IceCube Neutrino Science

Elisa Resconi, T.U. Munich

Astrophysics From The South Pole: Status And Future Prospects, 4th Of April 2011
High Energy (> 100 GeV) Neutrino Astronomy

- Discovery Areas:
  - Origin of Galactic / Extra-galactic Cosmic Rays
  - Indirect Search for Dark Matter
  - Beyond the Standard Model of Particle Physics

- Specifically to IceCube:
  - Core-collapse SuperNovae Explosion (time profile)
Cosmic Rays: Galactic

- Diffusive shock acceleration in SNRs (collision-less)
- Good up to few TeV (Gamma-ray Telescopes)
- Nearby molecular clouds, multi-TeV emission possible
- High energy neutrinos: unambiguous prove of hadronic acceleration / interaction

Elisa Resconi

Monday, April 4, 2011
Cosmic Rays: Extra-galactic

- Cosmic particles up to $10^{20}$ eV

- Unresolved astrophysical sources intrinsic spectrum $\propto E^{-2}$
  Diffuse neutrino flux
  Waxman-Bahcall upper bound

- AGN, GRBs

- Cosmogenic neutrinos (EHE): cosmic-rays interacting with the cosmic microwave background
  GZK cutoff?

The Auger Collaboration
How do we search for Cosmic Ray Sources?

IceCube is a discovery instrument  no guaranteed recipe

- All-sky searches: diffuse flux, muon neutrinos sky map
- Pre-defined list of candidate neutrino sources
- Search for transients (GRBs, flares, periodic)
- On-line
  - Neutrinos from SuperNovae Core Collapse
  - Neutrino Alerts to Rotse, PTF, Swift, Magic
All-sky Searches: Diffuse Flux

The IceCube Collaboration, corresponding author: S. Grullon

FIG. 7. Simulated neutrino energy distribution (left plot) and the simulated reconstructed muon energy loss distribution (right plot) of the final event sample for the Honda et. al conventional atmospheric $\nu_\mu$ (green) flux model, the Enberg et al. prompt atmospheric $\nu_\mu$ (light blue) flux model, and an astrophysical $E^{-2}$ (purple) flux with a normalization of $N = 10^{-7}$GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Profile likelihood construction method
Systematic errors as nuisance parameters
All-sky Searches: Diffuse Flux

Largest systematics on-going actions / ideas

- overall normalization of atmospheric neutrino flux (± 25%)
  identification of fully contained events

- prompt component atmospheric neutrinos (−44% to +25%)
  search of the prompt component in the muons

- uncertainty absolute sensitivity digital optical module (± 10%)
  map of the detector with flashers, muons; multi-wavelength LED;
  hole ice investigations ...

- measured properties of the glacial ice at the South Pole (± 10%)
  new ice model under implementation
IC-40 Diffuse Neutrino Flux Upper Limit

* Models Excluded at 5σ

The IceCube Collaboration, corresponding author: H. Johansson, S. Grullon, A. Ishihara

Monday, April 4, 2011
All-sky Searches: Point Sources

\[ S_i(|x_i - x_s|, E_i, \gamma) = \frac{1}{2\pi \sigma_i^2} \exp \left( -\frac{|x_i - x_s|^2}{2\sigma_i^2} \right) P_{\text{Sig\_Nch}}(E_i|\gamma) \]

\[ B(x_i, E_i) = P_{\text{Bkg\_Dec}}(x_i) P_{\text{Bkg\_Nch}}(E_i) \]

The IceCube Collaboration, corresponding author: J. Dumm
1997, AMANDA-B10, 642 events

1 year IceCube predicted
1 year IceCube-40 best upper limit
(2 order of mag improvement!)
all-sky p-value = 18%
not significant, no evidence of neutrino source

Lifetime = 375.5 days
# Events = 36900
(14121 up-going,
22779 down-going)

Hottest location in the all-sky search is:
Ra=113.75, Dec=15.15

Pre-trial $-\log_{10}(p\text{-value}) = 5.28$
Best-fit # of source events = 11.0
Best-fit spectral index = 2.05

The IceCube Collaboration, corresponding author: J. Dumm
Pre-defined list of candidates
(to reduce the “trial” factor)

