Inverse Compton emission revealed by observations up to TeV energies of GRB190114C

Elena Moretti
on behalf of the
MAGIC collaboration

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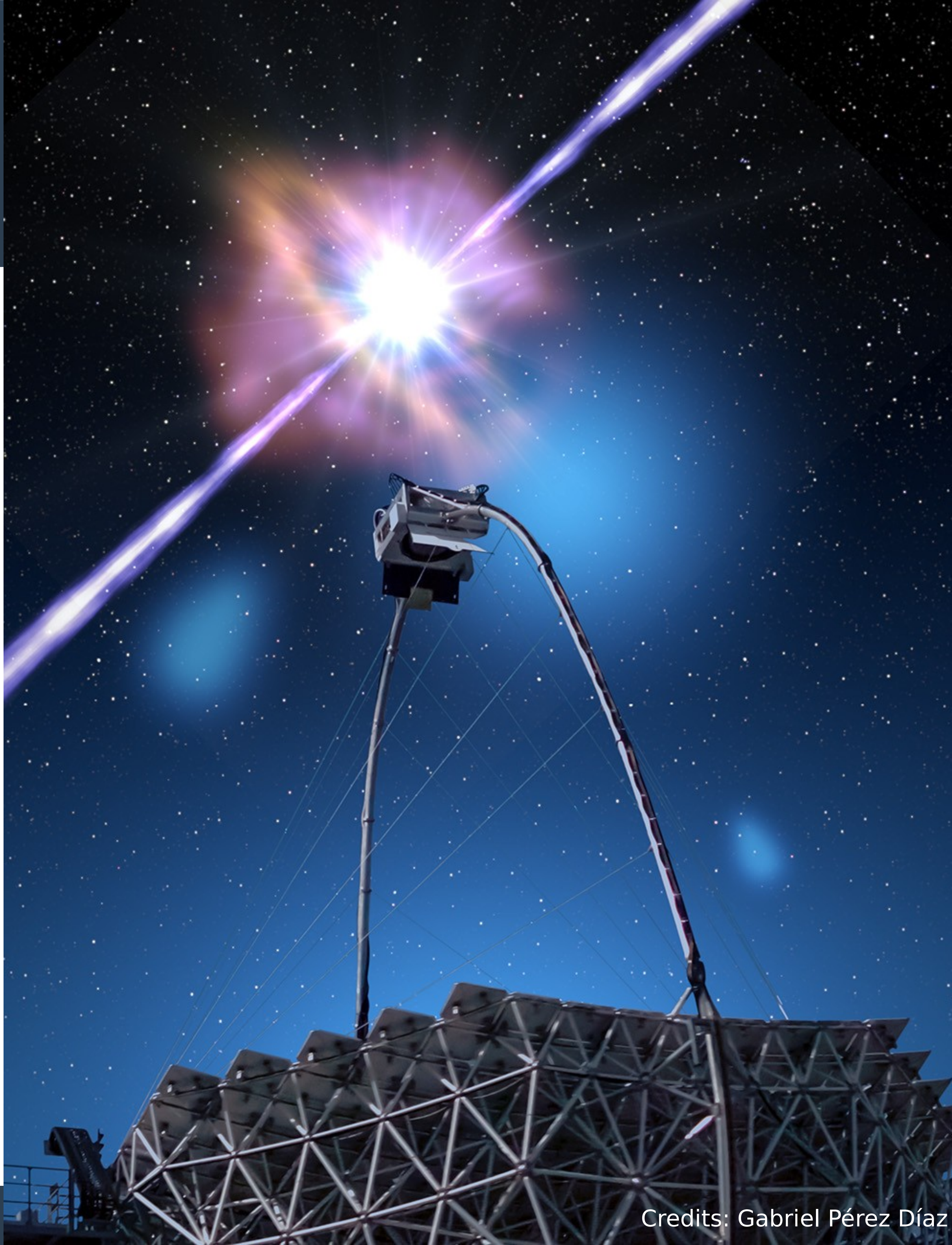
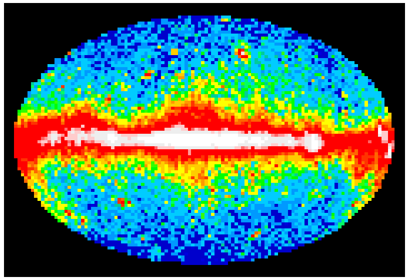
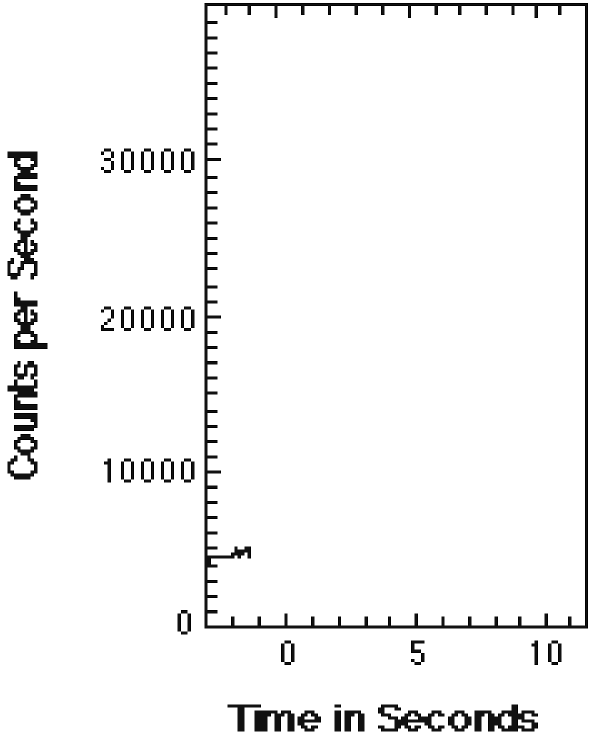


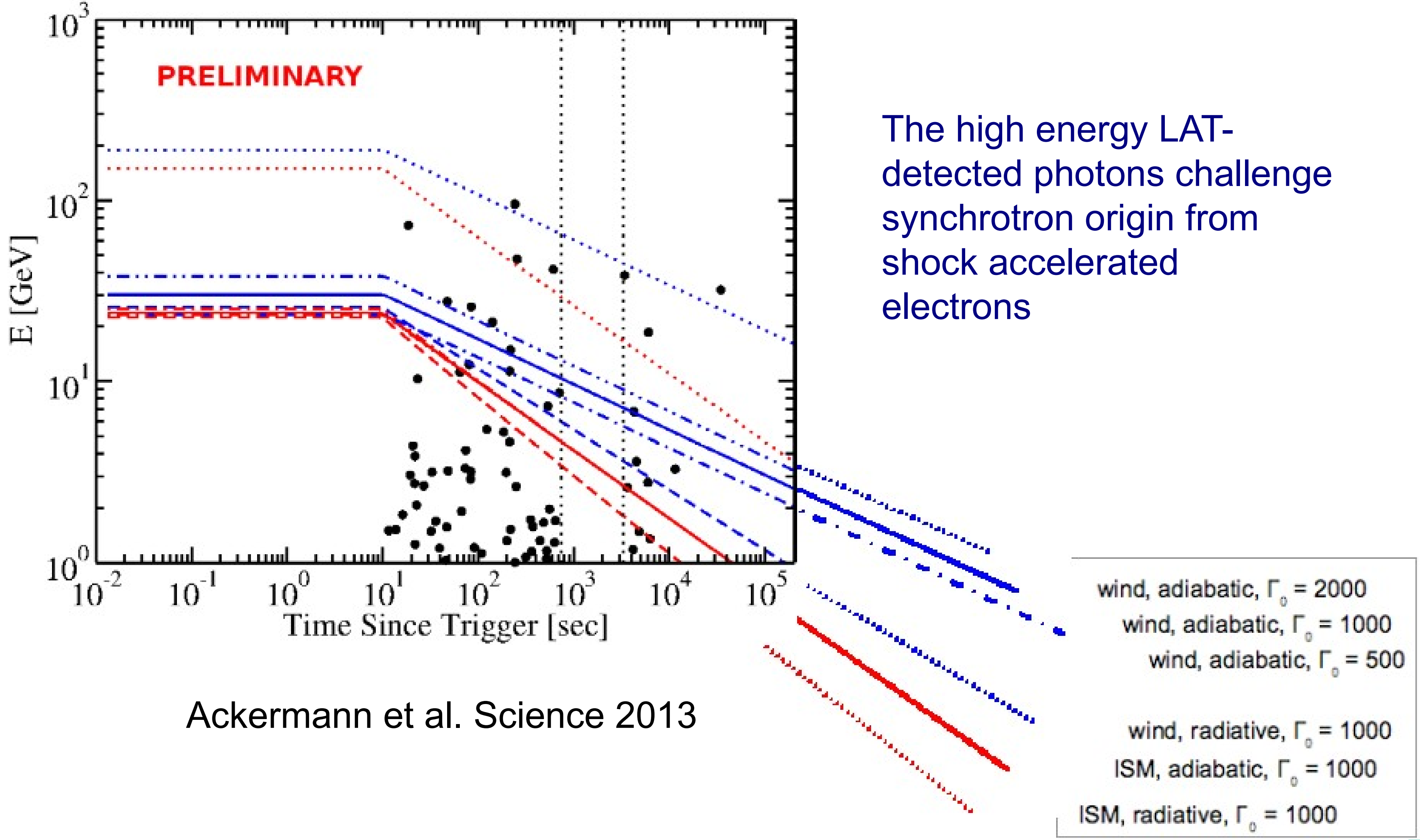
GRBs: general properties

- Very bright sources
- Occurs ~1 per day
- Non-repeatable
- Isotropically distributed in the sky
- Cosmological distances (z~9 highest redshift)
- Observed Flux: $\sim 10^{-7}$ - 10^{-4} erg cm^{-2} s^{-1}
- Total energy emitted 10^{50}-10^{54} erg
- Typical observed energy: <~ MeV





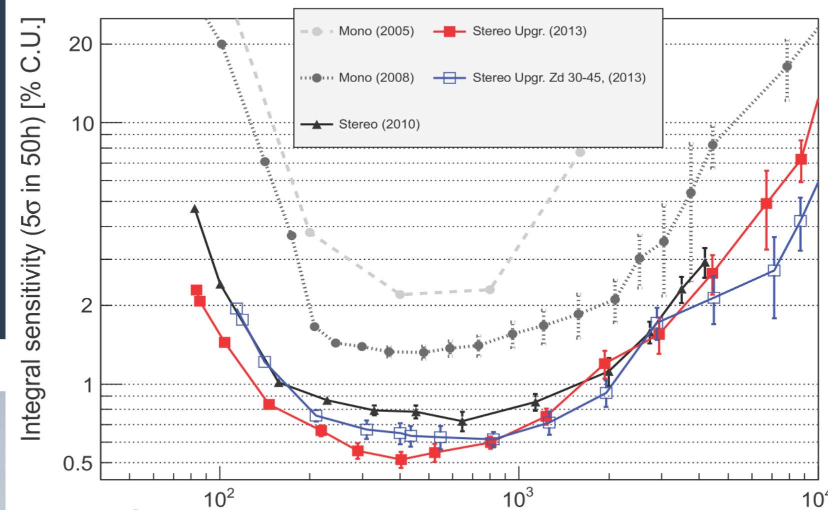
GRB130427A Synchrotron emission?



The high energy LAT-detected photons challenge synchrotron origin from shock accelerated electrons

Ackermann et al. Science 2013

MAGIC

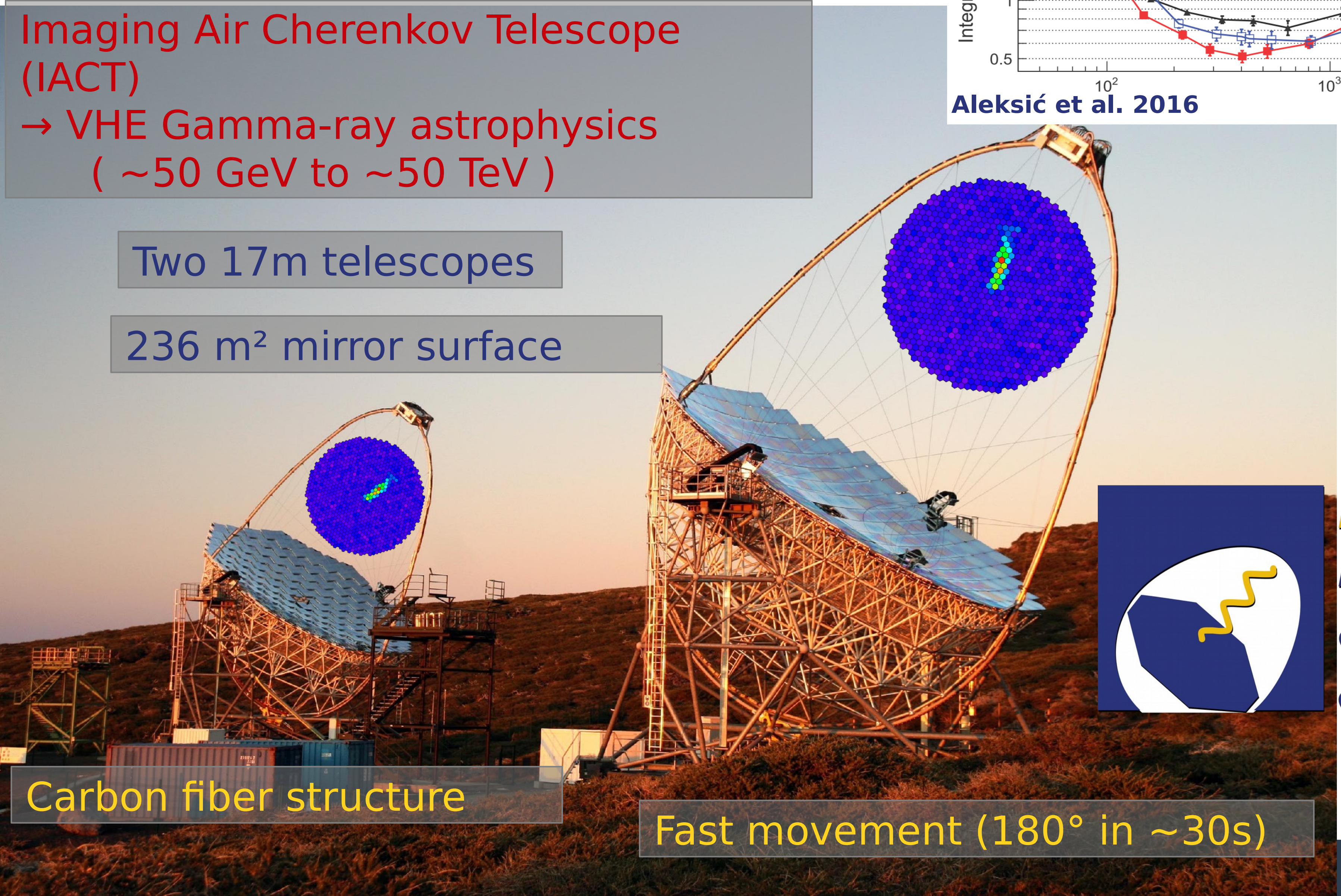


Aleksić et al. 2016

Imaging Air Cherenkov Telescope (IACT)
→ VHE Gamma-ray astrophysics
(~50 GeV to ~50 TeV)

