Neutrino Astrophysics

Tom Weiler
Vanderbilt University

μ

Outline

* General UHE ν remarks
* ν Fluxes an Detectors
* ν Flavor Physics
* The LSND-ino/miniBooNE-ino
*

Tom Weiler,
Vanderbilt University

Neutrino-rays versus Cosmic-Rays and Photons

νs come from central engines

- near R_s of massive BHs
- even from dense “hidden” sources
  cf. νs vs. γs from the sun

νs not affected by cosmic radiation

(except for annihilation resonance)

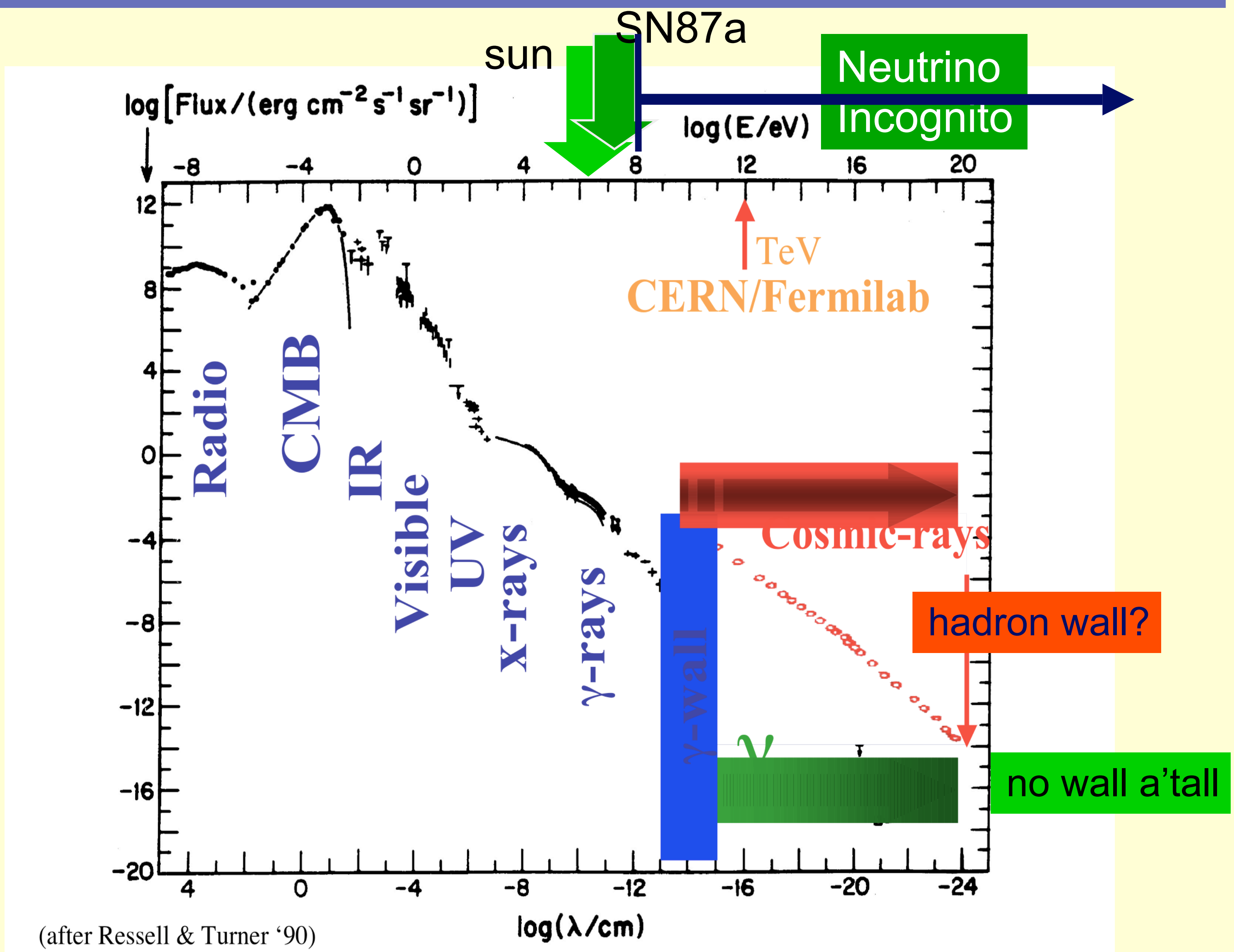
νs not bent by magnetic fields

- enables neutrino astronomy

Also, besides Energy and Direction, ν’s carry Flavor

The Neutrino Flux

Cosmic Photon- Proton-Spectra



(after Ressell & Turner '90)

Tom Weiler,
Vanderbilt University

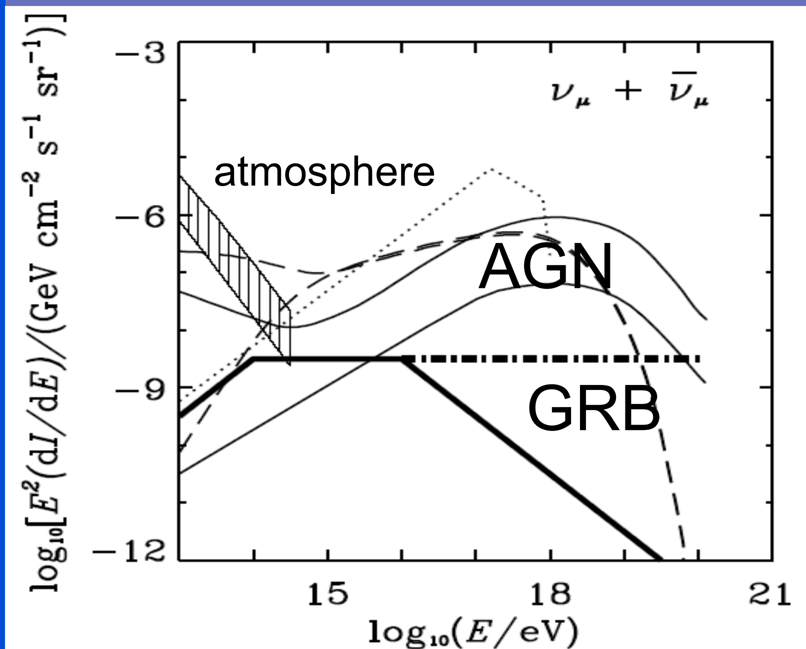
General Remarks on Neutrinos

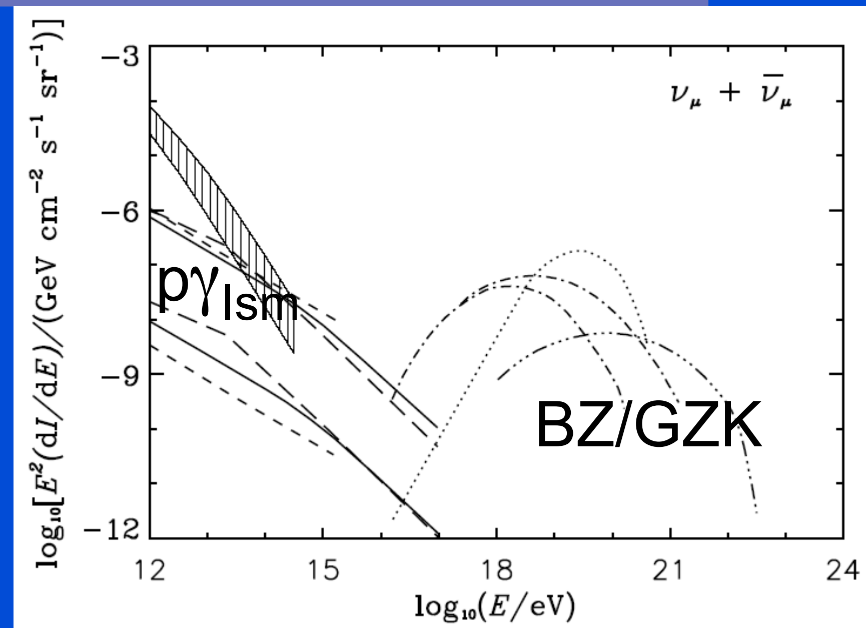
Existence of Xgal neutrinos inferred from CR spectrum, up to 10^{20} eV,
and similarly, Galactic up to 10^{18} eV,

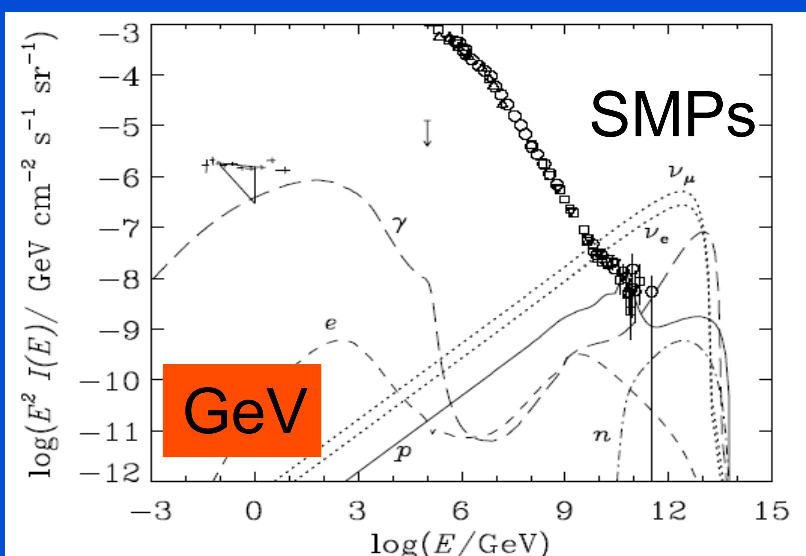
Need gigaton (km^3) mass (volume) for TeV to PeV detection [e.g. IceCube Xpt]
but a teraton of mass at 10^{19} eV
➔ SPACE-BASED [e.g. EUSO Xpt]

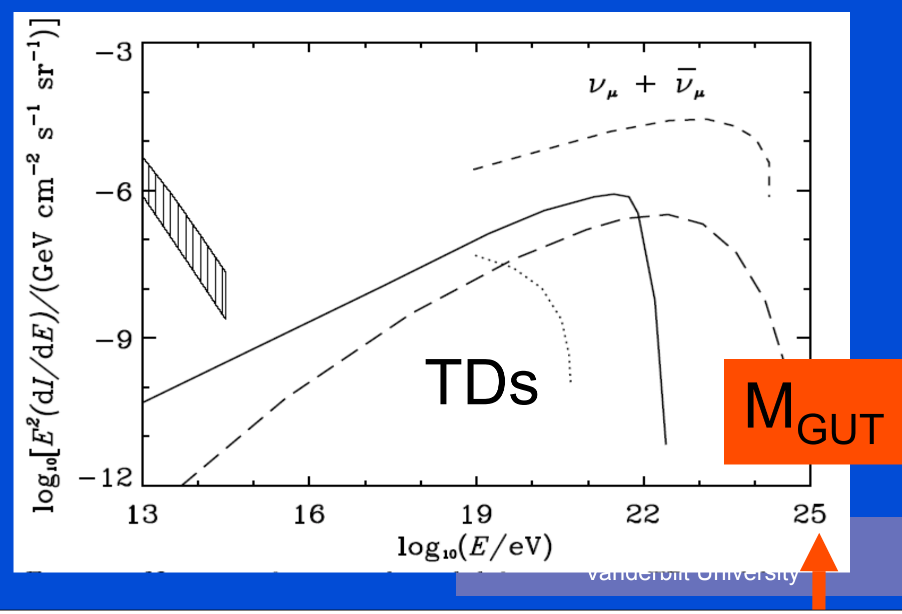
Neutrino eyes see farther (z>1),
and deeper (into compact objects) than gamma-photons,
and straighter than HECRs,
with no absorption at (almost) any energy

