Credit: DESY, Science Communication Lab

Very Bright Gamma-Ray Burst Early Afterglow from Magnetic Bullet

ICRR
Institute for Cosmic Ray Research
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This research is motivated by

Kusafuka et al. (2023)

← Check it !!!

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Collaborator: Katsuaki Asano (ICRR)

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Magnetic Bullets

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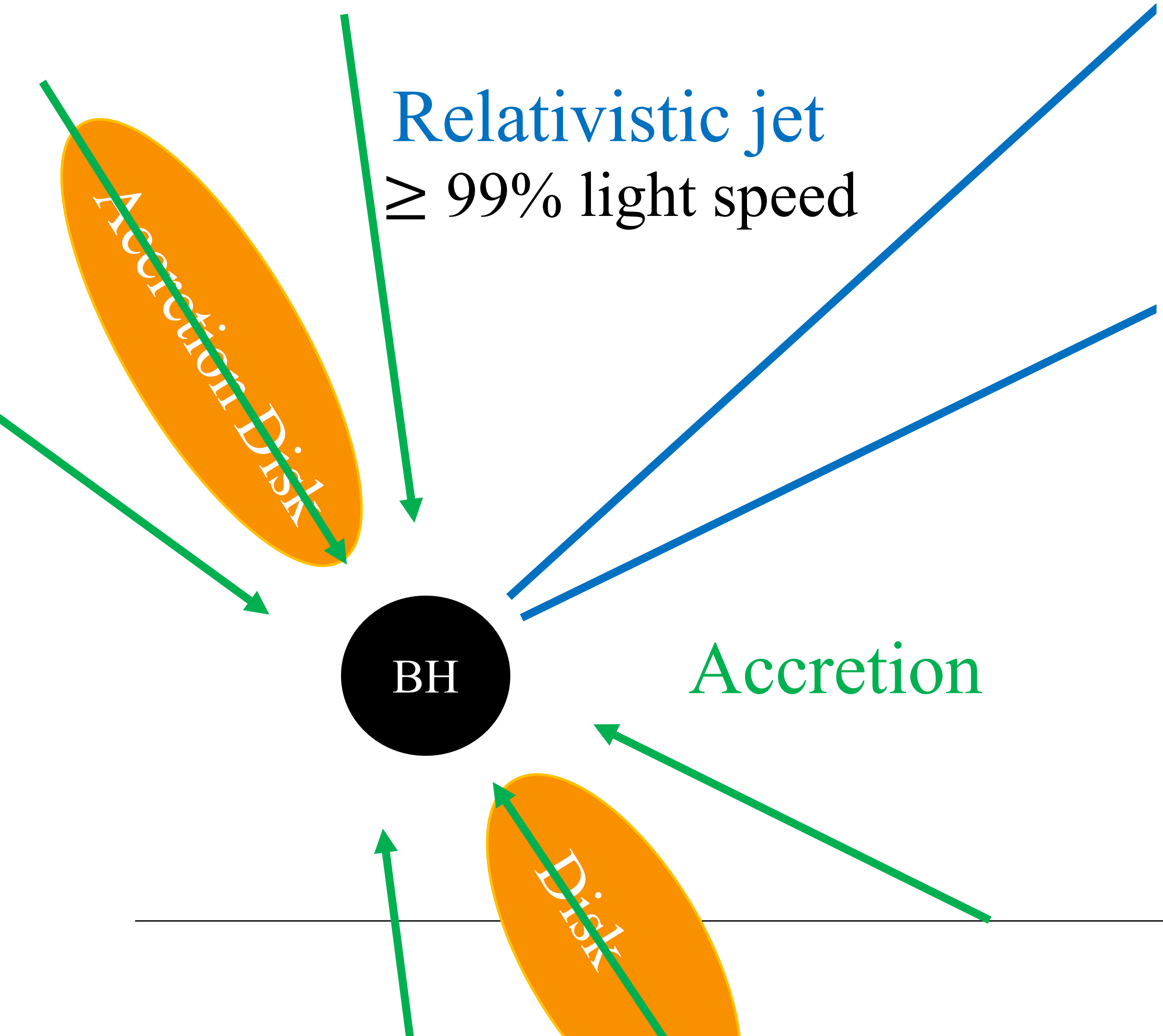
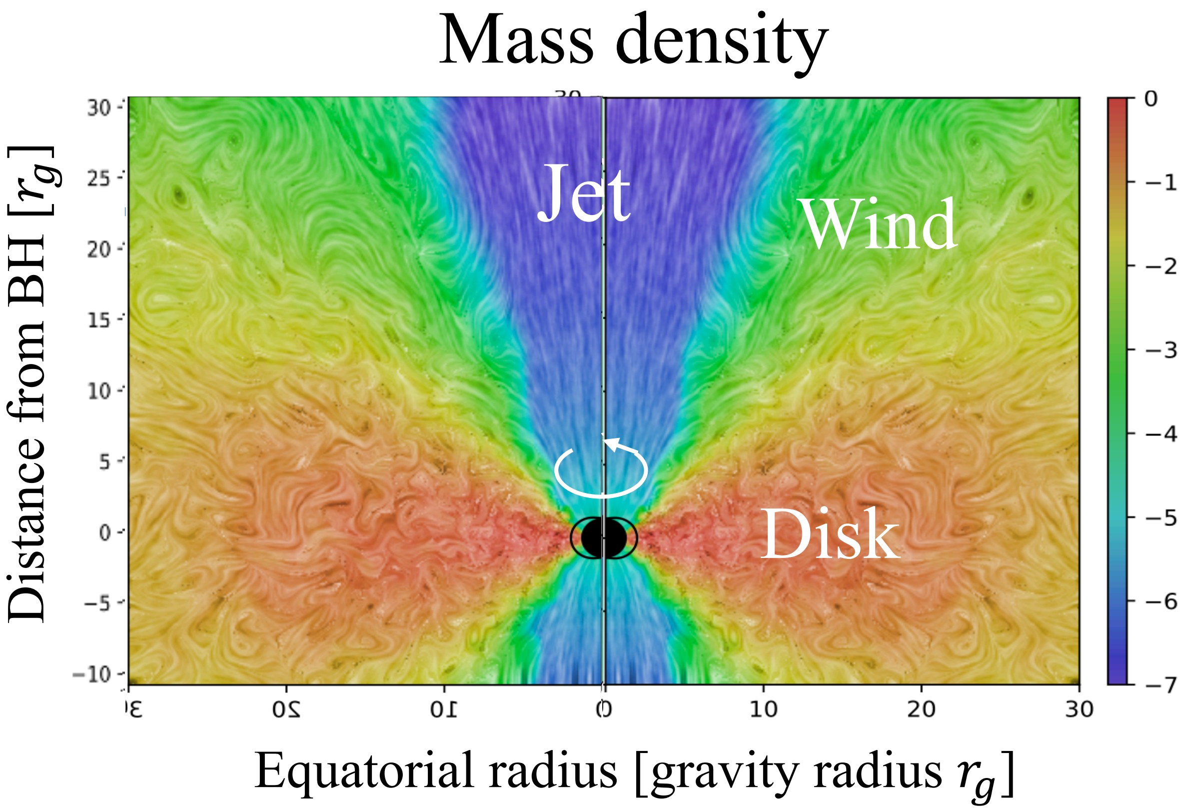
- Case 2: Wind

