Lecture 2 Plan:

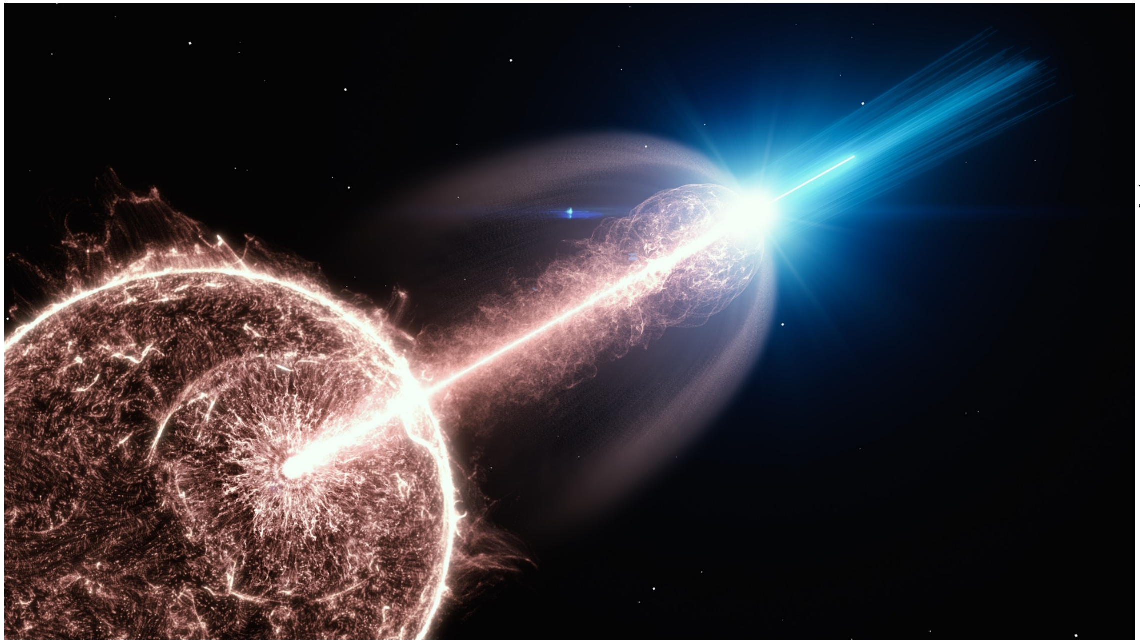
1) The requirements on sources capable of accelerating particles up to ultra high energies

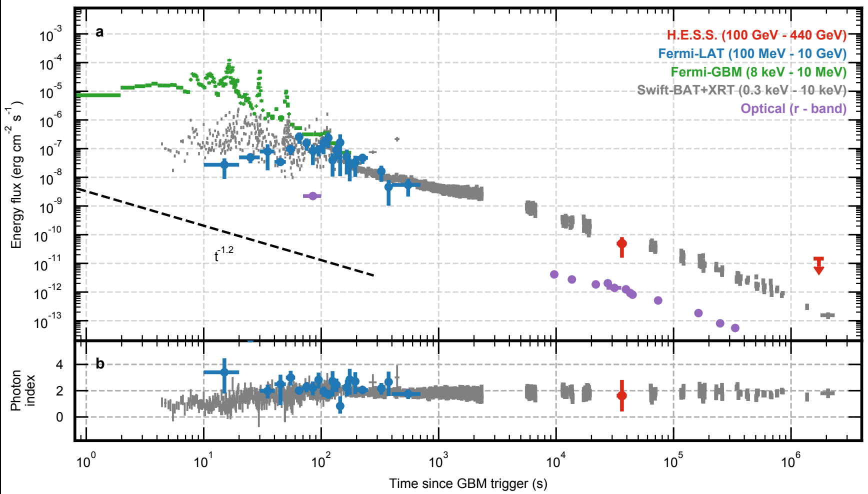
2) The physics of relativistic hydrodynamic (HD) shocks

3) The pressure fractions of magnetic fields and non-thermal particles at MHD shocks

4) The radiative signatures expected from efficient relativistic shocks

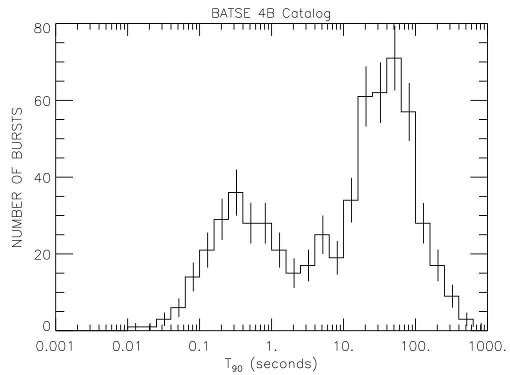
Gamma-Ray Burst Afterglow Physics





[HESS Coll. Nature 2019]

Caveat! The Gamma-Ray emission I will be focusing on here is the radiation observed during the “afterglow” phase of long GRBs



[NASA Webpage]

Why are GRBs Interesting?

Why question- requires background information to answer

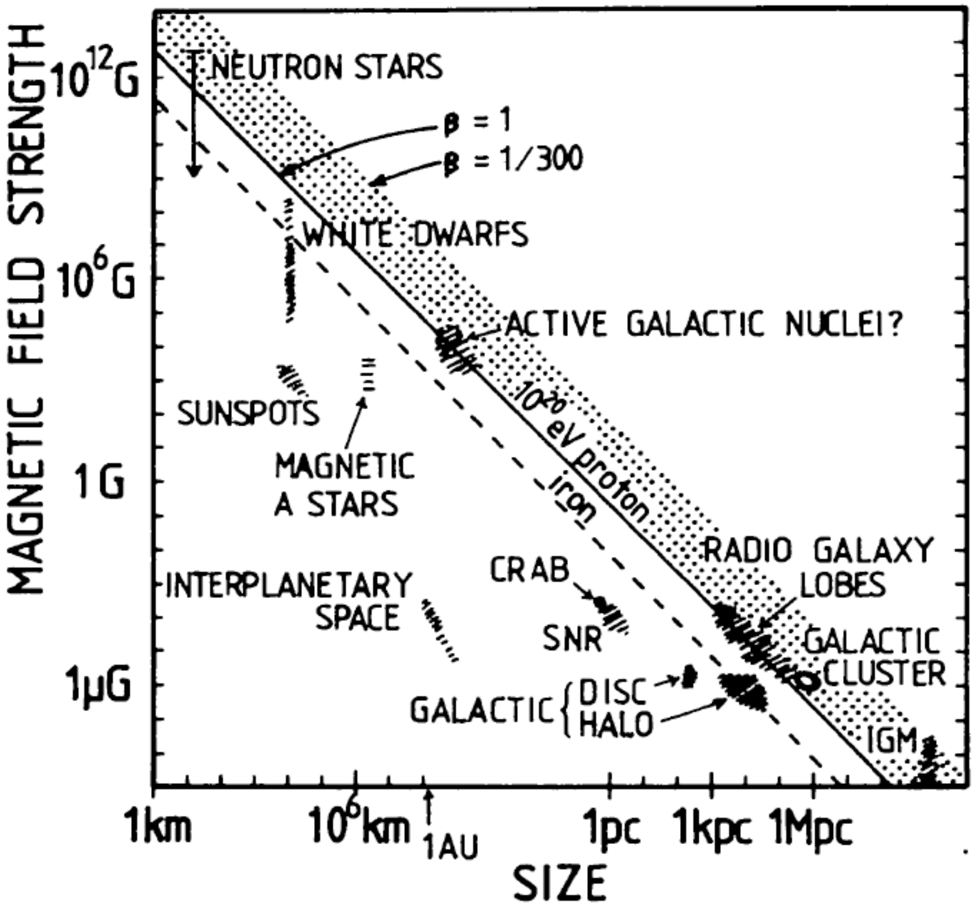
Cosmic Ray Source Requirements

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

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

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

[AM Hillas (1984)]



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

Particle Accelerator Limits

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

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

[AM Hillas (1984)]

$$\mathbf{E_{max}} = \beta\mathbf{eBR}$$

$$\mathbf{L_B} = \mathbf{U_B} 4\pi \mathbf{R}^{\mathbf{2}} \beta \mathbf{c}$$

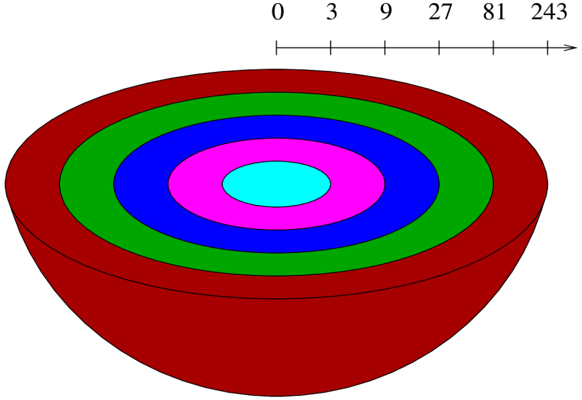
Under the assumption of equipartition of energy between kinetic energy and magnetic field:

[Lovelace et al. (1976)]

$$\mathbf{E_{max}} \lesssim \frac{\mathbf{Z}}{\eta} (\beta \mathbf{L_{KE}} \alpha \hbar)^{\mathbf{1/2}} \approx \mathbf{10}\ \frac{\mathbf{Z}}{\eta} \left(\frac{\beta \mathbf{L_{KE}}}{\mathbf{3} \times \mathbf{10^{43}\ erg\ s^{-1}}} \right)^{\mathbf{1/2}} \mathbf{EeV}$$

Cosmic Ray Sources Have to be Local

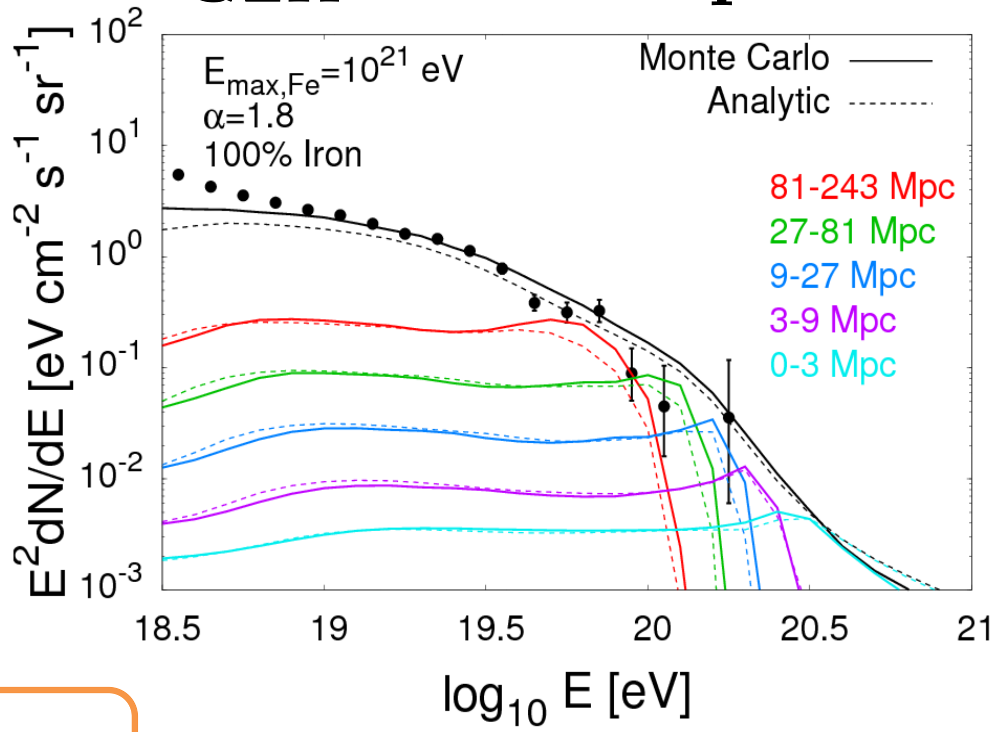
(logarithmic scale)



[A. Taylor et al., Phys Rev D (2011)]

[R. Lang and A. Taylor in prep.]

$$d_{GZK} \sim 100 \text{ Mpc}$$



$$\mathcal{L}_0 \approx 4 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

[E. Waxman, Astrophys. J. 452 (1995)]

$$\mathcal{L}_0 \approx L_0 n_0 \approx E_0 \dot{n}_0$$

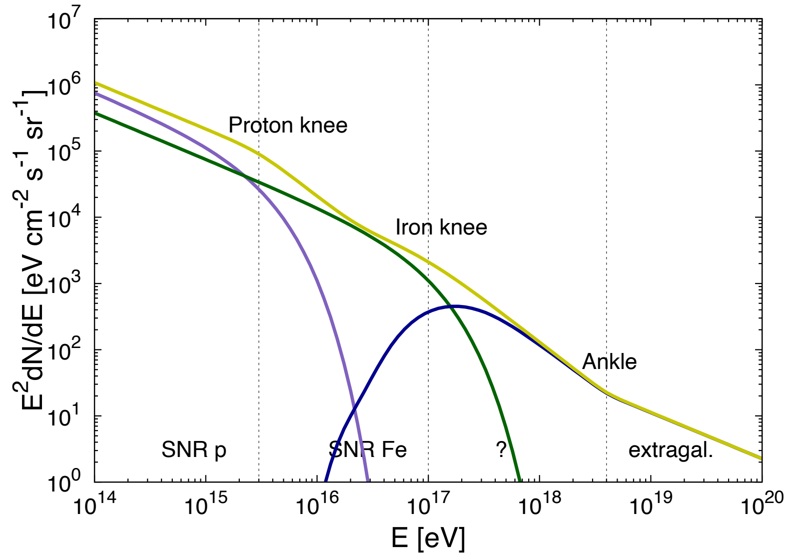
⇒

$$n_0 \sim 10^{-5} \text{ Mpc}^{-3}$$

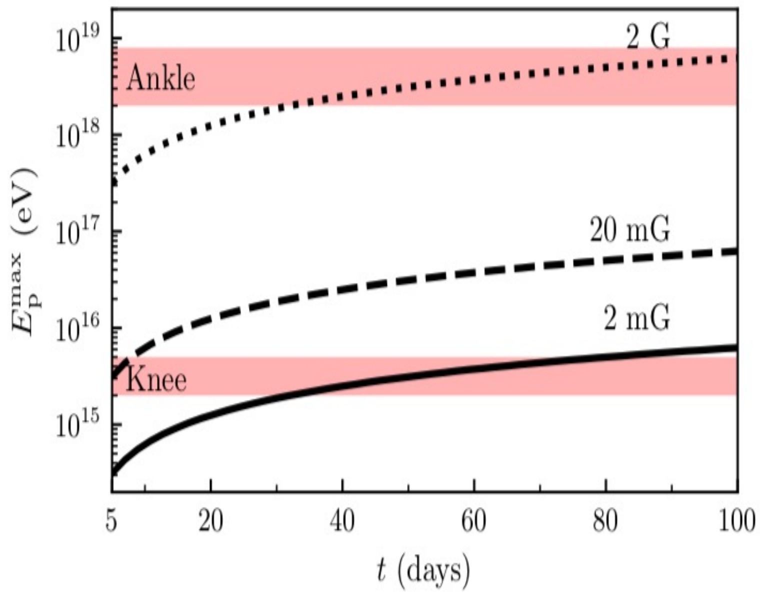
$$\dot{n}_0 \sim 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$$

Only AGN and GRB appears to satisfy these requirements as the sources of extragalactic cosmic rays

GRB Outflows as a Cosmic Ray Sources



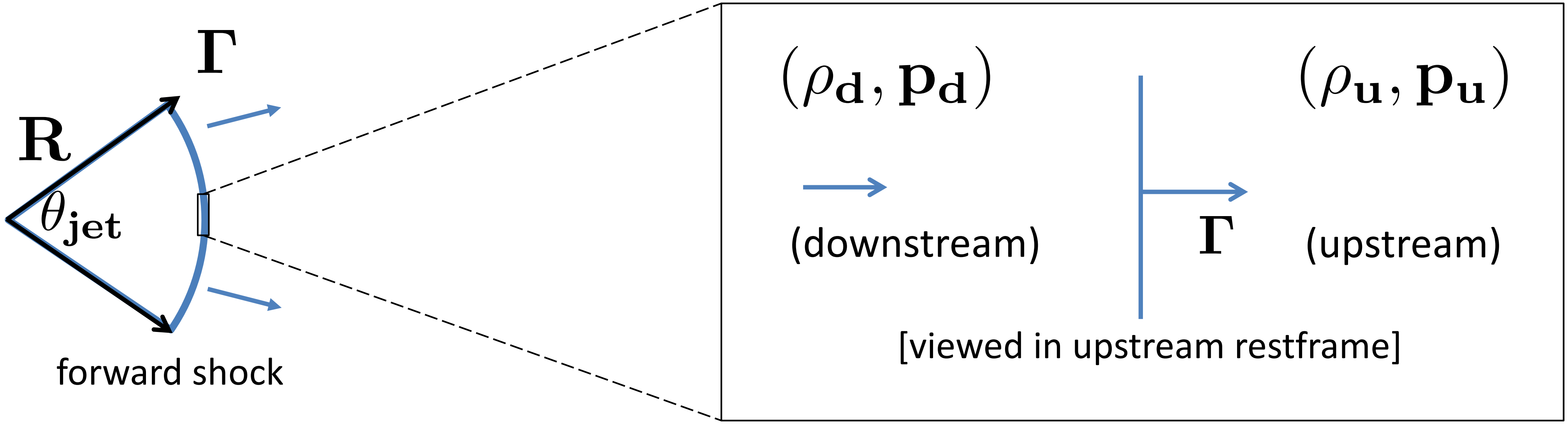
- As the source expands, **CRs** can be accelerated to energies between the **knee and the ankle**
- If the *B*-field is as large as ~G -> possibility of **UHECRs**



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

What are GRBs?

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

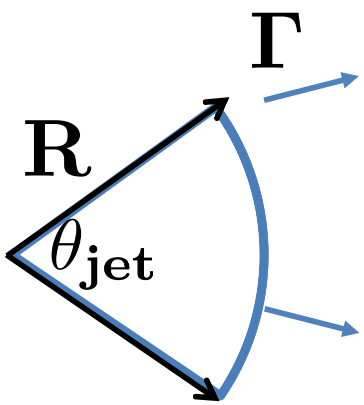


- Not actually isotropic outflows, but can be considered as "quasi-isotropic" since $\theta_{jet}>1/\Gamma$

- 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

Evolutionary Phases of Blastwave



[viewed in upstream restframe]

[R. Blandford + McKee 1976]

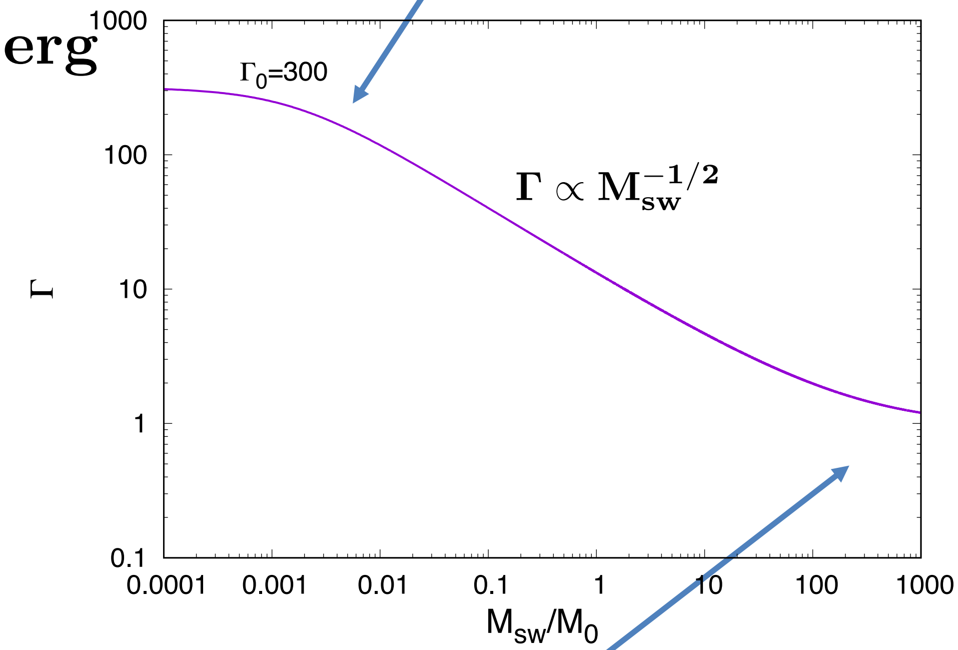
End of free expansion phase once swept up mass is ~M_0/Γ_0

$$E_{iso} \approx 10^{52} \left(\frac{\Gamma_0}{300}\right)\left(\frac{M_0}{3\times 10^{-5}\ M_\odot}\right)\ \mathrm{erg}$$

$$E = (\Gamma - 1)M = E_{iso}$$

1) Deceleration rate

$$\frac{dM}{dR} = \Gamma 4\pi\rho R^2$$



Blast wave becomes non-relativistic once swept up mass is ~$M_0\Gamma_0$

$$\Gamma \propto M_{\mathbf{sw}}^{-1/2}$$

PAUSE

Obtain the above expected evolution of the Lorentz factor with swept-up mass

Evolutionary Phases of Blastwave

1) Deceleration rate

$$\frac{\mathbf{dM}}{\mathbf{dR}} = \Gamma 4\pi\rho \mathbf{R}^2 - \frac{1}{\Gamma}\frac{\mathbf{dE_{rad}}}{\mathbf{dr}}$$

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

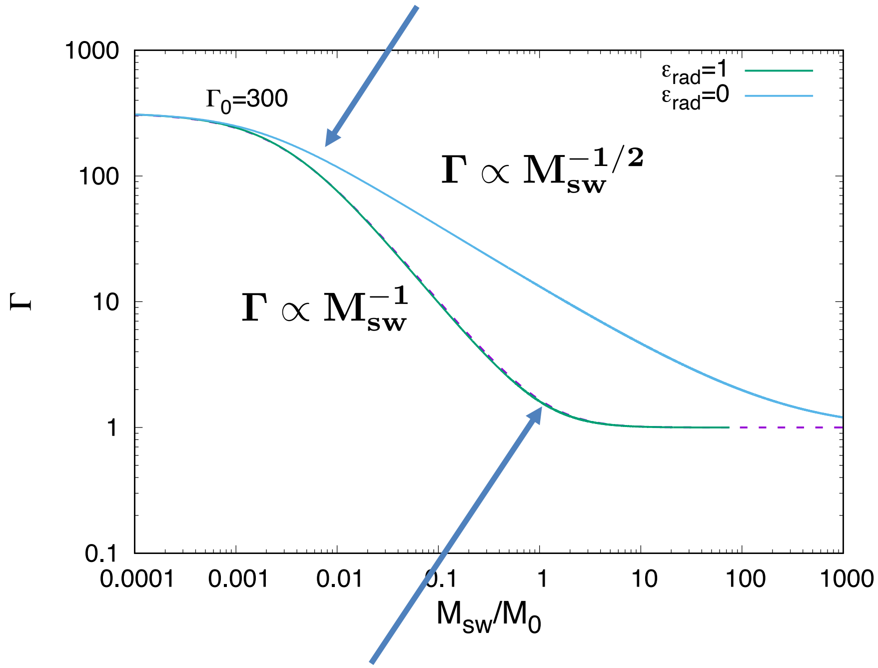
1) Radiative loss rate

$$\mathbf{E} = \mathbf{E_{iso}} - \mathbf{E_{rad}}$$

$$\frac{\mathbf{dE_{rad}}}{\mathbf{dR}} = -\varepsilon_{\mathbf{rad}} 4\pi\rho \mathbf{R}^2 \Gamma(\Gamma - \mathbf{1})$$

[R. Blandford + McKee 1976]

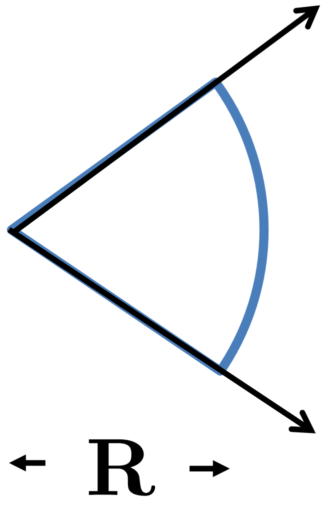
End of free expansion phase once swept up mass is ~M_0/Γ_0

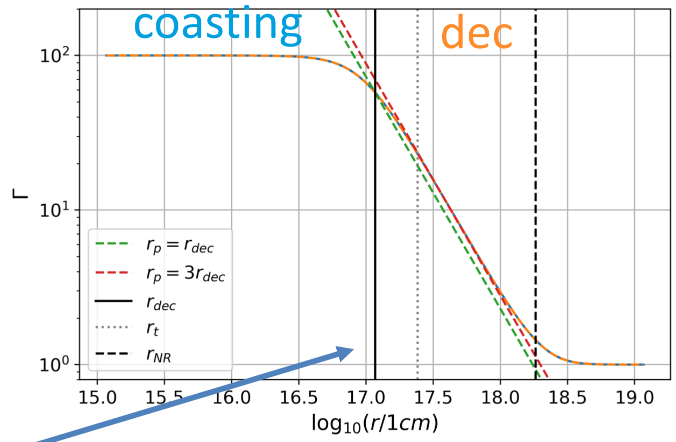


Blast wave becomes non-relativistic once swept up mass is ~M_0

Temporal Compression of Signal

For a constant density medium,
during the deceleration phase,



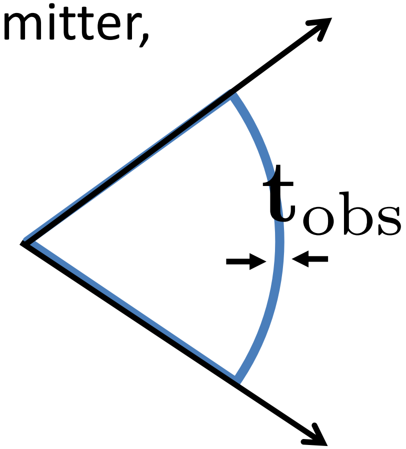


[Plot Courtesy of M. Klinger]

$$R_{dec} \approx 10^{16} \left(\frac{E_{iso}}{10^{52}\ erg}\right)^{1/3} \left(\frac{n}{1\ cm^{-3}}\right)^{-1/3} \left(\frac{\Gamma_0}{300}\right)^{-2/3} cm$$

Since radiation is emitted by a relativistically
moving emitter,

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



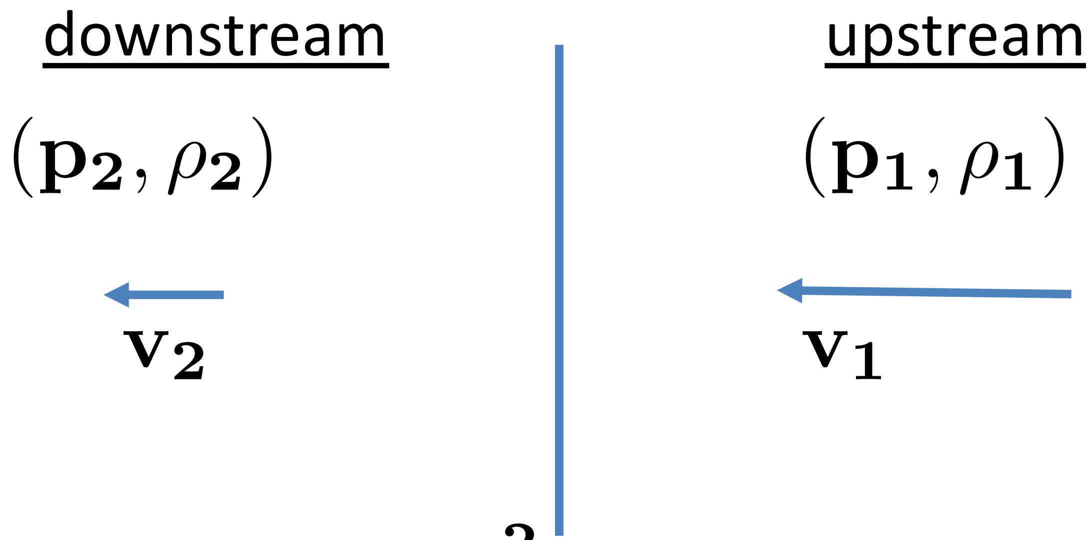
$$t_{dec}^{obs} \approx \frac{R_{dec}}{c\Gamma^2} = 10 \left(\frac{R_{dec}}{10^{16}\ cm}\right) \left(\frac{\Gamma}{300}\right)^{-2} s$$

$$\Gamma \approx 10 \left(\frac{E_{iso}}{10^{52}\ erg}\right)^{1/8} \left(\frac{n}{1\ cm^{-3}}\right)^{-1/8} \left(\frac{t_{obs}}{10^4\ s}\right)^{-3/8}$$

What Do Shocks Do?

