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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

GRBs AS TOOLS TO STUDY LIV

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ISTITUTO NAZIONALE DI ASTROFISICA

ANNECY

FEBRUARY 2026

BOUNDS ON LIV FROM GRBS

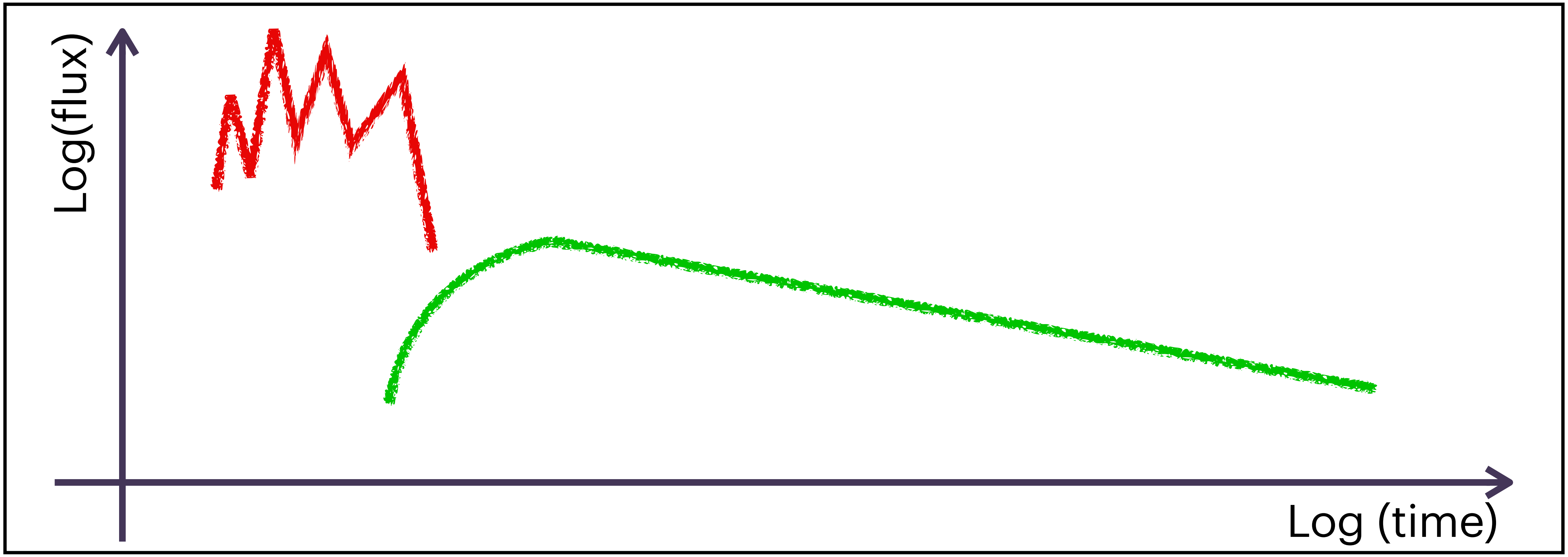
Investigation of possible effects on time of flight: energy dependent time delay between photons

Best conditions to detect a LIV-induced time delay:
- large source distances
- large photon energy
- short timescale variability

GRBs are good candidates

EMISSION FROM GRBS: AN OVERVIEW

TWO DISTINCT EMISSION PHASES



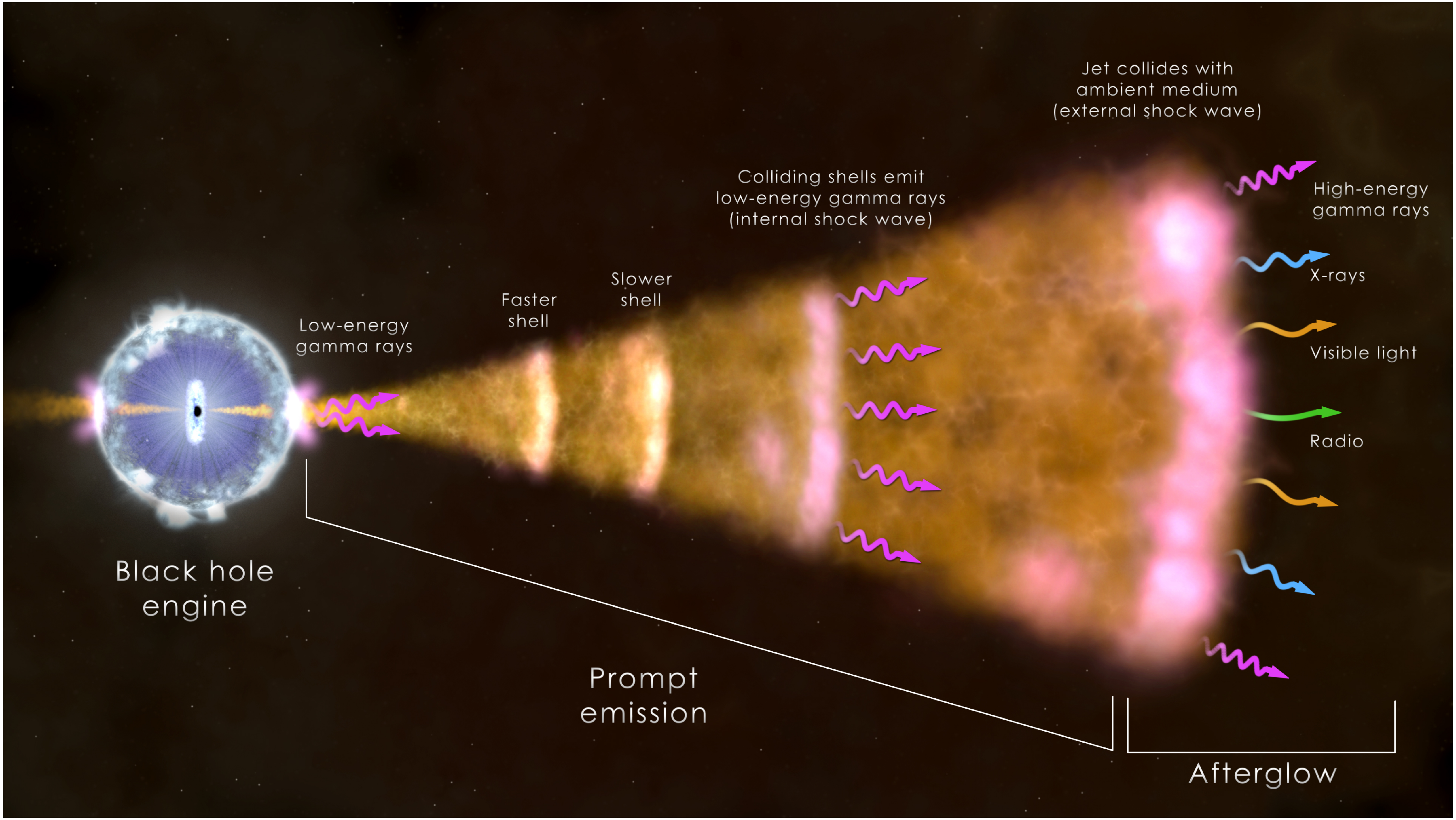
PROMPT

- from 10 keV to 10 MeV
- non-thermal spectra
- 0.1 seconds to 10^3 seconds
- highly variable flux

AFTERGLOW

- from radio to TeV
- non-thermal spectra
- days - weeks
- smooth (PL) lightcurve

GAMMA-RAY BURSTS - THE STANDARD MODEL



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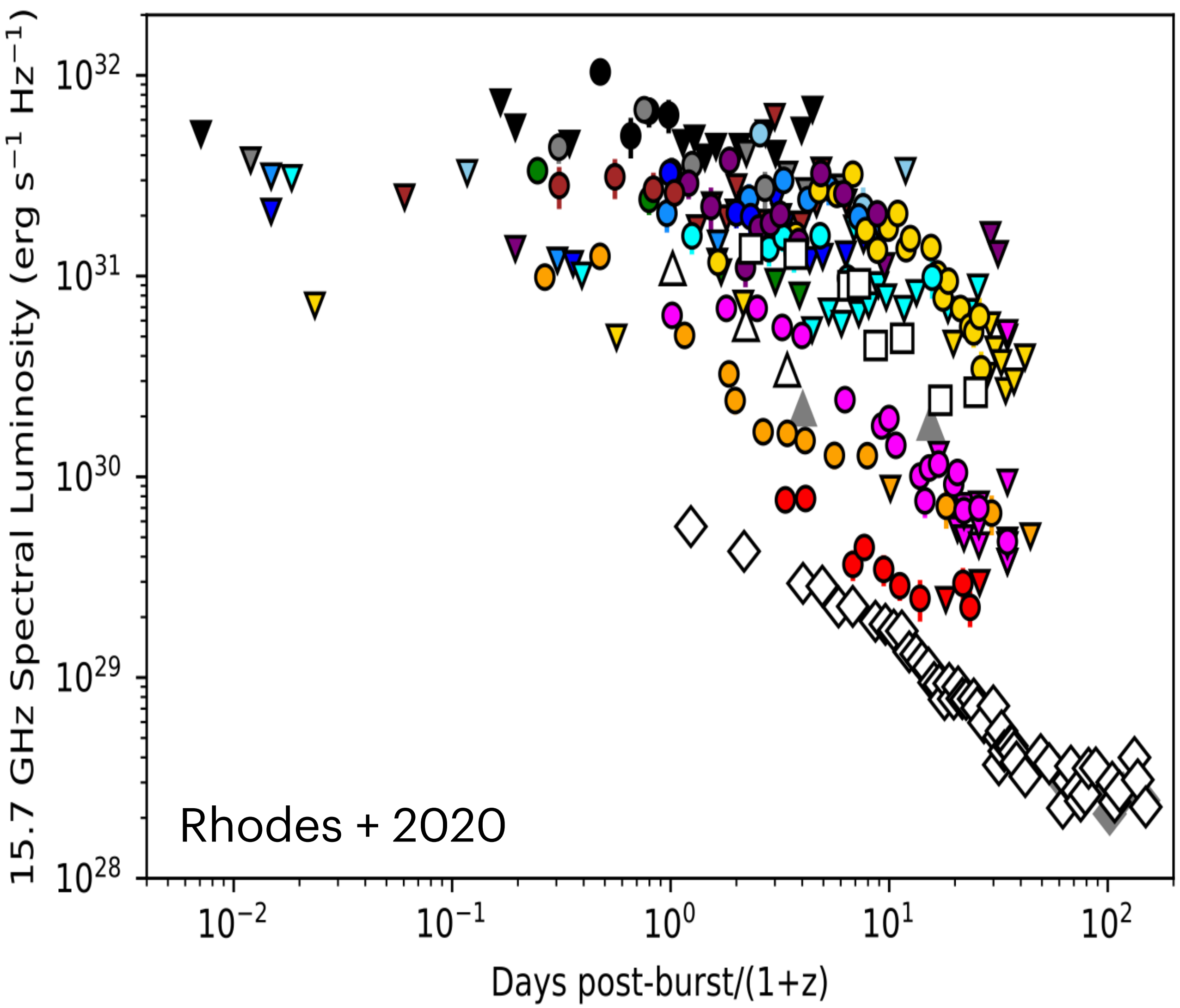
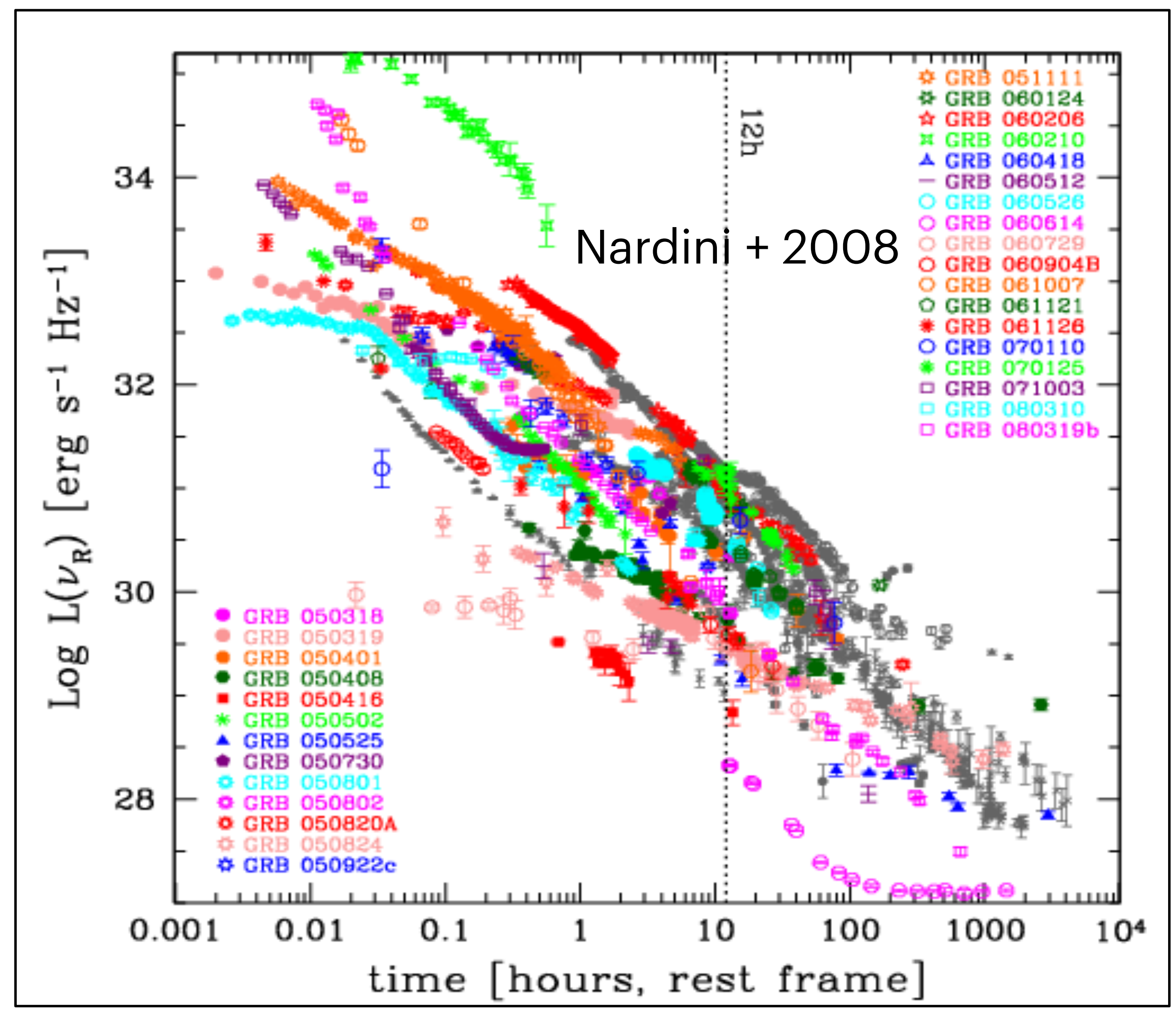
AFTERGLOW EMISSION LIGHTCURVES

