on the origin and propagation of cosmic rays
results from IceCube Observatory

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Outline

- galactic cosmic rays and their possible origin
  - reconstructing their history with $\gamma$ rays and neutrinos
    - spectrum and anisotropy (sources & propagation)
cosmic rays spectrum

- cosmic ray all-particle spectrum shows almost a power law behavior

- three main features are “evident”
  - a knee @ $\approx 3 \times 10^{15}$ eV
  - an ankle @ $\approx 3 \times 10^{18} - 10^{19}$ eV
  - a cutoff @ $\approx 10^{20}$ eV
cosmic rays spectrum
direct observations

- energy spectrum has **fine structures**
- **broken** power law or spectral **structures**

CREAM, ATIC, Bess-Polar
TRACER, TIGER

PAMELA, Fermi,
Gamma-400,...

AMS2, Calet,
ISS-CREAM,...
cosmic rays spectrum
indirect observations

- at **high energy** flux too small for direct observations

- ground-based, under-ground / water / ice detection

\[ \approx E^{-2.7} \]
\[ \approx E^{-3.1} \]

- atmosphere & interaction properties
- energy & mass observations tangled
- lower mass resolution
cosmic rays spectrum
fine structures

- precision measurement of **spectral shape** and **anisotropy** of protons, antiprotons, nuclei, electrons, positrons

- **origin** of particles and of energy and **acceleration** mechanisms
  - distribution and type of sources

- **propagation** of high energy particles in the interstellar magnetic field
  - **diffusion** and **turbulence** spectrum of the magnetic field
  - global and local structure of galactic magnetic field
Possible origin of cosmic ray particles

- **mass** composition similar to our interstellar neighborhood
- **nuclear fragmentation** effects in collisions with interstellar medium
- **isotopic composition** \(^{22}\text{Ne}/^{20}\text{Ne}\) provide connections to OB Associations
- **confined** in the Milky way for ~10 Myr \(^{10}\text{Be}/^{9}\text{Be}\) observation
possible origin of cosmic ray energy

- **energy** needed to maintain galactic cosmic ray population

\[ E_{GCR} \approx 10^{41} \text{ erg s}^{-1} = 10^{34} \text{ W} \]

- energy released by **supernovae** that goes into particle acceleration

\[ E_{SN} \approx \frac{10^{44} \text{ J}}{30 \text{ yr}} \times 10\% \approx 10^{34} \text{ W} \]
cosmic ray acceleration in supernova remnants

- **diffusive shock acceleration** in galactic supernova remnants
- rigidity dependence (Peters cycle)
- non-linear effects & B amplification
cosmic rays
propagation effects

- cosmic ray spectrum affected by propagation
- escape faster with energy: diffusion coefficient

\[
\frac{dN_{CR}}{dE} \approx E^{-\gamma_{inj} - \delta} \\
D(E) \propto E^\delta \\
\delta \sim 0.3 - 0.6
\]

- stochastic effects from individual sources
- spectral features & anisotropy

- simple diffusion model not sufficient
- non-diffusive processes within mean free path
cosmic rays
reconstruct their history

\[ p + N \rightarrow p(n) + \pi^+ + \pi^- + \pi^0 \]

\[ \mu^+ + \nu_\mu \]

\[ e^+ + \nu_e + \bar{\nu}_\mu \]

hadronic emission

\[ e^\pm + B \rightarrow e^\pm + \gamma_{\text{synchrotron}} \]

\[ e^\pm + \gamma_{\text{soft}} \rightarrow e^\pm + \gamma_{\text{Inverse Compton}} \]

electromagnetic emission
cosmic rays
reconstruct their history

\[ \gamma \text{ rays} \]

Fermi - LAT
200 MeV - 100 GeV
diffuse gamma ray sky

galactic coordinates

\[ \text{neutrino} \]

IceCube-59+40
probability of >100 GeV neutrino point-like excess from random fluctuations
equatorial coordinates
cosmic rays
reconstruct their history

- cosmic rays interact with interstellar medium producing diffuse gamma rays that trace the galactic matter profile

\[ \pi^0 \text{ decay} \]

\[ \text{IC} \]

\[ \text{brems.} \]

\[ \text{DGE models} \]

\[ \gamma \text{ rays} \]