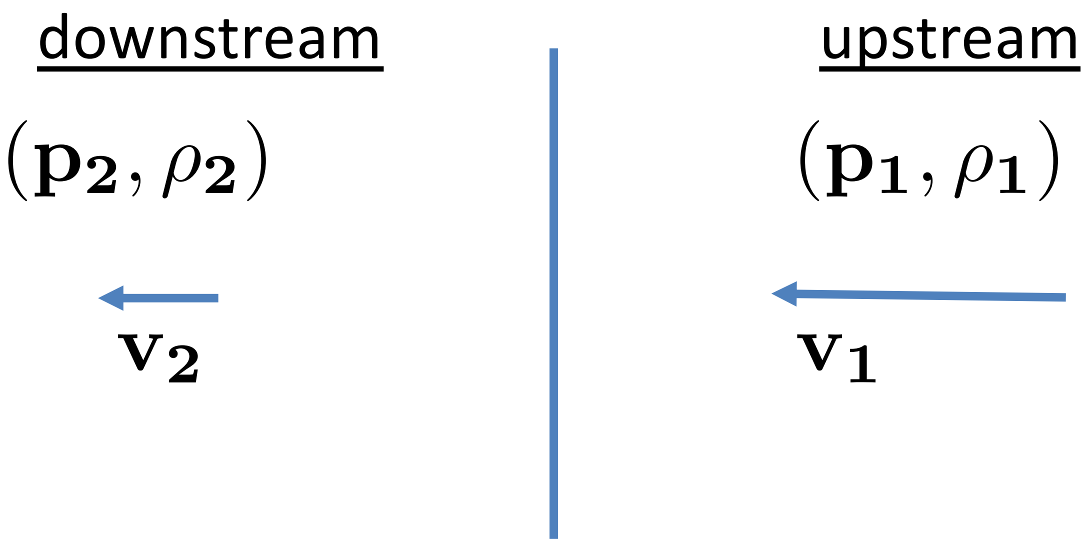
Reminder: (Non-Rel.) Shocks

The fastest speed information in plasmas can be transmitted is the sound speed. When plasmas travel faster than this, they set up a shock- the upstream region is not able to know what is coming (**a surprise**!).



Shock converts ram pressure ($\rho \mathbf{v}^\mathbf{2}$) into thermal pressure ($\mathbf{p}$)

Collisional Shock- Conservation Conditions



Number Flux: $$\rho_\mathbf{1}\mathbf{v_1} = \rho_\mathbf{2}\mathbf{v_2}$$

Momentum Flux: $$\mathbf{p_1} + \rho_\mathbf{1}\mathbf{v_1^2} = \mathbf{p_2} + \rho_\mathbf{2}\mathbf{v_2^2}$$

Energy Flux: $$\mathbf{w_1 v_1} + \frac{\mathbf{1}}{\mathbf{2}}\rho_\mathbf{1}\mathbf{v_1^3} = \mathbf{w_2 v_2} + \frac{\mathbf{1}}{\mathbf{2}}\rho_\mathbf{2}\mathbf{v_2^3}$$

Collisional Shock- Enthalpy

$$\gamma = \frac{\mathbf{w}_{\mathbf{nonrel.}}}{\mathbf{e}}$$

$$= \frac{\mathbf{e} + \mathbf{p}}{\mathbf{e}}$$

$$\mathbf{e} = \frac{\mathbf{p}}{\gamma - \mathbf{1}}$$

$$\mathbf{w}_{\mathbf{nonrel.}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p}$$

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

$$= \mathbf{w}_{\mathbf{nonrel.}} + \rho$$

Collisional Shock- Cold Shock Case

Momentum Flux:

$$\rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$

$$\frac{p_2}{\rho_1 v_1^2} = \left(1 - \frac{v_2}{v_1}\right)$$

Energy Flux:

$$\frac{1}{2}\rho_1 v_1^3 = \left(\frac{\gamma}{\gamma - 1}\right) p_2 v_2 + \frac{1}{2}\rho_2 v_2^3$$

$$\frac{2\gamma}{\gamma - 1}\frac{p_2 v_2}{\rho_1 v_1^3} = \left(1 - \left(\frac{v_2}{v_1}\right)^2\right) = \left(1 - \frac{v_2}{v_1}\right)\left(1 + \frac{v_2}{v_1}\right)$$

Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(1-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-1}{2\gamma}\right)\left(1-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^2\right)$$

$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-1\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-1}{\gamma+1}\right)\right)=0$$

So what are collisional shocks good for?

Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

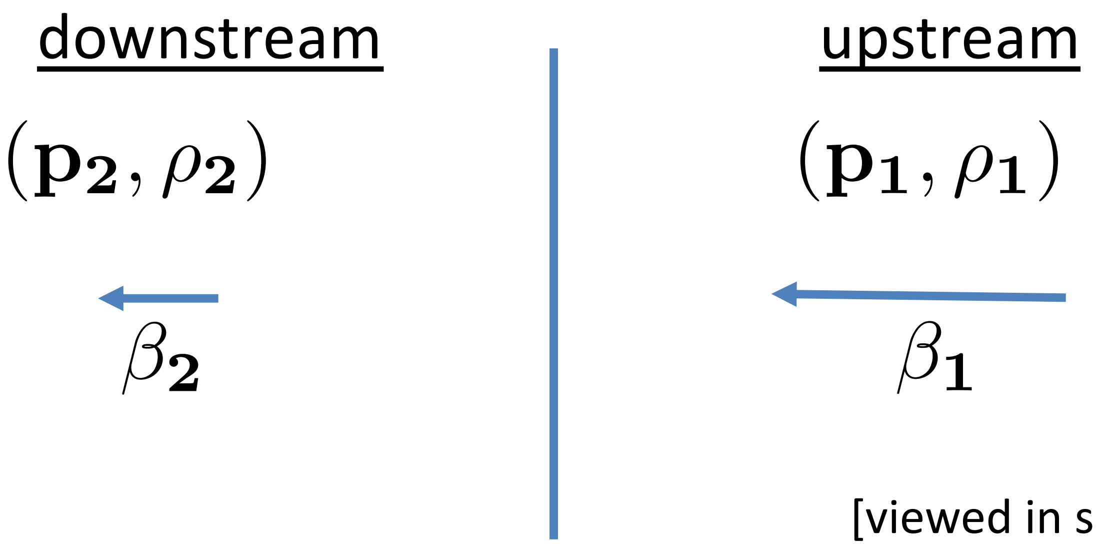
$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\mathbf{1}\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-\mathbf{1}}{\gamma+\mathbf{1}}\right)\right)=\mathbf{0}$$

Eg: $\gamma=\frac{\mathbf{5}}{\mathbf{3}}$ → $\frac{\beta_{\mathbf{2}}}{\beta_{\mathbf{1}}}=\frac{\mathbf{1}}{\mathbf{4}}$

So what are collisional shocks good for?
Stimulating the unstimulated degrees of freedom in the system where momentum/energy can be stored

Relativistic Shocks

How does the compression ratio result change for relativistic shocks



[viewed in shock restframe]

Number Flux: $$\rho_1\beta_1\Gamma_1 = \rho_2\beta_2\Gamma_2$$

Momentum Flux: $$\mathbf{p_1} + \mathbf{w_1}\beta_1^2\Gamma_1^2 = \mathbf{p_2} + \mathbf{w_2}\beta_2^2\Gamma_2^2$$

Energy Flux: $$\mathbf{w_1}\beta_1\Gamma_1^2 = \mathbf{w_2}\beta_2\Gamma_2^2$$

Upsream and Downstream Enthalpy

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

$$\mathbf{w_1} = \rho_\mathbf{1}$$

$$\mathbf{w_2} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}$$

Relativistic Shocks

Momentum Flux:

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

Energy Flux:

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

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:

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

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

PAUSE

Why not have a go at find the roots for this relativistic shock case

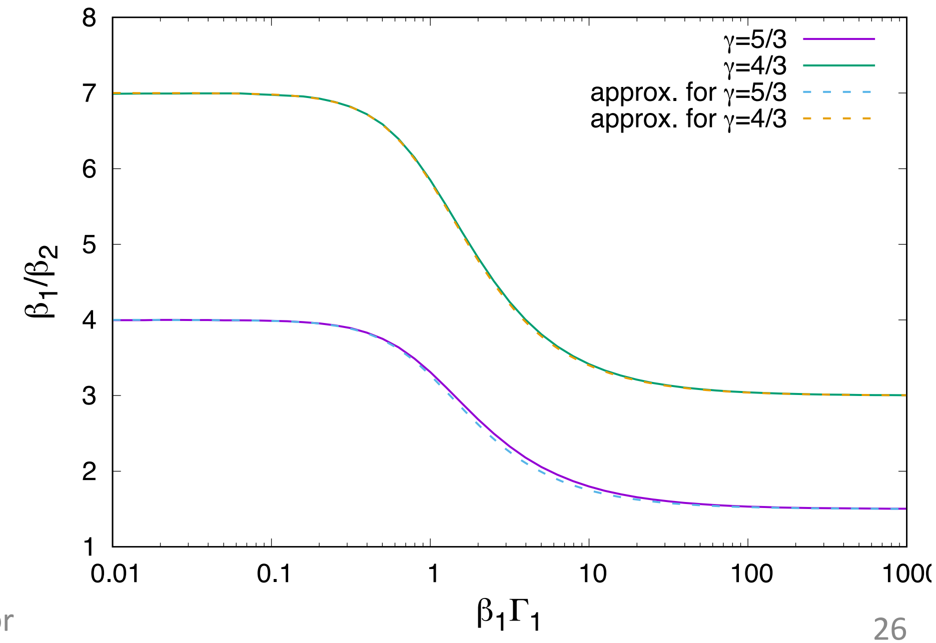
Relativistic Shocks

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

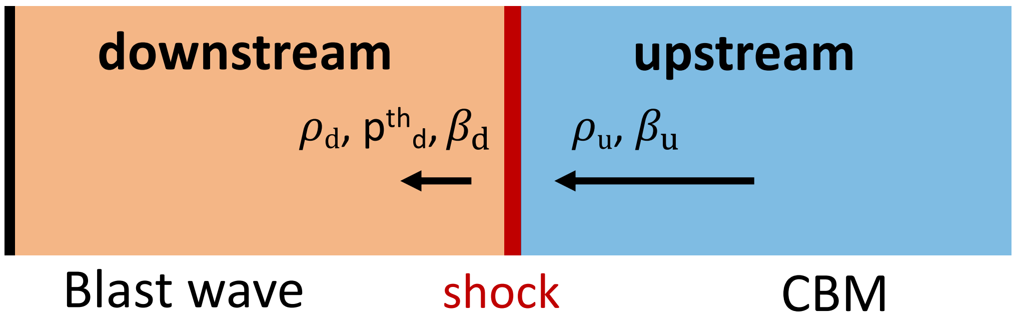
$$1+\Gamma_2^2\beta_2^2\left(\frac{\gamma}{\gamma-1}\right)=\Gamma_2^2\beta_2\left(\frac{\gamma}{\gamma-1}\right)$$

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

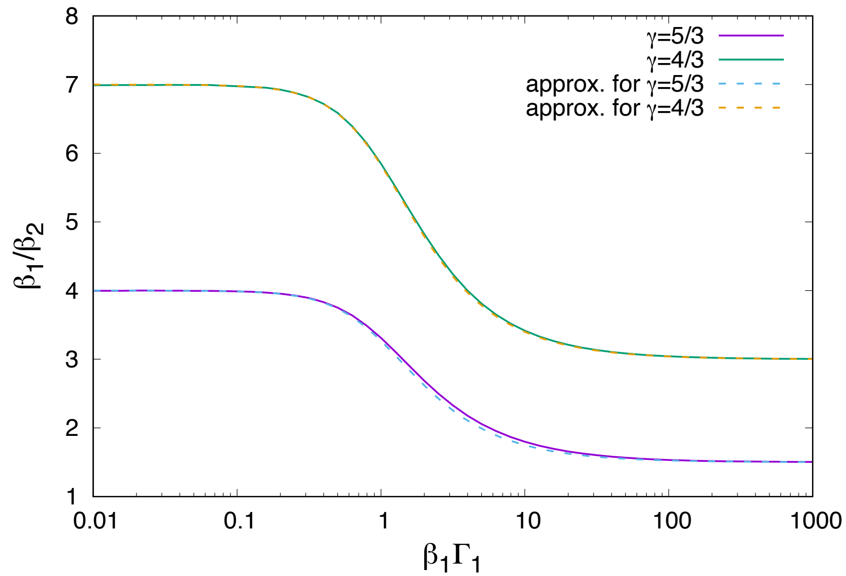
Eg: $\gamma=\frac{4}{3}$ → $\frac{\beta_2}{\beta_1}=\frac{1}{3}$



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



[viewed in shock restframe]



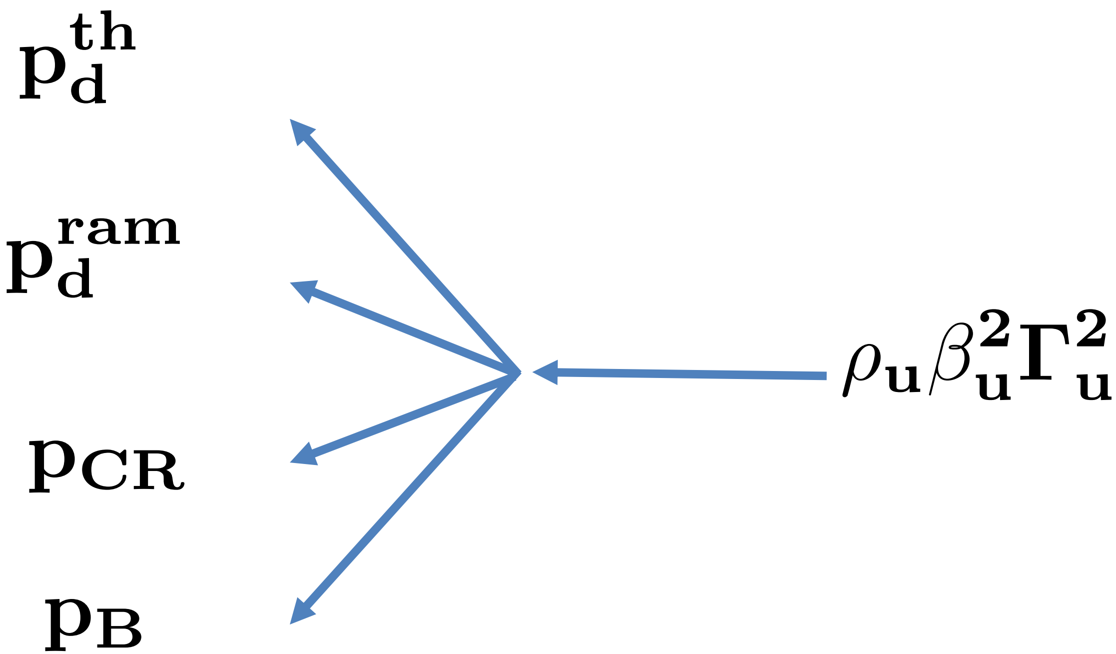
$$\mathbf{p_d^{th}} = \frac{2}{3}\rho_\mathbf{u}\beta_\mathbf{u}^2\Gamma_\mathbf{u}^2$$

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

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

But Does This Describe Astrophysical Shocks?

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



$$\varepsilon = \frac{p}{\rho_u \beta_u^2 \Gamma_u^2}$$

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:

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

For

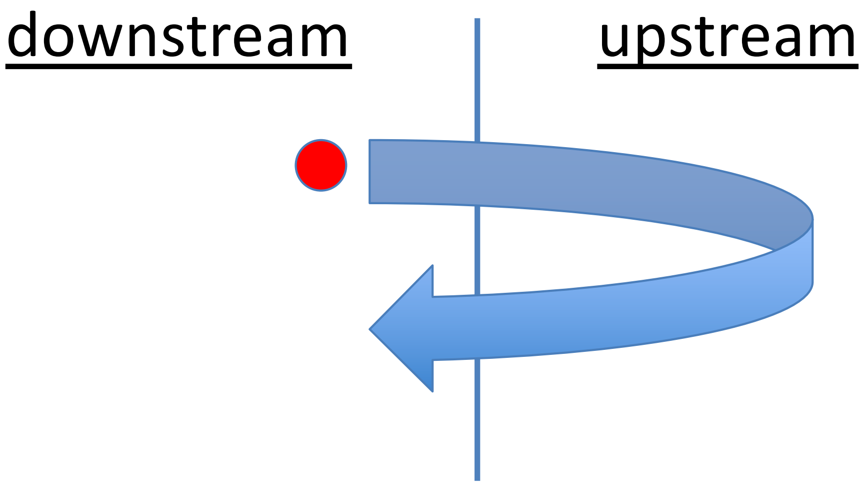
$\varepsilon_{\mathbf{B}} = \mathbf{0.1}$ $\quad \mathbf{n_u = 1\ cm^{-3}}$ $\quad \beta_{\mathbf{u}}\mathbf{\Gamma_u = 10}$

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

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

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

Particle Acceleration and Magnetic Turbulence



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

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

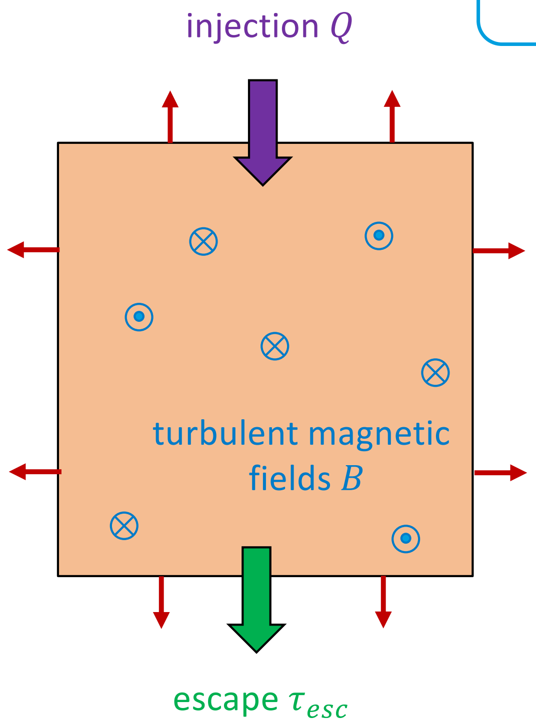
$$\mathbf{t_{scat}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}}$$

- 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

How Can We Probe ε_B and η in GRB?

One Zone Model (Spectral)



[Diagram + plot Courtesy of M. Klinger]

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

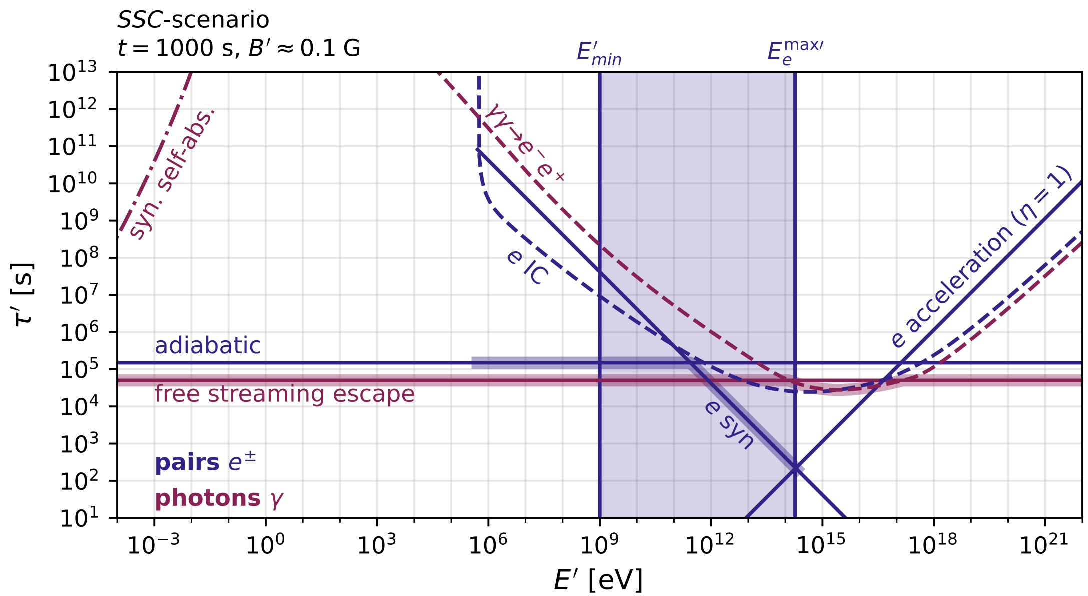
Note the absence of spatial information in these transport equations

Electron Spectrum Produced in Sources

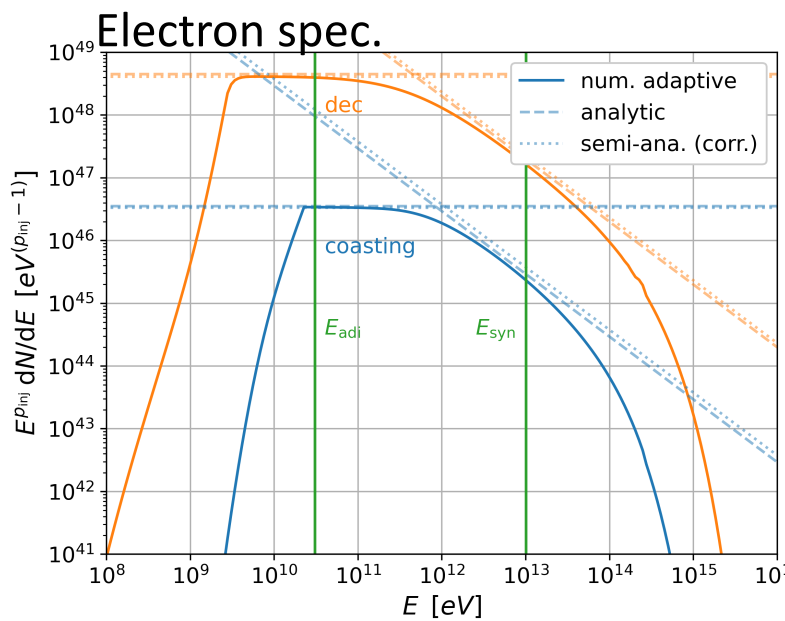
Steady state

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

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



Andrew Taylor



$$\mathbf{n_{ss}} = \frac{\tau_{\mathbf{cool}}}{\mathbf{E}} \int_{\mathbf{E}}^{\infty} \mathbf{Q}(\mathbf{E}')\mathbf{dE}'$$

PAUSE

Assuming Q(E) is a power-law, which end of the integral will dominate? (and for what values of the power-law slope?

