

Inverse Compton emission revealed by multi-wavelength observations of a gamma-ray burst

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1 **Long-duration gamma-ray bursts (GRBs) originate from ultra-relativistic jets launched from**
2 **the collapsing cores of dying massive stars. They are characterised by an initial phase of**
3 **bright (typical observed fluxes $10^{-7} - 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$) and highly variable ($\ll 1$ second)**
4 **radiation in the 0.1-1 MeV band that is likely produced within the jet and lasts from millisec-**
5 **onds to minutes, known as the prompt emission. Following the prompt emission, the interac-**
6 **tion of the ultra-relativistic jet with the external medium generates external shocks, respon-**
7 **sible for the so-called afterglow emission, which lasts from days to months, and occurs over**
8 **a broad energy range, including the soft X-ray, optical and radio bands¹⁻⁵. The origin of the**
9 **afterglow emission is explained and modeled as synchrotron radiation from the shock accel-**
10 **erated electrons⁶⁻⁹. Recently, the Major Atmospheric Gamma Imaging Cherenkov (MAGIC)**
11 **telescopes revealed for the first time intense, long-lasting emission between 0.2 and 1 TeV**
12 **from GRB 190114C¹⁰. Here we present the results of our multi-frequency observational cam-**
13 **paign, and study the evolution in time of the GRB emission across 17 orders of magnitude in**
14 **energy, from 5×10^{-6} up to 10^{12} eV. We find that the broadband spectral energy distribution**
15 **is double-peaked, with the TeV emission constituting a distinct spectral component that has**
16 **power comparable to the synchrotron component. This component is associated with the**
17 **afterglow, and is satisfactorily explained by inverse Compton upscattering of synchrotron**
18 **photons by high-energy electrons. The inclusion of TeV observations in GRB studies gives**
19 **additional information to pinpoint the conditions of the source.**
20 **We find that the inferred conditions required to explain the presence of the TeV component**
21 **and its temporal behaviour are not atypical. Our results support the possibility that inverse**

22 **Compton emission is commonly produced in GRBs.**

23 On 14 January 2019, following an alert from the Neil Gehrels Swift Observatory (hereafter
24 *Swift*) and the *Fermi* satellites, MAGIC observed and detected radiation up to at least 1 TeV from
25 GRB 190114C. **Before the MAGIC detection, GRBs have been detected only at much lower**
26 **energies, $\lesssim 100$ GeV. A hint for the presence of \sim TeV emission ($\gtrsim 650$ GeV) was found by**
27 **the Milagrito experiment from observations of GRB 970417A¹¹. GeV emission has been**
28 **detected first by *CGRO/EGRET* in a handful of cases, and more recently by *AGILE/GRID***
29 **and *Fermi/LAT* (see ¹² for a recent review).**

30 **Detection of TeV radiation** opens a new window in the electromagnetic spectrum for the
31 study of GRBs¹⁰. Its announcement¹³ triggered an extensive campaign of follow-up observations.
32 Owing to the relatively low redshift $z = 0.4245 \pm 0.0005$ (see Methods) of the GRB (corresponding
33 to a luminosity distance of ~ 2.3 Gpc) a comprehensive set of multi-wavelength data could be
34 collected. We present observations gathered from instruments onboard six satellites and 15 ground
35 telescopes (radio, submm and NIR/optical/UV and very high energy gamma-rays; see Methods)
36 for the first ten days after the burst. The frequency range covered by these observations spans more
37 than 17 orders of magnitude, from 1 to $\sim 2 \times 10^{17}$ GHz, the most extensive to date for a GRB. The
38 light curves of GRB 190114C at different frequencies are shown in Fig. 1.

39 The prompt emission of GRB 190114C was simultaneously observed by several space mis-
40 sions (see Methods), covering the spectral range from 8 keV to ~ 100 GeV. The prompt light curve
41 shows a complex temporal structure, with several emission peaks (Methods; Extended Data Fig. 1),

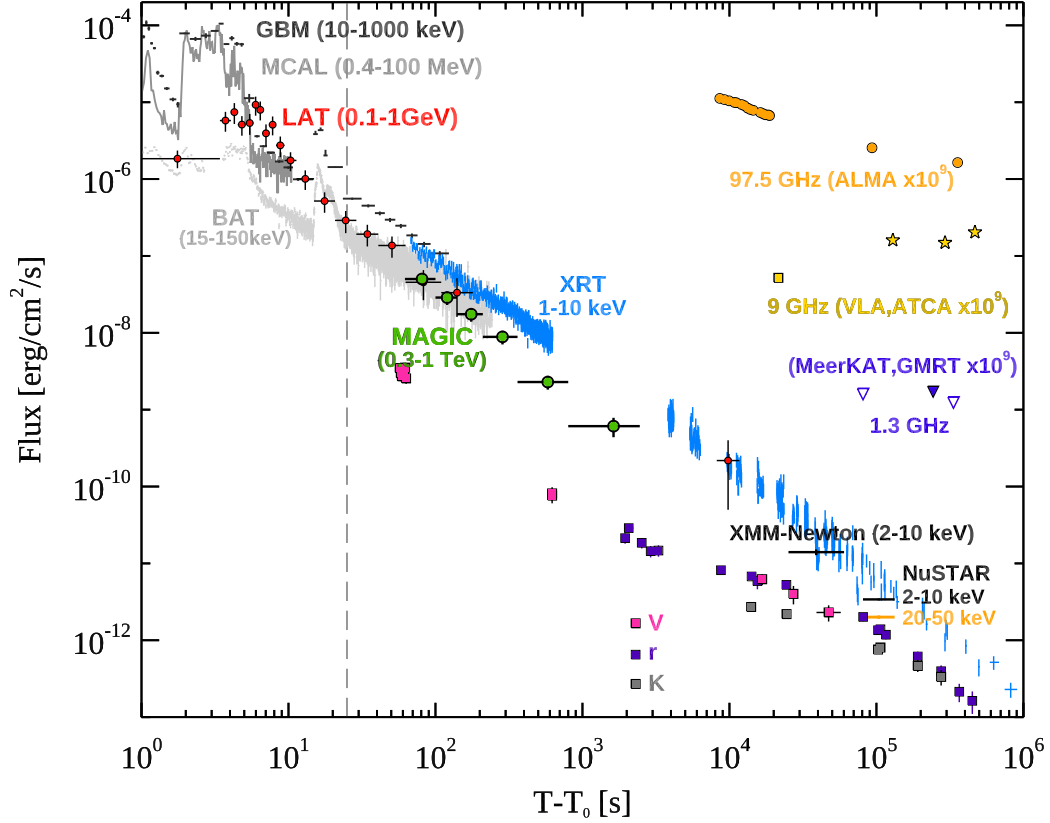


Figure 1: **Multi-wavelength light curves of GRB 190114C.** Energy flux at different wavelengths, from radio to gamma-rays, versus time since the BAT trigger time $T_0 = 20:57:03.19$ UT on 14 January 2019. The light curve for the energy range 0.3-1 TeV (green circles) is compared with light curves at lower frequencies. Those for VLA (yellow square), ATCA (yellow stars), ALMA (orange circles), GMRT (purple filled triangle), and MeerKAT (purple empty triangles) have been multiplied by 10^9 for clarity. The vertical dashed line marks approximately the end of the prompt emission phase, identified with the end of the last flaring episode. For the data points, vertical bars show the $1-\sigma$ errors on the flux, while horizontal bars represent the duration of the observation.

42 with total duration ~ 25 s (see dashed line in Fig. 1) and total radiated energy $E_{\gamma,\text{iso}} = (2.5 \pm 0.1)$
 43 $\times 10^{53}$ ergs¹⁴ (isotropic equivalent in the energy range 1-10000 keV). During the time of inter-burst
 44 quiescence at $t \sim [5 - 15]$ seconds and after the end of the last prompt pulse at $t \gtrsim 25$ s, the flux
 45 decays smoothly, following a power law in time $F \propto t^\alpha$, with $\alpha_{10-1000\text{keV}} = -1.10 \pm 0.01$ ¹⁴. The
 46 temporal and spectral characteristics of this smoothly varying component support an interpretation
 47 in terms of afterglow synchrotron radiation^{14,15}, making this one of the few clear cases of afterglow
 48 emission detected in the band $10 - 10^4$ keV during the prompt emission phase. The onset of the
 49 afterglow component is then estimated to occur around $t \sim 5 - 10$ s^{14,15}, implying an initial bulk
 50 Lorentz factor between 300 and 700 (Methods).

51 After about one minute from the start of the prompt emission, two additional high-energy
 52 telescopes began observations: MAGIC and the XRT, onboard *Swift*. The XRT and MAGIC light
 53 curves (1-10 keV, blue data points in Fig. 1, and 0.3-1 TeV, green data points, respectively) de-
 54 cay with time as a power law, and display the following decay rates: $\alpha_X \sim -1.36 \pm 0.02$ and
 55 $\alpha_{\text{TeV}} \sim -1.51 \pm 0.04$. The 0.3-1 TeV light curve shown in Fig. 1 was obtained after correcting for
 56 attenuation by the extragalactic background light (EBL)¹⁰. The TeV-band emission is observable
 57 until ~ 40 minutes, which is much longer than the nominal duration of the prompt emission phase.
 58 The NIR-optical light curves (square symbols) show a more complex behaviour. Initially, a fast
 59 decay is seen, where the emission is most likely dominated by the reverse shock component¹⁶.
 60 This is followed by a shallower decay, and subsequently a faster decay at $\sim 10^5$ s. The latter be-
 61 haviour is not atypical, **but is usually seen at earlier times and** indicates that the characteristic
 62 synchrotron frequency ν_m is crossing the optical band (**Extended Data Fig. 11**). **The relatively**

63 **late time where the break appears in GRB 190114C would then imply a very large value**
64 **of ν_m , placing it in the X-ray band at $\sim 10^2$ s.** The millimeter light curves (orange symbols)
65 also show an initial fast decay where the emission is dominated by the reverse shock, followed by
66 emission at late times with nearly constant flux (Extended Data Fig. 10).

67 The spectral energy distributions (SEDs) of the radiation detected by MAGIC are shown in
68 Fig. 2, where the whole duration of the emission detected by MAGIC is divided into five time in-
69 tervals. For the first two time intervals, observations in the GeV and X-ray bands are also available.
70 During the first time interval (68-110 s, blue data points and blue confidence regions), *Swift*/XRT-
71 BAT and *Fermi*/GBM data show that the afterglow synchrotron component is peaking in the X-ray
72 band. At higher energies, up to \lesssim GeV, the SED is a decreasing function of energy, as supported
73 by the *Fermi*/LAT flux between 0.1 and 0.4 GeV (see Methods). On the other hand, at even higher
74 energies, the MAGIC flux above 0.2 TeV implies a spectral hardening. This evidence is indepen-
75 dent from the EBL model adopted to correct for the attenuation (Methods). This demonstrates that
76 the newly discovered TeV radiation is not a simple extension of the known afterglow synchrotron
77 emission, but rather a separate spectral component that has not been clearly seen before.

78 The extended duration and the smooth, power-law temporal decay of the radiation detected
79 by MAGIC (see green data points in Fig. 1) suggest an intimate connection between the TeV
80 emission and the broadband afterglow emission. The most natural candidate is synchrotron self-
81 Compton (SSC) radiation in the external forward shock: the same population of relativistic elec-
82 trons responsible for the afterglow synchrotron emission Compton upscatters the synchrotron pho-

83 tons, leading to a second spectral component that peaks at higher energies. TeV afterglow emission
84 can also be produced by hadronic processes such as synchrotron radiation by protons accelerated
85 to ultra-high energies in the forward shock^{17–19}. However, due to their typically low efficiency
86 of radiation⁵, reproducing the luminous TeV emission as observed here by such processes would
87 imply unrealistically large power in accelerated protons¹⁰. TeV photons can also be produced via
88 the SSC mechanism in internal shock synchrotron models of the prompt emission. However, nu-
89 merical modeling (Methods) shows that prompt SSC radiation can account at most for a limited
90 fraction ($\lesssim 20\%$) of the observed TeV flux, and only at early times ($t \lesssim 100$ s). Henceforth, we
91 focus on the SSC process in the afterglow.

