Synchrotron and SSC emission components in GRBs detected at VHEs

Jagdish C. Joshi
School of Astronomy and Space Science, Nanjing University, China

南京大學

16th Marcell-Grossmann Meeting

05/July/2021

Collaborators: Soebur Razzaque, CAPP, Johannesburg
Vikas Chand, Nanjing University, China

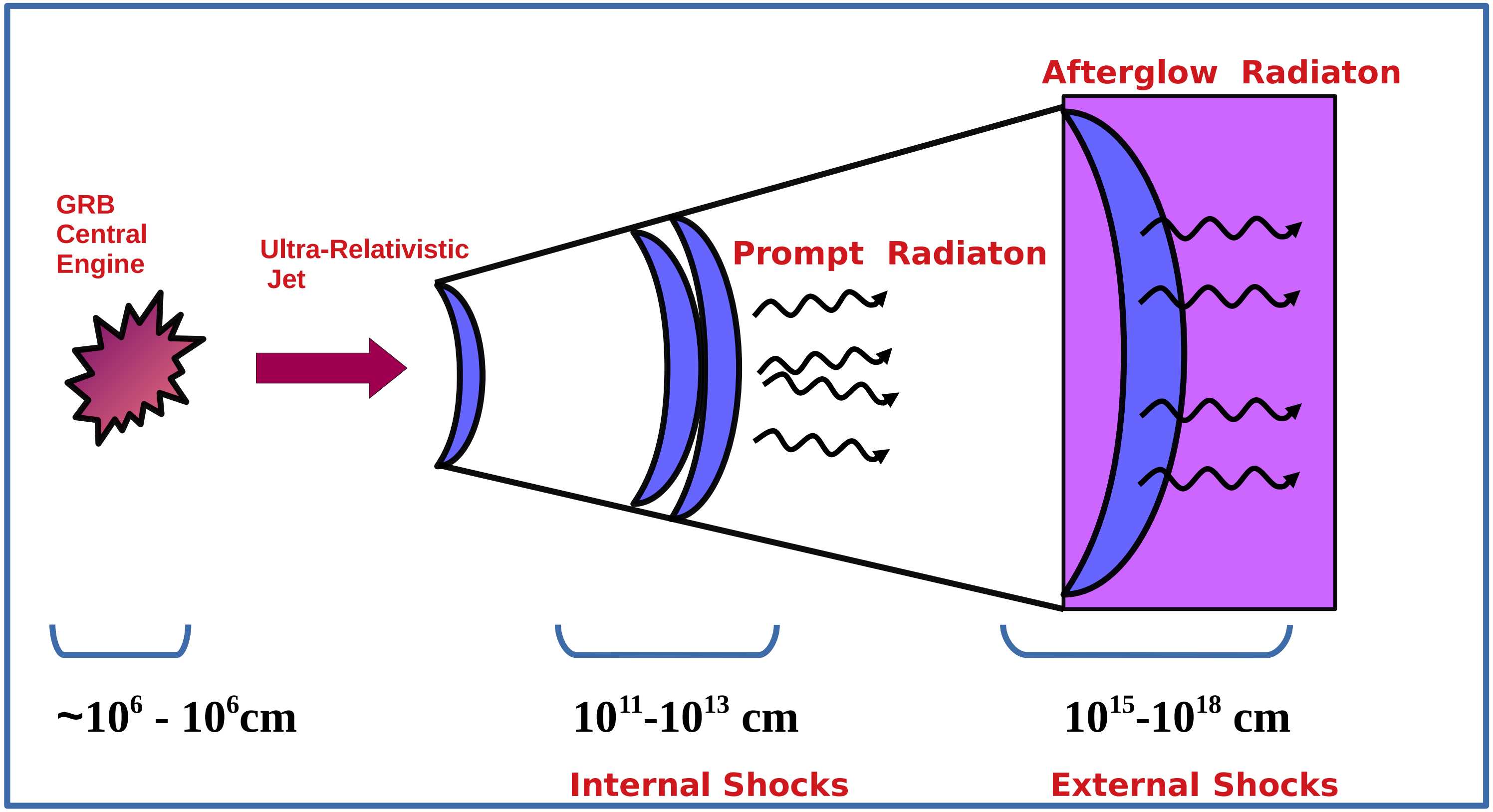
Outline

- Afterglow Emission in GRBs
- Synchrotron and Synchrotron self-Compton (SSC) Model
- HE Gamma-ray afterglow components in GRBs

- Discovery of VHE component
  - Implication for radiative models

- Summary and Conclusions

Blastwave Expansion: Shock Formation



Expansion due to radiation pressure:

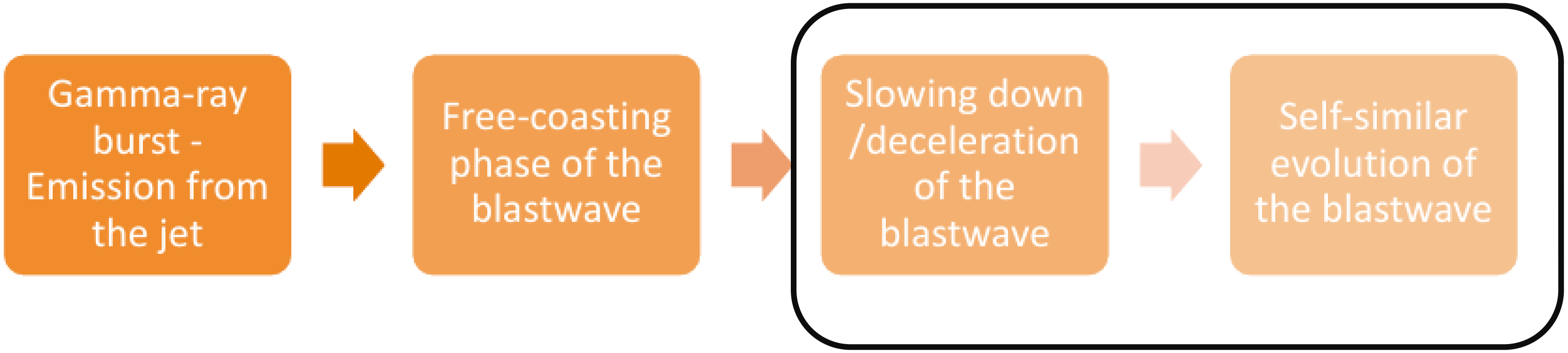
$$R_0 \approx 10^7 \text{ cm}, \qquad L \sim 10^{52} \text{erg/s}$$

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

External Shocks form when:

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

Blastwave: Self-similar Evolution



Afterglow Model Parameters:

- $\mathbf{E_k}$: Isotropic equivalent kinetic energy
- $\mathbf{\Gamma_0}$: Bulk Lorentz factor
- **n** : Circumburst medium density
- **p** : Spectral index of accelerated particles
- $\boldsymbol{\varepsilon_{B,}\varepsilon_e}$: Fraction of shock energy going to electrons and magnetic field.

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

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

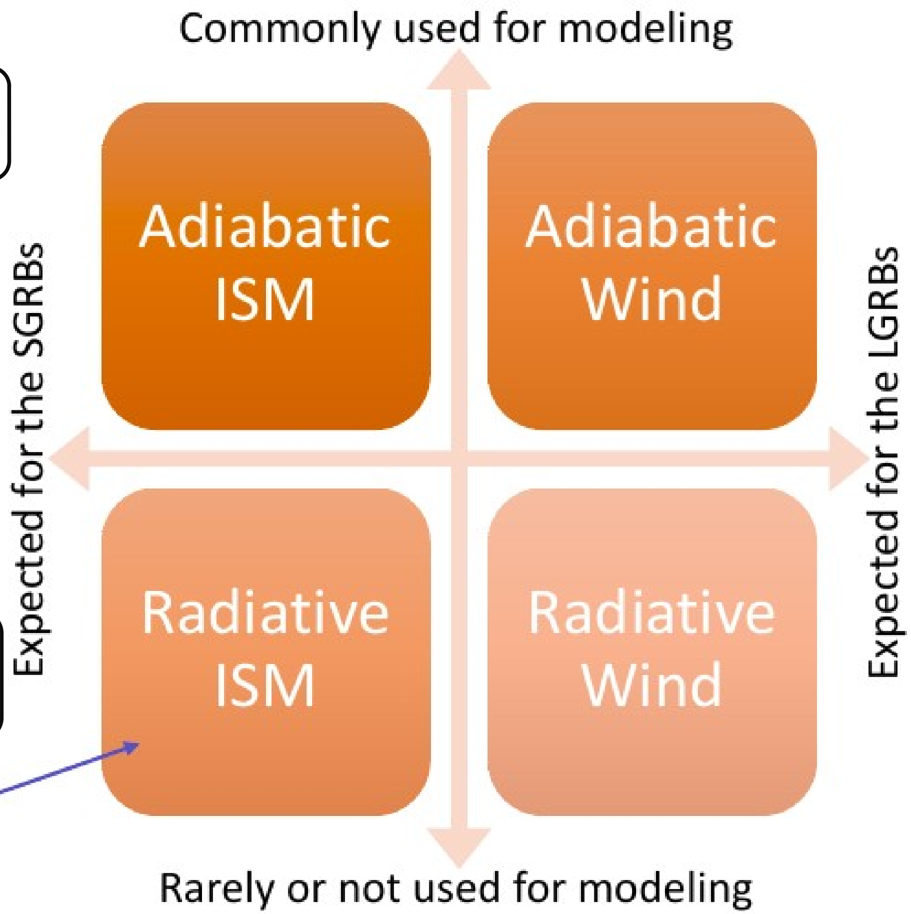
Blandford & Mckee (1976), Phys. Fluids 19, 1130
Meszaros & Rees (1997), ApJ 476, 232