Model ν fluxes (Protheroe review 1996)





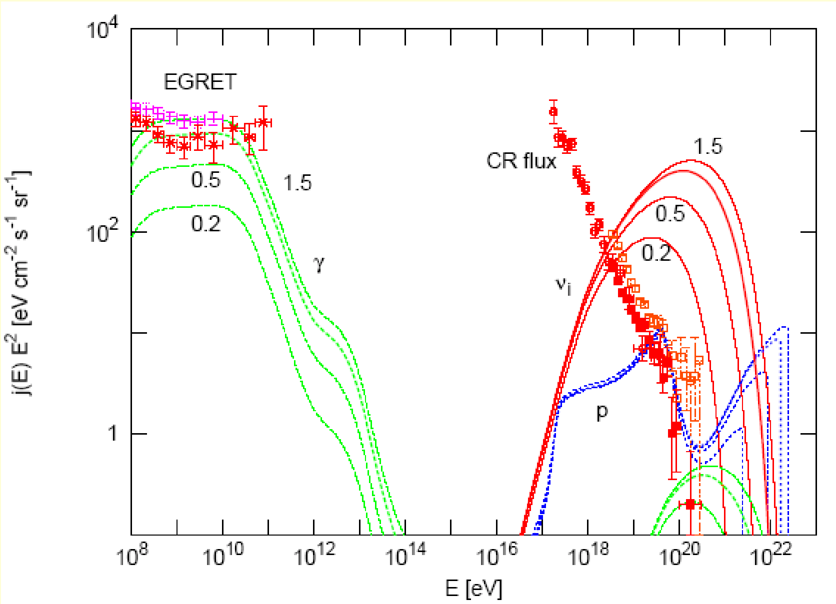


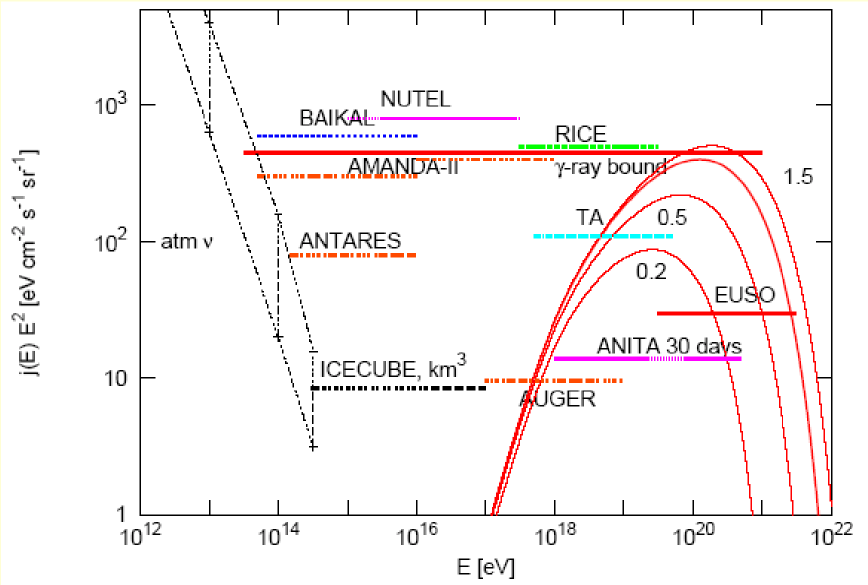


“Essentially Guaranteed” Xgalactic Cosmogenic ν Flux

Cosmogenic ν’s:

$F_\nu(E_p/5/4) = F_p(E>5\ 10^{19})\ x\ 20$



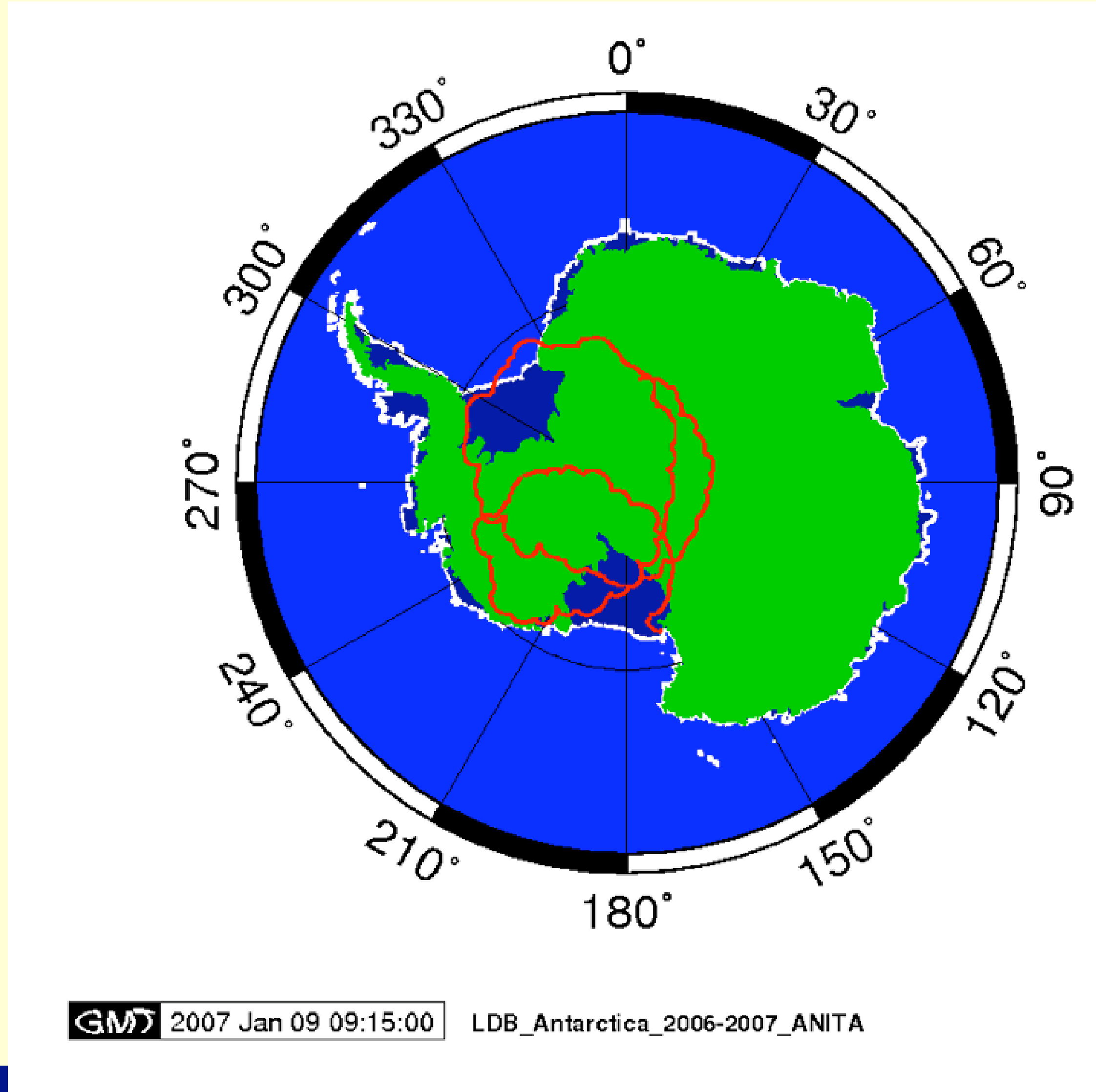


graphs from Semikoz and Sigl

Tom Weiler,
Vanderbilt University

Anita

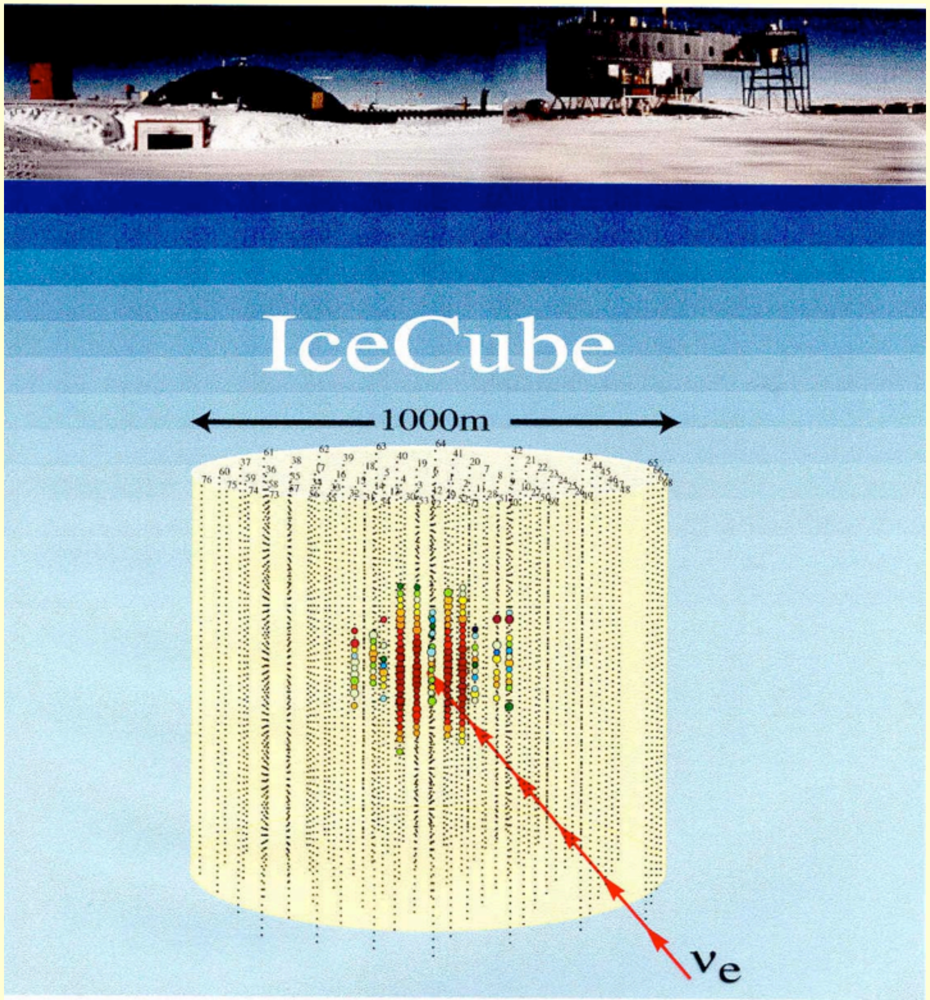
ANITA flight path, launched 15Dec2006

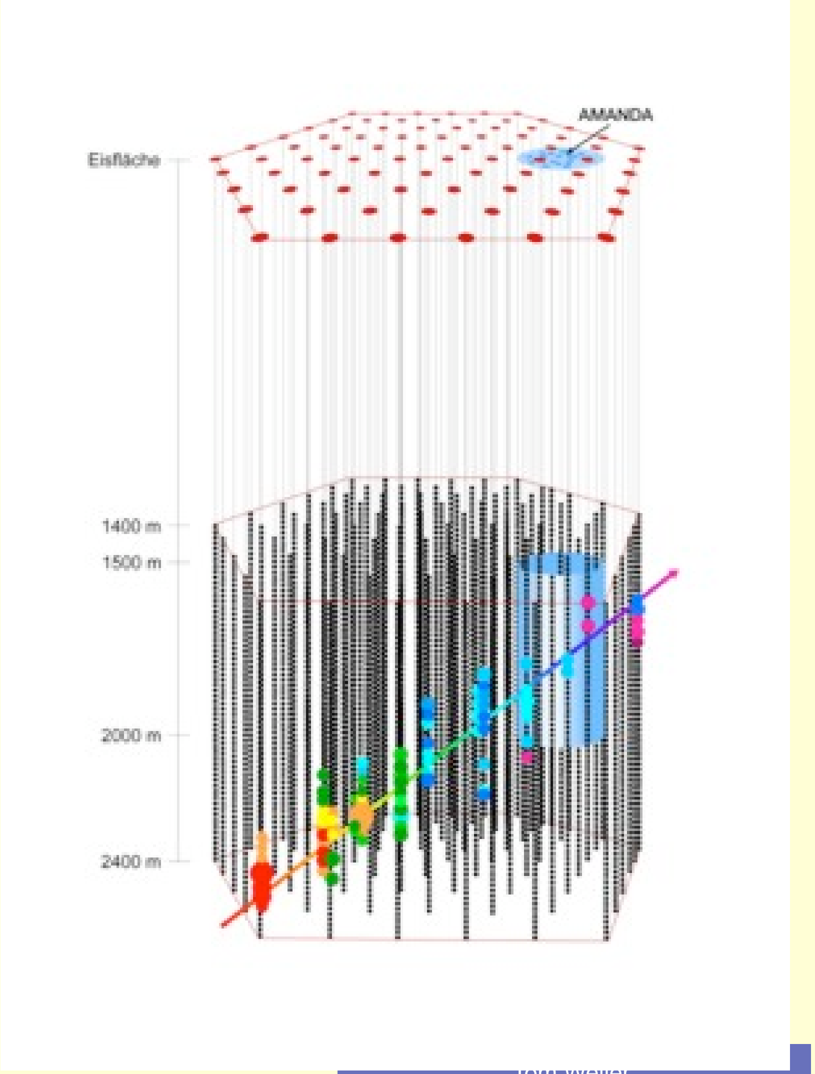


AMANDA, RICE, Anita, IceCube, AURA, ARIANNA: Antarctic Cap = Neutrino Trap

Tom Weiler,
Vanderbilt University

IceCube

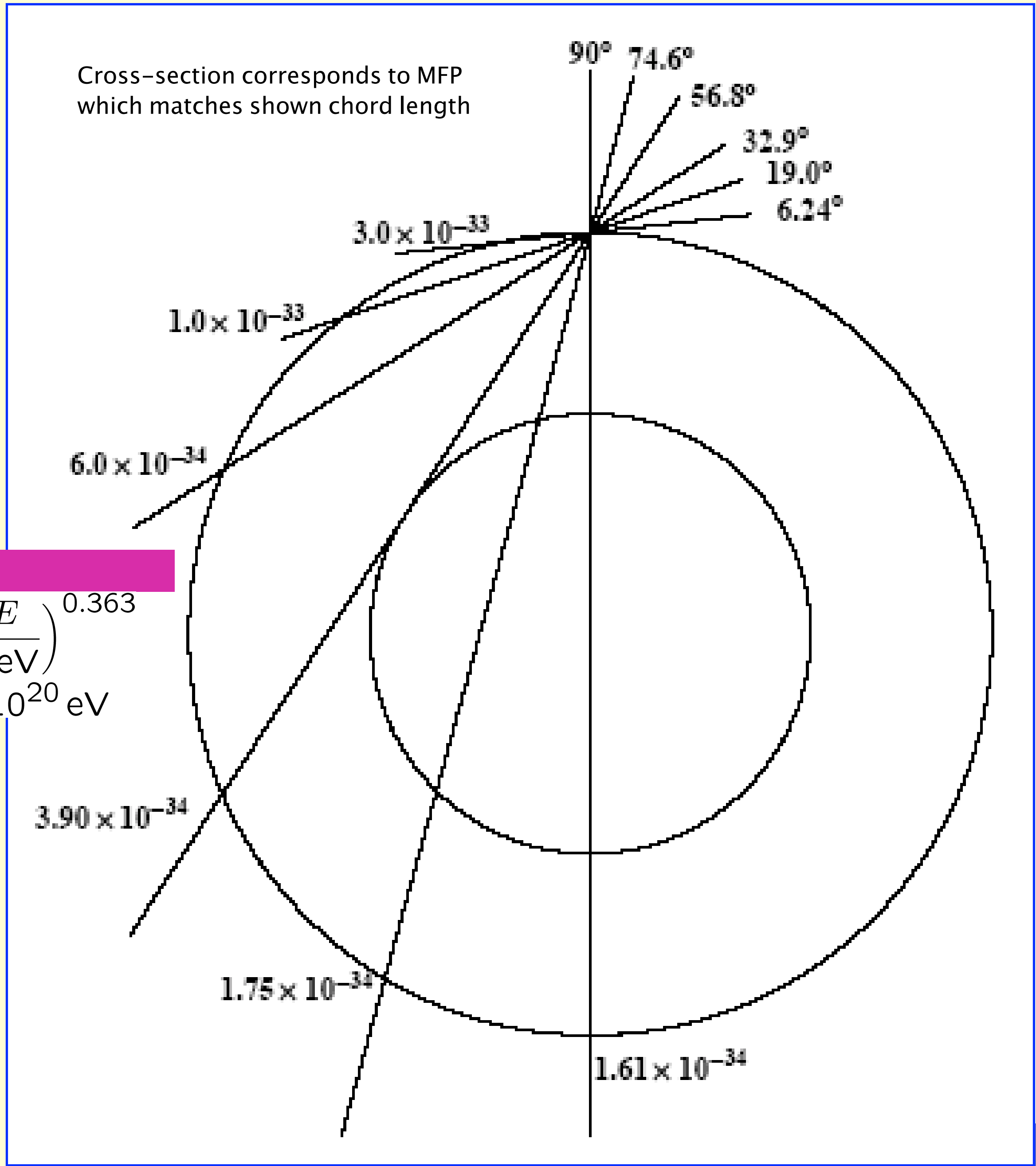

IceCube
1000m
ν_e


AMANDA
Eisfläche
1400 m
1500 m
2000 m
2400 m

Security at the CUBE

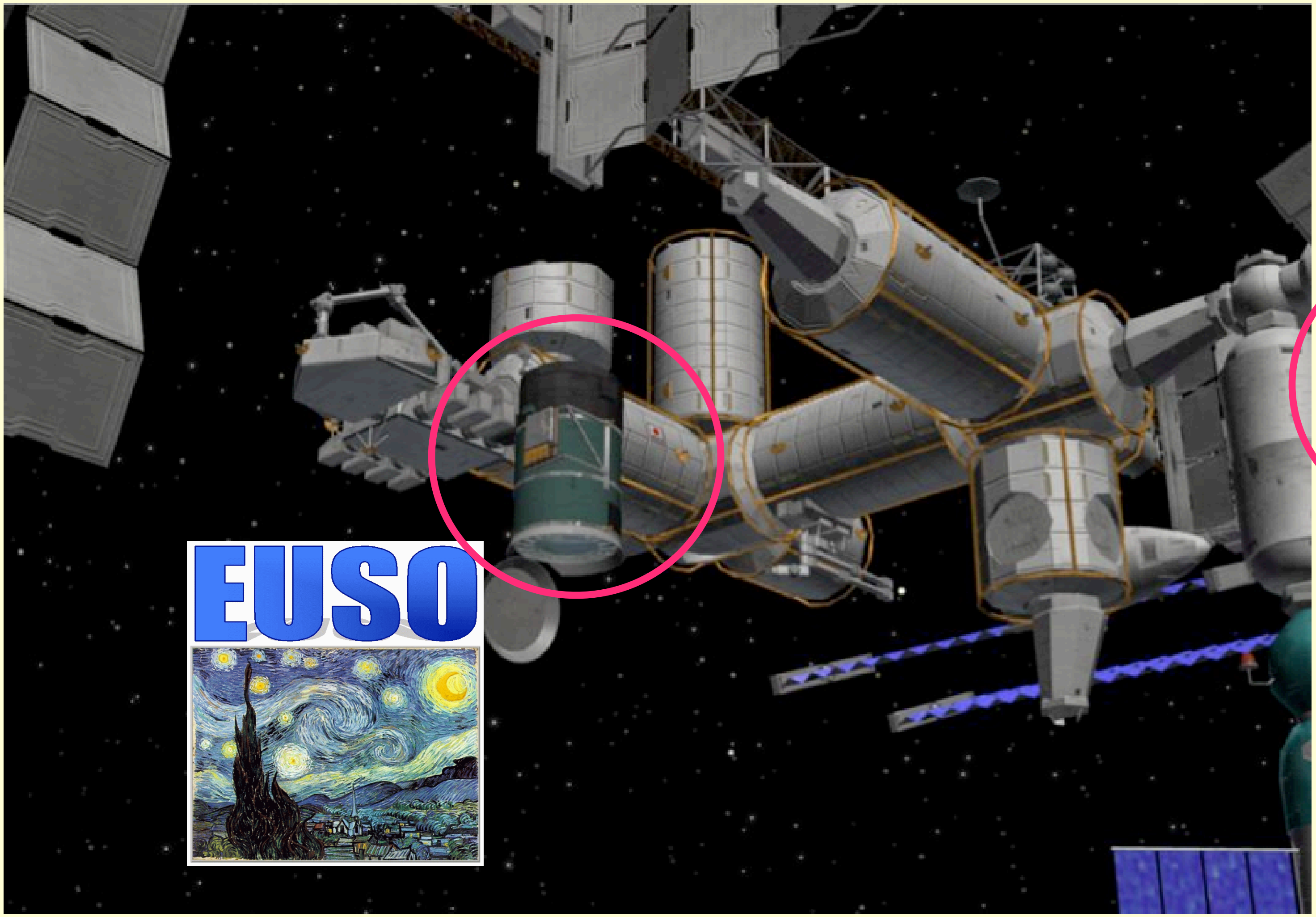
Tom Weiler,
Vanderbilt University

Earth Absorption versus Neutrino Cross-Section



$$\sigma_{\mathrm{GQRS}} = 0.5 \times 10^{-33}\,\mathrm{cm}^2 \left(\frac{E}{\mathrm{PeV}}\right)^{0.363}$$
$$= 0.5 \times 10^{-31}\,\mathrm{cm}^2 \text{ at } 10^{20}\,\mathrm{eV}$$

JEM-EUSO: Extreme Universe Space Observatory



ν HAS event rate is small at Extreme Energy

$$\text{Rate}(\nu) = 2\pi\, A_{\text{FOV}}\; P(\text{see}\,\nu)\; F_\nu\; (\text{duty cycle})$$

$\text{P}(\text{see}\ \nu) \sim \sigma_{\nu N}\, \rho(0)\, h$

and for EUSO,

$2\pi\, A_{\text{FOV}} \sim 10^6\, \text{km}^2\, \text{ster}$

i.e. 2 teratons!!

