Experimental/Theory: TeV GRB Afterglows

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The Extreme Non-Thermal Universe: CDY Initiative

15th September 2021

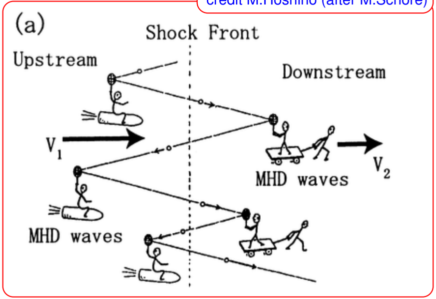
Overview

1. Detection of GRBs in the VHE regime: importance & challenges
2. GRB Afterglow with Fermi/LAT
3. Observation of GRBs in the VHE regime
4. Modeling of GRB Afterglow
5. GRB 190829A: Result implications
6. Summary

GRB is relativistic version of SN explosions

- Shock acceleration is a very important mechanism for production of cosmic rays
- It is fairly well understood in the non-relativistic regime, but **not in the relativistic one**
- GRB afterglows are produced by relativistic shocks in their simplest realization
- Detection of IC emission helps to constrain the downstream conditions and define energy of synchrotron emitting electrons
- Because of the synchrotron burn-off limit, emission detected in the VHE regime is expected to be **of IC origin**

credit M.Hoshino (after M.Schore)



Diffusive shock acceleration

- Power-law spectrum with $\frac{dN}{dE} \propto E^{-s}$ where $s = \frac{v_1/v_2+2}{v_1/v_2-1} \approx 2$
- Acceleration time $t_{\rm ACC} \approx \frac{2\pi r_{\rm G}}{c}\left(\frac{c}{v_1}\right)^2$

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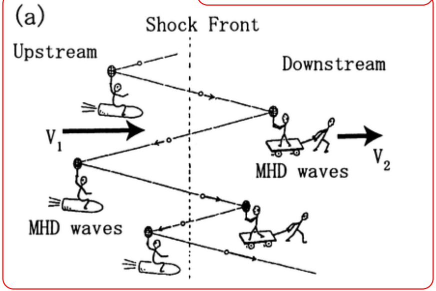

Relativistic shocks

- Particles can get a significant energy by shock crossing, but
- Particles **do not** have time to **isotropize** in the downstream

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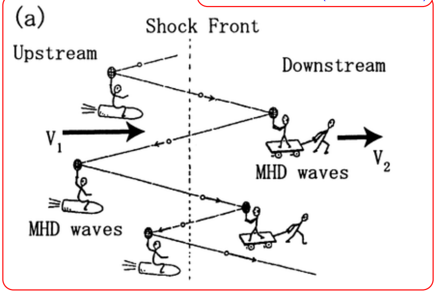

Relativistic shocks

- Forward shock propagates through ISM medium (or stellar wind)
- There is a self-similar hydrodynamic model (Blandford&McKee1976)

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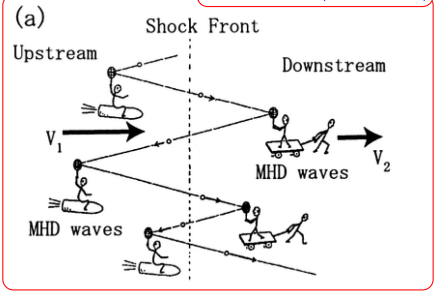

Leptonic source

- Interpretation of synchrotron emission is ambiguous because of "magnetic field" – "electron energy" degeneracy
- Detection of **IC** helps to resolve it

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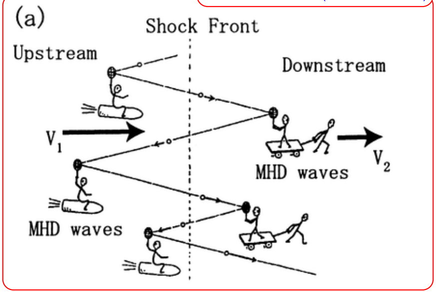
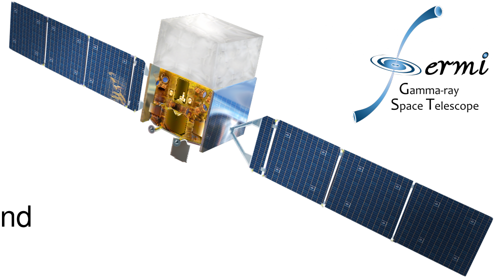


Synchrotron burn-off limit

- Synchrotron cooling time: $t_{\rm SYN} \approx 400 E_{\rm TeV}^{-1} B_{\rm B}^{-2}$ s
- Acceleration time: $t_{\rm ACC} \approx 0.1\eta E_{\rm TeV} B_{\rm B}^{-1}$
- Max energy: $\hbar\omega < 200\frac{\Gamma}{\eta}$ MeV

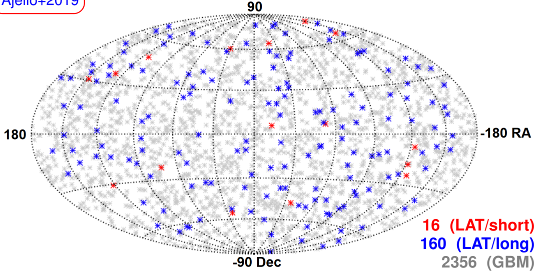
Hunt for GRB IC emission: Fermi/LAT



Fermi/LAT is an (almost) ideal instrument for GRB study

- ✔ GBM!
- ✔ Large FoV
- ✔ Synchrotron – IC energy band
- ✘ Small collection area

Ajello+2019

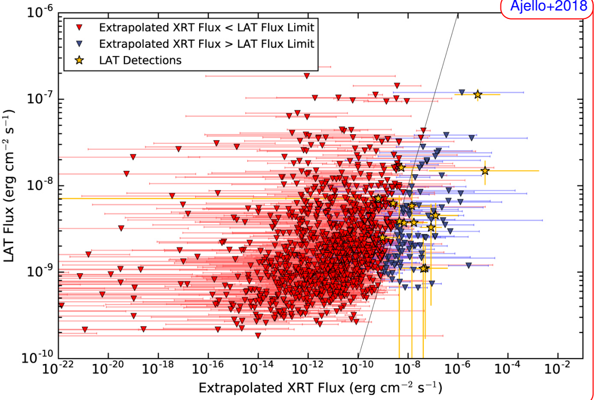


Which emission component do we see from GRB after-glows with LAT?
Is it synchrotron?
Which fraction?
Should we see IC?
What is Γ bulk?

Fermi/LAT observation of GRB afterglow

- 1156 time intervals for 386 GRBs
- Swift XRT detection
- Fermi/LAT upper limit / detection
- Compare Fermi results to the extrapolation from X-ray to HE band

Measured LAT flux, or upper limit, vs. the XRT-extrapolated flux for a given interval when the burst location was within the LAT FOV.



“we find no evidence of high-energy emission in the LAT-detected population significantly in excess of the flux expected from the electron synchrotron spectrum fit to the observed X-ray emission” (Ajello+2018)

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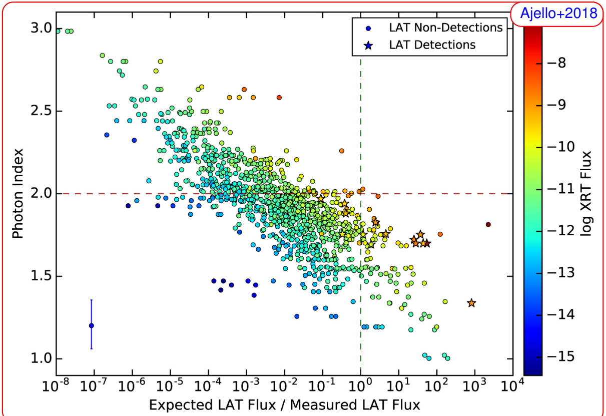
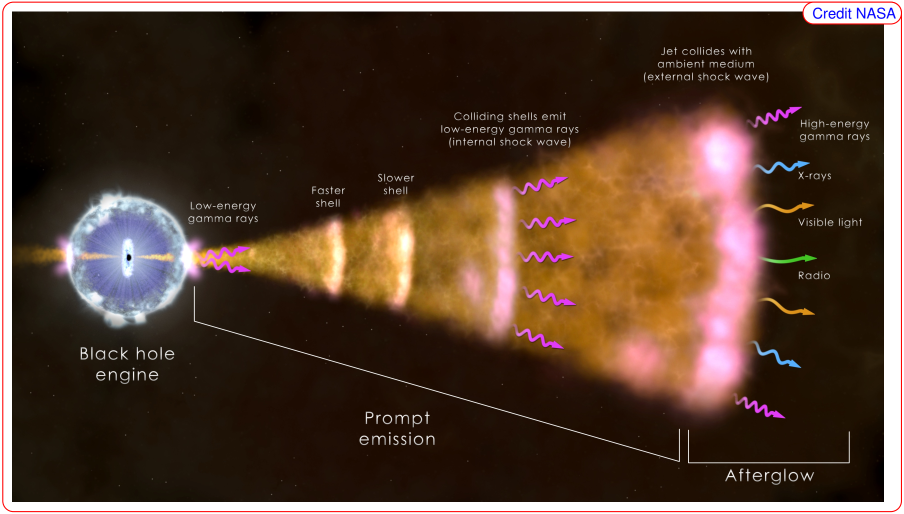
Time-averaged afterglow photon index, as measured by XRT, vs. the ratio of the XRT-extrapolated flux in the LAT energy range to the LAT upper limit.