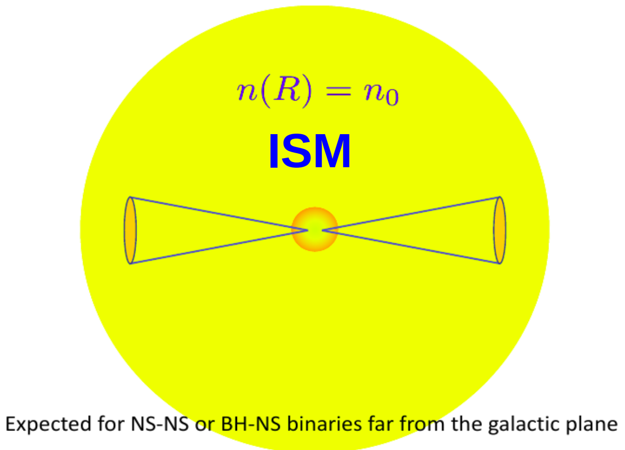
Blastwave: Evolution Scenarios

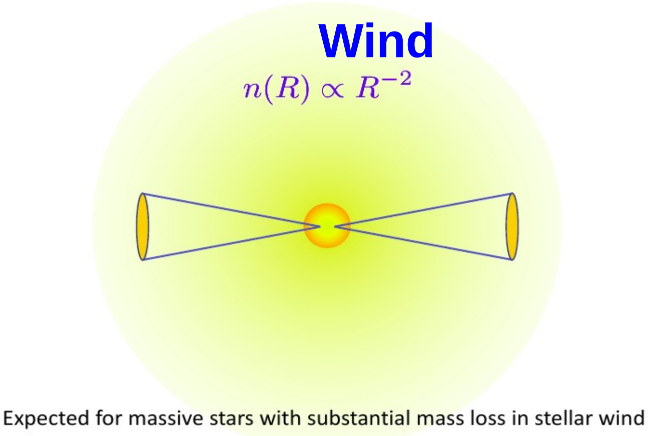
$\varepsilon_e < 0.3$

$\varepsilon_e > 0.5$

Ghisellini+2010



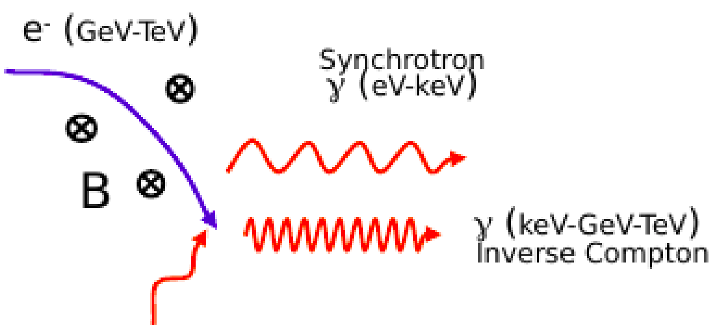




Ghisellini et al. (2010), MNRAS 403, 926

External Shocks: Synchrotron Emission

Cooling of electrons



$$E^{\max}_{e^-,\mathrm{sync}} \approx 100\Gamma\ \mathrm{MeV}$$

Cooling of protons (**Less luminous!!**)

$$\left(\frac{F_{\nu,\max,\mathrm{p}}}{F_{\nu,\max,\mathrm{e}}}\right)^{\mathrm{Sync}} \propto m_e/m_p$$

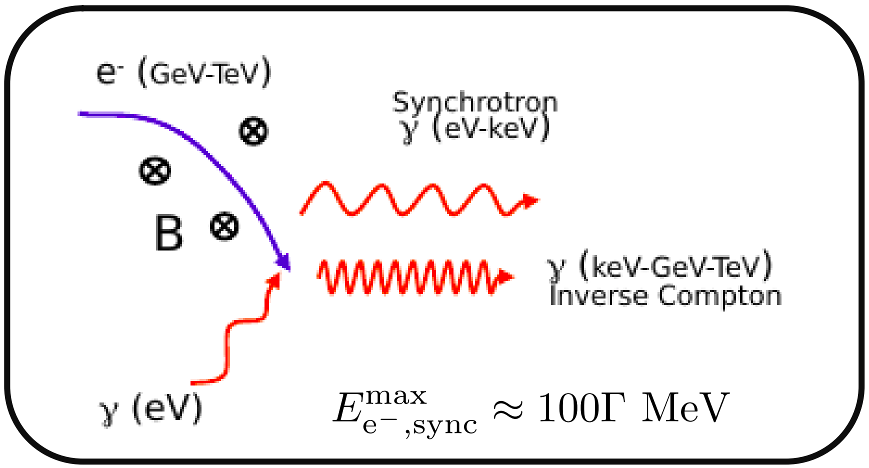
More on p-Sync

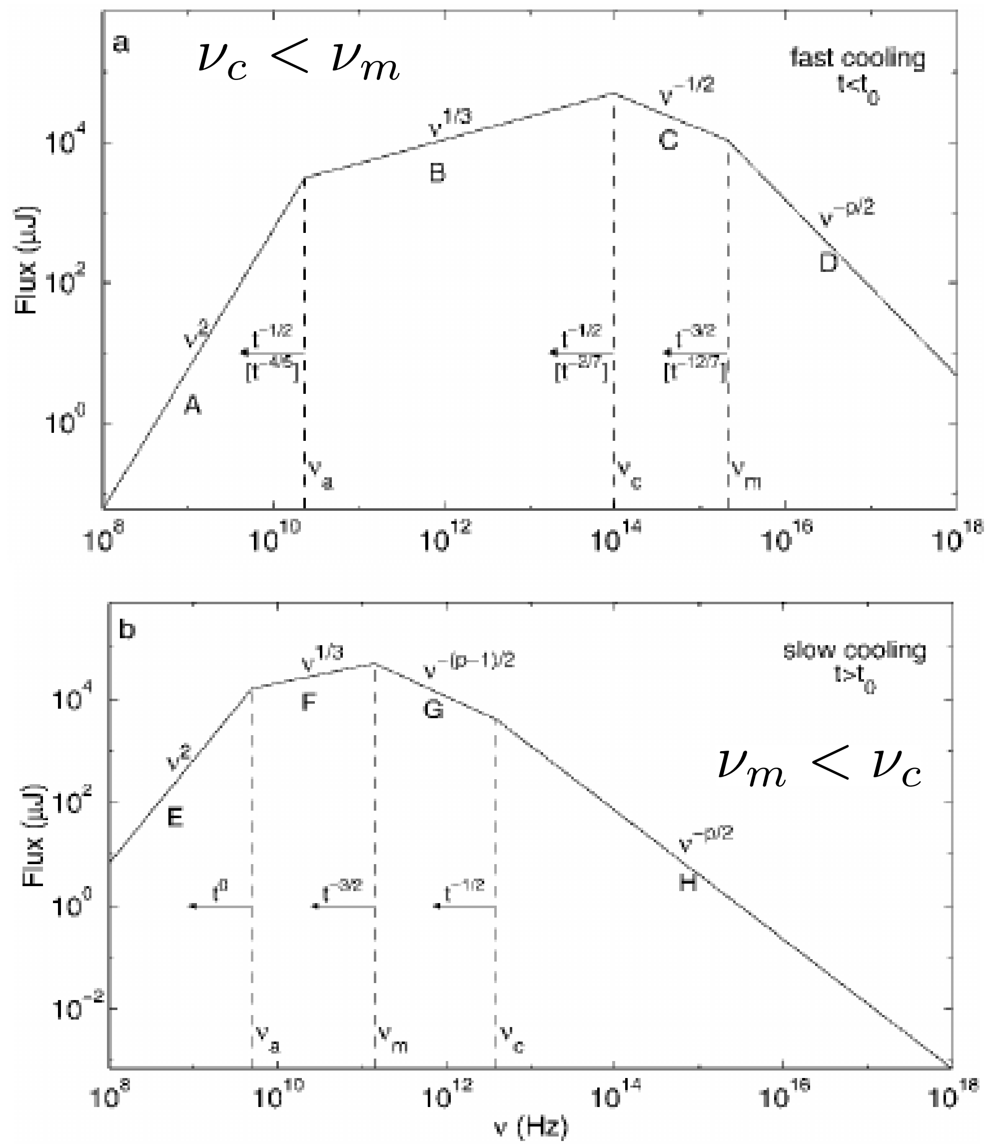
Zhang & Meszaros (2001)

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

External Shocks: Synchrotron Emission

Cooling of electrons





Cooling of protons (**Less luminous!!**)

$$\left(\frac{F_{\nu,\mathrm{max,p}}}{F_{\nu,\mathrm{max,e}}}\right)^{\mathrm{Sync}} \propto m_e/m_p$$

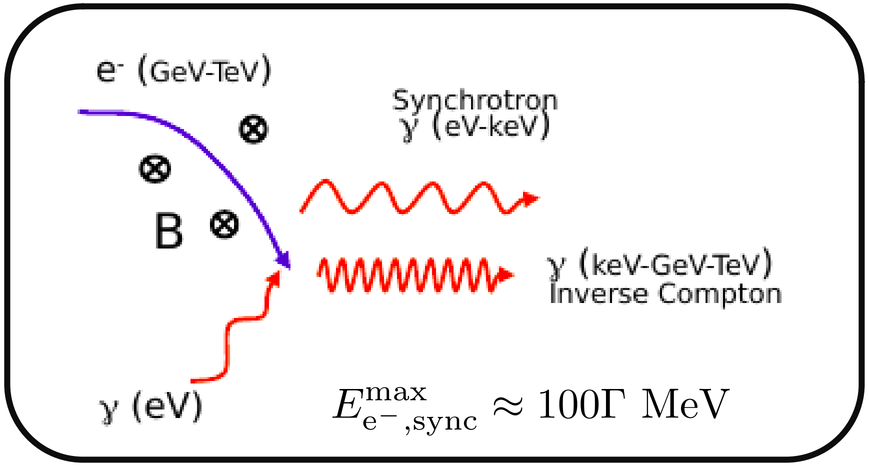
More on p-Sync

Zhang & Meszaros (2001)

