Astronomia con i raggi gamma

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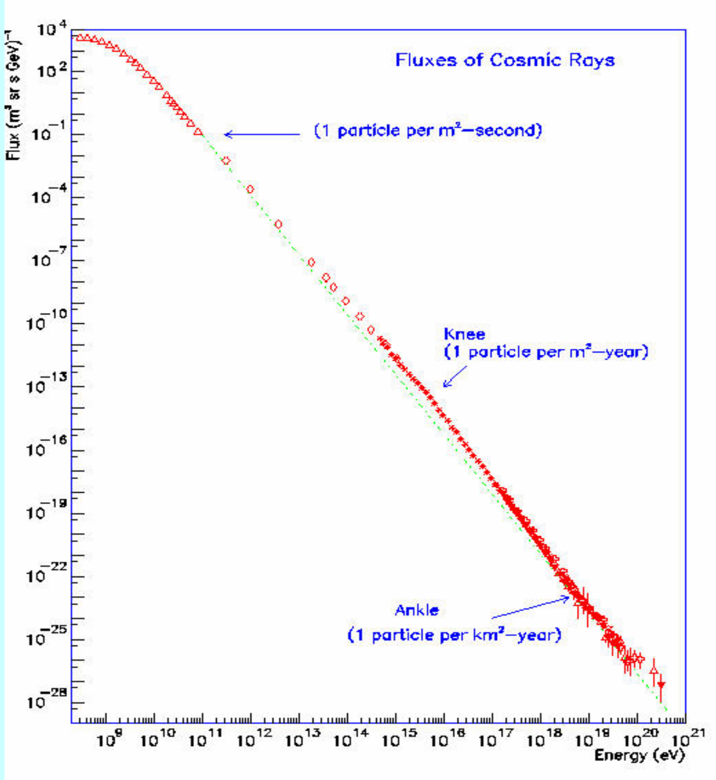
Search for Cosmic Accelerators

• γ-rays are only a very small fraction (≈ 10^{-3}) of the cosmic ray flux, however they are currently the best messengers of ultra-relativistic processes in the Universe

• Charged cosmic rays are deflected by the galactic magnetic fields and cannot be correlated with specific cosmic sites



→ γ-rays are important in searching for the cosmic accelerators

Two categories of emission models:

1) Leptonic models, in which γ-rays are produced via Inverse Compton scattering of low energy photons by relativistic electrons (good fits)
2) Hadronic models, in which γ-rays are associated with π^0 decays resulting from the collision between accelerated hadrons and surrounding gas (yet to be proved)

Instruments

• Satellite experiments (Cafagna's talk):

investigation of energies up to ~100 GeV

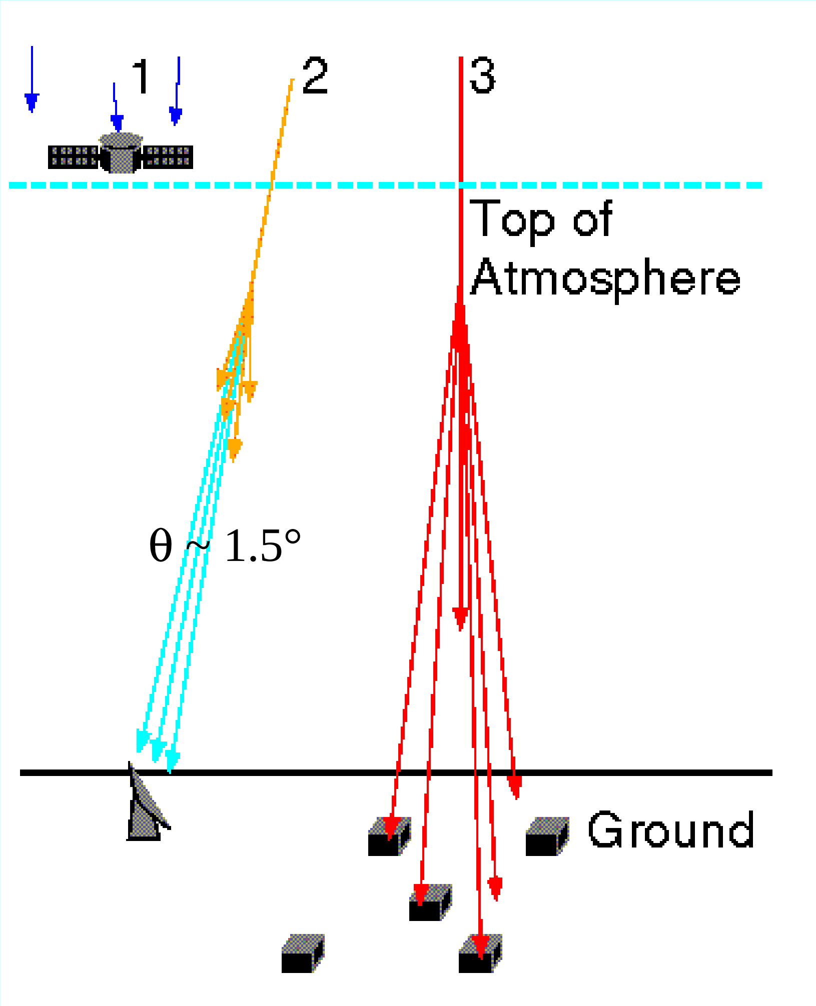
• Ground-based detectors (this talk):

investigation of the Very High Energy band (E >50 GeV)

The γ-ray flux decreases with increasing energy and therefore in the VHE band ground-based detectors with collection areas much larger than that of satellite experiments have to be used

Extensive Air Showers

Interaction of a γ-ray with the Earth atmosphere results in the development of a cascade of e^-, e^+ and photons: the Extensive Air Shower (EAS)



1) direct detection of γ-rays
2) charged particles radiate Cherenkov light beamed to the ground
3) a fraction of the shower particles reaches the ground

EAS Detectors

Cherenkov telescopes

Advantages:
- high sensitivity
- good angular resolution
- good energy resolution
- low energy threshold
- good γ/h separation

Disadvantages:
- low duty-cycle
- small field of view

EAS arrays

Advantages:
- high duty-cycle
- wide field of view

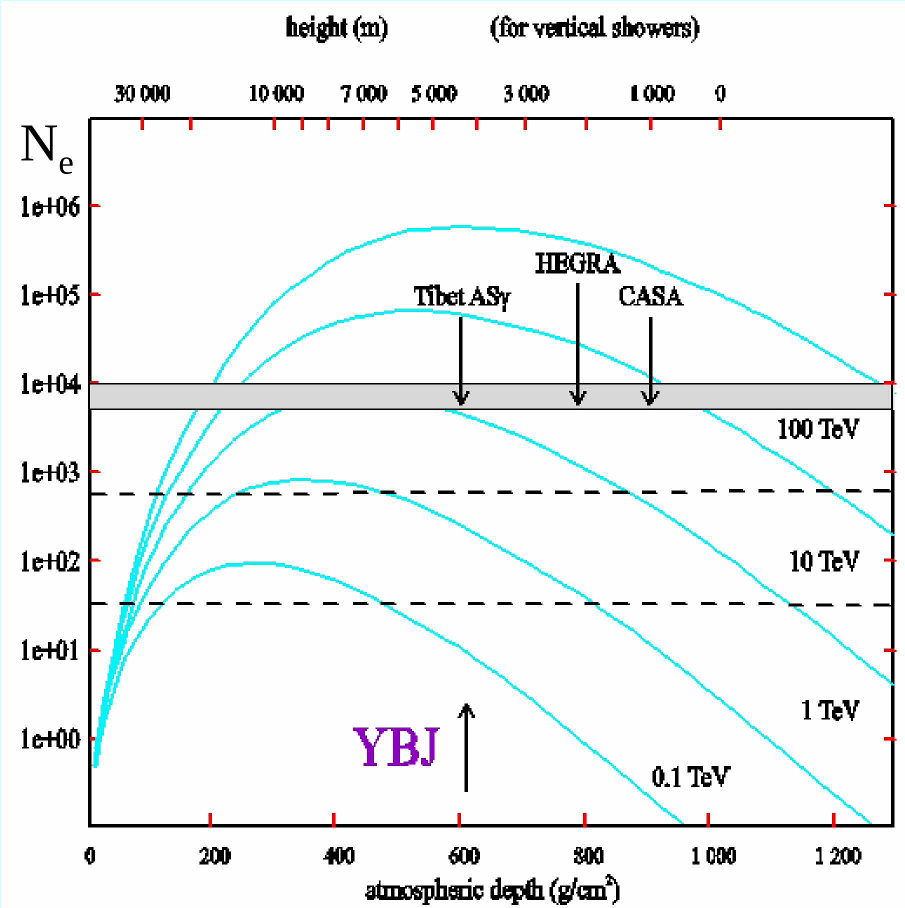
Disadvantages:
- moderate sensitivity
- moderate angular resolution
- moderate energy resolution
- high energy threshold
- poor γ/h separation

⇒ These two ground-based techniques are complementary!

