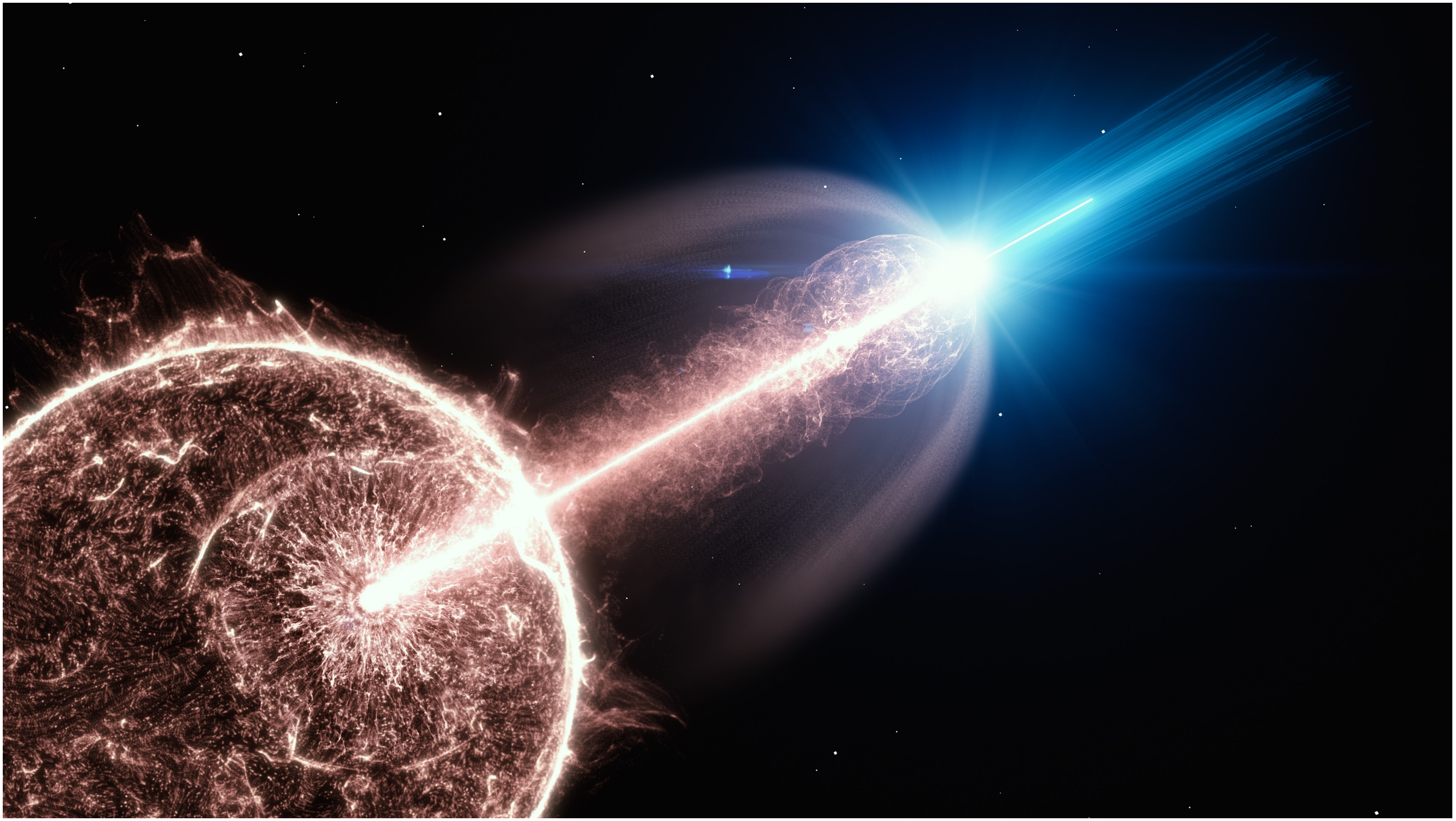
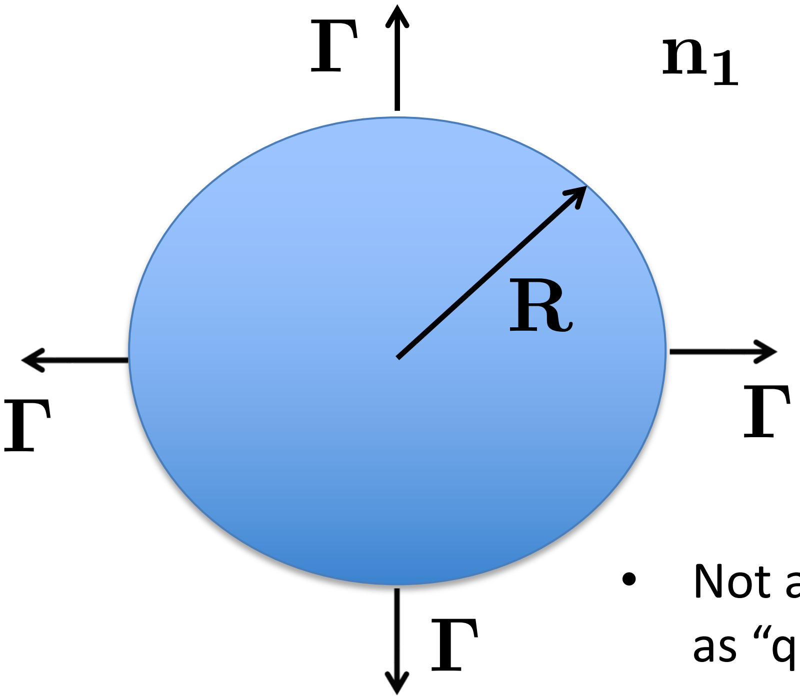
Gamma-Ray Emission from GRBs Outflows- An Overview

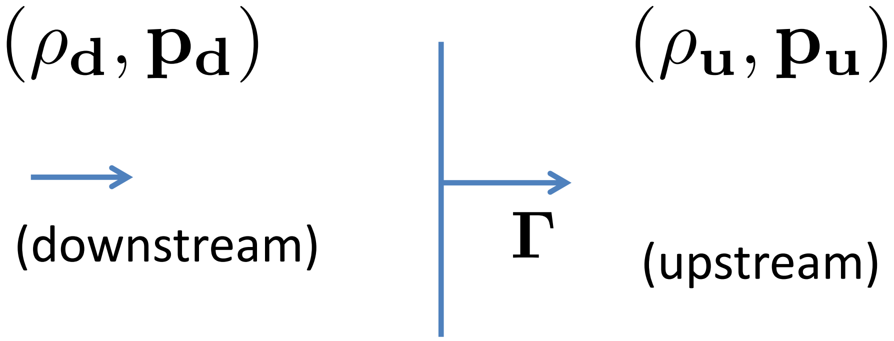


Caveat! The Gamma-Ray emission I will be focusing on here is the radiation observed during the "afterglow" phase of the GRB

Andrew Taylor

What Are GRBs?





[viewed in upstream restframe]

- Not actually isotropic outflows, but can be considered as “quasi-isotropic” since $\theta_{jet}>1/\Gamma$
- Isotropic equivalent energy in gamma-rays, E_{iso}, around 10^{54} erg, is close to Gravitational binding energy limit
- Extremely efficient emitters in terms of converting kinetic energy flux to radiation

Evolutionary Phases of Blastwave

Assuming shock is radiative (ie. incoming KE flux radiated away)

[R. Blandford + McKee 1976]

$$\mathbf{\frac{dE_k}{dt} = -4\pi R^2 \beta(\Gamma^2 \rho - \Gamma \rho)}$$

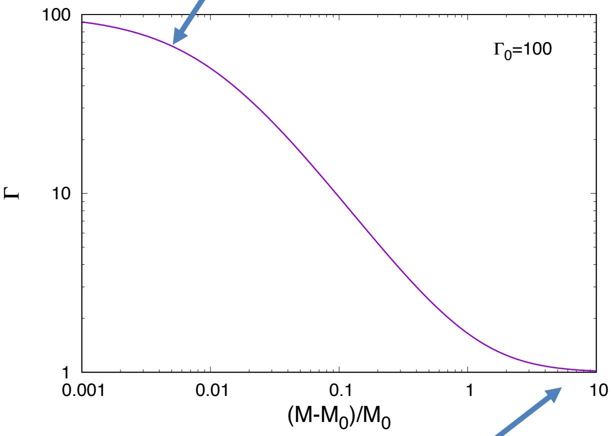
$$\mathbf{E_k = \frac{\rho 4\pi R^3}{3}(\Gamma - 1)}$$

$$\mathbf{\frac{d\Gamma}{dM} = -\frac{(\Gamma^2 - 1)}{M}}$$

This has the solution

$$\boxed{\mathbf{\Gamma - 1 = 2\left(\frac{M^2(\Gamma_0 + 1)}{M_0^2(\Gamma_0 - 1)} - 1\right)^{-1}}}$$

Critical mass where free expansion changes to deceleration phase

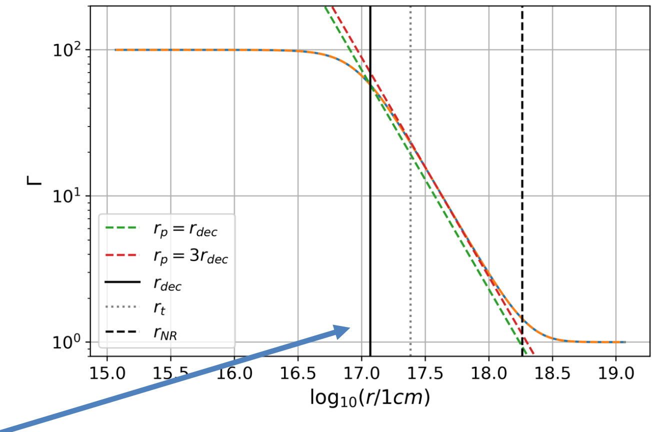


Blast wave becomes non-relativistic

Temporal Compression of Observed Signal

For a constant density medium, during the deceleration phase,

$$\boxed{\Gamma \propto r^{-3/2}}$$



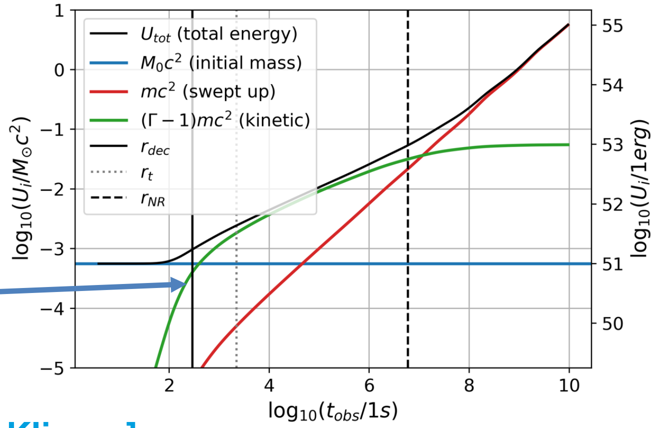
$$R_{dec} \approx 10^{17} \left(\frac{E_{iso}}{10^{53}\ erg}\right)^{1/3} \left(\frac{n}{1\ cm^{-3}}\right)^{-1/3} \left(\frac{\Gamma}{100}\right)^{-2/3}\ cm$$

Since moving emitter is observed along the beam direction

$$c\,dt_{obs} = (1-\beta)dr \approx dr/2\Gamma^2$$

$$\boxed{\Gamma \propto t_{obs}^{-3/8}}$$

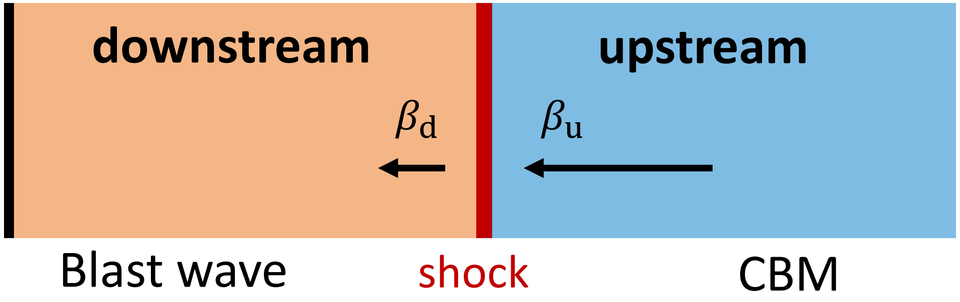
$$t_{dec}^{obs} \approx \frac{R}{c\Gamma^2} = 300 \left(\frac{R}{10^{17}\ cm}\right) \left(\frac{\Gamma}{100}\right)^{-2}\ s$$



[Plots Courtesy of M. Klinger]

Relativistic Hydro Shocks

What's the compression ratio for relativistic shocks?



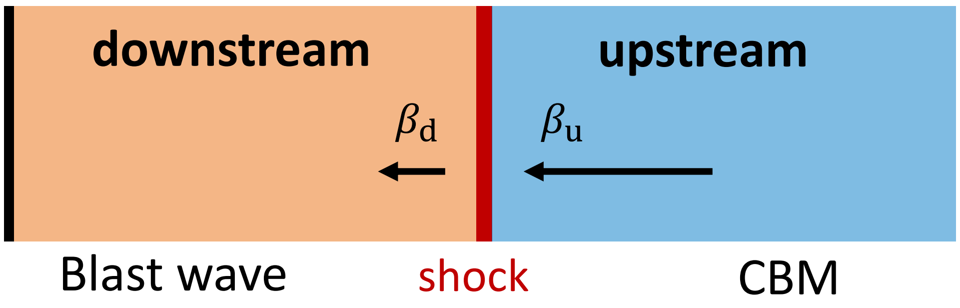
Mass Flux: $$\rho_u \beta_u \Gamma_u = \rho_d \beta_d \Gamma_d$$

Momentum Flux: $$p_u + w_u \beta_u^2 \Gamma_u^2 = p_d + w_d \beta_d^2 \Gamma_d^2$$

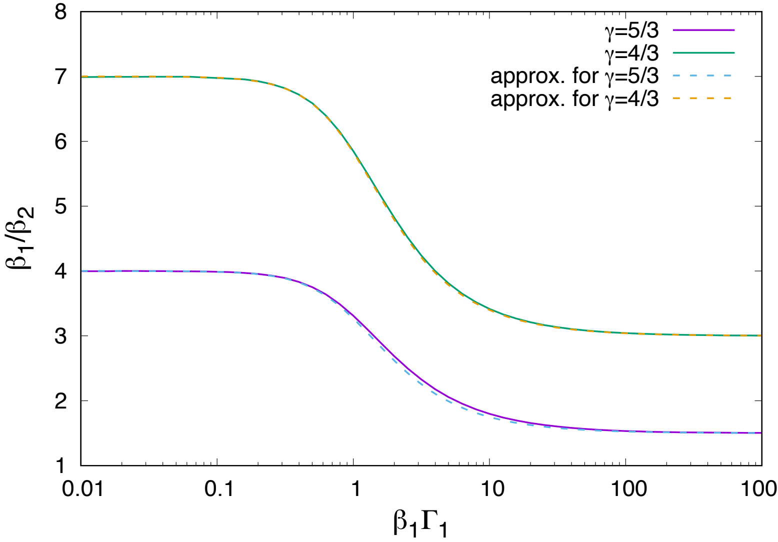
Energy Flux: $$w_u \beta_u \Gamma_u^2 = w_d \beta_d \Gamma_d^2$$

$$\boxed{w_{rel.} = \frac{\gamma}{\gamma - 1} p + \rho}$$

Rel. Hydro Shock- Downstream Partition of the Upstream Ram Pressure



[viewed in shock restframe]