"we find no evidence of high-energy emission in the LAT-detected population significantly in excess of the flux expected from the electron synchrotron spectrum fit to the observed X-ray emission" (Ajello+2018)

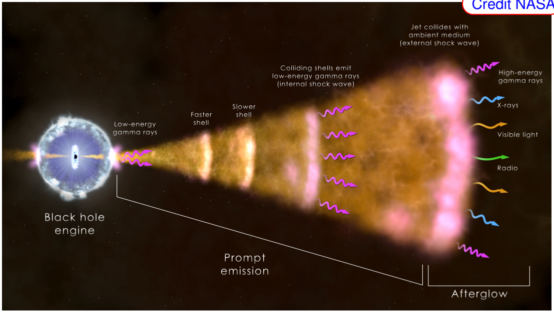
Does this exclude IC in the Fermi/LAT band?

Long GRBs: physical scenario



Long GRBs: physical scenario

- Long GRBs are most likely produced at collapse of massive stars
- Magnetic field accumulated at the BH horizon launches a B&Z jet
- Prompt emission: initial jet outburst, internal jet emission, dominates for the first 10^{2-3} s
- Afterglow: jet–circumburst medium interaction, start dominating after 10^{2-3} s, last for weeks



Blandford&McKee (1976) self-similar solution for a relativistic blast wave (the relativistic version of the Sedov's solution for SNR):

$$E = \Gamma^2 Mc^2, \ \text{assuming} \ \rho \propto r^{-s} \Rightarrow \Gamma \propto R^{(s-3)/2} \Rightarrow \Delta t \approx \int_0^R \frac{dr}{2c\Gamma(r)^2}$$

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Based on the explosion energy, E, and density of the circumburst medium, $\rho = \rho_0(r/r_0)^{-s}$ we obtain

- Bulk Lorentz factor of the shell
$$\Gamma \approx 40\left(\frac{E_{53}}{\rho_0 t_3^3}\right)^{1/8}\Big|_{s=0} \approx 20\left(\frac{E_{53}v_8}{\dot{m}_{21}t_3}\right)^{1/4}\Big|_{s=2}$$
- Shell radius
$$R \approx 2\cdot 10^{17}\,\mathrm{cm}\left(\frac{t_3 E_{53}}{\rho_0}\right)^{1/4}\Big|_{s=0}$$
$$3\cdot 10^{16}\,\mathrm{cm}\left(\frac{t_3 E_{53} v_8}{\dot{m}_{21}}\right)^{1/2}\Big|_{s=2}$$
- Integernal energy of the plasma: $\varepsilon \approx \Gamma^2\rho$

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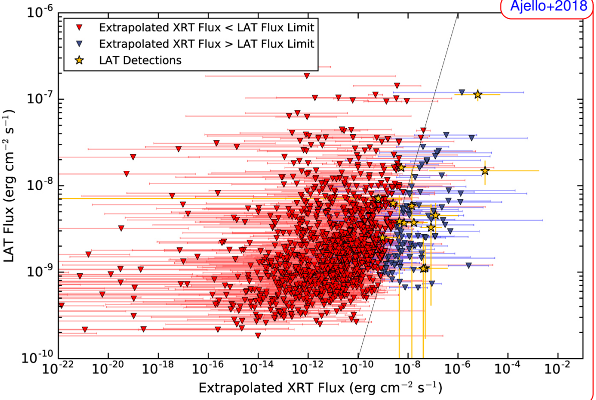
Can we exclude the IC component in the LAT data?

- There is no IC component dominating over the (extrapolation of) synchrotron one
- There are photons above the synchrotron limit
- The Fermi/LAS spectrum still might be consistent with the extrapolation from the lower energies
- There could be an IC component emerging above $\sim 10\,\mathrm{GeV}$

Ajello+2018



Apparently, there is no GeV emission component that is brighter than the X-ray extrapolation; detection of photons with energy exceeding the burn-off limit requires either a very efficient acceleration process or IC emission; (possible) spectral hardening could be naturally explained by the IC component. Is that significant enough?

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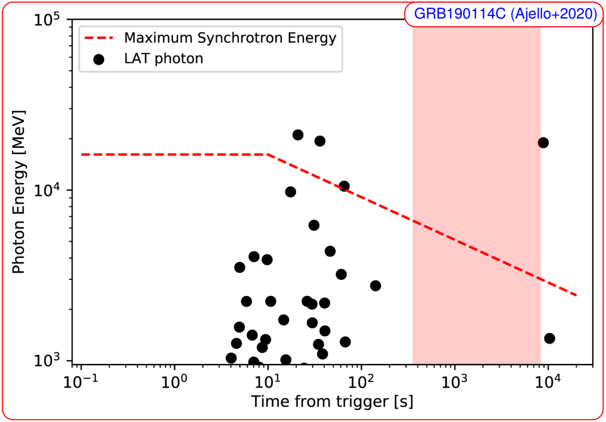

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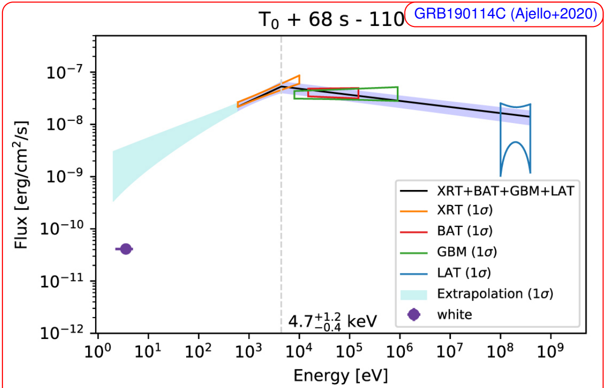
GRB190114C (Ajello+2020)



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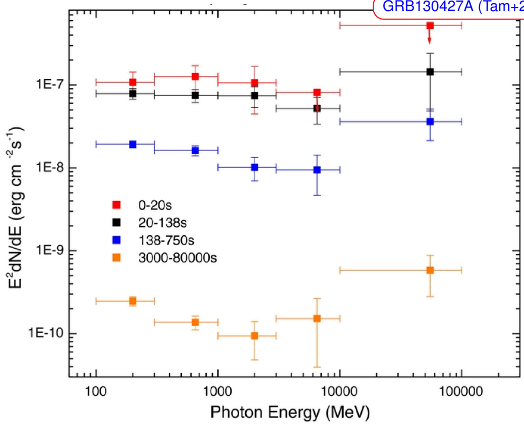
GRB130427A (Tam+2013)



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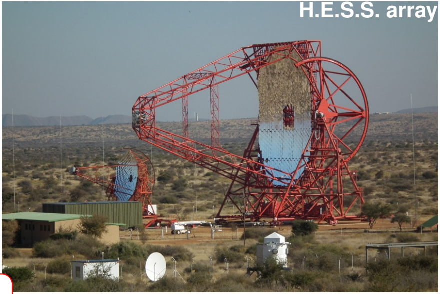
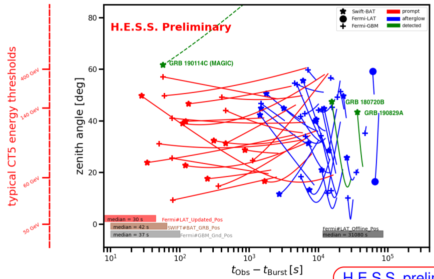
Hunt for GRBs in the VHE band

Why do we expect to see GRBs@VHE?