Relativistic Jets from Compact Objects

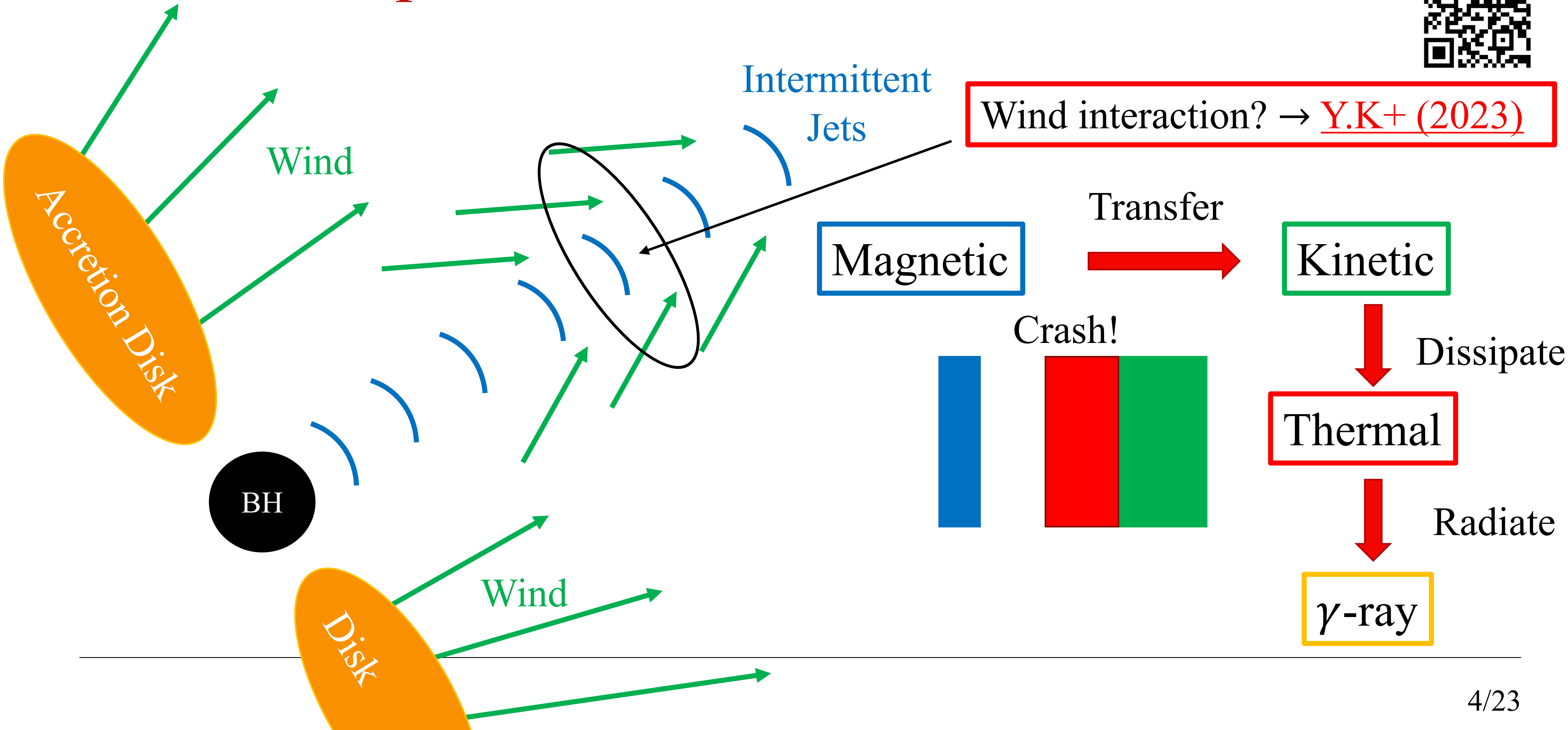




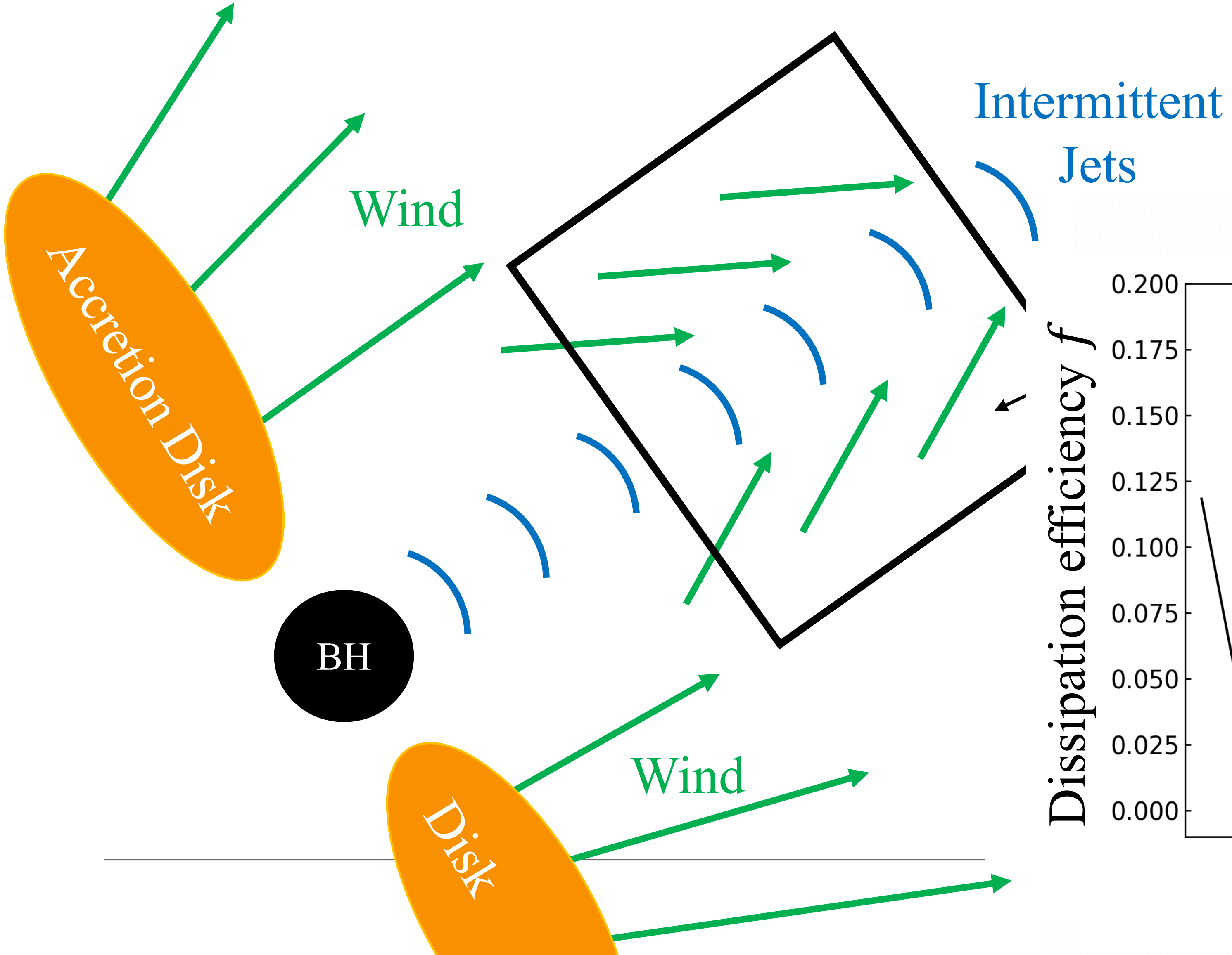
Porth et al., (2019)

Shock dissipation of Intermittent Jets and Wind

Y.K+ (2023)

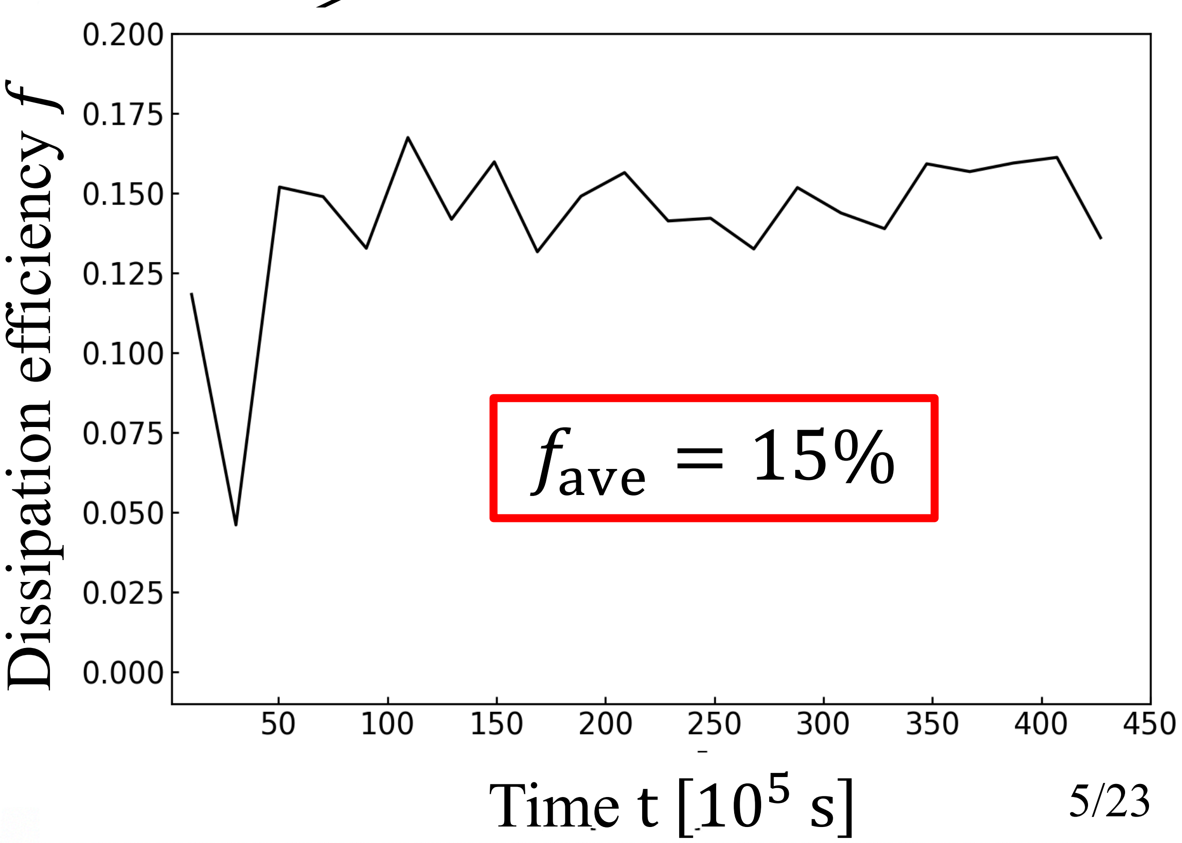


Efficient Magnetic Energy Dissipation by Internal Shocks

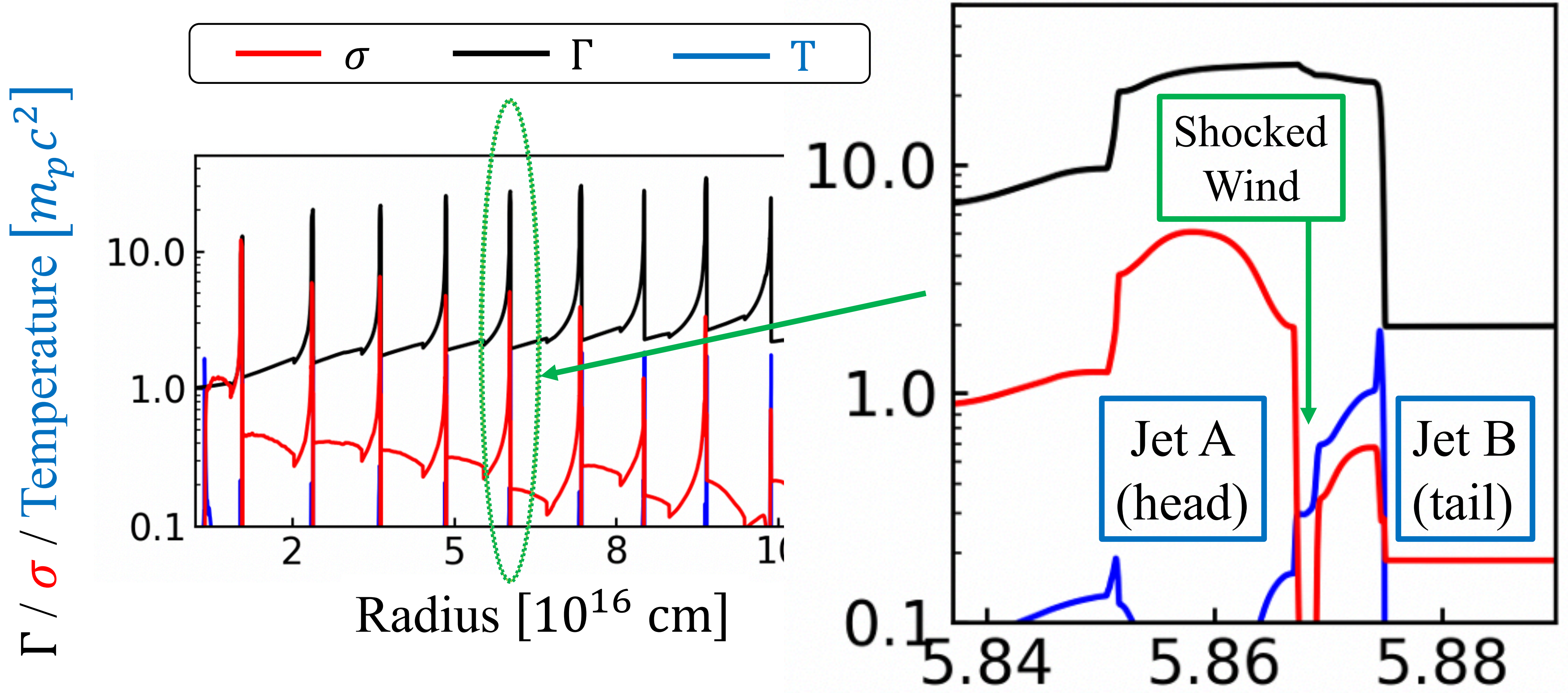


How efficient ? → Y.K+ (2023)

1D Relativistic MHD simulation



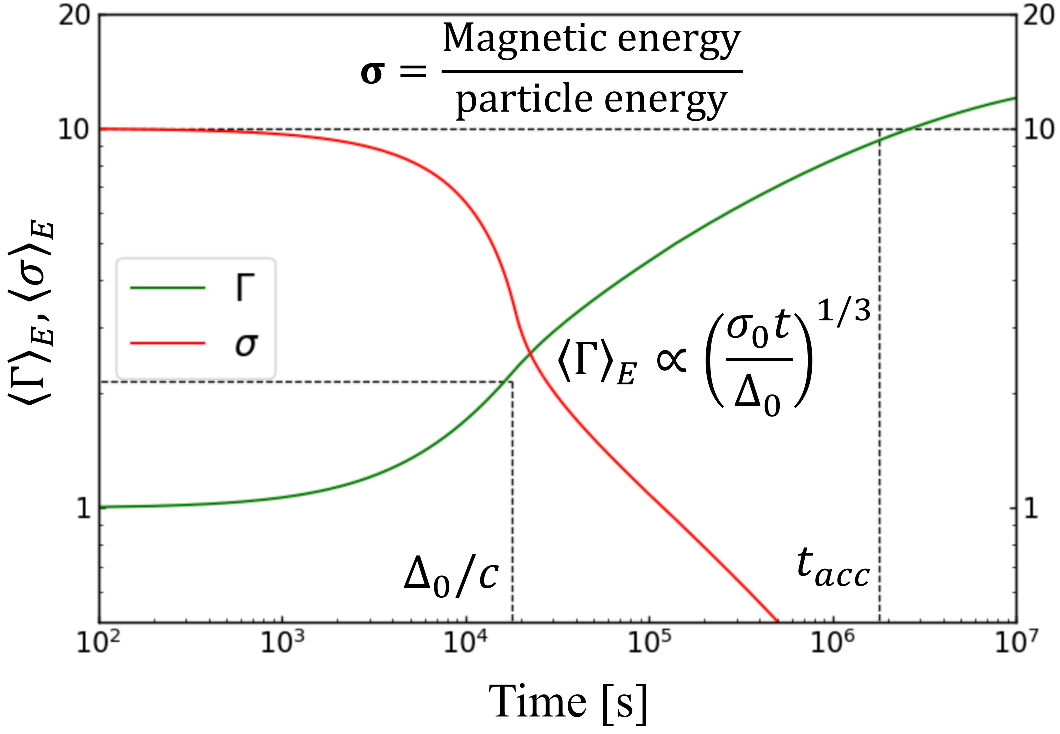
Still high-$\boldsymbol{\sigma}$ in afterglow phase?

