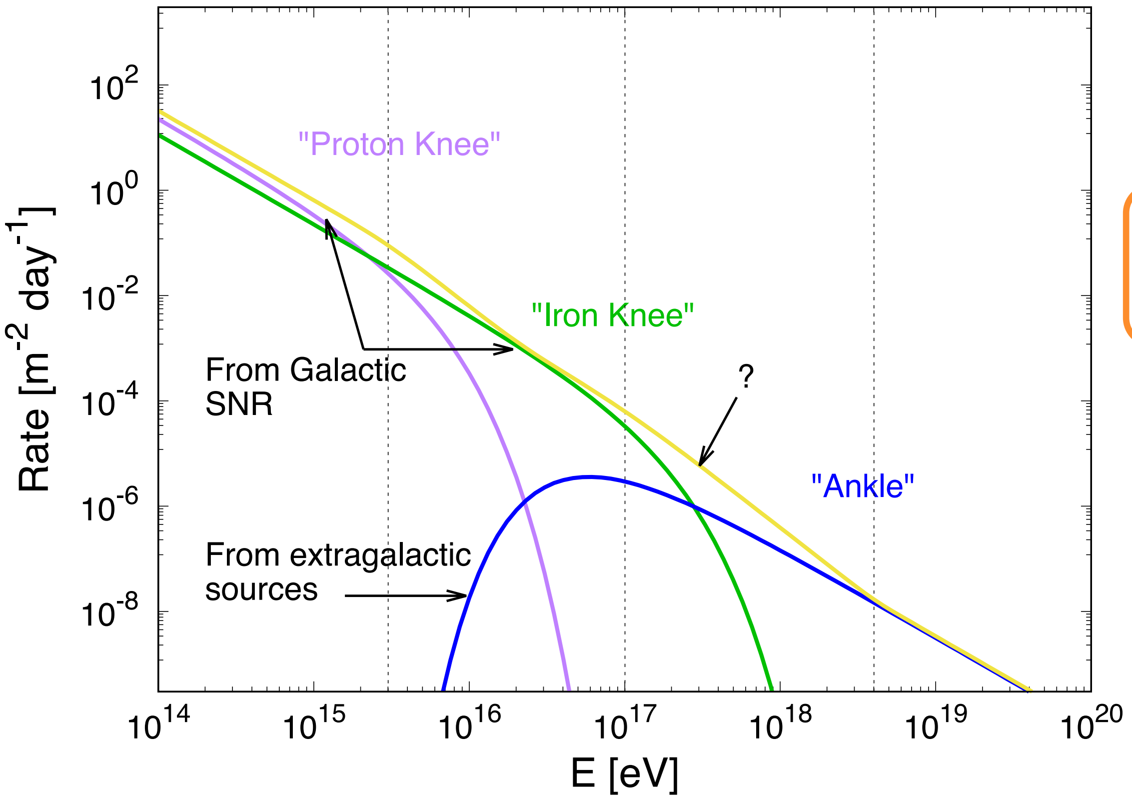
Relativistic Shock Studies from/with Multiple Perspectives/Probes



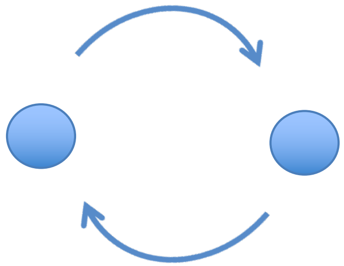
$$t_{acc} = \eta \frac{R_{lar}}{c\beta^2}$$

$$t_{esc.} = \frac{R^2}{\eta c R_{lar}}$$

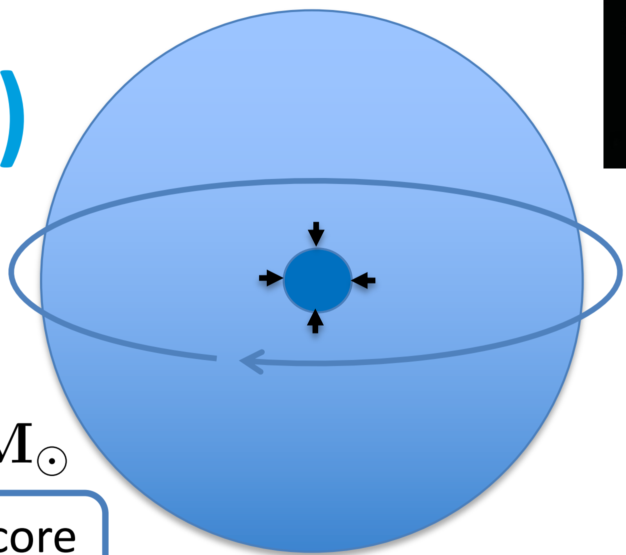
$$R_{lar} = \frac{\beta}{\eta} R$$

The acceleration of cosmic rays up to 10^{20} eV force attention to be focused on relativistic outflows of extremely energetic explosive astrophysical events

Binary NS Mergers (Short GRB Progenitor)



Stellar Core Collapse (Long GRB Progenitor)



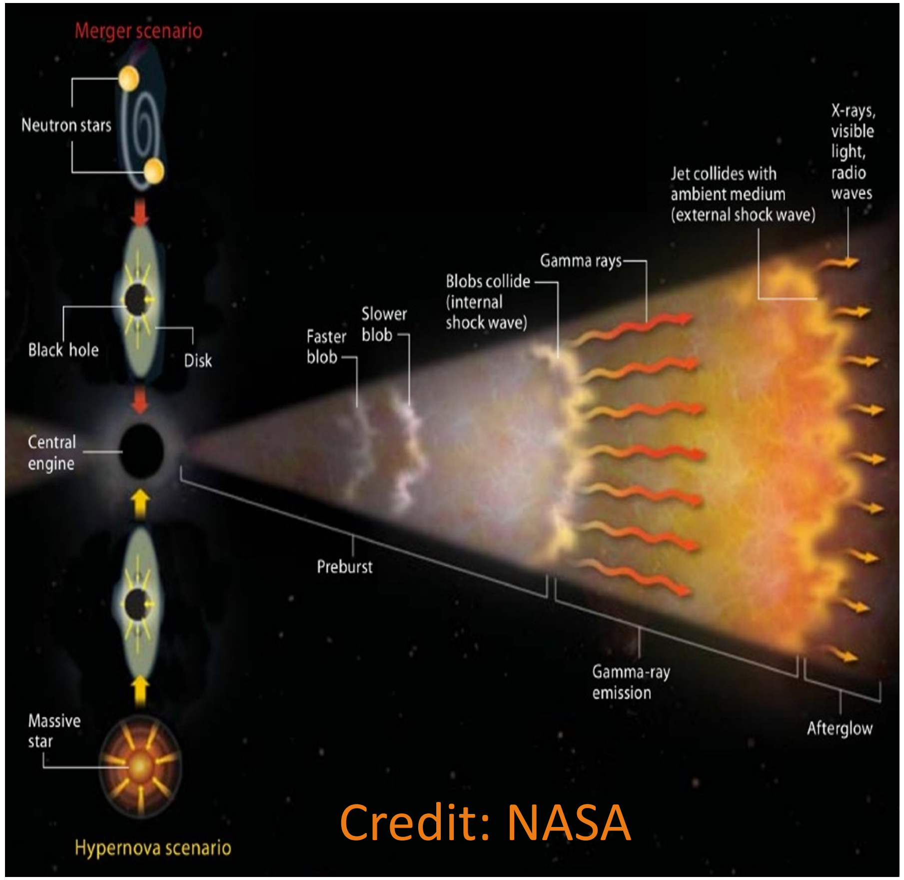
$$\mathrm{M} \gtrsim 8\mathrm{M}_\odot$$

Around 0.1% of core collapse SN → GRB

DESY.

Andrew Taylor

GRB Progenitors



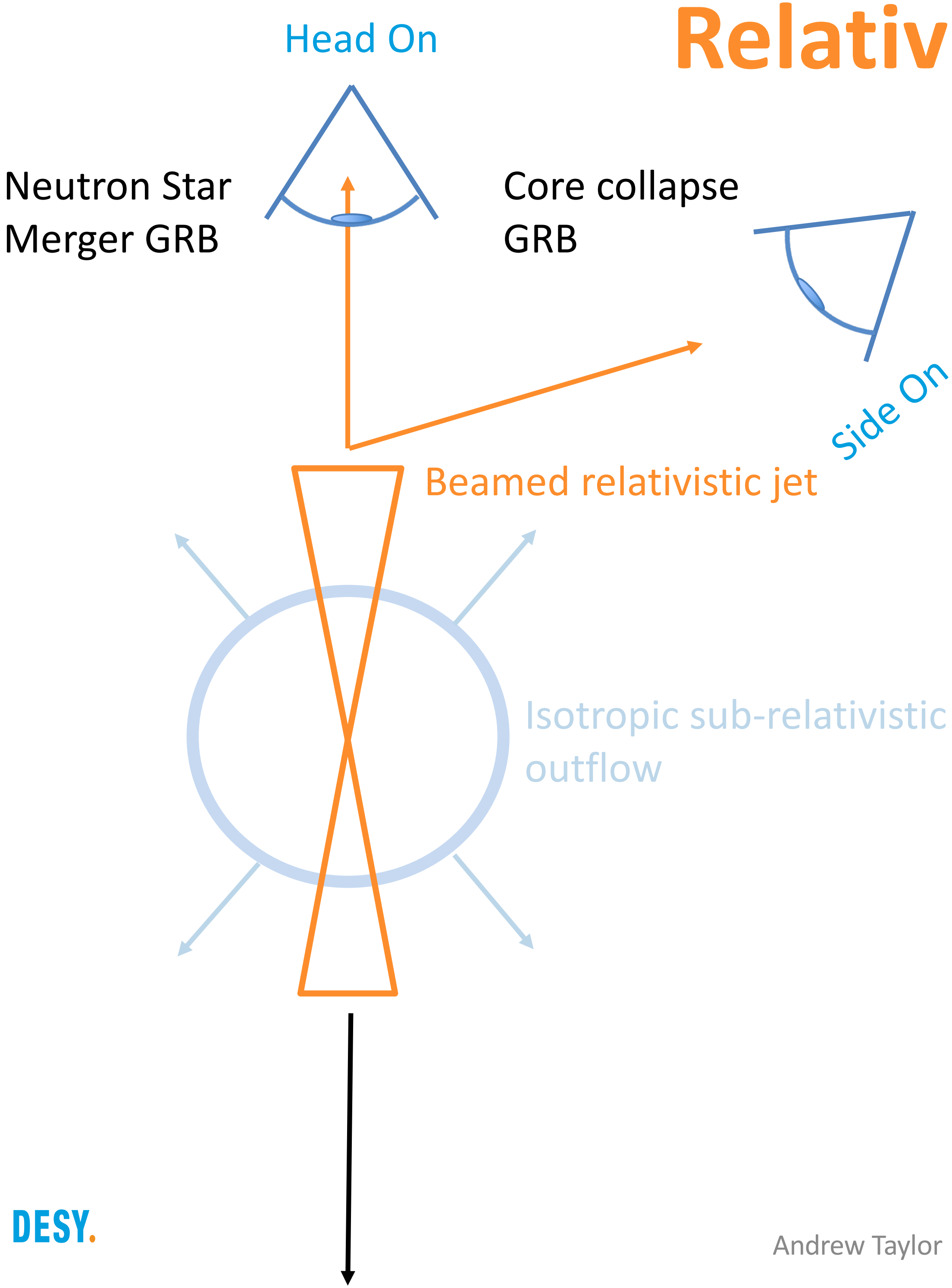
Credit: NASA

However:

[*Nature Ast.*](#) **Vol 5**,
pg 911–916 (2021)
"Short" Core collapse GRB

"Long" Neutron Star Merger GRB

Relativistic Jet Emission



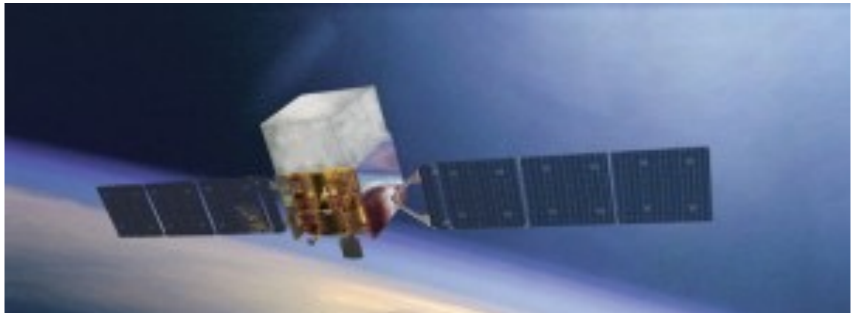
Non-thermal emission from relativistic jet observed:

- head on is **bright** & **evolves rapidly** (temporal compression)
- side on is **dim** & **evolves slowly**

The nature of the environment surrounding the progenitor plays an important role in the jet's evolution

The jet actually possesses a velocity structure (not single valued) which can be probed by side on observations

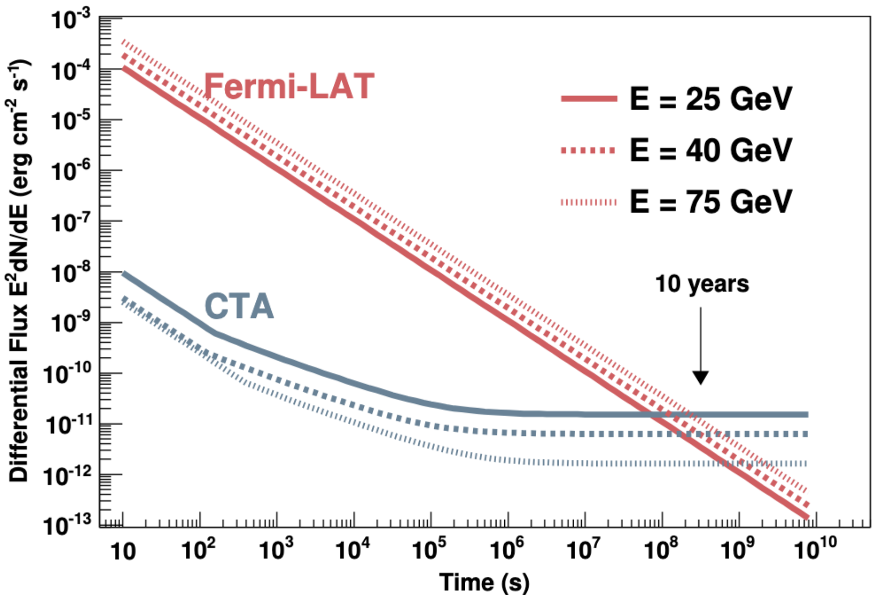
Effective Area of Gamma-Ray Instruments



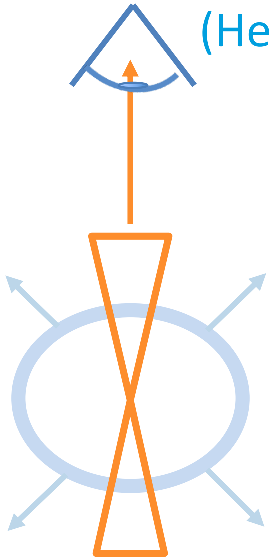
Fermi-LAT has a 1 m^2 effective area…..so a large flux is needed for a reasonable detection rate to be achieved- **good for initial detection, but not for tracking evolution**

Instead, the Earth's atmosphere itself can be used as part of the particle detector (providing a transparent target material). For ground-based gamma-ray telescopes, this allows an effective area of 10^5 m^2 to be achieved! **Good for tracking evolution**

NOTE- effective area is a "macroscopic cross-section" for a particle detector



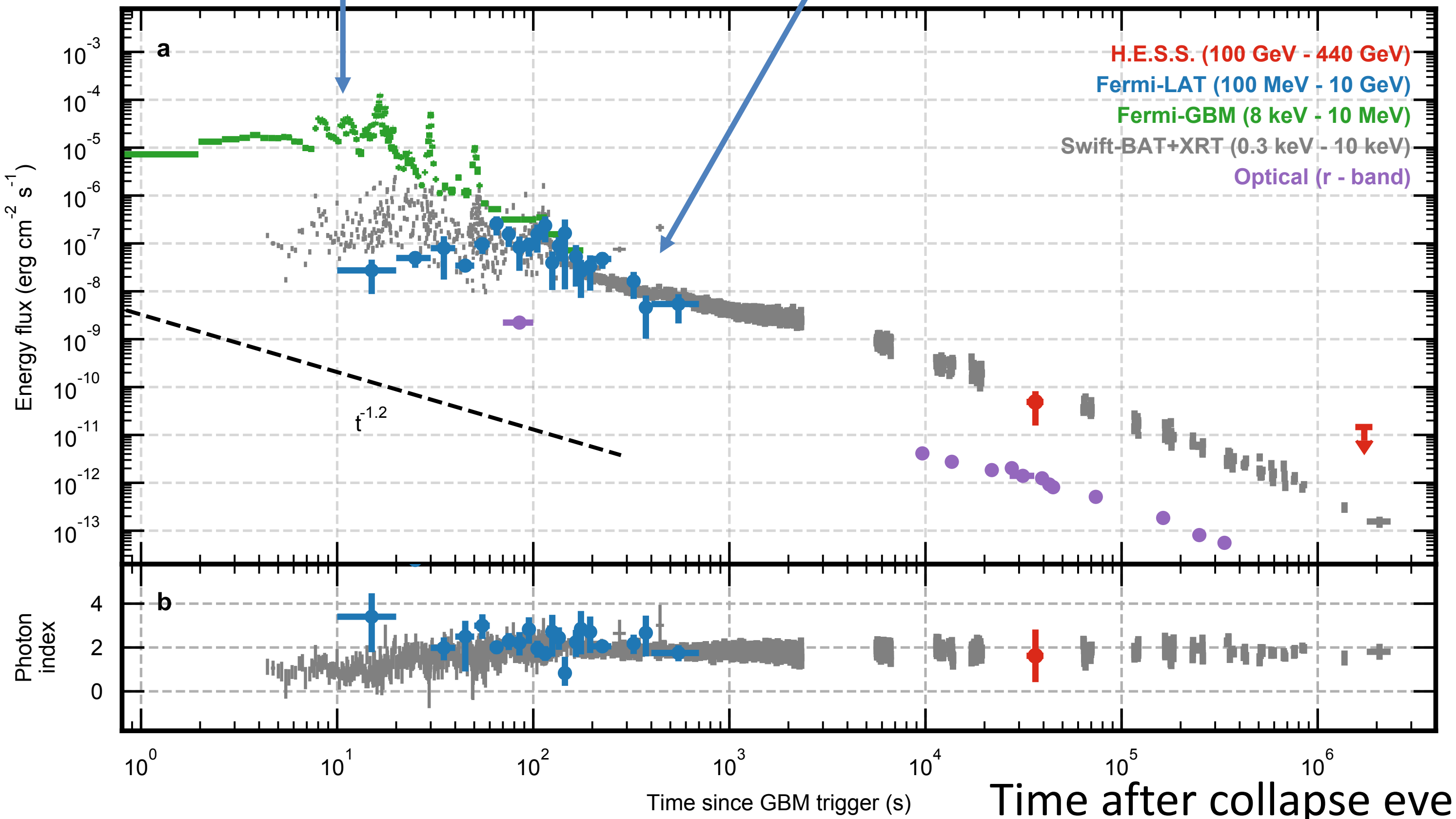
Non-Thermal GRB Jet Signatures



Prompt Photon emission

Afterglow Photon emission

[HESS Coll. Nature 2019]

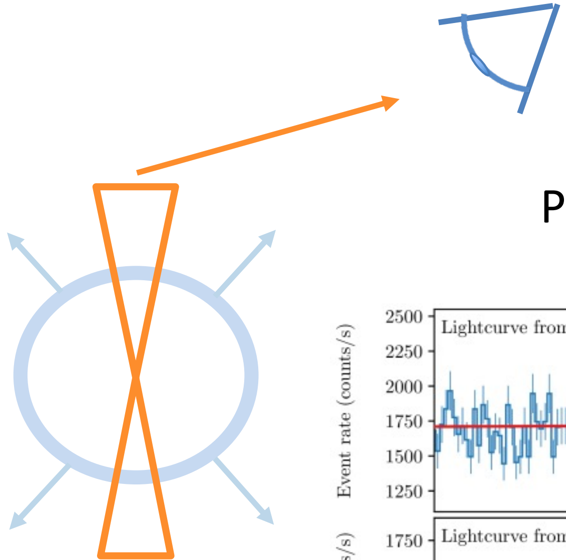


Time after collapse event

Neutrinos? (although neutrinos detected from core-collapse for SN 1987A)

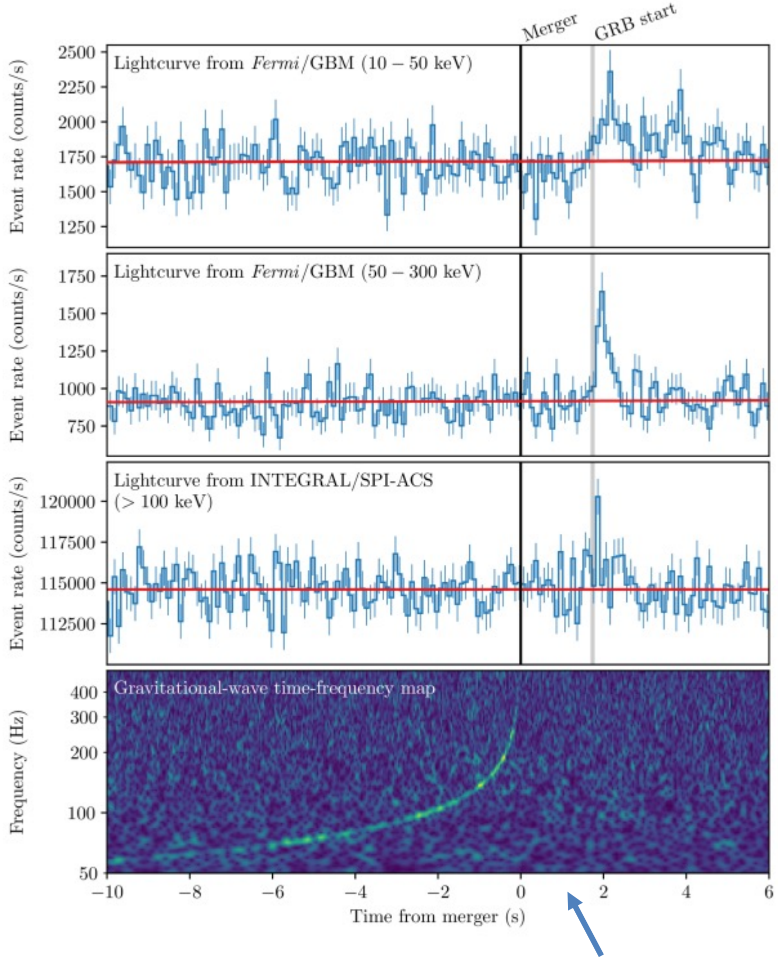
Gravitational Waves?

