Study of astrophysical transients with the MAGIC telescopes

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Astro-Particle Physics mini-workshop@MPP

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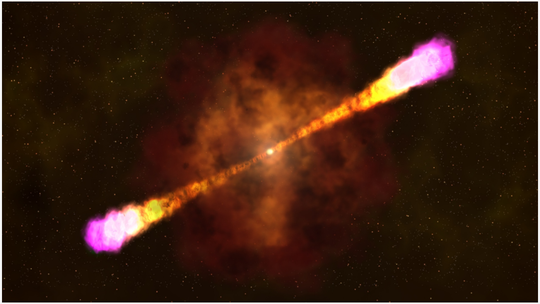
Outline

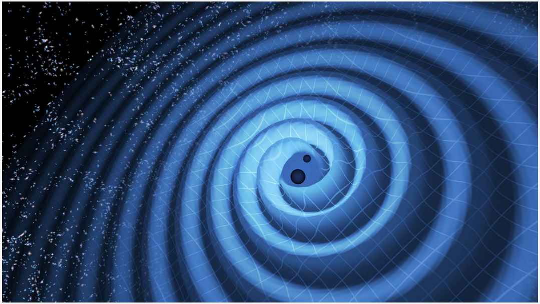
Transient sources

- Transients: explosive or flaring episodes
- They are, most of times, unpredictable
- Nonetheless, their study gives information about the sources producing them
- In my thesis, two transients classes were considered:

Gamma-Ray Bursts (GRBs)



Gravitational Waves (GWs)



The MAGIC stereoscopic system

- MAGIC = *Major Atmospheric Gamma-ray Imaging Cherenkov*
- Two Cherenkov telescopes of 17 m diameter in La Palma, Canary Island
- Indirect detection of gamma-rays from $\sim$50 GeV to few TeV (Very High Energies, VHE)
- Field of view: 3.5°
- Energy threshold is 50 GeV at trigger level
- Sensitivity: $\lesssim 0.7\%$ Crab Nebula flux above 220 GeV ($\sim 2 \times 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) in 50 h
- Fast repositioning for transient: few tens of seconds

Short introduction to Gamma-Ray Bursts

Spatial properties

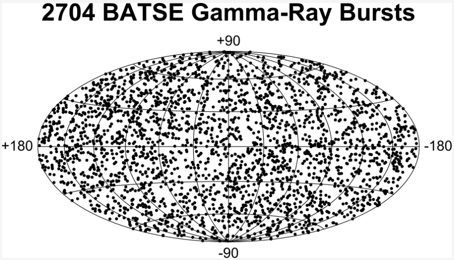
Isotropically distributed
Cosmological sources

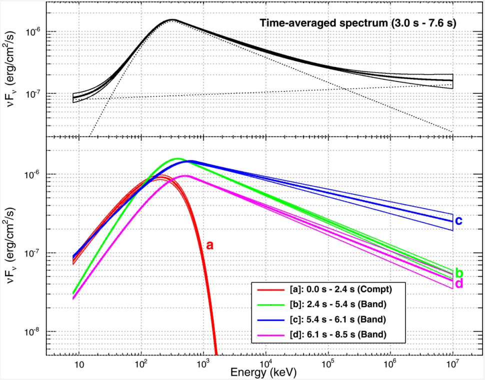
Emission properties

Non-thermal spectrum
Prompt: bulk emission in hard-X, γ bands; duration: ms $\rightarrow \mathcal{O}(10^2)$s
Afterglow: fainter emission, visible in other bands (UV, IR, optical, radio, X); lasts from hours to days to months
$E_{\mathrm{iso}} \sim 10^{42}$-$10^{48}$ J ($\sim M_{\odot} c^2$)

Temporal properties

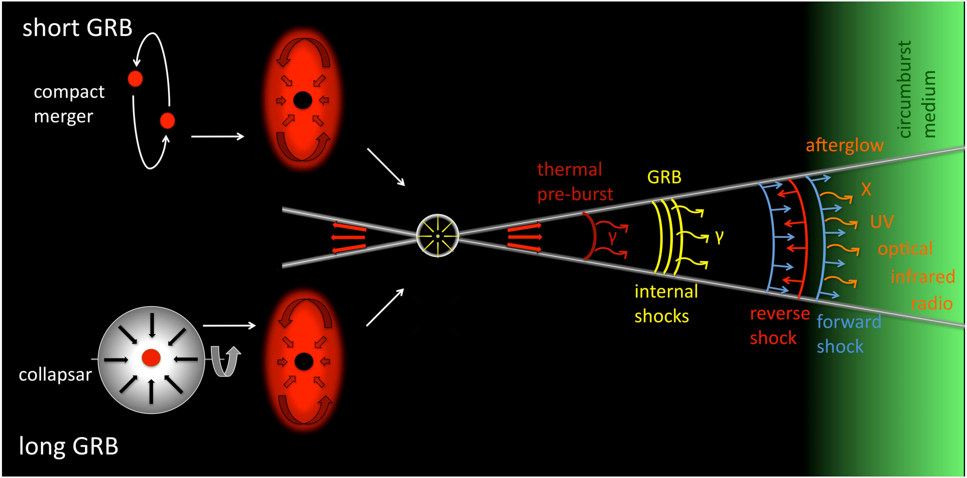
short GRBs: $T_{90} < 2$ s
long GRBs: $T_{90} > 2$ s





Fireball model and progenitors of GRBs

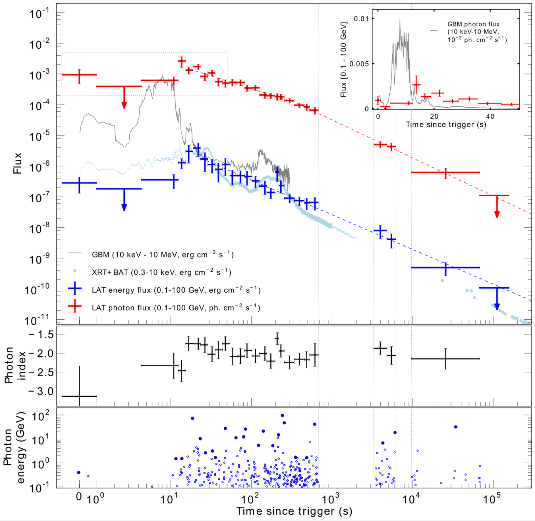
Progenitor: object(s) before GRB explosion
Fireball model: explains GRBs emission as internal/external shocks



Feautures of High Energy (HE) emission from GRBs

Most of the information about HE (up to $\sim$ 100 GeV) emission by GRBs comes from *Fermi* satellite (LAT+GBM), but also AGILE

- GBM rate: $\sim 250\,\mathrm{yr}^{-1}$; $\sim 4-5\%$ detected also by LAT at $E > 100$ MeV
- $\sim$ half of LAT detected GRBs has > 1 GeV photons (rate: $\sim 5\,\mathrm{yr}^{-1}$)
- Highest energy photon from GRB130427A: 94 GeV
- HE emission extended in time
- HE emission is delayed
- GeV emission decays as t^{-1} (at least for late times)
- Extra spectral component for the prompt phase



HE/VHE models

Plethora of models... (see for example Fan & Piran 2009)

External-shock models

- Inverse Compton by electrons
- Synchrotron by protons
- Photo-meson cascade emission
- Self-Synchrotron Compton (SSC)

Internal-shock models

- SSC
- Inverse Compton
- Hadronic models
- Cascade emission from p-n collisions

- Fermi has a limited statistic in the few tens of GeV range
- Most of the previous model have a signature beyond this energy
- Sensitivity of Fermi at hundreds GeV is low
- IACT like MAGIC are most suitable in this energy range
- Find out process at play in HE band by detecting GRBs in VHE band

GRB follow-up by MAGIC

Gamma-ray Coordinates Network (GCN)

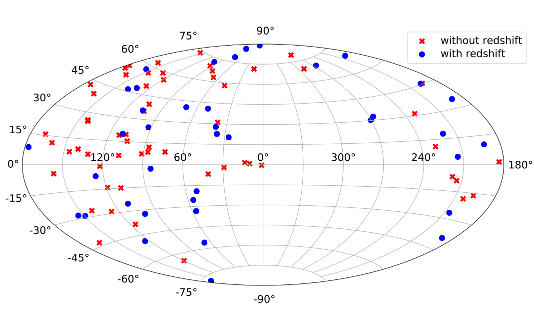
- GRBs are serendipitous sources and MAGIC has a small FoV
- An external trigger is needed
- The GCN disseminates GRB triggers

Fast follow-up

- Fast (automated) processing of alerts
- If observable, fast repointing
- New procedure since 2013

Follow-up numbers

Since 2005, 94 GRBs observed in good conditions



GRB analysis with MAGIC

List of GRBs considered in my thesis

GRB	Satellite	T_{90}	Redshift	Zenith	Condition	Delay
GRB130504A	Swift	50	-	56-45	Dark, dim-moon	455
GRB130606A	Swift	276.58	5.913	46.1	Dark	634
GRB130701A	Swift	4.4	1.155	27-16	Moderate moon	60
GRB130903A	INTEGRAL	69	-	51-63	Dark	11412
GRB140430A	Swift	173.6	1.60	45-54	Dark	1110
GRB140709A	Swift	98.6	-	25-37	Dark	7414
GRB141026A	Swift	146	3.35	10-50	Low T_{9km}	151
GRB141220A	Swift	7.21	1.32	29-19	Dark	55
GRB150213A	Fermi	4.1	-	44-60.5	Dark	86
GRB150819A	Swift	52.1	-	40-60	Dark	4888
GRB151118A	Swift	23.4	-	40-58	Dark	54
GRB151215A	Swift	17.8	2.59	15-59	Dark	30

Is there VHE emission from any of them?