92 SSC emission has been predicted for GRB afterglows^{9,12,18,20–27}. However, **its** quantitative
93 significance for the latter was uncertain, as the SSC luminosity and spectral properties depend
94 strongly on poorly constrained physical conditions in the emission region (e.g., the magnetic field
95 strength). The detection of the TeV component in GRB 190114C and the availability of broad
96 band observations offer the opportunity to investigate the relevant physics at a deeper level. **A hint**
97 **of SSC component might have been detected in very bright GRBs, such as GRB 130427A.**
98 **The GRB 130427A extended emission with photons up to ~ 100 GeV is hardly modeled by**
99 **synchrotron processes, suggesting a different origin of the photons^{28–30}.**

100 With this aim, we model the full data set (from radio band to TeV energies, for the first week
101 after the explosion) as synchrotron plus SSC radiation, within the framework of the theory of af-
102 terglow emission from external reverse-forward shocks. The detailed modeling of the broadband

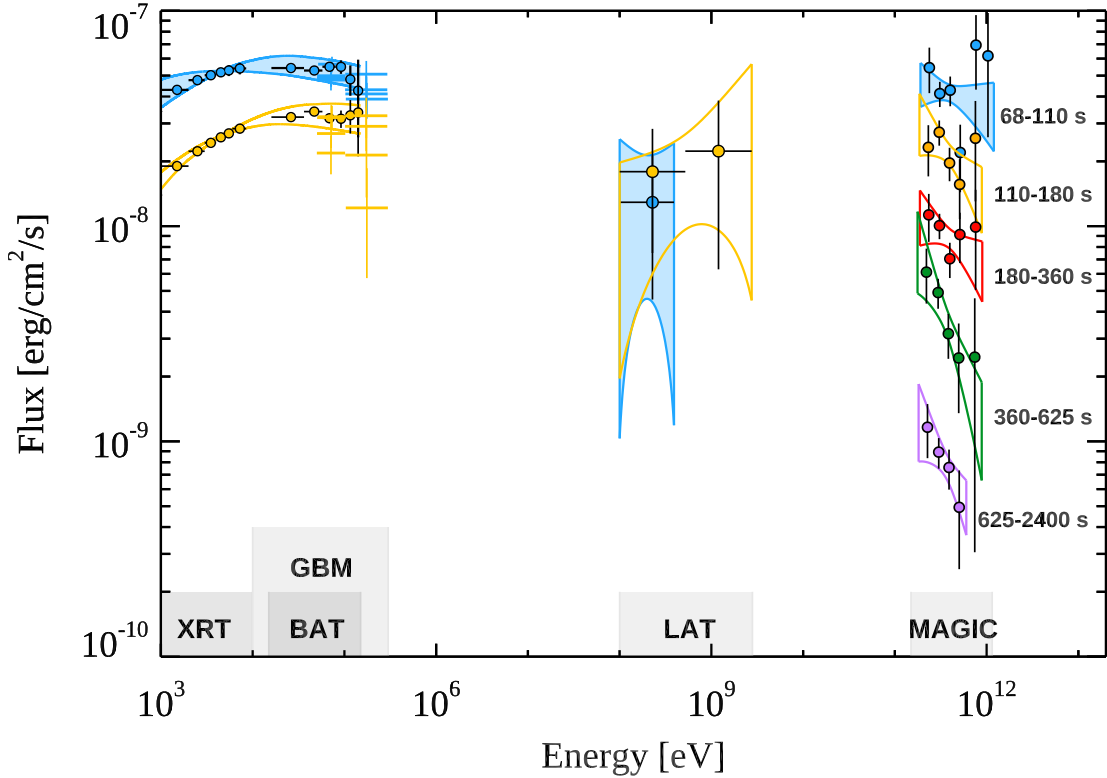


Figure 2: **Broadband spectra in the time interval 68-2400 s.** Five time intervals are considered: 68-110 s (blue), 110-180 s (yellow), 180-360 s (red), 360-625 s (green), 625-2400 s (purple). MAGIC data points have been corrected for attenuation caused by the Extragalactic Background Light. Data from other instruments are shown for the first two time-intervals: *Swift*/XRT, *Swift*/BAT, *Fermi*/GBM, and *Fermi*/LAT. For each time interval, LAT contour regions are shown limiting the energy range to the range where photons are detected. MAGIC and LAT contour regions are drawn from the $1\text{-}\sigma$ error of their best-fit power law functions. For *Swift* data, the regions show the 90% confidence contours for the joint fit XRT-BAT obtained fitting to the data a smoothly broken power law. Filled regions are used for the first time interval (68-110 s, blue color).

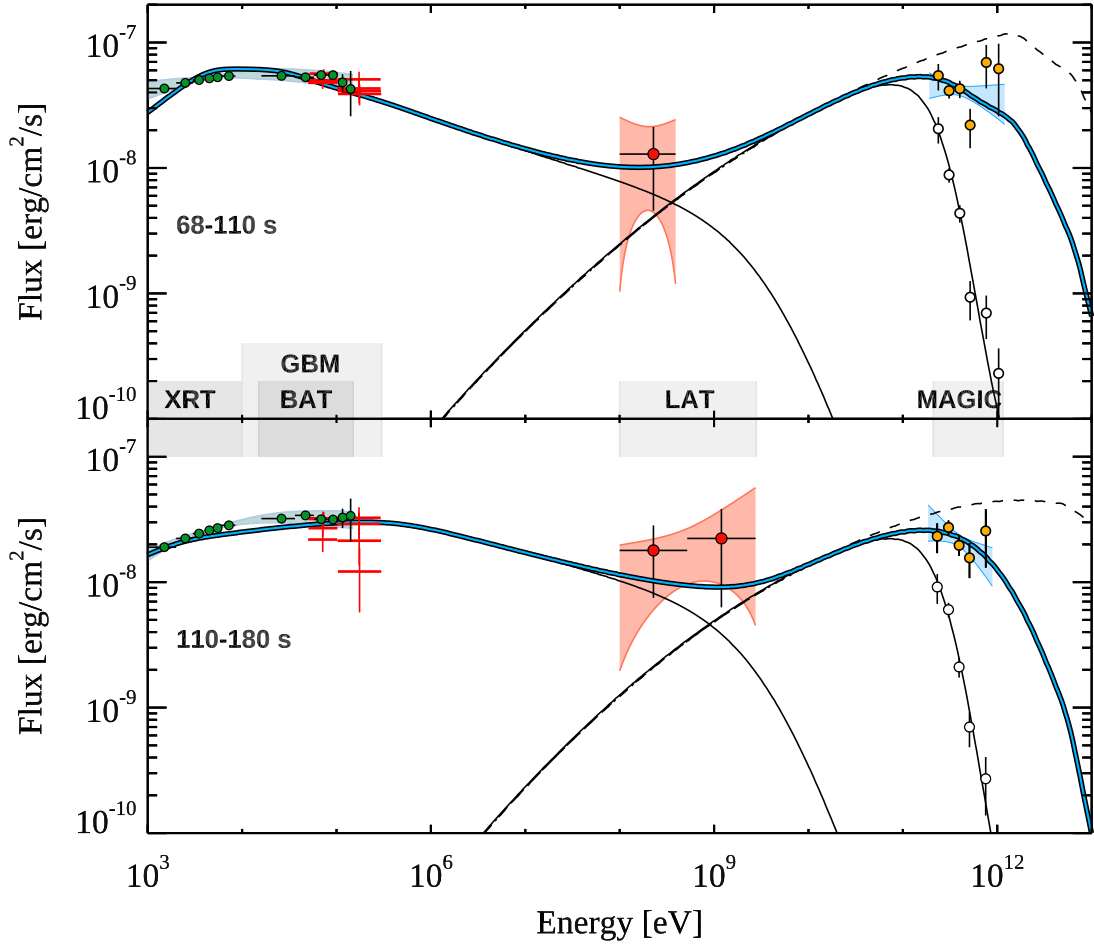


Figure 3: **Modeling of the broadband spectra in the time intervals 68-110 s and 110-180 s.**

Thick blue curve: modeling of the broadband data in the synchrotron and SSC afterglow scenario.

Thin solid lines: synchrotron and SSC (observed spectrum) components; dashed lines: SSC if in-

ternal γ - γ opacity is neglected. For the adopted parameters, see the Text. Empty circles show the

observed MAGIC spectrum, i.e. not corrected by attenuation caused by the Extragalactic Back-

ground Light. Contour regions and data points as in Fig. 2.

103 emission and its evolution with time is presented in Section Methods. We discuss here the impli-
 104 cations for the early time ($t < 2400$ s), high energy (> 1 keV) emission. Information inferred from
 105 late time optical data, allows to identify the peak of the synchrotron component visible in the X-ray
 106 band at ~ 100 s as the characteristic frequency ν_m . The soft spectra (photon index $\Gamma_{\text{TeV}} < -2$) in
 107 the 0.2-1 TeV energy range (see Extended Data Table 1) constrain the peak of the SSC component
 108 to be below this energy range. The relatively small ratio between the spectral peak energies of the
 109 SSC ($E_p^{\text{SSC}} \lesssim 200$ GeV) and synchrotron ($E_p^{\text{syn}} \sim 10$ keV) components implies a relatively low
 110 value for the minimum Lorentz factor of the electrons ($\gamma_m \sim 2 \times 10^3$). This value is inconsistent
 111 with the observation of the synchrotron peak at \gtrsim keV energies, leading to the conclusion that
 112 Klein-Nishina (KN) scattering effects and/or internal opacity caused by γ - γ pair production have
 113 a substantial impact on the spectra. We find that in order to explain the soft spectrum detected by
 114 MAGIC, it is necessary to invoke KN-regime scattering for the electrons radiating at the spectral
 115 peak as well as internal γ - γ absorption.

116 While both effects tend to become less important with time, the spectral index in the 0.2-
 117 1 TeV band remains constant in time (or possibly evolves to softer values; Extended Data Table 1).
 118 This implies that the SSC peak energy is moving to lower energies and crossing the MAGIC energy
 119 band. This places robust constraints on the minimum energy of the electrons: $\gamma_m = (1 - 5) \times 10^4$.
 120 The energy at which attenuation by internal pair production becomes important indicates that the
 121 bulk Lorentz factor is ~ 120 - 140 at 100 s.

122 An example of the theoretical modeling in this scenario is shown in Fig. 3 (blue solid curve,

123 see Methods for details). The dashed line shows the SSC spectrum when internal absorption is
124 neglected. The thin solid line shows the model spectrum including EBL attenuation, in comparison
125 to MAGIC observations (empty circles).

126 We find that acceptable models of the broadband SED can be obtained if the conditions at the
127 source are the following: the initial kinetic energy of the blastwave is $E_k \gtrsim 2 \times 10^{53}$ erg (isotropic-
128 equivalent). At least a fraction $\xi_e \sim 0.1$ in number of the electrons swept up from the external
129 medium are efficiently injected into the acceleration process, and carry a fraction $\epsilon_e \sim 0.05 - 0.15$
130 of the energy dissipated at the shock. The acceleration mechanism produces an electron population
131 characterized by a non-thermal energy distribution, described by a power law with index $p \sim$
132 $2.4 - 2.5$, injection Lorentz factor $\gamma_m = 10^4 - 5 \times 10^4$ and maximum Lorentz factor $\gamma_{e,\max} \sim 10^7$
133 (at ~ 100 s). The magnetic field behind the shock conveys a fraction $\epsilon_B \sim (0.05 - 1) \times 10^{-3}$ of
134 the dissipated energy. At $t \sim 100$ s, corresponding to $R \sim (6 - 8) \times 10^{16}$ cm, the density of the
135 external medium is $n > 1 \text{ cm}^{-3}$, and the magnetic field strength is $B \sim 0.1 - 10$ Gauss. The
136 latter implies that the magnetic field was efficiently amplified from values of a few μGauss that are
137 typical of the unshocked ambient medium, due to plasma instabilities or other mechanisms⁵.

