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

## Elena Moretti
on behalf of the MAGIC collaboration

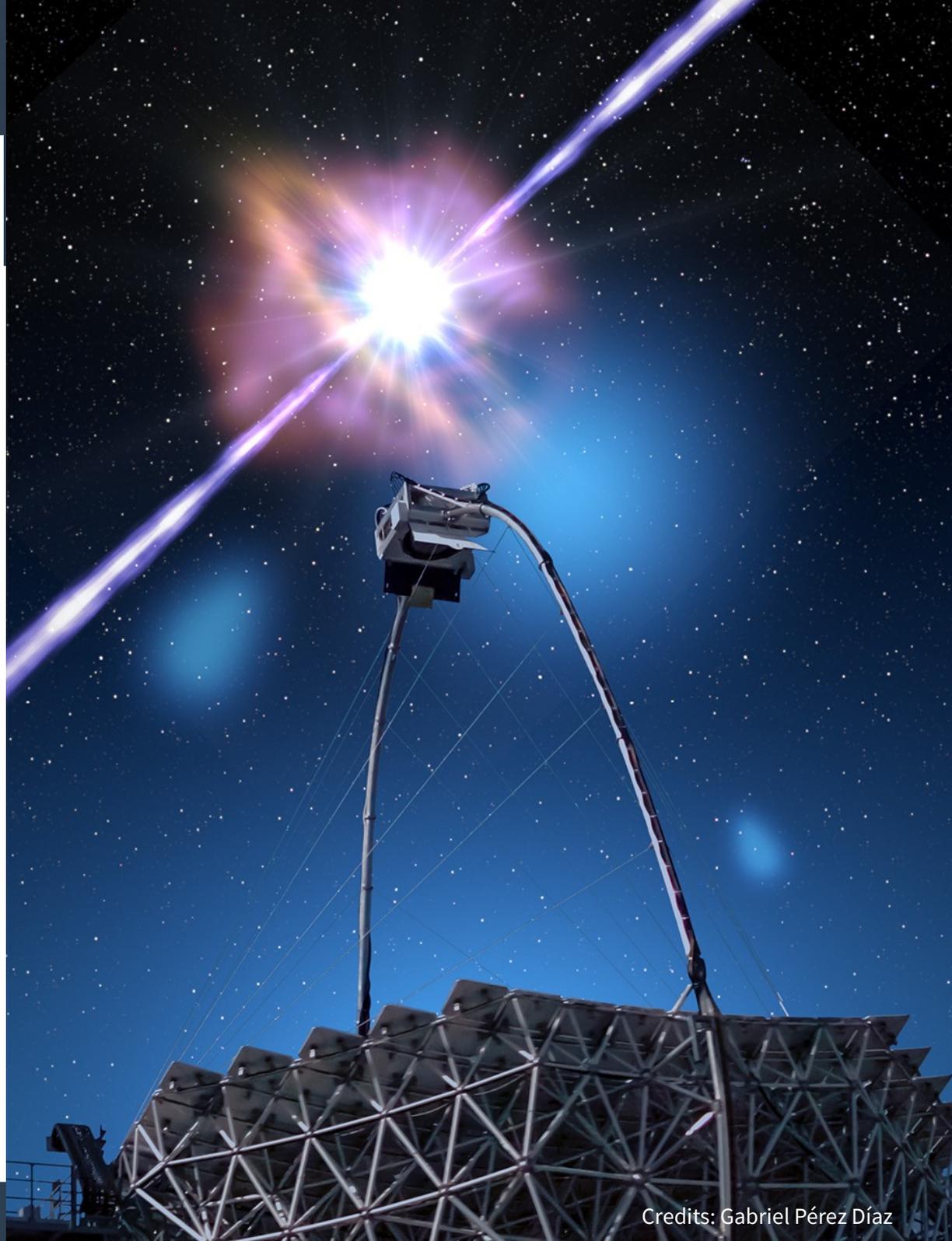Institut de Física d'Altes
Energies (IFAE)

**MAGIC**

Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

Credits: Gabriel Pérez Díaz

EXCELENCIA SEVERO OCHOA

BIST — Barcelona Institute of Science and Technology

# Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

## 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

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

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

## 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

# 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: ~$10^{-7}$ - $10^{-4}$ erg cm$^{-2}$ s$^{-1}$
- Total energy emitted $10^{50}$-$10^{54}$ erg
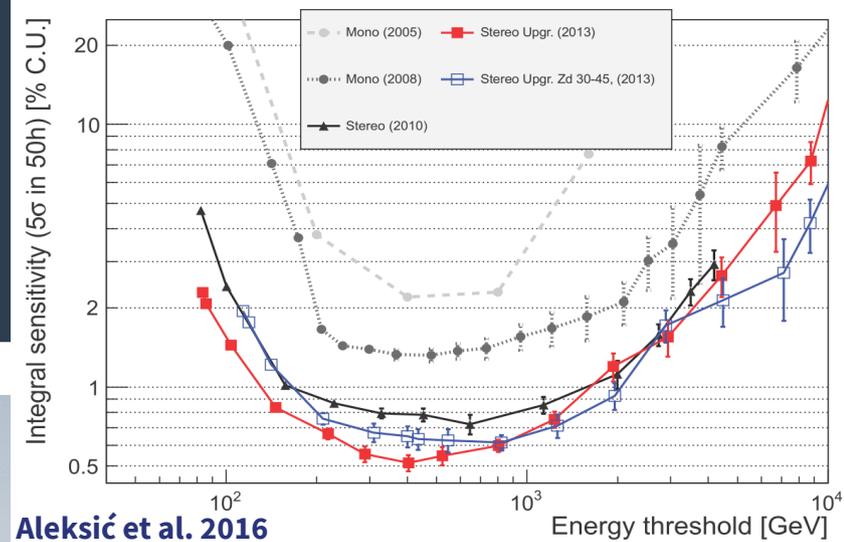- Typical observed energy: <~ MeV
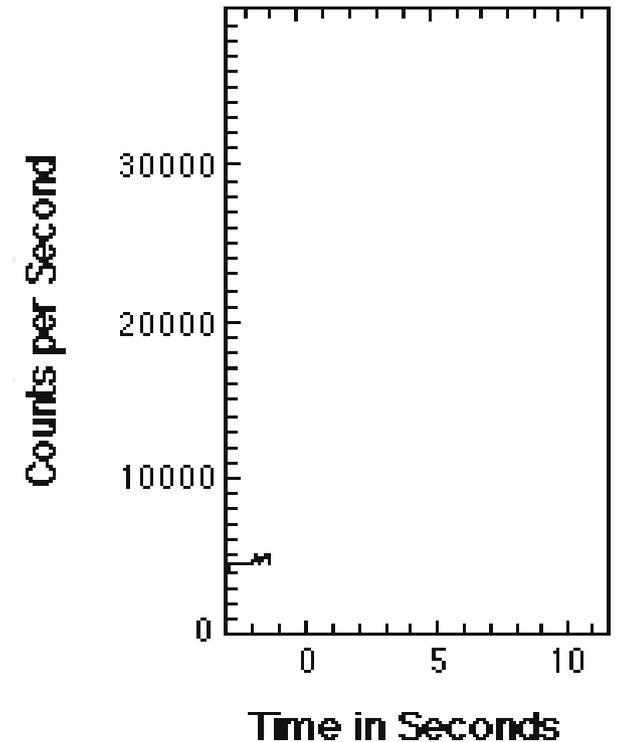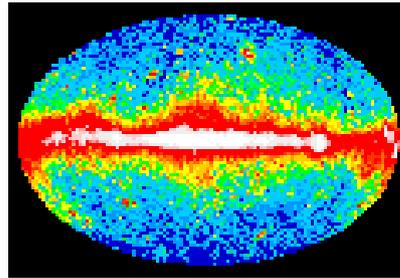
# MAGIC

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

Two 17m telescopes

236 m² mirror surface
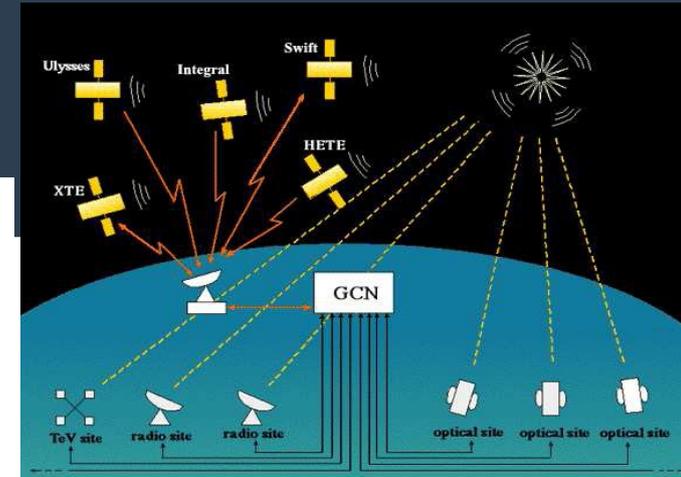
Carbon fiber structure

Fast movement (180° in ~30s)

