TS2020+ - Virtual Meeting – 4 June, 2021

First detections of gamma-ray bursts at very high energy: consequences and open questions

GRB 180720B (HESS)
GRB 190114C (MAGIC): most detailed multi-wavelength follow-up

[GRB190829A (HESS) ⟼ Fabian Schüssler's presentation]

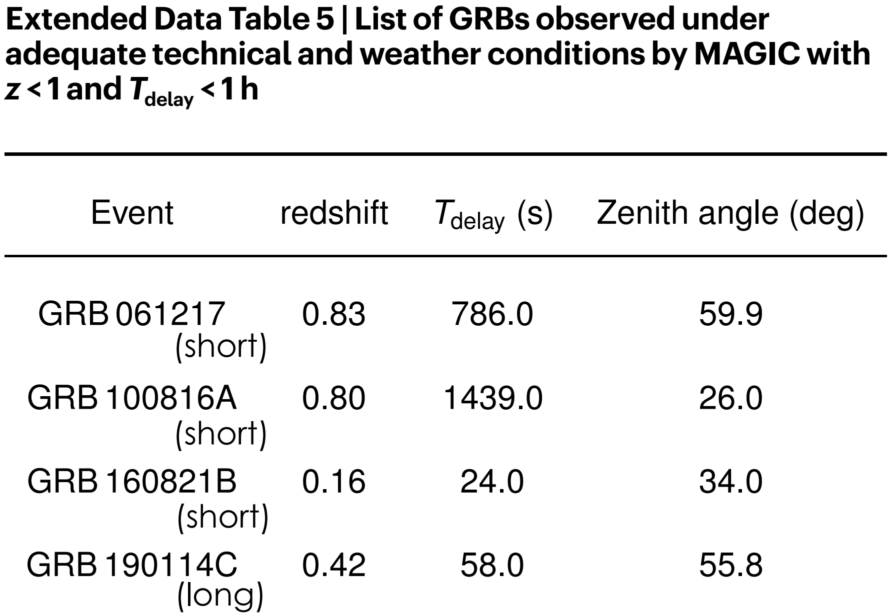
Basic facts:

- **GRB180720B, GRB 190114C are classical long GRBs (z ~ 0.6 and ~ 0.4)**
- **GRB 190829A is a low-luminosity long GRB at very low redshift (z ~ 0.08)**

  Only three cases but already some diversity among the long GRB population.
- No VHE information yet on short GRBs
- A lesson from the first detections:

Low z + « suitable » observing conditions
rather than
special intrinsic properties?

MAGIC 2004-2019:
follow-up of 105 GRBs,
only four at z<1 with delay < 1h and
good observing conditions.



Extended Data Table 5 | List of GRBs observed under adequate technical and weather conditions by MAGIC with $z < 1$ and $T_{\mathrm{delay}} < 1$ h

Event	redshift	T_{delay} (s)	Zenith angle (deg)
GRB 061217 (short)	0.83	786.0	59.9
GRB 100816A (short)	0.80	1439.0	26.0
GRB 160821B (short)	0.16	24.0	34.0
GRB 190114C (long)	0.42	58.0	55.8

***Teraelectronvolt emission from the γ-ray burst GRB 190114C**, MAGIC collaboration; Nature 575, 455-458 (2019)*

Basic facts: GRB180720B and GRB190114C

- **GRB180720B:**
  - Redshift: $z = 0.653$ – Duration: $T_{90} \sim 50$ s (**long cosmological GRB**)
  - $E_{iso} = 6.0 \pm 0.1\ 10^{53}$ erg (50-300 keV)
  - Detected by GBM & BAT (trigger), LAT (during 12 min), XRT and many others
  - Afterglow detectable for ~ 30 days
  - **HESS: VHE detection 10 hours after the burst: afterglow phase**
  - Fermi/GRM: 7th brightest GRB ; Swift/XRT: 2nd brightest afterglow

- **GRB190114C:**
  - Redshift: $z = 0.4245$ – Duration: $T_{90} \sim 116$ s (GBM) – 362 s (BAT) (**long cosmological GRB**)
  - $E_{iso} = 3\ 10^{53}$ erg (1-10000 keV)
  - Detected by BAT & GBM (trigger), INTEGRAL, LAT (during 12 min), AGILE, XRT and many other
  - **MAGIC: VHE detection (0.2-1 TeV) 1 minute after the burst at 50 sigmas during the first 20 min – observed for 40 min**

    at 80 s: $3\ 10^{49}$ erg/s (0.3-1 TeV) = most luminous source known at VHE

    Total observation: $4\ 10^{51}$ erg (0.3-1 TeV)

GRB 180720B (HESS)