Present VHE γ-ray Experiments

Experiment	Type	Location	Altitude
CACTUS	CT-Sampling	USA	640 m
CANGAROO	CT-Imaging	Australia	165 m
HESS	CT-Imaging	Namibia	1800 m
MAGIC	CT-Imaging	Spain	2250 m
PACT	CT-Sampling	India	1075 m
SHALON	CT-Imaging	Kazakhstan	3338 m
STACEE	CT-Sampling	USA	1700 m
TACTIC	CT-Imaging	India	1400 m
VERITAS	CT-Imaging	USA	1275 m
Whipple	CT-Imaging	USA	2250 m
ARGO-YBJ	EAS array	China	4300 m
GRAPES	EAS array	India	2200 m
Milagro	EAS array	USA	2630 m
Tibet ASγ	EAS array	China	4300 m

Dependence on Altitude

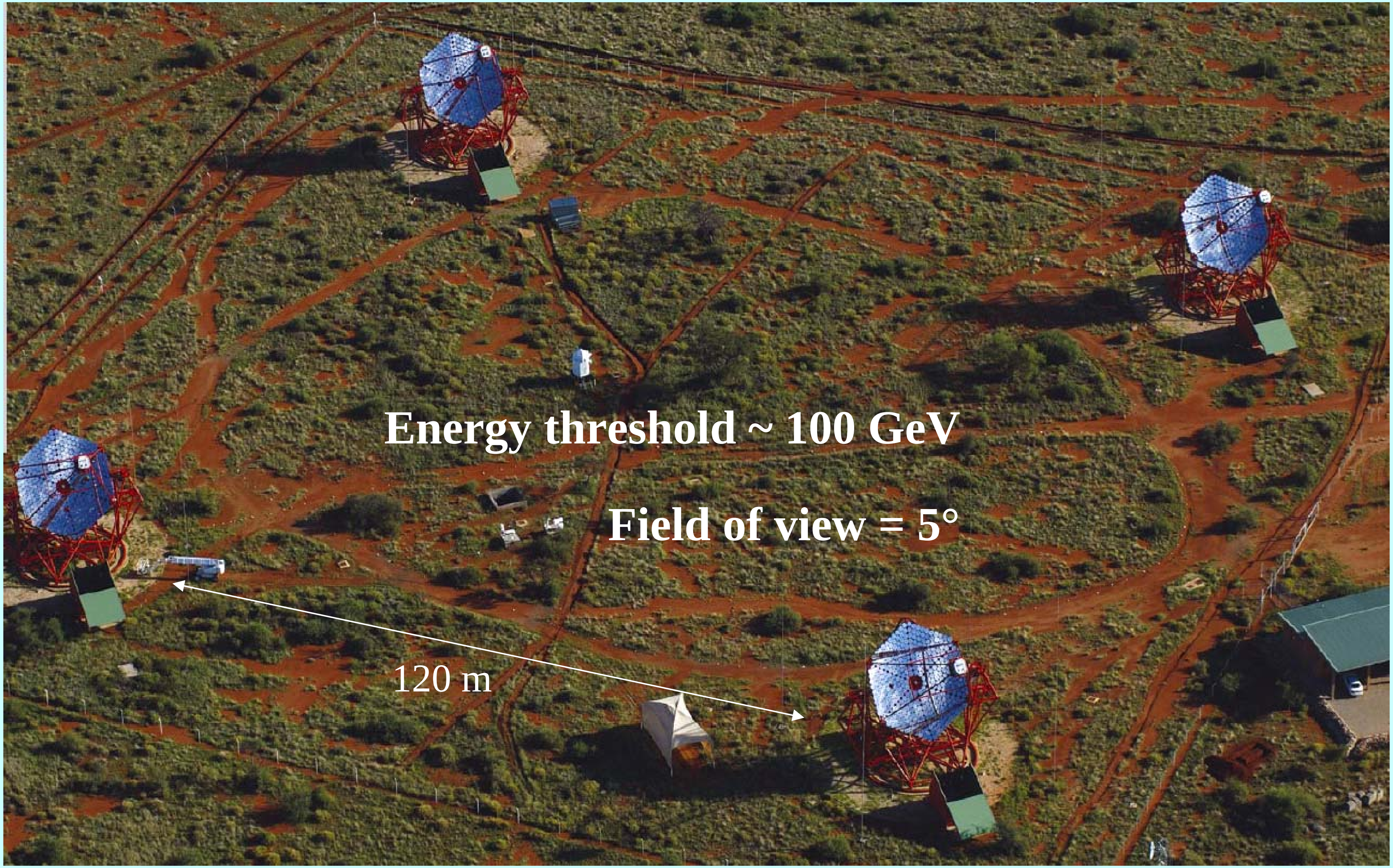


Longitudinal development of an EAS as a function of the primary γ-ray energy: the energy threshold lowers with increasing altitude

YBJ → YangBaJing, the currently highest site for VHE experiments (4300 m)

HESS

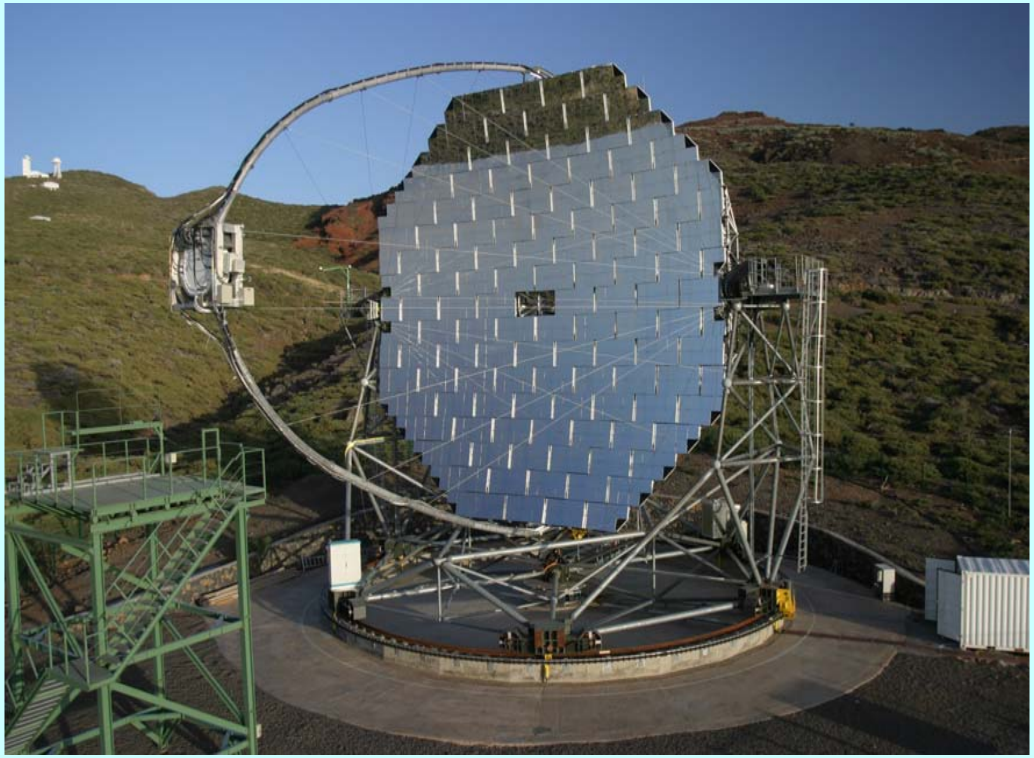
Stereo imaging with four 12 m diameter Cherenkov telescopes



