

Towards Elucidation of the Diversity of GRB Afterglows

Open Source Multi-Messenger Emission Simulator
-Magglow.jl-

Image Credit: DESY, Science Communication Lab

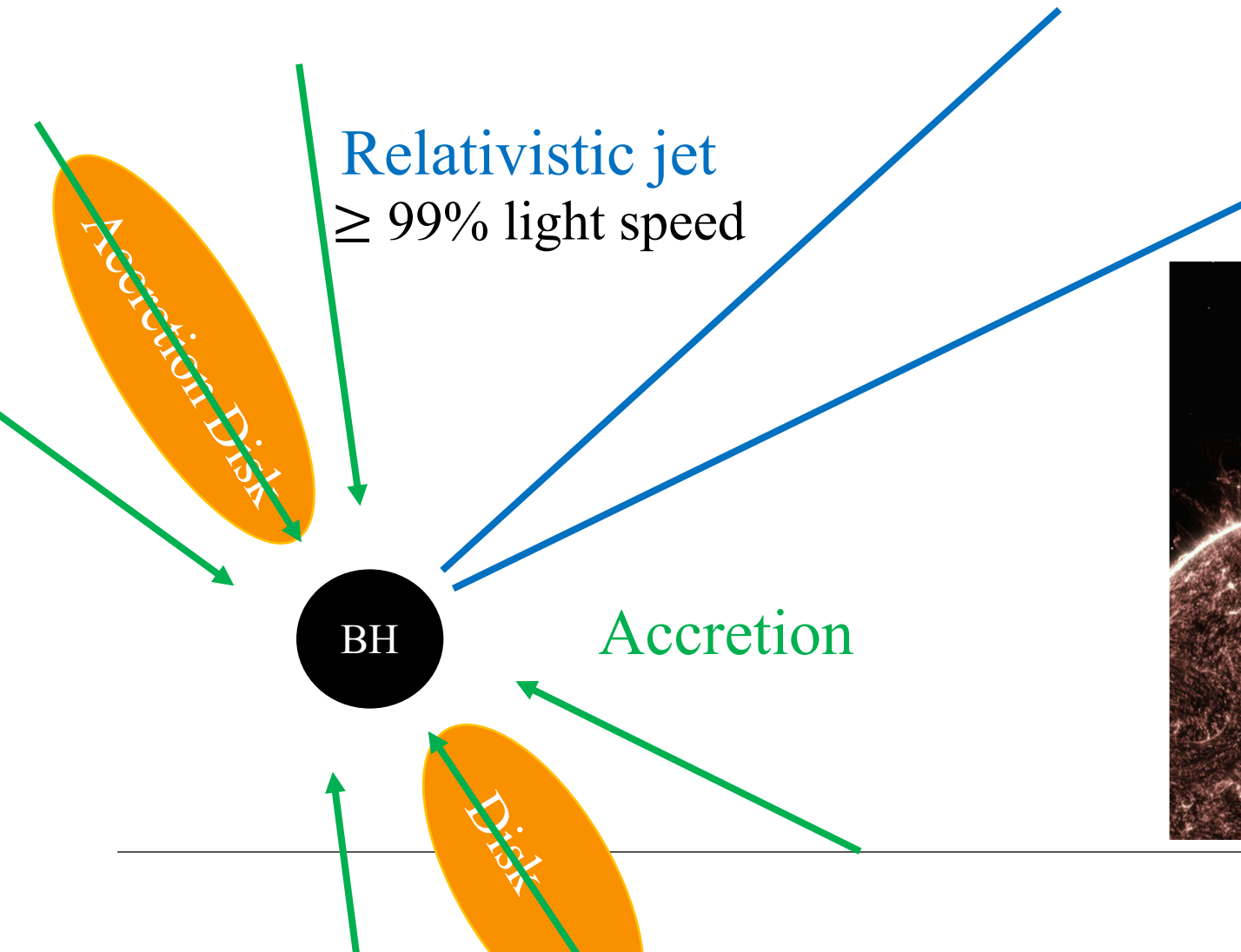


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Ryo Yamazaki (U-AG)

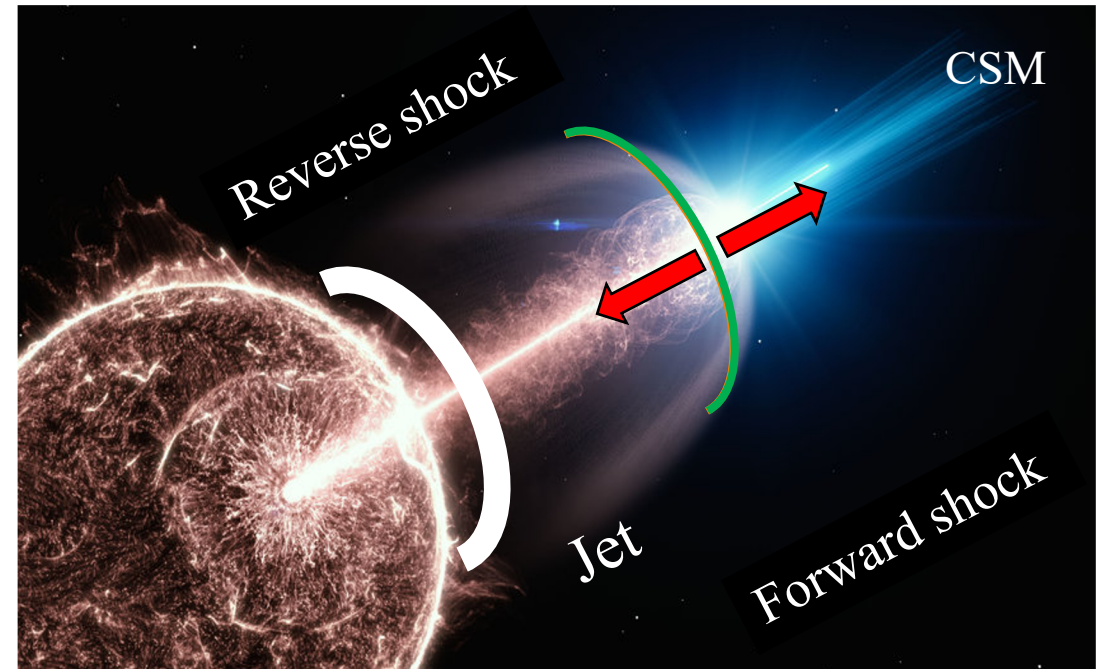
Relativistic Jets from Compact Objects



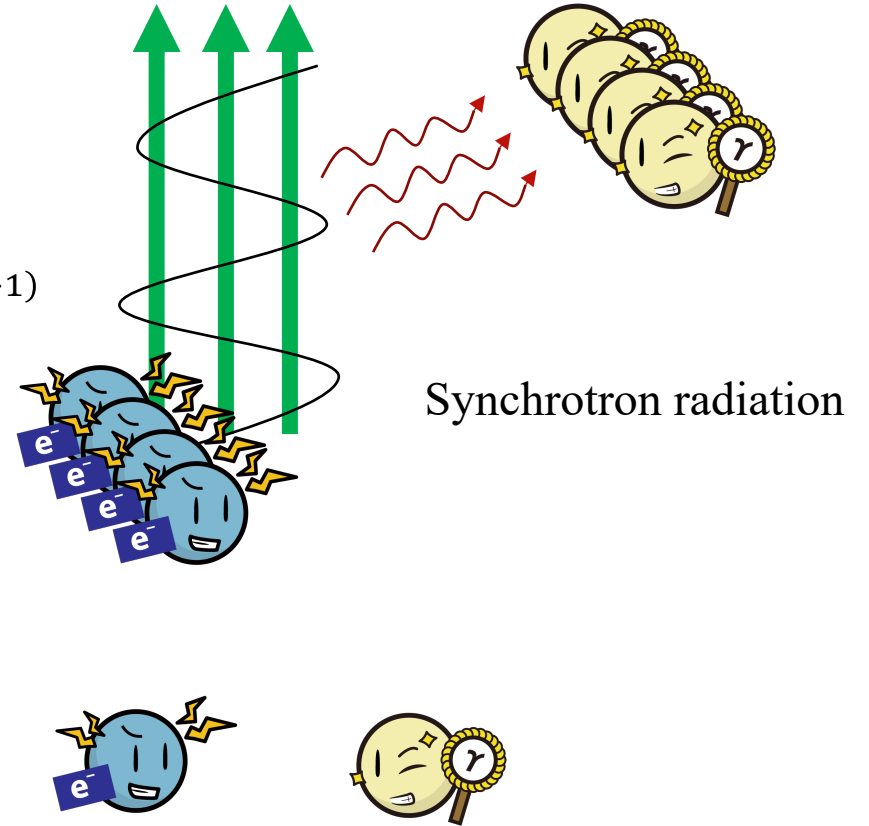
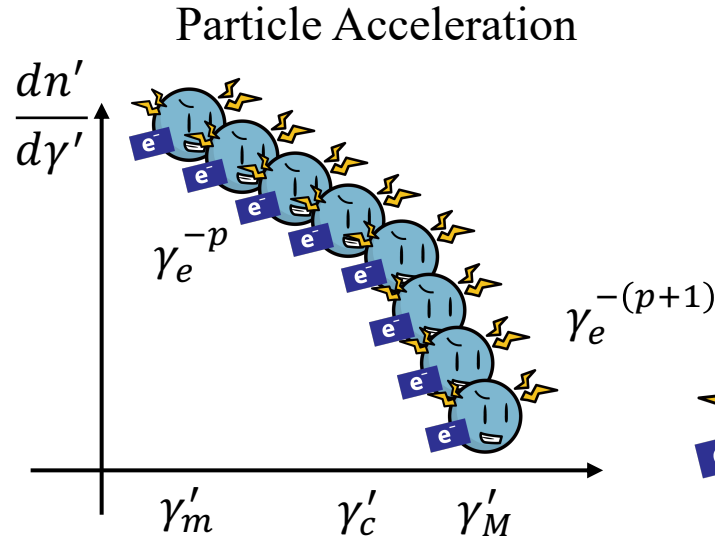
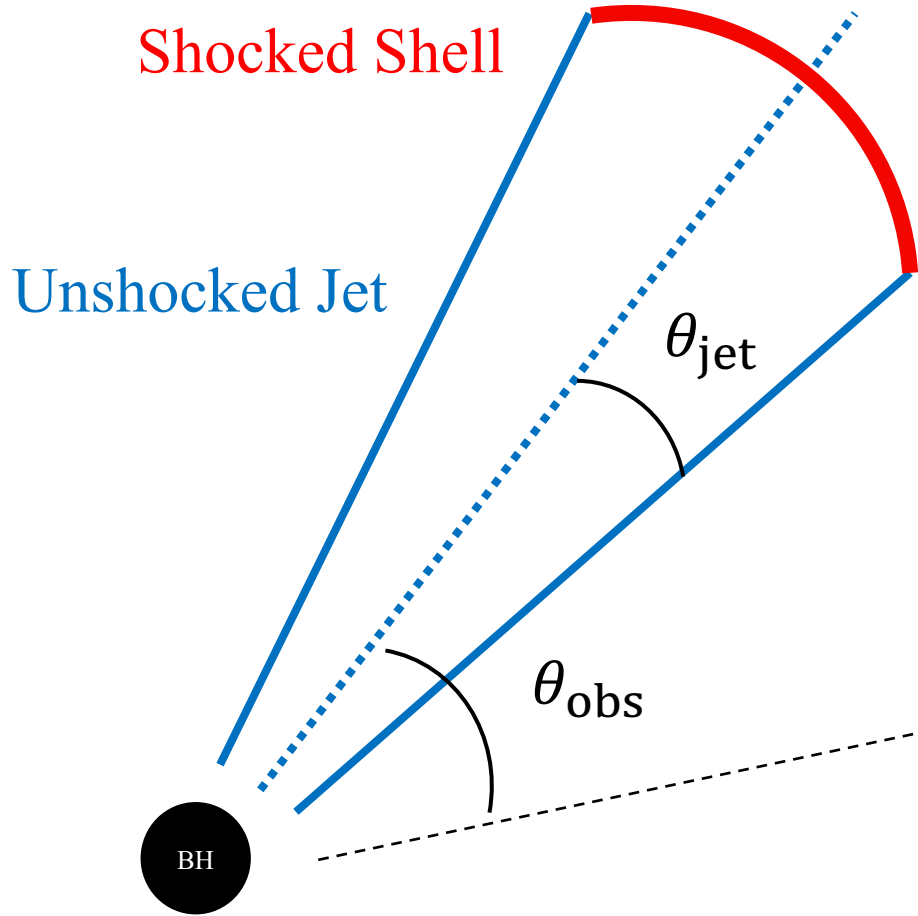
Interaction with Jet and CircumStellar Medium