Two 17m telescopes

236 m² mirror surface



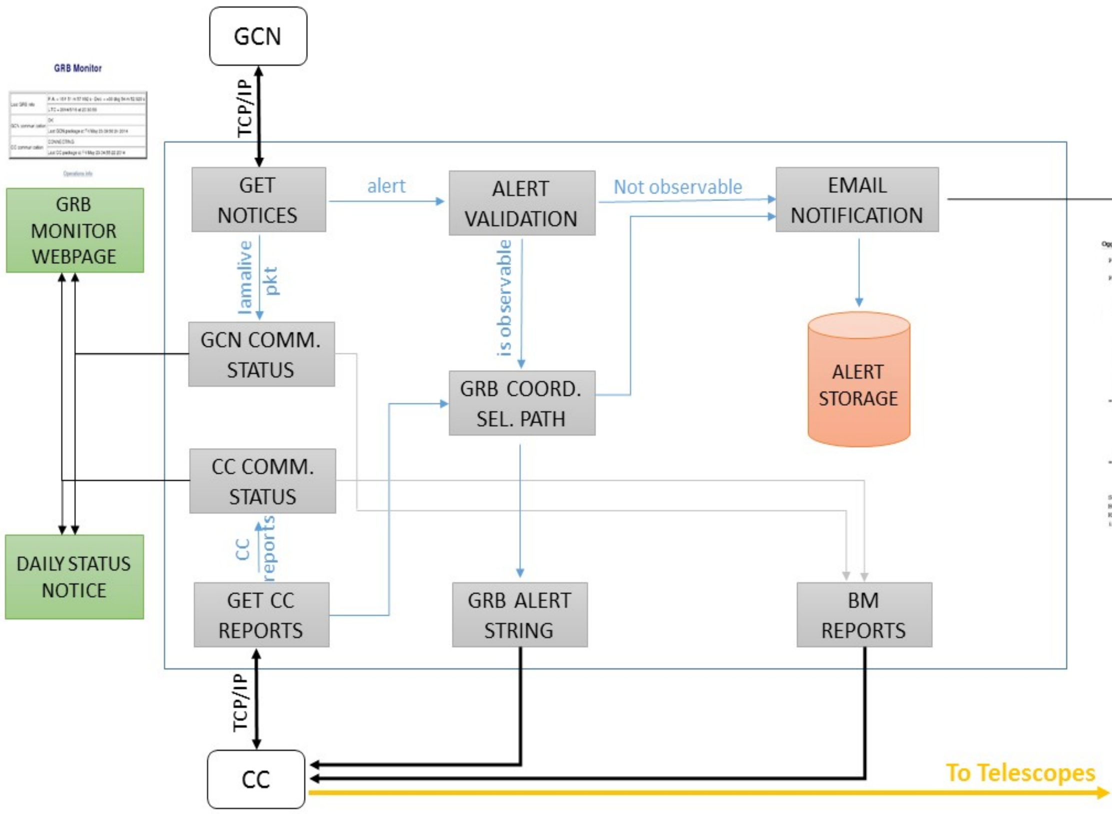
Carbon fiber structure

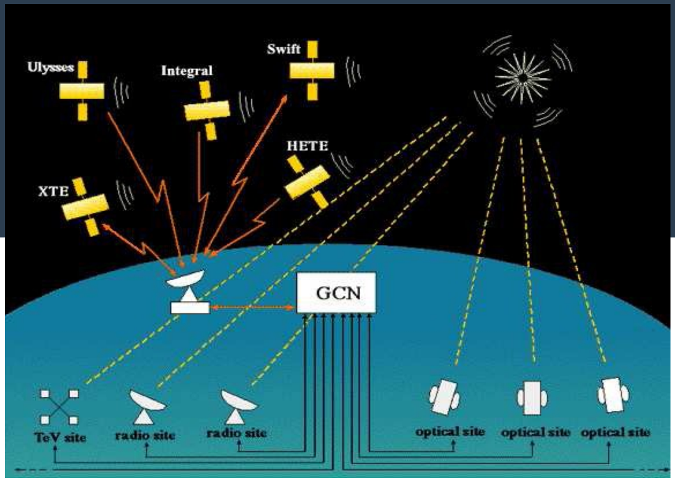
Fast movement (180° in ~30s)

MAGIC

Major Atmospheric Gamma Imaging Cerenkov Telescopes

Alert system





A multi-thread C program manages the communication between GCN and Telescope control

Alerts are validated

(max obs time: 4h)

Zd sun < 103.0
Zd GRB < 60.0
Moon dist. > 30.0

+ Fermi GBM dedicated filters

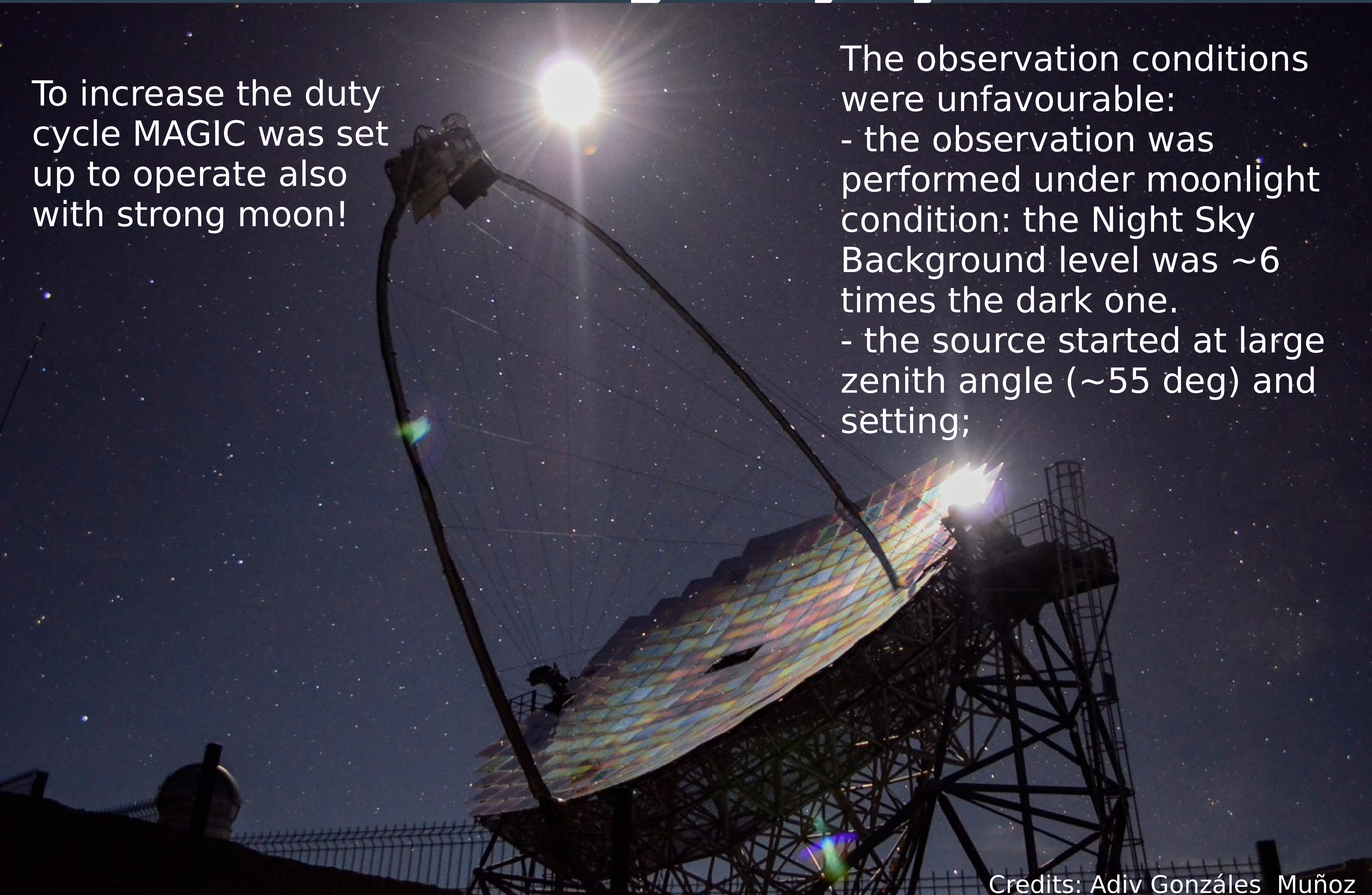
8-10 GRB follow-up/year.

Duty cycle ~10%

Alerts: increasing duty cycle

To increase the duty cycle MAGIC was set up to operate also with strong moon!

The observation conditions were unfavourable:
- the observation was performed under moonlight condition: the Night Sky Background level was ~6 times the dark one.
- the source started at large zenith angle (~55 deg) and setting;



Credits: Adiv Gonzáles Muñoz

Alert and follow up

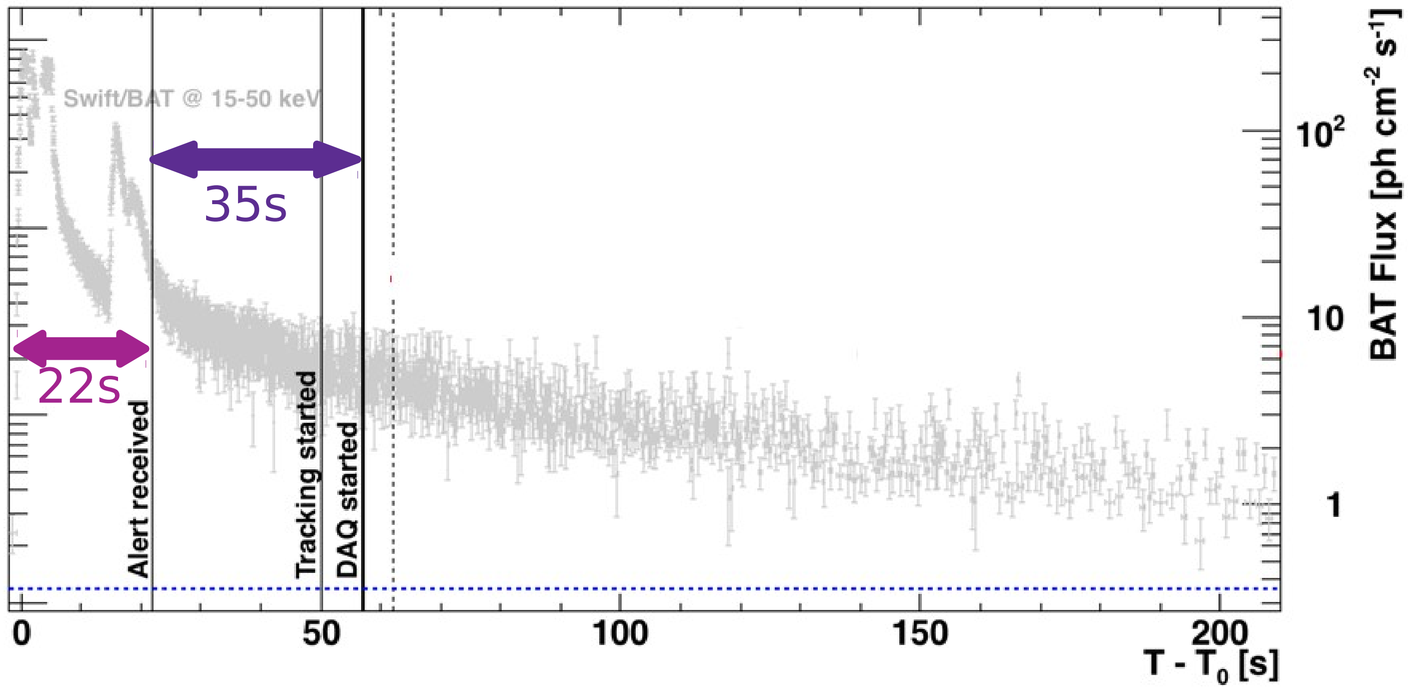
At T0 = 20:57:03 UT Swift/BAT and Fermi/GBM triggered on GRB190114C

T0+22s MAGIC received the alert

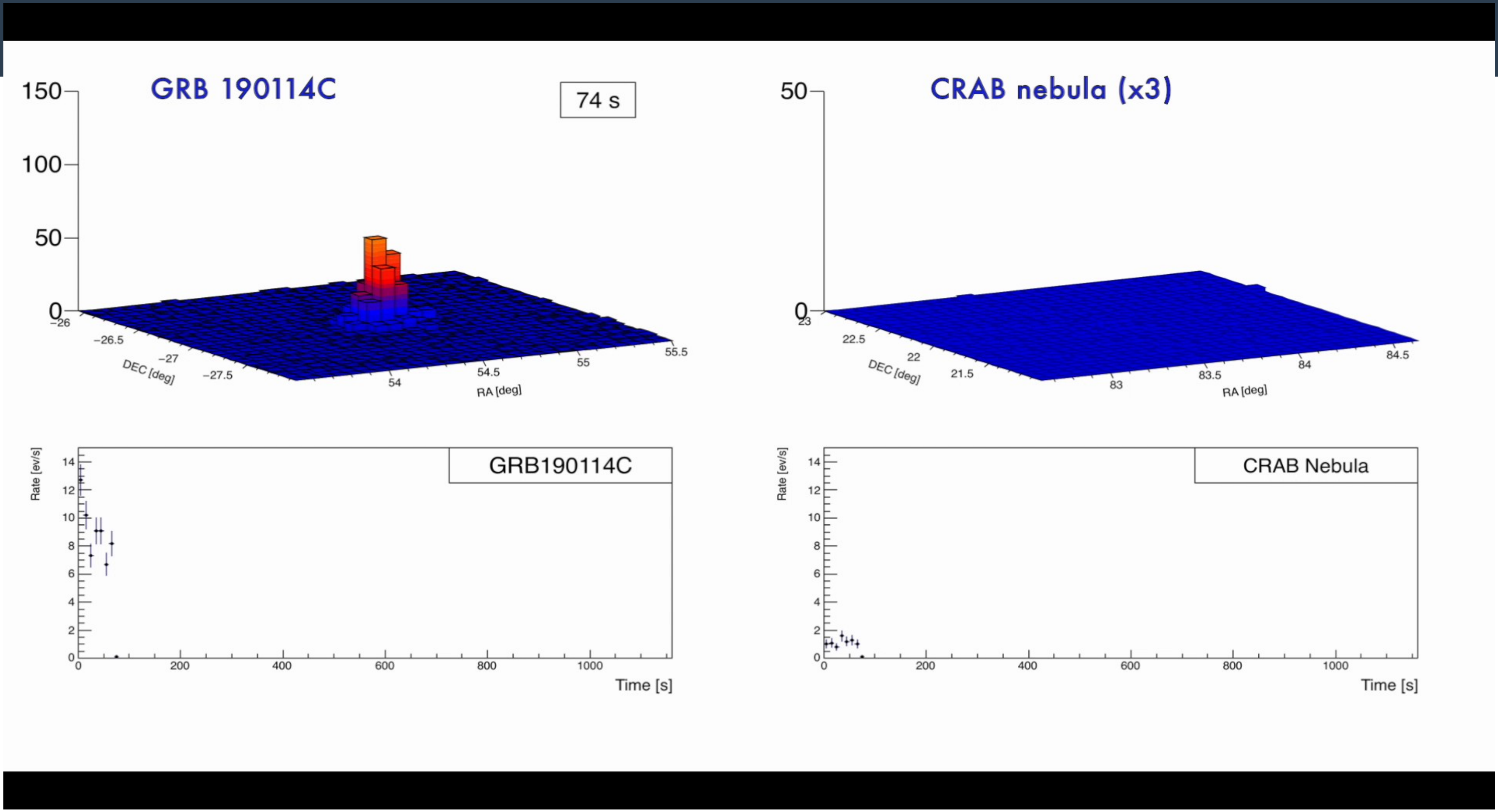
T0+50s MAGIC started tracking

T0+57s MAGIC started data acquisition (35s after the alert)

