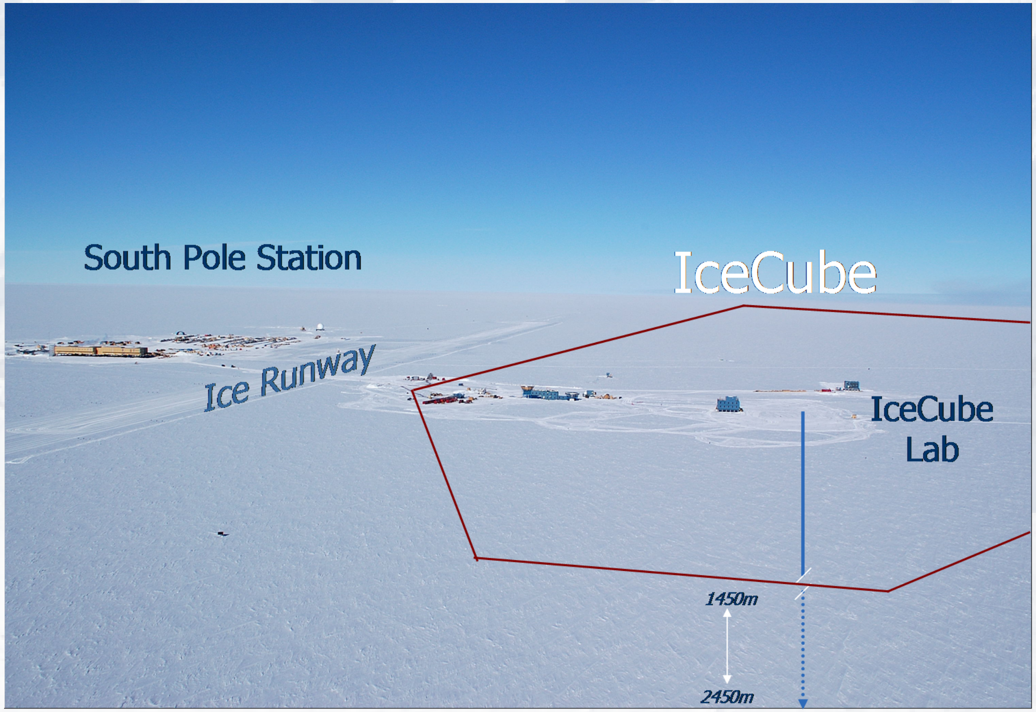
Group 3 – Wojtek, Sandy and Cheryl

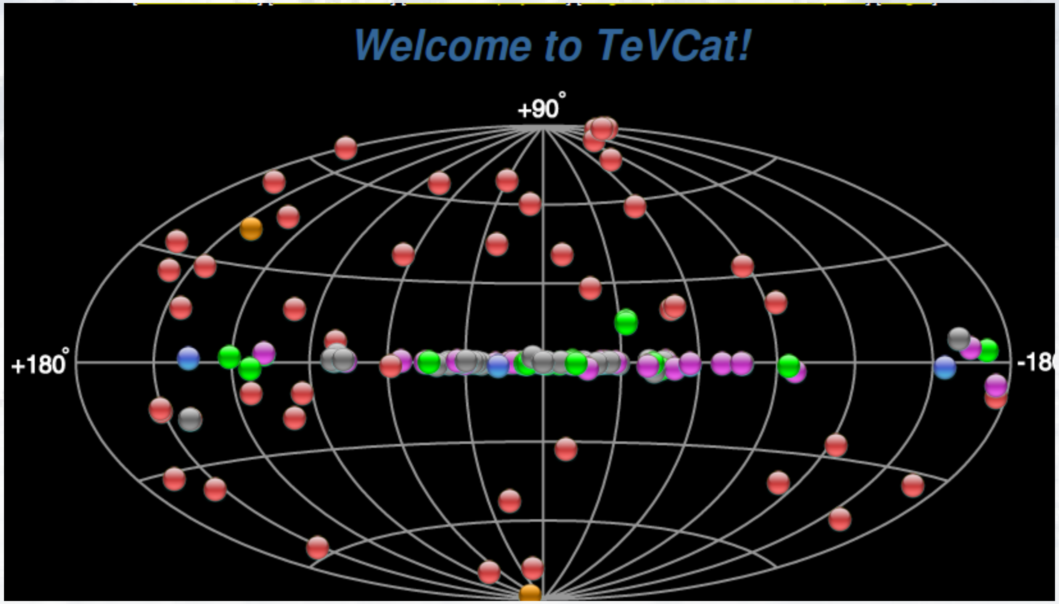
Neutrinos & Astrophysics question 25



Sources for IceCube

A. Find a neutrino emitter

Choose a TeV source from http://tevcat.uchicago.edu that could be a good neutrino emitter for the IceCube experiment at the South Pole – and say why.