- Relativistic outflows
- Bright non-thermal sources
- A few GRBs per week





H.E.S.S. preliminary

Why did it take so long to detect GRBs in the VHE regime?

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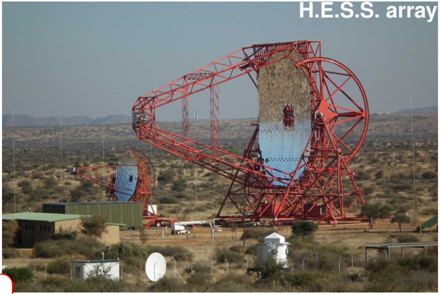

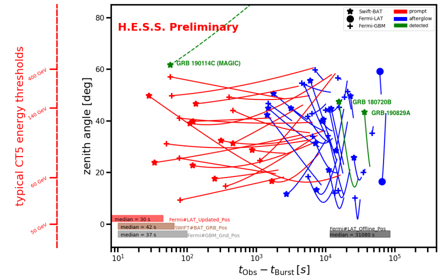

- Highly variable sources
- Bright synchrotron emission
  - IC can be suppressed
  - Internal absorption
- Cosmological distances, EBL attenuation ⇒

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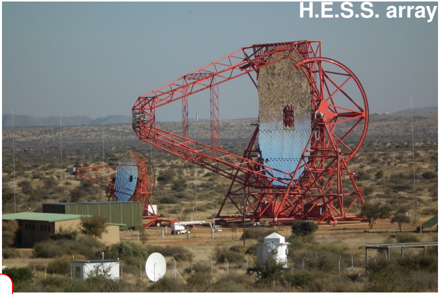

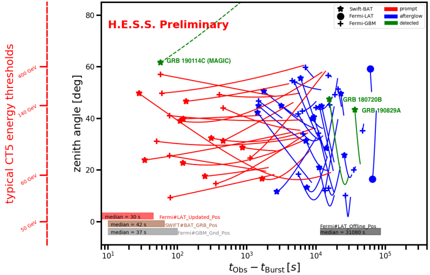

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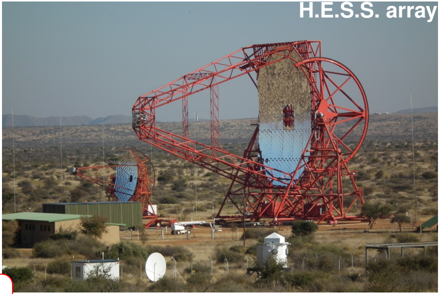

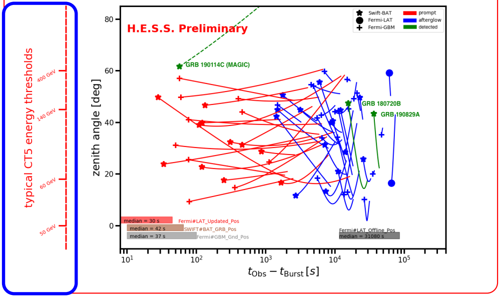

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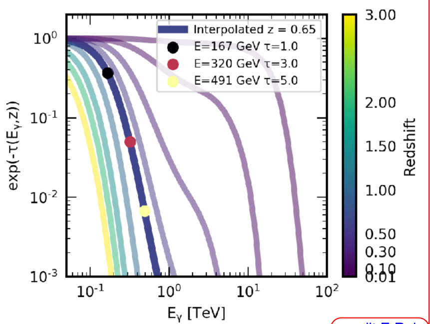
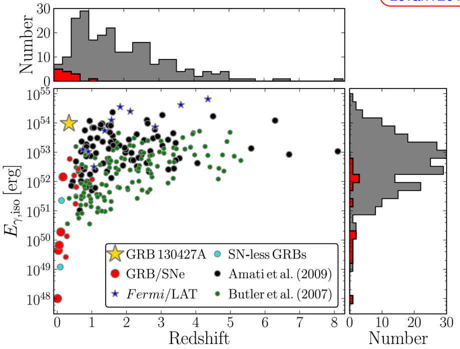
EBL attenuation

- GRBs are typically registered from $z_{rs} > 1$
- The EBL attenuation for TeV γ rays from cosmological distances is severe



credit E.Ruiz



Levan+2016

One of the key challenges

- Operating Cherenkov telescopes have a threshold at $\sim 100\,\mathrm{GeV}$
- $300\,\mathrm{GeV}$ γ rays traveling from $z_{rs} = 0.5$ are attenuated by a factor of 10

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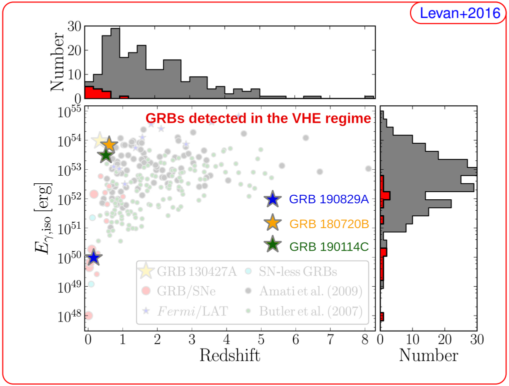

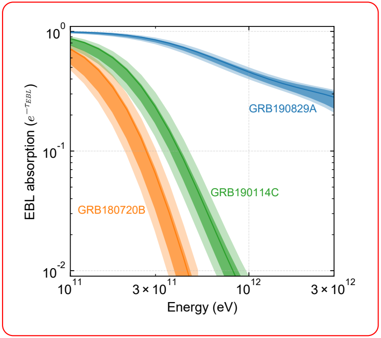

GRBs detected in the VHE regime:

- GRB 190829A: $z_{\rm rs} \approx 0.08$ and $L_{\rm iso} = 2 \times 10^{50}$ erg
- GRB 190114C: $z_{\rm rs} \approx 0.42$ and $L_{\rm iso} = 3 \times 10^{53}$ erg
- GRB 180720B: $z_{\rm rs} \approx 0.65$ and $L_{\rm iso} = 6 \times 10^{53}$ erg

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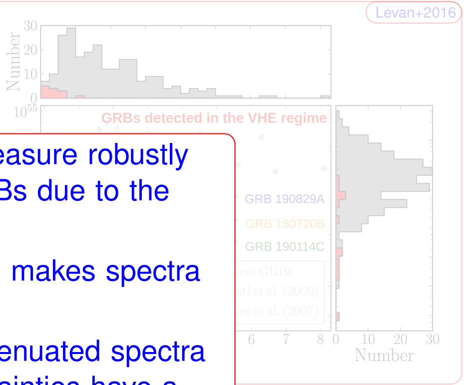
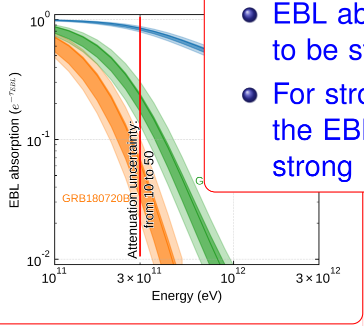


It is very hard to measure robustly VHE spectra of GRBs due to the EBL attenuation:

- EBL absorption makes spectra to be steep
- For strongly attenuated spectra the EBL uncertainties have a strong impact



...E regime:

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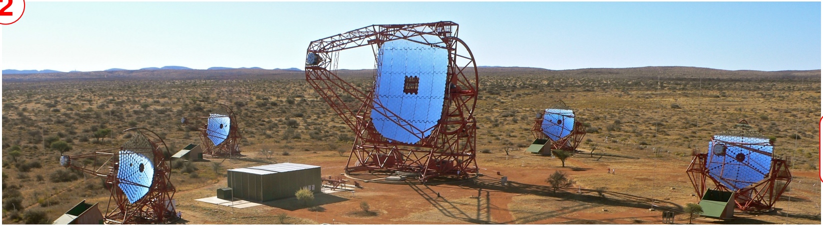
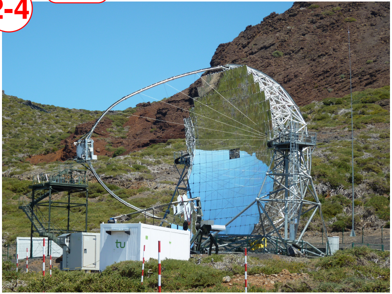
GRBs detected in the VHE regime ($\sim 0.1\,\mathrm{TeV}$)

2



H.E.S.S.

