Very high energy observations of gamma-ray bursts with Cherenkov telescopes

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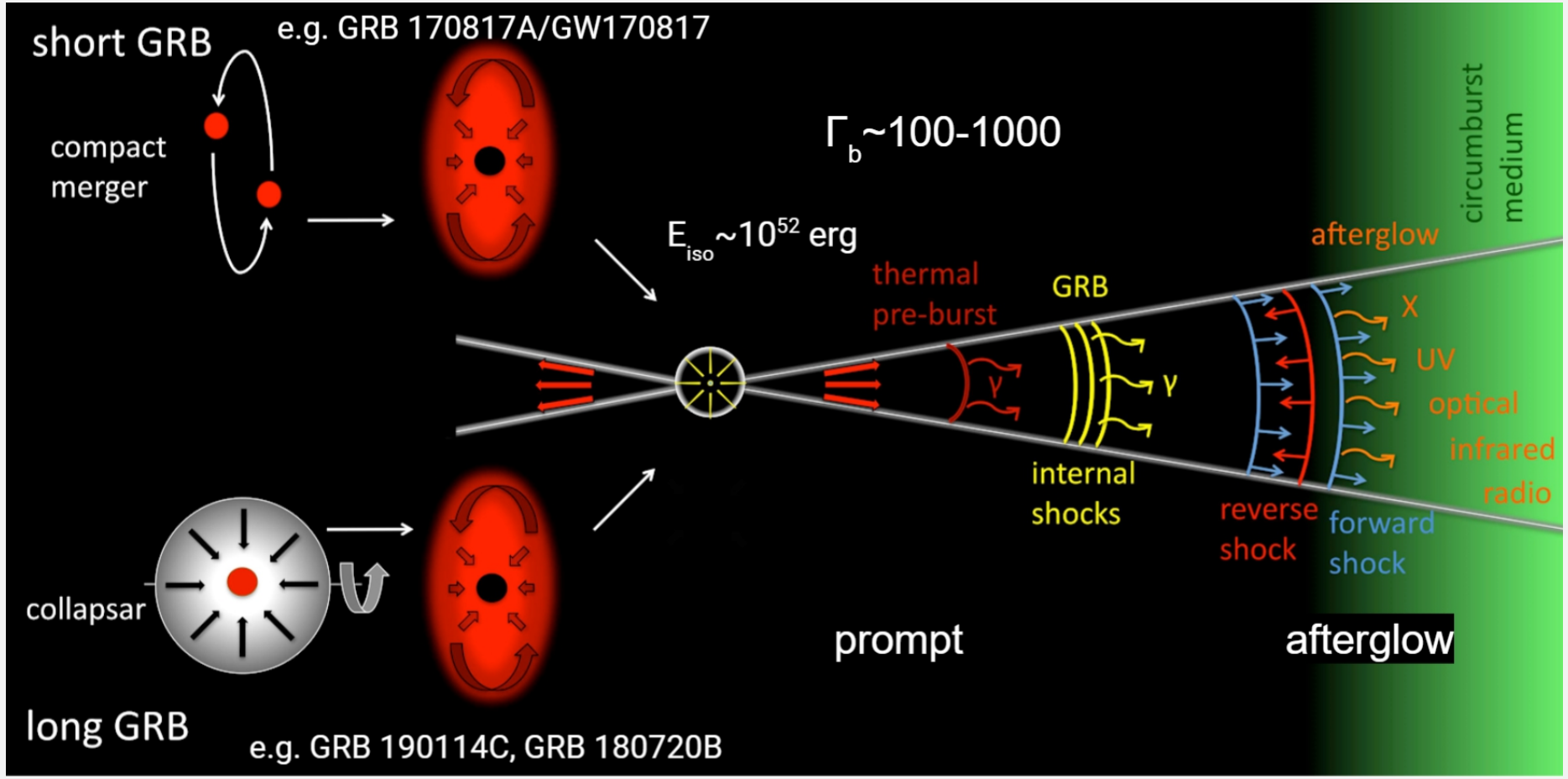
Gamma-ray bursts: a short intro



Current generation IACTs with GRBs follow-up programs

Detecting gamma rays with energies above ~100 GeV up to some tens of TeV

VERITAS

MAGIC

H.E.S.S.

