A MEASUREMENT OF THE COSMIC RAY ANISOTROPY AT AND ABOVE 10^{14} eV

ONCE UPON A TIME: THE EAS-TOP ARRAY

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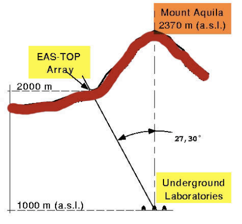
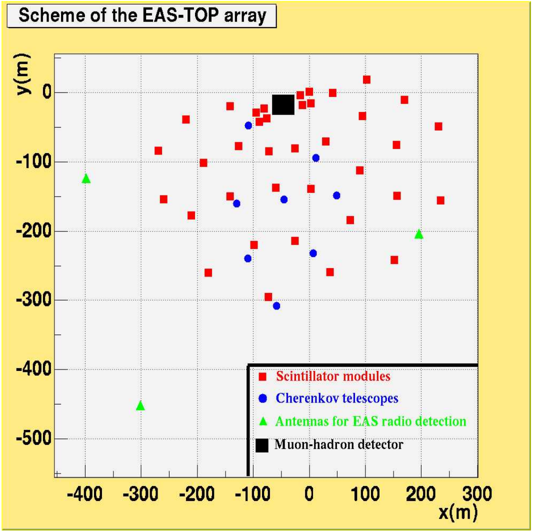
OUTLINE

A brief history

- EAS-TOP was conceived in the “Cygnus X-3 era”, at the end of 1980s. With other experiments born at the same time (CASA, CYGNUS, HEGRA, Tibet ASγ) was meant to do γ-ray astronomy at 100 TeV (i.e., to find the sources of hadronic cosmic-rays)
- Located above the Gran Sasso Laboratories, EAS-TOP was in fact mainly intended to study all aspects of galactic cosmic rays in the “knee” region: spectrum, composition, anisotropies.
- It was a “multi-component” detector, including an array of scintillators, a muon-hadron calorimeter, Cherenkov telescopes, radio antennas. It could detect EAS in coincidence with the TeV muon detectors underground



EAS-TOP scheme



- Located at Campo Imperatore (2005 m a.s.l., lat. 42.4°, long. 13.6°) above the Gran Sasso Laboratory
- EAS array + muon-hadron calorimeter + Cherenkov telescopes + radio antennas
- **EAS array**: 35 scintillator modules ($10 m^2$ each) over an area of about 10^5 m^2
- 4-fold trigger mode, rate $\approx$ 30 Hz
- Median energy $\approx$ 100 TeV

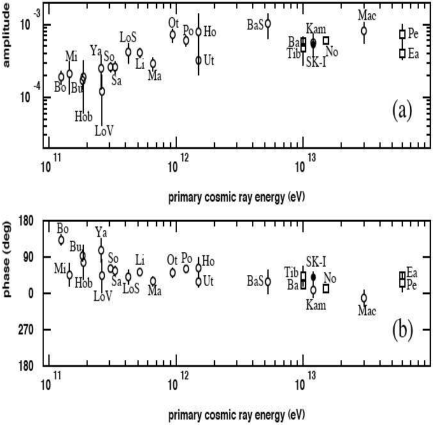
THE EAS-TOP ARRAY - winter view

THE EAS-TOP ARRAY - summer view

View post EAS-TOP

EAS-TOP was de-commissioned in 2000 due to an Italian law for environment protection. Its scintillators were added to Kascade (FZK, Karlsrhue, Germany) to build the Kascade-GRANDE array

LARGE SCALE ANISOTROPY AND RESULTS BEFORE EAS-TOP



- The amplitude and phase of the CR anisotropy were well established experimentally between 10^{11} eV and 10^{13} eV (by EAS arrays and underground μ detectors)
- Amplitude and phase rather constant over this energy range: (A: $(3 \div 6)\ 10^{-4}$); ϕ: ((0 $\div$ 4) h LST)
- **At higher energies (100 TeV and above) the anisotropy could provide an indication on the origin of the “knee” of the spectrum**

LARGE SCALE ANISOTROPY AND THE KNEE

Composition studies have shown that the knee is related to the steepening of the lightest primaries (protons, helium, CNO). Possible reasons for the knee:

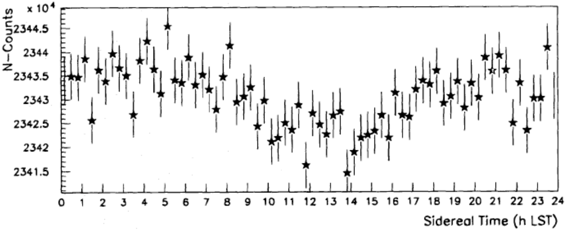
- Energy limits of the acceleration process at the source, e.g. diffusive shock acceleration in supernova remnants
- Change in the properties of CR propagation inside the Galaxy, described through diffusion models.

