GRB 190829A — long afterglow measurement with H.E.S.S.

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H.E.S.S.

OVERVIEW

Detection of GRBs in the VHE regime: importance & challenges

Observation of GRB 190829A with H.E.S.S.

GRB 190829A: Modeling

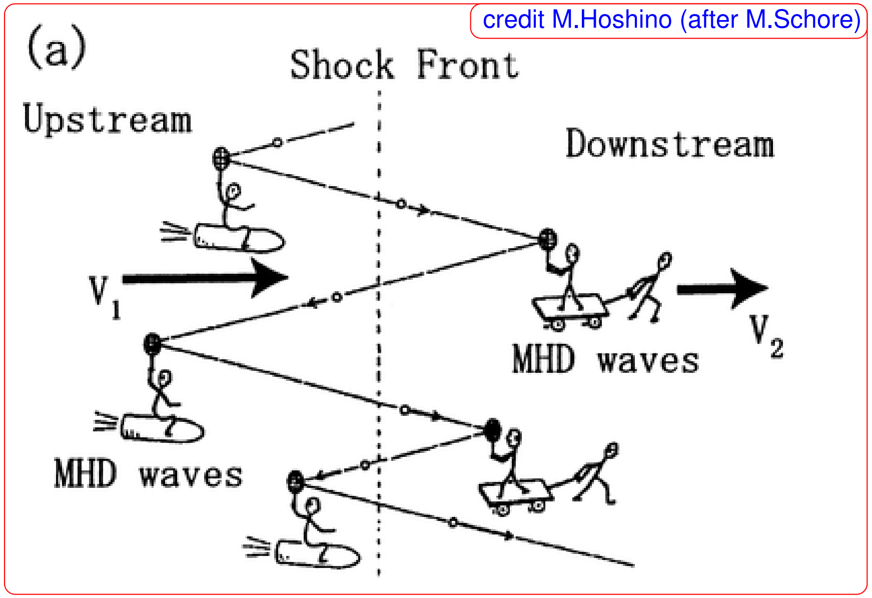
GRB 190829A: Result implications

H.E.S.S.

Detection of GRBs in the VHE regime: importance & challenges

GRB is relativistic version of SN explosions

- **Shock acceleration is a very important mechanism for production of cosmic rays**



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 $t_{\rm ACC} \approx \frac{2\pi r_{\rm G}}{c}\left(\frac{c}{v_1}\right)^2$

GRB is relativistic version of SN explosions

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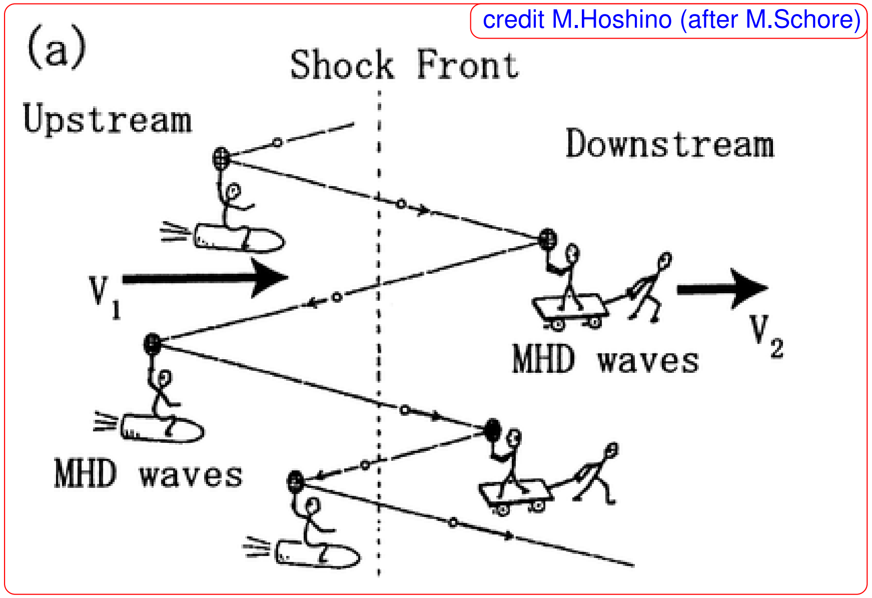
- **It is fairly well understood in the non-relativistic regime, but not in the relativistic one**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Relativistic shocks

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

GRB is relativistic version of SN explosions

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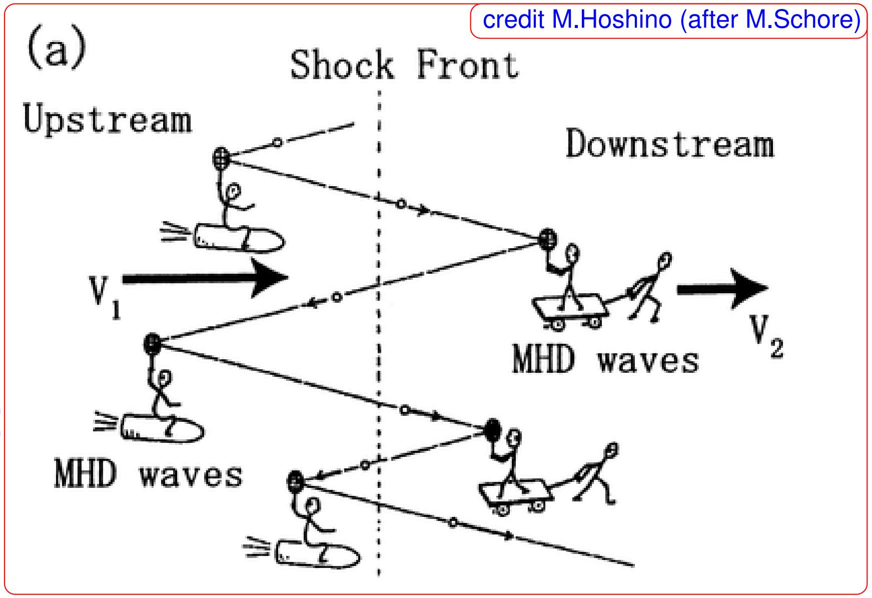
- It is fairly well understood in the non-relativistic regime, but **not in the relativistic one**
- **GRB afterglows are produced by relativistic shocks in their simplest realization**



Relativistic shocks

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

GRB is relativistic version of SN explosions

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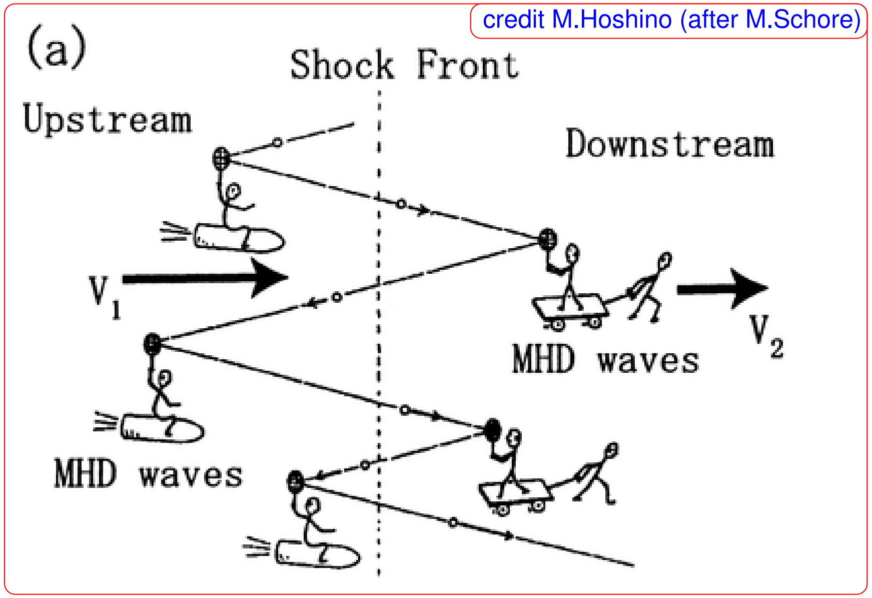
- GRB afterglows are produced by relativistic shocks in their simplest realization
- **Detection of IC emission helps to constrain the downstream conditions and define energy of synchrotron emitting electrons**



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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

GRB is relativistic version of SN explosions

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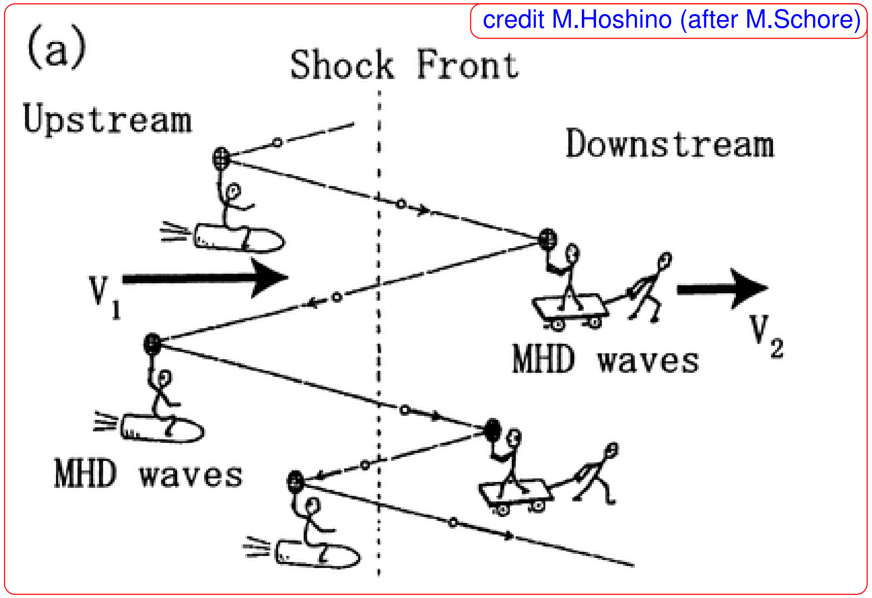
- It is fairly well understood in the non-relativistic regime, but **not in the relativistic one**
- GRB afterglows are produced by relativistic shocks in their simplest realization
- Detection of IC emission helps to constrain the downstream conditions and define energy of synchrotron emitting electrons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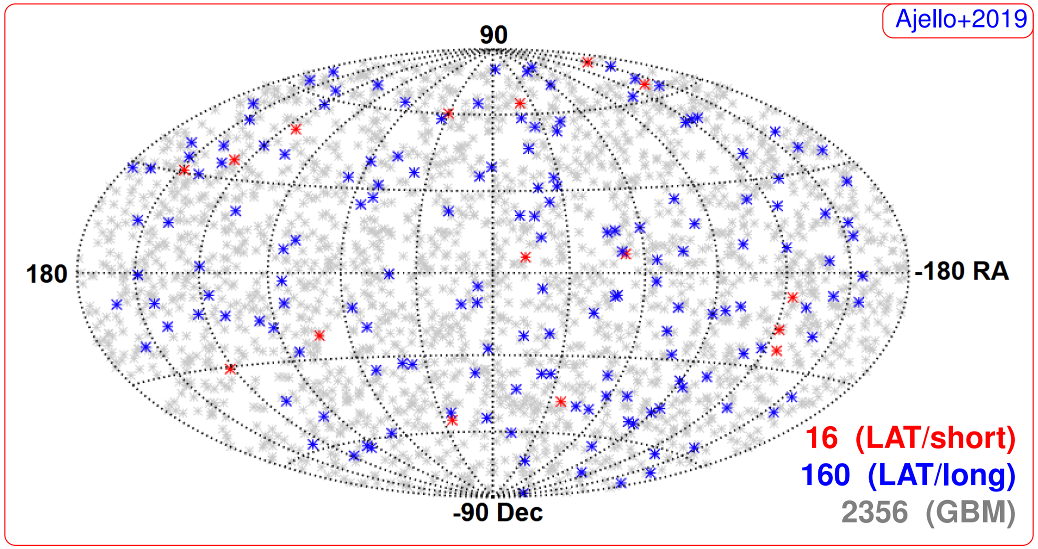
Synchrotron burn-off limit

