FACULTY OF PHYSICS
AND APPLIED INFORMATICS
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Science with LST/MAGIC

J. Sitarek on behalf of the LST/CTA Collaboration
and MAGIC Collaboration

2023.12.13, Swiss CTAO days, (Bern/remote)

Why talking about MAGIC in CTAO-CH meeting?

- The science of the future CTAO should stem from what we have learned from the current generation of Cherenkov telescopes
- MAGIC is located in the same place as CTAO-North, making it also possible for joint operations of MAGIC+LST-1

Outline

- Cherenkov telescopes: current and future
- Selected MAGIC results and early LST-1 results
- Joining old and new: MAGIC+LST-1

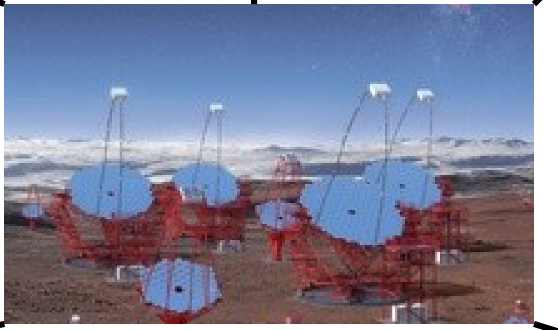
Cherenkov telescopes: current and future

Physics with IACTs

Galactic Science:
SNRs, PWNe, Gal. Cent., Pulsars, novae ...

Extragalactic Science:
AGNs and beyond

Transients and Multi-Messanger:
Follow up of GRBs, GW, ν, ...



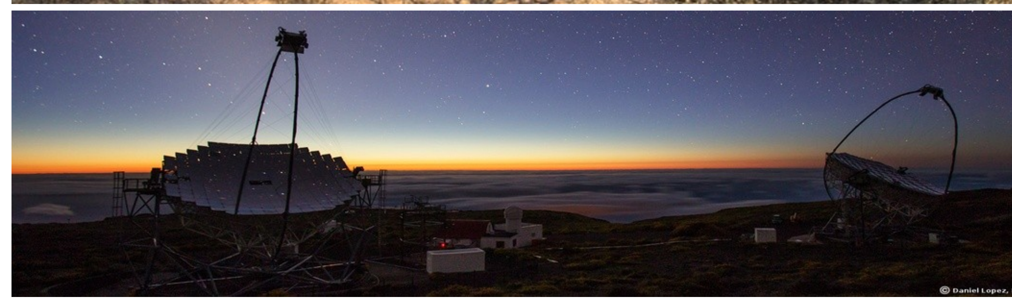
Fundamental Physics and Cosmology:
Probing Dark Matter, LIV, EBL, IGMF, ...

More than gamma rays:
Cosmic Rays, Intensity interferometry, optical measurements, ...

IACT are versatile instruments: many different scientific targets

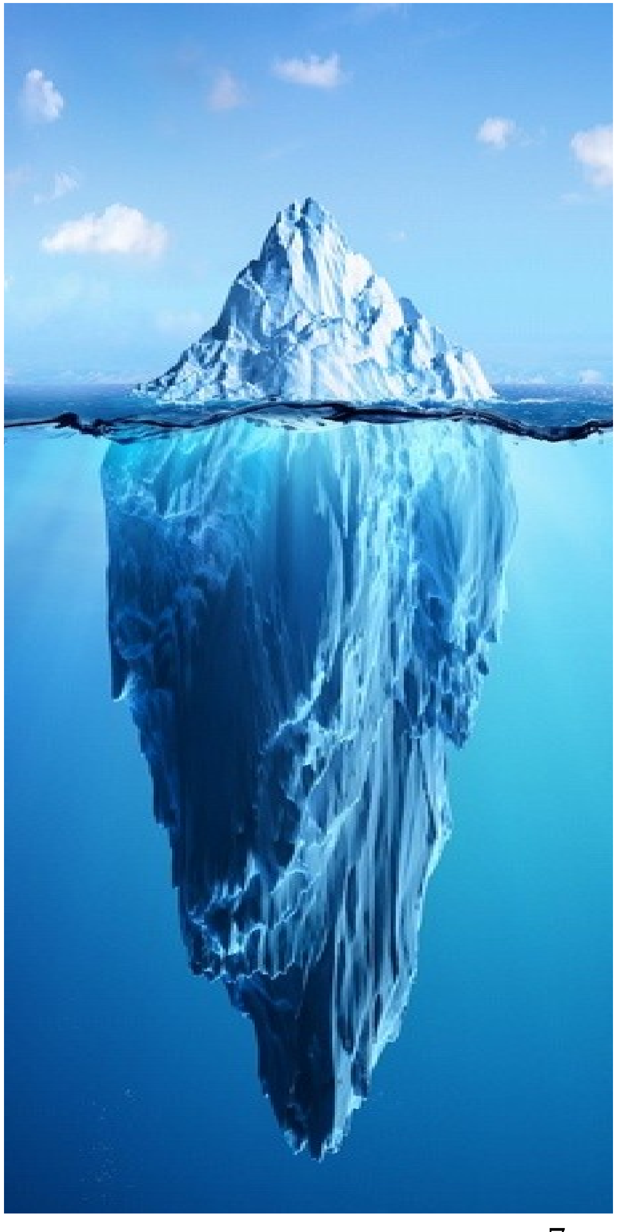
Currently operating IACTs

- H.E.S.S. : 4 x 12m + 1 x 28m in Namibia
- MAGIC: 2 x 17m in La Palma, Spain (with a nearby 1 x 23m LST-1)
- VERITAS: 4 x 12m in Arizona, USA



- More telescopes = better sensitivity
- Bigger telescopes = lower energy threshold

What will improve with CTA?



- What we have heard many times so far:
  - Sensitivity
  - Energy range
  - Angular resolution
  - Size of the FoV (possibility for large scans)
- CTA is based on the same general principles and technologies of the current generation of IACTs (but with many innovations at individual subsystem levels!) - the improvement comes from upscaling it to large number of better and specialized (3 types) telescopes
- We expect to deepen the knowledge where we see the tip of the iceberg now, and to discover new phenomena that are beyond the reach of current instrument sensitivity.

What is also important?

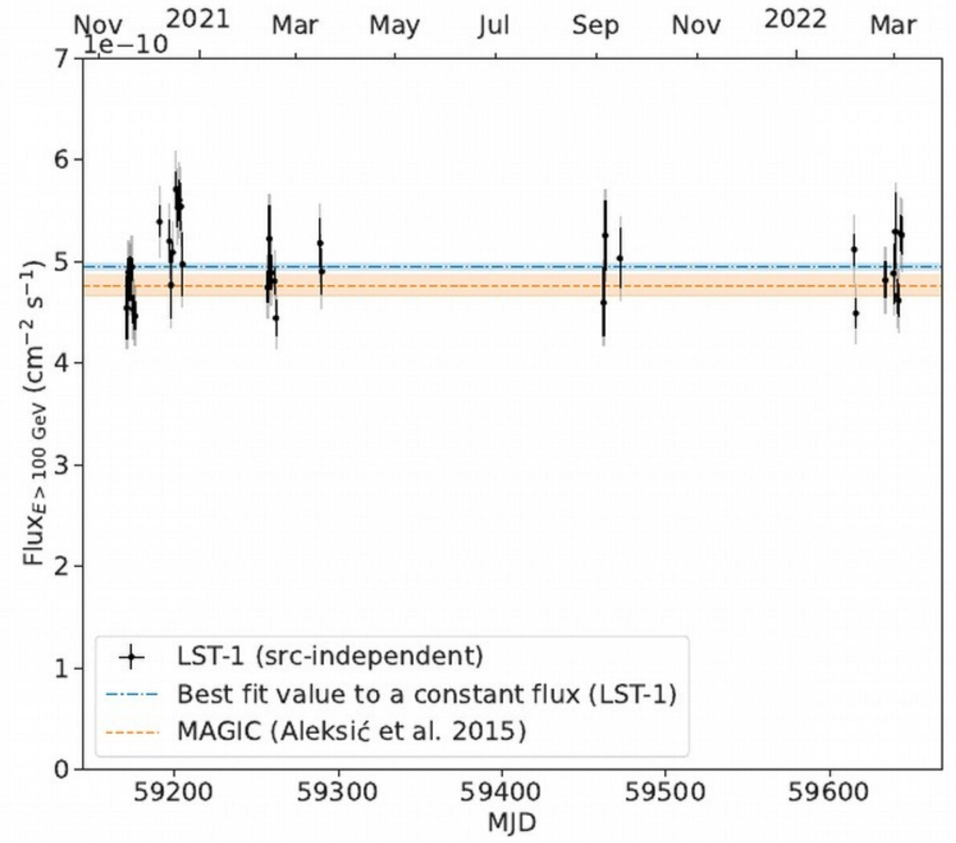
- For a Crab-like source MAGIC telescopes can measure the flux with statistical accuracy of ~30% within ~1.5 minutes – **bright sources are limited by systematic uncertainties even for very short observation times**
- CTA is also expected (and must in order to profit from the gain in sensitivity!) to improve the systematic uncertainties (careful selection of requirements, plus advanced atmospheric monitoring).

What will not improve?

- Current generation of telescopes:
  ~ 1000 hrs (H.E.S.S.) + ~1000 hrs (MAGIC) + ~800 hrs (VERITAS, with monsoon season) = ~ 2800 hrs of good weather dark time per year
- CTA: 1000 hrs North + 1000 hrs South = ~2000 hrs
- **Every hour of CTA time will be precious**
- **We need to make an effort to exploit the current generation of IACTs (and the first telescopes of CTA) for the tasks that do not require the full power of CTA.**

Crab observations with LST-1

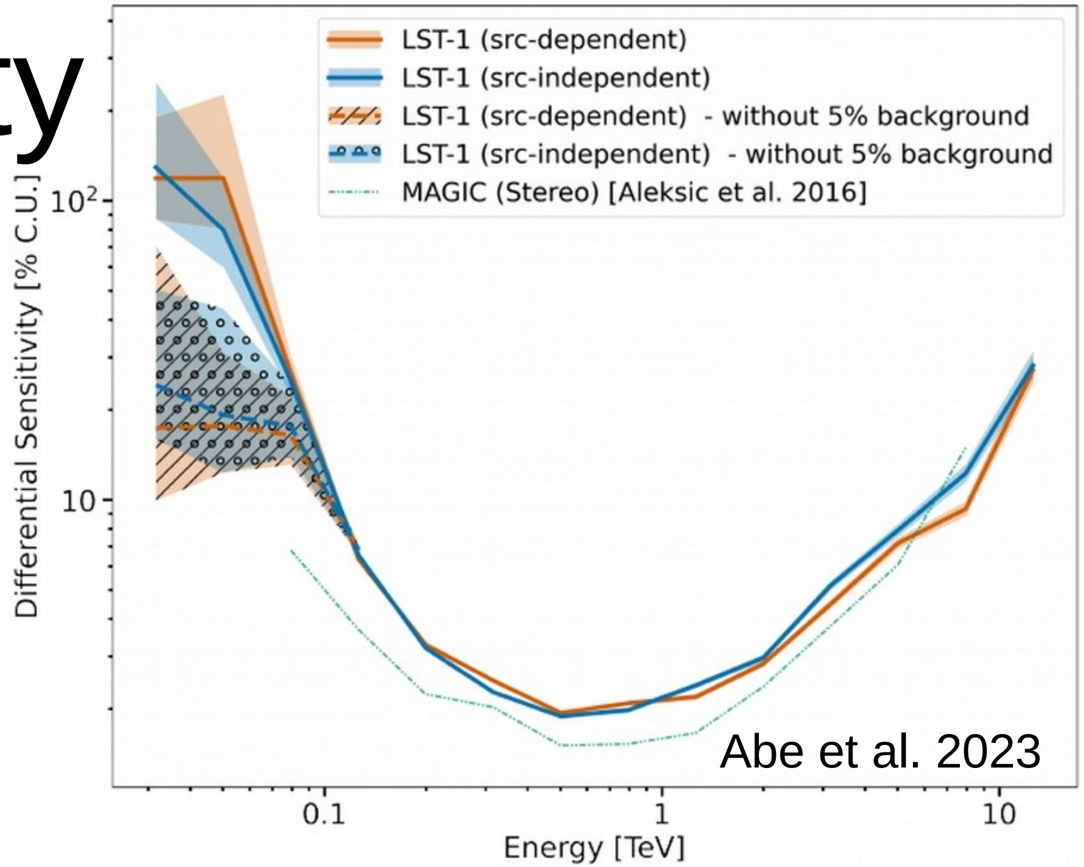
- The understanding of a new IACT instrument usually starts with reproduction of the results from the VHE standard candle: Crab Nebula
- A detailed performance paper using Crab data has been prepared by the LST collaboration