GRB nomenclature: GRB YYMMDD + a letter if more than one is detected on the same day

GRB analysis results

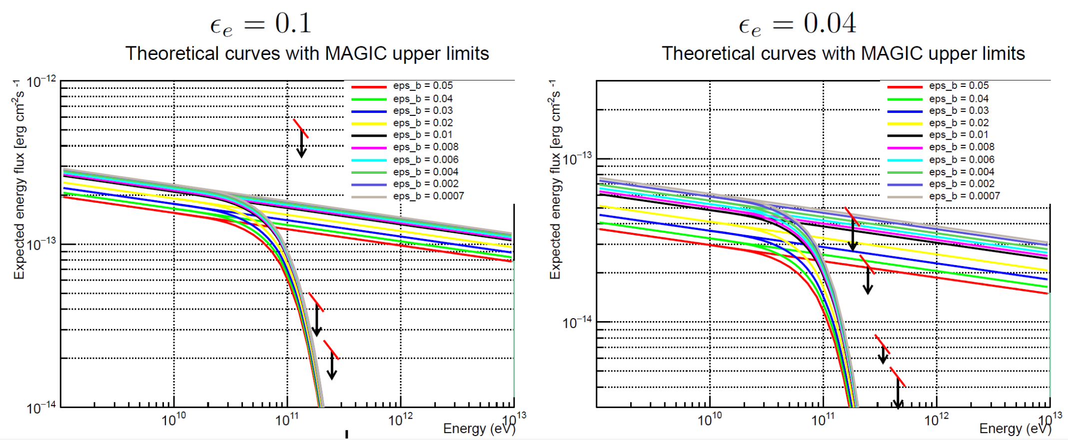
- None of the GRB analyzed show VHE signal
- Only upper limits (95% C.L) could be derived for the flux (integral and differential)
- Upper limits were computed with the Rolke method, assuming 30% systematic on the efficiency of cuts

GRB	Significance [σ]	E_{thr} [GeV]	UL [$cm^{-2}\,s^{-1}$]
GRB130504A	-0.79	187	7.04e-12
GRB130606A	-1.03	80	1.99e-11
GRB130701A	+0.03	100	2.99e-11
GRB130903A	-0.73	281	1.04e-11
GRB140430A	-0.92	188	1.46e-11
GRB140709A	+0.65	92	6.17e-11
GRB141026A	-2.07	110	3.44e-11
GRB141220A	+2.10	77	4.74e-11
GRB150213A	+0.17	203	8.26e-12
GRB150819A	+0.57	175	3.17e-11
GRB151118A	-0.26	170	9.08e-12
GRB151215A	+0.66	90	3.24e-11

GRB emission modeling and comparison

- SSC is one of the most popular emission mechanisms for GRBs HE/VHE emission (e.g. Sari & Esin 2001 or Zhang & Meszaros 2001)

GRB160509A (z=1.17) observed on May 13th

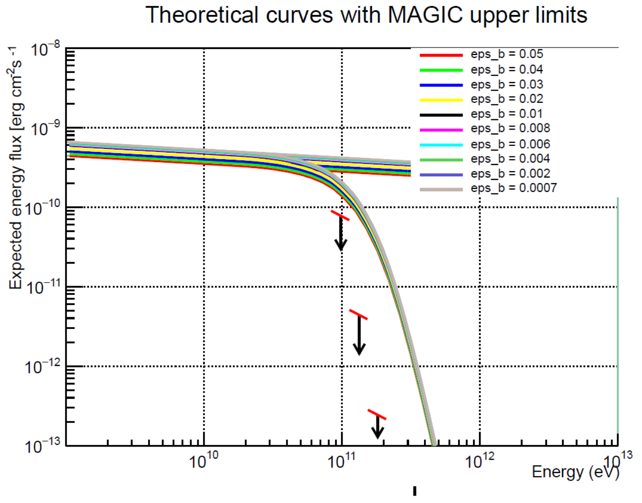


Credit: Davide Miceli (UniTs)

GRB emission modeling and comparison

- What if the delay is lower?

Example: one minute delay ($\epsilon_e = 0.1$)



Credit: Davide Miceli (UniTs)

GRBs: summary

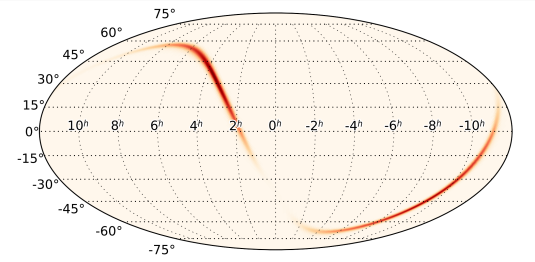
- GRBs emission in the HE/VHE range is not well understood
- I searched for a gamma-ray signal in a sample of GRBs observed by MAGIC
- None of them showed any hint of signal
- Upper limits (integral and differential) were derived
- EBL absorption for most of them plays a major role, in other observation conditions were not optimal
- A paper is being prepared with all the GRBs observed by MAGIC between 2013 and 2015 (19 in total)

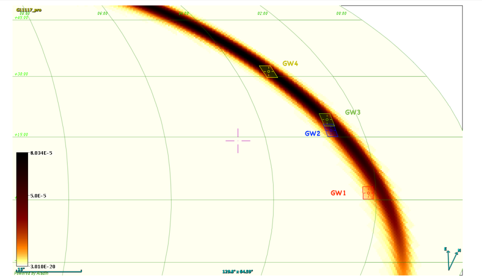
GW emitted by compact mergers

- The detections of GW signals from BBH and BNS systems opened the era of GW astronomy
- Multi-messenger observations (photons, GW, neutrinos, CRs) are fundamental
- The progenitors of short GRBs are thought to be binary systems of NS-NS or NS-BH
- These kind of systems produce GWs that in principle are at reach for LIGO/Virgo
- Kill two birds with one stone: detect GW from such objects and solve the progenitor problem for short GRBs
- How? Detect a temporally and spatially coincident GW-EM signal
- A follow-up of EM observers is crucial! MAGIC is one of them

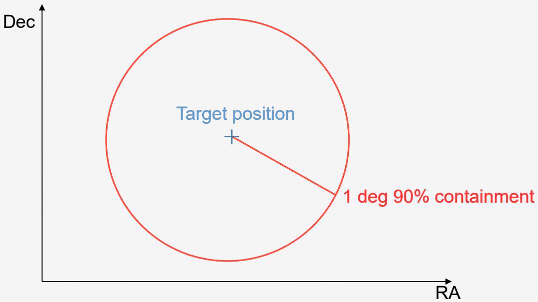
MAGIC follow-up of GW candidate events: GW151226

- After LIGO started its first observation run, MAGIC signed a Memorandum of Understanding in order to perform follow-ups of Gravitational Waves candidate events + proposal within the MAGIC collaboration
- Second GW detection event, GW151226, was observable by MAGIC on 28th of December
- Observation of four targets based on other observatories and probability skymap
- Analysis and cross-check promptly performed, but not enough for this kind of observations $\longrightarrow$ a new analysis tool was created for this kind of situation



