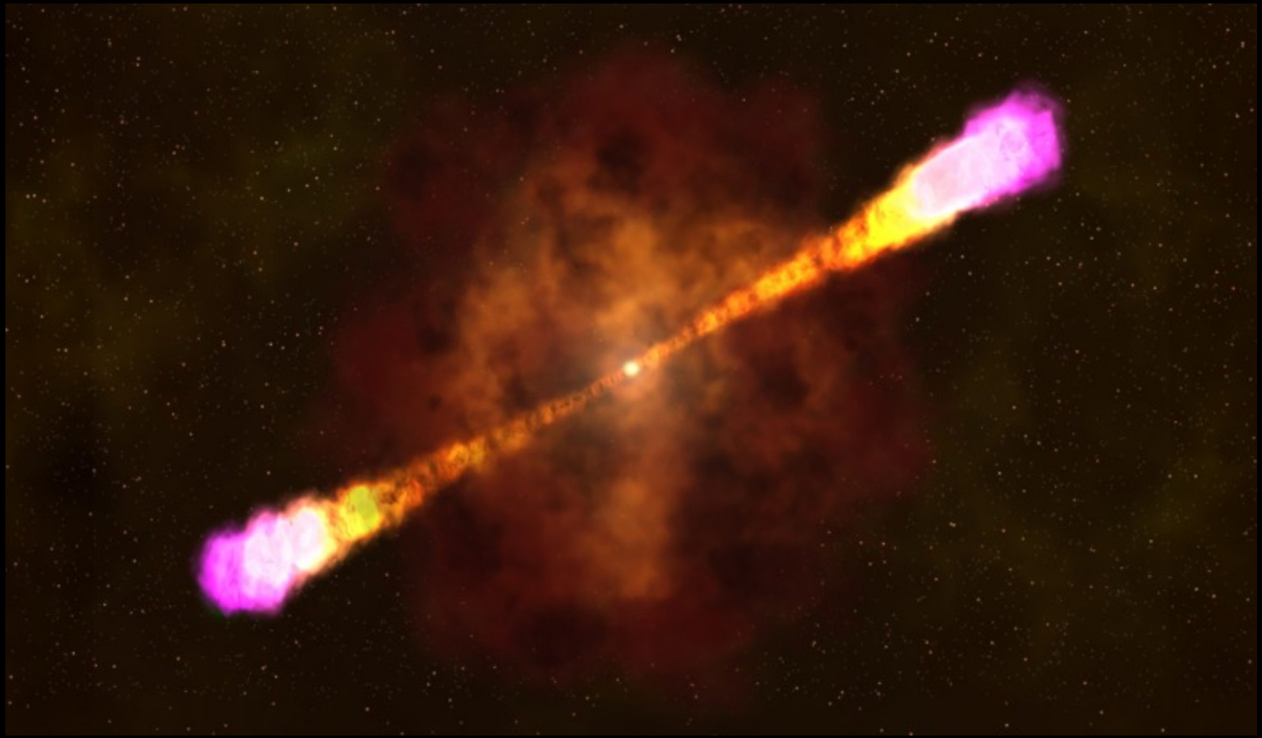
Recent developments on GRB afterglow modeling in the VHE era



Bing Theodore Zhang

2023/2/27

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

The physics of GRBs

Energetic and luminous

$$E_{\gamma,\mathrm{iso}} \sim 10^{49} - 10^{55}\ \mathrm{erg}$$

$$L_{\gamma,\mathrm{iso}} \sim 10^{46} - 10^{54}\ \mathrm{erg\ s^{-1}}$$

Relativistic outflow

$$\Gamma > 100$$

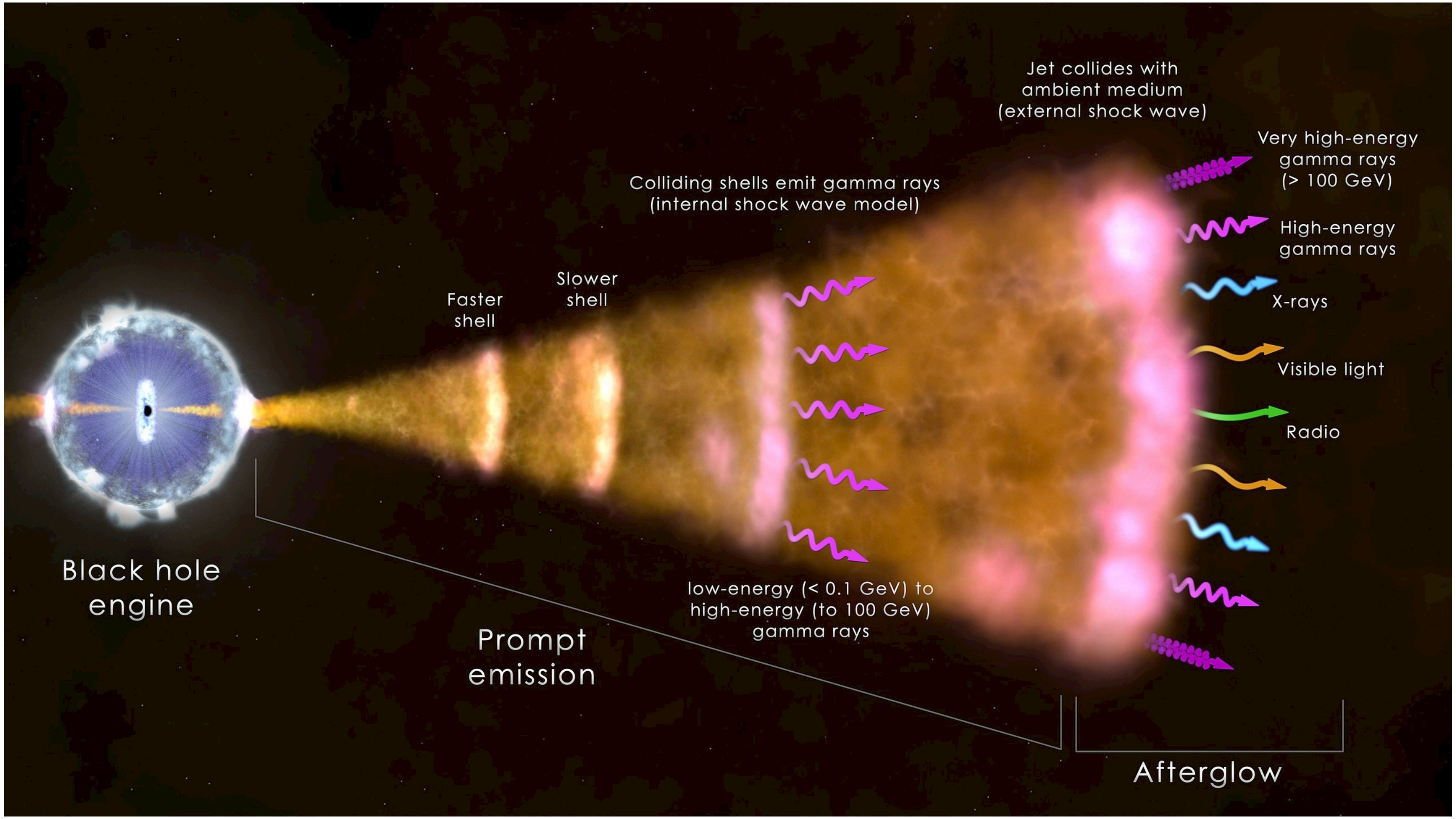
Rapid variability

Below ~ 0.1 seconds

Low-luminosity GRBs

$$\Gamma \gtrsim 10$$

Short GRBs (double neutron star merger)