2-4 MAGIC



0 Veritas

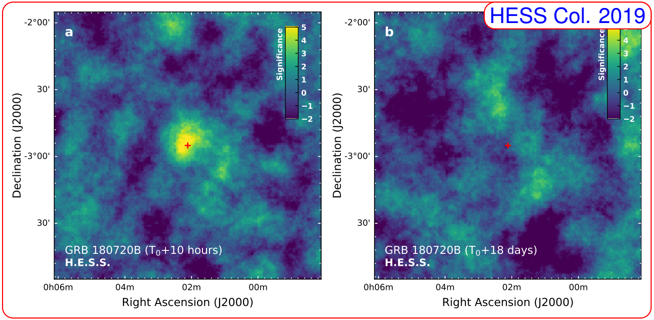
GRBs detected in the VHE regime ($\sim 0.1\,\mathrm{TeV}$)

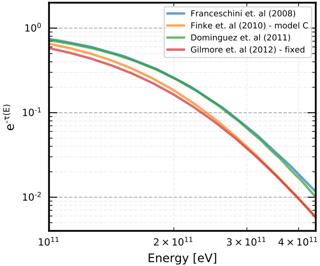
- ? GRB160821B: 3σ detection of a nearby short GRB ($z = 0.162$) above $0.5\,\mathrm{TeV}$ 4h after the trigger (MAGIC Col, 2021)
- ✔ GRB180720B: 5σ detection of a long GRB from $z = 0.65$ above $0.1\,\mathrm{TeV}$ **10h** after the trigger (HESS Col, 2019)
- ✔ GRB190114C: $\sim 50\sigma$ detection of a long GRB from $z = 0.42$ above $0.2\,\mathrm{TeV}$ $\sim$min after the trigger (MAGIC Col, 2019)
- ✔ GRB190829A: 20σ detection of a long GRB from $z = 0.08$ at energies $0.18 - 3.3\,\mathrm{TeV}$ **4-50h** after the trigger (HESS Col, 2021)
- ? GRB201015A: $> 3\sigma$ detection of a long GRB at $z = 0.43$ (MAGIC Col, Atel)
- ? GRB201216C: $> 5\sigma$ detection of a long GRB at $z = 1.1$ (MAGIC Col, Atel)

GRB180720B

GRB180720B

- ✔ 5σ detection
- ✔ $E_{\rm iso} = 10^{54}\,{\rm erg}$ super bright!
- ? $z = 0.65$ or $D = 1.5\,{\rm Gpc}$
- ✘ $t_{\rm vhe} = 10\,{\rm h}$ time decay measured in X-rays: $L_{\rm X} \propto t^{-1.2}$

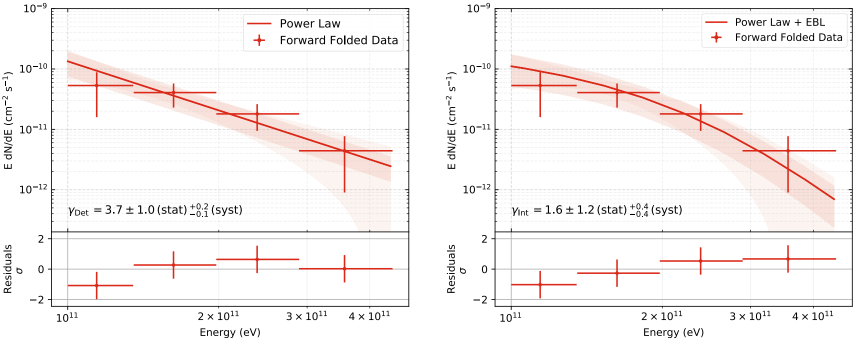




- The first GRB detected in the VHE regime (second reported – tough internal cross checks, relatively weak signal)
- Quite late observing opportunity (how many GRBs one could detect during the last 10yr? Still very bright...)
- EBL absorption is very significant at **$300\,{\rm GeV}$**

GRB180720B

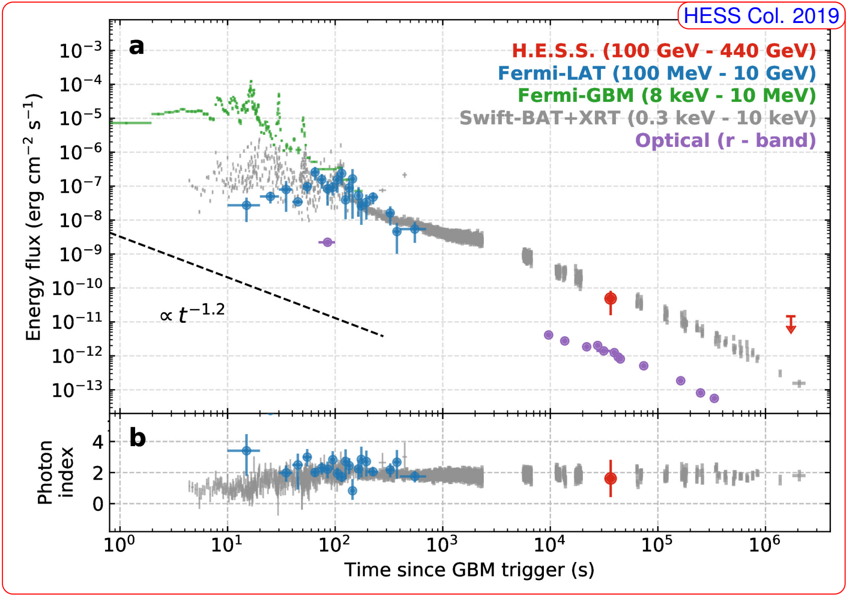
HESS Col. 2019



$$\frac{dN}{d\omega} = \omega^{-\gamma_{int}} e^{-\tau(\omega,z)}$$

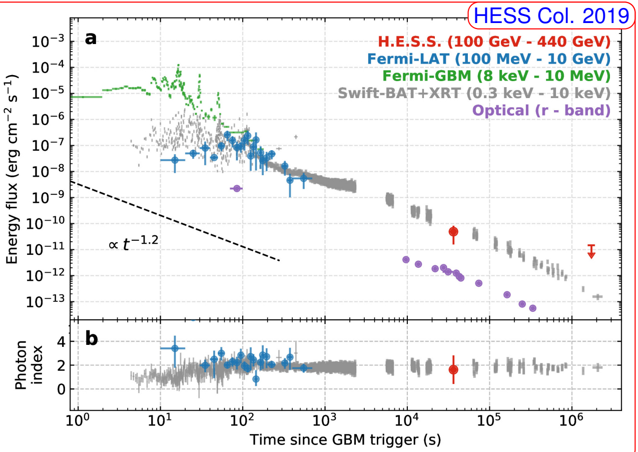
- Spectrum measured between **100** and **400 GeV**
- Intrinsic spectrum is hard, $\gamma_{int} < 2$
- Gamma-ray flux is comparable to X-ray flux at the same epoch

GRB180720B


HESS Col. 2019
a
H.E.S.S. (100 GeV - 440 GeV)
Fermi-LAT (100 MeV - 10 GeV)
Fermi-GBM (8 keV - 10 MeV)
Swift-BAT+XRT (0.3 keV - 10 keV)
Optical (r - band)
$\propto t^{-1.2}$
Energy flux (erg cm^{-2} s^{-1})
10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
b
Photon index
4 2 0
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Time since GBM trigger (s)

GRB180720B

- Optical, X-ray, HE components decay by the same law
- X-ray, HE, and VHE components have the similar photon index
- X-ray, HE, and VHE components have the same flux
- ☞ Straight line is a good fit



GRB180720B

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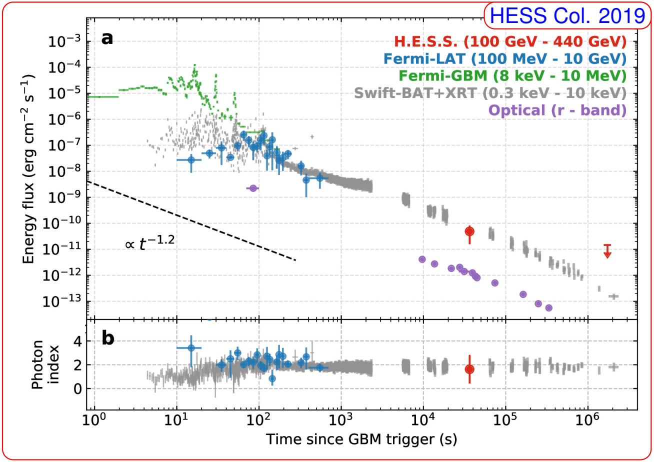


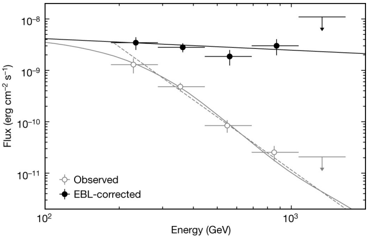
What do we see?

