Highlights of the H.E.S.S. Experiment

H.E.S.S.

D. Khangulyan for H.E.S.S. Collaboration

2021 TeV Particle Astrophysics Conference

TIANFU Cosmic Ray Research Center

26th October 2021

- The H.E.S.S. telescopes are located in the Khomas Highland of Namibia ($23^\circ 16' 18'' S$, $16^\circ 30' 00'' E$) at $1,800\,\mathrm{m}$ asl
- H.E.S.S. phase I: four 12m air Cherenkov telescopes; FoV 5°; first light 2002
- H.E.S.S. phase II: 28m telescope; FoV 3.5°; first light 2012
- Observations: $\sim 10^3$hr/yr; stereoscopic reconstruction; angular resolution $\approx 10'$; energy threshold $30\,\mathrm{GeV}$
- Camera upgrade in 2015-2016 (H.E.S.S. I) and in 2020-2021 (H.E.S.S. II)

H.E.S.S. contributions at TeVPA 2021

- "Search for dark matter in the Galactic Centre region with the H.E.S.S. Inner Galaxy Survey " by Alessandro MONTANARI (Session 1 on October 26^{th})
- "H.E.S.S. observations of galactic molecular clouds" by Atreyee SINHA (Session 2 on October 26^{th})
- **"Highlights of the H.E.S.S. Experiment" (limited to extragalactic sources, this talk)**
- "Search for long term variability of HESS J1745-290 at the centre of the Galaxy" by Samuel ZOUARI (Session 1 on October 28^{th})

Overview

Resolving VHE jets of Centaurus A

Detection of GRBs in the VHE regime

Observation of GRB 180720B with H.E.S.S.

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

Summary

H.E.S.S.

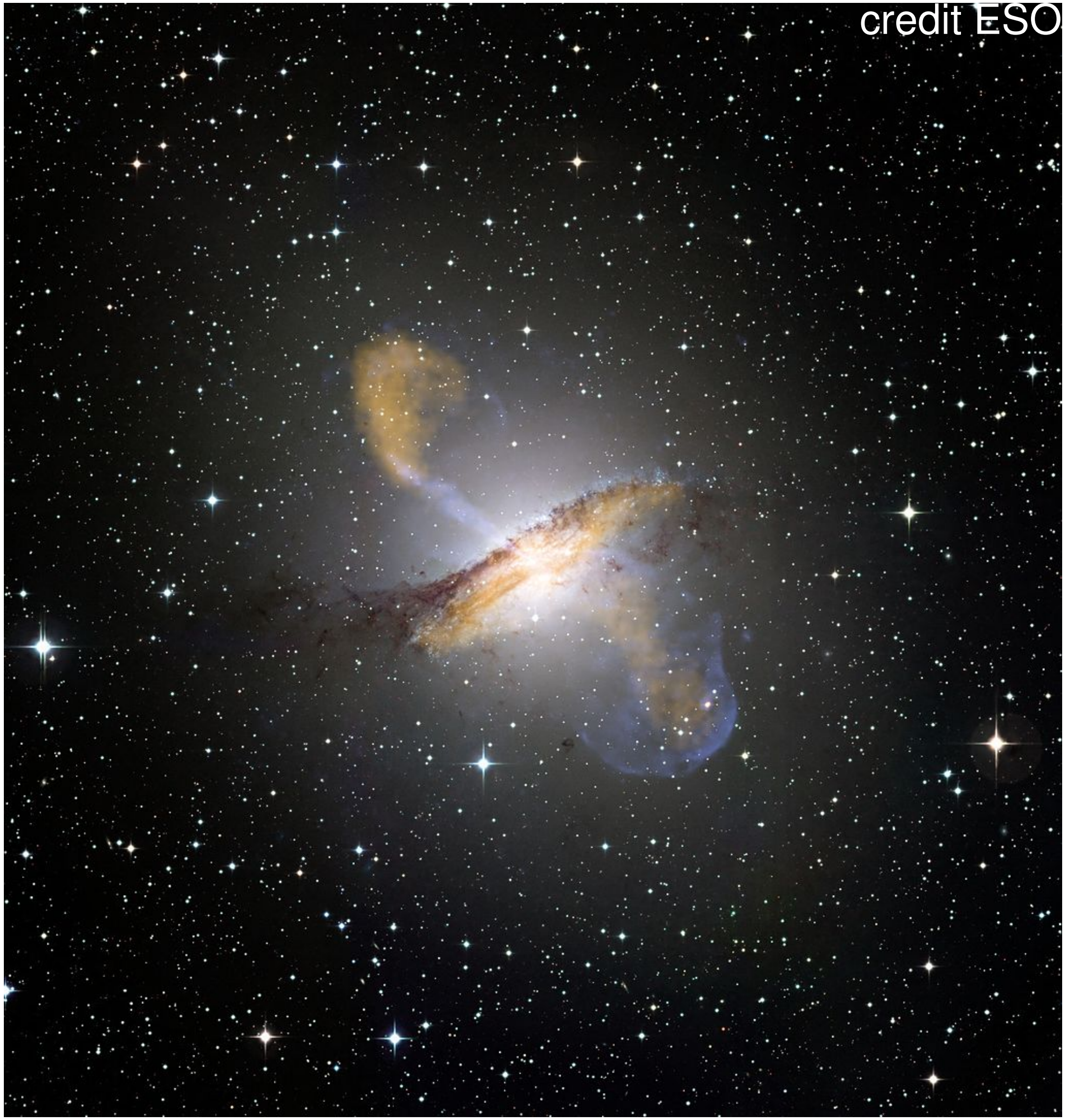
Resolving VHE jets of Centaurus A

Centaurus A

The most nearby radio galaxy seen from the southern hemisphere

- Distance: $\approx 4\,\mathrm{Mpc}$
- SMBH mass: $\approx 6 \times 10^7 M_\odot$
- Jet scale: from kpc (X-ray) to Mpc (radio)

- X-ray emission from large-scale jet might be of either synchrotron or IC origin
- Synchrotron mechanism implies presence of TeV electrons and efficient in-situ acceleration of VHE particles and **IC TeV emission**
- Even at the Centaurus A distance, $1\,\mathrm{kpc}$ corresponds to sub-arcmin angular size, i.e., significantly smaller than PSF of VHE instruments



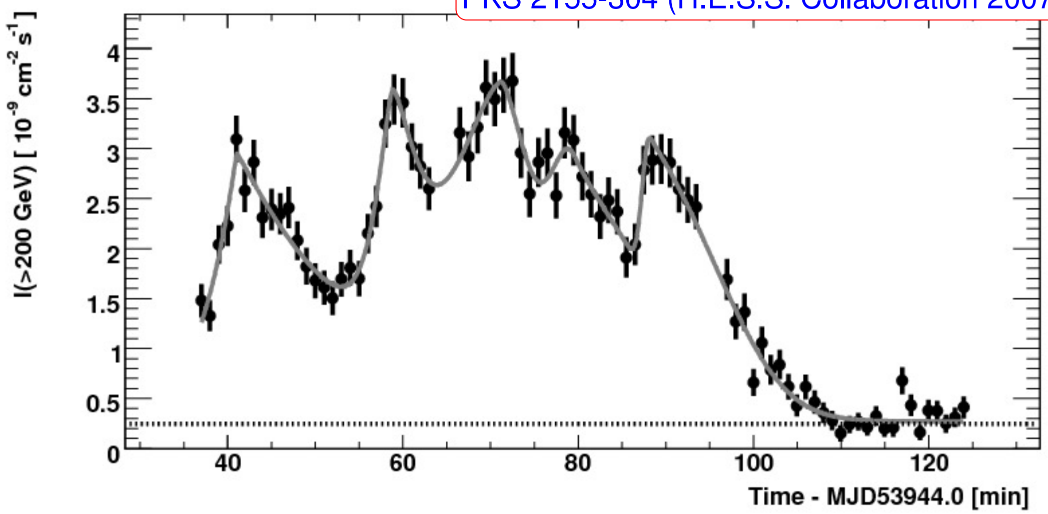
Study of extragalactic relativistic jets in the VHE regime

Lack of gamma-ray morphology implies significant uncertainties for "defining" the level of diffuse TeV emission. This limitation can be partially alleviated by

- time variability of VHE emission
- simultaneous multi-wave observations

Obviously, these approaches imply that the final conclusion is derived based on some *theoretical study* and/or *spectral modeling*. Therefore, a direct measurement of VHE morphology is an important observational challenge. This requires sub-PSF measurements, which can be done, if one knows the telescope well enough.

PKS 2155-304 (H.E.S.S. Collaboration 2007)



H.E.S.S. found variability times scale of ≈ **100** s, which appeared to be shorter than r_g/c. This triggered development of alternative scenarios for the VHE emission from AGN: SMBH magnetosphere (e.g., Levinoson&Rieger 2011), jet-in-jet (Giannios+2009), star-in-jet (e.g., Barkov+2012)