- diffuse neutrino emission expected to trace pion spacial distribution and (hadronic) gamma ray spectrum
cosmic rays
reconstruct their history

- protons accelerated during Sedov phase of SNR expansion \( O(1000 \text{ yr}) \)

- **young SNR** emit high energy gamma rays and neutrinos in the **expanding shell** (too early to observe cosmic rays)

- **old SNR** have associated gamma ray and neutrino emission in **surrounding molecular clouds** (maybe too late to observe high energy cosmic rays)
cosmic rays
reconstruct their history: γ rays

- evidence of pion decay
- proton acceleration

- for underlying protons
  - $\approx E^{-2.4}$
  - $E_{\text{break}}^{IC\ 443} \approx 240\ GeV$
  - $E_{\text{break}}^{W44} \approx 20\ GeV$

middle age SNR $\sim 10,000 - 20,000\ yr$
cosmic rays
reconstruct their history: γ rays

- gamma rays sample molecular cloud distribution close to cosmic ray sources (i.e. harder spectrum)

\[
d\frac{N}{dE} \approx E^{-2.3}
\]

\[
\approx E^{-2.7}
\]

middle age SNR > 10,000 yr

Friday, June 14, 2013
cosmic rays reconstruct their history: $\gamma$ rays

- **hadronic emission** found in most galactic SNR

- **hard** MeV-TeV $p$ spectra indistinguishable from leptonic emissions

- **soft** $p$ spectra provide hadronic bump over leptonic emission

Mandelartz & Becker Tjus 2013
cosmic rays
reconstruct their history: **neutrinos**

- **not** many sources with >10 TeV gamma rays → what about **neutrinos**?

- PeV cosmic rays associated to ~100 TeV gamma rays (Pev-atrons)

- no typical cosmic ray source: (accidental) **nearby sources**?
The IceCube Collaboration

University of Alberta

Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls

International Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)
IceCube Observatory

Digital Optical Module - DOM with 10” PMT & local DAQ electronics

- Air shower detection @ 2835 m altitude (680 g/cm²)
- Muon detection @ 1450-2450 m depth

IceTop
- 81 Stations
- 324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strips
- 5160 optical sensors

Amanda II Array
- Precursor to IceCube

DeepCore
- 8 strings-spacing optimized for lower
- 480 optical sensors

Eiffel Tower
- 324 m
growing IceCube & event collection

<table>
<thead>
<tr>
<th>Year</th>
<th>μ rate (SMT8)</th>
<th>CR shower rate (STA3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>500 Hz</td>
<td>13 Hz</td>
</tr>
<tr>
<td>2008</td>
<td>1100 Hz</td>
<td>15 Hz</td>
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<tr>
<td>2009</td>
<td>1700 Hz</td>
<td>25 Hz</td>
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<td>2010</td>
<td>2000 Hz</td>
<td>30 Hz</td>
</tr>
<tr>
<td>2011+</td>
<td>2200 Hz</td>
<td>35 Hz</td>
</tr>
</tbody>
</table>
detection principle

$\nu_\mu$ CC-int

$\nu_e, \nu_T$ CC-int & $\nu_i$ NC-int

cascade

Cherenkov light

muon track
event identification

Atmospheric Neutrinos

-~20-50% neutrino efficiency

Extra-terrestrial Neutrinos

- IceCube upper limit
- Waxman-Bahcall bound 1998
- IceCube, DeepCore
- Prompt GRB, Razzaque et al. 2008

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all-sky steady point source searches
IceCube-40+59+79

- **108,317** up-going $\nu$ / **146,018** down-going $\nu$
- in **316** d (IC79), **348** d (IC59), **375** d (IC40)

PRELIMINARY atmospheric neutrinos

HE atmospheric muons

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diffuse source searches
high energy cosmic rays

- **high energy** neutrinos from *unresolved* sources

- neutrinos from sources of cosmic rays expected to have spectrum $\sim E^{-2}$
diffuse source searches
ultra-high energy frontier

- **ultra-high energy** neutrinos GZK cut-off
- 616 d (IC79 + IC86 excluding burn sample)
- events associated to extreme processes (Pev-atrons ? No γ ray counterpart ?)

