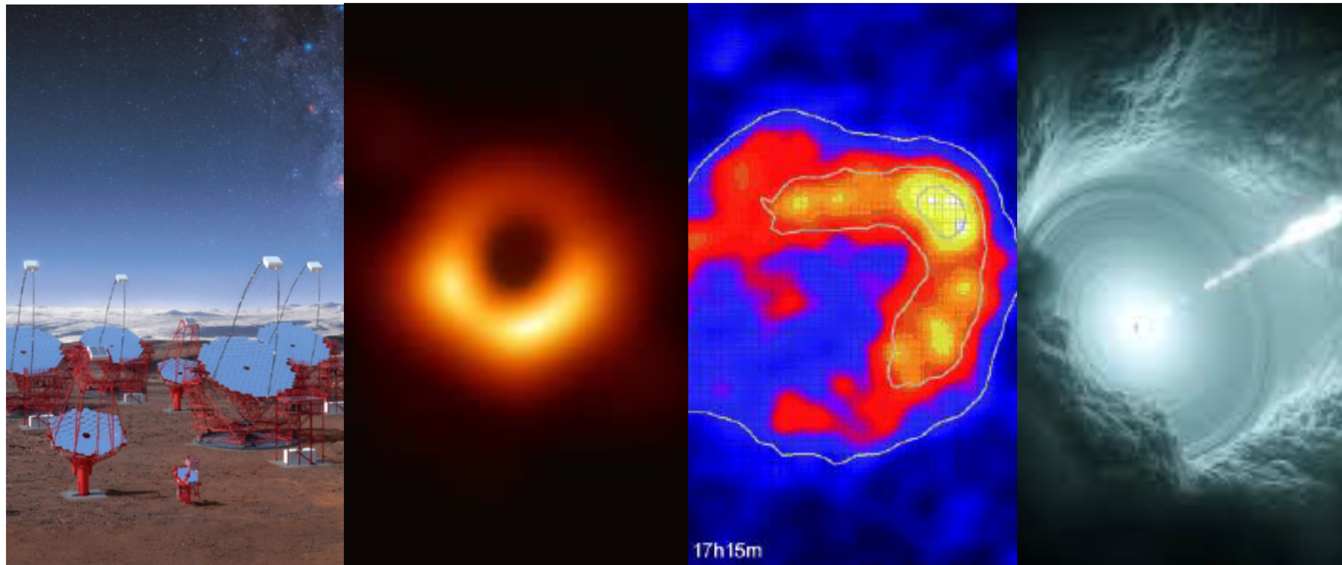

TeV ASTRONOMY

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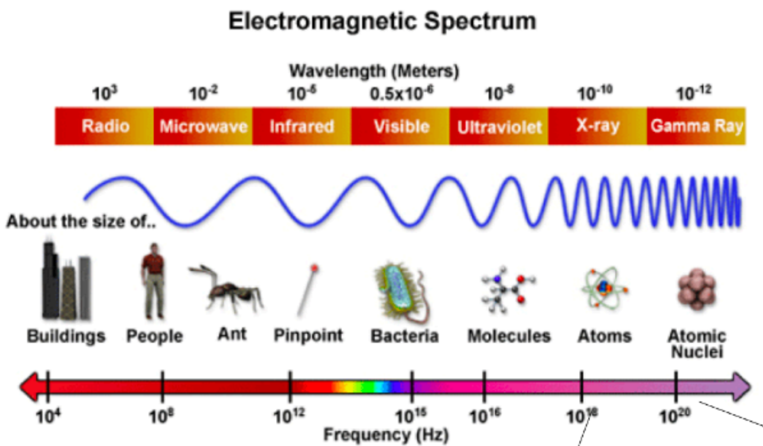
Université Paris Cité
Astroparticule et Cosmologie (APC)

Athens
January 17, 2024

GAMMA-RAY ASTRONOMY



Not all gamma-rays are the same!

The threshold energies are arbitrary:
Each band has a different
detection technique

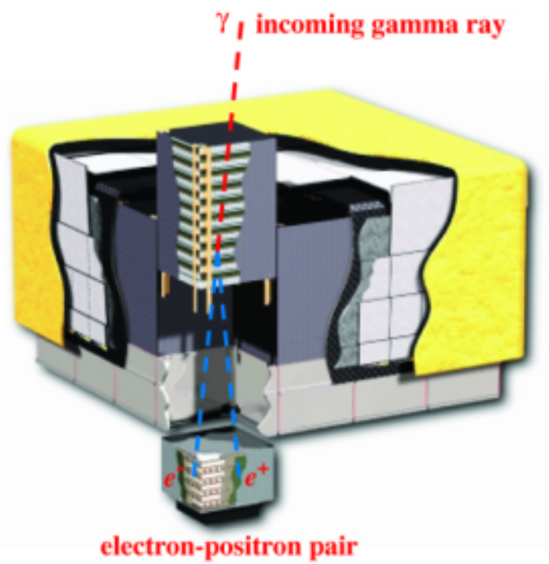
Soft γ rays	High energy γ rays (Fermi-LAT)	Very High energy γ rays (Cherenkov telescopes)

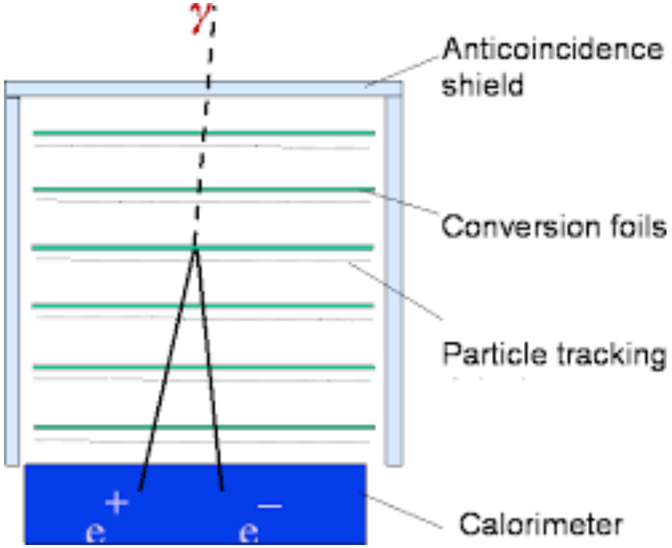
~100 keV ~100 MeV ~100 GeV ~100 TeV

Very-high-energies! VHE: E > 100 GeV

GeV ASTRONOMY

Pair conversion instruments (Fermi-LAT)

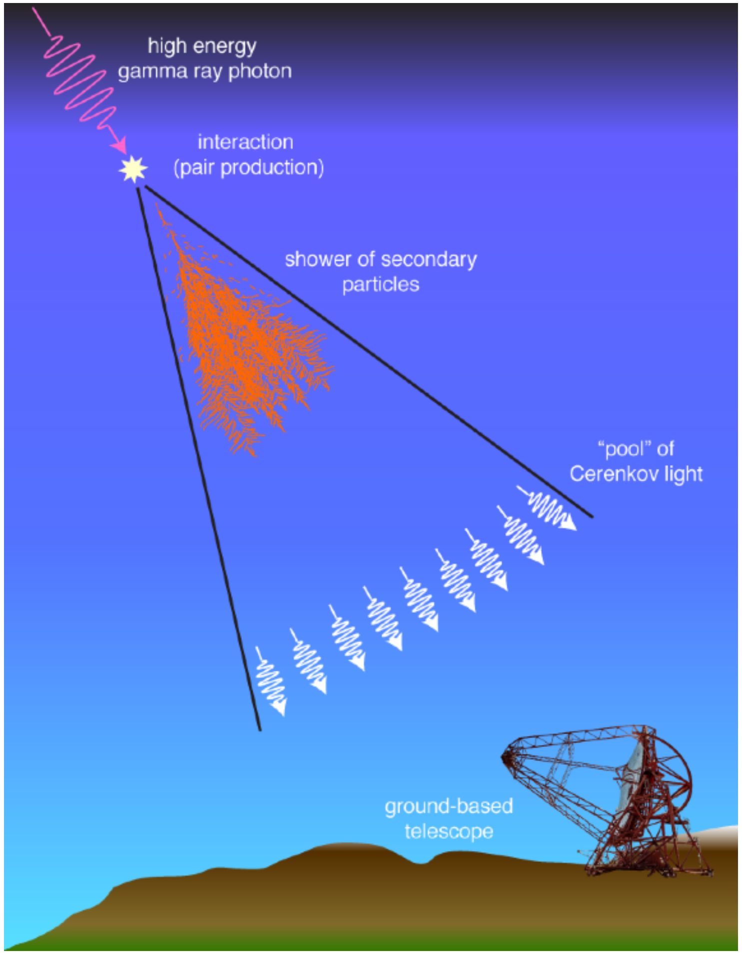




It CAN detect TeV photons!
But to compensate for reduced fluxes (power law function) the effective area has to increase a lot

TeV ASTRONOMY

We observe from the ground!



The photon pair produces on the atmosphere's atoms;

Cascade of secondary electrons/ positrons;

They are superluminal in the medium;

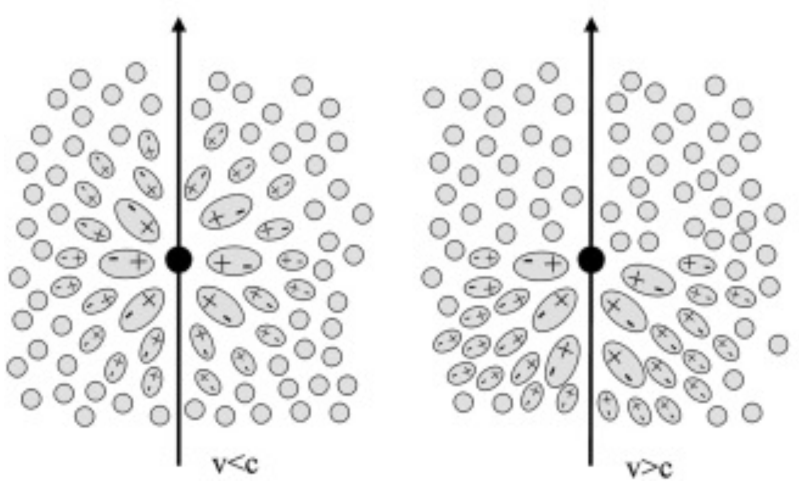
Cherenkov light can be observed from the ground

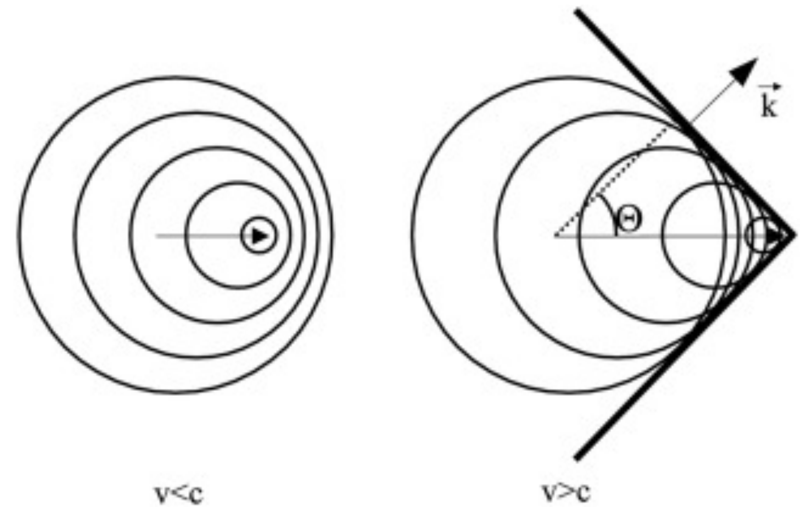
The effective area is much larger than direct detections!
(But the reconstruction gets more complex)

CHERENKOV RADIATION

Reminder:

Almost the same as supersonic bang, but related to polarization/depolarization of the medium by a charged particle. If v>c, the depolarization emission has constructive interference





WHAT DO YOU NEED TO OBSERVE IT?

Or, why didn't we do it earlier?
(or, can't I see it with my eyes?)

1) The Cherenkov cascades are flashes
that last only nanoseconds

2) they are very faint!
Any background light is a killer

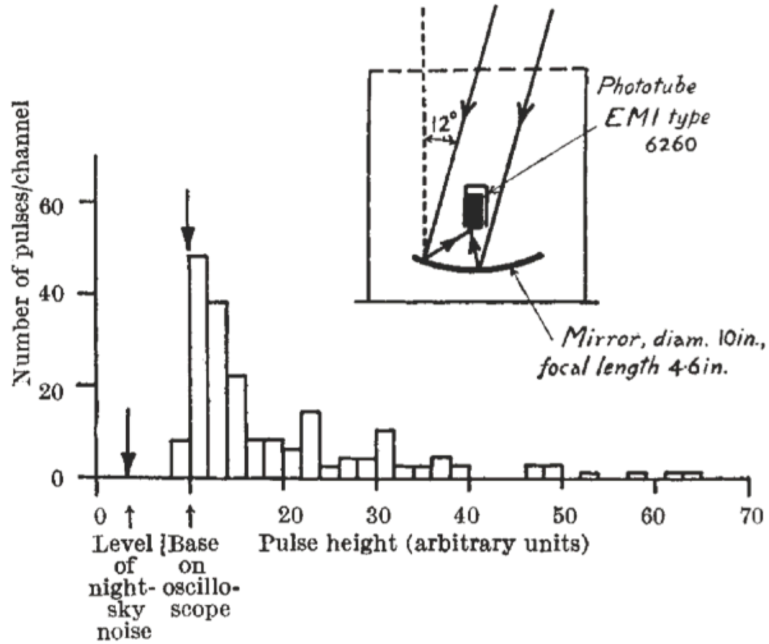
3) cosmic rays also produce cascades, see later
(i.e. to do astronomy is even more challenging)

TeV astronomy needs large collection areas
(10s of meters); photomultipliers
and fast electronics

HISTORY OF TeV ASTRONOMY

The first challenge is to detect Cherenkov light from particle showers

Light Pulses from the Night Sky associated with Cosmic Rays



Achieved in 1953 by Galbraith & Jelley

…then 35 years pass…

HISTORY OF TeV ASTRONOMY

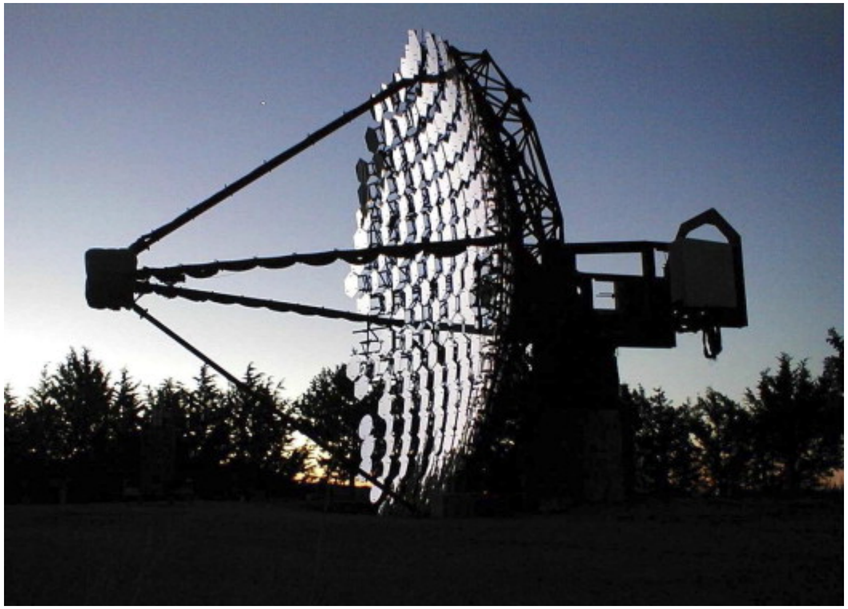
Second generation of Cherenkov Telescopes (~1990-2005)

