Major Progress in Understanding of GRBs: Discovery of TeraelectronVolt Gamma-Ray Emission

Razmik Mirzoyan
On behalf of the MAGIC Collaboration

Max-Planck-Institute for Physics
Munich, Germany

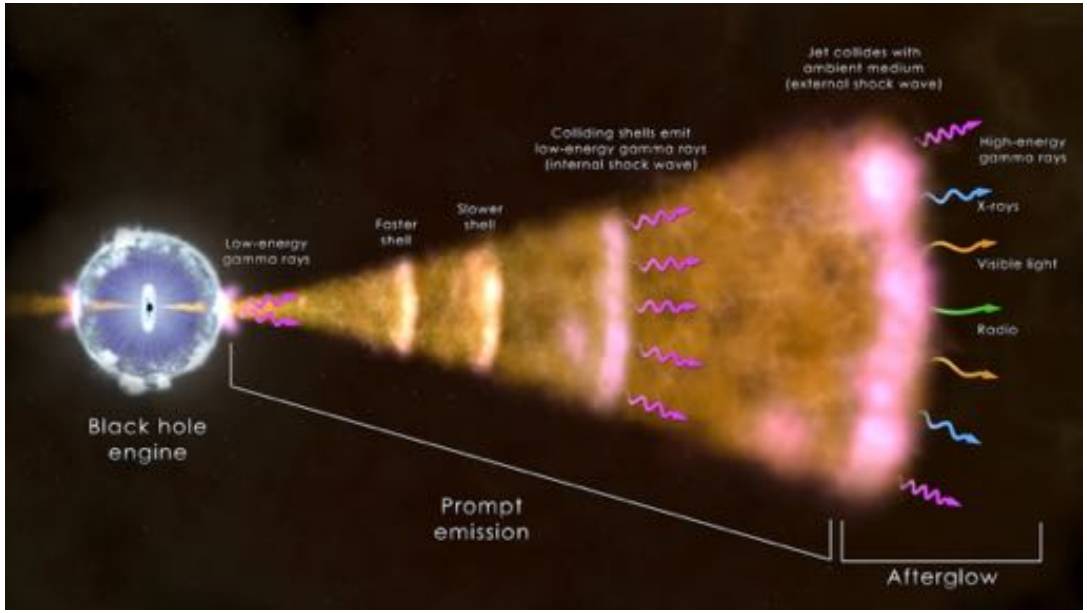
Last year we celebrated the 30 year jubilee of ground-based VHE γ-ray astronomy

- The first 9σ detection of the Crab Nebula marked the birth of the VHE γ-ray astronomy as an independent branch of astronomy

- This detection was reported by the 10m diameter Whipple IACT team in Arizona, lead by the pioneer of VHE γ-ray astronomy Trevor Weekes, in 1989

- With the detection of the first gigantic signal from the GRB190114C (in the first 30 s the gamma-ray rate was x 130 Crab!) one year ago we celebrated the 30 years jubilee of VHE γ-ray astronomy !

Gamma Ray Bursts



- Most powerful, violent, distant explosions in the Universe
- 2 different populations, short and long bursts
- Long GRBs: T > ~ 2s; massive star collapse > ultra-relativistic jet
- Recent detection of a gravitational wave signal consistent with a binary neutron star merger and associated to a short GRB
- Both long and short GRBs have been detected at E < 100 GeV
- No strict division in time between prompt and afterglow

Past Hint from a GRB @ E ≥ 20 TeV AIROBICC & GRB 920925c

- AIROBICC in 1990's was an open air Cherenkov integrating array of 7x7 PMT-based stations (40cm Ø light guide) of ≥ 0.032 km^2
- From GRB 920925c one expected 0.93 events while 11 were observed.
- But the "signal" preceded the WATCH trigger by < 1 minute and was ~9° away from its location.
- Evidence ~2.7 σ (post-trial) from AIROBICC above 20 TeV from GRB 920925c was reported

Padilla et al., 1998

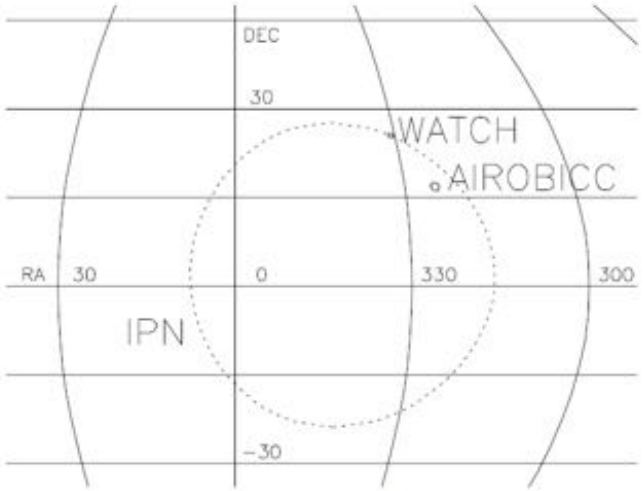
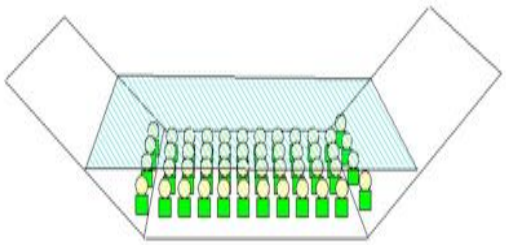


Fig. 6. Map with the situation of the WATCH GRB 920925c and the IPN ring as calculated from the WATCH and ULYSSES observations. The location of the excess detected by AIROBICC nearly coincident in time with WATCH is also shown.

Keeping in mind the unknown redshift and the possible EBL absorption, this should be a spurious event

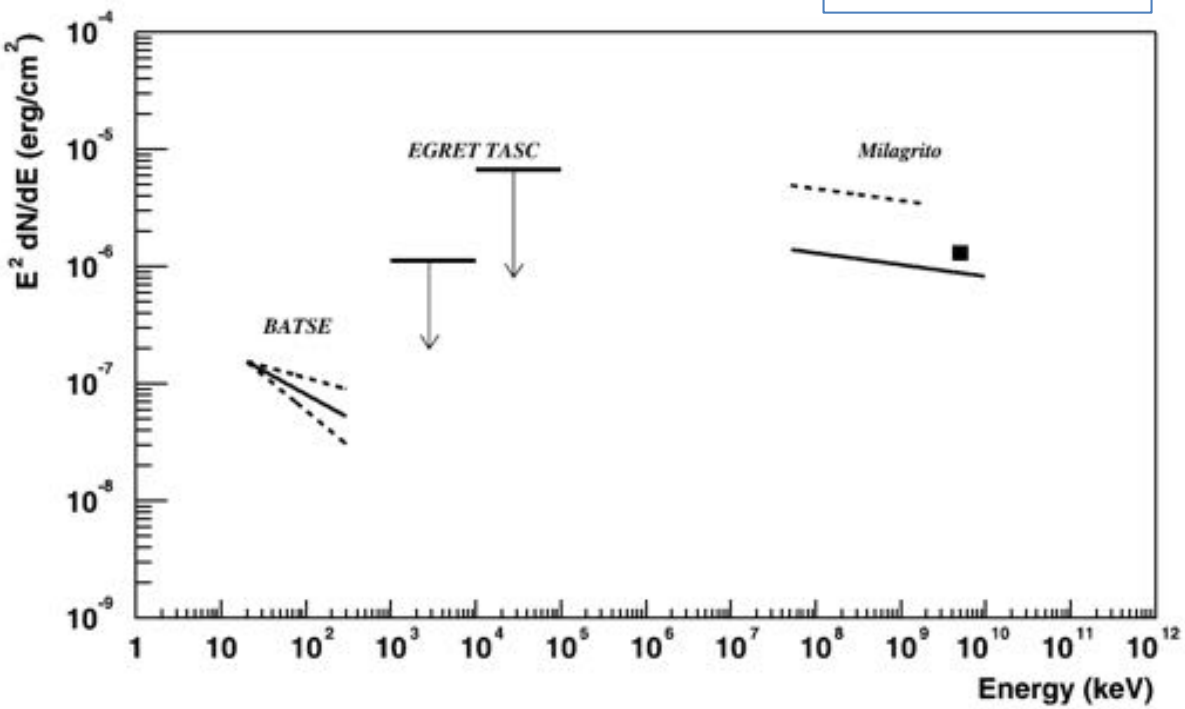


Past Hints from GRBs @ sub-TeV Milagrito & GRB 970417a

- GRB 970417a was a weak, soft GRB as observed by BATSE. The fluence in the 50–300 keV range was 1.5 x 10^{-7} ergs cm^{-2} and the T90 period was 7.9 s.
- Milagrito, a prototype of Milagro, consisted of a planar array of 228 PMTs of 8'' size submerged in a light-tight water reservoir with a size of ~ 42 x 42 m^2. Milagrito reported evidence for emission above 650 GeV from GRB 970417a, with a (posttrials) probability of 1.5 x 10^{-3} of being a background fluctuation (Atkins et al. 2000; Atkins et al. 2003)

MILAGRITO and GRB 970417a

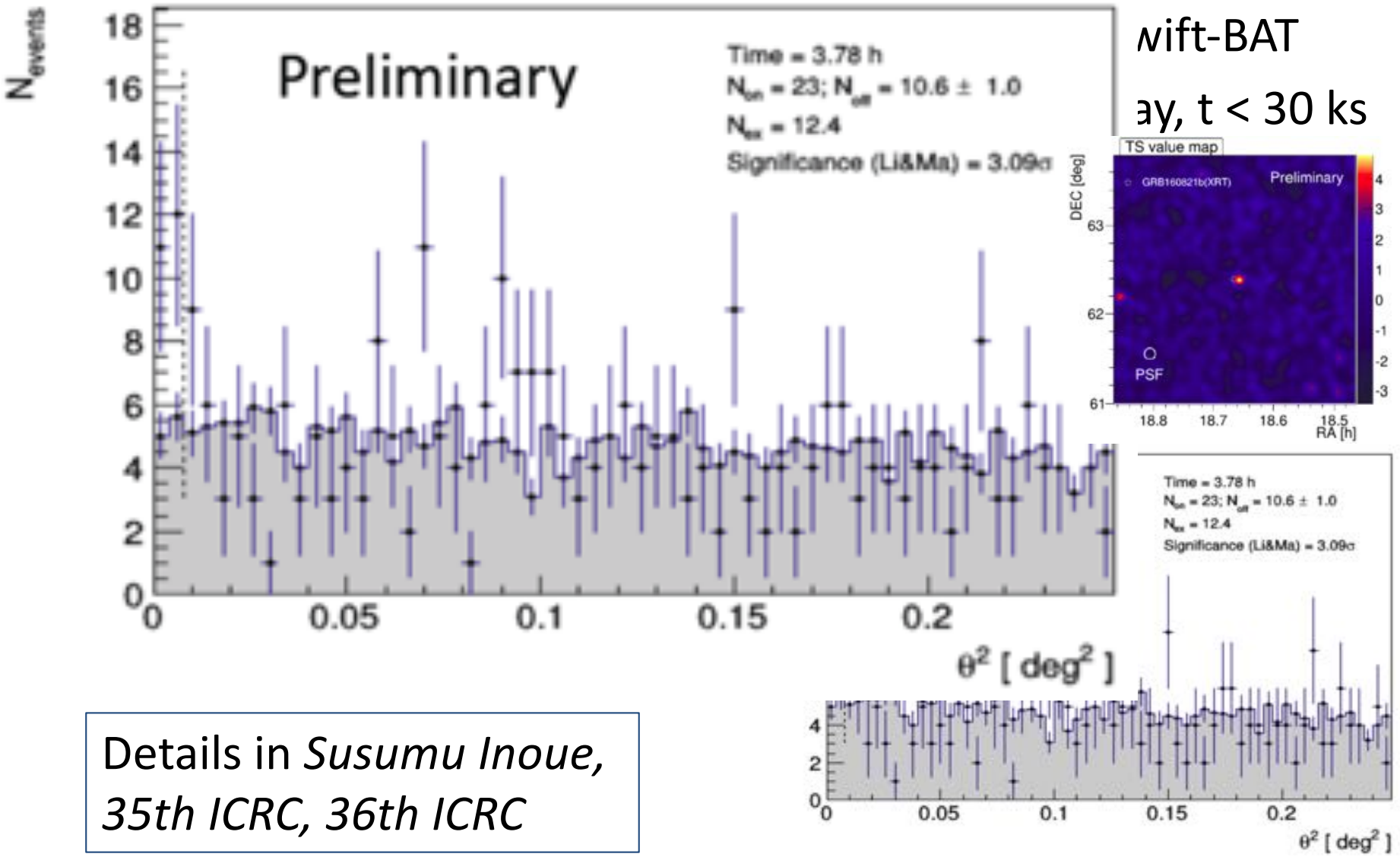
Atkins et al., 2003



- The VHE fluence must be at least an order of magnitude greater than sub-MeV fluence measured by BATSE
- A way out: if the actual peak of the SED may lie below the energy range of BATSE ?

Fig. 9.—Spectral energy distribution for GRB 970417a, showing a single power-law fit to the BATSE data, upper limits at 1 and 10 MeV from the EGRET TASC detector, and three possible spectral forms consistent with the Milagrito observations.

MAGIC Hint From GRB 160821B



ʍift-BAT

ay, t < 30 ks

Details in *Susumu Inoue, 35th ICRC, 36th ICRC*

Observing Transients with TeV Instruments

- All the major TeV instruments like **Veritas, H.E.S.S., HAWC, MAGIC, LHASSO,…** are pursuing intense programs for following transient alerts: GRBs, Gravitational wave sources, Neutrino ToO, Fast Radio Bursts, Novae, etc.
- While for a wide angle detector like HAWC the transient just needs to happen in their field of view, the narrow field of view IACTs need to possibly fast slew and track the alerted position
- All the IACTs optimized their operation for possibly fast sluing to the alerted position and starting observations
- Despite the really large number of followed GRBs by the above collaborations over many years, until recently only upper limits were reported

4 publications appeared in Nature in November 21st 2019 issue

Teraelectronvolt emission from the γ-ray burst GRB 190114C

Acciari, et al., MAGIC Collaboration

Observations of teraelectronvolt-energy γ-rays starting about one minute after the γ-ray burst GRB 190114C reveal a distinct component of the afterglow emission with power comparable to the synchrotron emission.

Observation of inverse Compton emission from a long γ-ray burst

MAGIC Collaboration, et al.,

A multi-frequency observing campaign of the γ-ray burst GRB 190114C reveals a broadband double-peaked spectral energy distribution, and the teraelectronvolt emission could be attributed to inverse Compton scattering.

A very-high-energy component deep in the γ-ray burst afterglow

Abdalla, et al., H.E.S.S. Collaboration

Very-high-energy γ-rays observed ten hours after the prompt emission of the γ-ray burst 180720B can be attributed to either an inverse Compton or an extreme synchrotron process.

News & Views | 20 November 2019

Bing Zhang

Extreme emission seen from γ-ray bursts

The 17m Ø MAGIC IACT project for VHE γ astrophysics at E ~ 30 GeV - 100 TeV

Fast Motion of the MAGIC Telescopes

MAGIC is Using a Fully-Automatic System for Following the Transient Alerts

- When obtaining an alert the software checks several criteria

if the alert should be followed

- If yes, the telescopes start fast rotation and within ≤ 25 s

slue to any given position in the sky and start tracking it

- While the telescopes are in fast motion, the software closes

data-taking files of the previous observation, downloads the look-up tables for the aimed for elevation angle and by using the AMC system re-adjusts the individual mirror positions, adjusts the discriminator thresholds to the estimated brightness of the position

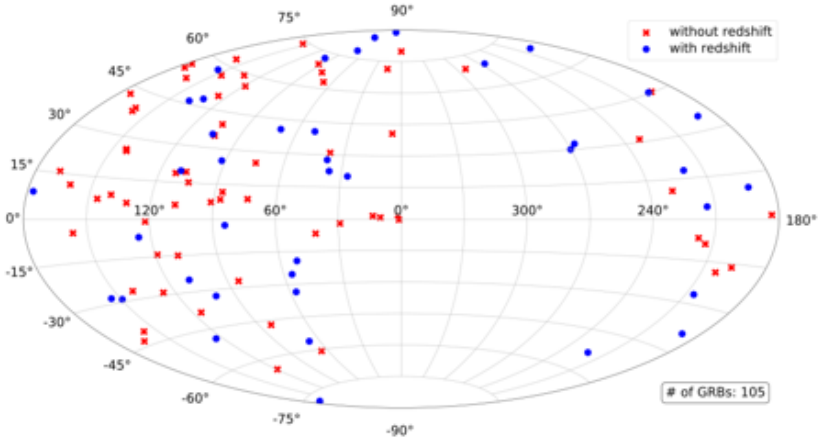
- We used to issue fake alerts once per shift for debugging

MAGIC: 180 Astro-Physicists From 12 Countries

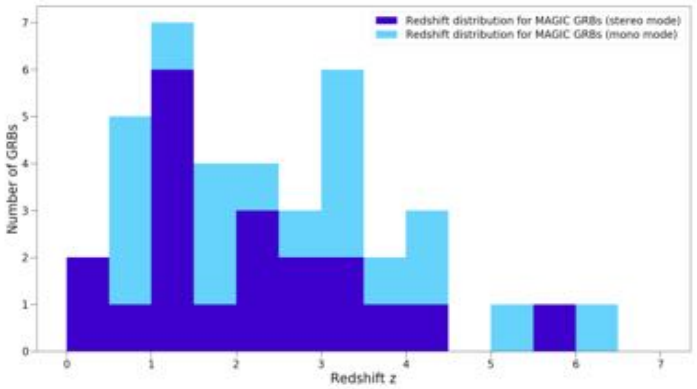
Armenia	ICRANet and Alikhanian Broth. Nat. Lab.
Bulgaria	Sofia nuclear Physics Institute
Brazil	CBPF Rio de Janeiro
Croatia	Consortium (Zagreb, +…)
Finland	Consortium (Tuorla, +…)
Germany	DESY Zeuthen, U. Dortmund, MPI Munich, U. Würzburg
Japan	Consortium (Kyoto, +…)
Italy	INFN & U. Padova, INFN Pisa & U. Siena, INFN Como/Milano Bicocca, INFN Udine/Trieste & U. Udine, INAF (Consortium: Rome, +…)
Poland	U. Lodz
Spain	U. Barcelona, UAB Barcelona, IEEC-CSIC Barcelona, IFAE Barcelona, IAA Granada, IAC Tenerife, U. Complutense Madrid, CIEMAT Madrid
Switzerland	ETH Zurich
India	Kolkata

GRB follow-ups

- Since 2005 we observed 105 GRBs
- On average 8-10 GRB/year
- Afterglow observations since 2013
- 24 with < 100 s delay & stereo,
  4 out of which with z < 1.5

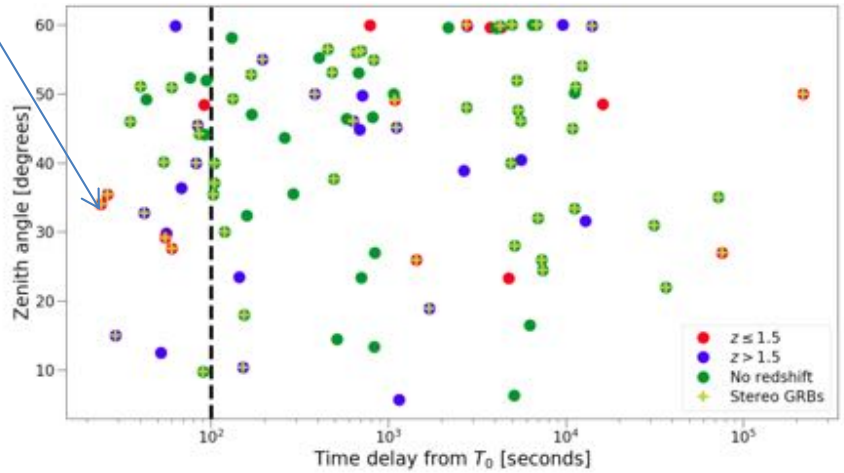


Red-shift distribution



GRB 160821B

Delay versus observation angle



List of MAGIC GRBs observed under good technical and weather conditions with $z < 1$ and $T_{delay} < 1$ h

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

MAGIC capability to observe at the presence of **partial Moon** and at **large zenith angles** were of key importance for this detection

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

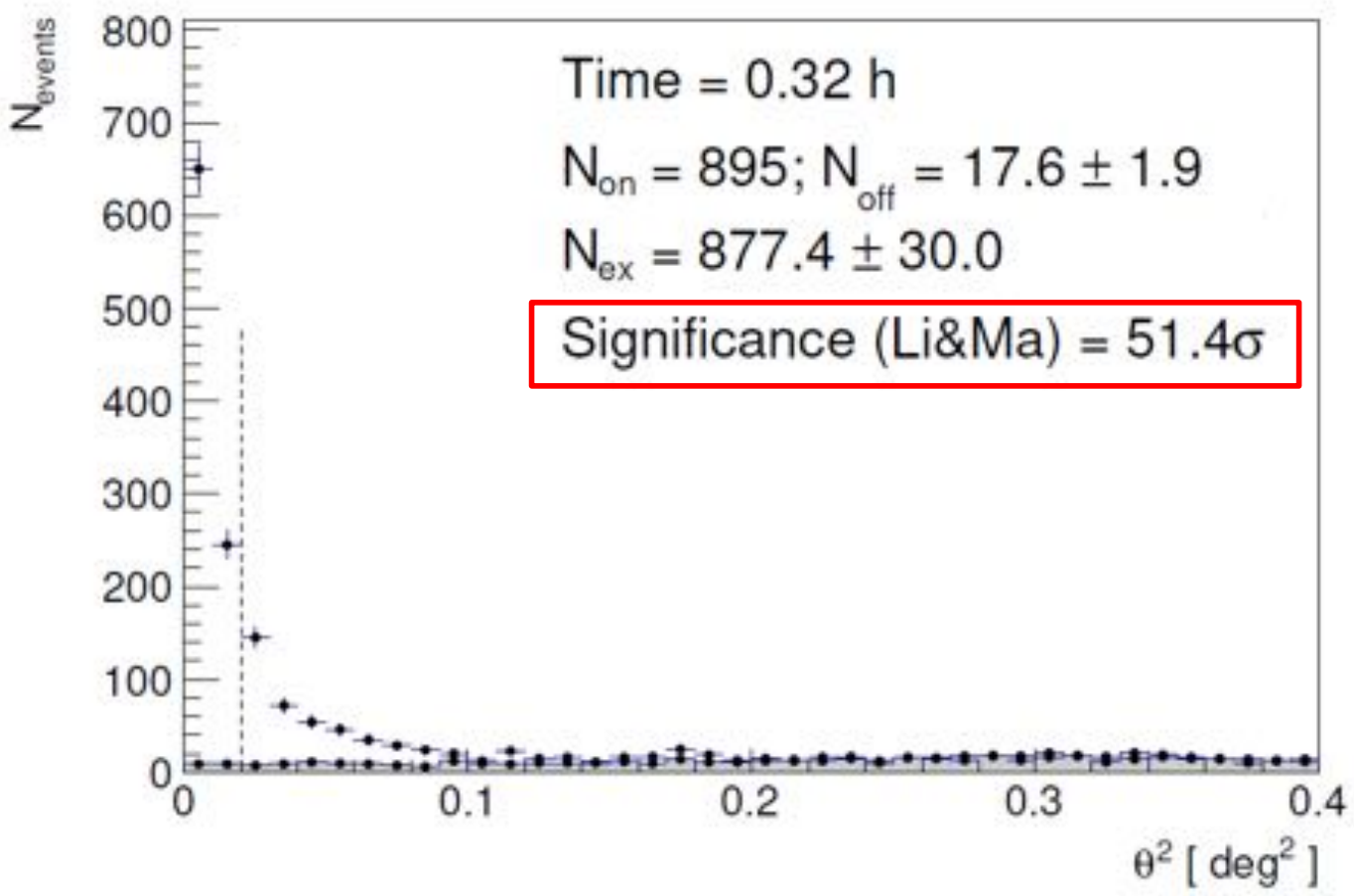
ATel issued 4h after GRB onset

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

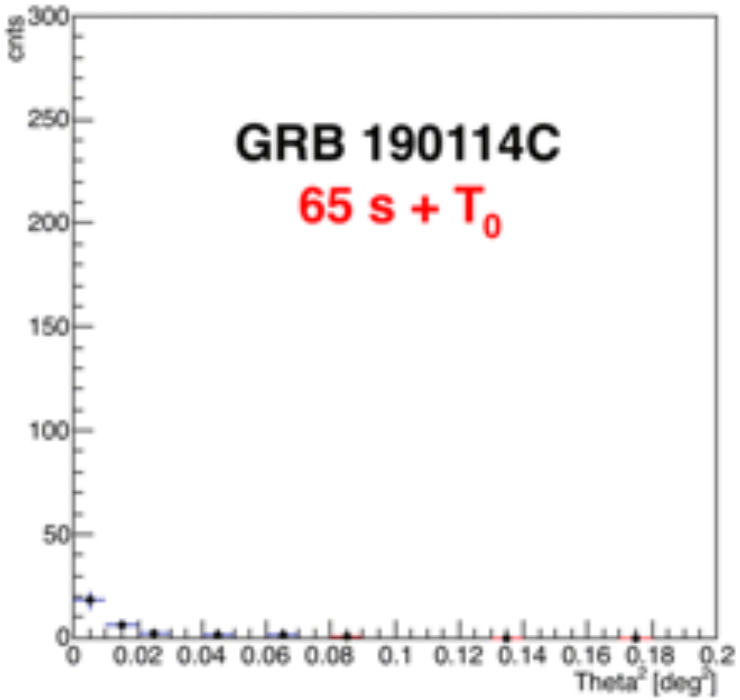
The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to

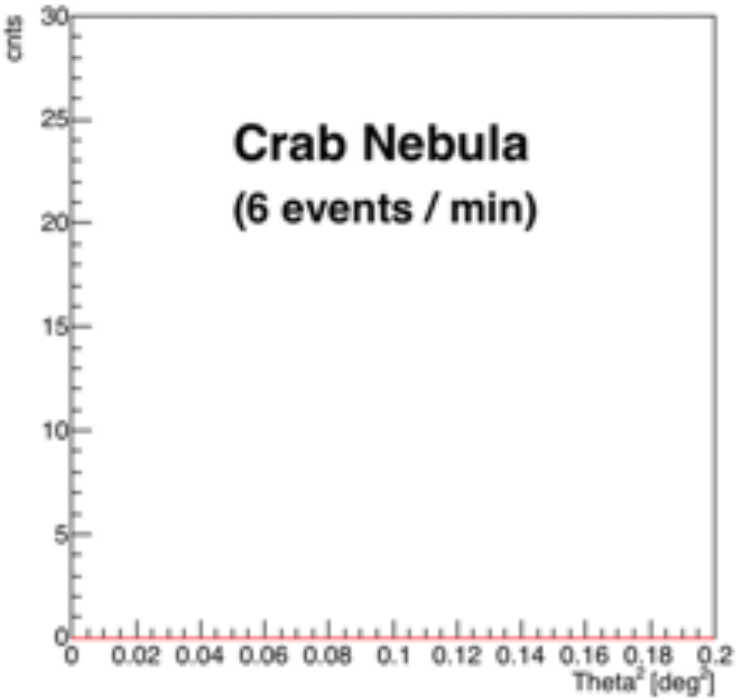
The most intense, purest signal in VHE γ-ray astrophysics: GRB190114C detection by MAGIC at E ≥ 200 GeV



γ-rate from GRB190114C & Crab Nebula by MAGIC for the first ~100 s of data taking; during the first 30s the rate is ~ 0.13 kCrab

Please note the Y-axes scale difference of x 10 for the GRB190114C



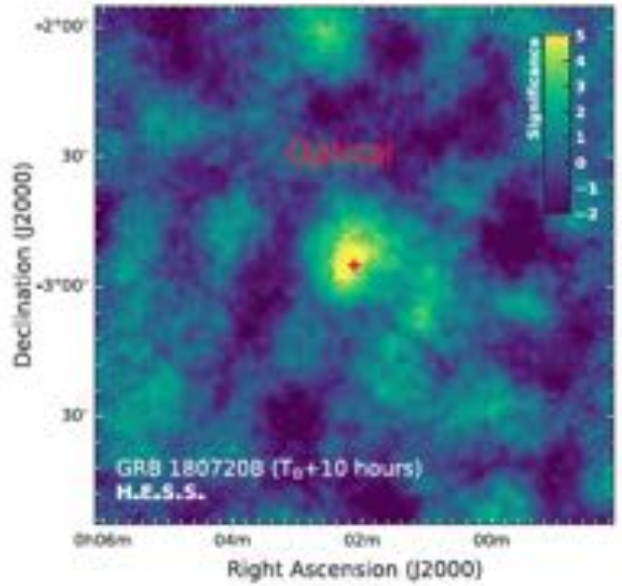


@ CTA symposium in Bologna in May 2019
H.E.S.S. reported on GRB 180721B

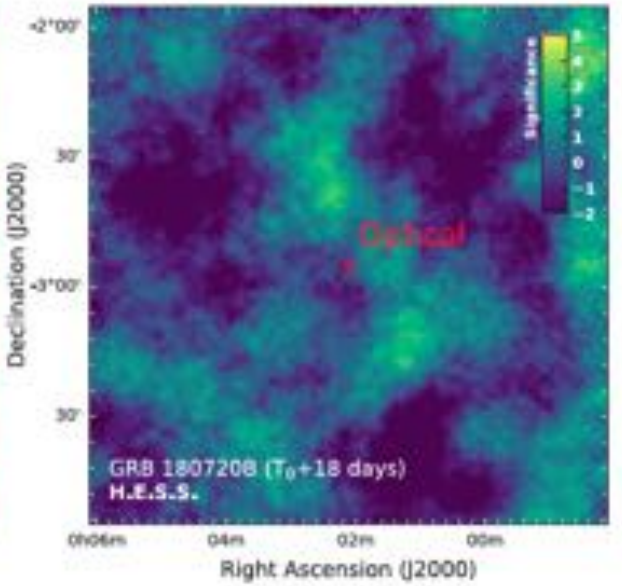
The GRB180720B detection

- 10 hours after the Swift trigger
- Redshift z = 0.653 (ESO-VLT/X-shooter)