Why observations of GRBs at VHE?

- Why is the follow-up of GRBs at very high energies (VHE, E>100 GeV) so important? There are many key questions without answer:
  - do GRBs emit at VHE?
  - is VHE emission from GRBs energetically relevant?
  - what is the emission process or processes?
  - can this emission process contribute also at lower energies?
  - is there VHE emission in both the prompt and the afterglow?
  - do both short and long GRBs have VHE emission? If they do, are the properties of the emission similar?
  - ...
- But observing GRBs with IACTs is challenging:
  - strong EBL absorption (GRBs at typical moderate-high redshift, stronger absorption in VHE range)
  - small FoV, need to repoint the telescopes, need to observe in many different sky conditions etc...

Current generation IACTs with GRBs follow-up programs

- MAGIC and H.E.S.S. have fully automated reactions to GRB alerts; VERITAS needs confirmation by onsite observers

- Several GRB follow-ups
  - ~140 GRBs with MAGIC, since 2004 (both in mono and stereo)
  - ~200 GRBs with VERITAS
  - ~60 GRBs with H.E.S.S. with 5 full telescope array (since 2012)

- All IACTs are extending their observation windows after lessons learned from recent detections (see next slides)

GRBs detected by Cherenkov telescopes

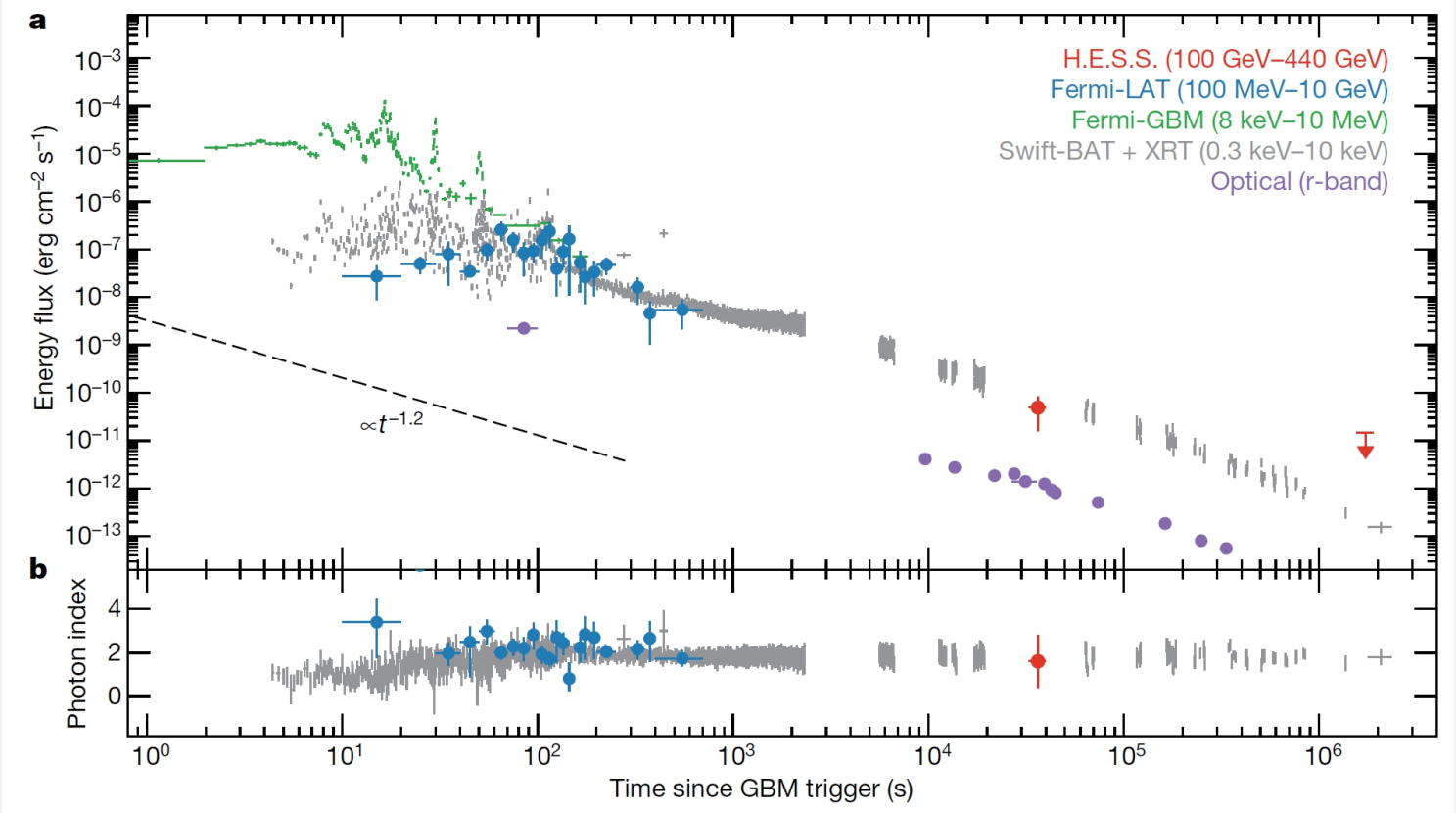
- A hunt going on since ~2 decades, finally getting the reward after several trials