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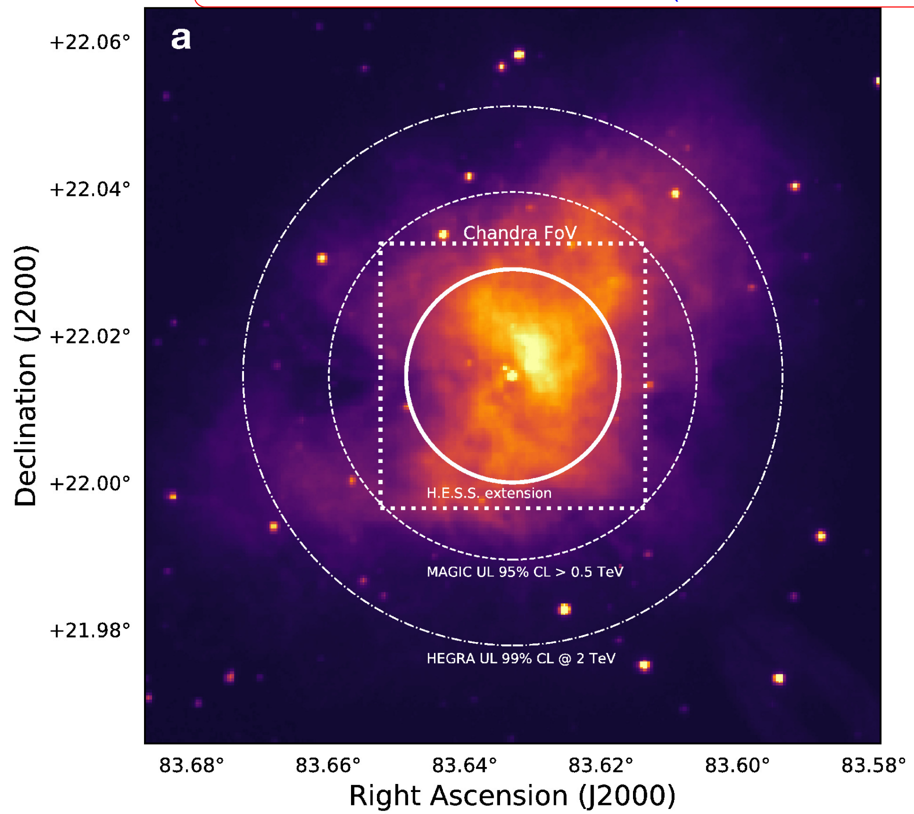
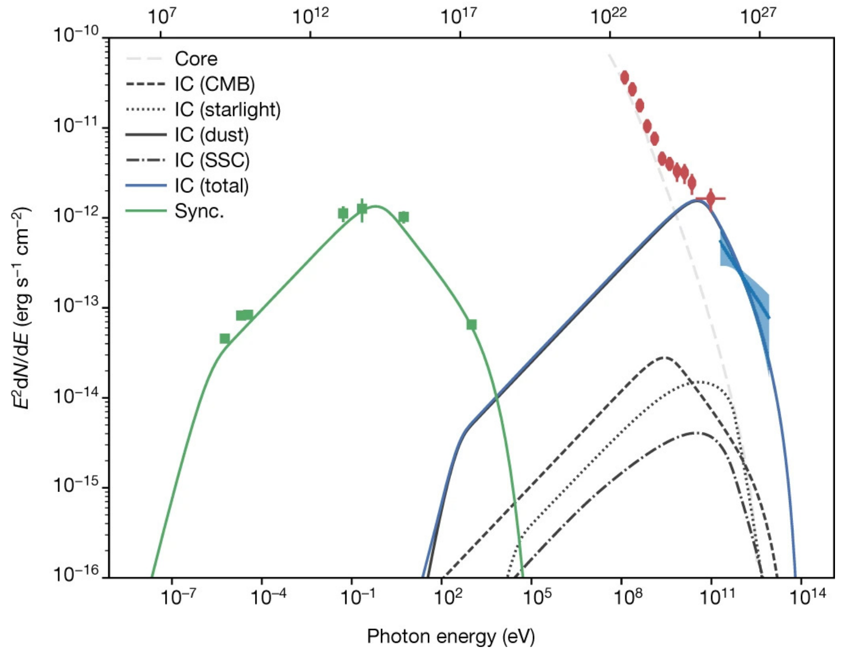
VHE extension of the Crab Nebula (H.E.S.S. Col. 2019



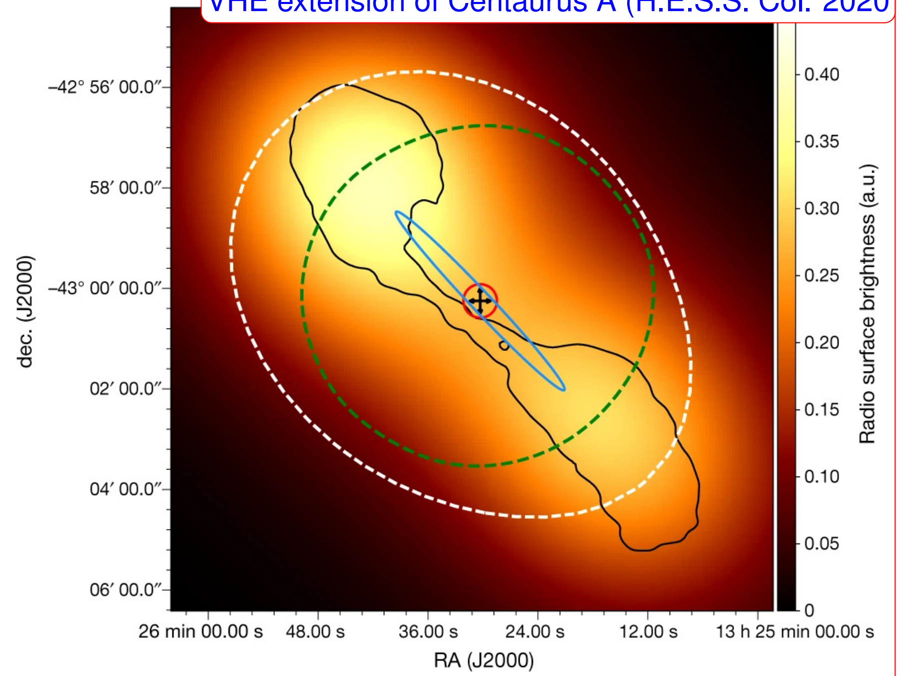
Crab Nebula is a pc-source at kpc-distance, and Centaurus A is a kpc-source at Mpc-distance.

Resolving VHE jet of Centaurus A with H.E.S.S.

SED of the jet of Centaurus A (H.E.S.S. Col. 2020



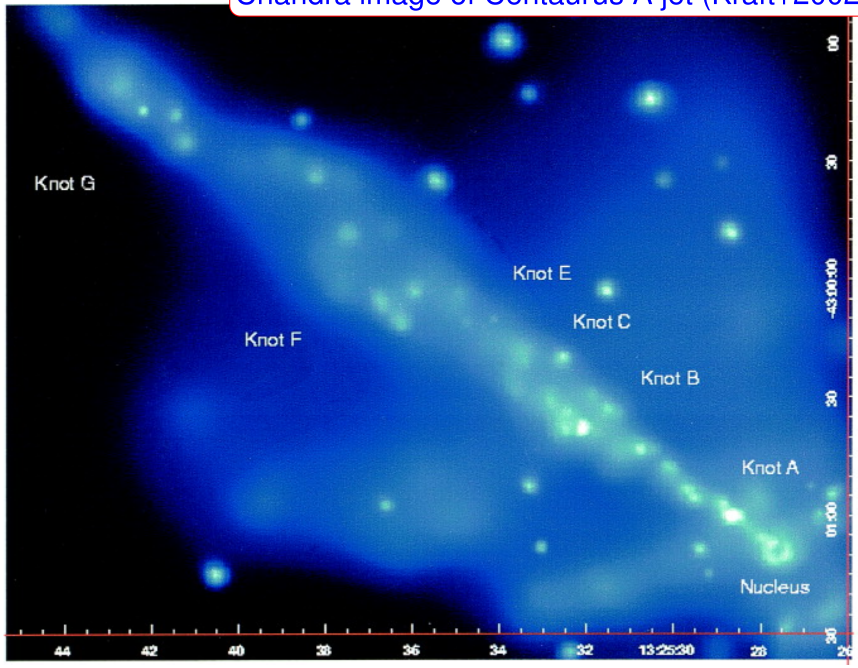
VHE extension of Centaurus A (H.E.S.S. Col. 2020



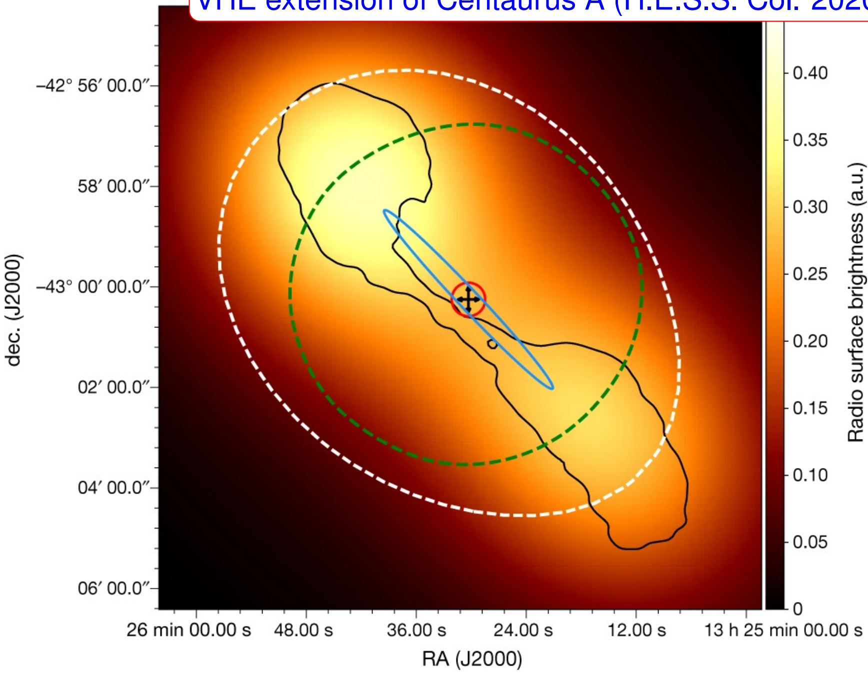
Morphology of the VHE emission from Centaurus A is consistent with the jet orientation seen in the radio/X-ray bands. Measured extension translates to projected length of $\sim 6\,\mathrm{kpc}$. This proves (re)acceleration of VHE electrons in the extended jet of Centaurus A. Only background photon fields can provide important target for IC, which allows constraining magnetic field strength, $B \approx 23\,\mu\mathrm{G}$.

Resolving VHE jet of Centaurus A with H.E.S.S.

Chandra image of Centaurus A jet (Kraft+2002)



VHE extension of Centaurus A (H.E.S.S. Col. 2020



If one considers the conditions required for the formation of the diffuse TeV/X-ray emission together with compact X-ray knots in the jet, it is possible to constrain the physical parameters further. In particular the jet of Centaurus A has to be weakly magnetized and the emission in the knots is generated in the slow cooling regime. High-energy particles escaping the jet carry sufficient energy to power the diffuse emission (Sudoh+2020)

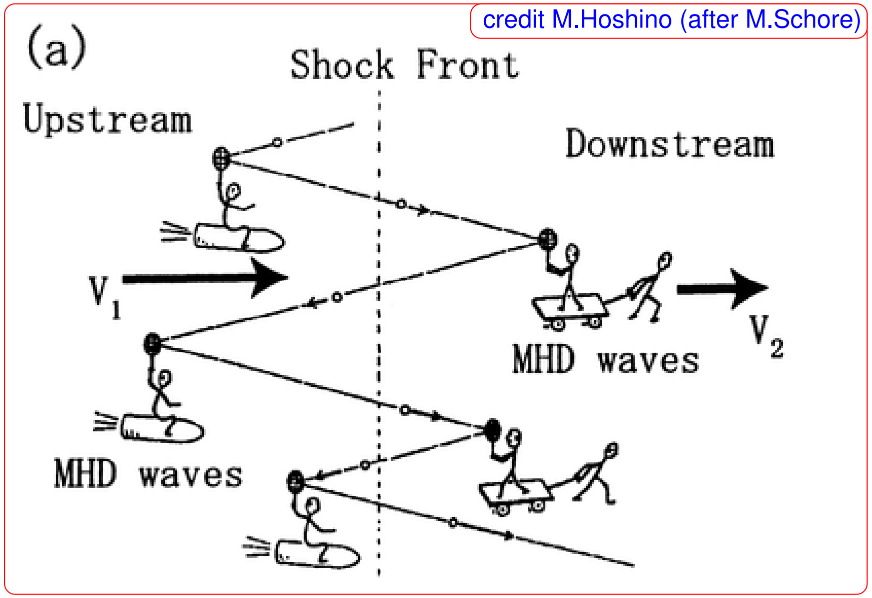
Detection of GRBs in the VHE regime

H.E.S.S.