Steady State Electron Spectra

$$\mathbf{Q(E')} = \mathbf{Q_0}\left(\frac{\mathbf{E'}}{\mathbf{E}}\right)^{-\alpha}$$

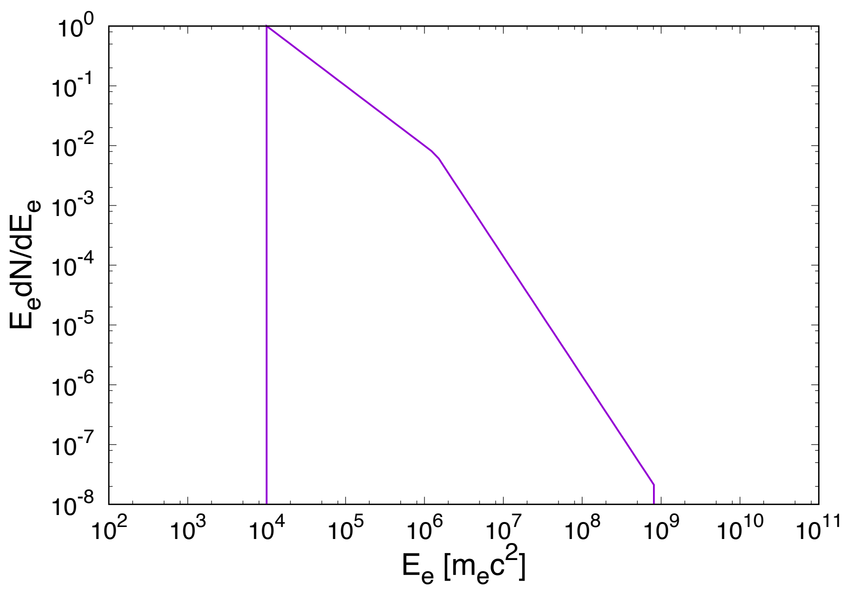
$$\mathbf{n_{ss}} = \frac{\tau_{\mathbf{cool}}}{\mathbf{E}}\int_{\mathbf{E}}^{\infty}\mathbf{Q_0}\left(\frac{\mathbf{E'}}{\mathbf{E}}\right)^{-\alpha}\mathbf{dE'}$$

$$= \frac{\tau_{\mathbf{cool}}\mathbf{Q_0}}{(\alpha - \mathbf{1})}$$

Steady State Electron Spectra

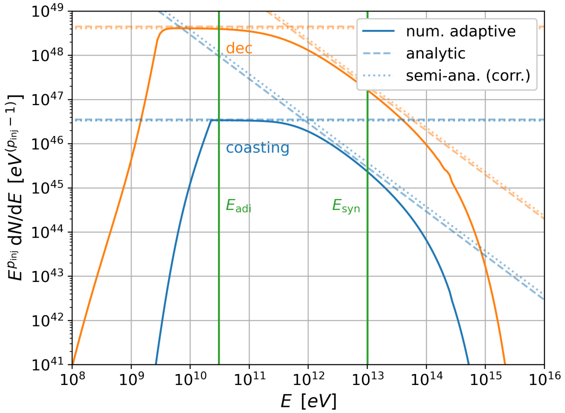
$$\mathbf{n_{ss}} = \frac{\tau_{\mathbf{cool}}}{\mathbf{E}} \int_{\mathbf{E}}^{\infty} \mathbf{Q(E')dE'}$$

$$\mathbf{n_{ss}} \approx \mathbf{Q}\tau_{\mathbf{cool}}$$



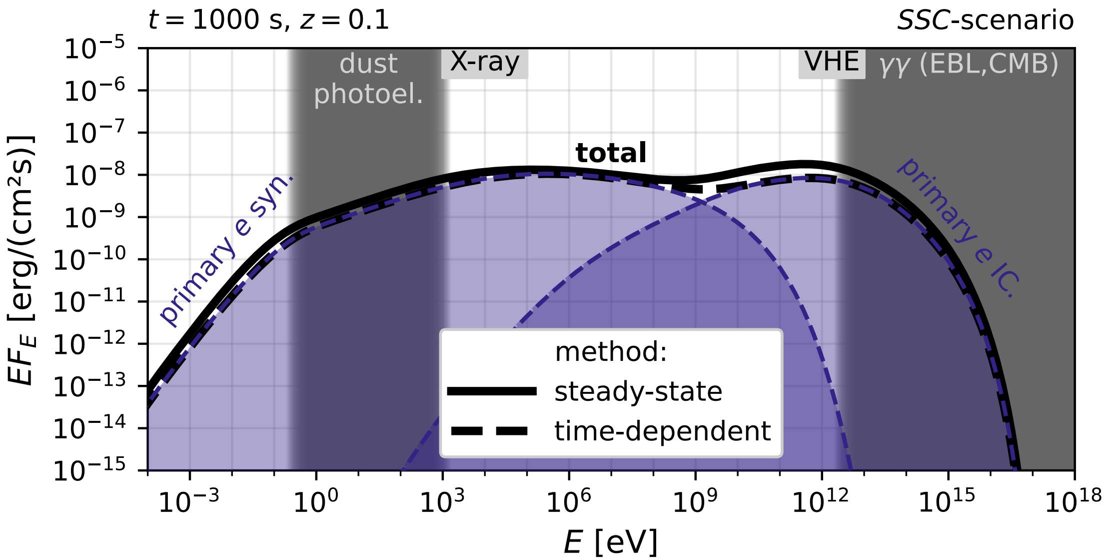
Afterglow GRB SED- Expected from SSC Model

Electron spec.



Photon spec.

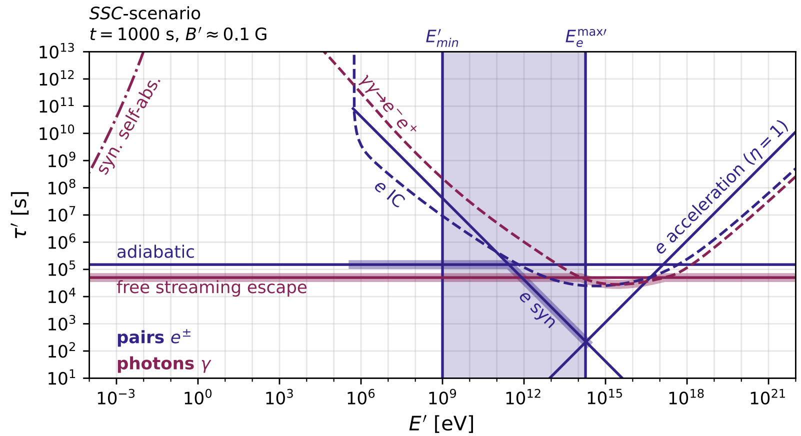
$\mathbf{U_B}$ $\mathbf{U_\gamma^{sync}}$



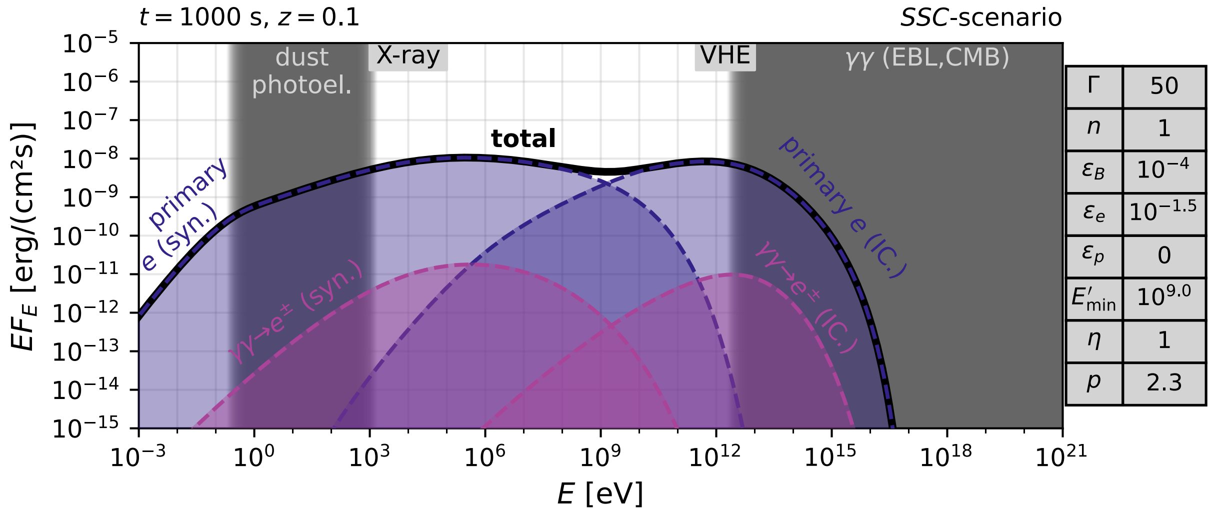
$$\mathbf{n_p \approx Q\tau_{loss}}$$

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.



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

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

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

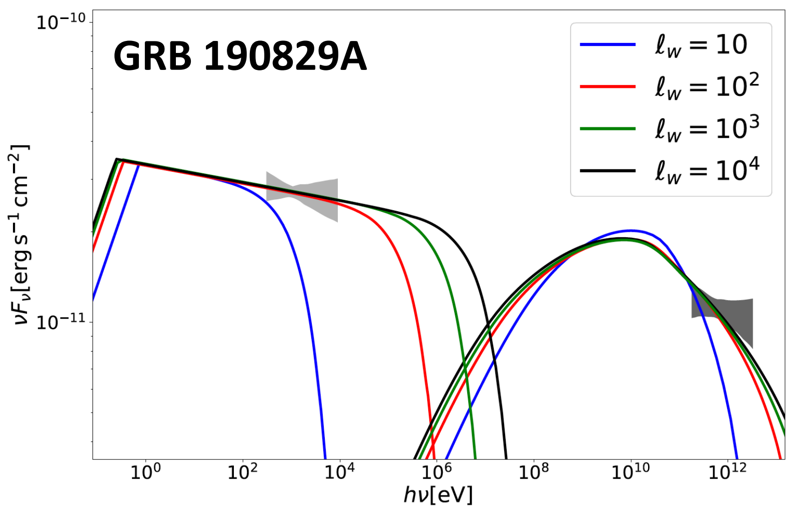
$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

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

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)]



Comparison to Observation

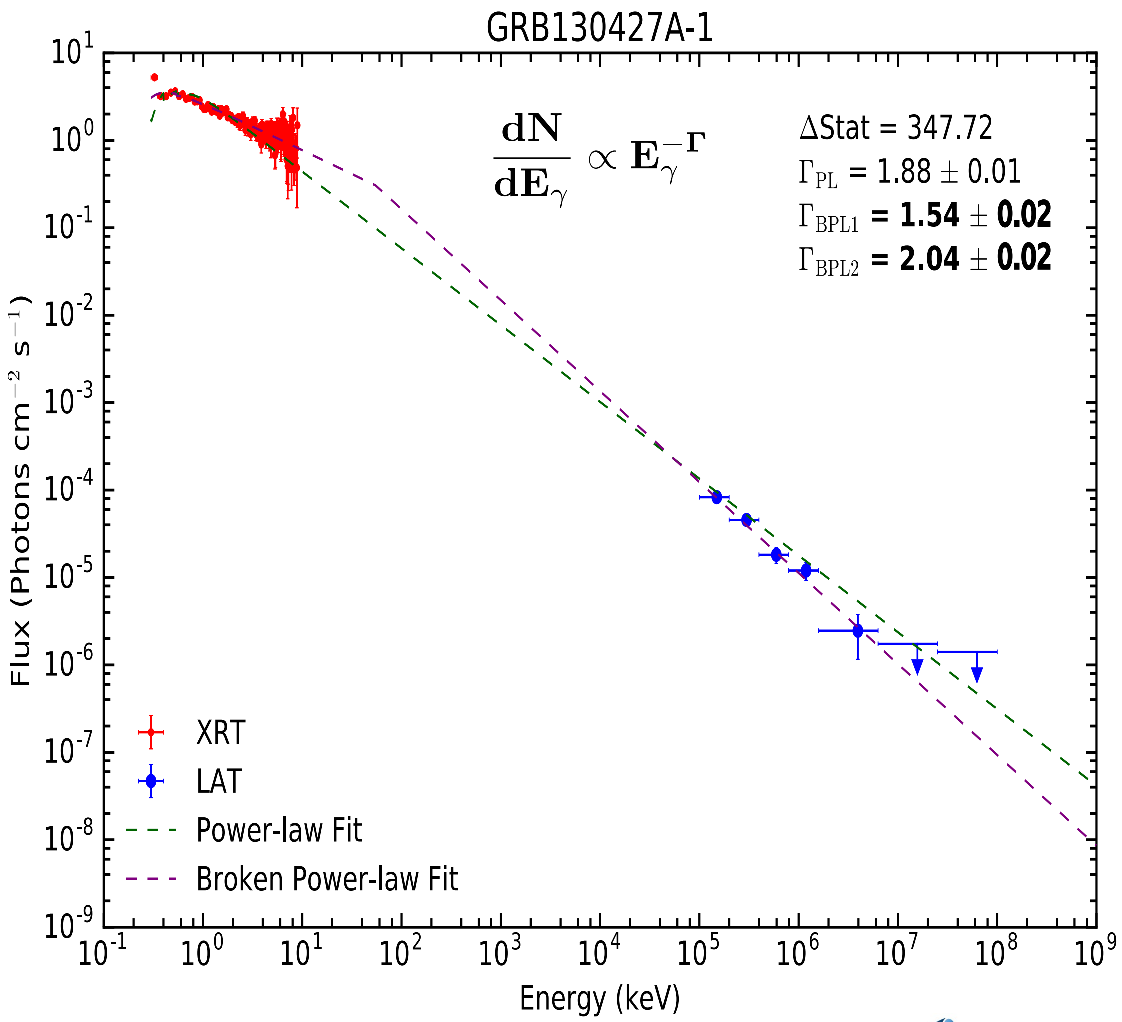
No Synchrotron Cutoff of the (2nd) Brightest GRB Seen by Fermi-LAT

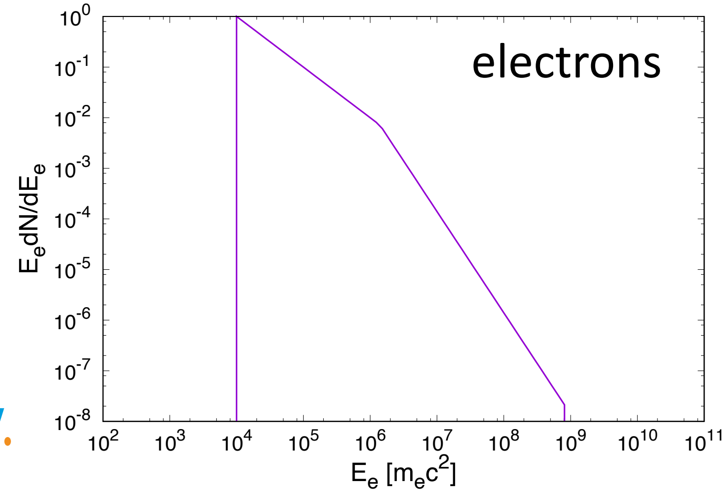
- GRBs at HE and VHE:
  ~12 GRBs per year Fermi-LAT

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

VHE emission has been a decades-long mystery

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

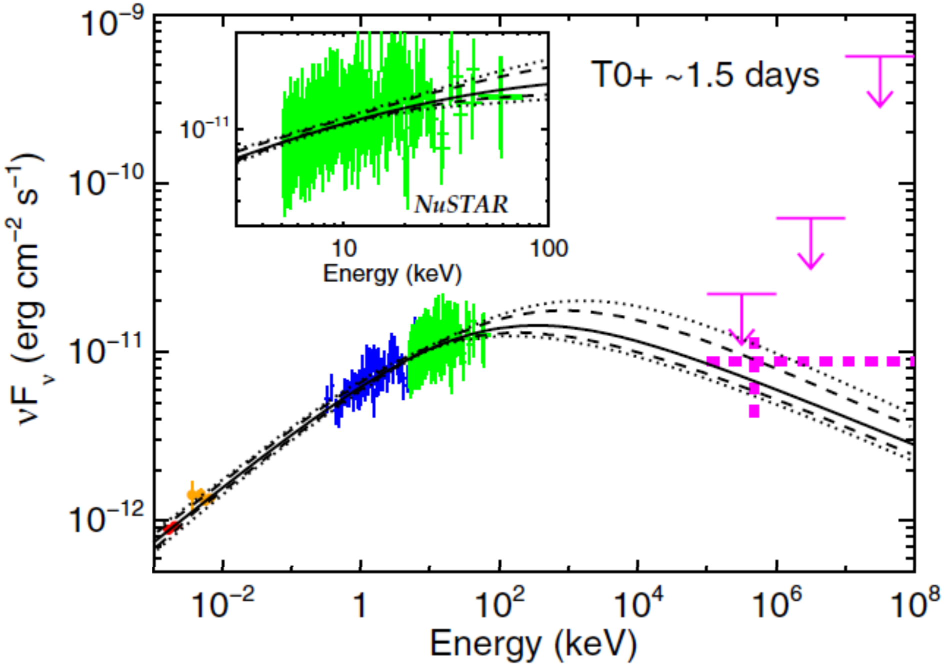




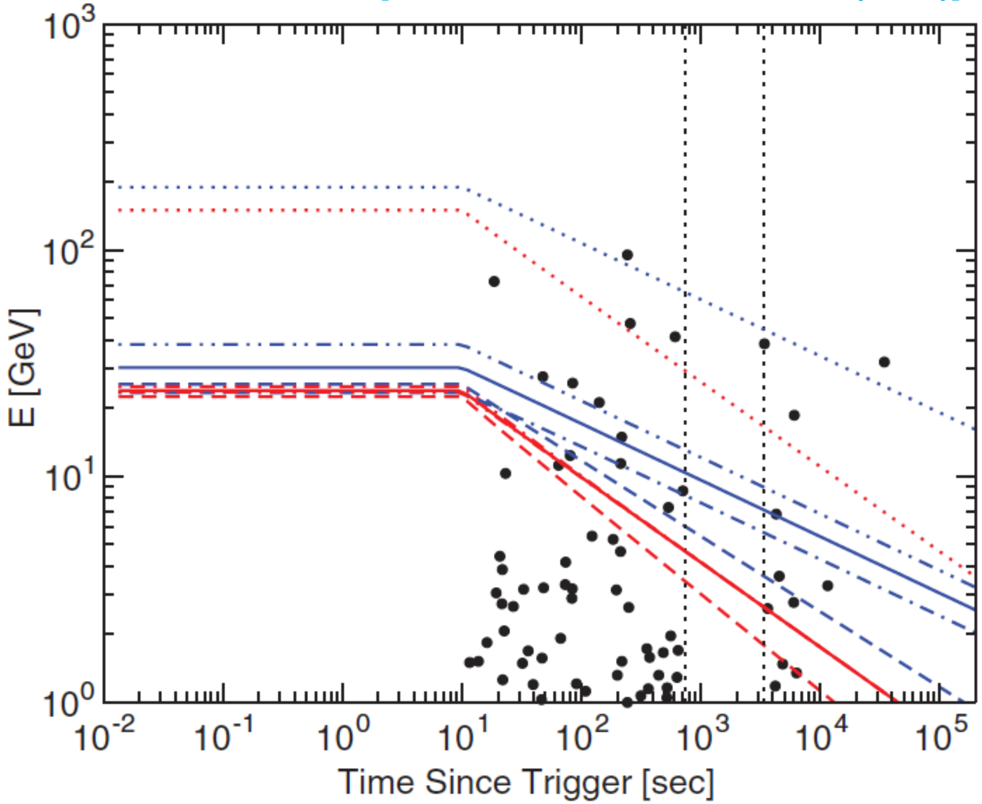
t^{GBM}_{90} ~ 140 s, t^{BAT}_{90} ~ 160 s
z = 0.34

No Synchrotron Cutoff of the (2nd) Brightest GRB Seen by Fermi-LAT

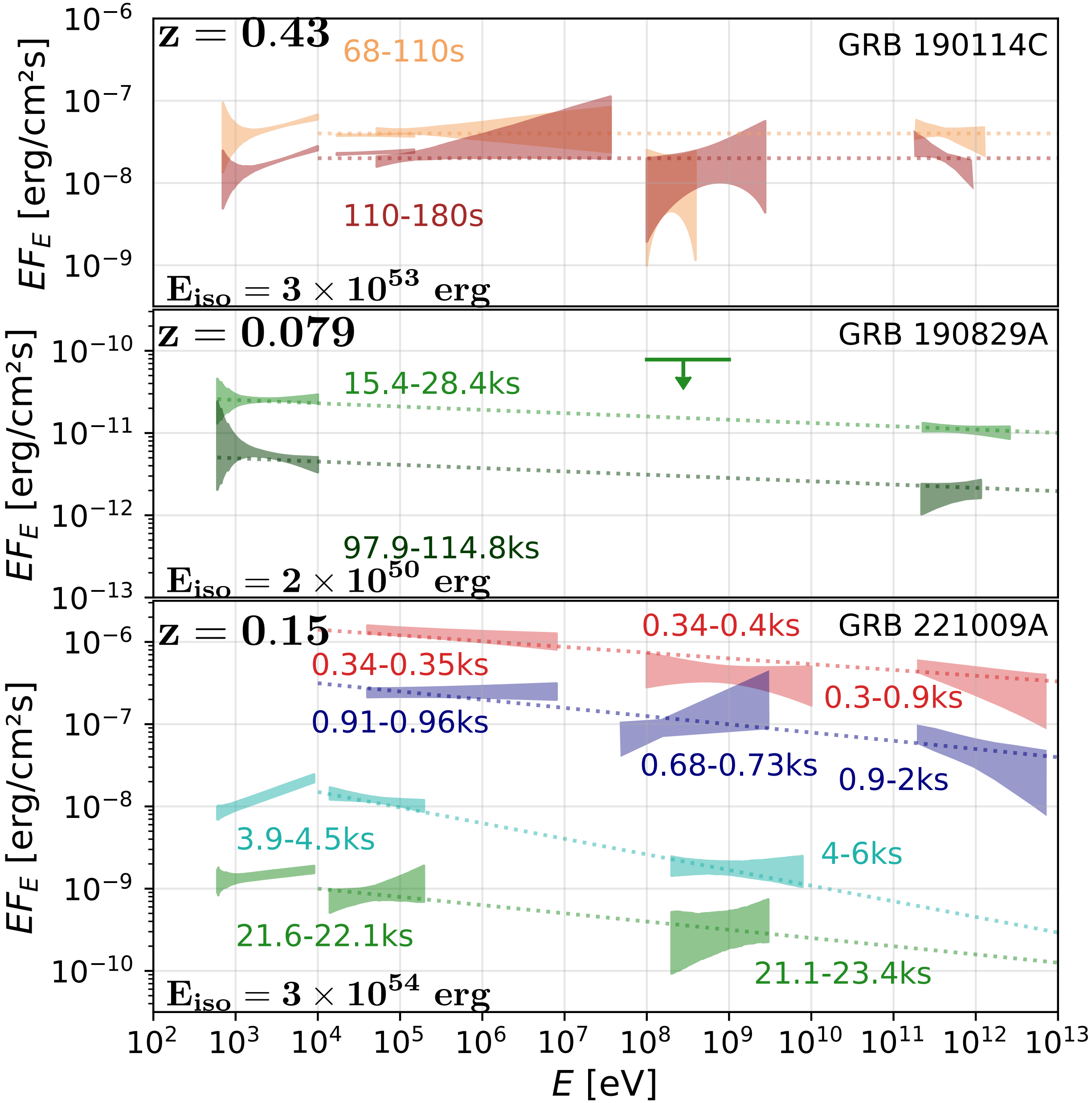
[Kouveliotou et al., ApJL 779 (2013)]



[Ackermann et al., Science 343 (2014)]



VHE GRB SED- Lessons Learnt Since 2018

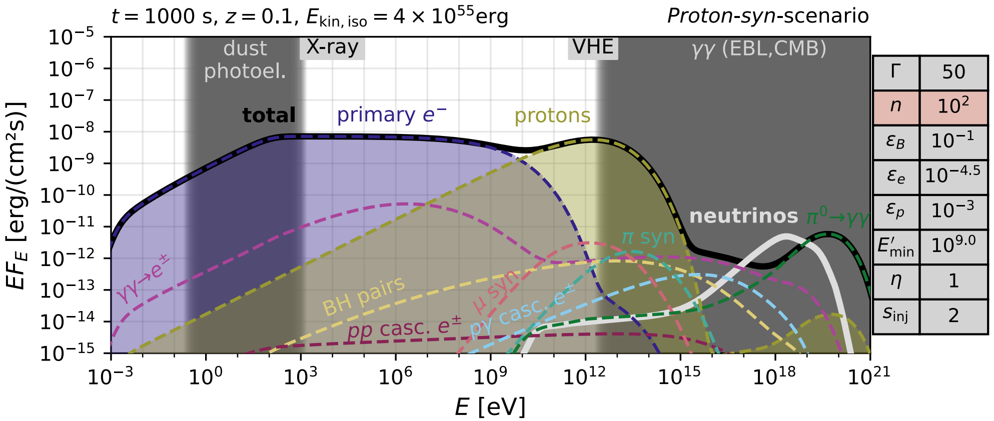


- Observed at a wide range of afterglow times (wide range of Γ)
- Striking how flat the MWL photon spectra are!
- The SSC model predicts a curved spectrum which may be in contradiction with these observations

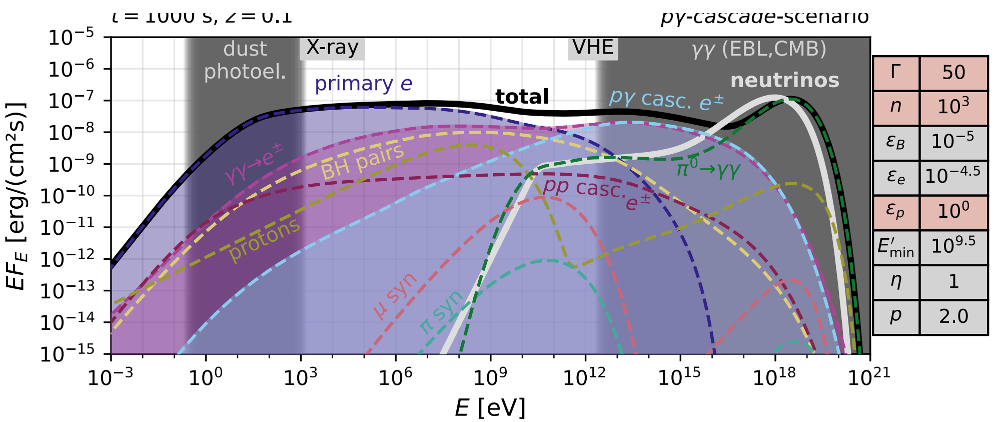
[MAGIC Coll. Nature 2019]
[HESS Coll. Science 2021]
[LHAASO Coll., Science 2023]

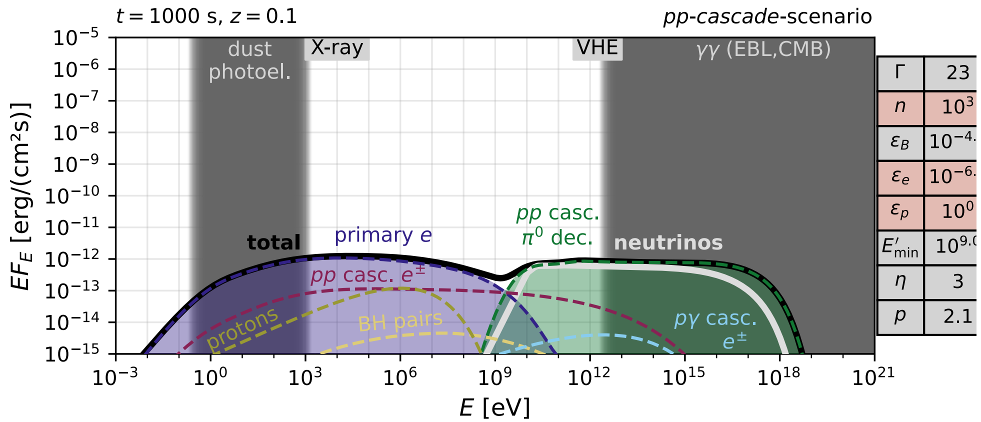
[Klinger et al. arxiv:2403.13902]

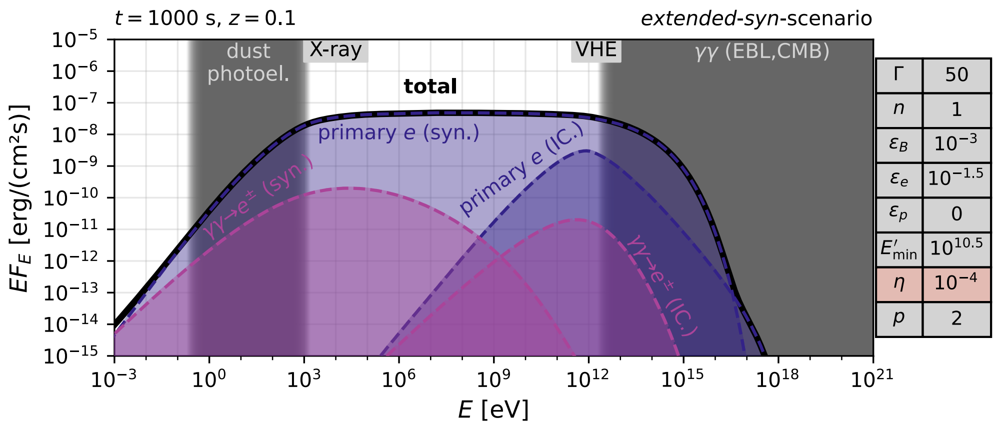
Alternative 1-Zone Scenarios?



