Observation of the gamma-ray sky from the ground: the IACT technique

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Disclaimer

I belong to the MAGIC collaboration since 2015, and to the LST one since 2018, so some of the discussions or results shown in this presentation may be biased towards them :)

Gamma-ray astronomy

- Its purpose is the study of how astrophysical sources produce gamma rays, and ultimately the possible relation with the origin of cosmic rays

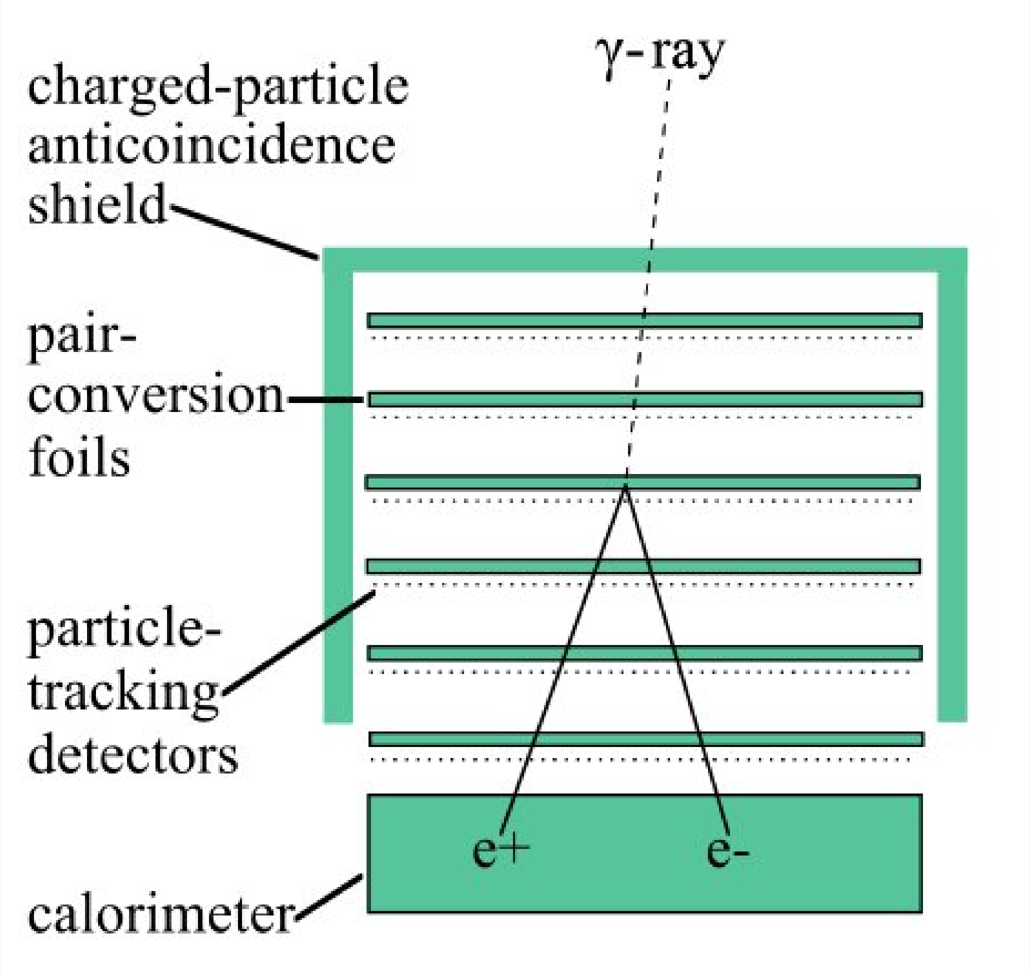
- It is customary to divide the gamma-ray energy range in the following bands:
  - High Energy (HE): 0.1 —> 100 GeV
    - satellite-based instruments e.g. Fermi-LAT
  - Very High Energy (VHE): 100 GeV —> 10-100 TeV
    - ground-based instruments: indirect detection e.g. via the imaging atmospheric Cherenkov technique (IACT) —> this talk

Detection with satellites

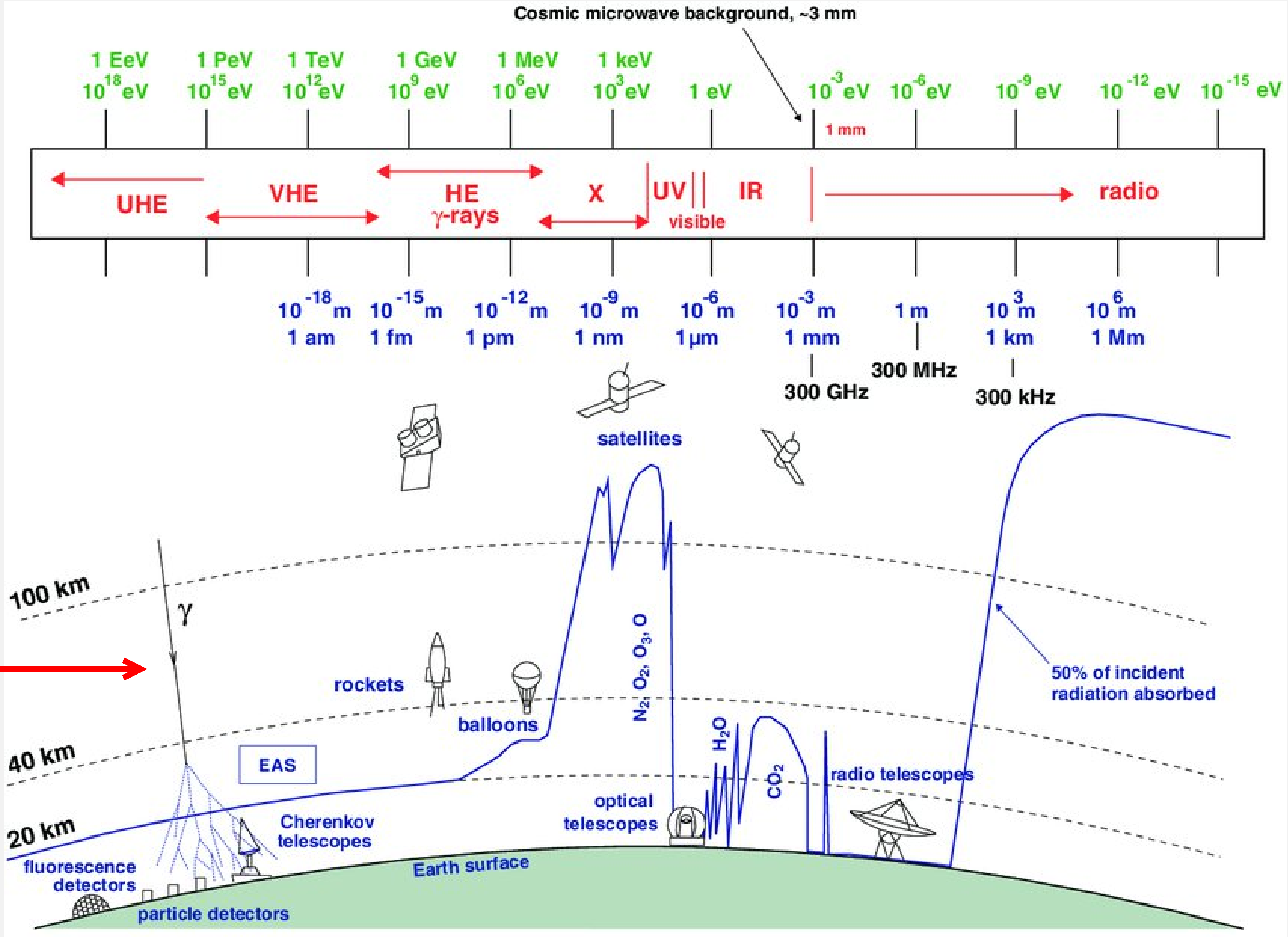
- The prime example is Fermi-LAT i.e. a pair conversion gamma-ray telescope

- But, limitations for energies above ~10 GeV
  - limited amount of high-Z material for the conversion of the incoming gamma into electron-positron pairs —> small effective area
  - limited size of the calorimeter for the energy reconstruction —> biased energy reconstruction

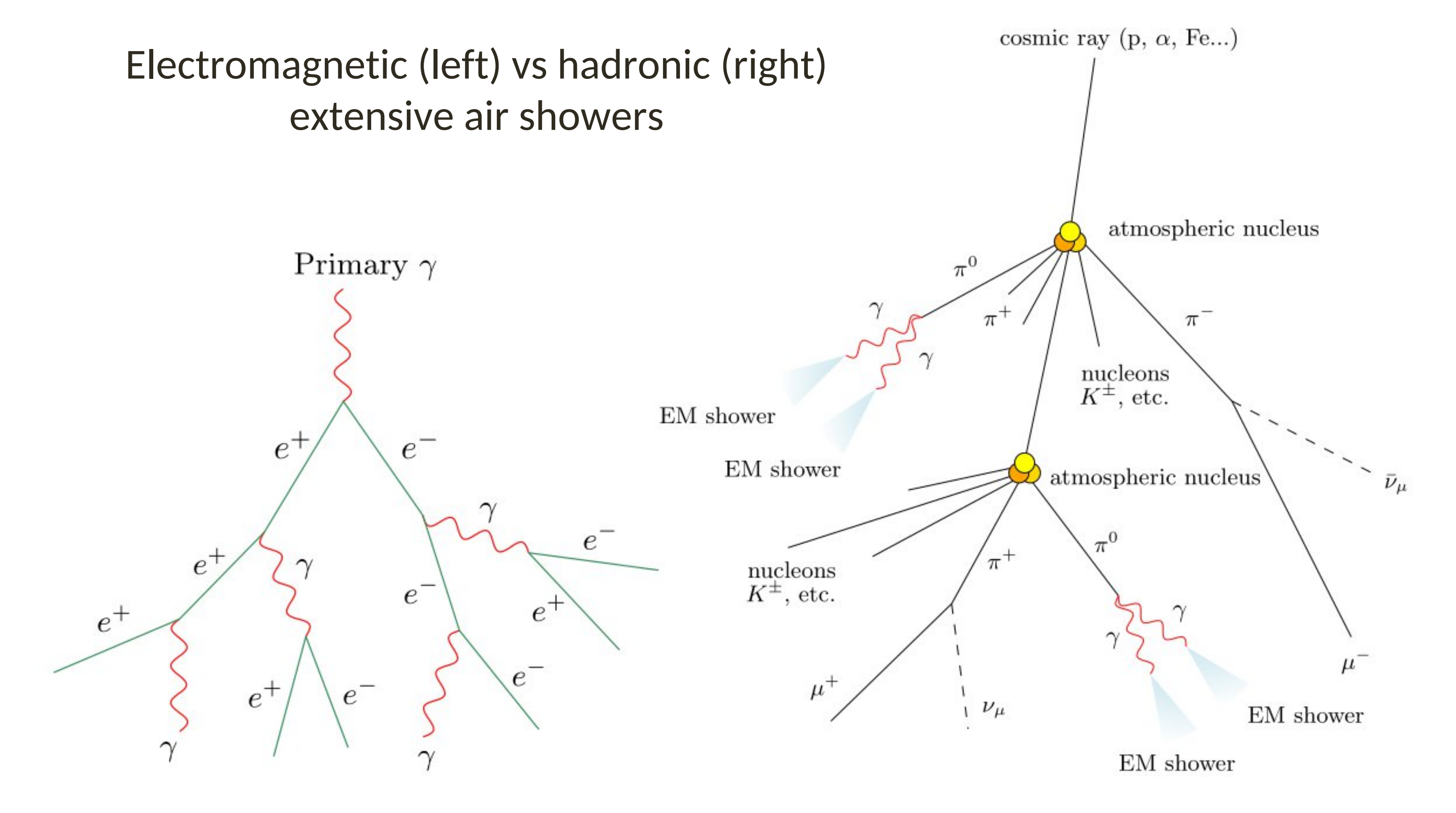
- Another technique is needed to detected the low flux of gamma rays at E>100 GeV!



