GRBs at Very High Energies

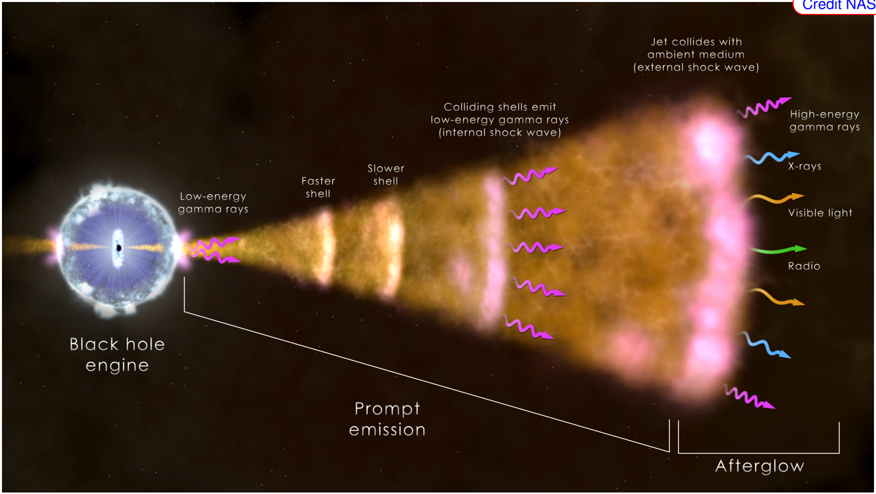
D. Khangulyan (Rikkyo University)

“Synergies at new frontiers at gamma-rays, neutrinos and gravitational waves”

25$^{\text{th}}$ March 2022

OVERVIEW

Long GRBs: physical scenario

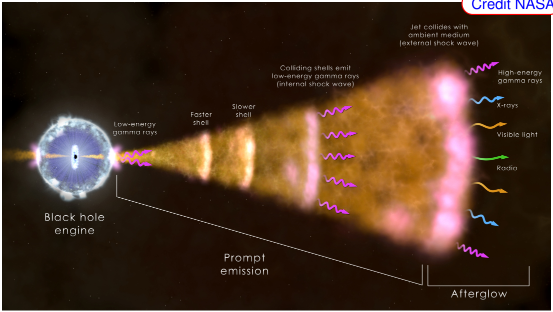


Credit NASA

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^{2-3} 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):

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

Long GRBs: physical scenario

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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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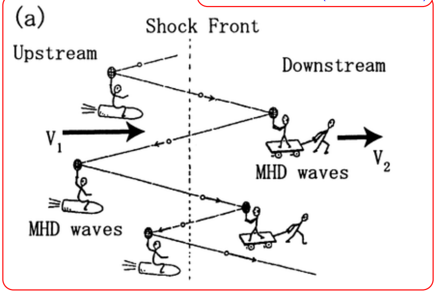
GRB is relativistic version of SN explosions

- 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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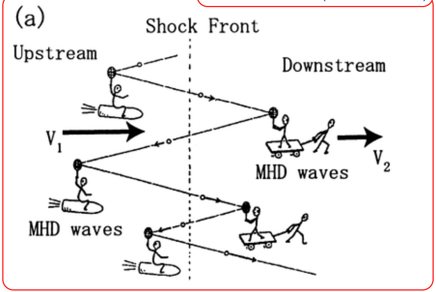

Relativistic shocks

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

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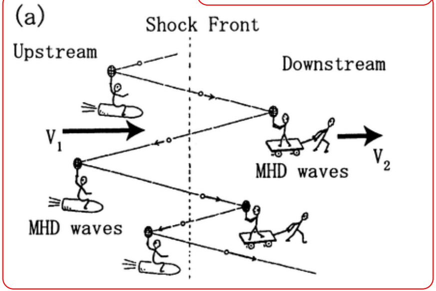

Relativistic shocks

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

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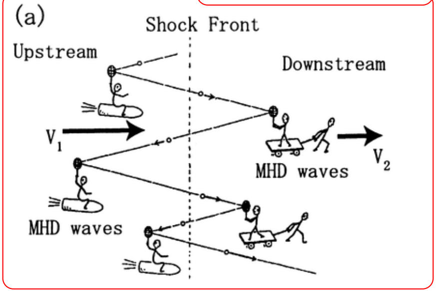

Leptonic source

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

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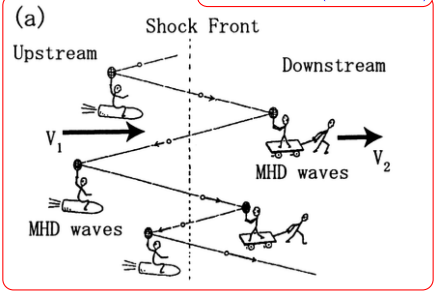


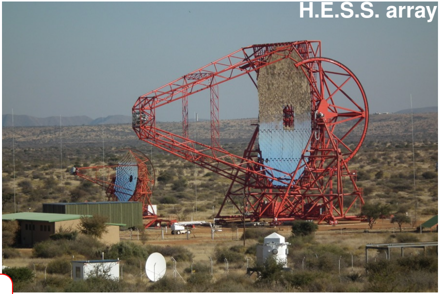
Synchrotron burn-off limit

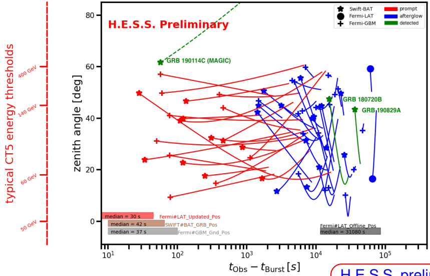
- Synchrotron cooling time: $t_{\rm SYN} \approx 400 E_{\rm TeV}^{-1} B_{\rm B}^{-2}$ s
- Acceleration time: $t_{\rm ACC} \approx 0.1 \eta E_{\rm TeV} B_{\rm B}^{-1}$
- Max energy: $\hbar\omega < 200 \frac{\Gamma}{\eta}$ MeV