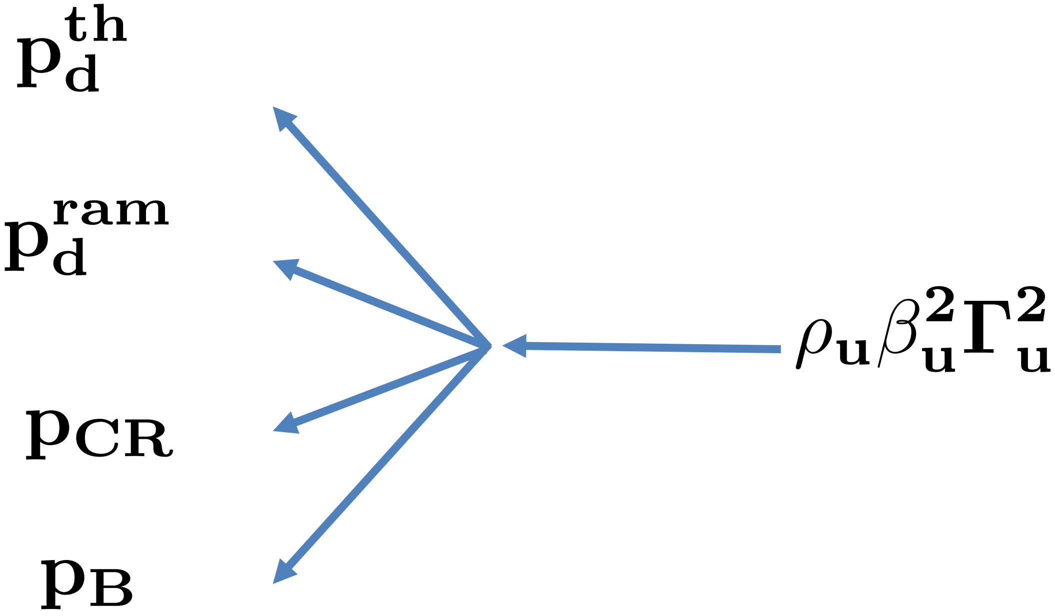


$$\mathbf{p_d} = \frac{2}{3}\rho_\mathbf{u}\beta_\mathbf{u}^2\Gamma_\mathbf{u}^2$$

$$\rho_\mathbf{d}\beta_\mathbf{d}^2\Gamma_\mathbf{d}^2 = \frac{1}{3}\rho_\mathbf{u}\beta_\mathbf{u}^2\Gamma_\mathbf{u}^2$$

$$\rho_\mathbf{u}\beta_\mathbf{u}^2\Gamma_\mathbf{u}^2$$

Rel. MHD Shock- Downstream Partition of the Upstream Ram Pressure



$\mathbf{p_d^{th}}$

$\mathbf{p_d^{ram}}$

$\mathbf{p_{CR}}$

$\mathbf{p_B}$

$\rho_{\mathbf{u}}\beta_{\mathbf{u}}^{\mathbf{2}}\mathbf{\Gamma}_{\mathbf{u}}^{\mathbf{2}}$

$$\varepsilon = \frac{\mathbf{p}}{\rho_{\mathbf{u}}\beta_{\mathbf{u}}^{\mathbf{2}}\mathbf{\Gamma}_{\mathbf{u}}^{\mathbf{2}}}$$

Relativistic MHD Shocks

Downstream magnetic field partition of upstream ram pressure:

$$\varepsilon_{\mathbf{B}} = \frac{\mathbf{U_B}}{\rho_{\mathbf{u}}\beta_{\mathbf{u}}^{\mathbf{2}}\mathbf{\Gamma}_{\mathbf{u}}^{\mathbf{2}}}$$

For

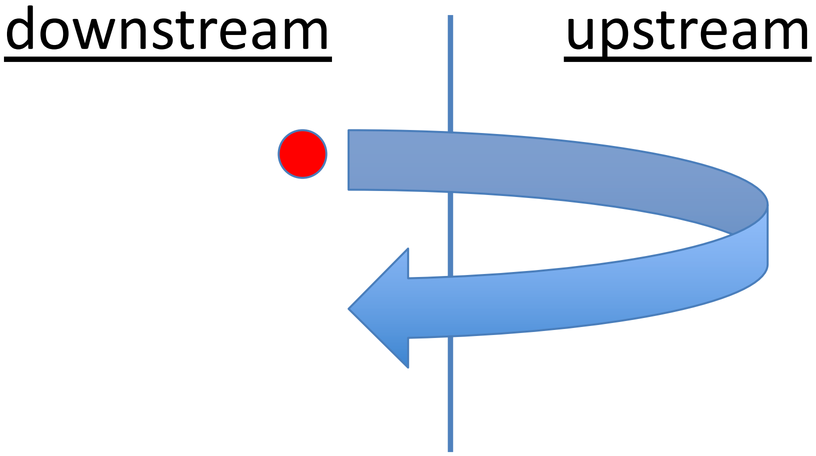
$$\varepsilon_{\mathbf{B}} = \mathbf{0.1} \qquad \mathbf{n_u = 1\ cm^{-3}} \qquad \beta_{\mathbf{u}}\mathbf{\Gamma_u = 10}$$

$$\mathbf{B \approx 0.6\ G}$$

$$\varepsilon_{\mathbf{B}} = \mathbf{10^{-5}} \qquad \mathbf{n_u = 1\ cm^{-3}} \qquad \beta_{\mathbf{u}}\mathbf{\Gamma_u = 10}$$

$$\mathbf{B \approx 6\ mG}$$

Particle Acceleration and Magnetic Turbulence



$$\mathbf{t_{acc.}} = \boldsymbol{\Delta}\mathbf{t_{cyc}}\left(\mathbf{E}/\boldsymbol{\Delta}\mathbf{E_{cyc}}\right)$$
$$= \mathbf{t_{scat}}/\beta^{2}$$

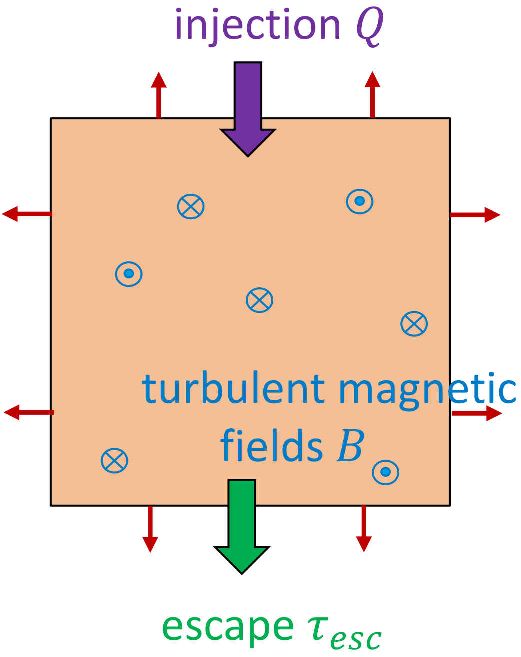
- Isotropisation is caused by magnetic turbulence, its rate is described by the scattering time, which in Larmor time units is **η**

$$\mathbf{t_{scat}} = \eta\frac{\mathbf{R_{lar}}}{\mathbf{c}}$$

- Scattering agent velocity **β** dictates energy gain each crossing cycle

One Zone Model

$$\boxed{\frac{\partial \mathbf{n_p}}{\partial \mathbf{t}} = -\nabla_{\mathbf{p}} \cdot \left[\frac{\mathbf{p}}{\tau_{\mathbf{acc}}(\mathbf{p})}\mathbf{n_p} - \frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})}\mathbf{n_p}\right] - \frac{\mathbf{n_p}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}}$$



[Diagram Courtesy of M. Klinger]

Note the absence of spatial information in the transport equation

Hadronic Particle Acceleration in Sources

$$\cancel{\frac{\partial n_p}{\partial t}} = -\nabla_p \cdot \left[\frac{p}{\tau_{acc}(p)} n_p - \cancel{\frac{p}{\tau_{loss}(p)}} n_p\right] - \frac{n_p}{\tau_{esc}(p)} + Q$$

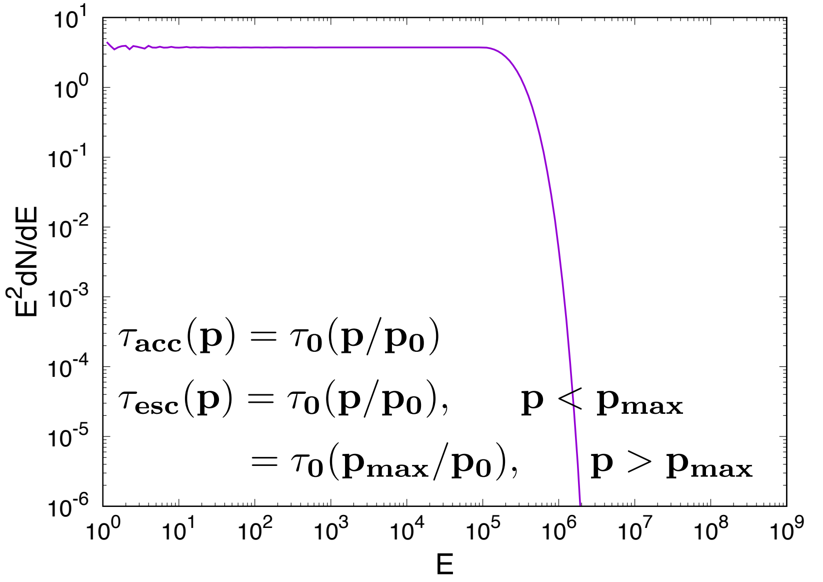
Steady state

No losses

Delta injection

$$n_p = Q\left(\frac{p}{p_0}\right)^{-\left(1+\frac{\tau_{acc}}{\tau_{esc}}\right)}$$

Note- shock acceleration is
not the only acceleration process on the
block



$$\tau_{acc}(p) = \tau_0(p/p_0)$$

$$\tau_{esc}(p) = \tau_0(p/p_0), \qquad p < p_{max}$$

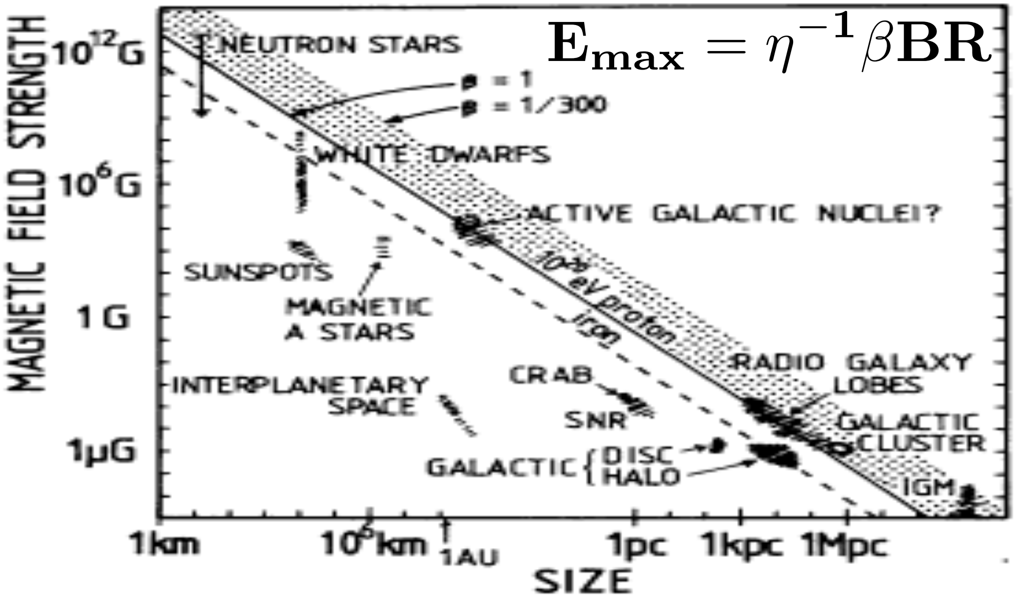
$$= \tau_0(p_{max}/p_0), \qquad p > p_{max}$$

Cosmic Ray Source Requirements

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{esc.}} = \frac{\mathbf{R}}{\mathbf{c}\beta}$$

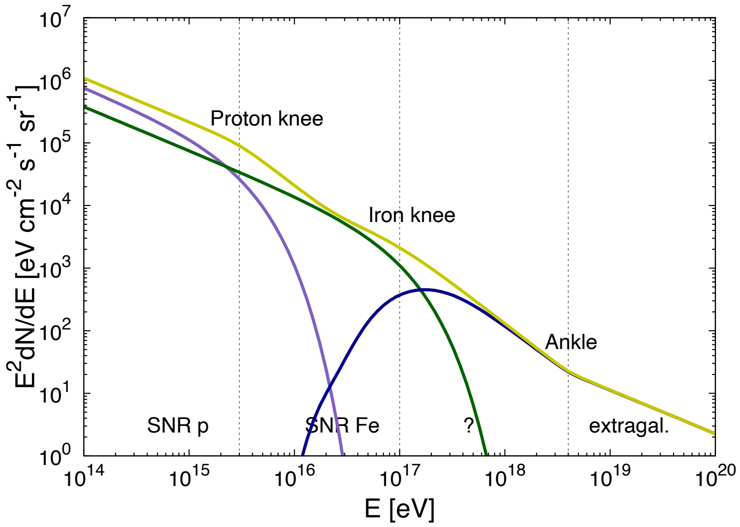
[AM Hillas (1984)]



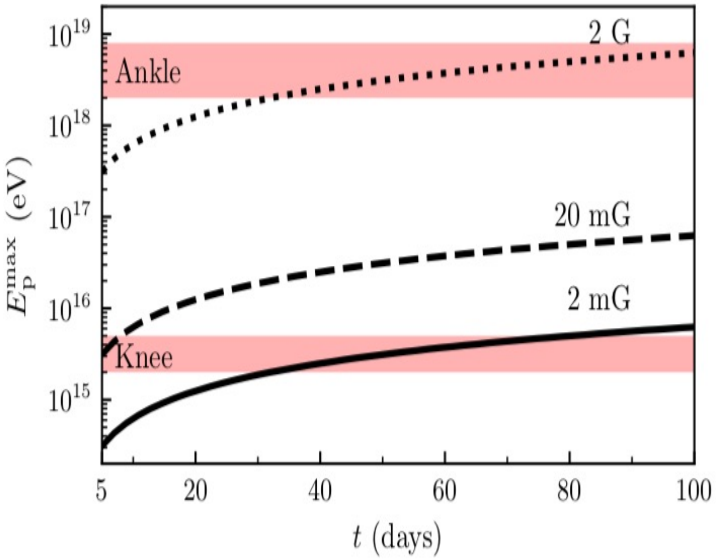
$$\mathbf{E_{max}} = \eta^{-\mathbf{1}} \beta \mathbf{BR}$$

Not many objects appear capable of accelerating cosmic rays up to EeV energies. Blackhole related phenomena seem most promising- AGN and GRB

