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MHD simulations of collision-induced magnetic reconnection in Poynting-flux-dominated jets and a unified interpretation of polarization properties of GRBs and blazars

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Ref: 1. Deng et al. 2015 ApJ; 2. Deng et al. 2016 ApJL

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

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

  (e.g. IS, Photosphere)

  and/or

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

  (e.g. ICMART, etc.)

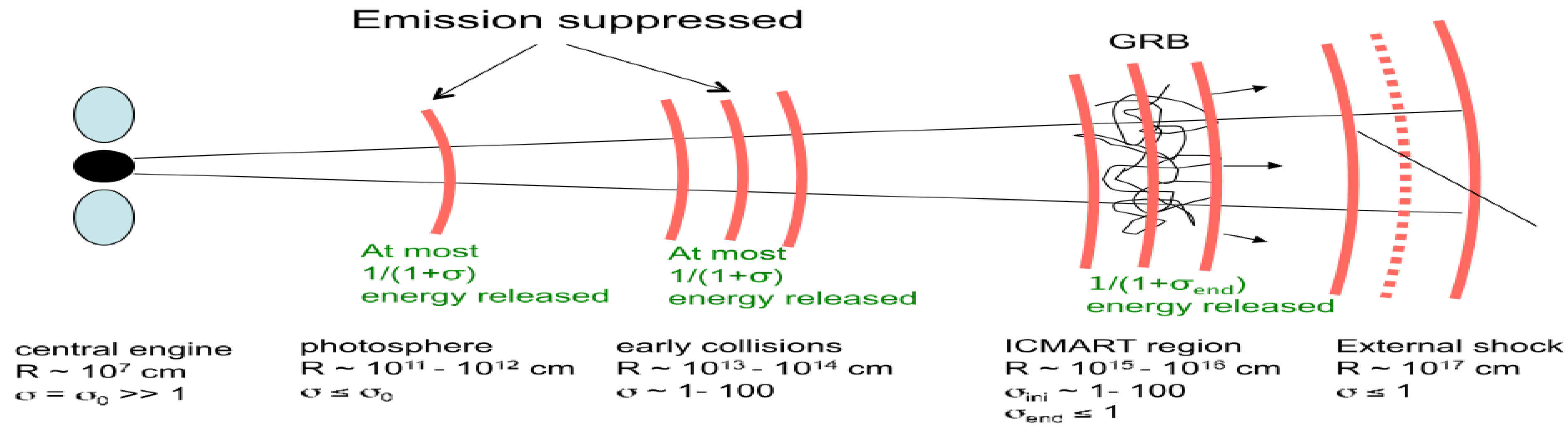
Affect the following:

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

PFD-- ICMART model

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

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

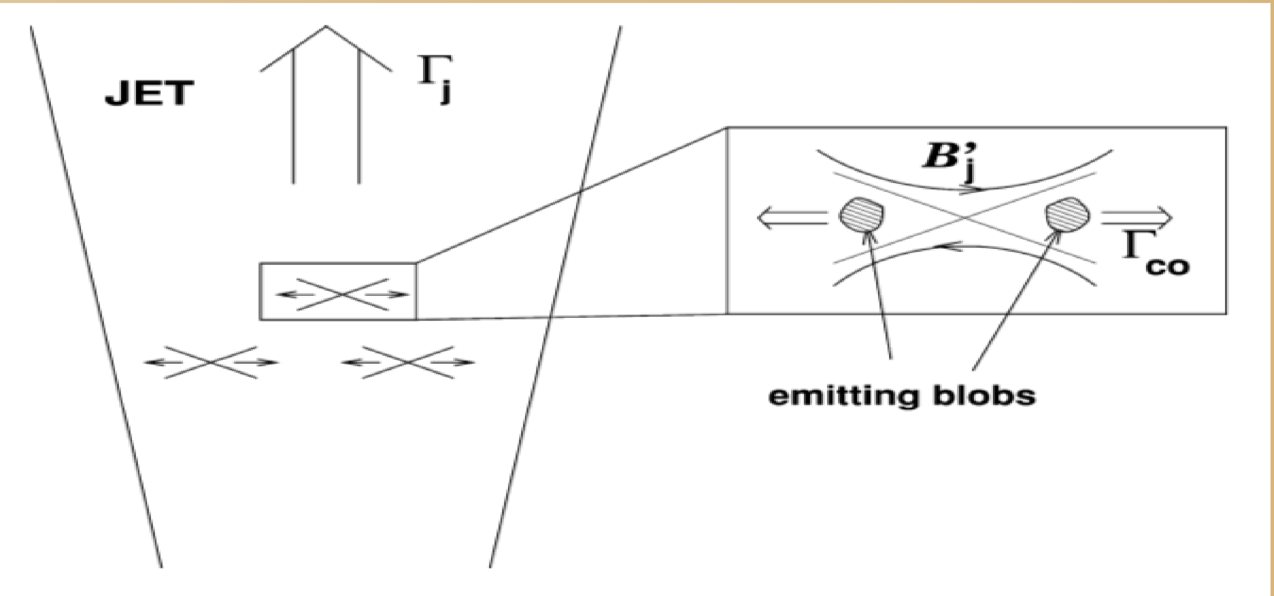


Zhang & Yan (2011, ApJ, 726, 90)

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

Giannios et al. (MNRAS 2009)

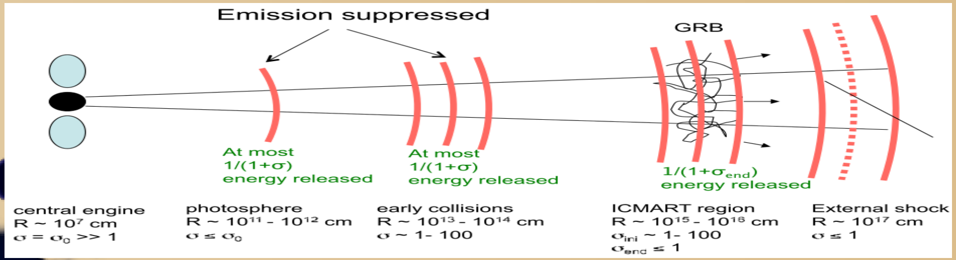
- Mini-jets due to local reconnection; double Lorentz boost; interpret fast TeV variability of some blazars.

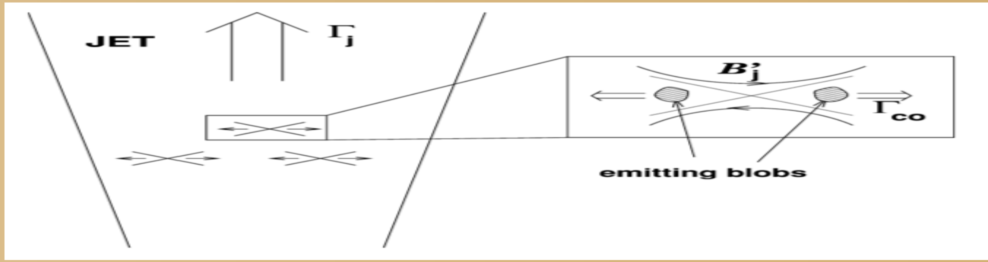


Giannios et al. (MNRAS 2009)

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, multiple mini jets 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

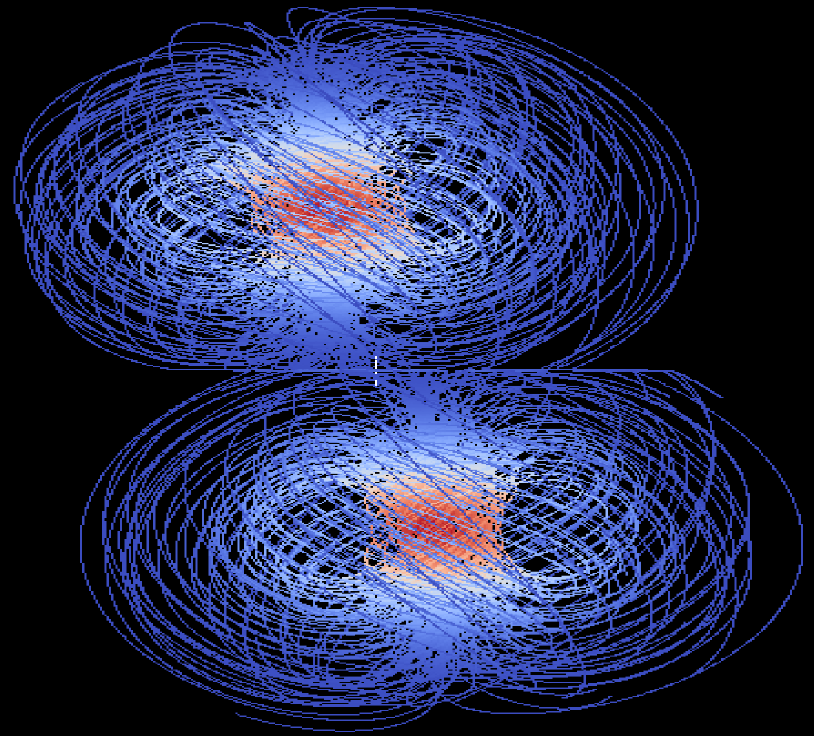
- We use a 3D SRMHD code which solves the conservative form of the ideal MHD equations. This code is a development version of the "LA-COMPASS" MHD code which was firstly developed by Li & Li (2003) at LANL.

- Field configuration: model (mag. tower) from Li et al. (2006), considering the "dynamo" of the central engine, contains both poloidal and toroidal components.

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

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

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



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

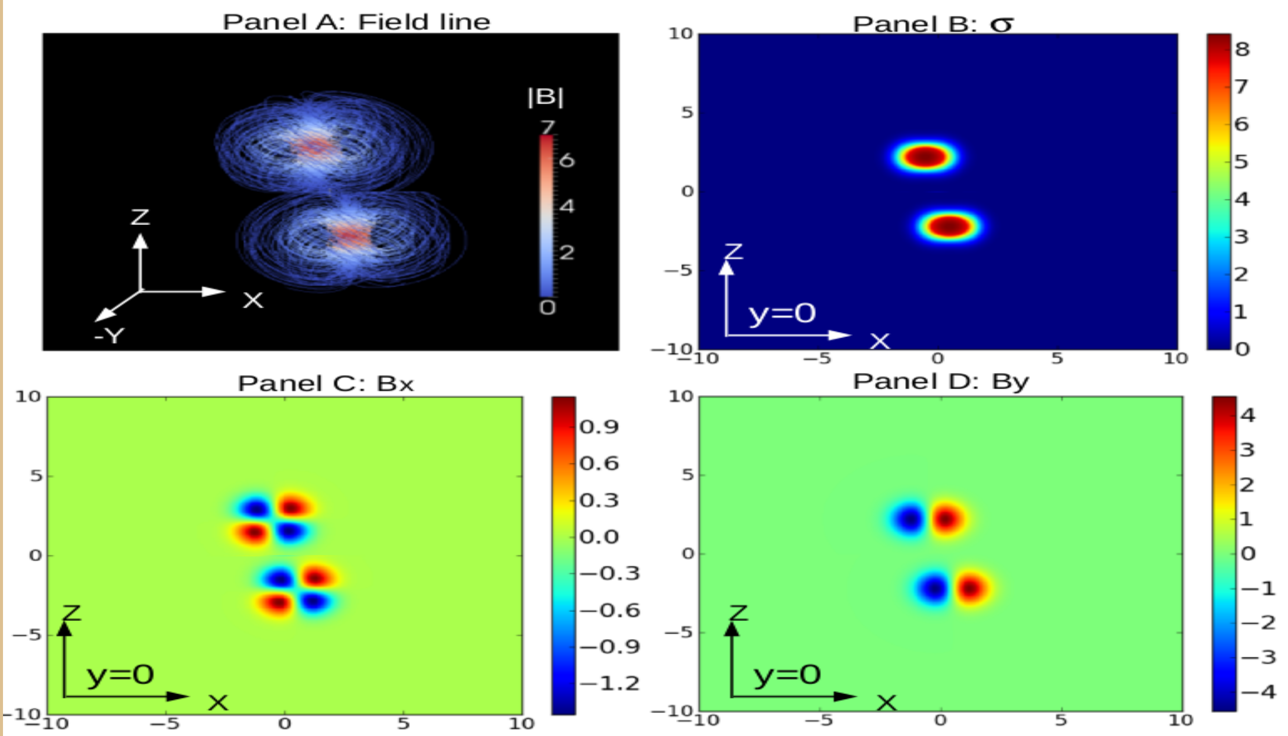
$$B_z = \frac{1}{r}\frac{\partial \Phi}{\partial r} = 2B_{\mathrm{b},0}(1-\frac{r^2}{r_0^2})\exp(-\frac{r^2+z^2}{r_0^2})$$

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

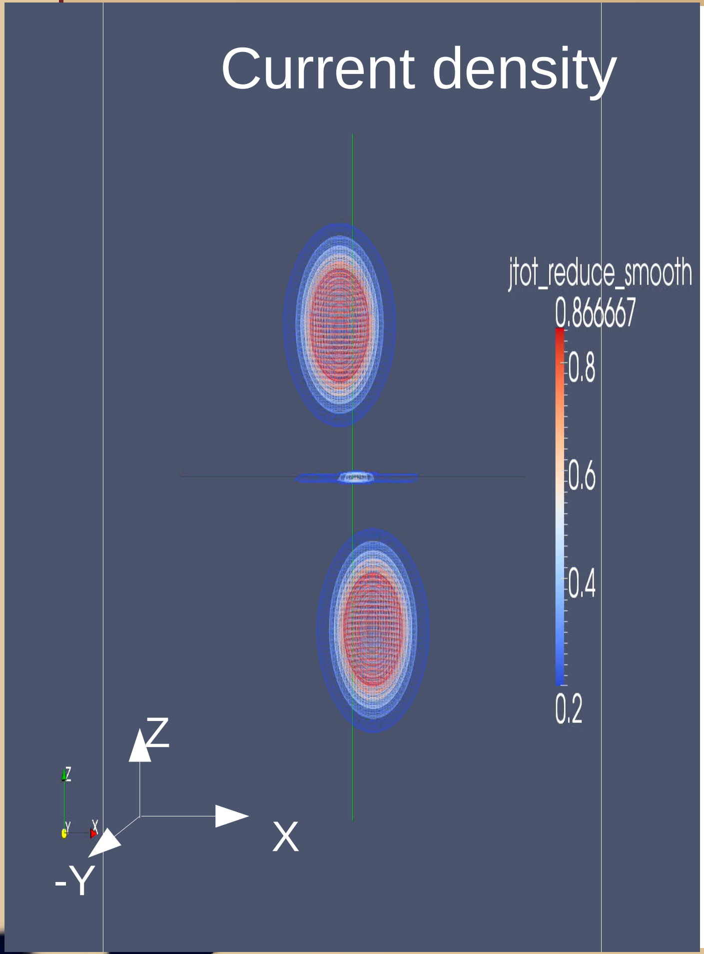
An example case: Initial parameters and cuts

