GeV-TeV Radiation in GRBs and Insights on Cosmis Rays

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Abhijit Roy, Khushboo Sharma (ARIES)

Outline

Introduction

- Gamma Ray Bursts Emission
- Radiation Mechanism in GRBs

GeV-TeV GRBs in Afterglows

- Constrains on the Radiation Mechanisms

Neutrino from GRBs

- GRB Classes and Neutrino/CR Fluxes

Summary and Conclusion

Gamma Ray Bursts (GRBs)

- GRBs are transient and extra-galactic objects: Red-shift (z): 0.008 to 9.4.
- The Isotropic gamma-ray (keV-MeV) energy released during the prompt phase: 10^{49} to 10^{55} erg. $[M_{\odot} c^2 \sim 2 \times 10^{54} \ \mathrm{erg}]$
- The GRB event lasts from ms to 1000’s second, however, the afterglow duration is prolonged.

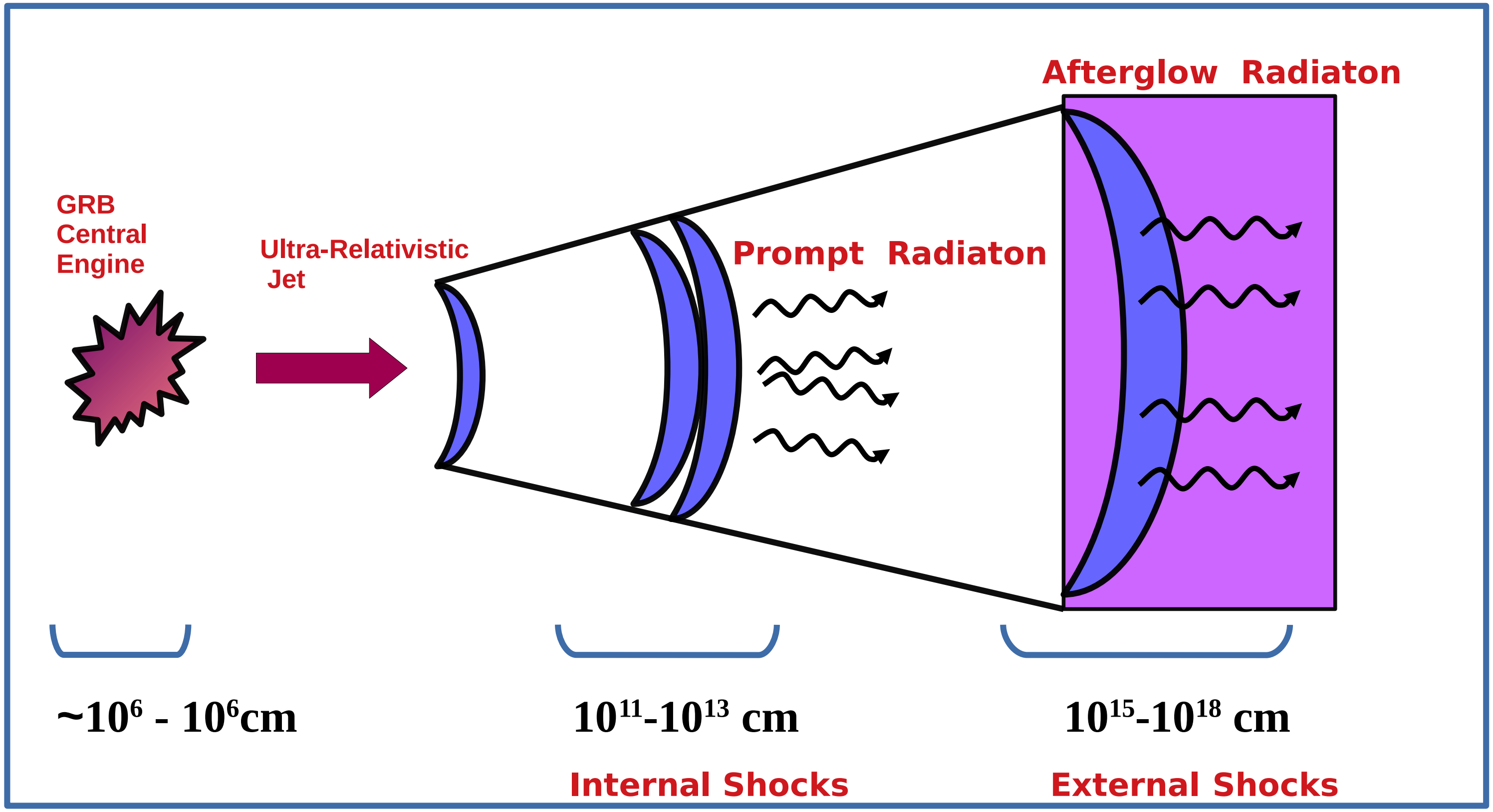
Eletromagnetic signature:

- Radio to TeV gamma rays.

Non-electromagnetic signature:

- Cosmic Rays and Neutrinos + Gravitational waves.

Fireball Model: Shock Formation



Expansion due to radiation pressure:

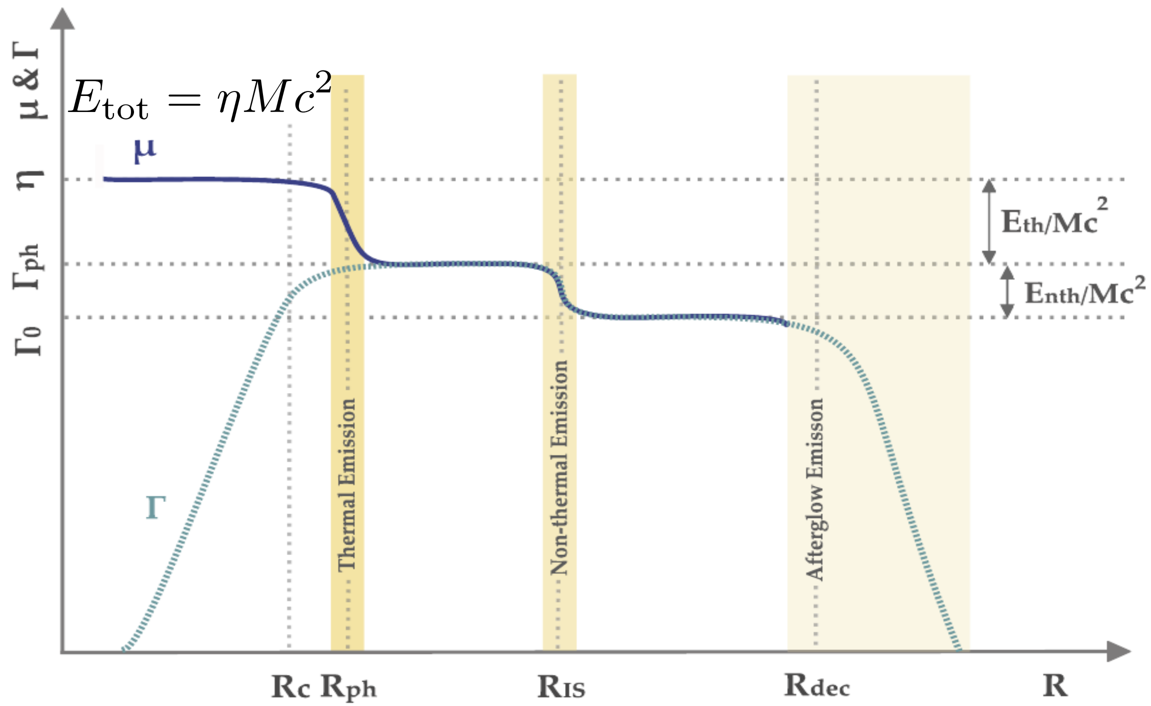
$$R_0 \approx 10^7 \text{ cm}, \qquad L \sim 10^{52}\text{erg/s}$$

$$L = 4\pi r_0^2 \sigma T^4, \quad T = 1.7\text{MeV}$$

External Shocks form when:

$$\frac{E_k}{2} = \Gamma_0^2 M_{\text{sw}} c^2$$

GRB: Properties

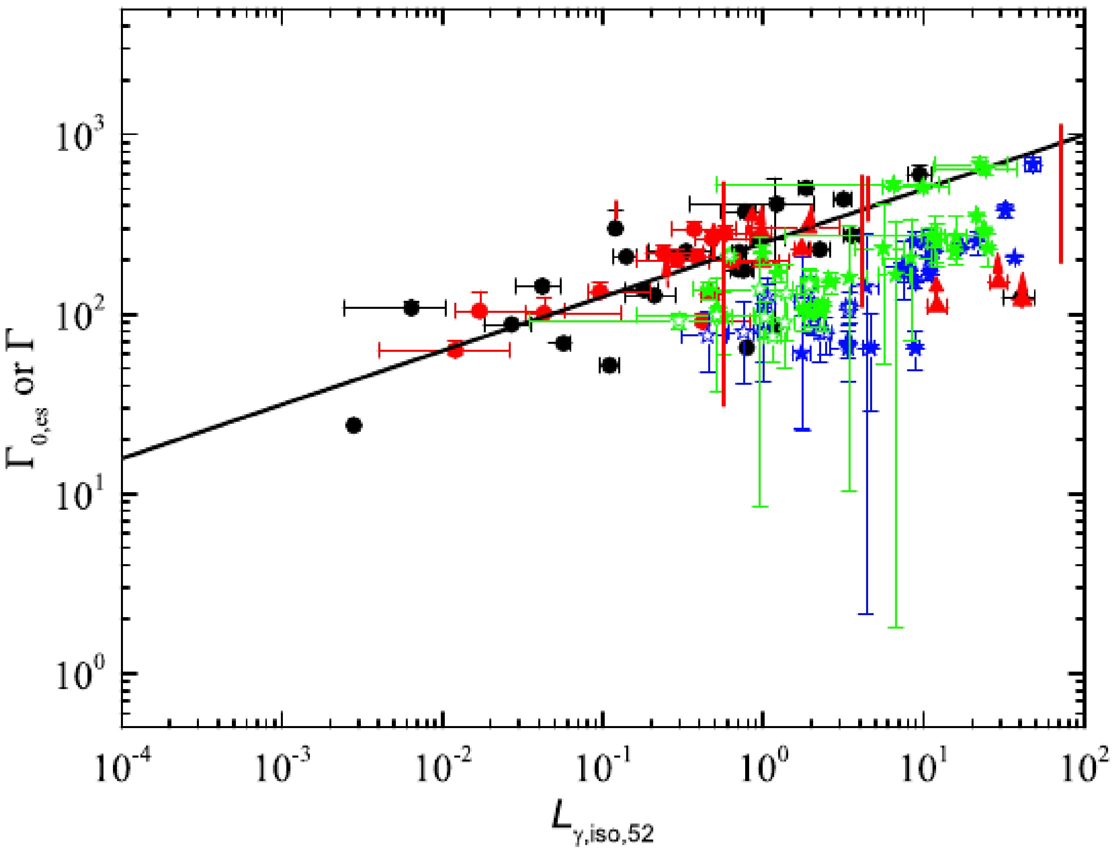


Prompt Phase **Afterglow Phase**

$$\Gamma_0 = \left[\left(\frac{3-s}{2^{5-s}\pi}\right)\left(\frac{E_k}{n_0 m_p c^{5-s}}\right)\right]^{1/(8-2s)}\left(\frac{t_p}{(1+z)}\right)^{-\frac{3-s}{8-2s}} ; \quad s = 0 \text{ [ISM]}, \ \text{s} = 2 \text{ [Wind]}$$

Zhang, Wang & Li (2021), ApJL 909, L3
Sari & Piran (1999), ApJ, 520, 641

GRB Luminosity vs Lorentz Factor



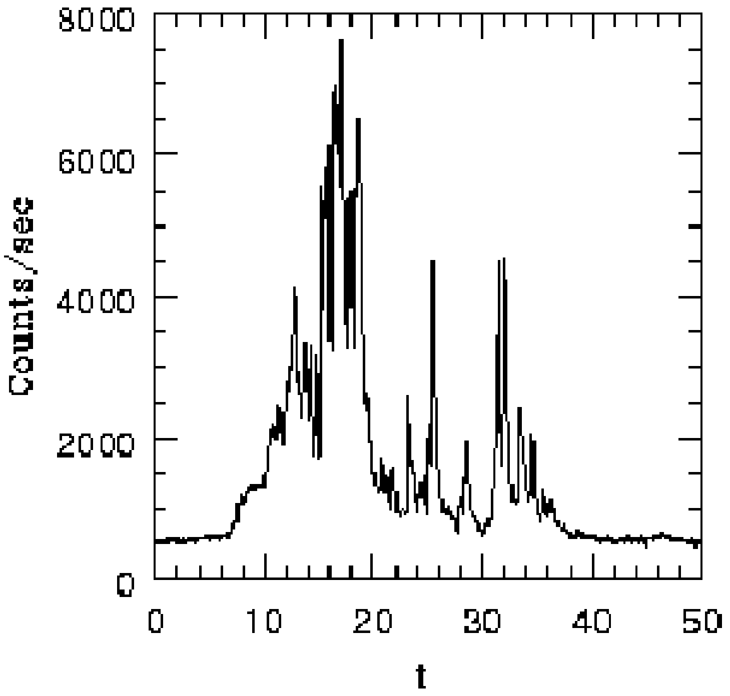
Based on the kinetic energy in the afterglow and circumburst medium density.

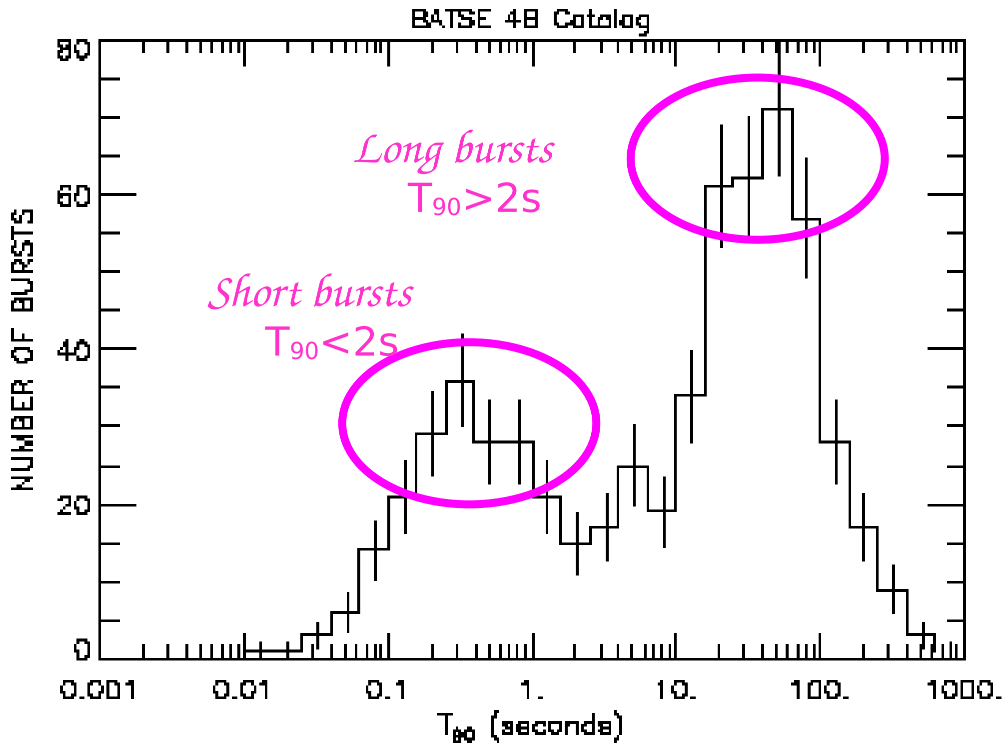
Jing Li et al. (2022), ApJ 943, 145

GRBs: Prompt Radiation

- Highly variable prompt gamma-ray emission.

$$R_s \leq \Gamma c \delta t; \quad \Gamma[100-1000] \quad \delta t[\mathrm{ms}-\mathrm{s}]$$





Two source population!!

Based on the duration of prompt gamma-ray emission.