- livetime: 616 days
- bkg: 0.082 ± 0.004 (stat) \(+0.041-0.057\) (sys)
- significance: 2.8σ (p-value = 2.9×10\(^{-3}\))
neutrino searches

high-energy starting events

- **follow-up search** to improve sensitivity @ PeV

- bright events starting inside IceCube

- 26 new events found from 30 TeV to PeV
neutrino searches
high-energy starting events

- transition from conventional & prompt atmospheric neutrinos to astrophysical neutrinos?

- flavor & angular distribution hints of astrophysical origin?
  - 7 track-line events (1° ang res)
  - 21 track-line events (10°-45° ang res)
  - no γ ray counterpart?

- bkg atm μ: 6 ± 3.4
- bkg atm ν: 4.6 + 1.5 +2.9,-1.9 (π, K + prompt)
- significance of 26+2 events: 4.3σ
IceTop-only all-particle spectrum

- composition is determined using IceCube-IceTop coincident events
- muon/e.m. components sensitive to energy/mass
- mass & spectral structures

- new frontier in precision high energy cosmic ray observations
IceTop-only all-particle spectrum

IT73 reconstructed using H4a composition

H4a model total flux

The method is only sensitive to composition, i.e. relative ratio of elements per energy bin.

General features of the spectrum have little effect on the reconstructed energy
cosmic rays spectrum indirect observations

- all-particle spectrum can be interpreted as a sequence of cosmic ray populations (Peters cycles)

- constrains
  - @ low energy: direct measurements
  - @ high energy: InA observations

- populations?
  - nearby sources, propagation effects? → anisotropy
Cosmic Ray Anisotropy
cosmic ray anisotropy large scale

IceCube

relative intensity equatorial coordinates

NOTE: anisotropy is not a dipole  
**anisotropy is flipped** at high energy

transition of heliospheric influence?  
PD & Lazarian 2013

cosmic ray anisotropy large scale
IceTop

relative intensity | equatorial coordinates

Low Energy | IceTop-59/73/81

360° | 0°

-1.5 -1 -0.5 0 0.5 1 1.5

Relative intensity [×10⁻³]

High Energy | IceTop-59/73/81

360° | 0°

-3 -2 -1 0 1 2 3

Relative intensity [×10⁻³]


NOTE: global topology does not change above ~100 TeV

deficit amplitude increases with energy
cosmic ray anisotropy

large scale

- extend observation above PeV range
- primary mass dependency
- primary spectrum at excess/deficit

IceCube

IceTop

PRELIMINARY

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cosmic ray anisotropy \textit{large scale energy dependency}


- \textbf{ARGO-YBJ} Zhang 31\textsuperscript{st} ICRC Łódź-Poland, 2009
- \textbf{ARGO-YBJ} 32\textsuperscript{nd} ICRC Beijing China, 2011

- \textbf{modulation in amplitude of dipole component}
- \textbf{corresponds to transition in anisotropy topology}

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cosmic ray anisotropy small scale

IceCube

relative intensity raw map

IceCube-59 20 TeV

\[ \chi^2/\text{ndf} = 14743.4 / 14187 \text{ (prob = 0.05\%)} \]

2D dipole + quadrupole fit


high multipole \( \ell \) components remaining

high space gradients in cosmic ray flux

angular power spectrum

residuals
cosmic ray anisotropy

- full sky map at comparable energy
- to better determine low θ spherical harmonic components
- to analyze fine angular structures across the sky
- small scale features likely from nearby processes
- non-diffusive propagation in LISM and/or heliosphere

Tibet-III
Amenomori et al., ICRC 2011

IceCube-59

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

Milagro
Abdo et al., PRL, 101, 221101, 2008

IceCube-59
cosmic ray anisotropy
IceCube 2007-2012

- 1.4 x 10^{11} events from 2007 to 2012
- sensitivity to 5° structures with relative intensity of O(10^{-4})
cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- stochastic effect of nearby & recent sources & temporal correlations
  - Erlykin & Wolfendale, Astropart. 2006
  - Blasi & Amato, 2011
  - Ptuskin+, 2012
  - Pohl & Eichler, 2012
  - Sveshnikova+, 2013