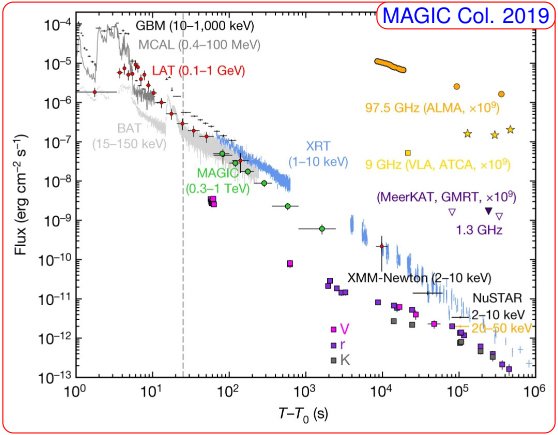
- ✔ We do detect photons with energy exceeding the synchrotron burn-off limit
- ✘ We do not see a TeV component emerging above the emission in the Fermi/LAT band

GRB190114C

GRB190114C

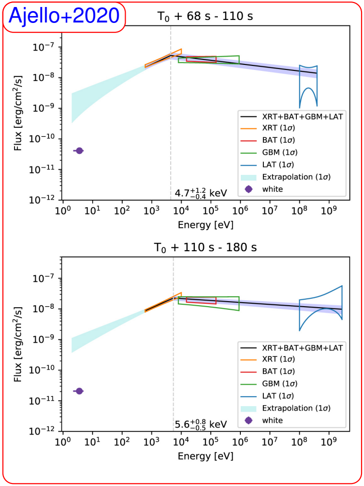
- ✔ **50σ detection**
- ✔ $E_{iso} = 3 \times 10^{53}$ erg
- ? $z = 0.42$
  or $D \approx 1$ Gpc
- ✔ $t_{vhe} \sim$ min
  time decay measured
  in X-rays/VHE: $L \propto t^{-1.6}$



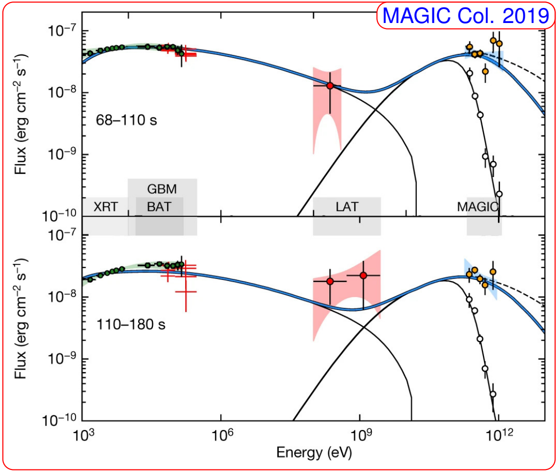


- The first GRB detection reported in the VHE regime
- Bright late prompt – early afterglow emission
- EBL absorption is very significant at ~ 500 GeV

GRB190114C

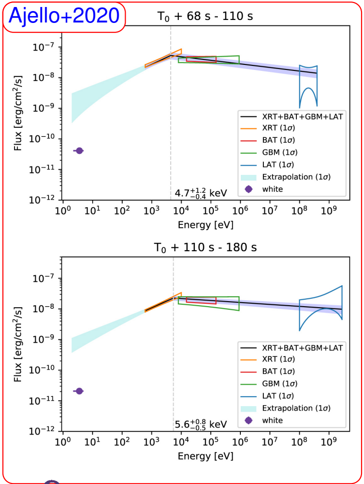


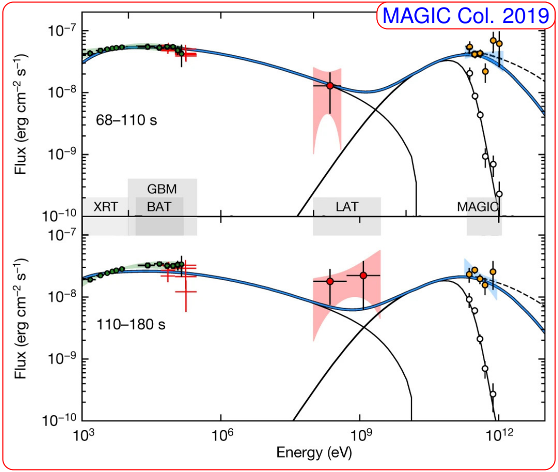
Ajello+2020
T0 + 68 s - 110 s
Flux [erg/cm2/s]
Energy [eV]
XRT+BAT+GBM+LAT
XRT (1σ)
BAT (1σ)
GBM (1σ)
LAT (1σ)
Extrapolation (1σ)
white
4.7+1.2−0.4 keV
T0 + 110 s - 180 s
5.6+0.8−0.5 keV



MAGIC Col. 2019
Flux (erg cm−2 s−1)
68–110 s
110–180 s
XRT
GBM
BAT
LAT
MAGIC
Energy (eV)

GRB190114C





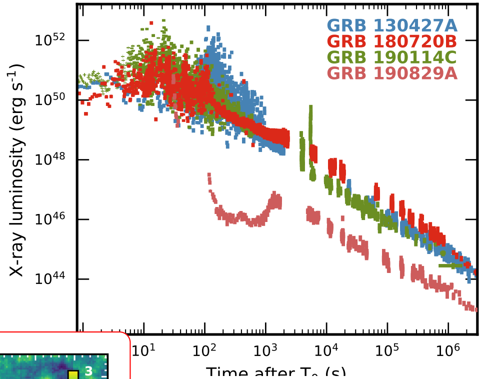
✔ We do detect photons with energy exceeding the synchrotron burn-off limit

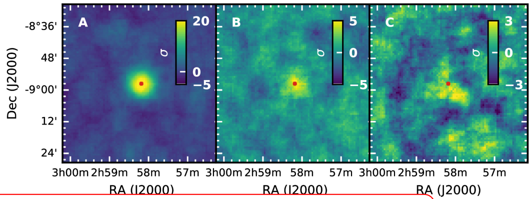
✘ Maybe we see / don't see a TeV component emerging above the emission in the Fermi/LAT band in the 2/3 min.

GRB 190829A

- Very close: $z = 0.0785^{+0.0005}_{-0.0005}$
- Detected by GBM and BAT
- Prompt luminosity $\sim 10^{50}\,\mathrm{erg}$ per decade in the X-ray band
- Afterglow luminosity $5 \times 10^{50}\,\mathrm{erg}$

Hinton (Taup2019)





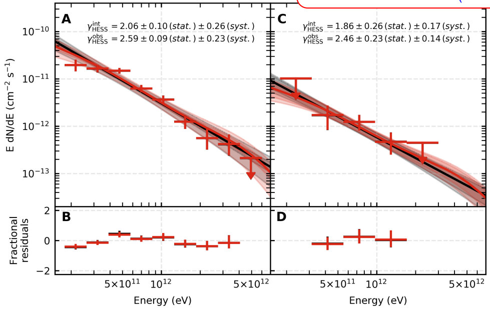
detected with H.E.S.S. for **3 nights (H.E.S.S. Collaboration 2021)**

- $T_0 + 4.3\mathrm{h}$: **21.7**$\boldsymbol{\sigma}$
- $T_0 + 27.2\mathrm{h}$: 5.5σ
- $\boldsymbol{T_0 + 51.2\mathrm{h}}$: 2.4σ

