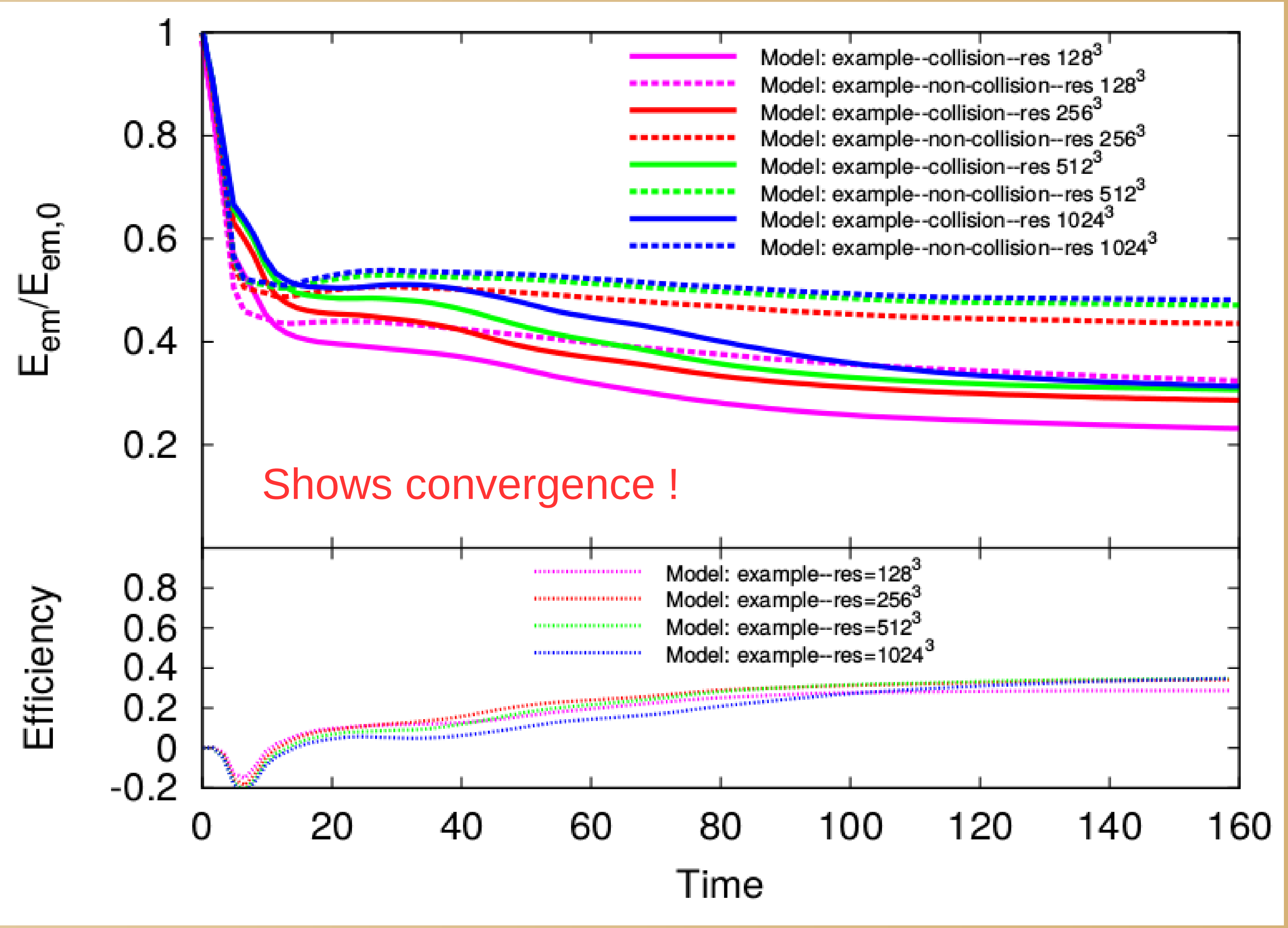
Quantitatively analyses — EMF energy dissipation efficiency: example

- No matter collision or not, initially, not in completely force balance, undergoing fast expansion to establish the force balance.
- Need non-collision case as reference
- Initial “self adjustment” t<10



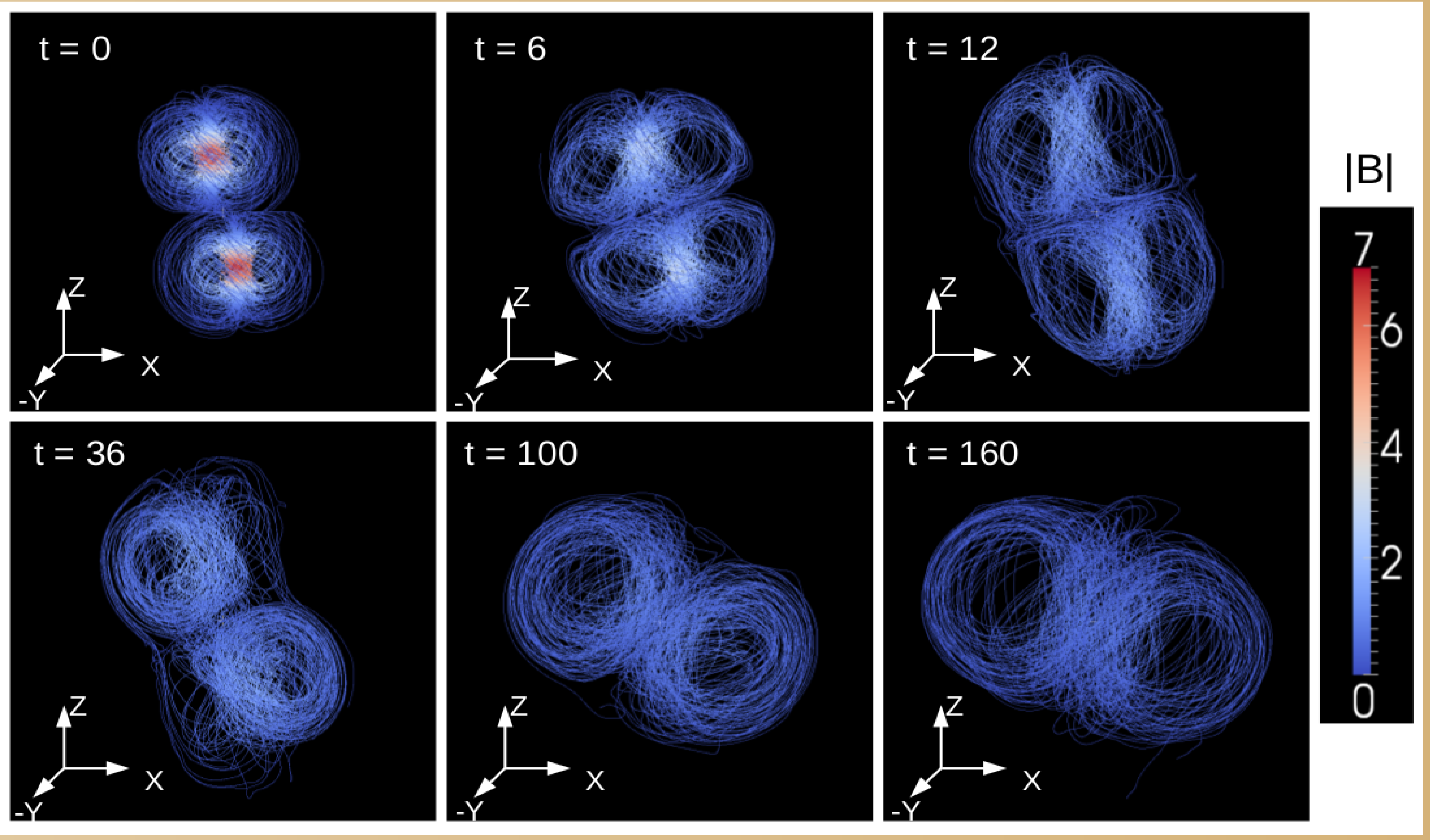
Efficiency ~ 35%, much higher than the IS collisions !

Quantitatively analyses — EMF energy dissipation efficiency: resolution study



Quantitatively analyses — EMF energy dissipation efficiency: Physical analyses

- Zhang & Yan (2011) gave an 1st order analytical estimation based on the situation of completely inelastic collision.



Physical analyses, σ evolution

- Energy conservation:

  (Zhang & Yan 2011)

$$\eta = \frac{1}{1+\sigma_{\rm b,f}} - \frac{\Gamma_m(m_1+m_2)}{(\Gamma_1 m_1 + \Gamma_2 m_2)(1+\sigma_{\rm b,i})}$$

- Simplification:

$$\eta = \frac{1}{1+\sigma_{\rm b,f}} - \frac{1}{\Gamma(1+\sigma_{\rm b,i})}$$

$\sigma_{b,f}$ is calculated from the simulation results (threshold = 1). The efficiency got from this hybrid method is similar to the efficiency got from the energy evolution of the simulations.

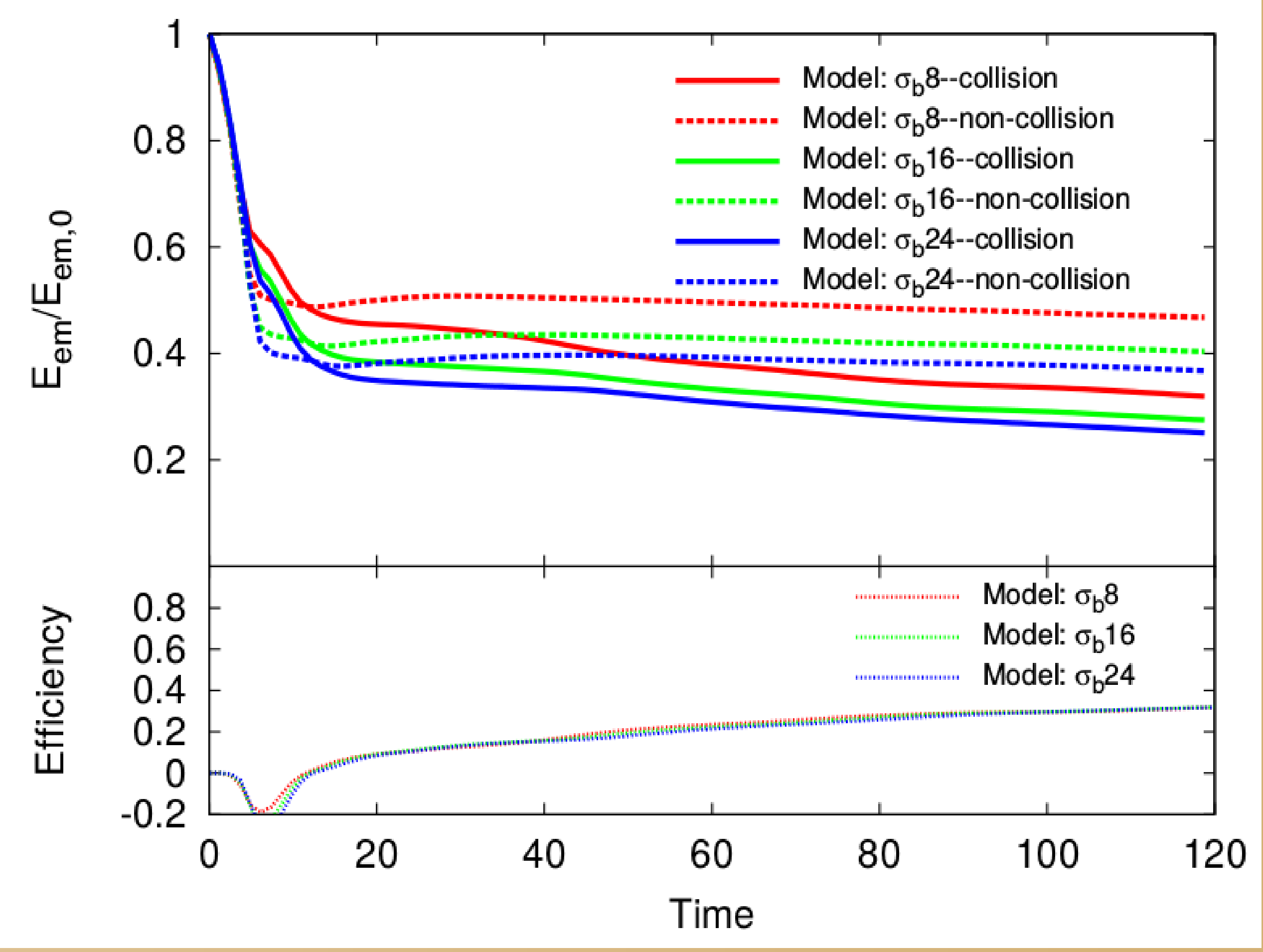
$\sigma_{\rm b,i}$	$\sigma_{\rm b,f}$	Efficiency
8	1.16	35.2%

