Image Credit: DESY, Science Communication Lab

A New Insight for Early Afterglows “Magnetic Bullet”

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Yo Kusafuka

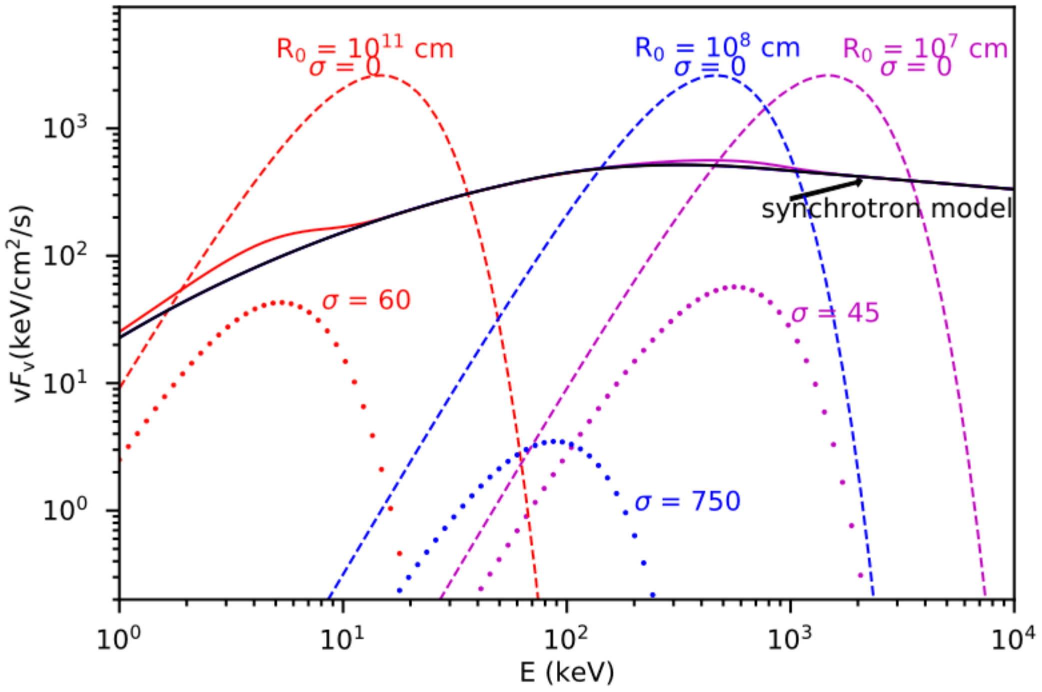
ICRR, the University of Tokyo, PhD Student

Collaborator: Katsuaki Asano (ICRR)

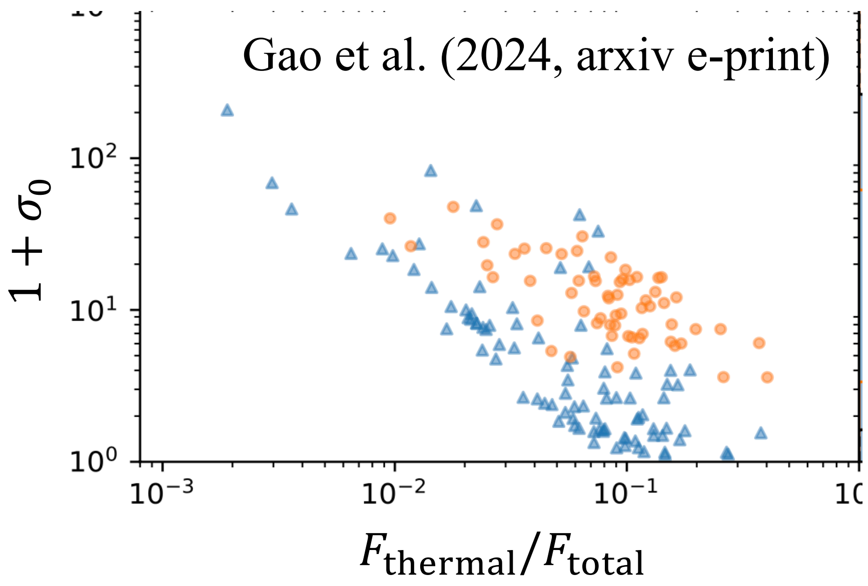
High-σ GRB Ejecta

$$\boxed{\sigma\text{-parameter} \equiv \frac{\text{Poynting flux}}{\text{Enthalpy flux}}}$$

Thermal components in Band spectra constrain σ

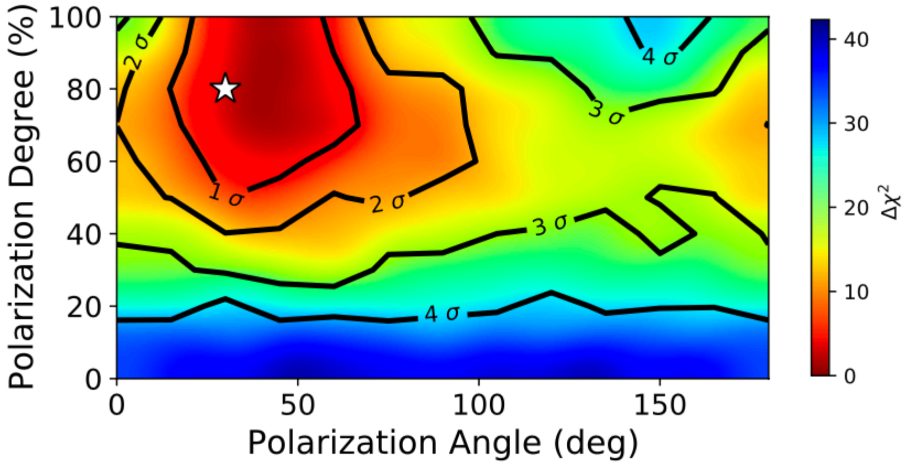


GRB221009A, Yang et al. (2023)



Gao et al. (2024, arxiv e-print)

Some GRBs
↓
$\sigma \geq 10$



High PD
↓
High-σ?

GRB180720B, Veres et al. (2024, arxiv e-print)

Magnetic Bullet Simulation

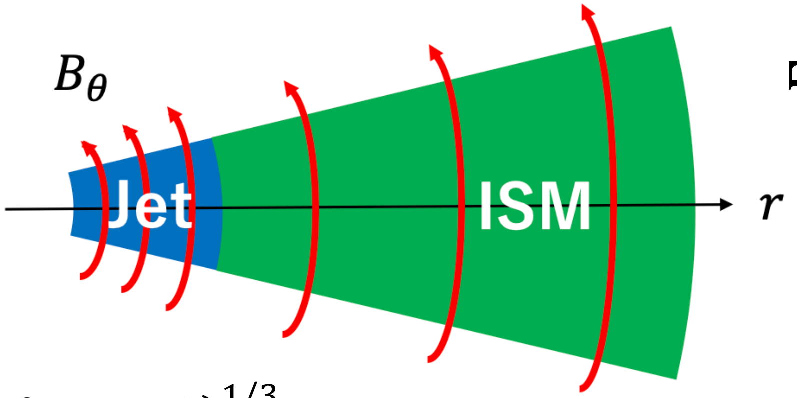
σ, Δ affect FS dynamics

1DSRMHD code (Kusafuka & Asano (2024))