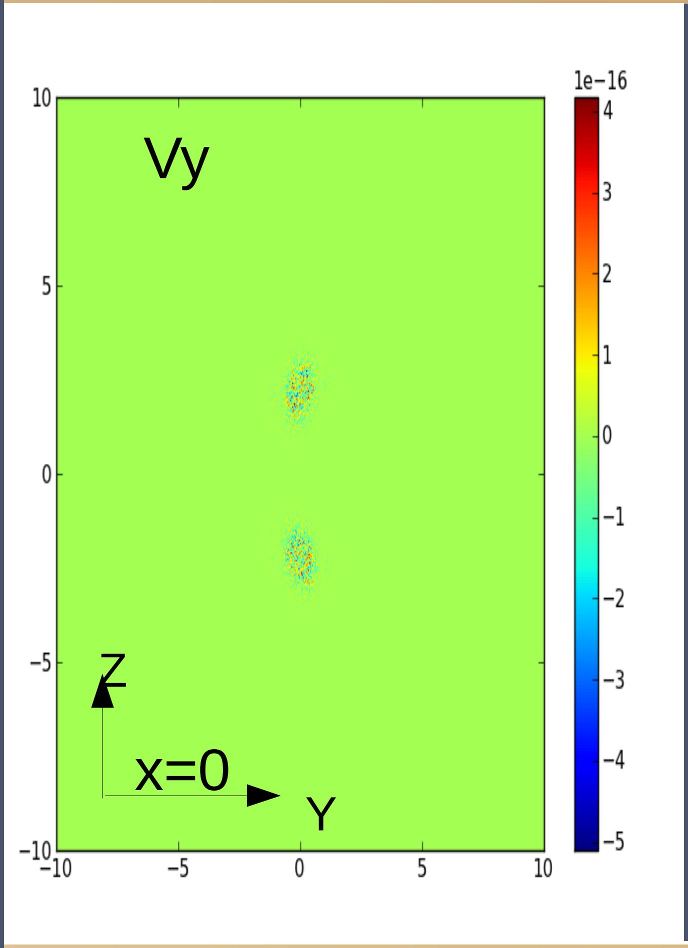
- Initial typical radius of blobs $r_0=1$
- Collision along Z direction
- Misalignment in X direction (x_s)
- Box size: 20^3 ; Resolution: 1024^3

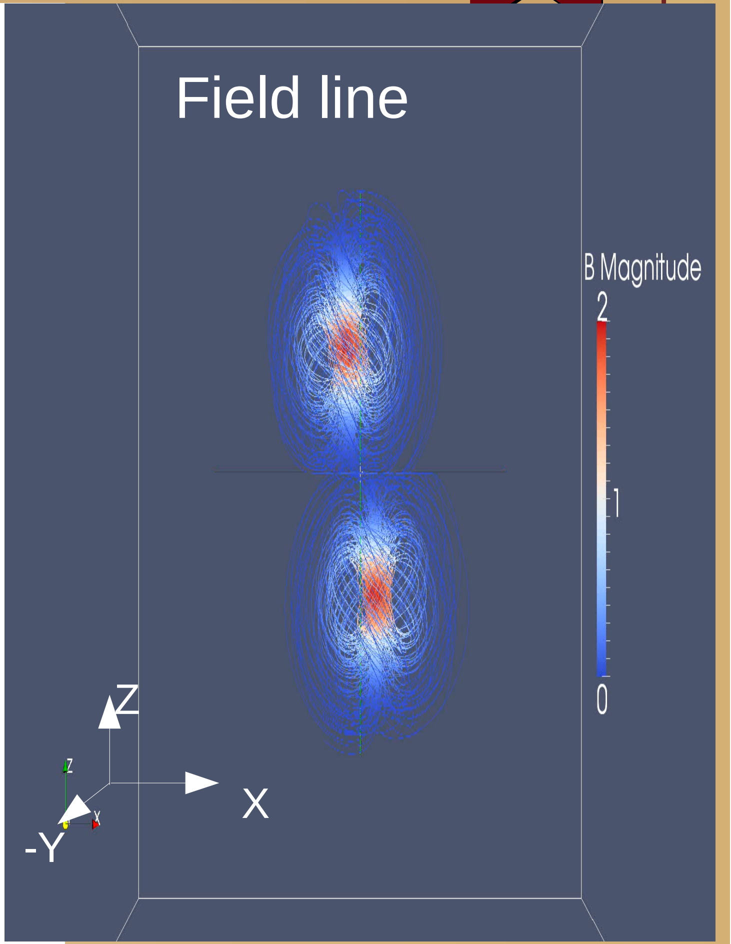
$\sigma_{b,i}$	$B_{b,0}$	$V_{b,z}$	P	ρ_{bkg}	z_d	x_s
8	$\sqrt{4\pi}$	0.3c	10^{-2}	10^{-1}	4.4	1.0

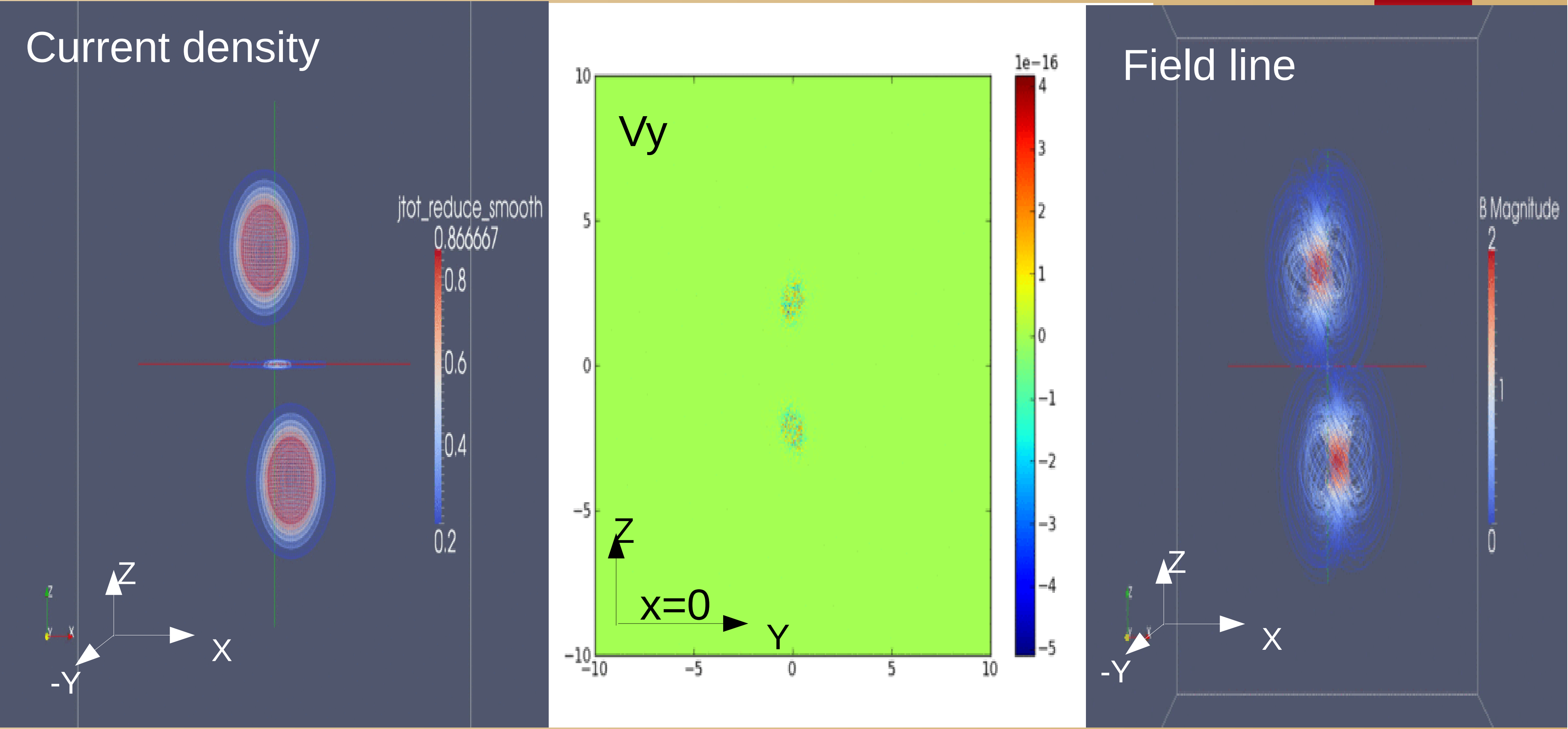


Movies for current and outflows





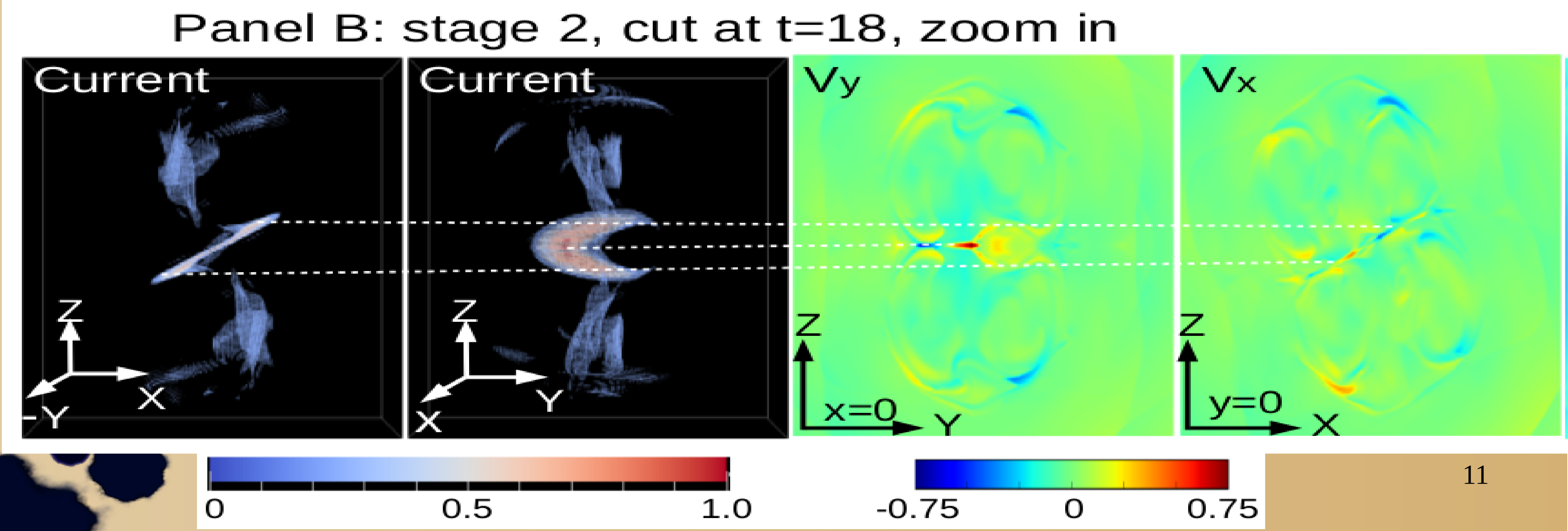




- Observe clear reconnection features.
- Kink-like instability is generated in the outflow.

