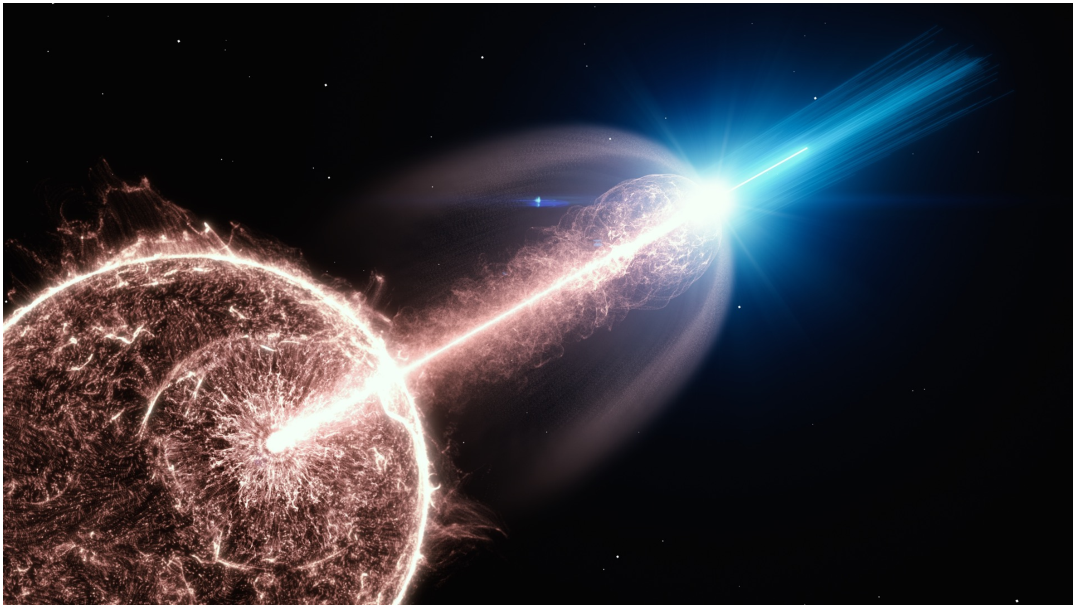
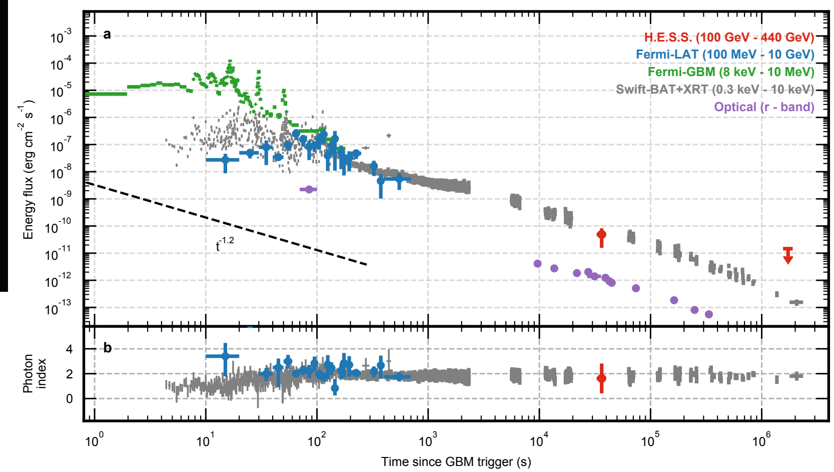
Gamma-Ray Emission from GRBs Afterglows- A Brief Overview

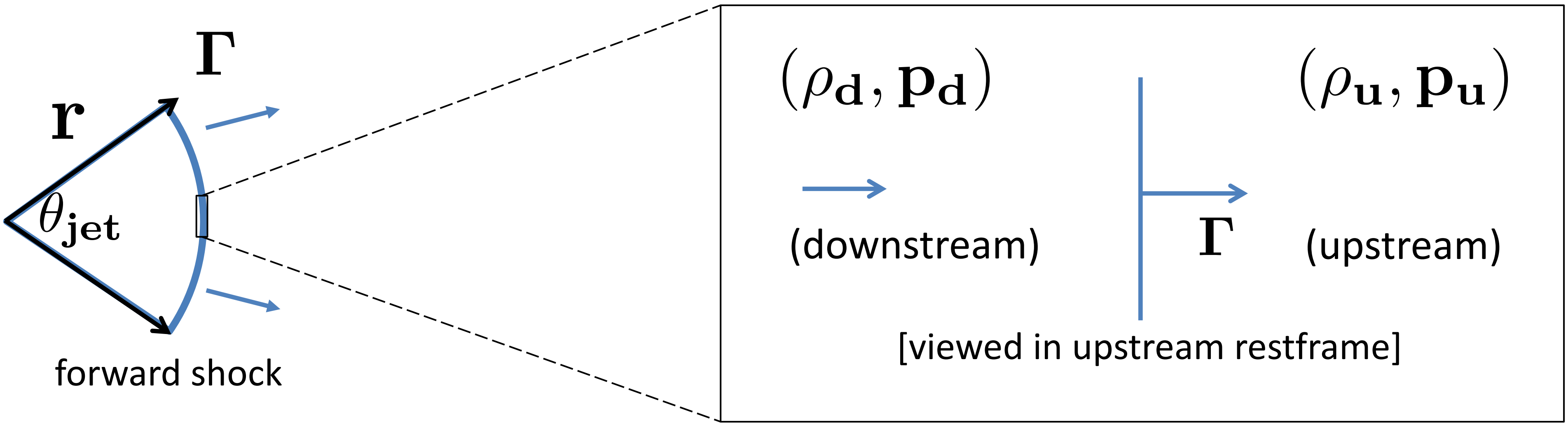




[HESS Coll. Nature 2019]

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

GRBs: Natures Machines for Converting Rel. Ram Pressure into Gamma-Rays



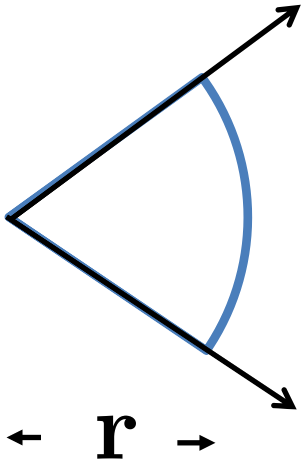
- Not actually isotropic outflows, but can be considered as "quasi-isotropic" since $\theta_{jet} > 1/\Gamma$

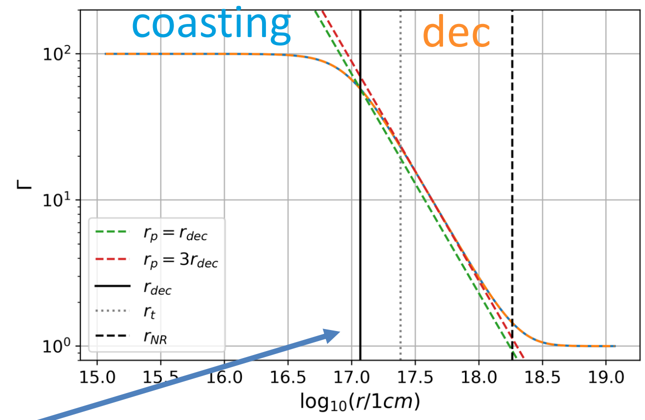
- Isotropic equivalent energy in gamma-rays, E_{iso}, up to 10^{54} erg, close to Gravitational binding energy limit

- Extremely efficient emitters in terms of converting kinetic energy flux to radiation

Temporal Compression of Signal

For a constant density medium, during the deceleration phase,



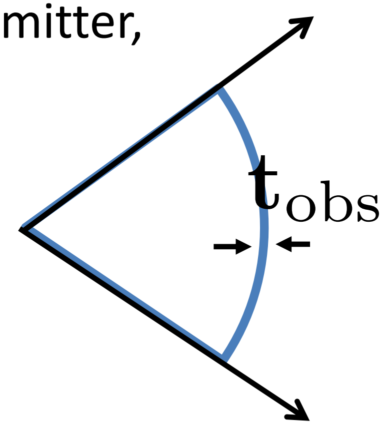


[Plot Courtesy of M. Klinger]

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

Since radiation is emitted by a relativistically moving emitter,

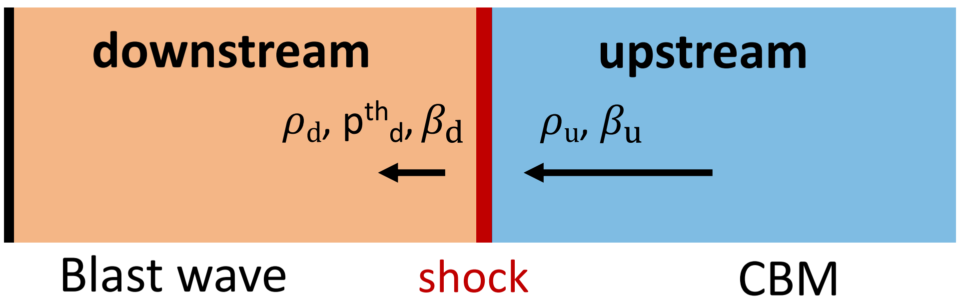
$$\mathbf{ct_{obs} = (1-\beta)r}$$



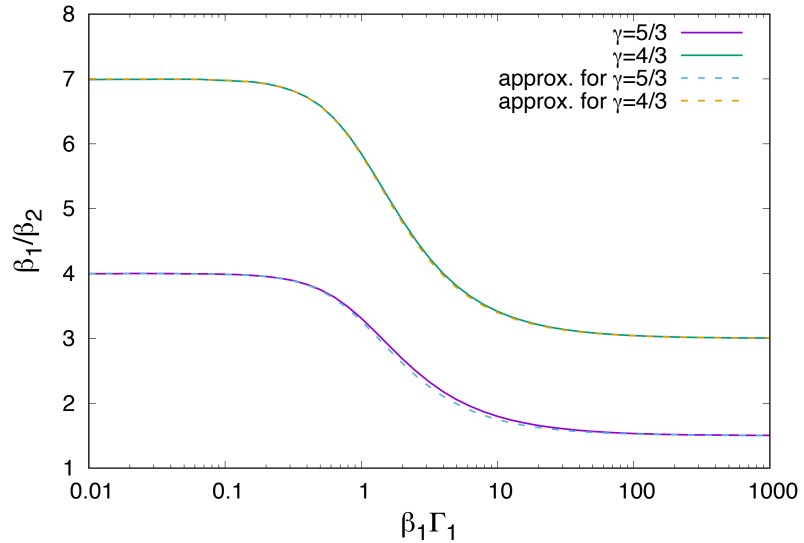
$$\mathbf{t_{dec}^{obs} \approx \frac{R}{c\Gamma^2} = 300 \left(\frac{R}{10^{17}\ cm}\right) \left(\frac{\Gamma}{100}\right)^{-2} s}$$

DESY.

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



[viewed in shock restframe]

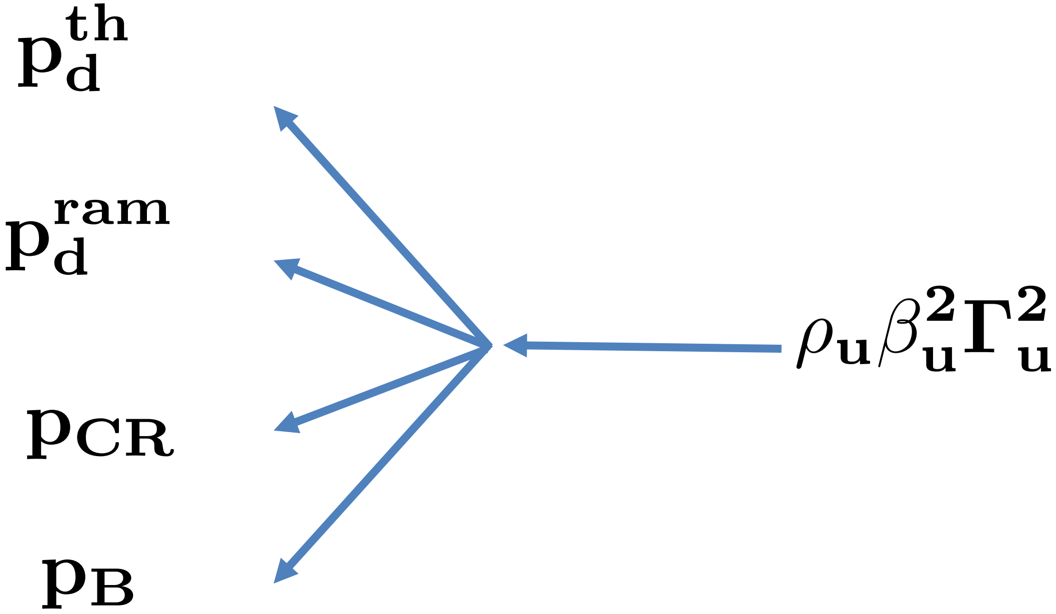


$$\mathbf{p_d^{th}} = \frac{\mathbf{2}}{\mathbf{3}} \rho_\mathbf{u} \beta_\mathbf{u}^\mathbf{2} \mathbf{\Gamma_u^2}$$

$$\mathbf{w_d} \beta_\mathbf{d}^\mathbf{2} \mathbf{\Gamma_d^2} = \frac{\mathbf{1}}{\mathbf{3}} \rho_\mathbf{u} \beta_\mathbf{u}^\mathbf{2} \mathbf{\Gamma_u^2}$$

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

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



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

1. ε- key parameters which we don't apriori know, but which we may probe with observations

Relativistic MHD Shocks

Downstream magnetic field partition of upstream ram pressure:

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

For

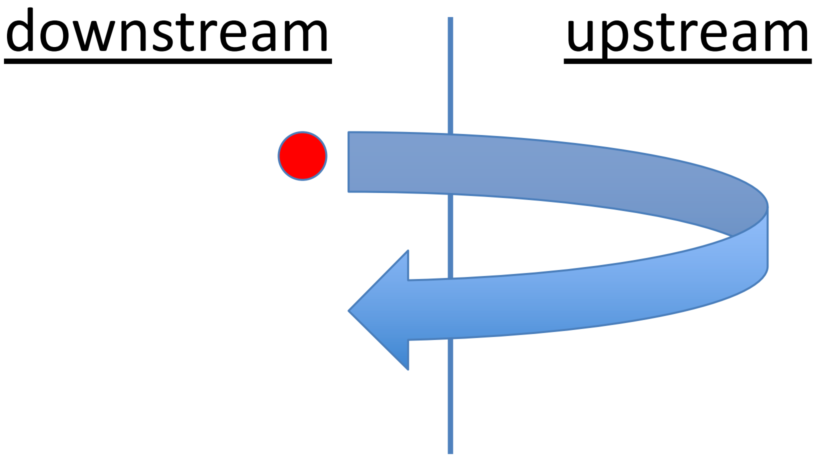
$$\varepsilon_{\mathbf{B}} = \mathbf{0.1} \qquad \mathbf{n_u = 1\ cm^{-3}} \qquad \beta_{\mathbf{u}}\Gamma_{\mathbf{u}} = \mathbf{10}$$

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

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

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

Particle Acceleration and Magnetic Turbulence



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

- 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

2. η- key parameter which again we don’t apriori know, but which we may probe with observations

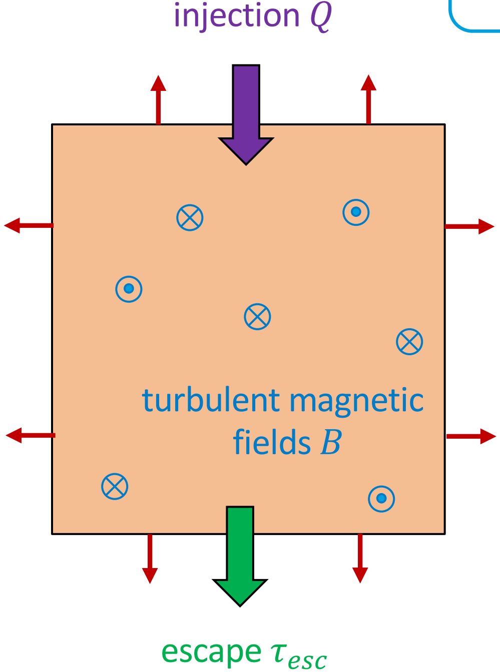
One Zone Model (Spectral)

electron number

electrons drive expansion of box

shock injects relativistic particles

$$\partial_t N_{E,el} = \partial_E \left[\left(\frac{E}{\tau_{syn}(E,t)} + \frac{E}{\tau_{iC}(E,t)} + \frac{E}{\tau_{adi}(t)} \right) N_{E,el} \right] + Q_{inj}(E,t) - \frac{N_{E,el}}{\tau_{pp}(E,t)} + Q_{pa}(E,t)$$



synchrotron

inverse Compton scattering

$e^- e^+ \rightarrow \gamma\gamma$

$\gamma\gamma \rightarrow e^- e^+$

photon number

$$\partial_t N_{E,\gamma} = -\frac{N_{E,\gamma}}{\tau_{esc}(t)} + Q_{syn}(E,t) + Q_{iC}(E,t) + Q_{pp}(E,t) - \frac{N_{E,\gamma}}{\tau_{pa}(E,t)}$$

photons can escape from box

[Diagram + plot Courtesy of M. Klinger]

