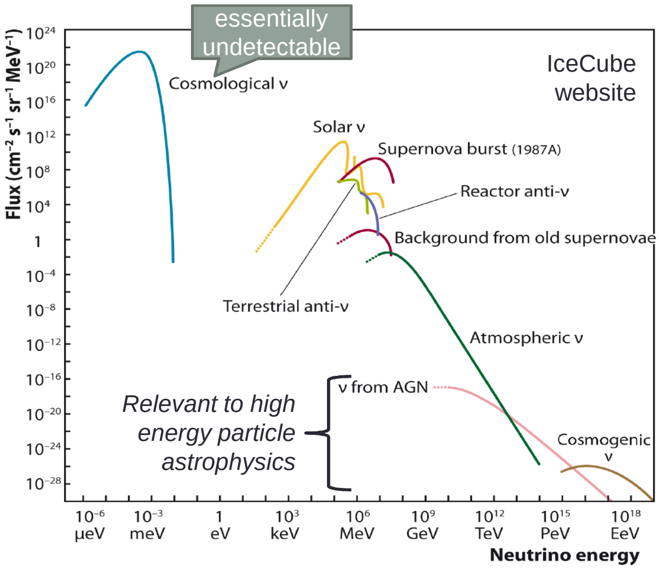
PHY418 PARTICLE ASTROPHYSICS

High Energy Neutrinos

Neutrino astrophysics

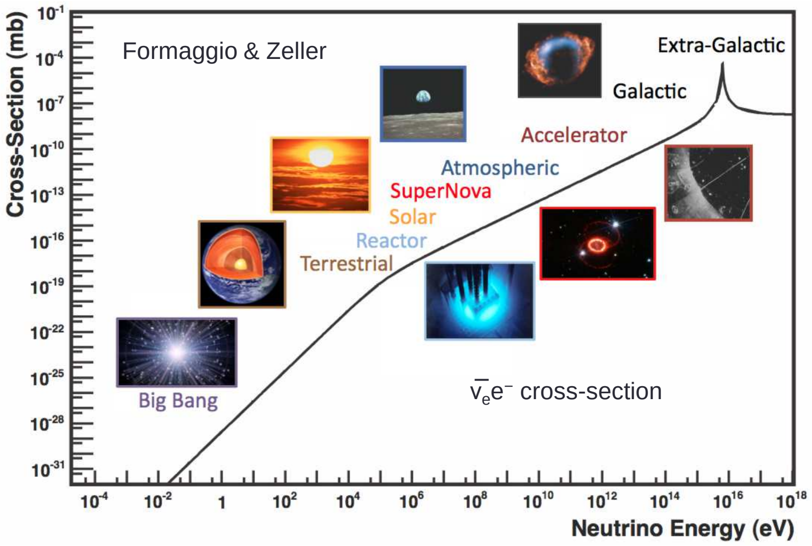


essentially undetectable

IceCube website

Relevant to high energy particle astrophysics

Neutrino astrophysics



HIGH ENERGY NEUTRINOS

Emission Mechanisms

Charged pion decay

- If an object accelerates protons to high energies, we should get charged pion production via $p + p \rightarrow p + n + \pi^+$
    - (i.e. energetic proton hits ambient gas; as protons are more common than neutrons this reaction will be more common than $p + n \rightarrow p + p + \pi^-$)
  - π^+ then decays to $\mu^+\nu_\mu$ (π^- to $\mu^-\bar{\nu}_\mu$)
  - other flavours of neutrino will be produced in flight by neutrino oscillation
- This is essentially the same mechanism that produces high-energy γ-rays from π^0 decay
  - any source that is known (from its spectrum) to produce π^0 decay photons is ***guaranteed*** to be a neutrino source (but possibly not a *detectable* neutrino source, because of the low cross-section)

Waxman-Bahcall bound

- We know the spectrum of high-energy cosmic rays, and pγ interactions with ambient radiation—e.g. CMB photons—must occur and also produce pions, mainly via the Δ resonance
  - therefore we can calculate the expected neutrino flux from this source
  - this is the ***Waxman-Bahcall bound***
- Assume an energy spectrum $\propto E^{-2}$
  - then energy production rate in CRs between E_p and $E_p + dE_p$ is

$$\dot{\mathcal{E}}(E_\mathrm{p})\mathrm{d}E_\mathrm{p} = \dot{N}_\mathrm{p}(E_\mathrm{p}) \times E_\mathrm{p}\mathrm{d}E_\mathrm{p} = \frac{\dot{N}_0}{E_\mathrm{p}}\mathrm{d}E_\mathrm{p}$$

  - Integrate this between 10^{19} and 10^{21} eV, substitute in measured CR energy flux of 5×10^{37} J Mpc^{-3} yr^{-1}
  - solve for $\dot{N}_0$ to get ~10^{37} J Mpc^{-3} yr^{-1}