Physical analyses, σ evolution

- σ dependence study: Efficiency is nearly σ independent, which is also confirmed by the hybrid method.

$\sigma_{b,i}$	$\sigma_{b,f}$	Efficiency
8	1.16	35.2%
12	1.25	36.8%
16	1.33	37.0%
20	1.41	36.7%
24	1.49	36.2%

$$\eta = \frac{1}{1+\sigma_{b,f}} - \frac{1}{\Gamma(1+\sigma_{b,i})}$$

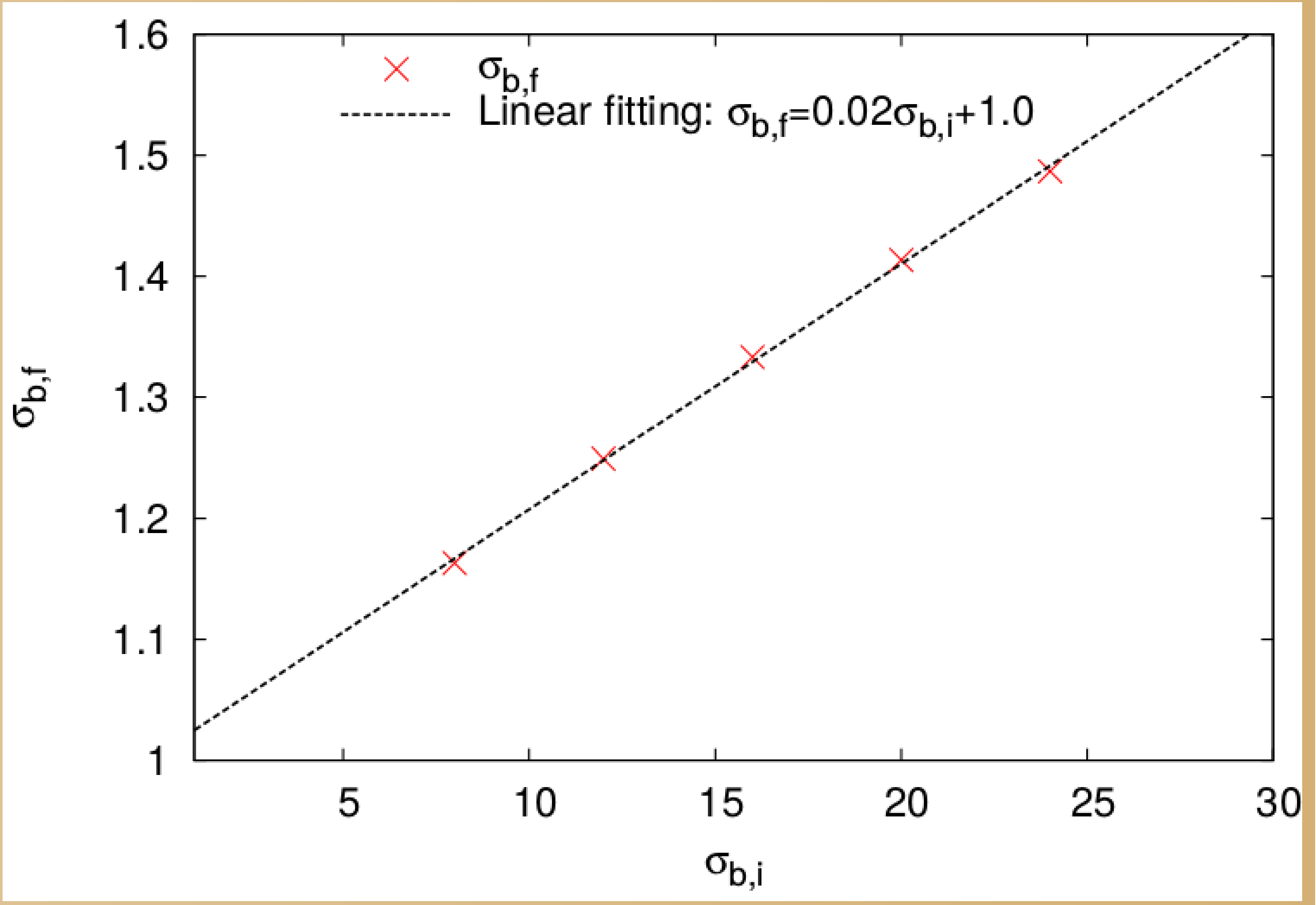


Physical analyses, σ evolution

- $\sigma_{b,i}$ - $\sigma_{b,f}$ relationship study: Interesting linear relationship

$\sigma_{b,i}$	$\sigma_{b,f}$	Efficiency
8	1.16	35.2%
12	1.25	36.8%
16	1.33	37.0%
20	1.41	36.7%
24	1.49	36.2%

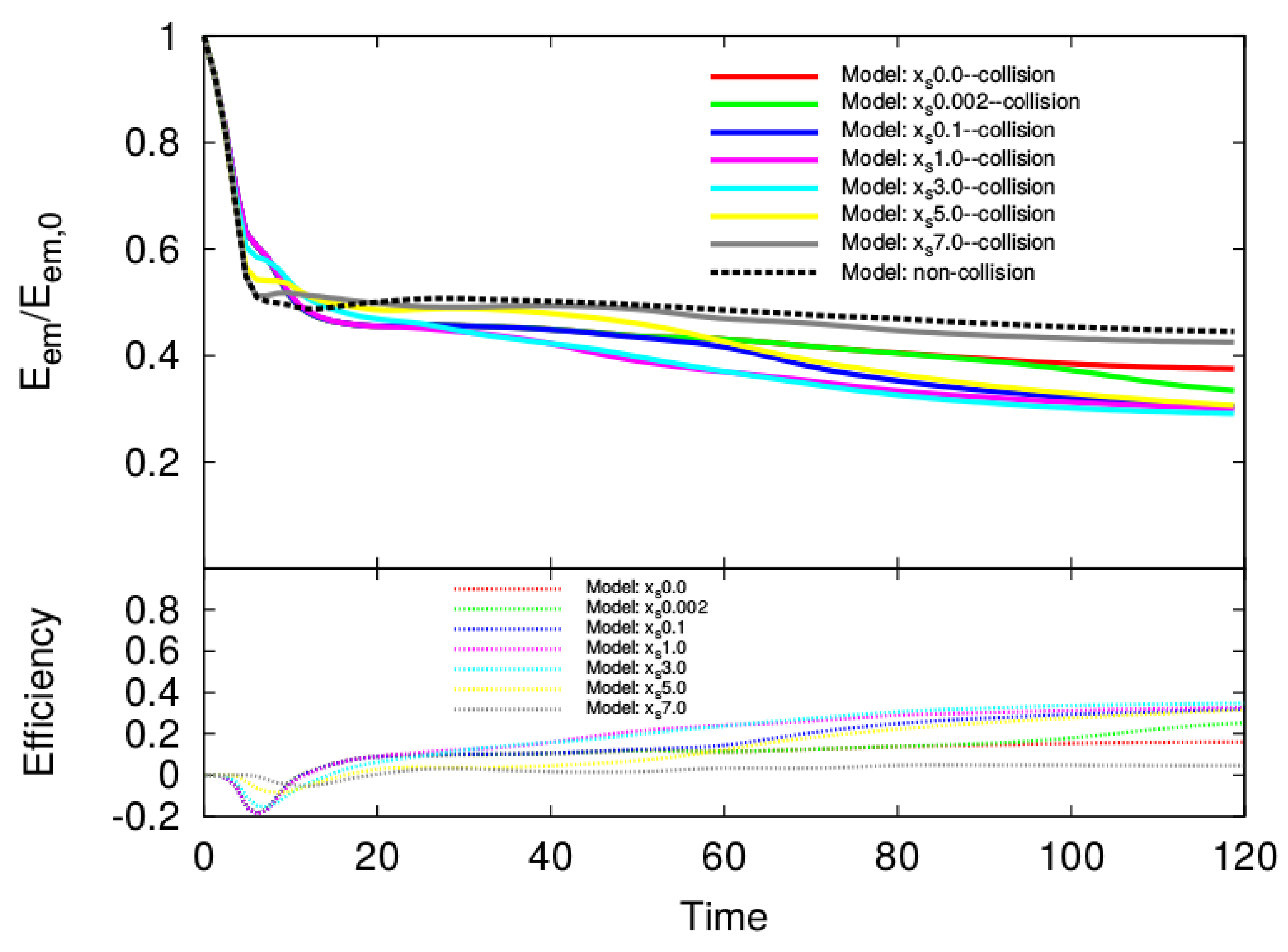
We can constrain one of them if we can estimate another one.



Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

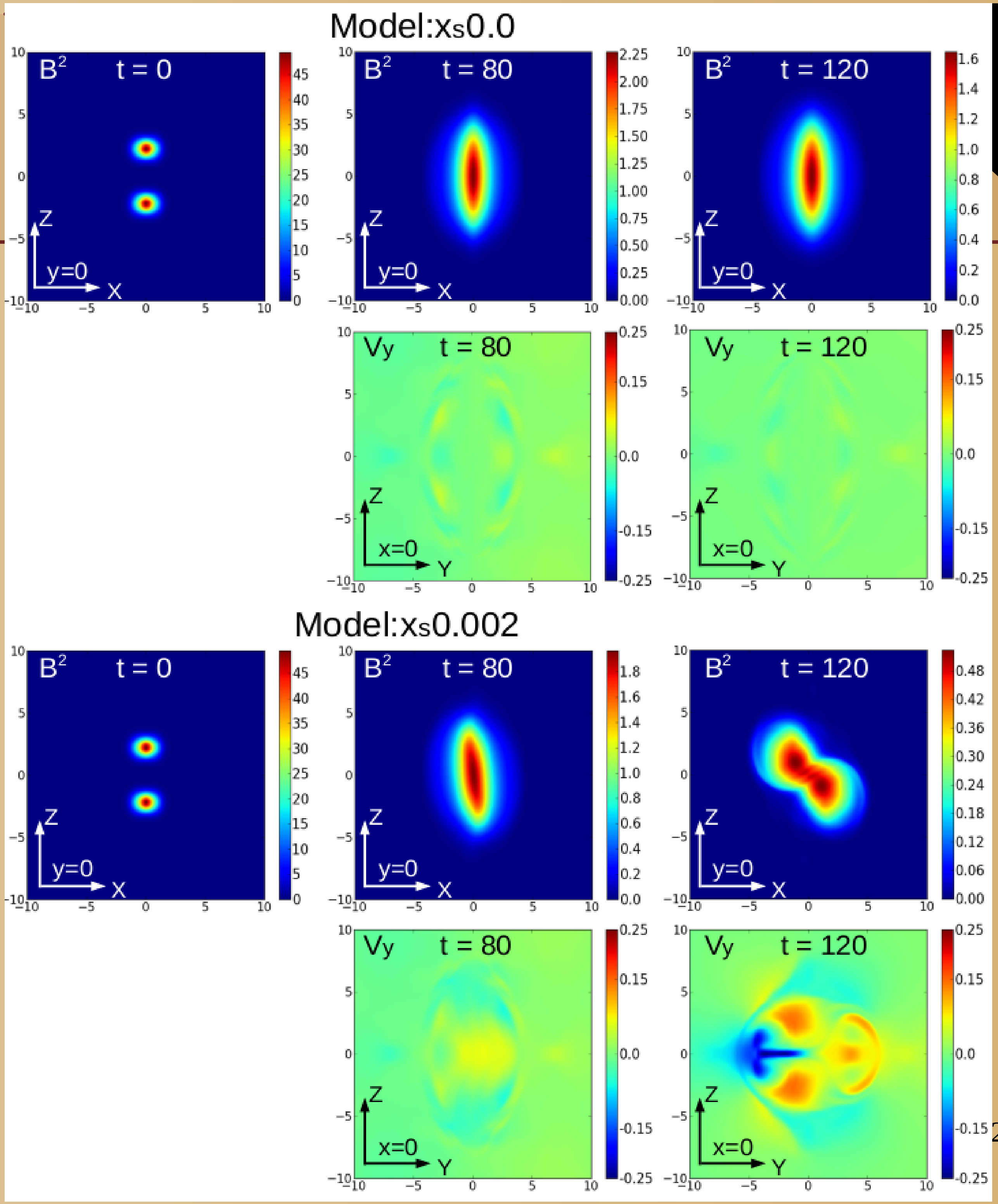
- Xs

Smaller Xs delays the additional dissipation, but reaches similar level eventually.



Comparison of Two Xs cases:

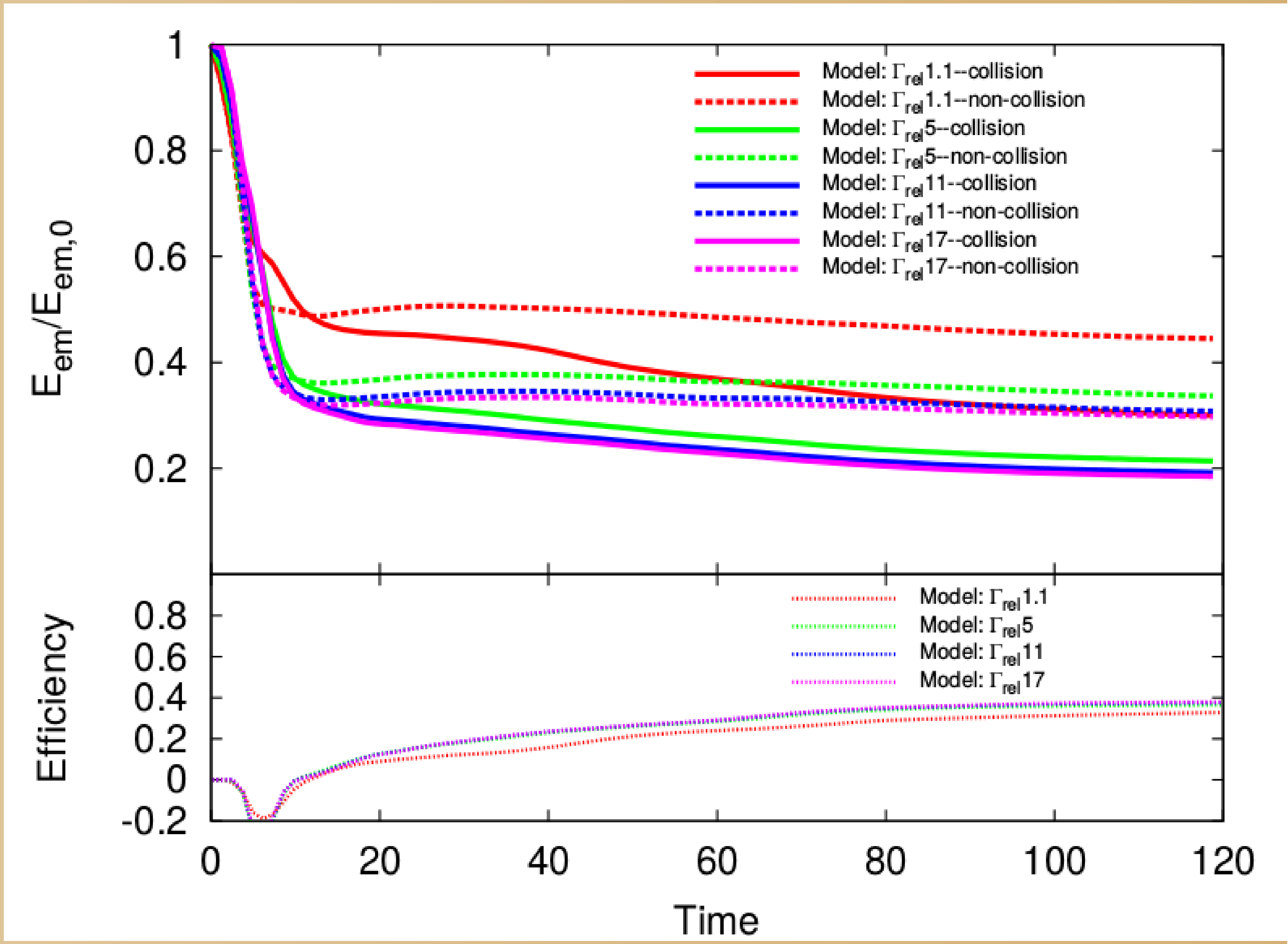
- Initially similar;
- Trigger additional reconnection for misalignment case.



Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

- Vel.

Higher Vel. gives higher dissipation efficiency

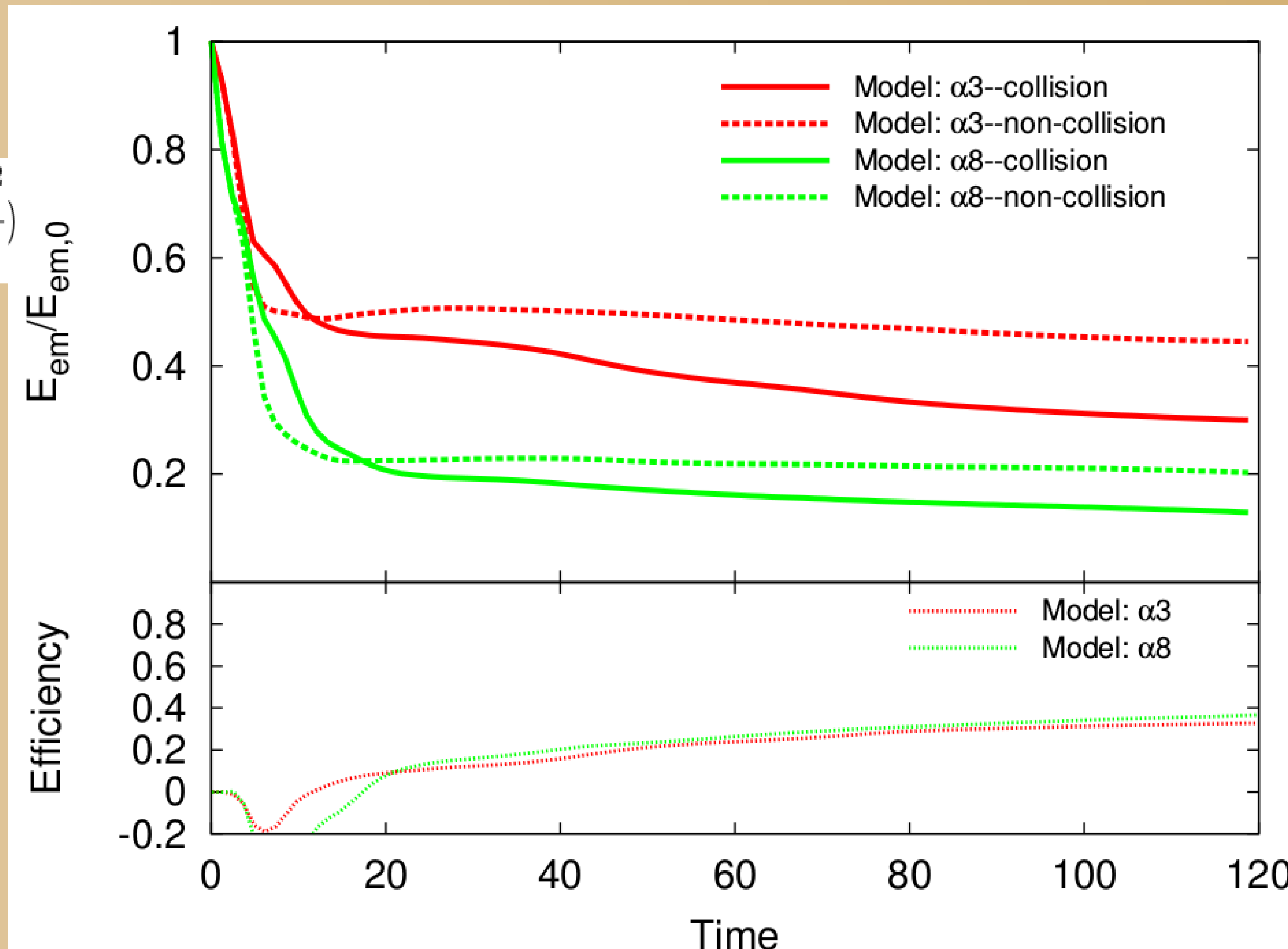


Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

- α

$$B_\phi = \frac{\alpha\Phi}{r} = B_{b,0}\alpha r \exp\left(-\frac{r^2+z^2}{r_0^2}\right)$$