T0+62a MAGIC data acquisition stabilised

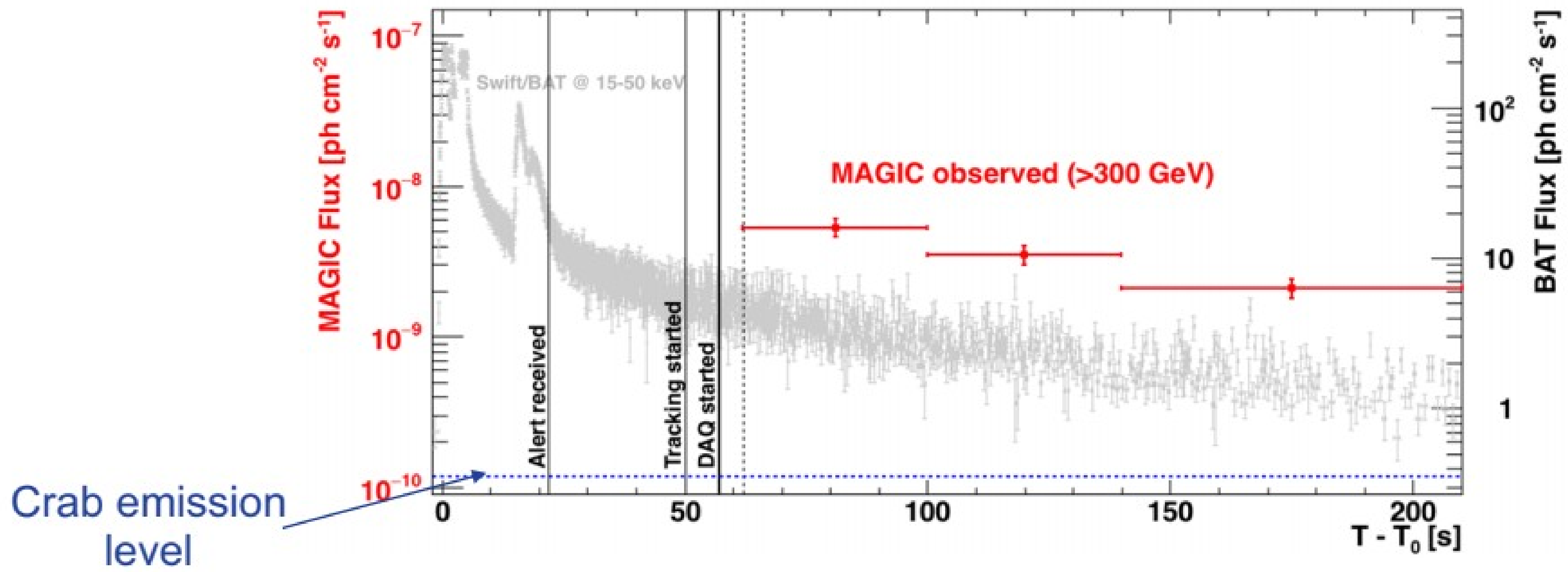


The signal MAGIC saw



In the first 30 seconds of observation, GRB190114C was the brightest source to date at 0.3 TeV, with flux about 100 times higher than from the Crab Nebula. Detection @ 50 sigma!

The signal MAGIC saw

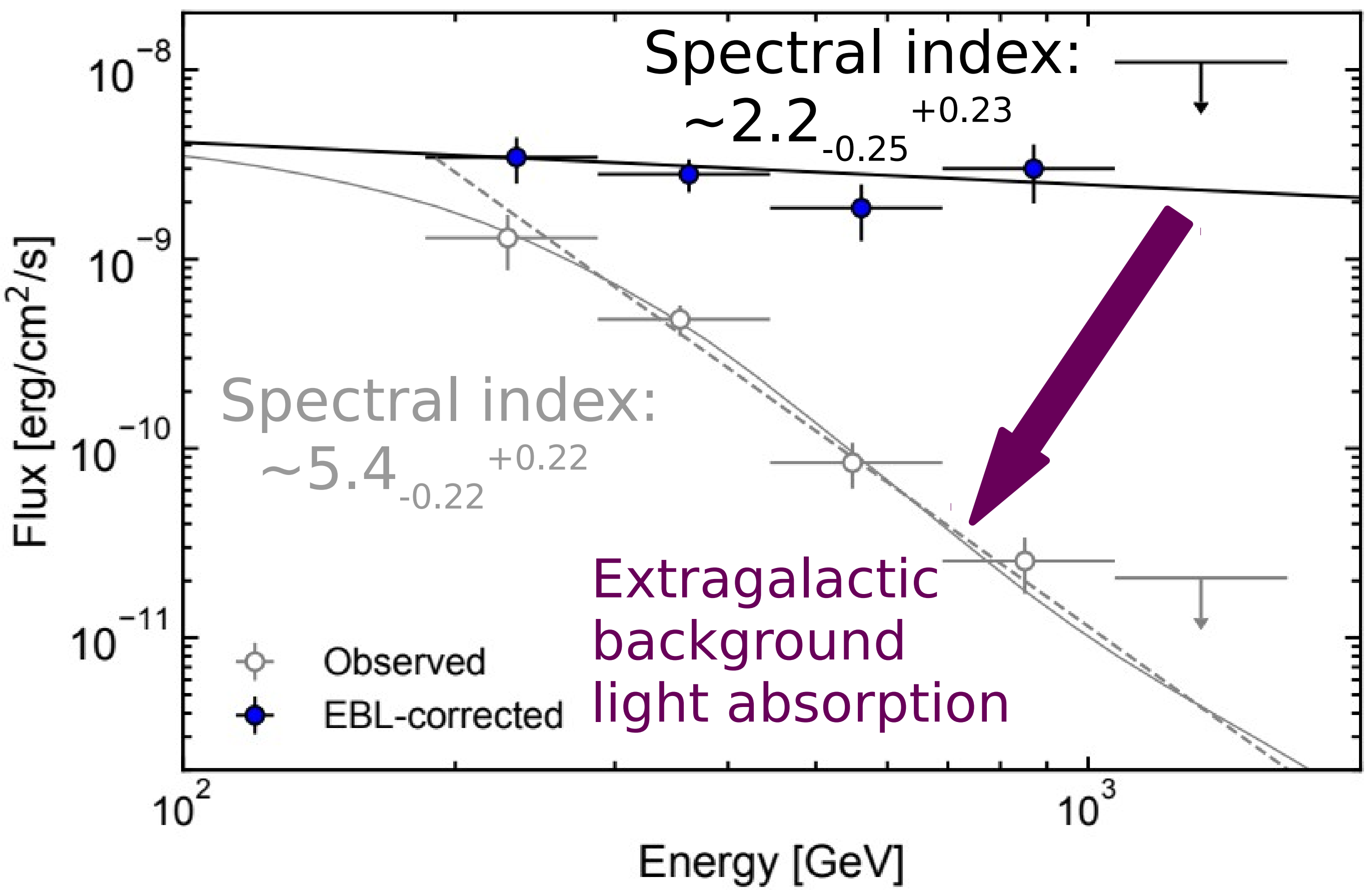


In the first 30 seconds of observation, GRB190114C was the brightest source to date at 0.3 TeV, with flux about 100 times higher than from the Crab Nebula. Detection @ 50 sigma!

Highest energy from a GRB ~1 TeV

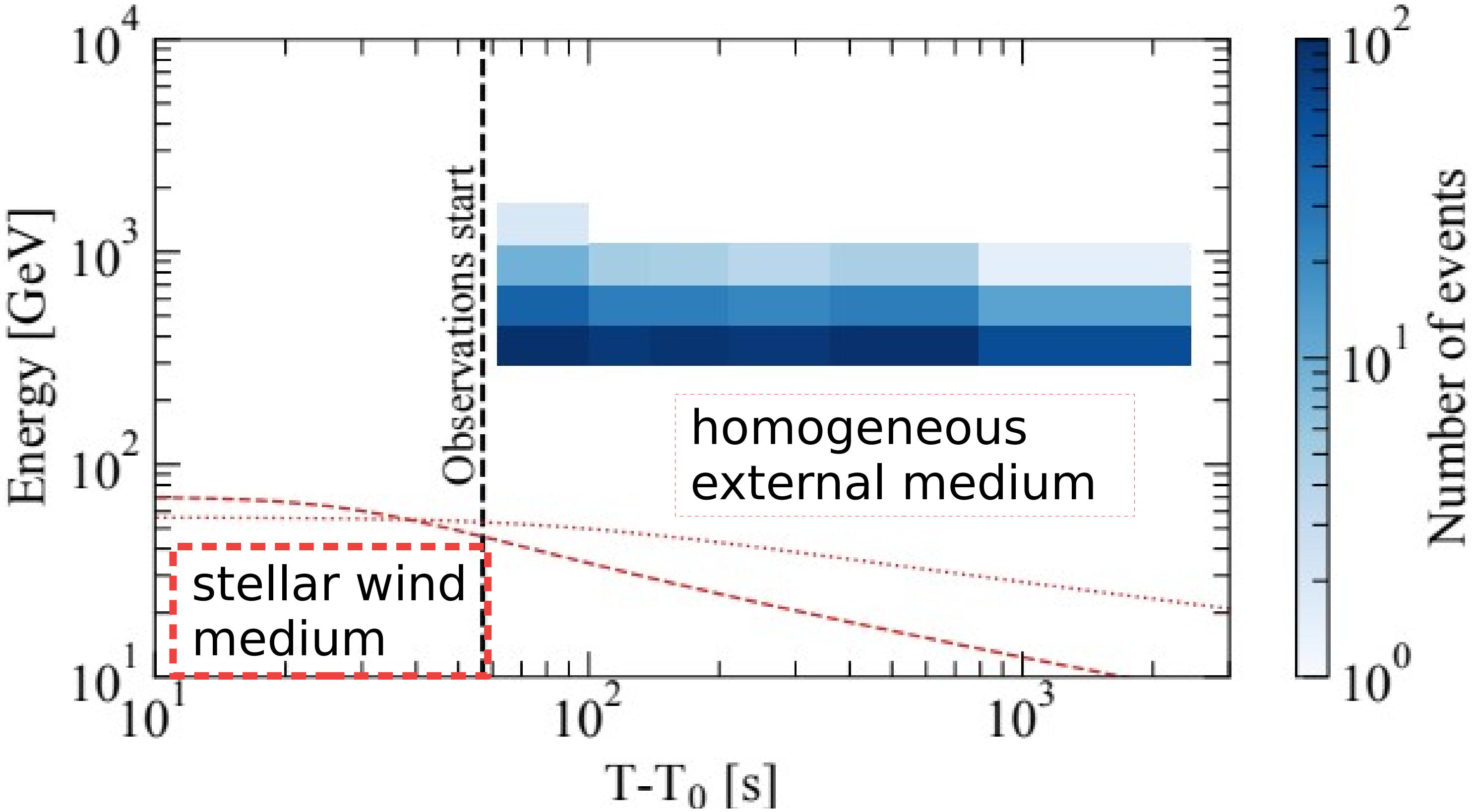
The spectrum from T0+68s – T0+2454s shows us a roughly equal distribution of the power in the 0.2-1TeV band, without break or cutoff.

Energy flux emitted @ sub TeV about half of the one emitted in X-ray (between 60-2454s)



Beyond synchrotron emission

In the interpretation that the sub TeV emission comes from leptonic origins and part of the afterglow phase, the energies detected by MAGIC are much above the synchrotron burn off limit (even accounting for extreme values of density and efficiency).



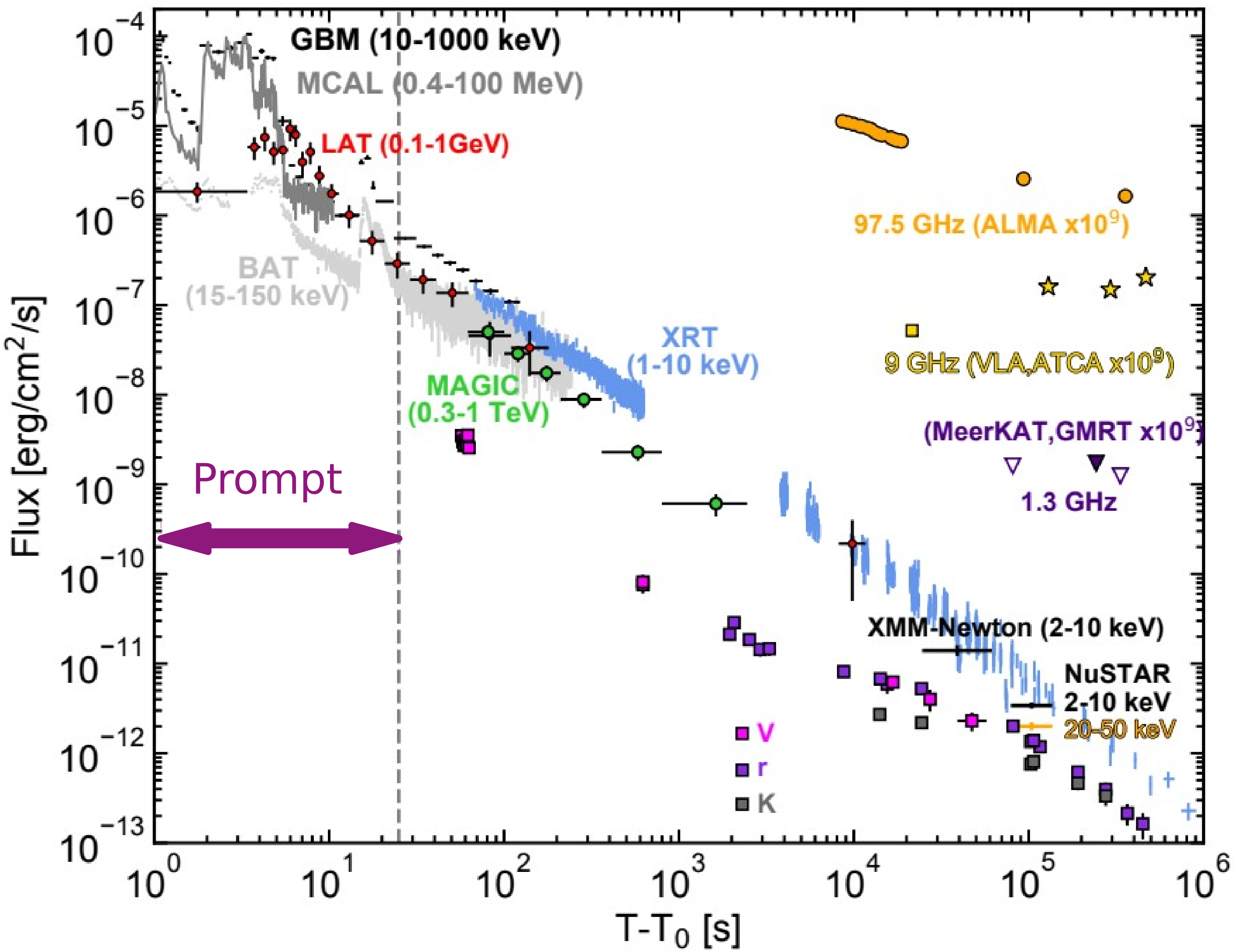
Proton emission?

Could they be the source of the sub TeV emission?

- ✔ Protons could naturally emit via synchrotron radiation to higher energies and overcome the leptonic limit.
- ✔ Protons are also present in the GRB ejected plasma.

- ✗ They require a high blastwave energy to be able to emit up to 1 TeV in about 100s.
- ✗ The required blastwave energy is even higher ($>2\times10^{59}$erg, $\sim10^{6}$ times typical energies) if they would be responsible for the photon flux detected between 0.2-1 TeV.