Note the absence of spatial information in these transport equations

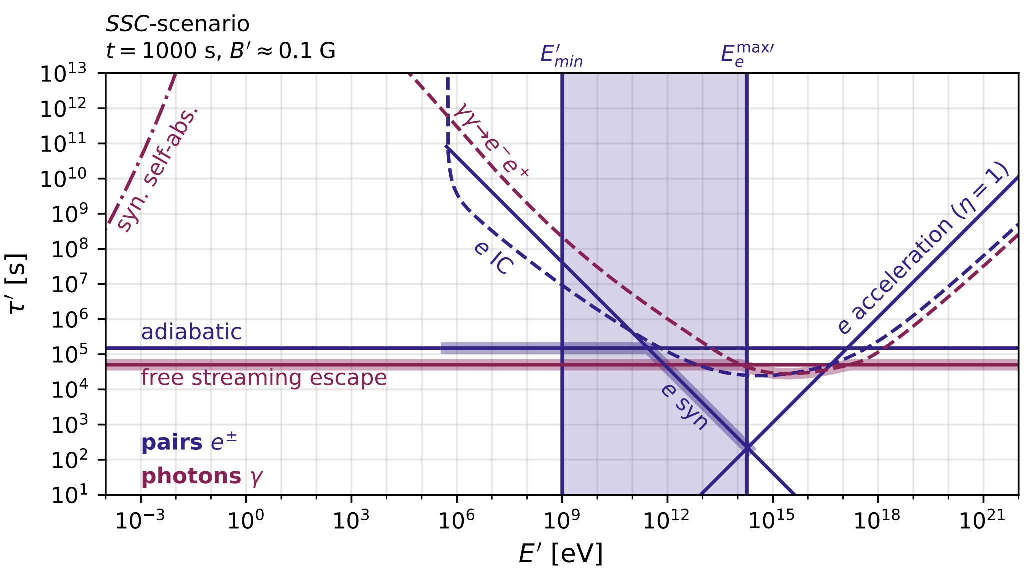
Electron Spectrum Produced in Sources

Steady state

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

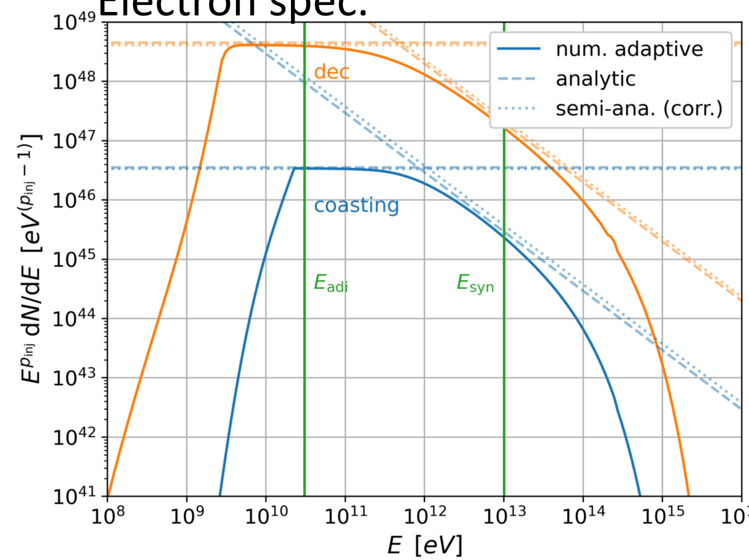
$$\tau_{\mathbf{loss}} = \left(\tau_{\mathbf{adi}}^{-1} + \tau_{\mathbf{sync}}^{-1} + \tau_{\mathbf{IC}}^{-1} \right)^{-1}$$

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



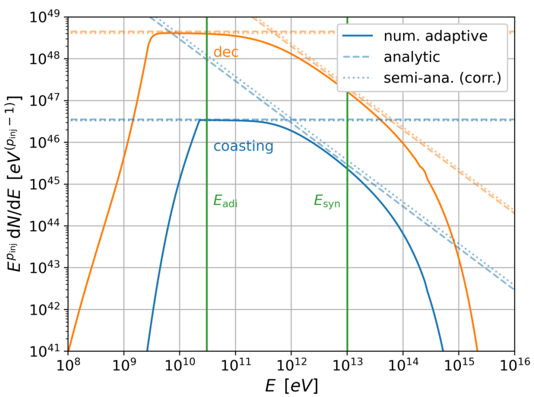
Andrew Taylor

Electron spec.



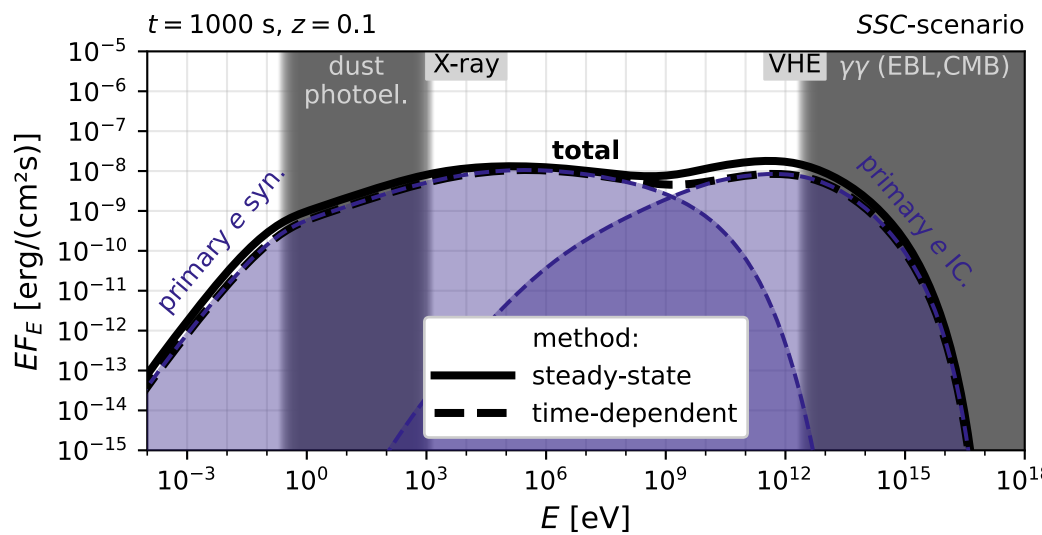
Afterglow GRB SED- Expected from SSC Model

Electron spec.



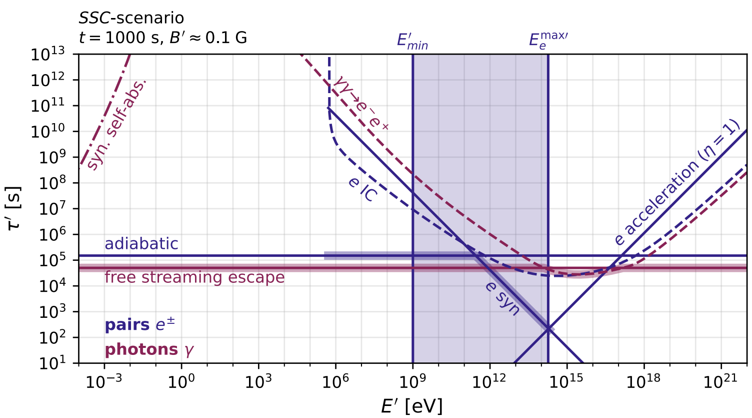
$$\mathbf{n_p \approx Q\tau_{loss}}$$

Photon spec. $\mathbf{U_B}$ $\mathbf{U_\gamma^{sync}}$

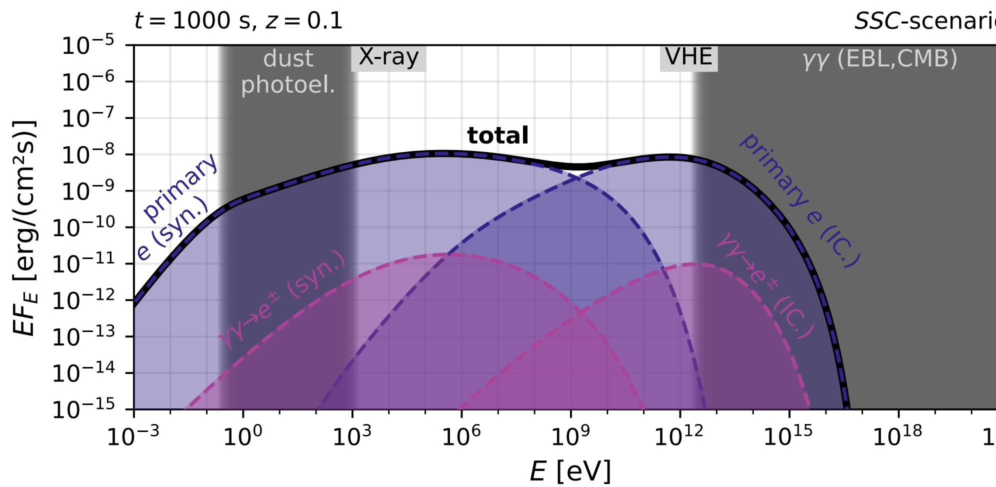


The "steady-state" approximation provides a reasonable description for the spectrum → ie. ~agrees with the full time-dependent result

Afterglow GRB SED- Expected from SSC Model



Photon spec.



Γ	50
n	1
ε_B	10^{-4}
ε_e	$10^{-1.5}$
ε_p	0
E'_{min}	$10^{9.0}$
η	1
p	2.3

Note- to get IC peak to sit at a comparable level to the synchrotron peak requires a "triple point" in the cooling time plot to exist [Klinger et al. MNRAS 520 (2023)]

Note curvature of SSC spectrum in the VHE band

Where is the signature of ε^{th}? results above/in most others works, set the thermal particles components to 0, is this realistic?

Is η=1 realistic?

Electron Acceleration with Cooling

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

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

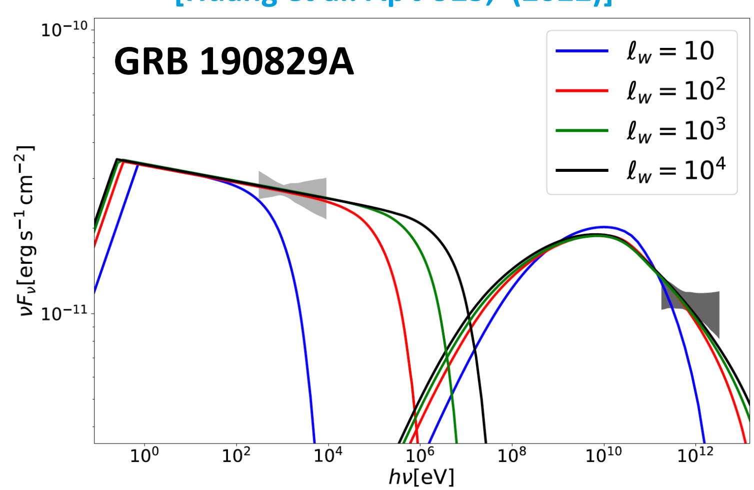
$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

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

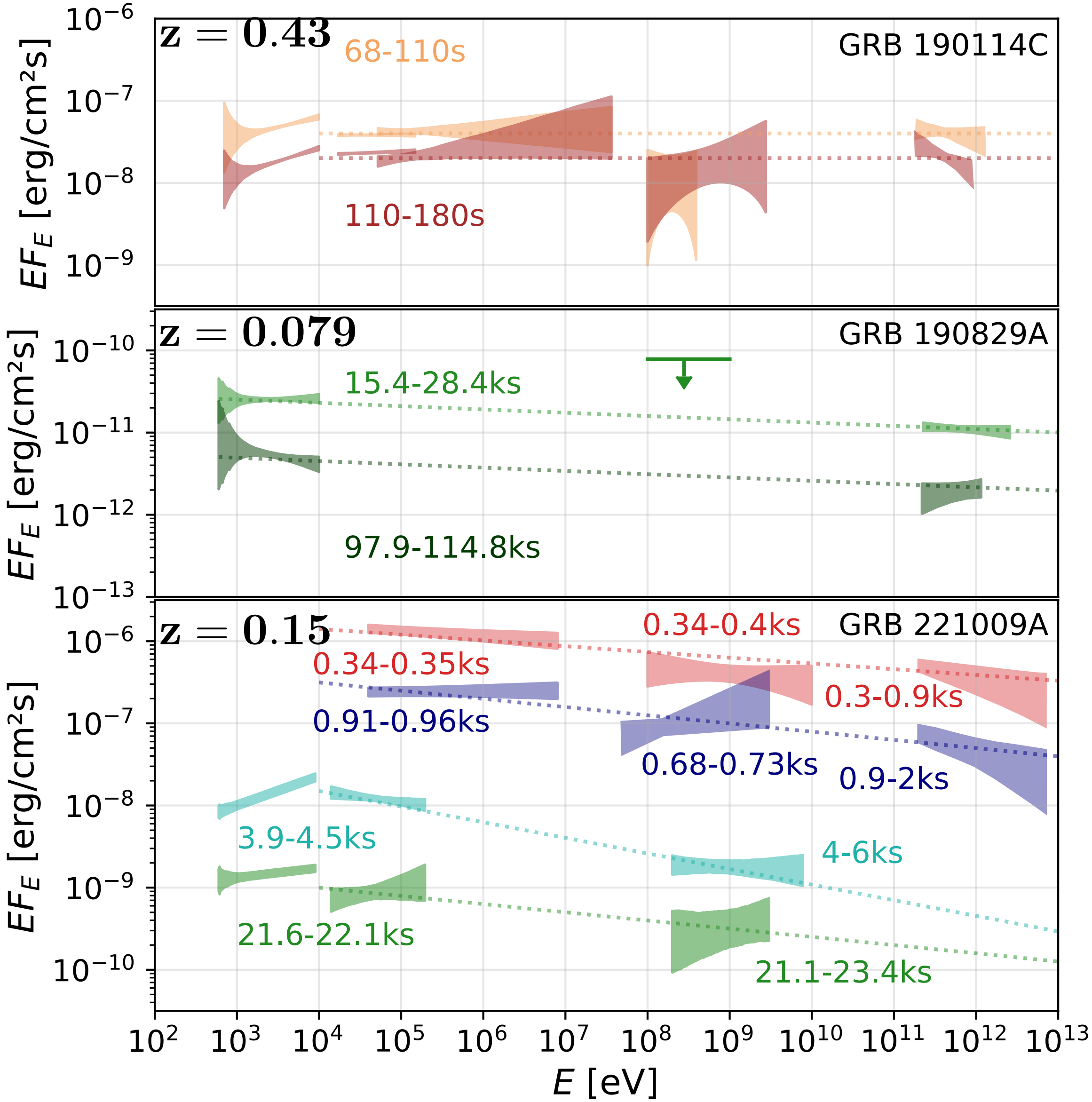
Maximum synchrotron energy tells us how efficient accelerator is!