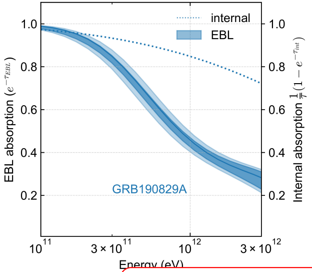
GRB 190829A: VHE spectrum

- Almost model independent of EBL absorption
- Weak internal absorption
- Fit the intrinsic spectrum

$$\frac{dN}{dE} \propto E^{-\gamma_{\rm VHE}^{\rm int}} e^{-\tau_{\rm EBL}} \propto E^{-\gamma_{\rm VHE}^{\rm obs}}$$



H.E.S.S. Collaboration (2021)



H.E.S.S. Collaboration (2021)

Observed spectrum

- night 1: $\gamma_{\rm VHE}^{\rm obs} = 2.59^{+0.09}_{-0.09}$
- night 2: $\gamma_{\rm VHE}^{\rm obs} = 2.46^{+0.23}_{-0.23}$

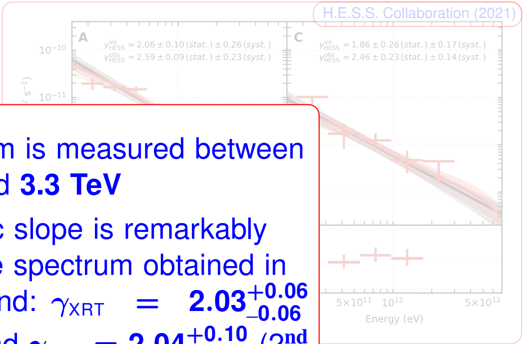
Intrinsic spectrum

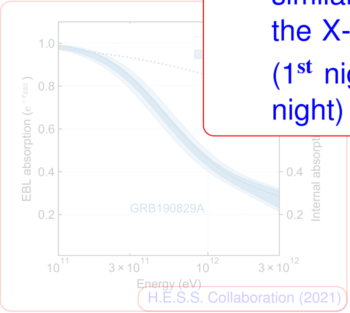
- night 1: $\gamma_{\rm VHE}^{\rm int} = 2.06^{+0.1}_{-0.1}$
- night 2: $\gamma_{\rm VHE}^{\rm int} = 1.86^{+0.26}_{-0.26}$
- all: $\gamma_{\rm VHE}^{\rm int} = 2.07^{+0.09}_{-0.09}$

GRB 190829A: VHE spectrum

- Almost model independent of EBL absorption
- Weak internal absorption
- Fit the intrins…

$$\frac{dN}{dE} \propto E^{-\gamma^{\rm in}_{\rm VH}}…$$





- The spectrum is measured between **180 GeV** and **3.3 TeV**
- VHE intrinsic slope is remarkably similar to the spectrum obtained in the X-ray band: $\gamma_{\rm XRT} = \mathbf{2.03^{+0.06}_{-0.06}}$ (1st night) and $\gamma_{\rm XRT} = \mathbf{2.04^{+0.10}_{-0.10}}$ (2nd night)

Observed spectrum

- night 1: $\gamma^{\rm obs}_{\rm VHE} = 2.59^{+0.09}_{-0.09}$
- night 2: $\gamma^{\rm obs}_{\rm VHE} = 2.46^{+0.23}_{-0.23}$

…pectrum

- night 1: $\gamma^{\rm int}_{\rm VHE} = 2.06^{+0.1}_{-0.1}$
- night 2: $\gamma^{\rm int}_{\rm VHE} = 1.86^{+0.26}_{-0.26}$
- all: $\gamma^{\rm int}_{\rm VHE} = 2.07^{+0.09}_{-0.09}$

GRB 190829A: light-curve

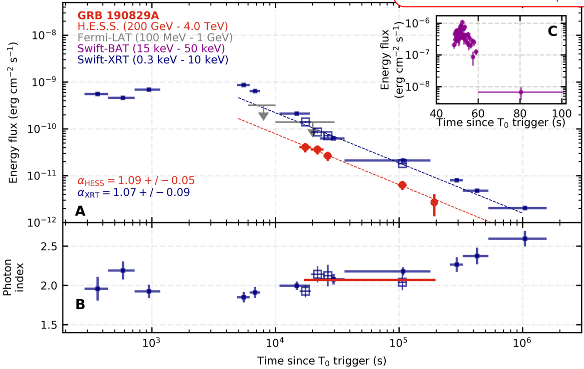
- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray light-curve
- Fit the flux with a power-law decay

$$F_{\rm VHE} \propto t^{-\alpha_{\rm VHE}}$$

$$F_{\rm XRT} \propto t^{-\alpha_{\rm XRT}}$$

- Remarkably consistent slopes ⇒

H.E.S.S. Collaboration (2021)



<u>X-ray decay</u>

$$\alpha_{\rm XRT} = \mathbf{1.07^{+0.09}_{-0.09}}$$

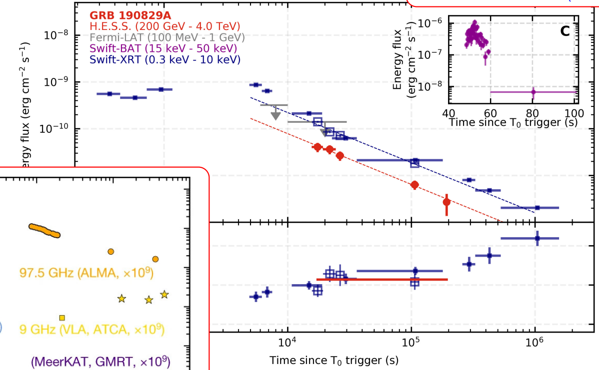
<u>H.E.S.S. decay</u>

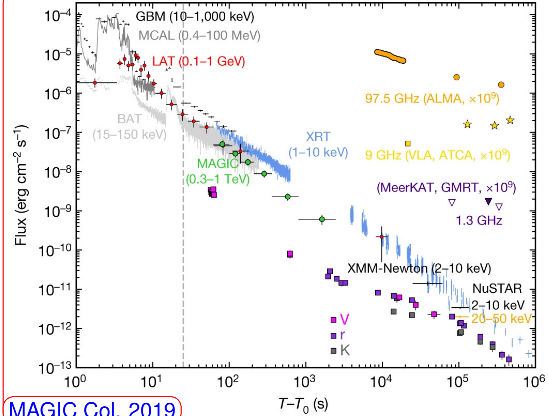
$$\alpha_{\rm VHE} = \mathbf{1.09^{+0.05}_{-0.05}}$$

GRB 190829A: light-curve

- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray

H.E.S.S. Collaboration (2021)





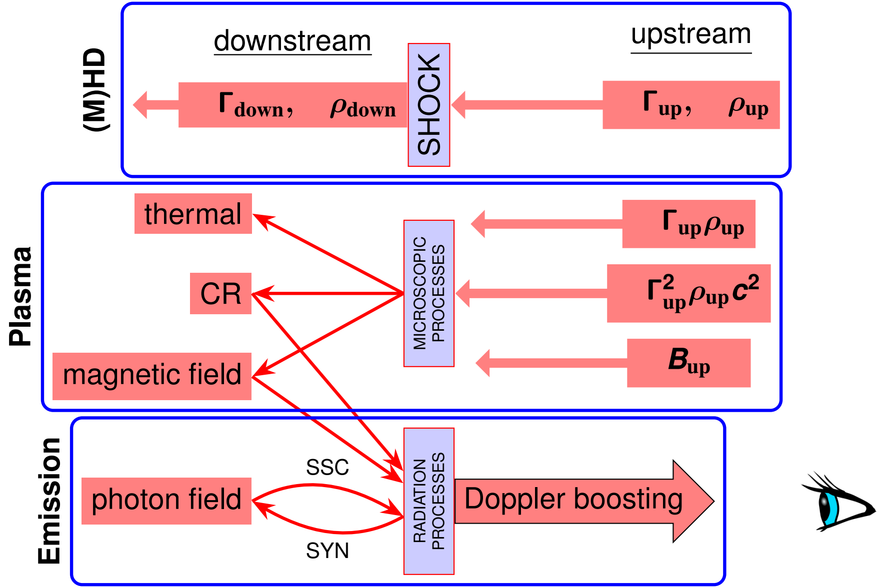
MAGIC Col. 2019

- ✔ For two GRBs with VHE light-curves we see decays identical to the X-ray band
- ✔ Slopes are quite different **1.1** vs **1.6**

