Formation of hard VHE spectra in X-ray dominated sources

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in collaboration with F.Aharonian&A.Taylor

"The extreme Universe viewed in very-high-energy gamma rays 2022"

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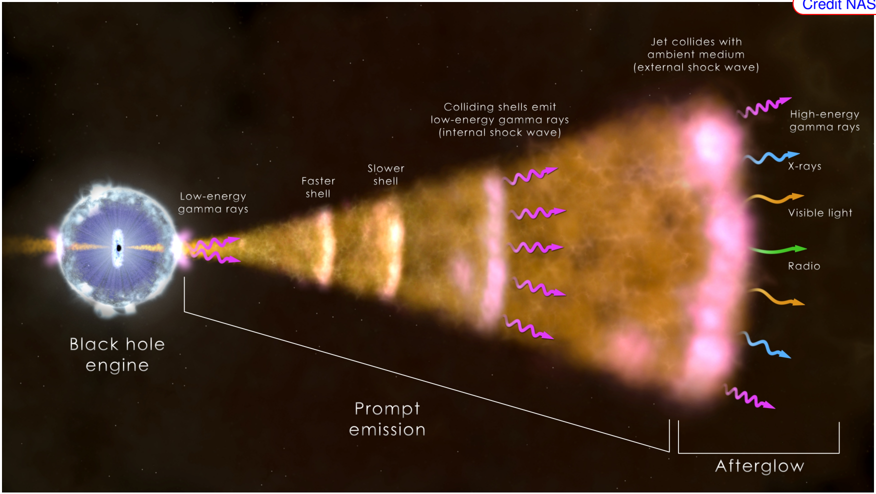
Overview

1. Motivation
2. Properties of IC emission
3. Two-zone model for GRB190829A

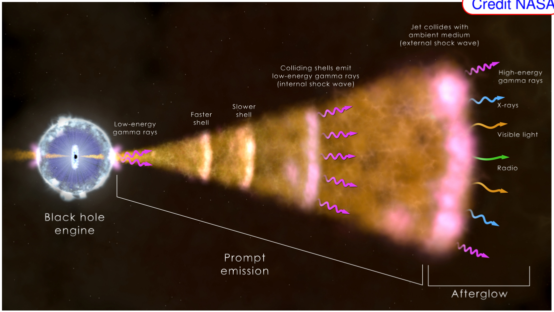
Long GRBs



Credit NASA

Long GRBs

- Long GRBs are most likely produced at collapse of massive stars
- Magnetic field accumulated at the BH horizon launches a B&Z jet
- Prompt emission: initial jet outburst, internal jet emission, dominates for the first 10^{2-3} s
- Afterglow: jet–circumburst medium interaction, start dominating after 10^{2-3} s, last for weeks



Blandford&McKee (1976) self-similar solution for a relativistic blast wave (the relativistic version of the Sedov's solution for SNR):

$$E = \Gamma^2 Mc^2, \text{ assuming } \rho \propto r^{-s} \Rightarrow \Gamma \propto R^{(s-3)/2} \Rightarrow \Delta t \approx \int\limits_0^R \frac{dr}{2c\Gamma(r)^2}$$

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Based on the explosion energy, E, and density of the circumburst medium, $\rho = \rho_0 (r/r_0)^{-s}$ we obtain

- Bulk Lorentz factor of the shell

$$\Gamma \approx 40 \left(\frac{E_{53}}{\rho_0 t_3^3}\right)^{1/8}\Big|_{s=0} \approx 20 \left(\frac{E_{53} v_8}{\dot{m}_{21} t_3}\right)^{1/4}\Big|_{s=2}$$

- Shell radius

$$R \approx 2\cdot 10^{17}\,\mathrm{cm} \left(\frac{t_3 E_{53}}{\rho_0}\right)^{1/4}\Big|_{s=0}$$
$$3\cdot 10^{16}\,\mathrm{cm} \left(\frac{t_3 E_{53} v_8}{\dot{m}_{21}}\right)^{1/2}\Big|_{s=2}$$