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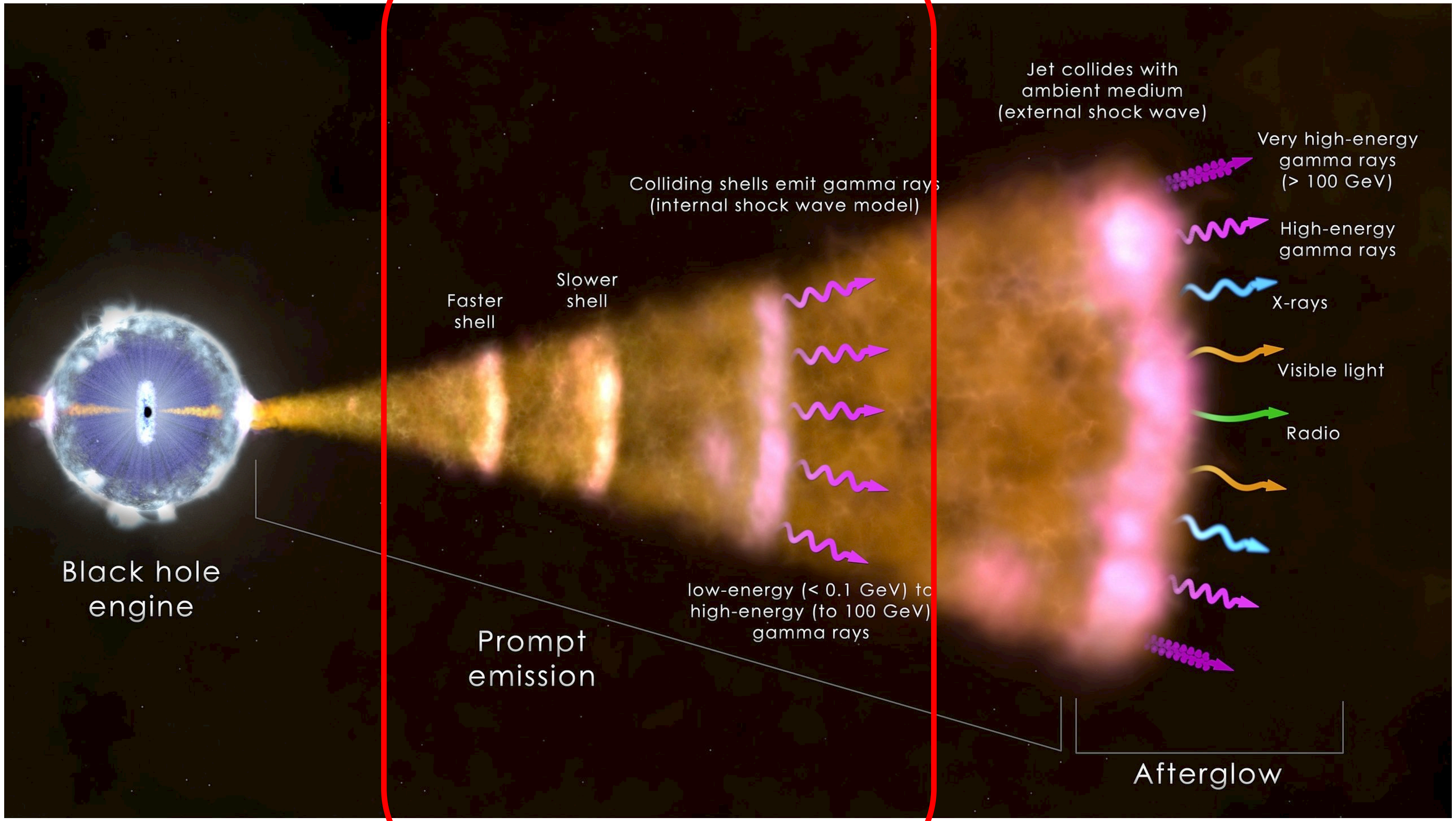

Internal shock

$$R_{\mathrm{IS}} \simeq 2\Gamma^2 c\delta t = 6\times 10^{12}\Gamma_2^2\delta t_{-2}\ \mathrm{cm}$$

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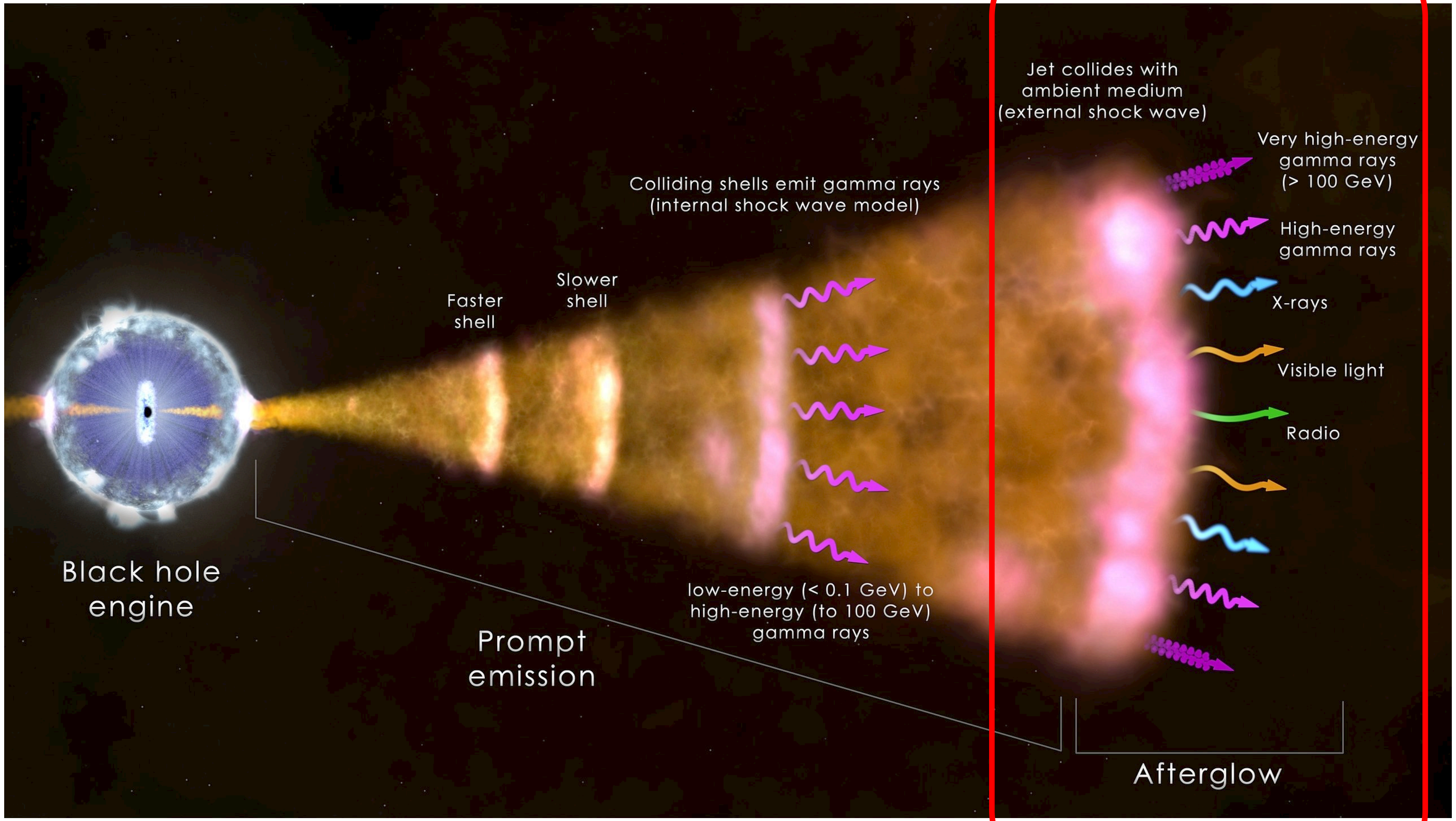


