Multi-messenger searches with MAGIC and LST-1

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Data analysis for Multi-messenger Astrophysics - AHEAD2020

MAGIC and LST-1

- MAGIC and LST-1 are Cherenkov telescopes tailored to the low energies in the very-high-energy gamma-ray band (threshold at tens of GeV)
- MAGIC operates in ORM (Observatorio Roque de Los Muchachos, La Palma, Spain) since 2003 in mono mode, since 2009 in stereoscopic mode
- LST-1 is the first Large-Sized Telescope prototype (out of 4) that will belong to the CTAO Northern Array, which again is at ORM
- Possibility of performing joint observations with the two systems --> increased sensitivity

Follow-up of transients with MAGIC and LST-1

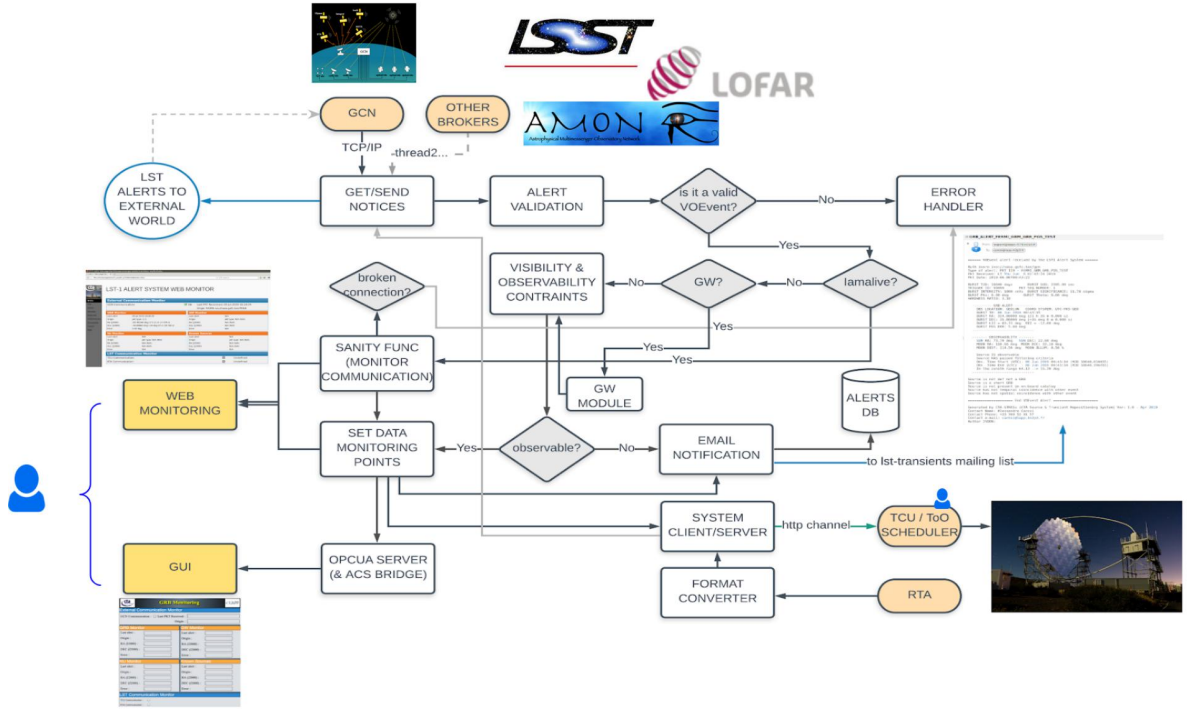
Both MAGIC and LST-1 devote a large fraction of time to the follow-up transient sources

- as an example, ~20% of the time given to proposals with guaranteed observations in MAGIC are proposals dedicated to transient observations (GRBs, GW, neutrinos)
- even if we look for gamma-ray emission, we implicitly or explicitly perform also multi-messenger observations
    - follow-up of gamma-ray bursts (e.g. GW 170817/GRB 170817A)
    - follow-up of GW events by the LVK network
    - follow-up of high energy astrophysical neutrinos by IceCube (and KM3Net in the future)

- Given the peculiarities of IACTs like MAGIC and LST-1 (small FoV, limited duty cycle, possible absorption of the emission, possible large uncertainties in the localization of the events etc.), we need a pipeline that processes the alerts and triggers, when needed, the reaction of the telescope
    - in general, we call this a “transient handler”