Hunt for 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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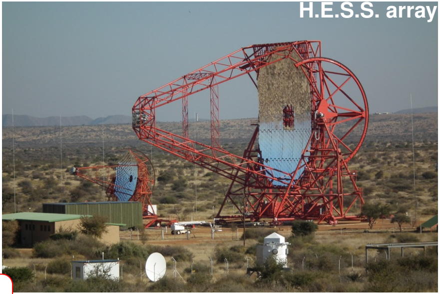

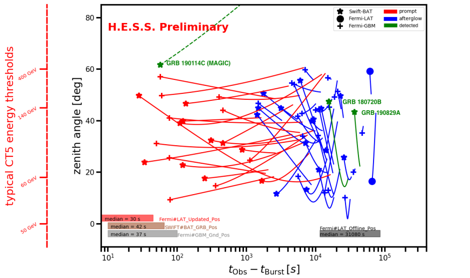

- Highly variable sources
- Bright synchrotron emission
  - IC can be suppressed
  - Internal absorption
- Cosmological distances, EBL attenuation $\Rightarrow$

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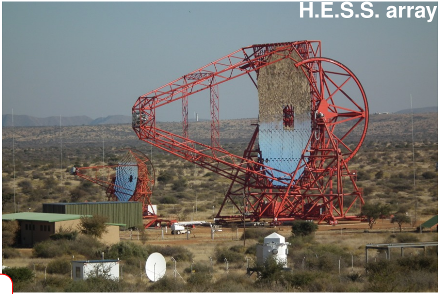

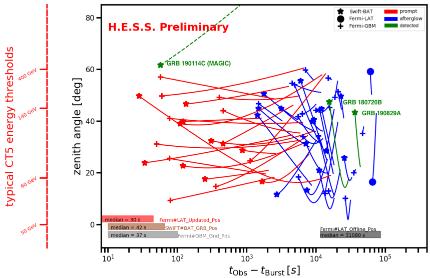

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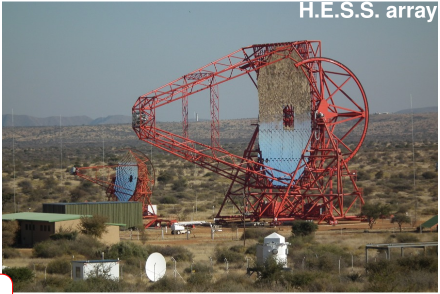

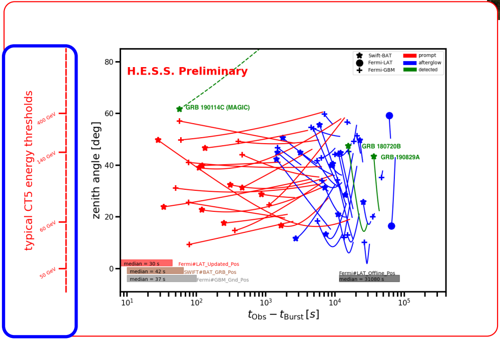

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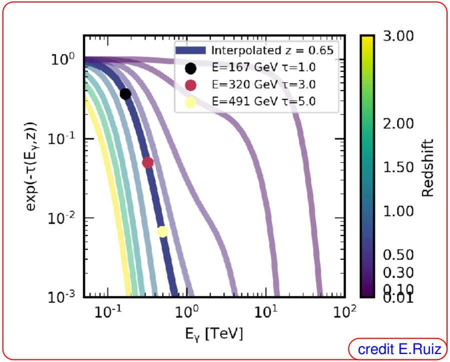
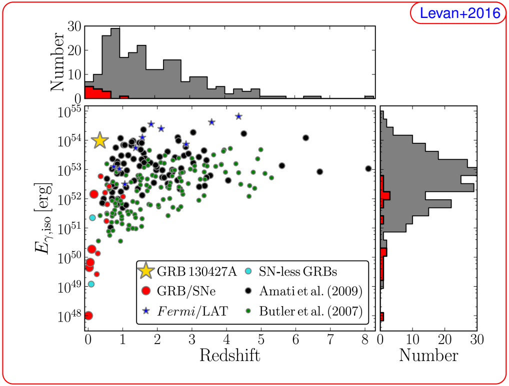
EBL attenuation

- 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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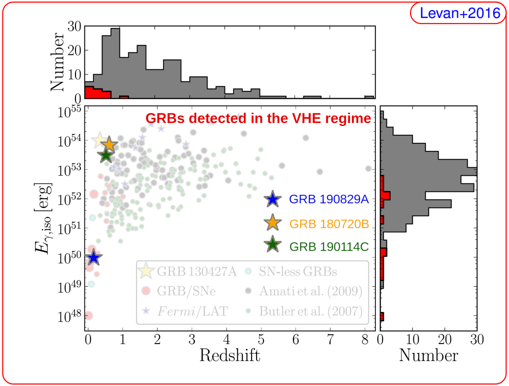