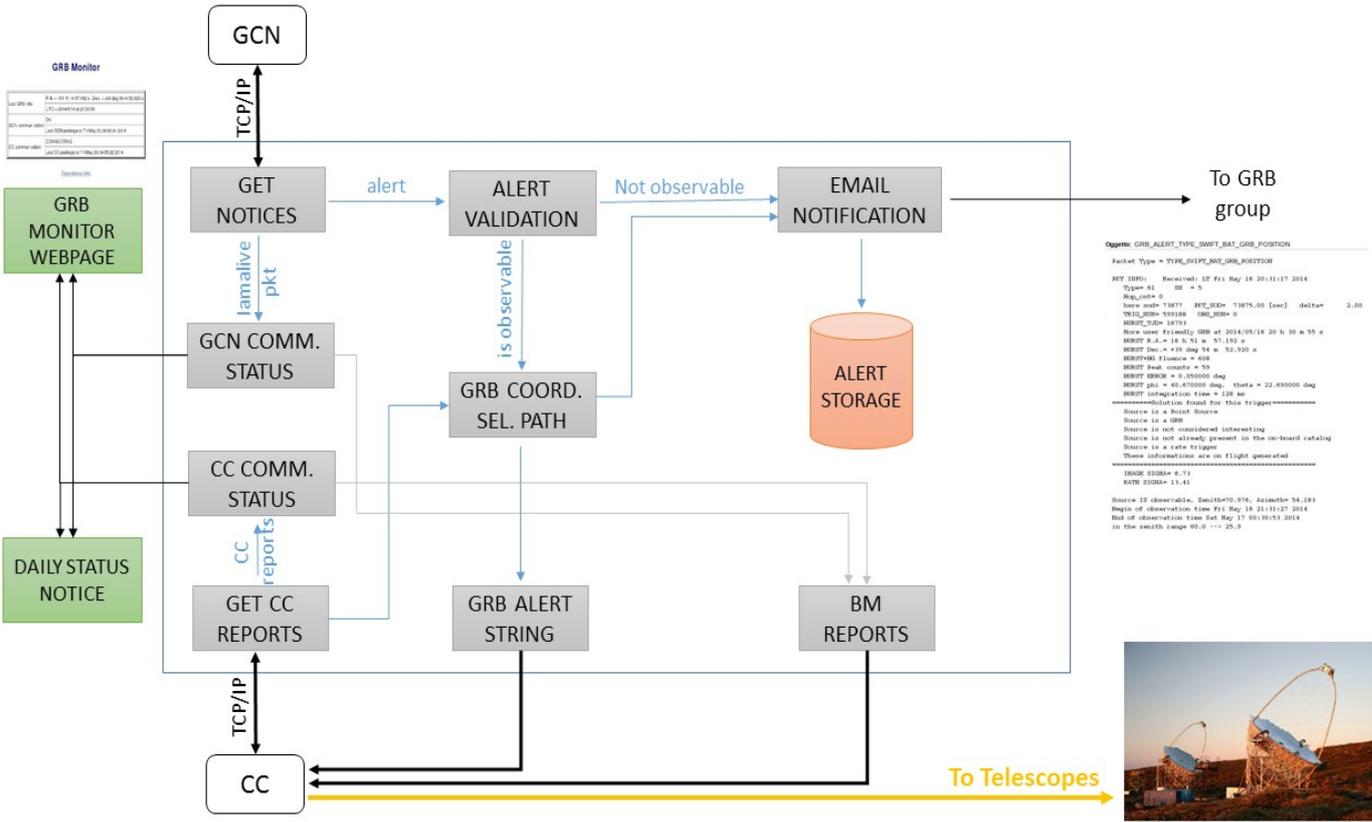Aleksić et al. 2016

**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 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.

Credits: Adiv Gonzáles Muñoz

# Alert and follow up

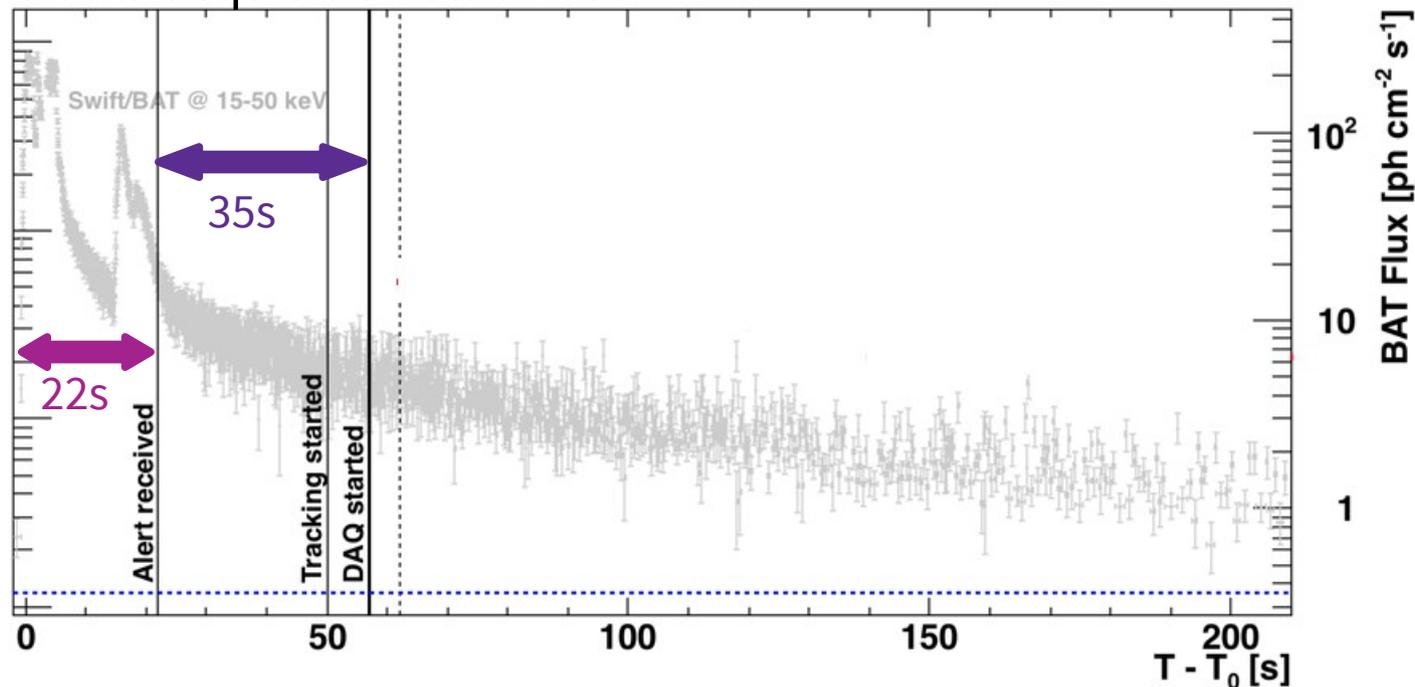At T0 = 20:57:03 UT Swift/BAT and Fermi/GBM triggered on GRB190114C

T0+22s MAGIC received the alert
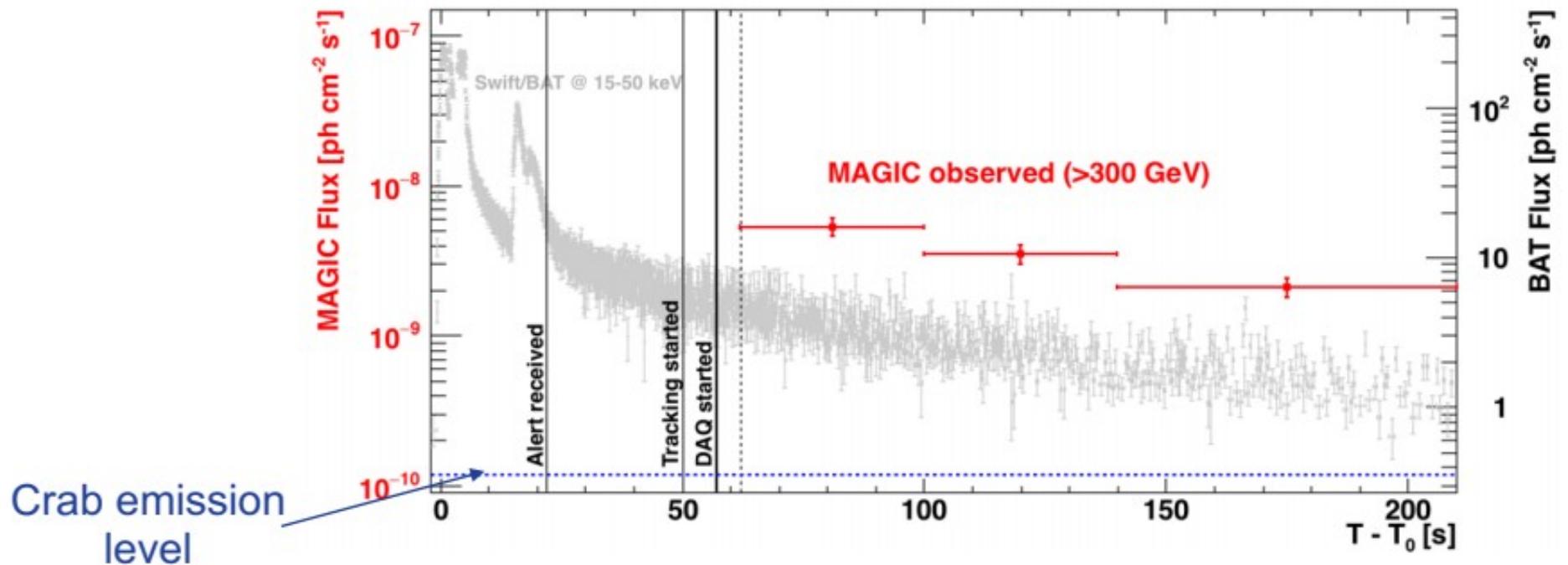
T0+50s MAGIC started tracking

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.

# 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)



Spectral index:
~2.2$_{-0.25}^{+0.23}$

Spectral index:
~5.4$_{-0.22}^{+0.22}$

Extragalactic background light absorption
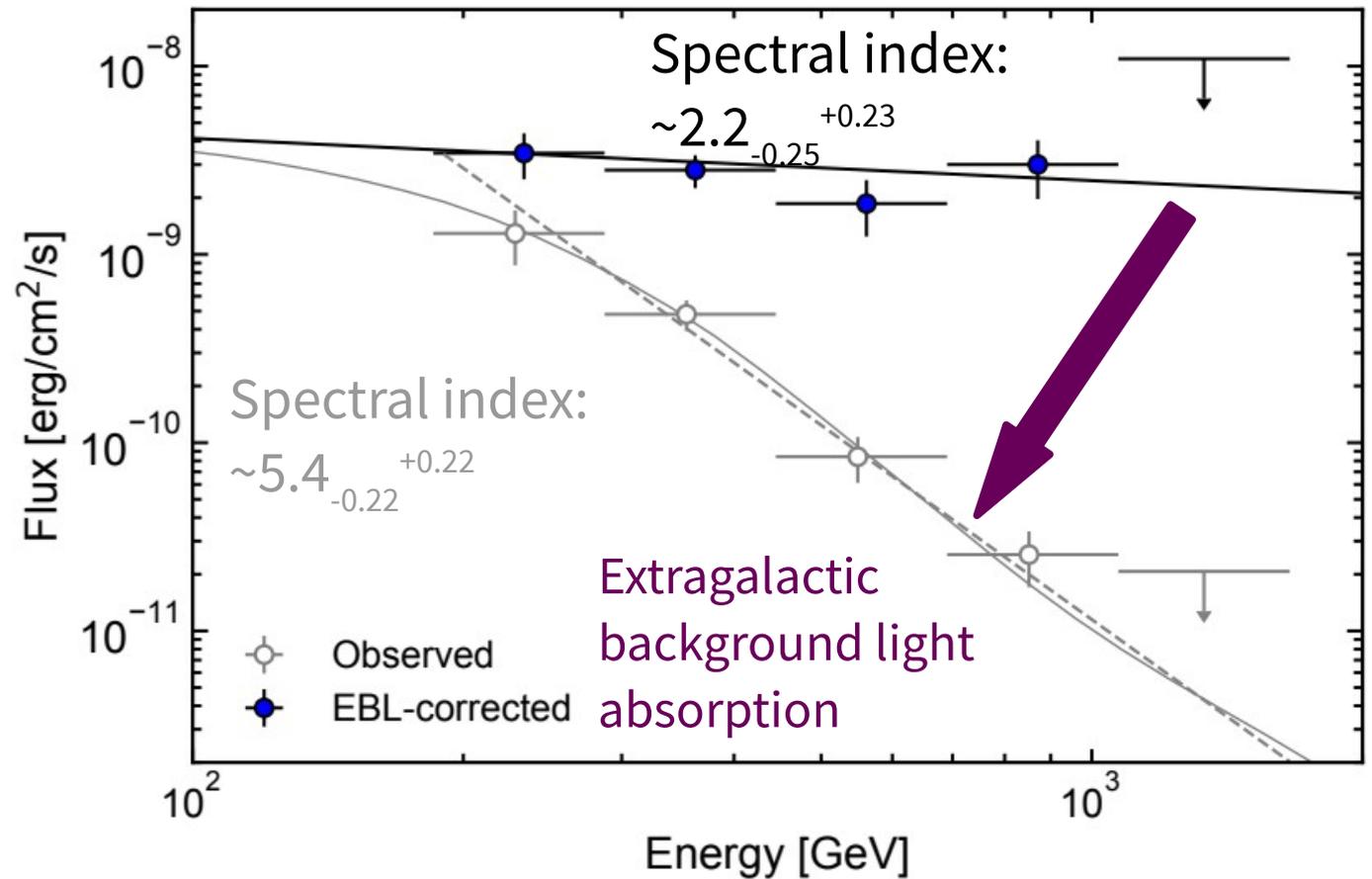
# Beyond synchrotron emission