- Now we have 4 detected GRBs:
  - GRB 180720B (H.E.S.S.)
  - GRB 190114C (MAGIC)
  - GRB 190829A (H.E.S.S.)
  - GRB 201216C (MAGIC)

- All detected GRBs are of the long class
  - for the short class, we have a strong hint from the short GRB 160821B by MAGIC
    - kilonova associated --> interesting prospects for joined GW/GRB detection in next LIGO-Virgo-KAGRA observation run

GRB 180720B

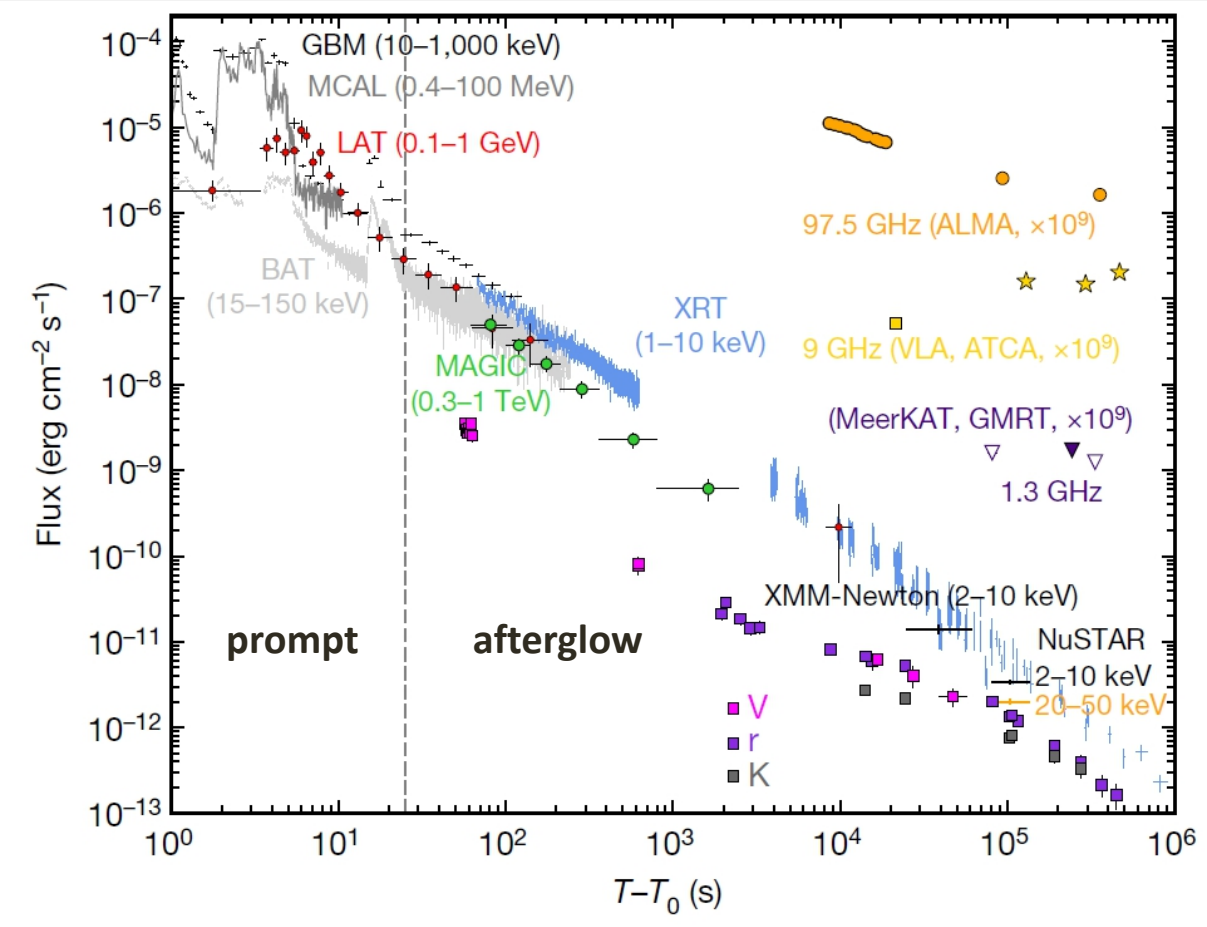
- Bright long GRB
  - T_{90}~48.9 s
  - E_{iso}~6x10^{53} (50-300 keV)
  - z=0.653
- Follow-up by H.E.S.S. at T_0+10.1h for 2 hours, detection at 5σ level
- Flux level for 100 GeV < E < 440 GeV similar to that in X-ray band
- Synchrotron and synchrotron self-Compton (SSC) as possible emission scenarios



Nature 575, 464-467 (2019)