GRB180720B: light-curve

$$\alpha_{XRT} \sim \alpha_{opt} \sim -1.3/-1.2$$

$$\alpha_{LAT} \sim -1.8 \; ; \; \gamma_{LAT} \sim -2.1$$

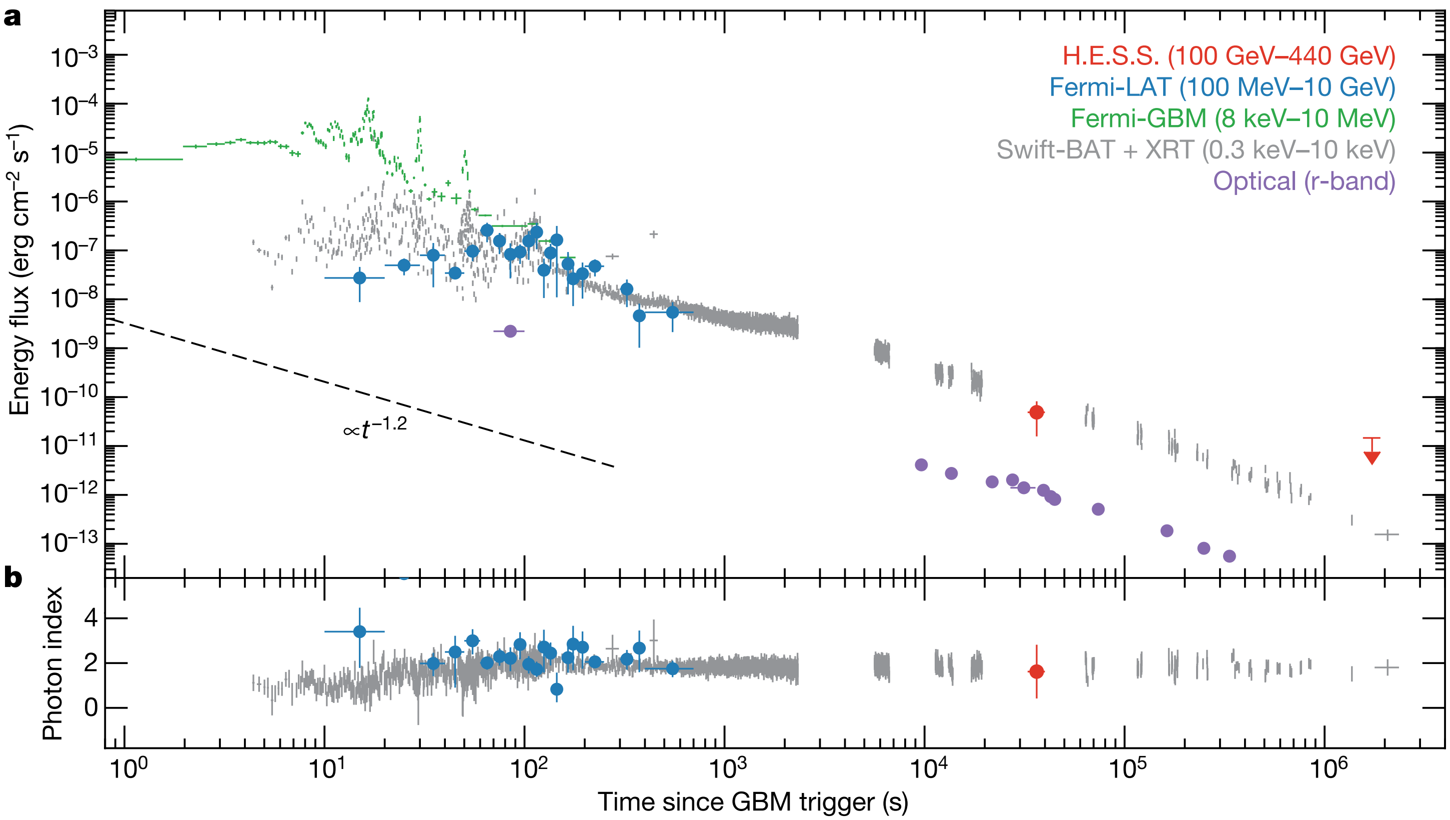
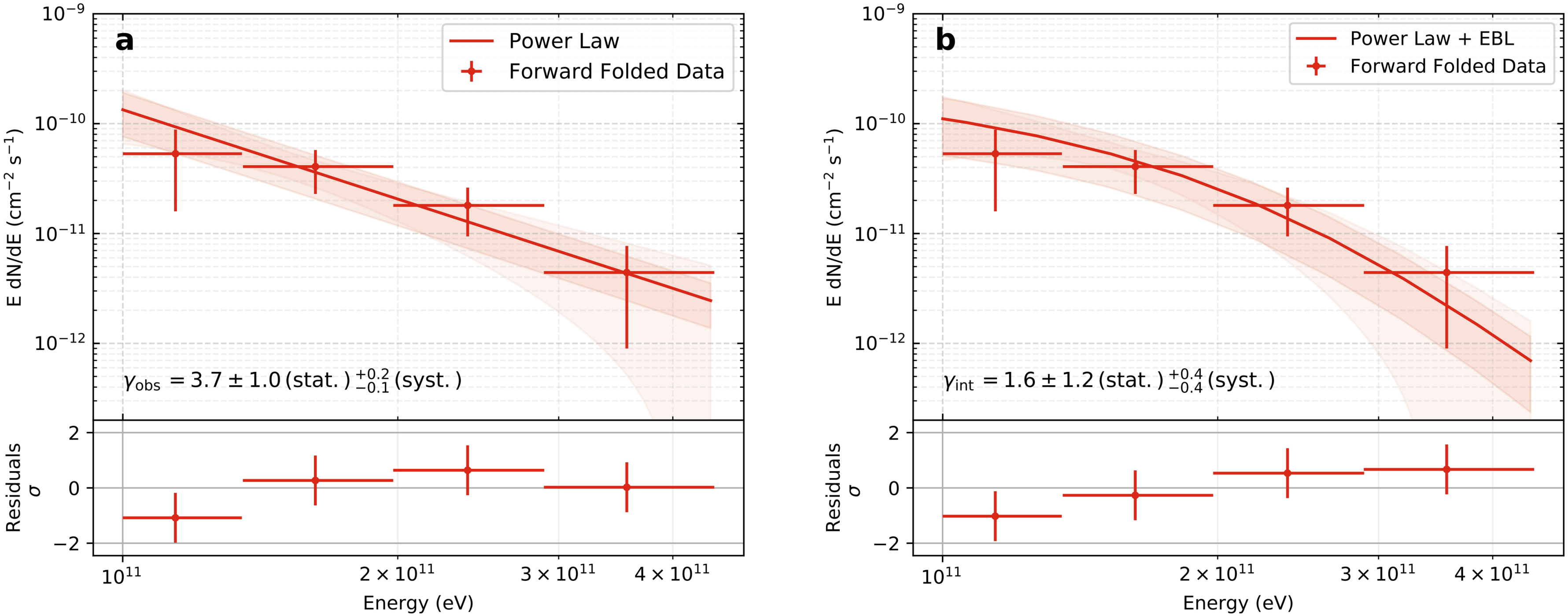


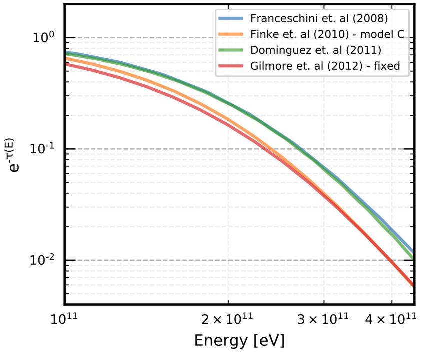
Fig. 1 | Multi-wavelength light curve of GRB 180720B. a, Energy-flux light curve detected by Fermi-GBM (band fit; green), Fermi-LAT (power law; blue), H.E.S.S. (power-law intrinsic; red) and the optical r-band (purple). The Swift-BAT spectra (15 keV–150 keV) are extrapolated to the XRT band (0.3–10 keV) to produce a combined light curve (grey) and an upper limit (95% confidence level) for the second H.E.S.S. observation window (power-law intrinsic, red arrow). The black dashed line indicates a temporal decay with $\alpha = -1.2$. **b**, Photon index of the Fermi-LAT, Swift and H.E.S.S. spectra. Error bars correspond to 1σ.

A very-high-energy component deep in the γ-ray burst afterglow, H.E.S.S. collaboration; *Nature 575*, 464-467 (2019)