OBSERVATIONS AT DIFFERENT FREQUENCIES

radio

optical

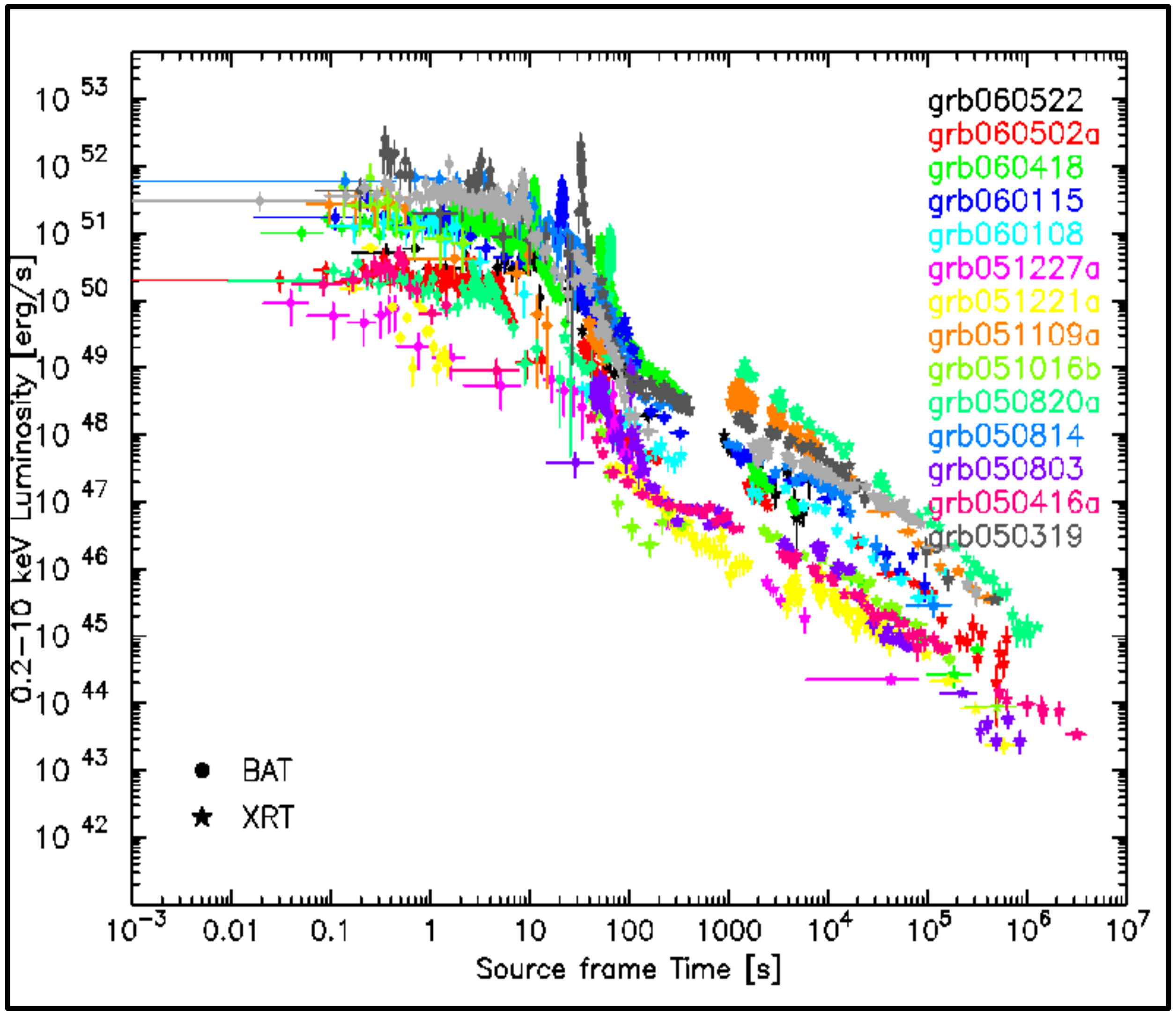




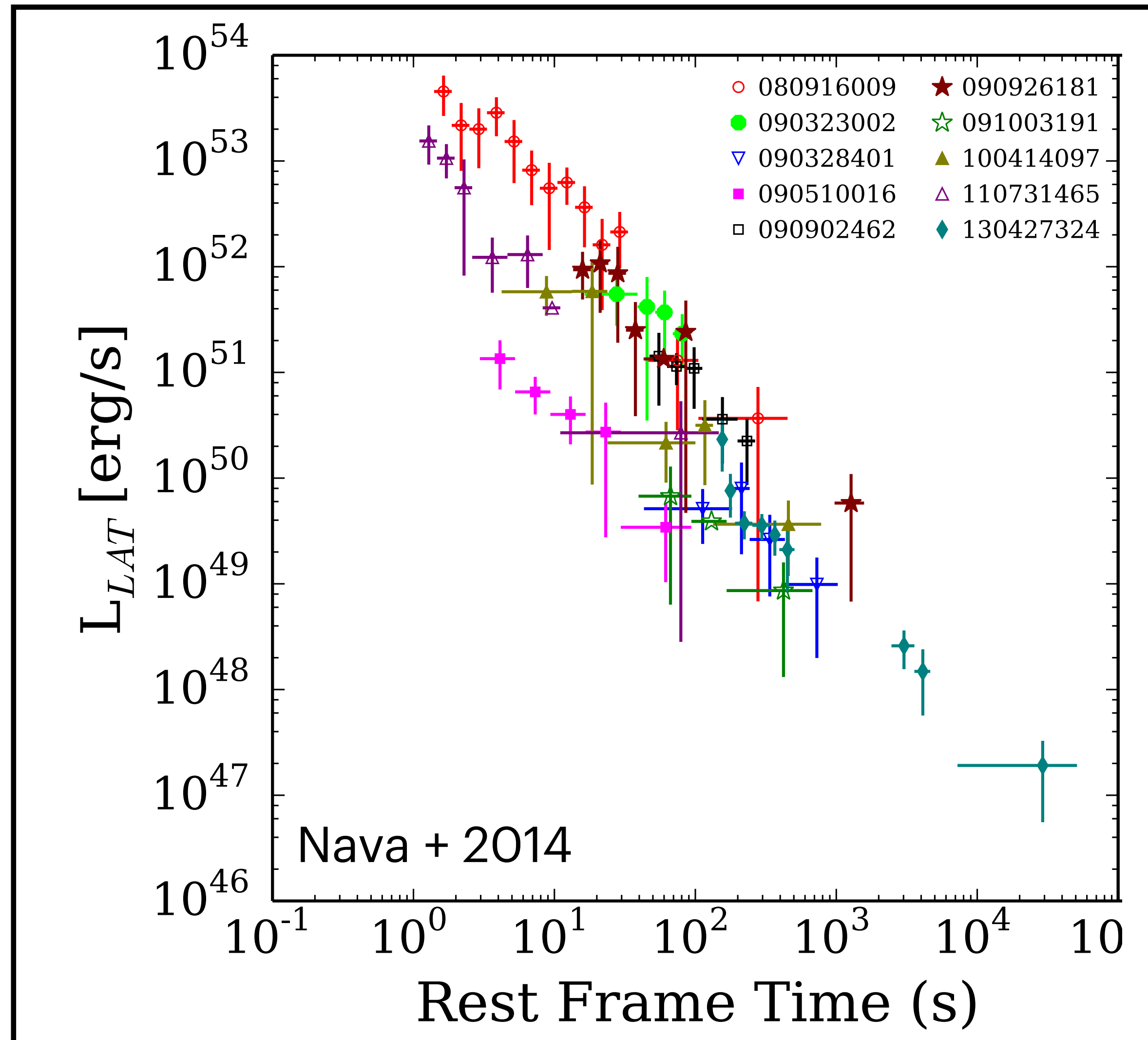
AFTERGLOW EMISSION LIGHTCURVES

OBSERVATIONS AT DIFFERENT FREQUENCIES

X-ray

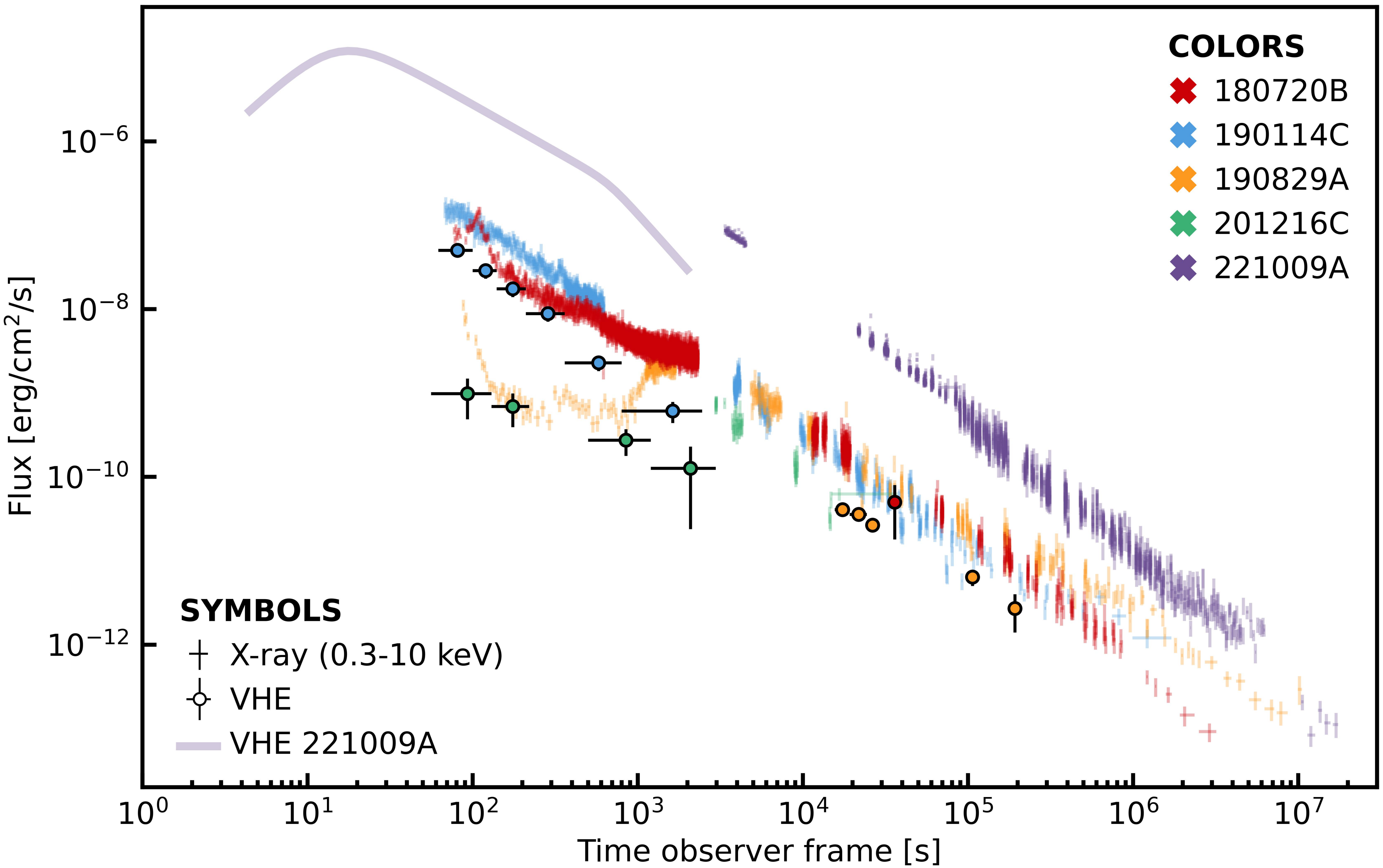


GeV (0.1-10 GeV)

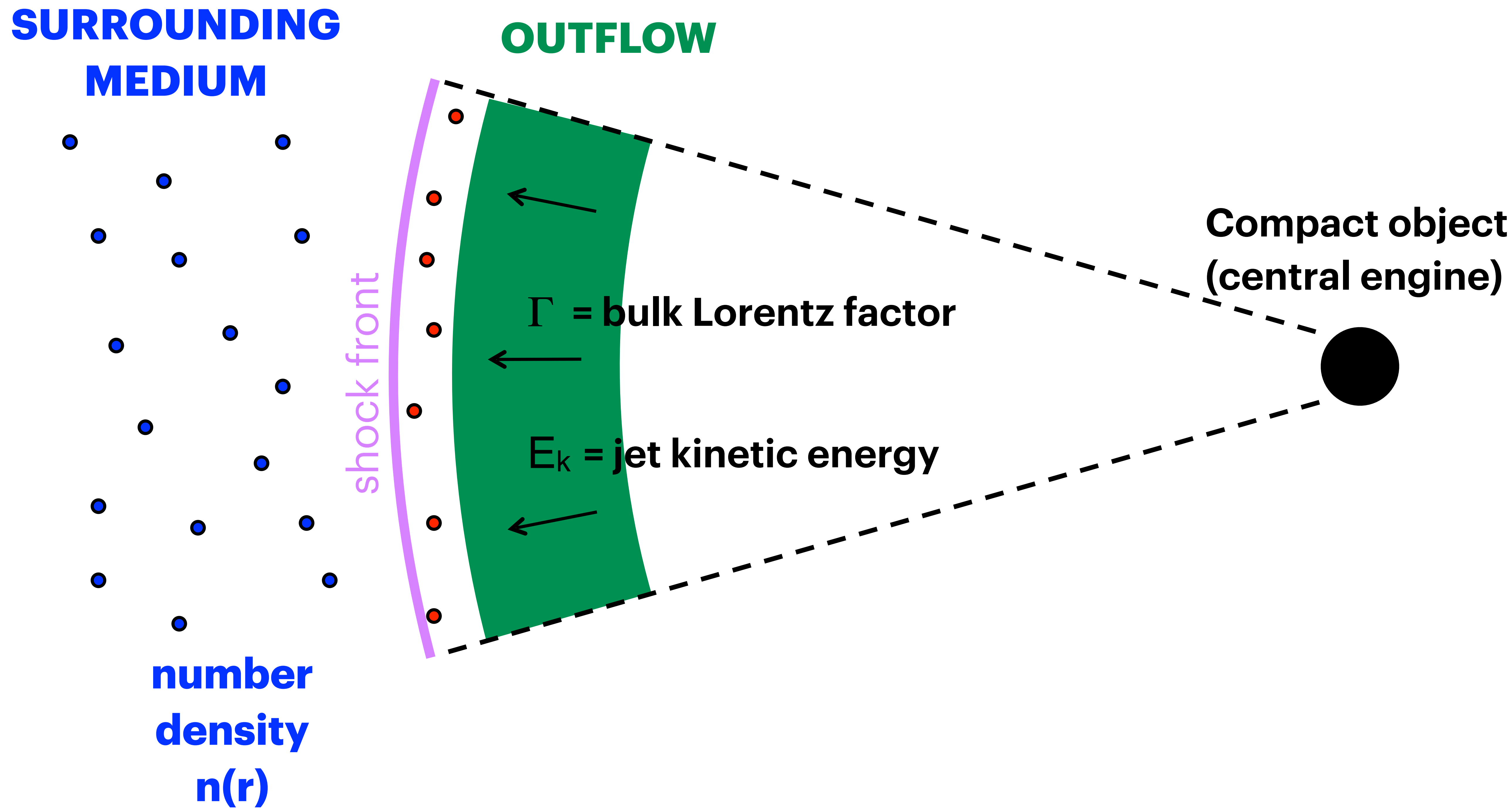


VHE AFTERGLOW EMISSION (SINCE 2019)

Miceli D. & Nava L., 2022, Galaxies, 10, 66

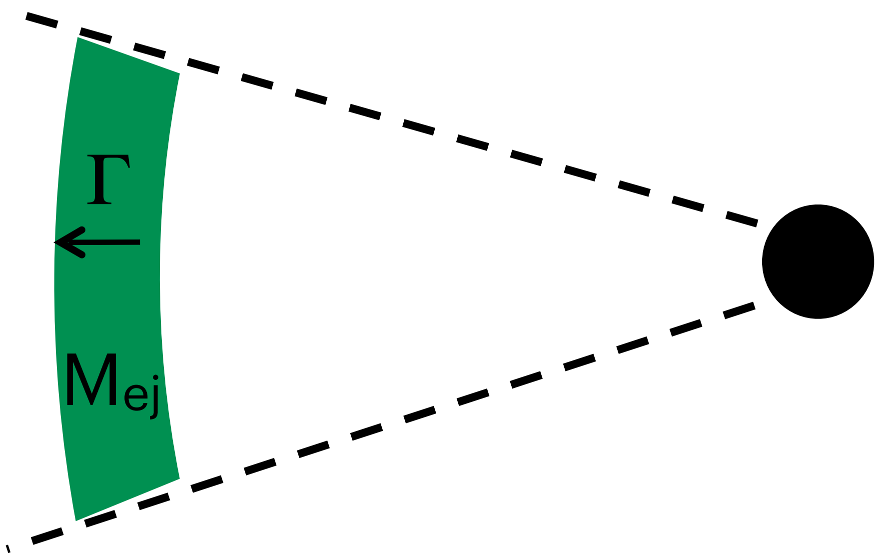


AFTERGLOW MODEL



DYNAMICS

Collision between jet of kinetic energy $E_k = \Gamma_0 M_{ej} c^2$ and the external medium with number density $n(r) = A\, r^{-s}$



At distance r, the collected mass is

$$m(r) = \int 4\pi\, r^2\, n(r)\, m_p\, dr \propto r^{3-s}$$

Conservation of energy and momentum

BEFORE COLLISION		AFTER THE COLLISION
$\Gamma_0 M_{ej}\, c^2 + m(r)c^2$	$=$	$\Gamma(r)\,[M_{ej} + m(r) + \epsilon'(r)/c^2]\, c^2$
$\Gamma_0 \beta_0 M_{ej}\, c$	$=$	$\Gamma(r)\beta(r)[M_{ej} + m(r) + \epsilon'(r)/c^2]\, c$

DYNAMICS

$$\Gamma(r) = \frac{\Gamma_0 M_{ej} + m(r)}{\sqrt{m^2(r) + 2\Gamma_0 M_{ej} m(r) + M_{ej}^2}}$$

- $m(r) < \frac{M_{ej}}{2\,\Gamma_0}$ — $\Gamma(r) = \Gamma_0$ — coasting phase
- $\frac{M_{ej}}{\Gamma_0} < m(r) < M_{ej}\Gamma_0$ — $\Gamma(r) \simeq \sqrt{\frac{E_k}{m(r)}}$ — deceleration phase
  see Blandford & McKee 1976
- $m(r) > M_{ej}\Gamma_0$ — $\Gamma(r) \to 1$ — non-relativistic phase

DYNAMICS

A closer look to the deceleration phase

see Blandford & McKee 1976

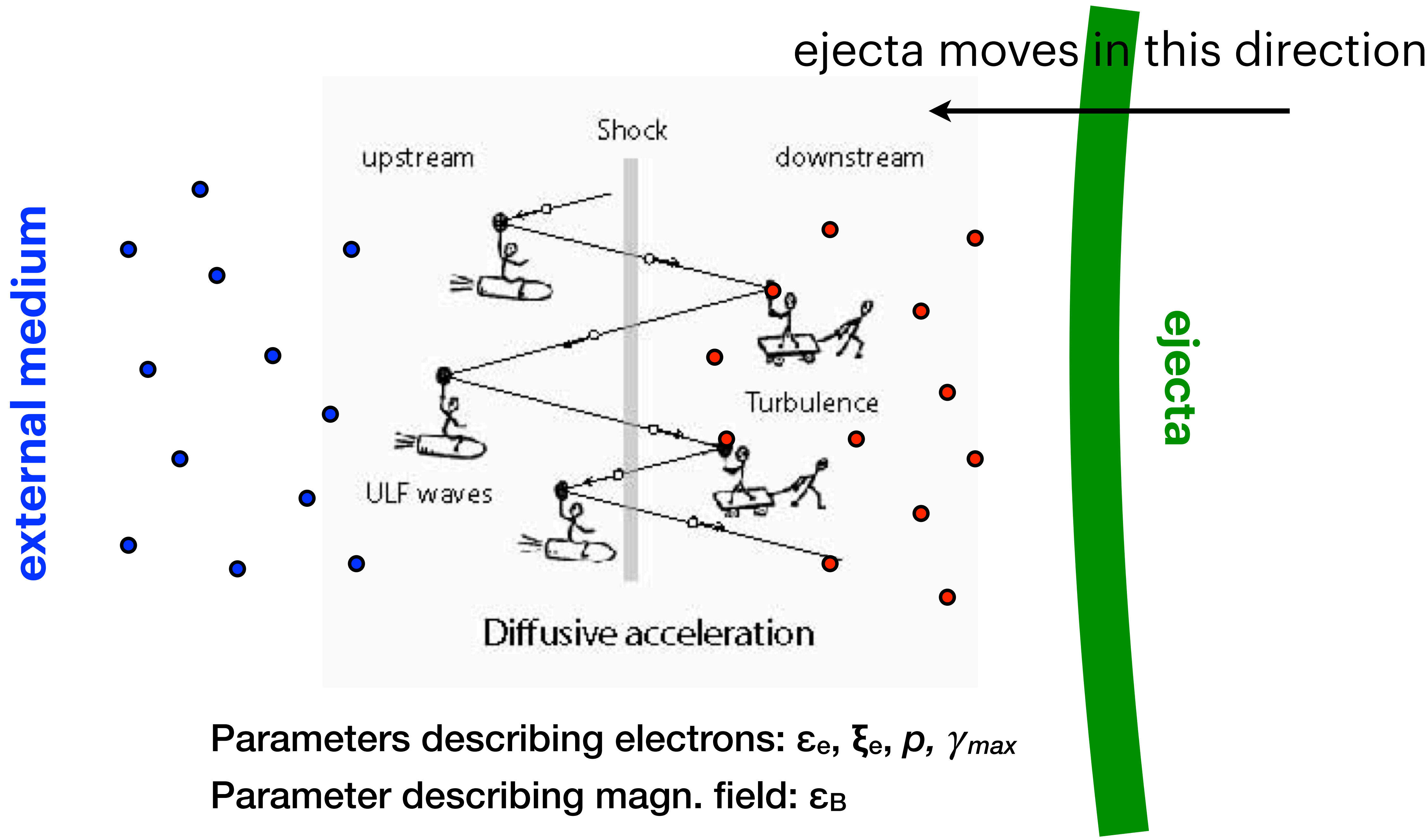
$$\frac{M_{ej}}{\Gamma_0} < m(r) < M_{ej}\Gamma_0 \quad \longrightarrow \quad \Gamma(r) \simeq \sqrt{\frac{E_k}{m(r)}} \propto r^{-\frac{(3-s)}{2}}$$

Given the relation between radius and time:

$$t_{obs} \simeq (1+z)\frac{r}{c\Gamma^2} \quad \longrightarrow \quad \Gamma(t_{obs}) \propto t_{obs}^{\frac{3-s}{8-2s}}$$

RELATIVISTIC SHOCKS

DIFFUSIVE SHOCK ACCELERATION (FERMI MECHANISM)



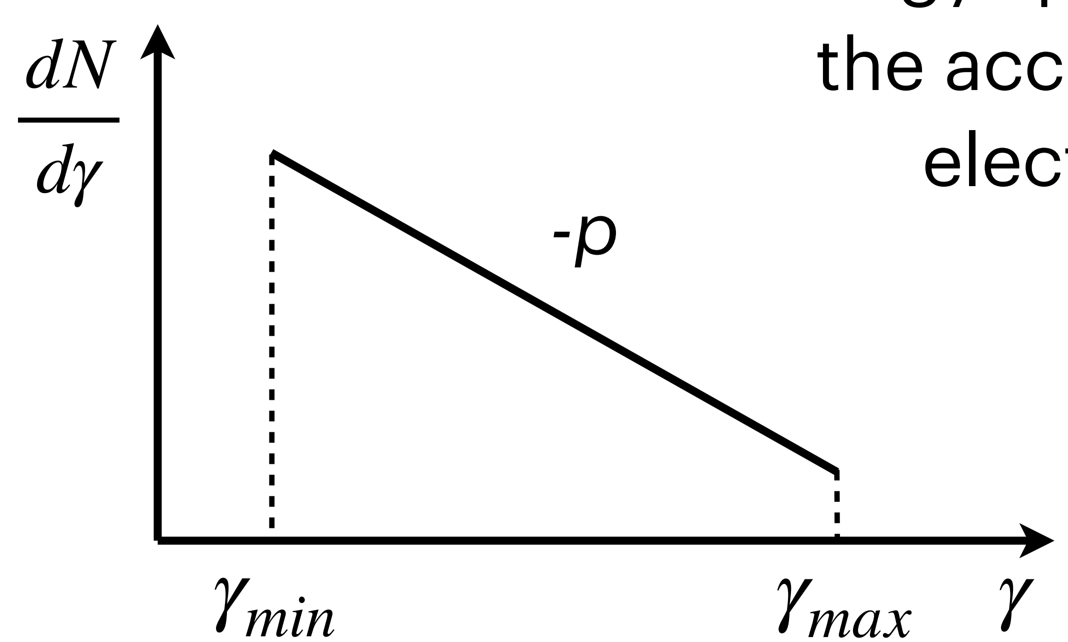
Parameters describing electrons: ϵ_e, ξ_e, p, γ_{max}

Parameter describing magn. field: ϵ_B

RELATIVISTIC SHOCKS

PARTICLE ACCELERATION

A fraction of the dissipated energy is used to accelerate particles through **collisionless** (no Coulomb collision) **shocks**. The output of this acceleration process is a power-law particle spectrum with index *p = 2.2 - 2.4*