MAGIC

Largest imaging Cherenkov telescope with 17 m mirror diameter

Energy threshold ~ 50 GeV

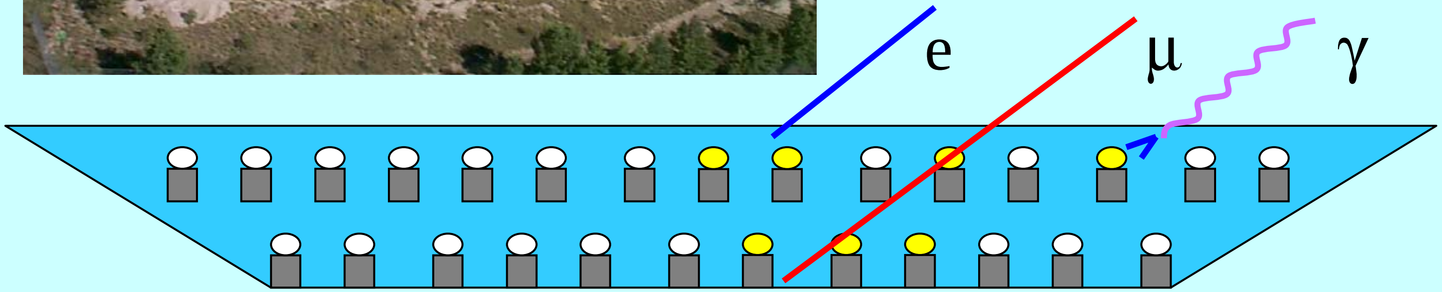


Field of view = 3.5°

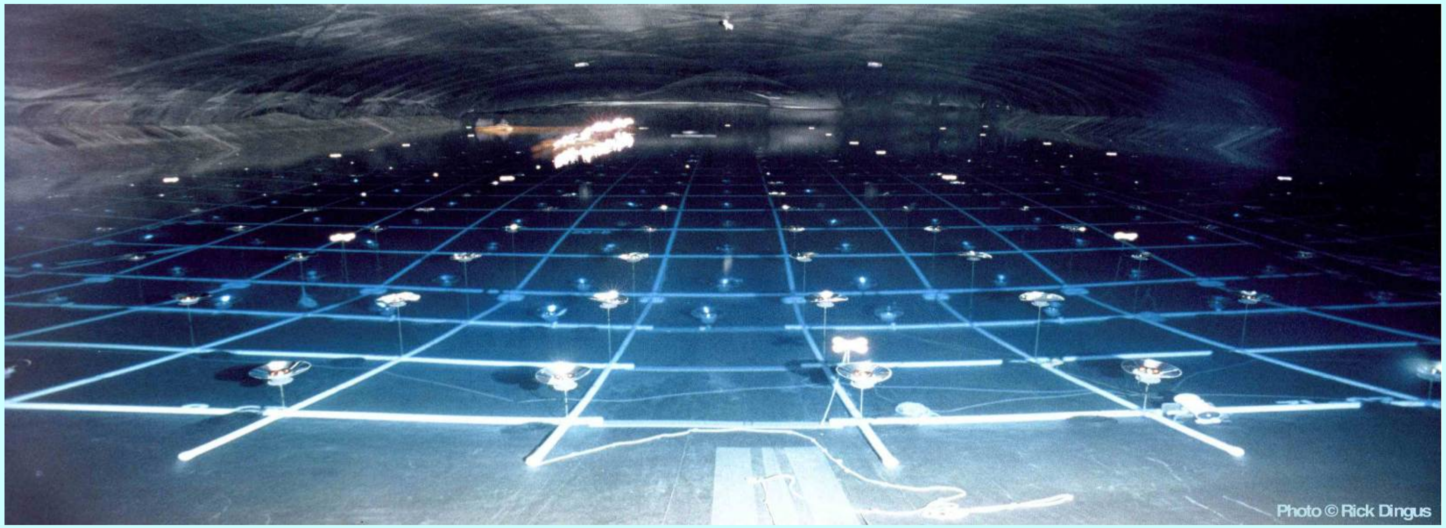
Fast repositioning system!

Milagro

Water Cherenkov Detector



Deep (8 m) pond with a dense grid of PMTs detecting the Cherenkov light of EAS particles

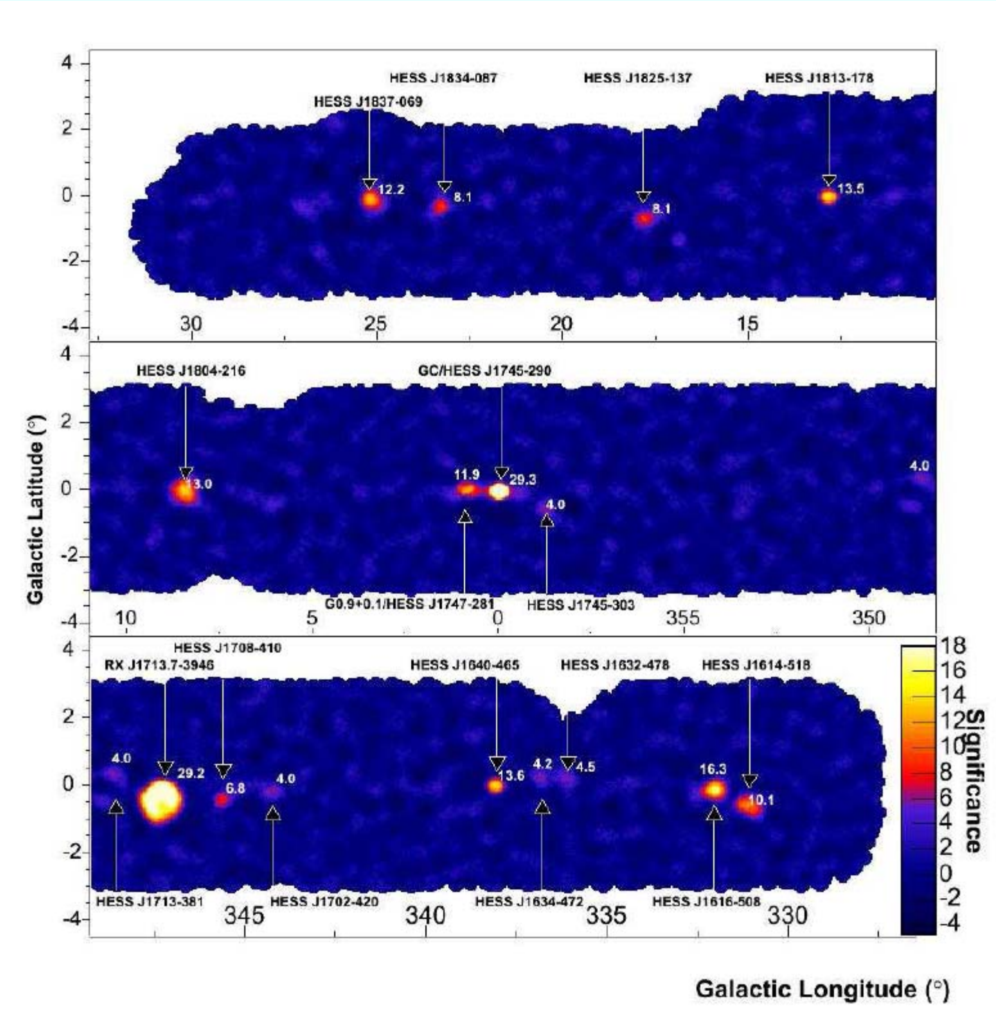


External water tanks later added to increase the sensitive area

ARGO-YBJ

High Altitude Full Coverage Detector

HESS Galactic Plane Survey



Great success by HESS (2005)

Discovery of many new sources in the Galactic plane

Some can be associated to known astronomical objects

Other sources are unidentified

Galactic VHE Sources

Pulsar Wind Nebulae:	Crab Nebula (up to 80 TeV!)
	G0.9+0.1
	MSH 15-52
	Vela X
	G313.3+0.1
Supernova Remnants:	RX J1713-3946
	Vela Junior
	Cas A
Microquasars:	LS 5039
	LSI+61303
Binary Pulsar:	PSR B1259-63
Galactic Centre:	SGR A

