icebound

neutrinos

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IceCube Deployment

IceTop
Air shower detector
Threshold ~ 300 TeV

22 strings
1320 digital modules
52 surface detectors

2004-2005: 1 string
First data in 2005
First upgoing muon: July 18, 2005

InIce
planned 80 strings of 60 optical modules each
17 m between modules
125 m string separation

2005-2006: 8 strings
2006-2007: 13 strings deployed

AMANDA
19 strings
677 modules

Completion by 2011
1 km$^3$·yr reached 2 years before detector is complete (2011)

close to 4 km$^3$·yr at the beginning of 2$^{nd}$ year of full array operation
IceCube
accumulated exposure at 100 TeV

[Graph showing accumulated exposure over time with markers for Antares construction and KM3Net TDR.]
IceCube: interdisciplinary science

- cosmic rays: extragalactic cosmic problem
- TeV gamma ray astronomy: galactic cosmic ray problem
- particle physics: from dark matter to the Planck scale
neutrinos associated with cosmic rays
cosmic rays

Nature accelerates particles $10^7$ times the energy of LHC!

where?

how?

Nature accelerates particles $10^7$ times the energy of LHC!
galactic and extragalactic cosmic rays

Knee: 1 event km\(^{-2}\) yr\(^{-1}\)

Ankle: extragalactic cosmic rays

All particle spectrum
JACEE[11] ×
Akera[12] ▲
Tien Shan[13] ±
MSU[14] ×
KASCADE[20] *
CASA-BLANCA[19] *
DICE[17] *
HEGRA[18] *
CasaMia[16] *
Tibet[15] *

Fixed target
HERA
RHIC
TEVATRON
LHC

E \(\frac{dN}{dE}\) (GeV cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\))

\(E^2 \frac{dN}{dE}\) (GeV cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\))
solar flare shock acceleration

coronal mass ejection → 10 GeV particles
Acceleration to $10^{21} \text{ eV}$?

$\sim 10^2 \text{ Joules}$

$\sim 0.01 M_{\text{GUT}}$

dense regions with exceptional gravitational force creating relativistic flows of charged particles, e.g.

- dense cores of exploding stars
- supermassive black holes
- merging galaxies
active galaxy

- supermassive black hole
- accretion disk
- jet
collapse of massive star produces a gamma ray burst

spinning black hole

highest energy particles
galactic and extragalactic cosmic rays

1 event km$^{-2}$ yr$^{-1}$

Knee

Ankle

extragalactic cosmic rays
flux of extra-galactic cosmic rays

ankle $\rightarrow$ one $10^{19}$ eV particle per km squared per year per sr

$$E^2 \frac{dN}{dE} = \frac{10^{19} \text{ eV}}{(10^{10} \text{ cm}^2)(3 \times 10^7 \text{ sec}) \text{ sr}}$$

$$= 3 \times 10^{-11} \text{ TeV cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$
total flux = velocity x density:

\[ 4\pi \int dE (E \frac{dN}{dE}) = c \rho_E \]

\[ \rho_E = \frac{4\pi}{c} \int \frac{3 \times 10^{-11}}{E} dE \frac{TeV}{cm^3} \]

\[ \approx \log \frac{E_{\text{max}}}{E_{\text{min}}} \approx 10^{-19} \frac{TeV}{cm^3} \]
energy in extragalactic cosmic rays:
\[ \sim 3 \times 10^{-19} \text{erg/cm}^3 \text{ or } \sim 10^{44} \text{erg/yr per (Mpc)}^3 \text{ for } 10^{10} \text{ years} \]

- \(3 \times 10^{39} \text{erg/s per galaxy}\)
- \(3 \times 10^{44} \text{erg/s per active galaxy}\)
- \(2 \times 10^{52} \text{erg per gamma ray burst}\)

\rightarrow \text{energy in cosmic rays ~ equal to the energy in light!}

1 TeV = 1.6 erg
NEUTRINO BEAMS: HEAVEN & EARTH

- Accelerator
- Target
- Proton
- Directional beam
- Magnetic fields
- Neutrino beams

Black Hole

Radiation Enveloping Black Hole

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray + neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray + gamma} \]
energy in extra-galactic cosmic rays:

\[ \sim 3 \times 10^{-19} \text{ erg/cm}^3 \text{ or} \]
\[ \sim 10^{44} \text{ erg/yr per (Mpc)}^3 \text{ for } 10^{10} \text{ years} \]

3x10^{39} \text{ erg/s per galaxy}
3x10^{44} \text{ erg/s per active galaxy}
2x10^{52} \text{ erg per gamma ray burst}

energy in

\text{cosmic rays} \sim \text{photons} \sim \text{neutrinos}
Waxman-Bahcall Flux

\[ \Phi_v = \frac{1}{2} \times \frac{1}{2} \times \Phi_{CR} \times \frac{d_H}{d_{CMB}} \approx \Phi_{CR} \]

oscillations

\[ \nu_\mu + \nu_\mu \quad \nu_e + e \]

in \( \pi^+ \) decay
Diffuse muon neutrino flux

\[ \Phi E_\nu^2 \text{ [GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2}] \]

- Atmospheric
- AMANDA-II (1yr)
- MPR (4yr)
- AMANDA (4yr)
- HBL blazars
- Full IceCube, 1 year
- MPR bound
- WB

100 - 500 events per km$^2$ year
• events per km² year:

\[
N = 2\pi \times \text{area} \times \text{time} \times \int \frac{dN}{dE} P_{\nu \rightarrow \mu} dE
\]

\[
\frac{3 \times 10^{-11}}{E} \text{ TeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]

\[
10^{-6} E(\text{TeV})
\]

\[
N \approx 80 \times \log \frac{E_{\nu \text{ max}}}{E_{\nu \text{ min}}} \approx 500 \text{ events}
\]
Active Galaxy

Radiation Field: Ask Astronomers

- energy in protons ~ energy in electrons
- photon target observed in lines
- >> few events per year km²
0 seconds
fireball protons and photons interact

~ 10 seconds
fireball protons interact with remnant of the star

afterwards
afterglow protons interact with interstellar medium

0 seconds
fireball protons and photons interact

PeV

TeV

EeV
cosmic rays interact with the microwave background

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

cosmic rays disappear, neutrinos appear

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

\[ E_\nu \geq 2 \times 10^6 \text{TeV} \]

1 event per kilometer squared per year
GZK event: cosmic ray + cmb photon $\rightarrow$ 10 EeV neutrino
neutrinos associated with TeV gamma rays
Cas A Supernova Remnant in X-rays

Shock fronts

Fermi acceleration when particles gyrate across high B-fields
key issue: magnetic field

Chandra Cassiopeia A

Chandra SN 1006
HESS: RX J1713 Spectrum

18 h 2003 data
supernova
beam
dump

- Dense molecular cloud
- Shock wave
- $\pi^0$ decay $\rightarrow \gamma$-rays
- Inverse Compton scattering $\rightarrow \gamma$-rays
- Compressed shell of hot gas

Supernova remnant

RX J1713-3946
TeV photons trace the density of the molecular clouds
cygnus region: Milagro and Tibet

Milagro

- Contours are pion model with no sources.
- Crosses are EGRET unidentified sources.
- TeV/matter correlation is good.
- Chance noncorrelation is $1.5 \times 10^{-6}$.

2~4 neutrinos in IceCube per source.
\( \gamma \)’s associated with galactic cosmic rays

A SNR at \( d = 1 \) kpc transfers \( W = 10^{50} \) erg to cosmic rays interacting with molecular clouds with density \( n = 1 \) cm\(^{-3}\)

\[
E \frac{dN_\gamma}{dE}(> 1 \text{ TeV}) = 10^{-11} \frac{ph}{cm^2 s} \frac{W}{10^{50} \text{ erg}} \frac{n}{1 \text{ cm}^3} \left( \frac{d}{1 \text{kpc}} \right)^{-2}
\]

2 SN per century supply the observed density of galactic cosmic rays

E.g. RX J1713.7-3946
\[ E_\gamma \frac{dN_\gamma}{dE_\gamma} (> \text{TeV}) = \frac{1}{4\pi d^2} L_\gamma \]

\[ L_\gamma = V Q_\gamma = \frac{W}{\rho_{cr}} Q_\gamma \]

- **volume of the remnant**
- **energy in >TeV photons produced by cosmic rays per cm\(^3\) sec**

\[ d = 1 \text{kpc} \quad n = 1 \text{cm}^{-3} \quad W = 10^{50} \text{erg} \]
energy in $>\text{TeV}$ photons produced by cosmic rays on density $n$ per cm$^3$ per second

\[ Q_\gamma (> \text{TeV}) = \left\langle \frac{E_\gamma}{E_p} \right\rangle \left[ \frac{c}{\lambda_{pp\rightarrow \pi}} \right] n_{cr} (E_\gamma) \]

\[ \lambda_{pp\rightarrow \pi} = n \sigma_{pp\rightarrow \pi} \text{ and } \rho_{cr}, n_{cr}, Q_\gamma \text{ are energies} \]

\[ d = 1 \text{kpc} \quad n = 1 \text{cm}^{-3} \quad W = 10^{50} \text{erg} \]
\[
\langle \frac{E_{\pi}}{E_p} \rangle = 0.2
\]

\[
\rho_{cr} \approx 10^{-12} \text{ erg cm}^{-3}
\]

\[
\sigma_{pp \rightarrow \pi} = 40 \text{ mb} = 4 \times 10^{-26} \text{ cm}^2
\]

\[
n_{cr}(> \text{TeV}) = 4 \times 10^{-14} \text{ TeV cm}^{-2} \text{ s}^{-1}
\]

\[
d = 1 \text{kpc} \quad n = 1 \text{ cm}^{-3} \quad W = 10^{50} \text{ erg}
\]
neutral pions are observed as gamma rays
charged pions are observed as neutrinos