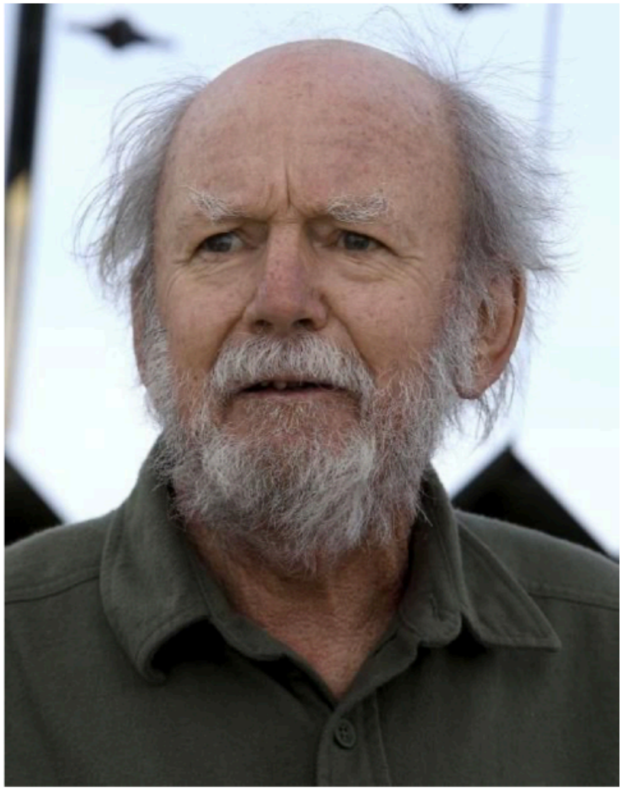
photon identification, and first sources:
Whipple (Arizona)
CAT (France)
HEGRA (Canary Islands)



HISTORY OF TeV ASTRONOMY

The Whipple 10-m Telescope and Trevor Weekes opened the window of TeV astronomy





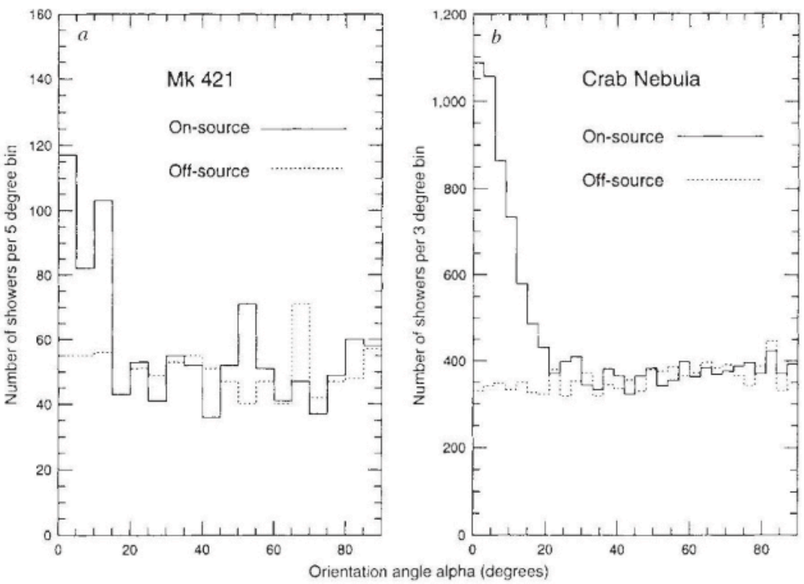
HISTORY OF TeV ASTRONOMY

The Whipple 10-m Observatory and Trevor Weekes opened the window of TeV astronomy

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

Received 1988 August 1; accepted 1988 December 9



Detection of TeV photons from the active galaxy Markarian 421

M. Punch*†, C. W. Akerlof‡, M. F. Cawley§, M. Chantell*, D. J. Fegan†, S. Fennell*†, J. A. Gaidos||, J. Hagan†, A. M. Hillas¶, Y. Jiang*, A. D. Kerrick#, R. C. Lamb#, M. A. Lawrence*, D. A. Lewis#, D. I. Meyer‡, G. Mohanty#, K. S. O'Flaherty†, P. T. Reynolds#, A. C. Rovero*, M. S. Schubnell‡, G. Sembroski||, T. C. Weekes*, T. Whitaker* & C. Wilson||

TeV ASTRONOMY: THE PRESENT

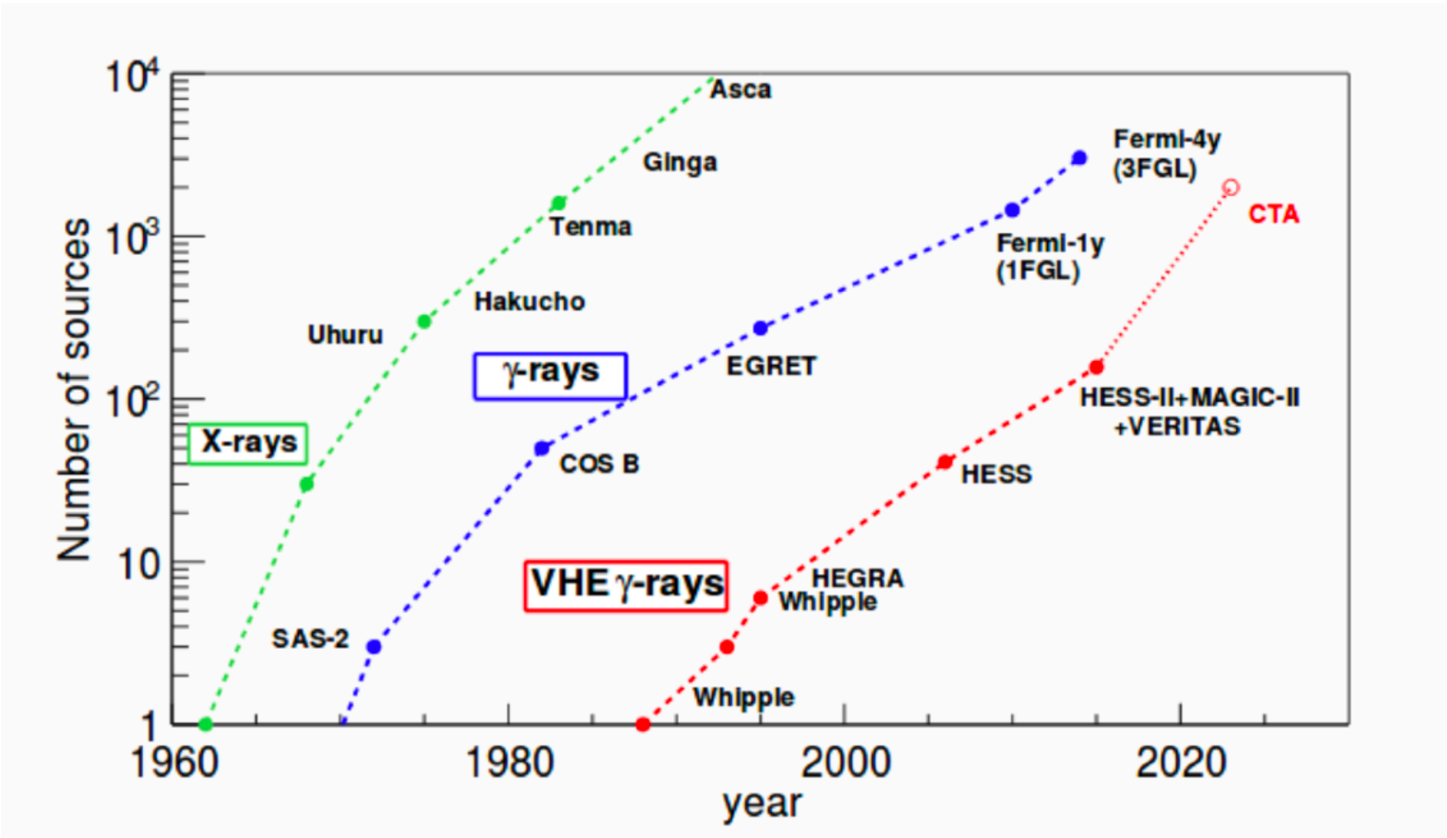
The third generation (2005-today) :
stereoscopy, and larger mirrors

VERITAS (Arizona, at the same site as Whipple)
HESS (Namibia)
MAGIC (Canary Islands, same site as HEGRA)



TeV ASTRONOMY: THE PRESENT

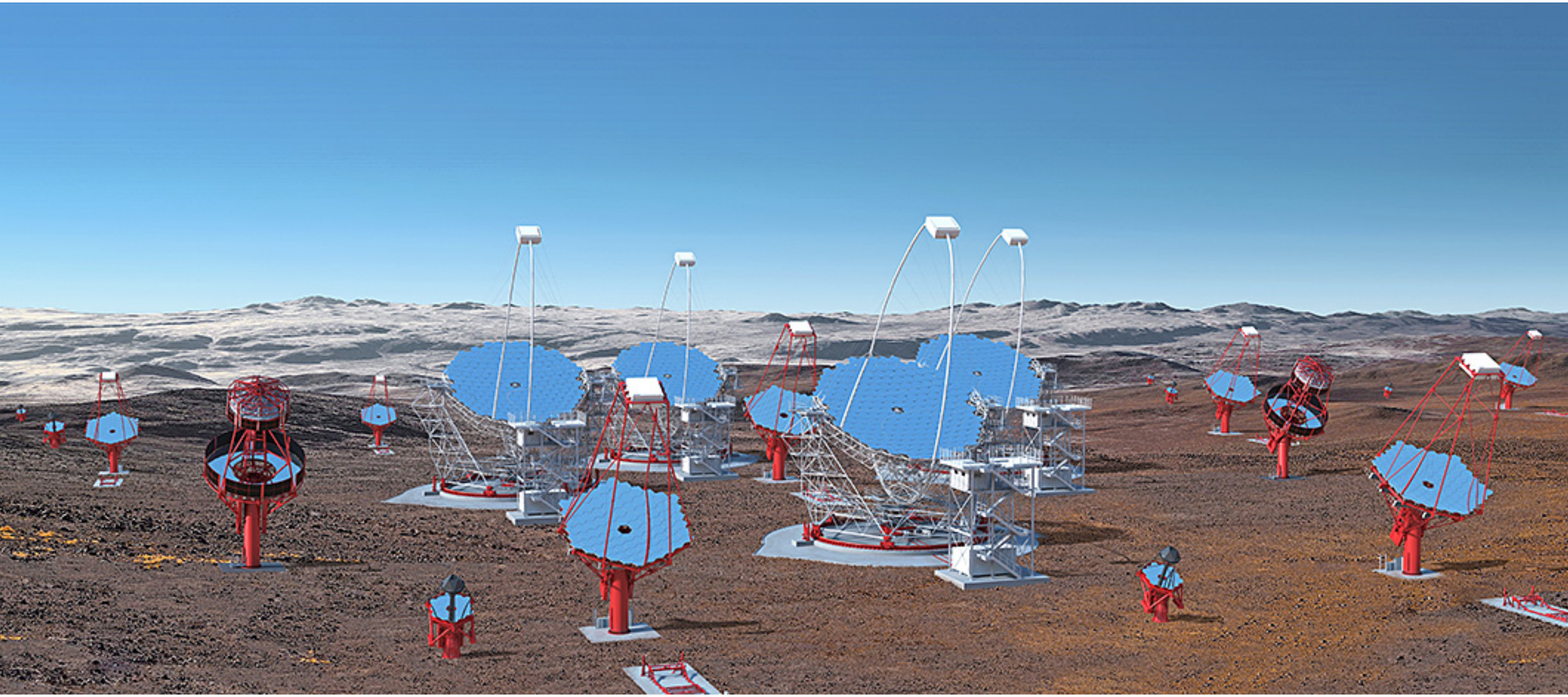
Kifune plot



From de Naurois & Mazin, 2015

TeV ASTRONOMY: THE FUTURE

The Cherenkov Telescope Array (CTA)

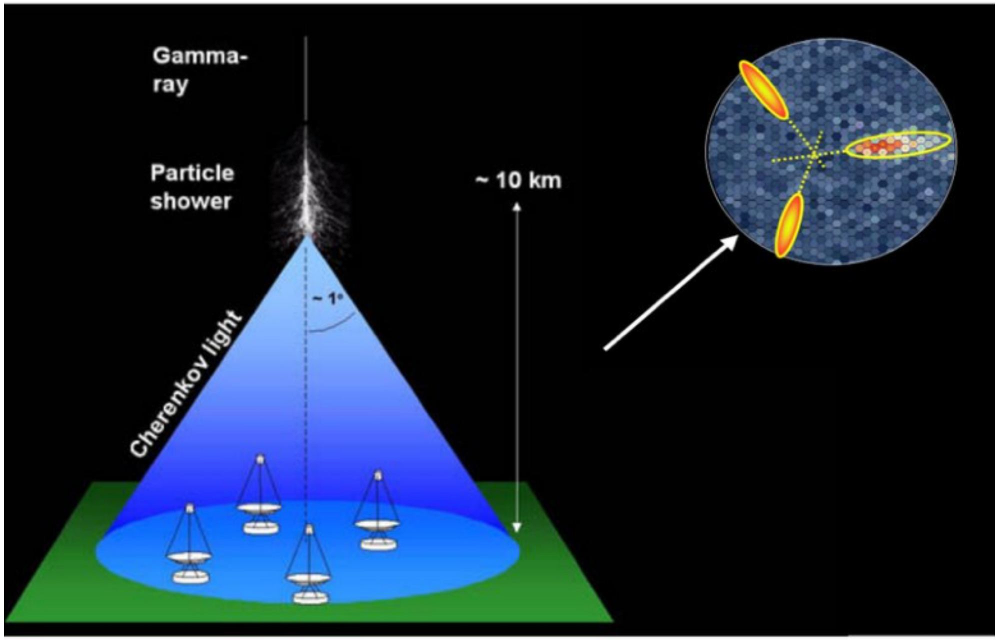


Details in next talk

DETECTION TECHNIQUE

First step: cascade images recording

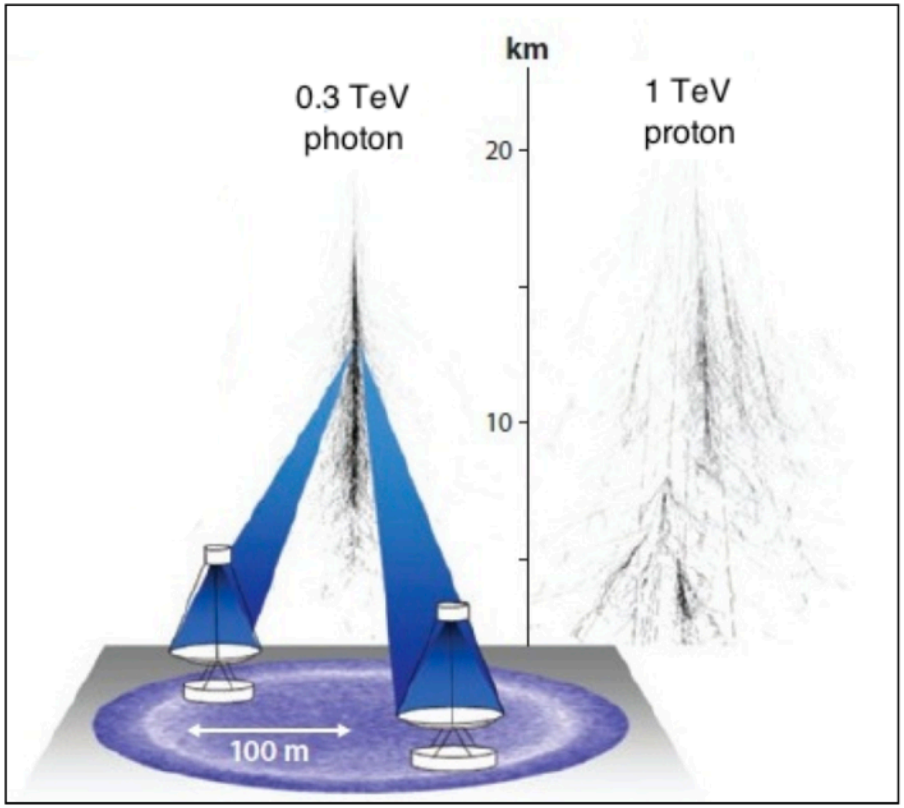
(Trigger for multi-telescope stereoscopy; Calibration.
First background: cascades seen over the optical night-sky background)