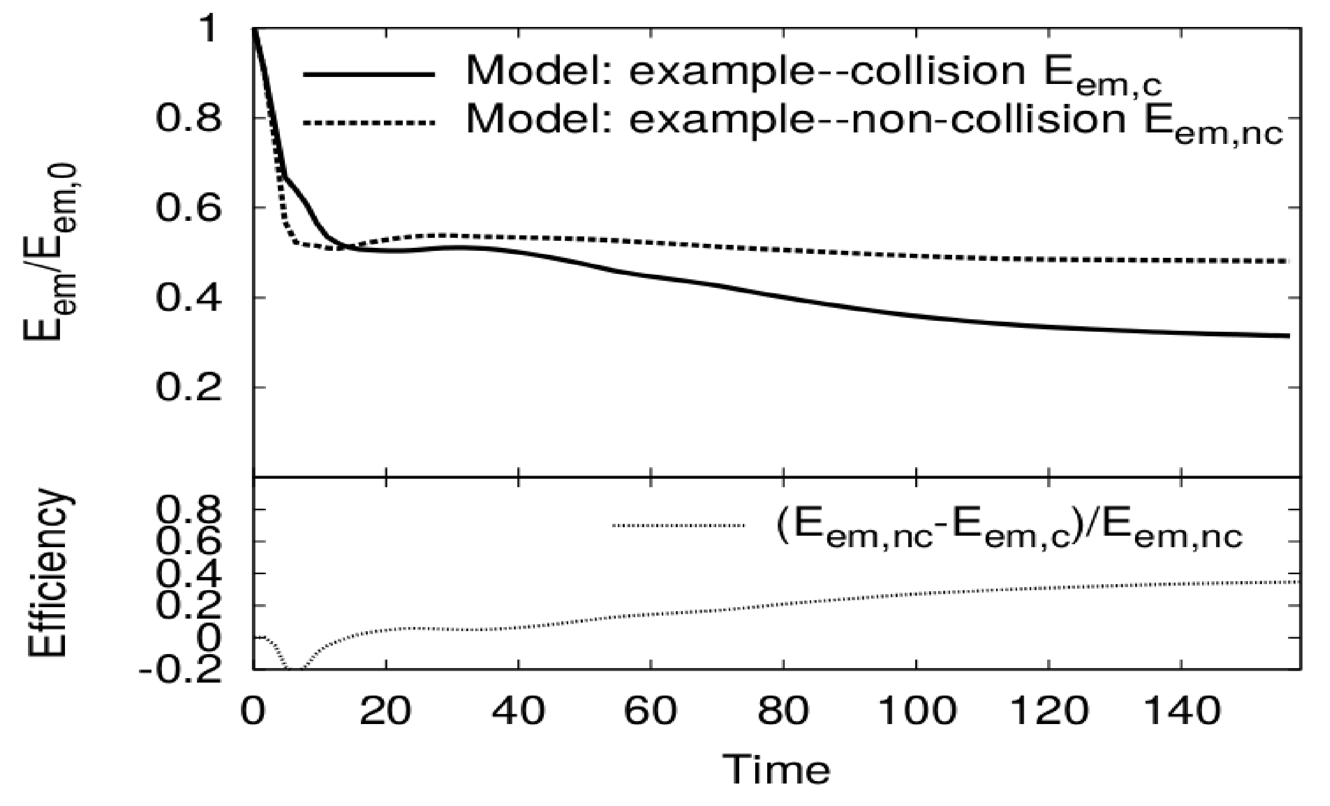
Qualitatively analyses — outflow study

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



Quantitatively analyses — EMF energy dissipation efficiency: example

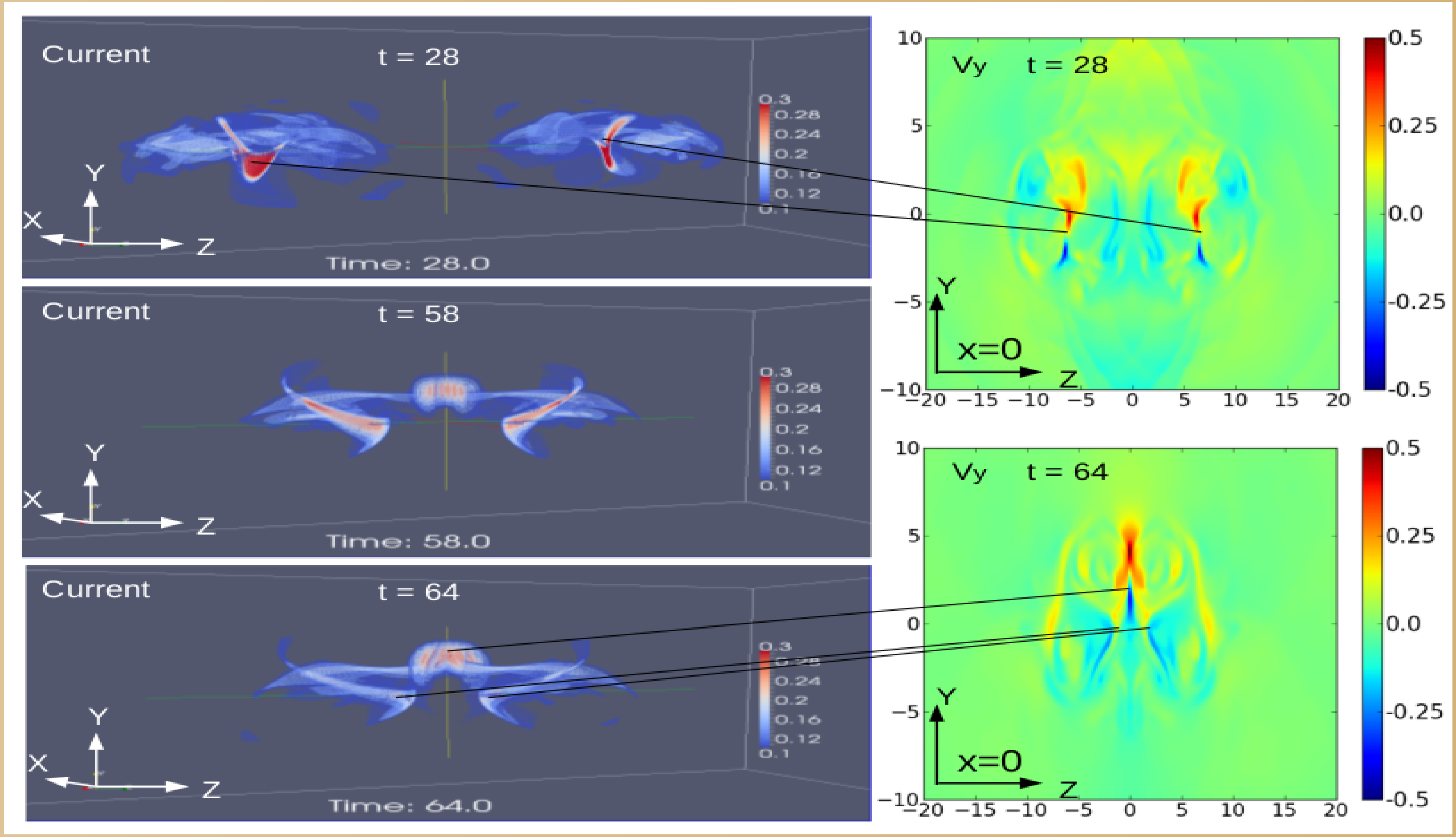
- No matter collision or not, initially, not in completely force balance, undergoing fast expansion to establish the force balance.
- Need non-collision case as reference
- Initial “self adjustment” t<10



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

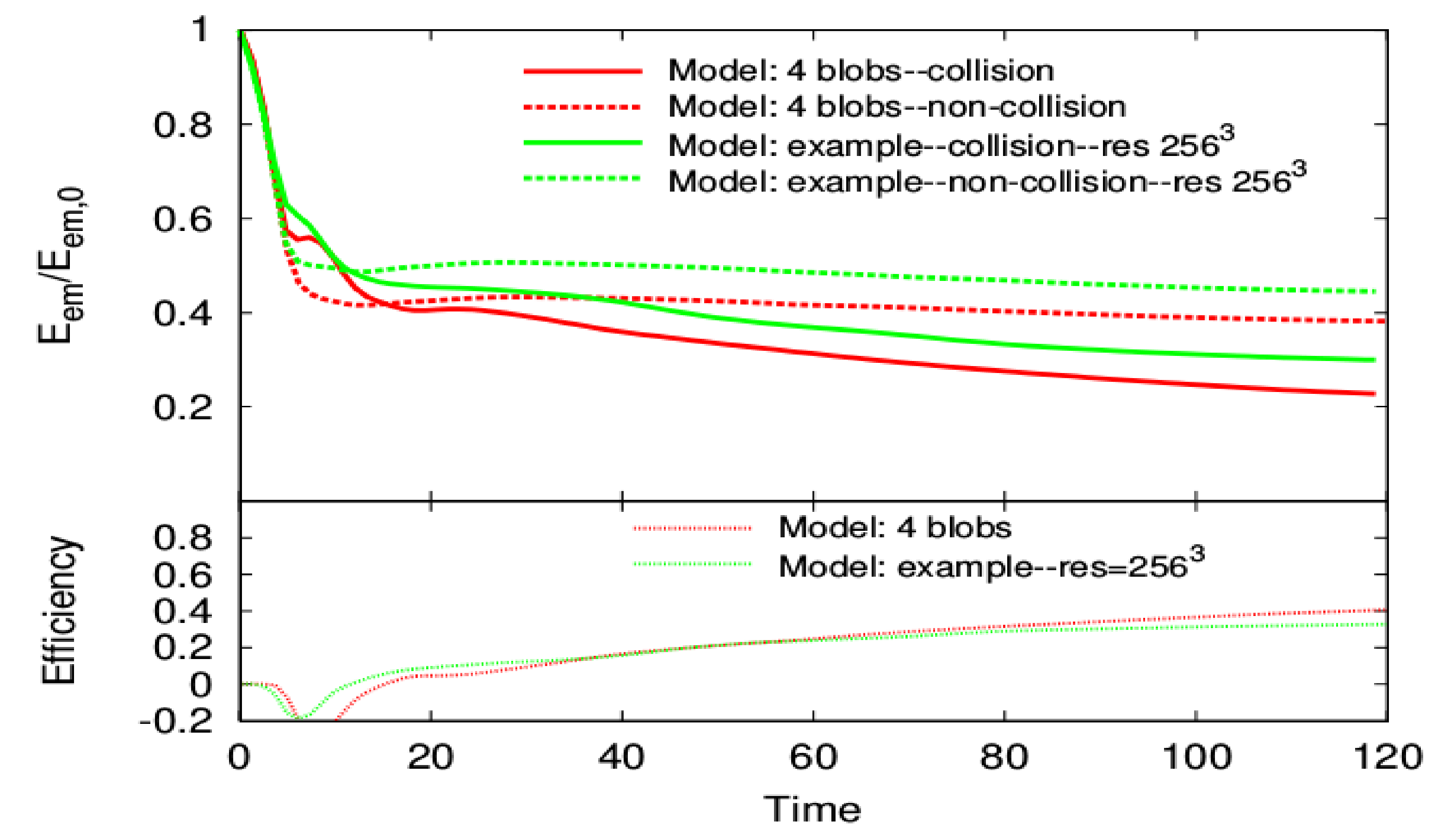
Multi-collisions — outflow

4 blobs;
More multi-direction mini-jets



Multi-collisions — EMF energy dissipation efficiency

Higher efficiency



Conclusion

- High energy dissipation efficiency ~40%;
- Great potential to generate multiple relativistic mini-jets;
- GRB prompt emission and Blazar emission zone may share similar physical process and energy environment
- $\sigma_{b,i}$ - $\sigma_{b,f}$: interesting linear relationship;

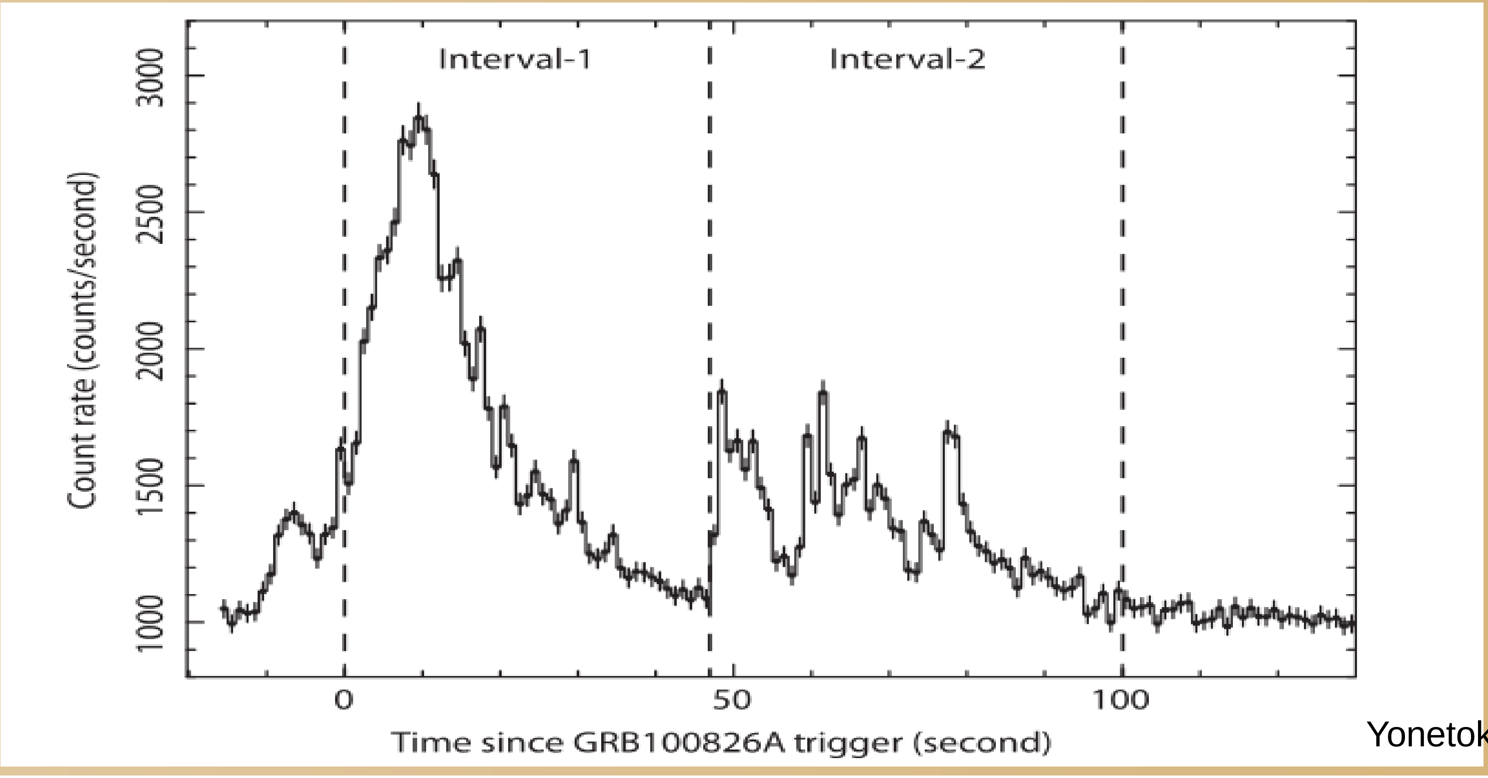
(Ref: Deng et al. 2015 ApJ)

Application: Simultaneously interpret polarization obs. for both GRBs & Blazars

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

Ref: Deng et al. 2016 ApJL

Obs. 1 (GRB 100826A)