Non-Thermal GRB Jet Signatures



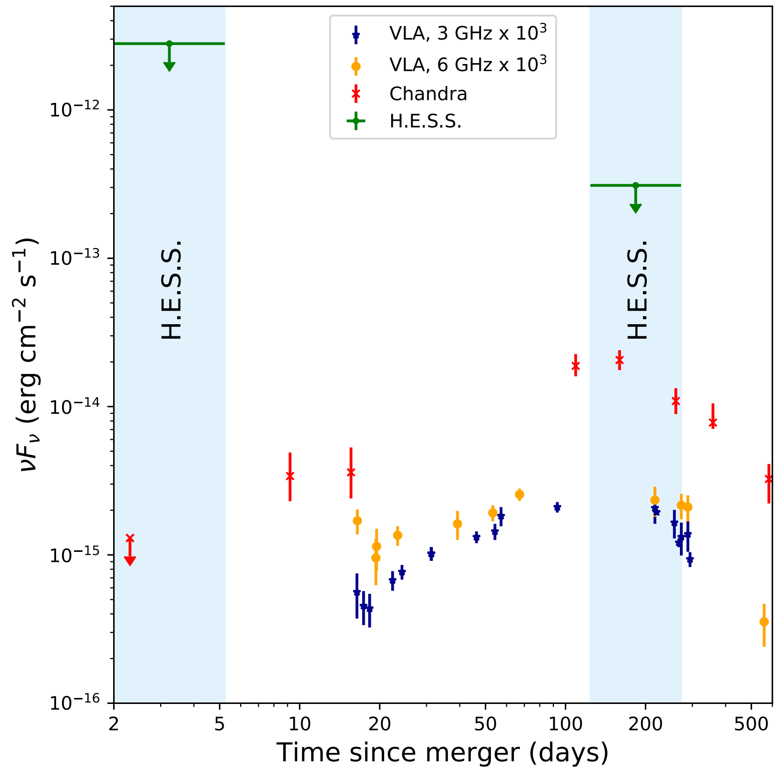
(Side On)

Prompt Photon emission



Gravitational Waves

Afterglow Photon emission



Next generation instruments (CTAO) will have 10x improved sensitivity, so probing the very high energy emission for side on GRB jets is more promising

DESY.

The Failure to Efficiently Detect Side On GRB Jets

Non-Thermal Jet Emission

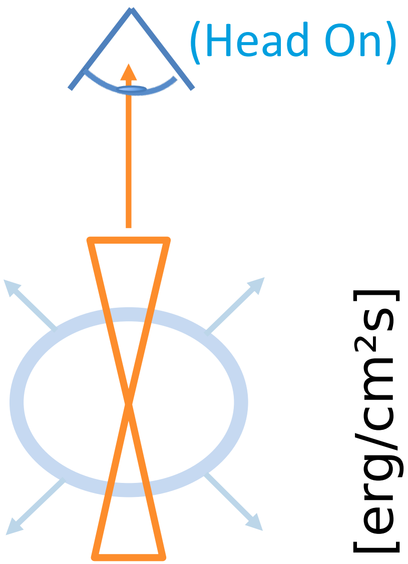
	Neutron Star Merger GRB	Core Collapse GRB
Head On	✓	✓
Side On	✓(1)	✗

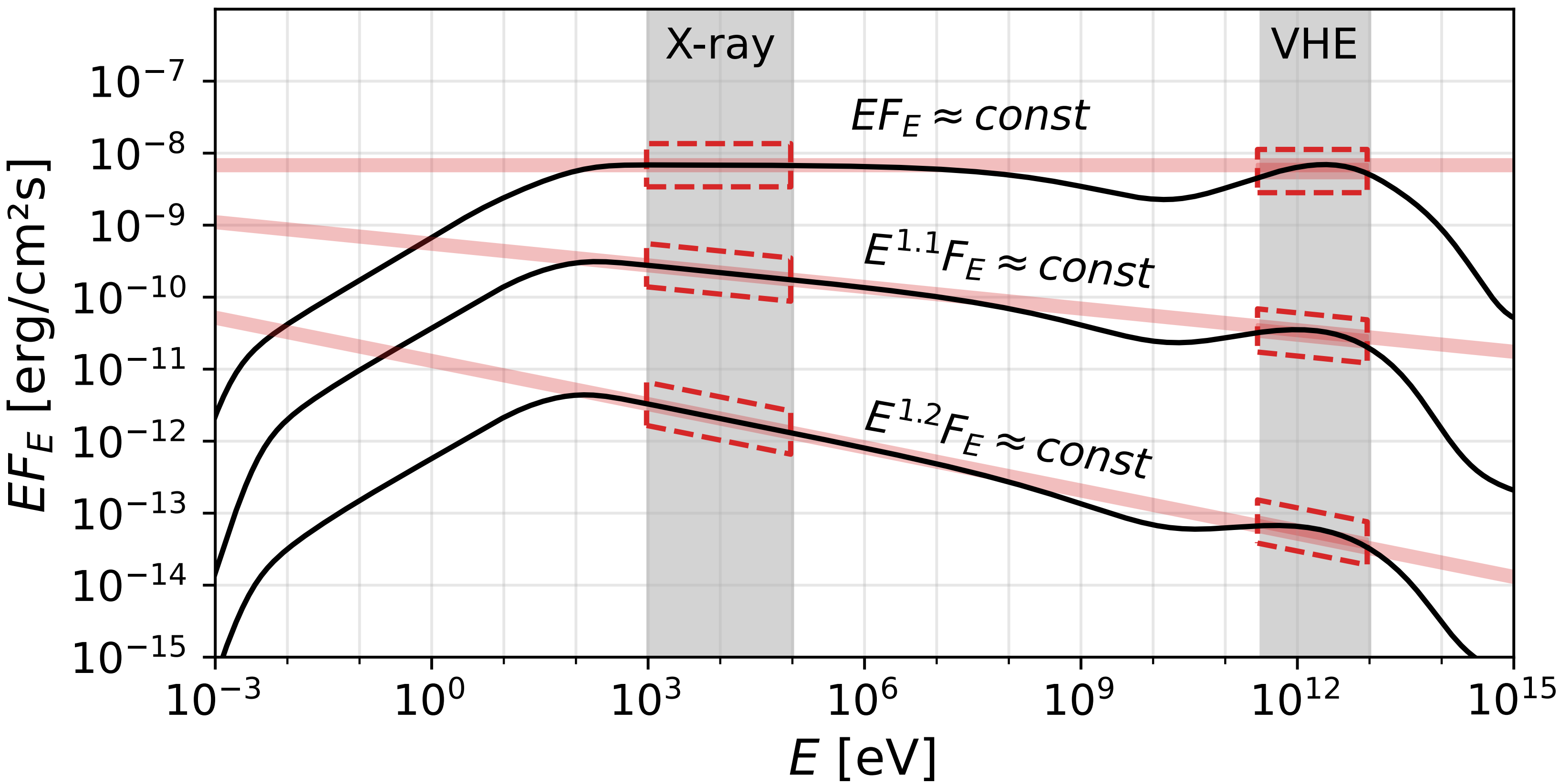
….Very High Energy Non-Thermal Emission

	Neutron Star Merger GRB	Core Collapse GRB
Head On	? (3σ)	✓
Side On	✗ (CTA?)	✗

- GW instruments and new transient detector facilities offer new opportunities for probing **side on** GRBs

GRB Jet Energy Spectrum- General Finding from Observations Over the Last 5 Years





A Cosmic Lab for Studying Relativistic Shocks?

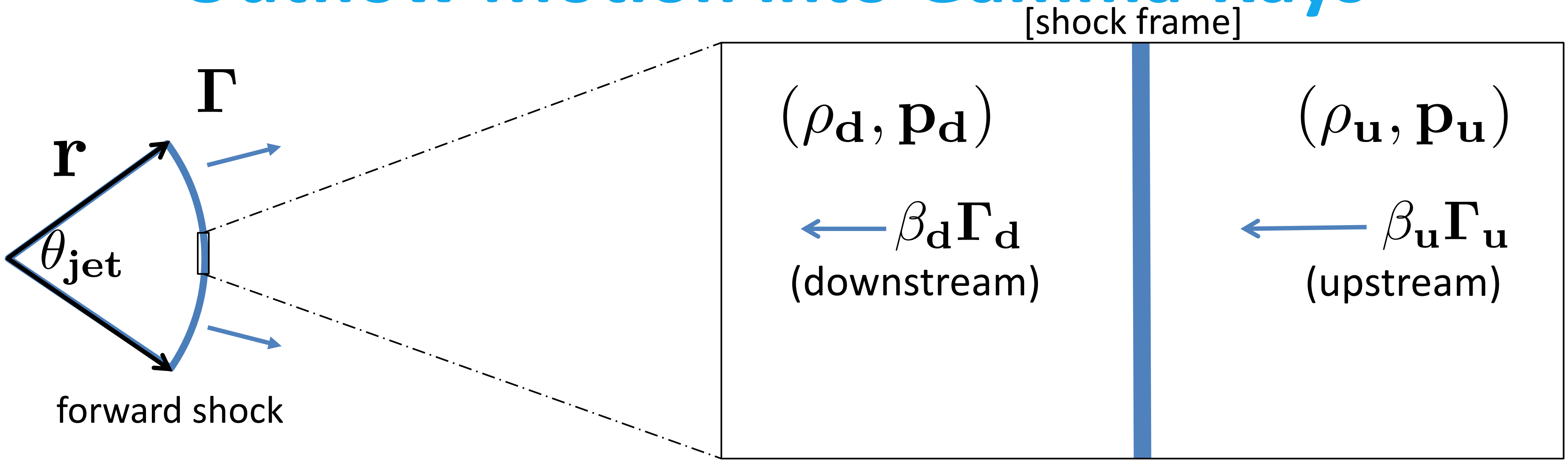
Why should we consider GRB jet afterglows as good test labs for relativistic shocks?

- The energy injection time is well defined
- The energy injection period is relatively short in duration
- The external medium at late times should be rather simple in structure

Questions we may try to ask for these systems:

- What is the particle acceleration rate in the shock?
- What is the downstream magnetisation fraction?
- What fraction of the upstream KE goes into a non-thermal particle population?

GRB Jets: Natures Machines for Converting Outflow Motion into Gamma-Rays



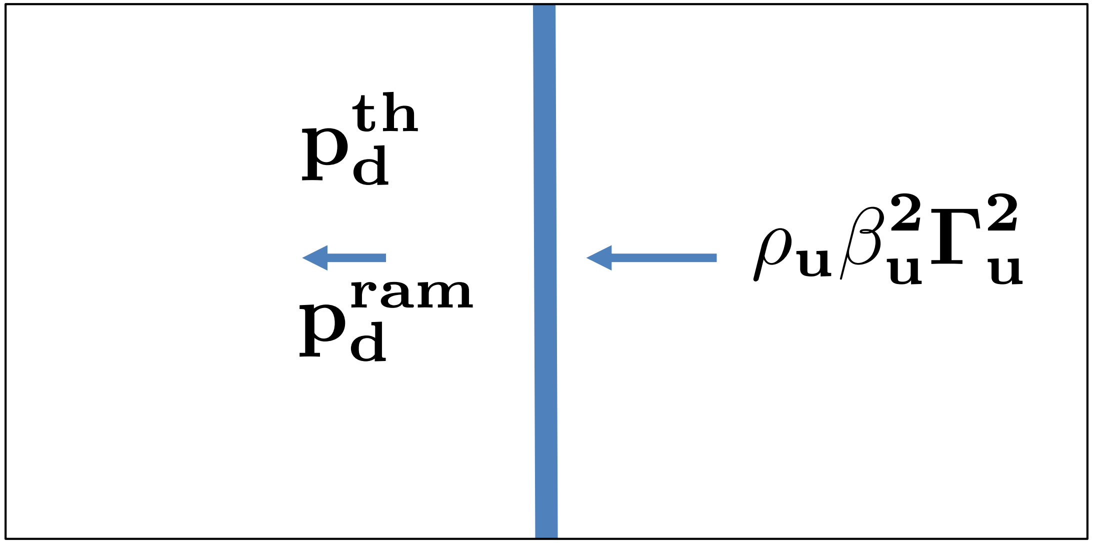
- Total energy in gamma-rays observed up to 1% of the Gravitational binding energy budget limit

- Extremely efficient emitters in terms of converting kinetic energy flux into accelerated particles, into radiation

GRB Jet Model Parameters

For a hydrodynamic relativistic shock

[shock frame]



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

$$\varepsilon_\mathbf{d}^\mathbf{th} = \frac{\mathbf{2}}{\mathbf{3}} \qquad \varepsilon_\mathbf{d}^\mathbf{ram} = \frac{\mathbf{1}}{\mathbf{3}}$$

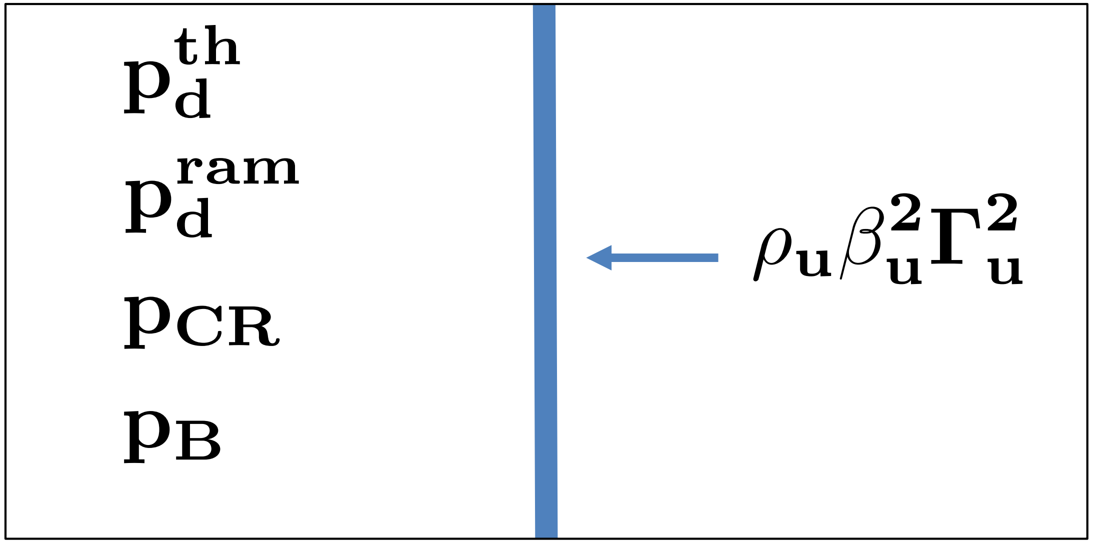
Scattering rate dictates acceleration rate

DESY.

GRB Jet Model Parameters

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

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



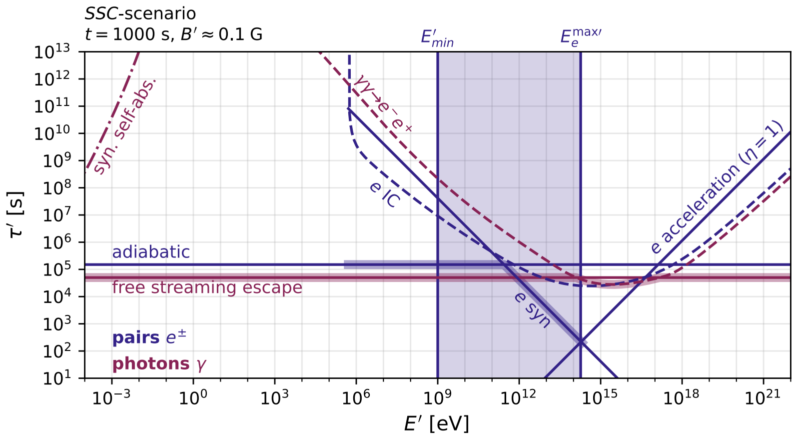
2. η- key parameter which again we don't apriori know, but which we may probe with observations

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

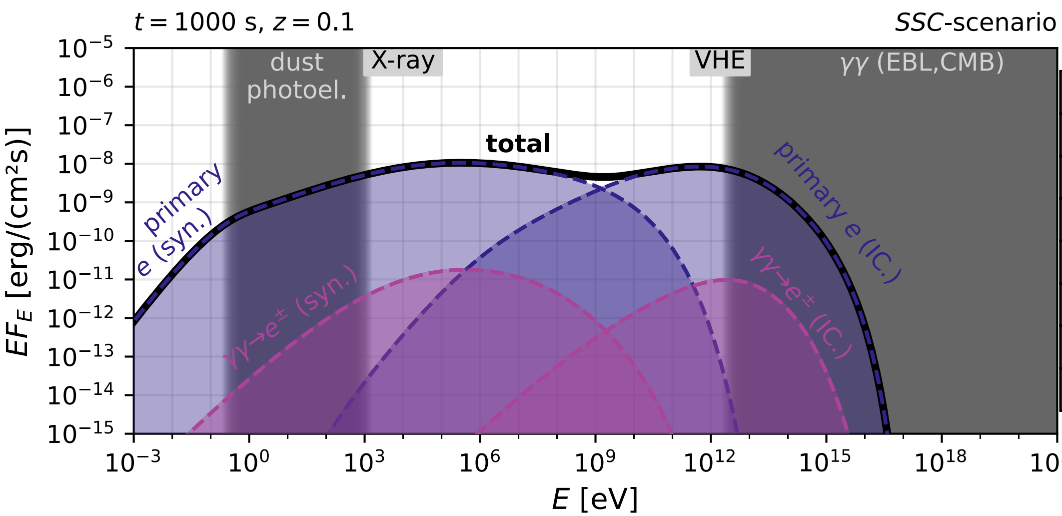
Scattering rate dictates acceleration rate

3. E_{iso} and n collectively dictate how Γ evolves in space

Example Afterglow GRB SED Model (SSC)



Photon energy spectrum



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

[Klinger et al. MNRAS 520 (2023)]

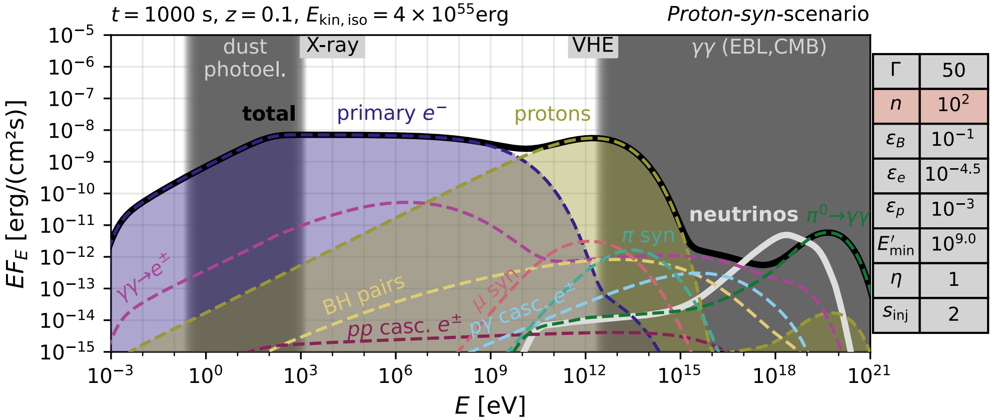
However, not all parameters are physically reasonable

Note that the thermal particle component is set to 0, seemingly unphysical

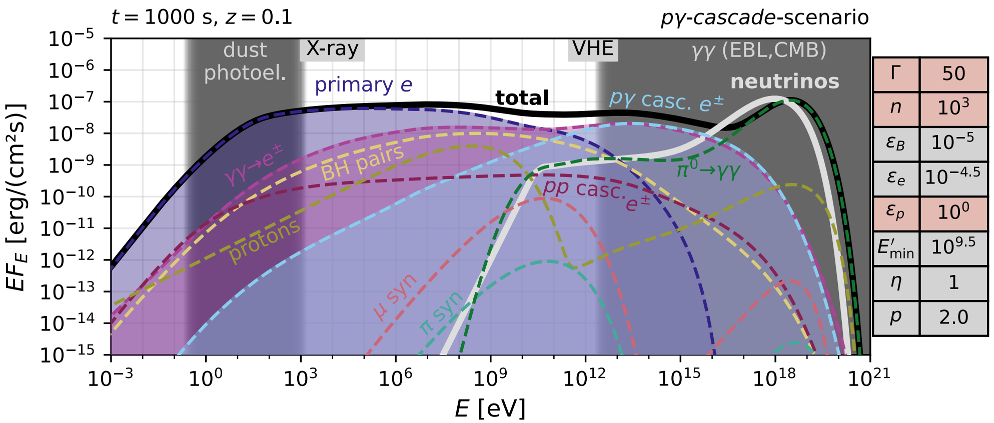
The scattering efficiency η=1 is at the extreme limit of what is possible (Bohm limit)

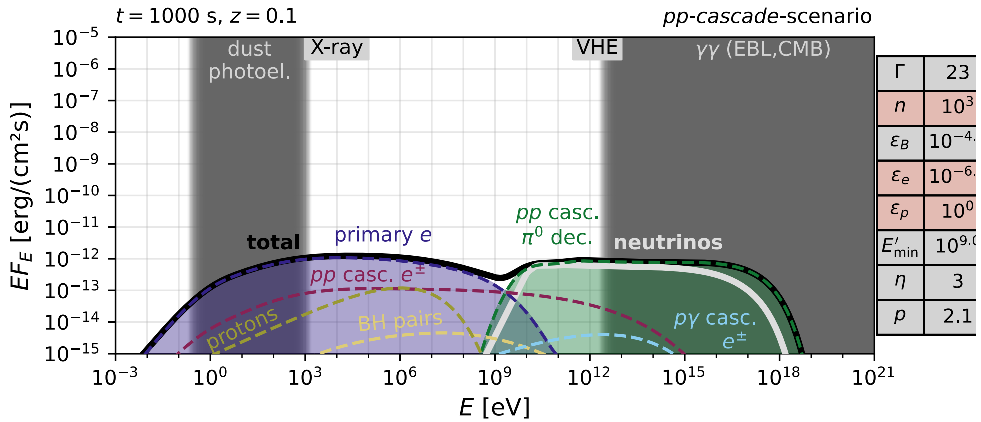
DESY.