GRB Outflows as a Cosmic Ray Sources



- As the source expands, **CRs** can be accelerated to energies between the **knee and the ankle**
- If the *B*-field is as large as ~G -> possibility of **UHECRs**



[X. Rodrigues, A. Taylor, et al., ApJ 2019]

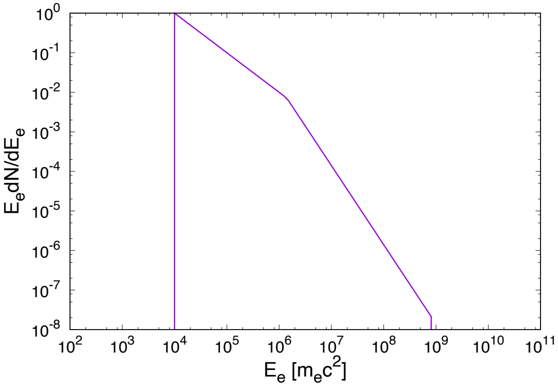
Electron Spectrum Produced in Sources

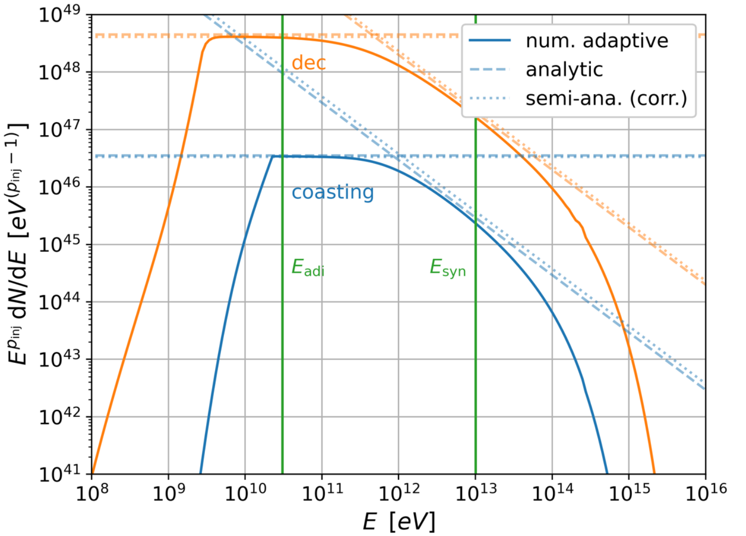
$$\boxed{\cancel{\frac{\partial \mathbf{n_p}}{\partial \mathbf{t}}} = -\nabla_{\mathbf{p}} \cdot \left(-\frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})} \mathbf{n_p} \right) - \frac{\mathbf{n_p}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}}$$

Steady state

$$\tau_{\mathbf{eff}} = \left(\tau_{\mathbf{loss}}^{-1} + \tau_{\mathbf{esc}}^{-1}\right)^{-1}$$

$$\mathbf{n_p} \approx \mathbf{Q}\tau_{\mathbf{eff}}$$





Electron Acceleration with Cooling

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{2}}$$

$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{U_{Bcrit}}}{\mathbf{U_B}}\right)\left(\frac{\mathbf{h}}{\mathbf{E_e}}\right)$$

$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

$$\mathbf{E_e^{max}} = \left(\frac{\eta^{-\mathbf{1/2}}}{\alpha^{\mathbf{1/2}}(\mathbf{B}/\mathbf{B}_{\text{crit}})^{\mathbf{1/2}}}\right)\mathbf{m_e c^2}$$

Maximum synchrotron energy tells us how efficient accelerator is!

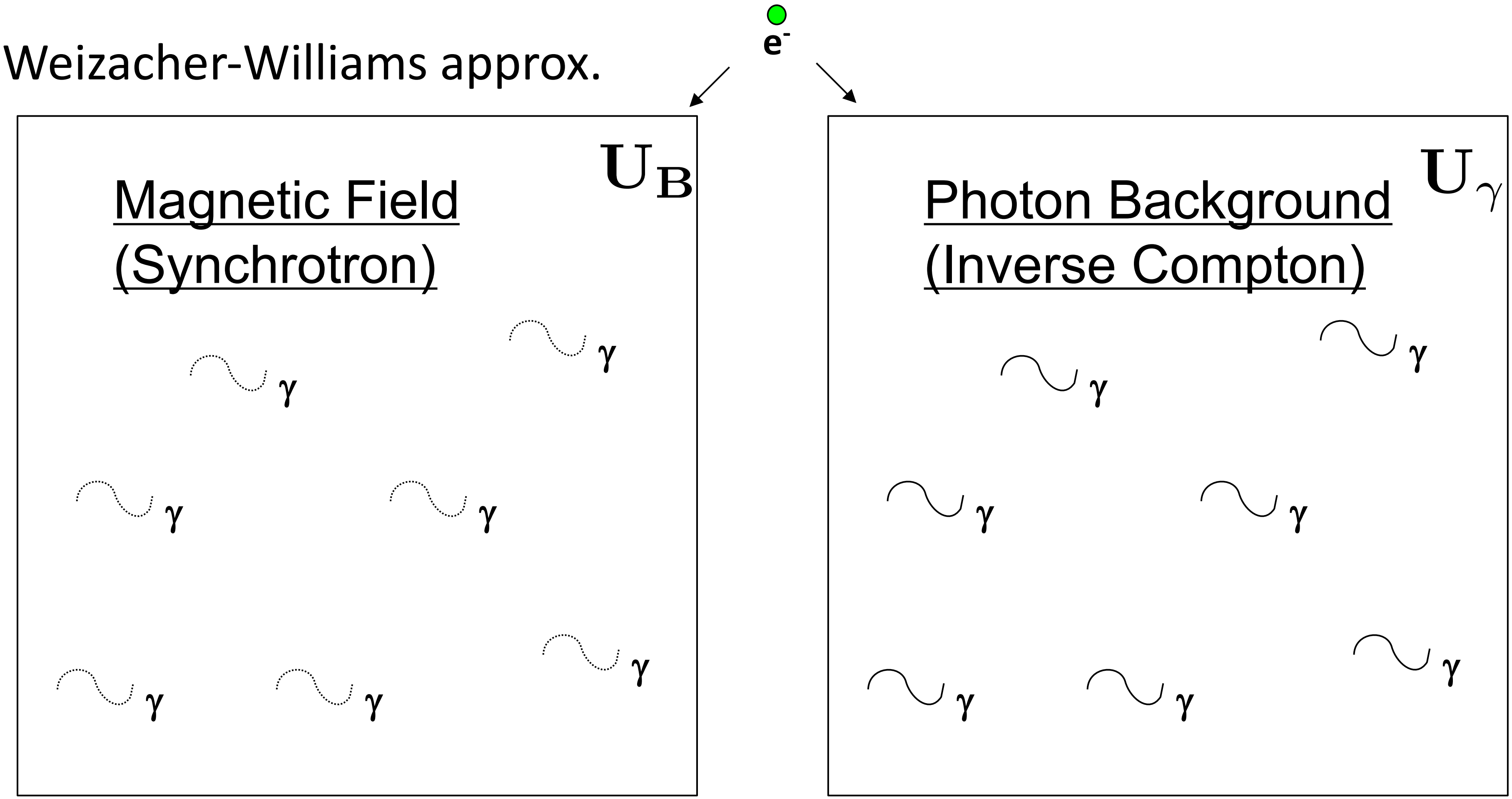
$$\mathbf{E}_{\gamma}^{\mathbf{sync}} \approx \frac{\mathbf{9}}{\mathbf{4}}\eta^{-\mathbf{1}}\beta^{\mathbf{2}}\frac{\mathbf{m_e}}{\alpha}$$

→

Where do synchrotron cutoffs for AGN and GRB sit in energy?

Possible VHE Emission Processes

Weizacher-Williams approx.



Magnetic Field (Synchrotron)

Photon Background (Inverse Compton)

Virtual Photons

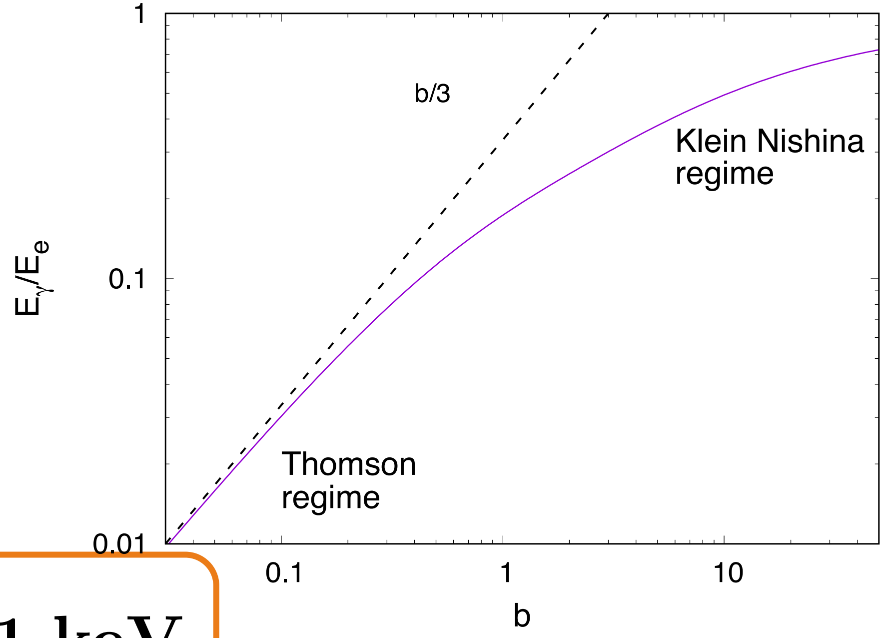
$$E_\gamma^{\rm target} = \left(\frac{B}{B_{\rm crit}}\right) m_e c^2$$

Real Photons

$$E_\gamma^{\rm target}$$

Efficiency Transfer Efficiency for Inverse Compton Emission

$$\mathbf{E_\gamma^{IC} \approx \left(\frac{b}{1+b}\right) E_e}$$

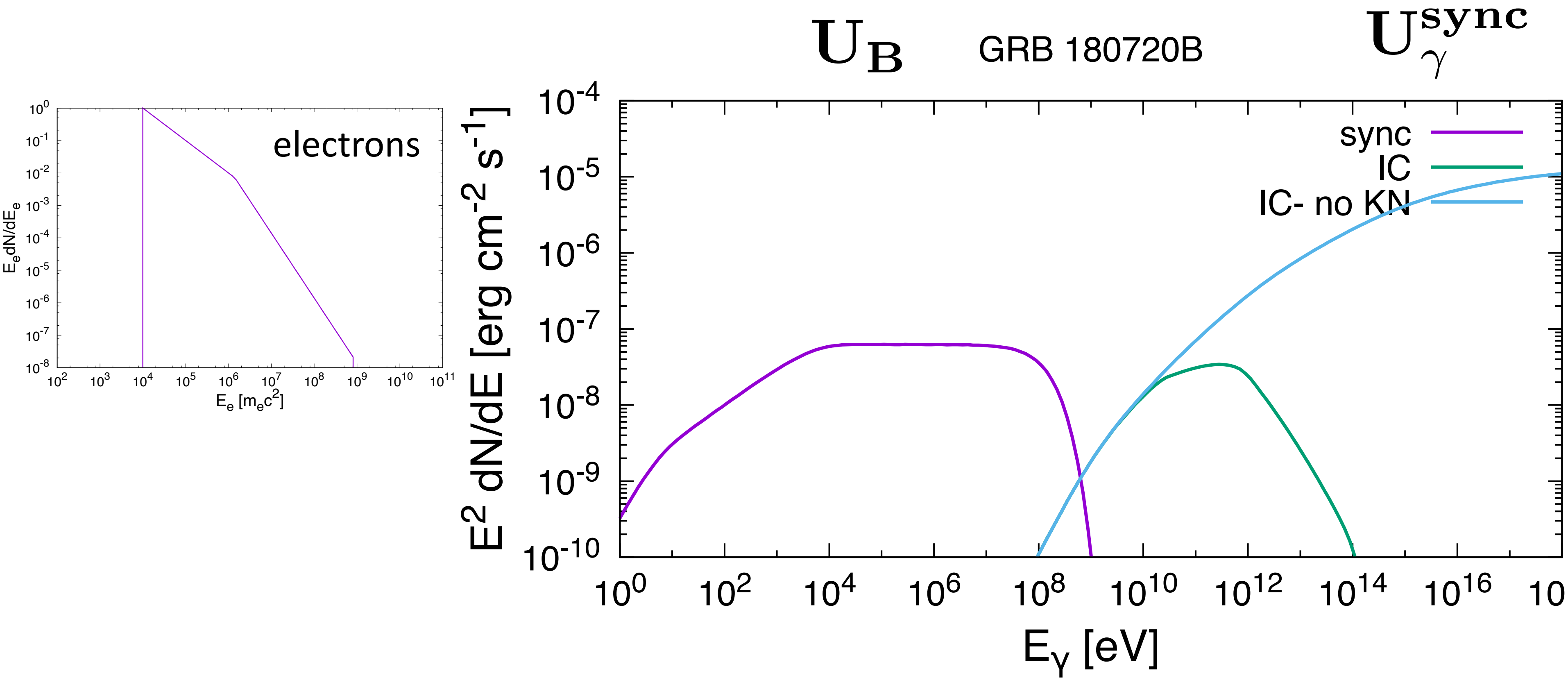


$$\mathbf{b = \frac{4E_eE_\gamma^{target}}{(m_ec^2)^2}}$$

$$\mathbf{E_e = 1\ TeV} \qquad \mathbf{E_\gamma^{target} = 1\ keV}$$

$$\mathbf{\left(\frac{b}{1+b}\right) \approx 1}$$

Afterglow GRB SED- Expected from SSC Model



Without KN effects, the ratio of the heights of the IC to Synchrotron bumps would scale with U_e/U_B (ie. $\varepsilon_e/\varepsilon_B$)

An SSC origin of the VHE emission has been adopted by others to describe early time VHE emission

[Nature 575, 459-463 (2019)]

GRB Energy Flux Histogram

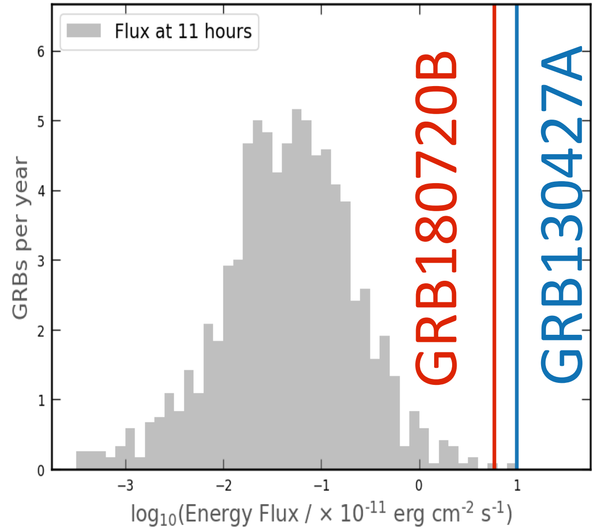
- GRBs at HE and VHE:
  ~12 GRBs per year Fermi-LAT

- However, most science learnt from brightest event- GRB130427A: 94 GeV max energy photon.