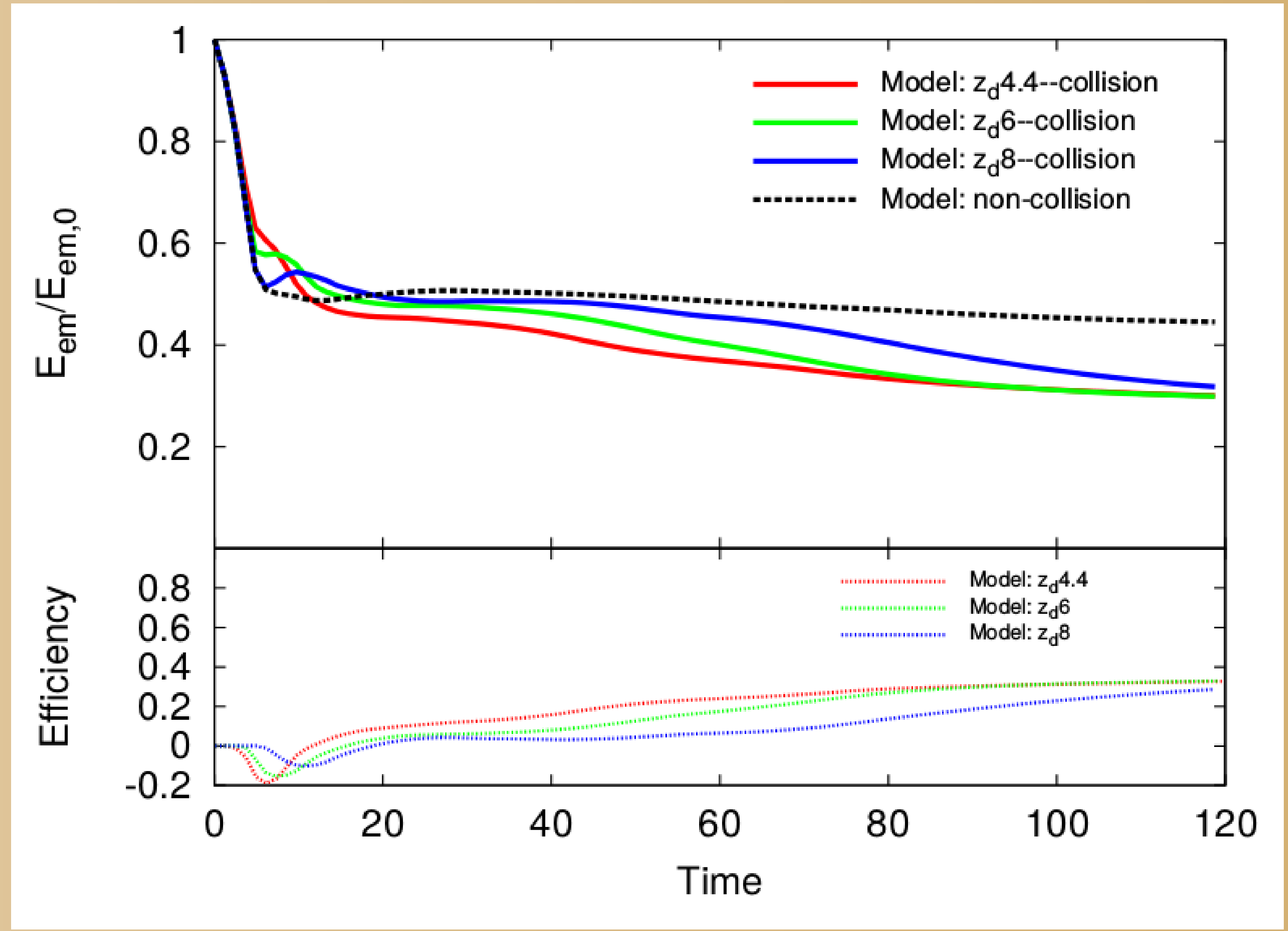
Toroidal B Is probably even higher in real systems. Higher η.



Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

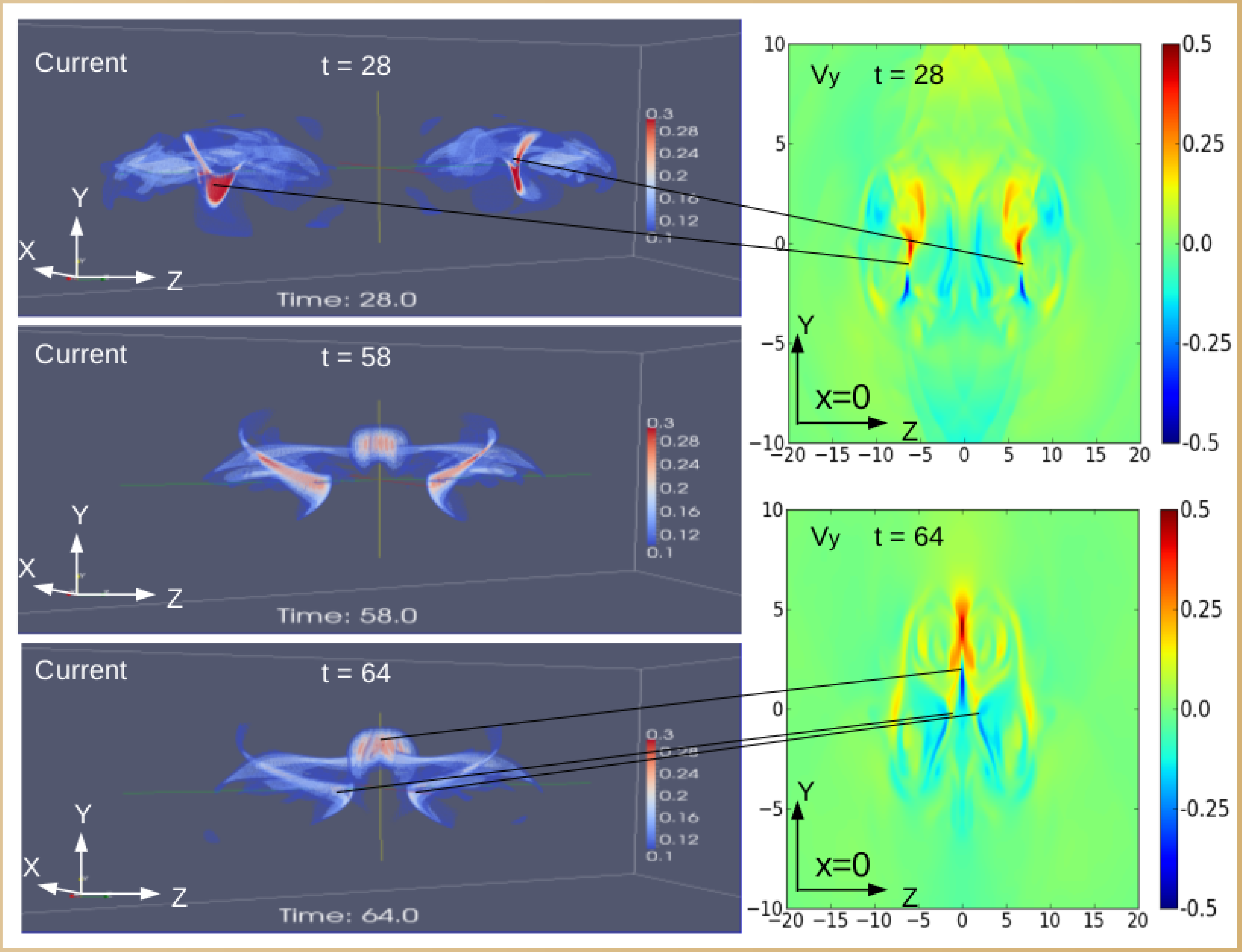
- Zd

Collision happens in different expansion stage doesn't affect the final level too much.