Choosing a source

- Supernova remnant, pulsar wind nebula, or gamma ray burst source
  - *Good sources of accelerated neutrinos*
- High energy neutrinos (> 1TeV)
  - *Little atmospheric background at those energies*
  - *High energy gamma → high energy neutrinos*
- High flux (around 0.5 Crab or more)
  - *Or will be swamped by background*
- In northern hemisphere (approx 0-60°*N)*
  - *Earth filters background, but core degrades signal*

Candidate 1: Crab Nebula

- Supernova remnant
- High flux - 1 Crab
- In northern hemisphere *(dec =* 22°)

BUT...

- Lower energy neutrinos (700 GeV)

Candidate 1: Crab Nebula

- Supernova remnant
- High flux - 1 Crab
- In northern hemisphere (*dec* = 22°)

BUT...

- Lower energy (700 GeV)

REJECTED

Candidate 2: Vela Jr

- Supernova remnant
- High flux - 1 Crab
- High energy (1TeV)

BUT...

- In southern hemisphere *(dec = 132°)*

Candidate 2: Vela Jr

- Supernova remnant
- High flux - 1 Crab
- High energy (1TeV)

BUT...

- In southern hemisphere *(dec = 132°)*

REJECTED

Candidate 3: Boomerang Nebula

- Supernova remnant / Pulsar Wind Nebula
- High flux - 0.44 Crabs
- High energy (35TeV)
- In northern hemisphere *(dec = 61°)*

Candidate 3: Boomerang Nebula

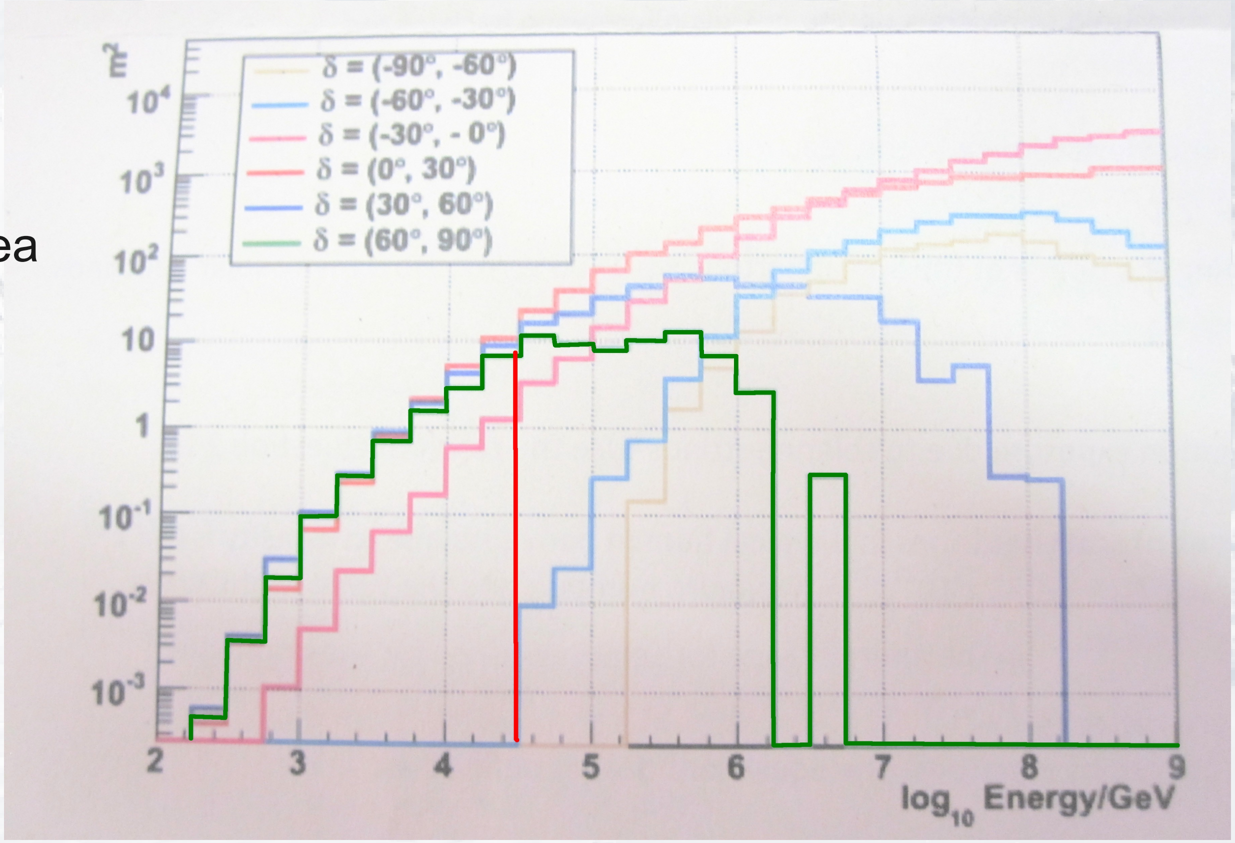
- Supernova remnan nd Nebula
- High flux - .44 C
- High ene
- In northern *61°)*