![Dipole amplitude graph](image)

- dipole components of the anisotropy

![Equatorial dipole d_E](image)

- not dipole observations

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cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- propagation effect from a near by source to produce localized excess
cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- propagation effect from turbulent realization of interstellar magnetic field within scattering mean free path

\[
\text{mean free path in ISM}
\]

\[E_{\text{A}}(\text{GeV})
\]

\[l_{\text{mfp}}(\text{pc})
\]

\[
\text{Giacinti \& Sigl, 2012}
\]

\[
\text{Biermann+}, 2012
\]

\[
\text{Paolo Desiati}
\]

FIG. 1. Renormalized CR flux predicted at Earth for a concrete realization of the turbulent magnetic field, after subtracting the dipole and smoothing on 20° radius circles. Primaries with rigidities \(p/Z = 10^{16} \text{eV}\) (left panel) and \(5 \times 10^{16} \text{eV}\) (right panel). See text for the field parameters and boundary conditions on the sphere of radius \(R = 250 \text{pc}\).
cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- diffusion coefficient hardly a single power law, homogeneous and isotropic
  
- would not produce a simple dipole anisotropy
  
- anisotropy of electron/positron propagation
cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- interstellar magnetic field affected by inhomogeneities

- LISMF relatively uniform (∼30°) over spacial scales of order 100-200 pc (inter-arm)

local ISMF shaped by LOOP I expansion sub-shell (with center ∼90 pc away in Scorpius-Centaurus OB Association)

local cloudlets fragments of the shell moving at similar velocities

Redfield & Linsky, 2008
Frisch+, 2011

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cosmic ray anisotropy
probing sources & propagation of cosmic rays?

- heliosphere as $O(100-1000)$ AU magnetic perturbation of local ISMF
- influence on $\leq 10$ TeV protons ($R_L \leq 700$ AU, in 3 $\mu$G)
- cosmic rays $>100$ TeV influenced by interstellar magnetic field
- outer heliosphere electric fields from motion in interstellar medium

PD & Lazarian, 2013

Drury, 2013
cosmic ray anisotropy & scattering
heliospheric influence

LIMF direction compatible with
• Ca II absorption & H I lines, Frisch (1996)
• radio emission from inner heliosheath, Lallement et al. (2005), Opher et al. (2007)
• polarization measurements, Frisch (2010)

Funsten et al. (2009)
Schwadron et al. (2009)
Heerikhuisen et al. (2010)

PD & Lazarian 2013

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

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scattering on heliospheric boundary
toy model

anisotropy re-directed due to pitch angle scattering on magnetic perturbations on the heliospheric boundary by non-diffusive processes
spectral feature associated to anisotropy


Milagro & ARGO-YBJ

harder spectrum in region A

\[ \gamma < 2.7 \text{ at } 4.6 \sigma \text{ level} \]

\[ E_c = 3 - 25 \text{ TeV} \]

similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2
origin of spectral hardening?

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail

- turbulence makes reconnection fast and not affected by ohmic dissipation

Sweet 1959, Parker 1957

Lazarian & Vishniac 1999

Pogorelov+ 2009
origin of spectral hardening?

- magnetic mirror @ single reconnection as site of acceleration (test particle)
- scattering dissipate energy away from tail line of sight

$Lazarian & PD, 2010$
$PD & Lazarian, 2012$

\[ N(E)dE \sim E^{-5/2}dE \]

\[ E_{max} \approx 0.5 \left( \frac{B}{1 \mu G} \right) \left( \frac{L_{zone}}{100 \text{ AU}} \right) \text{TeV} \sim 0.5 - 6 \text{ TeV} \]
summary

do we know anything about cosmic rays?

- cosmic rays (up to the ~knee) are made of interstellar material

- **decoding** spectrum and composition to infer their origin and propagation

  - **multi-wavelength** observations (i.e. broad EM spectrum)

    - **multi-messenger** observations (i.e. γ rays and neutrinos)

- unclear where the bulk of cosmic rays come from: perhaps nearby old sources?