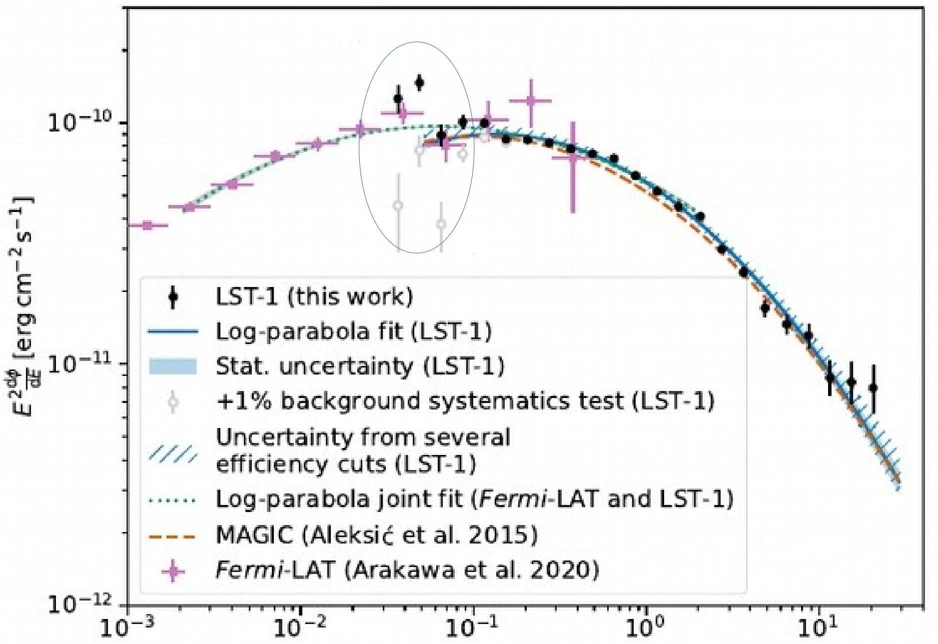


Abe et al. 2023

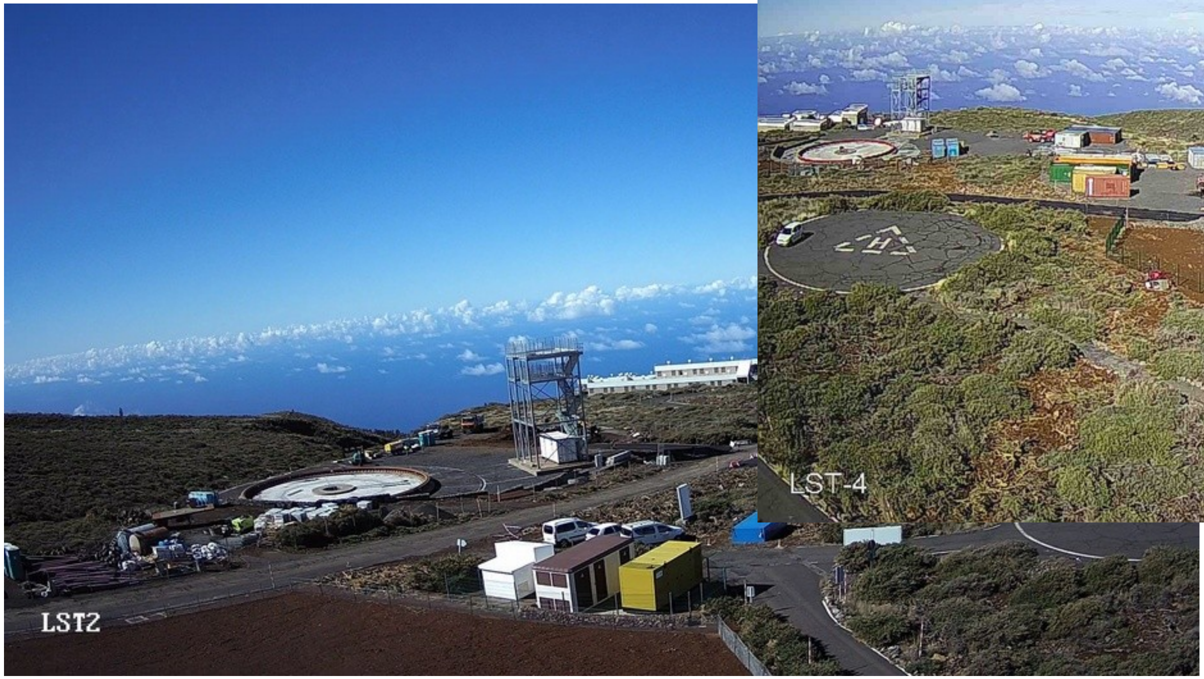
LST-1 sensitivity

- LST-1 is still a single telescope.
  - MAGIC has ~1.5 factor better sensitivity than LST-1
  - At the lowest energies single IACTs suffer heavily from muon background.
  - Large background rates limit the sensitivity due to systematic constraints





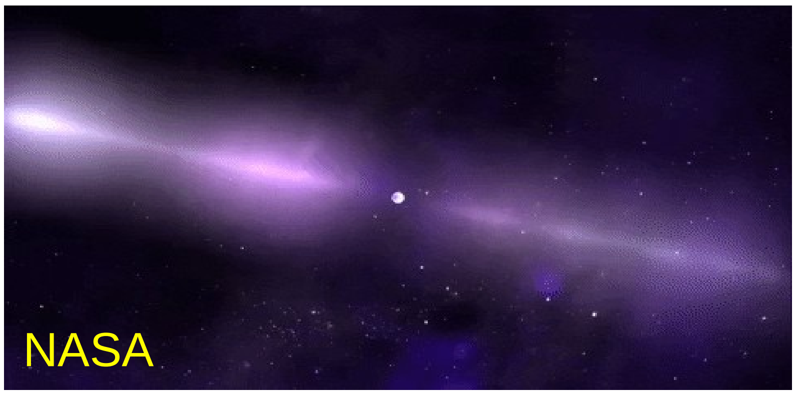
LST going stereo ?



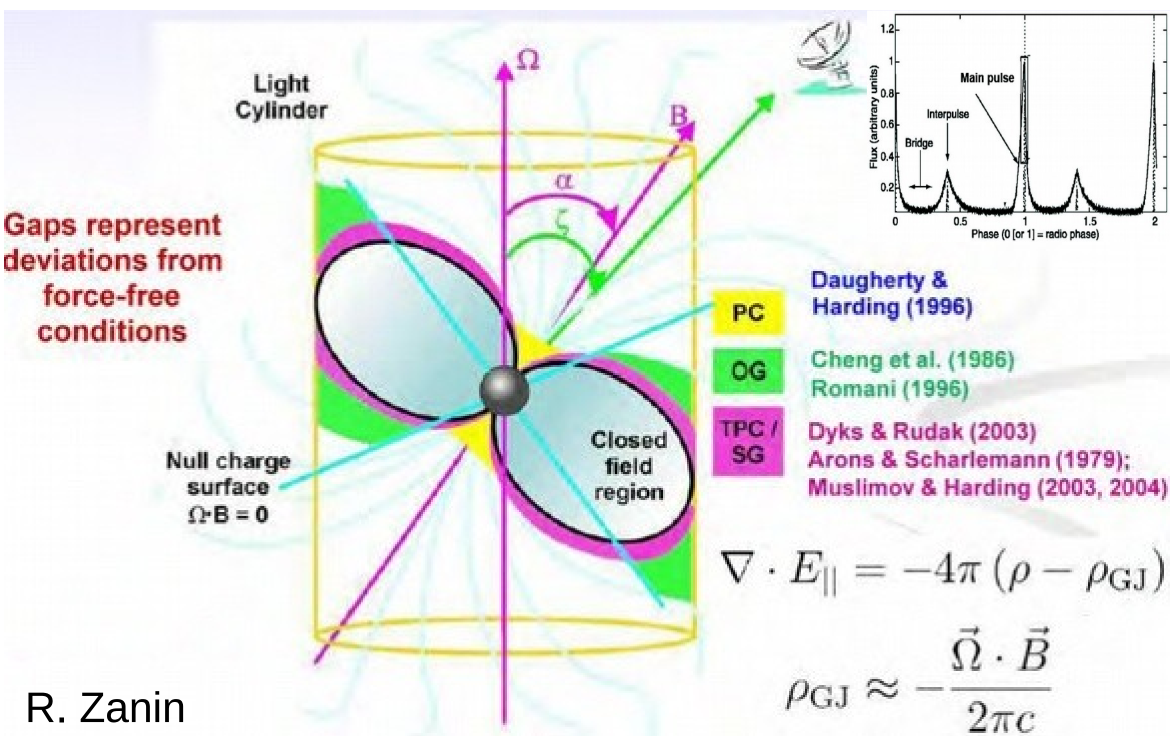
- The constructions of the remaining LST telescopes are progressing rapidly (details in previous talk)
- The LST array once completed will have an unprecedented sensitivity in the sub-100 GeV range

Selected MAGIC results and early LST-1 results

Pulsars

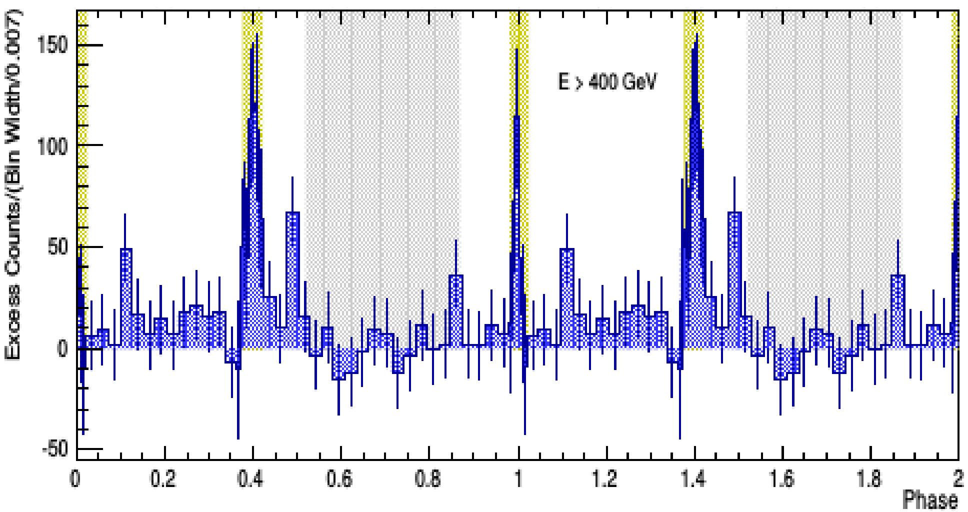


- Rapidly rotating neutron star with a beam of radiation sweeping over the observer
- Different regions where particles can be accelerated because the electric field is not counteracted by the charge pulled out from the surface of the neutron star

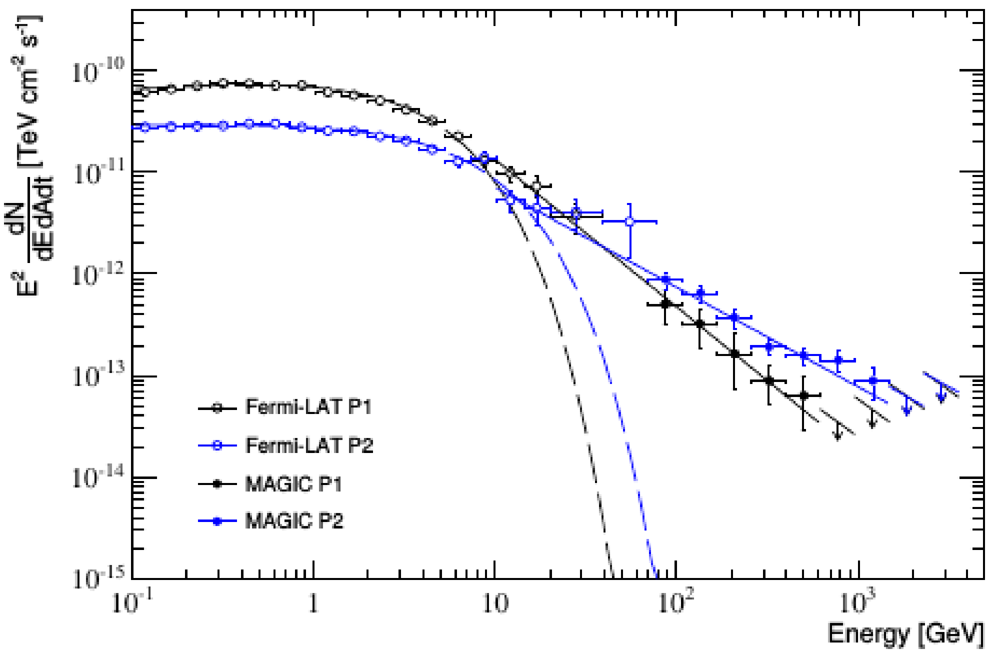


R. Zanin

Pulsars at VHE: Crab

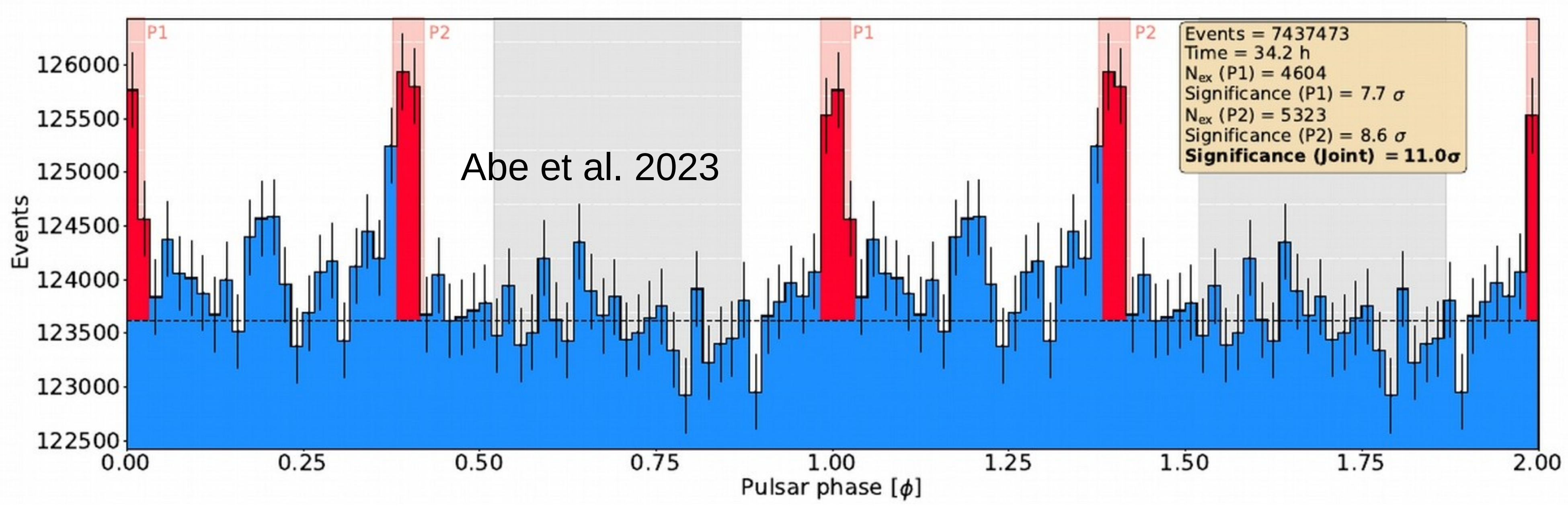


Ansoldi et al. 2016



- Before 2008: two models considered polar gap and outer gap – different type of cutoff expected at few tens of GeV
- Aliu et al., 2008
  First detection of > 25GeV emission from a pulsar
- Aliu et al., 2011 (VERITAS)
  First detection of emission > 120-250 GeV
- Aleksić et al., 2011
  First phase resolved spectra 25-100 & 50-400 GeV
- Aleksić et al., 2014
  Bridge Emission ≥ 50 GeV
- Ansoldi et al., 2016
  Aggregating 320h of data: pulsar spectrum extends up to TeV energies => troubles for models, the emission might be produced much farther away