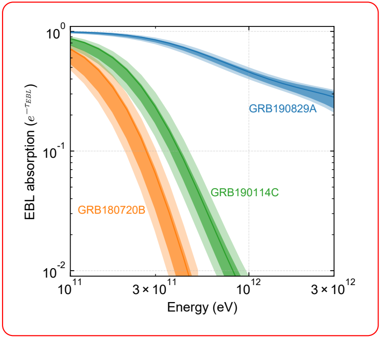

GRBs detected in the VHE regime:

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

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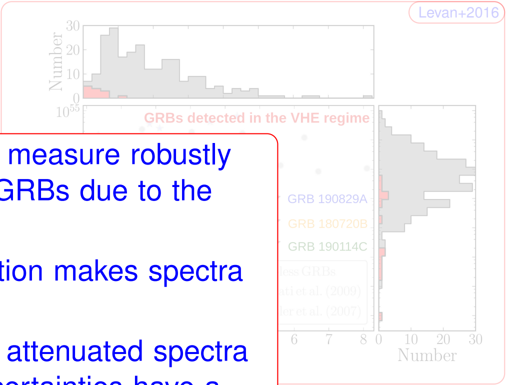

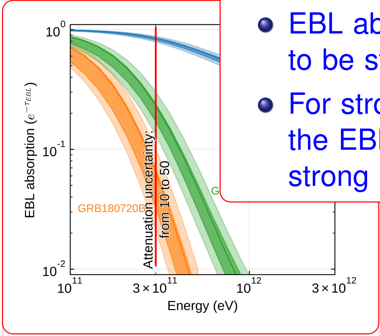

It is very hard to measure robustly VHE spectra of GRBs due to the EBL attenuation:

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

E regime:

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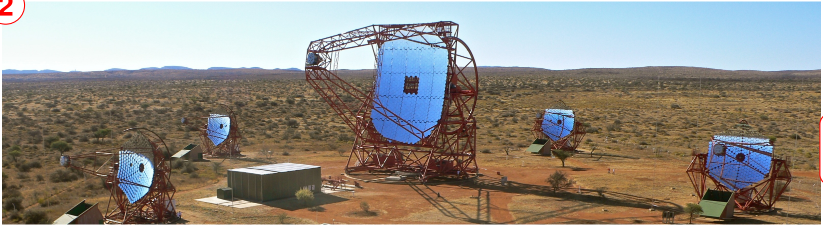
Energy (eV)

GRBs detected in the VHE regime (~ 0.1 TeV)

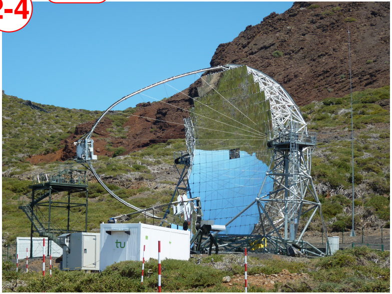
2



H.E.S.S.

2-4

MAGIC



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Veritas

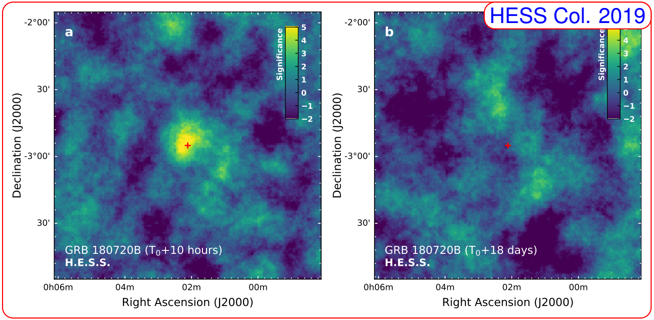
GRBs detected in the VHE regime ($\sim 0.1\,\mathrm{TeV}$)

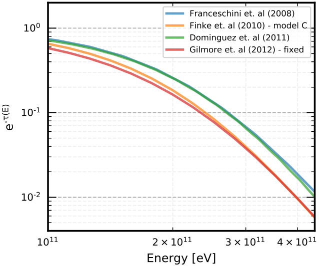
- ? GRB160821B: 3σ detection of a nearby short GRB ($z = 0.162$) above $0.5\,\mathrm{TeV}$ 4h after the trigger (MAGIC Col, 2021)
- ✔ GRB180720B: 5σ detection of a long GRB from $z = 0.65$ above $0.1\,\mathrm{TeV}$ **10h** after the trigger (HESS Col, 2019)
- ✔ GRB190114C: $\sim 50\sigma$ detection of 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
- ✔ $E_{\rm iso} = 10^{54}$ erg
  super bright!
- ? $z = 0.65$
  or $D = 1.5$ Gpc
- ✘ $t_{\rm vhe} = 10$ h
  time decay measured
  in X-rays: $L_{\rm X} \propto t^{-1.2}$

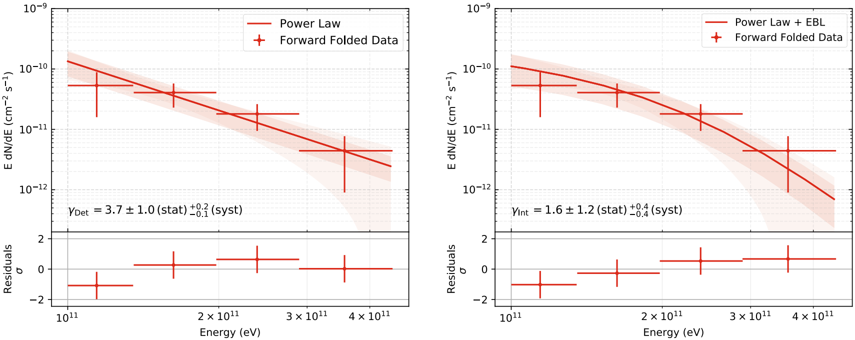




- The first GRB detected in the VHE regime (second reported – tough internal cross checks, relatively weak signal)
- Quite late observing opportunity (how many GRBs one could detect during the last 10yr? Still very bright...)
- EBL absorption is very significant at **300 GeV**