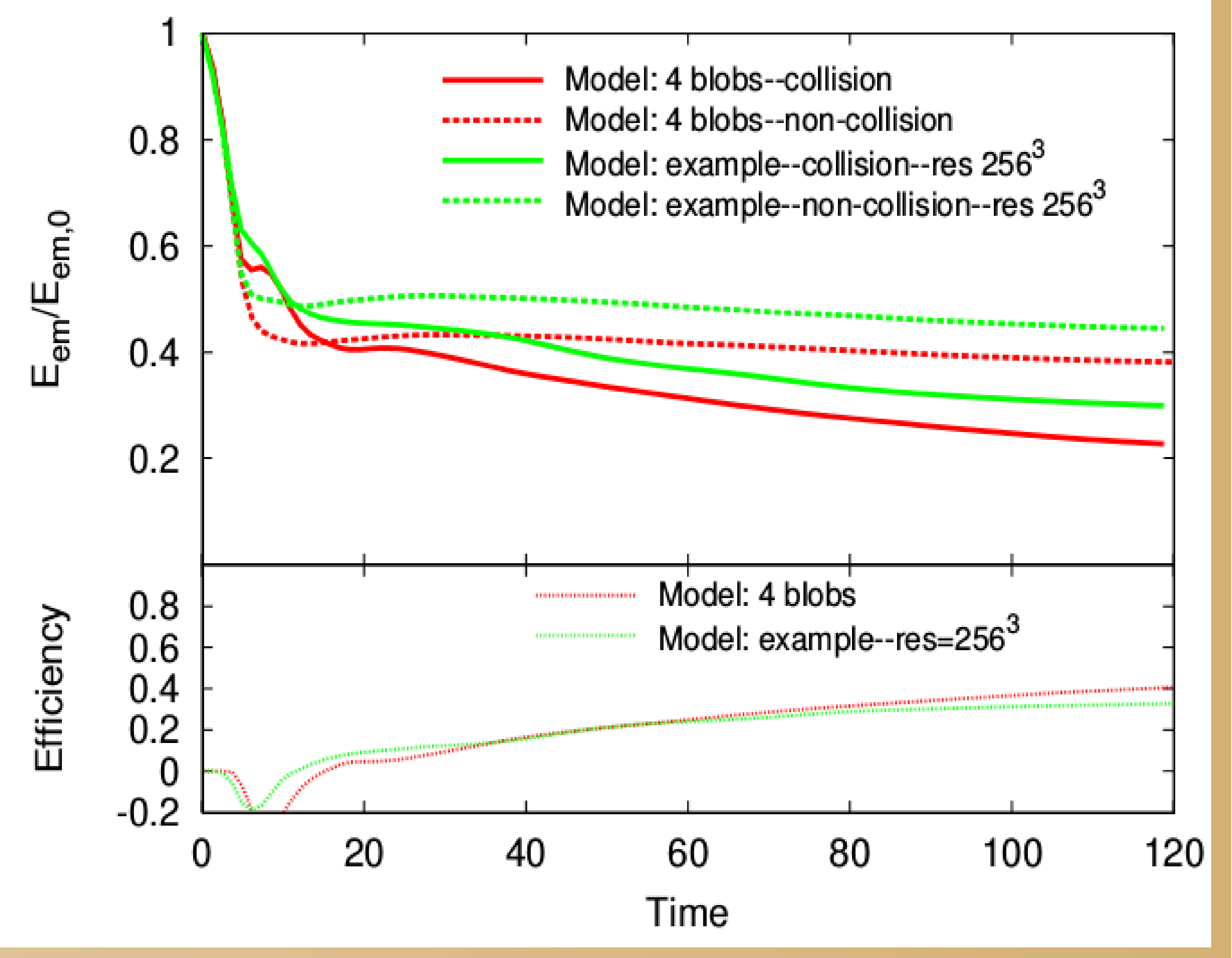
Multi-collisions — outflow

4 blobs;
More multi-direction mini-jets



Multi-collisions — EMF energy dissipation efficiency

Higher efficiency



Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

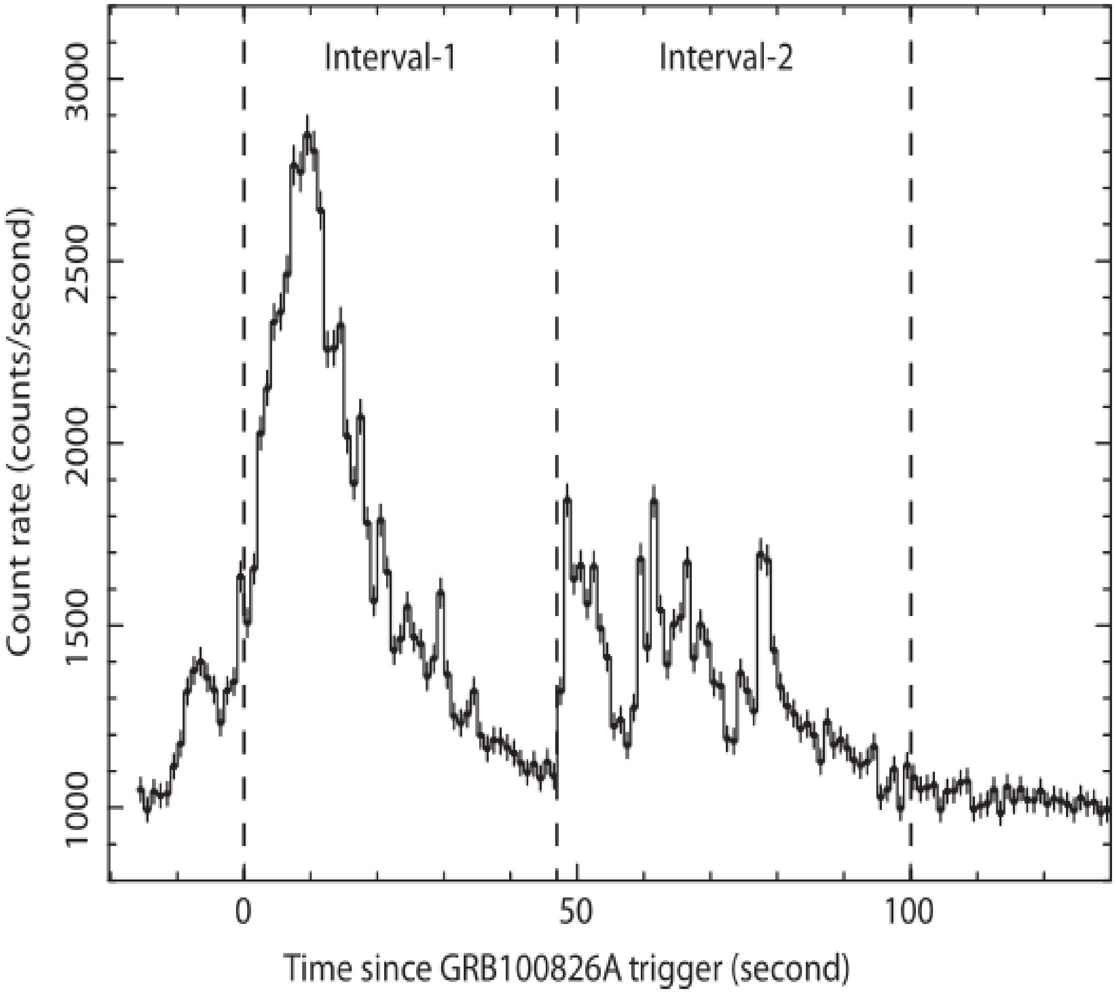
- High dissipation efficiency can be reached for most of the parameters, >40%

Application: polarization

- On going

Collaborators: Haocheng Zhang, Bing Zhang, Hui Li, Shengtai Li

Obs. 1

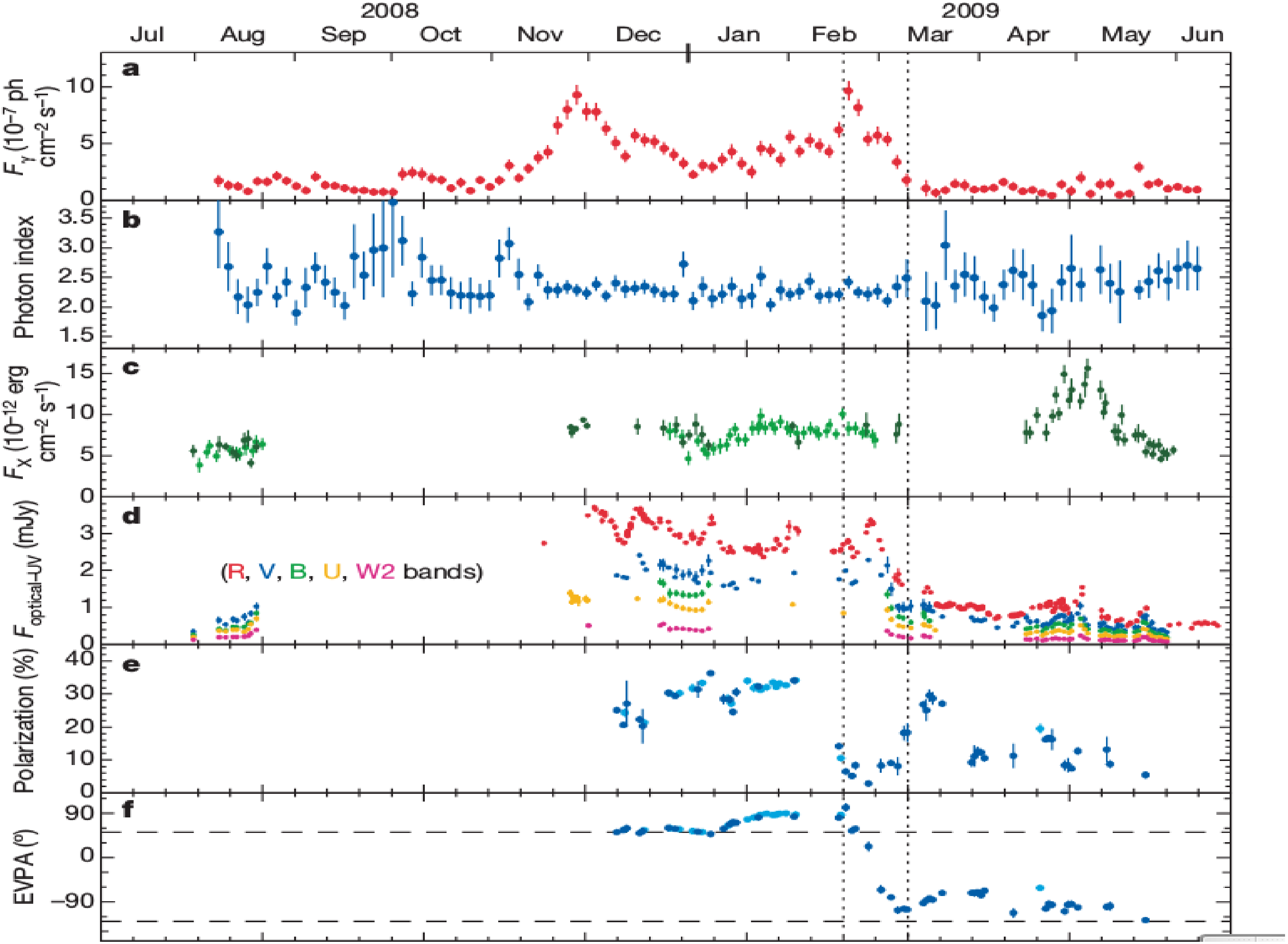


GRB 100826A

Yonetoku 2011

are $\Pi_1 = 25\% \pm 15\%$ with $\phi_{p1} = 159 \pm 18$ deg for Interval-1
and $\Pi_2 = 31\% \pm 21\%$ with $\phi_{p2} = 75 \pm 20$ deg for Interval-2,

