Neutrino Astrophysics: Theoretical Overview

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Physics potential – what might we learn?

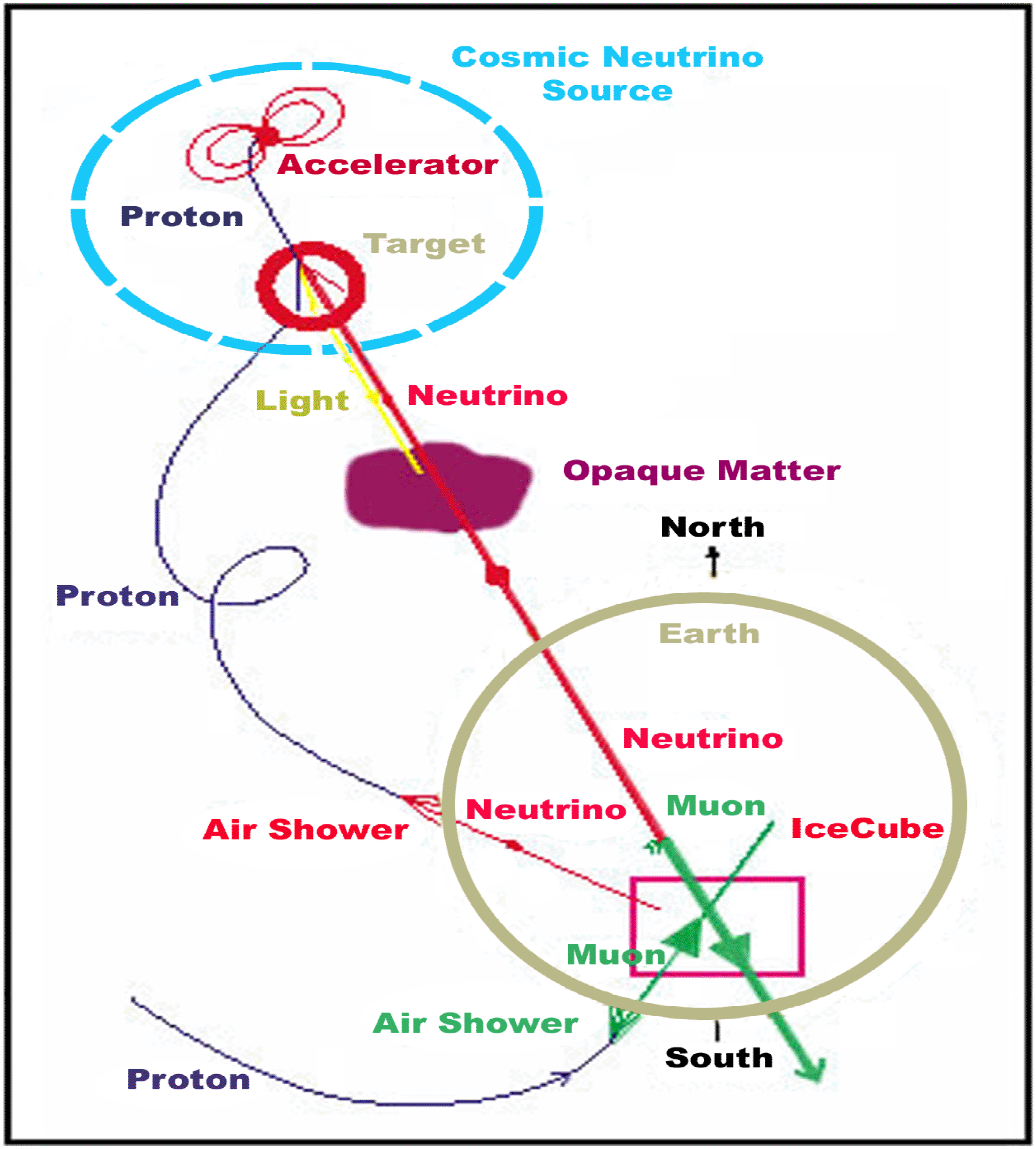
- Conditions at the astrophysical source
- Exotic neutrino properties
- Probe neutrino cross sections at extreme energies, where new physics might show up

To uncover new physics, we need to discriminate flavors

High energy neutrino messengers

- Neutrinos interact weakly, so are not attenuated
- They are not deflected by magnetic fields – their arrival direction points back to the source

So, we can use them to probe astrophysical sources/cosmology that is not accessible with photons


Cosmic Neutrino Source
Accelerator
Proton
Target
Light
Neutrino
Opaque Matter
North
Proton
Earth
Neutrino
Air Shower
Neutrino
Muon
IceCube
Muon
Air Shower
South
Proton

UHE neutrino sources

- “Cosmic beam dumps”, eg, active galactic nuclei, gamma ray bursts, supernovae remnants.

- Annihilation of WIMPs

- Decay of topological defects, monopoles.

- Interaction of UHE cosmic rays with the microwave background radiation, the GZK neutrinos, a “guaranteed” neutrino source.

Astrophysical Neutrino Sources

High energy neutrino fluxes expected to be produced in
“cosmic accelerators” which accelerate protons.

Eg, Gamma Ray Bursts (GRBs) and Actice Galactic Nuclei (AGNs)

pp and pγ collisions produce charged pions → Decay to neutrinos

$$\begin{array}{l} \pi^{+} \rightarrow \nu_{\mu} + \mu^{+} \\ \qquad\qquad\quad\;\; \downarrow \\ \qquad\qquad\quad\;\; \bar{\nu}_{\mu} + e^{+} + \nu_{e} \end{array}$$

Expected flavor ratio at the source: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

The ratio of flavours at the source is expected to be

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

In the limit of exact $\nu_\mu - \nu_\tau$ symmetry, the ratios in the mass basis are:

$$\nu_1 : \nu_2 : \nu_3 = 1:1:1$$

Exact mu-tau symmetry occurs when: $\theta_{\text{atm}} = 45^\circ$ and $\theta_{13} = 0$

independent of the solar angle

Since: oscillation length is <<< distance to source

→ Averaged oscillations (incoherent mixture of mass eigenstates)

→ 1:1:1 in the flavor basis (or any basis)

If we don’t see 1:1:1

Different flavor ratio at the source

Eg. 0:1:0 (Rachen and Meszaros, 1998)

→ becomes 0.5 : 1 : 1 at Earth

Exotic neutrino properties

- Neutrino decay
- CPT violation
- Oscillation to steriles with very tiny delta δm^2
- Pseudo-Dirac mixing
- 3+1 or 2+2 mixing
- Magnetic moment transitions

Inverting the observed flavor ratios to obtain the mixture at the source:

The generic prediction is 1:1:1, but since new physics could show up as deviations to these ratios, its important to determine the ratios experimentally.

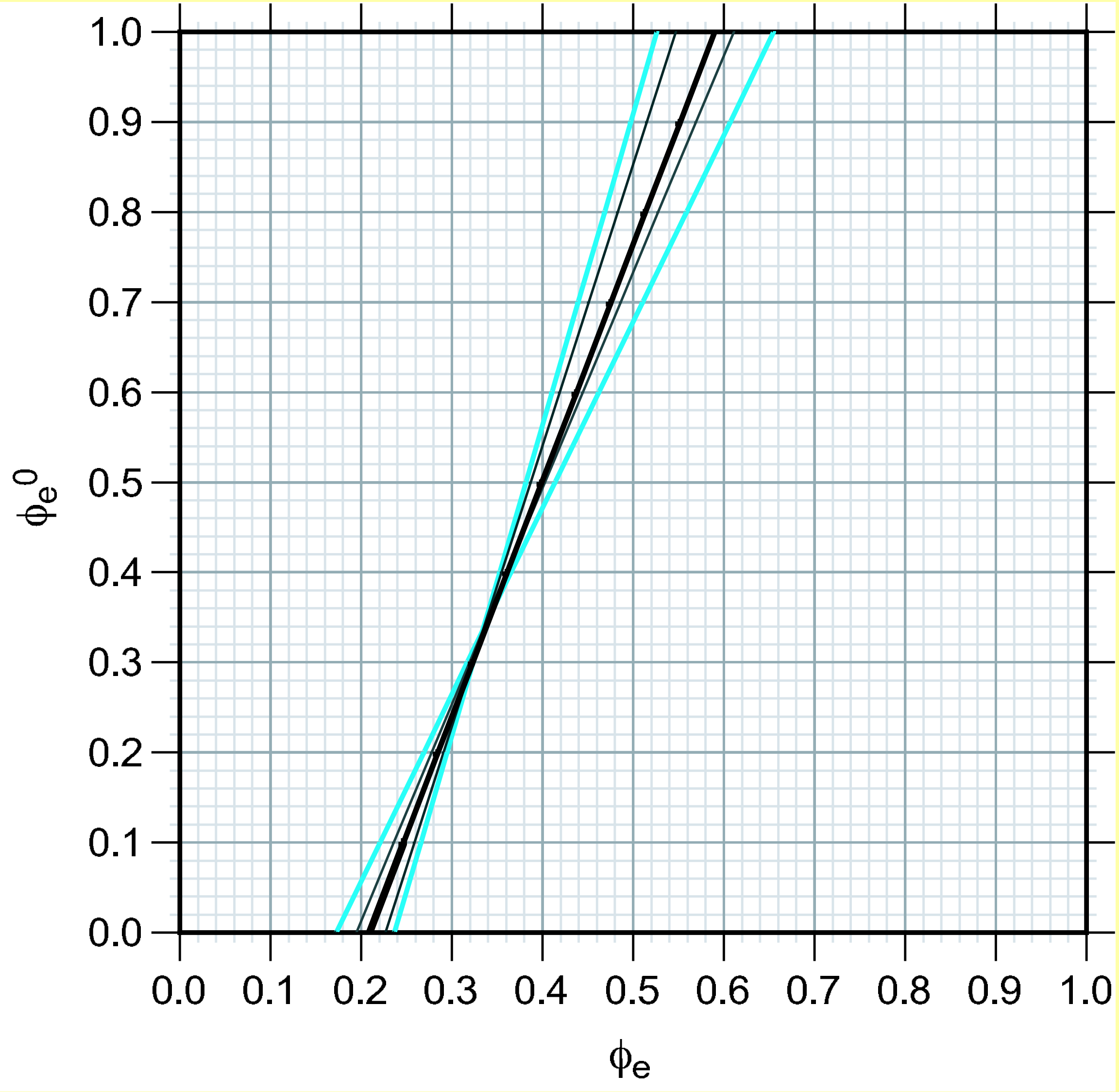
Since ν_μ and ν_τ are are maximally mixed, it is not possible to uniquely invert the measured flavor rations to obtain all three source fluxes.