GRB180720B

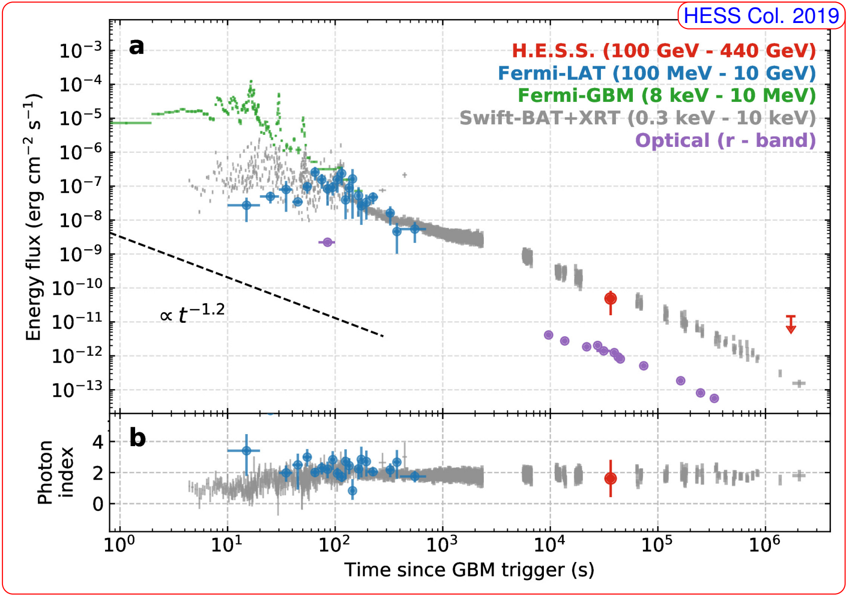
HESS Col. 2019



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

- 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

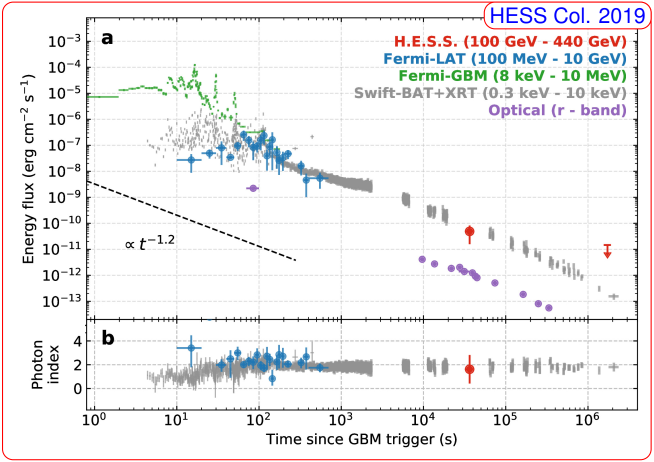
GRB180720B



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



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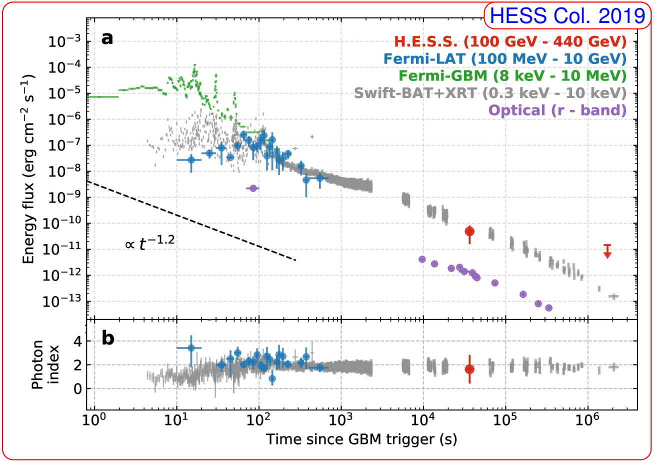


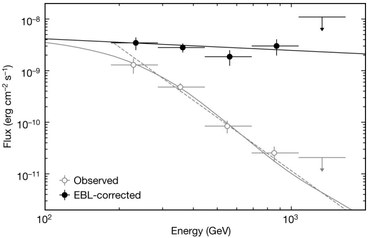
What do we see?

