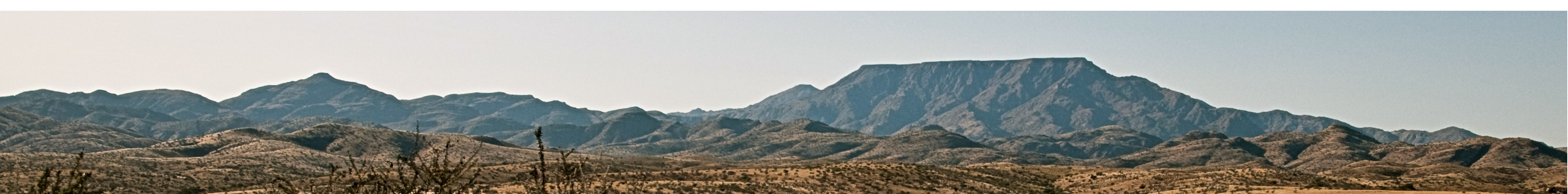
A window on the TeV sky

recent results from H.E.S.S. II

Matteo Cerruti
CNRS, LPNHE, Paris

OCA Seminar, Nice,
01-09-2018

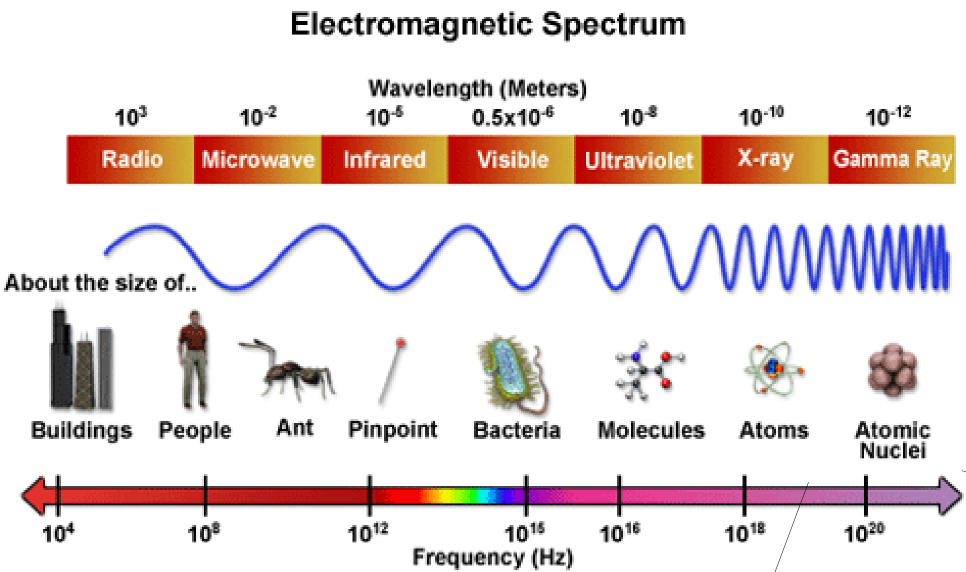


Plan of the seminar

- ***How*** do we detect TeV photons?
- ***What do we see*** at TeV energies?

- What did ***H.E.S.S. I*** (2004-2012) do?
- What is ***H.E.S.S. II*** doing?
- What will ***CTA*** do?

TeV astronomy



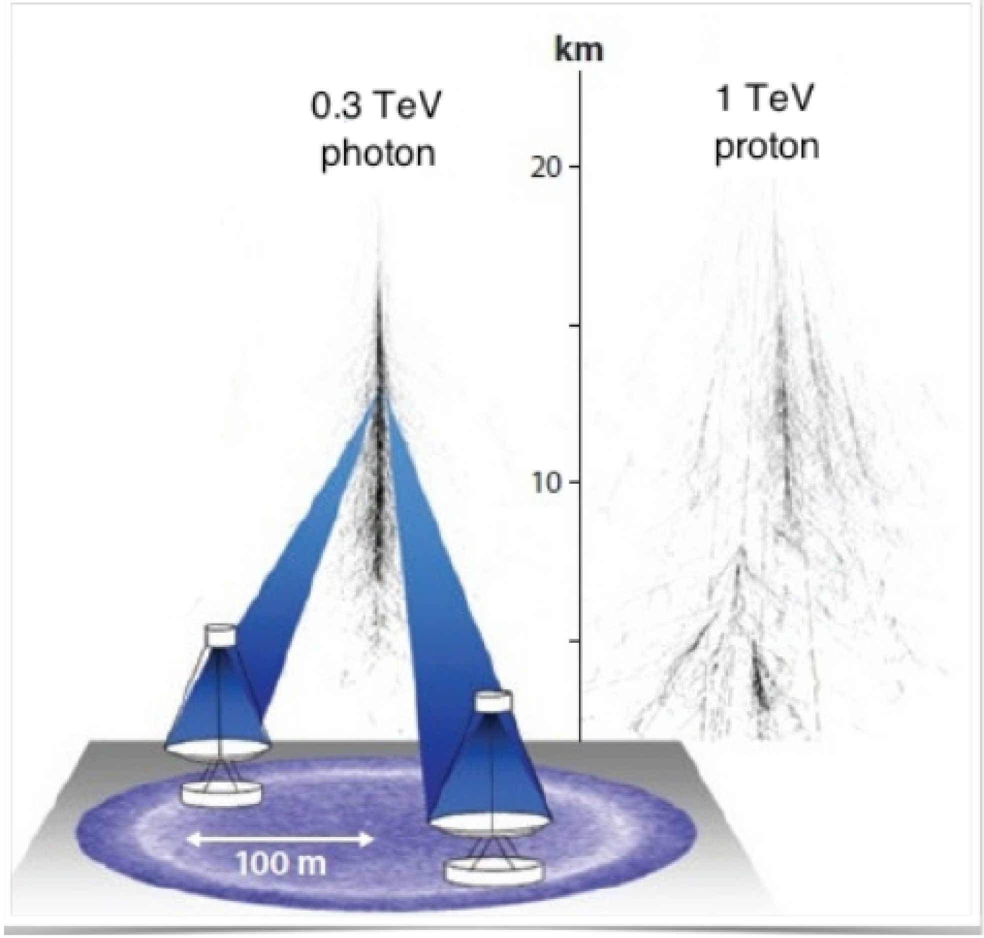
Soft γ rays (INTEGRAL)	High energy γ rays (Fermi-LAT)	Very High energy γ rays (Cherenkov telescopes)

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

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

TeV astronomy

Indirect detection technique: We observe the Cherenkov light emitted from cascades produced in the interaction of the TeV photon with the Earth atmosphere



Cherenkov telescope data analysis in a nutshell:

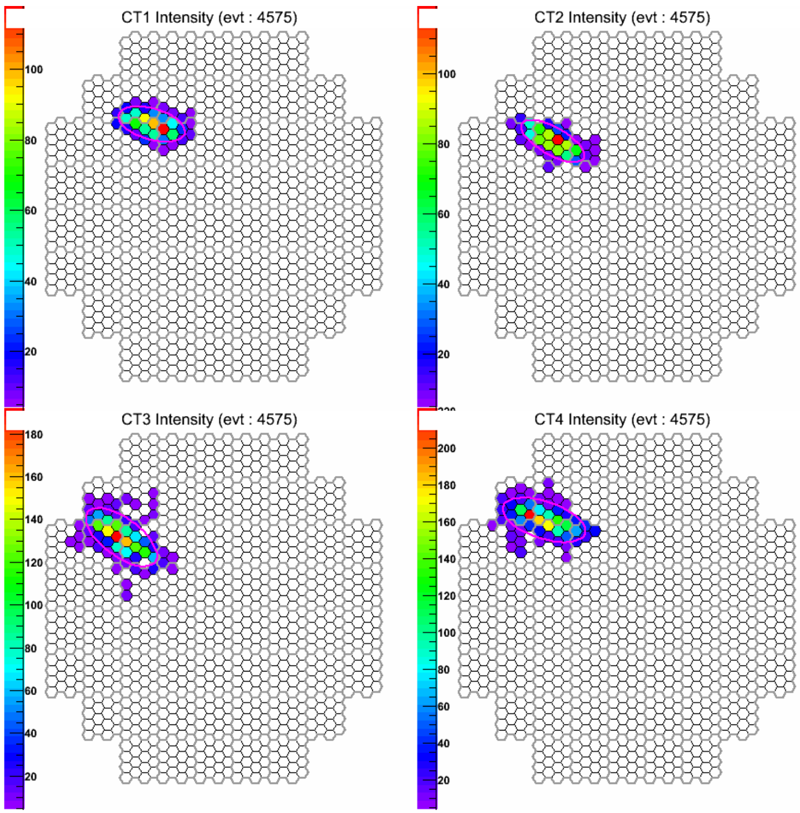
- Background rejection (our background is composed of cascades from cosmic rays)

- From candidate photon-showers → estimation of incoming direction and energy

- With event list, direction, energy and time we can do TeV astronomy: sky maps, energy spectra, light-curves

TeV astronomy

Indirect detection technique: We observe the Cherenkov light emitted from cascades produced in the interaction of the TeV photon with the Earth atmosphere



Cherenkov telescope data analysis in a nutshell:

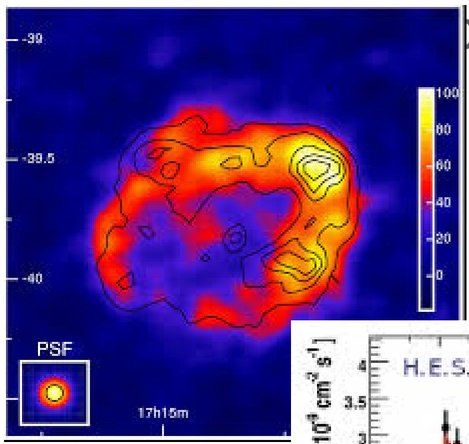
- Background rejection (our background is composed of cascades from cosmic rays)

- From candidate photon-showers → estimation of incoming direction and energy

- With event list, direction, energy and time we can do TeV astronomy: sky maps, energy spectra, light-curves

TeV astronomy

Indirect detection technique: We observe the Cherenkov light emitted from cascades produced in the interaction of the TeV photon with the



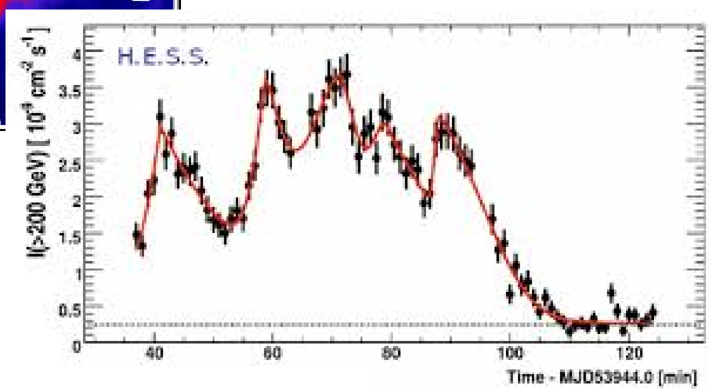
phere

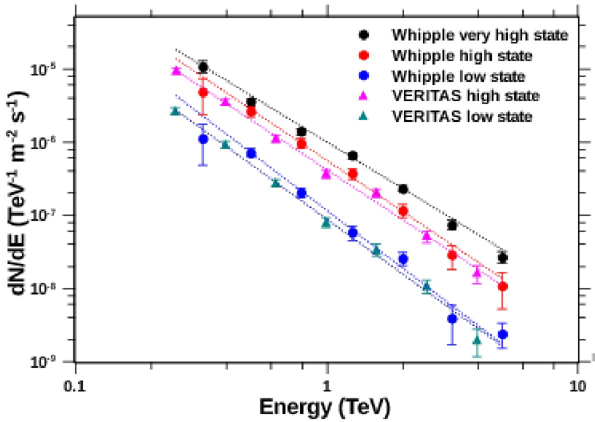
Cherenkov telescope data analysis in a nutshell:

- Background rejection (our background is composed of cascades from cosmic rays)

- From candidate photon-showers → estimation of incoming direction and energy

- With event list, direction, energy and time we can do TeV astronomy: sky maps, energy spectra, light-curves





A bit of history of TeV astronomy

The first observational challenge was to detect Cherenkov light from particle showers at all (i.e. first let's look at cosmic rays, than we can think how to discriminate photons)
Why complex task? ***Very faint, and very fast*** (nanoseconds)

1953: Galbraith & Jelley "Light pulses from the night sky associated with cosmic rays"

A bit of history of TeV astronomy

The first observational challenge was to detect Cherenkov light from particle showers at all (i.e. first let’s look at cosmic rays, than we can think how to discriminate photons)
Why complex task? ***Very faint, and very fast*** (nanoseconds)

1953: Galbraith & Jelley “Light pulses from the night sky associated with cosmic rays”

The problem was then, ***how can we discriminate*** photons from cosmic rays?

1989: Weekes et al. (the Whipple Collaboration) : *“Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique”*

Gamma-hadron separation done following the Hillas’method:
the Cherenkov image is parametrized with an ellipse → rejection of hadrons, determination of incoming direction, estimation of the energy

1992: Punch et al. (the Whipple Collaboration):
First extragalactic VHE source: the blazar Markarian 421

VHE astronomy has 29 years only!