The atmosphere is opaque to gamma rays, and they can be detected indirectly from its byproduct: extensive air showers!

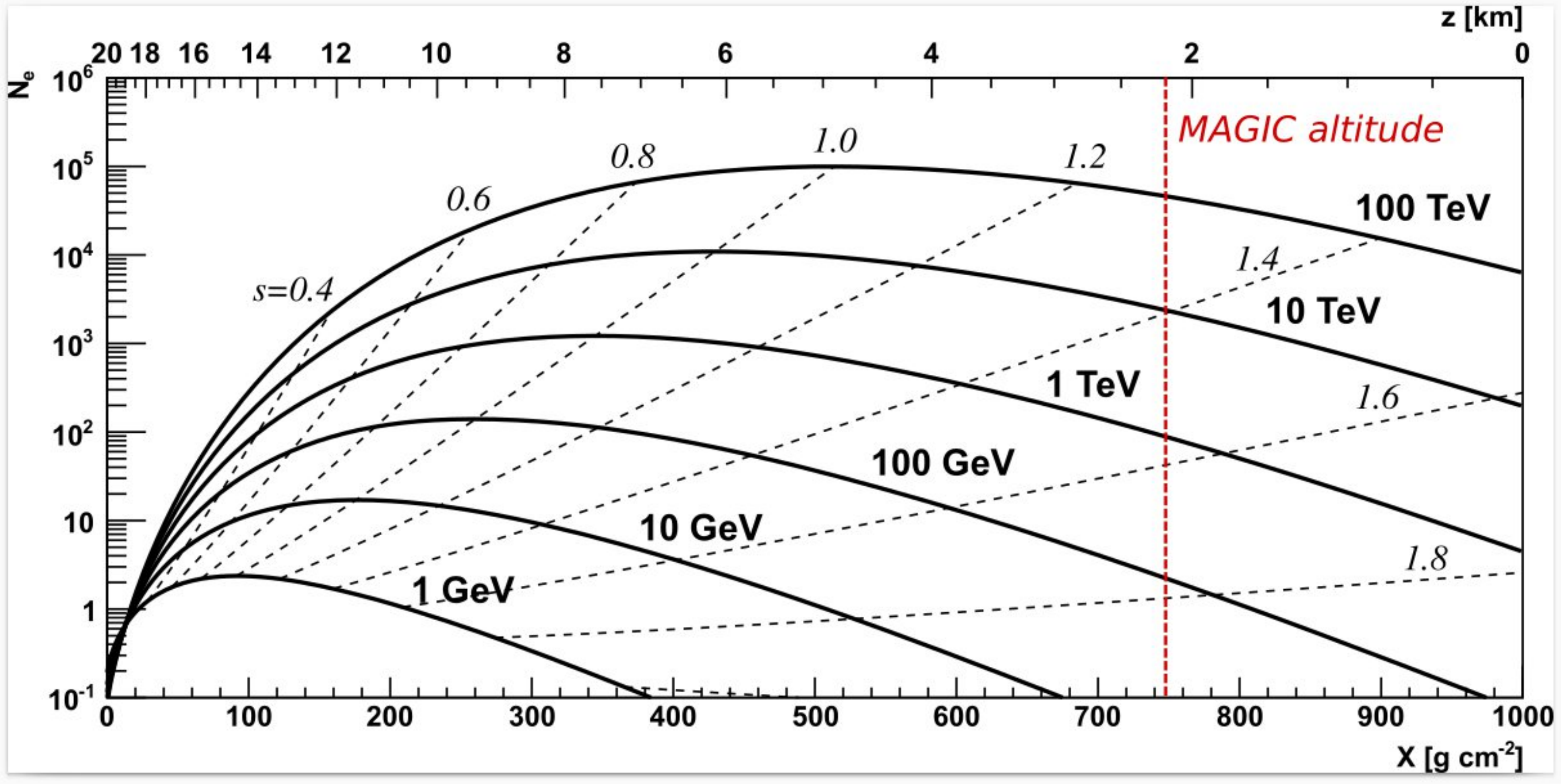


Extensive air showers



For EM showers, the shower keeps developing until electrons/positrons energy is greater than the critical energy E_c ~ 83 MeV in air (ionization energy loss prevails over bremmstrhalung and pair production)

Longitudinal development of EM showers

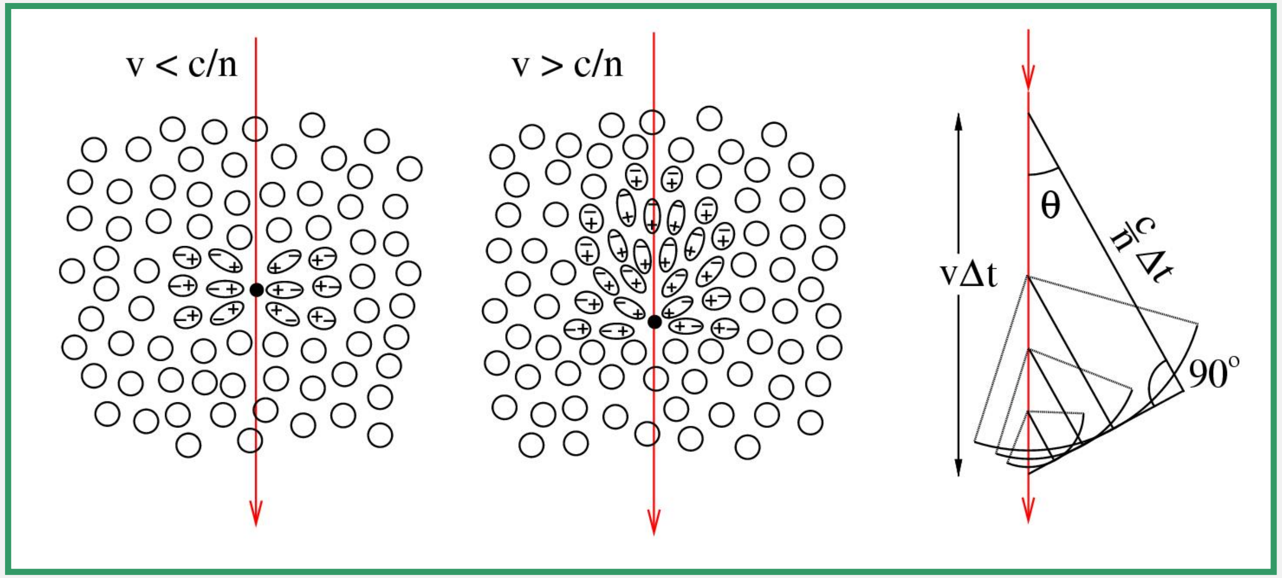


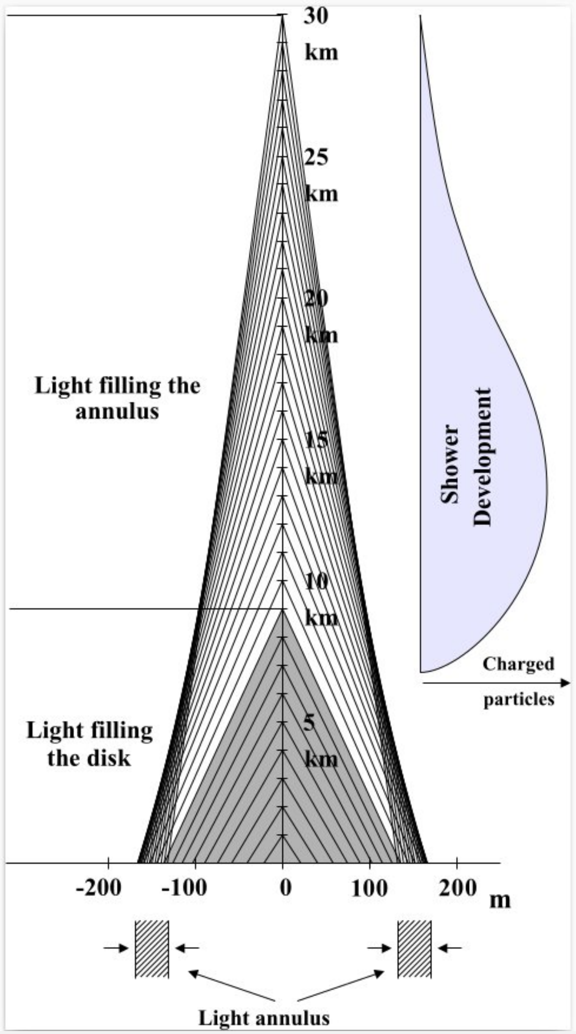
Very low number of particles surviving at “reasonable” altitudes —> we need something else to probe the shower and get information about the primary particle!
Or, you put your detector at higher altitudes to have enough particles to sample the EAS —> see Jim’s talk later!