GRB180720B: VHE spectrum



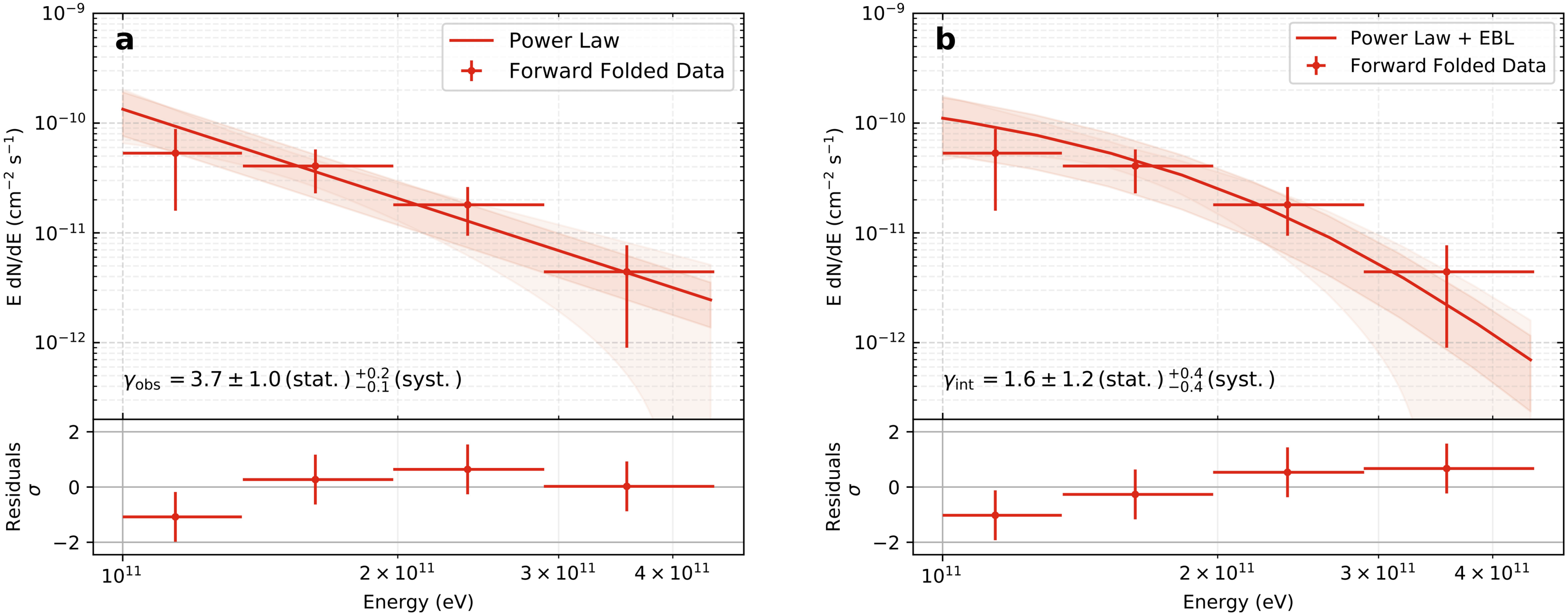
Extended Data Fig. 1 | VHE spectral fit of GRB 180720B. H.E.S.S. spectral fit to the measured emission in the energy range 100–440 GeV. **a**, Fit using a simple power-law model (with photon index γ_{obs}). **b**, Fit with a power-law model (with photon index γ_{int}) with EBL attenuation for a source at $z = 0.653$ (ref. [13]). In both cases the residual data points with 1σ uncertainties are obtained from the forward-folded method. The shaded areas show the statistical and systematic uncertainties in each fit (1σ confidence level). The bottom panels show the significance of the residuals between the fitted model and the data points.



Extended Data Fig. 2 | EBL absorption coefficient. Absorption coefficient $e^{-\tau(E)}$ for a source emitting at a redshift of 0.653. The values are shown in the energy range of the detected emission of GRB 180720B (100–440 GeV) for the four EBL models considered[13,39–41].

A very-high-energy component deep in the γ-ray burst afterglow, H.E.S.S. collaboration; *Nature 575*, 464-467 (2019)

GRB180720B: VHE spectrum



Extended Data Fig. 1 | VHE spectral fit of GRB 180720B. H.E.S.S. spectral fit to the measured emission in the energy range 100–440 GeV. **a**, Fit using a simple power-law model (with photon index $\gamma_{\rm obs}$). **b**, Fit with a power-law model (with photon index $\gamma_{\rm int}$) with EBL attenuation for a source at $z = 0.653$ (ref. [13]). In both cases the residual data points with 1σ uncertainties are obtained from the forward-folded method. The shaded areas show the statistical and systematic uncertainties in each fit (1σ confidence level). The bottom panels show the significance of the residuals between the fitted model and the data points.

Extended Data Table 1 | VHE spectral information from GRB 180720B

Spectral model	F_0 [$\times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1}]	γ	E$_0$ [TeV]
$F_0 \times \frac{E}{E_0}^{-\gamma}$	$2.71 \pm 0.74\,^{+1.43}_{-1.16}$	$3.7 \pm 1.0\,^{+0.2}_{-0.1}$	0.154
$F_0 \times \frac{E}{E_0}^{-\gamma} \times e^{-\tau(z,E)}$	$7.52 \pm 2.03\,^{+4.53}_{-3.84}$	$1.6 \pm 1.2\,^{+0.4}_{-0.4}$	0.154
$F_0 \times \frac{E}{E_0}^{-2} \times e^{-\tau(z,E)}$	$16.12 \pm 4.37\,^{+10.59}_{-9.25}$	2.0 [Fixed]	0.105

Spectral parameters of the fits to the H.E.S.S. observed emission in the energy range 100–440 GeV. The intrinsic spectrum with $\gamma = 2.0$ (third row) is provided as a reference to the Fermi-LAT mean photon index detected in several other GRBs at high energies[14]. All reported uncertainties are statistical and systematic, in that order.

A very-high-energy component deep in the γ-ray burst afterglow, H.E.S.S. collaboration; *Nature 575*, 464-467 (2019)

GRB180720B: interpretation

- **Afterglow / Forward Shock**

- **Dominant: accelerated electrons**
  - Direct synchrotron: unlikely

    $$E_{\mathrm{sync}}^{\max} = 9\Gamma mc^2/(4\alpha_{\mathrm{F}}) \approx 100\Gamma\,\mathrm{MeV}$$

    Needs Γ>1000 at 10h!
  - **SSC**
    (VHE photons produced by
    IC scatterings of IR-UV photons
    by electrons at the highest energy)

  Klein-Nishina attenuation?
  $$E \gtrsim 50(\Gamma/20)^2[E_{\mathrm{t}}/(1\,\mathrm{keV})]^{-1}\,\mathrm{GeV}.$$

  Detailed modelling is required…

- Weak proton emission?

Synchrotron (« burnoff ») limit

Very efficient acceleration:

$$t_{\mathrm{syn}}(\gamma_{\max}) \sim t_{\mathrm{acc}} \sim \frac{R_{\mathrm{L}}}{c}$$

with

$$t_{\mathrm{syn}}(\gamma) \propto B^{-2}\gamma^{-1}$$

$$t_{\mathrm{acc}}(\gamma) \sim \frac{R_{\mathrm{L}}}{c} \propto \gamma B^{-1}$$

then $\gamma_{\max} \propto B^{-1/2}$

$$E_{\mathrm{syn}}(\gamma_{\max}) \propto \Gamma B \gamma_{\max}^2 \propto \Gamma$$