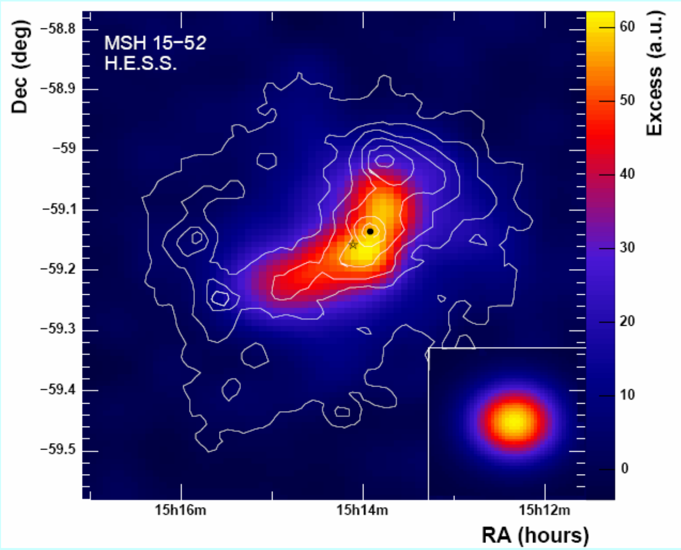
+ 19 unidentified sources (with some tentative associations)

PWN MSH 15-52

MSH 15-52: SNR + 150 ms PSR + PWN

First evidence for an extended PWN at VHE

Single power law spectrum up to 40 TeV with differential index Γ = 2.27 (flux ~ 15% Crab)



However, no detection of pulsed emission at VHE from this or other pulsars:

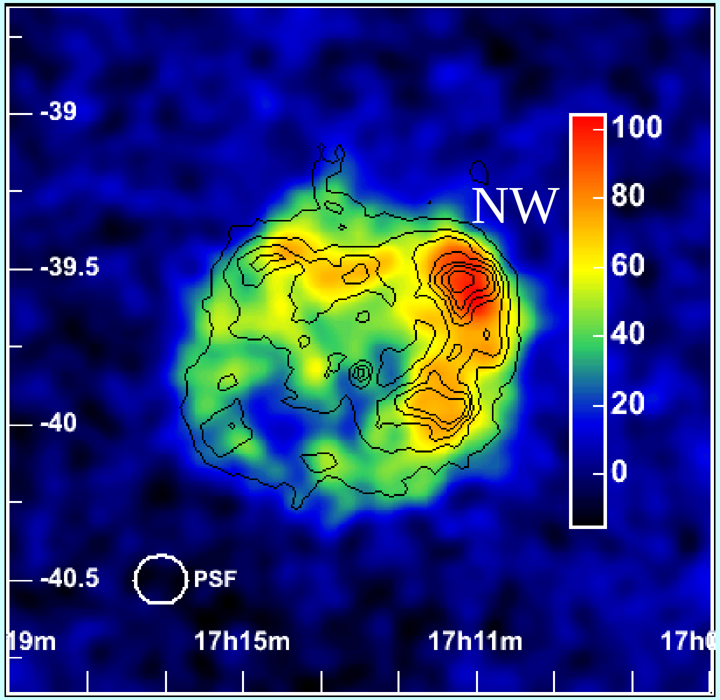
- EGRET on CGRO detected pulsed emission from 8 pulsars in the GeV range, whose origin is still mysterious
- theoretical models predict cutoffs in the 1–100 GeV range.
- upper limits on the VHE pulsed flux from Crab are given by HESS, MAGIC, PACT, STACEE and CELESTE

SNR RX J1713-3946

Large (~ 1°) SNR discovered by CANGAROO

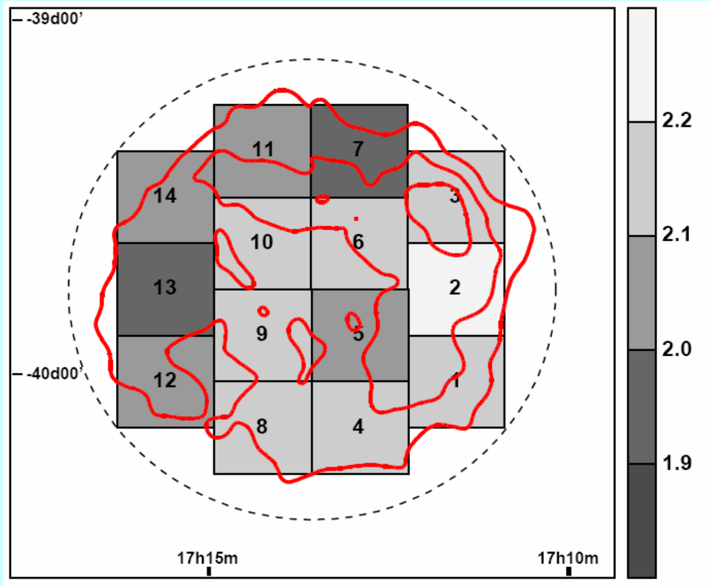
Then HESS reconstructed the morphology of VHE emission, matching with X-rays

CO data show density peaks coincident with the increased TeV flux from the NorthWestern side
⇒ evidence for proton-dense gas interaction
⇒ candidate source for neutrino telescopes !



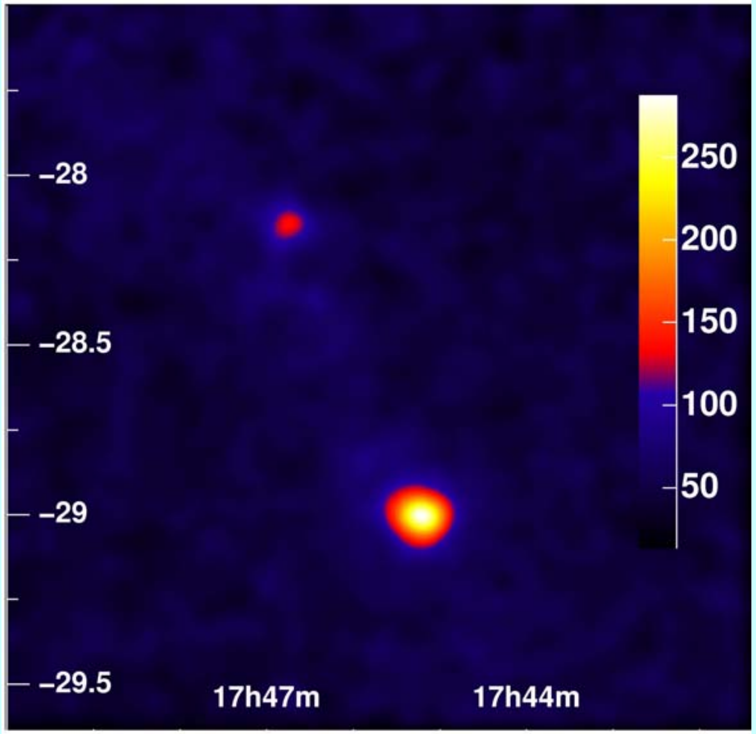
Energy spectrum well reconstructed from 200 GeV to 30 TeV: Γ ~ 2.2 with some curvature

Quality of HESS data allowed to measure the spectrum in 14 different regions, finding no significant variation



Galactic Centre

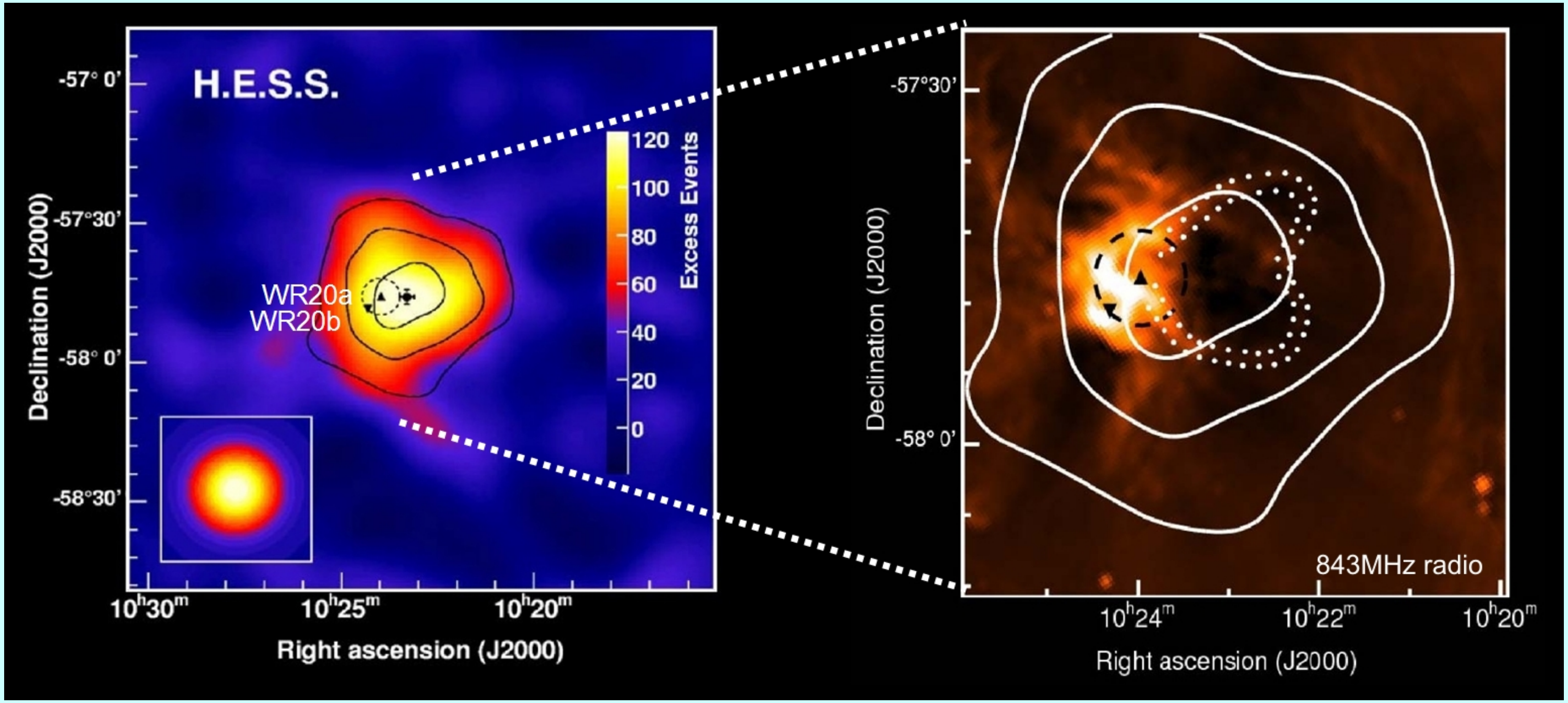
- Luminosity ~ 0.5 Crab
- HESS and MAGIC emission centroids are compatible with SGR A* (the putative BH)
- HESS data also show extended emission, compatible with SNR SGR A East
- HESS spectrum (160 GeV–10 TeV): Γ=2.2
- MAGIC spectrum (> 600 GeV): Γ= 2.3, obtained with GC at large zenith angles



Nature of this strong emission:

- shock acceleration at the SNR SGR A East
- interactions of stellar winds or cosmic rays with ambient material
- non-thermal processes associated with the BH
- neutralino annihilation process

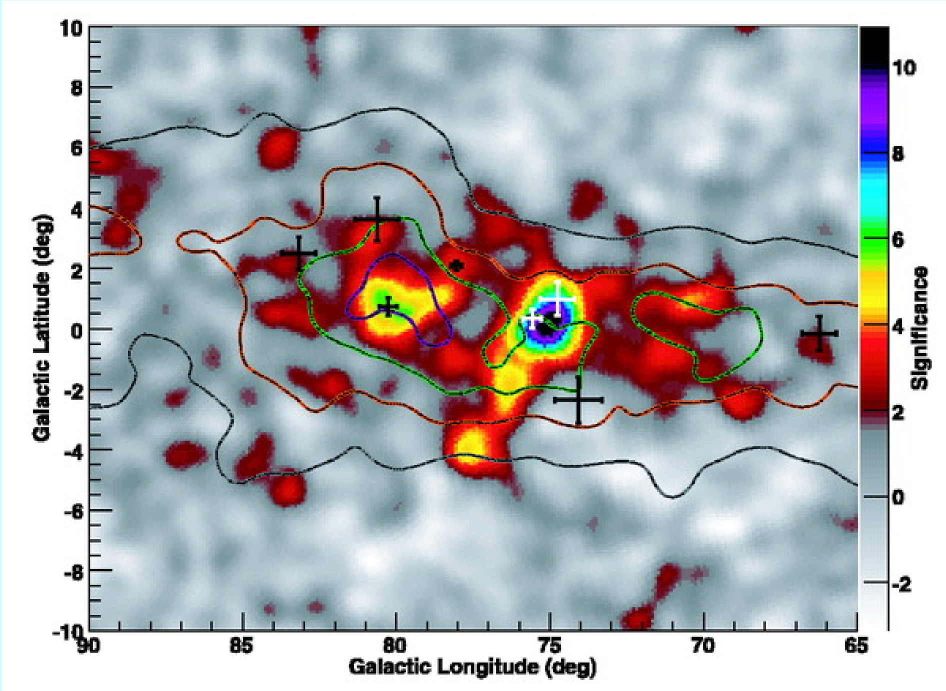
New Type of VHE Source (Feb 2007)



- Extended emission associated with the stellar cluster Westerlund 2, which contains extremely massive stars, known as Wolf-Rayet (WR) stars
- One of these, WR 20a, is the most massive of all measured binary systems in our Galaxy
- Bubbles blown by WR winds are visible in the radio image of the region
- The shocked winds are well suited to accelerate particles to high energies

Diffuse Sources: the Cygnus Region with Milagro

- Brightest extended region of the entire northern sky
- TeV emission observed by Milagro is correlated with matter density
- The source MGRO J2019+37 is observed at 10.9σ (median energy ~12 TeV) and is the second brightest source of the northern sky after Crab

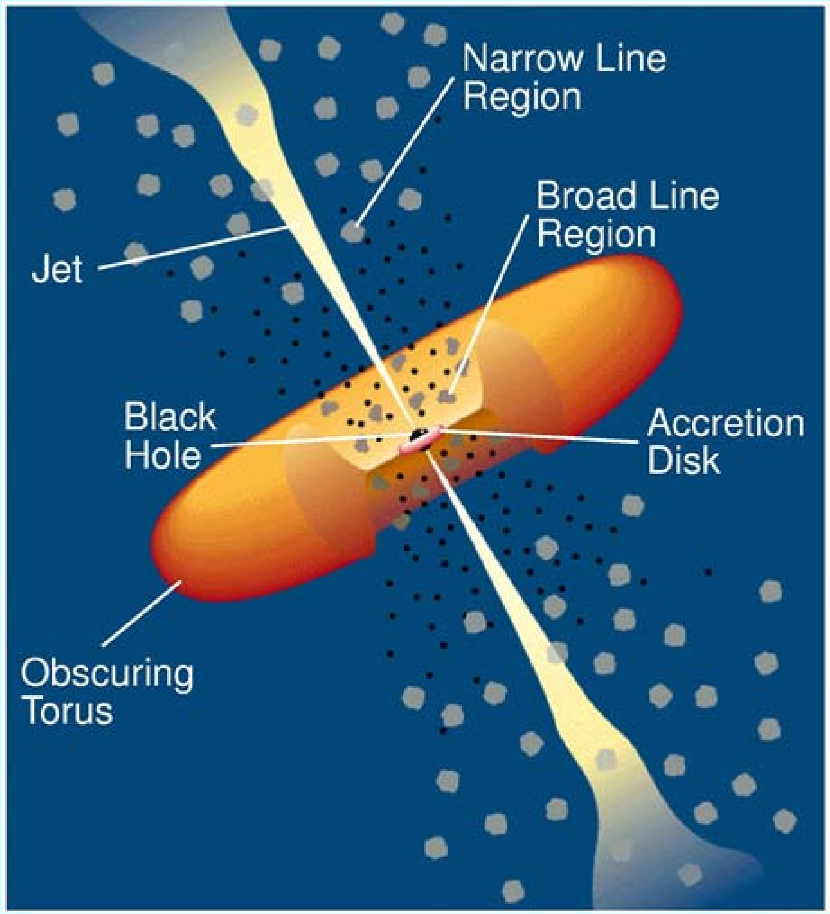


- The location of MGRO J2019+37 is consistent with two EGRET sources (white crosses in figure). Analysis indicates that is most likely an extended source or multiple unresolved sources.
- The other source to the left is consistent with an EGRET source and the unidentified HEGRA source J2032+413. Comparison indicates that Milagro observed an additional contribution due to the diffuse flux in the region.