- ✔ 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

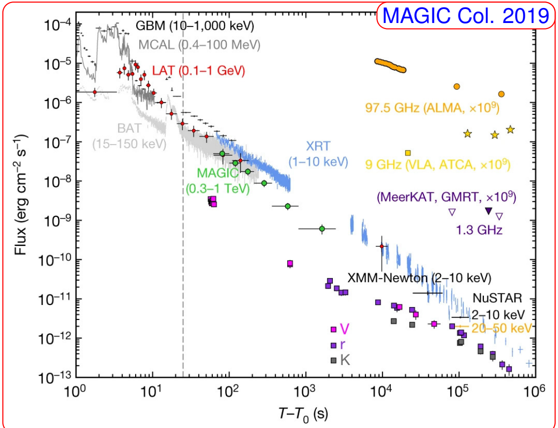
GRB190114C

GRB190114C

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



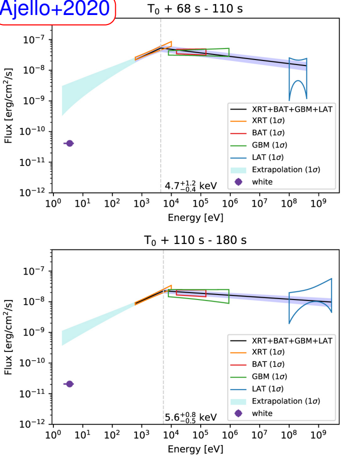
MAGIC Col. 2019



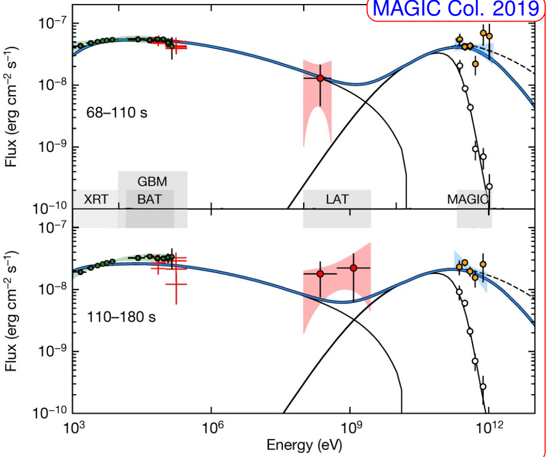
- The first GRB detection reported in the VHE regime
- Bright late prompt – early afterglow emission
- EBL absorption is very significant at $\sim 500\,{\rm GeV}$

GRB190114C

Ajello+2020



MAGIC Col. 2019



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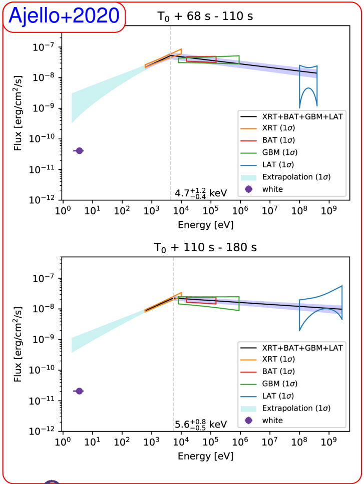
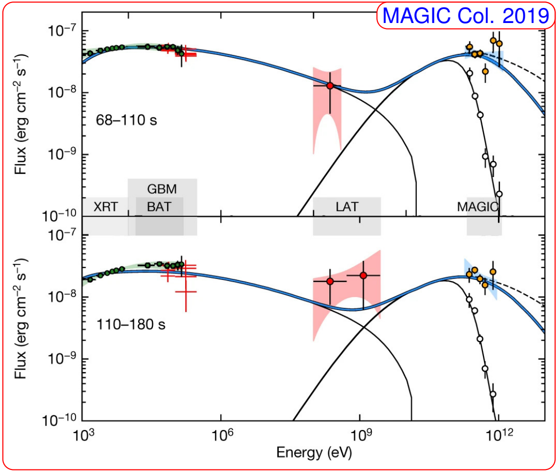
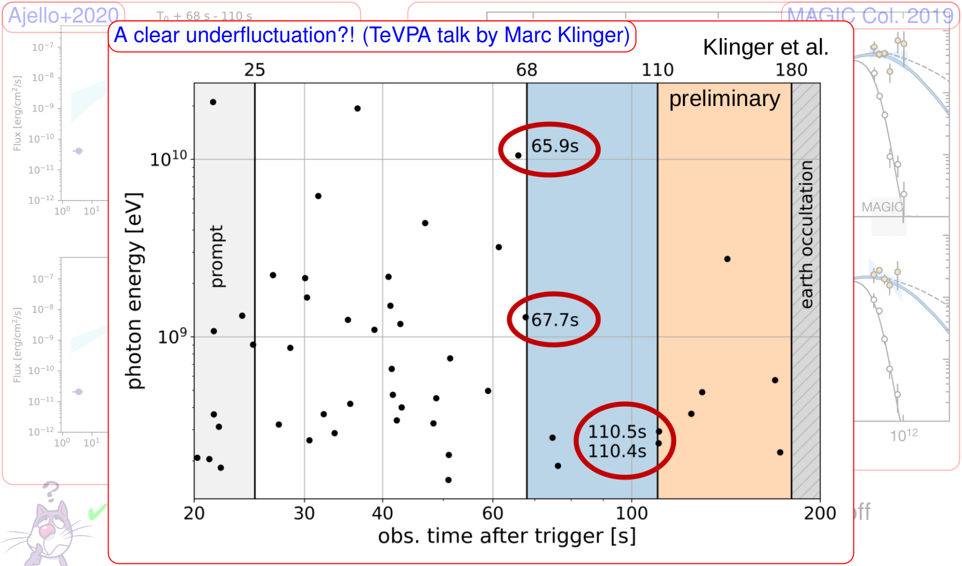




- ✔ We do detect photons with energy exceeding the synchrotron burn-off limit
- ✘ Maybe we see / don't see a TeV component emerging above the emission in the Fermi/LAT band in the 2/3 min.

GRB190114C

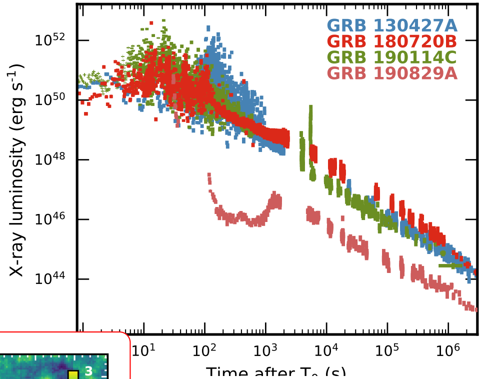


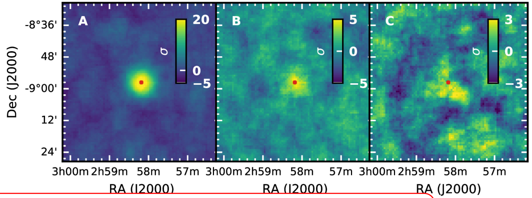
✘ Maybe we see / don't see a TeV component emerging above the emission in the Fermi/LAT band in the 2/3 min.