Internal shock

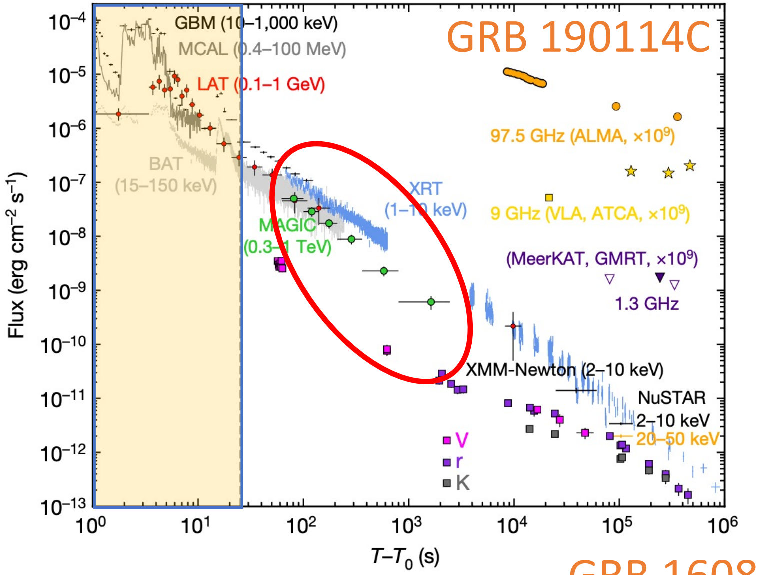
Reverse-forward shock

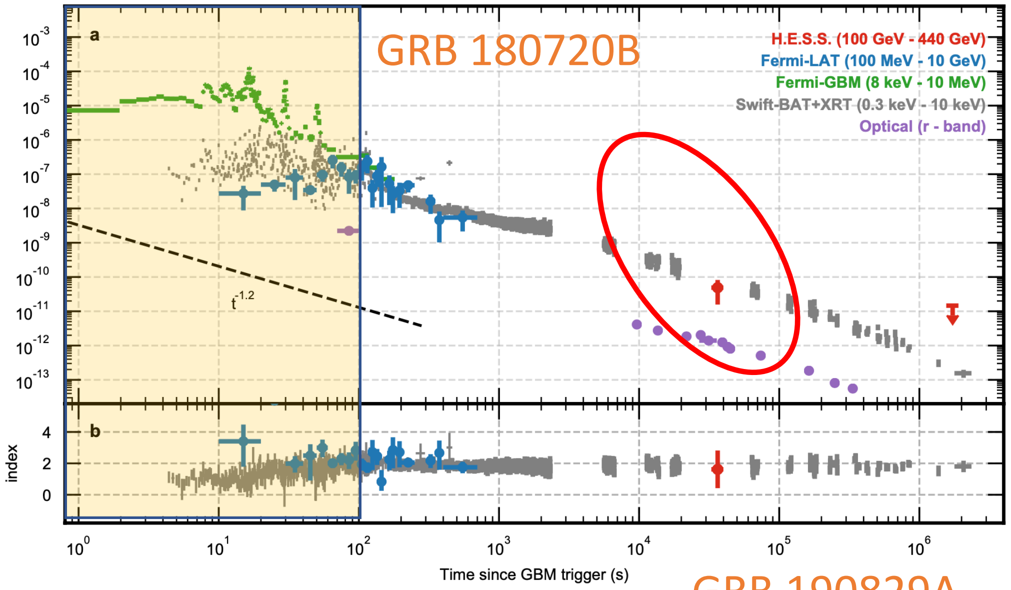
$R_{\mathrm{IS}} \simeq 2\Gamma^2 c\delta t = 6 \times 10^{12}\Gamma_2^2 \delta t_{-2}$ cm

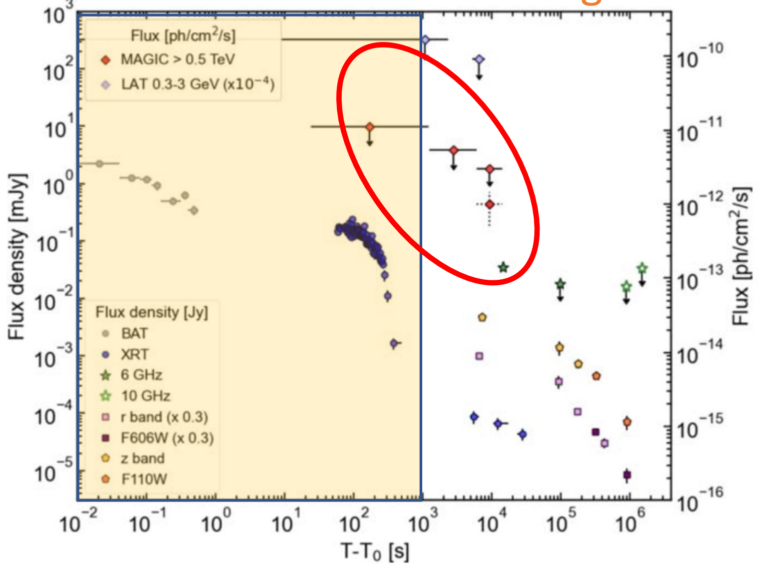
$R_{\mathrm{dec}} \simeq 6.2 \times 10^{16} \mathcal{E}_{52}^{1/3} \Gamma_{0,2}^{-2/3} n^{-1/3}$ cm

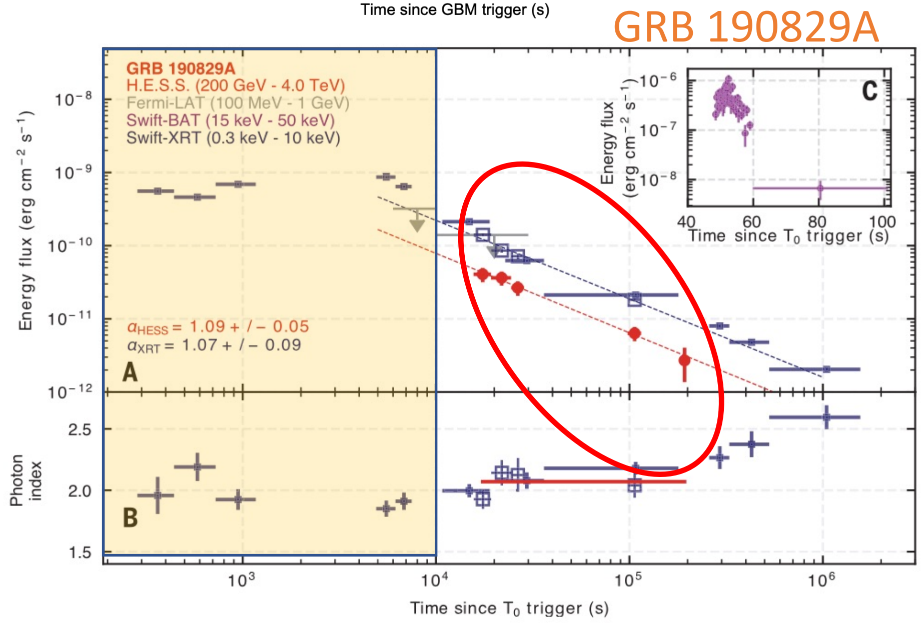
Lightcurves of VHE GRBs

GRB 221009A !









TeV photons from afterglow phase

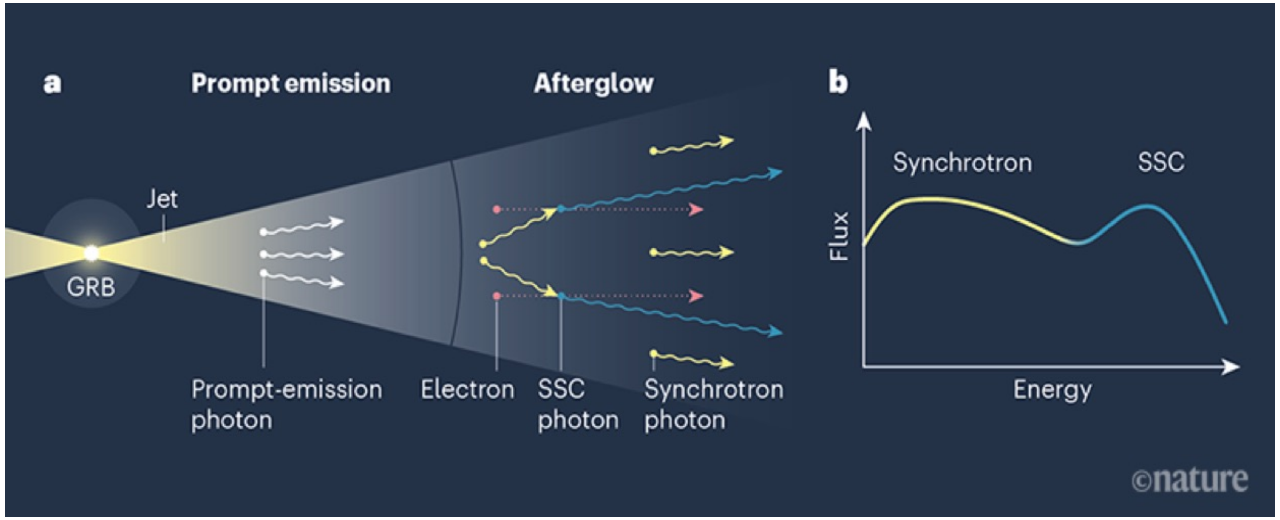
Opening the possibility to renovate and boost afterglow studies

What we can learn from afterglow modeling?

High-luminosity (typical) long GRB (GRB 190114C, GRB 180720B, GRB 221009A, …)

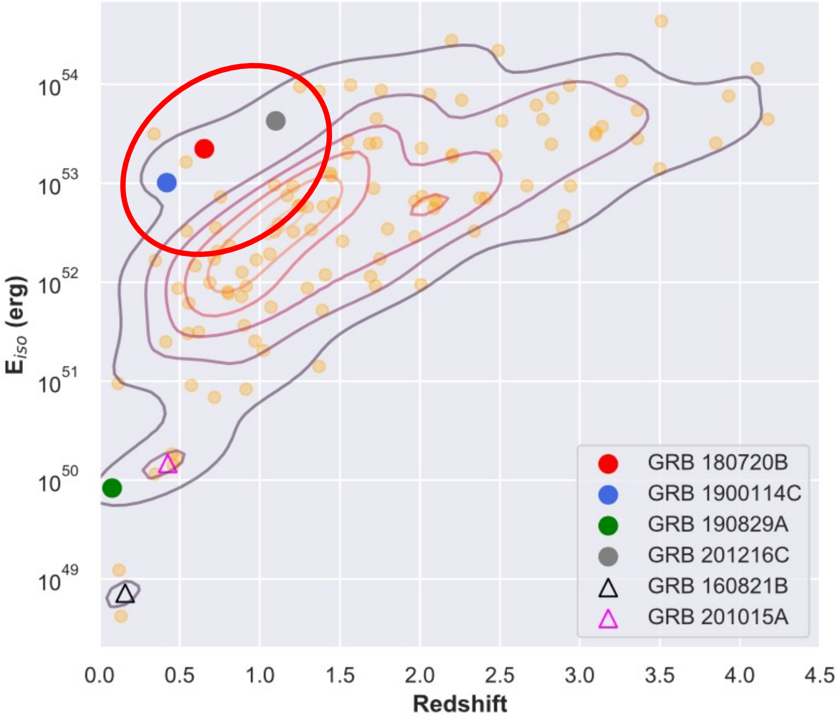
Consistent with the SSC one-zone afterglow model (GRB 190114C, GRB 180720B, GRB 221009A, …)

Low-energy radio to optical data?