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

[Huang et al. Ap J 925, (2022)]



VHE GRB SED- Lessons Learnt Since 2018



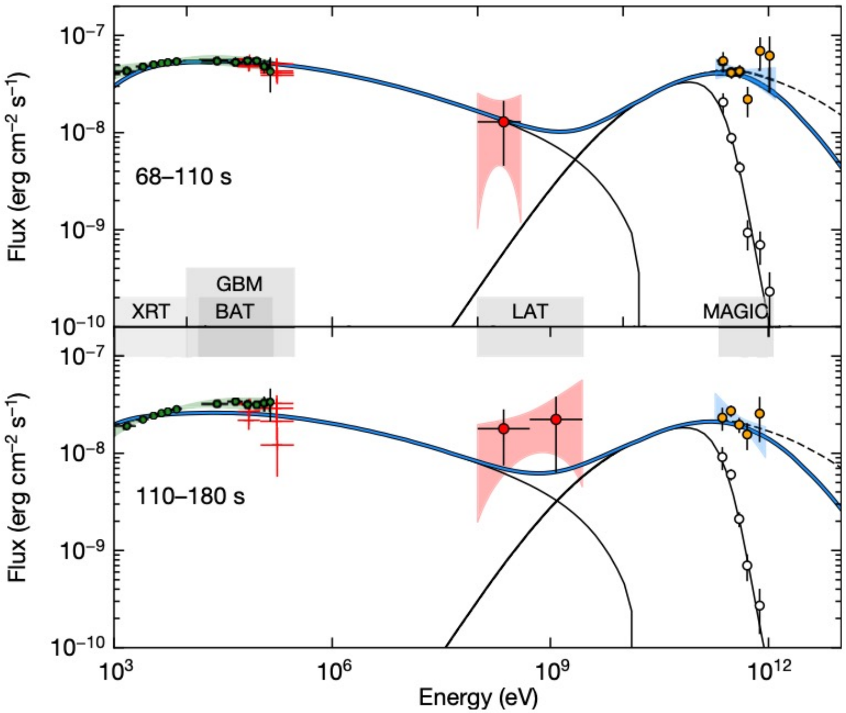
- Striking how flat the MWL photon spectra are!
- The SSC model predicts a curved spectrum which may be contradiction with these observations

[MAGIC Coll. Nature 2019]
[HESS Coll. Science 2021]
[LHAASO Coll., Science 2023]

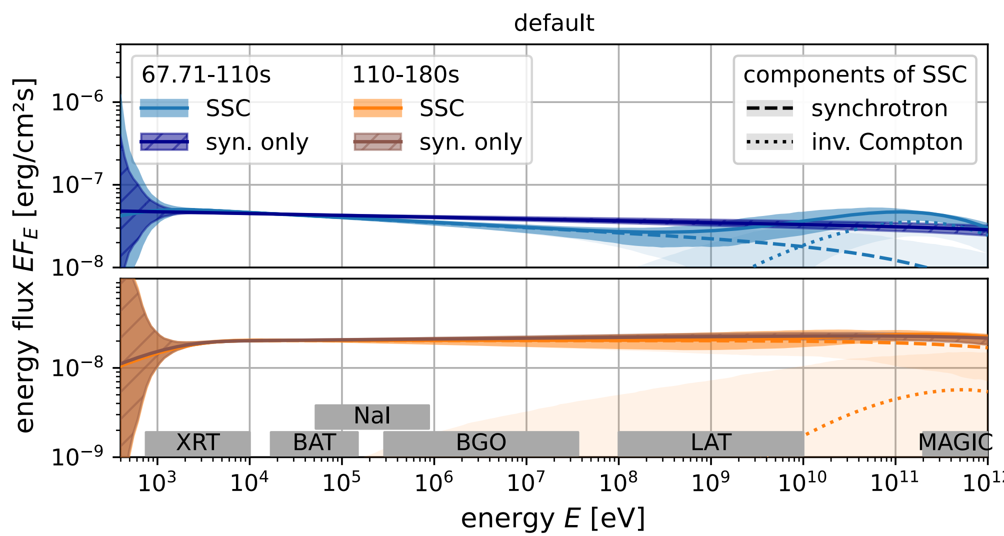
[Klinger et al. arxiv:2403.13902]

Statistical Tests- A Spectral Model Fit for GRB 190114C

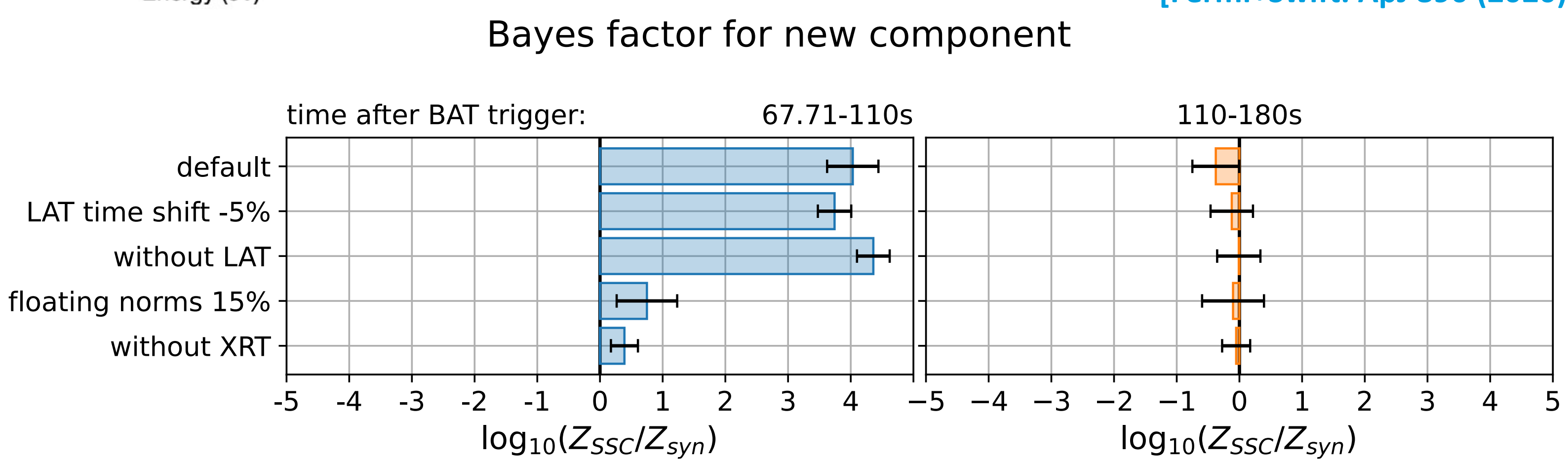
[MAGIC Coll. Nature 2019]



[Klinger et al. MNRAS 520 (2023)]

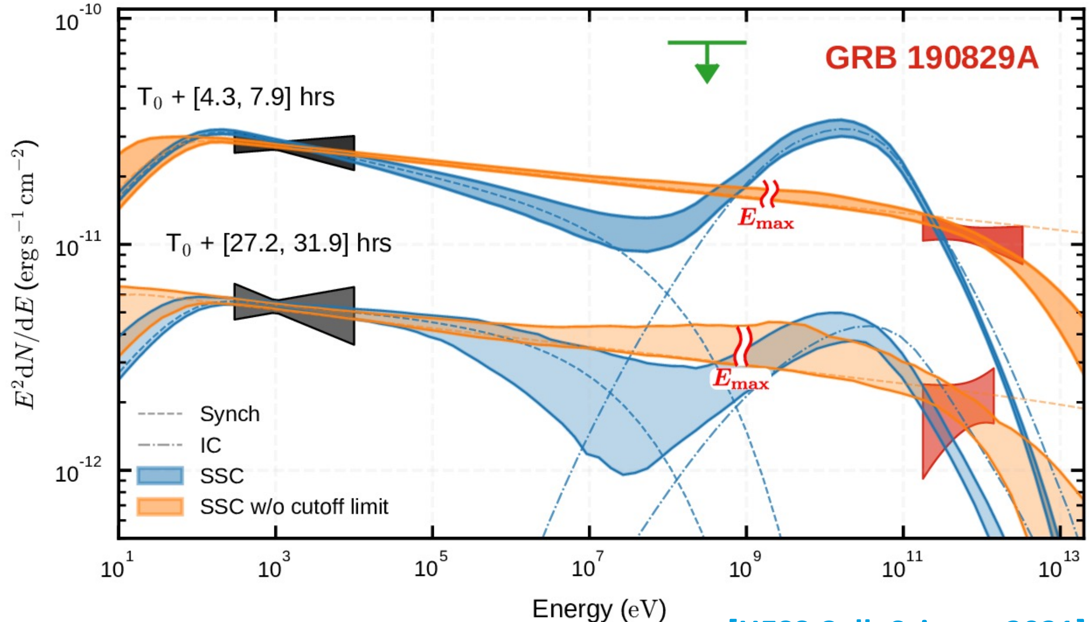


[Fermi+Swift. ApJ 890 (2020)]



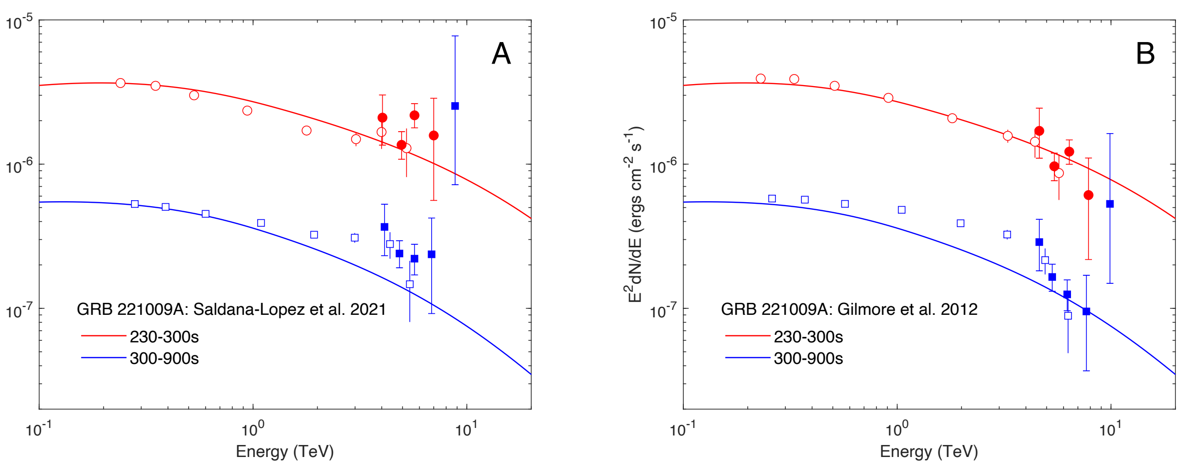
DESY.

Statistical Tests- Spectral Model Fits other GRB



[HESS Coll. Science 2021]

GRB 190829A
[15-28 ks]

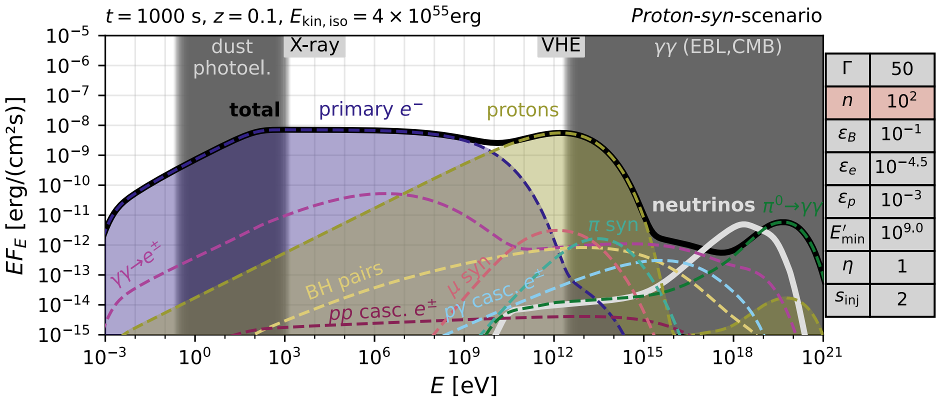


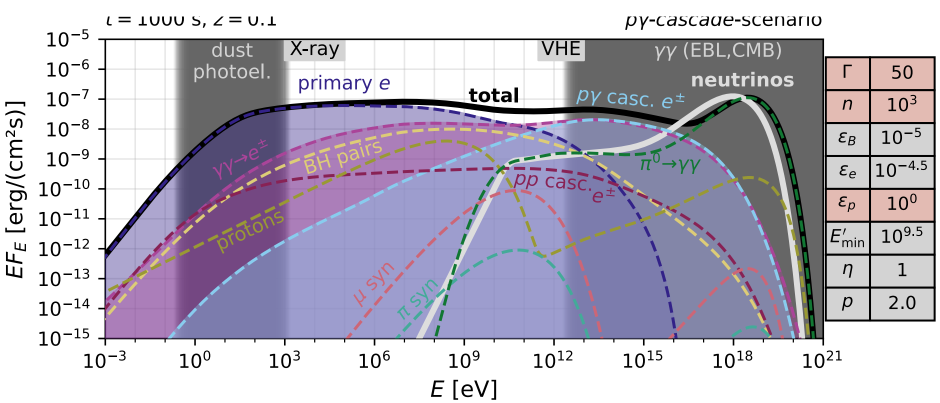
[LHAASO Coll. Science 2023]

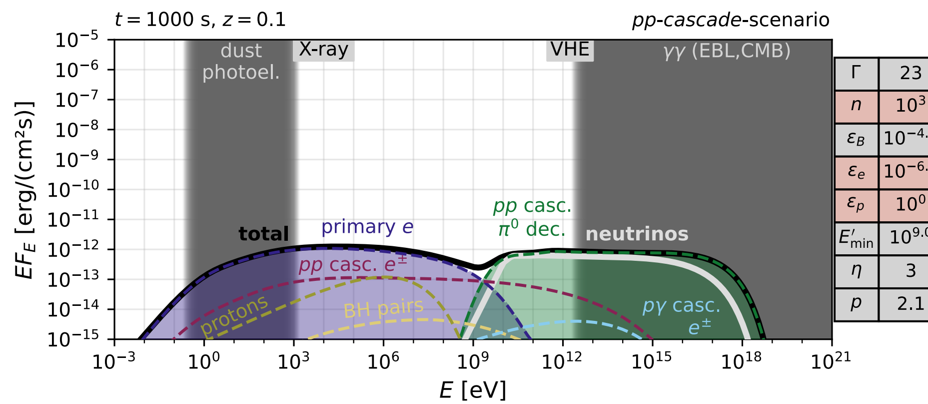
GRB 221009A
[0.2-0.9 ks]

DESY.

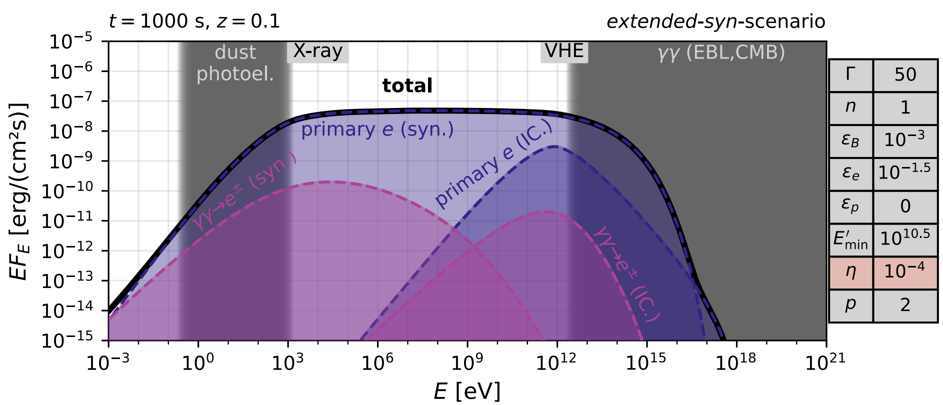
Alternative 1-Zone Scenarios?







Before raising the number of degrees of freedom, other parts of parameter space should first be explored



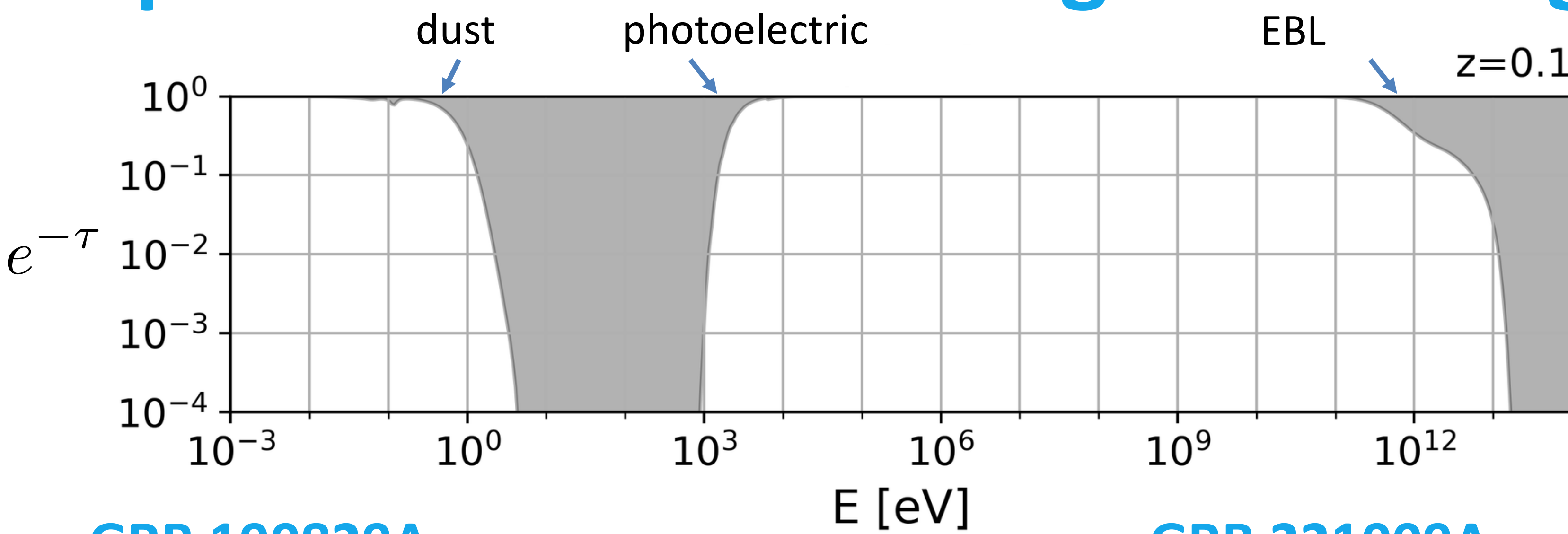
Each scenario requires rather extreme parameter values (see highlighted box)