Cherenkov effect in EAS

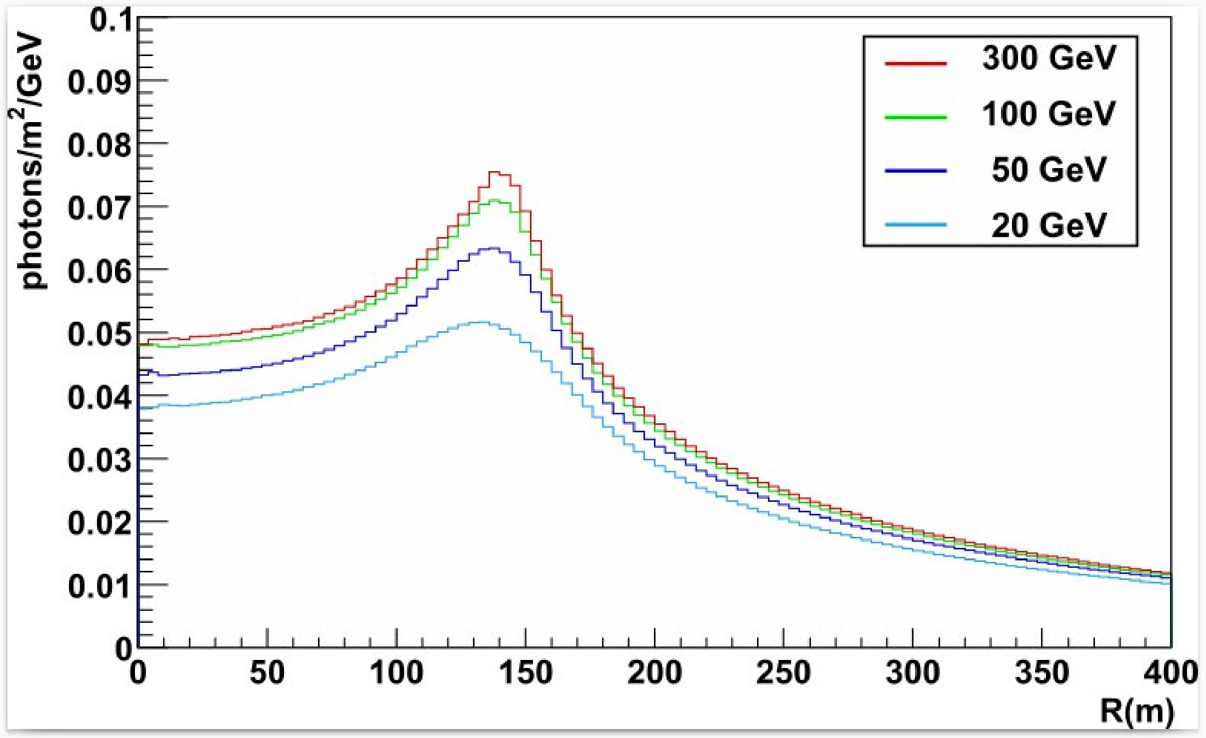
- It happens when a charged particle moves in a medium at a speed larger than that of light in that medium

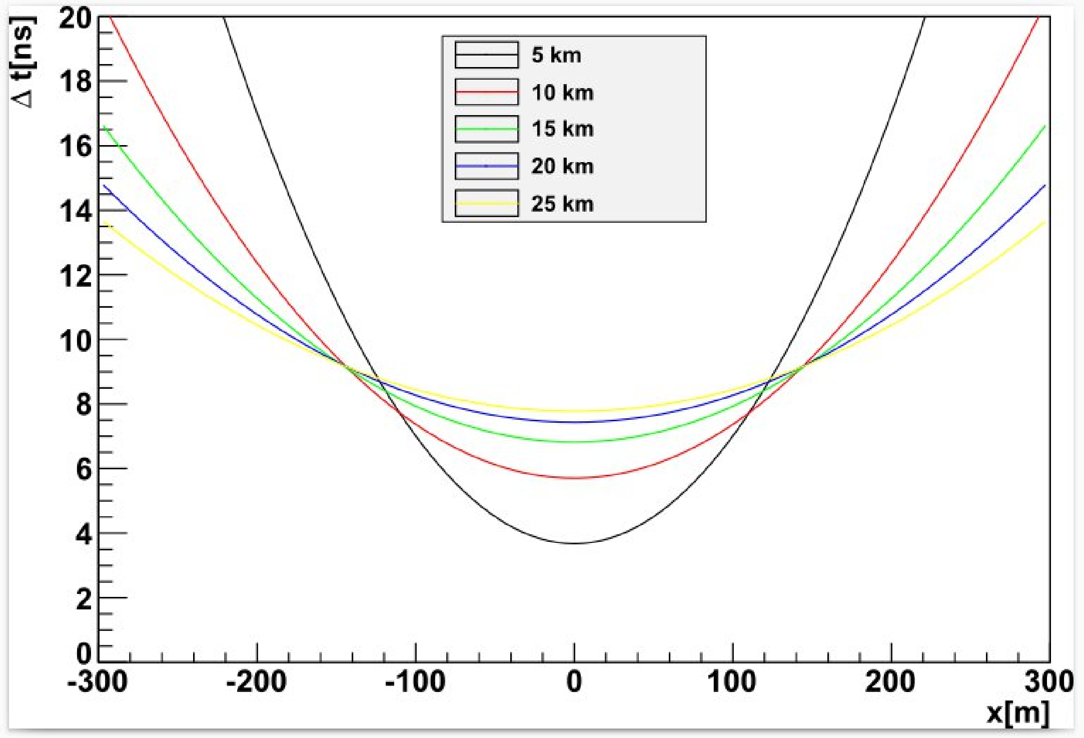
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v>c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse





Cherenkov effect in EAS

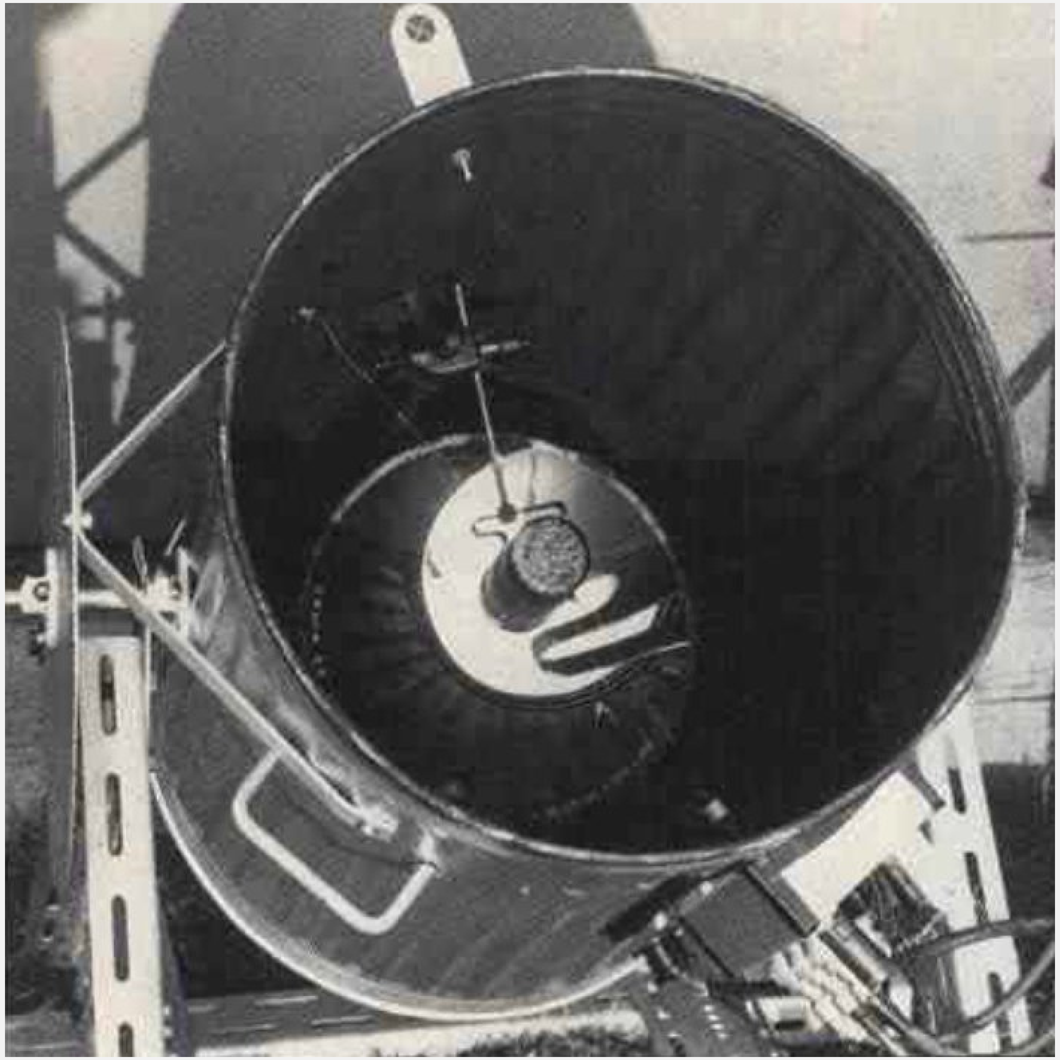




- Cherenkov light in EAS creates a light pool with a radius of ~100-150m with almost constant density of photons.
- Also, one can show that the number of Cherenkov photons is proportional to E_0, the energy of the primary particle —> a calorimetric measurement is possible!