An example of alert system: LST-1

- Processes the alerts from brokers (at the moment GCN ones via Kafka)
  - for GW and other not well-localized sources, tiling via **tilepy** (APJS 274:1, 2024)
- Connected to the LST-1 Telescope Control Unit (TCU) --> triggers automatic observations depending on predefined criteria
- MAGIC has a similar system, but at the moment they are still decoupled (also criteria are slightly different)

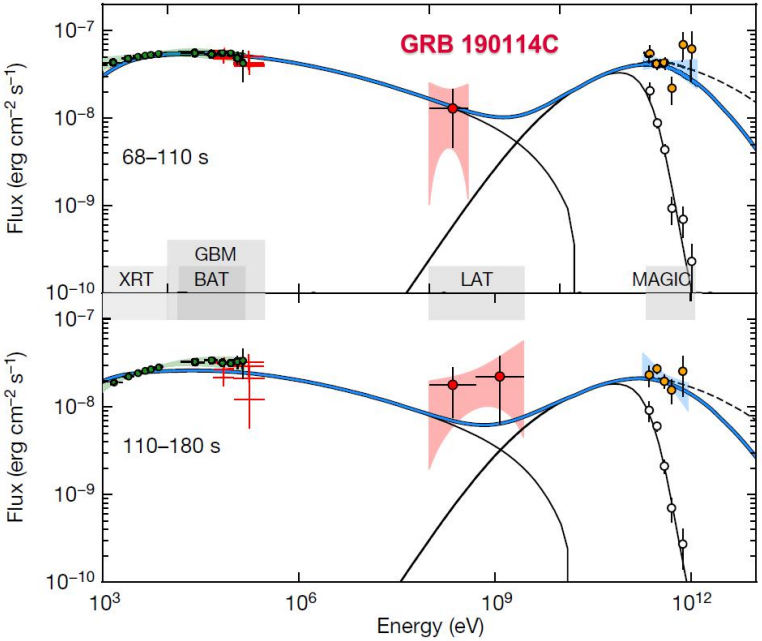


GRBs with MAGIC and LST-1

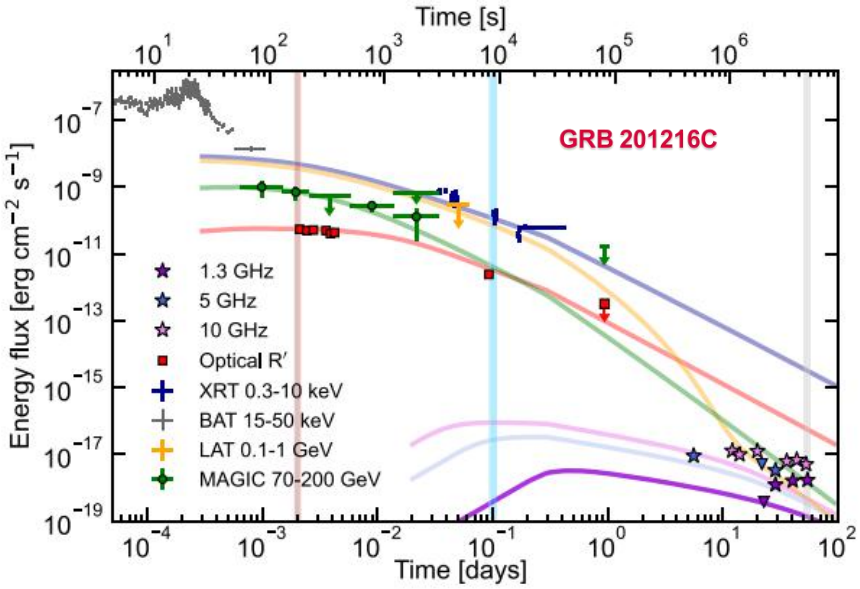
We mainly follow-up well localized GRBs

- Swift-BAT, INTEGRAL, Fermi-LAT
- maximum allowed delay depends from information available (e.g. it has HE emission)
- also follow-up of Fermi-GBM alerts
  - here tiling strategies may be adopted
- plan to follow-up automatically SVOM alerts when they will be distributed via GCN

GRBs at VHE with MAGIC



Nature, 575, 459 (2019)



MNRAS 527, 5856 (2024)