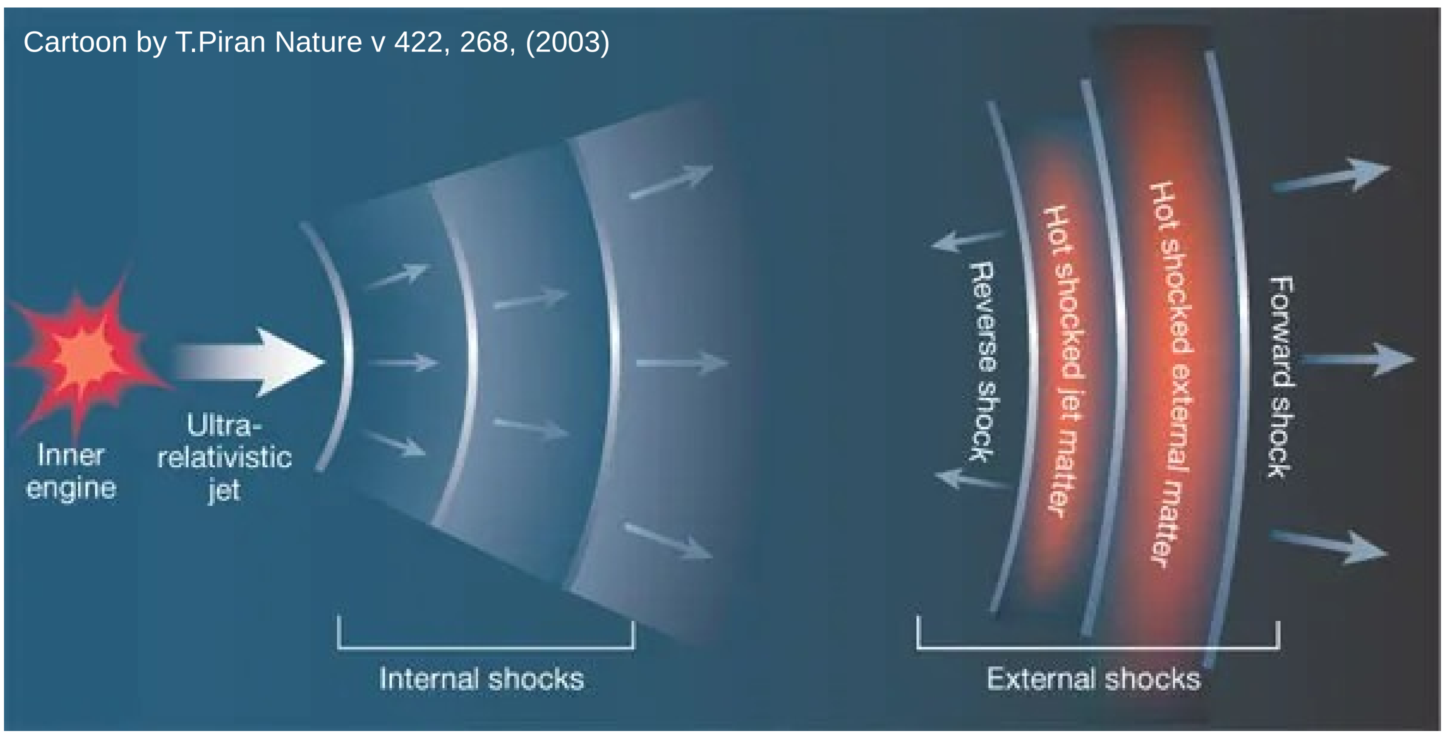
Multi-wavelength temporal profile



- The prompt phase lasts for ~12s;
- MAGIC start its observations in the so-called early afterglow phase;
- Because of its temporal profile the sub-TeV emission is produced in the same conditions as the GeV and X-ray emissions.

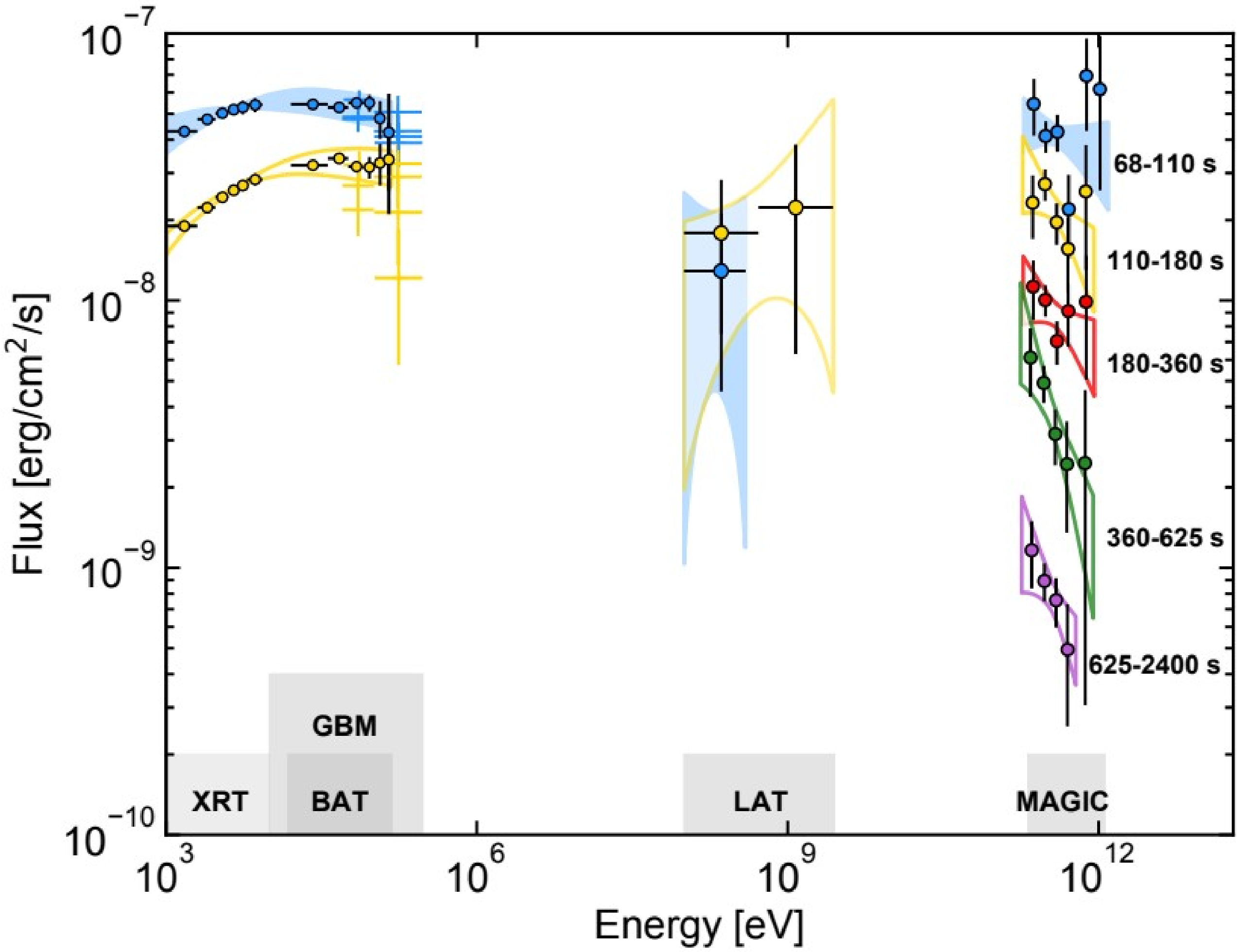
Sub-TeV emission origin

Multi-wavelength emission in the early afterglow phase seems to be generated all in the forward external shocks of the ejected plasma with the external medium.



Cartoon by T.Piran Nature v 422, 268, (2003)

Forward shock, but same process?



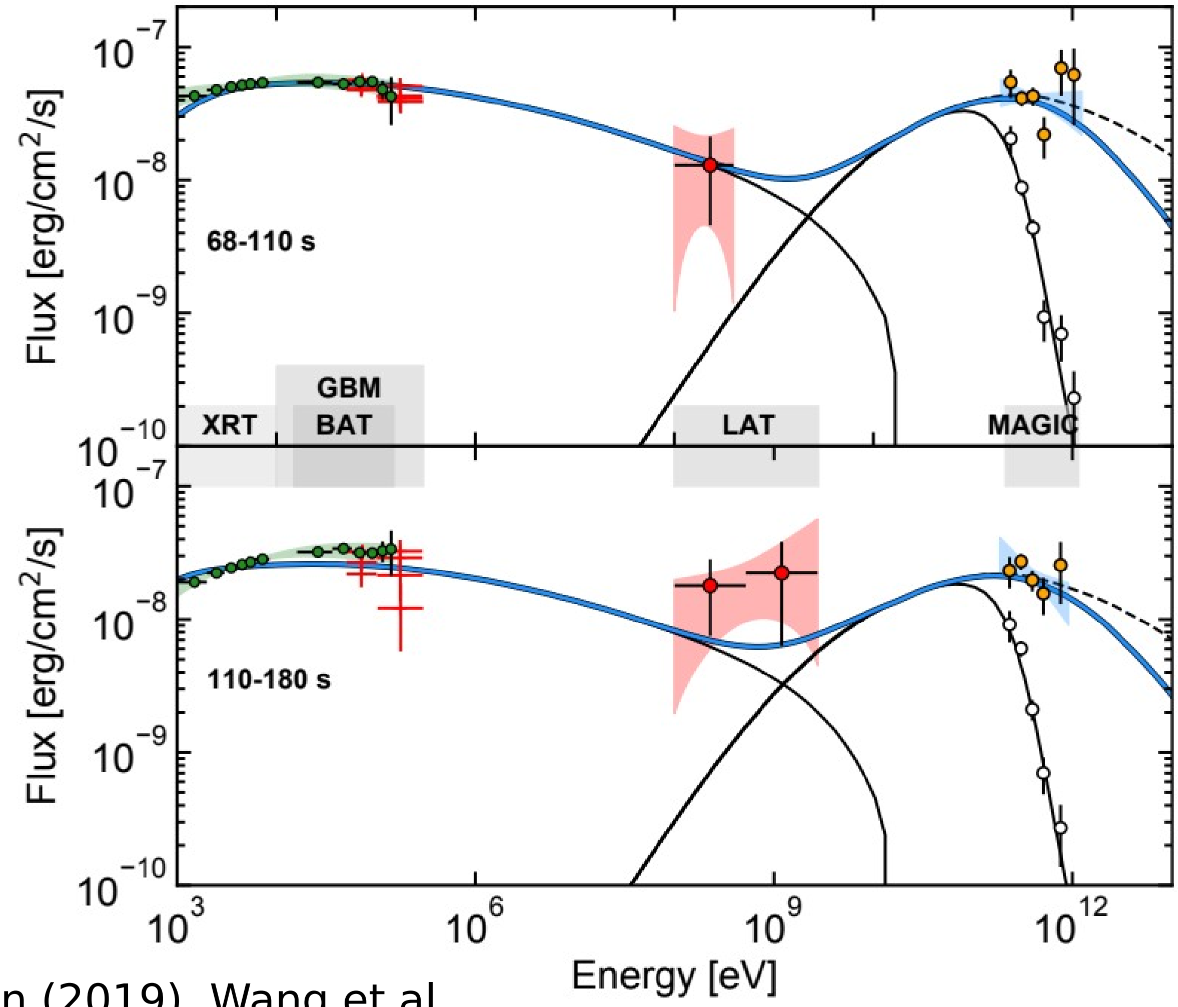
The spectra from X-ray to TeV show the need for an extra spectral component to explain the flux increase at the highest energies.

==> Same forward shock, but different emission processes.

Synchrotron Self-Compton

The extra component is generated by the synchrotron photons Compton up-scattered by the same electrons accelerated in the shocks.

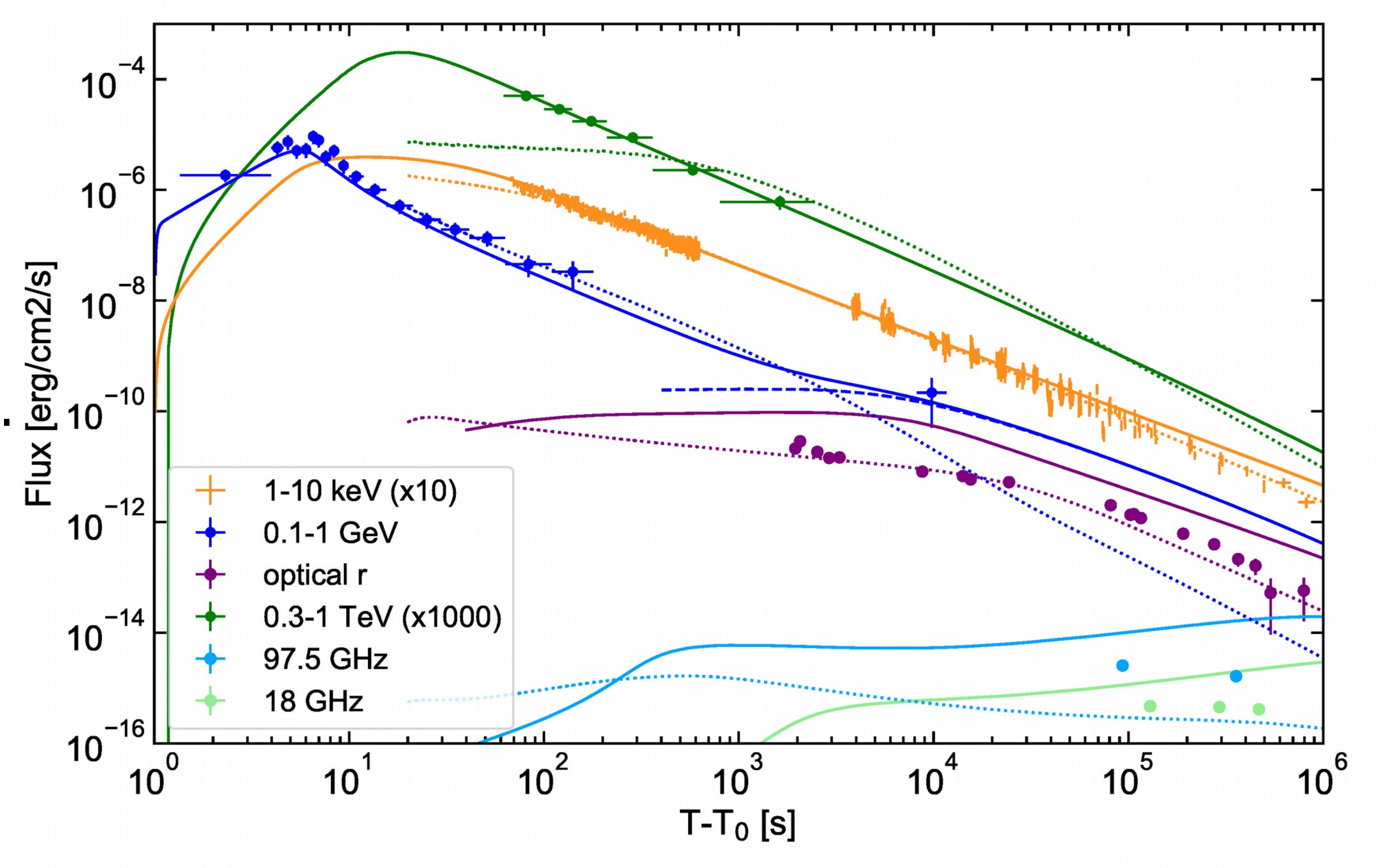
To model the MAGIC data other 2 processes need to be considered: Klein-Nishina Effect (suppression of the highest energy photons) and photo-absorption (γ-γ absorption).



SSC also suggested in Derishev & Piran (2019), Wang et al. (2019), Fraija et al. (2019), Zhang et al. (2019)

Modelling of the temporal profile

The model optimised for the very high energy data (solid lines) slightly over-predicts the optical and radio components. While a model optimised for the low energies (dotted curves) fails to predict the VHE data.