- Integernal energy of the plasma: $\varepsilon \approx \Gamma^2 \rho$

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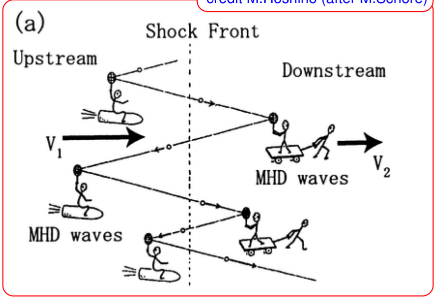
GRB is relativistic version of SN explosions

- Shock acceleration is a very important mechanism for production of cosmic rays
- It is fairly well understood in the non-relativistic regime, but **not in the relativistic one**
- GRB afterglows are produced by relativistic shocks in their simplest realization
- Conditions at the FS disfavor hadronic processes
- Because of the synchrotron burn-off limit, emission detected in the VHE regime is expected to be **of IC origin**

credit M.Hoshino (after M.Schore)



Diffusive shock acceleration

- Power-law spectrum with $\frac{dN}{dE} \propto E^{-s}$ where $s = \frac{v_1/v_2+2}{v_1/v_2-1} \approx 2$
- Acceleration time $t_{\rm ACC} \approx \frac{2\pi r_{\rm G}}{c}\left(\frac{c}{v_1}\right)^2$

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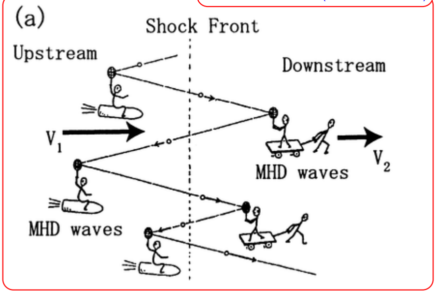

Relativistic shocks

- Particles can get a significant energy by shock crossing, but
- Particles **do not** have time to **isotropize** in the downstream

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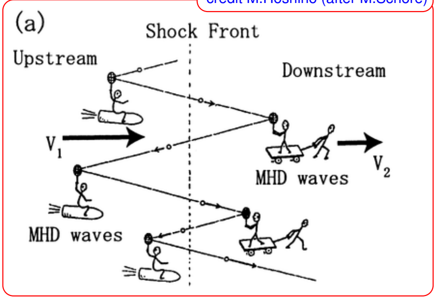

Relativistic shocks

- Forward shock propagates through ISM medium (or stellar wind)
- There is a self-similar hydrodynamic model (Blandford&McKee1976)

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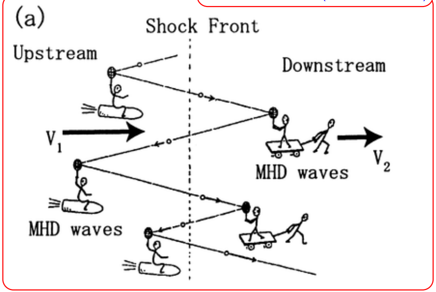

Hadronic processes' efficiency

- Dynamic time-scale: $t_{\rm dyn} = R/(c\Gamma)$
- Efficiency: $\kappa = t_{\rm dyn}/t_{\rm cool}$
- proton-proton $\kappa_{pp} \sim 10^{-7}\left(R/10^{18}\,{\rm cm}\right) n_0$

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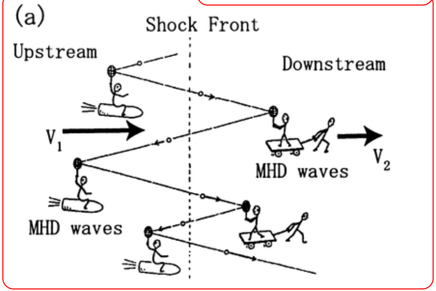