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

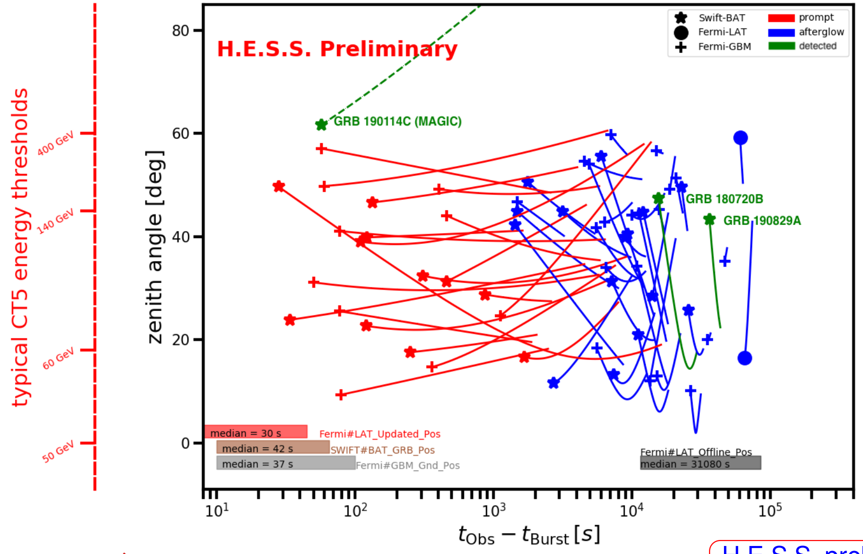
Hunt for GRBs

Why do we expect to see GRBs@VHE?

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



Ajello+2019



H.E.S.S. preliminary

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

Hunt for GRBs

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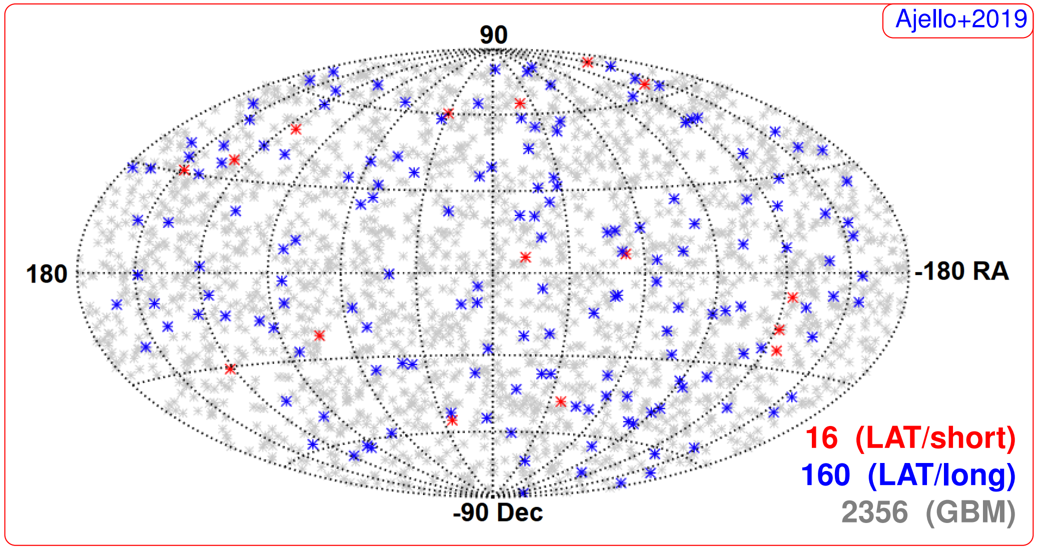

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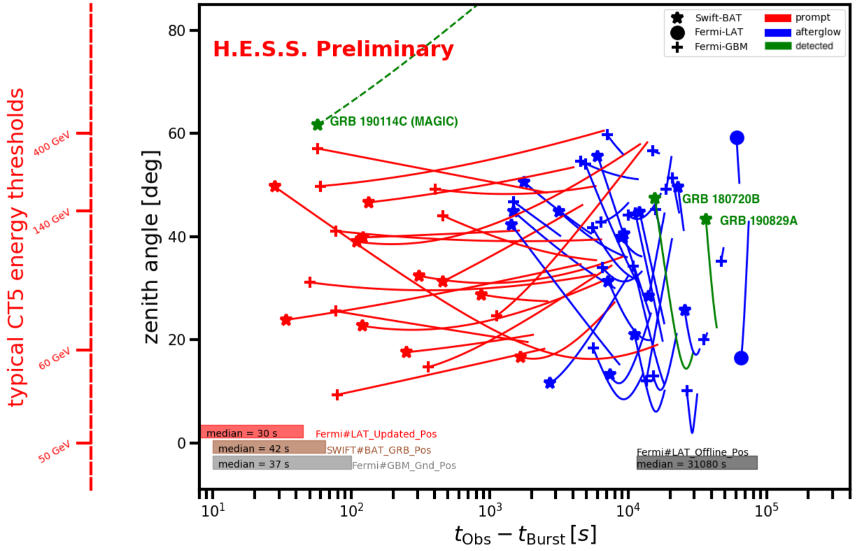

Observation difficulties

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

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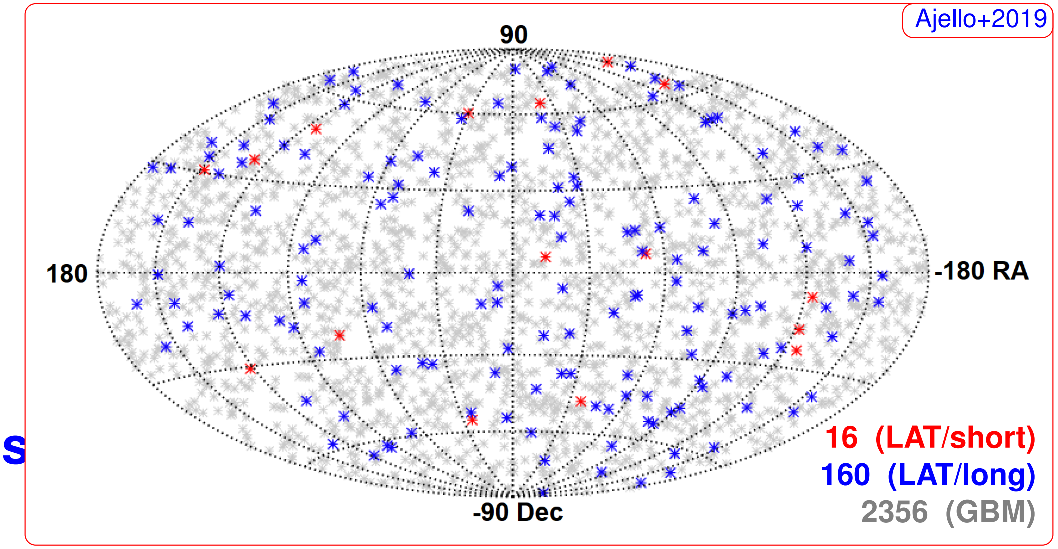