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)





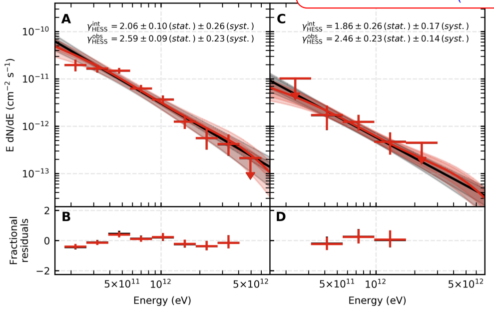
detected with H.E.S.S. for **3 nights (H.E.S.S. Collaboration 2021)**

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

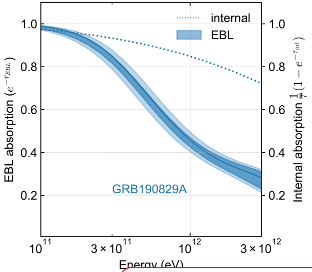
GRB 190829A: VHE spectrum

- 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: $\gamma_{\rm VHE}^{\rm obs} = 2.46^{+0.23}_{-0.23}$

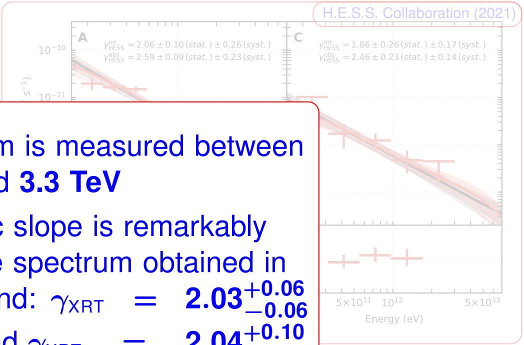
Intrinsic spectrum

- 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: $\gamma_{\rm VHE}^{\rm int} = 2.07^{+0.09}_{-0.09}$

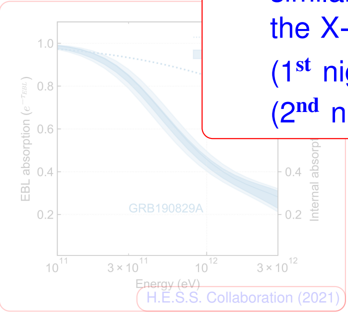
GRB 190829A: VHE spectrum

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

$$\frac{dN}{dE} \propto E^{-\gamma_{\rm VH}^{\rm in}}$$



- 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)



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

GRB 190829A: light-curve

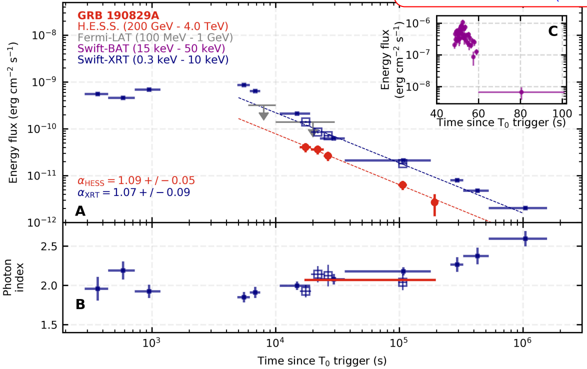
- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray light-curve
- Fit the flux with a power-law decay

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

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

- Remarkably consistent slopes ⇒

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



X-ray decay

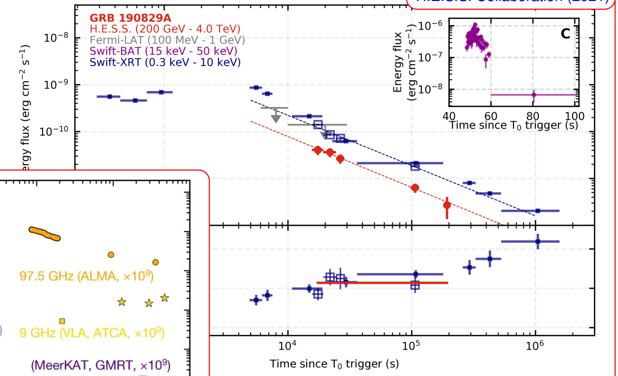
$$\alpha_{\mathrm{XRT}} = 1.07^{+0.09}_{-0.09}$$

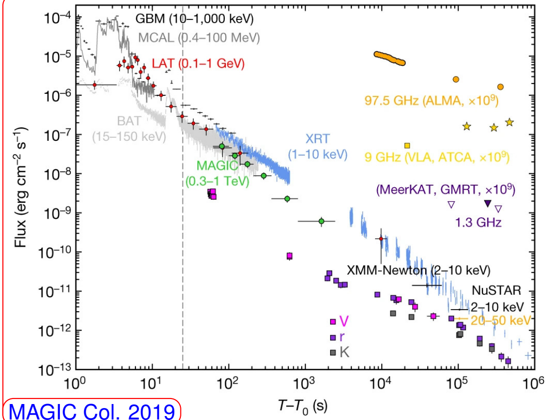
H.E.S.S. decay

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

GRB 190829A: light-curve

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





- ✔ 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

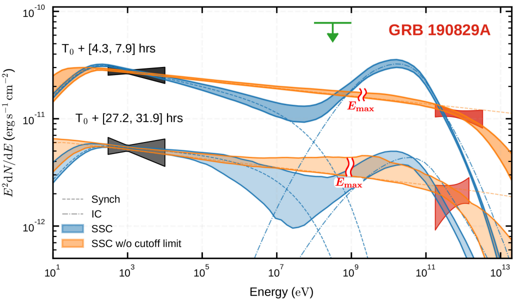
- Remarkably broad spectrum measurement, between **180 GeV** and **3.3 TeV**
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Spectrum measurement close independent on EBL model
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Multi-day VHE light-curve, between **4 h** and **56 h**
  - 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 1st 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.**

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

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

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

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

Can we exclude SSC scenario?