However, we may reconstruct the ν_e fraction.

$$\phi_e^{\text{source}} = \frac{\phi_e - x}{1 - 3x} \qquad x = \frac{1}{4}\sin^2 2\theta_{12}$$

Barenboim and Quigg

G. Barenboim and C. Quigg,
PRD67, 073024 (2003)



Neutrino Lifetimes

The strongest model-dependent limit on the neutrino lifetime is quite weak:

$$\tau / m \leq 10^{-4} \quad \mathrm{s/eV}$$

Neutrinos might have "invisible" decay modes of the form:

$$\nu_2 \to \nu_1 + \phi$$

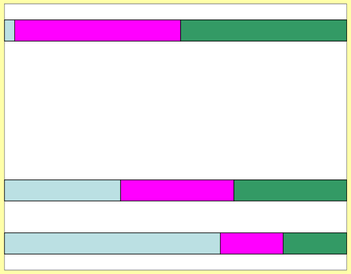
Where ϕ is a very light or massless scalar/pseudo-scalar (e.g. a Majoron)

The L/E or τ/m reach with astrophysical sources can improve the lifetime limit by about 7 orders of magnitude

Decay – Flavor Ratios

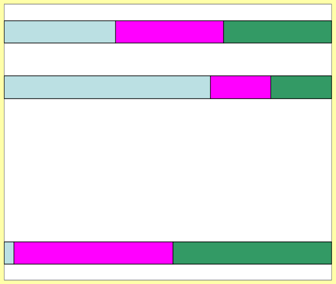
The lightest neutrino should be stable.

Normal hierarchy



$\nu_e : \nu_\mu : \nu_\tau$ = 5:1:1

Inverted hierarchy



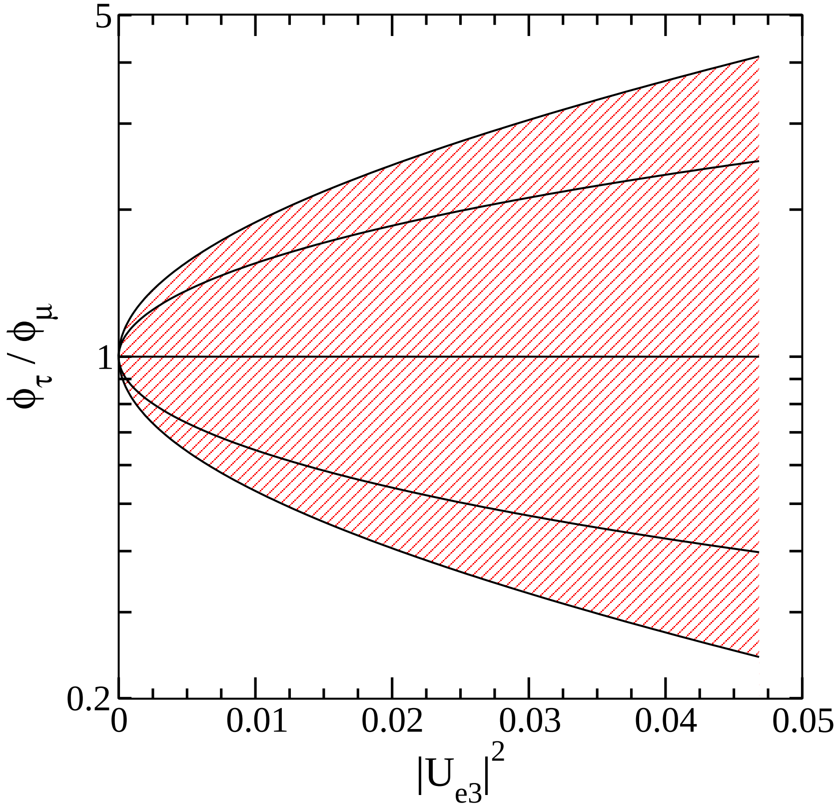
$\nu_e : \nu_\mu : \nu_\tau$ = 0:1:1

Such extreme deviations of the expect ratios, 1:1:1, should be identifiable in current or planned neutrino telescopes, such as IceCube

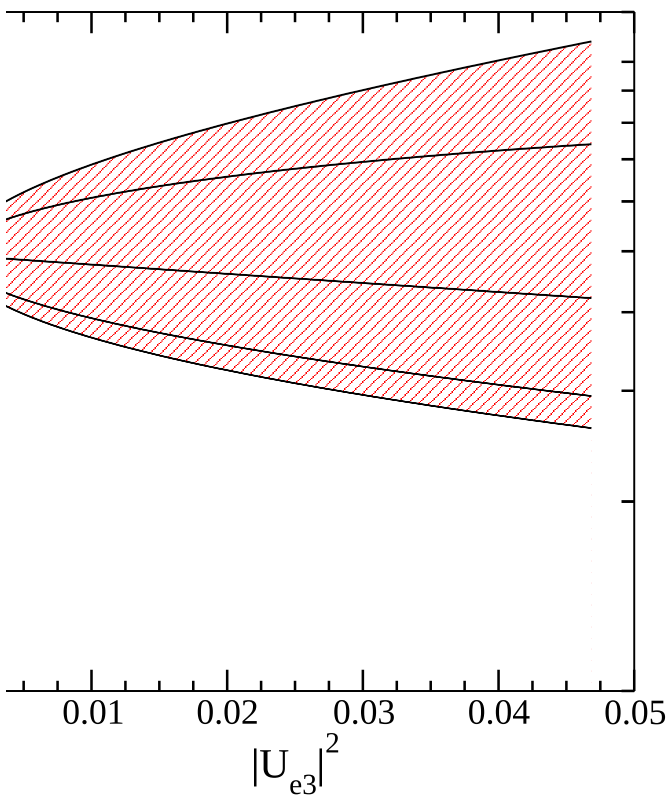
Neutrino decay, and sensitivity to θ_{13} and the CP phase δ