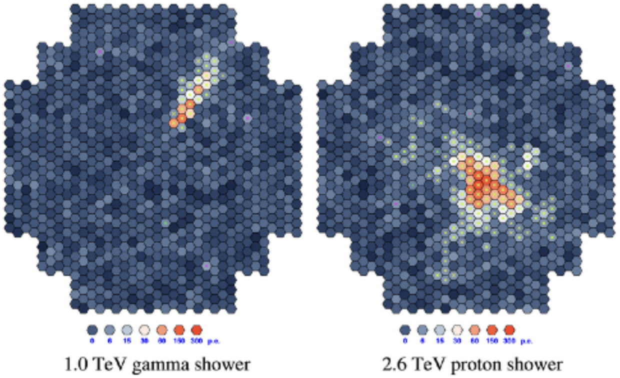


Arrival time very precise (ns);
Energy proportional to brightness
Direction more easily reconstructed with stereoscopic view

DETECTION TECHNIQUE

Main limitation of the technique:
Background dominated!
For every photon, there are 10^4 cascades produced by cosmic rays (second background to be removed)



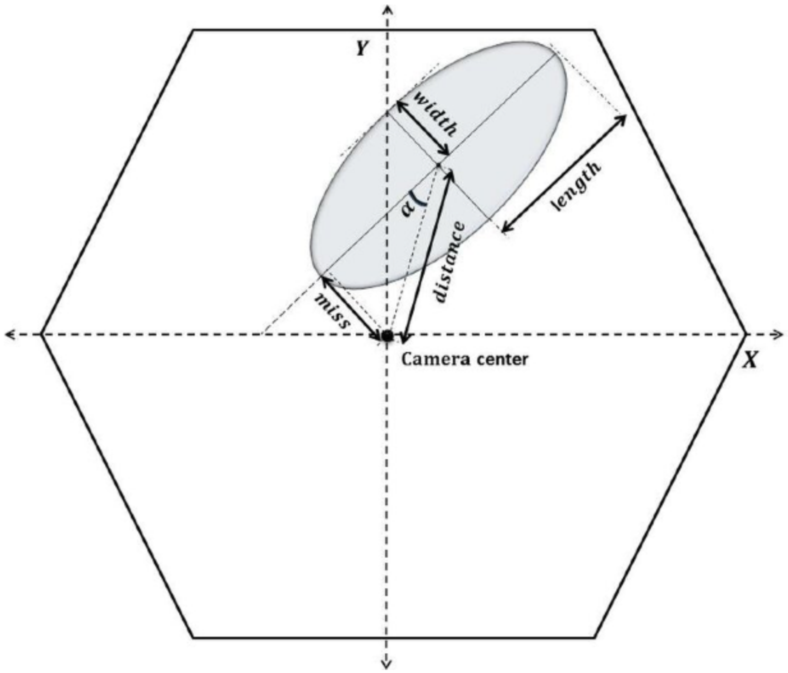


… but the shape of the images are a bit different…

DETECTION TECHNIQUE

The Hillas parameters

We fit the image with an ellipsoid and apply cuts to select ‘gamma-like’ events



DETECTION TECHNIQUE

The Hillas parameters were used by the second generation to achieve the first discoveries

Nowadays we have some more powerful tools to discriminate between photons and backgrounds:

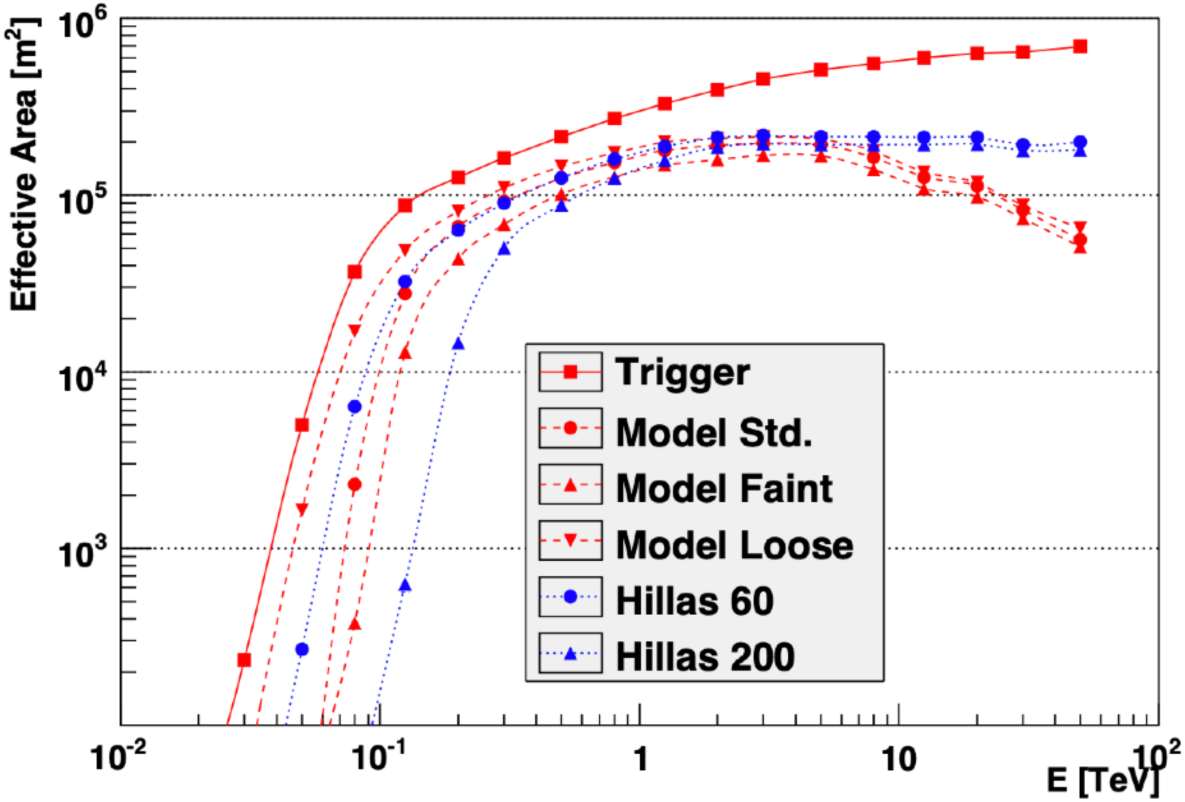
- compare real images with a library of image templates (‘model’ approach)
- Boosted decision trees trained on simulated data and applied to real data

(It is a problem of image classification.
Typical science case for machine learning algorithms)

DETECTION TECHNIQUE

We talk about ‘configs’ or ‘cuts’

They are optimized on simulations to achieved the scientific goal
i.e. the best sensitivity at low/mid/high energies
the best spatial reconstruction
the cleanest sample



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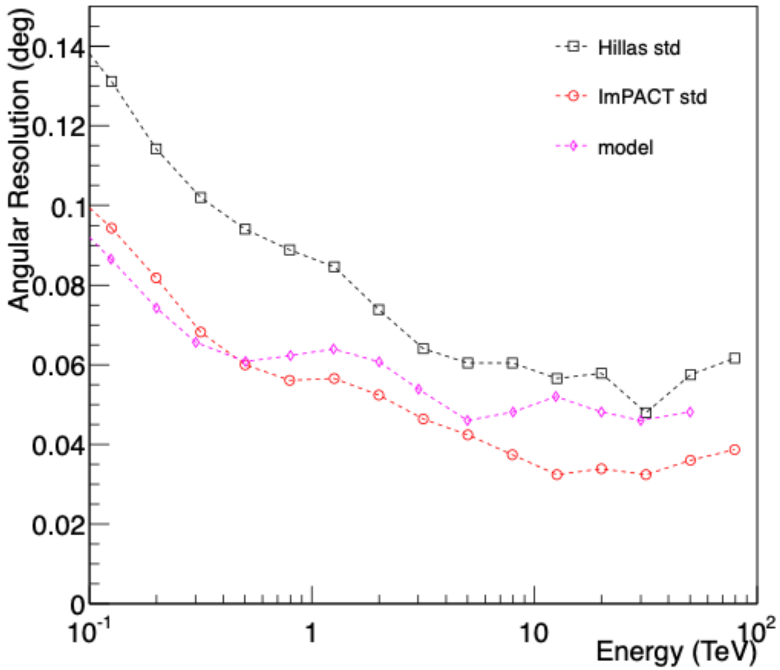
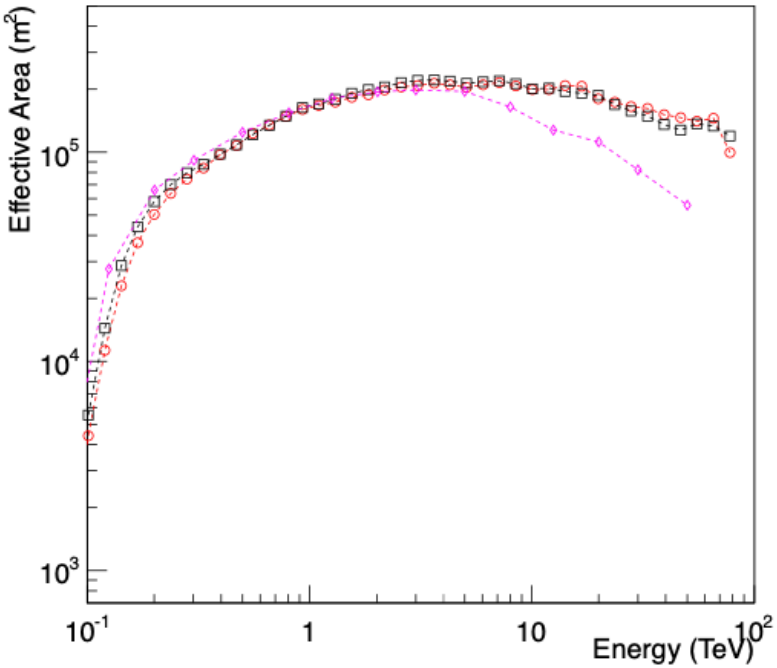




DETECTION TECHNIQUE

Still a few issues to solve:

- Photon/hadron discrimination will never be 100% effective
- Electrons/positrons also produce cascades that are very gamma-like! (see later)

Third background subtraction:
photons are measured for the ON region
and for other OFF region(s). We then look at photon excesses

DETECTION TECHNIQUE

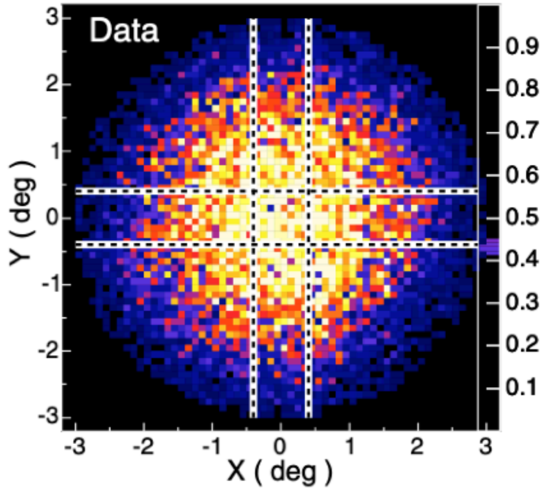
Few thoughts:

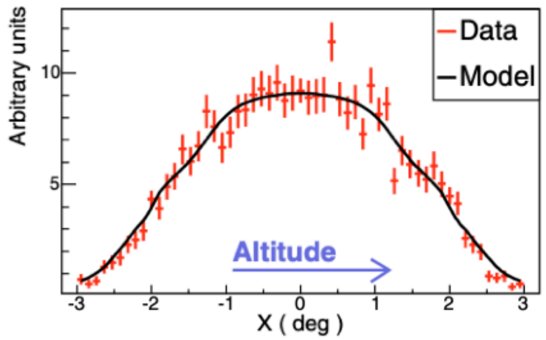
1) we can take a ON exposure and an OFF exposure

issue: the response of the instrument depend on the pointing direction and on the atmosphere! We are adding systematics

2) we can extract the OFF from the same field of view

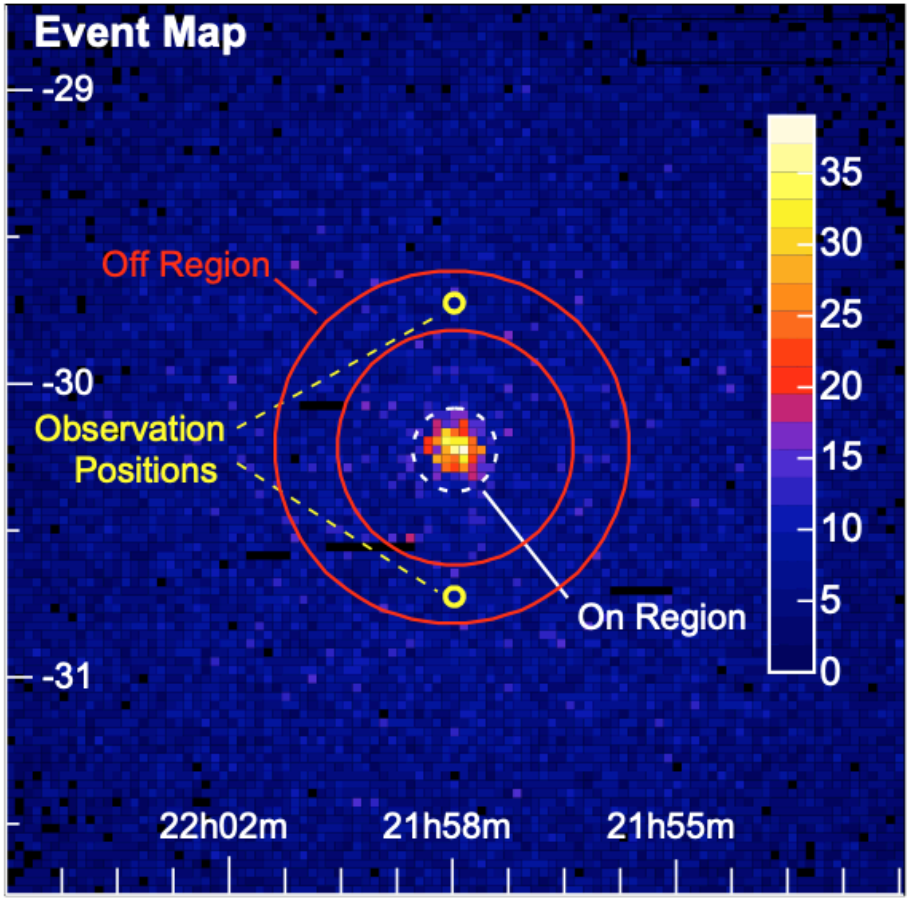
Issue: the acceptance is not uniform! But it has a radial dependency

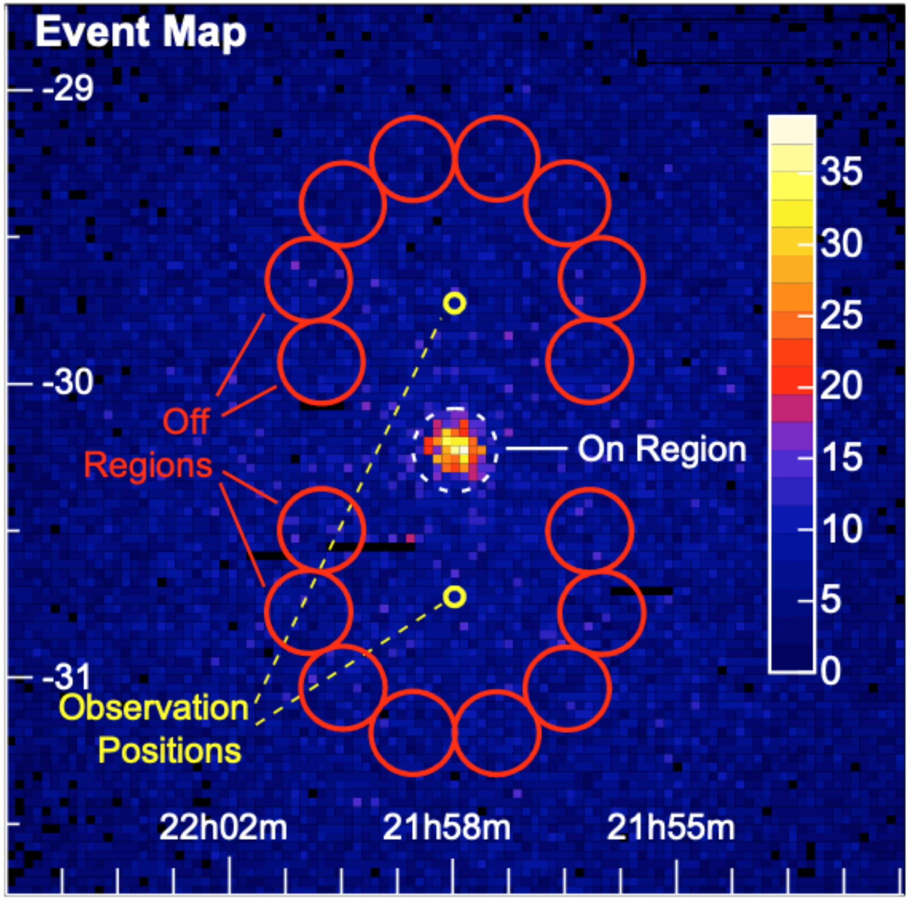




DETECTION TECHNIQUE

Solution:
Wobble pointing with symmetric ON/OFF





DETECTION TECHNIQUE

Or, background modeling and fitting

(À la Fermi-LAT)

