IceCube: building a new window on the Universe

francis halzen

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

• IceCube: a cubic kilometer detector

• the discovery (and confirmation) of cosmic neutrinos

• from discovery to astronomy

IceCube.wisc.edu
Cosmic Horizons – Microwave Radiation
380,000 years after the Big Bang

wavelength = 1 mm ↔ energy = $10^{-4}$ eV
Cosmic Horizons – Optical Sky

wavelength = $10^{-6}$ m $\iff$ energy = 1 eV
Cosmic Horizons – Gamma Radiation

wavelength = $10^{-15}$ m $\leftrightarrow$ energy = $10^9$ eV
Cosmic Horizons – Gamma Radiation

energy = $10^{15}$ eV
Multi-Messenger Astronomy

Gravitational waves - ripples in space-time

20% of the Universe is opaque to the EM spectrum

terra incognita: only revealed by neutrinos
Cosmic Rays? Charged – Do not point
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape.
neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
  \[ n \rightarrow p + e + \nu_e \]
- … but difficult to detect
Radio
CMB
Visible
GeV γ-rays

Ressell and Turner 1990

flux of light in the Universe

log[Flux → cm⁻² s⁻¹ sr⁻¹)]

energy (eV) →

LHC

ν
TeV γ - rays

γ - rays

energy (eV)

LHC

PeV ν

cosmic rays

Ressell and Turner 1990

particle flux in the Universe

flux of light in the Universe

log [Flux $\rightarrow$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
TeV
γ
cosmic rays

Radio
CMB
Visible

GeV γ-rays

energy (eV)

LHC
ν

cosmic rays

particle flux in the Universe

Ressell and Turner 1990
extragalactic cosmic rays

$\gamma + p \rightarrow n + \pi^+$

GZK neutrino

1969
cosmic rays interact with the microwave background

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

cosmic rays disappear, neutrinos with EeV (10^6 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!
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the sun constructs an accelerator
- accelerator must contain the particles

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

\[
E \leq v \, qBR
\]

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
flux < 1% of astrophysical neutrino flux observed
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 km³ detector
atmospheric neutrinos (... and muons!)

Atmospheric neutrino source:

- \( \pi^+ \rightarrow \mu^+ + \nu_\mu \)
- \( \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \)
- \( e^+ + \nu_e + \bar{\nu}_\mu \)
- \( e^- + \bar{\nu}_e + \nu_\mu \)
atmospheric neutrino spectrum

< 1 atmospheric neutrino event per cubic kilometer per year
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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
89 TeV

radius $\sim$ number of photons

time $\sim$ red $\rightarrow$ purple
ultra-transparent ice below 1.5 km
photomultiplier tube -10 inch
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
93 TeV muon: # photons ~ energy

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Az: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99
energy measurement (> 1 TeV)

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

improving angular and energy resolution
IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- 0.2-0.4 deg muon track ~ 10 degree shower
- 10% energy resolution

completed December 2010
Signals and Backgrounds

...K, charm

cosmic ray

atmospheric neutrino

astrophysical neutrino

atmospheric muon
… 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
The Daily Breakdown

Monday
April 18
- First magnificent Aurora display!

Tuesday
April 19
- Stress test reveals that the DIMMs of ichub75 are indeed kaputt.

Wednesday
April 20
- Jim Braun successfully deployed I3MS version 1.0.13 to SPS.

Thursday
April 21
- Quiet.

Friday
April 22
- Quiet.

Saturday
April 23
- Quiet.

Sunday
April 24
- Quiet.

TDRSS Satellite Transfer

![Graph showing TDRSS Satellite Transfer](image)
V_\mu

Color indicates the arrival time of photons
red - first  green - later

Each white dot is a DOM

Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4 TeV
radius $\sim$ number of photons

time $\sim$ red $\rightarrow$ purple

89 TeV

Run 113641 Event 33553254 [O ns, 16748 ns]
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
muon neutrinos through the Earth $\rightarrow$ 6 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

Events per bin vs. $\log_{10}(\text{median neutrino energy} / \text{GeV})$
after 7 years: 3.7 $\rightarrow$ 6 sigma

- **Best-fit astrophysical normalization:**
  
  $0.97^{+0.27}_{-0.25} \times 10^{-18}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$

- **Best-fit spectral index:**
  
  $\gamma_{\text{astro}} = 2.16 \pm 0.11$

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

- Atmospheric-only hypothesis excluded by 6.0$\sigma$
astronomy here: through-going muons with resolution 0.2~0.4°
highest energy $\nu_\mu$: astronomy with best resolution!
muon neutrinos through the Earth $\rightarrow$ 5.6 sigma
Assuming best-fit power law:
- Unfolding (stat. error)
- Unfolding (incl. best-fit uncert.)
- Astrophysical $\nu_\mu + \bar{\nu}_\mu$
- Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
- Combined $\nu_\mu + \bar{\nu}_\mu$