Nonzero θ_{13} breaks mu-tau symmetry

Tau/mu components of ν_1



e/mu ratio in decay scenario



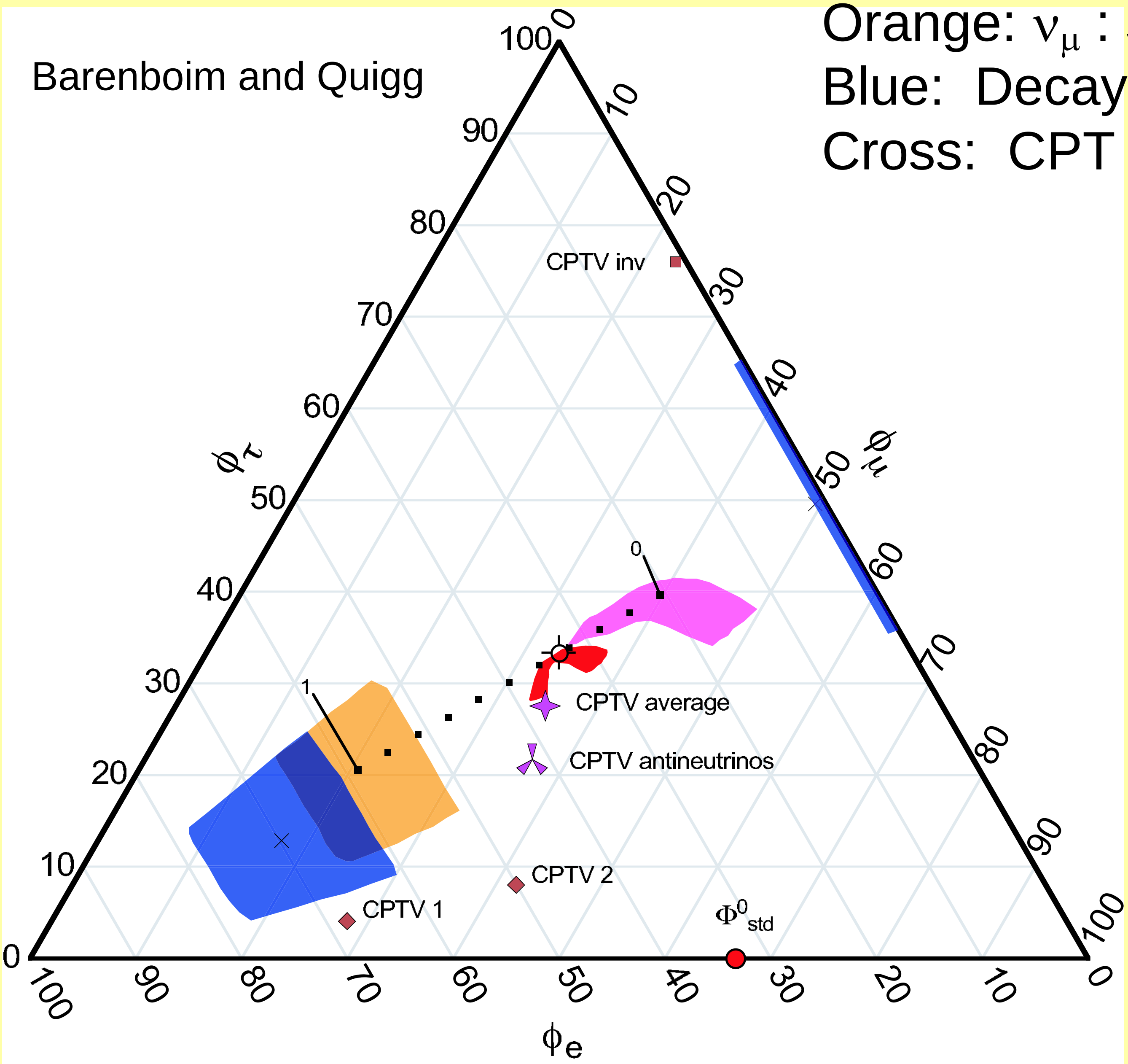
Beacom, Bell, Hooper, Pakvasa & Weiler

Pink: ν_e source

Orange: ν_μ : source

Blue: Decay

Cross: CPT violating scenario



Ultimate Long Baseline Experiment

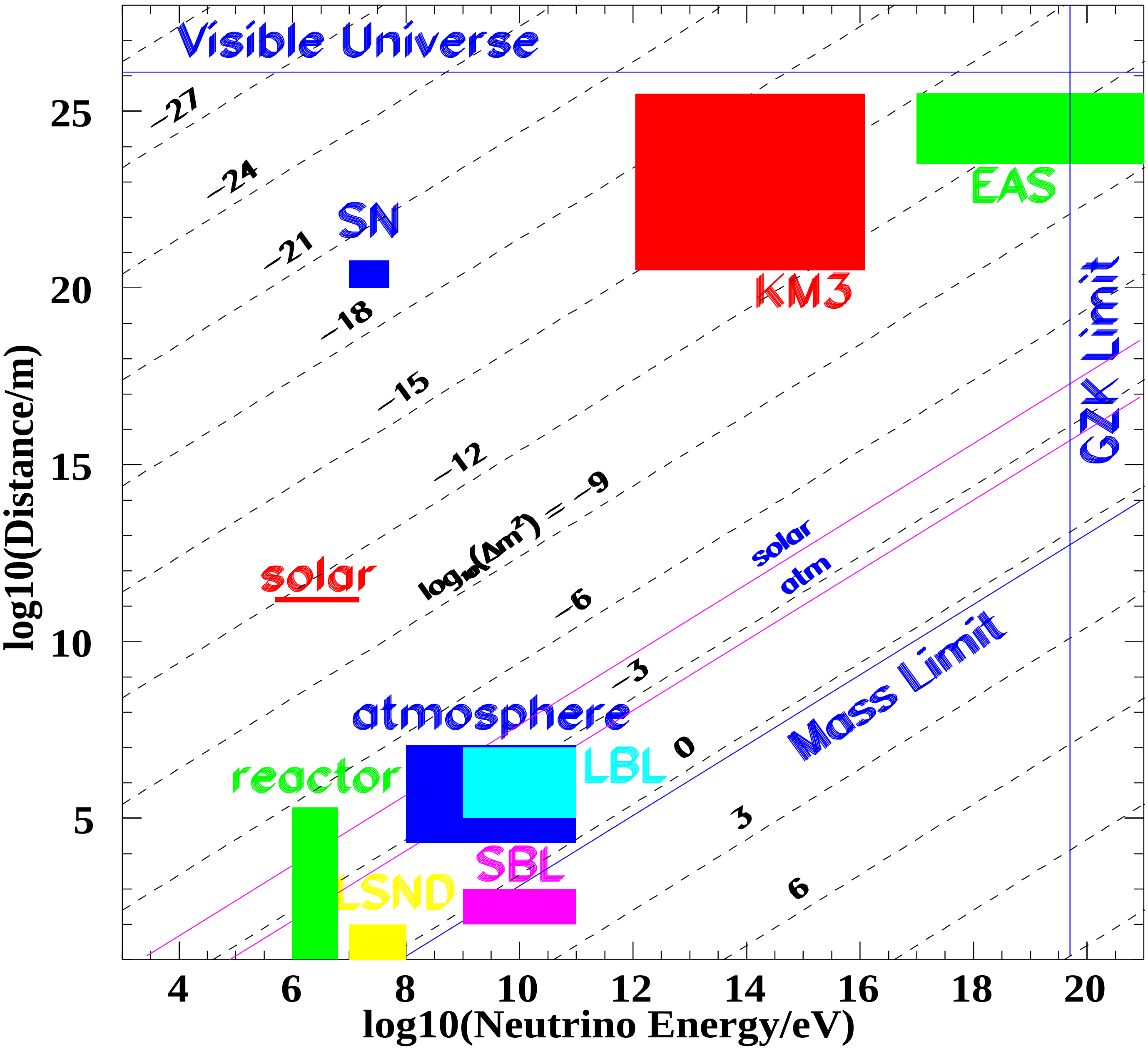
Astrophysical sources provide baselines almost as big as the visible universe.

This allows a sensitivity to oscillations with tiny δm^2

Eg. Active-sterile oscillation modes that have a sub-dominant or completely negligible effect on the solar or atmospheric neutrinos may show up here.

Crocker, Melia and Volkas (2000, 2002)
Berezinsky, Narayan and Vissani (2002)
Keranen, Maalampi, Myyrylainen and Riittinen (2003)

The “Learned Plot”



Pseudo-Dirac Neutrinos

Suppose:

Neutrinoless double beta decay experiments reach a sensitivity where we expect a positive signal (say, because we had confirmed the inverted hierarchy) but we get a null result.

Does that mean neutrino masses are of Dirac type?

Not necessarily: they might be pseudo-Dirac. (Wolfenstein)

Majorana mass terms might be subdominate in size to Dirac terms.

The fundamental question would still remain:
Do Majorana mass terms (of any size) exist in nature?

Generic (Majorana) mass matrix:

$$\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

Pseudo-Dirac limit is where:

$$m_{L,R} << m_D$$

Two closely degenerate, maximally mixed active and sterile states

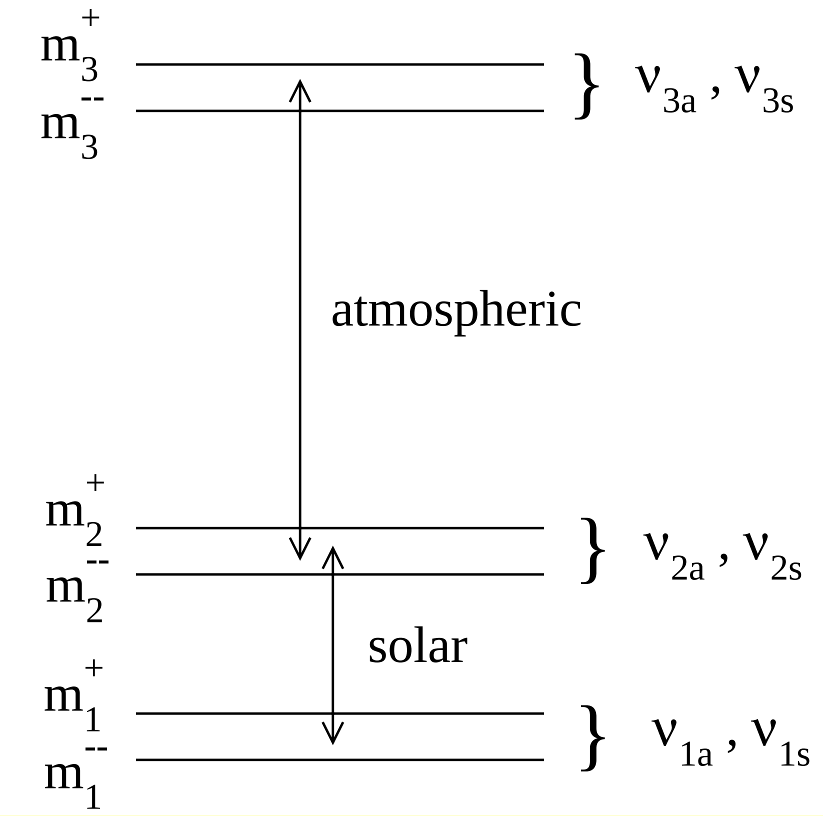
$$\nu_\alpha = \frac{1}{\sqrt{2}}\left(\nu^+ + i\,\nu^-\right) \qquad \nu_s = \frac{1}{\sqrt{2}}\left(\nu^+ - i\,\nu^-\right)$$

$$m^+ \approx m^- \qquad \delta m^2 << m^2 \qquad \theta \approx 45°$$

The two closely degenerate states have opposite CP parity
– so their contributions cancel in neutrinoless double beta decay

$$\langle m \rangle_{\mathrm{eff}}^{0\nu\beta\beta} = \sum_j U_{ej}^2\left(m_j^+ - m_j^-\right) \approx 0$$

Pseudo-Dirac mass spectrum



If the $\{\nu_{2,}^{+}\nu_{2,}^{-}\}$ and $\{\nu_{3,}^{+}\nu_{3,}^{-}\}$ oscillations have averaged out, but not the $\{\nu_{1,}^{+}\nu_{1,}^{-}\}$, the flavour ratios become:

$$1.5 : 1 : 1$$

Magnetic Moments

Magnetic moment transitions might change the flavor ratios
(Enqvist, Keränen, Maalampi, 1998)

