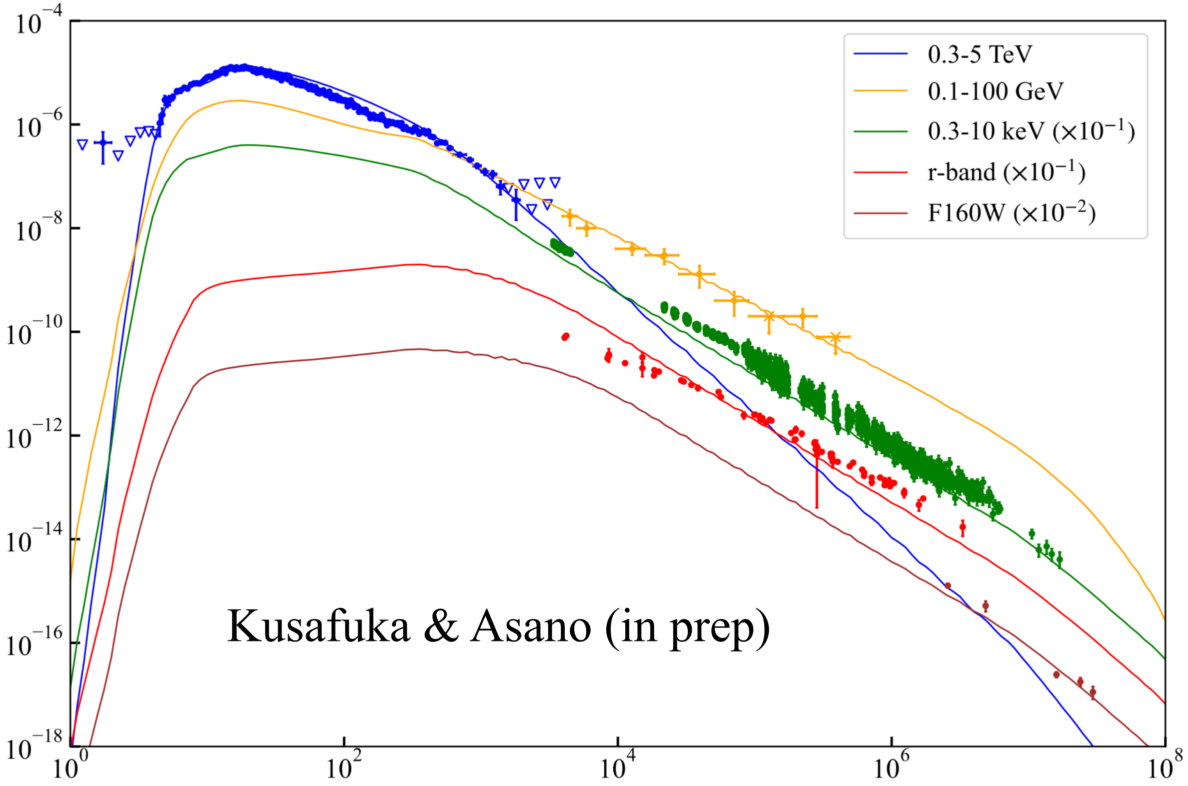
Characteristic Gev/TeV Gamma-Rays from Magnetic Bullets



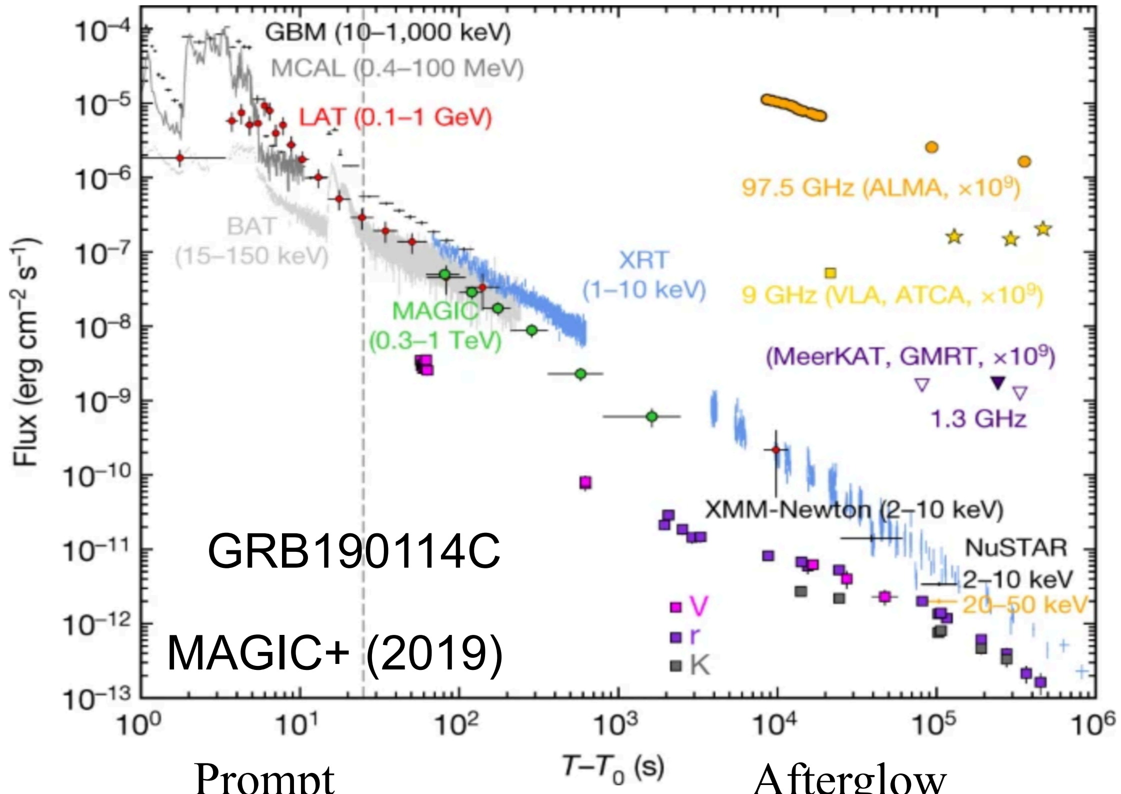
Yo Kusafuka

ICRR, the University of Tokyo, PhD Student

Collaborator: Katsuaki Asano (ICRR)

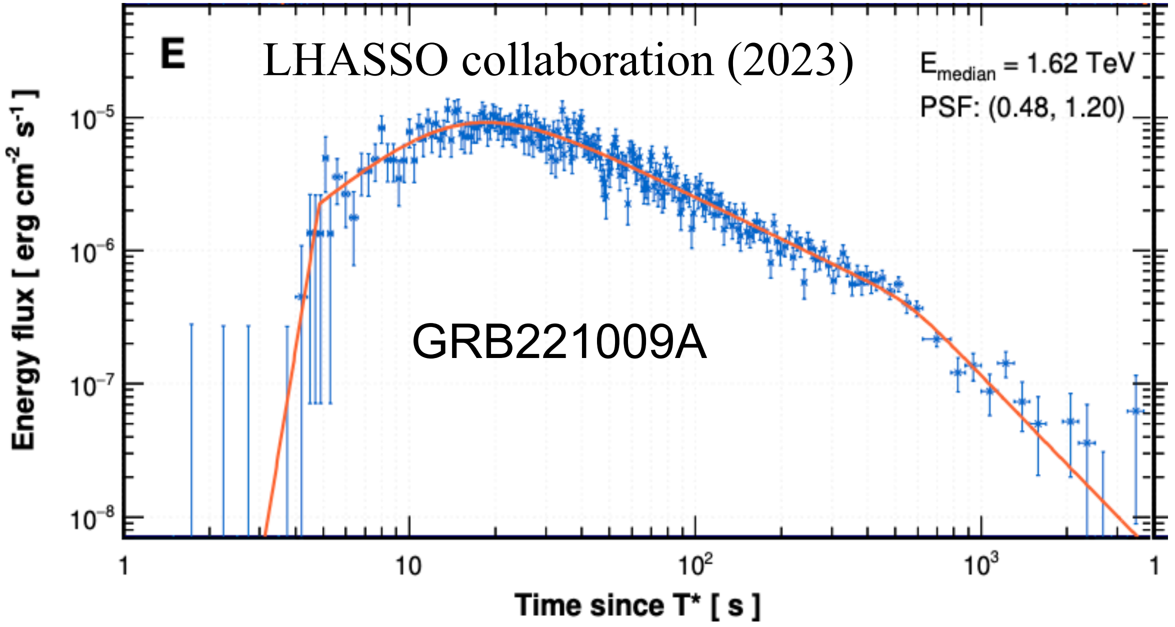
Gamma-Ray Bursts (GRBs)

Fast variable + Smooth power law



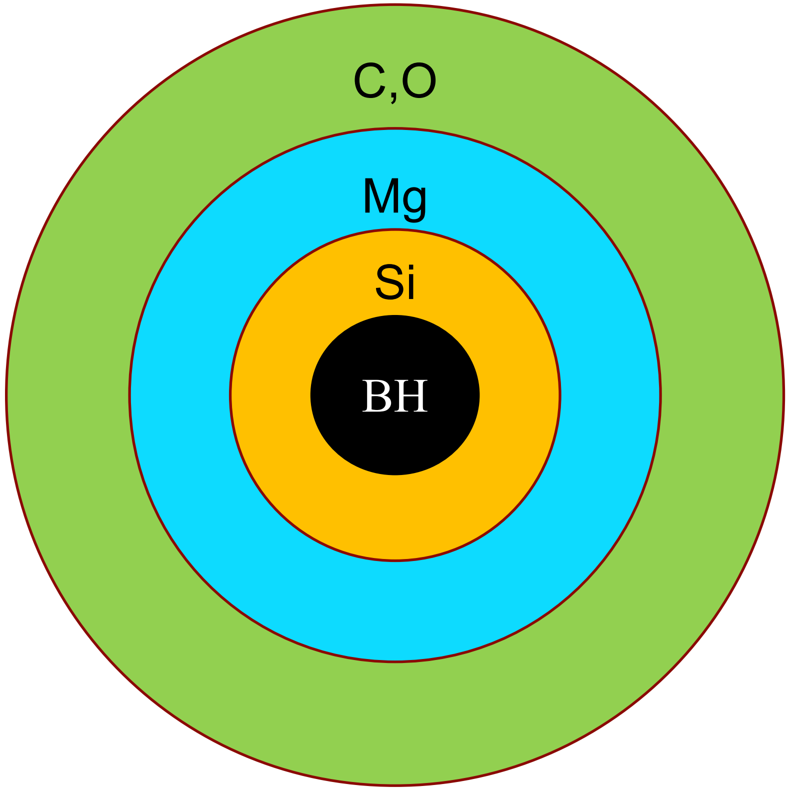
Prompt Afterglow

Early increasing phase + Late decreasing phase



Origin of Long GRBs

SN (IcBL)