Extragalactic VHE Sources

		Redshift
Radio Galaxy:	M87	0.004
Blazars:	Markarian 421	0.031
	Markarian 501	0.034
	1ES 2344+514	0.044
	Markarian 180	0.045
	1ES 1959+650	0.047
	BL Lacertae	0.069
	PKS 0548-322	0.069
	PKS 2005-489	0.071
	PKS 2155-304	0.116
	H 1426+428	0.129
	1ES 0229+200	0.139
	H 2356-309	0.165
	1ES 1218+304	0.182
	1ES 1101-232	0.186
	1ES 0347-121	0.188
	PG 1553+11	0.3 ?

Blazars: the Most Common VHE Sources



Active Galactic Nuclei with jet pointing toward the observer

Interaction with the Extragalactic Background Light

Pair production:
$\gamma + \gamma \rightarrow e^+ + e^-$

$E \equiv \gamma$-ray energy

$\varepsilon \equiv$ soft photon energy

An e^+e^- pair is produced if : $\varepsilon > \varepsilon_{min} = \dfrac{2\,(m_e c^2)^2}{E(1-\cos\theta)\,(1+z)^2}$

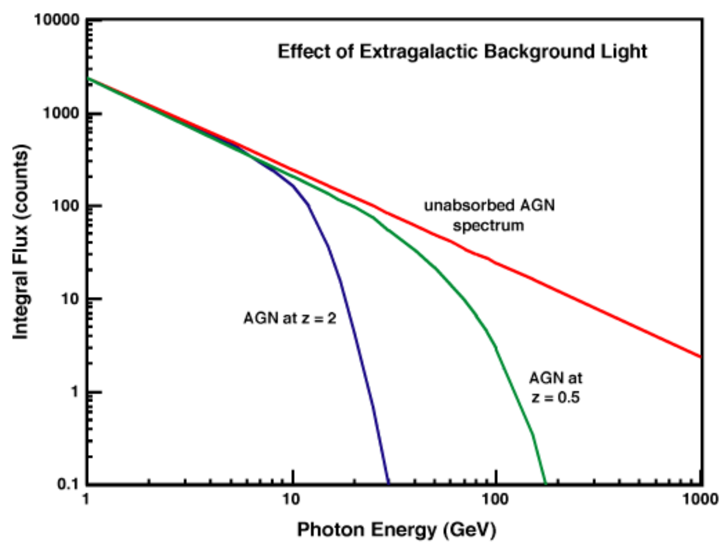
The interaction cross section is maximized when : $\varepsilon \cong 2\varepsilon_{min}$

→ VHE photons interact with IR/opt/UV photons
of the Extragalactic Background Light (EBL),
i.e., the total radiation from stars and dust re-emission
integrated over the luminosity history of the universe

Exponential cutoff of the power law spectrum: $F(E) = KE^{-\Gamma}\exp(-\tau(E,z))$

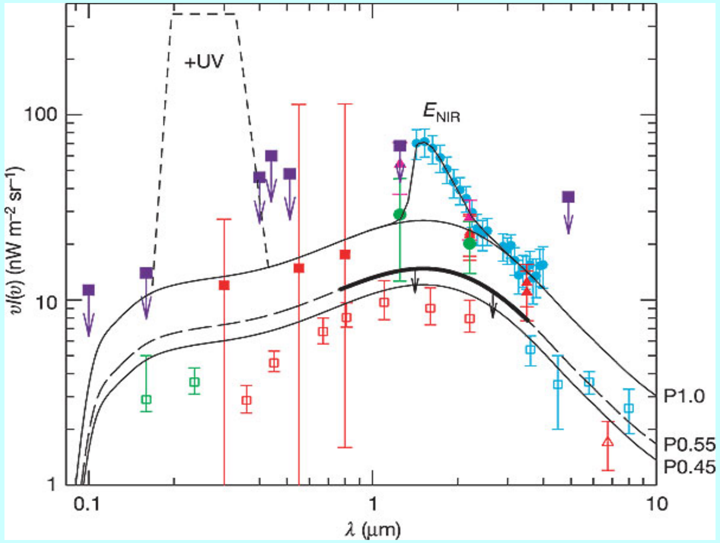
where the optical depth $\tau(E,z)$ depends on the EBL photon density $n(\varepsilon)$ and on the cosmological parameters

Constraints on EBL from VHE Blazar Spectra



the most distant VHE blazars can put constraints to the still poorly known EBL density

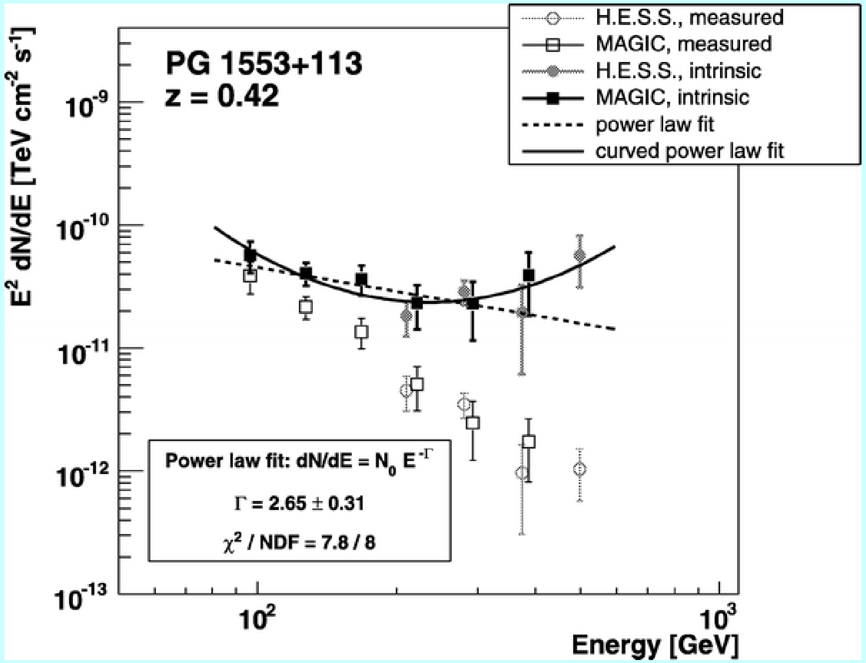
Aharonian et al. (2006):
upper limits are approaching the lower limits set by counting resolved galaxies



Universe more transparent to VHE photons than previously thought!