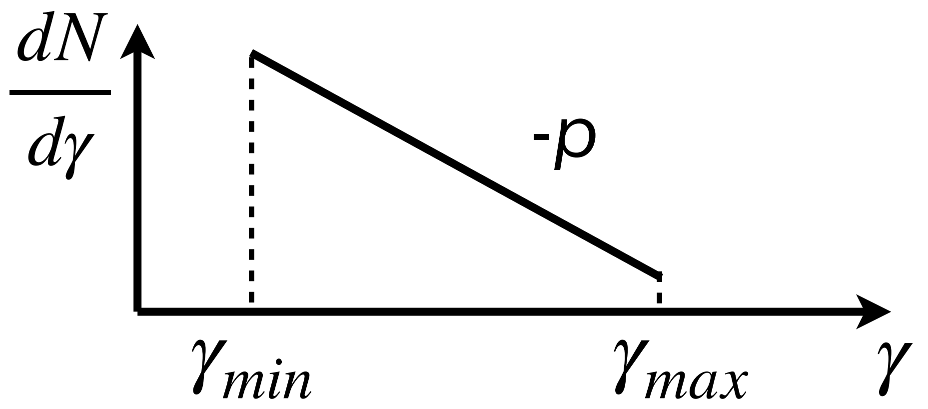


energy spectrum of the accelerated electrons

RELATIVISTIC SHOCKS

PARTICLE ACCELERATION

Derivation of the average and minimum Lorentz factor (<γ> and γ_{min}) of the electrons



- $N_e < \gamma > m_e c^2 = \epsilon_e N_p m_p c^2 (\Gamma - 1)$

$$\Rightarrow < \gamma > = \epsilon_e \frac{m_p}{m_e} (\Gamma - 1) \simeq 2 \times 10^4 \epsilon_{e,-1} \Gamma_2$$

- $$< \gamma > = \frac{\int_{\gamma_{min}}^{\gamma_{max}} \frac{dN}{d\gamma} \gamma d\gamma}{\int_{\gamma_{min}}^{\gamma_{max}} \frac{dN}{d\gamma} d\gamma} = \frac{\int_{\gamma_{min}}^{\gamma_{max}} \gamma^{-p+1} d\gamma}{\int_{\gamma_{min}}^{\gamma_{max}} \gamma^{-p} d\gamma}$$

for $\gamma_{max} >> \gamma_{min}$ and $p > 2$

$$\Rightarrow \quad \gamma_{min} = \epsilon_e \frac{m_p}{m_e} \frac{p-2}{p-1} (\Gamma - 1)$$

RELATIVISTIC SHOCKS

Magnetic Field Amplification

Derivation of the magnetic field strength

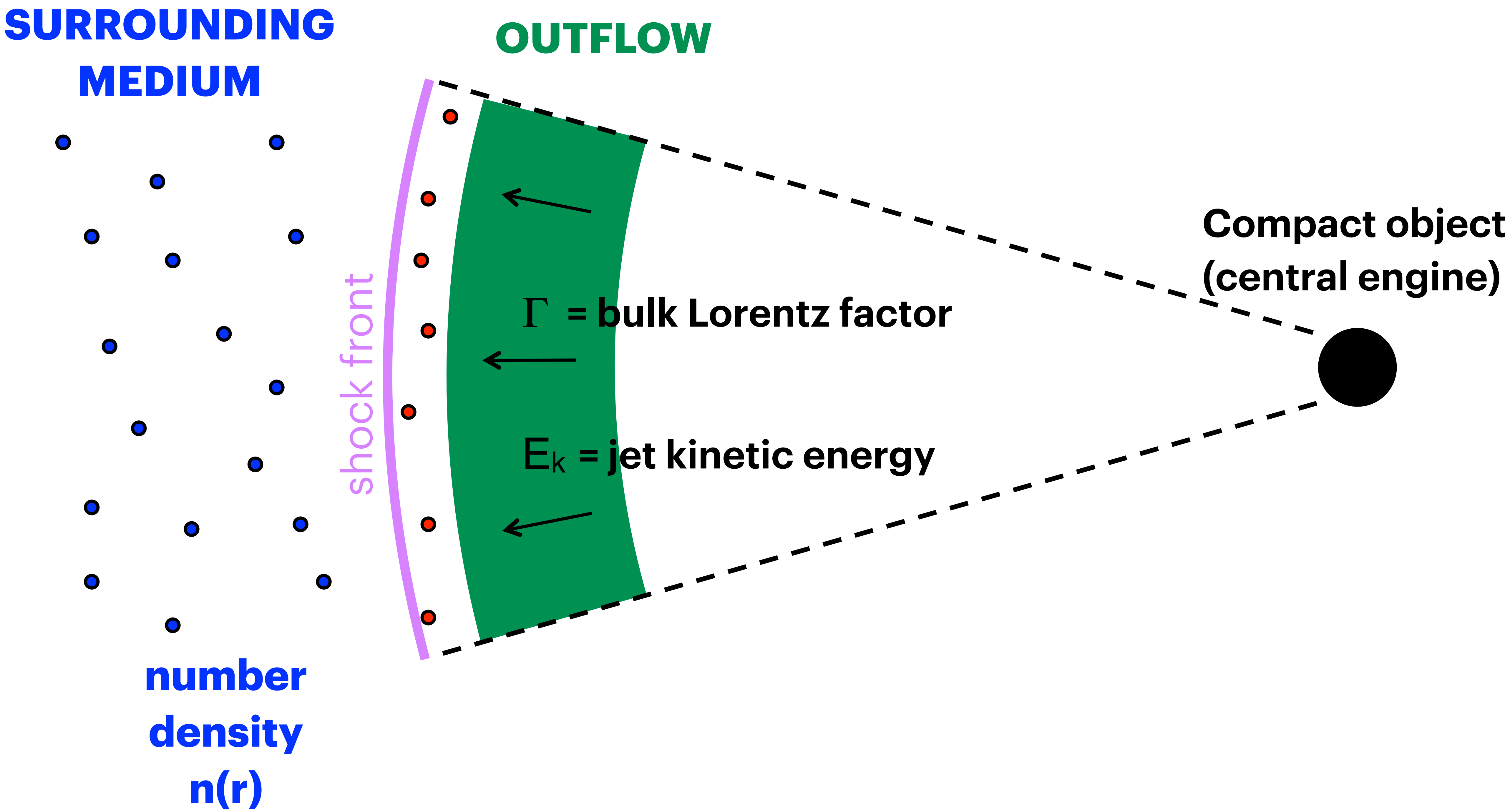
- $\epsilon_B \, n' \, m_p \, c^2 \, (\Gamma - 1) = \dfrac{B'^2}{8\pi}$

$$n'_p = \frac{N_p}{V'} = \frac{N_p}{V/\Gamma} = n_p \, \Gamma$$

factor 4 due to shock compression $\quad \Longrightarrow \quad n' = 4 \, \Gamma \, n$

$$\Longrightarrow \quad B' = \sqrt{32\pi\epsilon_B \, n \, m_p \, c^2} \, \Gamma$$

AFTERGLOW MODEL

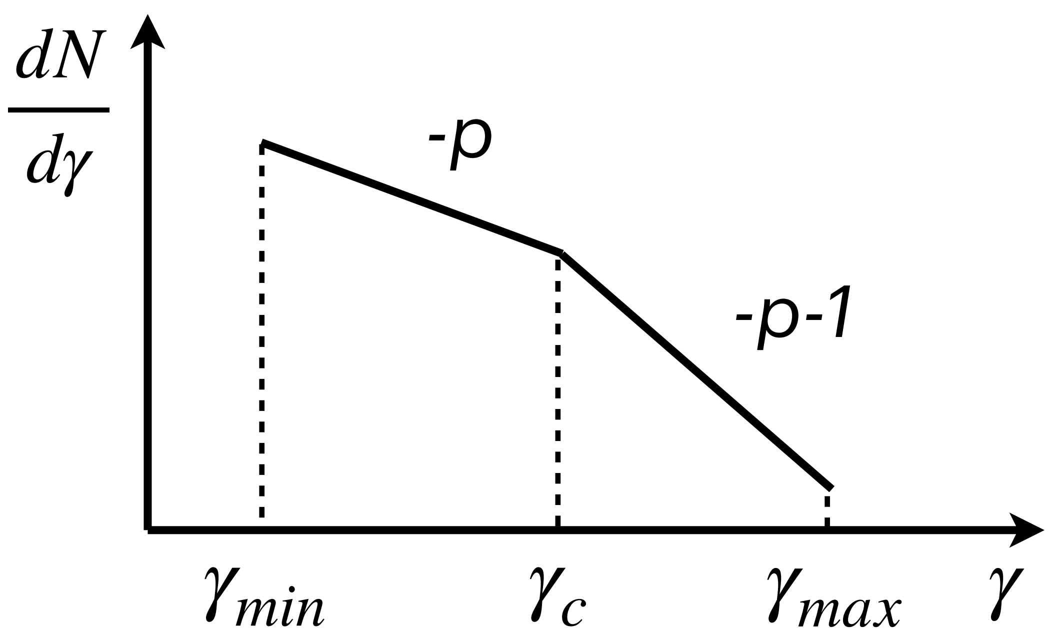


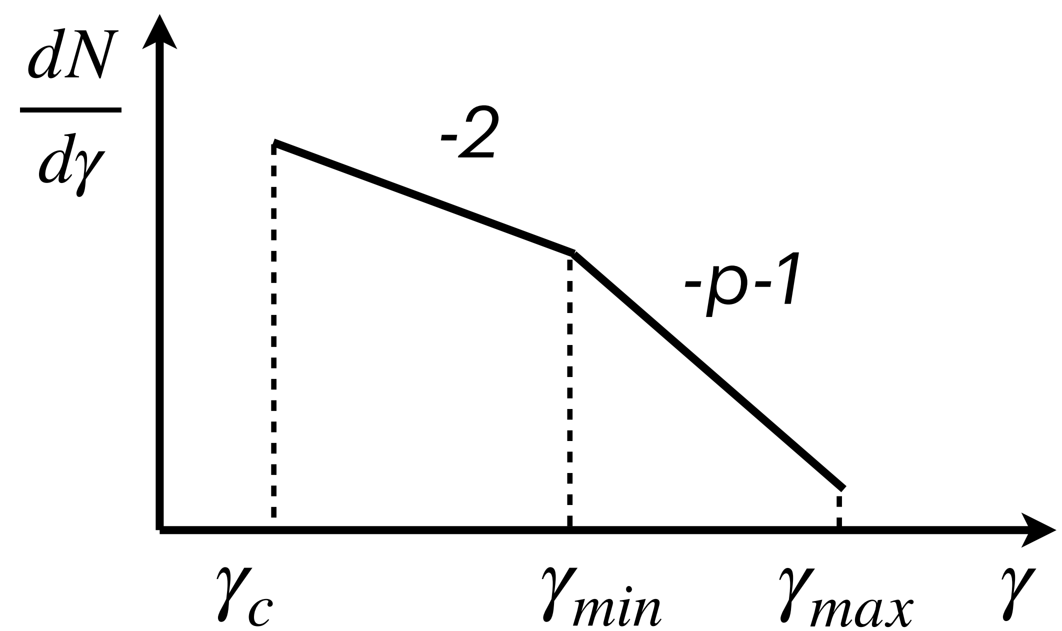
SYNCHROTRON+INVERSE COMPTON EMISSION

Synchrotron + IC cooling time

$$t'_c(\gamma, B') = \frac{E(\gamma)}{P(\gamma, B')} = \frac{6\,\pi\, m_e\, c}{\sigma_T\, \gamma\, B'^2(1+Y)}$$

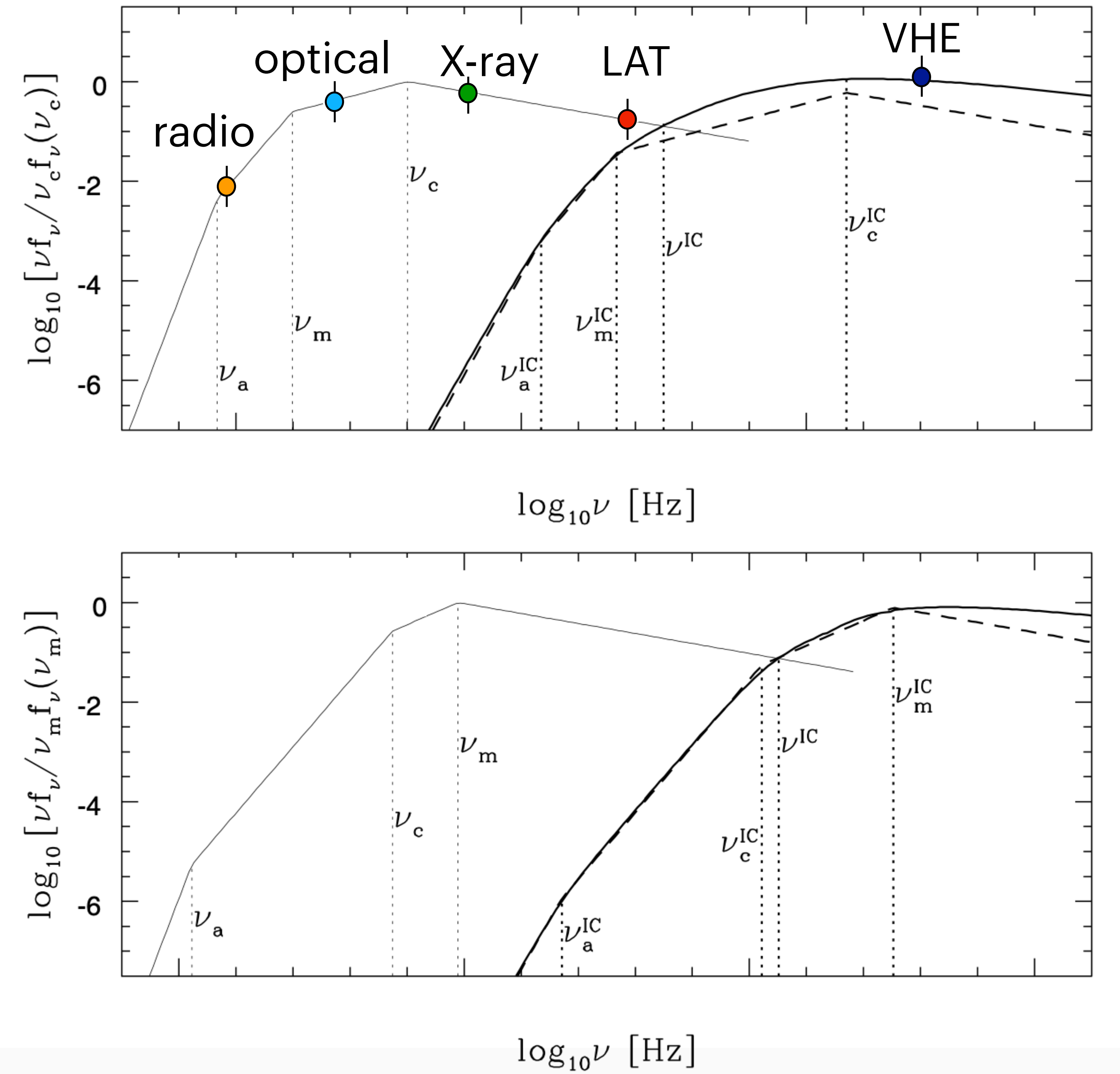
$$\gamma_c = \frac{6\,\pi\, m_e\, c}{\sigma_T\, t'\, B'^2(1+Y)}$$





Valid in Thomson regime, otherwise Y(γ)

SYNCHROTRON SELF COMPTON SPECTRUM

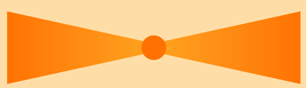


slow cooling

fast cooling

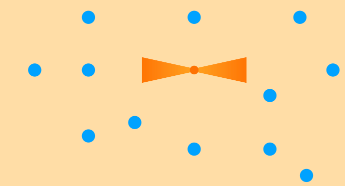
AFTERGLOW MODEL: SUMMARY OF MODEL PARAMETERS

JET



- E_{kin}
- Γ_0
- ϑ_{jet}, ϑ_{view}, structure

SURROUNDING MEDIUM



$n = n_0 R^{-s}$

- normalization n_0
- radial profile s

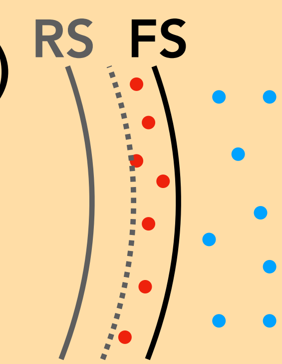
AFTERGLOW LIGHTCURVES AND SPECTRA from RADIO to TeV

ABSORPTION

- Optical
- X-ray
- VHE (EBL)

SHOCK PHYSICS

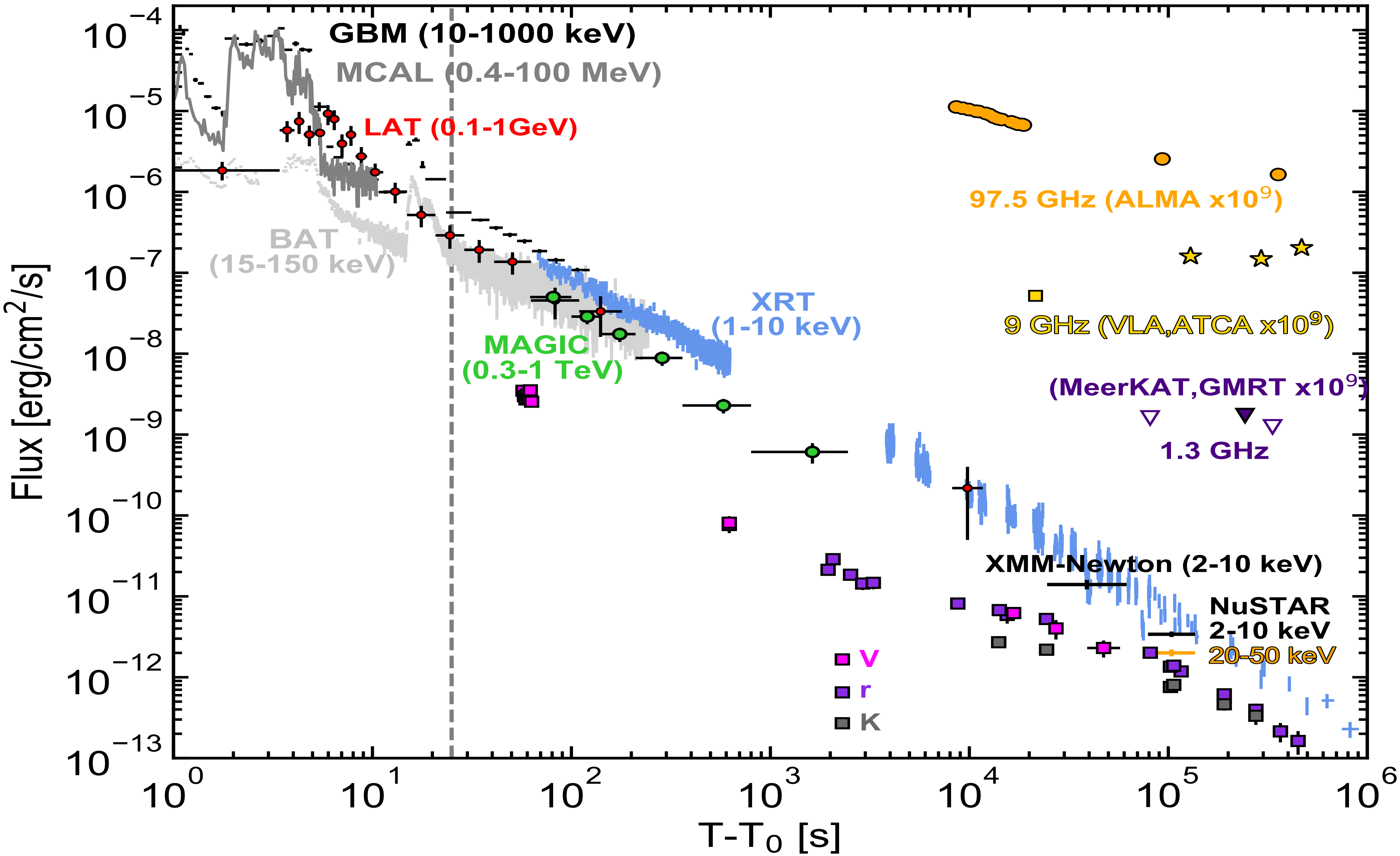
- e^- (ε_e, ξ_e, p, γ_{max})
- magn. field (ε_B)
- protons
- reverse shock



