Nature’s accelerators have delivered the highest energy protons, photons and neutrinos. Closing in on the cosmic ray accelerators? New tests of three-flavor neutrino framework. Probing new physics: sterile neutrinos, Lorentz invariance, quantum structure of space-time...
“The only thing that requires more optimism than doing particle astrophysics is to try to summarize it in 30 minutes”

J.J. Gomez-Cadenas
Nature’s accelerators?

- protons $10^8\,\text{TeV}$
- photons $10^2\,\text{TeV}$
- neutrinos $10^4\,\text{TeV}$
cosmic ray accelerators: where, how?

gravitational energy from collapsing star converted into particle acceleration

LHC filling the orbit of Mercury
cosmic ray accelerators: where, how?
gravitational energy from collapsing star converted into particle acceleration
supernova remnants

Chandra Cassiopeia A

gamma ray bursts
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353
active galaxy

particle flows near supermassive black hole
Neutrino Beams: Heaven & Earth

The accelerator is powered by large gravitational energy.

- Black hole
- Neutron star
- Radiation and dust

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray} + \text{neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray} + \text{gamma} \]
above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient 1 km$^3$ detector

100 TeV
IceCube

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

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

IceTop
81 Stations
324 optical sensors

5160 PMs in 1 km$^3$
muon track: color is time; number of photons is energy
GZK neutrino search: two neutrinos with > 1,000 TeV

date: August 9, 2011
energy: 1.04 PeV
topology: shower
nickname: Bert
tracks and showers

PeV $\nu_e$ and $\nu_\tau$ showers:
- 10 m long
- volume $\sim 5$ m$^3$
- isotropic after 25~50m
High Energy Starting Events

- select events interacting inside the detector only
- no light in the veto region
- veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- energy measurement: total absorption calorimetry
Charge Threshold

- Bkg. Atmospheric Muon Flux (Tagged Data)
- Bkg. Atmospheric Neutrinos (π/K)
- Bkg. Uncertainties (All Atm. Neutrinos)
- Atmospheric Neutrinos (90% CL Charm Limit)
- Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
- Bkg.+Signal Best-Fit Astrophysical (fixed slope $E^{-2}$)
- All Events (Trigger Level)
- Data

IceCube Preliminary

Events per 1347 Days

Total Collected PMT Charge (Photoelectrons)
above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

\[ \frac{dN}{dE} \sim E^2 \]

10—100 events per year for fully efficient 1 km³ detector
- lattice of photomultipliers
- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

muon

interaction

neutrino
cosmic neutrinos in 2 years of data at 3.7 sigma
muon neutrinos through the Earth → 6 sigma

Assuming best-fit power law:

+++ Unfolding

Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$

Astrophysical $\nu_\mu + \bar{\nu}_\mu$

IceCube Preliminary

neutrino energy pdf
(highest-energy event)
for 5.5 years of data: $3.7 \rightarrow 6.0$ sigma and $E^{-2}$ above 200 TeV!

- **Best-fit astrophysical normalization:**
  \[(0.78^{+0.29}_{-0.25}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\]

- **Best-fit spectral index:**
  \[\gamma_{\text{astro}} = 2.06 \pm 0.13\]

- **Energy ranges:**
  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0\(\sigma\)
date: June 11, 2014
most probable energy: 9 PeV
topology: track
confirmation!

flux of muon neutrinos through the Earth

eutrinos of all flavors interacting inside IceCube

4 year
7 sigma
Particle Physics
Beyond Laboratory Energies

Francis Halzen
Wisconsin IceCube Particle Astrophysics Center

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where do they come from?
correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg
• we observe a diffuse flux of neutrinos from extragalactic sources

• a subdominant Galactic component cannot be excluded

• where are the PeV gamma rays that accompany PeV neutrinos?
Neutrino Beams: Heaven & Earth

**accelerator** is powered by large gravitational energy

**black hole**

**neutron star**

- Radiation and dust

\[ p + \gamma \rightarrow n + \pi^+ \]

\[ \sim \text{cosmic ray} + \text{neutrino} \]

\[ \rightarrow p + \pi^0 \]

\[ \sim \text{cosmic ray} + \text{gamma} \]
hadronic gamma rays?

\[ \pi^+ = \pi^- = \pi^0 \]
electromagnetic cascades in CMB

hadronic gamma rays
$E^2 \phi_{\nu+\nu} \quad [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$E^{-2.15}$

Fermi gammas

cosmic neutrinos

$p p$ scenario

SFR evolution

IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)

IceCube combined (2015)

Fermi IGRB (2014)
energy in the Universe in gamma rays, neutrinos and cosmic rays
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)
- at some level common Fermi-IceCube sources?
blazars

particle flows near supermassive black hole
• there is more
towards lower energies: a second component?

warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth
1.01 \times \text{atmospheric } \pi/K \nu 
+ 1.47 \times \text{penetrating } \mu 
+ 2.24 \left( \frac{E}{100 \ \text{TeV}} \right)^{-2.49} 
\times 10^{-18} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} 

Southern sky  
\(-1.0 < \sin \delta \leq -0.2\) 

Northern sky  
\(-0.2 < \sin \delta \leq 1.0\) 

Events in 641 days 

Deposited energy [GeV]
yet lower energies....
expect surprises: produced by Galactic dark matter halo?

decay of PeV-mass dark matter particle
Particle Physics  
Beyond Laboratory Energies  

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oscillate over cosmic distances to 1:1:1
- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. $\mu$ background
- large samples of track-like and cascade-like events

assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ at Earth $\rightarrow$

unbroken power-law between 25 TeV and 2.8 PeV
spectral index $-2.5 \pm 0.09$ (-2 disfavored at 3.8 $\sigma$)
flux at 100 TeV $(6.7 \pm 1.2) \times 10^{-18}$ (GeV $\cdot$ cm$^2$ $\cdot$ s $\cdot$ sr)$^{-1}$

the best fit flavor composition disfavors 1:0:0 at source at 3.6 $\sigma$
Glashow resonance dictates $\nu_e - \nu_\tau$ mixture events per year:

\[
\begin{array}{cccc}
\Phi_{\nu_e} & \text{interaction} & \text{pp source} \\
[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}] & \text{type} & \text{IC-86} & \text{240m} & \text{360m} \\
1.0 \times 10^{-18} (E/100 \text{ TeV})^{-2.0} & \text{GR} & 0.88 & 7.2 & 16 \\
1.5 \times 10^{-18} (E/100 \text{ TeV})^{-2.3} & \text{DIS} & 0.09 & 0.8 & 1.6 \\
2.4 \times 10^{-18} (E/100 \text{ TeV})^{-2.7} & \text{GR} & 0.38 & 3.1 & 6.8 \\
& \text{DIS} & 0.04 & 0.3 & 0.7 \\
\end{array}
\]

\[\quad e + e \rightarrow W\]
one half million atmospheric neutrinos...
**Average energies**

- FC: ~1 GeV
- PC: ~10 GeV
- UpMu: ~100 GeV

**IceCube**

6 GeV < $E_{\text{reco}}$ < 56 GeV

**SuperK**

~ 1 GeV
electron neutrino oscillates into sterile $\rightarrow$ modifies matter effect of the atmospheric neutrino beam observed through the Earth

happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(\text{TeV})$$

$\Delta m_{41}^2 = 1.0\text{eV}^2$

$\sin(2\theta_{24})^2 = 0.01$

solid : $\bar{\nu}$

dashed : $\nu$

---

eV sterile neutrino $\rightarrow$ Earth MSW resonance for 3 TeV neutrinos
no telltale structure in the zenith angle distribution
Particle Physics
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conclusions
progress through instrumentation

- larger (TA) and improved (Auger) air shower arrays
- CTA giant ground based photon array
- more (KM3NeT, GVD, ORCA) and next generation (IceCube-Gen2, PINGU) neutrino detectors
- gravitational waves!
quantized space: matter where the geometry is activated

$$\lambda \sim \frac{1}{E} \rightarrow 10^{-33} \text{cm}$$
Lorentz violation from Planck scale

- speed of photons and neutrinos depends on their energy, like photons in a crystal
- Planck scale vacuum fluctuations probed by high energy particles

\[ E^2 = p^2 + m^2 \pm E^2 \left( \frac{E}{M_{\text{QG}}} \right)^n \pm \ldots \]

- modification to dispersion relation leads to an energy dependent speed of light: Lorentz invariance violation
Fermi GRB 090510

\[ M_{QG} \geq M_{Planck} \]
• the existence of PeV neutrino events yields dramatic limits on any possible Lorentz invariance violation: superluminal particles lose their energy to Cherenkov radiation, even in vacuum

\[ \nu \rightarrow \nu e^+ e^- \]

• sensitivity \( \delta \) increases dramatically with distance \( d \) and observed energy \( E \)

\[ \delta = \frac{v^2 - c^2}{c^2} = a d^{-\frac{1}{3}} E^{-\frac{5}{3}} \]
conclusions
progress through instrumentation

• larger (TA) and improved (Auger) air shower arrays
• CTA giant ground based photon array
• more (KM3NeT, GVD, ORCA) and next generation (IceCube-Gen2, PINGU) neutrino detectors
• gravitational waves!
- energy
  1,041 TeV
  1,141 TeV
  (15% resolution)

- not atmospheric: probability of no accompanying muon is $10^{-3}$ per event

→ flux at present level of diffuse limit
limits on $\delta$ (relative velocity between flavors only)

test of: equivalence principle, quantum gravity and Lorentz invariance

spacetime is smooth at energies near and slightly above the Planck mass.

“general relativity will not last tao hundred years”
M. Turner

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