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







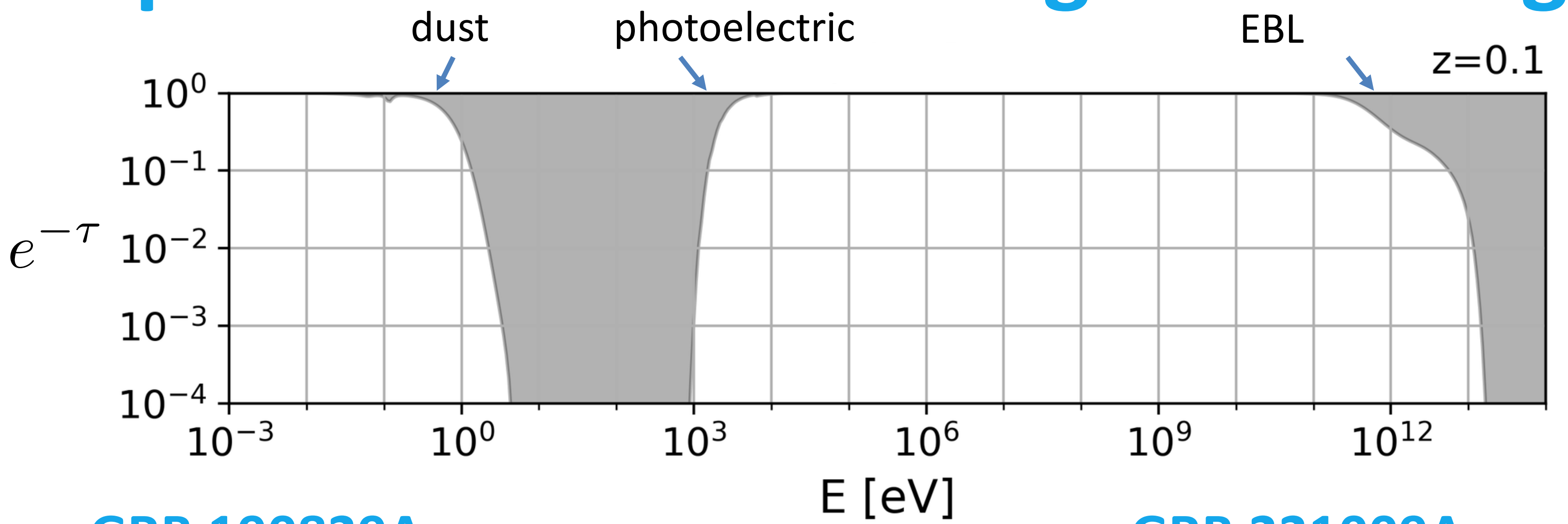
Each scenario requires rather extreme parameter values (see highlighted box)

[Klinger et al., arxiv:2403.13902

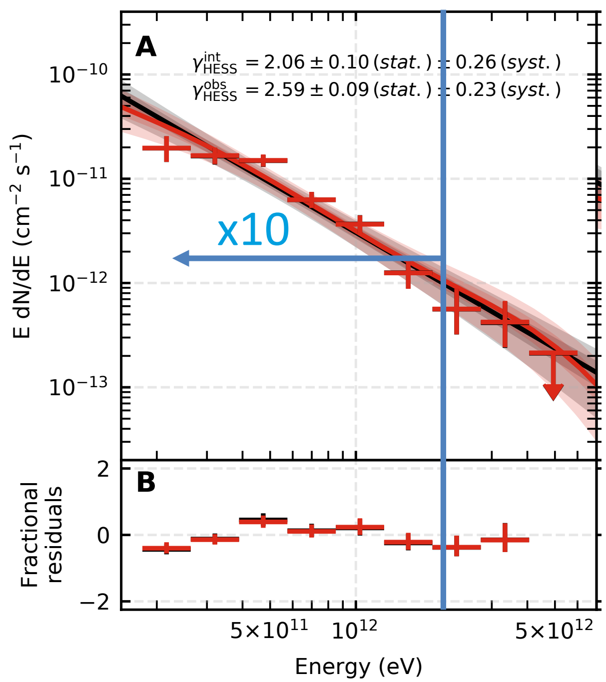
[Khangulyan et al., Ap. J. 914 (2021)]

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

Importance of Minimising EBL Damage

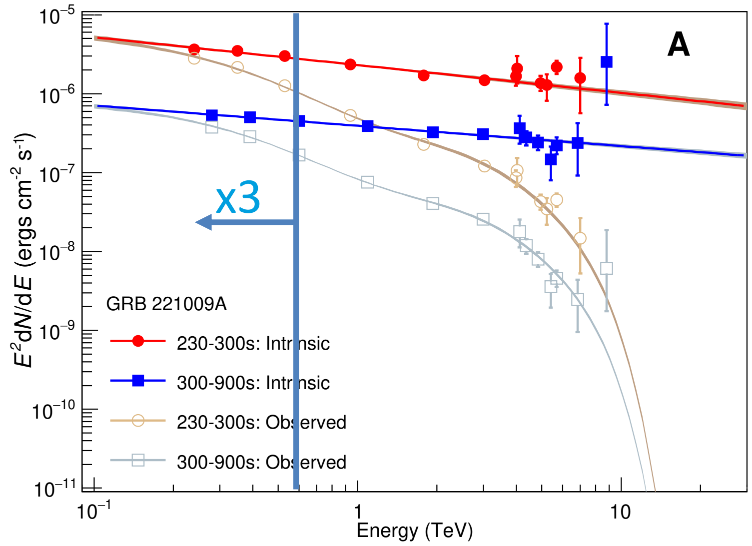


GRB 190829A



[HESS Coll. Science 2021]

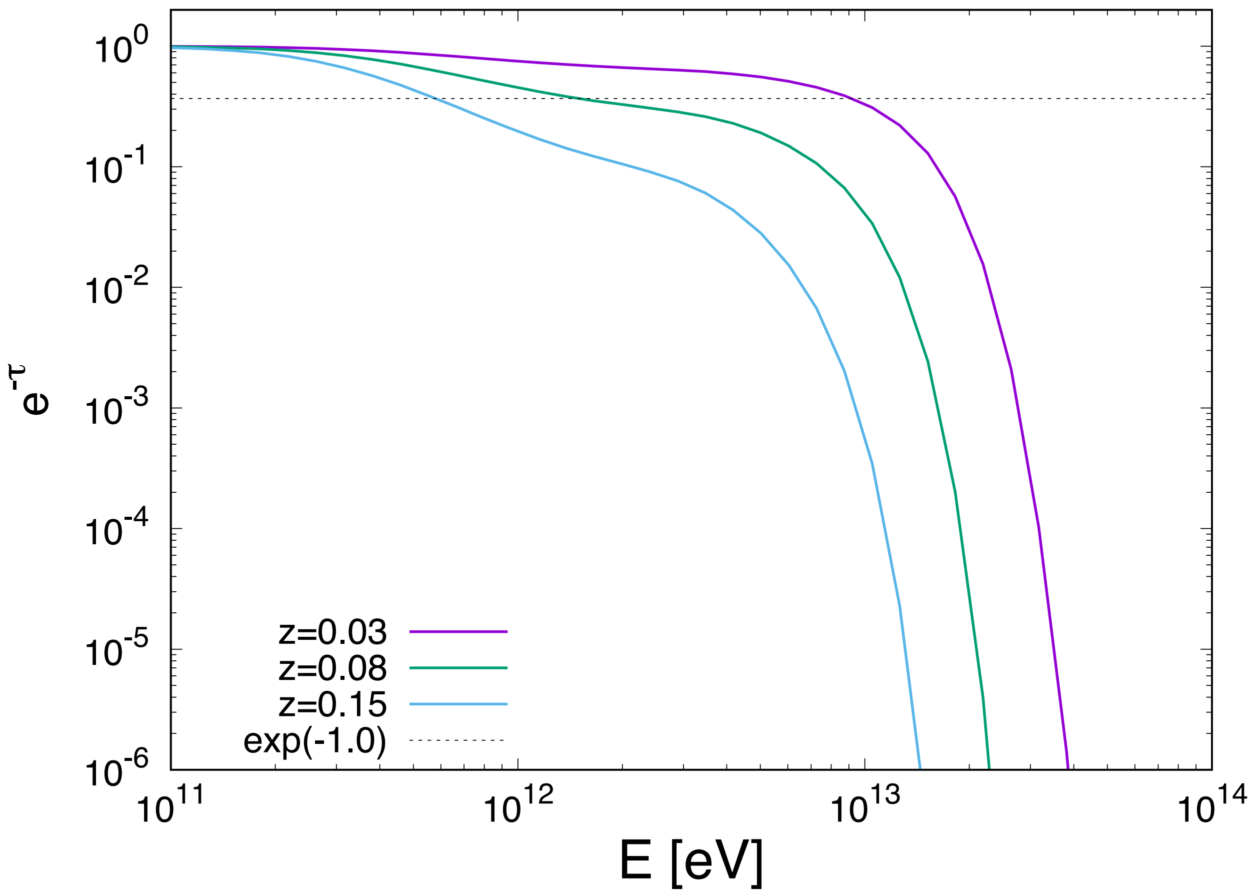
GRB 221009A



[LHAASO Coll. Science 2023]

What Can We Hope From Future Observations?

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

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

DESY.

Conclusions

- Fast (rel.) shocks in the ejecta of GRB jets appear to operate as particle acceleration machines

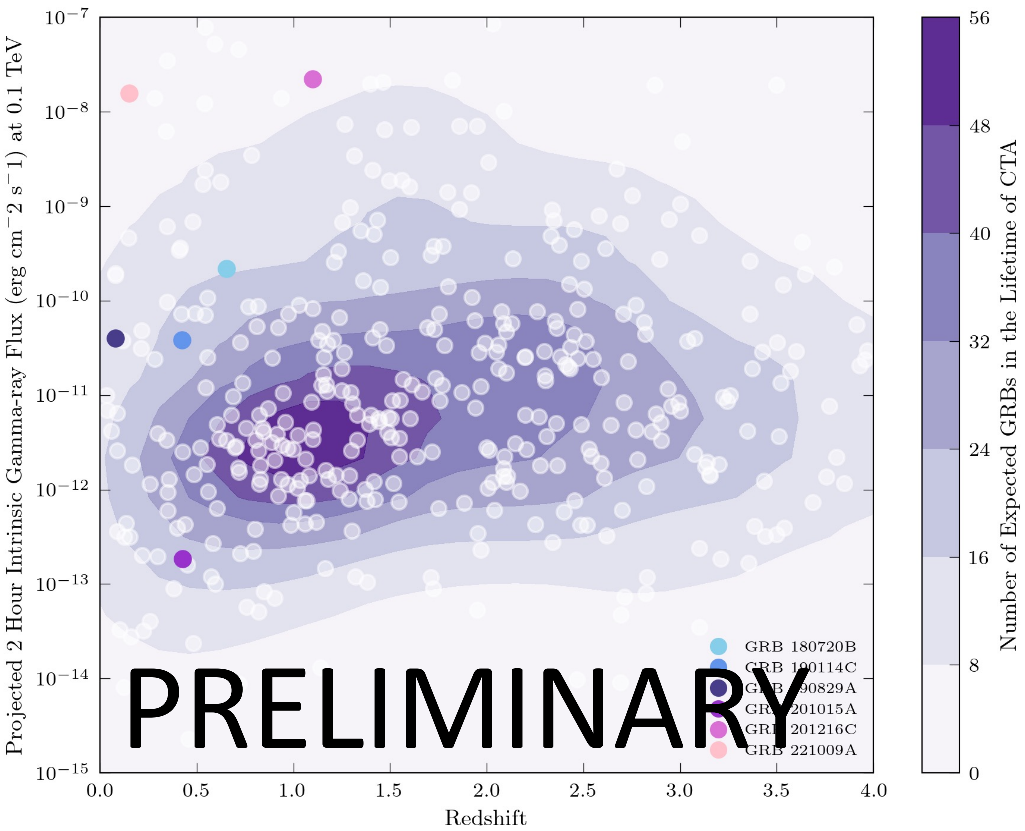
- Synchrotron emission from long GRB can tell us directly how efficient these sources operate as cosmic ray accelerators

- 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

Prospective Rates for Testing the GRB Emission Process with CTA



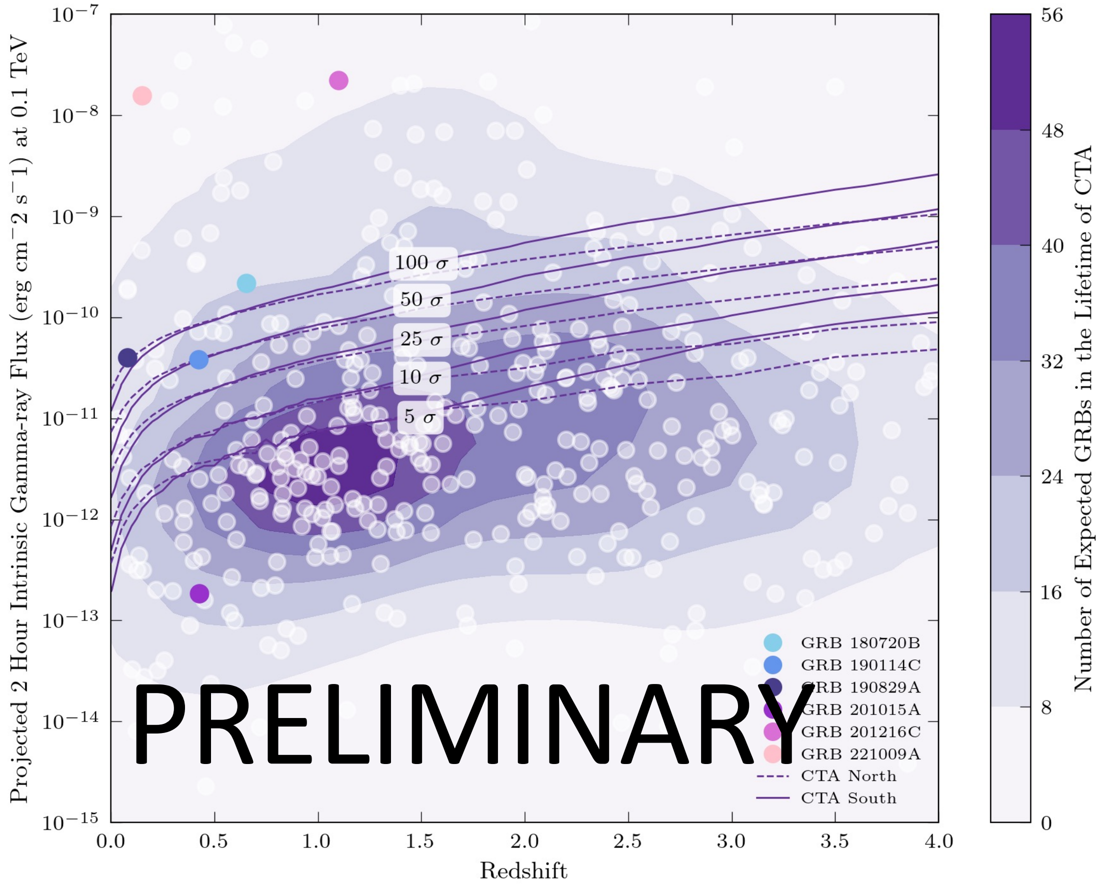
[Provided by J. Pfeil and D. Parsons]

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

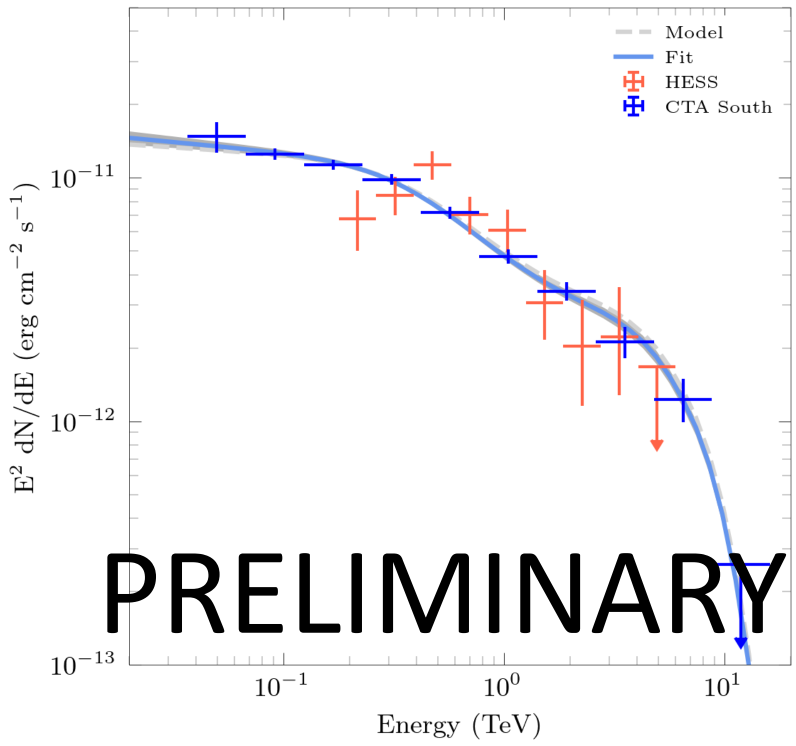
- For CTA, a rate of up to 4 yr $^{-1}$ is possible to expect, consistent with other estimates
  [Ashkar et al., ApJ 964 57]

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

Prospects for Testing the GRB Emission Process with CTA



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



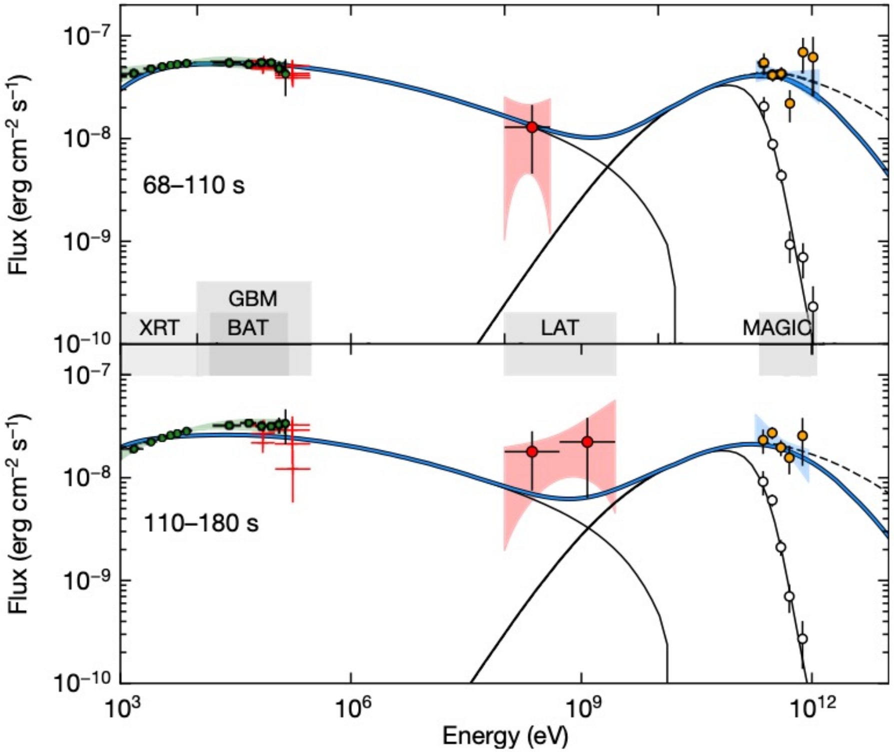
	EBL Attenuated Power Law	
Fit Parameter	HESS	CTA South
γ^{int}	$2.06 \pm 0.10 \pm 0.26$	2.09 ± 0.02

[Provided by J. Pfeil and D. Parsons]

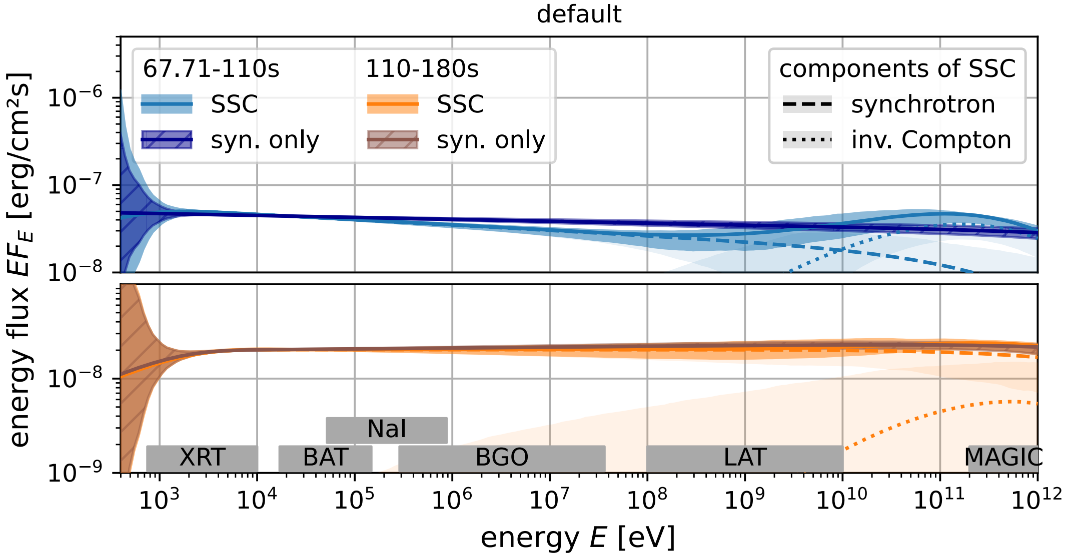
DESY.

Statistical Tests- A Spectral Model Fit for GRB 190114C

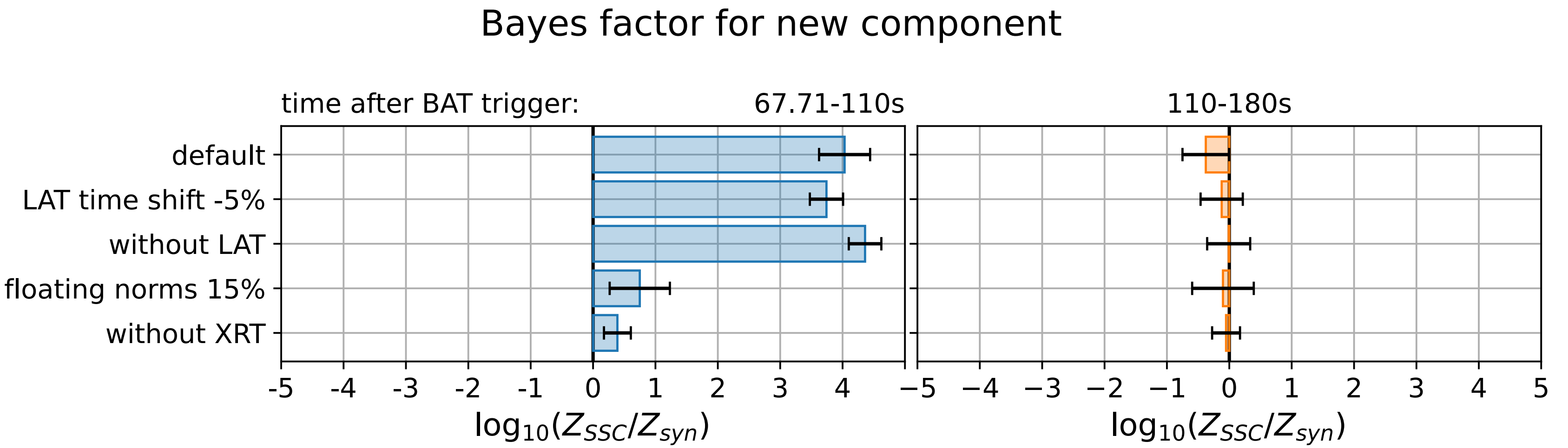
[MAGIC Coll. Nature 2019]



[Klinger et al. MNRAS 520 (2023)]

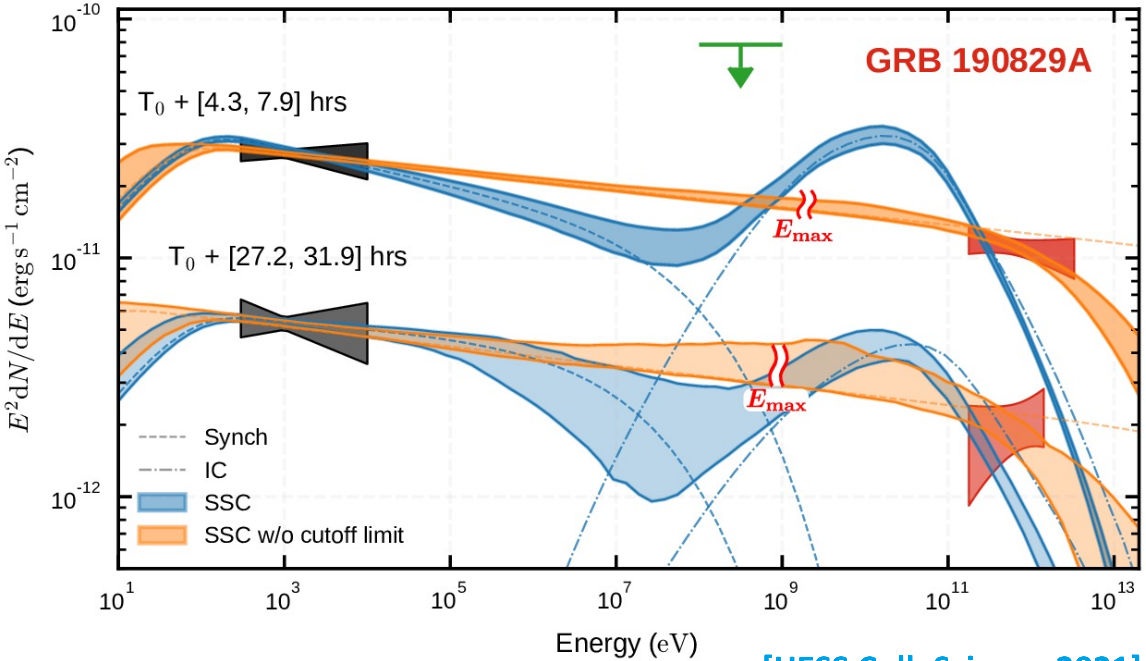


[Fermi+Swift. ApJ 890 (2020)]



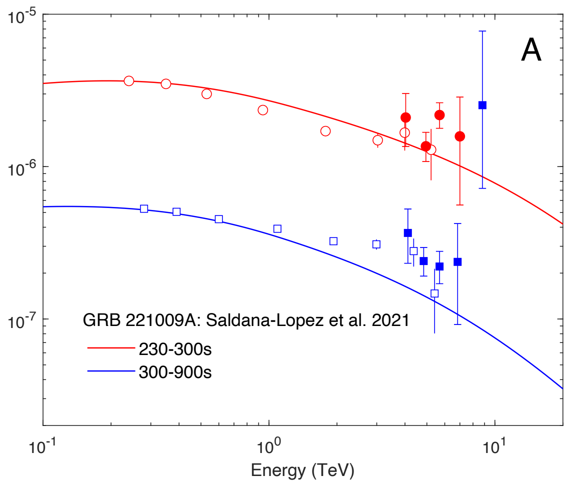
DESY.