VHE emission has been a decades-long mystery

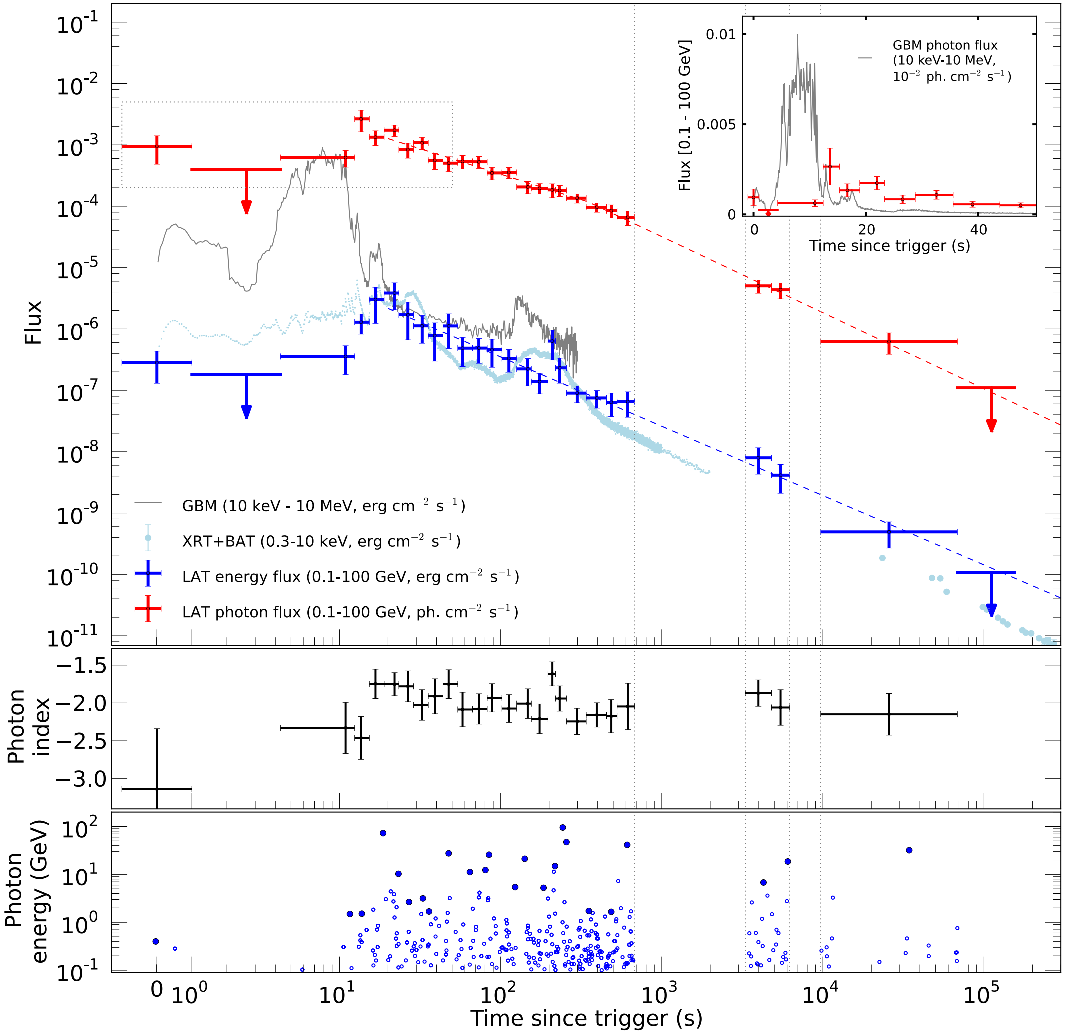
- Fermi-LAT detection from T_0 to T_0+10000 s (max. energy photon >90 GeV).
- Extremely bright burst:
  - 2nd brightest afterglow measured by Swift-XRT.

Swift-XRT GRBs
energy flux distribution at 11 hours



t^{GBM}_{90} ~ 138 s, t^{BAT}_{90}~ 163 s
z = 0.34

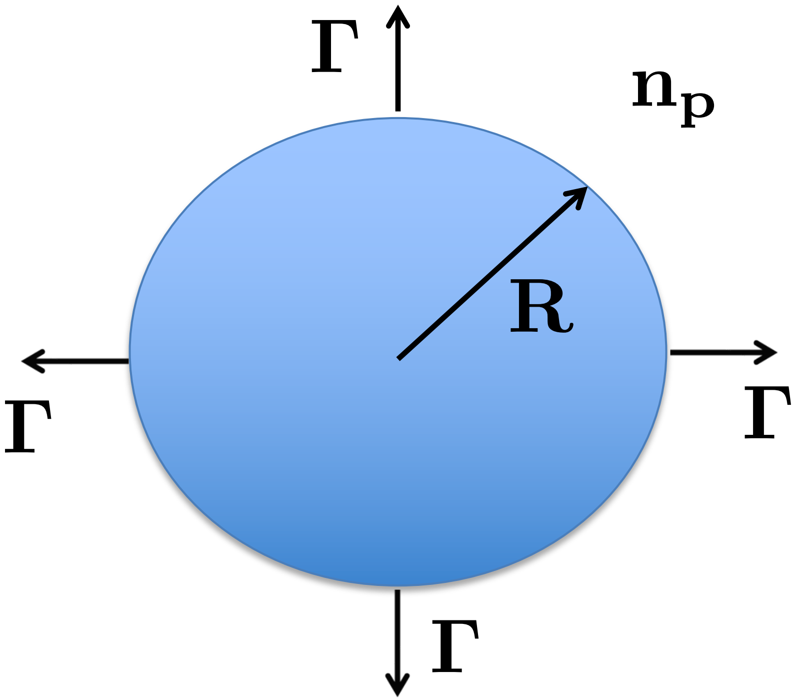
GRB 130427A Lightcurve

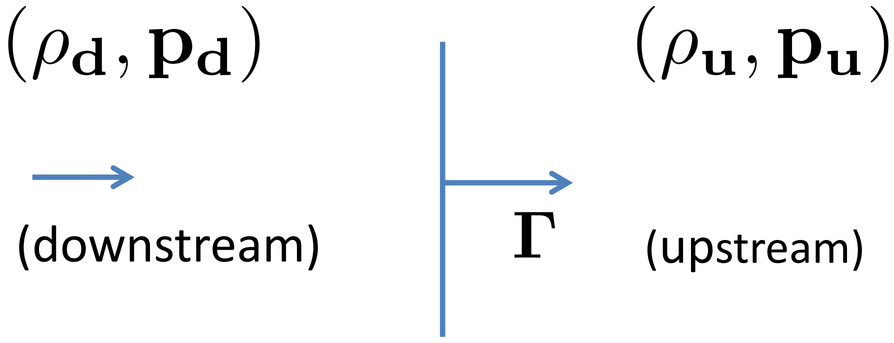


$$L_{XRT} \propto t^{-\alpha}$$

$$\alpha = 1.17 \pm 0.06$$

Origin of Temporal Decay Structure





[viewed in upstream restframe]

Assuming η_γ is constant in time…..

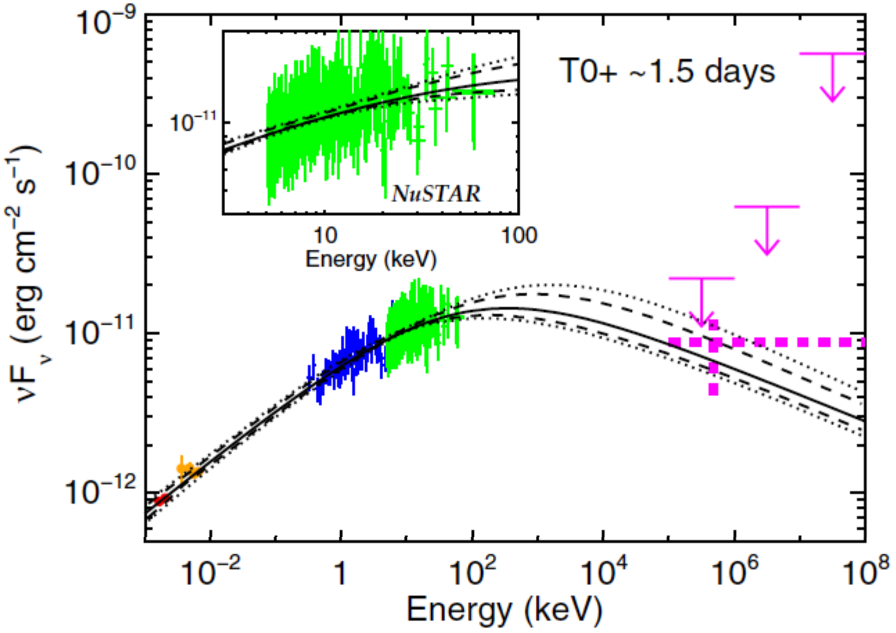
$$\frac{\mathbf{L^{iso}_{sync}}}{4\pi\Gamma^2\mathbf{R}^2\mathbf{c}} = \varepsilon_\mathbf{rad}\Gamma^2\mathbf{n_p m_p c^2}$$

$$\Gamma \propto \mathbf{t}^{-3/8} \qquad \mathbf{R} \propto \mathbf{t}^{1/4}$$

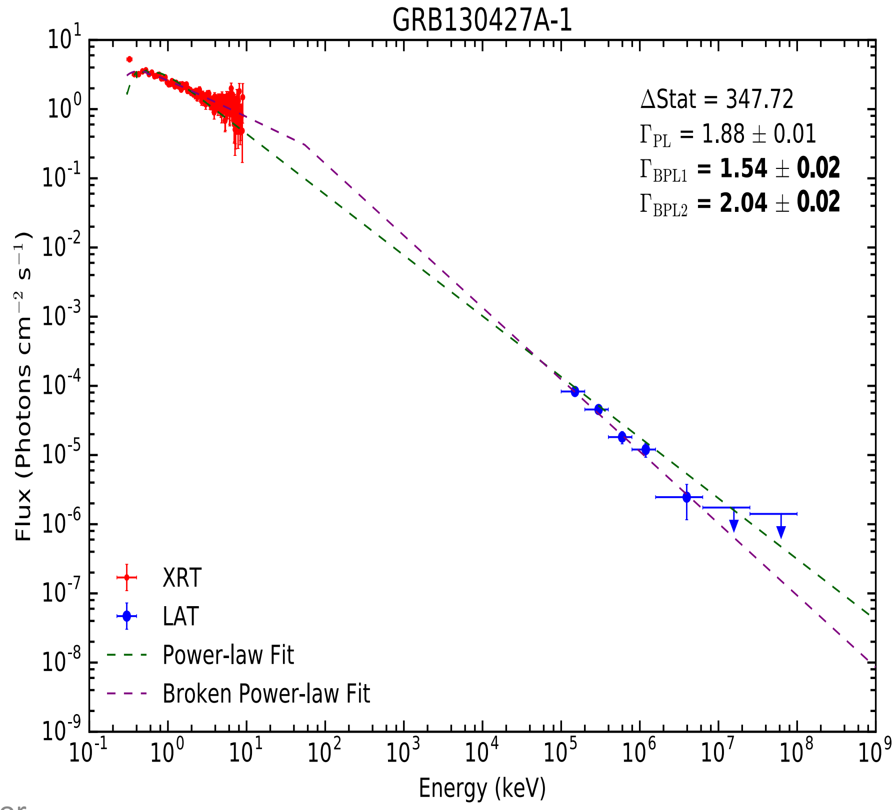
$$\mathbf{L^{iso}_{sync}} \propto \mathbf{t}^{-1}$$

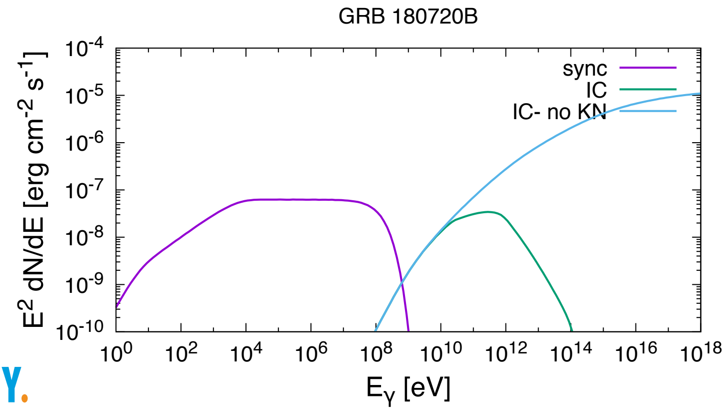
No Synchrotron Cutoff of GRB 130427A Seen in X-rays and Gamma-Rays

[Kouveliotou et al., ApJL 779 (2013)]

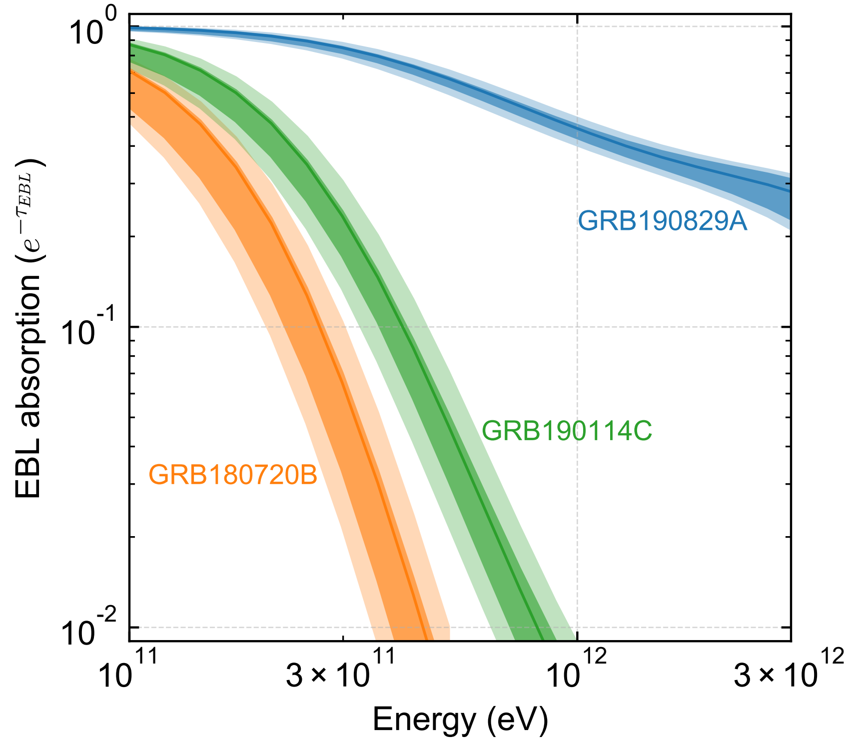


[Ajello et al., ApJ 863 138 (2018)]