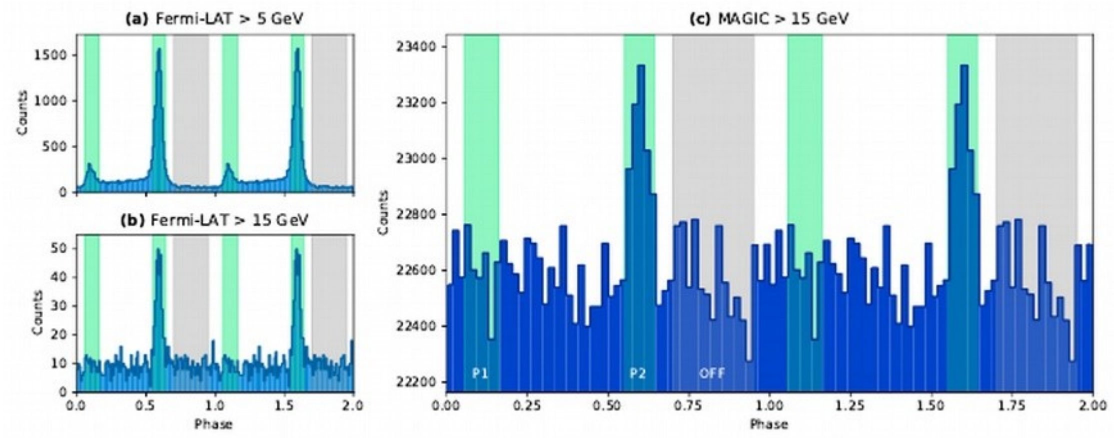
LST-1 view of Crab pulsar



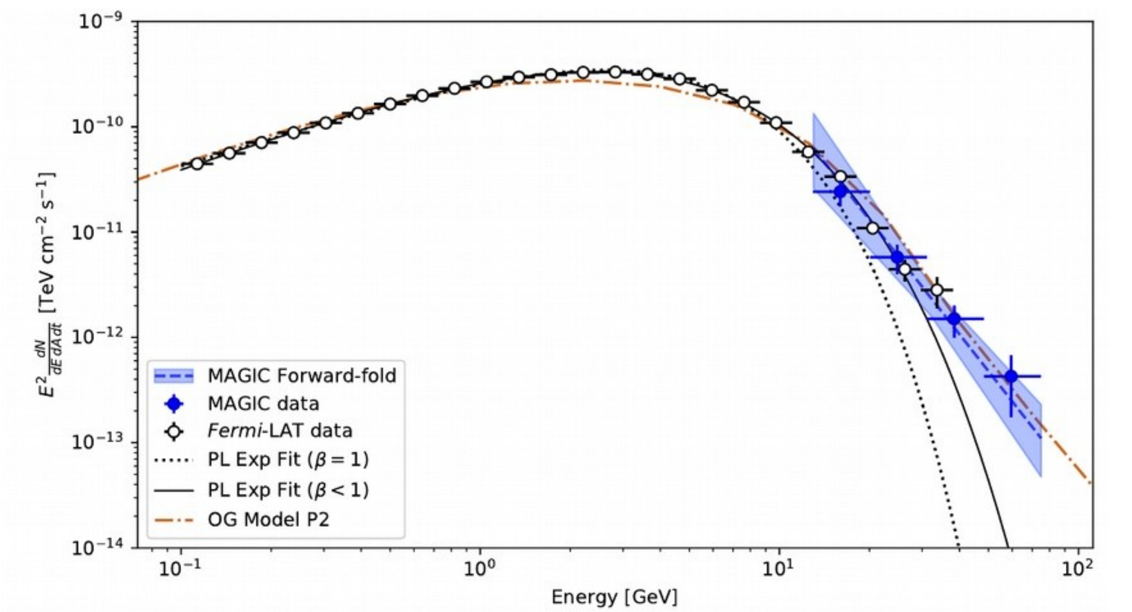
- Clear detection of both peaks in just 34 hrs of LST-1 data
- The low energy threshold of LST-1 is a big advantage here and will allow precise studies of the pulse profiles.

Geminga pulsar

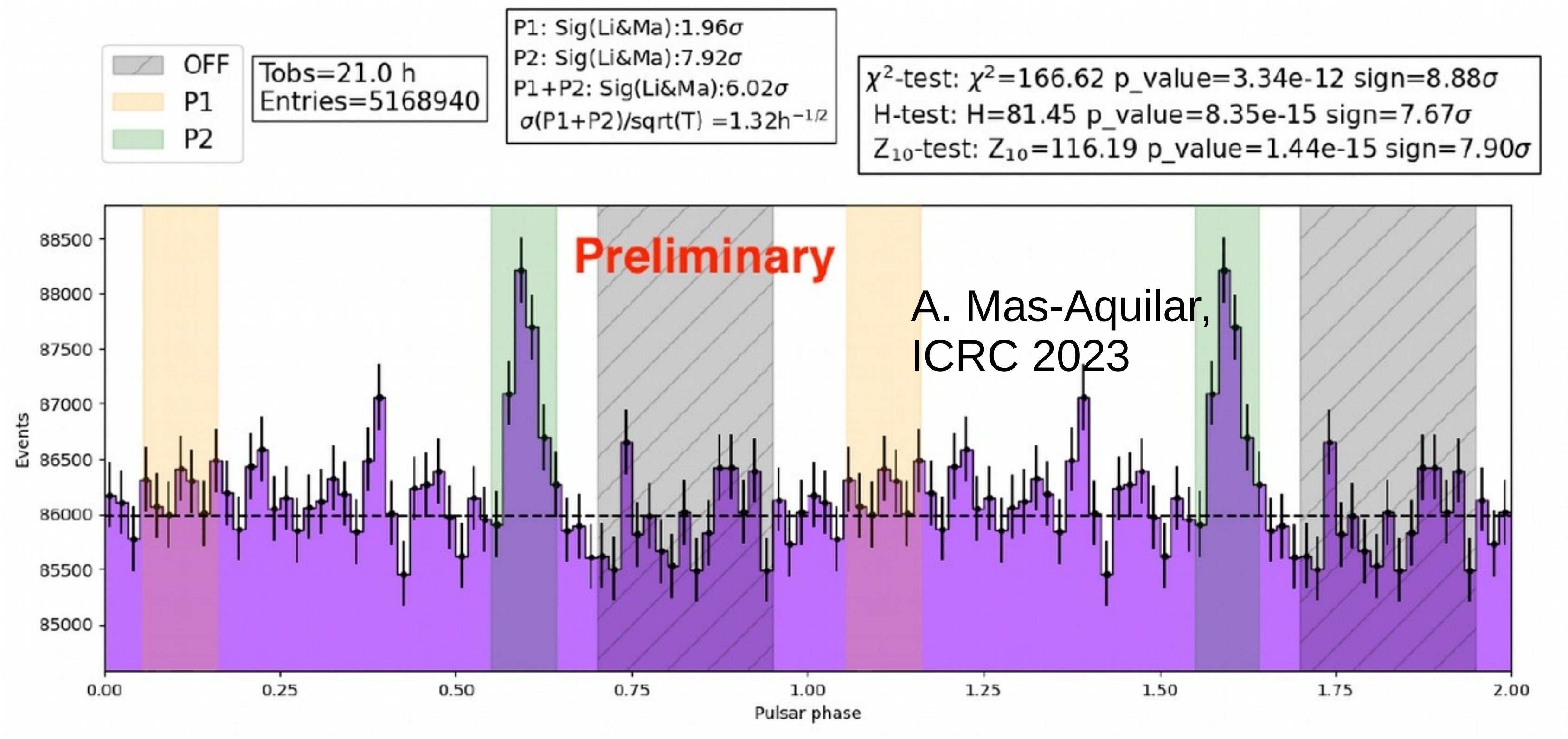
- Old, radio-quiet pulsar (different w.r.t Crab)
- The softest source ever detected by IACTs: very challenging; required special trigger (Dazzi et al. 2021) and 80 hrs of observations to detect it!



Acciari et al. 2020



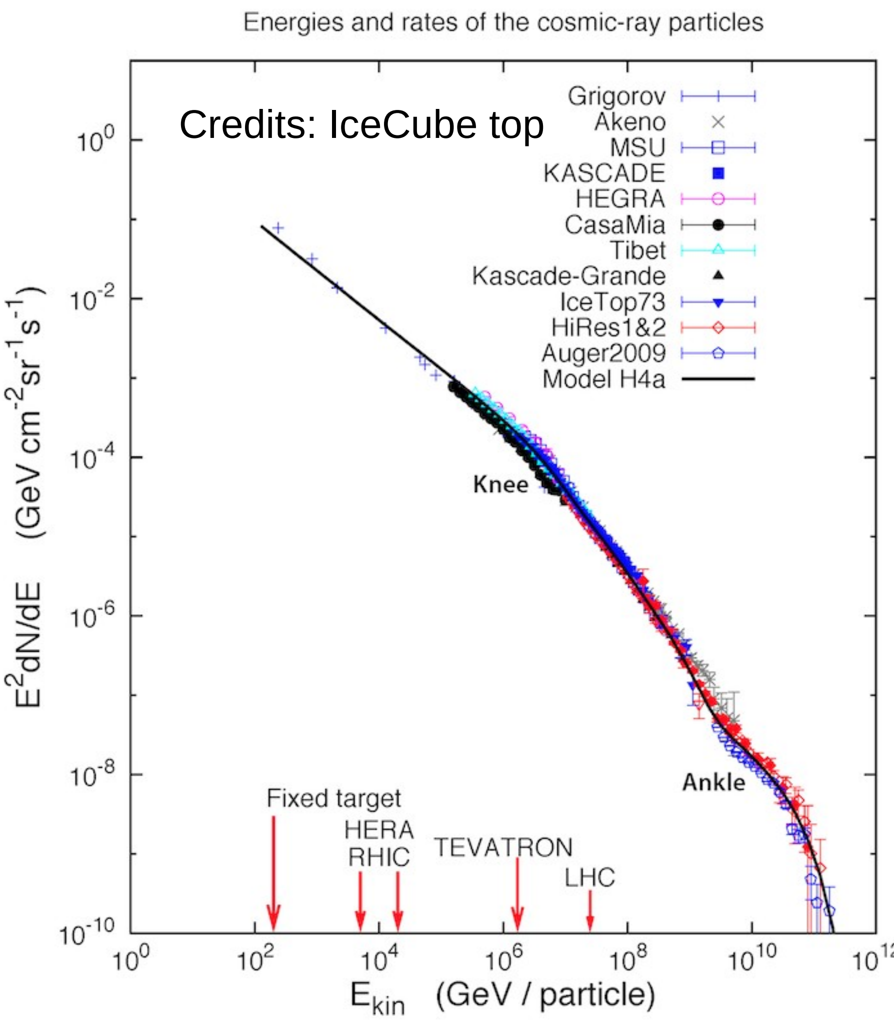
LST-1 view of Geminga pulsar



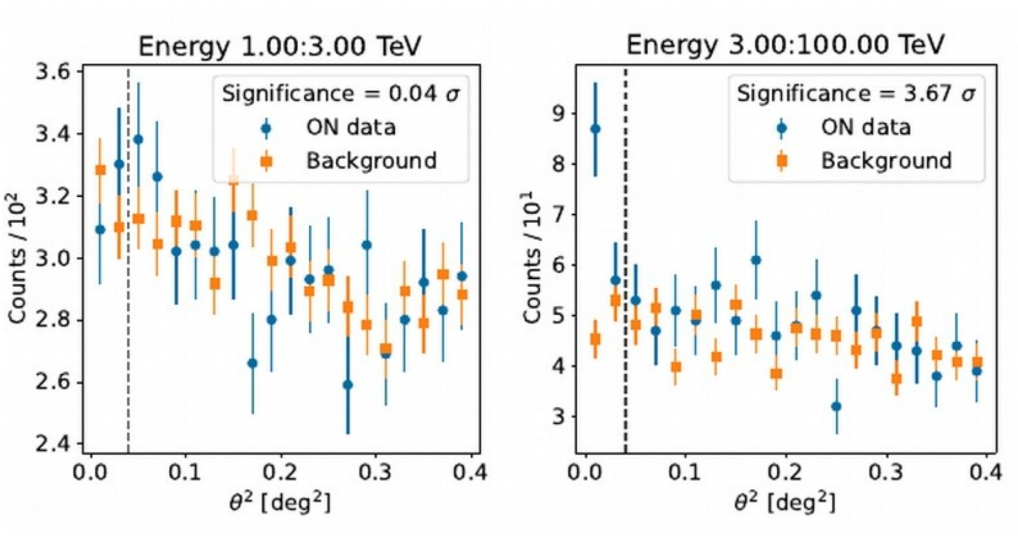
- Clear detection of P2 with just 20 hours of observations (5σ in 8 hours)
- Showing the power of the low energy threshold of LST-1