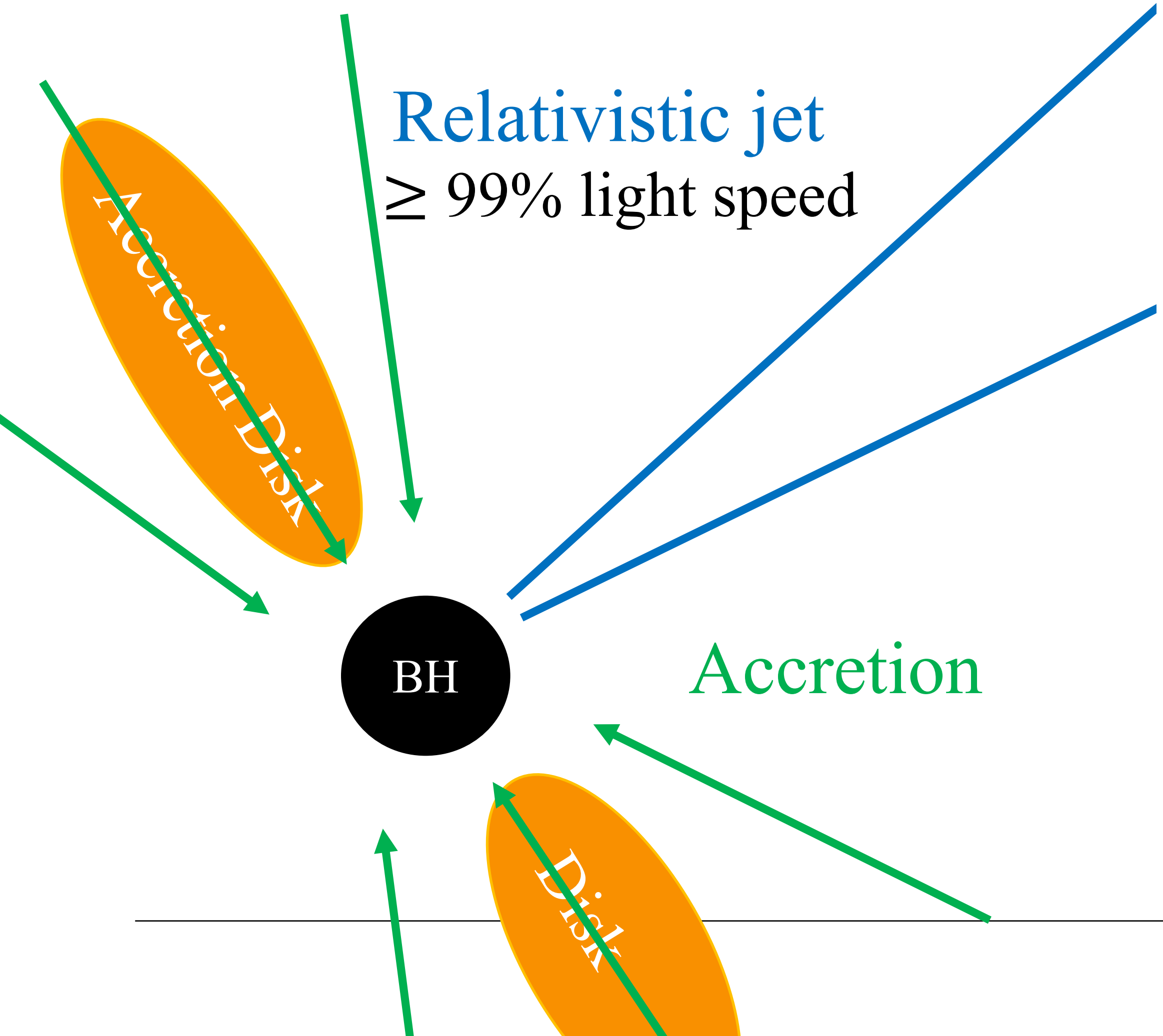
Origin of Short GRBs

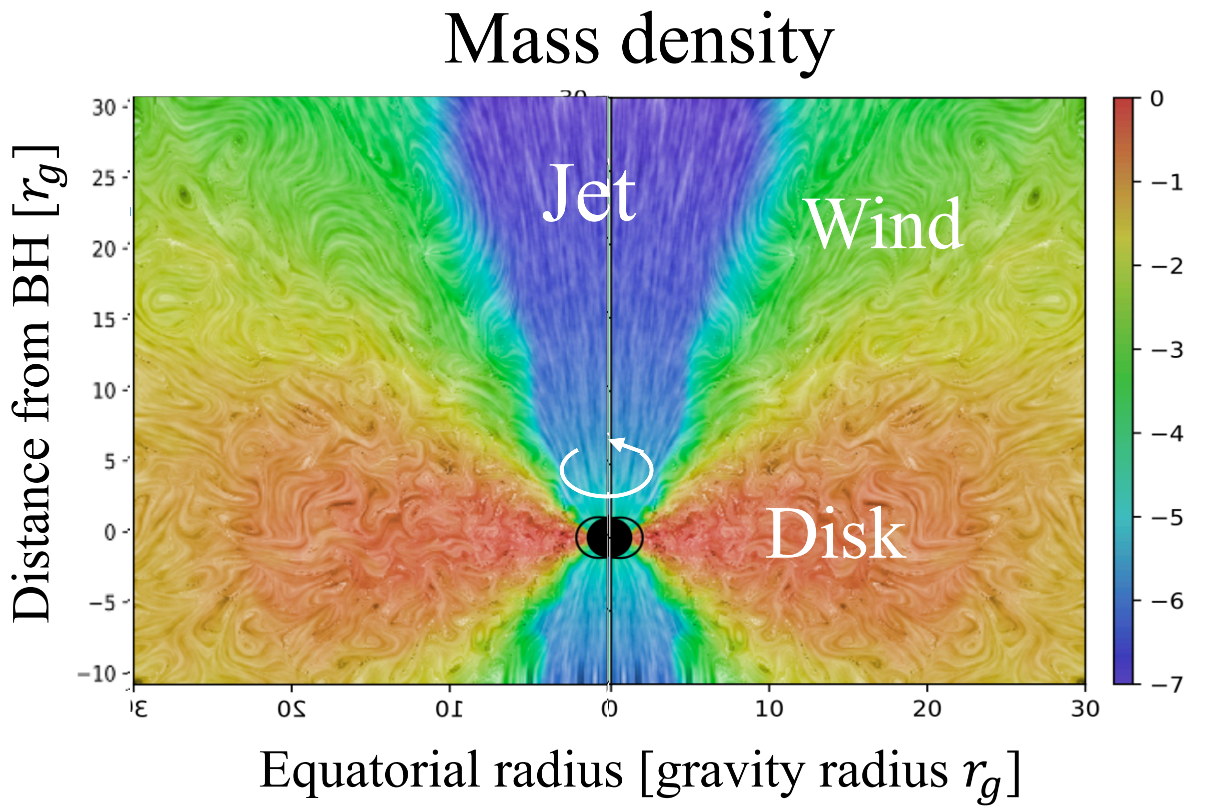
BNS merger

Origin of Short GRBs

BNS merger

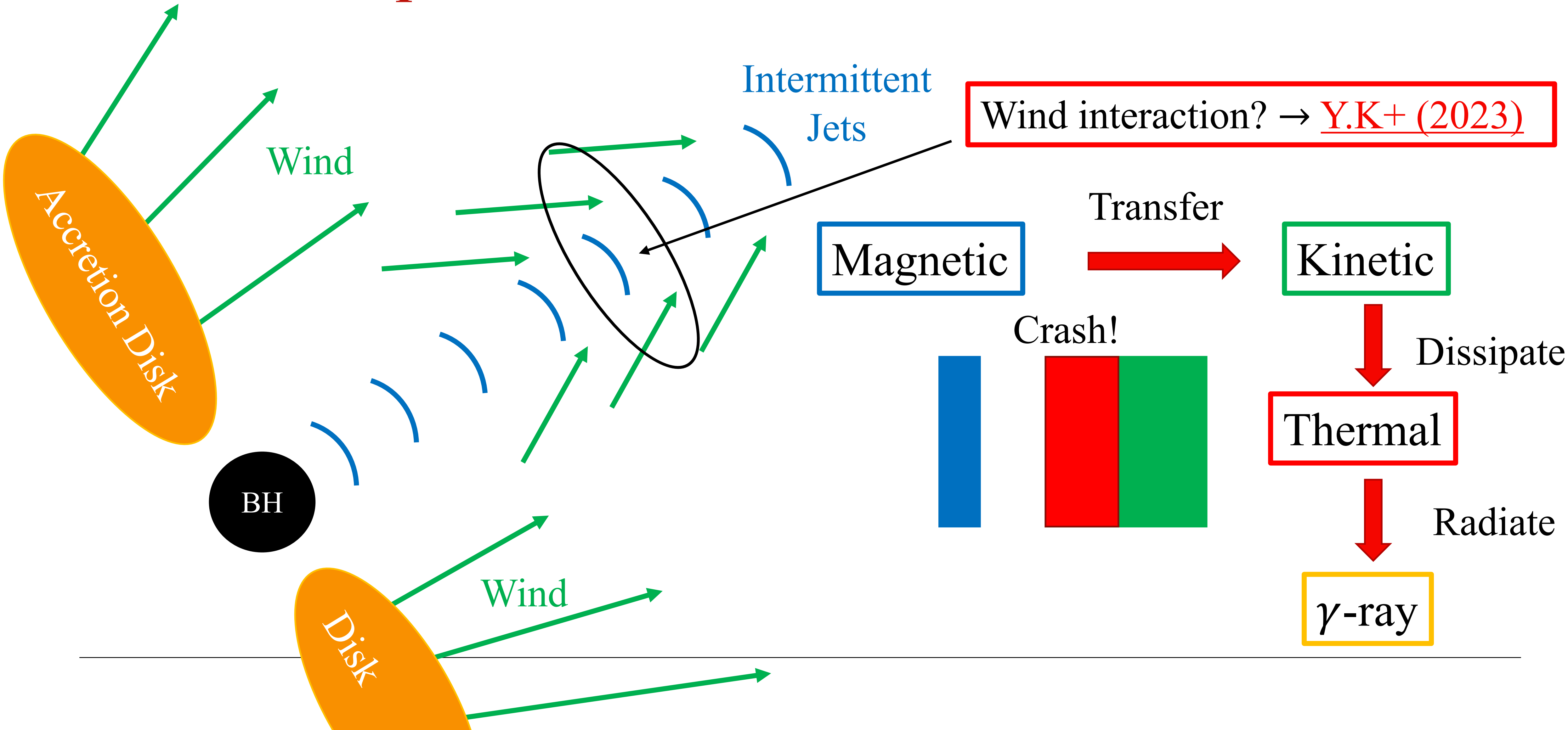
Relativistic Jets from Compact Objects



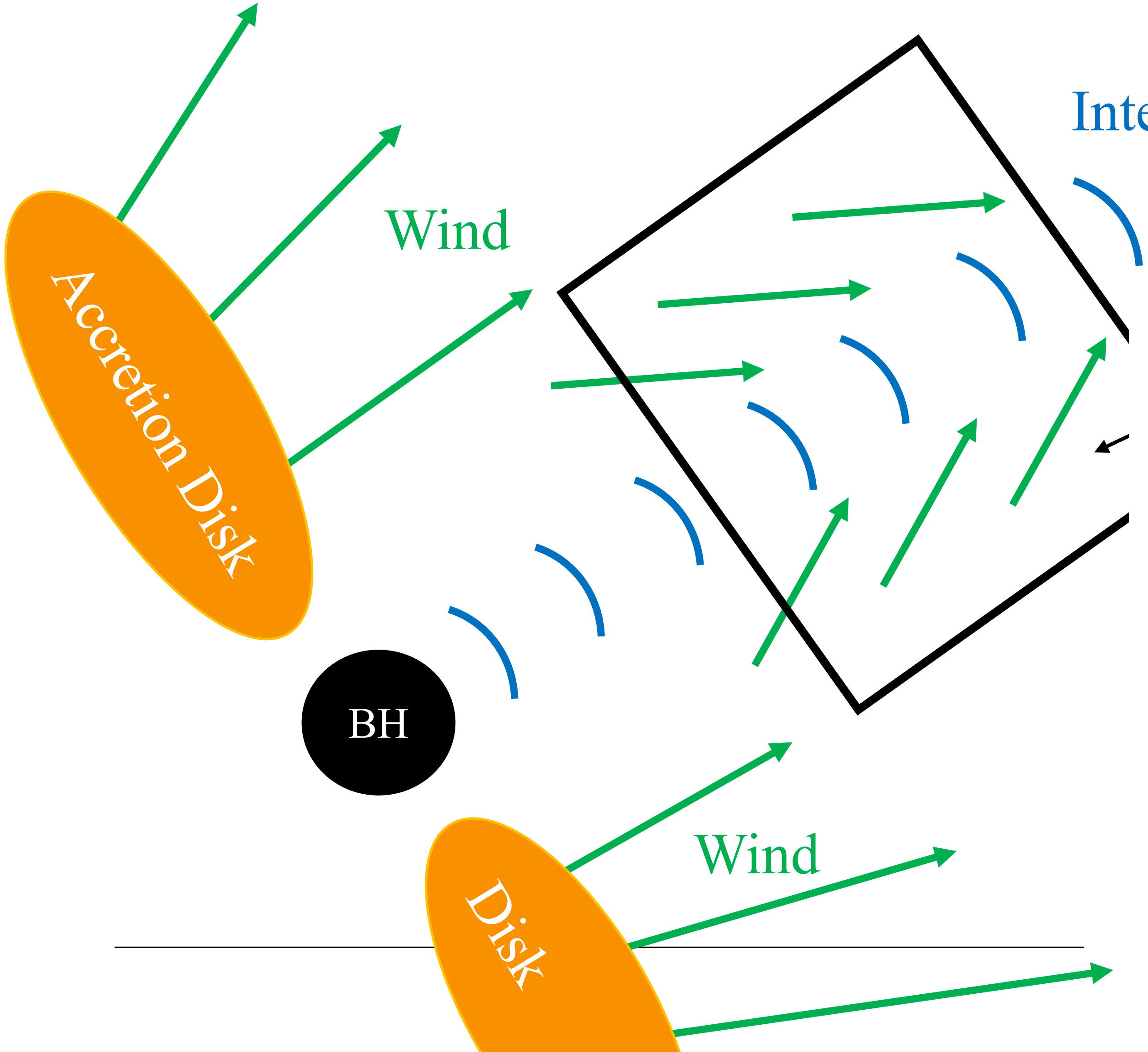


Porth et al., (2019)