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)



Synchrotron burn-off limit

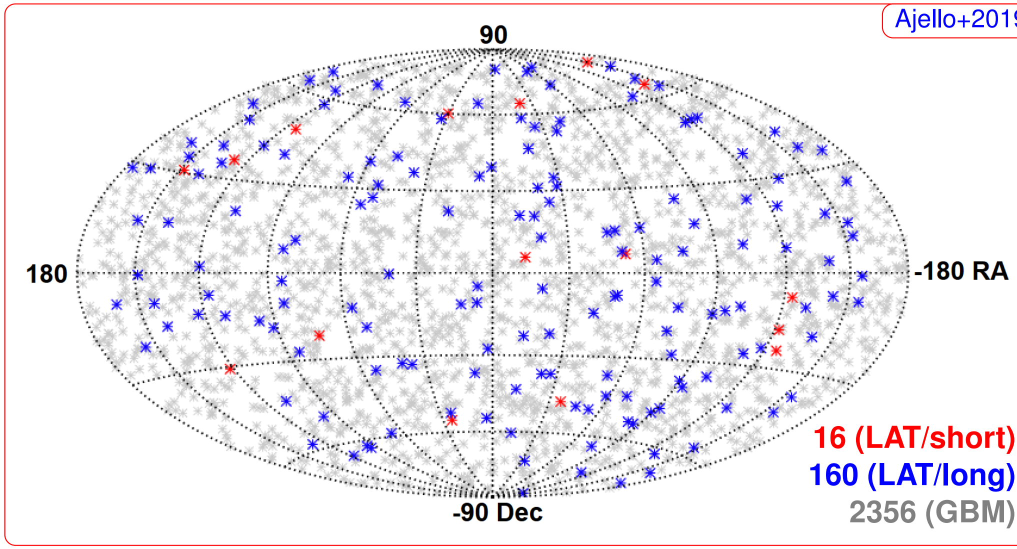
- Synchrotron cooling time: $t_{\rm SYN} \approx 400 E_{\rm TeV}^{-1} B_{\rm B}^{-2}\,{\rm s}$
- Acceleration time: $t_{\rm ACC} \approx 0.1 \eta E_{\rm TeV} B_{\rm B}^{-1}$
- Max energy: $\hbar\omega < 200\frac{\Gamma}{\eta}\,{\rm MeV}$

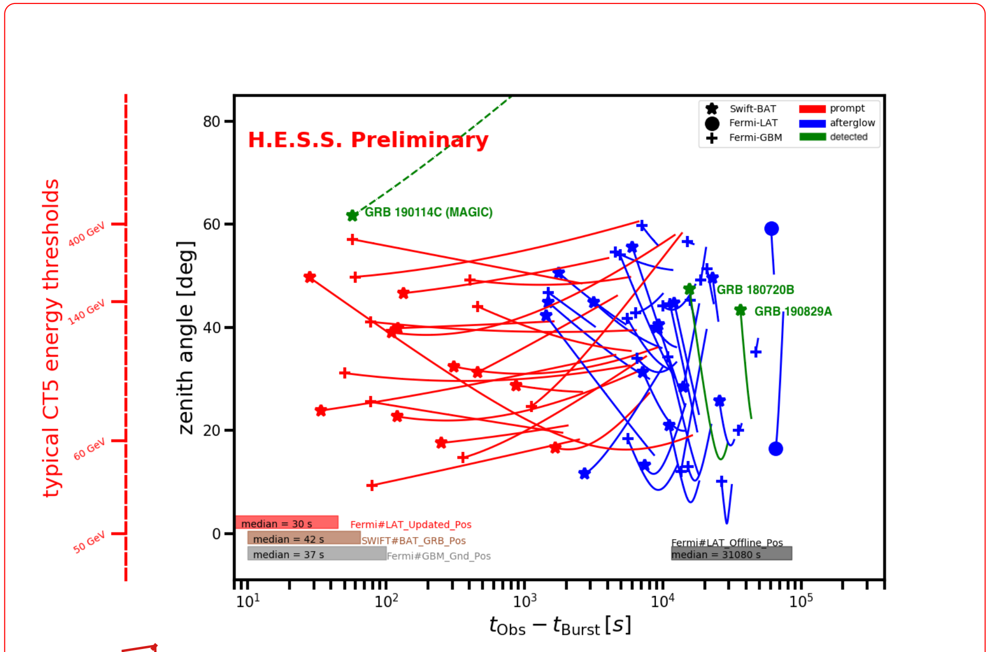
(Guilbert+1983)

Hunt for GRBs

Why do we expect to see GRBs@VHE?

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





Observation difficulties

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

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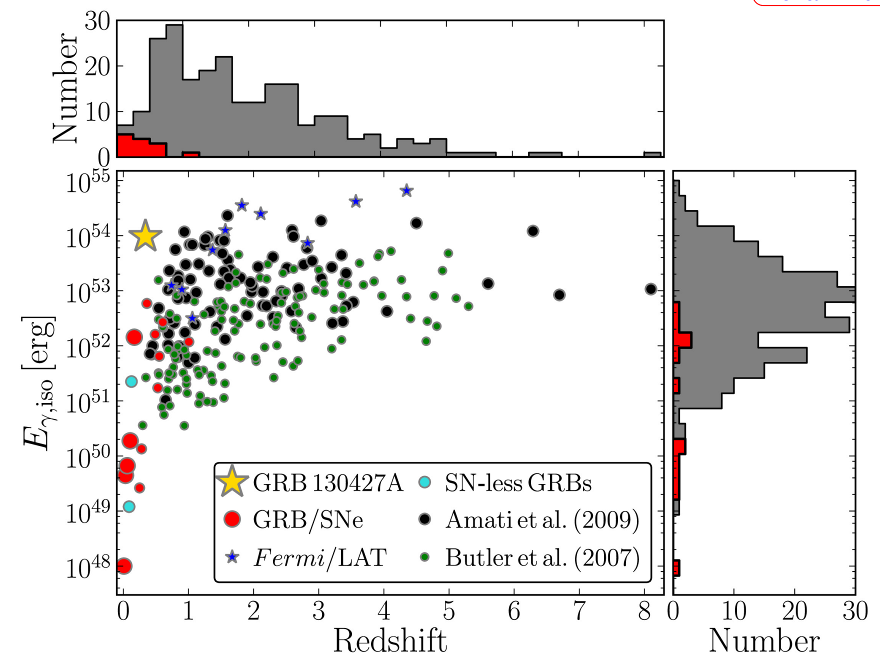
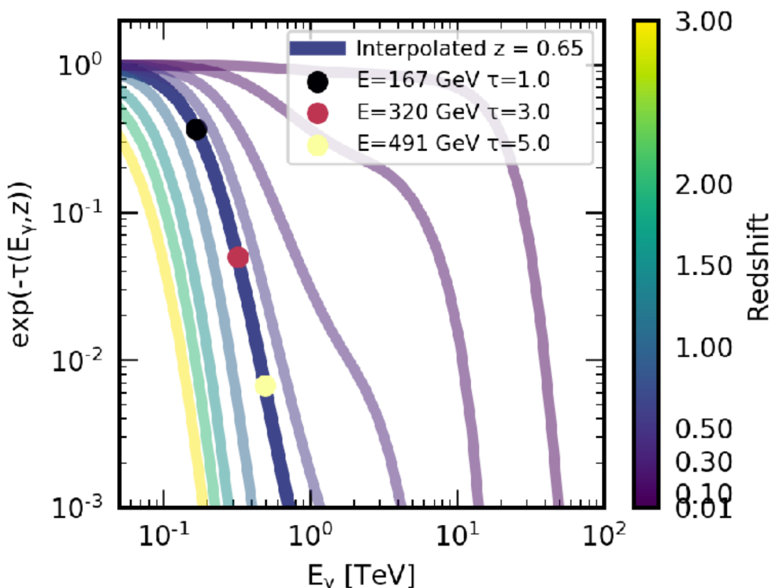
EBL attenuation

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





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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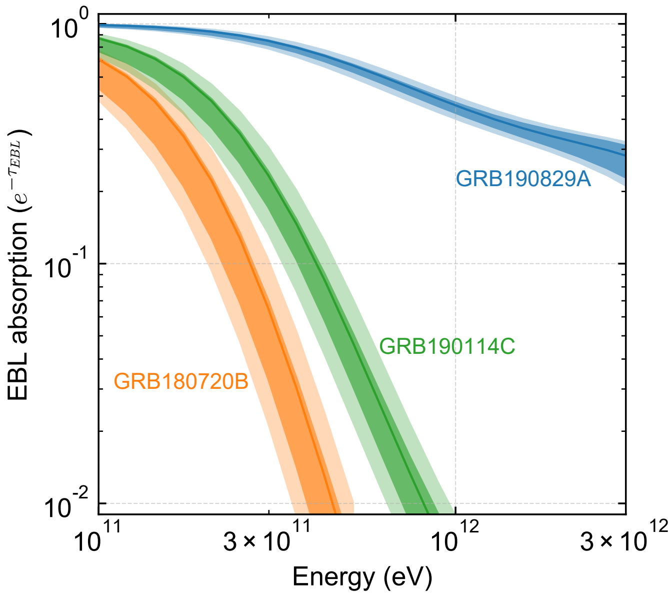