- The Cherenkov light literally creates a flash that lasts some nanoseconds

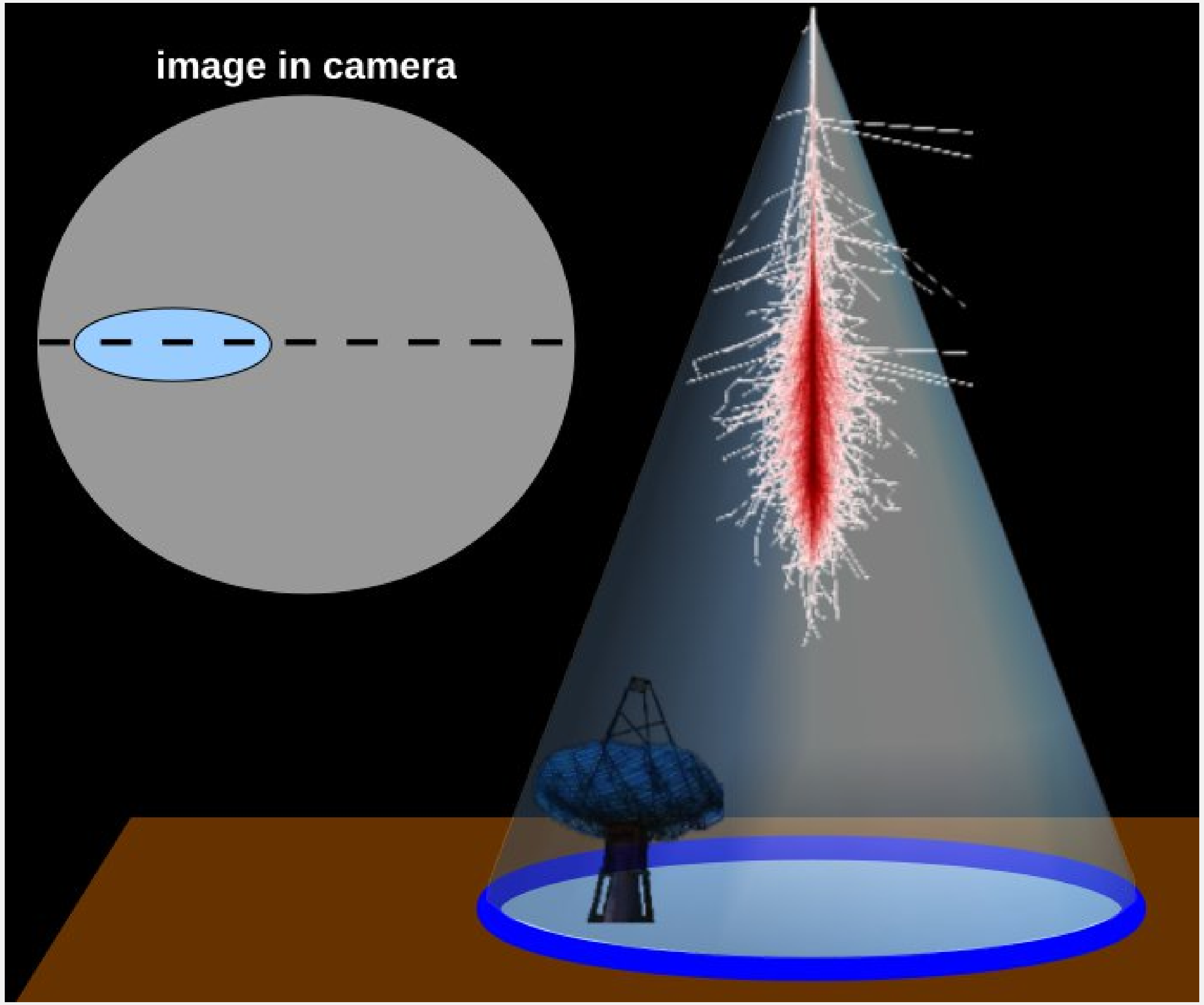
An atmospheric Cherenkov telescope



- A garbage can with a small mirror on the bottom, and a photomultiplier tube (light detector) on its focal point
- Jokes aside, a system like this, even quite rudimental, can detect the fast flashes from Cherenkov light emitted in a EAS
- What it cannot do
  - get any information about the primary particle e.g. cannot distinguish between EM and hadronic showers

Gailbraith and Jelley apparatus, 1955

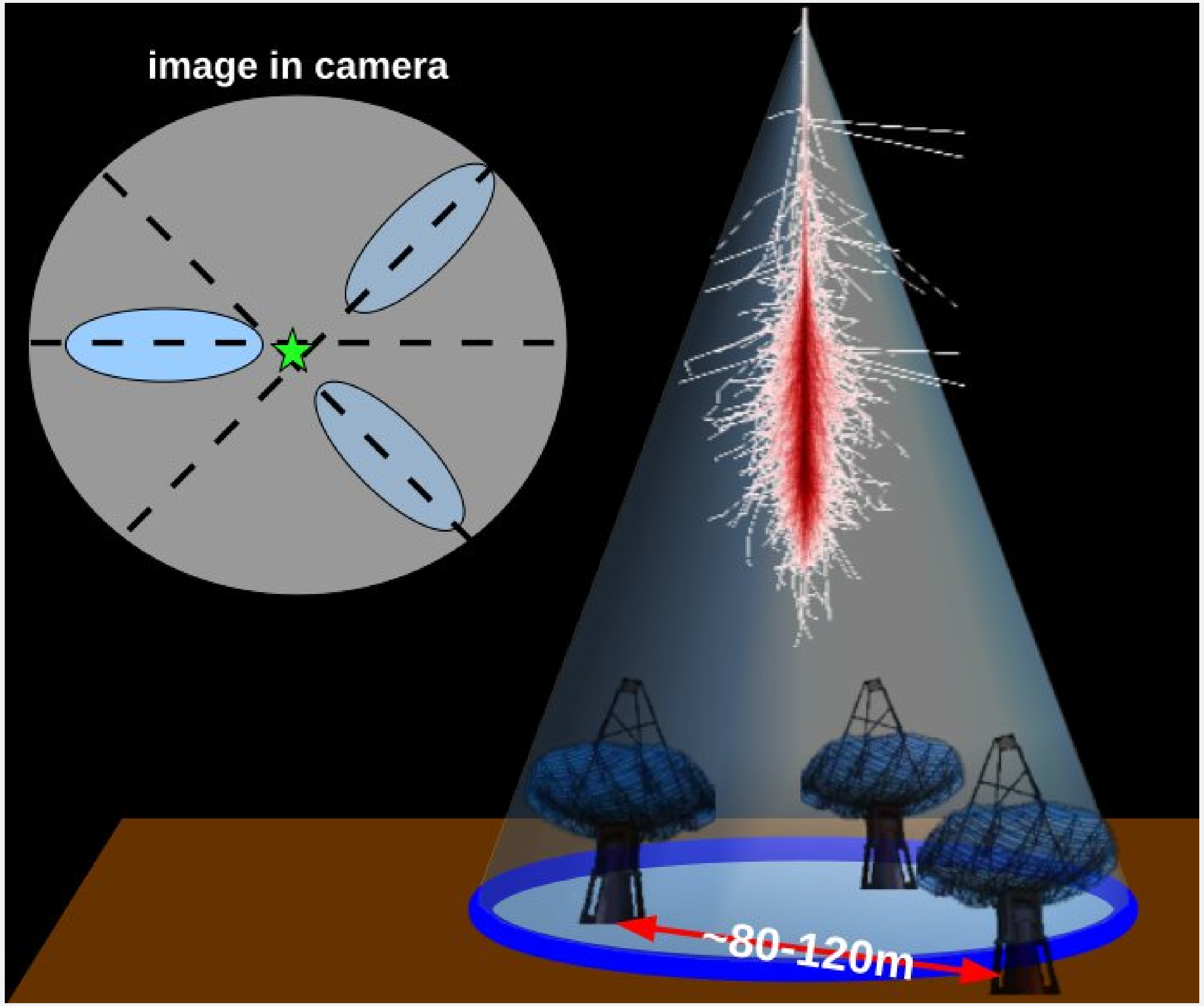
Imaging atmospheric Cherenkov technique



- If a telescope with a large mirror (ten-twenty meter diameter) and a camera at the focus equipped with many light detectors is within the Cherenkov light pool, it will detect and **image** the shower —> huge effective area (>10^3 m^2)

- Of course there are caveats
    - Cherenkov light intensity from EAS is low, so a IACT can work only during the night —> low duty cycle
    - if the primary energy is too low, there will not be enough Cherenkov photons to trigger the telescope (i.e. not distinguishable from the night sky background)
    - the field of view of IACTs is limited, from a few to ten degrees in diameter —> need to point sources
    - if you want to detect gamma rays, you are drowning in background: for each gamma-ray shower, there are ~10000 hadronic ones

Imaging atmospheric Cherenkov technique

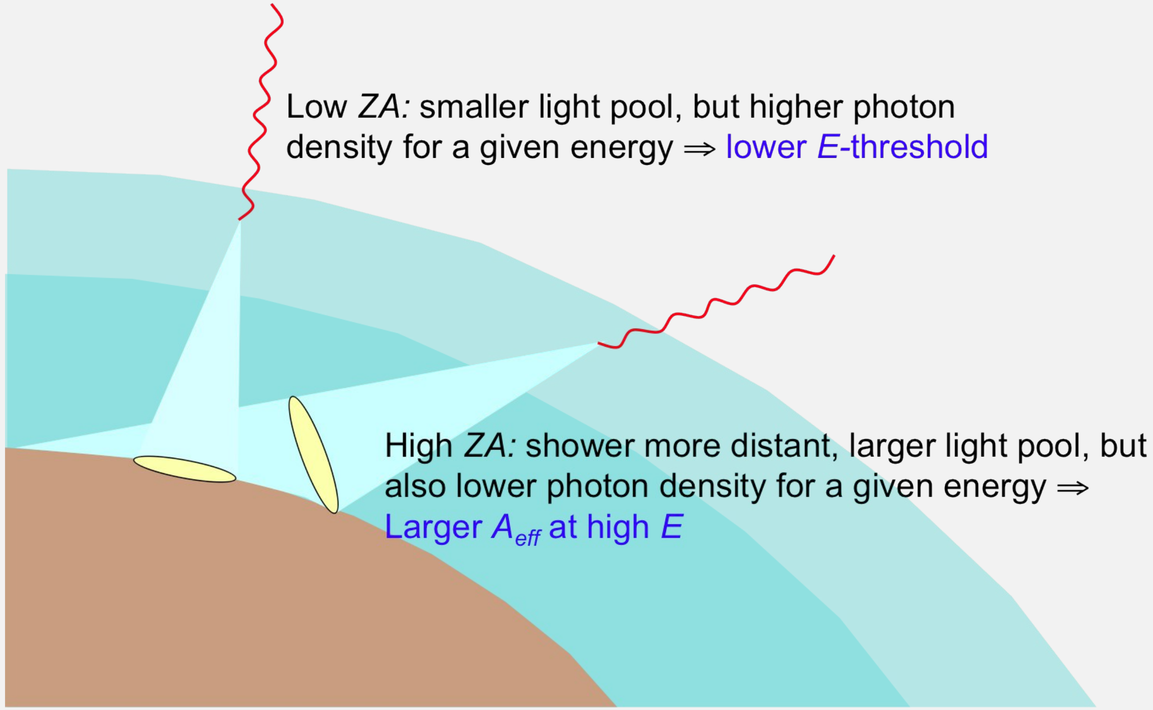


- An array of IACTs at distances comparable with the size of the light pool (~100m) can trigger on the same shower

- The same event is seen from a different “perspective”, and a 3D geometrical reconstruction is possible
  - stereoscopic technique

- It improves background rejection, event reconstruction (e.g. direction) and also energy reconstruction
  - utlimately, better sensitivity!