Shock dissipation of Intermittent Jets and Wind

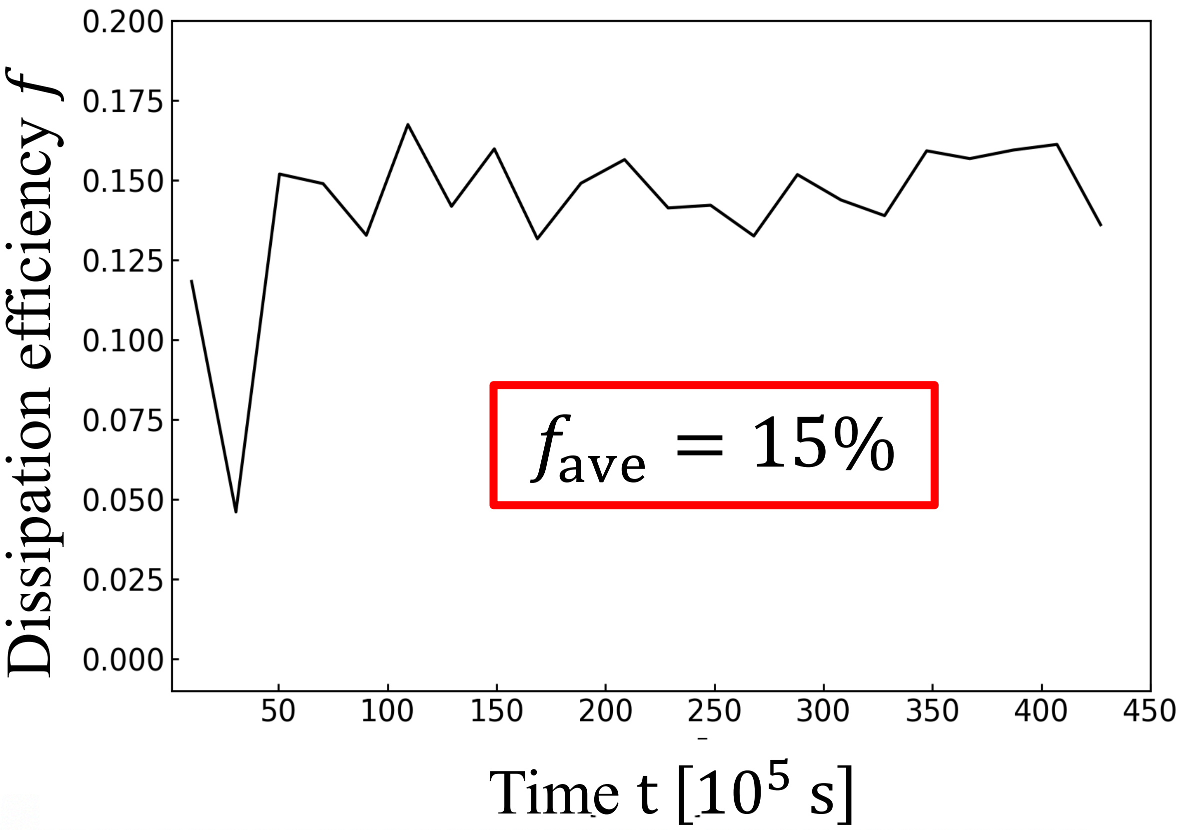


Efficient Magnetic Energy Dissipation by Internal Shocks



How efficient ? → Y.K+ (2023)

1D Relativistic MHD simulation



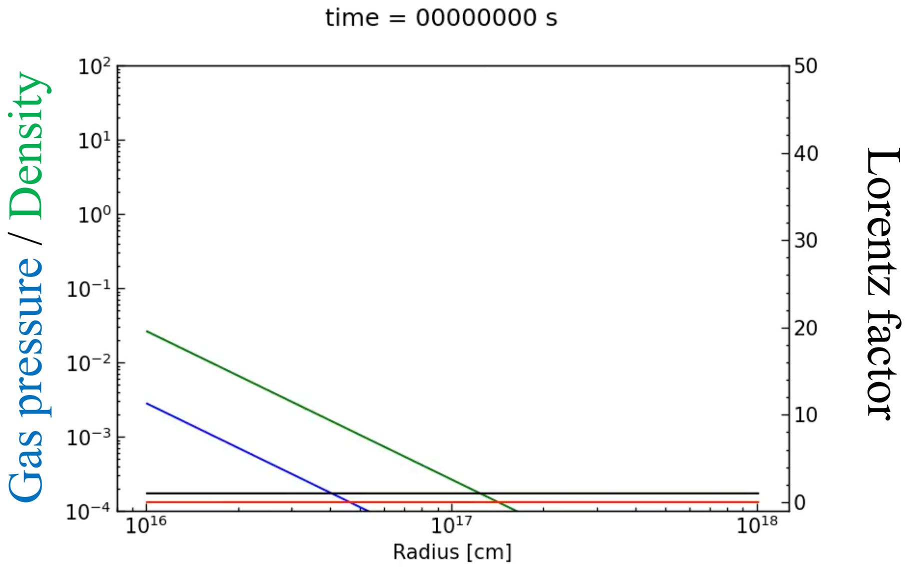
1D Internal Shocks Radiation

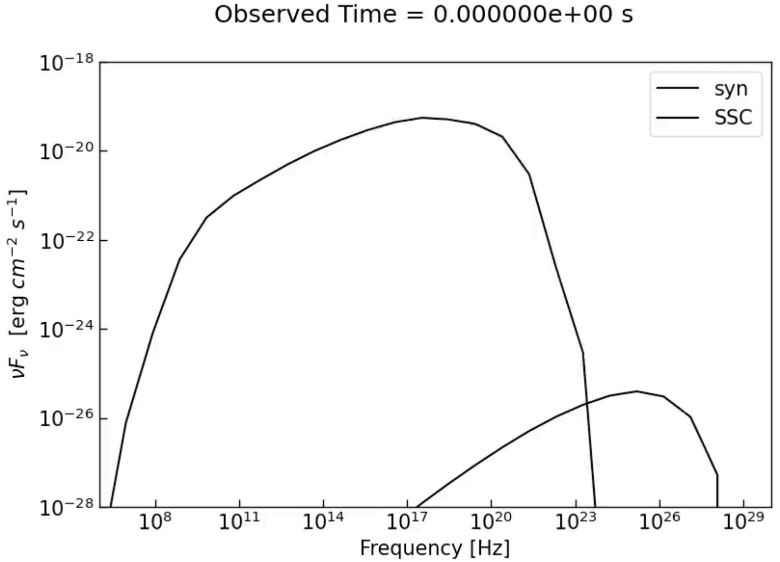
1D Radiation code (Kusafuka+)

- **1DSRMHD** (Kusafuka & Asano 2024)
- **Lagrange Particle** (Vaidya et al. 2018)
- **Radiative Transfer** (Hummer & Rybicki 1971)
- **Synchrotron / Synchrotron Self-Compton**
- ***pp* collision (γ-ray / secondary $e^{\pm}$ / ν_e, ν_μ)**

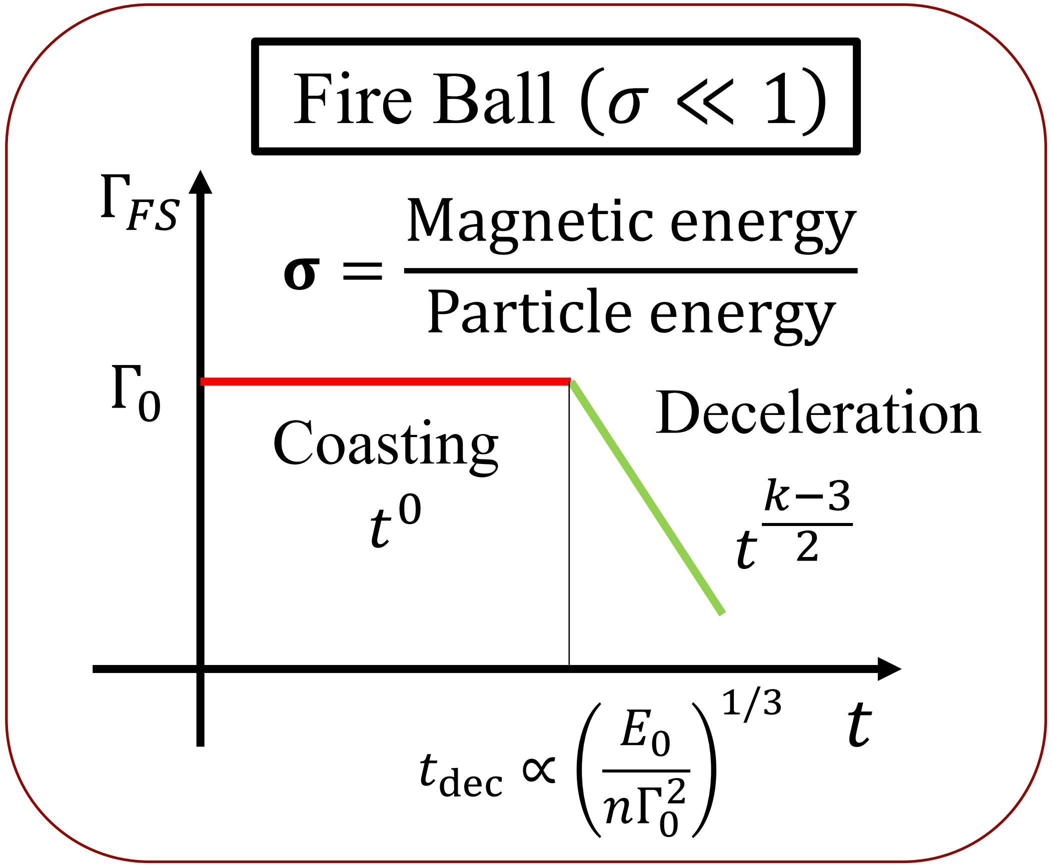
Application to GRB / Blazar / Microquasar / PWN

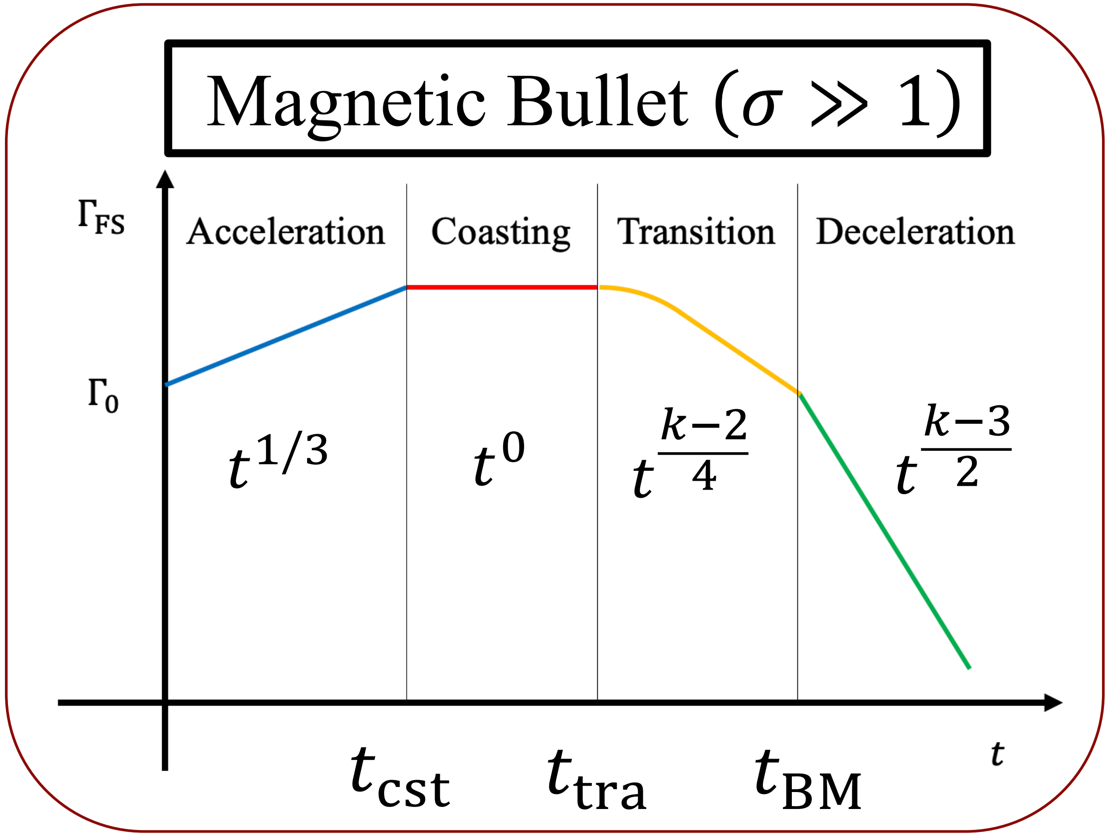
I'm sorry, waiting for the next year!