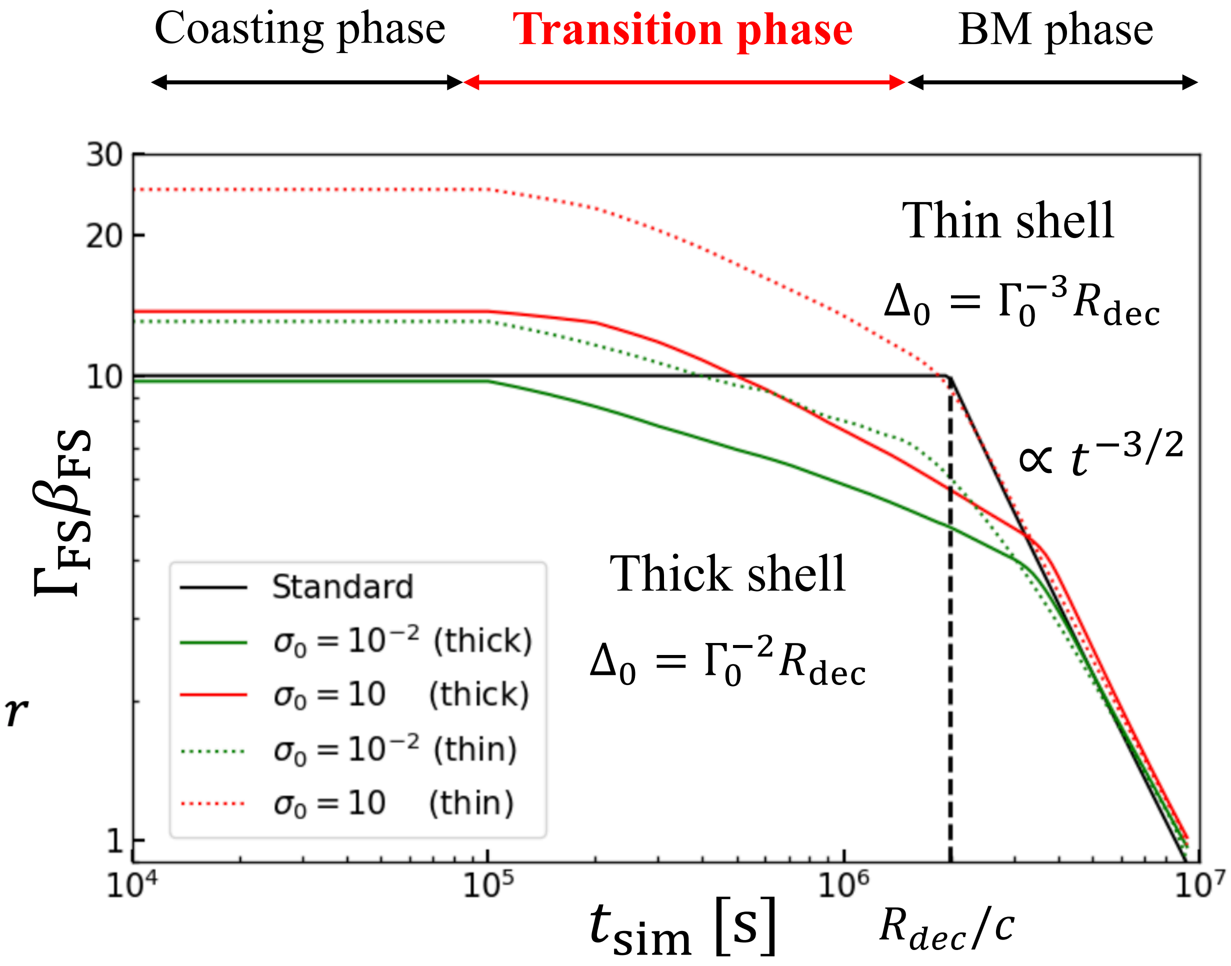
- 7th order **MP7** (Suresh & Huynh 1997)
- 3rd order **SSPRK(3,3)** (Gottlieb & Shu 1999)
- **AMR** (Berger & Oliger 1984)
- **Moving Window** (Mimica et al. 2004)

Params

- $E_0 = 10^{50}$ erg
- $\Gamma_0 = 10$
- $n_0 = 1$ /cc



$$R_{dec} = \left(3E_0/4\pi\Gamma_0^2 n_0 m_p c^2\right)^{1/3}$$



Magnetic Bullet Afterglow

Afterglow code (Kusafuka & Asano (2024))

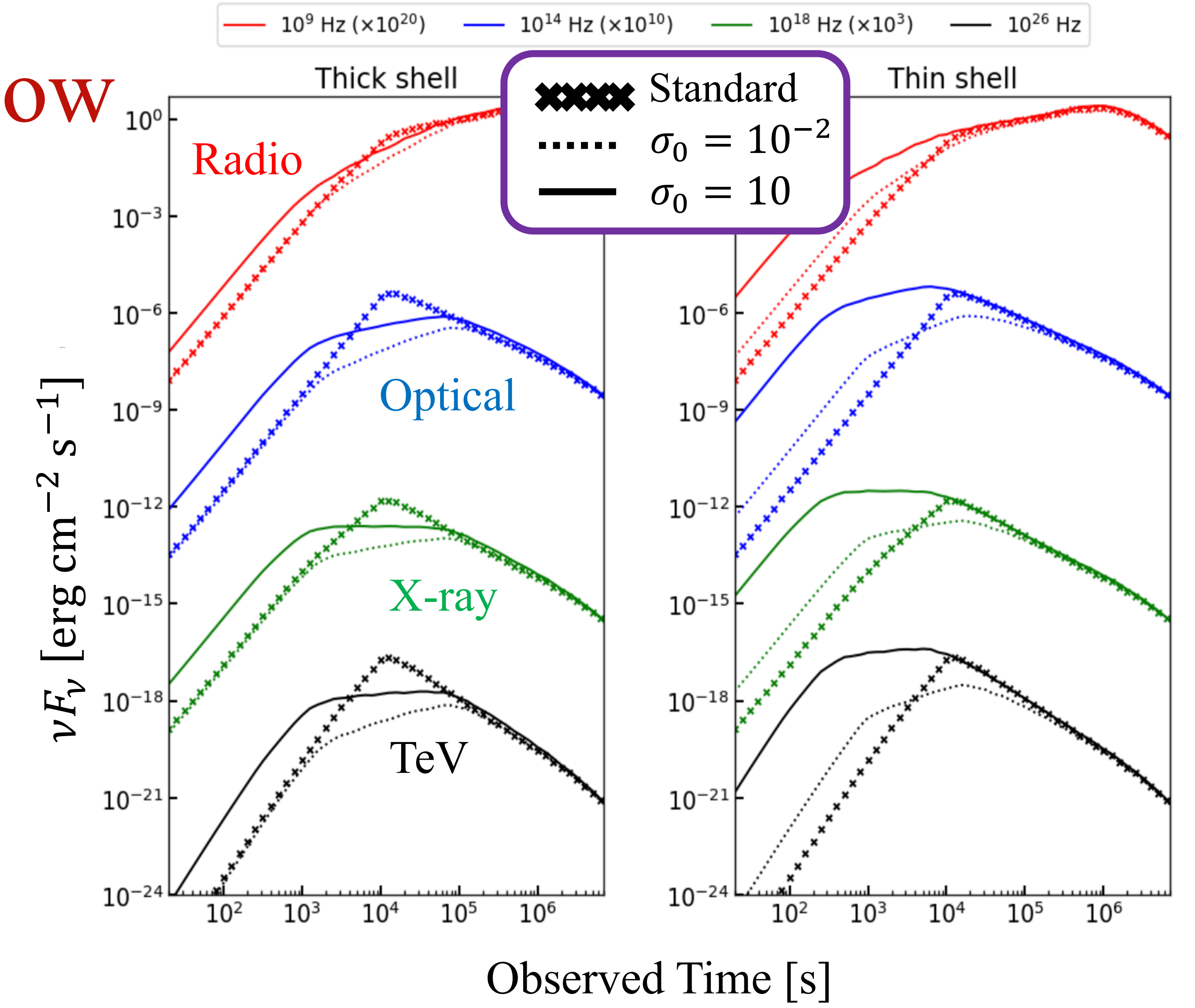
- Synchrotron & Synchrotron Self-Absorption
- Synchrotron Self-Compton & $\gamma\gamma$ annihilation
- Klien-Nishina effect (SSC & Compton Y)
- Equal Arrival Time Surface (Granot 2005)