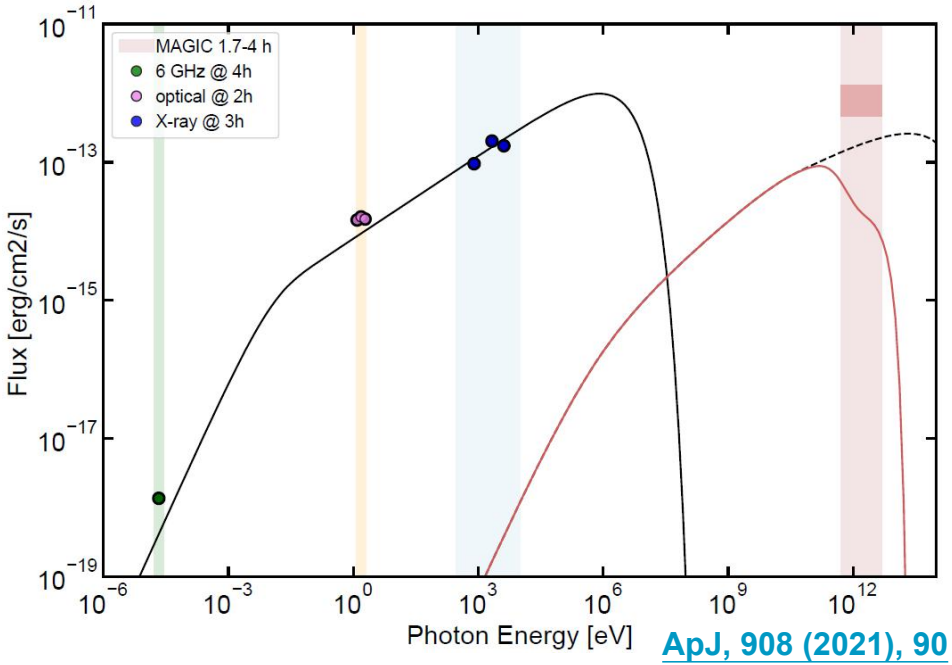
GRBs at VHE with MAGIC: GRB 160821B

- Short GRB at low redshift (z=0.16), fast follow-up by MAGIC (24s)

- Data affected by moon and partially by bad weather
- Hint of detection at 3.1 sigma pre-trial, 2.9 post-trial, the only one from IACT to date

- Kilonova emission confirmed --> progenitor most probably a BNS system
- Simplest emission model (synchrotron + SSC at external forward shock) is in tension with the TeV predicted flux

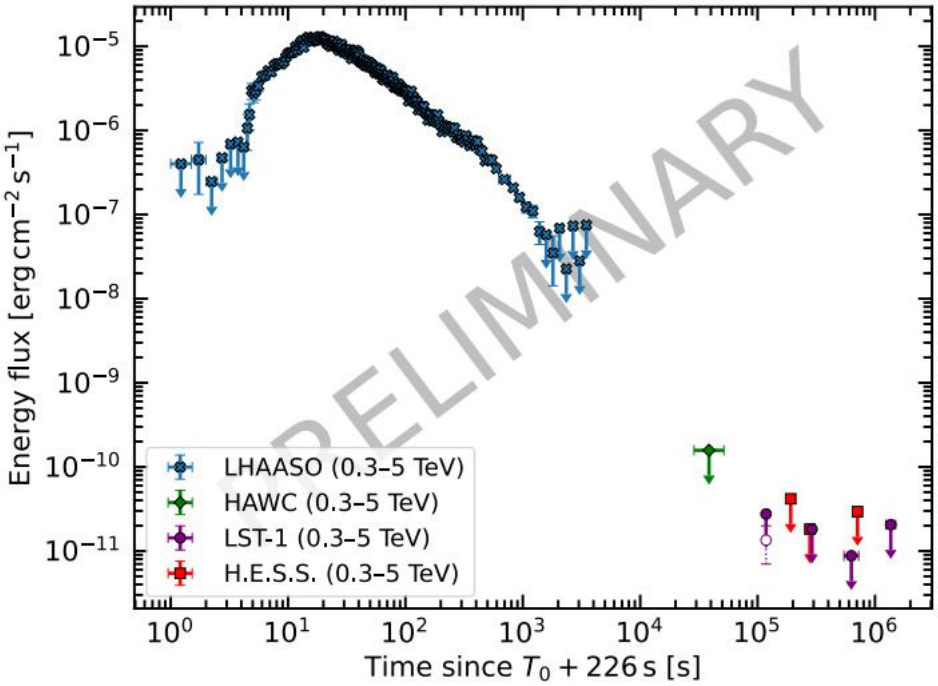
- Exciting perspectives for current and next observational runs



ApJ, 908 (2021), 90

The BOAT: GRB 221009A

- Light curve with LHAASO, HAWC, LST-1 and H.E.S.S.
- LST-1 performed the first follow-up among IACTs, under very strong moonlight
  - hint at ~4 sigma the first day of follow-up (T0+1.33 days)
- LST-1 ULs are ~1 order of magnitude lower than HAWC, and at a similar level as H.E.S.S.