Waxman-Bahcall bound

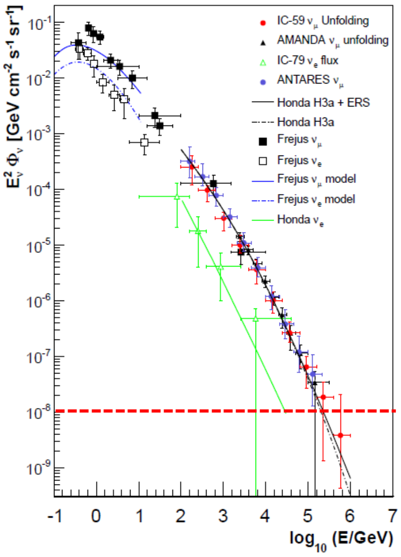
- Now suppose that each proton loses some fraction η of its energy in pion production before it escapes from the source
  - roughly ¼ of that goes into neutrinos
  - resulting neutrino energy density is

$$E_\nu^2 \frac{\mathrm{d}N_\nu}{dE_\nu} \simeq \frac{1}{4}\xi_z \eta t_\mathrm{H} E_\mathrm{p}^2 \frac{\mathrm{d}\dot{N}_\mathrm{p}}{\mathrm{d}E_\mathrm{p}}$$

    - t_H is the Hubble time, ξ_z is an evolution factor which is probably of order 3 or so (to allow for more cosmic ray production in earlier epochs because of more massive stars and AGN)
  - convert from energy density to flux by multiplying by *c*/4π (volume of neutrinos crossing unit area in unit time is *c*; divide by 4π to get flux per unit solid angle)
  - putting in numbers we get $E_\nu^2 \Phi_{\nu_\mu} \simeq \xi_z \eta \times 10^4$ GeV m^{-2} s^{-1} sr^{-1}

High-energy neutrino astrophysics

- Neutrino telescopes are capable of reaching Waxman-Bahcall bound
  - problem is that there is an irreducible background of neutrinos from CR interactions in our atmosphere—“atmospheric neutrinos”
- Neutrinos from astrophysical sources are identifiable only at extremely high energies, above about 100 TeV
  - therefore the expected fluxes are extremely low



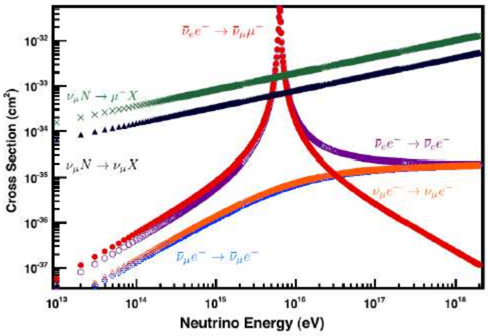
HIGH ENERGY NEUTRINOS

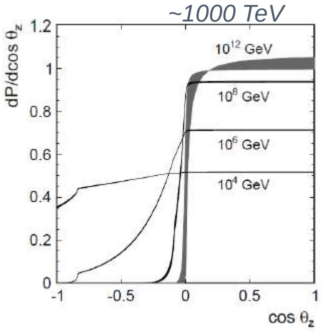
Neutrino interactions with matter

Neutrino interactions with matter

- Neutrinos are weakly interacting
  - this makes them difficult to detect
  - mean free path of 10^{15} eV neutrino in water is $\ell = 1/n\sigma \approx 17000$ km
- Generally $\sigma \propto E$ for scattering off nuclei
  - scattering of $\bar{\nu}_e$ off e^- can excite W resonance

Earth opaque to neutrinos above ~1000 TeV





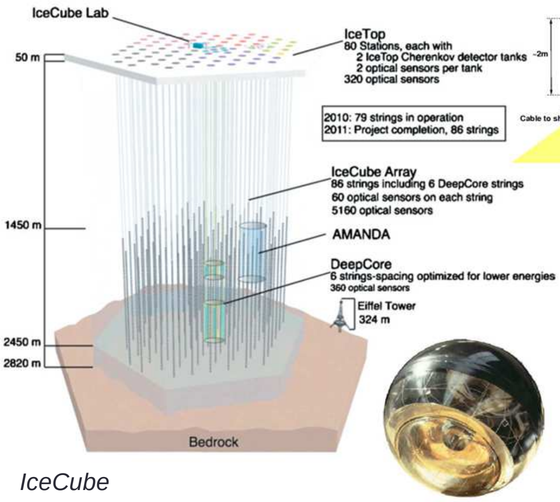
HIGH ENERGY NEUTRINOS

Detection

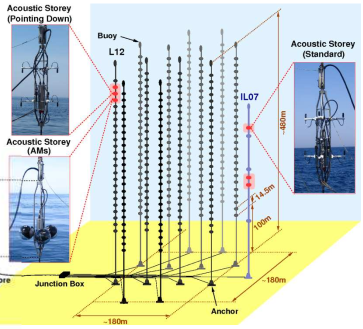
Detection of high-energy neutrinos

- Neutrino interacts by either W exchange or Z exchange
    - W exchange produces charged lepton, which you detect
    - Z exchange at sufficiently high momentum transfer may cause hadronic shower (break-up of struck nucleon) which you also detect
- Detection is normally by Cherenkov radiation in water (liquid water or ice)
    - for ultra-high-energy neutrinos use natural bodies of water/ice to get large effective volumes
        - Lake Baikal, Mediterranean Sea (ANTARES), South Pole (IceCube)
- Muons will leave track, electrons will shower
    - fairly good direction resolution (tenths of a degree) for ν_μ, but poor for ν_e; ν_τ OK if τ decay is seen (“double bang” event)