Comparison to standard model

Early phase: High luminosity for high-σ

Middle phase: **Flat or gradual increase**

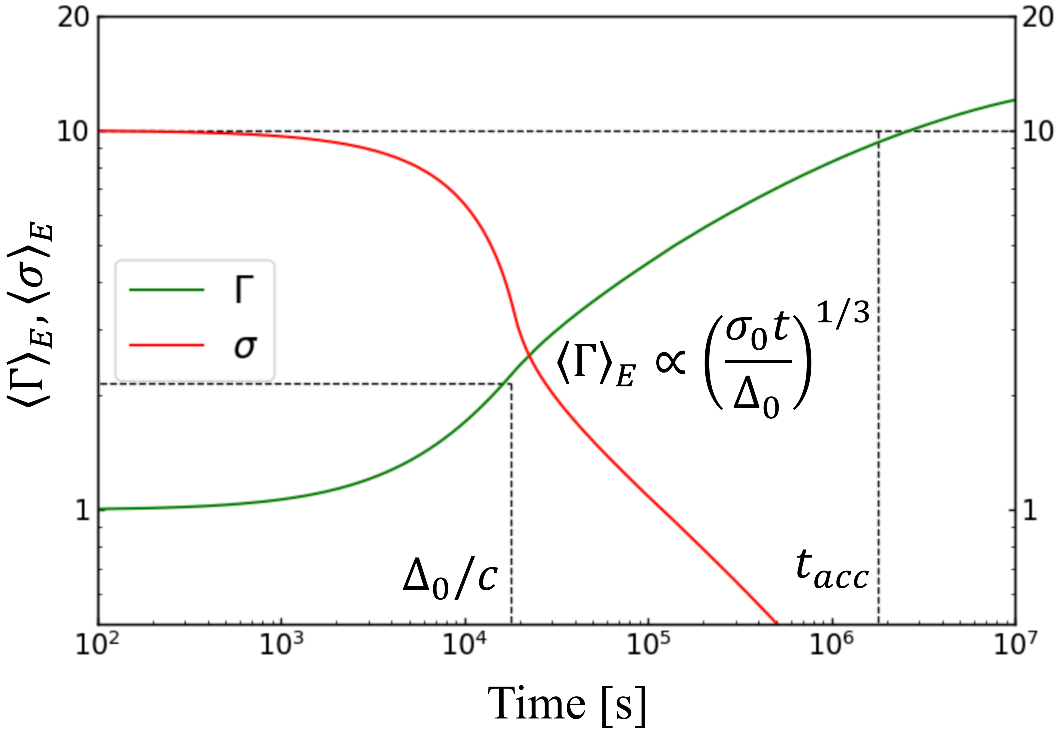
Late phase: **long onset time for thick shell**

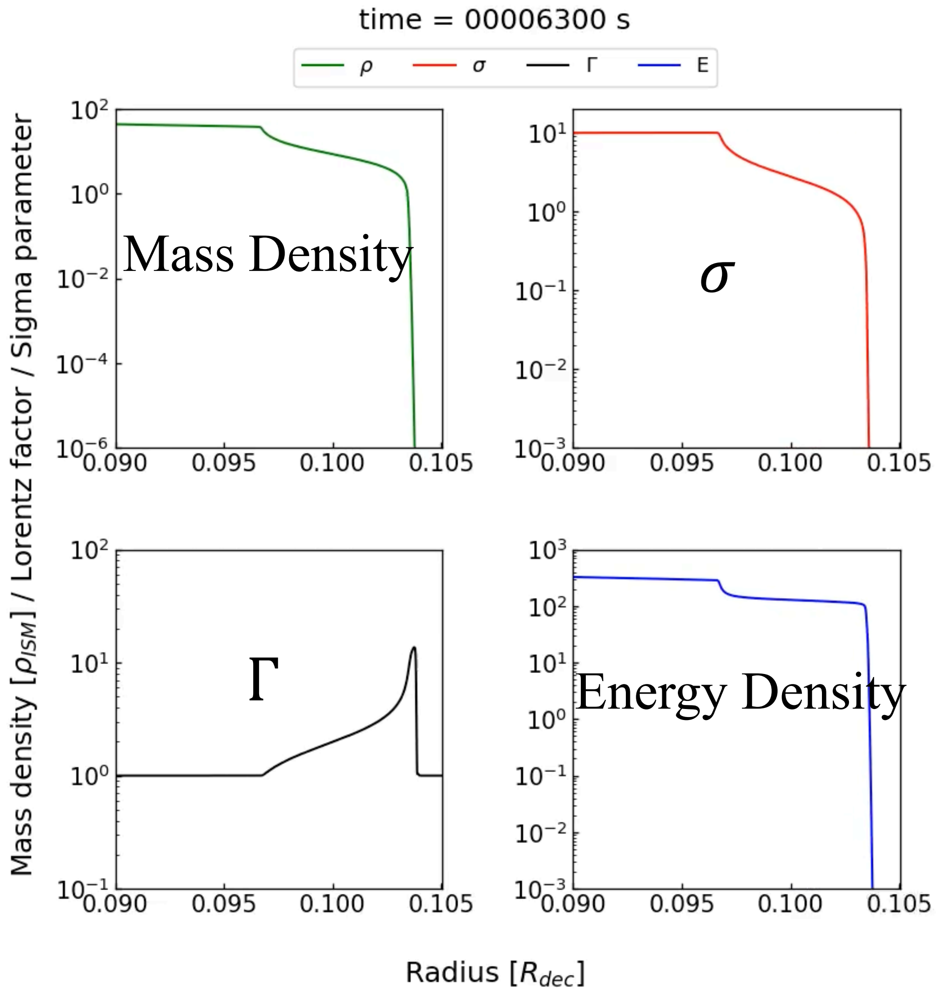


Semi-Analytic Modeling 1. Magnetic Acceleration

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

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





cf. Impulsive acceleration: Granot et al. (2011)