KN limit

$$\gamma h\nu' > m_{\mathrm{e}}c^2$$

$h\nu'$: seed photon γ: electron

GRB180720B: interpretation

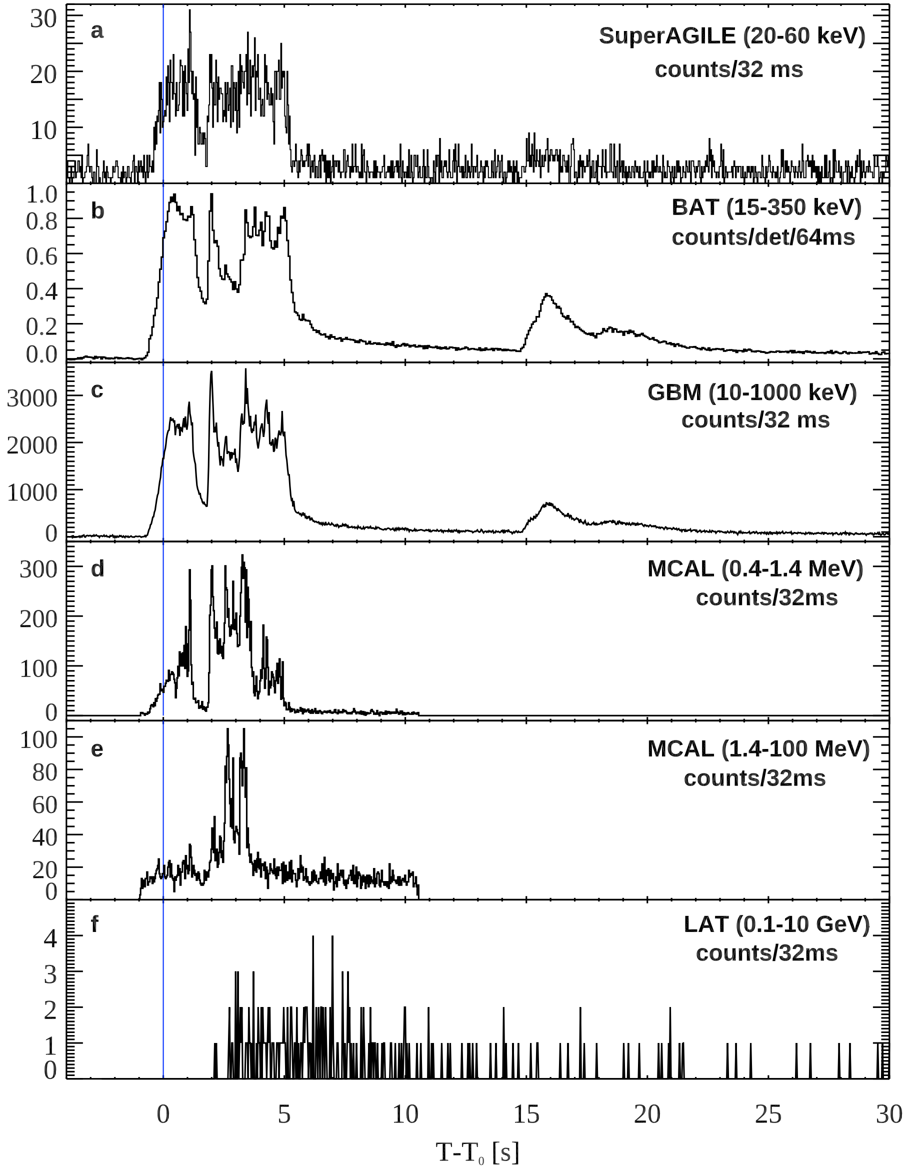
- Photo-hadronic scenario?

  see e.g. Sahu & Fortin, arXiv:2005.12383

  usual problem: low efficiency

GRB 190114C (MAGIC)

GRB190114C: prompt lightcurve



Extended Data Fig. 1 | Prompt-emission light curves for different detectors. **a**–**f**, Light curves for Super-AGILE (**a**; 20–60 keV), Swift-BAT (**b**; 15–150 keV), Fermi-GBM (**c**; 10–1,000 keV), AGILE-MCAL (**d**; 0.4–1.4 MeV), AGILE-MCAL (**e**; 1.4–100 MeV) and Fermi-LAT (**f**; 0.1–10 GeV). The light curve of AGILE-MCAL is split into two bands to show the energy dependence of the first peak. Error bars show 1σ statistical errors.

GRB190114C: lightcurve XRT-LAT-MAGIC

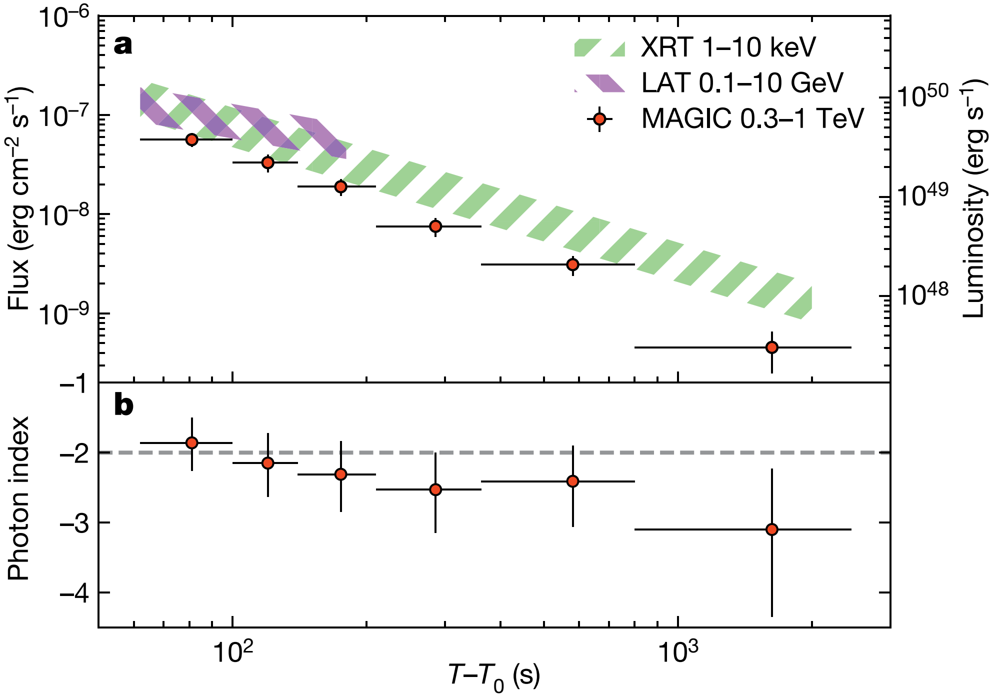
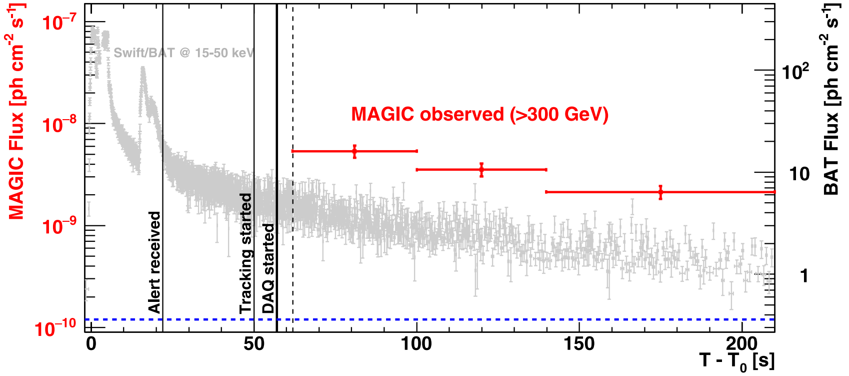


Fig. 1 | Light curves in the kiloelectronvolt, gigaelectronvolt and teraelectronvolt bands, and spectral evolution in the teraelectronvolt band for GRB 190114C. a, Light curves in units of energy flux (left axis) and apparent luminosity (right axis), for MAGIC at 0.3–1 TeV (red symbols), the Fermi Large Area Telescope (LAT) at 0.1–10 GeV (purple band) and the Swift X-ray Telescope (XRT) at 1–10 keV (green band). For the MAGIC data, the intrinsic flux is shown, corrected for EBL attenuation[25] from the observed flux. **b**, Temporal evolution of the power-law photon index, determined from time-resolved intrinsic spectra. The horizontal dashed line indicates the value −2. The errors shown in both panels are statistical only (one standard deviation).

$\alpha_{\mathrm{MAGIC}} \sim -1.6$

Early times: MAGIC vs BAT



Extended Data Fig. 1 | Light curves in the teraelectronvolt and kiloelectronvolt bands for GRB 190114C. Photon flux light curve above 0.3 TeV measured by MAGIC (red; from $T_0 + 62$ s to $T_0 + 210$ s), compared with that between 15 keV and 50 keV measured by Swift-BAT[73] (grey; from T_0 to $T_0 + 210$ s) and the photon flux above 0.3 TeV of the Crab Nebula (blue dashed line). The errors on the MAGIC photon fluxes correspond to one standard deviation. Vertical lines indicate the times when the alert was received ($T_0 + 22$ s) by MAGIC, when the tracking of the GRB by the telescopes started ($T_0 + 50$ s), when the data acquisition started ($T_0 + 57$ s), and when the data acquisition system (DAQ) became stable ($T_0 + 62$ s; dotted line).

