

# The First High-Energy Extragalactic Neutrinos

*Dan Hooper*

*Particle Astrophysics Center*

*Fermi National Accelerator Laboratory*

*dhooper@fnal.gov*

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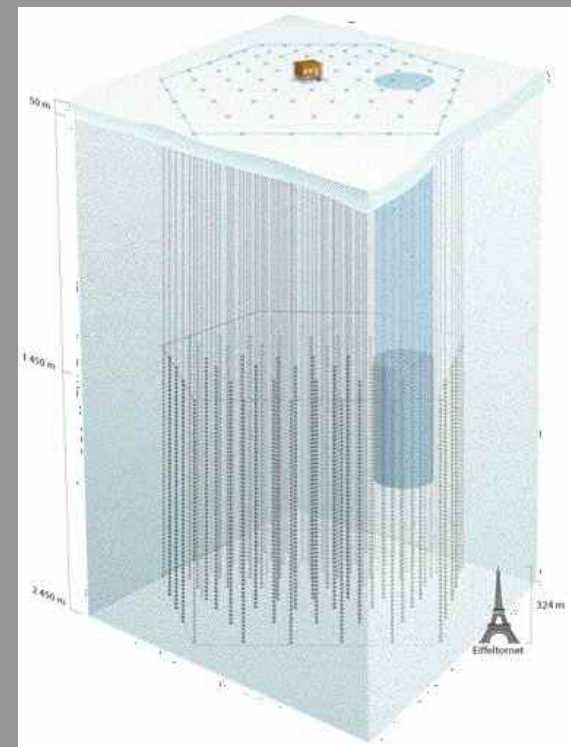


# The Neutrinos Are Coming!

- To date, no (confirmed) sources of high or ultra-high energy neutrinos have been discovered
- This is likely to change soon
- Experimental sensitivity is rapidly approaching that needed to detect the first galactic and extra-galactic sources of high energy cosmic neutrinos



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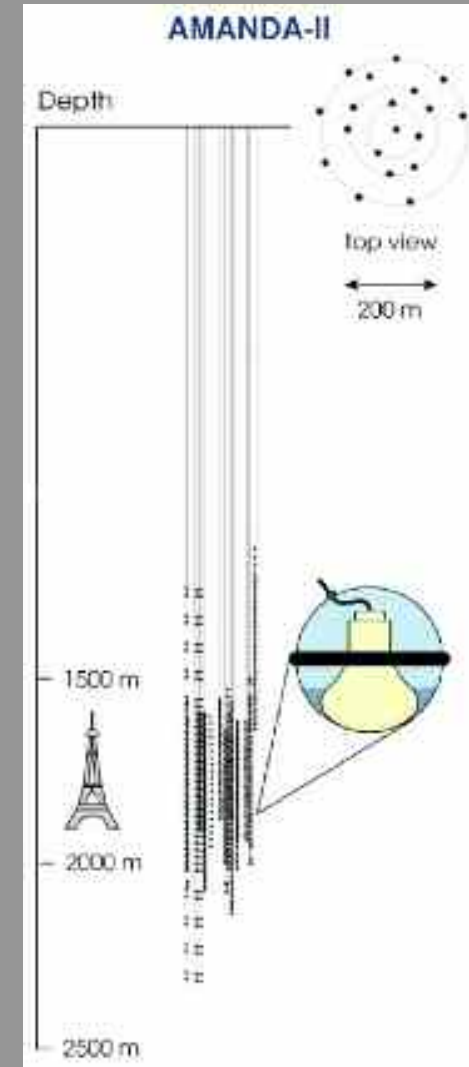
# Tools of the Trade: The First Generation

## AMANDA:

- Below ~2 kilometers of Antarctic ice
- Optical Cerenkov,  $E_{\mu,th} \sim 30$  GeV
- Effective Area of ~50,000 sq meters
- Sensitive to muons, EM/hadronic showers
- ~7 years of data in current form

## ANTARES:

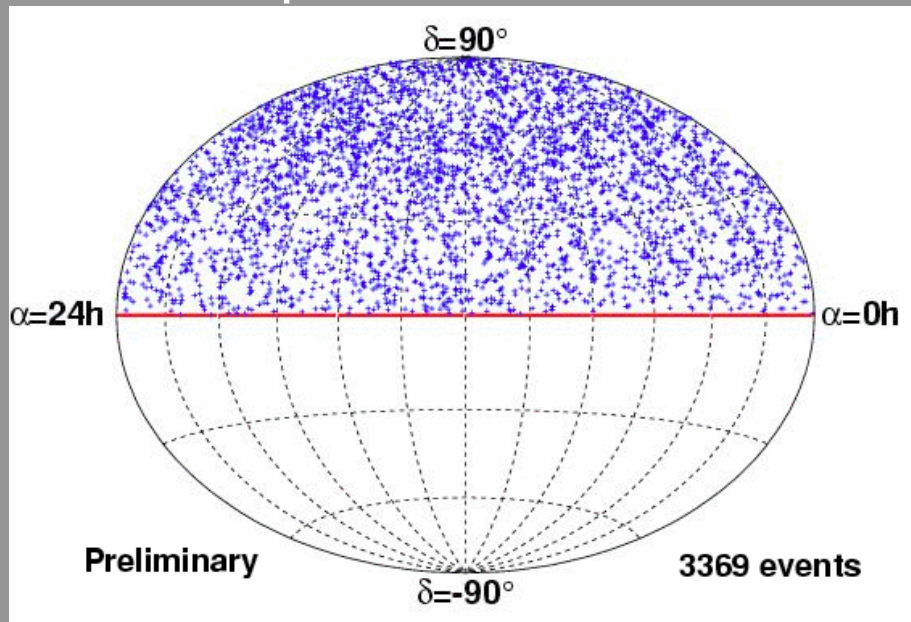
- Under construction in Mediterranean Sea
- Somewhat larger effective area, and lower energy threshold than AMANDA
- Northern hemisphere location