Other effects relevant for Cherenkov light in the atmosphere



- Zenith dependence of the energy threshold: higher for larger zenith, due to absorption of Cherenkov light in the atmosphere

- Geomagnetic field: it deviates electrons and positrons in opposite directions and influences the density distribution in the light pool

- Clouds and aerosols can also absorb the Cherenkov light, leading to a wrong energy reconstruction

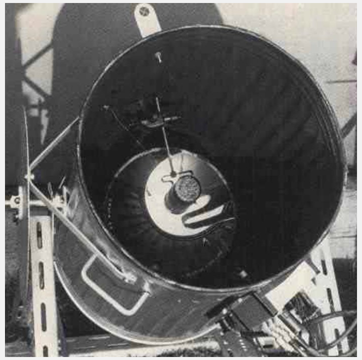
Pros and cons of IACTs

- Large effective area
  - Detection of low fluxes in “short” times
- “Fast”: capability of probing short time flux variability
- Low threshold, down to 10-20 GeV (E_{thr} α $1/A_{mirror}$)
- Good angular resolution, down to less than 0.1deg at hundreds of GeV —> good for morphological studies
- Good energy resolution for spectral features detection

- Reduced duty cycle (20-30%)
  - Affected by weather conditions
- Small field of view
  - Pointing telescopes
- Background dominated
  - Stereoscopic observation with IACT arrays drastically improves background rejection and event reconstruction
- Absorption of the VHE flux by the EBL

IACT generations

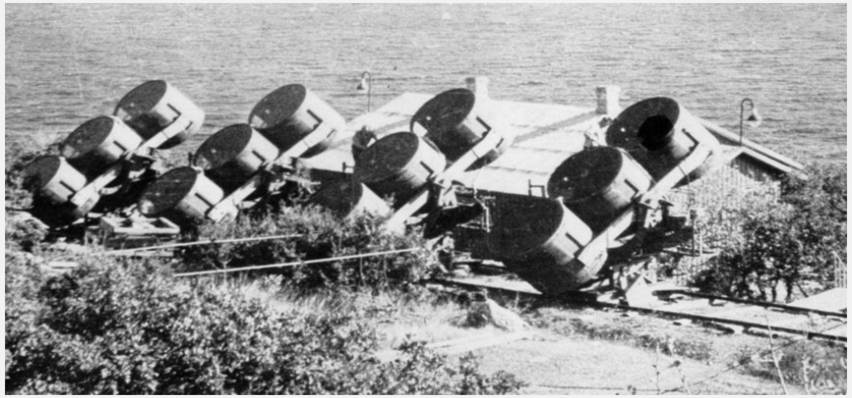
Gailbraith and Jelley apparatus, 1955



1st generation:
no imaging
capabilities

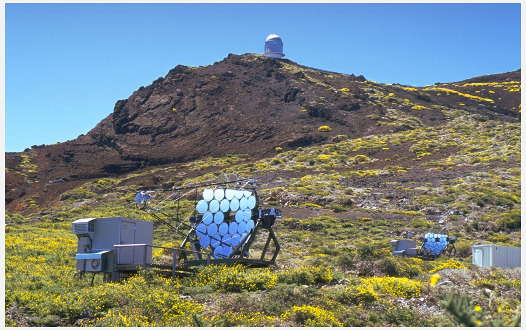
Whipple
1968 - 19?

Chudakov, 1960-1964



2nd generation:
imaging and
stereoscopy.

First gamma-ray
sources!!!



HEGRA
1992-2002

IACT generations

3rd generation:
larger reflectors, better technology, stereoscopy

VERITAS (2007-)

H.E.S.S. (2002-)

MAGIC (2003-)

Future: Cherenkov Telescope Array

2 arrays of multiple telescopes in Northern and Southern hemispheres

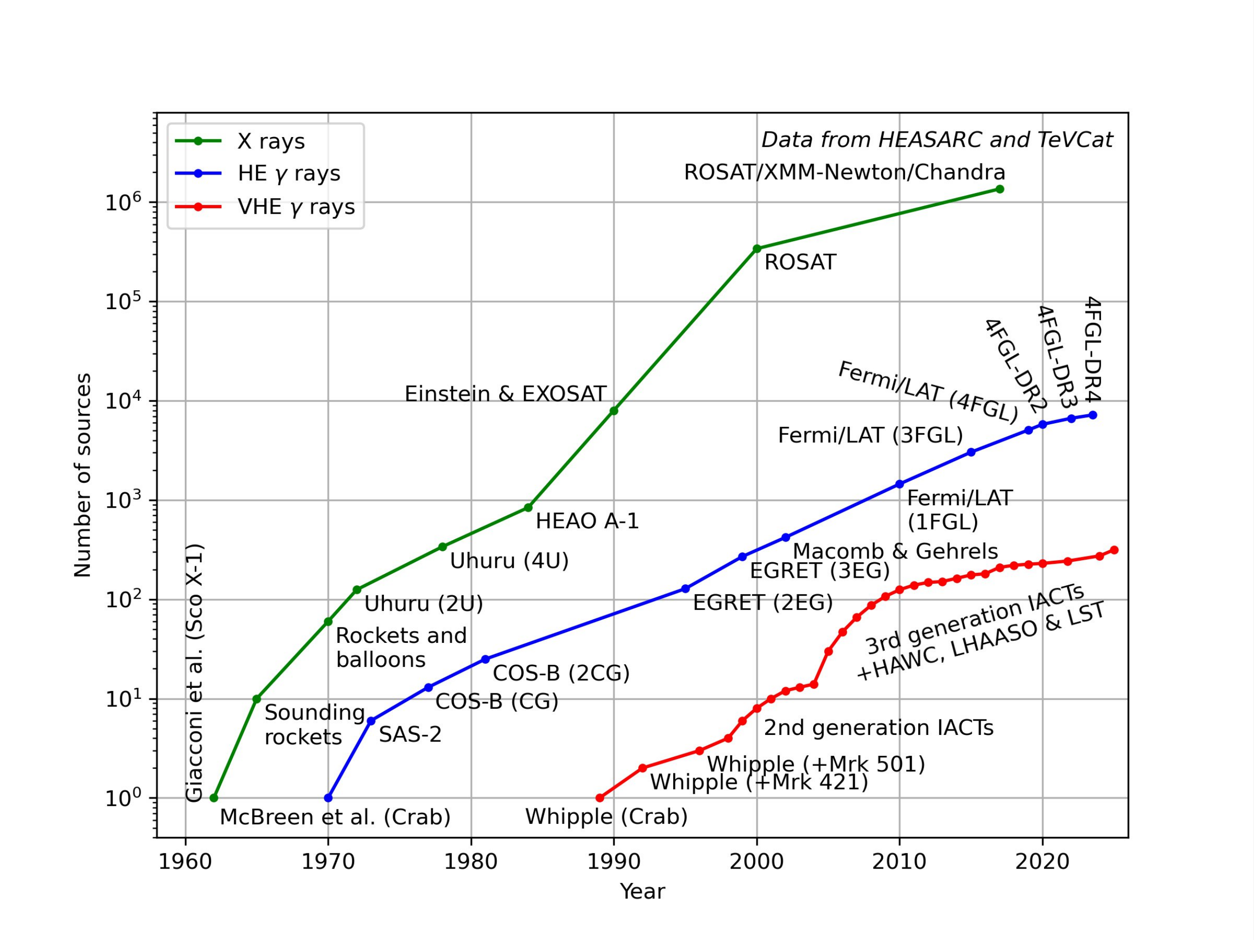
See the next talk by Paolo!

LST-1 (2018-)

Is the technique succesful?