Zhang, 2019

Noda & Parsons, 2022



Isotropic energy output of the GRBs (in the 50–300 keV range)

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Low-energy radio to optical data?

Proton synchrotron model? Totani 1998, Zhang & Meszaros, 2001, Murase et al, 2008, Asano et al, 2009, Isravel et al, 2022; BTZ, Murase, Ioka et al, 2022

Low-luminosity long GRB (GRB 190829A)

Difficult to explain within the SSC one-zone afterglow model H.E.S.S. Collaboration et al, 2021

External inverse-Compton (flare)? BTZ, Murase, Veres and Meszaros, 2021

Two-component jet Sato el al, 2022 (including BTZ)

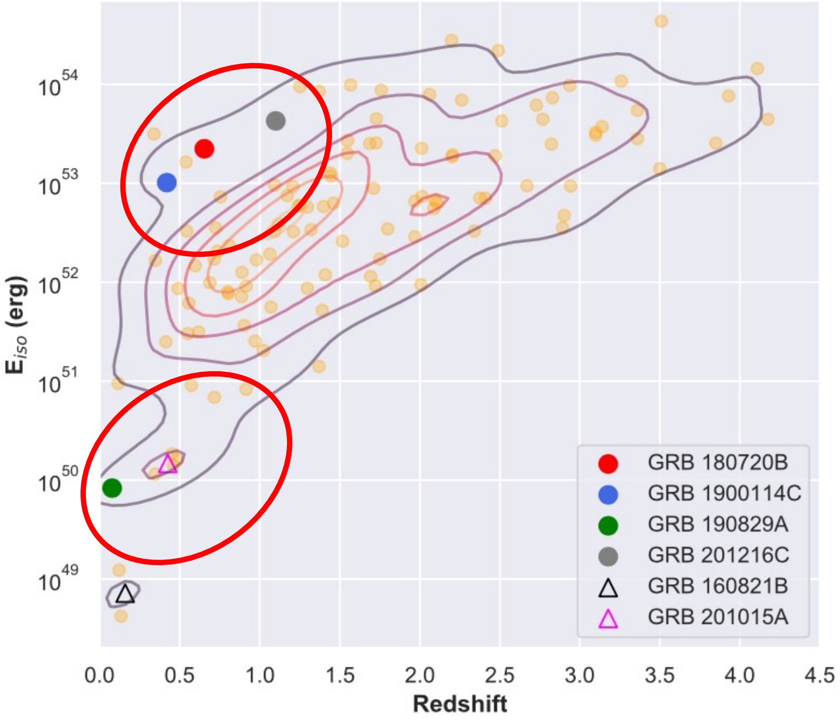
Reverse shock Salafia el al, 2022

Two-zone SSC model Khangulyan el al, 2022

Short GRB (GRB 160821B)

Difficult to explain with the SSC one-zone afterglow model Magic Collaboration, 2021

External inverse-Compton (flare)? BTZ, Murase, Yuan, Kimura and Meszaros, 2021



Isotropic energy output of the GRBs (in the 50–300 keV range)

Numerical modeling on GRB afterglow

One-zone SSC model

Useful for performing MCMC fitting

Simple analytical models – Fast and useful for MCMC fitting, not accurate (especially for SSC cooling and SSC component)

Detailed numerical models – More physical processes, time consuming for MCMC fitting

With the help of machine learning

Neutral network emulation Boersma et al. 2023

(AMES) Astrophysical Multi-messenger Emission Simulator

- Code generate neutrino and EM light curves and spectra
- Model parameters are standard ones used in each community given multiwavelength data
- “Source dependent” python interface
- Physics processes are based on C++

Status:

- ❑ GRB (ex. Zhang et al. 2021)
- ❑ SN (ex. Murase 2018, Murase et al. 2019)
- ❑ PWN (ex. Murase et al. 2021)
- ❑ ANG (ex. Zhang & Murase 2023)

One-zone SSC model – Code comparison

Numerical calculation of the afterglow emission

AMES

EATS, SSC cooling, gamma-gamma attenuation, structured jet, off-axis

Ryan et el, 2020 (Afterglowpy)

EATS, Synchrotron component only, structured jet, off-axis

Granot & Sari, 2002

EATS, Synchrotron component only

Mecili & Nava, 2022

SSC cooling, gamma-gamma attenuation, EATS (Waxman 1997)

…

The basics of GRB Afterglow

$\mathcal{E}_k$: Isotrpic-equivalent kinetic energy

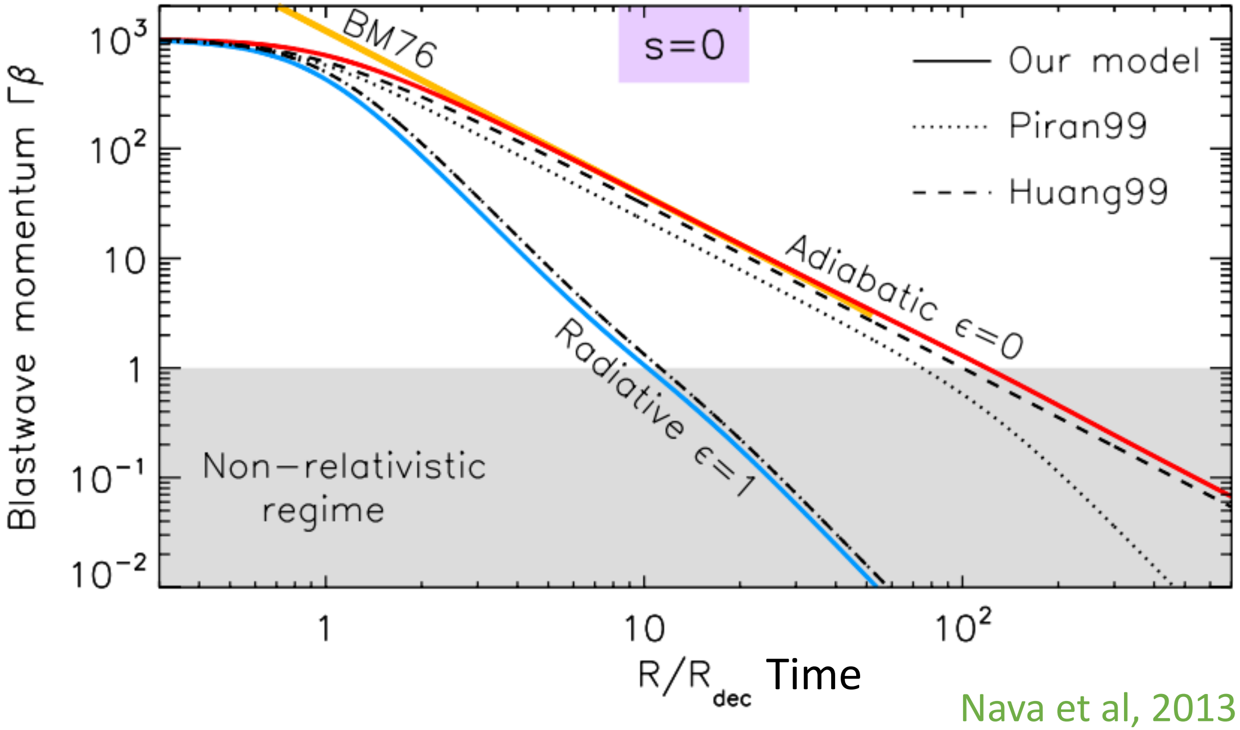
$n_{\rm ex}$: External matter density

Γ_0 : Initial Lorentz factor

θ_j : Jet openning angle

Macroparameters

How the shock front radius and the Lorentz factor of the blastwave fluid just behind the shock evolves as a function of the observer time t