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

SSC Emission: Radio to TeV Radiation

Cooling of electrons

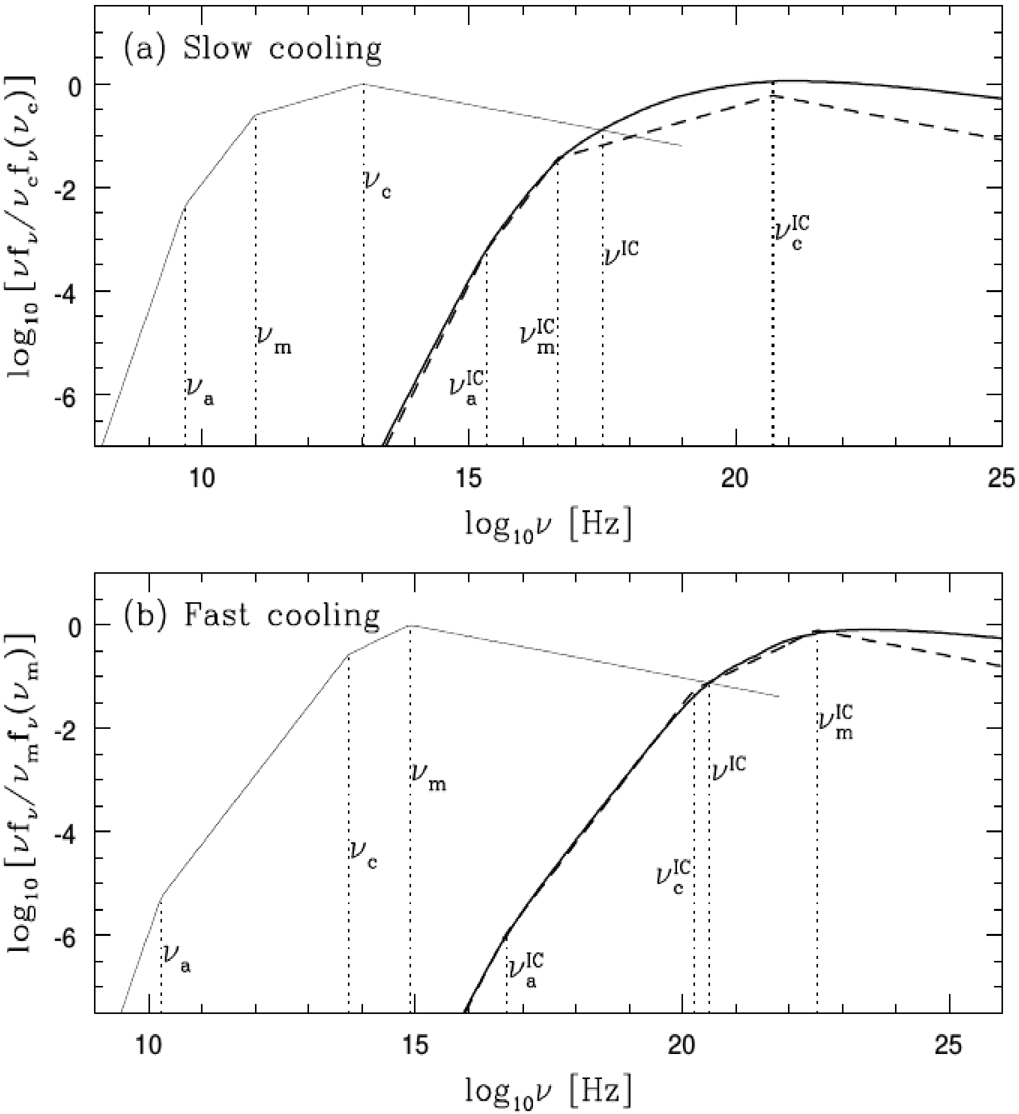


$$E^{max}_{e-,sync} \approx 100\Gamma \text{ MeV}$$

Max energy of SSC photons

$$E_{SSC,Th} \propto \gamma_e^2 E_{sync} \quad > \text{GeV}$$

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

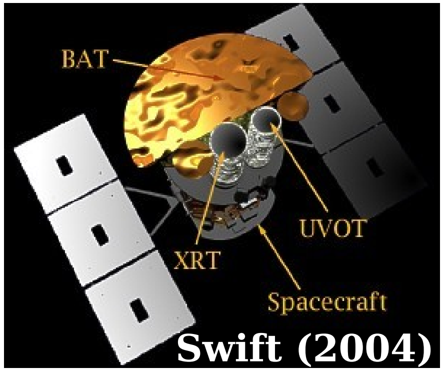


Sari, Piran & Narayan (1998), ApJL 497, 17
Zhang & Meszaros (2001), ApJ 559,110
Piran & Nakar (2010) ApJL 718, 63

Radio to TeV Detectors

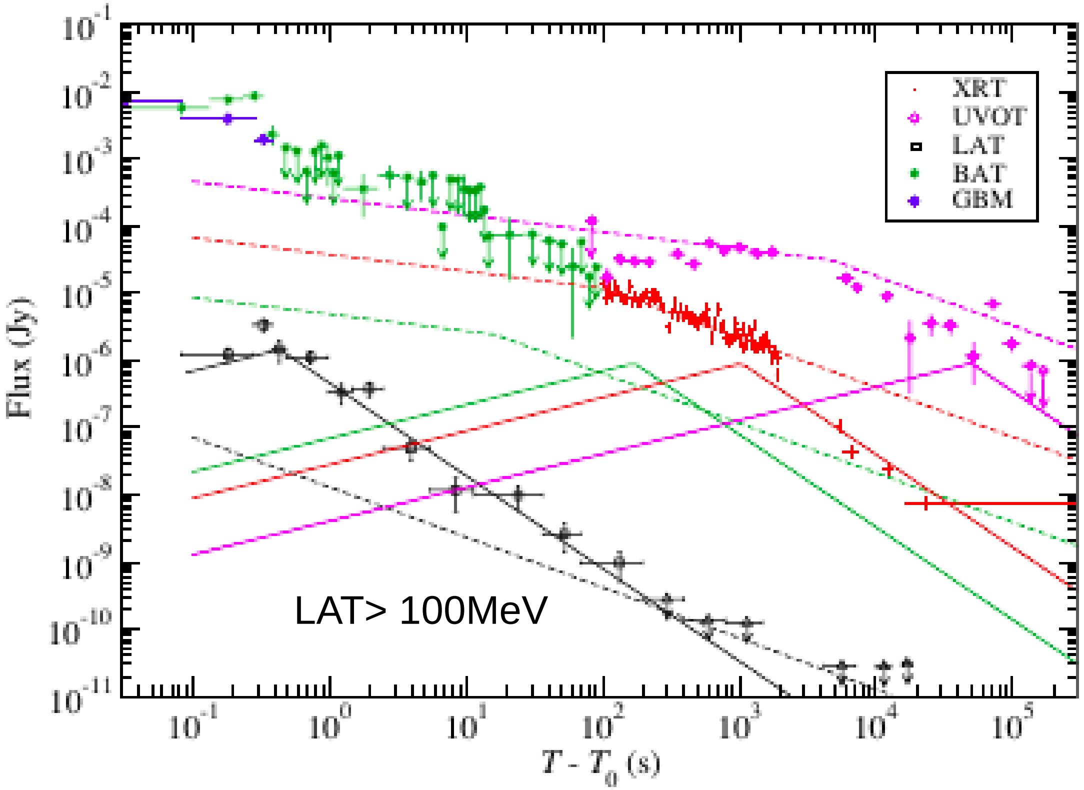
- AGILE, INTEGRAL, Konus-Wind (gamma-ray), SVOM (X-ray), AstroSAT (X-ray), nuSTAR (X-ray) and Radio detectors etc.
- HESS(2003), MAGIC(2004), VERITAS(2005), HAWC(2013), LHASSO(2019) and CTA. (Few x 100 GeV – Few x 100 TeV).
- Swift BAT locates the GRB and then the afterglow emission is followed.

- **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).



0.1-100 GeV Gamma-ray Afterglow Components in GRBs

Afterglow Emission: GRB 090510

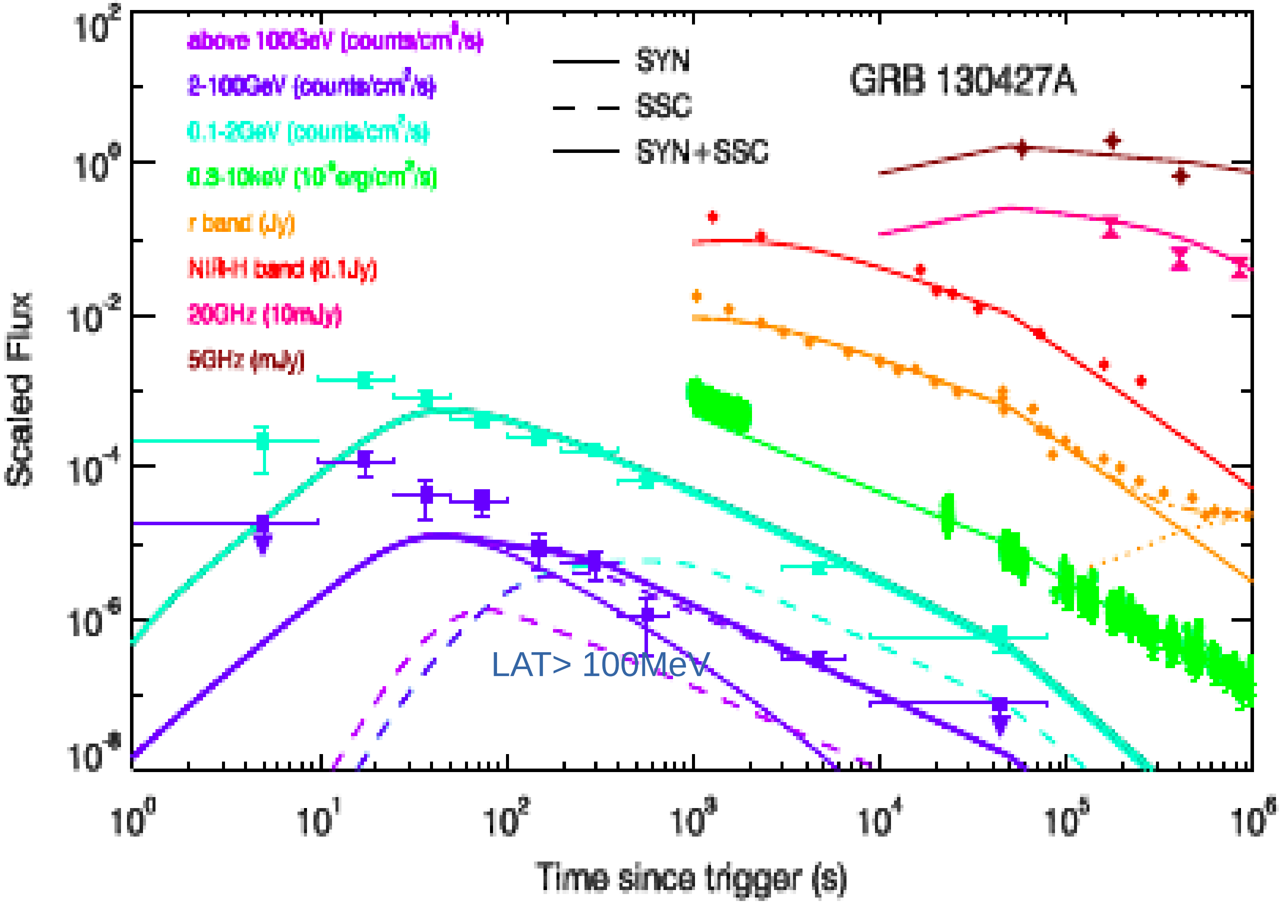


- A short GRB, z=0.903,
- Lepto-hadronic model for MW emission,
- >100 MeV: p-sync,
- X-rays and UV: e_sync

E_k (Erg)	2×10^{55}
Γ_0	2400
ε_e	0.0001
ε_p	0.5
ε_B	0.3
n (cm^3)	3

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

Afterglow Emission: GRB 130427A



- 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,
- Afterglow via SSC model.