GRBs: Prompt Radiation

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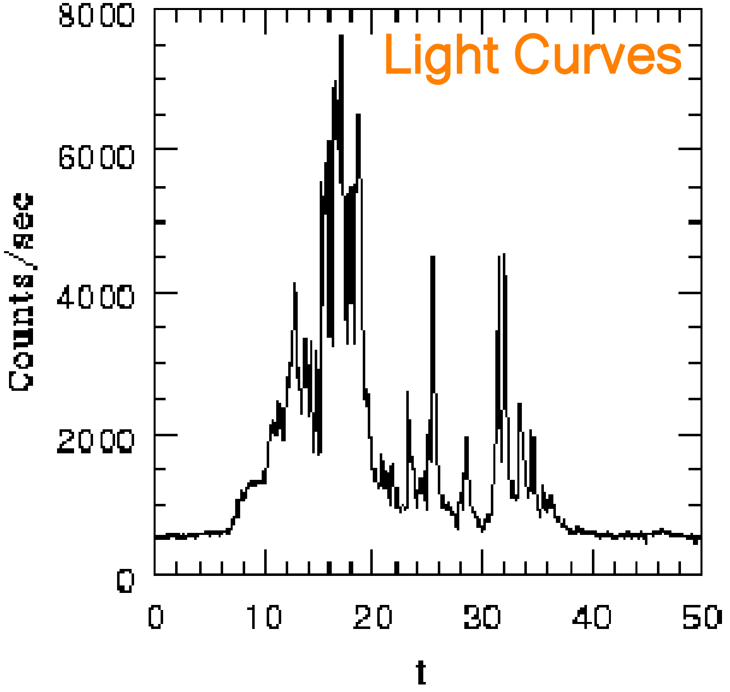
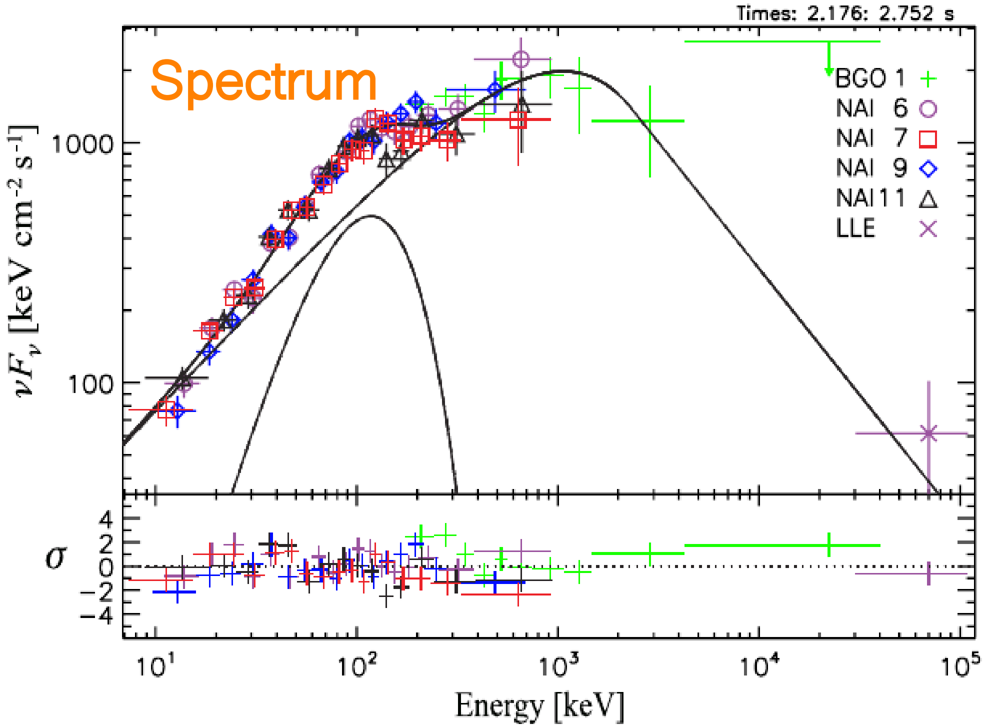


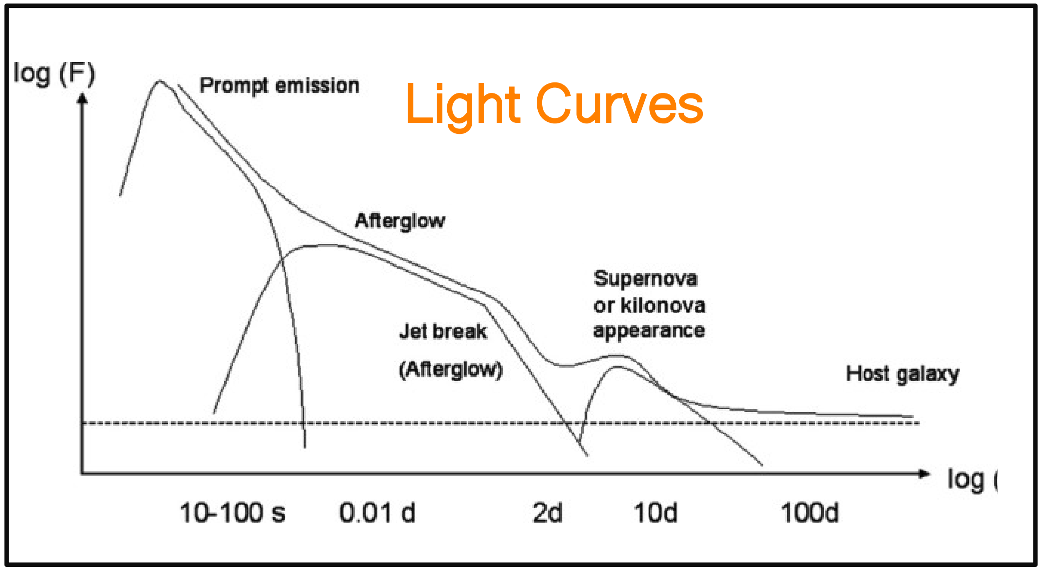


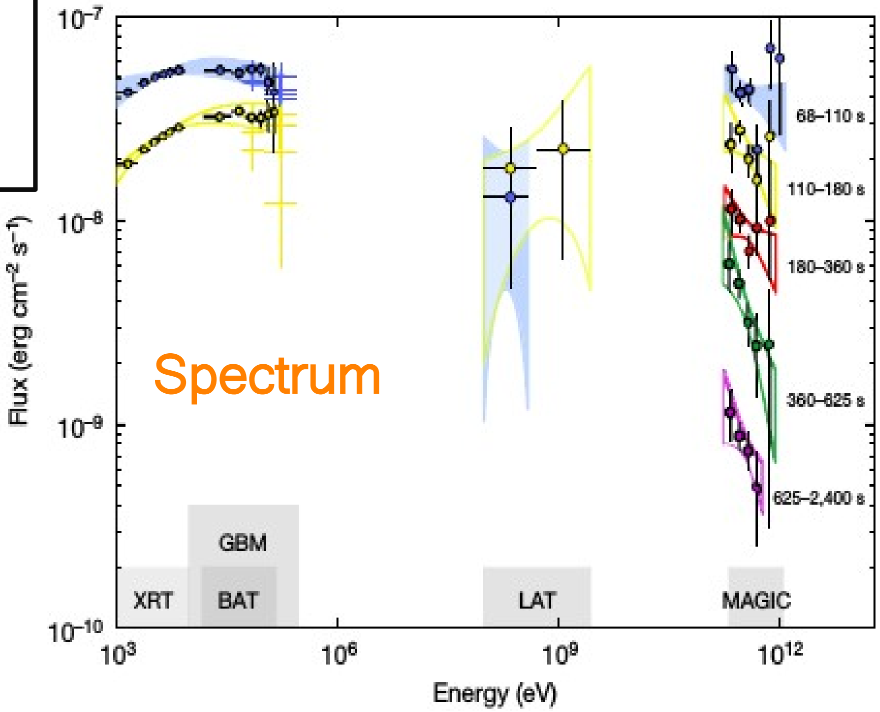
Thermal + non-thermal: Matter jet
Non-thermal only: Poynting jet

S. Iyyani et al. (2013), MNRAS 433, 2739

GRBs: Afterglow Radiation

- After the prompt radiation a prolonged radiation is observed.





A. Volnova et al. (2021), book series (CCIS,volume 1427)

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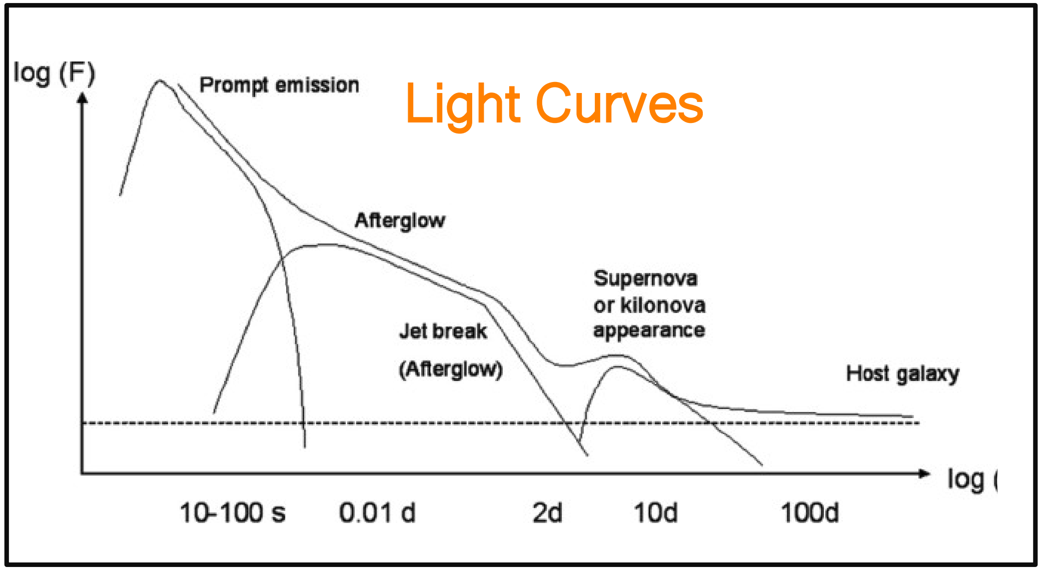
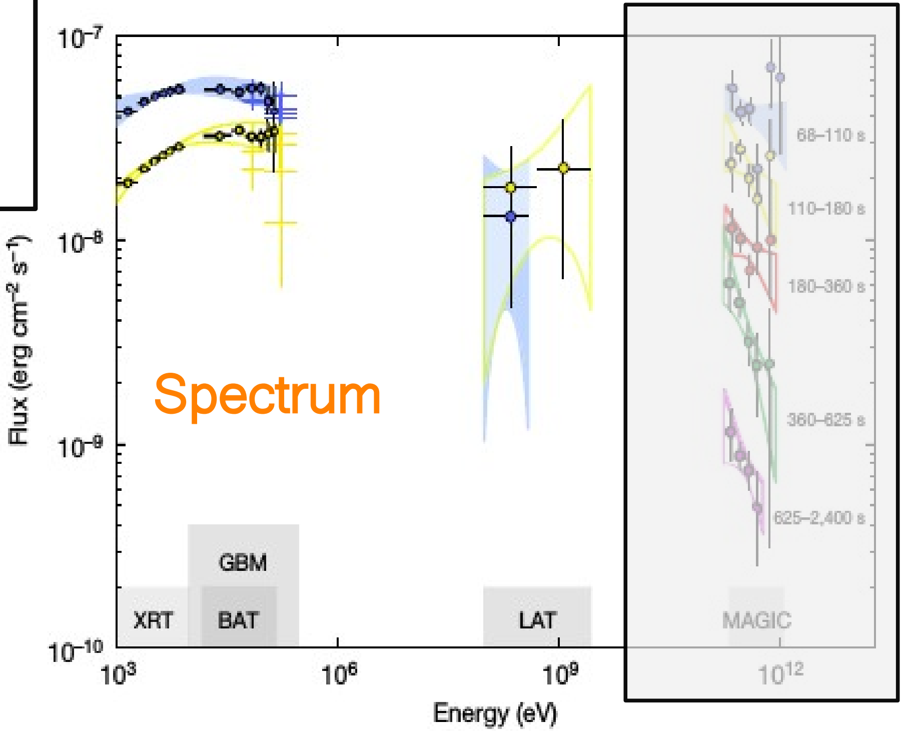


Detection of GeV-TeV component has been possible due to fast response from Cherenkov telescopes!!



A. Volnova et al. (2021), book series (CCIS,volume 1427)

Open Questions: Prompt/Afterglow

- GRB jet composition and their radiative efficiency
- Energy dissipation mechanisms in the jet: Thermal vs Non-thermal,
- Radius of the prompt and afterglow emission,
- Radiation mechanism: Radio to TeV emission,
- Do GRBs produce cosmic rays and neutrinos?

Meszaros & Rees (1997), ApJ 476, 232
Zhang, Wang & Li (2021), ApJL 909, L3

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Zhang, Wang & Li (2021), ApJL 909, L3

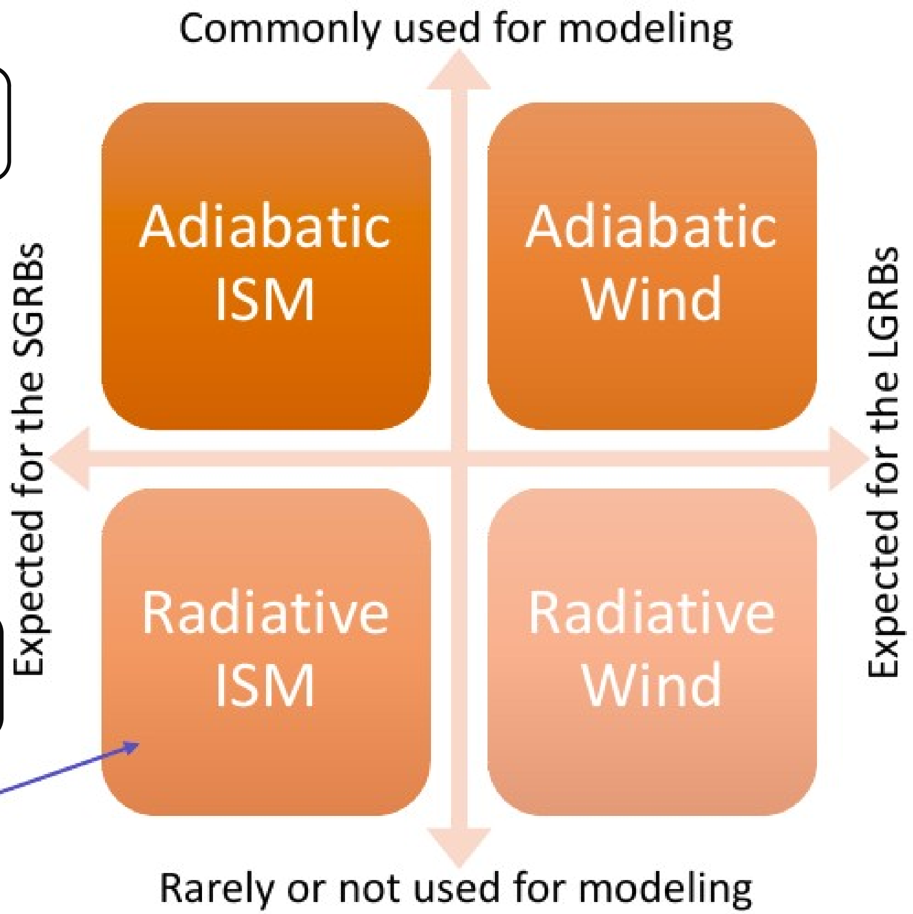
Radiation Mechanism in GRBs: Radio to TeV Afterglows

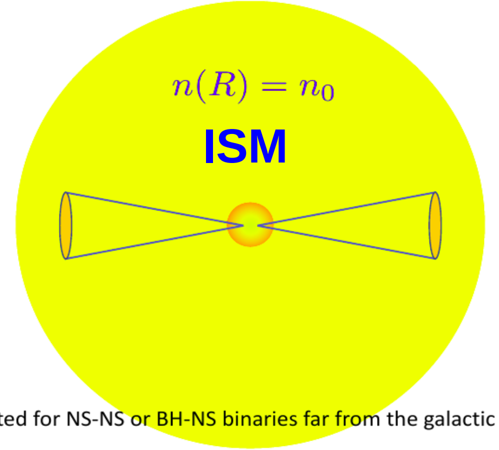
Afterglow Radiation and Environments

$\varepsilon_e < 0.3$

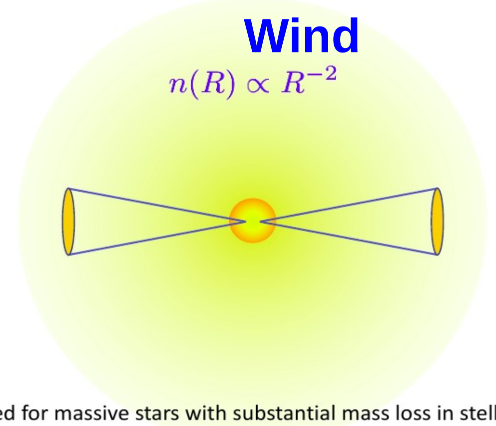
$\varepsilon_e > 0.5$

Ghisellini+2010





Expected for NS-NS or BH-NS binaries far from the galactic plane



Expected for massive stars with substantial mass loss in stellar wind

Ghisellini et al. (2010), MNRAS 403, 926

Blast Wave Dynamics: Parameters

The BLF (Γ) of the external shock:

$$\Gamma \simeq \begin{cases} \left(\frac{E_k v_w}{4\dot{M} c^3 t}\right)^{1/4} ; & \text{WIND} \\ \left(\frac{3E_k}{8\pi\rho_0 c^5 t^3}\right)^{1/8} ; & \text{ISM} \end{cases}$$

Afterglow Model Parameters:

- **E_k** : Isotropic equivalent kinetic energy in afterglow
- **Γ_0** : Bulk Lorentz factor
- **A^*, n_0** : Circumburst medium density
- **p** : Spectral index of accelerated particles
- **$\varepsilon_B, \varepsilon_e$** : Fraction of shock energy going to electrons and magnetic field.