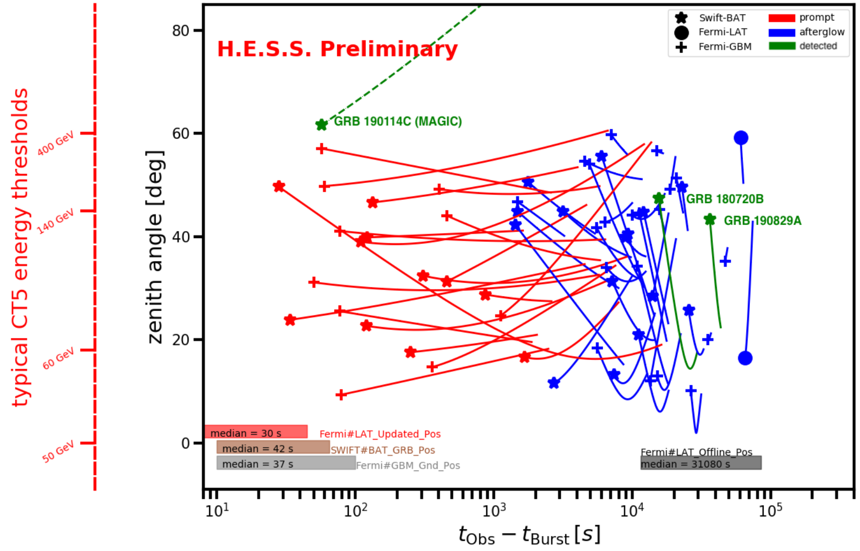

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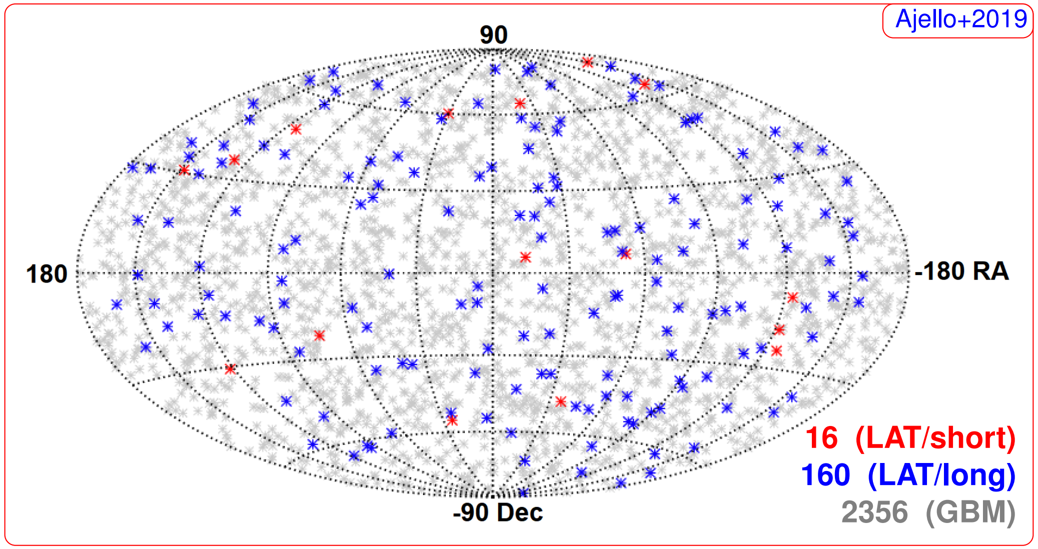

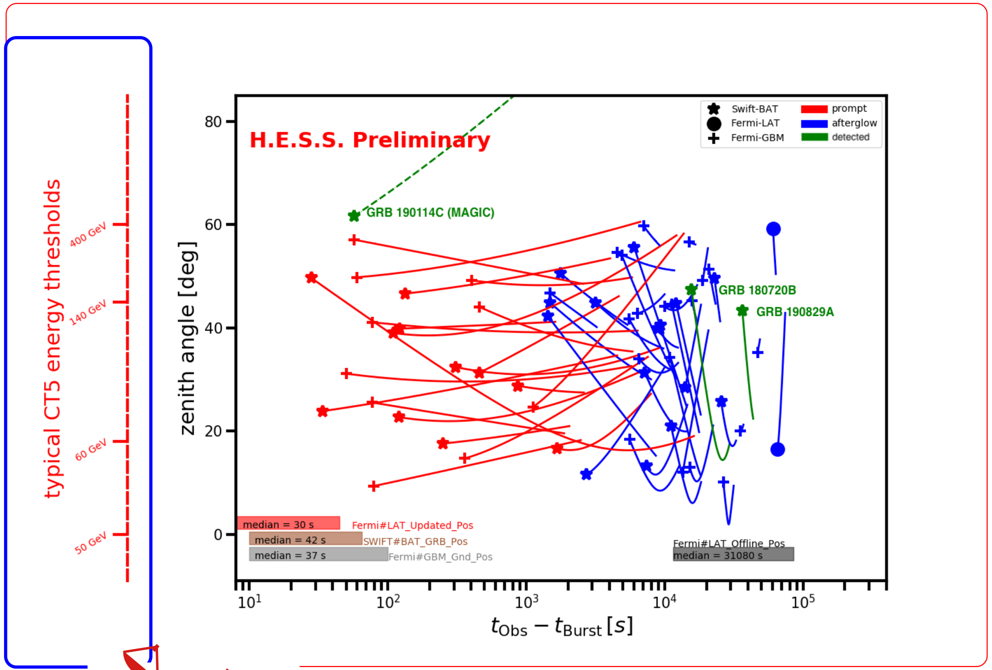

Observation difficulties

- Highly variable sources
- Bright synchrotron emission
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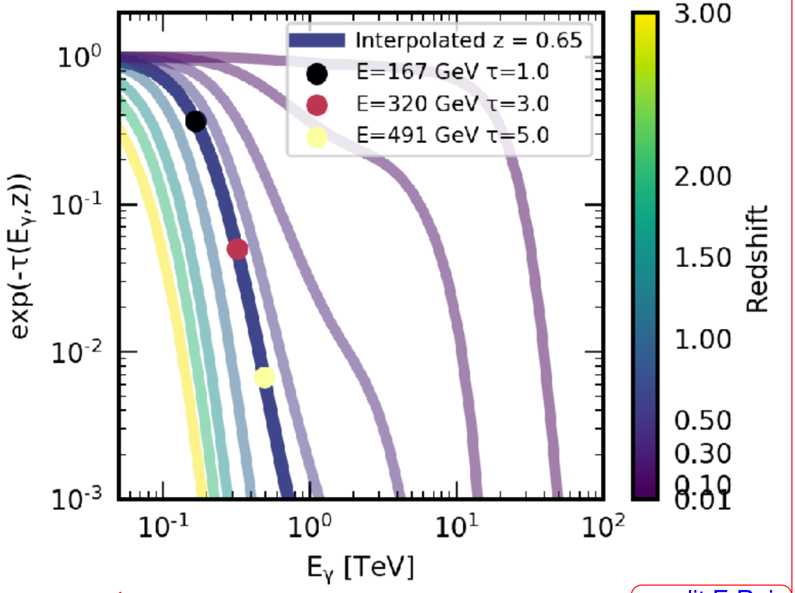
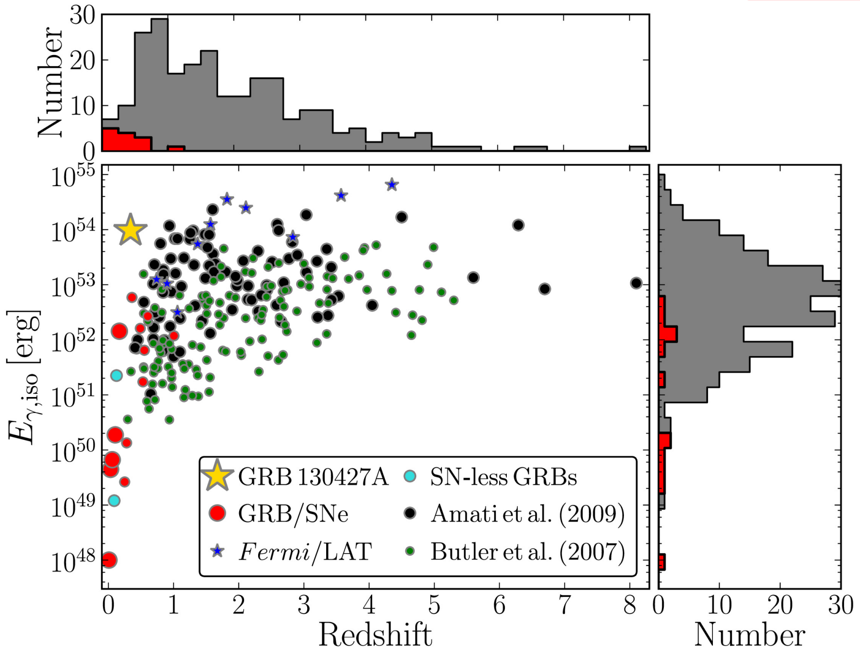
- **Cosmological distances, EBL attenuation ⇒**

EBL attenuation

- GRBs are typically registered from $z_{\rm rs} > 1$
- 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 $z_{\rm rs} = 0.5$ are attenuated by a factor of 10

EBL attenuation

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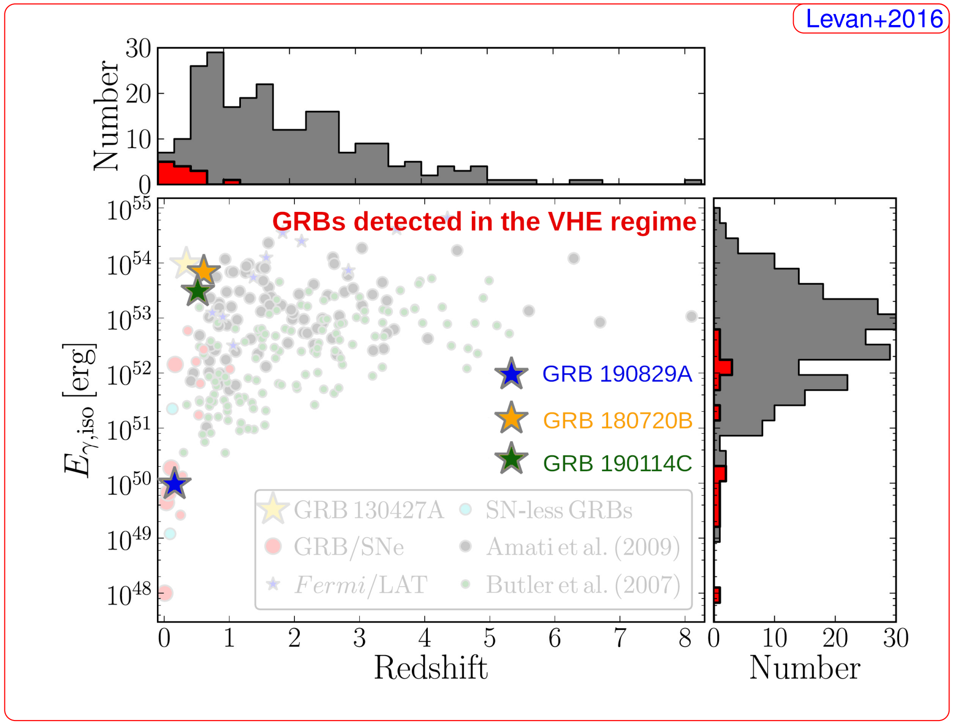
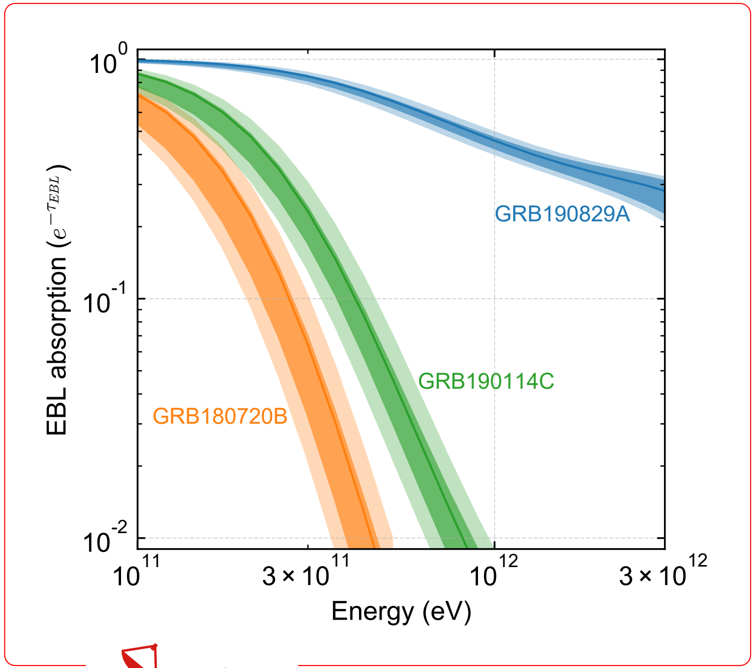