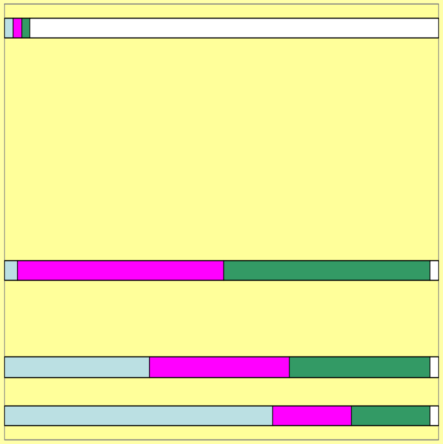
- Majorana neutrinos:

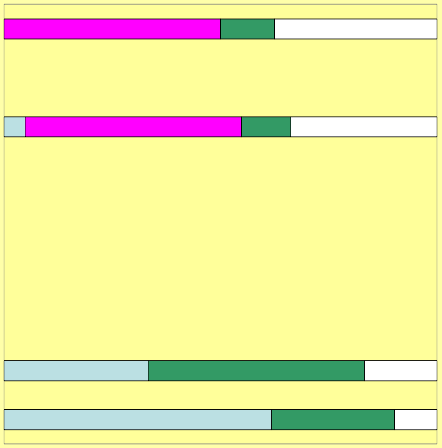
Symmetry between i→j and j→i transitions. Therefore, no observable effect if the ratio of mass eigenstates is 1:1:1 as expected.

- Dirac neutrinos:

Diagonal magnetic moments can turn active neutrinos into sterile, and may thus alter the flavor mix.

Active-sterile (LSND)





3+1 mixing scheme

2+2 mixing scheme.

Sterile approximately decoupled
from the 3 active neutrinos.

→Standard ratios ~ 1 : 1 : 1

→Non-standard ratios,
eg ~ 0.5 : 1 : 1

Dutta, Reno and Sarcevic (2001)

Event types

- Muon tracks

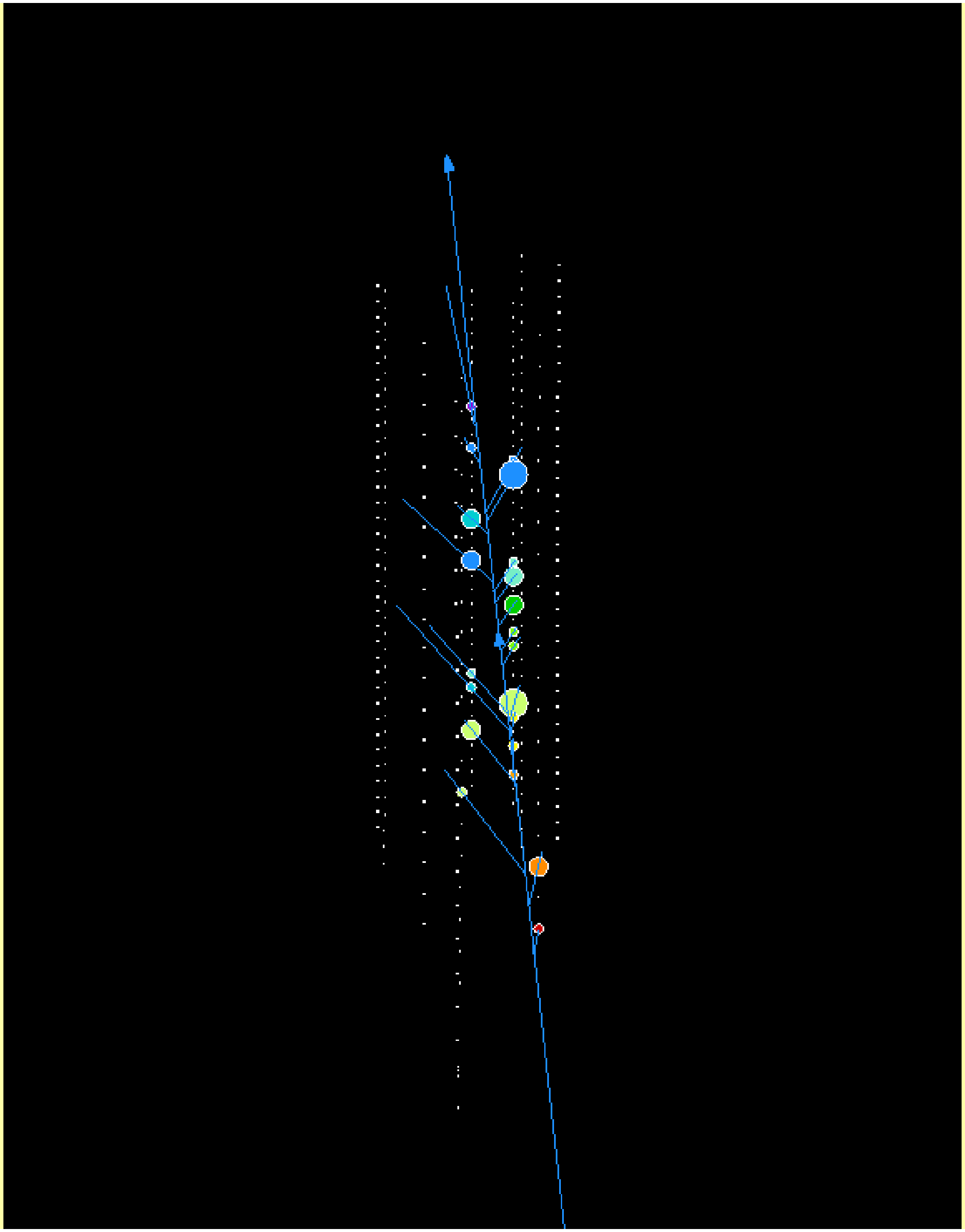
- Showers – neutral current interactions of all three flavors, plus CC interactions of ν_e and ν_{τ}.

- Double bang and lollipop events for ν_τ

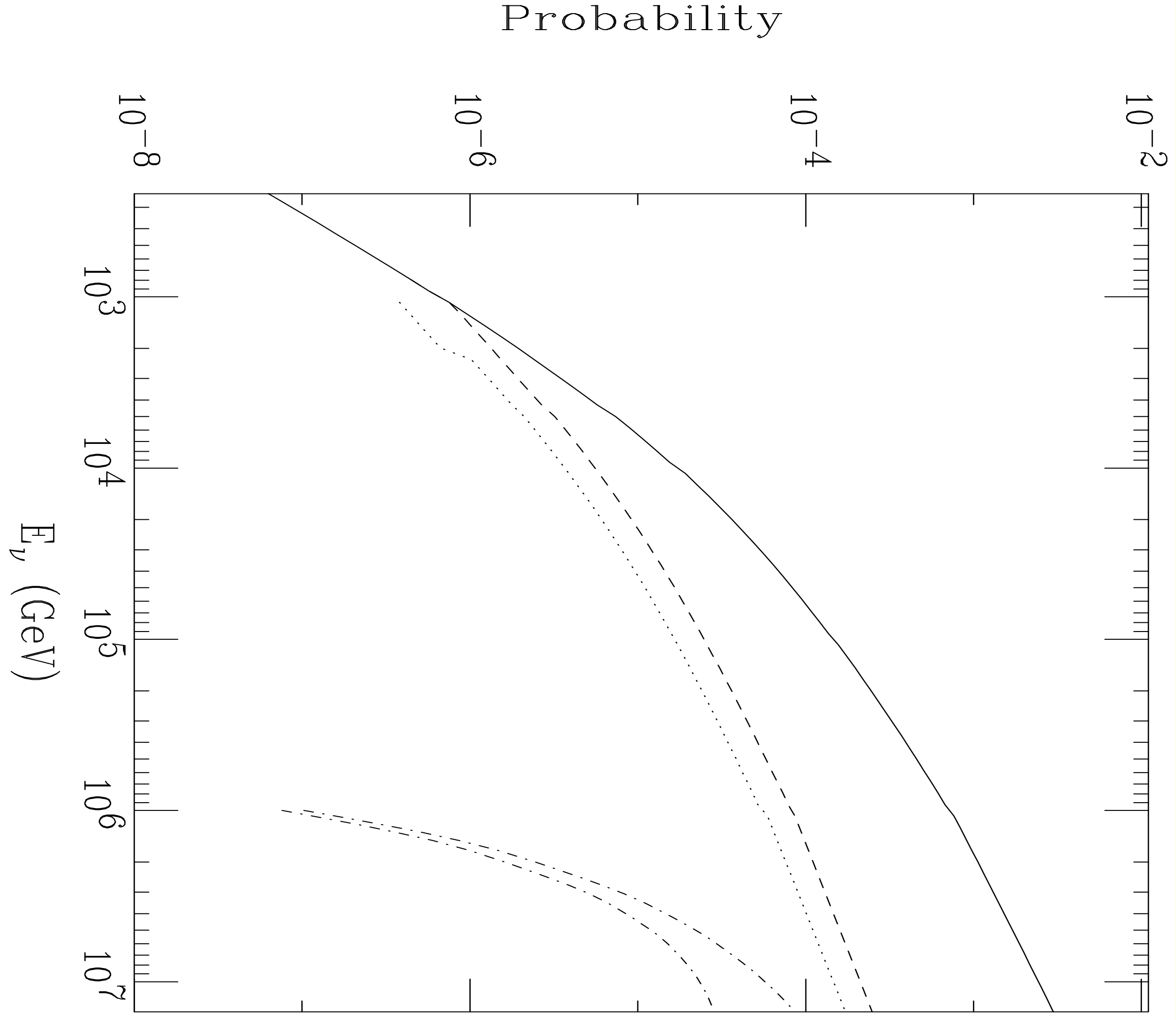
To determine the ν_e / ν_{μ}. ratio, we can compare the number of muon tracks to showers. The observation of double-bangs/lollipops would provide additional information.