Obs. 2

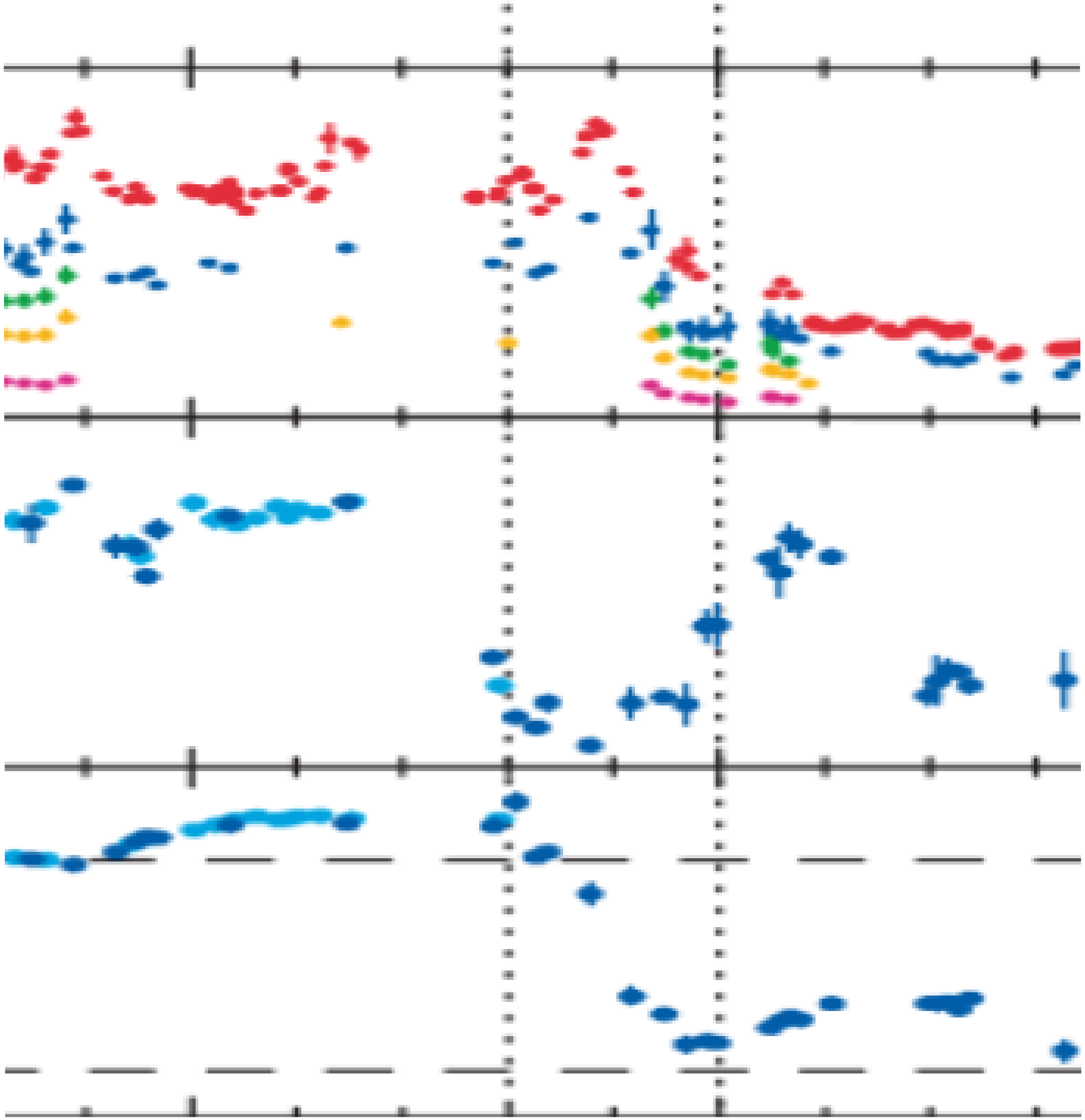


Blazar 3C279

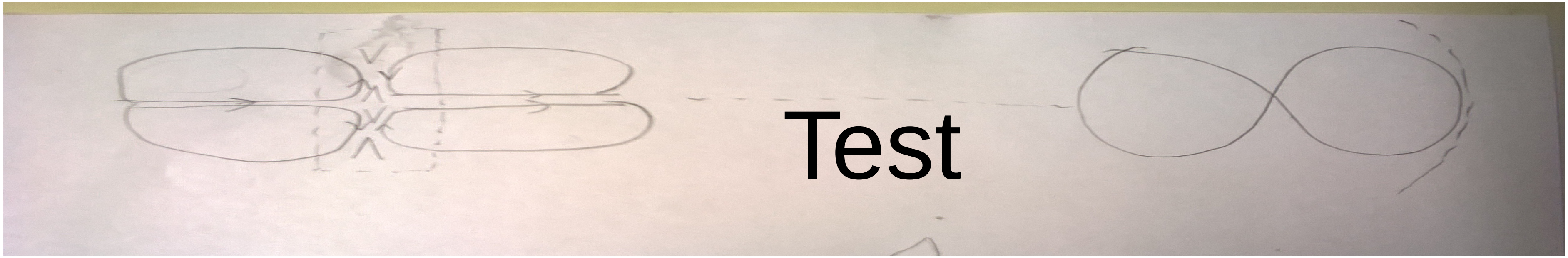
Abdo et al. 2010

Obs. 2

- Zoom-in



Abdo et al. 2010



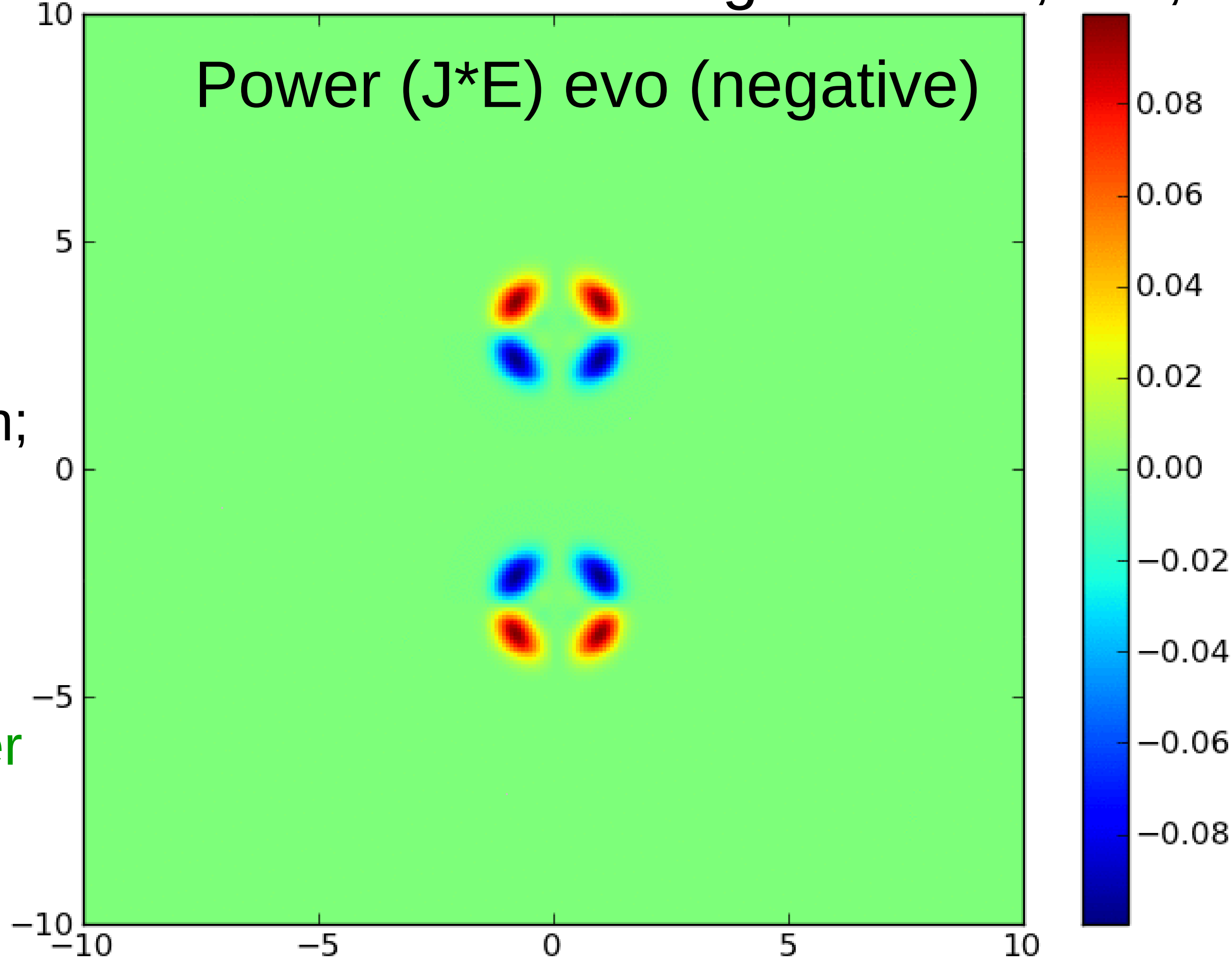
Test

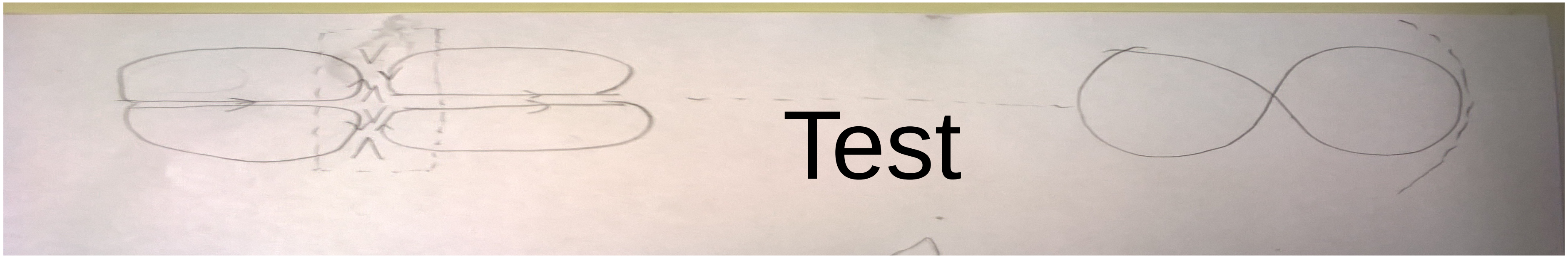
Consider that particles are accelerated in the rec. region;

Choose local box around reconnection region z=+-1, r=5;

σ=10

- Inject non-thermal particles in the reconnection region;
- n_e is normalized by the power in each cell;
- Before Pol. caculation, B*Power calculation is more essential.



