From YangBaJing
Cosmic Ray
Experiments to LHAASO

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Cosmic ray Spectra

- Spectra contain very rich information (e.g., Blackbody spectrum, beta decay electron spectrum).
- The knee @ ~4PeV was discovery in 1958.
  1. Acceleration limit of the galactic sources;
  2. Rigidity dependent diffusion;
  3. New Physics?

\[
E^2 \frac{dN}{dE}
\]
Extensive Air Shower
A schematic view
Advantage of High Altitude Observatory

- Number of secondary reach maximum, in favor of knee physics, including composition and spectrum measurement.
- Low energy threshold, in favor of γ ray astronomy
- Better angular, energy resolution

γ ray astronomy

knee

(Ona)
**Sino-Italian ARGO-YBJ**: \( \sim 100M \times 100M \)

**Sino-Japanese AS\(\gamma\)**: \( \sim 270M \times 270M \)

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**ARGO hall, floored with RPC**

- **CRs Spectrum:** \(100\text{TeV}-100\text{PeV}\)
- **CRs anisotropy:** \(10\text{TeV}-\text{PeV}\)
- **\(\gamma\) rays:** \(\sim 3\text{TeV}, \text{Sensitivity:} \sim 1\text{Crab};\)

**AS\(\gamma\) scintillation counter**

- **Wide field of view Cherenkov Telescope (2006-)**
  - 4.7 m\(^2\) spherical mirror composed of 20 hexagon-shaped segments
  - 256 PMTs (16 \(\times\) 16 array)
  - pixel size 1\(^\circ\)
  - FOV: 14\(^\circ\) x 14\(^\circ\)

**CRs spectrum:** \(5\text{TeV}-5\text{PeV}\)
**Crs anisotropy:** \(1\text{TeV}-20\text{TeV}\)
**\(\gamma\) rays:** \(\sim 300\text{GeV}, \text{Sensitivity:} \sim 0.6\text{Crab}\)
ASγ: Crab at $>3\text{TeV}$ (1996-99) (5.5σ)

ASγ:Mrk501

Active:
Mrk421 (6.9σ)

AS γ was able to make a continuous observation of Mrk421 between 2000-2001
ARGO-YBJ: 6 TeV sources + 5 candidates

Identifying the first TeV super bubble

7 large flarings etc: verifying SSC mechanism
Diffuse $\gamma$-rays are produced by relativistic electrons by bremsstrahlung or inverse Compton scattering on bkg radiation fields, or by protons and nuclei via the decay of $\pi^0$ produced in hadronic interactions with interstellar gas. The space distribution of this emission can trace the location of the CR sources and the distribution of interstellar gas.

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

This result is obtained after masking all the sources detected in the region (in particular the TeV counterpart of the Cygnus Cocoon) and removing the residual contamination.

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.
All-particle spectrum measured by Tibet-III array

A very sharp knee around 4 PeV was observed.

Indication of a single source? What is the other underline mechanism?

If knee is dominated by He, the corresponding Lorentz factor is:

\[ \sim \frac{4 \text{PeV}}{4 \text{GeV}} = 10^6 \]
The spectrum of H & He: ~700 TeV

Suppose this break is dominated by proton. The corresponding Lorentz factor is:

\[ \sim 0.7 \text{PeV/1GeV} \]

\[ = 0.7 \times 10^6 \]
Electron spectrum up to 20 TeV

~700-900 GeV cutoff corresponds to a Lorentz factor of $1.4-1.8 \times 10^6$
Do the PeV knee and TeV cutoff share same origin?

Considering the rather large uncertainties in determining the composition of cosmic rays around the knee energy, it is probable that Lorentz factors of cosmic ray “knees” are same, and close to that electron’s cutoff.

A naive suggestion is:

\[ m_{X'} \leq 10^6 m_X \]

\[ m_{X'} \leq m_e; m_X \leq 1\text{eV} \]

Interaction time for CR:

\[ 2 \times 10^8 (R/1\text{GV})^{-0.6} \text{ year} \]

Interaction time for TeV electron:

\[ \sim 10^5 \text{ years} \]
Step-like Xsec function for two recent electron spectra

\[ \sigma(E) = \begin{cases} 
0, & (E < E_{\text{th}}) \\
\sigma_0 \left(1 - \exp \left[-\frac{(E - E_{\text{th}})}{\Delta E}\right]\right), & (E \geq E_{\text{th}}) 
\end{cases} \]

\[ \Delta E = 2E_{\text{th}} \]

\[ \eta n_x \sigma_{p_x \rightarrow p_x} = 6 \times 10^{-21} \text{ cm}^{-1} \]

**Table:**

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<th>HESS 2017</th>
<th>DAMPE</th>
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<td>(m_x) (eV)</td>
<td>1.07</td>
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<td>(\eta n_x \sigma_e)</td>
<td>2</td>
<td>2.8</td>
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<tr>
<td>((\times 10^{-23} \text{ cm}^{-1}))</td>
<td></td>
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<td>(\xi)</td>
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Global propagation of GCR: co-rotation with environments

CMB anisotropy by COBE

Intensity @ E~300TeV

Amp=0.16% w/o corotation; Observation: 0.03% ± 0.03%.