Nava et al, 2013

Costing phase: $\Gamma = \Gamma_0, r \propto t$

Deceleration phase: $\Gamma \propto t^{-3/8}, r \propto t^{1/4}$

Non-relativistic phase: $\beta \propto t^{-3/5}, r \propto t^{2/5}$

Particle acceleration and radiation

Comoving frame shock-dissipated energy

$$u'_{\rm sh} = 4\Gamma(\Gamma - 1) n m_p c^2$$

$$u'_B = \epsilon_B u'_{\rm sh}$$ Comoving frame magnetic energy

$$u'_e = \epsilon_e u'_{\rm sh}$$ Comoving frame accelerated electron energy

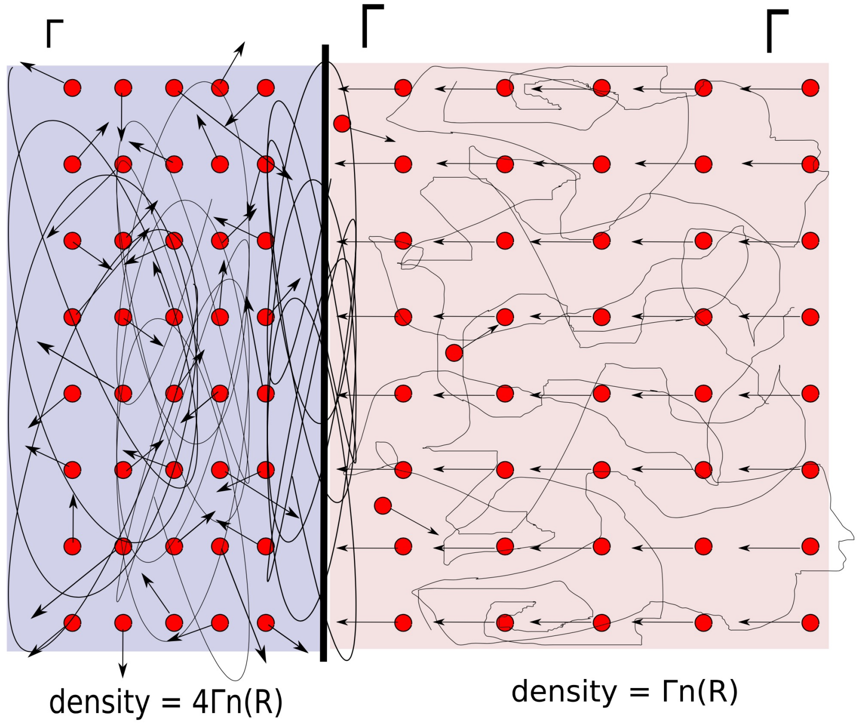
$$n(\gamma_e) d\gamma_e \propto \gamma_e^{-s_e} d\gamma_e$$

$$\gamma_{\rm min} = \frac{\epsilon_e}{f_e} \frac{m_p}{m_e} \frac{s_e - 2}{s_e - 1} (\Gamma - 1)$$

$$\frac{\partial n_{\gamma_e}(t')}{\partial t'} + \frac{\partial}{\partial \gamma_e}(n_{\gamma_e}(t') \dot{\gamma}_e) + \frac{n_{\gamma_e}(t')}{t'_{\rm esc}} = \dot{n}^{\rm inj}_{\gamma_e}(t')$$

Cooling processes: synchrotron cooling, inverse-Compton cooling, adiabatic cooling

Photon escape



Kumar and Zhang, 2014

Highly relativistic shock as viewed from the mean rest frame of the shocked fluid

Cold, upstream, particles stream toward the shocked plasma with Lorentz factor Γ as viewed in this frame

Particle acceleration and radiation

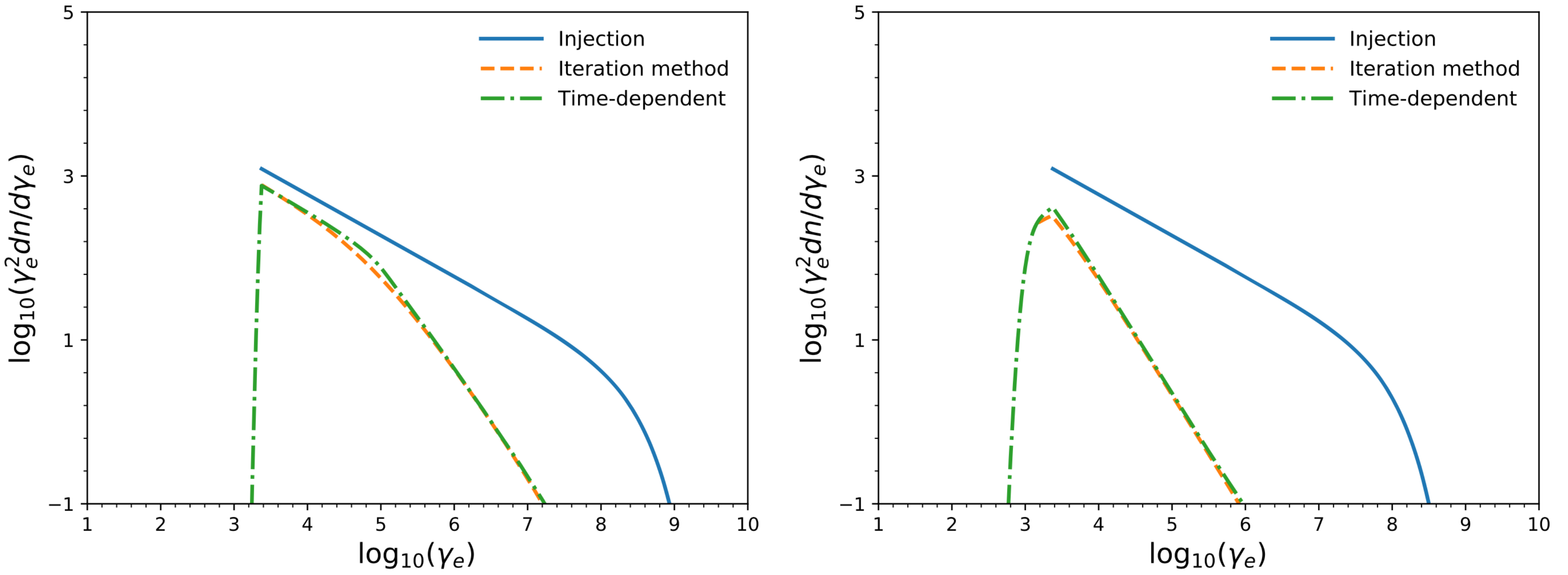


Figure B1. Comparison of the electron energy spectra derived by the iteration method used for the main results and by solving the kinetic equation at $t' = 100$ s. We use $\mathcal{E}_k = 1 \times 10^{52}$ erg, $n_{\rm ex} = 1$ cm^{-3}, $\epsilon_e = 0.3$, $f_e = 1.$, $s = 2.5$, $\Gamma_0 = 50$. Left panel: slow cooling regime, $\epsilon_B = 10^{-3}$. Right panel: fast-cooling regime, $\epsilon_B = 10^{-1}$.

Iteration method is useful for modeling electron quasi steady-state distribution

Fast and SSC cooliing included

$$n_{\gamma_e}(t) = \frac{1}{t_{\rm cool}^{-1}} \frac{1}{\gamma_e} \int d\gamma_e' \dot{n}_{\gamma_e}(t)$$