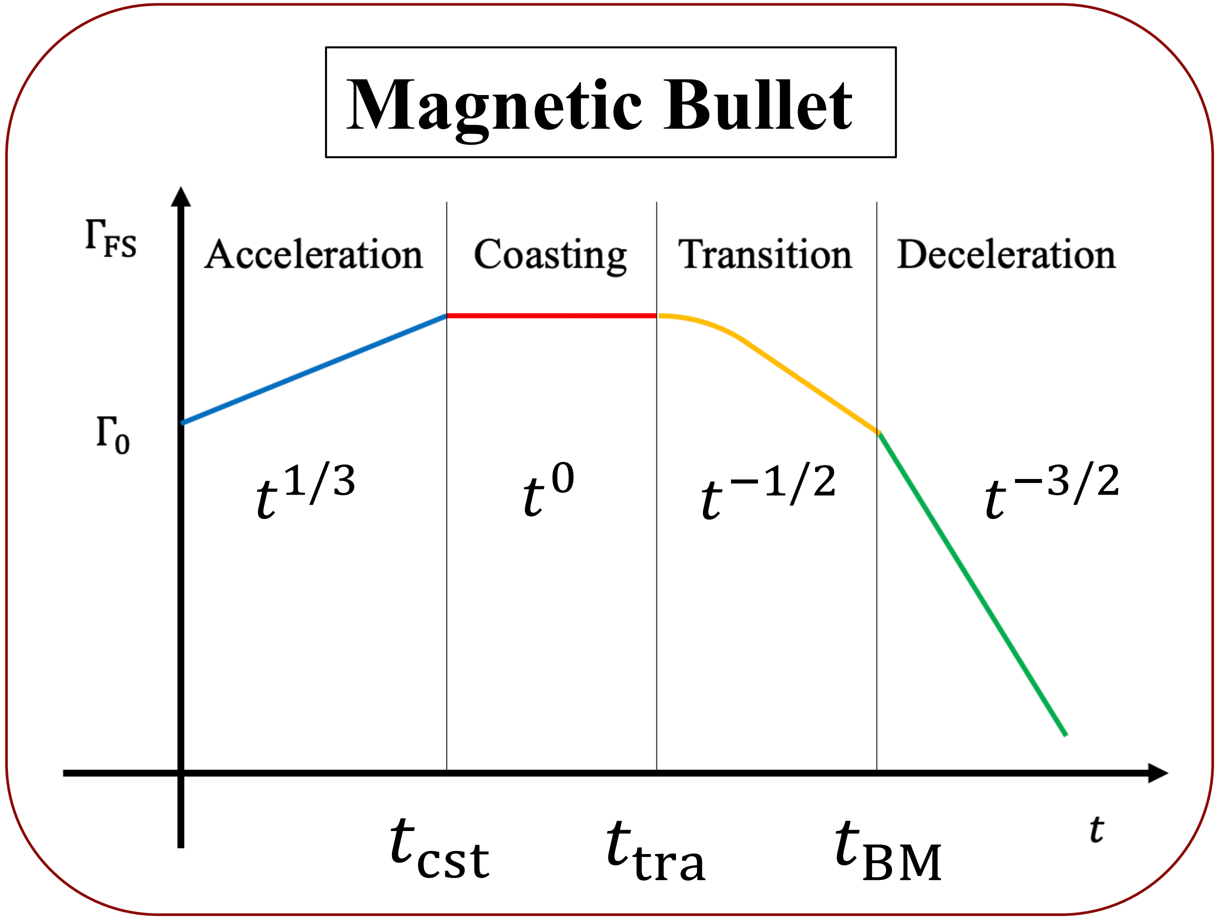


Today's Topic - Magnetic Bullet Afterglow



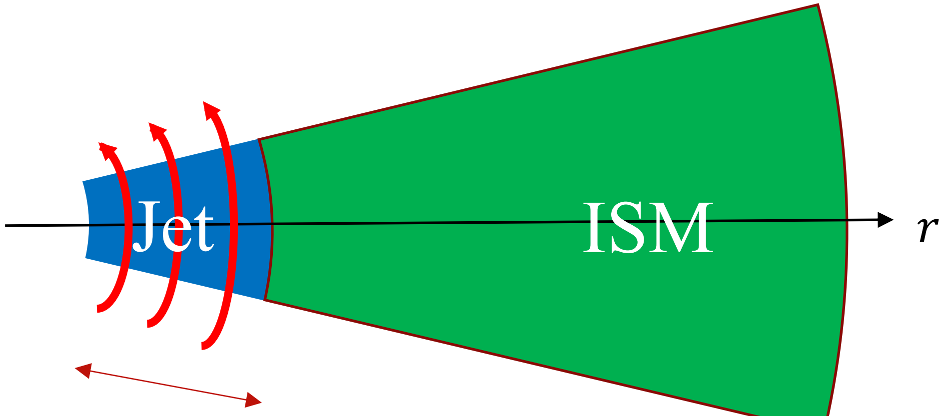


Semi-Analytic Model of Magnetic Bullet Afterglow



Two additional parameters are included

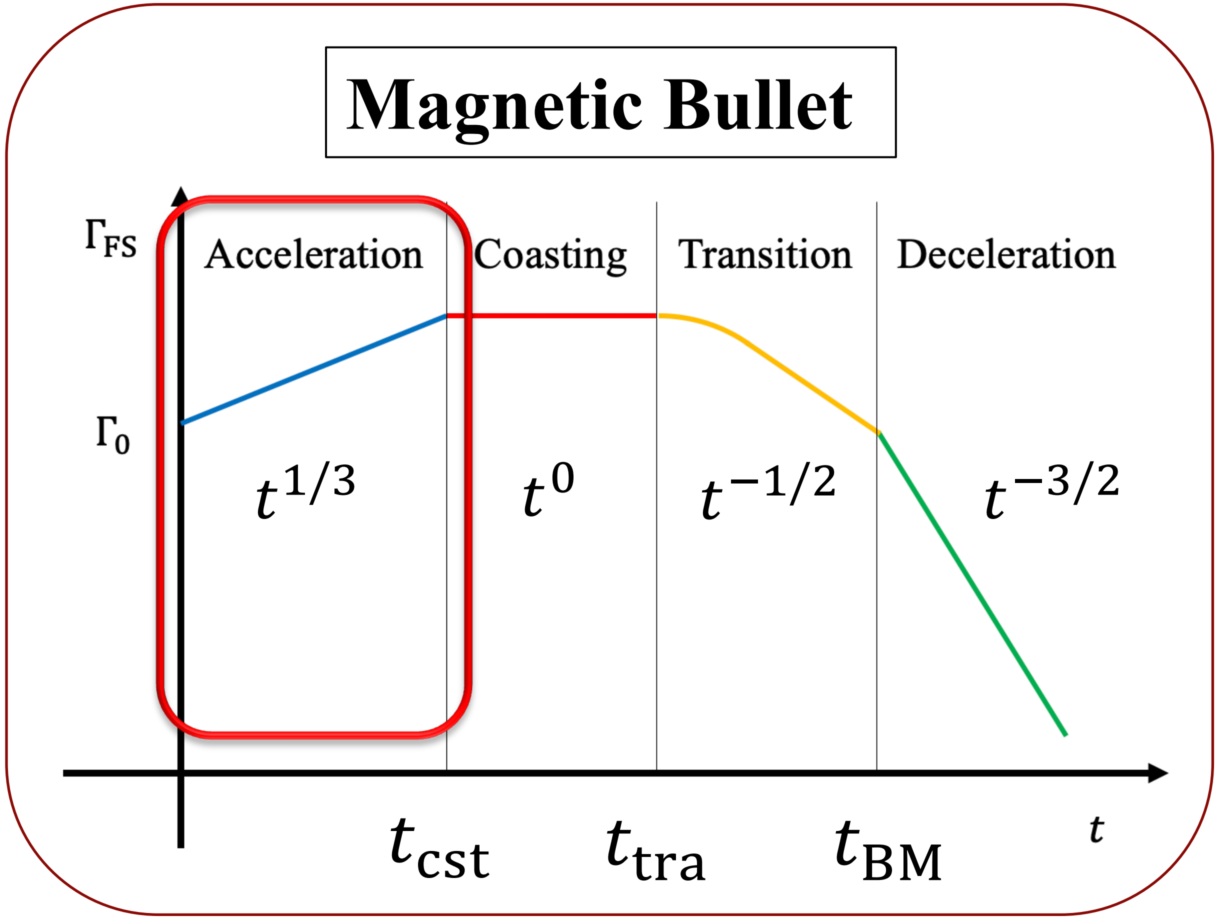
$$\boldsymbol{\sigma} \equiv \frac{\text{Poynting flux}}{\text{Matter flux}} = \frac{B^2}{4\pi\rho c^2}$$



$\boldsymbol{\Delta} \equiv$ Shell width

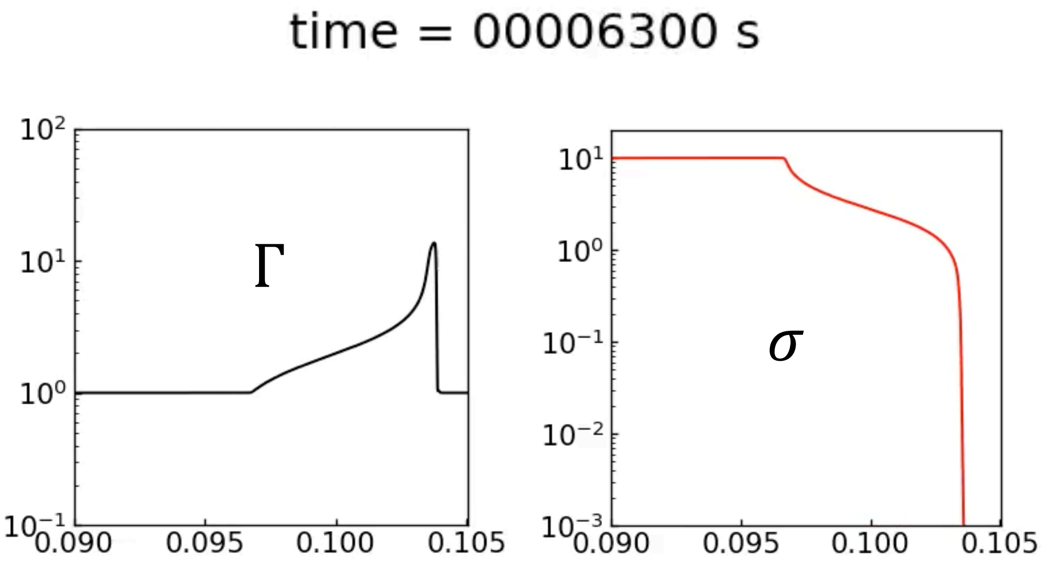
Kusafuka & Asano (2024)