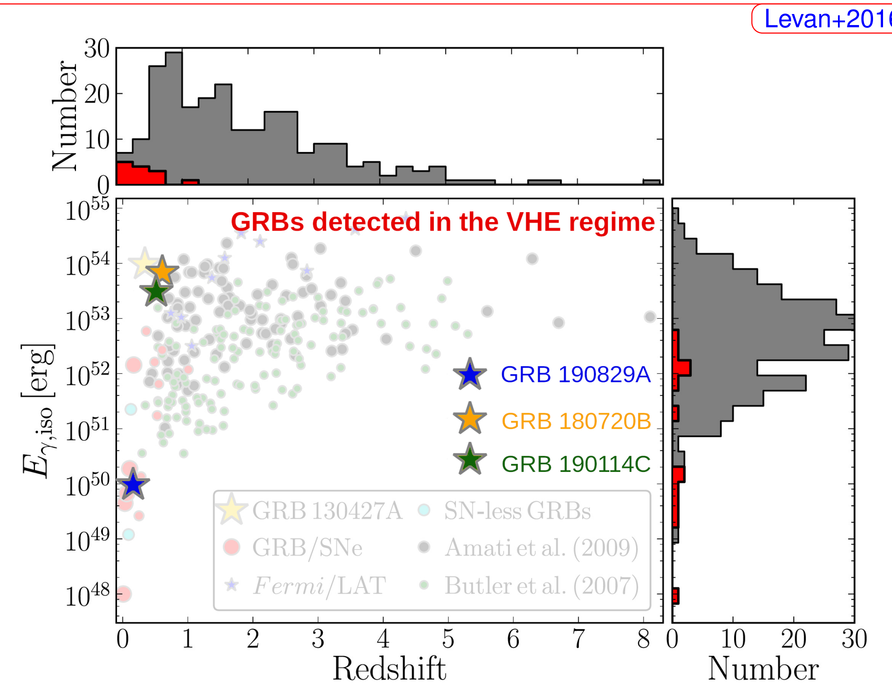

GRBs detected in the VHE regime:

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

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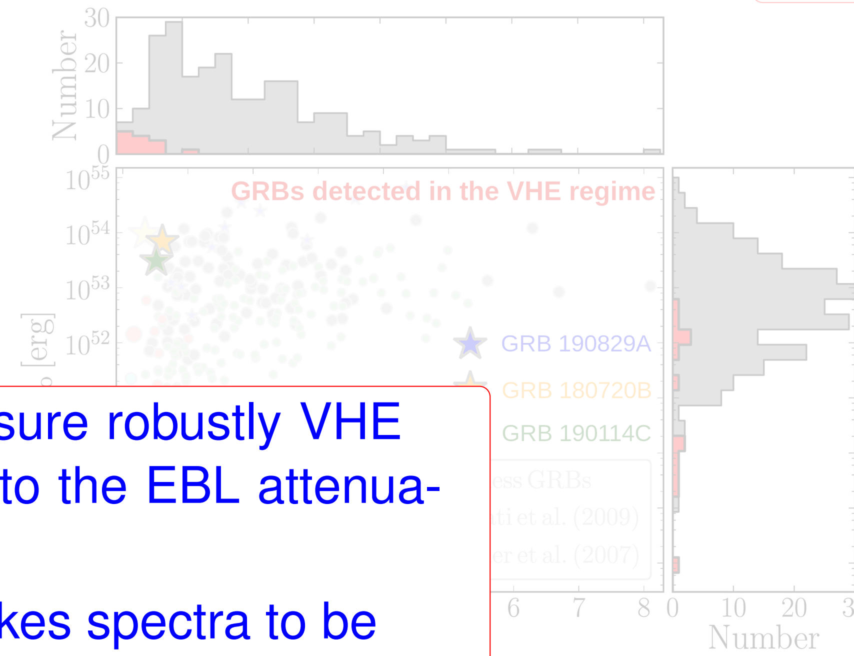
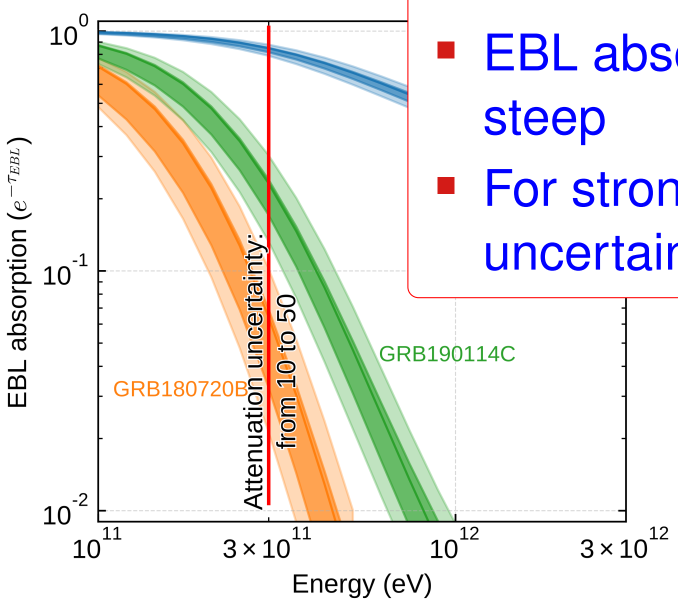


It is very hard to measure robustly VHE spectra of GRBs due to the EBL attenuation:

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



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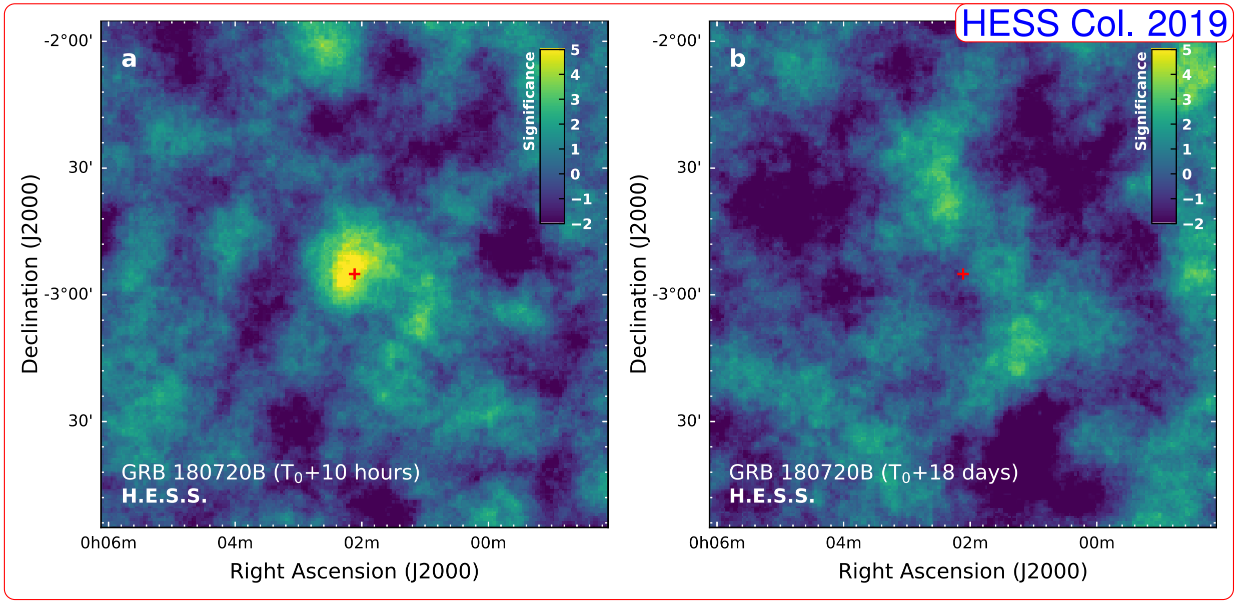
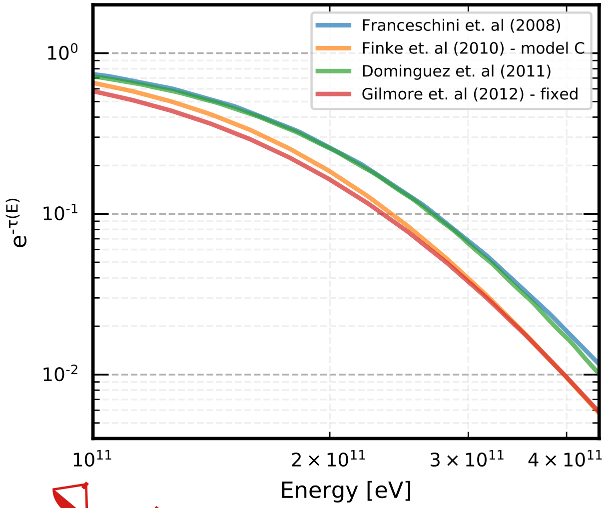
Observation of GRB 180720B with H.E.S.S.

GRB180720B

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

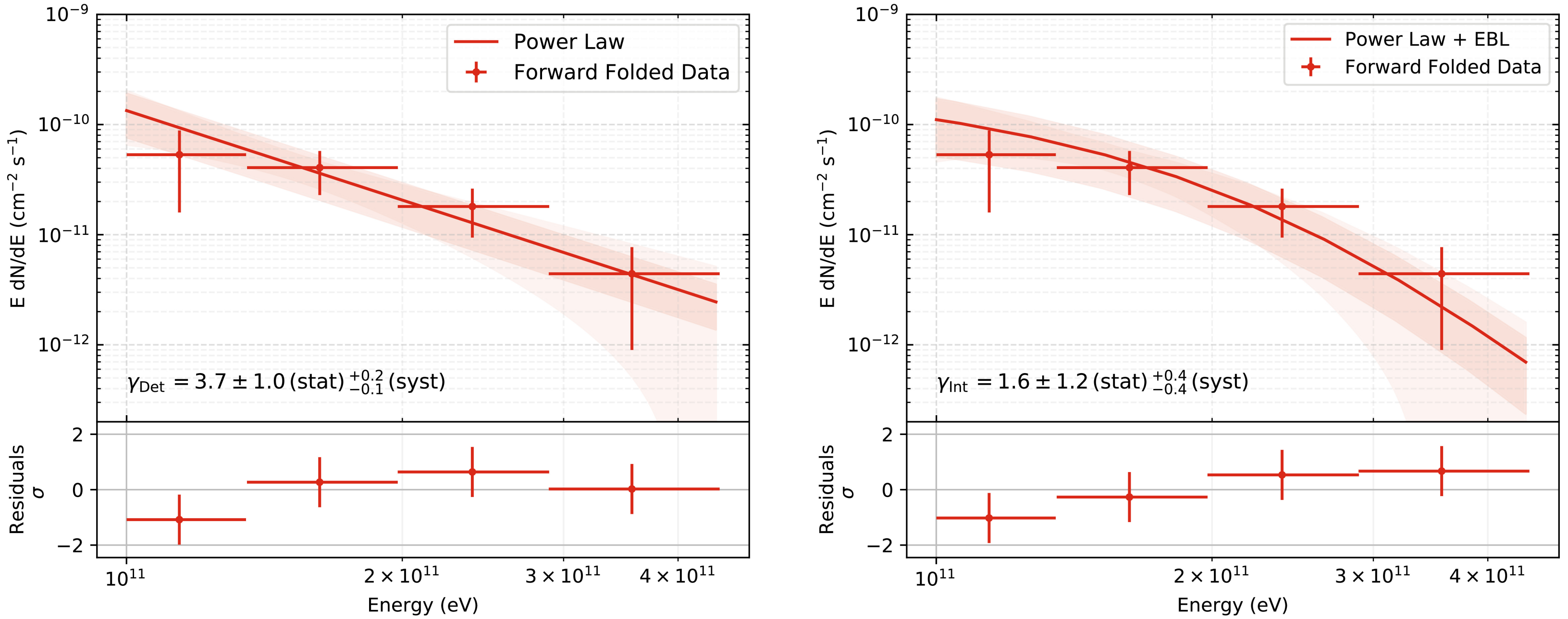




- The first GRB detected in the VHE regime (second reported – tough internal cross checks, relatively weak signal)
- Quite late observing opportunity, but it was a very bright GRB
- EBL absorption is very significant at **300** GeV