TeV astronomy

The Whipple instrument and Trevor Weekes, have had a huge impact on the field, showing that VHE astronomy was possible and opening a new window on the sky

Second generation of Cherenkov telescopes
(from ~1990 to ~2005):
Whipple (in Arizona),
CAT (Cherenkov Array at Themis, on Pyrenees),
HEGRA (in Canary islands)

These telescopes discovered several more TeV emitters, and in particular the number of TeV extragalactic sources were 7

TeV astronomy

Third generation of Cherenkov telescopes
(~2005 to nowadays)

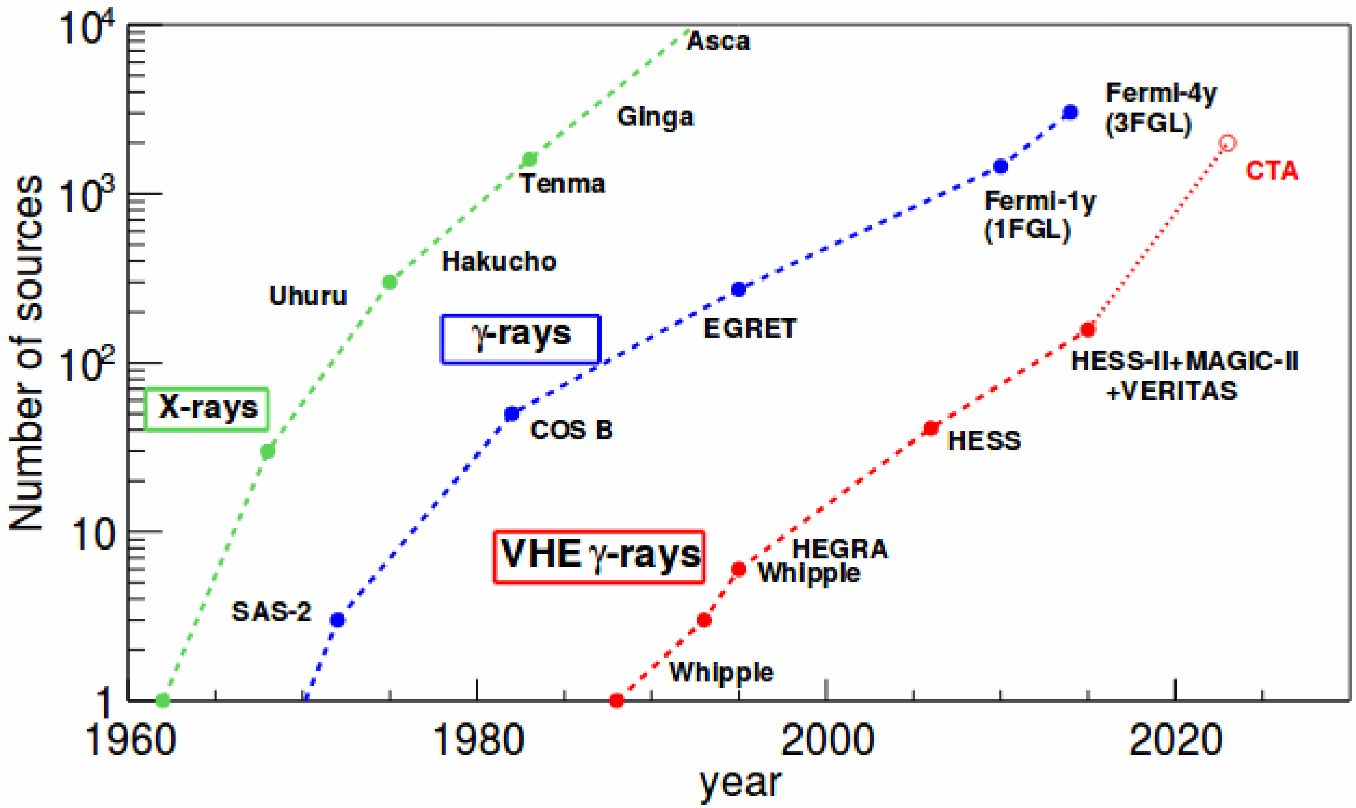
Three major collaborations:

VERITAS (in Arizona, four 12-m telescopes)
H.E.S.S. (in Namibia, four 12-m telescopes + one 28-m telescope
MAGIC (in Canary islands, two 20-m telescopes)

The number of known TeV emitters is now ~200

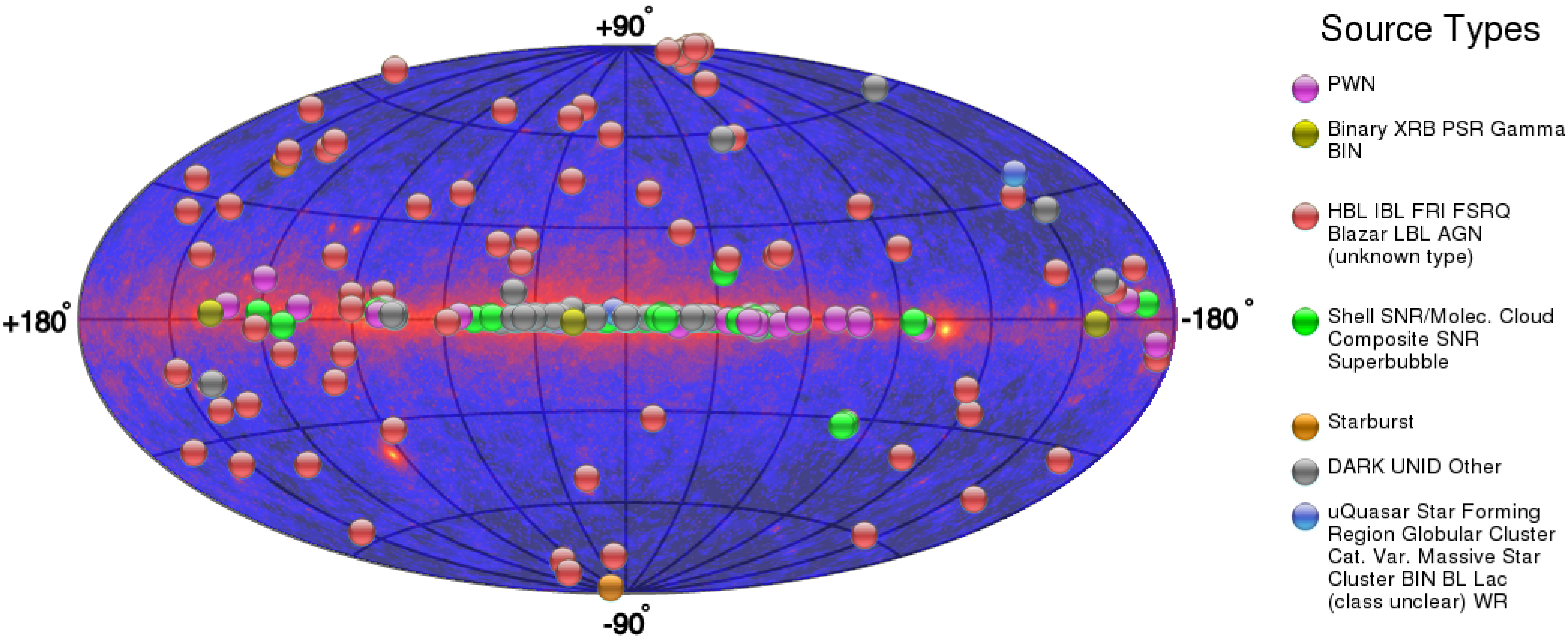
TeV astronomy

Kifune plot



From de Naurois & Mazin, 2015

THE TeV SKY



Key numbers:

Field of view: 3° to 5°
Angular resolution: 0.1°
Energy resolution: 10%

tevcat.uchicago.edu

THE TeV GALACTIC SKY

Galactic science in the TeV band

Pulsars (only 2!) and their wind nebulae (very common)
Gamma-ray binaries
Supernova remnants / molecular clouds

More unique objects:
- Sgr A*
- Super bubbles (30 Dor C)
- Globular clusters (Terzan 5)

THE TeV EXTRAGALACTIC SKY

Extragalactic science in the TeV band

AGN (mainly blazars, three radio galaxies)
Starburst galaxies (only 2!)

THE TeV SKY

- Physics of compact objects
(neutron stars & black holes)

- Physics of cosmic rays
(galactic & extragalactic)

- Cosmology & fundamental physics
(dark matter, extragalactic background light,
Lorentz Invariance violations,...)

H.E.S.S. I

Array of 4 Cherenkov telescopes located on Khomas Highland, Namibia
(23°16‘ S, 16°30‘ E)

2004: first light of the array
2012: installation of the central telescope (CT5)

Detection of photons above 100 GeV
Energy resolution: ~10% at 1 TeV
Angular resolution: ~0.1° at 1 TeV

H.E.S.S. I

Three main scientific working groups

Galactic sources

Extragalactic sources

Astroparticle and fundamental physics

H.E.S.S. I GALACTIC RESULTS

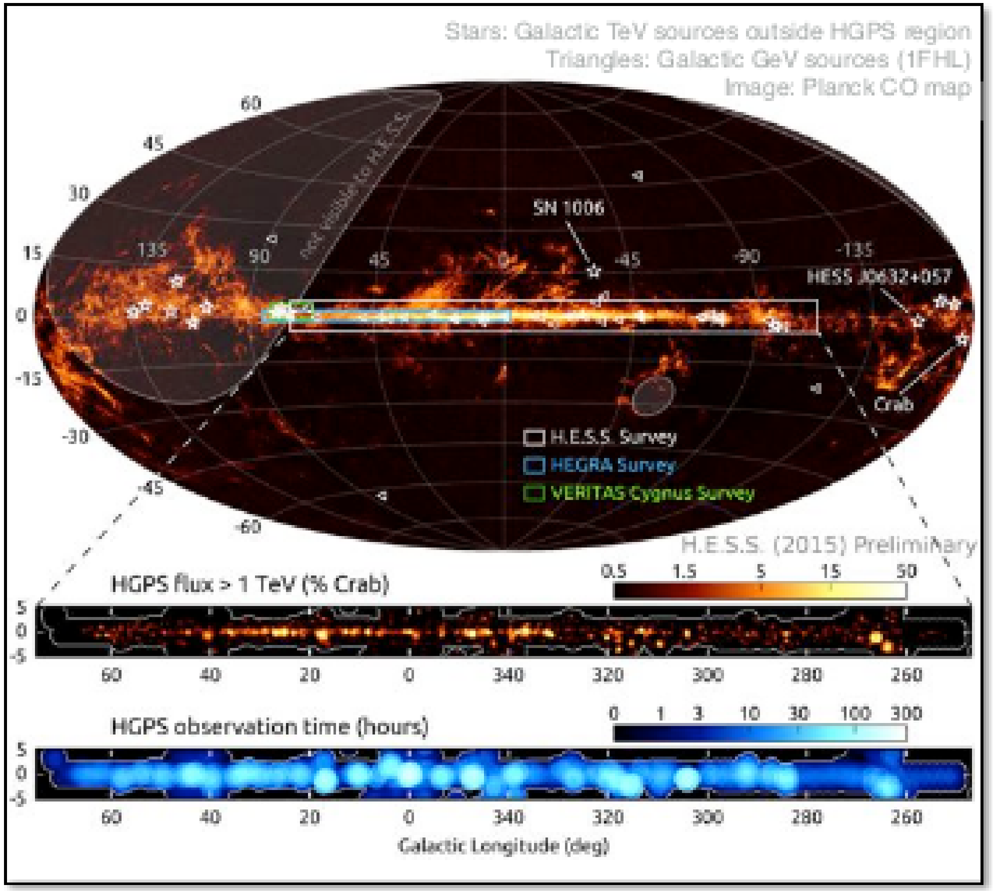
The HESS Galactic Plane Survey (HGPS)
This is the ONLY survey of the milky way in the VHE band

2673 hours of data
From 2004 to 2013

-110° < l < 65°
-3.5° < b < 3.5

Inhomogeneous exposure

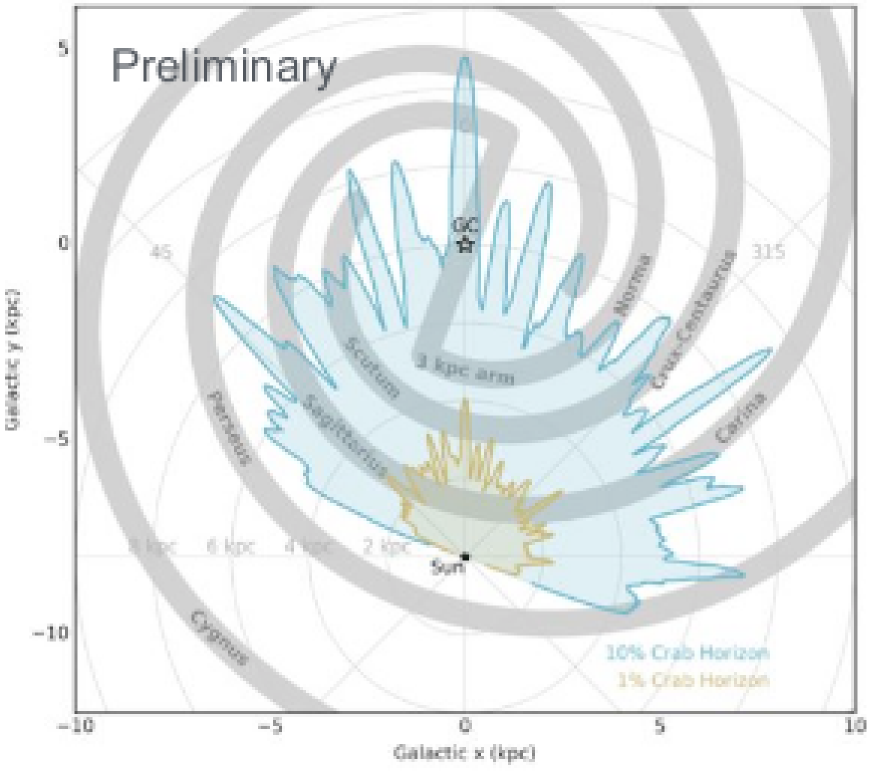
A&A special issue on the HGPS and HESS I galactic legacy to be published very soon!