Synchrotron burn-off limit

- Synchrotron cooling time: $t_{\rm SYN} \approx 400 E_{\rm TeV}^{-1} B_{\rm B}^{-2}$ s
- Acceleration time: $t_{\rm ACC} \approx 0.1 \eta E_{\rm TeV} B_{\rm B}^{-1}$
- Max energy: $\hbar\omega < 200 \frac{\Gamma}{\eta}$ MeV

Internal $\gamma-\gamma$ absorption and the Klein-Nishina effect

GRB produces a lot of high-energy photons, these photons make an important target for the IC emission and may provide target for VHE gamma rays. There are important consequences:

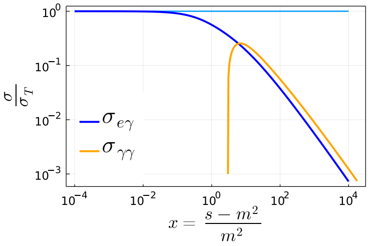
- The Klein-Nishina cutoff
- Internal $\gamma-\gamma$ attenuation

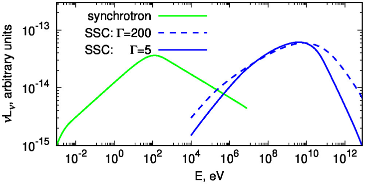
These effects are important if

$$1 < \frac{\hbar\omega_{\rm syn} E}{\Gamma^2 m_e^2 c^4} \approx \frac{4\times 10^3}{\Gamma^2}\omega_{\rm syn,keV} E_{\rm TeV}$$

Internal $\gamma-\gamma$ optical depth

$$\tau \approx \frac{\sigma_{\gamma\gamma} L_{\rm X}}{10\varepsilon_{\rm X} c R \Gamma^2} \propto E^{-1/2}$$

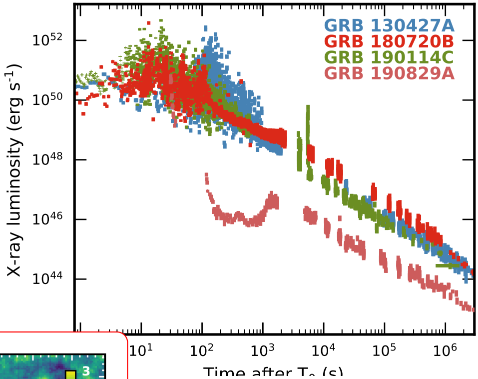


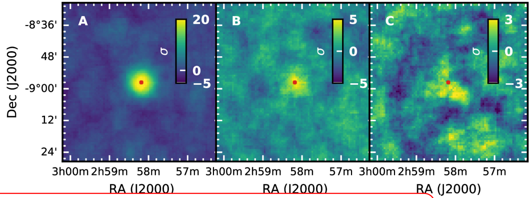


GRB 190829A

- Very close:
  $z = 0.0785 \pm 0.0005$
- Detected by GBM and BAT
- Prompt luminosity
  $\sim 10^{50}\,\mathrm{erg}$ per decade
  in the X-ray band
- Afterglow luminosity
  $5 \times 10^{50}\,\mathrm{erg}$

Hinton (Taup2019)





detected with H.E.S.S. for **3 nights (H.E.S.S. Collaboration 2021)**

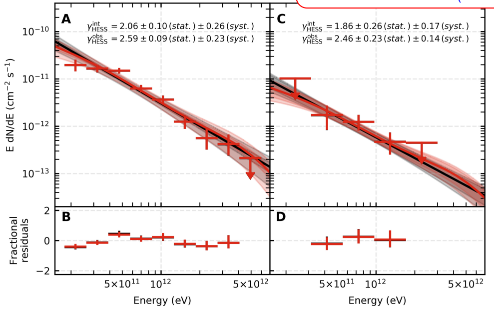
- $T_0 + 4.3\mathrm{h}$: **21.7σ**
- $T_0 + 27.2\mathrm{h}$: 5.5σ
- **$T_0 + 51.2\mathrm{h}$**: 2.4σ