In order to compare showers with tracks, it is useful to measure the spectral shape.

Muon Track event



Detection probabilities:



Muon track - horizontal ν_μ

Muon track - downgoing ν_μ
ν_e showers

ν_τ double-bangs and
lollipops (shower events)

Beacom, Bell, Hooper, Pakvasa, Weiler

Double Bangs and Lollipops

Double Bang: Hadronic shower from $\nu_{\tau.}$ CC interaction folllowed by second shower when the tau lepton decays, connected by a tau track

Lollipop: The second of these two bangs (plus the tau track)

$$P_{\mathrm{DoubleBang}}(E_\nu) = \rho N_A \sigma [(L - x_{\mathrm{min}} - R)e^{-x_{\mathrm{min}/}R} + \mathrm{R}\mathrm{e}^{-L/R}]_{y=<y>}$$

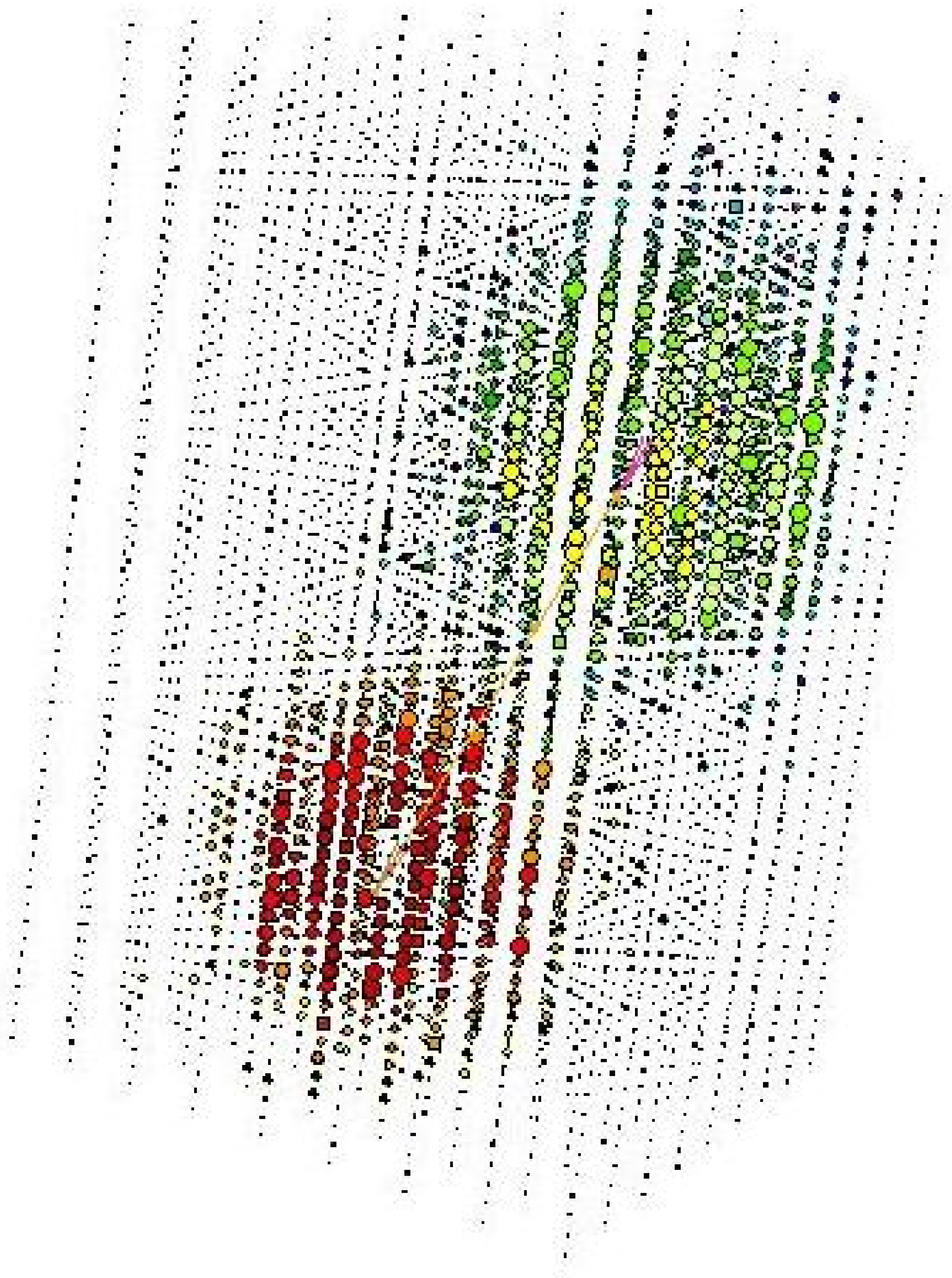
$$P_{\mathrm{Lollipop}}(E_\nu) = \rho N_A \sigma (L - x_{\mathrm{min}})[e^{-x_{\mathrm{min}/}R}]_{y=<y>}$$

Beacom, Bell, Hooper, Pakvasa & Weiler

L=detector size ~ 1km
R = tau decay length,
x_{min}=minimum shower separation / track length

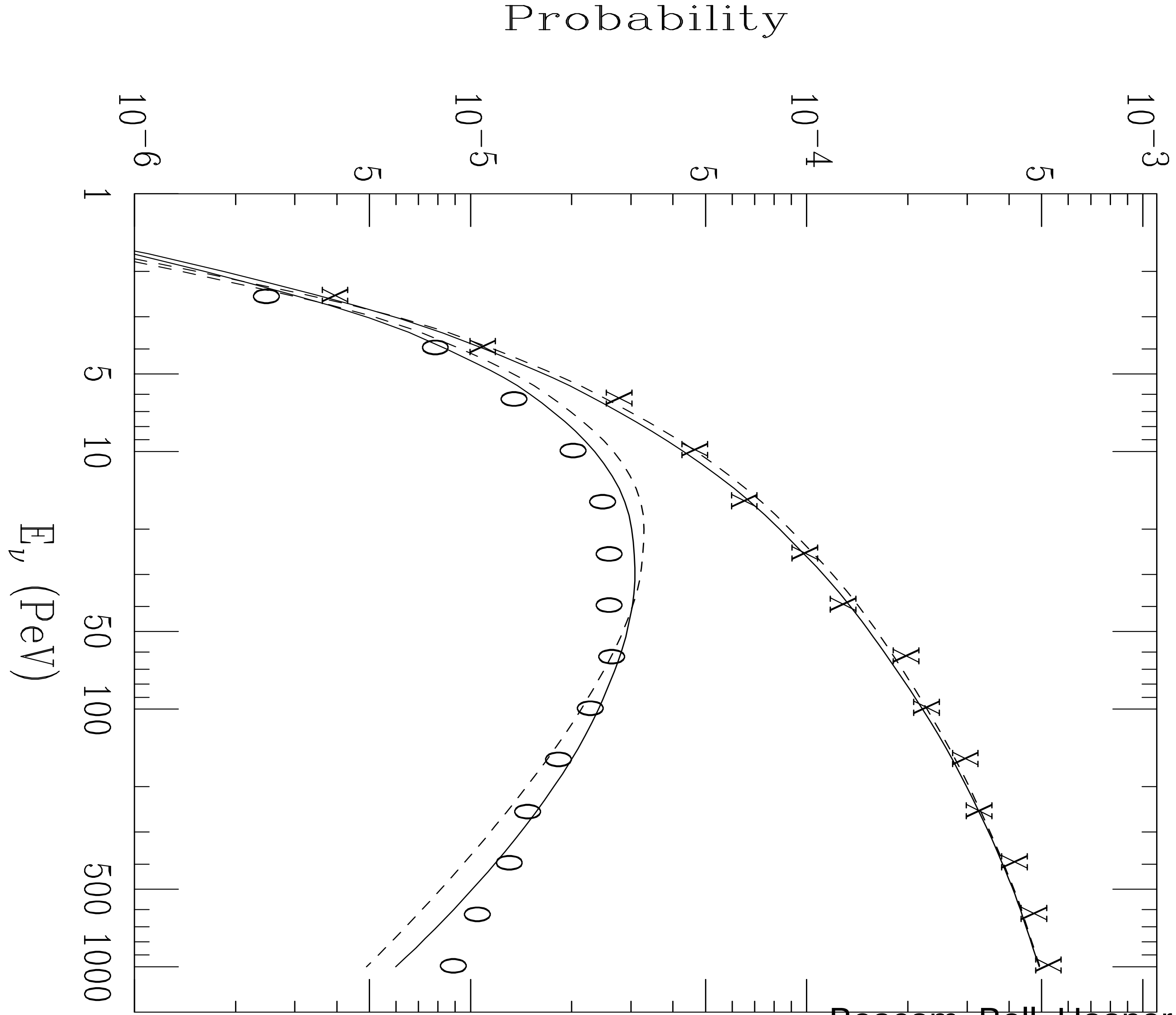
See also: Jones, Mocioiu, Reno and Sarcevic (2003).