E_k (Erg)	2×10^{53}
Γ_0	200
ε_e	0.6
ε_B	10^{-5}
n (cm^3)	1

Tam et al. (2013), ApJL 771, 13
Liu, R. et al. (2013), ApJL 773, 20

Discovery of VHE (0.1-100 TeV) Component: Cherenkov Telescopes

Multiwavelength Observations

GRB 190114C

$$T_{90} > 100\text{s}, \quad z \sim 0.4245$$

$$E_{\gamma,\text{iso}}^{\text{prompt}} \sim 3 \times 10^{53}\text{erg}$$

MAGIC Detection
(0.3 -1 TeV)

~55 s onwards

$$E_{\gamma,\text{iso},\text{VHE}}^{\text{afterglow}} \sim 10^{-3} E_{\gamma,\text{iso}}^{\text{prompt}}$$

MAGIC Collaboration (2019), Nature 575, 455
MAGIC Collaboration (2019), Nature 575, 459

Multiwavelength Observations

GRB 190114C

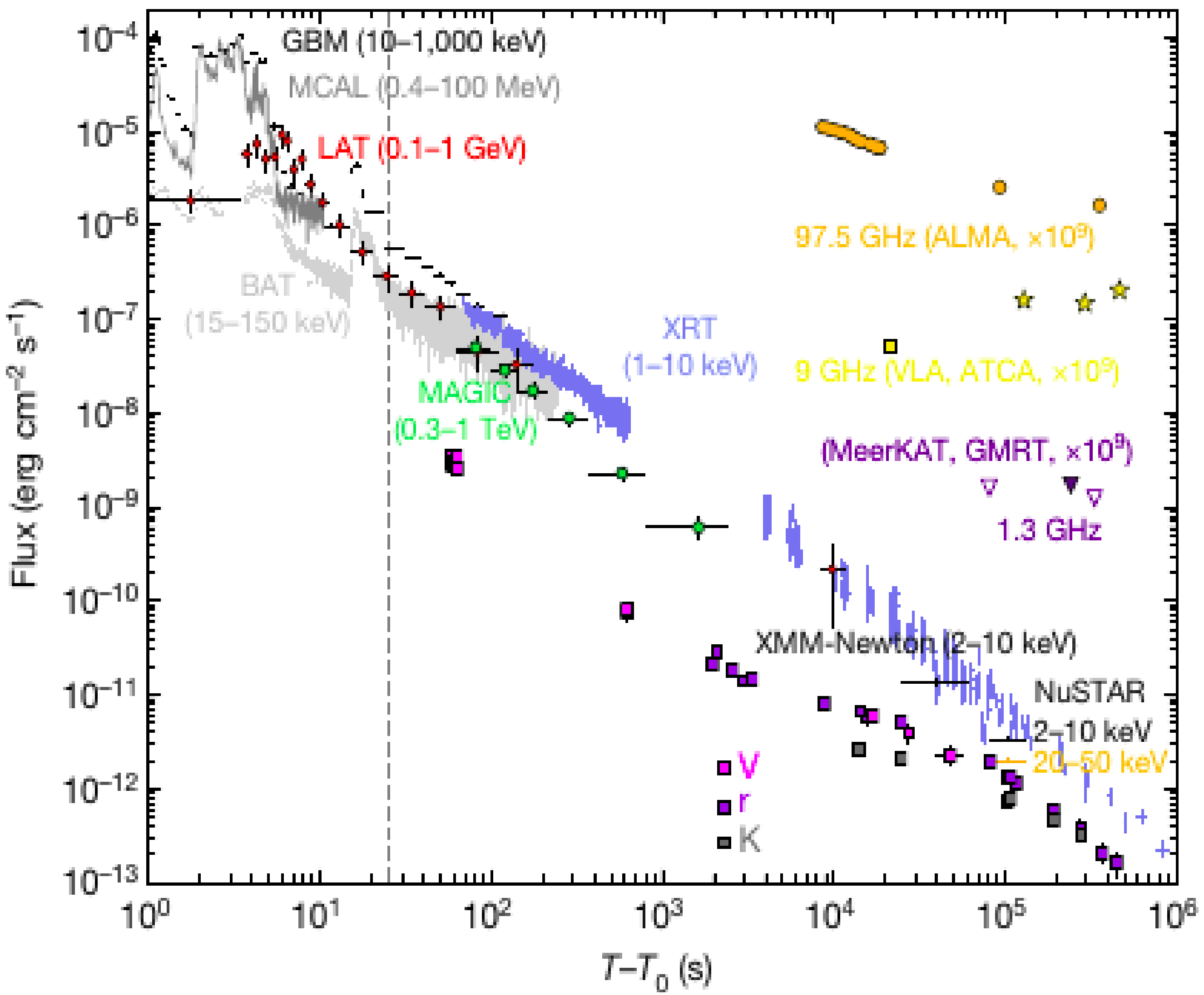
$$T_{90} > 100\text{s}, \quad z \sim 0.4245$$

$$E_{\gamma,\text{iso}}^{\text{prompt}} \sim 3 \times 10^{53}\text{erg}$$

MAGIC Detection
(0.3 -1 TeV)

~55 s onwards

$$E_{\gamma,\text{iso,VHE}}^{\text{afterglow}} \sim 10^{-3} E_{\gamma,\text{iso}}^{\text{prompt}}$$

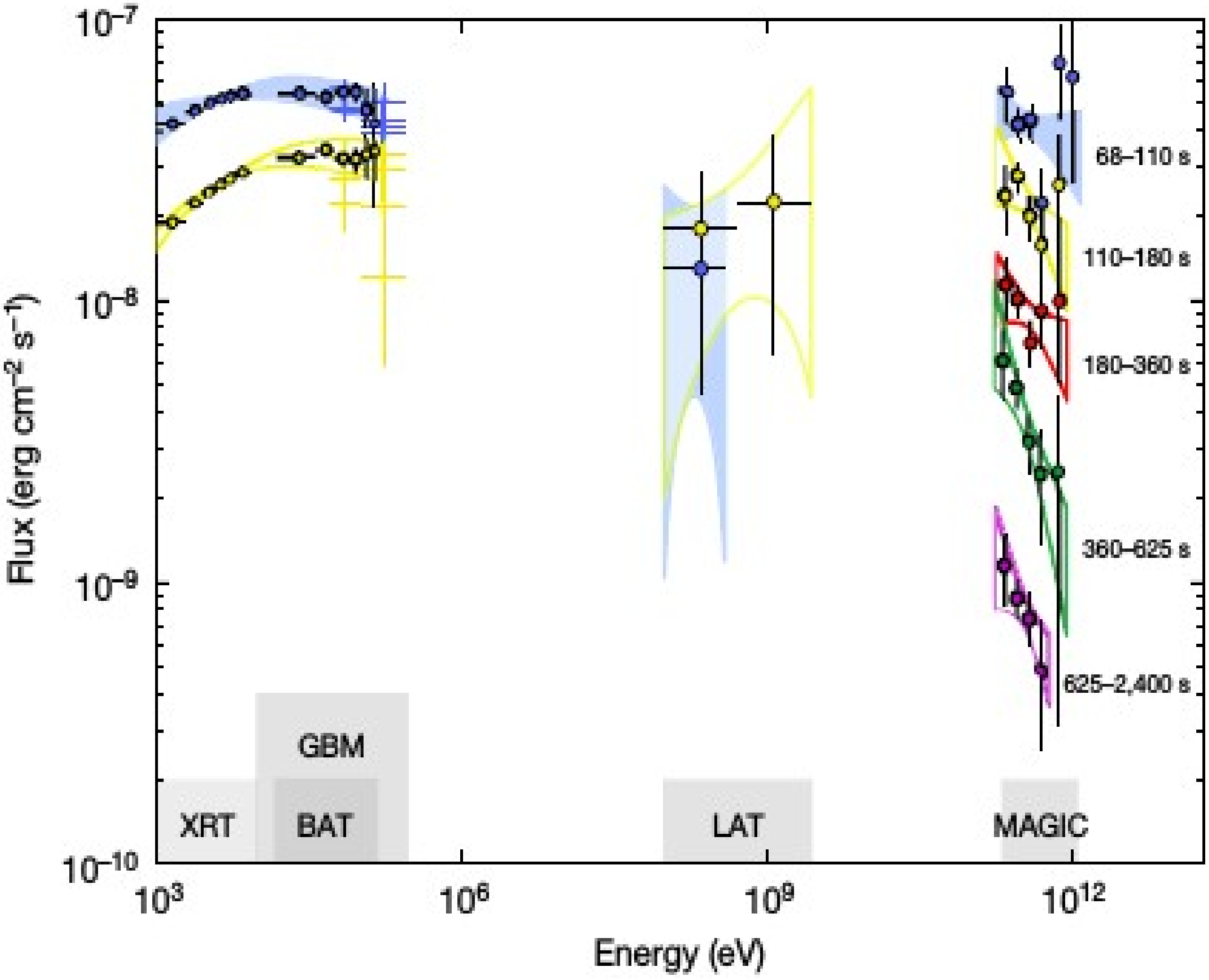


MAGIC Collaboration (2019), Nature 575, 455
MAGIC Collaboration (2019), Nature 575, 459

Spectral Energy Distribution

GRB 190114C

$$F_{\mathrm{X-ray}} \sim F_{\mathrm{TeV}}$$



MAGIC Collaboration (2019), Nature 575, 455
MAGIC Collaboration (2019), Nature 575, 459

Multiwavelength Observations

GRB 180720B

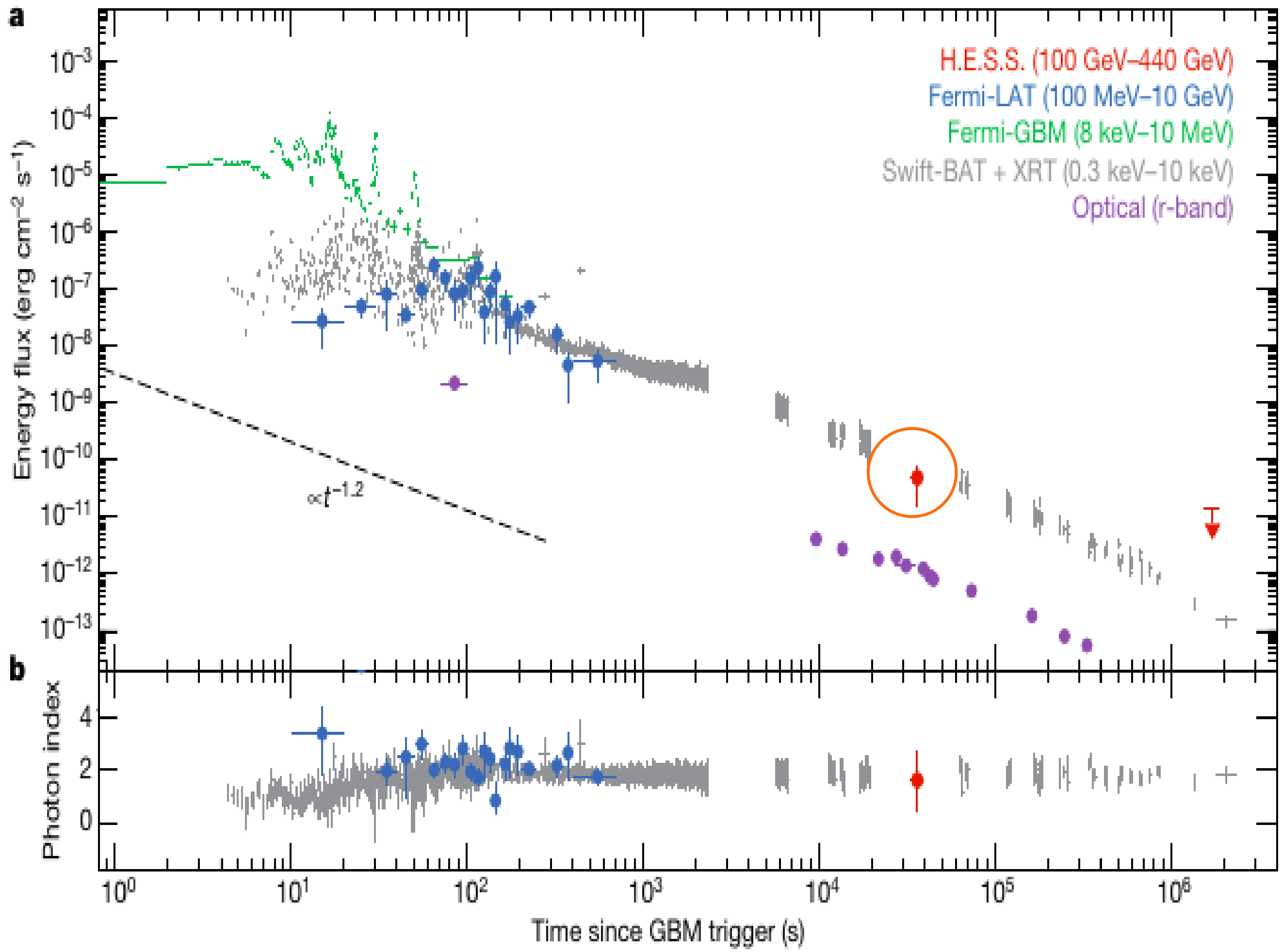
$T_{90} \sim 49\text{s}, \quad z \sim 0.653$