BTZ, Murase, Veres and Meszaros, 2021

Code comparison – case I

For synchrotron component, consistent within a factor of ~2

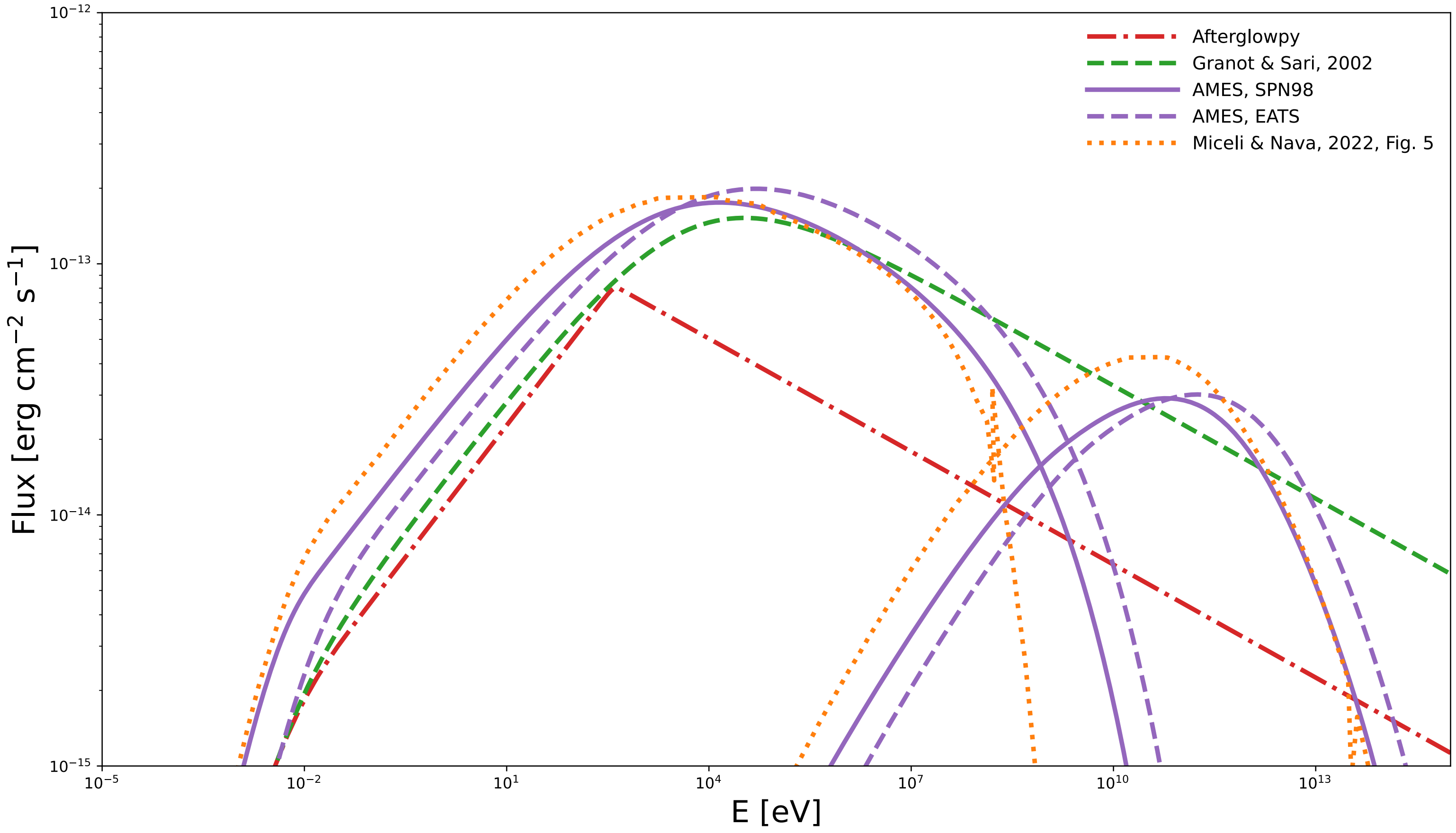
Afterglowpy have issue around and beyond cooling frequency

Difference between EATS method (especially from radio to infrared energy range)

The discrepancy on SSC component is larger

- Target photons depends on electron distribution

Observed energy spectrum at T_obs = 10000 seconds



$$\mathcal{E}_k = 1\times10^{52}\ \mathrm{erg}, \mathrm{n_{ex}} = 1\ \mathrm{cm}^{-3}, \epsilon_\mathrm{B} = 5\times10^{-4}, \epsilon_\mathrm{e} = 0.05, \mathrm{f_e} = 1., \mathrm{s} = 2.3, \Gamma_0 = 600, \mathrm{z} = 1$$

Code comparison – Case II

T_obs = 90 seconds

Observed energy spectrum at 90 seconds (e.g. GRB 190114C)

The discrepancy is larger between MAGIC, 2019 spectrum and others

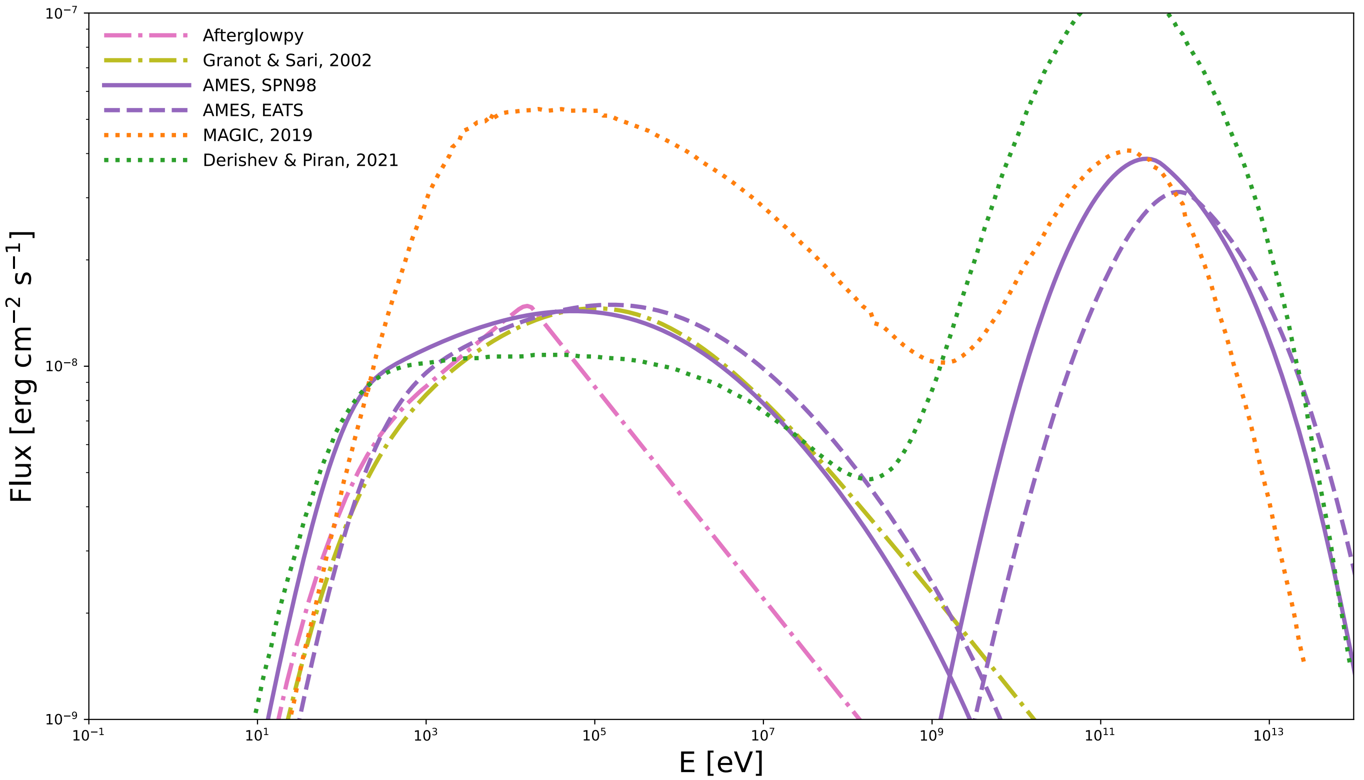
Different tratment of electron cooling and photon escape time scales ?

$$t_{\rm dyn} = C\Gamma T_{\rm obs}/(1+z)$$

$$t_{\rm eff,ph} \sim t_{\rm dyn}(C \sim 1)$$ Derishev & Piran, 2021

$$t_{\rm eff,ph} \sim t_{\rm dyn}(C \sim 1/3)$$ AMES (EATS)

C depends on the geometric effect



$$\mathcal{E}_k = 8\times10^{53}\ {\rm erg}, {\rm n_{ex}} = 0.5\ {\rm cm^{-3}}, \epsilon_{\rm B} = 8\times10^{-5}, \epsilon_{\rm e} = 0.07, {\rm f_e} = 1., {\rm s} = 2.6, \Gamma_0 = 1000, {\rm z} = 0.4245$$

