Observing soft-spectrum gamma-ray sources with the dedicated ALTO observatory

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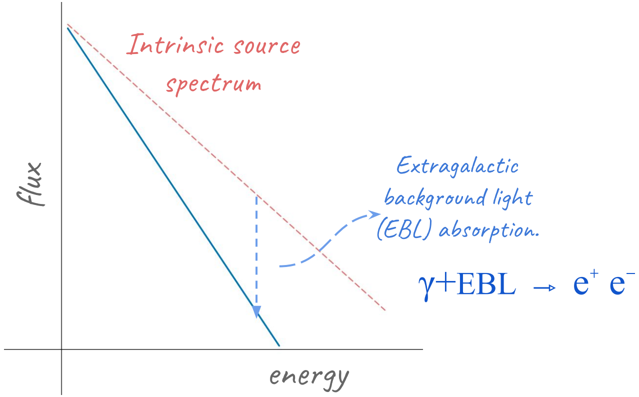
Nature of very-high-energy (VHE) γ-rays

- The astronomical observation of VHE (100 GeV - 100 TeV) gamma-rays helps to understand the particle acceleration in extreme environments of the Universe.
- The observation also acts as a probe as for instance, to test Lorentz-Invariance Violation and effects of axion-like particles.
- The jets in active galaxies (AGNs), gamma-ray bursts (GRBs), remnants of Supernova explosion are some example sites of the origin of VHE γ-ray sources.
- For high redshift sources, VHE γ-ray attenuate due to EBL absorption. This makes its spectrum softer, meaning more flux in lower energies (< 10 TeV).

The BL Lac PKS 2155-304 in R-band. z=0.116

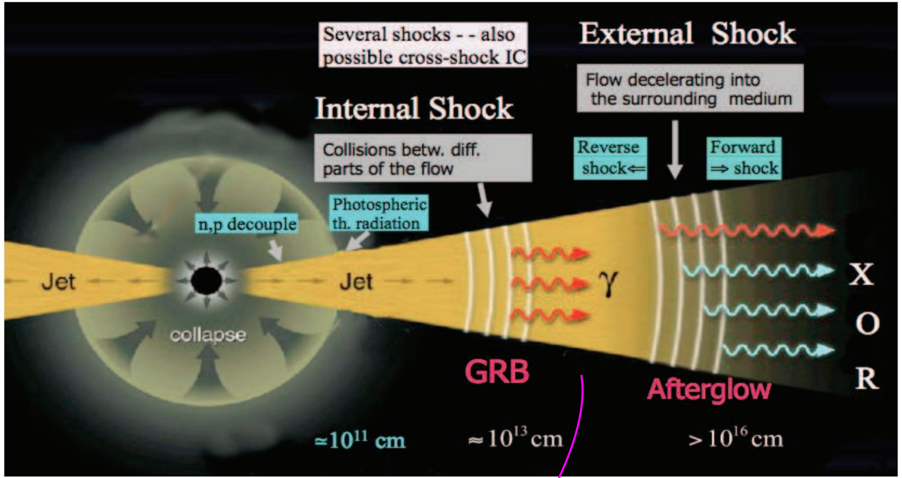
(source:Wiki, ESO-NTT)



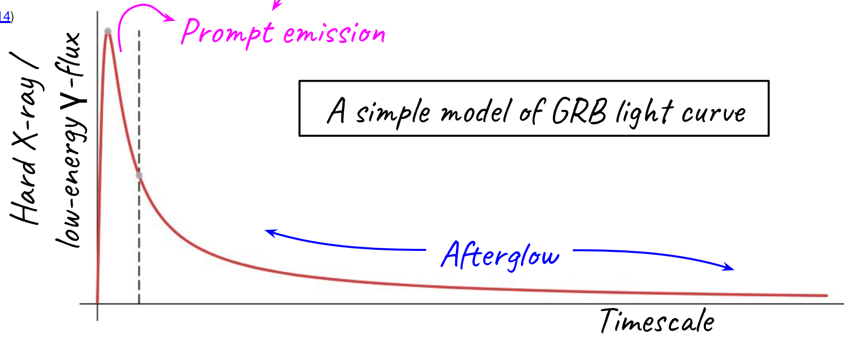
γ+EBL → $e^+ e^-$

Gamma-ray bursts

- Astronomical transient events with initial “prompt” emission followed by a long “afterglow”.
- Afterglow occurs in all electromagnetic wavelengths.
- The first ever VHE γ-rays from GRB afterglow emission is observed by Imaging Atmospheric Cherenkov Telescopes in recent year.
  - [GRB 180720B](#) → 100 - 440 GeV → $T_0 + 10$ hr
  - [GRB 190114C](#) → 200 - 1000 GeV → $T_0 + 57$s
- The afterglow VHE spectrum of these GRBs are soft spectrum.