Presented at Gamma 2024
(https://indico.ict.inaf.it/event/2661/contributions/19210/)

GW events with MAGIC and LST-1

The follow-up of GW events poses several challenges

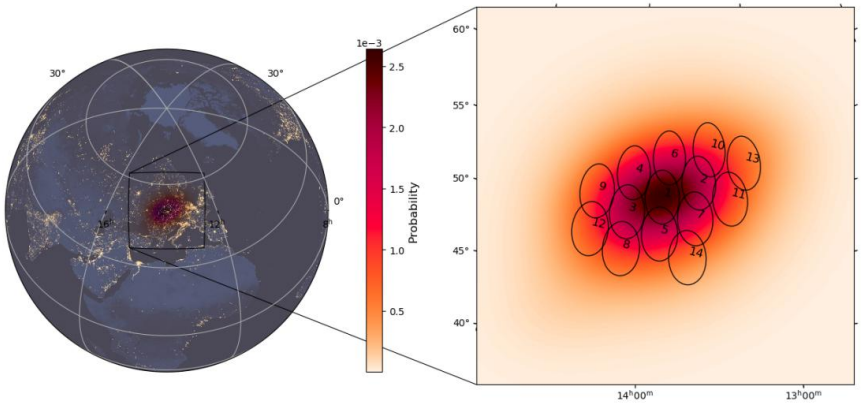
- localization can go from few tens to hundreds/thousands of deg^2, which can be as large as an IACT field of view in the best case scenario --> no clear source

- additional delay introduced to get the signal from interferometers (~few minutes)

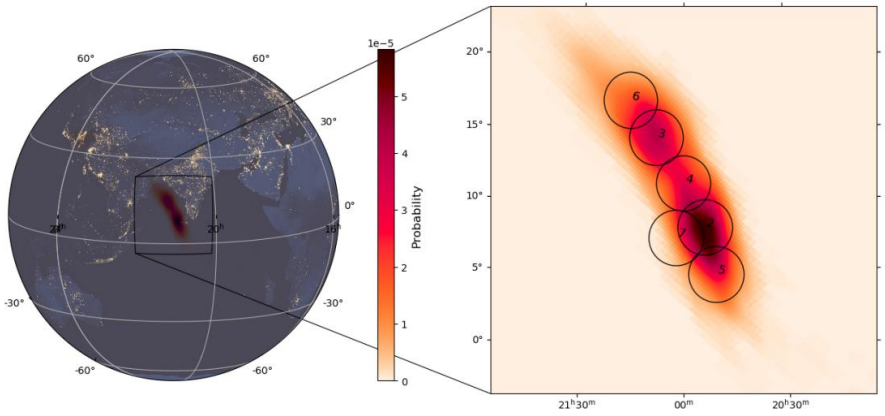
- in the case of BNS systems, the resulting GRBs may be off-axis, thus reducing the incoming flux when the jet “opens up” along the line of sight
    - depending on the viewing angle, this may lead to a very faint GRB prompt (e.g. GRB 170817A), or to orphan afterglows

The only way to cope with all these issues is to devise an observational strategy for the follow up of the EM counterpart of GW events