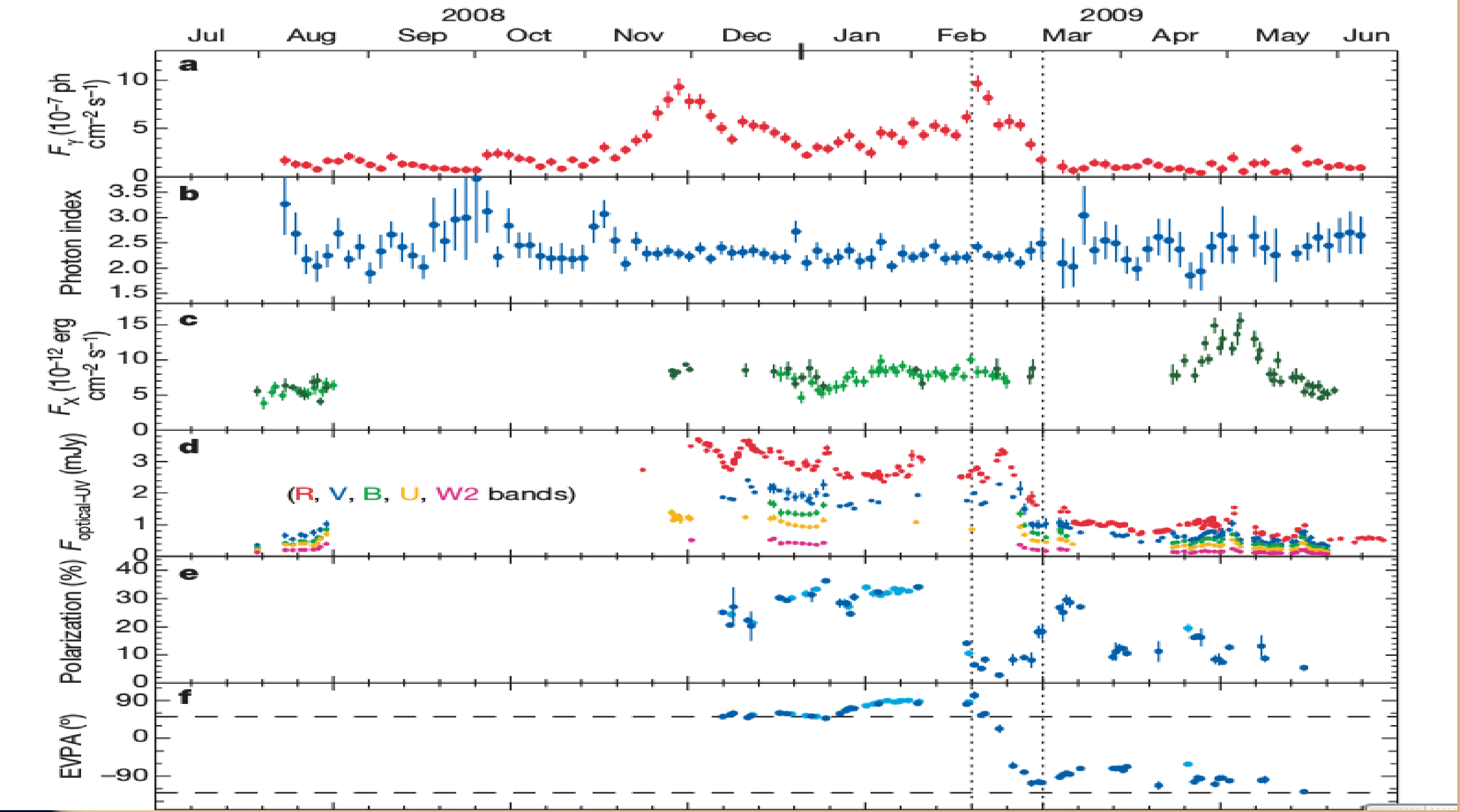


Yonetoku 2011

90 degrees PA change

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,

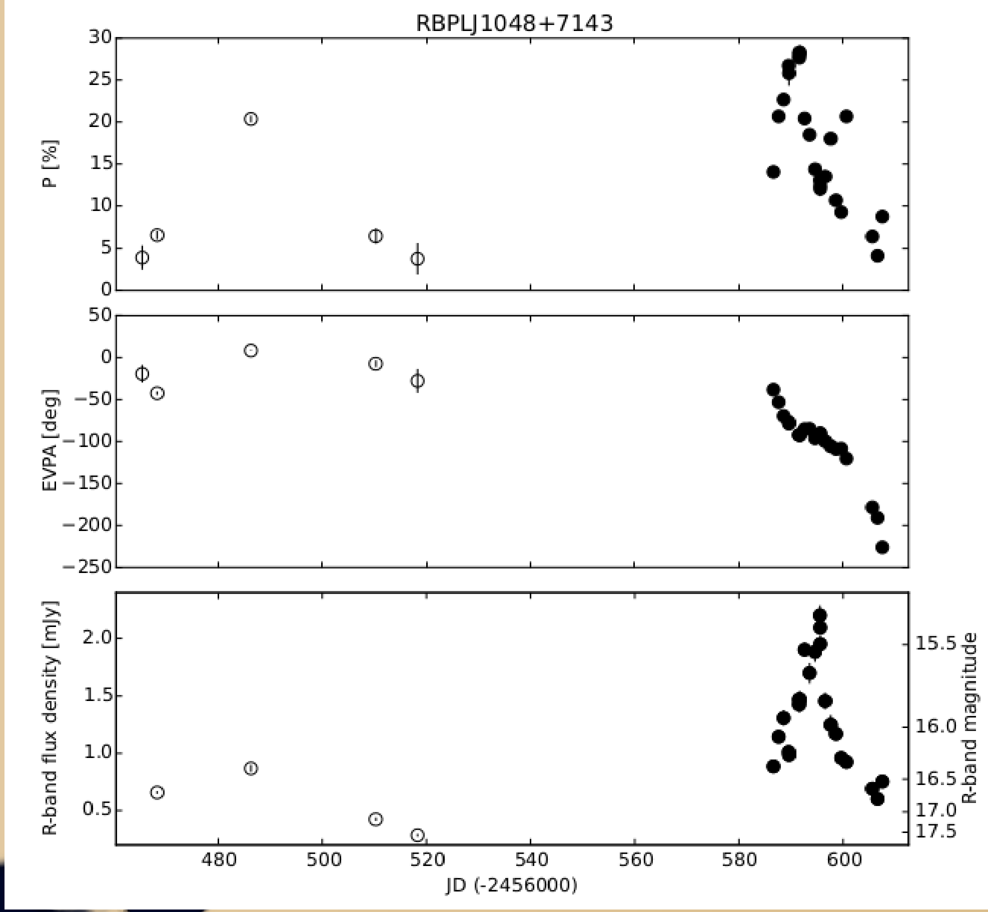
Obs. 2 (Blazar 3C279)

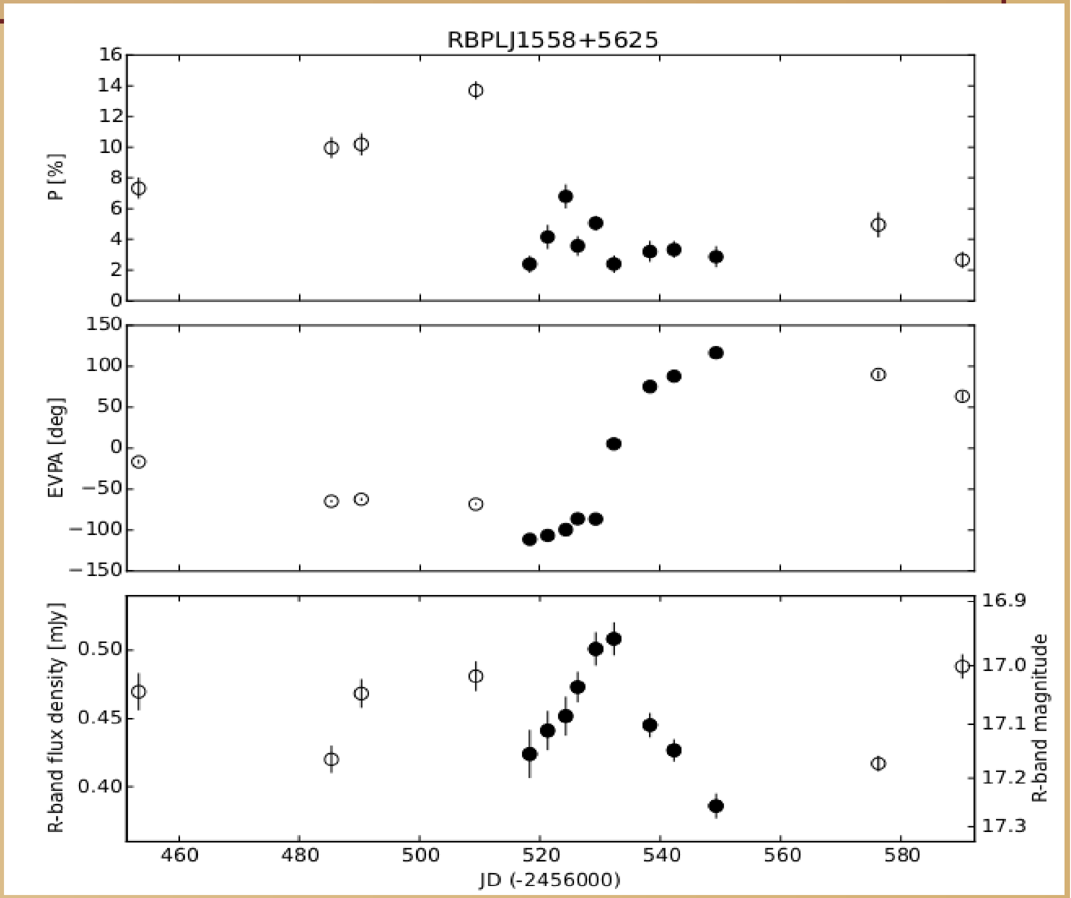


180 degrees PA change

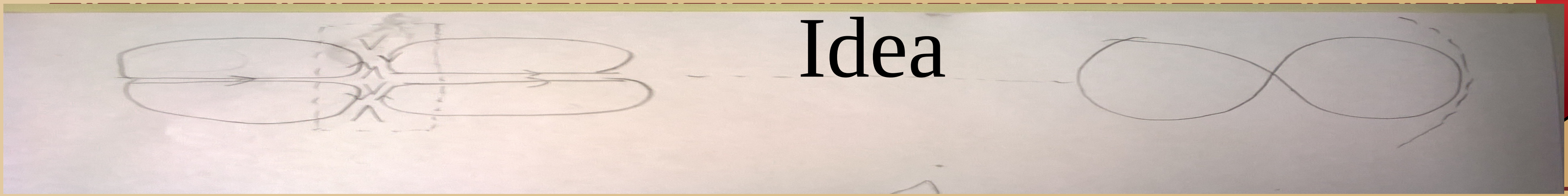
Abdo et al. 2010

More polarization obs. of blazars (RoboPol)





Blinov et al. 2015

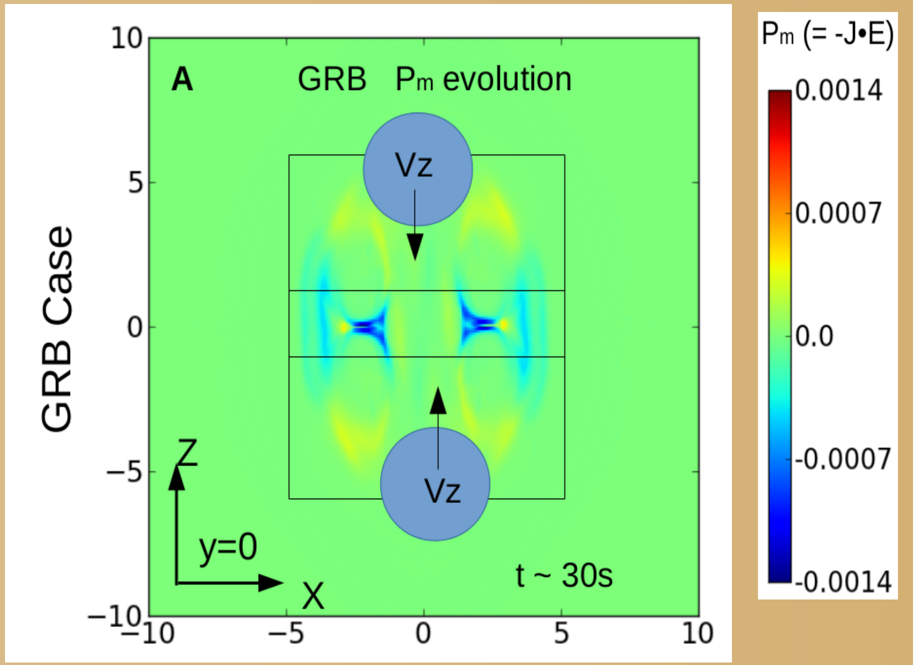


Idea

- Consider that particles are accelerated in the rec. region;

- Inject non-thermal particles in the reconnection region cell by cell;
- n_e of each cell is normalized by local J*E;
- Comoving observer views along with the x-axis.
- Connect the Syn. radiation+polarization code “3DPol” (Zhang, H. et al. 2014) to get our final results