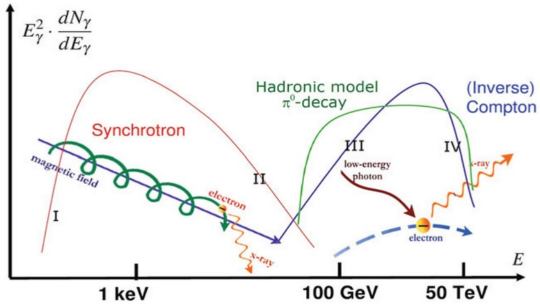
- Total shock energy is distributed among particles and magnetic fields.

$$\varepsilon_B + \varepsilon_e + \varepsilon_A \sim 1$$

Blandford & Mckee (1976), Phys. Fluids 19, 1130
Meszaros & Rees (1997), ApJ 476, 232

Radiative process efficiency: VHE

$$\kappa = \frac{t_{\rm dyn}}{t_{\rm cool}} \geq 1 \quad \Longrightarrow \quad \text{Efficient Process}$$



Hadronic $\Longrightarrow$

$$\kappa_{p-\gamma} \approx 3 \times 10^{-4} \left[\frac{\Gamma}{20}\right]^2 \left[\frac{R}{10^{18}\rm cm}\right] \left[\frac{\epsilon_t}{1\rm keV}\right]^{-1} n_0$$

$$\kappa_{p-p} \approx 10^{-7} \left[\frac{R}{10^{18}\rm cm}\right] n_0$$

Leptonic $\Longrightarrow$

$$\kappa_{\rm sync} \approx 5 \times 10^{7} \left[\frac{R}{10^{18}\rm cm}\right] \left[\frac{\epsilon_B}{0.1}\right]^{3/4} n_0^{3/4}$$

$$\kappa_{\rm IC} = 3 \left[\frac{\Gamma}{20}\right] \left[\frac{R}{10^{18}\rm cm}\right] \left[\frac{\epsilon_t}{1\rm keV}\right]^{-1/2} n_0$$

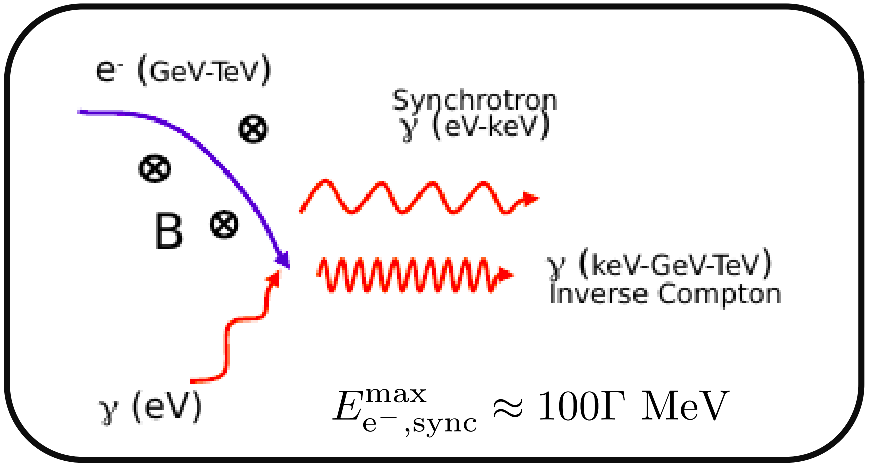
HESS Collaboration (2019), Nature 575, 464
M. Spurio, Particles & Astrophysics, Springer

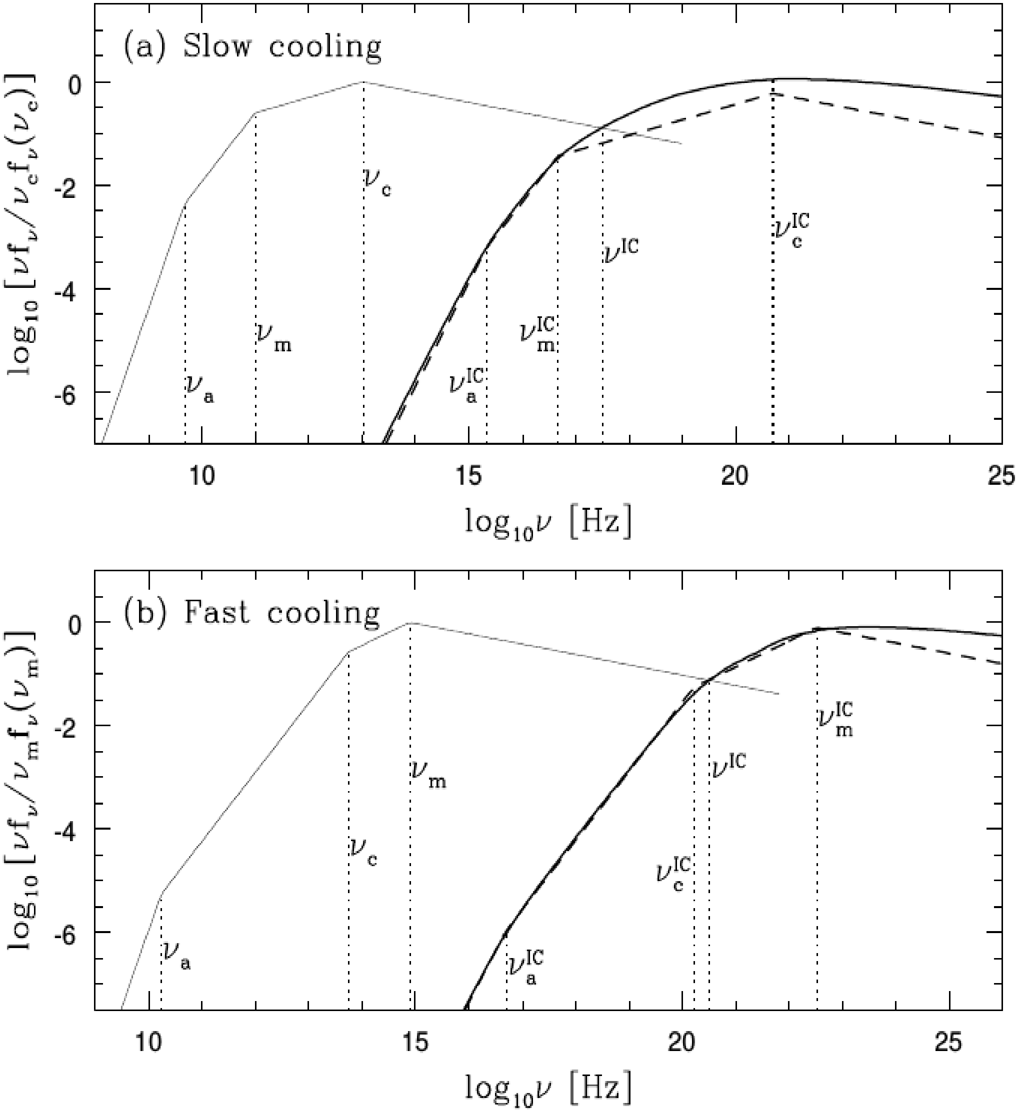
SSC Emission: Radio to TeV Radiation

Energy of SSC photons:

$$E_{\rm SSC,Th} \propto \gamma_e^2 E_{\rm sync} \qquad > {\rm GeV}$$

$$E_{\rm SSC,KN} \propto \Gamma \gamma_e m_e c^2 \qquad > {\rm GeV}$$





Sari, Piran & Narayan (1998), ApJL 497, 17
Zhang & Meszaros (2001), ApJ 559,110
Piran & Nakar (2010) ApJL 718, 63

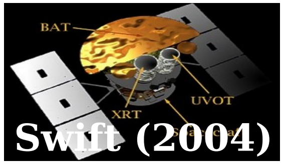
GeV-TeV GRBs in Afterglows

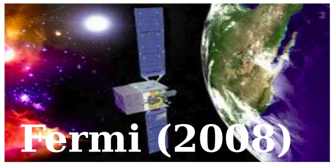
Radio to TeV Detectors

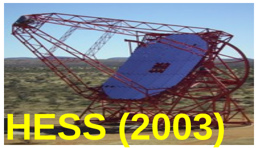
AGILE, INTEGRAL, Konus-Wind (gamma-ray), SVOM (X-ray), AstroSAT (X-ray), nuSTAR (X-ray) and Radio detectors etc.

- HESS(2003), MAGIC(2004), VERITAS(2005), HAWC(2013), LHASSO(2019), MACE (2020) and Upcoming CTA, (Few x 100 GeV – Few x 100 TeV).
- Swift BAT locates the GRB and then the afterglow emission is followed.

- **Swift (2004 onwards):** Burst Alert Telescope (BAT, 15-150 keV)
  X-ray telescope (XRT, 0.3-10 keV)
  Optical telescope (UVOT, 170-600 nm).
- **Fermi (2008 onwards):** Gamma-ray burst moniter (GBM, 8 keV – 30 MeV)
  Large Area Telescope (LAT, 20 MeV- 300 GeV).







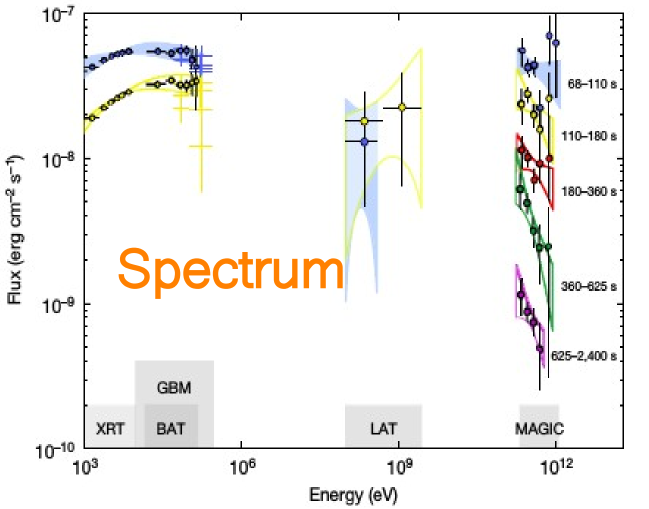
GeV-TeV GRB Sample

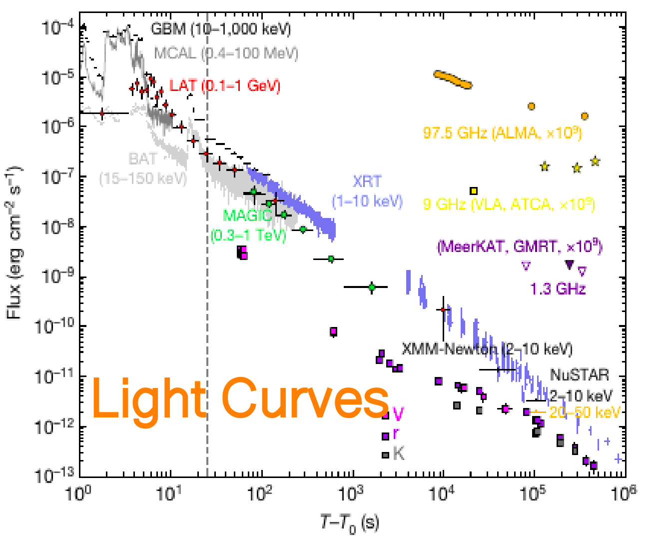
Objects	Energy Range	Type	Eg,iso (erg)	Redshift
GRB 180720B	H.E.S.S. [100 - 440] GeV	Standard LGRB	6×10^{53}	0.658
GRB190114C	MAGIC [0.3 - 1] TeV	Standard LGRB	3×10^{53}	0.4245
GRB 190829A	H.E.S.S. [0.2 - 4] TeV	Low-Luminosity	2×10^{50}	0.0785
GRB 221009A	LHAASO [0.1- 7] TeV	LGRB/BOAT	3×10^{54}	0.151
GRB 201216C	MAGIC [70 -200] GeV	Standard LGRB	6×10^{53}	1.1

TeV Catalog, http://tevcat.uchicago.edu/

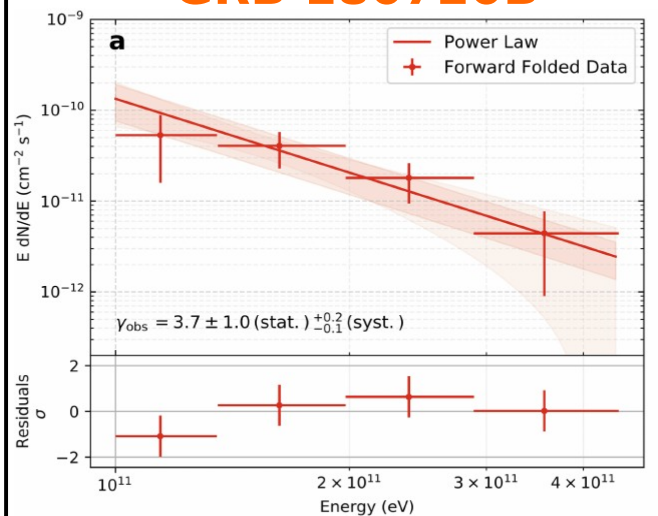
Multi-Wavelength Observations: SED

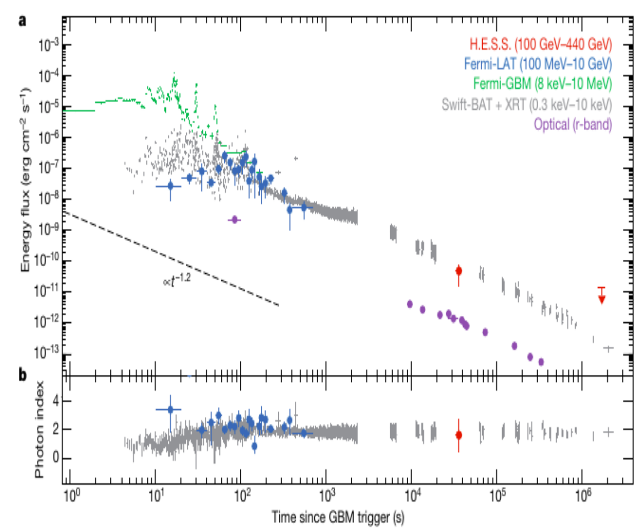
GRB 190114C



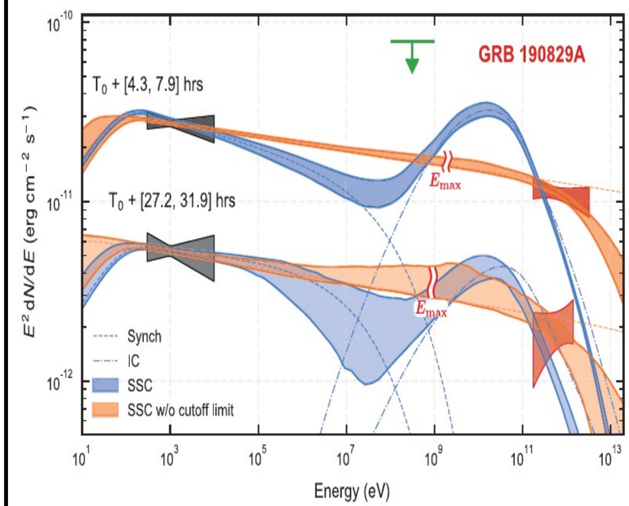


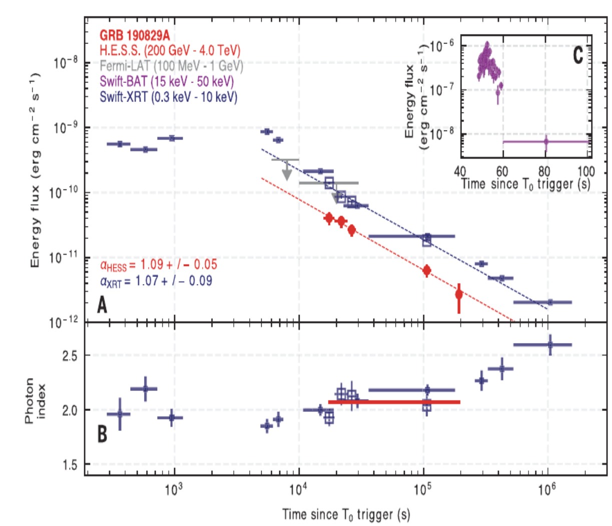
GRB 180720B





GRB 190829A

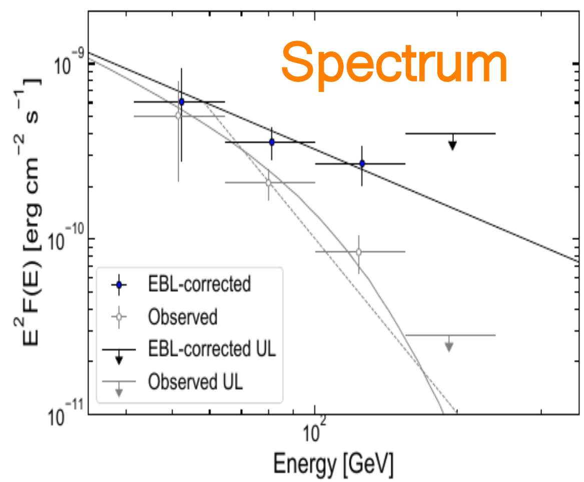


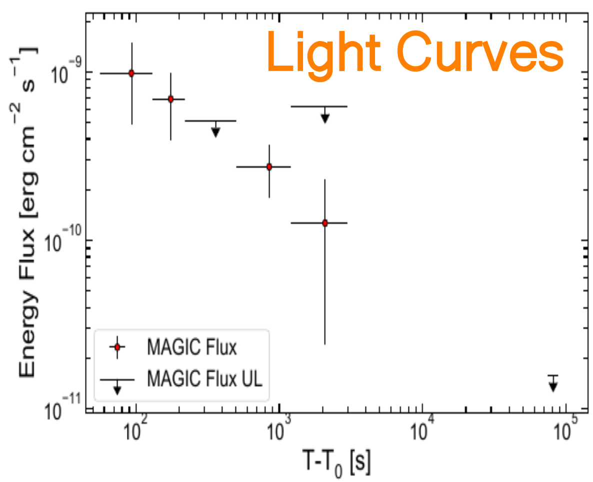


MAGIC Collaboration (2019), Nature 575, 455
HESS Collaboration (2019), Nature 575, 464
HESS Collaboration (2021), Science 372, 1081