Simulation of Double-Bang event



IceCube

Lollipop and Double Bang detection probabilities in IceCube



Beacom, Bell, Hooper, Pakvasa & Weiler

Backgrounds

Atmosphere neutrino background a problem below ~ 100 TeV

→Overcome this by looking at known point sources – the temporal and angular resolution can be used to effectively remove backgrounds

Absorption in the Earth

Earth start to become opaque to neutrinos at ~ 100 TeV

Tau regeneration

Halzen and Saltzberg

ν_e and ν_μ are absorbed in the Earth via charged current interactions

Above 10-100 TeV the Earth is opaque to ν_e and ν_μ.

But, the Earth never becomes completely opaque to ν_τ

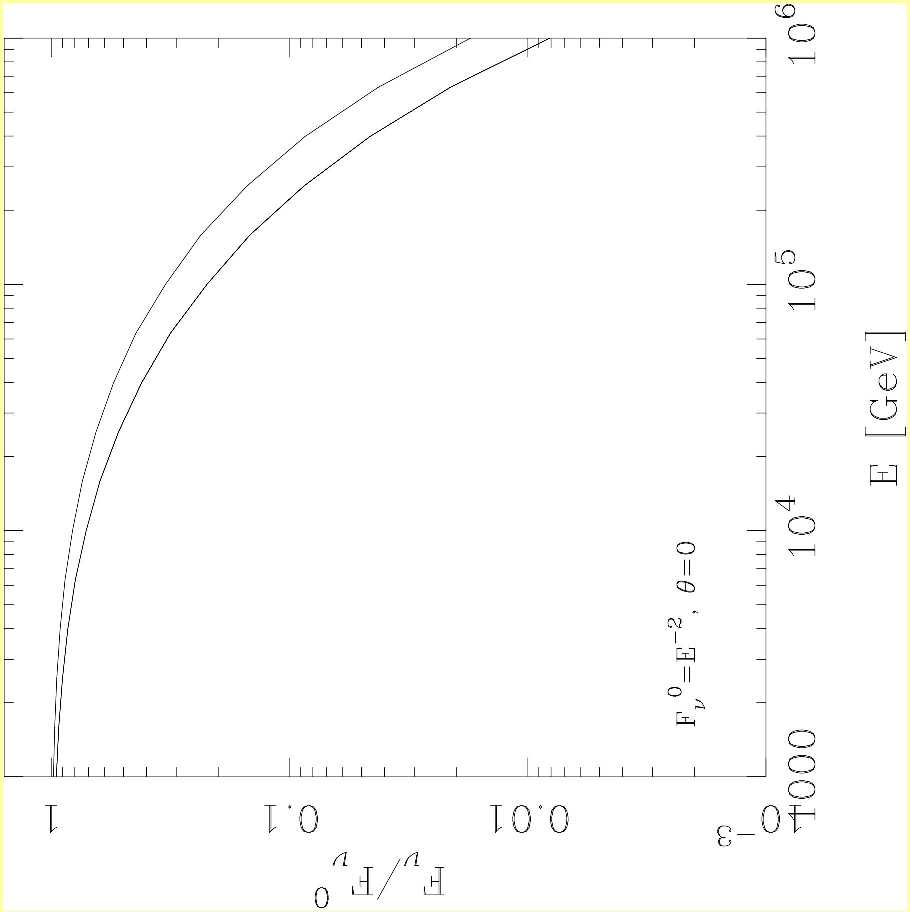
Due to the short τ lifetime, τ's produced in ν_τ charged-current interactions decay back into ν_τ

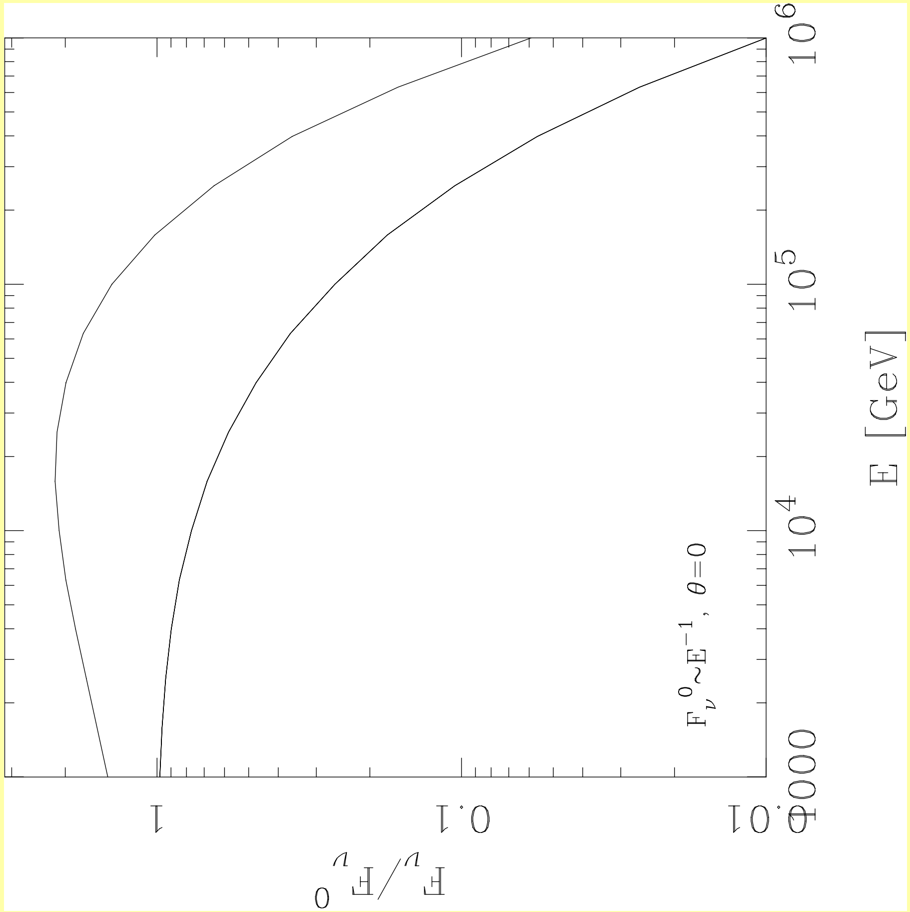
$$\nu_\tau \to \tau \to \nu_\tau \to \ldots$$

Also, secondary ν_e and ν_μ fluxes are produced in the tau decays.

