Risultati recenti e prospettive sui raggi cosmici da esperimenti a terra

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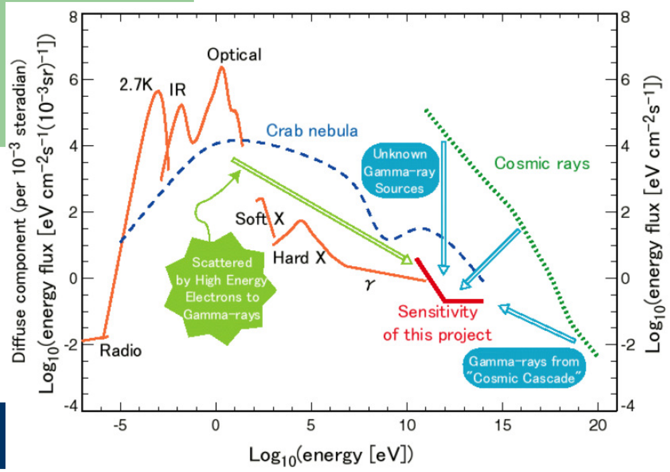
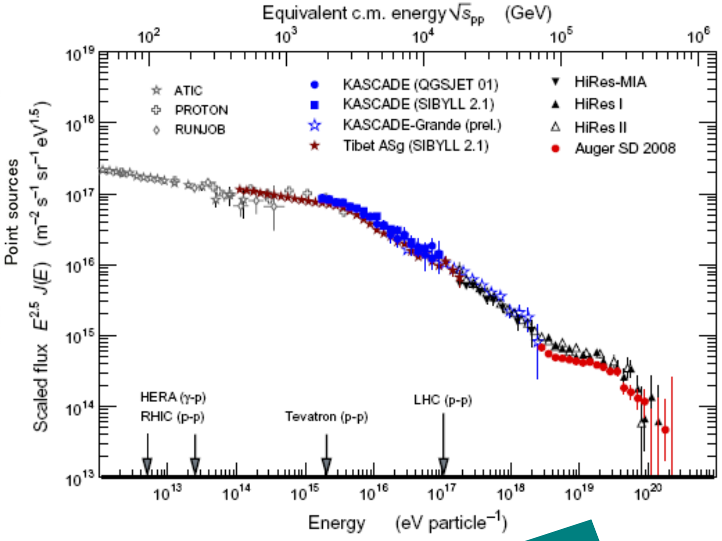
CANGAROO III Project Description





Cosmic rays

D. Allard, N.G Busca, G. Decerprit, A.V. Olinto, E. Parizot, JCAP 0810, 033

- where do they come from? (AGN, SNR, …)
- how can they be accelerated? (BH, GRB, shock waves, …)
- which kind of particles they are? (protons, nuclei, neutrinos, …)
- which are the details of their propagation? (interaction with media, magnetic fields, GZK…)
- which are the mechanisms for the production of VHE γ in the universe (in AGN, SNR, GRB, pulsars, binary systems, microquasars)?

CR ground experiments

While CR's extend over more than 13 orders of magnitude, the dynamic range of a detector is limited to roughly 2-3 orders of magnitude. This means that we need different experimental setups to cover all the spectrum.

Ground based experiments operate from E ~ 10^{11} to E ~ 10^{20} eV. They use the atmosphere as a calorimeter to detect primary particles through the secondaries they produce (charged particles, fluorescence and Cherenkov light). The interpretation of the results needs the help of MC simulations (shower physics, detector performances).

- Space-borne γ-Astronomy is limited to E < few GeV. Old (pre-1990) γ-ray ground based telescopes, on the other hand, had typically an energy threshold of several hundred GeV. Last generation IACT's bridge this gap thanks to a threshold energy of ~ 20-50 GeV.
- (E)AS experiments see the lateral distribution of secondary particle arriving to Earth (full coverage or sampling of a given area). Their energy range depends on the configuration.

LE experiments

HS = high sensitivity, LA = large aperture
LDC = low duty cycle, HDC = high duty cycle

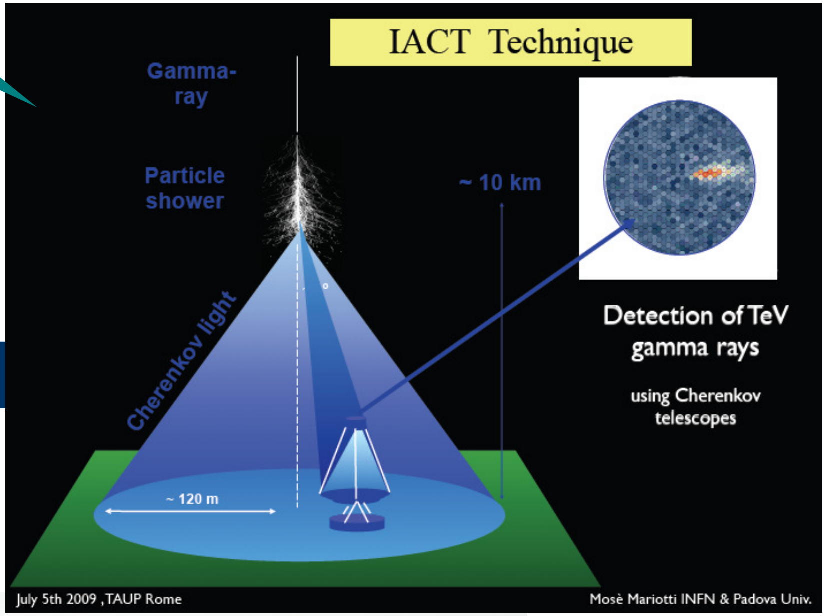
Experiment	Type	Threshold	Detectors	Scientific goals
CANGAROO	HS, LDC	> 100 GeV	4x10m IACT	SNR, pul., AGN, GRB
VERITAS	HS, LDC	> 50 GeV	4x12m IACT	SNR, pul., AGN, GRB
HESS	HS, LDC	> 100 GeV	4x13m IACT	SNR, pul., AGN, GRB
MAGIC	LA, HDC	>25 GeV	2x17m IACT	SNR, pul., AGN, GRB
MILAGRO	LA, HDC	> TeV	water Cherenkov	AGN, GRB, CR, sol. pys.
TIBET	LA, HDC	> TeV	plastic scintillators	SNR, pul., CR, sol. pys.
ARGO-JBJ	LA, HDC	> GeV	RPC	SNR, pul., AGN, GRB, CR, sol. phys.
HAWC	LA, HDC	100 GeV ÷ 100 TeV	water Cherenkov	AGN, GRB, CR, sol. phys.

The Physic

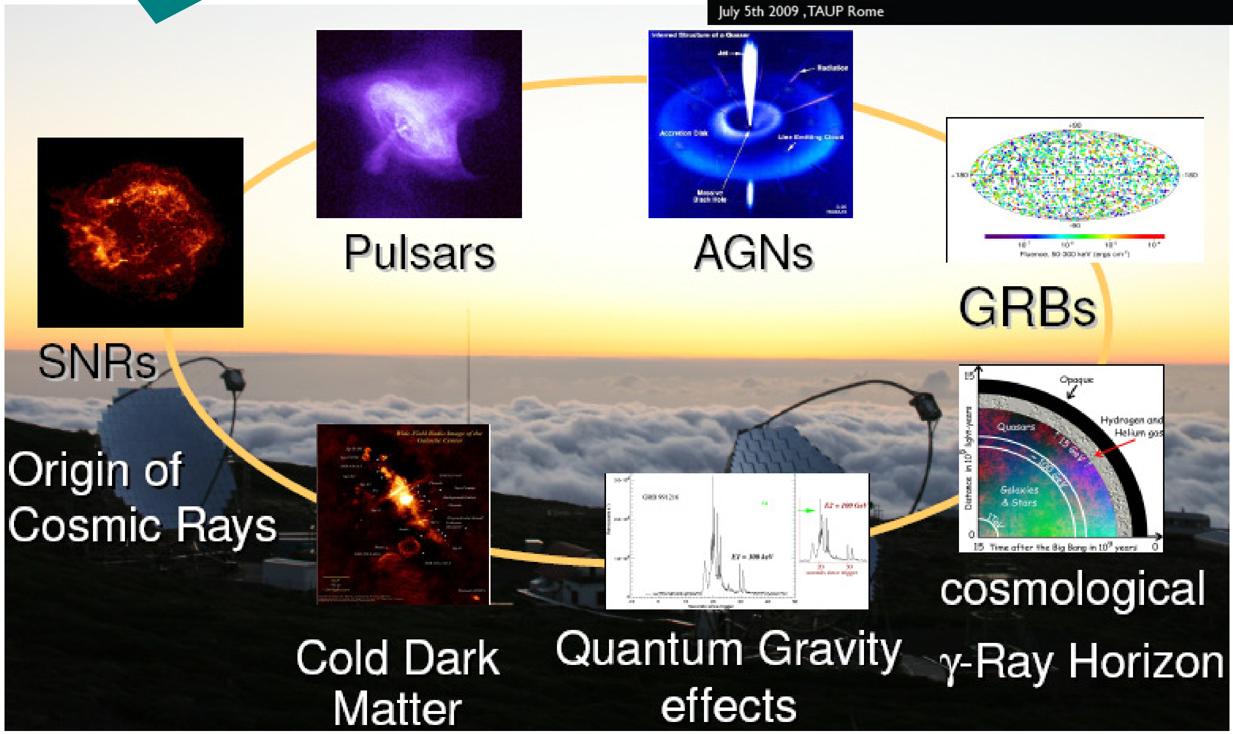
- the details of production and acceleration of γ-rays in jets of AGN: leptonic (SSC or EIC) or hadronic?
- the acceleration in pulsars: PC or OG?
- is it true that GRB emission goes above tens of GeV?
- which are the values of the production cross-section of CR in atmosphere?
- which is the mass composition of CR’s at the knee?
- …