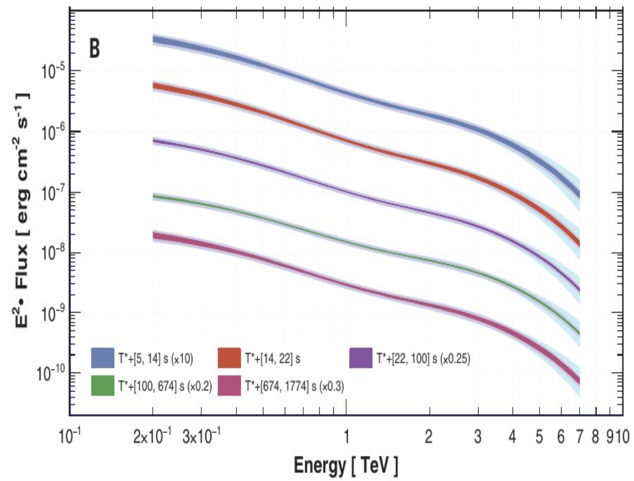
Multi-Wavelength Observations: SED

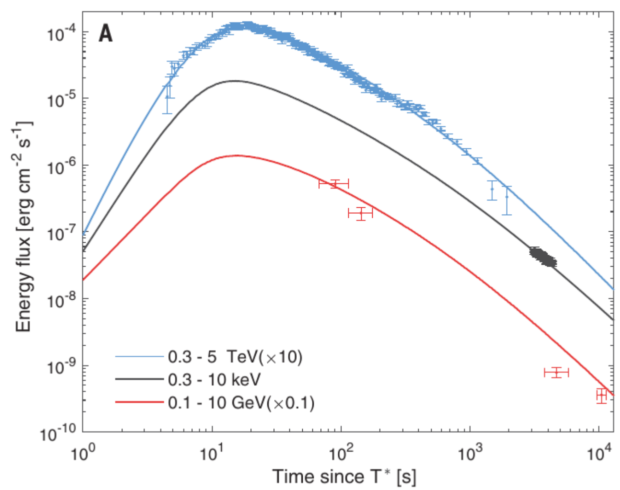
GRB 201216C





GRB 221009A



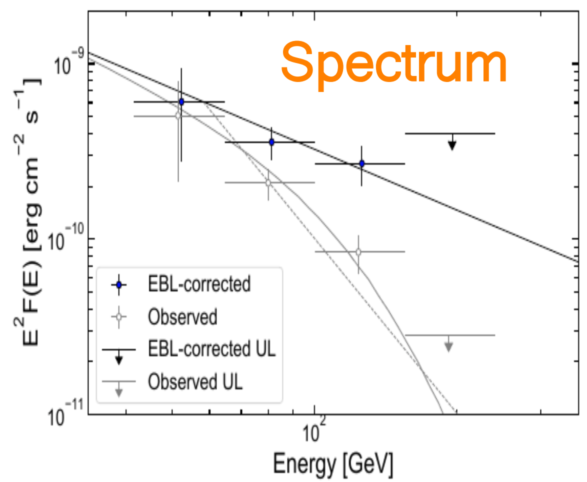


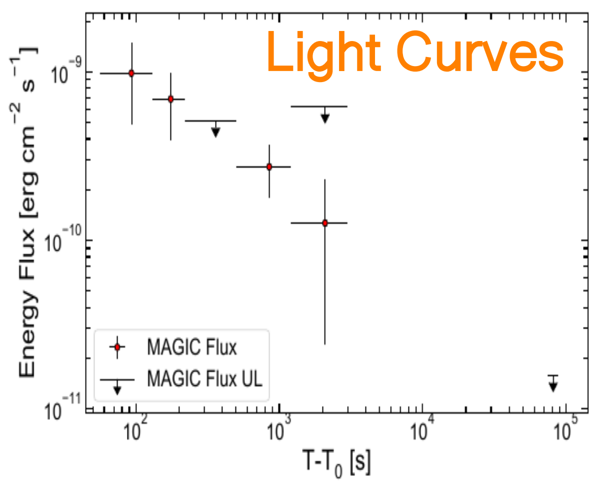
Properties!!

MAGIC Collaboration (2023), MNRAS 527, 3
LHAASO Collaboration (2023), Science 380, 1390

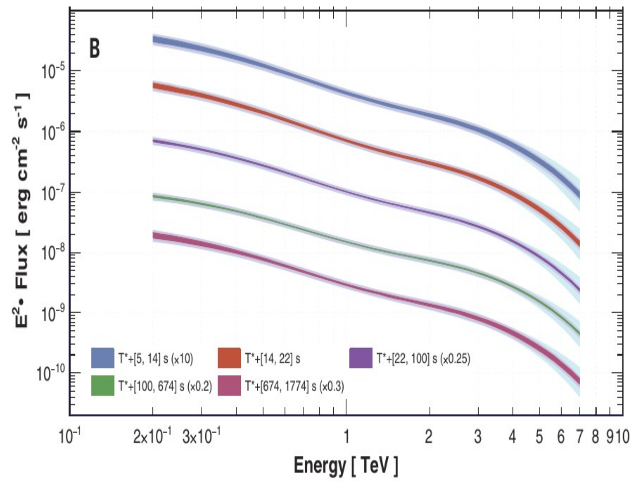
Multi-Wavelength Observations: SED

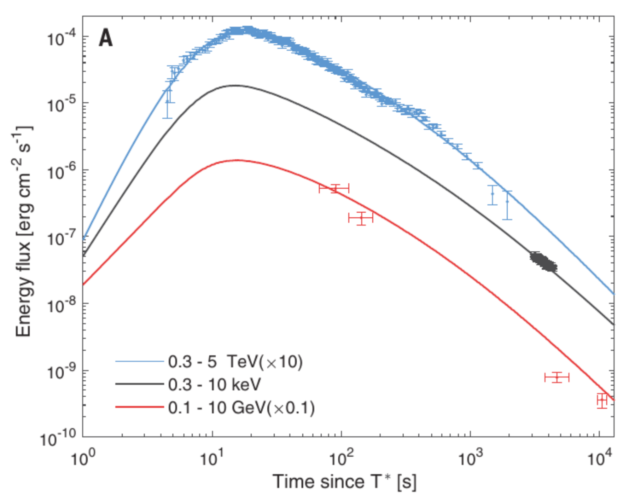
GRB 201216C



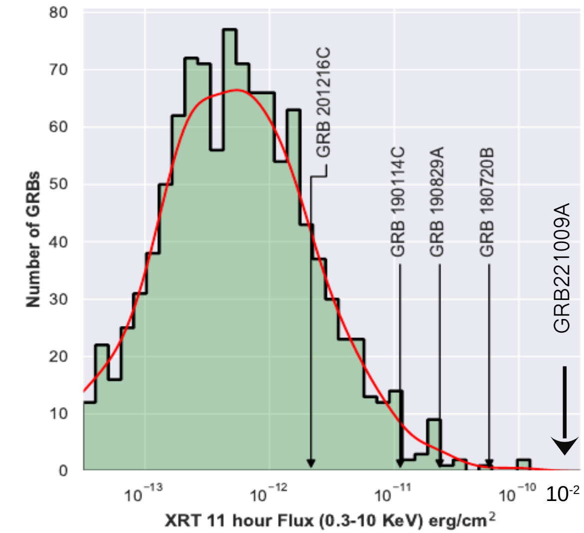


GRB 221009A





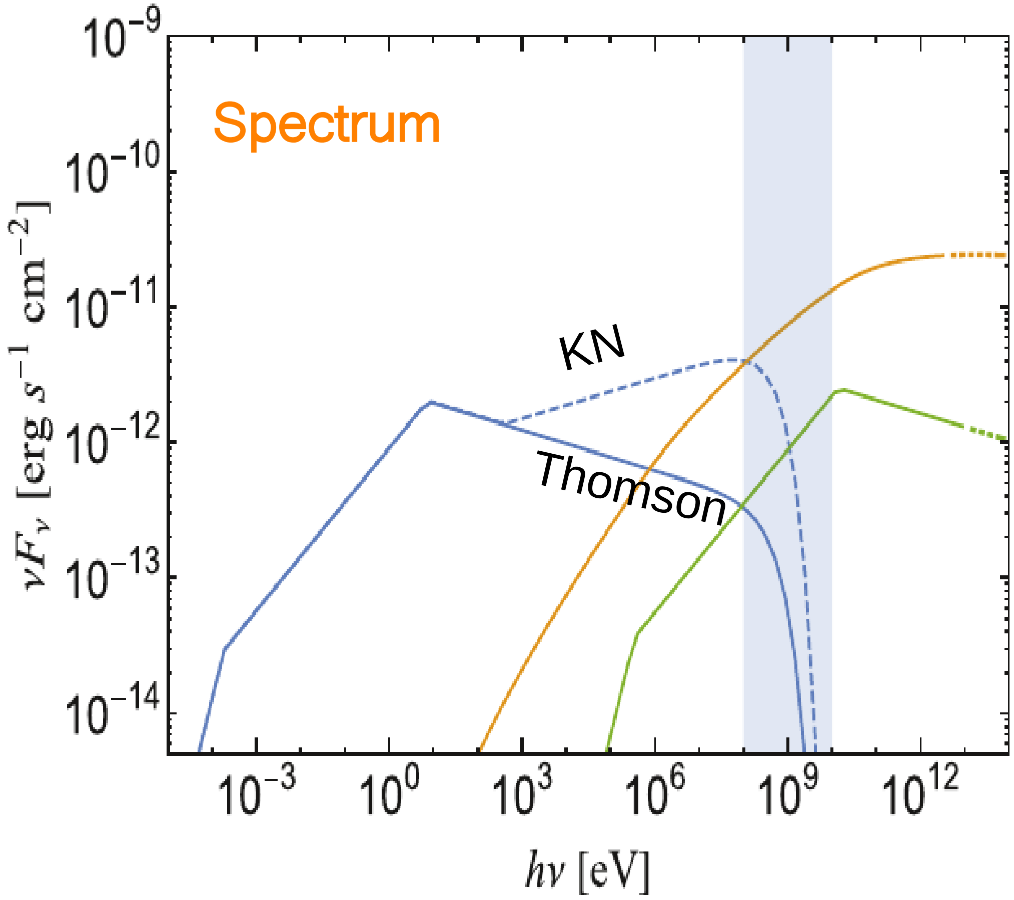
Properties!!



MAGIC Collaboration (2023), MNRAS 527, 3
LHAASO Collaboration (2023), Science 380, 1390

Current Radiation Models: VHE Emission in GRBs

Signatures of IC Radiation

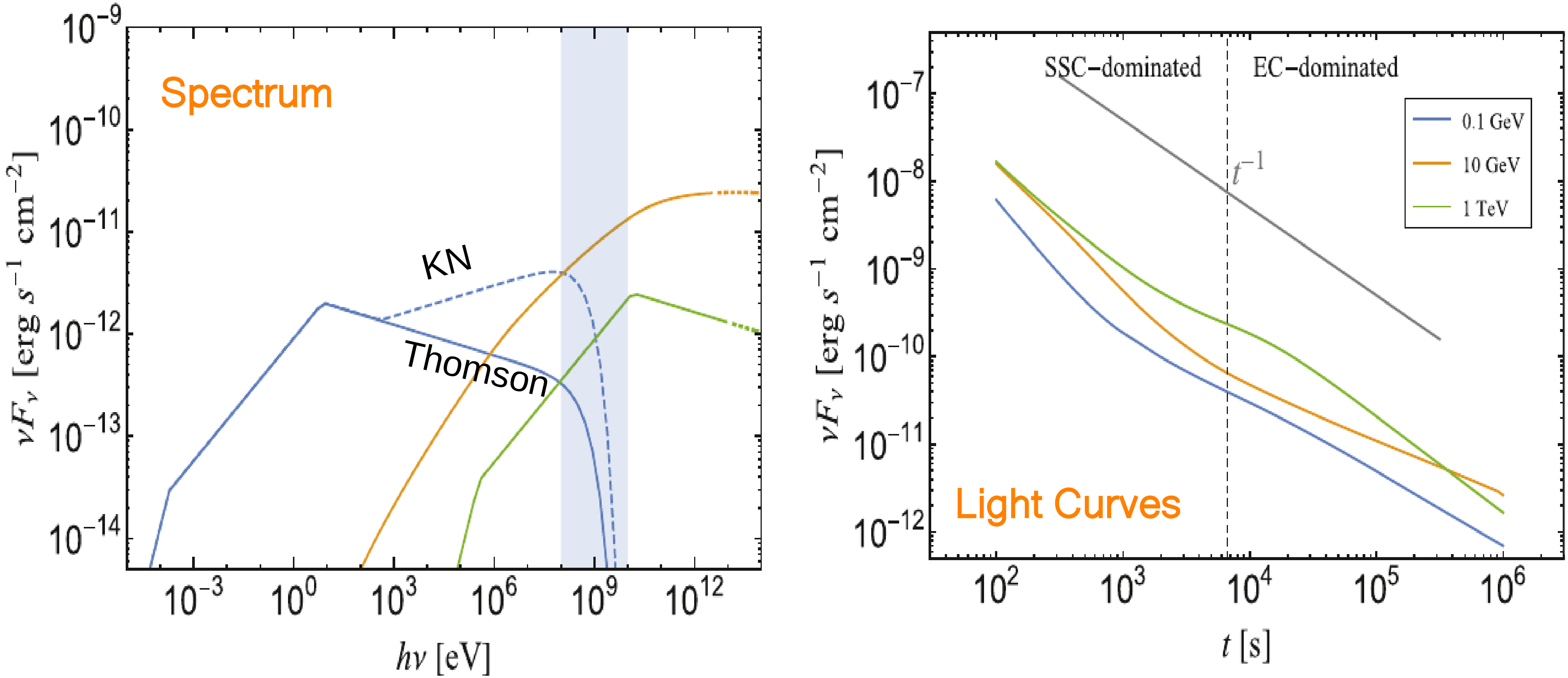


Max photon energy in the Thomson regime:

$$E_{\gamma,\mathrm{cut}}^{\mathrm{ssc}} \approx \frac{m_e^2 c^4}{\epsilon_t} \frac{\Gamma^2}{(1+z)^2}$$

H. Zhang et al. (2020), MNRAS 974, 2020

Signatures of IC Radiation



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H. Zhang et al. (2020), MNRAS 974, 2020

GRB 190114C: SSC Model

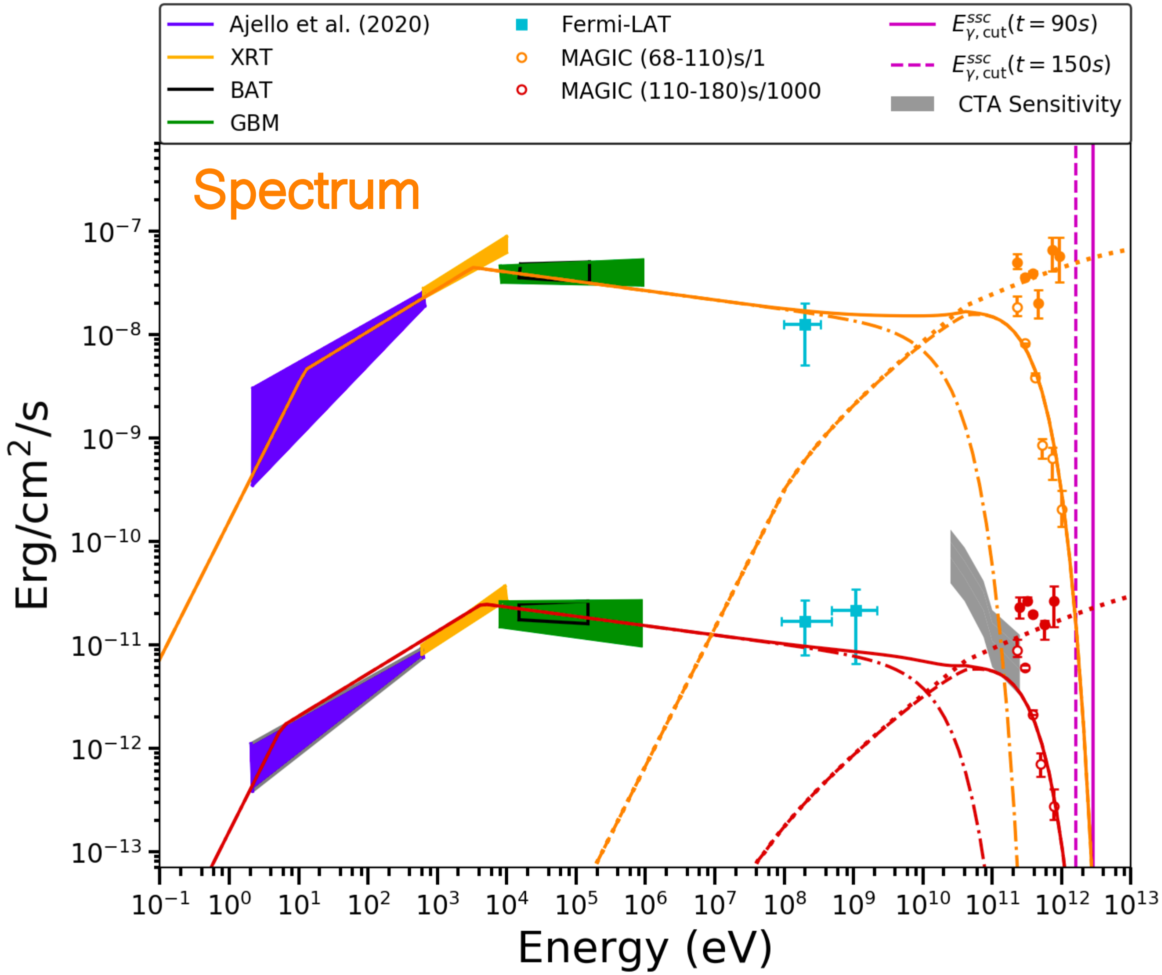
$T_{90} > 100\text{s}$

MAGIC Detection (0.3 -1 TeV)