PG 1553+11: a VHE Blazar with Unknown Redshift

- Assuming a minimum density for the EBL, the combined HESS and MAGIC very soft spectrum (Γ= 4.1) can be corrected for the absorption
- At the redshift z =0.42 a broken power law becomes statistically preferred over a single power law
- None of the other VHE blazars shows such a spectral break



Mazin & Goebel (2007)

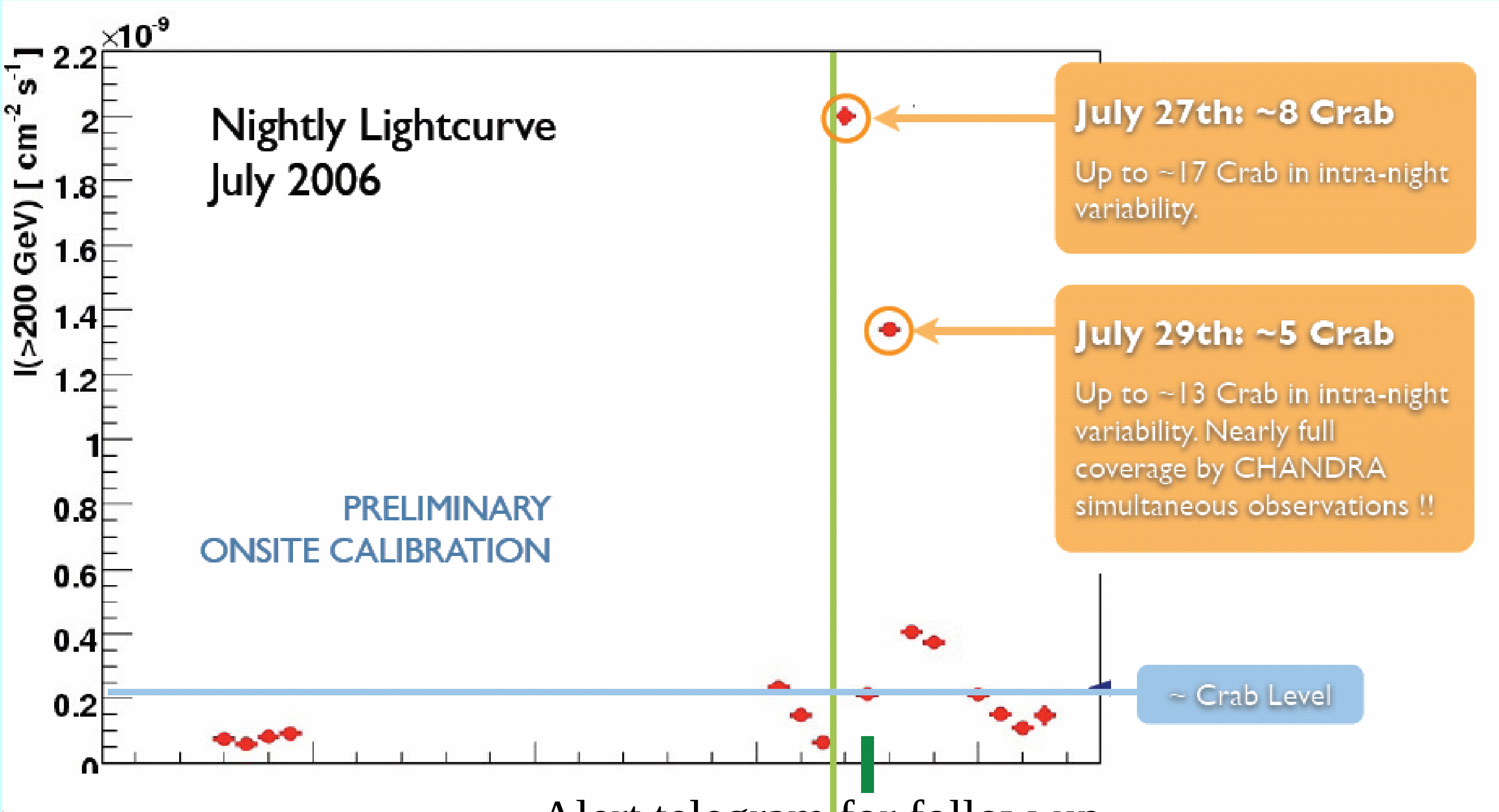
Upper limit of z < 0.42 set for PG 1553+11

or

first time that a second emitting component is detected in a VHE blazar spectrum

PKS 2155-304: Giant TeV Flares in July 2006

- PKS 2155-304 was the first extragalactic source detected in the southern hemisphere, and so far is the brightest
- At the end of July 2006 HESS detected flares up to 17 Crabs (E > 200 GeV) on time scales of 5 minutes



Alert telegram for follow-up

Gamma Ray Bursts

- Accidentally discovered in 1967
- Cosmological origin determined in 1997 implies that they are the most energetic explosions in the Universe
- Energy output $\approx 10^{51}$ erg
- Emission interpreted as due to a relativistically expanding "fireball" where particles are accelerated via shocks
- VHE emission still debated
- The EGRET instrument on the CGRO detected emission above 1 GeV from 3 GRBs, with photons up to 18 GeV (GRB940217)
- TeV photons are absorbed by $\gamma\gamma$ pair production in the EBL, unless the GRB is at low redshift

Upper Limits in the GeV–TeV Region

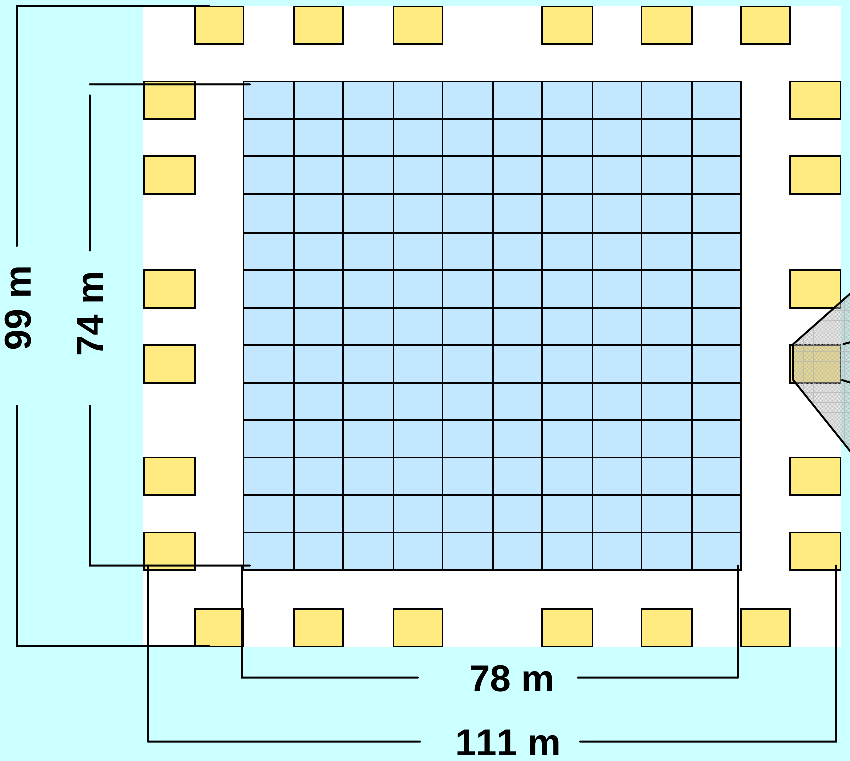
Cherenkov telescopes

- Thanks to its fast repositioning system (delay down to only 40 s), MAGIC pointed 9 GRBs with an energy threshold between 80 and 200 GeV, but no evidence for VHE emission was found: upper limits for the first 30 minutes of data were determined
- Whipple pointed 7 GRBs at times > 4 hr: upper limits for 28 minute scans above ~ 400 GeV were determined
- The STACEE solar array pointed 14 GRBs, in two cases with a data-taking starting less than 4 minutes after the GRB trigger

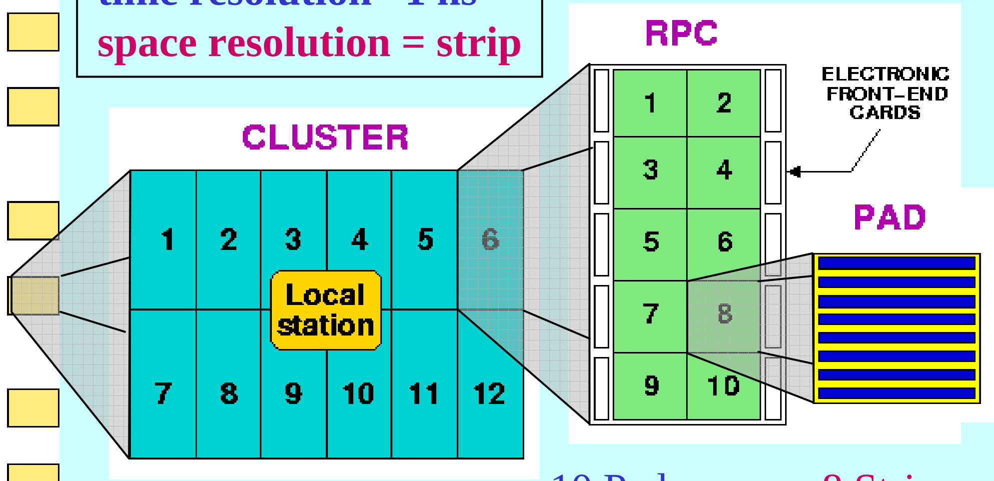
EAS arrays

- Upper limits with data simultaneous to the GRB prompt emission were determined by ARGO-YBJ, INCA, EAS-TOP and Milagro in the wide energy range 1 GeV–1000 TeV