138 The blastwave energy inferred from the modeling is comparable to the amount of energy
139 released in the form of radiation during the prompt phase. The prompt emission mechanism must
140 then have dissipated and radiated no more than half of the initial jet energy, leaving the other half
141 available for the afterglow phase. The modeling of the broadband data also allows us to infer
142 how the total energy is shared between the synchrotron and the SSC components. SSC would be

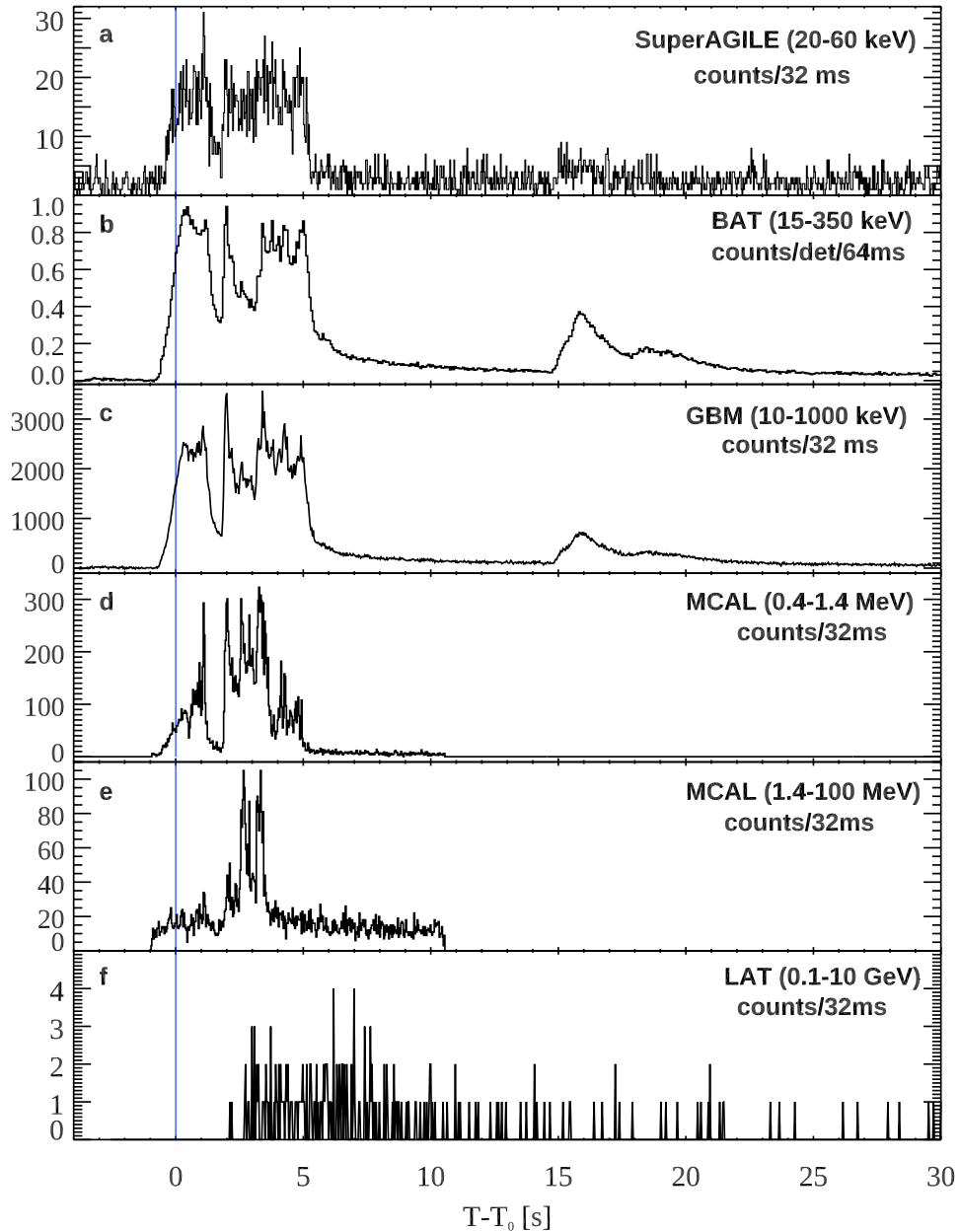
143 2-3 times more energetic than synchrotron if internal γ - γ absorption is neglected, but the latter
144 substantially affects SSC such that the resultant power in the two components are comparable.
145 We estimate that the energy in the synchrotron and SSC component are $\sim 6.5 \times 10^{51}$ erg and
146 $\sim 1.0 \times 10^{52}$ erg respectively in the time interval 68-110 s, and $\sim 9.6 \times 10^{51}$ erg and $\sim 1.6 \times 10^{52}$ erg
147 respectively in the time interval 110-180 s. Thus, previous studies of GRBs may have been missing
148 a significant fraction of the energy **emitted during the afterglow phase** that is essential for its
149 understanding.

150 Finally, we note that the values of the afterglow parameters inferred from the modeling fall
151 within the range of typical values inferred from broadband (radio-to-GeV) afterglow studies. This
152 points to the possibility that SSC emission in GRBs may be a relatively common process that does
153 not require special conditions to be produced with power similar to synchrotron radiation. **Not**
154 **surprisingly, the inferred parameters imply that the energy density of the radiation field is**
155 **much larger than the energy density of the magnetic field^{18,20}, i.e. $\epsilon_e > \epsilon_B$).** The SSC com-
156 ponent may then be detectable in other relatively energetic GRBs (**and might have been already**
157 **detected in past events²⁸⁻³⁰**), as long as the redshift is low enough to avoid severe attenuation by
158 the EBL.

159 **Methods**

160 **Prompt emission observations** On 14 January 2019, the prompt emission from GRB 190114C
161 triggered several space instruments, including *Fermi*/GBM³¹, *Fermi*/LAT³², *Swift*/BAT³³, Super-
162 AGILE³⁴, AGILE/MCAL³⁴, KONUS/Wind³⁵, INTEGRAL/SPI-ACS³⁶, and *Insight*/HXMT³⁷. The
163 prompt emission light curves from AGILE, *Fermi*, and *Swift* are shown in Fig. 1 and in Extended
164 Data Fig. 1, where the trigger time T_0 (here and elsewhere) refers to the BAT trigger time
165 (20:57:03.19 UT). The prompt emission lasts approximately for 25 s, where the last flaring emis-
166 sion episode ends. Nominally, the T_{90} , i.e. the time interval during which a fraction between 5%
167 and 95% of the total emission is observed, is much longer (> 100 s, depending on the instrument¹⁴),
168 but is clearly contaminated by the afterglow component (Fig. 1) and does not provide a good mea-
169 sure of the actual duration of the prompt emission. A more detailed study of the prompt emission
170 phase is reported in ¹⁴.

171 **AGILE** (The Astrorivelatore Gamma ad Immagini LEggero³⁸) could observe GRB 190114C until
172 T_0+330 s, before it became occulted by the Earth. GRB 190114C triggered the Mini-CALorimeter
173 (MCAL) from $T_0-0.95$ s to $T_0+10.95$ s. The MCAL light flux curve in Fig. 1 has been produced
174 using two different spectral models. From $T_0-0.95$ s to $T_0+1.8$ s, the spectrum is fitted by a
175 power law with photon index $\Gamma_{\text{ph}} = -1.97_{-0.70}^{+0.47}$ ($dN/dE \propto E^{\Gamma_{\text{ph}}}$) From $T_0+1.8$ s to $T_0 + 5.5$ s
176 the best fit model is a broken power law with $\Gamma_{\text{ph},1} = -1.87_{-0.19}^{+0.54}$, $\Gamma_{\text{ph},2} = -2.63_{-0.07}^{+0.07}$, and
177 break energy $E_b = 756_{-159}^{+137}$ keV. The total fluence in the 0.4–100 MeV energy range is $F =$
178 1.75×10^{-4} erg cm⁻². The Super-AGILE detector also detected the burst, but the large off-axis
179 angle prevented any X-ray imaging of the burst, as well as spectral analysis. Panels **a**, **d**, and **e**



Extended Data Figure 1: **Prompt emission light curves for different detectors.** The different panels show light curves for: **a**, SuperAGILE (20-60 keV); **b**, *Swift*/BAT (15-150 keV); **c**, *Fermi*/GBM (10-1000 keV); **d**, *AGILE*/MCAL (0.4-1.4 MeV); **e**, *AGILE*/MCAL (1.4-100 MeV); **f**, *Fermi*/LAT (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 the $1-\sigma$ statistical errors.

180 in Extended Data Fig. 1 show the GRB 190114C light curves acquired by the Super-AGILE de-
 181 tector (20 – 60 keV) and by the MCAL detector in the low- (0.4 – 1.4 MeV) and high-energy
 182 (1.4 – 100 MeV) bands.

183 **Fermi/GBM** At the time of the MAGIC observations there are indications that some of the de-
 184 tectors are partially blocked by structure on the *Fermi* Spacecraft that is not modeled in the GBM
 185 detectors’ response. This affects the low-energy part of the spectrum³⁹. For this reason, out of cau-
 186 tion we elected to exclude the energy channels below 50 keV. The spectra detected by the *Fermi*-
 187 Gamma-ray Burst Monitor (GBM)⁴⁰ during the T_0+68 s to T_0+110 s and T_0+110 s to T_0+180 s
 188 intervals are best described by a power law model with photon index $\Gamma_{\text{ph}} = -2.10 \pm 0.08$ and
 189 $\Gamma_{\text{ph}} = -2.05 \pm 0.10$ respectively (Fig. 2 and Fig. 3). The 10-1000 keV light curve in Extended
 190 Data Fig. 1 (panel c) was constructed by summing photon counts for the bright NaI detectors.

191 **Swift/BAT** The 15 – 350 keV mask-weighted light curve of the Burst Alert Telescope (BAT⁴¹)
 192 shows a multi-peaked structure that starts at T_0-7 s (Extended Data Fig. 1, panel b). The 68 – 110 s
 193 and 110 – 180 s spectra shown in Figs. 2 and 3 were derived from joint XRT-BAT fit. The best-
 194 fitting parameters for the whole interval (68 – 180 s) are: column density $N_{\text{H}} = (7.53^{+0.74}_{-1.74}) \times$
 195 10^{22} cm^{-2} at $z = 0.42$, in addition to the galactic value of $7.5 \times 10^{19} \text{ cm}^{-2}$, low-energy photon index
 196 $\Gamma_{\text{ph},1} = -1.21^{+0.40}_{-1.26}$, high-energy spectral index $\Gamma_{\text{ph},2} = -2.19^{+0.39}_{-0.19}$, peak energy $E_{\text{pk}} > 14.5$ keV.
 197 Errors are given at 90% confidence level.

198 **Fermi/LAT** The *Fermi* Large Area Telescope (LAT)⁴² detected a gamma-ray counterpart since the
 199 prompt phase⁴³. The burst left the LAT FoV at T_0+150 s and remained outside the LAT field of

200 view until T_0+8600 s. The count light curve in the energy range 0.1-10 GeV is shown in Extended
 201 Data Fig. 1 (panel **f**). The LAT spectra in the time bins 68–110 s and 110–180 s (Figs. 2 and 3)
 202 are described by a power law with pivot energies of, respectively, 200 MeV and 500 MeV, photon
 203 indices $\Gamma_{\text{ph}}(68 - 110) = -2.02 \pm 0.95$ and $\Gamma_{\text{ph}}(110 - 180) = -1.69 \pm 0.42$, and corresponding
 204 normalisations of $N_{0,68-110} = (2.02 \pm 1.31) \times 10^{-7} \text{ ph MeV}^{-1}\text{cm}^{-2} \text{ s}$ and $N_{0,110-180} = (4.48 \pm$
 205 $2.10) \times 10^{-8} \text{ ph MeV}^{-1}\text{cm}^{-2} \text{ s}$. In each time-interval, the analysis has been performed limited to
 206 the energy range where photons have been detected. The LAT light curve integrated in the energy
 207 range 0.1-1 GeV is shown in Fig. 1.

208 **MAGIC** We used the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) standard soft-
 209 ware ⁴⁴ and followed the steps optimised for the data taking under moderate moon illumination⁴⁵
 210 to analyse the data. The spectral fitting is performed by a forward-folding method assuming a
 211 simple power law as for an intrinsic spectrum taking into account of the Extragalactic Background
 212 Light (EBL) effect using the model of Domínguez et al.⁴⁶. Extended Data Table 1 shows the fitting
 213 results for various time bins (the pivot energy is chosen to minimise the correlation between nor-
 214 malisation and photon index parameters). The data points shown in both Fig. 2 and 3 are obtained
 215 from the observed excess rates in estimated energy whose fluxes are evaluated in true energy using
 216 effective time and a spill-over corrected effective area obtained as a resultant of the best fit.