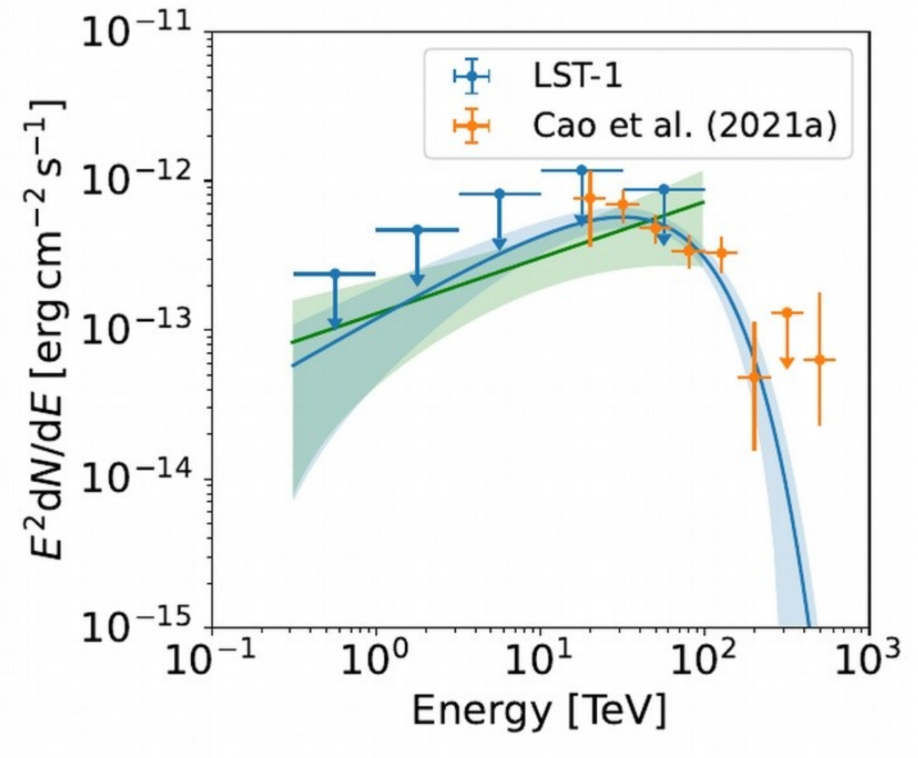
Galactic sources above 100 TeV ?

- To understand the knee in CRs we need to understand where the PeV protons are produced
- PeV protons will produce in hadronic interactions ~100 TeV gamma rays
- A lot of progress recently thanks to LHAASO (see also a dedicated LHAASO talk on Thursday)
- ...but ~100 TeV photons can be also made in leptonic interactions
- Spectral and morphologic information of the O(100TeV) sources (+MWL information) needs to be studied to find true PeVatrons



LHAASO J2108+5157 in LST-1 eye

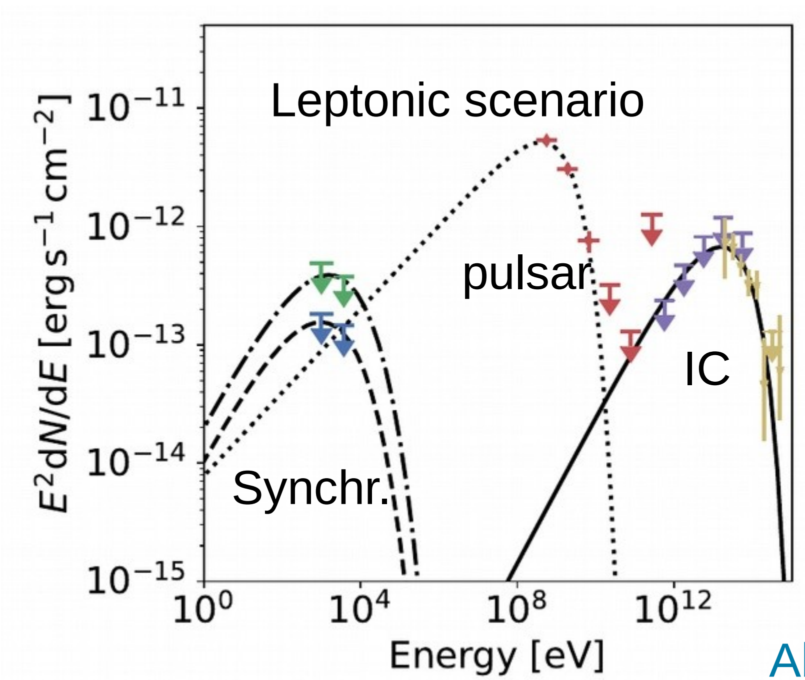


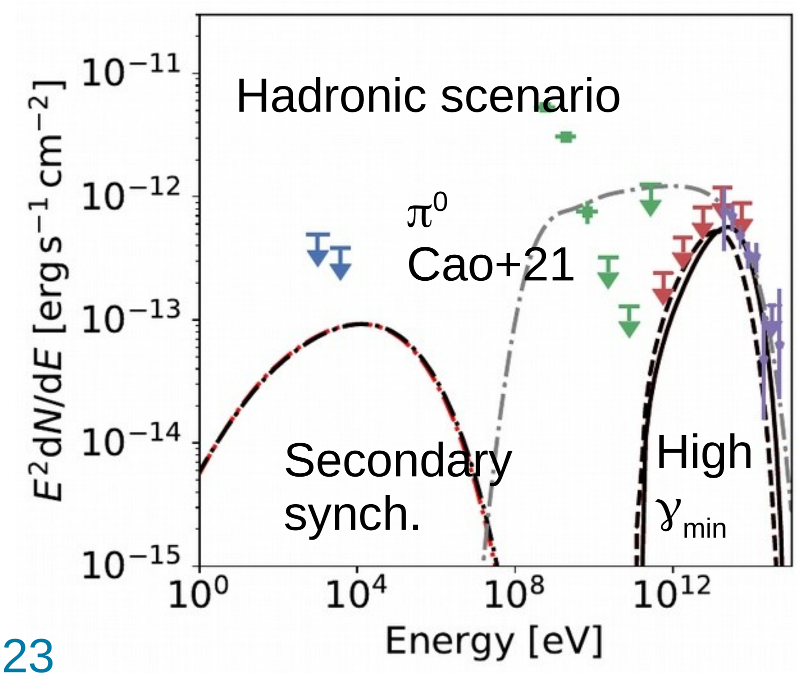


Abe et al 2023

- Deep exposure of a LHAASO-detected source
- Hint of emission at 3-10 TeV band
- (sub-)TeV emission strongly constrains the spectral shape

Leptonic or hadronic?





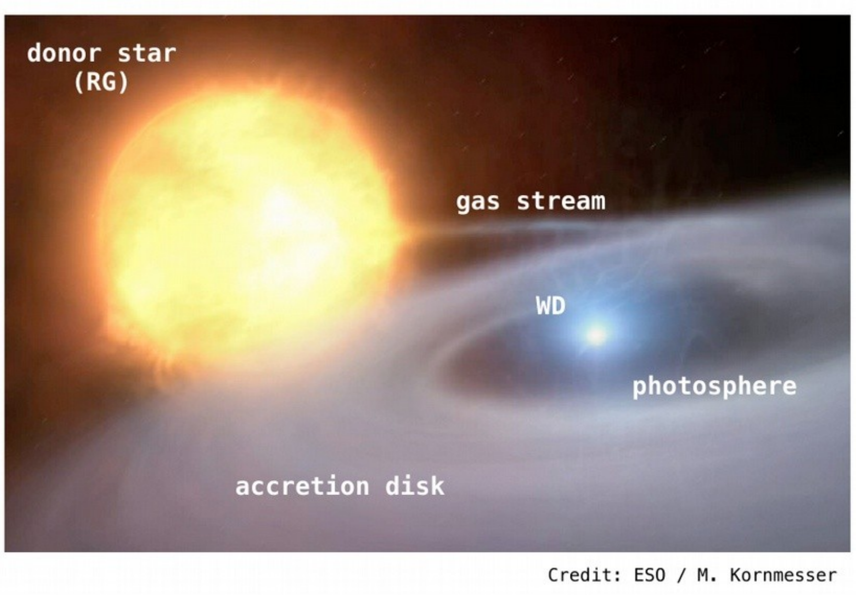
Abe et al 2023

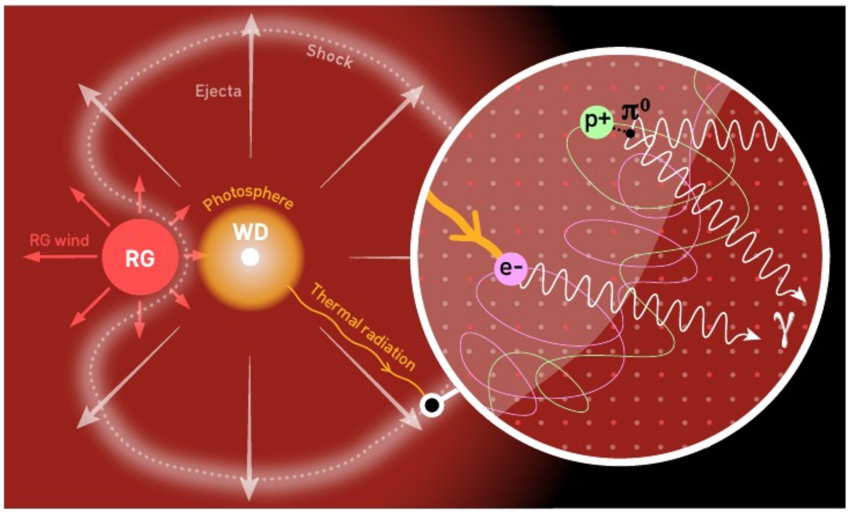
- PWN or TeV halo
- But no pulsar detected to power the emission

- Pion production in molecular clouds
- No explanation for the GeV emission
- Injection of protons with high minimal Lorentz factor (1.6×10^5) is required

Novae

- Cataclysmic variable binary systems of a white dwarf (WD) and a donor star.
- Mass transfer from the donor star causes thermonuclear explosions of the hydrogen accumulated on the WD.
- If the donor star is a RG, the system is immersed in its wind, creating a **symbiotic binary**.
- Some novae have WD very close to the mass limit, causing repetition of outbursts in human lifespan (<100 years) – **recurrent novae**.
- Due to high optical brightness (lasting for weeks/months) they have been studied for centuries
- Since a decade also known GeV emitters but leptonic/hadronic origin was unknown