Power proxy (-J*E) evolution



Parameters

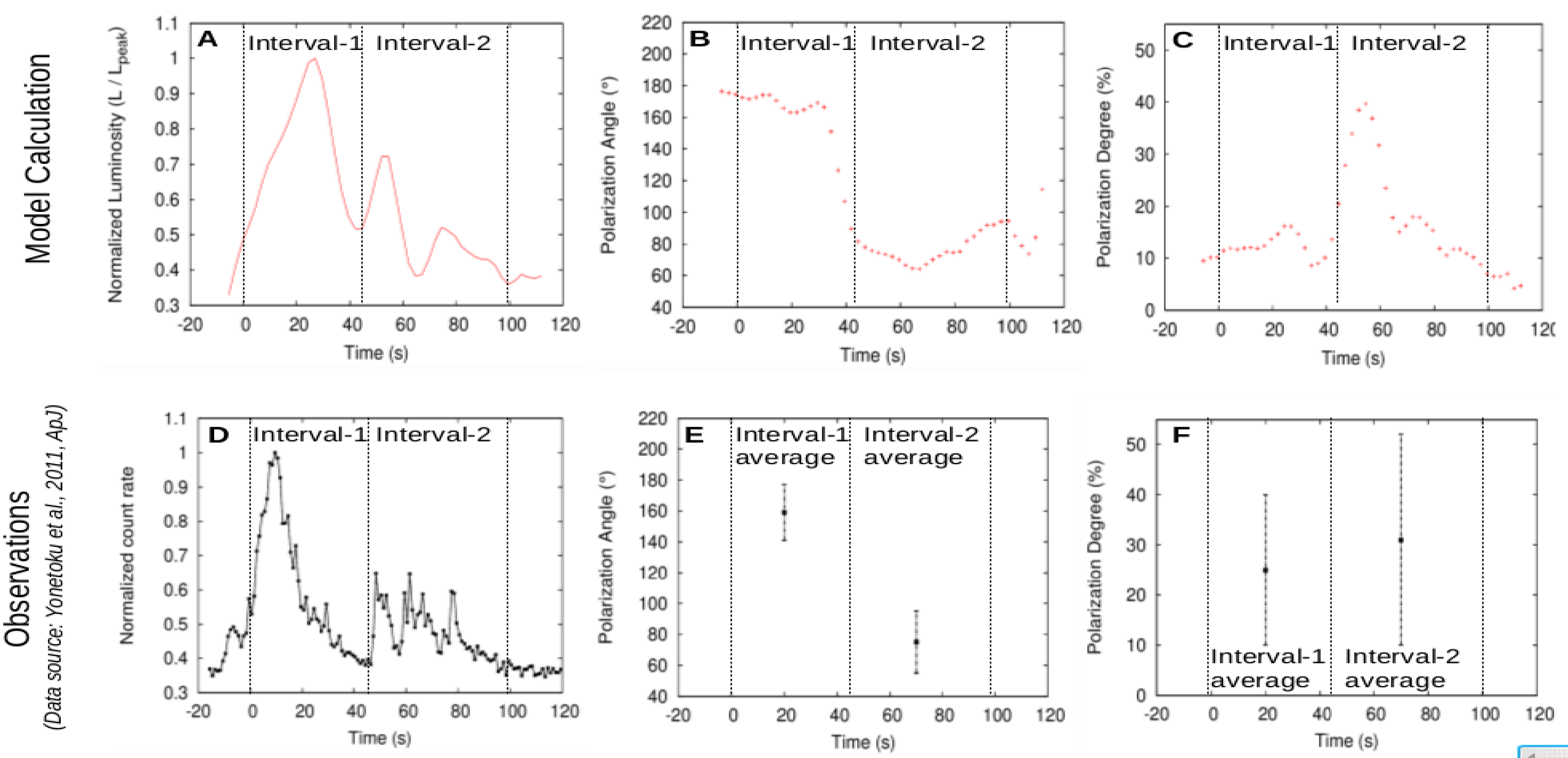
$$n(\gamma_e) = \begin{cases} n_0(\gamma_e/\gamma_m)^{-1}, & 10^2 < \gamma_e < \gamma_m, \\ n_0(\gamma_e/\gamma_m)^{-3.2}, & \gamma_m < \gamma_e < 10^6, \end{cases}$$

$$n(\gamma_e) = n_0\gamma_e^{-2}, \qquad 10^3 < \gamma_e < 5 \times 10^4,$$

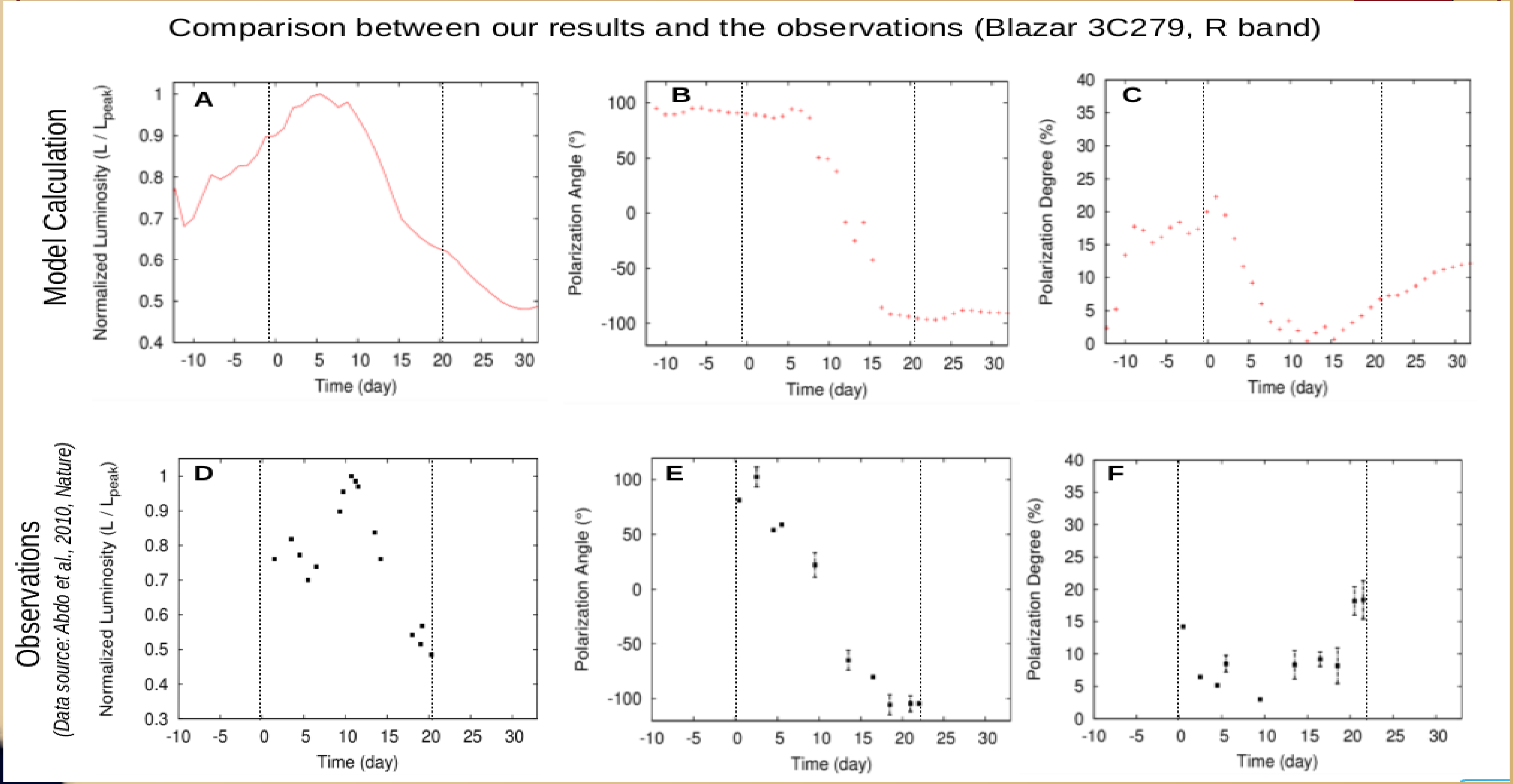
Case	GRB 100826A		Blazar 3C279	
Parameter	Code	Physical	Code	Physical
σ_c	6	6	2	2
$\overline{B}$	0.25	750 (G)	0.35	0.35 (G)
$\lvert V_z \rvert$	0.3	0.3c	0.8	0.8c
t_0	1	375 (s)	1	9.5×10^5 (s)
L_0	1	1.13×10^{13} (cm)	1	2.86×10^{16} (cm)
x_s	0.01	1.13×10^{11} (cm)	1	2.86×10^{16} (cm)
r_0	2	2.25×10^{13} (cm)	2.5	7.15×10^{16} (cm)
α	3	3	3	3
P	10^{-2}	9×10^4 (ergs/cm^3)	10^{-2}	10^{-2} (ergs/cm^3)
ρ_{bkg}	10^{-1}	10^{-15} (g/cm^3)	10^{-1}	1.1×10^{-22} (g/cm^3)

Connect the polarization code 3DPol (Zhang, H. et al. 2014) with MHD simulations to get our final results

Comparison between our results and the observations (GRB 100826A, *70-300 KeV*)

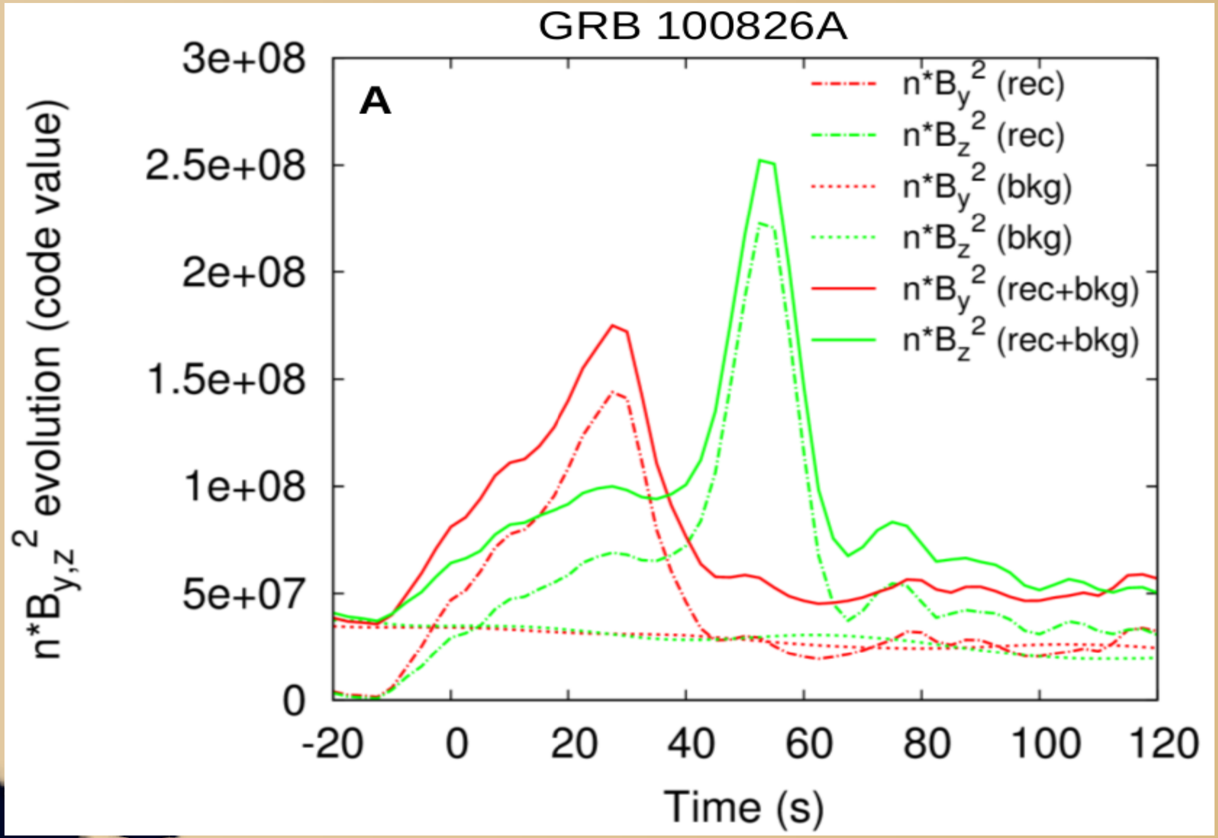


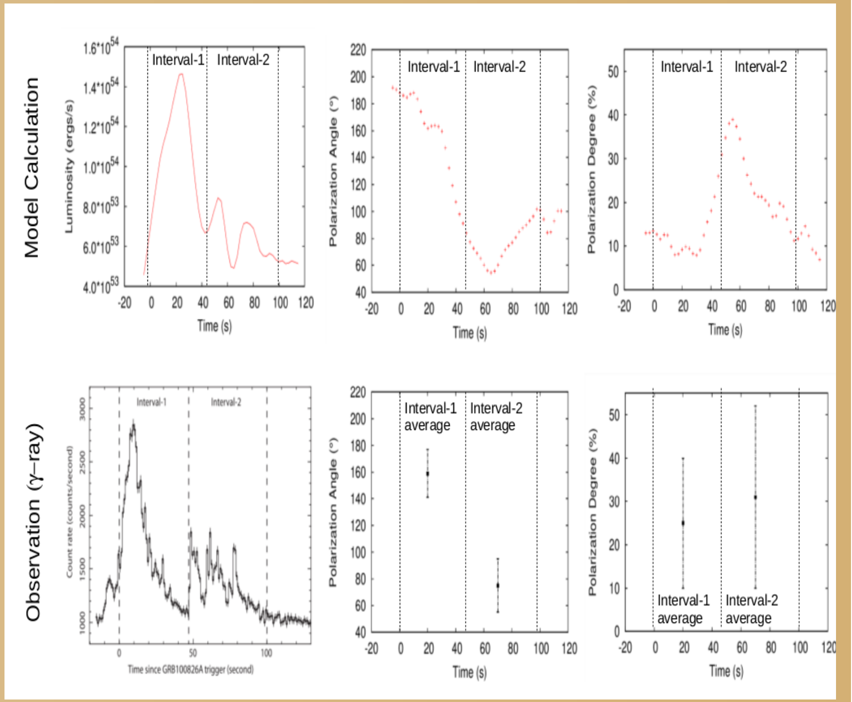
Connect the polarization code 3DPol (Zhang, H. et al. 2014) with MHD simulations to get our final results