But to do this you need to build a background model for the whole field of view (Typically the shape of the BG is fixed, and it is then refitted in normalization)

DETECTION TECHNIQUE

Main consequence of all this:
Cherenkov Telescopes measure ‘excesses’
Any extended emission as big as the field of view is very difficult to measure

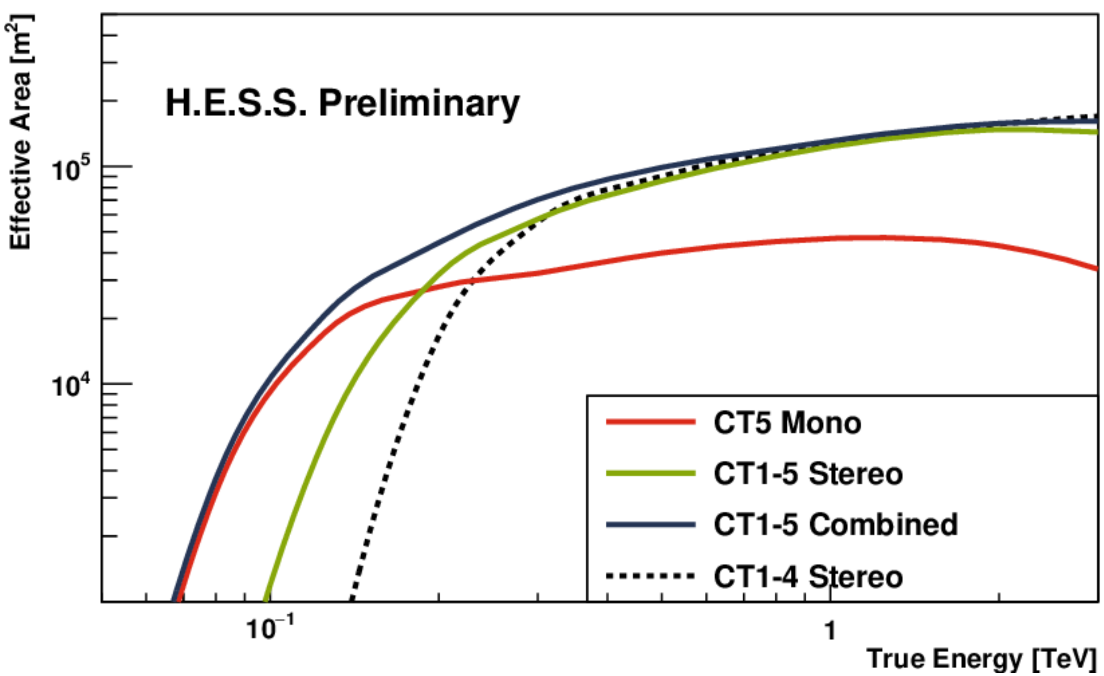
Fluxes are then estimated via Montecarlo simulations of the WHOLE chain:
TeV photons -> cascade evolution ->
Cherenkov light -> detection

DETECTION TECHNIQUE

Some peculiarities of TeV astronomy:

1) there is a threshold energy: 'The faintest cascades we can see'

This depends on the collection area of the telescope -> larger mirrors allow to see the lowest energies

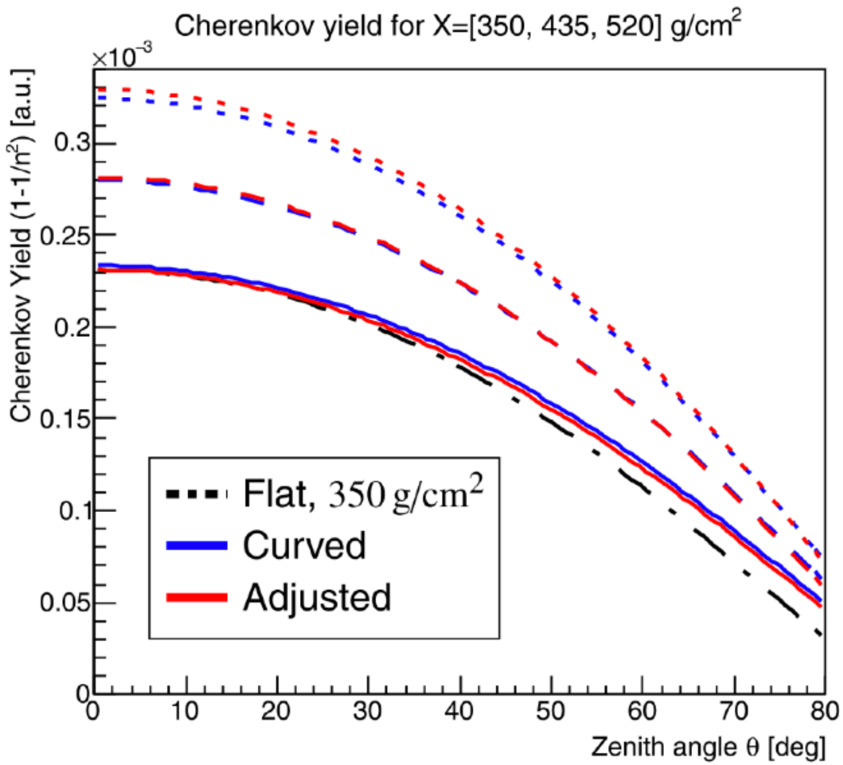


DETECTION TECHNIQUE

Some peculiarities of TeV astronomy:

2) the best detection is for cascades close to zenith. If closer to the horizon, the distance from the cascade increases, and we lose the faint ones

The zenith angle of the observation SETS the energy threshold! As the source moves in the sky, the threshold energy varies!



DETECTION TECHNIQUE

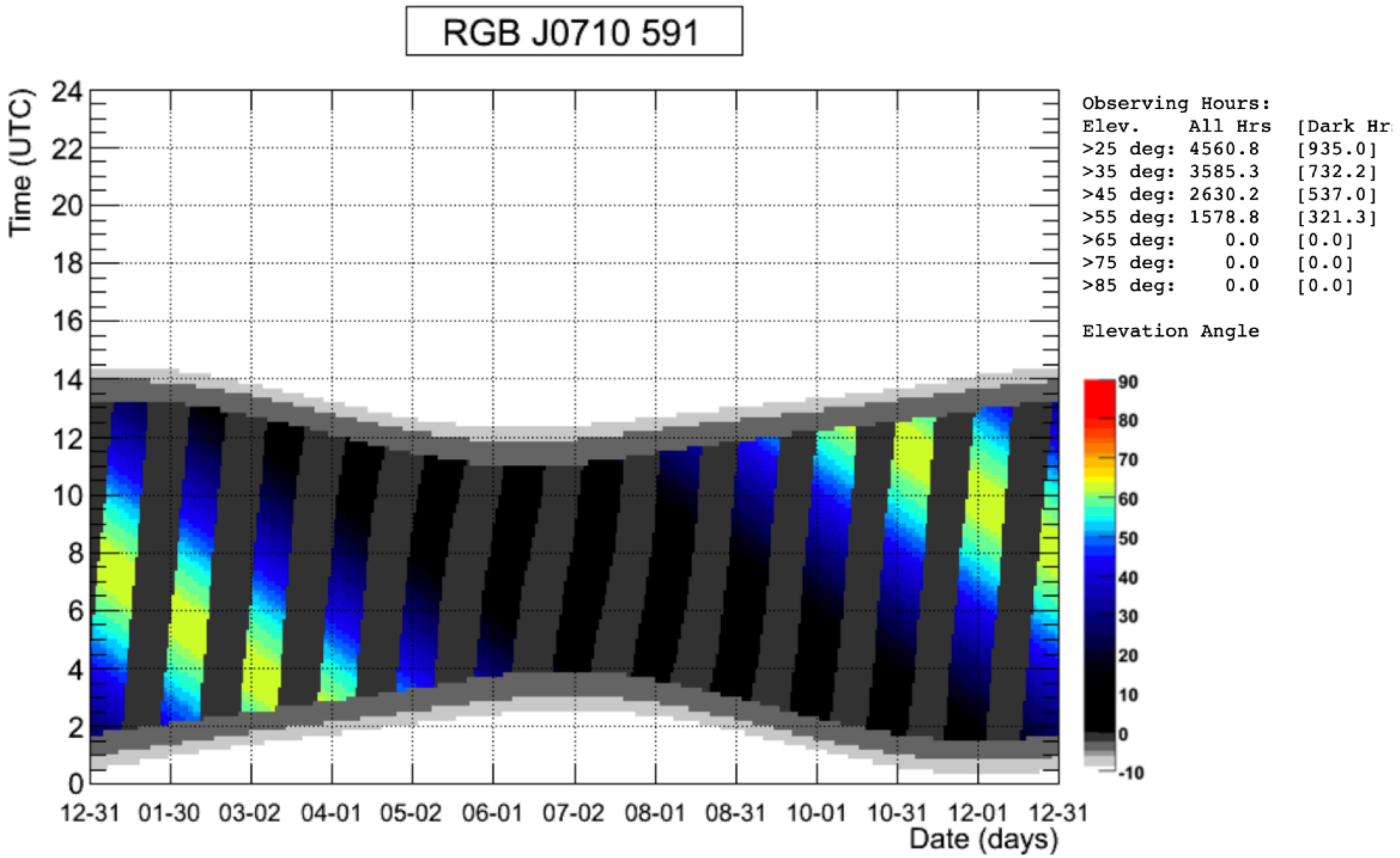
Cherenkov cascades are faint, and photo-multipliers are very sensitive

Standard observation mode is only during dark time. The moonlight increases the night-sky-background and degrade PMTs

Typical duty cycle is limited (zenith constraint, plus moon constraint)

DETECTION TECHNIQUE

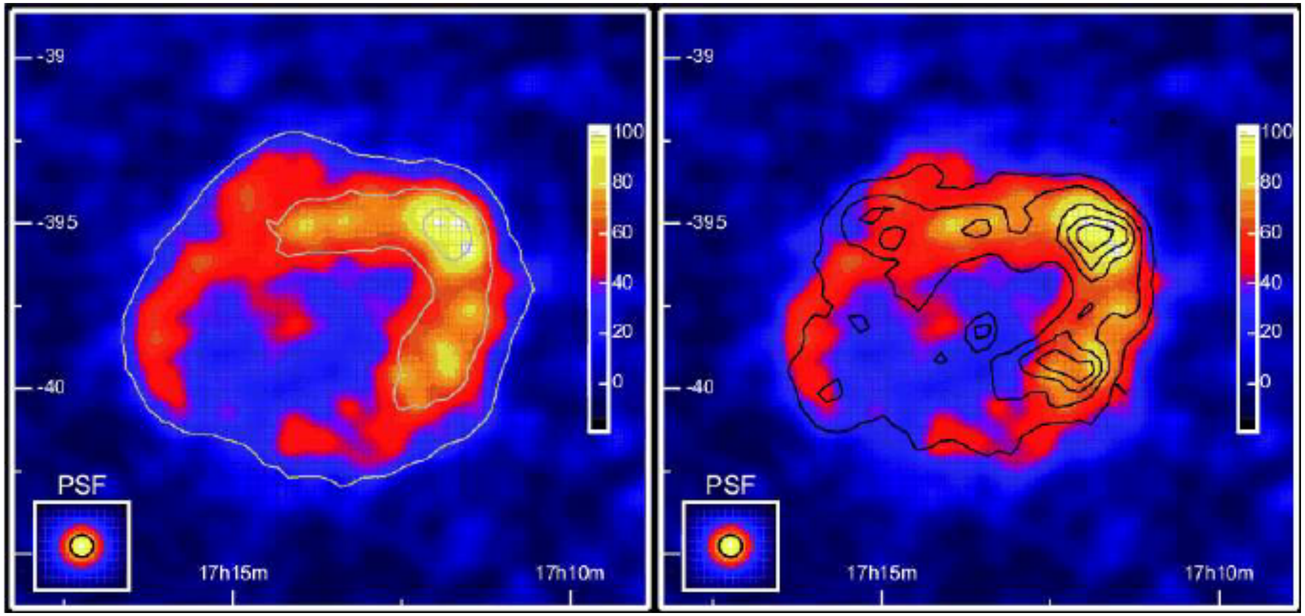
Typical visibility plot



Plotted RGB J0710 591 RA,Dec = (107.610000,59.150000) for year 2024.000000 at lat,lon = 31.680000,-110.860000