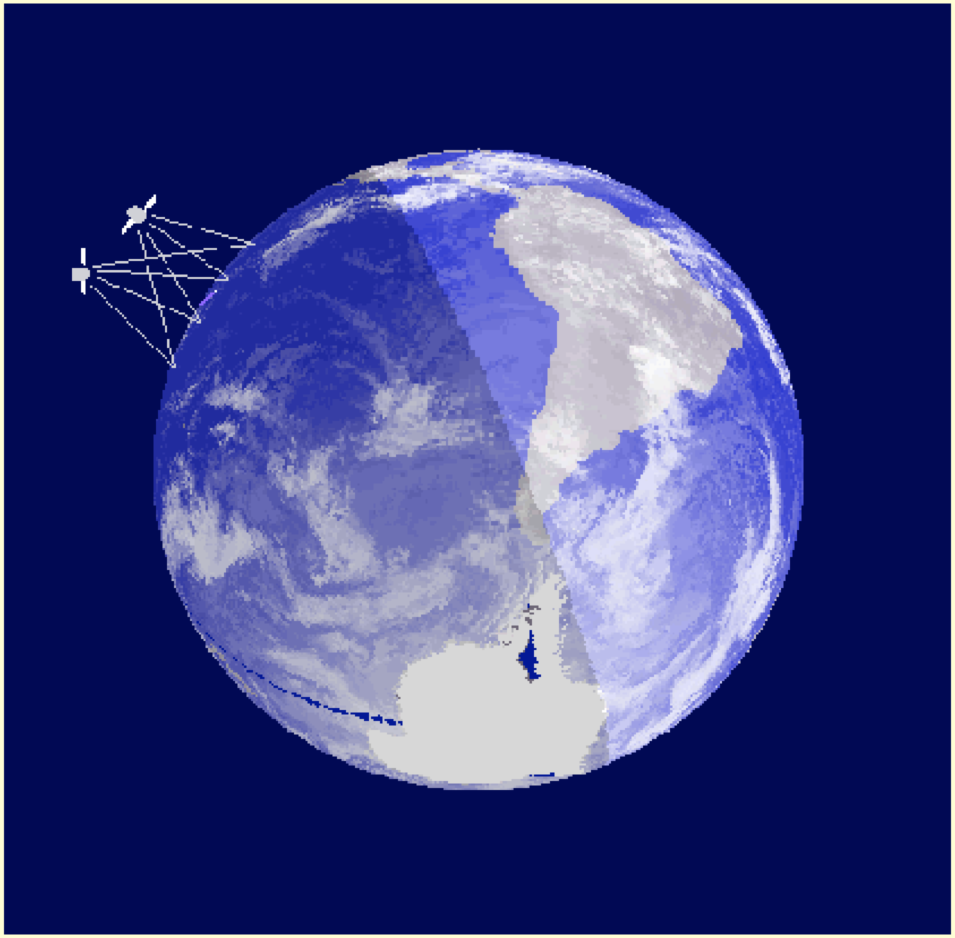
and,

duty cycle $\sim$ 15%.

$$\Rightarrow \frac{1}{\text{yr}}\, \sigma_{\text{GQRS}}\, \frac{F_\nu}{\text{km}^{-2}\,\text{ster}^{-1}\,\text{yr}^{-1}} \quad \text{at } 10^{20}\ \text{eV}$$

e.g. F_{CR} implies 10^{-2} events/yr at 10^{20} eV;
and 10 events/yr at 10^{19} eV.

Orbiting Wide-angle Lens (OWL)



3000 events/year above 10^{20}eV

and UHE Neutrinos!

Tom Weiler,
Vanderbilt University

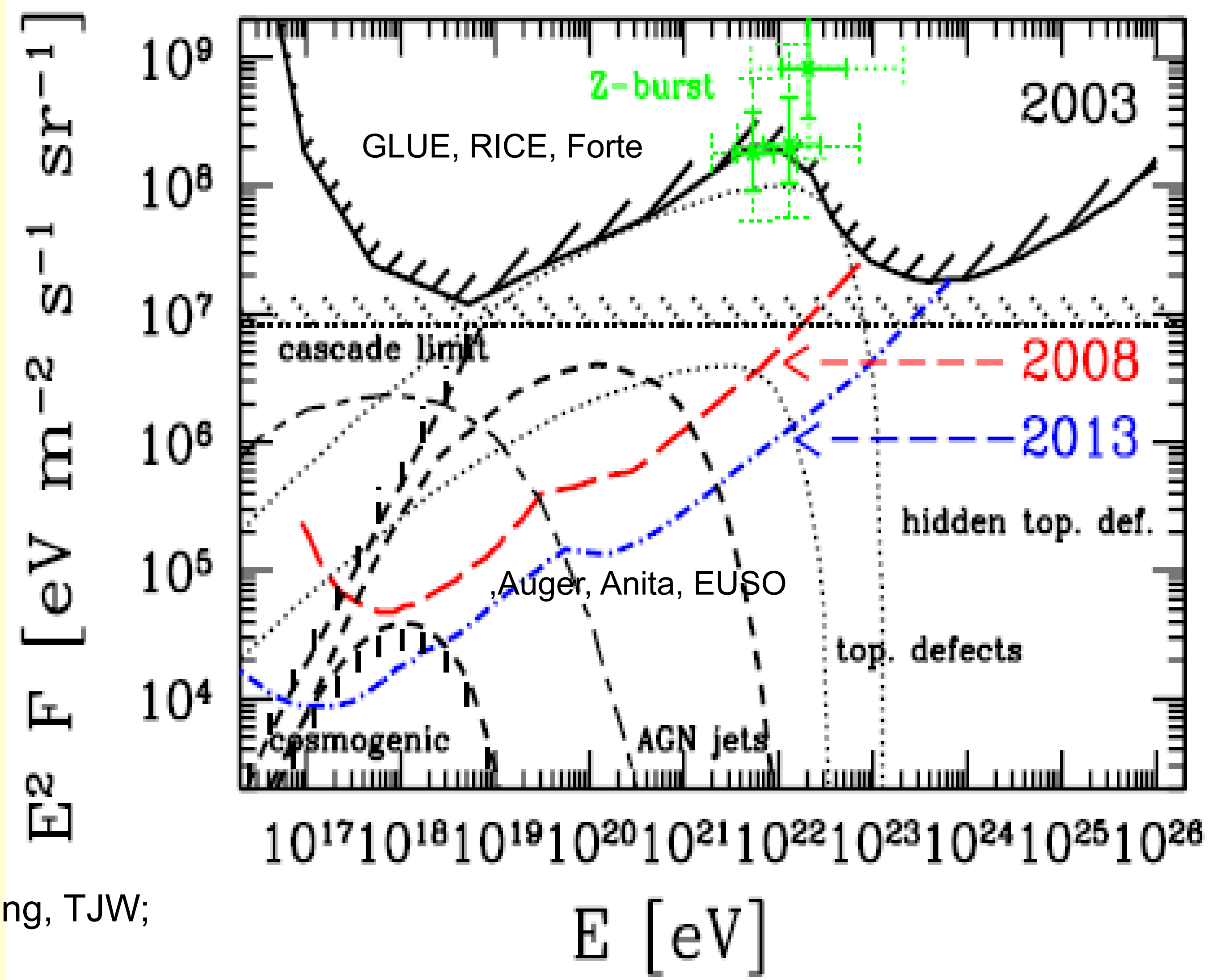
Goldstone Lunar Radio (Cherenkov) Experiment (GLUE)

GLUE

is related to RICE, FORTE, ANITA, and

eventually, to Lofar, ARIANA, and SalSa

Model Neutrino Fluxes and Future Limits



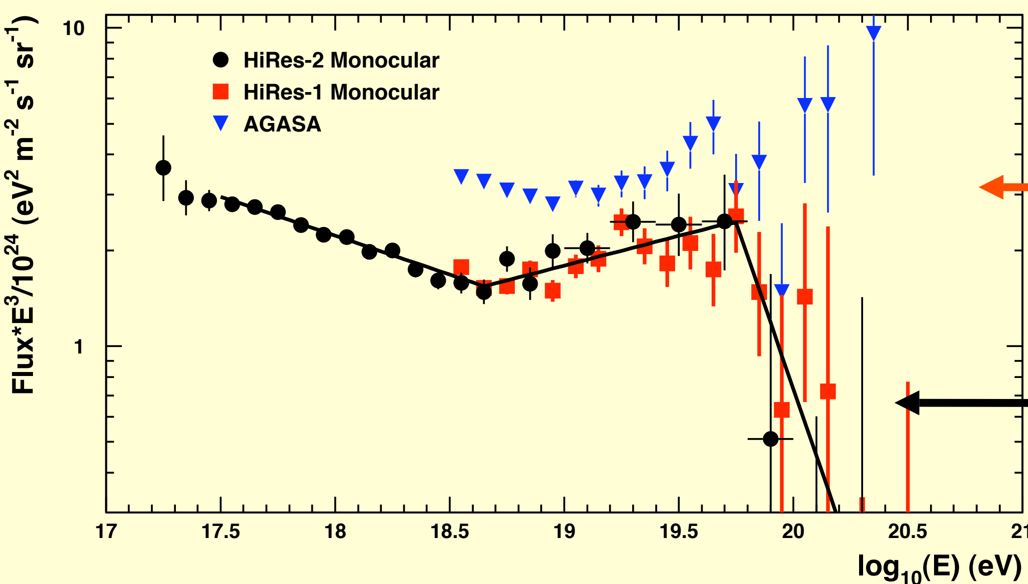
From Eberle, AR, Song, TJW; Semikoz and Sigl

Greisen-Zatsepin-Kuzmin suppression

arXiv:astro-ph/0703099v1 6 Mar 2007

Observation of the GZK Cutoff by the HiRes Experiment

The High Resolution Fly's Eye (HiRes) experiment has observed the GZK cutoff. HiRes' measurement of the flux of cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, exactly the expected cutoff energy. We observe the "Ankle" of the cosmic ray spectrum as well, at an energy of 4×10^{18} eV. We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of a ~ 5 standard deviation observation of the GZK cutoff is described.

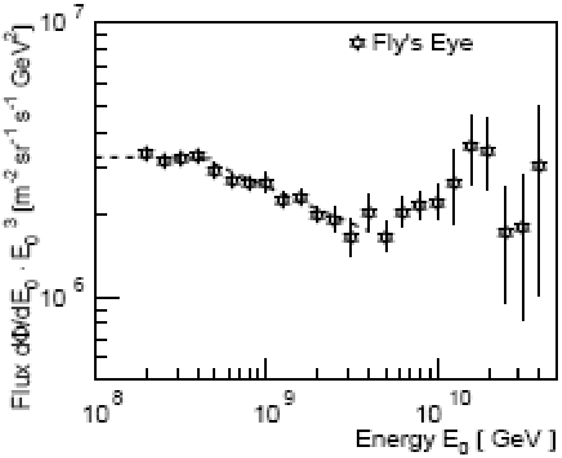


opportunity

GZK recovery ?
Z-burst uncovery ?