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

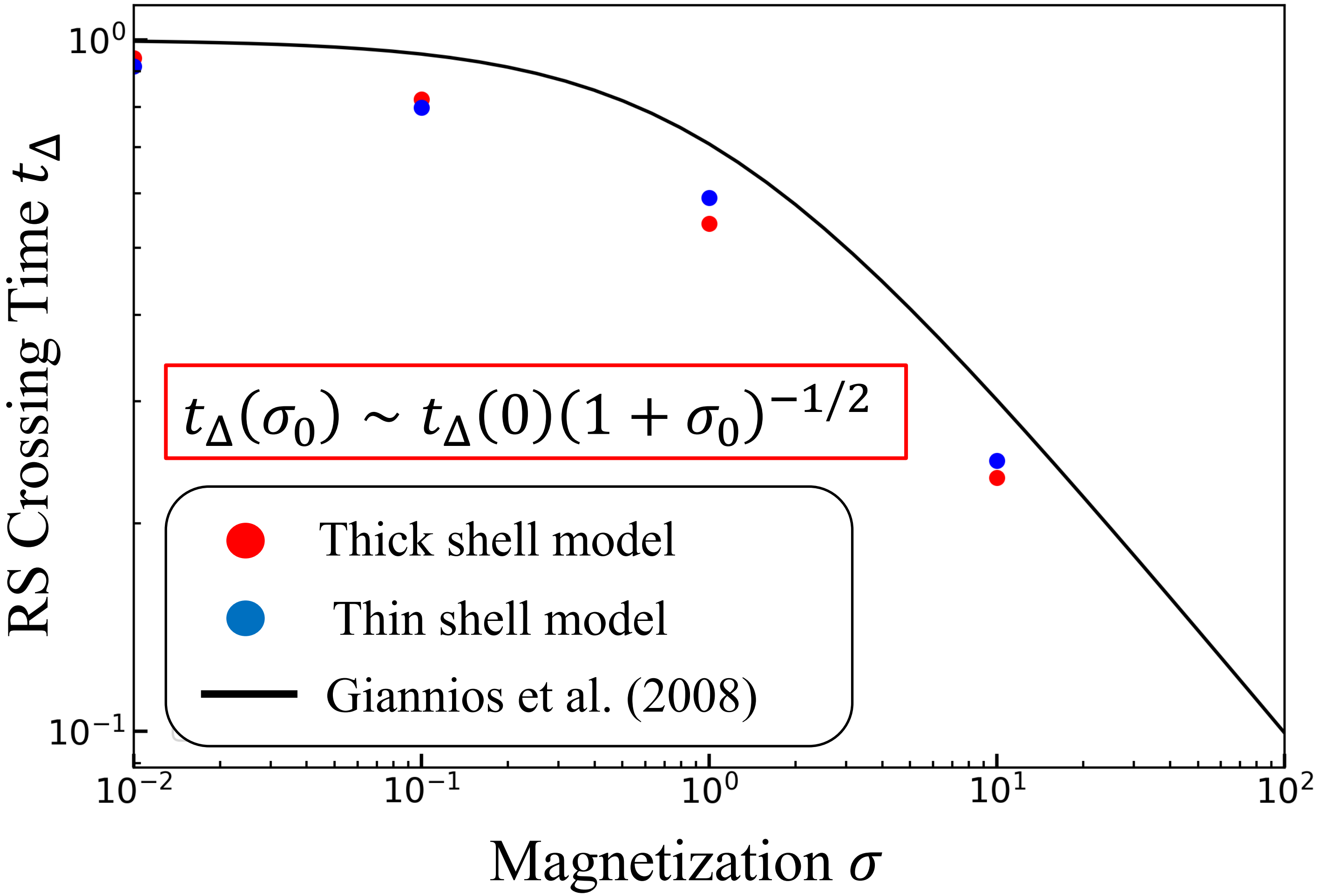
RS crossing timescale

$$t_\Delta(\sigma_0 = 0) = \Gamma_0^{1/2} R_{\rm dec}^{3/4} \Delta_0^{1/4}$$

Sari & Piran (1995)

RS radiation peaks at t_Δ

Shell spreading stops at t_Δ



$$t_\Delta(\sigma_0) \sim t_\Delta(0)(1+\sigma_0)^{-1/2}$$

Semi-Analytic Modeling 3. Coasting to Transition

Pressure balance at contact discontinuity

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

$$\Gamma_{\rm rel} = \Gamma_{\rm RS}\Gamma_{\rm sat}(1-\beta_{\rm RS}\beta_{\rm sat})$$

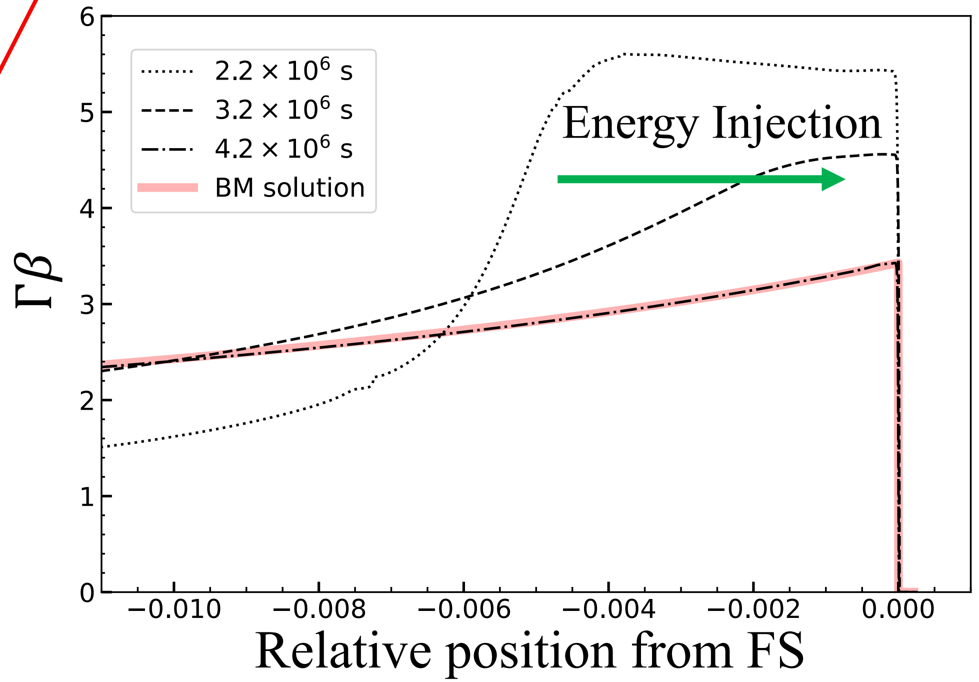
Panaitescu & Kumar (2004) ($\sigma_{RS} = 0$ case)