GRB afterglow



Afterglow Radiation



Inverse Compton scattering

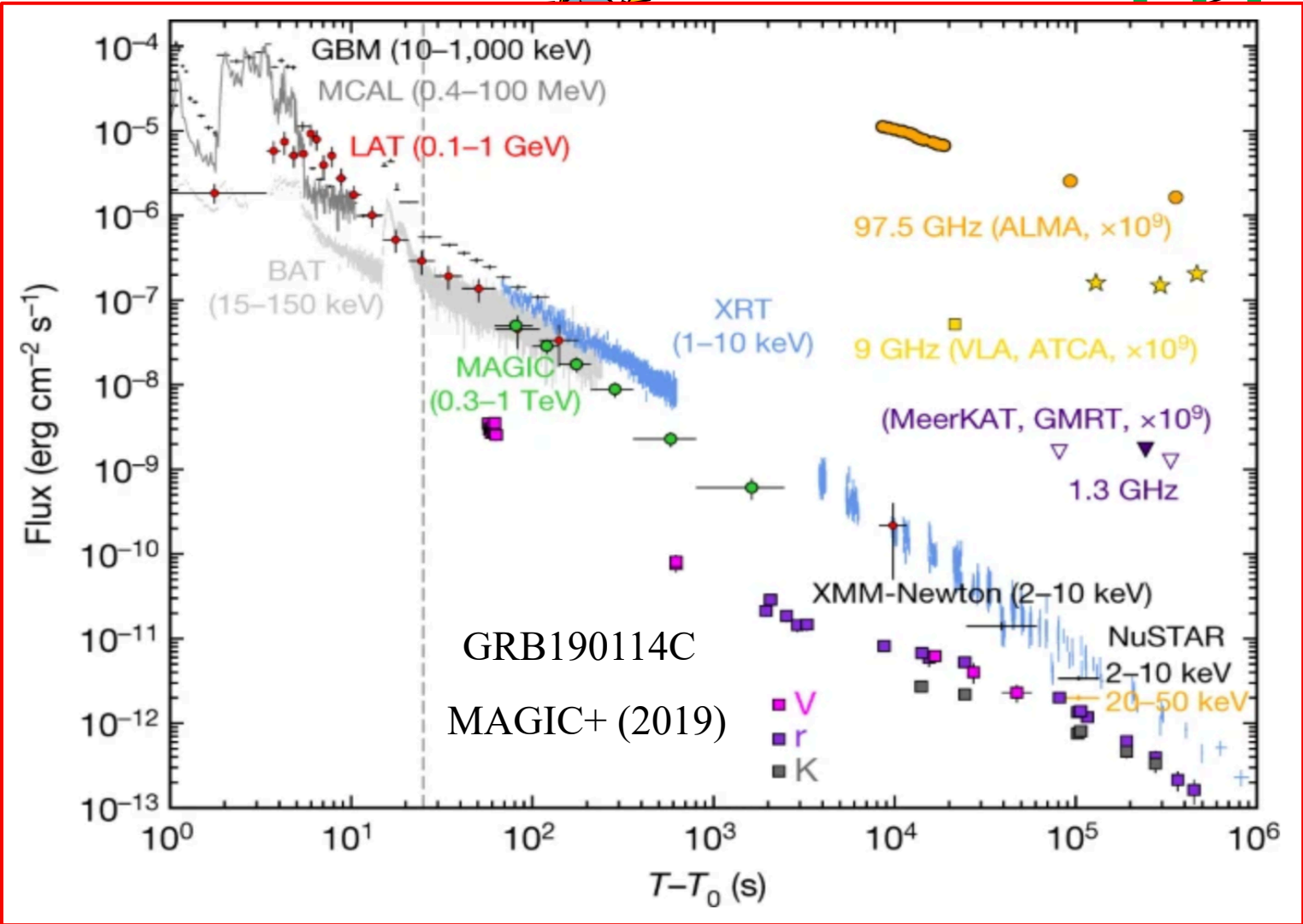
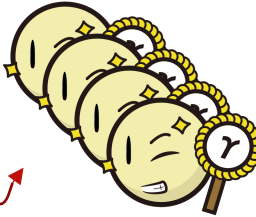
Afterglow Radiation

Shocked Shell

Unshocked Jet



Particle Acceleration dn'



Synchrotron radiation



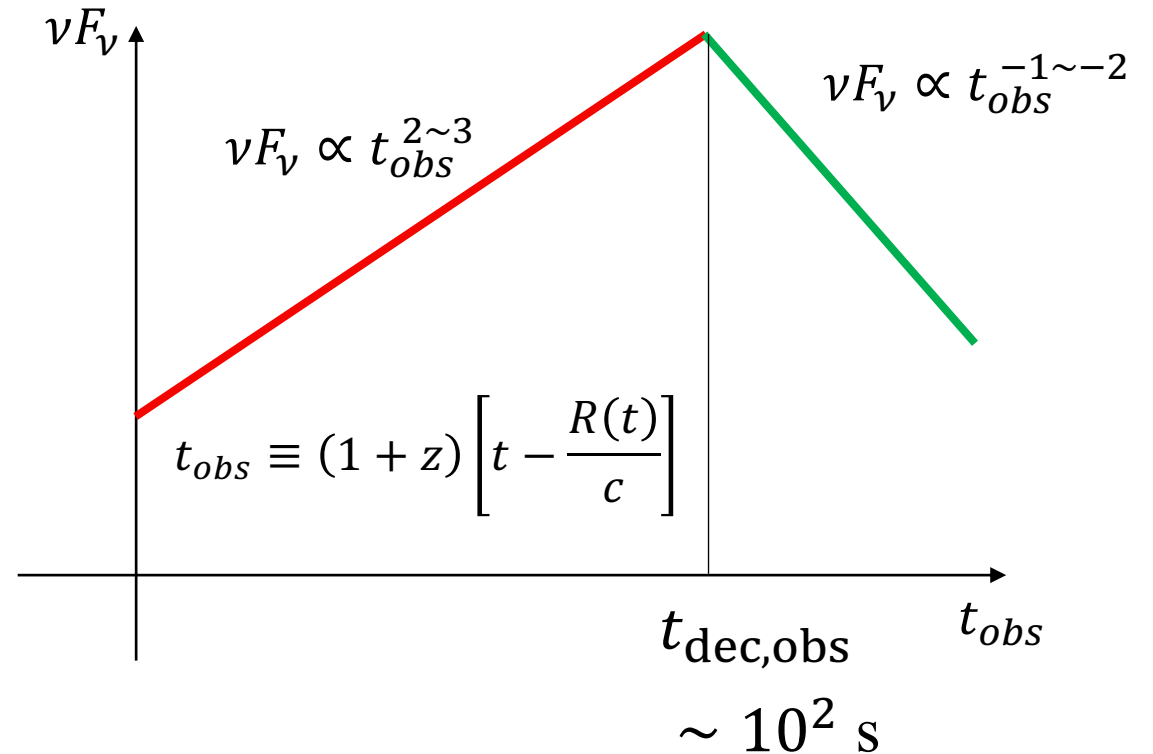
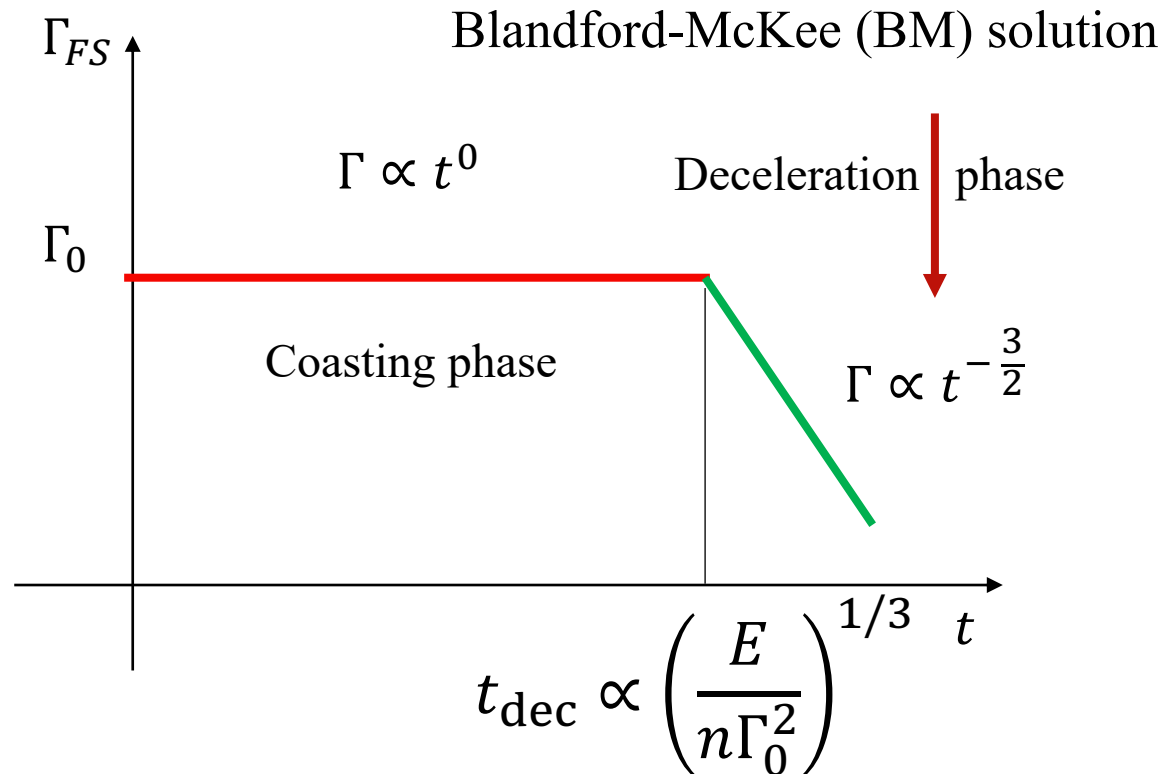
Inverse Compton scattering