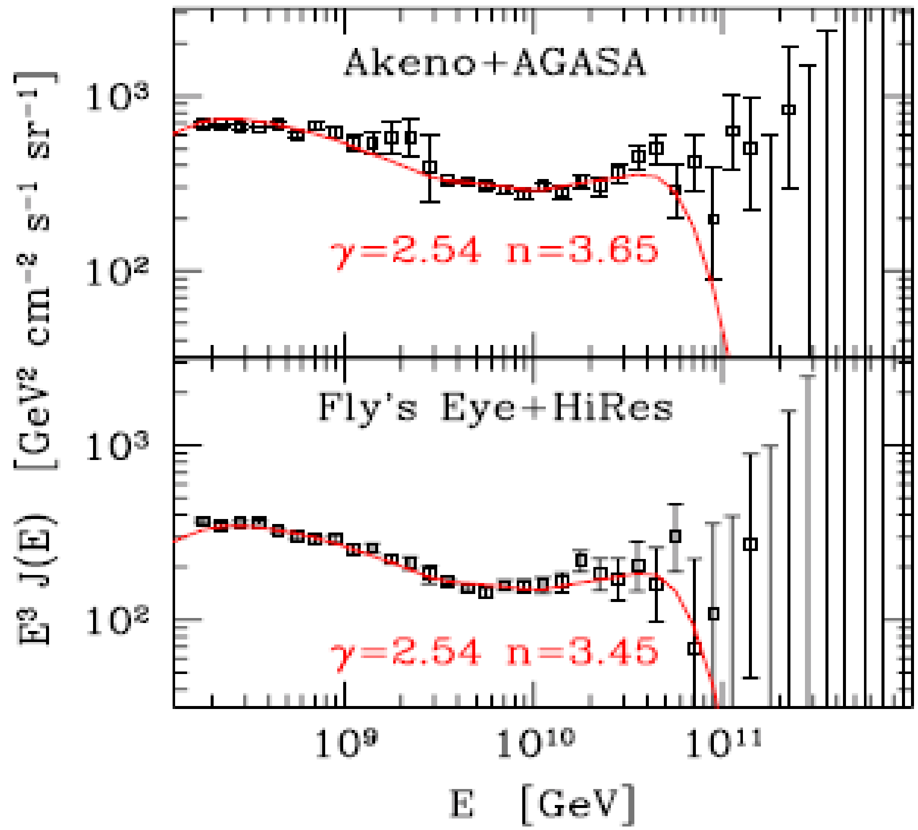
Auger reach 70 x better,
EUSO reach 10^3 x better !

Low Crossover Fits to CRs, and Berezinsky Neutrinos



The second knee from Fly's Eye data (Bird et al 1994).

FIG. 2: Best fits to the ultra-high energy cosmic ray spectrum as observed by Akeno + AGASA and Fly's Eye + HiRes. We set $E_{\rm min} = 10^{8.6}$ GeV, $E_{\rm max} = 10^{11}$ GeV, $z_{\rm min} = 0.012$, $z_{\rm max=2}$, and $E_{i,{\rm max}} = 10^{12.5}$ GeV.



Theory threshold for $p\gamma_{2.7K} \rightarrow pe^+e^-$ and data (knee) are at $10^{17.6}$ eV.

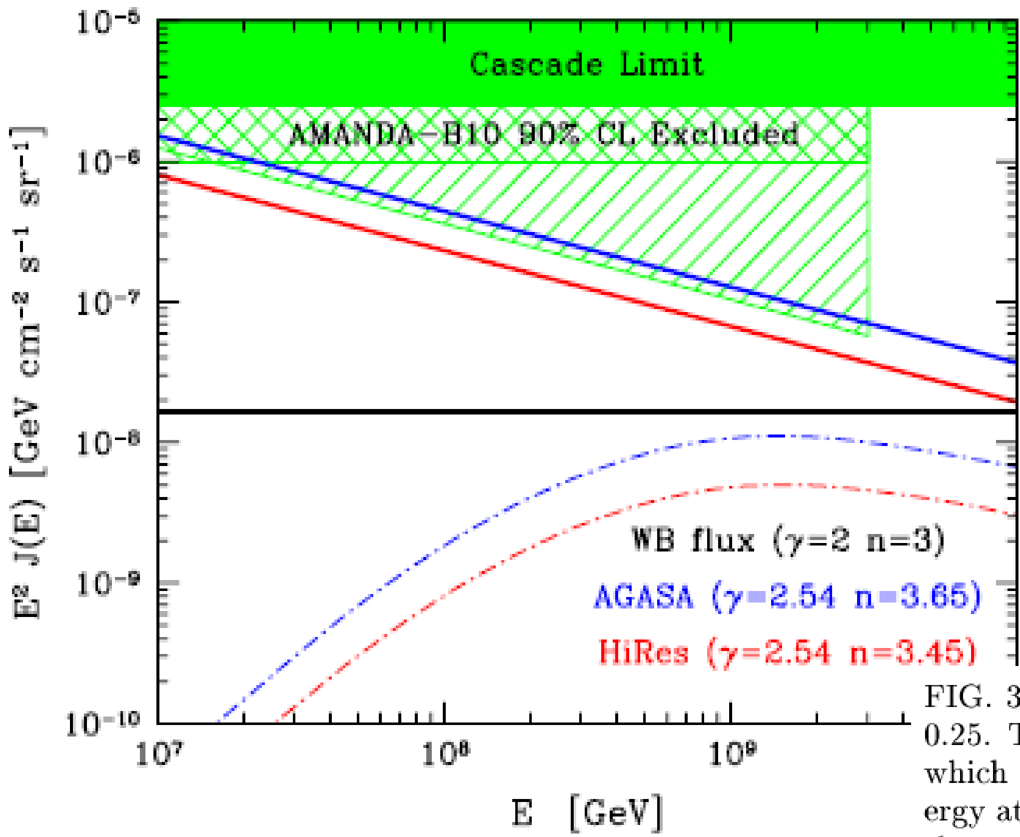


FIG. 3: Neutrino fluxes from optically thin sources for $\epsilon_\pi = 0.25$. The horizontal solid line indicates the WB prediction which corresponds to a Galactic/extra-galactic crossover energy at the ankle, $\sim 10^{10}$ GeV. The falling solid lines indicate the expected neutrino flux normalized to HiRes (lower) and AGASA (upper) data, if one assumes the onset of dominance by the extra-galactic component is at $10^{8.6}$ GeV. The dashed lines indicate the fluxes of cosmogenic neutrinos associated with flux predictions given by the falling solid lines. The cross-hatched region is excluded at the 90% CL by measurements of AMANDA-B10 [26]. The single hatched region is obtained by rescaling the AMANDA integrated bolometric flux limit to an $E_\nu^{-2.54}$ power law.

Good news:
Source ν's exceed cosmogenic ν's at all energies!

➔ F_ν ~ 30 x Waxman-Bahcall at 10^{17} eV, comparable at 10^{19} eV

((AARWGH, 2005)

Some neutrino Flavor physics

Besides energy and direction, cosmic quanta carry intrinsic information.

For cosmic-rays, it is A and Z;

For photons, it is spin polarization;

For neutrinos, it is flavor:

- **electron-neutrino (which showers)**
- **muon neutrino (whose CC tracks)**
- **tau neutrino (which showers below a PeV, tracks above)**

Moreover, the flavors mix in a calculable/known way,
which means the flavors oscillate in an L/E-dependent way,
enabling:

Neutrino Interferometry over Cosmic baselines !!

AMANDA/IceCube ν_μ event

Muon tracks with good S/N are ID'd above 100 GeV;
Non-tracking events (Showers) are ID'd above a TeV

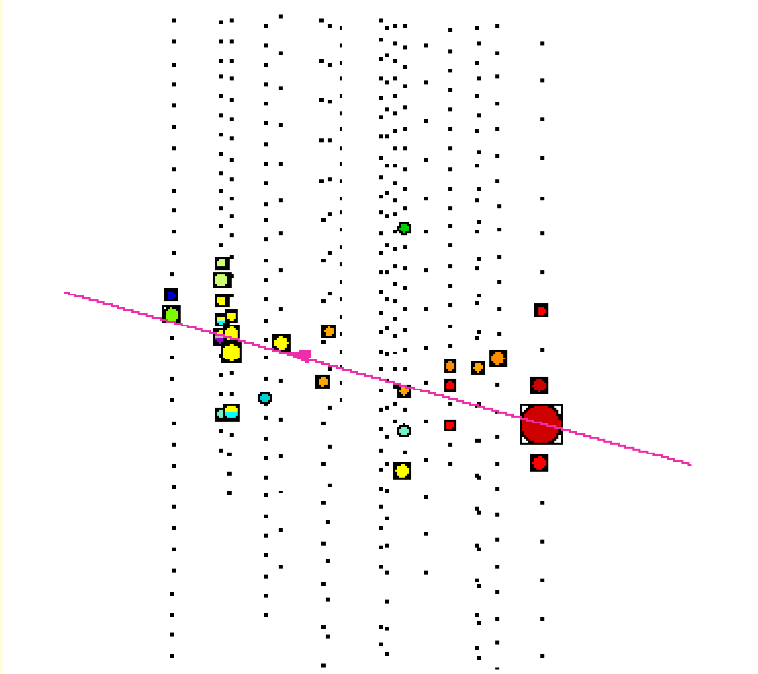


Figure 20: A muon neutrino event in AMANDA. Shown is the central part of the detector. The colorscale and symbol size correspond to hit time and amplitude [471].

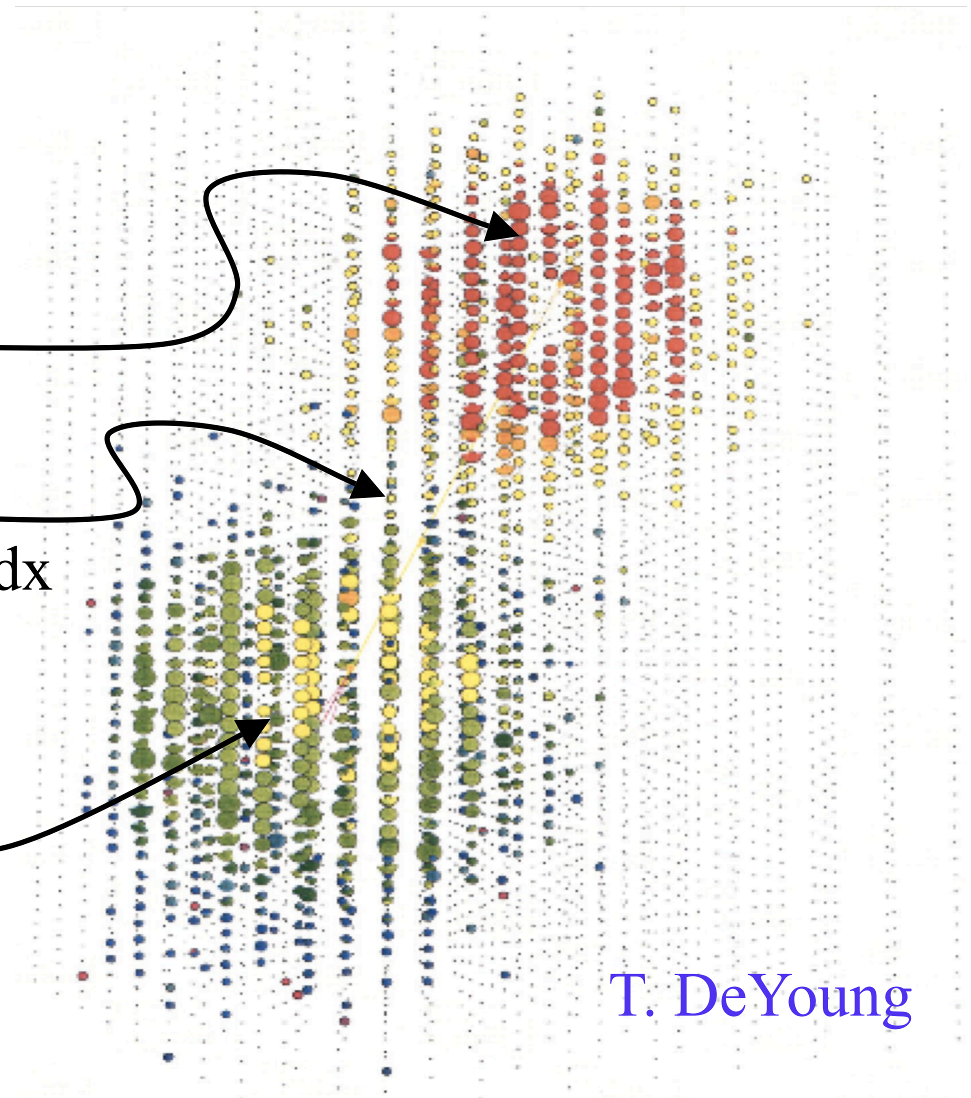
and coming in the Mediterranean: **Nestor**, **Antares**