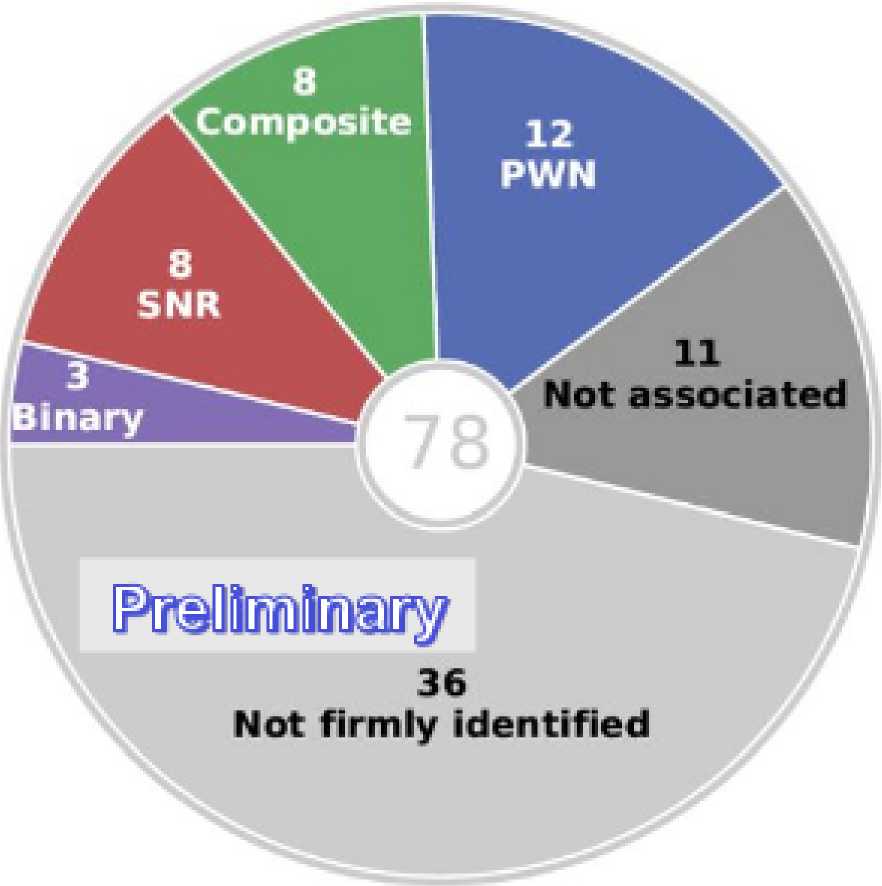


HESS Collaboration 2018

H.E.S.S. I GALACTIC RESULTS

The HESS Galactic Plane Survey (HGPS)
This is the ONLY survey of the milky way in the VHE band



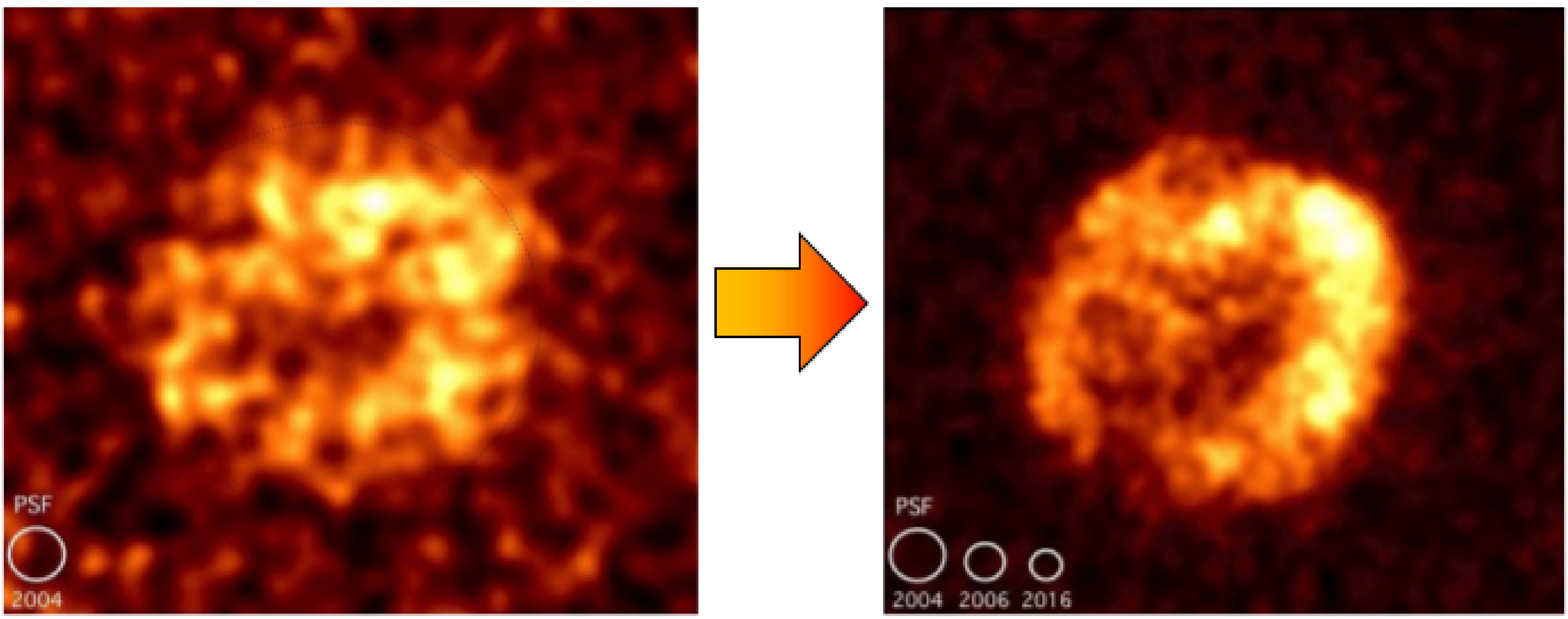


HESS Collaboration 2018

H.E.S.S. I GALACTIC RESULTS

Discovery of extended VHE emission from supernova remnants

RX J1713-3946: from discovery paper in 2004 to last paper in 2016
~factor 2 improvement in statistics



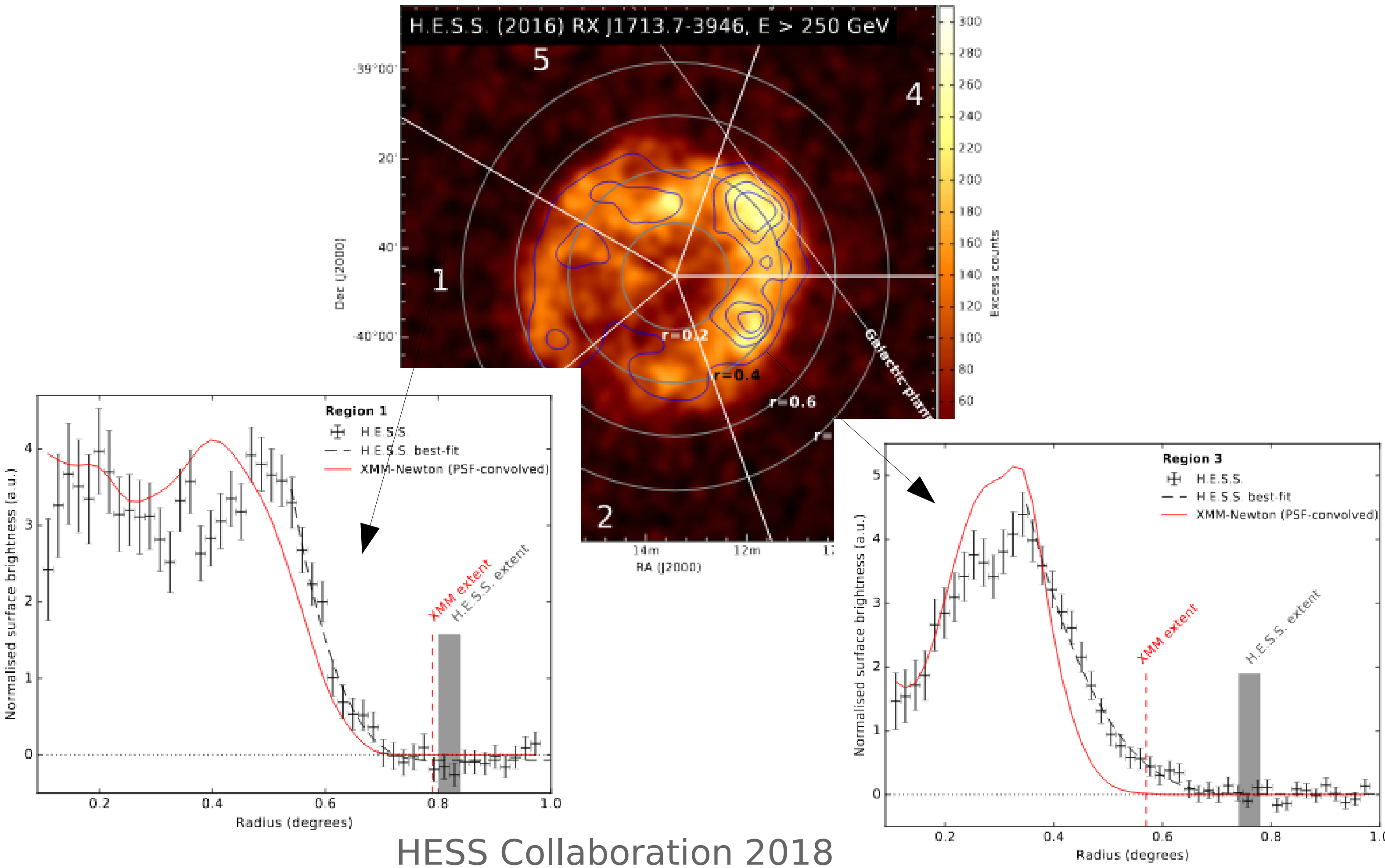
HESS Collaboration 2018

...but also improved analysis methods!

Gamma-hadron separation has been significantly improved since 2004

H.E.S.S. I GALACTIC RESULTS

Clear morphological difference between X-rays and gamma-rays
→ Particles escaping the acceleration shock



HESS Collaboration 2018

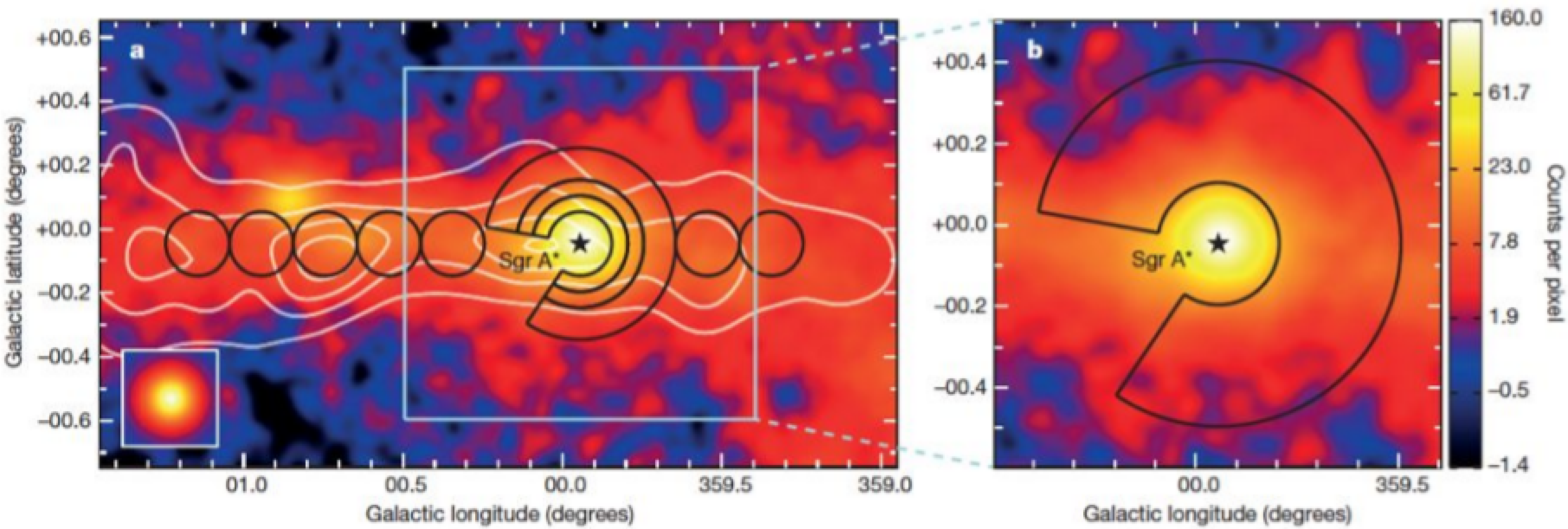
H.E.S.S. I GALACTIC RESULTS

Where are the PeV cosmic rays produced? in the Galactic Center!

TeV emission from SgrA* is pointlike, on top of a diffuse emission

Diffuse emission with no spectral cut-off, and 1/r profile

→ consistent with CR (up to 3 PeV) interacting with inter-stellar medium



HESS Collaboration 2016

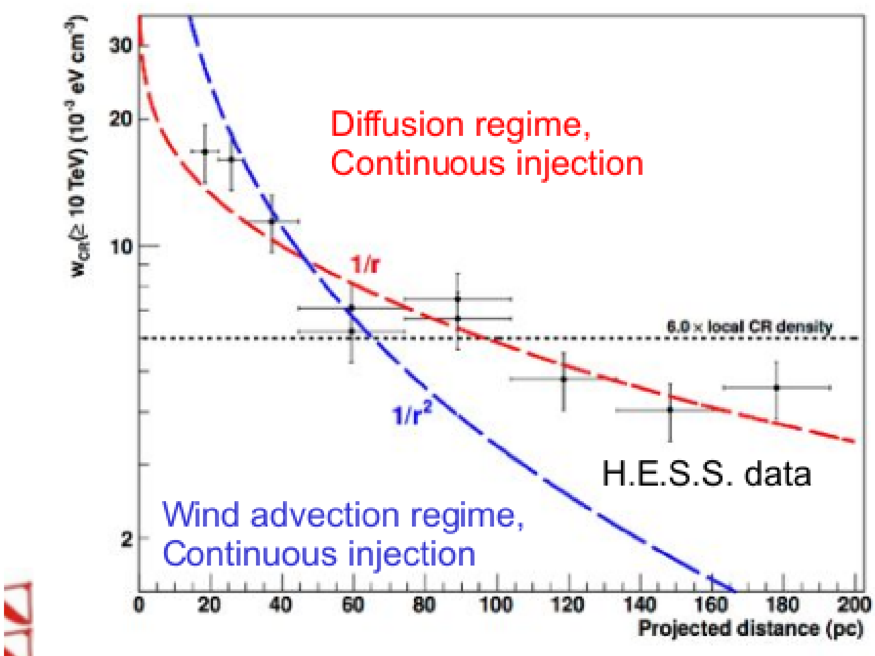
H.E.S.S. I GALACTIC RESULTS

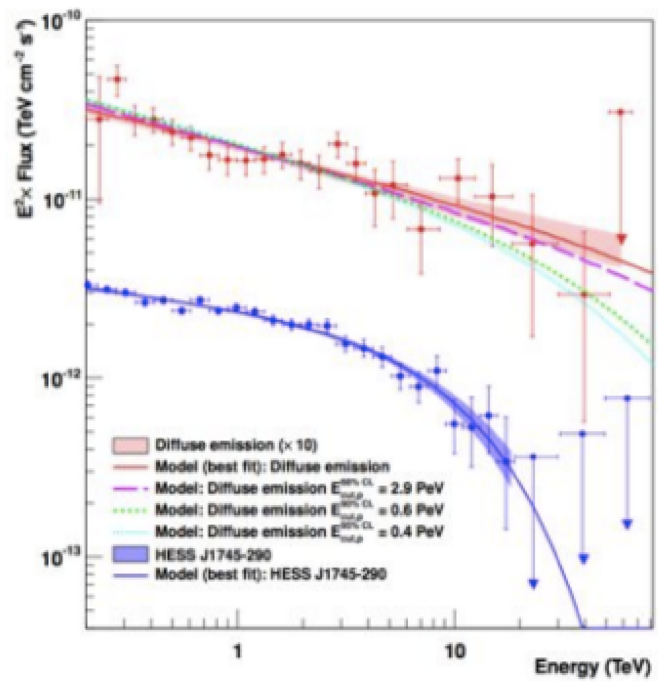
Where are the PeV cosmic rays produced? in the Galactic Center!