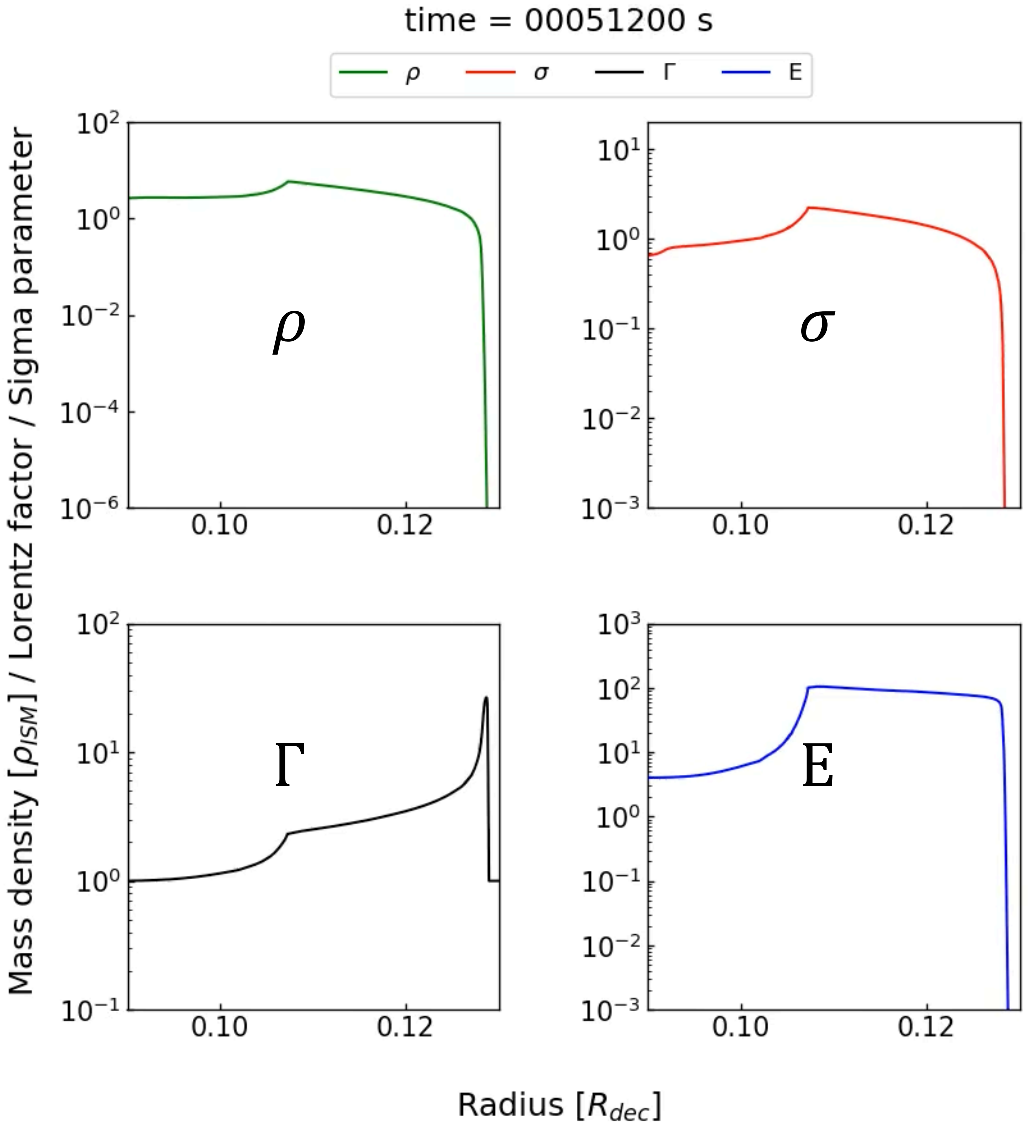


Impulsive Acceleration

Acceleration time scale: $ct_{acc} = \sigma_0^2 \Delta_0$

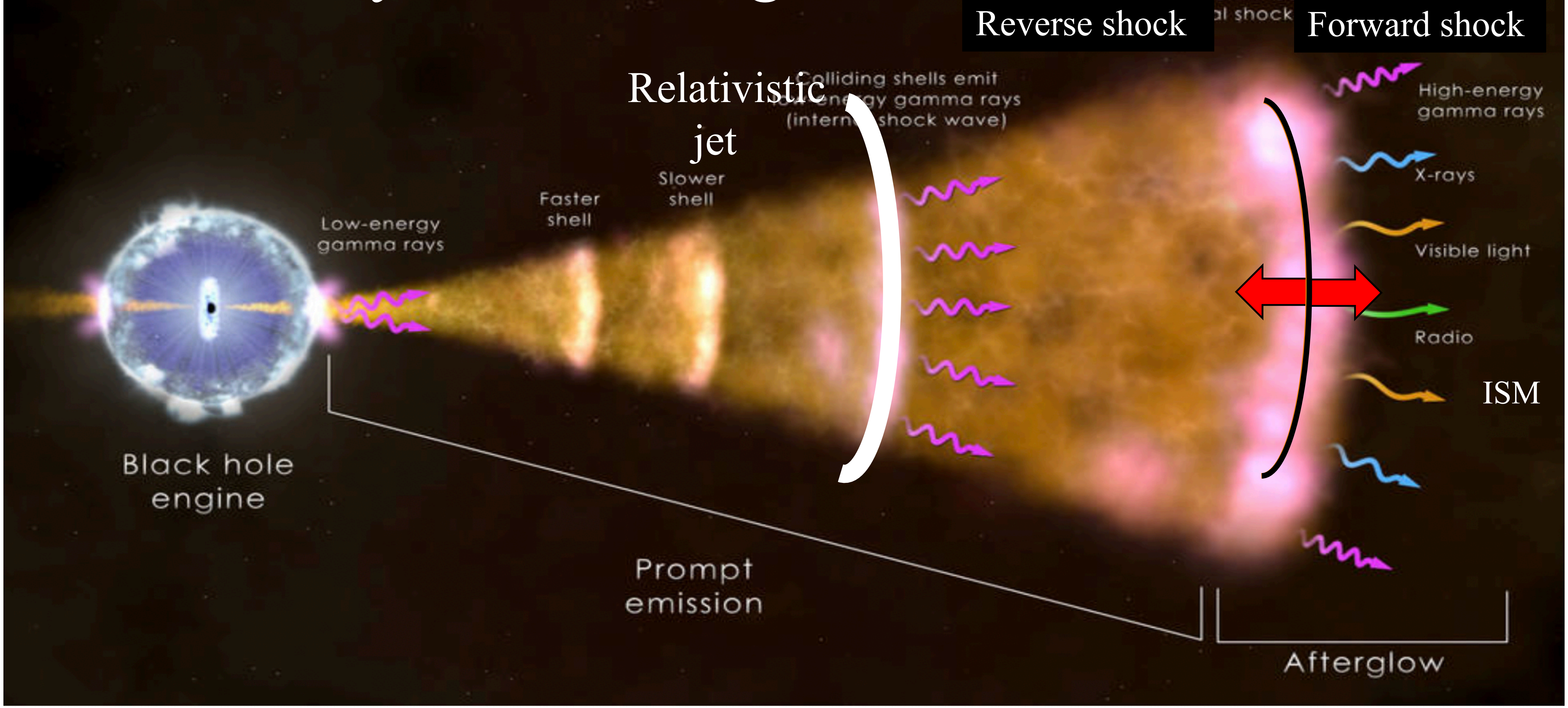
Acceleration rate: $\langle\Gamma\rangle_E = \left(\frac{\sigma_0 ct}{\Delta_0}\right)^{1/3}$