A cartoon of GRB jet from a collapsing star
(credit: [Meszaros and Rees, 2014](#))



Very-high-energy < 10 TeV dedicated project: ALTO

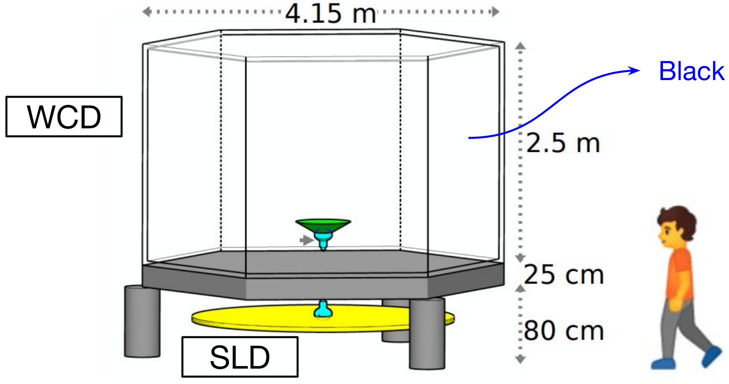
ALTO is a R&D project dedicated for ground-based very high energy gamma-ray observatory based on water Cherenkov technique. The key features include,

- Regular monitoring → **Observations may be done 24h per day**
- Wide field of view → **~ 2 steradian**
- At high altitude (> 5 km) → **Low threshold E ≥ 200 GeV**
- Excellent timing accuracy → Improved angular resolution (~ 0.1° at few TeV)
- Modular design → Phased construction and easy maintenance
- Simple to construct → Minimize human intervention at high-altitude
- Long duration → Should operate for 30 years
- Open Observatory → Distribute data to the community

Crucial for AGN/GRB observation.

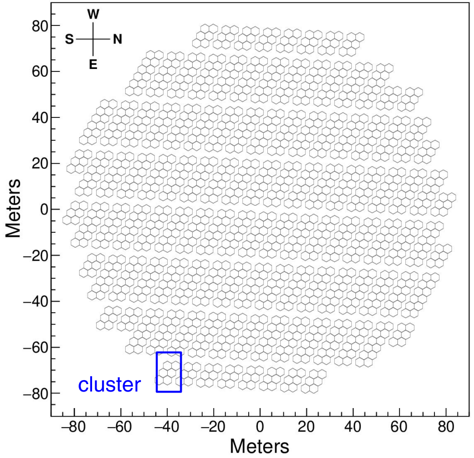
ALTO Detector Design

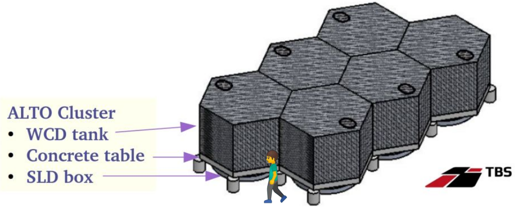
A unit of water Cherenkov detector (WCD) with Scintillator (SLD) underneath



Black coated inside

An array of 1242 units



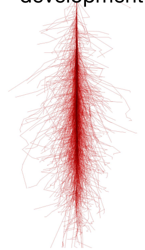


A cluster of 6 units

Summary of Monte Carlo Simulation & Reconstruction

Corsika - Shower Simulation

Simulation of gamma-ray air shower development.

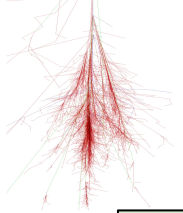


$\Gamma_{\text{gamma}} = 2$ at 18^{o} Zenith

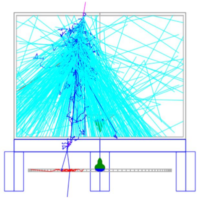
$\Gamma_{\text{proton}} = 2.7$ between 15^{o} - 21^{o}

dN/dE = E^-Γ

Simulation of Cosmic-ray air shower development.

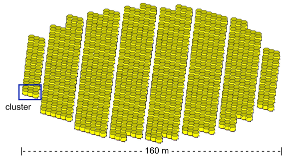


GEANT4



Detector, array geometry simulation.

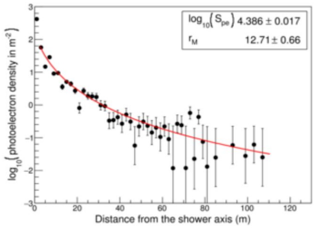
Response to corsika-simulated air shower.



Satyendra Thoudam

Shower parameters reconstruction

- **Shower core** - lateral shower particle distribution function.
- **Shower direction** - hyperbolic wavefront model.
- X^2 minimisation is used to fit the simulated data.



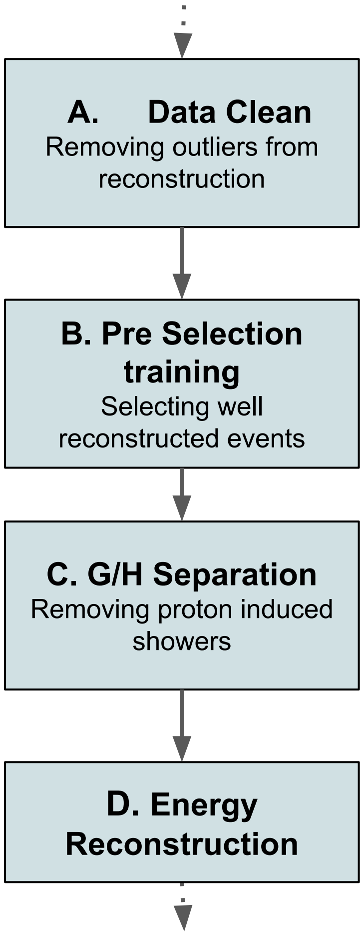
Challenge 1 : Selecting well reconstructed events

Challenge 2 : Gamma-over-hadron Separation

Challenge 3 : Reconstructing energy of the primary

… follows performance evaluation.