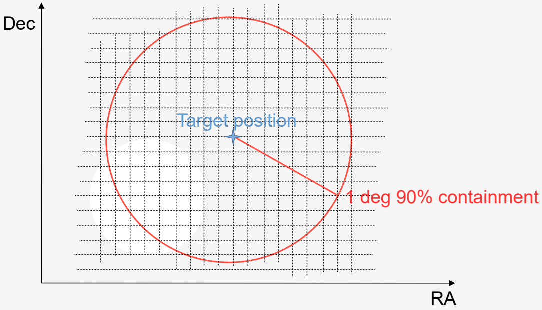


Motivation for a new analysis tool



- MAGIC is involved in follow-up campaigns e.g. LIGO/Virgo GWs events and Ice Cube Neutrino events (HESE tracks)
- Large error in the candidate source position (1° or more)
- Calculation of flux and flux upper limits only on source position is not enough

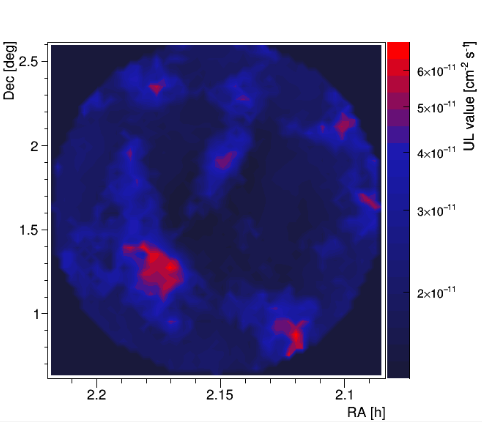
Solution proposed

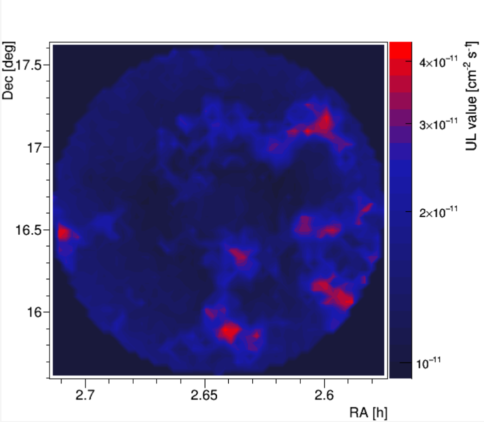


1. Create grid of sky positions around the source
2. Calculate flux and flux upper limit for each grid point
3. Create a binned skymap
4. Pros: uses already existing, well tested and robust programs from MAGIC analysis software
5. Cons: takes a lot of time (depends on number of points and files to be processed)

Tool applied to GW151226 4 pointings

UL skymaps: 1° radius, $E > 150$ GeV
GW1 (left), GW2 (right)

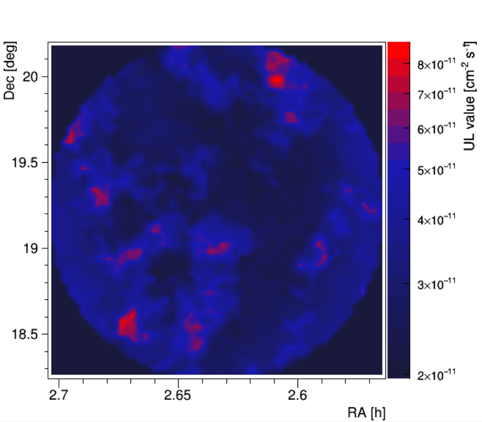


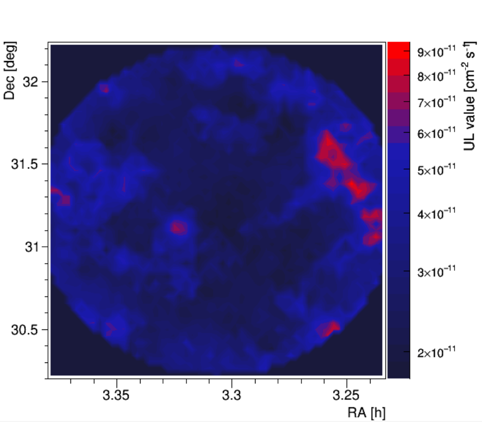


UL are $\lesssim 10\%$ of the Crab Nebula flux above 150 GeV ($\sim 3 \times 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)

Tool applied to GW151226 4 pointings

UL skymaps: 1° radius, $E > 150$ GeV
GW3 (left), GW4 (right)





UL are higher because GW3 and GW4 were observed under moon conditions

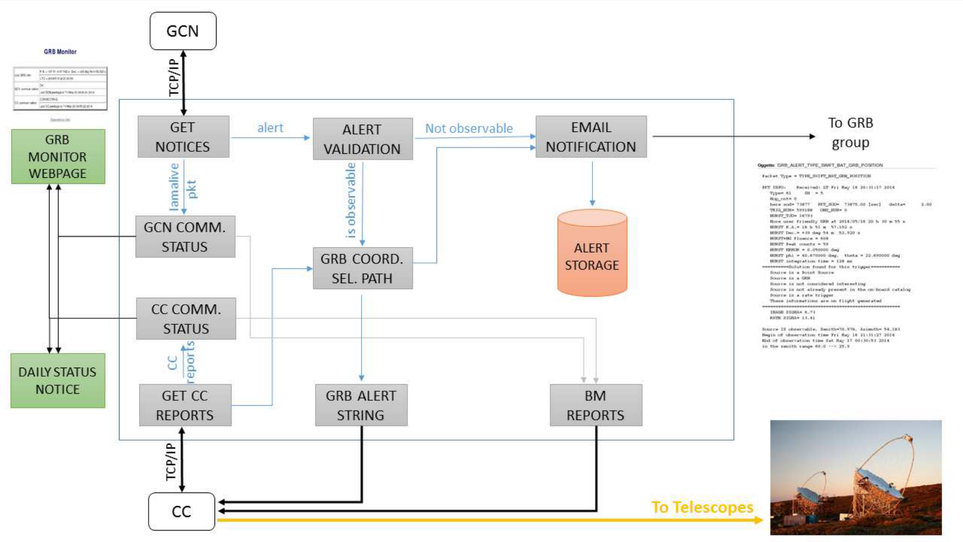
GW follow-up: summary

- MAGIC is one of the electromagnetic observers joining the follow-up of GW candidate events given by LIGO/Virgo
- At the beginning of O1 run, MAGIC followed-up GW151226, with 4 pointings
- A new analysis tool was developed to cope with the large error boxes given by LIGO skymap
- The tool was tested and applied to a known source, the Crab Nebula
- After testing, it was applied to the 4 pointings to produce ULs skymaps
- Data are compatible with background-only hypothesis
- Moreover, it was used also by people of the neutrino working group applying it to neutrino alerts follow-up

Why an automatic system to re-point the telescopes?

- By definition, transients are unpredictable events
- The FoV of a IACT is small (3.5° for MAGIC)
- If a transient source is detected, we should be able to follow-up as soon as possible: therefore the response to alerts should be fast (=automatized)
- Since first light, MAGIC has an automatic system to receive and validate alerts coming from the GCN, named `GSPOT` (Gamma Sources POinting Trigger)

GSPOT work-flow



GSPOT: current situation and wish-list

- GSPOT receives and processes alerts from the GCN
- The alerts are not only for GRBs, but for other transients as well (neutrino, GW, flares)
- For GRB-type alerts, the response is automatic: GSPOT checks the observability and if the target can be pointed within 4 h from the onset it will re-point the telescopes
- For neutrino- and GW-like alerts, no automatic response is implemented yet
- As one of the new GSPOT maintainers (the only one by now), I decided to implement the automatic response to neutrino-like alerts
- Two types of neutrino alerts: High Energy Starting Events (HESE) and Extreme High Energy (EHE)

Why neutrino follow-up?

- Sources of VHE neutrinos are still unknown
- EM follow-up becomes crucial
- Also related to CR production, since neutrinos imply hadronic interactions
- Recent Atel by MAGIC of the detection of a blazar within the error region of a neutrino (EHE-170922)

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845

Tweet Recommend 15

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). 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.

Implementing the automatic response of HESE/EHE alerts

- `GSPOT` needs what we call the *observation strategy*
- Observation strategy = set of constraints to be followed when checking the target observability
- Examples:
  - maximum time of observation from trigger time
  - maximum zenith of observation
  - minimum distance from Moon
  - other constraints on target parameters

The proposed *neutrino observation strategy*:

- Sun zenith $> 103^\circ$
- Max observation time: 3 h from T_0
- Target max zenith angle: 50°
- Minimum distance from Moon: 30°

Testing the implementation

- After having implemented the observation strategy in `GSPOT` code, I tested (offline) the implementation
- To test `GSPOT` offline i.e. a local copy on my laptop, a tool called *gcnsim* is available
- *gcnsim* fakes the GCN server and lets the user to send fake alerts to `GSPOT`
- Goal of the test(s):
  1. implement HESE/EHE alerts in *gcnsim*
  2. check if `GSPOT` follows the neutrino observation strategy

Example of a test

Performed during the night of the 2017-07-14. The table shows the settings for the alert.