The ARGO–YBJ Experiment



time resolution ~1 ns
space resolution = strip



1 CLUSTER = 12 RPC
(~43 m^2)

10 Pads
(56 x 62 cm^2)
for each RPC

8 Strips
(6.5 x 62 cm^2)
for each Pad

Layer (~ 92% active surface) of Resistive Plate Chambers (RPCs), covering a large area (5600 m^2)
+ sampling guard ring
+ 0.5 cm lead converter

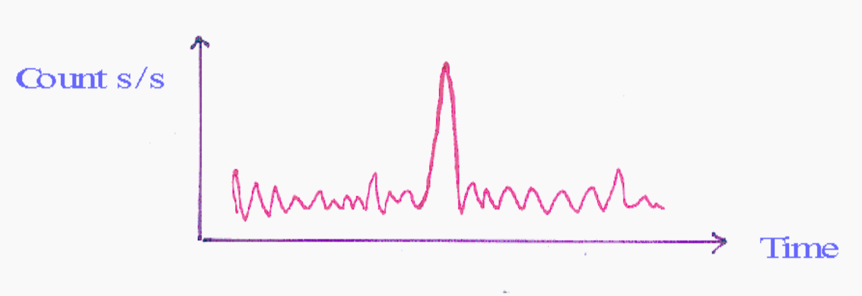
RPC gas mixture:
Ar/Iso/TFE = 15/10/75 %

Data Acquisition

The detector carpet is connected to two different DAQ systems, which work independently:

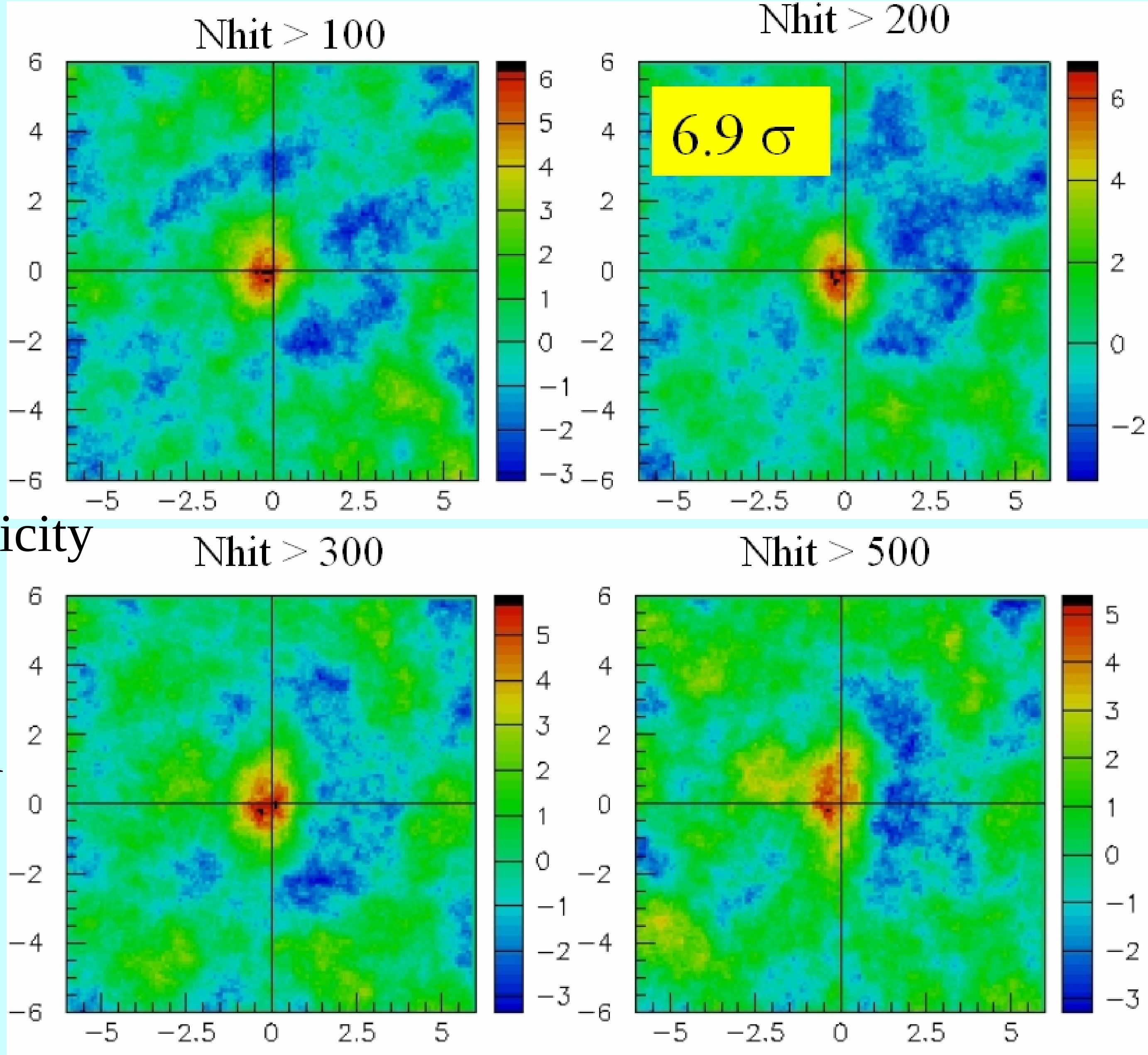
Shower mode:
for each event the location and timing of each detected particle is recorded, allowing the reconstruction of the lateral distribution and of the arrival direction
(more details in De Mitri's talk)

Scaler mode:
the counting rate of each CLUSTER is measured every 0.5 s, with no information on the space distribution and arrival direction of the detected particles
(used in search for GRBs)



Preliminary Shadow of the Moon

Data obtained observing the Moon with 130 CLUSTERS for 65.9 hr



Nhit = Pad Multiplicity

Pointing calibration for future sky maps

Upper Limits Set by ARGO-YBJ

• Using scaler mode data, up to now no emission has been observed in coincidence with GRBs detected by satellites within the ARGO-YBJ field of view (zenith angle ≤ 45°)

• Upper limits were set to the high energy γ-ray emission from 21 GRBs

• The fluence (flux integrated over GRB duration) 3σ upper limits in the 1–100 GeV range vary between $5 \cdot 10^{-6}$ and $1 \cdot 10^{-2}$ erg/cm^2

• Up to now these are the best upper limits in this energy range

Upgrades and Future Experiments

Cherenkov telescopes:

- VERITAS just started operating with four 12 m diameter telescopes
- MAGIC-II will work with a second 17 m diameter reflector
- HESS-II will have a 28 m diameter telescope at the center of the current square array
- CTA should consist of a northern and a southern observatory, each made of ~10 huge and ~100 small telescopes, for a sensitivity ~10 times better than HESS and MAGIC between a few tens of GeV and 100 TeV

EAS arrays:

- ARGO-YBJ RPC carpet will be covered with a 0.5 cm layer of lead to convert the more numerous EAS photons ($N_\gamma \approx 7\ N_e$)
- HAWC should consist of a 300 m × 300 m pond of water instrumented with a large number of PMTs and located at an elevation > 4000 m for a substantial lowering of the energy threshold of Milagro

Conclusions

• The new generation of VHE experiments has yielded outstanding results, including the discovery of many more VHE sources (now ~50)
• The Galactic plane is rich in number and type of VHE sources
• A number of new sources do not have obvious counterparts at other wavelengths: new class of astrophysical objects ?
• The discovery of new blazars at greater redshift values, with unbroken power law spectra up to the highest energies detected, makes the Universe more transparent to VHE photons than previously thought (larger window for the first detection of VHE emission from GRBs)
• Future experiments should continue the rapid development of VHE astrophysics

Quest for cosmic ray accelerators still open !