The Boomerang – Vital Statistics

- Gamma flux
  $= 7.1 \times 10^{-16} (1/\text{TeV cm}^2 \text{ sec})$
- 35 TeV gamma energy threshold
- Distance 0.8 kpc = 2.5×10^{19} m
- 61° north
- Temperature 1K – coldest place in the universe (and you thought that was the lunch room)

The Boomerang – Vital Statistics

IceCube 40 Strings effective area



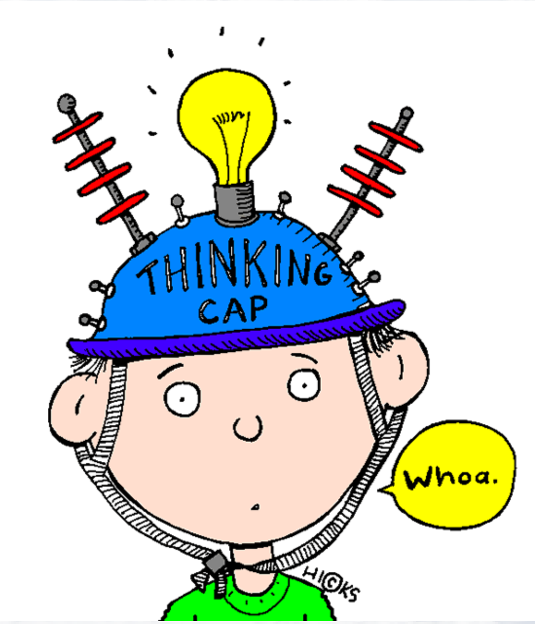
Our combination of energy and declination angle gives us optimum sensitivity

What is a pulsar wind nebula?

- Found in the shells of supernova remnants
- Charged particles accelerated to relativistic speeds by spinning pulsar's magnetic field
- Pulsar wind creates shockwave
- Leptonic and hadronic interactions

B. Find the flux

- Investigate neutrino and gamma emission processes
- Find or guess the dominant process
- Use gamma flux to estimate neutrino flux



Hadronic and leptonic processes

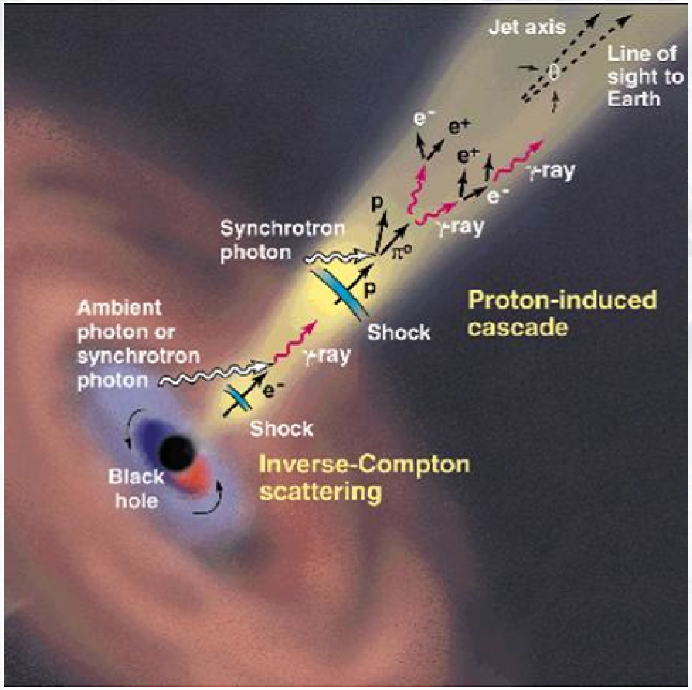


Figure: Cascade model (Mannheim 1993)