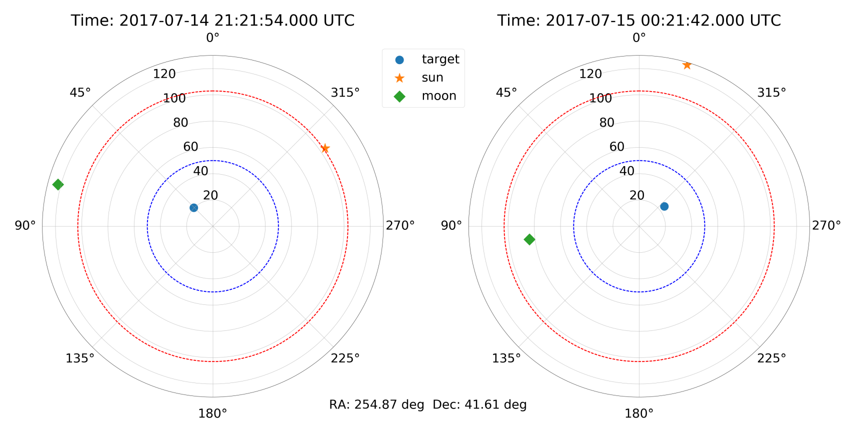
PKT_TYPE	PKT_SOD [s]	PKT_TIME [UTC]	BURST_SOD [s]	T_0 [UTC]	AZ [°]	ZD [°]
HESE	76914	21:21:54	76904	21:21:44	45.6	20.3

Since at the time the alert was sent it was already dark night ($zd_{sun} > 103°$), the expectation was that the target should be promptly observable, so that the starting observation time is the same as PKT_TIME, while the end observation time should be just $T_0 + 3\,h = 00{:}21{:}44$ UTC

Results of the tests

$t_{begin,exp}$ UTC	$t_{begin,GSPOT}$ UTC	$t_{end,exp}$ UTC	$t_{end,GSPOT}$ UTC	Observable?
21:21:54	21:21:54	00:21:44	00:21:42	Yes

Why discrepancy between $t_{end,exp}$ and $t_{end,GSPOT}$? Rounding effect and condition checking in while loop, giving 2 seconds offset



Tests on new neutrino automatic procedure: summary

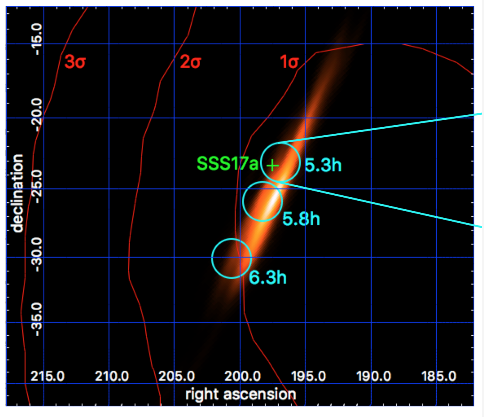
- Tests show that `GSPOT` processes correctly HESE/EHE alerts
- The neutrino observation strategy criteria are followed: the implementation works
- Next is the deployment of the new version of `GSPOT` in the La Palma servers
- Real tests at the MAGIC site are planned after this presentation (I am at the MAGIC site for a shift)

GRBs

- Starting point: automatic procedure works very well
- Delays are as low as few tens of seconds, larger only when observational or weather constraints do not allow immediate follow-up
- Improvement of automatic procedure
- Aiming for lower threshold: Sum Trigger or Topo Trigger
- Hints of detection (GRB160821B): keep trying!

GWs

- Continue follow-up in O3 (late 2018)
- LIGO and Virgo are expected to work together again with better sensitivities
- Large localizations (100-1000 $\deg^2$): follow-up of EM possible/certain counterparts
- Small localizations ($\sim \mathcal{O}(10 \deg^2)$): automatic tiling/scanning with few pointings
- Refine the follow-up strategy using 3D information on distance



Automatic alert system

- Going on with update and maintenance gspot
- Deploying automatic response to neutrino alerts
- Revision of GBM packets interpretation
- Implementation of GW follow-up strategy
- Migration to VOEvents

The future: Cherenkov Telescope Array (CTA)

CTA North

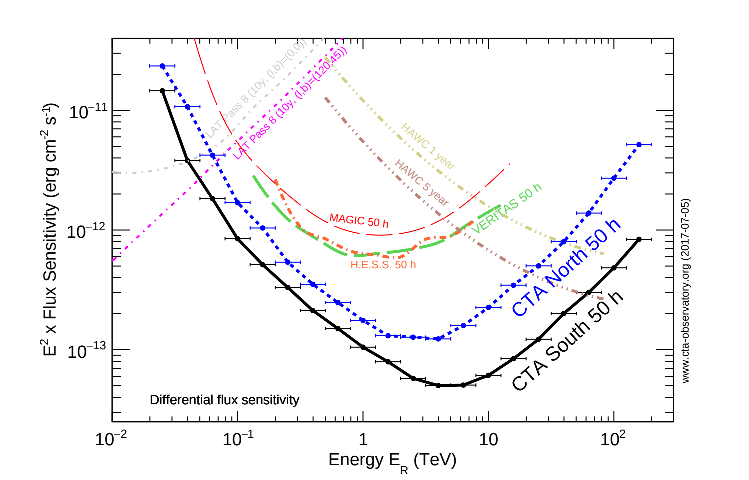
- 4 Large Size Telescopes (LSTs)
- 15 Medium Size Telescopes (MSTs)

CTA South

- 4 Large Size Telescopes (LSTs)
- 25 Medium Size Telescopes (MSTs)
- 70 Small Size Telescopes (SSTs)

The future: Cherenkov Telescope Array (CTA)

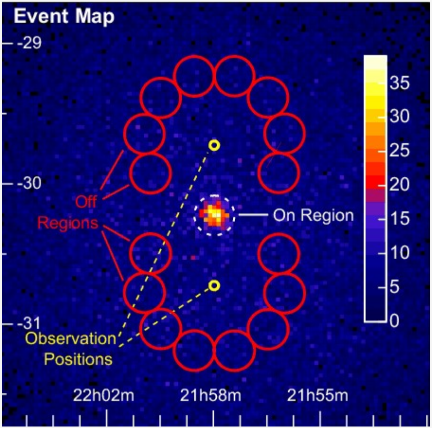
- First LST is being built in La Palma (`https://www.cta-observatory.org/about/array-locations/la-palma/`)
- Lower energy threshold $\sim 20\,\text{GeV}$, high sensitivity at low energies and fast repositioning ($< 20\,\text{s}$!): key-instrument for transients follow-up
- The idea is to continue my research activity on transients also with CTA-LST

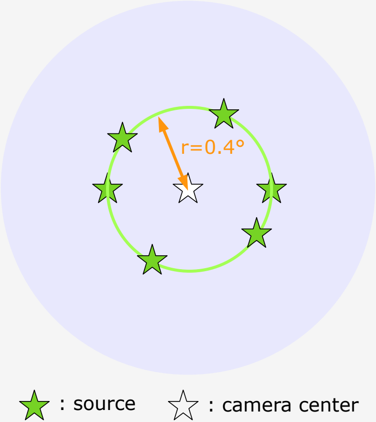


Backup

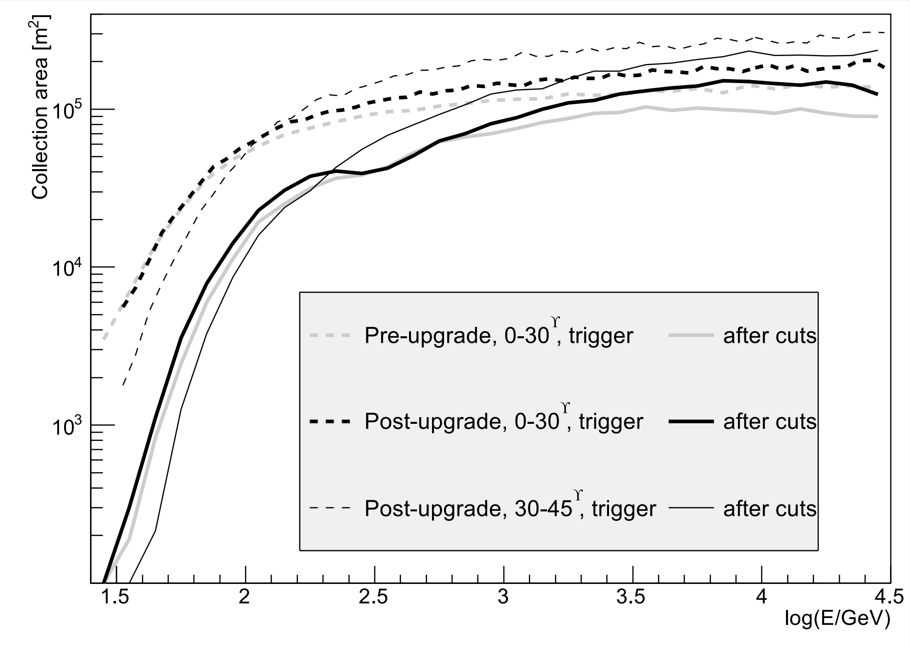
MAGIC pointing mode: wobble

- MAGIC (and other IACT) use the so-called *wobble* pointing mode
- The source is not pointed directly but a position with a certain offset is observed (*false-source tracking*)
- Both signal and background events (cosmic rays) are recorded at the same time