TeV emission from SgrA* is pointlike, on top of a diffuse emission

Diffuse emission with no spectral cut-off, and 1/r profile

→ consistent with CR (up to 3 PeV) interacting with inter-stellar medium





H.E.S.S. I

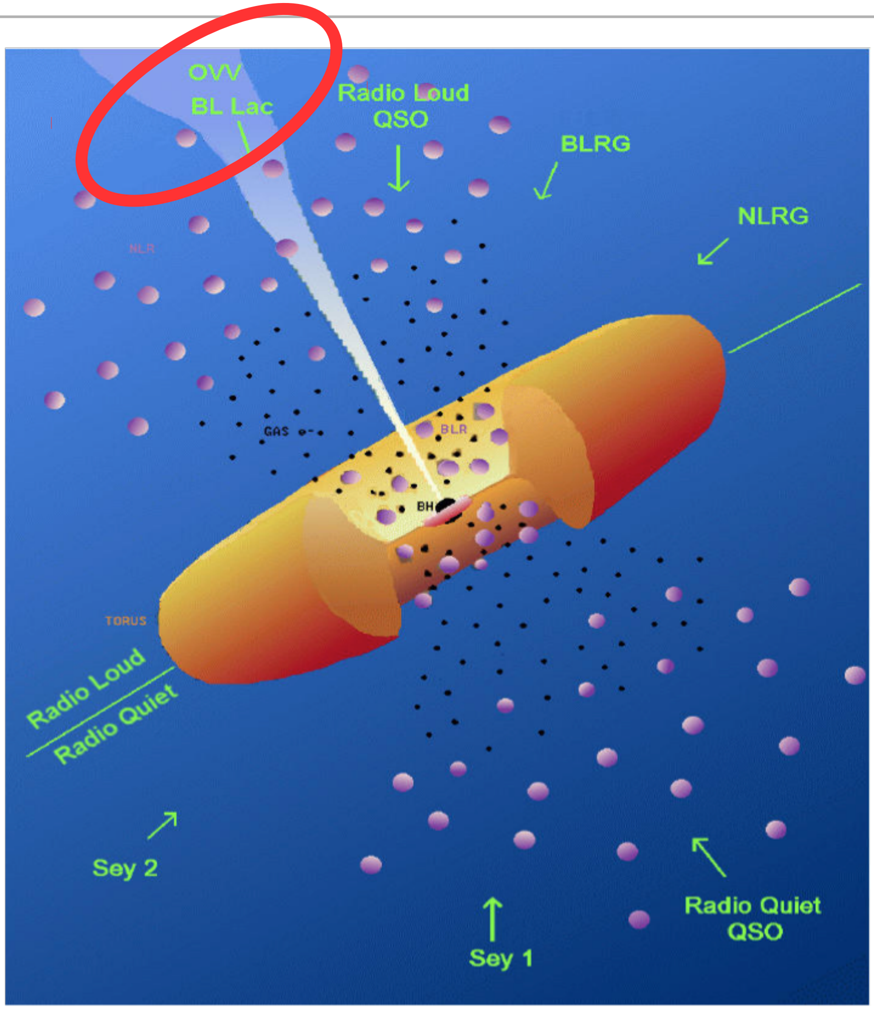
Three main scientific working groups

Galactic sources

Extragalactic sources

Astroparticle and fundamental physics

BLAZARS



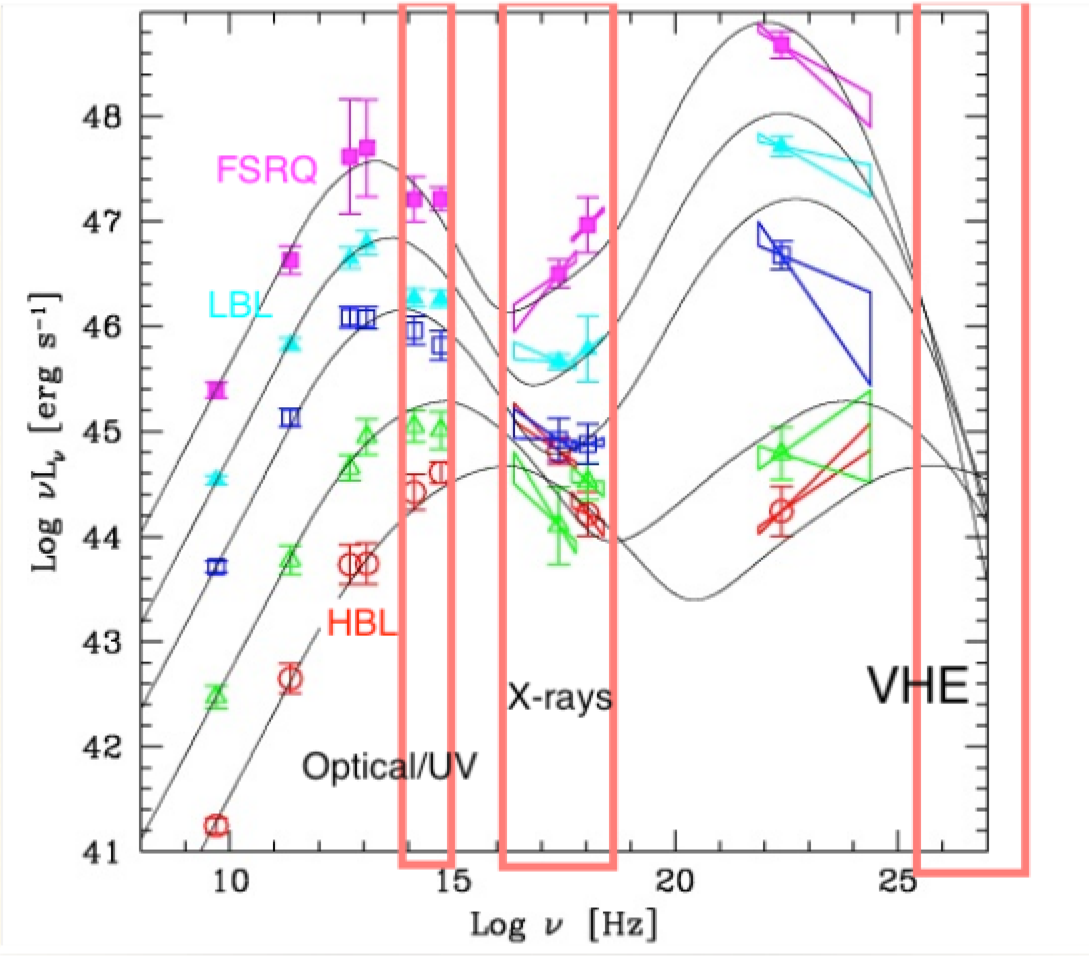
Blazar : radio-loud AGN whose relativistic jet points in the direction of the observer

→ emission from the jet dominates over any other AGN component (the disk, the BLR, the X-ray corona,…)

→ non-thermal emission from radio to gamma-rays, and extreme variability

- Flat-Spectrum-Radio-Quasars: optical spectrum with broad emission lines
- BL Lacertae objects : optical spectrum featureless

BLAZARS



Fossati et al. 1998

Spectral energy distribution (SED) two distinct components

FSRQs show a peak in IR

BL Lac objects are classified in:

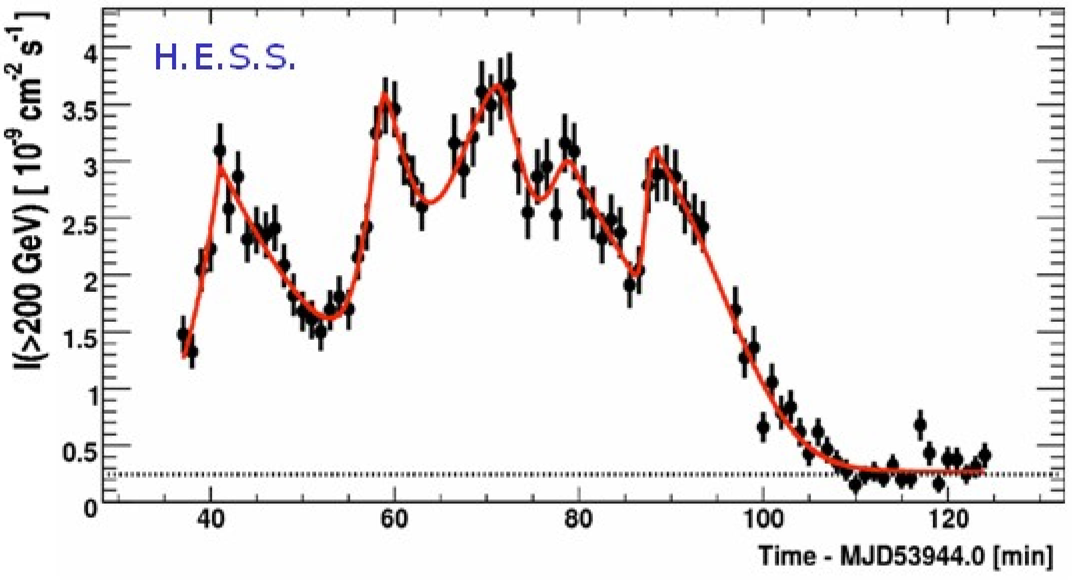
- peak in optical : Low-frequency peaked (LBLs)
- peak en UV/X : High-frequency peaked (HBLs)
- peak >10 KeV : Ultra-high-frequency peaked (UHBLs)

H.E.S.S. I EXTRAGALACTIC RESULTS

PKS 2155-304, high-frequency-peaked BL Lac, z=0.116

One of the brightest TeV sources (and one of the few detected with the previous generation of Cherenkov telescopes)

In 2006, the H.E.S.S. telescopes were monitoring the source when they observed this eruption



Aharonian et al. 2007

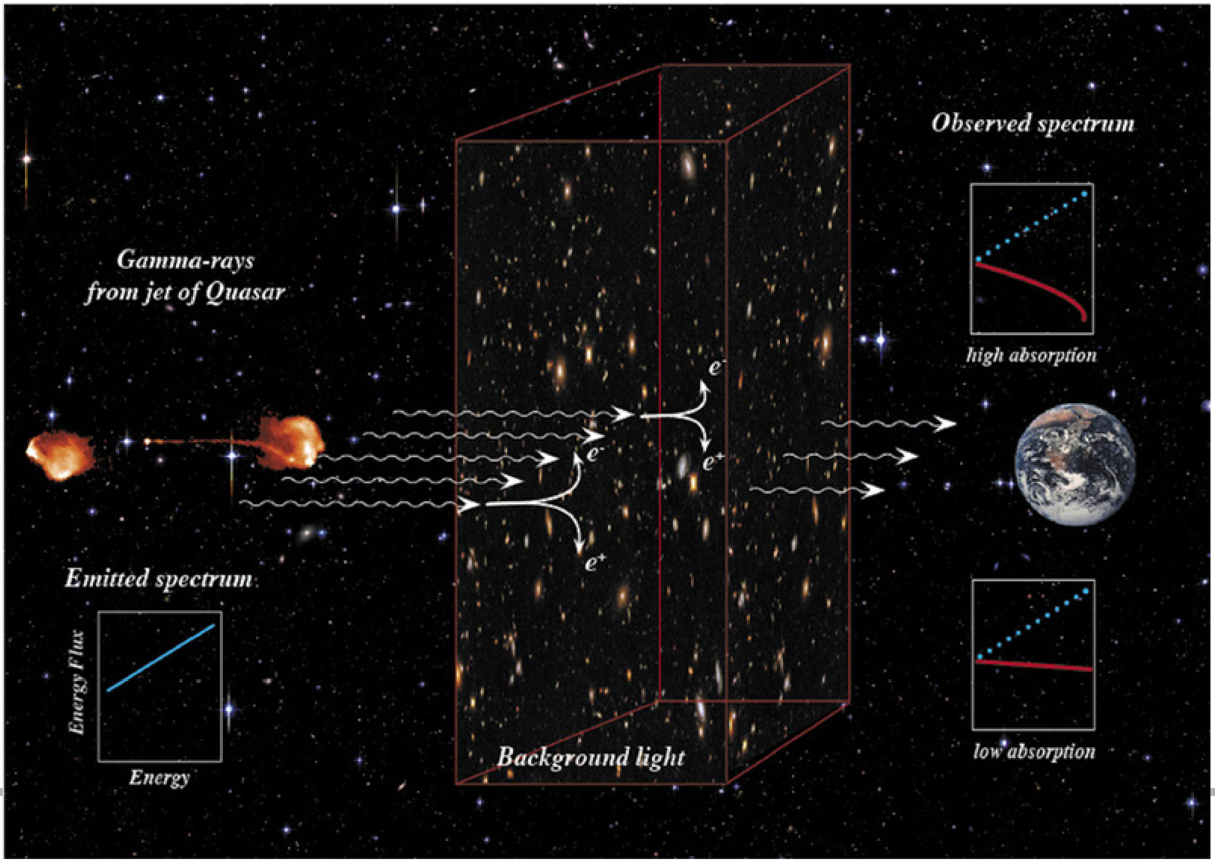
1-min long bins
Peak emission is about 15 times the Crab nebula, the brightest (persistent) TeV emitter
Fastest variability is at ~100 seconds

H.E.S.S. I EXTRAGALACTIC RESULTS

Important property of TeV astronomy: the TeV universe has a horizon :-(

$$\gamma_{TeV} + \gamma_{IR} \rightarrow e^{+} + e^{-}$$

Pair production over ANY infrared/optical photon field induces an absorption; the extragalactic background light (EBL) acts as a fog for us