Probe electron acceleration efficiency with VHE gamma-rays

The effect of maixmum acceleration energy

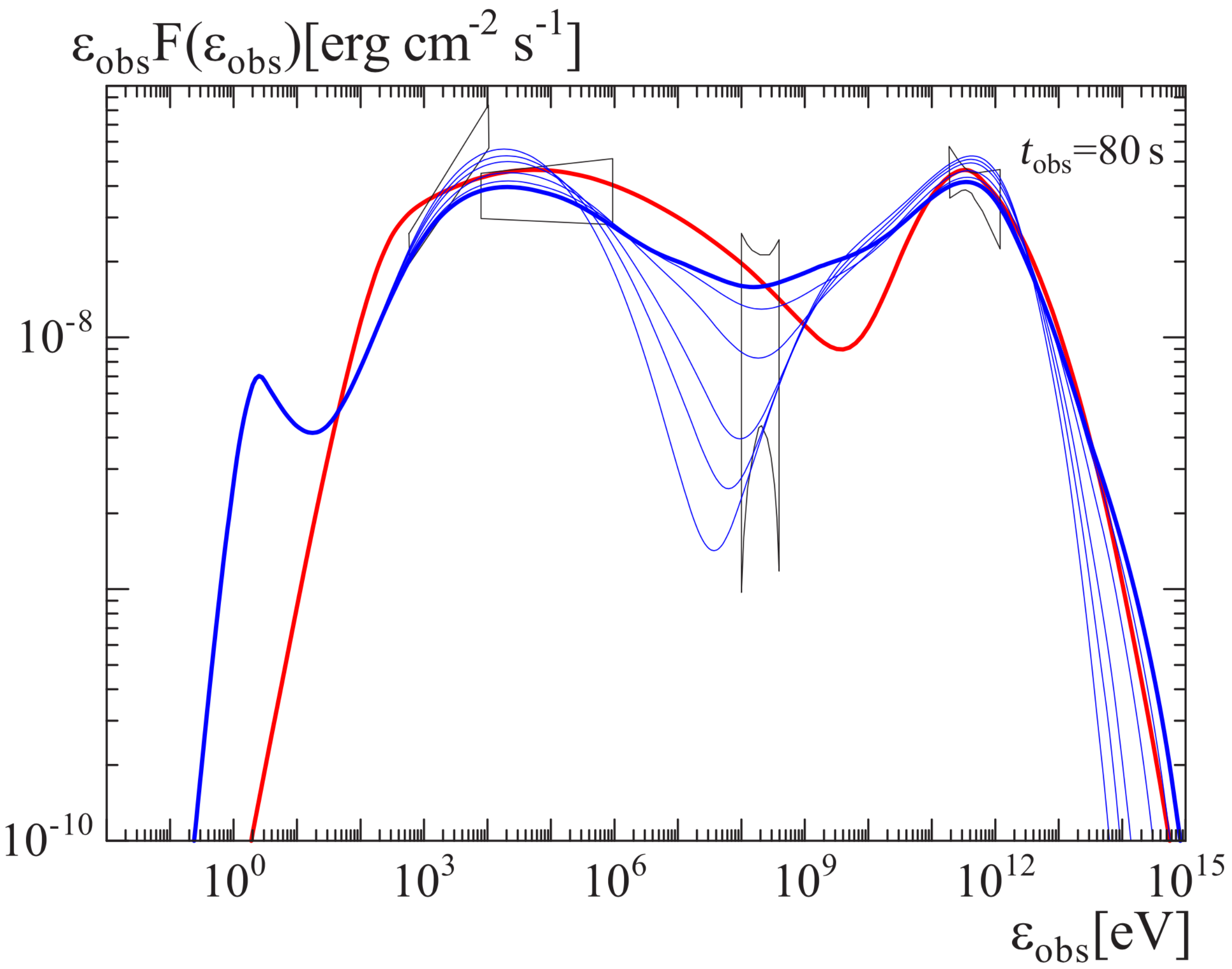
$$t_{\rm acc} = \eta t_L \sim (r_L/\lambda_{\rm coh}) t_L$$

The ratio between Larmor radius and the coherence length scale of plasma turbulence

Thick line: eta = 1
Thin lins: eta = 10, 100, 1000, 3000

eta < 100: flux detected above 0.1 GeV

SSC component not sensitive to the coefficient



Asano, Murase and Toma, 2020

Probe proton acceleration efficiency with VHE gamma-rays

Energy spectrum of proton synchrotron emission from reverse shock

UHECR acceleration is possible in reverse shock, but difficult for forward shock

Gallant and Achterberg 1999, Murase et al. 2008, Sironi et al. 2015

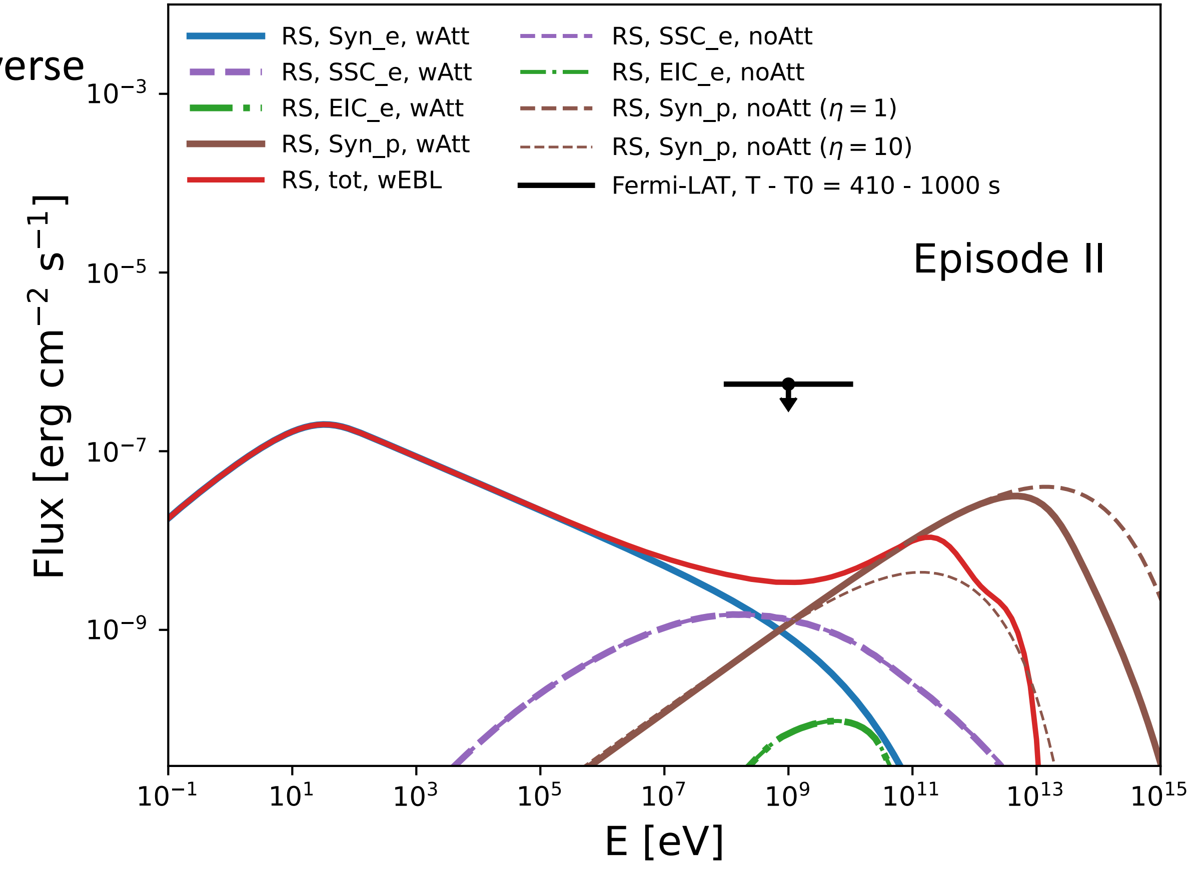
$$t_{\mathrm{acc}} = \eta t_L$$

Thick-dashed brown line: eta = 1
Thin-dashed brown line: eta = 10

Acceleration at tran-relativistic reverse shock

Ordered upstream magnetic field ?

Large-scale MHD turbulence?



BTZ, Murase, Ioka et al, 2022

(Could be tested by VHE gamma-rays, e.g. GRB 221009A) RS component may be need for fitting early afterglow data