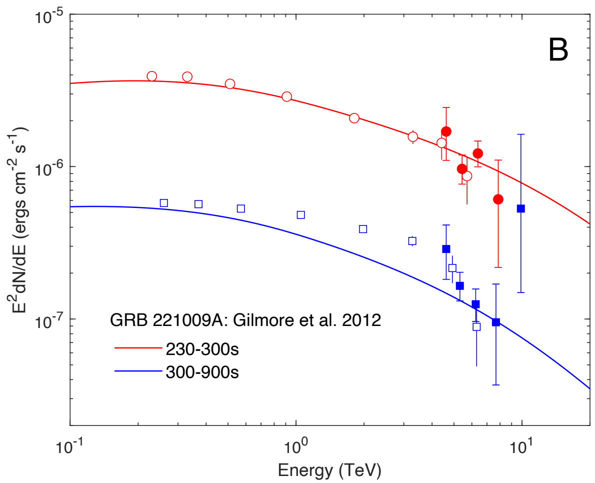
Statistical Tests- Spectral Model Fits other GRB



GRB 190829A
[15-28 ks]

[HESS Coll. Science 2021]



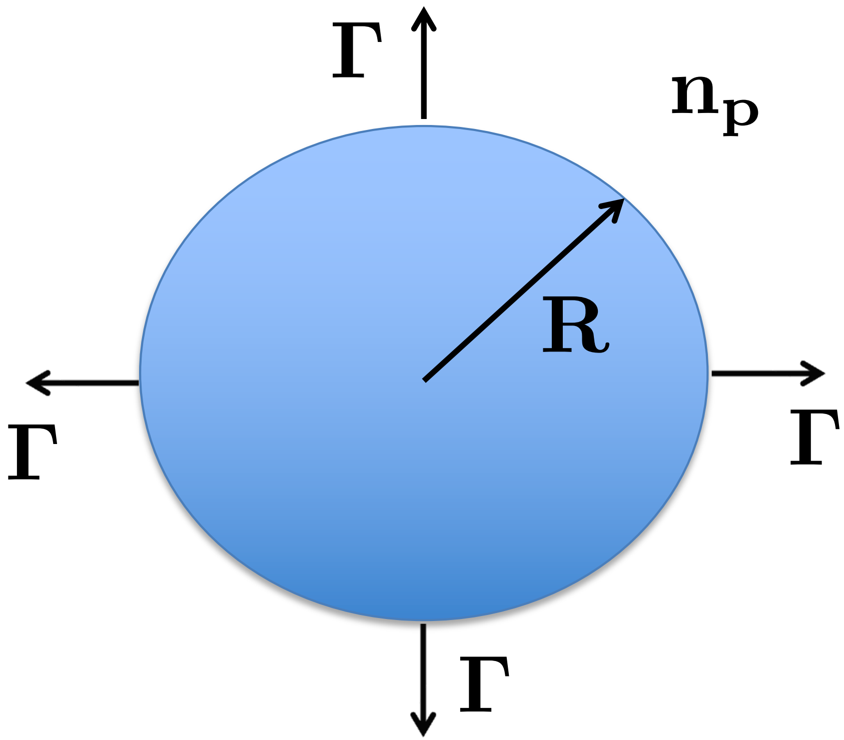


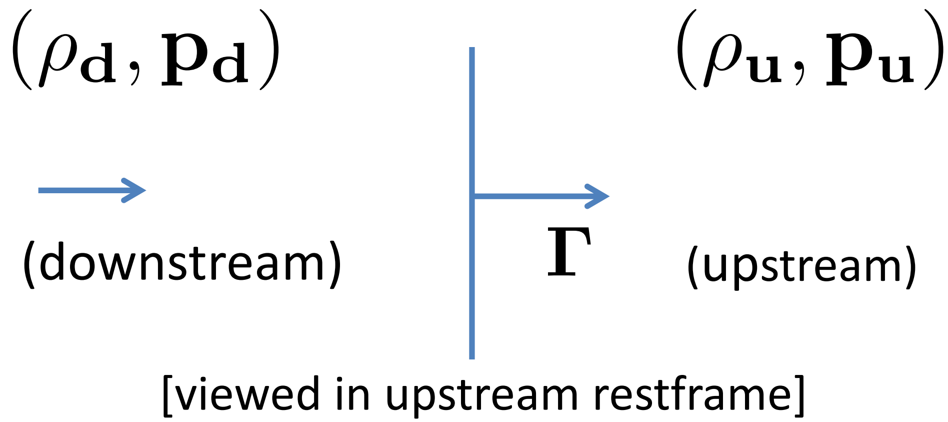
GRB 221009A
[0.2-0.9 ks]

[LHAASO Coll. Science 2023]

DESY.

Origin of Temporal Decay Structure





Assuming η_γ is constant in time.....

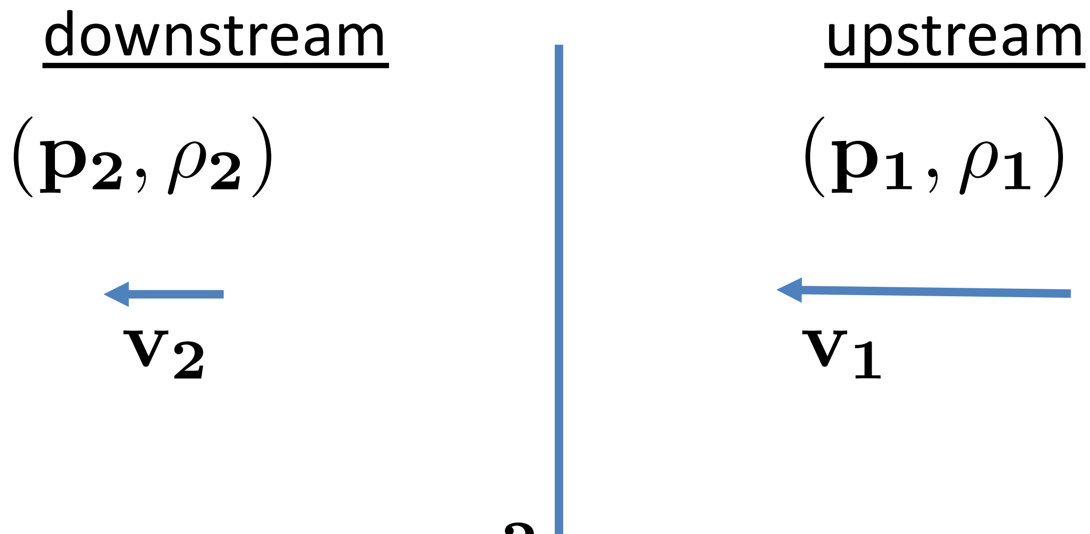
$$\frac{L_{sync}^{iso}}{4\pi\Gamma^2 R^2 c} = \varepsilon_{rad}\Gamma^2 n_p m_p c^2$$

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

$$L_{sync}^{iso} \propto t^{-1}$$

Reminder: (Non-Rel.) Shocks

The fastest speed information in plasmas can be transmitted is the sound speed. When plasmas travel faster than this, they set up a shock- the upstream region is not able to know what is coming (**a surprise**!).



Shock converts ram pressure ($\rho\mathbf{v}^\mathbf{2}$) into thermal pressure ($\mathbf{p}$)

Collisional Shock- Conservation Conditions

<u>downstream</u> | <u>upstream</u>

$(\mathbf{p_2}, \rho_2)$ | $(\mathbf{p_1}, \rho_1)$

$\leftarrow \mathbf{v_2}$ | $\leftarrow \mathbf{v_1}$

Number Flux: $$\rho_1 \mathbf{v_1} = \rho_2 \mathbf{v_2}$$

Momentum Flux: $$\mathbf{p_1} + \rho_1 \mathbf{v_1^2} = \mathbf{p_2} + \rho_2 \mathbf{v_2^2}$$

Energy Flux: $$\mathbf{w_1 v_1} + \frac{1}{2}\rho_1 \mathbf{v_1^3} = \mathbf{w_2 v_2} + \frac{1}{2}\rho_2 \mathbf{v_2^3}$$

Collisional Shock- Enthalpy

$$\gamma = \frac{\mathbf{w}_{\mathbf{nonrel.}}}{\mathbf{e}}$$

$$= \frac{\mathbf{e} + \mathbf{p}}{\mathbf{e}}$$

$$\mathbf{e} = \frac{\mathbf{p}}{\gamma - \mathbf{1}}$$

$$\mathbf{w}_{\mathbf{nonrel.}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p}$$

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

$$= \mathbf{w}_{\mathbf{nonrel.}} + \rho$$

Collisional Shock- Cold Shock Case

Momentum Flux:

$$\rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$

$$\frac{p_2}{\rho_1 v_1^2} = \left(1 - \frac{v_2}{v_1}\right)$$

Energy Flux:

$$\frac{1}{2}\rho_1 v_1^3 = \left(\frac{\gamma}{\gamma - 1}\right) p_2 v_2 + \frac{1}{2}\rho_2 v_2^3$$

$$\frac{2\gamma}{\gamma - 1}\frac{p_2 v_2}{\rho_1 v_1^3} = \left(1 - \left(\frac{v_2}{v_1}\right)^2\right) = \left(1 - \frac{v_2}{v_1}\right)\left(1 + \frac{v_2}{v_1}\right)$$

Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\mathbf{1}\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-\mathbf{1}}{\gamma+\mathbf{1}}\right)\right)=\mathbf{0}$$

So what are collisional shocks good for?

Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\mathbf{1}\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-\mathbf{1}}{\gamma+\mathbf{1}}\right)\right)=\mathbf{0}$$

Eg: $\gamma=\frac{\mathbf{5}}{\mathbf{3}}$ → $\frac{\beta_{\mathbf{2}}}{\beta_{\mathbf{1}}}=\frac{\mathbf{1}}{\mathbf{4}}$

So what are collisional shocks good for?
Stimulating the unstimulated degrees of freedom in the system where momentum/energy can be stored

Cold Relativistic Shocks

Momentum Flux:

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

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

Energy Flux:

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

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

Particle Accelerator Limits

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

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

[AM Hillas (1984)]

$$\mathbf{E_{max}} = \beta \mathbf{eBR}$$

$$\mathbf{L_B} = \mathbf{U_B} 4\pi \mathbf{R^2} \beta \mathbf{c}$$

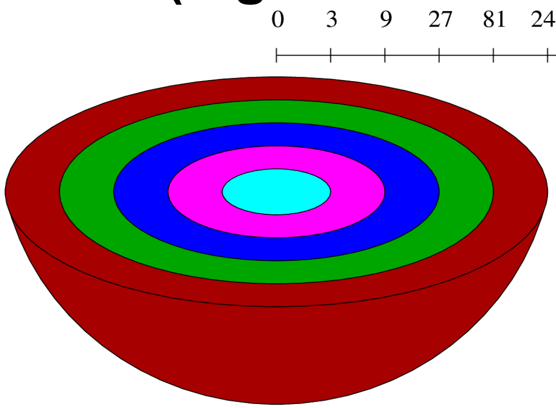
Under the assumption of equipartition of energy between kinetic energy and magnetic field:

[Lovelace et al. (1976)]

$$\mathbf{E_{max}} \lesssim \frac{\mathbf{Z}}{\eta} (\beta \mathbf{L_{KE}} \alpha \hbar)^{\mathbf{1/2}} \approx \mathbf{10} \frac{\mathbf{Z}}{\eta} \left(\frac{\beta \mathbf{L_{KE}}}{\mathbf{3} \times \mathbf{10^{43}\ erg\ s^{-1}}} \right)^{\mathbf{1/2}} \mathbf{EeV}$$

Cosmic Ray Sources Have to be Local

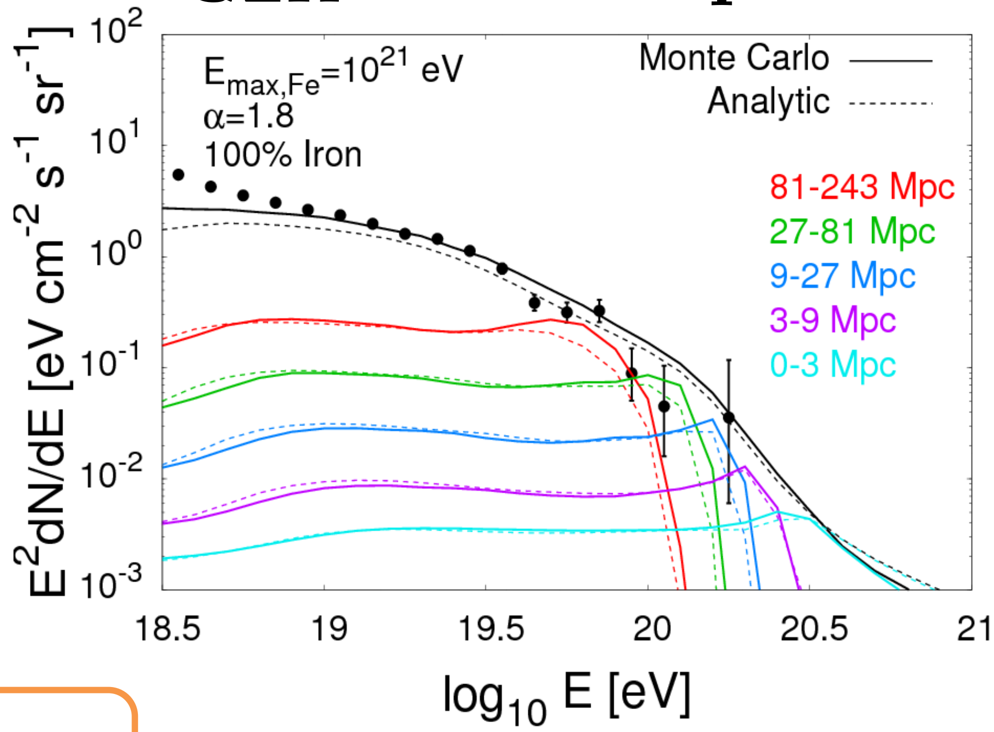
(logarithmic scale)



[A. Taylor et al., Phys Rev D (2011)]

[R. Lang and A. Taylor in prep.]

$$d_{GZK} \sim 100 \text{ Mpc}$$



$$\mathcal{L}_0 \approx 4 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

[E. Waxman, Astrophys. J. 452 (1995)]

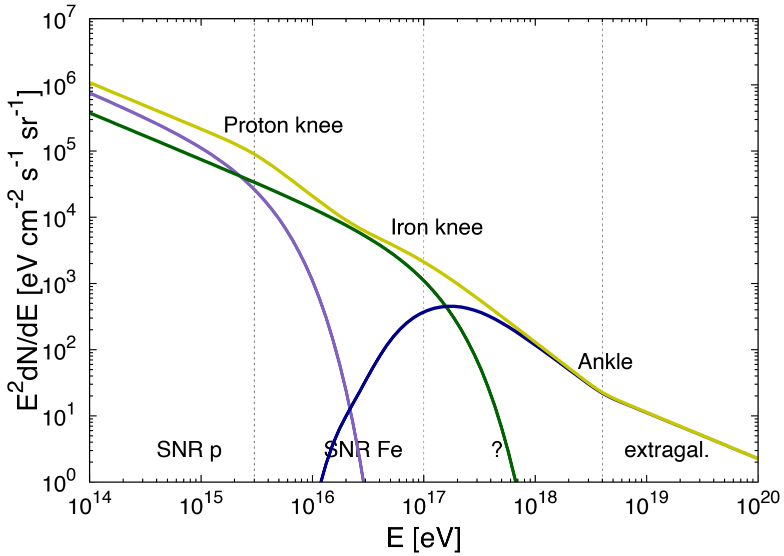
$$\mathcal{L}_0 \approx L_0 n_0$$
$$\approx E_0 \dot{n}_0$$

⇒

$$n_0 \sim 10^{-5} \text{ Mpc}^{-3}$$
$$\dot{n}_0 \sim 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$$

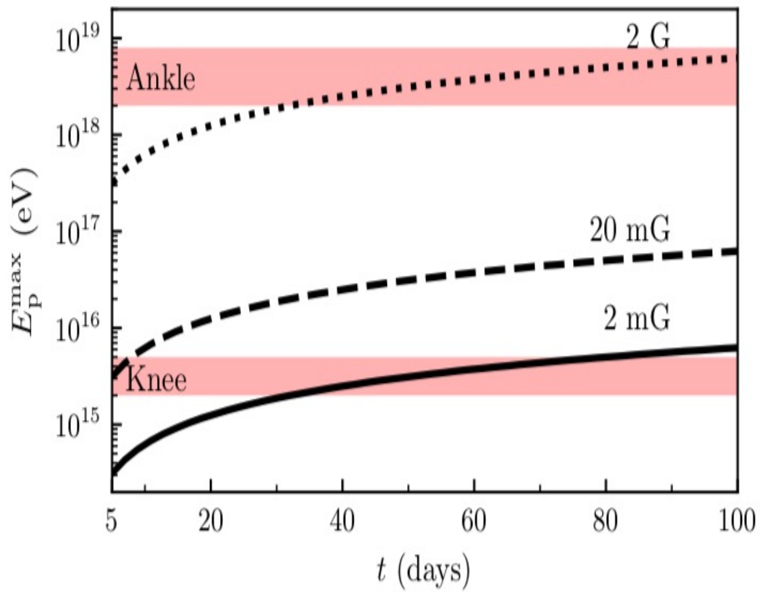
Only AGN and GRB appears to satisfy these requirements as the sources of extragalactic cosmic rays

GRB Outflows as a Cosmic Ray Source



- 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]

Hydro Turbulence

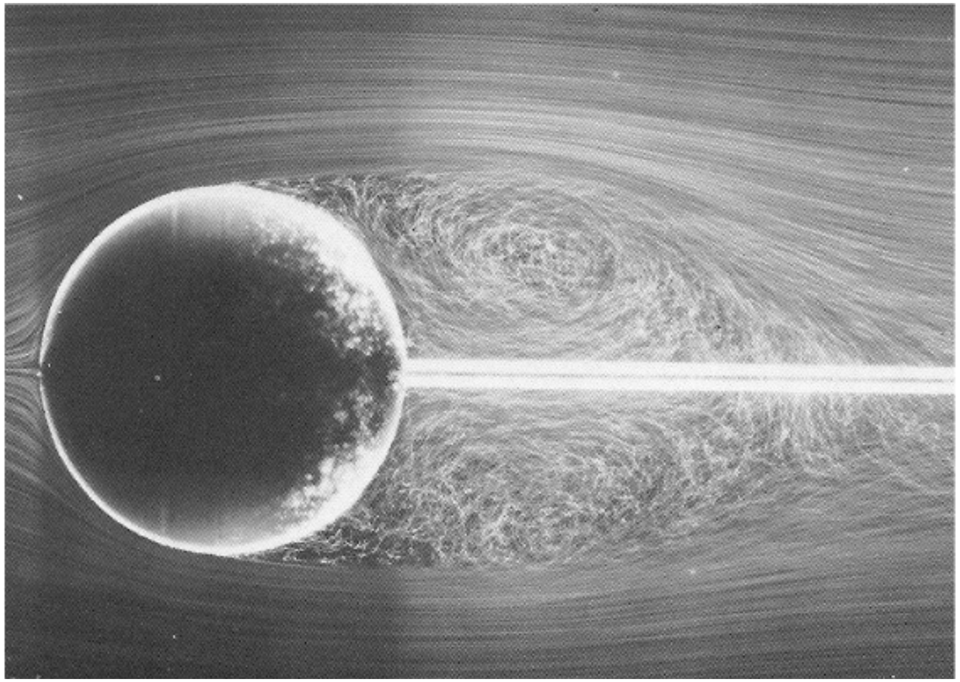
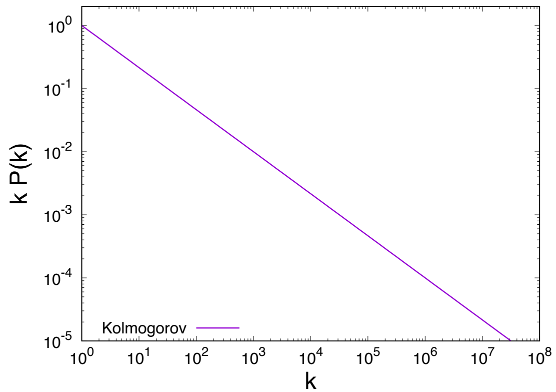
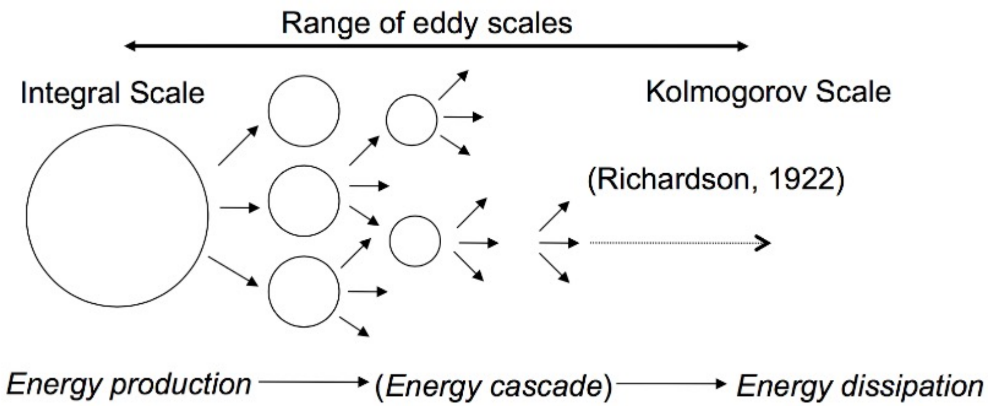


Image from University of Sydney

Richardson, 1922

> *Big whorls have little whorls*
> *That feed on their velocity;*
> *And little whorls have lesser whorls*
> *And so on to viscosity.*





Hydrodynamics

A brief comment-

$$\frac{\partial \rho \mathbf{v}}{\partial \mathbf{t}} + \nabla \cdot \mathbf{P} = \rho \mathbf{g}$$

Momentum flux conservation

$$\mathbf{P} = \mathbf{pI} + \rho \mathbf{vv}$$

Spatial part of stress energy tensor

$$\rho \frac{\partial \mathbf{v}}{\partial \mathbf{t}} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \mathbf{p} + \rho \mathbf{g}$$

Magneto-Hydrodynamics

A brief comment-

$$\frac{\partial \rho \mathbf{v}}{\partial \mathbf{t}} + \nabla \cdot (\mathbf{P} - \mathbf{P_M}) = \rho \mathbf{g}$$

Momentum flux conservation

$$\mathbf{P} = \mathbf{pI} + \rho \mathbf{vv}$$

$$\mathbf{P_M} = -\frac{\mathbf{B^2}}{\mathbf{8}\pi}\mathbf{I} + \frac{\mathbf{BB}}{\mathbf{4}\pi}$$