Compton-Gettings Effect


See Yi Zhang’s talk
For details
New anisotropy component and corotation evidence of the GCR (Science 314(2006)439-443)

Celestial Intensity map (E~3TeV)

New anisotropy component

Intensity @ E~300TeV

Amp=0.16% w/o corotation; Observation: 0.03% ± 0.03%.
TeV CRs anisotropy in the Galactic coordinates

3 directions for the CRs motion

3 anisotropy components, some are global CRs motions?
Assume all are global, the electricity currents
\[ \Rightarrow \text{global magnetic field} \]

Galactic halo magnetic field observed by astronomer

By Applying Copernicus’ principle

Up: CRs anisotropies;
Down: calculated magnetic field;
PeV anisotropy of cosmic rays By ASγ

~[-80σ,50σ]
15TeV

~[-20σ,15σ]
50TeV

~[-11σ,6σ]
100TeV

~[-6σ,7σ]
300TeV

~[-5σ,6σ]
1PeV

Consistent with IceTop result

PeV CRs anisotropy in Galactic coordinate

Consistent with the GLOBAL diffusion prediction;
An indication that PeV CRs are galactic origin.
CRs Anisotropy measured by ARGO-YBJ


See Songzhan Chen’s talk For details
Stable Multi-TeV anisotropy by ASγ & ARGO


HAWC: A Next Generation All-Sky VHE Gamma-Ray Telescope

40000M², full coverage, 50mCrab
GG. Sinnis, A. Smith, J.E. McEnery, astro-ph/0403096
HAWC Sky Map

Equatorial coordinates

17 months

360°

0°

PRELIMINARY

~40 sources seen in first year
~10 of these are new!

Source catalog currently in preparation

HAWC complements HESS Galactic Plane survey
Sensitivity with Tibet III-Muon @100TeV
Demonstration on the $\gamma$/CR separation power

100m$^2$ muon detector

Large High Altitude Air Shower Observatory (LHAASO) Project

Site at 4400 m a.s.l.

Main Array:
- 5195 scintillator detectors every 15 m
- 1171 μ–detectors every 30 m

Water Cherenkov Detector
- 78,000 m²

CR Detectors:
- 18 Wide field View Cherenkov telescopes & Large Dynamic WCDA++:
  precision measurement of CR spectrum
LHAASO layout

- 1 km² array, including 5195 scintillator detectors 1 m² each, with 15 m spacing.

- An overlapping 1 km² array of 1171, underground water Cherenkov tanks 36 m² each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m²).

KM2A:

30X TibetIII-Muon

WCDA:

>8X ARGO • A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m².

4X HAWC • 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.
LHAASO sensitivity

- WCDA ~ 1% I_{crab} @3TeV
- KM2A ~ 2% I_{crab} @30TeV
- KM2A ~ 10% I_{crab} @100TeV
Domestic Collaboration
20 institutions

International collaborations

France: IPNO, OMEGA
Italy: U. Rome I, II, III, U. Torino
Switzerland: U. Geneva
Russia: RAS, INPR
Thailand:成東分院：山地所，生物所
LHAASO site

- Location: 29°21’27.6”N, 100°08’19.7”E, 4400 m a.s.l;
- 8 km to Daocheng-Yading Airport (4411 m a.s.l.);
- 50 km to Daocheng City (3750 m a.s.l.), Sichuan Province.
LHAASO: infrastructure

1. Base and Data Center (3750m a.s.l.)
   - Dom, Assembling Hall, storage rooms, utility rooms, kitchen and cafeteria

2. Observatory (4410m a.s.l.)
   - Roads 21 km,
   - Flood Prevention Channel 1.3 km,
   - Power Stations and 35 kV Power-line of 30 km
   - Water Supply System with 0.8 km Pipe-line

Water supply system
Kitchen & Cafeteria
Assembling, Storage and Utility
Construction of LHAASO-1/4