Basic Scenario

Shock Dynamics



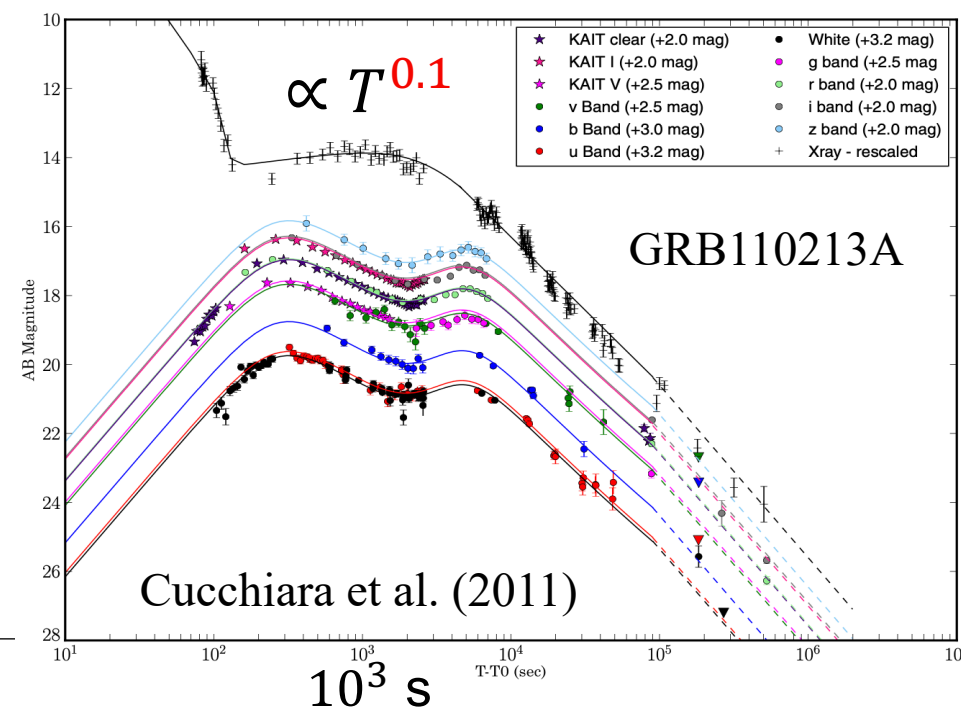
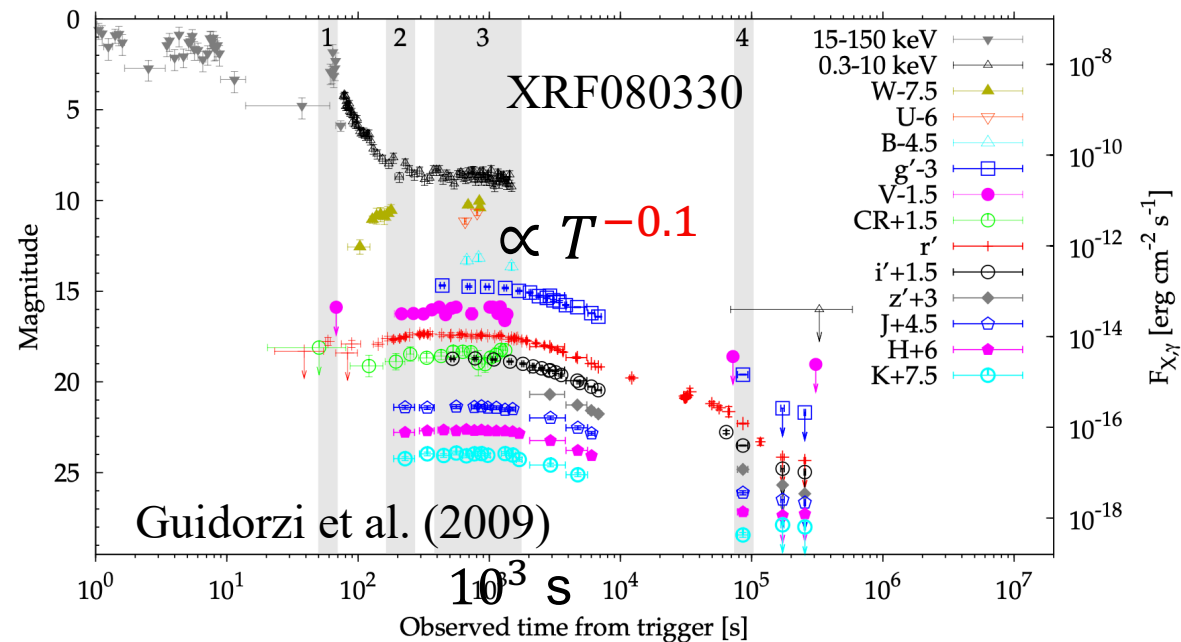
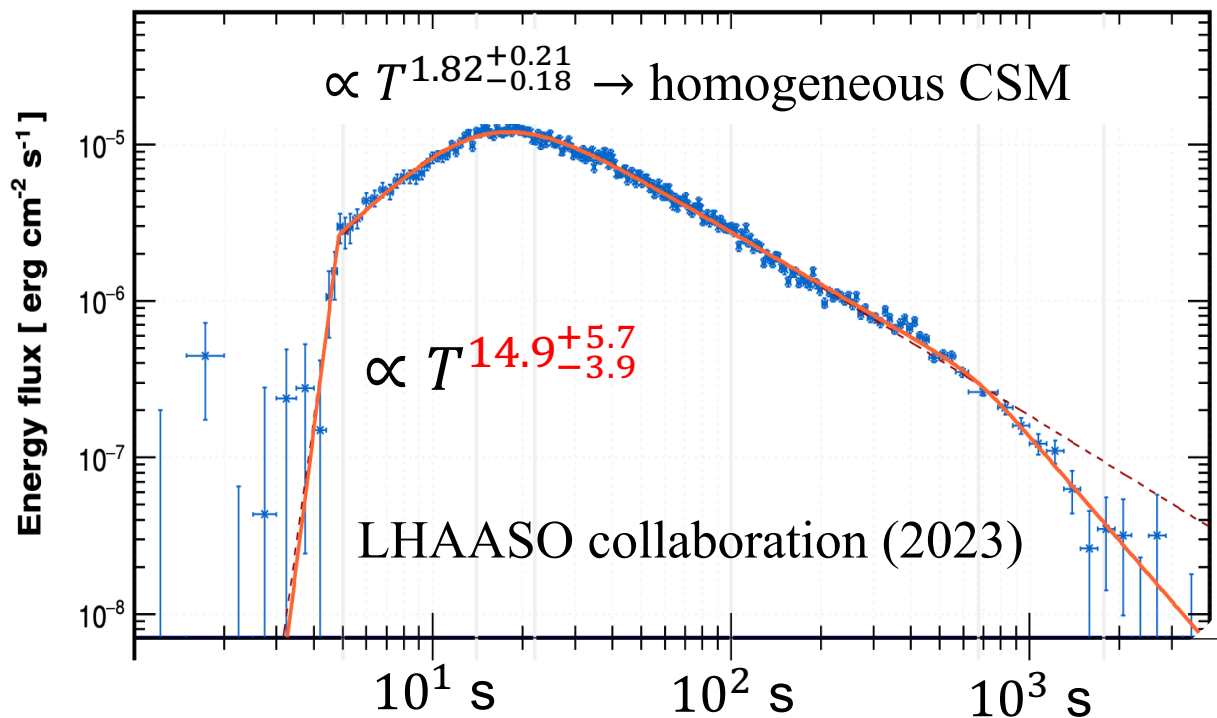
Light Curve



Most late-phase afterglows are well explained, but ...

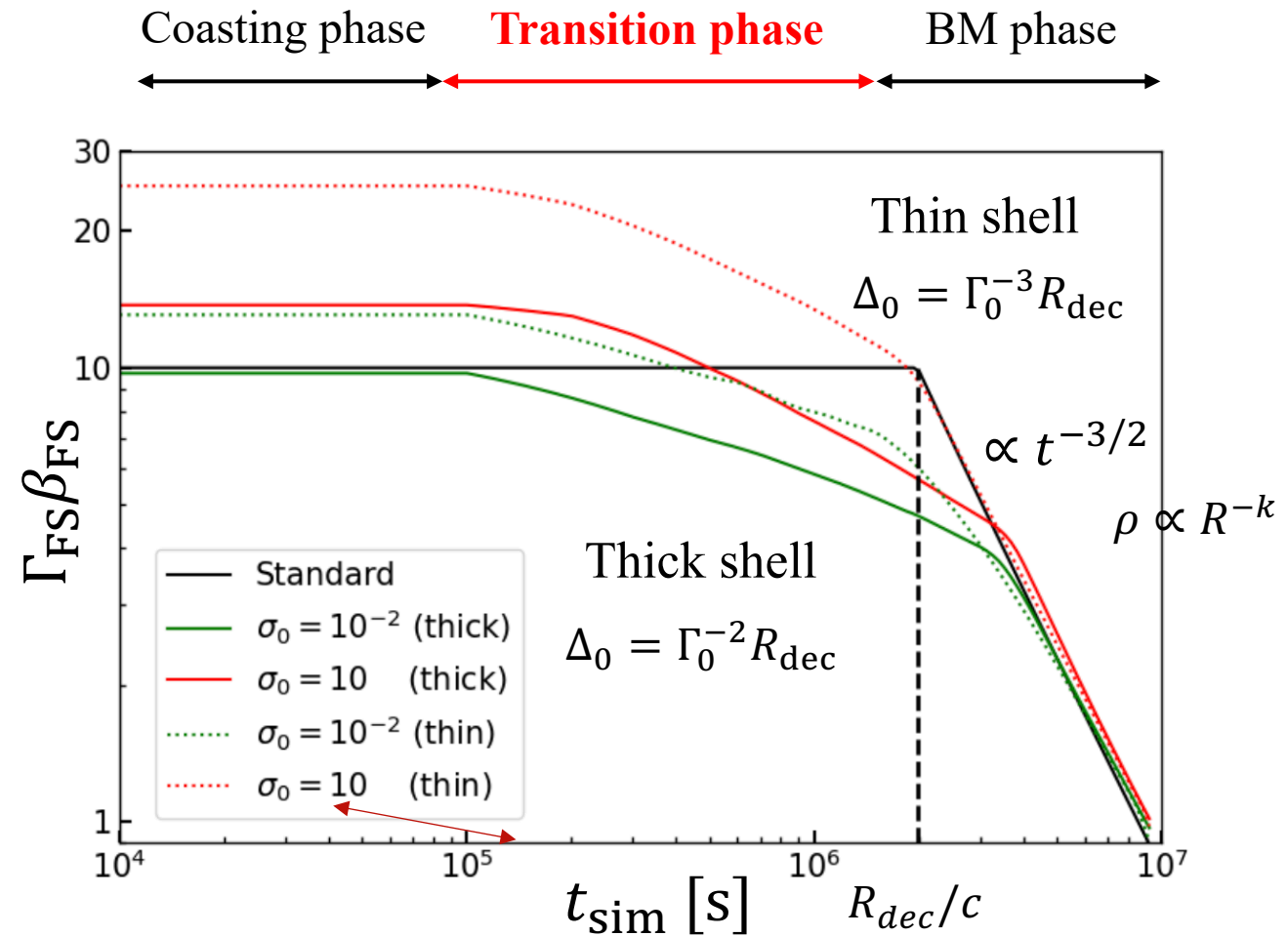
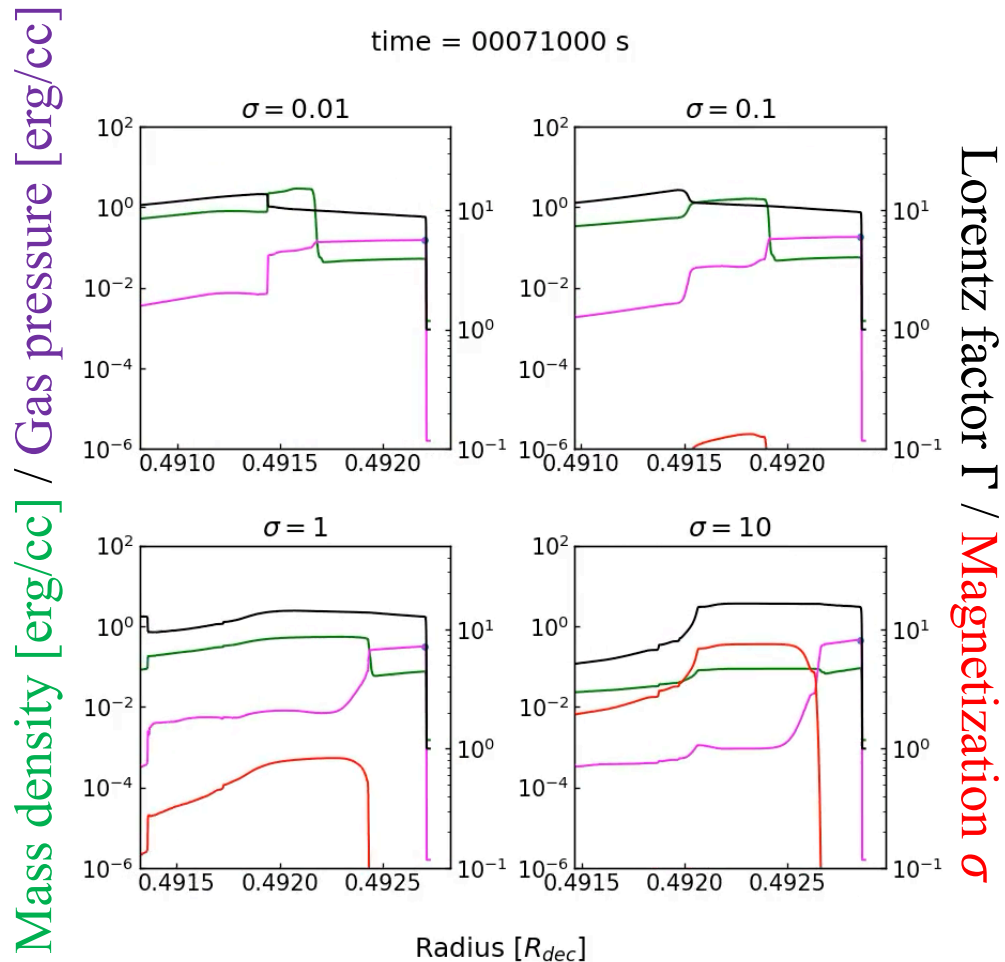
Diversity of GRB Afterglows

X-ray shallow decay ($> 50\%$)
Optical Plateau / Double-peak
TeV Very Rapid Increase etc.



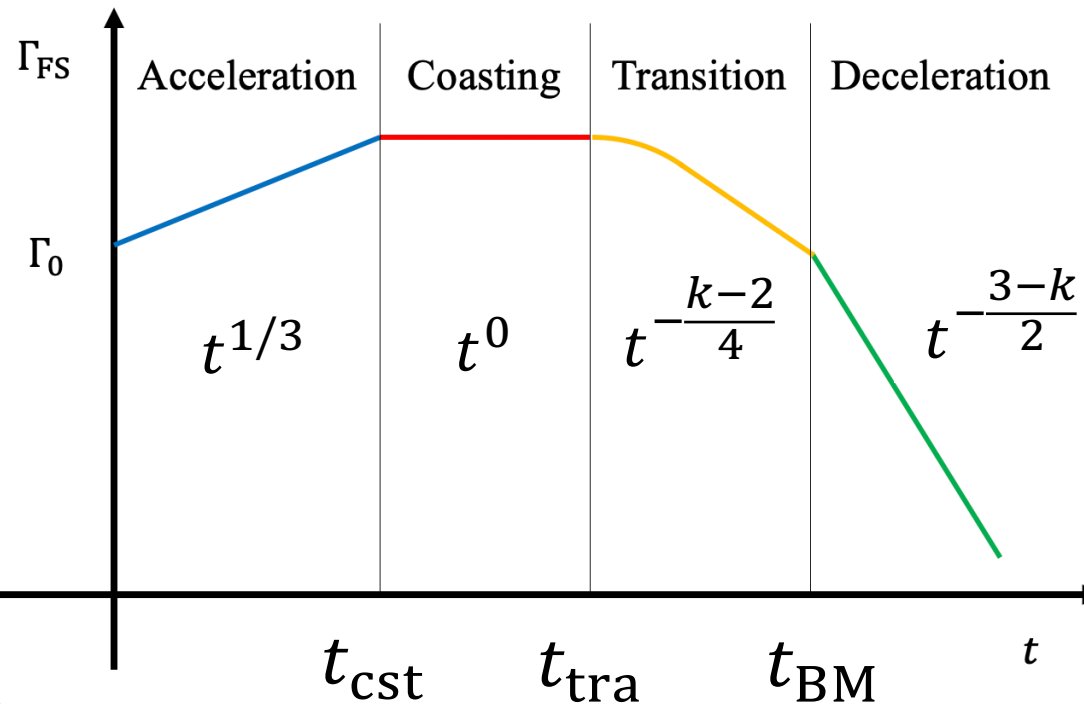
Magnetic Bullet Simulation

σ, Δ affect FS dynamics



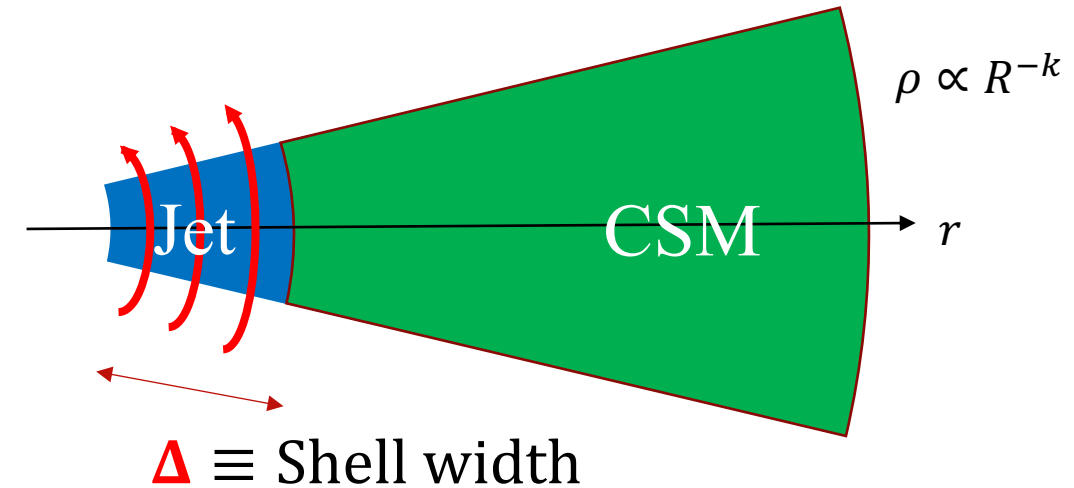
Semi-Analytic Model of Magnetic Bullet Afterglow

Magnetic Bullet

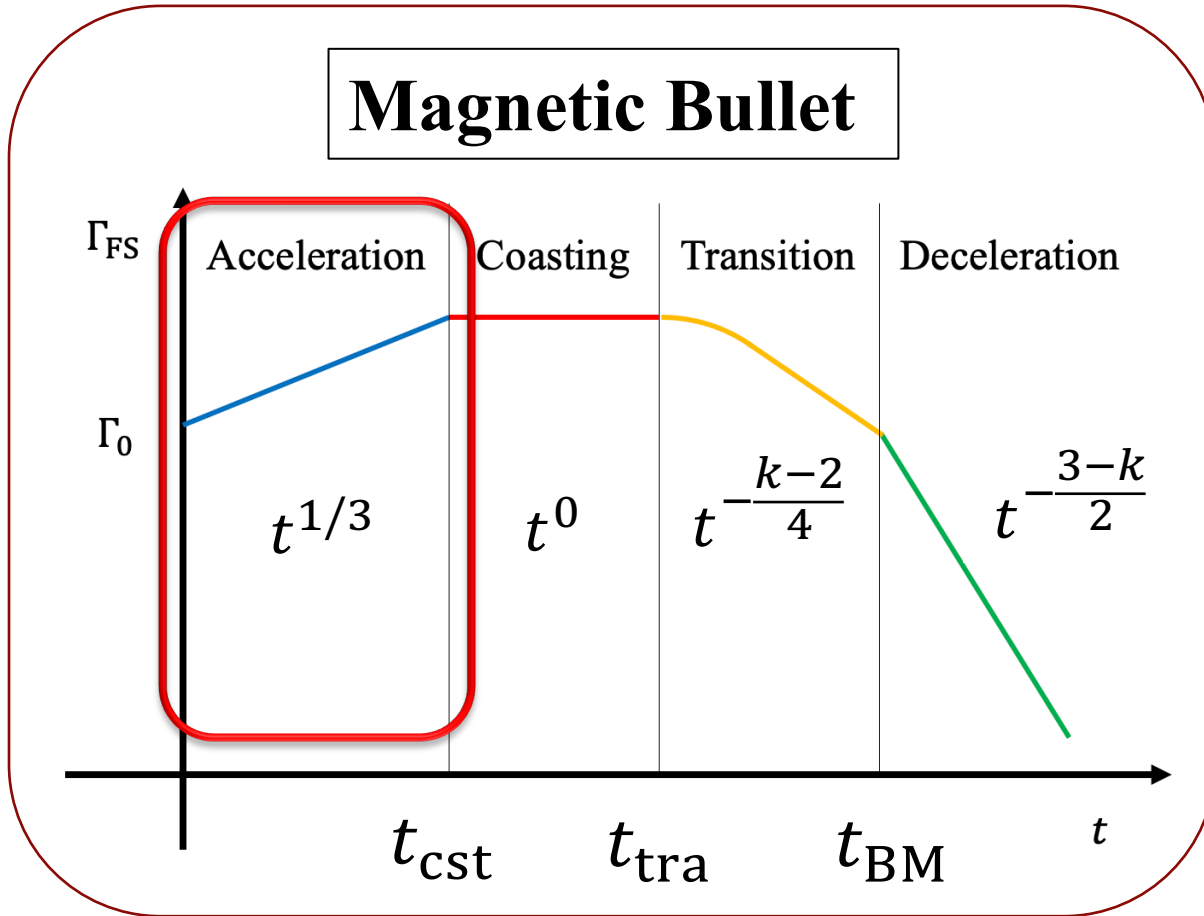


Two additional parameters are included

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



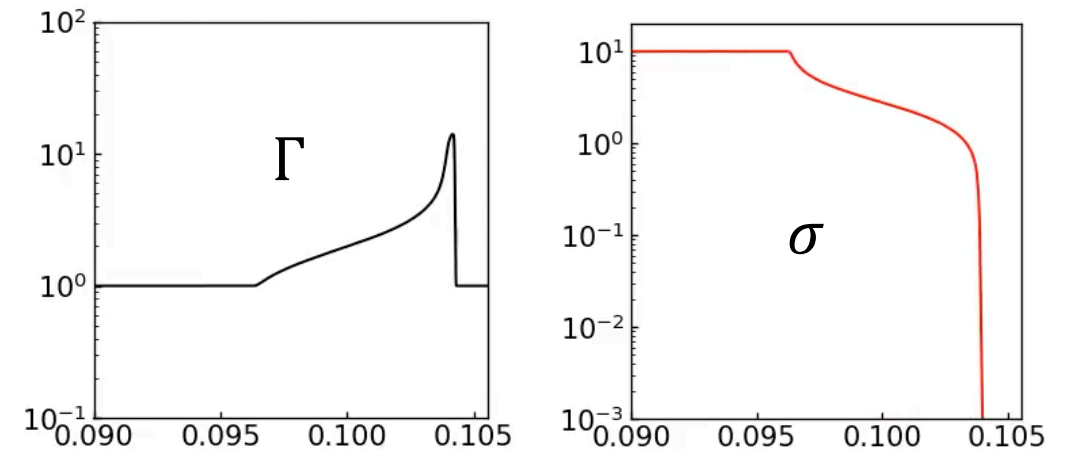
Semi-Analytic Modeling 1. Magnetic Acceleration



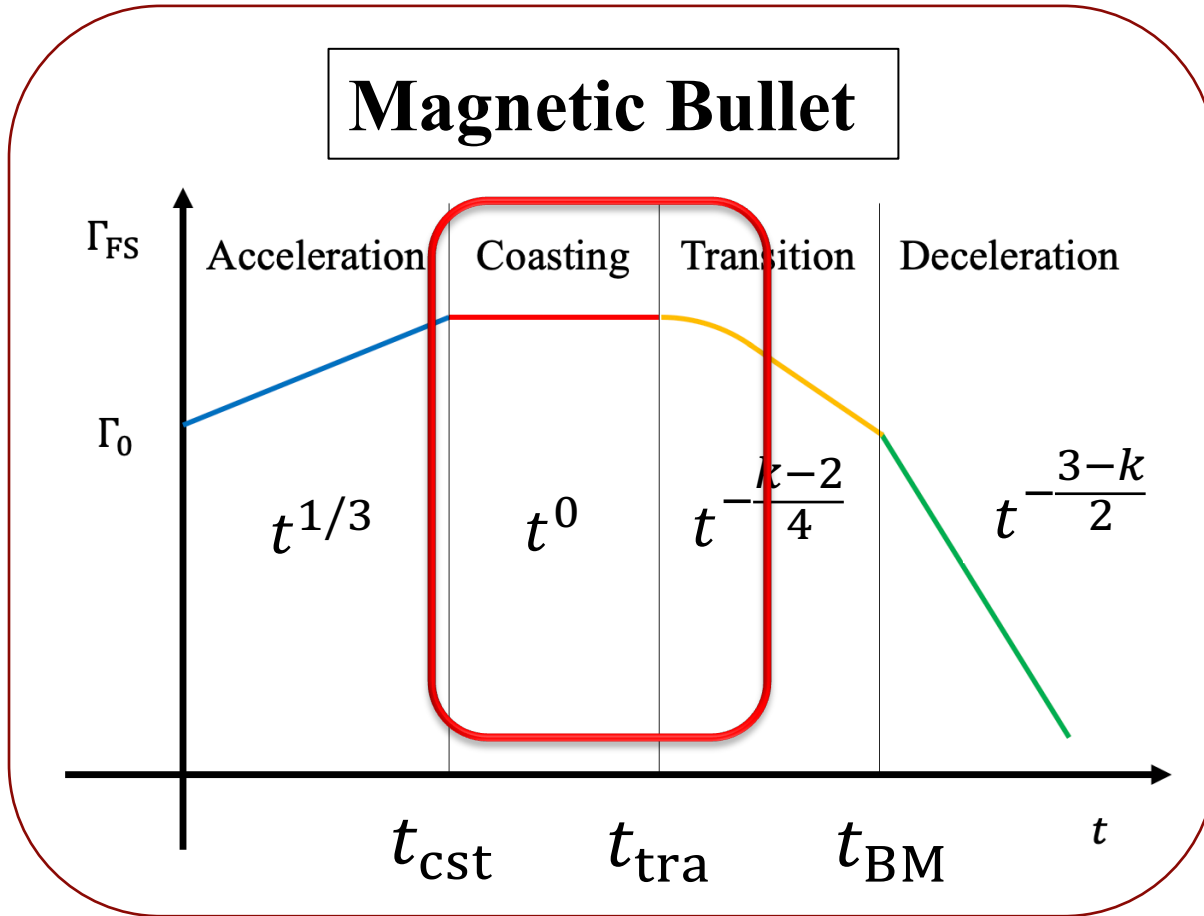
Impulsive acceleration: Granot et al. (2011)

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

time = 00006300 s



Semi-Analytic Modeling 2. Reverse Shock Timescale



RS ignition condition

$$\frac{B_{\text{ej}}'^2}{8\pi} = \frac{4}{3} \Gamma_{\text{FS}}^2 n_0 m_p c^2$$

Zhang & Kobayashi (2005)

Acceleration stops at RS ignition

RS crossing timescale

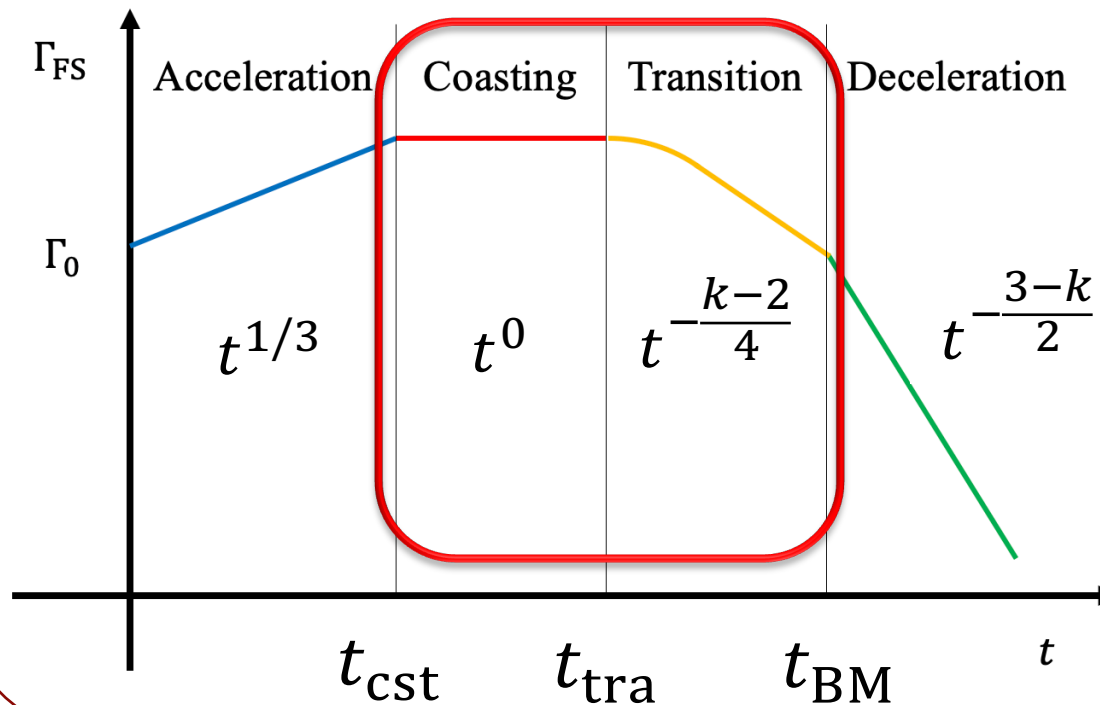
$$t_{\Delta}(\sigma_0) = \Gamma_0^{1/2} R_{\text{dec}}^{3/4} \Delta_0^{1/4} (1 + \sigma_0)^{-1/2}$$

