Results from IceCube on high-energy neutrinos and cosmic rays

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The IceCube observatory

**Deployment**
- **04/05** 1 string (IC01)
- **05/06** 9 strings (IC09)
- **06/07** 22 strings (IC22)
- **07/08** 40 strings (IC40)
- **08/09** 59 strings (IC59)
- **09/10** 79 strings (IC59) (including DeepCore)
- **10/11** 86 strings (IC86)

**Dec, 2011**
→ installation completed

**May, 2011**
→ operation of IC86 array

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Detection method

time series of photon hits

likelihood reconstruction

cascade like → $\nu_e$, all flavour

event selection

muon bundle like → cosmic rays

track like → $\nu_\mu$, point sources

detailed optical properties
$\nu_\mu$ energy and pointing resolution

**Pointing resolution**
- energy dependent

- $\sigma(\theta_\nu) \approx 1^\circ$ at 1TeV

**Pointing verification**
- $\pm 4^\circ$ window around moon
- $\rightarrow 13\sigma$ underfluctuation in IC59
  (14 moon cycles)

**Energy resolution**
- estimated from $dE/dx$ of muons
- dominated by stochastic losses

- $\sigma(E_\mu) \approx 0.3 \log_{10}(E_\mu)$
Neutrinos
Point source searches

Dataset

- lifetime 723 days (IC40+IC59)
- 43339 up-going events, 64230 down-going events

Hottest spot

- RA: 75.45°
- DEC: -15.18°
- $-\log_{10}(p) = 4.65$

$\Rightarrow 74.2\%$ chance probability
$\Rightarrow$ no close-by candidates
Prompt and diffuse $\nu_e$ flux

Atmospheric neutrinos

- conventional flux
- $\nu_e$-flux = $\sim 10^{-2}$ $\nu_\mu$-flux
- prompt flux
  - decay of charmed mesons (e.g. $D^\pm, D_0, \Lambda_c$)
  - measurement allows to probe hadronic interaction models

Electron neutrino flux

- distant neutrino sources
  - neutrino oscillations
    - flavour ratio (1:1:1)
- experimental challenges
  - limited pointing resolution
  - background from bremsstrahlung cascades

→ approaching needed sensitivity
Gamma ray bursts

Fireball model (long GRBs)
- collapse of massive star
- ultra-relativistic jets
- shock front collision
- \( \rightarrow \) PeV neutrino emission
- total energy release \( \sim 10^{52} \) ergs
- \( \rightarrow \) good candidate for extragalactic cosmic ray flux

IceCube GRB analysis
- \( \sim 220 \) GRBs from GCN
- coincidence analysis
- \( \rightarrow \) time window (\( \Delta T \approx 0.1-100 \)s)
- \( \rightarrow \) direction (\( \Delta \Psi_{\text{IceCube}} \approx 1^\circ \))
- per-alert emission model
  - 8.4 events expected
  - no events observed
- \( \rightarrow \) serious constraint on GRB models
Idea
- trigger follow-up observation by neutrinos in IceCube → online neutrino analysis

Online analysis
- neutrino selection (~75% purity)
- multiplet analysis (ΔT < 100s, ΔΨ < 4°) → alert (~5 min latency)

Follow-up programs
- optical: ROTSE, PTF → first limit on jet in SNe
- X-rays: SWIFT
- γ-rays: MAGIC, VERITAS
Indirect searches

- $\chi\chi \rightarrow W^+W^-/b\bar{b} \rightarrow \nu\nu$ annihilation in galactic halo [Phys.Rev. D84 (2011) 022004]
  - $<\sigma_A \cdot v> < 10^{22}$ cm$^3$ s$^{-1}$
- gravitational traps (sun, earth)
  - probe spin-dependent cross-section

IceCube+AMANDA results

- best limit on spin-dependent cross-sections
  - IC86 will constrain global SUSY fits
Cosmic rays
Charged cosmic rays

IceTop
- sample shower on the ground
- $e^\pm \gtrsim 10$ MeV

IceCube
- high-energy muon core
- $\mu^\pm \gtrsim 300$ GeV

$\rightarrow$ 3D air-shower array

Combined
- $A_{\text{eff}} \cdot \Omega \approx 0.3$ km$^2$ sr
- $E_{\text{prim}} \gtrsim 300$ TeV
  $\rightarrow 10^{10}$ showers per year
  $\rightarrow 10^7$ with InIce signal

Physics program
- spectrum
- composition
- anisotropies
- hadronic interactions
- $\nu$-veto
Multi-scale cosmic ray anisotropies

Anisotropy analysis
- $10^{-3}$ intensity variation
- energy dependent

Dipole moment
- does not correspond to the relative motion in the Galaxy (Compton-Getting effect)

Hot-spot analysis
- subtract dipole and quadrupole
- smooth map on different scales
  $\rightarrow$ multiple hot-spots observable

Tibet-III
IceCube-59

arXiv:1109.1017
Radio emission from air-showers
- geosynchrotron mechanism
- $e^\pm$ deflected in earth B-field
  $\rightarrow$ 10ns radio pulse
  (10-150MHz)

Physics gain
+ increased $A_{\text{eff}} \cdot \Omega$ (veto!)
- signal proportional to integral $e^\pm$ component
  $\rightarrow$ additional energy estimator
+ additional sensitivity to $X_{\text{max}}$
- overconstrain shower parameters
  $\rightarrow$ improve systematics

Technology
- phased array of radio antennas
- low-cost, fast deployment
Summary

IceCube detector
• array completed since December 2010
• fully operational since May 2011
  ➔ exceeding design goals
  ➔ well-understood performance

Neutrino sources
• no significant point-sources with $\frac{3}{4}$ of array
  ➔ expect ~5 years for discovery
• seriously challenging models for GRBs, WIMPs, ...

Cosmic rays
• unique 3D cosmic-ray laboratory
• unfolded spectrum and composition with InIce data
  ➔ cosmic rays become heavier at the knee
• anisotropies observed on multiple scales
  ➔ unknown origin