• #1 pool (150X150 m²) is built up.
• 2018/01/31, roof installation
• Now, internal installation
• 2018/04, #2 & #3 pools are started simultaneously

• 2018/02/04, first 33 scintillator detectors deployed.
  The 1ˢᵗ LHAASO event
Construction

1st water pool

1st fan-less WR switch produced domestically

- Liner

1st muon detector
Technical upgrading: SiPM camera on C-Teles

Fully portable telescopes allow reconfiguring the array for CR detection in 3 energy ranges

- Movable telescope housing
- Rotating from $0^\circ$ to $90^\circ$ in elevation
- $5 \text{ m}^2$ spherical aluminized mirror
- Reflectivity of 85%
- $32 \times 32$ SiPM array
- FoV of $16^\circ \times 16^\circ$
- 0.5° pixel
- 1–4000 PE nonlinearity less than 5%
- $4 \times 4 20\mu\text{m}$ SiPM sub-cluster
- 50 MHz FADC
- Temperature-compensation power supply
- T-stamp from WR network
- Aluminized Winston cones
- Cut-off angle $30^\circ$ with efficiency of 93%
- Filter transmission of 92% in 310–550 nm

Elevation of 60 toward North with full-moon duty cycle >30% above 100 TeV


Statistic error ~10% @100TeV, LHAASO is capable to distinguish leptonic and hadronic sources

AD model: Li Hui & Chen Yang, 2010, 2012

Statistic error ~10% @100TeV, LHAASO is capable to distinguish leptonic and hadronic sources

(1) ARGO J3031+4157;  (2) Superbubble;  (3) Extended source, ~4°;
(4) Candidate hadronic source, total energy ~1.5x10^{50} erg, E_{cut}=150\,\text{TeV}
LHAASO: 100TeV Diffuse Gammas in the Galactic Disk

No data yet in the range around 100TeV
Trace the PeV CRs in the Galaxy and find their ESD
Potential of finding something new
Fermi Bubbles

$10^{37-38}$ erg/s

$E^2 \frac{dN}{dE}$

Fermi-LAT (2014)  
HAWC (2016)  
LHAASO 1 yr

1/4 LHAASO Sensitivity/3yr  
Power Law -2.75  
π0 Decay (Crocke)  
π0 Decay (Knee Cut-Off)  
Fermi-Bubbles(Collaboration, 2014)  
HAWC (2016)
What LHAASO Can Do at G.C.?

LHAASO is not at the right latitude. However, a observation at 100 TeV could be very crucial for the radiation mechanism and acceleration models.

Y. Guo et al., astro-ph/1604.08301
Expected AGN observation with LHAASO

Y. Zhao et al., International Journal of Modern Physics D, Volume 25, Issue 1, id. 1650006

- 38 detectable with D11 model
- 33 sources with K06 model
- 39 sources with F08
- 34 sources with F10
- 40 sources with G12 model

- 30-40 Blac objects with redshift available in Fermi 2LAC sources will be detectable by LHAASO in TeV;
- ~100 AGNs is expected considering another half of 2LAC BL sources have no measured redshift
GRB with 100GeV photons such as GRB090510

LHAASO: ~500 photons are expected at 100GeV
Cosmic Ray Physics with LHAASO

![Graph showing cosmic ray fluxes at various energies](image)

LHAASO 5years
Electron Spectrum
LHAASO: above 10 TeV

After AMS02 and DAMPE, potential hot spot for DM searching
Summary

• The last generation high altitude EAS experiments at YangBaJing were successful in gamma rays and cosmic rays observation.

• The new generation high altitude EAS experiment LHAASO will improve the gamma rays sensitivity over the old generation by a factor of 100 from TeV-100TeV. Besides, multi-parameters measurement ensures the precision measurement of cosmic rays spectra and anisotropy. Rich physics are expected from LHAASO.
Identification of individual source: \( \gamma \) rays observation

The standard candle Crab: a typical electron source

\[ \gamma^0 \rightarrow \gamma \gamma \]

\(100 \text{TeV}\)

hadroni c:
Brief history of the ASγ experiment

3TeV;115Hz;0.9°;
Tibet II/HD Air Shower Array (1996)
36,300 m²
5,500 m²

EC,BD(1996)

3TeV;1500Hz;0.9°
Tibet III Array (2002)
2002
Milestone of ARGO-YBJ

- 1994-1995: idea of full coverage at YBJ
- 1998: 50m² RPC carpet at YBJ
- 1999-2000: official approval of ARGO-YBJ
- 2001.6: 10000M² RPC hall
- 2006.6: center carpet installed/operated
- 2007-2012: fully operated