GW events with LST-1



GRB 200303A by Fermi-GBM

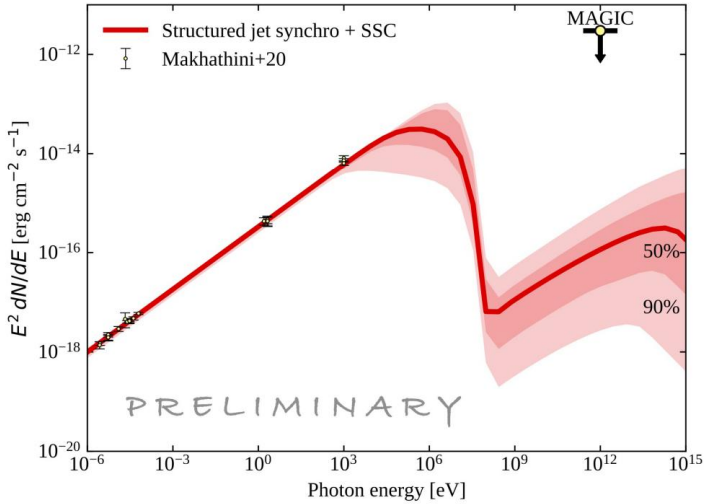


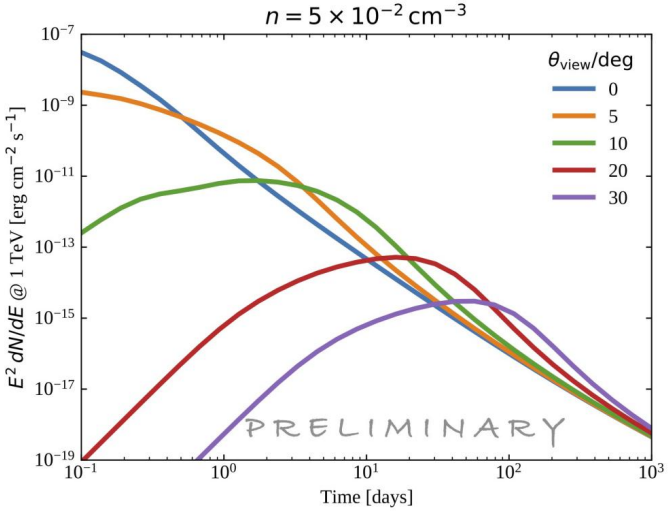
GW190915_235702 by LVC

Since localization is too large, we only consider significant GW events and apply cuts on localization/parameters, then get a list of pointing (software used: tilepy)

- using tools like Astro-COLIBRI to make informed decisions on follow-up strategies
- not only GWs, tiling can be applied also to poorly localized GRBs
- at the moment, MAGIC uses a different tool to get the pointings, but it is also moving to tilepy, which would allow for joint GW observations

GW events with MAGIC: GW 170817





https://pos.sissa.it/395/944/

- MAGIC follow-up of GW170817A
  - at the time of the alert, the EM counterpart was too low on the horizon
  - follow-up ~150 days after merger, but UL not sensitive to constrain possible TeV emission
  - a larger medium density and smaller viewing angle make the emission brighter, and so possibly detectable

Follow-up of neutrino events with MAGIC and LST-1

IceCube is the experiment currently sending neutrino alerts

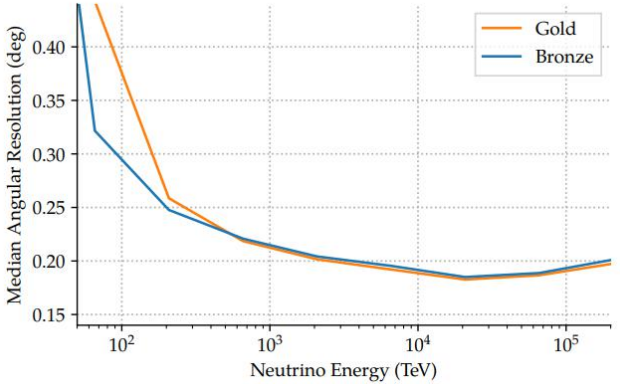
- two public streams
  - GOLD, events having on average 50% probability of being astrophysical
  - BRONZE, events having on average 30% probability of being astrophysical

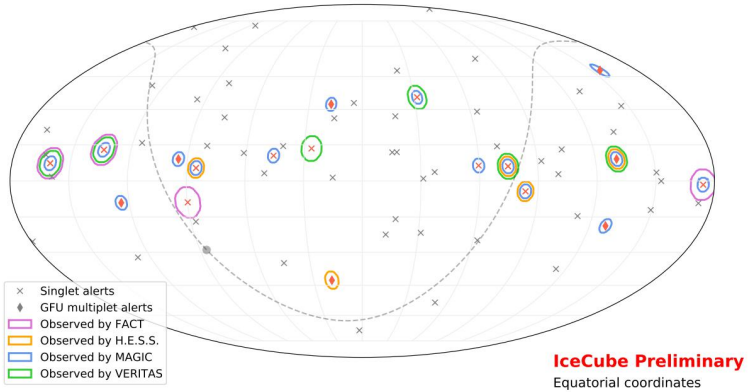
- two private streams (through a memorandum of understanding between interested parties), soon to become public
  - multiplets coming from specific source
  - all-sky multiplets