IACT Technique & Physics

M. Mariotti, TAUP 2009



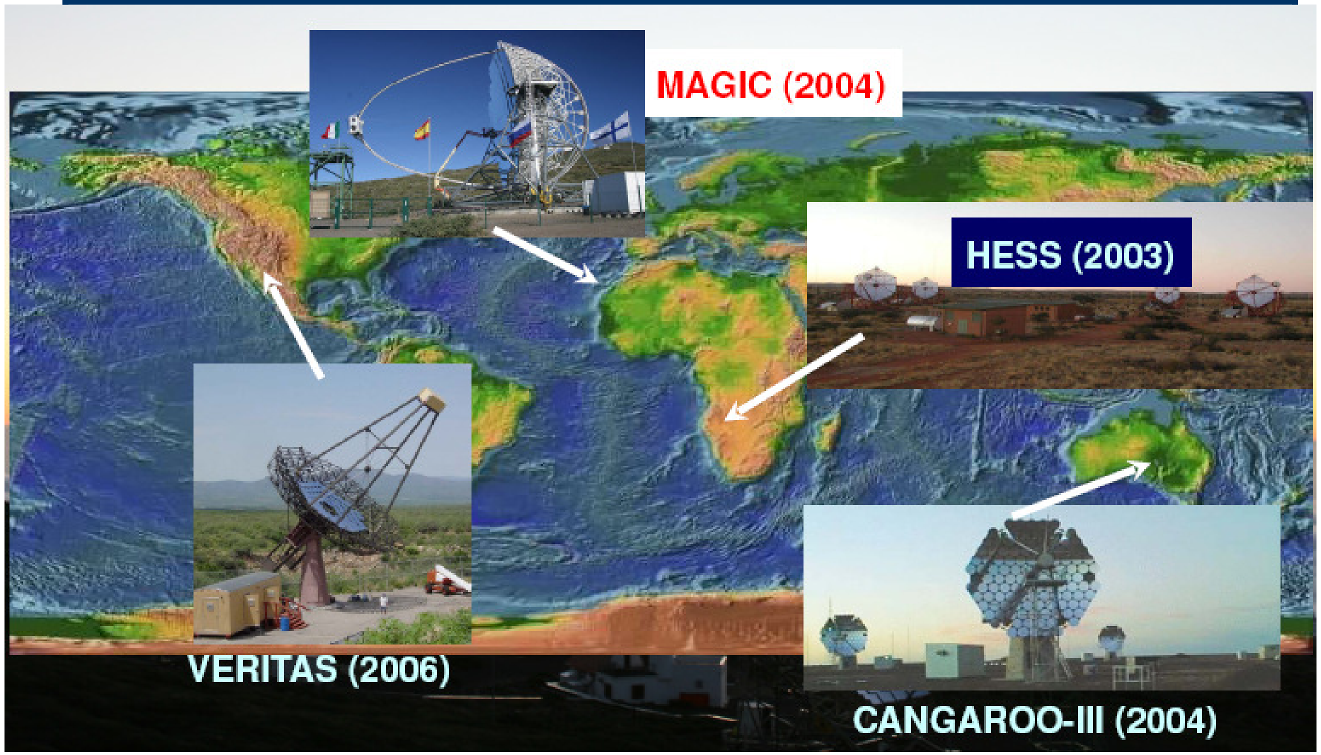
E. Prandini, MAGIC Didattico-Outreach



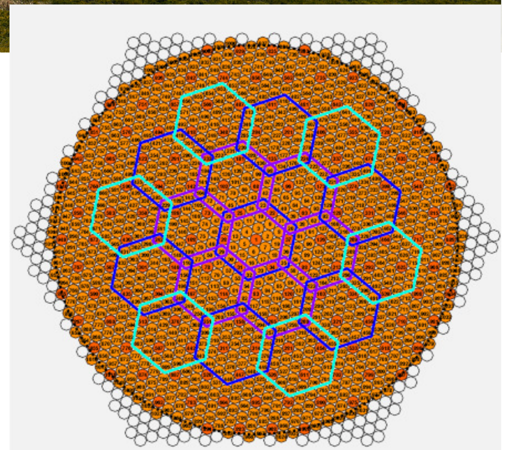
E. Prandini,
MAGIC Didattico-Outreach

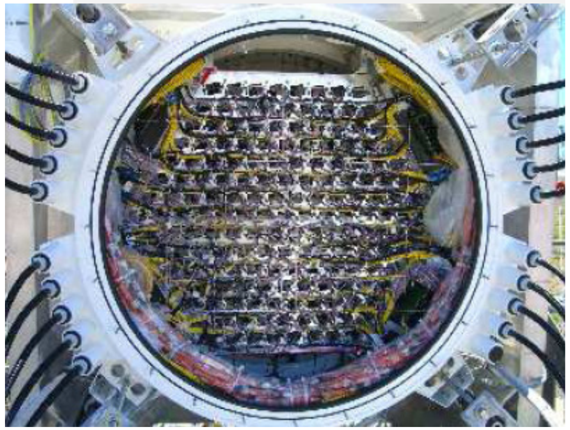
IACT sites

Experiment	CANGAROO-III	VERITAS	HESS	MAGIC
Site	Australia	Arizona	Namibia	Canary Island



MAGIC



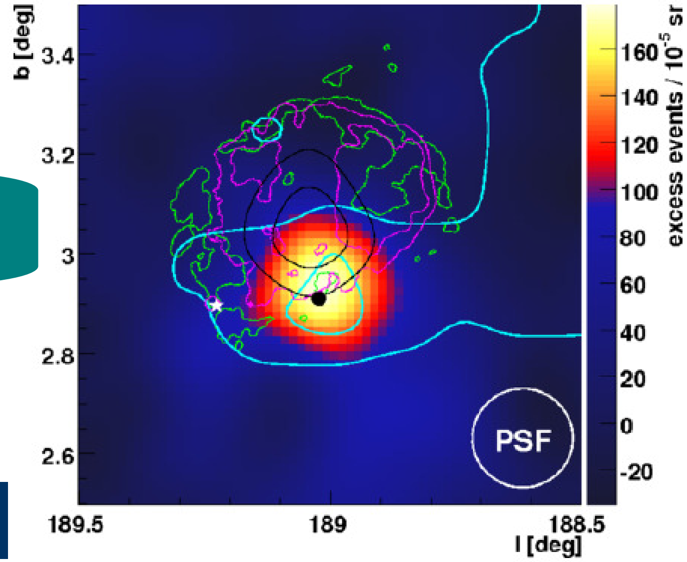


- 10 participating countries.
- Located on La Palma (Canary Islands) at 2200 m a.s.l.
- Two IACTs (the largest ones in operation) of 17m, 234 m^2. FOV: 3.5°. Angular resolution: 0.1° for E>500 GeV. Detection of γ-rays for E>50 GeV. Sensitivity: 5σ detection at 1.6% of CrabN flux in 50 hours. Reposition within 30-60 s to any sky position at a GRB alert. Simultaneous optical observations with the near KVA telescope.
- Physics goals: AGN, SNR, GRB, dark matter, γ-ray horizon.

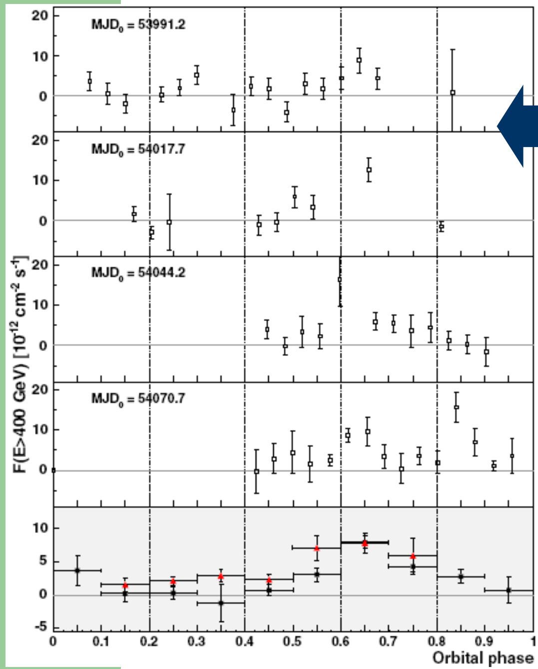
MAGIC observations

Shell-type SNR IC-443 at 1.5 Kpc

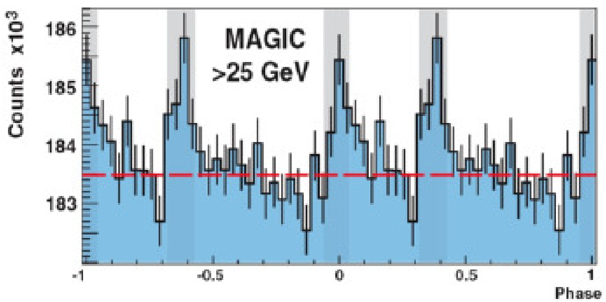
P.Majumdar for MAGIC,
Nucl.Phys.Proc.Suppl. 196, 221