Semi-Analytic Modeling 1. Magnetic Acceleration

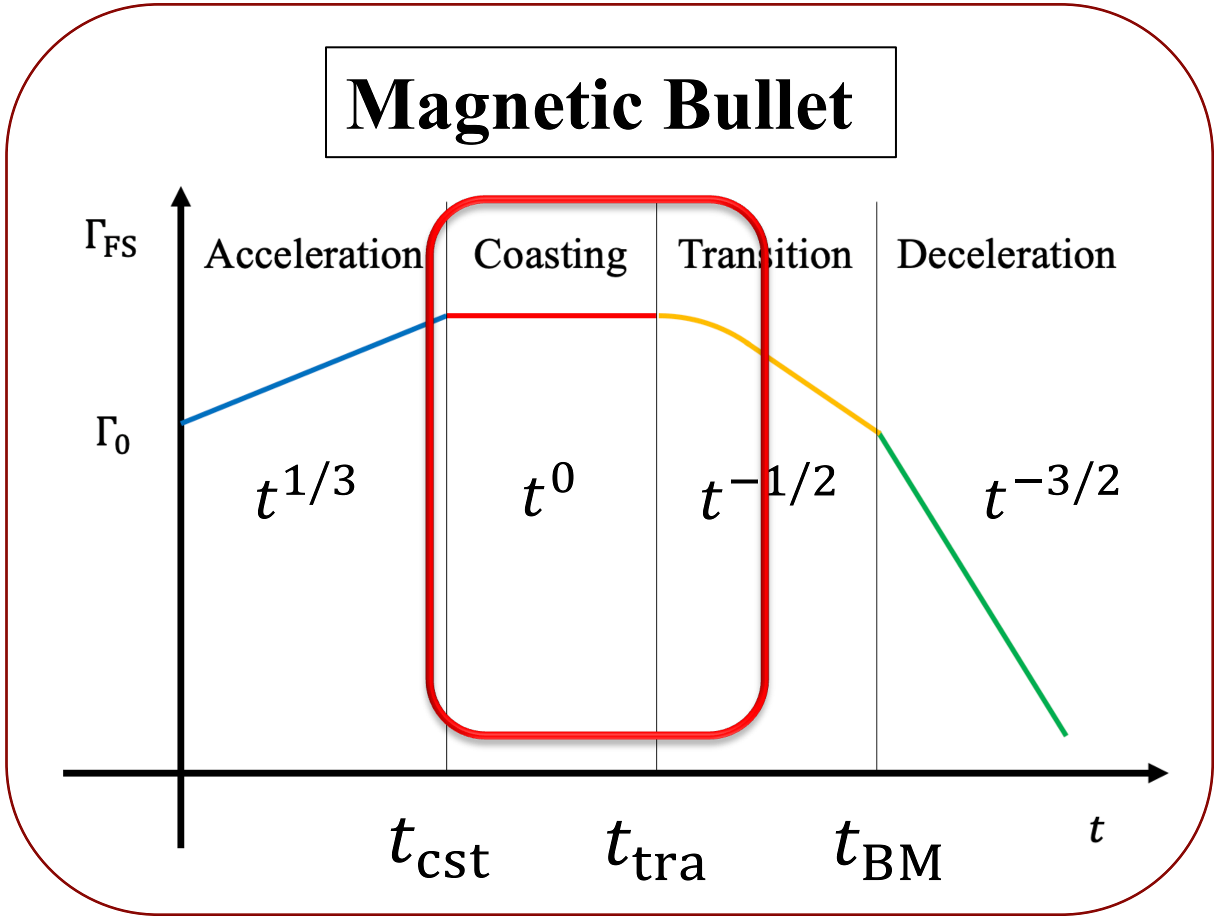


Impulsive acceleration: Granot et al. (2011)

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



Semi-Analytic Modeling 2. Reverse Shock Timescale



RS ignition condition

$$\frac{B'^2_{\rm ej}}{8\pi} = \frac{4}{3}\Gamma^2_{\rm FS} n_0 m_{\rm p} c^2$$

Zhang & Kobayashi (2005)

Acceleration stops at RS ignition

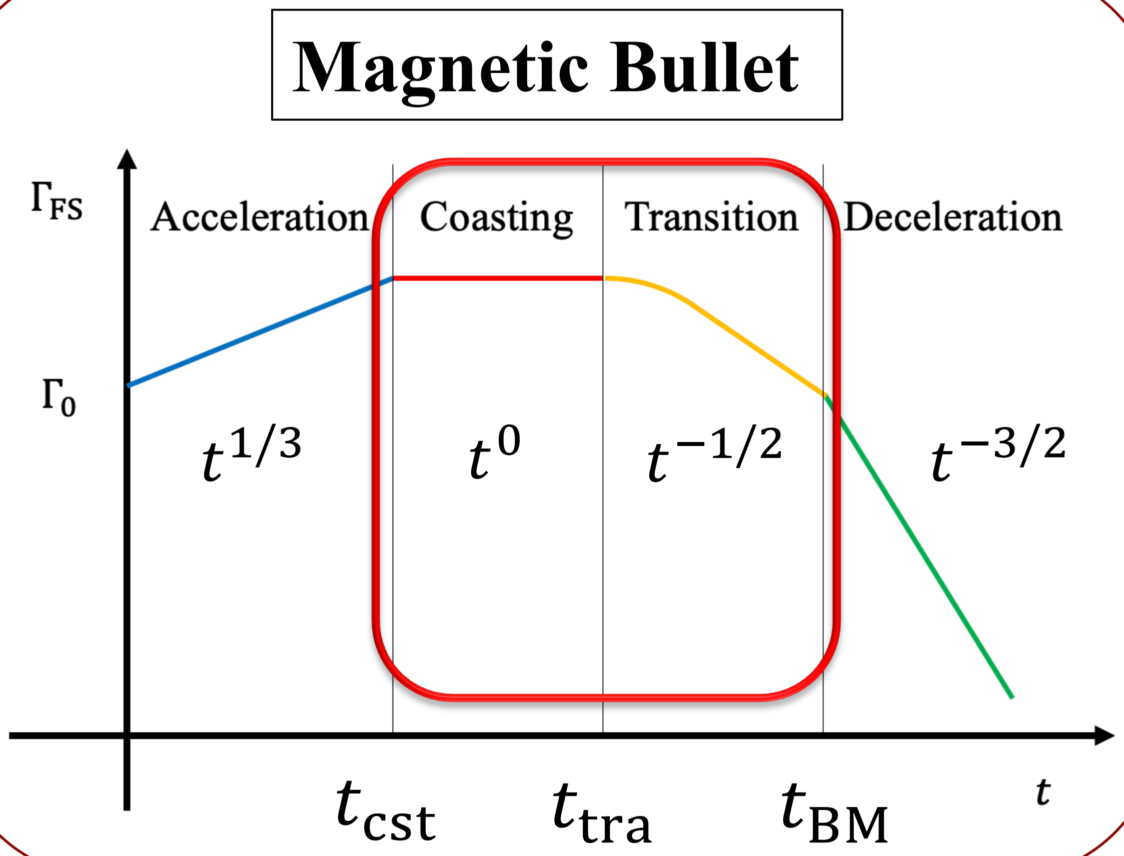
RS crossing timescale

$$t_\Delta(\sigma_0) = \Gamma_0^{1/2} R_{\rm dec}^{3/4} \Delta_0^{1/4} (1+\sigma_0)^{-1/2}$$

Giannios, Mimica & Aloy (2008)

Shell spreading stops at RS crossing

Semi-Analytic Modeling 3. Coasting to Transition



Pressure balance at contact discontinuity

$$(1+\sigma_{RS})(4\Gamma_{rel}+3)(\Gamma_{rel}-1)n_{ej} = 4\Gamma_{FS}^2 n_0$$

$$\Gamma_{FS} = \Gamma_{RS} \simeq \frac{\Gamma_{cst}}{\left[1+2\Gamma_{cst}\sqrt{\frac{n_0}{n_{ej}(1+\sigma_{RS})}}\right]^{1/2}}$$

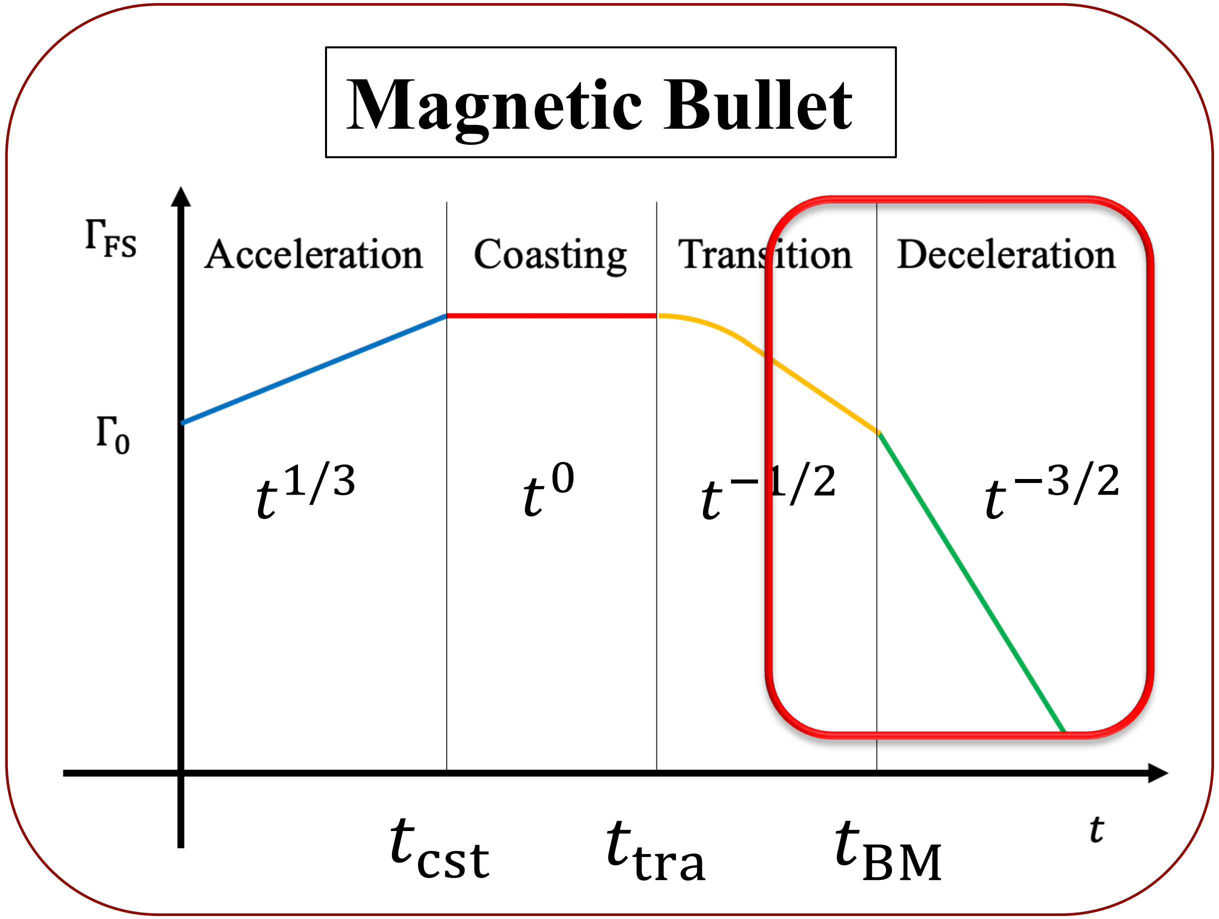
Panaitescu & Kumar (2004)
Murase (2007)

(for $\sigma_{RS}=0$ case)

Coasting Phase: $\Gamma = \Gamma_{cst}$

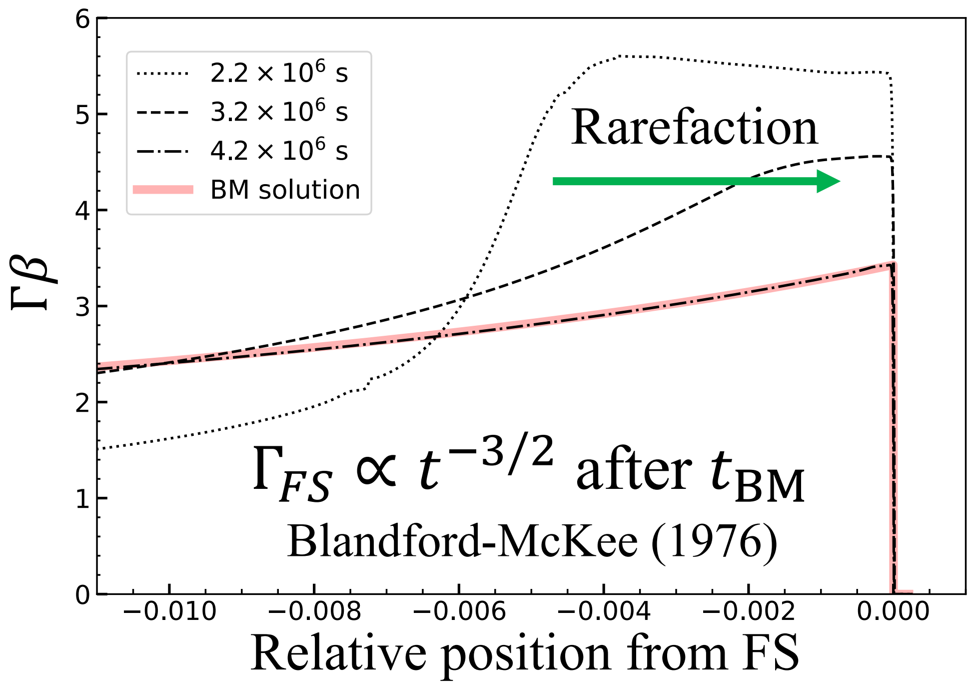
Transition Phase: $\Gamma \propto t^{-1/2}$