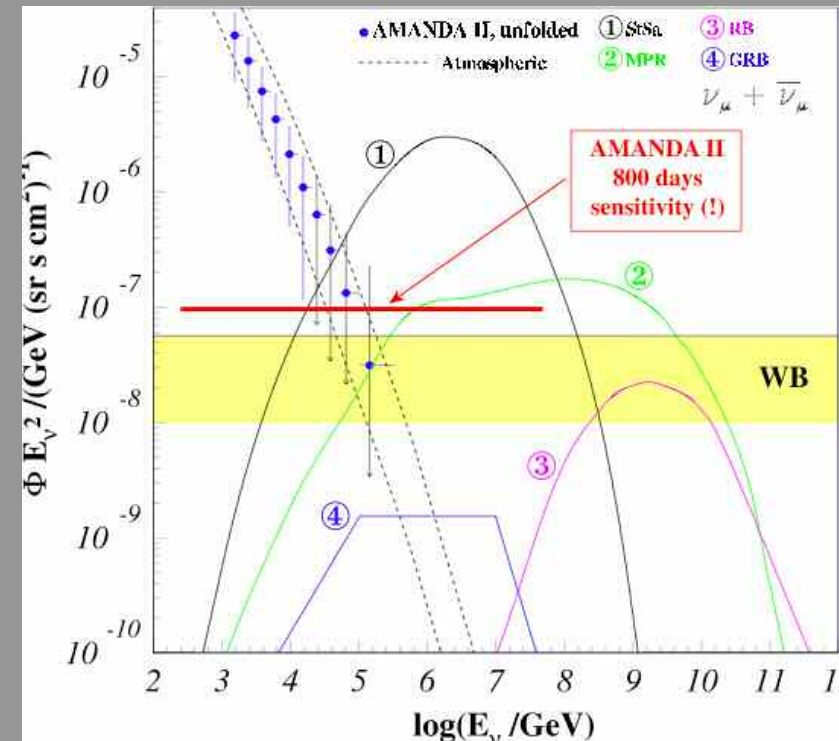
# Tools of the Trade: The First Generation

## The Successes of AMANDA

- 800 live days analyzed (over 4 years); atmospheric neutrino spectrum measured to  $\sim 100$  TeV; consistent with theoretical expectations
- Sensitivity to diffuse neutrino flux in 100 GeV-100 PeV range approaching  $10^{-7}$  GeV cm $^{-2}$  s $^{-1}$  sr $^{-1}$
- Limits on point sources at the level of  $6 \times 10^{-8}$  GeV cm $^{-2}$  s $^{-1}$



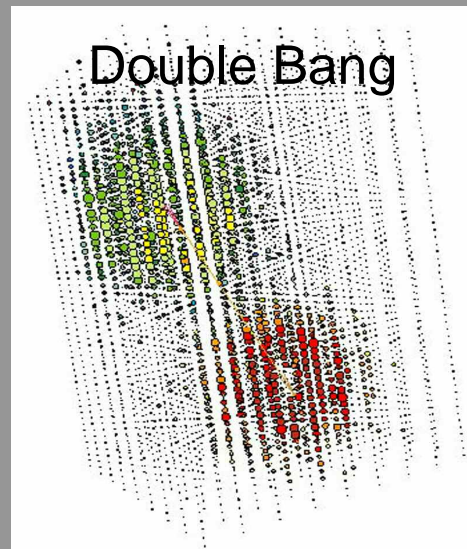
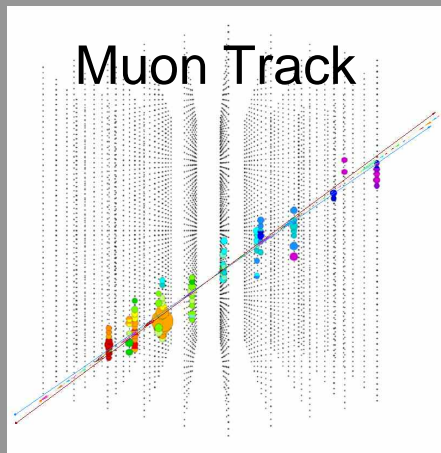
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# Tools of the Trade: The Next Generation

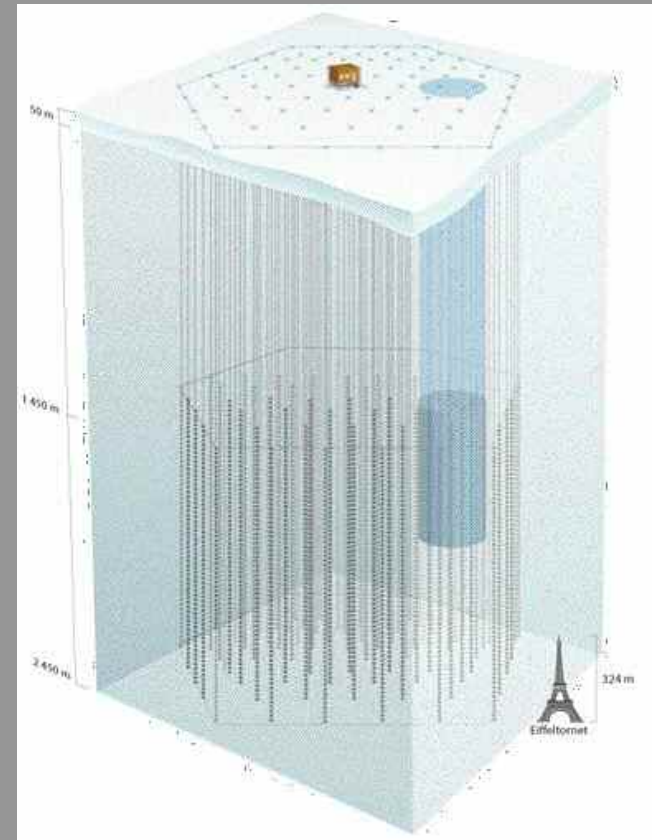
## IceCube

- Full Cubic Kilometer Instrumented Volume
- 22 (of 80) strings currently deployed (13 this season)
- Sensitive to muon tracks, EM/hadronic showers, and tau-unique events (above  $\sim$ PeV)