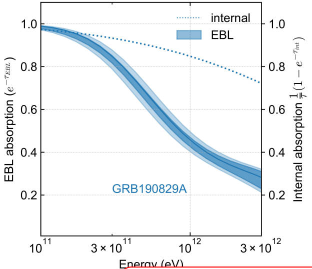
GRB 190829A: VHE spectrum

- Almost model independent of EBL absorption
- Weak internal absorption
- Fit the intrinsic spectrum

$$\frac{dN}{dE} \propto E^{-\gamma_{\mathrm{VHE}}^{\mathrm{int}}} e^{-\tau_{\mathrm{EBL}}} \propto E^{-\gamma_{\mathrm{VHE}}^{\mathrm{obs}}}$$

H.E.S.S. Collaboration (2021)





H.E.S.S. Collaboration (2021)

Observed spectrum

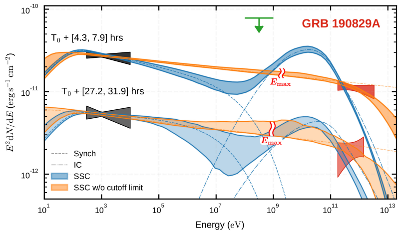
- night 1: $\gamma_{\mathrm{VHE}}^{\mathrm{obs}} = 2.59^{+0.09}_{-0.09}$
- night 2: $\gamma_{\mathrm{VHE}}^{\mathrm{obs}} = 2.46^{+0.23}_{-0.23}$

Intrinsic spectrum

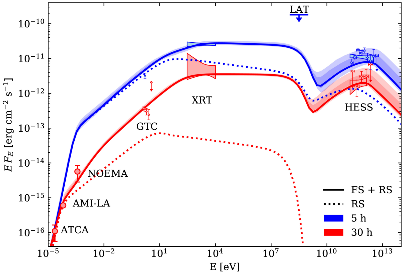
- night 1: $\gamma_{\mathrm{VHE}}^{\mathrm{int}} = 2.06^{+0.1}_{-0.1}$
- night 2: $\gamma_{\mathrm{VHE}}^{\mathrm{int}} = 1.86^{+0.26}_{-0.26}$
- all: $\gamma_{\mathrm{VHE}}^{\mathrm{int}} = 2.07^{+0.09}_{-0.09}$

GRB 190829A: Modelling

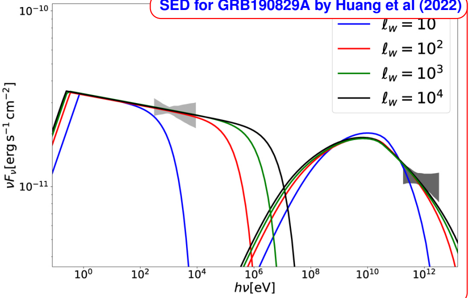
H.E.S.S. Collaboration (2021)



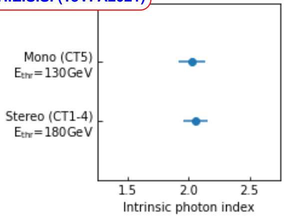
SSC model for GRB190829A from Salafia+(2021)



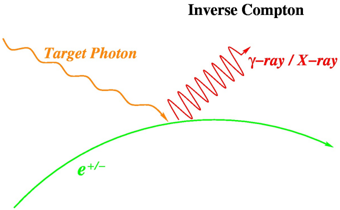
SED for GRB190829A by Huang et al (2022)



H.E.S.S. (TeVPA2021)



Well-known properties of IC



$$(pk) = E_e\varepsilon(1 - \beta\cos\theta) \sim E_e\varepsilon < m_e^2c^4$$

yes:

- Scattering rate: $\propto w_{\rm ph}$
- Characteristic energy: $\approx \varepsilon\gamma^2$
- Spectral slope: $(\alpha + 1)/2$

no:

- Scattering rate: $\propto n_{\rm ph}$
- Characteristic energy: $\approx m_e c^2\gamma$
- Spectral slope: $\alpha + 1$