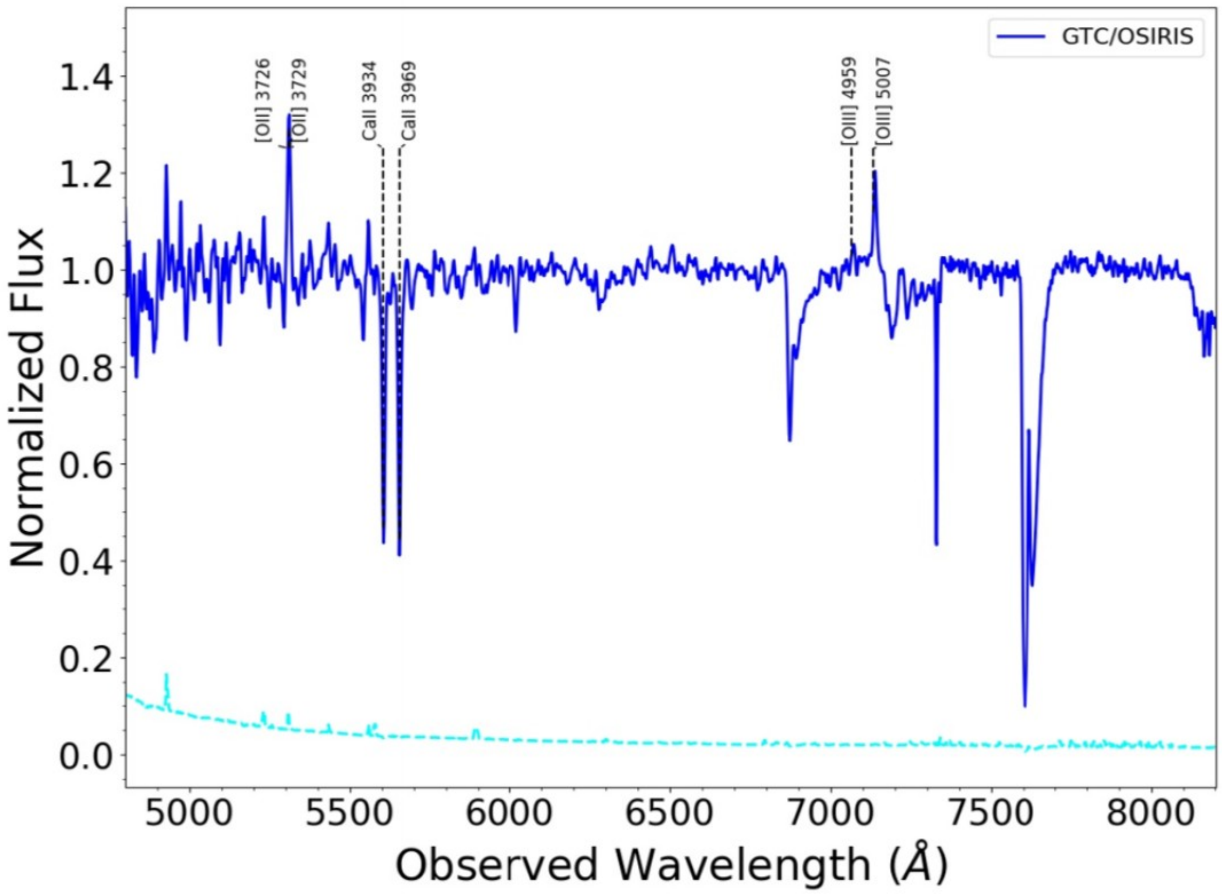
Few numbers from the model

From the modelling the values of few physical parameters that describe the outflow can be derived.

- Isotropic energy in synchrotron component (68-110s): 1.5×10^{52} erg
- Isotropic energy in synchrotron self-compton component (68-110s): 6.0×10^{51} erg
  - → Important fraction of energy in SSC, missed up to now!
- Magnetic field at the shocks (t=100s) B= 0.5 -5 G
  - → Large amplification from the few μG of the stellar medium
- Fraction of dissipated energy into magnetic field: $\varepsilon_b = (0.05 - 1) \times 10^{-3}$
- → Fraction of dissipated energy into electrons: $\varepsilon_e = 0.05 - 0.15$
  - → Typical value for GRB
- Initial bulk Lorentz factor: $\Gamma_0 \sim 500$ (dependent on the medium density)
  - → Typical value for GRB
- Isotropic kinetic energy of the blast wave: $E_k = 3 \times 10^{53}$ erg
  - → Typical value for GRB

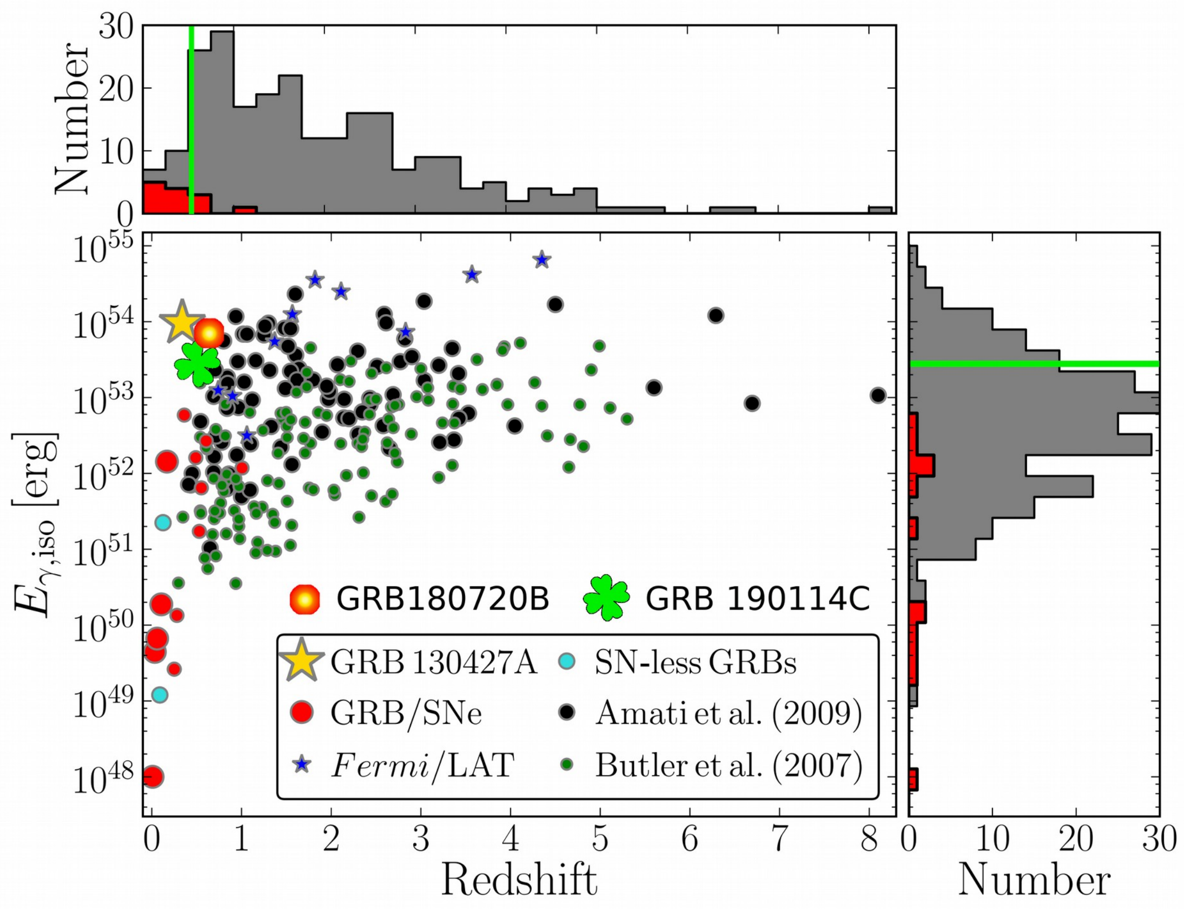
Redshift measurement

2.6 hr post-burst GTC equipped with OSIRIS spectrograph took 2 images of the GRB location and measured the redshift: z = 0.4245 ± 0.0005 (A. J. Castro-Tirado GCN 23708).



Not extraordinary guy!
(Part I, intrinsic)

Levan et al. Space Science Reviews, V 202, I 1-4



GRB 190114C has low redshift and medium-bright burst.

The energetics and the values of the parameters obtained from the modelling indicate that it is a relatively common kind of bursts.

An extraordinary observation

MAGIC observed more than 100 GRBs so far (only 40 with measured redshift).
If we select only those which have z <1 and the starting of the observation in less than 1h we obtain just 4 GRBs.
MAGIC sees a 3.1σ signal from the short GRB160821B (see ICRC 2017)

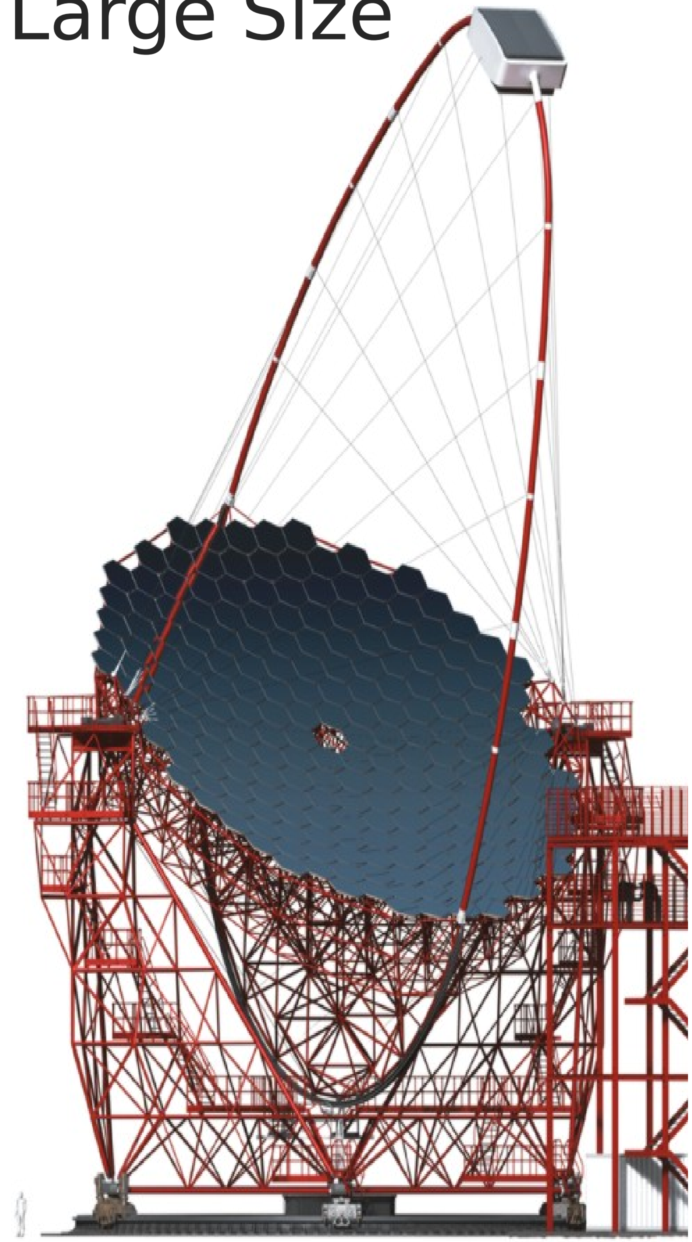
Event	redshift	T_{delay} (s)	Zenith angle (deg)
GRB 061217	0.83	786.0	59.9
GRB 100816A	0.80	1439.0	26.0
GRB 160821B	0.16	24.0	34.0
GRB 190114C	0.42	58.0	55.8

The observation conditions were unfavourable:
- the source started at large zenith angle (~55 deg) and setting;
- the observation was performed under moonlight condition: the Night Sky Background level was ~6 times the dark one.

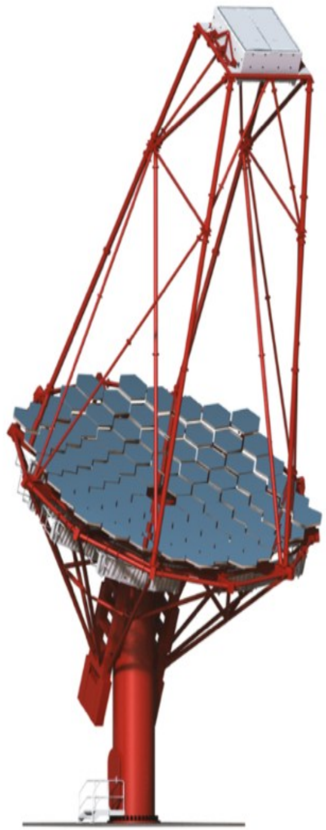
Future extraordinary observations?

The close future: CTA

Large Size



Medium Size



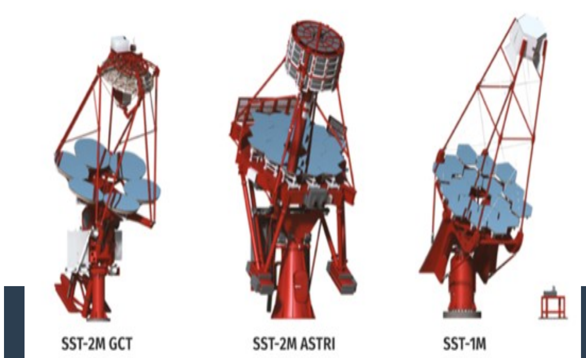
2017 Begin Pre-Construction

2022 Begin Operation

2022-25 Commissioning and Early Science

2025 Construction completion

Small Size



The “now” future: LST

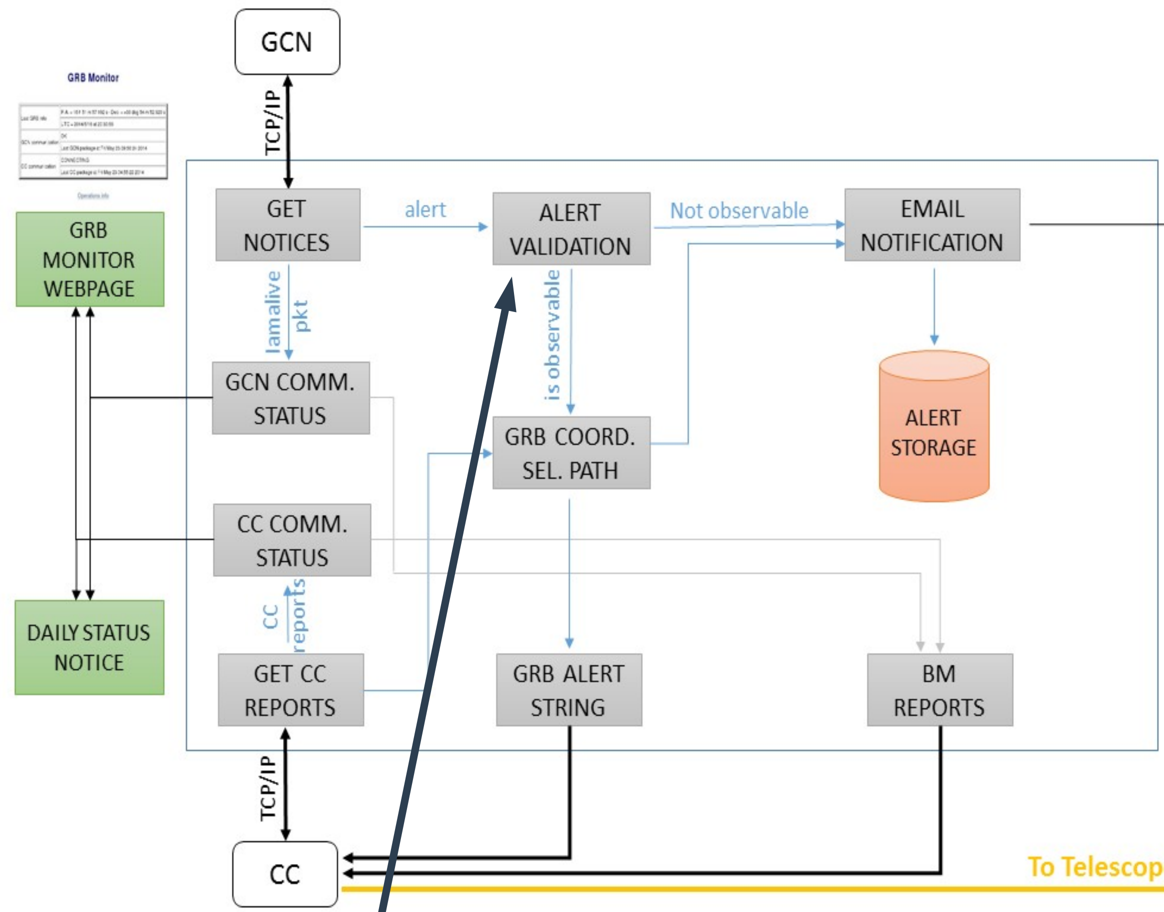
Thanks to its low threshold energy ~20 GeV, the expected detection rate < ~0.5 GRB yr^{-1}!
(depending on the assumed GRB model and array layout and performance)

Working on the implementation of a procedure for LST to respond to the GRB (and transient in general) alerts.