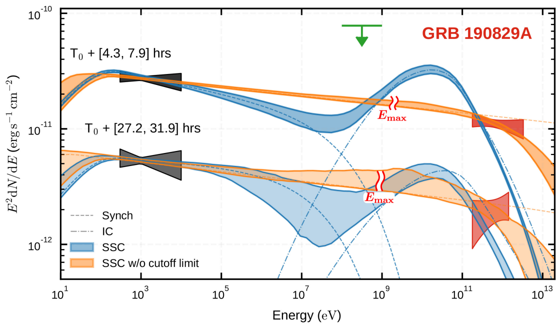
Our numerical analysis is limited to a

- 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)



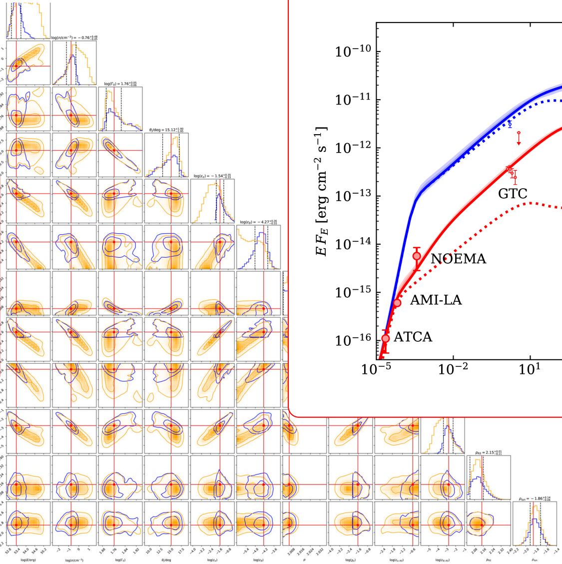
Under our assumptions we obtained that

- 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

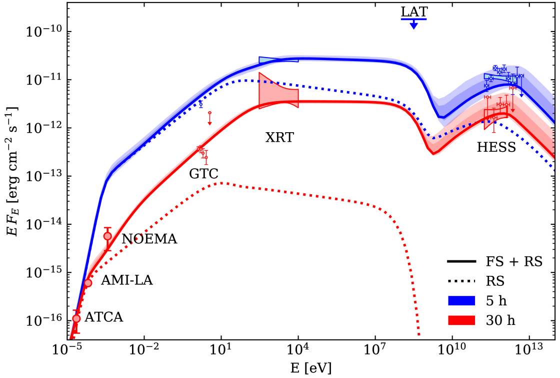
Can we exclude SSC scenario?

12-parameter SSC model

Corner plot from Salafia+(2021)

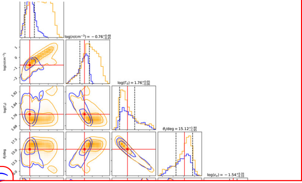


SSC model for GRB190829A from Salafia+(2021)

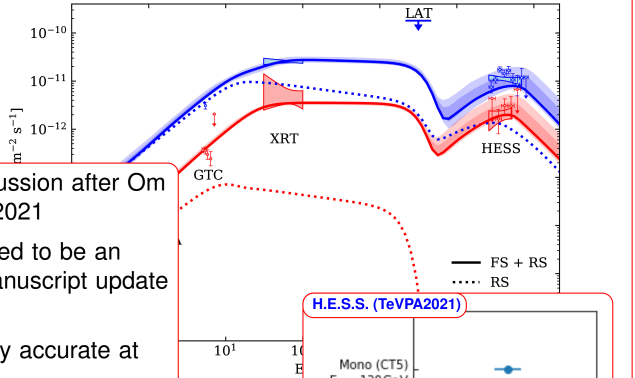


Can we exclude SSC scenario?

12-parameter SSC model



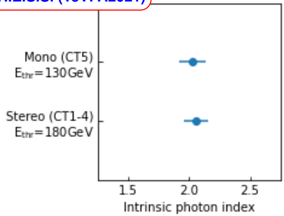
SSC model for GRB190829A from Salafia+(2021)