Energy Spectrum Information



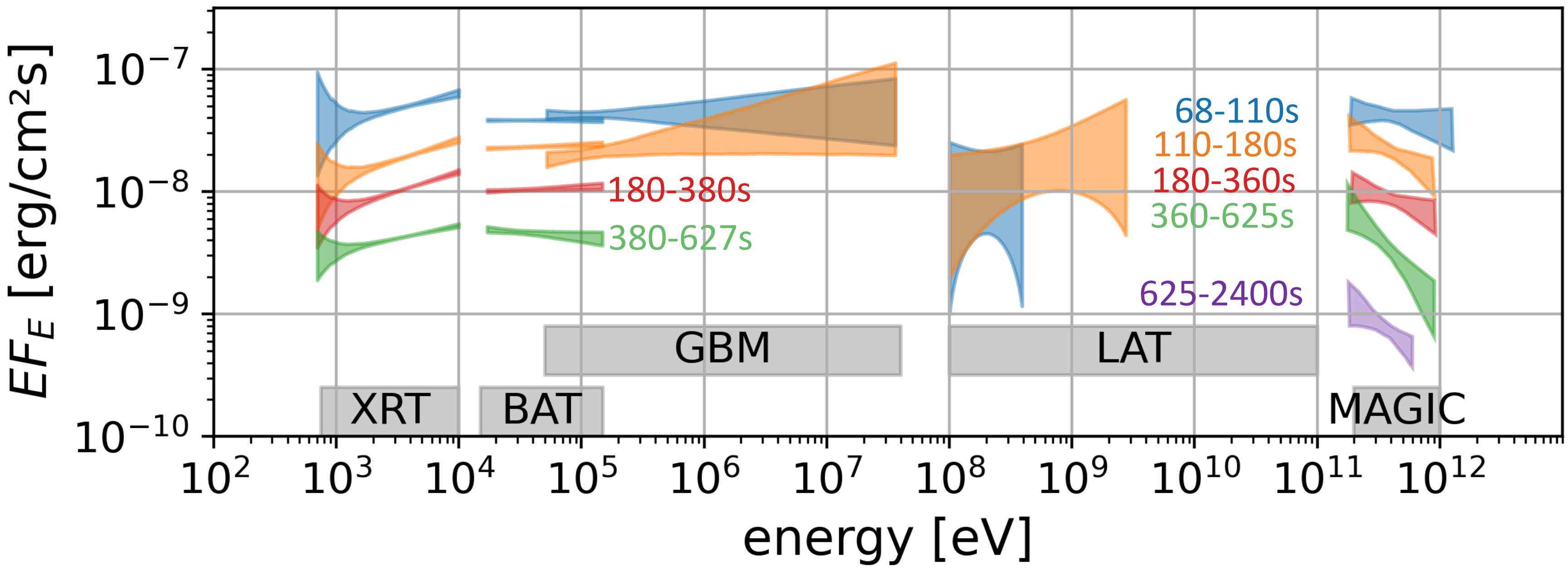
The effect of the EBL on the (optically thin) attenuation for a nearby (z=0.08) source for E_γ<6 TeV is a softening of the spectrum by around $\Delta\Gamma \approx 0.5$, starting around 250 GeV.

[HESS- A. Taylor, et al., Science 2021]

Conclusions

- Fast shocks from massive energy release events are the most viable sources of extragalactic cosmic rays
- Synchrotron emission from long GRB tell us directly how efficient these sources operate as cosmic ray accelerators
- We are finally starting to probe the very high energy (TeV) gamma-ray emission from GRB, allowing us to start probing the magnetic fields in the source
- Whether a new component in the GRB spectrum is present remains unclear- the VHE GRB detections appear compatible with a continuation of the synchrotron emission beyond the expected supposed theoretical limit

GRB 190114C (Detected by MAGIC)

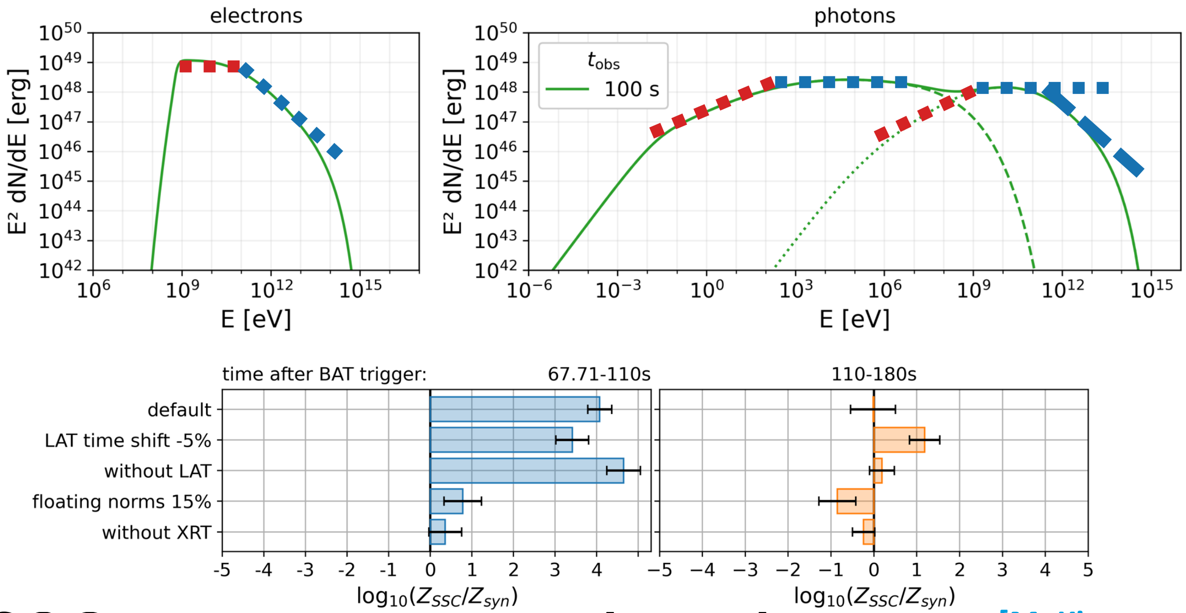


[Nature 575, 459-463 (2019)]

- remarkably flat over 9 orders of magnitude in energy!

DESY.

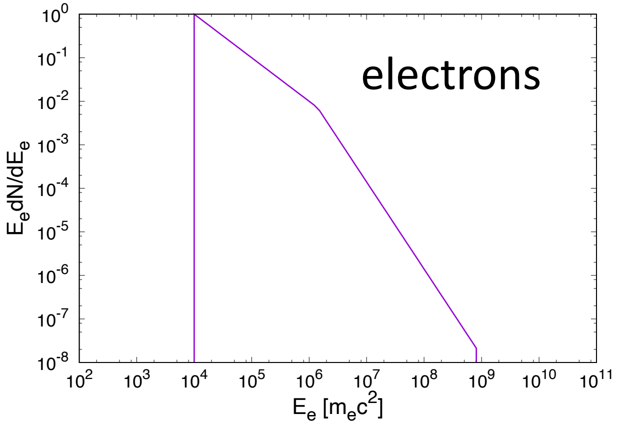
Evidence for a New Component?



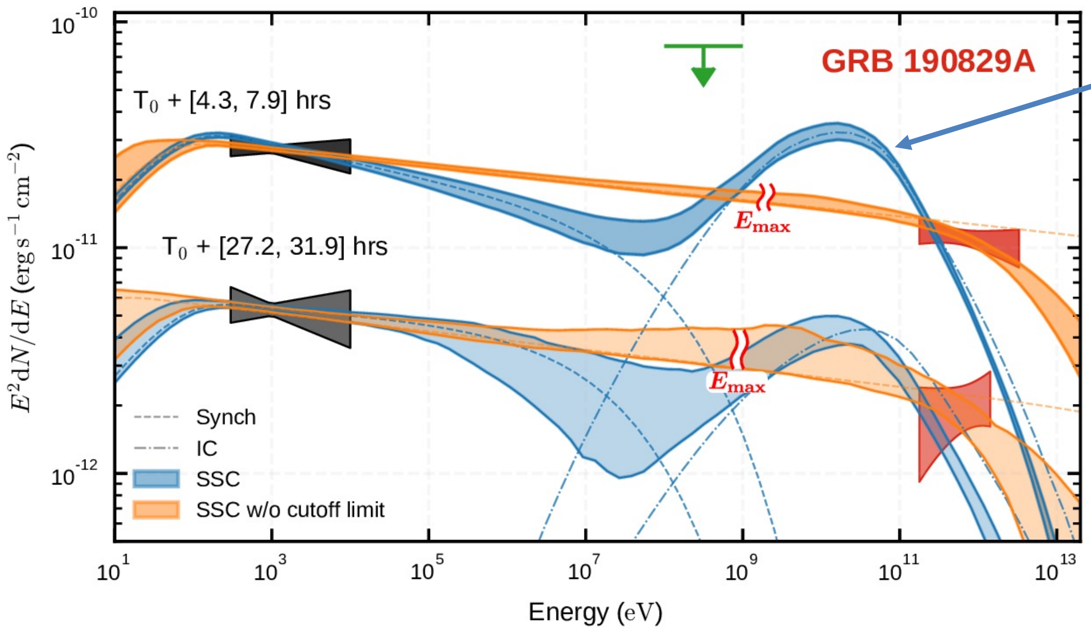
[M. Kinger et al., MNRAS 501 2023]

- SSC spectra are mirroring a smoothly BPL electron distribution
- We need more **bright, nearby** GRBs (without moonlight!)
- GRB 190114C shows no clear evidence for the onset of a new component

GRB 190829A- Testing the “Standard” and Non-Standard VHE Emission Scenarios



MCMC fits to Night 1



Synchrotron + SSC

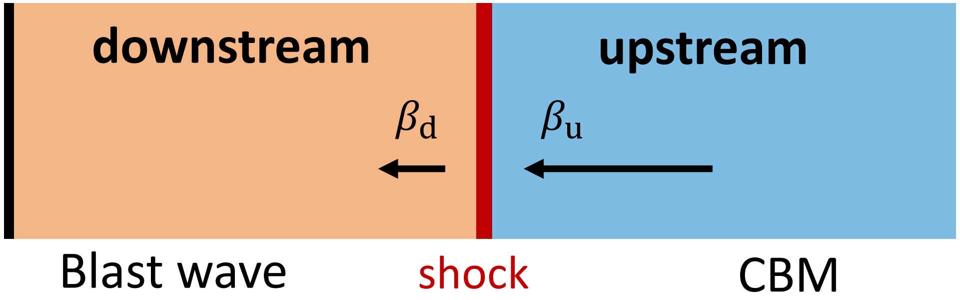
$\mathbf{E_e > 400\ GeV}$

Synchrotron Only

$\mathbf{E_e > 1}\ \mathrm{PeV}$

[HESS- A. Taylor, et al., Science 2021]

Non-Rel. Hydro Shock- Downstream Partition of the Upstream Ram Pressure



[viewed in shock restframe]

$$\mathbf{p_d} = \frac{3}{4}\rho_\mathbf{u}\beta_\mathbf{u}^2$$

$$\rho_\mathbf{d}\beta_\mathbf{d}^2 = \frac{1}{4}\rho_\mathbf{u}\beta_\mathbf{u}^2$$

$$\rho_\mathbf{u}\beta_\mathbf{u}^2$$

Energy Transfer Efficiency for Synchrotron Emission

$$\boxed{\mathbf{E_\gamma^{sync} \approx \frac{b}{3} E_e}}$$

$$\mathbf{b} = \frac{\mathbf{4E_eE_\gamma^{\mathrm{target}}}}{(\mathbf{m_ec^2})^{\mathbf{2}}}$$

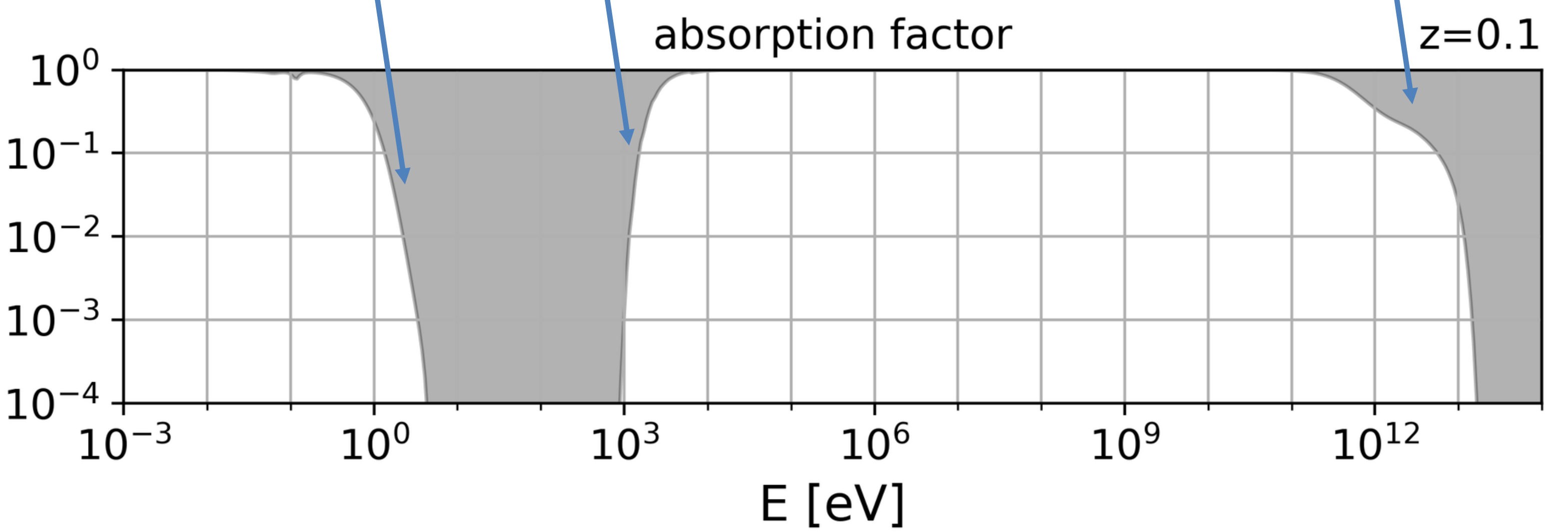
$$\mathbf{E_\gamma^{target}} = \left(\frac{\mathbf{B}}{\mathbf{B_{crit}}}\right) \mathbf{m_ec^2}$$

$$(\mathbf{B}_{\mathrm{crit}} = \mathbf{4} \times \mathbf{10^{13}}\ \mathrm{G})$$

$$\mathbf{E_e} = \mathbf{1}\ \mathbf{TeV} \qquad\qquad \mathbf{B} = \mathbf{1}\ \mathrm{G}$$

$$\mathbf{b} \approx \mathbf{10^{-7}}$$

The Observational Challenges for GRBs Absorption!