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).
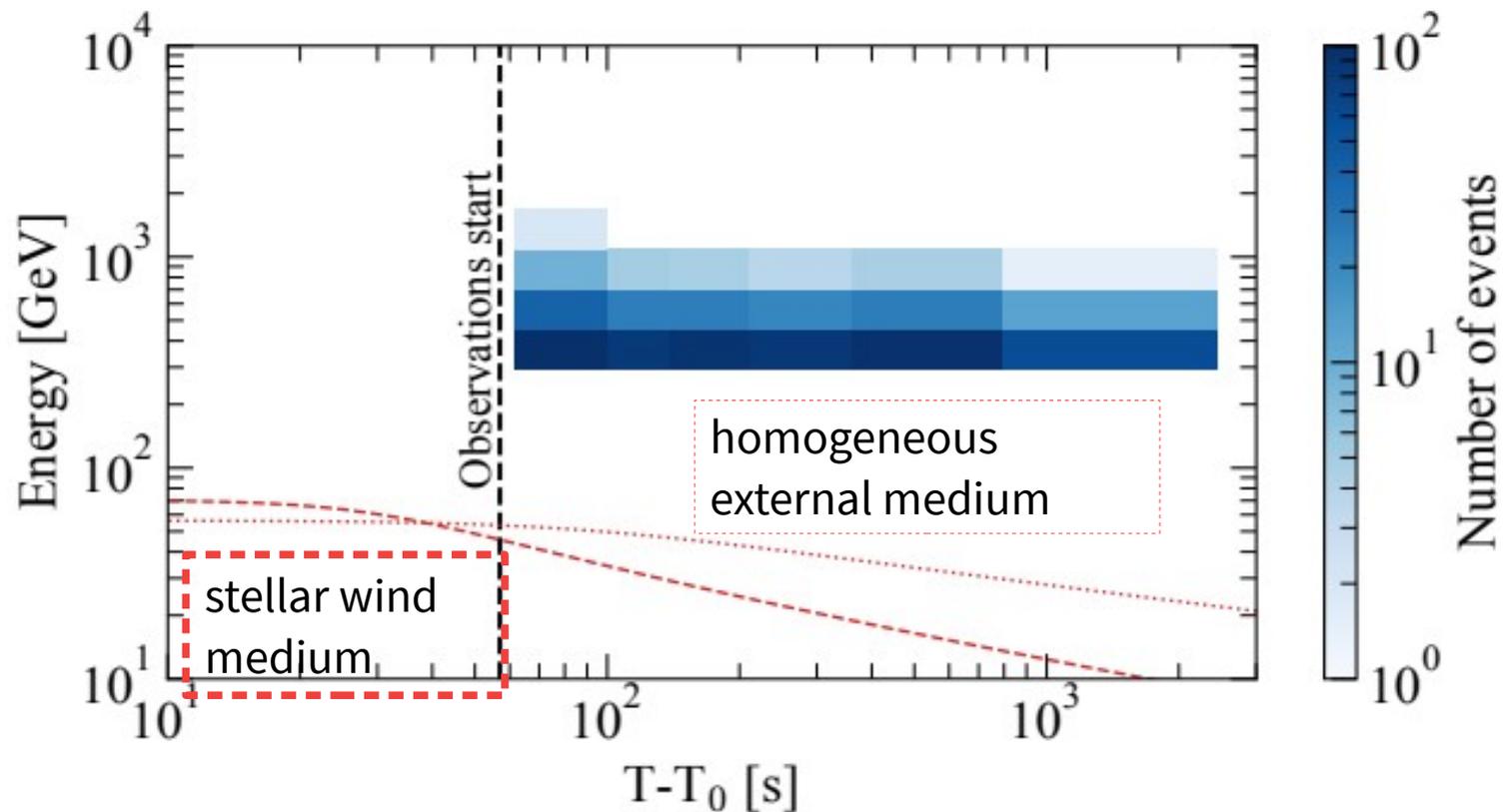
# Proton emission?

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 (>$2x10^{59}$erg, ~$10^6$ times typical energies) if they would be responsible for the photon flux detected between 0.2-1 TeV.

# Multi-wavelength temporal profile
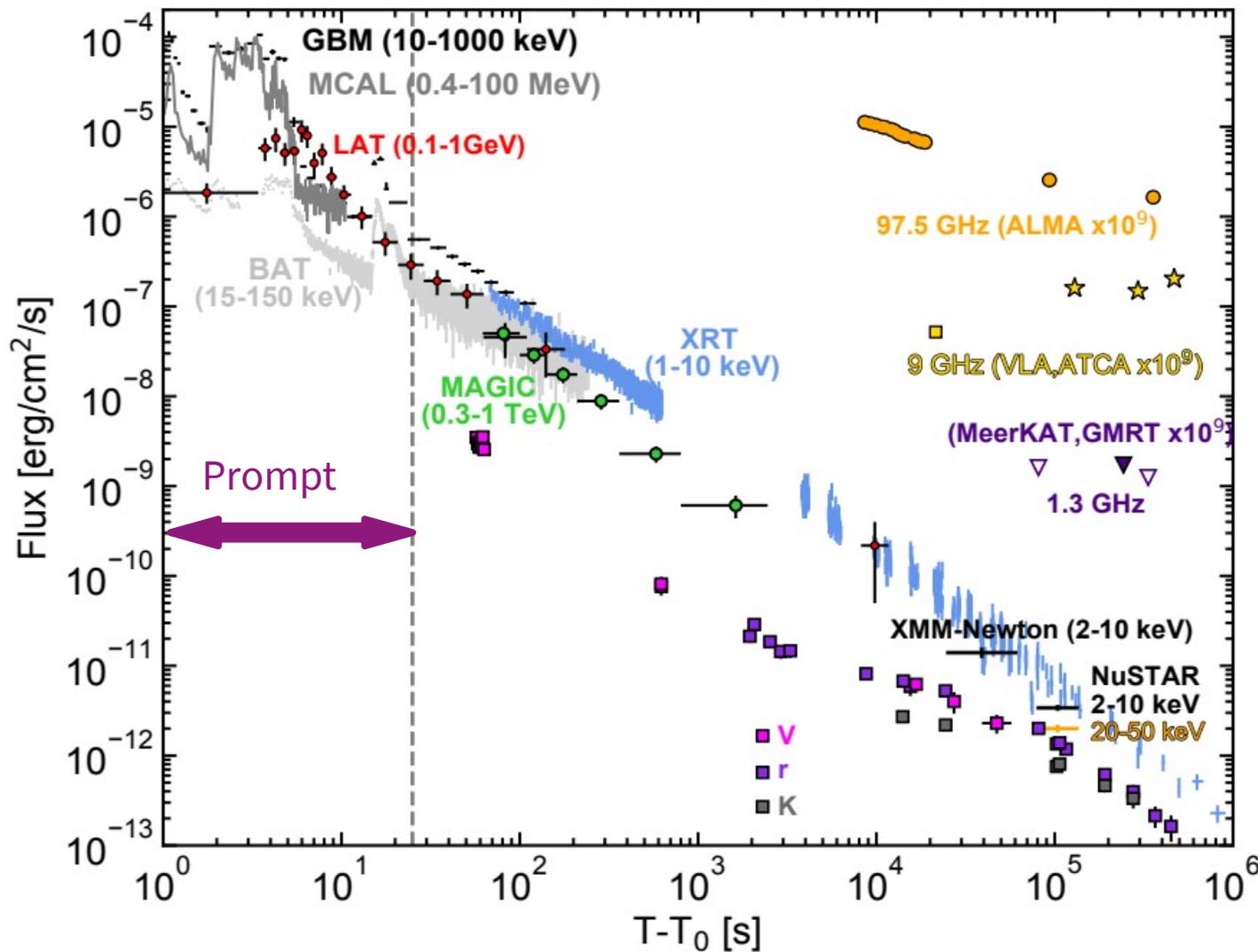


- The prompt phase lasts for ~12s;
- MAGIC start its observations in the so-called early afterglow phase;
- Because of its temporal profile the sub-TeV emission is produced in the same conditions as the GeV and X-ray emissions.