GRB180720B

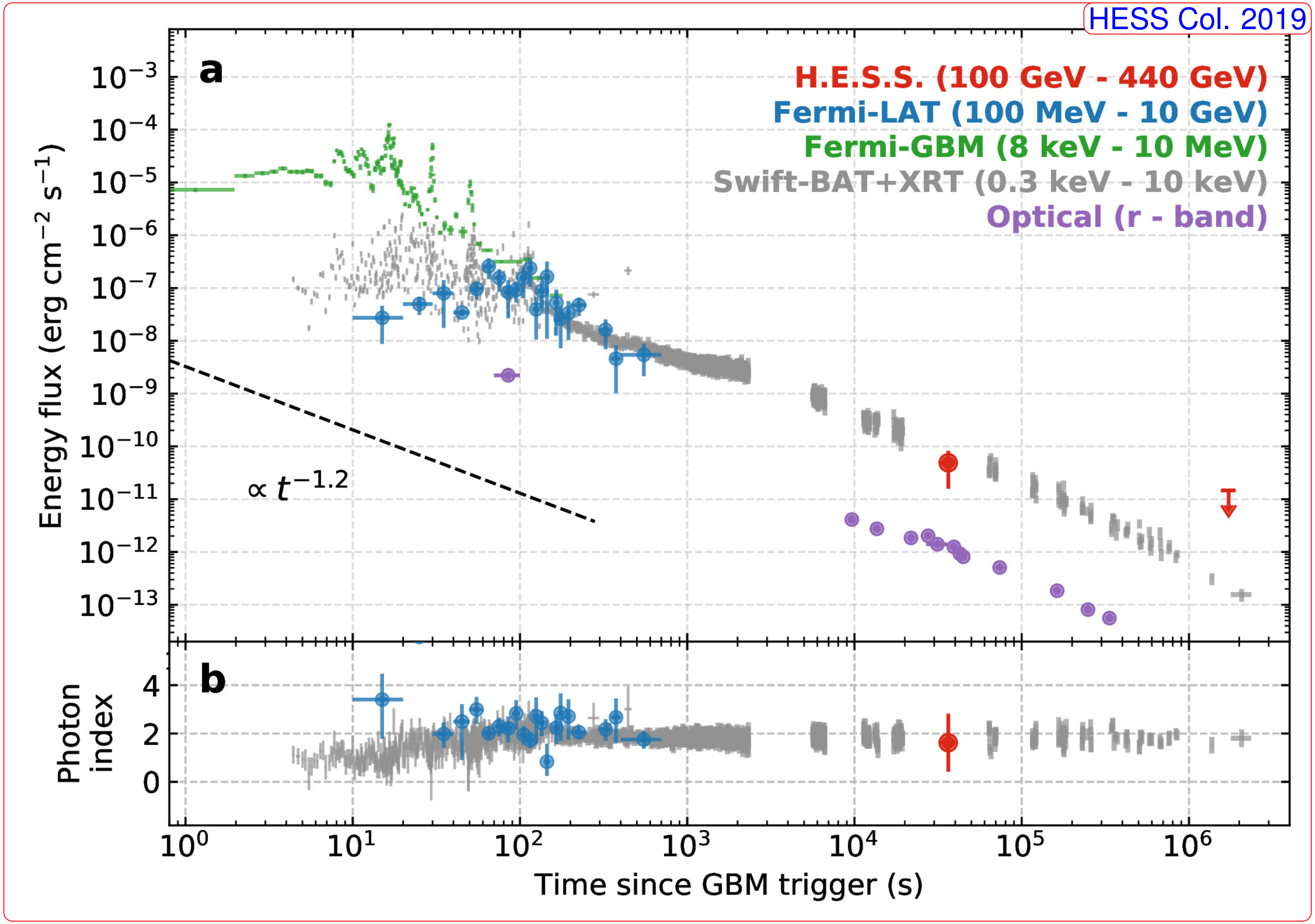
HESS Col. 2019



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

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

GRB180720B

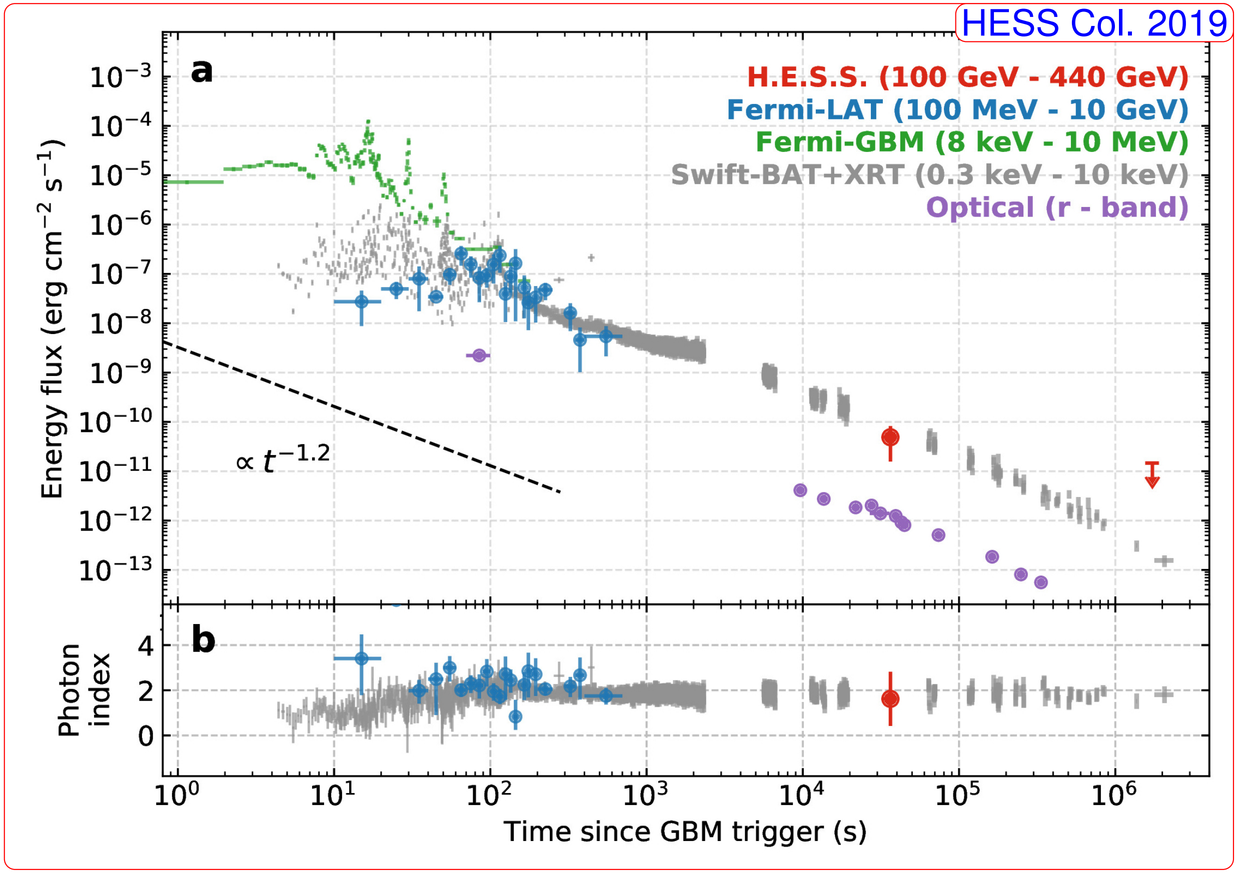


HESS Col. 2019
a
b
H.E.S.S. (100 GeV - 440 GeV)
Fermi-LAT (100 MeV - 10 GeV)
Fermi-GBM (8 keV - 10 MeV)
Swift-BAT+XRT (0.3 keV - 10 keV)
Optical (r - band)
$\propto t^{-1.2}$
Energy flux (erg cm^{-2} s^{-1})
Photon index
Time since GBM trigger (s)

GRB180720B

- Optical, X-ray, HE components decay by the same law
- X-ray, HE, and VHE components have similar photon indexes
- X-ray, HE, and VHE components have the same flux level