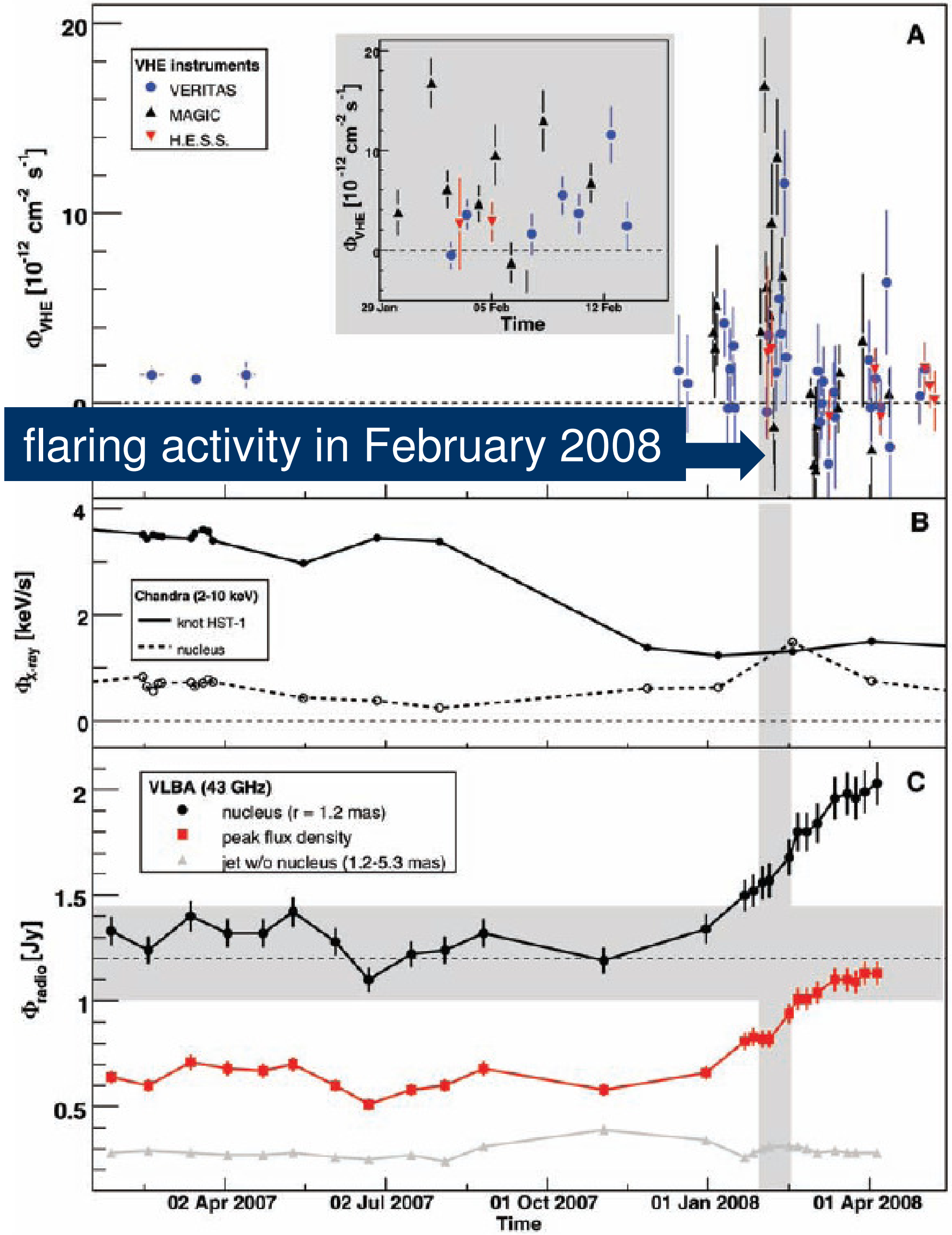
X-ray Binary LSI +61 303



- VHE radiation from IC-443 compatible with decay of π^0 from interaction of CR with dense molecular cloud.
- Emission from LSI +61 303 is periodic in nature.
    - Measurement of the CrabN spectrum down to 60 GeV. Detection of the periodic emission of the Crab pulsar down to 25 GeV (from EGRET up to ~10 GeV).
    - Flaring activity of M87 (16 Mpc) (see next page).

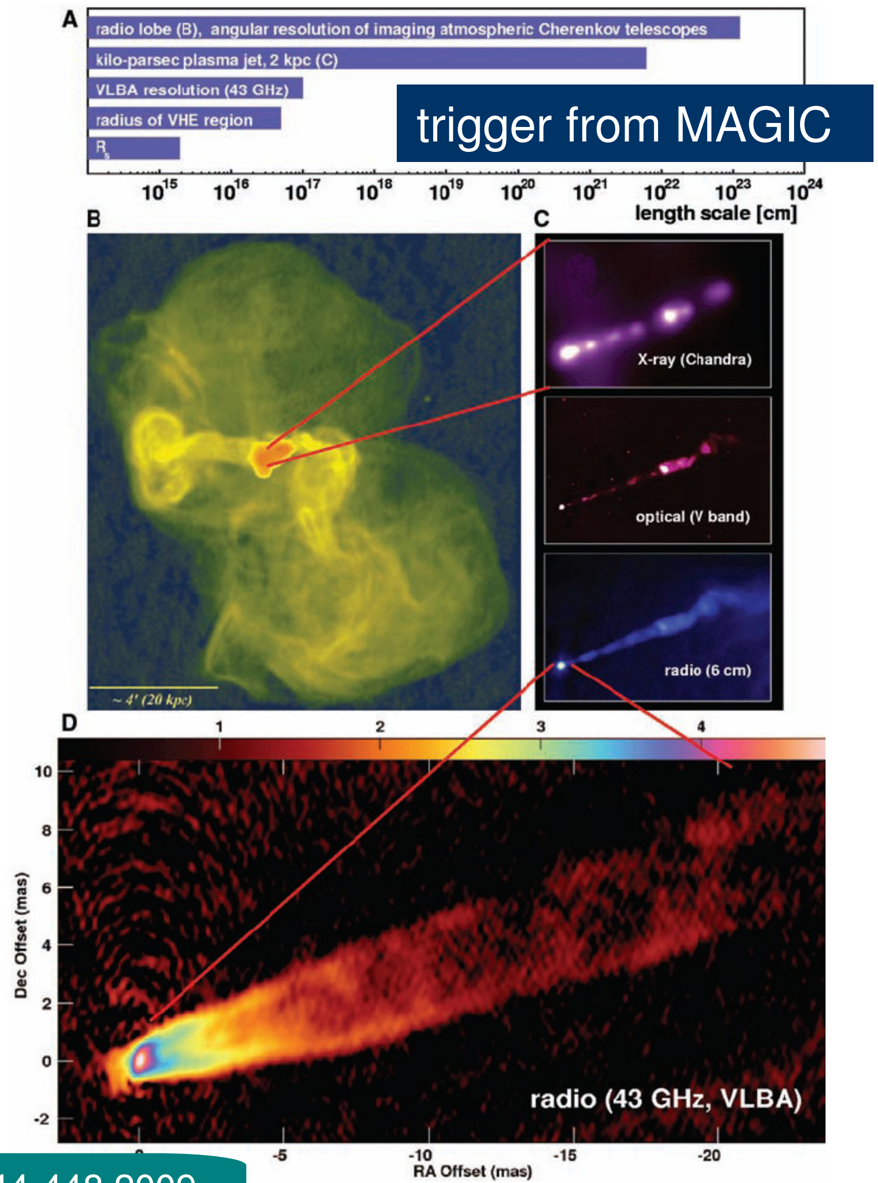


VERITAS, H.E.S.S., MAGIC, VLBA joint study of M87 (50 nights in 2008)



flaring activity in February 2008

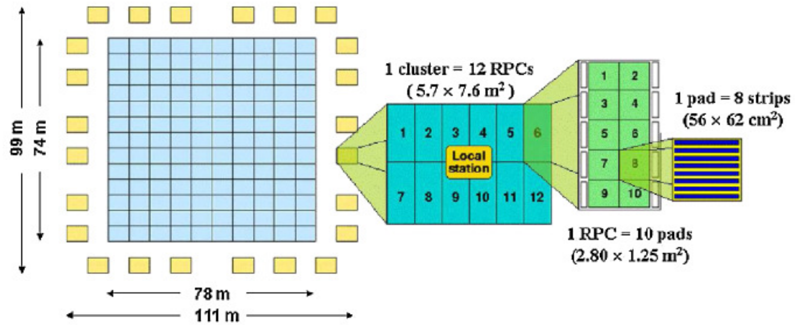
trigger from MAGIC



Science 325:444-448,2009

ARGO-YBJ

- 2 participating countries.
- 5800 m^2 instrumented at Yang-bajing (Tibet) at 4300 m a.s.l.
- Clusters of 12 RPCs, each one of 10 pads (timing pixels) of 8 strips.
- Two independent DAS: “shower” (1-1000 TeV) and “scaler” mode (E_{th}= 1 GeV).

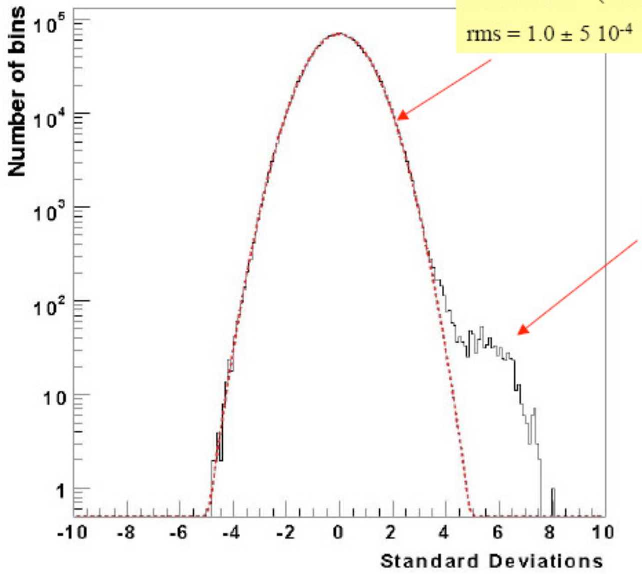


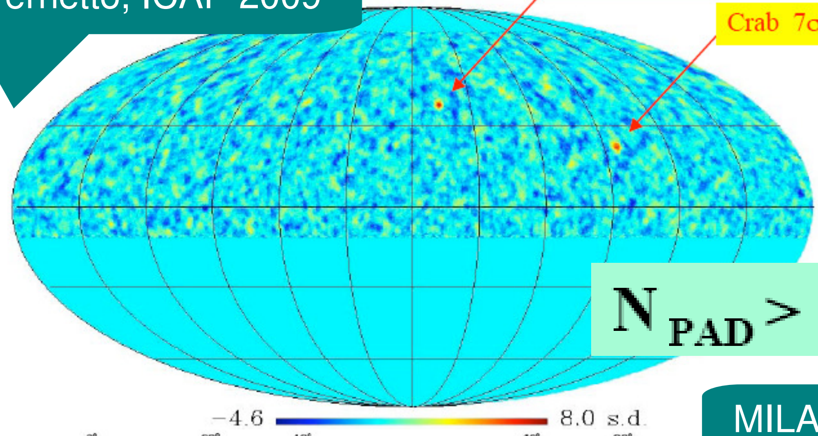
- Angular resolution (shower mode) of 0.2° at E>10 TeV, 2.5° for E~100 GeV for primary protons (Moon shadow).
- Well suited for GRB physics (scaler mode), due to large FOV (~2 sr) and high duty cycle (>90%).
- Physics goals: CR physics, γ-astronomy, GRB, SNR, solar physics.

Argo γ-Astronomy

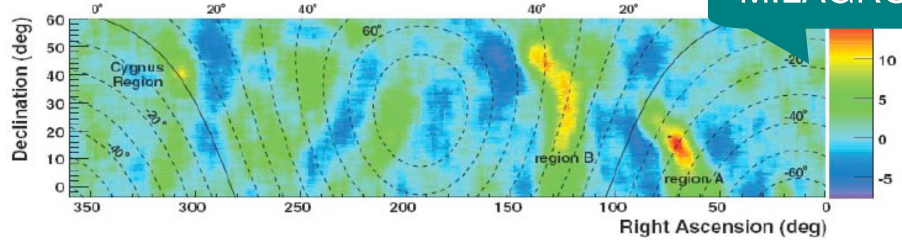
S. Vernetto, ICAP 2009

424 equivalent days



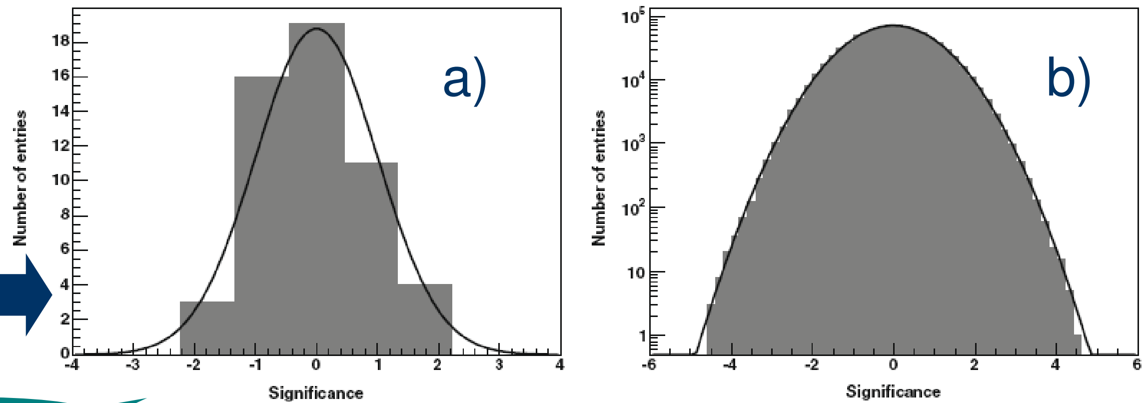


MILAGRO



Excesses distribution gives a signal for CrabN and Mrk421.