Classic Tau Signature:
Double Bang (Learned and Pakvasa, 1995)

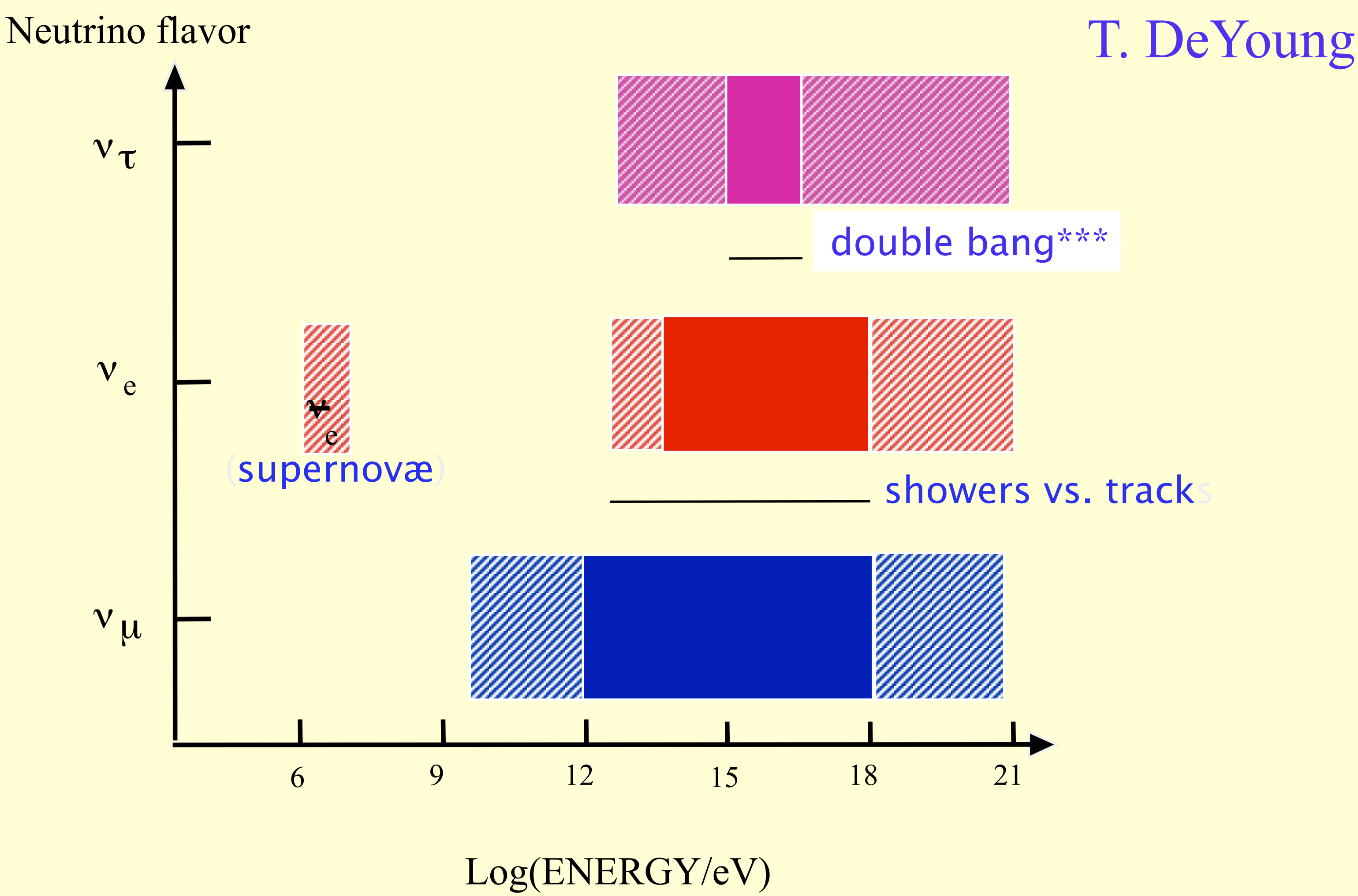
νtau-N --> tau interaction

tau lepton track
~50m/PeV, neglecting dE/dx

tau decay



IceCube Windows for Flavor ID



Decohering the PMNS/tribimaximal neutrino-mixing matrix

$U =$ **R(theta32) R(theta13*) R(theta21) x MajoranaPhases =**

$$\begin{array}{cc} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} & \left[\begin{array}{ccc} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array}\right] \end{array}$$

$$\times \,\mathrm{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$

$$\text{Decoherence} \rightarrow\ |U_{\alpha j}|^2 = \frac{1}{6}\begin{pmatrix} 4 & 2 & 0 \\ 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix}$$

Decohering the PMNS/tribimaximal neutrino-mixing matrix

$$\text{Decoherence} \rightarrow \; |U_{\alpha j}|^2 = \frac{1}{6} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \left(\begin{array}{ccc} 4 & 2 & 0 \\ 1 & 2 & 3 \\ 1 & 2 & 3 \end{array}\right) \end{array} \begin{array}{c} \\ \nu_e \\ \nu_m \\ \nu_t \end{array}$$

Cosmic Beta-beam:

$\nu_e = 2/3\,\nu_1 + 1/3\,\nu_2 \rightarrow$

$$\nu_e : \nu_\mu : \nu_\tau \;=\; 5:2:2$$

The cosmic ν flavor-mixing theorem

If theta_{32} is maximal (it is),
And if $\text{Re}(U_{e3})$ is minimal (it is),
Then ν_μ and ν_τ equilibrate;

Further, if initial ν_e flux is 1/3
(as from pion-muon decay chain),
Then all three flavors equilibrate.

$\Rightarrow$ $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth

Tom Weiler,
Vanderbilt University

Neutrino Flavor Ratios for various Astro processes

Process:	Flavors at Source $(\nu_e{:}\nu_\mu{:}\nu_\tau)$	Flavors at Earth $(\nu_e{:}\nu_\mu{:}\nu_\tau)$
Complete $\pi^\pm \to e^\pm \overset{(-)}{\nu_e} \; \nu_\mu \overline{\nu}_\mu$ decay	1:1:1	1:1:1
Incomplete $\pi^\pm \to \mu^\pm \overset{(-)}{\nu_\mu}$	0:1:0	4:7:7
β-beam	pure $\overline{\nu}_e$	5:2:2
Virtual Black Hole Spacetime	Any	1:1:1

Tom Weiler,
Vanderbilt University

Democracy Broken:

1. Galactic β-beam

2. Source dynamics

3. ν decay (15 minutes of fame)

4. Vacuum resonance
   (MaVaNs, LIV vector)

5. Pseudo-Dirac ν oscillations

Meszaros/Waxman-AARWGH

Predict change in cosmic flavor ratio with energy:

From complete pi-decay chain,
➔1:1:1 at Earth,

To partial pi-decay chain (~ pure ν_μ beam),
➔ 4:7:7 at Earth;

Diagnostic for ambient density:
decay mfp vs. interaction mfp.

ν–decay (via majoron emission)

$$P(\text{survive}) = e^{-t/\tau} = e^{-(L/E)(m/\tau_0)}$$

Flavor content of ν_1

$\Theta_{13} = 0$

$\left(\frac{3}{4}, \frac{1}{8}, \frac{1}{8}\right)$

$\sin\Theta_{13} = 0.2$
$\delta = 0$
$(\delta = \pi$ flips $\mu \leftrightarrow \tau)$

(75%, 21%, 4%)

$$\text{i.e.} \quad \frac{\mu}{e+\tau} = \begin{cases} 14\% & (\Theta_{13} = 0) \\ 27\% & (\sin\Theta_{13} = 0.2) \end{cases}$$

Beacom, Bell, Hooper, Pakvasa, TJW, PRL2003

ν diagnostic of astro-engines: $pp \rightarrow \pi$ vs. $p\gamma \rightarrow \pi$

The process $\underline{\nu}_e + e^- \rightarrow W^-$ is resonant at 6.4 PeV;

pp make nearly equal $\pi^+\pi^-$, with $P_\pi/P_{CR} \sim 0.6$

$\rightarrow \nu_\mu:\underline{\nu}_\mu:\nu_e:\underline{\nu}_e = 2:2:1:1$

$\rightarrow$ flavor democracy, $\underline{\nu}_e = 1/6$ total

$p\gamma$ via Δ^+ make π^+ (per two π^0), with $P_\pi/P_{CR} \sim 0.25$

$\rightarrow \nu_\mu:\underline{\nu}_\mu:\nu_e = 1:1:1$ (no $\underline{\nu}_e$)

$\rightarrow \underline{\nu}_e = 1/15$ total

IceCube will have flavor ID, and $\Delta E/E$ of 25%,
and so can measure On-Res/Off-Res ratio
to resolve this (AGHW, 2004)