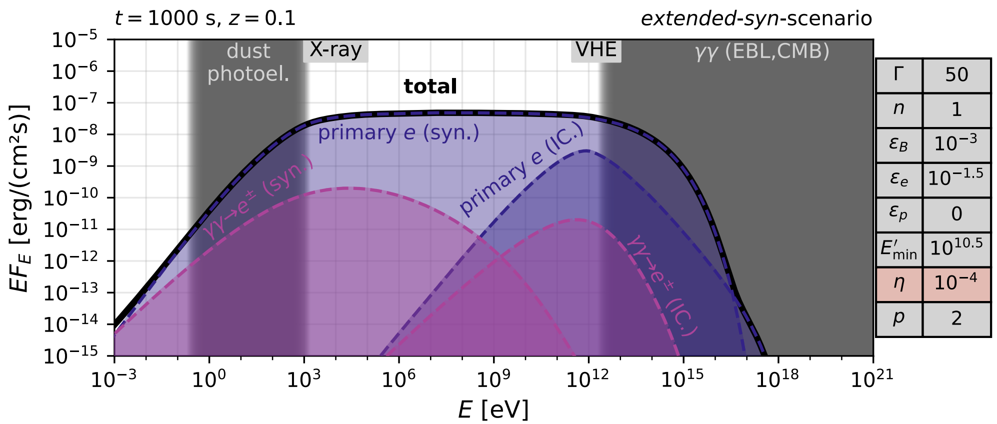
Alternative 1-Zone Scenarios?



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







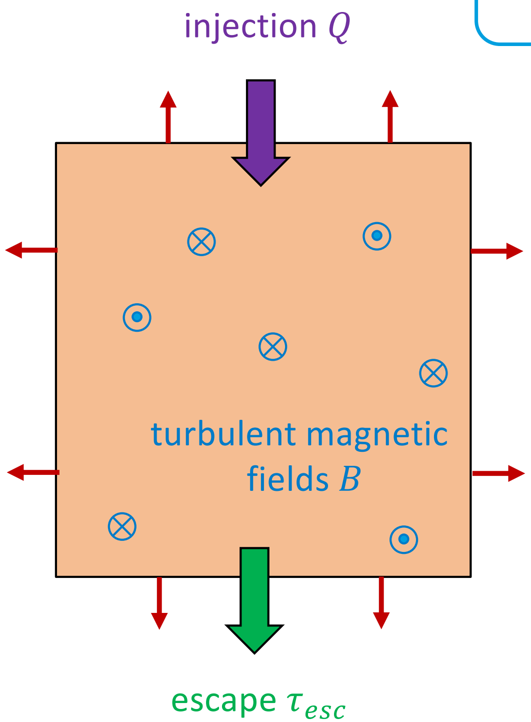
Each scenario here requires rather extreme parameter values (see highlighted box)

[Klinger et al., arxiv:2403.13902

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

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

Fast Coupled Differential Equation Solver



[Diagram + plot Courtesy of M. Klinger]

electrons drive expansion of box

shock injects relativistic particles

electron number

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

synchrotron

inverse Compton scattering

$e^- e^+ \to \gamma\gamma$

$\gamma\gamma \to e^- e^+$

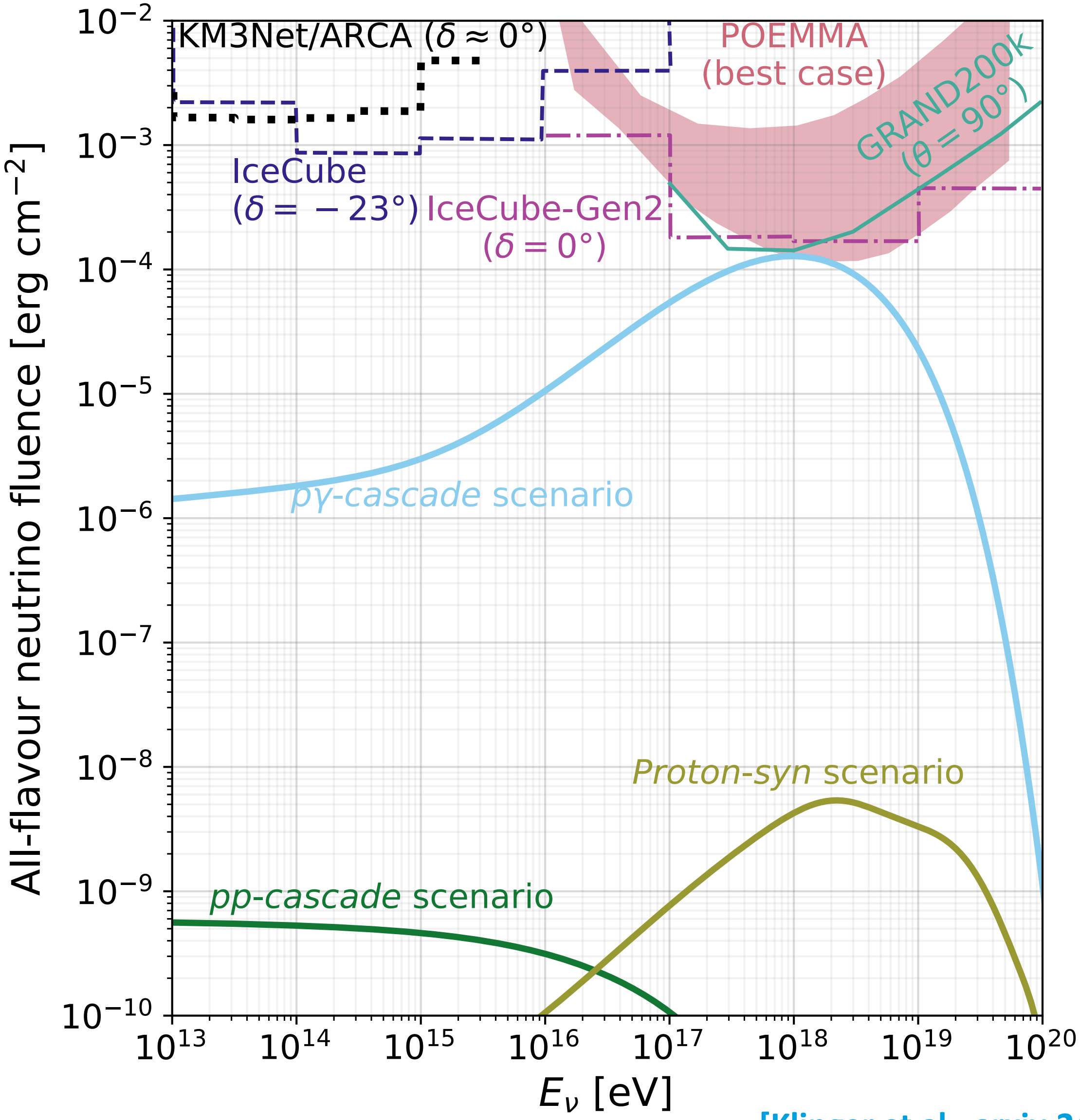
photon number

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

photons can escape from box

Note the absence of spatial information in these transport equations

Testing the pγ Scenario with Future Neutrino Detectors



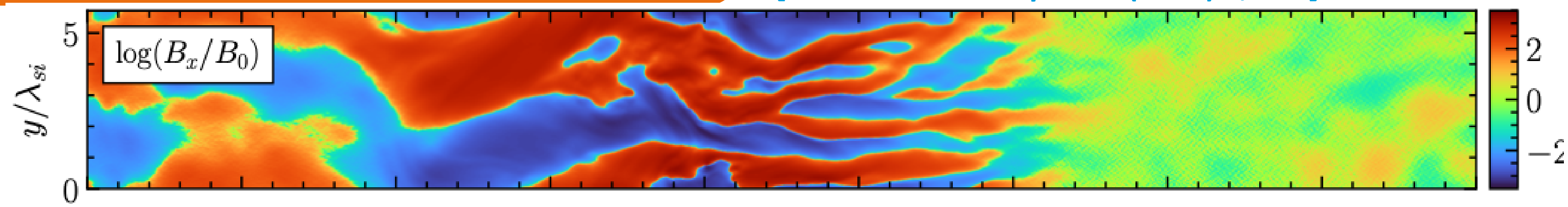
[Klinger et al., arxiv:2403.13902]

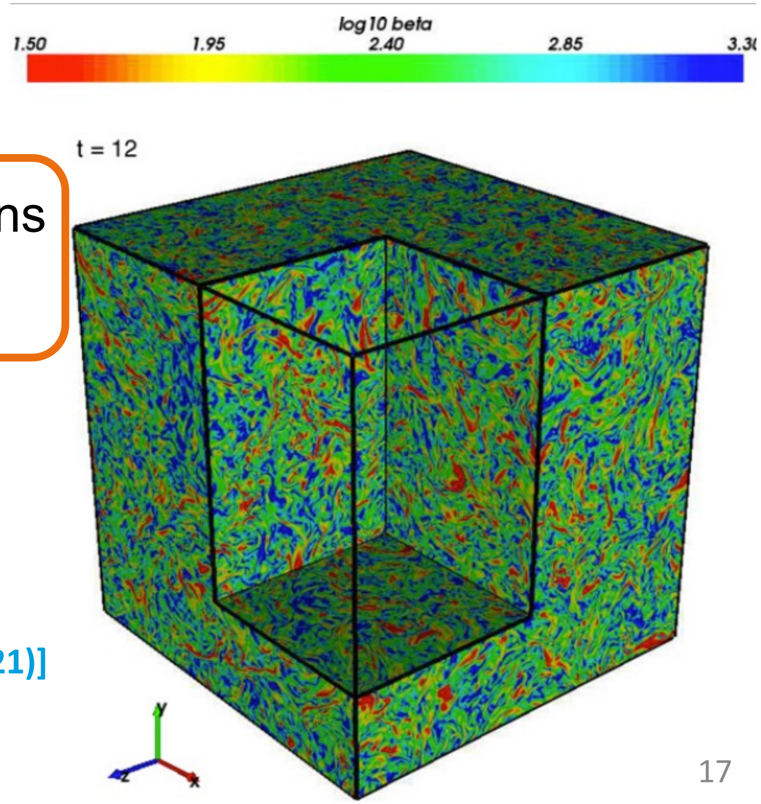
Theoretical Studies to Predict the Magnetisation and Scattering Rate

Small Scales: particle in cell (PIC) simulations

$\varepsilon_{\mathbf{B}} \sim \mathbf{10^{-3}}$ $\eta \sim \mathbf{10^{5}}$

[Karol *et al* 2023 *ApJ* 959 (2023) 2, 119]





Large Scales: magnetohydrodynamics (MHD) simulations

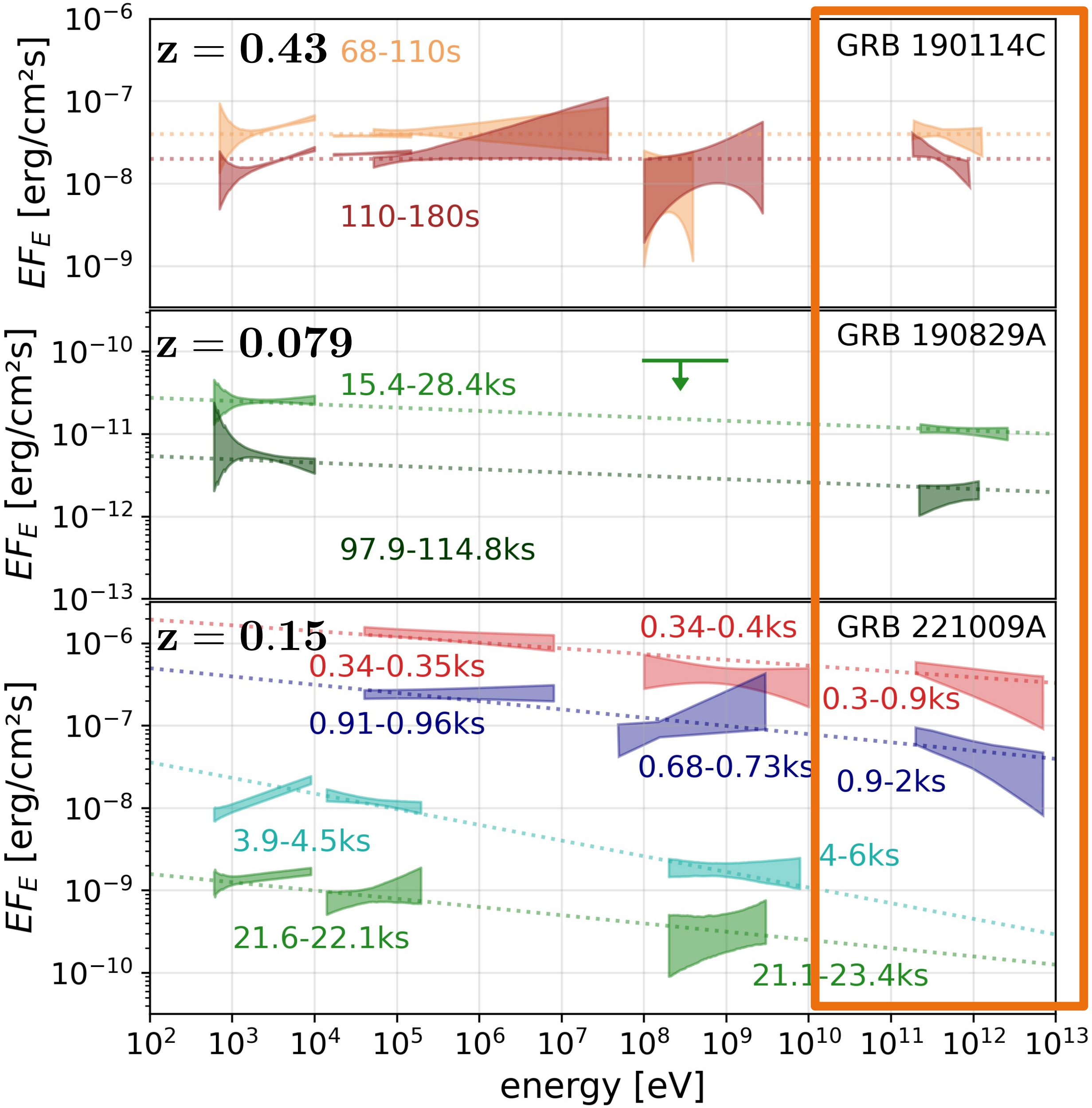
$\varepsilon_{\mathbf{B}} \sim \mathbf{10^{-3}}$ $\eta \sim \mathbf{10^{0}}$

[Zhang *et al* 2009 *ApJ* 692 L40]
[Khangulyan et al., Ap. J. 914 (2021)]

Conclusions

- GRB jets offer a test lab for probing relativistic shocks.
- We are now (since 2018) starting to probe the very high energy (TeV) gamma-ray emission from GRB jets orientated **head on**.
- Progress on probing GRB jets **side on** is proving challenging (yet to be achieved in very high energy gamma-rays).
- The emission process responsible for the TeV gamma-ray emission is unclear: 5 potential mechanisms along with testable predictions found.
- Emission scenarios require relativistic shocks are extremely efficient accelerators.
- Determination of the mechanism for the growth of magnetic field at the shock is now a prime focus of the community.

VHE GRB SED- Lessons Learnt Since 2018



→ MAGIC:

→ HESS:

→ LHAASO:

[Klinger et al. arxiv:2403.13902]

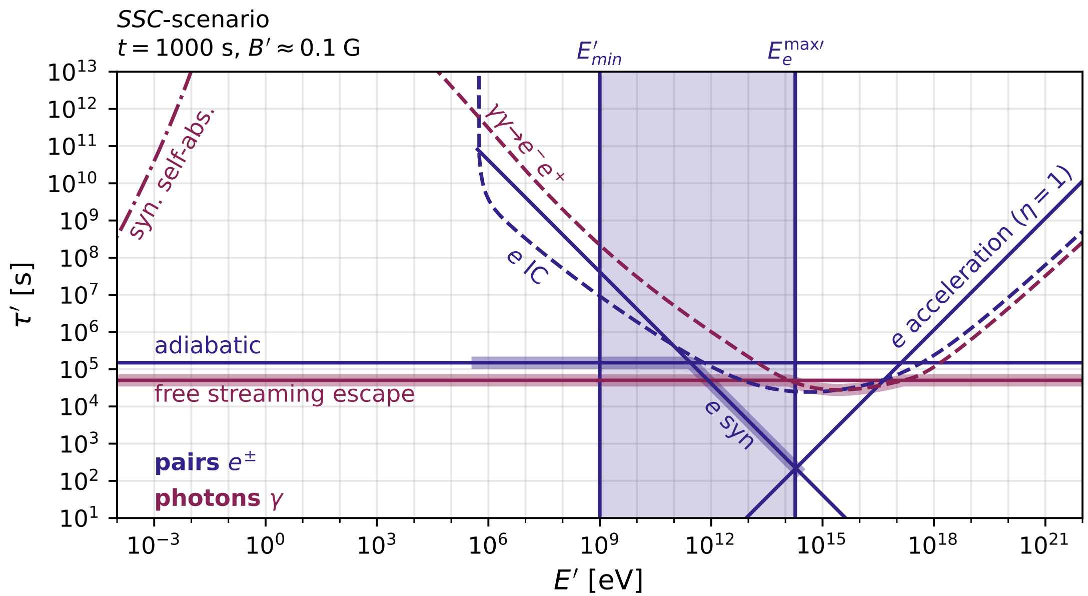
Electron Spectrum Produced in Sources

Steady state

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

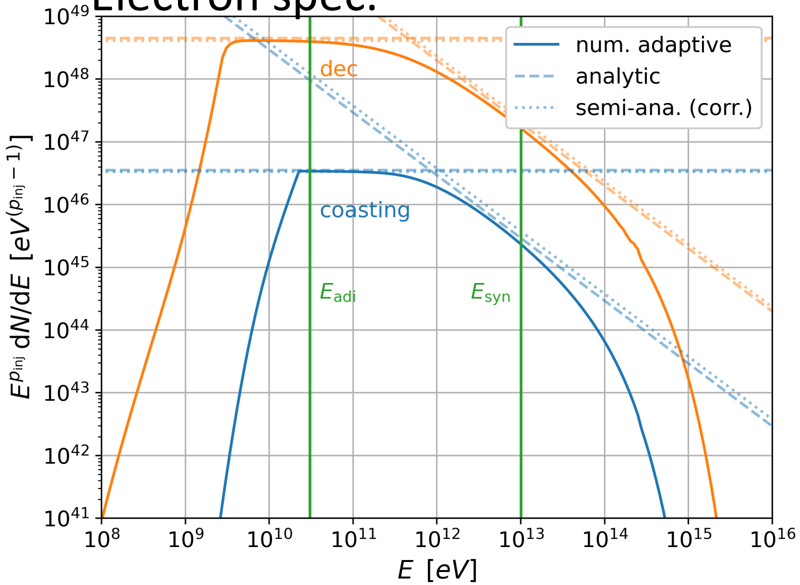
$$\tau_{\mathbf{eff}} = \left(\tau_{\mathbf{adi}}^{-1} + \tau_{\mathbf{sync}}^{-1} + \tau_{\mathbf{IC}}^{-1} \right)^{-1}$$

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



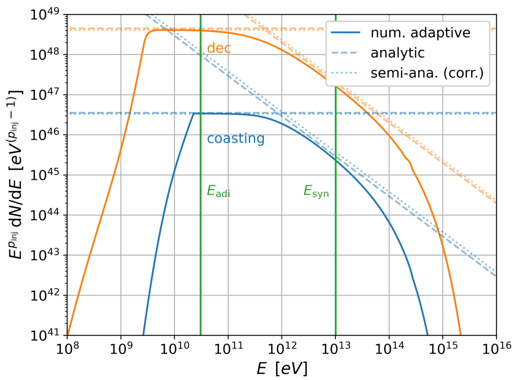
Andrew Taylor

Electron spec.



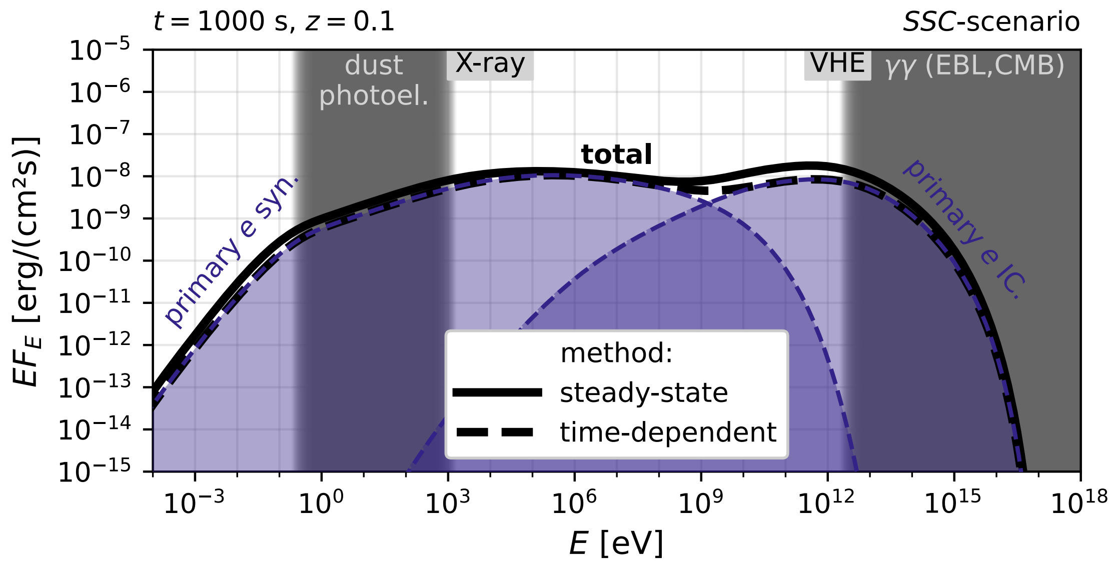
Afterglow GRB SED- Expected from SSC Model

Electron spec.



Photon spec.