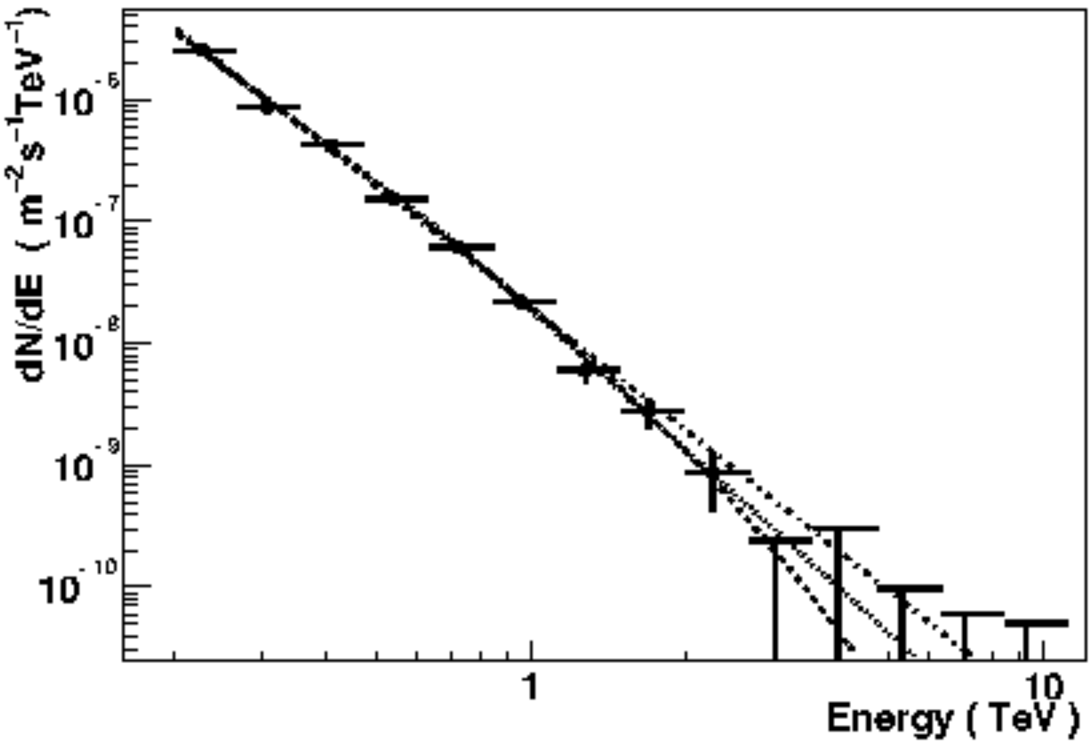
THE TeV SKY

… after all this…



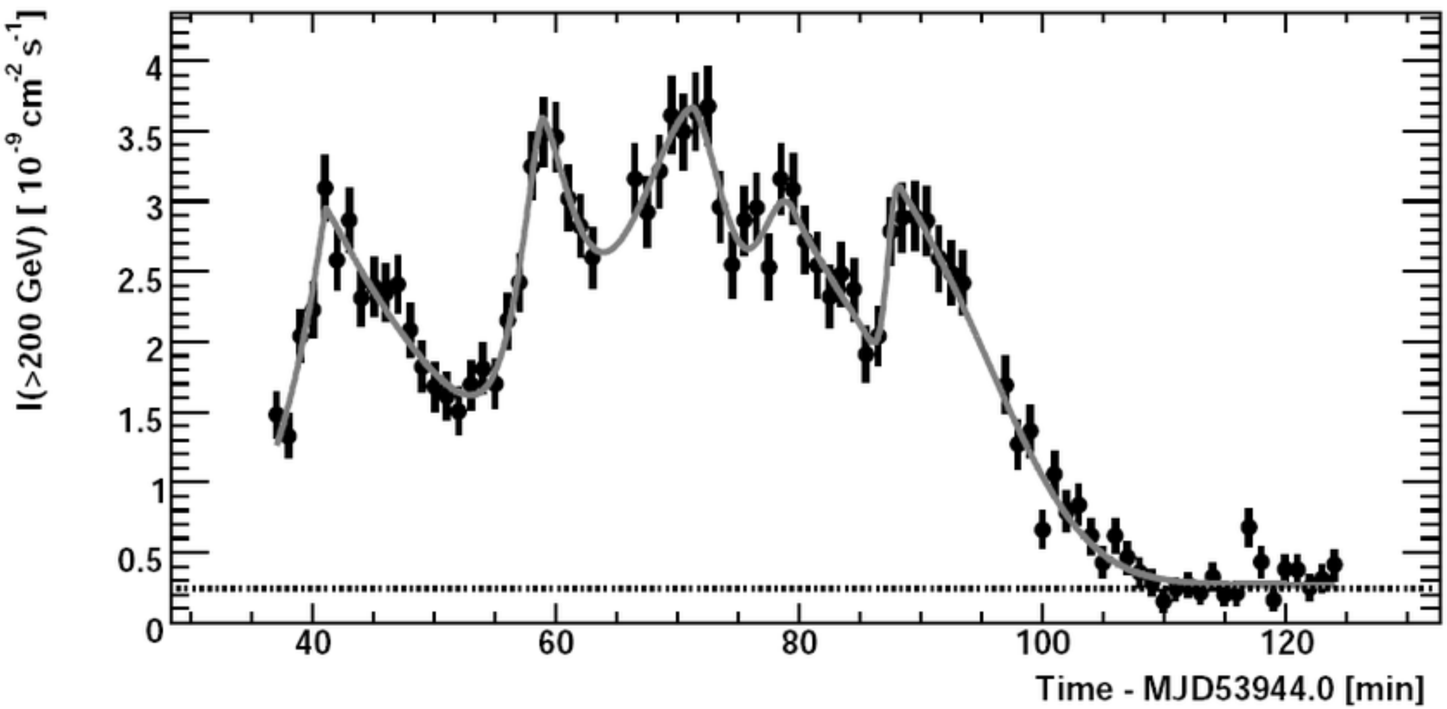
THE TeV SKY

… after all this…



THE TeV SKY

… after all this…



PeV ASTRONOMY

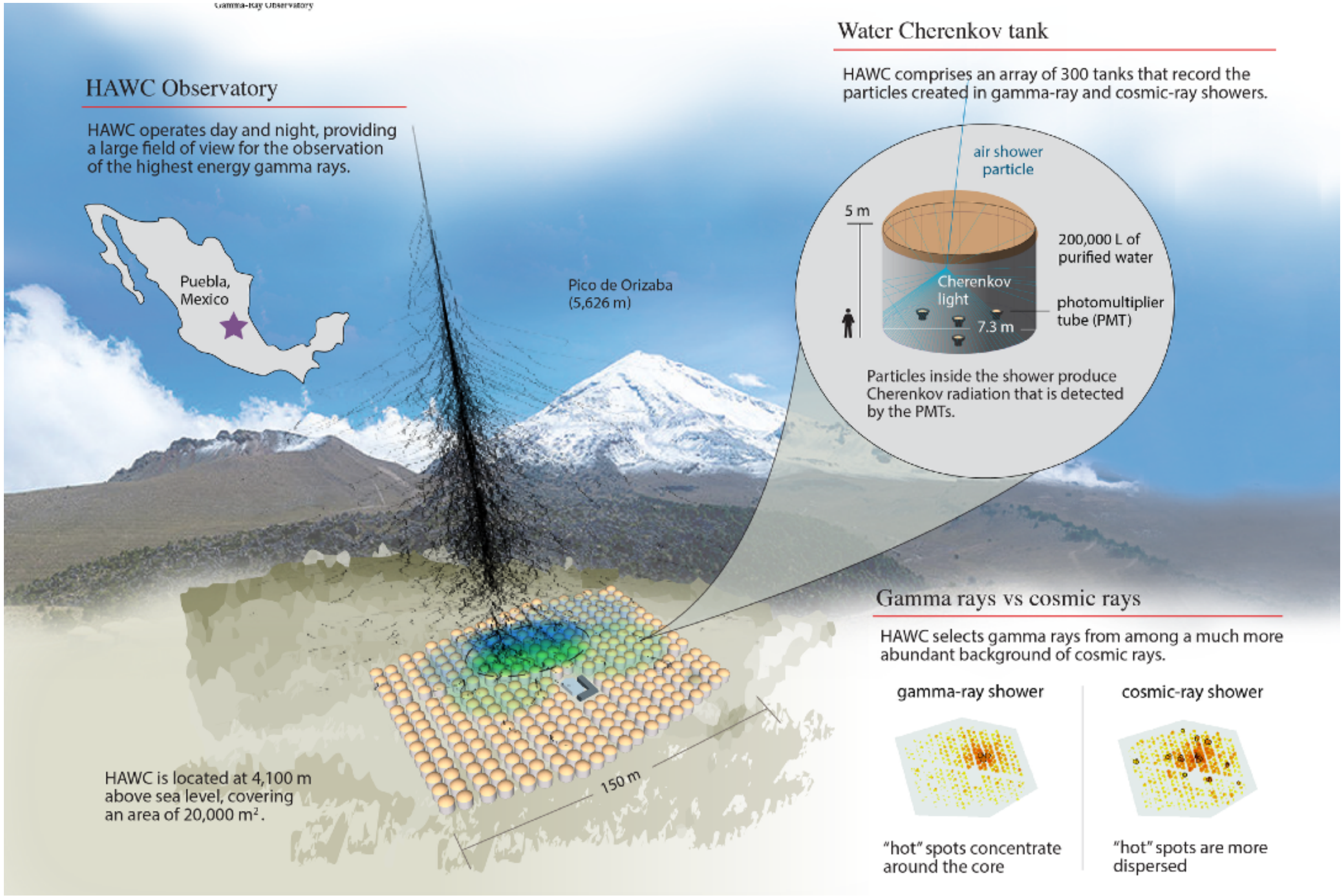
Why do we stop at tens of TeV?

1) cascades get brighter and closer
(If larger than field of view, it's over)

2) the fluxes go down as power-law functions
We need to increase the effective area

PeV ASTRONOMY

Change in detection technique! Water Cherenkov Tanks



We intercept the cascade and reconstruct the incoming photon from the cascade footprint

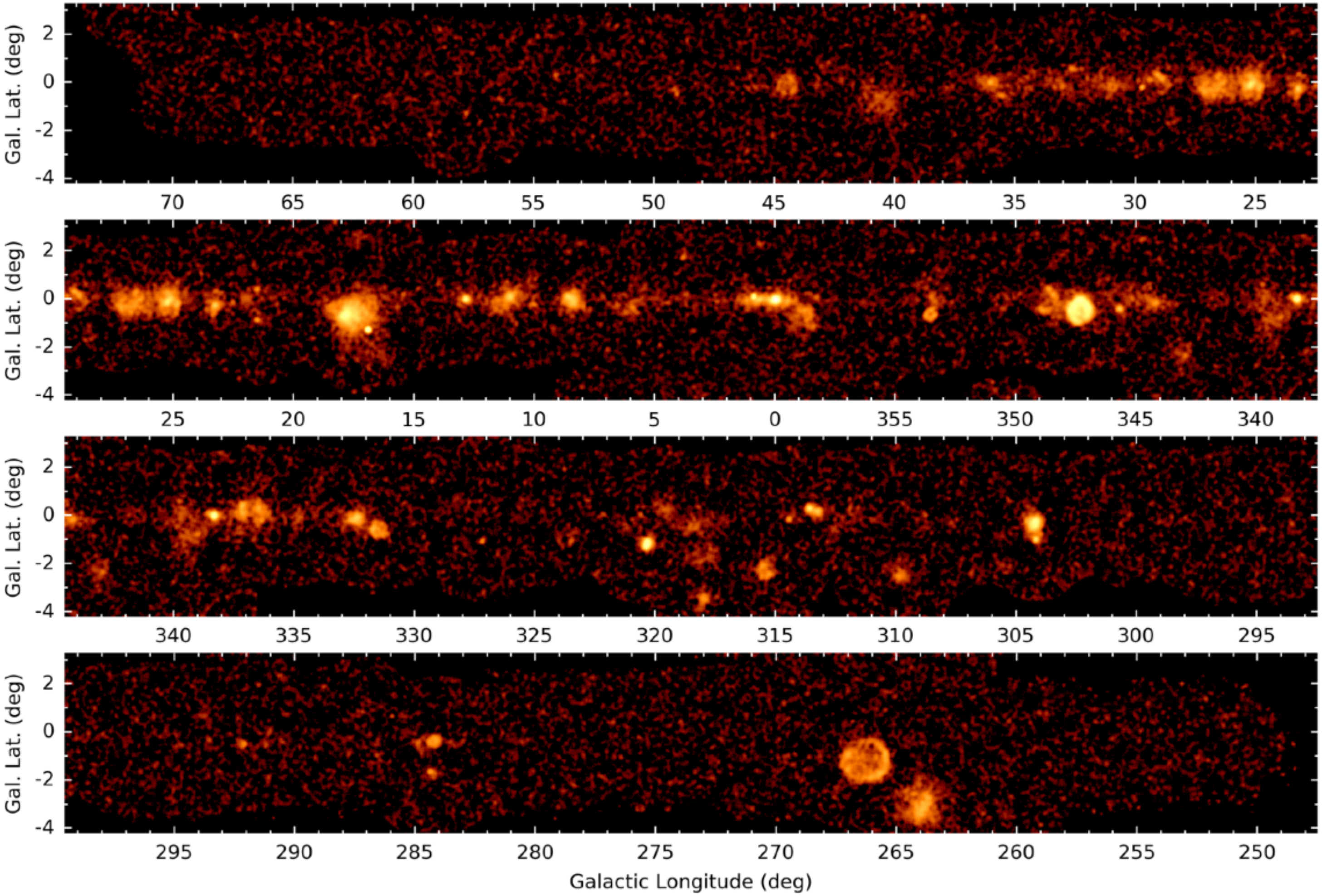
PeV ASTRONOMY

HAWC (Mexico) and LHAASO (China)