# 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)
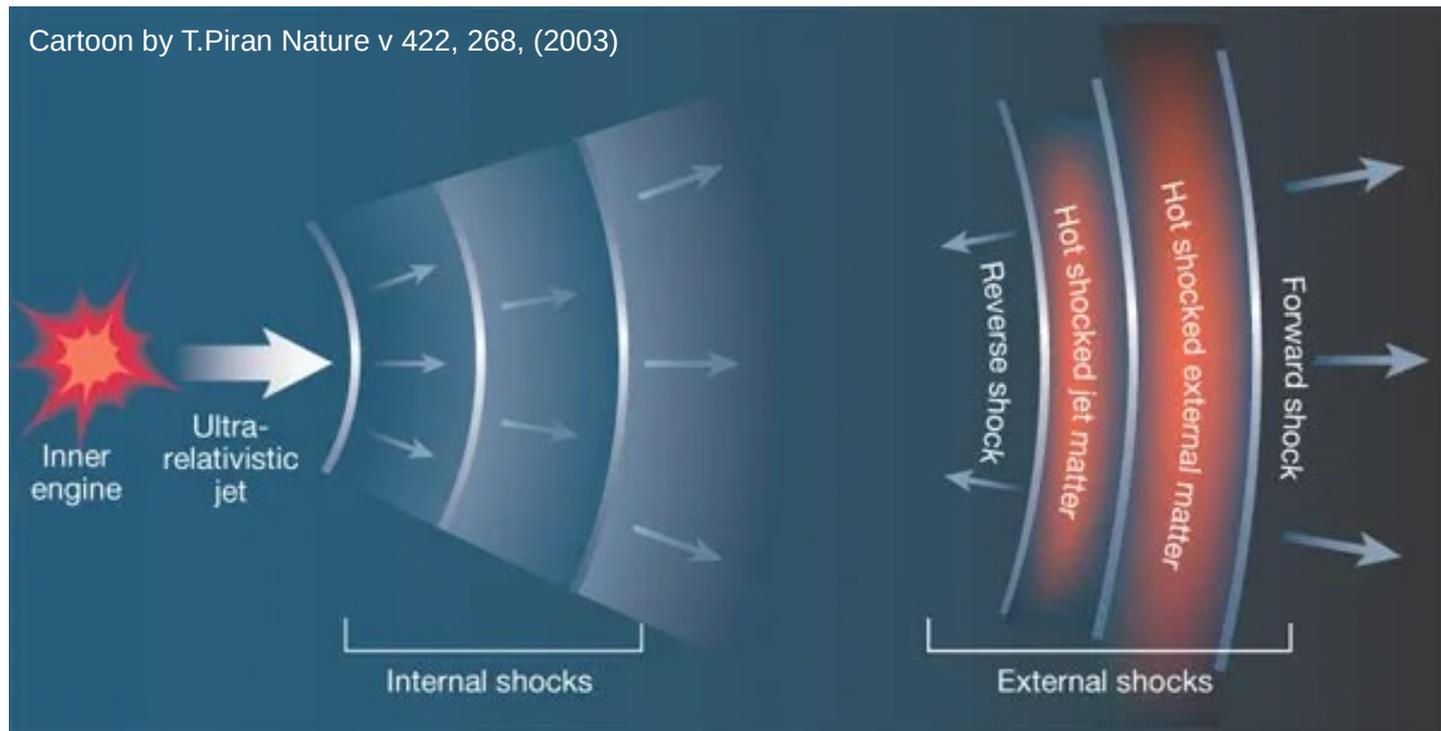
# Forward shock, but same process?
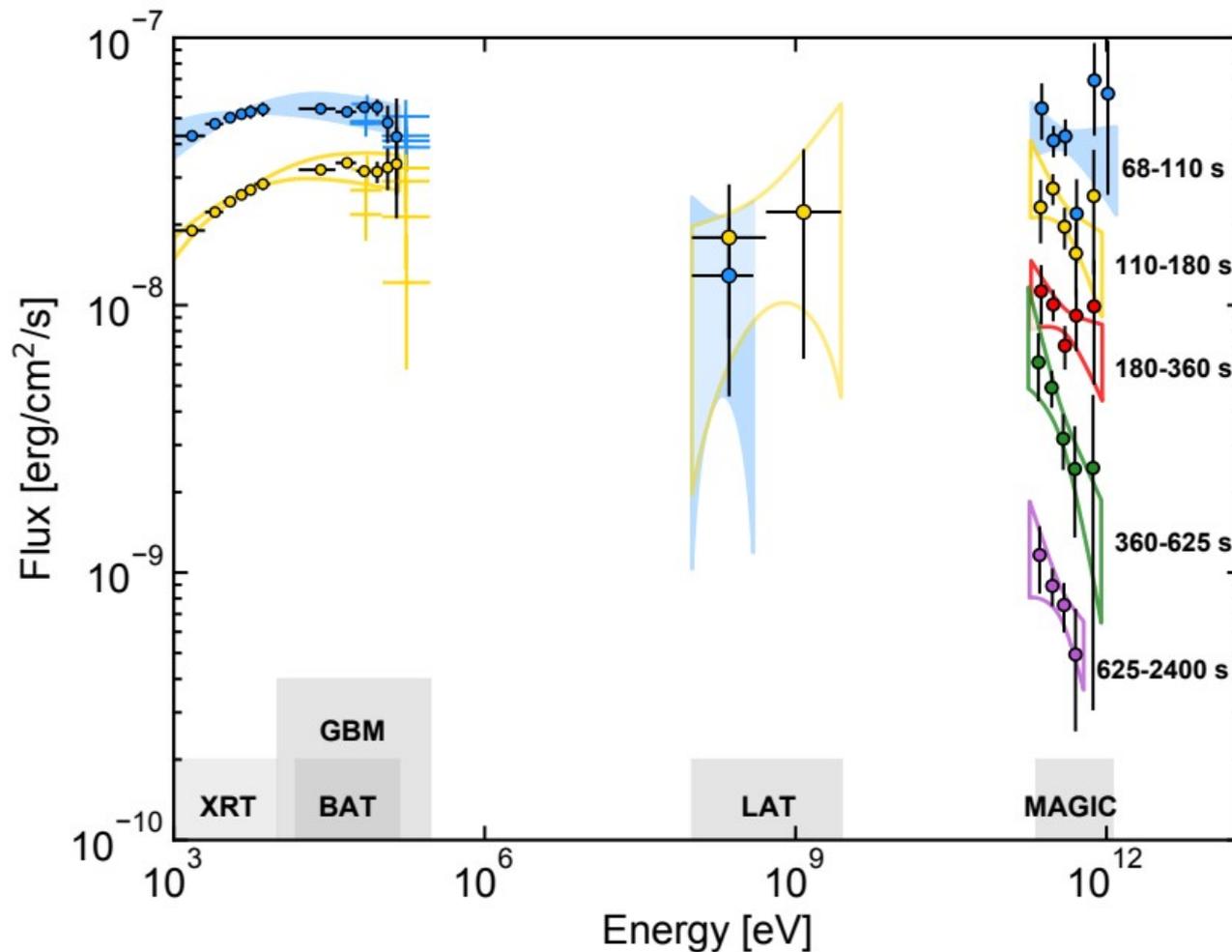


The spectra from X-ray to TeV show the need for an extra spectral component to explain the flux increase at the highest energies.

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

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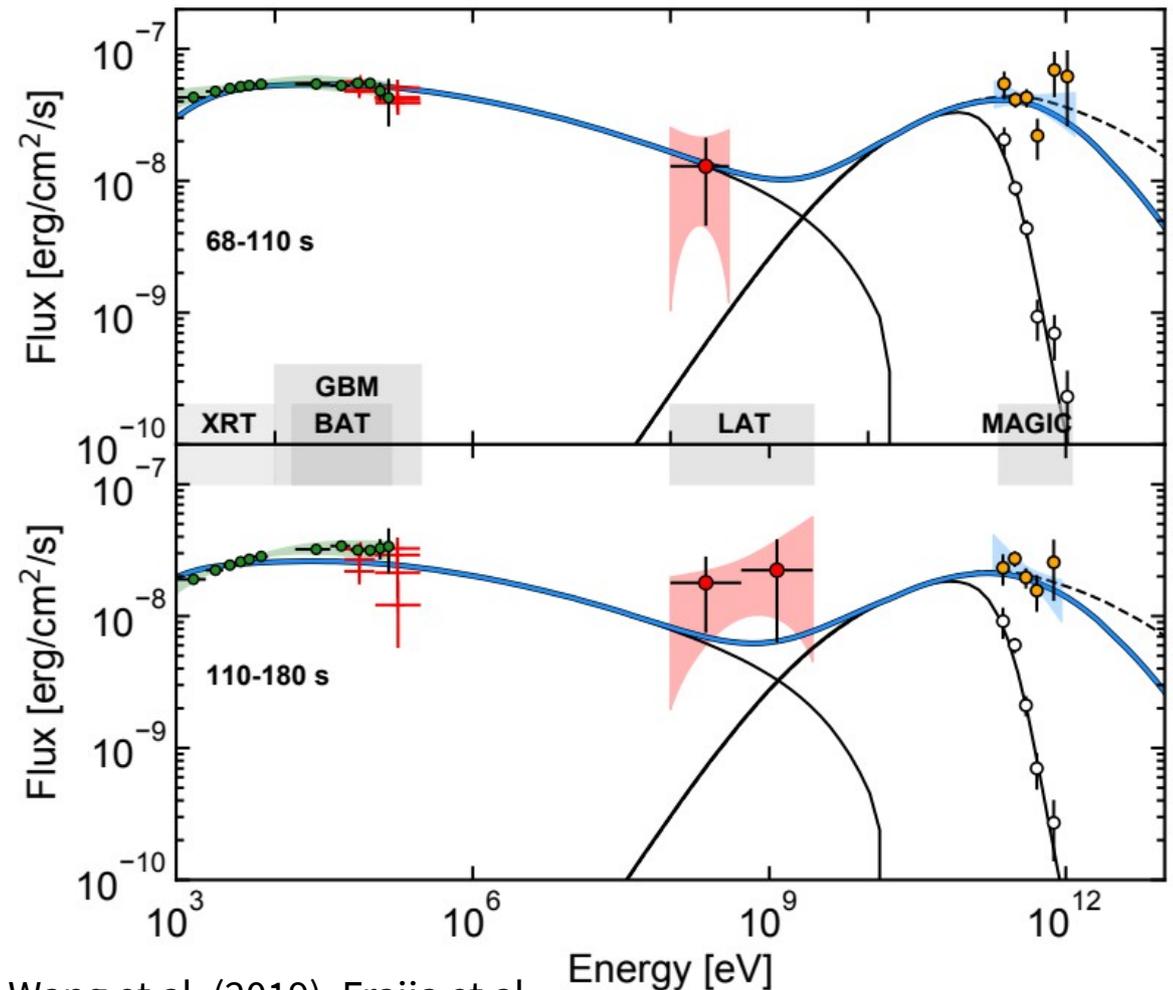
SSC also suggested in Derishev & Piran (2019), Wang et al. (2019), Fraija et al. (2019), Zhang et al. (2019)

# 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.

Creator:matplotlib 2.2.3, http://matplot
LanguageLevel:2

# 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): $1.5 \times 10^{52}$ erg
- Isotropic energy in synchrotron self-compton component (68-110s): $6.0 \times 10^{51}$ 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

# Not extraordinary guy! (Part I, intrinsic)



Levan et al. Space Science Reviews, V 202, I 1-4
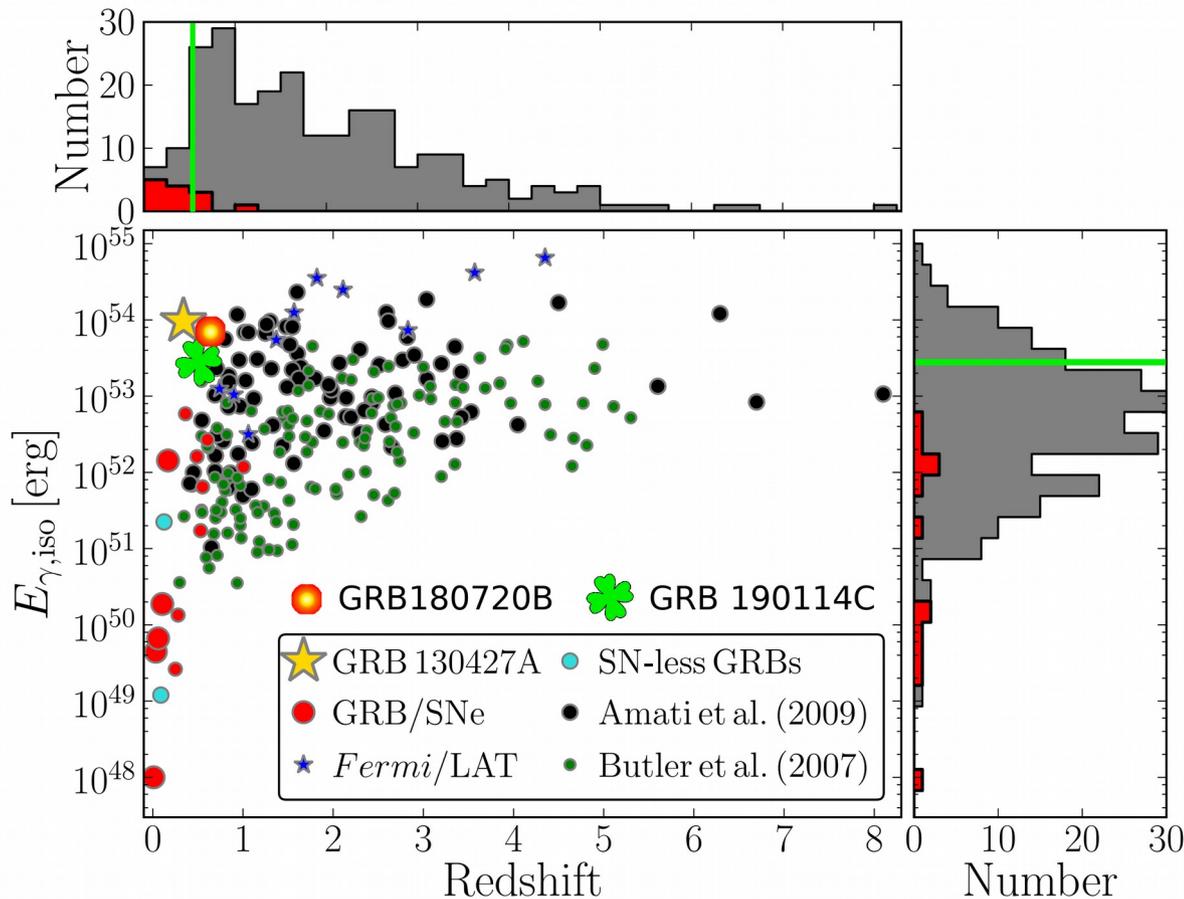
GRB 190114C has low redshift: z = 0.4245 ± 0.0005 (A. J. Castro-Tirado GCN 23708) and medium-bright burst.