Both MAGIC and LST-1 follow-up neutrino alerts, with preference on GOLD alerts for the public stream

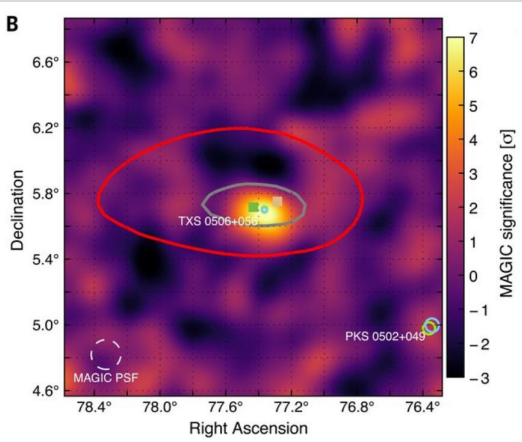
- also follow-up of multiplets alerts

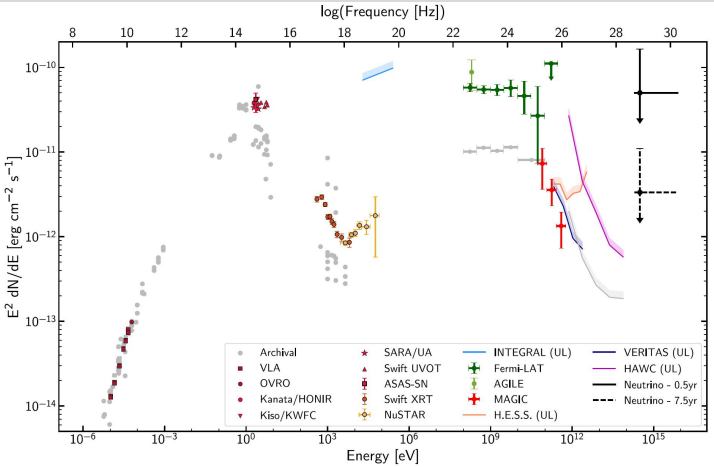
- MoU with KM3Net in the works





Neutrino events with MAGIC: TXS 0506+056

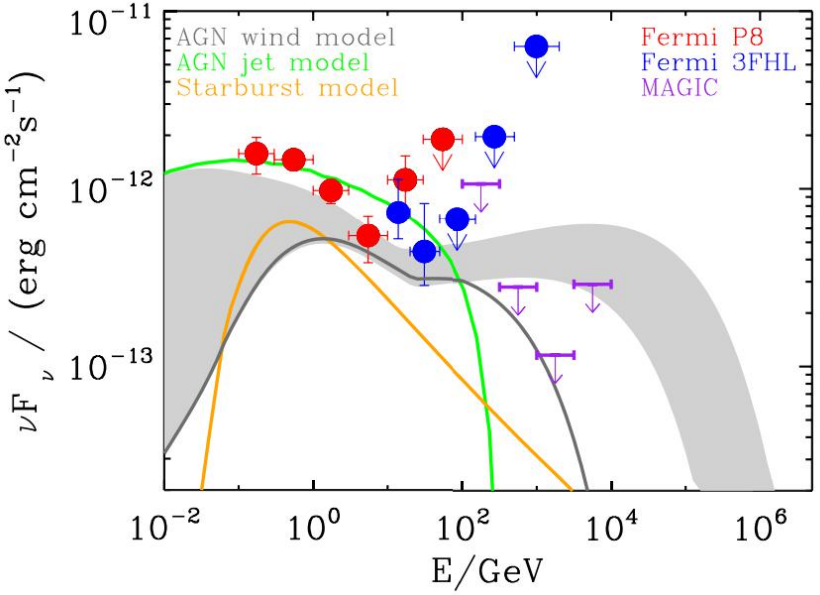




IceCube et al., Science 361, 146 (2018)