GRB 190114C

$z = 0.42$

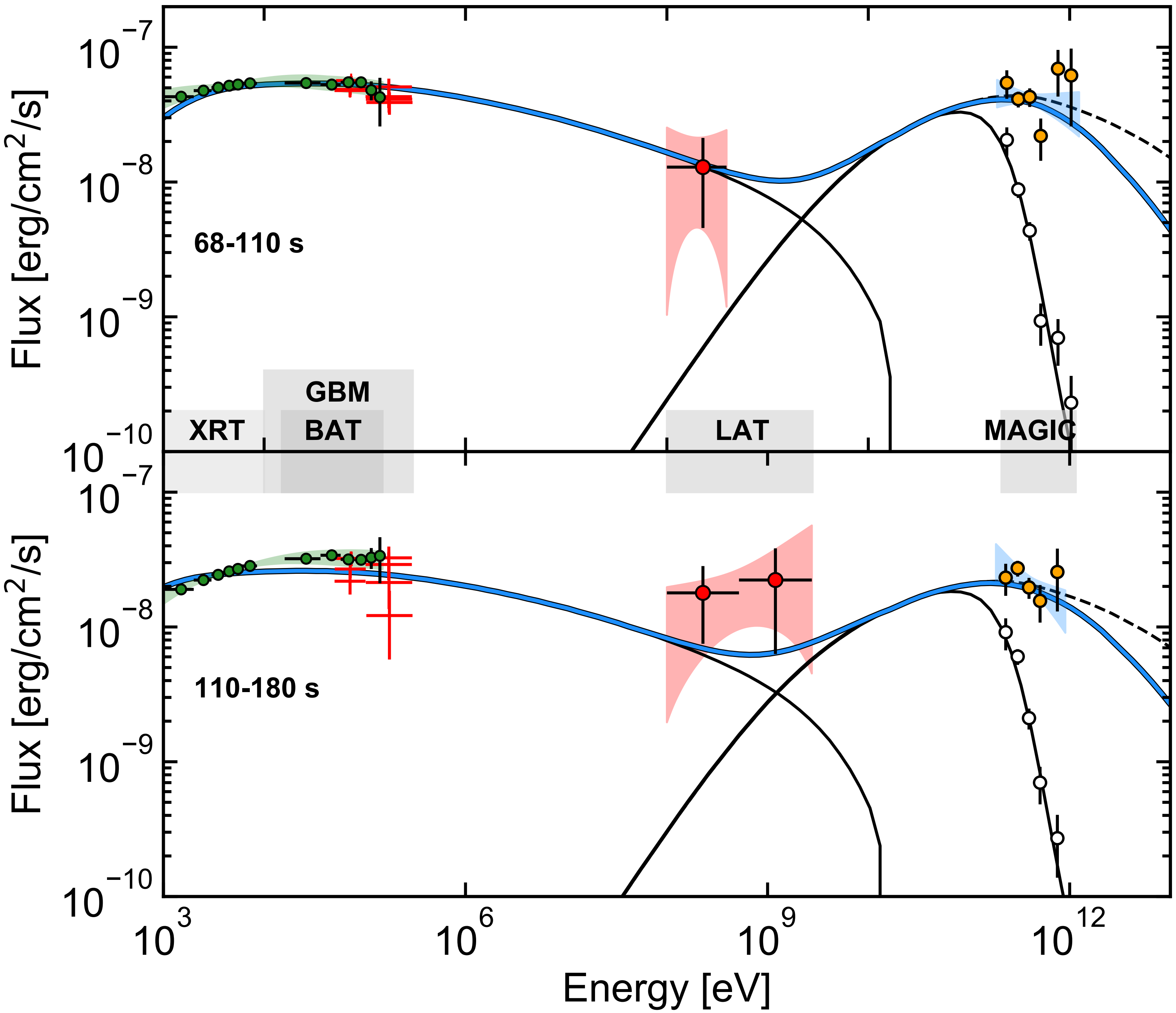
MAGIC 2019, Nature, 575, 459



GRB 190114C

z = 0.42

MAGIC 2019, Nature, 575, 459

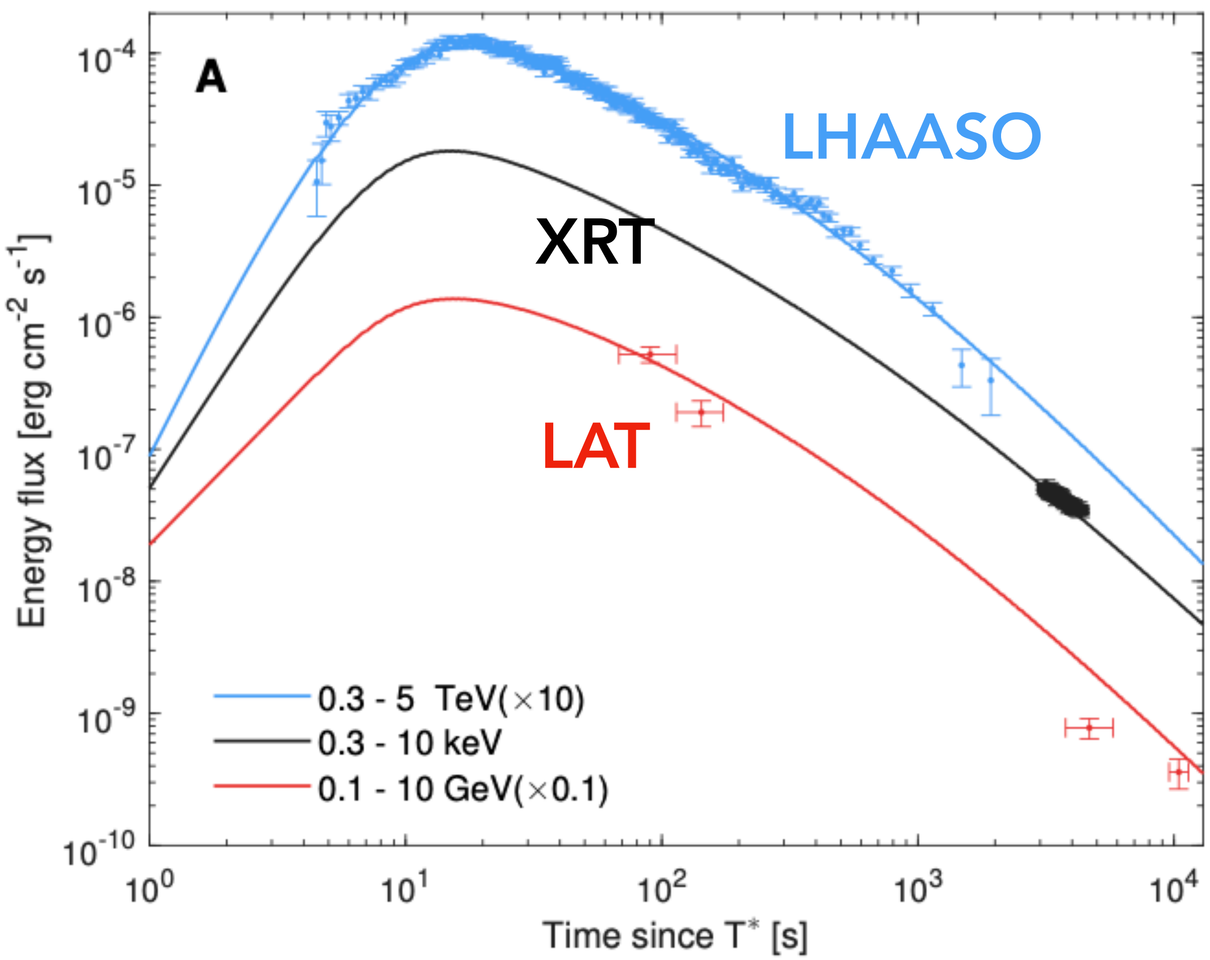


GRB 221009A

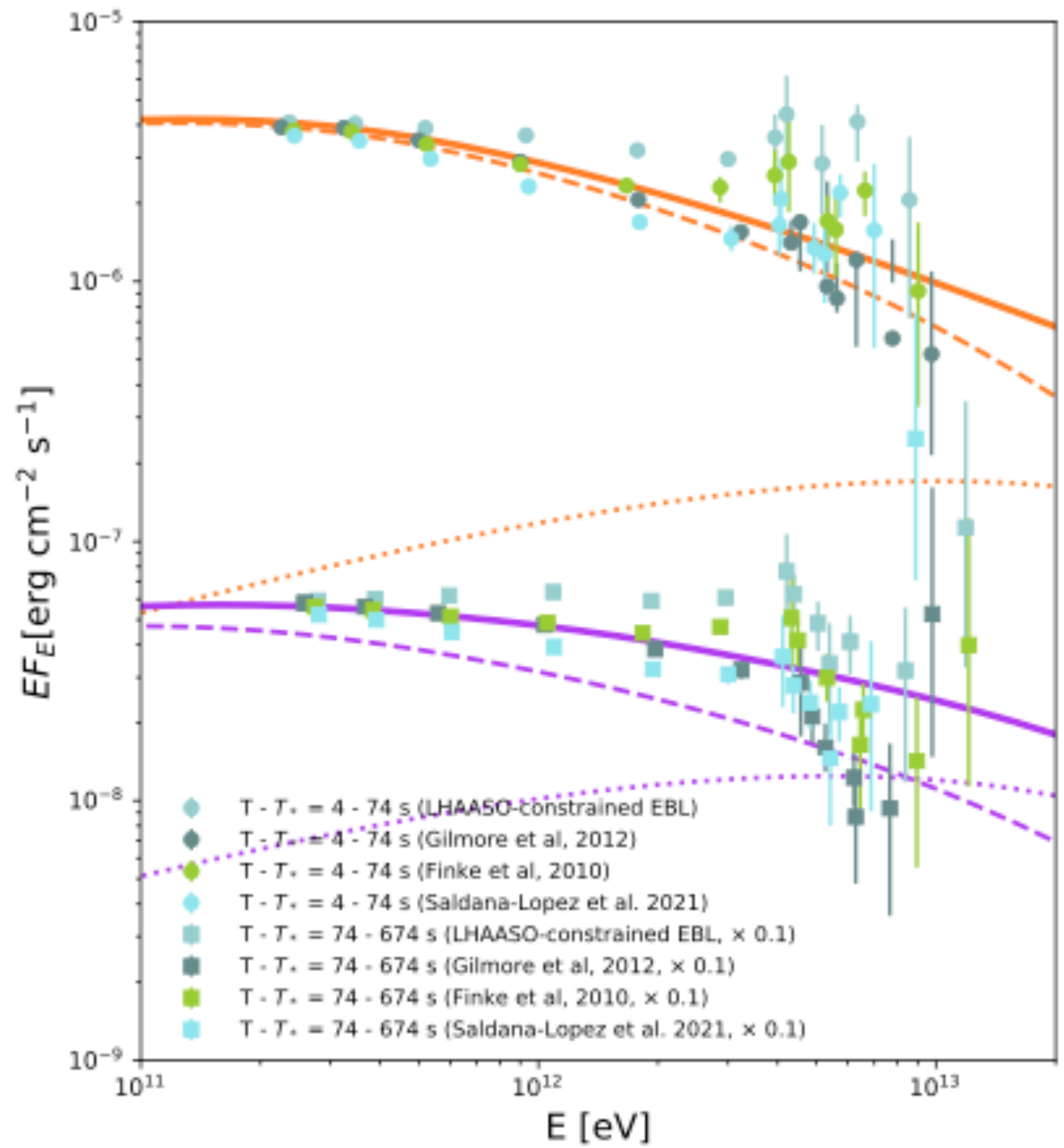
z = 0.15

LHAASO collab. 2023

lightcurves



TeV spectra



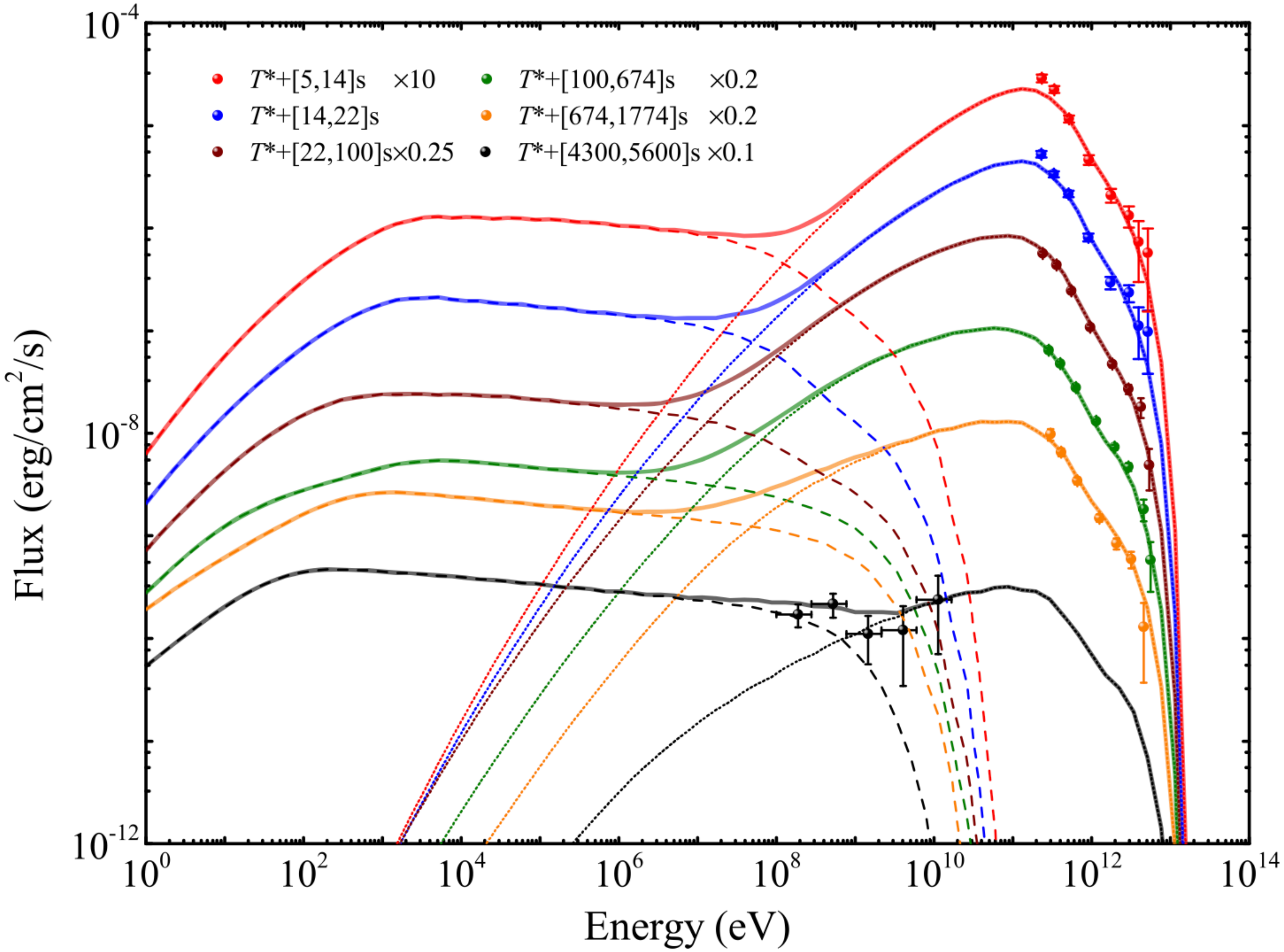
GRB 221009A

z = 0.15

Ren, Wang & Dai 2024

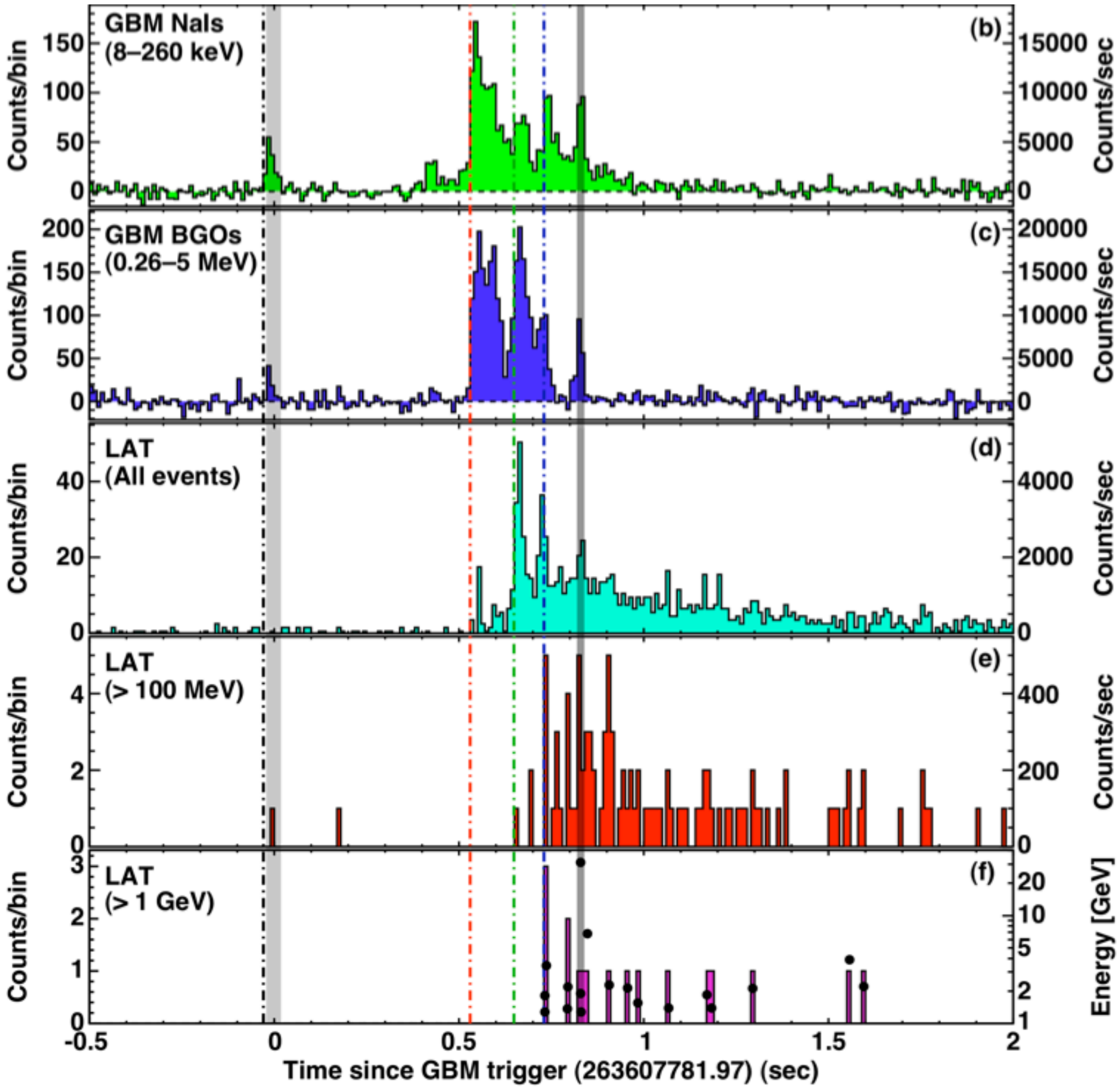
Modeling of all multi wavelength data

Structured jet: narrow cone (VHE from SSC) + wings (lower frequencies)



SED

THE SHORT GRB 090510 DETECTED UP TO 31 GEV



BOUNDS ON LIV FROM GRBS

GRB	090510		190114C		221009A	
	Fermi/LAT		MAGIC		LHAASO	
Redshift	0.9		0.42		0.15	
Photon energy	31 GeV		2 TeV		13 TeV	
Timescale	seconds		10^{2}-10^{3} s			
	sub	super	sub	super	sub	super
$E_{QG,1}$ [10^{19}GeV]	2.2 9.3	3.9 13	0.58	0.55	10	11
$E_{QG,2}$ [10^{10} GeV]	4.9 13	3.7 9.4	6.3	5.6	69	70