Klein-Nishina cutoff in SSC

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}\omega\mathrm{d}t} = c\int \mathrm{d}E_e\mathrm{d}\varepsilon\ldots\frac{\mathrm{d}\sigma_{\rm ic}}{\mathrm{d}\omega}n_e n_{\rm ph}$$

for the majority of the photon energies, a faction of the target is up-scattered in the Thomson regime. Since the "Thomson cross-section" is larger than the "Klein-Nishina cross-section", this could be the most important contribution:

$$\frac{\mathrm{d}N_\gamma^{\rm T}}{\mathrm{d}\omega\mathrm{d}t} \propto \int \mathrm{d}E_e\mathrm{d}\varepsilon\frac{1}{\omega}E^2\varepsilon n_e(E)n_{\rm ph}(\varepsilon)\delta\left(\omega-\varepsilon E^2\right)$$

For power-law distributions of electrons, $n_e \propto E_e^{-\alpha}$, and photons, $n_{\rm ph} \propto \varepsilon^{-\beta}$, it is trivial to get the analytic result:

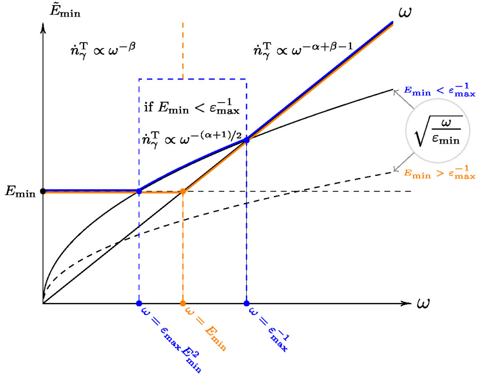
$$\frac{\mathrm{d}N_\gamma^{\rm T}}{\mathrm{d}\omega\mathrm{d}t} \propto \frac{\omega^{-\beta}}{2\beta-\alpha-1}\left(\tilde{E}_{\rm max}^{2\beta-\alpha-1}-\tilde{E}_{\rm min}^{2\beta-\alpha-1}\right)$$

If $\alpha > 2\beta - 1$

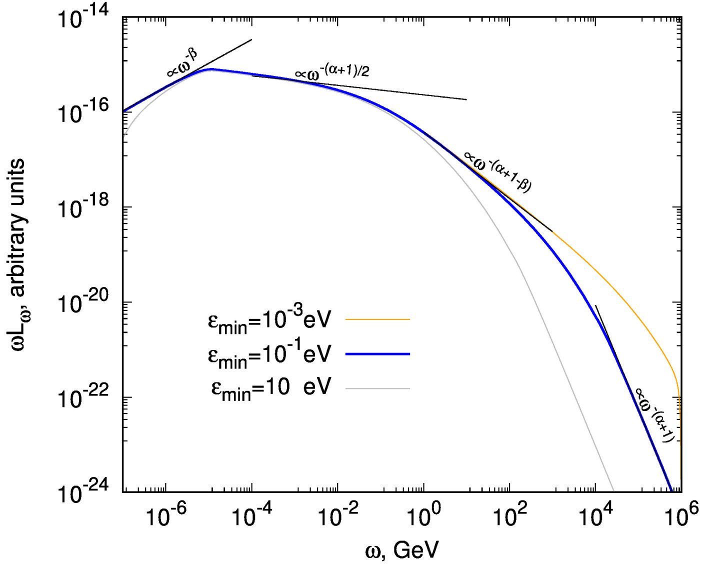
$$\frac{dN_\gamma^T}{d\omega dt} \propto \begin{cases} \omega^{-\beta} & \text{if} \quad \omega < \varepsilon_{max} E_{min}^2 \quad \text{and} \quad \omega < E_{min}\,, \\ \omega^{-(\alpha+1)/2} & \text{if} \quad \omega > \varepsilon_{max} E_{min}^2 \quad \text{and} \quad \omega < \dfrac{1}{\varepsilon_{max}}\,, \\ \omega^{-(\alpha+1)+\beta} & \text{if} \quad \omega > E_{min} \quad \text{and} \quad \omega > \dfrac{1}{\varepsilon_{max}}\,. \end{cases}$$