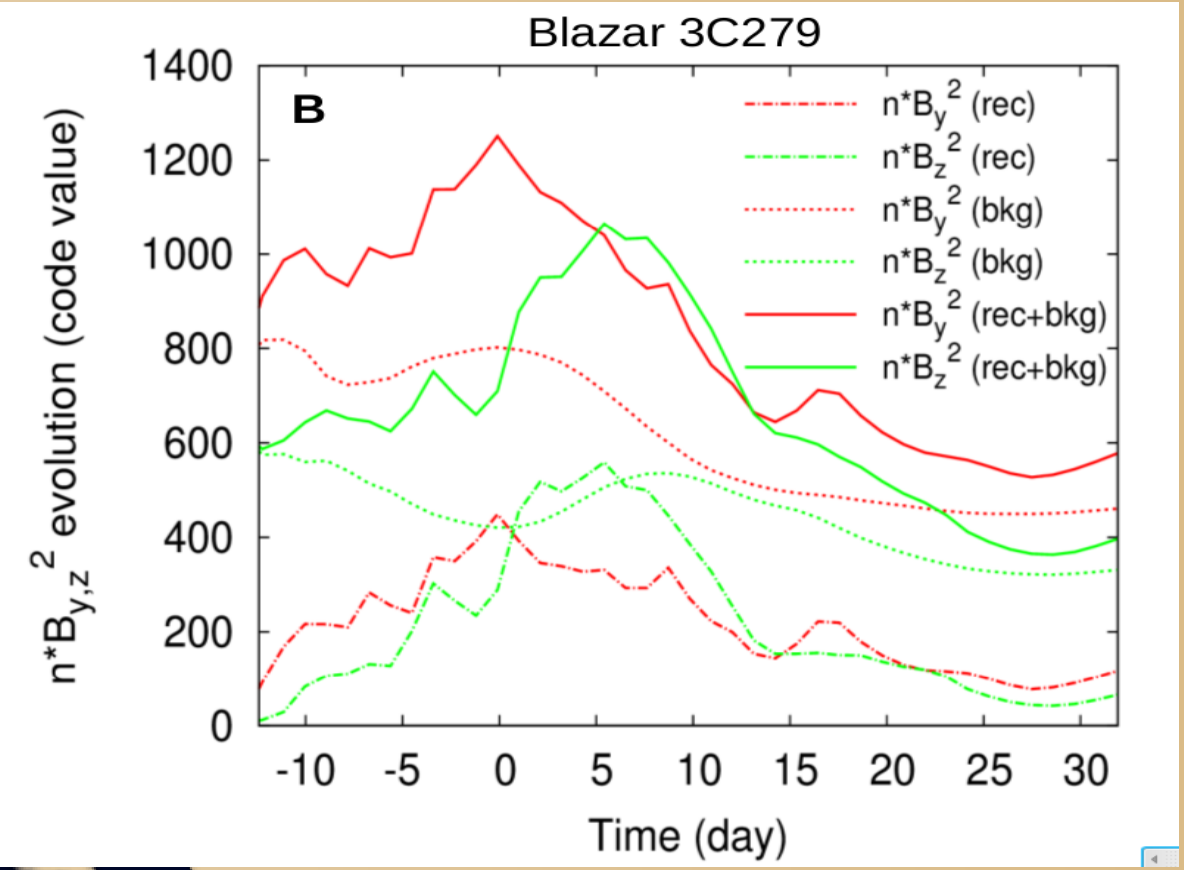
Comoving observer views along with the x-axis; Calculate n_e*B^2 for two B field components (y,z) separately: determine which component is dominant.

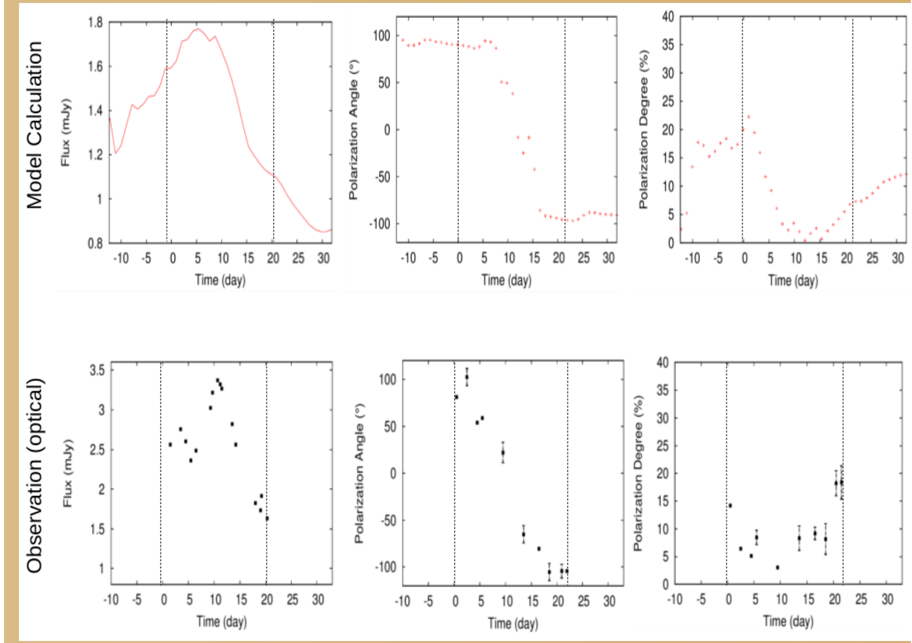
GRB case





Blazar case

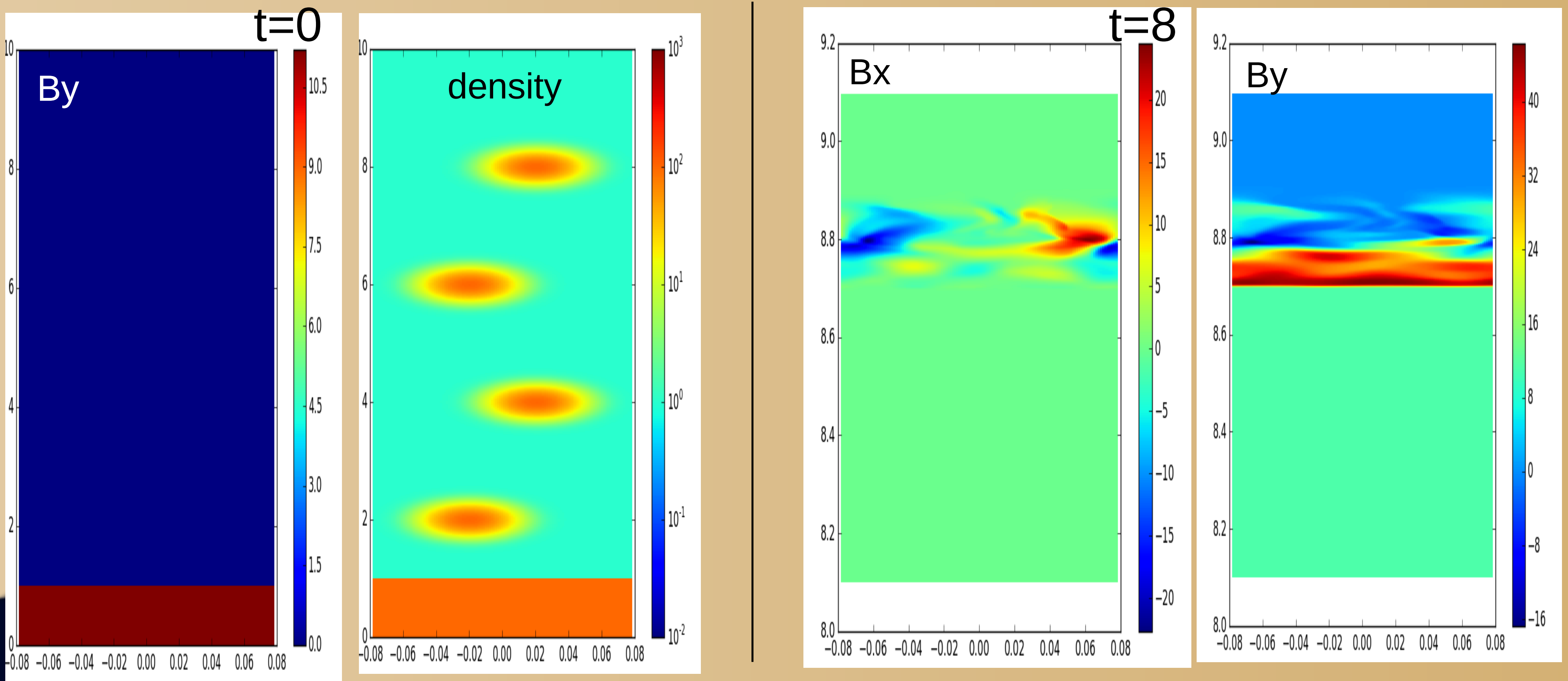

Blazar 3C279
B
n*B_y^2 (rec)
n*B_z^2 (rec)
n*B_y^2 (bkg)
n*B_z^2 (bkg)
n*B_y^2 (rec+bkg)
n*B_z^2 (rec+bkg)
n*B_{y,z}^2 evolution (code value)
Time (day)


Model Calculation
Observation (optical)
Flux (mJy)
Polarization Angle (°)
Polarization Degree (%)
Time (day)

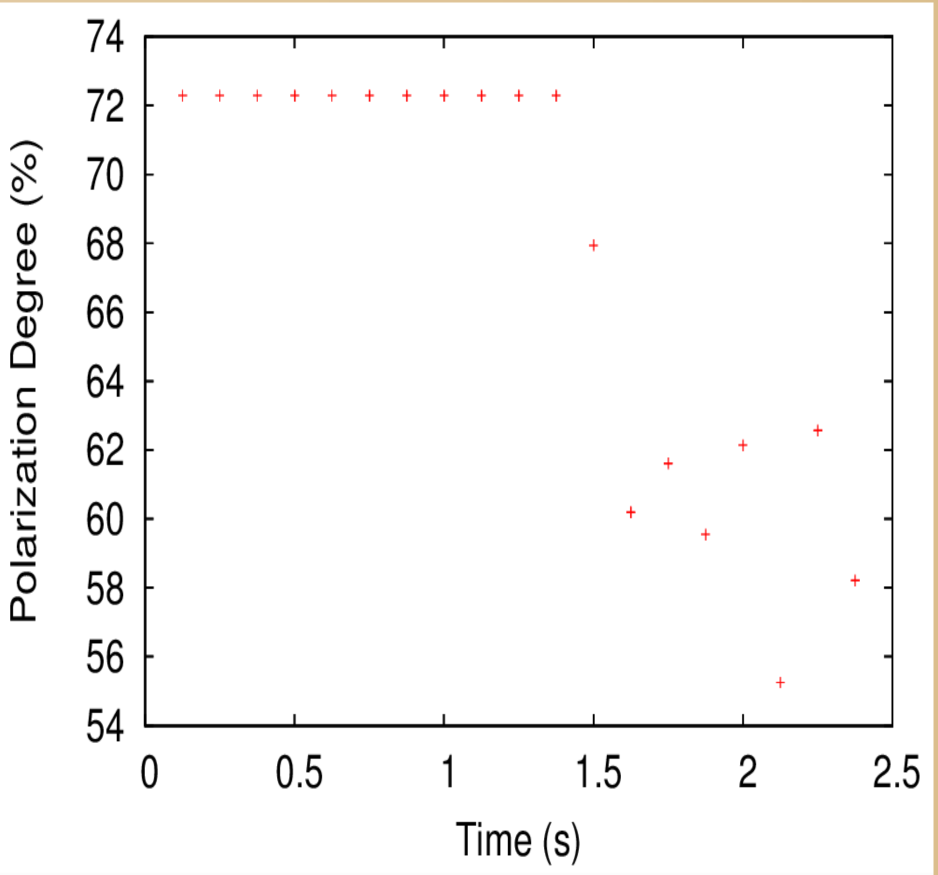
Conclusion

- Use MHD simulations to evolve the magnetic field topology instead of the ad hoc magnetic field configuration, fully taking into account the collision-induced reconnection and rotation effect due to mis-alignment.
- The unified interpretation of the polarization properties of both GRBs and blazars suggest that similar underlying physics is likely in operation in black hole relativistic jet systems. (PFD, collision-induced reconnection)

Deng et al. in prep: Magnetized RS affected by amb. density fluctuation and the pol. Evolution (motivated by the pol. obs. in early afterglow)



In prep: Magnetized RS affected by amb. density fluctuation and the pol. evolution



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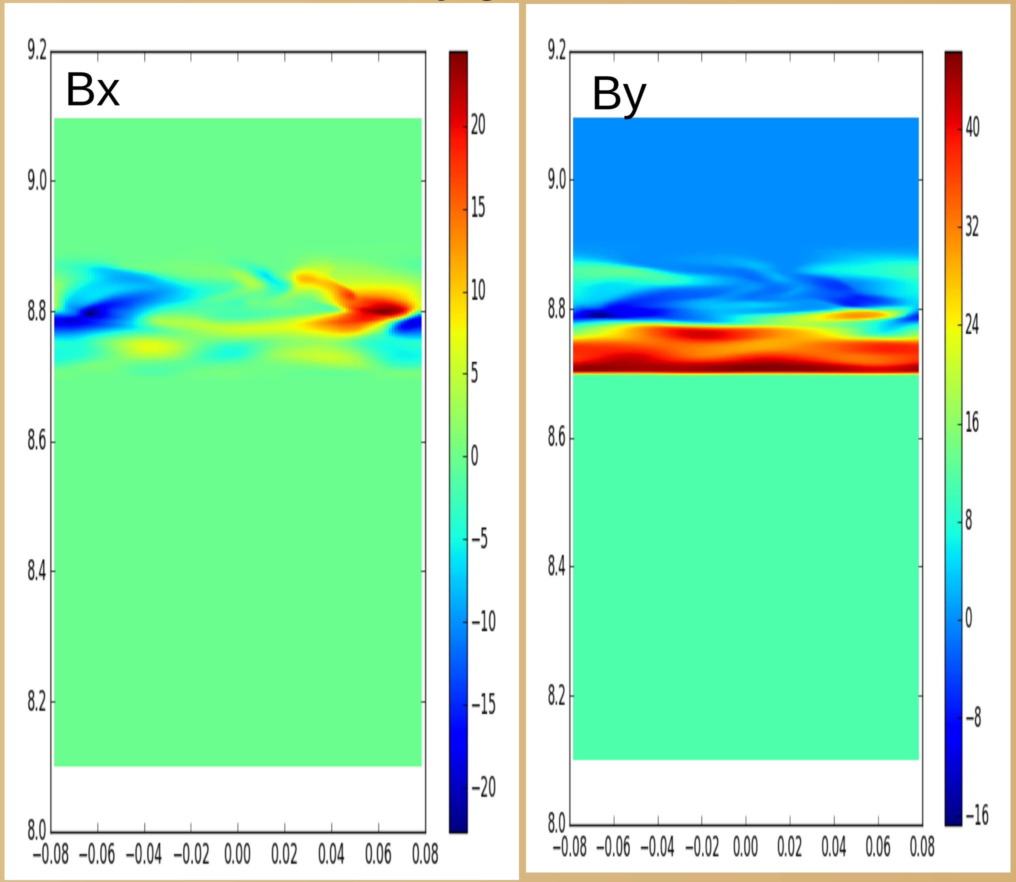

Summary

- High energy dissipation efficiency;
- Multiple relativistic mini-jets generation;
- Good interpretation for polarization obs. for both GRB and Blazar;

Great potential, engage us to do more following studies.