- **propagation effects** important to understand spectral features and anisotropy

- **heliospheric structure** to describe TeV anisotropy and spectral structures @ TeV
thanks for your attention

SEPTEMBER 26-28, 2013
Union South — 1308 W Dayton St — Madison, WI

Scientific Program
The goal of the workshop is to bring together different scientific communities to discuss the origin of the anisotropy of cosmic rays and their spectral anomalies in a variety of energy ranges. We invite experts in the detection of cosmic rays on the ground, with balloons, or in space and from a variety of fields — cosmic ray physics, astrophysics, plasma physics, heliospheric physics, interstellar medium, and particle interactions in magnetic fields. Participants will explore scenarios on the origin of cosmic rays and their acceleration and transport in the interstellar medium and in the heliosphere.

Topics
- Cosmic ray anisotropy
- Cosmic ray spectrum and composition
- Cosmic ray origin, acceleration and propagation
- Interstellar medium and interstellar magnetic field
- Isotopic composition of cosmic rays
- Heliosphere and its boundary region with the interstellar medium

Organizing Committees
Scientific Committee:
- Pasquale Blasi
- Priscilla Frisch
- Nikolai Pogorelov
- Eun-Suk Seo
- Gus Sinnis

Local Committee:
- Markus Ahlers
- Segev BenZvi
- Paolo Desiati
- Francis Halzen
- Albrecht Karle
- Kim Kreiger
- Marcos Santander
- Stefan Westerhoff

http://wipac.wisc.edu/CRA2013
spare slides
cosmic ray acceleration in supernova remnants

Hillas-plot
(candidate sites for $E=100$ EeV and $E=1$ ZeV)

- Neutron star
- GRB
- Protons (100 EeV)
- Protons (1 ZeV)
- White dwarf
- Active galaxies
- Colliding galaxies
- SNR
- Galactic disk halo
- Clusters

$E_{\text{max}}$ ZBL $^\dagger$ (Fermi)
$E_{\text{max}}$ ZBL $G$ (Ultra-relativistic shocks-GRB)
detection of high energy cosmic ray

- indirect measurements $> 10^{14}$ eV
- model-dependent measurement spectrum for individual mass components
propagation depth of protons and gamma rays
cosmic rays
reconstruct their history: γ rays

- indirect proton acceleration evidence from multi-wavelength observations

- hadronic acceleration models to explain the broad band observations

- complementary result for IC 443 (Tavani+, 2010)

middle age SNR ~ 10,000 - 20,000 yr
event identification

<table>
<thead>
<tr>
<th>Strings</th>
<th>Year</th>
<th>$\mu$ rate</th>
<th>final $\nu_\mu$ rate</th>
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<tbody>
<tr>
<td>IC22</td>
<td>2007</td>
<td>500 Hz</td>
<td>18 / day</td>
</tr>
<tr>
<td>IC40</td>
<td>2008</td>
<td>1100 Hz</td>
<td>40 / day</td>
</tr>
<tr>
<td>IC59</td>
<td>2009</td>
<td>1700 Hz</td>
<td>130 / day</td>
</tr>
<tr>
<td>IC79</td>
<td>2010</td>
<td>2000 Hz</td>
<td>~170 / day</td>
</tr>
<tr>
<td>IC86</td>
<td>2011</td>
<td>2100 Hz</td>
<td>~200 / day</td>
</tr>
</tbody>
</table>

atmospheric neutrinos

extra-terrestrial neutrinos
all-sky steady point sources

energy distribution for $E^{-2} \nu_\mu$ spectrum

- up-ward $\nu$-dominated
- down-ward $\mu$-dominated
- atm $\nu$ rejected by HE selection

angular resolution / degrees

log10 (neutrino energy / GeV)

zenith angle / degrees

0° 30° 60° 90° 120° 150° 180°

vertical down-ward

vertical up-ward

horizon
all-sky steady point sources

43,339 up-ward + 64,230 downward in 375 days (IC40) + 348 days (IC59)

all-sky steady point sources

43,339 up-ward + 64,230 downward in 375 days (IC40) + 348 days (IC59)

all-sky steady point sources

43,339 up-ward + 64,230 downward in 375 days (IC40) + 348 days (IC59)

highest upper fluctuation

\(-\log_{10}(p\text{-value}) = 4.65\)