GRB 190114C

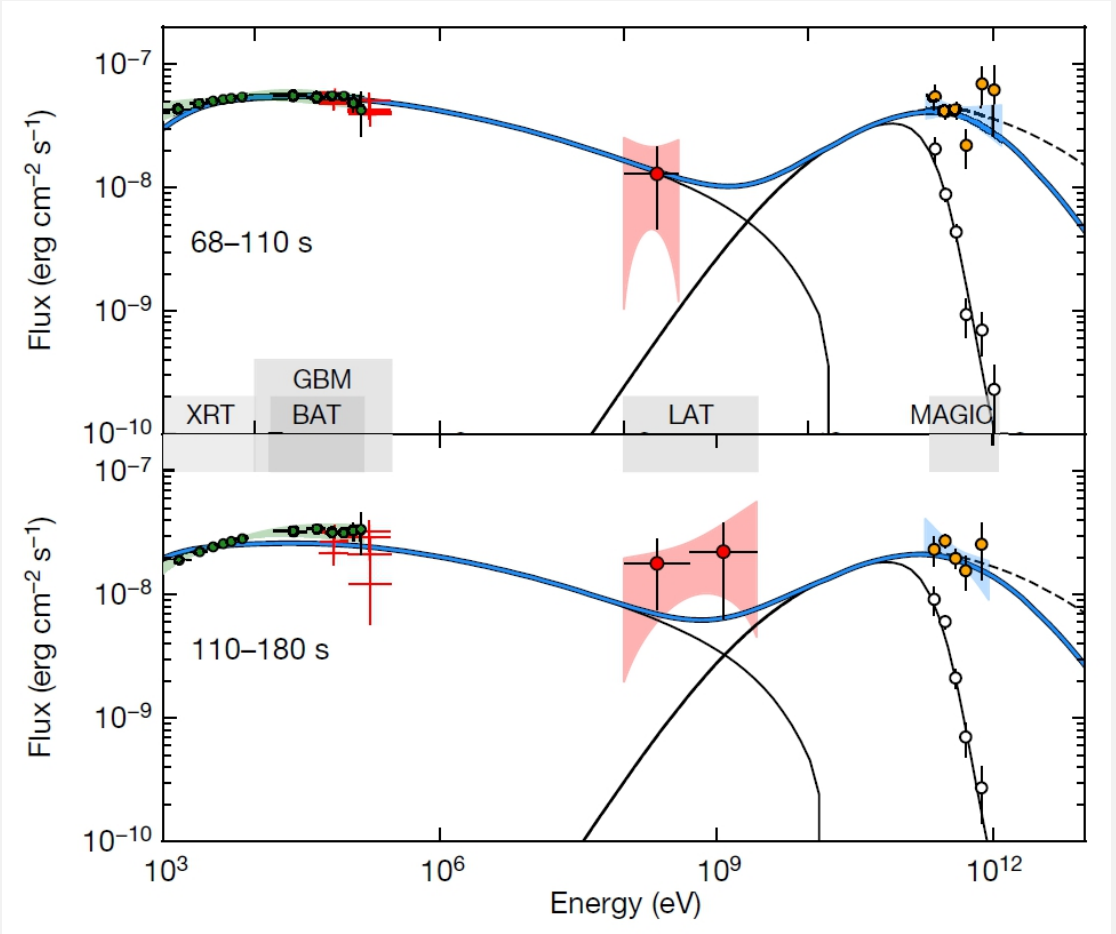
- Bright long GRB
  - T_{90}~360 s
  - E_{iso}~3x10^{53} (1-10000 keV)
  - z=0.4245
- Follow-up by MAGIC from T_0+57s for 4.4h hours, detection at 50σ level in the first 20 minutes above 300 GeV up to 1 TeV
- Flux level between 200 GeV and 1 TeV similar to that in X-ray band
- Flux decay in TeV and X-rays is similar, link between the two processes



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

GRB 190114C

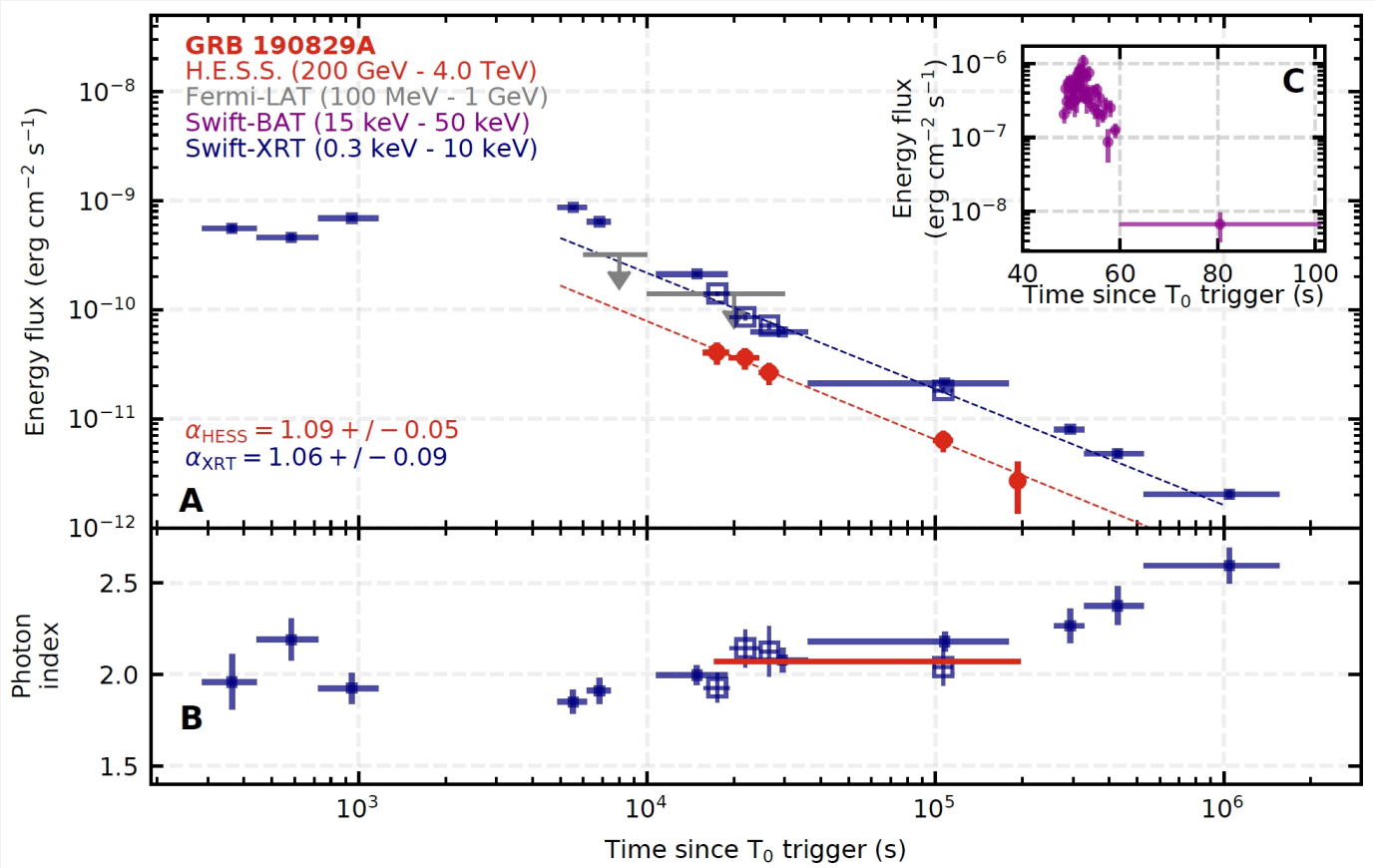
- Energies of photons detected by MAGIC well above the synchrotron burnoff limit for a one zone model (<~ 100 GeV for all the MAGIC observation duration)
  - emission process cannot be synchrotron!
- MAGIC TeV data well described by SSC process, with Klein-Nishina and internal g-g absorption considered
  - possibility of fitting only one synchrotron component? see GRB 190829A in the next slides
- **Discovery of a new emission component in the afterglow of a GRB!**
- Modeling parameters in agreement with previous GRB aferglow studies, and GRB 190114C does not seem exceptional
  - VHE emission might be common



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

GRB 190829A

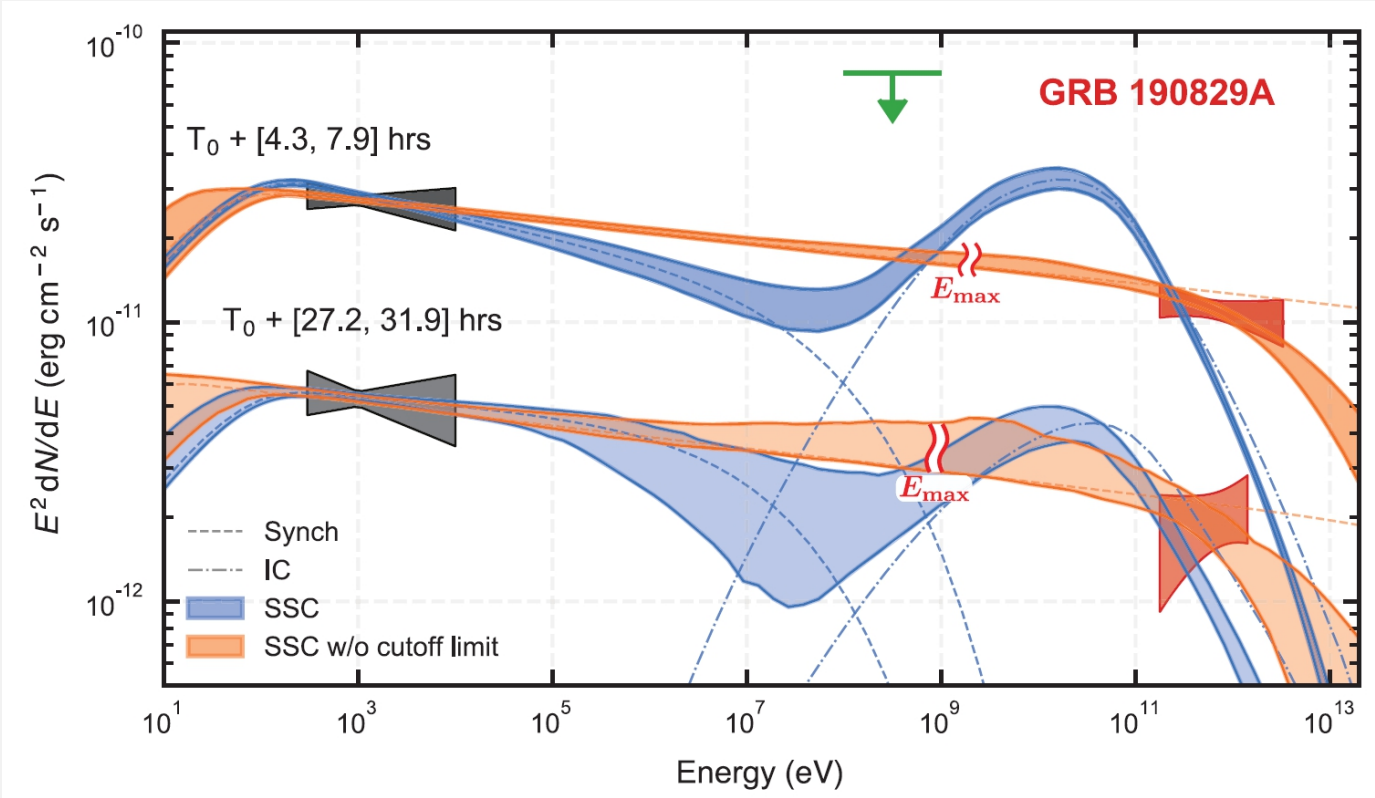
- Low-luminosity long GRB
  - T_{90}~58 s
  - E_{iso}~2x10^{50} (10-1000 keV)
  - z=0.0785
- Follow-up by H.E.S.S. for 3 consecutive nights
  - T_0+4.3h for 3.6h (21.7σ)
  - T_0+27.2h for 4.7h (5.5σ)
  - T_0+51.2h for 4.7h (2.4σ)
- Also in this case, decay of VHE and X-ray light curves is similar



Science 372, 6546, 1081-1085 (2021)

GRB 190829A

- Synchrotron proposed as the possible process responsible for VHE emission
- No maximum energy for the synchrotron process is favored at 5σ level over SSC, given the low Lorentz factor expected (and decreasing over time)
- But see e.g. Salafia et al. to see a possible modeling of VHE emission from GRB 190829A with SSC
  - triggering interesting discussion



Science 372, 6546, 1081-1085 (2021)

GRB 201216C

- Bright long GRB
  - T_{90}~48 s
  - E_{iso}~5x10^{53} (1-10000 keV)
  - **z=1.1!!!**
- Follow-up by MAGIC from ~1min after T_0, detection above 5σ
  - farthest source detected at VHE
- Detection reported in GCN 29075
- Work ongoing for proper modeling of VHE emission