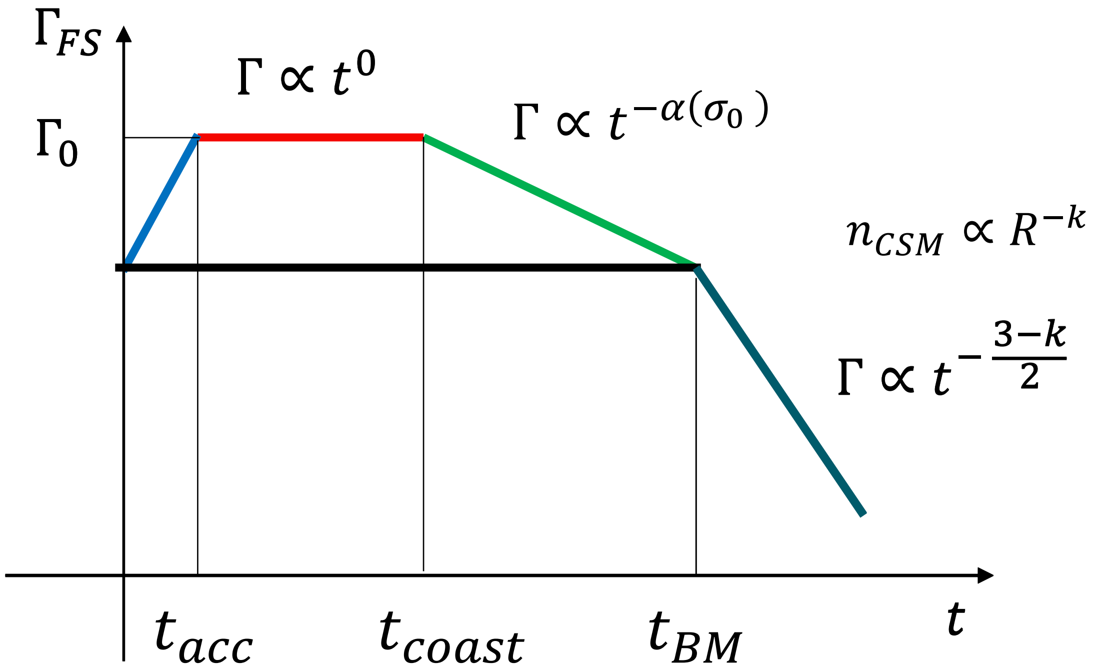
Credit: NASA

Gamma-Ray Burst Afterglow

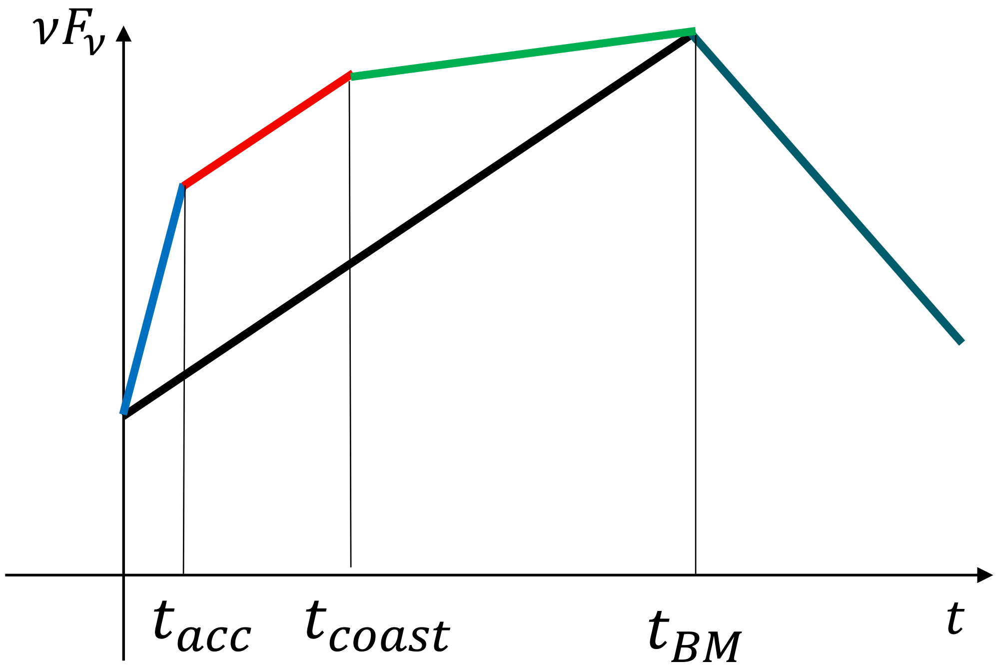


Expectation

Magnetic Bullet



Bright Early Afterglow



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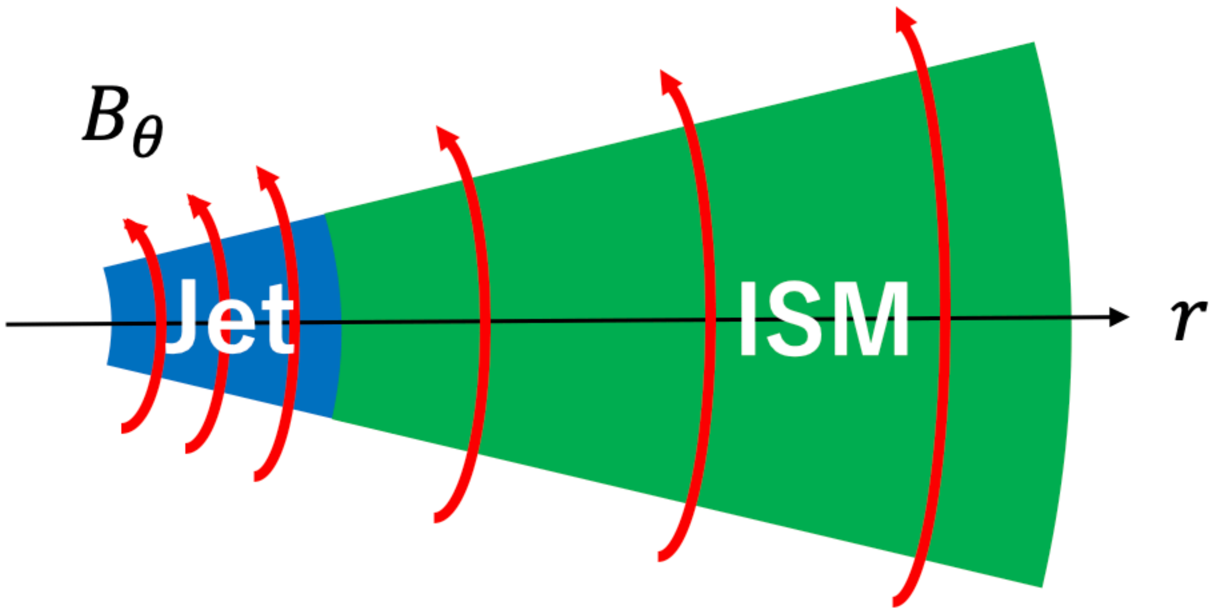
Fundamental Equations

<u>1D Special Relativistic MHD system equations</u>

- $\frac{\partial \rho\Gamma}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(\rho\Gamma v_r) = 0$: Mass
- $\frac{\partial \tau}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(w\Gamma^2 v_r - \rho\Gamma v_r) = 0$: Energy
- $\frac{\partial S}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} r^2(w\Gamma^2 v_r^2 + p) = \frac{2p}{r}$: Momentum
- $\frac{\partial B_\theta}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r(B_\theta v_r) = 0$: Induction
- $p_g = (\hat{\gamma} - 1)(\epsilon - \rho)$: EoS

$\tau = w\Gamma^2 - p - \rho\Gamma$: total energy density
$S = w\Gamma^2 v_r$: momentum density
$w = \varepsilon + p_g + 2p_m$: total enthalpy
$\rho, p_g, p_m, \varepsilon$: **comoving** mass density/gas pressure
magnetic pressure/energy density



The heat ratio : $\hat{\gamma} = 1 + \frac{\epsilon+\rho}{3\epsilon}$

$\boldsymbol{v} = (v_r, 0, 0), \boldsymbol{B} = (0, B_\theta, 0)$: assumption

Magnetization : $\sigma = \frac{B_\theta^2}{4\pi(\varepsilon+p_g)\Gamma^2}$

Simulation Setup

Jet

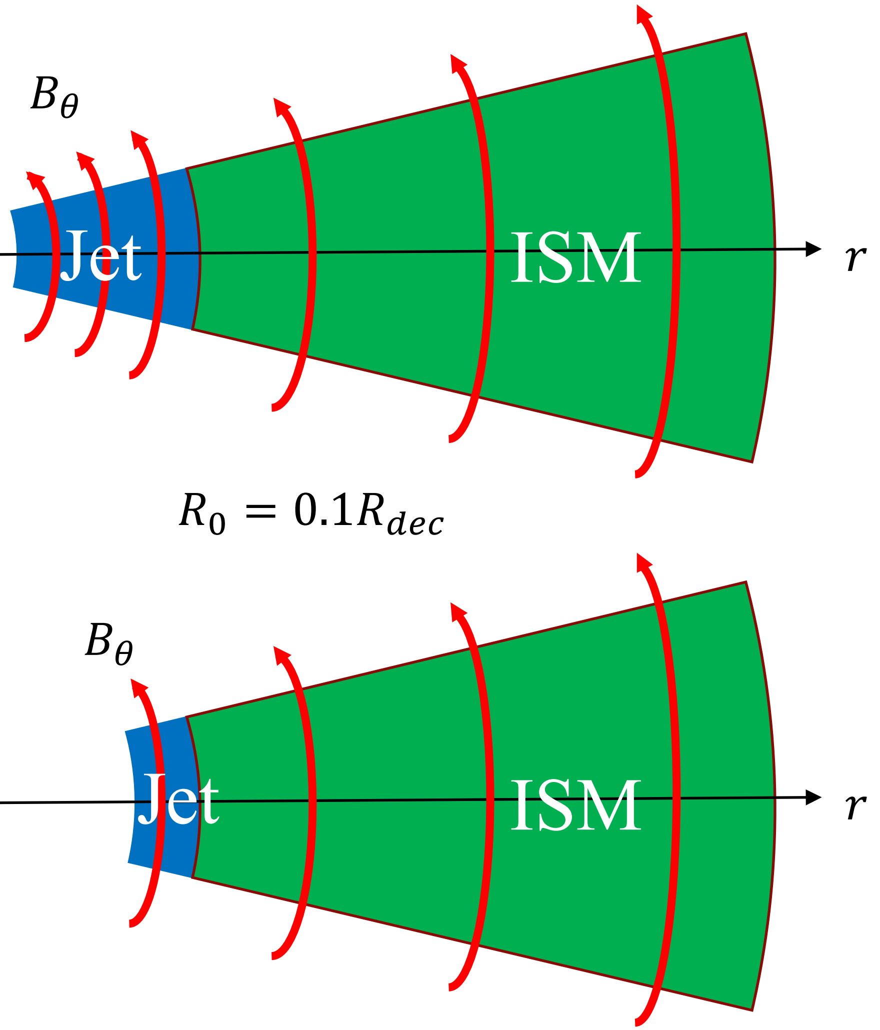
- $E_{\rm jet} = 10^{50}$ erg
- $\Gamma = 10$
- $\rho \propto r^{-2}$
- $T = 100$ MeV
- $\sigma_0 = 10^{-2} \sim 10$

Thick shell

$\Delta_0 = 0.01 R_{\rm dec}$

Thin shell

$\Delta_0 = 0.001 R_{\rm dec}$



ISM

- $m_p = 938$ MeV
- $\Gamma = 1$ ($v = 0$)
- $n_{\rm ISM} = 1$ cm^{-3}
- $T = 1$ MeV
- $B_{\rm ISM} = 1$ μG

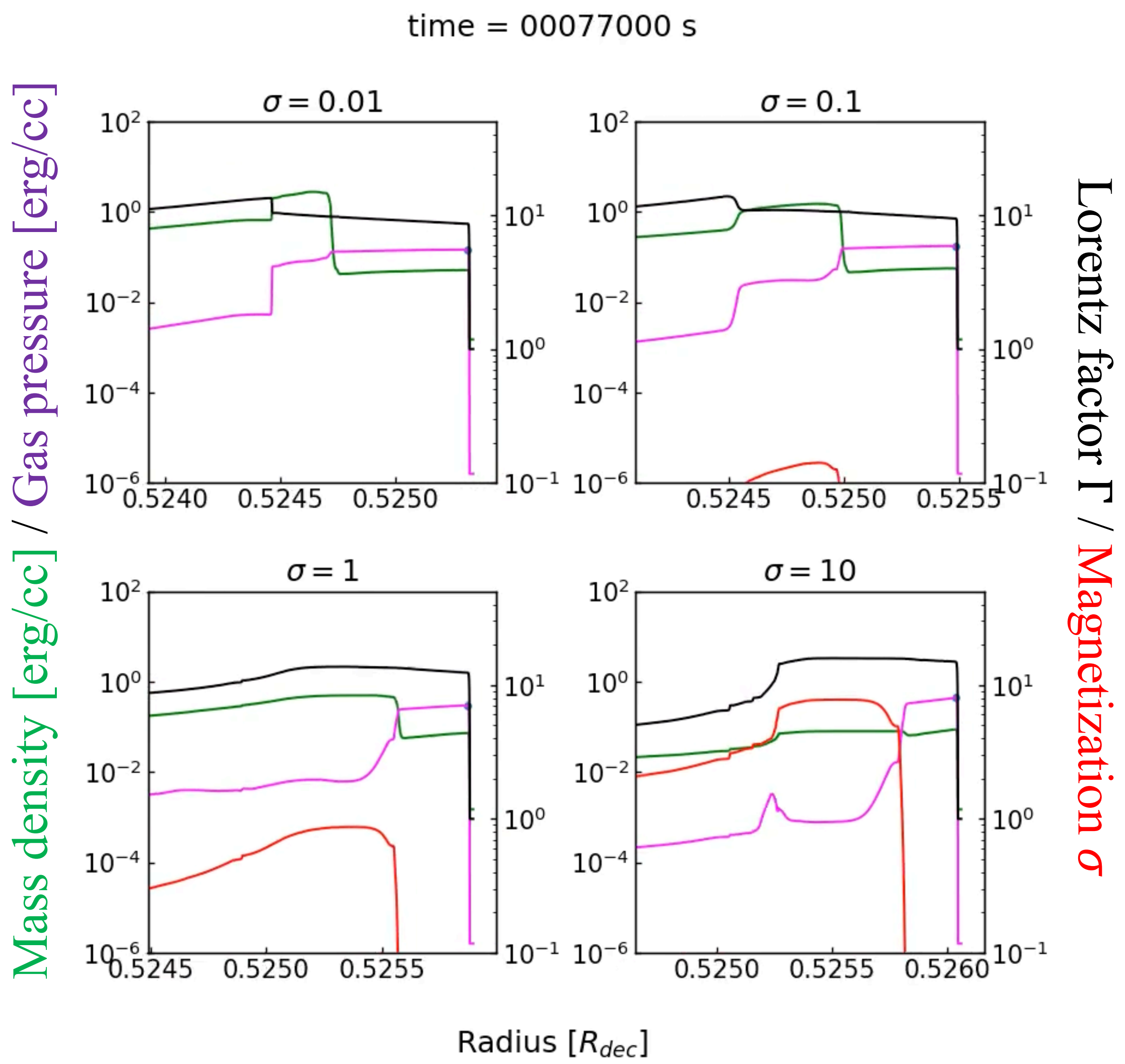
Results

1DSRMHD code (Kusafuka & Asano in prep)