Giannios, Mimica & Aloy (2008)

Shell spreading stops at RS crossing

Semi-Analytic Modeling 3. Coasting to Transition

Magnetic Bullet



Pressure balance at contact discontinuity

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

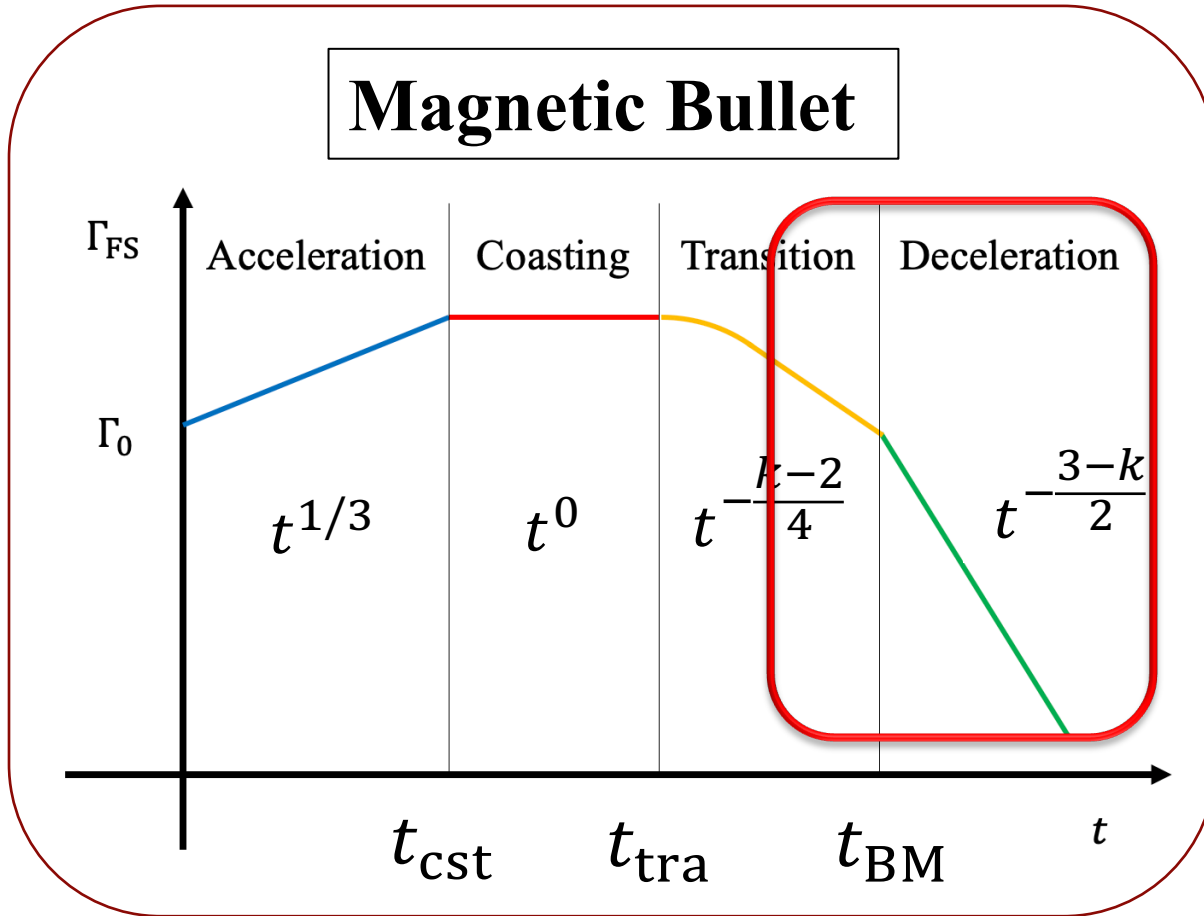
$$\Gamma_{FS} = \Gamma_{RS} \simeq \frac{\Gamma_{cst}}{\left[1 + 2\Gamma_{cst} \sqrt{\frac{n_{CSM}}{n_{ej}(1 + \sigma_{RS})}}\right]^{1/2}}$$

Panaitescu & Kumar (2004)
 Murase (2007) (for $\sigma_{RS} = 0$ case)

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

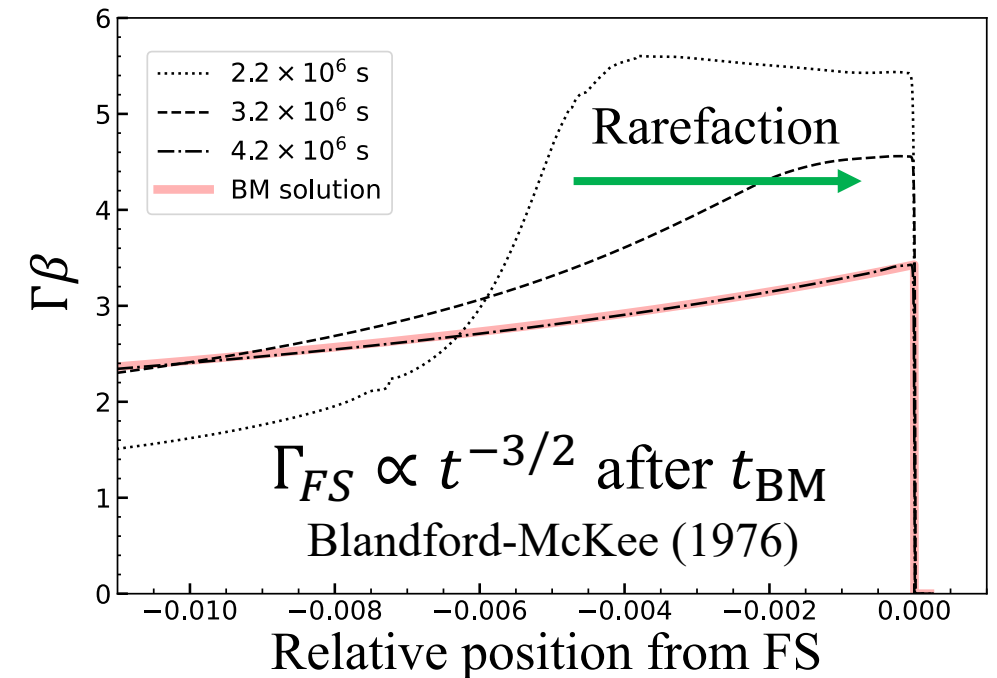
Transition Phase: $\Gamma \propto t^{-\frac{k-2}{4}}$

Semi-Analytic Modeling 4. Rarefaction Catch-up



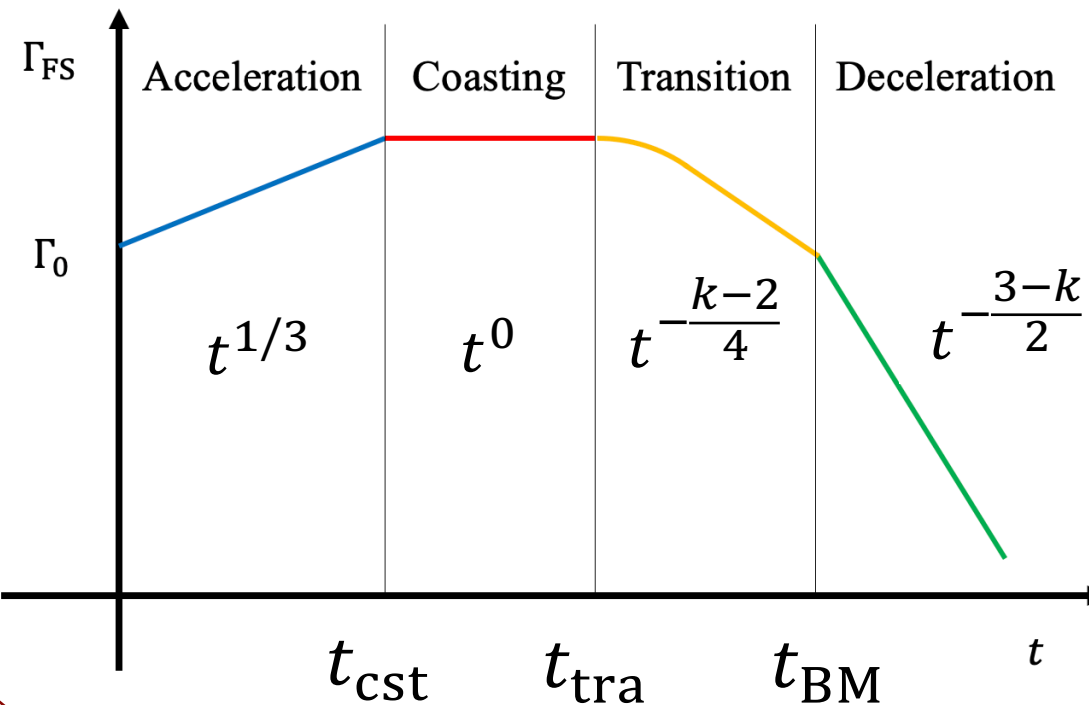
Rarefaction catch-up time t_{BM}

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



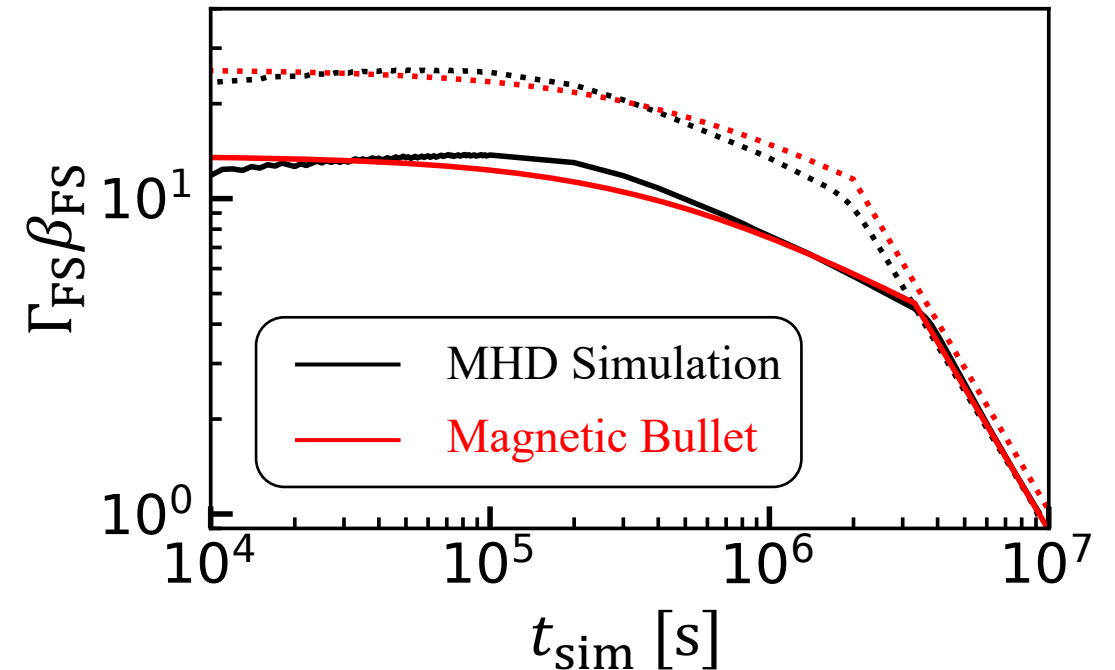
Semi-Analytic Model of Magnetic Bullet Afterglow