Signal Extraction using Machine Learning for ALTO (SEMLA)



A. Data Clean
Removing outliers from reconstruction

B. Pre Selection training
Selecting well reconstructed events

C. G/H Separation
Removing proton induced showers

D. Energy Reconstruction

- Three challenges are handled by SEMLA analysis in different phases.
- Each phase has a specific aim.
    - A - removing the outliers from reconstruction
    - B - selecting well-reconstructed events by multivariate analysis using artificial Neural Networks (ANN).
    - C - removing proton induced showers using ANN.
    - D - Reconstruction of primary energy using ANN.
- The definition of **signal** and **background,** in phase B, is one of the highlights of SEMLA.
- Phase B and C are performed in bins of shower size parameter.

SEMLA

signal : background = 0.9 : 0.05

A. Data Clean
Removing outliers from reconstruction

B. Pre Selection training
Selecting well reconstructed events

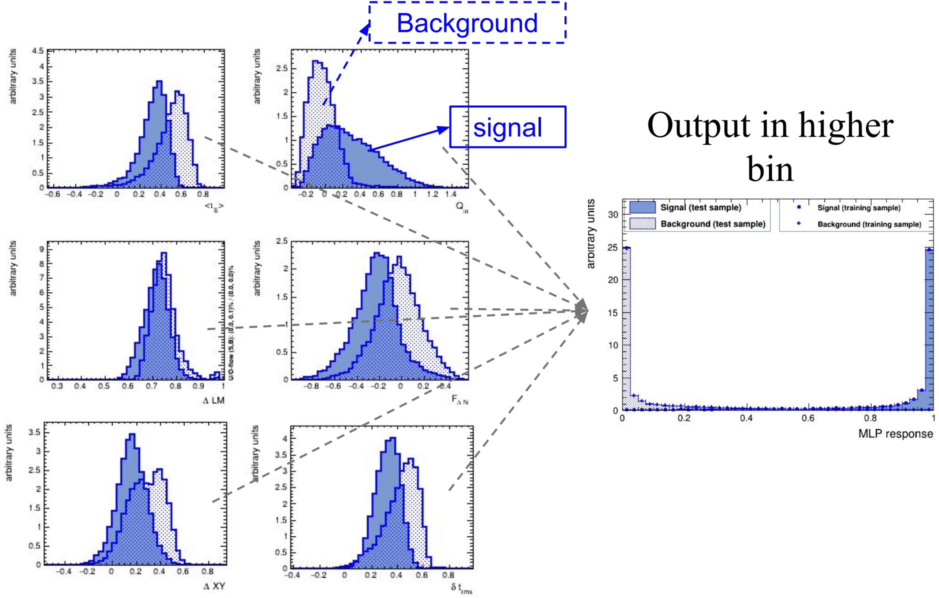
C. G/H Separation
Removing proton induced showers

D. Energy Reconstruction

Signal: well-reconstructed gamma-events

Background: badly-reconstructed gamma-events

6 Input parameters



Output in higher bin

The performance of the best training bin is shown.

SEMLA

A. Data Clean
Removing outliers from reconstruction

B. Pre Selection training
Selecting well reconstructed events

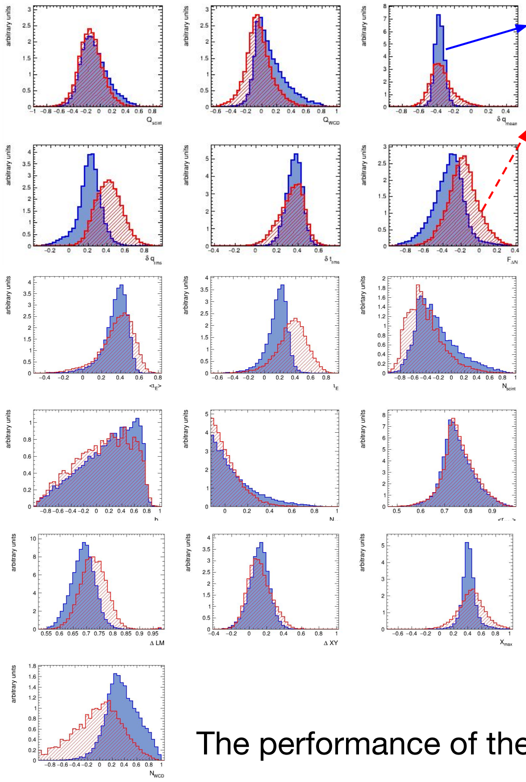
C. G/H Separation
Removing proton induced showers

D. Energy Reconstruction

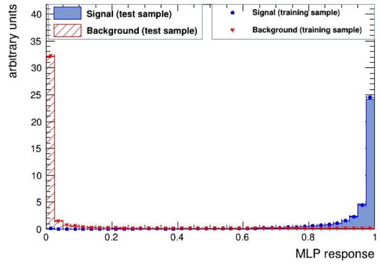
Signal: gamma-ray events
Background: proton events