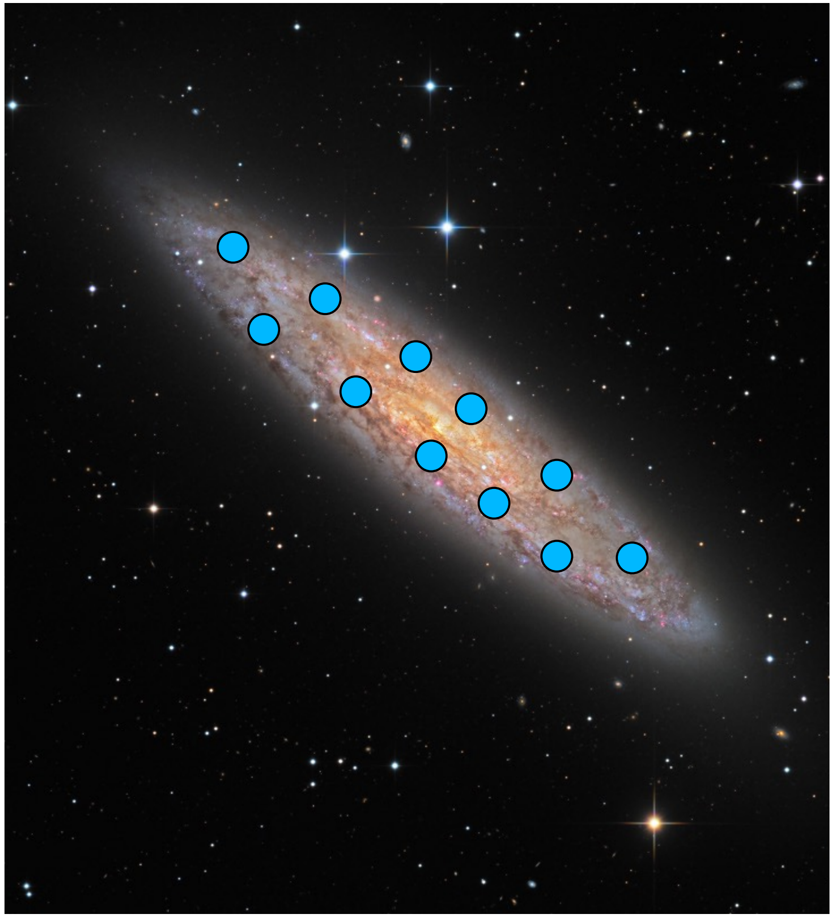
Maxwell stress tensor

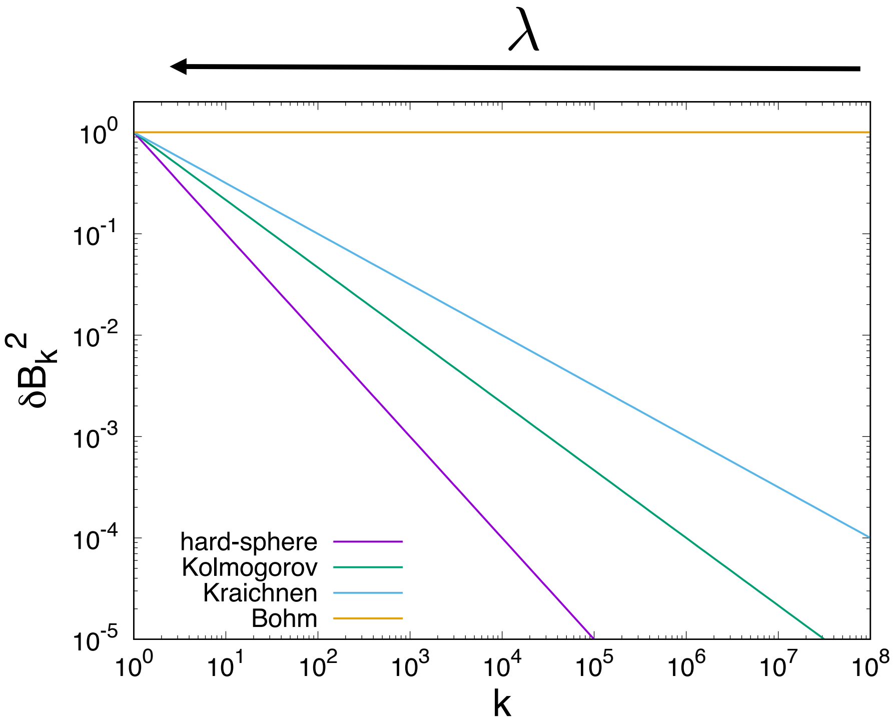
Galactic Magneto-Hydro Turbulence

One of the key drivers is thought to be Supernova explosions

$$\delta \mathbf{B^2} = \int \frac{\mathbf{d}(\delta \mathbf{B^2})}{\mathbf{d} \ln \mathbf{k}} \mathbf{d} \ln \mathbf{k} = \int \delta \mathbf{B_k^2} \mathbf{d} \ln \mathbf{k}$$

$$\delta \mathbf{B_k^2} = \delta \mathbf{B_0^2} \left(\frac{\mathbf{k}}{\mathbf{k_0}} \right)^{\mathbf{1}-\alpha}$$

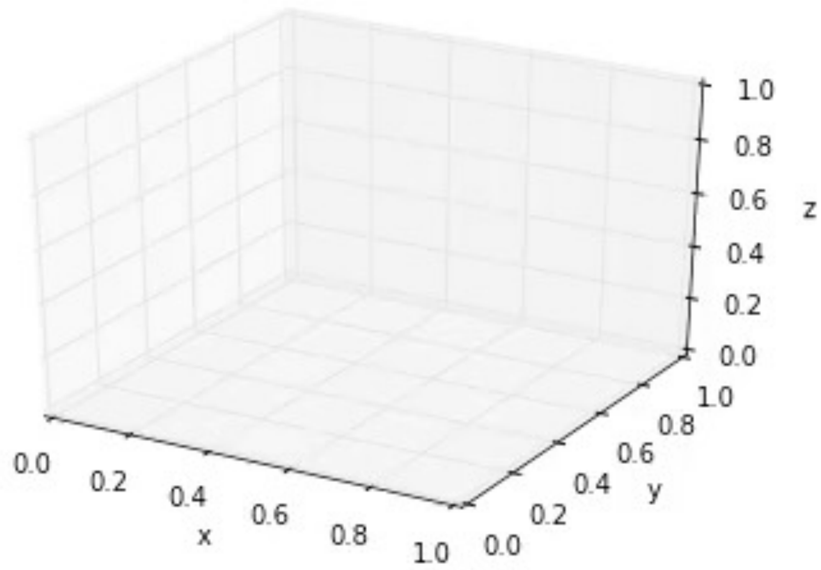


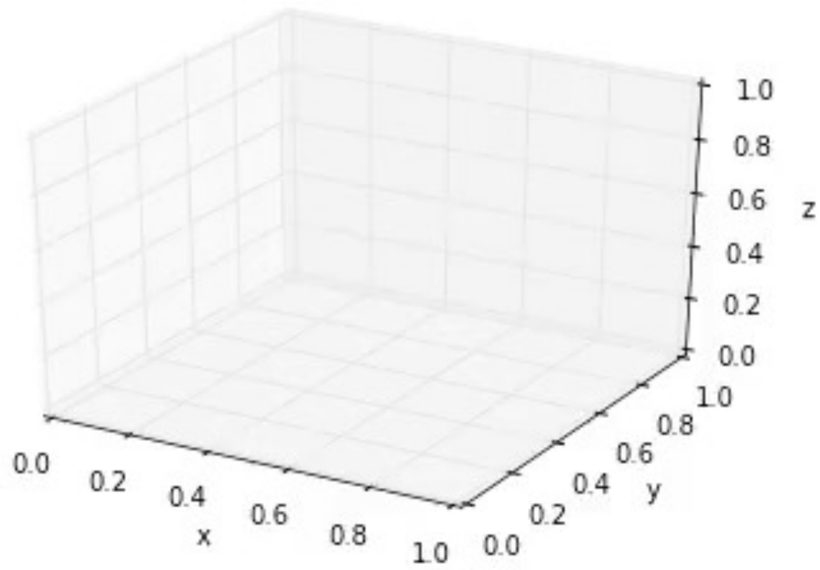


Note for MHD turbulence, the theoretically expected turbulence index is still debated

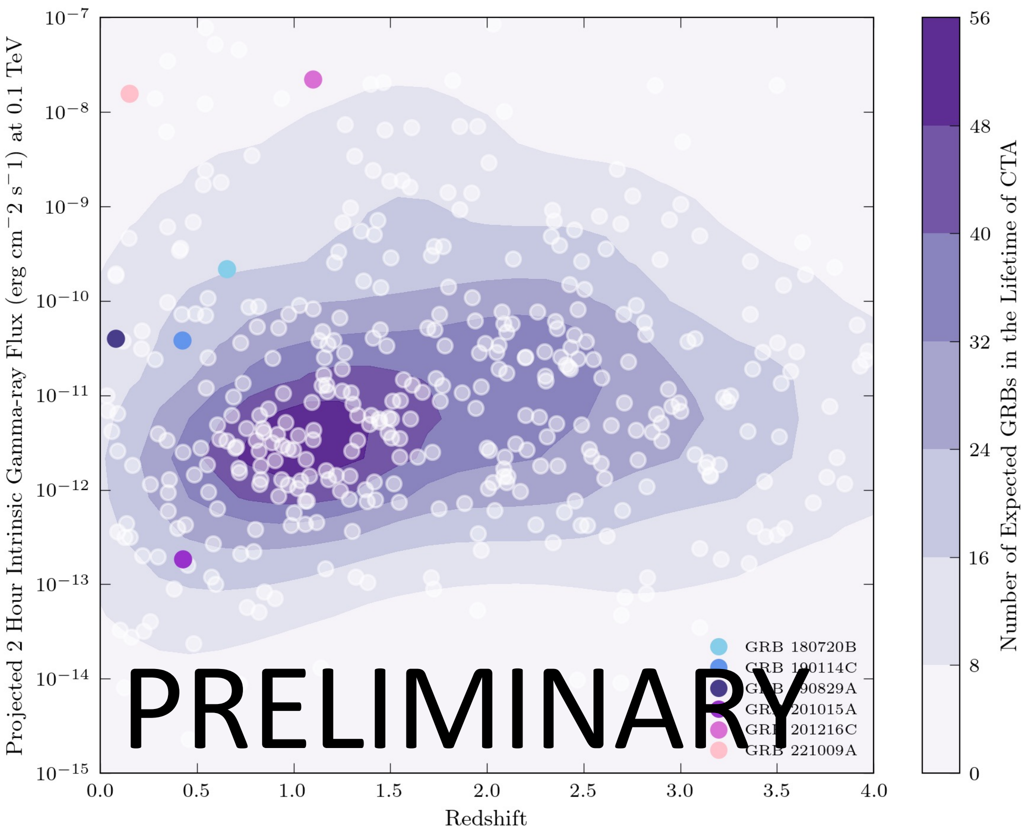
Charged Particles in Magnetic Fields

Note- a lot of what you **may have** studied about charged particle propagation in magnetic fields **likely** assumed magnetic field variation was on much longer length scales than particle Larmor radius.





Prospective Rates for Testing the GRB Emission Process with CTA



[Provided by J. Pfeil and D. Parsons]

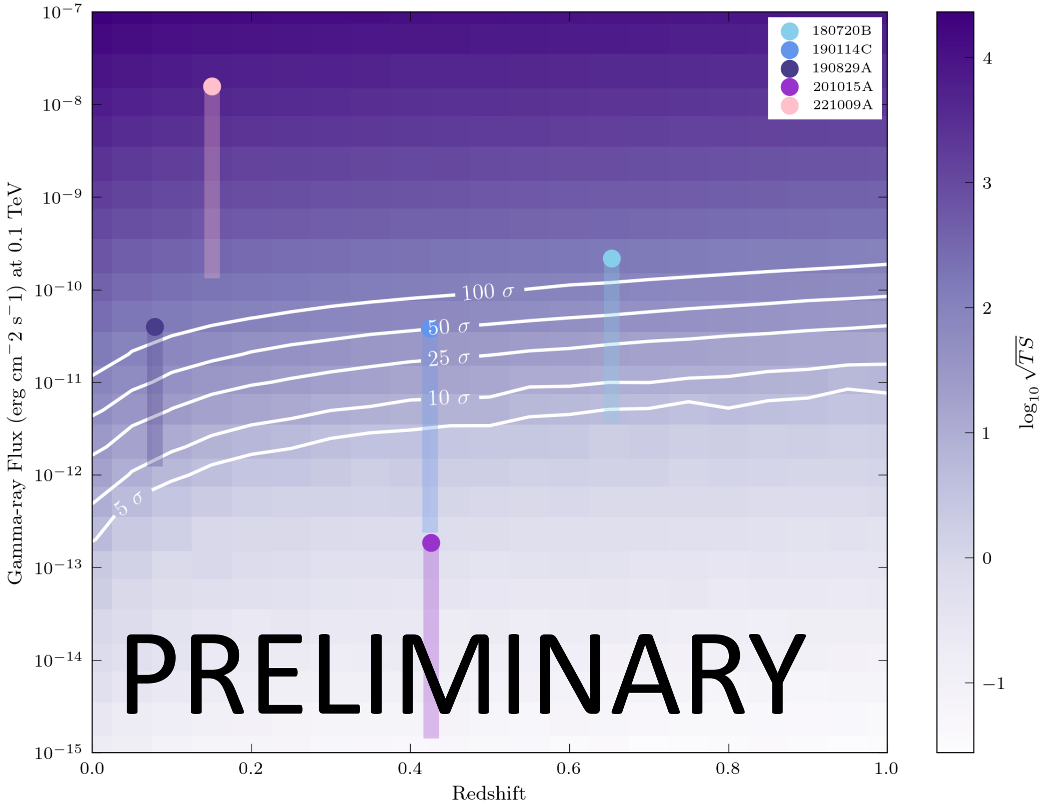
- Future GRBs for providing a stronger probe of the spectral emission model must be local and have bright afterglows
- For CTA, a rate of up to 4 yr $^{-1}$ is possible to expect, consistent with other estimates
  [Ashkar et al., ApJ 964 57]
- However, of these events, the local subset of particular interest will be rare (< 0.25 yr $^{-1}$)

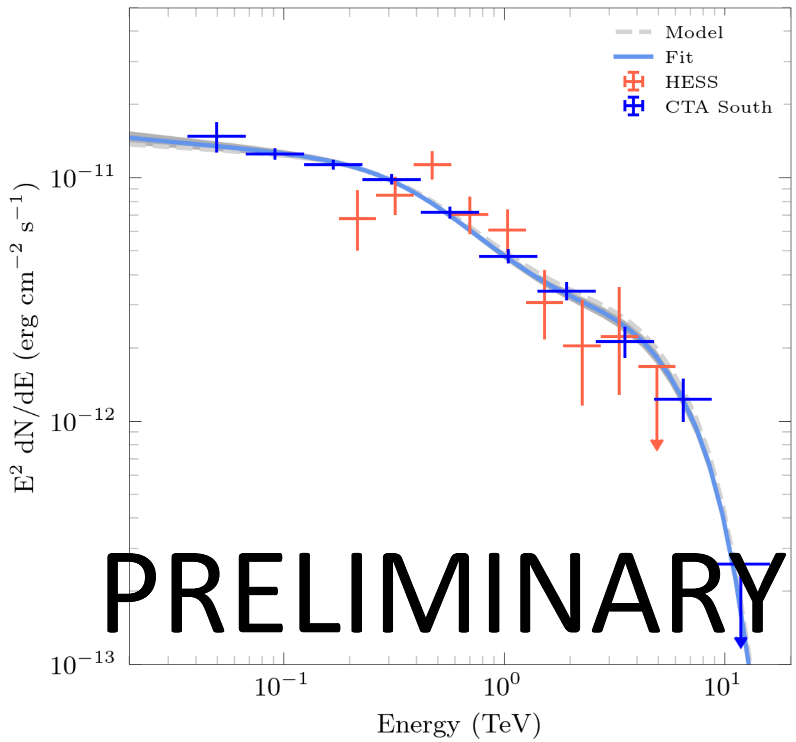
DESY.

A GRB 190829A Like Event for CTA

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

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





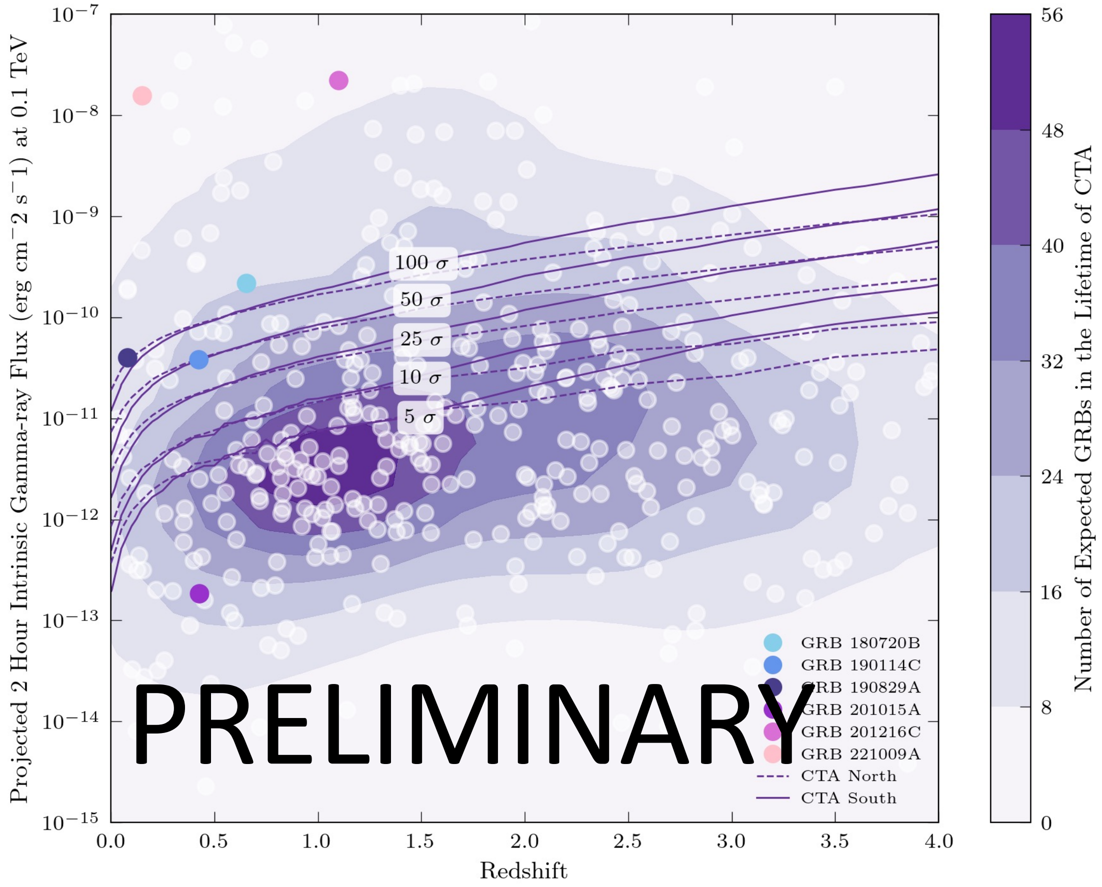
[Provided by J. Pfeil and D. Parsons]

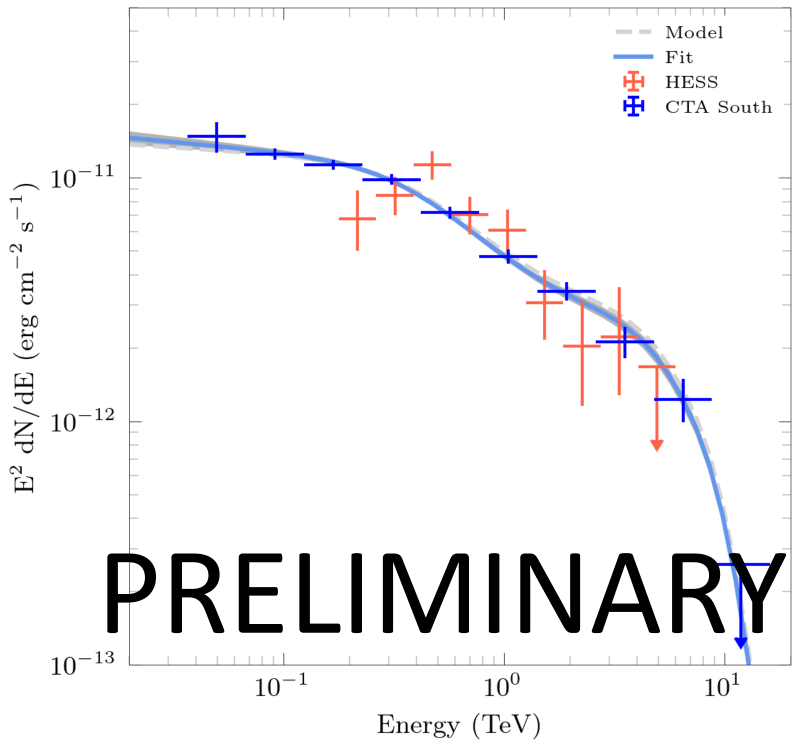
	EBL Attenuated Power Law	
Fit Parameter	HESS	CTA South
γ^{int}	$2.06 \pm 0.10 \pm 0.26$	2.09 ± 0.02

DESY.

Prospects for Testing the GRB Emission Process with CTA

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

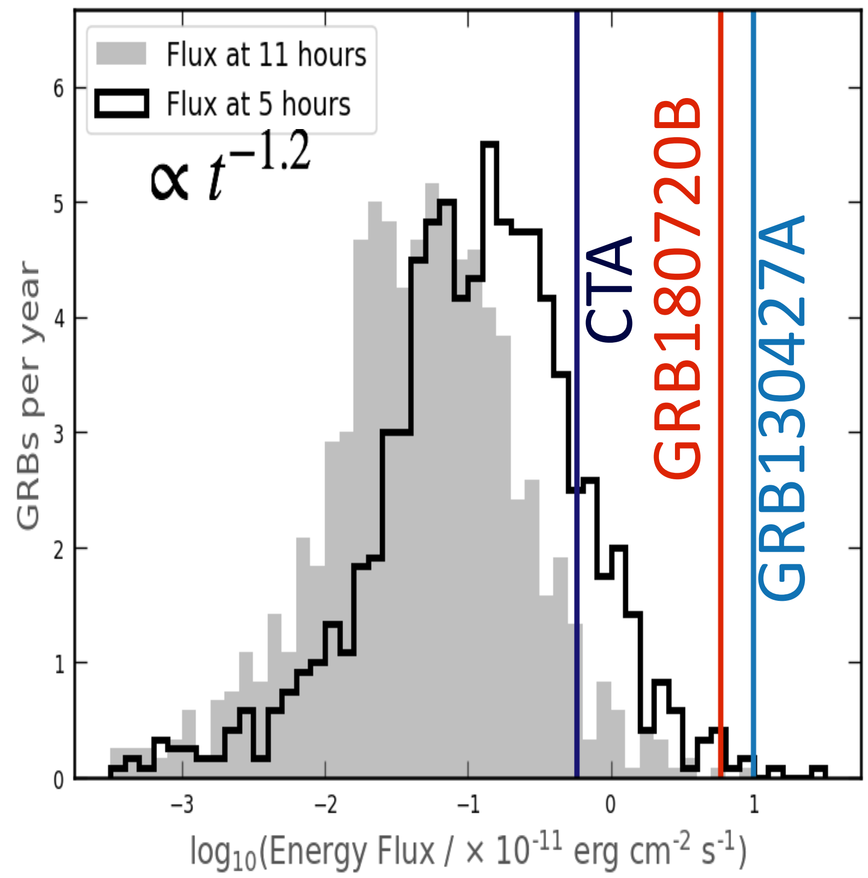
[Provided by J. Pfeil and D. Parsons]

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

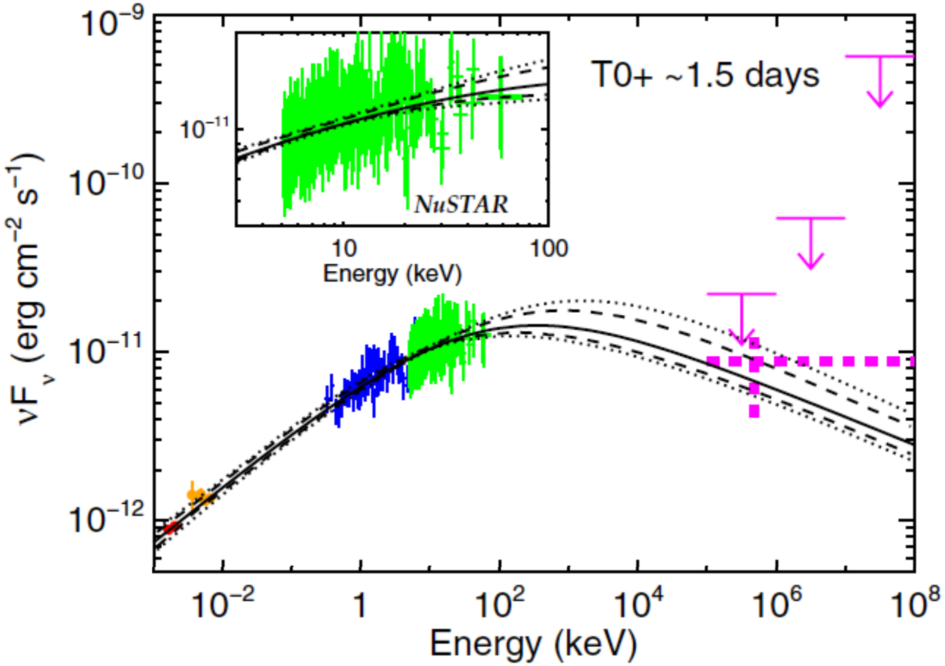


Ruiz-Velasco+ (1st CTA symposium)
HESS Collaboration *Nature* **575,** 464–467 (2019)

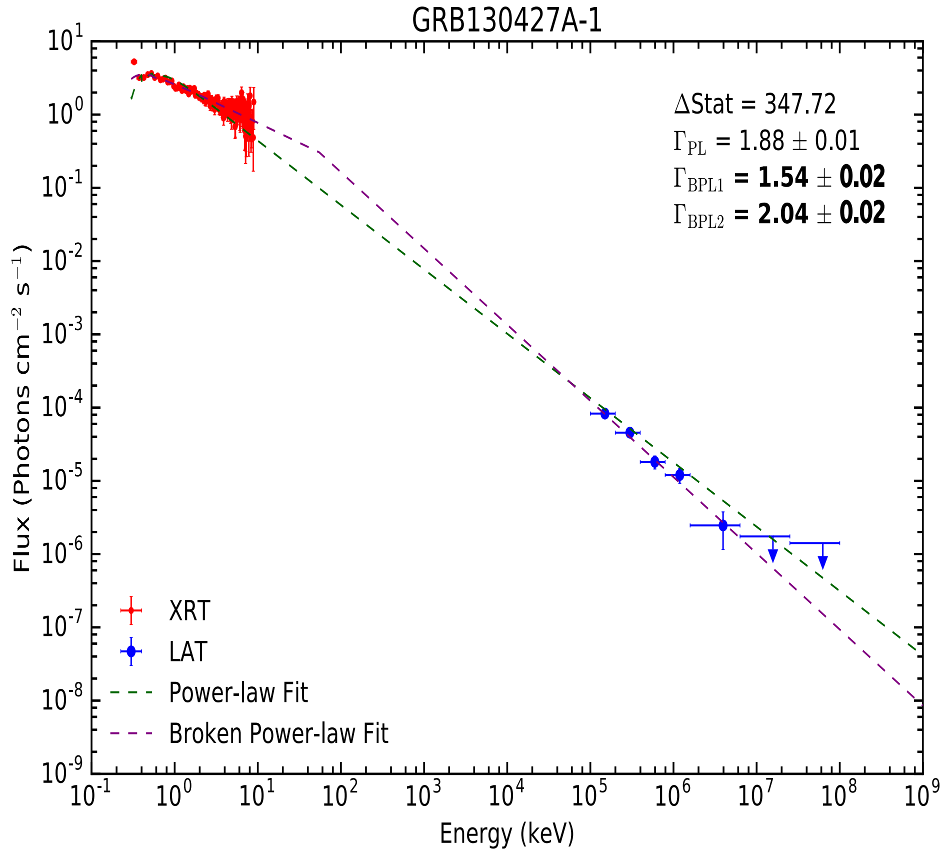
DESY.