Levan+2016



GRBs detected in the VHE regime:

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

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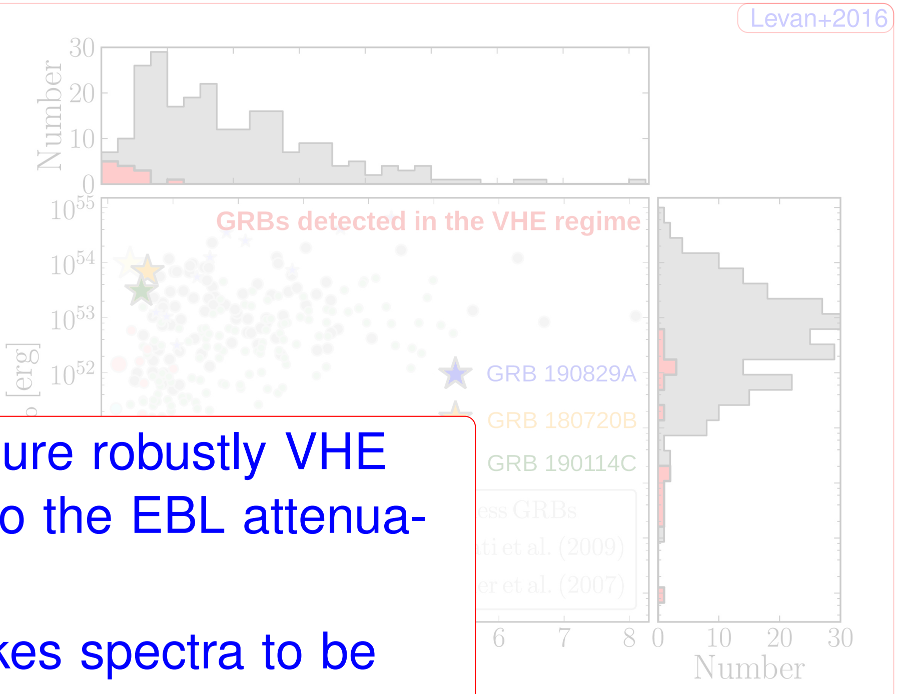
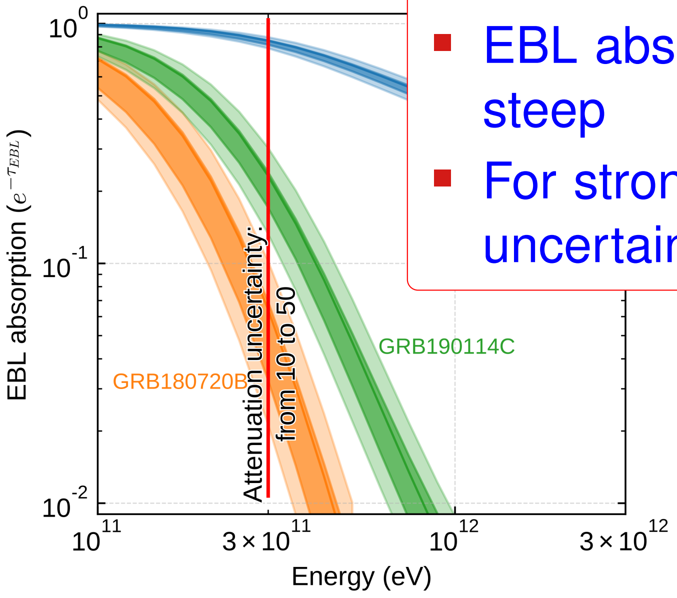


It is very hard to measure robustly VHE spectra of GRBs due to the EBL attenuation:

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



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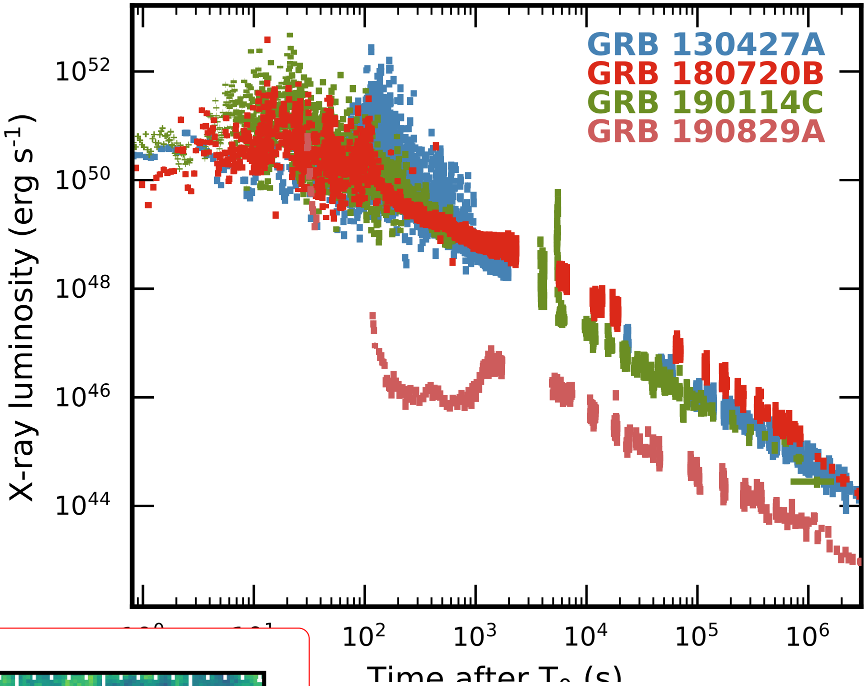
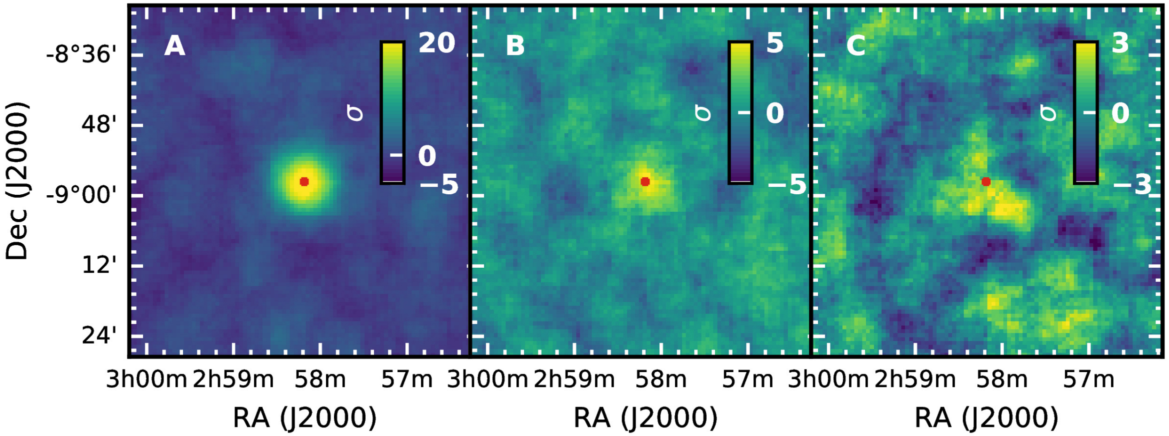
Observation of GRB 190829A with H.E.S.S.

GRB 190829A

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





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

H.E.S.S. detection

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

GRB detected during 3 nights! How is that possible?

Several facts contributed to this achievement

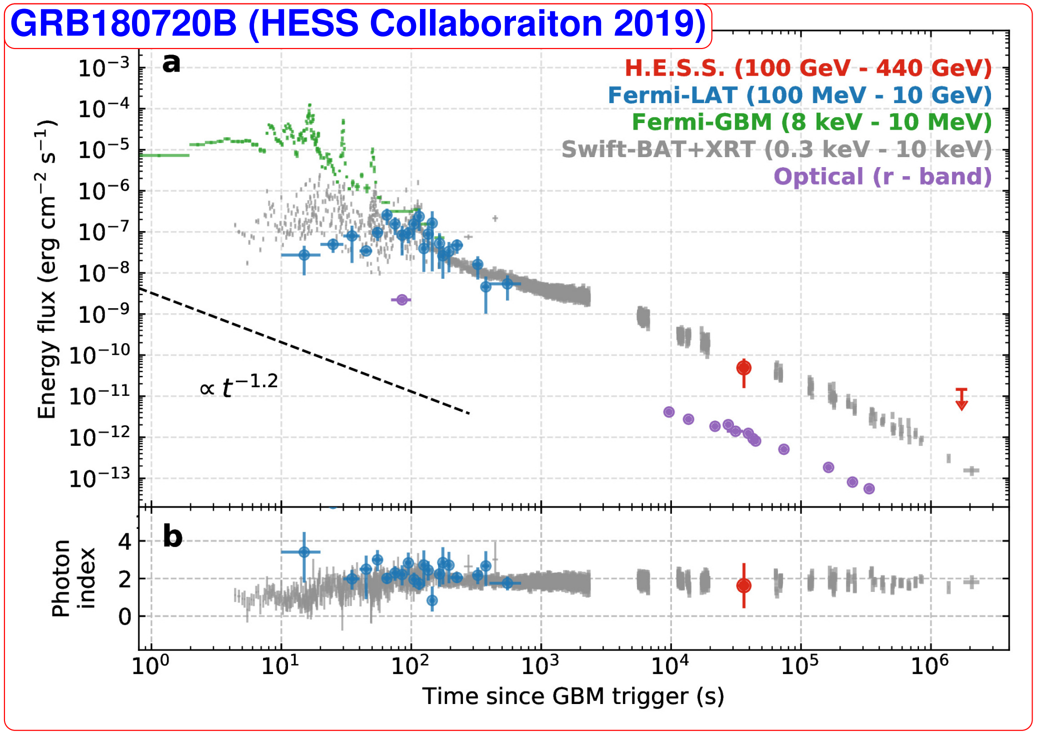
- H.E.S.S. is a very good instrument: the second night flux corresponds to 5% of Crab and it was detected in 4h with $> 5\sigma$ significance
- H.E.S.S. is in a good shape after 15 years of operation. All telescope cameras were upgrade in 2017 helped to improve the observation efficiency and increased the photon statistics by 10% (probably critical for light curve data point for third night)

credit V.Chander

GRB detected during 3 nights! How is that possible?