- 7th order **MP7** (Suresh & Huynh 1997)
- 3rd order **SSPRK(3,3)** (Gottlieb & Shu 1999)
- **AMR** (Berger & Oliger 1984)
- **Moving window** (Mimica et al. 2004)

Assumptions

- $\epsilon_e = 0.1, \epsilon_B = 0.01$ are constant
- FS position is at gas pressure maximum



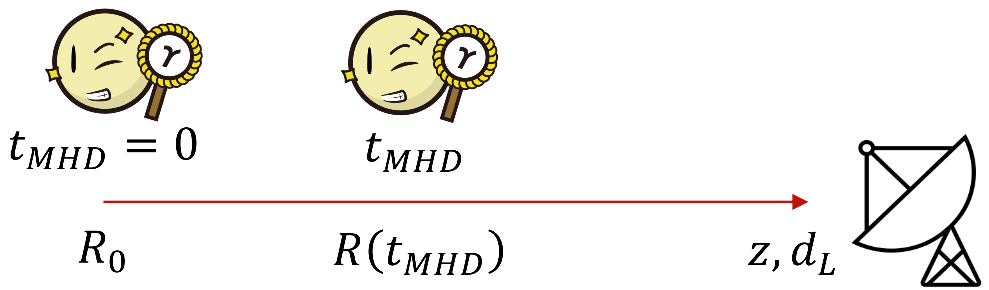
Credit: Higgstan

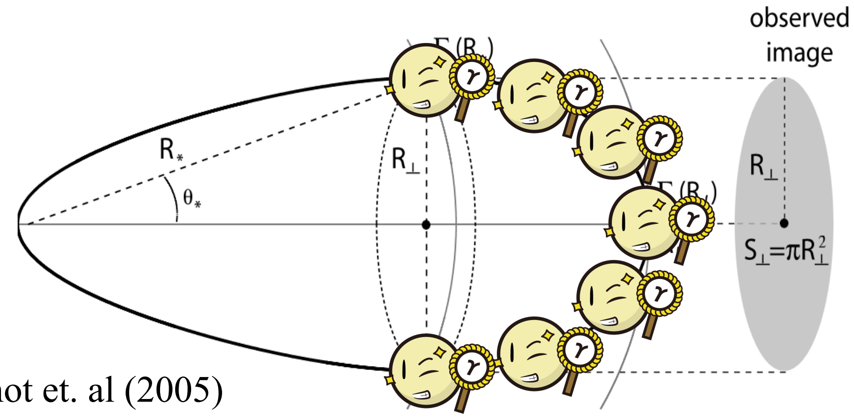
Forward Shock Evolution

$$\Gamma_{BM} \propto t_{MHD}^{-3/2} \propto t_{obs}^{-3/8}$$

Definition of observed time

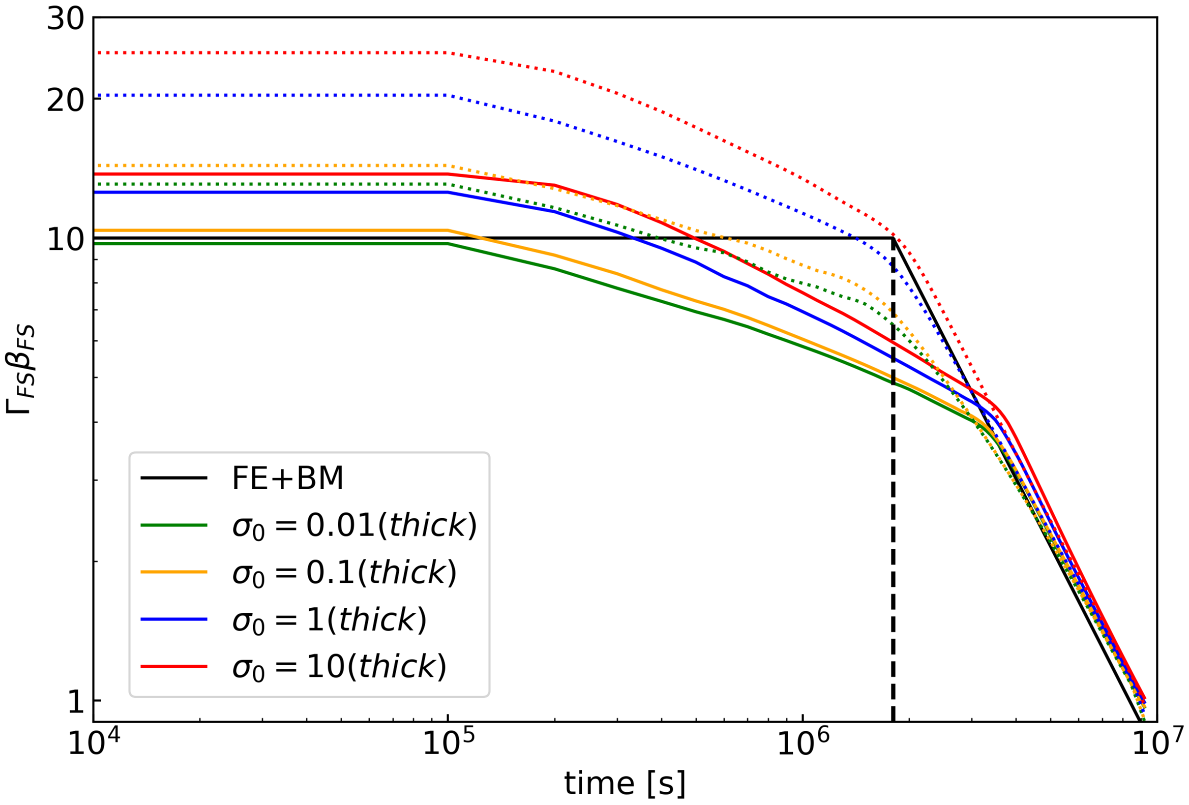
$$t_{obs}(\theta) \equiv (1+z)\frac{R(t_{MHD})(1-c\beta\cos\theta)}{c\beta}$$





Granot et. al (2005)

Coasting phase | **Transition phase** | BM phase

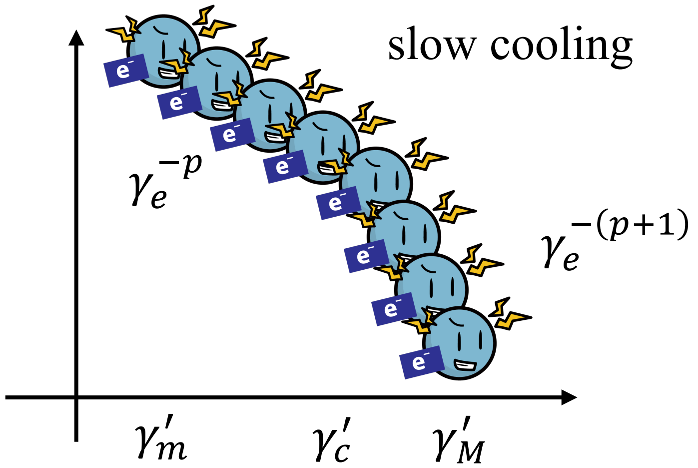


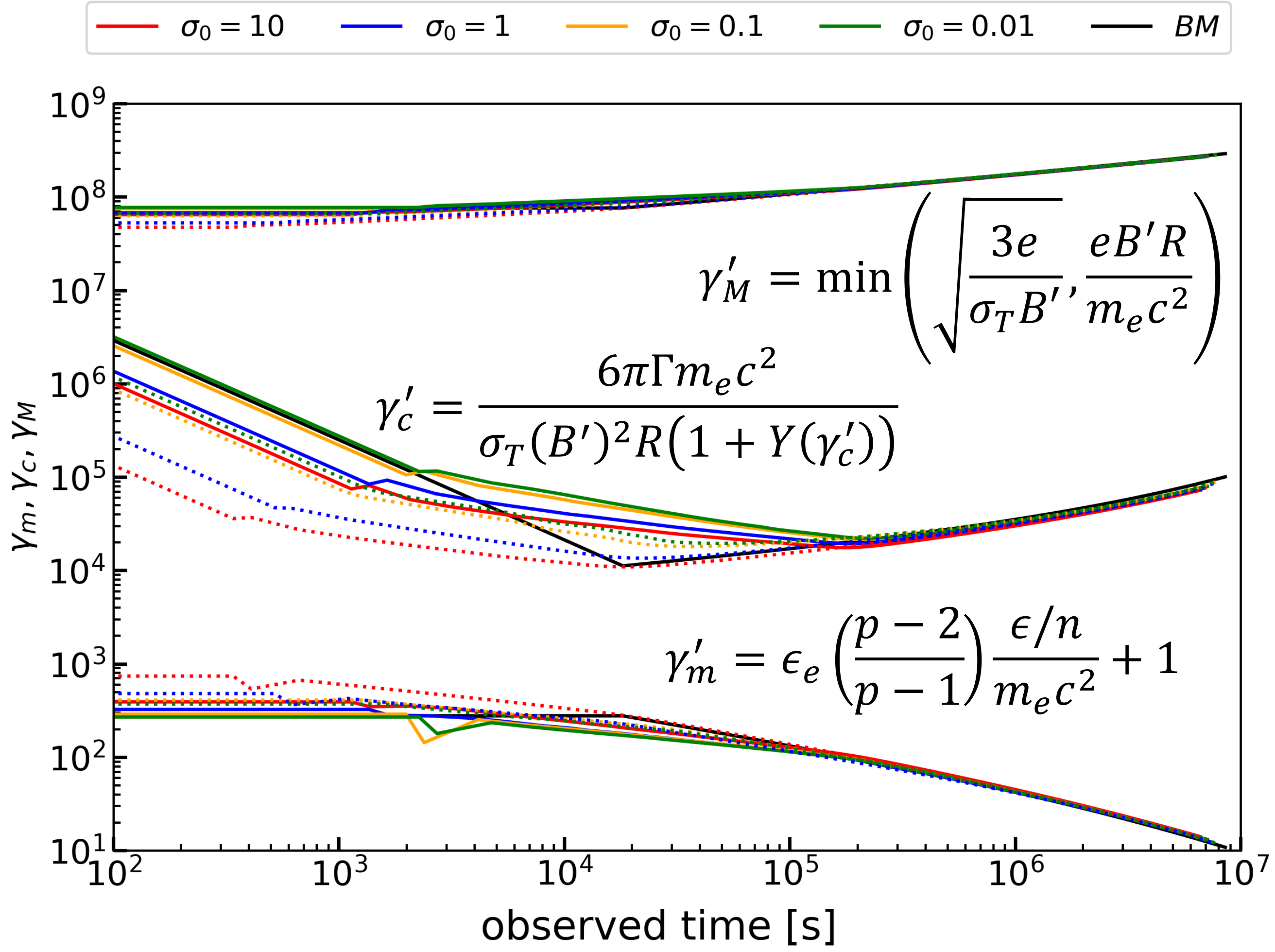
Electron Energy Distribution

Assumption: steady state

$$\frac{\partial n'_e}{\partial t'} + \frac{\partial}{\partial \gamma'_e}\left(n'_e \frac{d\gamma'_e}{dt'}\right) = Q \propto \gamma_e^{-2.2}$$