Neutrino telescopes

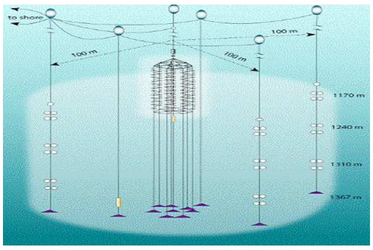


IceCube



ANTARES

Lake Baikal

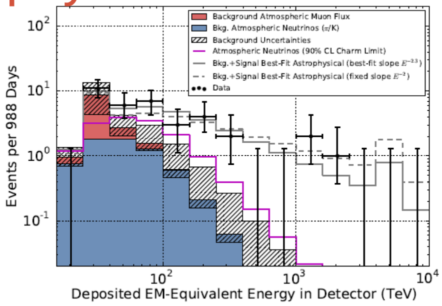


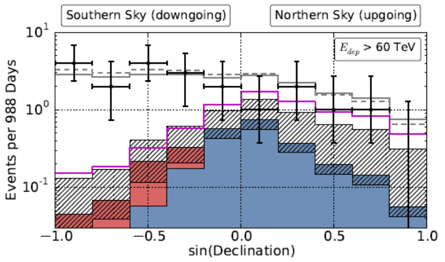
HIGH ENERGY NEUTRINOS

Observations

Observation of astrophysical neutrinos

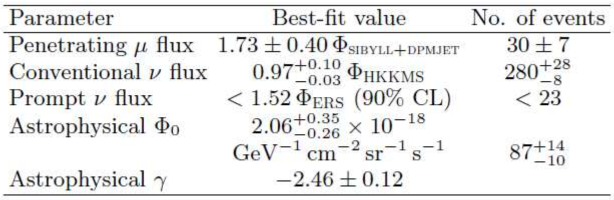
- In 3 years of data taking IceCube has detected 37 events above 30 TeV deposited energy
  - background estimates are 8.4±4.2 CR muons and $6.6^{+5.9}_{-1.6}$ atmospheric neutrinos
  - the excess events are at higher energy than the background and are downgoing
    - high-energy neutrinos have high enough cross-section to be absorbed by the Earth
  - signal significance >5σ owing to difference in distribution





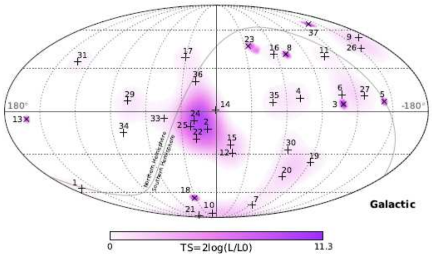
Observation of astrophysical neutrinos

- Derived flux is consistent with Waxman-Bahcall bound
  - spectral index somewhat larger than naïve expectation of 2
    - but this is true of CR spectra too
- No clear point sources
  - most significant cluster is near Galactic centre, but it is not statistically significant and is not confirmed by ANTARES
  - no correlation with Galactic plane
- Need more data!



Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\,\Phi_{\mathrm{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\,\Phi_{\mathrm{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\,\Phi_{\mathrm{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ $\mathrm{GeV^{-1}\,cm^{-2}\,sr^{-1}\,s^{-1}}$	87^{+14}_{-10}
Astrophysical γ	-2.46 ± 0.12	

IceCube arXiv:1410.1749 (astro-ph.HE)



Summary

You should read section 2.5 of the notes.

You should know about

- *π^+ decay*
- *the Waxman-Bahcall bound*
- *neutrino telescopes*
- *IceCube results*

- High-energy astrophysical neutrinos are produced by $\pi^\pm$ decay
  - the pions come from CR proton interactions
- As neutrinos interact extremely weakly, very large detectors are required
  - natural bodies of water/ice instrumented with PMTs to detect Cherenkov radiation from produced leptons or hadronic showers
- The main background is atmospheric neutrinos also produced by CR interactions
  - penetrating CR muons also contribute
- There is a signal (from IceCube) but as yet no identified point sources

Next: acceleration mechanisms

- Fermi second-order
- diffusive shock acceleration
- acceleration by relativistic shocks
- acceleration by magnetic reconnection
- propagation through Galaxy

Notes chapter 3