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



[Klinger et al. MNRAS 520 (2023)]

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

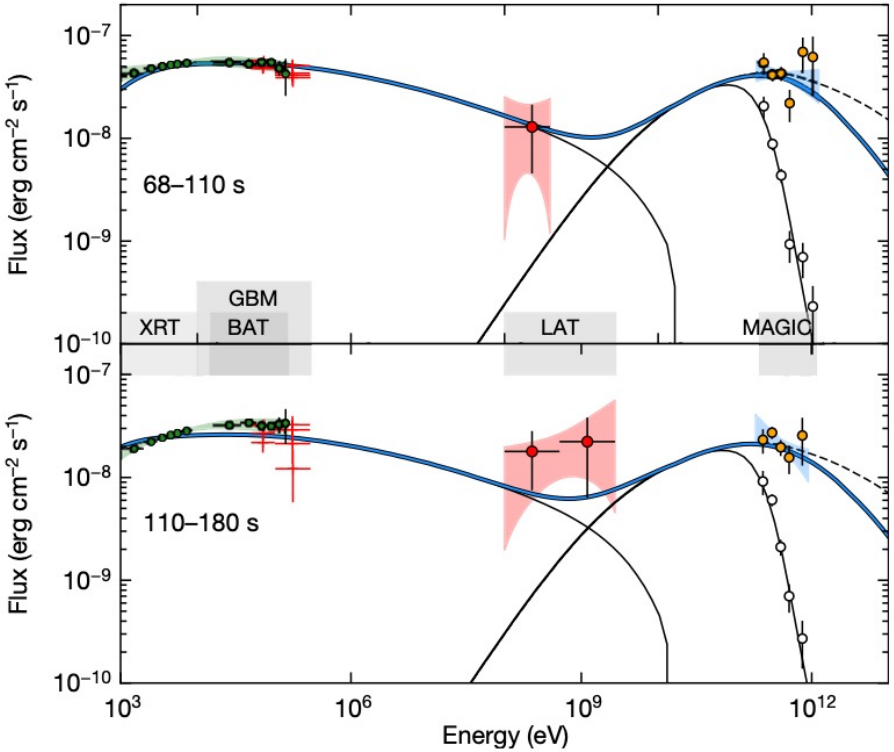
Both injection and effective cooling rate dictated by matter profile of surrounding environment

The "steady-state" approximation provides a reasonable description for the spectrum → ie. ~agrees with the full 1-zone time-dependent result

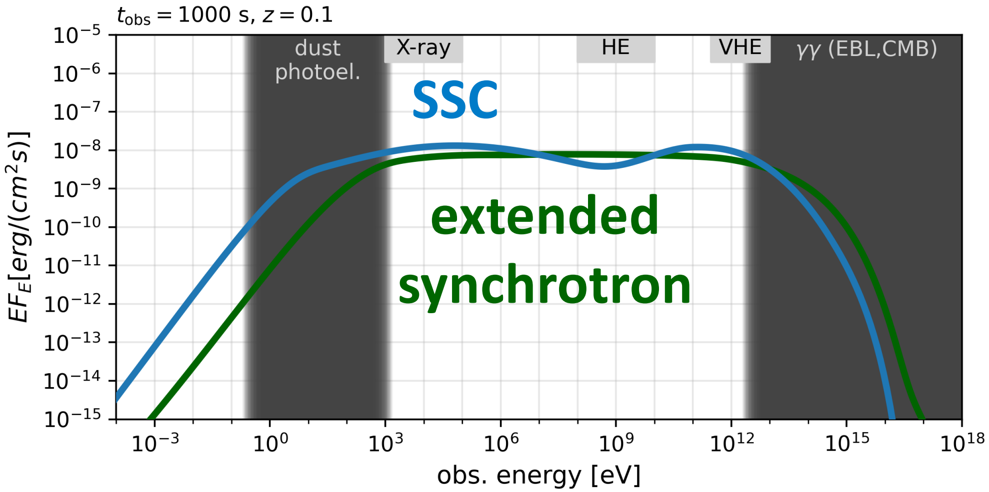
DESY.

Statistical Tests- A Spectral Model Fit for: MAGIC- GRB 190114C

[MAGIC Coll. Nature 2019]

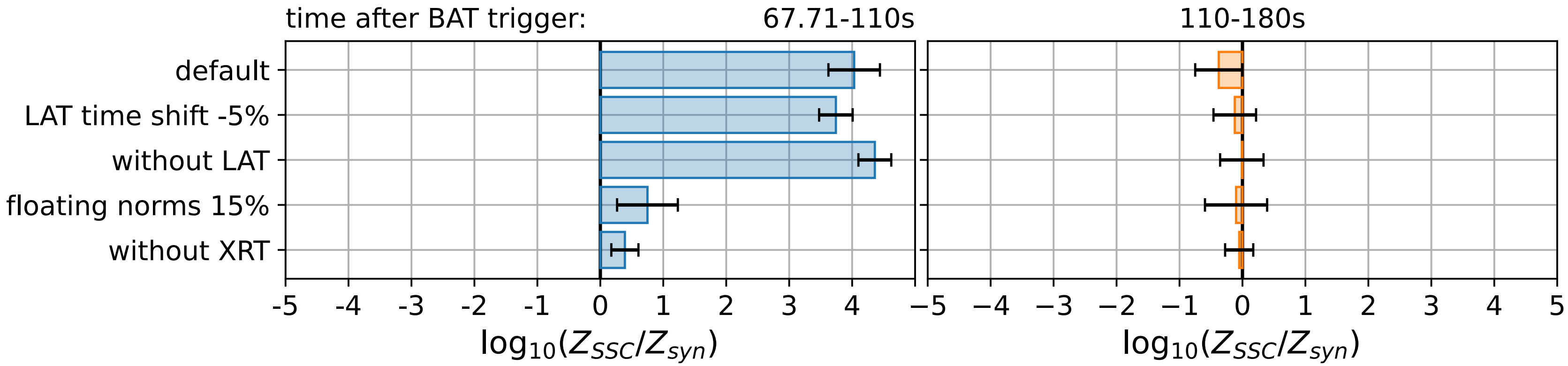


[Klinger et al. MNRAS 520 (2023)]



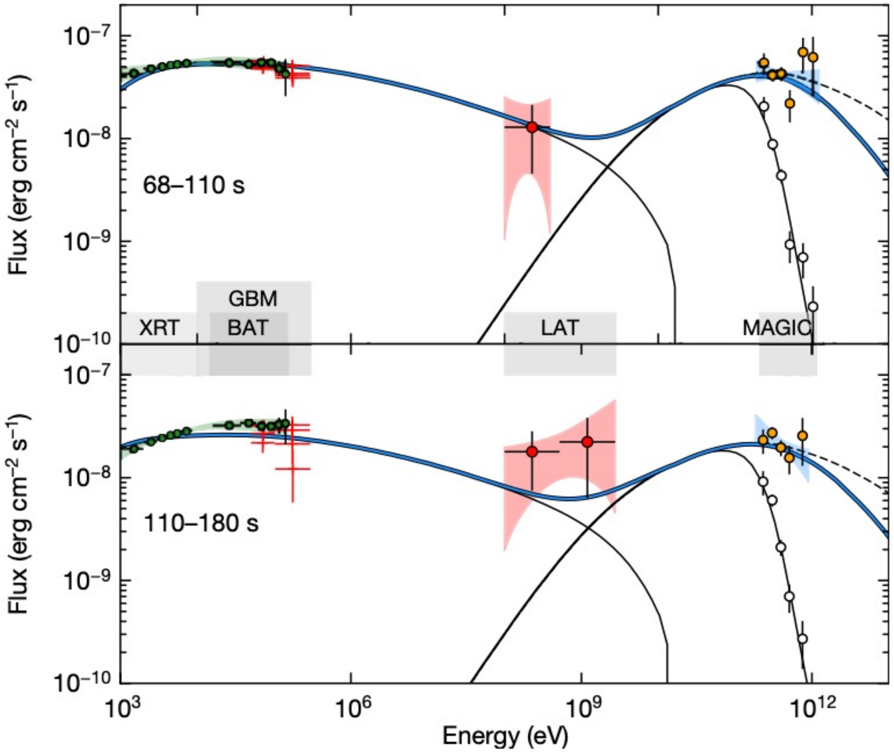
[Fermi+Swift. ApJ 890 (2020)]

Bayes factor for new component

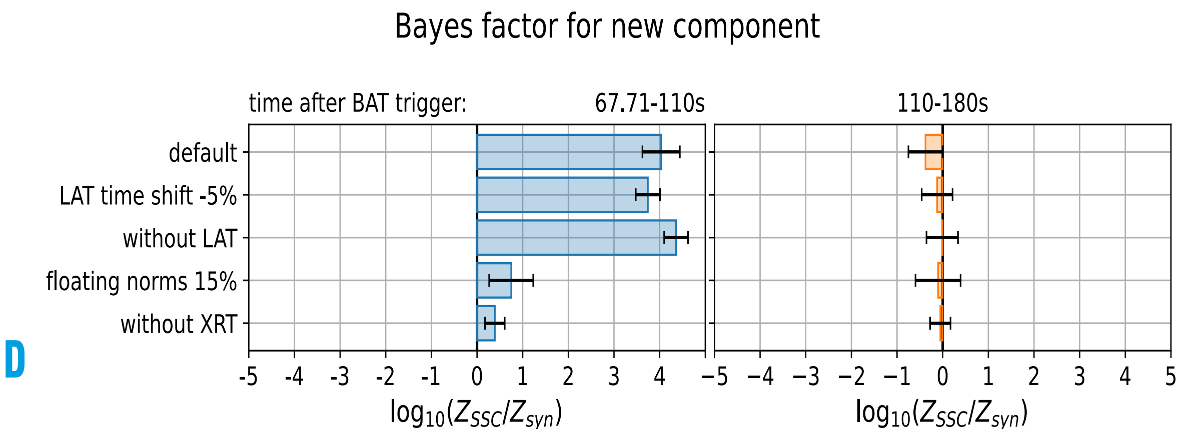


Statistical Tests- A Spectral Model Fit for: MAGIC- GRB 190114C

[MAGIC Coll. Nature 2019]



[Klinger et al. MNRAS 520 (2023)]



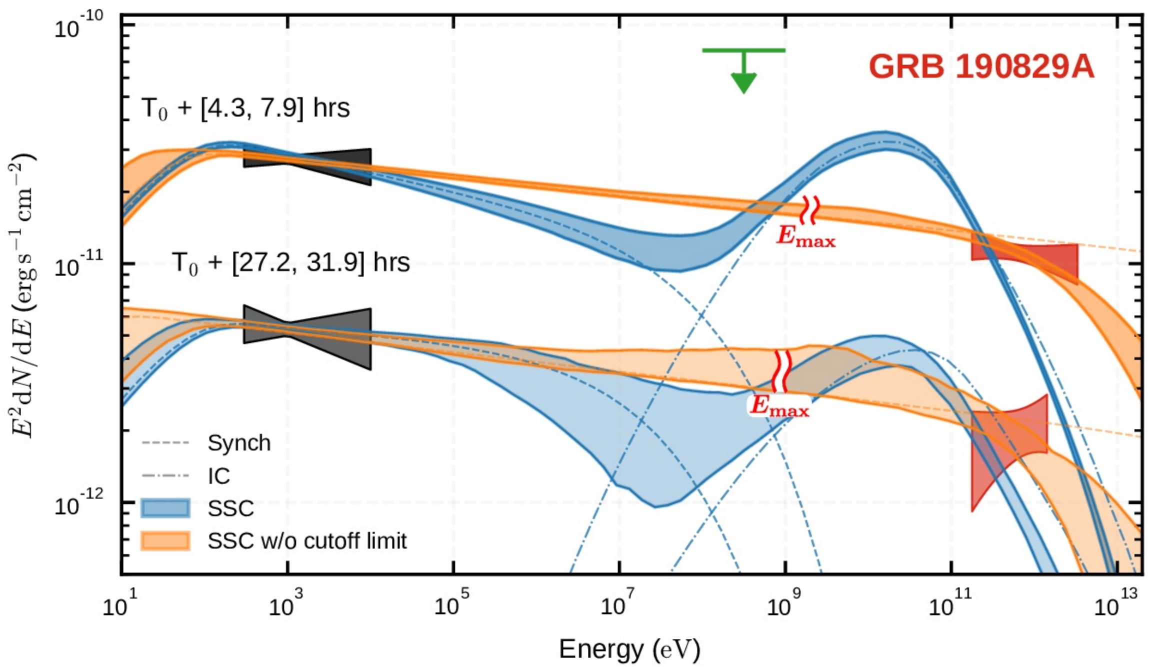
- MAGIC observation:
  $z = 0.43$ (EBL) + moonlight
  → uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$
- *Fermi*-LAT not constraining (5+6 photons)

counts level fit:

→ no robust preference for SSC!

Statistical Tests- Spectral Model Fits for: HESS- GRB 190829A

[15-28 ks]



[HESS Coll. Science 2021]

- $z = 0.08 \rightarrow$ low EBL abs.

$\rightarrow$ spectral index at TeV:
$\approx -2 \pm 0.1 \pm 0.26$

- poor MWL coverage

- counts level fit:

$\rightarrow$ preference for single component!

Electron Acceleration with Cooling

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

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

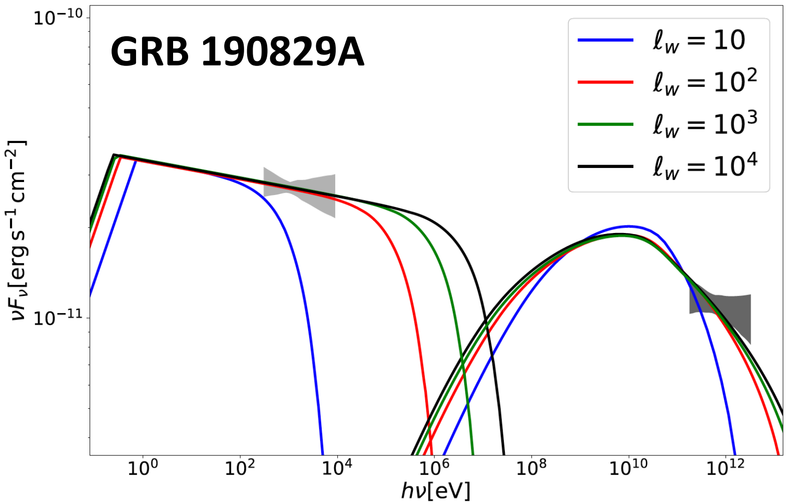
$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

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

Maximum synchrotron energy tells us how efficient accelerator is!

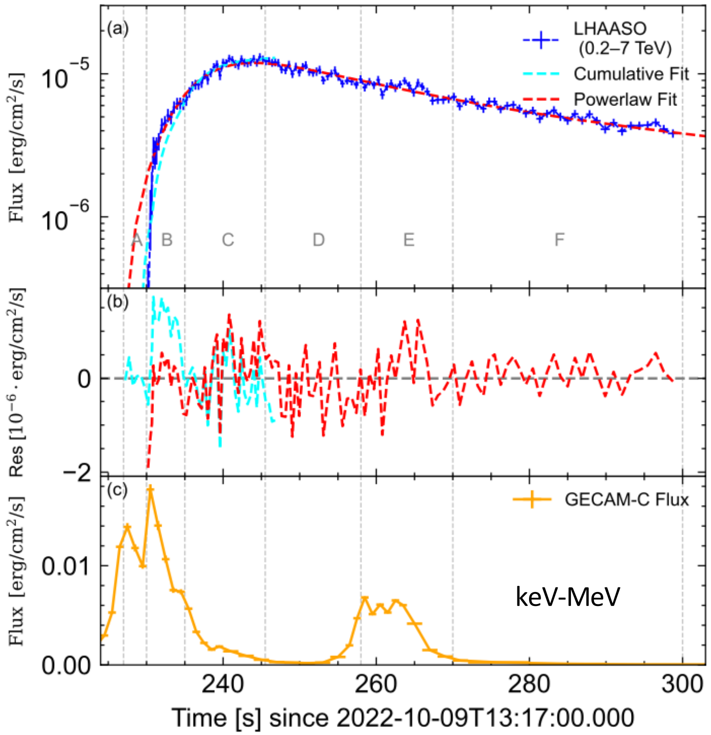
$$\mathbf{E_\gamma^{sync}} \approx \frac{\mathbf{9}}{\mathbf{4}}\eta^{-\mathbf{1}}\beta^{\mathbf{2}}\frac{\mathbf{m_e}}{\alpha}$$

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



Afterglow Onset of: LHAASO- GRB221009A

[Zhang, Y-Q et al. arxiv:2404.03229]



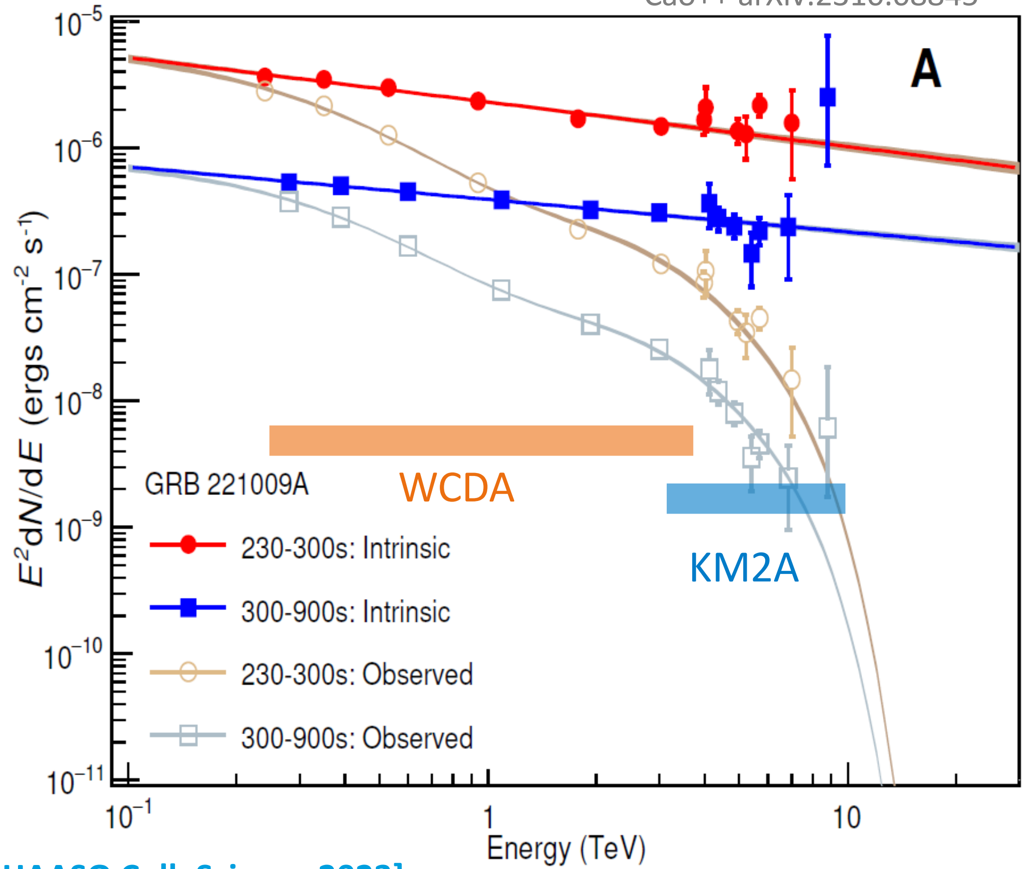
The steep growth of the LHAASO TeV lightcurve at early times is also something new- may be telling us about the activation of the accelerator or reduction in internal attenuation.

[Khangulyan, D. et al. arxiv: 2309.00673]

Statistical Tests- Spectral Model Fits for: LHAASO- GRB 221009A

[0.2-0.9 ks]

Cao++ arXiv:2310.08845



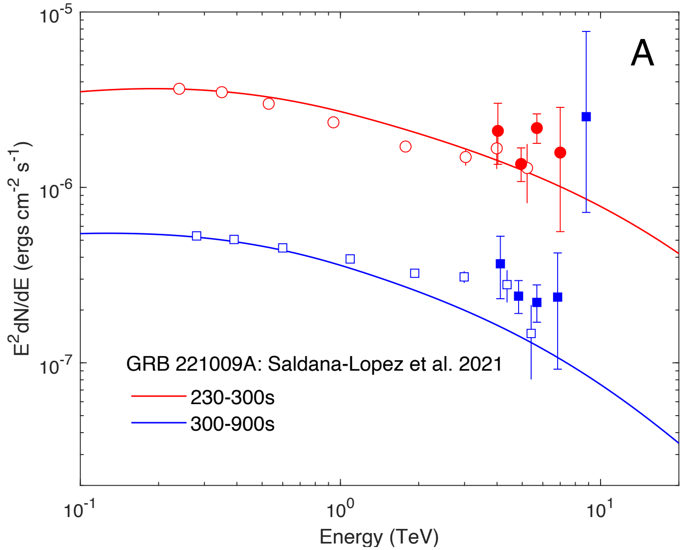
[LHAASO Coll. Science 2023]

LHAASO Collaboration 2023:

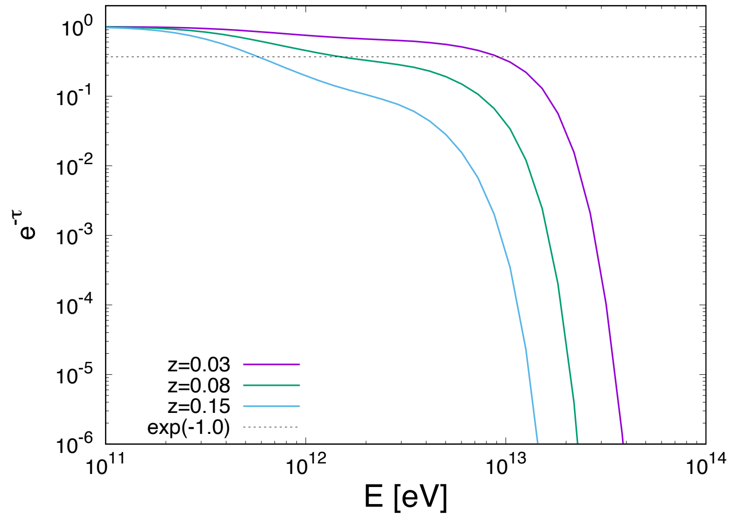
No softening up to at least 10 TeV apparent!