GRB 190829A: summary of the observational results

- Remarkably broad spectrum measurement, between **180 GeV** and **3.3 TeV**
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Spectrum measurement close independent on EBL model
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Multi-day VHE light-curve, between **4 h** and **56 h**
  - this required a close GRB of that power
- Intrinsic VHE spectral slope matches the slope of the X-ray spectrum
  - $\gamma_{\rm XRT} = \mathbf{2.03^{+0.06}_{-0.06}}$ and $\gamma^{\rm int}_{\rm VHE} = \mathbf{2.06^{+0.1}_{-0.1}}$ (both for 1$^{\rm st}$ night)
- VHE and X-ray fluxes have a similar time evolution
  - $\alpha_{\rm XRT} = \mathbf{1.07^{+0.09}_{-0.09}}$ and $\alpha^{\rm int}_{\rm VHE} = \mathbf{1.09^{+0.05}_{-0.05}}$
- **Extrapolation of the X-ray spectrum to the VHE domain matches the slope and flux level measured with H.E.S.S.**

Afterglow emission: simple radiative model



Radiation model GRB190829A: key numbers

- Bulk Lorentz factor (for constant density circumburst medium)

$$\Gamma \approx 5 \left(\frac{E_{50}}{n_0 t_{4h}^3}\right)^{1/8} \Big|_{s=0} \approx 2 \left(\frac{E_{50} v_8}{\dot{m}_{21} t_{4h}}\right)^{1/4} \Big|_{s=2}$$

  i.e., we cannot change the bulk Lorentz factor considerably

- Magnetic field strength

$$B' \approx 1\,\mathrm{G} \left(\frac{E_{50} n_0^3 \eta_B^4}{t_{4h}}\right)^{1/8} \Big|_{s=0} \approx 40\,\mathrm{G} \left(\frac{\dot{m}_{21}^3 \eta_B^2}{E_{50} t_{4h}^3 v_8^3}\right)^{1/4} \Big|_{s=2}$$

  i.e. magnetic field can vary depending on the assumptions,

- Synchrotron to inverse Compton (Thomson regime) component ratio is simply

$$\frac{L_{\rm syn}}{L_{\rm IC}} = \frac{\eta_B}{\eta}$$

  i.e., in the framework of this model we can obtain any ratio

- TeV electron produce synchrotron at

$$\hbar\omega_{\rm syn} \approx 300\mathrm{keV} \left(\frac{E_{50} n_0 \eta_B^2}{t_{4h}^2}\right)^{1/4} \Big|_{s=0} \approx 5\mathrm{MeV} \left(\frac{\dot{m}_{21}^2 \eta_B^2}{t_{4h}^4}\right)^{1/4} \Big|_{s=2}$$

  i.e., hard X-ray — VHE emission bands can be related

Internal $\gamma - \gamma$ absorption and the Klein-Nishina effect

GRBs produced a lot of high-energy photons, these photons make an important target for the IC emission and may provide target for VHE gamma rays. There are important consequences:

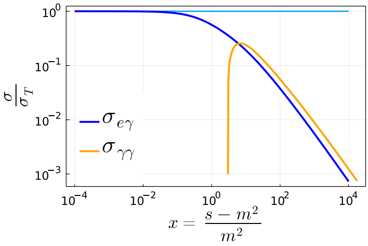
- The Klein-Nishina cutoff
- Internal $\gamma - \gamma$ attenuation

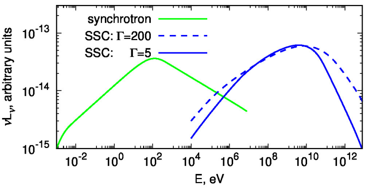
These effects are important if

$$1 < \frac{\hbar\omega_{\rm syn} E}{\Gamma^2 m_e^2 c^4} \approx \frac{4\times 10^3}{\Gamma^2}\omega_{\rm syn,keV} E_{\rm TeV}$$

Internal $\gamma - \gamma$ optical depth

$$\tau \approx \frac{\sigma_{\gamma\gamma} L_{\rm X}}{10\varepsilon_{\rm X} c R \Gamma^2} \propto E^{-1/2}$$





Internal $\gamma - \gamma$ absorption and the Klein-Nishina effect

GRBs produced a lot of high-energy photons, these photons make an important target for the IC emission and may provide target f... important c...

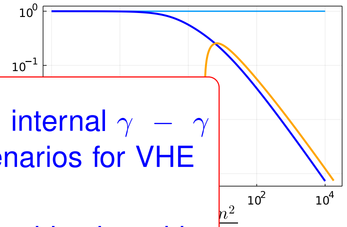
- The Kl...
- Interna...

These effec...

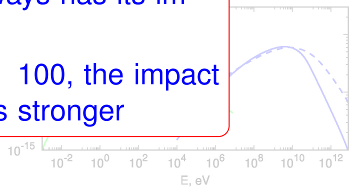
$$1 < \frac{\hbar\omega}{\Gamma^2 \ldots}$$

Internal $\gamma - \gamma$ optical depth

$$\tau \approx \frac{\sigma_{\gamma\gamma} L_X}{10 \varepsilon_X c R \Gamma^2} \propto E^{-1/2}$$



- The Klein-Nishina cutoff and internal $\gamma - \gamma$ need to be accounted in scenarios for VHE emission
- Internal $\gamma - \gamma$ can be considerably altered by a change in the model parameters
- The Klein-Nishina cutoff always has its imprint on the VHE spectrum
- At late epochs, when $\Gamma \ll 100$, the impact of the Klein-Nishina cutoff is stronger

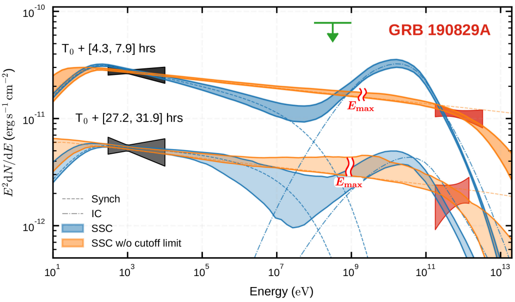


GRB 190829A: MWL modelling

Five dimensional MCMC fitting of the X-ray and TeV spectra

- magnetization, η_B
- energy in electrons, η_e
- cooling break, E_{br}
- cutoff energy, E_{cut}
- powerlaw slope, β_2

H.E.S.S. Collaboration (2021)



Electron spectrum

$$f(E') = \exp\left(-\frac{E'}{E_{cut}}\right) \begin{cases} AE'^{-(\beta_2-1)} & : E' < E_{br} \\ AE_{e,br}E'^{-\beta_2} & : E' > E_{br} \end{cases} \quad \begin{matrix} E_{cut} < E_{syn}^{MAX} \\ E_{cut} > E_{syn}^{MAX} \end{matrix}$$

Can we exclude SSC scenario?

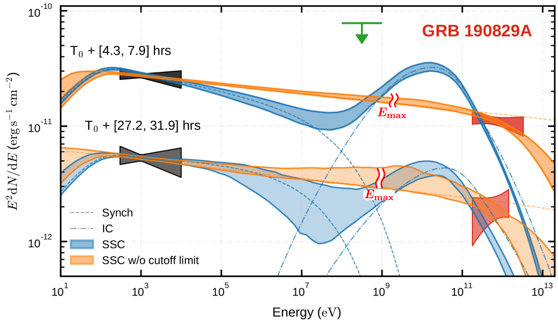
Our numerical analysis is limited to a

- One-zone model
- Power-law distribution of electrons
- Five-dimensional parameter space

Our analytic analysis takes some “must-have” elements

- One-zone model
- X-ray to VHE flux ratio
- X-ray spectral index
- VHE spectral index

H.E.S.S. Collaboration (2021)

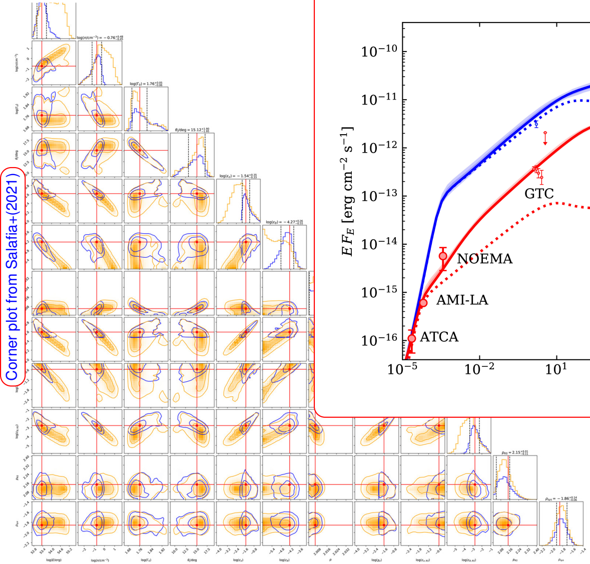


Under our assumptions we obtained that

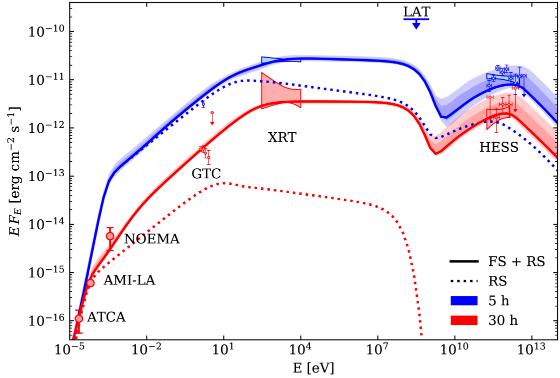
- SSC can be responsible only under extreme assumptions for the magnetic field strength (e.g., very weak) and low radiation efficiency
- Alternatively we can fit the data if adopt a much larger bulk Lorentz factor

Can we exclude SSC scenario?