- Someone said: if a telescope can within a few seconds evaporate a solid piece of steel, it can also measure gamma rays
- It is actually sublimation, but details :)

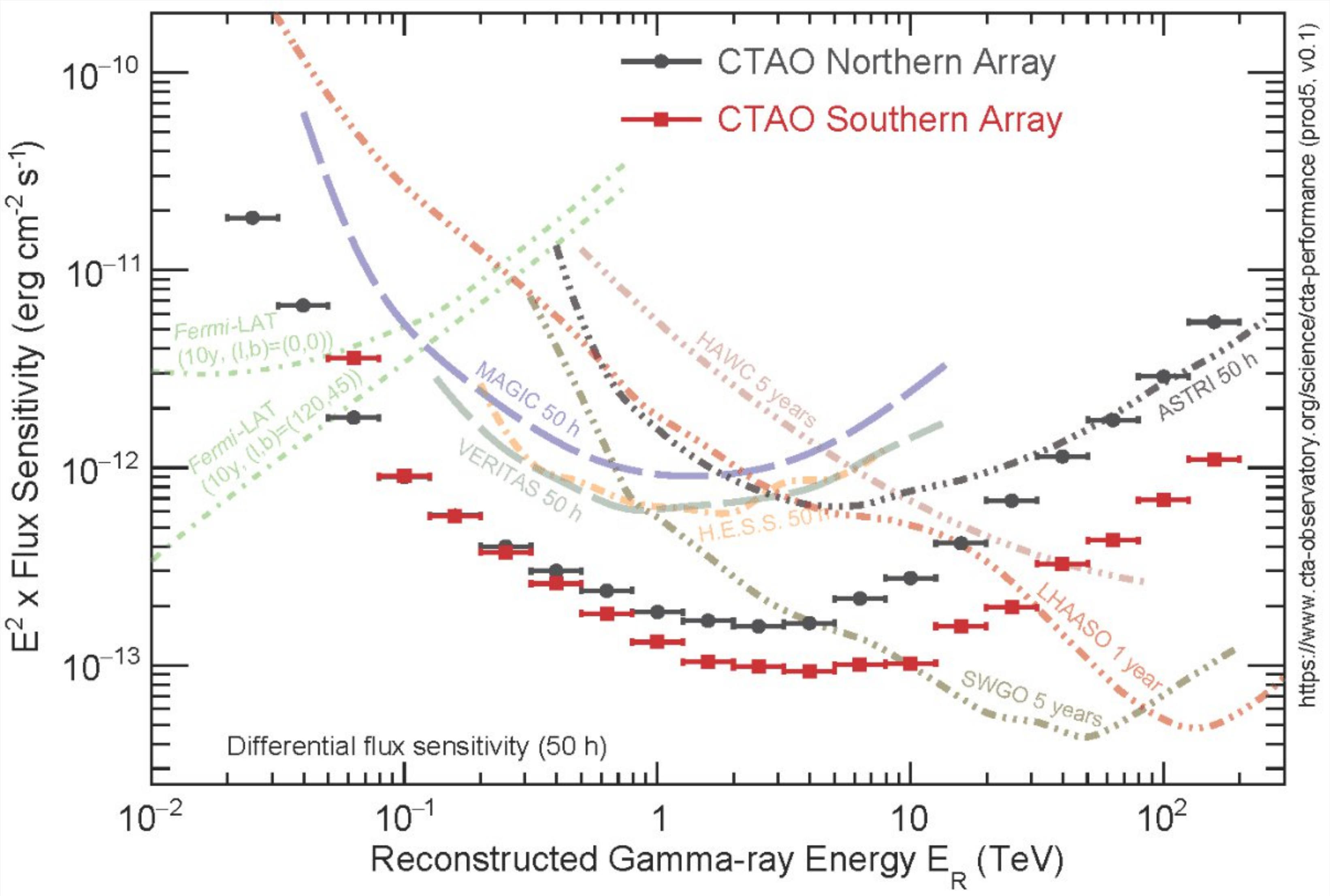
Is the technique succesful?



Updated figure from https://github.com/sfegan/kifune-plot/

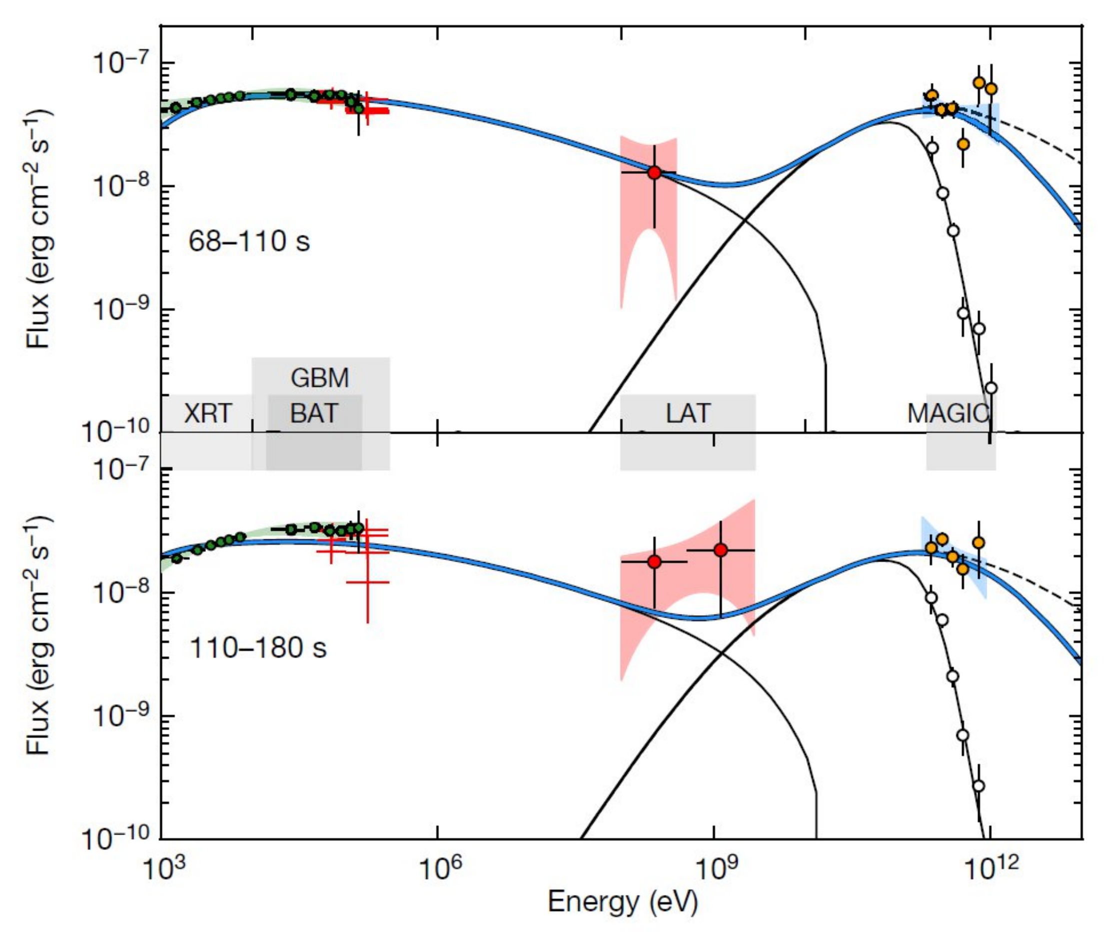
- Short answer: YES!
- "Kifune" plot, showing the evolution in time of the number of detected sources in different bands
- A clear increase with the 3rd generation of IACTs
- Mainly due to improvement in sensitivity, but also in observational strategies/campaigns
    - e.g. AGN flares, GRBs, novae