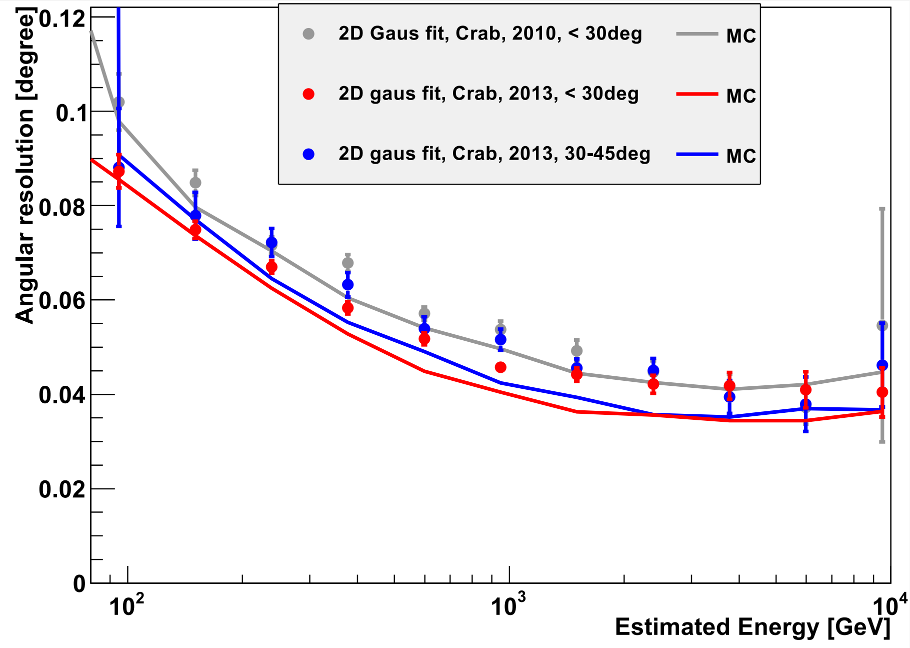




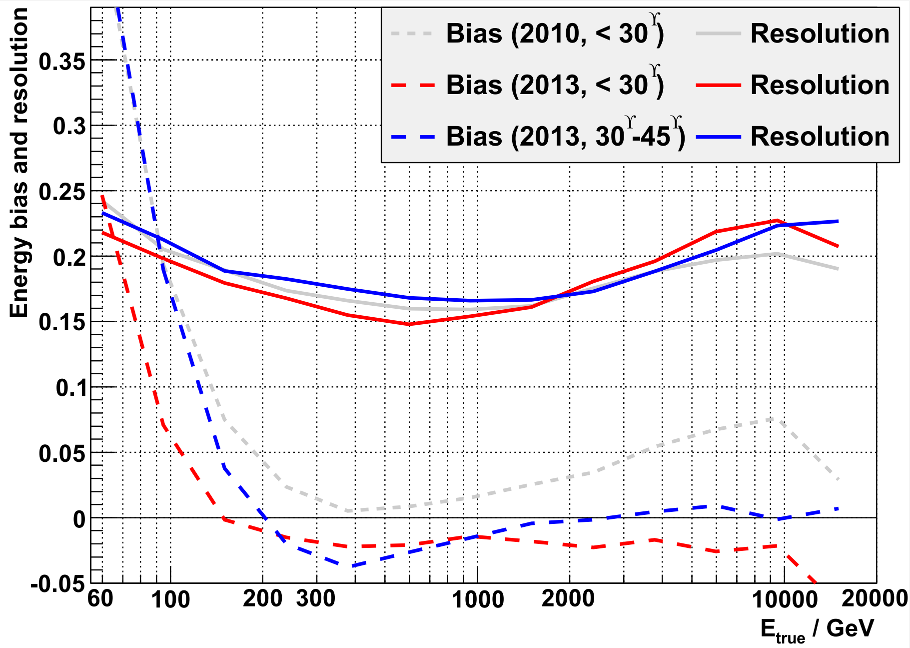
MAGIC effective area



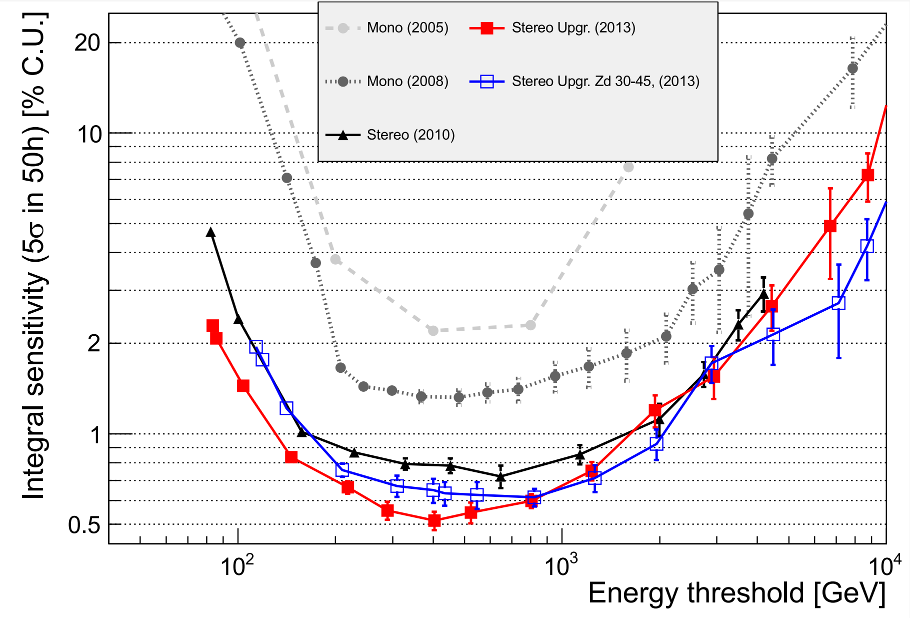
MAGIC angular resolution



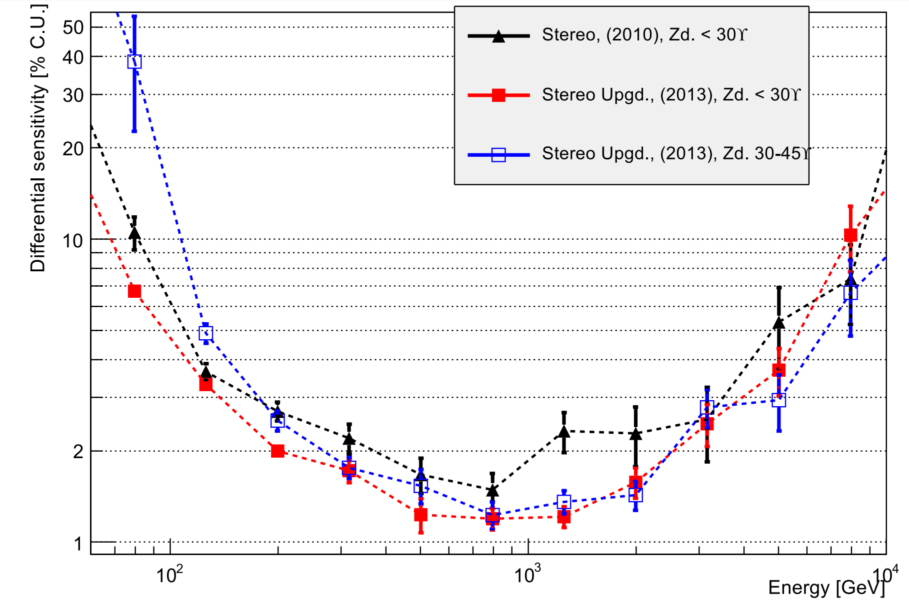
MAGIC energy resolution



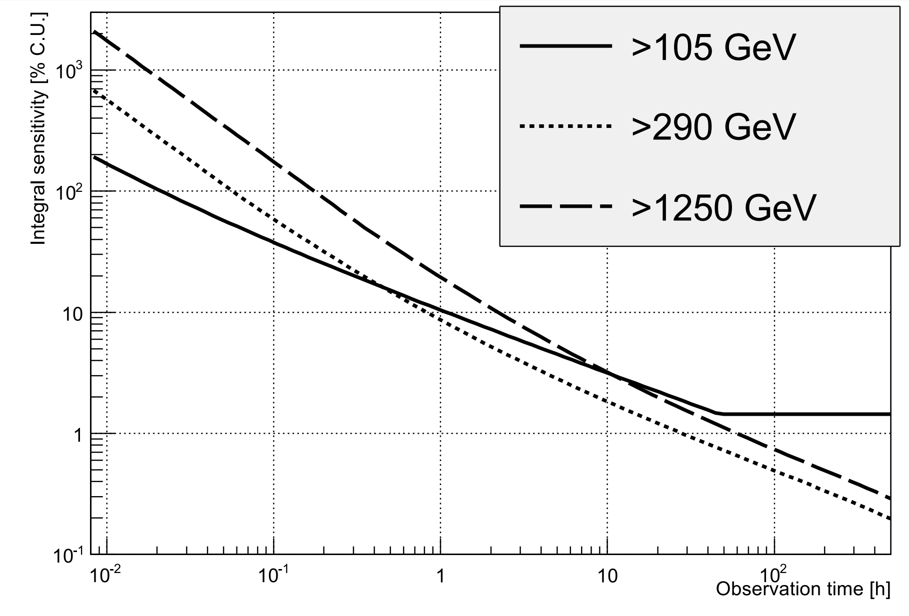
MAGIC integral sensitivity



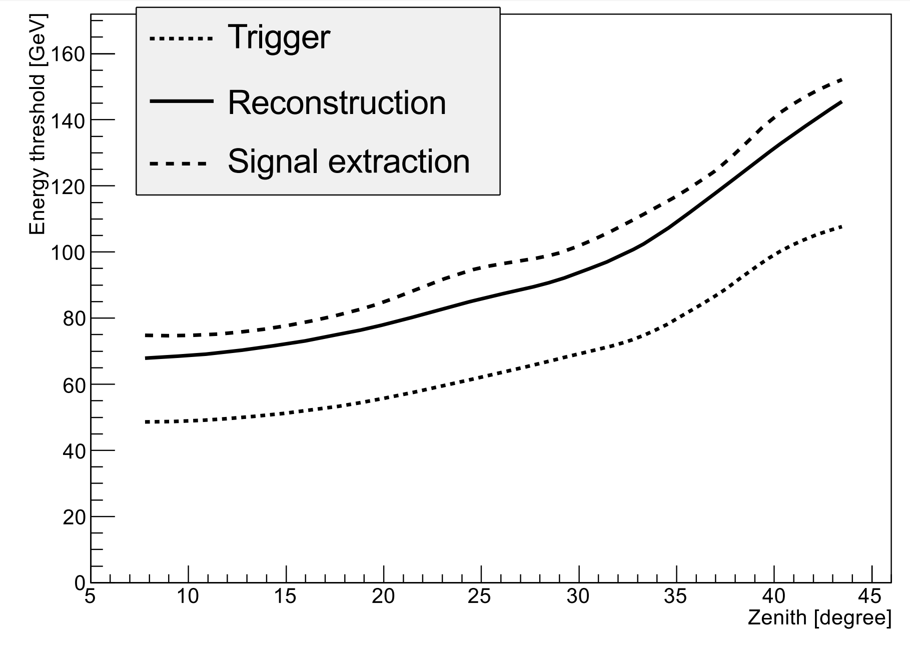
MAGIC differential sensitivity



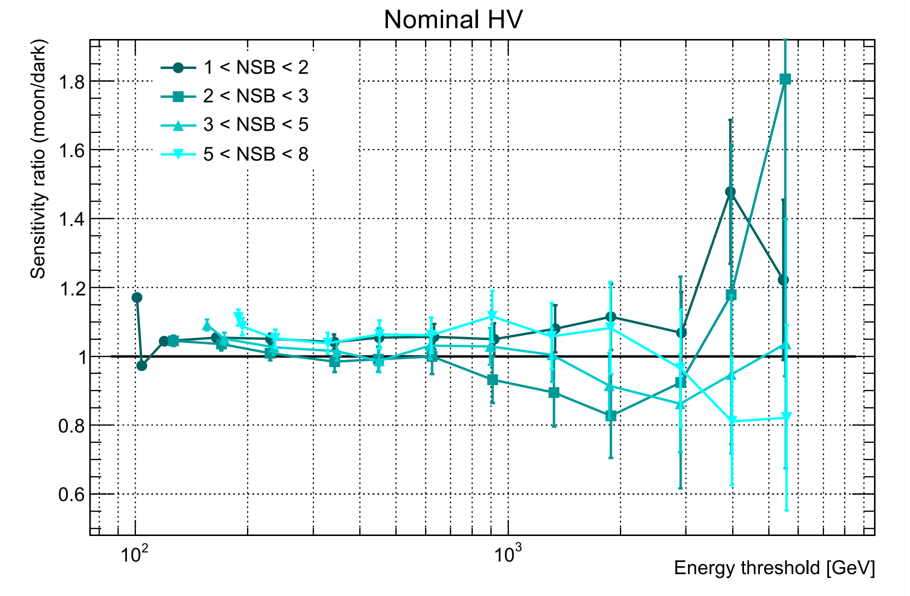
MAGIC sensitivity vs time



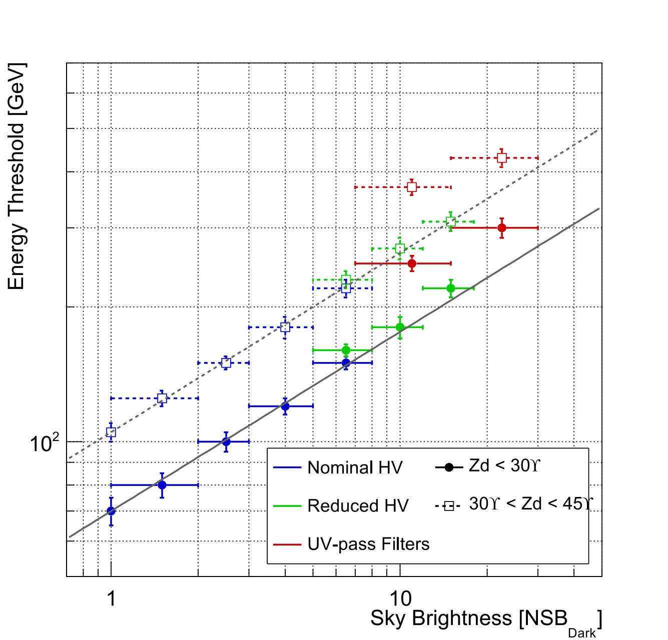