$$\tilde{E}_{min} = \max\left(\omega, E_{min}, \sqrt{\frac{\omega}{\varepsilon_{max}}}\right)$$

the interplay between these conditions is the easiest seen from the figure ⇒



numerical check



If $\alpha < 2\beta - 1$

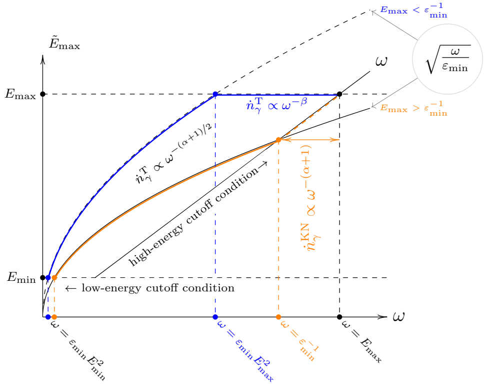
$$\frac{\mathrm{d}N_\gamma^{\mathrm{T}}}{\mathrm{d}\omega \mathrm{d}t} \propto \begin{cases} \omega^{-(\alpha+1)/2} & \text{if} \quad \omega < \varepsilon_{\min} E_{\max}^2 \,, \\ \omega^{-\beta} & \text{if} \quad \omega > \varepsilon_{\min} E_{\max}^2 \,. \end{cases}$$

$$\tilde{E}_{\max} = \min\left(E_{\max}, \sqrt{\frac{\omega}{\varepsilon_{\min}}}\right)$$

the interplay between these conditions and emerges of the cutoffs are the easiest seen from the figure ⇒

In particular, the spectra typical for the Klein-Nishina, $\alpha + 1$, should appear at energies:

$$\omega_{\mathrm{kn}} \sim \frac{m_e^2 c^4}{\varepsilon_{\min}}$$



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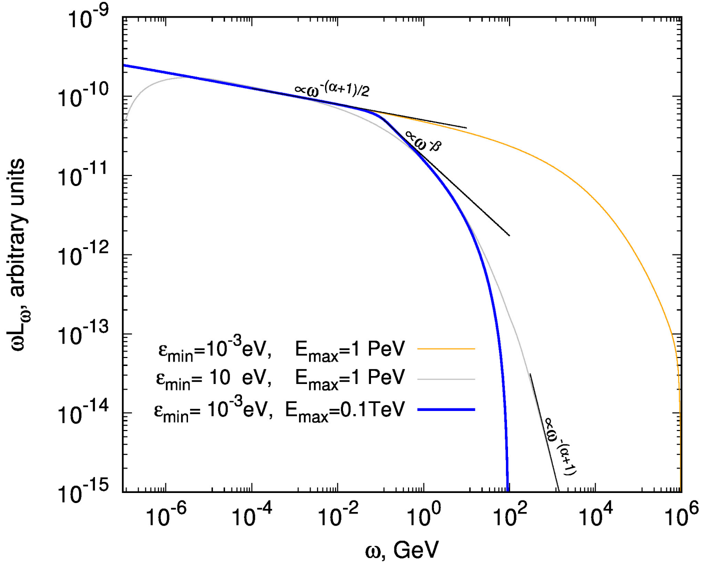


Hard VHE emission via IC?

Apparently, there are only two options to make IC spectrum hard:

- ☞ Form a hard electron distribution
- ☞ Have a low-energy target

- If the low-energy photons are local, then it requires a very fast synchrotron cooling (strong field)
- If the low-energy photons are external, then 2 day detection of GRB 190829A implies a huge physical size of the photon source

Doesn't work?