(note $z = 0.15 \rightarrow$ EBL abs. > few TeV)

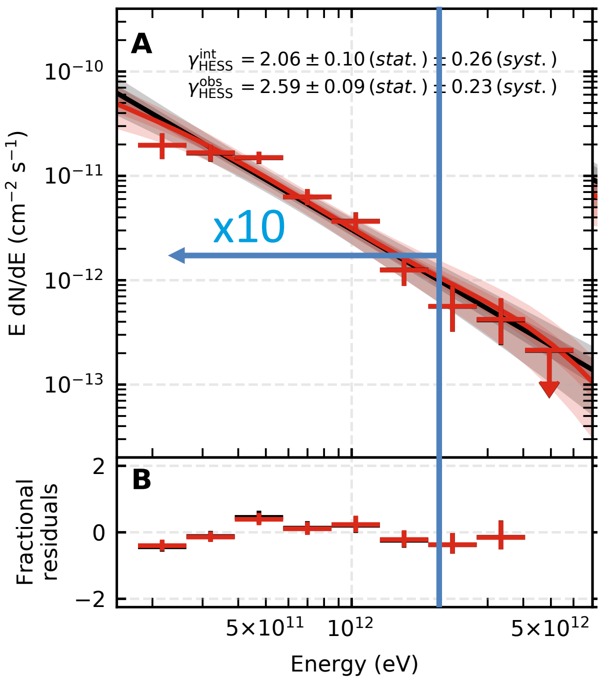
→ spectrum appears harder in the second time bin than expectations from SSC model



Importance of Minimising EBL Damage

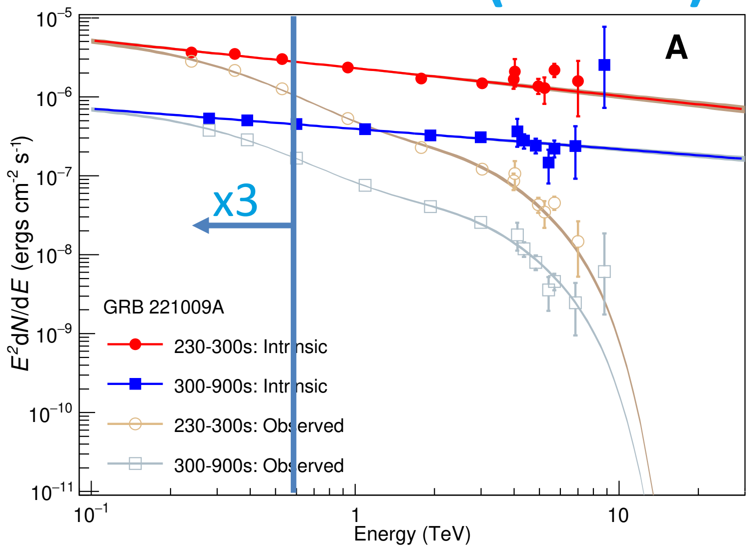


GRB 190829A (z~0.08)



[HESS Coll. Science 2021]

GRB 221009A (z~0.15)



[LHAASO Coll. Science 2023]

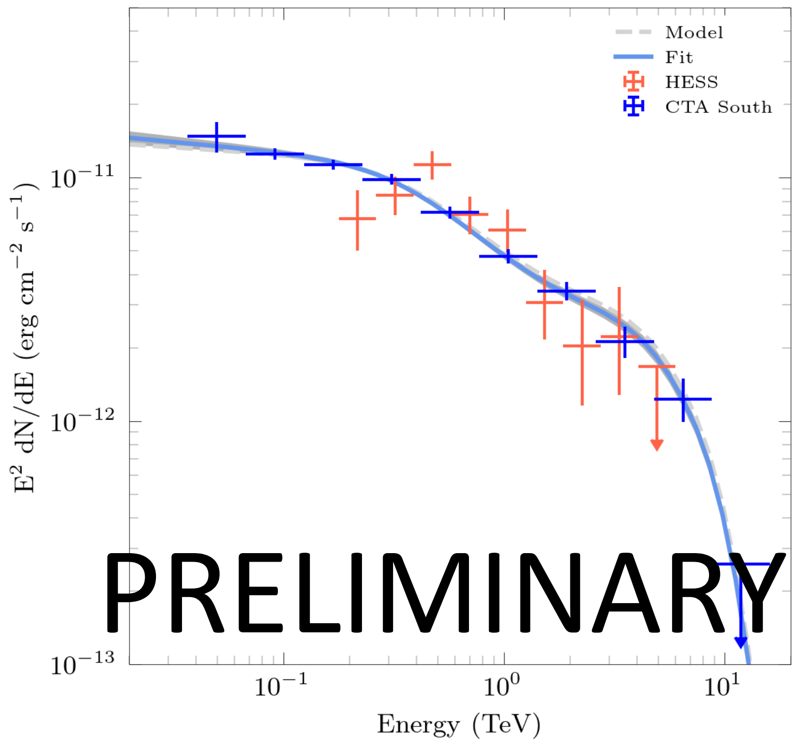
A GRB 190829A Like Event for CTA

- 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

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

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

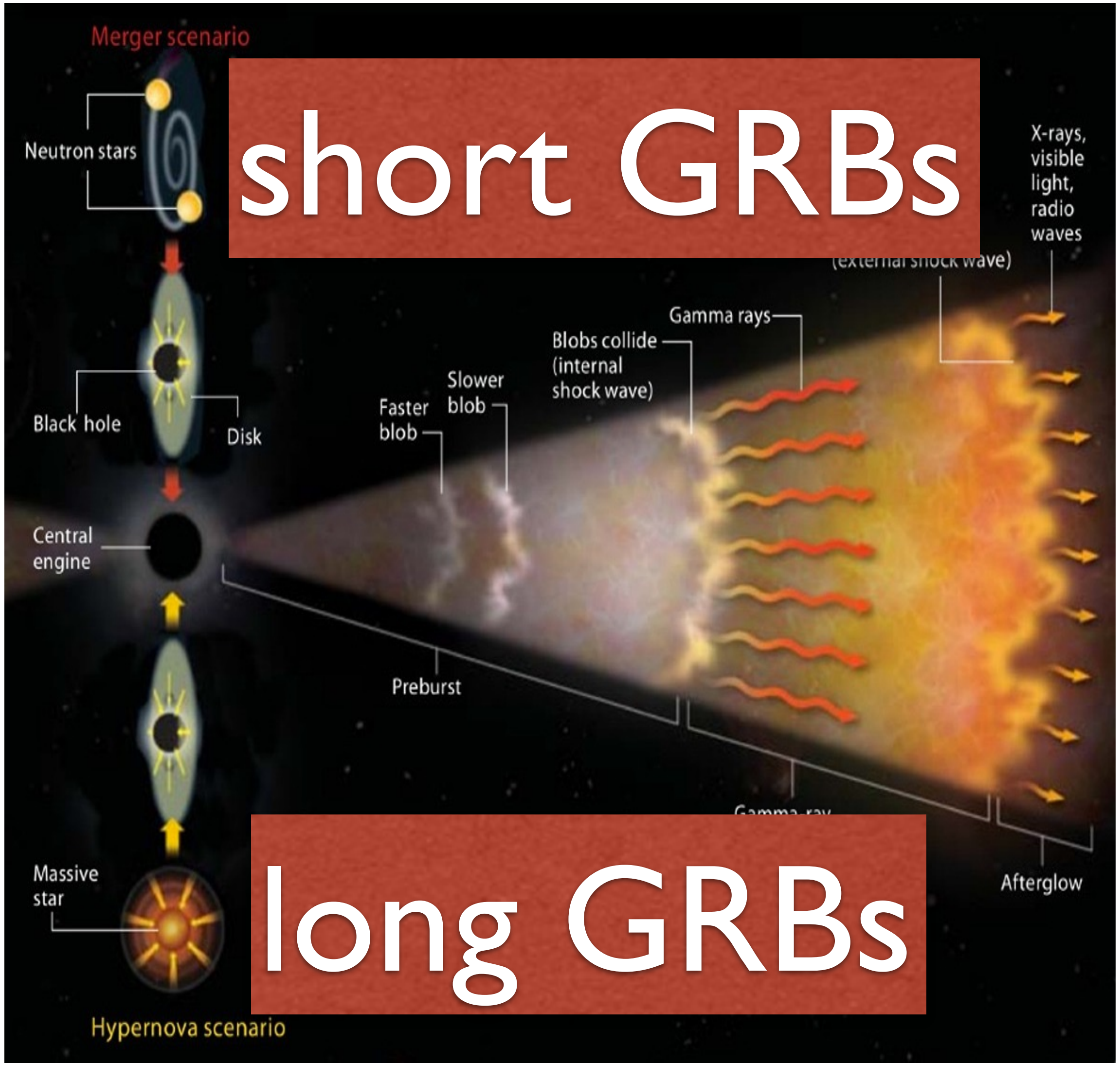


[Provided by J. Pfeil and D. Parsons]

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

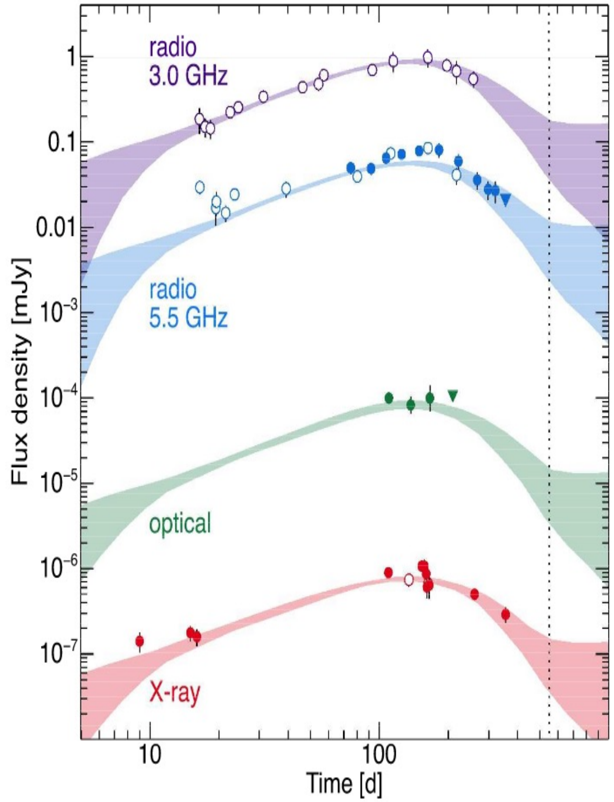
DESY.

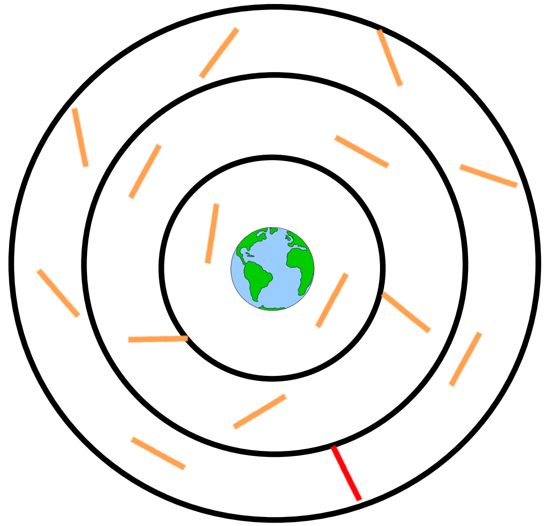
Local (Short) GRBs



Credit: NASA

Afterglow

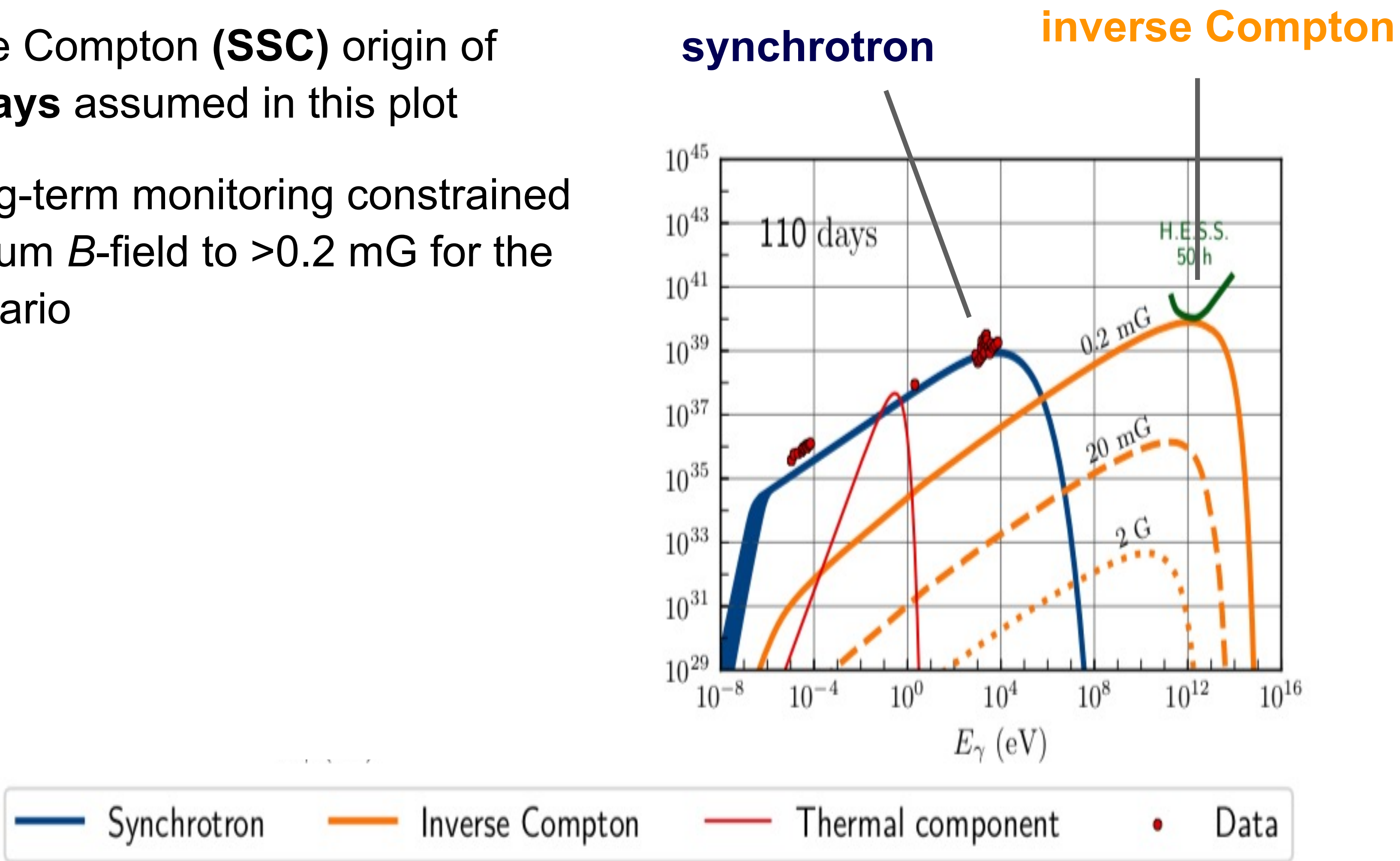




DESY.

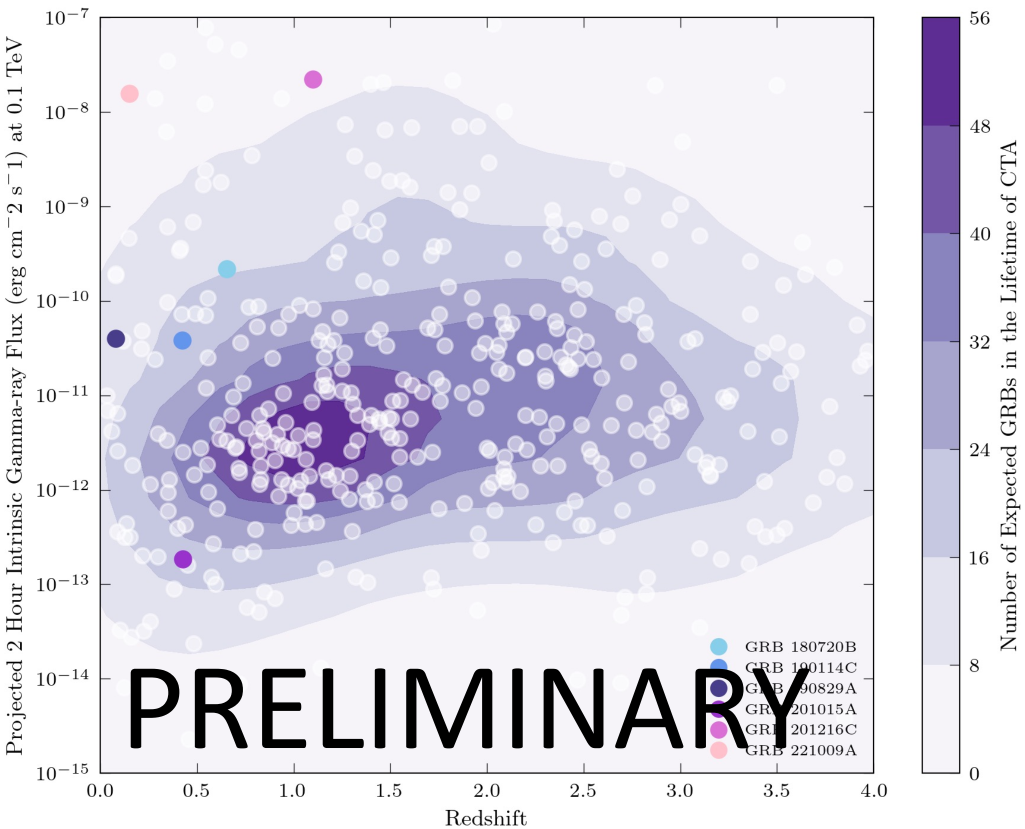
VHE Gamma rays from Off-Axis GRB (eg. GW 170817)

- An inverse Compton **(SSC)** origin of **gamma-rays** assumed in this plot
- HESS long-term monitoring constrained the minimum *B*-field to >0.2 mG for the SSC scenario



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

Prospective Rates for Testing the GRB Emission Process with CTA

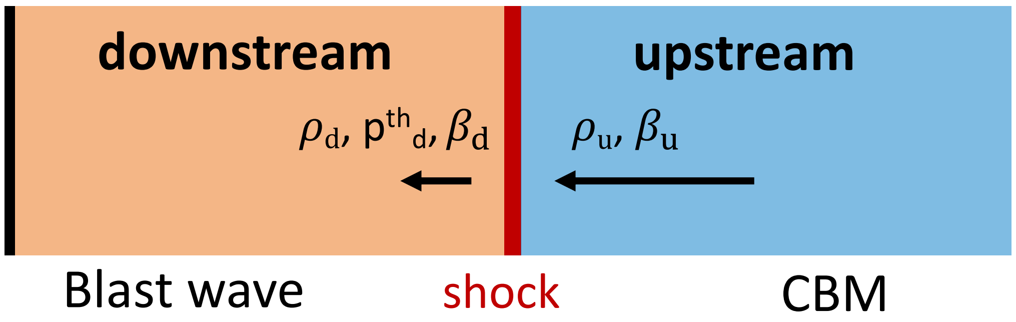


[Provided by J. Pfeil and D. Parsons]

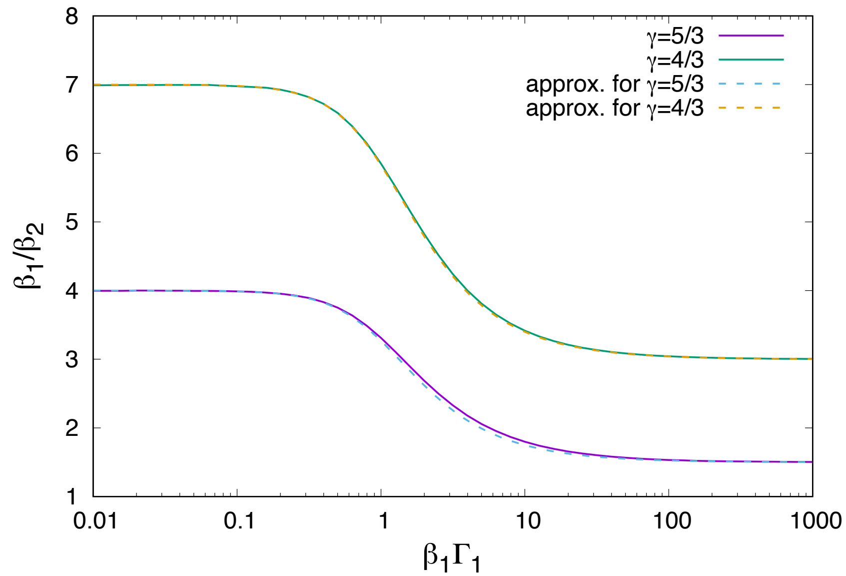
- Future GRBs for providing a stronger probe of the spectral emission model must be local and have bright afterglows
- For CTA, a rate of up to 4 yr $^{-1}$ is possible to expect, consistent with other estimates [Ashkar et al., ApJ 964 57]
- However, of these events, the local subset of particular interest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

DESY.

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



[viewed in shock restframe]



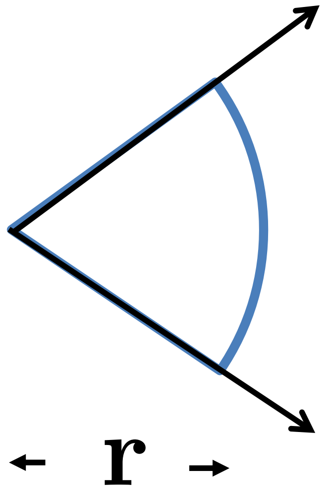
$$\mathbf{p_d^{th}} = \frac{\mathbf{2}}{\mathbf{3}}\rho_\mathbf{u}\beta_\mathbf{u}^\mathbf{2}\boldsymbol{\Gamma}_\mathbf{u}^\mathbf{2}$$

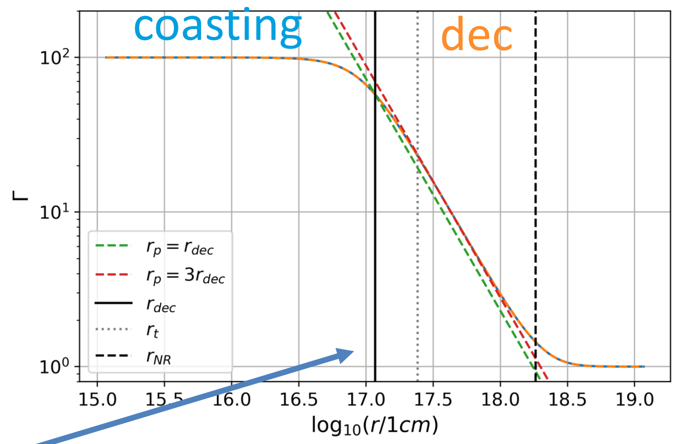
$$\mathbf{w_d}\beta_\mathbf{d}^\mathbf{2}\boldsymbol{\Gamma}_\mathbf{d}^\mathbf{2} = \frac{\mathbf{1}}{\mathbf{3}}\rho_\mathbf{u}\beta_\mathbf{u}^\mathbf{2}\boldsymbol{\Gamma}_\mathbf{u}^\mathbf{2}$$

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

Temporal Compression of Signal

For a constant density medium, during the deceleration phase,



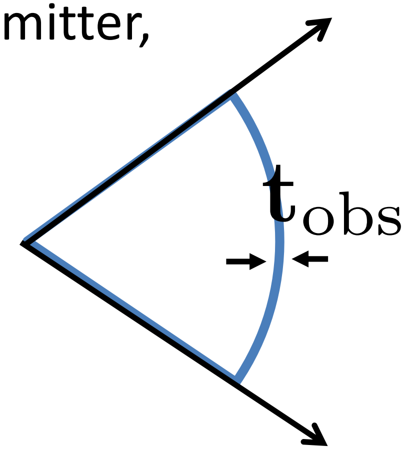


[Plot Courtesy of M. Klinger]

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

Since radiation is emitted by a relativistically moving emitter,

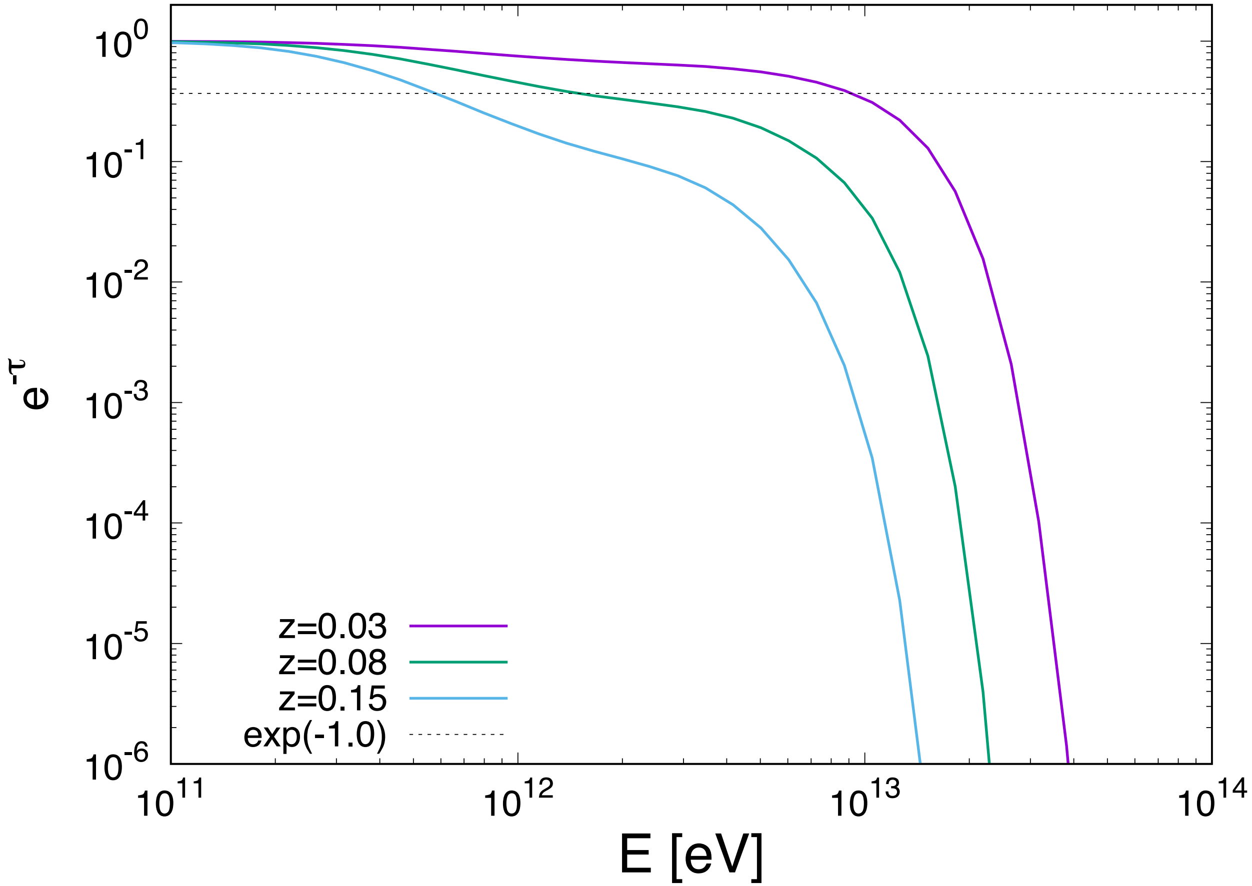
$$\mathbf{ct_{obs} = (1 - \beta) r}$$



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

DESY.