Teraelectronvolt emission from the γ-ray burst GRB 190114C, MAGIC collaboration; *Nature* 575, 455-458 (2019)

GRB190114C: multi-λ lightcurve

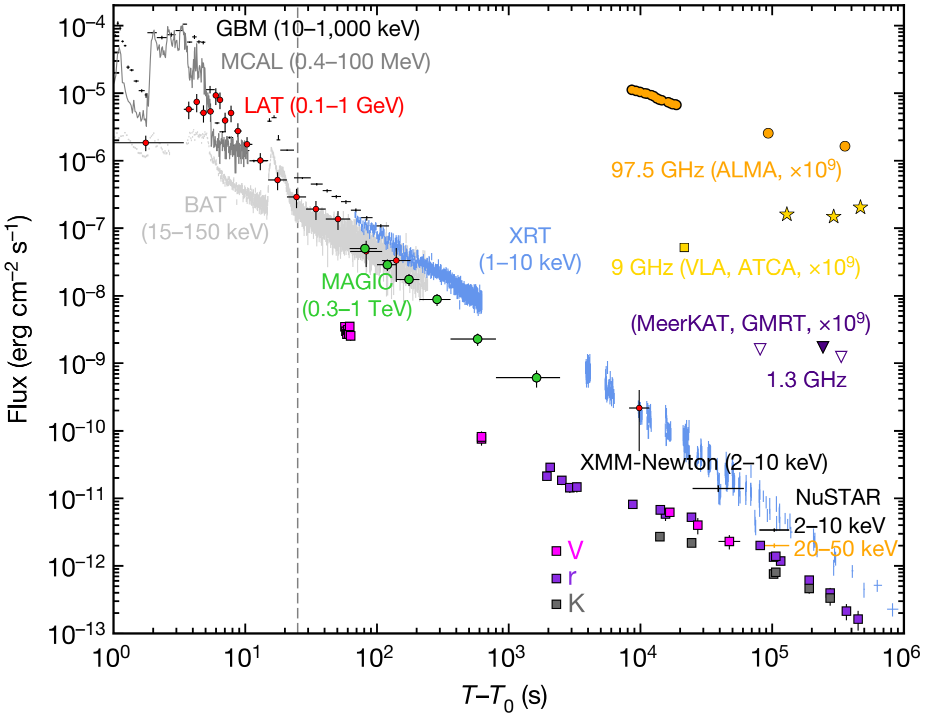


Fig. 1 | Multi-wavelength light curves of GRB 190114C. Energy flux at different wavelengths, from radio to γ-rays, versus time after the BAT trigger, at T_0 = 20:57:03.19 universal time (UT) on 14 January 2019. The light curve for the energy range 0.3–1 TeV (green circles) is compared with light curves at lower frequencies. Those for VLA (yellow square), ATCA (yellow stars), ALMA (orange circles), GMRT (purple filled triangle) and MeerKAT (purple open triangles) have been multiplied by 10^9 for clarity. The vertical dashed line marks approximately the end of the prompt-emission phase, identified as the end of the last flaring episode. For the data points, vertical bars show the 1σ errors on the flux, and horizontal bars represent the duration of the observation. The fluxes in the V, r and K filters (pink, purple and grey filled squares, respectively) have been corrected for extinction in the host and in our Galaxy; the contribution from the host galaxy has been subtracted.

$\alpha_{10\text{-}1000\text{ keV}}$ ~ -1.1 after 5-10 s

α_{XRT} ~ -1.4
α_{MAGIC} ~ -1.5

NIR-V (square symbols):
-Early: RS contribution?
-Then shallow decay/fast decay

Radio-mm:
-Early: RS contribution?
-Then ~cst flux

Observation of inverse Compton emission from a long γ-ray burst, MAGIC collaboration; *Nature* 575, 459-463 (2019)

GRB190114C: VHE spectrum

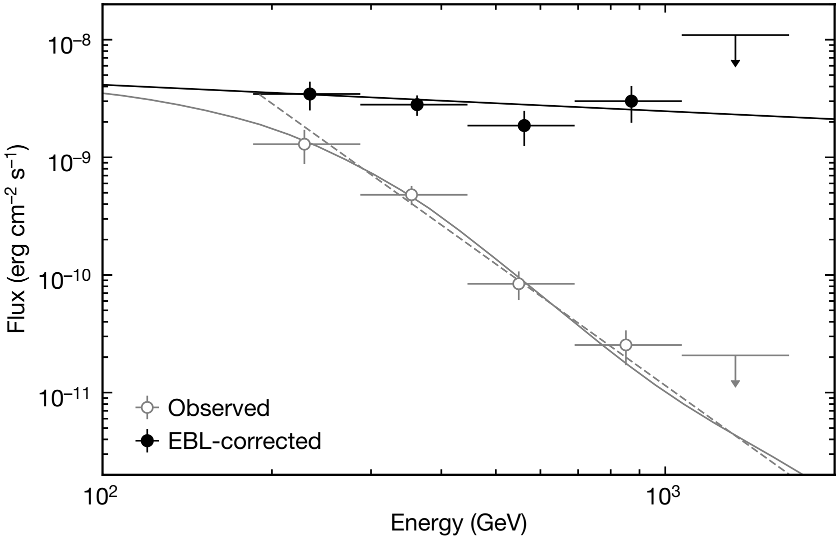
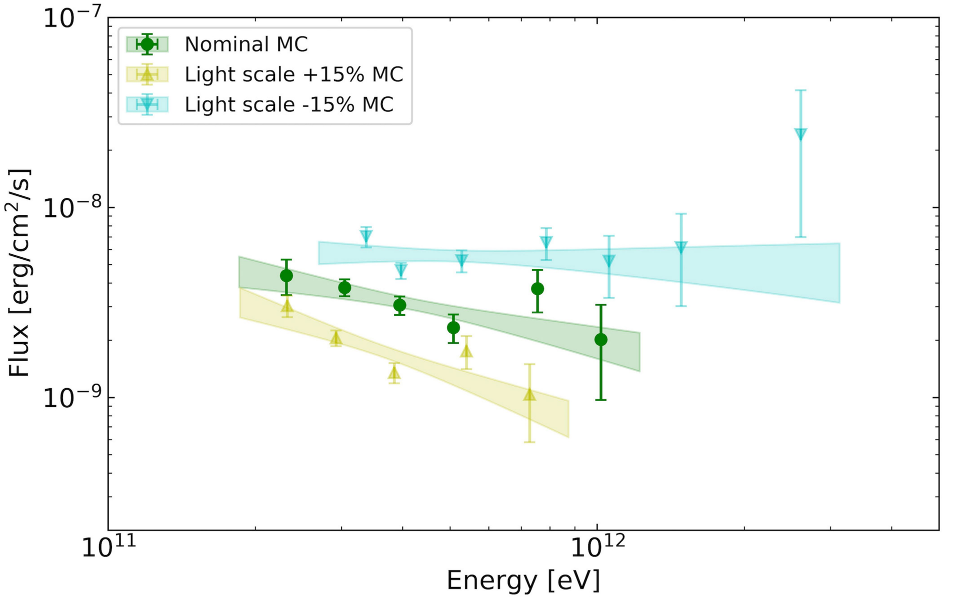


Fig. 2 | Spectrum above 0.2 TeV averaged over the period between $T_0 + 62$ s and $T_0 + 2{,}454$ s for GRB 190114C. Spectral-energy distributions for the spectrum observed by MAGIC (grey open circles) and the intrinsic spectrum corrected for EBL attenuation[25] (blue filled circles). The errors on the flux correspond to one standard deviation. The upper limits at 95% confidence level are shown for the first non-significant bin at high energies. Also shown is the best-fit model for the intrinsic spectrum (black curve) when assuming a power-law function. The grey solid curve for the observed spectrum is obtained by convolving this curve with the effect of EBL attenuation. The grey dashed curve is the forward-folding fit to the observed spectrum with a power-law function (Methods).