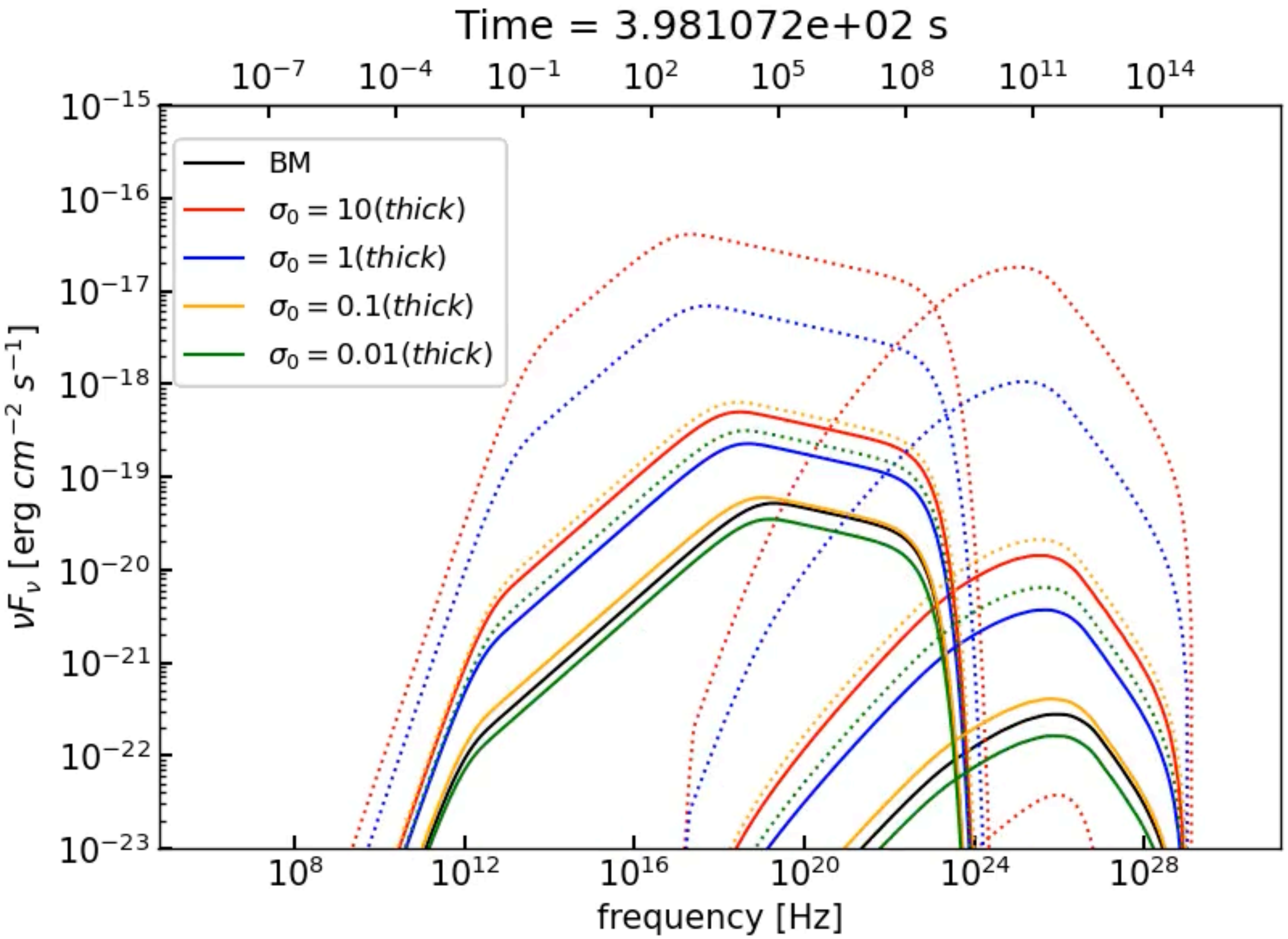
$$\frac{d\gamma'_e}{dt'} = -\frac{\sigma_T B'^2}{6\pi m_e c}\gamma_e'^2\left(1 + Y(\gamma'_e)\right)$$



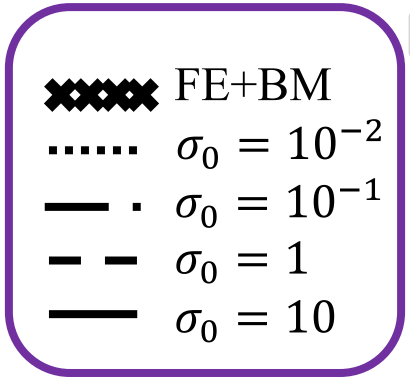


Observed Spectrum

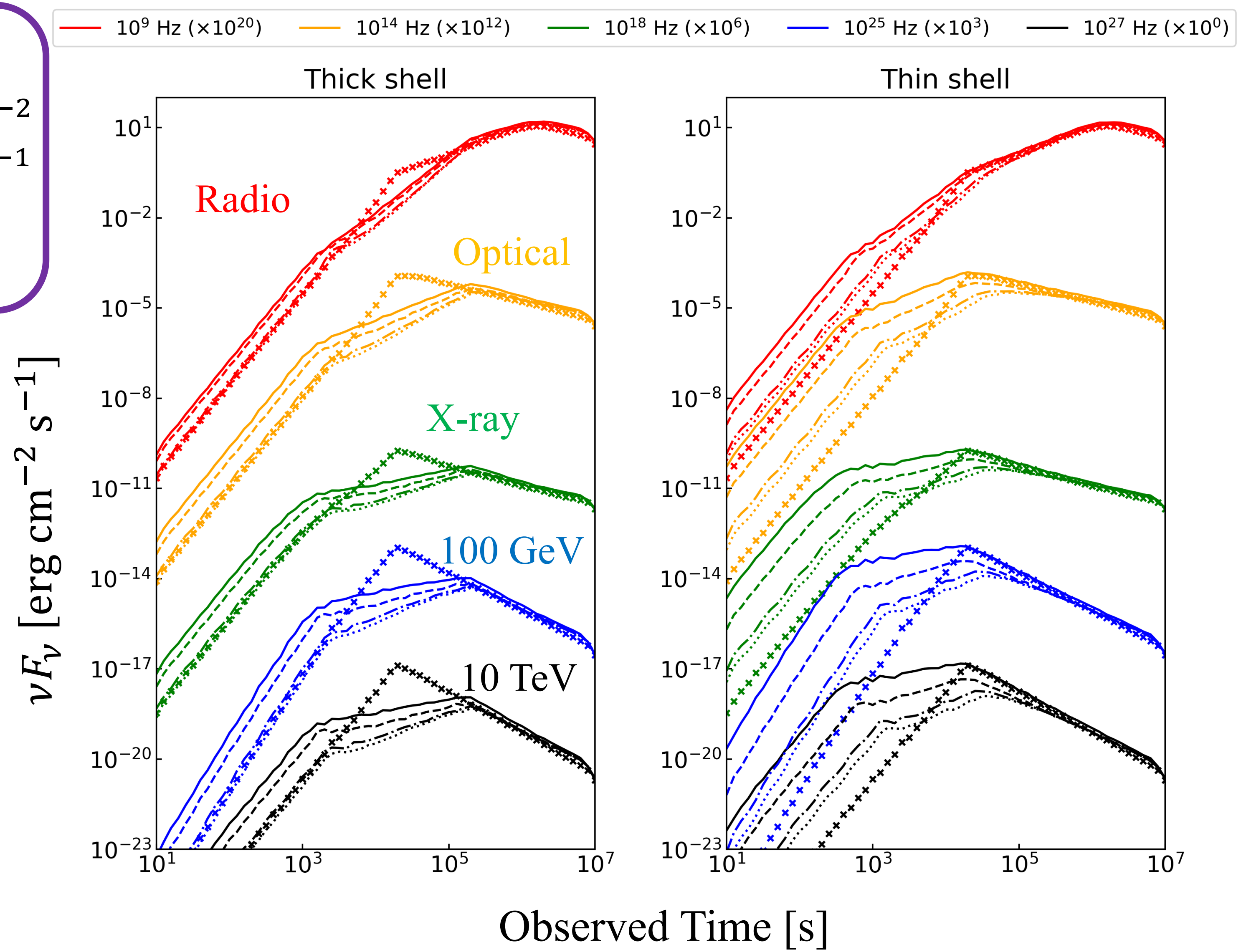
- Early phase
  - $\gg \sigma, \ll \Delta$ is high luminosity
- Middle phase
  - $\gg \sigma, \ll \Delta$ is high luminosity
- Late phase
  - Independent of initial σ, Δ



Lightcurve



- Coasting phase
  - $\nu F_\nu \propto t_{obs}^3$ for radio/optical/X-ray
  - $\nu F_\nu \propto t_{obs}^4$ for gamma-ray
- Transition phase
  - $\nu F_\nu \propto t_{obs}^\alpha, \quad \alpha = 0.5\sim2$
- Blandford-McKee phase
  - $\nu F_\nu \propto t_{obs}^1, t_{obs}^{-3(3-p)/4}$ for radio
  - $\nu F_\nu \propto t_{obs}^{-3(3-p)/4}$ for optical/X-ray
  - $\nu F_\nu \propto t_{obs}^{-3(2p-3)/4}$ for gamma-ray