Lower limits (95%) for the linear (n=1) and quadratic (n=2) cases

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Thank you for your attention

Back-up slides

GRB 190114C

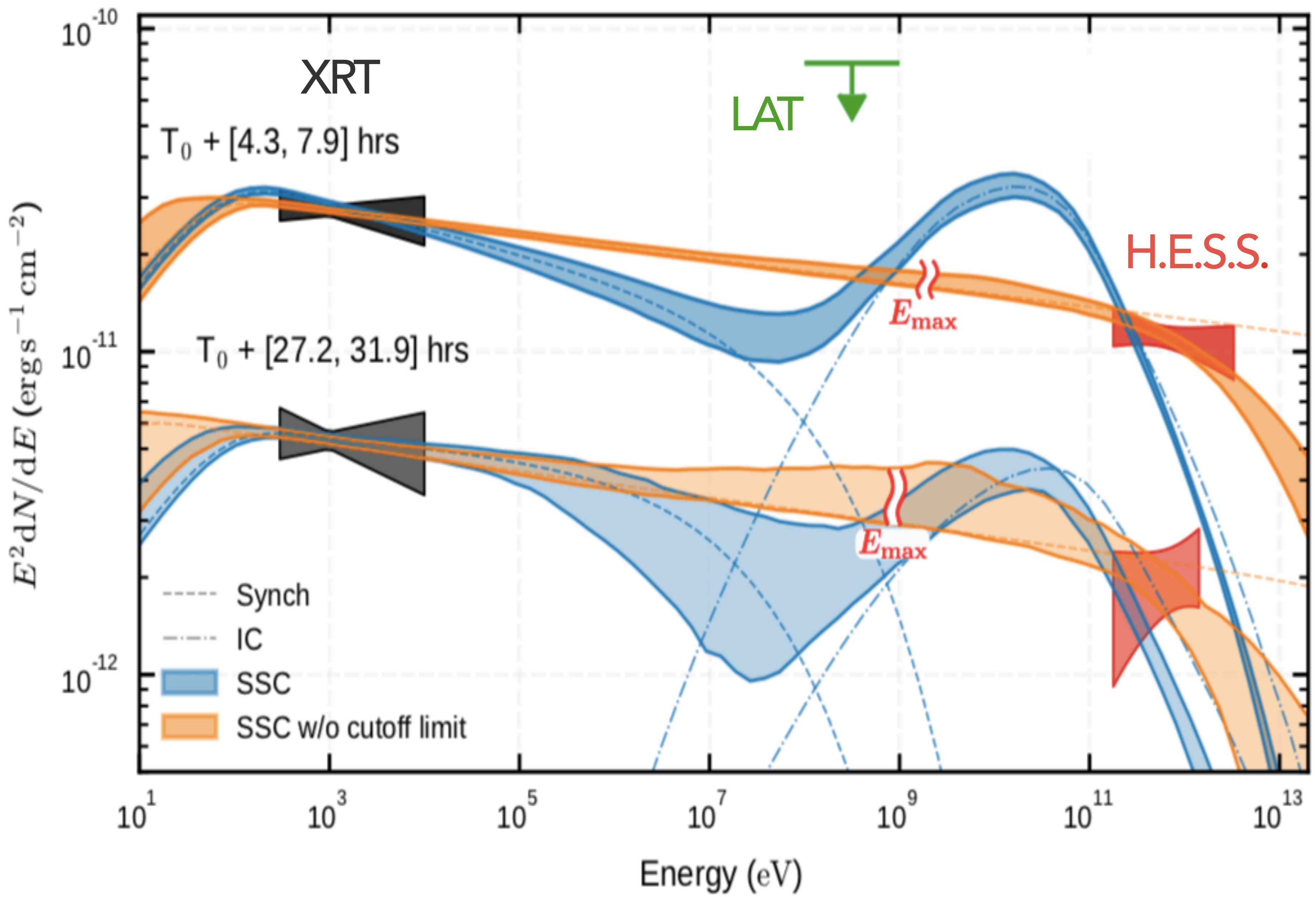
z = 0.42

Model parameters	E_k (erg)	Γ_0	n_0 (s=0)	A_* (s=2)	ε_e	ε_B	p
MAGIC et al. 2019	8×10^{53}	700	0.5	—	0.07	8×10^{-5}	2.6
Wang et al. 2019	6×10^{53}	300	0.3	—	0.07	4×10^{-5}	2.5
Zhang H. et al. 2020	5×10^{54}		0.1	—	0.05	5×10^{-6}	2.6
Asano et al. 2020	10^{54}	600	1.0	—	0.06	9×10^{-4}	2.3
Asano et al. 2020	10^{54}	300	—	0.1	0.08	1.2×10^{-3}	2.35
Joshi & Razzaque 2021	4×10^{54}	300		0.02	0.03	1.2×10^{-2}	2.18
Derishev & Piran 2021	3×10^{53}	—	2		0.11	$(3\text{-}6) \times 10^{-3}$	2.5
Derishev & Piran 2021	3×10^{53}	—			0.11	$(3\text{-}6) \times 10^{-3}$	2.5

GRB 190829A

$z = 0.08$

H.E.S.S. Collab, 2019, Nature, 575, 464



Tested models:

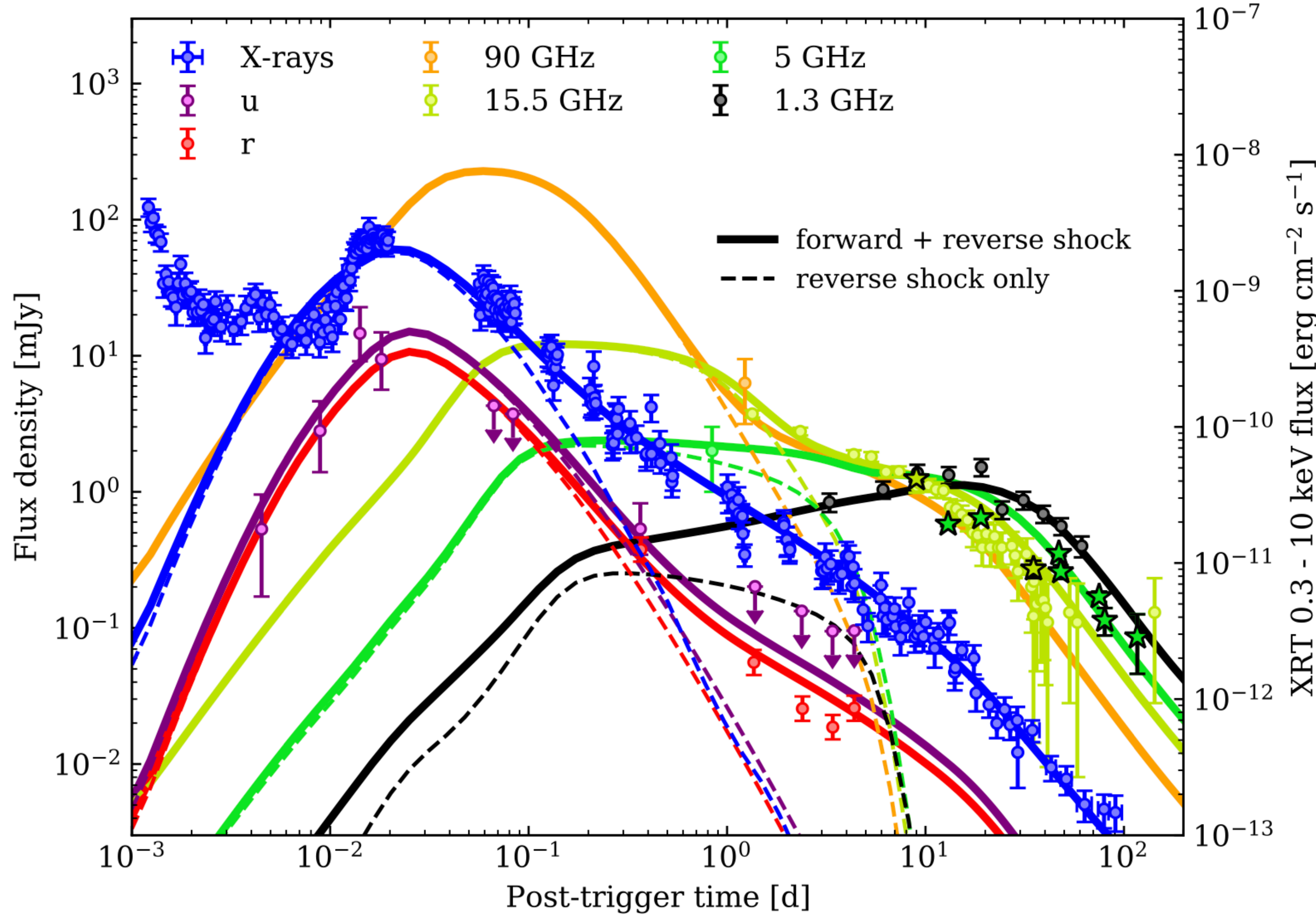
- syn only
- syn + SSC

syn+SSC interpretation: no good modeling found, but it is imposed:

- $E_k \equiv E_{iso} = 2 \times 10^{50}$erg
- $n_0 = 1$ cm^{-3}

MODELING OF AFTERGLOW LIGHTCURVES

EXAMPLE OF MODELING OF MULTI-WAVELENGTH AFTERGLOW LIGHTCURVES



Salafia + 2022

GRBS AT GEV ENERGIES

THE MAXIMAL SYNCHROTRON FREQUENCY

Maximal electron energy γ_{max} is reached when acceleration time is equal to cooling time: $t'_{acc}(\gamma) = t'_{syn}(\gamma)$

$$t'_{acc} \simeq \frac{r_L}{c} \simeq \frac{E'}{eB'c} = \frac{\gamma m_e c^2}{eB'c}$$

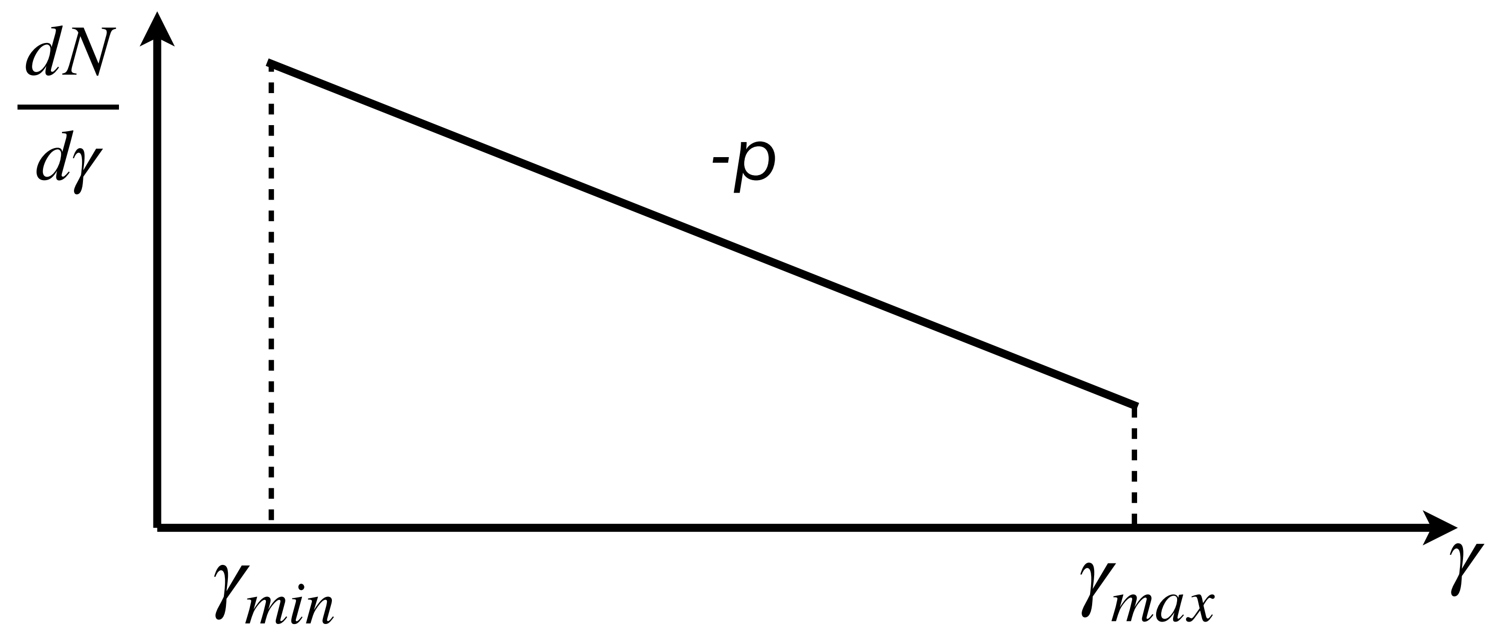
$$t'_{syn} = \frac{6\pi m_e c}{\sigma_T B'^2 \gamma}$$

$$\Rightarrow \quad \gamma_{max}^2 = \frac{6\pi e}{\sigma_T B'}$$

$$E_{max} = h\nu_{max} = h\nu'_{max} 2\Gamma = \gamma_{max}^2 \frac{eB'h}{2\pi m_e c} 2\Gamma = \frac{9 m_e c^2 h}{4\pi e^2} \Gamma \simeq 150\, MeV \times \Gamma$$

The Maximal Synchrotron Frequency

electron spectrum after acceleration



$\Downarrow$ $\Downarrow$

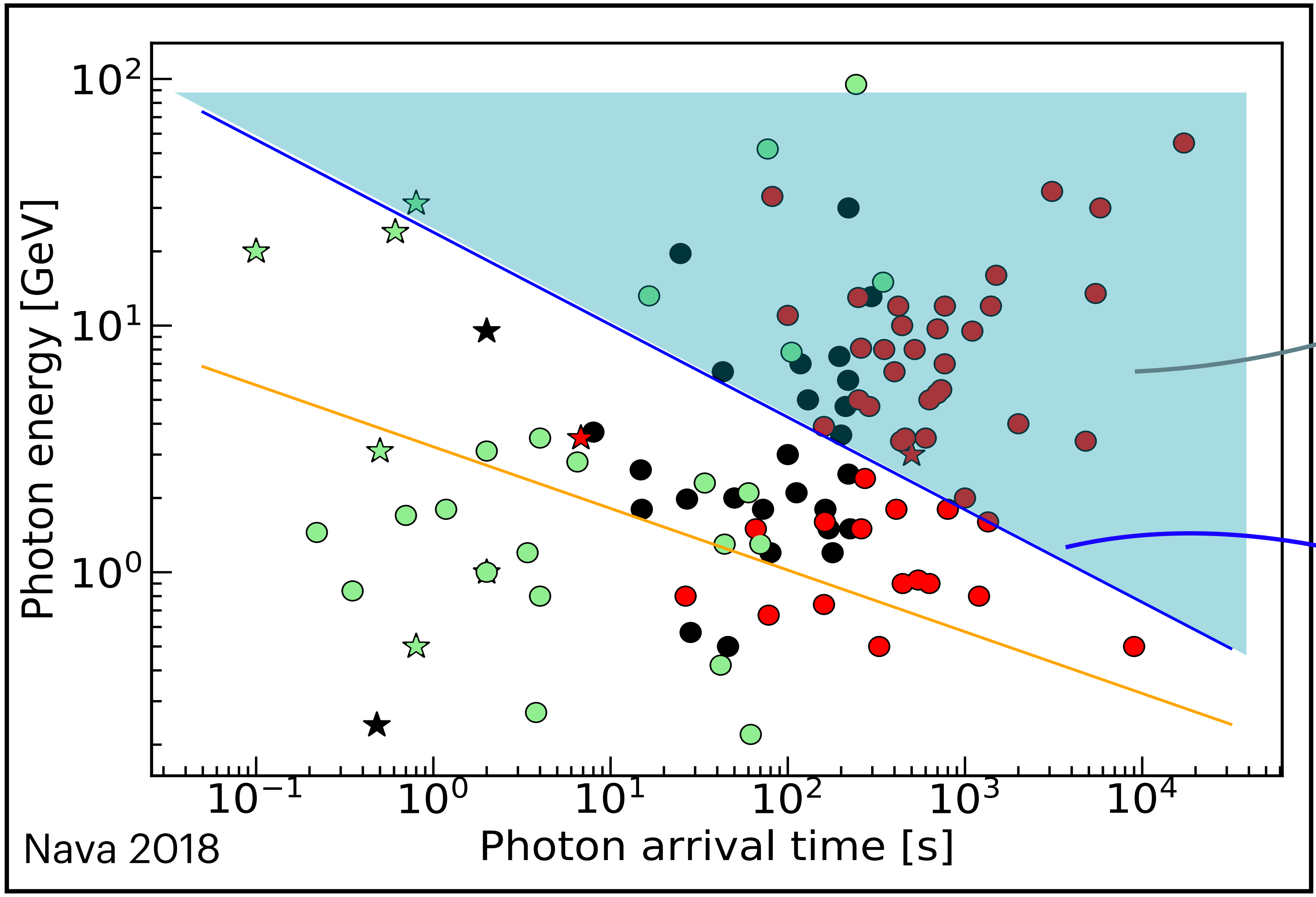
$$\nu'_{min} = \gamma^2_{min} \frac{e\,B'}{2\pi\, m_e\, c} \qquad \nu'_{max} = \gamma^2_{max} \frac{e\,B'}{2\pi\, m_e\, c}$$

maximal energy of accelerated electrons implies
maximal energy of synchrotron photons

GRBS AT GEV ENERGIES

PROBLEM WITH THE INTERPRETATION

Many photons detected from GRBs have energies exceeding the maximal synchrotron energy

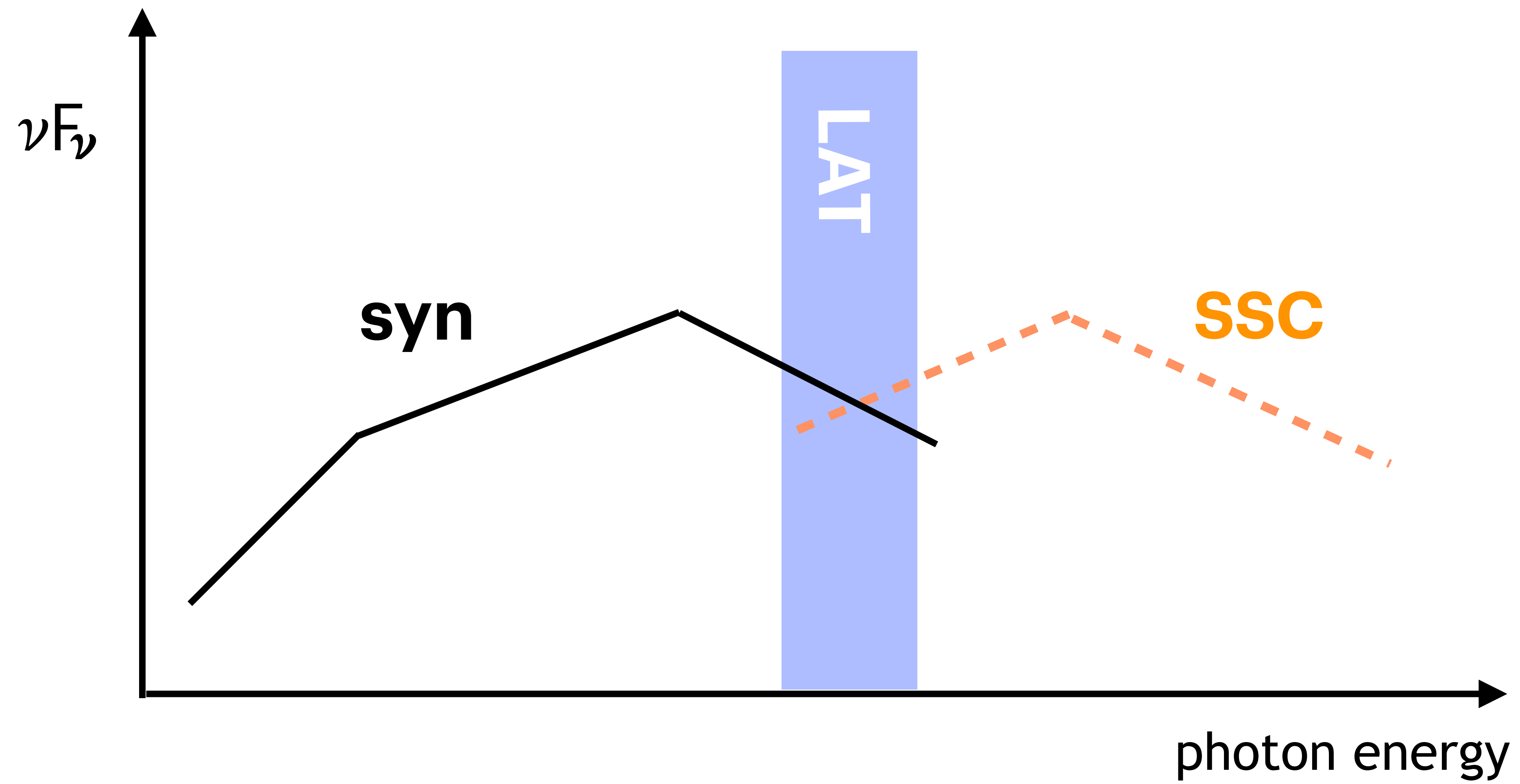


all these photons can not have synchrotron origin! ...inverse Compton?