May 2009 – May 2015
IceCube Preliminary
highest energy muon energy observed: 560 TeV
\[ \rightarrow \text{PeV } \nu_\mu \]
<table>
<thead>
<tr>
<th>Flux</th>
<th># of Events/year above Muon Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 TeV</td>
</tr>
<tr>
<td>$E^{-2}$</td>
<td>110</td>
</tr>
<tr>
<td>$E^{-2.3}$</td>
<td>220</td>
</tr>
<tr>
<td>$E^{-2.7}$</td>
<td>740</td>
</tr>
<tr>
<td>Atm.</td>
<td>15000</td>
</tr>
</tbody>
</table>
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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!
GZK neutrino search: two neutrinos with $> 1,000$ TeV

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

• 10 m long
• volume ~ 5 m³
• isotropic after 25~ 50m
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
430 TeV inside detector
PeV $\nu_\mu$
no air shower

all cosmic neutrinos are isolated
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration

Introduction:

Doubled the data since 2013

28 High Energy Events

2004 TeV event in year 3
total charge collected by PMTs of events with interaction inside the detector
after 6 years: $3.7 \rightarrow 6.0$ sigma
confirmation!

flux of muon neutrinos through the Earth

neutrinos of all flavors interacting inside IceCube
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

IceCube.wisc.edu
4 year HESE (6 soon)

Where do they come from?
3 year HESE

ICECUBE PRELIMINARY

Galactic

TS=2\log(L/L_0)

11.2917
correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg
oscillate over cosmic distances to 1:1:1
• 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

The accelerator is powered by large gravitational energy.

- **Black Hole Neutron Star**
- **Radiation and dust**

The reaction:

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

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

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

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

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

hadronic gamma rays
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth.

Neutrinos do not interact and image the sky in regions from which even X-rays cannot escape.
\[ E^{-2.15} \]

\[ \pi^+ = \pi^- = \pi^0 \]

Fermi gammas

cosmic neutrinos

pp scenario

SFR evolution
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 photons (and cosmic rays)

at some level common Fermi-IceCube sources? look for spatial and especially temporal coincidences
active galaxy

particle flows near supermassive black hole

high energy photons escape from regions with low density where neutrino production is suppressed. Not identical sources.
Multi-Messenger Astronomy

- Microwave
- Optical
- X-rays
- Gamma-rays
- Neutrinos
- Cosmic rays

Terra incognita: only revealed by neutrinos

Gravitational waves - ripples in space-time

20% of the Universe is opaque to the EM spectrum
energy in the Universe in gamma rays, neutrinos and cosmic rays
A census

- BL Lac class of Blazars dominates the high-energy gamma-ray emission
  - 86% (+16%/-14%) above 50 GeV

- Large uncertainties in radio-galaxy and star-forming galaxy contributions

- Real diffuse contributions must be small
  - UHECR interactions
  - WIMP annihilation
  - etc.

Markus Ackermann
number of muon neutrino events from gamma ray sources in 5 years
• 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
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}
yet lower energies....

IceCube Preliminary
• we observe a diffuse extragalactic flux

• active galaxies, most likely some form of blazars?

• correlation to catalogues should confirm this

• …. but correlation of cosmic neutrinos to < 30% of all Fermi blazars (subset if beaming angle neutrinos < light ?)
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• 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 → astronomical telescope
auto correlation: multiple neutrinos from the same source

The total number of events required to observe \( n \)-events multiplets from the closest sources is

\[
740 \times \left[ \frac{n}{2} \right] \times \left[ \frac{\rho_0}{10^{-5}} \right]^\frac{1}{3} \text{ events}
\]

for a observed diffuse cosmic flux and 0.4 degrees angular resolution.

Examples of local source densities (per Mpc\(^3\)):

- \( 10^{-3} - 10^{-2} \text{ Mpc}^{-3} \) for normal galaxies
- \( 10^{-5} - 10^{-4} \text{ Mpc}^{-3} \) for active galaxies
- \( 10^{-7} \text{ Mpc}^{-3} \) for massive galaxy clusters
- \( > 10^{-5} \text{ Mpc}^{-3} \) for UHE CR sources
absorption length of Cherenkov light

most transparent medium in nature, and in the lab

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

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

$\leftrightarrow 220\text{m} \ \rightarrow$
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 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
120 strings
depth 1.35 to 2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume for the 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
- …
Conclusions

• more to come from IceCube: many analyses have not exploited more than one year of data

• analyses are not in the background-dominated regime

• next-generation detector(s):
  1. discovery → astronomy (also KM3NeT, GVD)
  2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
  3. potential for discovery

• neutrinos are never boring!
one half million atmospheric neutrinos...
oscillations at 20 GeV
In the Earth for sterile neutrino $\Delta m^2 = O(1\text{eV}^2)$ the MSW effect happens when

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

• more to come from IceCube: many analyses have not exploited more than one year of data

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• neutrinos are never boring!
The IceCube–PINGU Collaboration

International Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
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- NSF–Physics Division
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
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- US National Science Foundation (NSF)