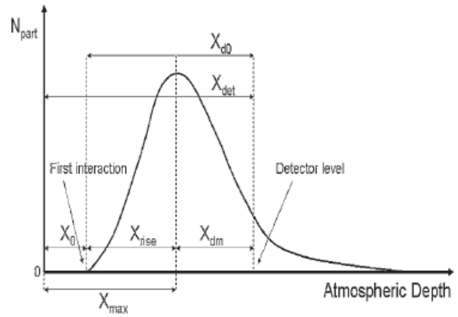
Statistical significance of a) 26 GRB and b) 2h of observations around the 26 GRB in Jul 2006-Jul 2007 and Nov 2007-Jan 2009.

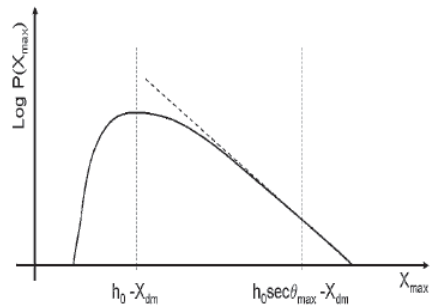


G. Aielli et al., Astrop. Phys. 32, 47

Argo p-air cross section

G. Aielli et al., Phys.Rev.D80, 092004





The angular distribution of showers, R(θ), is directly connected with the probability distribution of X_{max}, which depends on the depth of the first interaction (→ $\lambda_{p\text{-}air}$) and X_{rise}: measuring R(θ) gives the cross-section.

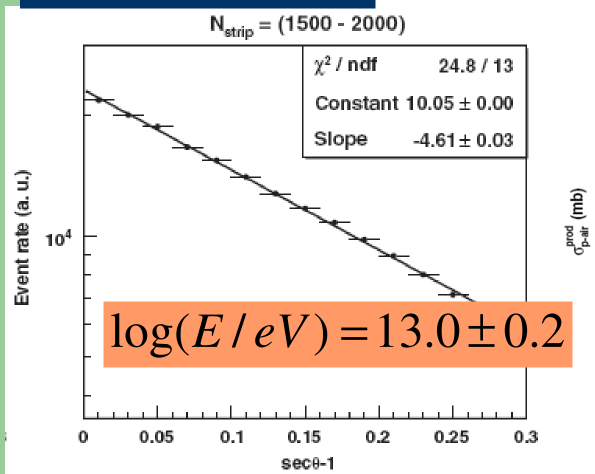
$$R(\theta) \sim e^{-\frac{h_0}{k\,\lambda_{p-air}}(\sec\theta - 1)}$$

h_0 = observation vertical depth

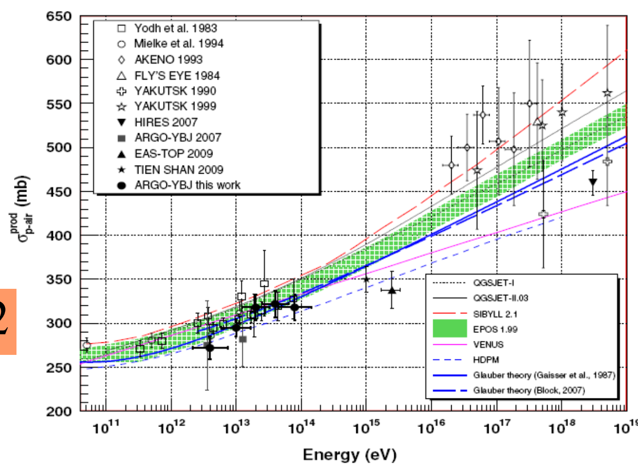
$\lambda_{p\text{-}air}$ (g/cm²) ≅ $2.41 \cdot 10^4 / \sigma_{p\text{-}air}$

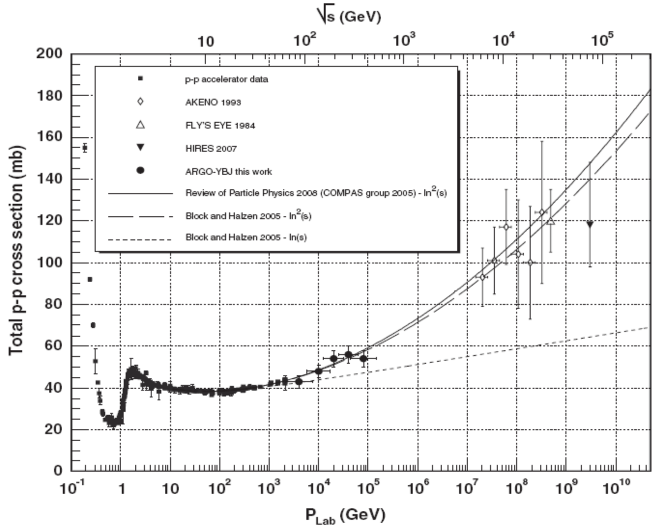
k takes into account hadronic dependence and shower fluctuations

$6.5 \cdot 10^8$ events



$$\log(E/eV) = 13.0 \pm 0.2$$





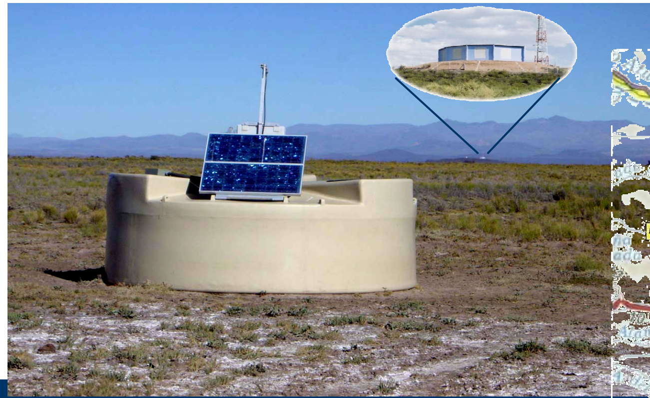
HE experiments

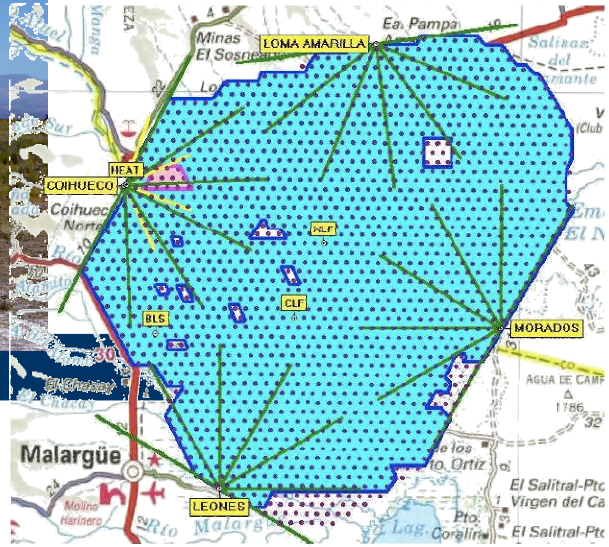
Experiment	Range	Detectors	Scientific goals
KASCADE-Grande&LOPES	0.5 PeV÷1 EeV	scintill.+radio	"knee"
HiRes	1 EeV	fluoresc.	"ankle", GZK, sources
TA&TALE	> $10^{16.5}$	scintil.+fluoresc.	"ankle", GZK, sources
PAO	> 10^{18}	water Cherenkov+fluorescence.+radio	"ankle", GZK, sources

The Physics

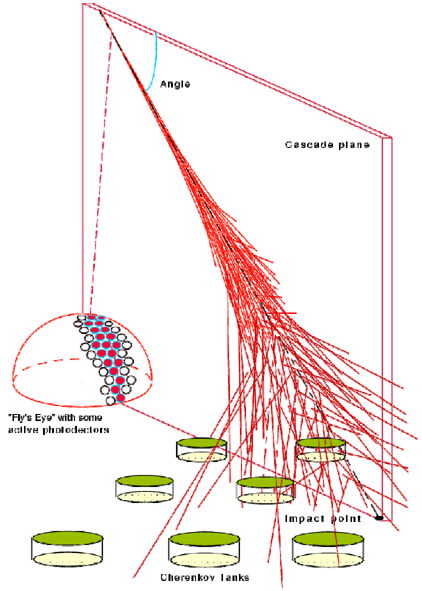
- which are the sources of CR?
- how is the relative importance of the GZK effect and of the effect of E_{max} in the sources in explaining the GZK feature?
- which is the mass composition of CR's at the highest energies?
- are there photons or neutrinos at the highest energies (TD models)?
- …

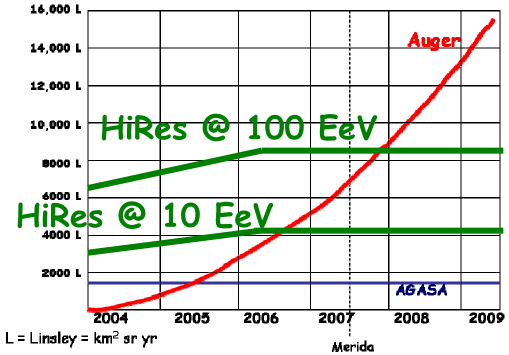
Pierre Auger Observatory

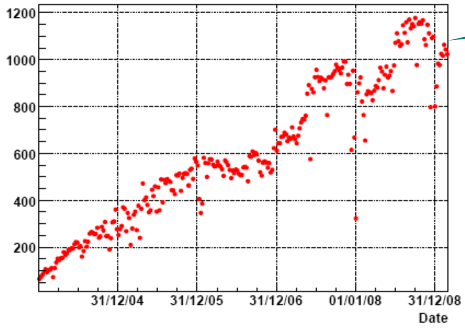




- 18 participating countries.
- Two sites in the two hemispheres: the Southern observatory, at Malargüe (Argentina), 1400 m a.s.l., completed in June 2008, and the Northern one in Colorado, 1300 m a.s.l., starting in 2011.
- Hybrid technique with SD (1600 water Cherenkov on 3000 km^2, 1.5 km spacing) and FD (24 fluorescence telescopes in 4 observation sites).
- Physics goals: cosmic ray spectrum above 10^{18} eV, mass composition, search for photons and neutrinos, UHECR sources via anisotropy.