Seeking jobs

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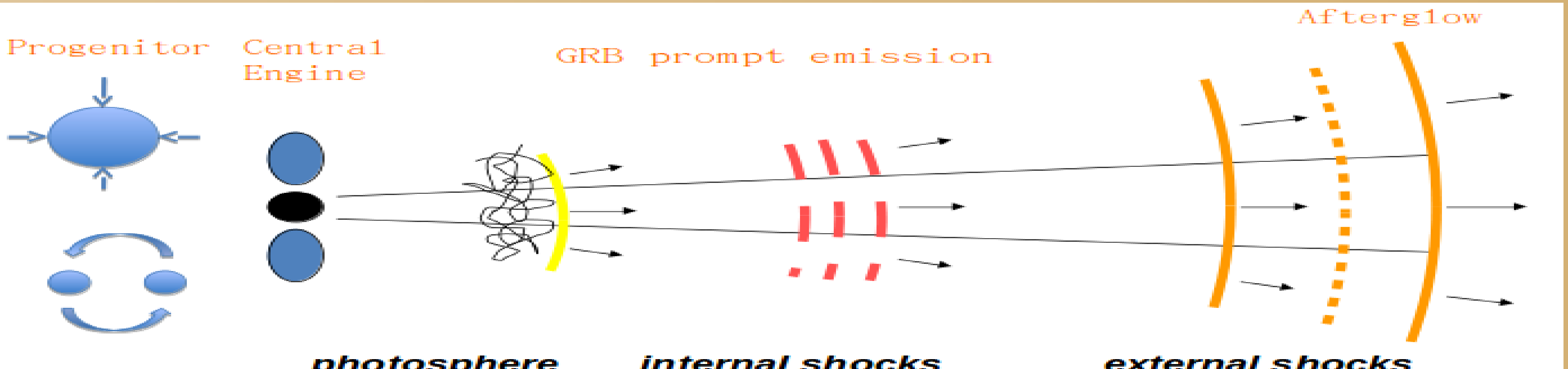
Back up slices

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 probl



Zhang (2014)

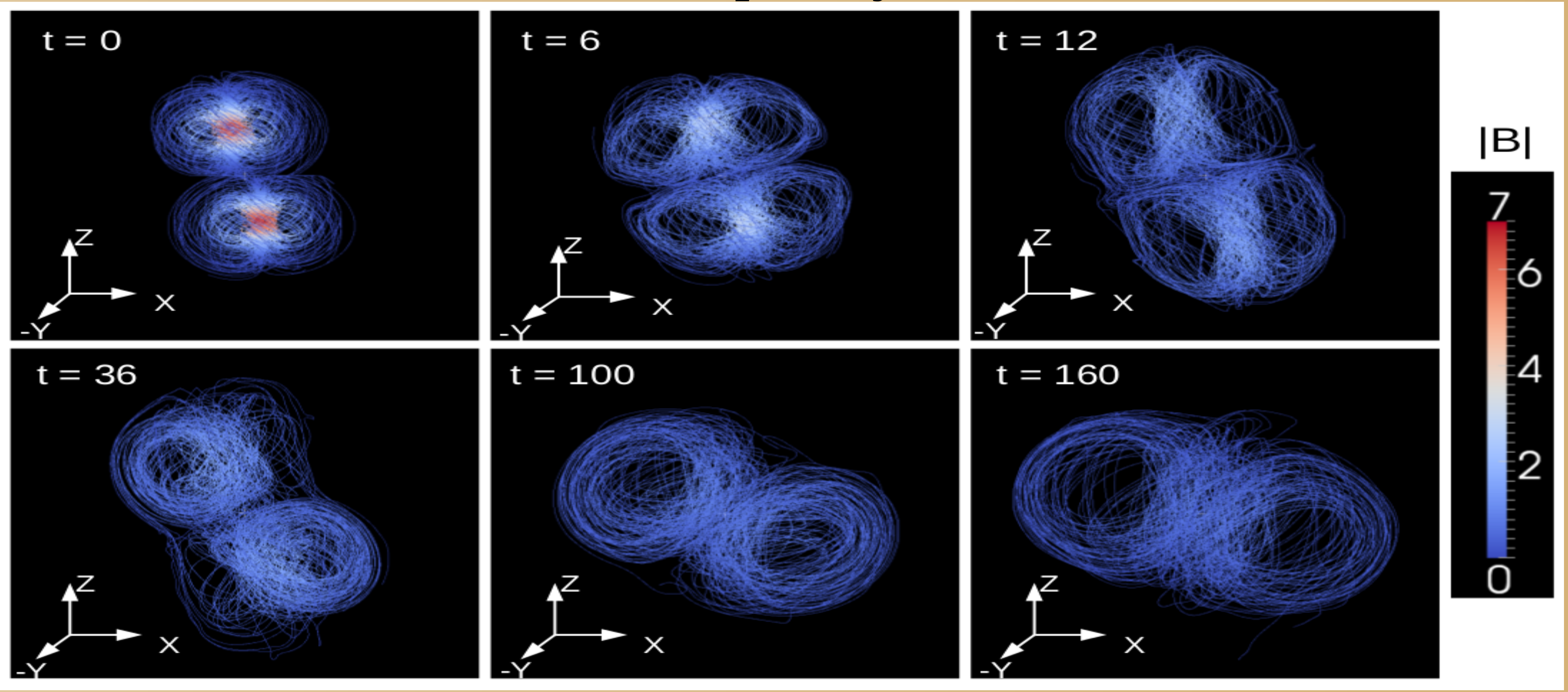
MFD – Dissipative photosphere model

(Beloborodov, 2010; Lazzati & Begelman, 2010)

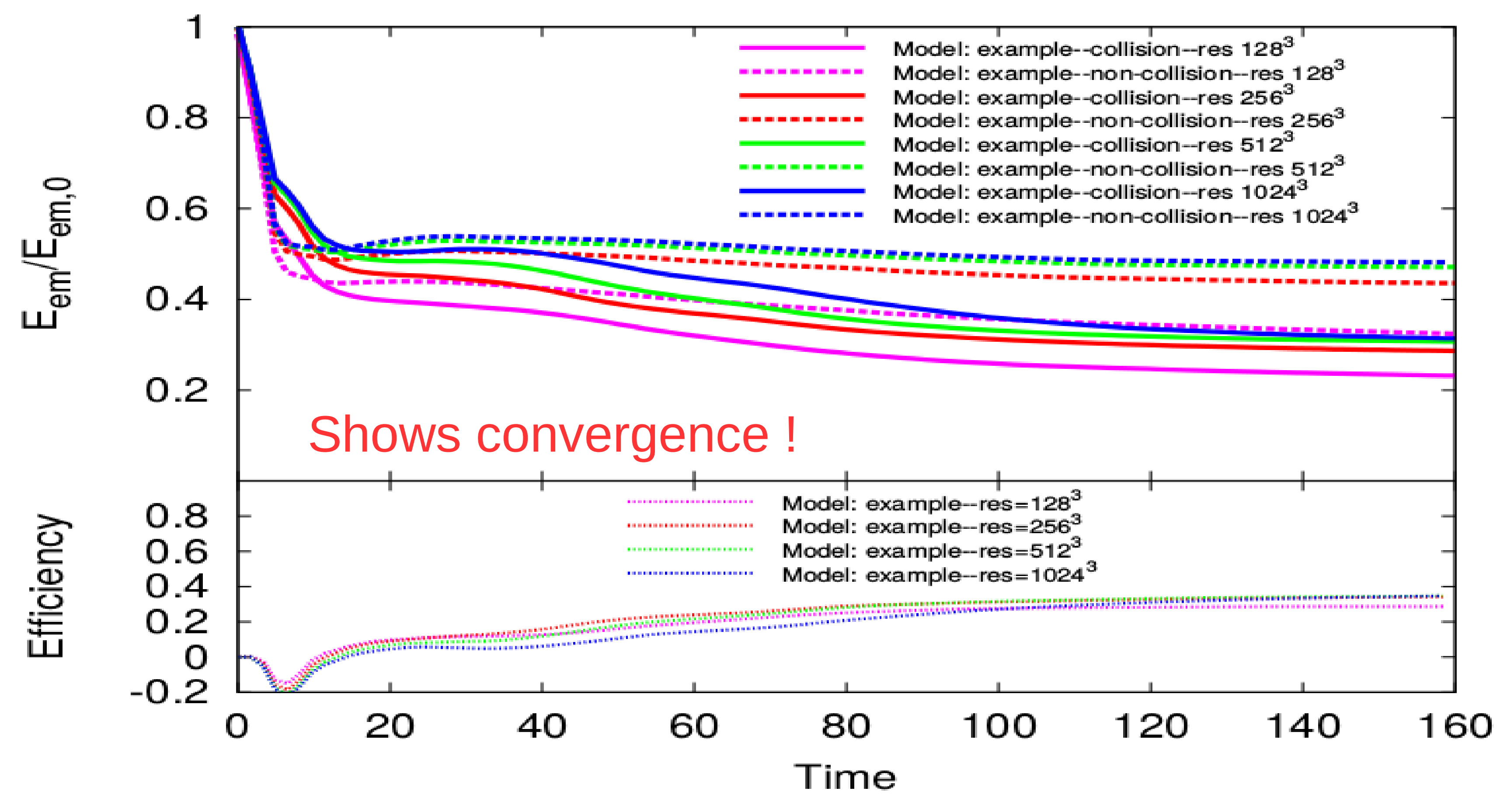
- Try to interpret the Band-function spectrum using the photosphere facilitated process.
- Merits: high efficiency of the photosphere emission; avoids the “missing bright photosphere” problem; can produce high energy spectrum segment by introducing up-scattering.
- Criticisms: Confliction with thermal+Band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

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.



Quantitatively analyses — EMF energy dissipation efficiency: resolution study



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...).

Physical analyses, σ evolution

- Energy conservation:

(Zhang & Yan 2011)

- Simplification:

$\sigma_{b,f}$ 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.

Physical analyses, σ evolution

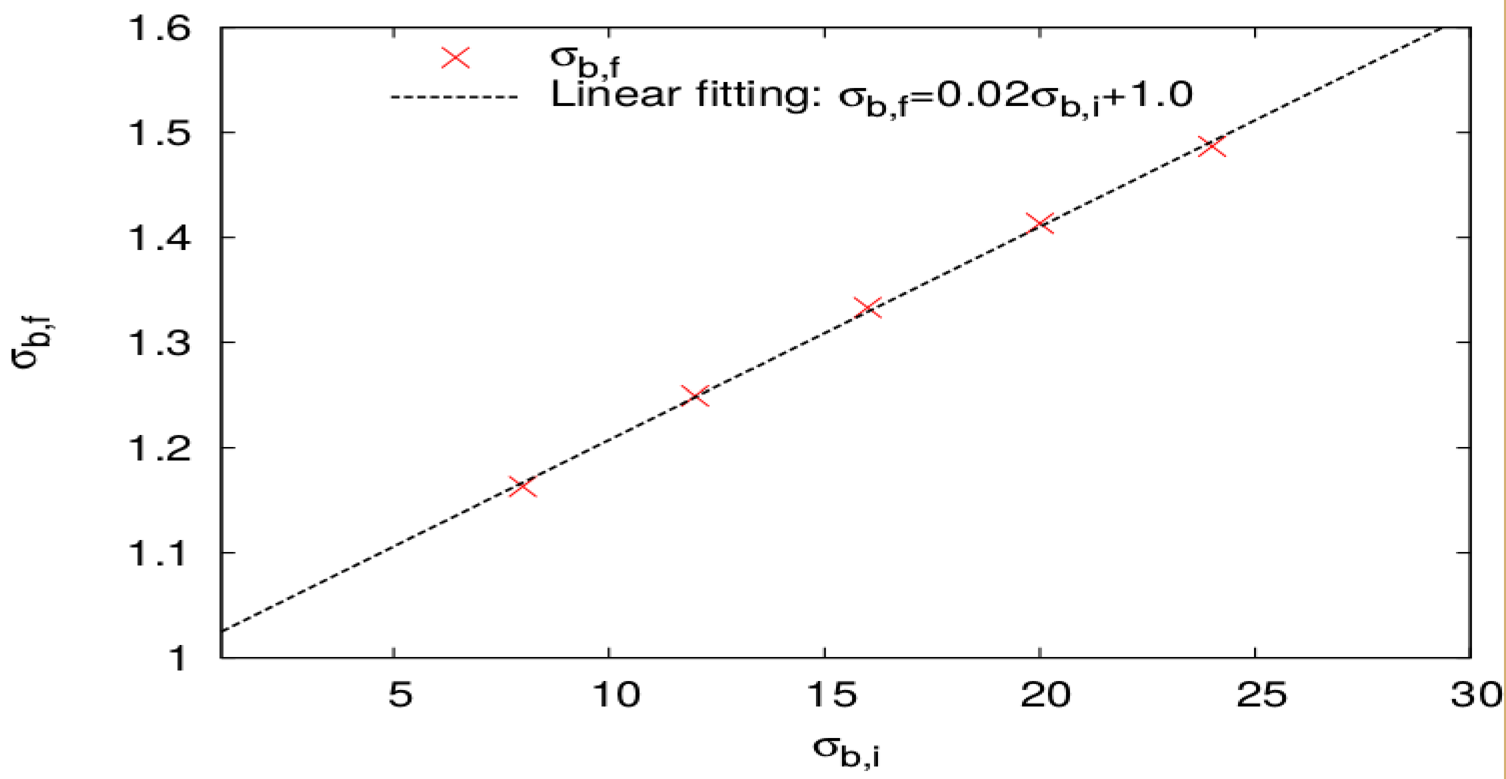
- σ dependence study: Efficiency is nearly σ independent, which is also confirmed by the hybrid method.

