Searching for Neutrino Sources with the ANTARES Telescope

Corey Reed (Nikhef)

Aspen Summer Workshop
GeV & TeV Sources in the Milky Way
Neutrino Astronomy

High energy photon sources have been found

Produced how?

Leptonic interactions?

Hadronic interactions?

[From H.E.S.S Press Release]
Neutrino Astronomy

High energy photon sources have been found

Produced how?

If source emits HE neutrinos, it is accelerating hadrons!

[From H.E.S.S Press Release]
Neutrino Astronomy

Main goal

Find cosmic neutrino sources
Determine association with cosmic ray accelerators
   GC, SNR, GRB, AGN, (unknown?)

But wait, there's more!

Indirect dark matter searches
Exotic particle searches
Geophysical, biological sciences
...

Neutrino Astronomy

ANTARES
Atmospheric Neutrinos
Cosmic Neutrinos

06.17.10
GeV & TeV Sources in the Milky Way

4
Neutrino Astronomy

**Benefit of (high energy) $\nu$'s**

- **Neutrinos reveal their source**
- Low cross section, no charge
- Photons: absorbed (in dust, etc.)
- Protons / ions: deflected by magnetic fields

**Challenge of $\nu$'s**

- **Hard to detect**
- Low cross section, no charge
Neutrino Astronomy

Detection principle

Neutrino interacts (with nucleus)
Neutrino Astronomy

Detection principle

Fast lepton produced

\[ \nu_\mu \rightarrow \mu \]
Neutrino Astronomy

Detection principle

Cherenkov radiation measured

Neutrino Astronomy

ANTARES
Atmospheric Neutrinos
Cosmic Neutrinos

GeV & TeV Sources in the Milky Way
Neutrino Astronomy

Mediterranean Sea

Cherenkov medium

Large target volume

Long scattering length for blue light

View of southern sky & galactic center
ANTARES Telescope

Installed off French coast, 2.5km under water
ANTARES Telescope

12 lines, 25 floors, each with 3 large PMT's
ANTARES Telescope

Completed in May, 2008!
Finding Neutrinos

Muons abound

Vast majority of data

Down-going

Use earth as filter

up-going $\Rightarrow$ $\nu$

[From Aart Heijboer, PhD thesis]
Finding Neutrinos

Reconstruct muon trajectory

Different methods can be used

Simple $\chi^2$:
Minimize residuals assuming hits from Cherenkov photons

More elaborate:
Maximize likelihood of residual distribution
Use PDF including Cherenkov and background photons
Finding Neutrinos

With elaborate tracking

Expect very good resolution
Long scattering length
of light in water!

Full PDF fit
Account for both direct
and background hits

Bkgnd must be understood
Huge progress over last ~year
Results coming very soon
Finding Neutrinos

With “simple” reconstruction on '07-'08 data

Strict hit selection
Fit only direct Cherenkov photons

Total active time of 341 days
Various detector configurations
5, 9, 10 and 12 lines
Finding Neutrinos

With “simple” reconstruction on '07-'08 data

Look at elevation of muon origin

341 days live time

Only well reconstructed tracks shown
Finding Neutrinos

With “simple” reconstruction on '07-'08 data

341 days live time

Simulation uncertainties

Theoretical Flux
Detector
PMT efficiency
Background hits

Elevation

Number of events

data
MC atm. $\mu$
MC atm. $\nu$
MC total

Preliminary
Finding Neutrinos

With “simple” reconstruction on '07-'08 data

341 days live time

ANTARES has seen neutrinos

1062 candidates

956 expected from simulation
Cosmic Neutrino Search

Most neutrinos seen are “atmospheric”

Cosmic ray interacts in atmosphere, produces $\nu$

Want cosmic $\nu$'s

ANTARES sees much of the sky

Complements IceCube
Cosmic Neutrino Search

ANTARES sees much of the sky

Do we see neutrinos from space?

Choose some interesting sources

Look for (excess of) neutrinos in source regions
Cosmic Neutrino Search

Very first look at early data...

2007, 5-line data (140 days live-time)

Use “simple” reconstruction
  - Remove background hits
Require well fit track
  - And poorly fit shower
Require up-going

→ 276 neutrino candidates
Cosmic Neutrino Search

How to tell if they're cosmic $\nu$'s?

