Gamma Ray Astronomy
with ARGO-YBJ

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The ARGO-YBJ experiment

Collaboration between:
- Istituto Nazionale di Fisica Nucleare (INFN) – Italy
- Chinese Academy of Science (CAS)

Site: YangBaJing Cosmic Ray Laboratory (Tibet, P.R. of China), 4300 m a.s.l.

Site Coordinates: longitude 90° 31’ 50” E, latitude 30° 06’ 38” N
The ARGO-YBJ collaboration

Collaboration Institutes:
✓ Chinese Academy of Science (CAS)
✓ Istituto Nazionale di Fisica Nucleare (INFN)

INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Università’, Napoli
INFN and Dpt. di Fisica Università’, Pavia
INFN and Dpt. di Fisica Università “Roma Tre”, Roma
INFN and Dpt. di Fisica Università “Tor Vergata”, Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania

IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming
Hebei Normal University, Shijiazhuang
Single layer of Resistive Plate Chambers (RPCs) with a full coverage (93% active surface) of a large area (5600 m²) + sampling guard ring (6700 m² in total)

⇒ detection of small showers (low energy threshold)
**Pad** = TIME PIXEL (18360 on the full detector)

**BigPad** = CHARGE READOUT PIXEL, 123 x 139 cm² (3120 on the central carpet)

BP amplitude: from mV to many Volts
ARGO-YBJ operation modes

The detector carpet is connected to two different DAQ systems, working 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. 
  \[ E_{th} \approx 300 \text{ GeV} \]

- **Scaler Mode:**
  the counting rate of each CLUSTER is measured every 0.5 s, with no information on both the space distribution and the arrival direction of the detected particles.
  \[ E_{th} \approx 1 \text{ GeV} \]
Shower Data

- Trigger: $\geq 20$ particles
- Trigger rate: $\sim 3.5$ kHz
- Duty cycle: $> 86\%$
- Dead time: $4\%$

- Start of the installation of the RPCs in 2001
- Commissioning of the central carpet in June 2006
- Start of data taking with full detector in November 2007
- End of data taking in February 2013
- $> 5 \times 10^{11}$ events collected
ARGO-YBJ: a multi-purpose experiment

- CR physics from 1 TeV to $10^4$ TeV
- Survey of the $\gamma$-ray sky in the band $-10^\circ \leq \text{decl.} \leq 70^\circ$
- High exposure for flaring activity ($\gamma$-ray sources, Gamma Ray Bursts, solar flares)
- CR $\bar{p}/p$ flux ratio at TeV energies
- Hadronic interactions (p-air and p-p cross sections)
- Solar and heliosphere physics

(p + He) spectrum
knee region
anisotropies
Selected results in gamma-ray astronomy

- Sky survey of the Northern hemisphere (-10° < δ < 70°)
- Crab Nebula
- Mrk 501
- Cygnus region
- Diffuse γ-rays from the Galactic plane
- Gamma Ray Bursts
Analysis of the Moon shadow

Phys. Rev. D 84 (2011) 022003

A natural tool to estimate the detector performance:

- Pointing accuracy
- Angular resolution
- Absolute energy calibration

The energy scale uncertainty is estimated to be < 13% in the rigidity range 1 – 30 TeV/Z
Sky survey

ARGO-YBJ sensitivity (5 years of data taking) : 0.24 Crab units

Cygnus region
Mrk501
Mrk421
CRAB Nebula

MGRO J1908+06
HESS J1841-055

6 sources with $S > 5$ s.d. + 5 hotspots with $S > 4$ s.d.
### List of detected and candidate sources