- Similar prospects for KM3Net

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# Extragalactic Sources of High Energy Neutrinos

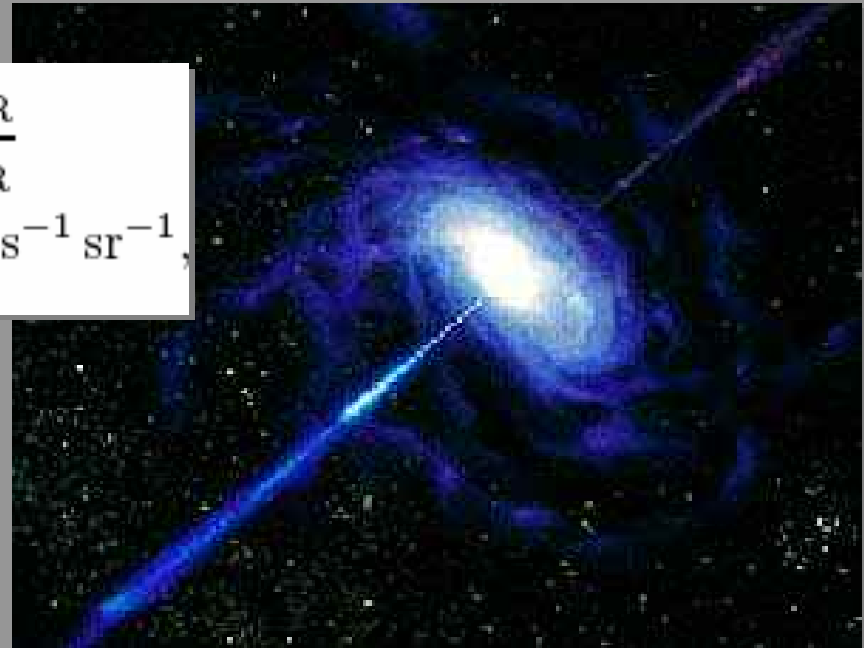
- Cosmic ray spectrum of protons/nuclei extends to  $\sim 10^{20}$  eV
- pp, p $\gamma$  interactions generate neutrinos from cosmic ray sources



# Extragalactic Sources of High Energy Neutrinos

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- pp, p $\gamma$  interactions generate neutrinos from cosmic ray sources
- The flux of neutrinos produced in UHE/HE sources can be tied to the cosmic ray spectrum
- “Waxman-Bahcall” Argument:

$$\begin{aligned} [E_\nu^2 \Phi_\nu]_{\text{WB}} &\approx (3/8) \xi_Z \epsilon_\pi t_H \frac{c}{4\pi} E_{\text{CR}}^2 \frac{d\dot{N}_{\text{CR}}}{dE_{\text{CR}}} \\ &\approx 2.3 \times 10^{-8} \epsilon_\pi \xi_Z \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \end{aligned}$$



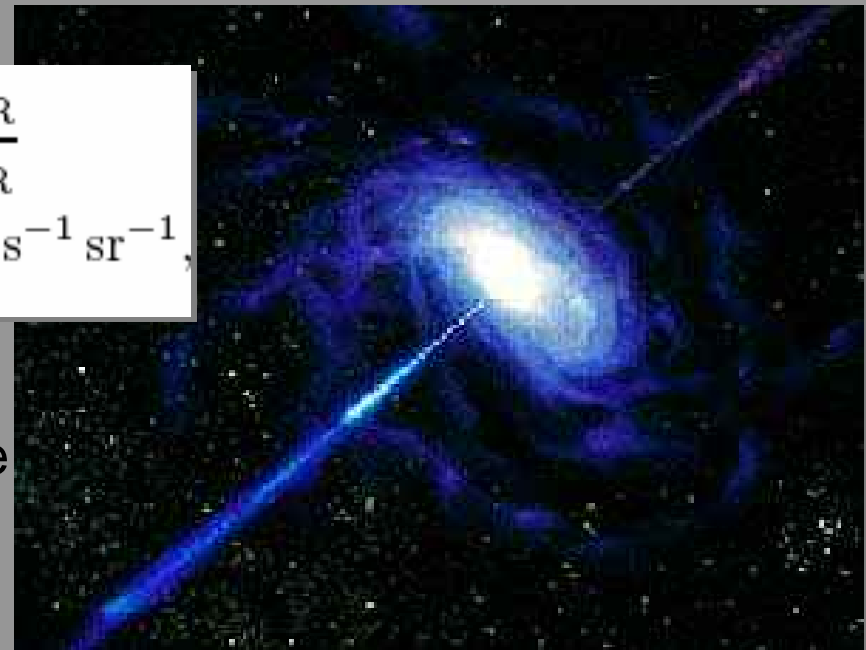
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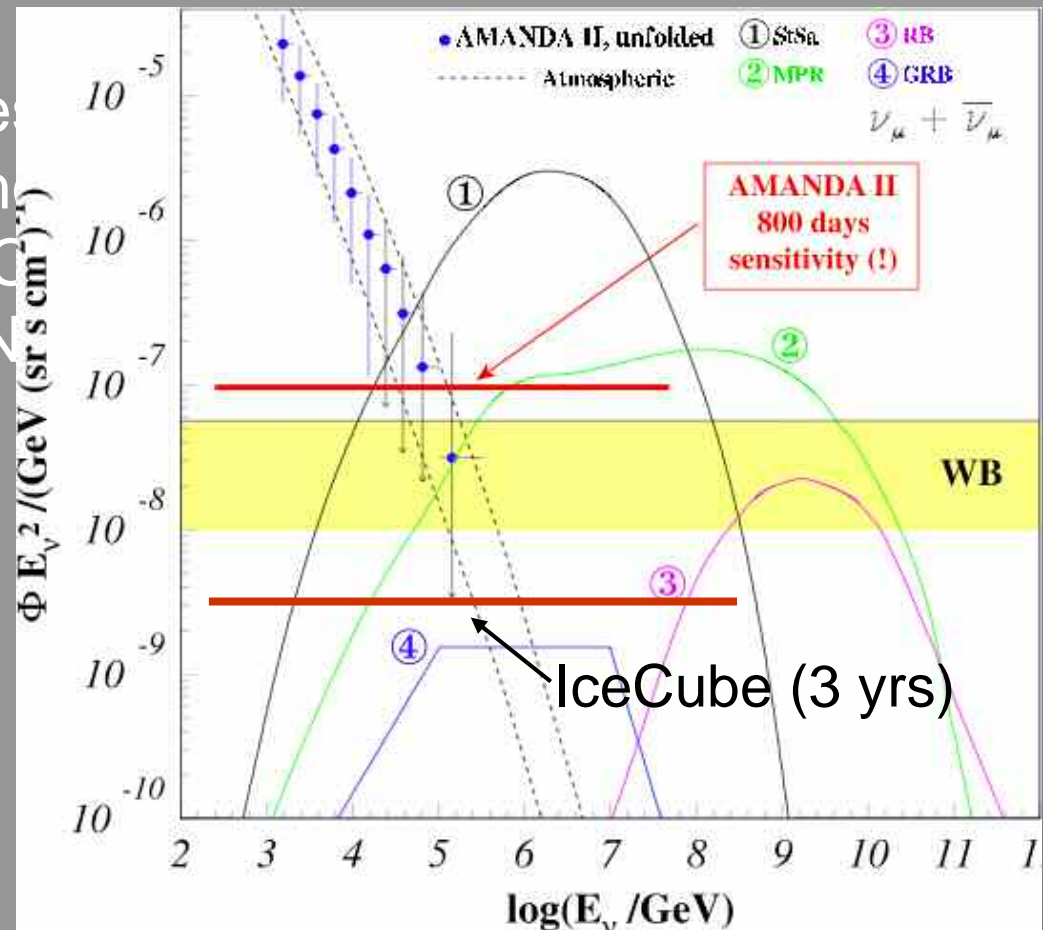
Fraction of proton energy to pions

Accounts for source evolution, etc. ( $\sim 1$ )



# Extragalactic Neutrino Flux

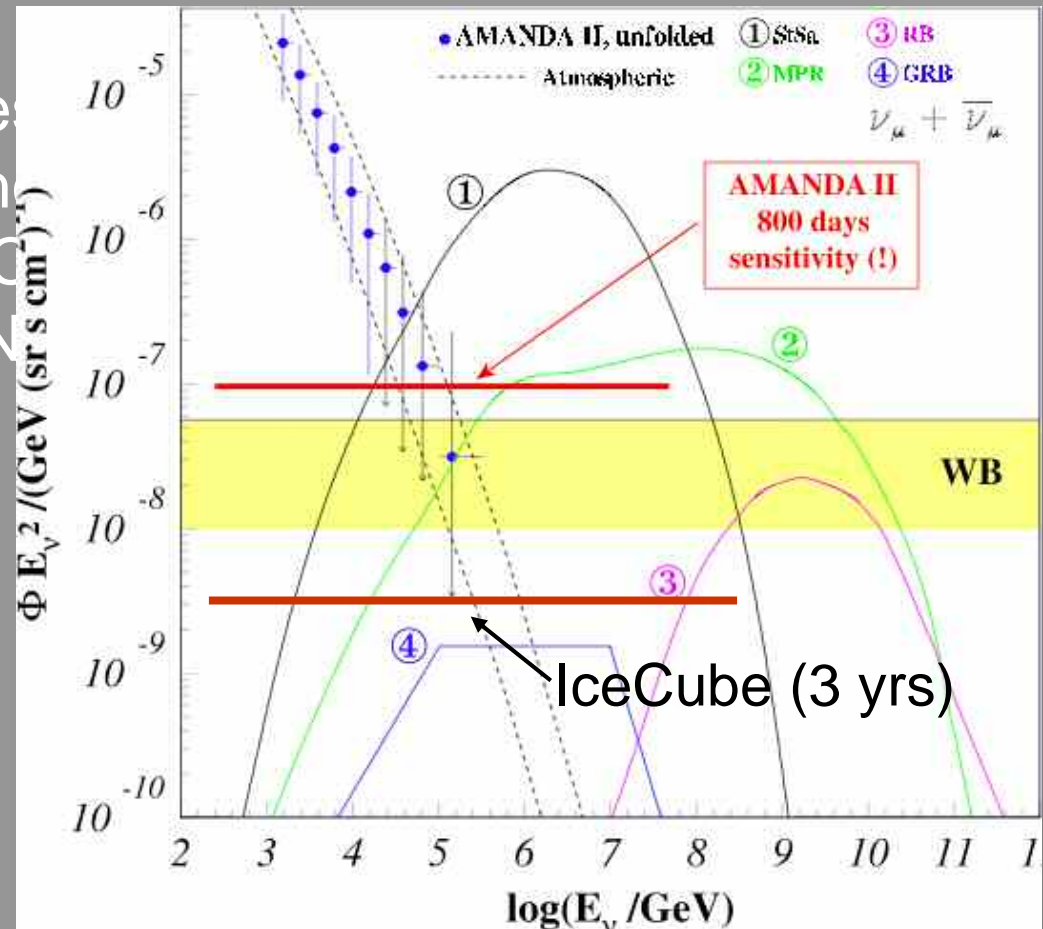
- IceCube will reach well below the predicted levels for  $\varepsilon_\gamma \sim 1$  (ie. the Waxman-Bahcall “Flux”)
- Models of gamma ray bursts, active galactic nuclei, and starburst galaxies predict a flux of neutrinos within the reach of IceCube (or KM3NeT)