SWGO planned in South America

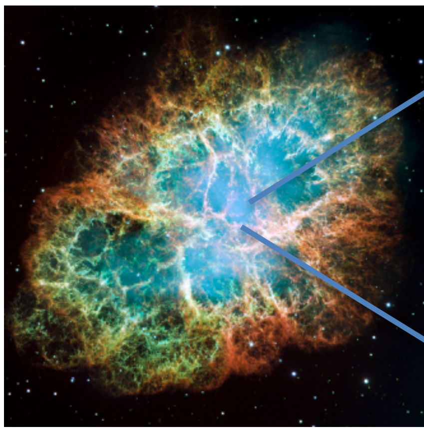
RESULTS

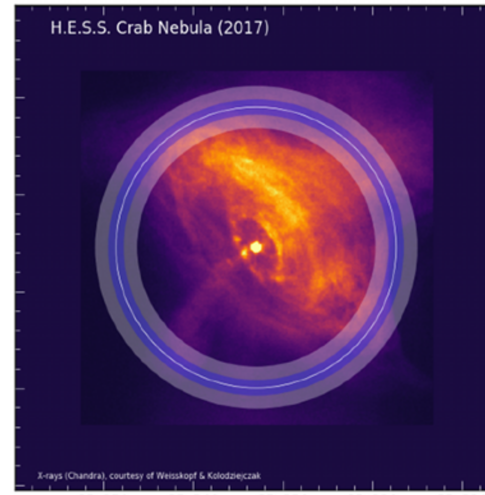
The Milky Way at TeV energies

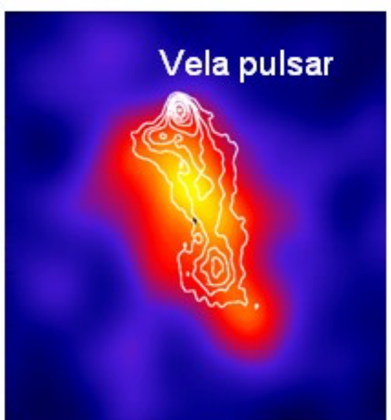


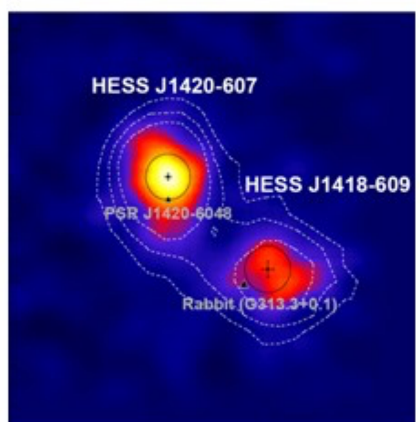
RESULTS

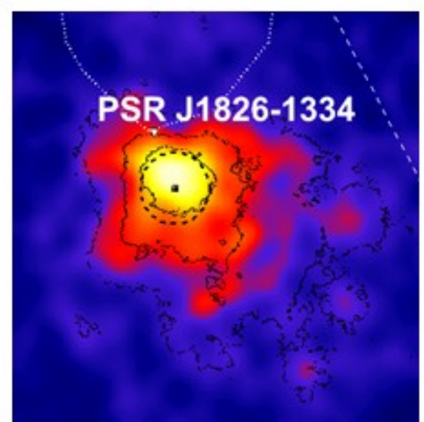
The MW: Pulsar Wind Nebulae





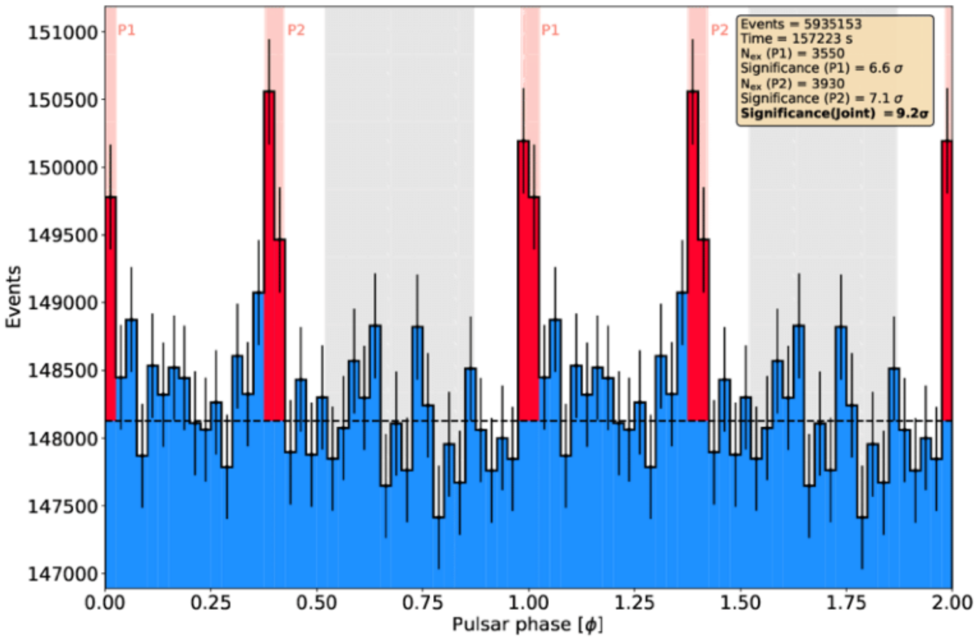


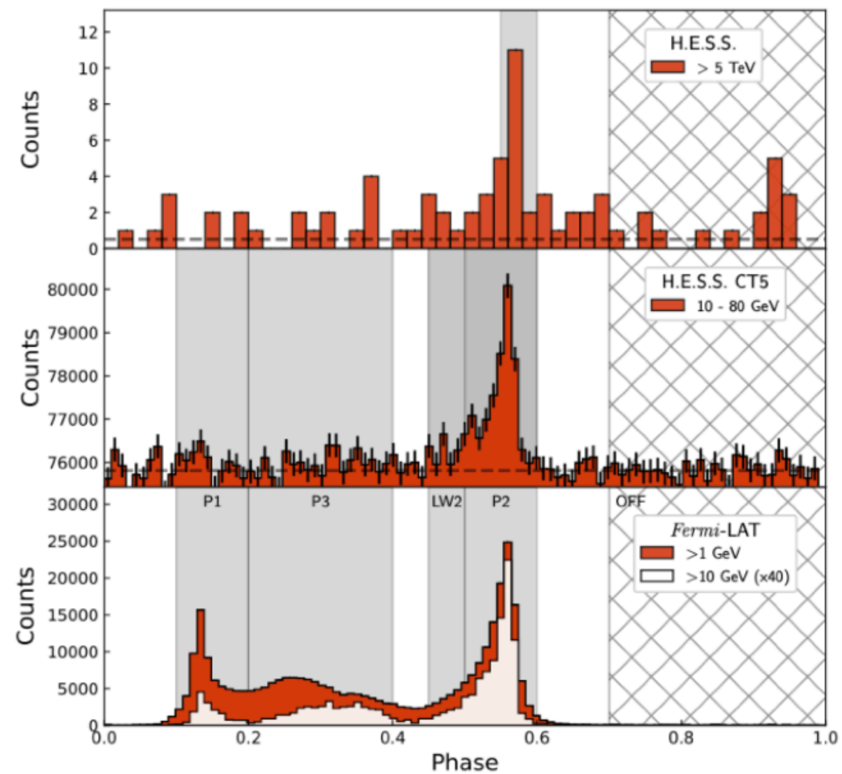




RESULTS

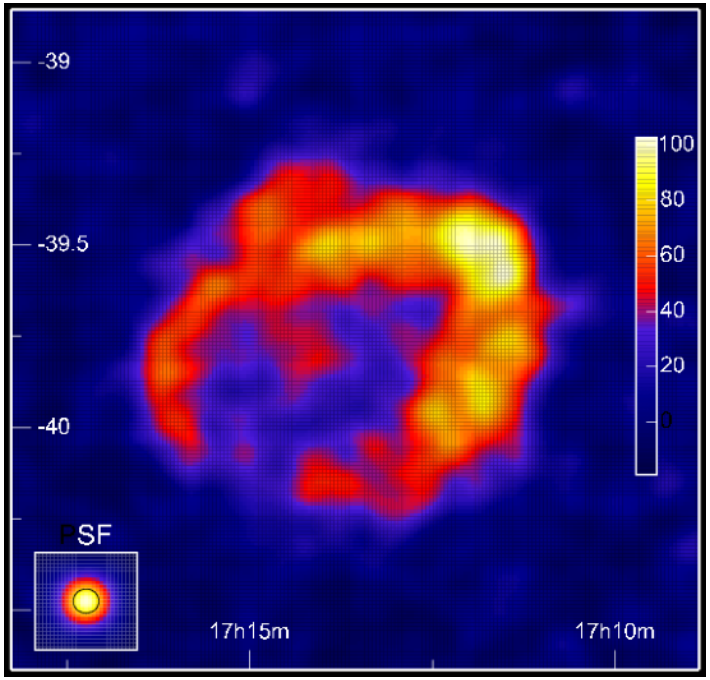
The MW: Pulsars

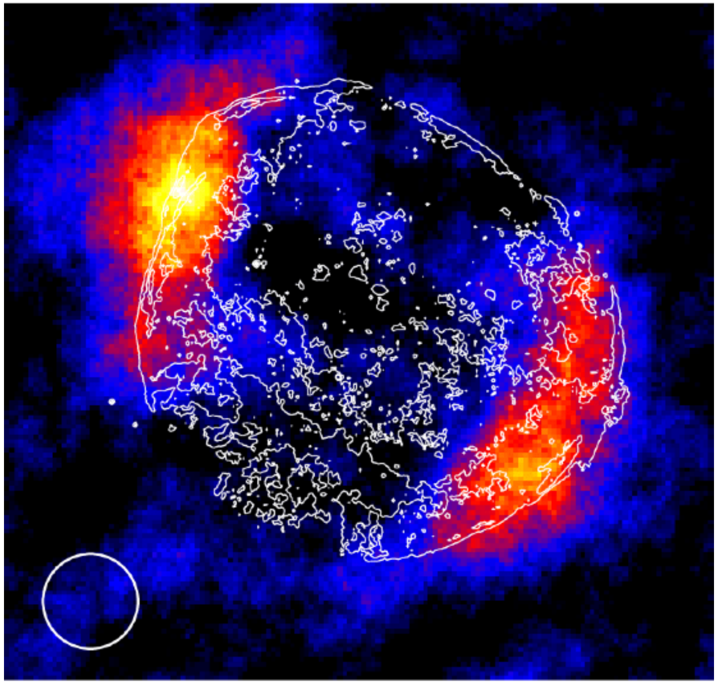




RESULTS

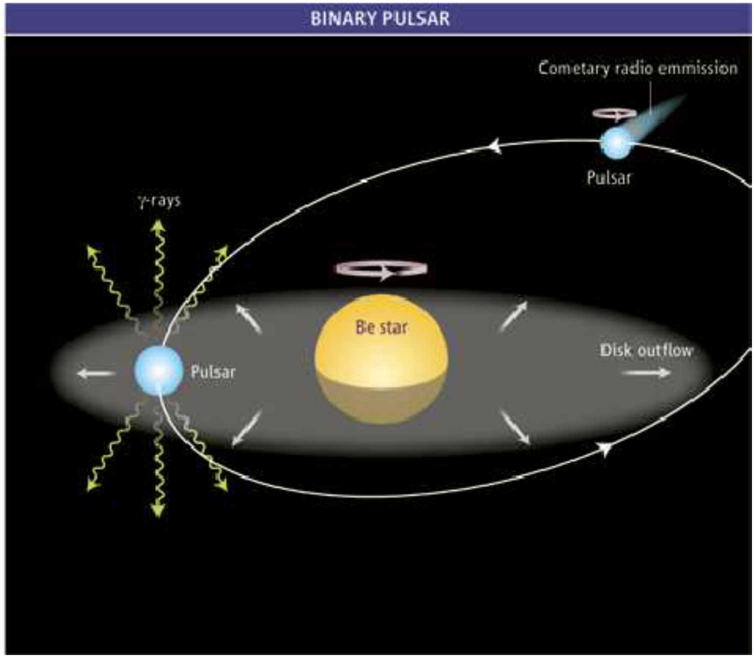
The MW: SuperNova Remnants

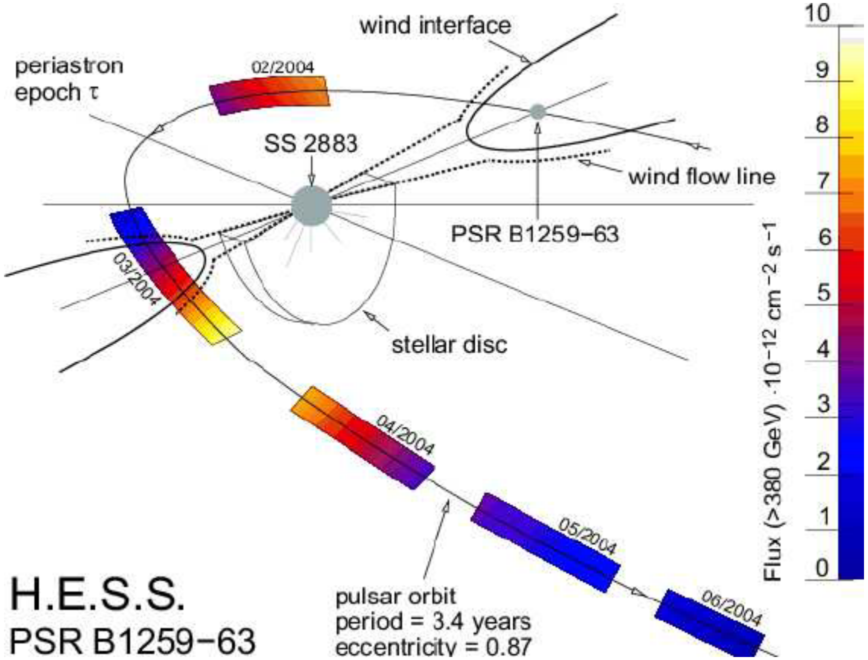




RESULTS

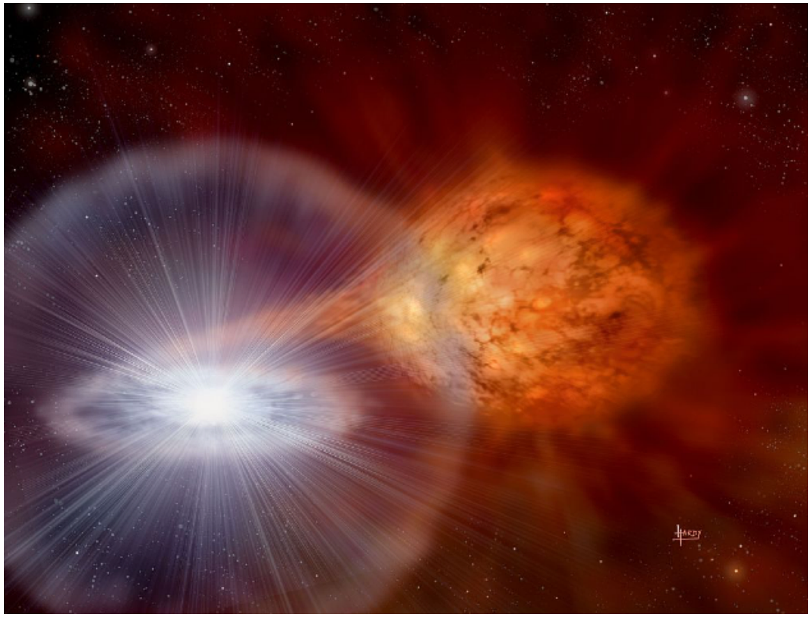
The MW: gamma-ray binaries