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TITLE:   GCN CIRCULAR
NUMBER:  29075
SUBJECT: GRB 201216C: MAGIC detection in very high energy gamma rays
DATE:    20/12/17 17:23:13 GMT
FROM:    Oscar Blanch at MAGIC Collaboration  <blanch@ifae.es>

O.Blanch (IFAE-BIST Barcelona), F. Longo (University and INFN Trieste), A. Berti (INFN Torino),
S. Fukami (ICRR University of Tokyo), Y. Suda (MPP Munich), S. Loporchio (University and INFN Bari),
S. Micanovic (University of Rijeka), J. G. Green (INAF Rome), V. Pinter (IFAE-BIST),
M. Takahashi (ICRR University of Tokyo), on behalf of the MAGIC collaboration report:

On December 16, 2020, the MAGIC telescopes observed GRB 201216C following the
trigger by Swift-BAT and Fermi-GBM (Beardmore et al., GCN 29061, Fermi/GBM team GCN 29063).
MAGIC started observations under good conditions about 57 seconds after the GRB onset.
The preliminary offline analyses show an excess above 5 sigma, compatible with the GRB position reported
by the Swift and Fermi teams. Refined off-line analyses of the data are ongoing.

We strongly encourage follow-up observations by other instruments at all wavelengths.

The MAGIC point of contact for this burst is O. Blanch (blanch@ifae.es).
Burst Advocate for this burst is F. Longo (francesco.longo@ts.infn.it).

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 greater than 50 TeV.
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GRBs at VHE: what did we learn?

1. Continued effort pays off at the end! No GRB firmly detected in ~15 years, now 4 in ~2 years
   - certainly technical developments played a role (alert systems, improvement in the sensitivity, lowered energy threshold, ability to observe in diverse weather conditions)
   - changes in strategies e.g. observe not only close to the onset, but also much later, especially for bright events

2. VHE emission is there, it can be detected if GRB is relatively close
   - for the moment 3 out 4 were bright GRBs, but GRB 190829A case tells us that even dim events can be detected if z is low

3. VHE emission is present both in the early and late afterglow
4. Similarities between flux level in X-ray and VHE bands, also similar time decay

5. MWL data crucial for proper modeling of the emission
   - golden data set for GRB 190114C

6. SSC as possible universal process to explain TeV emission or revisitation of synchrotron?
   - SSC can explain GRB 180720B, GRB 190114C and possibly GRB 190829A. Let's see for GRB 201216C. Still early to draw any conclusion
   - started debate on acceleration mechanisms withing GRBs

GRBs at VHE: next challenges

1. Our understanding of the afterglow emission is still uncertain despite the recent detected events
   - synchrotron+SSC vs synchrotron in discussion; alternative models (e.g. hadronic)?
   - **we need more GRBs detected at VHE!**

2. Another major breakthrough would be the detection of VHE emission during the prompt phase
   - crucial info on the emission process, still heavily debated
   - current and new ground-based wide field of view instruments (HAWC, LHAASO, SWGO...) may be better suited for this task

3. VHE emission from short GRBs? Strong hint from GRB 160821B by MAGIC
   - interesting in relation to GW searches (O4 starting in 2022)

4. New physics
   - Lorentz Invariance Violation (we would need a distant GRB detected in the prompt)
   - Axion-like particles (search for signatures in the spectra; GRBs detected at high redshift)
   - EBL studies?

GRBs at VHE: prospects

1. Feasability of GRB detection now proven with current generation telescopes: expect other events detected in the next years!

2. A big leap forward is expected with the Cherenkov Telescope Array (CTA), especially with the Large Size Telescope (LST)
   - first prototype in commissioning phase in La Palma, but already taking data on interesting sources
   - low energy threshold to detect GRBs up to high redshift
   - fast repositioning (any position in 20s) --> needed to try to catch prompt emission, but ground-based wide-field instruments may be better suited
   - possibility to detect dimmer events also at moderate redshifts

3. Searches also at even higher energies may provide interesting results
   - HAWC
   - LHAASO
   - SWGO