synchrotron limit: maximum energy for photons produced by synchrotron radiation

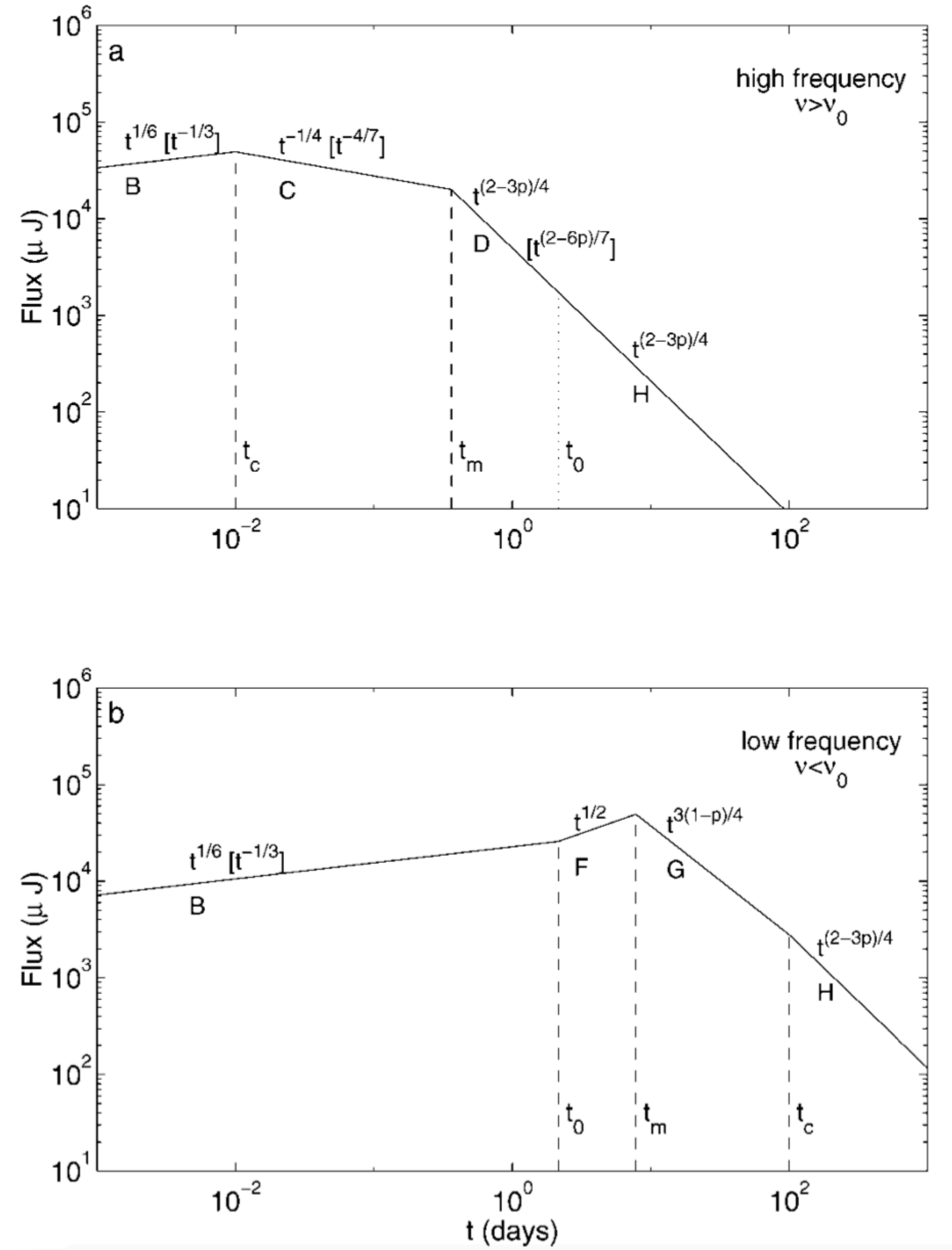
GRBS AT TEV ENERGIES???

PRESENCE OF SYNCHROTRON SELF COMPTON?



SYNCHROTRON LIGHTCURVES

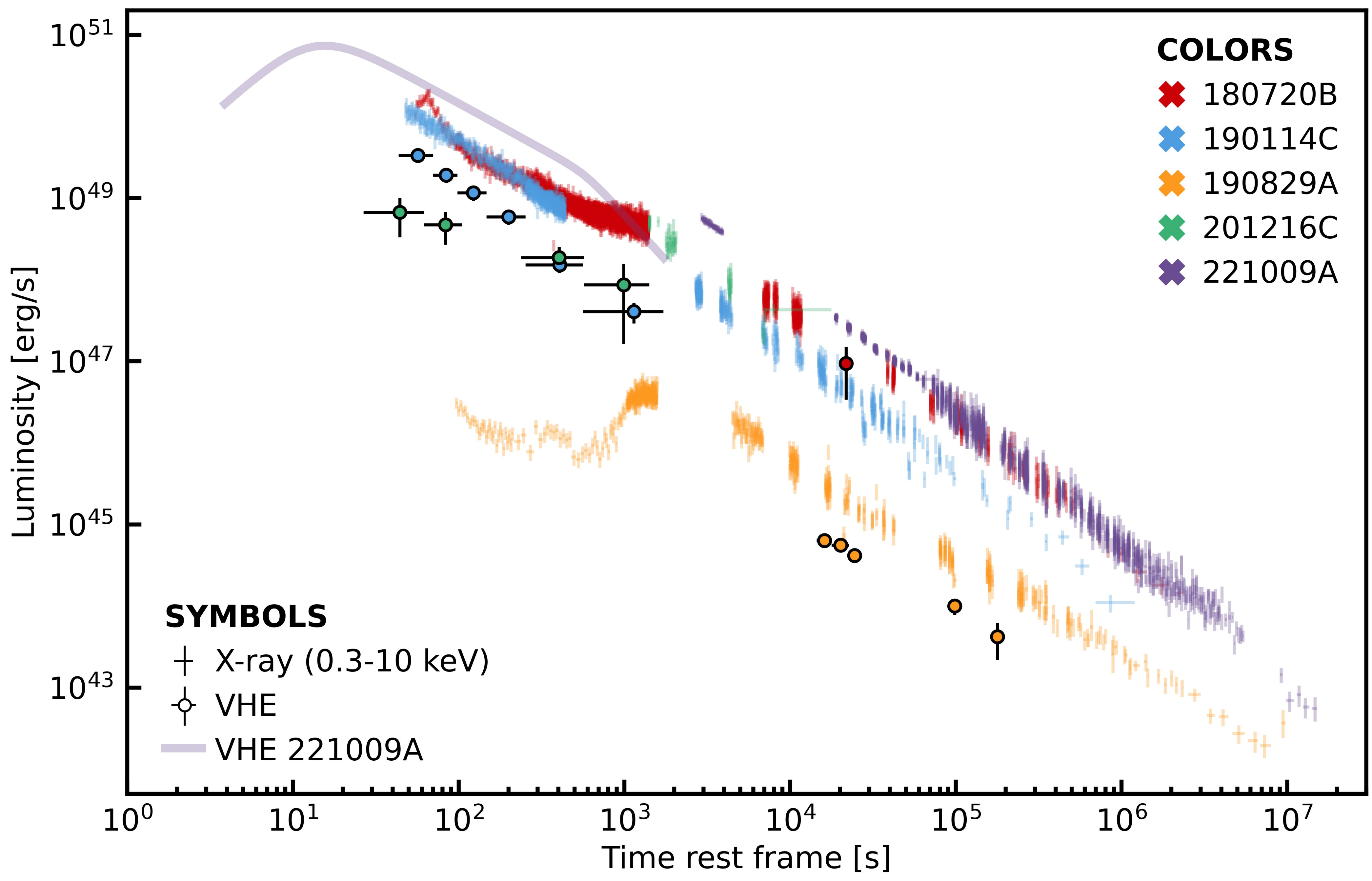
EXAMPLES OF EXPECTED AFTERGLOW LIGHTCURVES



Sari, Piran Narayan, 1998

X-ray and TeV luminosity light curves

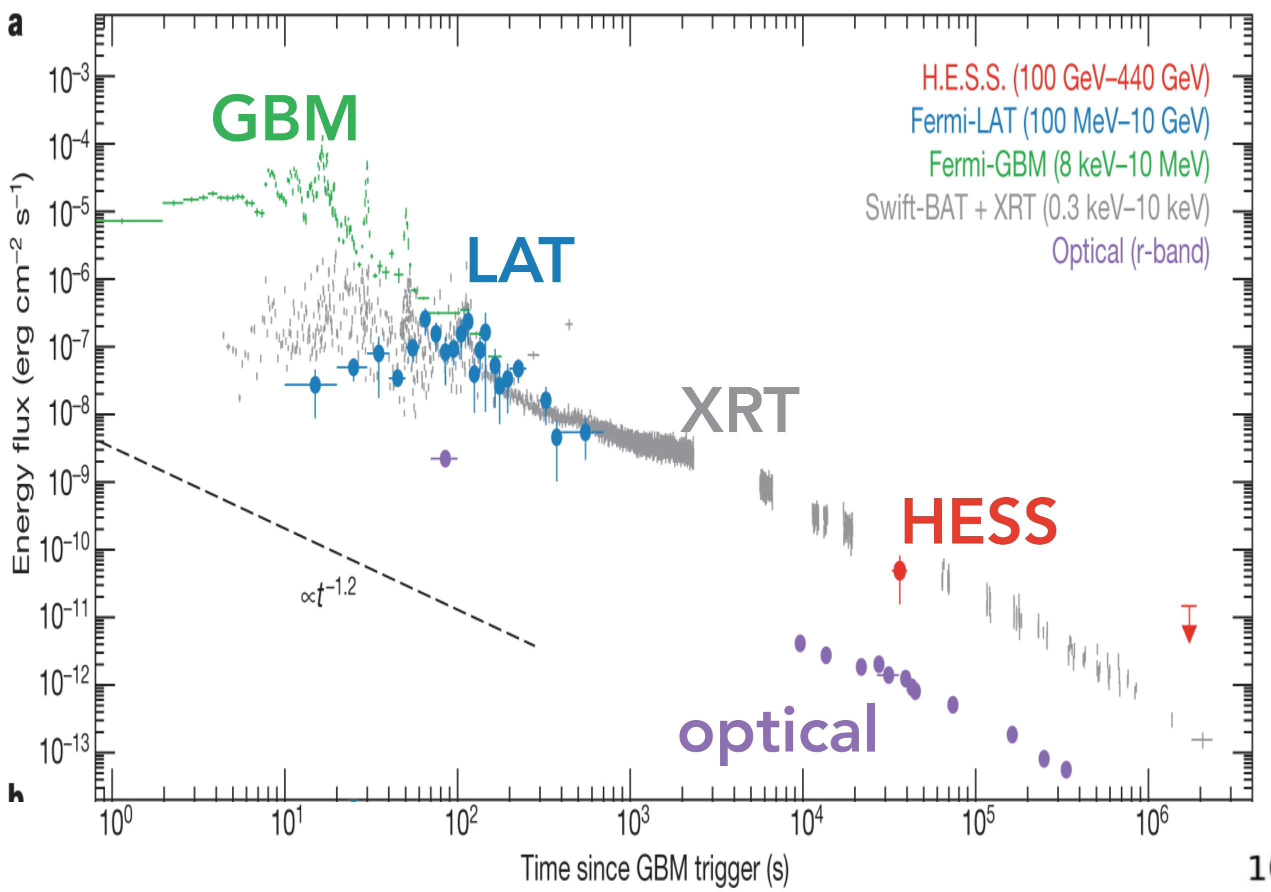
Miceli D. & Nava L., 2022, Galaxies, 10, 66

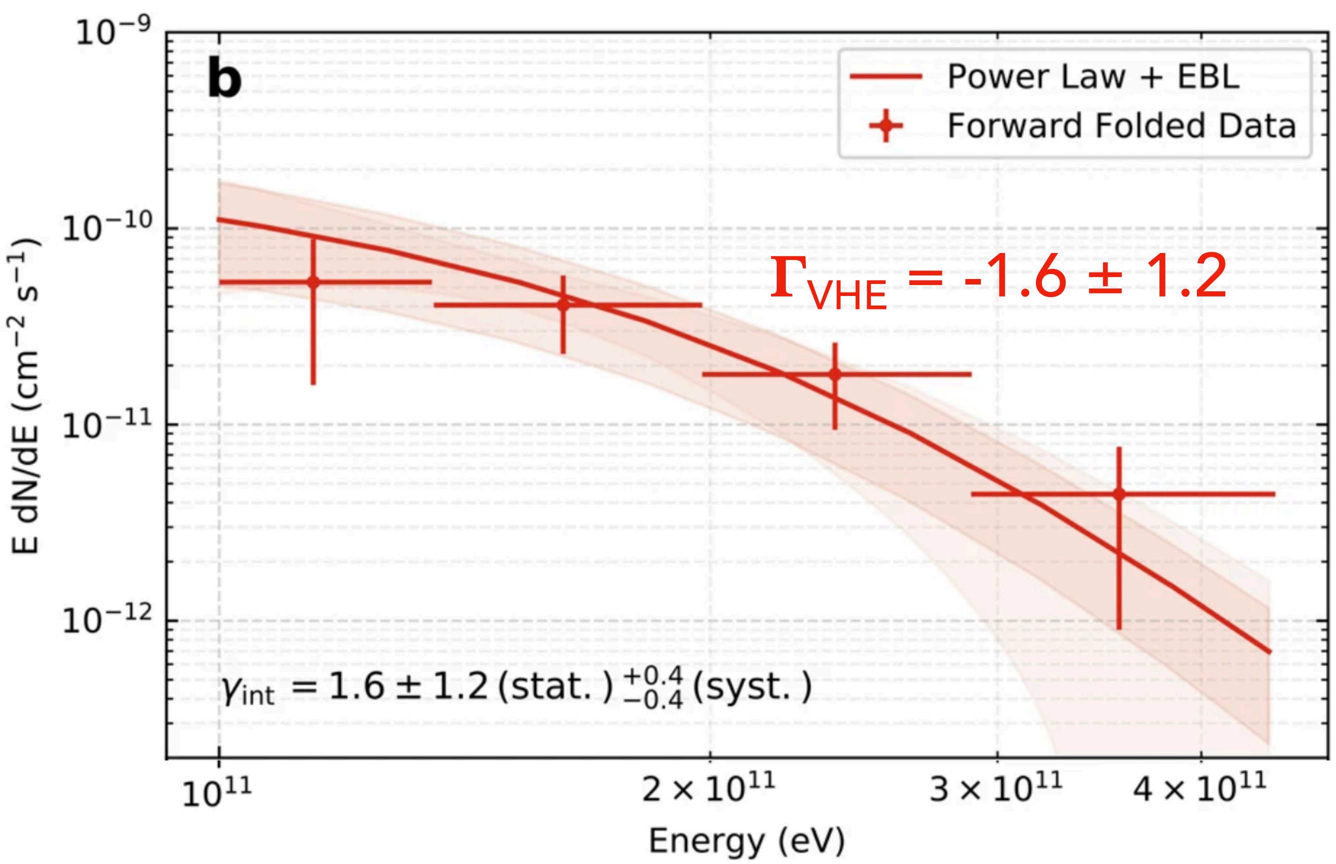


GRB 180720B

$z = 0.65$

HESS 2019, Nature, 575, 464

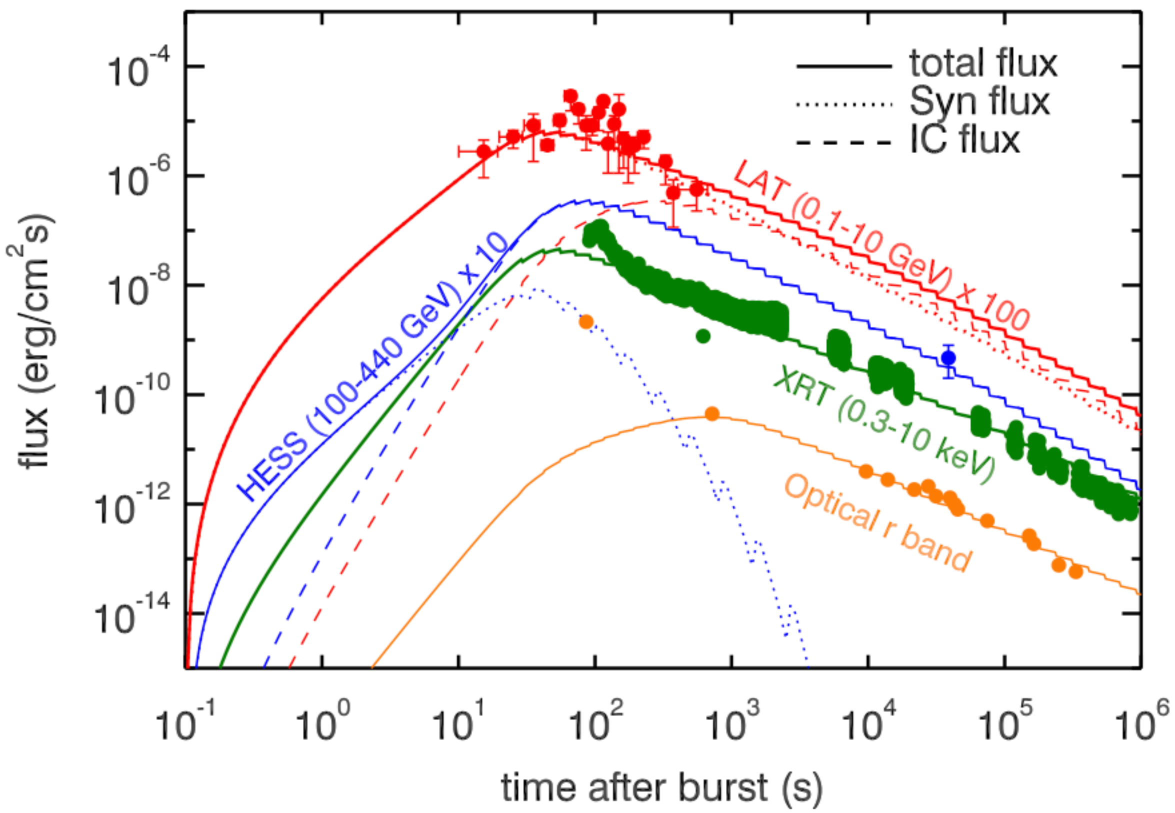


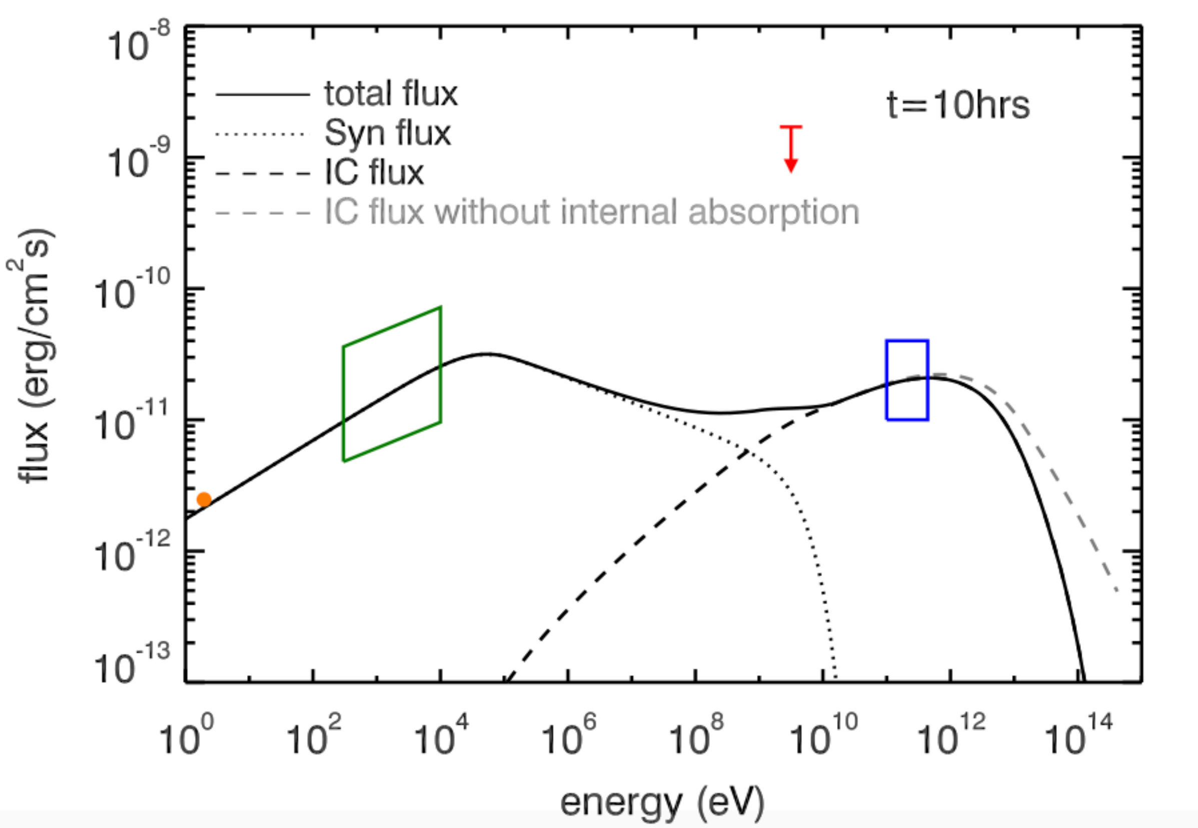


GRB 180720B

$z = 0.65$

Wang et al., 2019, ApJ, 884, 117





Interpretation: syn+SSC

E=10^{54} erg, Γ_0 = 300

n = 0.1cm^{-3} (s = 2 discarded: HESS observation would result in huge flux in the LAT range at 100 s)

ε_e =0.1, ε_B =10^{-4}, p=2.4.