MAGIC energy threshold vs zenith angle



MAGIC Sensitivity Moon



MAGIC energy threshold Moon

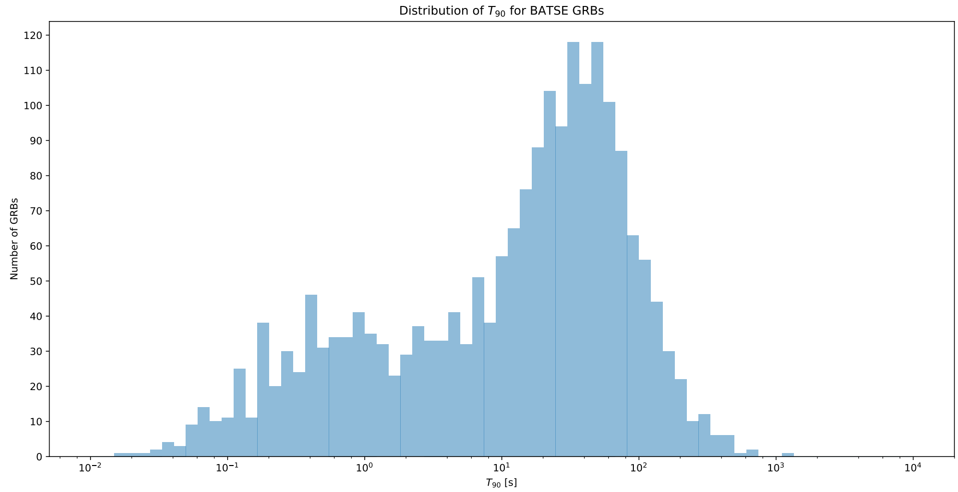


Significance

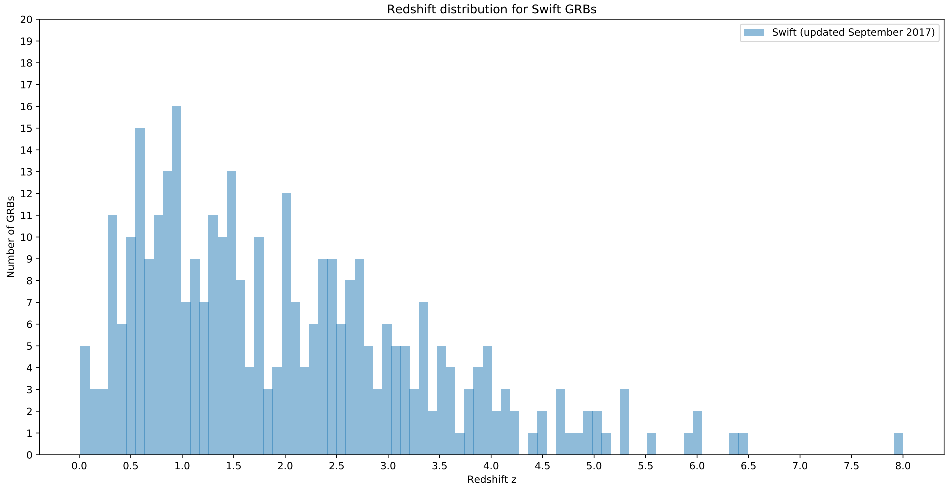
Li&Ma formula (based on a full maximum likelihood treatment)

$$S = \sqrt{2}\left\{N_{\text{on}}\log\left[(1+\tau)\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right] + N_{\text{off}}\log\left[\left(\frac{1+\tau}{\tau}\right)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]\right\}^{1/2}$$