- Most famous example: TXS 0506+056, where emission of (V)HE gamma rays was detected by Fermi-LAT, MAGIC and VERITAS
  - chance coincidence of neutrino and flare disfavored at 3sigma level
  - hadronic model is needed to account for the production of neutrinos, and for this acceleration of protons up to UHE is needed --> blazar may be acceleration sites for UHECRs
- But, picture is more complicated...
  - blazar may contribute to only part of the neutrinos
  - sources may be faint in gamma rays
  - other sources may contribute to neutrino flux e.g. tidal disruption events (AT2019dsg)

Neutrino events with MAGIC: NGC 1068



MAGIC Coll. et al., ApJ 883:115 (2019)

An example of gamma-faint source, NGC 1068

- starburst galaxy, already studied quite in depth
- IceCube identified it as a candidate source of high energy neutrinos
- MAGIC observed the source for ~125h, but no detection from the source
- This supports the evidence that different population of sources are responsible for the high energy neutrinos observed by IceCube, and therefore their gamma-ray behavior may also be different

- Despite the non-detection, MAGIC upper limits are quite constraining when it comes to different models for the source emssion

Sharing of observations/results for transient sources

- IACTs collaborations historically are closed, with private data and analysis software

- With CTA closing in, current IACTs are becoming more open and sharing more information
  - for example, started to share datasets in DL3 format (i.e. event list), from the Gamma-ray Astro Data Format (GADF, see https://gamma-astro-data-formats.readthedocs.io/en/v0.3/)

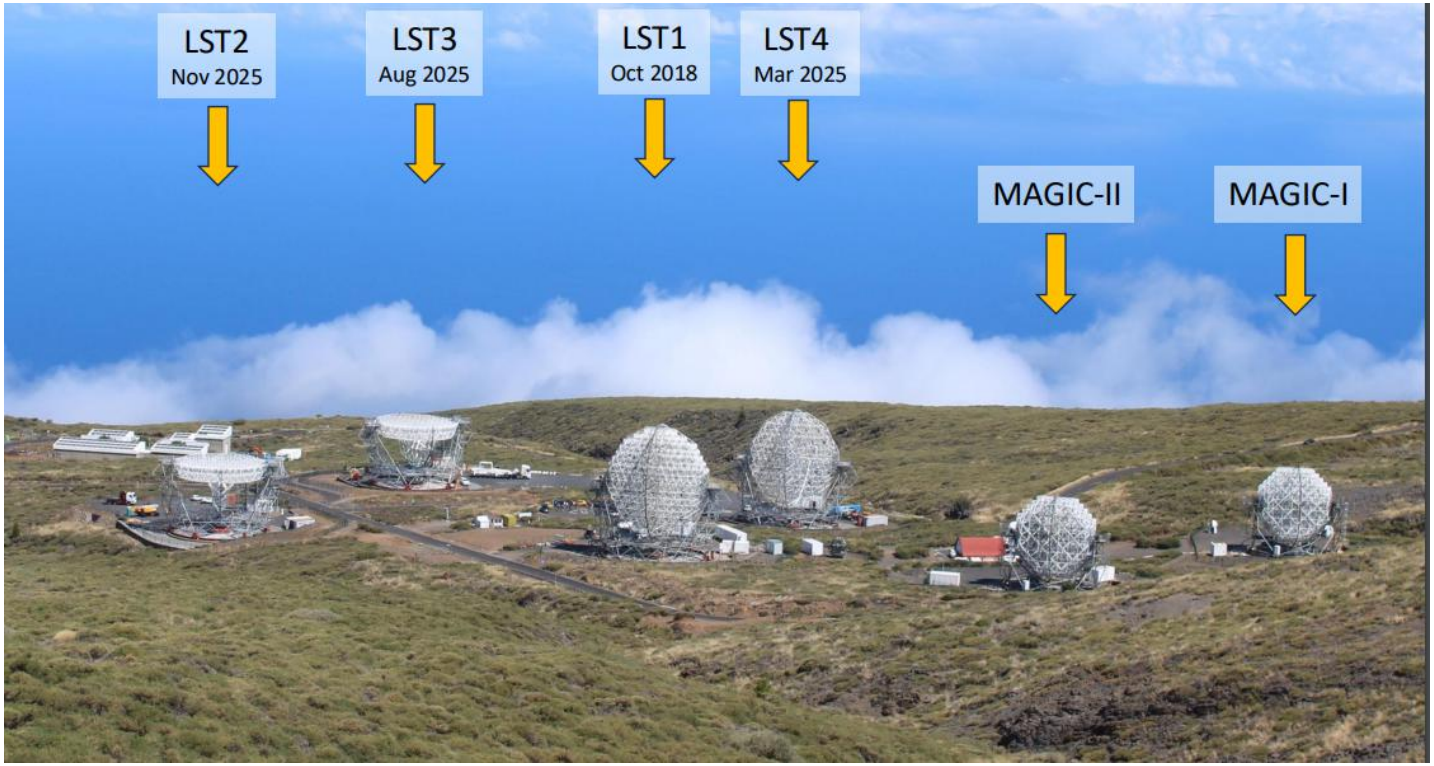
- Plan to extend the data format to include also neutrinos
  - Very-high-energy Open Data Format (VODF) initiative: https://github.com/vodf
  - endorsed by many current and future instruments/observatories in (V)HE and neutrino detection
  - step to use common science tools to analyze data from multiple instruments