Photon index
~-2.2

Limits on systematics:



Extended Data Fig. 2 | MAGIC time-integrated SEDs in the time interval 62–2,400 s after T_0. The green (yellow, blue) points and band show the results of the Monte Carlo (MC) simulations for the nominal and the varied light scale cases (+15%, −15%), which define the limits of the systematic uncertainties. The contour regions are drawn from the 1σ error of their best-fit power-law functions. The vertical bars of the data points show the 1σ errors on the flux.

Teraelectronvolt emission from the γ-ray burst GRB 190114C, MAGIC collaboration; *Nature* 575, 455-458 (2019)

Observation of inverse Compton emission from a long γ-ray burst, MAGIC collaboration; *Nature* 575, 459-463 (2019)

GRB190114C: multi-λ spectrum

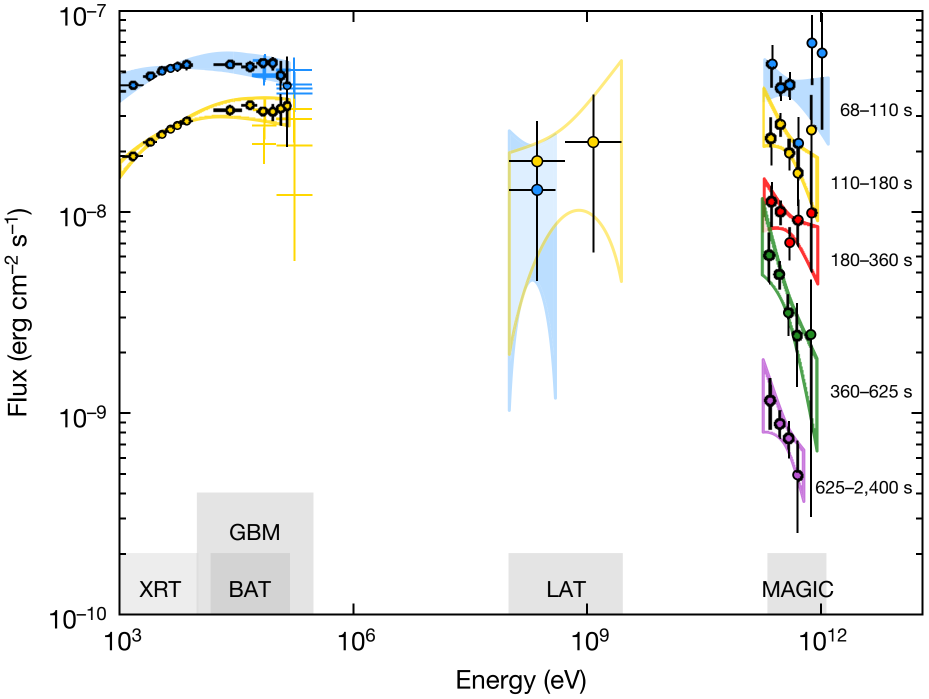


Fig. 2 | Multi-band spectra in the time interval 68–2,400 s. Five time intervals are considered: 68–110 s (blue), 110–180 s (yellow), 180–360 s (red), 360–625 s (green) and 625–2,400 s (purple). MAGIC data points have been corrected for attenuation caused by the EBL. Data from other instruments (Swift-XRT, Swift-BAT, Fermi-GBM and Fermi-LAT) are shown for the first two time intervals. For each time interval, LAT contour regions are shown, limiting the energy to the range in which photons are detected. MAGIC and LAT contour regions are drawn from the 1σ error of their best-fit power-law functions. For Swift data, the regions show the 90% confidence contours for the joint fit for XRT and BAT, obtained by fitting a smoothly broken power law to the data. Filled regions are used for the first time interval (68–110 s).

Two components (clear for the first two intervals)

Independent of the choice of an EBL model

SSC in external shock?

Observation of inverse Compton emission from a long γ-ray burst, MAGIC collaboration; *Nature* 575, 459-463 (2019)

GRB190114C: interpretation

- **Again: Afterglow / Forward Shock**
- **Subdominant prompt component at early times?**
  Discovery paper says : <20% during first 100 s (IS,rec) – Photosphere

  Duration of the prompt phase? T_{90} ~100-300 s (1st paper); duration ∞ 25 s (2nd paper)
  Onset of the afterglow phase: ~ 5-10 s ?

- **Dominant: accelerated electrons**
  up to LAT: synchrotron ; MAGIC: SSC $\varepsilon_{\mathrm{syn,max}} \approx 100(\Gamma_{\mathrm{b}}/1{,}000)\ \mathrm{GeV},$

- **SSC component is energetically important**

- Weak proton emission?

  - Proton synchrotron: $\varepsilon_{\mathrm{psyn,max}} = (7.6\ \mathrm{GeV})\eta^{-2}\epsilon_{\mathrm{B}}^{3/2}(n_0 E_{\mathrm{k,53}})^{3/4} t_{\mathrm{s}}^{-1/4}(1+z)^{-3/4}$

$$\varepsilon_{\mathrm{m}} = (3.7\times10^{-3}\ \mathrm{eV})\xi_{\mathrm{p}}^{-2}\epsilon_{\mathrm{p}}^{2}\epsilon_{\mathrm{B}}^{1/2}E_{\mathrm{k,53}}^{1/2}t_{\mathrm{s}}^{-3/2}(1+z)^{1/2}$$