The Lorentz factor evolution of FS/RS

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

Coasting Phase: $\Gamma = \Gamma_{\rm sat}$

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



Semi-Analytic Modeling 4. Rarefaction Catch-up

Shell spreading until RS crossing time t_Δ

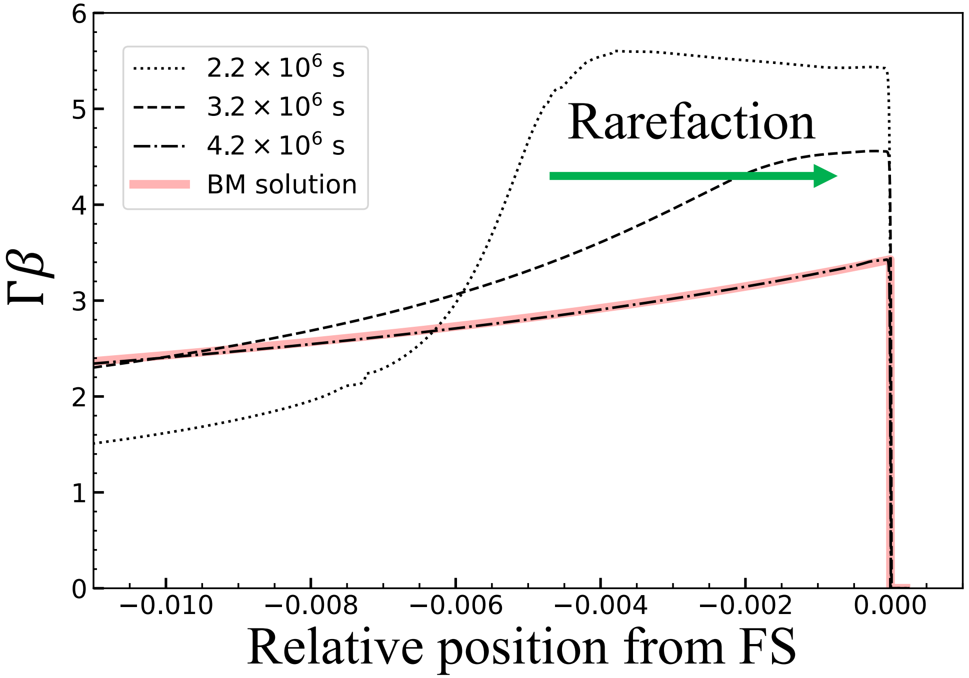
$$\Delta = \Delta_0 + \int_0^{t_\Delta} (v_{\mathrm{FS,front}} - v_{\mathrm{FS}})dt \simeq \Delta_0 + \int_0^{t_\Delta} \frac{cdt}{4\Gamma_{\mathrm{FS}}^2(t)}$$

Rarefaction catch-up time t_{BM} (*true deceleration*)

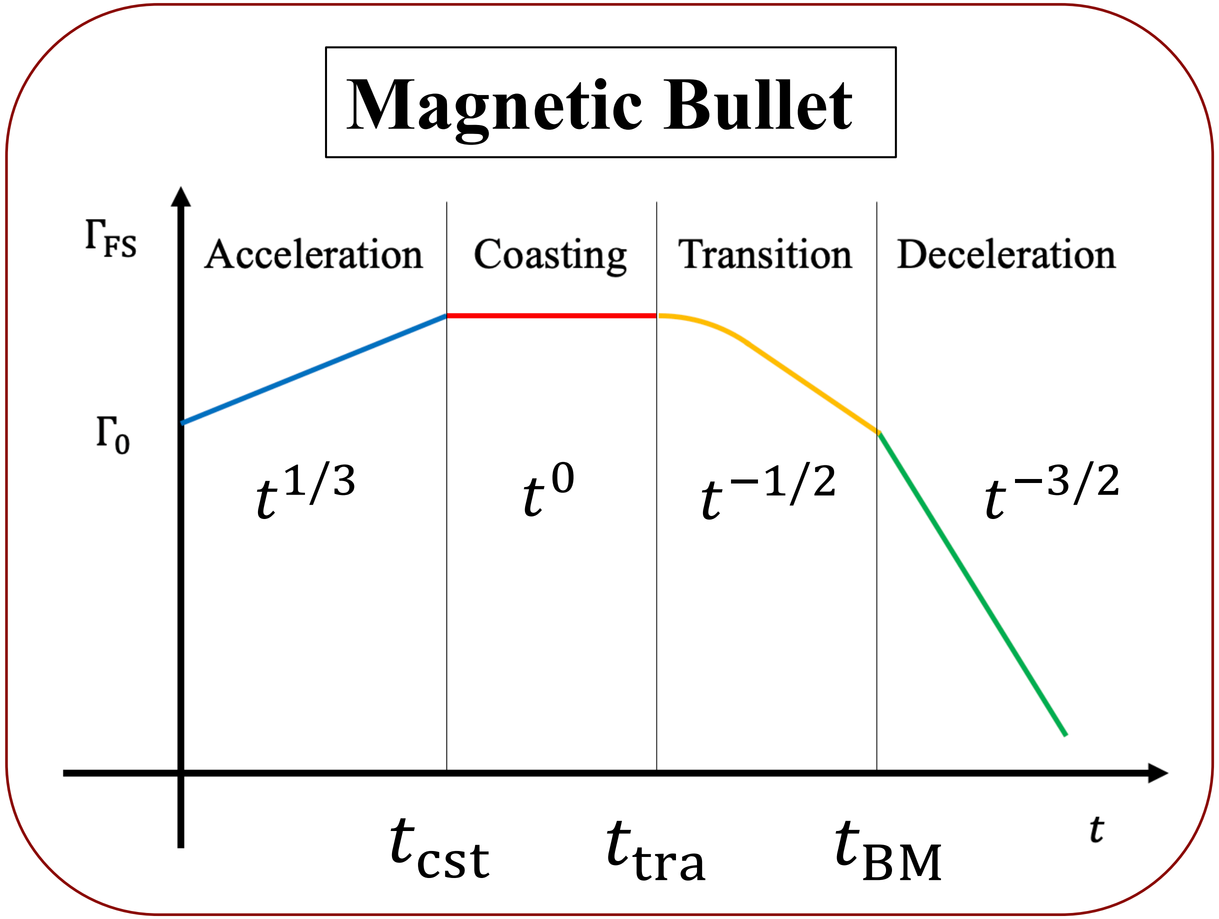
$$\Delta = \int_{t_\Delta}^{t_{\mathrm{BM}}} (c - v_{\mathrm{FS,front}})dt \simeq \int_{t_\Delta}^{t_{\mathrm{BM}}} \frac{cdt}{4\Gamma_{\mathrm{FS}}^2(t)}$$

BM solution (Blandford-McKee (1976))