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Semi-Analytic Modeling

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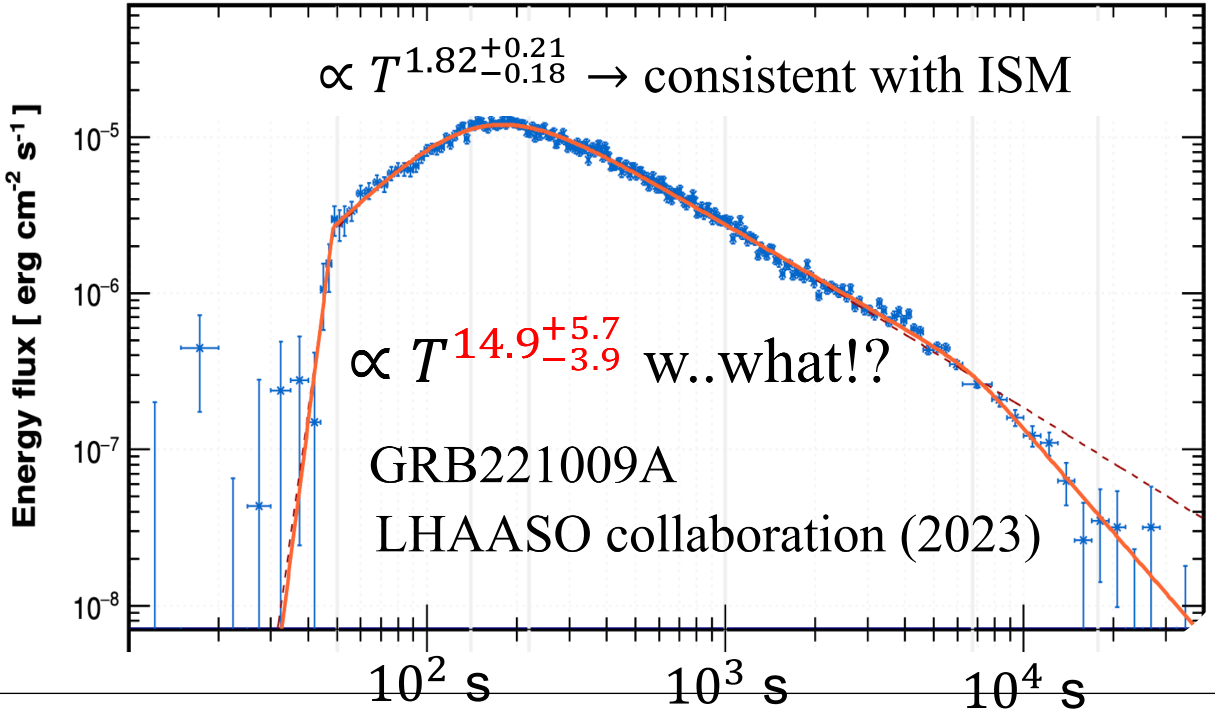
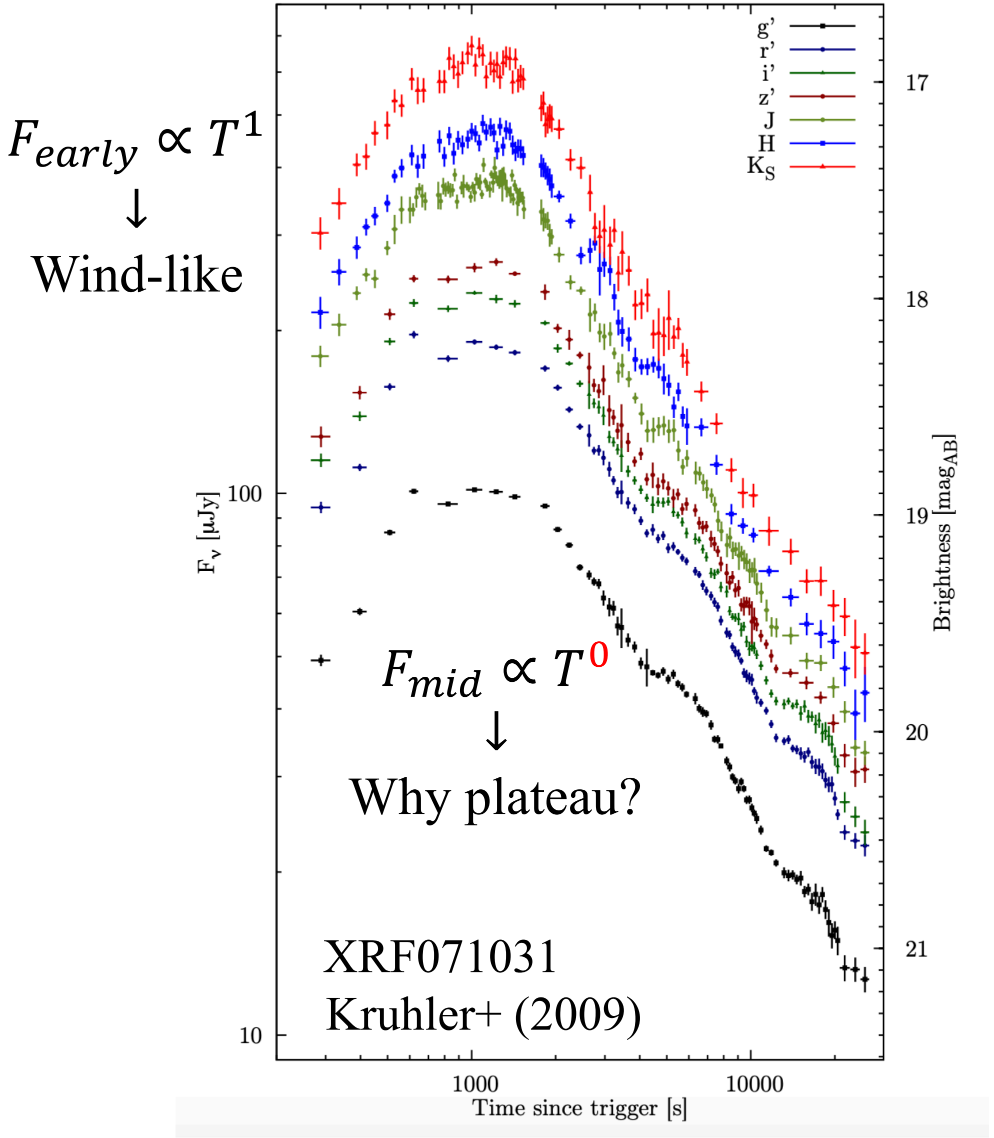
- **Case 2: Wind**

Semi-Analytic Modeling

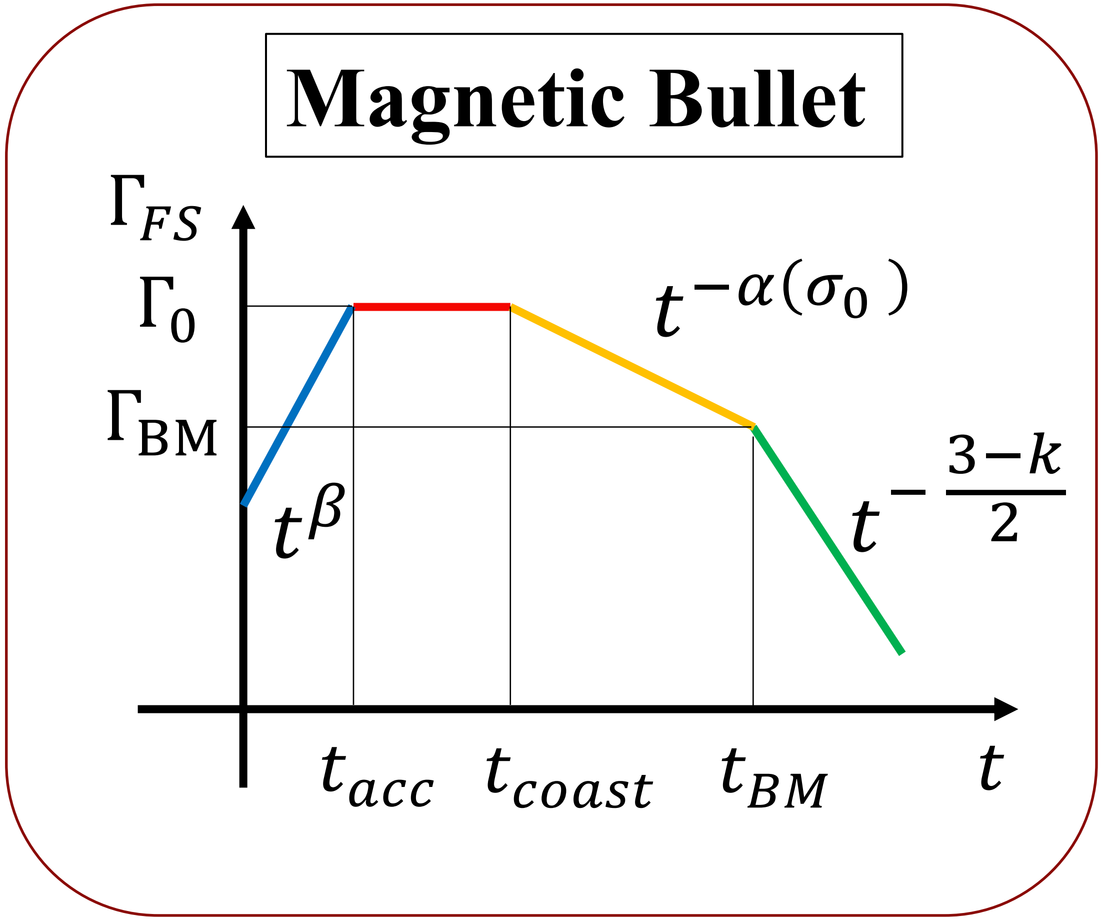
<u>Collaborators</u>

PhD1. Kaori Obayashi (U. Aoyama-gakuin)
Prof. Katsuaki Asano (ICRR)





Semi-Analytic Model of Magnetic Bullet



Based on our simulations (preliminary)
(Kusafuka & Asano in prep, KOA in prep)

$$\Gamma_{FS} \propto \begin{cases} t^{\beta} & t < t_{acc} \\ t^{-\alpha(\sigma_0)} & t_{coast} < t < t_{BM} \\ t^{-\frac{3-k}{2}} & t > t_{BM} \end{cases}$$

The timescales depend on $\sigma_0, \Delta_0, \Gamma_0$ (secret, I'm sorry)