CTA Alert system

Many transient events are coming online (GRBs, FRBs, GWs, Neutrinos, flaring stars ...)!

We need to choose carefully which events to follow-up to efficiently use the CTA time. Possible constrains could come from:
- passed time since transient trigger;
- energy threshold for observation;
- **redshift of the object (CTA universe limit z~1.5);**
- ....



GTC-MEGARA information?

Conclusions

- The capability of the MAGIC telescopes to react fast and operate during moonlight conditions was a crucial factor in realising the first detection of TeV gamma rays from a GRB.
- Very clean signal: almost background free! In the first 30s ~100 times than Crab Nebula (@0.3 TeV).
- First evidence of an extra-component beyond synchrotron emission from a GRB. A unique model was used to explain all the multi-wavelength data both for the spectral and temporal profile.
- Great interest for this burst by the community. The vast multi-wavelength follow-up brought a wealth of data for the interpretation.
- The GRB is rather common both in energetics and in the derived physical parameters. We could detect it because we repointed fast and it was close!
- **Lesson learned** for future observations and detections: check the redshift!

nature DOI: 10.1038/s41586-019-1750-x

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies

nature DOI: 10.1038/s41586-019-1754-6

Article | Published: 20 November 2019

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

MAGIC Collaboration, P. Veres, […] D. R. Young

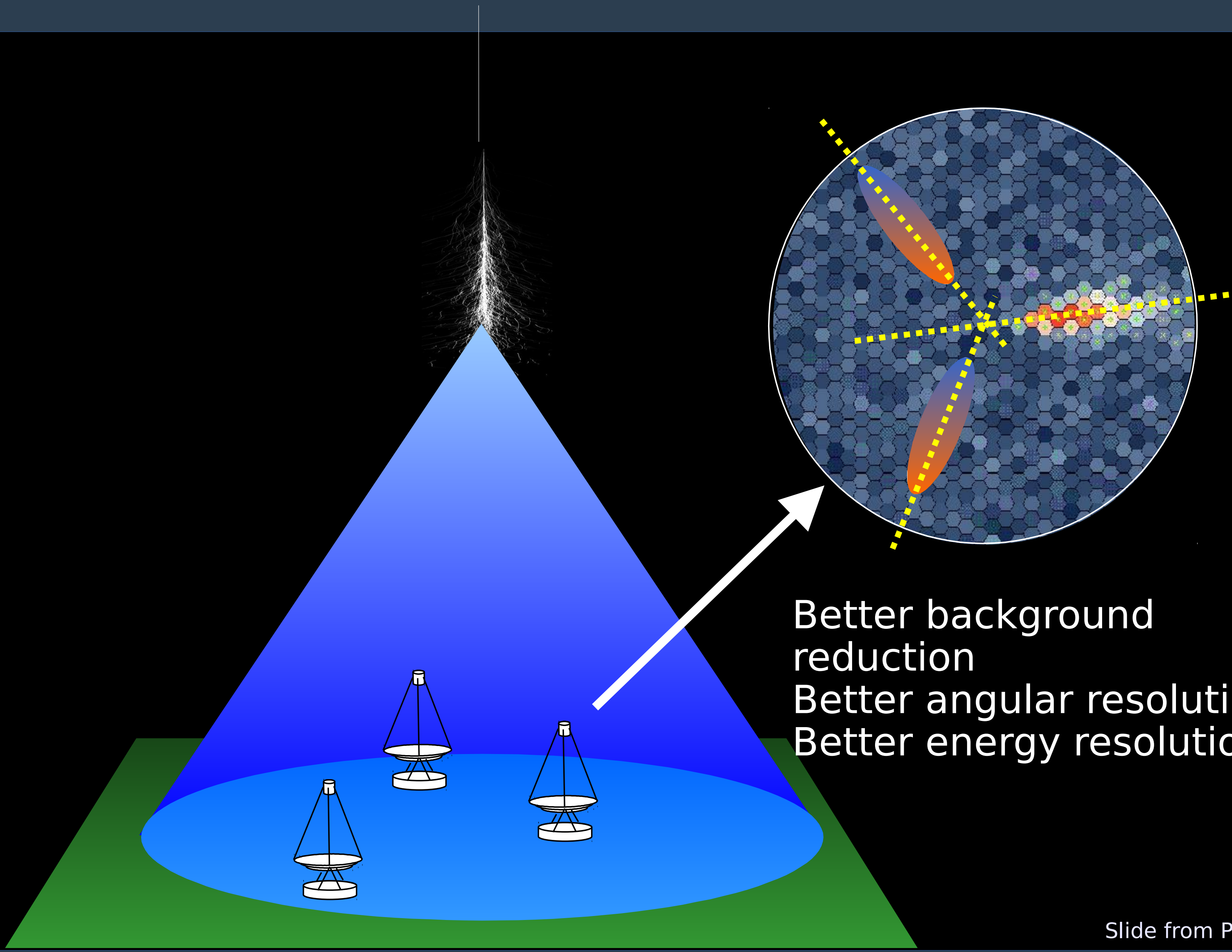
Nature **575**, 459–463(2019) | Cite this article

Abstract

Long-duration γ-ray bursts (GRBs) originate from ultra-relativistic jets launched from the collapsing cores of dying massive stars. They are characterized by an initial phase of bright and highly variable radiation in the kiloelectronvolt-to-megaelectronvolt band, which is probably produced within the jet and lasts from milliseconds to minutes, known as the prompt emission[1,2]. Subsequently, the interaction of the jet with the surrounding medium