- CR diffusion parameters obtained through composition studies (mainly from the ratio of secondary to primary nuclei) at energies well below 1 TeV.
- The diffusion coefficient, D, is found to increase with magnetic rigidity ($D \propto R^{0.6}$, or $D \propto R^{0.3}$ for models including reacceleration).
- The main observable at higher energies is the large scale anisotropy, related to the diffusion coefficient.

The study of the evolution of the anisotropy in the “knee” region can provide a test of diffusion models, and an insight for the discrimination between the two possible explanations of the knee.

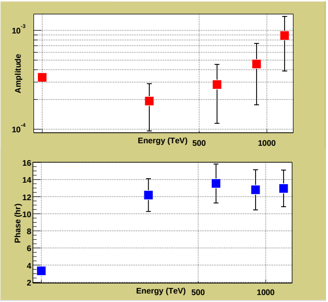
MEASUREMENT AT 100 TeV (Ap. J, 470 (1996) 501)

- 4 years of data (1990-1994). Number of events: 1.3×10^9
- Harmonic analysis on data corrected for atmospheric effects
- Observation of significant anisotropy (6 "σ" level) in sidereal time ($A_{sid} = (3.6 \pm 0.6)\ 10^{-4}$, $\phi_{sid} = (2.8 \pm 0.6)$ h LST)
- Observation of $\cos\delta$ dependence of the amplitude
- Observation at 7 "σ" level of the expected Compton Getting effect (due to Earth revolution around Sun) in solar time
- Absence of anti-sidereal signal
- **EAS-TOP extended the anisotropy measurement up to 100 TeV, showing the constancy (in amplitude and phase) with respect to lower energy ones**



MEASUREMENT ABOVE 100 TeV (ICRC 2003)

- 8 years of data (1992-1999). Number of events: 2×10^9
- Harmonic analysis on data corrected for atmospheric effects
- 5 energy bins (from 100 TeV to 1200 TeV)
- 100 TeV: observation of significant anisotropy (10 "σ" level) in sidereal time ($A_{sid} = (3.4 \pm 0.3)\ 10^{-4}$, $\phi_{sid} = (3.3 \pm 0.4)$ h LST)
- 100 TeV: observation at 7 "σ" level of the expected Compton Getting effect (due to Earth revolution around Sun) in solar time
- Change of phase above 300 TeV, but amplitudes not significant
- Absence of anti-sidereal signal
- **Upper limits set at energies above 300 TeV**



THE EAST-WEST METHOD (Ap.J 738 (2011) 67)

Based on counting rate differences between East and West directions, allowing to remove variations of atmospheric origin

$$\frac{dI}{dt} \simeq \frac{C_E(t) - C_W(t)}{\delta t}$$

$C_{E,W}(t)$=n. of counts from the East,West sectors in Δt=20 min
I=total intensity
δt=1.7 h = average hour angle between the vertical and each of the two sectors

The integrated wave shape:

$$I(t_{N_{int}}) = \frac{\Delta t}{N_{int}} \sum_{i=1}^{N_{int}} i \frac{C_E(i) - C_W(i)}{\delta t} + \langle I \rangle$$

where $N_{int} = 72$ intervals of solar / sidereal / anti-sidereal time and $t_{N_{int}} = N_{int} \cdot \Delta t$.