☞ Straight line is a good fit



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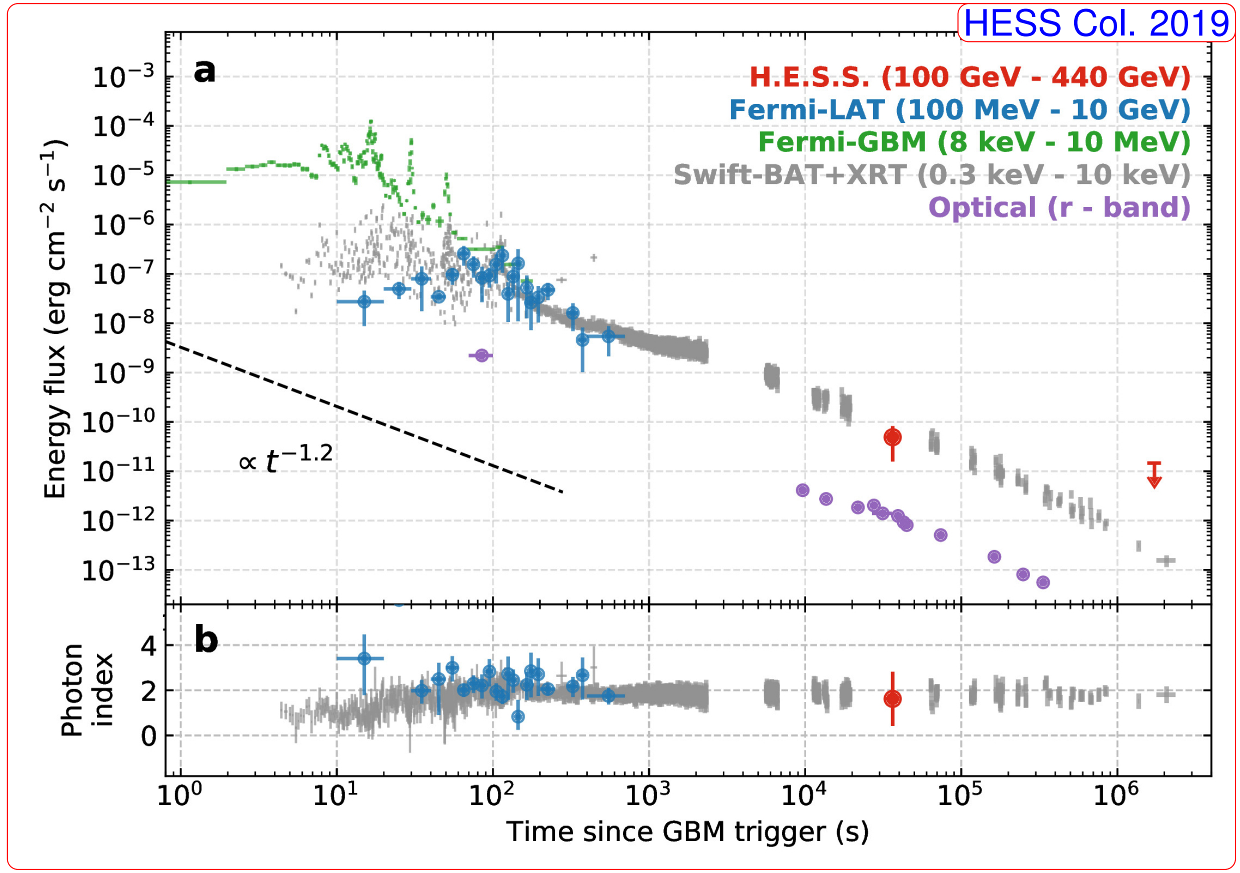


What do we see?

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

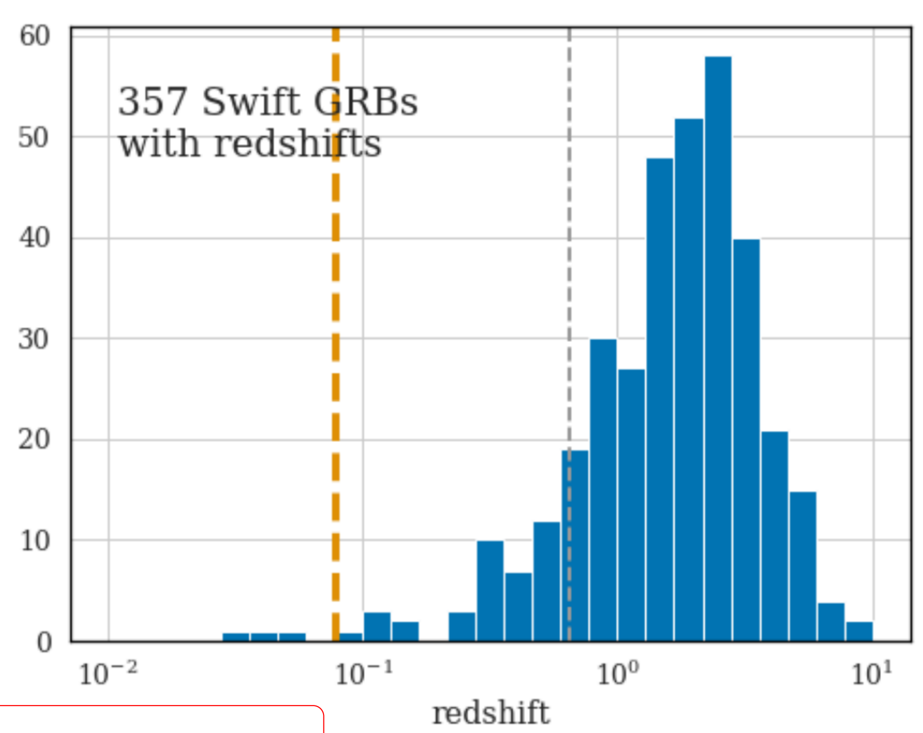
✘ We do not see a TeV component emerging above the emission in the Fermi/LAT band

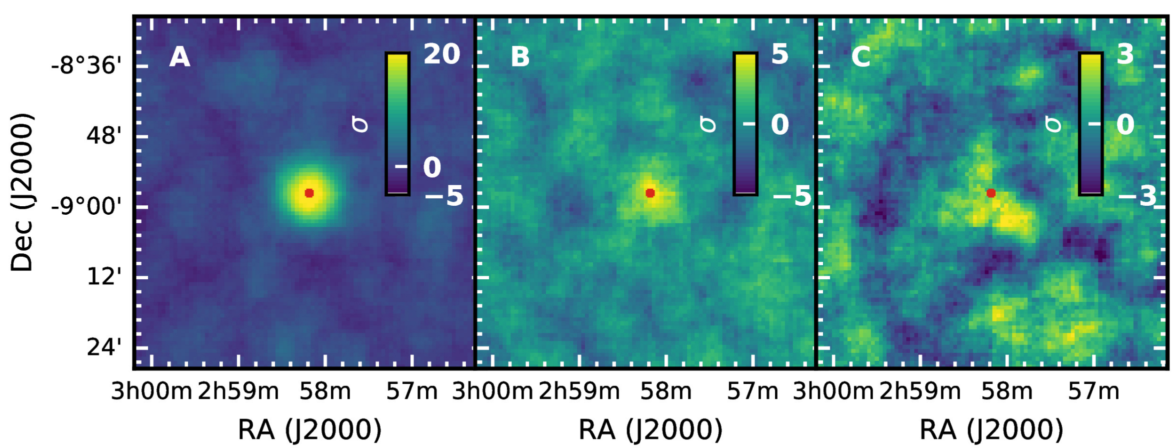
Observation of GRB 190829A with H.E.S.S.

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)**

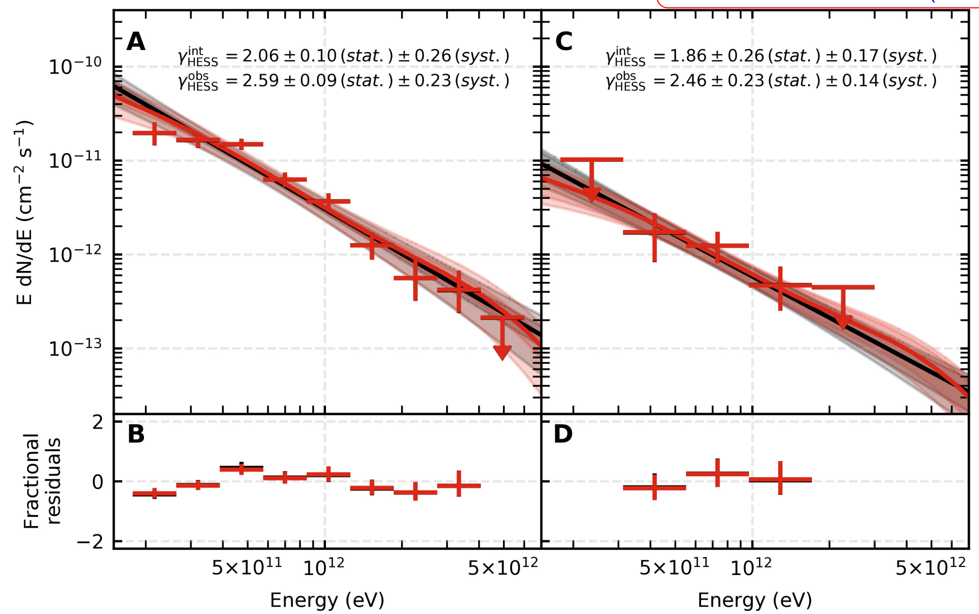
H.E.S.S. detection

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

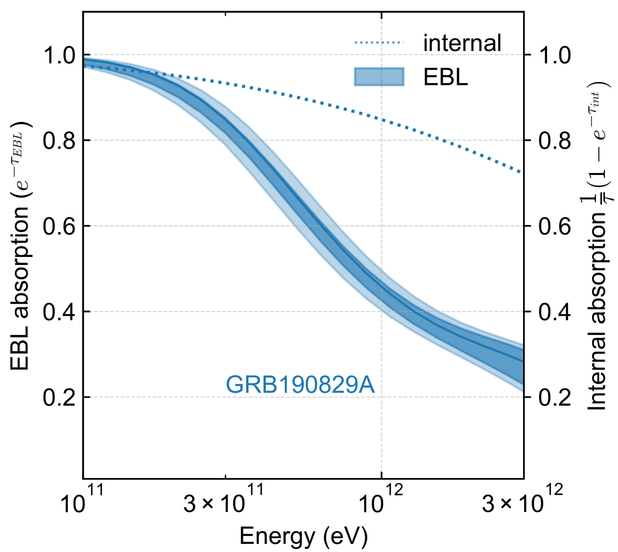
GRB 190829A: VHE spectrum

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

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



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: $\gamma^{\rm obs}_{\rm VHE} = 2.46 \pm 0.23$