✦ Extra-galactic sources
   - TeV, GeV-blazars, stacking of AGN families, stacking of cluster of galaxies

✦ Galactic sources (soft spectra)
   - Lower energies via inclusion of AMANDA, DeepCore

✦ Extended sources: Cygnus region
   - Multi-Point-Source method (2pt correlation function)
The Cygnus Region

Data sample: IC22+AMANDA

2-point correlation analysis for the entire extended region [method and region defined a-priori]
Lesson learned: 1% fluctuations tend to disappear!
The Cygnus Region

plot courtesy from Y. Sestayo

Neutrino flux from gamma-rays in the region (diffuse + sources)

Source spectrum: \( \Phi_0 E^{-2.6} \exp\left(-E/E_{\text{cutoff}}\right) \)
Indirect Dark Matter Search

Credit: Sky & Telescope / Gregg Dinderman.

Credit: Hinode JAXA/NASA/PPARC
Indirect Dark Matter Search
AMANDA 01-07, IC22, IC40 combined
Transients
Data sample: IC40

- GRBs, SN
- Flaring sources
- Periodic sources

FIG. 1. Number of counts versus azimuth angle. The numbers represent counts accumulated in 350 seconds in each 6° angular interval.
Gamma-Ray-Bursts

Data sample: IC22, IC40, IC59

The IceCube Collaboration, corresponding author: P. Redl
Blazars Flares
Data sample: IC40

No Evidence of Neutrino Flares up to IC40
On-line Programs

- Core Collapse SuperNovae
- Alerts to Rotse, PTF, Swift
- Alerts to Magic
Core Collapse SuperNovae

• IceCube is the world’s most precise detector for determining the neutrino light curve of close supernovae (2 ms timing resolution)

• IceCube sends real-time datagrams to Supernova Early Warning System (SNEWS)

• Sensitivity:
  • supernova @ galactic center like megaton-scale supernova search experiment
  • 20 standard deviations: ~30 kpc
  • 6 standard deviations: ~50 kpc (Large Magellanic Cloud)

Fig. 10. Expected rate distribution at 10 kpc distance for the Lawrence-Livermore model (dashed line) and O-Ne-Mg model by Hüdepohl et al. (2010) with the full set of neutrino opacities (solid line). The 1σ-band corresponding to measured detector noise (hatched area) has a width of about ±330 counts.
On-line alerts
Conclusions

- Cosmic ray physics: a modern puzzle, IceCube role of fundamental importance
- First models rejected, upper bound crossed with 1/2 of the detector
- Sensitivity scales faster then volume
- Indirect Dark Matter Searches: scan of the same parameter space region of then most sensitive direct detection experiments
- Supernovae Core Collapse: IceCube is the most precise experiment for neutrino light curves
- On-line programs: collaboration with astrophysical missions of great importance for the IceCube science
backup
Cosmic Rays - Neutrinos - TeV Gamma Rays

Energy spectra of all decay products - pp interaction - two energies of incident protons

\[ E_p : E_\gamma : E_\nu = 1 : 0.1 : 0.05 \]


Monday, April 4, 2011
Atmospheric neutrino spectrum

FIG. 8. The fitted muon energy loss distribution of the final event sample is shown. The best fit to the data (black, shown with 1σ error bars) consists only of conventional atmospheric $\nu_\mu$, and no evidence is found for a prompt atmospheric $\nu_\mu$ flux or an astrophysical $E^{-2}$ $\nu_\mu$ flux.
Core Collapse SuperNovae

- Count single rates on top of low noise background

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- 2 ms timing resolution

- IceCube sends real-time datagrams to Supernova Early Warning System (SNEWS)

- Sensitivity:
  - Supernova @ galactic center like megaton-scale supernova search experiment
  - 20 standard deviations: ~30 kpc
  - 6 standard deviations: ~50 kpc (Large Magellanic Cloud)

**Fig. 12.** Significance versus distance assuming the Lawrence-Livermore model. The significances are increased by neutrino oscillations in the star by typically 15% in case of a normal hierarchy (Scenario A) and 40% in case of an inverted hierarchy (Scenario B). The Magellanic Clouds as well as center and edge of the Milky Way are marked. The density of the data points reflect the star distribution.