(see also Beniamini, LN et al., 2015)

First optical point: reverse shock?

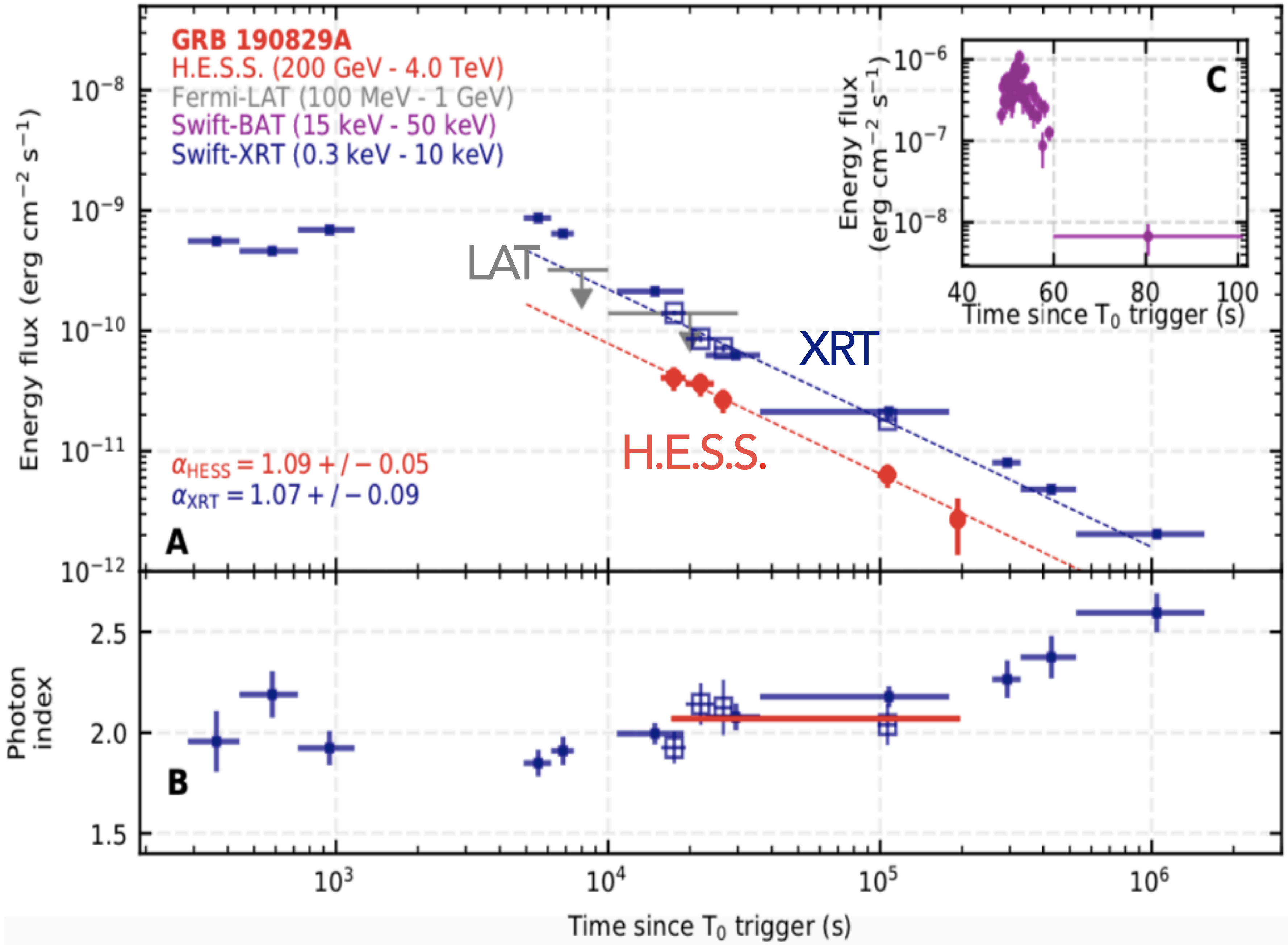
Arimoto et al., 2024, NatAs, 8, 134

Synchrotron maximum energy hidden by the rising of the SSC component

GRB 190829A

$z = 0.08$

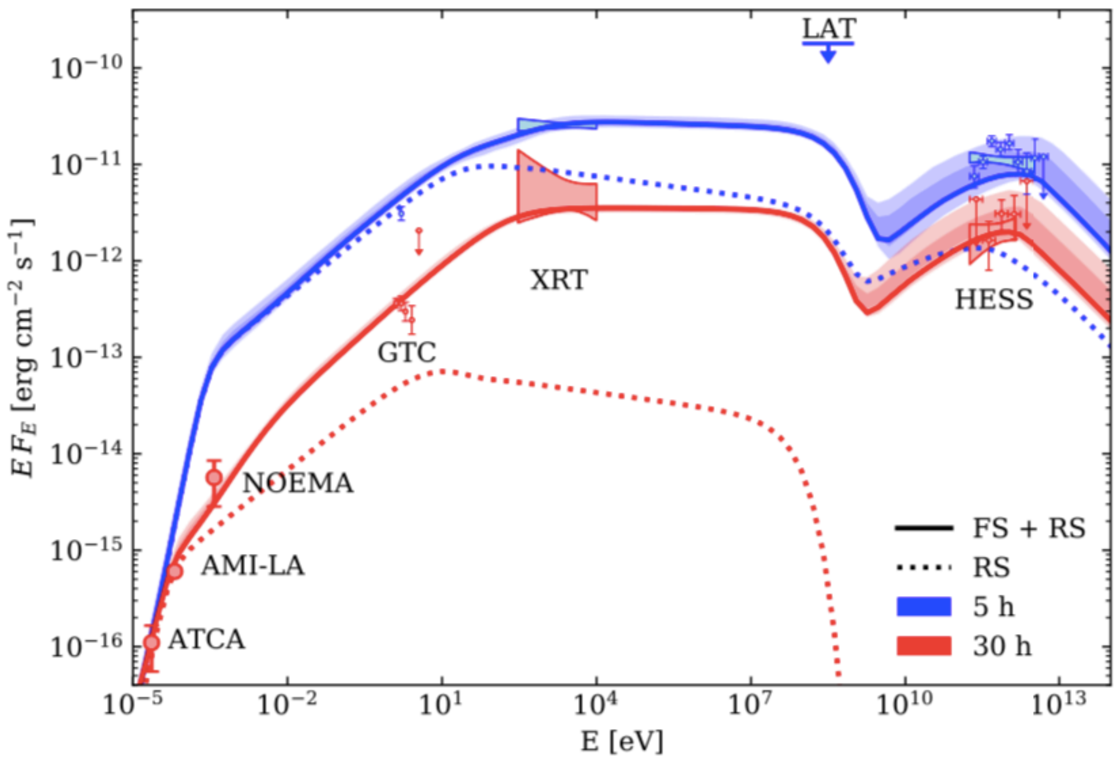
H.E.S.S. Collab, 2019, Nature, 575, 464

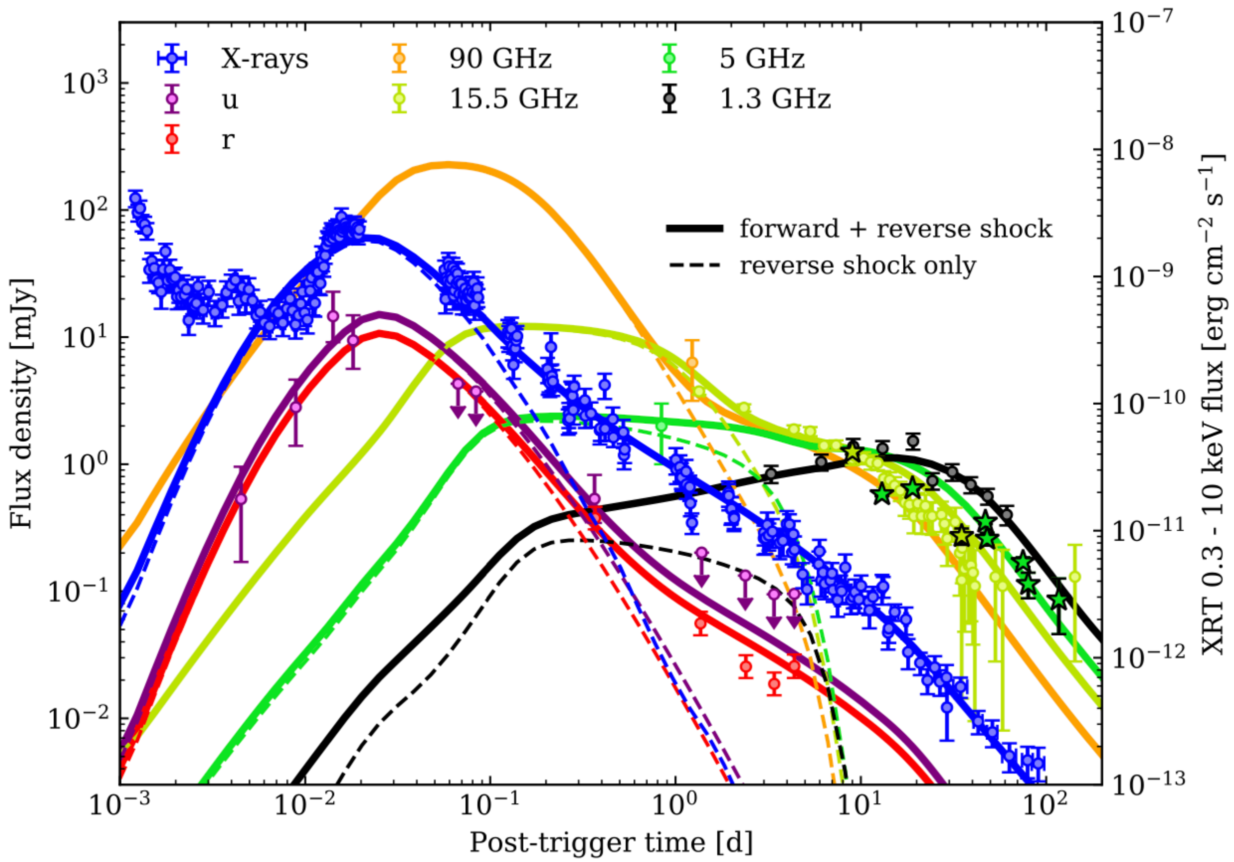


GRB 190829A

$z = 0.08$

Salafia,…,LN, 2022, ApJ, 931L, 19





Modeling with FS (syn+SSC) and RS (syn)

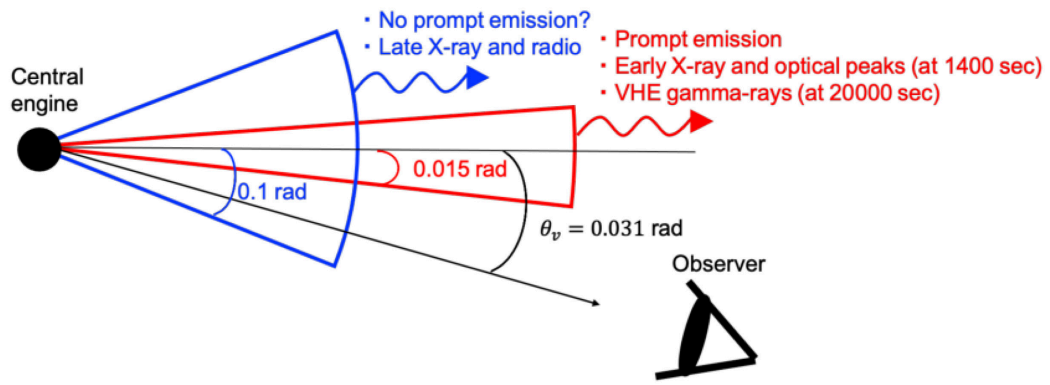
Parameter[a]	Narrow Prior	Wide Prior
$E_0/10^{53}$ erg	$2.5^{+1.9}_{-1.3}$	$8.6^{+26.0}_{-6.7}$
n/cm^{-3}	$0.21^{+0.37}_{-0.09}$	$0.87^{+4.96}_{-0.63}$
Γ_0	$56.6^{+3.3}_{-5.3}$	$55.0^{+3.4}_{-4.7}$
θ_j/deg	$15.4^{+1.2}_{-0.94}$	$15.8^{+1.3}_{-0.9}$
$\epsilon_{e,FS}$	$0.030^{+0.029}_{-0.017}$	$0.008^{+0.003}_{-0.006}$
$\epsilon_{B,FS}/10^{-5}$	$2.5^{+3.5}_{-1.3}$	<0.43
p_{FS}	$2.010^{+0.002}_{-0.002}$	$2.010^{+0.003}_{-0.002}$
$\chi_{e,FS}/10^{-2}$	<6.5	$0.7^{+2.1}_{-0.5}$
$\epsilon_{e,RS}$	$0.28^{+0.32}_{-0.16}$	$0.1^{+0.5}_{-0.08}$
$\epsilon_{B,RS}/10^{-3}$	$1.2^{+1.8}_{-0.8}$	$0.3^{+1.0}_{-0.2}$
p_{RS}	$2.13^{+0.04}_{-0.08}$	$2.12^{+0.05}_{-0.07}$
$\log(\rho_{sys})$	$-1.8^{+0.1}_{-0.1}$	$-1.8^{+0.1}_{-0.1}$
$E_{jet}/10^{51}$ erg	$9.4^{+8.9}_{-4.2}$	32^{+120}_{-25}
$\eta_\gamma/10^{-3}$	$1.1^{+1.2}_{-0.5}$	$0.34^{+1.1}_{-0.26}$