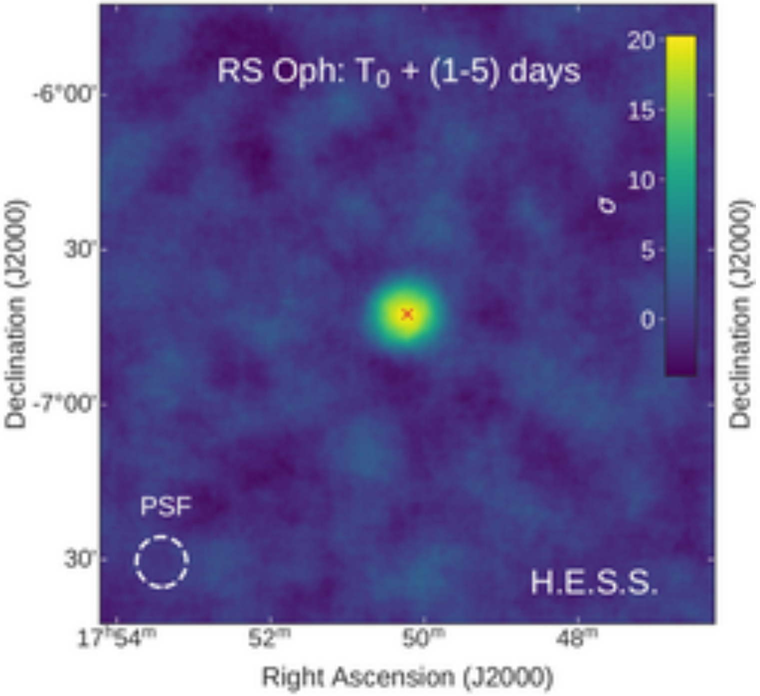




RESULTS

The MW: Novae

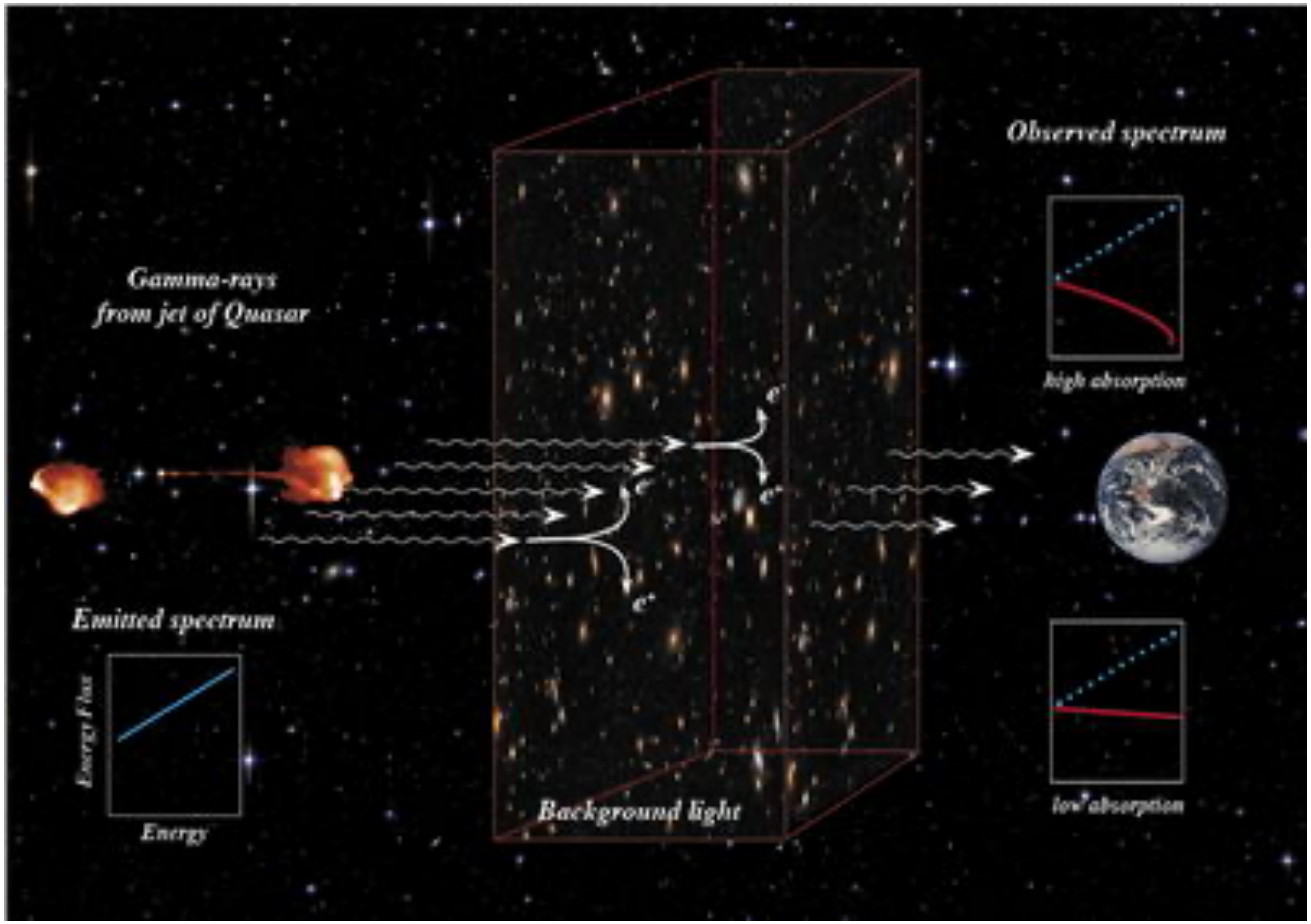




Matteo Cerruti

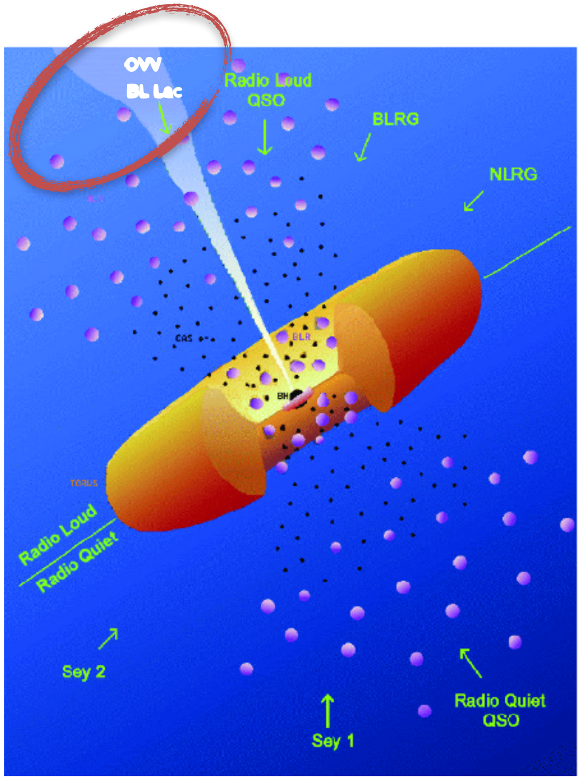
RESULTS

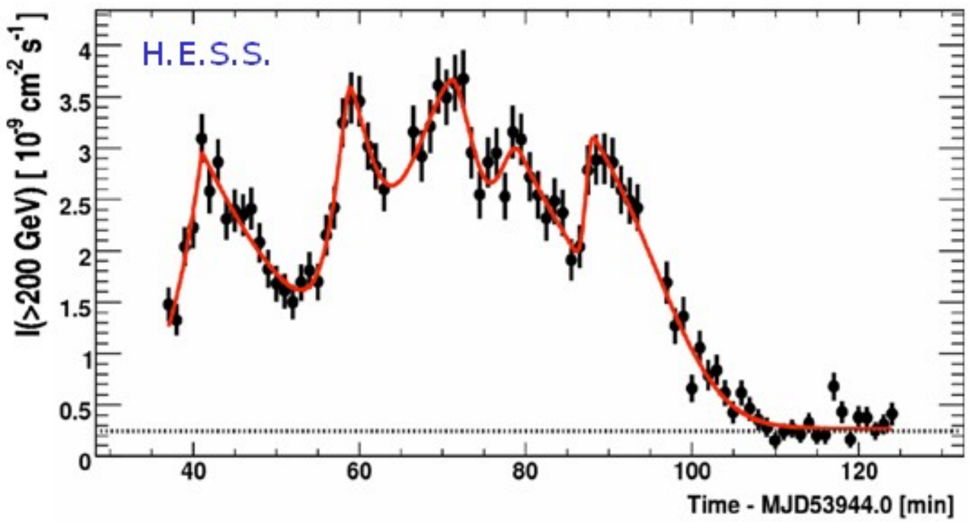
Parenthesis: gamma-gamma absorption on the EBL



RESULTS

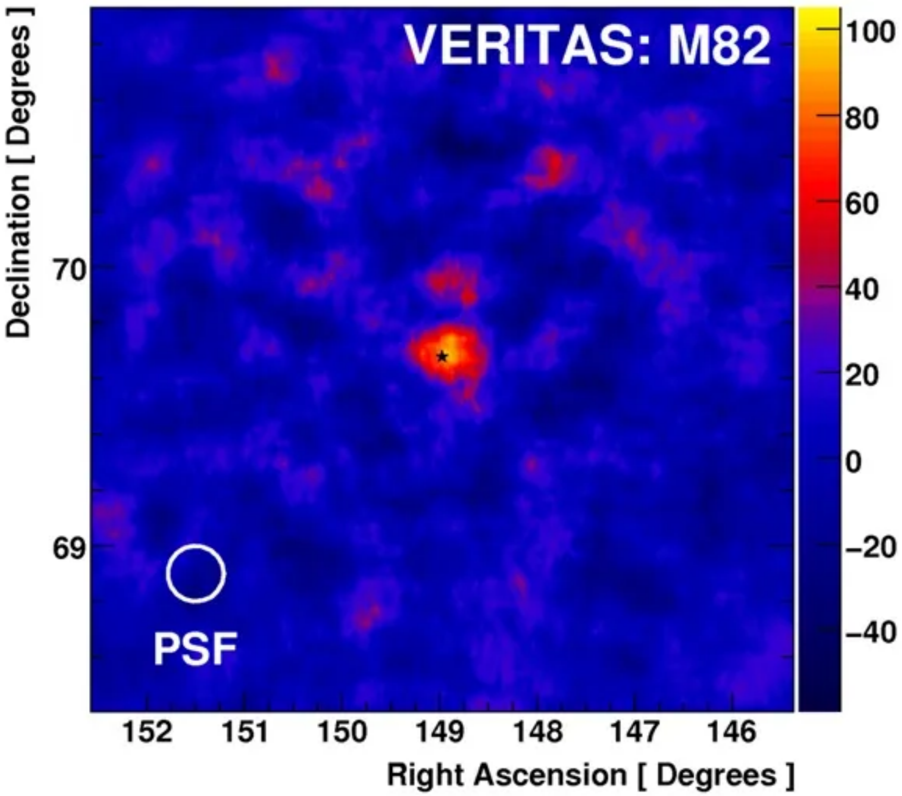
AGNs (mainly blazar type)





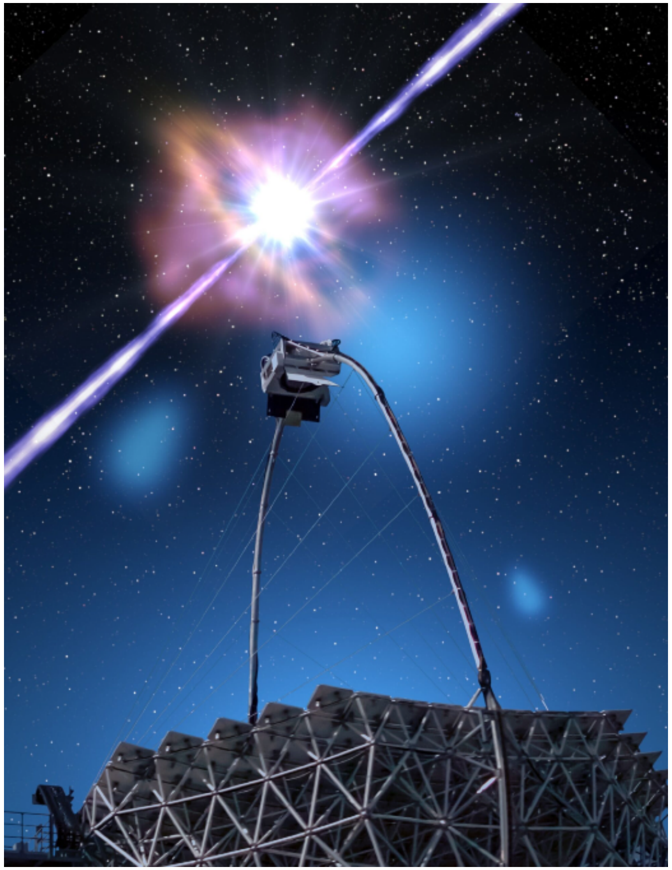
RESULTS

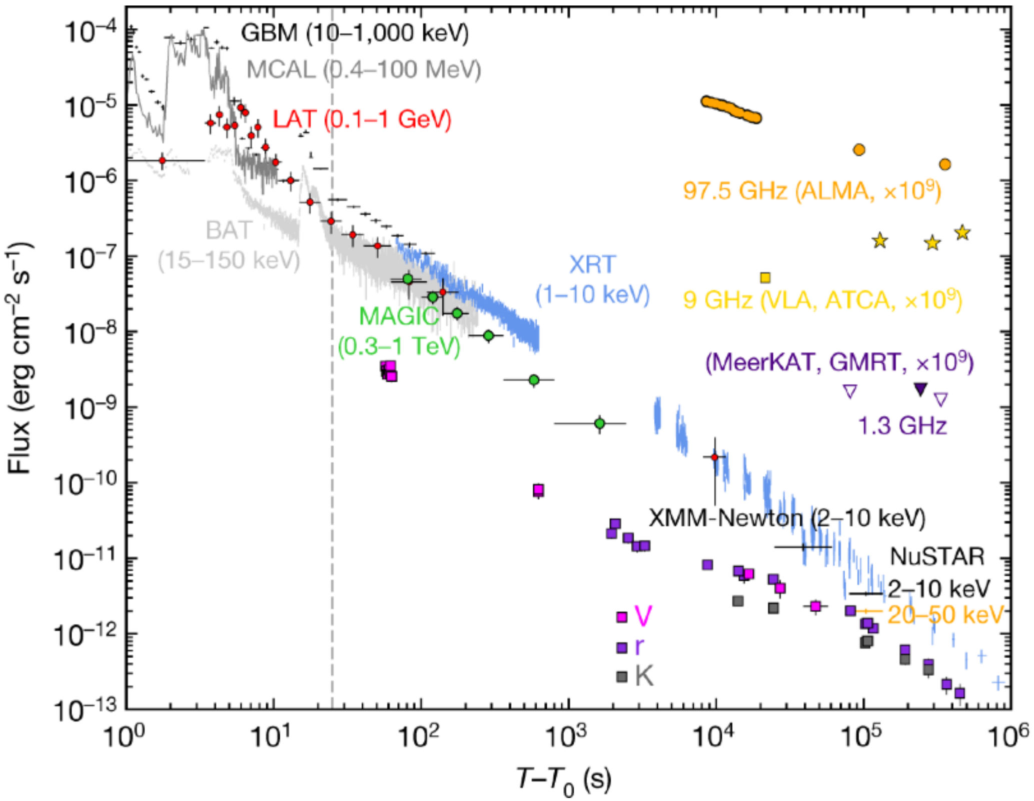
Starburst galaxies



RESULTS

Gamma-ray Bursts

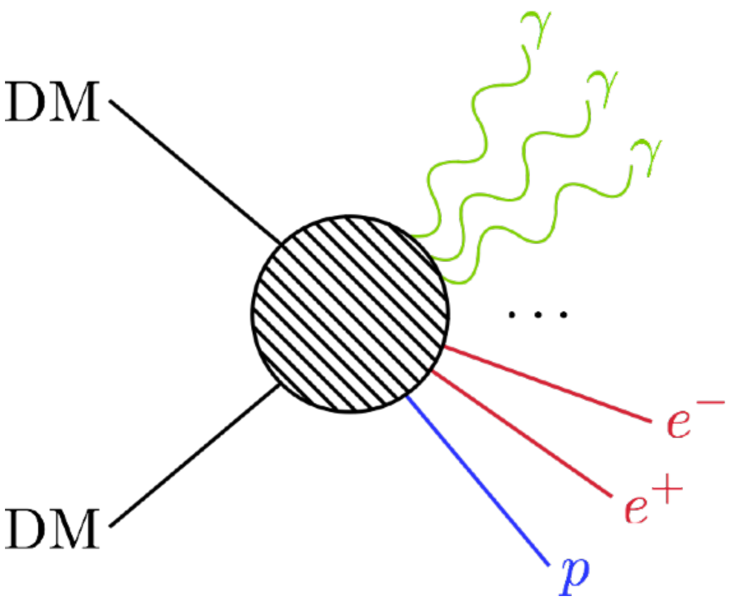


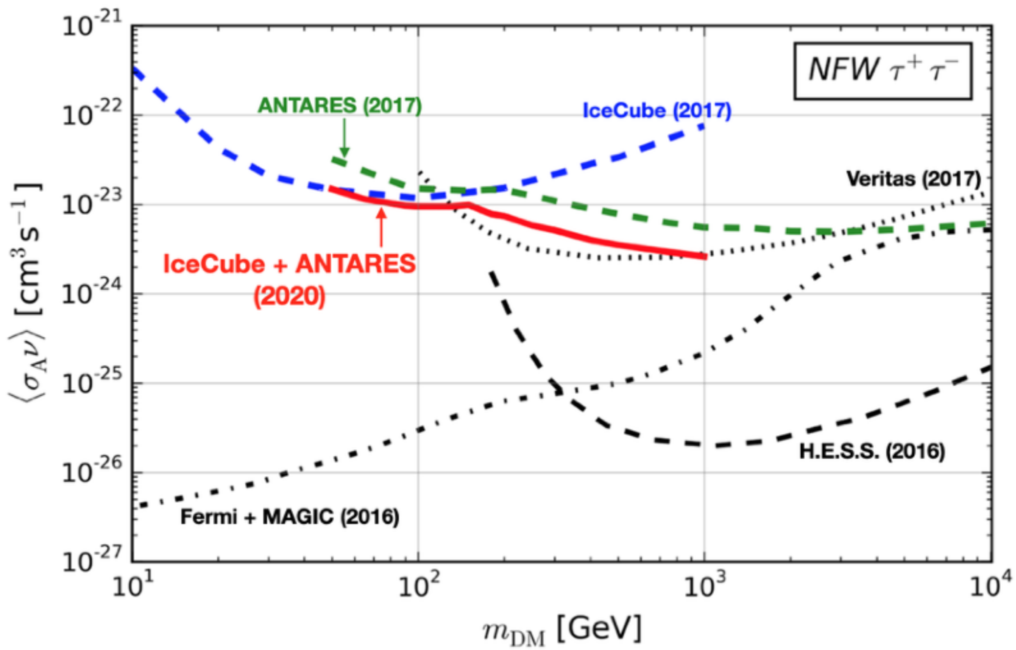


Matteo Cerruti

RESULTS

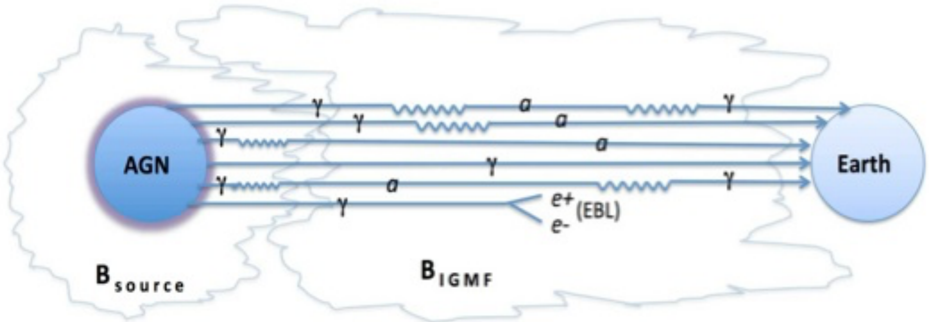
Physics beyond the Standard Model: Dark Matter (Indirect) Searches