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.
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)

Title:mirzoyan_EDtable5.dvi
Creator:dvips(k) 5.999 Copyright 2(
CreationDate:Mon Aug 19 10:05:2(
CreationDate:Mon Aug 19 10:05:2(

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.

# 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.

- Great interest for this burst by the community. The vast multi-wavelength follow-up brought a wealth of data for the interpretation.

- A unique model was used to explain all the multi-wavelength data both for the spectral and temporal profile. Within this model the extra-component is interpreted to come from synchrotron self-Compton emission processes.

- 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!

# Thank you

# Cherenkov telescope method



Better background reduction
Better angular resolution
Better energy resolution
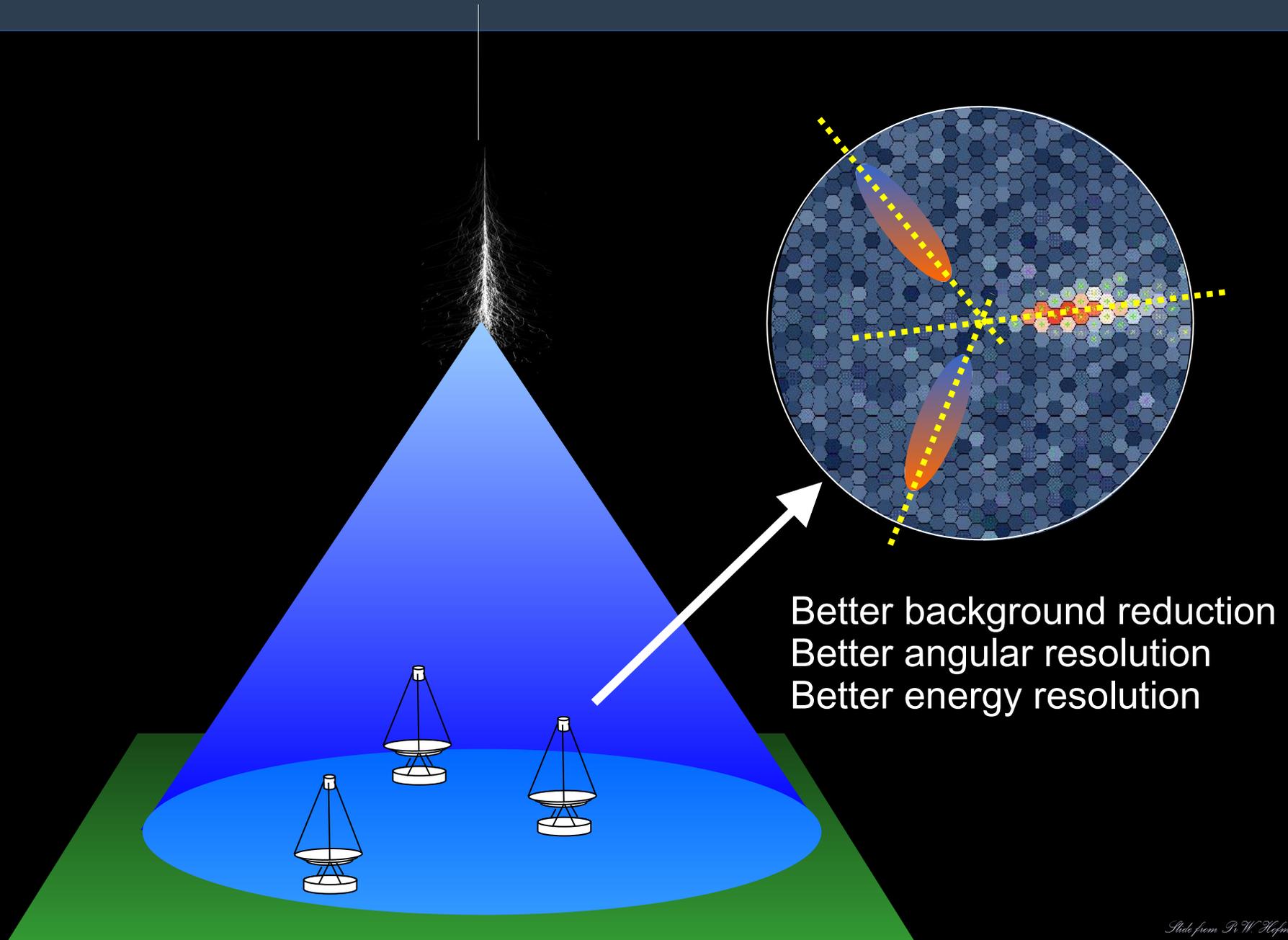
# The LAT and GBM on Fermi

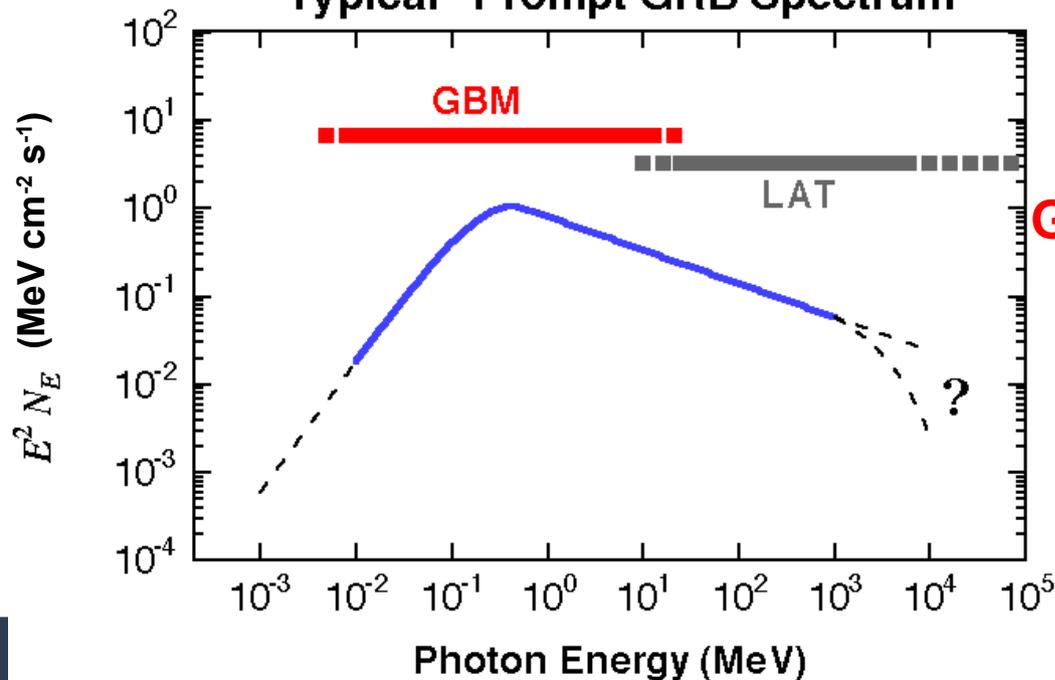**The GBM detects ~250 GRBs/year**
**~18% short**
**~50% in the LAT FoV**
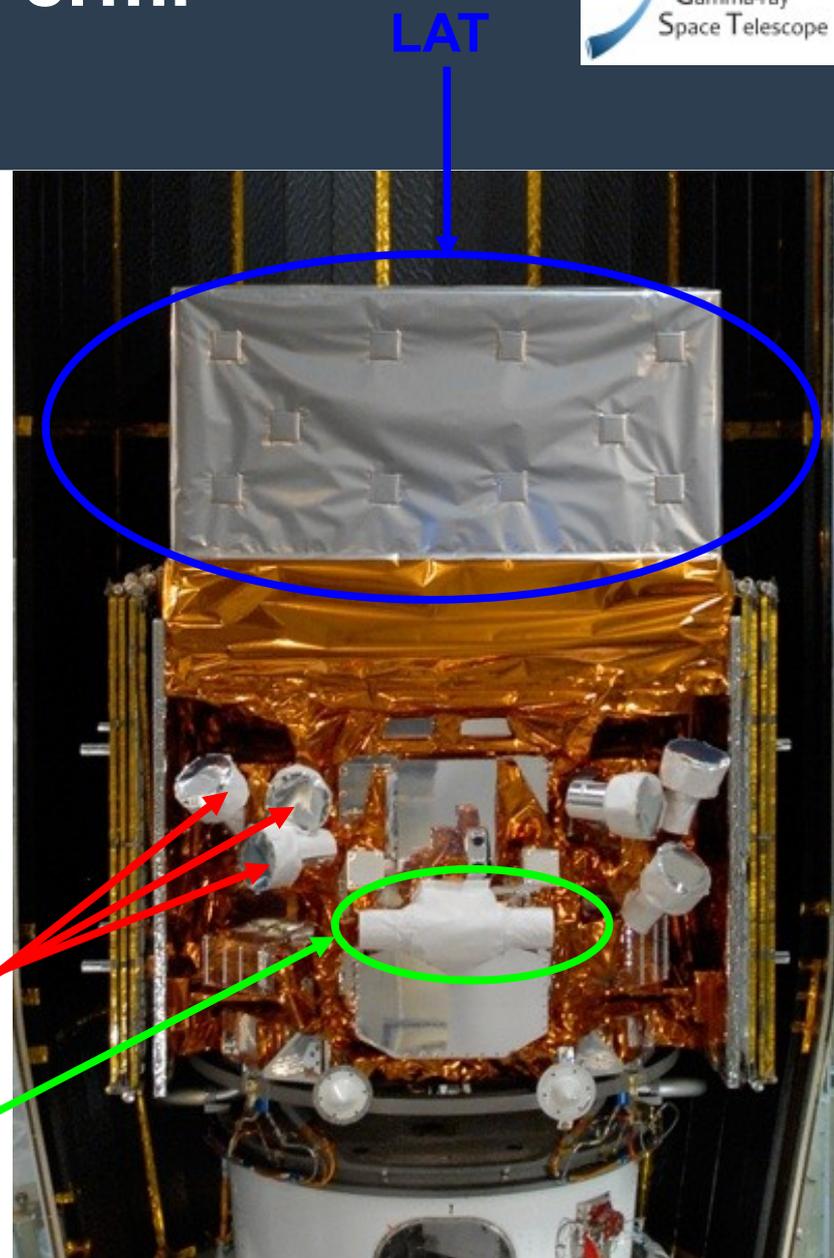**The LAT detects ~15 GRBs/year**

NaI: 8 keV - 1 MeV
BGO: 200 keV - 40 MeV
LAT: 30 MeV – 300 GeV



"Typical" Prompt GRB Spectrum

GBM NaI

GBM BGO

# 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.

Title:fig1_synchSpectra.eps
Creator:GIMP PostScript file plugin V 1.
CreationDate:Wed Nov 13 23:57:44 2019
CreationDate:Wed Nov 13 23:57:44 2019
LanguageLevel:2