$E^{\text{prompt}}_{\gamma,\text{iso}} \sim 6 \times 10^{53}\text{erg}$

HESS Detection
(0.1 -0.5 TeV)

~10 hr onwards

$E^{\text{afterglow}}_{\gamma,\text{iso,VHE}} \sim 10^{-6} E^{\text{prompt}}_{\gamma,\text{iso}}$



HESS Collaboration (2019), Nature 575, 464

Multiwavelength Observations

GRB 180720B

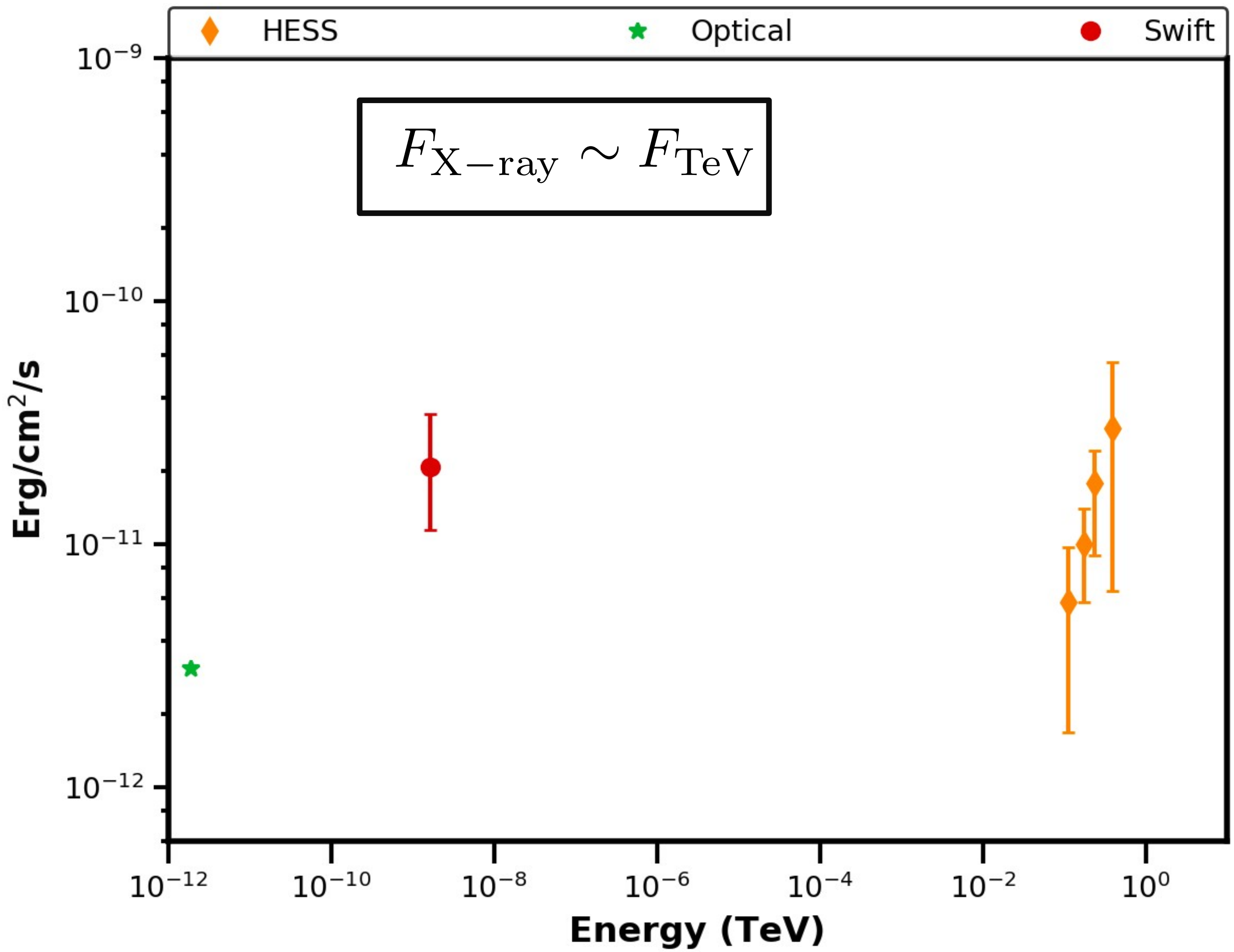
$$T_{90} \sim 49\text{s}, \quad z \sim 0.653$$

$$E_{\gamma,\text{iso}}^{\text{prompt}} \sim 6 \times 10^{53}\text{erg}$$

HESS Detection
(0.1 -0.5 TeV)

~10 hr onwards

$$E_{\gamma,\text{iso,VHE}}^{\text{afterglow}} \sim 10^{-6} E_{\gamma,\text{iso}}^{\text{prompt}}$$



Data is taken from A. Taylor's talk slides, 10th LHASSO meeting at Nanjing 2020

HESS Collaboration (2019), Nature 575, 464

VHE in Low-Luminosity GRB

GRB 190829A

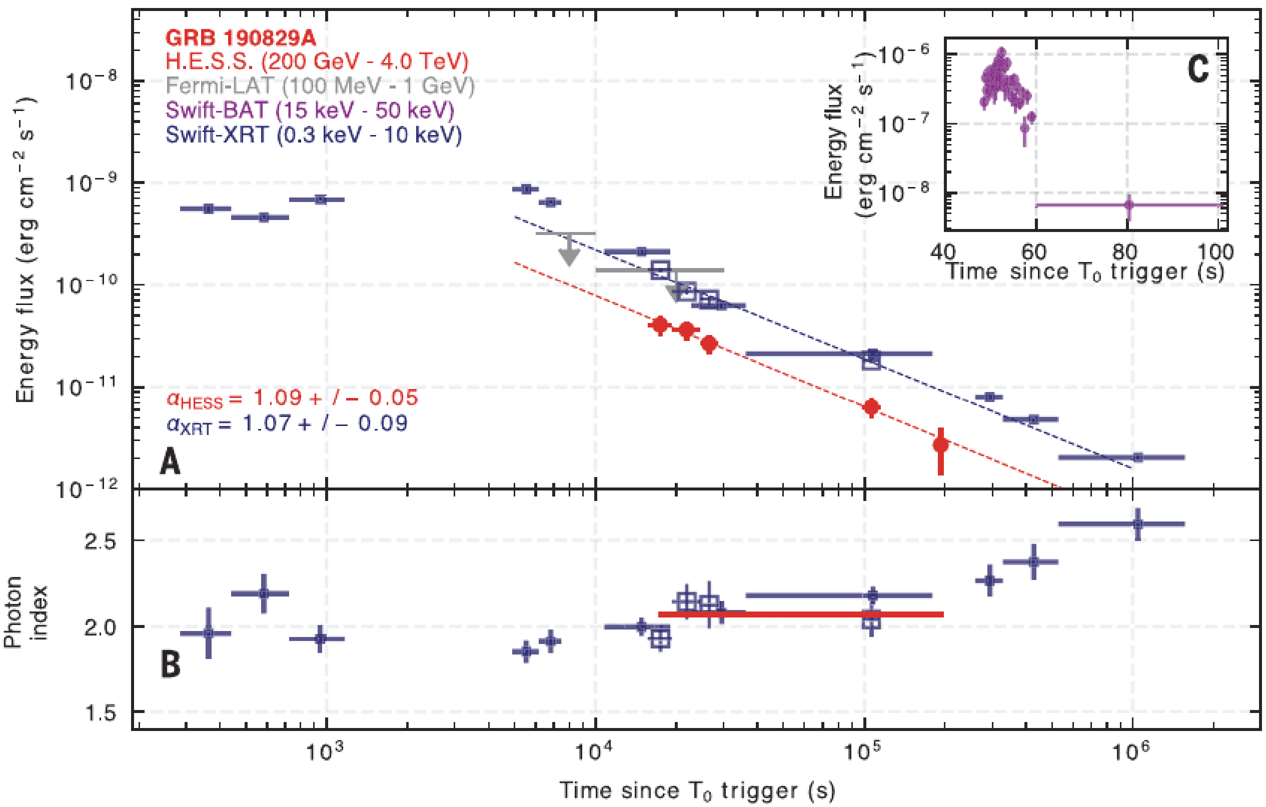
$$T_{90} \sim 6\text{s}, \quad z \sim 0.0785$$

$$E_{\gamma,\text{iso}}^{\text{prompt}} \sim 10^{50}\text{erg}$$

HESS Detection
(0.2 - 4 TeV)

~4.3 hr onwards

$$E_{\gamma,\text{iso,VHE}}^{\text{afterglow}} \sim 10^{-5} E_{\gamma,\text{iso}}^{\text{prompt}}$$