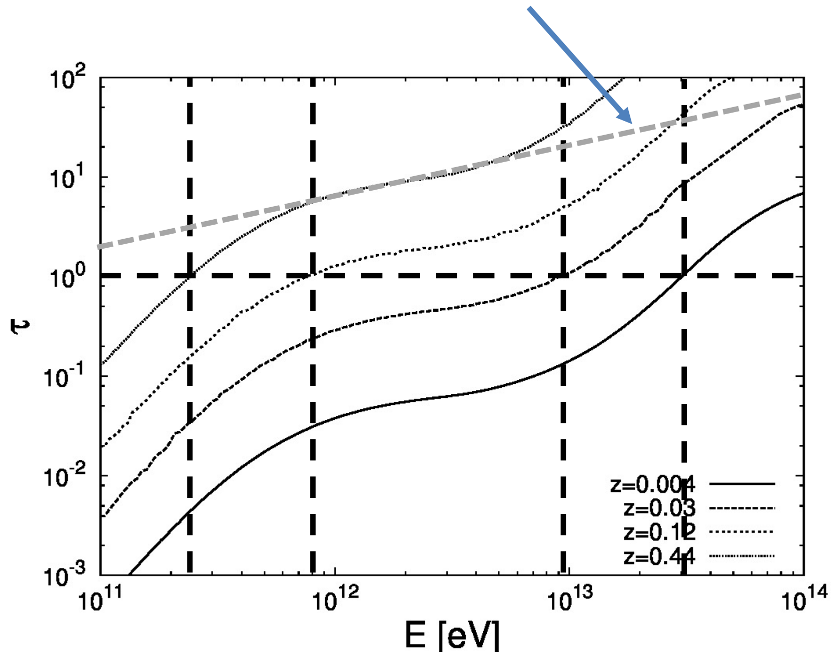
Dust absorption

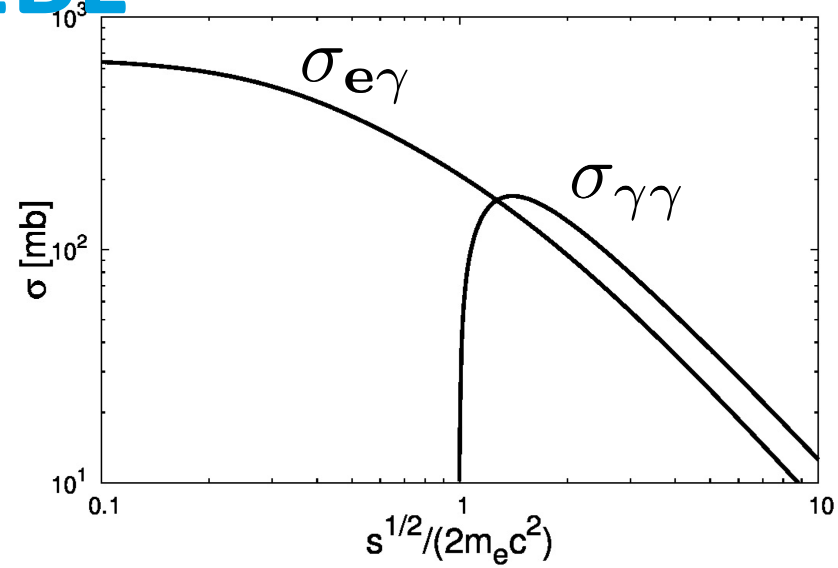
Photoelectric absorption

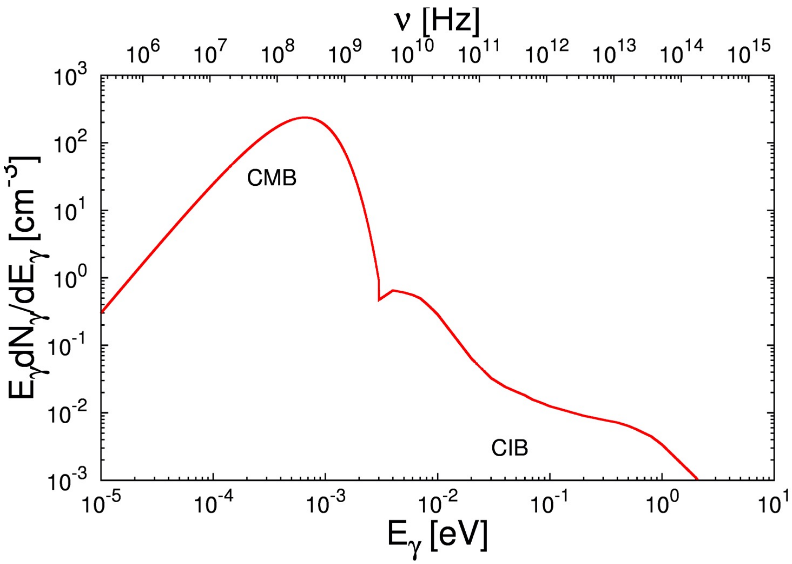
EBL absorption

Attenuation through Pair Production on the EBL

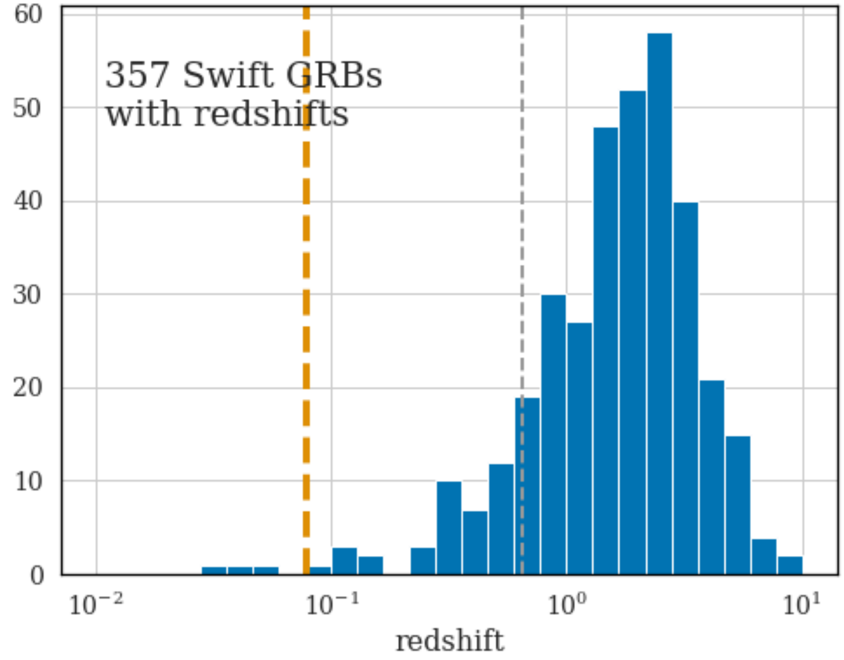
$\propto \mathbf{E^{1/2}}$



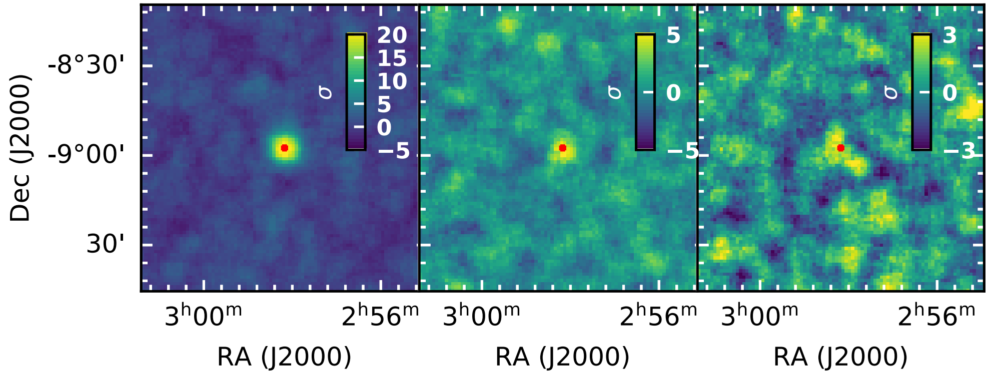




HESS Detection of GRB 190829A



First detection of a GRB in VHE band for multiple nights

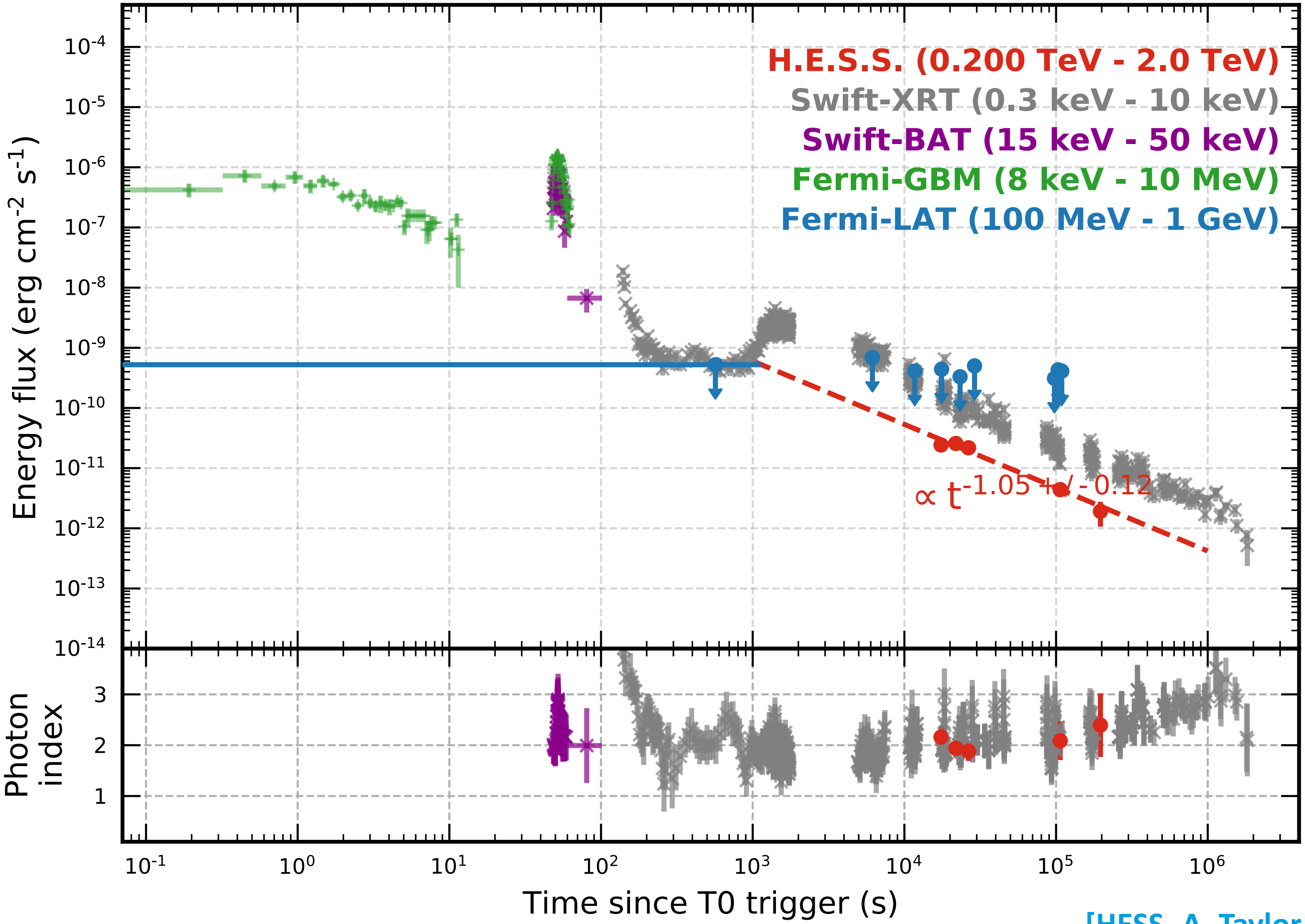


Night 1 Night 2 Night 3

[HESS- A. Taylor, et al., Science 2021]

t^{GBM}_{90} ~ 60 s, t^{BAT}_{90} ~ 60 s
z = 0.078

MWL Energy Flux Lightcurve



GRB was not detected by Fermi-LAT

[HESS- A. Taylor, et al., Science 2021]

X-ray and Gamma-ray energy fluxes decay in a remarkably similar way-

$$\mathbf{F(t) \propto t^{-\alpha}}$$

$$\alpha_{\mathrm{XRT}} = \mathbf{1.09 \pm 0.04}$$

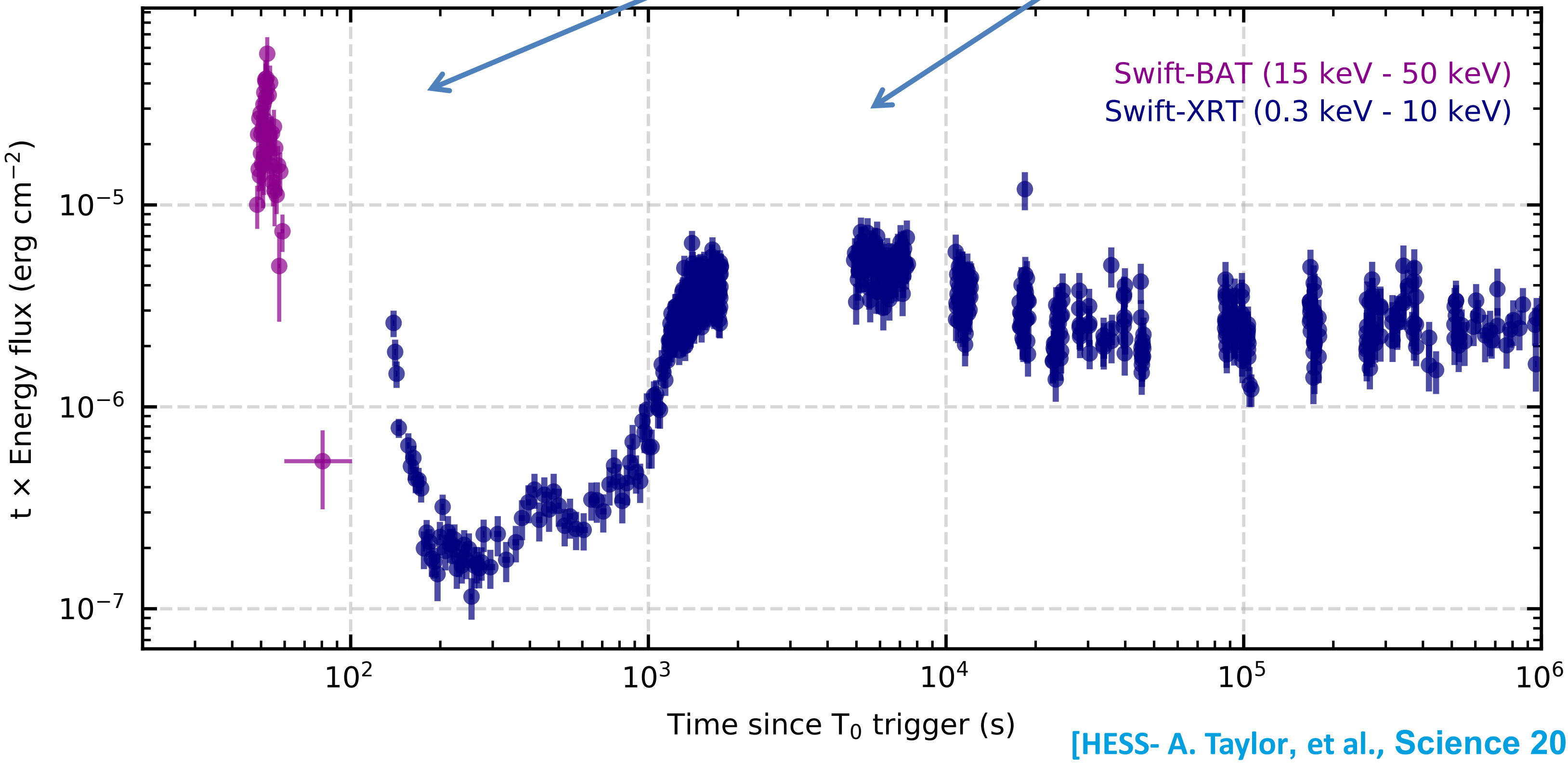
$$\alpha_{\mathrm{HESS}} = \mathbf{1.05 \pm 0.12}$$