# Spectral systematics @TeV
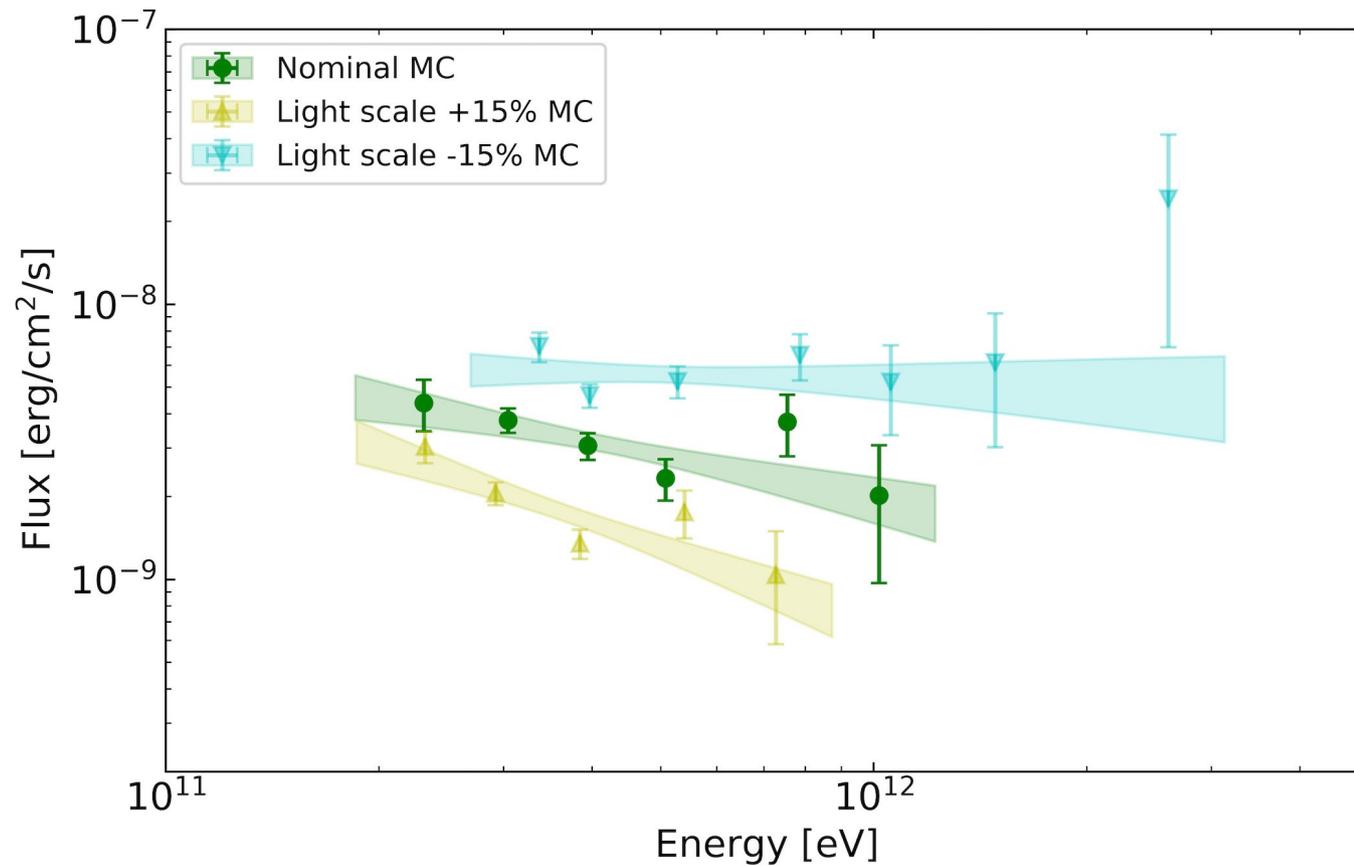
# Spectral detailed results @TeV

Title:mirzoyan_EDtable1.dvi
Creator:dvips(k) 5.999 Copyright 2019 Ra
CreationDate:Thu Nov 07 08:31:50 2019
CreationDate:Thu Nov 07 08:31:50 2019
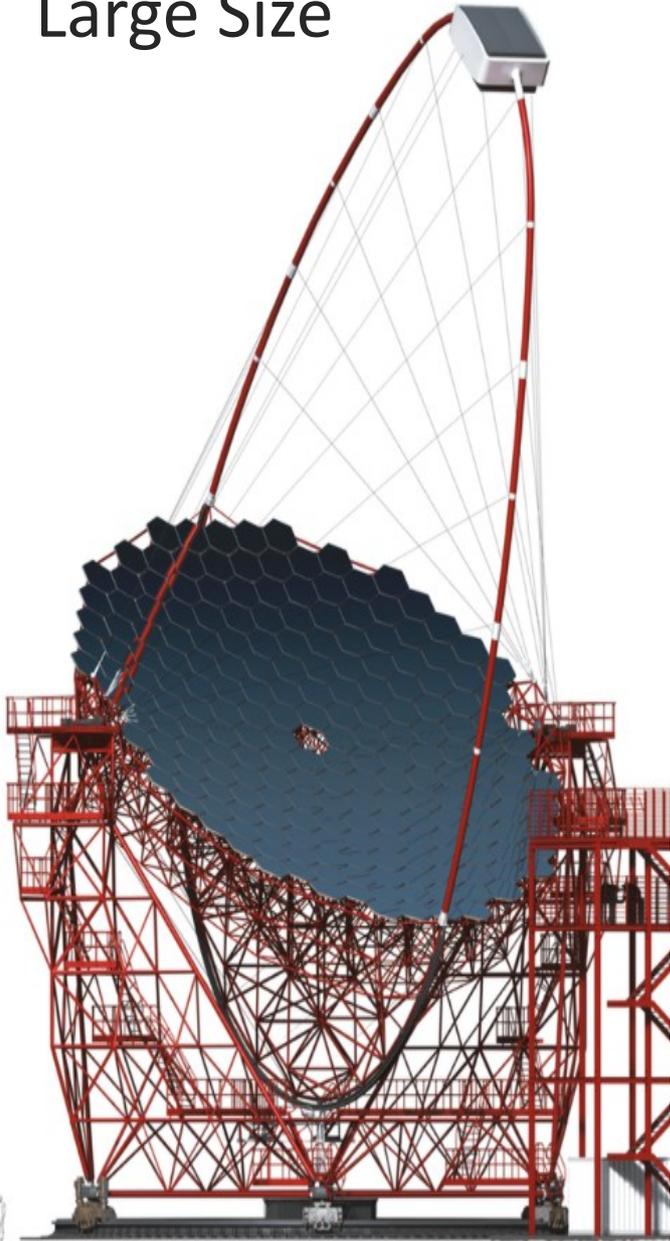
# Modelling of the radio and optical spectra

Title:Graphics produced by IDL
Creator:IDL 8.7.0 (darwin x86_64 m64)
CreationDate:Thu Jul 18 19:13:11 2019
CreationDate:Thu Jul 18 19:13:11 2019
LanguageLevel:1

# Redshift measurement

# 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



SST-2M GCT        SST-2M ASTRI        SST-1M

# The "now" future: LST

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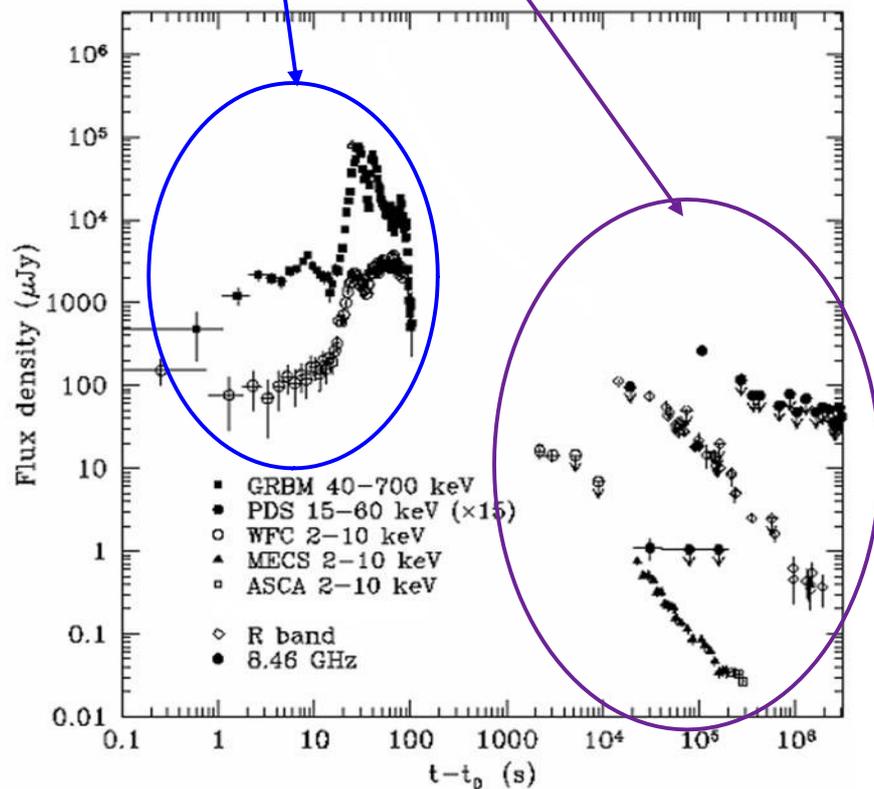(dependig on the assumed GRB model and array layout and performance)

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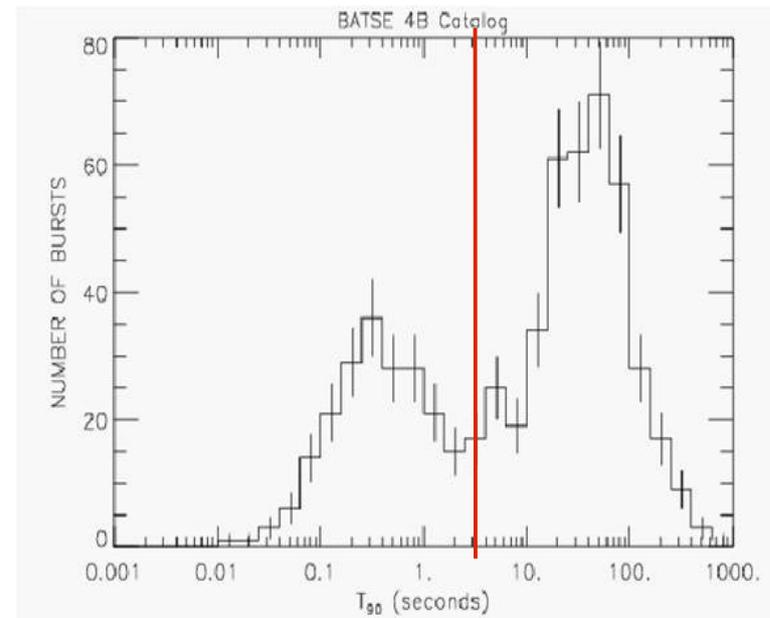
# GRBs: general properties