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**Likely to observe first cosmic high-energy neutrinos in coming years!**



# Radio Techniques

## RICE

- Array of radio antennas co-deployed with AMANDA
- Effective Volume of  $\sim 1 \text{ km}^3$  at 100 PeV; several  $\text{km}^3$  at 10 EeV
- Limits on diffuse neutrino flux in 200 PeV-200 EeV range of  $6 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Future radio deployments with IceCube promising

## ANITA-Lite, ANITA

- Balloon-based radio antennas
- ANITA-lite limit on diffuse flux above  $\sim \text{EeV}$  of  $\sim 10^{-6} \text{ GeV/cm}^2 \text{ s}^{-1} \text{ sr}^{-1}$
- 36 day ANITA flight ended Jan. 20  
 $\Rightarrow$  sensitivity of  $\sim 10^{-8} \text{ GeV/cm}^2 \text{ s sr}$   
observe the first UHE neutrino?



# Ultra High Energy Cosmic Ray Experiments

## The Pierre Auger Observatory

- Southern site currently under construction in Argentina
- First data released in 2005 (no neutrino data yet)
- Sensitive above  $10^8$  GeV, 3000 km<sup>2</sup> surface area
- Neutrino ID possible for quasi-horizontal showers and Earth-skimming, tau-induced showers
- AGASA experiment places limits on UHE neutrino fluxes

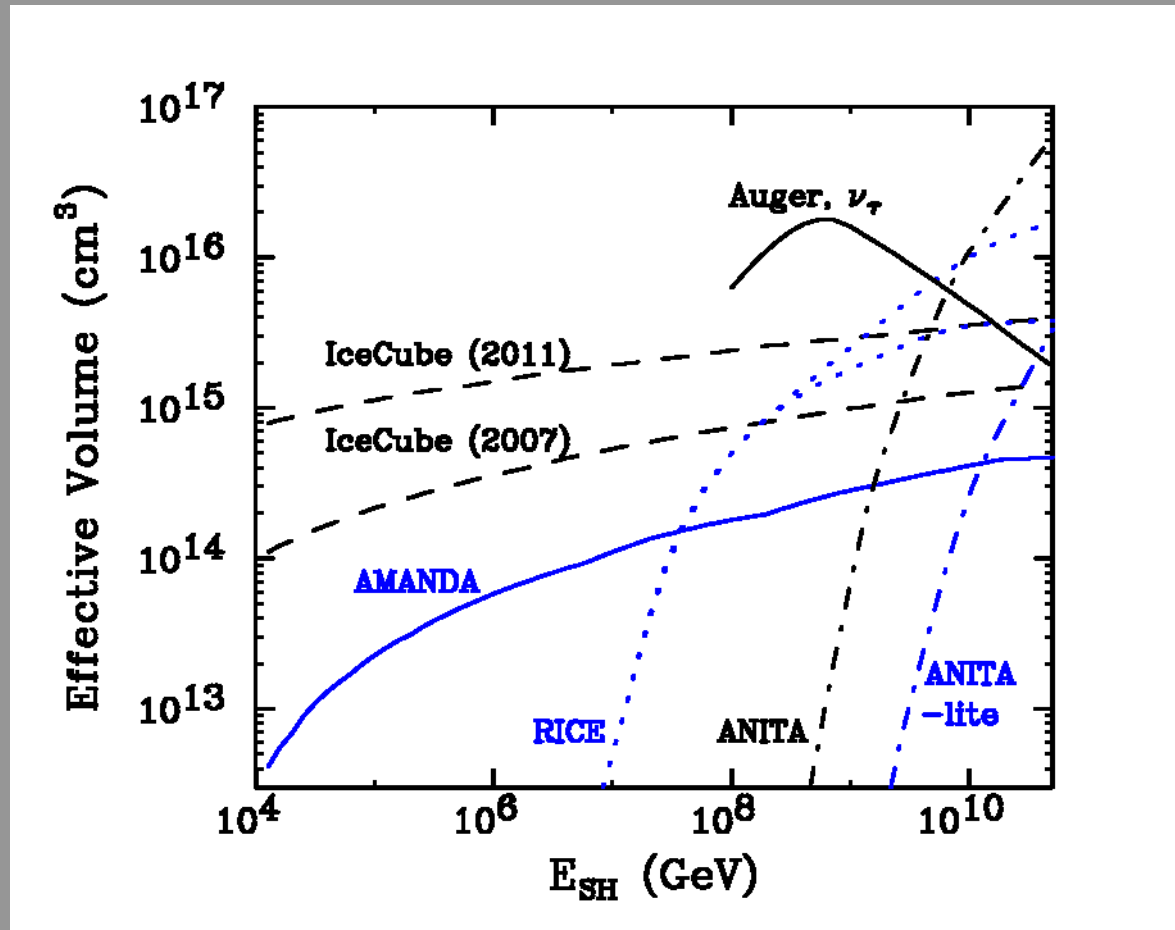
## EUSO/OWL

- Satellite/space station based
- Enormous aperture
- Future uncertain

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# The Future of Ultra-High Energy Neutrino Astronomy