[Klinger et al., arxiv:2403.13902

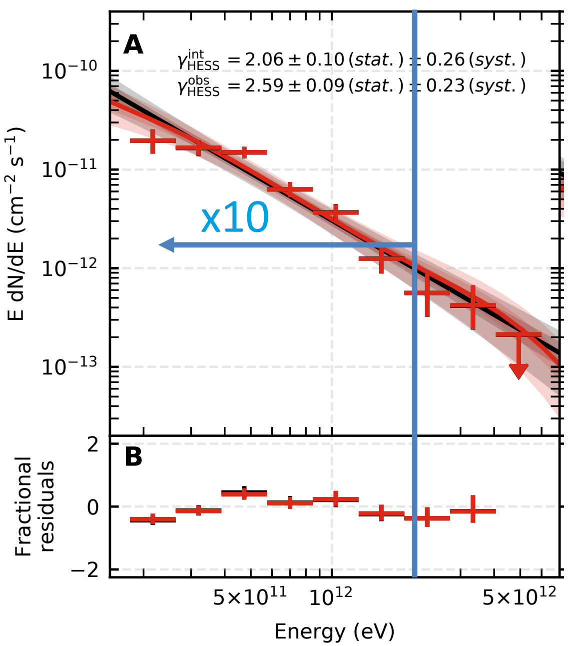
[Khangulyan et al., Ap. J. 914 (2021)]

[Isravel et al., Ap. J 955 (2023)]

Importance of Minimising EBL Damage

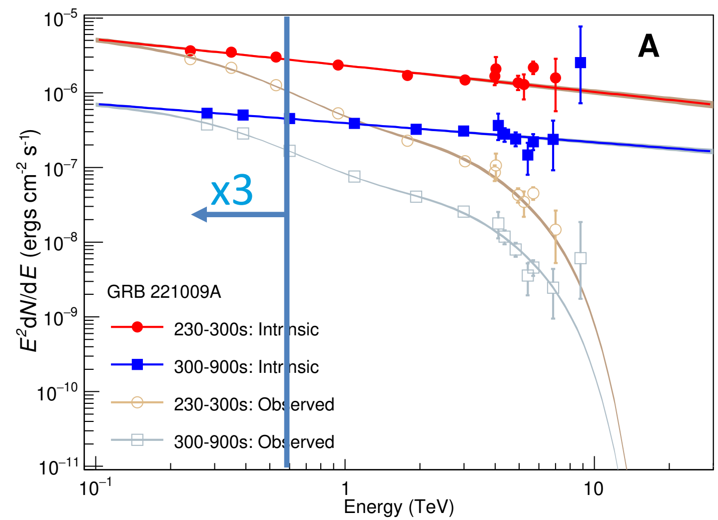


GRB 190829A



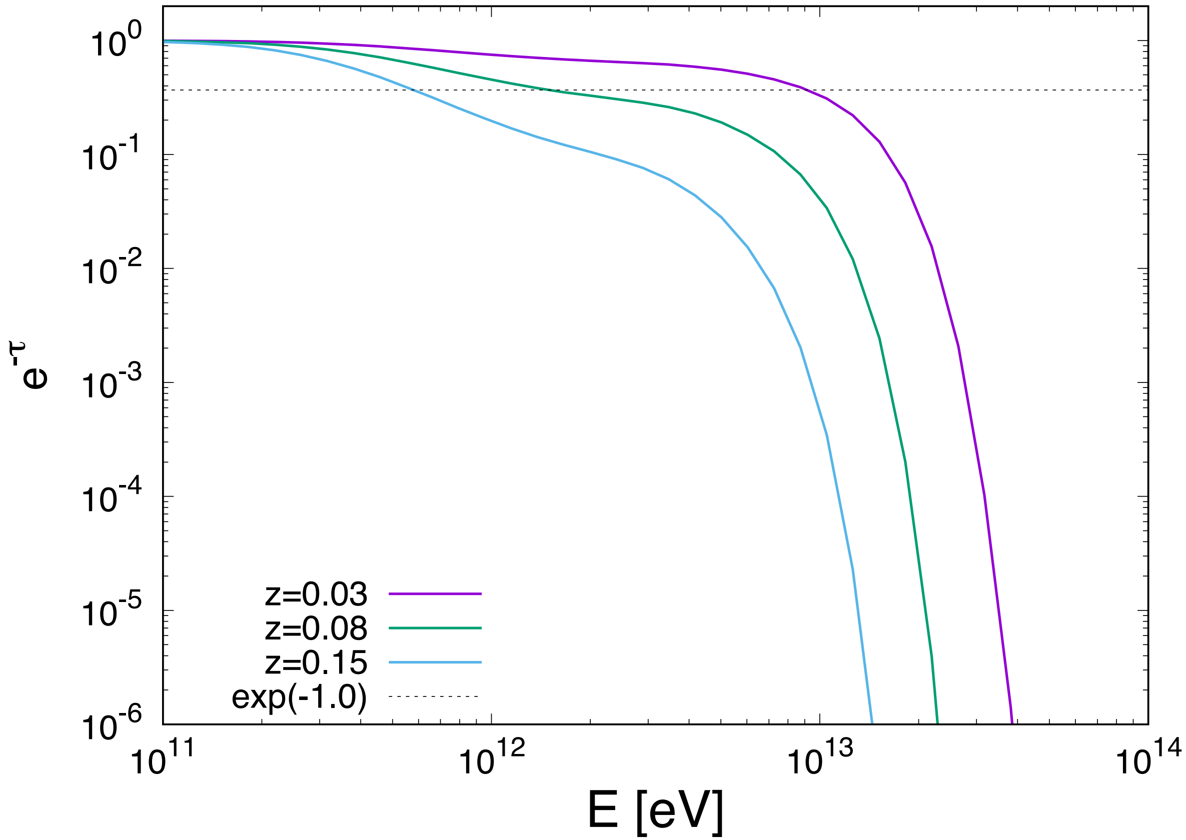
[HESS Coll. Science 2021]

GRB 221009A



[LHAASO Coll. Science 2023]

Key Phase Space for VHE GRB Detections?



Three key factors for GRB detection are apparent:

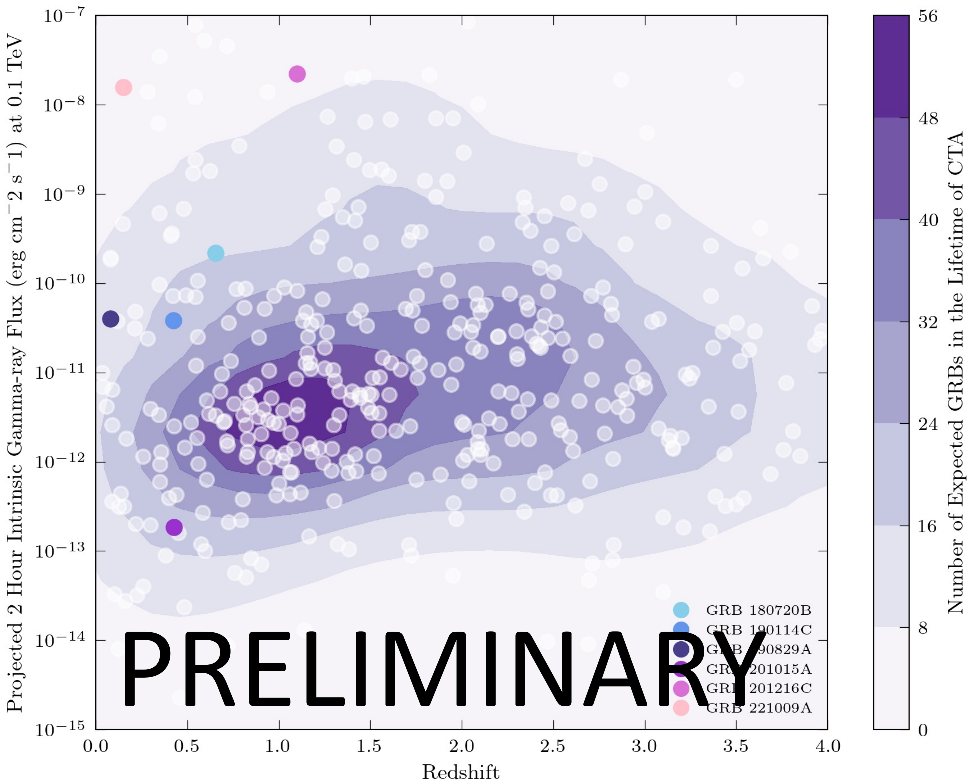
- Locality is crucial (EBL damage minimised)
- Brightness is crucial (allows detection at late times once Lorentz factor has decreased significantly)
- Simultaneous MWL coverage (in keV to multi-TeV energy range) is crucial

Within Swift's lifetime (~20 years so far), the most local GRB was z=0.03

DESY.

Spectra up to 10 TeV, with small EBL effects, may potentially be probeable

Prospective Rates for Testing the GRB Emission Process with CTA



[Provided by J. Pfeil and D. Parsons]

- Future GRBs for providing a stronger probe of the spectral emission model must be local and have bright afterglows

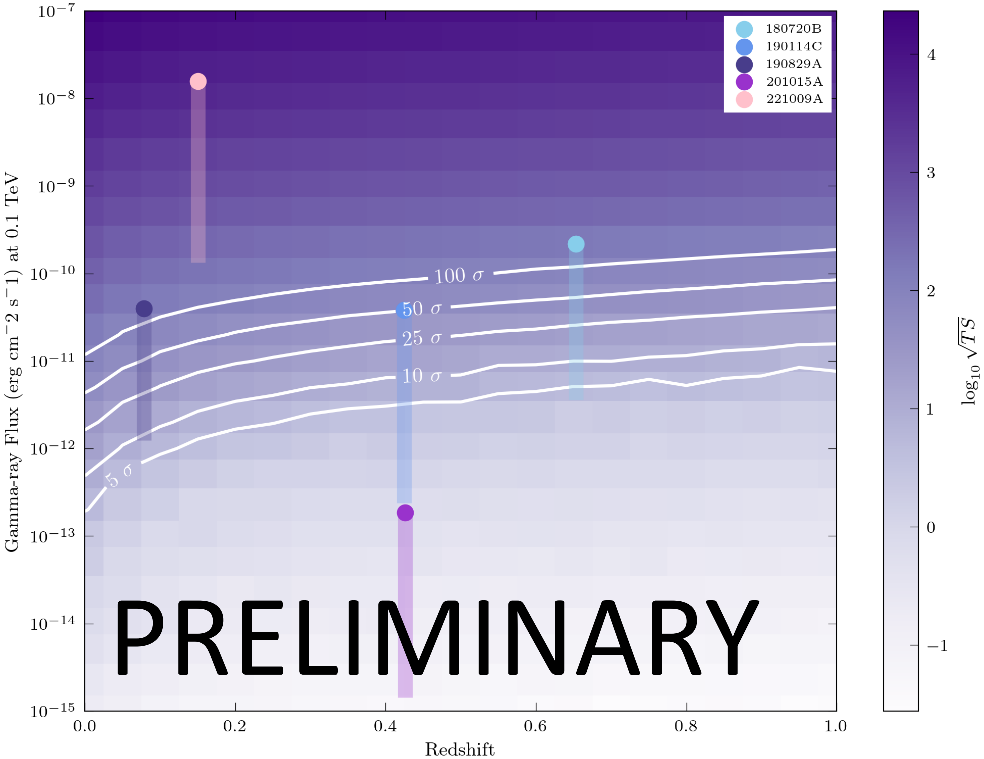
- For CTA, a rate of up to 4 yr $^{-1}$ is possible to expect, consistent with other estimates
  [Ashkar et al., ApJ 964 57]

- However, of these events, the local subset of particular interest will be rare (< 0.25 yr $^{-1}$)

DESY.

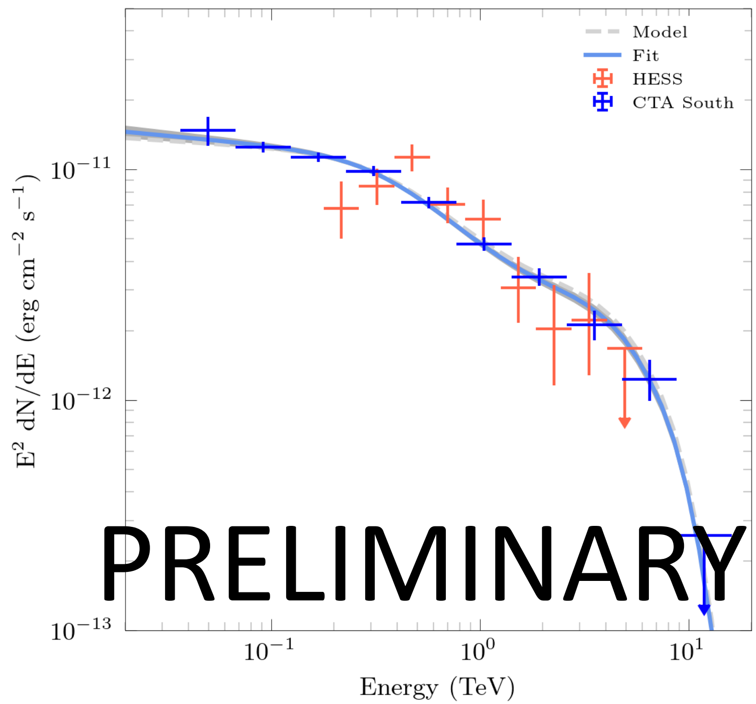
A GRB 190829A Like Event for CTA

Obs. assumed to start at T0 + 2hrs for 5 hrs



[Provided by J. Pfeil and D. Parsons]

Night 1/
3.6h obs. time
= HESS observation time



	EBL Attenuated Power Law	
Fit Parameter	HESS	CTA South
γ^{int}	$2.06 \pm 0.10 \pm 0.26$	2.09 ± 0.02

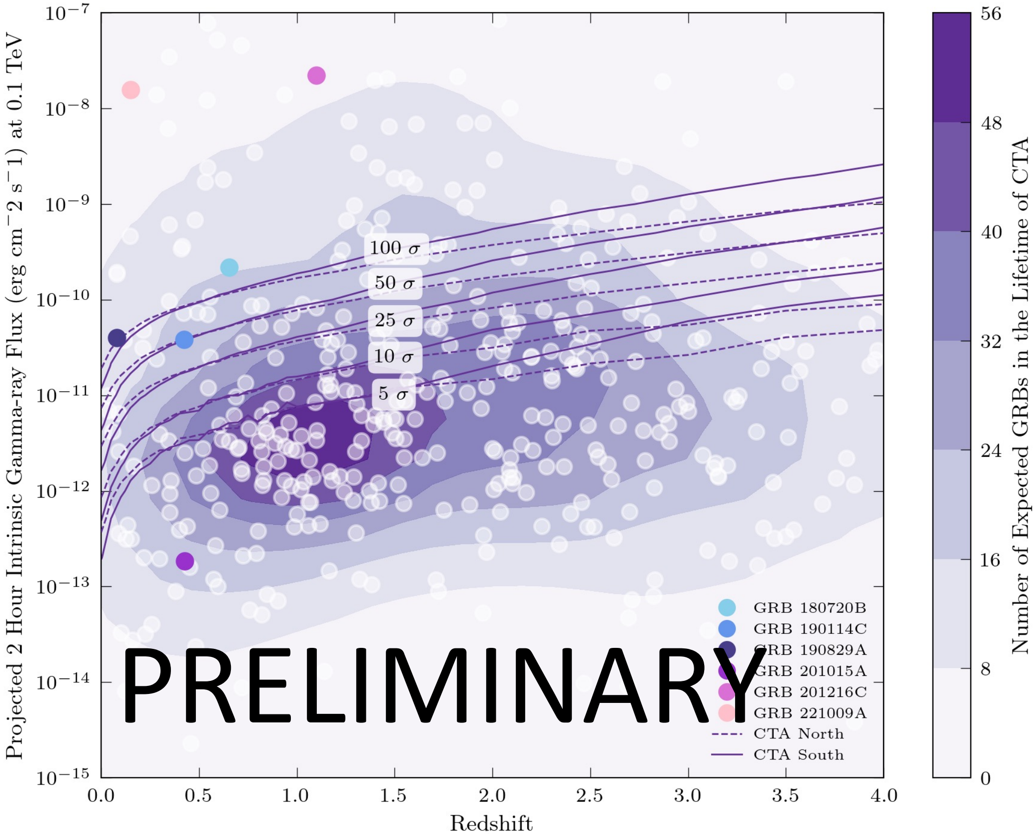
DESY.