\(N_s = 18.3\)

\(\gamma = 3.9\)

post-trial chance probability \(\sim 67\%\)

90% CL sensitivity for $E^{-2}$ steady point sources

discovery potential ($5\sigma$, 50% of trials) is about $\times 3$
other point source searches

- time varying sources
  - untriggered all-sky time scan
  - time scan for candidate variable sources from Fermi-LAT Bright Source List
  - triggered search based on flaring sources observed by Fermi (alerts from Public Release), H.E.S.S., MAGIC and VERITAS
  - periodic sources from catalogue of GeV-TeV binary systems

number of events needed for $5\sigma$ (50%) all-sky discovery potential at different flare scales

IC22+IC40


Discovery potential for 4 years of IceCube

**Preliminary**

Given $E^{-2}$ flux, find normalization for 5σ result

$E^2 \frac{dN}{dE} \text{[TeV cm}^{-2} \text{s}^{-1}]$

- IC86+79+59+40 Sensitivity
- IC79+59+40 Discovery Potential
- IC79+59+40 Sensitivity
- IC86+79+59+40 Discovery Potential

Normalization of MGRO J1908+06 model from Halzen et. al. ’08 (arxiv 0803.0314)

Discovery potential improves because of:
- More livetime
- Better angular resolution
- Bigger effective area
  - detector size, event selection
- Improved understanding of systematics
neutrinos from Gamma Ray Bursts

• search for stacked neutrinos in coincidence with observed γ ray from GRB in the northern hemisphere

• per-burst neutrino spectra calculated from γ ray spectra based on prescription by Guetta et al. Astrop. Phys. 20, 429 (2004)

Nature, 484, 351 (2012)

90% CL upper limit
8 evt expected
0 evt observed

assuming GRB as sources of UHE cosmic rays

e.g. Ahlers et al., Astrop. Phys. 35-2, 87 (2011)

Hümmer et al. arXiv:1112.1076
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neutrinos from diffuse sources

- search for neutrinos from unresolved sources in the Universe (e.g. AGN)
cosmogenic neutrinos

- cosmogenic neutrinos from photo-hadronic interactions of UHECR protons with the CMB
- constrain through the $e^-$, $e^+$ and $\gamma$-rays cascading on the CMB and intergalactic magnetic fields to lower energies and generating a $\gamma$-ray background in the GeV-TeV region
diffuse source searches
ultra-high energy frontier

- **ultra-high energy** neutrinos GZK cut-off

- 616 d (IC79 + IC86 excluding burn sample)

- events associated to extreme processes
  (Pev-atrons? No γ ray counterpart?)

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diffuse source searches
ultra-high energy frontier

〜500 m 〜1600 ft

unknown origin !

"Bert"

August 8, 2011
1.04 ± 0.16 PeV

"Ernie"

January 3, 2012
1.14 ± 0.17 PeV

‣ livetime: 616 days
‣ bkg: 0.082 ± 0.004 (stat) +0.041 -0.057 (sys)
‣ significance: 2.8σ (p-value = 2.9×10^{-3})
neutrino searches
high-energy starting events

- **follow-up search** to improve sensitivity @ PeV

- bright events starting inside IceCube

- 26 new events found from 30 TeV to PeV
neutrino searches
high-energy starting events

- **follow-up search** to improve sensitivity at PeV
- bright events starting inside IceCube
- 26 new events found from 30 TeV to PeV

- bkg atm $\mu$: $6 \pm 3.4$
- bkg atm $\nu$: $4.6 + 1.5^{+2.9}_{-1.9}$ ($\pi$, $K$ + prompt)
- significance of 26+2 events: $4.3\sigma$
neutrino searches
high-energy starting events

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neutrino searches
high-energy starting events

- follow-up search to improve sensitivity @ PeV
- bright events starting inside IceCube
- 26 new events found from 30 TeV to PeV

- 7 track-like events
  - 1° angular resolution
  - partial energy observed
- 21 cascade-like events
  - 10° - 45° angular resolution
  - 15% visible energy resolution
neutrino searches
high-energy starting events