16 Input parameters

signal : background = 0.9 : 0.03

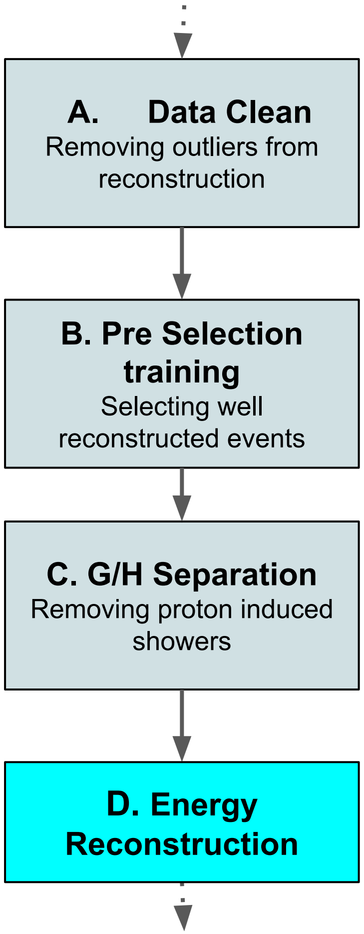


Output in higher bin



The performance of the best training bin is shown.

SEMLA



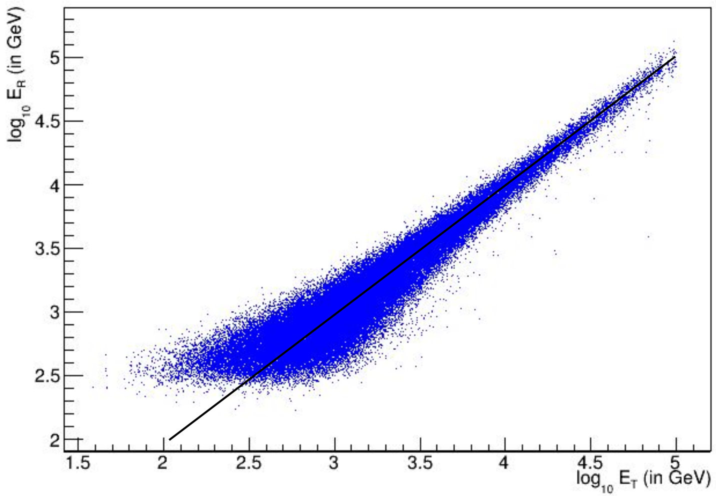
A. Data Clean
Removing outliers from reconstruction

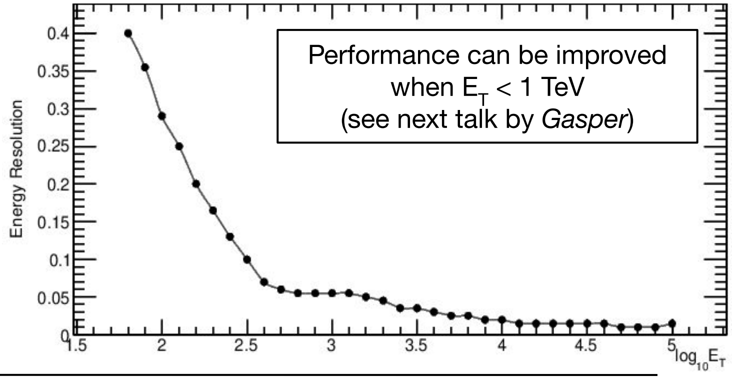
B. Pre Selection training
Selecting well reconstructed events