Table 2

<table>
<thead>
<tr>
<th>ARGO-YBJ Name</th>
<th>R.A. (^a) (deg)</th>
<th>Decl. (^a) (deg)</th>
<th>l (deg)</th>
<th>b (deg)</th>
<th>S (s.d.)</th>
<th>Associated TeV Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGO J0409−0627</td>
<td>62.35</td>
<td>−6.45</td>
<td>198.51</td>
<td>−38.73</td>
<td>4.8</td>
<td>Crab Nebula</td>
</tr>
<tr>
<td>ARGO J0535+2203</td>
<td>83.75</td>
<td>22.05</td>
<td>184.59</td>
<td>−5.67</td>
<td>20.8</td>
<td>Mrk 421</td>
</tr>
<tr>
<td>ARGO J1105+3821</td>
<td>166.25</td>
<td>38.35</td>
<td>179.43</td>
<td>65.09</td>
<td>14.1</td>
<td>Mrk 501</td>
</tr>
<tr>
<td>ARGO J1654+3945</td>
<td>253.55</td>
<td>39.75</td>
<td>63.59</td>
<td>38.80</td>
<td>9.4</td>
<td>HESS J1841−055</td>
</tr>
<tr>
<td>ARGO J1839−0627</td>
<td>279.95</td>
<td>−6.45</td>
<td>25.87</td>
<td>−0.36</td>
<td>6.0</td>
<td>HESS J1908+063</td>
</tr>
<tr>
<td>ARGO J1907+0627</td>
<td>286.95</td>
<td>6.45</td>
<td>40.53</td>
<td>−0.68</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>ARGO J1910+0720</td>
<td>287.65</td>
<td>7.35</td>
<td>41.65</td>
<td>−0.88</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>ARGO J1912+1026</td>
<td>288.05</td>
<td>10.45</td>
<td>44.59</td>
<td>0.20</td>
<td>4.2</td>
<td>HESS J1912+101</td>
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<tr>
<td>ARGO J2021+4038</td>
<td>305.25</td>
<td>40.65</td>
<td>78.34</td>
<td>2.28</td>
<td>4.3</td>
<td>VER J2019+407</td>
</tr>
<tr>
<td>ARGO J2031+4157</td>
<td>307.95</td>
<td>41.95</td>
<td>80.58</td>
<td>1.38</td>
<td>6.1</td>
<td>MGRO J2031+41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TeV J2032+4130</td>
</tr>
</tbody>
</table>

Note. \(^a\) R.A. and decl. are celestial coordinates in J2000 epoch.

\(N_{\text{pad}} \geq 20\)

\(N_{\text{pad}} \geq 100\)
Distribution of Significances

Fit for the whole sky map:
Gaussian distribution with mean value = 0.002 and r.m.s. = 1.02

Fit for the inner Galactic plane:
Gaussian distribution with mean value = 0.40 and r.m.s. = 1.04
Crab Nebula

• Measured Point Spread Function in agreement with MC simulations
• Energy spectrum in 0.3–20 TeV in agreement with other experiments

\[
dN/dE = (5.2 \pm 0.2) \cdot 10^{-12} \cdot (E/2 \text{ TeV})^{-2.63 \pm 0.05} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}
\]

Significance map for \( N_{\text{pad}} > 20 \)

Spectrum multiplied by \( E^2 \)
Crab event rate

Distribution of the daily excess significances in ~1800 days

Average rate: 16.5 ev/hour

\[ N_{pad} \geq 40 \]

\[ <s> = -0.014 \pm 0.026 \]

r.m.s. = 1.086 ± 0.019

Alternative check of the detector stability
Mrk 501: long-term monitoring and flare

Largest flare in 2011, from October 17 to November 22: TeV flux \( \sim 2 \) Crab units, \( \sim 6.6 \) the long-term steady state

\( N_{\text{pad}} \geq 60; \quad S_{\text{max}} = 6.1 \) s.d.
A simple one-zone SSC model is unable to reproduce the flaring emission at $E > 8$ TeV, while the long-term data are well fitted.
Extended Sources in the Galactic Plane

Cygnus region

Mrk501

Mrk421

CRAB Nebula

MGRO J1908+06

HESS J1841-055
- MGRO J2031+41/TeV J2032 +4130 → 6.4 s.d.
- No significant signal from MGRO J2019+37 (< 3.0 s.d.)
Cygnus region: MGRO J2031+41

- Extension $\sigma_{ext} = (0.2^{+0.4}_{-0.2})^\circ$ consistent with HEGRA and MAGIC $\sigma_{ext} \sim 0.1^\circ$
- Spectrum: $dN/dE \propto E^{-2.83 \pm 0.37}$ (assuming $\sigma_{ext} = 0.1^\circ$)
- Flux ($E > 1$ TeV) $\sim 0.3$ Crab unit, in agreement with Milagro but about a factor 10 higher than HEGRA and MAGIC results
ARGO J2031+4157 as the Cygnus Cocoon

A cocoon of freshly accelerated cosmic rays

The Fermi / LAT view
in the 10-100 GeV band:

The ARGO-YBJ view
at TeV energies ($N_{\text{pad}} \geq 20$)
after reanalysis with the full data:

$S_{\text{max}} = 6.1$ s.d.
$\sigma_{\text{ext}} = 1.8^\circ \pm 0.5^\circ$

Ackermann et al.,
Science 334 (2011) 1103

Paper submitted
**Spectrum of the Cygnus Cocoon**

Milagro data refer to MGRO J2031+41, at 12 TeV also corrected for the extrapolation of TeV J2032+4130

A pure hadronic model was assumed with a power law and a cutoff energy $E_c$

**Spectrum of ARGO J2031+4157:** $dN/dE \propto E^{-2.62\pm0.27}$

**Combined LAT&ARGO spectrum:** $dN/dE \propto E^{-2.16\pm0.04}$
Cygnus region: MGRO J2019+37

- The most intense Milagro source (12.4 s.d.) after the Crab
- Milagro spectrum: \( \frac{dN}{dE} = 5.4 \times 10^{-12} \cdot E^{-1.83} \exp(-E/22.4) \) cm\(^{-2}\) sec\(^{-1}\) TeV\(^{-1}\)
- Extension: \( \sigma_{ext} = (0.32 \pm 0.12)° \)

VER J2019+368 likely contributes to the bulk of the emission observed by Milagro and coincides with the PSR J2021+3651 and the star formation HII region Sh2-104

A few years of \( \Delta t \) (Milagro - ARGO) \( \rightarrow \) flux variability of the components?
Comments on extended sources

• Considering also the ARGO-YBJ results for MGRO J1908+06 (ApJ 760 (2012) 110) and HESS J1841-055 (ApJ 767 (2013) 99), as for the air shower array Milagro, the fluxes measured in extended sources are systematically larger than those measured with Cherenkov telescopes.

• A contribution is due to the diffuse emission from the Galactic plane, however it cannot explain the observed disagreement, being < 15 %.

• The overall systematic error on the flux has been estimated to be < 30%.
Diffuse $\gamma$-rays from the Galactic plane

**Cygnus region: $65^\circ < l < 85^\circ$ ; $|b| < 5^\circ$**

The different lines indicate the energy spectra expected from the Fermi/LAT template (with spectral index -2.6) in the different sky regions investigated by the detectors.

The TeV diffuse flux in the Cygnus region does not show a strong excess like that reported by Milagro at 15 TeV.

The difference may be due to the Cygnus Cocoon, not yet discovered at the time of the Milagro measurement.
206 GRBs in the ARGO f.o.v. from Dec. 2004 to Jan. 2013 (largest sample from ground!)

- With known redshift: 24
- Discovered by Fermi/GBM: 90 (including its 2nd GRB catalog)
- Detected by Fermi/LAT: 4
- Long duration GRBs ($>2s$): 179
- Short duration GRBs ($\leq2s$): 27

- No evidence of coincident signal during the GRB T90 duration
- In stacked analyses (time and phase) no evidence of any integral effect
Upper limits to GRB fluence

Sample of the 24 GRBs with known redshift

The Kneiske et al. (2004) model is adopted to take into account the extragalactic absorption

The red dot shows the extrapolated fluence of GRB090902B as observed by Fermi/LAT

Fluence upper limits (at 99\% c.l.) obtained with differential spectral indexes ranging from the value measured by satellites to $-2.5$

For GRB090902B the LAT index was used with $E_{\text{max}} = 30–100$ GeV
Upper limits to GRB cutoff energy

An upper limit to the GRB cutoff energy $E_{\text{cut}}$ is given by the intersection of the fluence upper limit, as a function of $E_{\text{cut}}$, with the extrapolation to $\Delta E = 1$ GeV$-E_{\text{cut}}$ of the fluence measured by satellites.

The spectra of these GRBs do not extend beyond $E_{\text{cut}}$ (with the index measured by satellites) at a 99% c.l. Red triangles represent GRBs with known redshift, while $z = 2$ and $z = 0.6$ are assumed for the other long and short GRBs, respectively.
Summary

- 6 sources detected and 5 source candidates in the sky survey of the Northern hemisphere (-10° < δ < 70°) with a sensitivity of 0.24 Crab
- The Crab Nebula spectrum is in agreement with other experiments
- Continuous long-term monitoring of the flaring sources Mrk 421 and Mrk 501
- The fluxes of the extended sources MGRO J2031+41, MGRO J1908+06 and HESS J1841-055 are in agreement with those measured by Milagro but larger than those measured by Cherenkov telescopes
- Detection of diffuse γ-rays from the Galactic plane
- Upper limits to the emission in the 1–100 GeV range for a sample of 206 Gamma Ray Bursts, the largest ever investigated with a ground-based detector