$\sigma_{b,i}$	$\sigma_{b,f}$	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%

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.

Shock model

- same procedure, but different simulation setting

Submitted to *The Astrophysical Journal*

Polarization-dependent Emission Modeling on Relativistic Magnetohydrodynamics - I. Shock in the Force-free Helical Magnetic Field

Haocheng Zhang[1,2], Wei Deng[3,2], Hui Li[2] and Markus Böttcher[4]

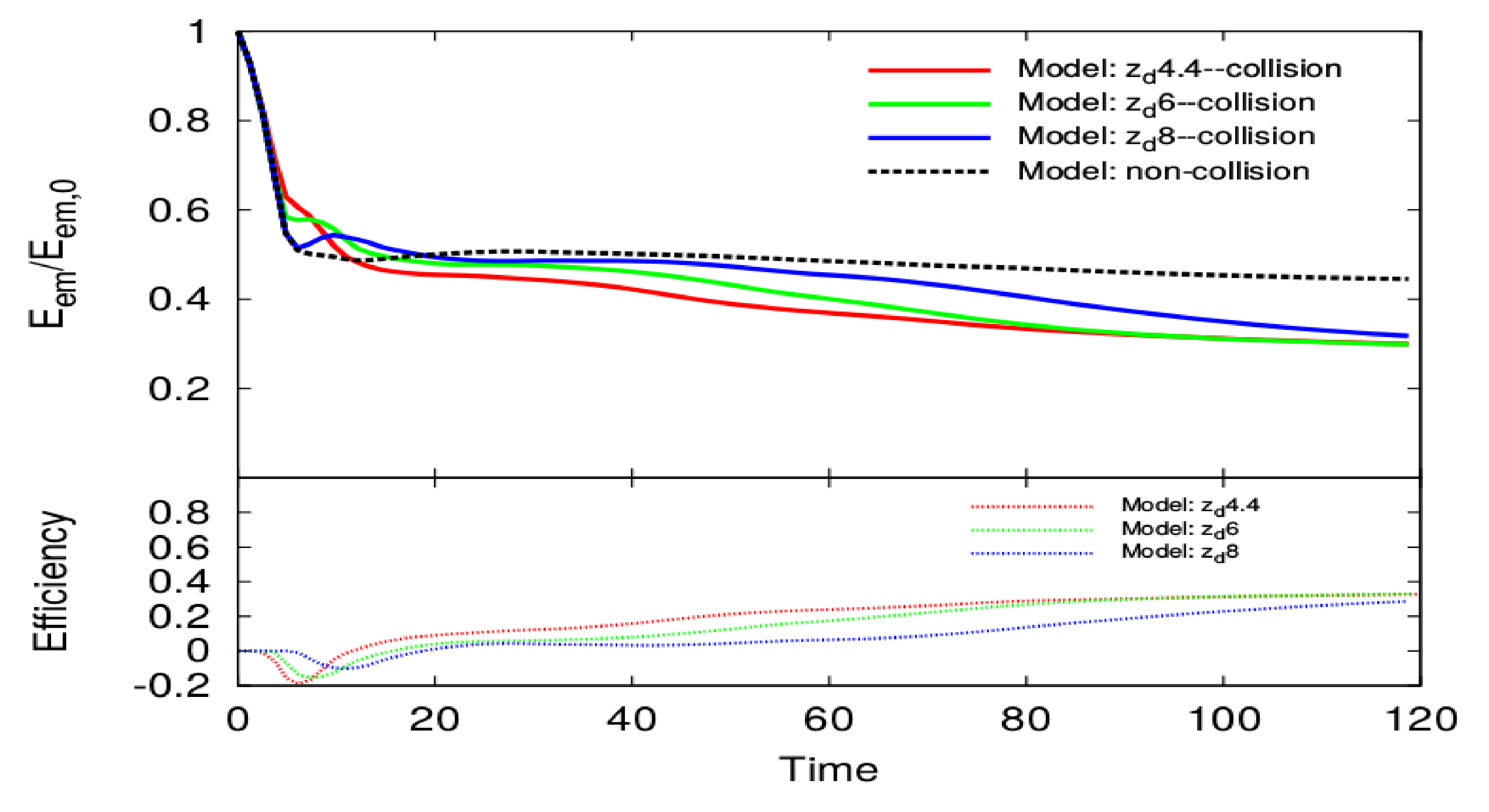
ABSTRACT

The radiation and polarization signatures in blazars are known to be highly variable during flaring activities. It is frequently argued that shocks are the main driver of the flaring events. However, the spectral variability modelings generally lack detailed considerations of the self-consistent magnetic field evolution modeling, thus so far the associated polarization signatures are poorly understood. We present the first simultaneous modeling of the radiation and polarization signatures based on 3D magnetohydrodynamic simulations of relativistic shocks in the blazar emission environment, with the simplest physical assumptions. By comparing the results with observations, we find that shocks in a weakly magnetized environment will largely lead to significant changes in the polarization signatures, which are seldom seen in observations. Hence an emission region with relatively strong magnetization is preferred. In such an environment, slow shocks may produce minor flares with either erratic polarization fluctuations or considerable polarization variations, depending on the parameters; fast shocks can produce major flares with smooth PA rotations. In addition, the magnetic fields in both cases are observed to actively revert to the original topology after the shocks. All these features are consistent with observations. Future observations on the radiation and polarization signatures will further constrain the

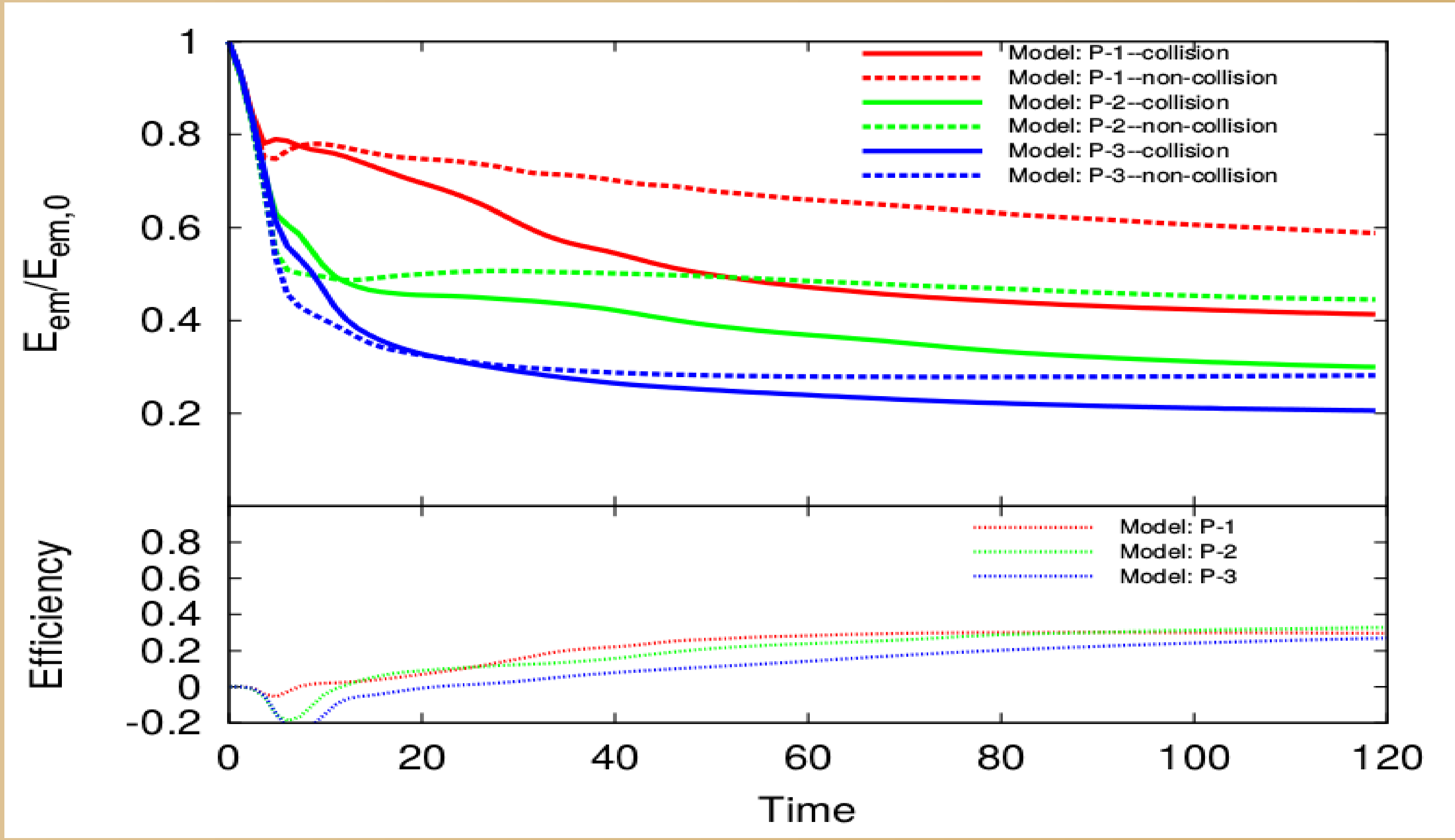
Quantitatively analyses — EMF energy dissipation efficiency: Parameter studies

- Zd

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

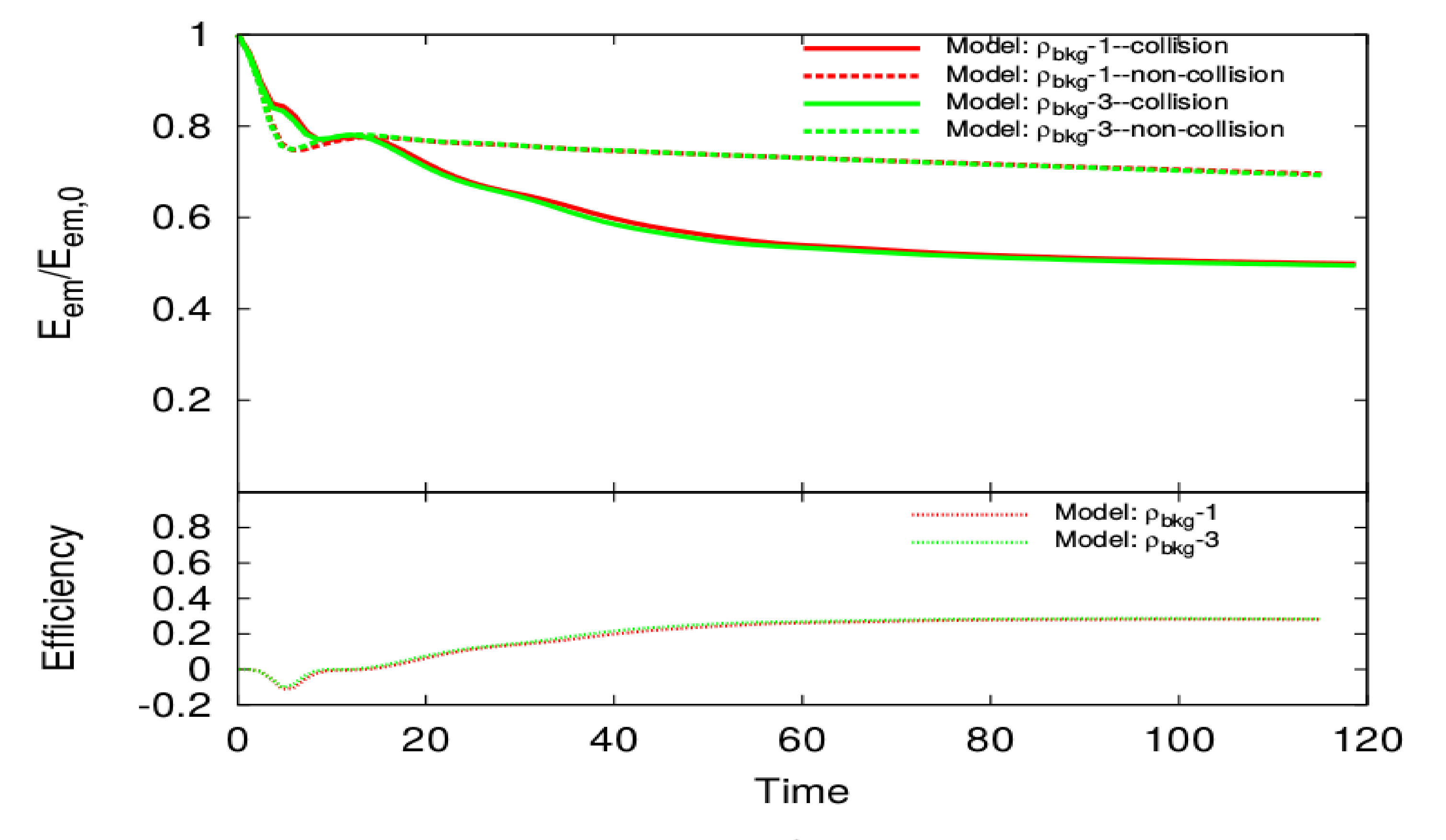


- Pressure



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

- Density



Model: ρbkg-1--collision
Model: ρbkg-1--non-collision
Model: ρbkg-3--collision
Model: ρbkg-3--non-collision
Eem/Eem,0
Model: ρbkg-1
Model: ρbkg-3
Efficiency
Time