Semi-Analytic Modeling 4. Rarefaction Catch-up

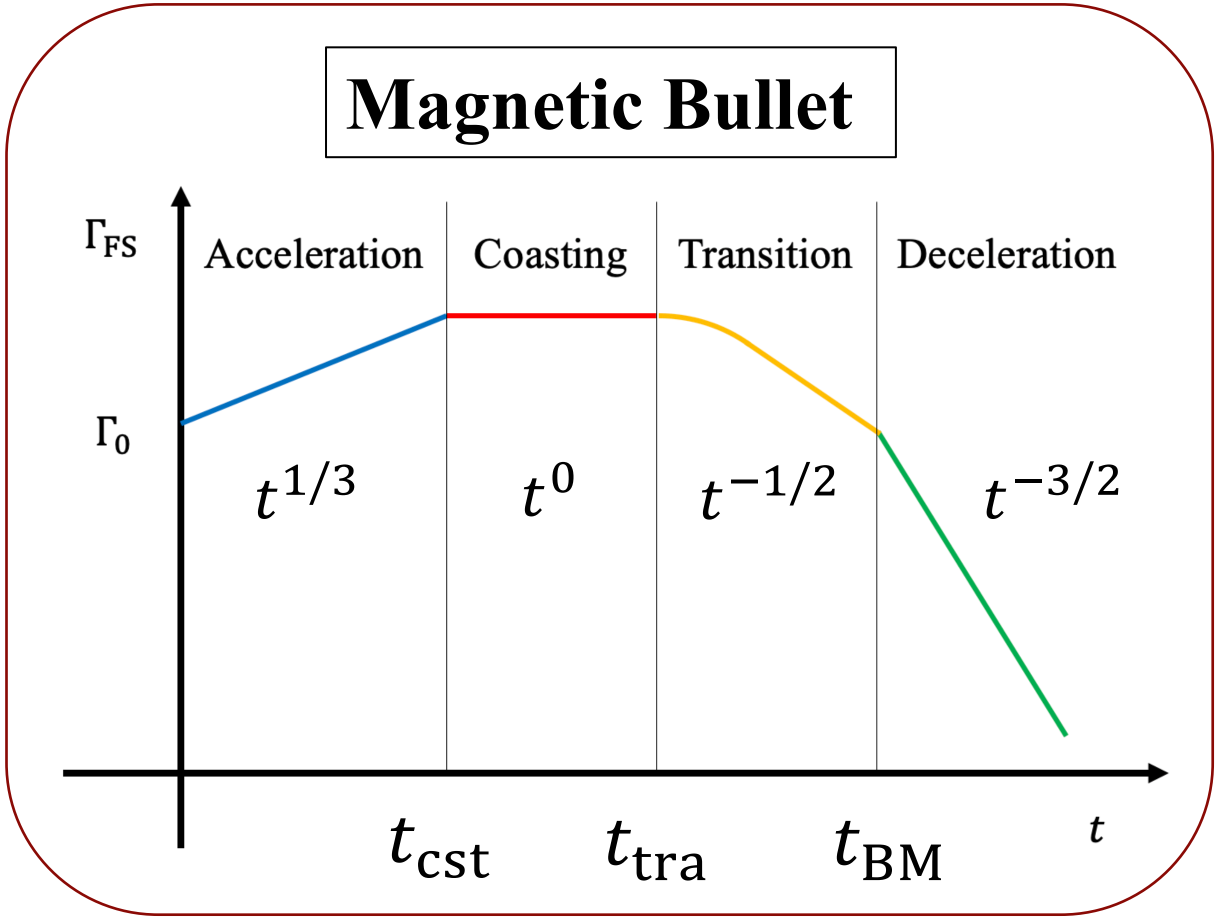


Rarefaction catch-up time t_{BM}

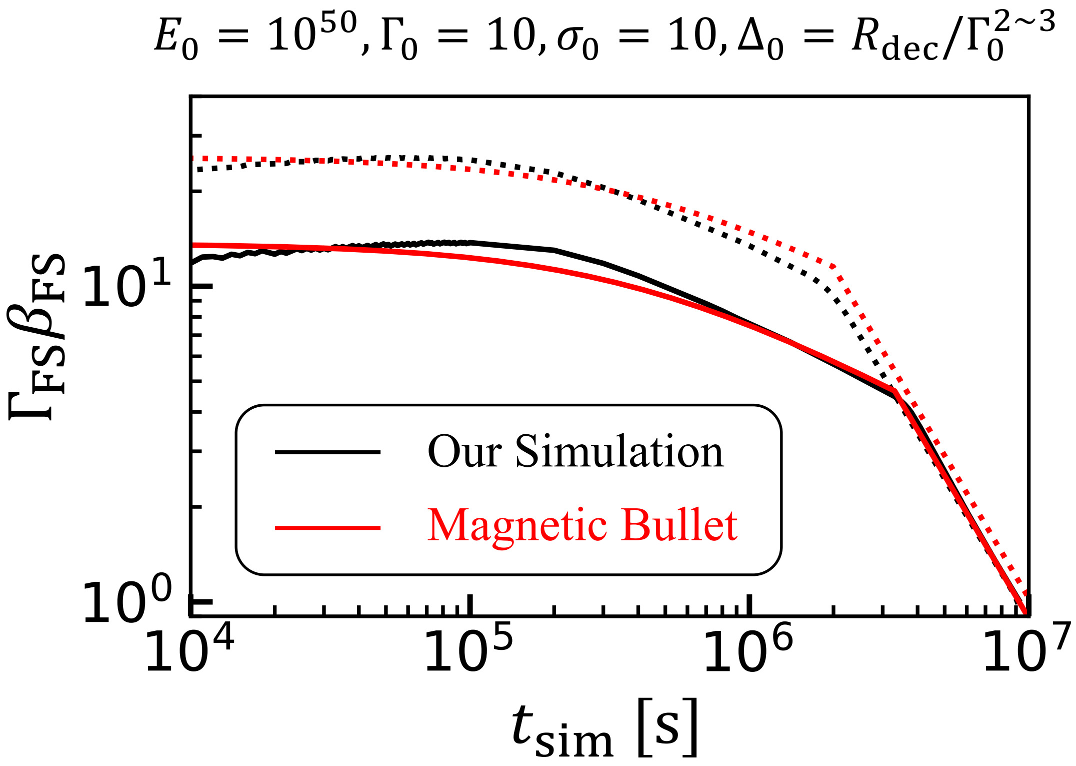
$$\Delta = \int_{t_\Delta}^{t_{BM}} (c - v_{FS,front})dt \simeq \int_{t_\Delta}^{t_{BM}} \frac{cdt}{4\Gamma_{FS}^2(t)}$$



Semi-Analytic Model of Magnetic Bullet Afterglow



Well consistent with simulation results



~BOAT GRB~
Evidence of Magnetic Acceleration in the Very Early TeV Afterglow

Yo Kusafuka

ICRR, the University of Tokyo, PhD Student

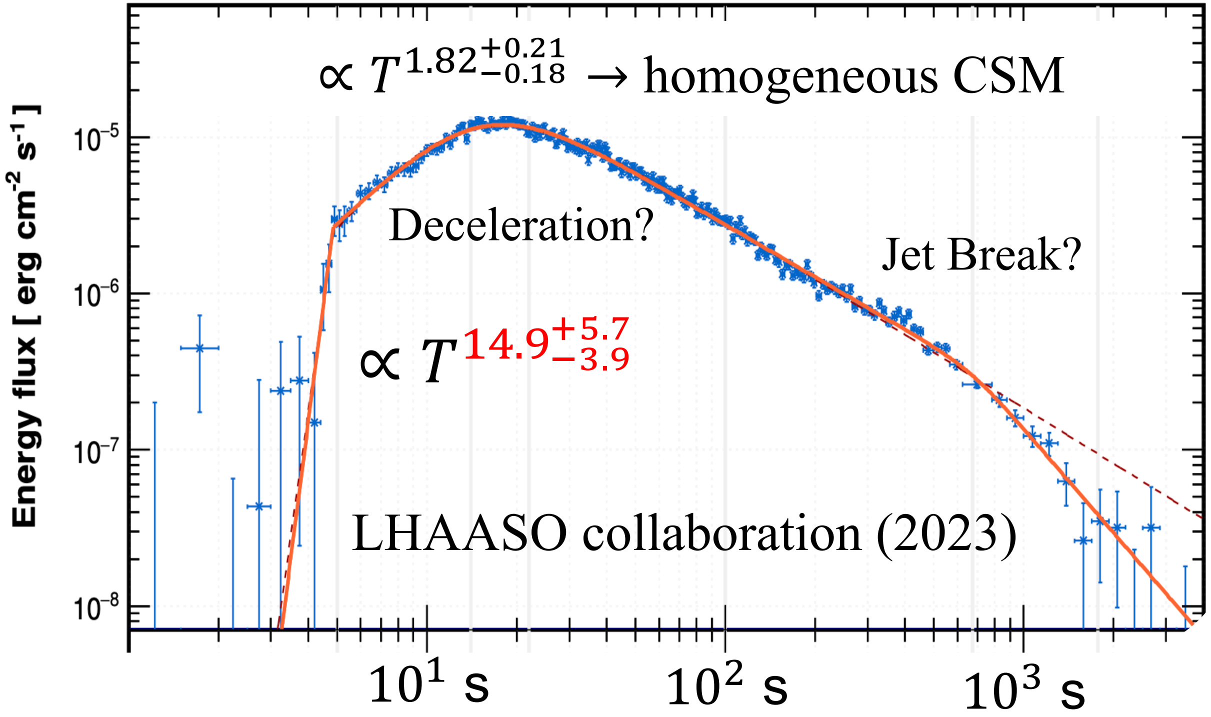
Collaborator: Katsuaki Asano (ICRR)

Credit: Nasa / Swift / Cruz deWilde

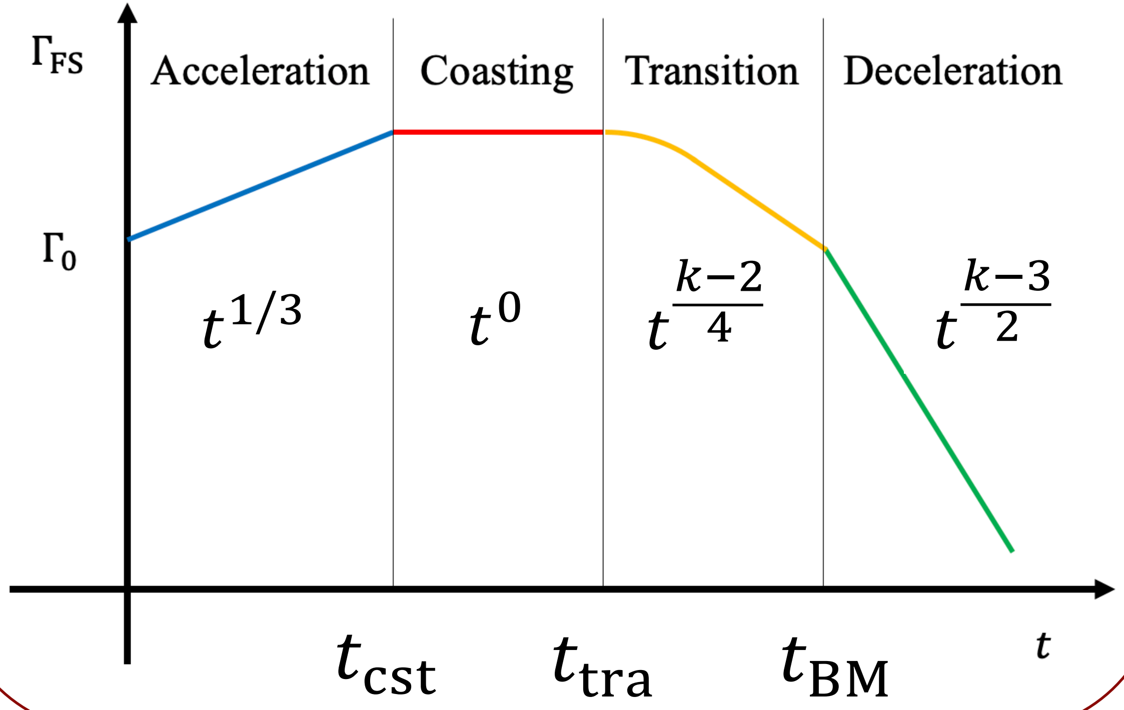
What a coincidence!?