Case 1: ISM

Parameter List

$\Gamma_0 = 100$

$\sigma_0 = 100$

$E_0 = 10^{55}$ erg

$\Delta_0 = R_{dec}/\Gamma_0^2$

$n_0 = 1\ \mathrm{cm}^{-3}$

$R_0 = 10^{13}$ cm

$\theta_j = 0.1$

$\epsilon_e = 0.1$

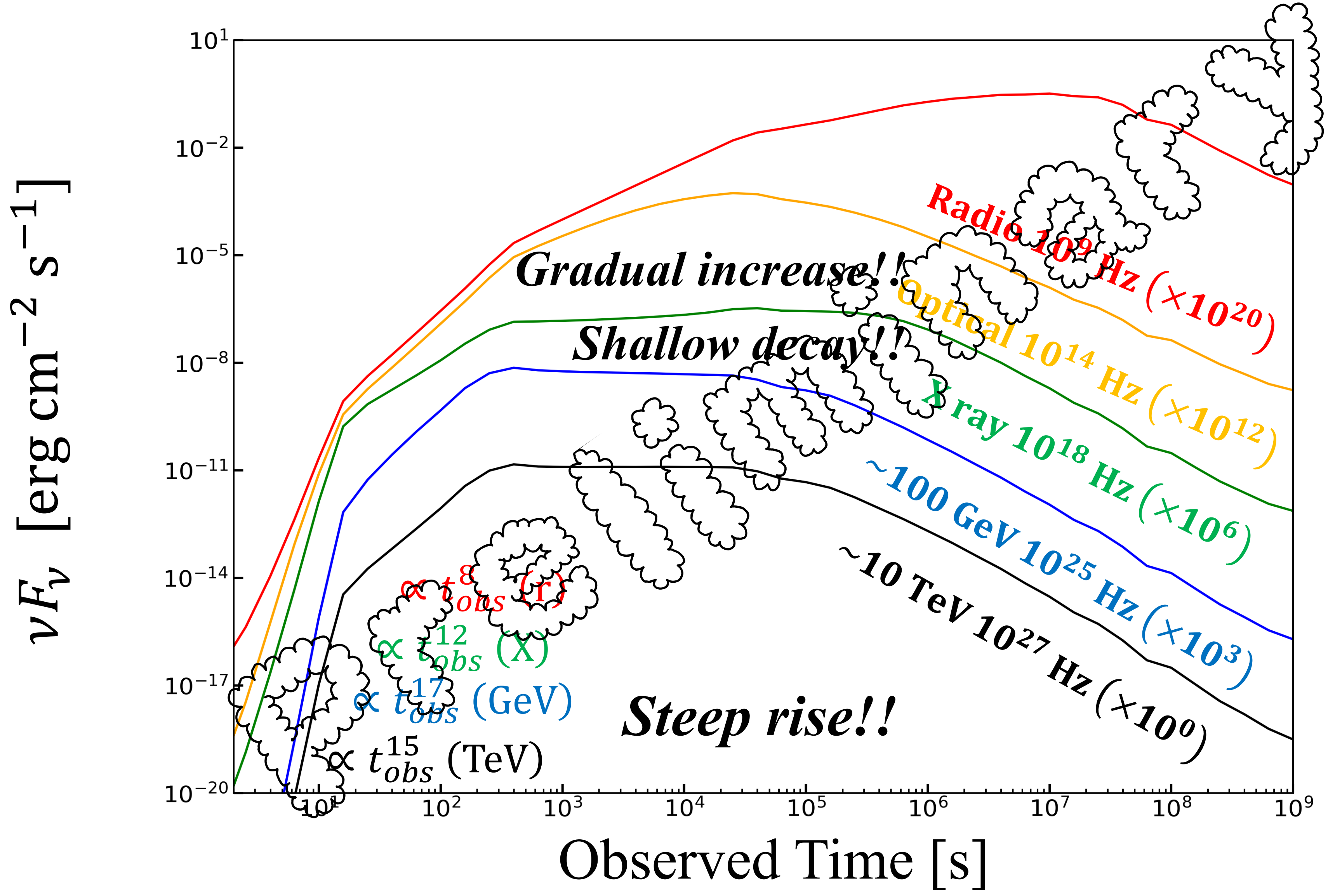
$\epsilon_B = 10^{-3}$

$f_e = 1$

$p = 2.2$

$z = 0.845$

$d_L = 10^{28}$ cm



Case 2: Wind

Parameter List

$\Gamma_0 = 50$

$\sigma_0 = 100$

$E_0 = 10^{53}$ erg

$\Delta_0 = R_{dec}/\Gamma_0^2$

$n_0 = 1$ cm^{-3}

$R_0 = 10^{16}$ cm

$\theta_j = 0.1$

$\epsilon_e = 10^{-2}$

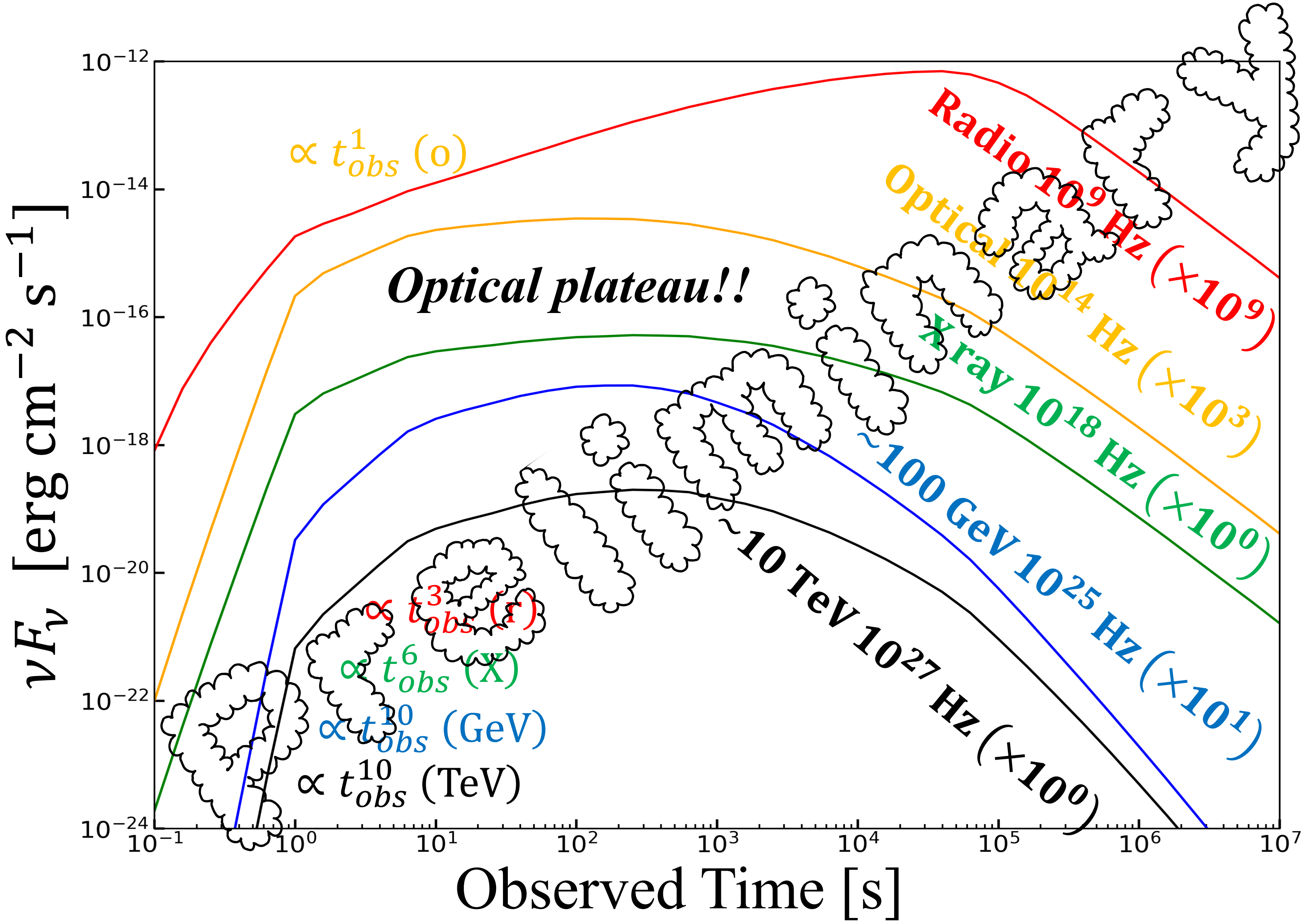
$\epsilon_B = 10^{-2}$

$f_e = 1$

$p = 2.2$

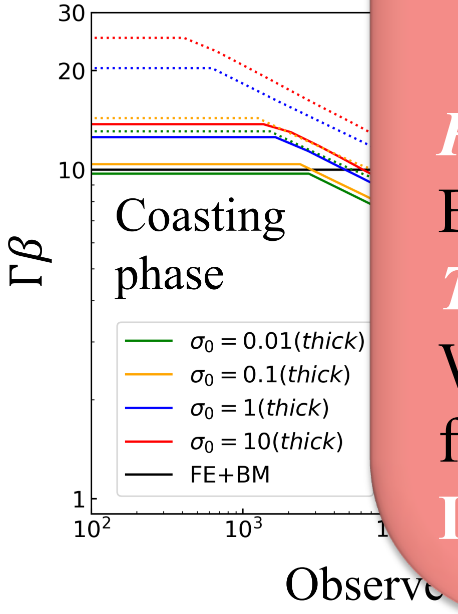
$z = 0.845$

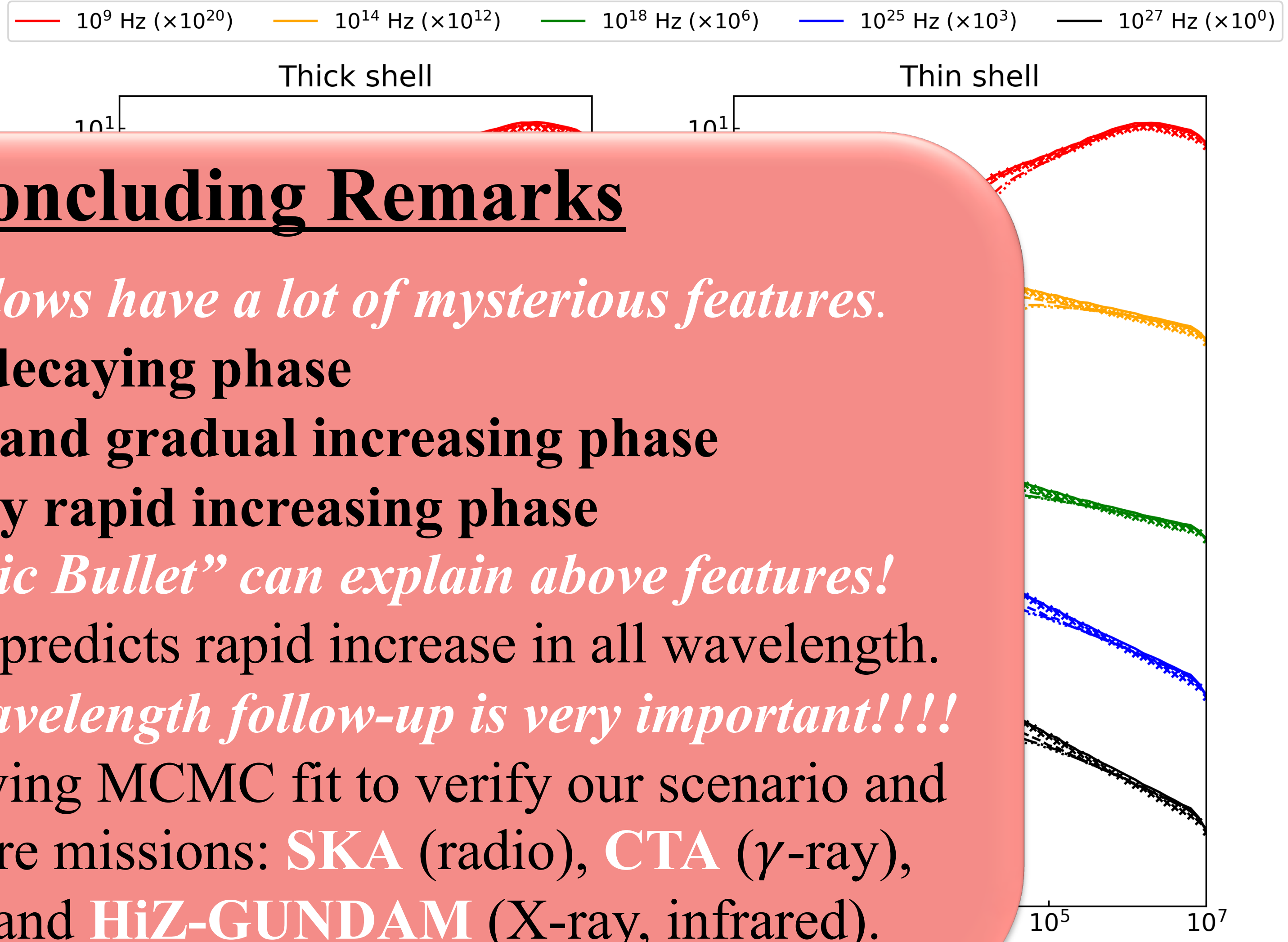
$d_L = 10^{28}$ cm



Summary

Thank you f





Concluding Remarks

Early phase afterglows have a lot of mysterious features.

- **X-ray shallow decaying phase**
- **optical plateau and gradual increasing phase**
- **gamma-ray very rapid increasing phase**

However, "Magnetic Bullet" can explain above features!

Besides, the model predicts rapid increase in all wavelength.

Therefore, Multiwavelength follow-up is very important!!!!

We are currently trying MCMC fit to verify our scenario and fueling fire for future missions: **SKA** (radio), **CTA** (γ-ray), **IMONY** (optical), and **HiZ-GUNDAM** (X-ray, infrared).