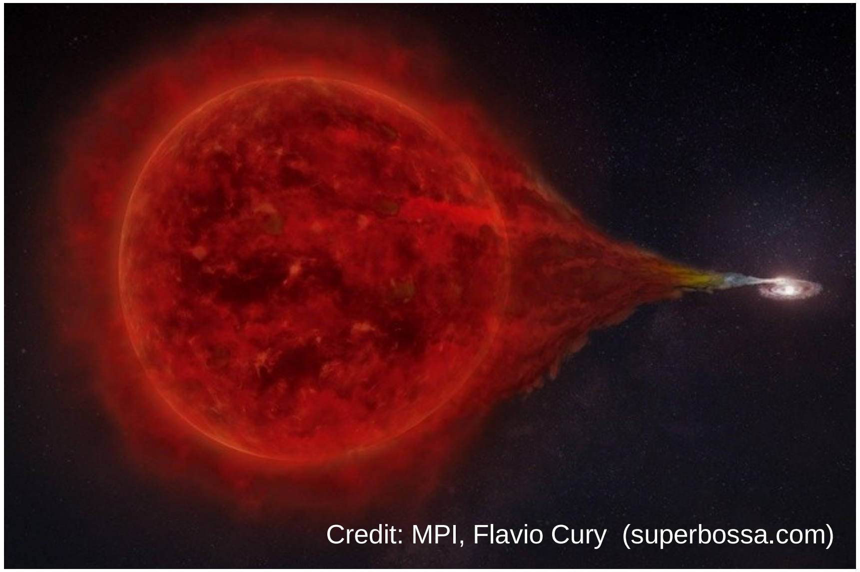




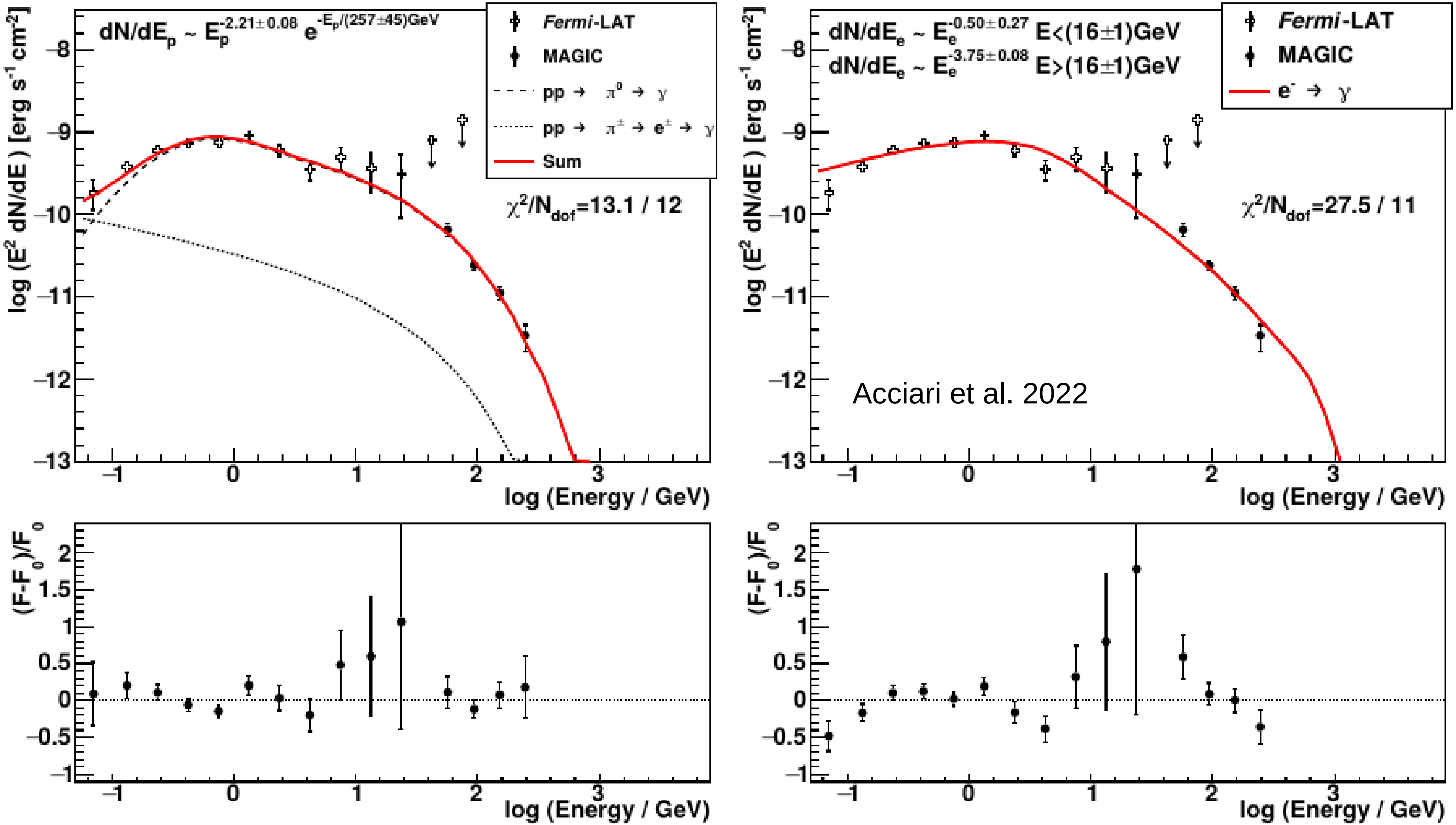
Acciari et al. 2022

RS Ophiuchi

- Recurrent symbiotic novae with outbursts every ~15 years
- Latest outburst on 2021.08.8 UT ~22:20
- Independently followed and detected by H.E.S.S. (Aharonian et al. 2022) and MAGIC (Acciari et al. 2022)
- **The first nova detected in VHE gamma rays**



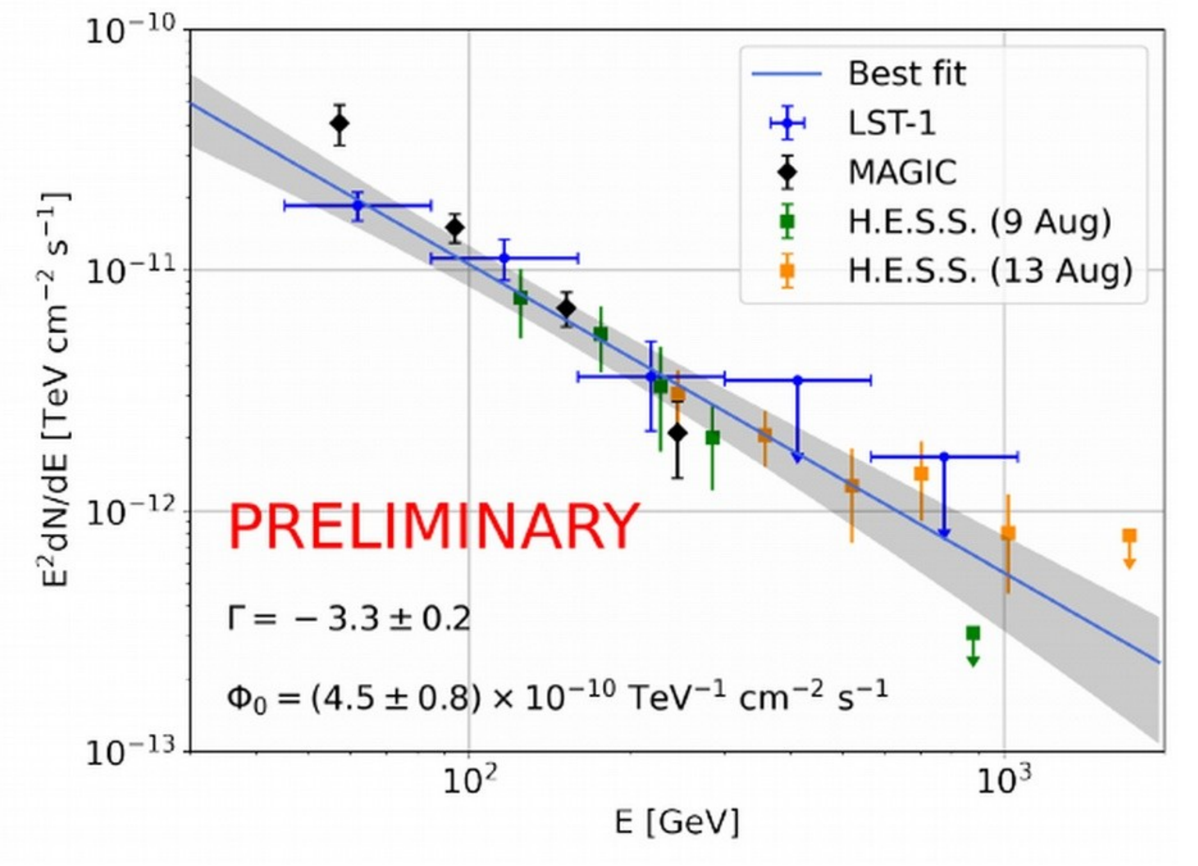
Proton vs electron models



- Electron model needs peculiar **injection** spectrum (with intrinsic, non-cooling, break) – **preference for protons**
- AIC test: electron model is only 4.7 x 10^{-4} times as probable as proton model – **another preference for protons**

LST-1 view of RS Oph

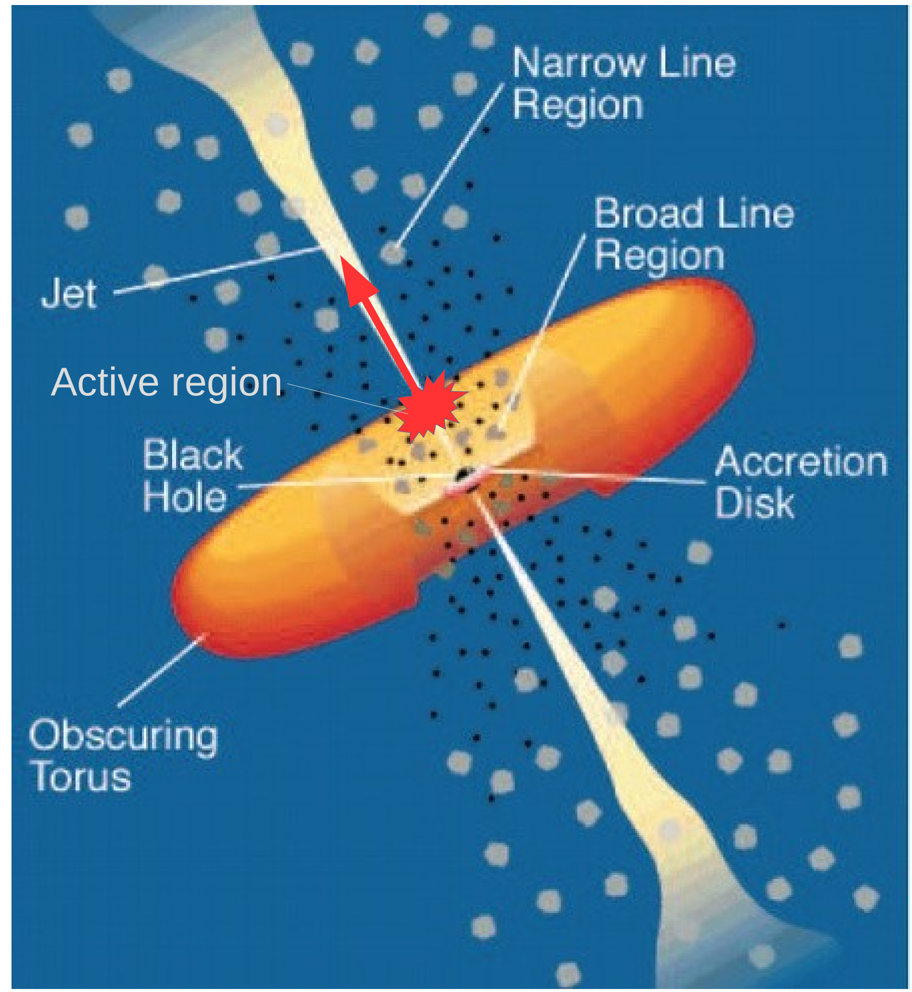
- RS Oph was also detected by LST-1
- The spectrum is consistent with MAGIC and H.E.S.S.
- Combination and modeling of the data ongoing



Aguesta-Cabot, Gamma2022

Active Galactic Nuclei

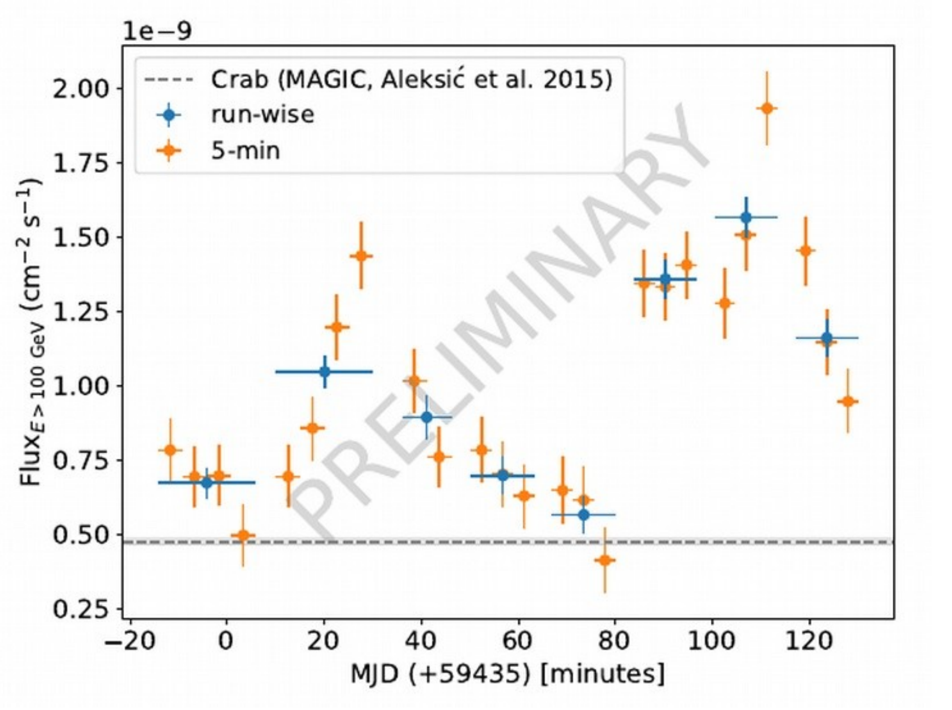
- AGNs are bright cores of some galaxies hosting supermassive black holes
- Gravitational collapse onto the black hole is powering ejection of relativistic jets
- Strongly variable non-thermal emission from radio up to TeV energies
- The most natural models assume that TeV (and MWL) emission comes from compact regions moving along the jet
- Many flares observed by the current generation of IACTs – often difficult to explain within simple models



Weekes 2003

BL Lac flare seen by LST-1

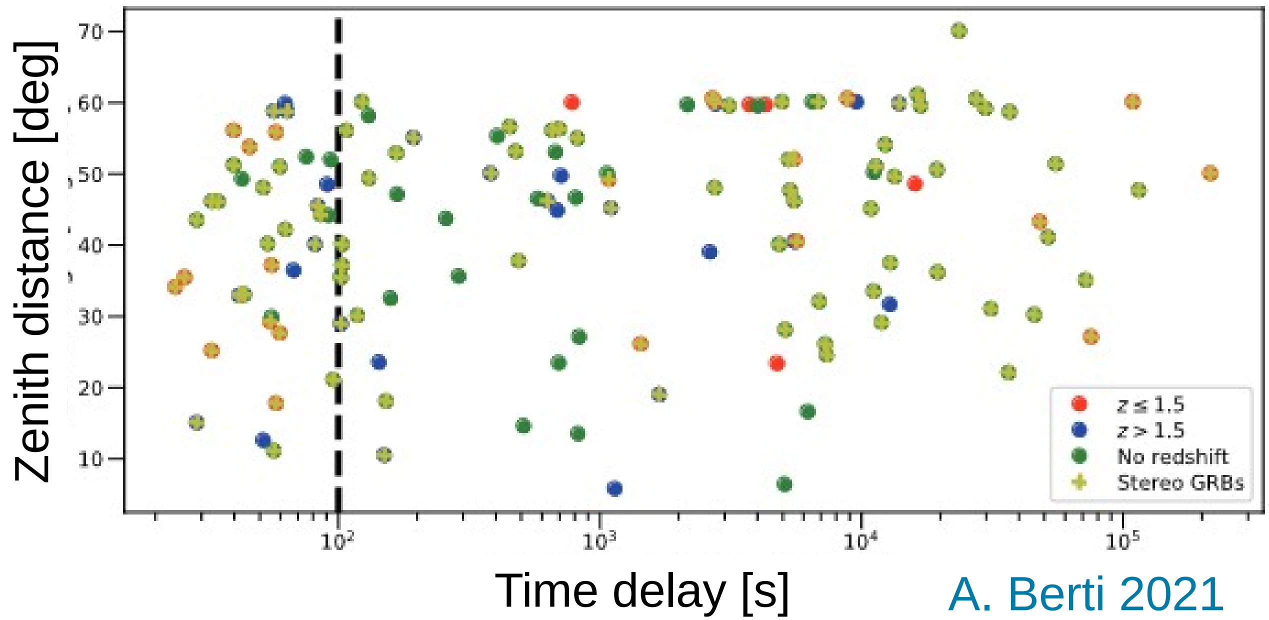
- Gamma ray spectra of blazars are (bend) power-law – the lower the energy threshold the larger event statistics
- Low energy threshold of LST allows studies at shorter time scales:
  - Possibility to probe acceleration and energy dissipation in the jet of an AGN
  - Bright flares provide data samples usable beyond the physics of individual sources: EBL, LIV, ALP, …
- Low threshold is also essential in studies of farther AGNs (due to absorption in EBL).