~55 s onwards

SSC in Thomson regime

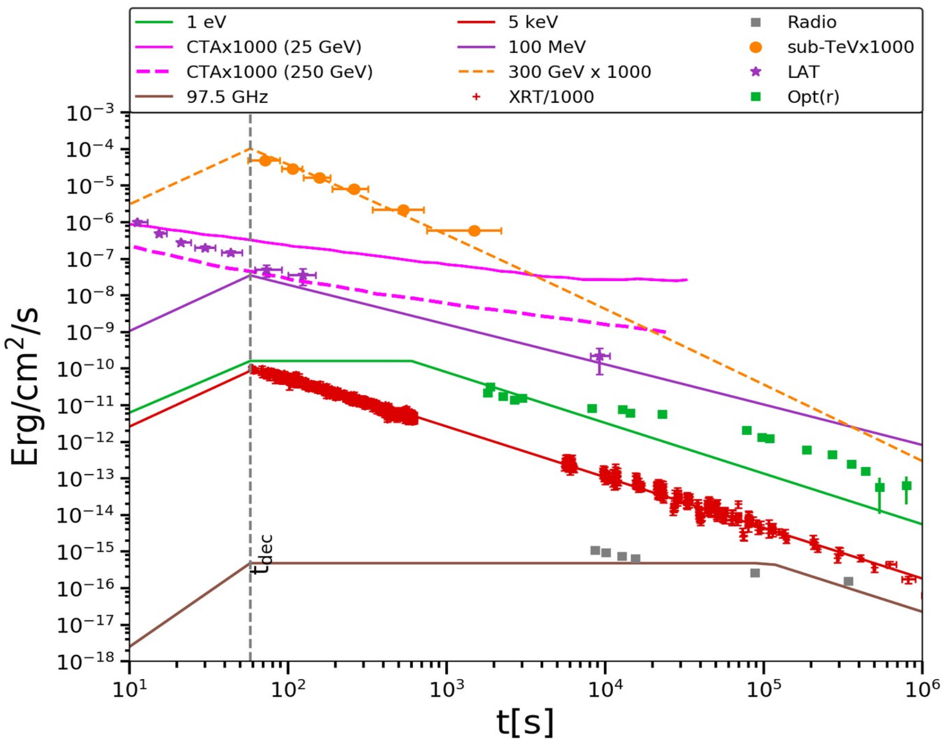
$$Y \equiv \frac{L_{\rm SSC}}{L_{\rm Sy}} \sim 1.3 t_2^{-0.1}$$

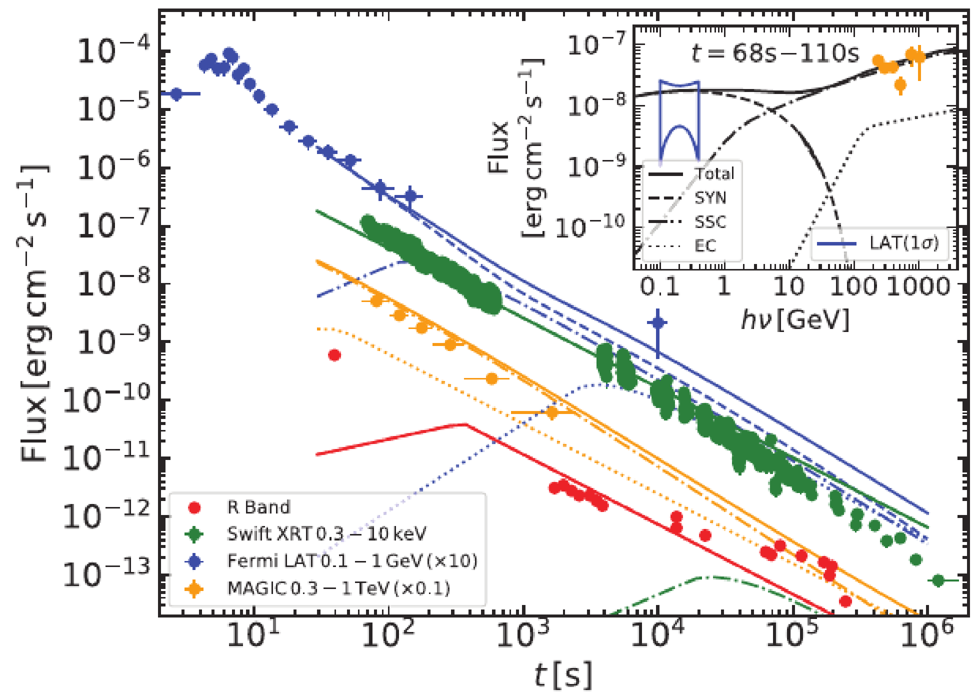


$$\tau_{\gamma\gamma} < 1, \quad \tau_{\rm EBL} \approx 200\text{GeV}$$

MAGIC Collaboration (2019), Nature 575, 459
Joshi & Razzaque (2021), MNRAS 505, 2

GRB 190114C: Light Curves





$$A^\star = \dot{M}_{-5}/v_{w,8}$$

E_k (Erg)	Γ_0	p	ε_e	ε_B	A^* or n_0
4×10^{54}	300	2.2	0.03	0.012	0.02 (WIND)
5×10^{54}	400	2.6	0.05	5×10^{-6}	0.1 (ISM)

MAGIC Collaboration (2019), Nature 575, 459
Joshi & Razzaque (2021), MNRAS 505, 2
H. Zhang et al. (2020), MNRAS 974, 2020

GRB 180720B: EC Model

EC dominance:

Energy density of external photons greater than magnetic field!!

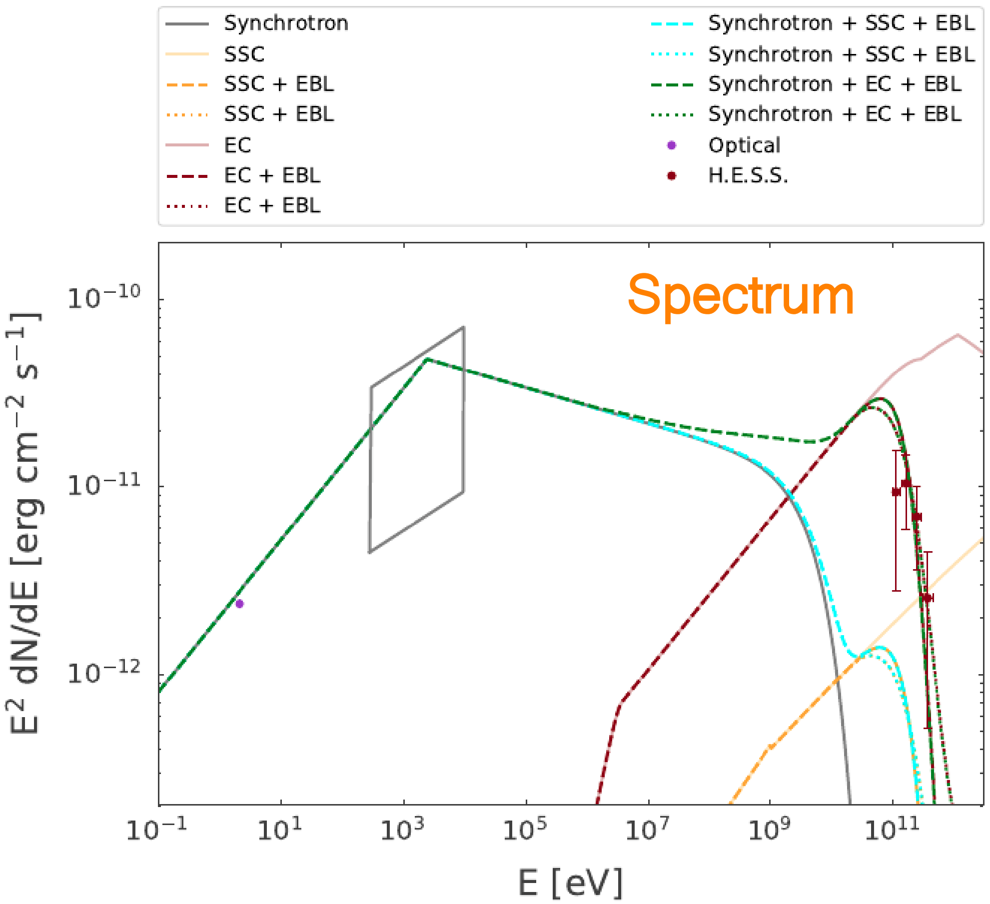
$$u_{\rm ex} \geq 4n(R)m_p c^2 \epsilon_B$$

$$T_{90} \sim 49\mathrm{s}$$

H.E.S.S. Detection

(0.1 -0.5 TeV)

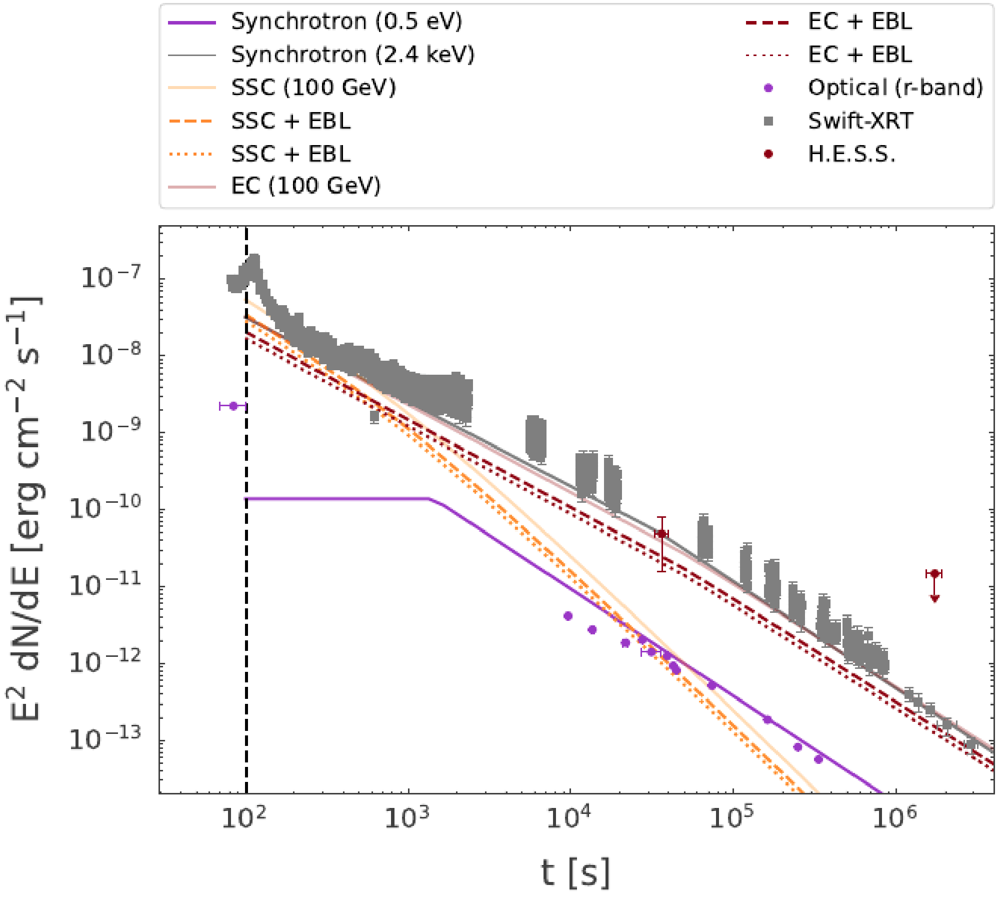
~10 hr onwards



Barnard, Razzaque & Joshi, (Accepted in MNRAS)

GRB 180720B: Light Curves

E_k (Erg)	6 x 10^{54}
Γ_0	372
p	2.2
ε_e	0.03
ε_B	0.03
A*	0.07



Late VHE afterglow can be explained by the EC component in this GRB.

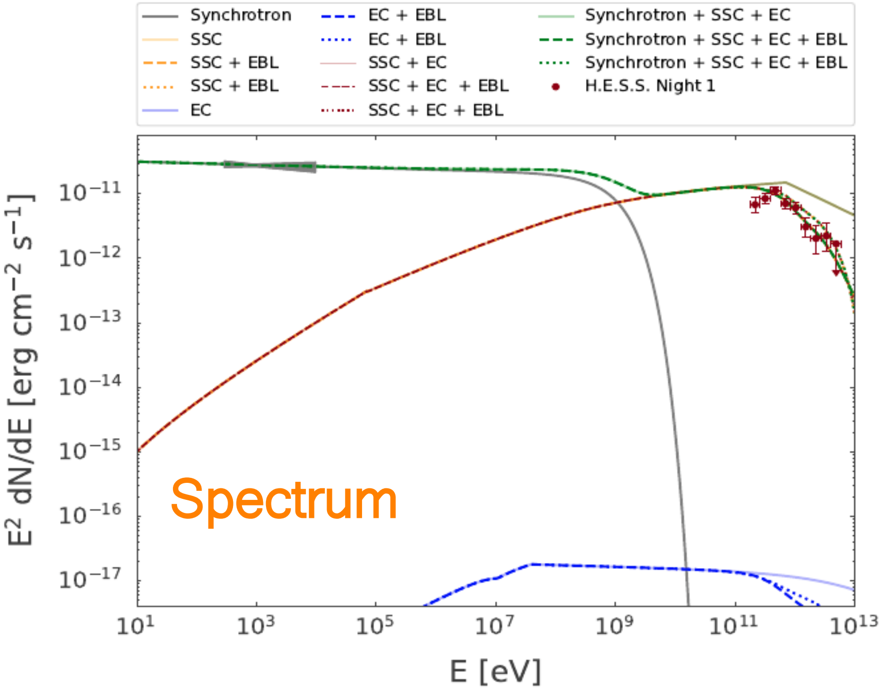
Barnard, Razzaque & Joshi, (Accepted in MNRAS)

GRB 190829A: SSC Model

$T_{90} \sim 6\mathrm{s}$

H.E.S.S. Detection
(0.2 - 4 TeV)

~4.3 hr onwards



E_k (Erg)	Γ_0	p	ε_e	ε_B	A*
2×10^{52}	42	2.1	0.1	0.1	0.1

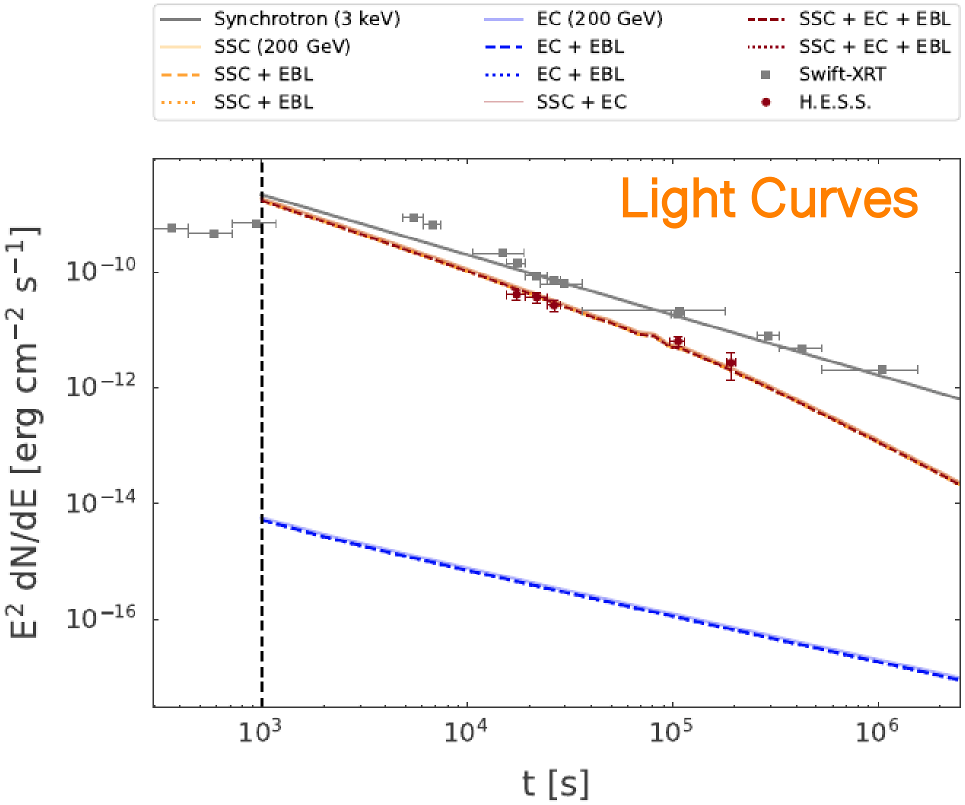
Barnard, Razzaque & Joshi, (Accepted in MNRAS)