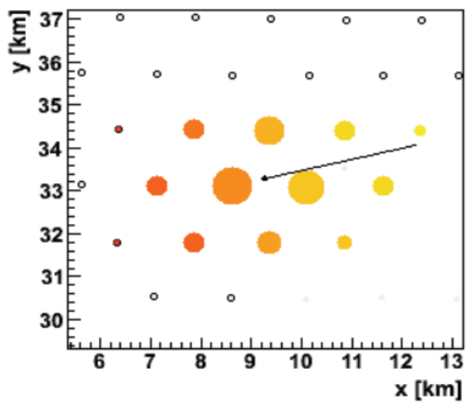


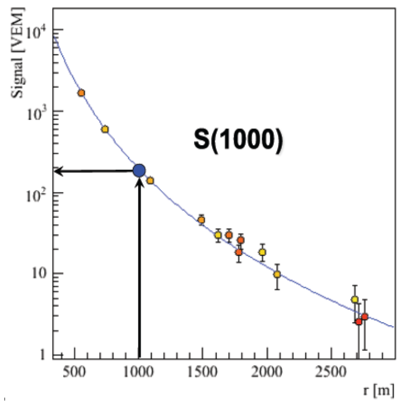
T. Suomijärvi, ICRC 2009

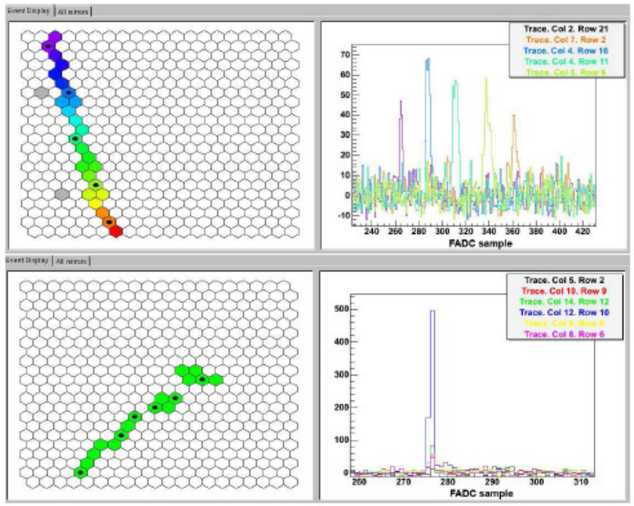
Precise monitoring of the array configuration (failures of electronics, power supply, comunication system,…)
evolution of the integrated exposure

G. Matthiae, TAUP 2009 &
P. Sommers, ICRC 2009

Reconstruction of a SD event



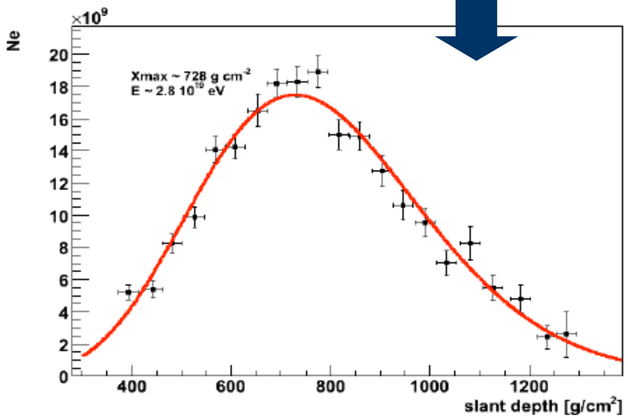




Shower profile from FD telescopes

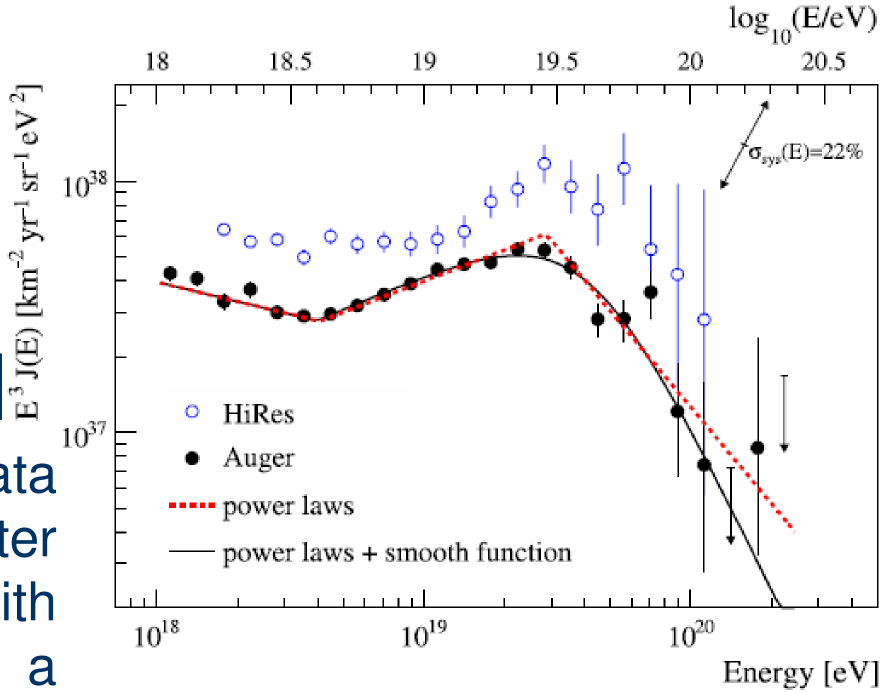
Gaisser-Hillas fit

$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max} - X_0}{\Lambda}} \exp\left(\frac{X_{max} - X}{\Lambda}\right)$$



J. Abraham et al., Phys. Lett. B685, 239

PAO spectrum



- Energy spectrum from hybrid data (Nov 2005-May 2008), with better energy resolution, combined with SD data (‘till Dec 2008) using a maximum likelihood method.
- Scale parameters for the fluxes: k_{SD}=1.01, k_{FD}=0.99 (agreement at 1% level).

Fitted parameters and their statistical uncertainties characterising the combined energy spectrum.

Parameter	Power laws	Power laws + smooth function
$\gamma_1(E < E_{\text{ankle}})$	3.26 ± 0.04	3.26 ± 0.04
$\log_{10}(E_{\text{ankle}}/\text{eV})$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{\text{ankle}})$	2.59 ± 0.02	2.55 ± 0.04
$\log_{10}(E_{\text{break}}/\text{eV})$	19.46 ± 0.03	
$\gamma_3(E > E_{\text{break}})$	4.3 ± 0.2	
$\log_{10}(E_{1/2}/\text{eV})$		19.61 ± 0.03
$\log_{10}(W_c/\text{eV})$		0.16 ± 0.03
χ^2/ndof	38.5/16	29.1/16

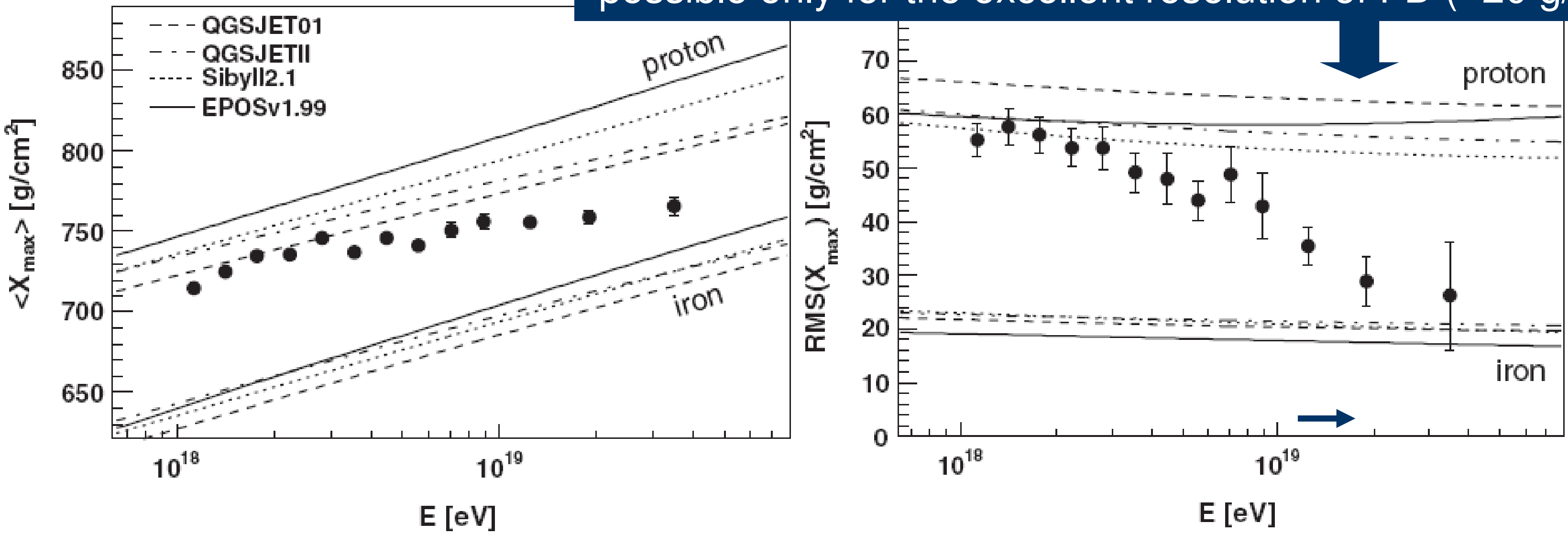
- Ankle at $10^{18.6}$ eV.
- Significance of the suppression larger than 20σ.