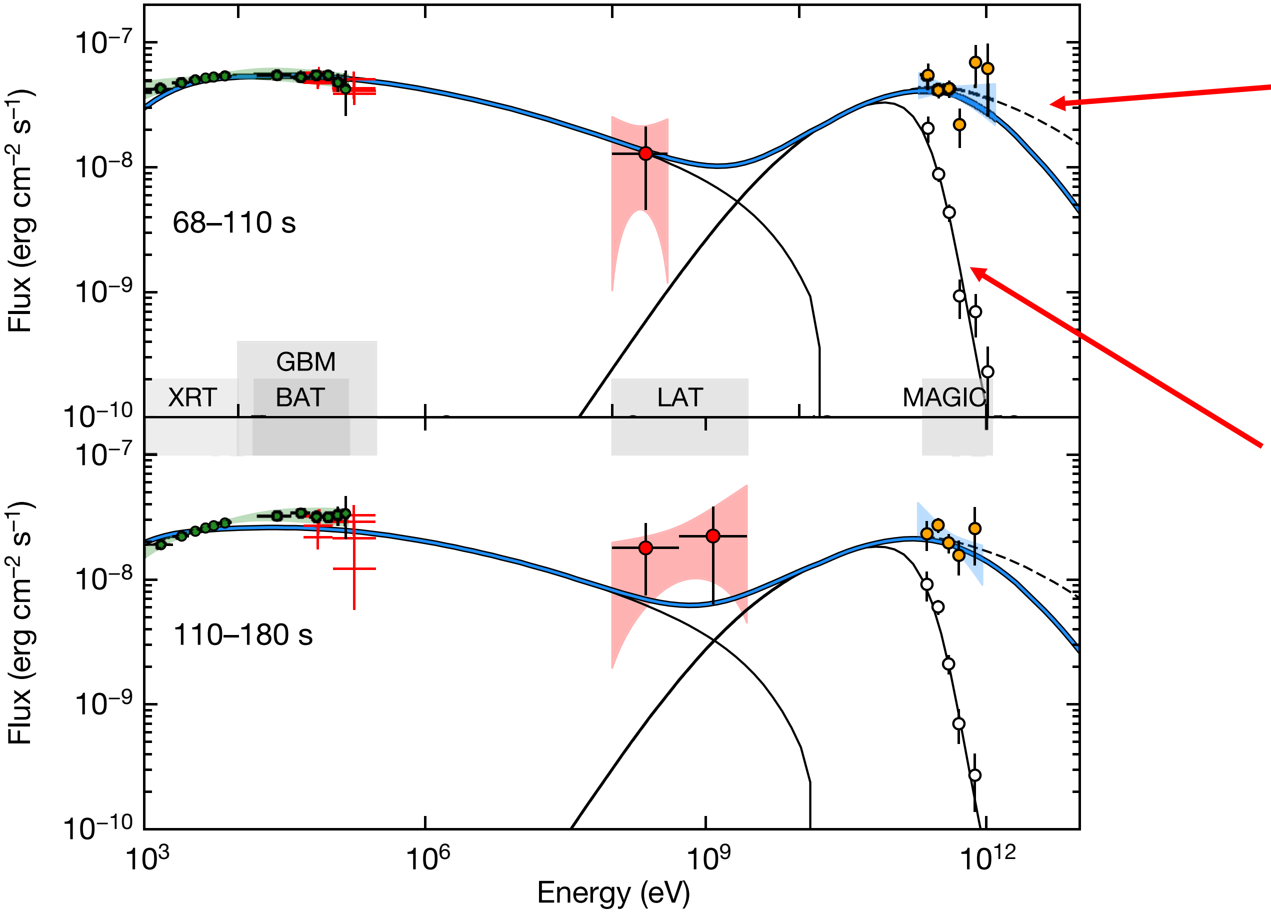
slope –(p+1)/2
above ν_m

$$f(\varepsilon=\varepsilon_{\mathrm{m}}) = (1.3\times10^{-28}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}) \times \xi_{\mathrm{p}}\epsilon_{\mathrm{B}}^{1/2}n_0^{1/2}E_{\mathrm{k,53}}D_{28}^{-2}(1+z)$$

$$F(\varepsilon=1\ \mathrm{TeV}) = (1.1\times10^{-16}\ \mathrm{erg\ cm^{-2}\ s^{-1}}) \times\epsilon_{\mathrm{p}}^{2}\xi_{\mathrm{p}}^{-1}\epsilon_{\mathrm{B}}n_0^{1/2}E_{\mathrm{k,53}}^{3/2}D_{28}^{-2}t_{\mathrm{s}}^{-3/2}(1+z)^{3/2}$$

$n_0^{1/2}E_{\mathrm{k,53}}^{3/2} \gtrsim 10^{11}$ at 100 s !

GRB190114C: model



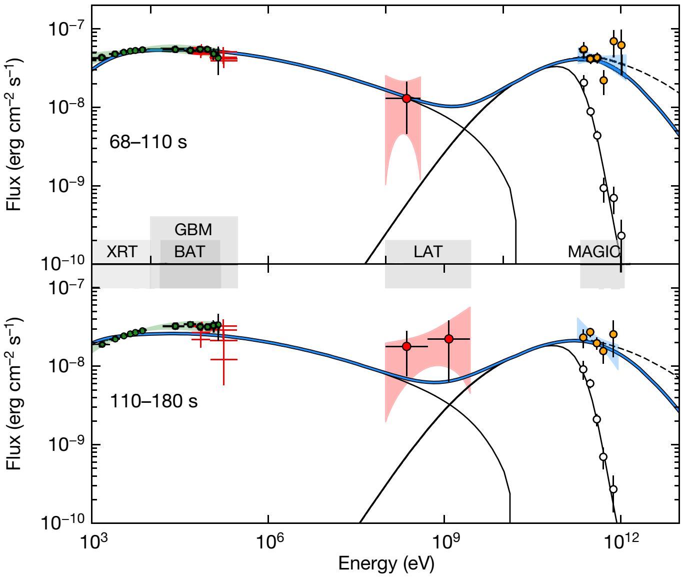
without $\gamma\gamma$

with EBL attenuation

Fig. 3 | Modelling of the broadband spectra in the time intervals 68–110 s and 110–180 s. Thick blue curve, modelling of the multi-band data in the synchrotron and SSC afterglow scenario. Thin solid lines, synchrotron and SSC (observed spectrum) components. Dashed lines, SSC when internal γ–γ opacity is neglected. The adopted parameters are: $s = 0$, $\varepsilon_e = 0.07$, $\varepsilon_B = 8 \times 10^{-5}$, $p = 2.6$, $n_0 = 0.5$ and $E_k = 8 \times 10^{53}$ erg; see Methods. Empty circles show the observed MAGIC spectrum, that is, uncorrected for attenuation caused by the EBL. Contour regions and data points are as in Fig. 2.

GRB190114C: model

Afterglow: external shock



Onset ~ 5-10 s
Initial Lorentz factor ~ 300-700
Lorentz factor at 100 s ~150

-Syn peak at ~10 keV
-IC peak at < TeV
(flat spectrum)

Then: $$\frac{4}{3}\gamma_{\mathrm{m}}^2 \sim \frac{200\,\mathrm{GeV}}{10\,\mathrm{keV}} \sim 2\,10^7$$

$$\gamma_{\mathrm{m}} \sim 4\,10^3$$

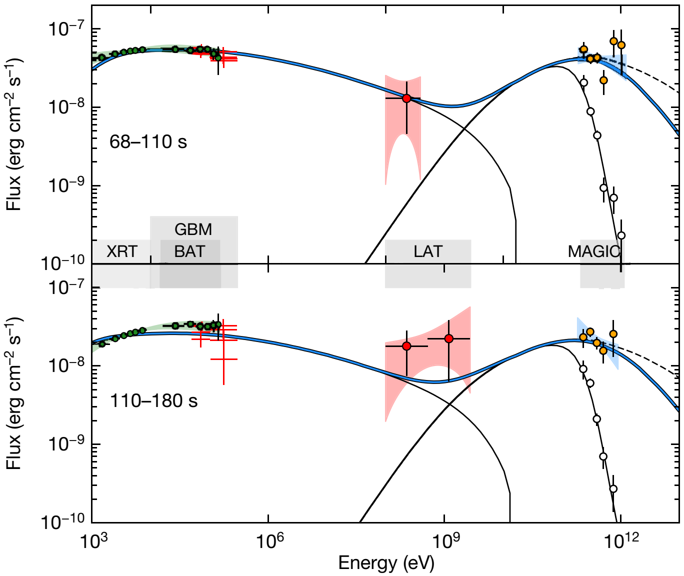
(2 10^3)

Synchrotron peak: $$h\nu_{\mathrm{m}} \simeq 30\,\mathrm{eV}\,\frac{\Gamma}{150}\,\frac{B}{1\,\mathrm{G}}\left(\frac{\gamma_{\mathrm{m}}}{4\,10^3}\right)^2$$ Then: $B \sim 400\,\mathrm{G}$

Problem: - low electron Lorentz factor: low ε_e
- high magnetic field: high ε_B
- **Then: low ε_e / ε_B implies a low efficiency for the simplest version of a SSC model**

This leads to a more complex model when the SSC peak is affected by KN & $\gamma\gamma$.