Several facts contributed to this achievment

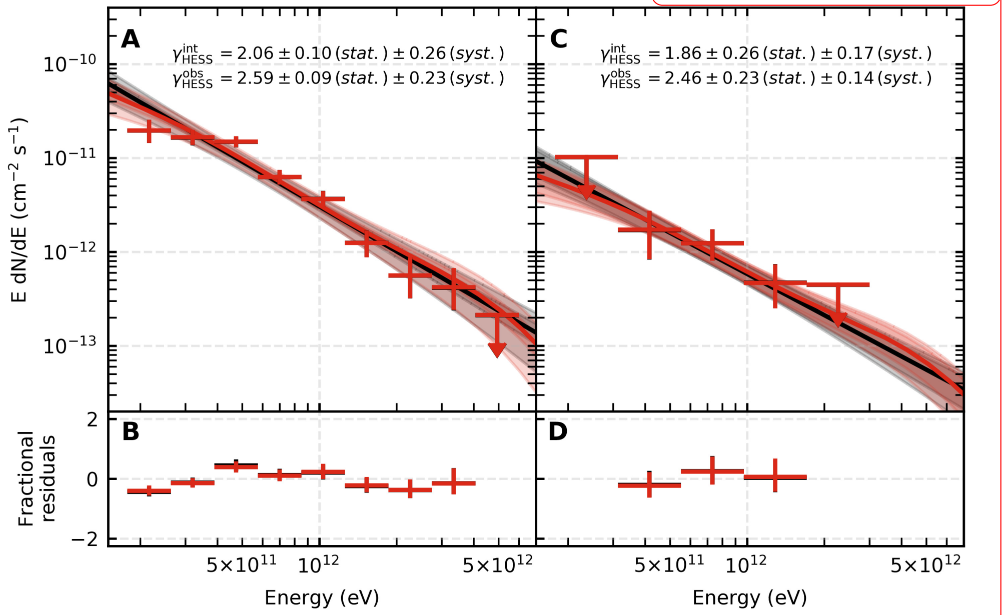
- H.E.S.S. Transients WG revised the strategy for GRB observations based on late afterglow detection from GRB 180720B, making possible starting observations of GRB 190829A more than 4h after the trigger
- The contribution of Reconstruction&Analysis WG was also critical. Based on the site analysis, one released Atel #13052 reporting GRB190829A detection within 3h, allowing follow-up observations in South America.


GRB180720B (HESS Collaboraiton 2019)

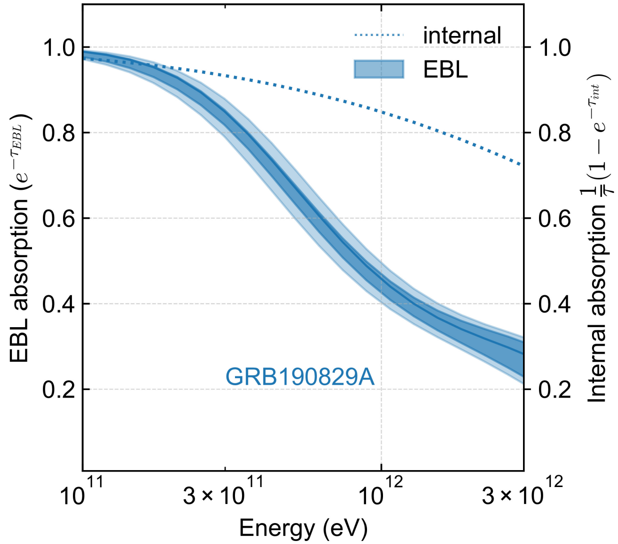
GRB 190829A: VHE spectrum

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

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



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



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

Observed spectrum

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

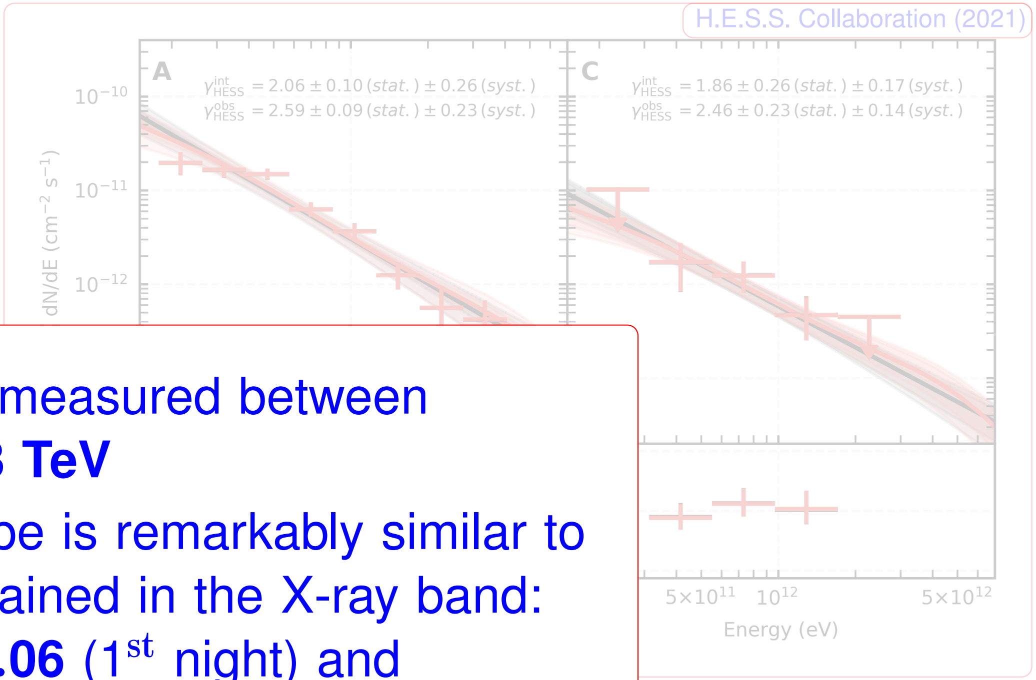
Intrinsic spectrum

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

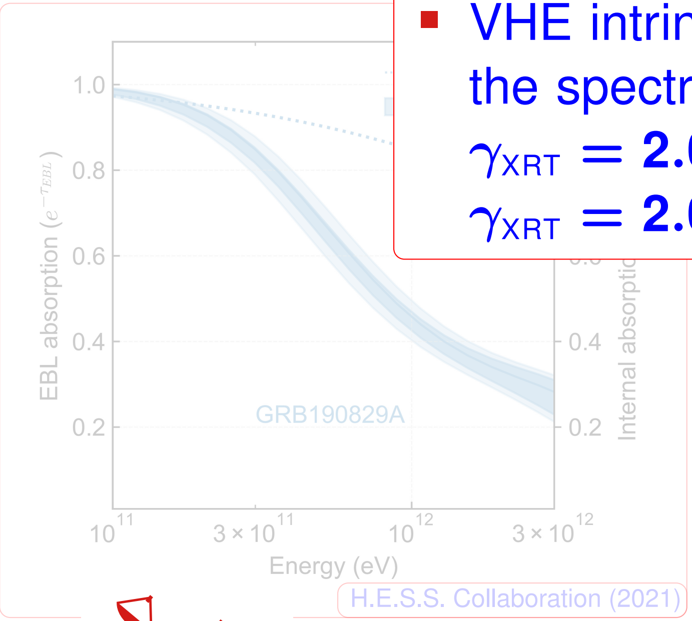
GRB 190829A: VHE spectrum

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

$\frac{dN}{dE} \propto E$



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



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

- 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: $\gamma_{\rm XRT} = \mathbf{2.03 \pm 0.06}$ ($1^{\rm st}$ night) and $\gamma_{\rm XRT} = \mathbf{2.04 \pm 0.10}$ ($2^{\rm nd}$ night)

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GRB 190829A: light-curve

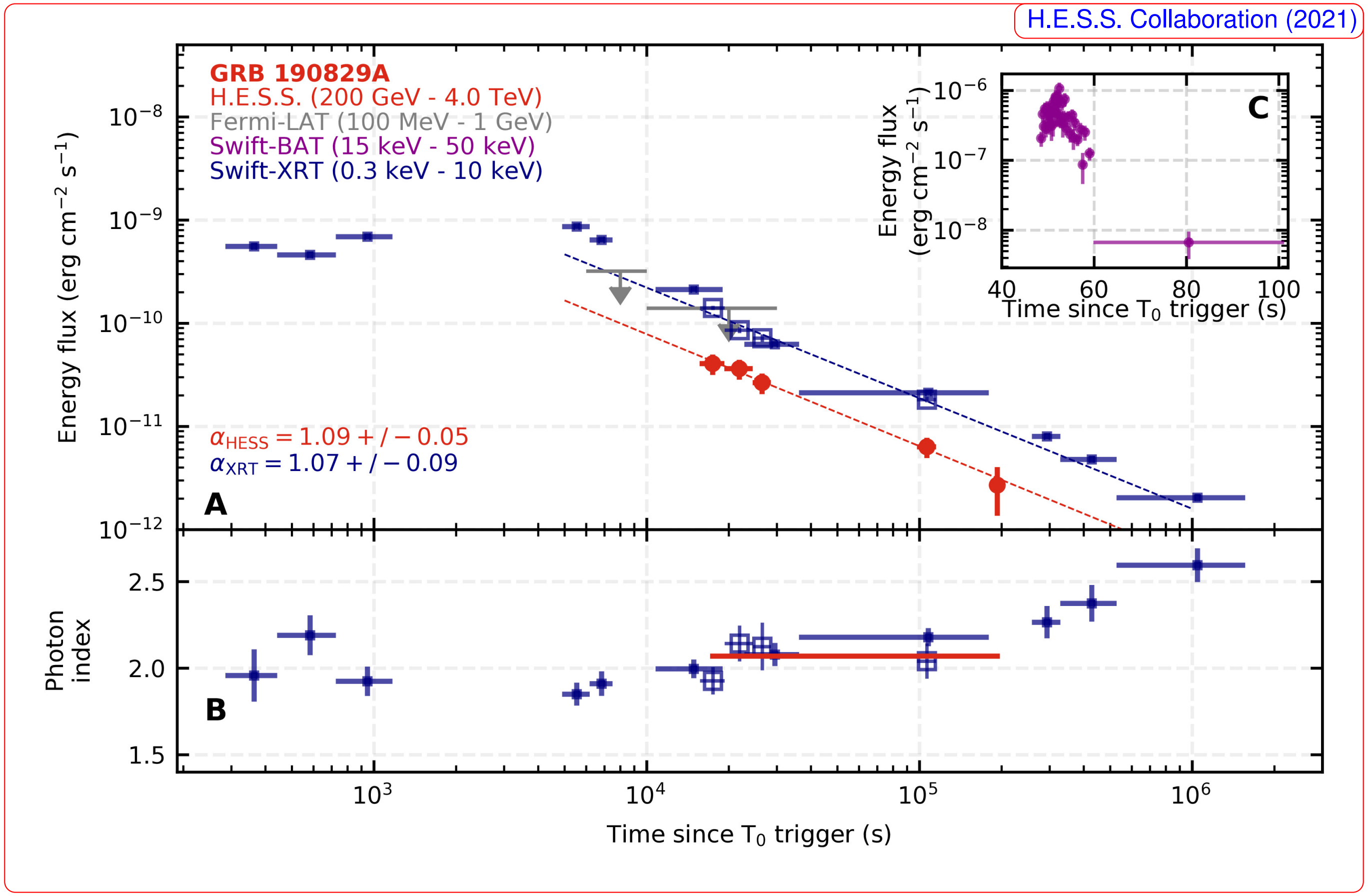
- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray light-curve
- Fit the flux with a power-law decay