Calculate a statistic given data

(Likelihood ratio)

Ask:

What are the odds to get this value (or better) if all data has no cosmic neutrinos?

i.e. all atmospheric $\nu$'s
Cosmic Neutrino Search

In other words:

If atmospheric $\nu$'s look like this:
Cosmic Neutrino Search

In other words:

If atmospheric ν's look like this:
And data is here:

Then probably data is only atmospheric neutrinos
Cosmic Neutrino Search

In other words:

If atmospheric $\nu$'s look like this:

But if data is here:

Then probably data has some cosmic neutrinos!
Cosmic Neutrino Search

Of course, need a good statistic

**Discriminating:**

Small when neutrinos are far apart

Big when neutrinos cluster
Cosmic Neutrino Search

Find statistic distribution for background

Estimate background from real data

(Applicable for Atmospheric neutrinos)

Parametrize: # background tracks vs declination
Cosmic Neutrino Search

Find statistic distribution for background

1) Sample background parametrization
Cosmic Neutrino Search

Find statistic distribution for background

1) Sample background parametrization

   Enough times to simulate live-time of data
Cosmic Neutrino Search

Find statistic distribution for background

1) Sample background parametrization
   Enough times to simulate live-time of data

2) Pick a source
Cosmic Neutrino Search

Find statistic distribution for background

1) Sample background parametrization
   Enough times to simulate live-time of data
2) Pick a source
3) Find statistic using background & this source
Cosmic Neutrino Search

Find statistic distribution for background

1) Sample background parametrization
   Enough times to simulate live-time of data
2) Pick a source
3) Find statistic using background & this source

Repeat many (many) times to get distribution
Cosmic Neutrino Search

Search in progress

But sensitivity is encouraging
Low resolution
Low live-time

Results coming soon!
Also with more data, better reconstruction
Cosmic Neutrino Search

We have collected a lot of data!

Multiple groups doing searches in parallel

2007-2008, 5-12 line detector (341 days live)
Scrambled positions! (still blinded)
Cosmic Neutrino Search

How much signal do we need?

Ask question:

“Consider my tests where I had $<N_s>$ signal tracks. In how many of them did I find the source?”

In other words..

“In what fraction of my test cases did my statistic have very little chance of coming from background only?”
Cosmic Neutrino Search

How much signal do we need?

Angular resolution is important for source discovery!

Results with better reconstruction on the way

Fraction of test cases with $P(\text{background only}) < 0.27\%$

- Red: Ang. Res. = 0.3°
- Blue: Ang. Res. = 0.9°

(full sky search)
Summary

ANTARES has been taking data since 2006

Has seen thousands of (atmospheric) neutrinos

Multiple groups searching for point sources

Publications expected very soon

2007, 5 lines, low resolution

Imminent

2007-2008, 10-12 lines, high resolution

Around end of summer
Open Questions

Obvious: Are there high energy neutrino sources?

When we have some...

What are the (brightest) neutrino sources?

If neutrinos are seen from source type X (i.e. SNR), will they always be seen from type X sources?

What are the ratios of neutrino flavors?

At Earth & at the source?

Are there hidden neutrino sources?
Cosmic Neutrino Search

Future telescope in the works

KM3NeT - large telescope in the Mediterranean

Finding sources gets easier

Many more events in a year
Measure higher energy neutrinos
Angular resolution improved
Neutrino Astronomy

High energy photon sources have been found

Produced how?

Leptonic?

- Synchrotron from electrons
- Inverse Compton scattering
Neutrino Astronomy

High energy photon sources have been found

Produced how?

Hadronic?

\[ p \gamma \rightarrow \pi^0 p \]
\[ \downarrow \]
\[ \gamma \gamma \]
Neutrino Astronomy

High energy photon sources have been found

Produced how?

Hadronic?

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

\[ \mu^+ \nu_\mu \]

\[ \nu_\mu \nu_e \]