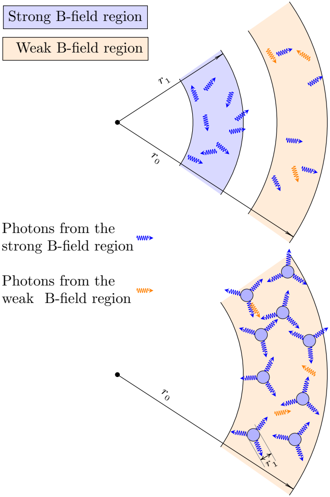
- $\propto n_e \propto \frac{1}{\dot\gamma}\int\limits_\gamma^\infty \mathrm{d}\gamma\, q$
- if synchrotron losses dominate, $\dot\gamma \propto \gamma^2$ then it is impossible (?) to make a sufficiently hard spectrum
- if IC losses dominate, then IC component should also dominate (which is not seen)

Doesn't work?

Multi-zone models

- ☞ Standard SSC or EIC models face certain difficulties in explaining VHE detection of GRB 190829A
- ☞ In which direction should one develop models? There are options, e.g.,
  - Particle acceleration process? (Derishev&Piran 2016, 2021)
  - Multi-zone setup?
  - ...
- ☞ What could be the different zones? ⇒
  - RS and FS
  - Magnetic field amplification regions

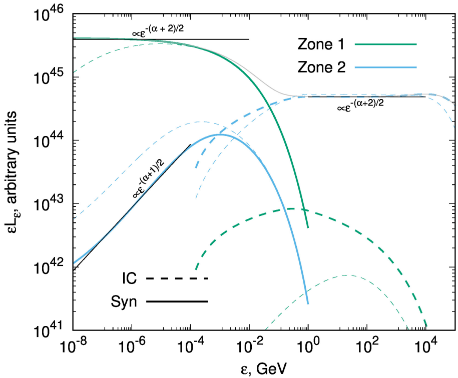
The circumburst magnetic field of $B_{\rm cbm} \sim 10\mu{\rm G}$ is enhanced by the shock compression to $B_0 \sim 1{\rm mG}$. Modelling however favor $\sim {\rm G}$ strength.



Two zones with very different magnetic fields

$$\frac{\partial n_1}{\partial t} + \frac{\partial \dot{E}_1 n_1}{\partial E} = q_1(E) - \frac{n_1}{\tau_{1\to2}} + \frac{n_2}{\tau_{2\to1}}\,,$$

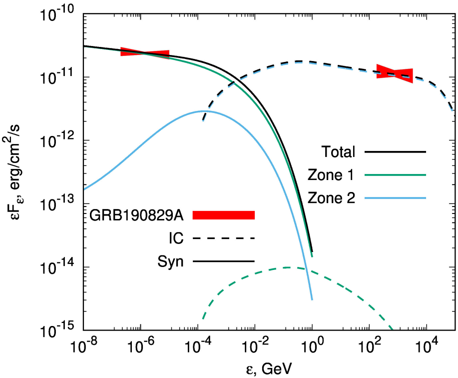
$$\frac{\partial n_2}{\partial t} + \frac{\partial \dot{E}_2 n_2}{\partial E} = q_2(E) + \frac{n_1}{\tau_{1\to2}} - \frac{n_2}{\tau_{2\to1}}\,.$$



Two zones with very different magnetic fields

$$\frac{\partial n_1}{\partial t} + \frac{\partial \dot{E}_1 n_1}{\partial E} = q_1(E) - \frac{n_1}{\tau_{1\to2}} + \frac{n_2}{\tau_{2\to1}},$$

$$\frac{\partial n_2}{\partial t} + \frac{\partial \dot{E}_2 n_2}{\partial E} = q_2(E) + \frac{n_1}{\tau_{1\to2}} - \frac{n_2}{\tau_{2\to1}}.$$



Summary

- Detection (at least some) of GRB afterglow in the VHE regime challenge the ability of the standard SSC model to reproduce the observations
- Alternative (hadronic or synchrotron-only) models require extreme assumptions, thus it is important to better understand the limitations of IC scenarios (SSC or EIC)
- Some basic properties of SSC models can be obtained analytically (under the δ-functional approximation), which helps to understand these limitations
- Multi-zone setup seems to be quite a natural feature of GRB forward shock, thus provides a feasible direction for SSC models
- Considering two-zone models with very different magnetic fields allows one to reproduce the hard VHE with a SSC model