217 The time resolved analysis hints to a possible spectral evolution from hard to soft values.
 218 Although we can not exclude that the photon indexes are compatible with a constant value of
 219 ~ -2.5 up to 2400 s. The signal and background in the considered time bins are both in the low-
 220 count Poisson regime. Therefore, the correct treatment of the MAGIC data provided here includes

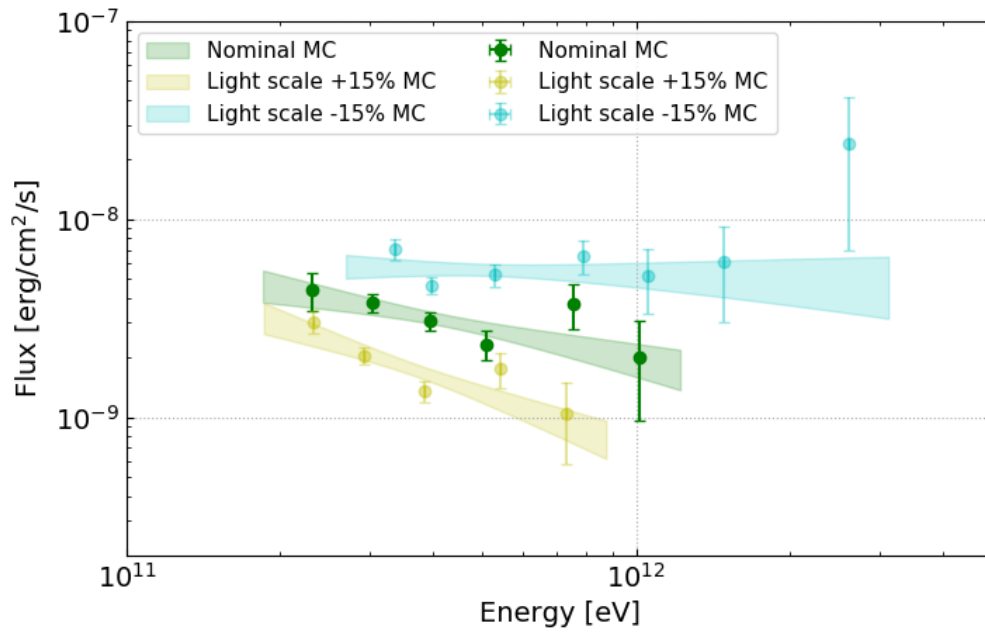
Time bin	Normalisation	Photon index	Pivot energy
[seconds after T_0]	[$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$]		[GeV]
62 - 90	$1.95^{+0.21}_{-0.20} \cdot 10^{-7}$	$-2.17^{+0.34}_{-0.36}$	395.5
68 - 180	$1.10^{+0.09}_{-0.08} \cdot 10^{-7}$	$-2.27^{+0.24}_{-0.25}$	404.7
180 - 625	$2.26^{+0.21}_{-0.20} \cdot 10^{-8}$	$-2.56^{+0.27}_{-0.29}$	395.5
68 - 110	$1.74^{+0.16}_{-0.15} \cdot 10^{-7}$	$-2.16^{+0.29}_{-0.31}$	386.5
110 - 180	$8.59^{+0.95}_{-0.91} \cdot 10^{-8}$	$-2.51^{+0.37}_{-0.41}$	395.5
180 - 360	$3.50^{+0.38}_{-0.36} \cdot 10^{-8}$	$-2.36^{+0.34}_{-0.37}$	395.5
360 - 625	$1.65^{+0.23}_{-0.23} \cdot 10^{-8}$	$-3.16^{+0.48}_{-0.54}$	369.1
625 - 2400	$3.52^{+0.47}_{-0.47} \cdot 10^{-9}$	$-2.80^{+0.48}_{-0.54}$	369.1
62 - 2400 (Nominal MC)	$1.07^{+0.08}_{-0.07} \cdot 10^{-8}$	$-2.51^{+0.20}_{-0.21}$	423.8
62 - 2400 (Light scale +15% MC)	$7.95^{+0.58}_{-0.56} \cdot 10^{-9}$	$-2.91^{+0.23}_{-0.25}$	369.1
62 - 2400 (Light scale -15% MC)	$1.34^{+0.09}_{-0.09} \cdot 10^{-8}$	$-2.07^{+0.18}_{-0.19}$	509.5

Extended Data Table 1: **MAGIC spectral fit parameters for GRB 190114C.** For each time bin, columns represent a) start time and end time of the bin; b) normalisation of the EBL-corrected differential flux at the pivot energy with statistical errors; c) photon indices with statistical errors; d) pivot energy of the fit (fixed).

221 along with the use of the Poisson statistic also the systematic errors. To estimate the main source
222 of systematic error caused by our imperfect knowledge of the absolute instrument calibration and
223 the total atmospheric transmission we vary the light-scale in our Monte Carlo (MC) simulation
224 as suggested in previous studies⁴⁴. The result is reported in the last two lines of Extended Data
225 Table 1 and in Extended Data Fig. 2.

226 The systematic effects deriving from the choice of one particular EBL model were also stud-
227 ied. The analysis performed to obtain the time integrated spectrum was repeated employing other
228 three models⁴⁷⁻⁴⁹ to deconvolve the effect of the EBL from the spectral data. The contribution to
229 the systematic error on the photon index caused by the uncertainty on the EBL model is $\sigma_\alpha = {}^{+0.10}_{-0.13}$
230 which is smaller than the statistical error only (1 standard deviation) as already seen in a previous
231 work¹⁰. On the other hand the contribution to the systematic error on the normalisation, due to
232 choice of the EBL model, is only partially at the same level of the statistical error (1 standard
233 deviation) $\sigma_N = {}^{+0.30}_{-0.08} \times 10^{-8}$. The chosen EBL model returns a lower normalisation with respect
234 to two of the other models and very close to the rest⁴⁷.

235 The MAGIC energy flux light curve that is presented in Fig. 1 was obtained by integrating
236 the best fit spectral model of each time bin from 0.3 to 1 TeV, in the same manner as a previous
237 publication¹⁰. The value of the fitted time constant reported here differs less than two standard
238 deviation from the one previously reported¹⁰. The difference is due to the poor constraints on the
239 spectral fit parameters of the last time bin, which influences the light curve fit.



Extended Data Figure 2: **MAGIC time integrated spectral energy distributions in the time interval 62-2400 s after T_0 .** The green (yellow, blue) points and band show the result with the nominal (+15%, -15%) light scale MC, defining the limits of the systematic uncertainties.

240 **X-ray afterglow observations**

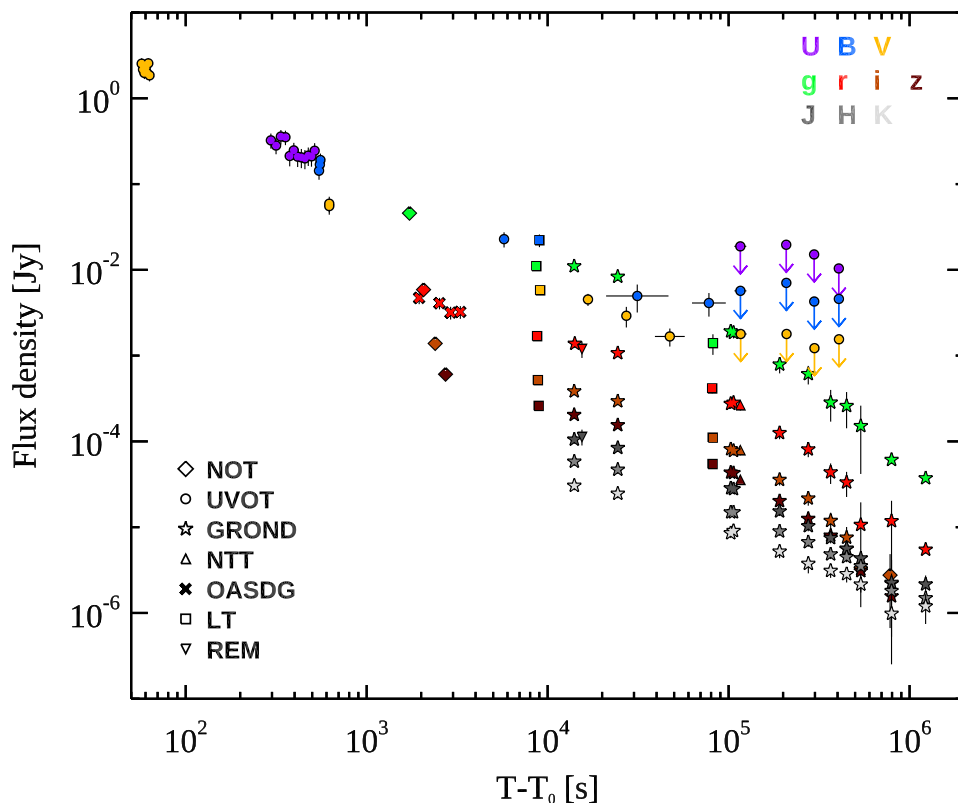
241 **Swift/XRT** The *Swift* X-Ray Telescope (XRT) started observing 68 s after T_0 . The source light
242 curve⁵⁰ was taken from the *Swift*/XRT light curve repository⁵¹ and converted into 1-10 keV flux
243 (Fig. 1) through dedicated spectral fits. The combined spectral fit XRT+BAT in Figs. 2 and 3 has
244 been described above.

245 **XMM-Newton and NuSTAR** The *XMM-Newton* X-ray Observatory and the the Nuclear Spec-
246 troscopic Telescope Array (*NuSTAR*) started observing GRB 190114C under DDT ToOs 7.5 hours
247 and 22.5 hrs (respectively) after the burst. The *XMM-Newton* and NuSTAR absorption-corrected
248 fluxes (see Fig. 1) were derived by fitting the spectrum with XSPEC adopting the same power law
249 model, with absorption in our Galaxy and at the redshift of the burst.

250 **NIR, Optical and UV afterglow observations**

251 Light curves from the different instruments presented in this section are shown in Extended Data
252 Fig. 3.

253 **GROND** The Gamma-ray Burst Optical/Near-infrared Detector (GROND⁵²) started observations
254 3.8 hours after the GRB trigger, and the follow-up continued until January 29, 2019. Image re-
255 duction and photometry were carried out with standard IRAF tasks⁵³, as described in^{54,55}. JHK_s
256 photometry was converted to AB magnitudes to have a common flux system. Final photometry is
257 given in Extended Data Table 2.



Extended Data Figure 3: **NIR/Optical/UV observations GRB 190114C.** Energy flux at different frequencies, as a function of the time since the initial burst T_0 . The flux has been corrected for extinction in the host and in our Galaxy. The contribution of the host galaxy and its companion has been subtracted. Fluxes have been rescaled (except for the r filter). The change in decay rate at $\sim 3 \times 10^3$ s is caused by the transition from the fast cooling to the slow cooling regime.

258 **GTC** The BOOTES-2 ultra-wide field camera⁵⁶, took an image at the GRB 190114C location,
259 starting at 20:57:18 UT (30 s exposure time) (see Extended Data Fig. 4). The Gran Canarias
260 Telescope (GTC) equipped with the OSIRIS spectrograph⁵⁷ started observations 2.6 hr post-burst.
261 The grisms R1000B and R2500I were used covering the wavelength range 3,700-10,000 Å (600 s
262 exposure times for each grism). The GTC detects a highly extinguished continuum, as well as CaII
263 H and K lines in absorption, and [OII], H β , and [OIII] in emission (see Extended Data Fig. 5), all
264 roughly at the same redshift $z = 0.4245 \pm 0.0005$ ⁵⁸. Comparing the derived rest-frame equivalent
265 widths (EWs) with the work by⁵⁹, GRB 190114C clearly shows higher than average, but not
266 unprecedented, values.

267 **HST** The *Hubble Space Telescope* (HST) imaged the afterglow and host galaxy of GRB 190114C
268 on 11 February and 12 March 2019. HST observations clearly reveal that the host galaxy is spiral
269 (Extended Data Fig. 6). A direct subtraction of the epochs of F850LP observations yields a faint
270 residual close to the nucleus of the host (Extended Data Fig. 7). From the position of the residual
271 we estimate that the burst originated within 250 pc of the host galaxy nucleus.

272 **LT** The robotic 2-m Liverpool Telescope (LT⁶⁰) slewed to the afterglow location at UTC 2019-
273 01-14.974 and on the second night, from UTC 2019-01-15.814 and acquired images in B , g , V , r ,
274 i and z bands (45 s exposure each in the first night and 60 s in the second). Aperture photometry
275 of the afterglow was performed using a custom IDL script with a fixed aperture radius of 1.5".
276 Photometric calibration was performed relative to stars from the Pan-STARRS1 catalogue⁶¹.

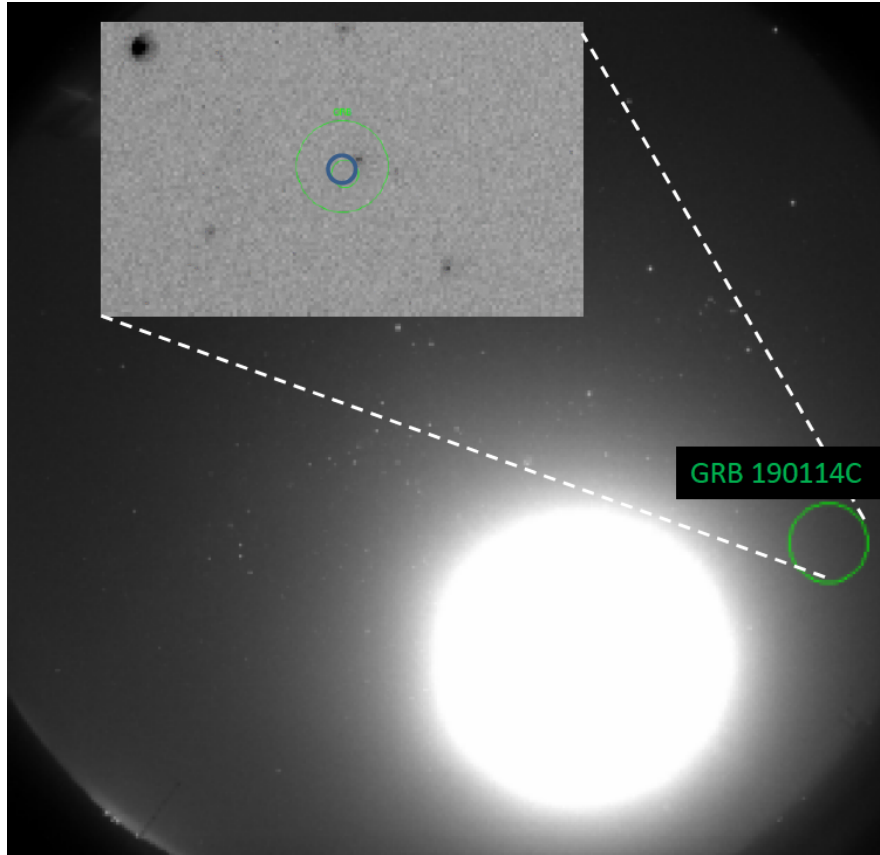
T_{GROND}	AB magnitude						
(s)	g'	r'	i'	z'	J	H	K_s
14029.94 ± 335.28	19.21 ± 0.03	18.46 ± 0.03	17.78 ± 0.03	17.33 ± 0.03	16.78 ± 0.05	16.30 ± 0.05	16.03 ± 0.07
24402.00 ± 345.66	19.50 ± 0.04	18.72 ± 0.03	18.05 ± 0.03	17.61 ± 0.03	17.02 ± 0.05	16.53 ± 0.05	16.26 ± 0.08
102697.17 ± 524.01	20.83 ± 0.06	20.00 ± 0.04	19.30 ± 0.04	18.87 ± 0.03	18.15 ± 0.05	17.75 ± 0.06	17.40 ± 0.09
106405.63 ± 519.87	20.86 ± 0.05	19.98 ± 0.03	19.34 ± 0.03	18.88 ± 0.03	18.17 ± 0.06	17.75 ± 0.06	17.34 ± 0.09
191466.77 ± 751.37	21.43 ± 0.07	20.61 ± 0.03	19.97 ± 0.03	19.52 ± 0.03	18.77 ± 0.06	18.28 ± 0.06	17.92 ± 0.14
275594.19 ± 747.59	21.57 ± 0.07	20.88 ± 0.04	20.31 ± 0.04	19.87 ± 0.04	19.14 ± 0.07	18.57 ± 0.06	18.26 ± 0.21
366390.74 ± 1105.79	21.87 ± 0.07	21.17 ± 0.04	20.62 ± 0.03	20.15 ± 0.03	19.43 ± 0.06	18.89 ± 0.06	18.46 ± 0.15
448791.55 ± 1201.33	21.90 ± 0.08	21.27 ± 0.04	20.79 ± 0.04	20.33 ± 0.03	19.66 ± 0.07	18.97 ± 0.07	18.55 ± 0.18
537481.41 ± 1132.16	22.02 ± 0.09	21.52 ± 0.05	21.00 ± 0.04	20.55 ± 0.03	19.87 ± 0.07	19.20 ± 0.07	18.83 ± 0.17
794992.63 ± 1200.69	22.14 ± 0.04	21.51 ± 0.03	21.05 ± 0.04	20.71 ± 0.05	20.31 ± 0.13	19.79 ± 0.14	19.59 ± 0.41
1226716.84 ± 1050.15	22.17 ± 0.04	21.59 ± 0.04	21.26 ± 0.04	20.97 ± 0.04	20.34 ± 0.12	19.95 ± 0.11	19.40 ± 0.34

Extended Data Table 2: **GROND photometry.** T_{GROND} in seconds after the BAT trigger.

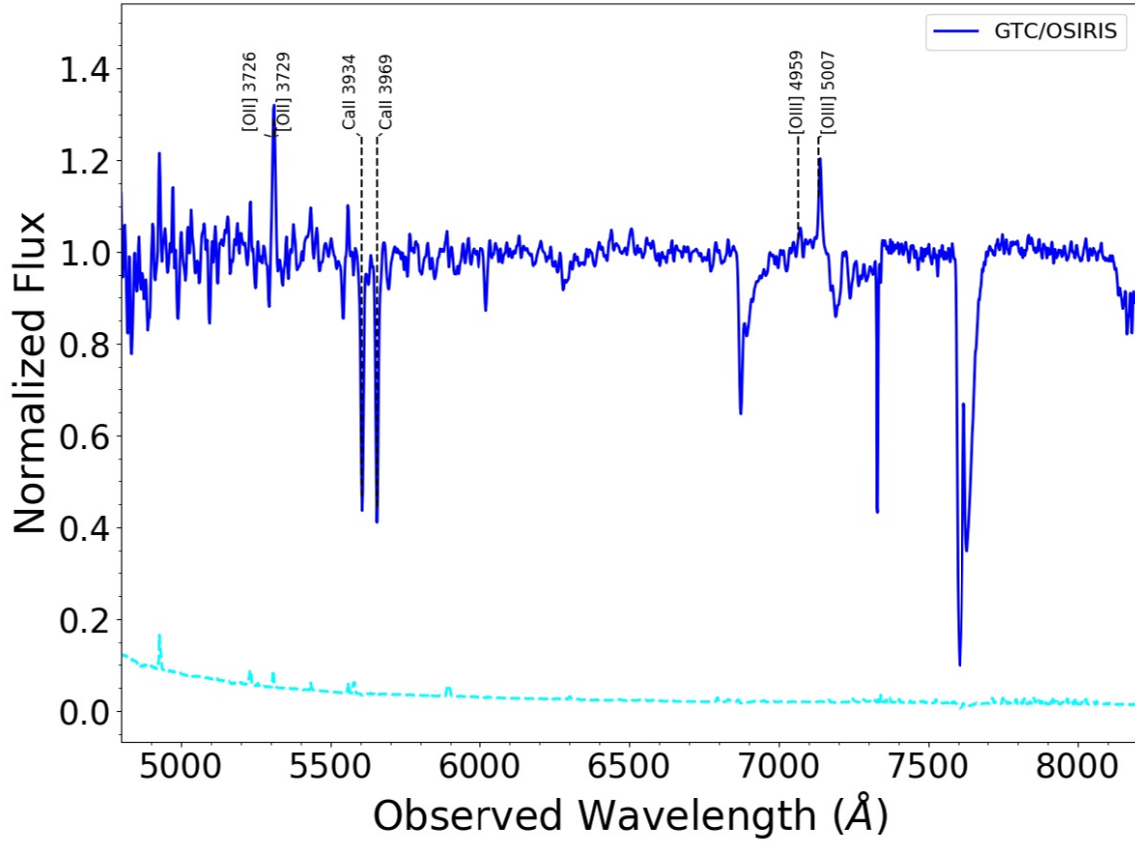
The AB magnitudes are not corrected for the Galactic foreground reddening.

UTC	Instrument	Filter	Exposure (s)	Magnitude
2019-01-14.975	LT/IO:O	g	45	19.08±0.06
2019-01-14.976	LT/IO:O	r	45	18.22±0.02
2019-01-14.977	LT/IO:O	i	45	17.49±0.02
2019-01-14.978	LT/IO:O	z	45	17.12±0.02
2019-01-14.979	LT/IO:O	B	45	19.55±0.15
2019-01-14.980	LT/IO:O	V	45	18.81±0.08
2019-01-15.814	LT/IO:O	r	60	19.61±0.05
2019-01-15.818	LT/IO:O	z	60	18.70±0.06
2019-01-15.820	LT/IO:O	i	60	19.04±0.04
2019-01-15.823	LT/IO:O	g	60	20.96±0.17

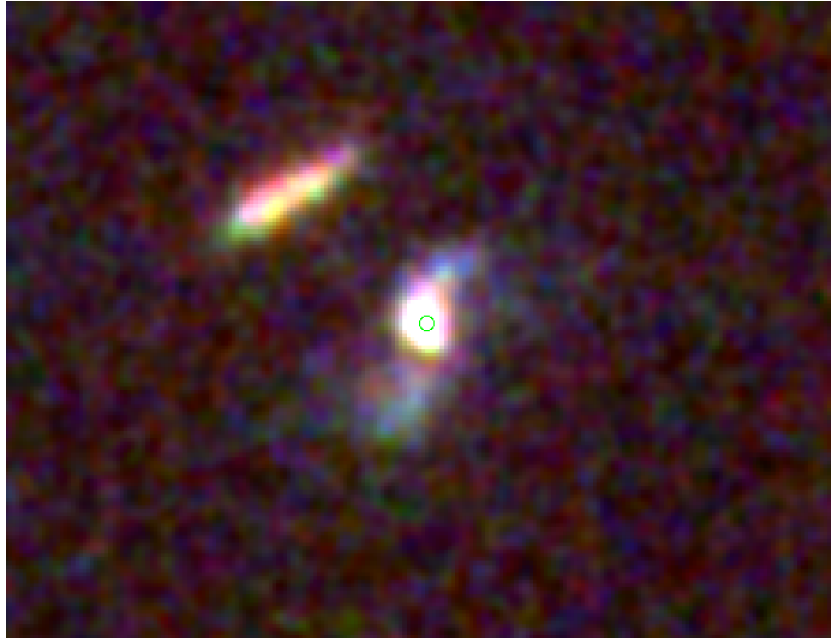
Extended Data Table 3: **Liverpool Telescope observations.** Magnitudes are SDSS AB-”like” for ugriz, Vega-”like” for BV and are not corrected for Galactic extinction.



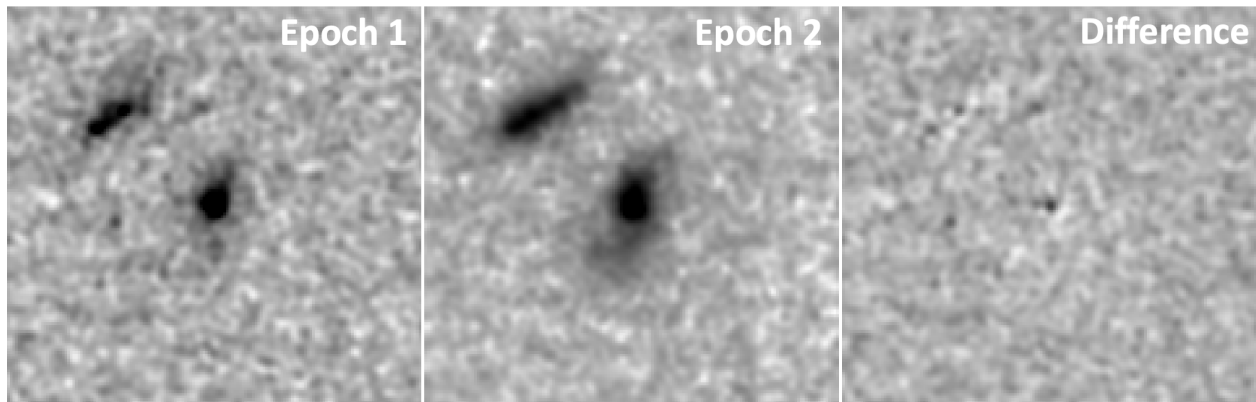
Extended Data Figure 4: **The CASANDRA-2 at the BOOTES-2 station all-sky image.** The image (30s exposure, unfiltered) was taken on Jan 14, 20:57:18 U.T. At the GRB190114C location (circle) no prompt optical emission is detected simultaneously to the gamma-ray photons (which started to arrive at 20:57:03 U.T.) See main text.



Extended Data Figure 5: **The GTC (+OSIRIS) spectrum.** The normalised spectrum of the GRB 190114C optical afterglow on Jan 14, 23:32:03 UT, taken with the R1000B and R2500I grisms. The emission lines of the underlying host galaxy are noticeable, besides the Ca II absorption lines in the afterglow spectrum (all of them are labelled). The cyan dotted line represents the noise. See main text.



Extended Data Figure 6: **Three-colour image of the host of GRB 190114C with the HST.** The host galaxy is a spiral galaxy, and the green circle indicates the location of the transient close to its host nucleus. The image is 8'' across, north is up and east to the left.



Extended Data Figure 7: **F850LP imaging of GRB 190114C taken with the HST.** Two epochs are shown (images are $4''$ across), as well as the result of the difference image. A faint transient is visible close to the nucleus of the galaxy, and we identify this as the late time afterglow of the burst.

277 **NTT** The ESO New Technology Telescope (NTT) observed the optical counterpart of GRB 190114C
 278 under the extended Public ESO Spectroscopic Survey for Transient Objects (ePESSTO) using the
 279 NTT/EFOOSC2 instrument in imaging mode⁶². Observations started at 04:36:53 UT on 2019 Jan-
 280 uary 16 with the g, r, i, z Gunn filters. Image reduction was carried out by following the standard
 281 procedures⁶³.

282 **OASDG** The 0.5 m remote telescope of the Osservatorio Astronomico “S. Di Giacomo” (OASDG),
 283 located in Agerola (Italy) started observations in the optical Rc -band 0.54 hours after the burst. The
 284 afterglow of GRB 190114C was clearly detected in all the images.