Acceleration Phase: $\Gamma \propto t^{1/3} \propto T$

Roughly: $F_{SSC} \propto R^4 \Gamma^3 \propto T^{15}$

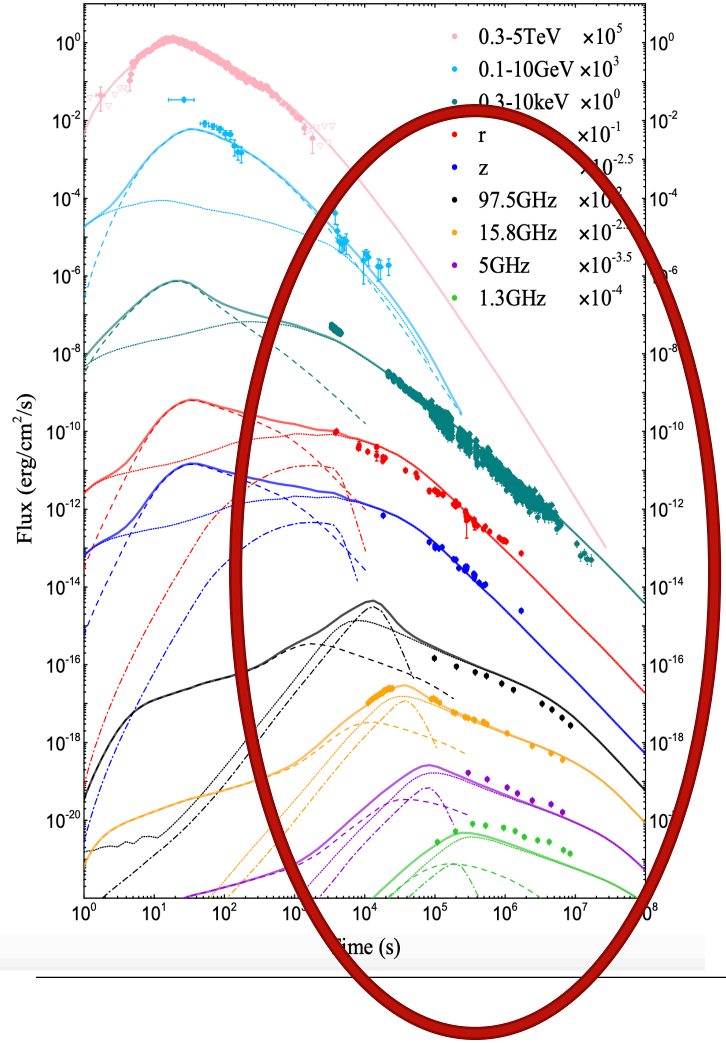


4 Phases in BOAT & Model



Inverted CSM Structure

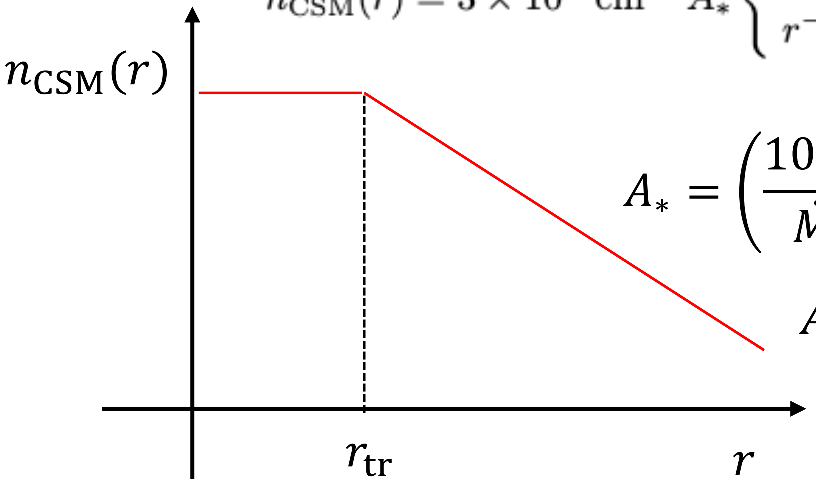
Ren et al. (2024)



Early-Phase
homogeneous

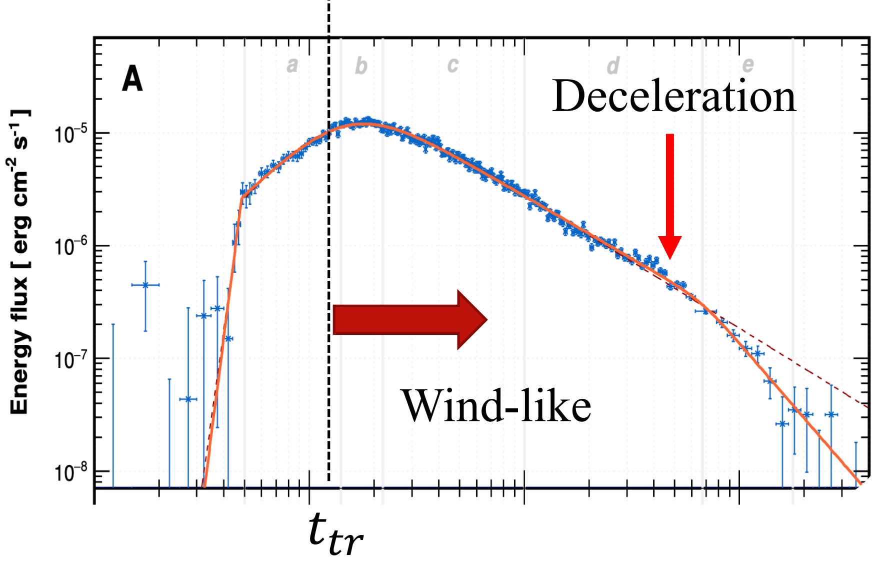
Late-Phase
Wind-like

$$n_{\rm CSM}(r) = 3\times10^{35}{\rm cm}^{-1}A_*\begin{cases} r_{\rm tr}^{-2} & r \leqq r_{\rm tr} \\ r^{-2} & r > r_{\rm tr}\end{cases}$$



$$A_* = \left(\frac{10^{-5}}{\dot{M}}\right) M_\odot\ {\rm yr}^{-1}$$

$$A_* = 0.1\sim10$$



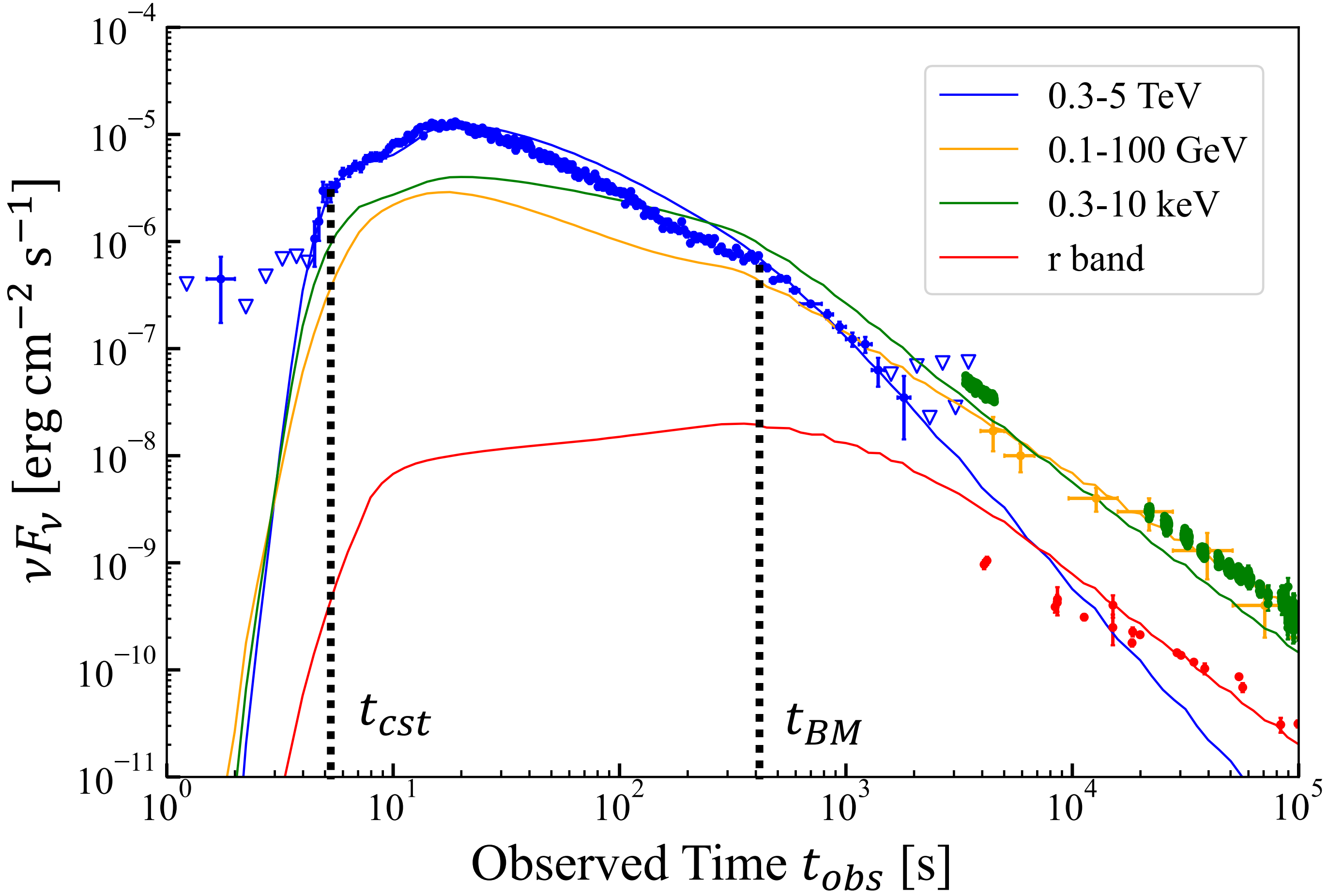
No Jet Break in TeV afterglow

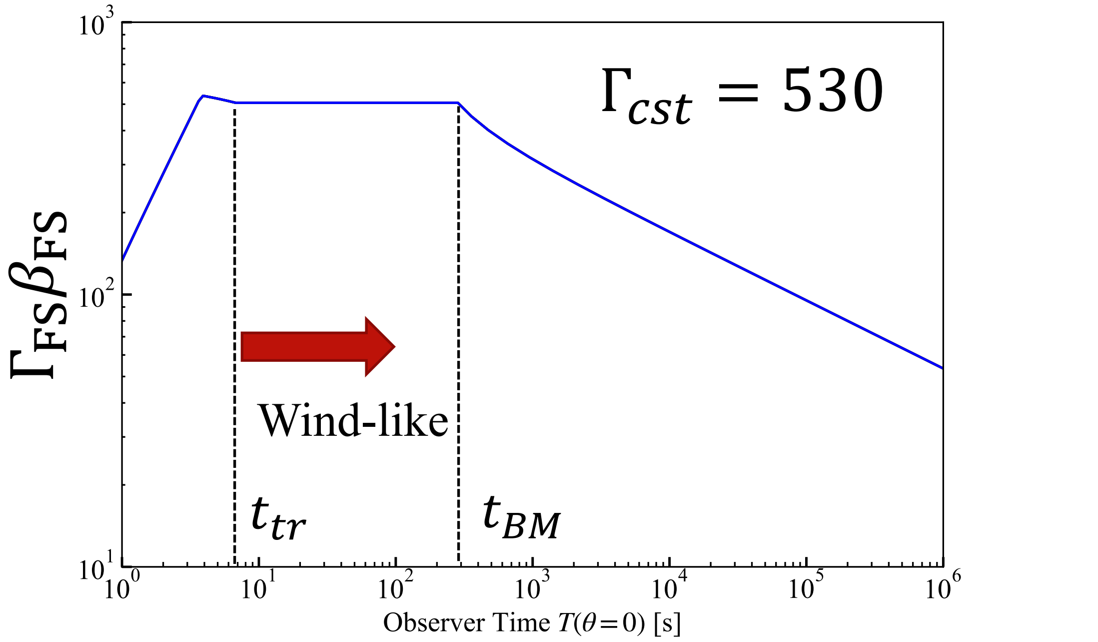
$E_{iso} = 4\times10^{55}$ erg $\quad p = 2.45$