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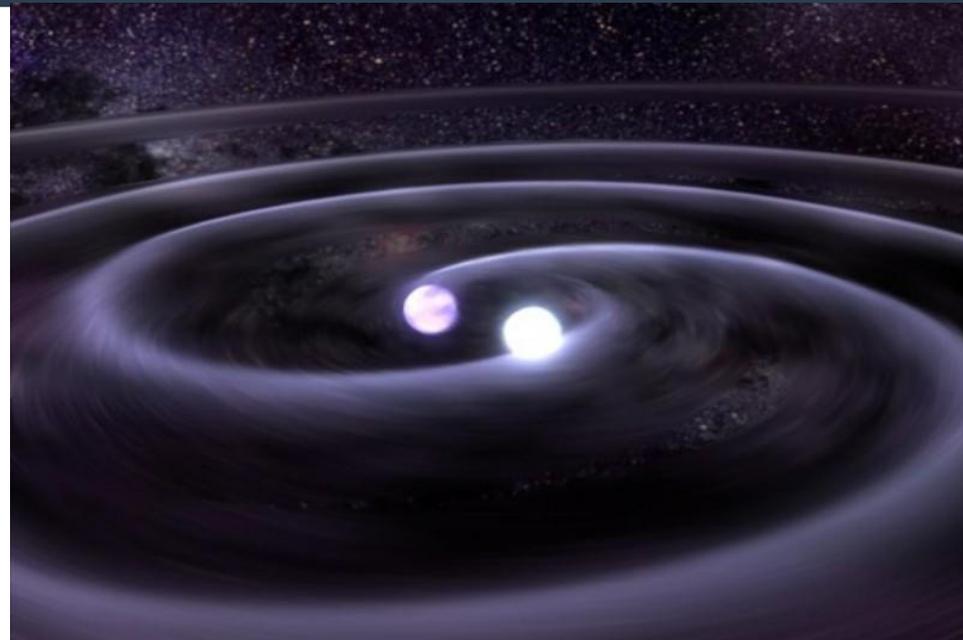● The AFTERGLOW phase lasting >3000s;

Two populations in time duration:
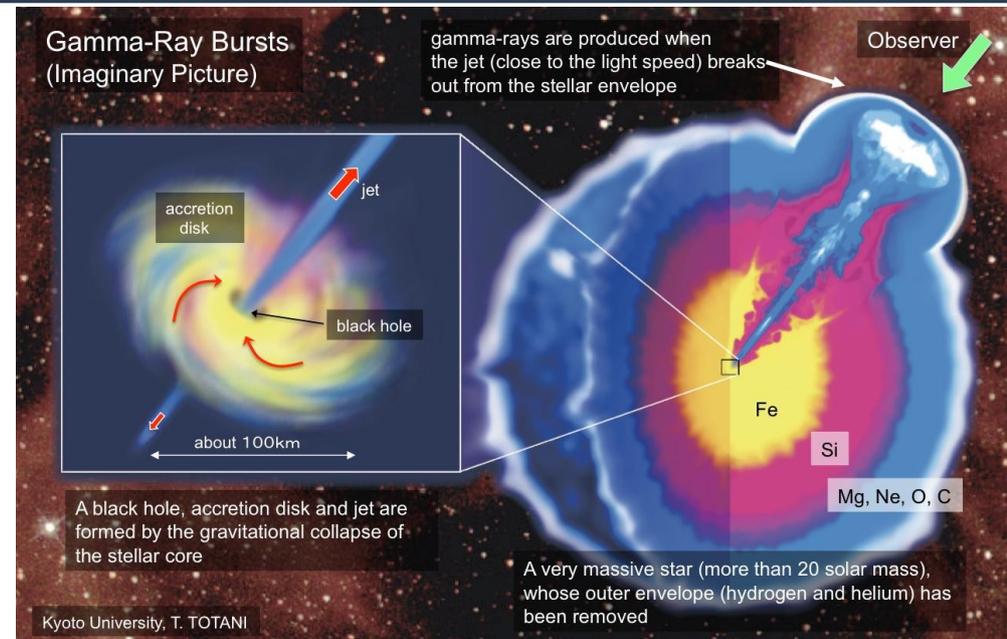● SHORT: duration of the prompt phase <2s;
● LONG: duration of the prompt phase >2s;

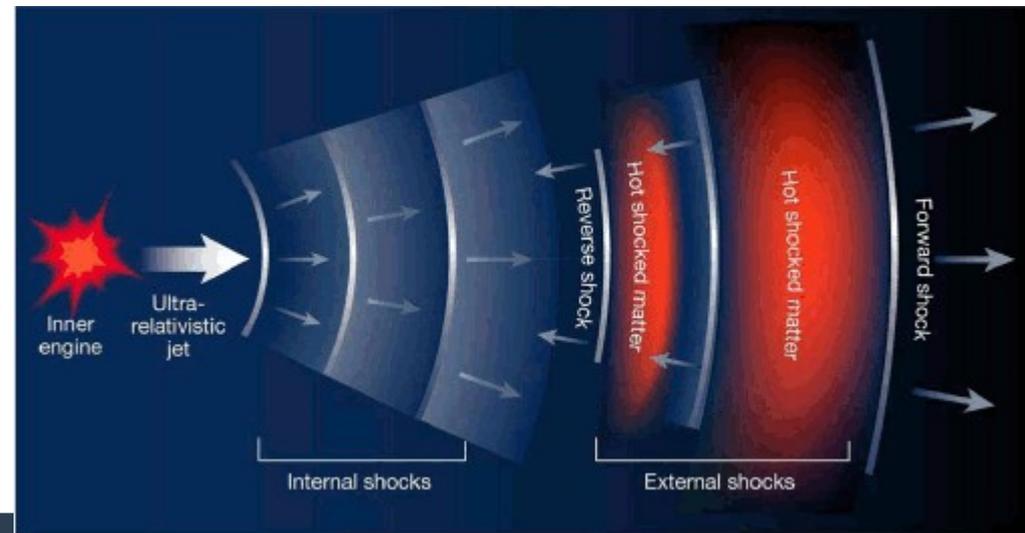# GRBs: general properties



or



Gravitational potential energy
→ "Fireball"
(Mészáros 2006)

$\Gamma \approx$ **few x 100**
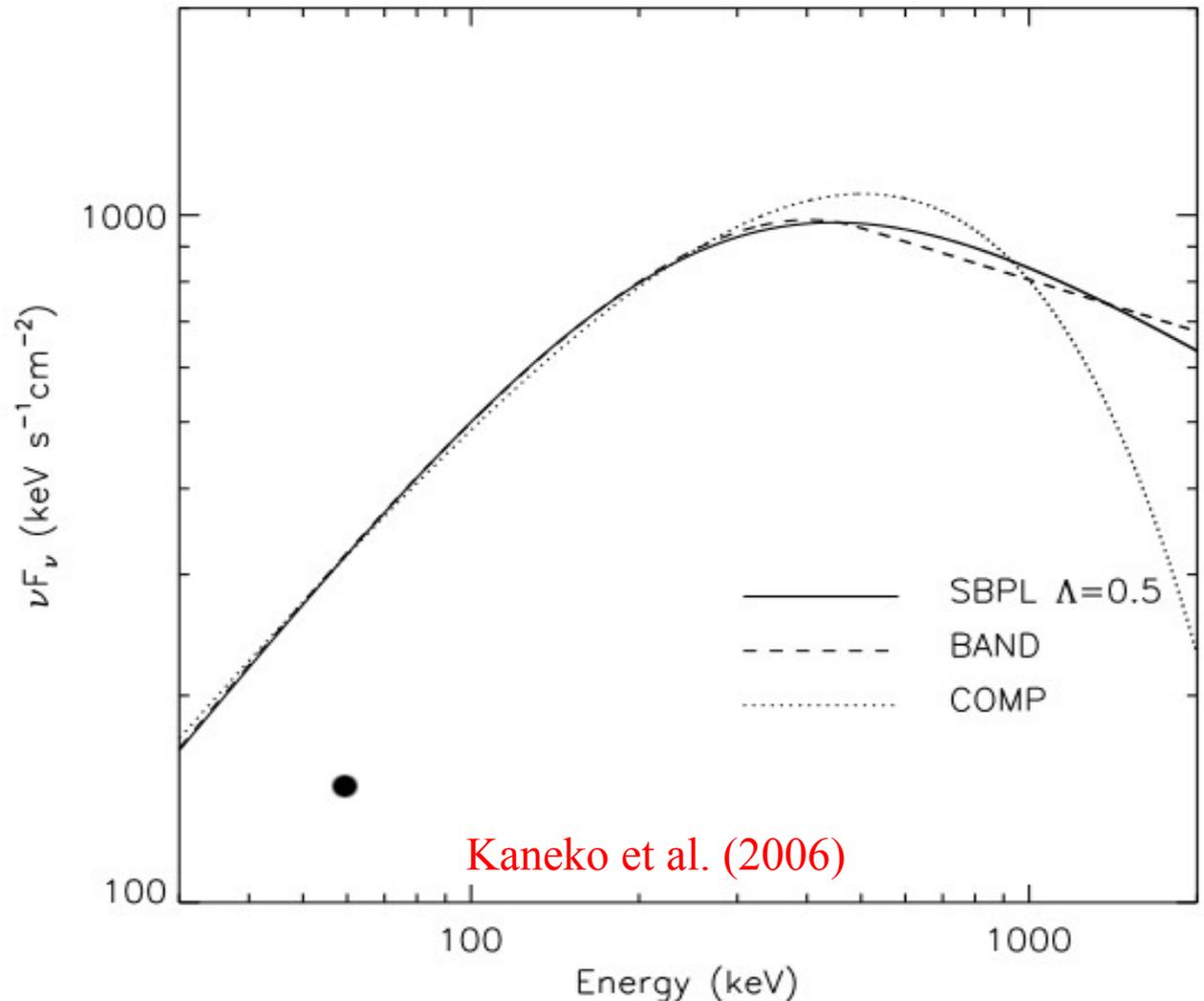($\Gamma \equiv [1 - \beta^2]^{-1/2}$, $\beta \equiv v/c$)
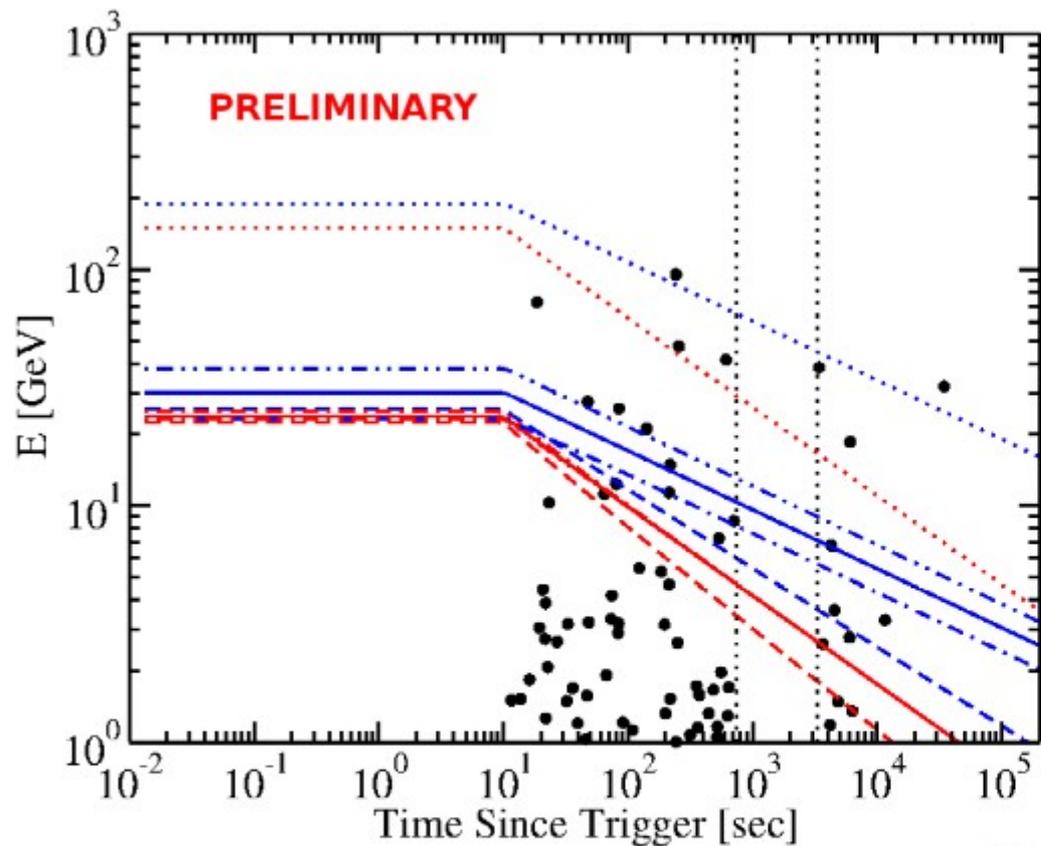
* connection with GW