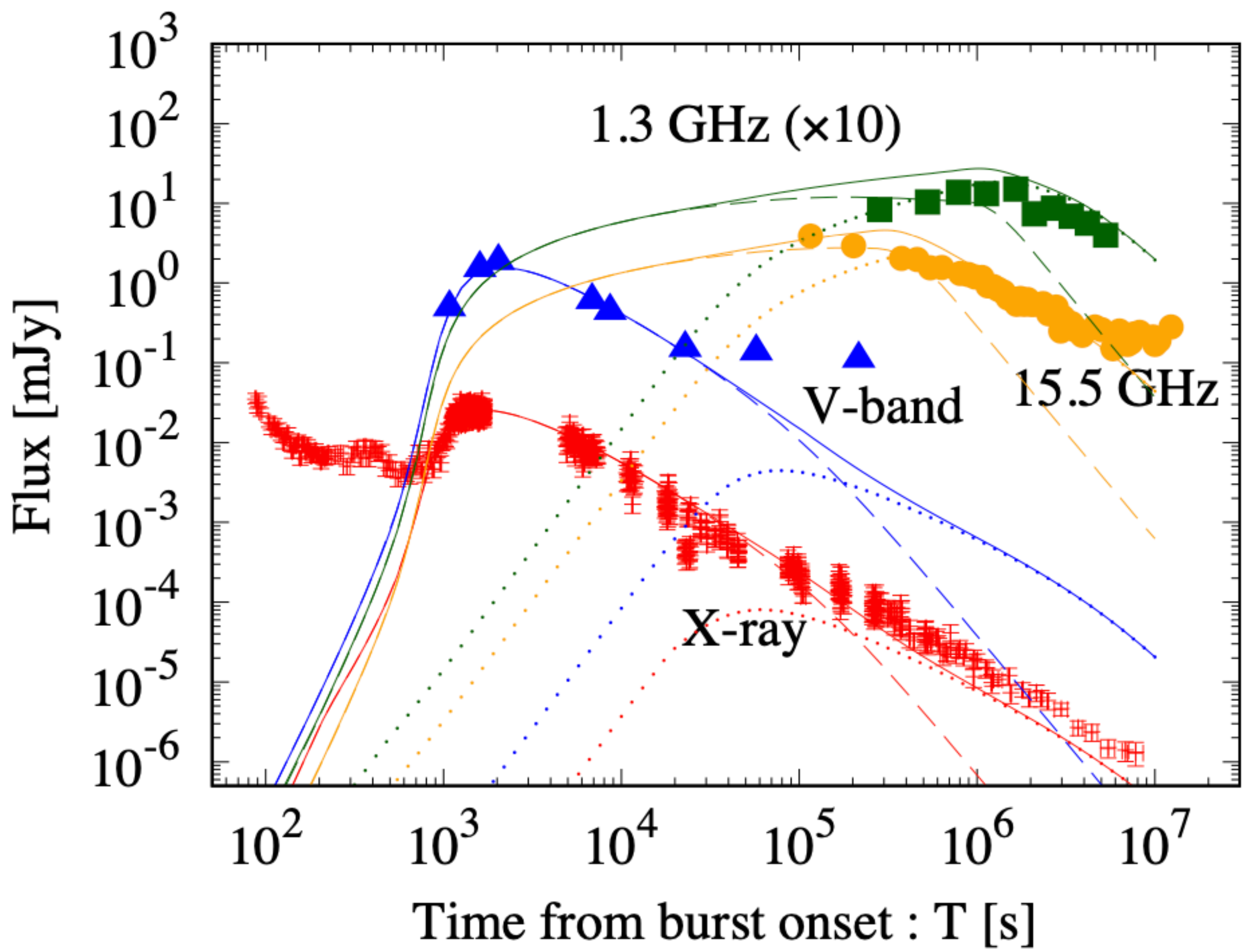
RS: see also Dichiara et al, 2022

GRB 190829A

$z = 0.08$

Sato et al., 2021, MNRAS 504, 5647

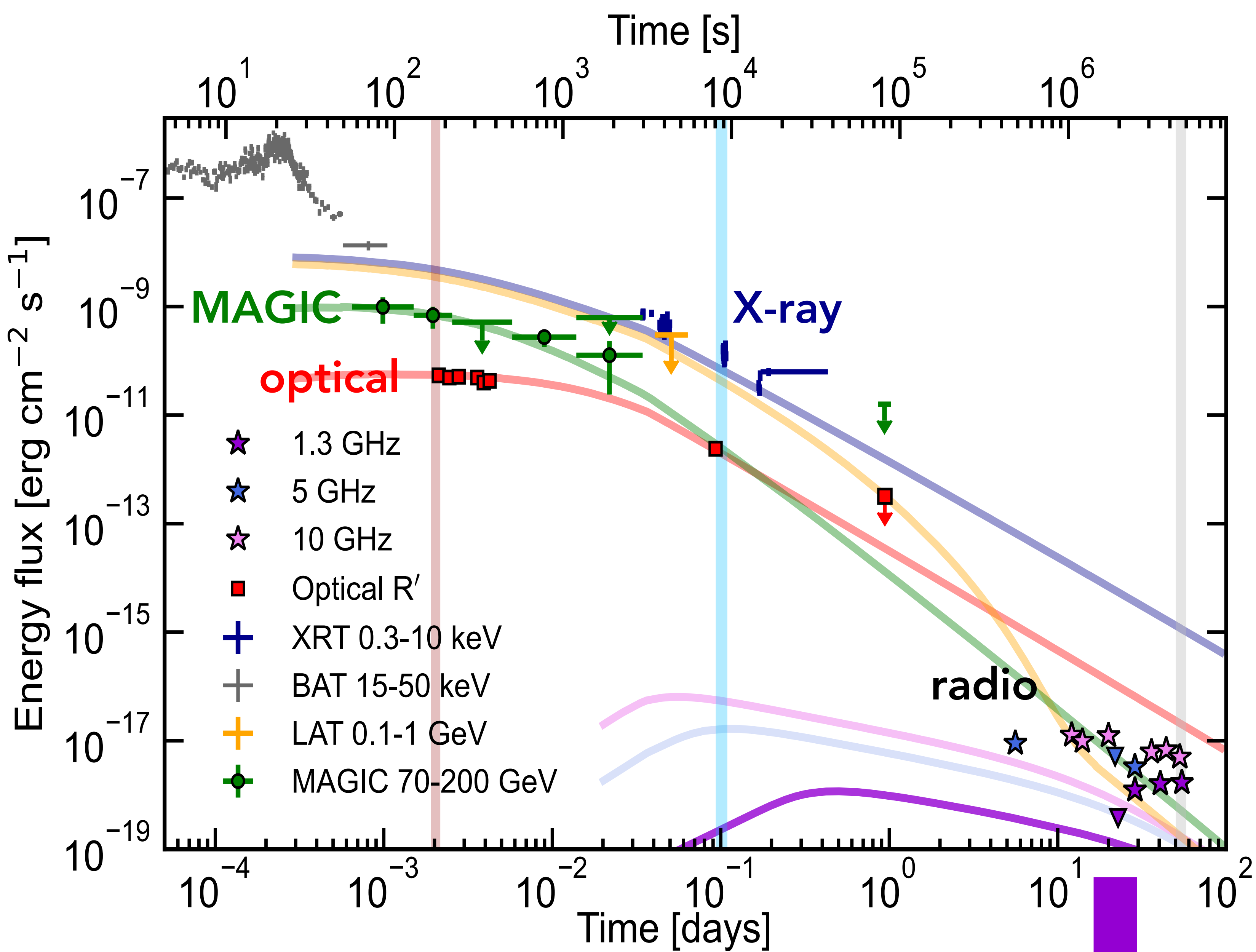




GRB 201216C

$z = 1.1$

MAGIC collabor., MNRAS, 527, 5856, 2024



Flat early optical + decaying VHE

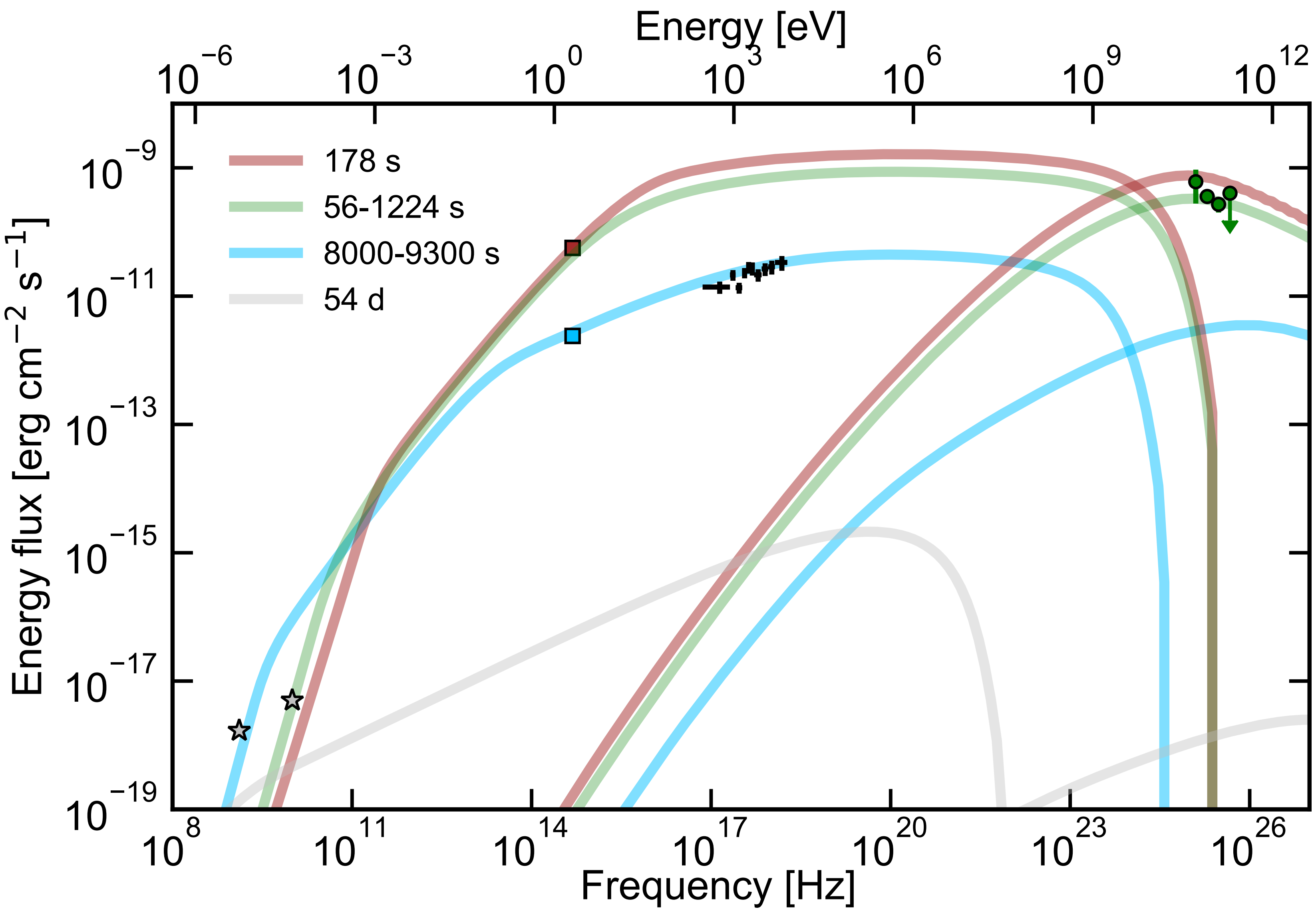
wind CBM and $\nu_m(3000s)=\nu_{opt}$

Radio data: synchrotron emission from slower and much less energetics wings (cocoon? See Rhodes et al, 2020, MNRAS, 496, 3326)

GRB 201216C

$z = 1.1$

MAGIC collabor., MNRAS, 527, 5856, 2024



Parameter	Best fit value
E_k [erg]	4×10^{53}
θ_{jet} [degrees]	1
Γ_0	180
n_0 [cm^{-3}] ($s = 0$)	-
$A_\star$ ($s = 2$)	2.5×10^{-2}
p	2.1
ϵ_e	0.08
ϵ_B	2.5×10^{-3}

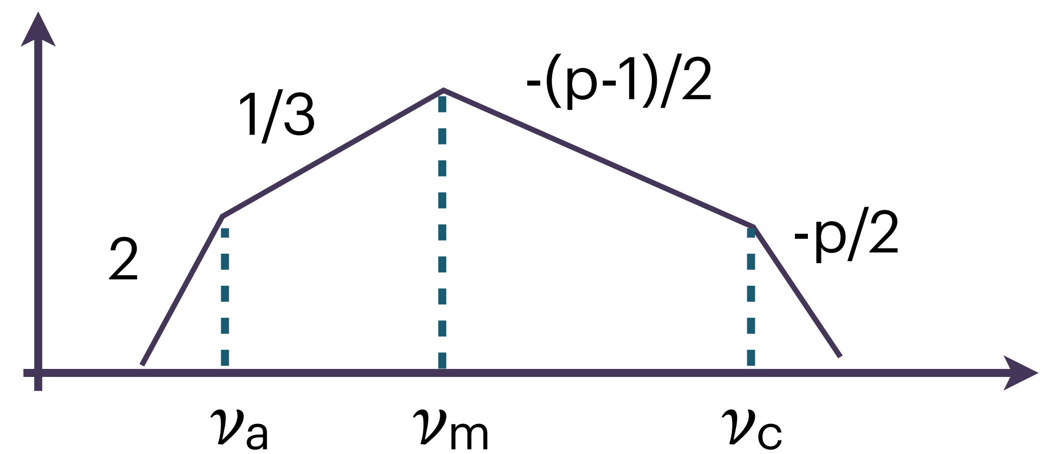
SYNCHROTRON SPECTRUM

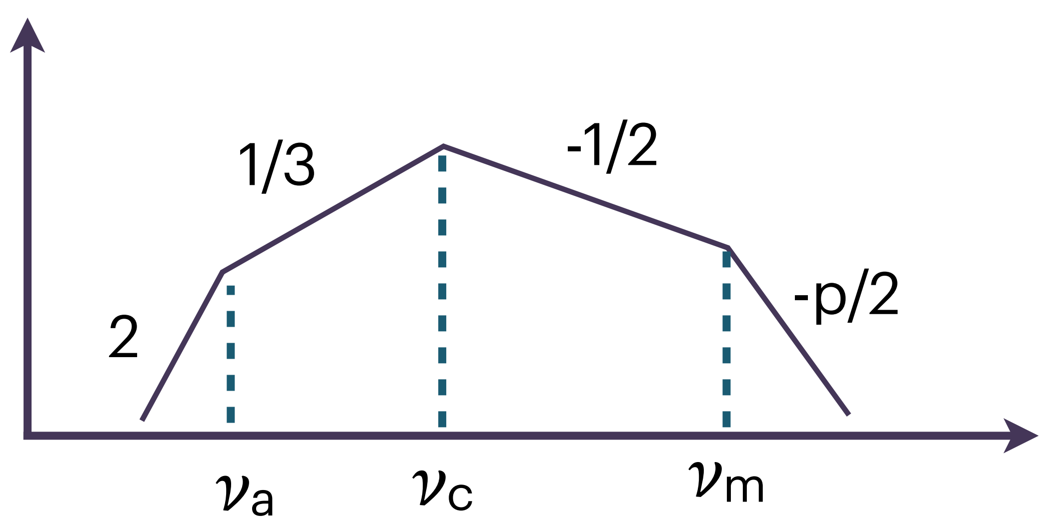
Spectrum From a Population of Electrons

$$\nu_{syn} = \gamma^2 \frac{q_e B}{2\pi m_e c} \Gamma$$

$$t < t_{\mathrm{cool}} \quad \Rightarrow \quad F(\nu) \propto \begin{cases} \nu^2 & \nu < \nu_{\mathrm{a}} \\ \nu^{1/3} & \nu_{\mathrm{a}} \leq \nu < \nu_m \\ \nu^{-\frac{p-1}{2}} & \nu_m \leq \nu < \nu_{\mathrm{cool}} \\ \nu^{-\frac{p}{2}} & \nu \geq \nu_{\mathrm{cool}} \end{cases}$$

$$t > t_{\mathrm{cool}} \quad \Rightarrow \quad F(\nu) \propto \begin{cases} \nu^2 & \nu < \nu_{\mathrm{a}} \\ \nu^{1/3} & \nu_{\mathrm{a}} \leq \nu < \nu_{\mathrm{cool}} \\ \nu^{-\frac{1}{2}} & \nu_{\mathrm{cool}} \leq \nu < \nu_m \\ \nu^{-\frac{p}{2}} & \nu \geq \nu_m \end{cases}$$

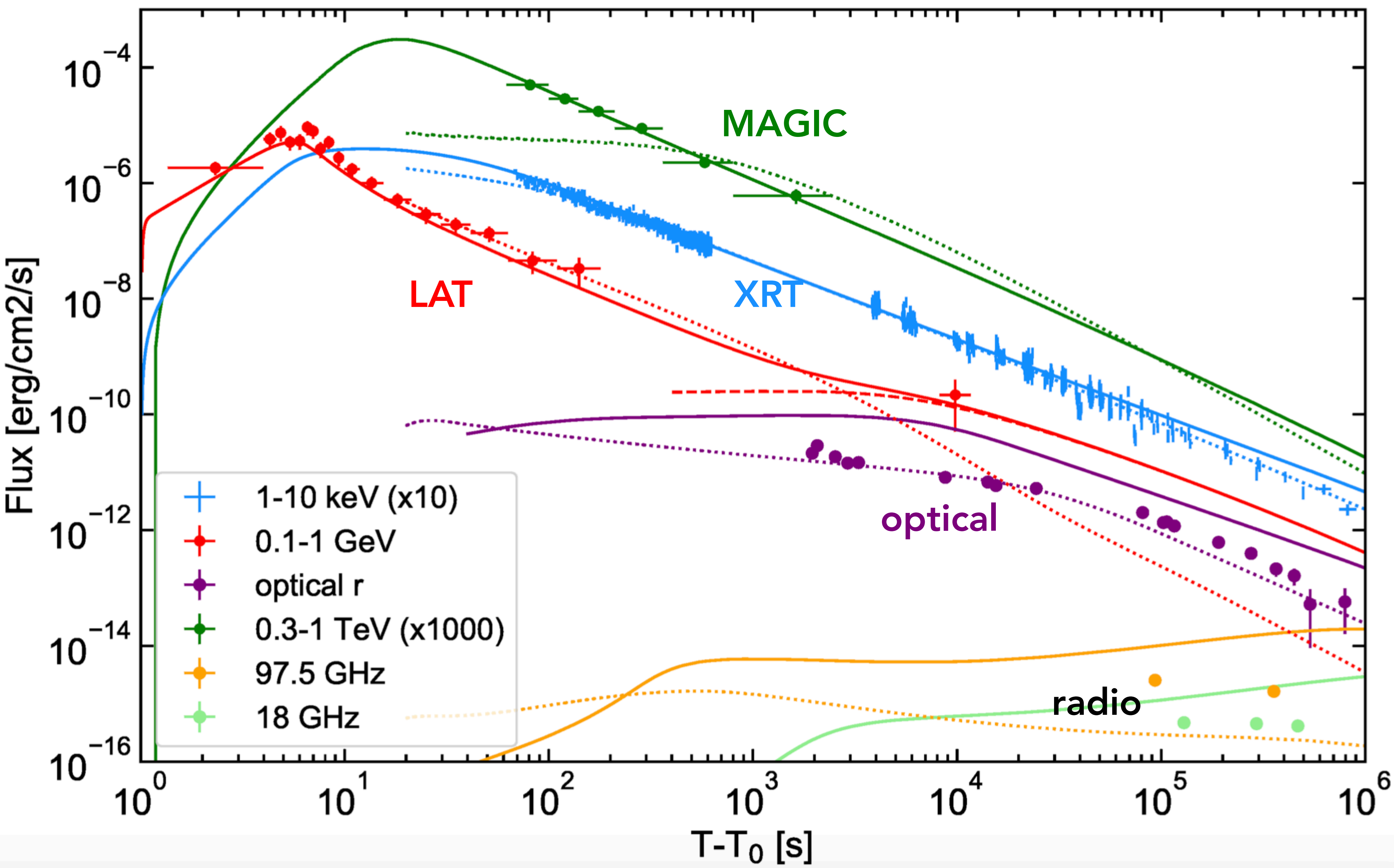




GRB 190114C

z = 0.42

MAGIC 2019, Nature, 575, 459

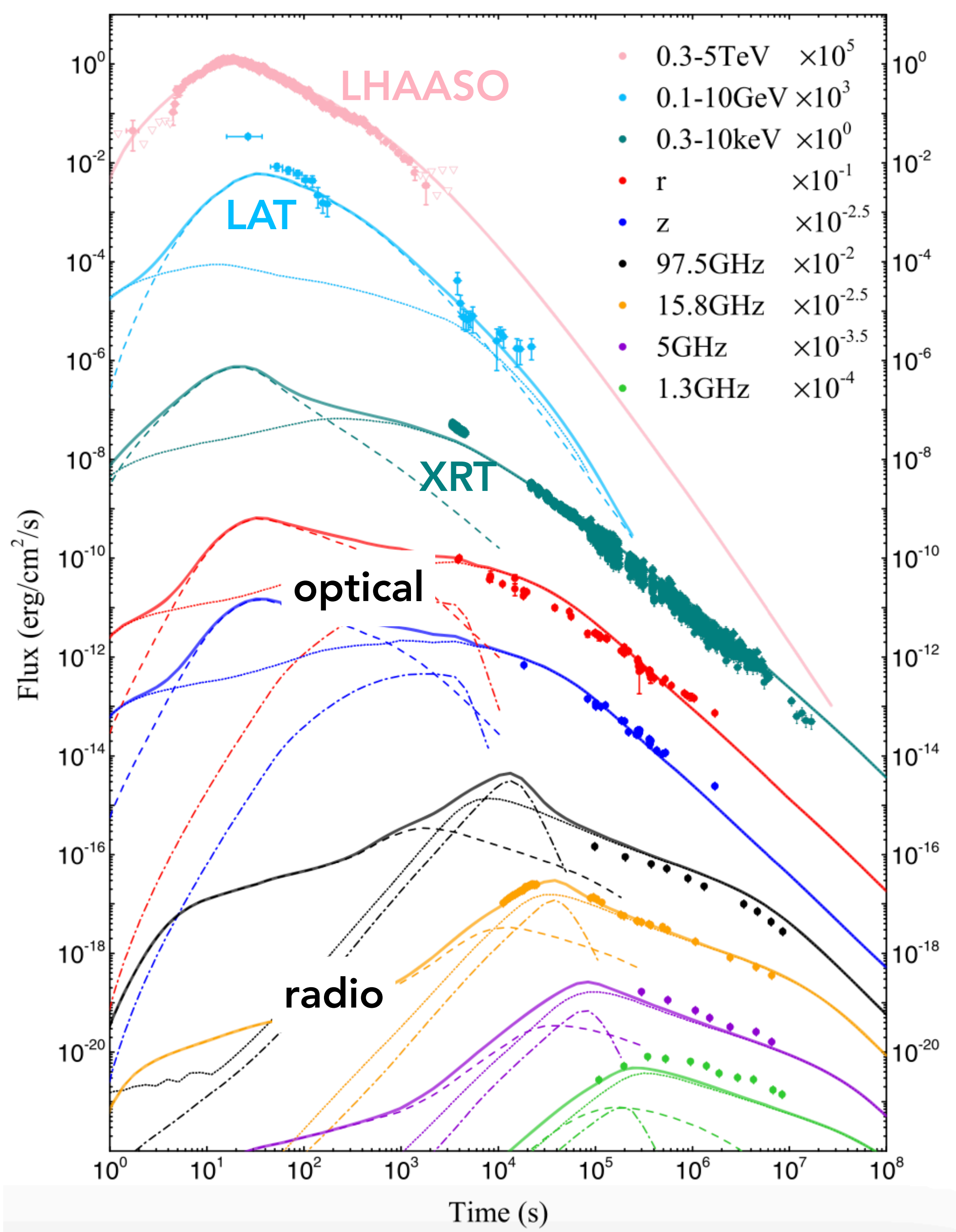


LHAASO: WCDA DATA

Ren, Wang & Dai 2024

Modeling of all multi wavelength data

Structured jet: narrow cone (VHE from SSC) + wings (lower frequencies)



lightcurves