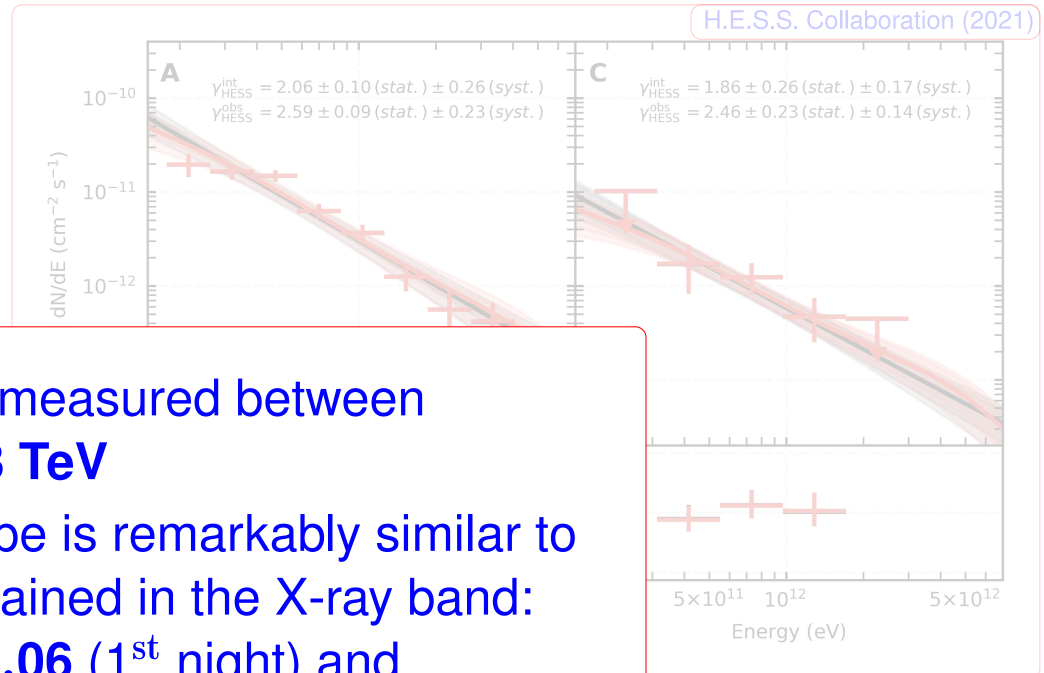
Intrinsic spectrum

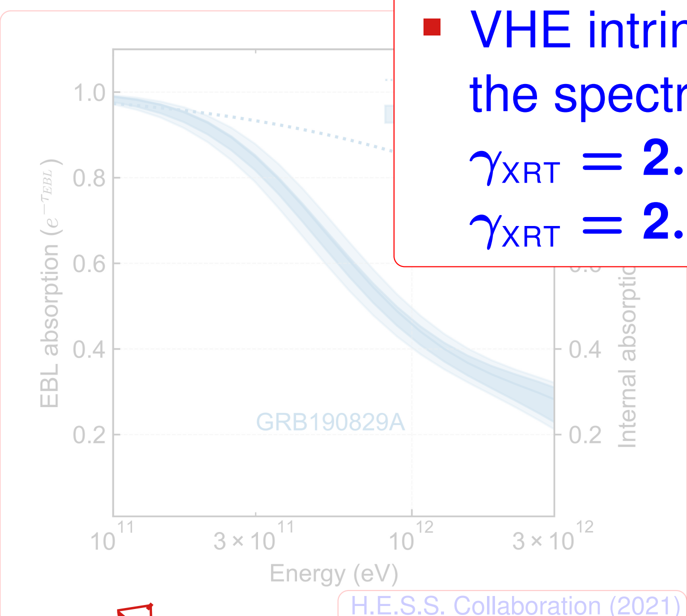
- night 1: $\gamma^{\rm int}_{\rm VHE} = 2.06 \pm 0.1$
- night 2: $\gamma^{\rm int}_{\rm VHE} = 1.86 \pm 0.26$
- all: $\gamma^{\rm int}_{\rm VHE} = 2.07 \pm 0.09$

GRB 190829A: VHE spectrum

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

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





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

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- all: $\gamma^{\rm int}_{\rm VHE} = 2.07 \pm 0.09$

GRB 190829A: light-curve

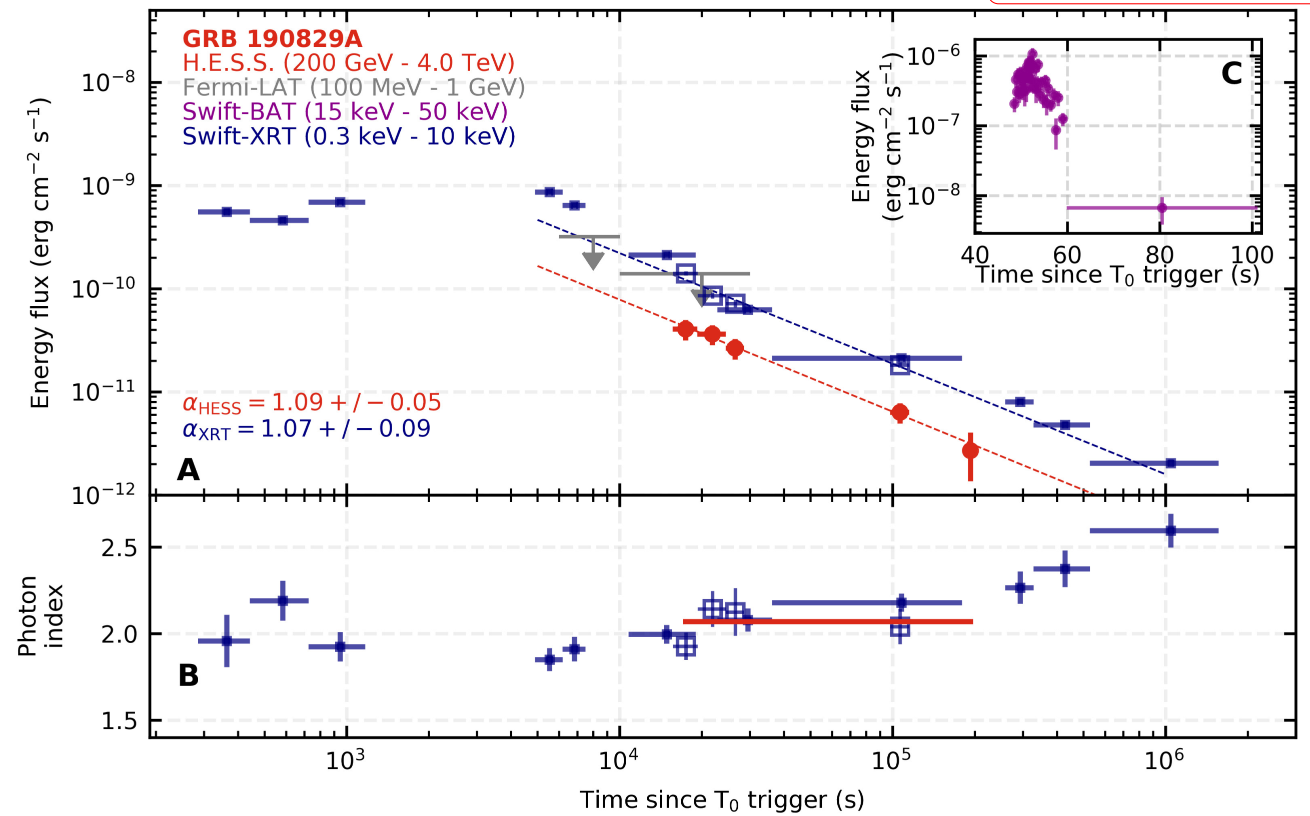
- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray light-curve
- Fit the flux with a power-law decay

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

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

- Remarkably consistent slopes

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



X-ray decay

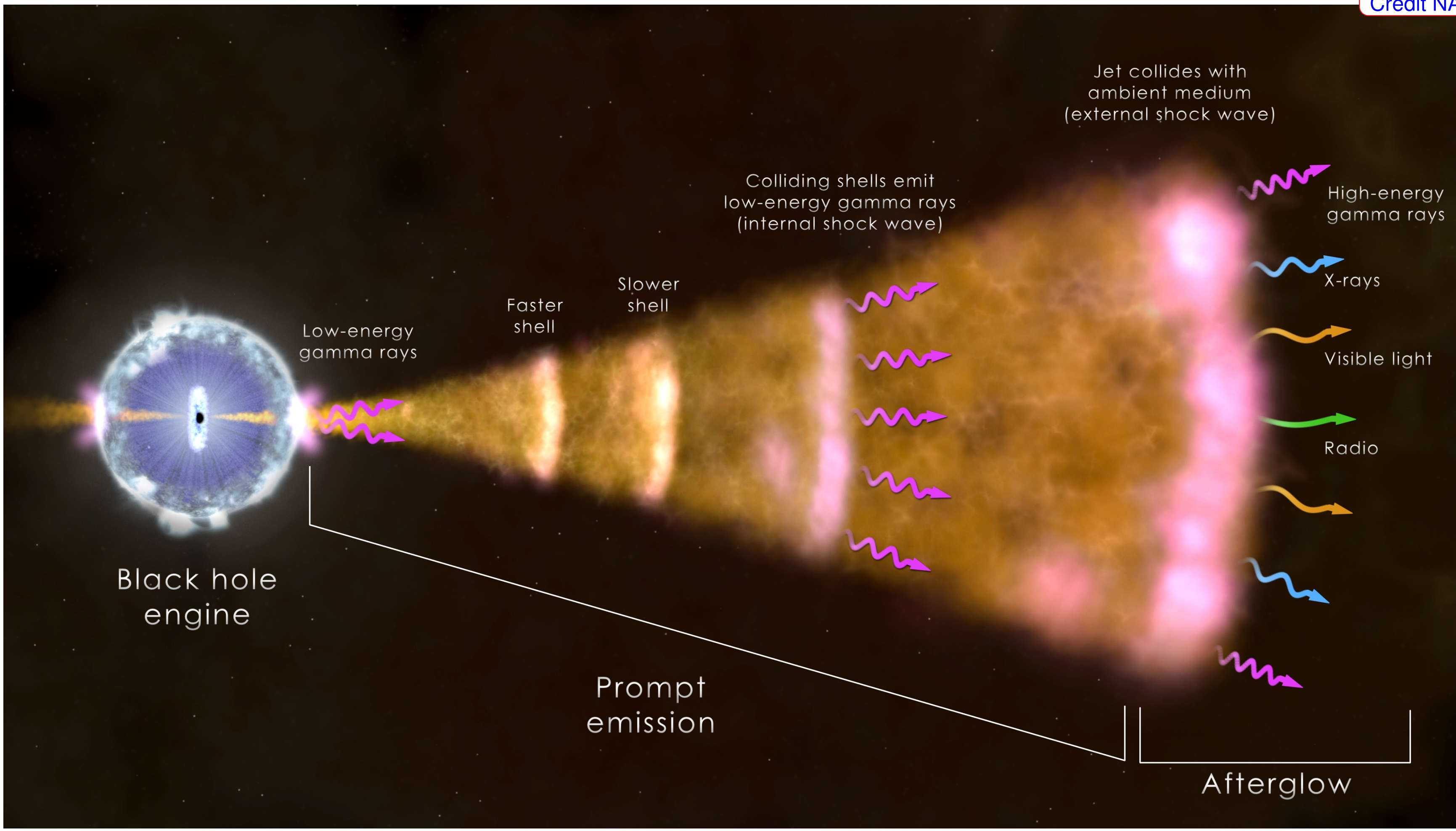
$\alpha_{\mathrm{XRT}} = \mathbf{1.07 \pm 0.09}$