C. G/H Separation
Removing proton induced showers

D. Energy Reconstruction

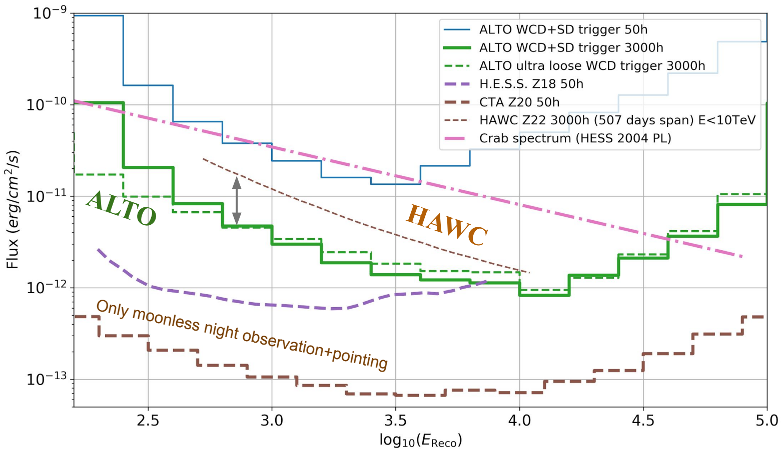
Input: gamma-ray events passing phase C



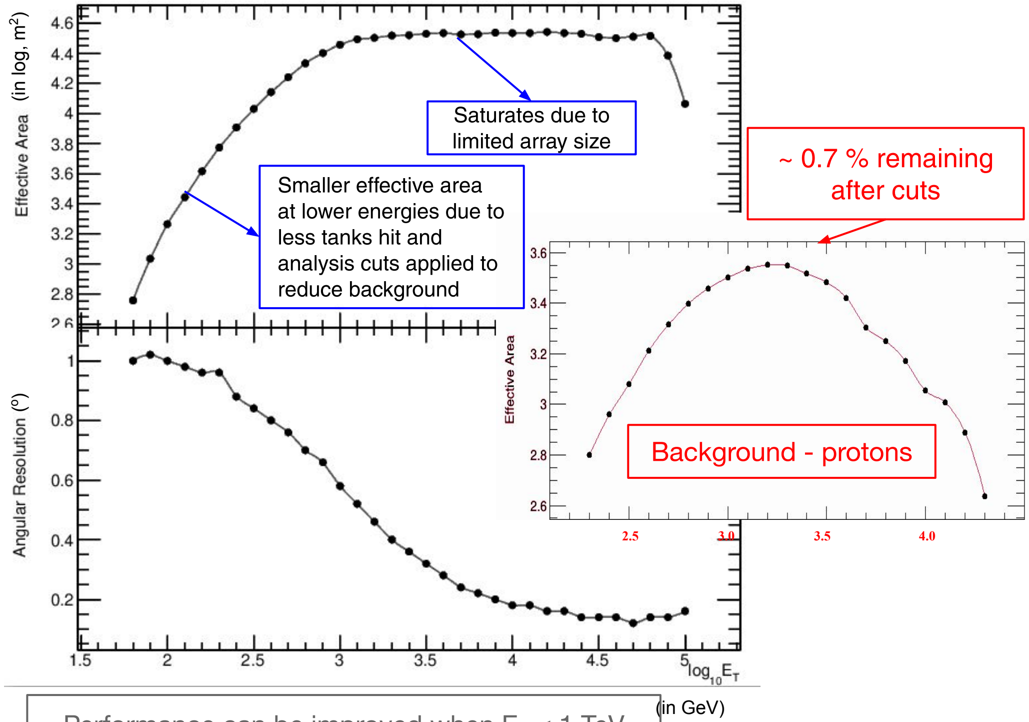


Performance can be improved when $E_T < 1$ TeV
(see next talk by *Gasper*)

Expected sensitivity of the ALTO array



Only moonless night observation+pointing



Saturates due to limited array size

Smaller effective area at lower energies due to less tanks hit and analysis cuts applied to reduce background

~ 0.7 % remaining after cuts

Background - protons

(in GeV)

Performance can be improved when $E_T < 1$ TeV (see next talk by *Gasper*)

Left: Expected sensitivity of current ALTO array to a point-like gamma-ray source at 18° zenith angle. (*WCD+SD trigger* - 2/12 cluster trigger; *ultra loose WCD trigger* - ⅙ trigger). References: H.E.S.S., HAWC, CTA.

Right: The effective area and angular resolution for a point-like gamma-ray source.

Performance evaluation

Expected ALTO performance in **low energies**,

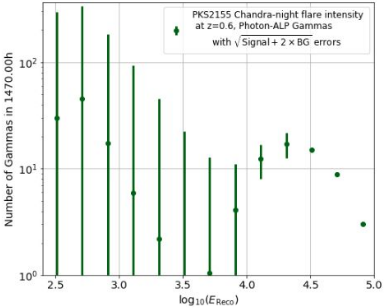
- GRB 180720B (z = 0.653), could be seen with ALTO
  - With **6.8 σ** in the first minute after the burst alert.
  - Due to decaying nature of the light curve of GRBs, the significance reduces to **4.5 σ** for the first 6 minutes of observation.
- GRB 190114C (z = 0.425)
  - **9.7 σ** during the first 40 minutes

Can also act as an alert system.

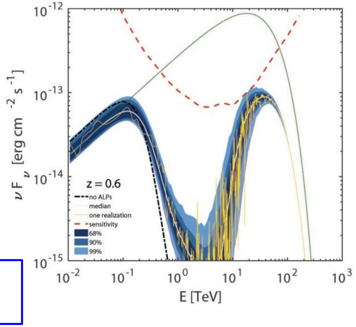
This demonstrates that ALTO , given the low energy threshold and good performance could detect GRBs (No GRBs so far detected with ground based particle detectors, for instance HAWC)**.**