$\Gamma_{FS} \propto t^{-3/2}$ after catch-up time t_{BM}

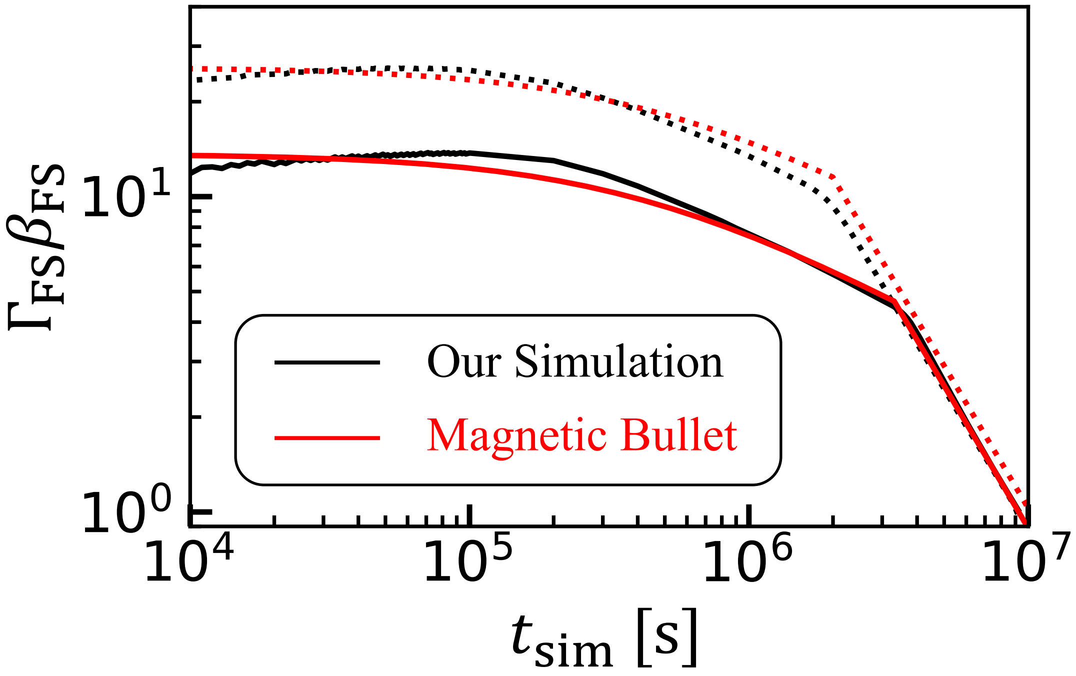


Semi-Analytic Model of Magnetic Bullet Afterglow



Well consistent with simulation results

$E_0 = 10^{50}, \Gamma_0 = 10, \sigma_0 = 10, \Delta_0 = R_{dec}/\Gamma_0^{2\sim3}$



Kusafuka & Asano (2024, arxiv e-print)

Shallow-decay…?

GRB model parameters

$E_{iso} = 10^{52}$ erg, $\Gamma_0 = 100, n_0 = 1$ /cc

$\epsilon_e = 10^{-1}, \epsilon_B = 10^{-2}, f_e = 1, p = 2.2$

Thick: $\Delta = 720$ s (cf. T_{90} of long-GRB)

Thin: $\Delta = 1.8$ s (cf. T_{90} of short-GRB)

X-ray shallow decay (obs)

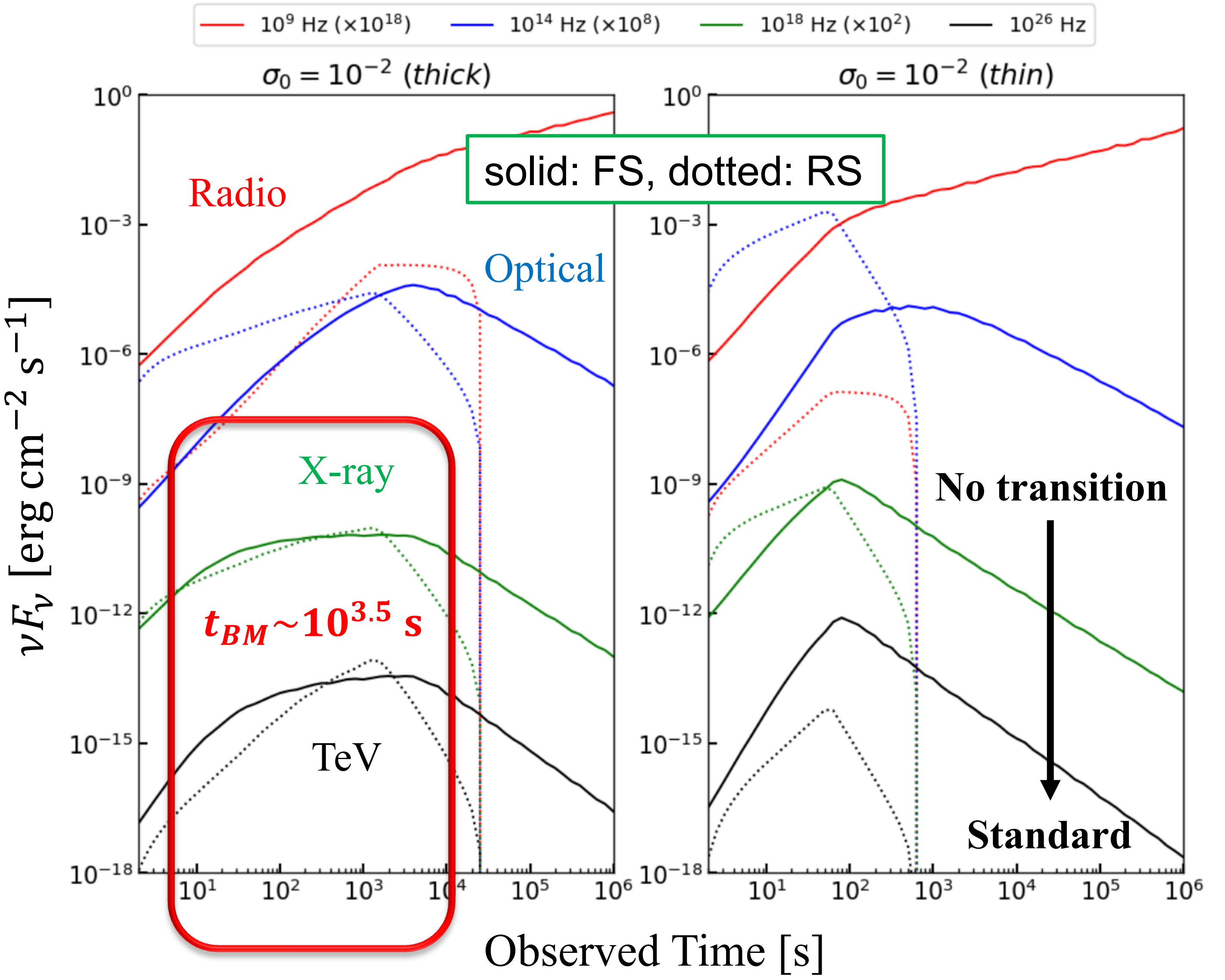
Decaying index ~ 0.11

Timescale ~ $10^{3.5}$ s

Tang et al. (2019)

GeV/TeV GRB has no shallow decay

Yamazaki et al. (2020)