Tom Weiler,
Vanderbilt University

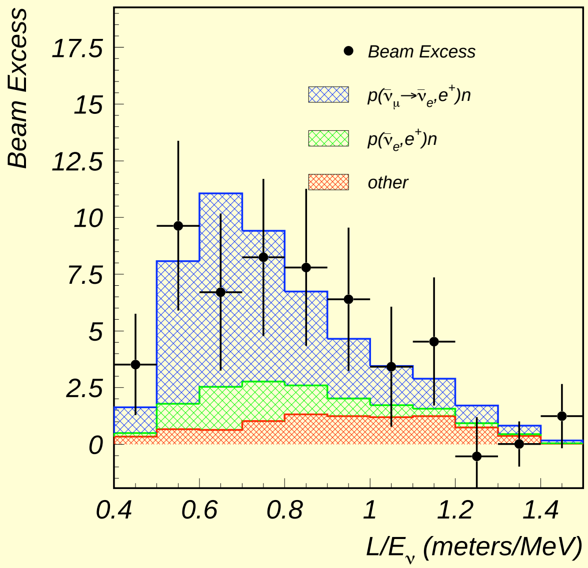
Summary

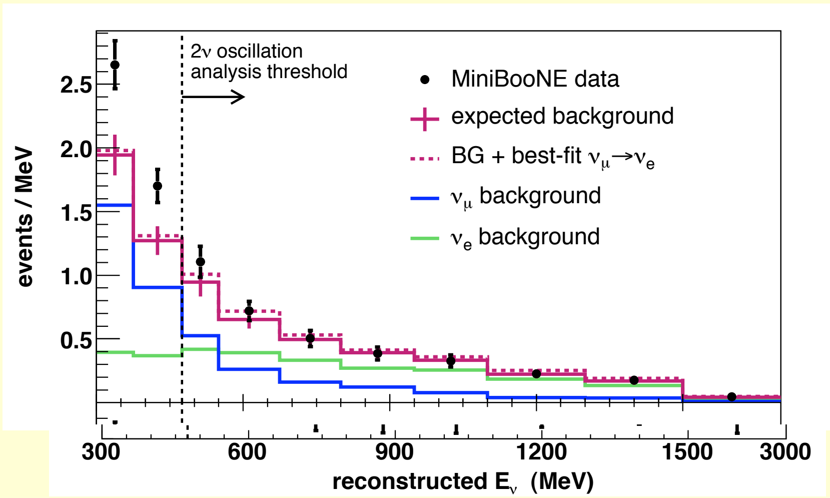
Neutrinos from the Cosmos:

First non-atmospheric event is “just around the corner”
[lik the Higgs and SUSY??]

Next one to ten years will be critical, and,
the deities/gods willing,
most fruitful !

The LSND-ino = miniBoo-ino ???
(with help from Extra Dimensions)





Tom Weiler,
Vanderbilt University

arXiv:hep-ph/0504096

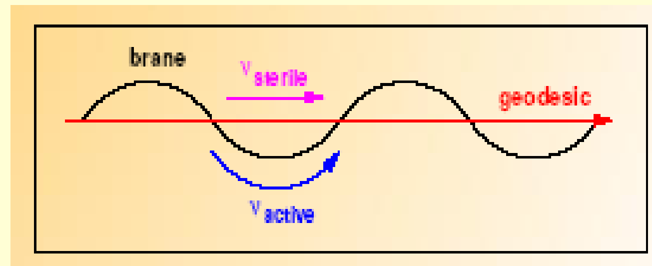
Sterile-active neutrino oscillations and shortcuts in the extra dimension

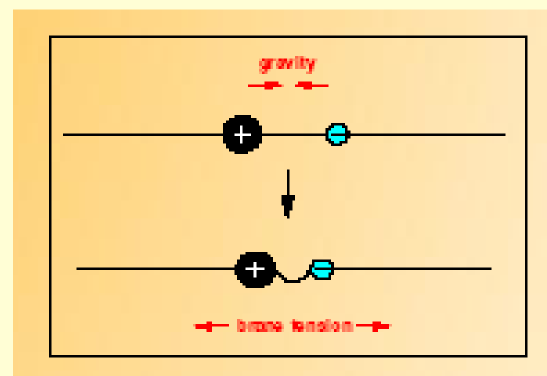
Heinrich Päs[1], Sandip Pakvasa[1], Thomas J. Weiler[2]

In QG/String Theory, brane is dynamical, fluctuating

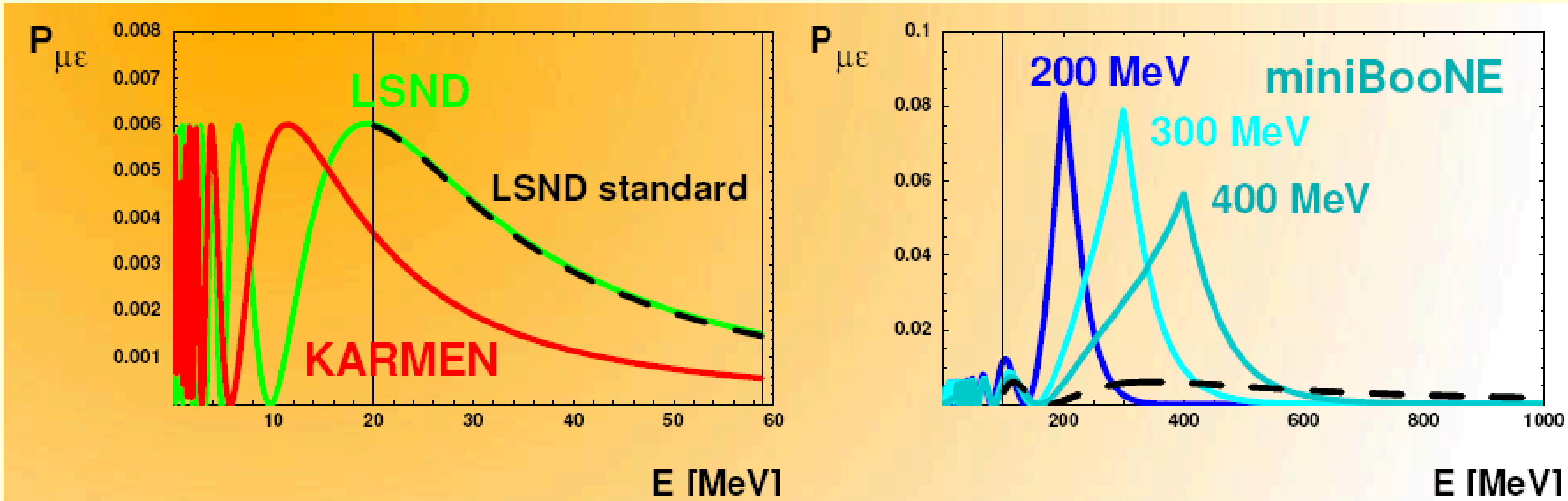
due to

- Quantum Mechanics
- Thermal Mechanics
- In-Brane stresses
  - (e.g. EM vs. gravity)
- Out of Brane experiences
  - (e.g. trans-brane gravity)





Examples: n00 MeV resonance



- $E_{\text{res}} = 200$ MeV, 300 MeV, 400 MeV; $\sin^2\theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV^2
- good fit to LSND spectrum, $P_{\text{LSND}} > P_{\text{KARMEN}}$
- enhanced miniBooNE signal in the energy range 100-600 MeV

And significant ν_μ disappearance for stopped-pion source (SNS)

Tom Weiler,
Vanderbilt University

Oscillation Phase from LIV / Bulk Travel

$$A(\nu_\alpha \to \nu_\beta) = \langle \nu_\alpha |\, e^{-iHt} | \nu_\beta \rangle \,. \tag{1}$$

The component of Ht which is common (i.e., proportional to the identity) cannot effect flavor change, so we may subtract it. We write the remainder as $\delta(Ht)$. With the assumption that the non-common contributions are small, we may further expand $\delta(Ht)$ as $(\delta H)t + H(\delta t)$. We are left with

$$A(\nu_\alpha \to \nu_\beta) = \langle \nu_\alpha |\, e^{-i[(\delta H)t + H(\delta t)]} | \nu_\beta \rangle \,. \tag{2}$$

As in standard oscillations, δH is diagonal in the mass-basis, and at lowest order is equal to

$$\delta H = \frac{1}{2\,E}\,\mathrm{diag}(m_1^2, m_2^2, \cdots)\,. \tag{3}$$

(LIV) has been shown to be phenomenologically equivalent to state-dependent limiting velocities [3, 4]. We note that with differing velocities, one has $\delta t = \delta(L/v) = -L\,\delta v/v^2$, which is $-L\,\delta v$ to lowest order. It is most natural to assign the limiting velocities to the interaction flavor eigenstates. In this case, the second term in (2) as written is already in a diagonal basis, and is equal to

$$\delta\, t = \mathrm{diag}(\delta t_\alpha, \delta t_\beta, \cdots) = -L\,\mathrm{diag}(\delta v_\alpha, \delta v_\beta, \cdots)\,. \tag{5}$$

With these assumptions, the effective Hamiltonian in (7) may be written as

$$H_{(F)} = \begin{pmatrix} U_{3\times3} & 0 \\ 0 & 1 \end{pmatrix} \left[\frac{1}{2\,E} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & R_{43} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta_{\mathrm{LSND}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & R_{43}^T \end{pmatrix} - E\,\epsilon \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \right] \begin{pmatrix} U^\dagger_{3\times3} & 0 \\ 0 & 1 \end{pmatrix} \tag{10}$$

Bulk Travel

The matrix in brackets in (10) is equal to

$$\frac{\Delta_{\mathrm{LSND}}}{2\,E}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & s_{43}^2 & s_{43}\,c_{43} \\ 0 & 0 & s_{43}\,c_{43} & \left(c_{43}^2 - \frac{2E^2\epsilon}{\Delta_{\mathrm{LSND}}}\right) \end{pmatrix}, \tag{11}$$

Resonant mixing occurs when the two diagonal elements in Eq. (11) are equal, i.e. when

$$E_{\mathrm{R}} = \sqrt{\frac{\cos 2\theta_{43}\,\Delta_{\mathrm{LSND}}}{2\epsilon}}\,.$$

New parameters are

1. running $\quad \tan 2\tilde{\theta} = \dfrac{\tan 2\theta_{43}}{1-\left(\frac{E}{E_{\mathrm{R}}}\right)^2}\,,$
2. E_{R}
3. Δ_{LSND}

Tom Weiler,
Vanderbilt University

Bulk Travel

neutrino survival probability is given by

$$P(\nu_a \to \nu_a) \;=\; \delta_{\alpha\beta} - 4\,V_{a3}^2 \times \begin{cases} \sin^2\left(\frac{L\,(\lambda_+ - \lambda_-)}{2}\right) & \sin^2\tilde{\theta}\,\cos^2\tilde{\theta}\;\; V_{a3}^2 \\ +\sin^2\left(\frac{L\,\lambda_+}{2}\right) & \sin^2\tilde{\theta}\;\;(1 - V_{a3}^2) \\ +\sin^2\left(\frac{L\,\lambda_-}{2}\right) & \cos^2\tilde{\theta}\;\;(1 - V_{a3}^2)\,. \end{cases} \tag{26}$$

The active-to-(different)active neutrino conversion probability is given by (and note the minus sign on the first term in brackets)

$$P(\nu_a \to \nu_b) \;=\; 4\,V_{a3}^2\,V_{b3}^2 \times \begin{cases} -\sin^2\left(\frac{L\,(\lambda_+ - \lambda_-)}{2}\right) & \sin^2\tilde{\theta}\,\cos^2\tilde{\theta} \\ +\sin^2\left(\frac{L\,\lambda_+}{2}\right) & \sin^2\tilde{\theta} \\ +\sin^2\left(\frac{L\,\lambda_-}{2}\right) & \cos^2\tilde{\theta}\,. \end{cases} \tag{27}$$

Barger, Huber, Learned, Marfatia, PPW (near future)

Extra “resource” slides

Pseudo-Dirac Neutrinos

Pseudo-Dirac Neutrinos, a Challenge for Neutrino Telescopes

John F. Beacom,[1] Nicole F. Bell,[1,2] Dan Hooper,[3]
John G. Learned,[4,2] Sandip Pakvasa,[4,2] and Thomas J. Weiler[5,2]

The generic mass matrix in the $(\nu_L, (\nu_R)^C)$ basis is

$$\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}. \tag{1}$$

A Dirac neutrino corresponds to the case where $m_L = m_R = 0$, and may be thought of as the limit of two degenerate Majorana neutrinos with opposite CP parity. Alternatively, we may form a pseudo-Dirac neutrino [1, 2] by the addition of tiny Majorana mass terms $m_L, m_R \ll m_D$, which have the effect of splitting the Dirac neutrino into a pair of almost degenerate Majorana neutrinos, each with mass $\sim m_D$. The mixing angle between the active and sterile states is very close to maximal, $\tan(2\theta) = 2m_D/(m_R - m_L) \gg 1$, and the mass-squared difference is $\delta m^2 \simeq 2m_D(m_L + m_R)$. For three generations, the mass spectrum is shown in Fig. 1. The mirror model can produce a very similar mass spectrum [3, 4].