Thank you

Cherenkov telescope method



Better background reduction
Better angular resolution
Better energy resolution

Slide from Pr W. Hofmann

The LAT and GBM on Fermi

The GBM detects ~250 GRBs/year

~18% short

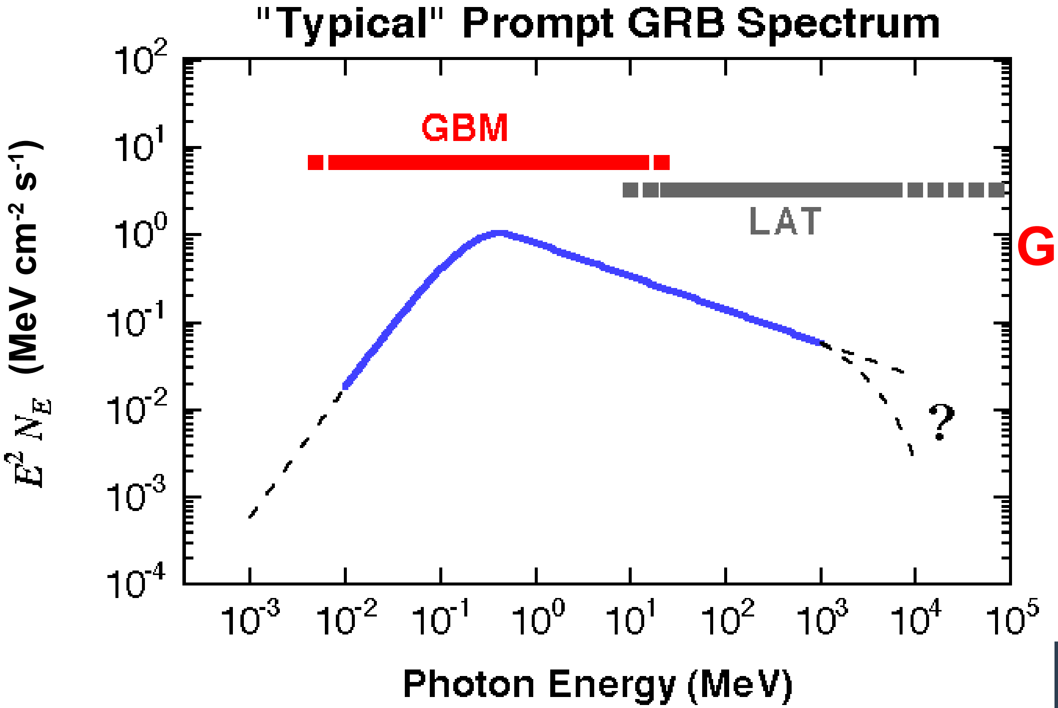
~50% in the LAT FoV

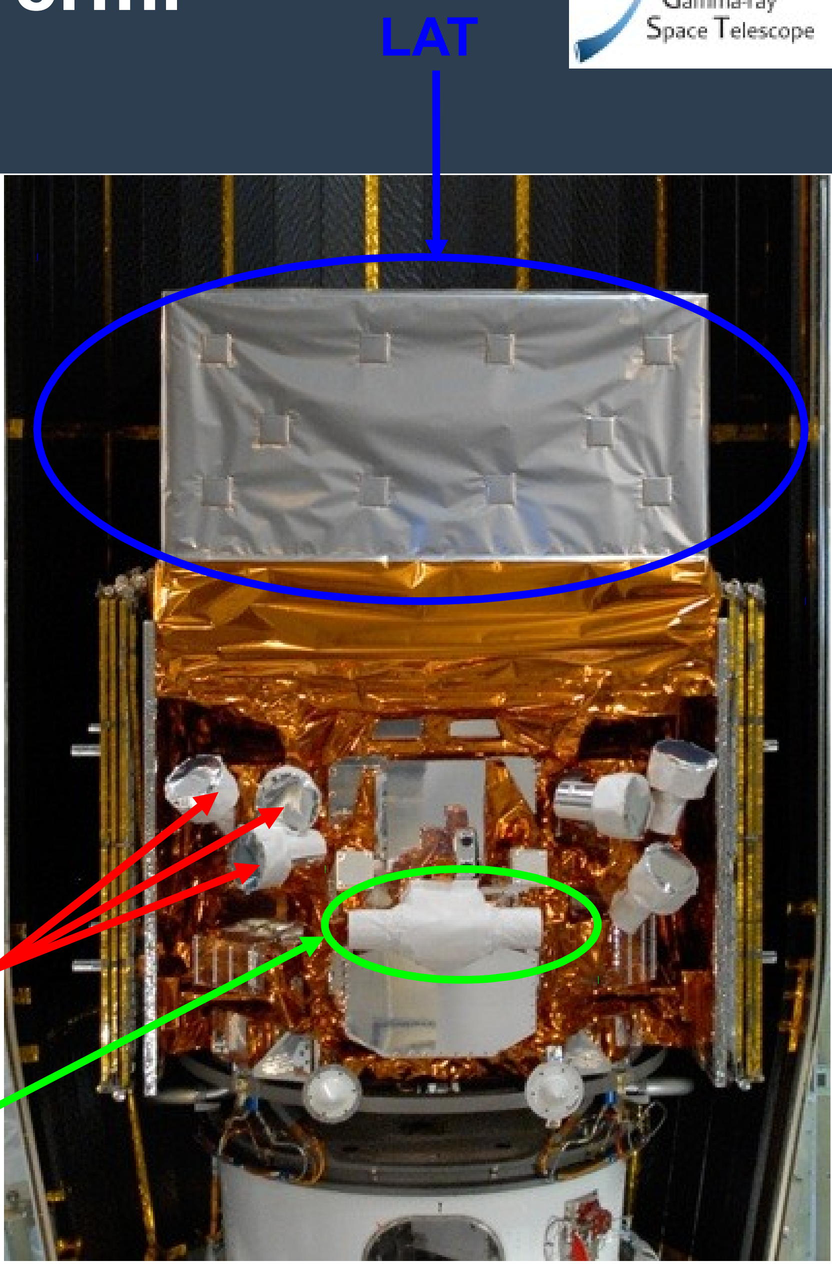
The LAT detects ~15 GRBs/year

NaI: 8 keV - 1 MeV

BGO: 200 keV - 40 MeV

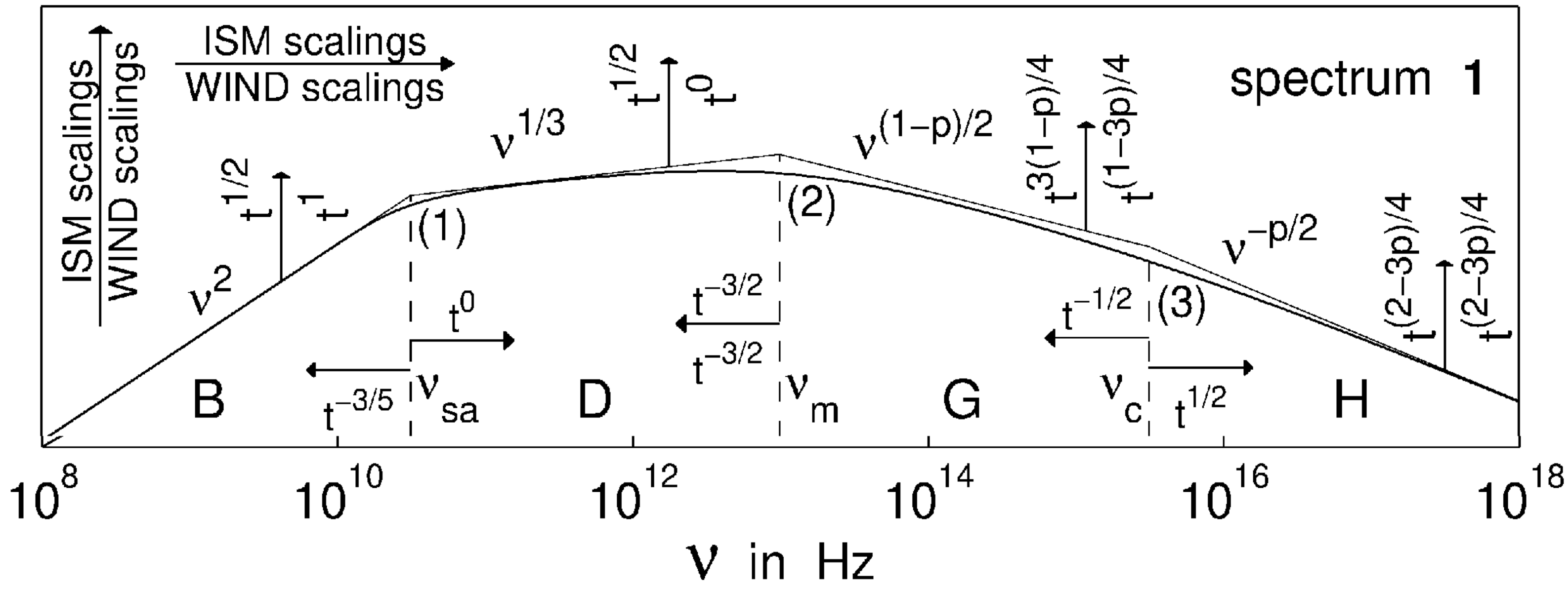
LAT: 30 MeV – 300 GeV



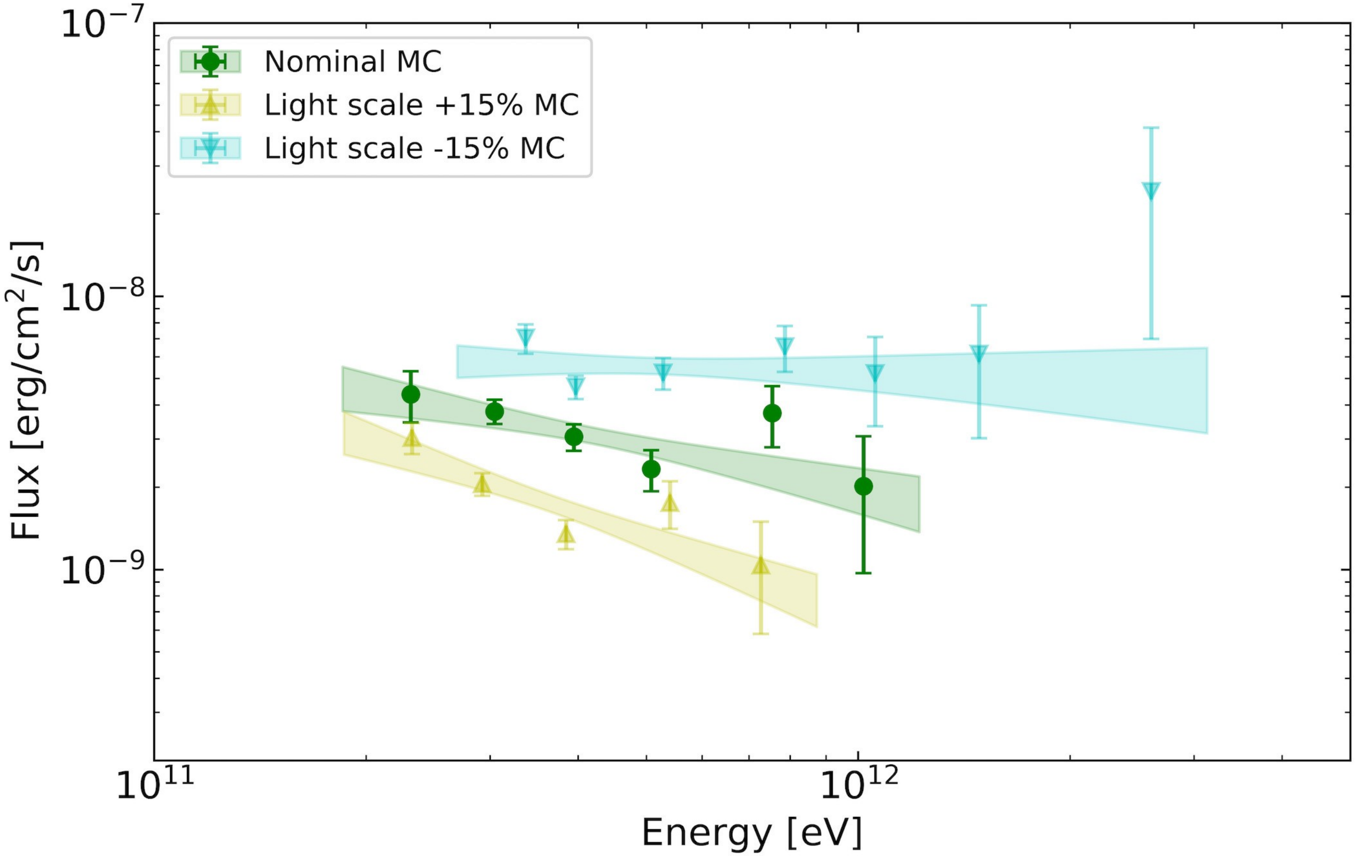


Afterglow synchrotron spectrum

The spectrum predicted in case of synchrotron emission in the afterglow phase has several breaks.
Its temporal evolution depends on the original electron spectrum and on the environment.



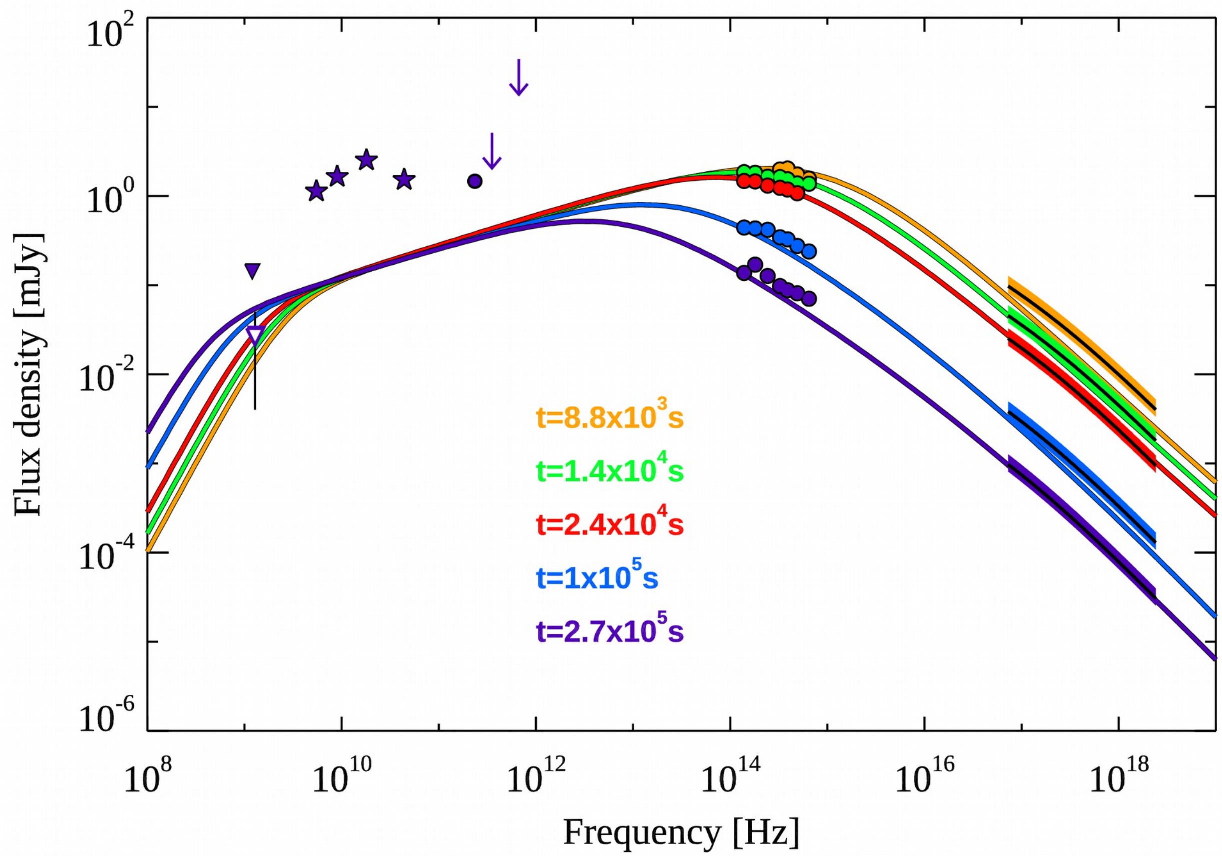
Spectral systematics @TeV



Spectral detailed results @TeV

Time bin [seconds after T_0]	Normalisation $[\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	Photon index	Pivot energy [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

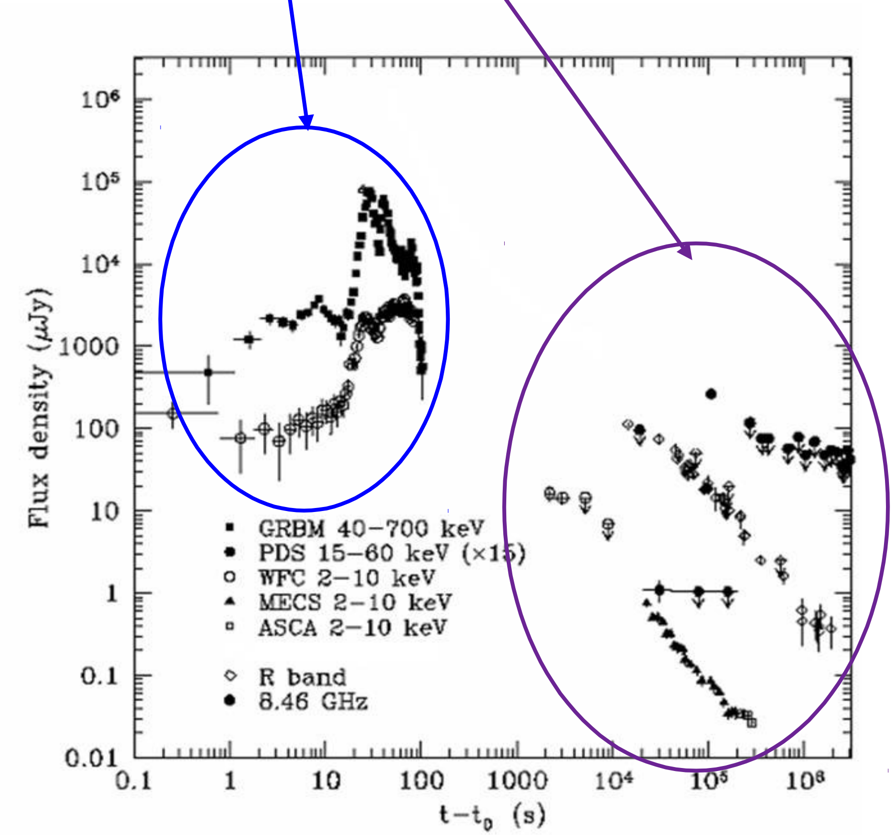
Modelling of the radio and optical spectra



GRBs: general properties

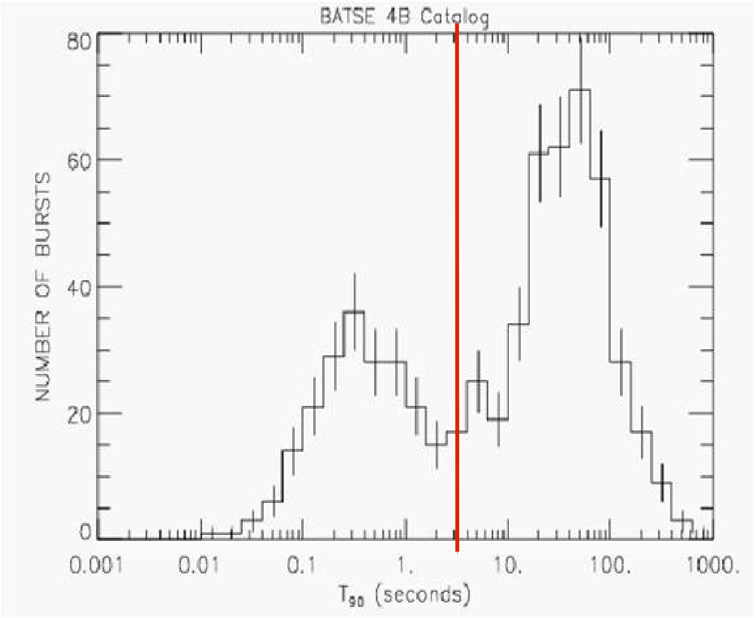
Two phases:

- The PROMPT phase: lasting ~ 100s main in the kev-MeV band;
- The AFTERGLOW phase lasting >3000s;

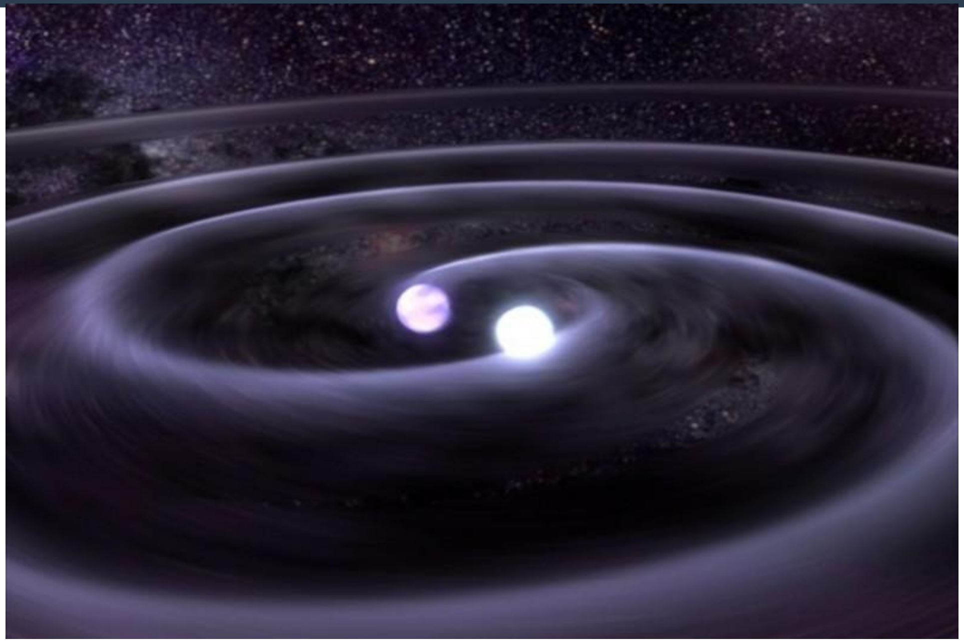


Two populations in time duration:

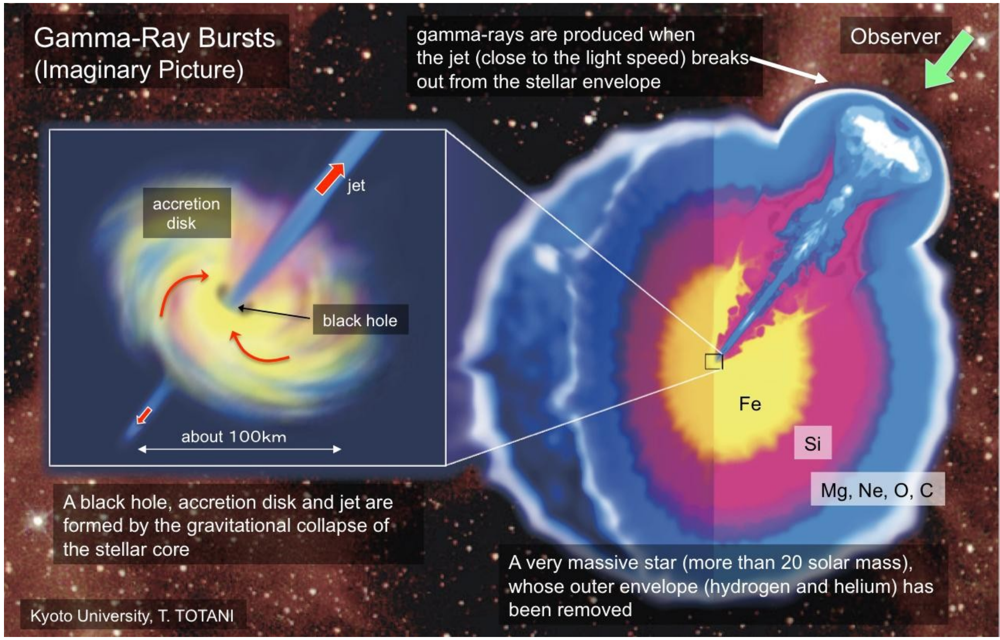
- SHORT: duration of the prompt phase <2s;
- LONG: duration of the prompt phase >2s;