- angular distribution not incompatible with atmospheric muon + neutrino background
neutrino searches
high-energy starting events

* All p-values are post-trial

ICECUBE PRELIMINARY

Most likely event direction
x track-like events
+ shower-like events

shower events
p-value = 8%

all events
p-value = 80%

NO EVIDENCE OF CLUSTERING
neutrino searches

high-energy starting events

- all-flavor search

- different sensitivity to different flavors
## Growing Observatory

<table>
<thead>
<tr>
<th>Season</th>
<th>No. Strings</th>
<th>No. Stations</th>
<th>Array Configuration</th>
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</tr>
<tr>
<td>2009-2010</td>
<td>79 strings</td>
<td>73 stations</td>
<td>IT73/IC79</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>2010-2011</td>
<td>86 strings</td>
<td>81 stations</td>
<td>IT81/IC86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IceTop shower reconstruction

\[ \Delta t(R) = aR^2 + b \left( \exp \left( -\frac{R^2}{2\sigma_i^2} \right) - 1 \right) \]

arrival times

\[ S(R) = S_{125} \left( \frac{R}{125m} \right)^\beta \kappa \log(R/125m) \]

\[ S_{125} = 216.75 \pm 11.14 \]
\[ \beta = 3.17 \pm 0.06 \]

\[ \kappa = 0.303 \text{ fixed} \]
IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011

\[ \cos \theta \geq 0.8 \]

IT73 data (preliminary)

- All
- 3, 4 stations
- 5, 6, 7 stations
- \( \geq 8 \) stations

\[ (\Delta \log_{10} S_{125} = 0.05) \]

events per bin per year

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IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011

Preliminary

Entries $3.731821 \pm 0.07$

$\sim 10$ PeV proton

$\sim 260$ PeV proton

5+ stations
$\cos \theta \geq 0.8$

2077 events/yr per bin

26 events/yr per bin
IceTop-only all-particle spectrum

effect of snow accumulation

\[ S_{corr} = S_0 e^{-\frac{z \cos \theta}{\lambda}} \]

IceTop-73
326 days livetime
Jun 2010 - May 2011
IceTop-only all-particle spectrum
estimating primary energy

the relationship between $S_{125}$ and primary energy depends on mass and zenith angle

$\Delta \log_{10}(S_{125}) = 0.05$

$\d N/\d E \sim E^{2.7}$

Proton, $\cos \theta >= 0.95$

$\log_{10}(S_{125}/VEM) = 0.05$

IceTop-73
326 days livetime
Jun 2010 - May 2011
IceTop-only all-particle spectrum resolutions

\[
\frac{dN}{d\ln(E)} = \frac{N_{\text{events}}}{\epsilon A \Delta \Omega T \ln(E_{i+1}/E_i)}
\]

inferred all-particle spectrum depends on assumed composition

pure proton assumed

\[ A_{\text{eff}} = \epsilon \times 0.52 \text{ km}^2 \]

pure iron assumed
IceTop-only all-particle spectrum

\[
\frac{dN}{d \ln(E)} = \frac{N_{\text{events}} / \text{bin}}{\epsilon A \Delta \Omega T \ln(E_{i+1}/E_i)}
\]

mixed composition assumed

5 nuclear components

3 populations

- galactic (e.g. SNR) - CREAM
- galactic II - Hillas
- extragalactic (p or mixed)

Gaisser, Astropart. Phys. 35 (2012) 801
IceTop-only all-particle spectrum

\[ E^{2.7} \times J(E) \text{ [GeV}^{1.7} \text{ m}^2 \text{ sr}^{-1} \text{s}^{-1}] \]

Primary Energy [GeV]

\[ 10^6 \quad 10^7 \quad 10^8 \]

Preliminary


IceTop/IceCube spectrum & composition

pure iron

pure proton

muon bundle size

electromagnetic size

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IceTop/IceCube spectrum & composition

IT-40/IC-40

mass-independent primary energy resolution of 0.05 in logE
simultaneous EM and hadronic component measurement
for spectrum/mass unfolding

experimental systematic uncertainties important

› study extended to IC59/IC59 & IT73/IC79
cosmic rays spectrum
indirect observations