When Does the Afterglow Fluence Saturate?

$$\mathbf{fluence} = \int_{\mathbf{t_{min}}}^{\mathbf{t_{max}}} \mathbf{F(t)dt}$$

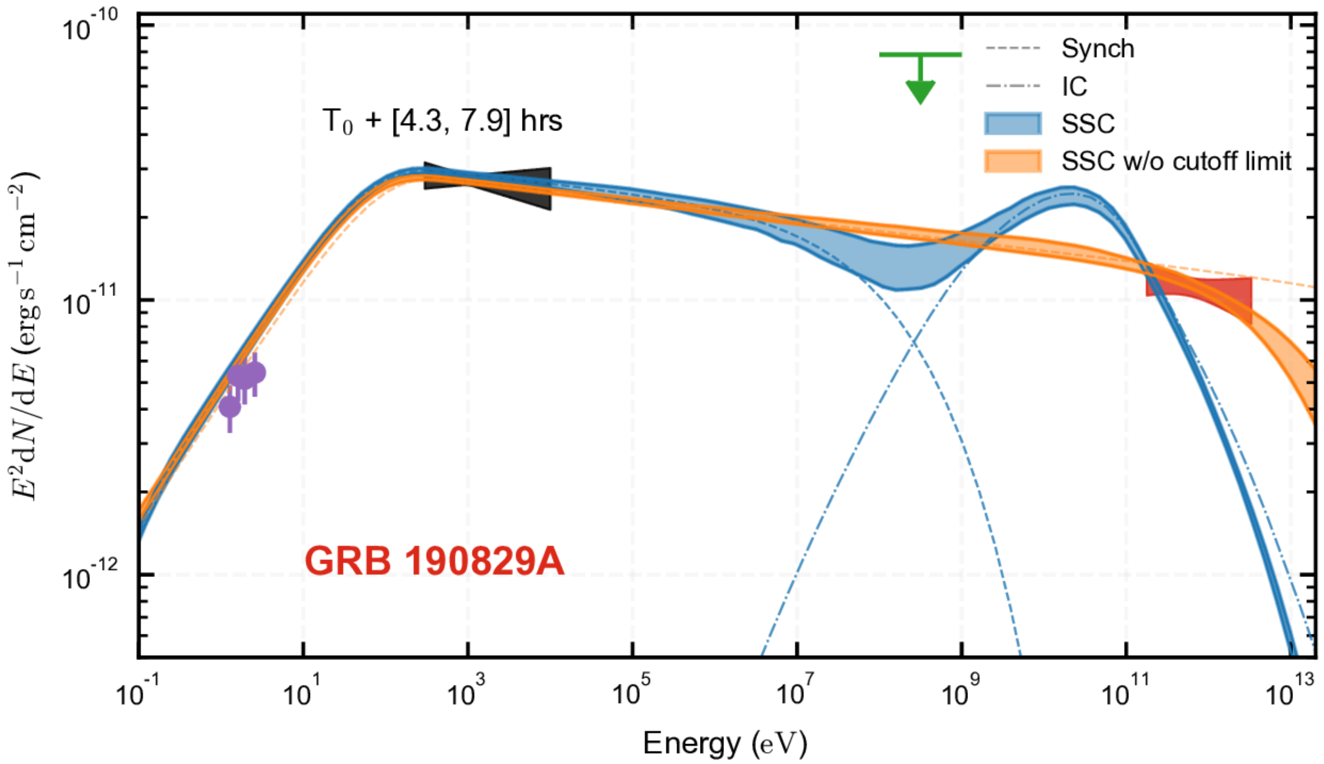
$$\mathbf{E^{iso}_{GBM} = 2 \times 10^{50}\ erg}$$

$$\mathbf{E^{iso}_{XRT} = 6 \times 10^{50}\ erg}$$

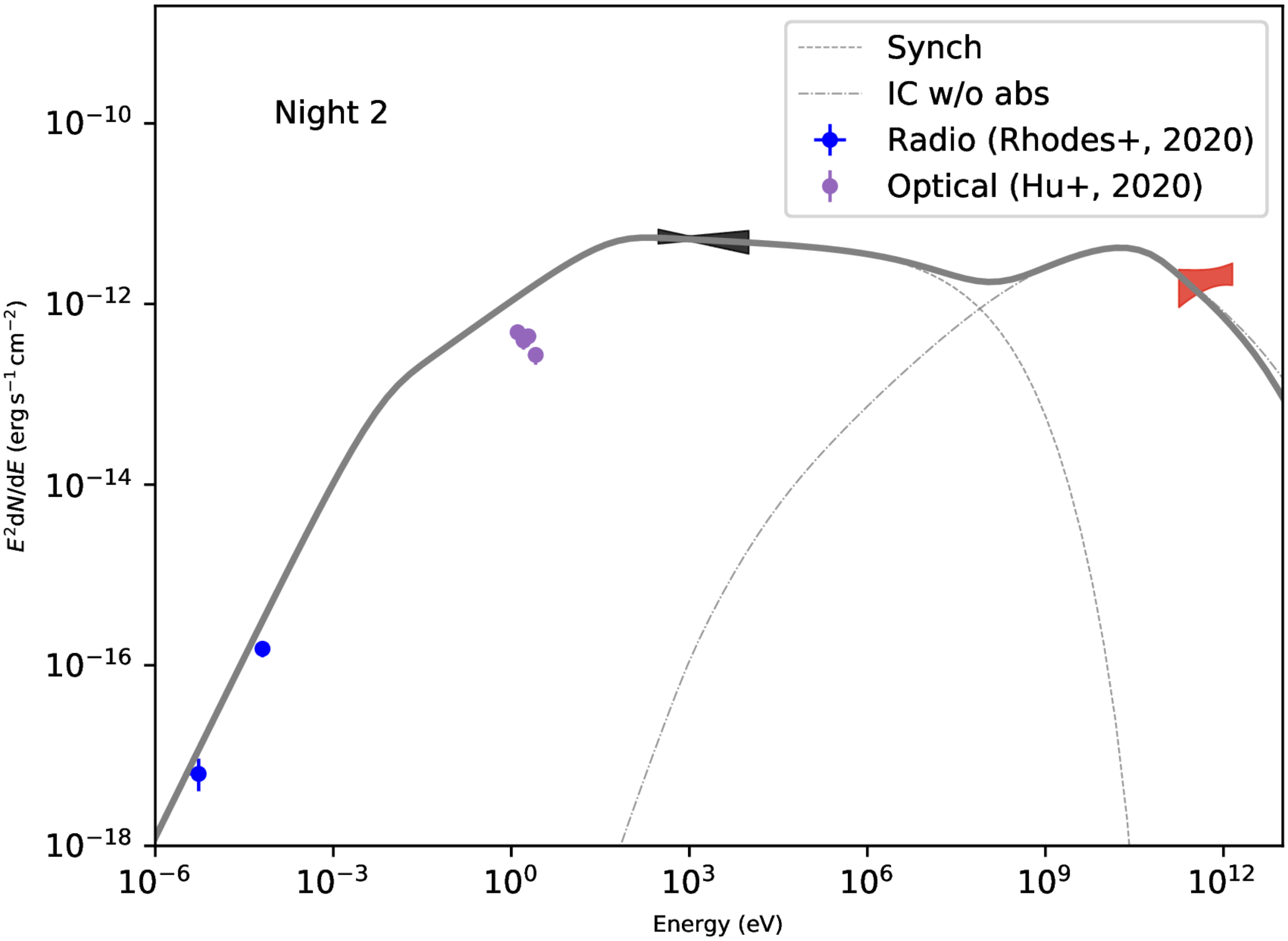


[HESS- A. Taylor, et al., Science 2021]