J. Abraham et al., Phys. Rev. Lett. 104, 091101

PAO mass composition

- Information on mass composition from the elongation rate, $<X_{max}>$ (E), and the shower-to-shower fluctuations of X_{max}, rms(X_{max}) (data in Dec 2004-March 2009).

possible only for the excellent resolution of FD (~20 g/cm^2)

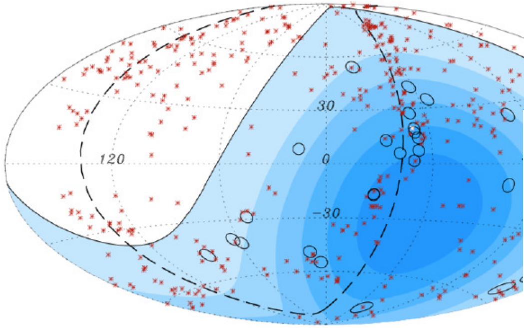


- The behaviours of $<X_{max}>$ (E) and rms(X_{max}) give indication of an increasing average mass of the primary particles with energy.

J. Abraham et al., Astrop. Phys., 29, 188

J. D. Hague, ICRC 2009

PAO arrival directions



Period	Exposure	GP	N	k	k_{iso}	P
I	4390	unmasked	14	9	2.9	
		masked	10	8	2.5	
II	4500	unmasked	13	9	2.7	2×10^{-4}
		masked	11	9	2.8	1×10^{-4}
III	8150	unmasked	31	8	6.5	0.33
		masked	24	8	6.0	0.22
II+III	12650	**unmasked**	**44**	**17**	**9.2**	$\mathbf{6 \times 10^{-3}}$
		masked	35	17	8.8	2×10^{-3}
I+II	8890	unmasked	27	18	5.7	
		masked	21	17	5.3	
I+II+III	17040	unmasked	58	26	12.2	
		masked	45	25	11.3	

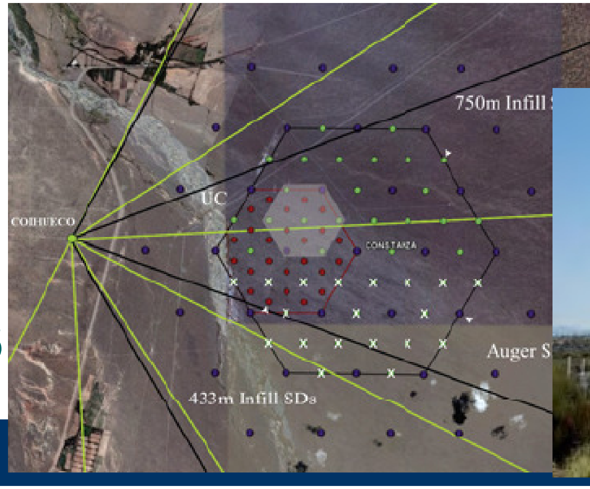
- Data set: events with $\theta \leq 60°$ and quality cuts (IE = 17040 km^2 sr yr).
- 27(1Jan2004-31Aug2007)+31(1Sep2007-31Mar2009) events with E>55 EeV and the 12° edition of VC AGN catalog.
- Statistical significance calculated by an esploratory scan (1 Jan 2004–26 May 2006) whose parameters (z_{max}, ψ_{max}, E_{th}) minimized the probability that k of N events from an isotropic flux were correlated (within an angle ψ) by chance with the selected AGN.

$$z_{\max} = 0.018; \psi_{\max} = 3.1°; E_{th} = 55\ EeV \rightarrow p_{iso} = 0.21$$

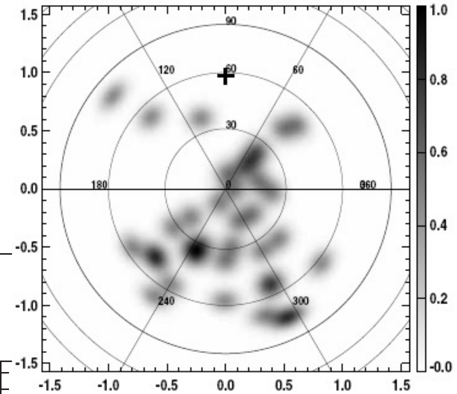
- Low galactic latitude troublesome (AGN catalog incomplete, magnetic deflection?); degree of correlation decreased, but parameters (z_{max}, ψ_{max}, E_{th}) stable.

M. Kleifges, M. Platino, A.M. Van der Berg, J.L. Harton, ICRC2009

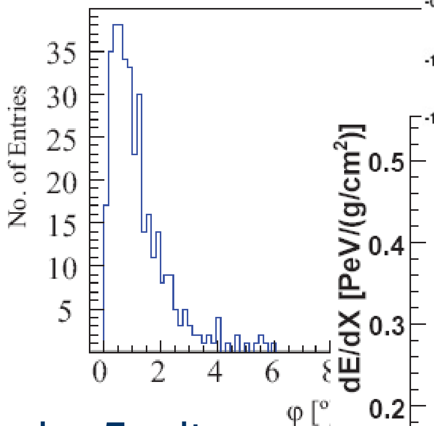
PAO enhancements



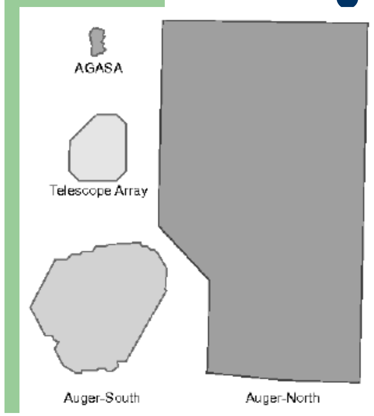
- AMIGA: an area with water Cherenkov at shorter distances (750&433 m) and a buried muon counter.
- HEAT: three telescopes, which can be tilted upwards by 29°, so to increase the FOV of the Coihueco telescopes.

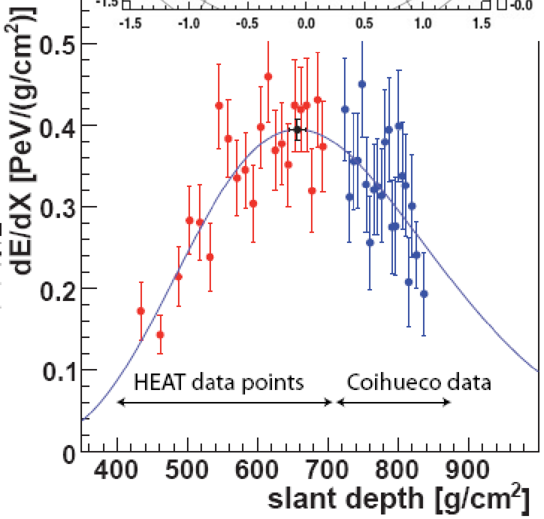


- AERA: 150 RD stations over 20 km², optimized to have a high sensitivity between 30 and 80 MHz.



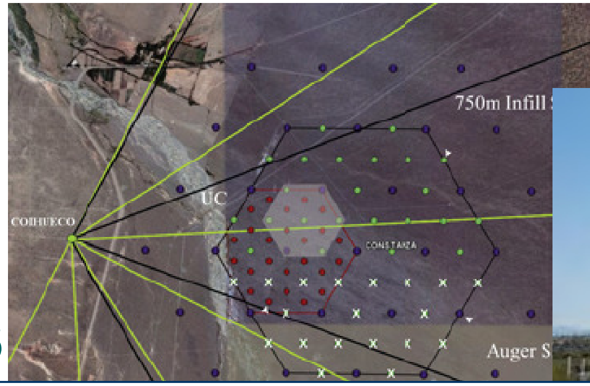
- AUGER NORTH: 20500 km² with 4000 water Cherenkov, 2.28 km spacing, and 39 FD telescopes in 5 sites, improved electronics. An “engineering array” for testing.



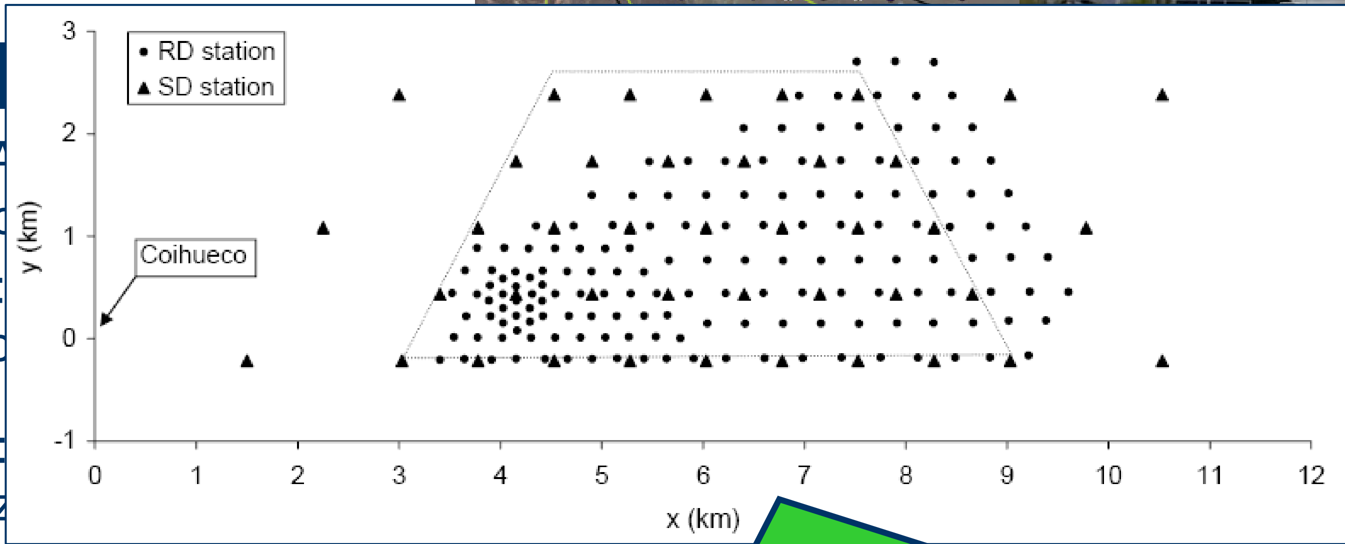


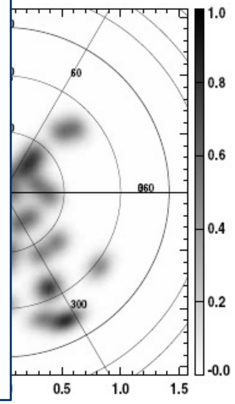
M. Kleifges, M. Platino, A.M. Van der Berg, J.L. Harton, ICRC2009

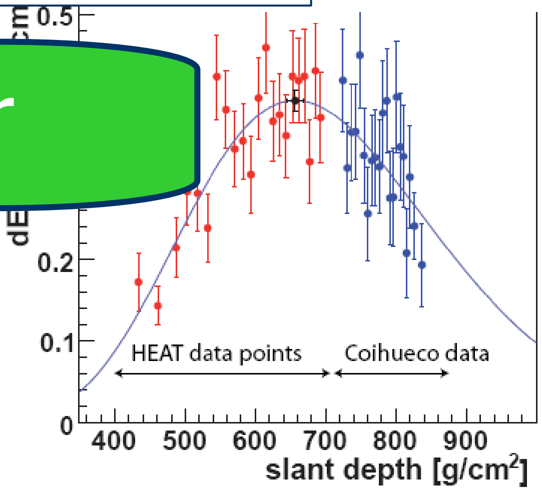
PAO enhancements



- AMIGA distanc
- HEAT: 29°, sc
- AERA: optimiz between 30 and 80 MHz.