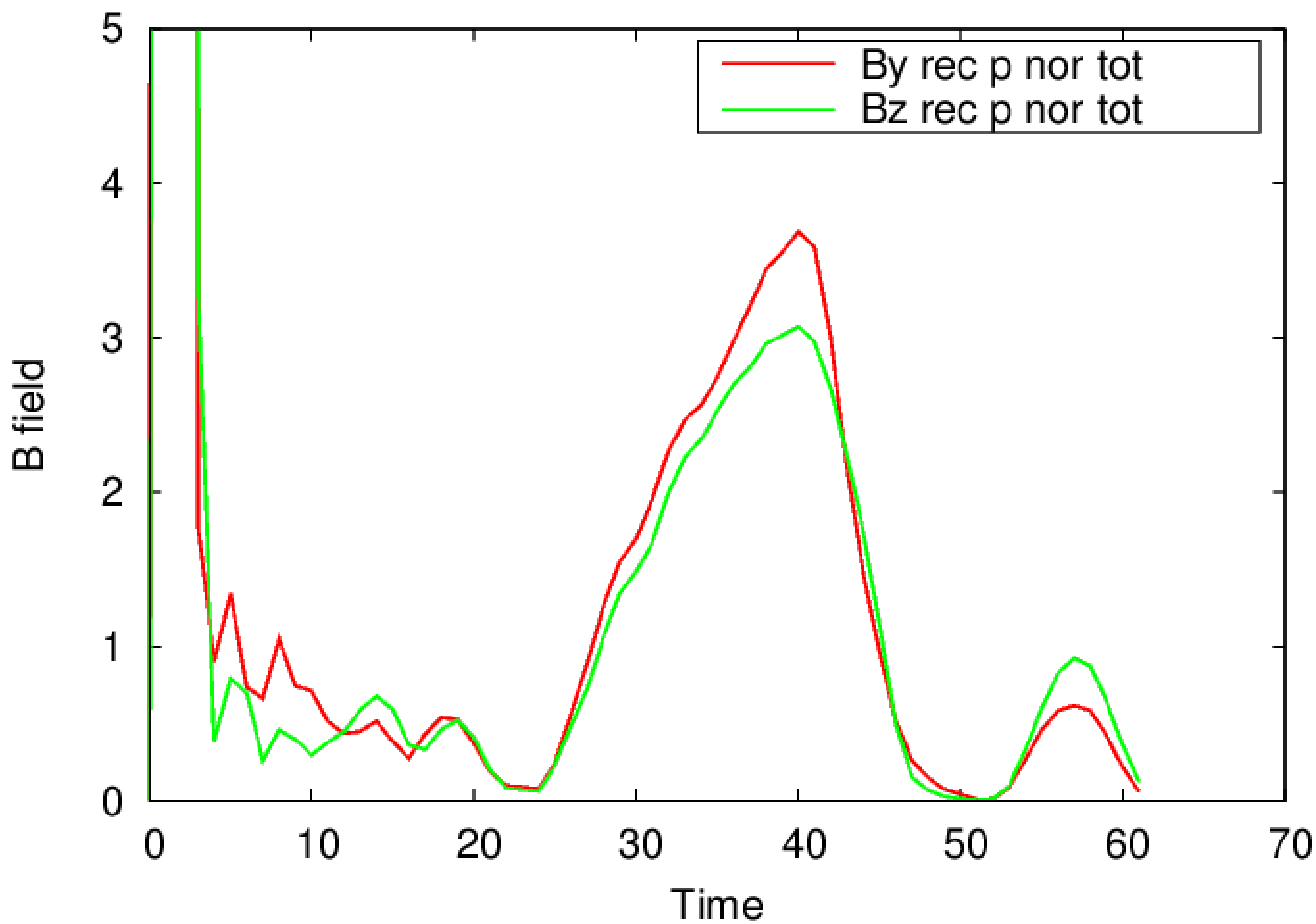


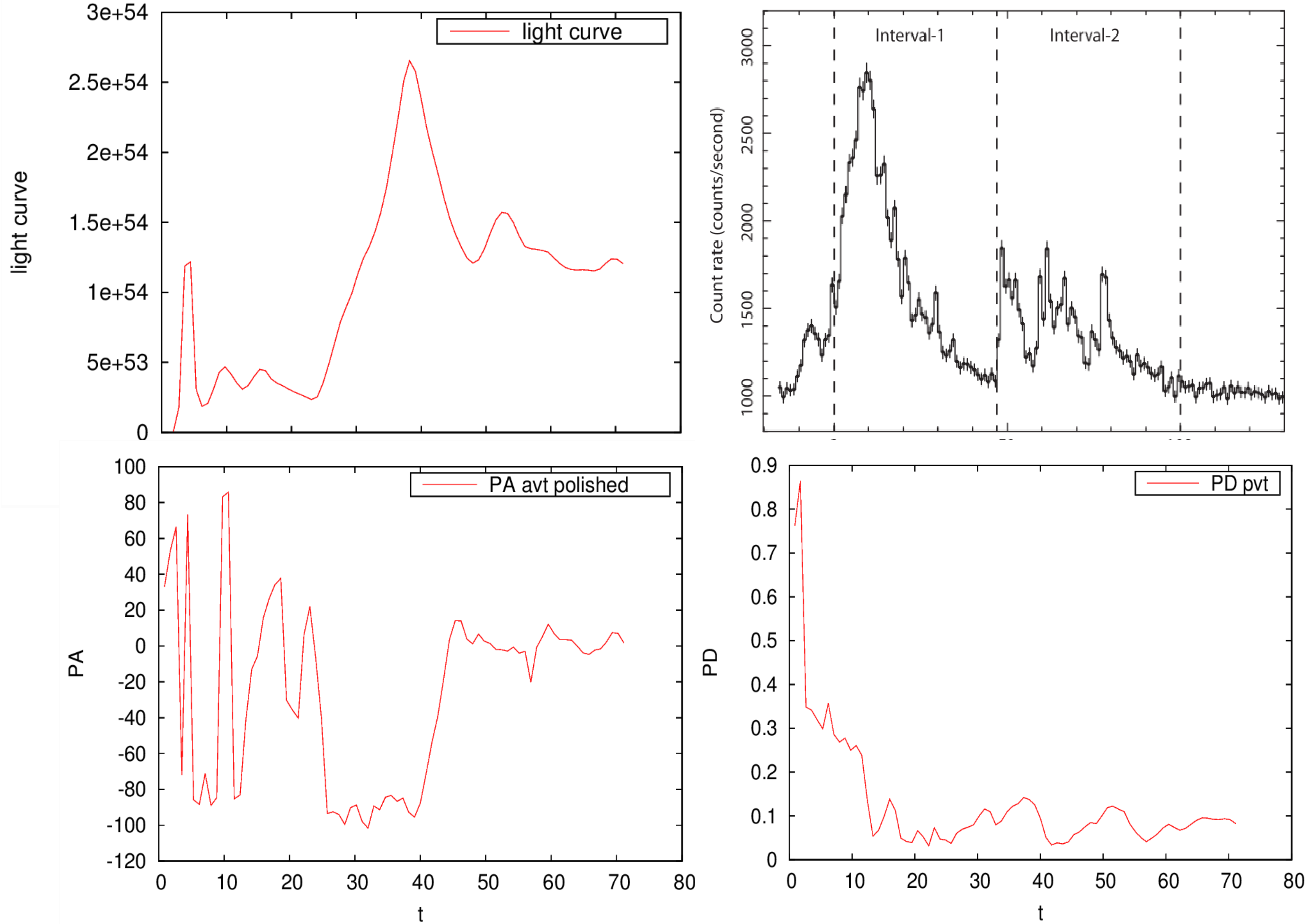
Test

Local box around reconnection region z=+-1, r=5;

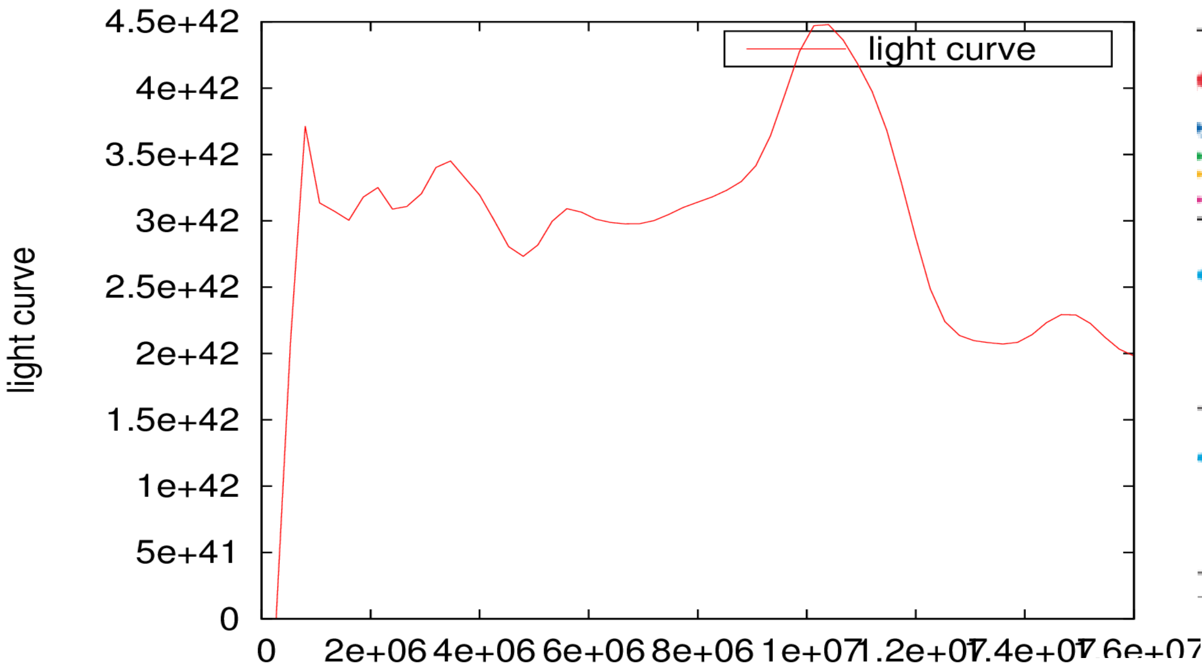
Calculate B*Power~P_{syn}*n_e for two B components separately: determine which component is dominant.

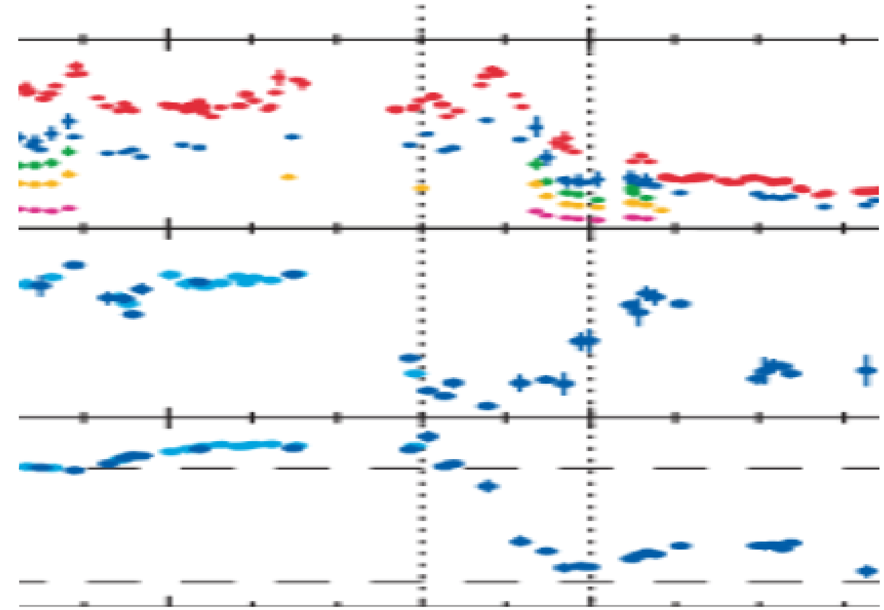
- Transition between two flares;
- Hints 90 degree PA change;