H.E.S.S. decay

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

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^{2-3} s
- Afterglow: jet–circumburst medium interaction, start dominating after 10^3 s, last for weeks

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

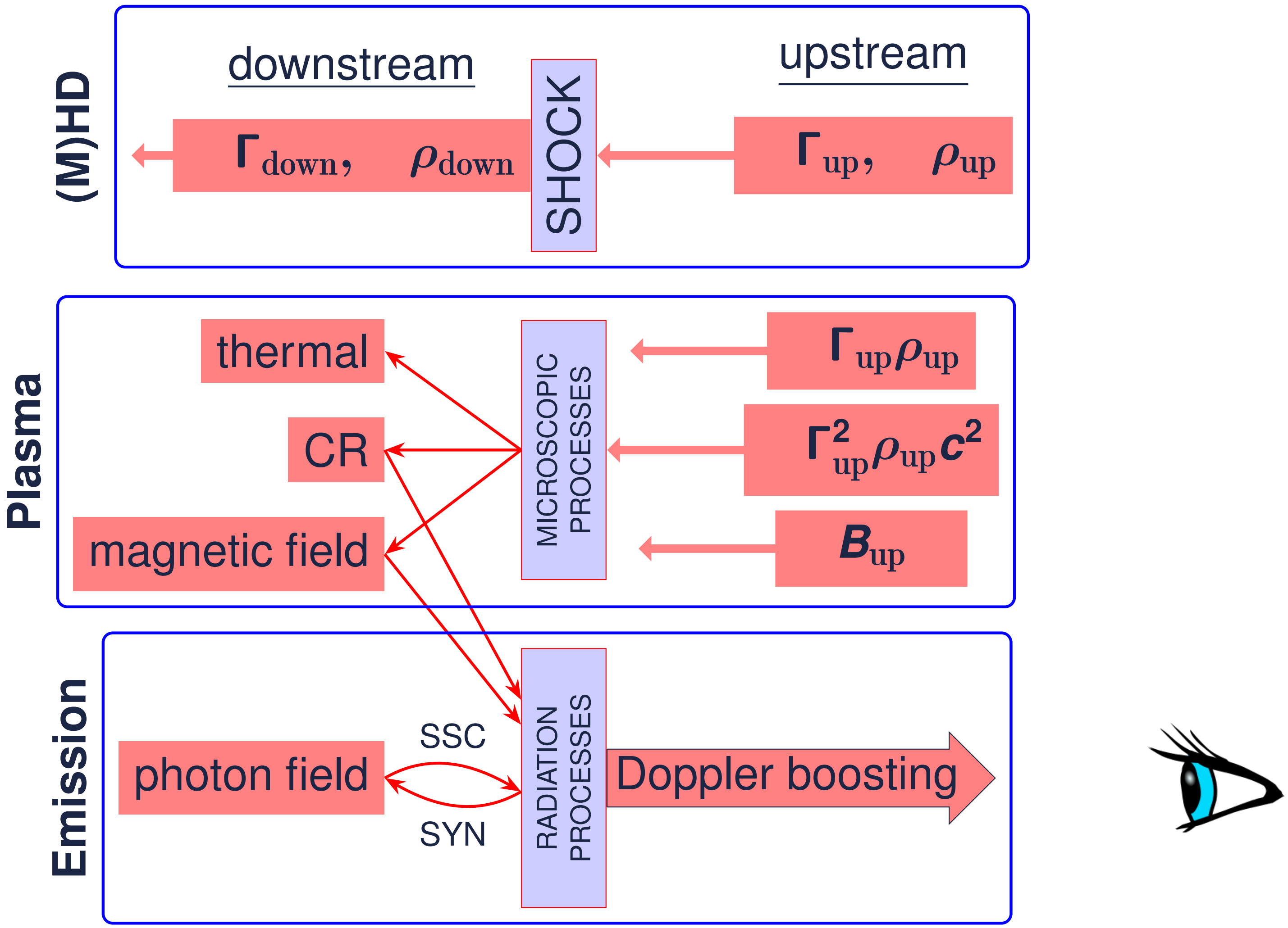
$$\varepsilon \propto \Gamma^2 \rho_0 \qquad \text{for } s = 0$$

This provides a robust basis for radiative models

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

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

Afterglow emission: simple radiative model

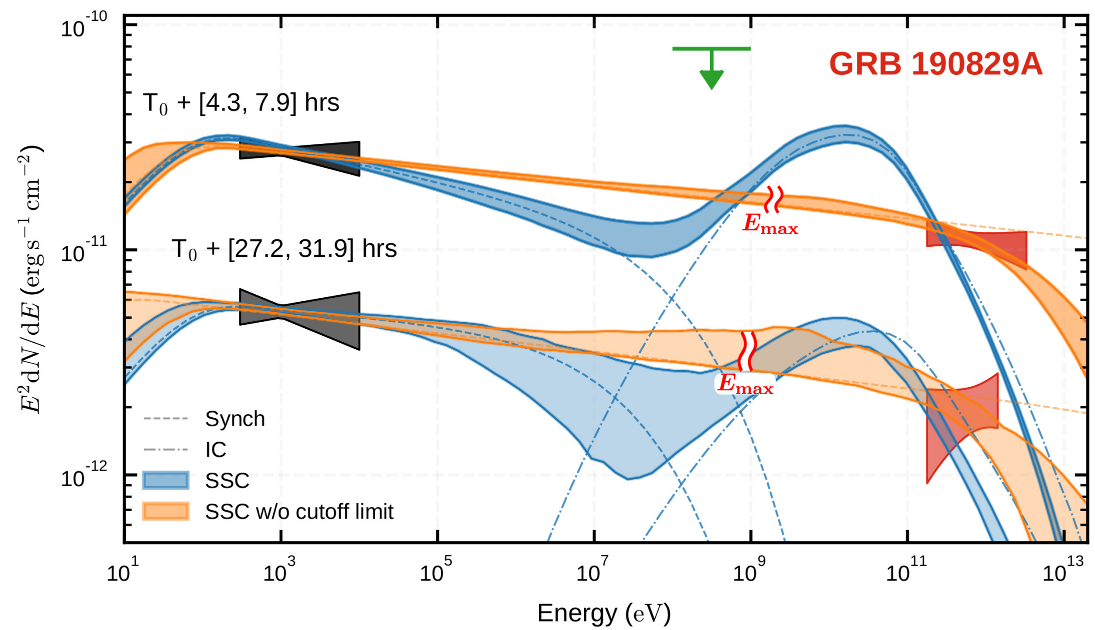


GRB 190829A: MWL modelling

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

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



Electron spectrum

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

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:

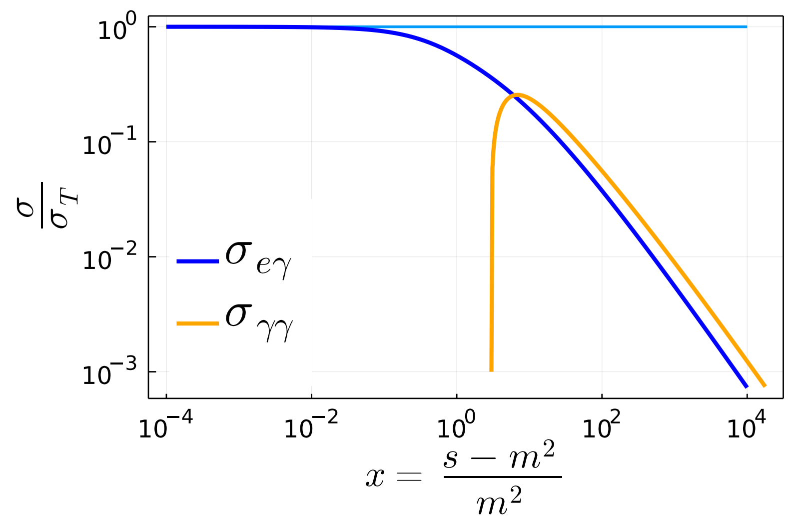
- The Klein-Nishina cutoff
- Internal $\gamma - \gamma$ attenuation

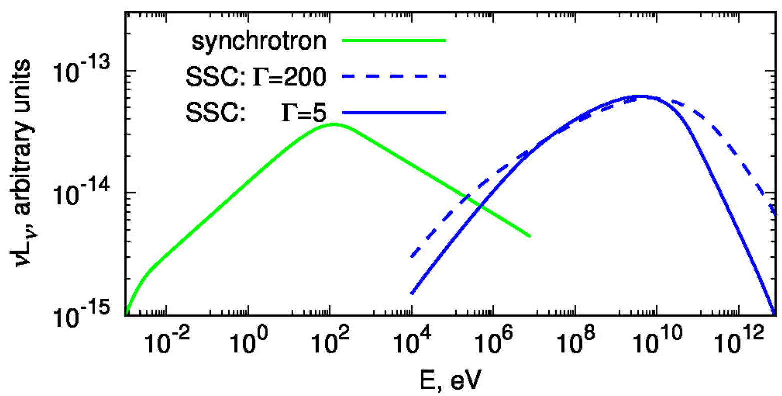
These effects are important if

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

Internal $\gamma - \gamma$ optical depth

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





H.E.S.S.

Summary

Summary I

- H.E.S.S. is in a good operational state, with upgraded cameras (very recently for H.E.S.S. II)
- Detection of the extended emission from kpc jet of radio galaxy Centaurus A allows studying the acceleration of VHE particles in relativistic jets of AGNs
- This study favored the synchrotron origin of the X-ray emission detected from large-scale AGN jets, implying an in-situ (re)acceleration of TeV electrons
- Modelling of the diffuse X-ray and TeV emission allows determining the magnetic field strength, which has important implications on the jet dynamics (and even allows pinpointing the acceleration sites, which are likely compact X-ray knots)
- Detection of GRB180720B 10h after the trigger confirmed that (at least some) GRBs emit detectable TeV emission for a long period after the explosion

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, $z_{\rm rs} = \mathbf{0.08}$, 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 (like require a multi-zone set up)
  - Reconsider relativistic shock (e.g., Derishev&Piran 2016)

H.E.S.S.

Thanks for your attention!