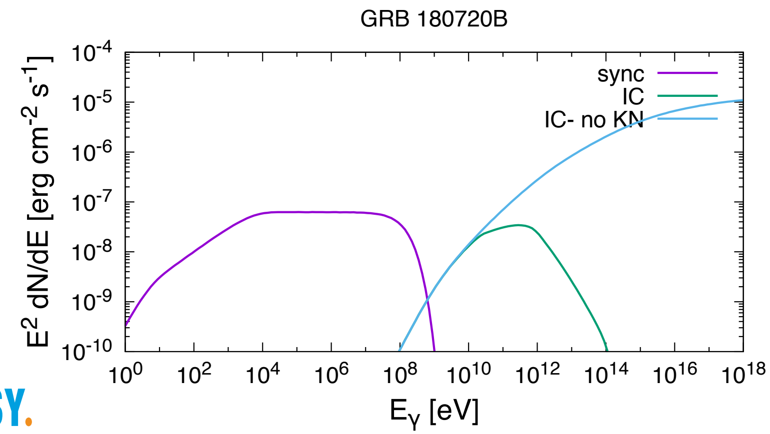
No Synchrotron Cutoff of GRB 130427A Seen in X-rays and Gamma-Rays

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

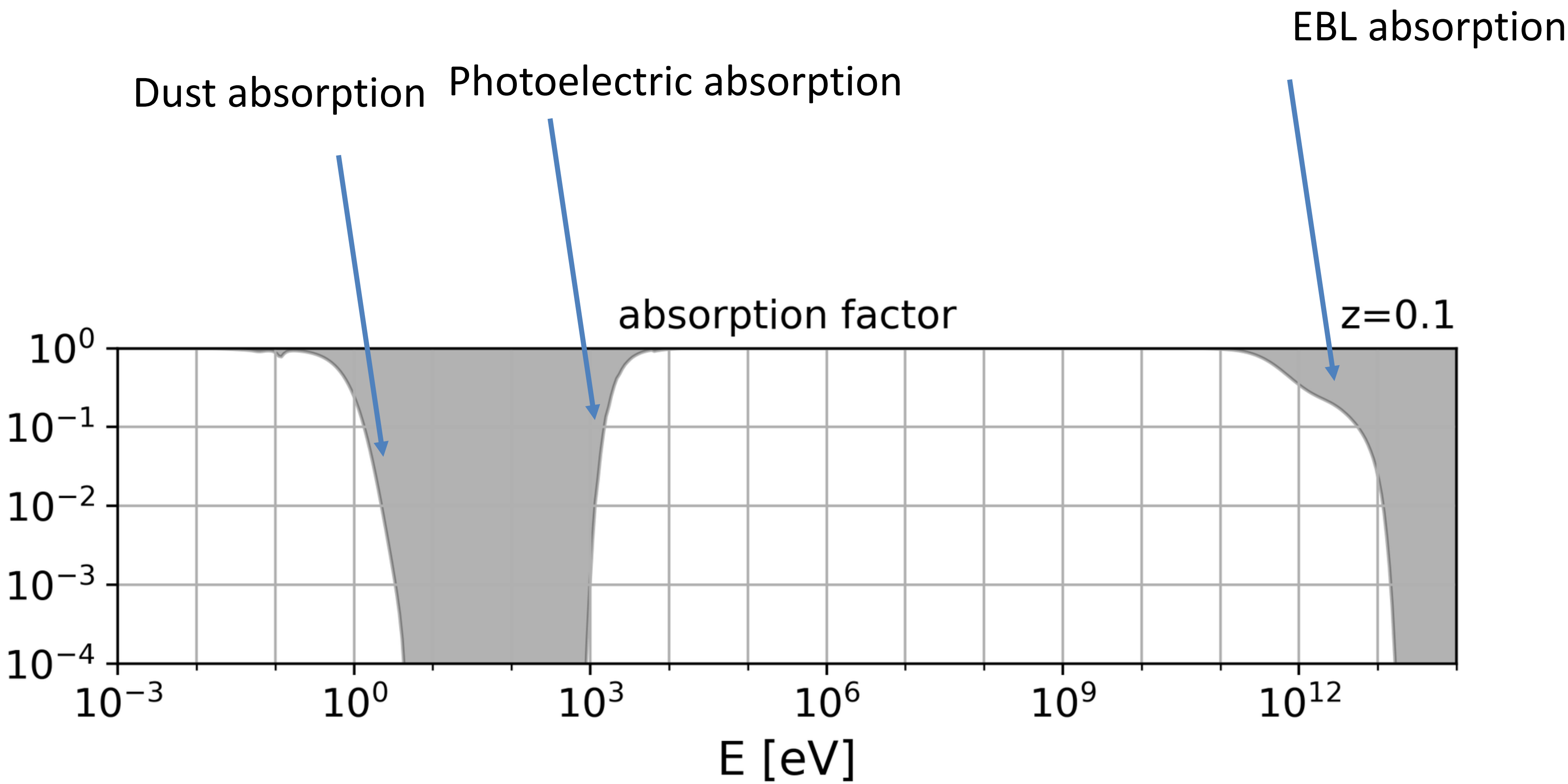


[Ajello et al., ApJ 863 138 (2018)]



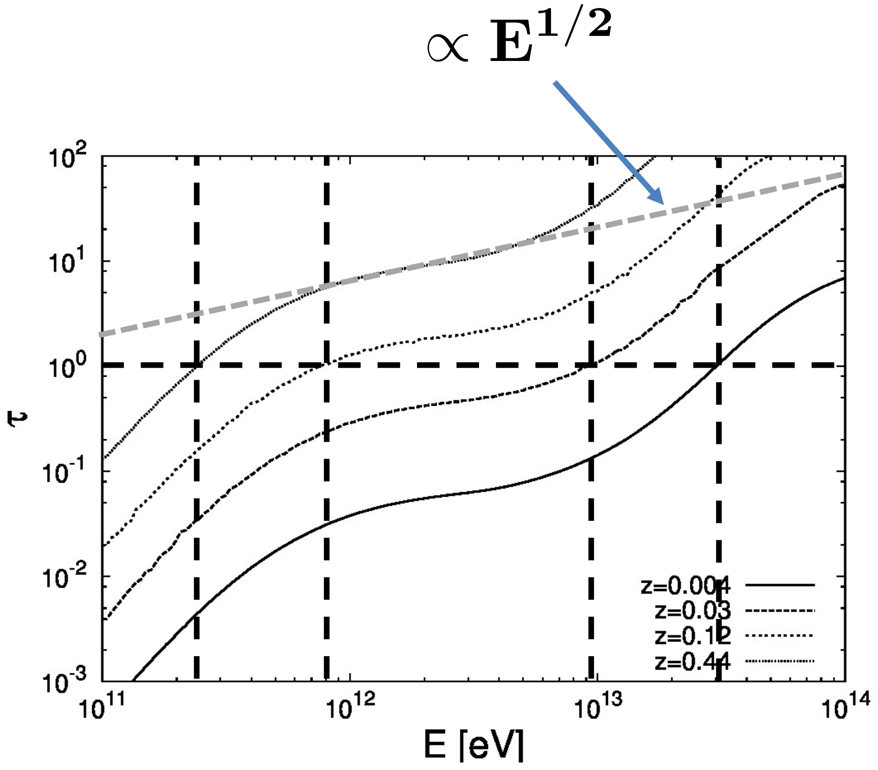


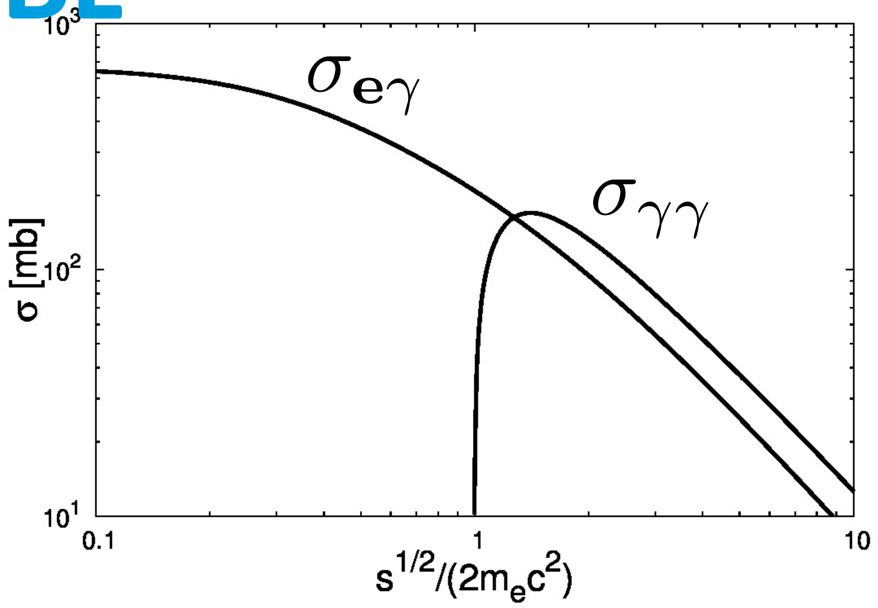
The Observational Challenges for GRBs
Absorption!

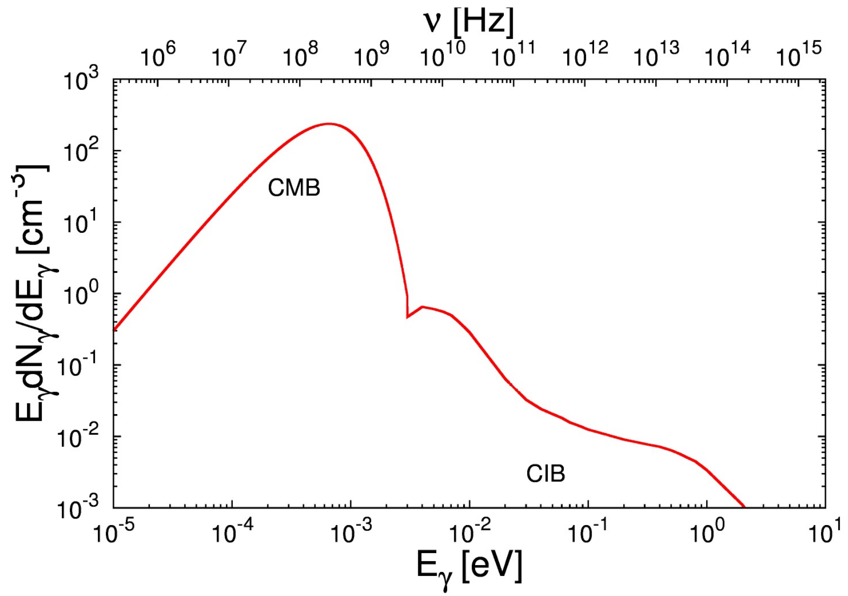


DESY.

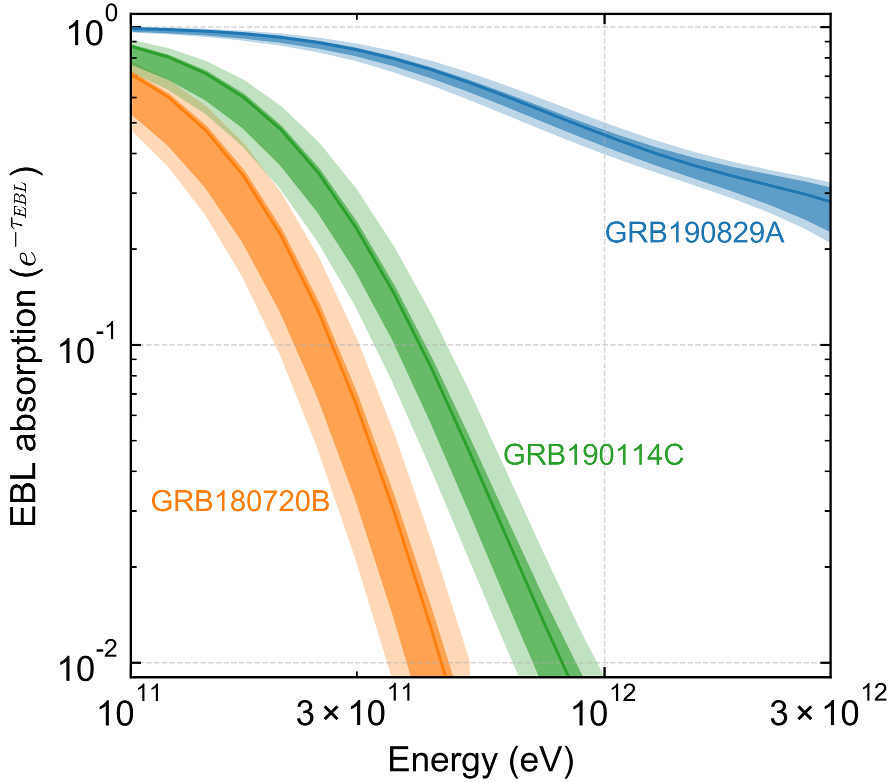
Attenuation through Pair Production on the EBL







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 $\Delta\Gamma \approx 0.5$, starting around 250 GeV.

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

Hadronic Particle Acceleration in Sources

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

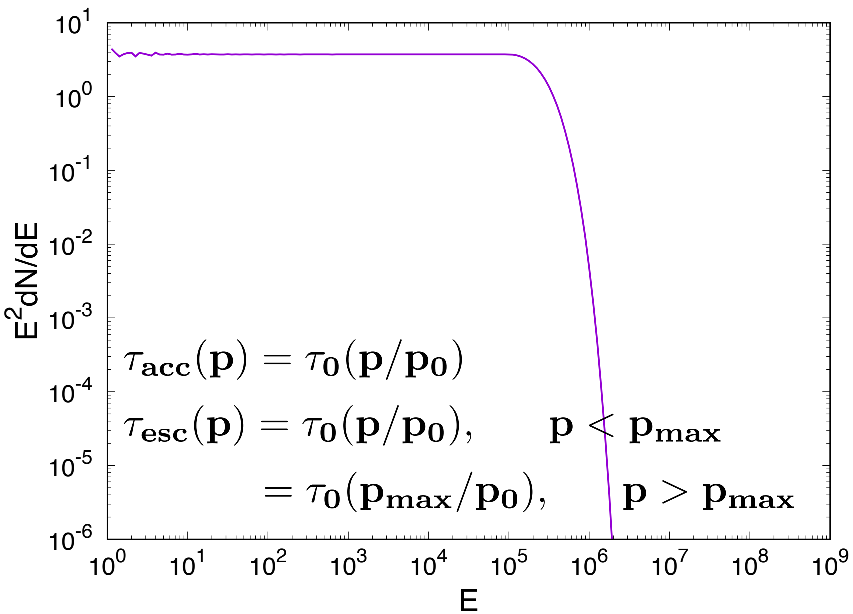
Steady state

No losses

Delta injection

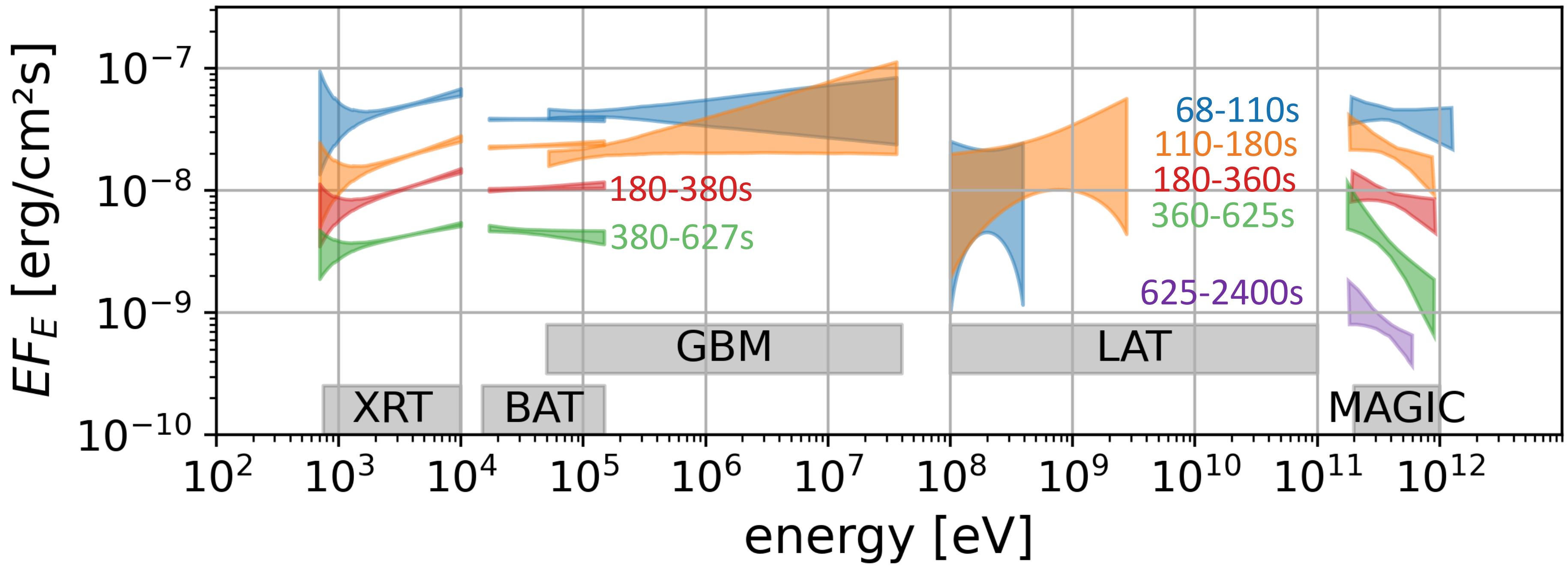
$$n_p = Q \left(\frac{p}{p_0} \right)^{-\left(1 + \frac{\tau_{acc}}{\tau_{esc}}\right)}$$

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



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

GRB 190114C (Detected by MAGIC)

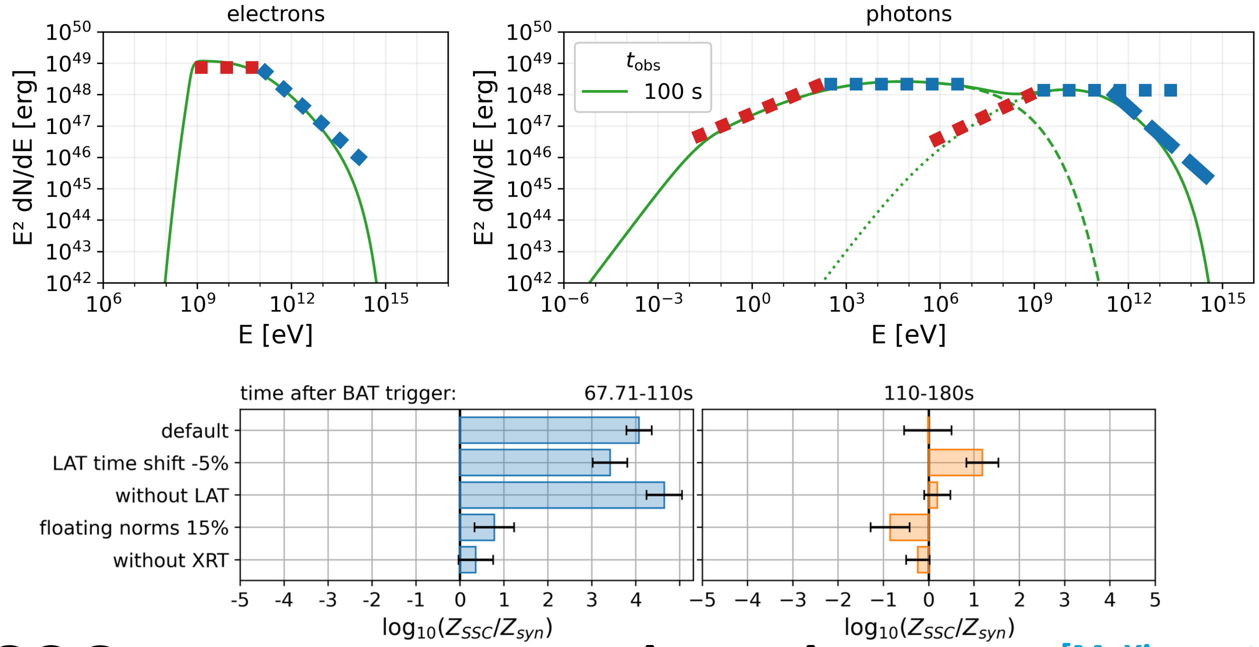


[Nature 575, 459-463 (2019)]

- remarkably flat over 9 orders of magnitude in energy!

DESY.

Evidence for a New Component?

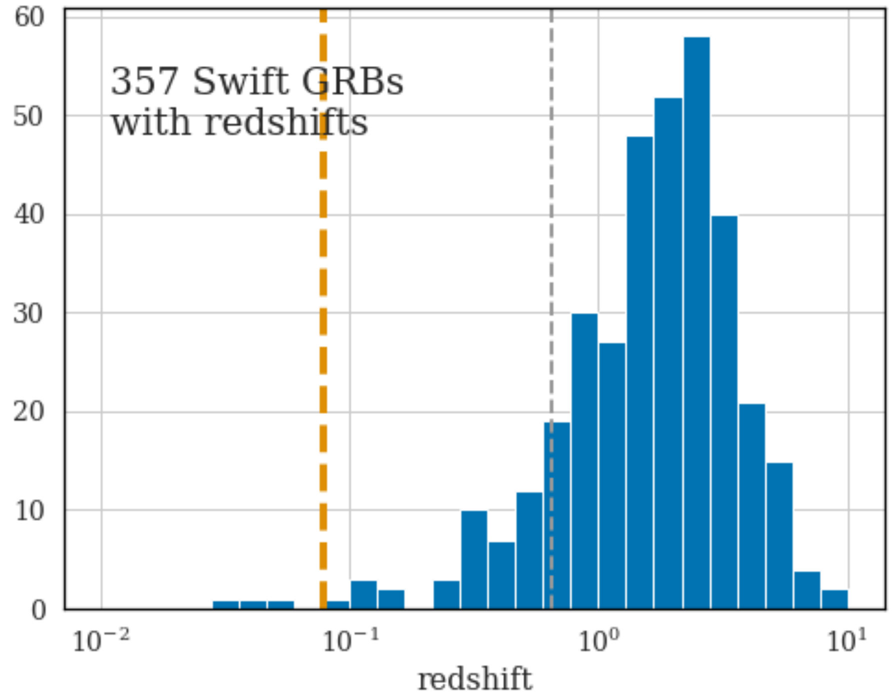


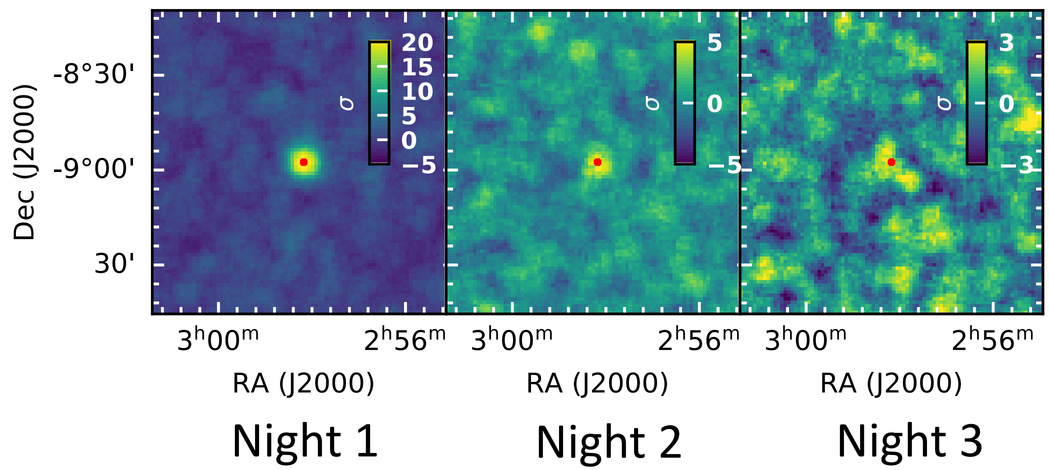
[M. Kinger et al., MNRAS 501 2023]