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

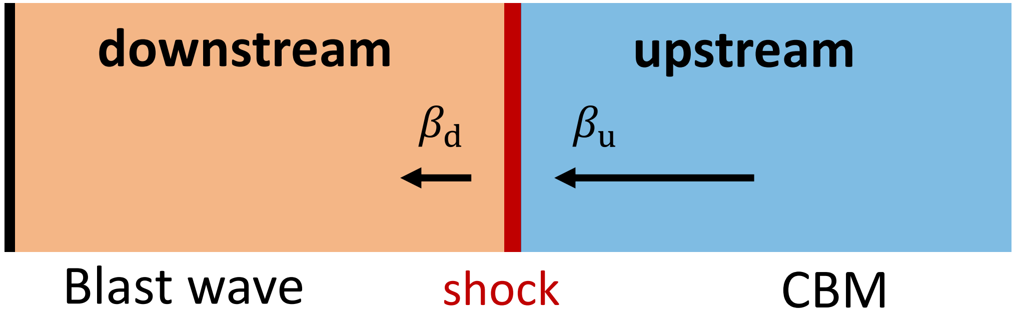
Within Swift's lifetime (~20 years so far), the most local GRB was z=0.03

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

DESY.

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

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

Evolutionary Phases of Blastwave

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

[R. Blandford + McKee 1976]

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

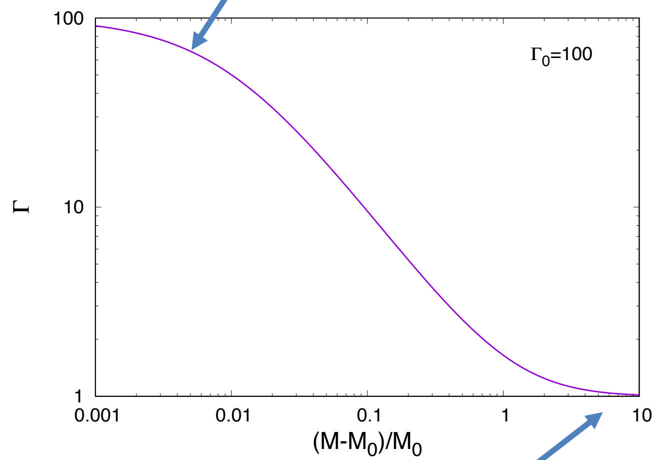
$$E_k = \frac{\rho 4\pi R^3}{3}(\Gamma - 1)$$

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

This has the solution

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

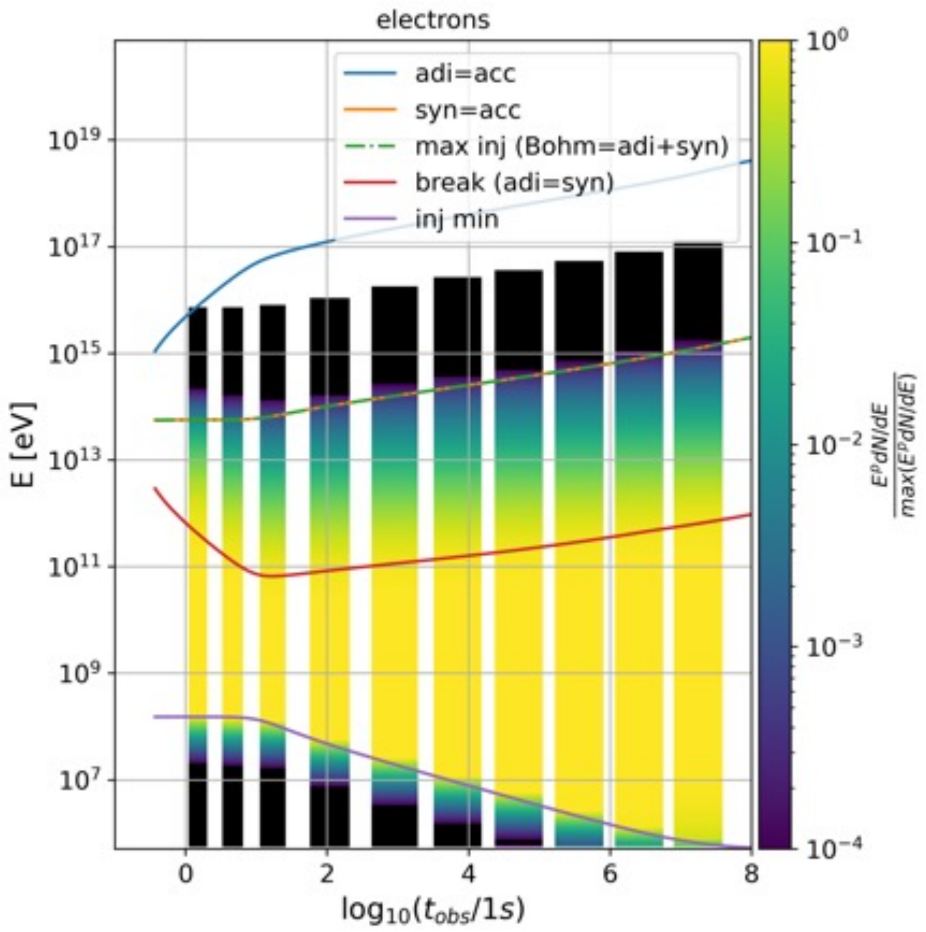
Critical mass where free expansion changes to deceleration phase

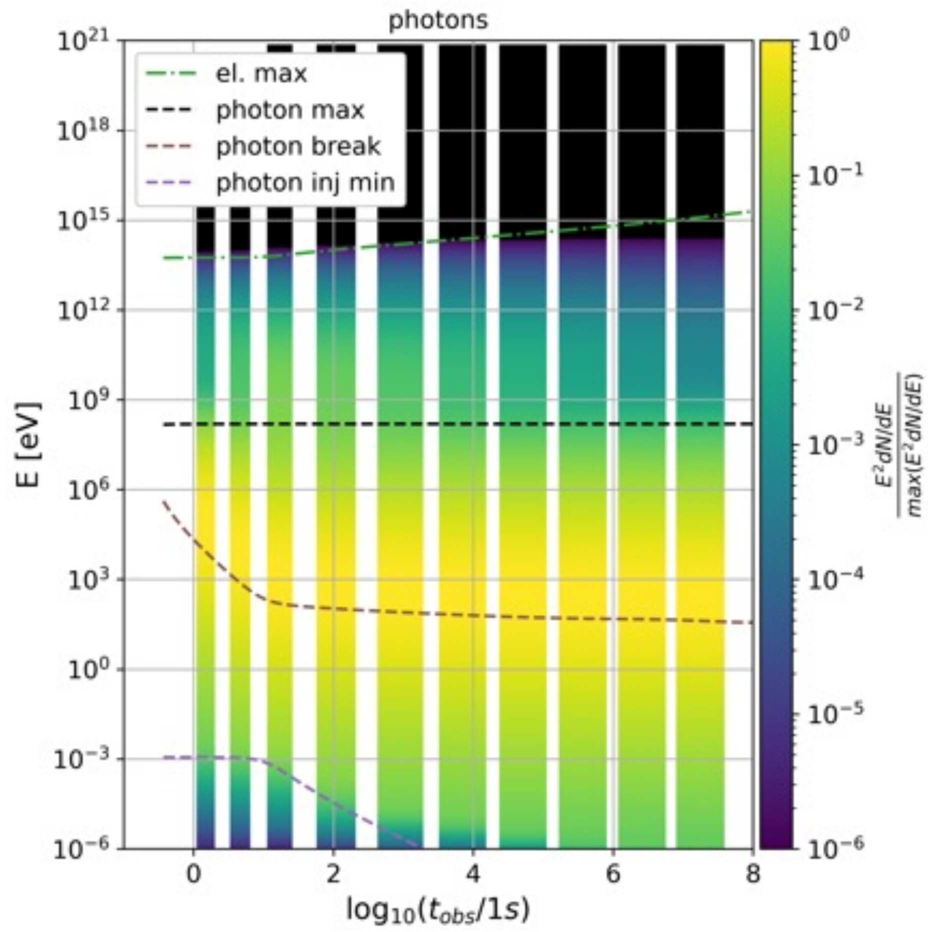


Blast wave becomes non-relativistic

DESY.

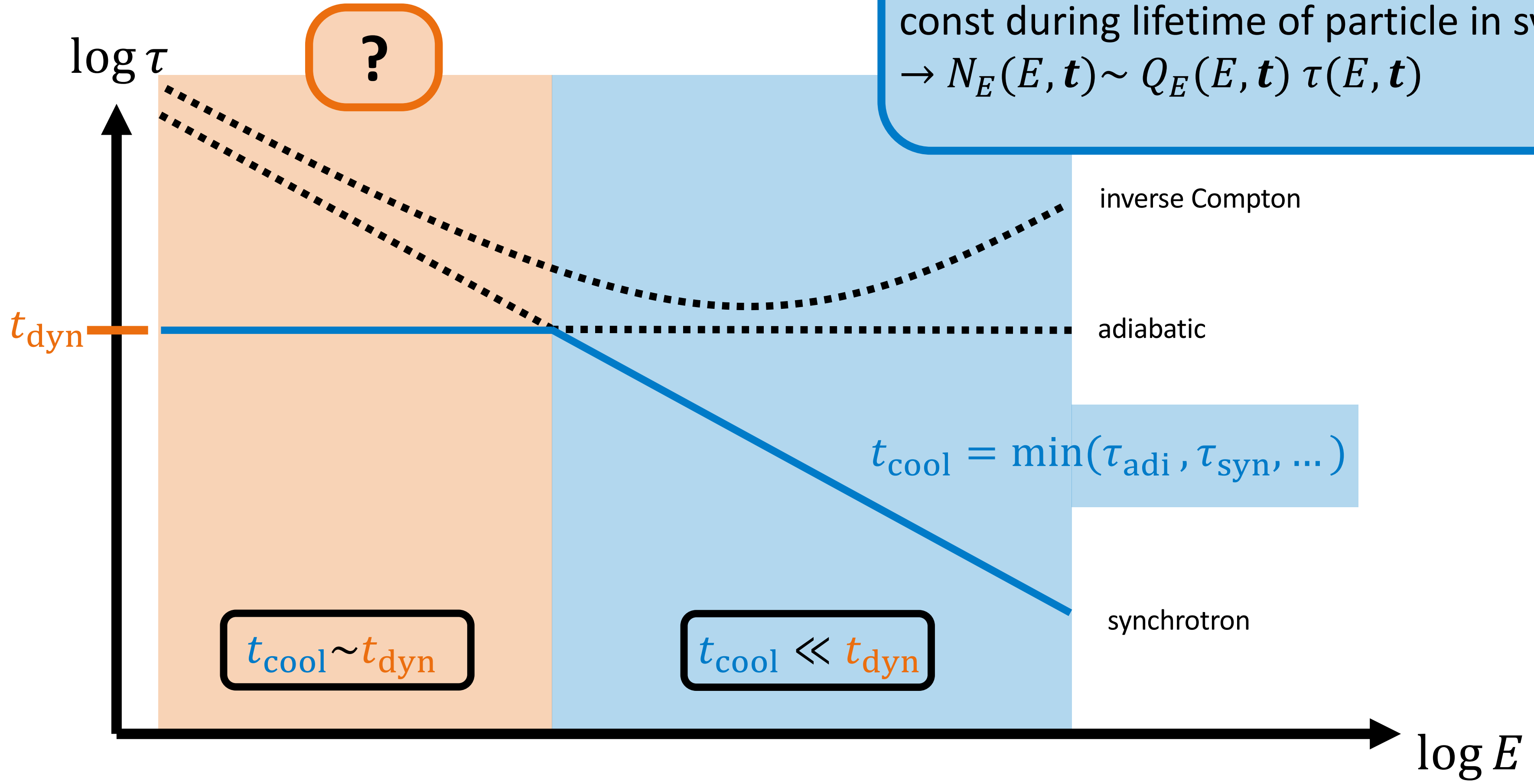
Evolution of Key Energies with Time





Time dependent modeling

quasi-steady state:
parameters of the one zone are approx. const during lifetime of particle in system
$\rightarrow N_E(E, \boldsymbol{t}) \sim Q_E(E, \boldsymbol{t})\ \tau(E, \boldsymbol{t})$



Adiabatic cooling regime ($\tau_{adi} \ll \tau_i$)

→ $$\partial_t N_{E,el} = \partial_E \left(\frac{E}{\tau_{\rm adi}(t)} N_{E,el} \right) + Q_E(E,t) \quad \text{(PDE)}$$

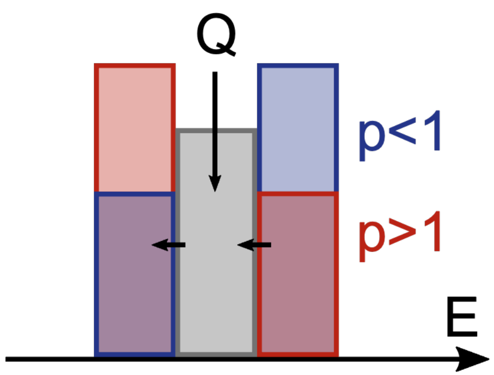
For intuition:
cooling term
≈ effective escape term

- $\tau_{adi}(t)$ only a function of time
- injection power law in E, $Q_E \sim E^{-p}$
- $N_E \sim E^{-p}$

$$\approx -(p-1)\frac{N_{E,el}}{\tau_{\rm adi}(t)} := -\frac{N_{E,el}}{\tau_{\rm eff}(t)}$$

$$\partial_t N_{E,el} + \frac{N_{E,el}}{\tau_{\rm eff}(t)} = Q_E(E,t) \quad (\approx\text{ODE})$$

Green's function in time?
→ how does $\tau_{\rm eff} = \frac{\tau_{\rm adi}}{p-1}$ scale with time?



One Zone Parameter's time dependence

it's all about the deceleration of the shock: $r(t_{\mathrm{obs}}), \Gamma(t_{\mathrm{obs}})$

1. conservation of energy: initial $E_0 = \Gamma^2 M_{\mathrm{sw}}(r) c^2$ heated swept up material
2. assume density profile $n(r) \sim r^{-w} \rightarrow \boxed{\Gamma(r) \sim r^{-\frac{(3-w)}{2}}}$
3. from Doppler boosting $t_{\mathrm{obs}} \approx \int \frac{\mathrm{d}r}{2\beta c \Gamma^2} \rightarrow r \sim t_{\mathrm{obs}}^{\frac{1}{4-w}}$

$\rightarrow r(t_{\mathrm{obs}}), \Gamma(t_{\mathrm{obs}}) \sim \left(\frac{E_0}{t_{\mathrm{obs}}^{3-w}}\right)^{\frac{1}{2(4-w)}}$ $\rightarrow$ ISM ($w = 0$): $\boxed{r \sim t_{\mathrm{obs}}^{1/4}}$, $\boxed{\Gamma \sim \left(\frac{E_0}{t_{\mathrm{obs}}^3}\right)^{\frac{1}{8}}}$

adiabatic cooling from size $\Delta \sim \frac{r}{\Gamma}$ (in "comoving" frame)

$$\boxed{\tau_{\mathrm{adi}}(t_{\mathrm{co}}) = \cdots = \frac{6}{9-w} \frac{5-w}{2} t_{\mathrm{co}}}$$

$\rightarrow$ **Green's function in time?**

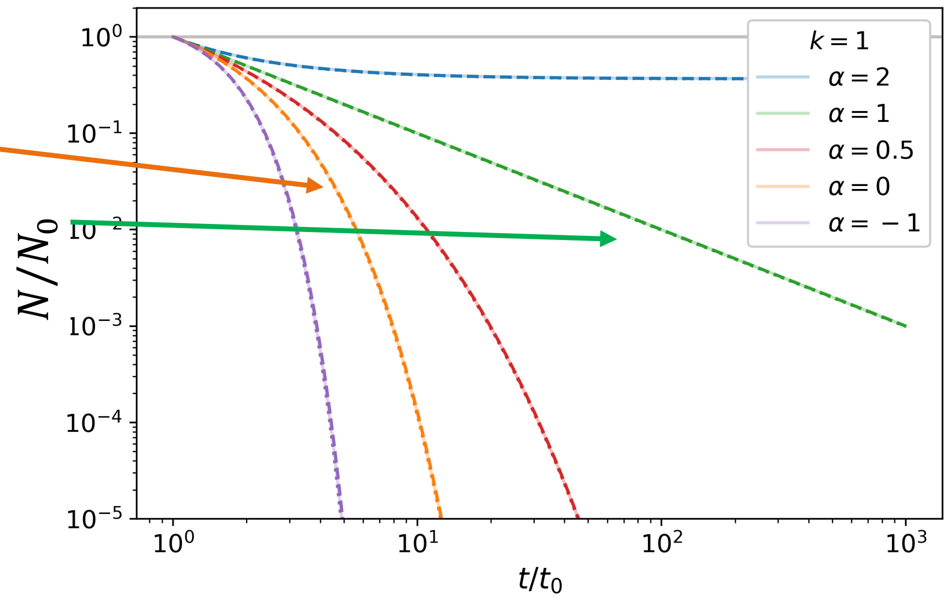
One Zone Parameter's time dependence

- $$\partial_t N_E = -\frac{N_E}{\tau_0\left(\frac{t}{\tau_0}\right)^{\alpha_\tau}}$$

  → for $\alpha_\tau = 0$: exponential decay

  → for $\alpha_\tau = 1$: power law decay

- relevant to see if early/late injections dominate spectrum



(Quasi) steady state

$$\alpha_Q = -\frac{2+(p-2)(3-w)}{5-w} \approx -0.4$$

$$\alpha_{adi} = (p-1)\frac{9-w}{3(5-w)} \approx 0.7$$

$\propto t'^{-\alpha_Q}$ $\quad$ $\propto t'^{-\alpha_{adi}}$

$$N_E(t) = \int_{t_0}^{t} d\log t' \;\; t' Q_E(t')\, G(t,t')$$

$$= Q_E(t)\tau_{adi}(t) \cdot \frac{1}{\alpha_Q+\alpha_{adi}+1}\frac{9-w}{3(5-w)} \cdot \left(1-\left(\frac{t}{t_0}\right)^{-\alpha_Q-\alpha_{adi}+1}\right)$$

≈ 0.7

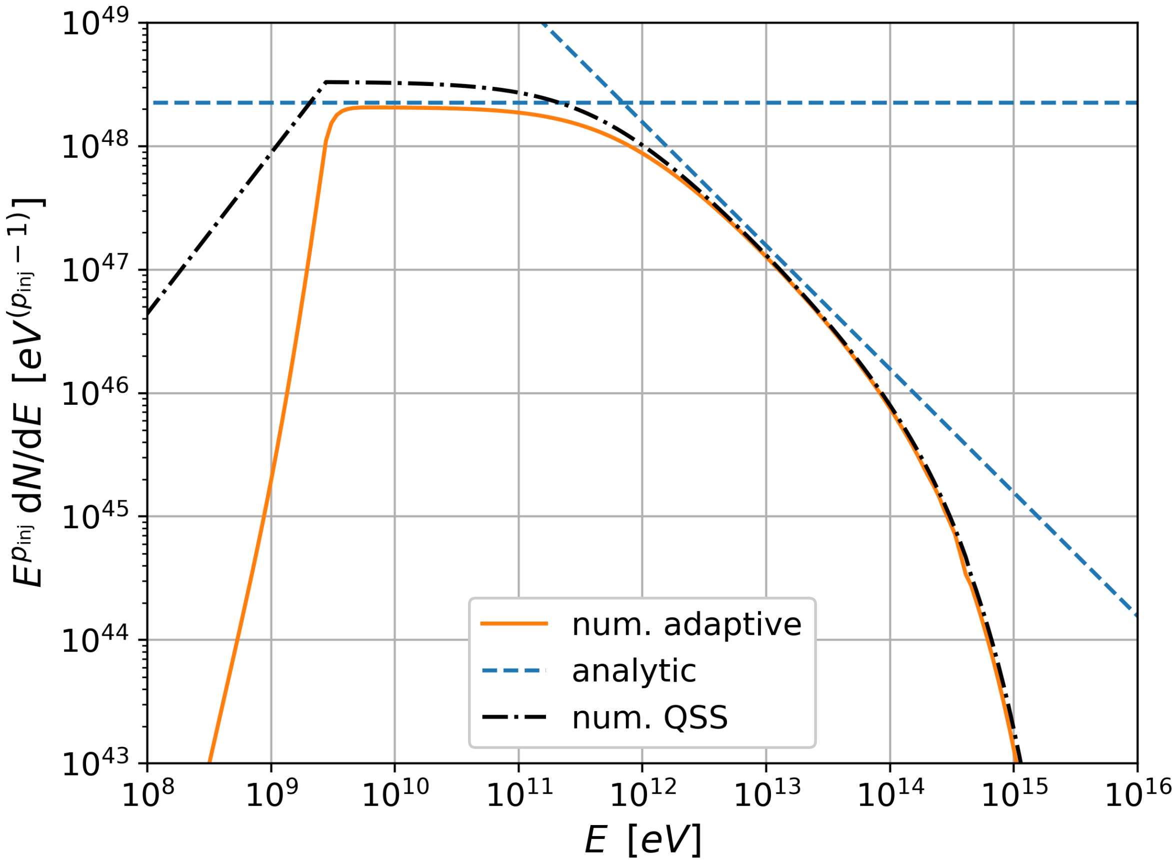
numerical factor $\mathcal{O}(1)$ $\quad$ convergence term

quasi steady state

(steady state with instantaneous parameters)