Beacom, Crotty and Kolb

Tau-neutrino pile-up

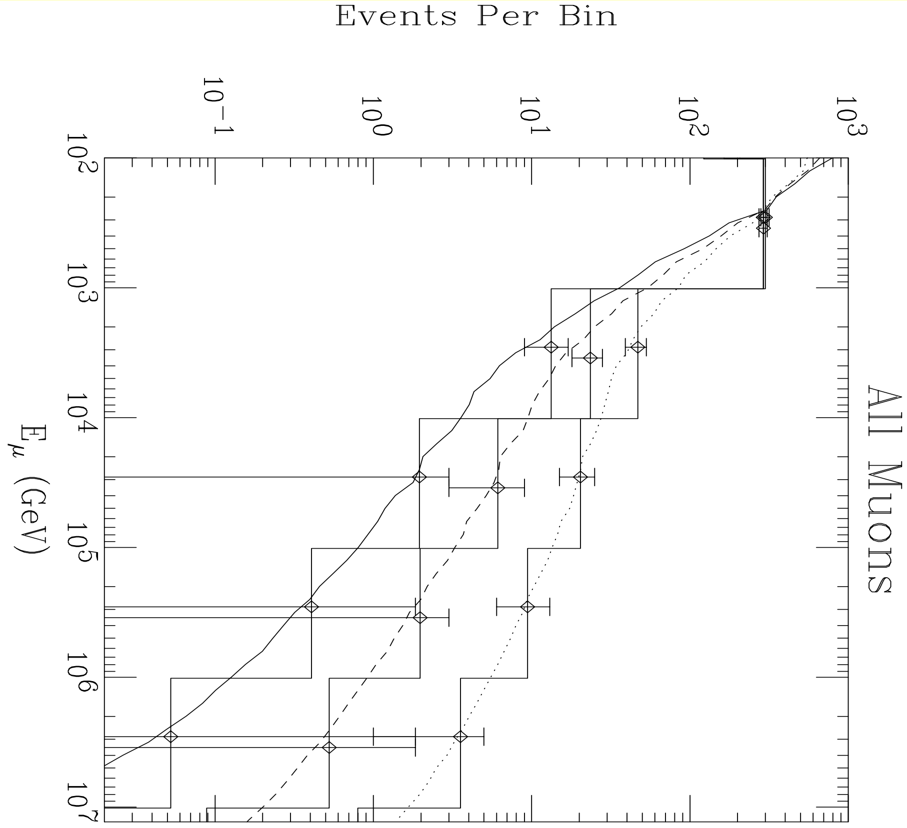


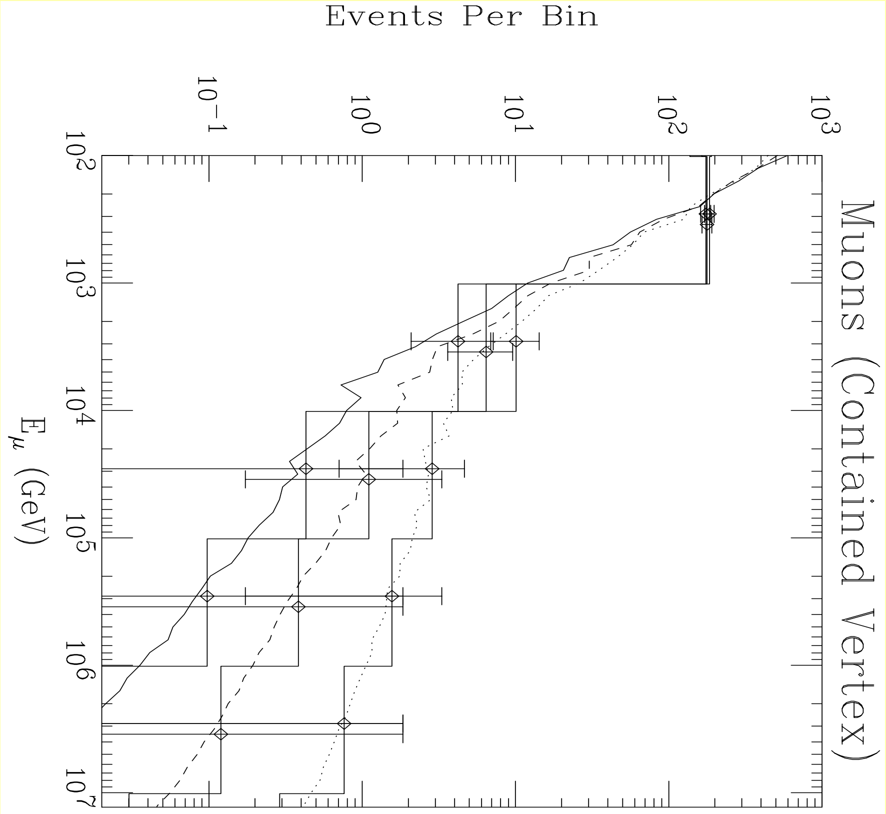


Dutta, Reno and Sarcevic, hep-ph/0302178

Measuring the spectral shape with muon track events

$$\mathrm{E}^2\, dN/dE = 10^{-7}\ \mathrm{GeV cm^{-2} s^{-1}}\ \text{ for 1 year}$$



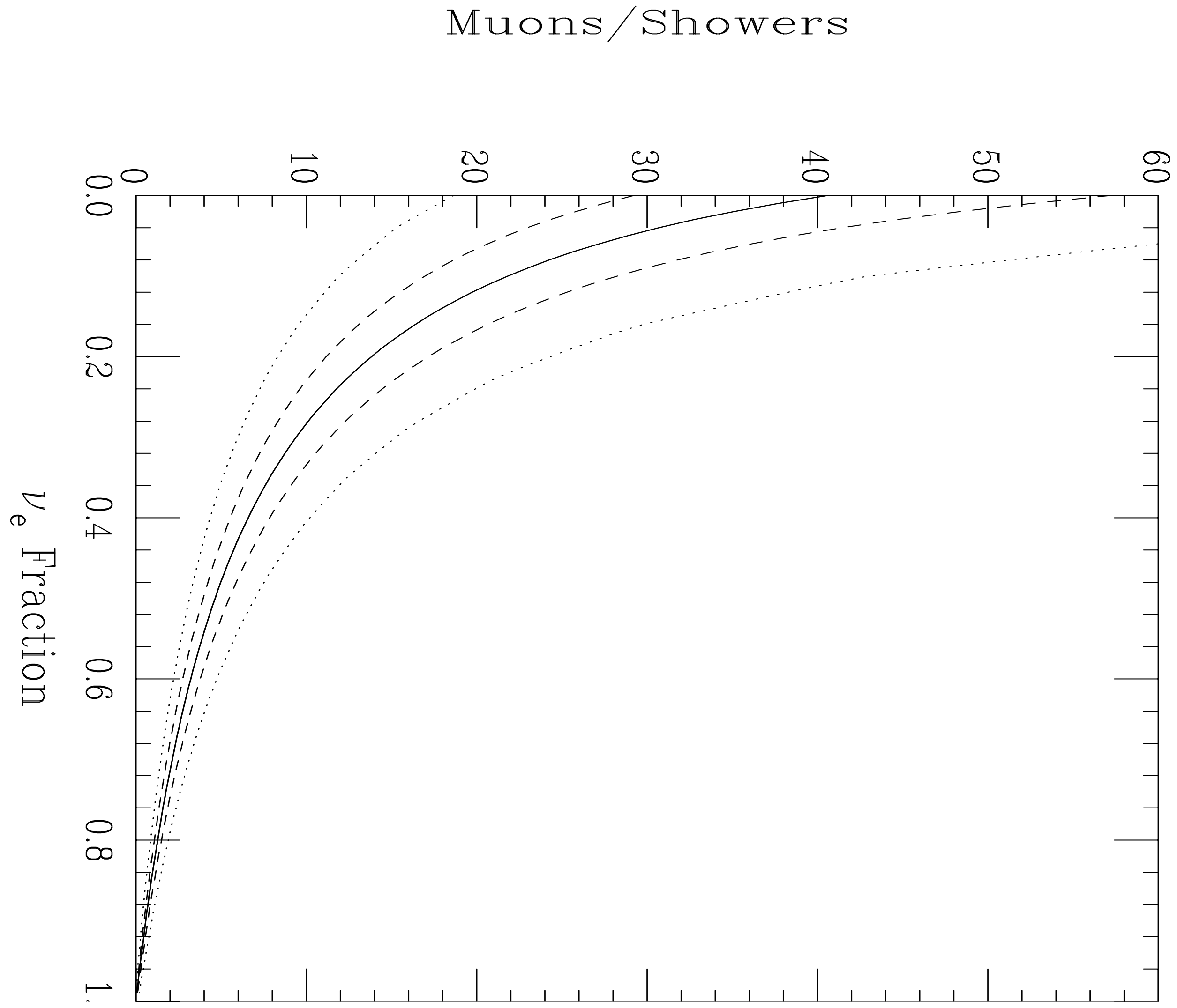


Neutrino spectra proportional to $E^{-1.8}$, E^{-2} and $E^{-2.2}$

Beacom, Bell, Hooper, Pakvasa & Weiler

Muons/Showers rate for different electron fractions.