Sensitivity improvement

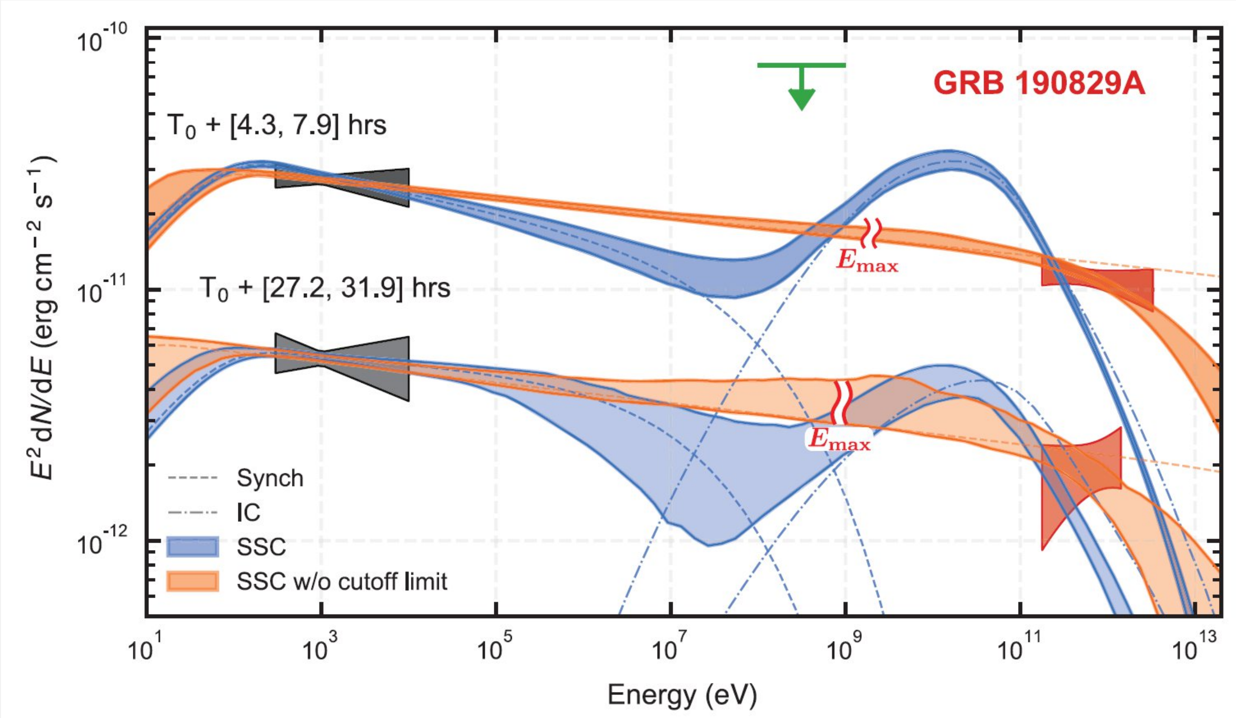


GRBs at VHE

GRB 190114C

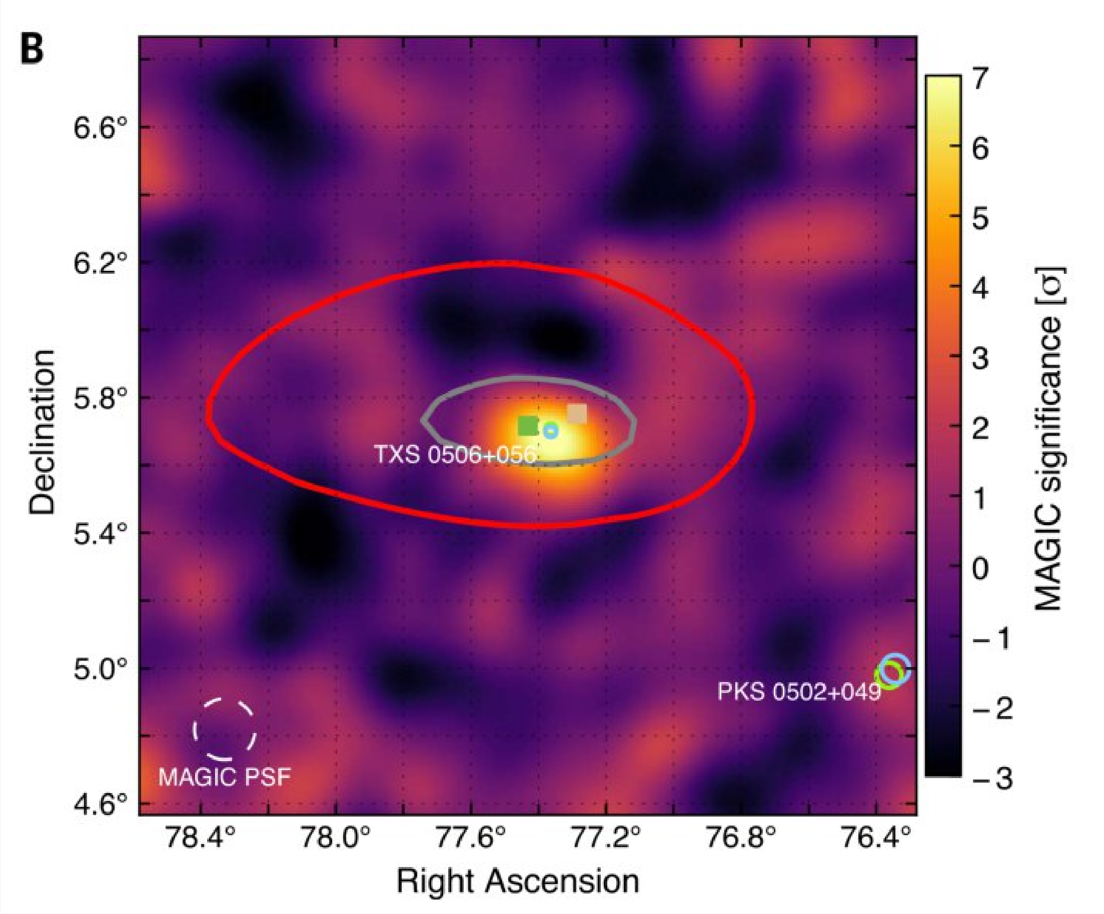


GRBs are VHE emitters!
4 GRBs detected by IACTs from 2018 to 2020
GRB 201216C farthest VHE source (z=1.1)



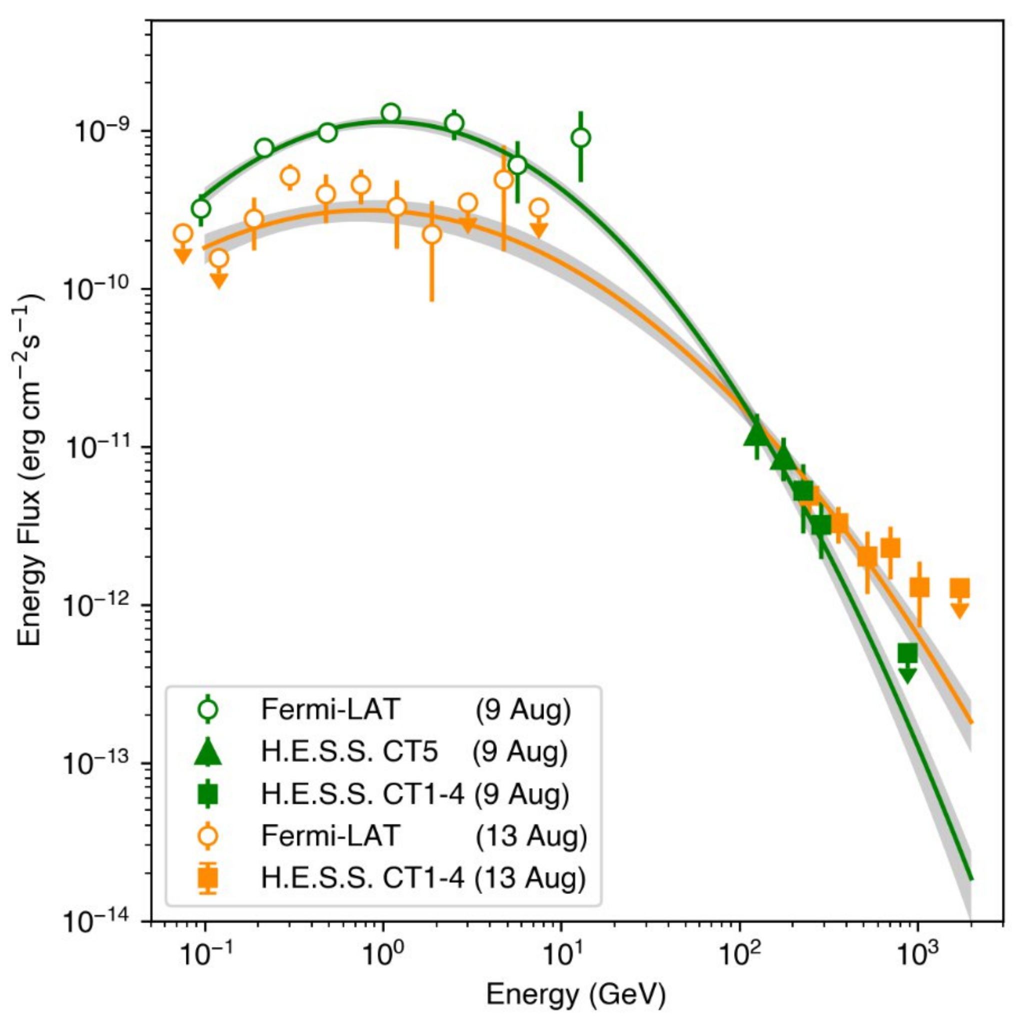
GRB 190829A

TXS 0506+056



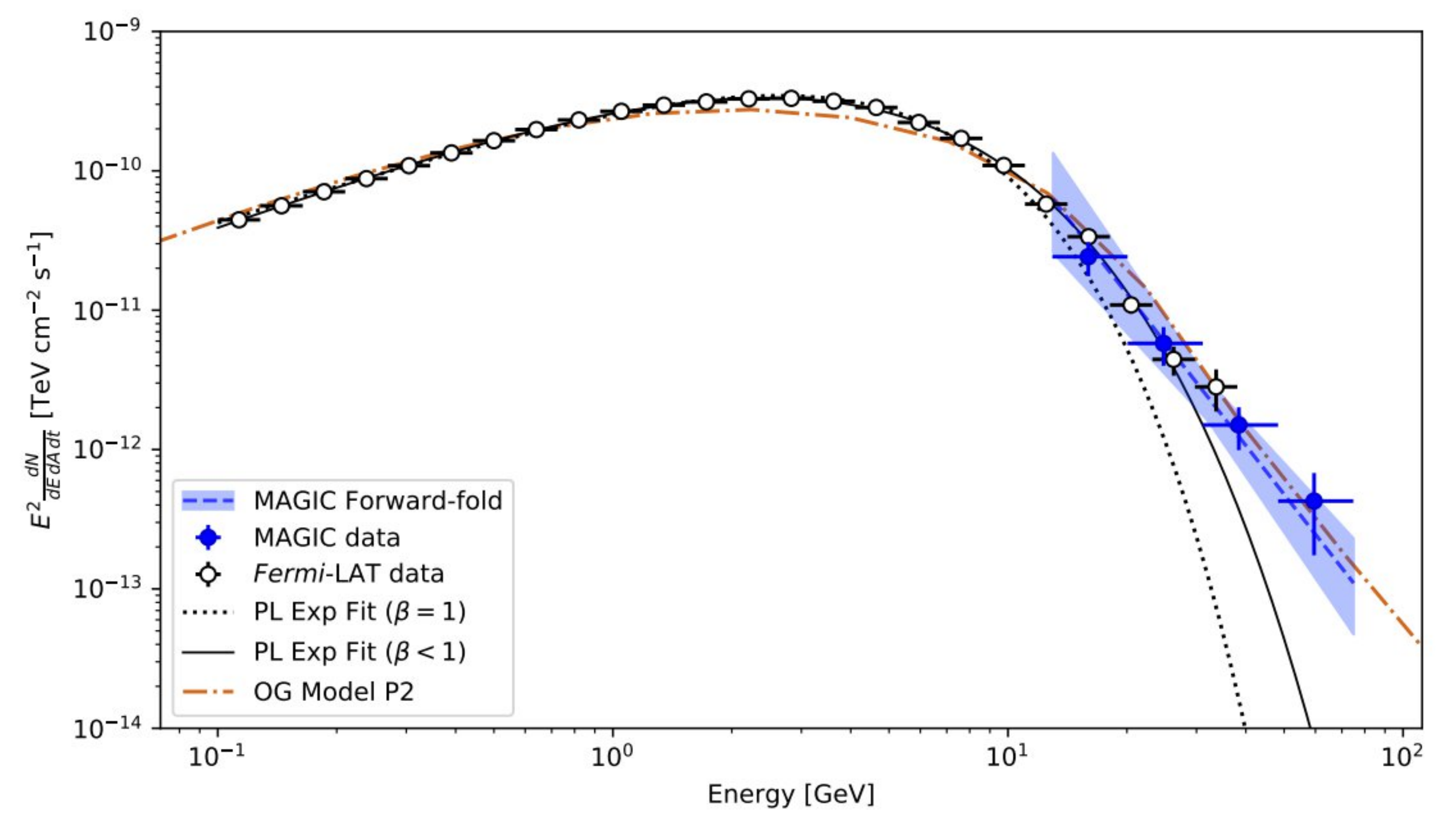
- Association of a high energy astrophysical neutrino (IC170922A) with an astrophysical source (TXS 0506+056, a blazar in this case)
- Detection by MAGIC and VERITAS
- Case of multi-messenger detection!
- Started the hunt for others candidate sources of high energy neutrinos (e.g. NGC 1068)