Effective Electron Spectrum

$p_{\text{inj}} = 2.3, w = 0$



→ **smoothly broken power law!**

Evolutionary Phases of Blastwave

1) Deceleration rate

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

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

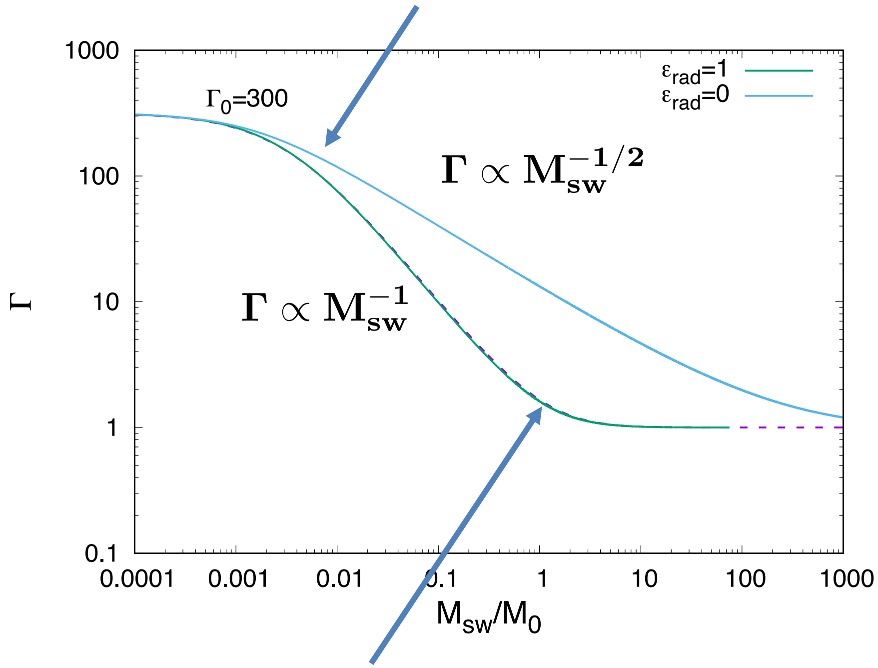
1) Radiative loss rate

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

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

[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

DESY.

Evolutionary Phases of Blastwave

1) Deceleration rate

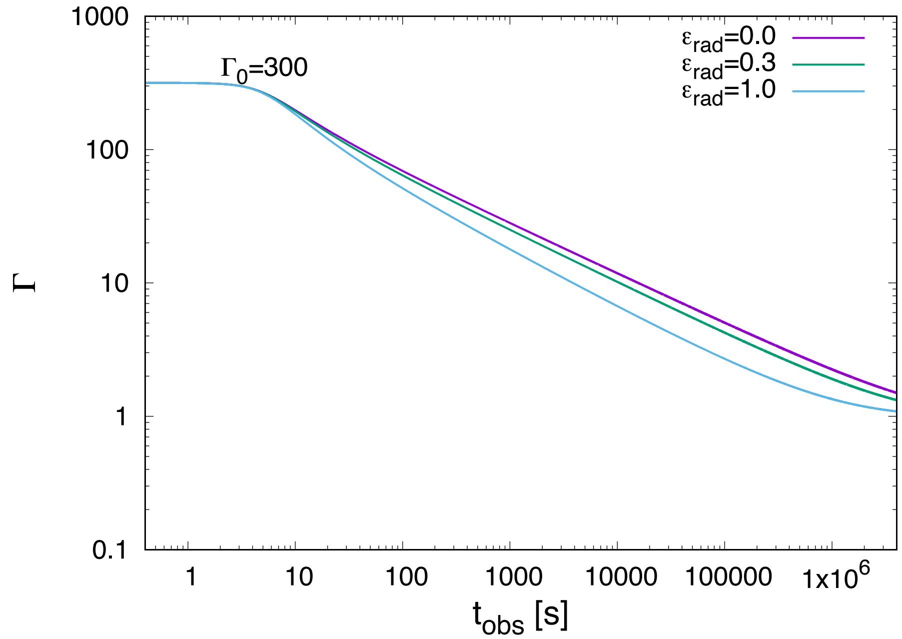
$$\frac{\mathbf{dM}}{\mathbf{dR}} = \mathbf{\Gamma} 4\pi\rho \mathbf{R}^2 - \frac{\mathbf{1}}{\mathbf{\Gamma}}\frac{\mathbf{dE_{rad}}}{\mathbf{dr}}$$

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

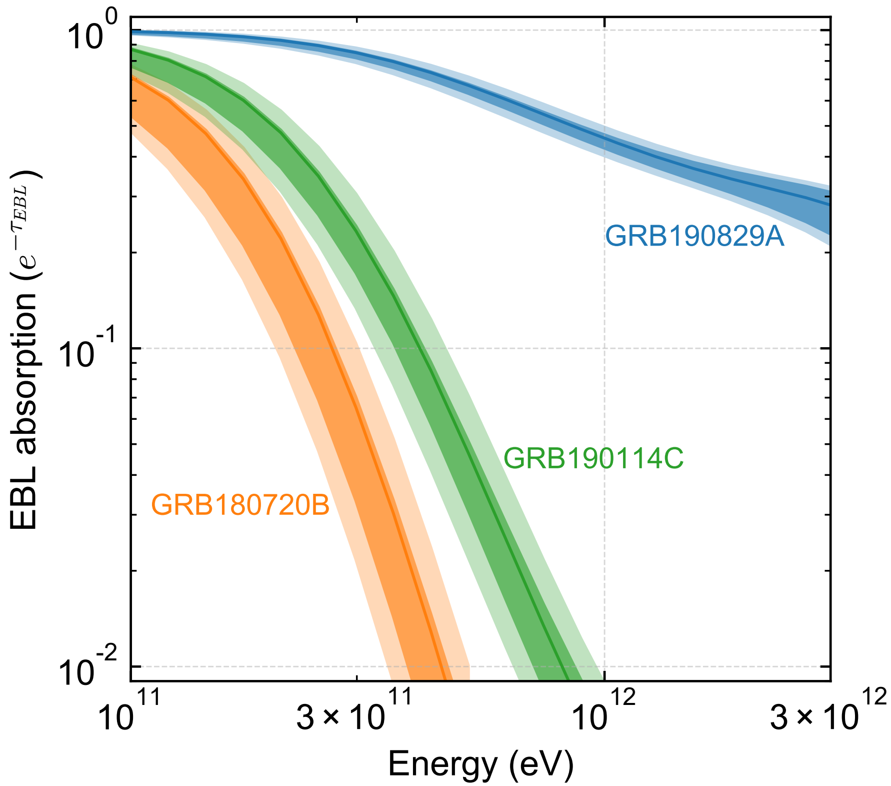
1) Radiative loss rate

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

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



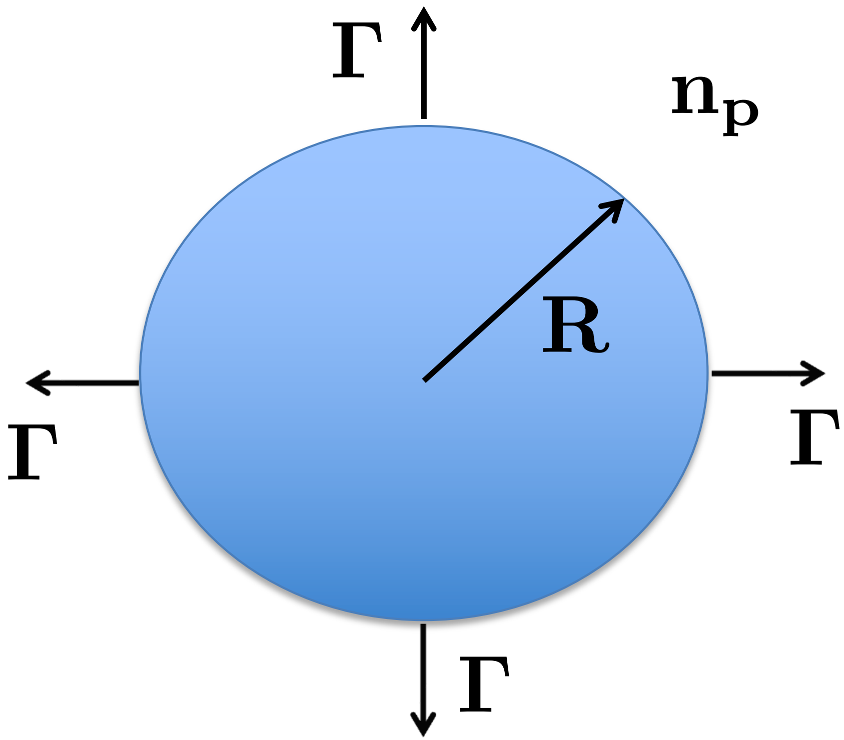
Energy Spectrum Information

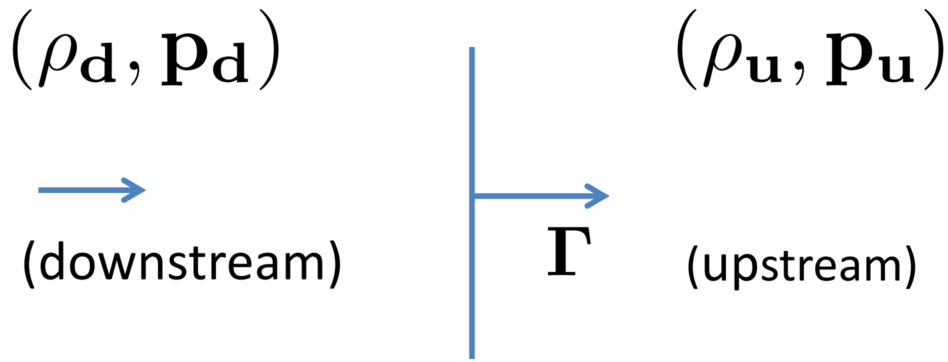


The effect of the EBL on the (optically thin) attenuation for a nearby (z=0.08) source for E_γ<6 TeV is a softening of the spectrum by around ΔΓ≈0.5, starting around 250 GeV.

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

Origin of Temporal Decay Structure





[viewed in upstream restframe]

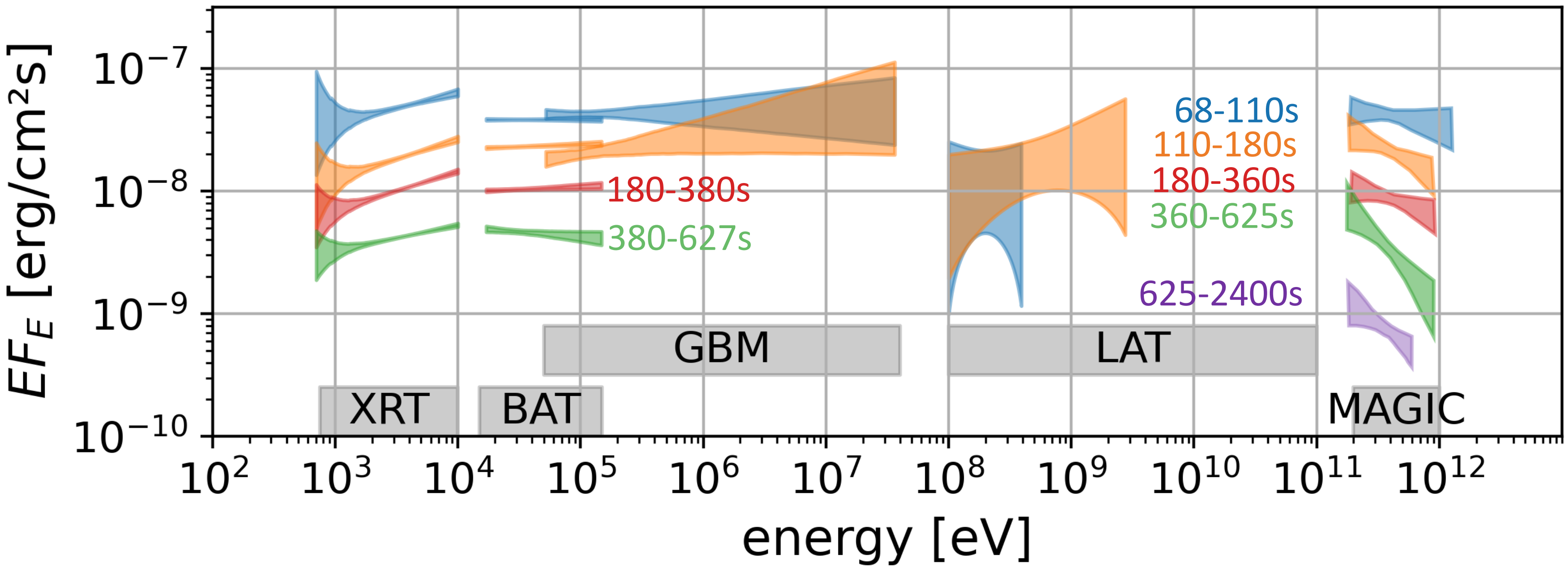
Assuming η_γ is constant in time.....

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

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

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

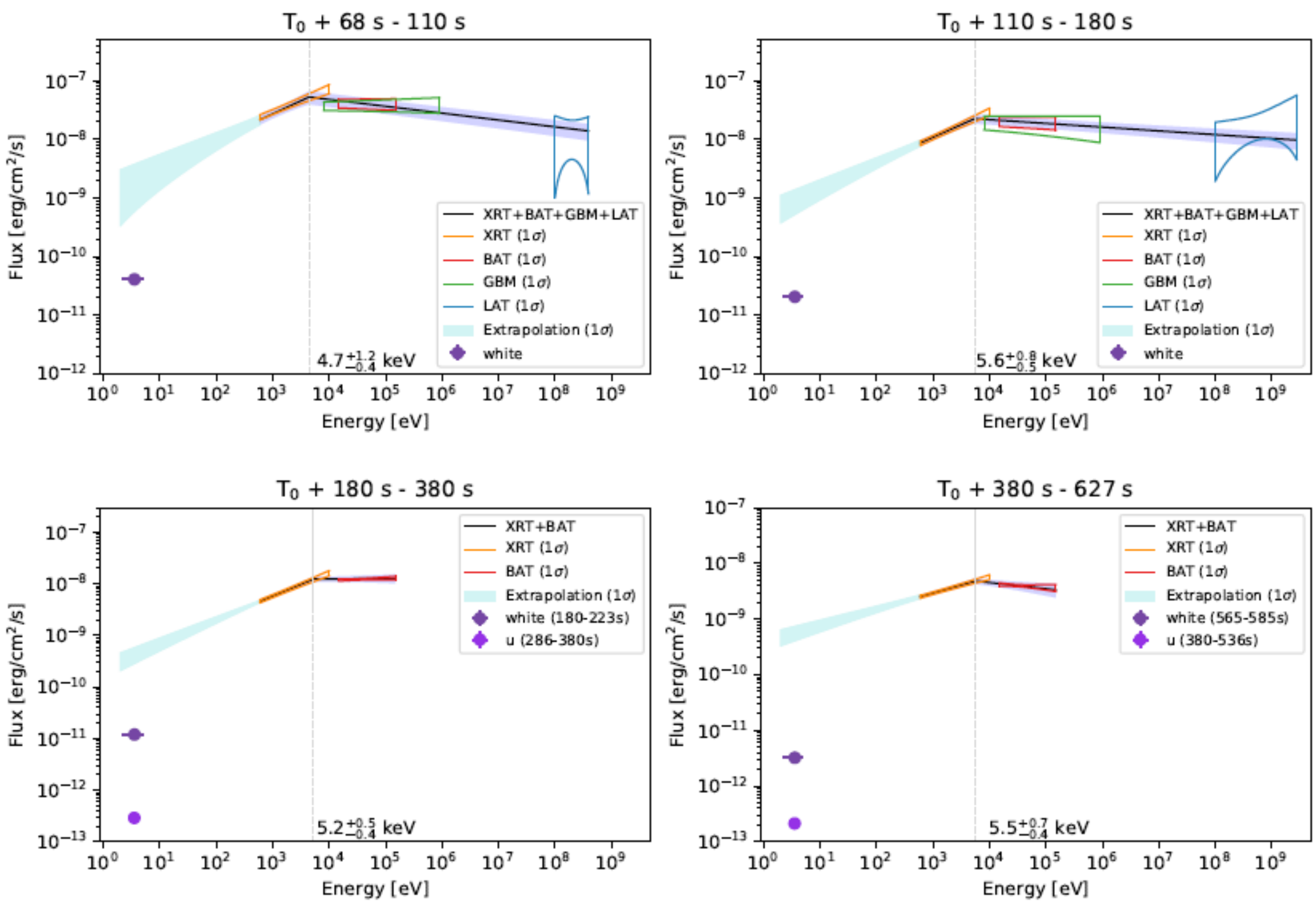
GRB 190114C (Detected by MAGIC)



[Nature 575, 459-463 (2019)]

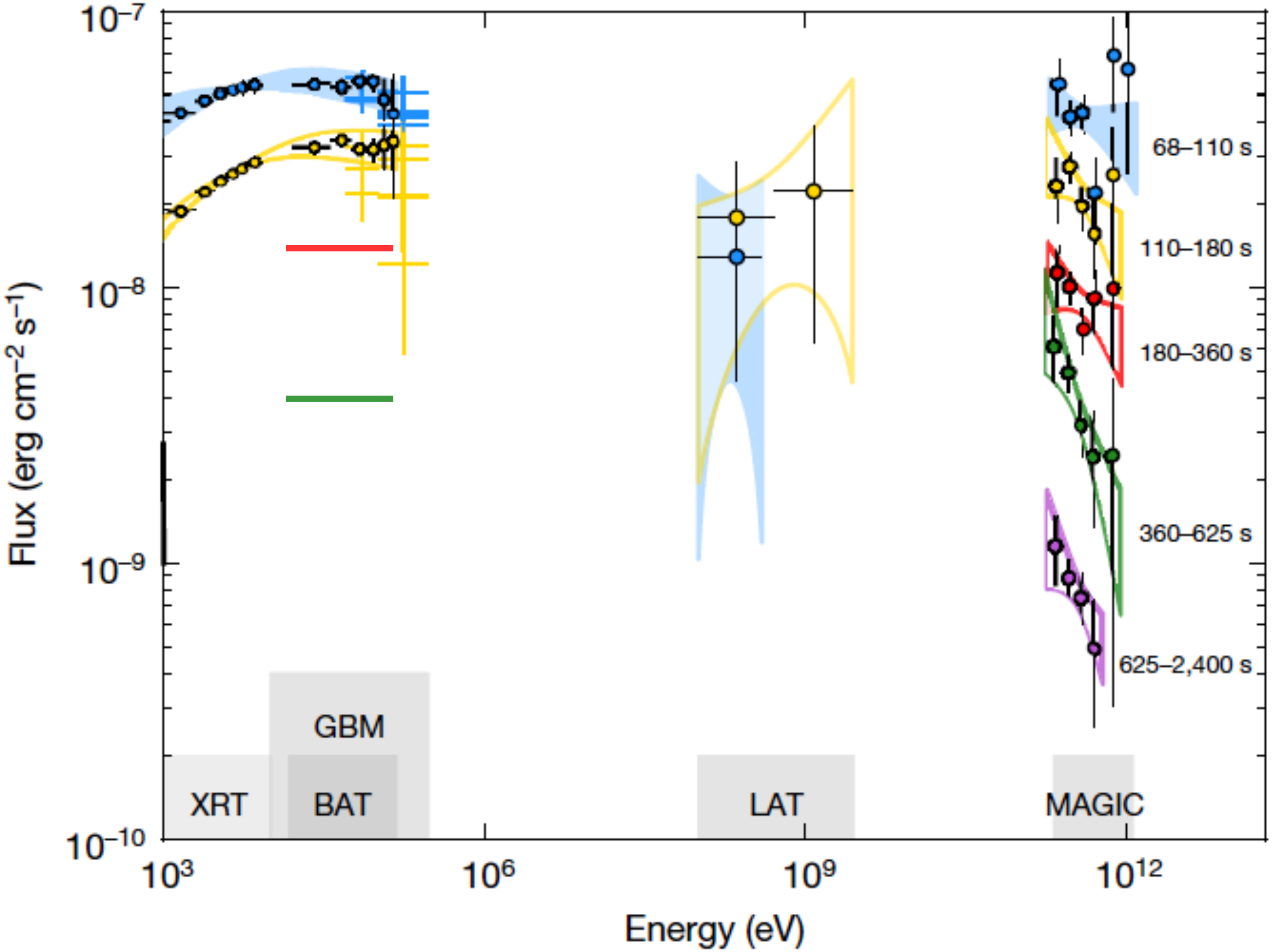
- remarkably flat over 9 orders of magnitude in energy!