Details in Gal10a by Quentin Piel



2 hours taken between 25° and 40° zenith angle

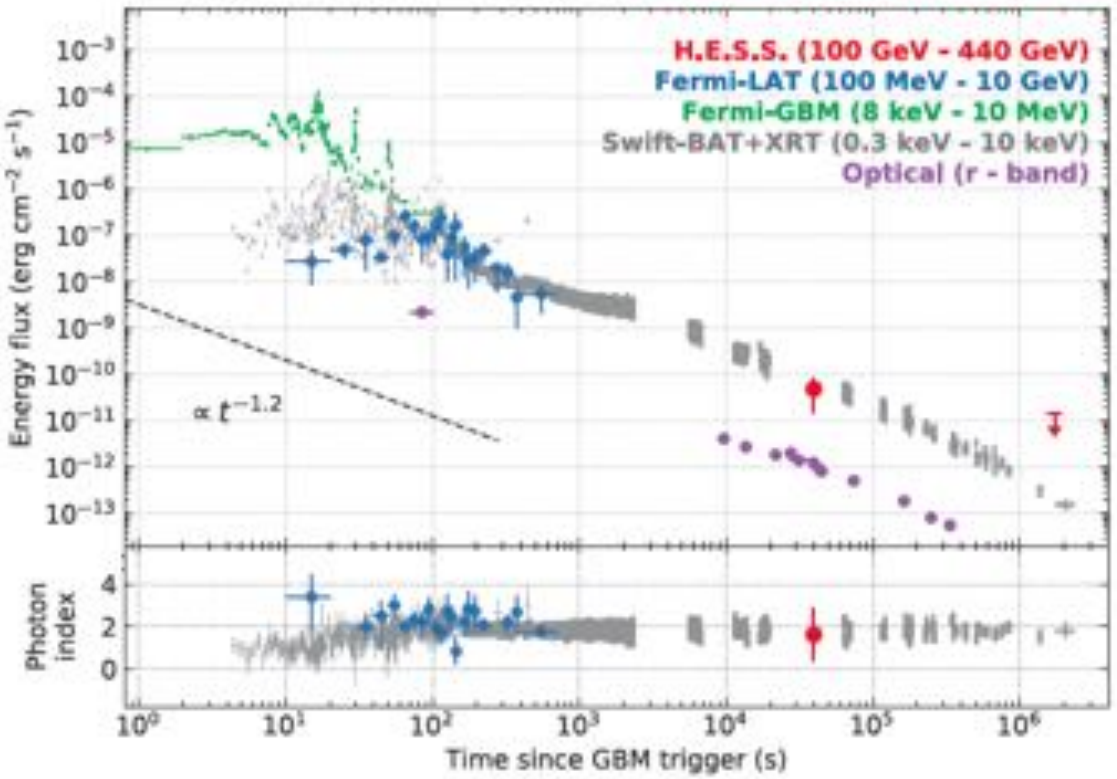


Between 18 days and 25 days after the burst

H.E.S.S. Detection of Afterglow From GRB180720B

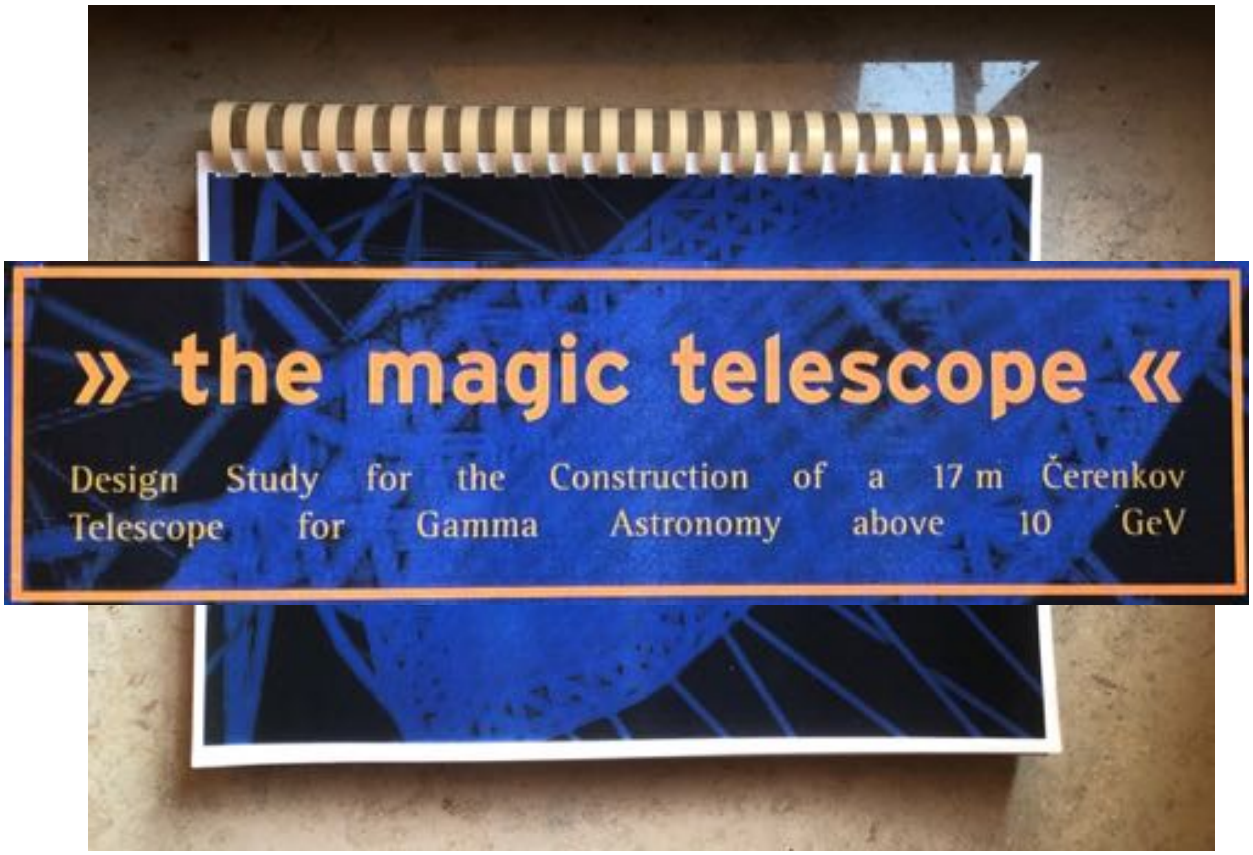
The GRB180720B detection

- Fermi-LAT detection up to 700 s after trigger wit a photon index close to -2.0.
- Coincident optical and X-ray temporal decay
- H.E.S.S. detection until 440 GeV and same level as X-ray domain



The Original Goals of the MAGIC Project: Measure GRBs, Pulsars, Distant AGN above the threshold energy 10 GeV

MAGIC Design Study, 1998



MAGIC is a pioneering IACT paving the road down to a few 10's of GeV energies

Introduced multiple novel techniques & technologies into the field

- Fast slew for transients
- Active Mirror Control
- T° controlled camera
- Analog signal via optic fibers, ~2ns fast signals
- Carbon-fiber structure,…

After 15 years of successful operation of MAGIC we thought we are ready to measure the next best GRB above the lowest threshold

- With time we improved the performance of the MAGIC telescopes and learnt to measure γ-ray signals from sources at E ≥ 20-30 GeV;
- Interested are invited to see the presentations by *G. Ceribella, "Crab Pulsar & Nebula" and* M. López, "*Geminga pulsar*", 36th ICRC
- We succeeded to measure the spectrum of a remote *FSRQ PKS1441* (z=0.939) at E ≥ 40 GeV *(Ahnen, et al, ApJL 2015)*
- So we were preparing and training ourselves to measure γ-rays at lowest energies ≥ 20-30 GeV from the next best GRB

The Surprise with the GRB 190114C

- But the reality looked quite different
- The burst of GRB 190114C happened at a **large zenith angle of ~60°** and moreover, **the Moon was up**
- Both effects together increased the threshold energy to ~200-300 GeV
- Why GRB happened at high zenith angle ? Because the observation chance is proportional to the solid angle
- Why at the time when the Moon was up ? Because the partial Moon observations seriously increase the duty cycle of IACTs
- Despite the high threshold we were surprised to measure in a shortest time a truly gigantic signal, the most intense signal in the 30 years history of VHE gamma astronomy

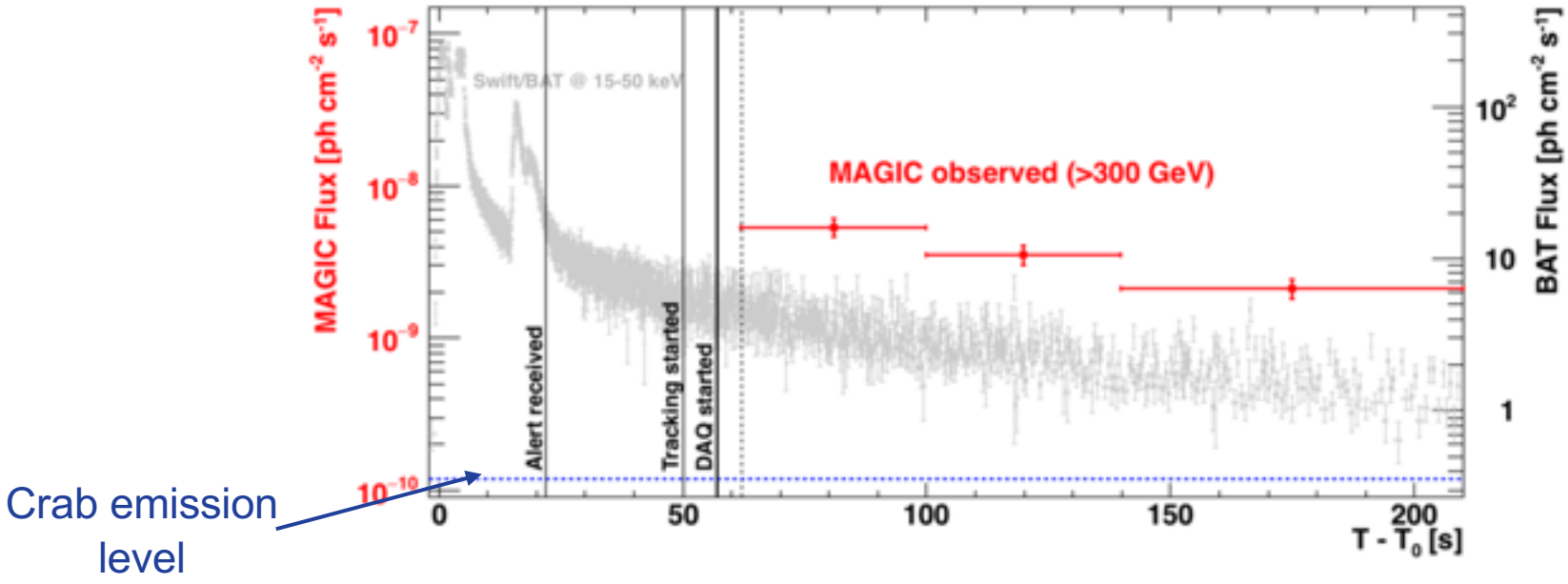
MAGIC Partial Moon Observations Were Crucial for Discovering the GRB 190114C

- Hence from the beginning of the project MAGIC is regularly observing at the presence of partial Moon, at Dusk and Dawn
- These provide significantly longer observations, albeit at somewhat higher threshold energy
- The Moon observations were inherited already from the HEGRA CT1 operation; back in 1997 we observed Mrk-501 for 244 h dark time and 134 h at partial moonlight. The latter was crucial for finding quasi-periodic γ-ray emission from

  Mrk-501, see *Kranich et al., 1999*
- MAGIC & Moon observ.: *Albert et al (2007); Ahnen et al (2017)*
- During the GRB 190114C observations the partial Moon increased the anode currents of PMTs by 6-8 times – fully O.k.

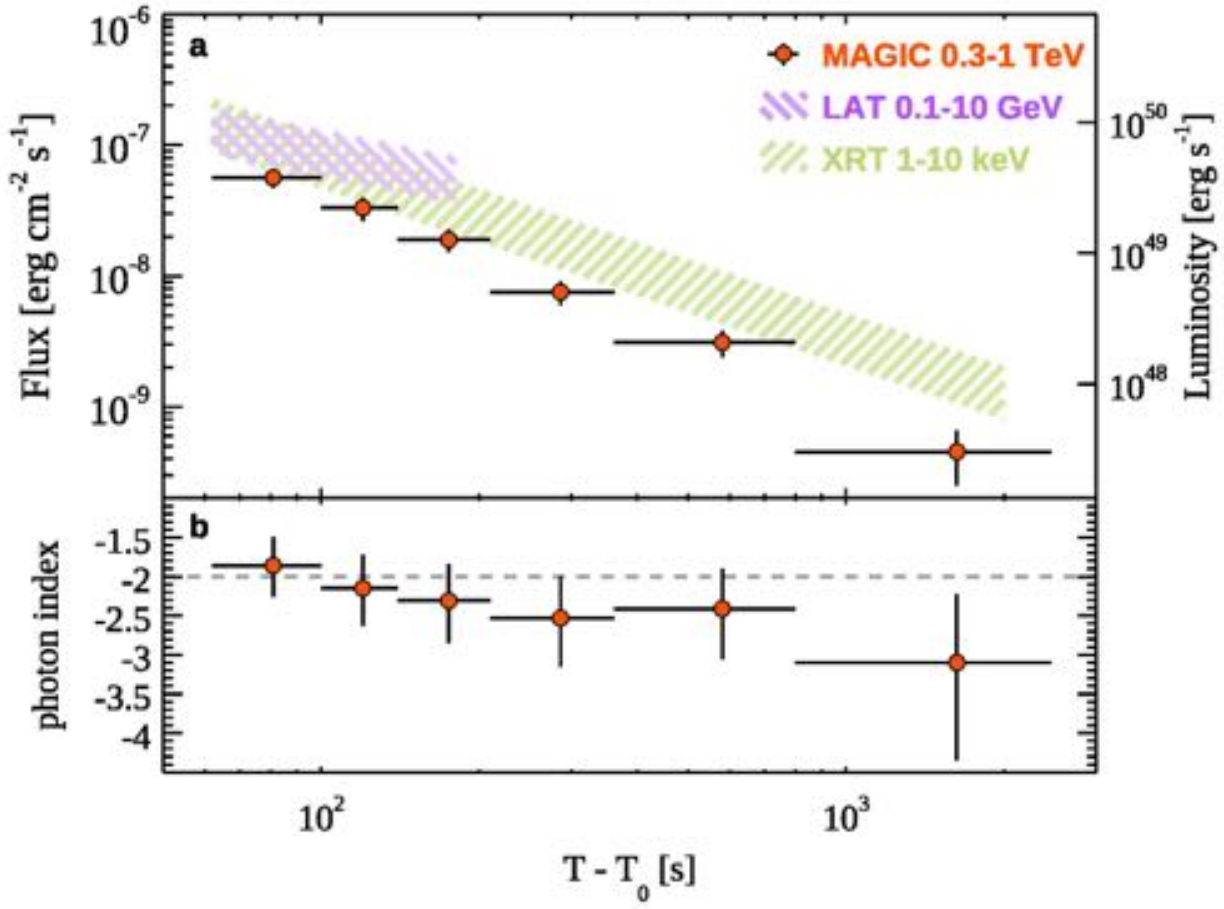
GRB 190114C signal footprint

- Very strong signal, almost background-free
- Signal detected up to ~40 minutes
- Energy flux emitted @ sub-TeV comparable within factor of two to the one emitted in X-rays (between 60-2000s)

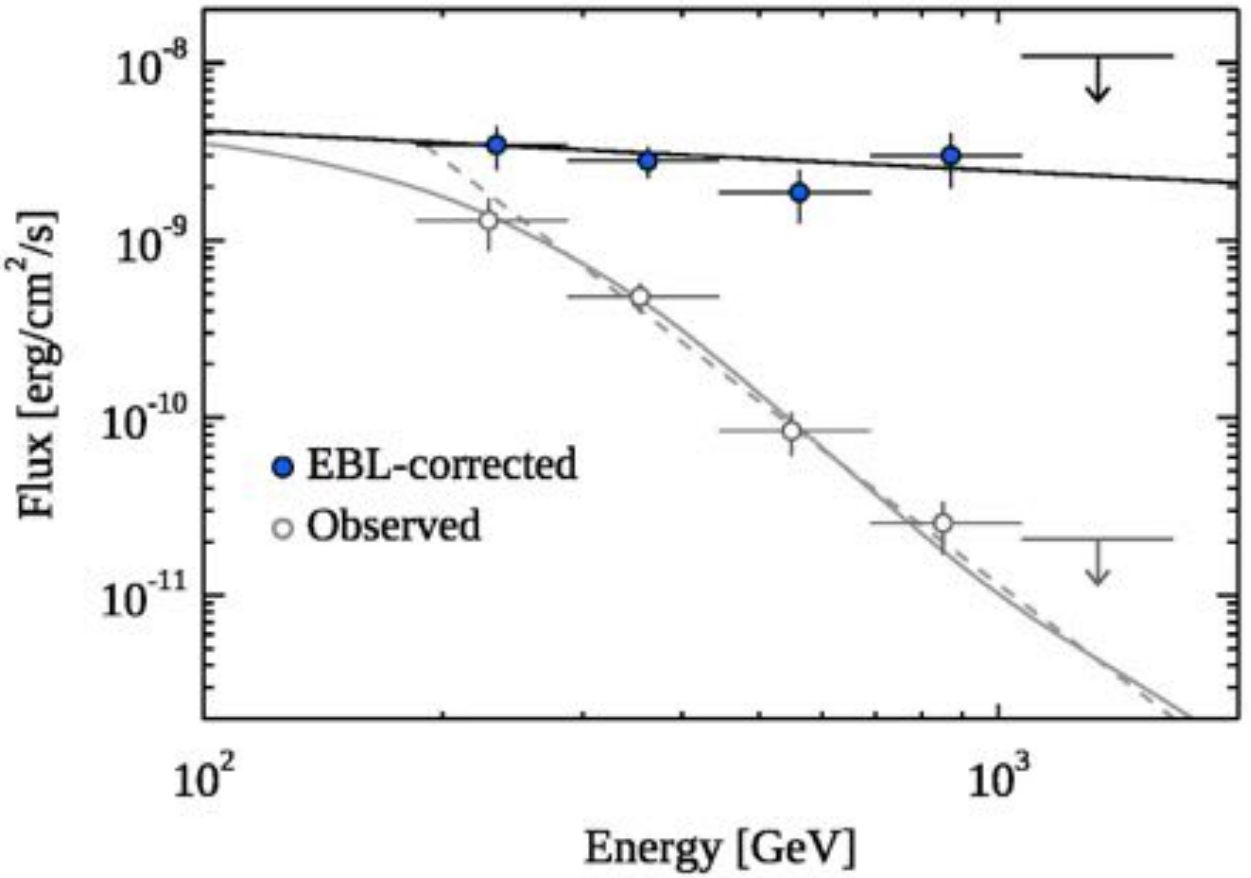


GRB 190114C light curves in the keV, GeV and TeV bands

MAGIC detected the afterglow phase of the GRB

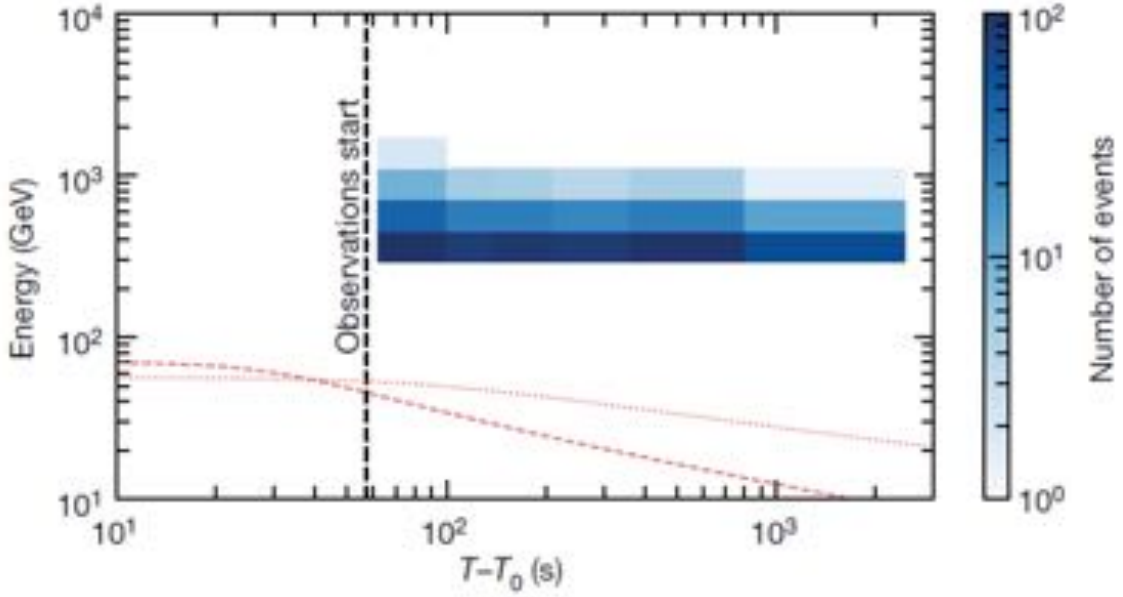


Spectrum above 0.2 TeV averaged over the period between *T*0 + 62 s & *T*0 + 2454 s for GRB 190114C



Distribution of TeV-band γ rays in energy versus time for GRB 190114C

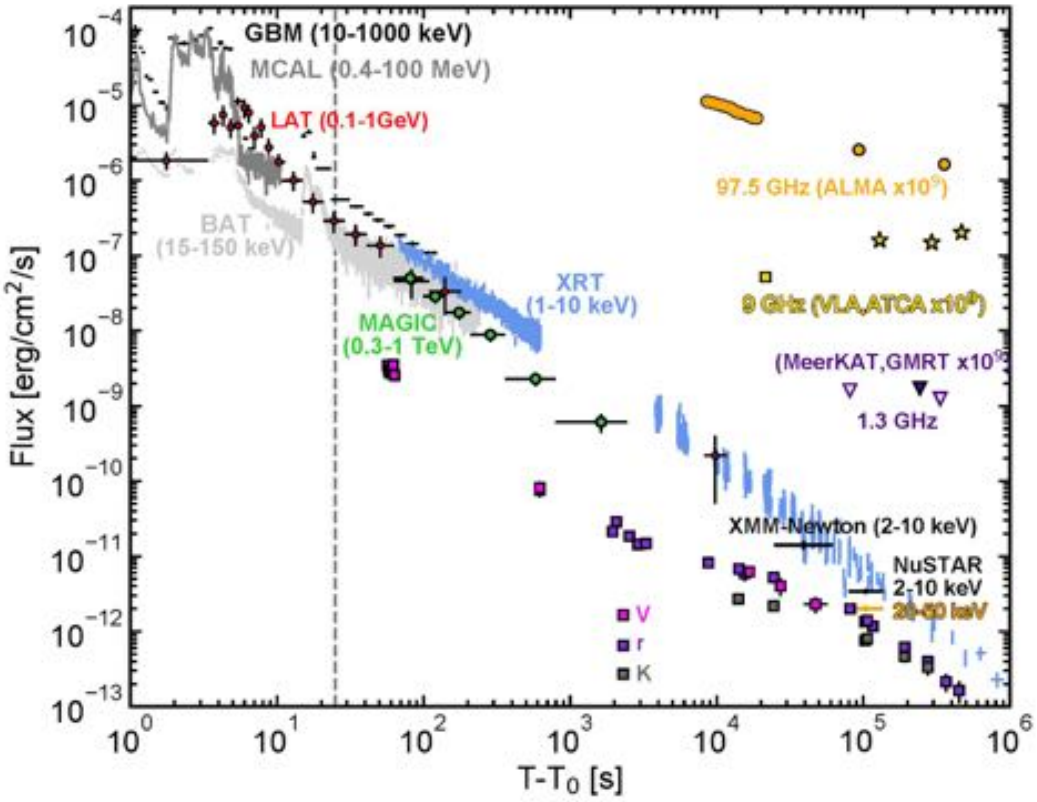
MAGIC detected an energetic component not yet seen in GRBs, different from synchrotron



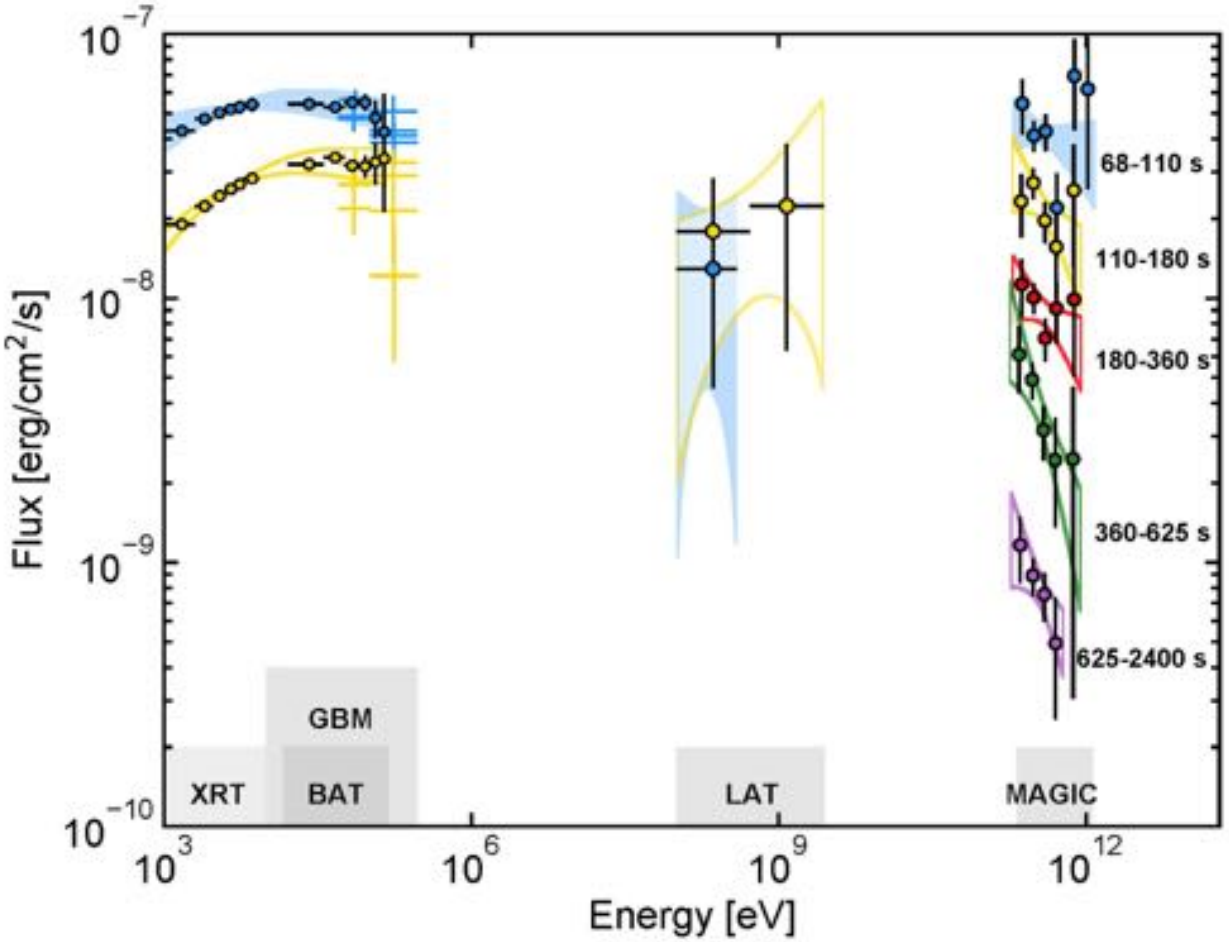
Bottom curves show the expected max. photon energy $\varepsilon_{syn,max}$ of electron synchrotron radiation in the standard afterglow theory, for two extreme cases; isotropic-equivalent blast wave kinetic energy $E_{k,aft} = 3 \cdot 10^{55}$ erg
dotted – n = const.
dashed – $n \sim 1/R^2$

Multi-wavelength light curves of GRB190114C measured > 20 space-born and ground-based instruments

- MAGIC detected the afterglow phase of the GRB
- A significant share of GRB energy is emitted in the TeV energy range



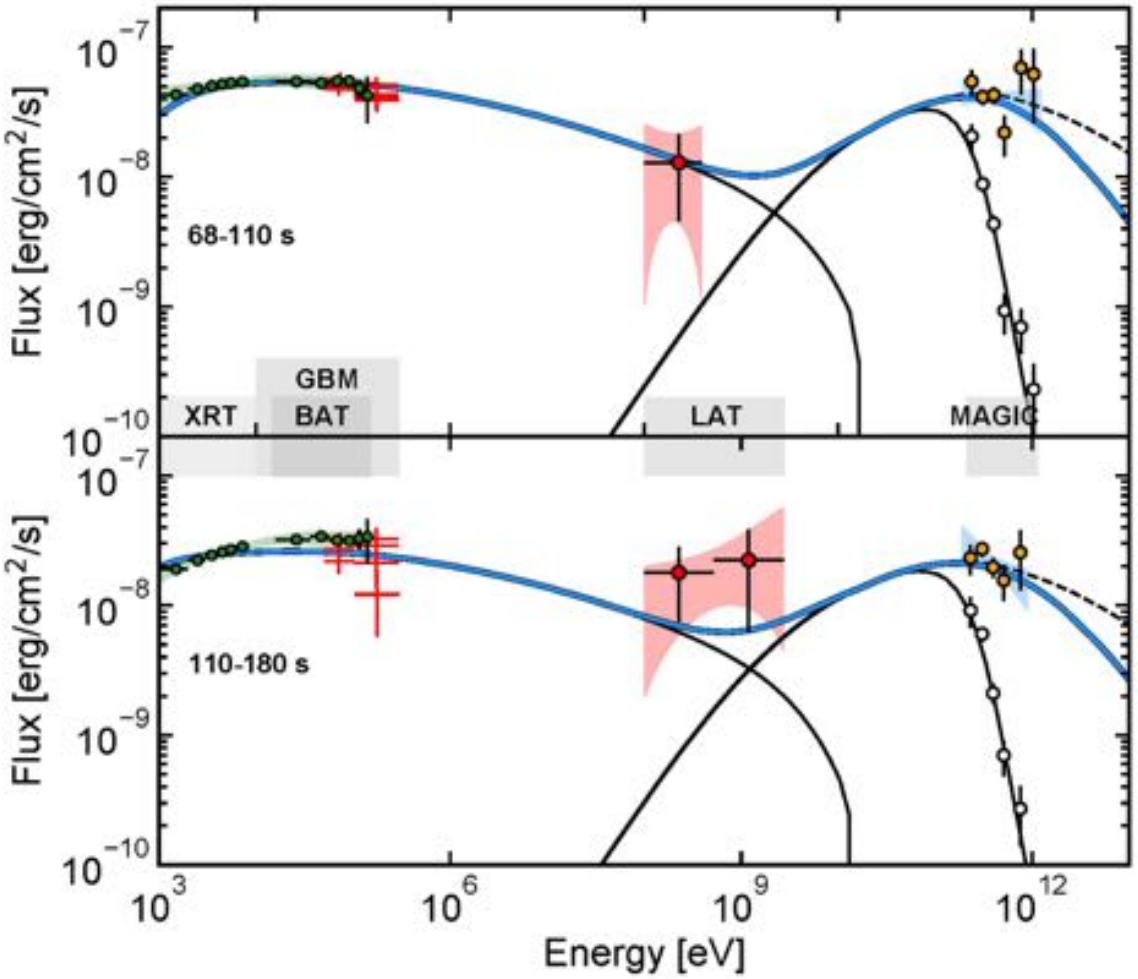
Dynamics of multi-wavelength spectra of GRB 190114C



A really unique event; the spectra have been measured during the

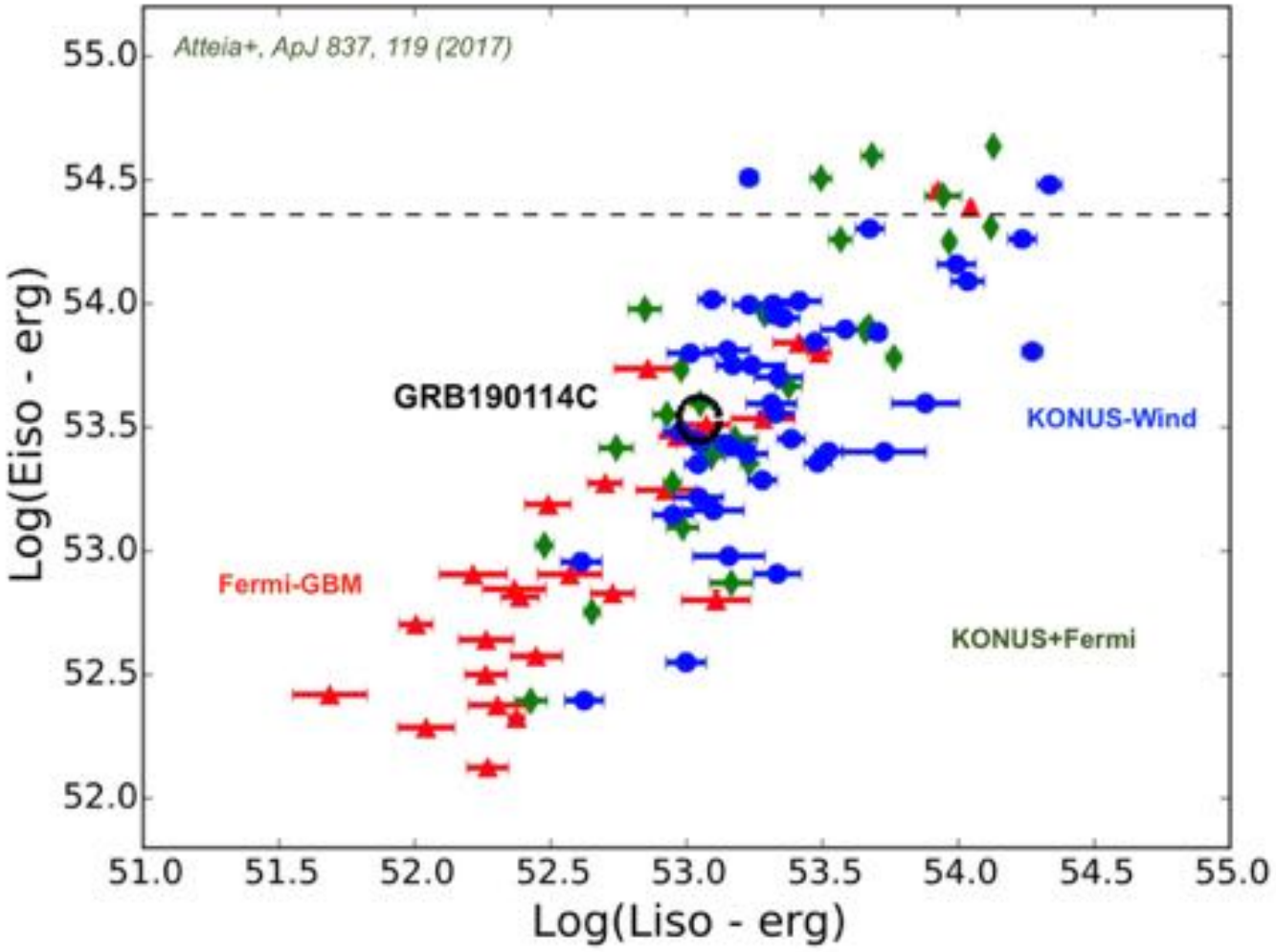
- 1st time bin for only 42 s,
- 2nd time bin for 70 s
- 3rd time bin 180 s

IC Emission from GRB 190114C



- Note the double-peak structure, resembling the well-known pattern from blazars SED
- The energy in the SSC peak is comparable to the energy in synchrotron

Luminosity of GRB 190114C as compared to other long GRBs: it is not too special



GRB190829A: Detection of VHE gamma-ray emission with H.E.S.S.

ATel #13052; *M. de Naurois (H. E.S. S. Collaboration)*
on 30 Aug 2019; 07:12 UT
Credential Certification: Fabian SchÃ□Â¼ssler (fabian.schussler@cea.fr)

Subjects: Gamma Ray, >GeV, TeV, VHE, Gamma-Ray Burst

Tweet

The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was used to carry out follow-up observations of the afterglow of GRB 190829A (Dichiara et al., GCN 25552). At a redshift of z = 0.0785 +/- 0.005 (A.F. Valeev et al., GCN 25565) this is one of the nearest GRBs detected to date. H.E.S.S. Observations started July 30 at 00:16 UTC (i.e. T0 + 4h20), lasted until 3h50 UTC and were taken under good conditions. A preliminary onsite analysis of the obtained data shows a >5sigma gamma-ray excess compatible with the direction of GRB190829A. Further analyses of the data are on-going and further H.E.S.S. observations are planned. We strongly encourage follow-up at all wavelengths. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, France, Germany, Ireland, Japan, the Netherlands, Poland, South Africa, Sweden, UK, and the host country, Namibia. For more details see https://www.mpi-hd.mpg.de/hfm/HESS/

Take away messages on the detection of GRB 190114C

- MAGIC detected an energetic component not yet seen in GRBs, different from synchrotron
- MAGIC clearly detected the afterglow phase of the GRB 190114C from redshift z=0.42
- The new component is energetic, extending till ~2 TeV
- This is the brightest source ever detected by IACTs, the peak rate of gamma-rays ~ 0.13 kCrab
- The flux observed at T0+80 s corresponds to apparent isotropic-equivalent luminosity $L_{iso} \sim 3 \times 10^{49}$ erg/s at E ≥ 0.3 TeV, making this the most luminous source known at these energies

Take away messages on the detection of GRBs

- Most GRBs may possibly possess TeV emission components similar to GRB 190114C, which may be detectable as long as redshift is low and the observing conditions are suitable
- H.E.S.S. reports on γ-ray emission of up to 400 GeV from GRB 180720B at z=0.653 10h after the burst – afterglow
- MAGIC has measured a 3σ hint from the *short* GRB 160821B
- H.E.S.S. detected GRB 190829A
- MAGIC has also detected a small signal from GRB 190829A
- This is just the beginning of the GRB era with IACTs

Backup

We devote this detection to the memory of Eckart Lorenz

- Those who had the privilege to work with him or simply had discussions with him knew his innovative spirit, charisma and optimism
- 25 years ago we were dreaming about measuring GRBs, Pulsars, AGN, …, at E > 10 GeV
- With his unquenchable energy, brilliant know-how of materials and experimental methods in physics he was the driver behind to meet the preparations for the GRB observations with MAGIC

This snapshot recorded the very happy last minute in the life of Eckart; he became member of the Polish Academy of Sciences

MAGIC is Using a Fully-Automatic System for Following the Transient Alerts

- A special attention is paid to the safety issues because for saving precious seconds, there is no human intervention
- All these operations follow detailed protocols, which over many years were improved, tested and debugged
- For keeping the system and the current crew on the observational shift in a good shape, during observations we used to issue fake alerts to imaginary GRB positions; typically these were chosen to be one of the known intense gamma-ray emitters – this way later on one could check if the action was successful
- Of course the initiators of the fake alerts kept information confidential

The Astronomer's Telegram

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

Offline analyses revealed signal > 50 σ

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to