Expected ALTO performance in **high energies**,

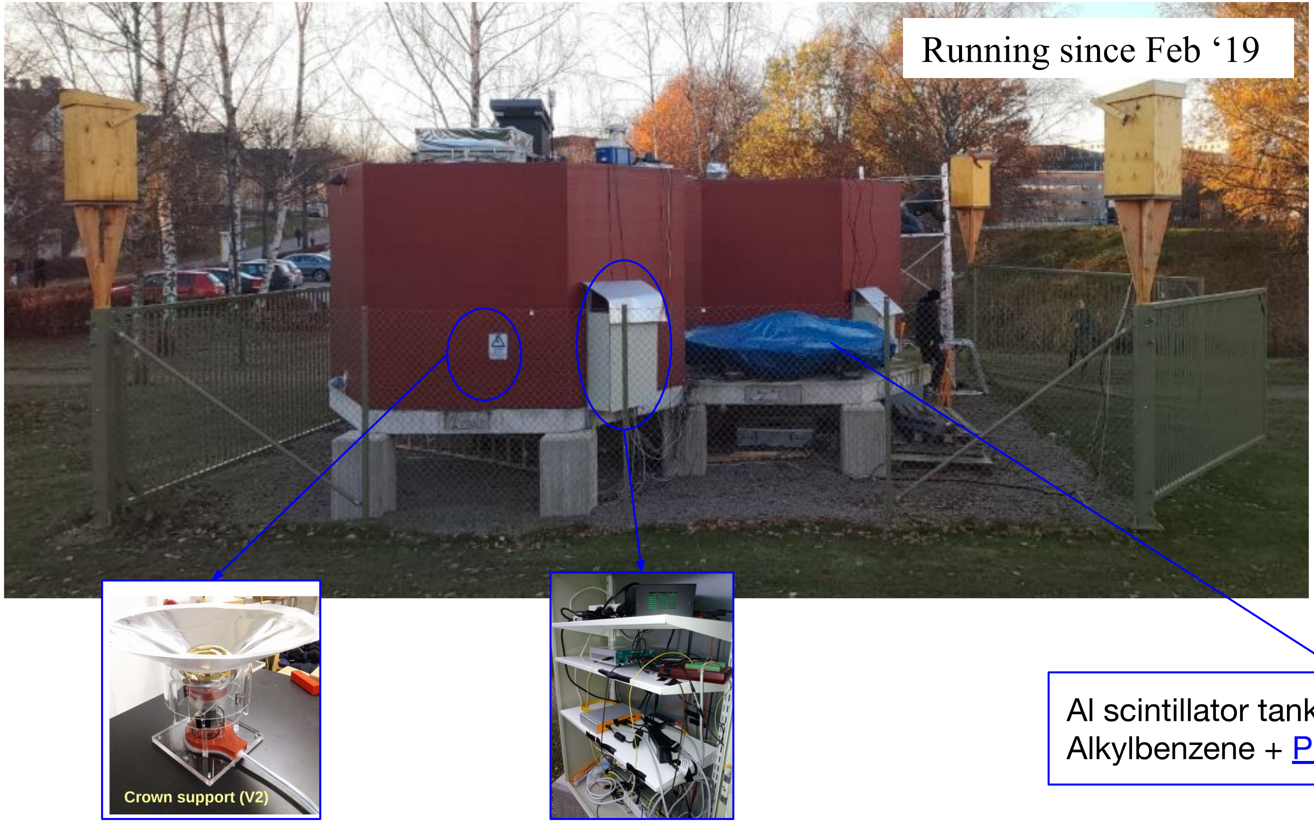
- PKS 2155-304 flare in 2006
- Assuming such an AGN flare,
  - at z = 0.6
  - flaring for two months
  - Viewed through gal. plane
  - **6.5 σ** in E > 10 TeV



G. Galanti et al. 2019
ALP Model



ALTO prototype at Linnaeus University

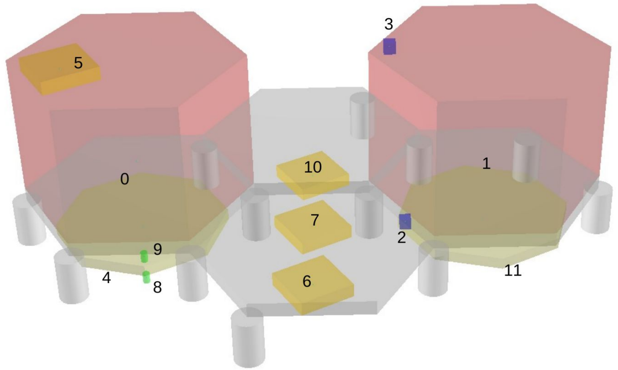


Running since Feb ‘19

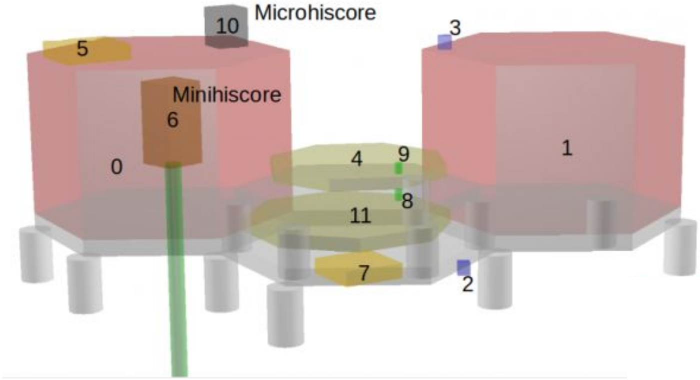
Al scintillator tanks filled with Linear Alkylbenzene + POPOP + PPO

ALTO prototype at Linnaeus University

Feb 2019 - Sep 2020



Since Sep 2020



- Used for monitoring the detectors (2,3; 8,9)
- Micro/Mini HiScore stations - refer next talk by *Gasper*.

Conclusion

ALTO is a R&D project dedicated for 100 GeV - 10 TeV extragalactic astronomy.

- From simulation studies,
    - The current design of ALTO works and provides room for further improvements (see next talk by *Gasper*).
    - Sensitive to detect bright GRBs. This constitutes a major achievement.

- From prototype activities,
    - ALTO prototype detectors are running smoothly.
    - Detector choices are reliable.

Publications: ALTO science paper & ALTO analysis paper (will be submitted before Christmas).