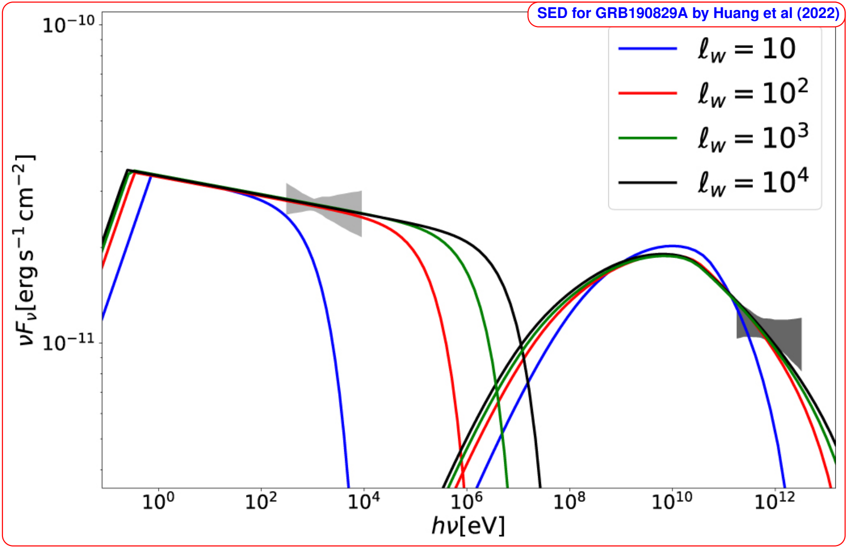
An update based on the discussion after Om Salafia's talk in DESY in fall 2021

- Radio extension appeared to be an artifact (also see the manuscript update in ArXiV)
- The calculations are only accurate at the 200-300% level
- No accurate real calculations of IC ("truncated Thomson" approximation)
- Questionable agreement on the VHE slope

H.E.S.S. (TeVPA2021)



Can we exclude SSC scenario?

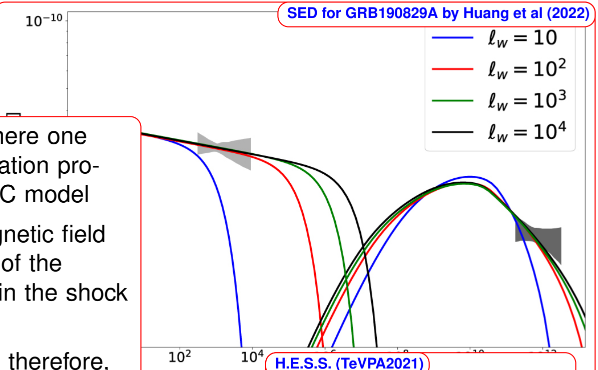


Can we exclude SSC scenario?

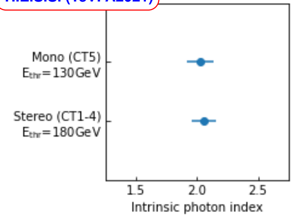
Based on Huang et al (2022), where one attempts to constrain the acceleration processes based on single-zone SSC model

- Scenarios in which the magnetic field damps rapidly downstream of the shock are clearly ruled out in the shock acceleration picture
- Larger-scale structures are, therefore, required but not seen to develop in the currently available simulations.
- Klein-Nishina suppression softens the spectrum in the VHE γ-ray band and presents a significant obstacle to simultaneously matching the X-ray and γ-ray data

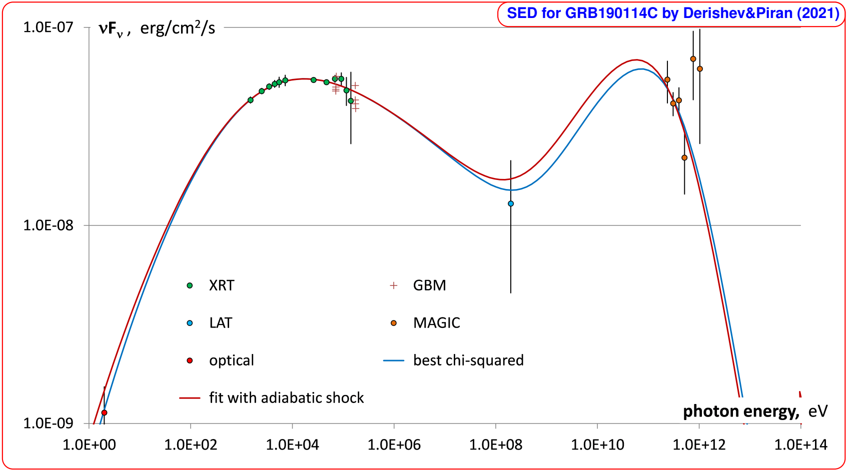
SED for GRB190829A by Huang et al (2022)



H.E.S.S. (TeVPA2021)



Can we exclude SSC scenario?

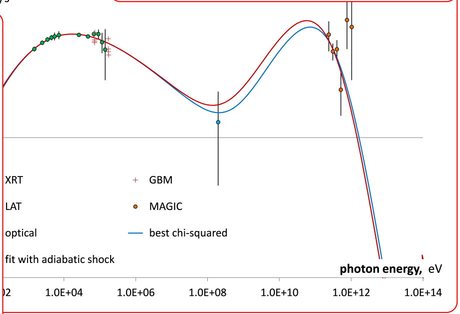


Can we exclude SSC scenario?

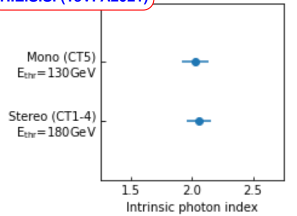
Based on Derishev&Piran (2016,2021) and Derishev's talk at "High Energy Astrophysics Today and Tomorrow" (December 2021)

- Relativistic shocks operate in a regime when pair production is important
- This results in switching-off the conventional shock acceleration and activation of the converter mechanism
- GRB190114C can be easily explained with this scenario (with underfluctuated Fermi/LAT data point)
- GRB190829A CANNOT be explained with this scenario (Derishev's conference talk)
- (Apparently) It is hard to reproduce with SSC models the hard PL VHE spectrum.

SED for GRB190114C by Derishev&Piran (2021)



H.E.S.S. (TeVPA2021)



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 ⇒

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 (note Derishev&Piran 2016 doesn't work)