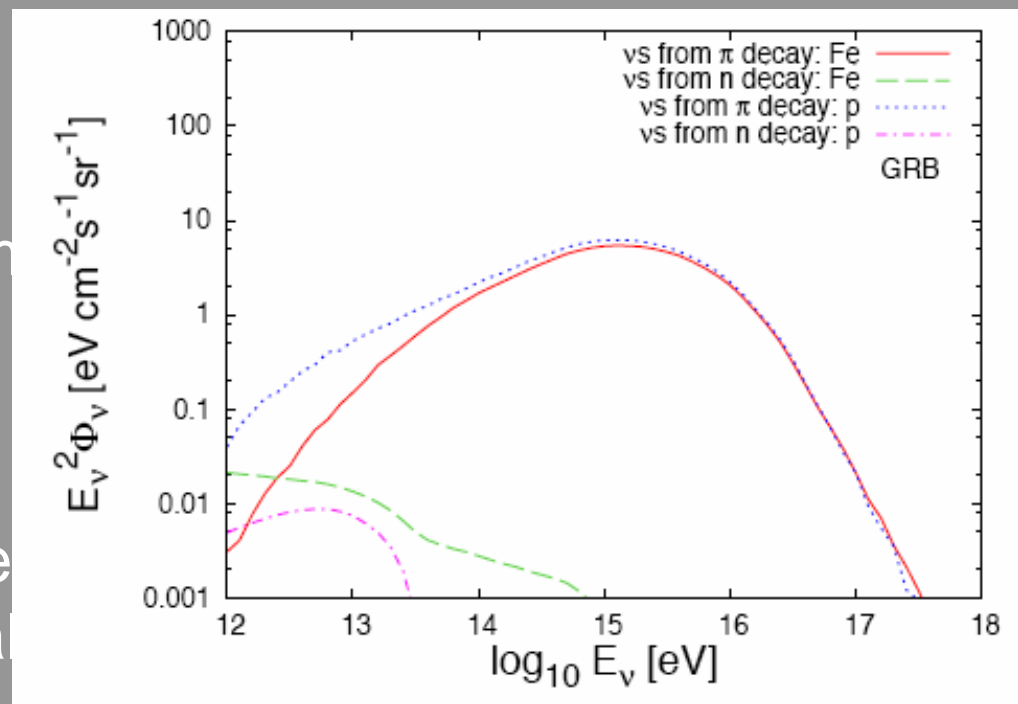
# Neutrinos From Cosmic Ray Accelerators

- Hillas Criterion requires very extreme properties for the sources of the observed UHECRs, which few known objects possess
- Among the most promising possibilities are:
  - Gamma Ray Bursts
  - Active Galactic Nuclei
  - Starburst Galaxies
- Could appear as a diffuse flux (up to WB bound), or as point sources (in space and/or time)



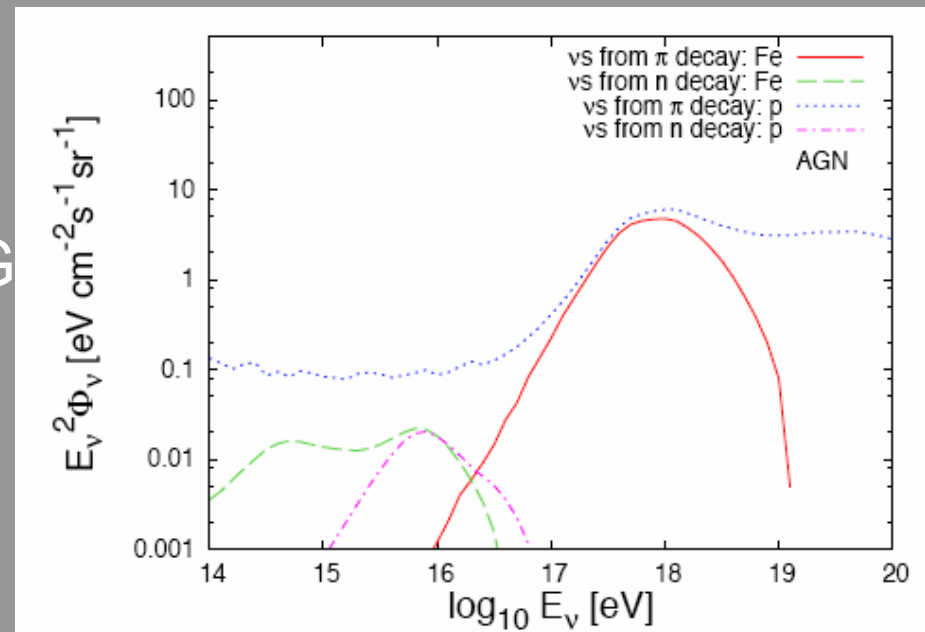
# Gamma Ray Bursts

- Total observed (gamma ray) luminosity in all GRBs is remarkably similar to the total flux of cosmic rays above the ankle
- If GRBs accelerate the highest energy cosmic rays, then they will also produce pions and neutrinos, the flux of which can be straightforwardly calculated/estimated
- Around  $\sim 10$  (PeV) neutrinos per year are expected in a kilometer-scale experiment
- Analysis in conjunction with gamma ray astronomy (*ie.* Swift) can be used to remove essential



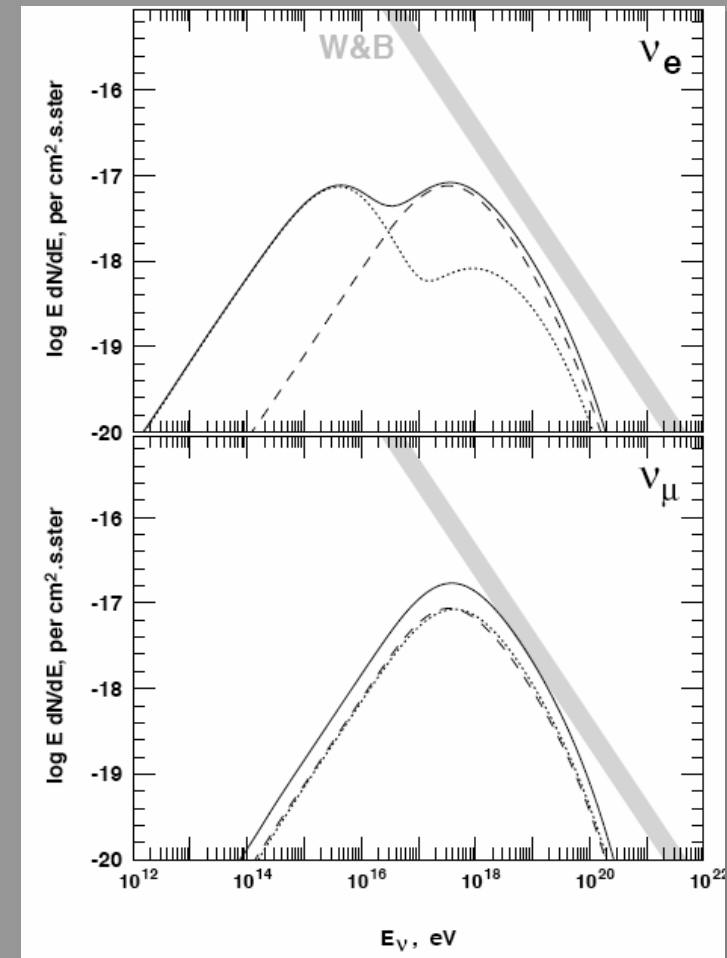
# Active Galactic Nuclei

- Along with GRBs, AGN are one of the few classes of astrophysical objects that can potentially accelerate particles to  $10^{20}$  eV (AGN are the most energetic sources in the universe)
- If AGN are the sources of the UHECRs, then it is plausible that they will also produce an observable flux of EeV neutrinos ( $\sim 1$  event/year in a  $\text{km}^3$  experiment - but estimates vary!)
- Known locations (point sources) along with flaring periods can be used to remove/reduce BG



# Cosmogenic Neutrinos

- Ultrahigh energy protons interaction with the CMB, producing pions, and subsequently neutrinos
- The resulting neutrino spectrum - the cosmogenic neutrino flux - has long been considered to be a “guaranteed” source of UHE neutrinos
- Event rate of  $\sim 1/\text{yr}$  is predicted at a kilometer-scale neutrino telescope

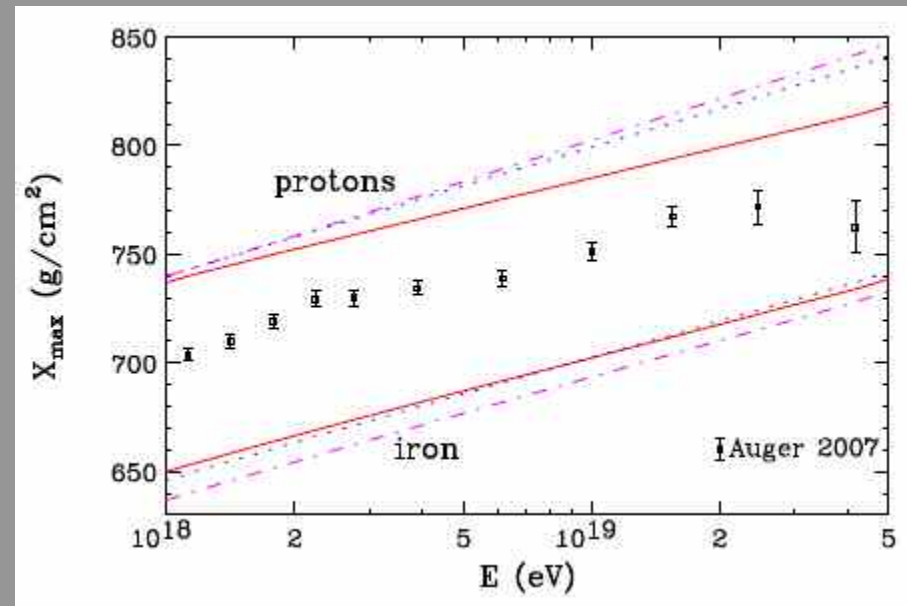
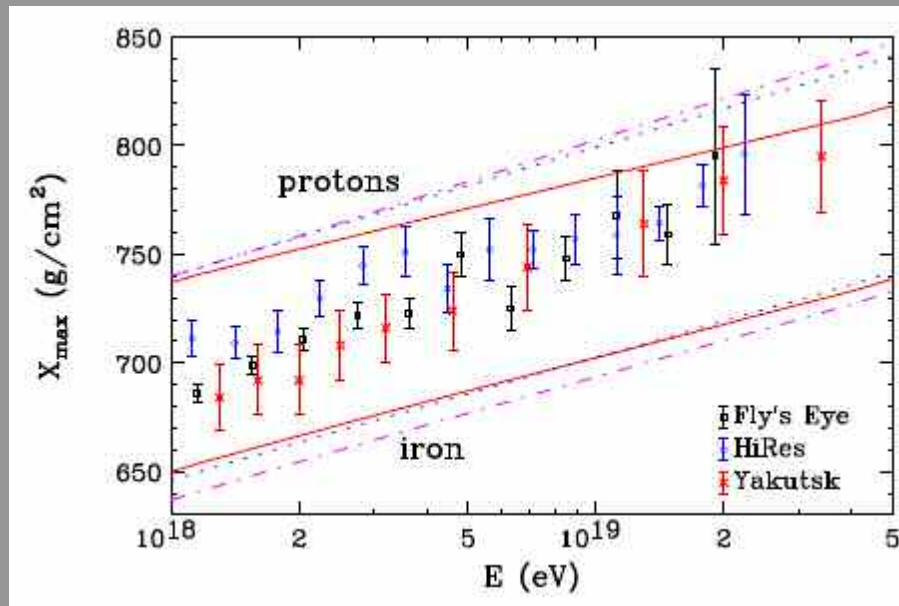


Engle, Seckel, and Stanev,  
PRD, astro-ph/0101216

# Cosmogenic Neutrinos And UHECR Nuclei

Motivations for nuclei domination in the UHECR spectrum:

- 1) Hillas criterion for the maximum energy produced in a cosmic ray accelerator scales with electric charge,  $Z$
- 2) Magnetic fields effect nuclei more strongly, helping to explain the lack of identified UHECR point sources
- 3) New data from Auger strongly favors a mixed proton-heavy nuclei composition ***Important implications for neutrino astronomy!***



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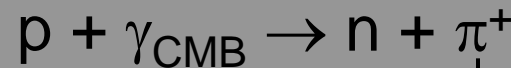
(See yesterday's talk by Angela Olinto)

# Cosmogenic Neutrinos And UHECR Nuclei

- In the of case nuclei UHECRs, UHE neutrinos are produced very differently than with protons
- For example:



... etc.



Neutrinos!

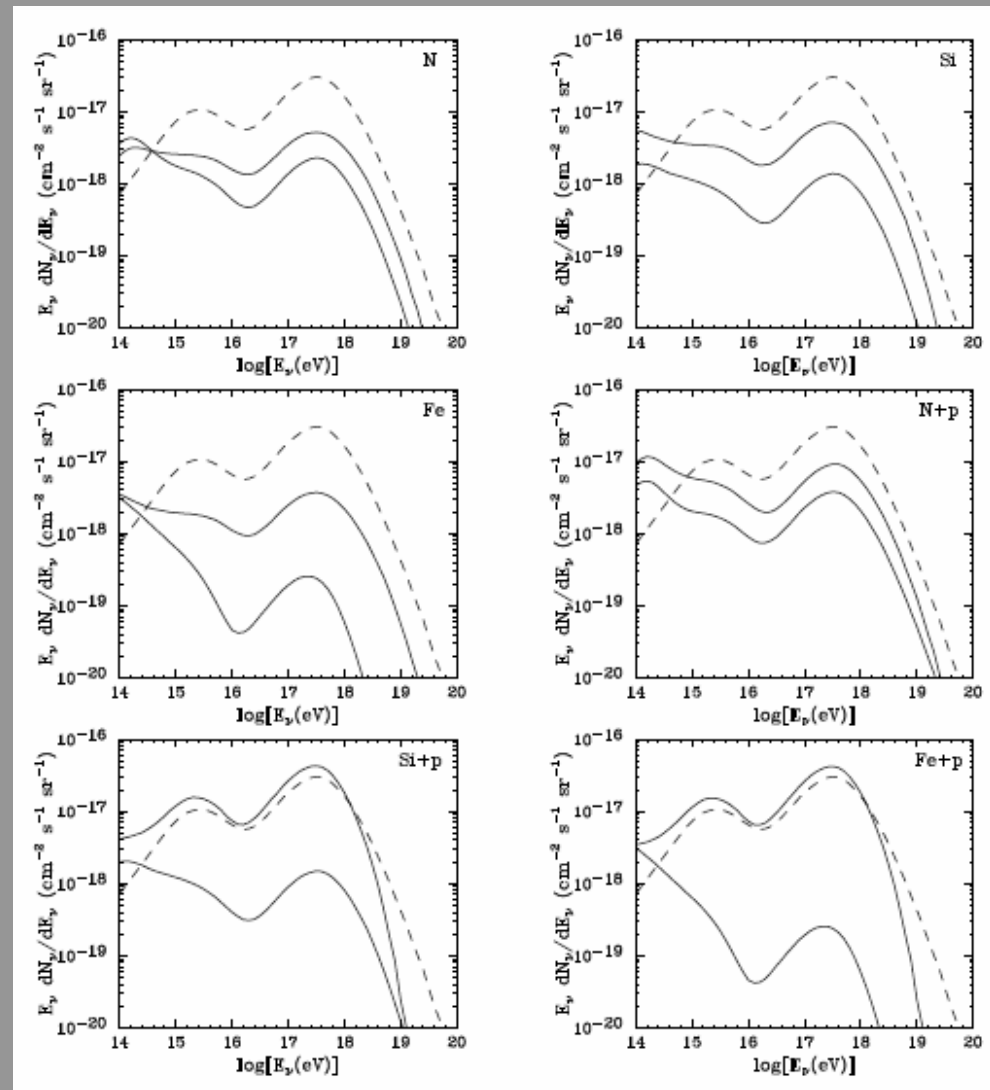
# Cosmic Ray Nuclei and Cosmogenic Neutrinos

- If the UHECR composition is a mixture of protons and heavy nuclei, the cosmogenic neutrino flux is only mildly affected

- If dominated by heavy/intermediate nuclei, however, the neutrino flux can be highly suppressed

- From Auger spectrum and composition measurements, we predict **1.4 to 0.015** events per year per km<sup>3</sup>

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Anchordoqui, Goldberg, Hooper, Sarkar and Taylor, in preparation

# Conclusions

- The experimental status of neutrino astronomy is fast approaching the sensitivity expected to be required to observe the first high and ultrahigh energy cosmic neutrinos (IceCube, Anita, Auger, etc...)
- Would-be UHE cosmic ray accelerators such as gamma ray bursts or active galactic nuclei remain among the most promising sources for extragalactic cosmic neutrinos  
(best guess of ~1-10 events per year in km scale experiments)
- The prospects for observing cosmogenic neutrinos depend critically on the composition and spectrum of the UHE cosmic rays as they are injected by their sources  
(protons with only a small component of heavy nuclei can lead to as many as ~1 event/yr at IceCube or ~1 event per flight at Anita; Nuclei domination can lead to as little as 1 event per century)

# THANKS!