Magnetic Bullet



Well consistent with simulation results

$$E_0 = 10^{50}, \Gamma_0 = 10, \sigma_0 = 10, \Delta_0 = R_{\text{dec}}/\Gamma_0^{2\sim 3}$$



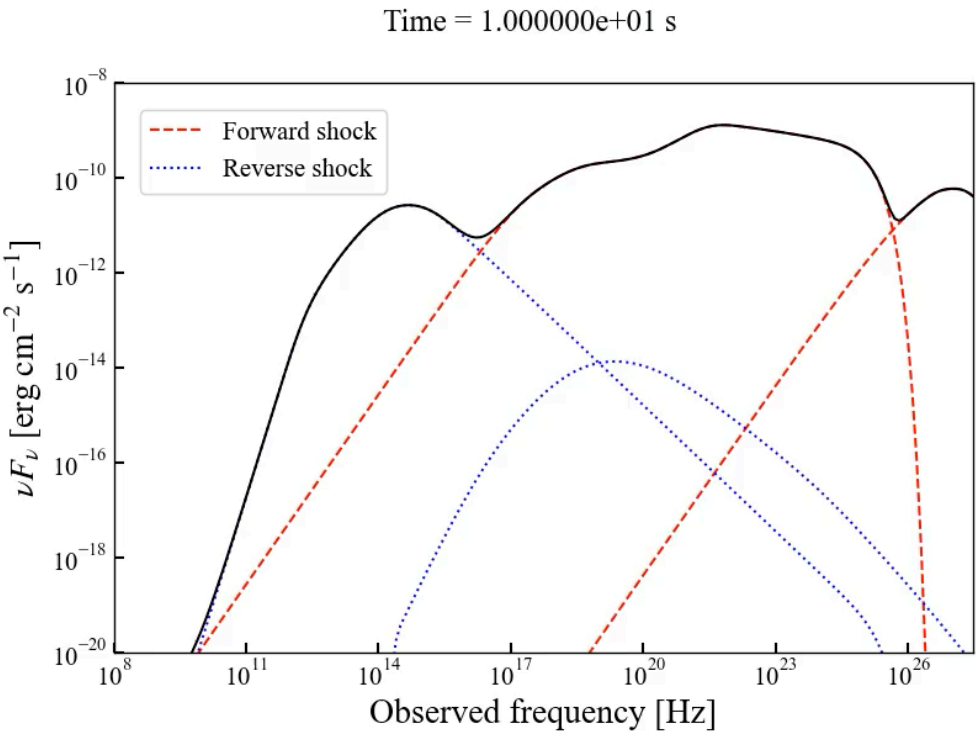
Open-Source Afterglow Simulator “Magglow.jl”

“Magglow” will elucidate the diversity of early afterglows

Magglow is a Multi-Messenger Early Afterglow Moderator

Name	MHD	RS	SSC	pp,py	CSM	Language
afterglowpy					ISM	Python/C
AMES		○	○	○	Both	Python/C++
PyBlastAfterglow		○	○		Any	Python/C++
jetsimpy		○	○		Any	Python/C++
VegasAfterglow	△	○	○		Any	Python/C++
Magglow	○	○	○	○	Any	Julia