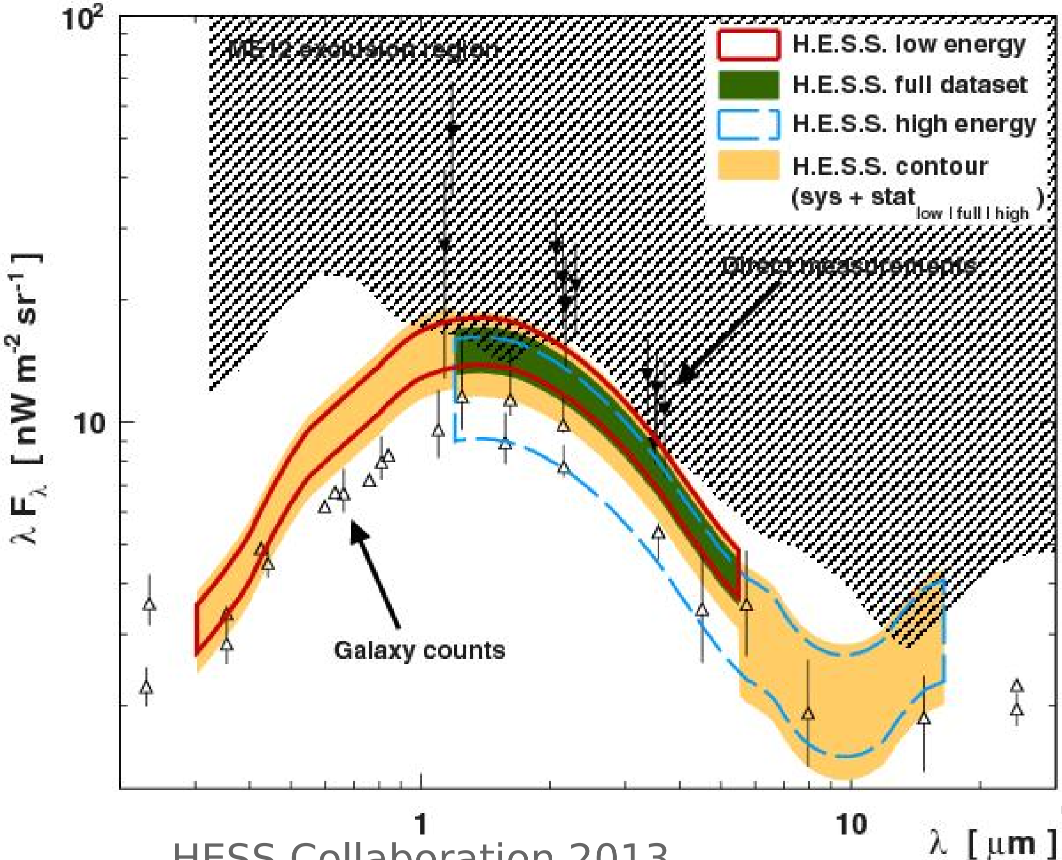


H.E.S.S. I EXTRAGALACTIC RESULTS

Currently, the most distant blazars are at z=0.94

But…we can use TeV astronomy to study the absorber!

→ EBL measurement from TeV blazars! (HESS Collaboration, 2013)



HESS Collaboration 2013

H.E.S.S. I

Three main scientific working groups

Galactic sources

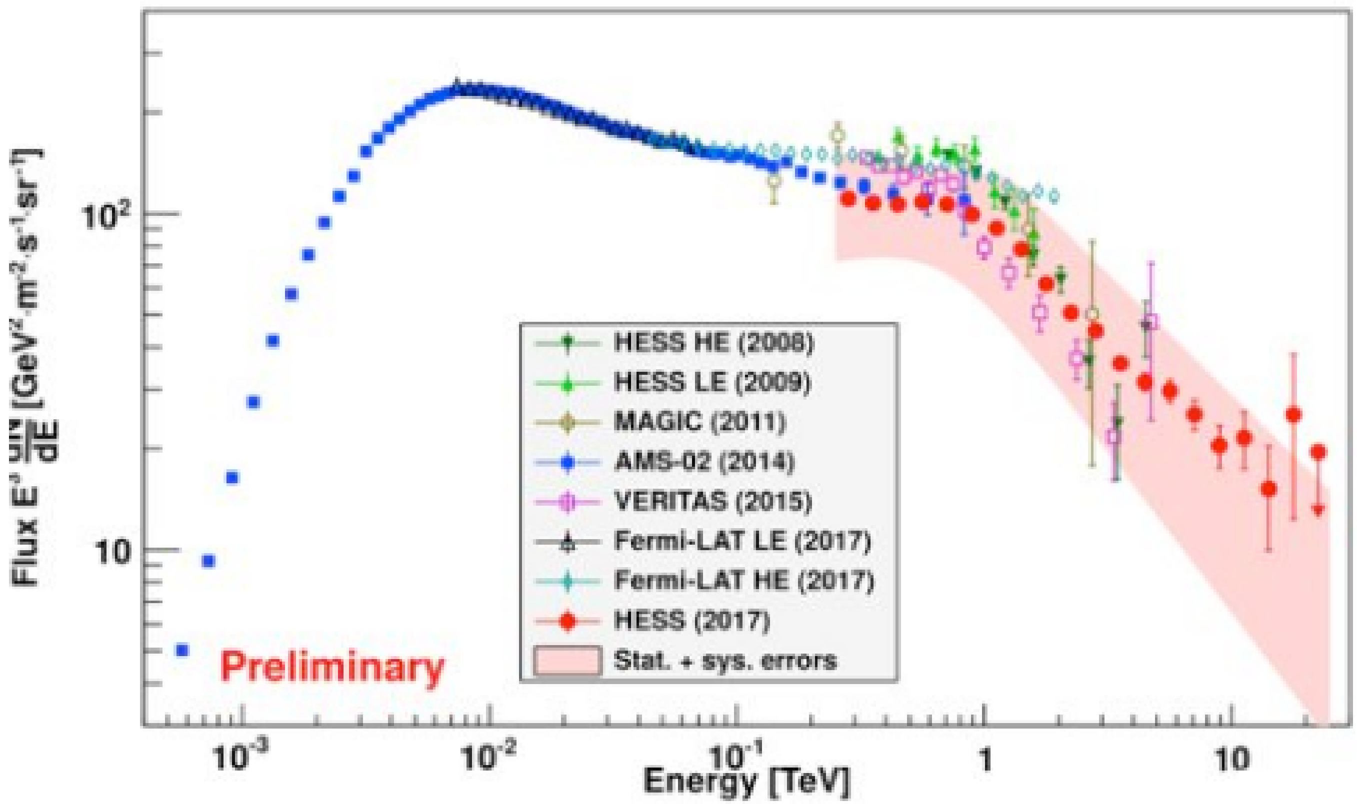
Extragalactic sources

Astroparticle and fundamental physics

H.E.S.S. I ASTROPARTICLE RESULTS

By looking at background extragalactic regions, we can extract the spectrum of electrons+positrons

Cherenkov telescopes provide the only measurement in the TeV band!

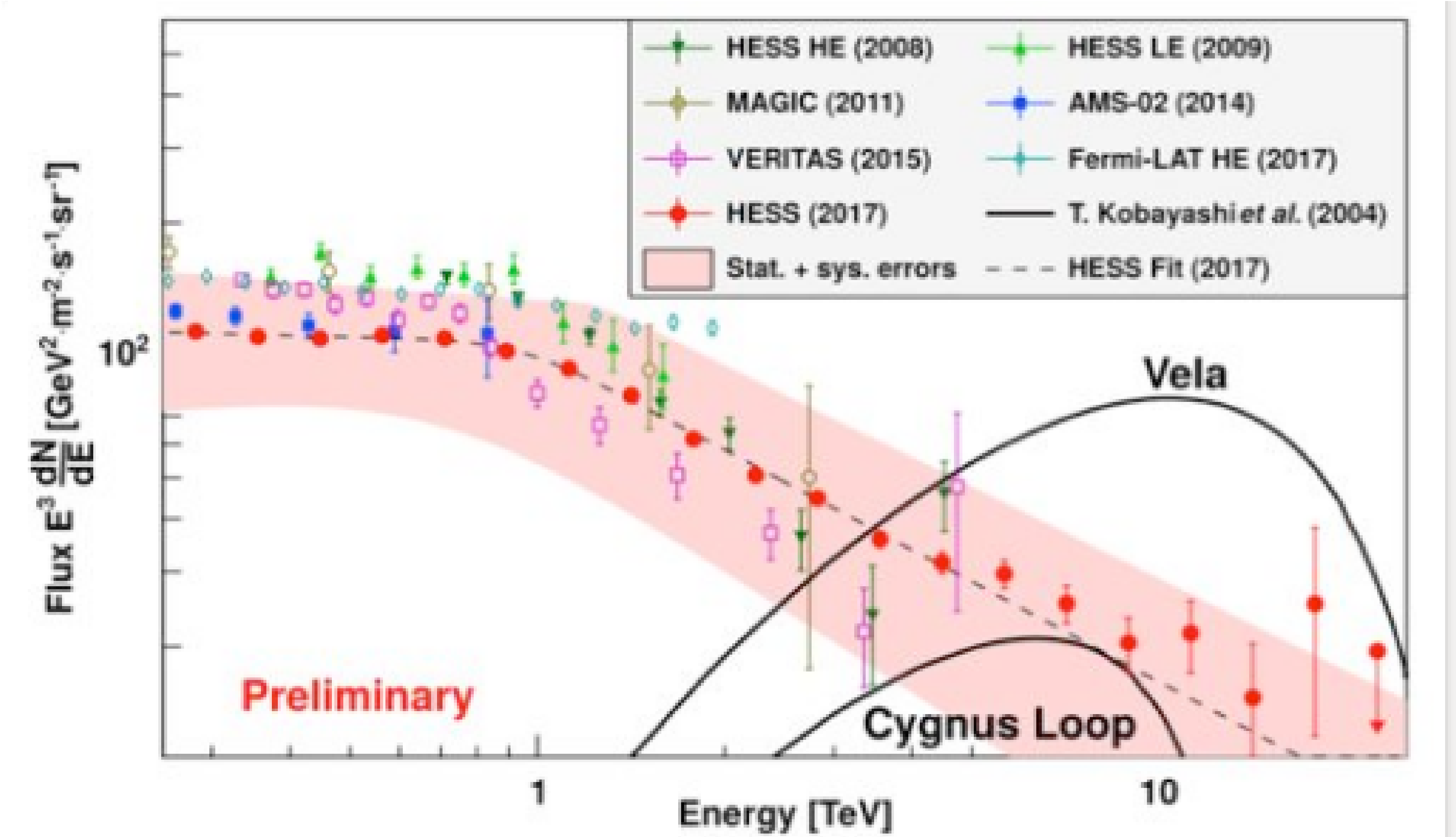


HESS Collaboration, ICRC 2017

H.E.S.S. I ASTROPARTICLE RESULTS

By looking at background extragalactic regions, we can extract the spectrum of electrons+positrons

Cherenkov telescopes provide the only measurement in the TeV band!



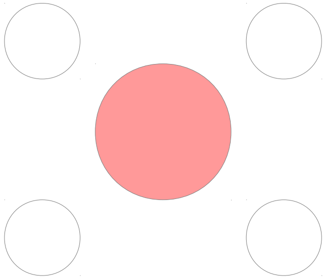
HESS Collaboration, ICRC 2017

H.E.S.S. II

Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia (23°16‘ S, 16°30‘ E)

Two different reconstructions:

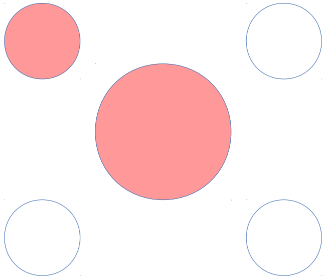
- Monoscopic (CT5 only)
- Stereoscopic (any 2 out of 5 telescopes)



H.E.S.S. II

Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia (23°16‘ S, 16°30‘ E)

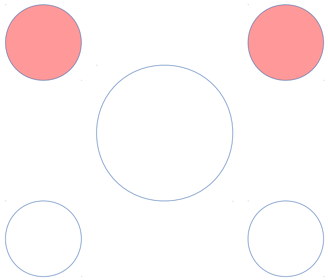
Two different reconstructions:
- Monoscopic (CT5 only)
- Stereoscopic (any 2 out of 5 telescopes)



H.E.S.S. II

Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia
(23°16‘ S, 16°30‘ E)

Two different reconstructions:
- Monoscopic (CT5 only)
- Stereoscopic (any 2 out of 5 telescopes)



WHY H.E.S.S. II?

1) The large telescope increase the sensitivity of the array for low-energy showers → Threshold down to tens of GeV

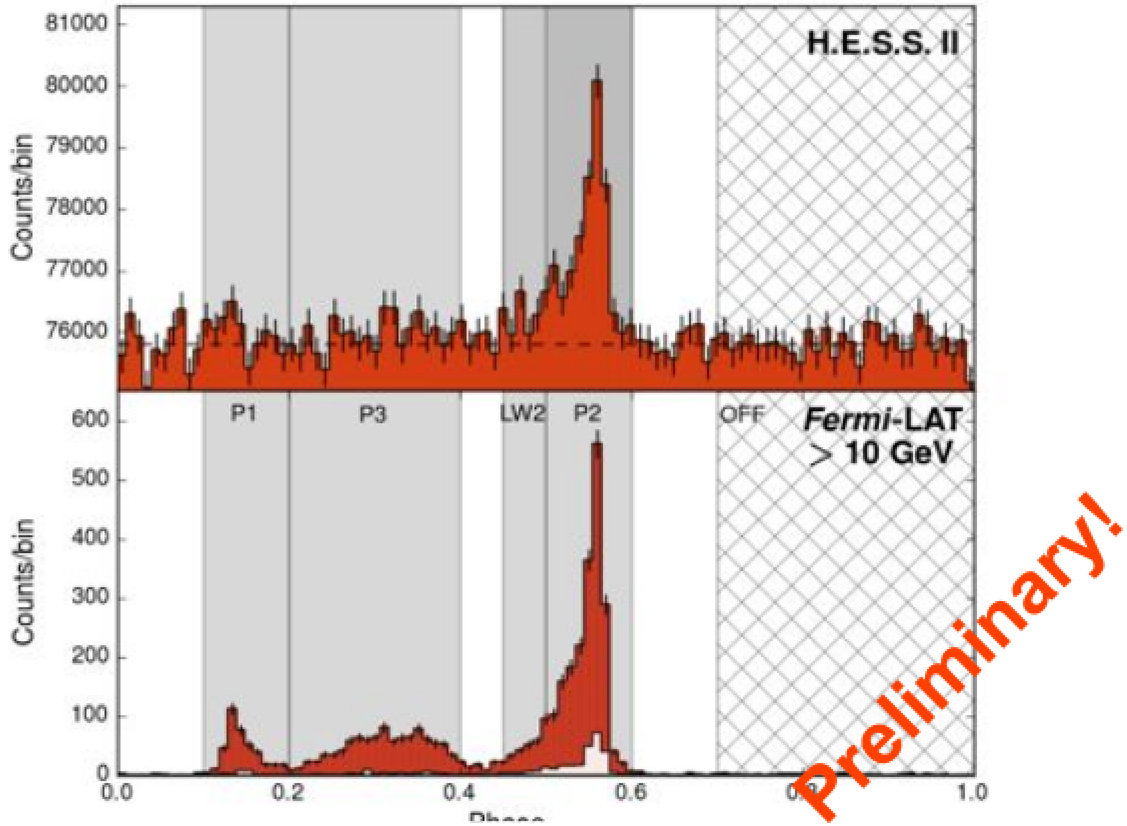
2) Very fast pointing system: it can follow up on real-time alerts and be on target in ~100 seconds