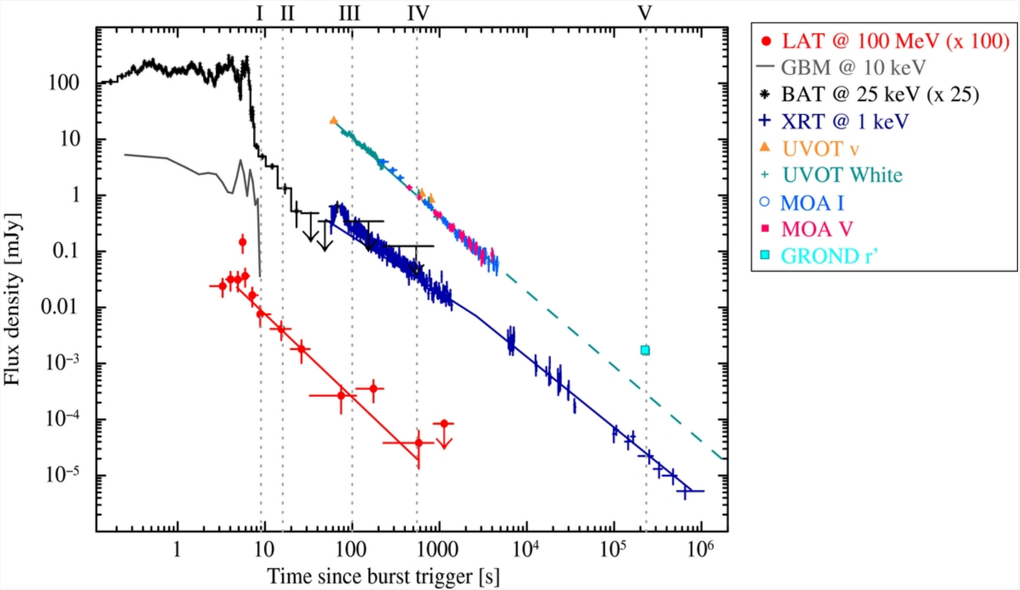
GRB classes: short and long



GRB classes: redshift distribution



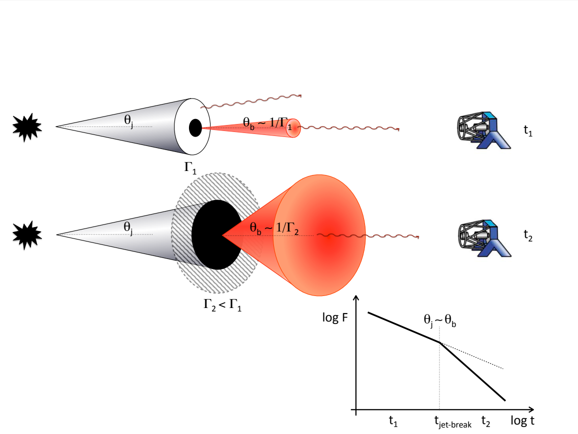
GRB prompt and afterglow



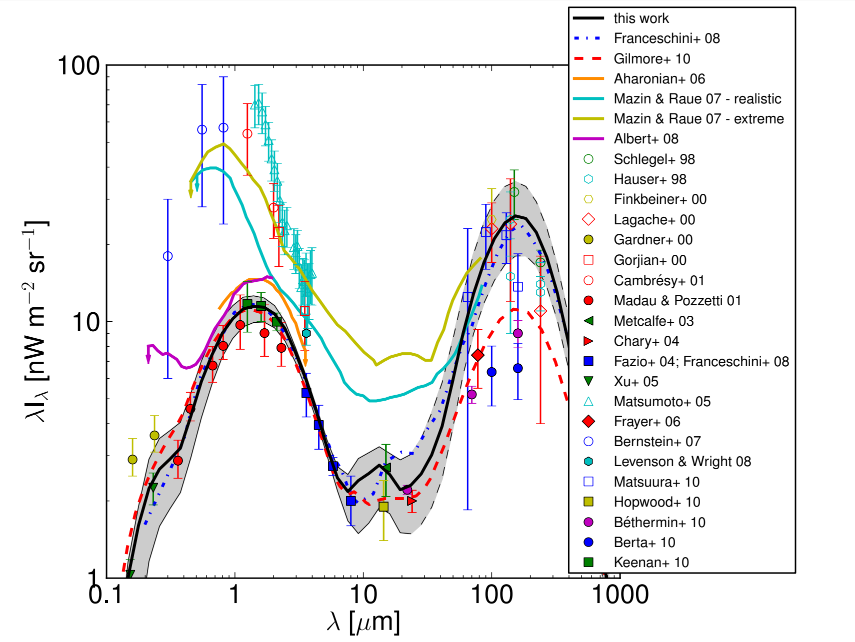
Outflow

- Moving relativistically: $\Gamma \gtrsim 100$
- Collimated

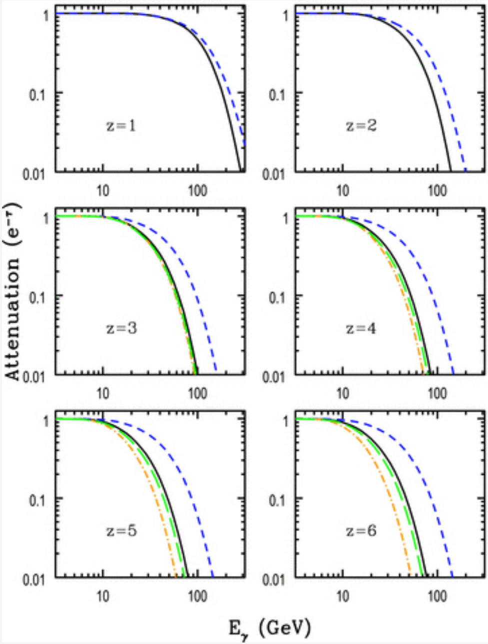
- Without relativistic motion, the spectrum should be non-thermal



EBL spectrum



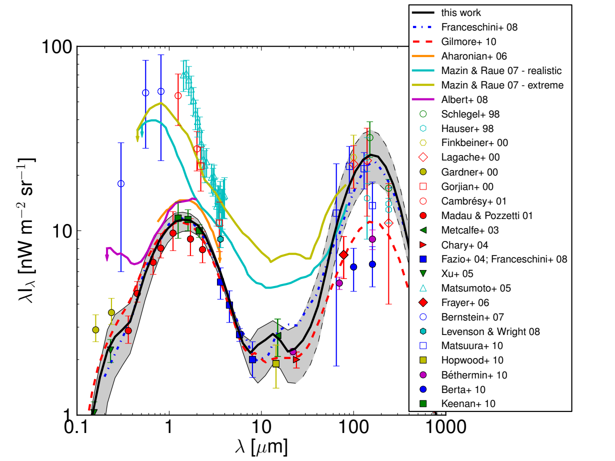
EBL absorption



Extragalactic Background Light (EBL)