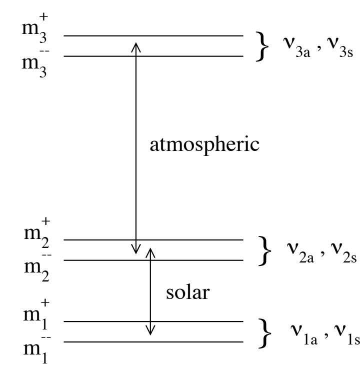


FIG. 1: The neutrino mass spectrum, showing the usual solar and atmospheric mass differences, as well as the pseudo-Dirac splittings in each generation (though shown as equal, we assume they are independent). The active and sterile components of each pseudo-Dirac pair are ν_{ja} and ν_{js}, and are maximal mixtures of the mass eigenstates ν_j^+ and ν_j^-. Neither the ordering of the active neutrino hierarchy, nor the signs of the pseudo-Dirac splittings, has any effect on our discussion.

Galactic Neutrino ß-beam

Fe + plasma $\xrightarrow[\text{GDR}]{}$ (n or p) + (A-1)*

→ (0.5 $\underline{\nu}_e$) + (A-1) + TeV γ

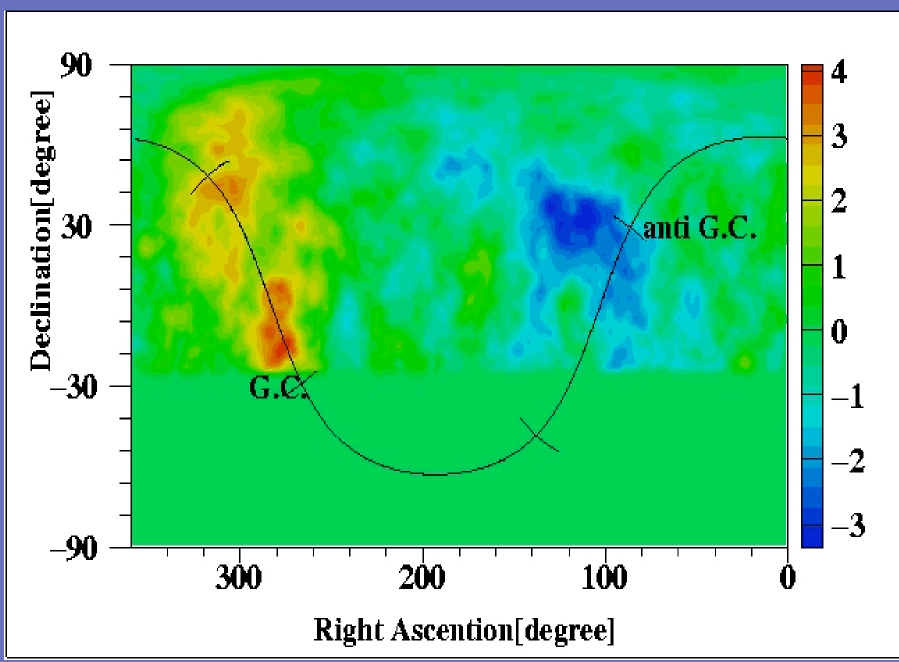
Neutron mfp:

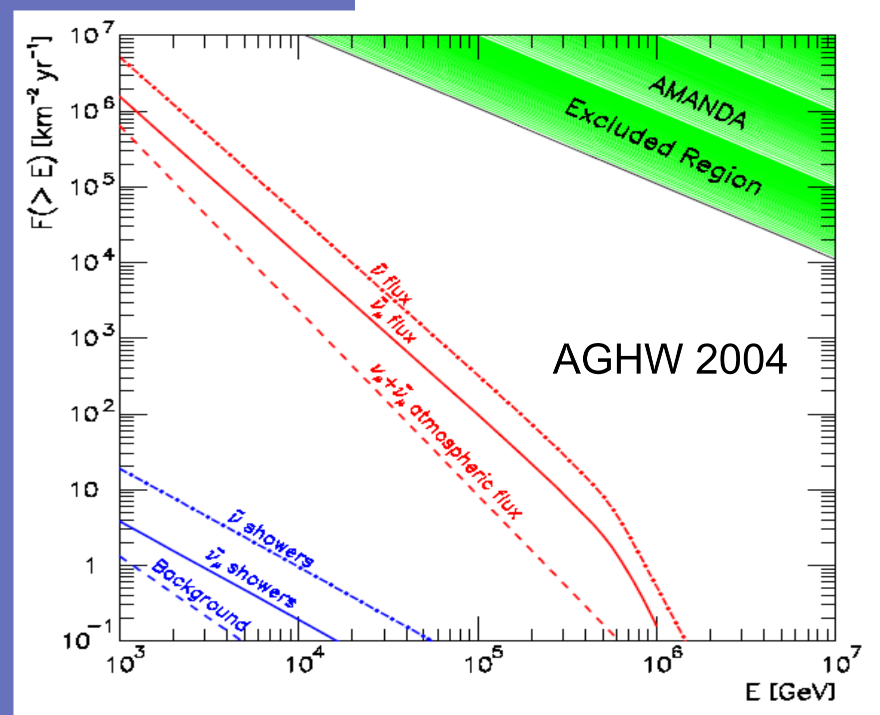
$c\tau_n$ = 10 kpc (E_n / EeV)

and

E_ν / E_n ~ Q / m_n ~ 0.8 x 10-3

→ E_ν ~ PeV, for E_n ~ EeV

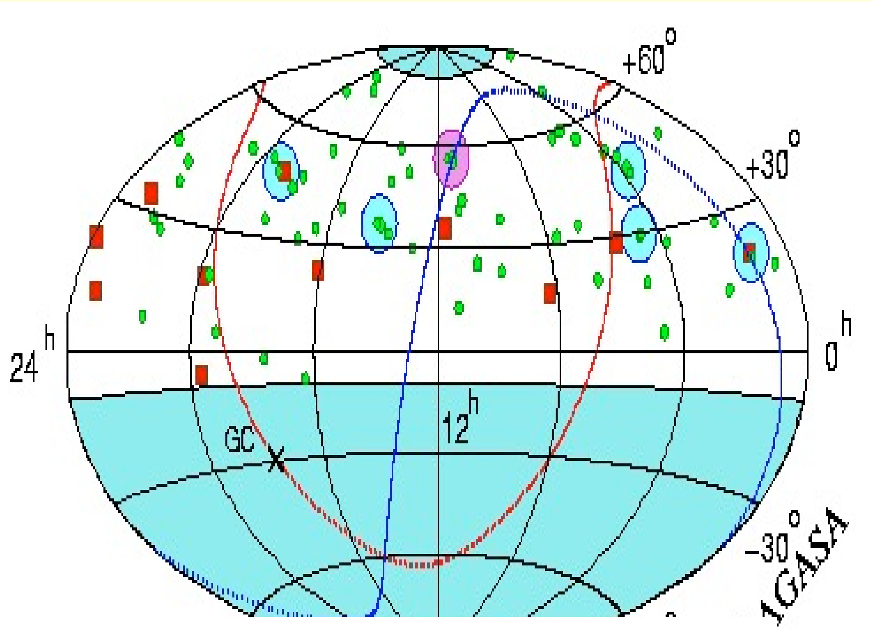




“AGASA”

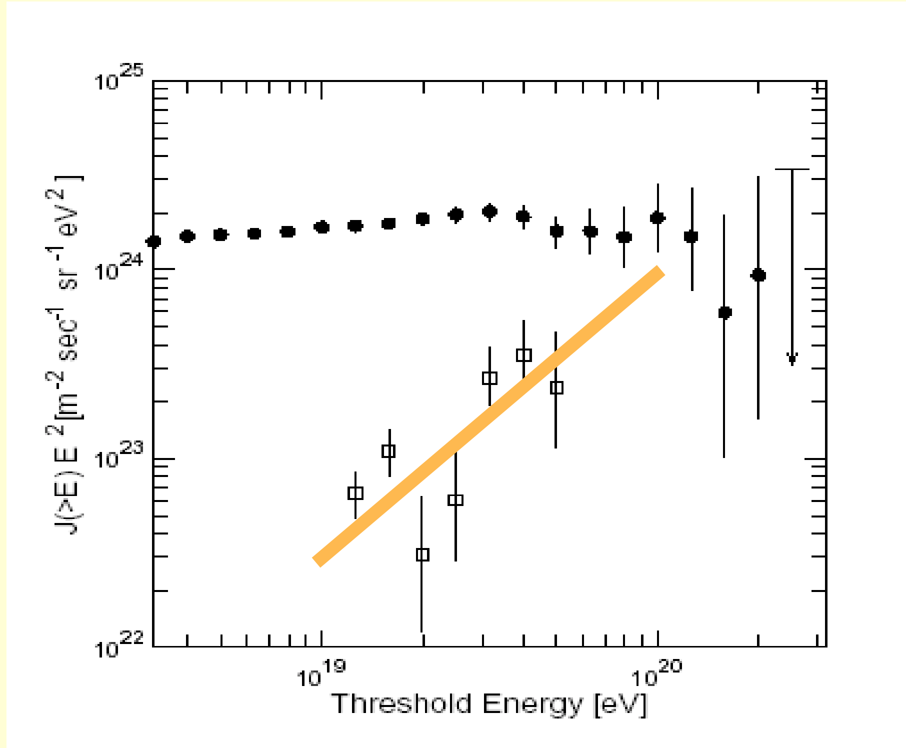
Hot-Spots

AGASA hot-spots -- Data



red: $E > 4\ 10^{19}$ eV

green: $E > \ 10^{20}$ eV



Cluster Component

$\sim E^{-1.8\pm0.5}$

Neutrinos will point better

Tom Weiler,
Vanderbilt University

AGASA hot-spots -- numbers

Within 2.5 degree circles,
AGASA identifies six doublet, one triplet,
Out of 57 events;

Opening the angle to just 2.6 degrees,
AGASA identifies seven doublets, two triplets;

Source number ~ $N_1^2/2N_2$ ~ 270 to 50%,
weighting with GZK suppression,
➔~ 10^{-5} /Mpc^3 for source density

Haverah Park contributes two more paired events
in AGASA directions.

NOT corroborated by HiRes, but …
HiRes sees pointing to BL-lacs!