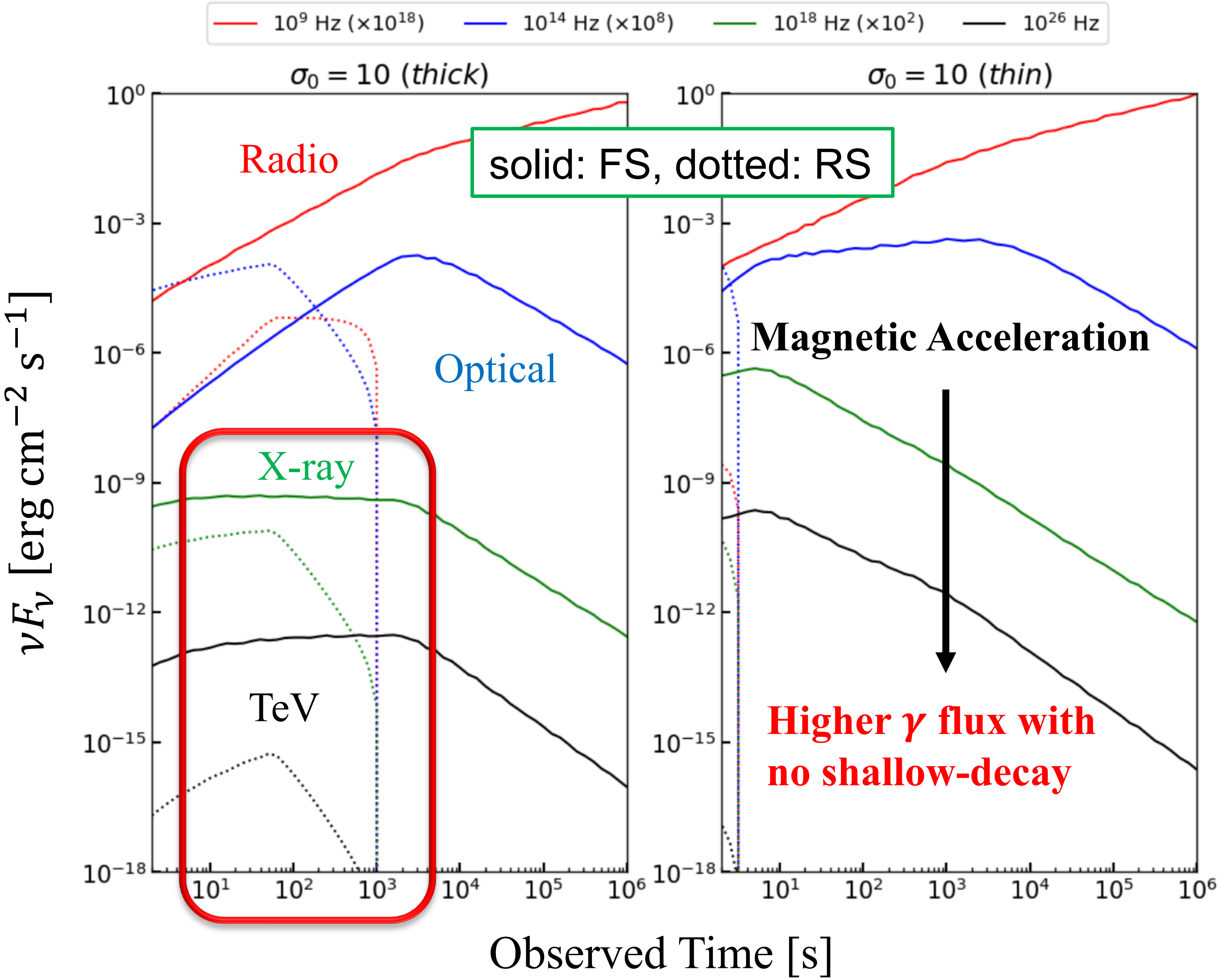
Kusafuka & Asano (2024, arxiv e-print)

Shallow-decay…?

Light Curve in Transition Phase

$$F_\nu \propto \begin{cases} t_{obs}^{4/3} & \nu < \min(\nu_m, \nu_c) \\ t_{obs}^{1/2} & \nu_c < \nu < \nu_m \\ t_{obs}^{-\frac{p-3}{2}} & \nu_m < \nu < \nu_c \\ t_{obs}^{-\frac{p-2}{2}} & \nu > \max(\nu_m, \nu_c) \end{cases}$$

For p=2.2, $\boldsymbol{F_\nu \propto t_{obs}^{-0.1}}$ for $\nu > \max(\nu_m, \nu_c)$



solid: FS, dotted: RS

Magnetic Acceleration

Higher γ flux with no shallow-decay

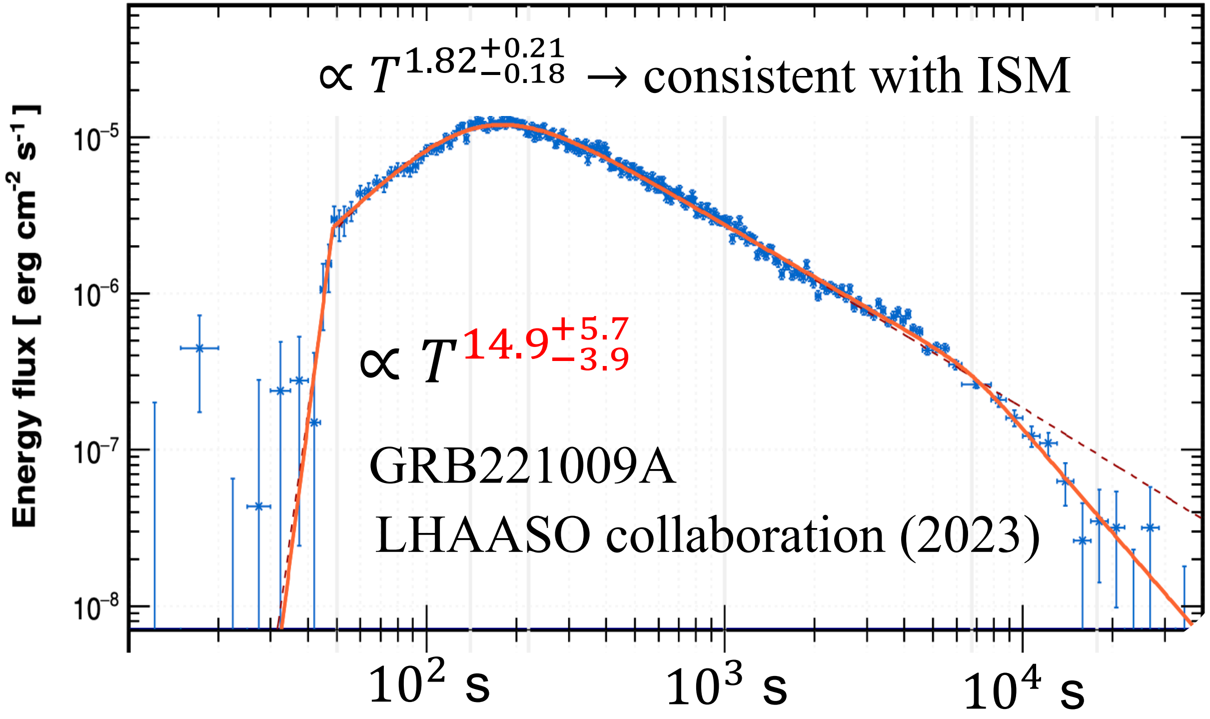
We are preparing MCMC fitting with Magnetic Bullet (Kusafuka, Obayashi, and Asano, in prep)

Evidence of Magnetic Acceleration…?