H.E.S.S. Collaboration (2021) Science 372, 1081

VHE in Low-Luminosity GRB

$$F_{\mathrm{X-ray}} > F_{\mathrm{TeV}}$$

GRB 190829A

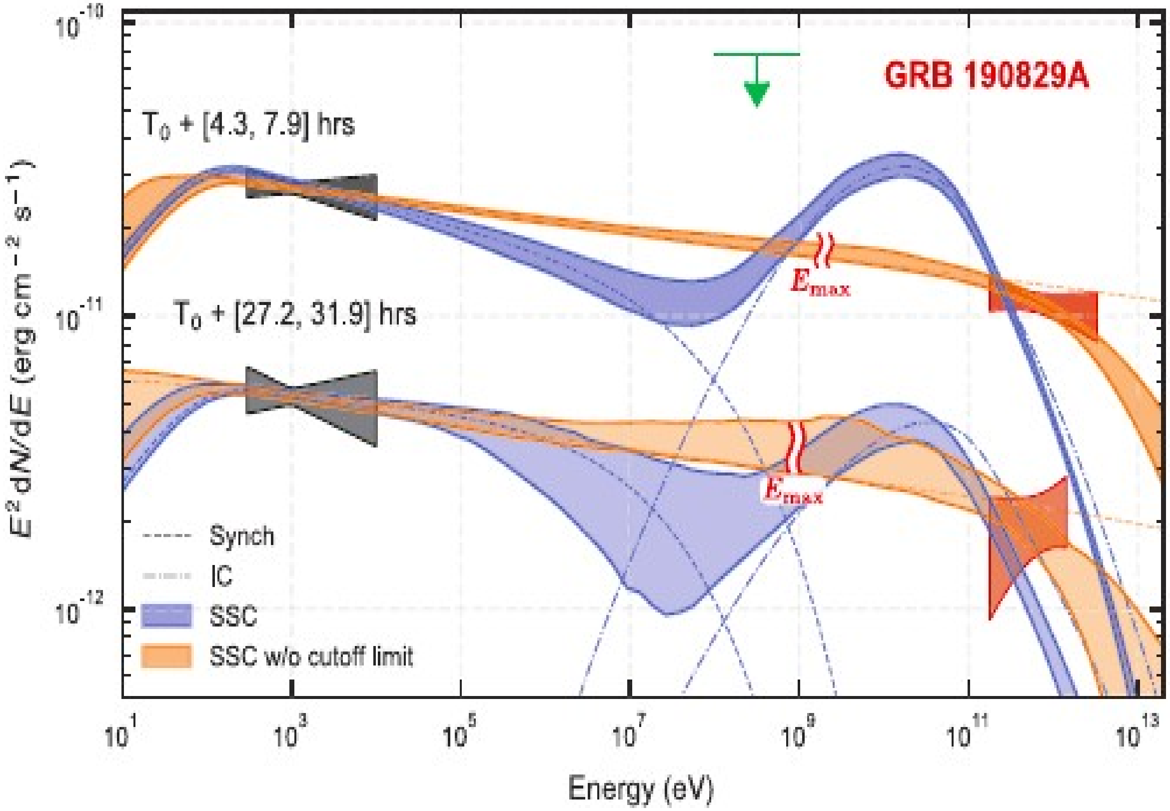
$$T_{90} \sim 6\mathrm{s}, \quad z \sim 0.0785$$

$$E^{\mathrm{prompt}}_{\gamma,\mathrm{iso}} \sim 10^{50}\mathrm{erg}$$

HESS Detection
(0.2 - 4 TeV)

~4.3 hr onwards

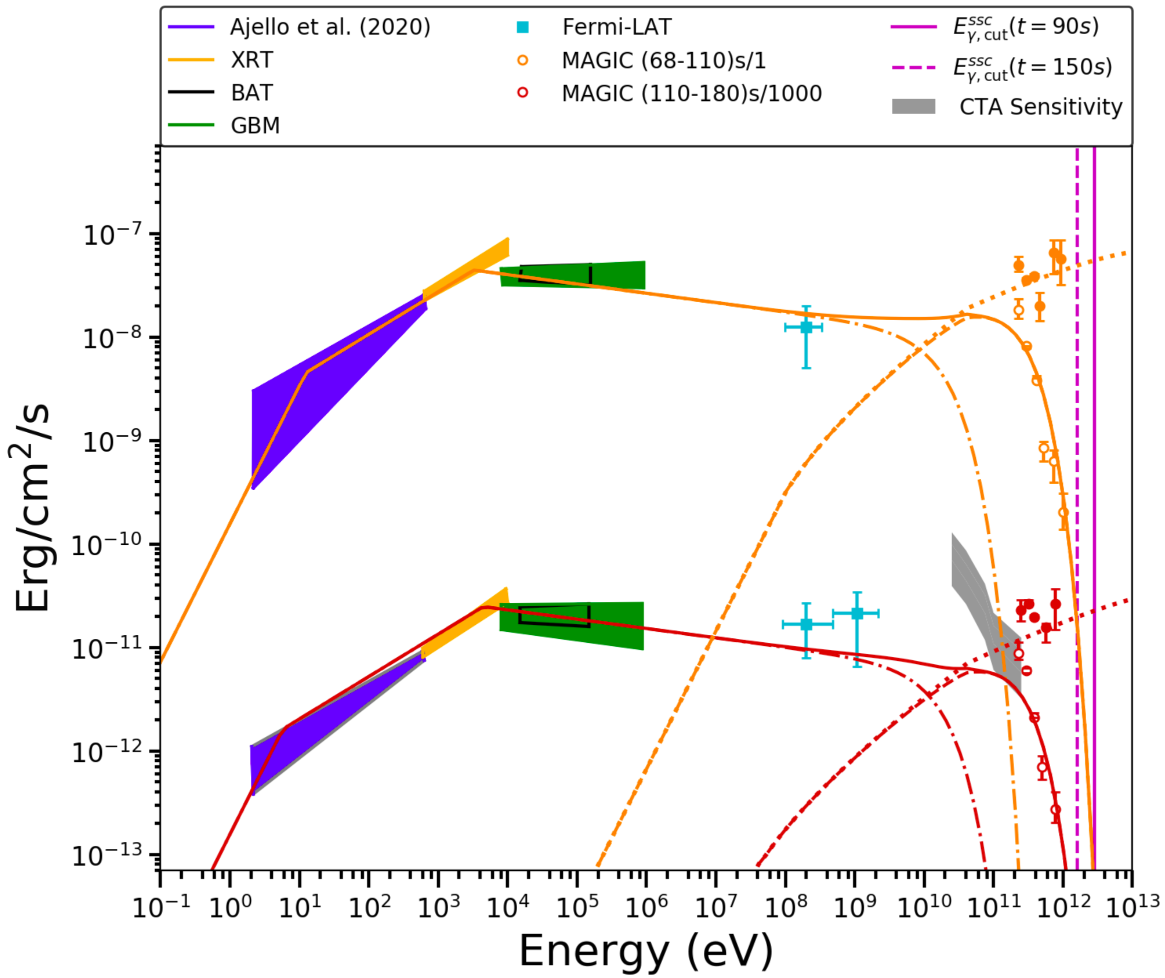
$$E^{\mathrm{afterglow}}_{\gamma,\mathrm{iso,VHE}} \sim 10^{-5} E^{\mathrm{prompt}}_{\gamma,\mathrm{iso}}$$



Challenges for 1 zone SSC model.

H.E.S.S. Collaboration (2021) Science 372, 1081

GRB 190114C: SSC Model



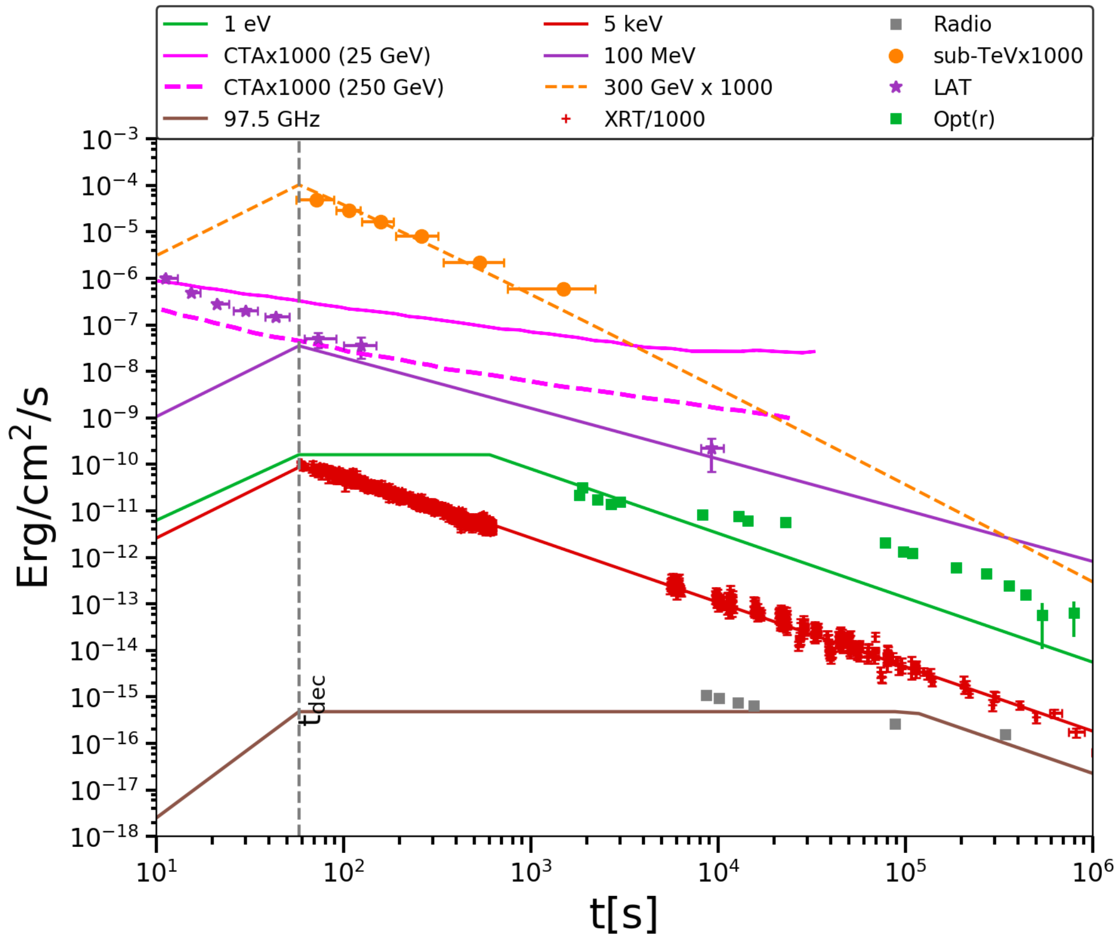
SSC in Thomson regime

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

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

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

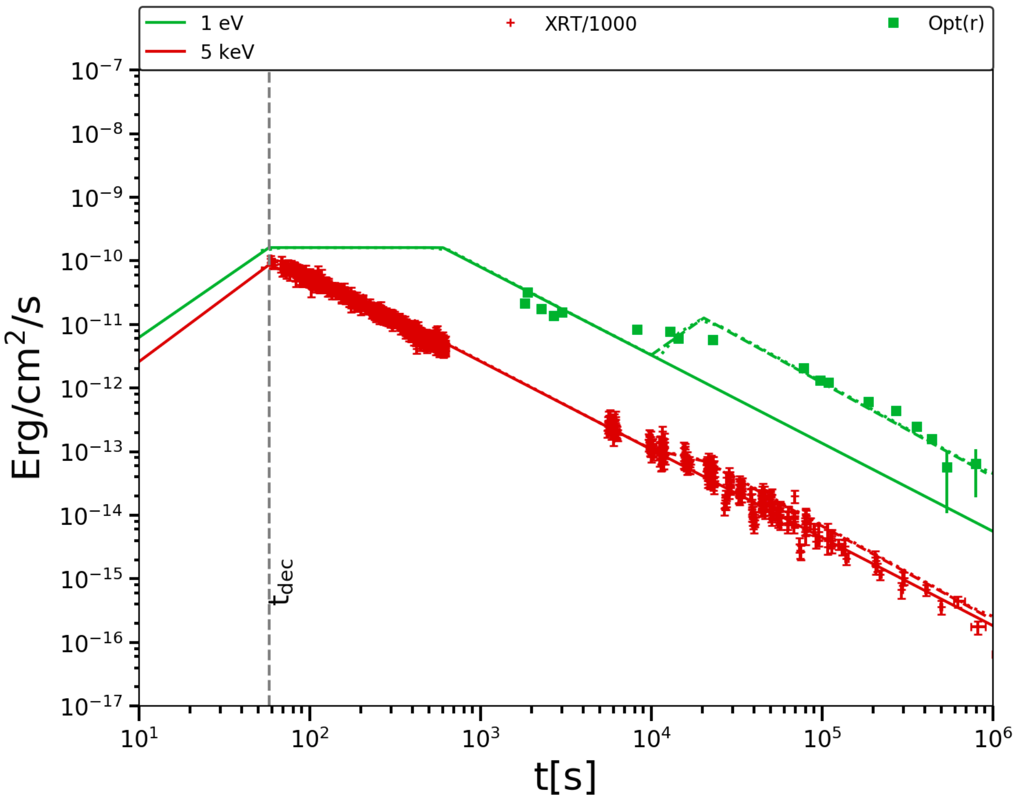
GRB 190114C: Light Curves



E_k (Erg)	3×10^{54}
Γ_0	300
p	2.15
ε_e	0.03
ε_B	0.01
A_*	0.03

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

GRB 190114C: Refreshed Shock @ Optical



} f=5

Refershed shock @ ~ 2x10[4] s.