GRB 190829A: SSC Model

$T_{90} \sim 6\mathrm{s}$

H.E.S.S. Detection
(0.2 - 4 TeV)

~4.3 hr onwards

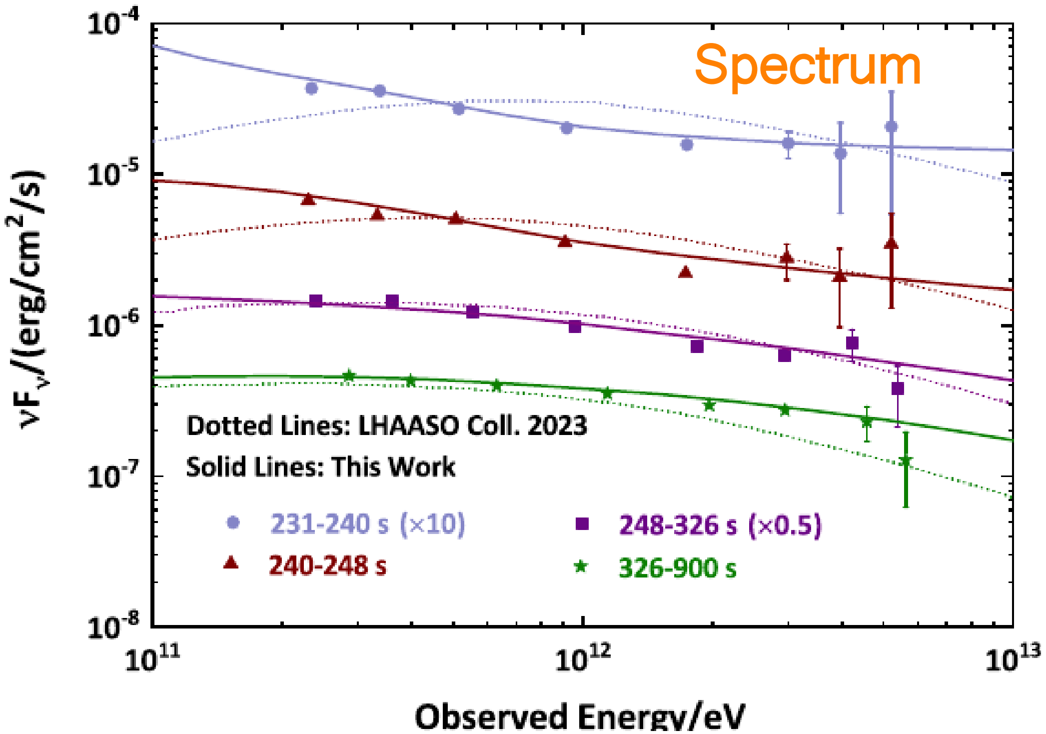


E_k (Erg)	Γ_0	p	ε_e	ε_B	A*
2×10^{52}	42	2.1	0.1	0.1	0.1

Barnard, Razzaque & Joshi, (Accepted in MNRAS)

GRB 221009A: BOAT

$T_{90} \sim 327\text{s}$



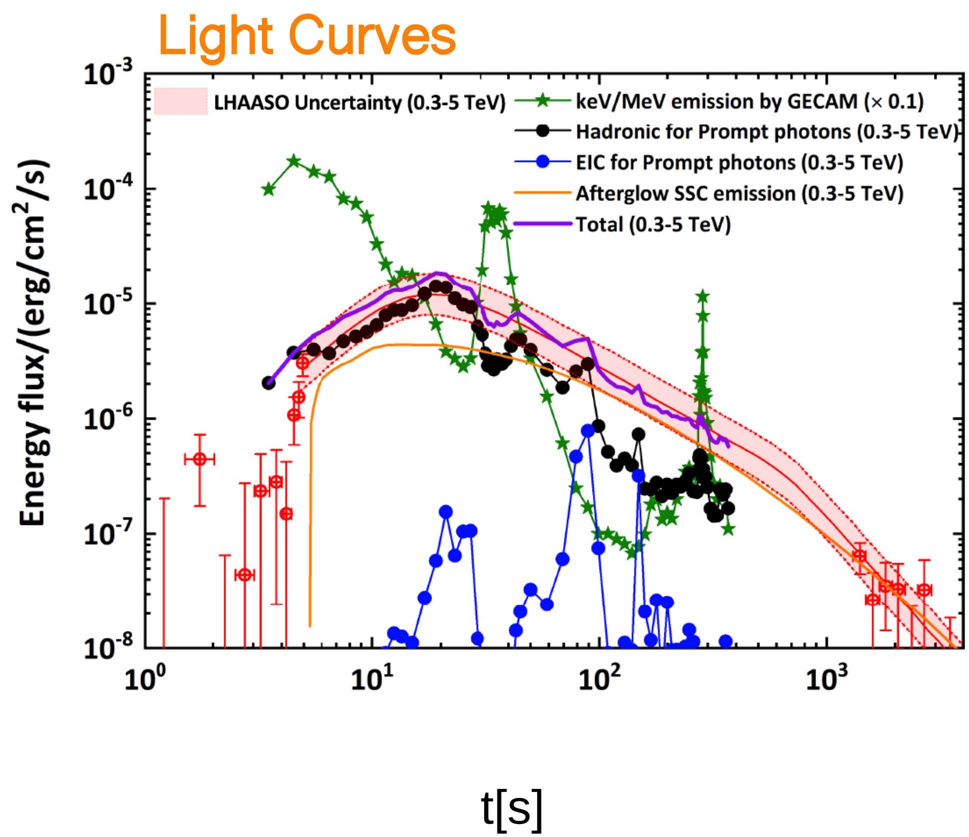
E_k (Erg)	1.5 x 10^{55}	10^{55}
Γ_0	560	260
p	2.2	2.42
ε_e	0.025	0.02
ε_B	$6\text{x}10^{-4}$	10^{-6}
n_0	0.4	A* = 1
Expected Neutrino		**0.33**

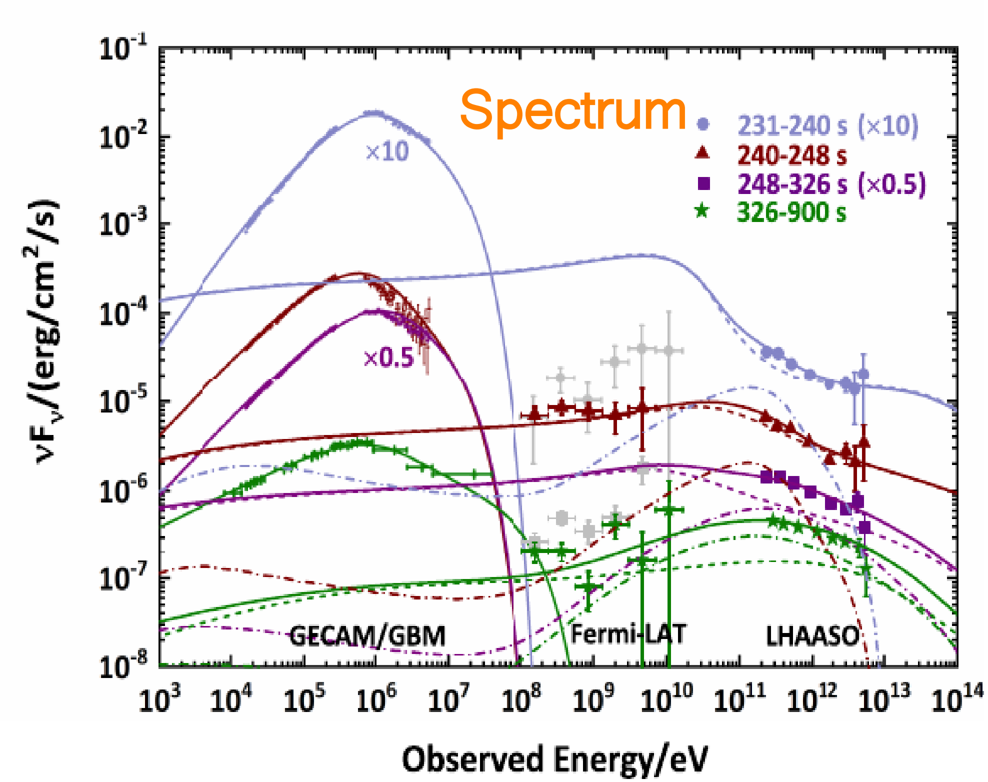
LHAASO: > 64000 photons [0.2- > 10 TeV]

LHAASO Collaboration (2023), Science 380, 6652
Kai Wang et al. (Arxiv 2310.11821)

GRB 221009A: BOAT

- SSC + EM cascade model



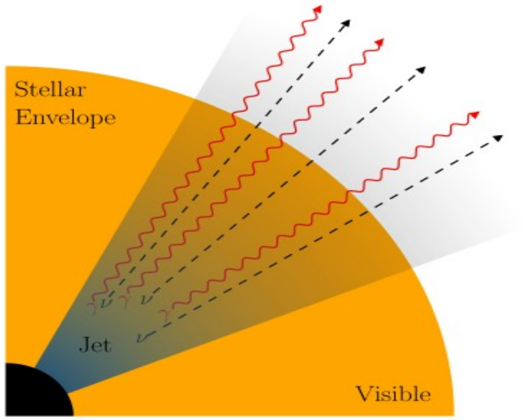


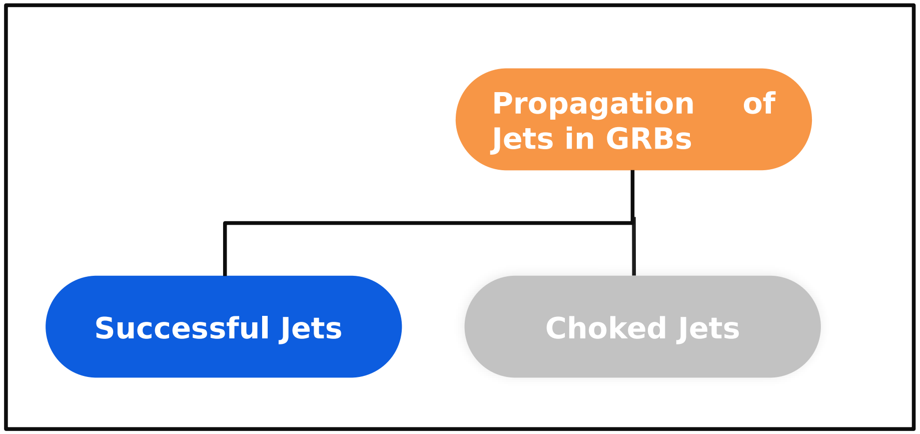
LHAASO: > 64000 photons [0.2- > 10 TeV]

LHAASO Collaboration (2023), Science 380, 6652
Kai Wang et al. (Arxiv 2310.11821)

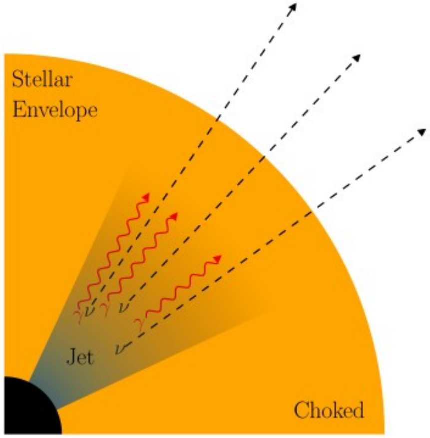
Insights on the Cosmic Rays and Neutrino's from GRBs

GRB Relativistic Jets: Properties





Standard and Low Luminosity (LL)-GRBs

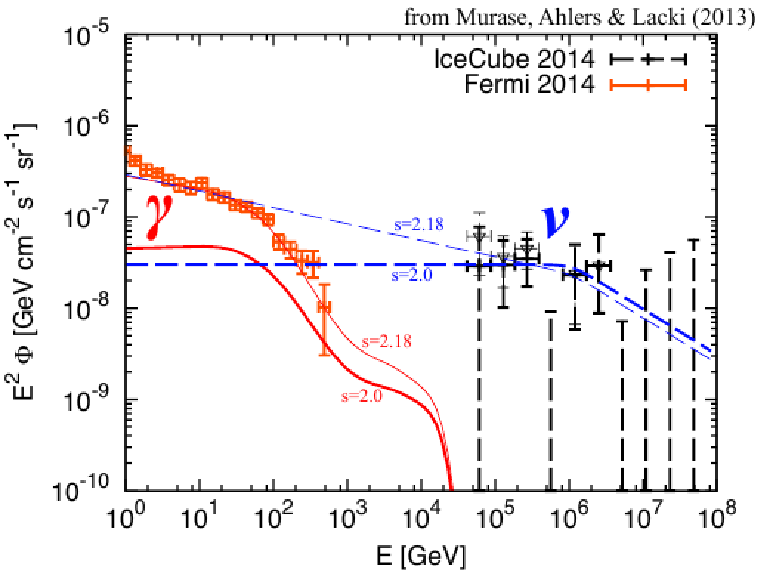


Luminosity < 10^{52} erg

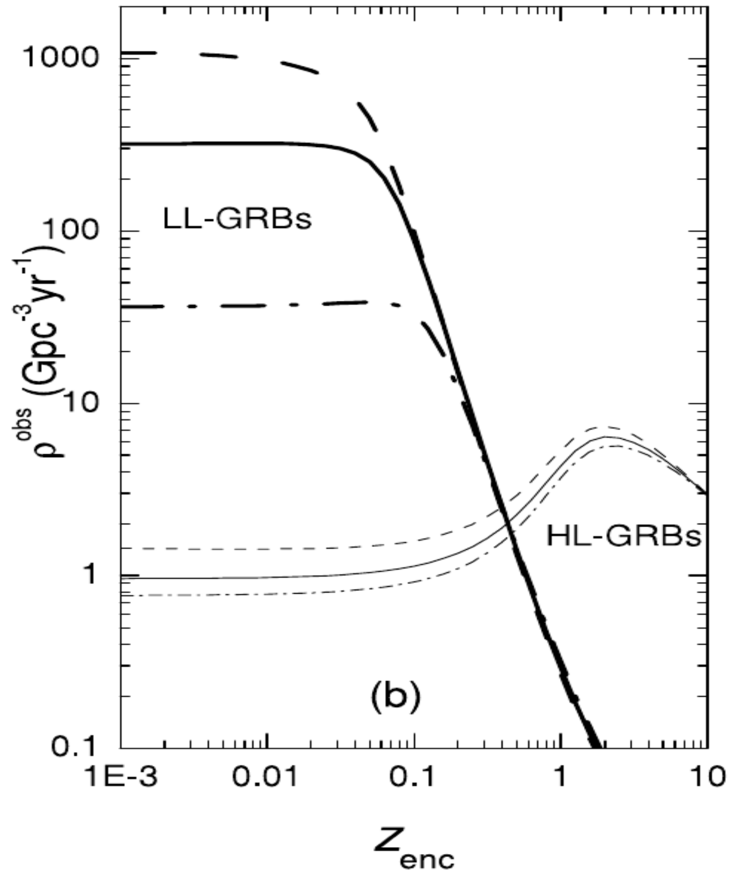
Motivations: Choked vs LLGRBs

Chocked GRBs:

Isotropic Fermi gamma-ray background suggest that IC neutrino sources might be hidden in gamma-rays!!



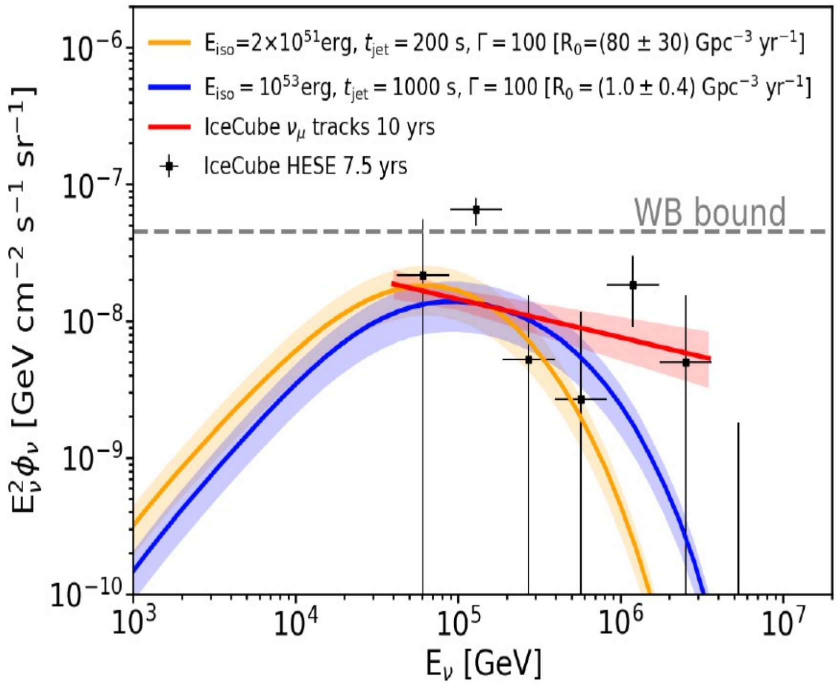
LLGRBs: Larger Rates!!