12-parameter SSC model

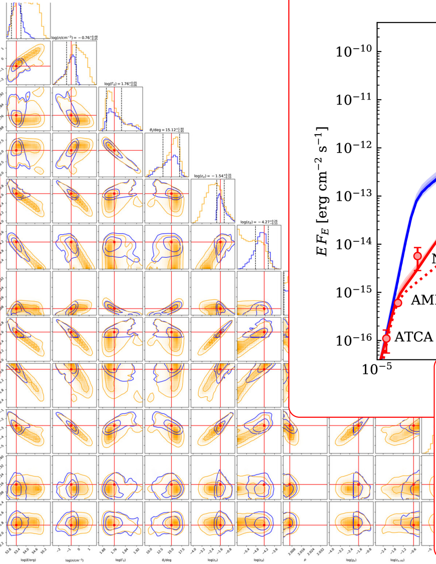


SSC model for GRB190829A from Salafia+(2021)



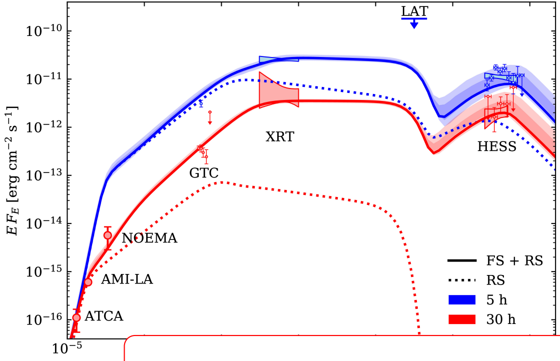
Can we exclude SSC scenario?

12-parameter SSC model



Corner plot from Salafia+(2021)

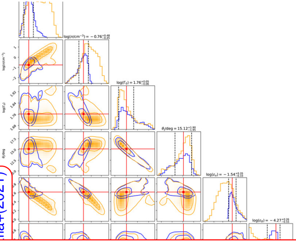
SSC model for GRB190829A from Salafia+(2021)



- Weak magnetization, low radiation efficiency
- FS and RS contributions
- ✘ Questionable agreement on the VHE slope

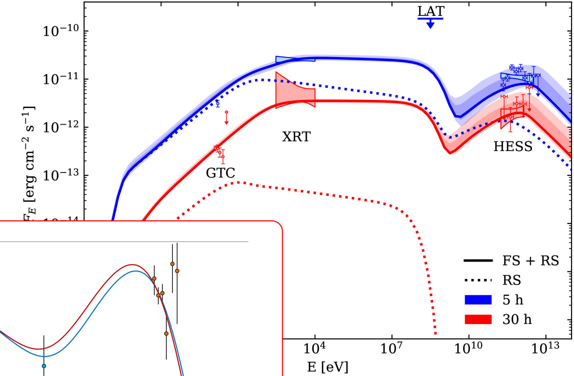
Can we exclude SSC scenario?

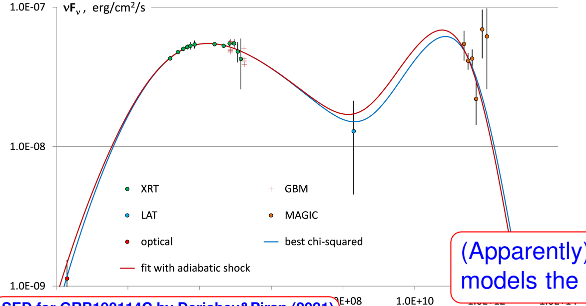
12-parameter SSC model



Salafia+(2021)

SSC model for GRB190829A from Salafia+(2021)



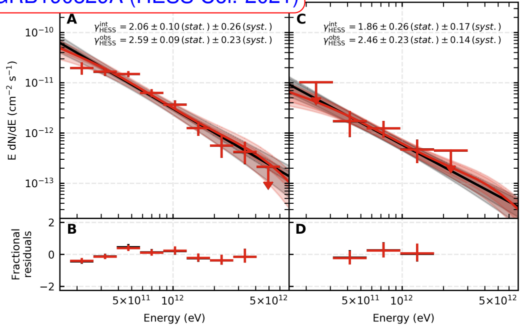


SED for GRB190114C by Derishev&Piran (2021)

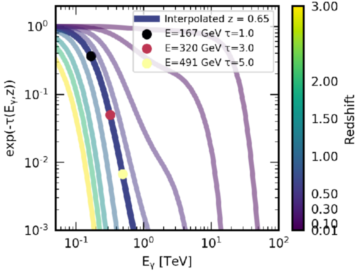
(Apparently) It is hard to reproduce with SSC models the hard PL VHE spectrum.

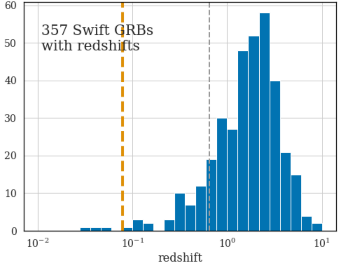
Is it easy to confirm a PL VHE GRB spectrum?

GRB190829A (HESS Col. 2021)



credit E.Ruiz





Because of the EBL absorption, it is hard to reliably distinguish "hump"-like intrinsic spectrum and a power-law spectrum deformed by EBL absorption from distant ($z > \mathbf{0.1}$) GRBs. It may take **years** to detect in the VHE regime another GRB from $z < \mathbf{0.1}$. So fare there were only **5** such GRBs ⇒

Summary I

- GRB afterglow are essential for studying relativistic shocks, including two processes with extremely broad implications: **magnetic field amplification** and **acceleration** of high-energy particles
- While there are little doubles that bright X-ray – soft-gamma-ray emission is synchrotron radiation of accelerated electrons, this component alone does not allow determining the particle energy
- Detection of the IC component is a key element for resolving magnetic field – particle energy degeneracy of the X-ray component
- Conventionally, synchrotron emission cannot extend beyond $\hbar\omega_{\rm MAX} = \mathbf{20(\Gamma/100)\,GeV}$, thus VHE band is the critical window for constraining the parameters of the downstream
  - defining the magnetic field amplification
  - constraining particle acceleration, in particular, the maximum energy
- Detection of GRB 190829A provides a unique chance for understanding the properties of relativistic shocks $\Rightarrow$

Summary II

- H.E.S.S. detection of GRB 190829A is
  - Exceptionally long: the signal was detected for three nights, up to **56** $\mathbf{h}$ after the trigger
  - A very broad spectral measurement: between **0.18** and **3.3** $\mathbf{TeV}$
- The fortunate proximity of the source, $z_{\rm rs} = \mathbf{0.08}$, allows an almost model indepent EBL deabsorption of the spectrum
- Measured spectrum is consistent with a power-law with a photon index of $\approx$ **2.1**, not favoring any curvature of the spectrum
- The VHE intrinsic spectral index and flux level match the extrapolation of the synchrotron X-ray spectrum to the VHE domain
- This challenges simple one-zone SSC scenarios, however, leaves a number of alternative options
  - Extreme condition (very weak magnetic field, low radiation efficiency)
  - SSC multi-zone models
  - Synchrotron only models (likely requires a multi-zone set up)
  - Reconsider relativistic shock (e.g., Derishev&Piran 2016)