3) First (and only) hybrid array of Cherenkov telescopes
→ propaedeutic to CTA

H.E.S.S. II GALACTIC RESULTS

The Vela pulsar in monoscopic reconstruction

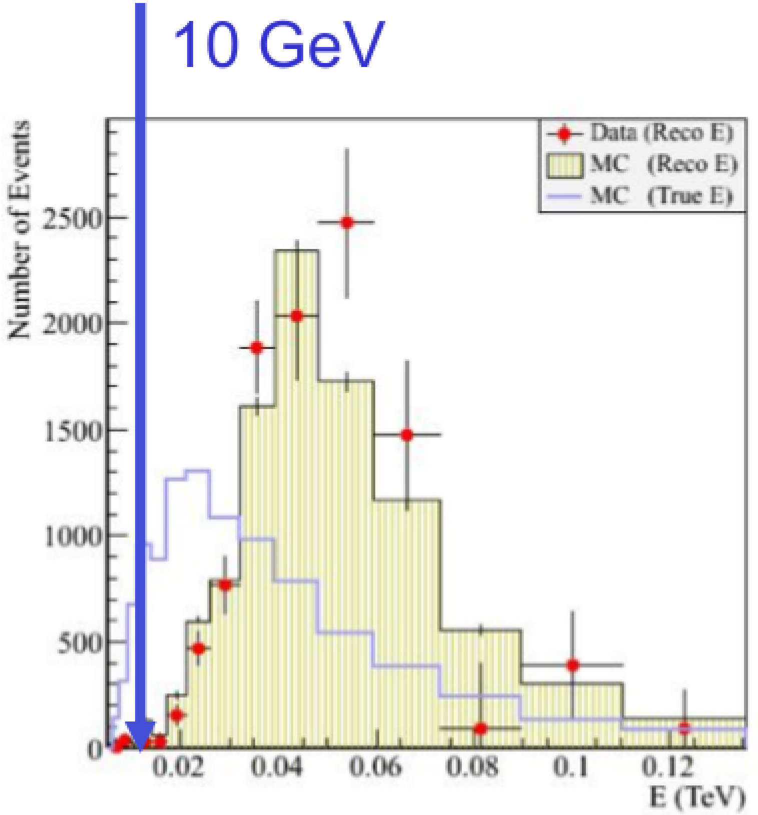
- second pulsar known to emit VHE photons (after the Crab)
- perfect agreement with Fermi-LAT spectrum
- H.E.S.S. II can detect photons down to 10 GeV

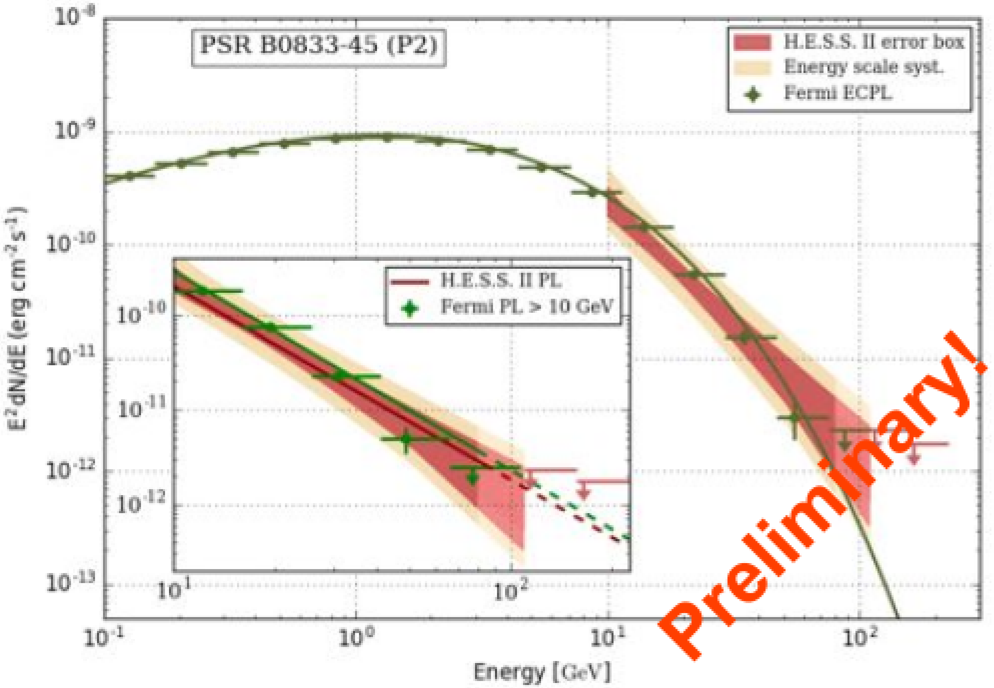


H.E.S.S. II GALACTIC RESULTS

The Vela pulsar in monoscopic reconstruction

- second pulsar known to emit VHE photons (after the Crab)
- perfect agreement with Fermi-LAT spectrum
- H.E.S.S. II can detect photons down to 10 GeV

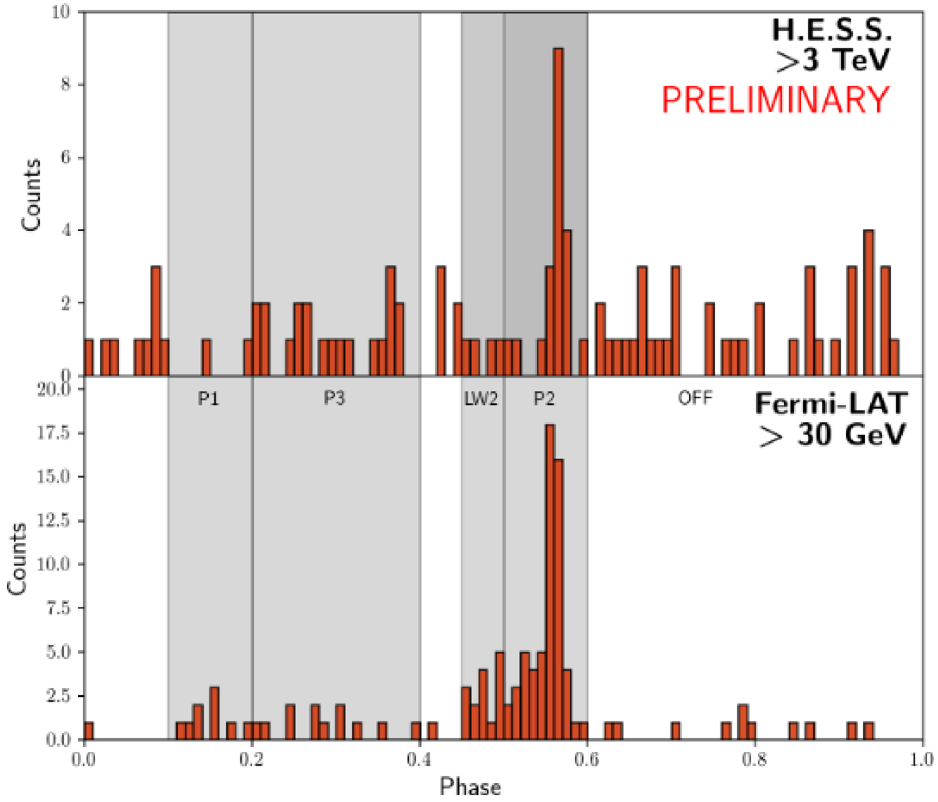




H.E.S.S. II GALACTIC RESULTS

The Vela pulsar in stereoscopic reconstruction

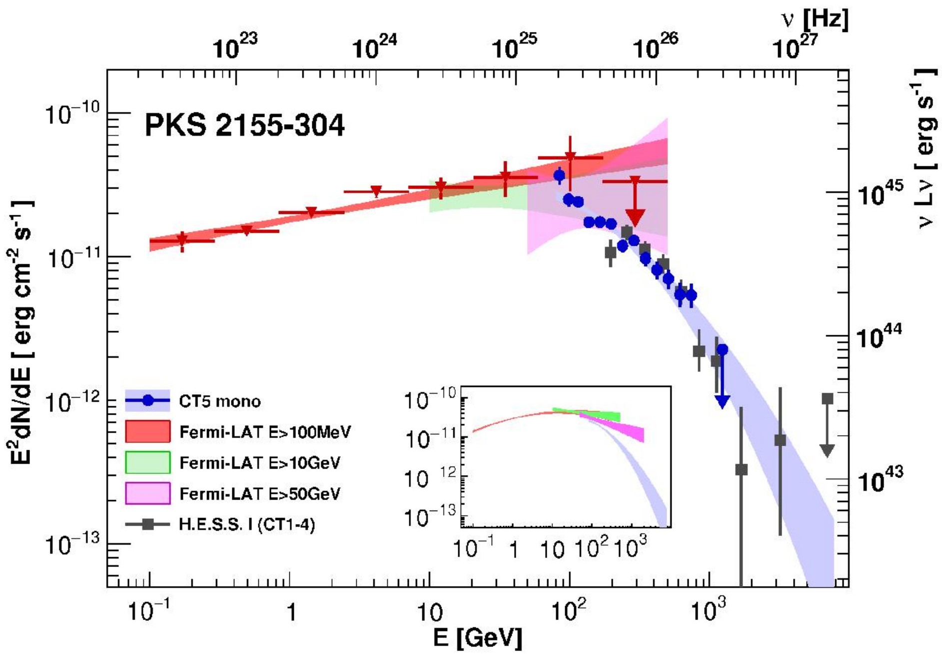
- detection in the TeV band!
- similar to the Crab
- challenges theoretical modeling → a new component in the TeV band?

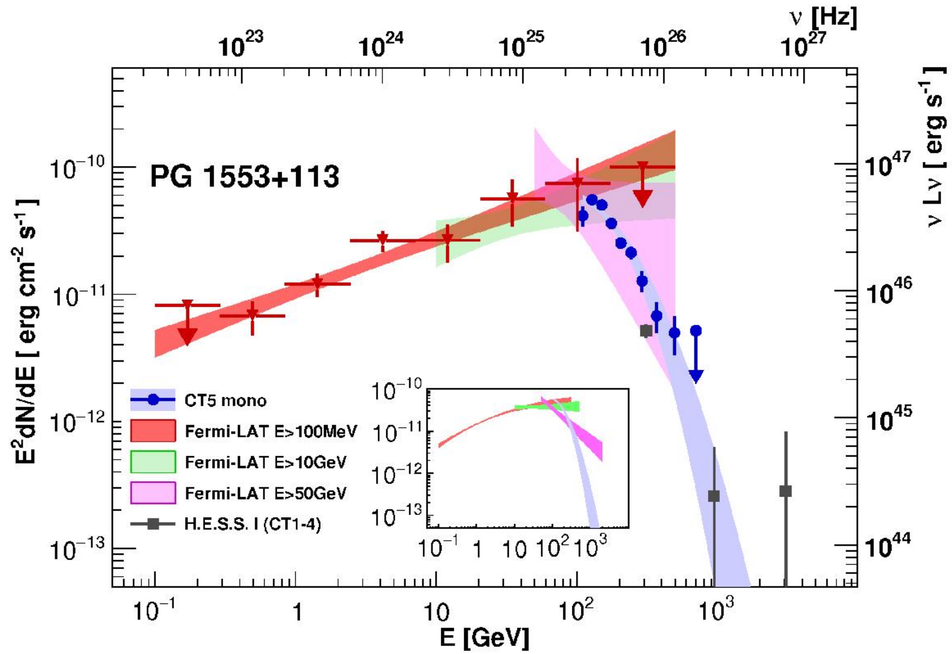


H.E.S.S. II EXTRAGALACTIC RESULTS

Spectra of bright blazars with improved energy threshold

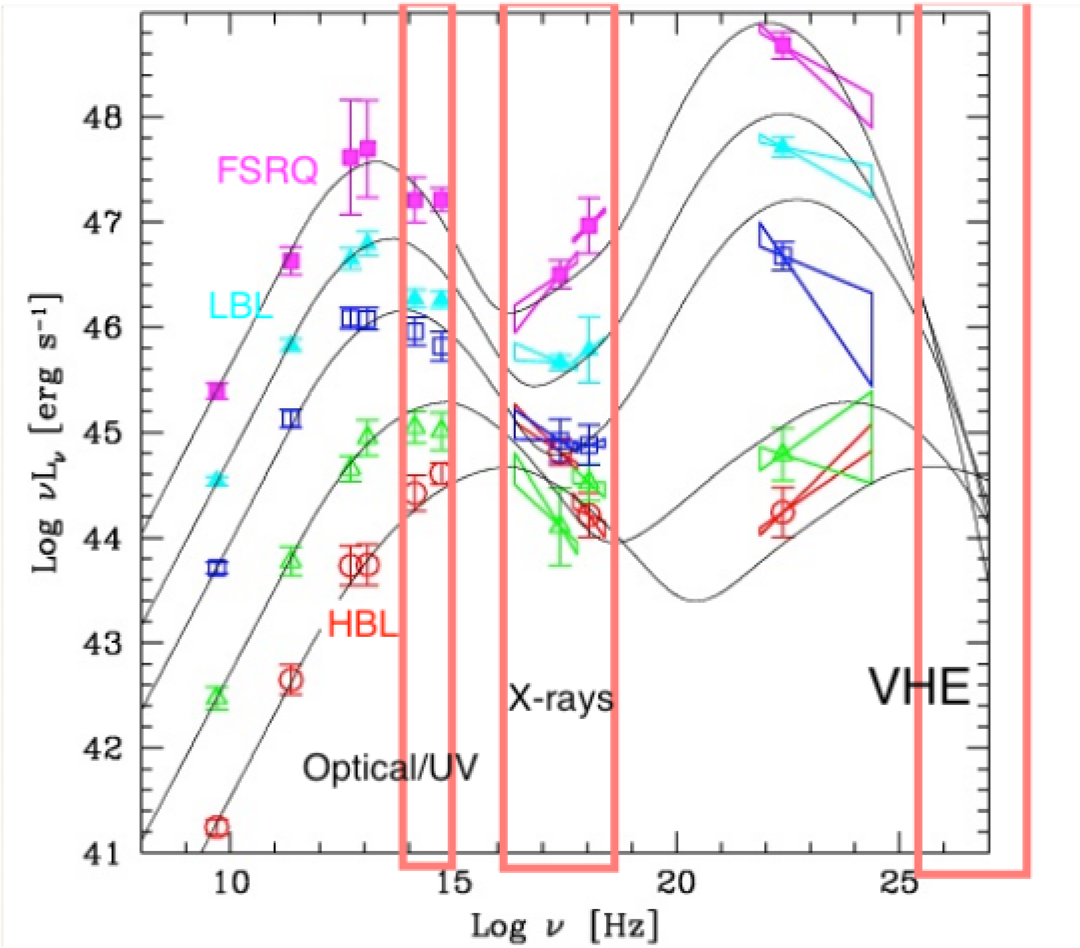
PKS 2155-304 and PG 1553+113





HESS Collaboration 2017

H.E.S.S. II EXTRAGALACTIC RESULTS



Flat-Spectrum Radio-Quasars with H.E.S.S. II

Blazar population with low-energy peak → strong benefit from the new low energy threshold