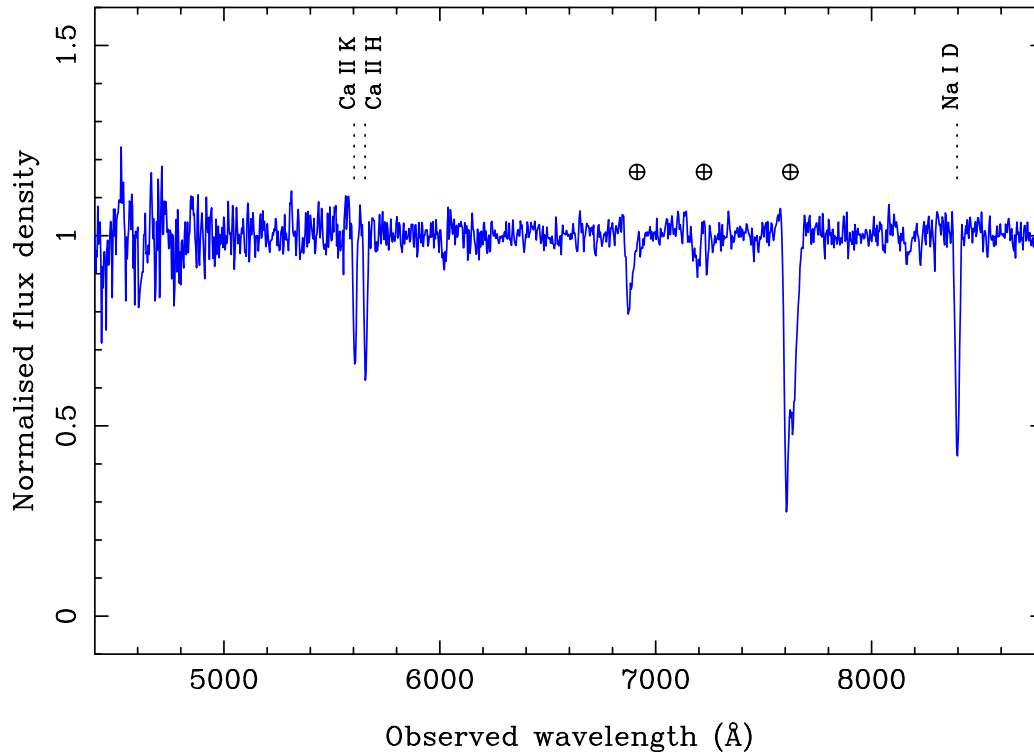
285 **NOT** The Nordic Optical Telescope (NOT) observed the optical afterglow of GRB 190114C with
 286 the Alhambra Faint Object Spectrograph and Camera (AlFOSC) instrument. Imaging was obtained

287 in the *griz* filters with 300 s exposures, starting at Jan 14 21:20:56 UT, 24 minutes after the BAT
288 trigger. The normalised spectrum (Extended Data Fig. 8) reveals strong host interstellar absorption
289 lines due to Ca H & K and Na I D, which provided a redshift of $z = 0.425$.

290 **REM** The Rapid Eye Mount telescope (REM) performed optical and NIR observations with
291 the REM 60 cm robotic telescope equipped with the ROS2 optical imager and the REMIR NIR
292 camera⁶⁴. Observations were performed starting about 3.8 hours after the burst in the *r*, and *J*
293 bands and lasted about one hour.

294 **Swift/UVOT** The *Swift* UltraViolet and Optical Telescope (UVOT⁶⁵) began observations at $T_0 + 54$
295 seconds in the UVOT *v* band. The first observation after settling started 74 s after the trigger for
296 150 s in the UVOT *white* band⁶⁶. A 50 s exposure with the UV grism was taken thereafter, followed
297 by multiple exposures rotating through all seven broad and intermediate-band filters until switching
298 to only UVOT's clear white filter on 2019-01-20. Standard photometric calibration and methods
299 were used for deriving the aperture photometry^{67,68}. The grism zeroth order the data were reduced
300 manually⁶⁹ to derive the *b*-magnitude and error.

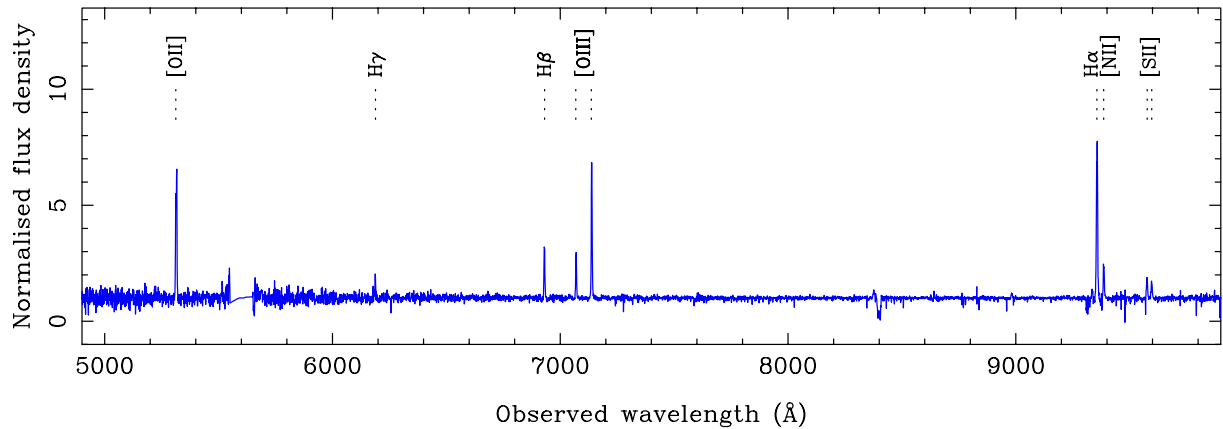
301 **VLT** The STARGATE collaboration used the Very Large Telescope (VLT) and observed GRB 190114C
302 using the X-shooter spectrograph. Detailed analysis will be presented in forthcoming papers. A
303 portion of the second spectrum is shown in Extended Data Fig. 9, illustrating the strong emission
304 lines characteristic of a strongly star-forming galaxy, whose light is largely dominating over the
305 afterglow at this epoch.



Extended Data Figure 8: **The NOT/AIFOSC spectrum.** The NOT/AIFOSC spectrum obtained at a mid-time 1 hr post-burst. The continuum is afterglow dominated at this time, and shows strong absorption features of Ca II and Na I (in addition to telluric absorption).

UTC	$t-t_0$ (d)	Filter	Exposure (s)	Magnitude (AB)
2019-01-14.89127	0.0183	<i>g</i>	1 × 300	17.72±0.03
2019-01-14.89512	0.0222	<i>r</i>	1 × 300	16.93±0.02
2019-01-14.89899	0.0260	<i>i</i>	1 × 300	16.42 ±0.04
2019-01-14.90286	0.0299	<i>z</i>	1 × 300	16.17 ±0.04
2019-01-23.8896	9.0167	<i>i</i>	6 × 300	21.02±0.05

Extended Data Table 4: **Nordic Optical Telescope/AIFOSC observations.** Magnitudes are in the SDSS AB system and are not corrected for Galactic extinction.



Extended Data Figure 9: **The VLT/X-shooter spectrum.** The visible light region of the VLT/X-shooter spectrum obtained approximately 3.2 d post-burst, showing strong emission lines from the star-forming host galaxy.

306 **Magnitudes of the underlying galaxies** The *HST* images show a spiral or tidally disrupted galaxy
307 whose bulge is coincident with the coordinates of GRB 190114C. A second galaxy is detected at an
308 angular distance of $1.3''$, towards the North East. The SED analysis was performed with LePhare
309 ^{70,71} using an iterative method that combined both the resolved photometry of the two galaxies
310 found in the *HST* and *VLT/HAWK-I* data and the blended photometry from *GALEX* and WISE,
311 where the spatial resolution was much lower. Further details will be given in a paper in preparation
312 (de Ugate Postigo et al.). The estimated photometry, for each object and their combination, is given
313 in Extended Data Table 5.

314 **Optical Extinction** The optical extinction toward the line of sight of a GRB is derived assuming
315 a a power law as intrinsic spectral shape⁷². Once the Galactic extinction ($E_{B-V} = 0.01^{73}$) is taken
316 into account and the fairly bright host galaxy contribution is properly subtracted, a good fit to the
317 data is obtained with the LMC recipe and $A_V = 1.83 \pm 0.15$. The spectral index β ($F_\nu \propto \nu^{\beta_o}$)
318 evolves from hard to soft across the temporal break in the optical light-curve at about 0.5 days,
319 moving from $\beta_{o,1} = 0.10 \pm 0.12$ to $\beta_{o,2} = 0.48 \pm 0.15$.

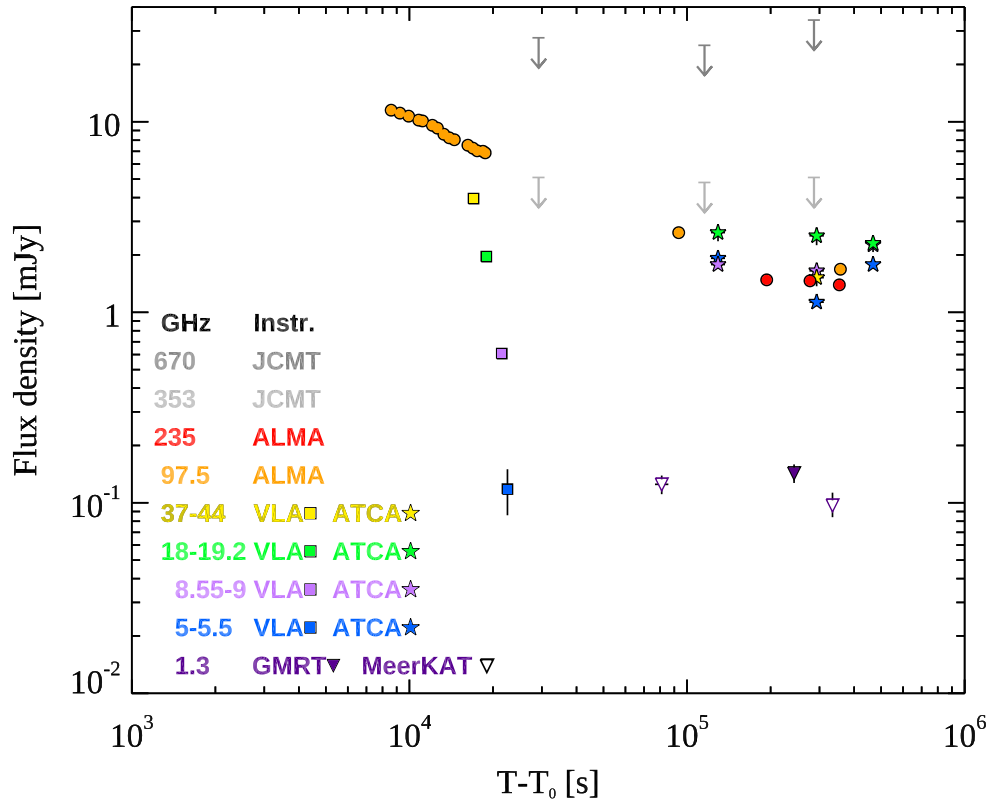
320 **Radio and Sub-mm afterglow observations**

321 The light curves from the different instruments is shown in Extended Data Fig. 10.

322 **ALMA** The Atacama Large Millimetre/Submillimetre Array (ALMA) observations are reported
323 in Band 3 (central observed frequency of 97.500 GHz) and Band 6 (235.0487 GHz), between 2019
324 January 15 and 2019 January 19. Data were calibrated within CASA (Common Astronomy Soft-
325 ware Applications, version 5.4.0⁷⁴) using the pipeline calibration. Photometric measurements were

Filter	Host	Companion	Combined
Sloan u	23.54	25.74	23.40
Sloan g	22.51	23.81	22.21
Sloan r	22.13	22.81	21.66
Sloan i	21.70	22.27	21.19
Sloan z	21.51	21.74	20.87
2MASS J	20.98	21.08	20.28
2MASS H	20.68	20.82	20.00
2MASS K_s	20.45	20.61	19.77

Extended Data Table 5: **Observations of the host galaxy.** For each filter, the estimated magnitudes are given for the host galaxy of GRB 190114C, the companion and the combination of the two objects.



Extended Data Figure 10: **Radio and sub-mm observations GRB 190114C:** energy flux at different frequencies, from 1.3 GHz to 670 GHz, as a function of the time since the initial burst T_0 .

326 also performed within CASA. ALMA early observations at 97.5 GHz are taken from ¹⁶.

327 **ATCA** The Australia Telescope Compact Array (ATCA) observations were made with the ATCA
328 4 cm receivers (band centres 5.5 and 9 GHz), 15 mm receivers (band centres 17 and 19 GHz), and
329 7 mm receivers (band centres 43 and 45 GHz). ATCA data were obtained using the CABB con-
330 tinuum mode ⁷⁵ and reduced with the software packages MIRIAD ⁷⁶ and CASA ⁷⁴ using standard
331 techniques. The quoted errors are 1σ , which include the RMS and Gaussian 1σ errors.

332 **GMRT** The upgraded Giant Metre-wave Radio Telescope ⁷⁷ (UGMRT) observed on 17th January
333 2019 13.44 UT (2.8 days after the burst) in band 5 (1000-1450 MHz) with 2048 channels spread
334 over 400 MHz. GMRT detected a weak source with a flux density of $73\pm 17 \mu\text{Jy}$ at the GRB
335 position ⁷⁸. The flux should be considered as an upper limit, as the contribution from the host ⁷⁹ has
336 not been subtracted.

337 **MeerKAT** The new MeerKAT radio observatory ^{80,81} observed on 15 and 18 January 2019, with
338 DDT requested by the ThunderKAT Large Survey Project ⁸². Both epochs used 63 antennas and
339 were done at L-band spanning 856 MHz and centered at 1284 MHz. MeerKAT flux estimation
340 was done by finding and fitting the source with the software PyBDSF v.1.8.15 ⁸³. Adding the RMS
341 noise in quadrature to the flux uncertainty leads to final flux measurements of $125\pm 14 \mu\text{Jy}/\text{beam}$
342 on 15 January and $97\pm 16 \mu\text{Jy}/\text{beam}$ on 18 January. The contribution from the host galaxy ⁷⁹ has
343 not been subtracted. Therefore, these measurements provide a maximum flux of the GRB.

344 **JCMT SCUBA-2 Sub-millimeter** Sub-millimeter observations were performed simultaneously
345 at $850 \mu\text{m}$ and $450 \mu\text{m}$ on three nights using the SCUBA-2 continuum camera ⁸⁴. GRB 190114C

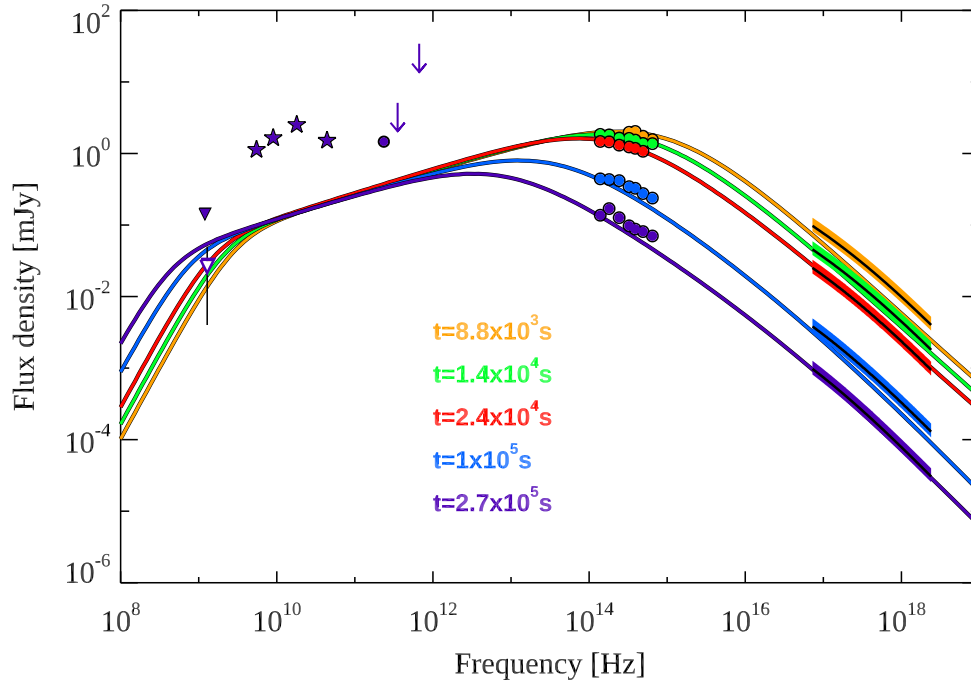
Start Date and Time	End Date and Time	Frequency GHz	Flux mJy
1/16/2019 6:47:00	1/16/2019 10:53:00	5.5	1.92±0.06
		9	1.78±0.06
		18	2.62±0.26
1/18/2019 1:45:00	1/18/2019 11:18:00	5.5	1.13±0.04
		9	1.65±0.05
		18	2.52±0.27
		44	1.52±0.15
1/20/2019 3:38	1/20/2019 10:25:00	5.5	1.78±0.06
		9	2.26±0.07
		18	2.30±0.23

Extended Data Table 6: **Observations by ATCA.** Start and end date and times (UTC) of the observations, frequency, and flux (1σ error).

UT Date	Time since trigger (days)	Time on source (hours)	Typical 225 GHz CSO Opacity ^a	Typical elevation (degrees)	850 μ m RMS density (mJy/beam)	450 μ m RMS density (mJy/beam)
2019-01-15	0.338	1.03	0.026	39	1.7	9.2
2019-01-16	1.338	1.03	0.024	39	1.6	8.4
2019-01-18	3.318	0.95	0.031	37	1.7	11.4

Extended Data Table 7: **JCMT SCUBA-2 sub-millimeter observations of GRB 190114C.**

^aThe CSO 225 GHz tau measures the zenith atmospheric attenuation.



Extended Data Figure 11: **Radio to X-rays SED at different epochs.** The synchrotron frequency ν_m crosses the optical band, moving from higher to lower frequencies. The break between 10^8 and 10^{10} Hz is caused by the self-absorption synchrotron frequency ν_{sa} . Optical (X-ray) data have been corrected for extinction (absorption).

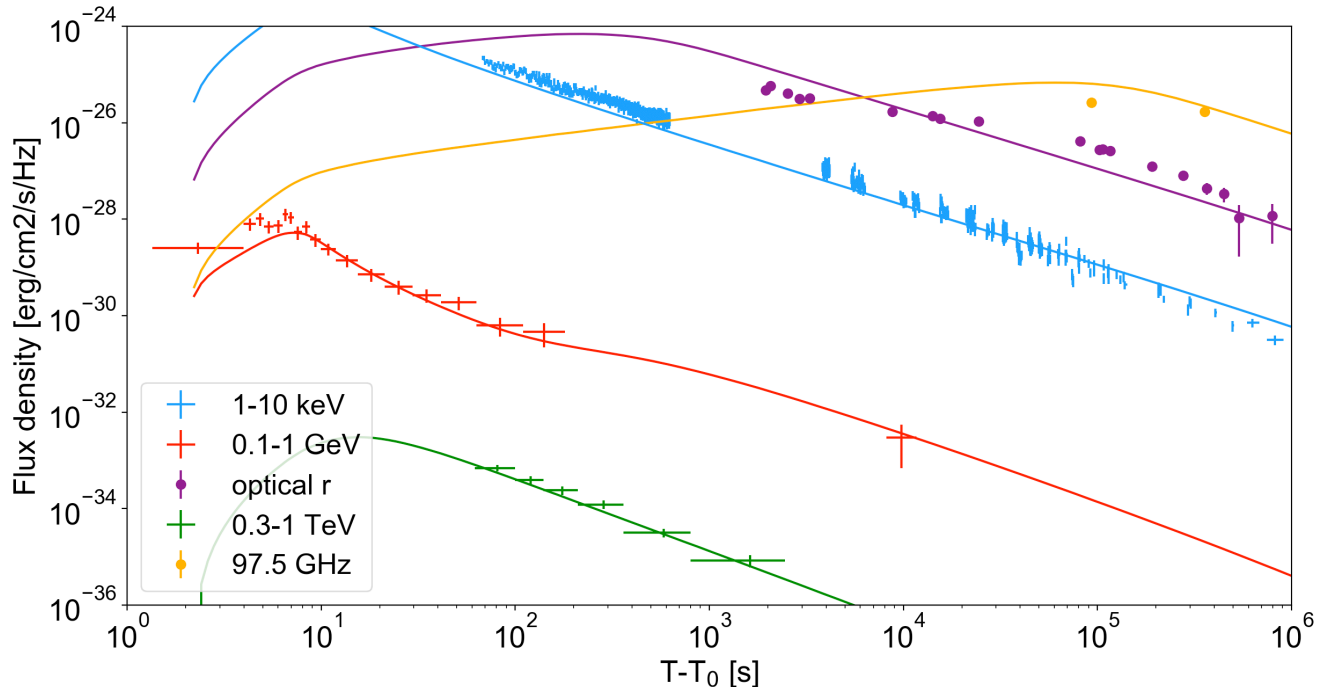
346 was not detected on any of the individual nights. Combining all the SCUBA-2 continuum camera⁸⁴
 347 observations, the RMS background noise is 0.95 mJy/beam at 850 μm and 5.4 mJy/beam at 450 μm
 348 at 1.67 days after the burst trigger.

349 **Prompt emission model for the early time MAGIC emission** In the standard picture the prompt
 350 sub-MeV spectrum is explained as a synchrotron radiation from relativistic accelerated electrons in
 351 the energy dissipation region. The associated inverse Compton component is sensitive to the details

352 of the dynamics: e.g. in the internal shock model if the peak energy is initially very high and the
 353 IC component is suppressed due to Klein-Nishina (KN) effects, the peak of the IC component
 354 may be delayed and become bright only at late times when scatterings occur in Thomson regime.
 355 Simulations showed that magnetic fields required to produce the GeV/TeV component are rather
 356 low⁸⁵, $\epsilon_B \sim 10^{-3}$. In this framework the contribution of the IC component to the observed flux
 357 at early times (62-90 s, see Extended Data Table 1) does not exceed $\sim 20\%$. Alternatively, if the
 358 prompt emission originates in reprocessed photospheric emission, the early TeV flux may arise
 359 from IC scatterings of thermal photons by freshly heated electrons below the photosphere at low
 360 optical depths. Another possibility for the generation of TeV photons might be the IC scattering of
 361 prompt MeV photons by electrons in the external forward shock region where electrons are heated
 362 to an average Lorentz factor of order 10^4 at early times.

363 **Afterglow model** Synchrotron and SSC radiation from electrons accelerated at the forward shock
 364 has been modelled within the external shock scenario^{7,8,20,25,86}. The results of the modeling are
 365 overlaid to the data in Fig. 3, and Extended Data Figs. 11 and 12.

366 We consider two types of power law radial profiles $n(R) = n_0 R^{-s}$ for the external environ-
 367 ment: $s = 0$ (homogeneous medium) and $s = 2$ (wind-like medium, typical of an environment
 368 shaped by the stellar wind of the progenitor). In the last case, we define $n_0 = 3 \times 10^{35} A_\star \text{ cm}^{-1}$.
 369 We assume that electrons swept up by the shock are efficiently accelerated into a PL distribution
 370 described by spectral index p : $dN/d\gamma_e \propto \gamma_e^{-p}$, where γ_e is the electron Lorentz factor. We call
 371 ν_m the characteristic synchrotron frequency of electrons with Lorentz factor γ_m , ν_c the cooling
 372 frequency, and ν_{sa} the synchrotron self-absorption frequency.



Extended Data Figure 12: **PRELIMINARY - Modeling of the broadband light curves.** Modeling of forward shock emission (solid curves) is compared to observations, at different frequencies (see legend). **This is for $s = 0$. The new modeling for $s = 2$ will be added.**

373 The early time optical emission (up to ~ 1000 s) and radio emission (up to $\sim 10^5$ s) are
 374 most likely dominated by reverse shock radiation¹⁶. Detailed modeling of this component is not
 375 discussed in this work, where we focus on forward shock radiation.

376 The XRT flux (Fig. 1, blue data points) decays as $F_X \propto t^{\alpha_X}$ with $\alpha_X = -1.36 \pm 0.02$. If
 377 $\nu_X > \max(\nu_m, \nu_c)$, the X-ray light curve is predicted to decay as $t^{(2-3p)/4}$, that implies $p \sim 2.5$.
 378 Another possibility is to assume $\nu_m < \nu_X < \nu_c$ for the whole observing time, which implies a slow
 379 cooling regime and $p = 2.1 - 2.2$ to explain the temporal decay. A broken power law fit provides a
 380 better fit (5.3×10^{-5} probability of chance improvement), with a break occurring around 4×10^4 s

381 and decay indices $\alpha_{X,1} \sim -1.32 \pm 0.03$ and $\alpha_{X,2} \sim -1.55 \pm 0.04$. This behaviour can be explained
 382 if the electrons are in a slow cooling regime at the time of the break, and assuming $p = 2.7$ for
 383 $s = 0$, and $p = 2.4 - 2.5$ for $s = 2$. In both cases, the temporal break can be explained by the
 384 frequency ν_c crossing the XRT band.