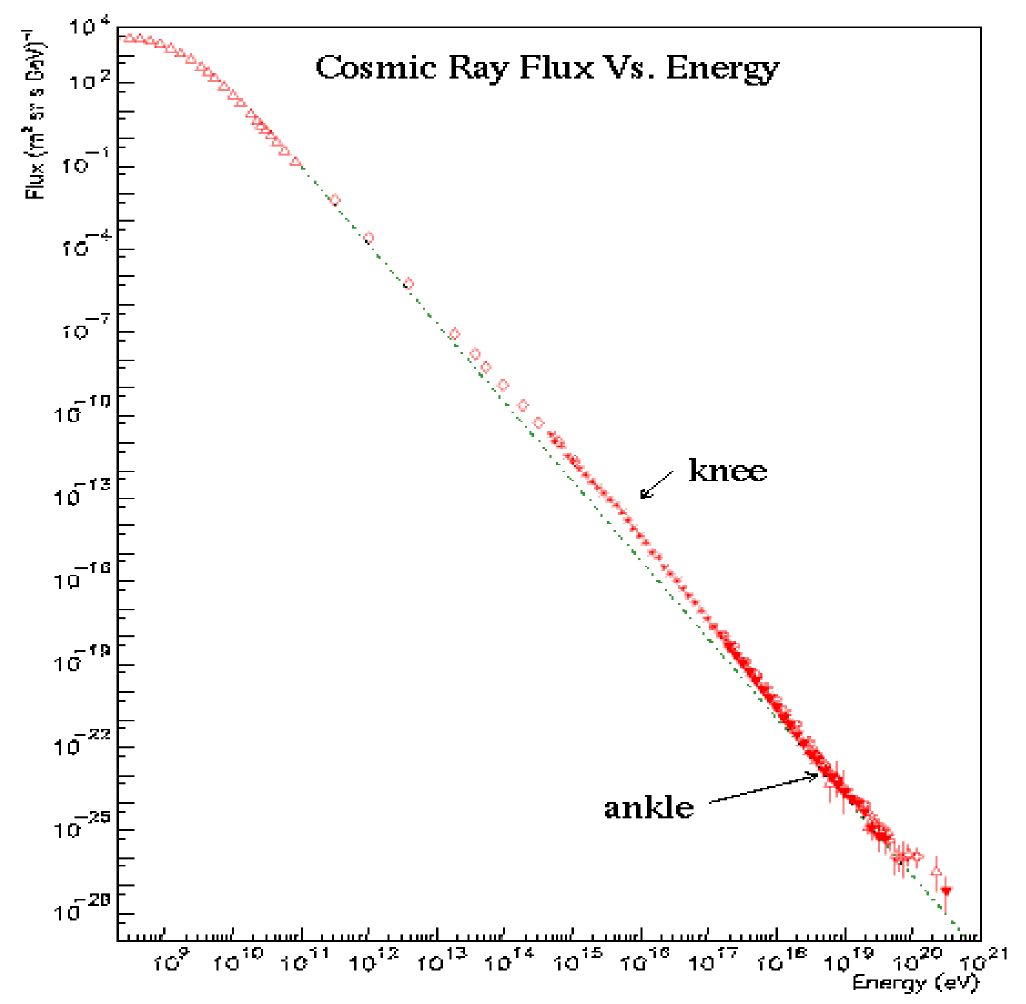
Mu-tau symmetry assumed



Beacom, Bell, Hooper, Pakvasa & Weiler

Neutrinos and Cosmic Rays

Cosmic Ray Spectrum



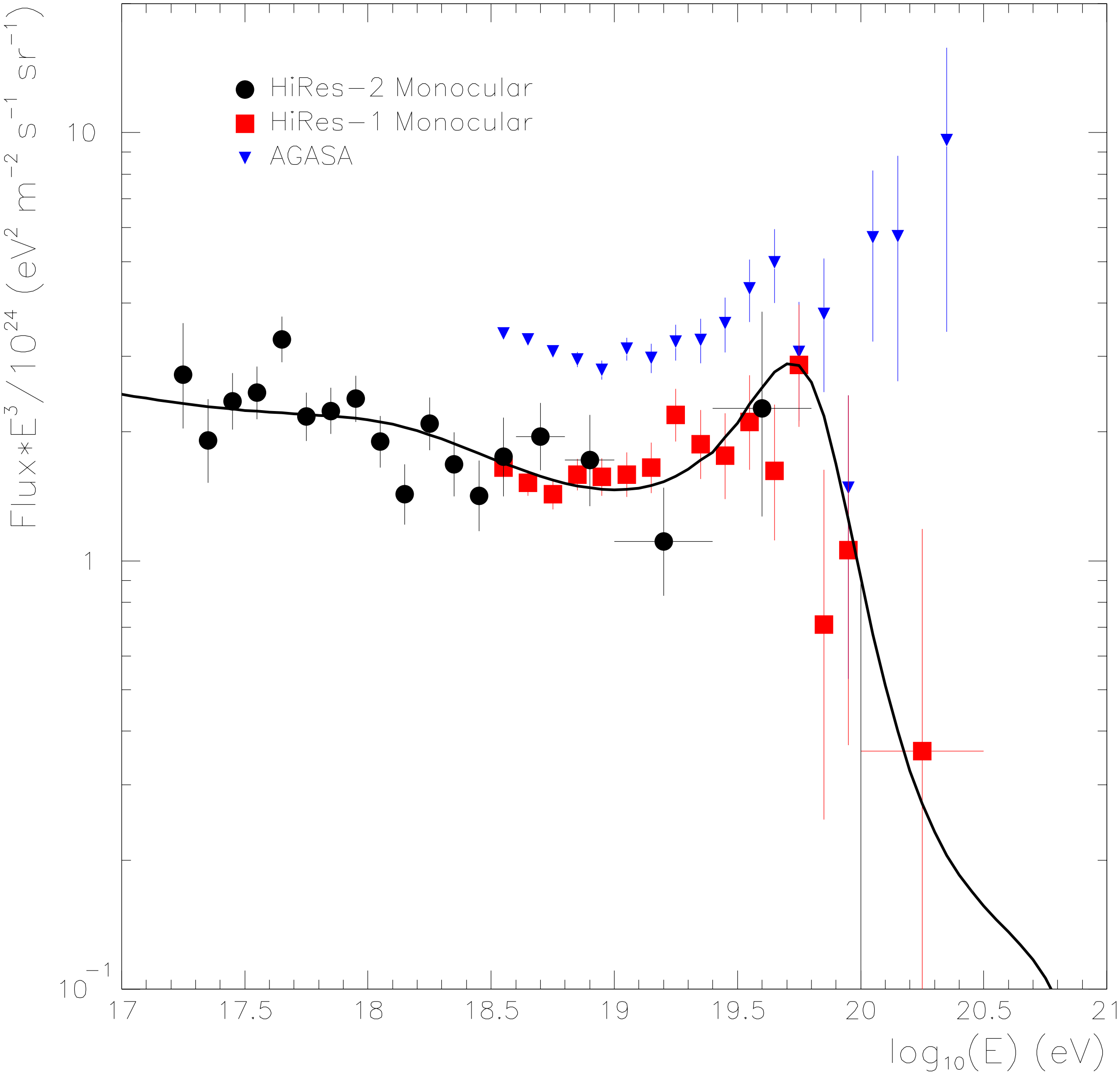
GZK cutoff mechanism

Greisen, Zatsepin and Kuzmin pointed out that there ought to be a cutoff in the cosmic ray spectrum around 10^{20} eV

Protons of energy above 10^{20} eV have a significant cross section for scattering from cosmic microwave background photons, producing particles of lower energy.

Intergalactic space should be opaque to protons of energy $>10^{19}$ eV

However, super-GZK events have (possibly) been observed


● HiRes−2 Monocular
■ HiRes−1 Monocular
▼ AGASA
Flux∗E³/10²⁴ (eV² m⁻² s⁻¹ sr⁻¹)
10
1
10⁻¹
17
17.5
18
18.5
19
19.5
20
20.5
21
log₁₀(E) (eV)

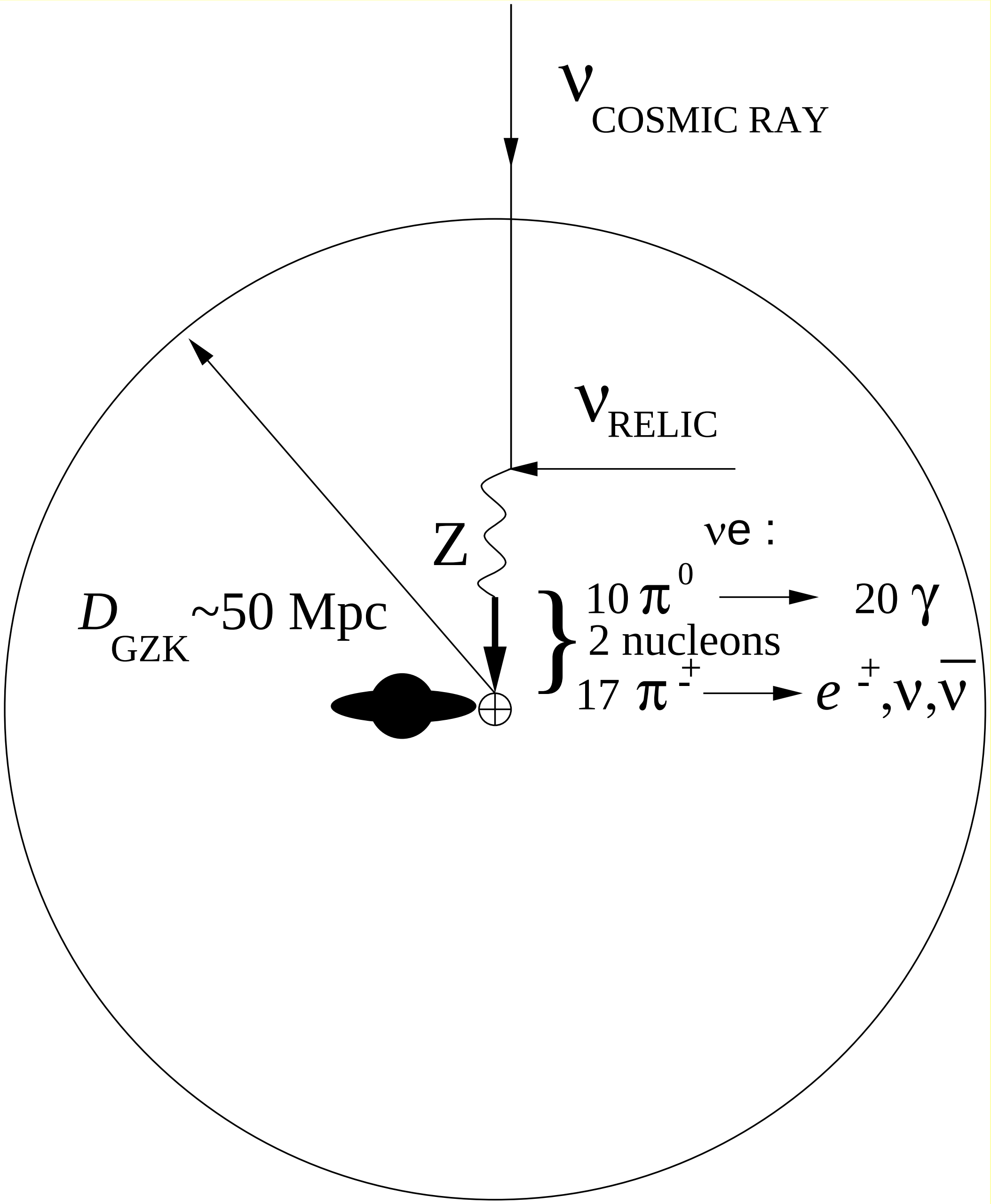
Can neutrinos help explain the highest energy cosmic rays?

Neutrinos can travel much greater distances without being attenuated.

Ultra-high energy neutrinos can interact with low energy relic neutrinos nearby. For neutrinos of energy 10^{21}-10^{22} eV, the centre of mass energy for scattering from an eV mass relic neutrino is about the mass of the Z^0 boson. (Weiler)

Energy for Z^0 resonance: $$E_\nu = \frac{M_Z^2}{2m_\nu} = \frac{4.2\times10^{21}\ \mathrm{eV}}{m_\nu(\mathrm{eV})}$$

Z- burst mechanism



Decay of the Z^0 would be a source for the cosmic rays beyond the GZK cutoff.

Weiler and Pas

Relic neutrino detection

If such ultra high energy neutrino fluxes existed then:

- Z-burst mechanism probes the neutrino mass

AND

- It would be an (indirect) way to detected the cosmic neutrino background

(All our knowledge of cosmic background neutrinos comes from big bang nucleosynthesis….we are never likely to directly detect them, since they are non-relativistic today.)

Z-burst uncertainties

What is the density of these relic neutrino targets?

Neutrino clustering in galaxy clusters would produce a local overdensity of relic neutrinos, if m>0.3eV. (Ma and Singh, 2002.)

Large chemical potential would result in extra relic neutrinos,
but big bang nucleosynthesis + large-angle mixing rules this out.
(Dolgov et al; Abazajian, Beacom & Bell, Wong; Lunardini & Smirnov)

What are the fluxes at such extreme energies???

Conclusions

- Ultra high energy neutrino observations offer us an opportunity to probe neutrino properties at energies and baselines far beyond those we can achieve in terrestrial experiments.

- Flavor discrimination will be very useful for uncovering possible new physics

Many new experiments are being planned
(see next talk by D. Besson!)