- Harmonic analysis on the differences $D(i) = C_E(i) - C_W(i)$
- Differential amplitude and phase are transformed into the integral ones: $r_I = \frac{r_D}{\delta t}$ and $\phi_I = \phi_D + \frac{\pi}{2}$
- Uncertainties on r_I and ϕ_I: $\sigma_{r_I} = \frac{1}{\delta t}\sqrt{\frac{2}{N_{EW}}}$ and $\sigma_{\phi_I} = \frac{\sigma_{r_I}}{r_I}$
- Rayleigh imitation probability: $P = exp\left(-\frac{r_I^2}{2\sigma_{r_I}^2}\right)$

THE FINAL DATASET

Class	$N_{modules}$	E_0 [eV]	N_{EW}
I	≥ 4	$1.1 \cdot 10^{14}$	$1.5 \cdot 10^{9}$
II	≥ 12	$3.7 \cdot 10^{14}$	$1.7 \cdot 10^{8}$

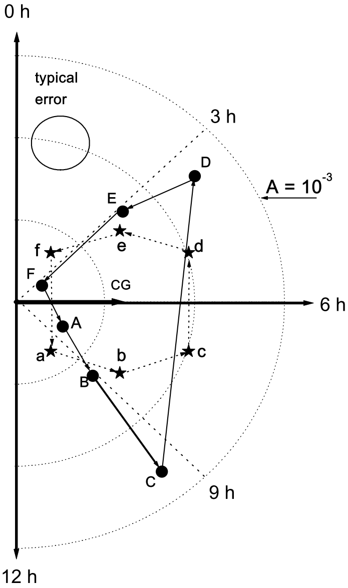
- 1431 full days between January 1992 and December 1999
- Counting rates every 20 min
- ϕ inside $\pm 45^\circ$ around the East and West directions
- $\theta < 40^\circ$
- Two primary energies: cuts in number of triggered modules (E_0 evaluated for primary protons and QGSJET01 hadron interaction model in CORSIKA)
- East-West analysis

HARMONIC ANALYSIS AT 100 and 400 TeV (Ap. J, 692 (2009) L130)

AT 1.1×10^{14} eV

$A_{sol}\ 10^4$	ϕ_{sol}[h]	$P(\%)$	$A_{sid}\ 10^4$	ϕ_{sid}[h]	$P(\%)$	$A_{asid}\ 10^4$	ϕ_{asid}[h]	$P(\%)$
2.8 ± 0.8	6.0 ± 1.1	0.2	2.6 ± 0.8	0.4 ± 1.2	0.5	1.2 ± 0.8	23.9 ± 2.8	32.5

- **Solar time analysis**: amplitude and phase in excellent agreement with expected Compton-Getting effect at our latitude, $A_{sol,CG} = 3.0\ 10^{-4}$, $\phi_{sol,CG} = 6.0$ h.
- **Sidereal time analysis**: amplitude and phase (chance probability 0.5%) consistent with our previous results
- **Anti-sidereal time analysis**: no significant amplitude. No additional correction is thus required due to residual seasonal effects



$\Longleftarrow$

Bi-monthly solar vectors of the I harmonic (black dots), and expected ones (black stars) from the measured solar and sidereal amplitudes.

- Expected anti-clockwise rotation of the solar vector clearly visible
- Instantaneous observed anisotropy = combination of solar and sidereal vectors
- Expected and measured rotations fully compatible within the statistical uncertainties

HARMONIC ANALYSIS AT 100 and 400 TeV (Ap. J, 692 (2009) L130)

AT 3.7×10^{14} eV

$A_{sol}\ 10^4$	ϕ_{sol}[h]	P(%)	$A_{sid}\ 10^4$	ϕ_{sid}[h]	P(%)	$A_{asid}\ 10^4$	ϕ_{asid}[h]	P(%)
3.2 ± 2.5	6.0 ± 3.4	44.1	6.4 ± 2.5	13.6 ± 1.5	3.8	3.4 ± 2.5	22.3 ± 3.2	39.7

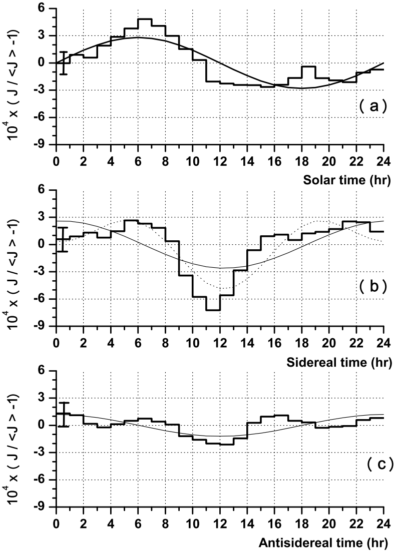
- **Solar time analysis**: significance of the first harmonic rather marginal (due to reduced statistics), but amplitude and phase still consistent with the Compton-Getting effect.
- **Sidereal time analysis**: indication of change of phase (from 0.4 to 13.6 h) and increase in amplitude by a factor 2.5 (chance probability 3.8%)
- **Anti-sidereal time**: no significant amplitude