Novae



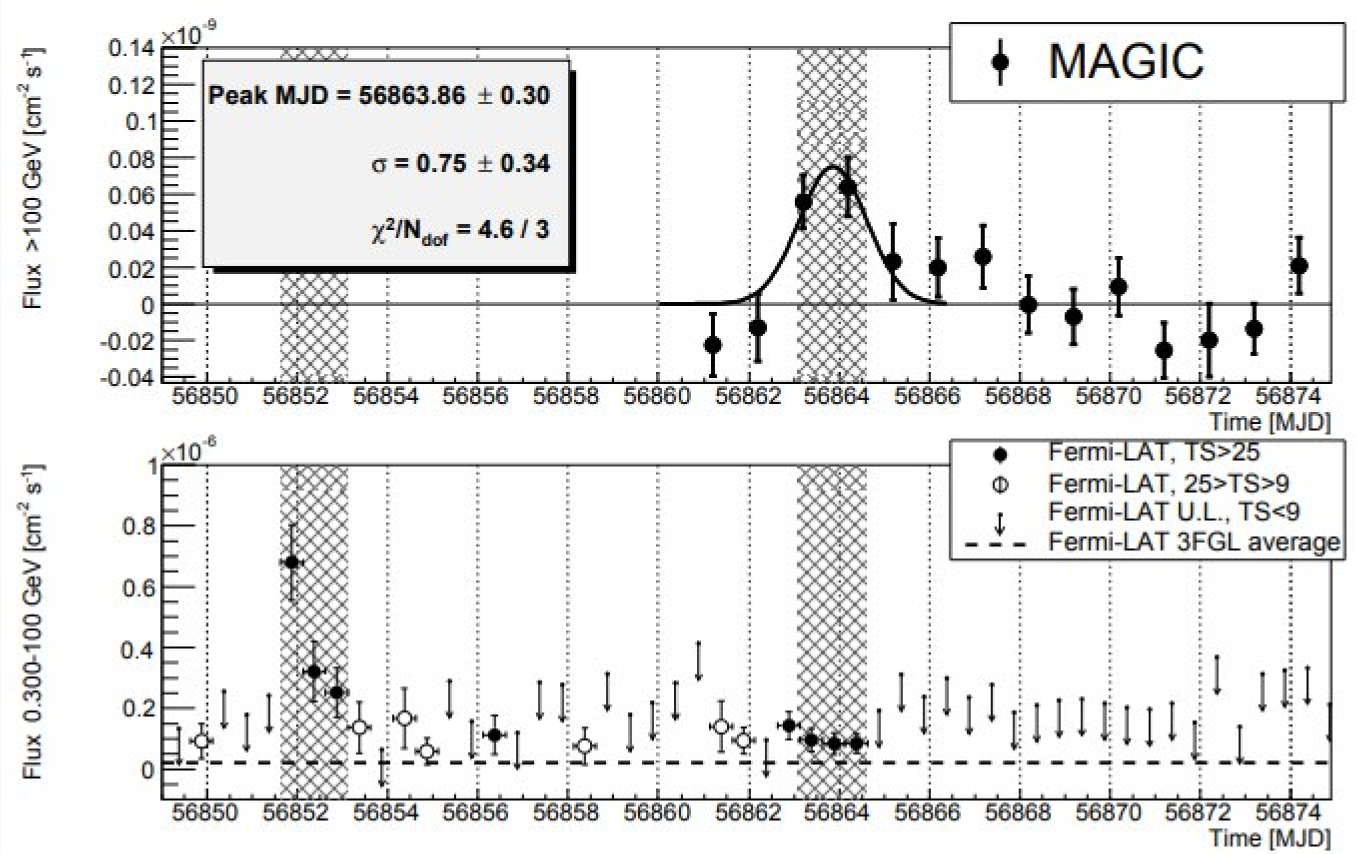
- New class of VHE emitter with the detection of the recurrent nova Rs Ophiuchi in 2021 by H.E.S.S. and then MAGIC
- Modeling suggests that there is acceleration of accelerated to hundreds of GeV in the nova shock
- Waiting for the explosion of another recurrent nova, T Coronae Borealis
  - could be any moment!
  - good target for stellar intensity interferometry with IACTs

Pulsars



- Only a few detected at VHE (Crab, Geminga, Vela, PSR B1706−44)
- Crab and Vela show pulsation up to 1 TeV
- Still debates on the location of the emission region

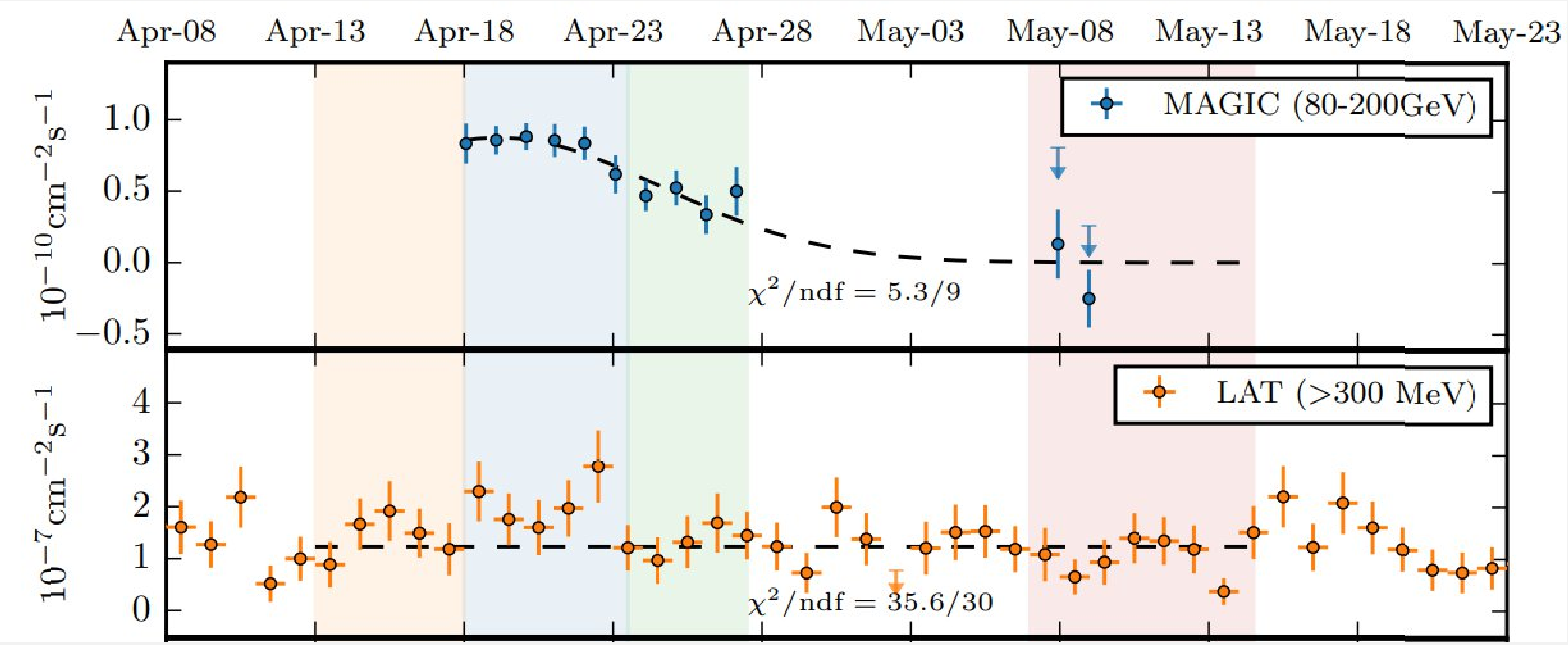
Gravitationally-lensed blazar



- QSO B0218+357: gravitationally lensed blazar located (z=0.944), splitting the radiation in two components delayed by 10-12 days

- MAGIC detected the VHE emission after Fermi-LAT detected an enhanced emission, with the delay expected

FSRQs: PKS 1441+25



- PKS 1441+25 is a FSRQ at z=0.94, detected by MAGIC after a flare in Fermi-LAT band in April 2015 (farthest source at the time)

OP 313

First detection of VHE gamma-ray emission from FSRQ OP 313 with LST-1

ATel #16381; *Juan Cortina (CIEMAT) for the CTAO LST collaboration*
*on **15 Dec 2023; 14:31 UT***
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, AGN, Blazar, Quasar

Referred to by ATel #: 16977

The Large-Sized Telescope (LST-1) on La Palma has been monitoring the very distant Flat Spectrum Radio Quasar (FSRQ) OP 313 (z=0.997, Schneider et al. 2010, AJ, 139, 2360) since November 2023. Following the announcement of enhanced gamma-ray emission by Fermi-LAT (ATel #16356) and several optical facilities (ATel #16360) in early December, the Fermi-LAT emission of OP 313 has been closely monitored using the FlaapLUC pipeline (Astronomy and Computing, Volume 22, p. 9-15, 2018). This monitoring revealed the detection of renewed activity in the high-energy (HE, E>100 MeV) band and so, Target of Opportunity observations with LST-1 were triggered on December 10th 2023. OP 313 was detected by LST-1 with a preliminary offline analysis using data from 2023/12/11 to 2023/12/14. It was detected with a significance greater than 5 sigma and an integrated flux, above 100 GeV, at 15% flux of the Crab Nebula. LST-1 observations on OP 313 will continue during the next few nights and therefore multi-wavelength observations are highly encouraged. LST-1 is a prototype of the Large-Sized Telescope for the Cherenkov Telescope Array Observatory, and is located on the Canary island of La Palma, Spain. The telescope design is optimized for observation of gamma rays in the range from 20 GeV to 3 TeV. The preliminary offline analysis has been performed by Daniel Morcuende (dmorcuende@iaa.es), Jorge Otero-Santos (joteros@iaa.es) and Seiya Nozaki (nozaki@mpp.mpg.de). The LST-1 contact persons for these observations are Masahiro Teshima (mteshima@mpp.mpg.de) and Juan Cortina (juan.cortina@ciemat.es).

- Another FSRQ at z=0.997
- Discovered by LST-1 in december 2023: first scientific discovery
  - low energy threshold necessary due to large absorption of the VHE flux
- Detected also by MAGIC

Summary

- The IACT technique is relatively young, and is still in development
- It provided many breakthroughs in VHE astrophysics, and possibly many more to come (DM? new physics?)
  – I did not mention many scientific results e.g. Galactic plane and Galactic center, M87, DM limits, ALPs limits etc. Sorry if I did not mention your favourite source or topic :/
- The current generation of IACTs are still providing important results
- The future is bright, with an observatory that is taking shape in these very years!