Thank you for your attention

For updates about the project please visit: astrogamma.se or @astrogamma

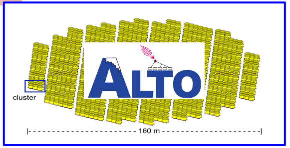
BACKUP SLIDES

Comments on GRB observation by current observatories

In GRB180720B, H.E.S.S. started observing after 10 hours due to daylight.
In GRB190114C, MAGIC took 57 seconds to point to its location. Even 57 seconds is too long to catch a short GRB (< 2 s). But for any type of ground-based VHE detection, this will be difficult.

Existing HAWC observatory hasn't observed GRBs yet.

Swift BAT and _Fermi_ GBM are outstanding in detecting, alerting and monitoring, in case of a GRB in their respective energy range.



The Fermi Gamma-ray Space Telescope (~ keV < E < 300 GeV)

HAWC (> ~1 TeV)

Swift X-ray telescope (< 150 keV)

H.E.S.S., MAGIC, VERITAS (> 100 GeV)

Space-based observation

Ground-based observation

100 keV	100 MeV	100 GeV	100 TeV	
… Hard X-rays	low-energy gamma-rays	high-energy gamma-rays	very-high-energy gamma-rays	UHE γ-rays ...

Importance of the scintillators

- In the current analysis scintillators are used in two places,
    - Triggering (under discussion)
    - Analysis

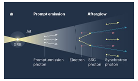
- In the analysis, scintillators improve the background discrimination by **10 - 15 %**

- Apart from background discrimination scintillator can be used for calibration and monitoring WCDs.

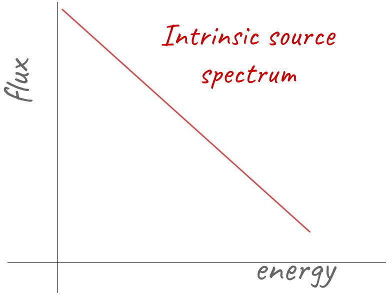
- Scintillators help in muon tagging and can be used for cosmic-ray composition studies.

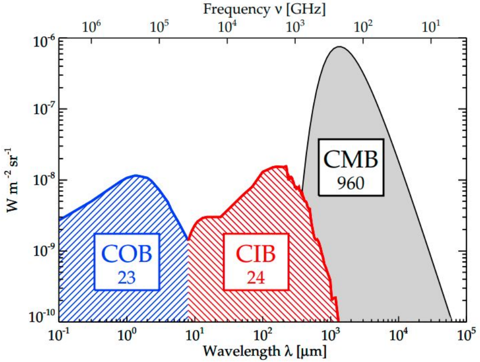
Attenuation in VHE Spectrum

z = 0.5



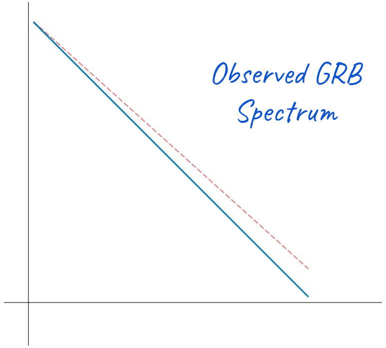
γ+EBL → $e^+ e^-$

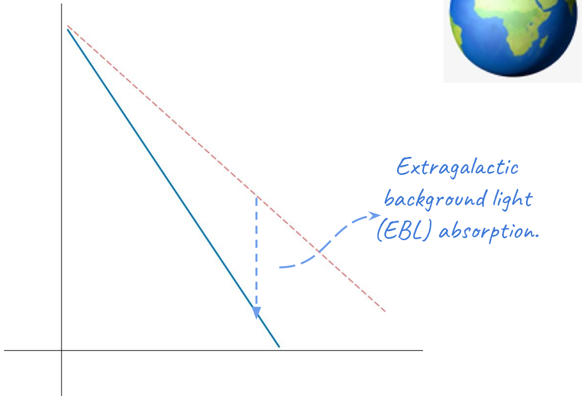




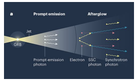
Cosmic Optical Background (COB) + Cosmic Infrared Background (CIB) = Extragalactic background light (EBL) spectrum.

(Credit: H. Dole et al., 2018)





z = 3



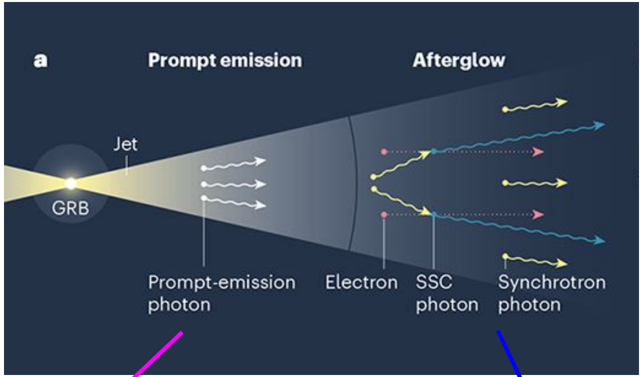
γ+EBL → $e^+ e^-$ γ+EBL → $e^+ e^-$

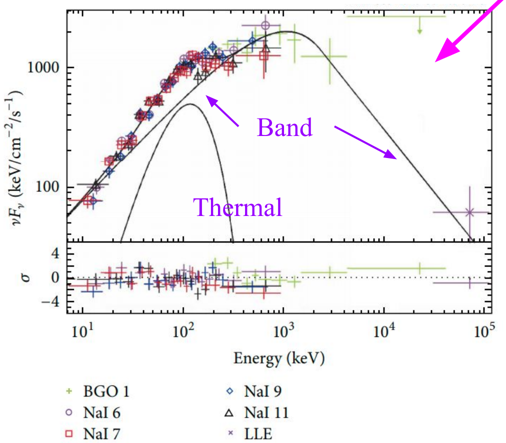
The farther the source & the higher the photon energy, the softer the spectrum

GRB Spectra

- Prompt emission spectrum: Band + Thermal
  - Band - empirical relation combining of two power laws : No physical interpretation.
  - Thermal - Planck function.