GRB190114C: model



Detailed model:

Kinetic energy > 3 10^{53} erg
Efficiency of prompt phase > 50%

Radius ~ (8-20) 10^{16} cm at 100 s

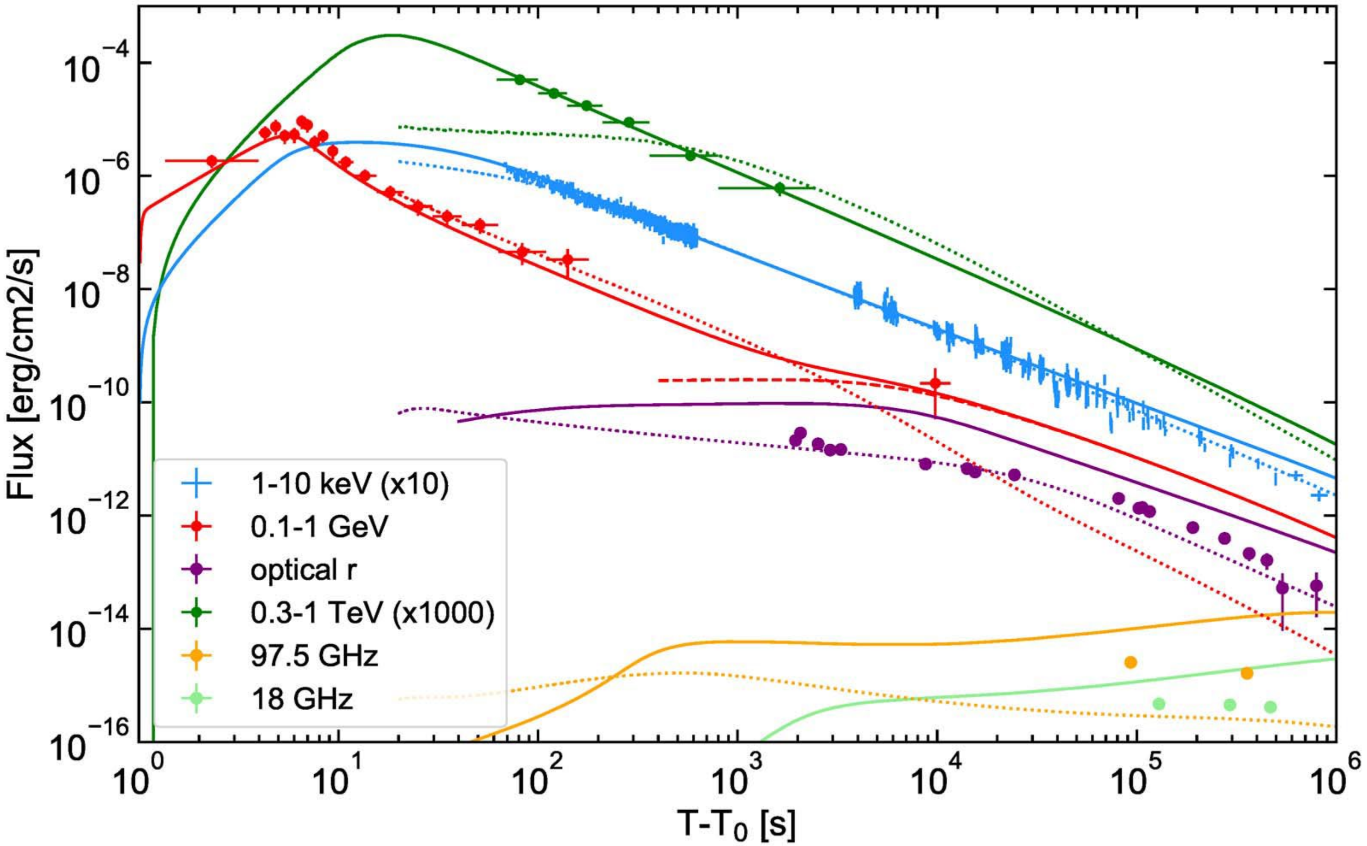
Microphysics:
ε_e ~ 0.05-0.15 ; p ~ 2.4-2.6 ; γ_m ~ (0.8-2) 10^4 at 100 s
ε_B ~ 0.00005-0.001 ; B ~ 0.5-5 G at 100 s

$\varepsilon_e >> \varepsilon_B$: efficient SSC
At 100 s: comparable powers syn and IC

Exernal medium:
- Wind does not work
- Uniform: n_{ext} ~ 0.5-5 cm^{-3}

GRB190114C: model

$s=0, \varepsilon_{\mathrm{e}}=0.07, \varepsilon_{\mathrm{B}}=8\times10^{-5}, p=2.6, n_0=0.5$ and $E_{\mathrm{k}}=8\times10^{53}$ erg



Extended Data Fig. 7 | Modelling of broadband light curves. Modelling results of forward shock emission are compared to observations at different frequencies (see key). The model shown with solid and dashed lines is optimized to describe the high-energy radiation (teraelectronvolt, gigaelectronvolt and X-ray) and has been obtained with the following parameters: $s=0, \varepsilon_{\mathrm{e}}=0.07, \varepsilon_{\mathrm{B}}=8\times10^{-5}, p=2.6, n_0=0.5$ and $E_{\mathrm{k}}=8\times10^{53}$ erg. Solid lines show the total flux (synchrotron and SSC) and the dashed line refers to the SSC contribution only. Dotted curves correspond to a better modelling of observations at lower frequencies, but fail to explain the behaviour of the teraelectronvolt light curve; they are obtained with the following model parameters: $s=2, \varepsilon_{\mathrm{e}}=0.6, \varepsilon_{\mathrm{B}}=10^{-4}, p=2.4, A_*=0.1$ and $E_{\mathrm{k}}=4\times10^{53}$ erg. Vertical bars on the data points show the 1σ errors on the flux, and horizontal bars represent the duration of the observation.

Early NIR-V not modeled (RS) – Late radio: not reproduced.

Summary:

- **Finally detections!**
- **A new window on GRB afterglows**
- **Optimistic prospects for CTA**

- **Afterglow physics: is the external shock + SSC explanation enough?**
  Model proposed with the discovery paper is nice but not fully satisfactory.

  Things to investigate in the same framework:
  effect of pair enrichment in external medium at early times,
  possible contribution of the RS (or of the prompt emission at early times),
  etc.

  Alternatives:
  - External IC (discussed for 190829A, Zhang et al. 2020)
  -Direct synchrotron beyond the burn-off limit?
  (e.g. with evolving B from acceleration to emission zone)
  -Converter acceleration (Derishev)
  - « Pair balance model » (Piran & Derishev)
  -Photo-hadronic processes? (low efficiency)
  - etc.

Summary:

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  etc.

- Prompt TeV emission?
- Transition Prompt-Afterglow?
  (IC scatterings of prompt photons by relativistic electrons in FS)

  Many possibilities to investigate

- Diversity among GRBs ? (short vs long, …)
  GRB190829A (HESS) = low-luminosity burst
  See Fabian Schüssler's presentation