E_k (Erg)	3 x 10^{54} (2x10^{53})
Γ_0	300 (36)
p	2.15 (2.5)
ε_e	0.03 (0.08)
ε_B	0.01 (0.07)
A_*	0.03

$$F_{\rm Sy,Ref} = (1 + f^{(3+p)/4}) F_{\rm Sy} \quad \nu < \nu_c$$

$$F_{\rm Sy,Ref} = (1 + f^{(2+p)/4}) F_{\rm Sy} \quad \nu > \nu_c$$

MAGIC Collaboration (2019), Nature 575, 459
Rees & Mészáros (1998) ApJL 496
J. Granot et al. (2003), Nature 426, 2

GRB 180720B: ISM Medium

ISM

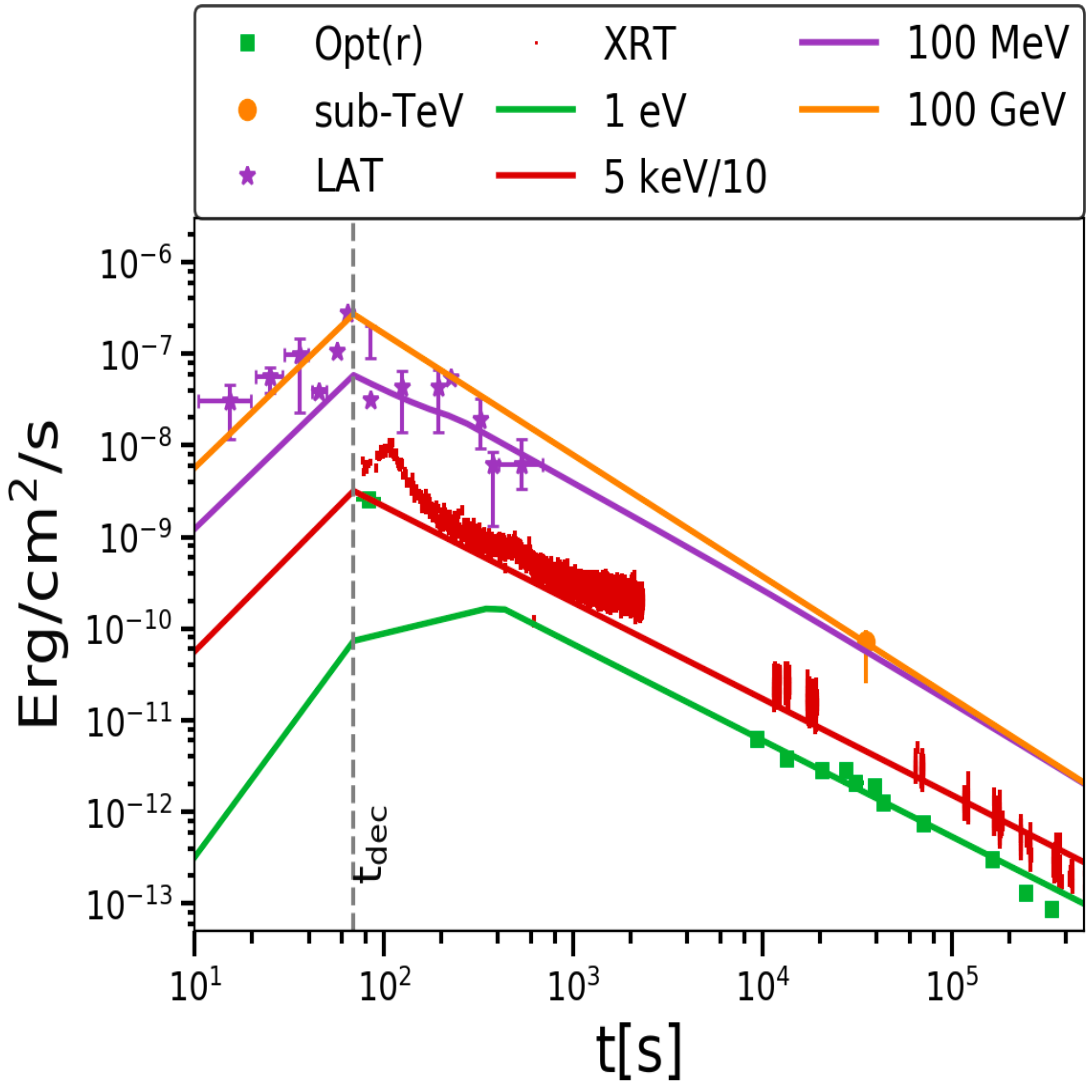
$$f_{\nu,\max} \propto t^{0}, \quad f^{\max}_{\nu,\mathrm{SSC}} \propto t^{1/4}$$

Wind

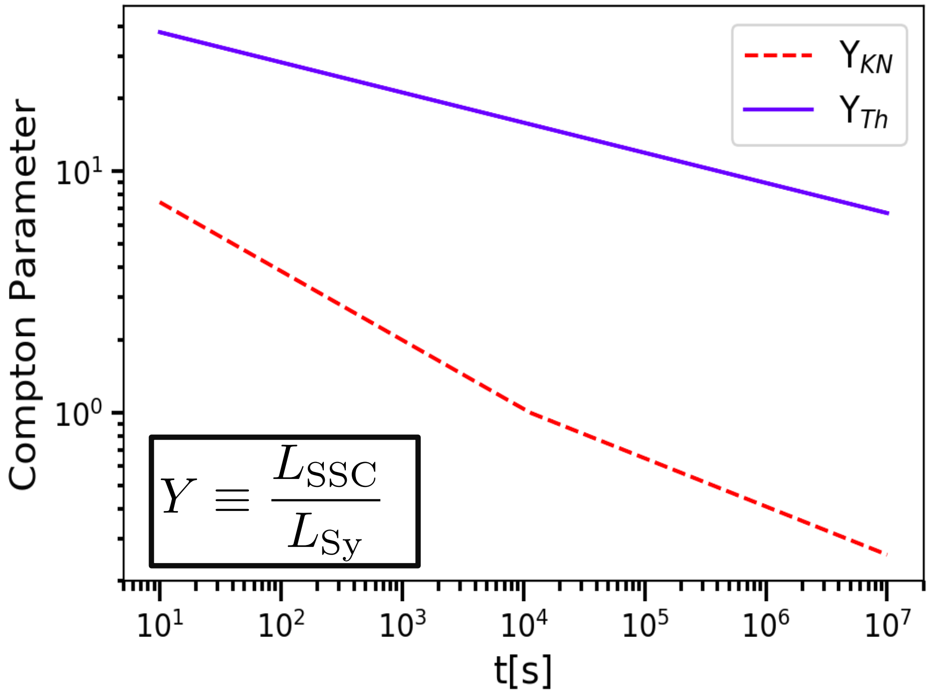
$$f_{\nu,\max} \propto t^{-1/2}, \quad f^{\max}_{\nu,\mathrm{SSC}} \propto t^{-1}$$

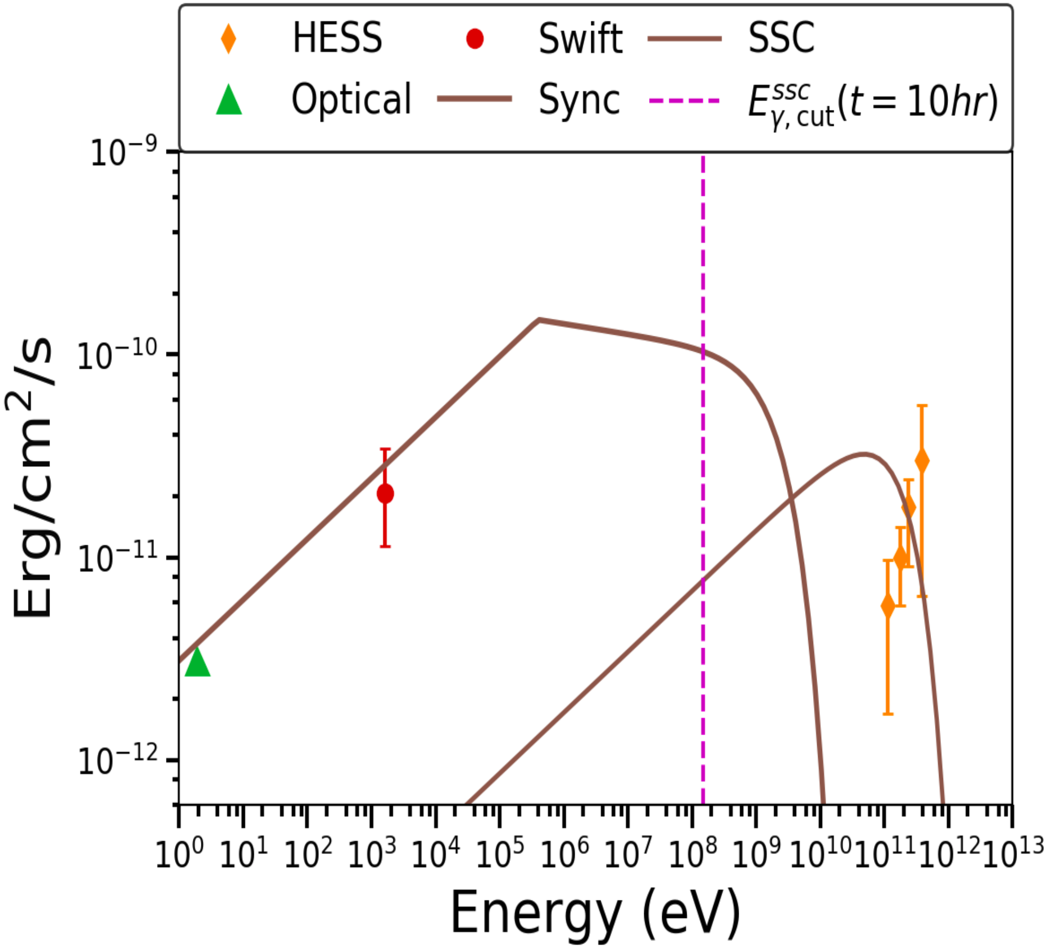
Xray flare & aftergow data is well explained using RS+FS @ ISM medium:

N. Fraija et al. (2019), ApJ 885, 29



GRB 180720B: ISM Medium

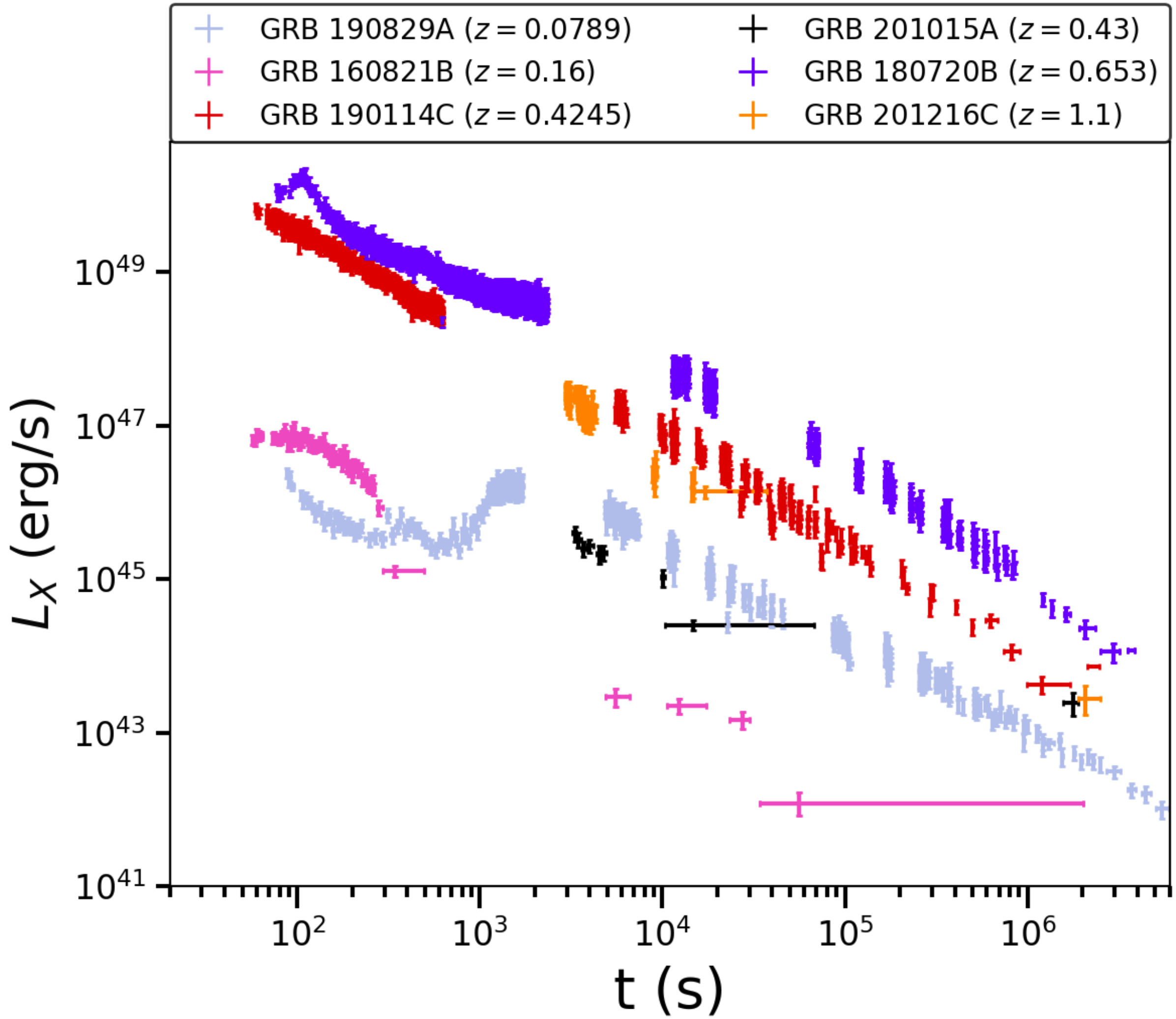




E_k (Erg)	4.5 x 10^{54}
Γ_0	400
p	2.4
ε_e	0.05
ε_B	1.2e-5
n (cm^3)	0.035

$$\tau_{\gamma\gamma} < 1, \quad \tau_{\rm EBL} \approx 160{\rm GeV}$$

X-ray Light Curves: VHE GRBs

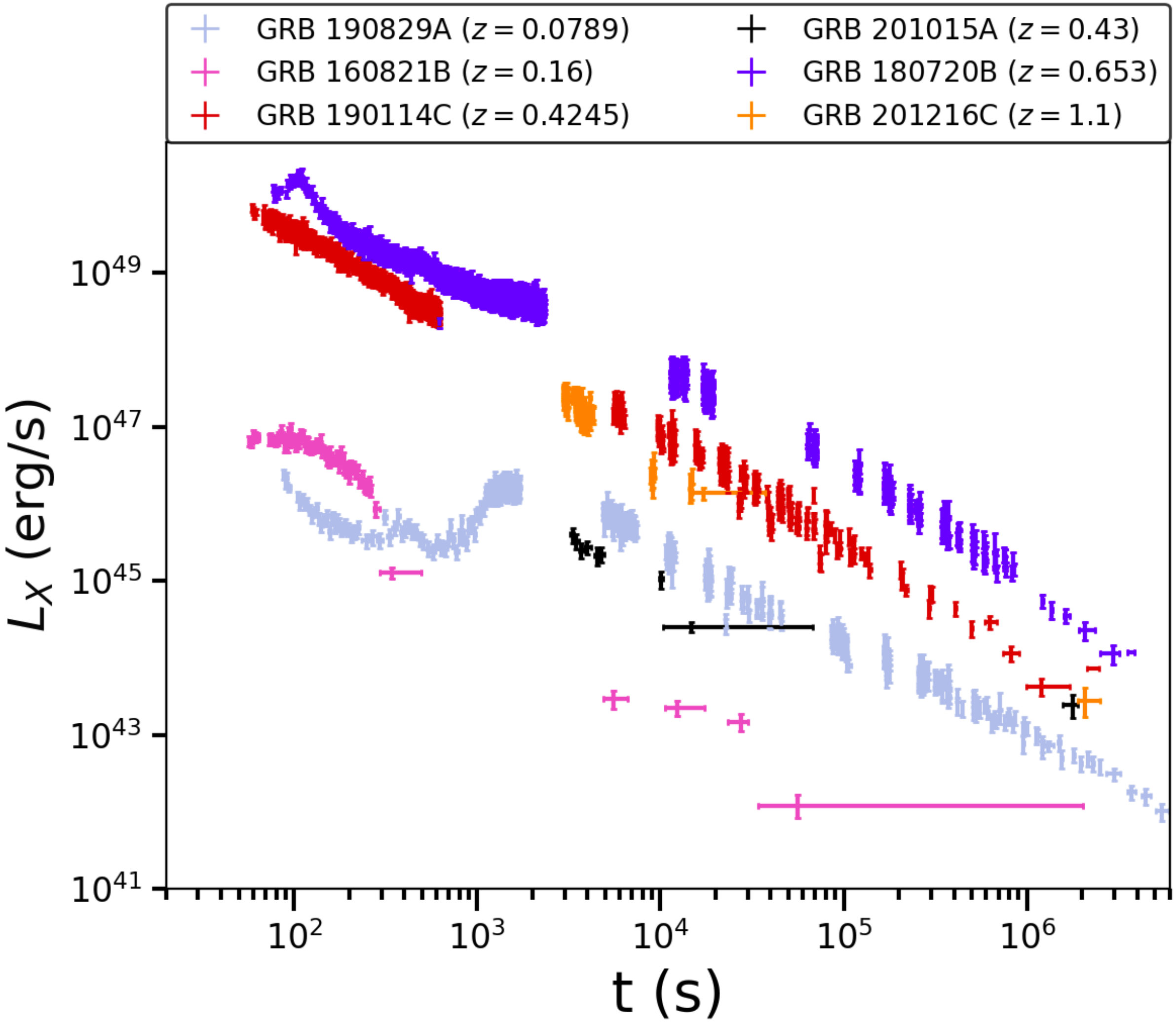


GRBs in TeV Catalogue

- 3 Confirmed VHE long GRBs,
- 2 long GRBs, data is not public,
- 1 short GRB, 3σ significance

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/**

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/

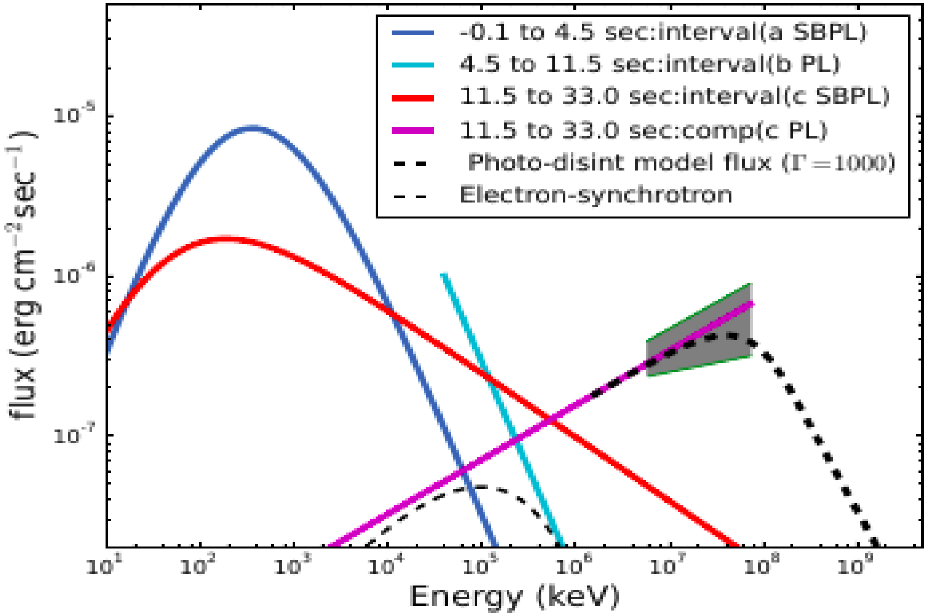
Summary

- **If the VHE energy component has luminosity similar to X-ray flux, SSC model is sufficient to explain the multiwavelength observations, at least for now.**

- **Low-Luminosity GRBs are promising sources in VHEs.**

Thank you for your attention

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