GRBs: general properties



or



Gravitational potential energy

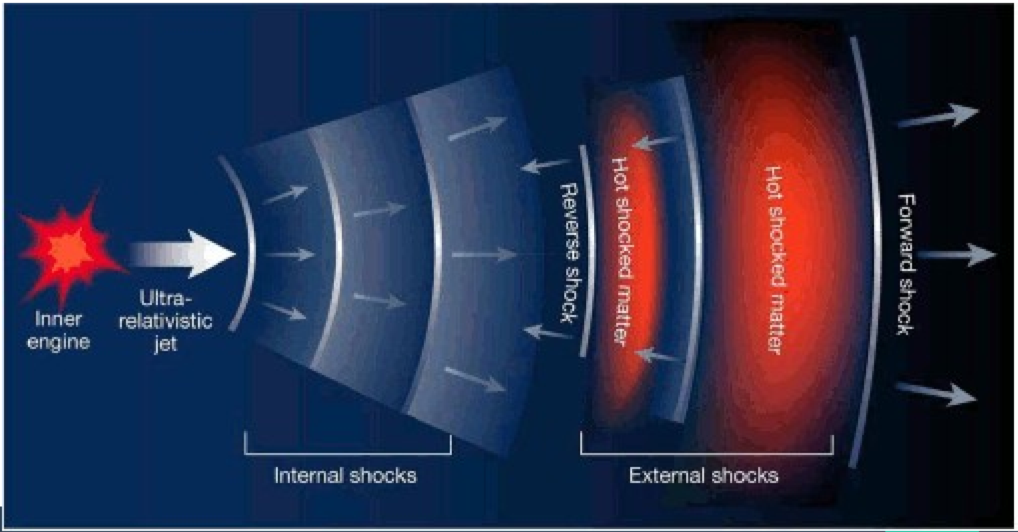
→ "Fireball"

(Mészáros 2006)

$\Gamma \approx$ few x 100

$(\Gamma \equiv [1-\beta^2]^{-1/2},\ \beta \equiv v/c)$

* connection with GW

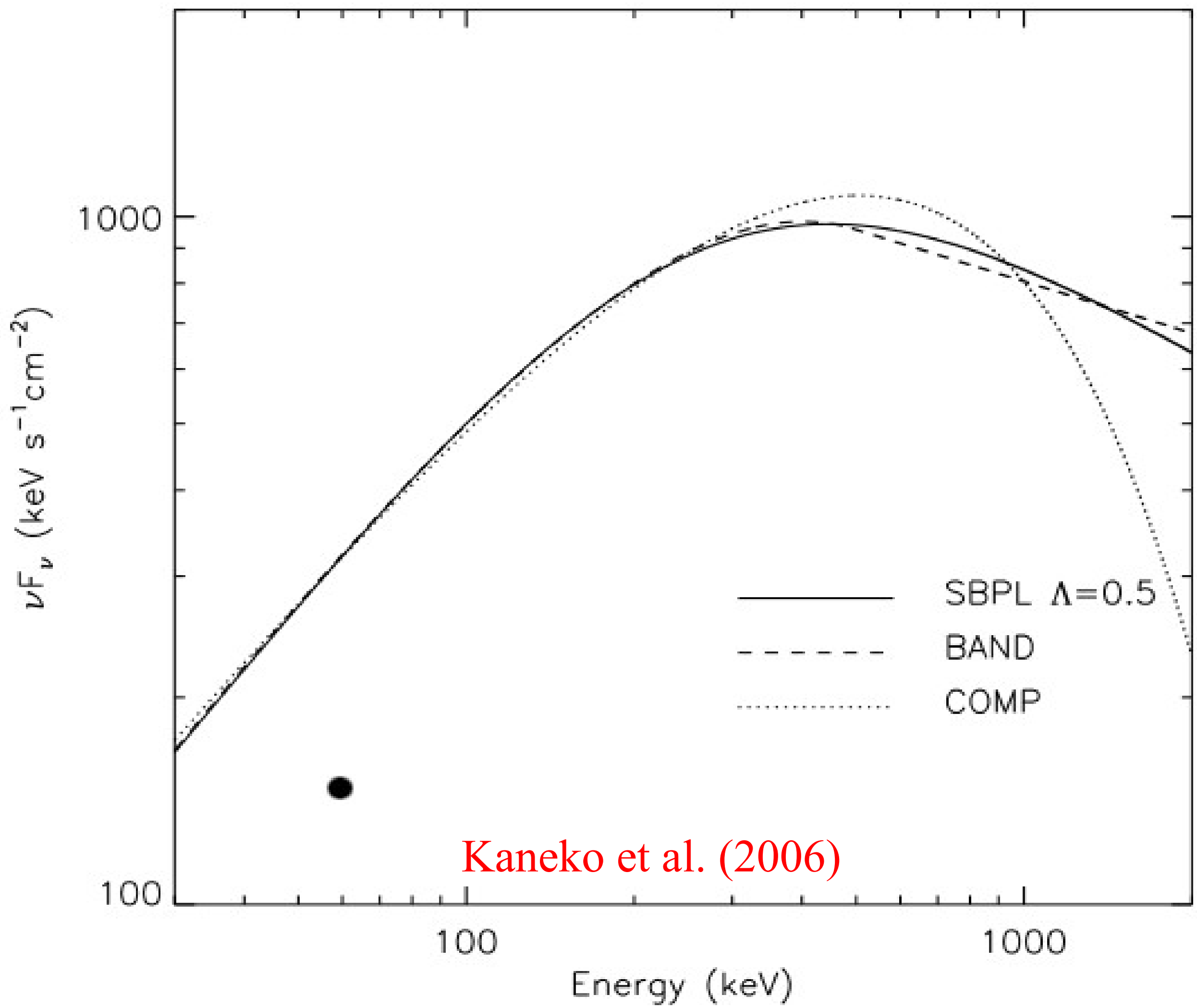


GRBs: general properties

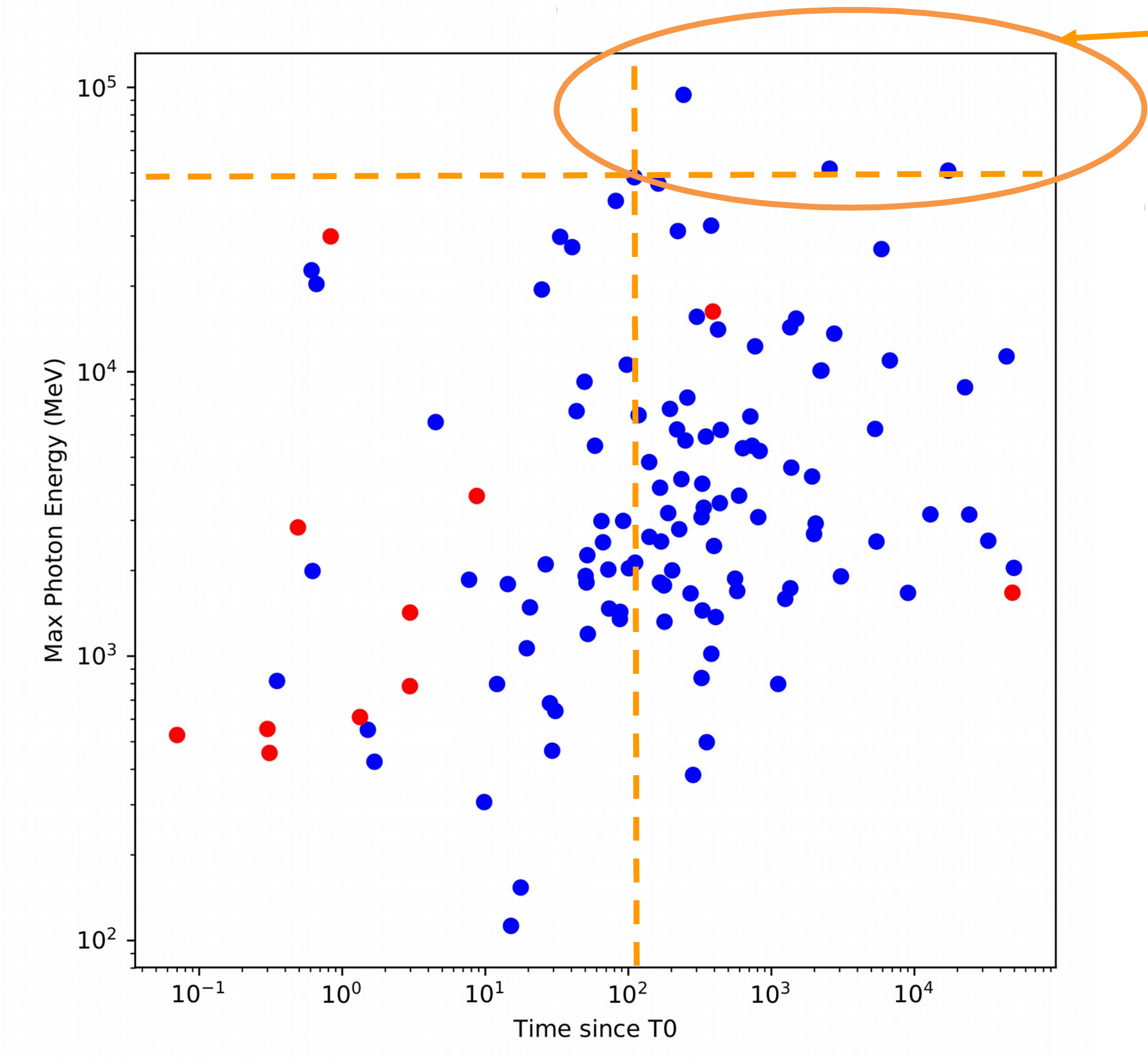
- The spectra are very similar → Band paradigm
- The general kind of spectrum is not thermal (synchrotron? Inverse Compton?)
- There are some exception that show a thermal spectrum

⬇

Wide energy range needed for GRB observations!



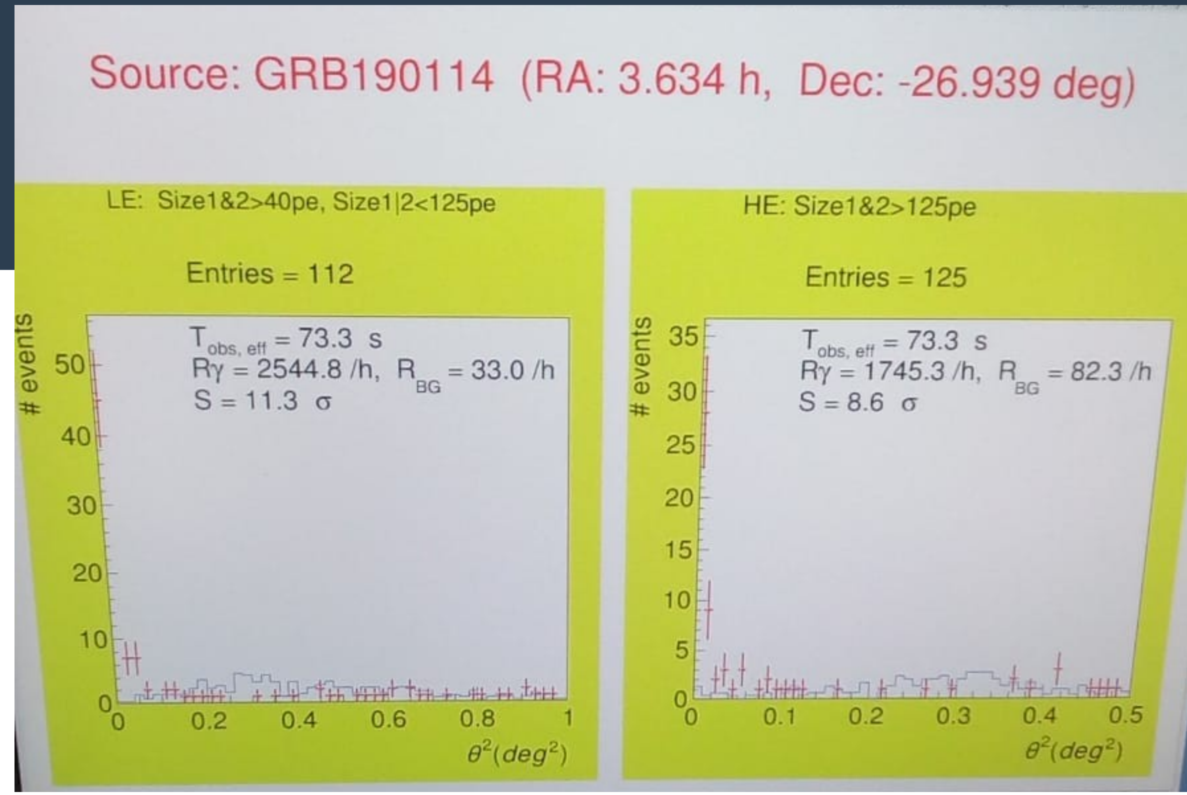
Fermi latest view



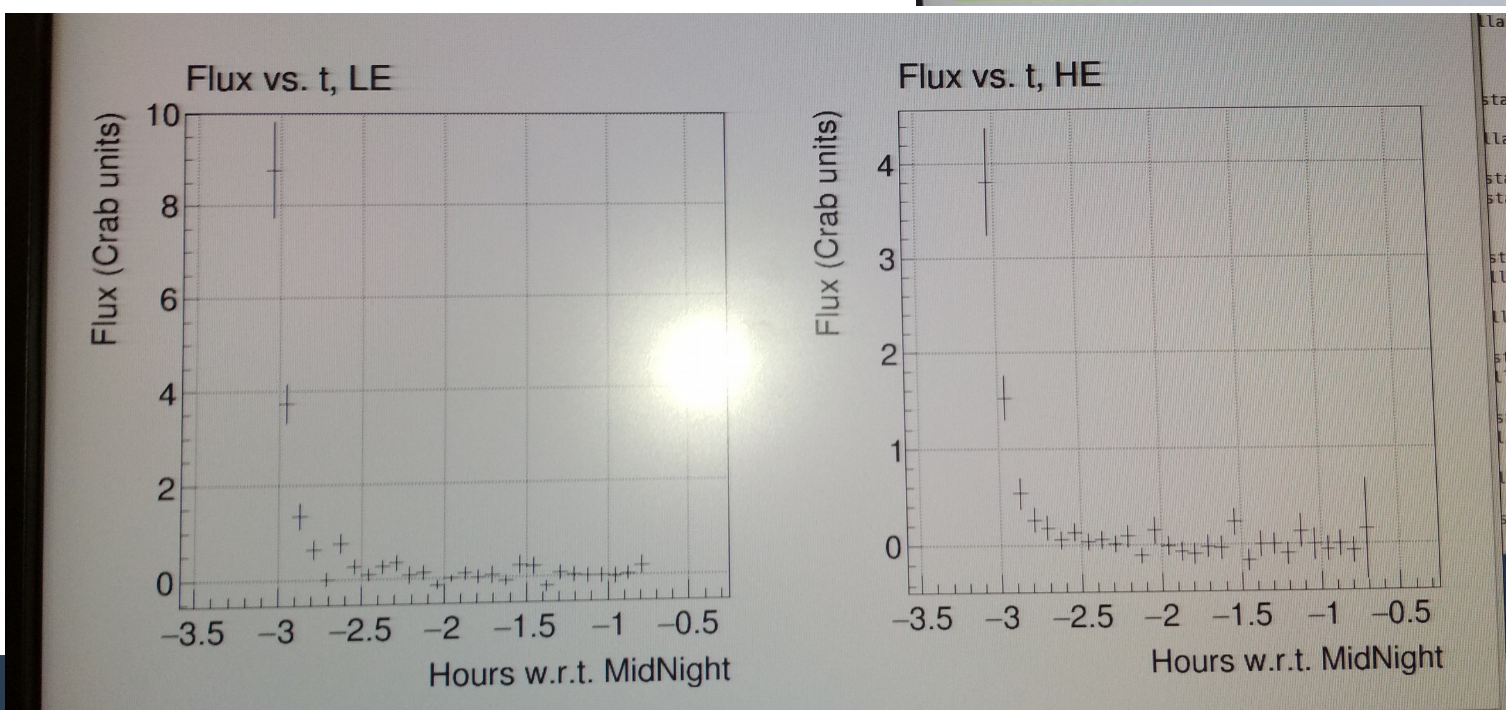
From the findings of the Fermi-LAT 10 year catalogue the prospects of detecting a GRB at very high energy are quite slim.

Ackermann et. al. 2019

That night



The signal was very clear, which allowed us to quickly send a notice to the whole astrophysical community.



The first time a GRB is unambiguously detected above 100 GeV!

The signal MAGIC saw