Nozaki et al. ICRC 2023

Hunt for gamma-ray burst

- Since their discovery in late 60s, various follow-up studies were aimed at understanding those rapid flashes of X-ray and gamma-ray radiation
- Current generation of IACTs have been trying for nearly 20 years to detect a GRB

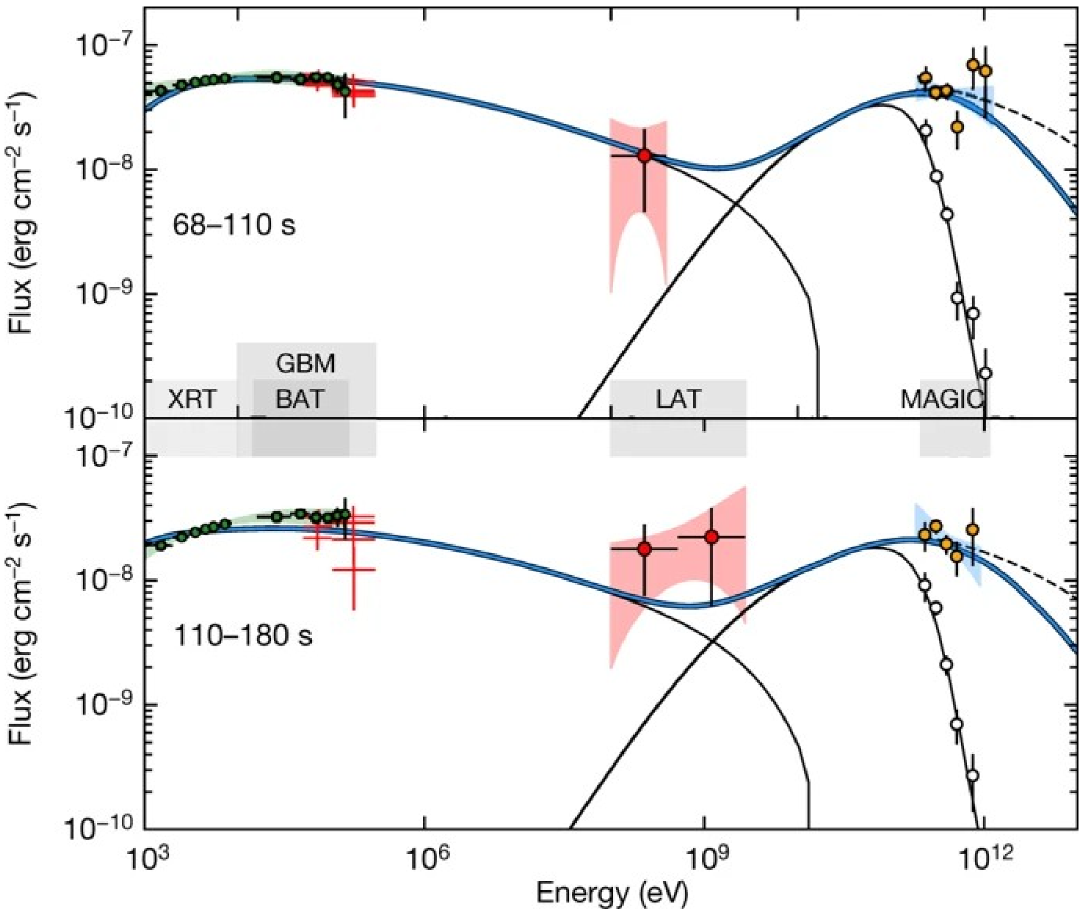


A. Berti 2021

- It is crucial to be:
  - fast (rapidly decaying emission)
  - sensitive at lowest energies (far away sources)
  - lucky (redshift and observation conditions)

GRB 190114C detection by MAGIC

- The first GRB reported to be detected in VHE gamma rays
- Highly significant signal of over 50σ
- Emission detected up to ~40 min from the onset of the burst
- Energy fluxes of TeV, GeV and X-ray ranges are comparable
- Spectrum reaching TeV energies – new emission component
- The most impressive GRB until the time of “BOAT” GRB 221009A detected by LHAASO

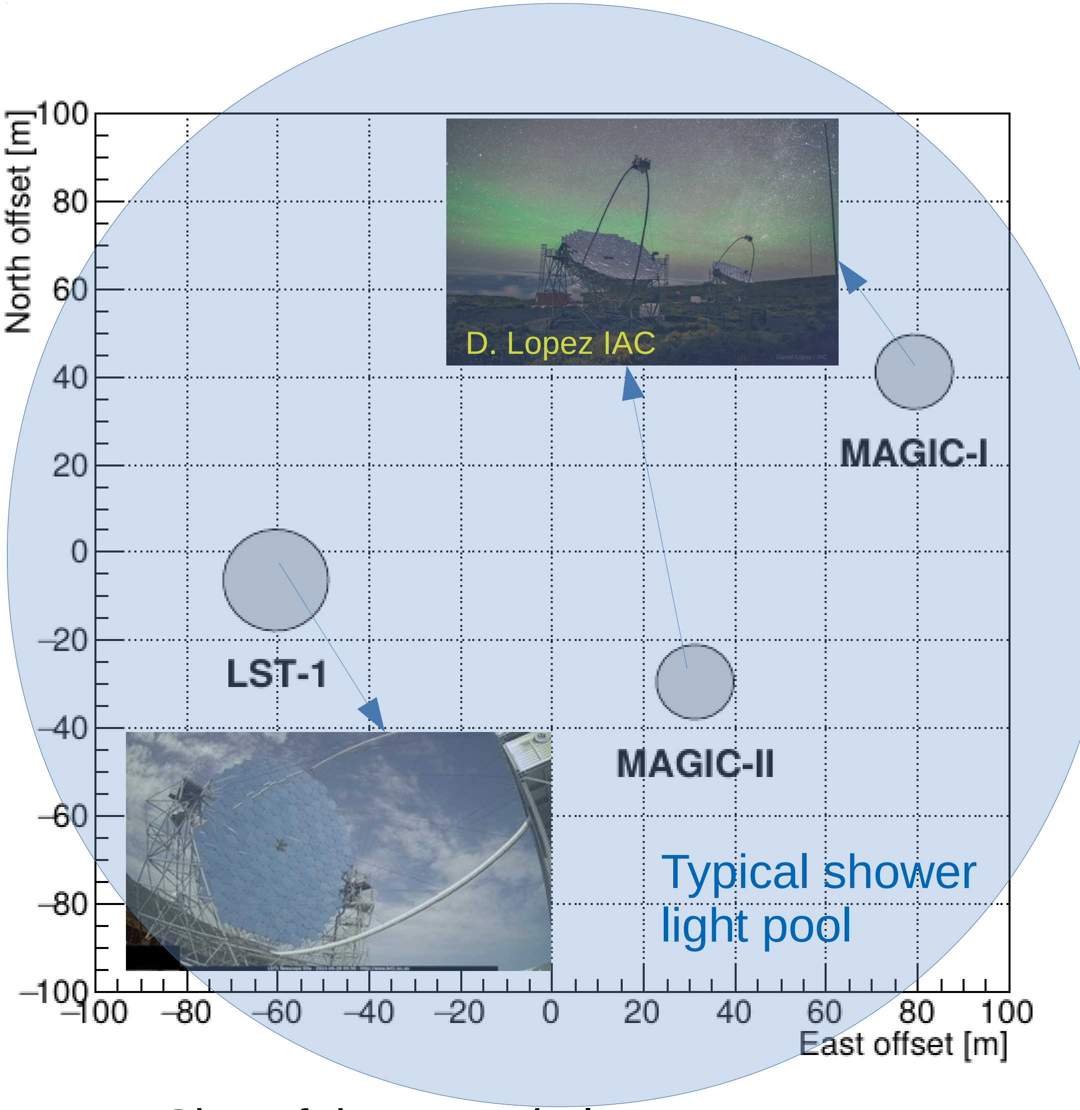


Acciari et al. 2019

Joining old and new: MAGIC+LST-1

MAGIC and LST-1

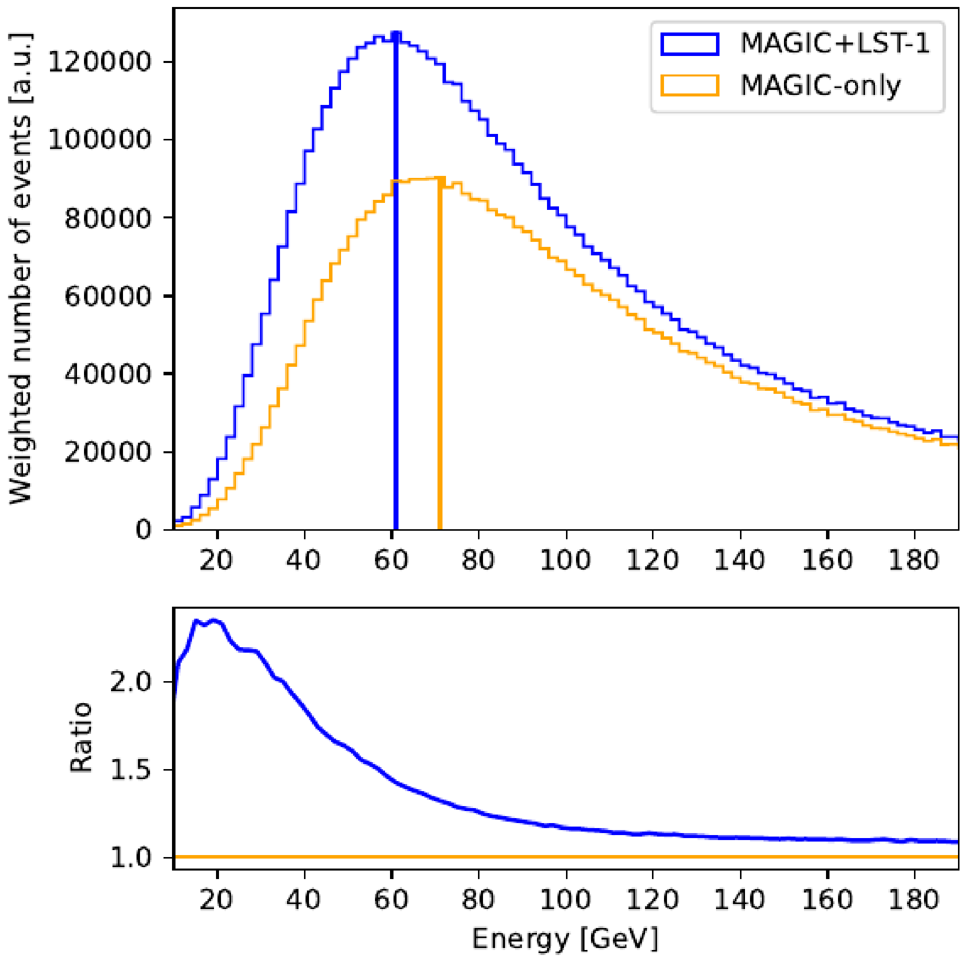
- Both MAGIC and LST-1 are located in the same site
- Proximity of both instruments allows common analysis of the same gamma-ray showers.
- For LST-1 this means going from mono to stereo ==> much better reconstruction and rejection of background
- For MAGIC this means a third telescope with larger light yield that catches nearly all showers seen by MAGIC-I and MAGIC-II