Elusive at VHE, with only 7 of them known

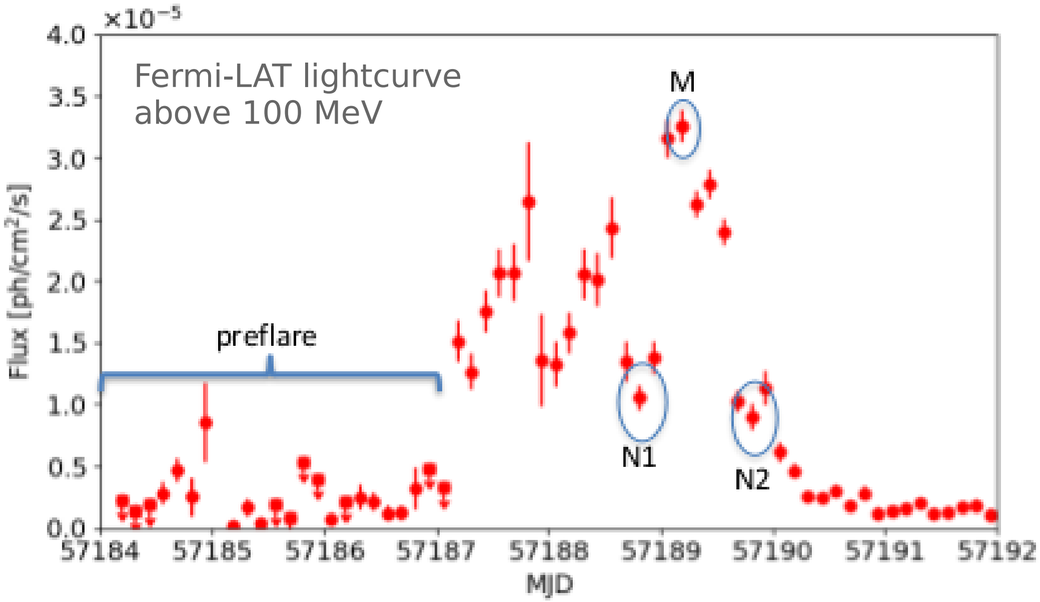
With H.E.S.S. II:
Discovery of PKS0736+017

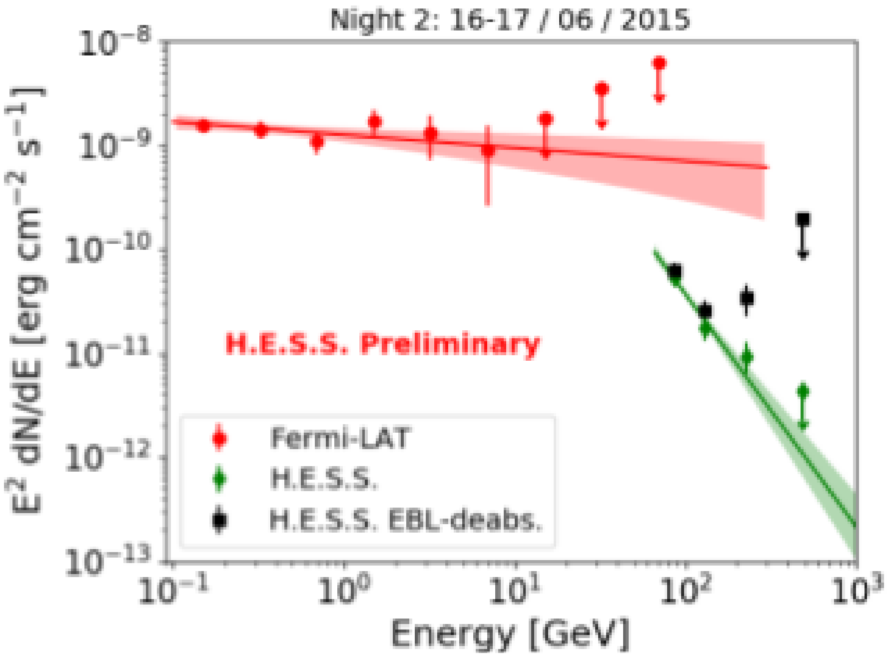
Detection of 3C279 during the 2015 flare

Detection of a rapid flare from PKS1510-089

H.E.S.S. II EXTRAGALACTIC RESULTS

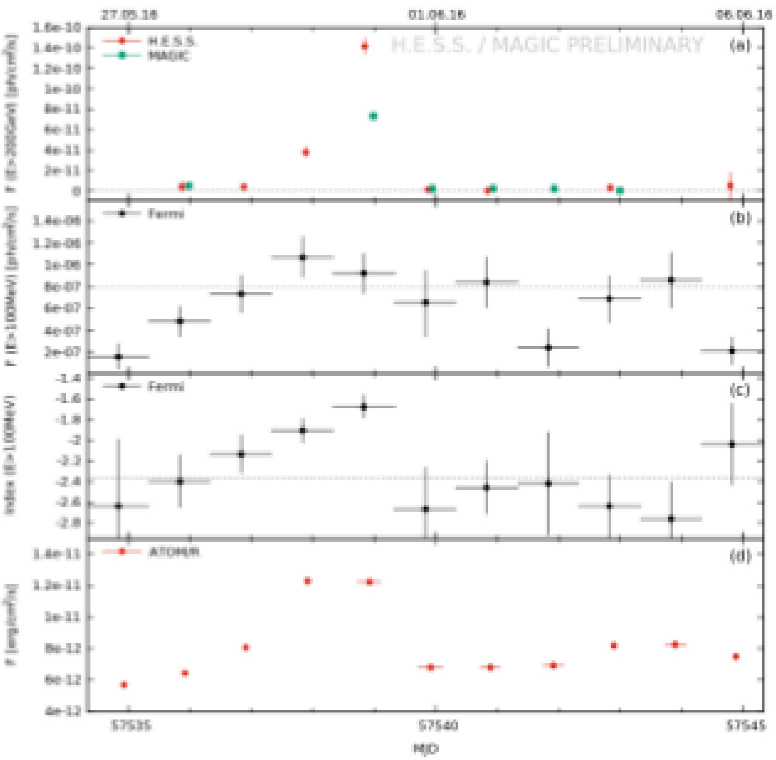
Detection of 3C279 during the 2015 flare



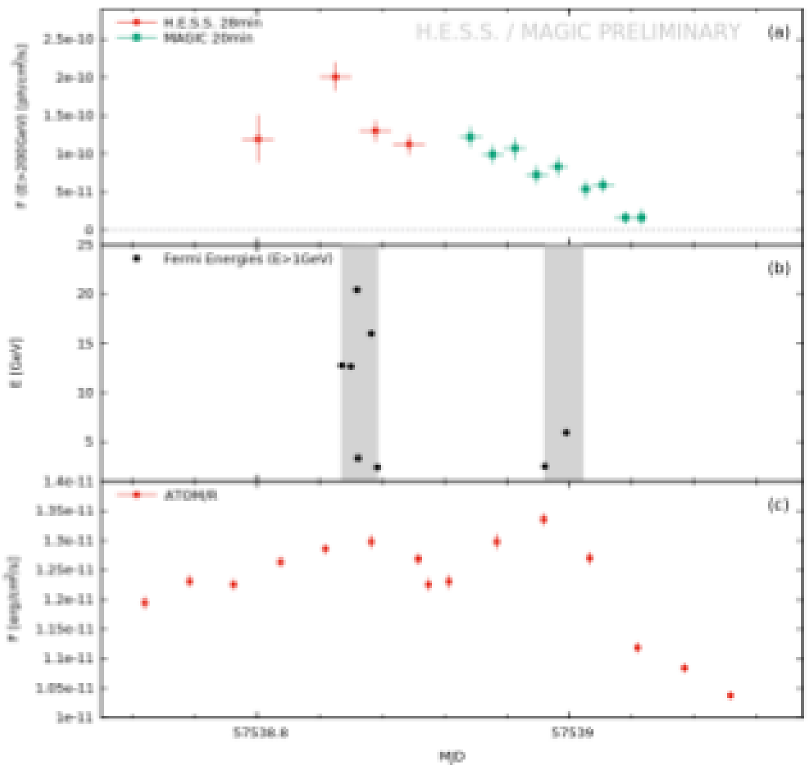


H.E.S.S. II EXTRAGALACTIC RESULTS

Detection of a rapid flare from PKS 1510-089

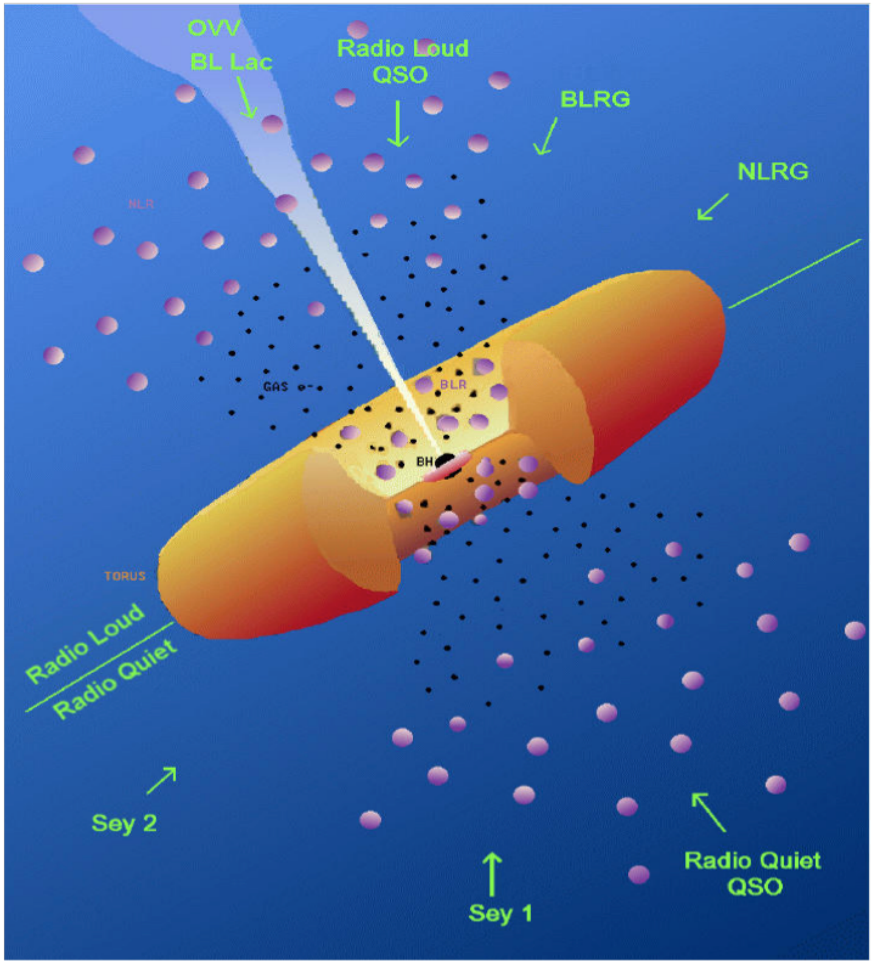


MWL lightcurve of the event with nightly averages: (a) H.E.S.S/MAGIC flux, (b) Fermi flux, (c) Fermi index, (d) ATOM flux



Detailed lightcurve of MJD 57538: (a) H.E.S.S/MAGIC flux, (b)Fermi energies, (c) ATOM flux

H.E.S.S. II EXTRAGALACTIC RESULTS



Most important conclusion:
On the location of the gamma-ray region

If the emitting region is close to the black hole, VHE photons can pair-produce on the BLR photons

→ the very detection of VHE FSRQ means that the emission comes from the BLR (~0.1 pc) or beyond!