- Inverse Compton scattering

$$p + \gamma \rightarrow p + \gamma'$$

- Pair production

$$p + \gamma \rightarrow p + e^+ + e^-$$

- Photomeson production

$$p + \gamma \rightarrow k\pi^+, k\pi^0, k\pi^- \ldots$$

- Proton-proton pion production

$$p + p \rightarrow k\pi^+, k\pi^0, k\pi^- \ldots$$

Hadronic and leptonic processes

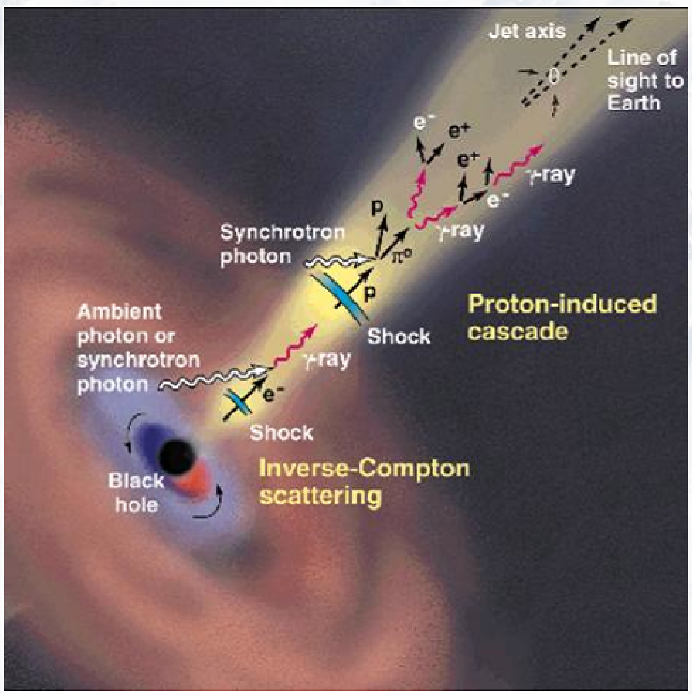


Figure: Cascade model (Mannheim 1993)

- Inverse Compton Scattering

  $p + \ldots$

- Pair produc…

  $p + \gamma \ldots$

- Photomeson pr…tion

  $$p + \gamma \to k\pi \ldots, k\pi^0, k\pi^- \ldots$$

- Proton-proton

  $$p + p \to k\pi^+, k\pi^0, k\pi^- \ldots$$

Dominates at high energies

Pion decays

$$\pi^0 \rightarrow \gamma\gamma$$

Two photons

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$$

Three (anti-)neutrinos

4 particles produced from π+/- vs 2 from π0 :

$$< E_\nu > \approx \frac{< E_\gamma >}{2}$$

How many neutrinos?

Pions produced mainly from kinetic energy, so ratio

$$\pi^0 : \pi^+ : \pi^- \approx 2 : 1 : 1 (highest\ energies)$$
$$\pi^0 : \pi^+ : \pi^- \approx 3 : 2 : 1 (lower\ energies)$$

We get

- 2 photons from a neutral pion
- 3 neutrinos from a charged pion

As an estimate, we can say that:

$$\frac{N_\nu}{N_\gamma} \approx \mathcal{O}(1)$$

What the flux?

$$\int_{E_{\gamma min}}^{E_{\gamma max}} E\frac{\phi E_{given}^{\alpha}}{E^{\alpha}}dE = \int_{E_{\nu min}}^{E_{\nu max}} E\frac{C}{E^2}dE$$

Use this to calculate C

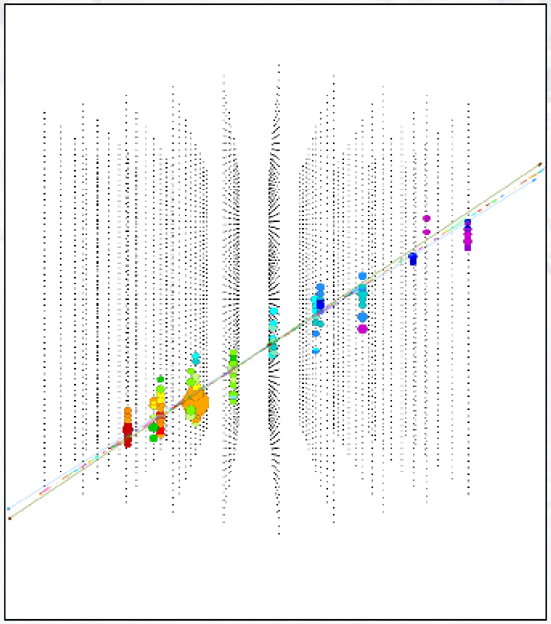
$$n_{\nu_\mu}[1/(cm^2s)] = \int_{E_{\nu min}}^{E_{\nu max}} \frac{C}{E^2}dE$$