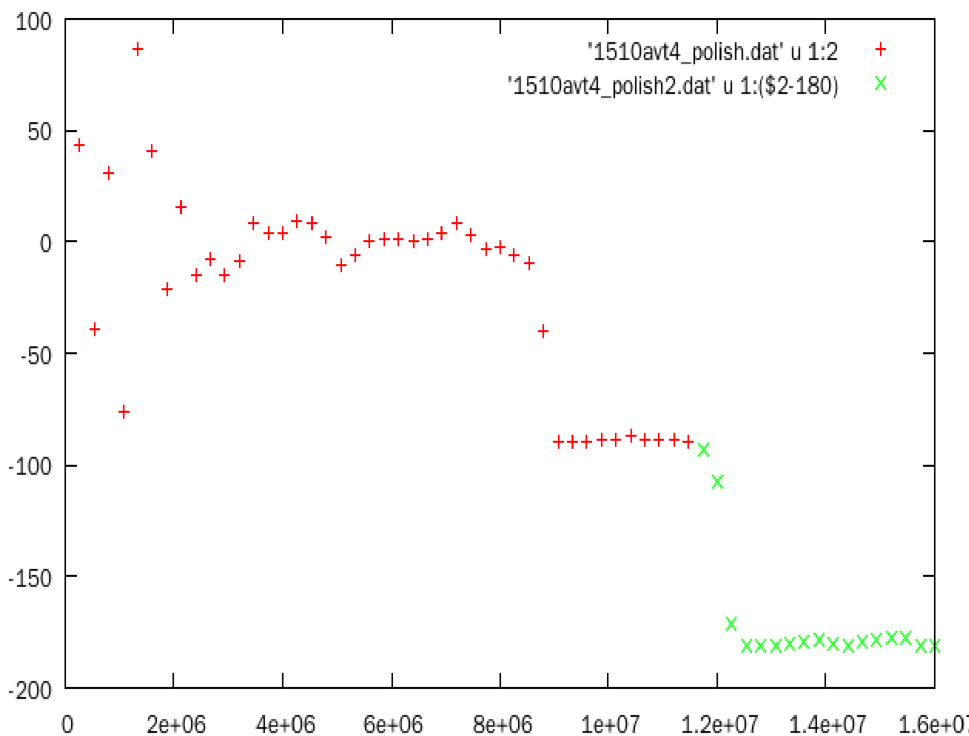


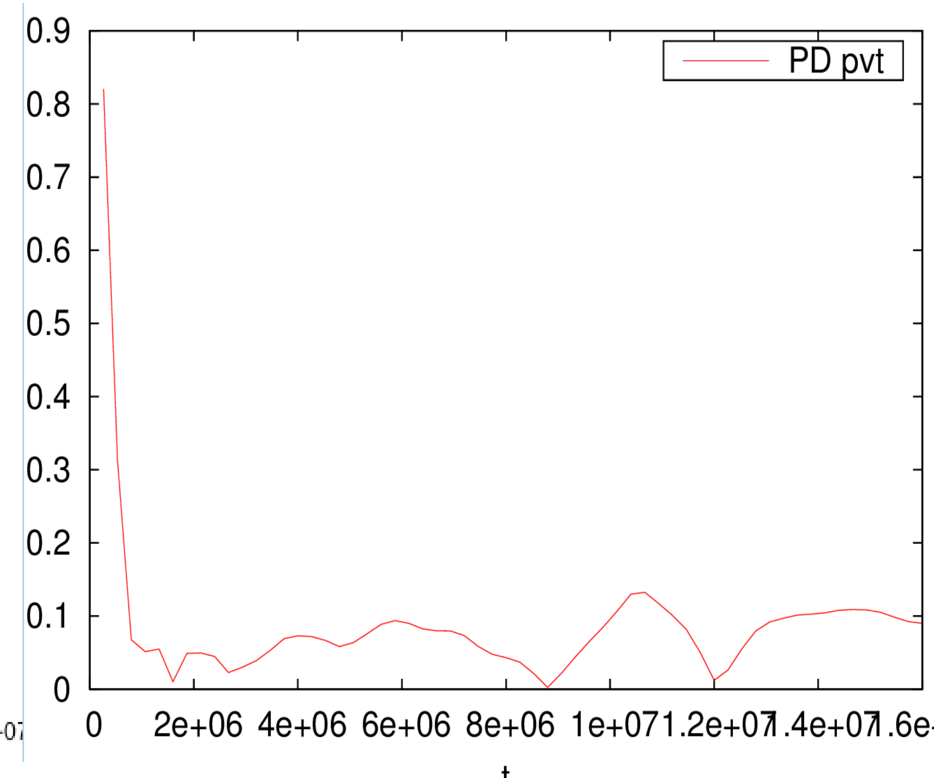


Put simulation results in the radiation code (Zhang, H.)









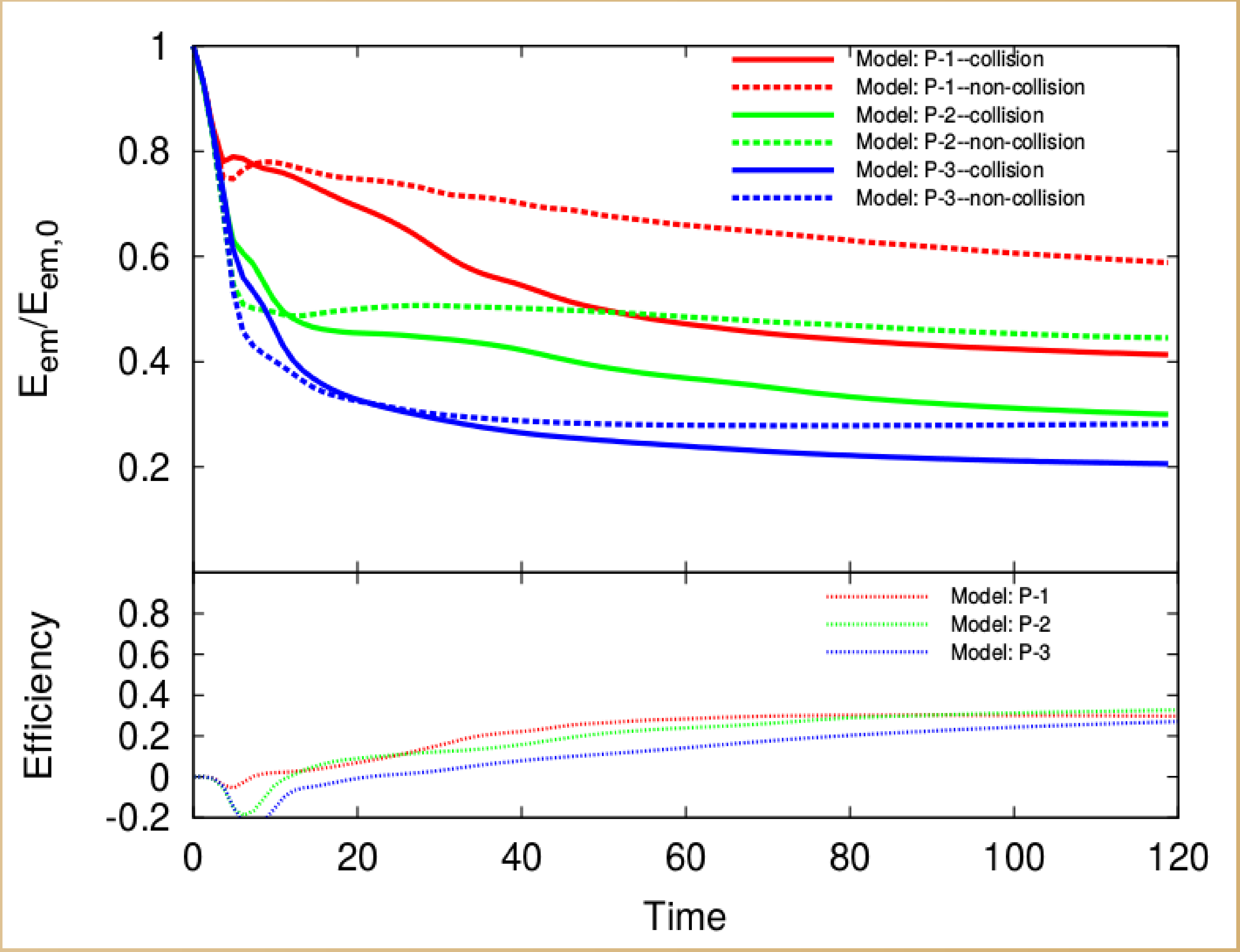
For Blazar 3c279 (similar procedure, add background particles)

Conclusion

- High energy dissipation efficiency;
- Great potential to generate multiple relativistic mini-jets;
- $\sigma_{b,i}$ - $\sigma_{b,f}$: interesting linear relationship;
- Interpret some polarization Obs.

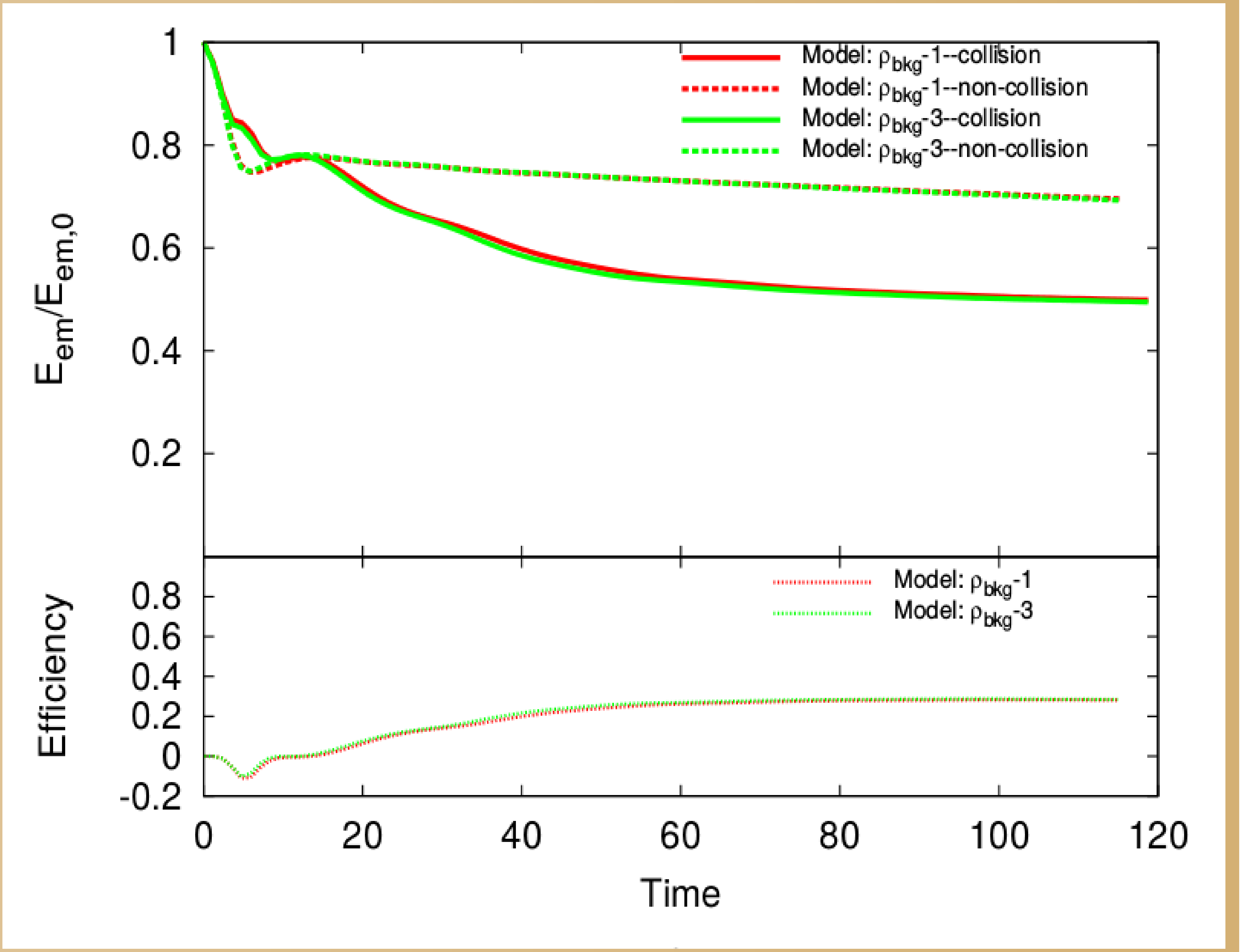

Thank you!

- Pressure



Model: P-1--collision
Model: P-1--non-collision
Model: P-2--collision
Model: P-2--non-collision
Model: P-3--collision
Model: P-3--non-collision
$E_{em}/E_{em,0}$
Efficiency
Model: P-1
Model: P-2
Model: P-3
Time

- Density



Model: ρbkg-1--collision
Model: ρbkg-1--non-collision
Model: ρbkg-3--collision
Model: ρbkg-3--non-collision
Eem/Eem,0
1
0.8
0.6
0.4
0.2
Model: ρbkg-1
Model: ρbkg-3
Efficiency
0.8
0.6
0.4
0.2
0
-0.2
0
20
40
60
80
100
120
Time