So far, only **Magglow** includes the dynamical effects of 1D simulation

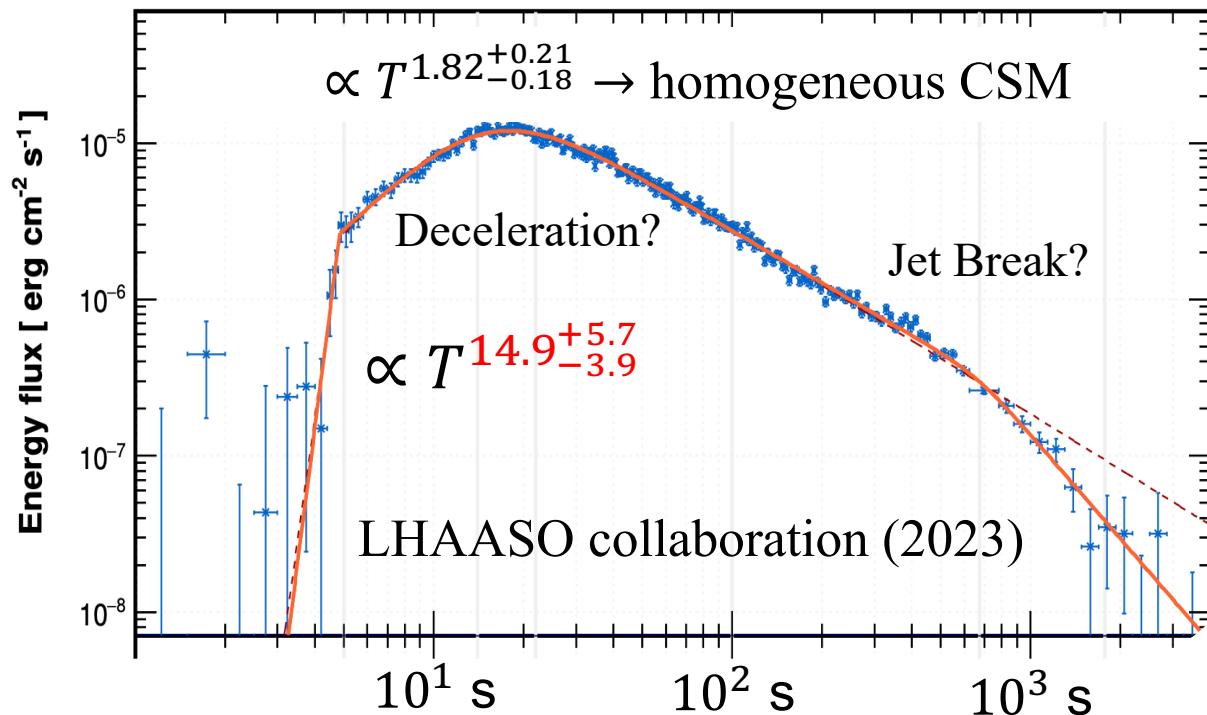


Application to GRB 221009A

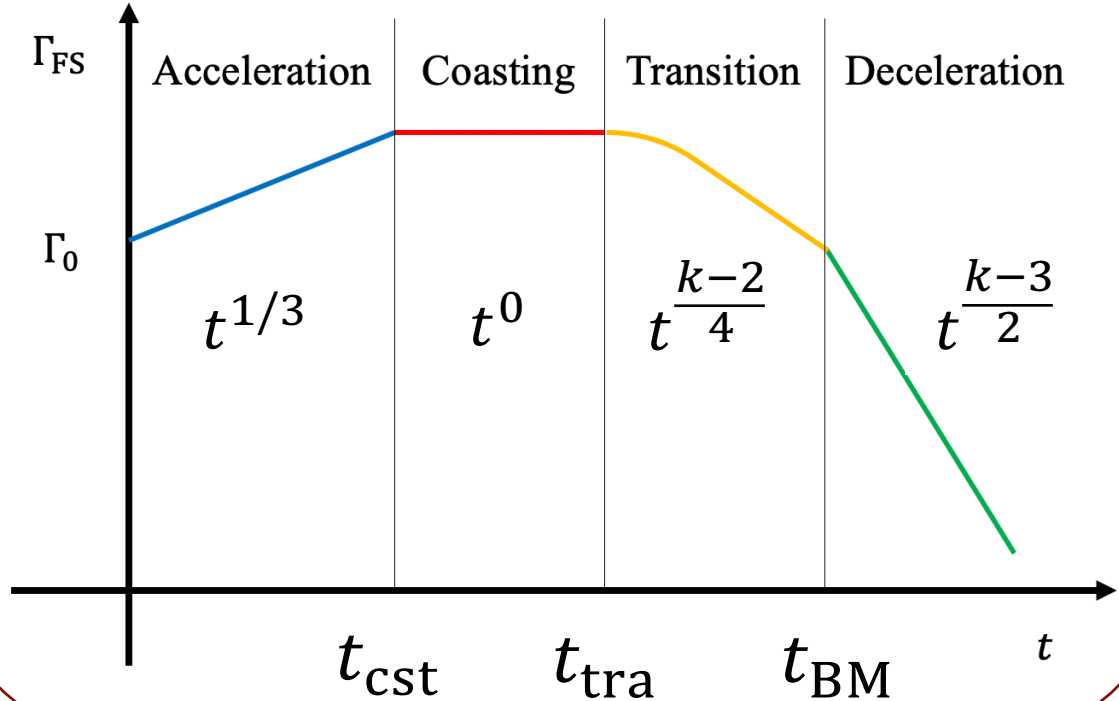
4 Phases in BOAT & Model

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

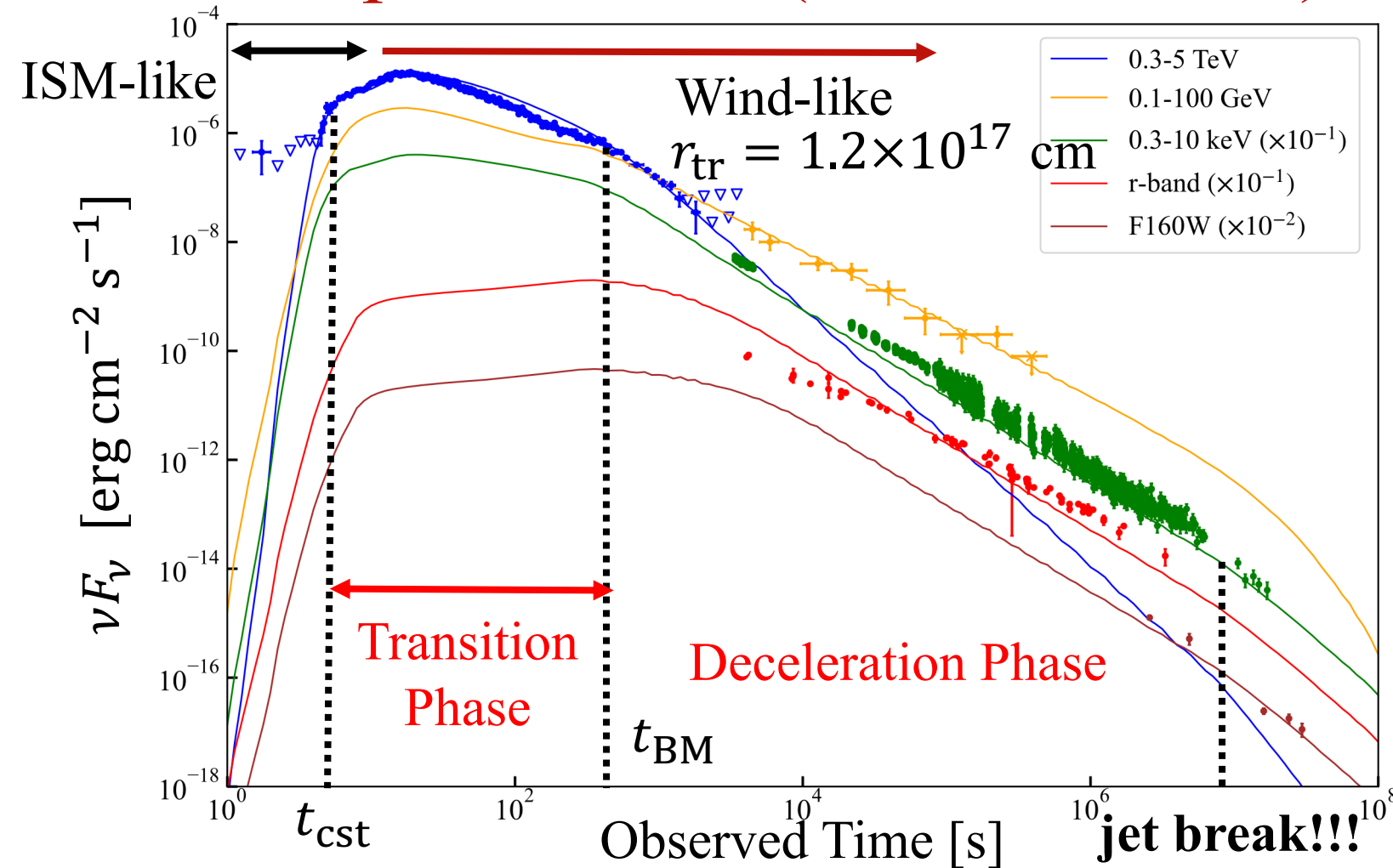
Roughly: $F_{SSC} \propto R^4 \Gamma^3 \propto T^{15}$



Magnetic Bullet



TeV Rapid Increase (GRB 221009A)



$$E_{iso} = 4 \times 10^{55} \quad A = 0.048$$

$$\Gamma_{cst} = 530 \quad p = 2.45$$

$$\sigma_{cst} = 23 \quad \epsilon_e = 3.0 \times 10^{-2}$$

$$\Delta_0 = 200c \quad \epsilon_B = 4.6 \times 10^{-5}$$

We don't need very narrow jet

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

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

$$E_{jet} = 2 \times 10^{52} \left(\frac{\theta_{jet}}{0.03 \text{ rad}} \right)^2 \text{ erg}$$

Shallow-decay...?

GRB model parameters

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

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

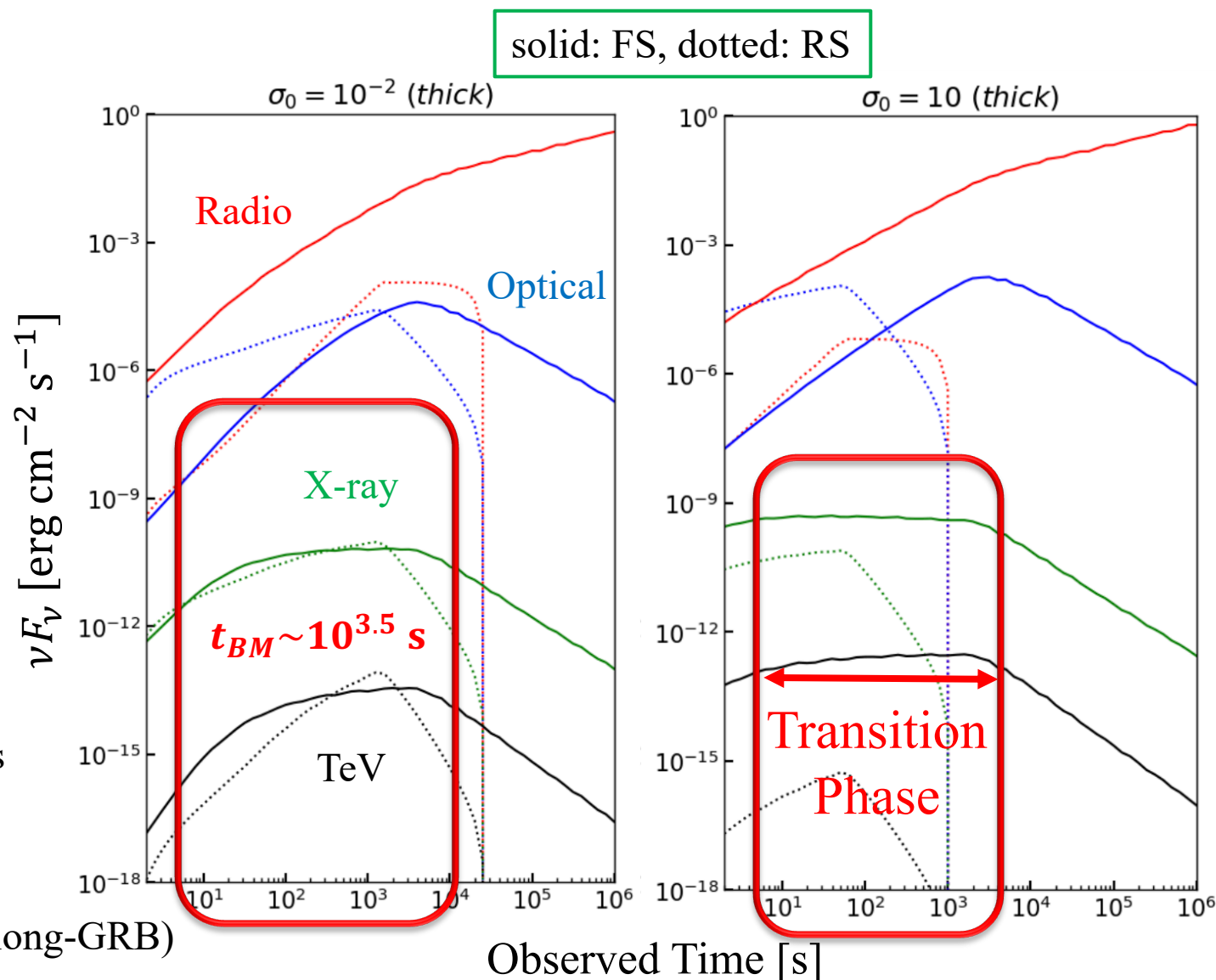
X-ray shallow decay (> 50%)

Decaying index ~ 0.11
 Timescale $\sim 10^{3.5} \text{ s}$
 Tang et al. (2019)

Our results naturally explain the observations

$$F_\nu \propto t_{obs}^{-\frac{p-2}{2}} \propto t_{obs}^{-0.1} \quad \text{for } \nu > \max(\nu_m, \nu_c)$$

$$t_{BM} \sim 10^{3.5} \text{ s} \quad \text{for } \Delta/c = 720 \text{ s (cf. } T_{90} \text{ of long-GRB)}$$



Towards Elucidation of the Diversity of GRB Afterglows

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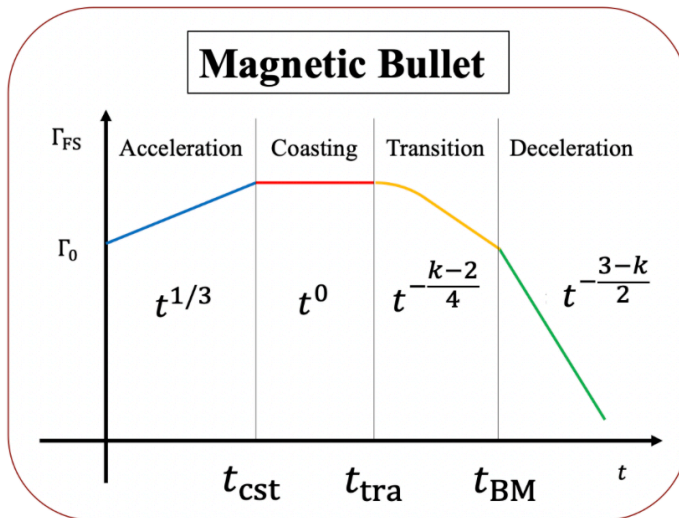
Open Source Multi-Messenger Emission Simulator
-Magglow.jl-

README MIT license

<https://github.com/yo3-sun/Magglow>



"Magglow" - Magnetic Bullet Afterglow



Magglow is a Julia module to calculate Gamma-ray Burst (GRB) afterglow light curves and spectra based on Magnetic Bullet model [Y. Kusafuka & K. Asano \(2024\)](#). The framework implements semi-analytic models for forward and reverse shock dynamics propagating in a stratified CSM and leptonic (synchrotron with self-absorption and self-Compton scattering with Klein-Nishina corrections) and hadronic (pp collisions and photomeson interactions) multimessenger emission mechanisms observed from arbitrary viewing angle.

Details of the methods can be found in [Y. Kusafuka, K. Obayashi, K. Asano, & R. Yamazaki \(in prep\)](#).

Summary

A new semi-analytic afterglow model, Magnetic Bullet Afterglow, has successfully included 1D dynamical effects in the shock wave dynamics. An open-source afterglow simulator, “Magglow”, will elucidate the diversity of GRB early afterglows. We should do beyond one-zone studies.