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

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

- Remarkably consistent slopes

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



X-ray decay

$$\alpha_{\mathrm{XRT}} = 1.07 \pm 0.09$$

H.E.S.S. decay

$$\alpha_{\mathrm{VHE}} = 1.09 \pm 0.05$$

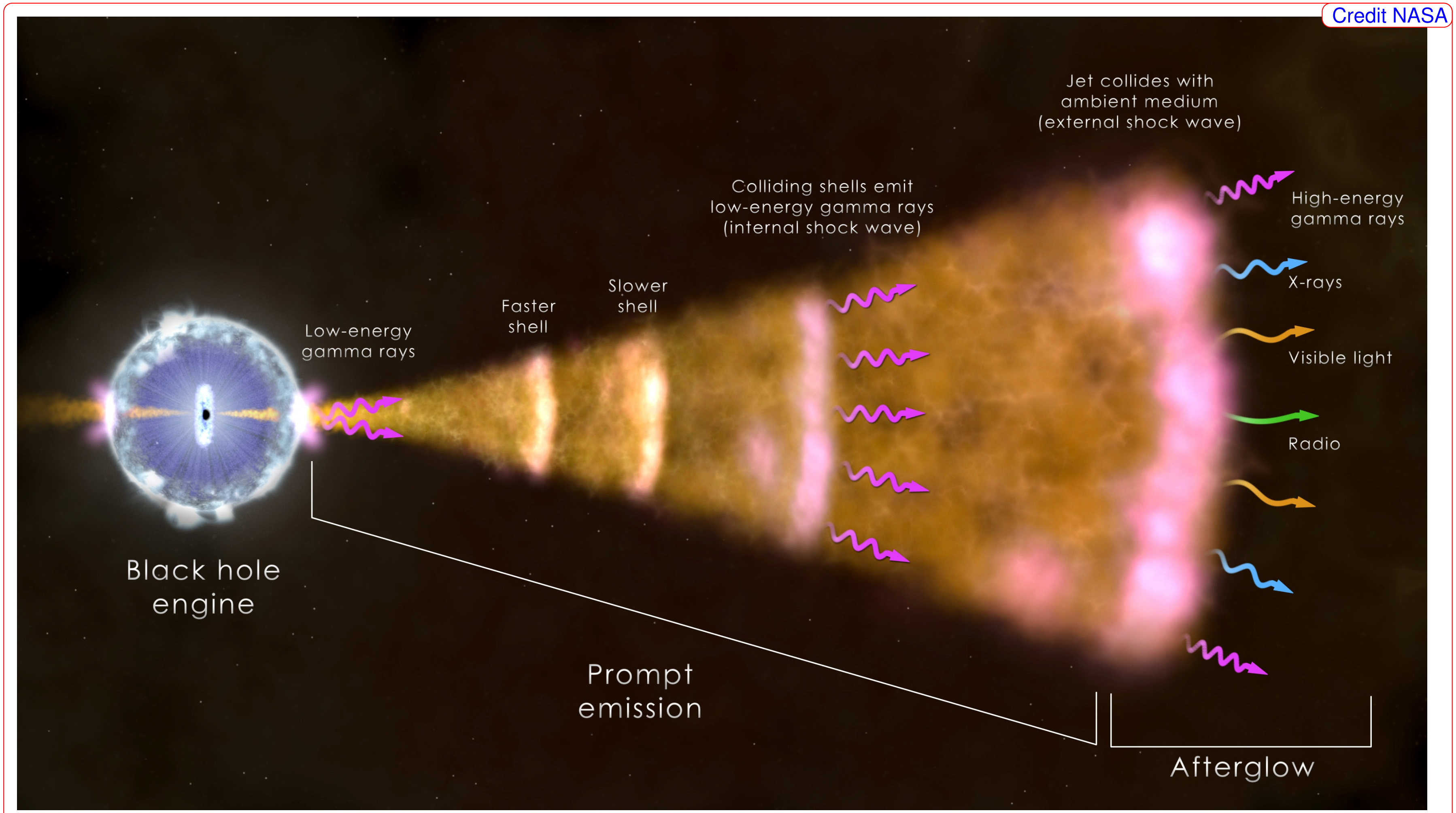
GRB 190829A: summary of the observational results

- 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
  - $\gamma_{\rm XRT} = \mathbf{2.03 \pm 0.06}$ and $\gamma_{\rm VHE}^{\rm int} = \mathbf{2.06 \pm 0.1}$ (both for 1$^{\rm st}$ night)
- VHE and X-ray fluxes have a similar time evolution
  - $\alpha_{\rm XRT} = \mathbf{1.07 \pm 0.09}$ and $\alpha_{\rm VHE}^{\rm int} = \mathbf{1.09 \pm 0.05}$
- **Extrapolation of the X-ray spectrum to the VHE domain matches the slope and flux level measured with H.E.S.S.**

H.E.S.S.

GRB 190829A: Modeling

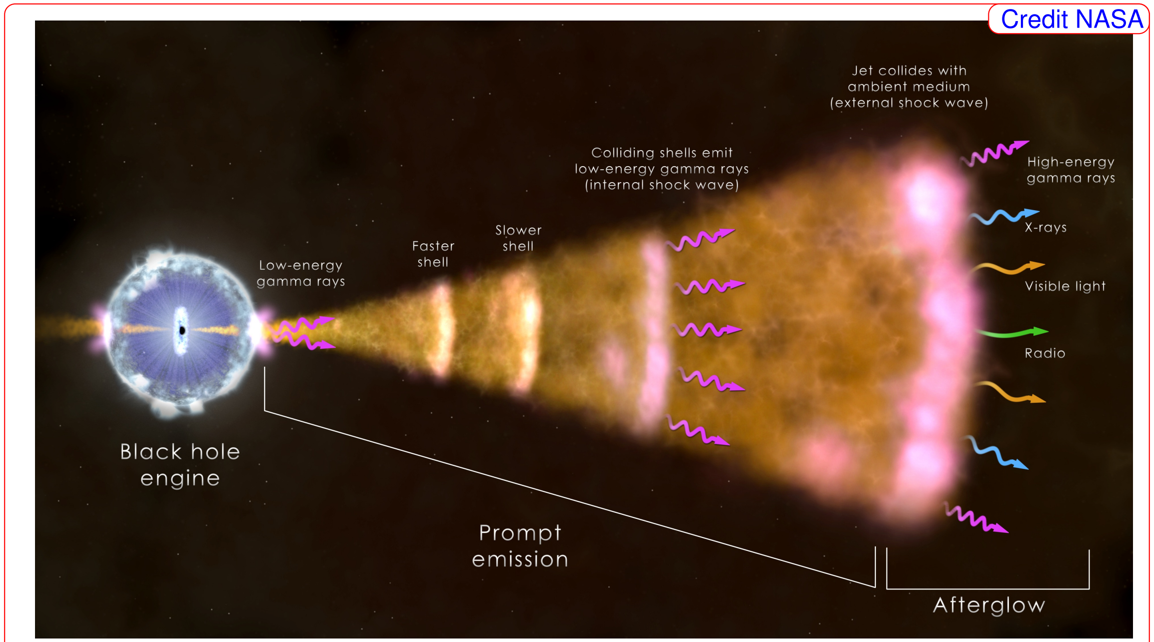
Long GRBs: physical scenario



Credit NASA

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 10^3 s
- Afterglow: jet–circumburst medium interaction, start dominating after 10^3 s, last for weeks



Credit NASA

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

$$\Gamma \propto \left(\frac{E}{\rho_0 t^3}\right)^{1/8} \qquad \text{for } s = 0$$