Kusafuka & Asano (in prep)

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

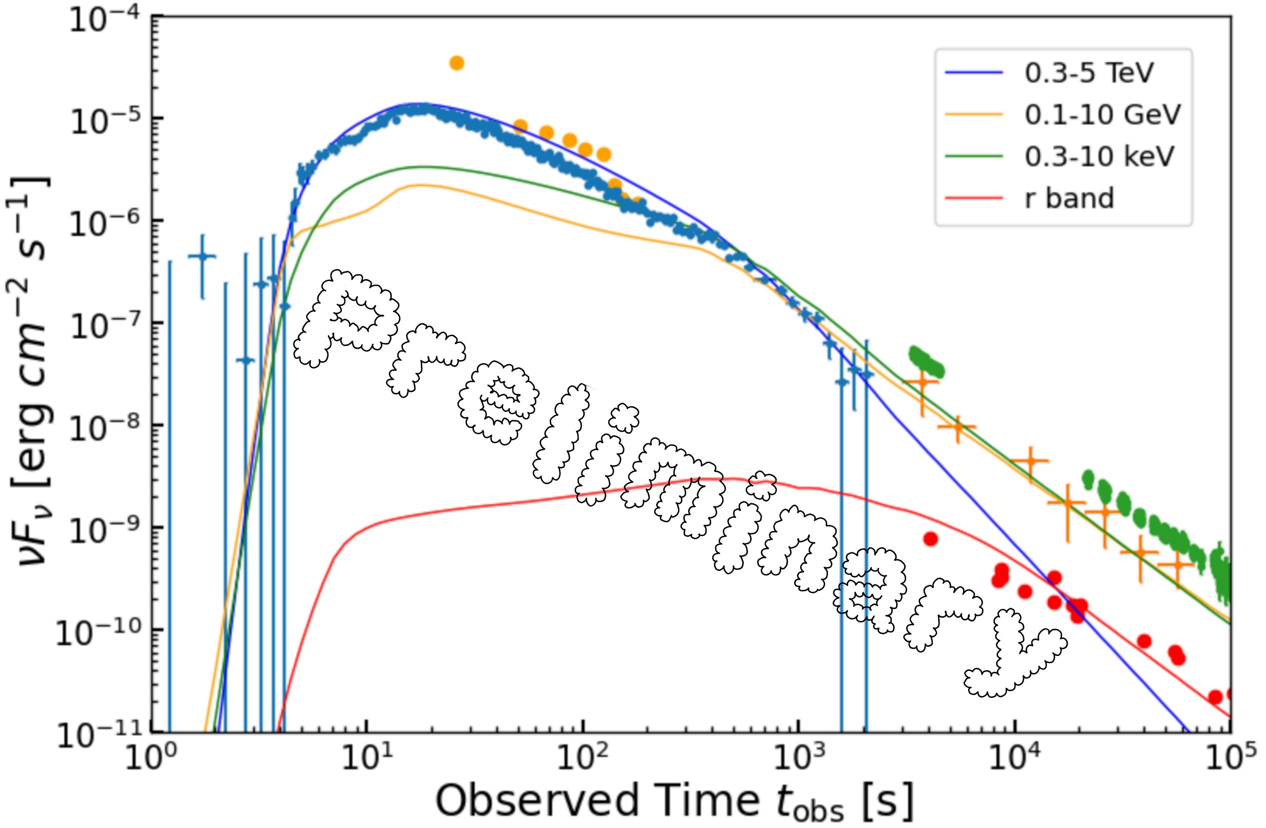
Roughly: $F_{SSC} \propto R^4 \Gamma^3 \propto t_{obs}^{15}$


$\propto T^{1.82^{+0.21}_{-0.18}}$ → consistent with ISM

$\propto T^{14.9^{+5.7}_{-3.9}}$

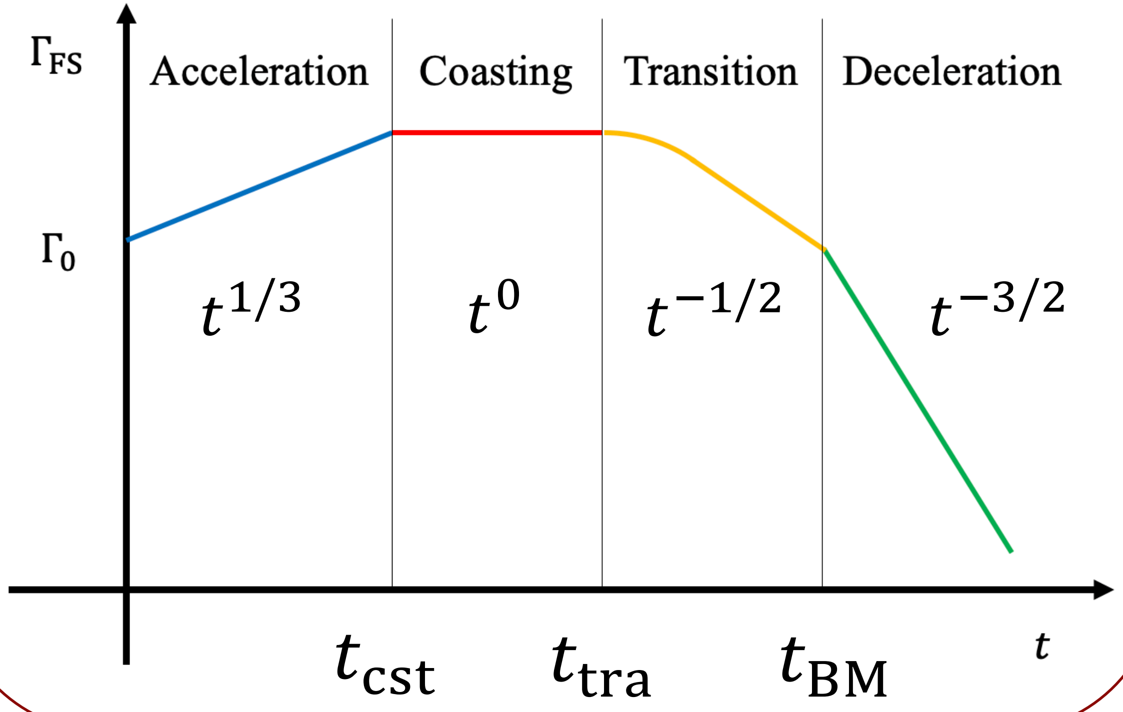
GRB221009A
LHAASO collaboration (2023)

$E_{iso} = 10^{55}, \epsilon_e = 0.074, \epsilon_B = 10^{-4}, f_e = 0.8, p = 2.4$



Summary

Magnetic Bullet



Kusafuka & Asano (2024)

MNRAS submitted

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!!