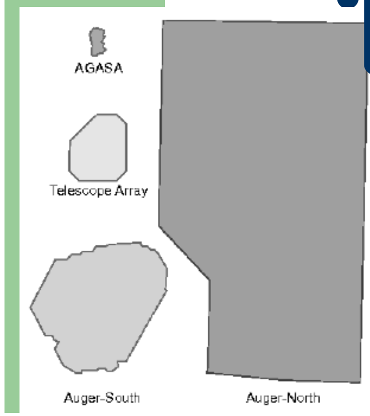






Super-hybrid detector

- Cherenkov, 2.28 km spacing, and 39 FD telescopes in 5 sites, improved electronics. An “engineering array” for testing.



The answers…

New data from experiments in different energy ranges and with different tecniques help us understanding the universe. We learned something:

- observed CR origin and acceleration seem to be well explained by BU models: AGN's, radio lobes, GRB's (photon flux disfavours TD models);
- a lot of VHE sky sources have been observed (confirmed);
- mass composition: X_{max} and RMS(X_{max}) indicate a trend towards heavy elements;
- propagation of CR: path length are similar for *p* and *Fe*, while intermediate nuclei are broken up due to photo-disintegration; interaction obeys to usual particle physics (GZK at ~20-30 EeV);
- CR's sources probably are where we expect: anysotropies indicate that there is a correlation of CR directions with matter in the universe within 100-200 Mpc.

But…

- sources of CR are AGN, a subclass of AGN, or some other sites correlated with them?
- how is the relative importance of the GZK effect and of the effect of E_{max} in the sources in explaining the GZK feature?
- which is the mass composition of CR's at the highest energies? proton (from the details of AGN correlations) or heavier(X_{max} and RMS(X_{max}))?
- where are the GZK (or TD models) photons and neutrinos?
- …

Backup slides

Production of VHE γ-rays

Most of the radiation coming from the universe is of thermal origin: the hotter the source, the higher the frequency of radiation. However, no material body can be hot enough to emit VHE gamma rays: these are generated in non-thermal conditions and often connected with relativistic motion:

- π_0 decay;
- inverse Compton scattering of relativistic electrons with low-energy photons;
- bremsstrahlung of charged particles inside a Coulomb field;
- synchrotron emisson of charged particles in a magnetic field;

All these conditions can occur in:

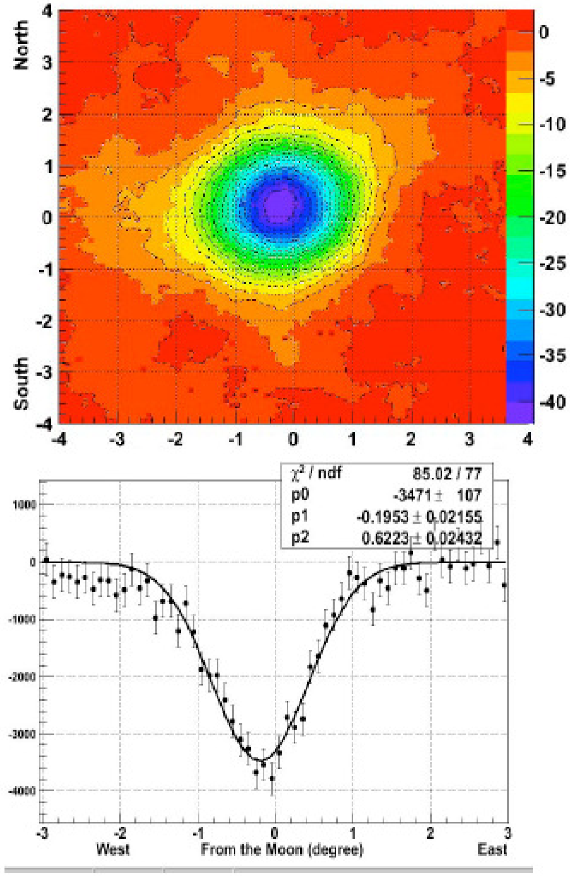
- AGN: ICS on synchrotron photons from the electron themselves (SSC) or thermal gamma from the accretion disk (EIC), or π_0 decay;
- SNR: ICS on synchrotron and background photons, or π_0 decay;
- binary systems: π_0 decay in the accreting material;
- microquasars: a scaled down version of a AGN with a binary system with relativistic jets;
- pulsars: charged particle accelerated in a magnetic field (PC or OG models).

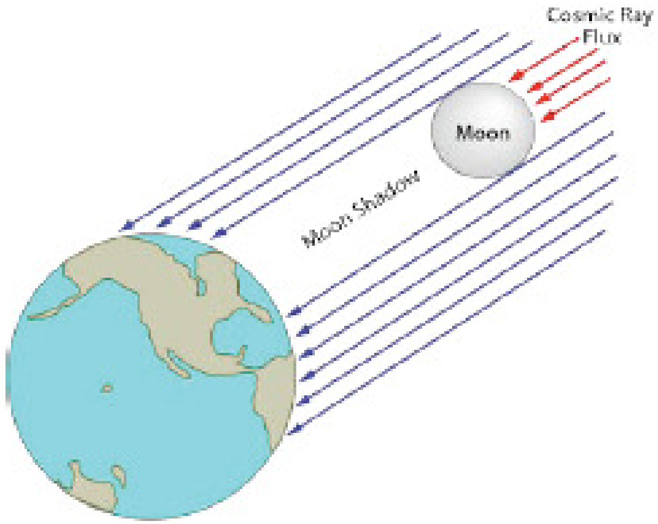
AGN general picture

E. Prandini,
MAGIC Didattico-Outreach

ARGO Moon shadow

S. Vernetto, ICAP 2009



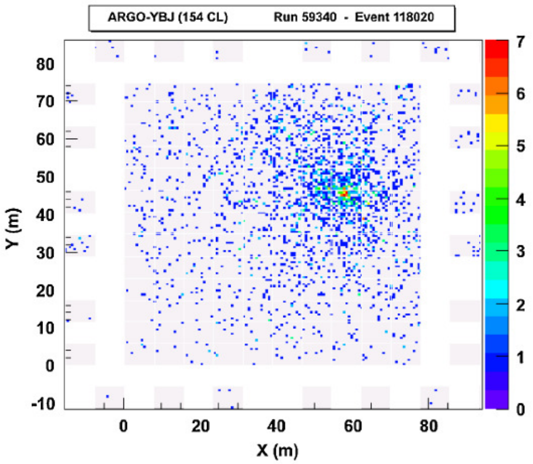


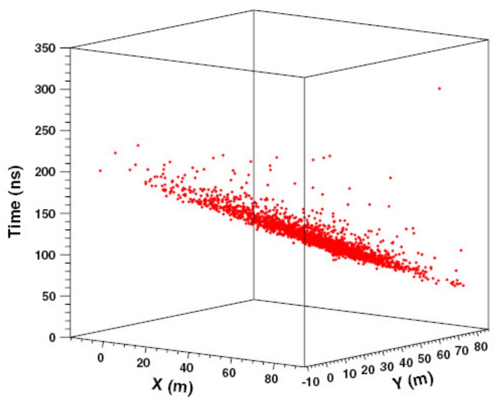
The size of deficit gives the angular resolution and the position the pointing accuracy.

Argo CR energy spectrum

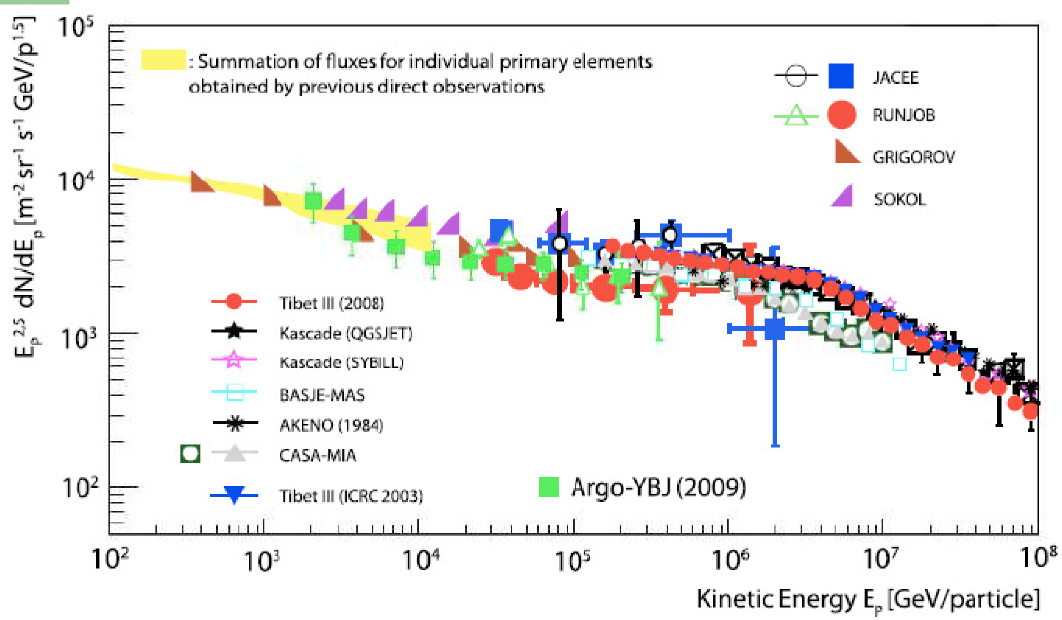
G. Aielli et al., Phys.Rev.D80, 092004

- Detected shower fronts fitted to a plane, then to a conical shape.
- Maximum-likelihood based algorithm of the shower core position, using a NKG-like lateral distribution function.





$$\frac{dN_e}{r\,dr} = N_e(E,X)\; C(s,r_1) \left(\frac{r}{r_1}\right)^{s-2} \left(1+\frac{r}{r_1}\right)^{s-4.5}$$



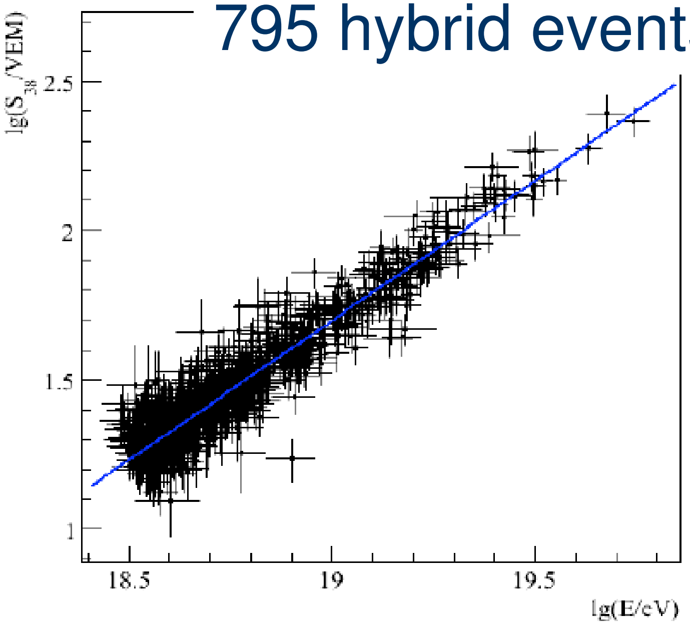
Extraction of the primary energy spectrum from the measured particle multiplicity spectrum at ground.