KASCADE-Grande
Apel et al 2013 - arXiv:1304.7114

light component
heavy component

Proton_total
He_total
C_total
O_total
Fe_total
Z=53 group
Z=80 group

Pamela Proton
CreamII Proton
CreamII He
CreamII C
CreamII O
CreamII Mg
CreamII Si
CreamII Fe

cosmic ray anisotropy observations
the legacy

Nagashima et al. (1998)
Hall et al. (1999)

equatorial coordinates

ABBASI ET AL. (2010)

Milagro
Abdo et al. (2009)

ARGO-YBJ
Zhang et al. (2009)

Tibet ASy
Amenomori et al. (2006)

Super Kamiokande
Guillian et al. (2007)

< 1 TeV
4 TeV
10 TeV
4 TeV
20 TeV
5 TeV

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cosmic ray anisotropy \textit{large scale} 

energy dependency

<table>
<thead>
<tr>
<th>Gyro-radius (pc)</th>
<th>Gyro-radius (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \times 10^{-5}$</td>
<td>7</td>
</tr>
<tr>
<td>$3 \times 10^{-4}$</td>
<td>70</td>
</tr>
<tr>
<td>$3 \times 10^{-3}$</td>
<td>700</td>
</tr>
<tr>
<td>$3 \times 10^{-2}$</td>
<td>7,000</td>
</tr>
<tr>
<td>0.3</td>
<td>70,000</td>
</tr>
</tbody>
</table>

a known anisotropy
Earth's motion around the Sun

\[ \frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta \]

\[ \gamma = 2.67 \pm 0.19 \]

\[ v = 29.8 \pm 0.5 \text{ km/s} \]


Compton & Getting, Phys. Rev. 47, 817 (1935)

point spread function
a known anisotropy
Earth's motion around the Sun

- the observation of the **solar dipole** supports the observation of the sidereal anisotropy in cosmic ray arrival direction

- **NO Compton-Getting Effect** signature from galactic rotation observed


origin of large scale anisotropy: Compton-Getting Effect?

- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is unknown
- at most one dipole component of the observation

\[
\frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta
\]
**cosmic ray anisotropy**

**Large scale**

**IceCube & IceTop**

**NOTE**: different energy response distribution

IceTop with *sharper* low energy threshold

might explain IC/IT amplitude differences
cosmic ray anisotropy
large scale

IceCube

20 TeV

400 TeV

1 PeV

10 PeV

PRELIMINARY

PRELIMINARY

IceCube

IceTop
cosmic ray anisotropy
IceCube 2007-2012

- 1.4 × 10^{11} events from 2007 to 2012
- sensitivity to 5° structures with relative intensity of O(10^{-4})
cosmic ray anisotropy

- Tibet-III
  - 5 TeV
  - Amenomori et al., ICRC 2011
- IceCube-59
  - 20 TeV

- HAWC
  - ~1 TeV

- IceCube-59
  - 20 TeV

- Lazarian & PD 2010
  - PD & Lazarian 2012, 2013

- full sky map at comparable energy
- to better determine low \( \ell \) spherical harmonic components
- to analyze fine angular structures across the sky
- small scale features likely from nearby processes
- non-diffusive propagation in LISM and/or heliosphere

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AMANDA and IceCube yearly data show long time-scale stability of global anisotropy within statistical uncertainties.

- no apparent effect correlated to solar cycles
cosmic ray anisotropy

AMANDA-IceCube 2000-2011

20 TeV
scattering on heliospheric boundary
toy model

• @ energy scale of 10 TeV - proton resonant scattering with perturbations at largest scale - scrambling of cosmic ray arrival directions

• < 10 TeV - resonant scattering with smaller scale perturbations - and adiabatic pitch angle variations from $p^2 \perp /B$

• > 10 TeV - non-resonant scattering with smaller scales - amplitude decreases, intensity gradient become smoother

• > 100 TeV - $r_L >$ heliosphere - heliospheric influence dissipates

› CR mass composition - smearing of transition scale

› re-directed anisotropy not a dipole