GRB 190114C

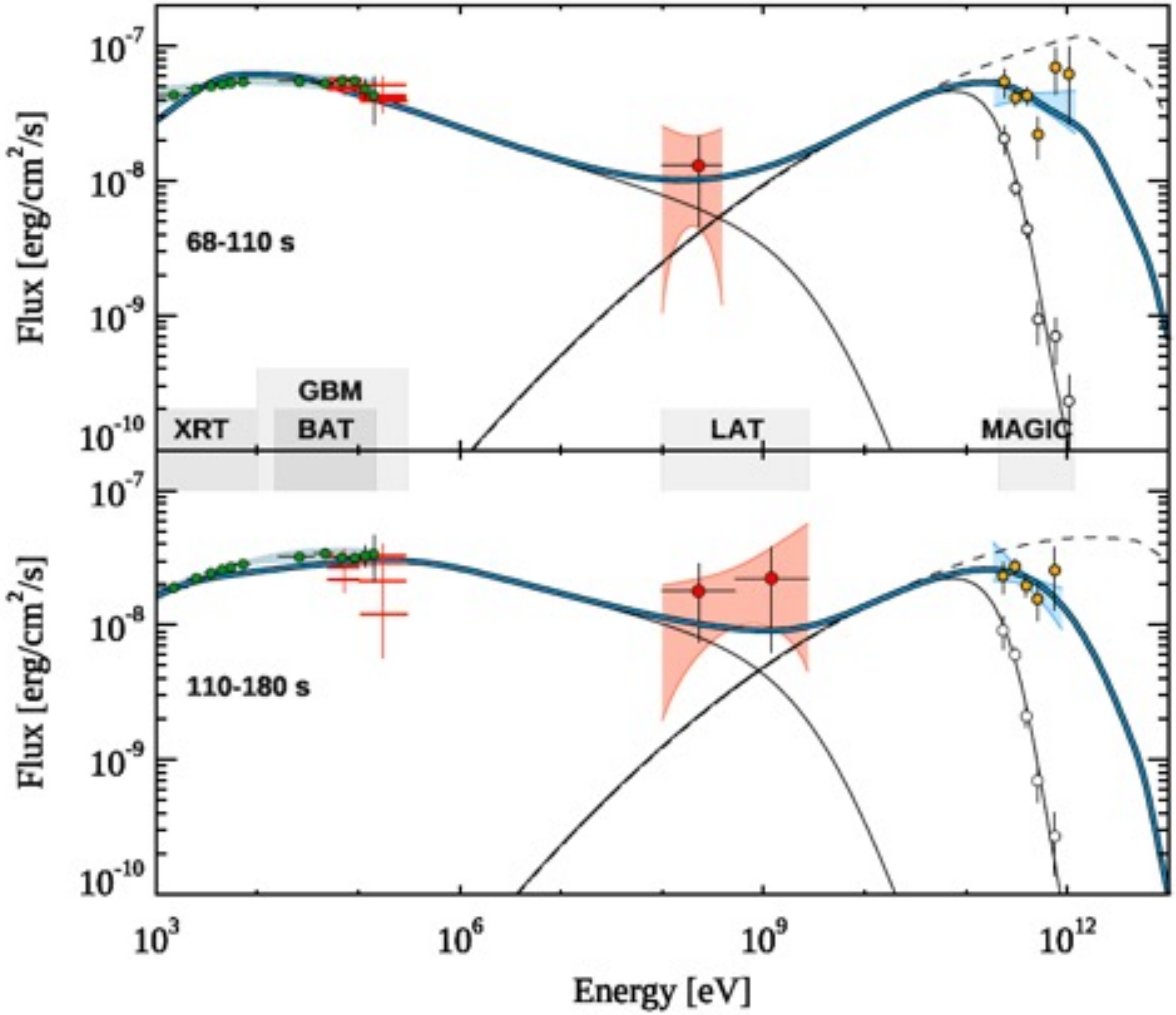


DESY.

GRB 190114C

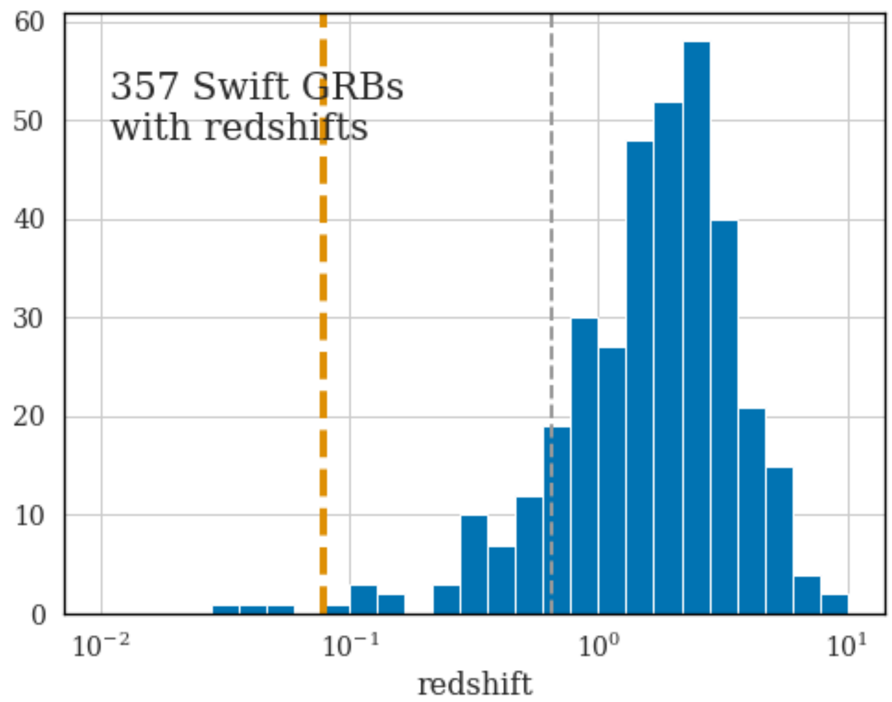

10−7
10−8
10−9
10−10
Flux (erg cm−2 s−1)
10³
10⁶
10⁹
10¹²
Energy (eV)
68–110 s
110–180 s
180–360 s
360–625 s
625–2,400 s
GBM
XRT
BAT
LAT
MAGIC

GRB 190114C

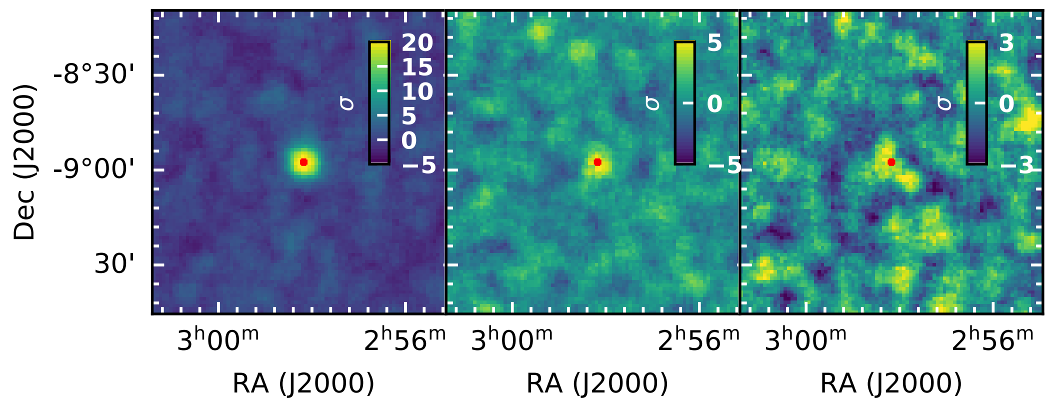


DESY.

HESS Detection of GRB 190829A



First detection of a GRB in VHE band for multiple nights

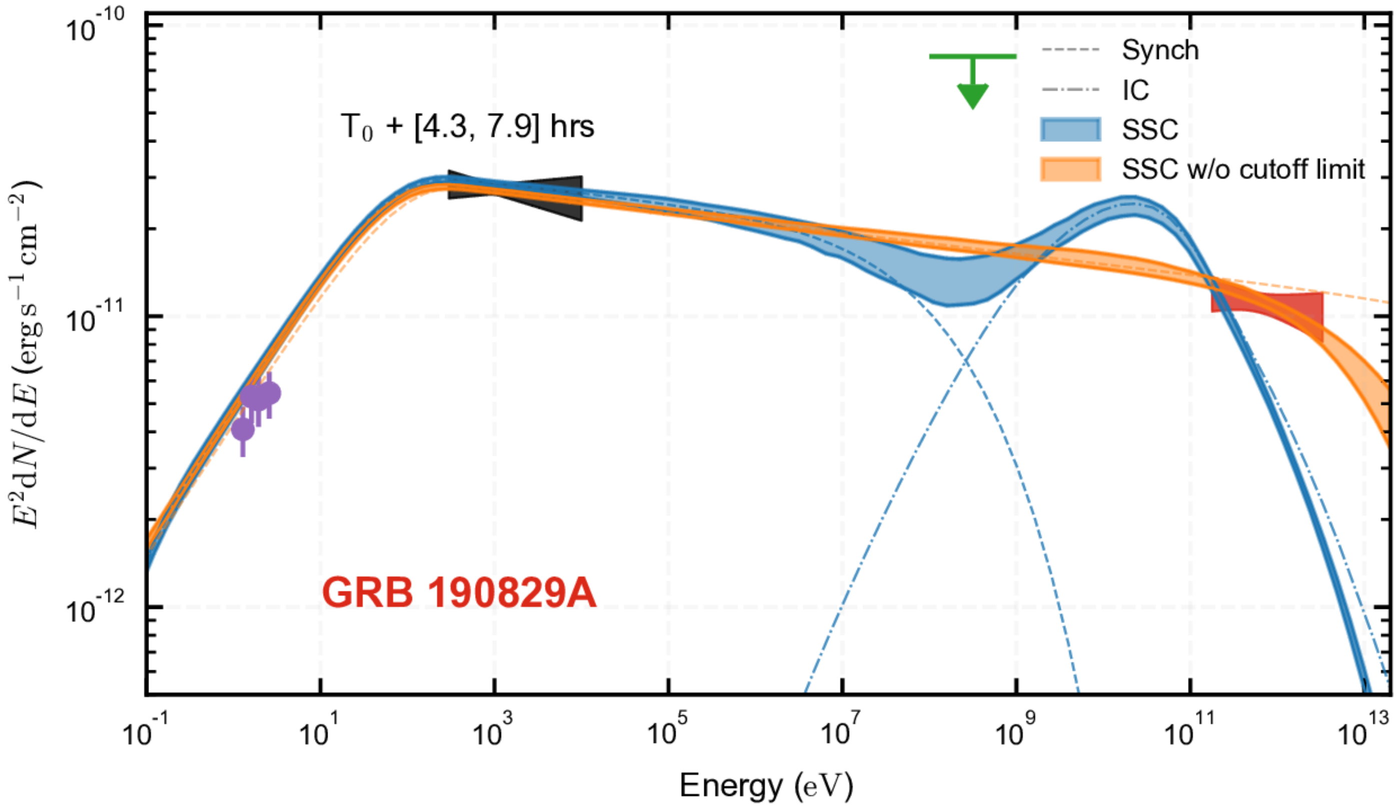


Night 1 Night 2 Night 3

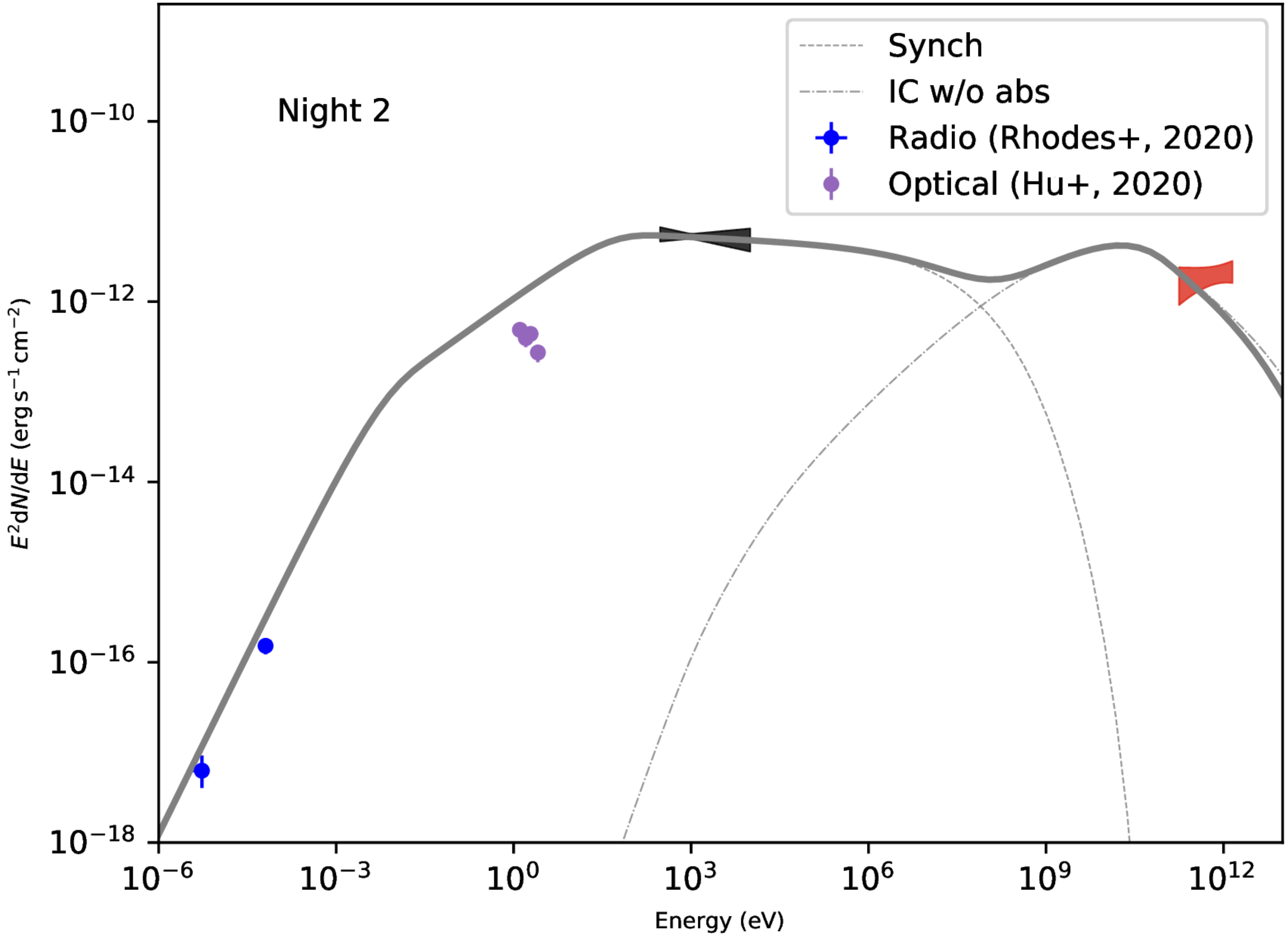
[HESS- A. Taylor, et al., Science 2021]

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

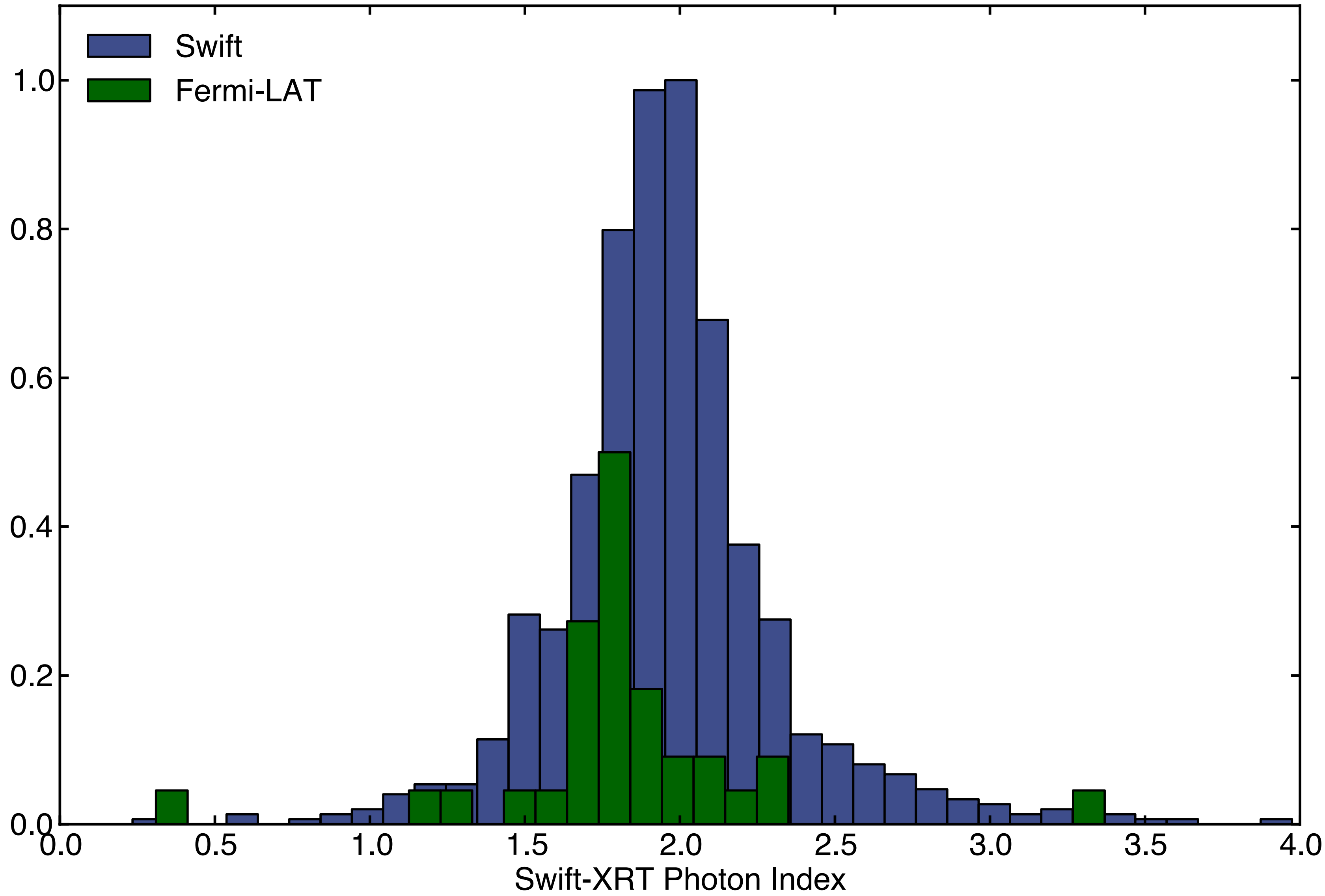
GRB 190829A- Optical Data



GRB 190829A- Radio Data

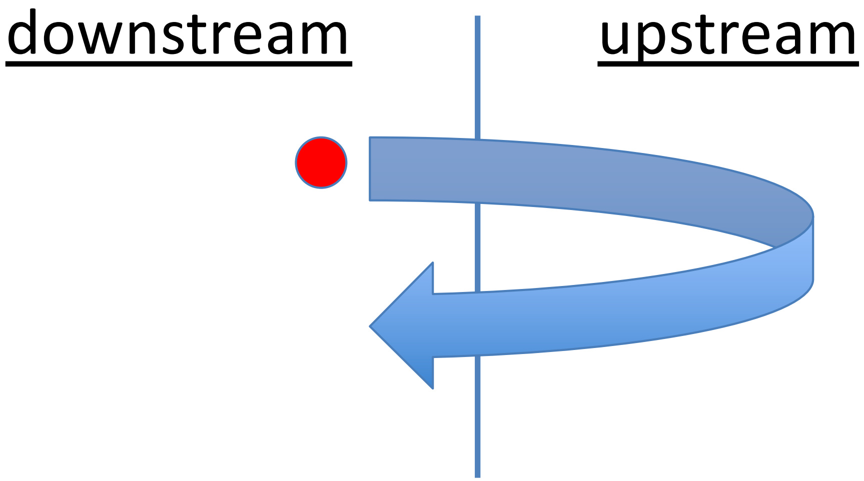


Swift XRT Photon Index Distribution



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

GRB Model Parameters 2: Acceleration Rate



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

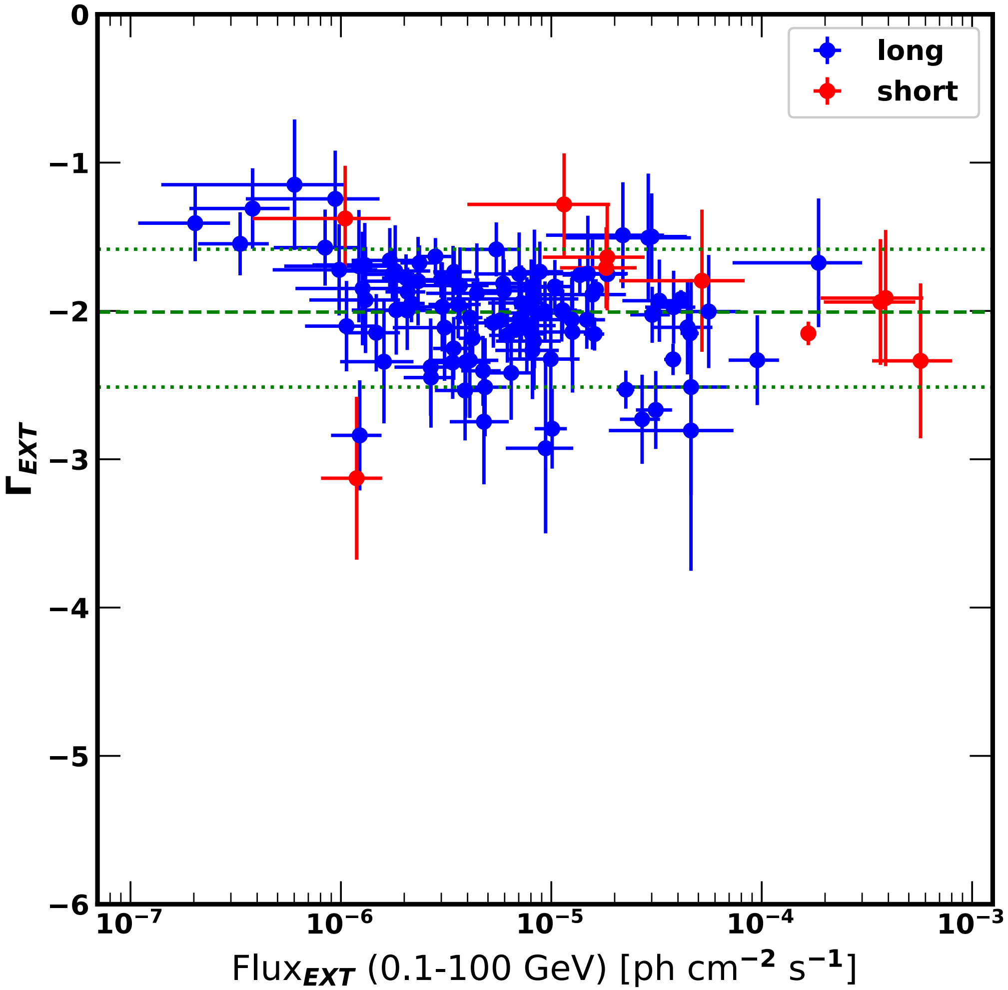
- Isotropisation is caused by magnetic turbulence, its rate is described by the scattering time, which in Larmor time units is **η**

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

- 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

Fermi-LAT Photon Index Distribution



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