- Shell radius

$$R \propto \left(\frac{tE}{\rho_0}\right)^{1/4} \qquad \text{for } s = 0$$

- Integernal energy of the plasma

$$\varepsilon \propto \Gamma^2 \rho_0 \qquad \text{for } s = 0$$

This provides a robust basis for radiative models

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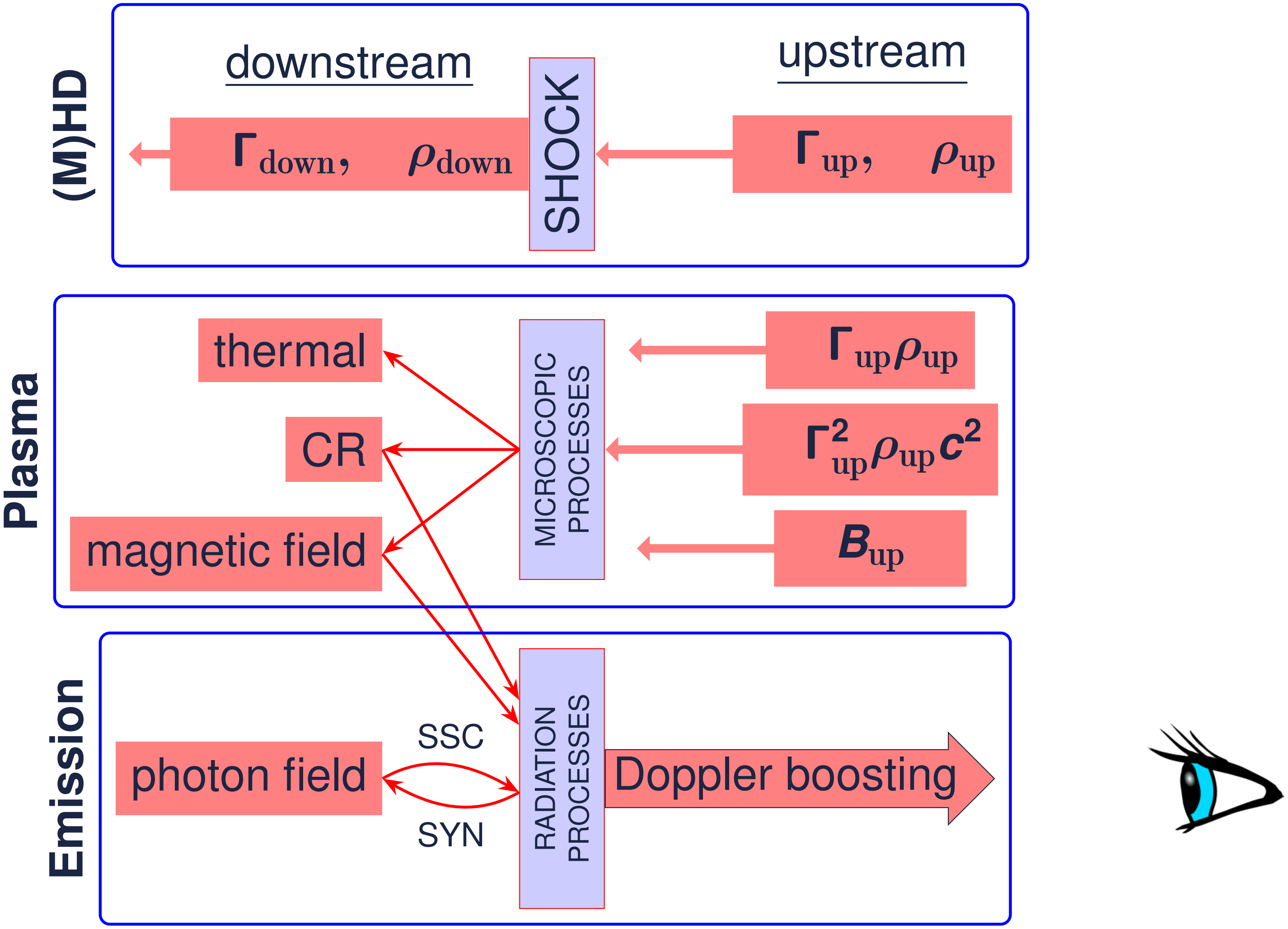
Afterglow emission: simple radiative model



(M)HD

downstream

upstream

$\Gamma_{\rm down}, \quad \rho_{\rm down}$

SHOCK

$\Gamma_{\rm up}, \quad \rho_{\rm up}$

Plasma

thermal

CR

magnetic field

MICROSCOPIC PROCESSES

$\Gamma_{\rm up}\rho_{\rm up}$

$\Gamma^2_{\rm up}\rho_{\rm up}c^2$

$B_{\rm up}$

Emission

photon field

SSC

SYN

RADIATION PROCESSES

Doppler boosting

Radiation model: key numbers

- Bulk Lorentz factor (for constant density circumburst medium)

$$\Gamma \approx 5 \left(\frac{E_{50}}{n_0 t_{4\mathrm{h}}^3} \right)^{1/8}$$

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

- Magnetic field strength

$$B' \approx 1 \left(\frac{E_{50} n_0^3 \eta_{\mathrm{B}}^4}{t_{4\mathrm{h}}} \right)^{1/8} \mathrm{G}$$

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

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

$$\frac{L_{\mathrm{syn}}}{L_{\mathrm{IC}}} = \frac{\eta_{\mathrm{B}}}{\eta}$$

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

- TeV electron produce synchrotron at

$$\hbar\omega_{\mathrm{syn}} \approx 300\mathrm{keV} \left(\frac{E_{50} n_0 \eta_{\mathrm{B}}^2}{t_{4\mathrm{h}}^2} \right)^{1/4}$$

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:

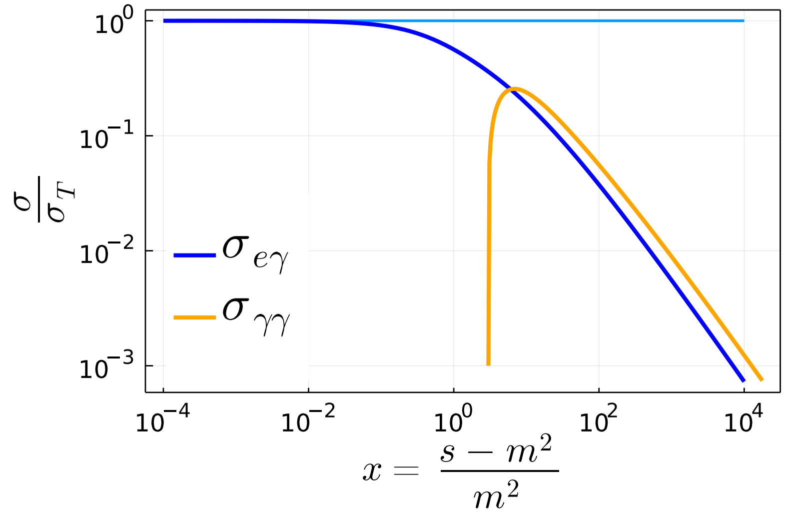
- The Klein-Nishina cutoff
- Internal $\gamma-\gamma$ attenuation

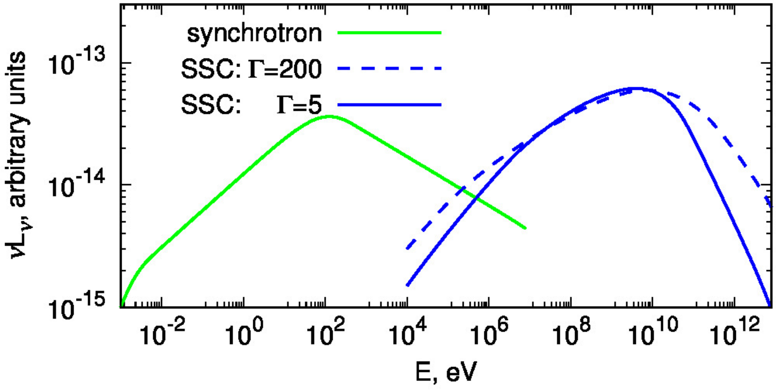
These effects are important if

$$1 < \frac{\hbar\omega_{\rm syn}E}{\Gamma^2 m_e^2 c^4} \approx \frac{4\times10^3}{\Gamma^2}\omega_{\rm syn,keV}E_{\rm TeV}$$

Internal $\gamma-\gamma$ optical depth

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

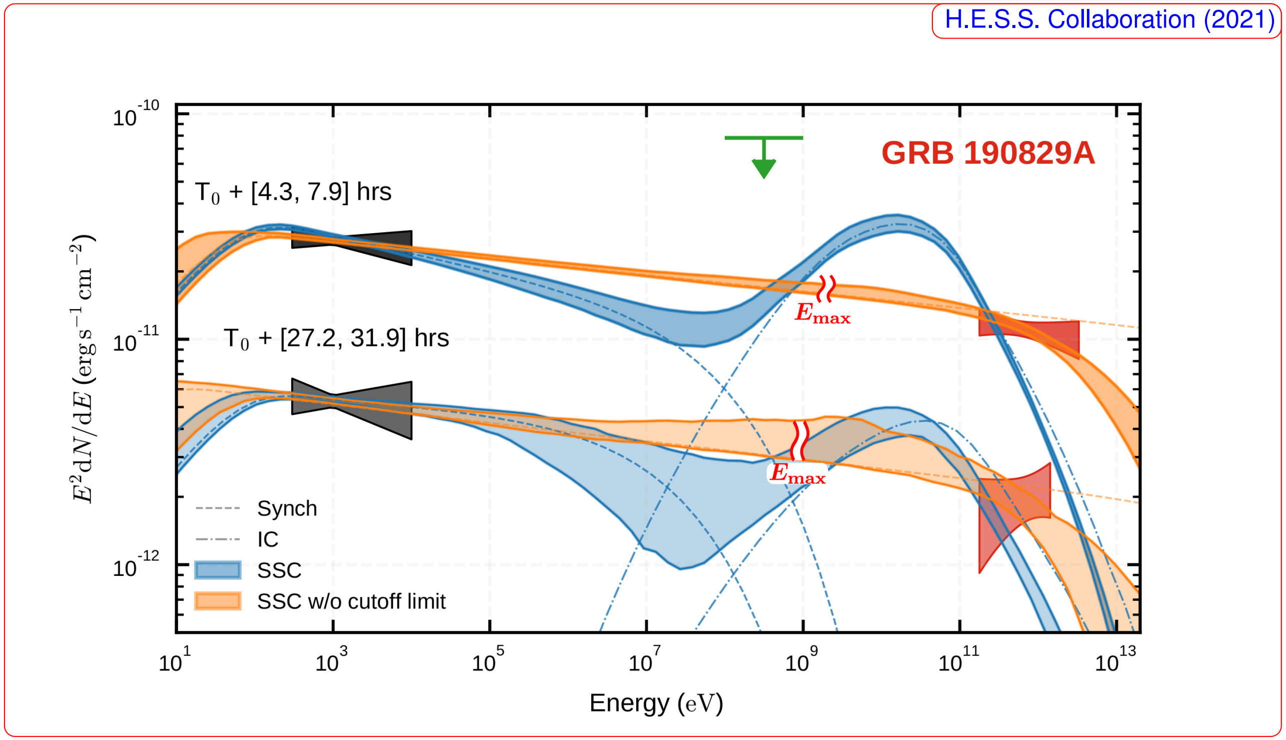




GRB 190829A: MWL modelling

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

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



Electron spectrum

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

$E_{\rm cut} < E_{\rm syn}^{\rm MAX}$

$E_{\rm cut} > E_{\rm syn}^{\rm MAX}$

H.E.S.S.