# 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!



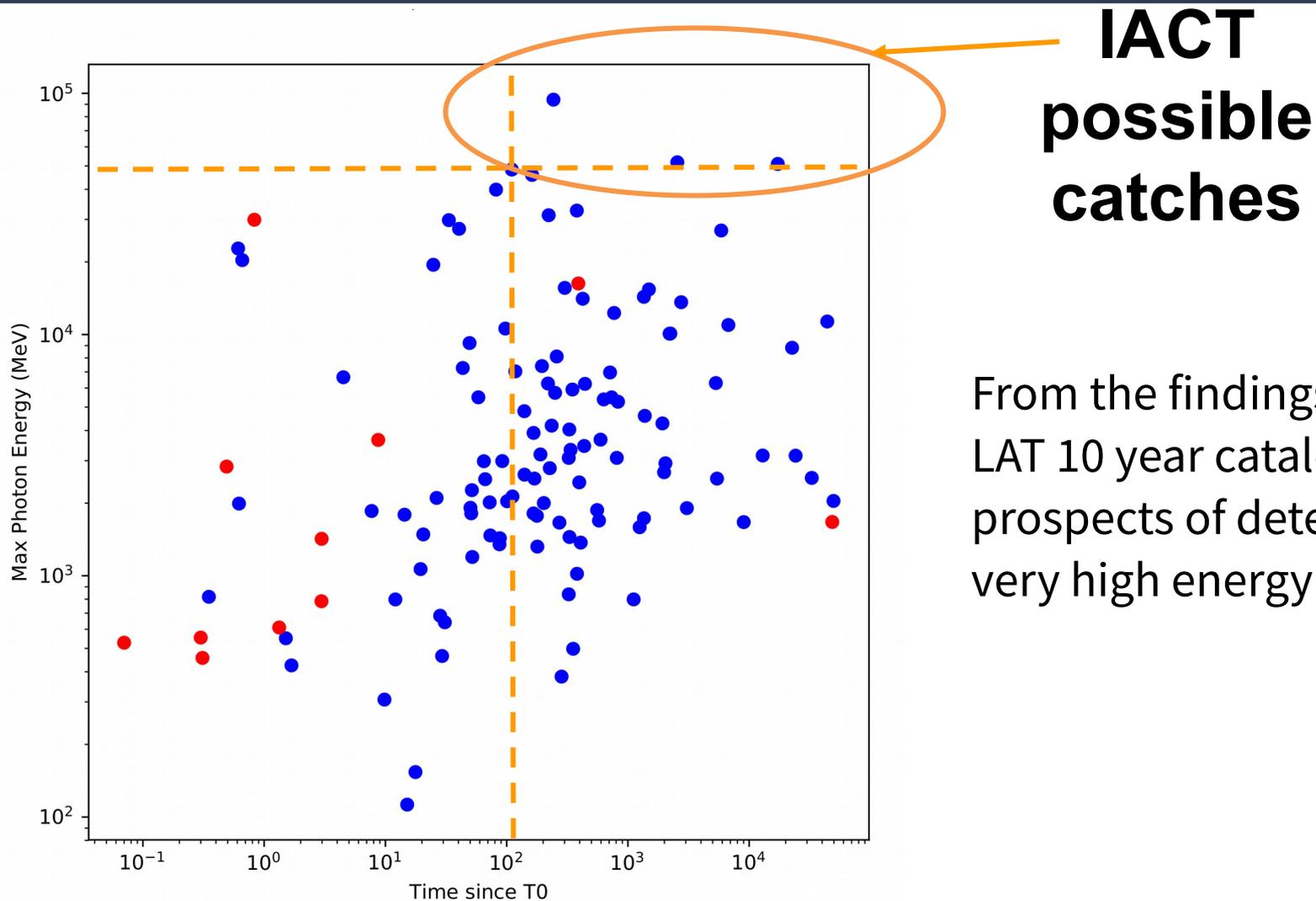Kaneko et al. (2006)

# GRB130427A Synchrotron emission?



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

Ackermann et al. Science 2013

wind, adiabatic, $\Gamma_0 = 2000$
wind, adiabatic, $\Gamma_0 = 1000$
wind, adiabatic, $\Gamma_0 = 500$

wind, radiative, $\Gamma_0 = 1000$
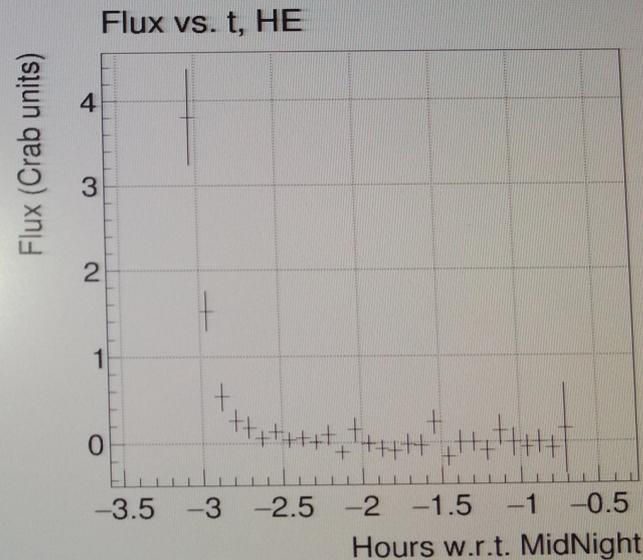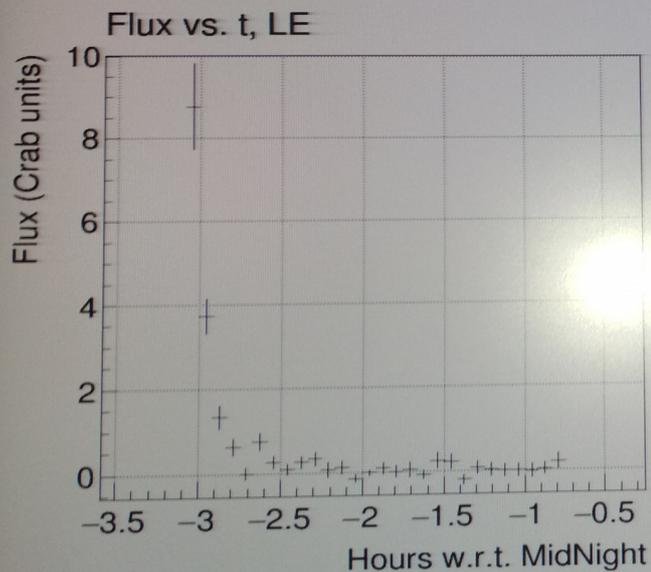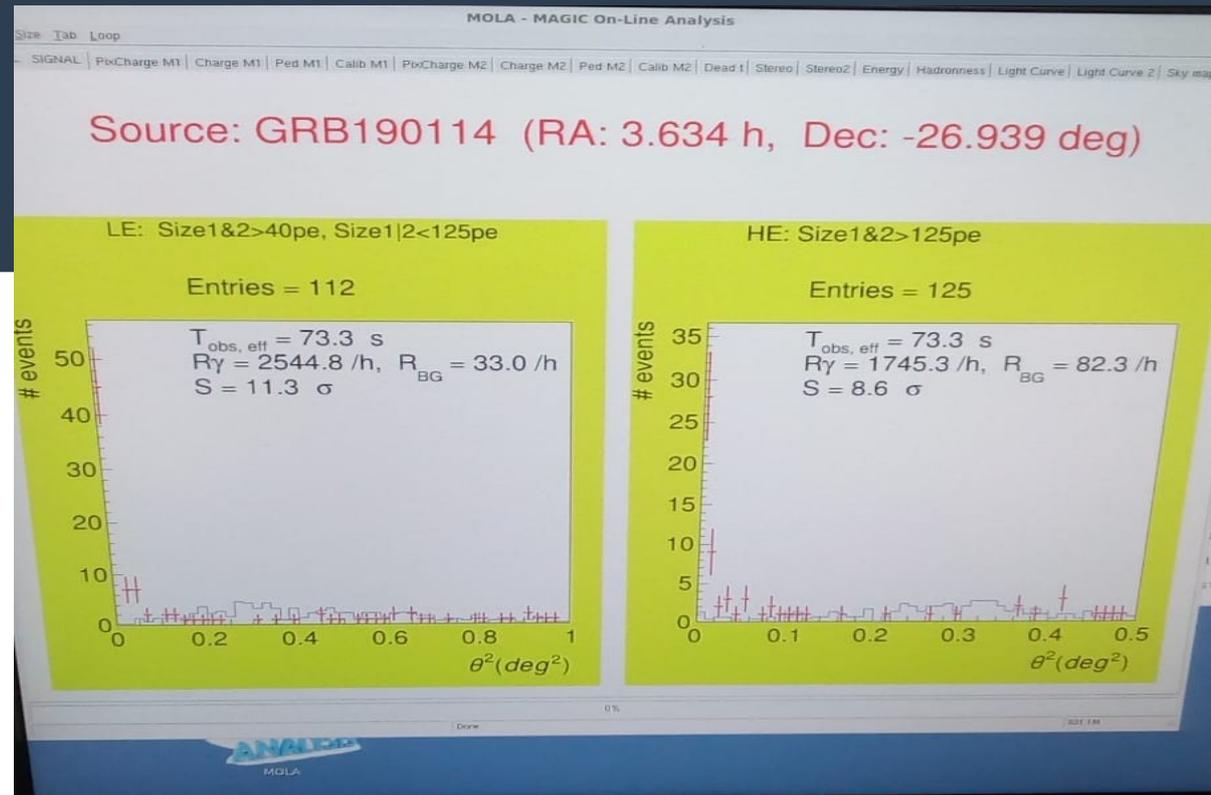ISM, adiabatic, $\Gamma_0 = 1000$

ISM, radiative, $\Gamma_0 = 1000$

# Fermi latest view



**IACT possible catches**

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