IceCube

francis halzen

• why would you want to build a kilometer scale neutrino detector?

• IceCube: a cubic kilometer detector

• the discovery (and confirmation) of cosmic neutrinos

• from discovery to astronomy
neutrino as a cosmic messenger:

• electrically neutral
• essentially massless
• essentially unabsorbed
• tracks nuclear processes
• ... but difficult to detect
1960 extragalactic cosmic rays

1969

energy (eV) →

log[Flux → cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

flux

-20 -16 -12 -8 -4 0 4 8 12 16 20

log($\lambda$/cm)

1969

e + p → n$^+$

GZK neutrino

extragalactic cosmic rays

Radio

CMB

Visible

GeV γ-rays
cosmic rays interact with the microwave background

\[ p + \gamma \rightarrow n + \pi^+ \text{ and } p + \pi^0 \]

cosmic rays disappear, neutrinos with EeV \((10^6 \text{ TeV})\) energy appear

\[ \pi \rightarrow \mu + \nu_{\mu} \rightarrow \{ e + \nu_{\mu} + \nu_e \} + \nu_{\mu} \]

1 event per cubic kilometer per year...but it points at its source!
IceCube
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• cosmogenic neutrinos
• the energetics of cosmic ray sources
• neutrinos associated with cosmic rays
• a cubic kilometer detector
• evidence for extraterrestrial neutrinos
• conclusions

IceCube.wisc.edu
the sun constructs an accelerator
• accelerator must contain the particles

\[ R_{\text{gyro}} \left( = \frac{E}{vqB} \right) \leq R \]

\[ E \leq viqBR \]

challenges of cosmic ray astrophysics:

• dimensional analysis, difficult to satisfy
• accelerator luminosity is high as well
the sun constructs an accelerator

coronal mass ejection →
10 GeV protons
supernova remnants

Chandra Cassiopeia A

gamma ray bursts
fireball calculations challenged
Nature 484 (2012) 351-353
active galaxy

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

accelerator is powered by large gravitational energy

black hole neutron star

radiation and dust

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
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
atmospheric neutrinos (… and muons!)

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

\[ \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
IceCube: the discovery of cosmic neutrinos
francis halzen

• cosmic ray accelerators
• IceCube: a discovery instrument
• the discovery of cosmic neutrinos
• where do they come from?
• beyond IceCube
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.
• 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
ultra-transparent ice below 1.5 km
IceCube

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

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

5160 PMs in 1 km³
photomultiplier tube -10 inch
architecture of independent DOMs

LED flasher board

main board

10 inch PMT

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...
nozzle delivers:
  • 200 gallons per minute
  • 7 Mpa
  • 90 degree C

4.8 megawatt heating plant →
muon track: time is color; number of photons is energy
93 TeV muon: light ~ energy
energy measurement ( > 1 TeV )

convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, ...)

1.1 km

improving angular and energy resolution
Signals and Backgrounds

...K, charm

cosmic ray

atmospheric neutrino

atmospheric muon

astrophysical neutrino

cosmic ray
... you looked at 10msec of data!

muons detected per year:

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

* 3000 per second  ** 1 every 6 minutes
89 TeV

radius ~ number of photons

time ~ red → purple
cosmic neutrinos in 2 years of data at 3.7 sigma
above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

atmospheric

100 TeV

cosmic
highest energy muon energy observed: 560 TeV
$\rightarrow$ PeV $\nu_\mu$
3 years: $4.3 \sigma$ and more PeV $\nu_\mu$

Reco. muon energy: 950 TeV
Reco. zenith: 90°
Date: Oct. 28 2010
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\[ \rightarrow + \rightarrow \left\{ e^+ + e^{-} \right\} + \]

1 event per cubic kilometer per year

...but it points at its source!
GZK neutrino search: two neutrinos with > 1,000 TeV
tracks and showers

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

cascade

Cherenkov light
size = energy

color = time = direction
reconstruction limited by computing, not ice!

Blue: best-fit direction, red: reversed direction
• 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
- 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
...and then there were 26 more...

data: 86 strings one year
...and then there were 26 more...

data: 86 strings one year
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration

Introduction: Neutrino observations are a unique probe of the universe's highest-energy processes. We report the detection of several high-energy neutrino events that have not been seen before.

28 High Energy Events

doubled the data since 2013

2004 TeV event in year 3
total charge collected by PMTs of events with interaction inside the detector
confirmation!
flux of muon neutrinos through the Earth

neutrinos of all flavors interacting inside IceCube

4 year
7 sigma
430 TeV

1 event: ~ 5 sigma discovery

$> \text{PeV } \nu_\mu$
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where do they come from?
2 year HESE
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 →

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 $\sigma$
new physics?

otherwise...

every model ends up in the triangle
• we observe a diffuse extragalactic flux

• a subdominant Galactic component cannot be excluded

• where are the PeV gamma rays that accompany PeV neutrinos?
hadronic gamma rays ?

$\pi^+ = \pi^- = \pi^0$
electromagnetic cascades in CMB

hadronic gamma rays
Fermi gammas

$E - 2.15$

$E^2 J \left[ \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right]$ vs. $E \left[ \text{TeV} \right]$

pp scenario
SFR evolution

cosmic neutrinos

HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
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
• we have observed a flux of 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

• hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

• gamma ray sources predict neutrinos. We are close to identifying point sources.
even for Galactic sources the photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters
even for Galactic sources the photon to neutrino conversion implies that we are close to detecting neutrinos from known high energy gamma ray emitters
• we observe a diffuse extragalactic flux
• active galaxies, most likely blazars, or starburst galaxies?
• correlation to catalogues should confirm this
IceCube: the discovery of cosmic neutrinos
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- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube
• 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 vs 100 now

• discovery instrument → astronomical telescope
most transparent medium in nature, and in the lab

absorption length of Cherenkov light

$\lambda_a (400 \text{ nm}) [\text{ m }] \text{ vs. depth [m]}$

$\leftarrow > 100 \text{ m} \rightarrow$

$\leftarrow 220 \text{ m} \rightarrow$
we are limited by computing, not the optics of the ice
measured optical properties $\rightarrow$ twice the string spacing

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

Spacing 1 (120m):
- IceCube (1 km³)
- + 98 strings (1.3 km³)
- = 2.3 km³

Spacing 2 (240m):
- IceCube (1 km³)
- + 99 strings (5.3 km³)
- = 6.3 km³

Spacing 3 (360m):
- IceCube (1 km³)
- + 95 strings (11.6 km³)
- = 12.6 km³
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
did not talk about:

- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- ….
one half million atmospheric neutrinos...
one half million atmospheric neutrinos…

neutrino oscillations hierarchy

non-standard neutrino interactions

$\delta c/c < 10^{-27}$

earth matter resonance for eV sterile neutrino

DeepCore
In the Earth for sterile neutrino $\Delta m^2 = O(1\text{eV}^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N} \sim O(\text{TeV})$$
oscillations at 20 GeV
SuperK

~ 1 GeV

IceCube

6 GeV < \( E_{\text{reco}} \) < 56 GeV

Average energies
- FC: \( \sim 1 \) GeV, PC: \( \sim 10 \) GeV, UpMu: \( \sim 100 \) GeV
and with PINGU...

(soon using PINGU methods)
Outlook:

- capitalize on discovery
- astronomy guaranteed
- neutrino physics at low cost and short timescale
- neutrinos are never boring!

from discovery to astronomical telescopes:
parallel development in the Mediterranean
ANTARES $\rightarrow$ KM3NeT
Baikal $\rightarrow$ GVD
distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube