High-energy Neutrino Astrophysics [1]

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1 Theory

1.A Idea

Neutrinos-

- Ideal astronomical messenger (indirect search for dark matter via neutrinos)
- Not affected by magnetic fields of cosmic ray accelerators in galaxies (black holes, supernovae, etc.).

1.B Cosmic rays

- Cosmic rays- high energy protons and heavy nuclei which bombard Earth (very high energy)
- High magnetic fields near black holes or neutron stars accelerate cosmic rays, which then interact with matter/radiation fields to produce ν's.
- Sources of Cosmic rays:
  - Collapse of massive stars: accelerate particles via shock waves. Examples: supernovae remnant, or gamma-ray burst (hard to observe)
  - Active galactic nuclei: region of high density accretion disk due to a supermassive black hole at the center of the galaxy. Cosmic rays are accelerated in shocks in the accretion disk/jets.

Methods (detect Cerenkov radiation):

1. ν_μ's interacting outside detector- long muon tracks passing through detection volume.
   (a) Limits neutrino view to single flavor and half sky.
   (b) Long tracks allow pointing back to their sources with 0.3^o resolution
   (c) Use Earth as filter for cosmic muon background
2. ν's interacting inside detector
   (a) Can identify neutrino from all directions of sky, and includes muon tracks, secondary showers (produced by ν_e and ν_τ), and neutral interactions (all flavors).
   (b) Detector functions as a total absorption calorimeter (IceCube experiment).
   (c) Need to reconstruct direction of showers, within $10^o - 15^o$.

Challenges:
Select pure ν samples ($\sim 100,000/$ year; background$\sim 10^{10}$ cosmic-ray muons);
identify neutrinos of astrophysical origin (~ 10 events/year);
below $\sim 100TeV$, atmospheric ν's are significant background.

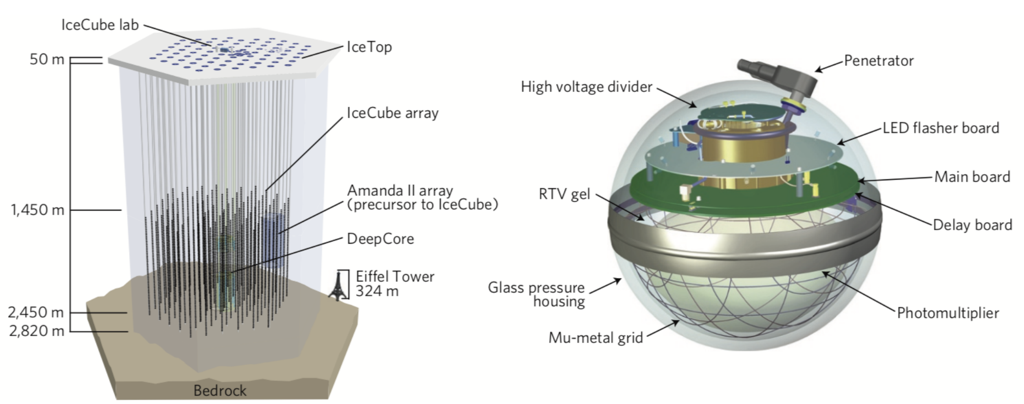

Figure 1: Left: IceCube observatory. Right: digital optical module

2 Results and Further Theory

2.A Results

Six years of data- ~ 100 GZK neutrino events, in the PeV range ($\sim 10^{15}$)

2.B Further Theory: Origin of Cosmic ν 's

- Experiment show neutrino flux has isotropic distribution of arrival directions, and equal contributions of all ν flavors.
- Connection of cosmic neutrinos to cosmic rays and gamma rays:
  - Supernovae: cosmic rays interact with hydrogen in Galactic disk, producing π's decaying to pionic photons (?) and ν's.
  - May have light extragalactic sources: accretion disk of active galactic nuclei, or gamma-ray burst.
  - The spectral production rates $\mathrm{d}N/\mathrm{d}E\mathrm{d}t$ of neutrinos and gamma rays are related by

    $$\frac{1}{3}\sum E_v^2 \frac{\mathrm{d}N_v}{\mathrm{d}E_v\mathrm{d}t}\left(E_v\right) \simeq \frac{K_\pi}{4} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma\mathrm{d}t}\left(E_\gamma\right)$$

    where N and E- number and energy of neutrinos and gamma rays.
- A common origin of the sources could suggest blazars.

3 High Energy Neutrinos and Dark Matter

- Isotropic arrival directions of cosmic neutrinos- might originate from the decay of PeV dark matter particles at Galactic halos.
- Look for annihilation of WIMPs at high density: the Sun, the Milky Way, nearby galaxies.
- The Sun:
  - WIMPs may scatter elastically with nuclei in the Sun ad become gravity bound.

- Indirect signature of halo dark matter: WIMPs annihilate to final states, which could decay to neutrinos escaping the Sun with minimal absorption.
- Example models: annihilation of WIMPs to heavy fermions or weak bosons, which may then decay, resulting in neutrinos. ($\chi\chi \rightarrow \tau\bar{\tau}$, $b\bar{b}$, or $W^+W^- \rightarrow$ high energy neutrinos ≥ 20 GeV and other particles)
- Signature of dark matter: an excess of neutrinos ($\geq$ GeV energy) over background (atmospheric neutrinos) in the direction of the Sun.
- IceCube experiment: established limits on WIMPs with spin-dependent interactions with protons.

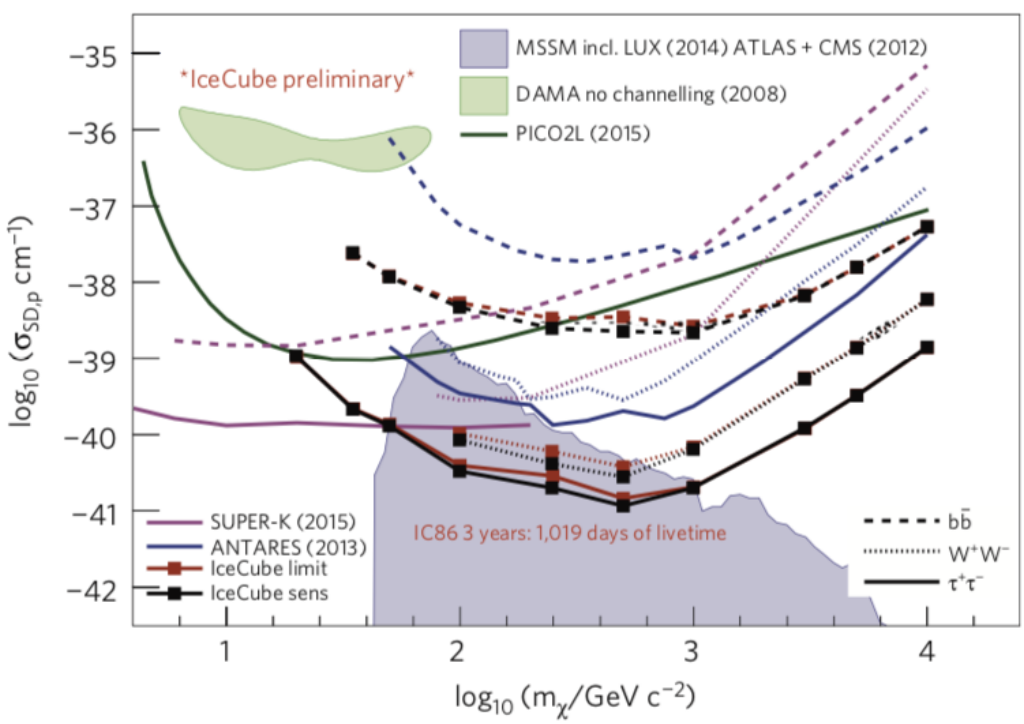

Figure 2: Dark matter cross section limits

References

[1] F. Halzen, “High-energy neutrino astrophysics,” *Nature Physics*, vol. 13, no. 3, p. 232–238, 2016.