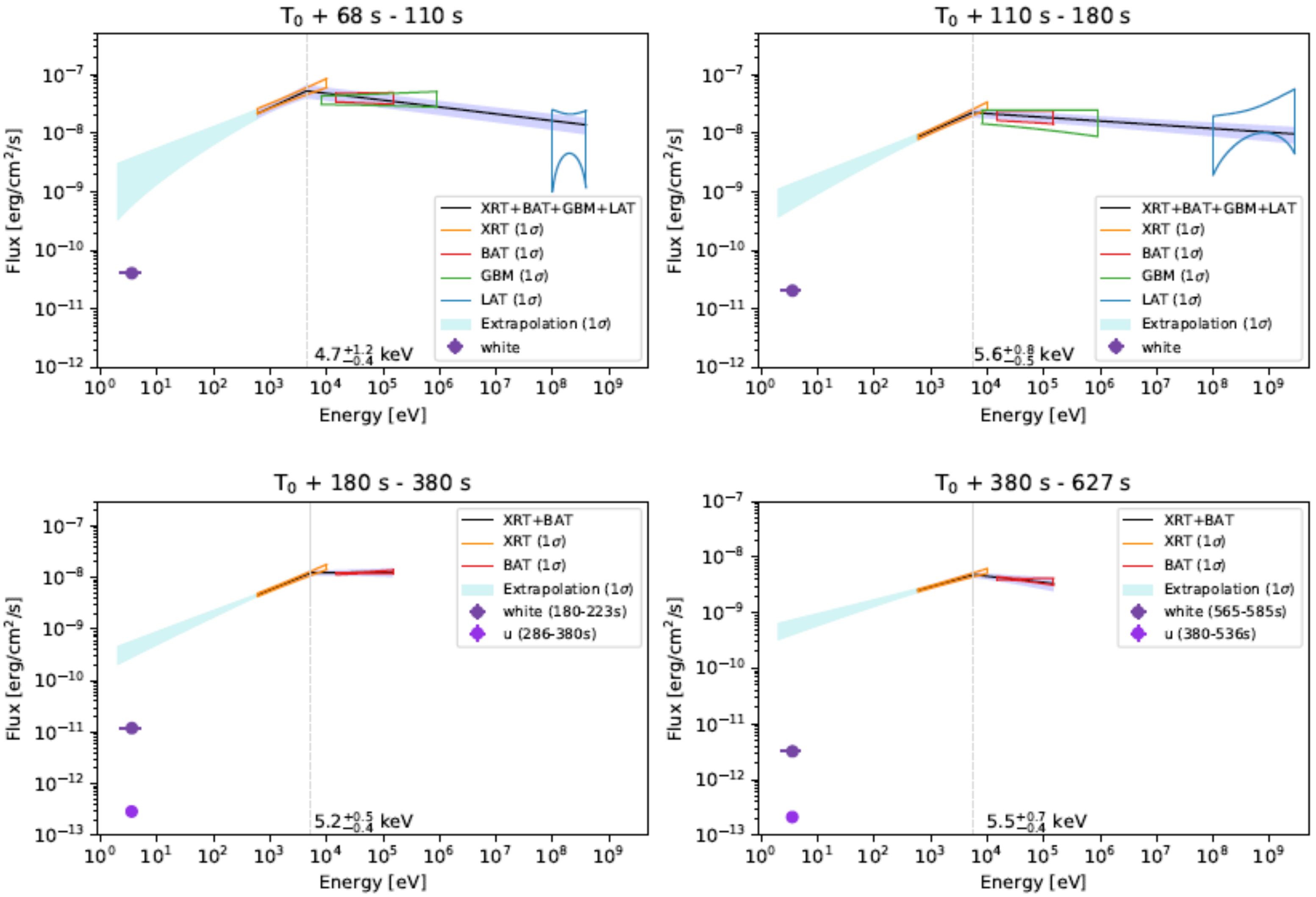
GRB 190829A- Optical Data



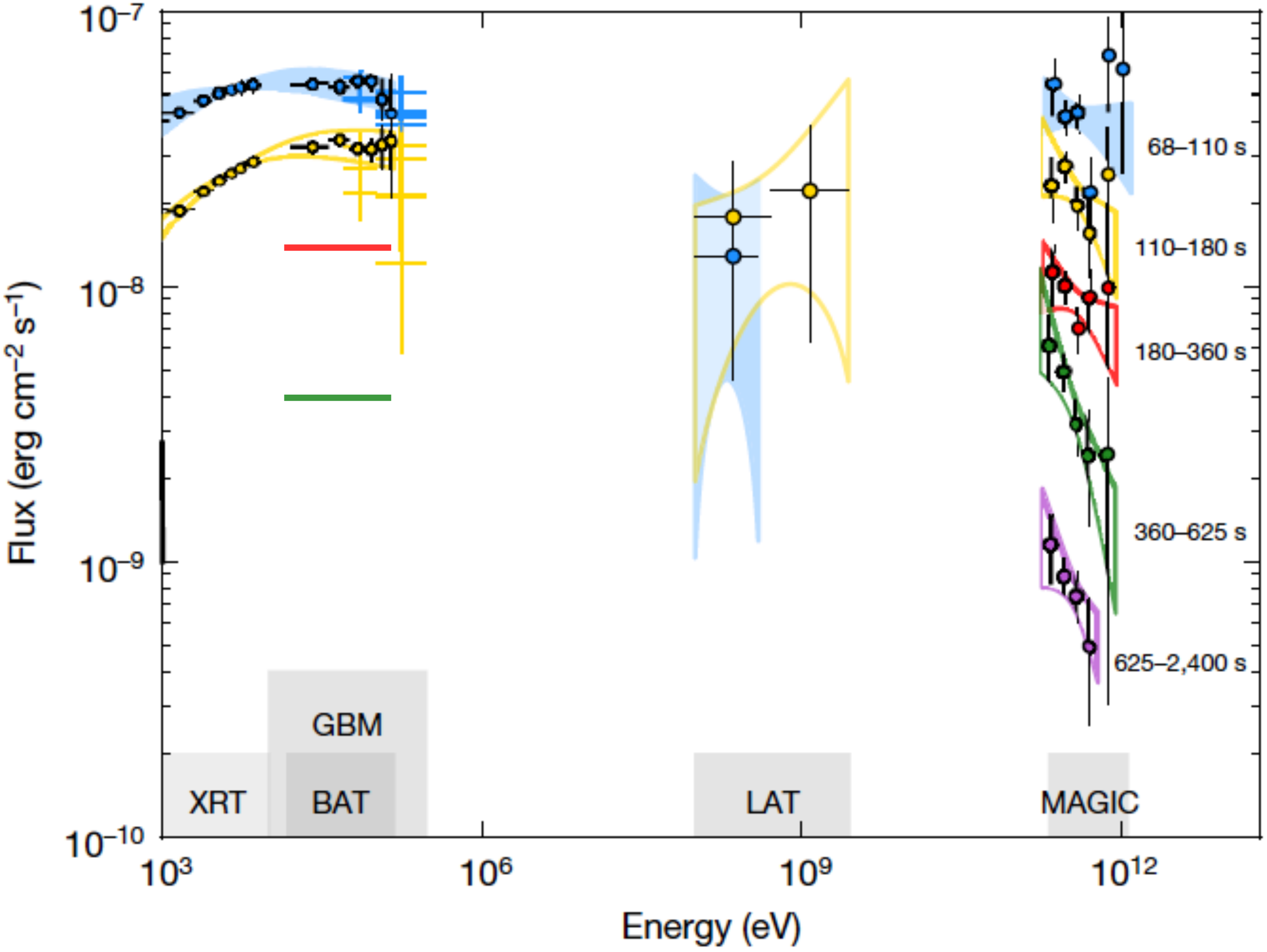
GRB 190829A- Radio Data



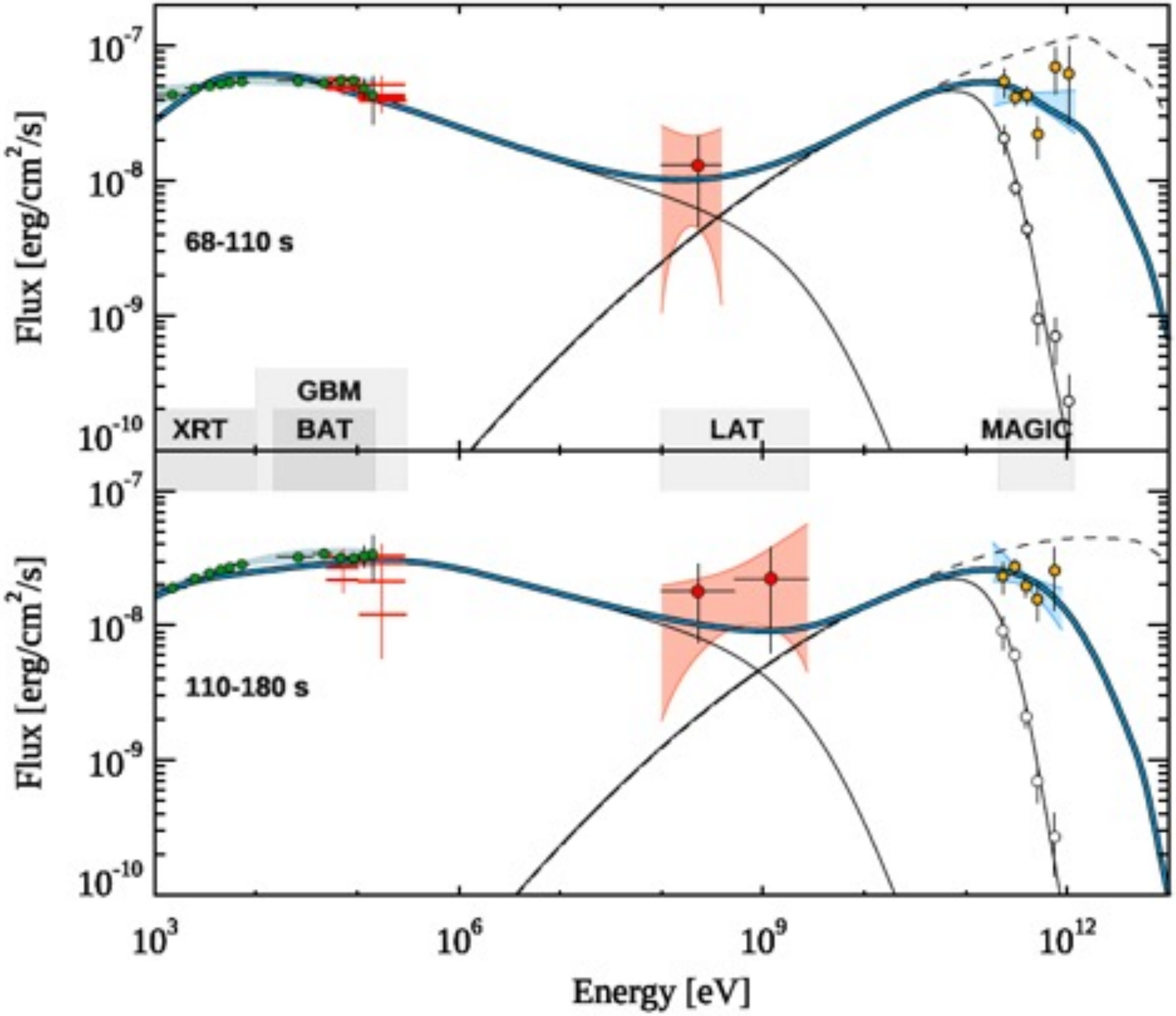
GRB 190114C


T$_0$ + 68 s - 110 s
T$_0$ + 110 s - 180 s
T$_0$ + 180 s - 380 s
T$_0$ + 380 s - 627 s
Flux [erg/cm^2/s]
Energy [eV]
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
XRT+BAT+GBM+LAT
XRT+BAT
XRT (1σ)
BAT (1σ)
GBM (1σ)
LAT (1σ)
Extrapolation (1σ)
white
white (180-223s)
u (286-380s)
white (565-585s)
u (380-536s)
$4.7^{+1.2}_{-0.4}$ keV
$5.6^{+0.8}_{-0.5}$ keV
$5.2^{+0.5}_{-0.4}$ keV
$5.5^{+0.7}_{-0.4}$ keV

GRB 190114C

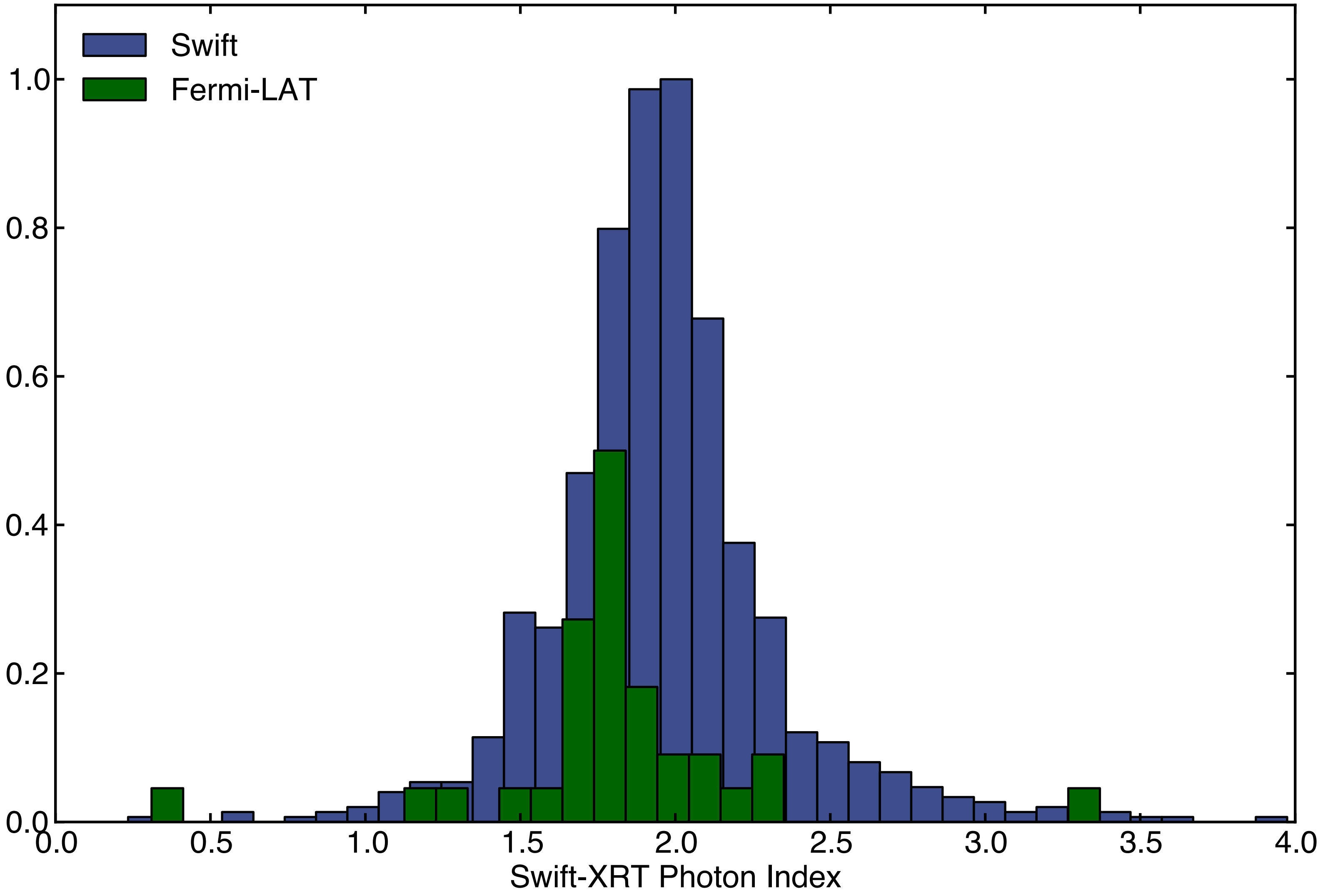

10−7
10−8
10−9
10−10
Flux (erg cm−2 s−1)
10³
10⁶
10⁹
10¹²
Energy (eV)
68–110 s
110–180 s
180–360 s
360–625 s
625–2,400 s
GBM
XRT
BAT
LAT
MAGIC

GRB 190114C



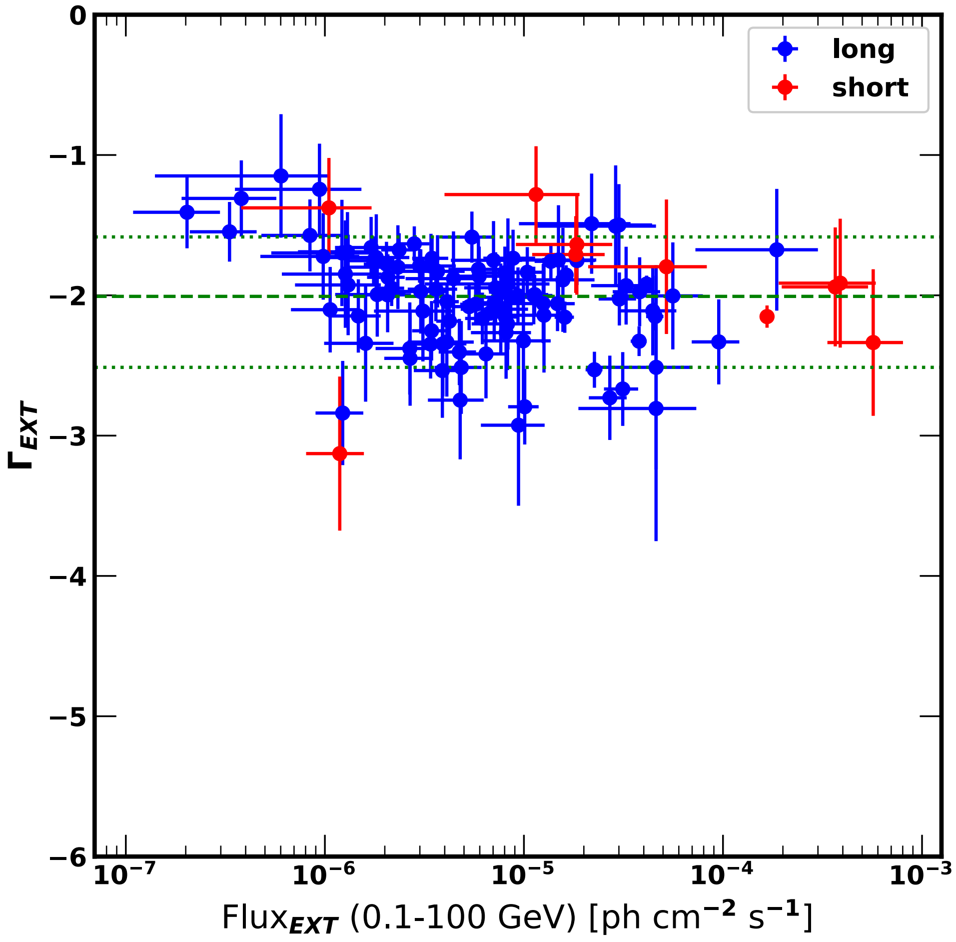
68-110 s
110-180 s
XRT
GBM
BAT
LAT
MAGIC
Flux [erg/cm²/s]
Energy [eV]
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10³
10⁶
10⁹
10¹²

Swift XRT Photon Index Distribution



[Ajello et al., Ap. J., 863 138, 2018]

Fermi-LAT Photon Index Distribution



[Ajello et al., Ap. J., 878:52, 2019]

Relativistic Shocks

Momentum Flux:

$$\mathbf{p_1} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}^\mathbf{2}\mathbf{\Gamma}_\mathbf{1}^\mathbf{2} = \mathbf{p_2} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}^\mathbf{2}\mathbf{\Gamma}_\mathbf{2}^\mathbf{2}$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}\mathbf{\Gamma}_\mathbf{1}^\mathbf{2} = \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}\mathbf{\Gamma}_\mathbf{2}^\mathbf{2}$$

Cold Relativistic Shocks

Momentum Flux:

$$\rho_1\beta_1^2\mathbf{\Gamma_1^2} = \mathbf{p_2} + \left(\frac{\gamma}{\gamma-\mathbf{1}}\mathbf{p_2} + \rho_2\right)\beta_2^2\mathbf{\Gamma_2^2}$$

$$\rho_1\beta_1^2\mathbf{\Gamma_1^2} - \rho_2\beta_2^2\mathbf{\Gamma_2^2} = \mathbf{p_2}\left[\mathbf{1} + \left(\frac{\gamma}{\gamma-\mathbf{1}}\right)\beta_2^2\mathbf{\Gamma_2^2}\right]$$

Energy Flux:

$$\rho_1\beta_1\mathbf{\Gamma_1^2} = \left(\frac{\gamma}{\gamma-\mathbf{1}}\mathbf{p_2} + \rho_2\right)\beta_2\mathbf{\Gamma_2^2}$$

$$\rho_1\beta_1\mathbf{\Gamma_1}(\mathbf{\Gamma_1} - \mathbf{1}) = \frac{\gamma}{\gamma-\mathbf{1}}\mathbf{p_2}\beta_2\mathbf{\Gamma_2^2} + \rho_2\beta_2\mathbf{\Gamma_2}(\mathbf{\Gamma_2} - \mathbf{1})$$

Relativistic Shocks

Momentum Flux:

$$\frac{\mathbf{p}_2}{\Gamma_1^2\beta_1^2\rho_1}\left[1+\Gamma_2^2\beta_2^2\left(\frac{\gamma}{\gamma-1}\right)\right]=\left(1-\frac{\Gamma_2\beta_2}{\Gamma_1\beta_1}\right)$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma-1}\right)\frac{\Gamma_2^2\mathbf{p}_2\beta_2}{\Gamma_1^2\rho_1\beta_1}=\left(1-\frac{(\Gamma_2-1)}{(\Gamma_1-1)}\right)$$

Relativistic Shocks

$$\frac{1-\frac{\Gamma_2\beta_2}{\Gamma_1\beta_1}}{1+\Gamma_2^2\beta_2^2\frac{\gamma}{\gamma-1}}=\frac{1-\frac{\Gamma_2-1}{\Gamma_1-1}}{\Gamma_2^2\beta_2\frac{\gamma}{\gamma-1}}$$

$$1+\Gamma_2^2\beta_2^2\left(\frac{\gamma}{\gamma-1}\right)=\Gamma_2^2\beta_2\left(\frac{\gamma}{\gamma-1}\right)$$

$$(\beta_2-1)(\beta_2-(\gamma-1))=0$$

Eg: $\gamma=\frac{4}{3}$ → $\frac{\beta_2}{\beta_1}=\frac{1}{3}$