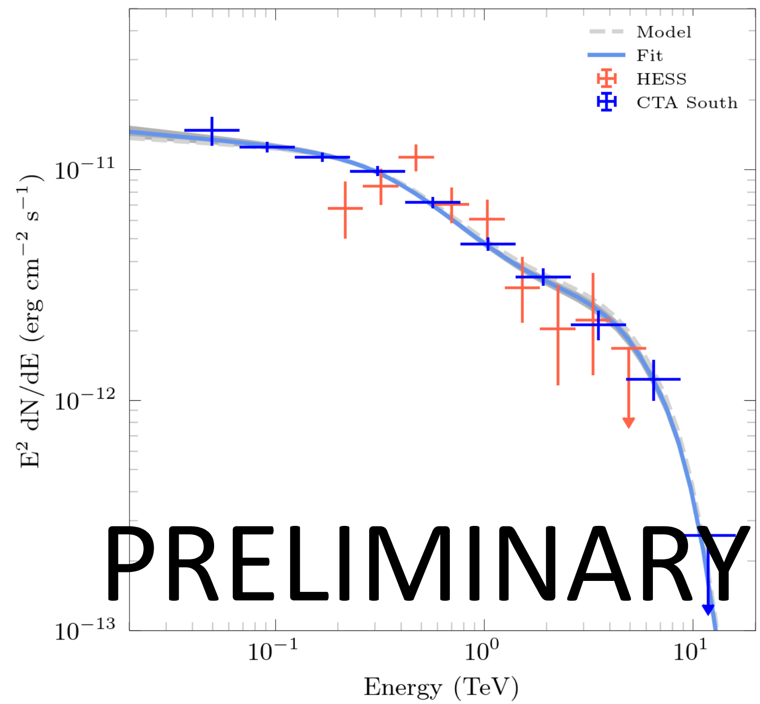
Conclusions

- Fast (rel.) shocks in the ejecta of GRB jets appear to operate as particle acceleration machines
- Synchrotron emission from long GRB can tell us directly how efficient these sources operate as cosmic ray accelerators
- We are now (since 2018) starting to probe the very high energy (TeV) gamma-ray emission from GRB, providing new insights into the source environment
- Whether a new component in the GRB spectrum is present remains unclear- curiously, the VHE GRB detections appear compatible with a continuation of the synchrotron emission beyond the expected supposed theoretical limit
- For CTA to answer this emission process question, the catching of extremely local GRB events will play a crucial role

Prospects for Testing the GRB Emission Process with CTA

Night 1/
3.6h obs. time
= HESS observation time





[Provided by J. Pfeil and D. Parsons]

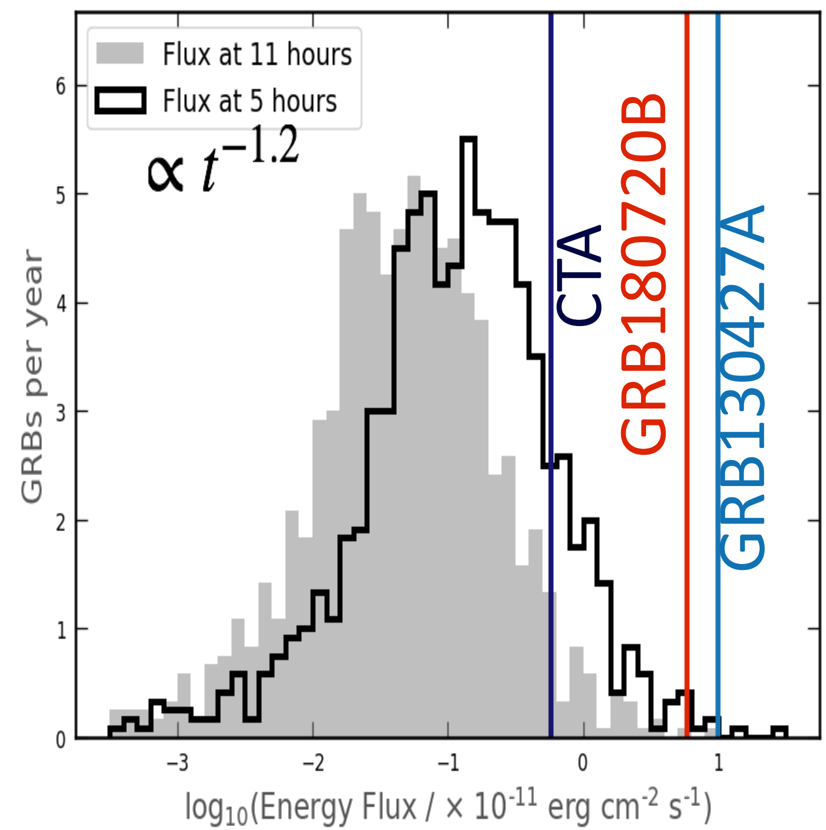
EBL Attenuated Power Law		
Fit Parameter	HESS	CTA South
γ^{int}	$2.06 \pm 0.10 \pm 0.26$	2.09 ± 0.02

DESY.

Prospects for Future Observatories

- CTA to have ~10 times better sensitivity than present ACTs
- Will be able to detect flux over many decades in time with detailed spectra information.
- Boost the detection of GRBs at VHE.
  - ~ 3 GRBs per year at 11 hours after burst.
  - ~ 11 GRBs per year at 5 hours after burst

Swift-XRT GRBs energy flux distribution



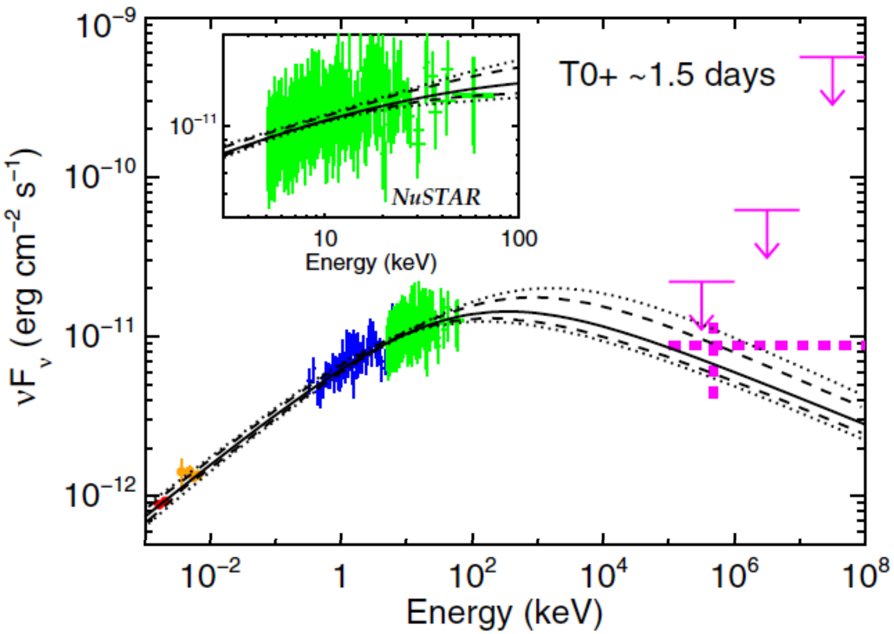
Ruiz-Velasco+ (1st CTA symposium)

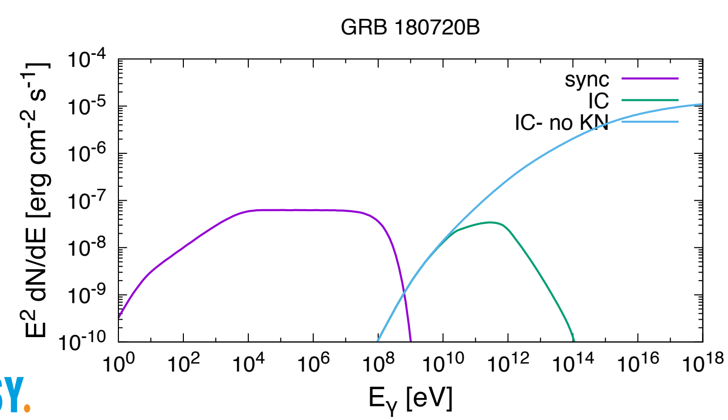
HESS Collaboration *Nature* **575,** 464–467 (2019)

DESY.

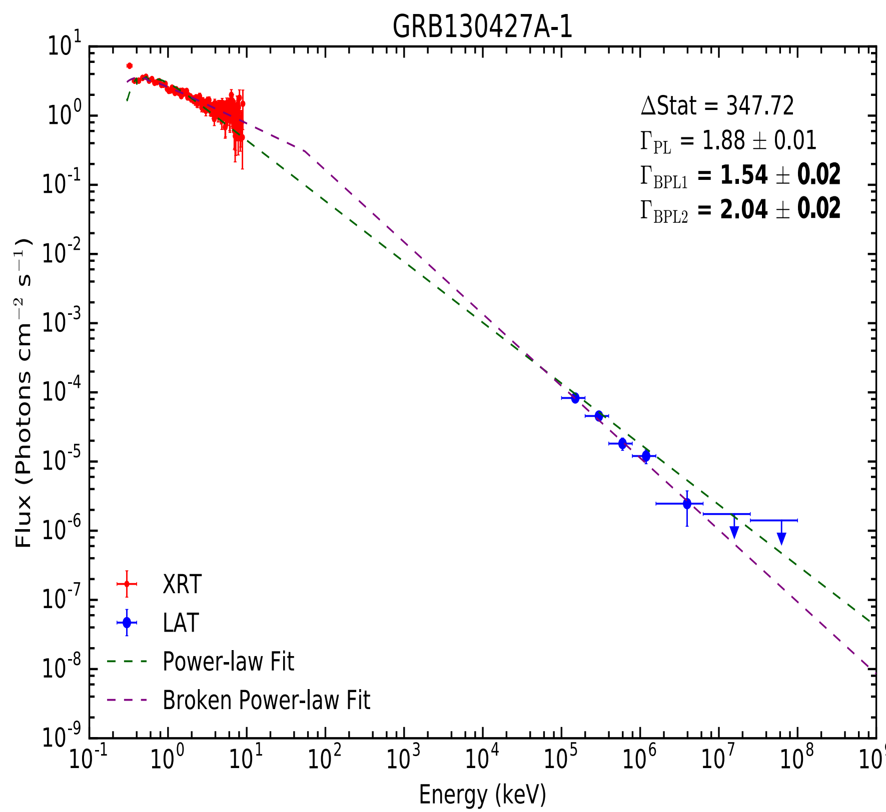
No Synchrotron Cutoff of GRB 130427A Seen in X-rays and Gamma-Rays

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

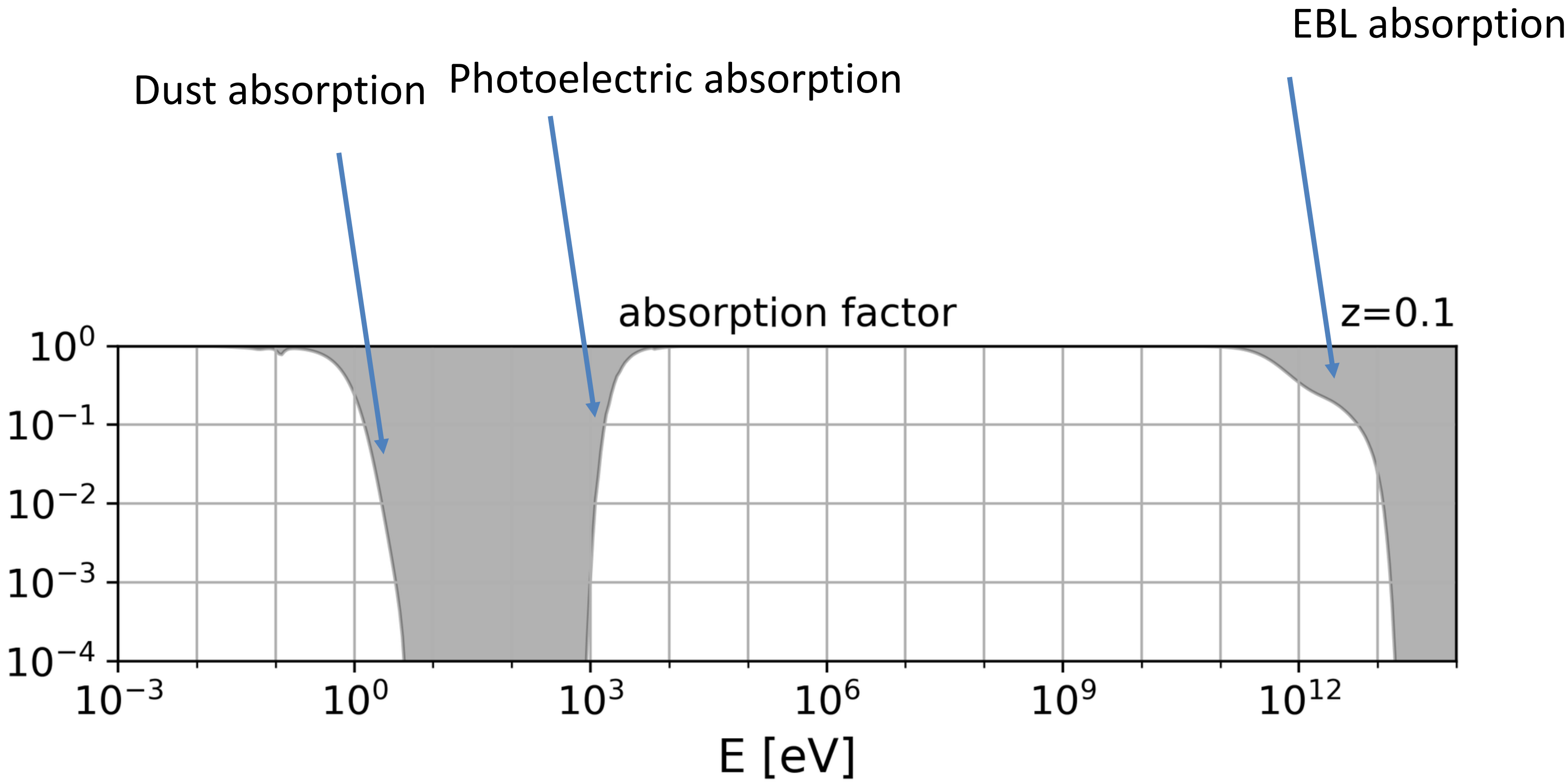




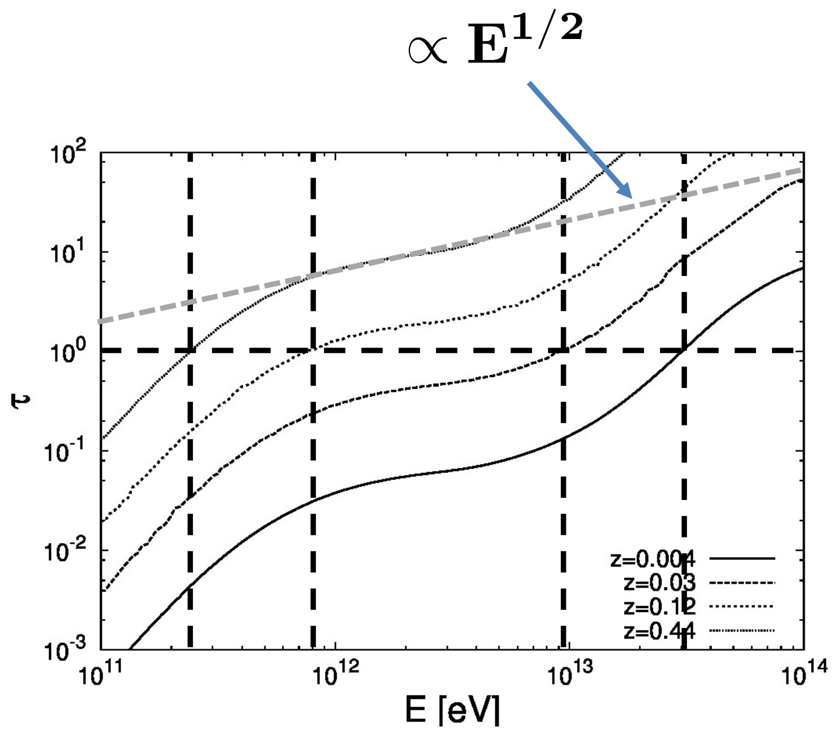
[Ajello et al., ApJ 863 138 (2018)]

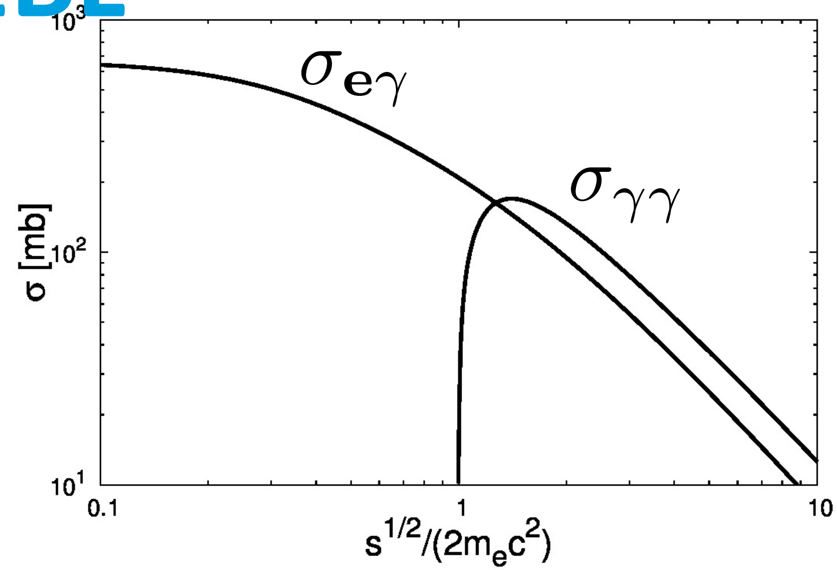


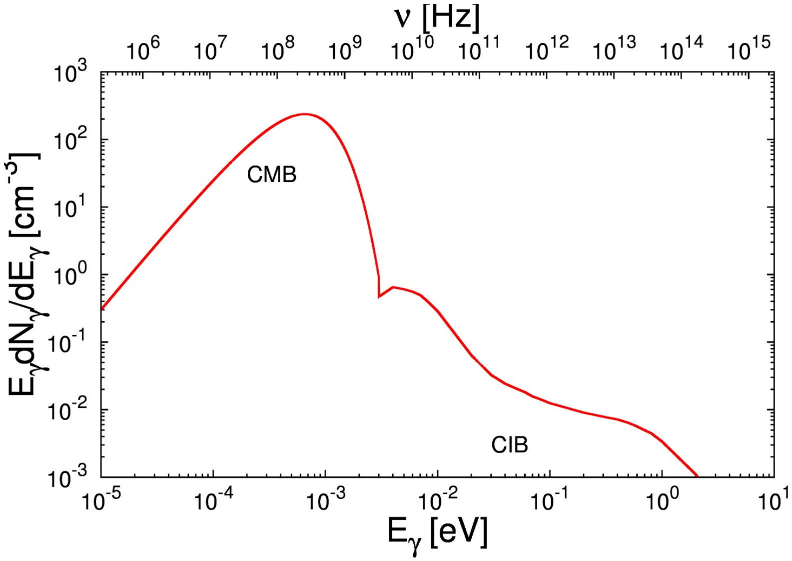
The Observational Challenges for GRBs
Absorption!