- Use the CTAO data format to analyze MAGIC and LST data
  - cta-lstchain to analyze LST-1 mono data (https://github.com/cta-observatory/cta-lstchain)
  - magic-cta-pipe pipeline (https://github.com/cta-observatory/magic-cta-pipe) to analyze joint MAGIC+LST-1 data (or MAGIC only) up to DL3 level (then gammapy can be used)
  - however, data are still private so not accessible to people outside the collaboration :(

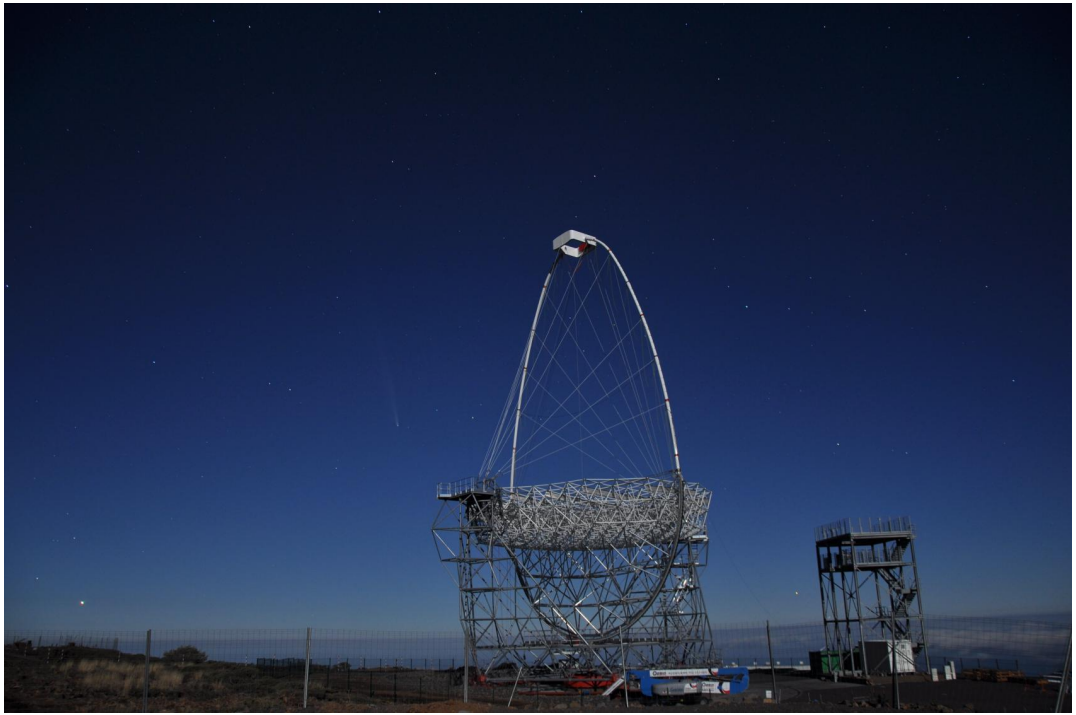
Summary

- MAGIC and LST-1 deeply involved in follow-up of transient sources, also in a multi-messenger context
- Already some key results (e.g. GRBs), thanks to extended observation programs and follow-up strategies
- Tools like Astro-COLIBRI can help in finding interesting events to observe, to organize follow-ups, and possibly to coordinate with other instruments/observatories
- Did not mention FRBs, Galactic transients (e.g. SGRs, novae) due to time, but they are very hot topics right now
  - e.g. T Coronae Borealis may explode soon!

LSTs are “growing” :)



LSTs are “growing” :)



Credits: A. Fiasson (LAPP)

BACKUP