Particle Physics
Beyond Laboratory Energies

Francis Halzen
Wisconsin IceCube Particle Astrophysics Center

- 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…
Nature’s accelerators?

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

gravitational energy from collapsing star converted into particle acceleration

LHC filling the orbit of Mercury
supernova remnants

Chandra Cassiopeia A

gamma ray bursts
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353
\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- ... but difficult to detect
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
Atmospheric neutrinos

(... and muons!)

Not only $\pi$, also K, D,...
architecture of independent DOMs

10 inch pmt

LED flasher board

main board

HV board
... each Digital Optical Module independently collects light signals like this, digitizes them, time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events...
muon track: color is time; number of photons is energy
events detected per year:

- atmospheric*  $\mu \sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu \sim 10^5$
- cosmic $\nu \rightarrow \mu < 10^2$

* 3000 per second  
** 1 every 6 minutes
GZK neutrino search: two neutrinos with $> 1,000$ TeV
tracks and showers

PeV $\nu_e$ and $\nu_\tau$ showers:
- 10 m long
- volume $\sim 5 \text{ m}^3$
- isotropic after 25~50m
size = energy

color = time = direction
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
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
• 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

- lattice of photomultipliers

muon

interaction

neutrino
cosmic neutrinos in 2 years of data at 3.7 sigma
muon neutrinos through the Earth $\rightarrow$ 5.6 sigma
for 5.5 years of data: 3.7 → 5.6 sigma and $E^{-2}$ above 200 TeV!

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

- **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
neutrinos of all flavors interacting inside IceCube

confirmation!
flux of muon neutrinos through the Earth

4 year 7 sigma

neutrinos of all flavors interacting inside IceCube
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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

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
hadronic gamma rays?

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

hadronic gamma rays
active galaxy

particle flows near supermassive black hole
blazars

particle flows near supermassive black hole
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?
• there is more
Fermi gammas

E^{-2.15}

pp scenario

SFR evolution

cosmic neutrinos
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
$1.01 \times \text{atmospheric } \pi/K \nu$

$+ 1.47 \times \text{penetrating } \mu$

$+ 2.24 \left( \frac{E}{100 \text{ TeV}} \right)^{-2.49}$

$\times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$

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Southern sky

$-1.0 < \sin \delta \leq -0.2$

Northern sky

$-0.2 < \sin \delta \leq 1.0$
yet lower energies….
not forward charm production

analogous to \( pp \rightarrow (K^+ \Lambda)p \)

upcoming events:
“extreme” charm model can fit the northern, not the southern hemisphere
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oscillate over cosmic distances to $1:1:1$
one half million atmospheric neutrinos...
SuperK

~ 1 GeV

Average energies
- FC: ~1 GeV, PC: ~10 GeV, UpMu: ~ 100 GeV

IceCube

6 GeV < E_{reco} < 56 GeV
electron neutrino oscillates into sterile → modifies matter effect of the atmospheric neutrino beam observed through the Earth happens when

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

\[\Delta m^2_{41} = 1.0 \text{eV}^2\]
\[\sin(2\theta_{24})^2 = 0.01\]
solid : \(\bar{\nu}\)
dashed : \(\nu\)

\(E_\nu [\text{GeV}]\) vs Oscillation Probability

eV sterile neutrino → Earth MSW resonance for 3 TeV neutrinos
no telltale structure in the zenith angle distribution
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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!
• a next-generation IceCube with a volume of 10 km$^3$ and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

• need 1,000 events versus 100 now in a few years

• discovery instrument $\rightarrow$ astronomical telescope
absorption length of Cherenkov light

most transparent medium in nature, and in the lab
measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

Spacing 1 (120m):
IceCube (1 km$^3$)  
+ 98 strings (1.3 km$^3$)  
= 2.3 km$^3$

Spacing 2 (240m):
IceCube (1 km$^3$)  
+ 99 strings (5.3 km$^3$)  
= 6.3 km$^3$

Spacing 3 (360m):
IceCube (1 km$^3$)  
+ 95 strings (11.6 km$^3$)  
= 12.6 km$^3$
PINGU infill
40 strings
GeV threshold

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 10
same budget as IceCube
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

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

- 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 \( E \)

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

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- 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
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

limits on $\delta$ (relative velocity between flavors only)

hep-ph/0502223