GRB 190829A: Result implications

Can we exclude SSC scenario?

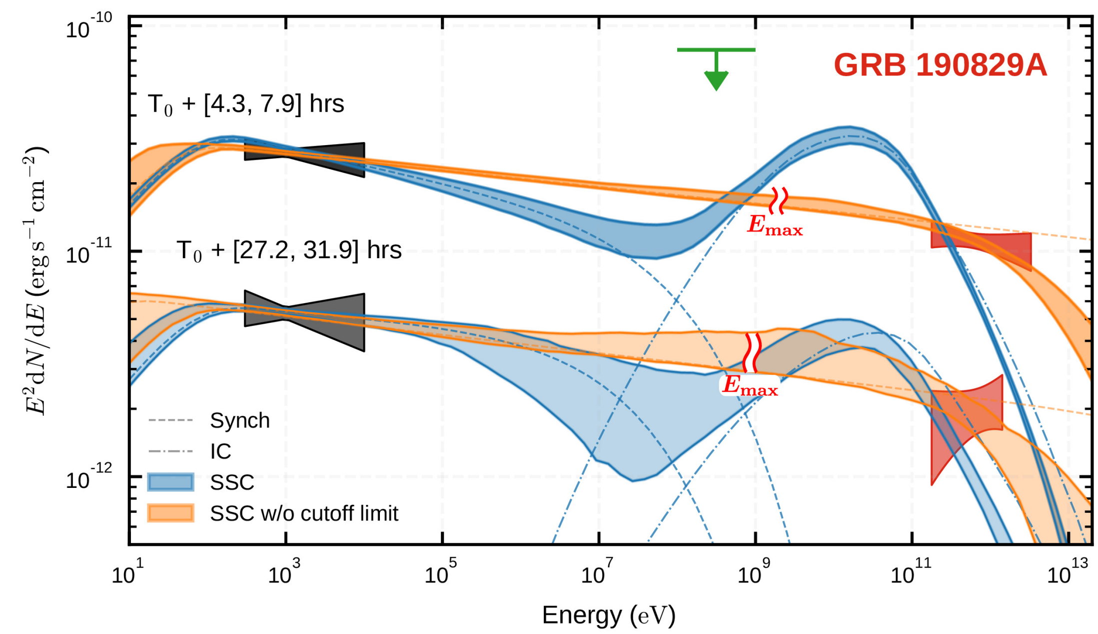
Our numerical analysis is limited to a

- 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)

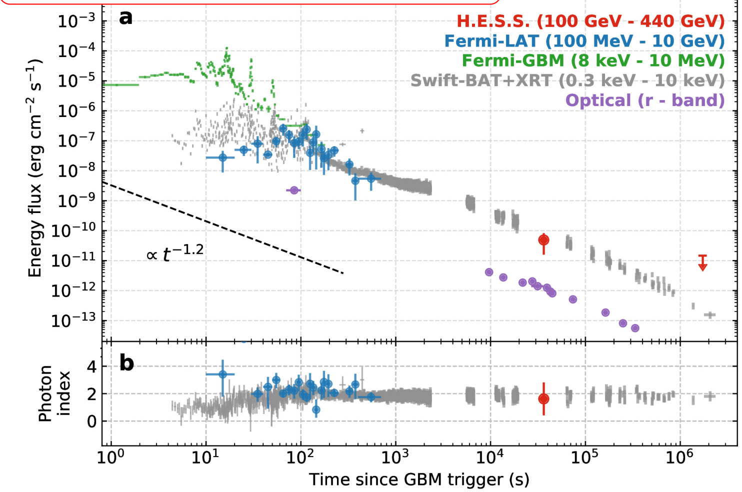


Under our assumptions we obtained that

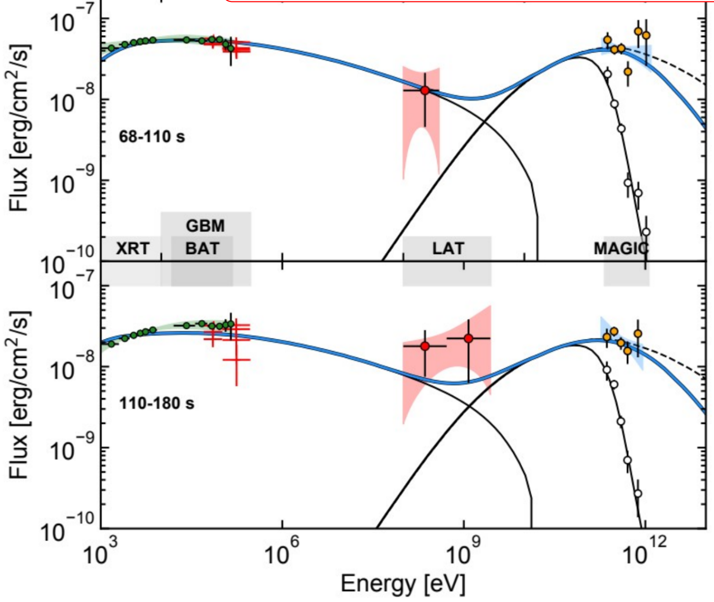
- SSC can be responsible only under extreme assumptions for the magnetic field strength (e.g., very weak) and low radiation efficiency
- Alternatively we can fit the data if adopt a much larger bulk Lorentz factor

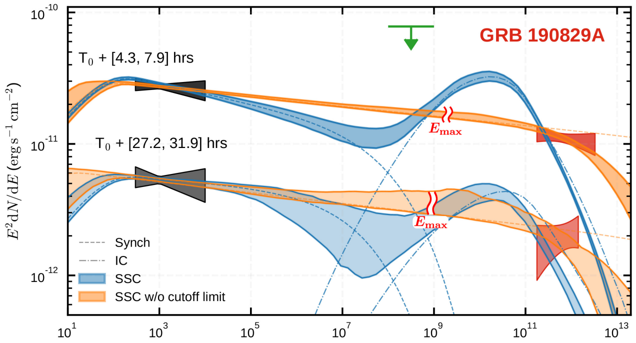
Three GRBs detected in VHE regime

GRB180720B (HESS Collaboraiton 2019)



GRB190114C (MAGIC Collaboraiton 2019)



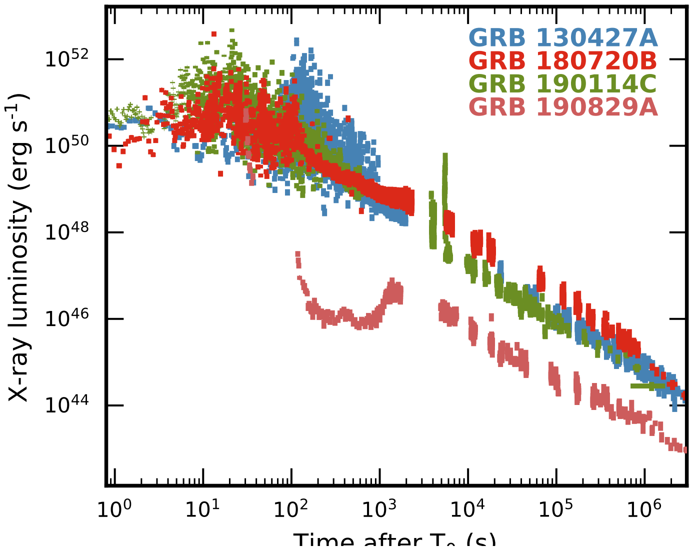


GRB190829A (HESS Collaboraiton 2021)

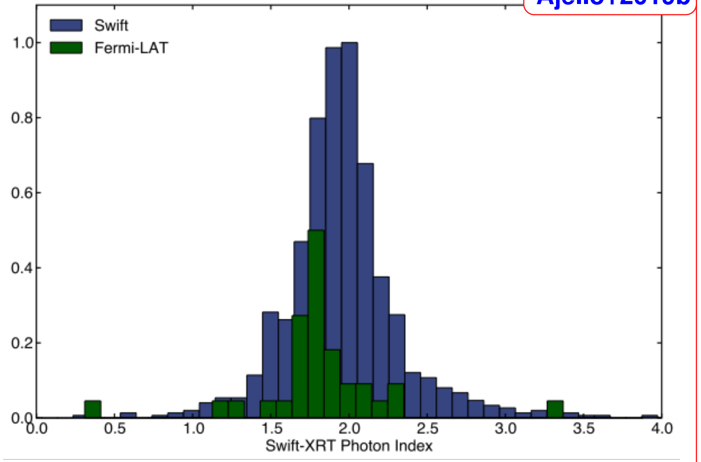
- In all three cases the VHE emission appears right at the extrapolation of the X-ray spectrum.
- H.E.S.S. observation do not show any curvature of the intrinsic spectrum, which seems to be an almost unavoidable feature of the IC emission in the Klein-Nishina regime

GRB 190829A in the context of other GRBs

Hinton (Taup2019)

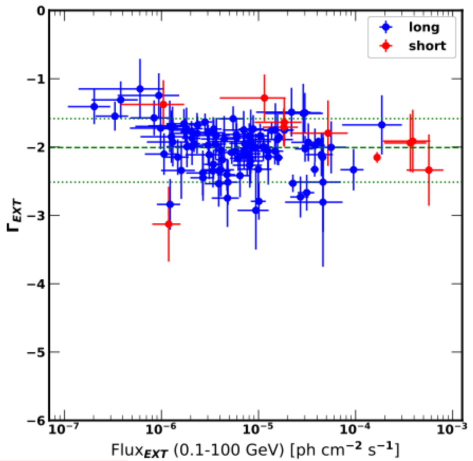


Ajello+2019b



GRB 190829A seems to be quite typical

- The X-ray photon index of $\gamma_{\rm XRT} = \mathbf{2.03 \pm 0.06}$
- VHE intrinsic photon index of $\gamma^{\rm int}_{\rm VHE} = \mathbf{2.07 \pm 0.09}$ agrees with Fermi/LAT typical photon index



Ajello+2019a

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 $\hbar\omega_{\rm MAX} = \mathbf{20(\Gamma/100)}\,\mathrm{GeV}$, 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** h after the trigger
  - A very broad spectral measurement: between **0.18** and **3.3** TeV
- The fortunate proximity of the source, $z_{\mathrm{rs}} = \mathbf{0.08}$, 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 (like require a multi-zone set up)
  - Reconsider relativistic shock (e.g., Derishev&Piran 2016)

H.E.S.S.

Thanks for your attention!