SECOND HARMONIC ANALYSIS

E_0 (TeV)	A_{sol} 10^4	ϕ_{sol}[h]	P(%)	A_{sid} 10^4	ϕ_{sid}[h]	P(%)	A_{asid} 10^4	ϕ_{asid}[h]	P(%)
110	1.4 ± 0.8	7.0 ± 1.2	21.6	2.3 ± 0.8	6.3 ± 0.7	1.6	0.6 ± 0.8	-	75.5
370	1.7 ± 2.5	-	79.4	1.5 ± 2.5	-	83.5	1.2 ± 2.5	-	89.1

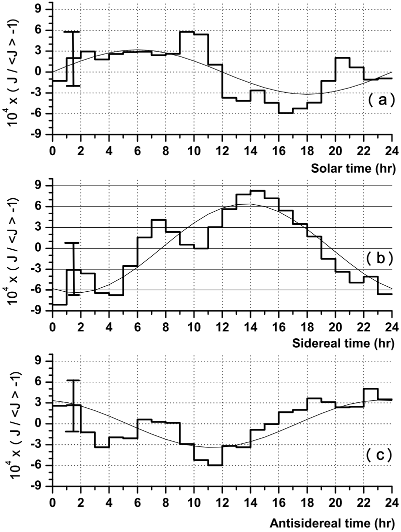
- Significant amplitude in sidereal time at 1.1×10^{14} eV (comparable with the first harmonic one: $A^{II} = (2.3 \pm 0.8)\ 10^{-4}$, $\phi^{II} = (6.3 \pm 0.7)$ h LST, $P = 1.6\%$)
- No other effects observed

Counting rate curve at 1.1×10^{14} eV



- **Solar wave**: Compton-Getting effect clearly seen
- **Sidereal wave**: shape in remarkable agreement with previous measurements (EAS and underground muon detectors)
- **Anti-sidereal wave**: no significant modulation.

Counting rate curves at 3.7×10^{14} eV



- **Solar wave**: Compton-Getting effect still visible
- **Sidereal wave**: rather different from the one at 100 TeV: broad excess around 13-16 h LST, and increased amplitude
- **Anti-sidereal wave**: no significant modulation

Final EAS-TOP results on large scale CR anisotropy

- confirms amplitude and phase of CR anisotropy **at 10^{14} eV:** $A^I_{sid} = (2.6 \pm 0.8) \cdot 10^{-4}$, $\phi^I_{sid} = (0.4 \pm 1.2)$ **h LST**, with Rayleigh imitation probability $P^I_{sid} = 0.5\%$
- The result is supported by the **observation of the Compton-Getting effect** due to the revolution of the Earth around the Sun, and by the **absence of anti-sidereal effects**
- It confirms the homogeneity of the anisotropy data over the energy range 10^{11}-10^{14} eV
- **At higher energies (around 4×10^{14} eV) the anisotropy shows a larger amplitude, $A^I_{sid} = (6.4 \pm 2.5) \times 10^{-4}$, and a different phase, $\phi^I_{sid} = (13.6 \pm 1.5)$ h LST, with an imitation probability of 3.8%.**

Final EAS-TOP results on large scale CR anisotropy

- Dependence of the anisotropy amplitude over primary energy ($A \propto E_0^{\delta}$) from the two EAS-TOP measurements: $\delta = 0.74 \pm 0.41$.
- At least in the energy range $(1-4) \cdot 10^{14}$ eV, dependence compatible with that of the diffusion coefficient as derived by composition measurements at lower energies
- Sharp increase of the anisotropy above 10^{14} eV (i.e. approaching the “knee”) indicative of a sharp evolution of the propagation properties, and therefore of the diffusion coefficient ?
- Or sharp increase (and change of phase) due to large fluctuations induced in the CR flux from local sources? (Blasi and Amato, arXiv:1105.4529)?
- Open problems:
  - will we succeed one day to get a theoretical description of the whole evolution of the diffusion processes vs E, and to understand its impact on the energy spectra at the "knee"?
  - wouldn’t it be of crucial significance to extend anisotropy measurements (with high sensitivity) to and above 10^{15} eV ?