Size of the grey circles represent the mirror diameters

MAGIC and LST-1

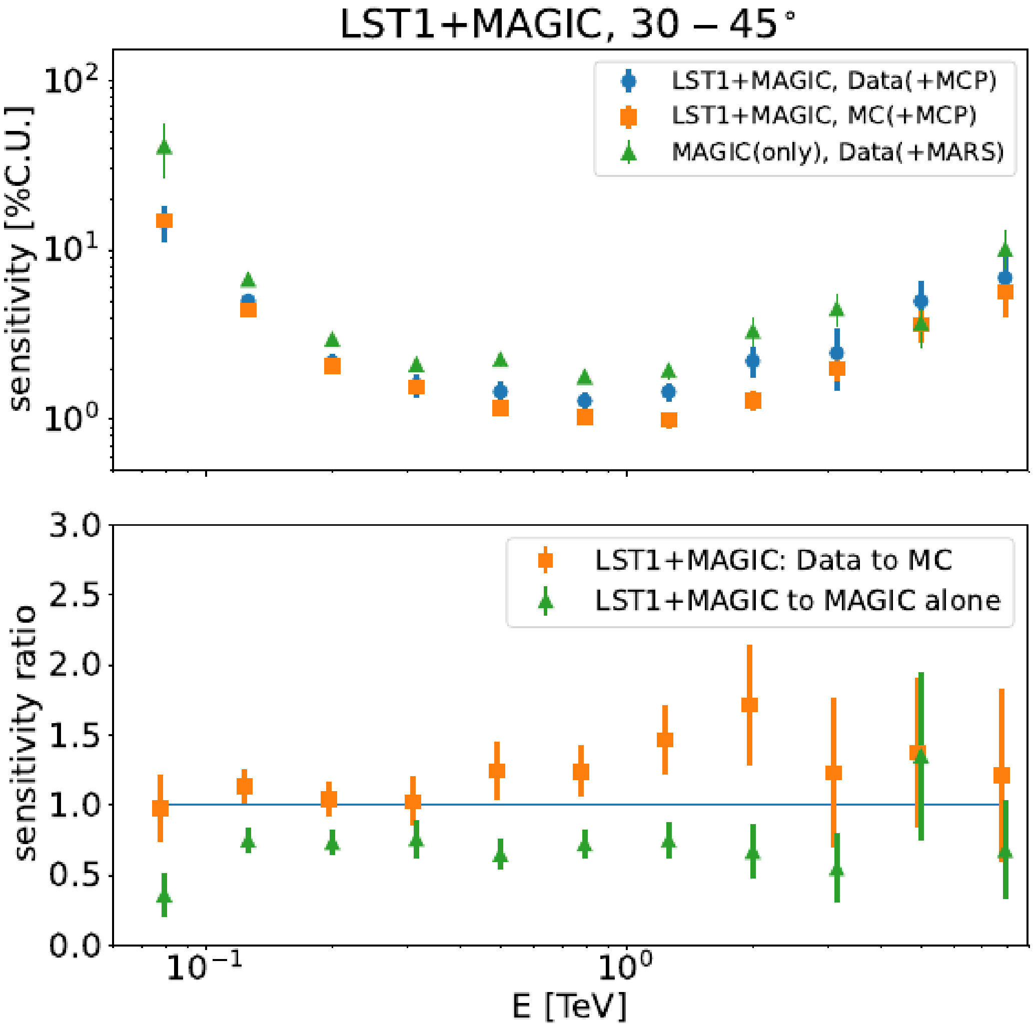
- For the moment MAGIC and LST-1 events are matched by using a software trigger exploiting event time stamps (hardware trigger under tests)
- Improved energy threshold and recovery of low energy events in which one of the MAGIC images does not survive the cleaning/quality cuts



Abe et al. 2023

Differential sensitivity

- Joint observations allow detection of 30% (40%) lower flux than MAGIC-alone (LST-1-alone).
- This corresponds to the detection of the same flux in twice (nearly three times) shorter time.
- **MAGIC and LST-1 when combined have a better performance than working separately.**



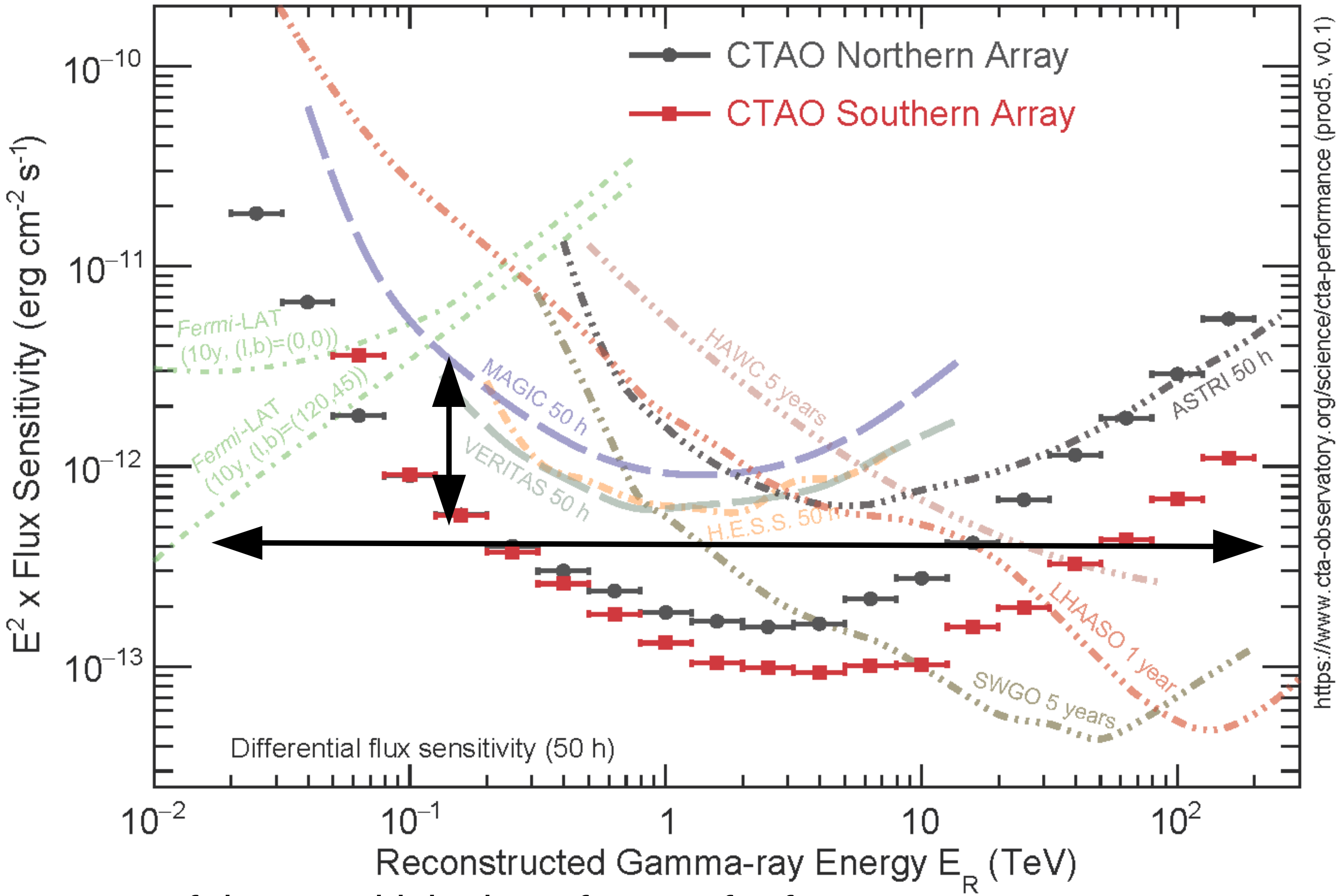
Abe et al. 2023

Summary

- MAGIC (and the other telescopes of the current generation of IACTs) managed to obtain a lot of interesting results
- LST-1 is the new kid in the block: still concluding the commissioning, but already providing important scientific data
- We do not simply wait for the whole CTAO to be finished: combination of LST-1 and MAGIC allows us to study sources with improved sensitivity

Backup

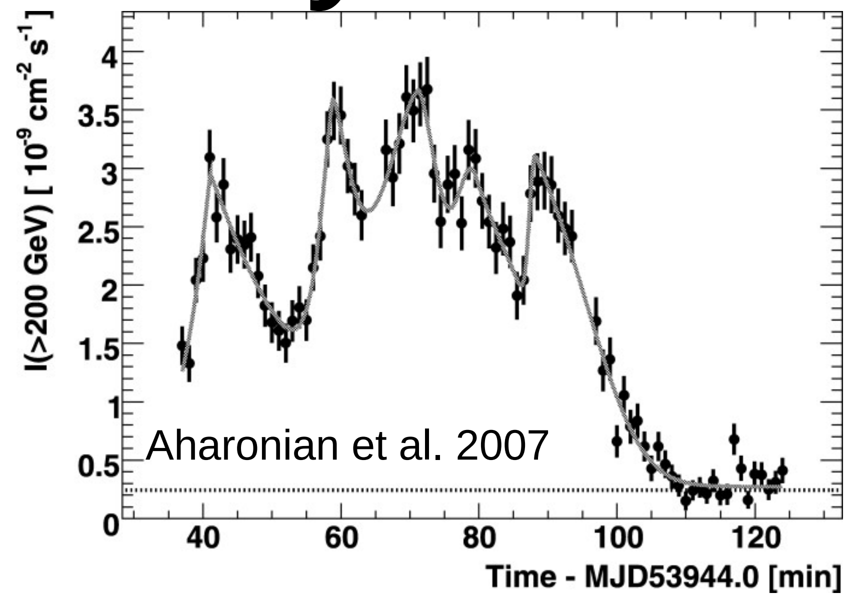
Sensitivity of CTA

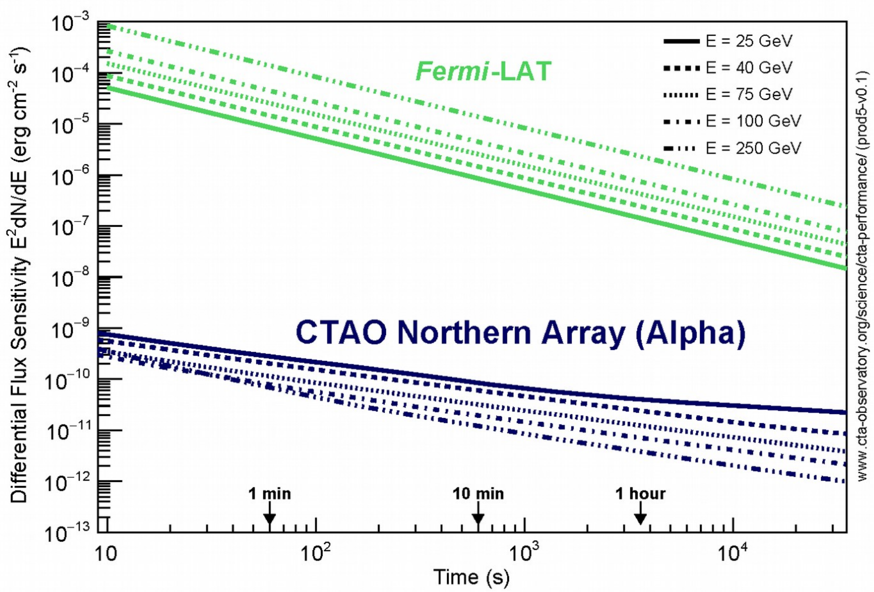


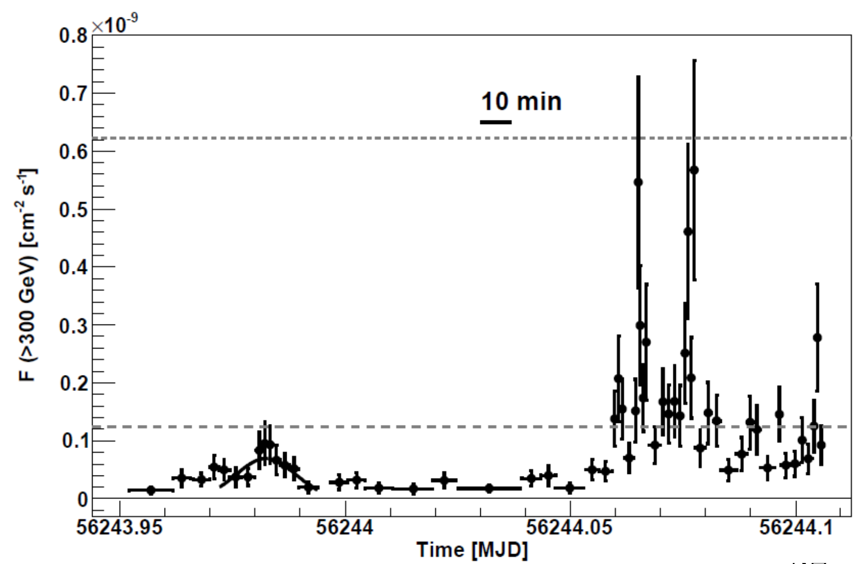
- Improvement of the sensitivity by a factor of a few
- Expanding the energy accessible to IACTs to tens of GeV and tens of TeV (synergies with Fermi and ground arrays like HAWC/LHAASO)

Fast variability

- Ultra fast variability with time scales of minutes is a challenge for the models
- Extremely beamed emission regions (Γ~50-100) and alternative emission scenarios (emission from the magnetosphere of a black hole, interaction with stars falling inside the jet, ...) has been proposed
- Detailed studies require excellent sensitivity and low energy threshold (higher statistics)