H.E.S.S. II EXTRAGALACTIC RESULTS

The recent years have been seen
the birth of multi-messenger astronomy

H.E.S.S. II as is actively participating in this effort:

- follow up of GW170817

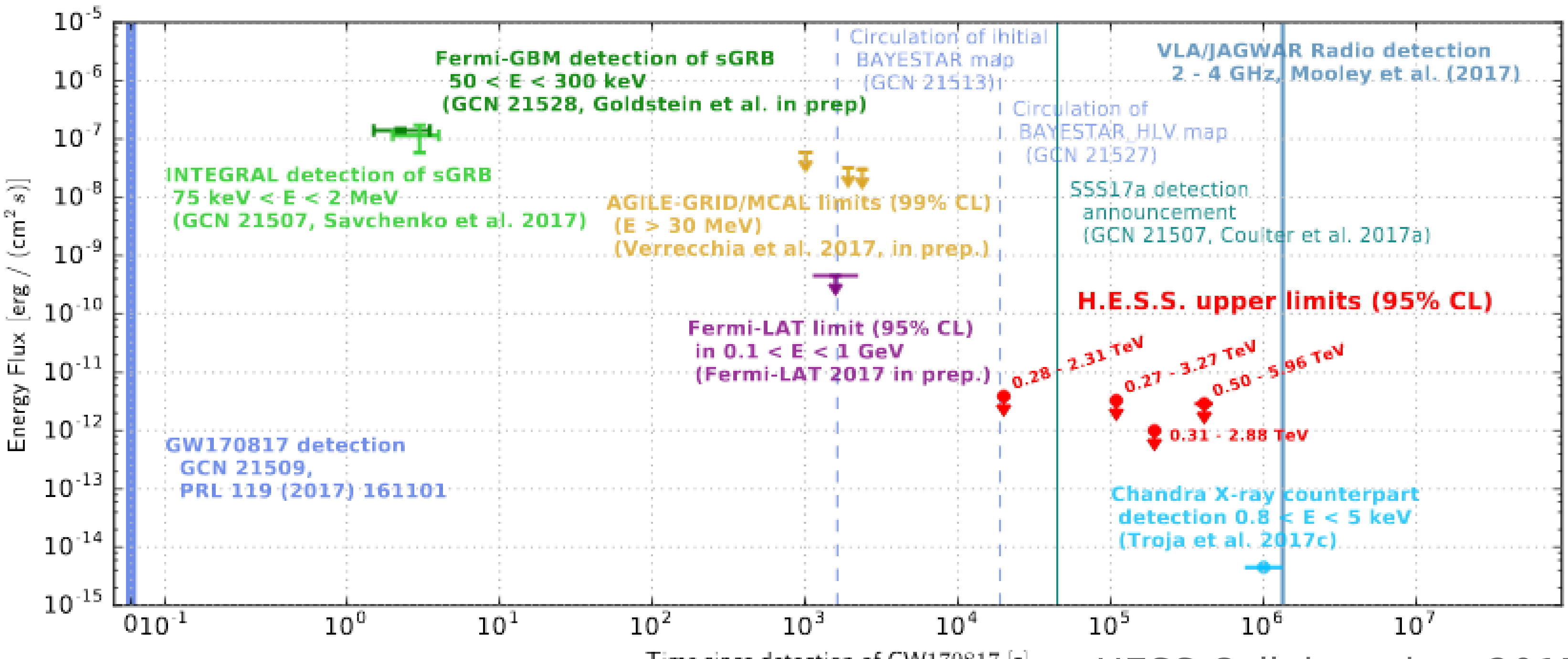
- follow up of neutrino alerts

H.E.S.S. II EXTRAGALACTIC RESULTS

The birth of multi-messenger astronomy: GW170817

Binary neutron star merger detected with LIGO/VIRGO
Coincident detection of a kilonova explosion with short GRB

H.E.S.S. started observing the source at T+5.3 hours
First ground based telescope to repoint!
No detection in TeV band…but upper limit at 1.5e-12 erg/cm2/s



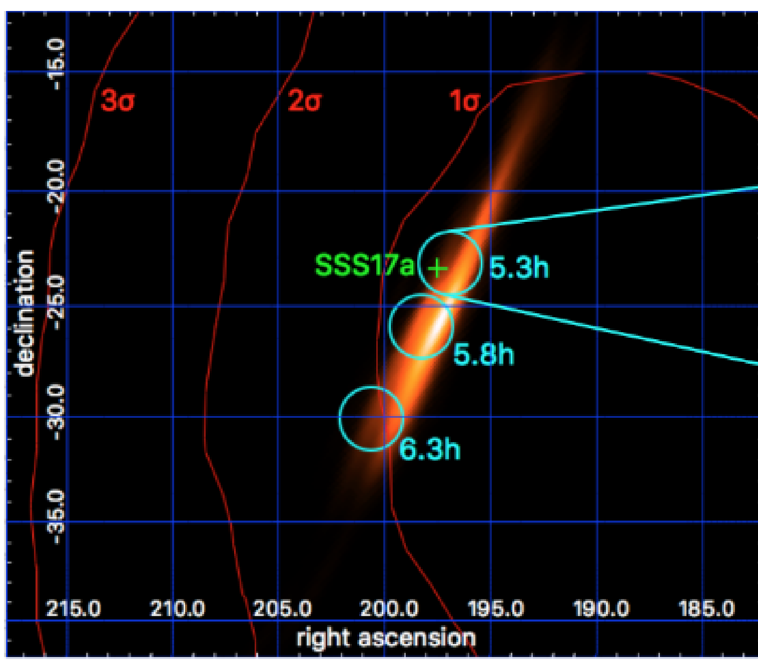
HESS Collaboration, 2017

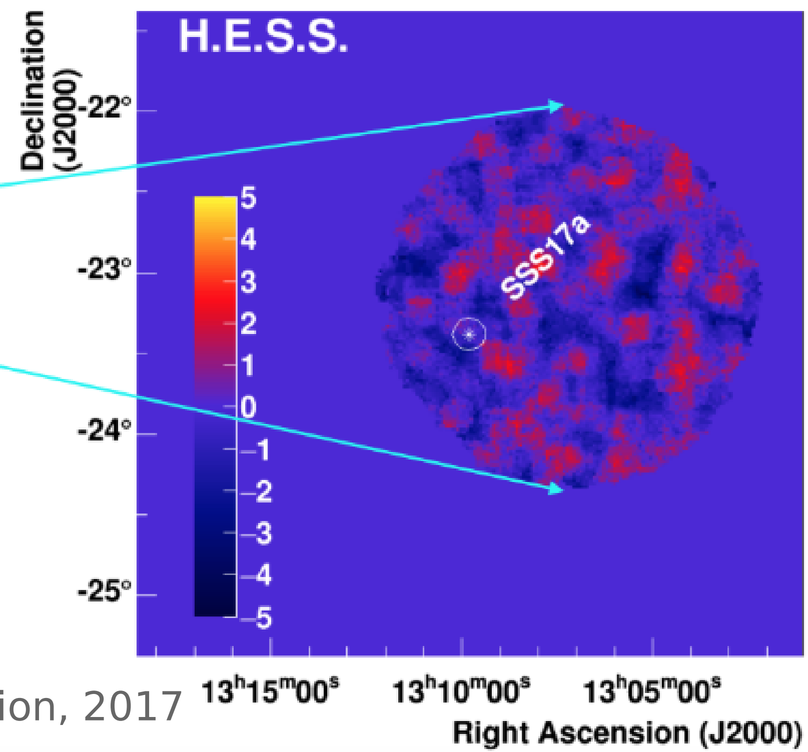
H.E.S.S. II EXTRAGALACTIC RESULTS

The birth of multi-messenger astronomy: GW170817

Binary neutron star merger detected with LIGO/VIRGO
Coincident detection of a kilonova explosion with short GRB

H.E.S.S. started observing the source at T+5.3 hours
First ground based telescope to repoint!
No detection in TeV band…but upper limit at 1.5e-12 erg/cm2/s





HESS Collaboration, 2017

H.E.S.S. II EXTRAGALACTIC RESULTS

Since the detection of the first astrophysical neutrinos, follow up of IceCube events, but no significant gamma-neutrino connection

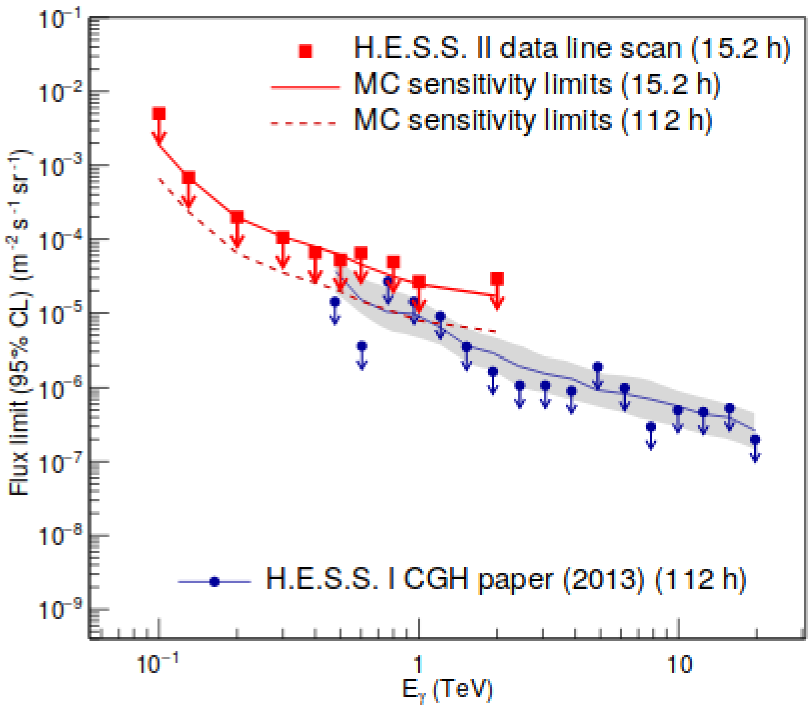
On September 22 2017, high-energy neutrino coincident with a blazar flare!
TXS 0506+056 detected by both Fermi-LAT and MAGIC

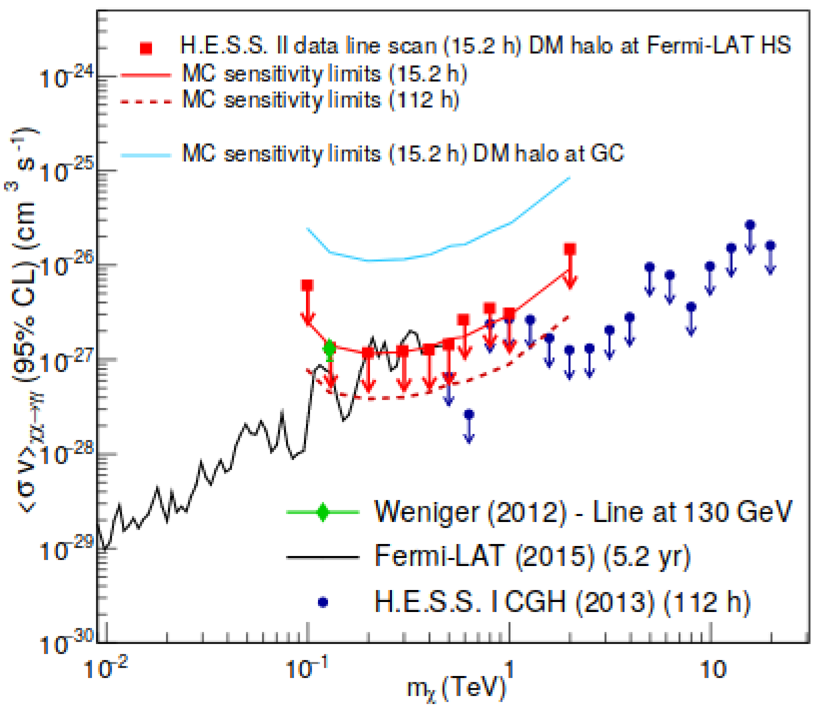
No picture sorry, but will appear soon!

H.E.S.S. II ASTROPARTICLE RESULTS

Dark matter searches with H.E.S.S. II:

Deep observations on Galactic Center and Dward spheroidals
Search for continuum emission and spectral lines

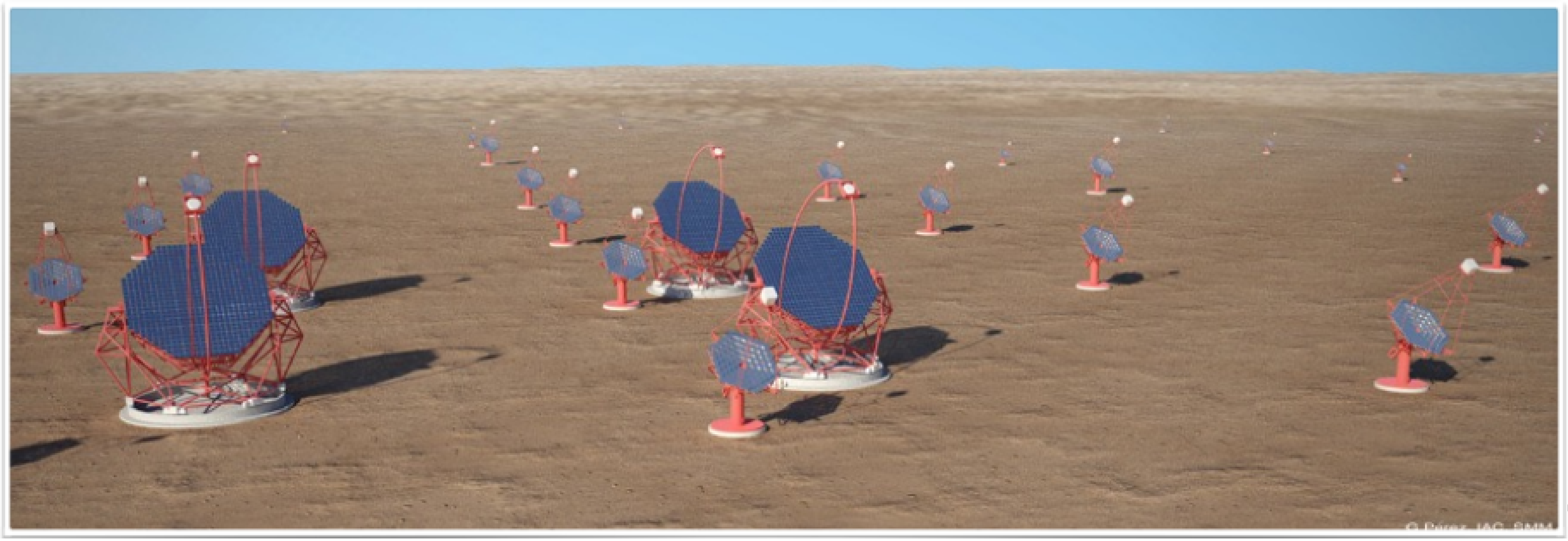




CTA

The VHE community has joined forces for the 4th-generation array, CTA

- Two observatories, North (Canary Island) and South (Chili)
- Three different kinds of telescopes (small/medium/large size), to cover a broader energy band (from ~10 GeV to ~100 TeV)
- Overall sensitivity about 10x better than current instruments



CTA

With CTA, TeV astronomy goes from private experiments (as in particle physics) to an open observatory (as in astronomy)

CTA will work as every other observatory/telescope: astronomers will have the opportunity to submit proposals, to analyze the data with publicly available tools, and use CTA results in their publications.

It is progressing fast: since 2017 it's a TGIR, budget of ~5M$ for 2018
Instruments are already being built: early science will be expected in a few years, with the observatory ready in 2021

CTA

https://www.cta-observatory.org/

The future of TeV astronomy is bright!