- EBL: light (integrated over the whole cosmic evolution period) from all the resolved and unresolved extragalactic sources
- VHE photons interact with EBL photons via the pair production process

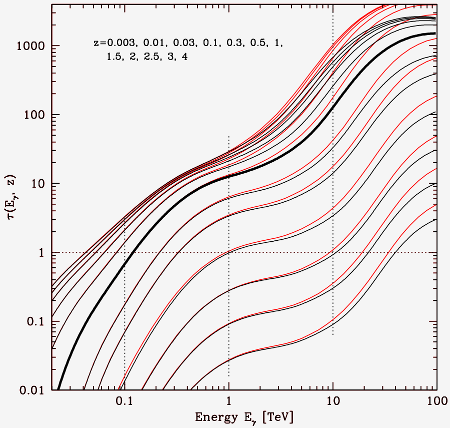
$$\gamma_{\mathrm{EBL}} + \gamma_{\mathrm{VHE}} \rightarrow e^{+} + e^{-} \qquad \epsilon(E) \simeq \left(\frac{900\ \mathrm{GeV}}{E}\right)\ \mathrm{eV}$$



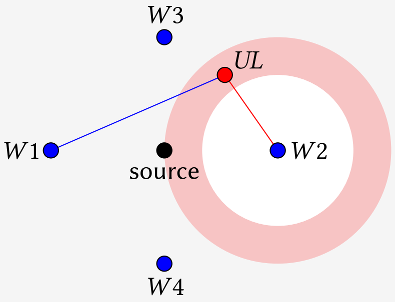
Effect of the EBL on gamma-ray spectra

- Absorption of gamma-rays → spectrum is modified: $\left(\frac{dN}{dE}\right)_{\text{obs}} = \left(\frac{dN}{dE}\right)_{\text{int}} e^{-\tau_{\gamma\gamma}(E_\gamma, z)}$

$$\tau_{\gamma\gamma}(E_0, z_s) = \int_0^{z_s} dz \frac{dl(z)}{dz} \int_{-1}^{1} d(\cos\varphi) \frac{1-\cos\varphi}{2} \int_{\epsilon_{\text{thr}}(E(z),\varphi)}^{\infty} d\epsilon(z)\, n_\gamma(\epsilon(z), z)\sigma_{\gamma\gamma}(\epsilon(z), E(z), \varphi)$$

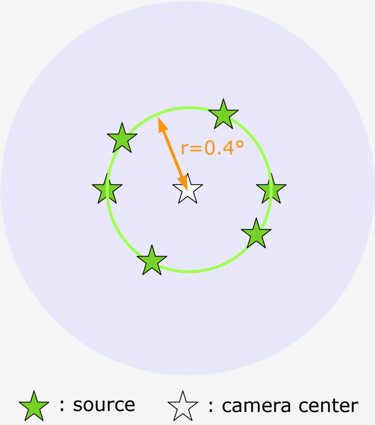


UL calculation with wobble pointing

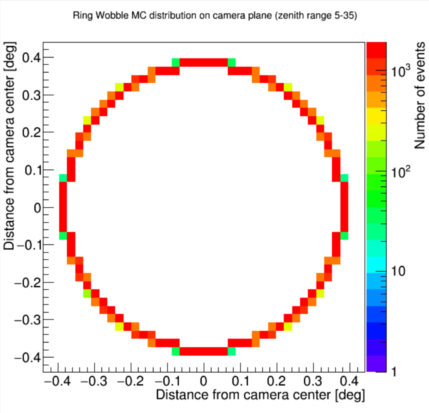


Ring wobble Monte Carlo

MAGIC std observation mode: wobble, 0.4° offset

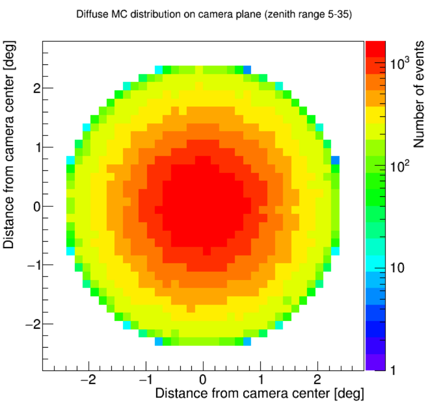


MAGIC std MC: ring-wobble

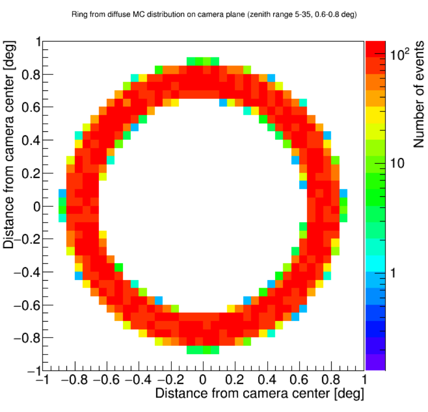


Diffuse Monte Carlo

What if source is observed with a different offset?
Special MC: diffuse

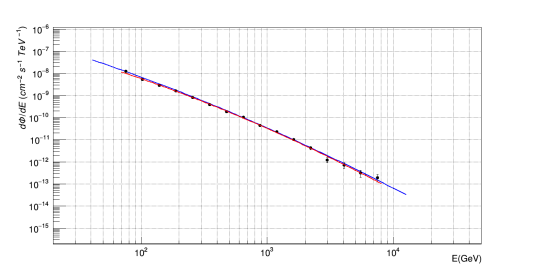


Source observed in wobble mode, 0.7° offset



Crab: reconstruct spectrum at different offsets

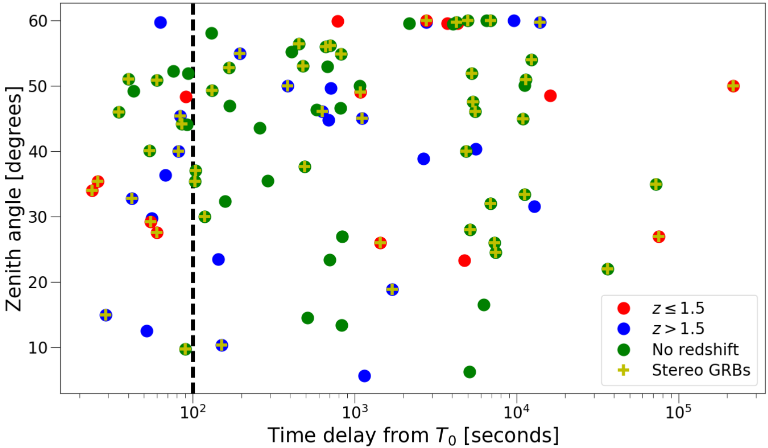
Crab spectrum for 1.0° offset



$$f_0 = (3.22 \pm 0.13) \times 10^{-11}\,\mathrm{cm^{-2}s^{-1}TeV^{-1}}$$
$$a = -2.52 \pm 0.04$$
$$b = -0.27 \pm 0.06$$
$$F(>100\,\mathrm{GeV}) = 4.94 \times 10^{-10}\,\mathrm{cm^{-2}\,s^{-1}}$$

- Goal of the test is to see if it the CrabNebula spectrum is well reconstructed by the tool
- Crab data taken with three wobble offsets: 0.4° (standard one), 0.7° and 1.0°
- The first test was to run our scripts to create a small 3×3 grid and focus on the grid point centered on Crab
- The fit for $E > 64$ GeV using the spectrum in the Performance Paper (PP):
  $$\frac{dN}{dE} = f_0 (E/1\,\mathrm{TeV})^{a+b\log_{10}(E/1\,\mathrm{TeV})}\mathrm{cm^{-2}s^{-1}TeV^{-1}}$$
  $$f_0 = (3.39 \pm 0.09) \times 10^{-11}\,\mathrm{cm^{-2}s^{-1}TeV^{-1}}$$
  $$a = -2.51 \pm 0.02$$
  $$b = -0.21 \pm 0.03$$
  $$F(>100\,\mathrm{GeV}) = 5.52 \times 10^{-10}\,\mathrm{cm^{-2}\,s^{-1}}$$

MAGIC GRBs delay vs zenith



MAGIC GRBs zenith distribution