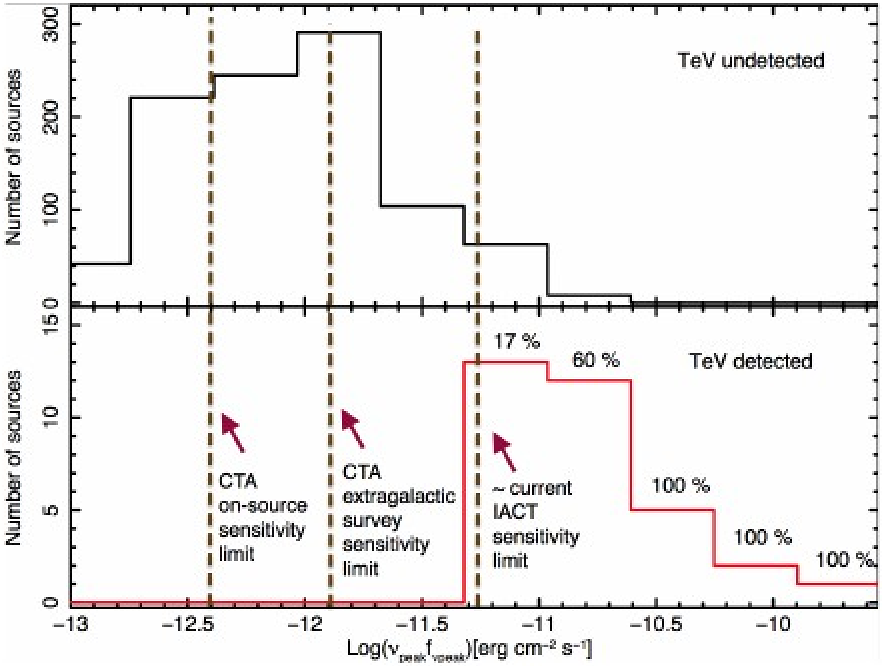




Aleksić et al., 2014

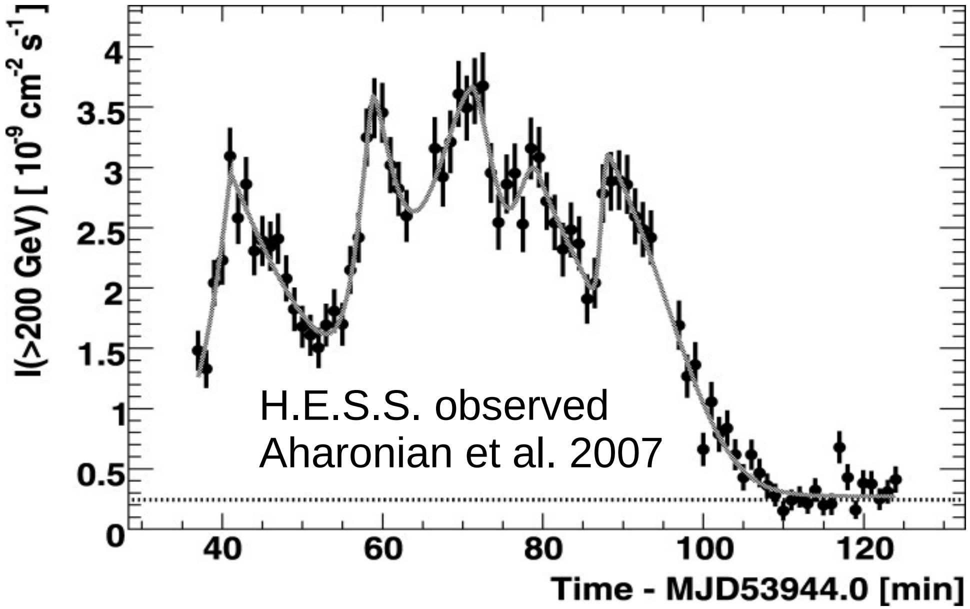
What can we do with CTA: detect more sources

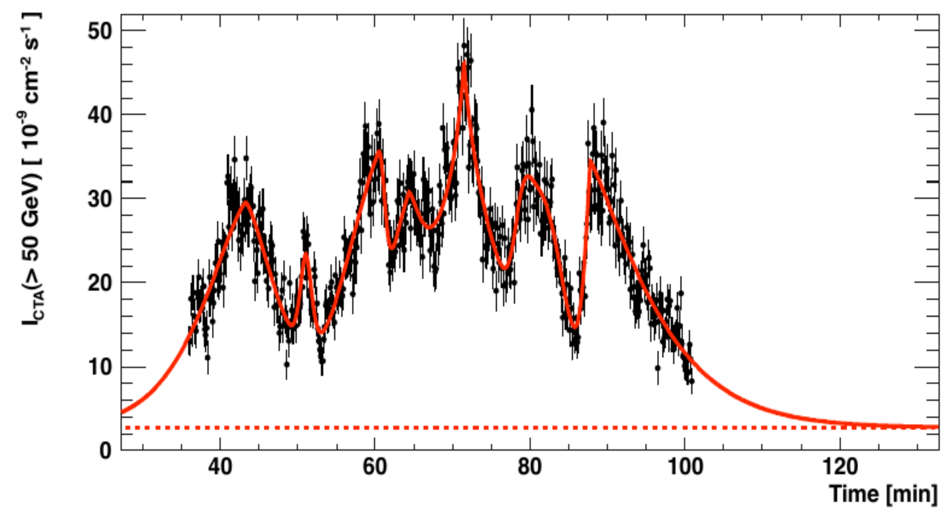
- Improved performance of CTA will allow us to detect more sources which are poorly populated in VHE band: pulsars, FSRQs, GRBs, starburst galaxies, …
- With increased number of detected sources of a given class we can move from studies of individual sources to population studies



What can we do with CTA: deep studies

- Not only we can detect more sources, but we can also study them more in details.
- More precise time and energy information will allow more precise modeling of those sources

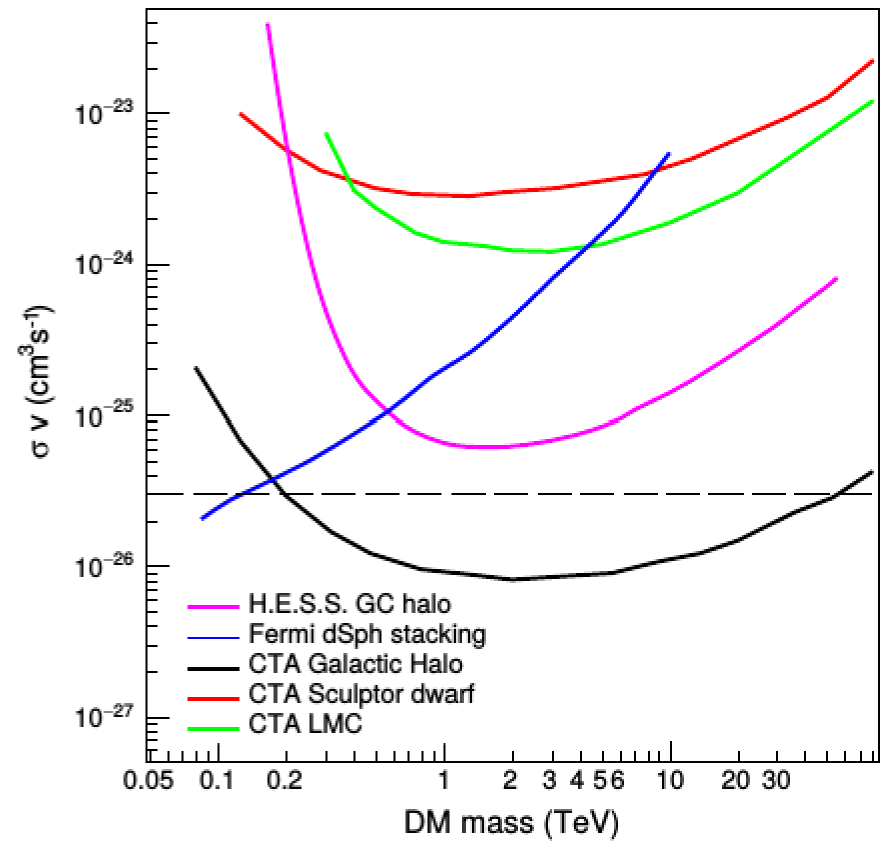




CTA simulated, Sol et al., 2013

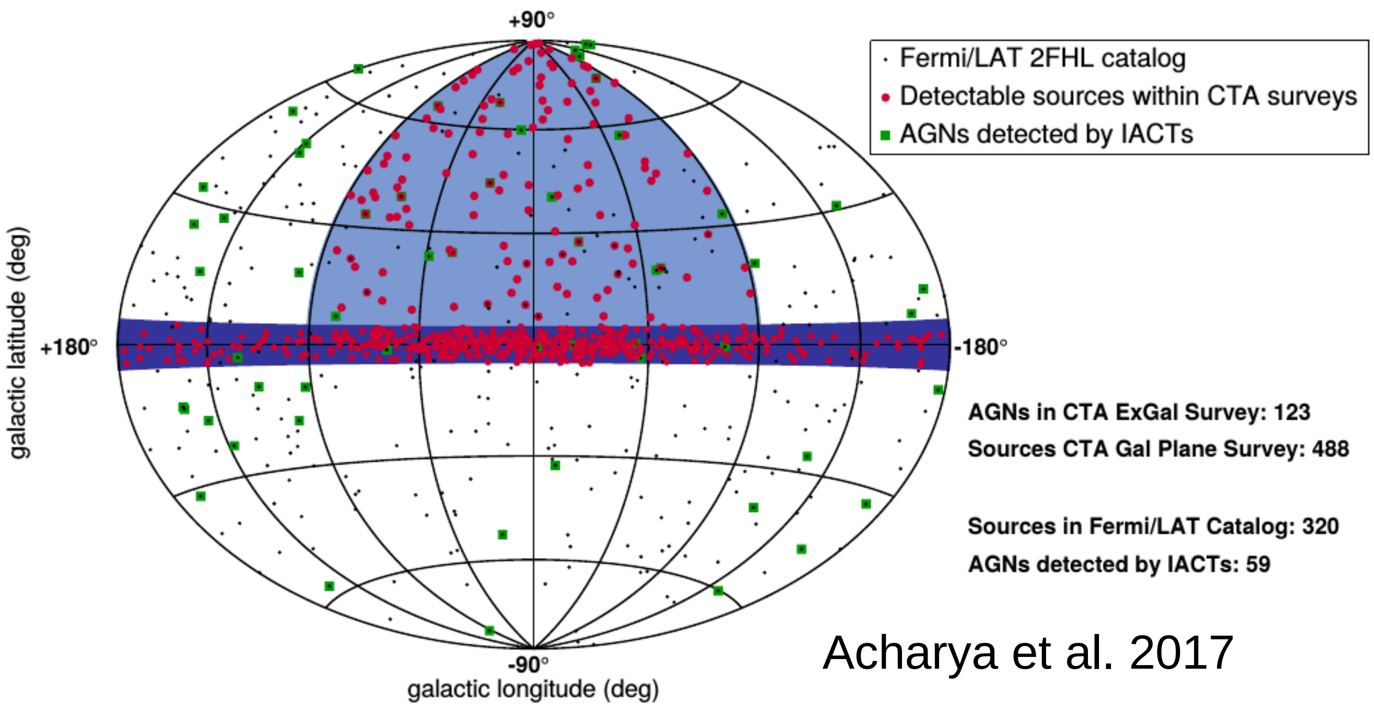
What can we do with CTA: detect new classes?

- Large gain in sensitivity will hopefully open the detection of classes of sources that have not yet been discovered at VHE: Counterparts of GW, Seyfert galaxies, novae, magnetars, Dark Matter, ...



Acharya et al. 2017

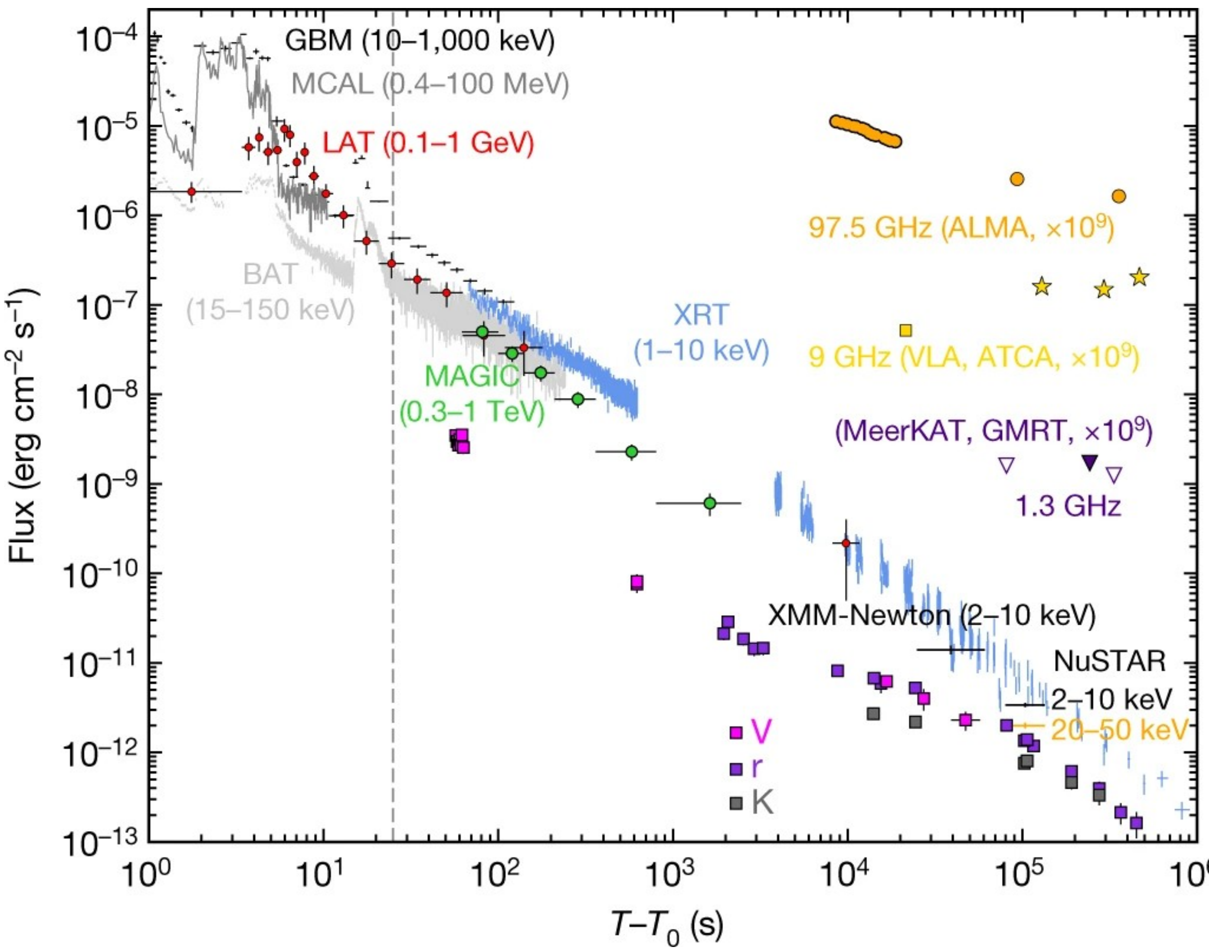
What can we do with CTA: scan of extragalactic sky



Acharya et al. 2017

- IACTs are pointing instruments, but (MST and SST) CTA telescopes will have a large field of view, which combined with special divergent pointing mode, can be used to perform an unbiased scan of a fraction of a sky.

GRB 190114C – light curve



Acciari et al. 2019