$$E_{\gamma min} = 35TeV, E_{\gamma max} = 100TeV, \alpha = 2.5, \phi = 7.1\cdot 10^{-12}[1/(TeVm^2s)]$$

$$n_\nu = 2\times 10^{-10}[1/m^2s]$$

arXiv:astro-ph/0404534v1

C. Event rate



- Calculate the muon-neutrino event rate per year
- Don't forget oscillations!

Event rate – method 1

$$\phi_\mu(E_\mu^{min},\theta) = \int_{E_\mu^{min}} P_\nu(E_\nu, E_\mu^{min}) \exp[-\sigma_{tot}(E_\nu) N_A X(\theta)]\, \phi_\nu(E_\nu,\theta)\, dE_\nu.$$

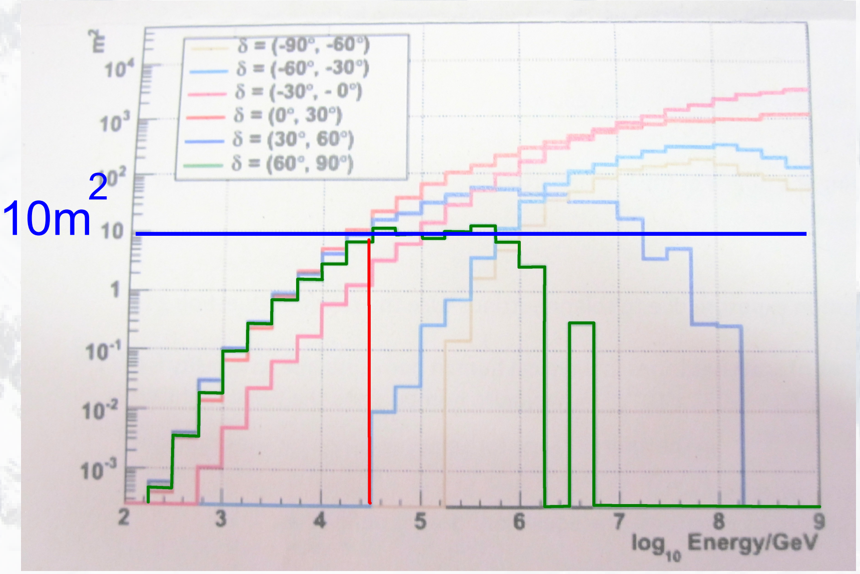
Gaisser Halzen Stanev 1995

ν → μ interaction probability

Probability neutrino survives to reach the detector =
- Neutrino cross-section (function of energy)
- Avogadro's number
- Equivalent density-distance through the earth at 151 deg zenith angle (density average ~ 4 g/cm^3)

Initial neutrino flux (calculated from Part B)

Event rate – method 2



$$N_\mu = \phi_{\nu_\mu} \times A_{eff}$$

- Effective area in our energy range is almost constant at $10m^2$
- Before oscillations

$$\nu_\mu : \nu_e : \nu_\tau = 2 : 1 : 0$$

- Because of oscillations:

$$\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1$$

- Must convert seconds to years!

Event rate – method 2

$$N_\mu = \phi_{\nu_\mu} \times A_{eff}$$

$$N_\mu = 2 \times 10^{-10} \times \frac{1}{3} \times 10 \times (86400 \times 365)$$

This is approximately 1 muon per hundred years (less than expected; strong dependence on spectral index of gammas).

The small print

Canonical Name: Boomerang
TeVCat Name: TeV J2228+611
Other Names: G106.6+2.9
0FGL J2229.0+6114
MGRO C4
MGRO J2228+61
Source Type: PWN
R.A.: 22 28 44 (hh mm ss)
Dec.: +61 10 00 (dd mm ss)
Gal Long: 106.57 (deg)
Gal Lat: 2.91 (deg)

Distance: 0.8 kpc
Flux: 0.44 (Crab Units)
Energy Threshold: 35000 GeV
Spectral Index:
Extended: Yes
Size (X): 0.00 (deg)
Size (Y): 0.00 (deg)
Discovery Date: 2009-04
Discovered By: Milagro
TeVCat SubCat: Default Catalog