- 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

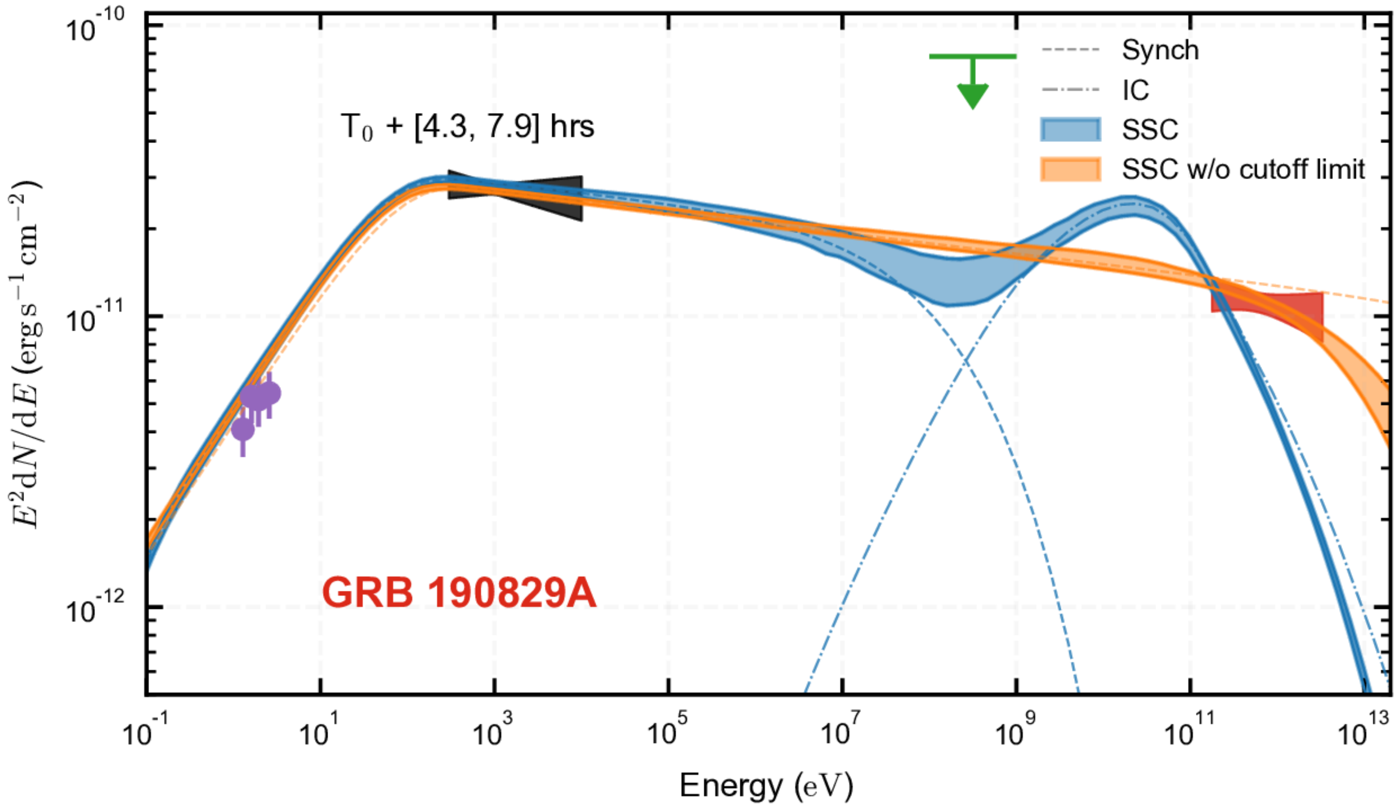




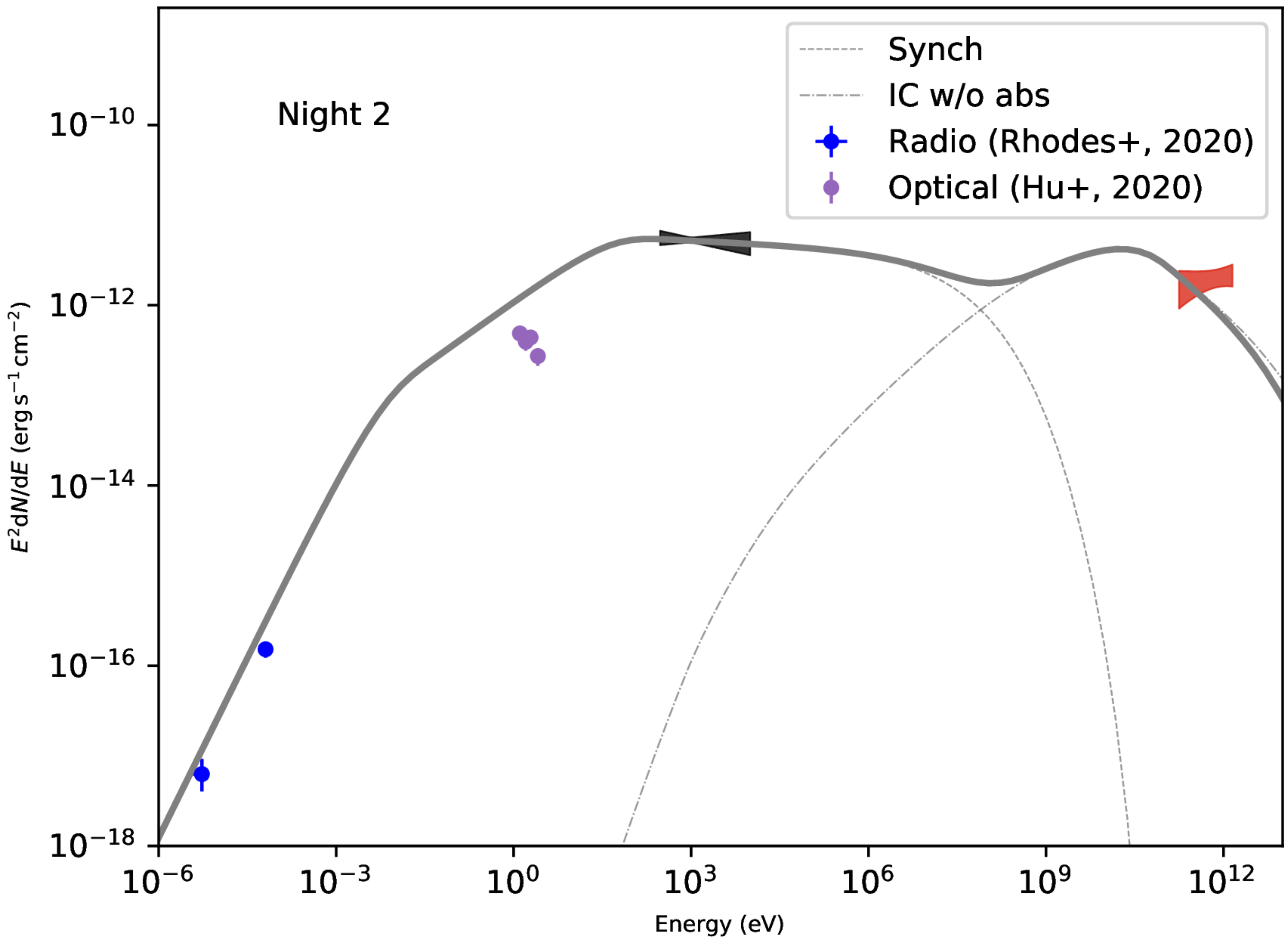
[HESS- A. Taylor, et al., Science 2021]

$t^{GBM}_{90} \sim 60$ s, $t^{BAT}_{90} \sim 60$ s
z = 0.078

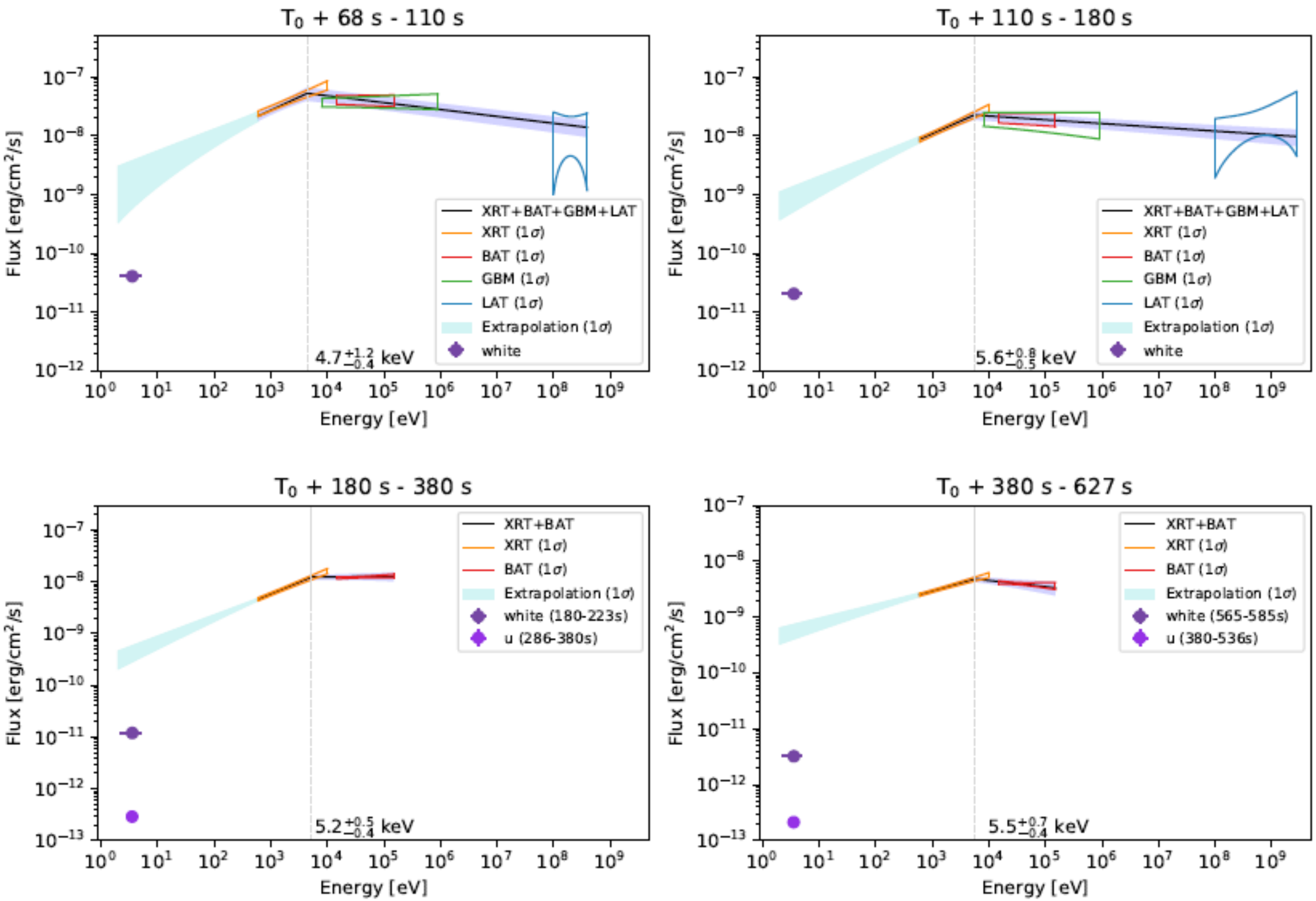
GRB 190829A- Optical Data



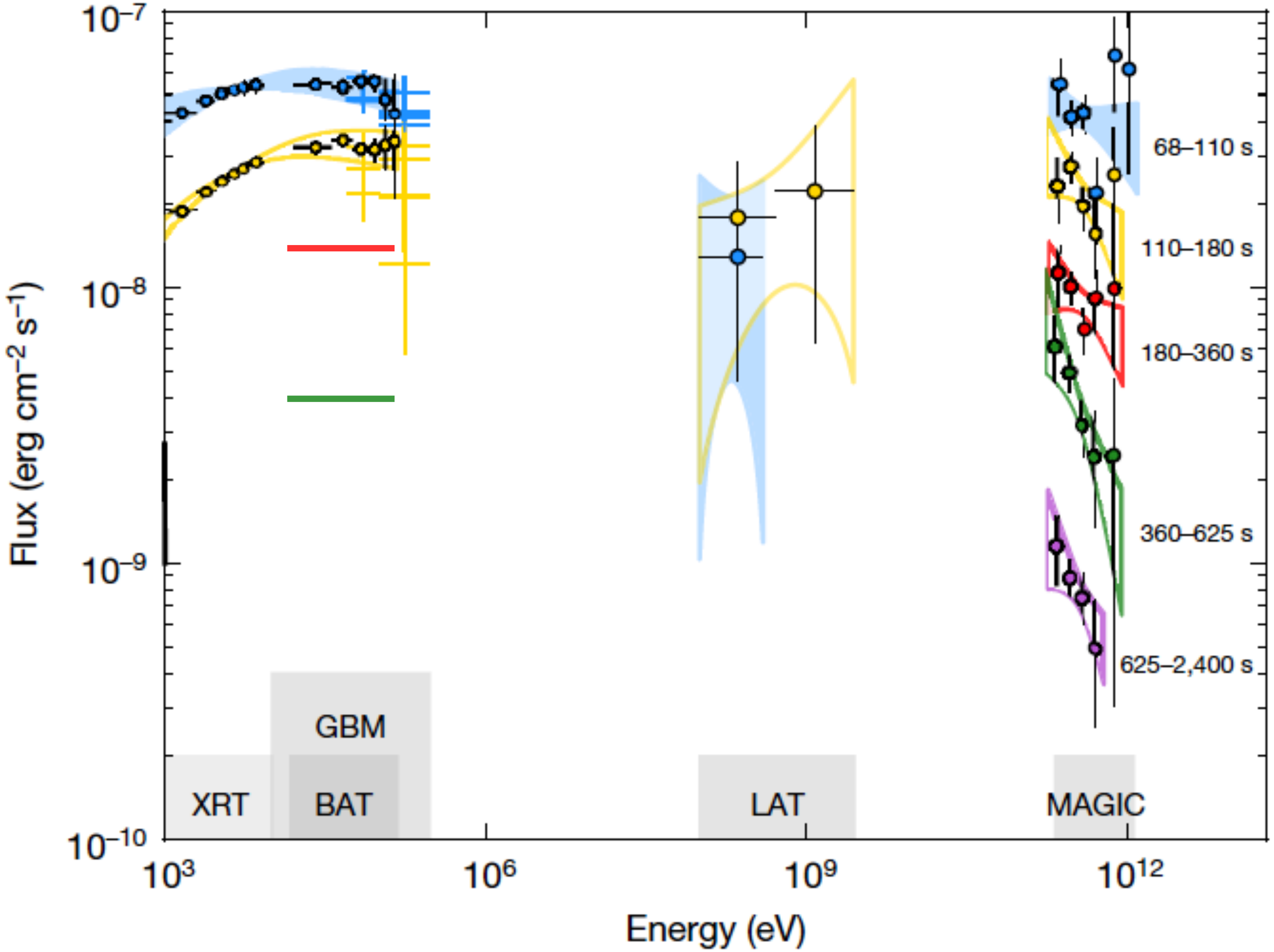
GRB 190829A- Radio Data



GRB 190114C

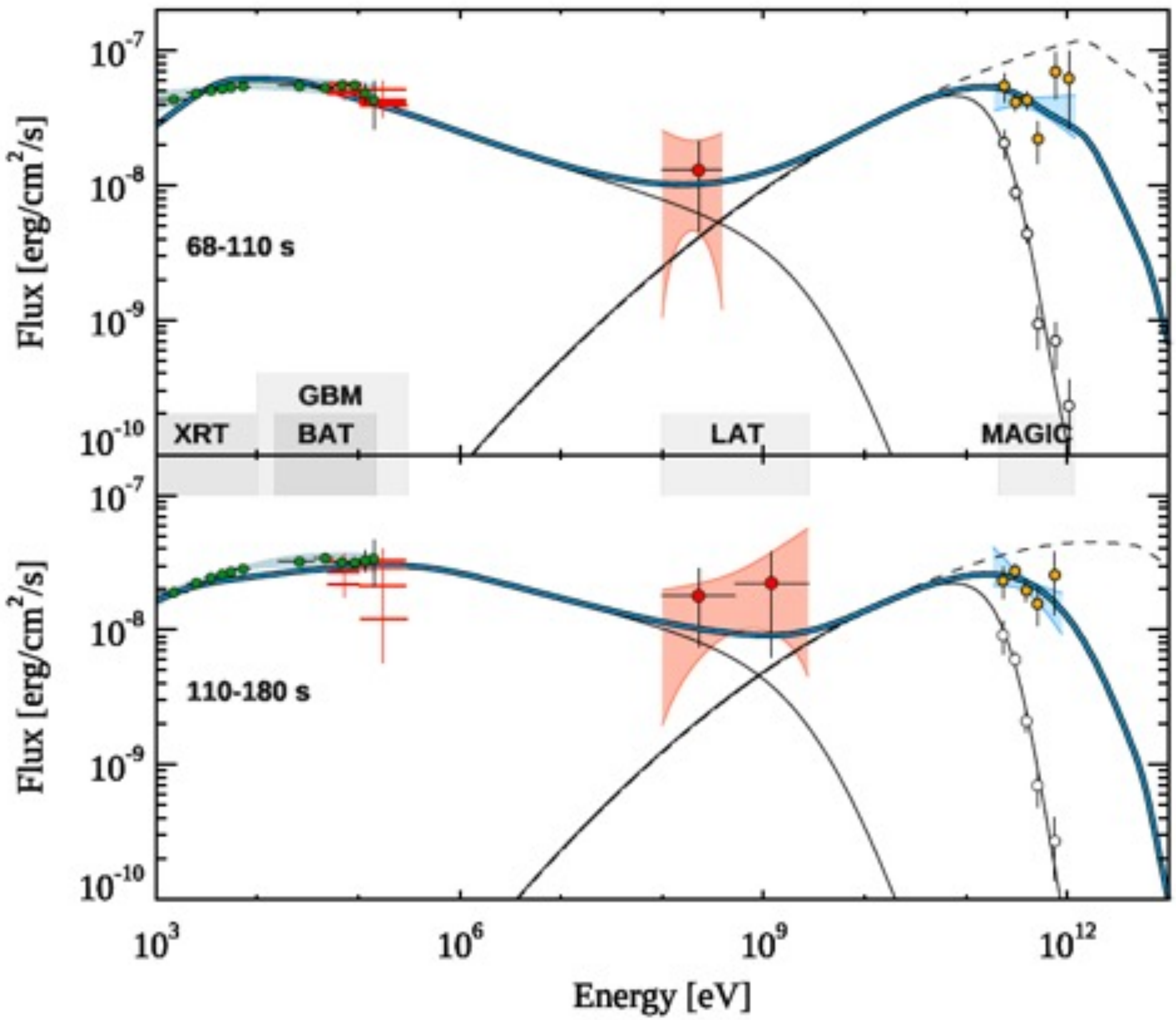

T0 + 68 s - 110 s
T0 + 110 s - 180 s
T0 + 180 s - 380 s
T0 + 380 s - 627 s
Flux [erg/cm²/s]
Energy [eV]
XRT+BAT+GBM+LAT
XRT+BAT
XRT (1σ)
BAT (1σ)
GBM (1σ)
LAT (1σ)
Extrapolation (1σ)
white
white (180-223s)
u (286-380s)
white (565-585s)
u (380-536s)
4.7 +1.2 −0.4 keV
5.6 +0.8 −0.5 keV
5.2 +0.5 −0.4 keV
5.5 +0.7 −0.4 keV

GRB 190114C

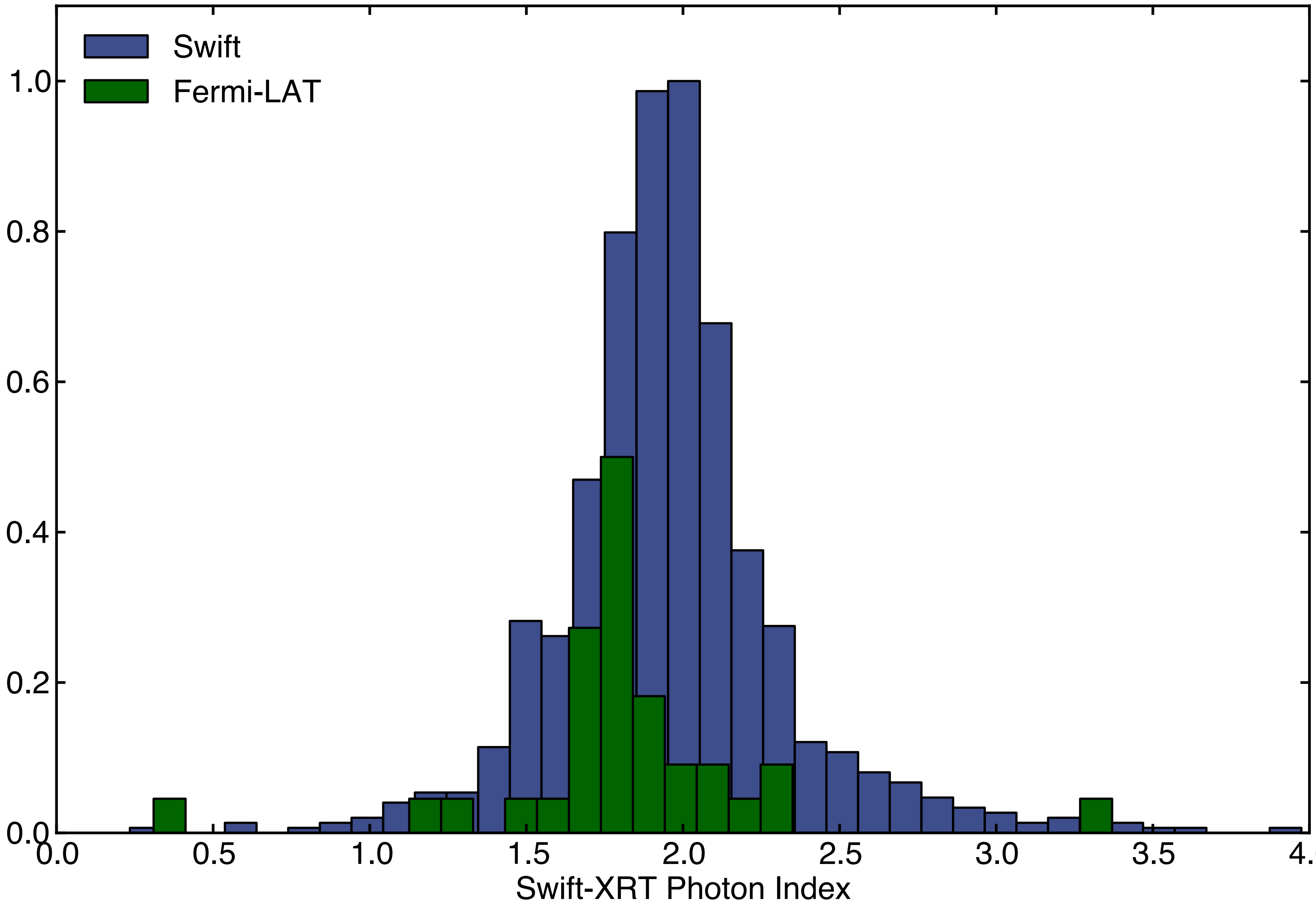


Flux (erg cm^{-2} s^{-1})
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
10^{6}
10^{9}
10^{12}
Energy (eV)
68–110 s
110–180 s
180–360 s
360–625 s
625–2,400 s
GBM
XRT
BAT
LAT
MAGIC

GRB 190114C

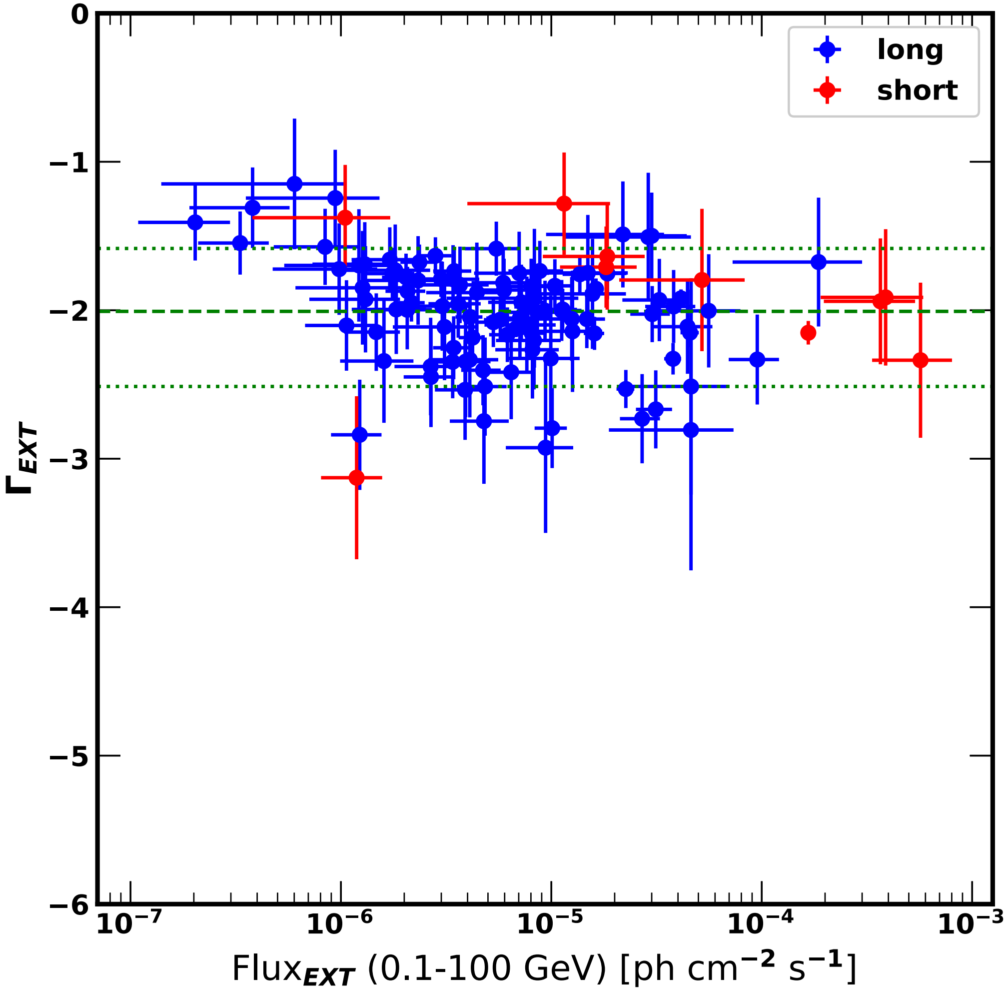


Swift XRT Photon Index Distribution



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

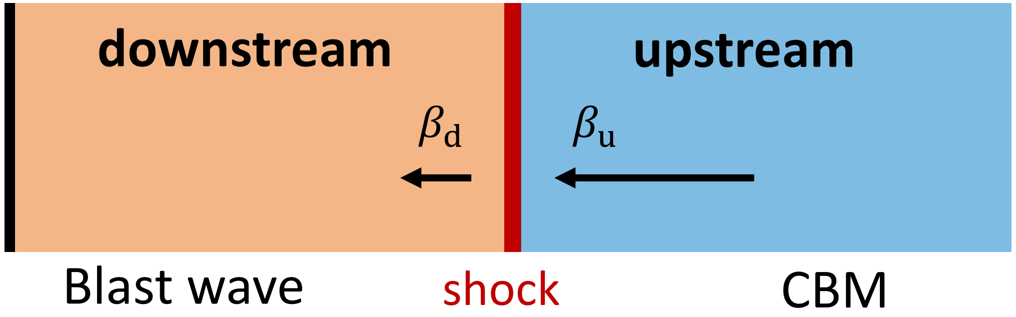
Fermi-LAT Photon Index Distribution



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

Relativistic Hydro Shocks

What's the compression ratio for relativistic shocks?



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

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

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

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

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

Evolution of Key Energies with Time