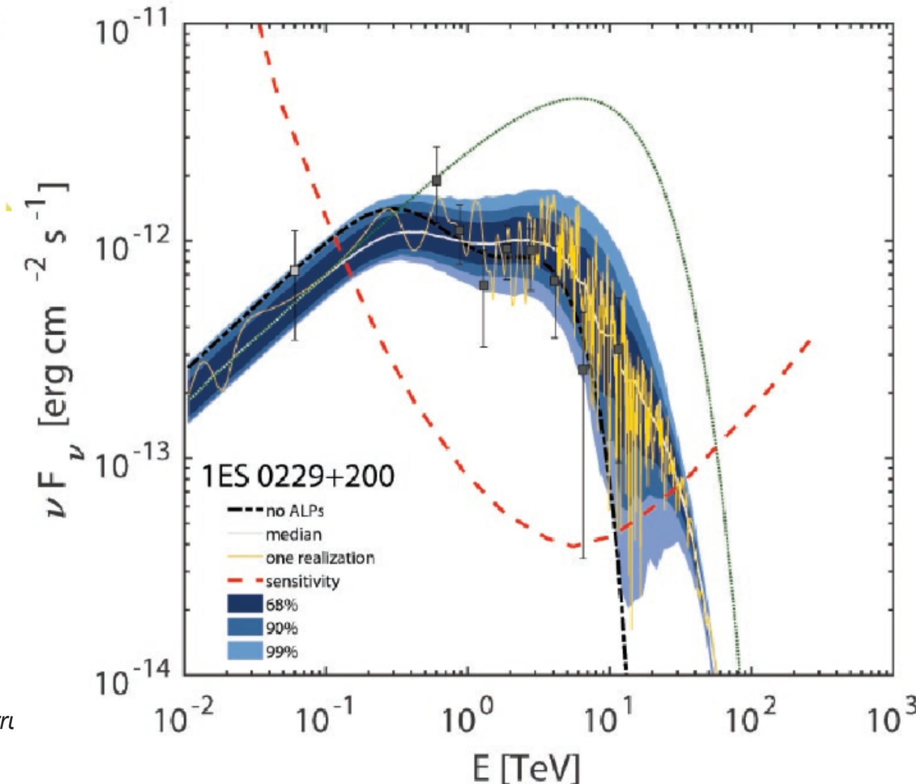




RESULTS

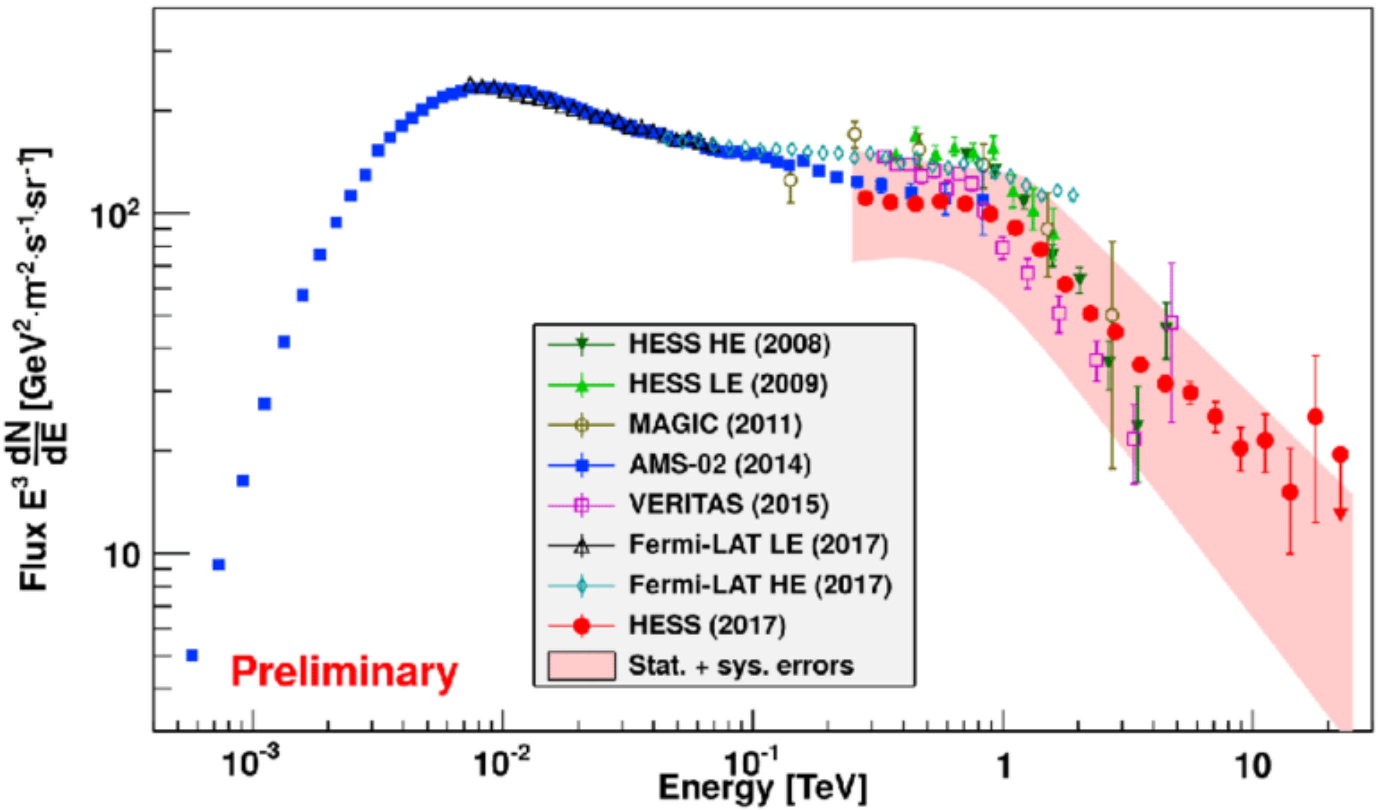
Physics beyond the Standard Model: Axions





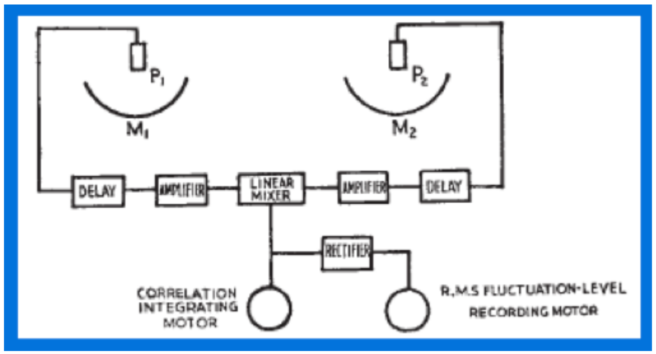
RESULTS

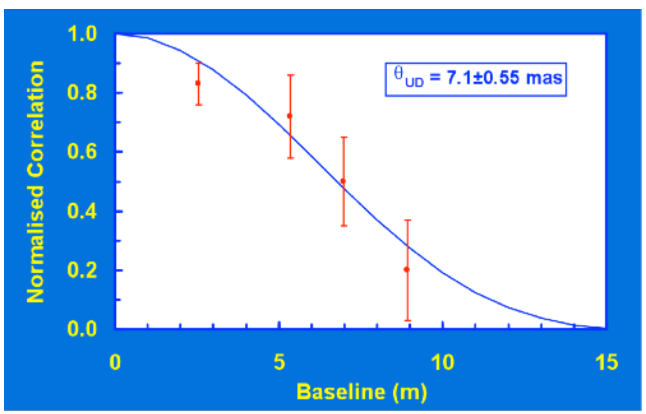
Cosmic Ray Direct:
The electron spectrum

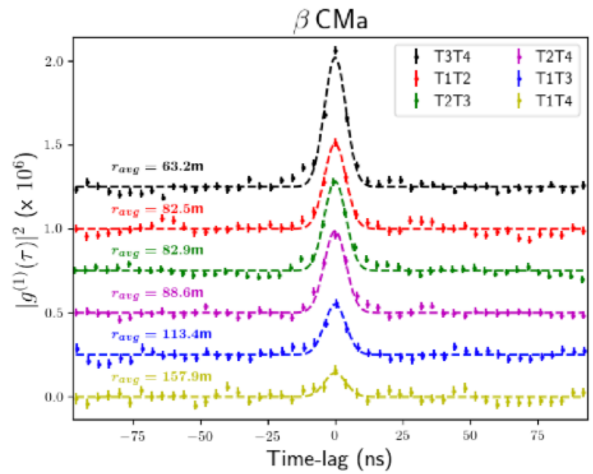


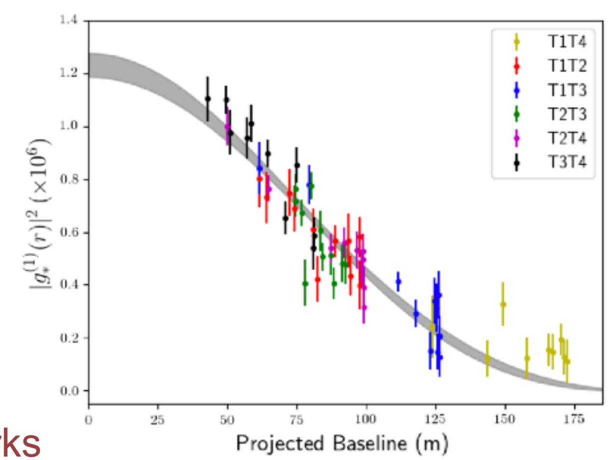
BONUS TRACK: INTENSITY INTERFEROMETRY

Study correlation of light fluctuations at two different telescopes
Ideal to measure diameter of stars







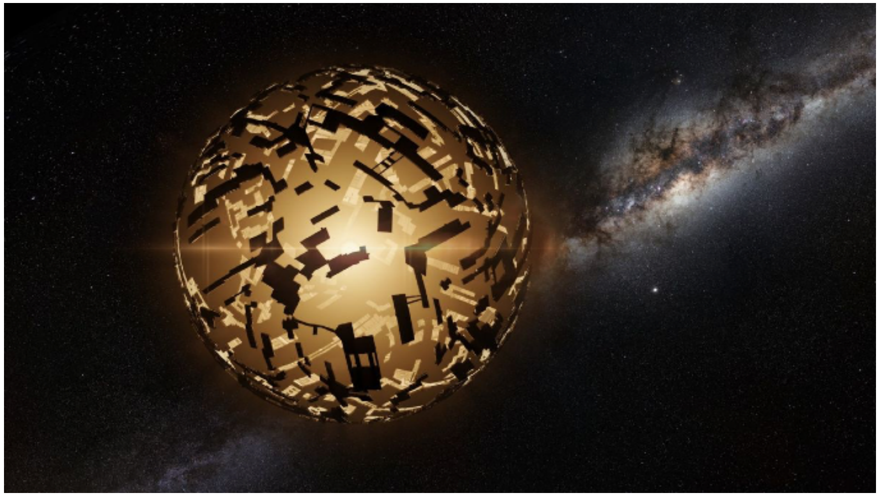


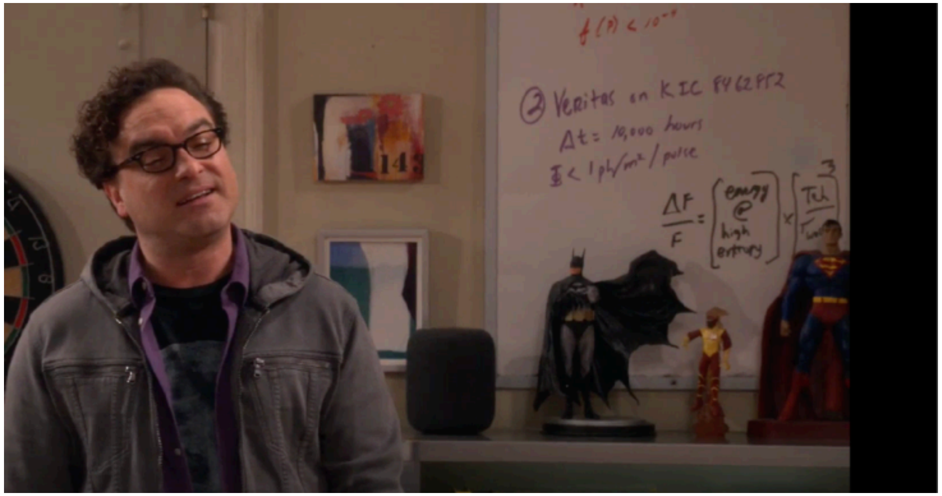
Cherenkov telescopes are perfect instruments!
(Just adding a dedicated camera). VERITAS proved it works

BONUS TRACK: SETI

Very fast optical measurements

Look for bright optical flashes from SETI targets

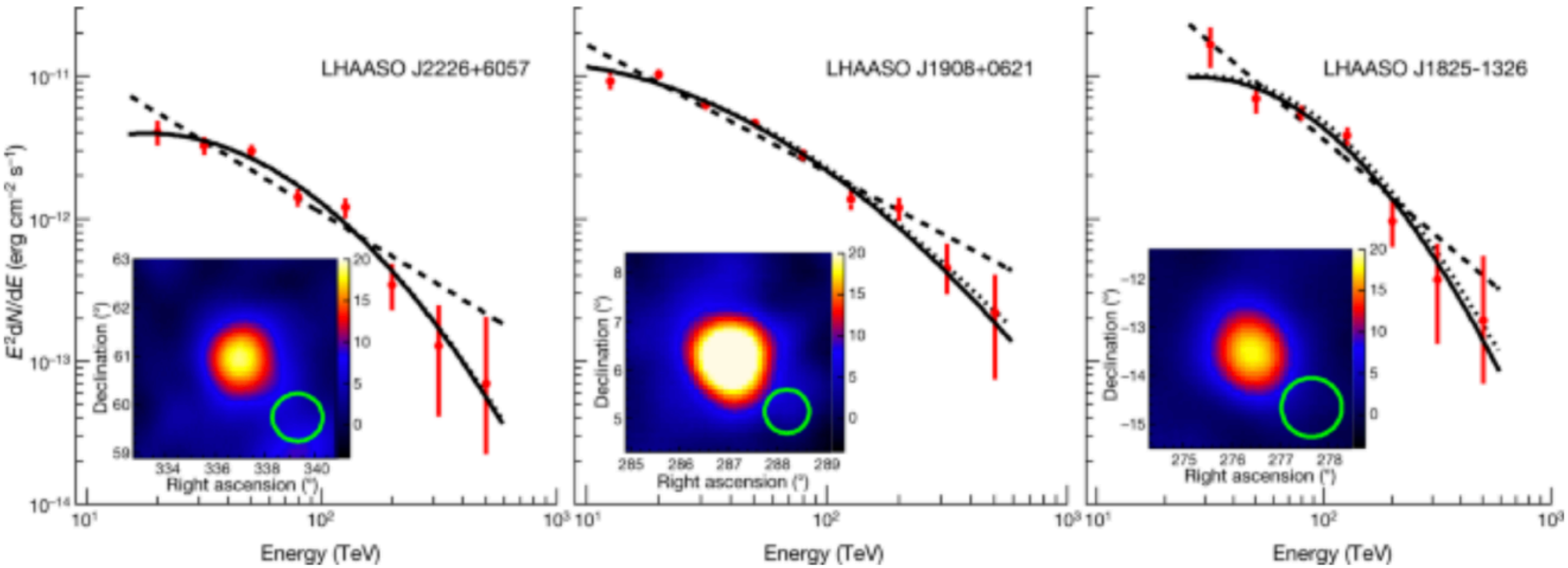




VERITAS: upper limit on photon flux from extraterrestrial civilization

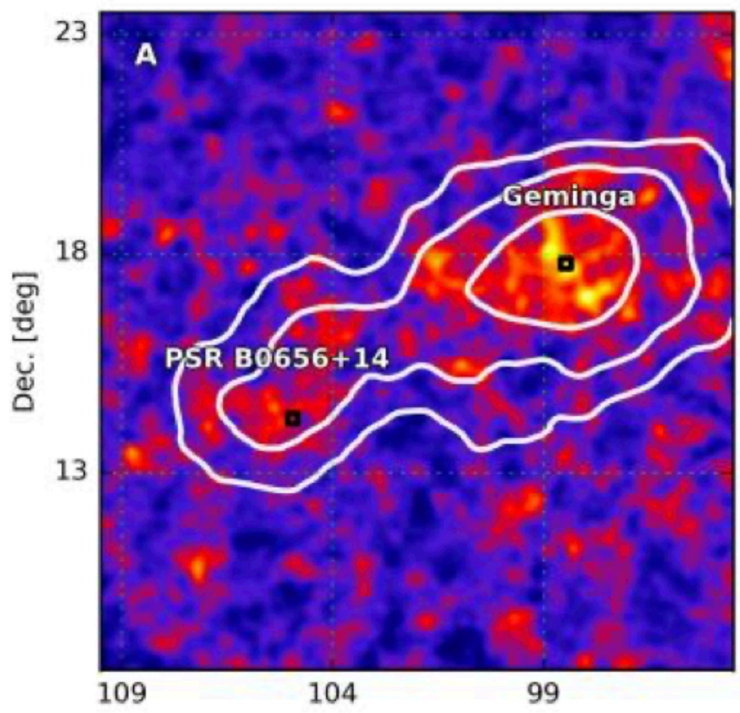
PeV ASTRONOMY: RESULTS

Detection of emission beyond 100 TeV



PeV ASTRONOMY: RESULTS

Besides higher energies, they can also observe more easily extended emission
(remember the background subtraction issues we discussed)



Detection of large-scale ‘TeV halos’ around pulsars