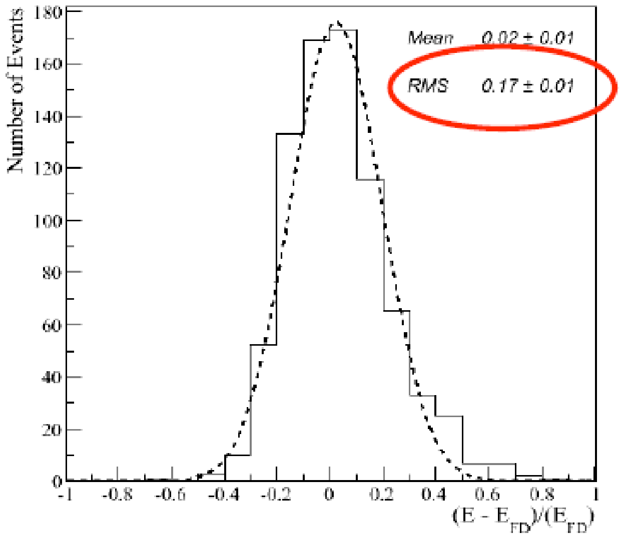
I. De Mitri, ICAP 2009

PAO energy calibration

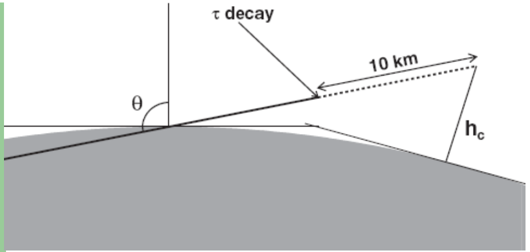
G. Matthiae, TAUP 2009

795 hybrid events

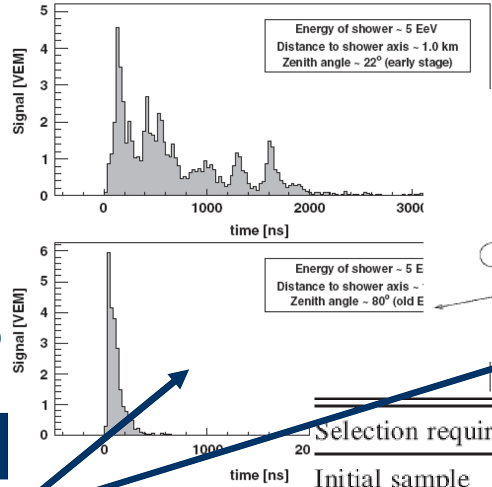




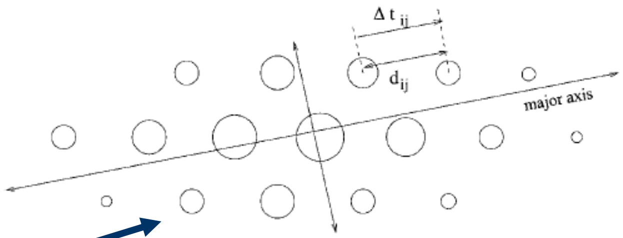
Energy resolution = 17%



PAO neutrinos

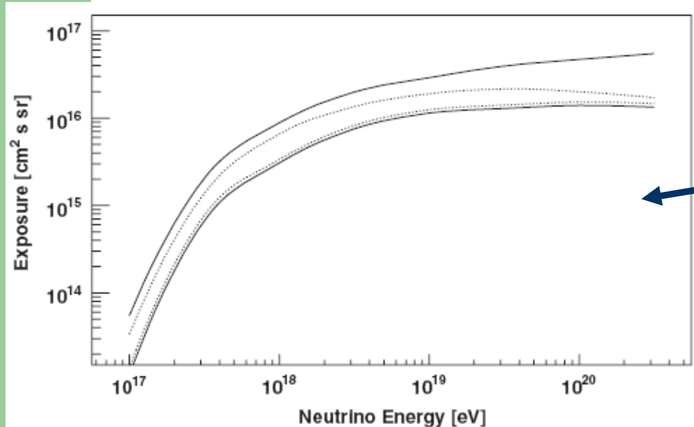


J. Abraham et al., Phys. Rev. D79, 102001



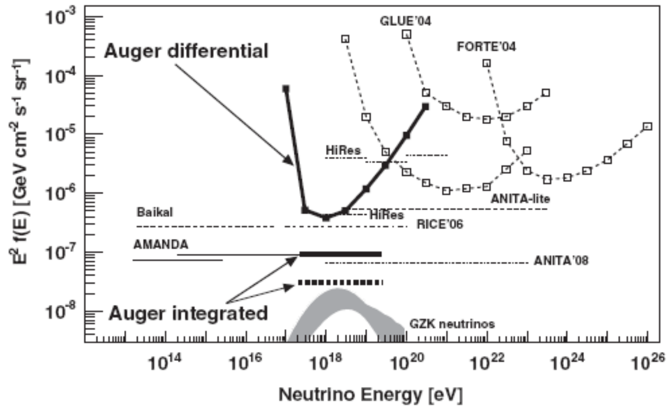
Selection requirement	MC efficiency	Number of real events
Initial sample	1.00	3.97×10^6
Young showers	0.88	6.68×10^5
Elongated footprint	0.87	8.37×10^3
Ground speed $\sim c$	0.84	0
Contained footprint	0.76	0

- Initial sample (Jan 2004-Apr 2008) over "good periods" restricted by cuts: 1) young showers; 2) shower footprint.



- ν aperture is calculated from simulation and then integrate for giving the exposure (~1.5 yr of the complete SD); systematic uncertainties are taken into account.

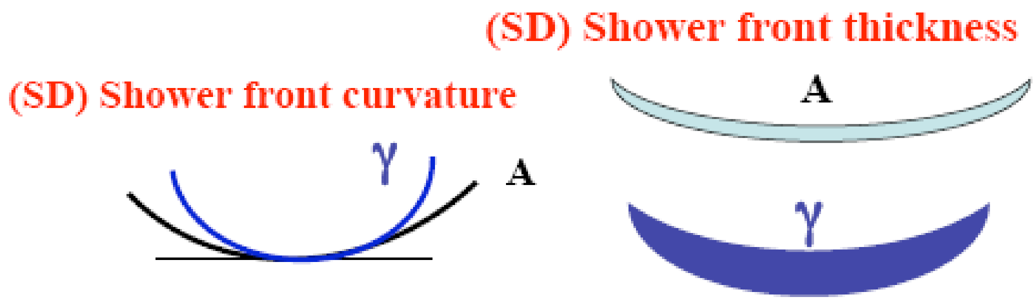
- For an injected E^{-2} neutrino flux a bound is derived for the energy range $2{\cdot}10^{17}$-$2{\cdot}10^{19}$ eV.



J. Abraham et al., Astrop. Phys., 31, 399

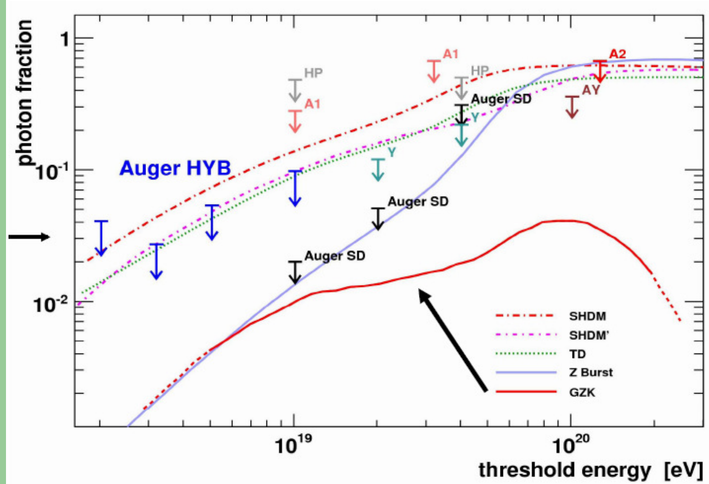
G. Matthiae, TAUP 2009

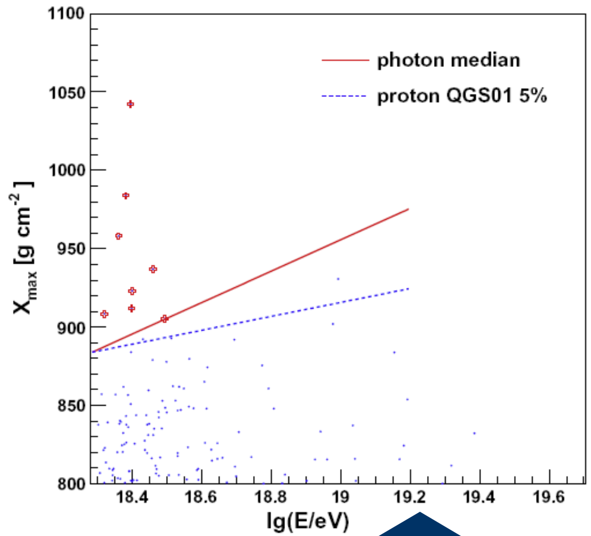
PAO photons



Photons at EeV energies are expected from standard GZK processes or TD scenarios. The basic idea of the analysis is to compare the measured X_{max} values to the ones for primary photons (photon showers have significantly deeper average X_{max}).

- data set: 1 Dec 2004–31 Dec 2007;
- quality cuts;
- cloud monitoring camera information used for selecting "clean" data;





Limit on photon fraction

Scatter plot of all events with E > 2 EeV