\[ e^+ \]
Candidate Sources

Table 4: Golden-list for the 5-line data analysis

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Equatorial coordinates</th>
<th>Galactic coordinates</th>
<th>Vis.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RA</td>
<td>δ</td>
<td>l</td>
</tr>
<tr>
<td>Galactic Sources</td>
<td></td>
<td>6h 32m 58s</td>
<td>5° 48' 20&quot;</td>
<td>205.66</td>
</tr>
<tr>
<td>HESS J0632+057</td>
<td>AMB</td>
<td>8h 52m 00s</td>
<td>-46° 22' 00&quot;</td>
<td>266.28</td>
</tr>
<tr>
<td>RX J0852.0-4622</td>
<td>SNR</td>
<td>10h 23m 18s</td>
<td>-57° 45' 50&quot;</td>
<td>284.19</td>
</tr>
<tr>
<td>HESS J1023-575</td>
<td>AMB</td>
<td>13h 02m 49s</td>
<td>-63° 50' 02&quot;</td>
<td>304.19</td>
</tr>
<tr>
<td>PSR B1259-63</td>
<td>Binary Pulsar</td>
<td>14h 42m 43s</td>
<td>-62° 29' 00&quot;</td>
<td>315.79</td>
</tr>
<tr>
<td>RCW 86</td>
<td>SNR</td>
<td>15h 20m 41s</td>
<td>-57° 10' 00.26&quot;</td>
<td>322.12</td>
</tr>
<tr>
<td>Cir X-1</td>
<td>XRB</td>
<td>16h 14m 19s</td>
<td>-51° 49' 12&quot;</td>
<td>331.52</td>
</tr>
<tr>
<td>HESS J1614-518</td>
<td>NCO</td>
<td>17h 02m 40s</td>
<td>-48° 47' 23&quot;</td>
<td>338.94</td>
</tr>
<tr>
<td>CX 339</td>
<td>XRB</td>
<td>17h 13m 00s</td>
<td>-39° 45' 00&quot;</td>
<td>347.28</td>
</tr>
<tr>
<td>RX J1713.7-2946</td>
<td>SNR</td>
<td>17h 45m 41s</td>
<td>-29° 00' 22&quot;</td>
<td>359.95</td>
</tr>
<tr>
<td>Galactic Center</td>
<td>AMB</td>
<td>18h 01m 42s</td>
<td>-23° 20' 06&quot;</td>
<td>6.66</td>
</tr>
<tr>
<td>W28</td>
<td>SNR</td>
<td>18h 26m 15s</td>
<td>-14° 49' 30&quot;</td>
<td>16.90</td>
</tr>
<tr>
<td>LS 5039</td>
<td>XRB</td>
<td>18h 37m 38s</td>
<td>-6° 57' 00&quot;</td>
<td>26.18</td>
</tr>
<tr>
<td>HESS J1837-069</td>
<td>AMB</td>
<td>19h 11m 50s</td>
<td>4° 58' 58&quot;</td>
<td>39.69</td>
</tr>
</tbody>
</table>

extra-Galactic Sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Equatorial coordinates</th>
<th>Galactic coordinates</th>
<th>Vis.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RA</td>
<td>δ</td>
<td>l</td>
</tr>
<tr>
<td>RGB J0152+017</td>
<td>HBL</td>
<td>1h 52m 40s</td>
<td>1° 47' 19&quot;</td>
<td>152.38</td>
</tr>
<tr>
<td>IES 0347-121</td>
<td>HBL</td>
<td>3h 49m 23s</td>
<td>-11° 59' 27&quot;</td>
<td>201.93</td>
</tr>
<tr>
<td>PKS 0548-322</td>
<td>HBL</td>
<td>5h 50m 40.6s</td>
<td>-32° 16' 16.4&quot;</td>
<td>237.56</td>
</tr>
<tr>
<td>IES 1101-232</td>
<td>HBL</td>
<td>11h 03m 38s</td>
<td>-23° 29' 31&quot;</td>
<td>273.19</td>
</tr>
<tr>
<td>3C 279</td>
<td>FSRO</td>
<td>12h 56m 11s</td>
<td>-5° 47' 21&quot;</td>
<td>305.10</td>
</tr>
<tr>
<td>Centaurus A</td>
<td>FRN</td>
<td>13h 25m 27.6s</td>
<td>-43° 01' 08.8&quot;</td>
<td>309.52</td>
</tr>
<tr>
<td>ESO 139-G12</td>
<td>Sy2</td>
<td>17h 37m 39.5s</td>
<td>-59° 56' 29&quot;</td>
<td>334.04</td>
</tr>
<tr>
<td>PKS 2005-489</td>
<td>HBL</td>
<td>20h 09m 29s</td>
<td>-48° 49' 19&quot;</td>
<td>350.39</td>
</tr>
<tr>
<td>PKS 2155-304</td>
<td>HBL</td>
<td>21h 58m 53s</td>
<td>-30° 13' 18&quot;</td>
<td>17.74</td>
</tr>
<tr>
<td>H 2356-309</td>
<td>HBL</td>
<td>23h 59m 08s</td>
<td>-30° 37' 39&quot;</td>
<td>12.84</td>
</tr>
</tbody>
</table>