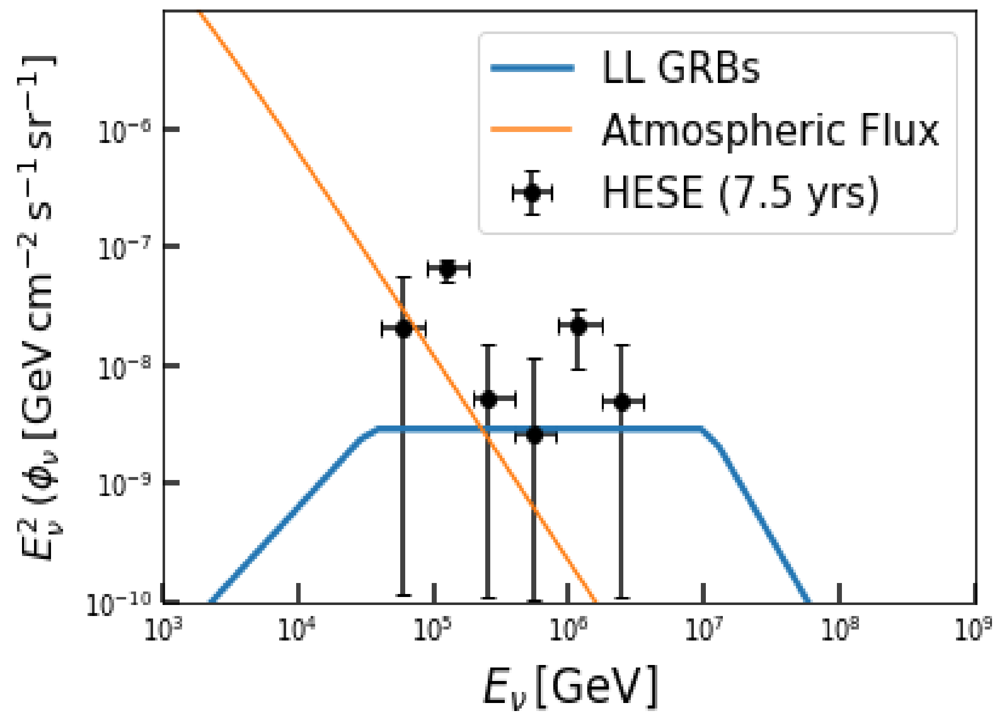
E. Liang et al. (2007), ApJ 662, 1111

Neutrino Flux: Choked vs LLGRBs

Chocked GRBs



$$\mathrm{L_{iso}}\ [\mathrm{erg/s}] = 10^{46} - 10^{50}, \ln(\bar{\Gamma}) = 1.1,\ \sigma = 0.1,$$
$$\ln(\bar{\mathrm{T}})\ [\mathrm{sec}] = 2.2,\ \sigma = 0.1,$$



CR Spectrum: → $$\frac{dN}{dE_p} \propto E_p^{-2}; [E_p \sim 10 - 10^7\ \mathrm{GeV}]$$

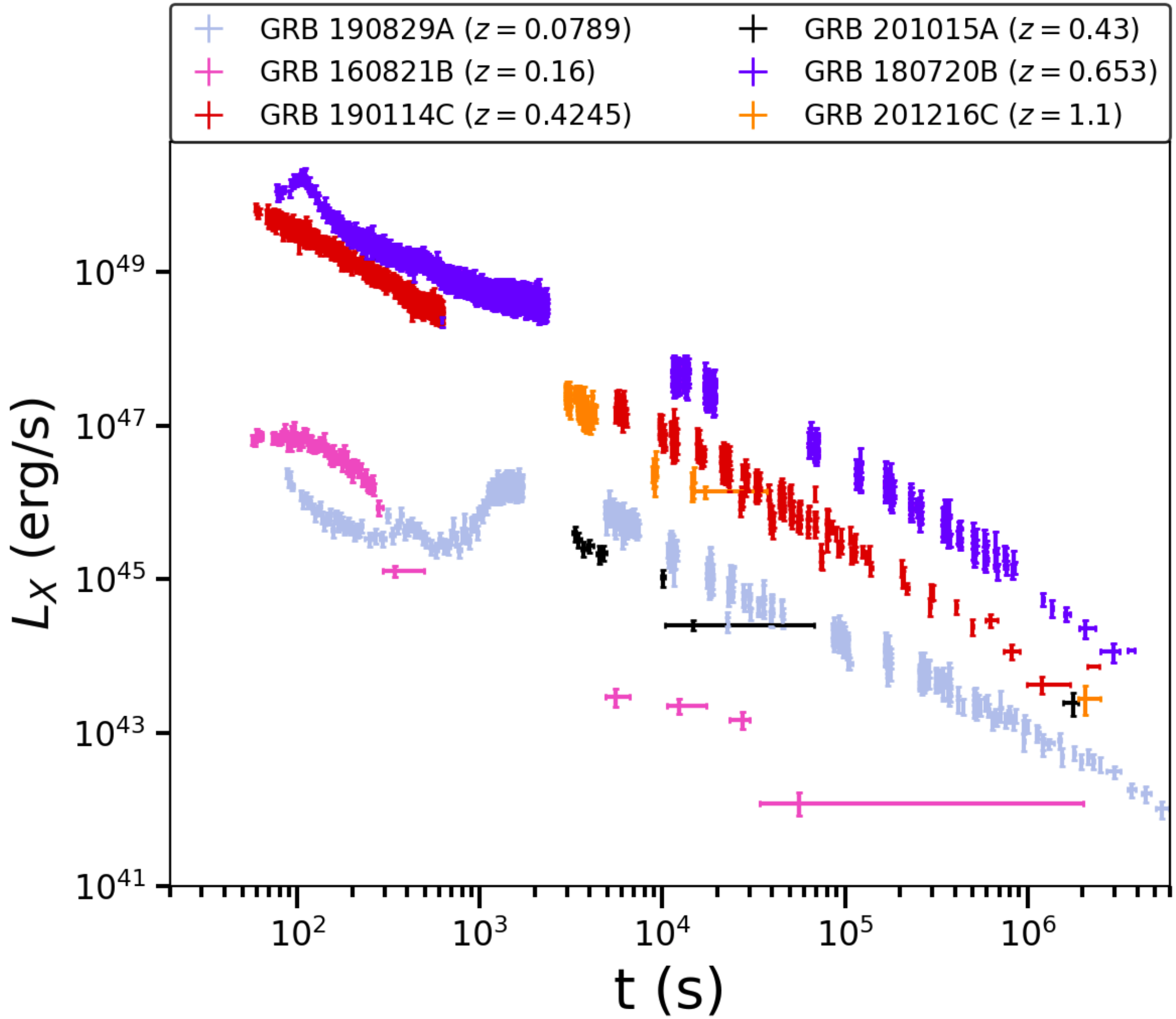
Gupta & Zhang (2007), Aphy 27, 386
M.Fasano et al. (2021), JCAP 09,044

Take Away

- **VHE emission in GRBs is consistent with the SSC and EC models.**
- **Thomson and Klien Nishina IC regimes can be investigated in details.**
- **In special cases: GRB 190829A or GRB 221009A hadronic models are also included.**
- **The jet composition: Mixed type (electrons and CR protons), but need to understand their fractions.**

Thank you for your attention

X-ray Light Curves: VHE GRBs



SSC models + External IC

Derishev and Piran (2019), ApJL 880, 27
X. Wang et al. (2019), ApJ 884, 117
N. Fraija et al. (2019), ApJL 879, 26
MAGIC Collaboration (2019), Nature 575, 459
Theodore et al. (2021), ArXiv 2012.07796
Fraija et al. (2020), arXiv: 2003.11252
Salafia et al. (2021), arXiv: 2106.07169

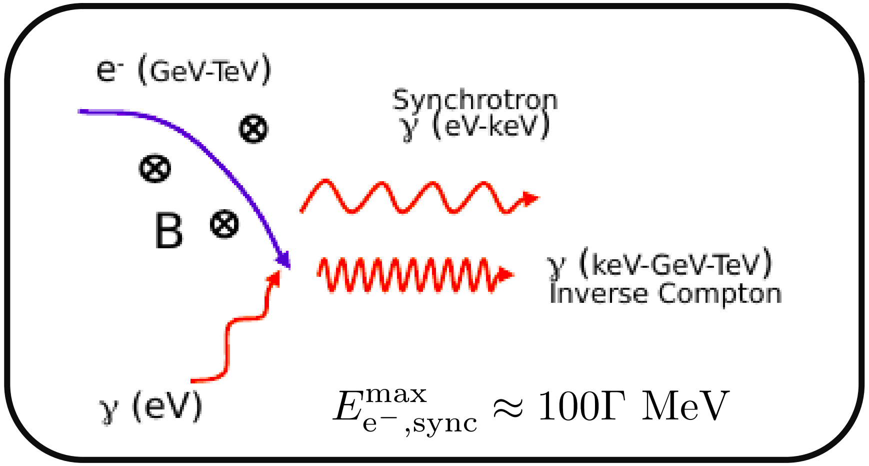
Particle Acceleration Models

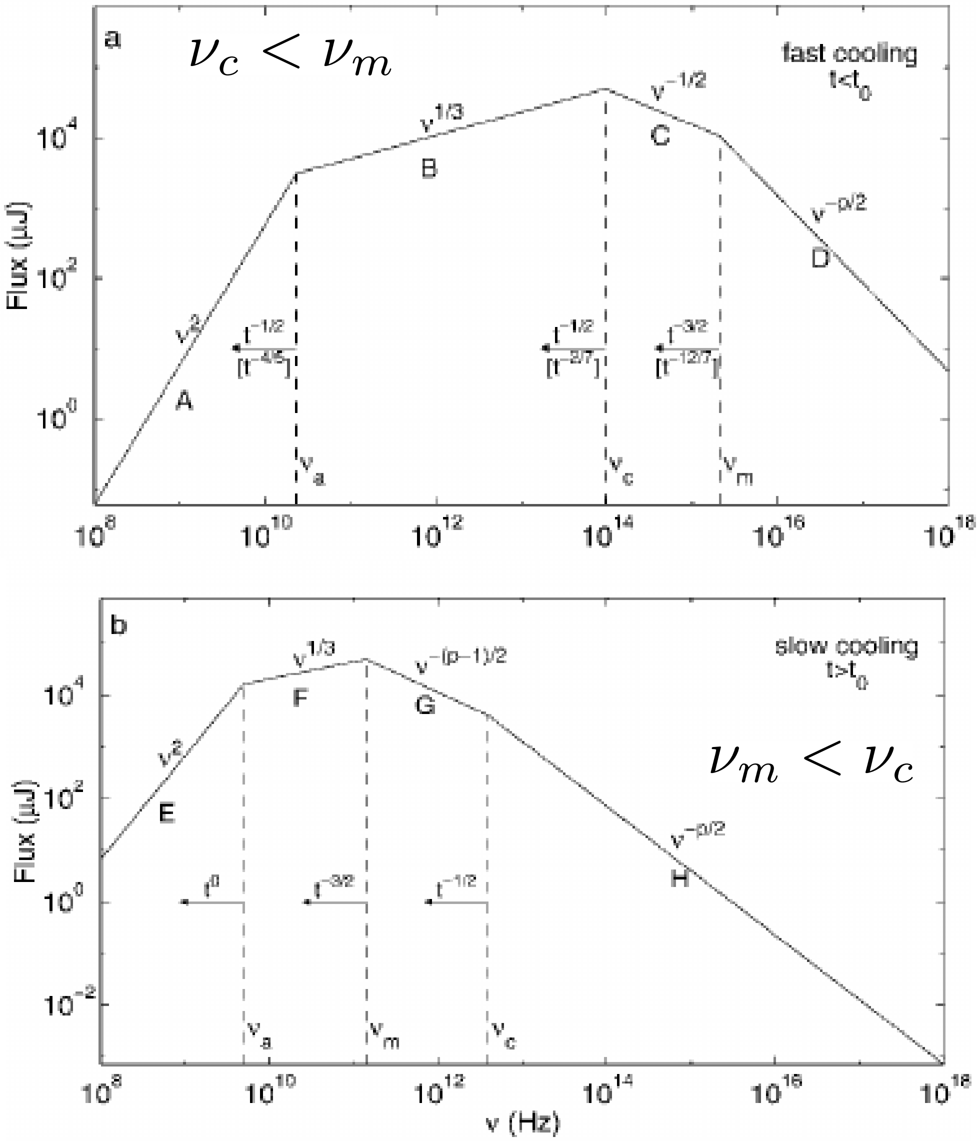
K. Asano et al. (2020), ApJ 905, 105

Data is taken from SWIFT-XRT Database. https://www.swift.ac.uk/analysis/xrt/
Currently GRB TeV Catalogue has appended 5 sources. http://tevcat.uchicago.edu/

External Shocks: Synchrotron Emission

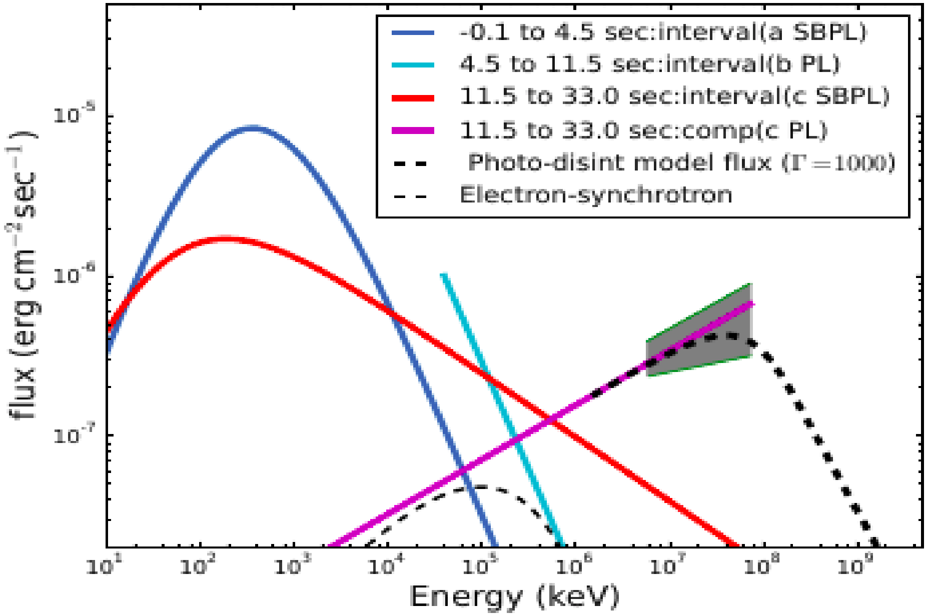
Cooling of electrons





Sari, Piran & Narayan (1998), ApJL 497, 17
Zhang & Meszaros (2001), ApJ 559,110
Piran & Nakar (2010) ApJL 718, 63

Jet Composition and Radiation Channels

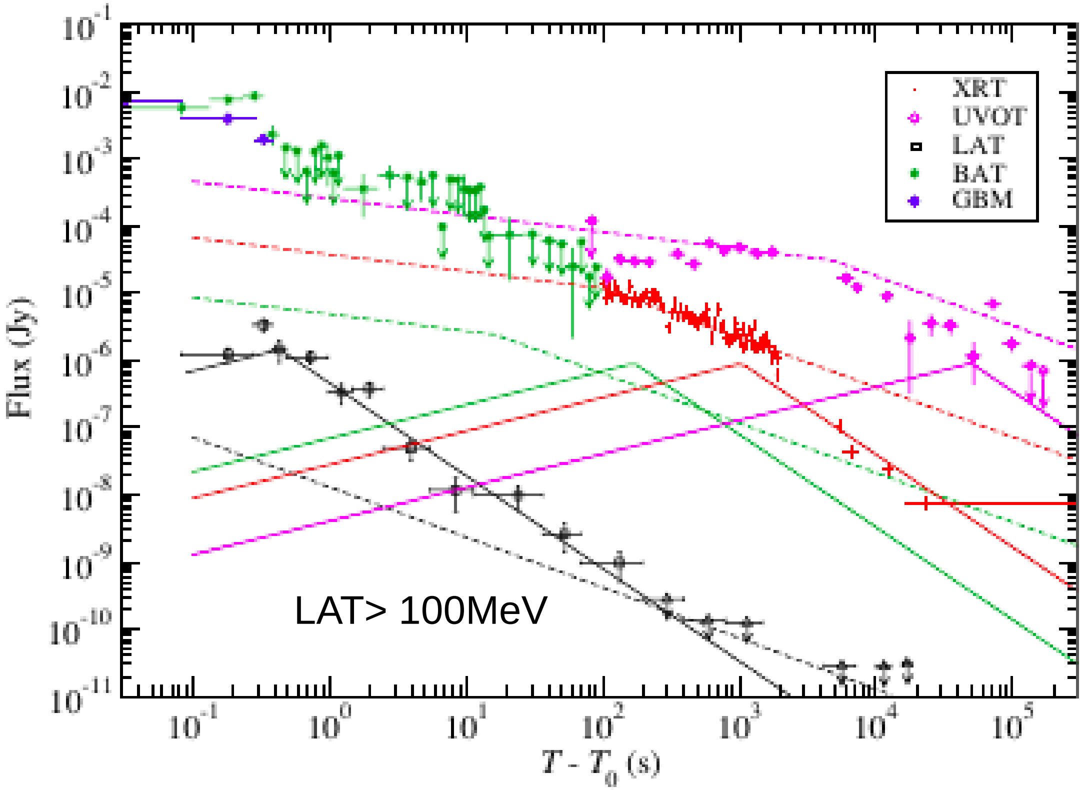


1-70 GeV PL Component

- Required BLF ~ 1000,
- Could be signature of Jet-composition.

Joshi, Razzaque & Moharana (2016), MNRASL 458,1

HE Emission: GRB 090510



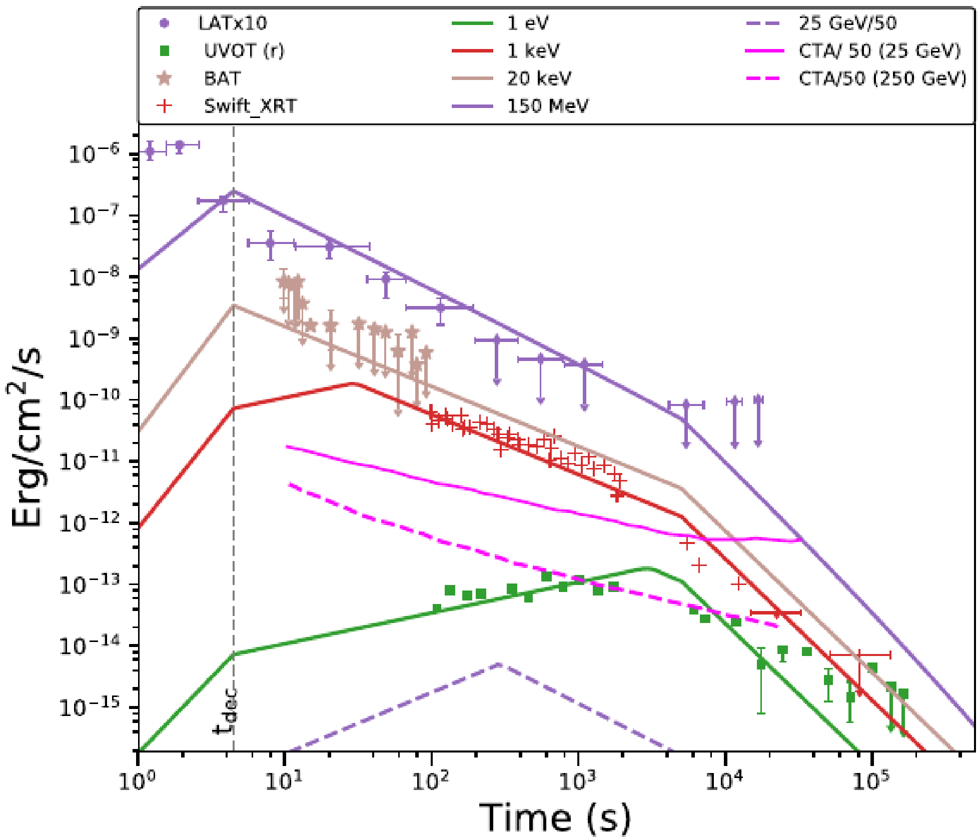
- A short GRB, z=0.903,
- **Lepto-hadronic model for MW emission,**
- >100 MeV: p-sync,
- X-rays and UV: e_sync

E_k	2 x 10^{55} erg
Γ_0	2400
ε_e	0.0001
ε_p	0.5
ε_B	0.3
n	3 cm^3
R	10^{17} cm

$$t_{\rm dec,i} = \left[\frac{17E_k(1+z)^3}{64\pi n m_p c^5 \Gamma^8}\right]^{1/3} = 59.6(1+z)n_0^{-1/3}\Gamma_{2.5}^{-8/3}E_{55}^{1/3} \text{ s}$$

Razzaque et al. (2010), ApJL 724, 109

HE Emission: GRB 090510



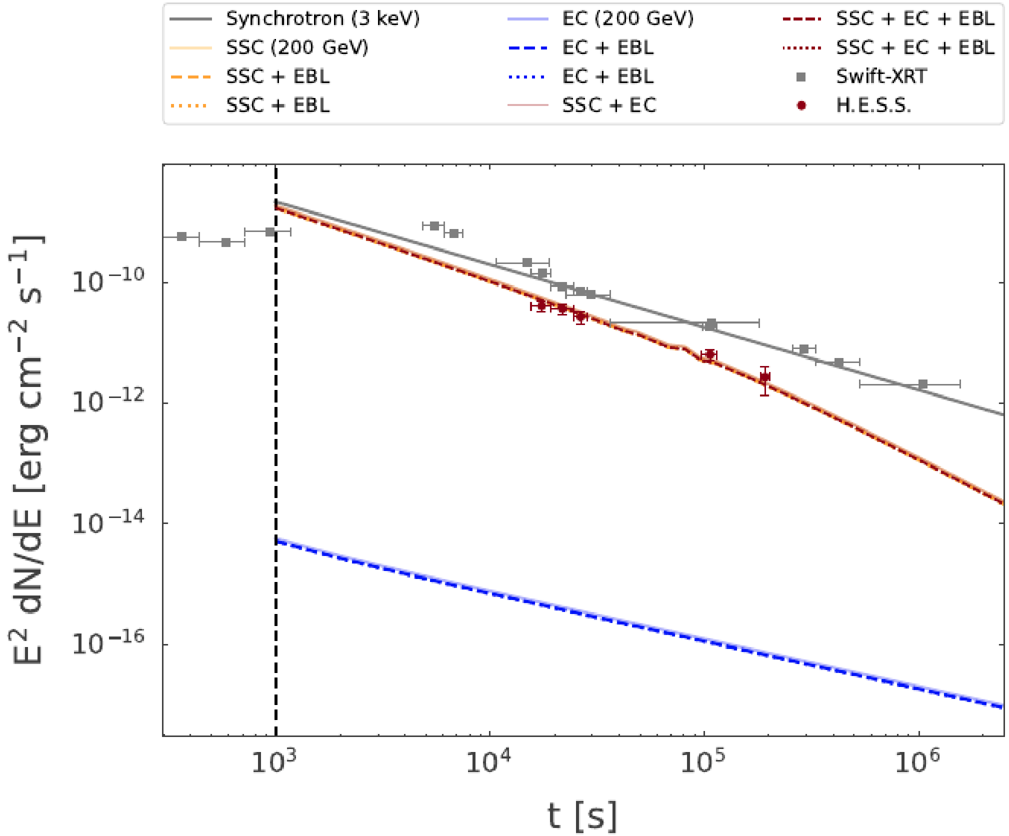
- SSC model for MW emission,

E_k	9×10^{51} erg
Γ_0	1500
ε_e	0.2
ε_B	0.02
n	10^{-5} cm^3
R	5×10^{16} cm

$$t_{\rm dec,i} = \left[\frac{17E_k(1+z)^3}{64\pi n m_p c^5 \Gamma^8}\right]^{1/3} = 59.6(1+z)n_0^{-1/3}\Gamma_{2.5}^{-8/3}E_{55}^{1/3}\ {\rm s}$$

Joshi & Razzaque (2021), MNRAS 505, 2

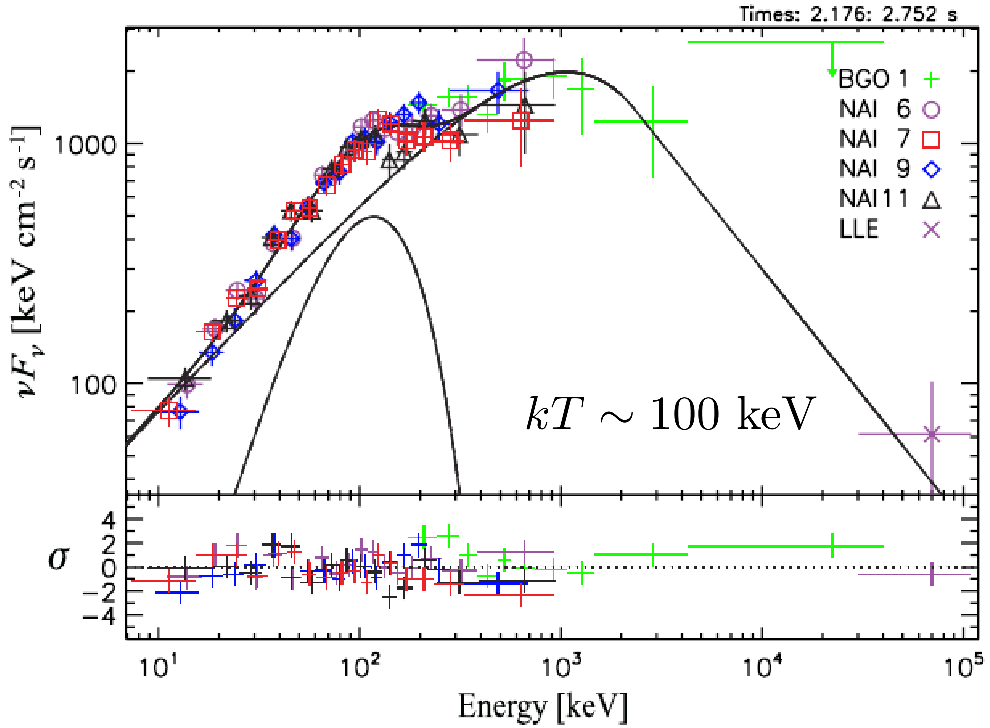
GRB 190829A: ISM Medium



E_k (Erg)	4.5 x 10^{54}
Γ_0	400
p	2.4
ε_e	0.05
ε_B	1.2e-5
n (cm^3)	0.035

GRB: Prompt Phase

- The radiation during the prompt phase moslty due to thermal or non-thermal radiation.



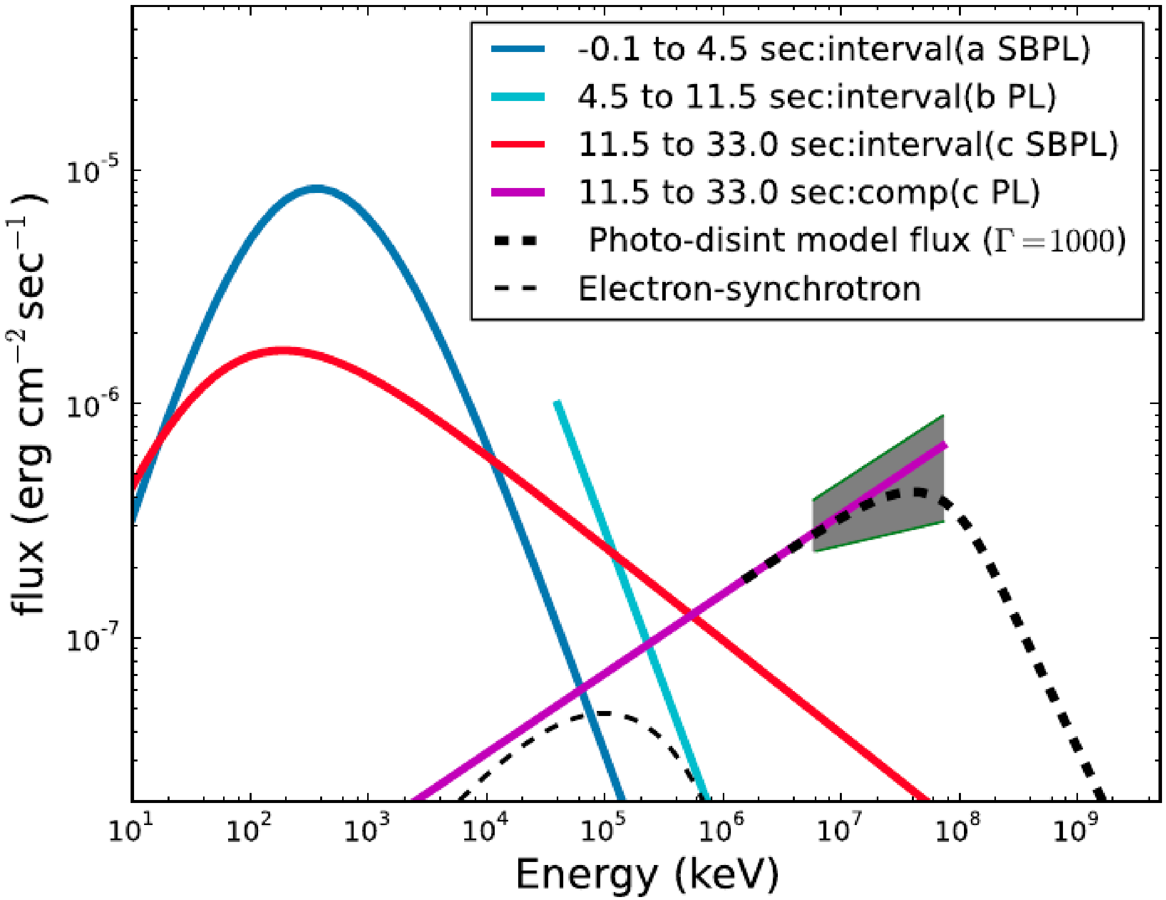
Thermal & non-thermam emission in GRB 110721A.

S. Iyyani et al. (2013), MNRAS 433, 2739

- A long GRB, z~[0.382, 3.512]
- Thermal Emission Component

$E_{g,iso}$ (erg)	10^{54}
Γ_0	1000
R	10^{12} cm

Prompt Phase and Fe Nuclei



$$\tau_{\gamma\gamma} \approx 1 \text{ at } E_\gamma \approx 70\,\text{GeV}$$

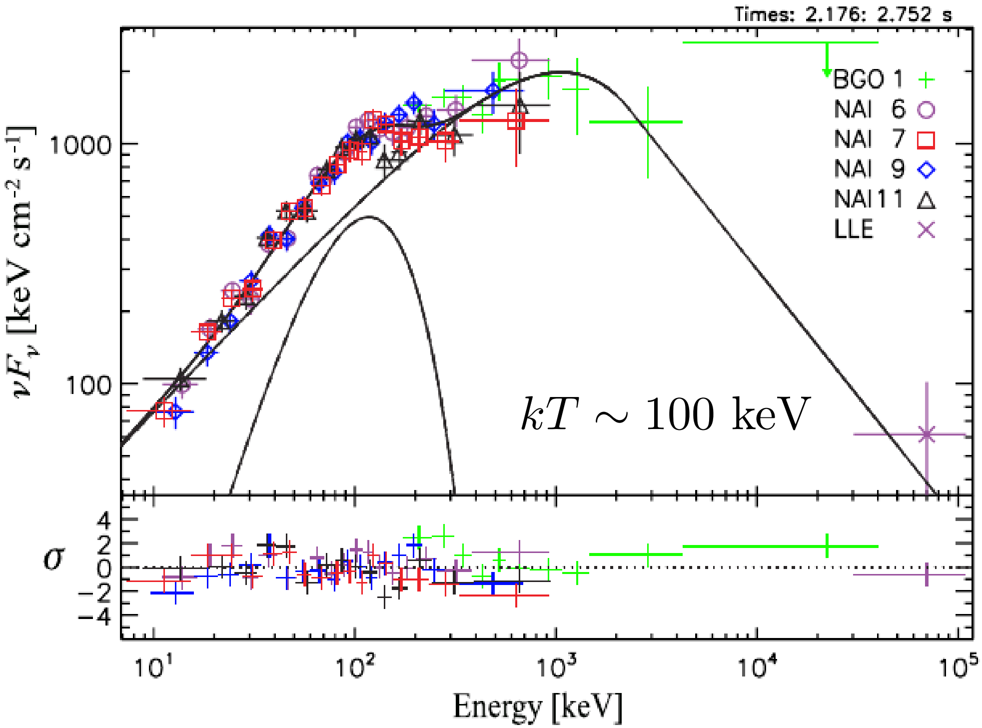
- A long GRB, z=0.34,
- 73 GeV photon at T_0+19s,
- 95 GeV photon at T_0+244s,
- Brightest X-ray light curve,
- Fe - loaded Jets.

$E_{g,iso}$ (erg)	10^{54}
Γ_0	1000
B	130 kG
R	10^{13} cm
$E_{Fe,\,iso}$	10^{53} erg

J. C. Joshi, S. Razzaque & R. Moharana (2016), MNRASL, 458, L79

GRB: Prompt Phase

- The radiation during the prompt phase moslty due to thermal or non-thermal radiation.



Thermal & non-thermam emission in GRB 110721A.

- A long GRB, z~[0.382, 3.512]
- Thermal Emission Component

$E_{g,iso}$ (erg)	10^{54}
Γ_0	1000
R	10^{12} cm

S. Iyyani et al. (2013), MNRAS 433, 2739

Synchrotron-self Compton

- We assume a continuous injection of electrons:

$$Q(\gamma) = Q_0 \times \begin{cases} 0\,; & \gamma < \gamma_m \\ \left(\frac{\gamma}{\gamma_m}\right)^{-p}\,; & \gamma > \gamma_m \end{cases}$$

Nakar, Ando & Sari (2009), ApJ 703, 675

Synchrotron-self Compton

- The continuity equation of the electron distribution:

$$\frac{\partial N(\gamma)}{\partial t} + \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma) N(\gamma)\right] = Q(\gamma)$$

$$\dot{\gamma} = -\frac{\sigma_T B^2}{6\pi m_e c}\gamma^2 [1 + Y(\gamma)]$$

$$Y(\gamma) = P_{\rm SSC}/P_{\rm syn}$$

Fast Cooling:

$$N(\gamma) \propto \begin{cases} \gamma^{-2}\,; & \gamma_c < \gamma < \gamma_m \\ \gamma^{-(p+1)}\,; & \gamma > \gamma_m \end{cases}$$

Slow Cooling:

$$N(\gamma) \propto \begin{cases} \gamma^{-p}\,; & \gamma_m < \gamma < \gamma_c \\ \gamma^{-(p+1)}\,; & \gamma > \gamma_c \end{cases}$$

Nakar, Ando & Sari (2009), ApJ 703, 675