385 From $\sim 2 \times 10^3$ s the optical light curve starts displaying a shallow decay in time (with
 386 temporal index poorly constrained, between -0.5 and -0.25), followed by a steepening around
 387 8×10^4 s, when the temporal decay becomes similar to the decay in X-ray band, suggesting that
 388 after this time the X-ray and optical band lie in the same part of the synchrotron spectrum. If the
 389 break is interpreted as the synchrotron characteristic frequency ν_m crossing the optical band, after
 390 the break the observed temporal decay requires a very steep value of $p \sim 3$ for $s = 0$ and a value
 391 between $p = 2.4$ and $p = 2.5$ for $s = 2$. This interpretation implies (independently of the density
 392 profile of the external medium and on the cooling regime of the electrons) that ν_m is in the X-ray
 393 band at 10^2 s:

$$\nu_m(t = 8 \times 10^4) = 3 \times 10^{18} \text{ Hz} \left(\frac{t}{100 \text{ s}} \right)^{-1.5} = 10^{14} \text{ Hz}. \quad (1)$$

394 The SED at ~ 100 s is indeed characterised by a peak in between 5-30 keV (Fig. 3), that we interpret
 395 as the characteristic synchrotron frequency ν_m . **Observations at 1 GHz provide information on**
 396 **the location of the synchrotron self-absorption frequency, that is located at $\nu_{\text{sa}} \sim 1$ GHz at**
 397 **10^5 s (Extended Data Fig. 11).**

398 Summarizing, **in a wind-like scenario** X-ray and optical emission and their evolution in time
 399 can be explained if $p = 2.4 - 2.5$, the emission is initially in fast cooling regime and transitions to
 400 a slow cooling regime around 3×10^3 s. The optical spectral index at late times is predicted to be

401 $(1 - p)/2 \sim -0.72$, in agreement with observations. ν_m crosses the optical band at $t \sim 8 \times 10^4$ s,
 402 explaining the steepening of the optical light curve and the flattening of the optical spectrum.
 403 The X-ray band initially lies above (or close to) ν_m , and the break frequency ν_c starts crossing
 404 the X-ray band around $2 - 4 \times 10^4$ s, producing the steepening in the decay rate (the cooling
 405 frequency increases with time for $s = 2$). In this case, before the temporal break, the decay rate
 406 is related to the spectral index of the electron energy distribution by $\alpha_{X,1} = (2 - 3p)/4 \sim -1.3$,
 407 for $p \sim 2.4 - 2.5$. Well after the break, this value of p predicts a decay rate $\alpha_{X,1} = (1 - 3p)/4 =$
 408 $-1.55 - 1.62$. Overall, this interpretation is also consistent with the fact that the late time ($t > 10^5$ s)
 409 X-ray and optical light curves display similar temporal decays (Fig.1), as they lie in the same part
 410 of the synchrotron spectrum ($\nu_m < \nu_{opt} < \nu_X < \nu_c$).

411 Alternatively, **assuming a homogeneous density medium**, observations can be modeled if
 412 $\nu_c > \nu_m$ at all times, implying that the emission is always produced in a slow cooling regime **to be**
 413 **completed with the details of the $s = 0$ modeling.**

414 **We now add to the picture the information brought by the TeV detection.** The modeling
 415 is built with reference to the MAGIC flux and spectral indices derived considering statistical errors
 416 only (see Extended Data Table 1 and green data points in Extended Data Fig. 2). **The light curve**
 417 **decays in time as $t^{-1.51}$ and the photon index is consistent within $\sim 1\sigma$ with $\Gamma_{ph,TeV} \sim -2.5$ for**
 418 **the entire duration of the emission, although there is evidence for an evolution from harder**
 419 **(~ -2) to softer (~ -2.8) values.** In the first broadband SED (Fig. 3, upper panel), LAT obser-
 420 vations provide strong evidence for the presence of two separated spectral peaks.

421 Assuming Thomson scattering, the SSC peak is given by:

$$\nu_{\text{peak}}^{\text{SSC}} \simeq 2 \gamma_e^2 \nu_{\text{peak}}^{\text{syn}} \quad (2)$$

422 while in KN regime, the SSC peak should be located at:

$$h\nu_{\text{peak}}^{\text{SSC}} \simeq 2 \gamma_e \Gamma m_e c^2 / (1 + z) \quad (3)$$

423 where $\gamma_e = \min(\gamma_c, \gamma_m)$. The synchrotron spectral peak is located at $E_{\text{peak}}^{\text{syn}} \sim 10 \text{ keV}$, while
 424 the peak of the SSC component must be below $E_{\text{peak}}^{\text{SSC}} \lesssim 100 \text{ GeV}$ to explain the MAGIC photon
 425 index. Both the KN and Thomson scattering regimes imply $\gamma_e \lesssim 10^3$. This small value faces
 426 two problems: i) if the bulk Lorentz factor Γ is larger than 150 (that is a necessary condition to
 427 avoid strong γ - γ opacity, see below), a small γ_m translates into a small efficiency of the electron
 428 acceleration, with $\epsilon_e < 0.05$, ii) the synchrotron peak energy can be located at $E_{\text{peak}}^{\text{syn}} \sim 10 \text{ keV}$
 429 only for $B \Gamma \gtrsim 10^5 \text{ G}$.

430 These calculations show that γ - γ opacity likely plays an role in shaping the observed peak
 431 energy of the SSC spectrum^{87,88}.

432 For a gamma-ray photon with energy E_γ , the $\tau_{\gamma\gamma}$ opacity is:

$$\tau_{\gamma\gamma}(E_\gamma) = \sigma_{\gamma\gamma}(R/\Gamma) n_t(E_\gamma), \quad (4)$$

433 where $n_t = L_t / (4 \pi R^2 c \Gamma E_t)$ is the density of target photons in the comoving frame, L_t is the
 434 luminosity and $E_t = (m_e c^2)^2 \Gamma^2 / E_\gamma / (1 + z)^2$ is the energy of target photons in the observer frame.
 435 Target photons for photons with energy $E_\gamma = 0.2 - 1 \text{ TeV}$ and for $\Gamma \sim 120 - 150$ have energies in
 436 the range $4 - 30 \text{ keV}$. **When $\gamma - \gamma$ absorption is relevant, the emission from the pairs can give**
 437 **a non-negligible contribution to the radiative output.**

438 **To properly model all the physical processes that are shaping the broad band radia-**
439 **tion, we build a numerical code that solves the evolution of the electron distributions and**
440 **derive the radiative output taking into account the following processes: synchrotron and**
441 **SSC losses, adiabatic losses, $\gamma - \gamma$ absorption, emission from the pairs, and synchrotron**
442 **self-absorption⁸⁹⁻⁹². We find that for the parameters assumed in the proposed modeling (see**
443 **below), the contribution from pairs to the emission is negligible.**

444 The MAGIC photon index (Extended Data Table 1) and its evolution with time constrains in
445 any case the SSC peak energy to be not much higher than 1 TeV: in general the internal opacity
446 decreases with time and KN effects become less relevant. A possible softening of the spectrum
447 with time, as the one suggested by the observations, requires that the spectral peak decreases with
448 time and crosses the MAGIC energy range. As the SSC spectrum is very broad around the peak,
449 KN and/or opacity still need to play a role also at late times (~ 2000 s) in order to explain soft
450 photon indices $\Gamma_{\text{TeV}} < -2$ (Extended Data Table 1). In the slow cooling regime, the SSC peak
451 evolves to higher frequencies for a wind-like medium and decreases very slowly ($\nu_{\text{peak}}^{\text{SSC}} \propto t^{-1/4}$)
452 for a constant-density medium (both in KN and Thomson regimes). In fast cooling regime the
453 evolution is faster ($\nu_{\text{peak}}^{\text{SSC}} \propto t^{-1/2} - t^{-9/4}$ depending on medium and regime).

454 We model the broadband observations **considering both $s = 0$ and $s = 2$** . The results are
455 shown in Extended Data Fig. 12. **We find that the fast temporal decay rate of the TeV light**
456 **curve can be more easily explained in a homogeneous medium.**

457 The results of the broad band modeling is shown in Fig.3, and Extended Data Figs. 11 and

458 12 where model curves are overlaid to observations. The model curves shown in these figures
459 have been derived using the following parameters: $\epsilon_e = ??$, $\epsilon_B = ??$, $\xi_e = ??$, $p = ??$, $n_{0\star} = ??$, and
460 $E_k = ??$. Using the constraints on the afterglow onset time ($t_{\text{peak}}^{\text{aft}} \sim 5 - 10$ s from the smooth
461 component detected during the prompt emission) the initial bulk Lorentz factor is constrained to
462 assume values $\Gamma_0 \sim 300$ and $\Gamma_0 \sim 700$ for $s = 2$ and $s = 0$, respectively.

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662 **Author Contributions** The MAGIC telescope system was designed and constructed by the MAGIC Col-
663 laboration. Operation, data processing, calibration, Monte Carlo simulations of the detector, and of theo-
664 retical models, and data analyses were performed by the members of the MAGIC Collaboration, who also
665 discussed and approved the scientific results. L. Nava coordinated the gathering of the data, developed the

666 theoretical interpretation, and wrote the main section and the section on Afterglow Modeling. E. Moretti
667 coordinated the analysis of the MAGIC data, wrote the relevant sections, and, together with F. Longo, co-
668 ordinated the collaboration with the Fermi team. D. Miceli, Y. Suda and S. Fukami performed the analysis
669 of the MAGIC data. S. Covino provided support with the analysis of the optical data and the writing of the
670 corresponding sections. Z. Bosnjak performed calculations for the contribution from prompt emission to
671 TeV radiation and wrote the corresponding section. S. Inoue, R. Mirzoyan, and A. Stamerra contributed in
672 structuring and editing the paper. All MAGIC collaborators contributed to the editing and comments to the
673 final version of the manuscript.

674 S. Campana and M. G. Bernardini extracted the spectra and performed the spectral analysis of *Swift*/BAT
675 and *Swift*/XRT data. N. P. M. Kuin derived the photometry for the *Swift*/UVOT event mode data, and the uv
676 grism exposure. M. H. Siegel derived the image mode Swift UVOT photometry. A. de Ugarte Postigo was
677 principal investigator of ALMA program 2018.1A.00020.T, triggered these observations and performed
678 photometry. S. Martin reduced the ALMA Band 6 data. C. C. Thöne, S. Schulze, D. A. Kann, and M.
679 Michałowski participated in the ALMA DDT proposal preparation, observations, and scientific analysis of
680 the data. D. A. Perley was principal investigator of ALMA program 2018.1.01410.T and triggered these
681 observations, and was also principal investigator of the LT programme and the JCMT programme. A. M.
682 Cockeram analyzed the ALMA Band 3 and LT data, and wrote the LT text. S. Schulze contributed to the
683 development of the ALMA Band 3 observing programme. I. A. Smith triggered the JCMT programme,
684 analyzed the data, and wrote the associated text. N. R. Tanvir contributed to the development of the JCMT
685 programme. D. A. Kann and C. C. Thöne triggered and coordinated the X-shooter observations. D. A. Kann
686 independently checked the optical light curve analysis. K. Misra was the principal investigator of the GMRT
687 programme 35_018. S. V. Cherukuri and V. Jaiswal analyzed the data. L. Resmi contributed to the observa-
688 tion plan and data analysis. E.T., I.H. and R.D. have performed the MeerKAT data analysis. G. Anderson,

689 A. Moin, S. Schulze and E. Troja were principal investigator of ATCA program CX424. G. Anderson, M.
690 Wieringa and J. Stevens carried out the observations. G. Anderson, G. Bernardi, S. Klose, M. Marongiu, A.
691 Moin, R. Ricci and M. Wieringa analysed these data. M. Bell, J. Miller-Jones and L. Piro participated to the
692 ATCA proposal preparation and scientific analysis of the data. The ePESSTO project was delivered by the
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694 comments to the manuscript: J. P. Anderson, N. Castro Segura, P. D'Avanzo, M. Gromadzki, C. Inserra,
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696 alyzed REM data and provided comments to the manuscript. J. Bolmer was responsible for observing the
697 GRB with GROND as well as for the data reduction and calibration. J. Bolmer and J. Greiner contributed to
698 the analysis of the data and writing of the text. E. Troja triggered the *NuSTAR* TOO observations performed
699 under DDT program, L. Piro requested the XMM-Newton data carried out under DDT program and carried
700 out the scientific analysis of XMM-Newton and *NuSTAR*. S. Lotti analyzed the *NuSTAR* data and wrote the
701 associated text. A. Tiengo and G. Novara analysed the XMM-Newton data and wrote the associated text.
702 AJCT led the observing BOOTES and GTC programs. AC, CJPP, EFG, IMC, SBP and XYL analyzed the
703 BOOTES data whereas AFV, MDCG, RSR, YDH and VVS analyzed the GTC data and interpreted them
704 accordingly. N. Tanvir created the X-shooter and AIFOSC figures. J. Fynbo, J. Japelj performed the analy-
705 sis of X-shooter and AIFOSC spectra. D. Xu, P. Jakobsson contributed to NOT programme and triggering.
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