$A = 0.048$

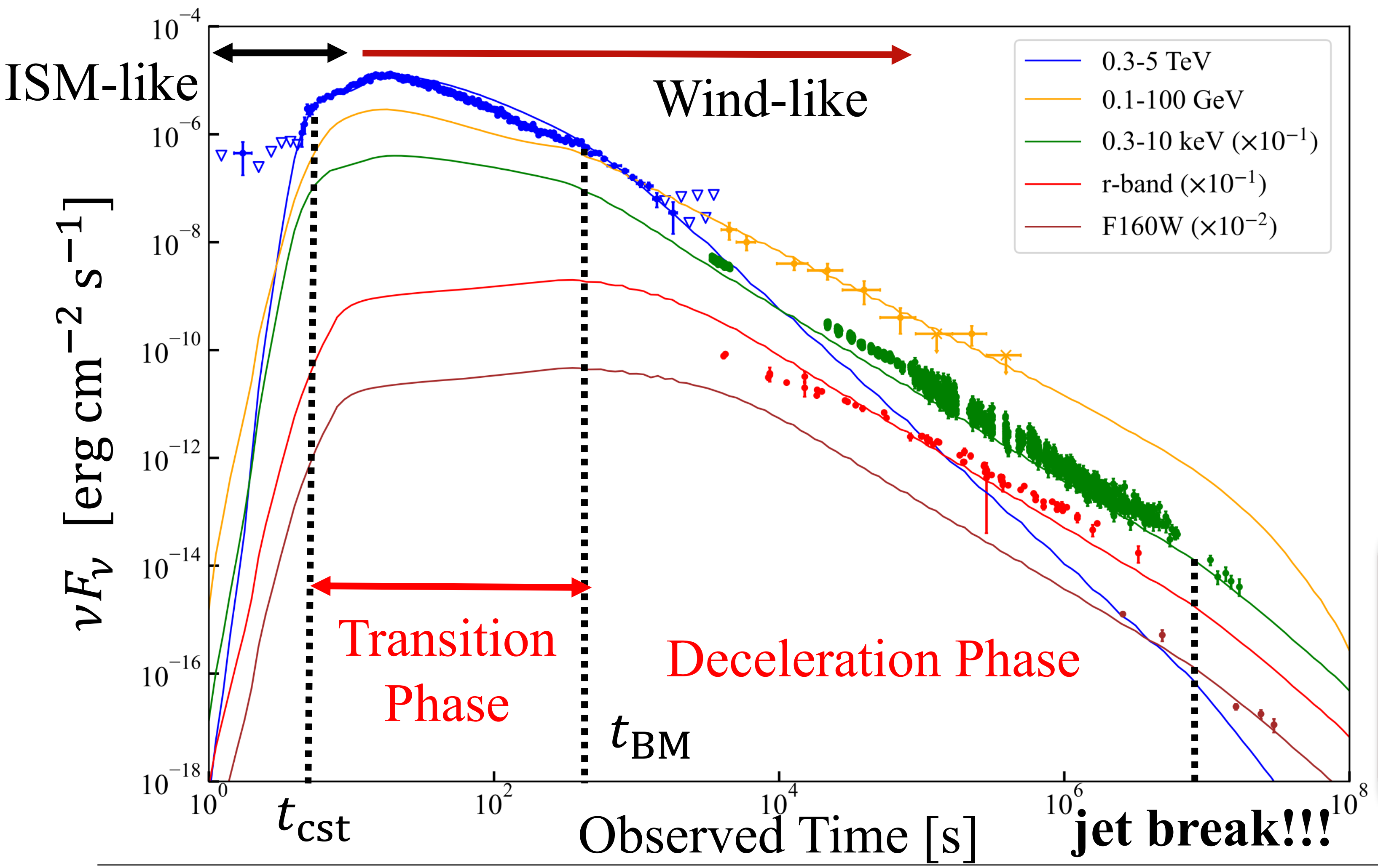
$\sigma_{cst} = 23 \quad \epsilon_e = 3.0\times10^{-2}$

$\Delta_0 = 200c\ (\sim T_{90}) \quad \epsilon_B = 4.6\times10^{-5}$

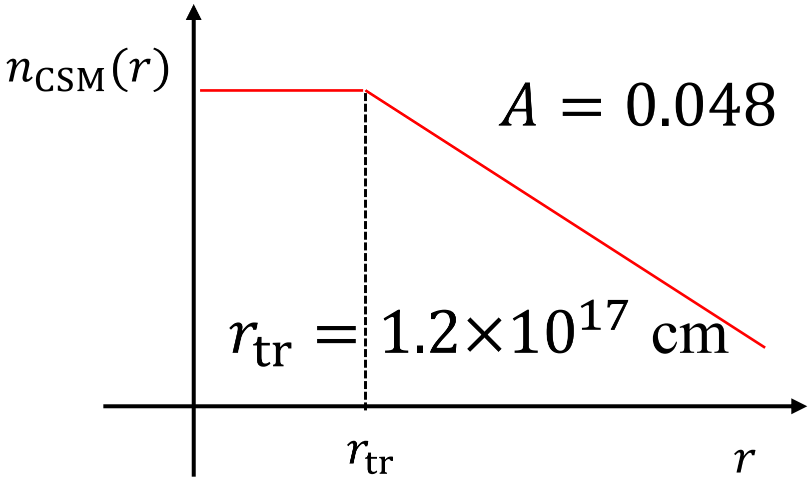




CSM Transition



$$A = \left(\frac{\dot{M}}{10^{-5} M_\odot \ \mathrm{yr}^{-1}}\right)\left(\frac{v_{wind}}{10^4 \ \mathrm{km \ s}^{-1}}\right)^{-1}$$

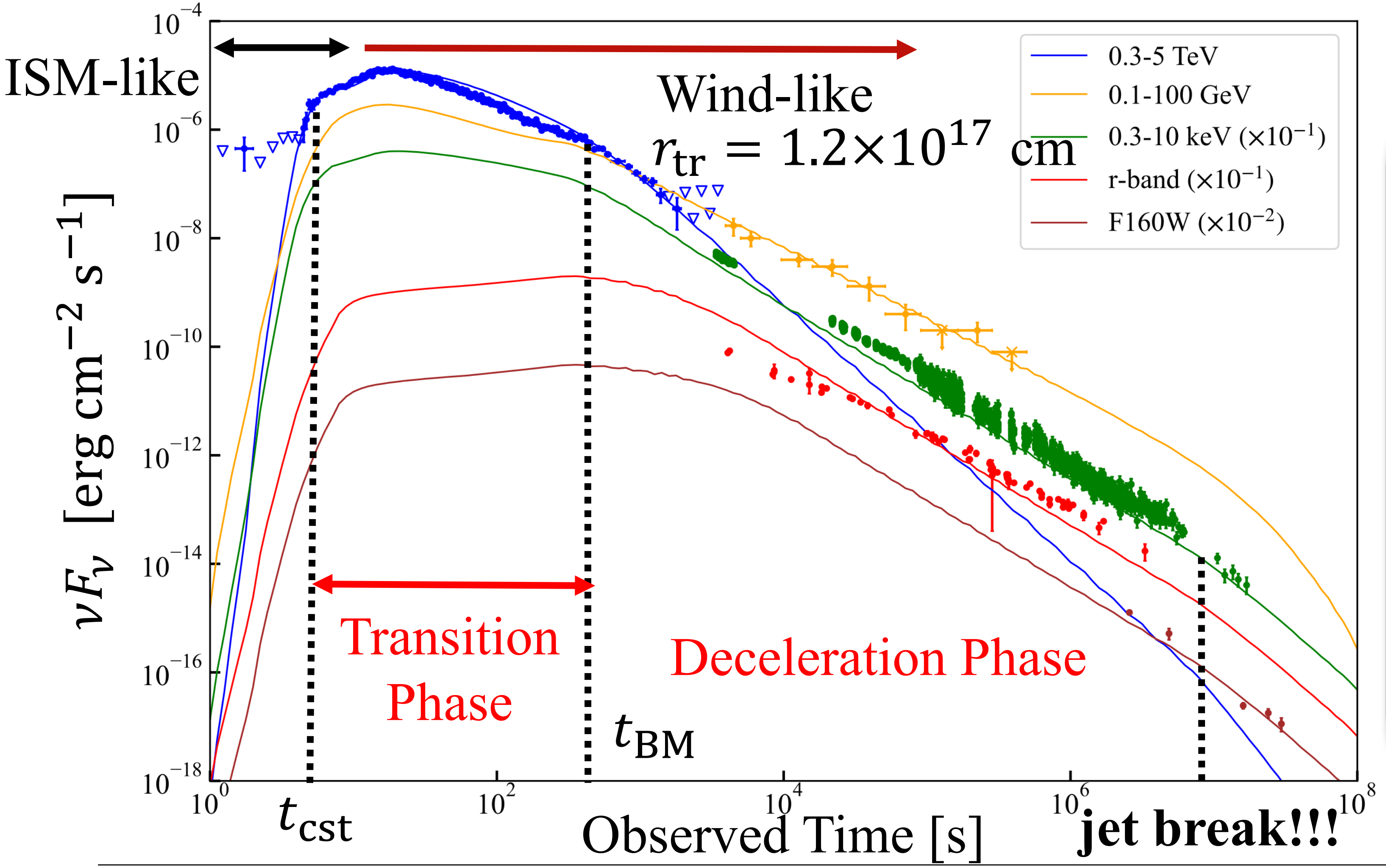


Emergence of a homogeneous medium

Decrease $\dot{M}$ or increase v_{wind} before SN

Early follow-up ~ 10^2 s is important

Late Jet Break



<u>Late jet break ~ 50 days</u>

$$\theta_{jet} = 0.03 \text{ rad } (= 1.7°)$$

$$\theta_{mean} = 2.5 \pm 1.0° \text{ (Wang+ 2018)}$$

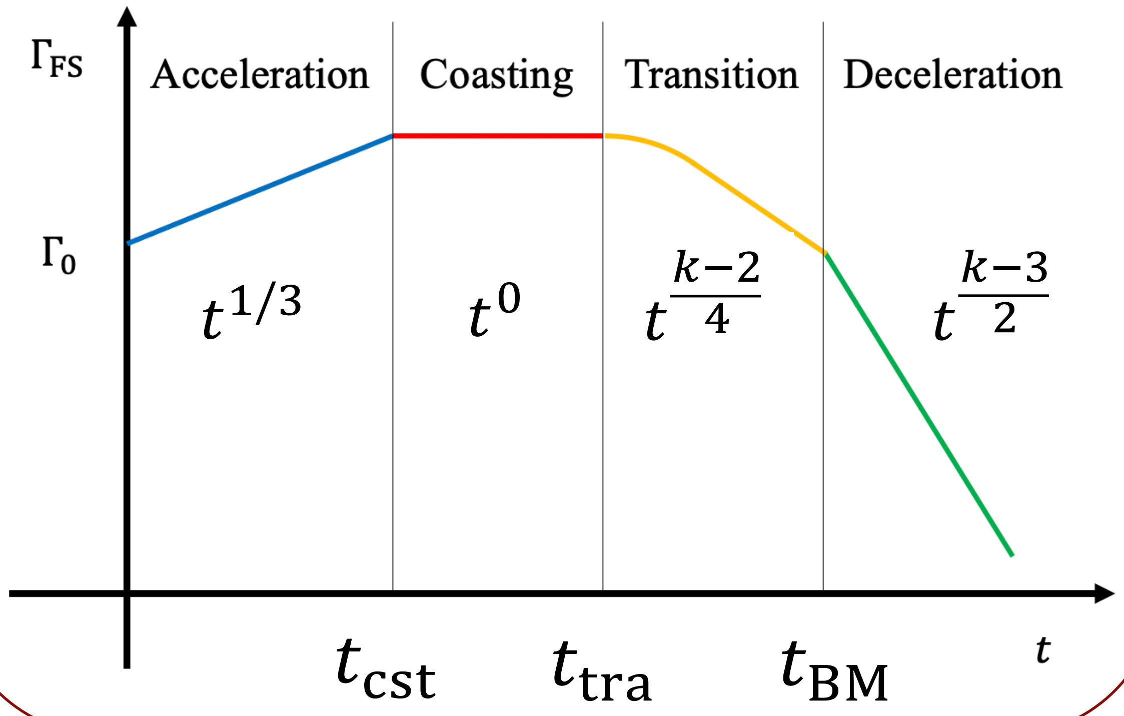
We don't need very narrow jet

$$E_{jet} = 2\times10^{52} \left(\frac{\theta_{jet}}{0.03 \text{ rad}}\right)^2 \text{ erg}$$

Comparable to SN energy

Summary

Magnetic Bullet



<u>**Kusafuka & Asano (2024)**</u>

MNRAS published

arxiv: 2408.10750

Magnetic Bullet can explain a lot of mysterious early afterglows within reasonable parameter sets. Very early TeV afterglow is the best evidence for magnetic acceleration, which may be detected by LHAASO & CTA.

Thank you for your attention!!