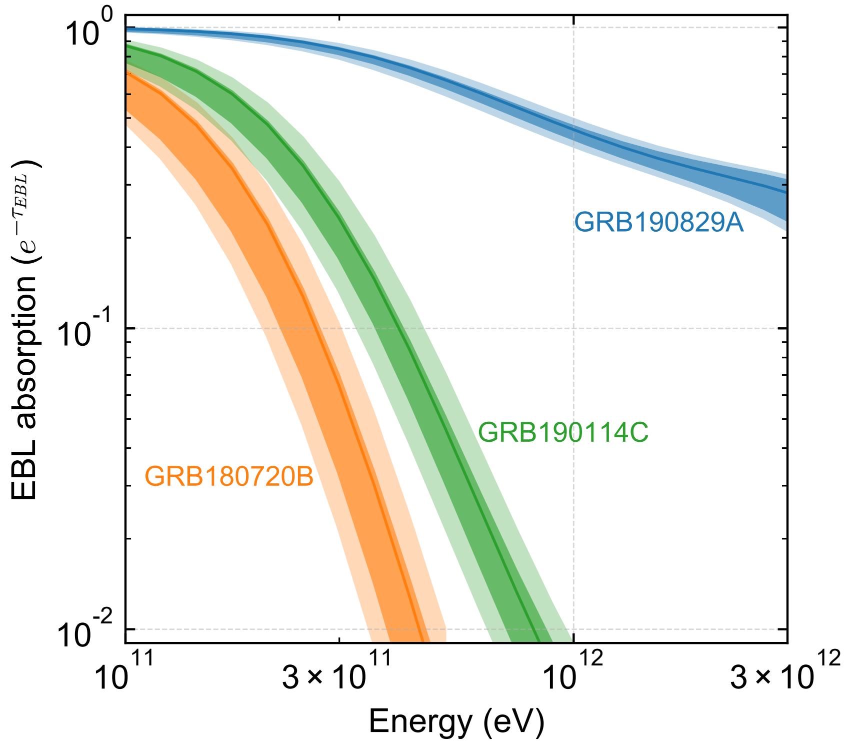
Attenuation through Pair Production on the EBL







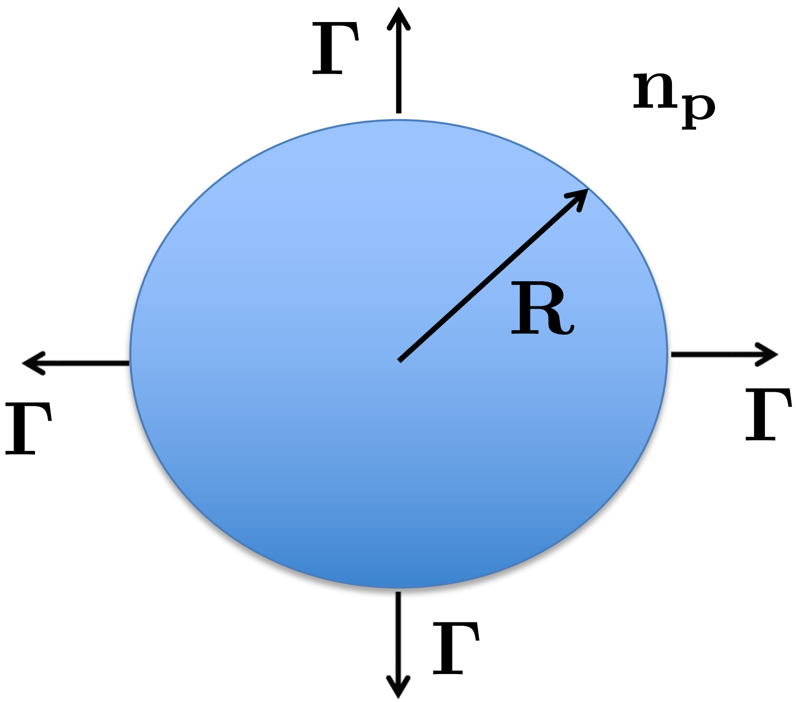
Energy Spectrum Information

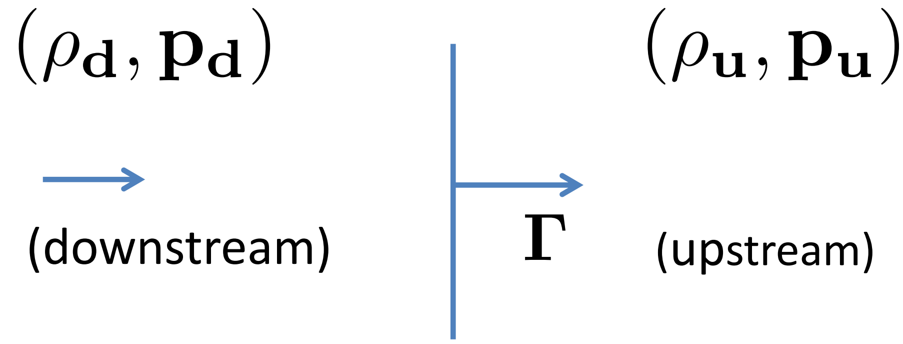


The effect of the EBL on the (optically thin) attenuation for a nearby (z=0.08) source for E_γ<6 TeV is a softening of the spectrum by around $\Delta\Gamma\approx0.5$, starting around 250 GeV.

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

Origin of Temporal Decay Structure





[viewed in upstream restframe]

Assuming η_γ is constant in time.....

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

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

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

Hadronic Particle Acceleration in Sources

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

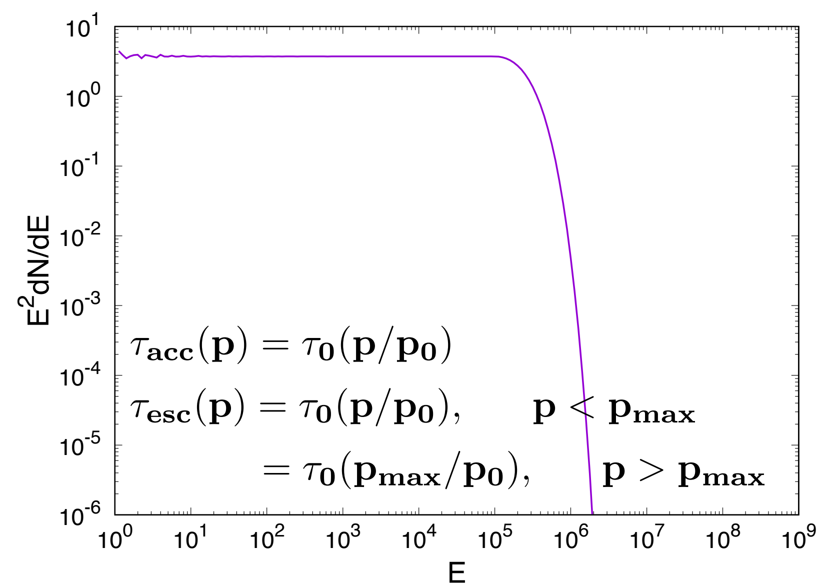
Steady state

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

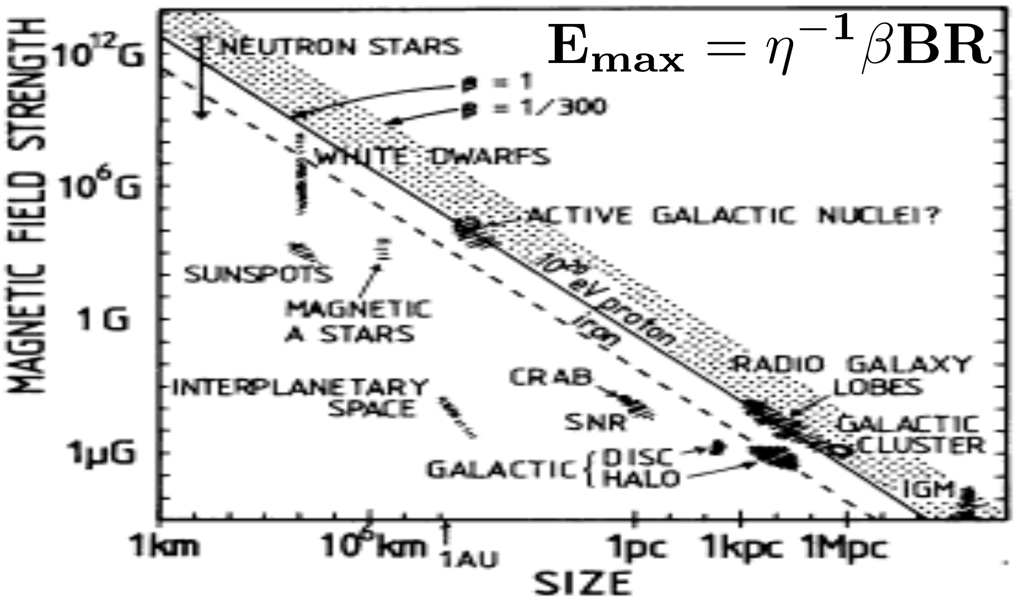


Cosmic Ray Source Requirements

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

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

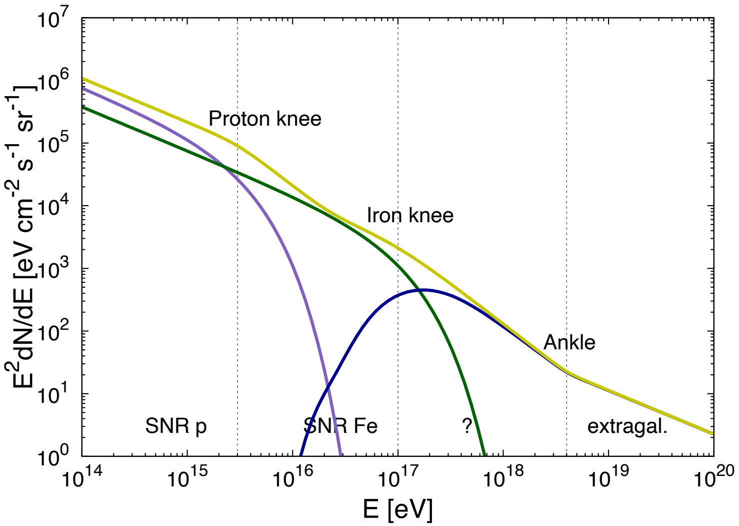
[AM Hillas (1984)]



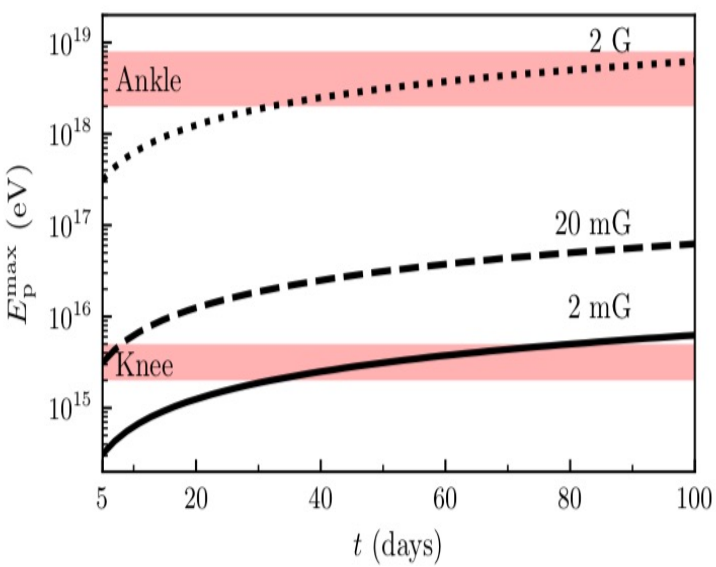
$$\mathbf{E_{max}} = \eta^{-1}\beta\mathbf{BR}$$

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

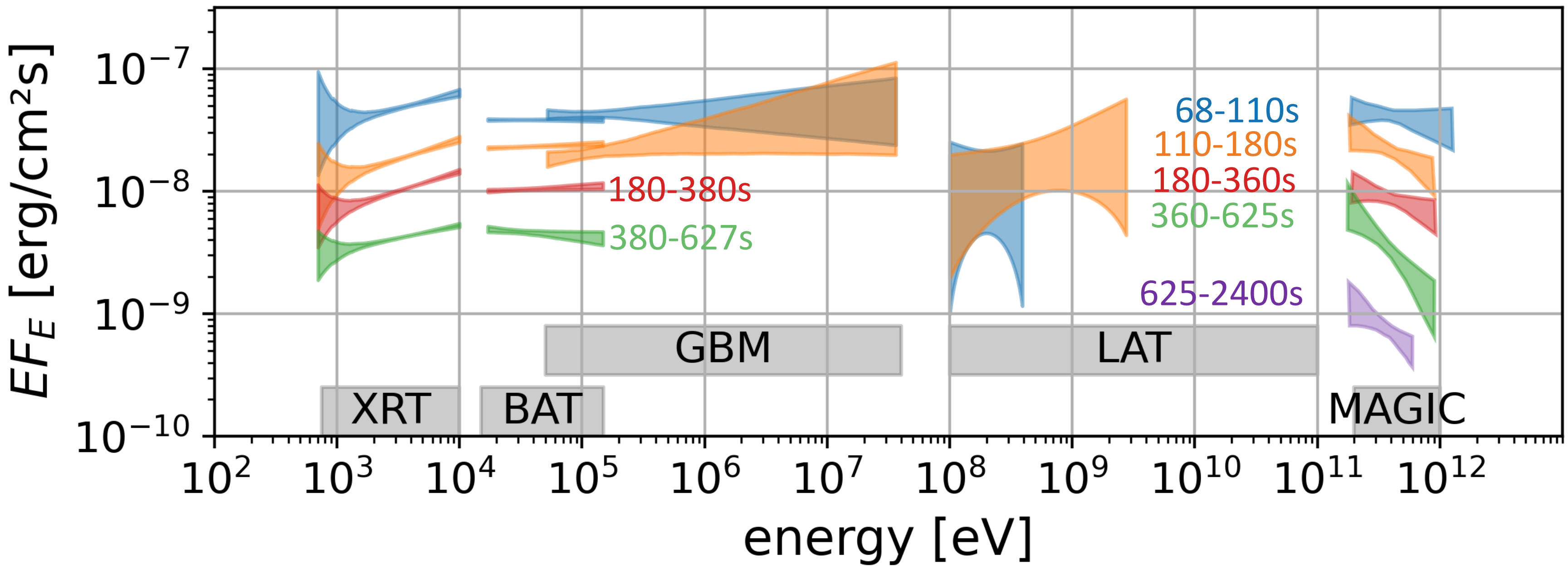


- As the source expands, **CRs** can be accelerated to energies between the **knee and the ankle**
- If the *B*-field is as large as ~G -> possibility of **UHECRs**



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

GRB 190114C (Detected by MAGIC)

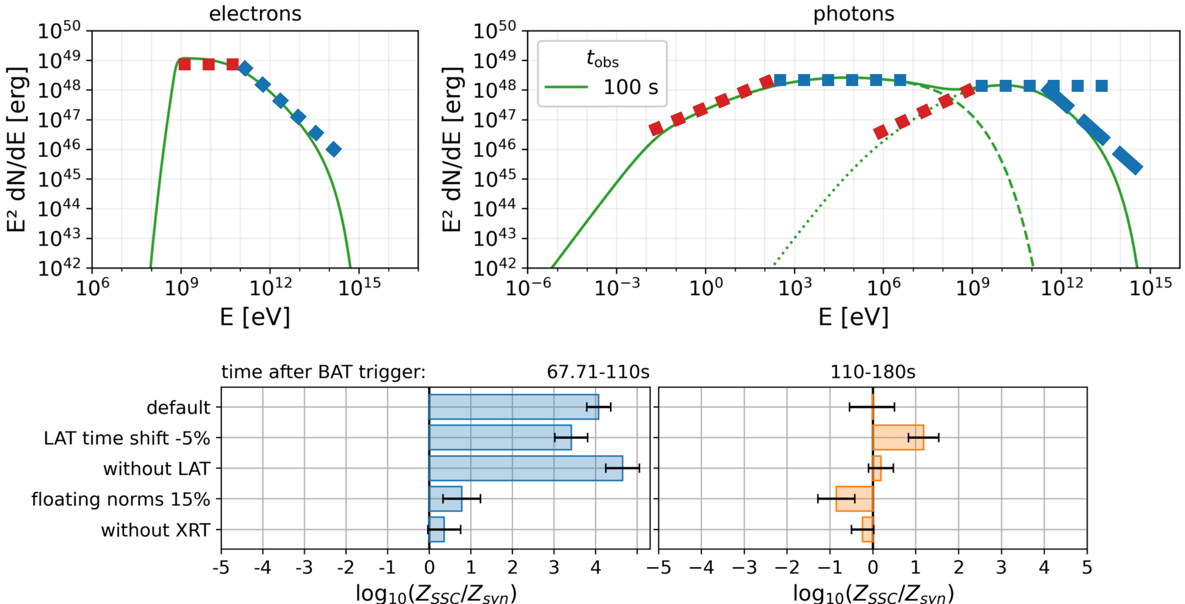


[Nature 575, 459-463 (2019)]

- remarkably flat over 9 orders of magnitude in energy!

DESY.

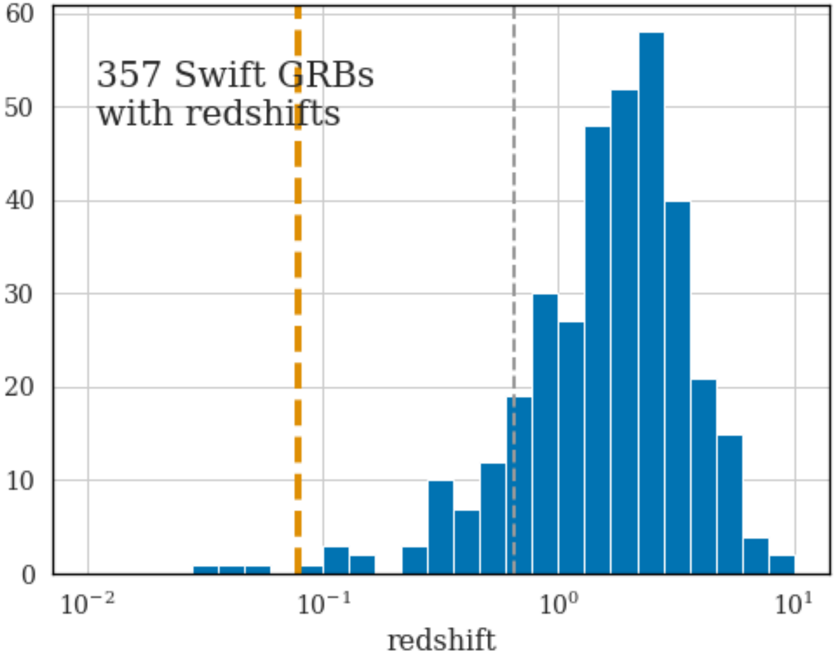
Evidence for a New Component?



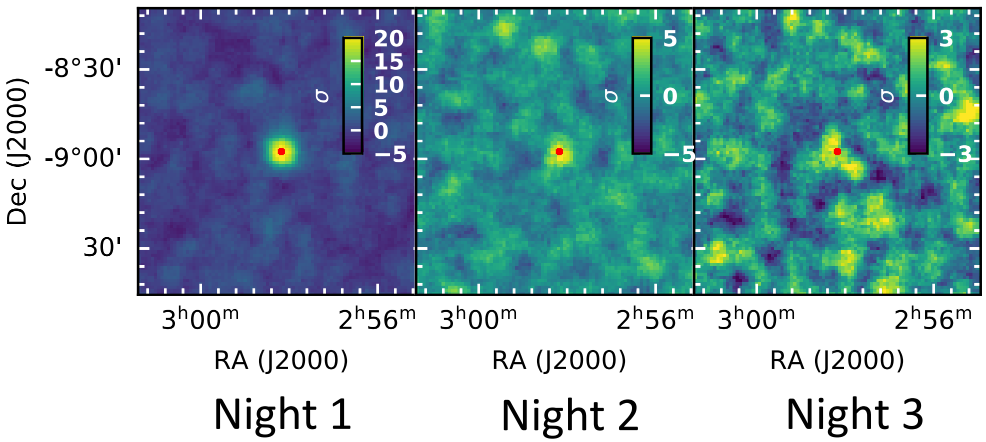
[M. Kinger et al., MNRAS 501 2023]

- 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

HESS Detection of GRB 190829A



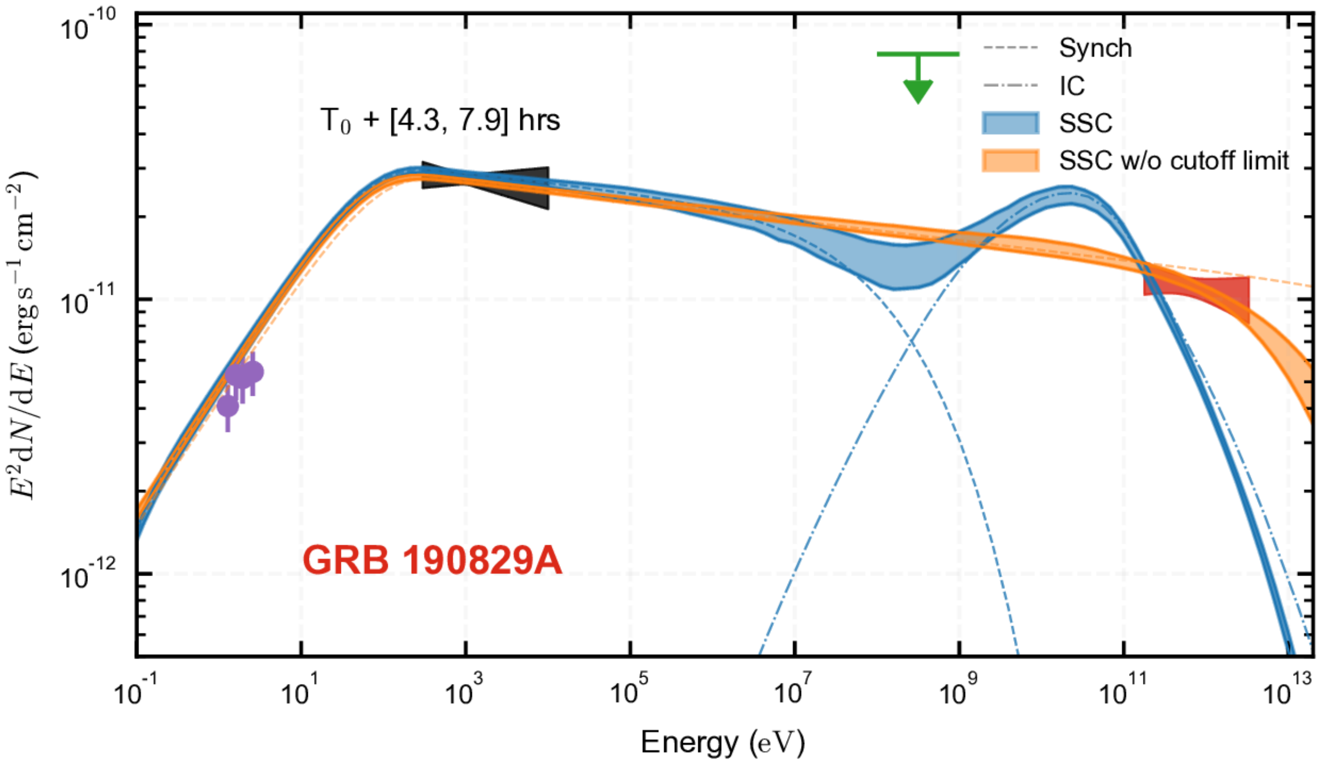
First detection of a GRB in VHE band for multiple nights



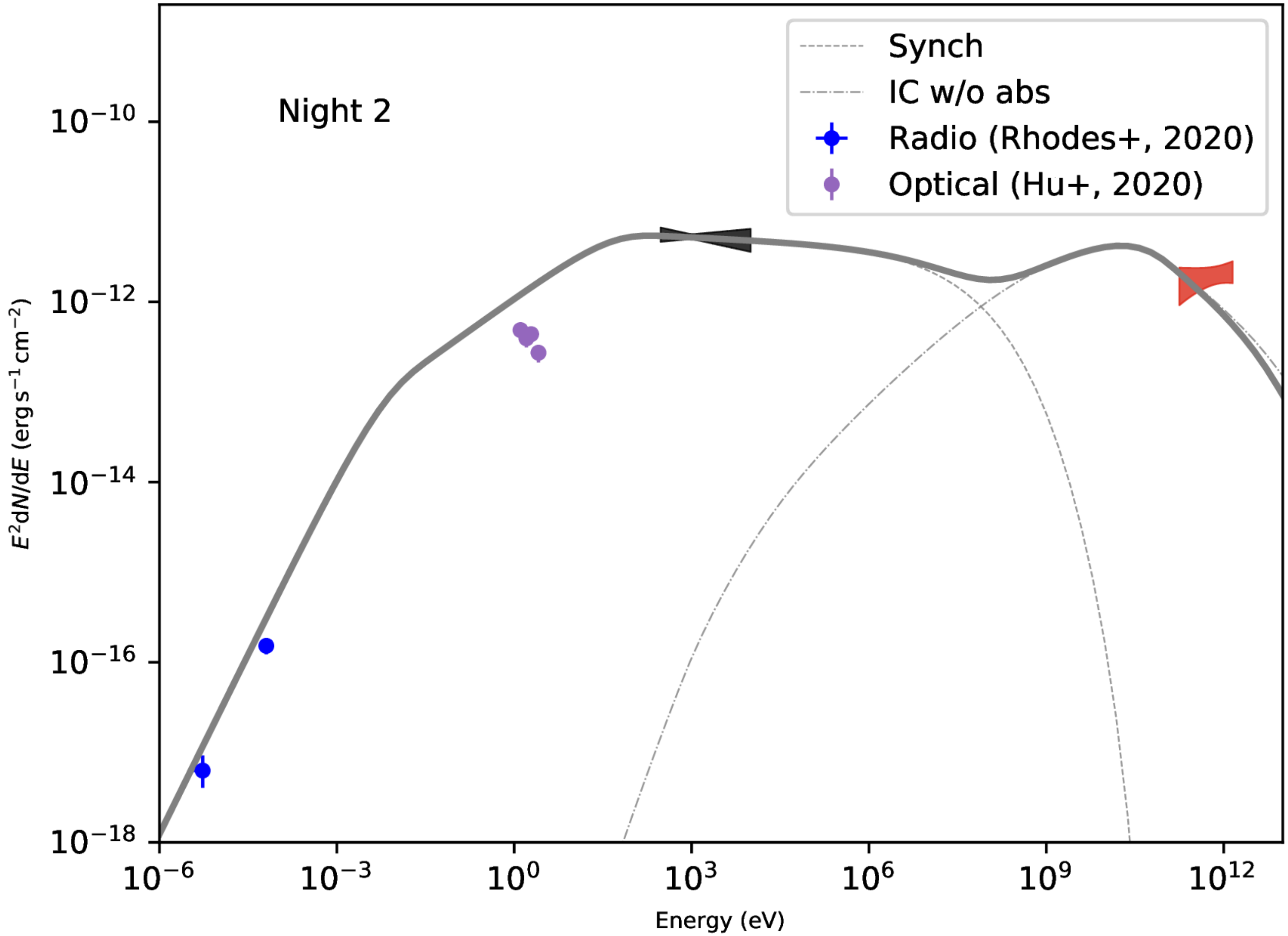
[HESS- A. Taylor, et al., Science 2021]