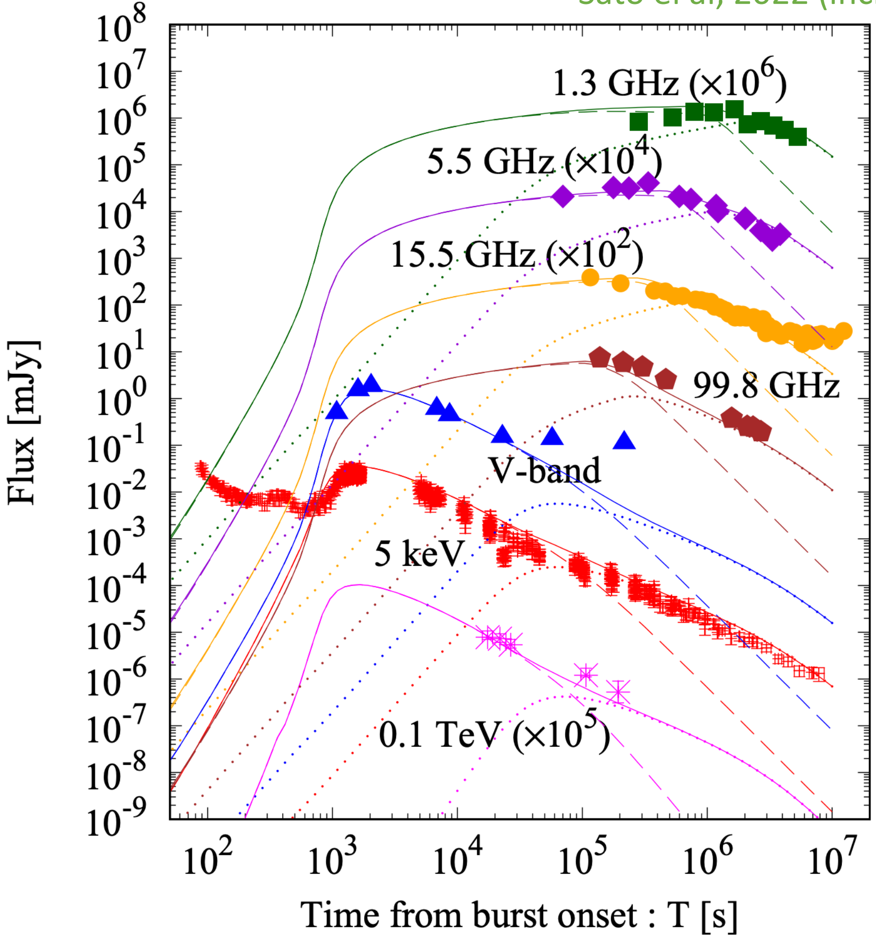
O'Connor et al, 2022

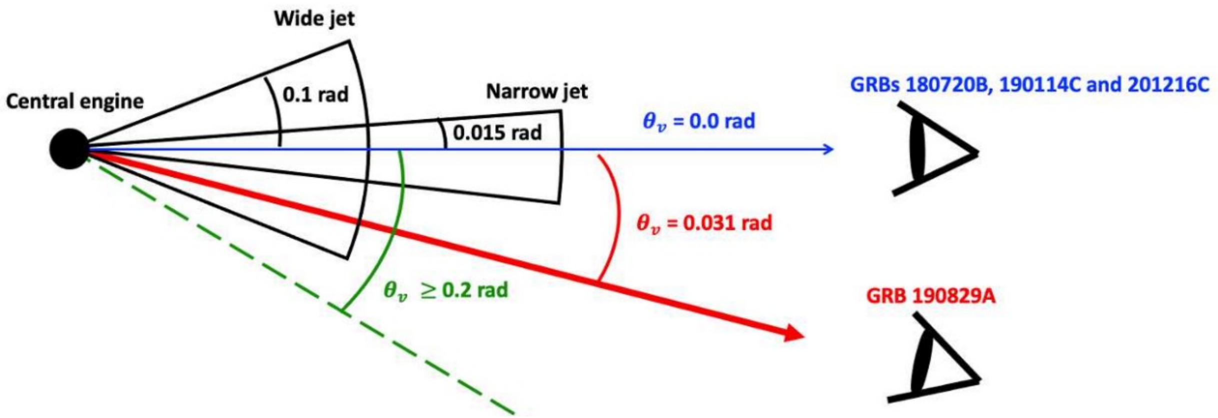
Two-component jet model

Or structured jet?

GRB 190829A

Sato el al, 2022 (including BTZ)





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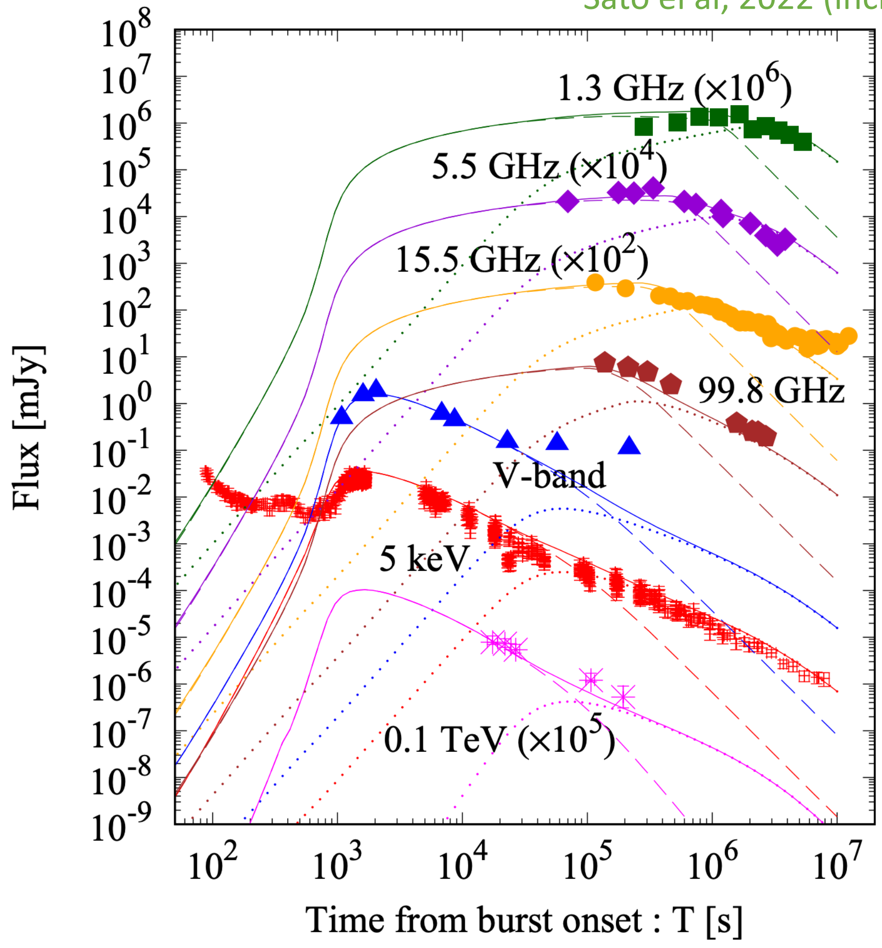
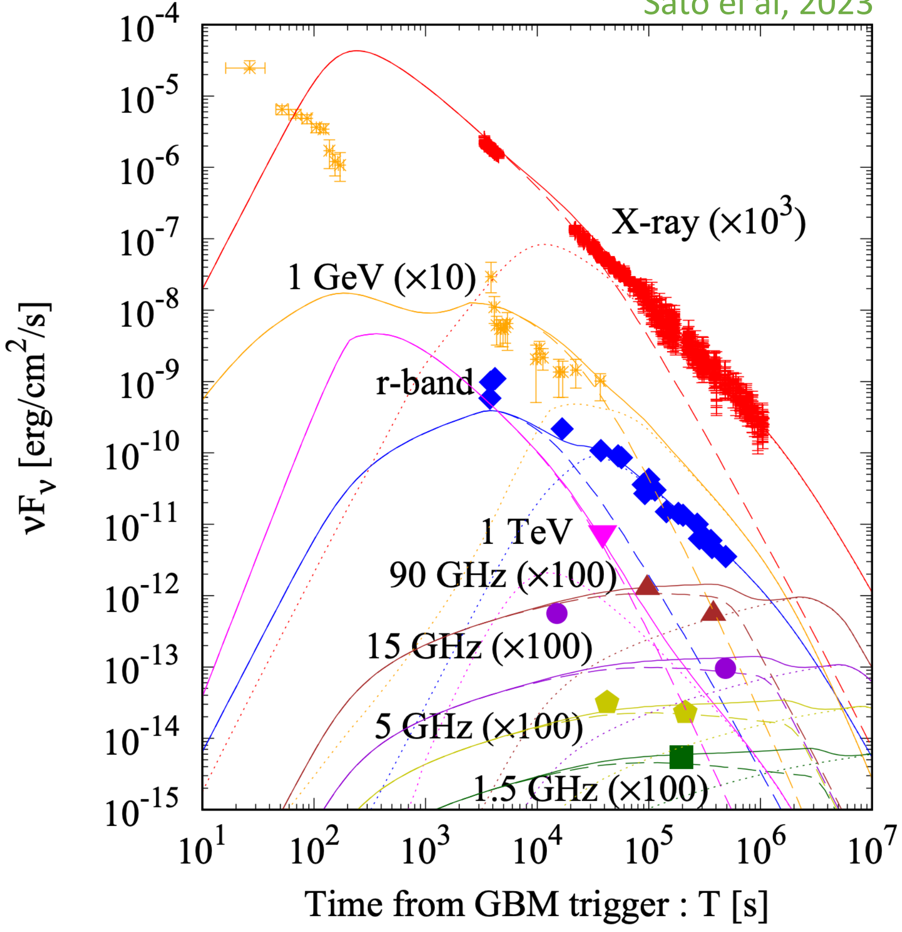


GRB 221009A

Sato el al, 2023



Summary and outlook

- The SSC one-zone afterglow model is consistent with the observed high-luminosity VHE GRBs
  - Fast and accurate mumerical modeling with detailed radiative processes
  - Reverse shock component ?
  - Two-component or structure jet ?
  - External inverse-Compton could enhance VHE gamma-ray flux

    e.g. important for low-luminosity GRBs and short GRBs

- VHE GRBs in multimessenger astrophysics
  - epsilon_B << 1 for the one-zone afterglow model
  - UHECR acceleration and proton synchrotron emission (epsilon_B > 0.1)

- AMES will be publicly available soon.

  Numerical modeling the high-energy processes that occurred in various high-energy sources

  (e.g. GRB, SN, PWN, AGN, …)