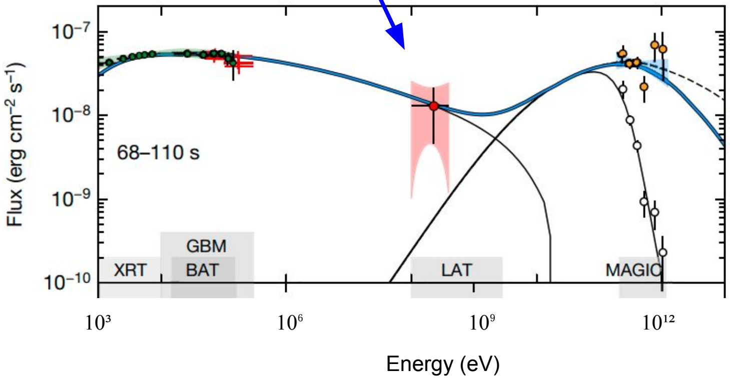
- Afterglow emission spectrum: Synchrotron + SSC
  - Non-thermal jet emission from electrons (leptonic model).





“Band + Thermal” model describing prompt GRB110721A spectrum observed by Fermi space telescope (in detail in the following slides).

(credit: Iyyani et al., 2014)



GRB190114C afterglow emission described by non-thermal Synchrotron Self Compton (SSC) model.

(credit: MAGIC, 2019)

GRB 180720B

z = 0.653

20 Jul 2018
14:21 UT (T_0)

T_0+ 10 min

T_0+ 10.1 hr

T_0+ 30 days

Fermi GBM
Swift BAT

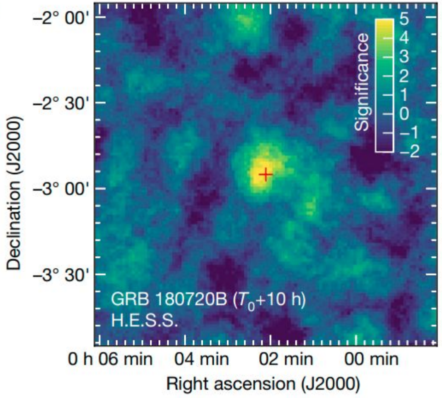
- Swift XRT: 2nd bright ever observed (0.3 - 10 keV).
- T_{90} = 48.9 s (long GRB)
- Fermi GBM: 7th brightest.

Fermi LAT

- 5 GeV is the maximum photon energy detected by Fermi LAT during the first 10 mins.
- Then there was no emission detected by LAT in 100 MeV - 100 GeV after 10 mins

H.E.S.S.

- Observed afterglow for two hours.
- **100 - 440 GeV**
- 5.3 σ detection in VHE domain for the very first time.



Significance map of GRB180720B observed by H.E.S.S.
(credit:nature)

Swift XRT

- Afterglow is observed for ~30 days in the energies < 10 keV

long burst ⇒ $T_{90} > 2$ s

GRB 190114C

z = 0.425

14 Jan 2019
20:57 UT (T_0)

T_0+ 57 s

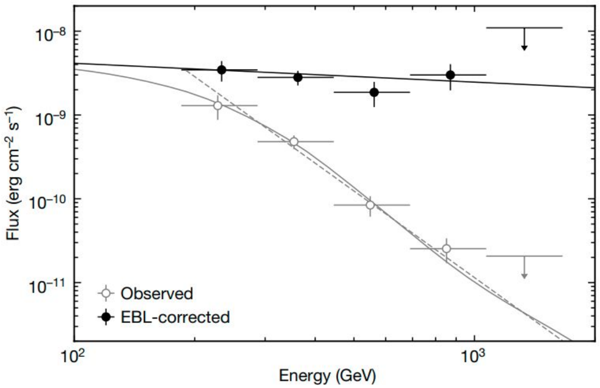
T_0+ 4.5 h

Swift BAT
Fermi GBM

- Swift-BAT :
  T_{90} = 362 s
- Fermi-GBM :
  T_{90} = 116 s
  (long GRB)

MAGIC

- Observing early stage of the afterglow emission in < 1 TeV for the first time.
- For first 20 mins, detected gamma-rays > 200 GeV with 50σ significance.



Spectrum observed by MAGIC during T_0+ 62 sec to T_0+ 41 mins
The plot also demonstrates the effect of EBL absorption.
(credit:nature)

MAGIC

- The most luminous object in the energy 0.3 - 1 TeV.

long burst ⇒ $T_{90} > 2$ s