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

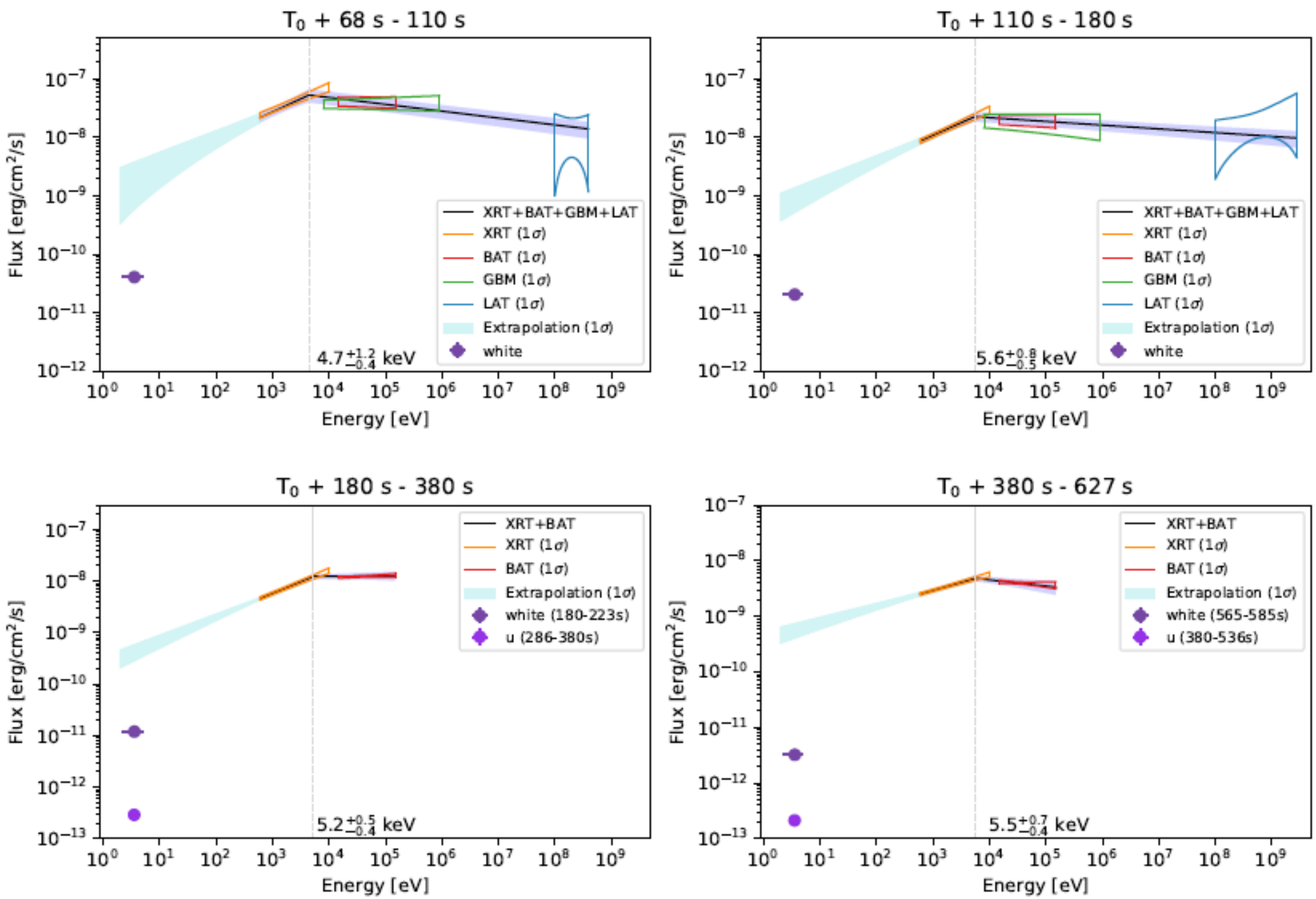
GRB 190829A- Optical Data



GRB 190829A- Radio Data

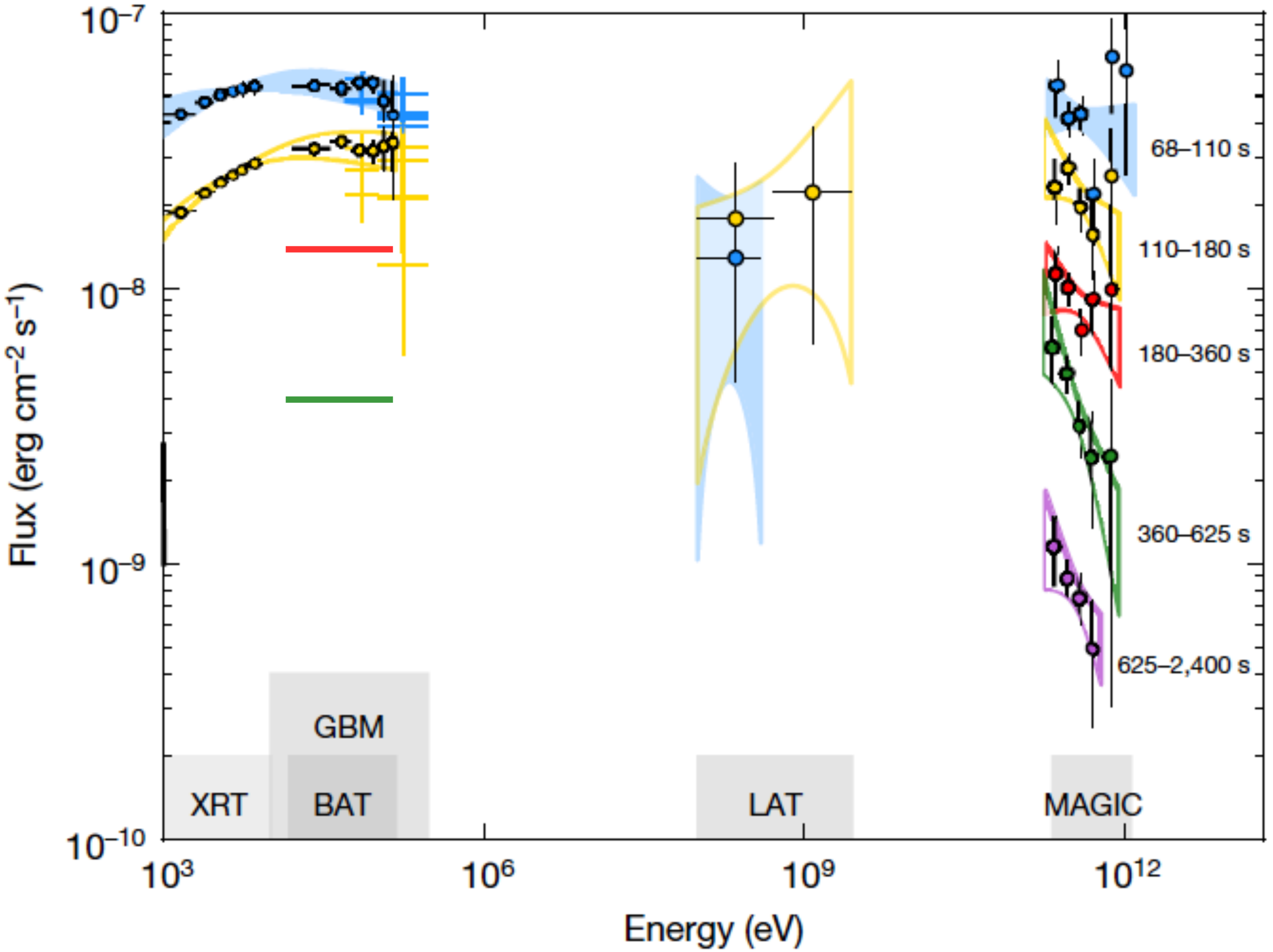


GRB 190114C



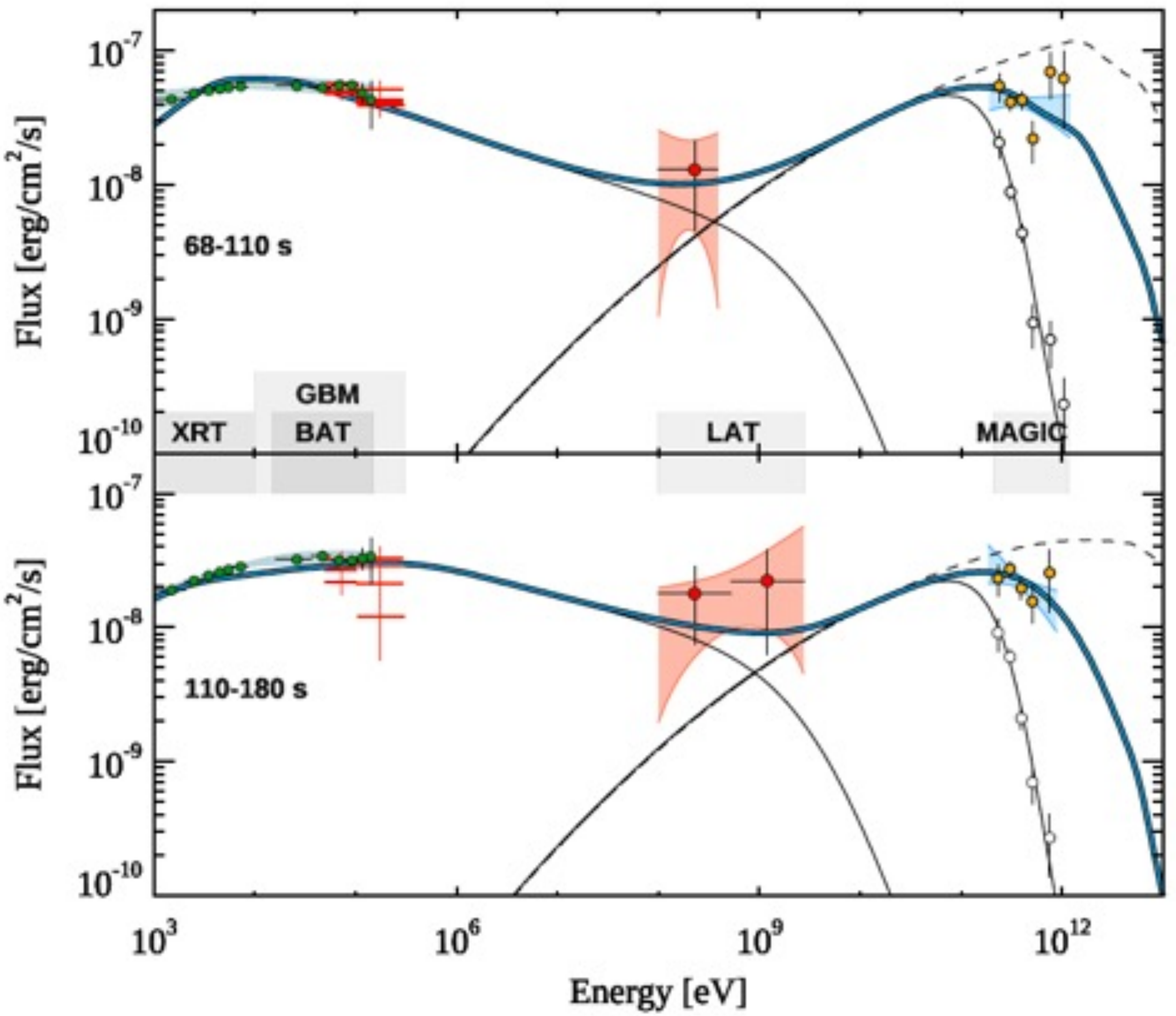
DESY.

GRB 190114C

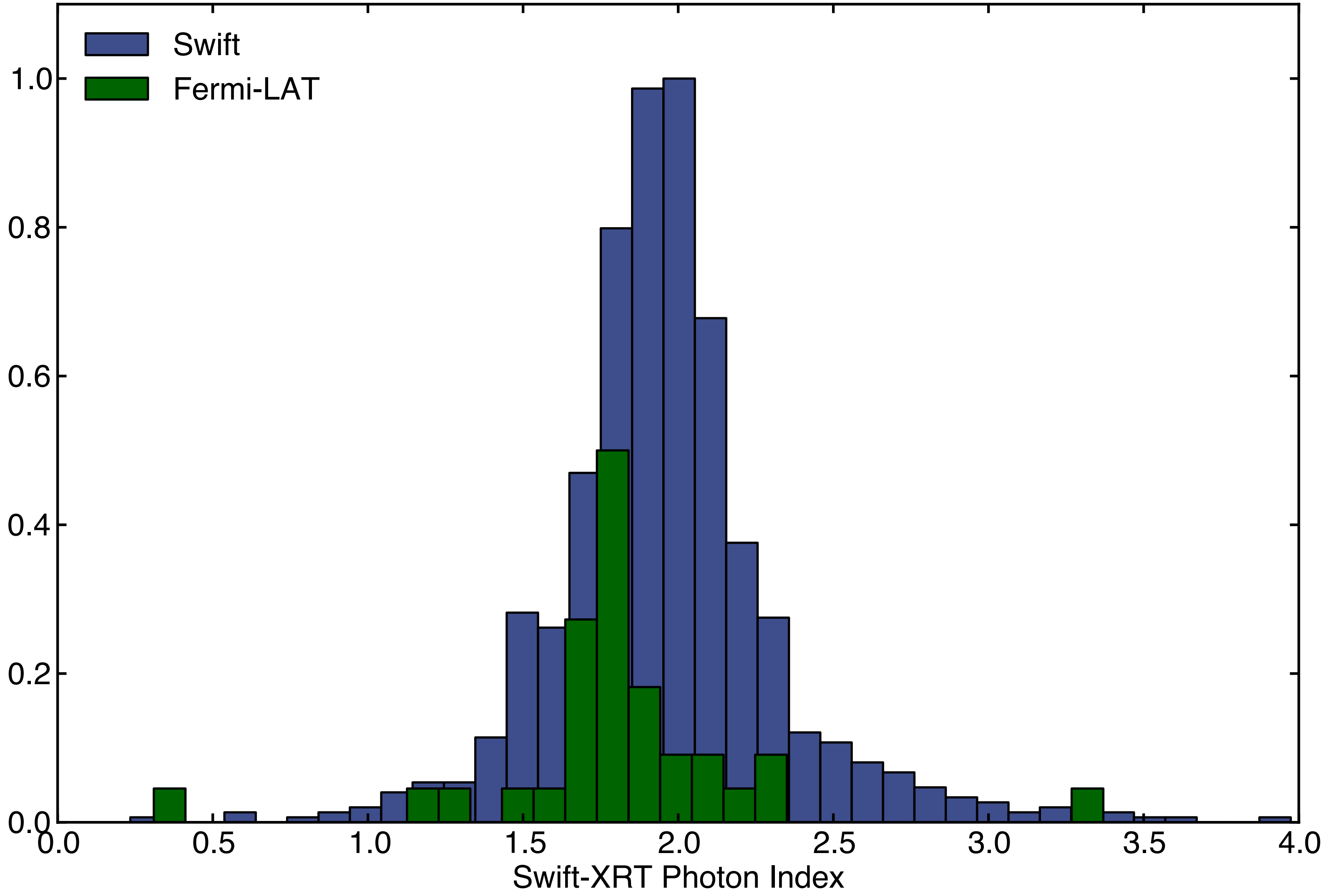


DESY.

GRB 190114C

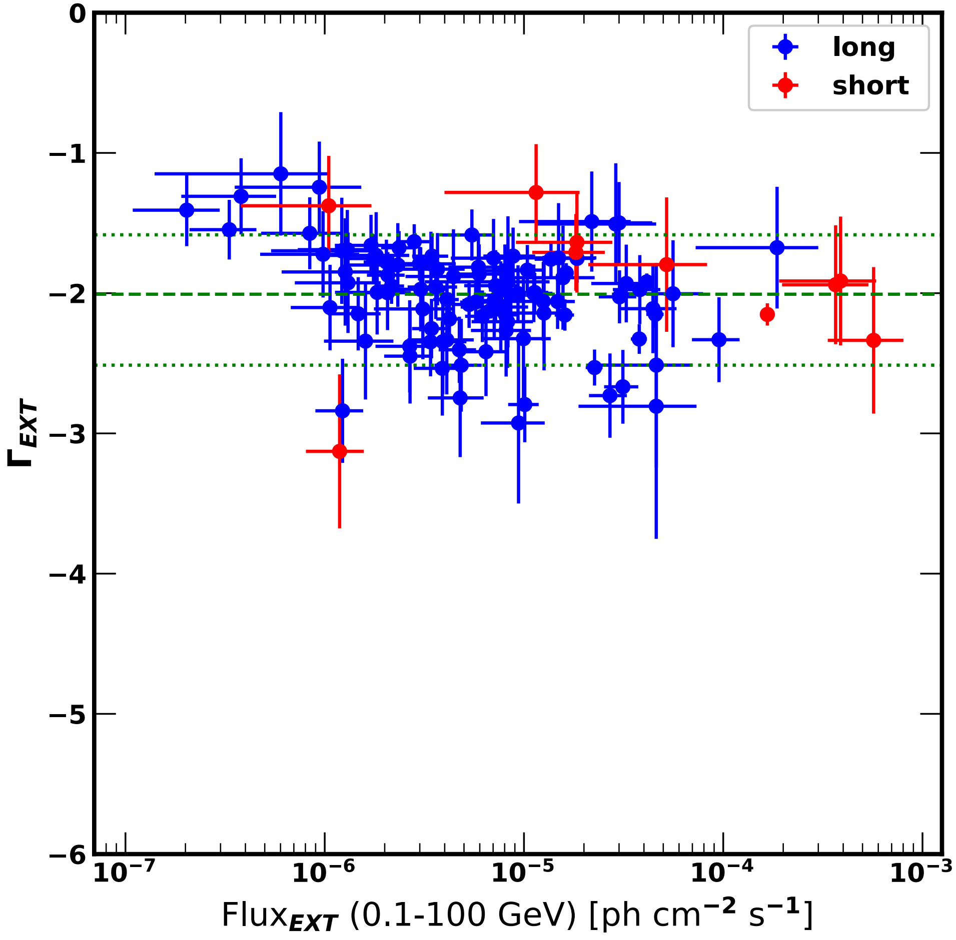


Swift XRT Photon Index Distribution



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

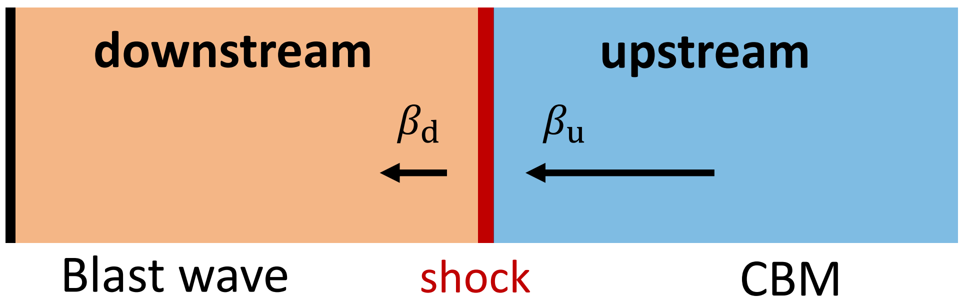
Fermi-LAT Photon Index Distribution



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

Relativistic Hydro Shocks

What's the compression ratio for relativistic shocks?



Mass Flux: $$\rho_{\mathbf{u}}\beta_{\mathbf{u}}\mathbf{\Gamma_u} = \rho_{\mathbf{d}}\beta_{\mathbf{d}}\mathbf{\Gamma_d}$$

Momentum Flux: $$\mathbf{p_u} + \mathbf{w_u}\beta_{\mathbf{u}}^{\mathbf{2}}\mathbf{\Gamma_u^2} = \mathbf{p_d} + \mathbf{w_d}\beta_{\mathbf{d}}^{\mathbf{2}}\mathbf{\Gamma_d^2}$$

Energy Flux: $$\mathbf{w_u}\beta_{\mathbf{u}}\mathbf{\Gamma_u^2} = \mathbf{w_d}\beta_{\mathbf{d}}\mathbf{\Gamma_d^2}$$

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

Relativistic Shocks

Momentum Flux:

$$\mathbf{p_1} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}^\mathbf{2}\mathbf{\Gamma_1^2} = \mathbf{p_2} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}^\mathbf{2}\mathbf{\Gamma_2^2}$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}\mathbf{\Gamma_1^2} = \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}\mathbf{\Gamma_2^2}$$

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:

$$\frac{\mathbf{p_2}}{\mathbf{\Gamma_1^2}\beta_\mathbf{1}^\mathbf{2}\rho_\mathbf{1}}\left[\mathbf{1}+\mathbf{\Gamma_2^2}\beta_\mathbf{2}^\mathbf{2}\left(\frac{\gamma}{\gamma-\mathbf{1}}\right)\right]=\left(\mathbf{1}-\frac{\mathbf{\Gamma_2}\beta_\mathbf{2}}{\mathbf{\Gamma_1}\beta_\mathbf{1}}\right)$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma-\mathbf{1}}\right)\frac{\mathbf{\Gamma_2^2 p_2}\beta_\mathbf{2}}{\mathbf{\Gamma_1^2}\rho_\mathbf{1}\beta_\mathbf{1}}=\left(\mathbf{1}-\frac{(\mathbf{\Gamma_2}-\mathbf{1})}{(\mathbf{\Gamma_1}-\mathbf{1})}\right)$$

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

Evolutionary Phases of Blastwave

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

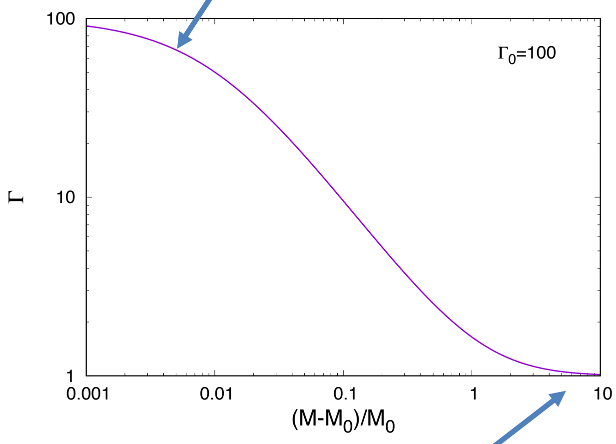
[R. Blandford + McKee 1976]

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

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

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

Critical mass where free expansion changes to deceleration phase



This has the solution

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

Blast wave becomes non-relativistic

DESY.

Evolution of Key Energies with Time