$\nu_\mu \sim \gamma / 2$
ν flux accompanying TeV gammas

\[ E \frac{dN_\nu}{dE} (> E) \cong \frac{1}{2} E \frac{dN_\gamma}{dE} (> E) \]

\[ = 10^{-11} \frac{\text{nus}}{\text{cm}^2 \text{s}} \text{ Area Time } P_{\nu \rightarrow \mu} \]

\[ = 1.5 \ln \left( \frac{E_{\text{max}}}{E_{\text{min}}} \right) \text{ events per km}^2 \text{ per year} \]

a “few” neutrinos
neutrinos: a second look

Milagro

contours are pion model with no sources
crosses are EGRET unidentified sources

TeV/matter correlation
good
chance noncorrelation $1.5 \times 10^{-6}$

2-3.5 neutrinos in IceCube per source
injection $Q_{cr}$

cosmic rays produce pions in interactions with interstellar medium
\[
\frac{dN_\gamma}{dt} = Q_{CR}(E) - \frac{N_\gamma}{\tau(E)}
\]

- $Q_{CR}(E)$ is the injected CR distribution
- $\tau(E)$ is the diffusion time, depends on $B$
- $T$ is the lifetime of the remnant (1,000 ~ 10,000 years)

\[
N_\gamma(E) = Q_{CR}(E)T \text{ for } \tau \gg T
\]
\[
N_\gamma(E) = Q_{CR}(E)\tau(E) \text{ for } \tau \ll T
\]

**evolution of the CR flux in the SN remnant**
1000 models ...

Legend:
- Black line: $s = -2.2$, $T = 1400$ years, $B = 0.1 \mu G$
- Red line: $s = -2.2$, $T = 5000$ years, $B = 1 \mu G$
- Green line: $s = -2.2$, $T = 5000$ years, $B = 10 \mu G$
- Blue line: $s = -2.2$, $T = 5000$ years, $B = 50 \mu G$

Egret Flux
- Milagro
AMANDA skyplot 2000-2003

3369 events below horizon
AMANDA neutrinos in galactic coordinates
Galactic Coordinates

Southern Hemisphere Sky

Standard Deviations

30° 210° 90° 65° 210° 90° 65° 30°
particle physics
• in the next 10 years IceCube will observe

\[ \sim 10^6 \text{ neutrinos with energies } 0.1—1,000 \text{ TeV} \]
\[ \sim 10 \text{ neutrinos with energy } > 10^6 \text{ TeV} \]

made in the interactions of cosmic rays with the Earth’s atmosphere and microwave photons.

• with \( m \sim 0.01 \text{ eV} \) and \( E \sim 100 \text{ TeV} \)
the gamma factor of the neutrino is

\[ \gamma = \frac{E_V}{m_V} \approx 10^{16} \]
**IceCube: particle physics with one million atmospheric neutrinos**

- **Astronomy:** new window on the Universe

- **Physics:**
  - measurement of the high-energy neutrino cross section
  - TeV-scale gravity, quantum decoherence
  - physics beyond 3-flavor oscillations
  - test special and general relativity with new precision
  - search for magnetic monopoles
  - search for neutralino (or other) dark matter
  - search for topological defects and cosmological remnants
  - search for non-standard model neutrino interactions
  - search for leptoquarks
  - ...

quantized space: like traveling through a crystal

\[ \lambda \sim \frac{1}{E} \rightarrow 10^{-33} \text{ cm} \]
Lorentz violation: $\Delta E$ vs $\Delta t$

Violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons from a source at a distance $d$; for instance a GRB.

energy scale $\approx \frac{d}{c} \frac{\Delta E}{\Delta t} \approx M_{Planck}$
neutrino “astronomy”

violation of Lorentz invariance may be a tool to study Planck scale physics

→ interaction with Planck mass particles distort spacetime

→ Planck scale vacuum fluctuations probed by high energy neutrinos

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

modification to dispersion relation leads to an energy dependent speed of light.
Lorentz violation: $\Delta E$ vs $\Delta t$

Violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons from a source at a distance $d$; for instance a GRB.

$$\Delta t \approx \frac{1 + n}{2} \left( \frac{d}{c} \right) \left( \frac{E_v}{\zeta M_{Planck}} \right)^n$$
WIMP capture in the sun
and annihilation in neutrinos

\[ \chi + \chi \rightarrow W + W \rightarrow \nu + \nu \]
IceCube: inner core detector

7 IceCube + 18 AMANDA strings
225 DOMs + 540 OM}s
IceCube: the contained event detector

2007 detector: 22 IceCube strings + AMANDA can be divided in veto and fiducial volume
muon vertices of events passing the on-line filter well inside the defined fiducial volume

blue: WIMPS           red: background
IceCube contained events

- threshold ~ 50 GeV
- 40,000 atmospheric neutrinos by Christmas
- oscillations, new physics, precision tests, WIMPs ...
a km squared year
data by 2008

2005, 2006, 2007 deployments

- 604 DOMs deployed to date
- Want to achieve steady state of 14 strings / season.
IceCube Collaboration

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