Neutrino Properties from High Energy Astrophysical Neutrinos

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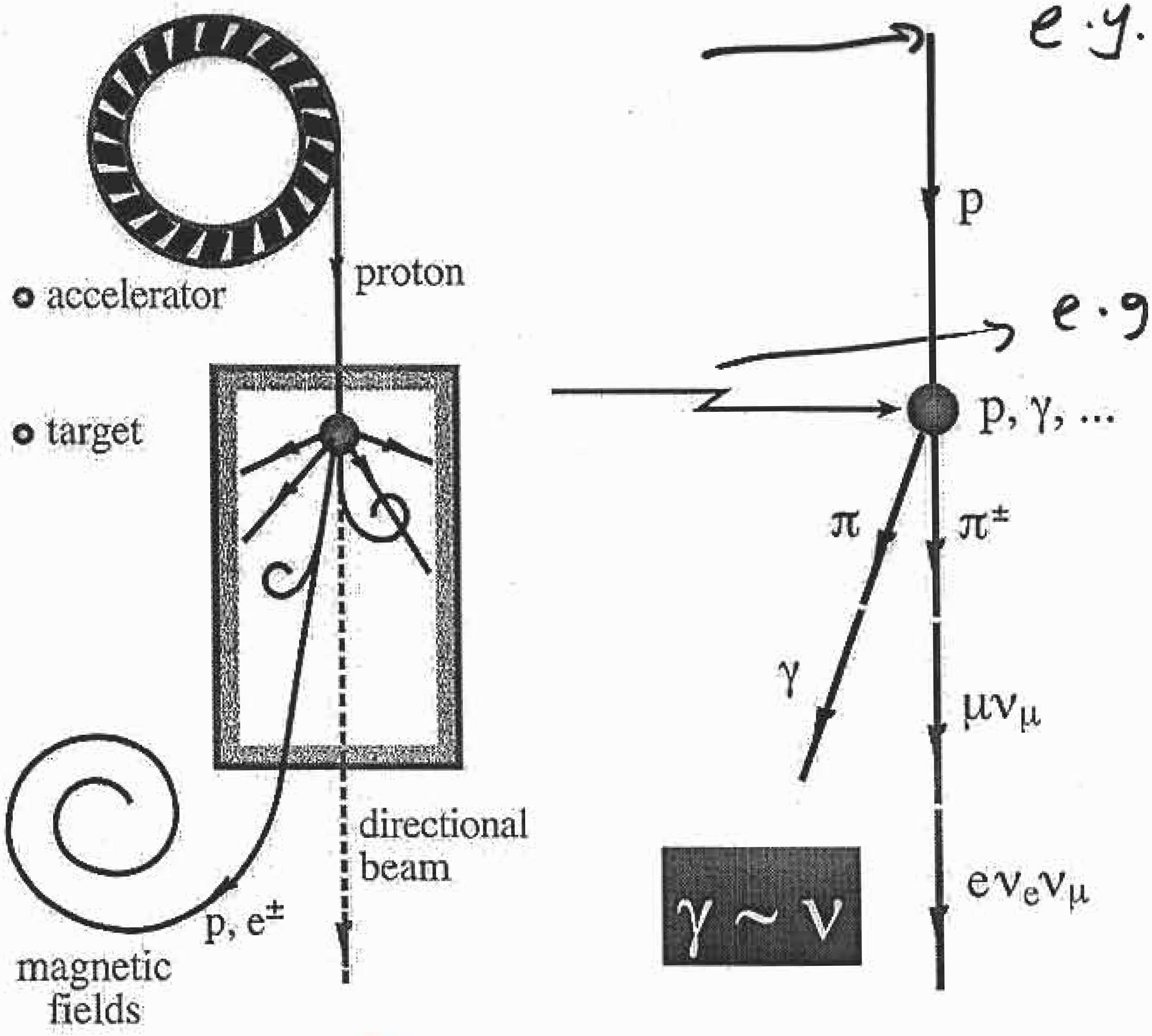
To proceed [redacted], make two working assumptions:

- Sources emitting v.H.E. ν's ($\gtrsim$ PEV) with significant fluxes to be detectable at earth at distances $\sim 10^3$ MPC
Best Candidates : AGN's.
GRB's at lower energies

- Existence of large ν Detectors : (pioneers: Baikal, DUMAND)
KM3 : ICECUBE @ South Pole
At least One in Medit [from ANTARES, NESTOR ...] [Water-ice $\hat{c}$]
Other technologies, larger :
AUGER, EUSO-OWL, ANITA, - - - -
Good instrumentation, E resolution, angular resolution, low E threshold — - -.

NEUTRINO BEAMS: HEAVEN & EARTH



e.g. Black hole

e.g. Radiation around B. H.

$p+\gamma \to \pi^{\pm} ..$
$p+p \to \pi^{\pm} ..$

Beam Dumps

Astrophysical Neutrino Sources

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

Eg, Gamma Ray Bursts (GRBs) and Active 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: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

Caveat: If μ's absorbed or lose energy $\underline{\text{no } \nu_e\text{'s}}$ $\longrightarrow 0:1:0$

Sub-dominant prompt ν's $\longrightarrow 1:2:\epsilon$

Effect of Oscillations on flavor mix ⑪

- all $\delta m^2 > 10^{-5}\,eV^2$
- osc. argument $\dfrac{\delta m^2 L}{E} \gg 1.$

(for $L > MPC$
$E \sim PeV$)

$$\Rightarrow \quad \sin^2\left(\frac{\delta m^2 L}{4E}\right) \simeq 1/2.$$

osc. average out.

Hence survival & conversion probabilities are:

$$P_{\alpha\alpha} = \sum_i |U_{\alpha i}|^4$$

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- There are no significant matter effects en-route.

It densities were high enuf for that, ν's would be absorbed anyway.

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:

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

(Learned & S.P. 1995)

Exact mu-tau symmetry occurs when: $\theta_{\text{atm}} = 45°$ 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)

Hence, for most conventional H.E. ν sources, we expect flavor mix at arrival:

$$e/\mu/\tau = 1/1/1$$

Learned, S.P. ('95)
Athar Husain et al. (99)

If this is observed in future ν - Telescopes. ⇒

- Confirms our knowledge of ν mixing
- Confirms the beam dump nature of ν production at source

More exciting if $e/\mu/\tau \neq 1/1/1$

→ Learn something new.

When can this happen?

If we don't see 1:1:1

Different flavor ratio at the source

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

→ becomes 0.5 : 1 : 1 at Earth

Exotic neutrino properties

- Neutrino decay upto 10^5 s/eV ⇒ measure mixing parametors!
- CPT violation
- Oscillation to steriles with very tiny delta δm² ⟶ upto 10^{-18} eV^2
- Pseudo-Dirac mixing
- 3+1 or 2+2 mixing
- Magnetic moment transitions (Dirac ν's)

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.

- Do neutrinos decay? (hep-ph/0004077)
- Since $m_i \neq 0$ & flavor mixing occurs, surely heavier ν decays to lighter ones.
- The only questions are:
    - what are the decay modes?
    - how long are the liftimes?
    - short enuf to be interesting?
- What can we say at the moment about these?
- We will assume all ν-masses in eV range or less.

Neutrino Lifetimes

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

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

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

$$\left.\begin{array}{l} \nu_2 \rightarrow \nu_1 + \phi \\ \quad \rightarrow \bar{\nu}_1 + \phi \end{array}\right\}$$

[Only mode that can have "fast" decay.
All others $\nu_2 \longrightarrow \nu_1 + \gamma$
$\nu_2 \longrightarrow \nu_1 \bar{\nu}_1 \nu_1$
ruled out]

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

Current Bounds on ν_i Lifetimes

- Invisible 2 body Modes

- ν_1 : SN1987A $\Longrightarrow \tau_1 \geq 10^5$ sec/eV

- ν_2 : Solar $\bar{\nu}_e$ limit (KamLand) $\Longrightarrow \tau_2 \geq \begin{cases} 5 \cdot 10^{-2} & \text{s/eV (QD)} \\ 10^{-5} & \text{s/eV (H)} \end{cases}$

- ν_3 : Atm. Neutrinos (Super-K Dip)

  $\tau_3 \geq 10^{-10}$ s/eV

  (Normal Hierarchy only)

[To explain LSND need $\tau \sim 10^{-12}$ s/ev]

What are the current bounds (or potential best bounds) on lifetimes of ν_i?

Source	flavor	which mass e-state	L/E	$\tau\,(m/eV)$
Lab	ν_μ, ν_e	ν_3, ν_2	30m/10MeV	10^{-14} s
ATM.	ν_μ ν_e	ν_3 ν_2	10^4km/GeV	10^{-10} s
Sun	ν_e	ν_2	500s/MeV	10^{-4} s
SN (Galact)	$\bar{\nu}_e$	$\bar{\nu}_2$	10kpc/10MeV	10^5 s
Relic SN	$\bar{\nu}_e$	$\bar{\nu}_2, \bar{\nu}_1$	10^3Mpc / 10MeV	10^{10} s
AGN	ν_μ	ν_3	100Mpc/TeV	10^4 s.

current

→ 10^{-2} s Kamland

(potential)

→ ν's may be unstable

Astrophysical ν's may place better bounds on reveal positive evidence for decay.

When is final flavor mix NOT
$\nu_e/\nu_\mu/\nu_\tau = 1/1/1$?

1. When initial flux is NOT
1/2/0. (environment at production)

2. ν Decay:

If ν_i is unstable, then in propagation matrix $|U_{\alpha i}|^2$ is now

$$|U_{\alpha i}|^2 \exp\left(-\frac{L}{E}\frac{m_i}{\tau_0^i}\right)$$

└ rest frame lifetime

If τ_0^i short enuf, this term goes to zero.

If only the lightest survives, then
either ν_1 (normal hierarchy)
or ν_3 (inverted ")
arrives at earth.

If ν_1 survives: (Normal Hierarchy)

Flavor mix on arrival:

$$\nu_e/\nu_\mu/\nu_\tau = |U_{e1}|^2/|U_{\mu 1}|^2/|U_{\tau 1}|^2$$

$$= c^2/\tfrac{1}{2}s^2/\tfrac{1}{2}s^2$$

$$= 6/1/1$$

(for $\theta \sim 30°$)

If ν_3 survives: (Inverted Hierarchy)

$$\nu_e/\nu_\mu/\nu_\tau = \varepsilon^2/1/1 \sim \underline{0/1/1}$$

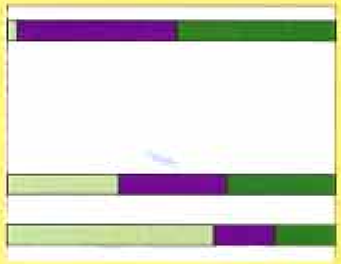
$$\varepsilon^2 < 0.04$$

These flavor mixes are very different from the 1/1/1 and from each other & distinguishable. <u>Signatures for Decays.</u>

Decay – Flavor Ratios

The lightest neutrino should be stable.

Normal hierarchy



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

$= U_{e1}^2 : U_{\mu 1}^2 : U_{\tau 1}^2$

Inverted hierarchy

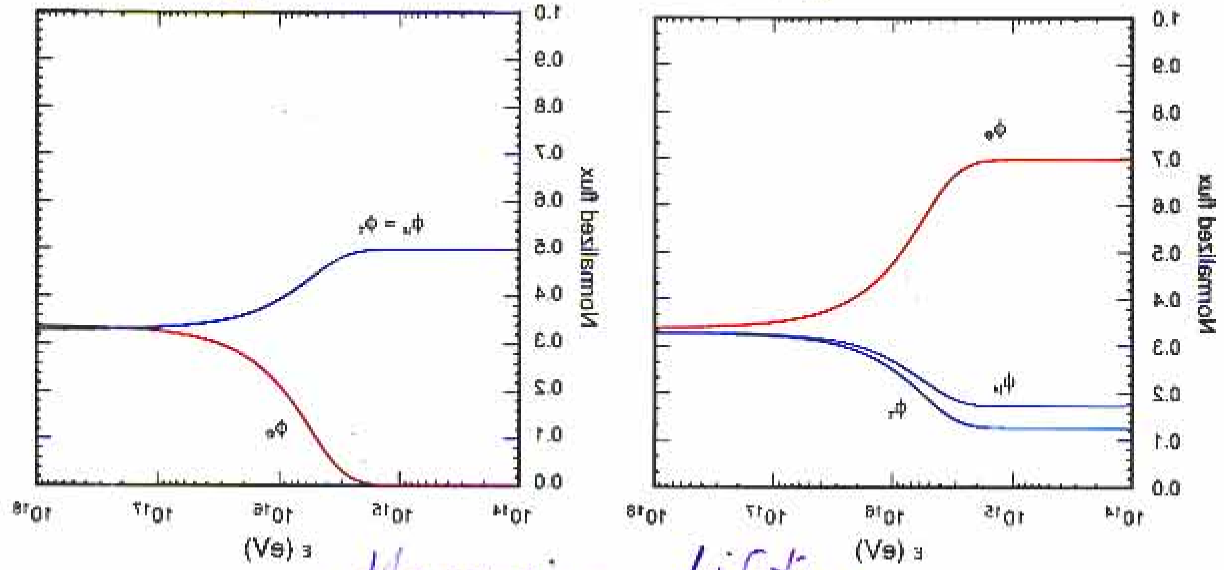
$\nu_e : \nu_\mu : \nu_\tau = 0:1:1$

$= |U_{e3}|^2 : |U_{\mu 3}|^2 : |U_{e3}|^2$

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

Inverted L/E →

Normal L/E →



Measuring Lifetime

FIG. 3: Energy dependence of normalized ν_e, ν_μ, and ν_τ fluxes, for the two-body decay of the two upper mass eigenstates, with the neutrino source at $L = 100$ Mpc from Earth and $\tau/m = 1$ s/eV. The left pane shows the result for a normal mass hierarchy; the right pane shows the result for an inverted mass hierarchy. With suitable rescaling of the neutrino energy (cf. Eqn. (13)), these plots apply for any combination of path length and reduced lifetime.

In practice, ultrahigh-energy neutrinos are likely to arrive from a multitude of sources at different distances from Earth, so the transition region will be blurred [25]. Nevertheless, it would be rewarding to observe the decay-to-survival transition, and to use Eqn. (14) to estimate—even within one or two orders of magnitude—the reduced lifetime. If no evidence appears for a flavor mix characteristic of neutrino decay, then Eqn. (14) provides a lower bound on the neutrino lifetime. For that purpose, the advantage falls to large values of L/E^*, and so to the lowest

Barenboin & Quigg

With many sources identified & variety of L/E

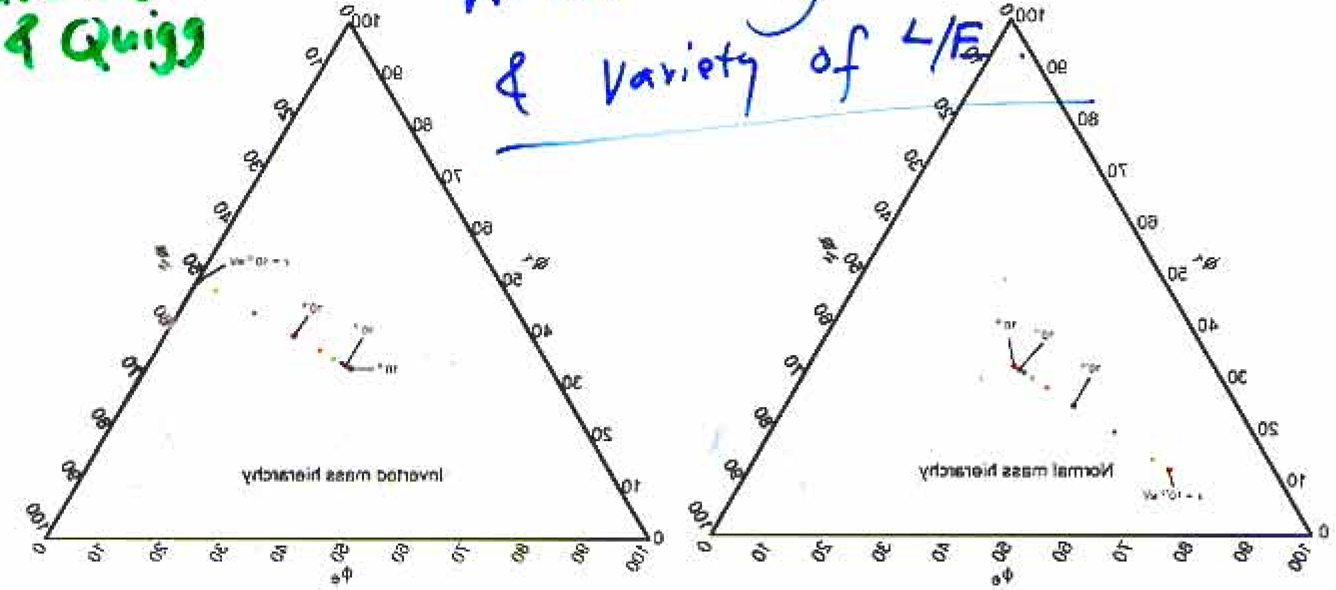
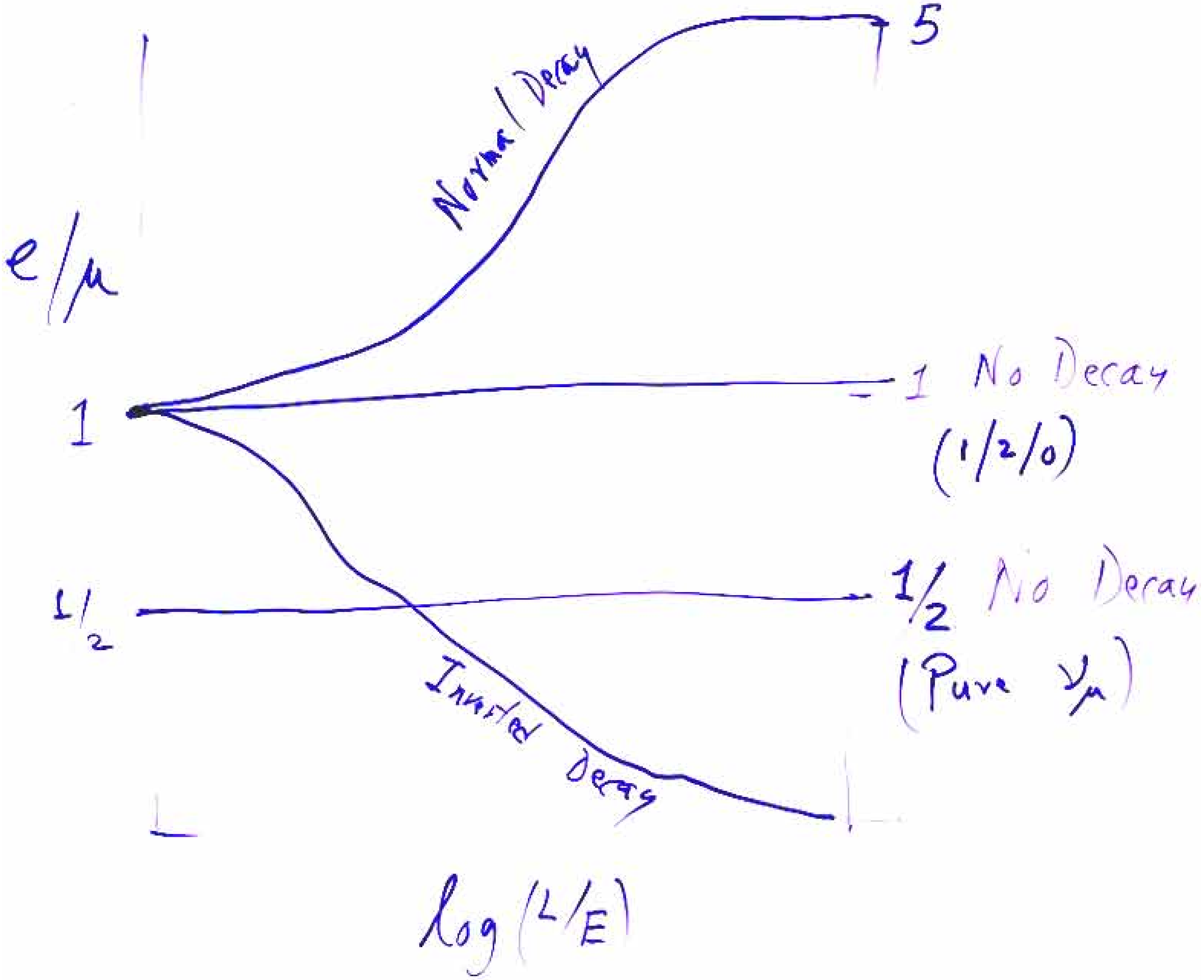


FIG. 4: Ternary plots showing the energy dependence of normalized ν_e, ν_μ, and ν_τ fluxes, for the two-body decay of the two upper mass eigenstates, with the neutrino source at $L = 100$ Mpc from Earth and $\tau/m = 1$ s/eV. The left pane shows the result for a normal mass hierarchy; the right pane shows the result for an inverted mass hierarchy. Each unlabeled step multiplies E by $10^{1/4}$. With suitable rescaling of the neutrino energy (cf. Eqn. (13)), these plots apply for any combination of path length and reduced lifetime.



Analog of Super-K
L/E Plot.

Oscillations give No Dip!

Decay Signatures in Relic Supernova $\bar{\nu}_e$'s

Complete Decay ($\tau_i < 10^{10}$ s/eV)

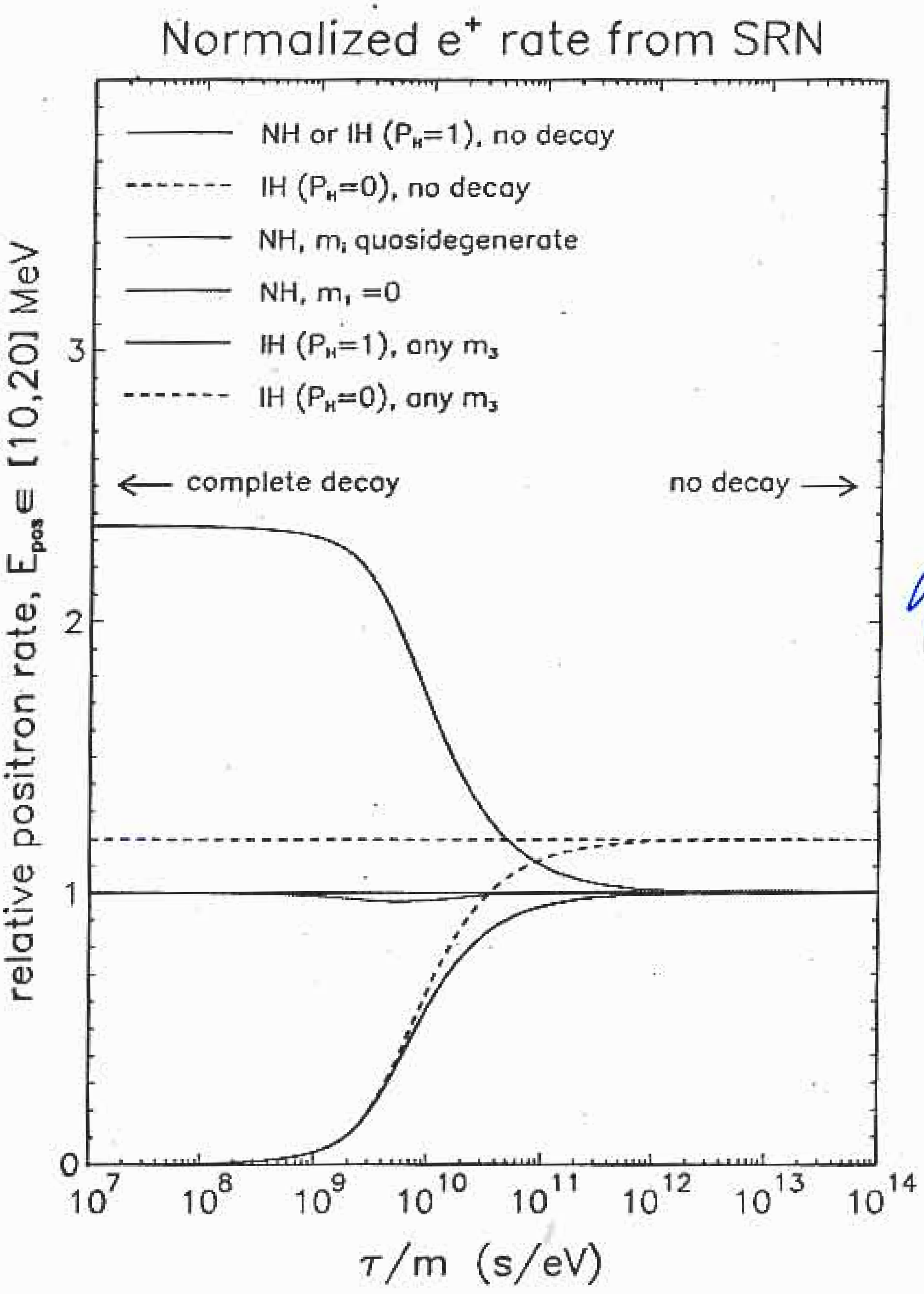
- Normal Hierarchy

  $\Longrightarrow$ CR enhanced by about a factor of 2.

- Inverted Hierarchy

  $\Longrightarrow$ CR $\longrightarrow$ 0.

Relic SN $\bar{\nu}_e$'s can probe τ to $10^{10}-10^{11}$ s/eV.



↑ $\frac{\bar{\nu}_e \text{ Rate}}{\bar{\nu}_e \text{ expected Rate}}$

: (Color online.) Positron event rates in the energy range [10, 20] MeV for various decay scenarios, lized to standard expectations for normal hierarchy and no decay. The τ/m range in abscissa is well the safe bound in Eq. (8). Notice how the expectations branch out (and then reach the complete limit) in the cosmologically relevant range $\tau/m \lesssim 10^{11}$ s/eV. See the text for details.

Fogli et al. hep-ph/0401227

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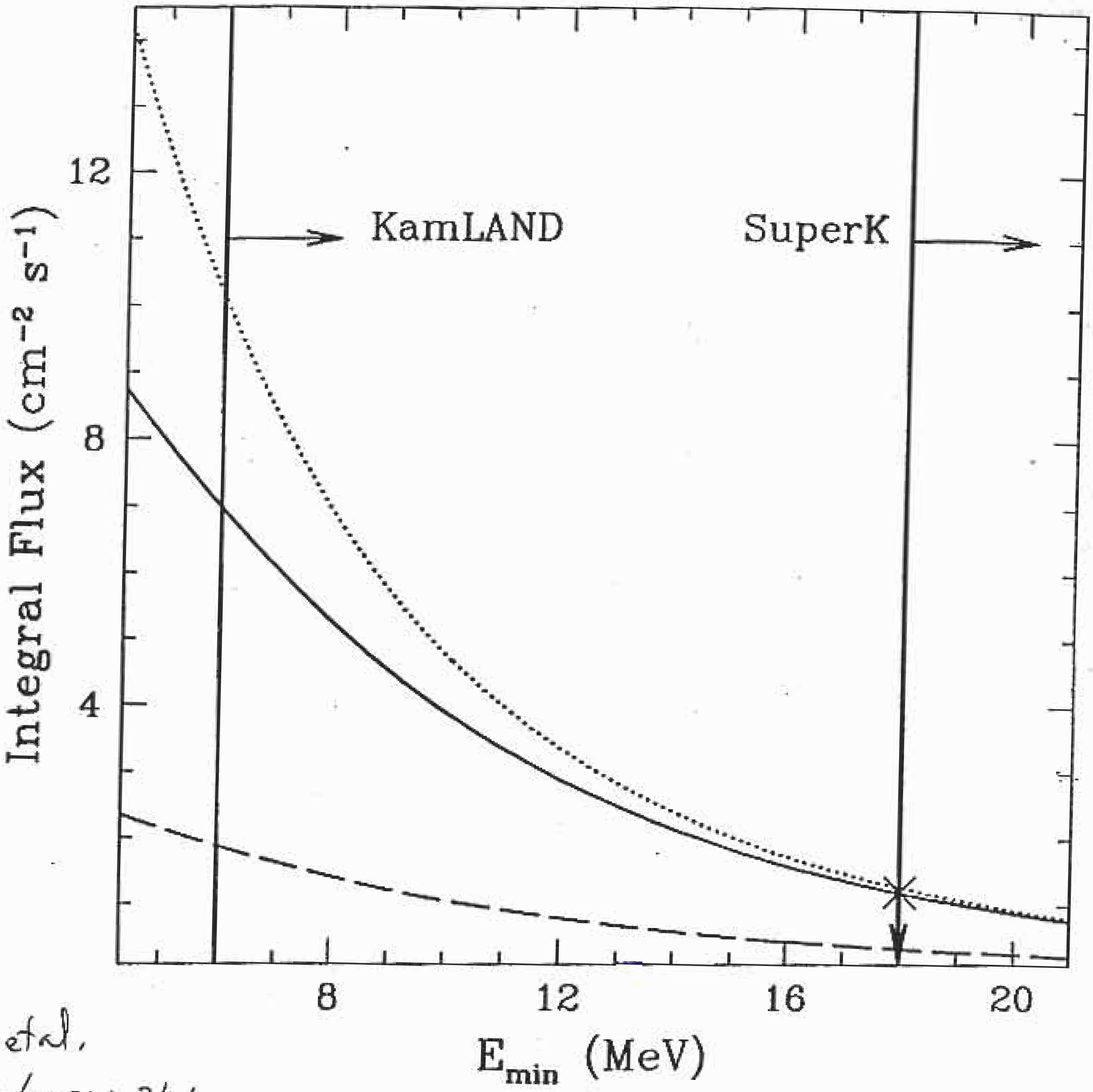

Stringari et al.
astro-ph/0312346

FIG. 2: Estimates of the supernova relic $\bar{\nu}_e$ integral flux positron energies $E > E_{\rm min}$, as a function of $E_{\rm min}$. The sc curve is motivated by median measurements for the slope the low and high redshift SN rates, with a consistent norm ization chosen to saturate the Super-K upper bound. T dotted curve shows the affect of increasing the slope of $z > 1$ SN rate. The lower curve represents an estimated lo bound to the SN rate based on the SDSS results. The Sup K upper bound is indicated by the cross. The sensitivity KamLAND and Super-K to SRN is shown by vertical lines.

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ν Mixing matrix may not be exactly:

$$\begin{pmatrix} c & s & 0 \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & 1/\sqrt{2} \\ \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & 1/\sqrt{2} \end{pmatrix}$$

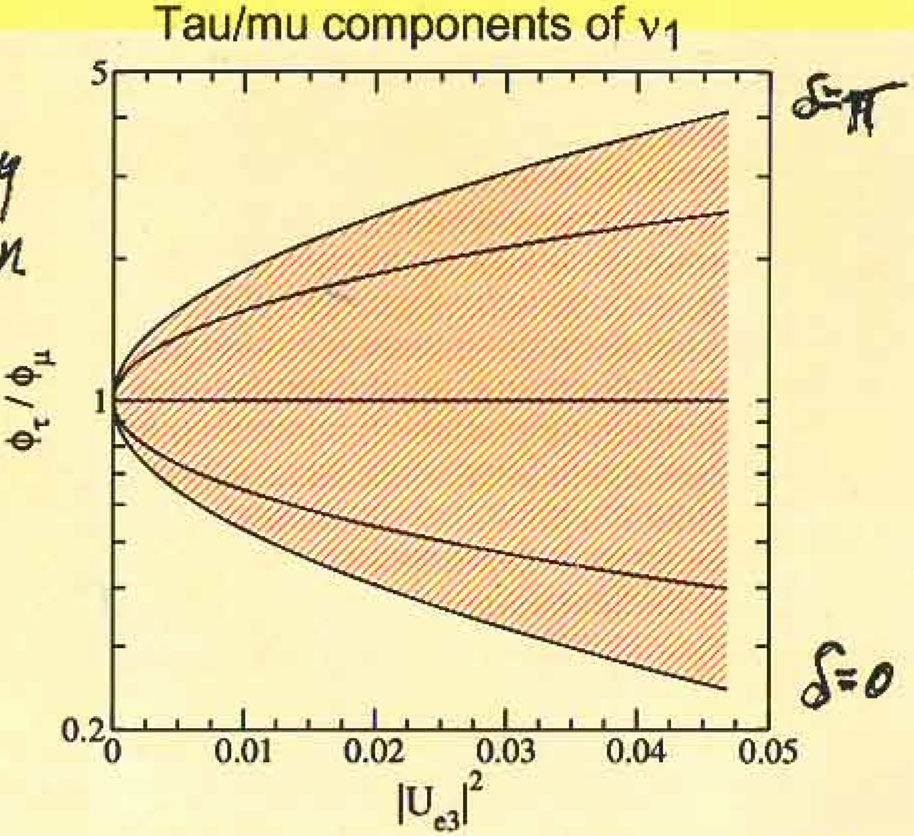
- $U_{e3} \neq 0$
- Then CPV phase $\delta \neq 0$
- What is Propagation matrix in this case & flavor mix? (in presence of decays)

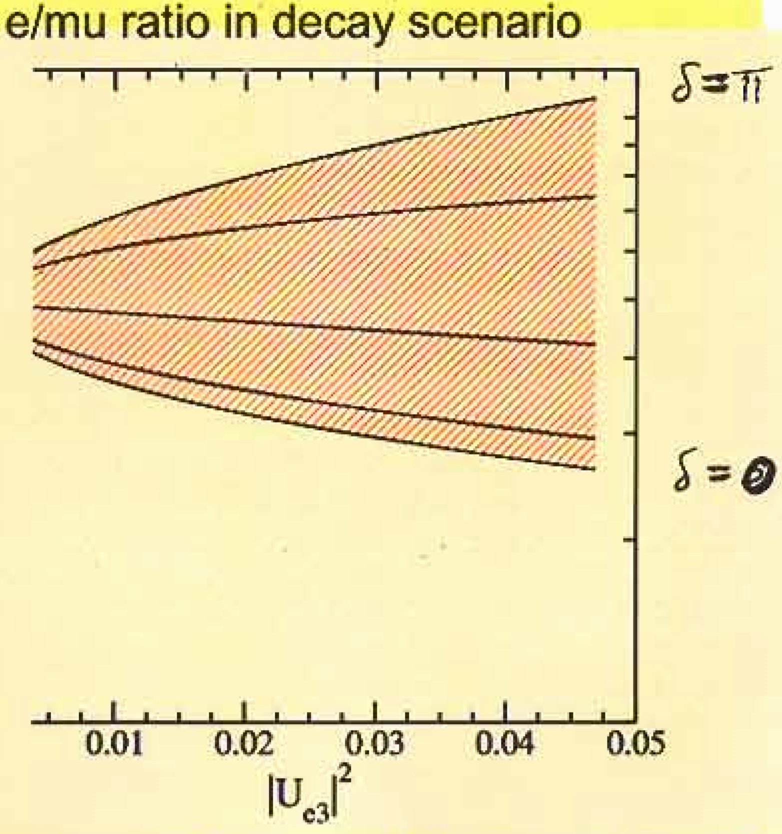
Measuring U_{e3} & δ ($\cos\delta$)

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

Nonzero θ_{13} breaks mu-tau symmetry

τ/μ
Symmetry
broken


Tau/mu components of ν_1


e/mu ratio in decay scenario

Beacom, Bell, Hooper, Pakvasa & Weiler

Normal Hierarchy

Ultimate Long Baseline Experiment

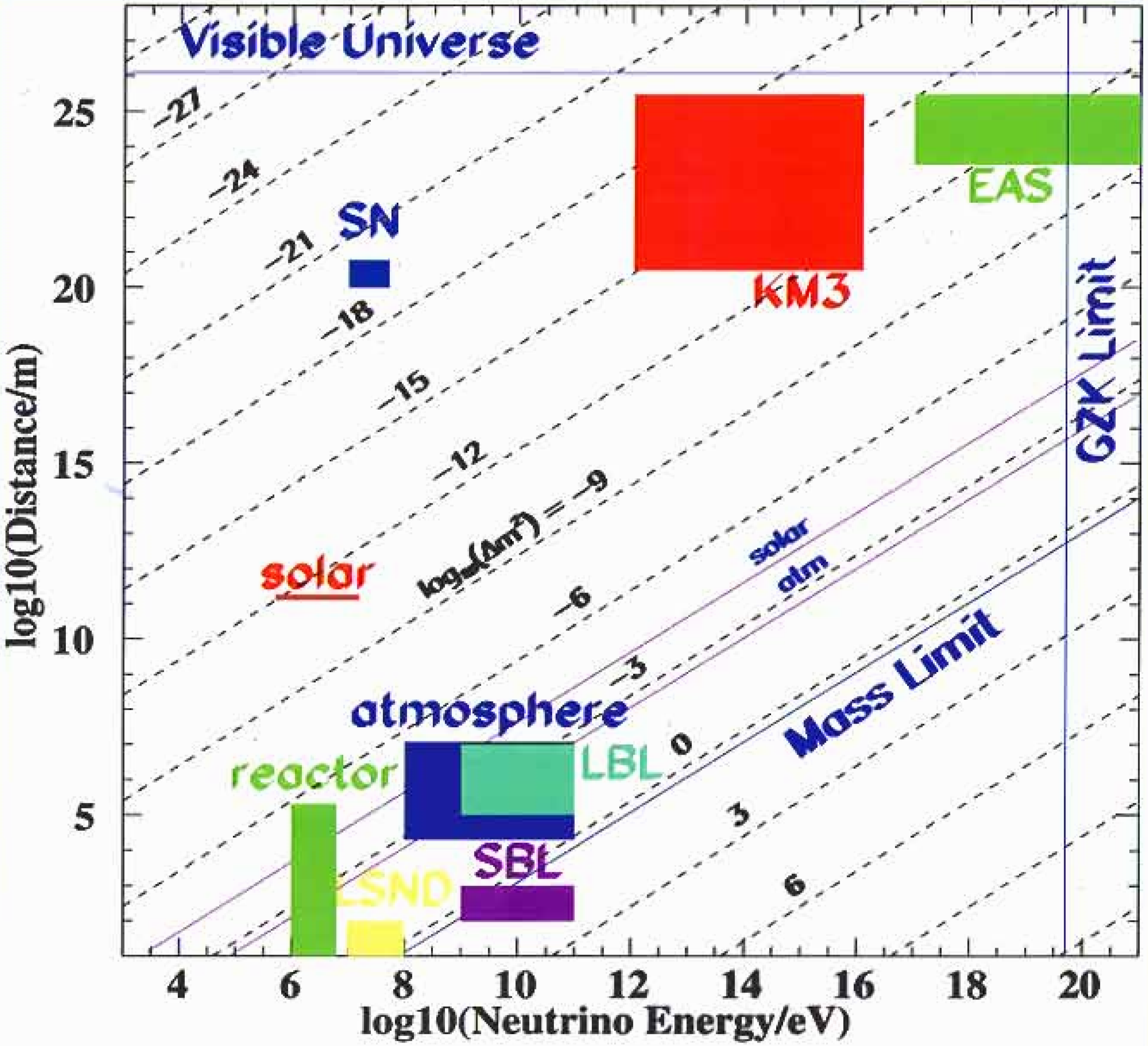
Astrophysical sources provide baselines almost as big as the visible universe.

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”



→ Lines correspond to $\frac{\delta m^2 L}{4E} \simeq O(\frac{\pi}{2})$ $\sim O(1)$

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?

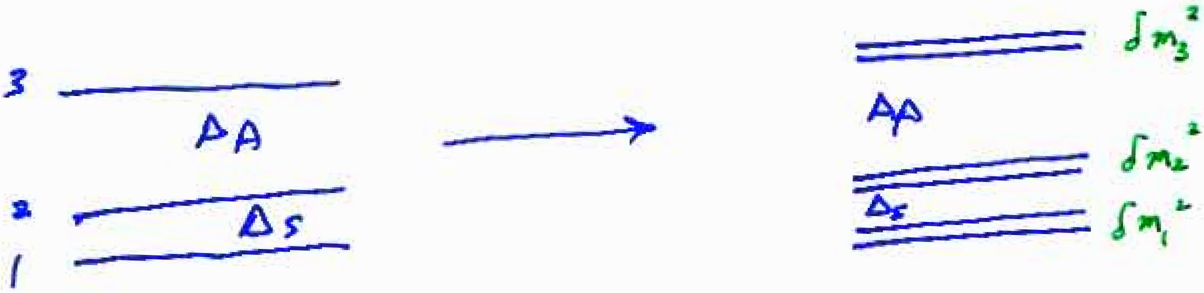
Not necessarily: they might be pseudo-Dirac. (Wolfenstein)

Majorana mass terms might be subdominat~~e~~ in size to Dirac terms.

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

Pseudo-Dirac Neutrinos with v. small δm^2.

- Old idea Bilenky & Pontecorvo (1982-3)
- Basic Proposal: Kobayashi & Lim (2001).



- $\delta m_i^2 << \Delta_A, \Delta_S$
  can be as small as one likes.
  if $\delta m_i^2 < 10^{-12}\,eV^2$ even solar ν's immune to effects.
- mixing between ν_i & $\bar{\nu}_i$ remains maximum $\Longrightarrow$
  - no new mixing angles
  - no new phases.
- can only be probed in H.E. Astro. ν's

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
(Kobayashi, Lim)

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

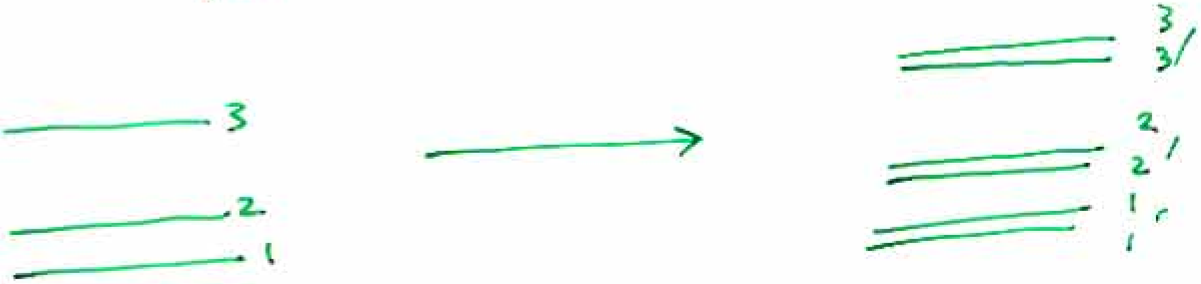
$$m^+ \approx m^- \qquad \delta m^2 << m^2 \qquad \theta \approx 45^\circ$$

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

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

Can Such small mass Differences be probed? How?

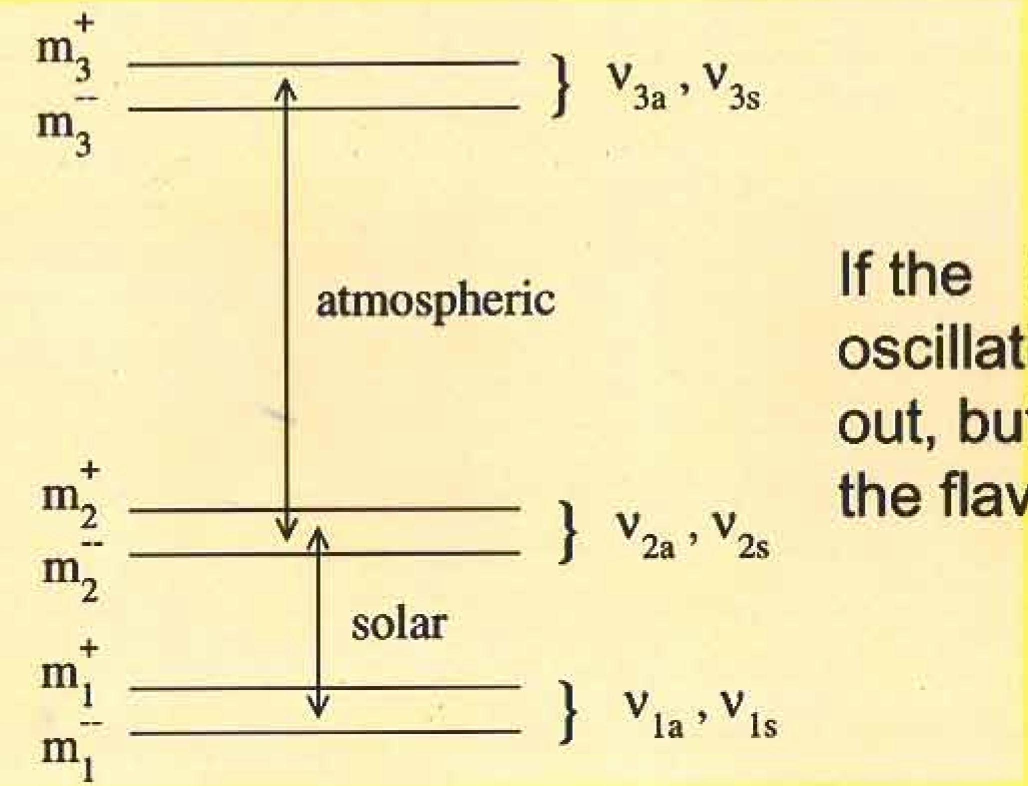
- Pseudo-Dirac Neutrinos with $10^{-18}\,eV^2 < \delta m^2 < 10^{-12}\,eV^2$



- no new mixing angles or phases
- $P_{\alpha\beta} \longrightarrow \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 - \sin^2 \frac{\delta m_j^2 L}{4E}\right]$
- $m^{\beta\beta}_{eff} \longrightarrow \sum_i U_{ei}^2\, \delta m_i^2 / 4 m_i^2 \rightarrow < 10^{-6}\,eV.$
- Effect on flavor Ratios

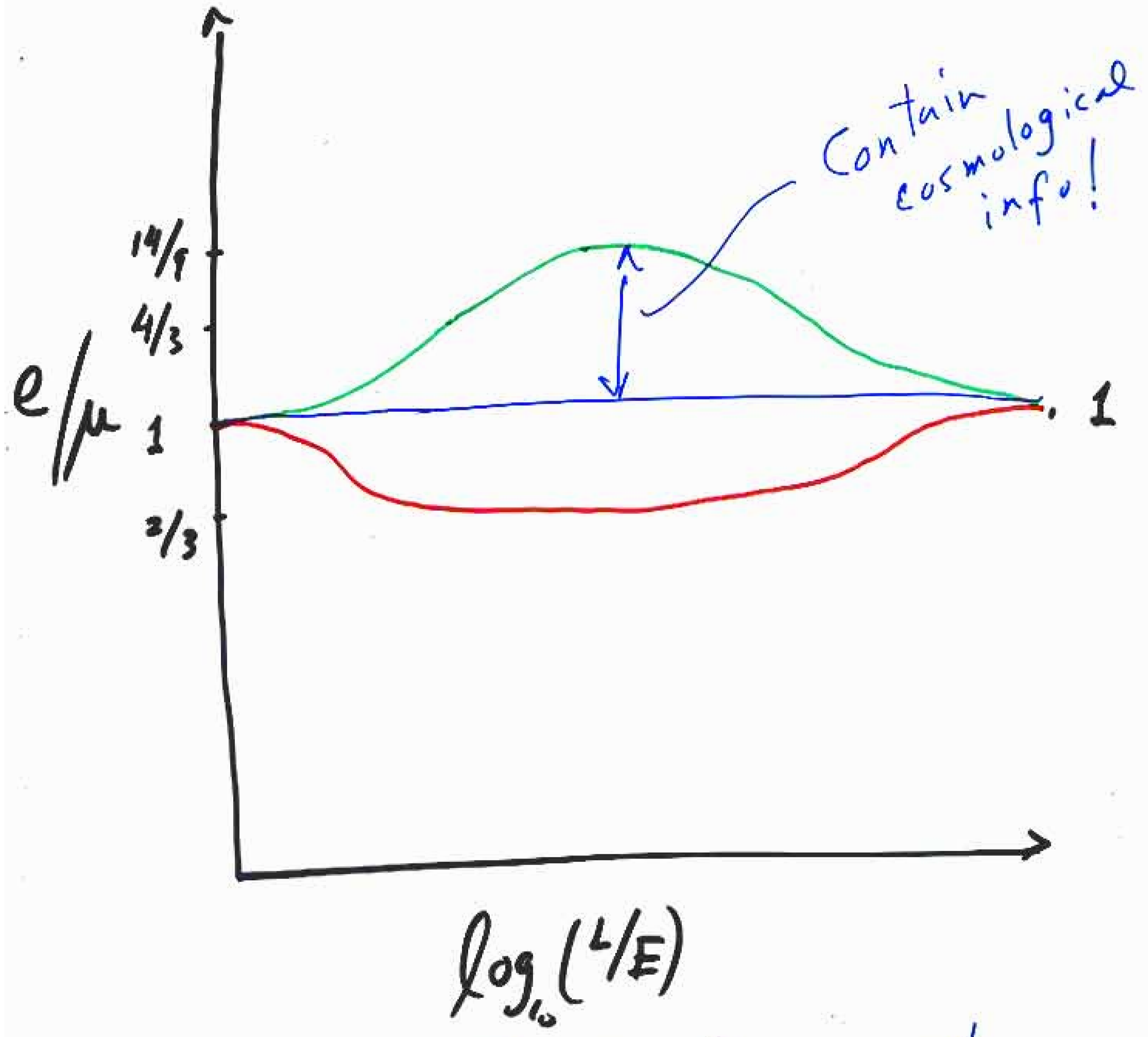
If $\delta m^2 < 10^{-12}\,eV^2$, no experiments with terrestrial (or solar) neutrinos can ever detect it.

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



Probing Pseudo-Dirac ν's with $10^{-16}\,eV^2 \lesssim \delta m^2 \lesssim 10^{-12}\,eV^2$

If $\delta m^2 < 10^{-12}\,eV^2 \Rightarrow$ Can Do

Cosmology with Neutrinos

- When distances are cosmological.

L in $\delta m^2 L/4E$ is replaced by

f where:

$$f = z/H \left[1 - \frac{(3+q_0)}{2} z - - - - \right]$$

So

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 (1 - \sin^2\phi_j)$$

$$\phi_j = \left(\frac{\delta m_j^2}{4E} \right) f$$

f contains Cosmological Information

(Weiler, Simmons, Learned, S.P.)
1994

If enough data available to fix δm_ν^2, then can determine: $\underline{z,\ H\ \&\ q_0}$

- Since only used microscopic information no dependence on evolution, standard candles ....
- First confirmation of Hubble red shift using particles other than photons.
  - ν Red Shifts $=$ γ Red Shifts?
- No need for distance. measurements

Ma Va Ns

Mass Varying Neutrinos

B. McKellar, G. Stephenson, T. Goldman
hep-ph/9603392

P.Q. Hung, hep-ph/0010126
R. Fardon, A. Nelson, N. Weiner, hep-ph/0309800

- Suppose a sterile ν couples to a scalar field ϕ. (with $V(\phi)$).

$$\longrightarrow \quad V'(\phi) + g\bar{\psi}\psi = 0$$

$$\psi \sim \psi(\phi).$$

- In presence of a ν BG.

$$\phi_0 \longrightarrow \phi_1 - \frac{g}{m_s^2}\langle\bar{\psi}\psi\rangle$$

ν mass $\longrightarrow$ $m_\nu = m_\nu(0) - \frac{g^2}{m_s^2}\langle\bar{\psi}\psi\rangle$

- ν's cluster
- ν mass depends on (a) location and (b) epoch !!
- Can account for Dark Energy if $m_\nu \sim 10^{-3}$ eV. $[\Lambda \sim (10^{-3}\,\mathrm{eV})^4 \sim (m_\nu)^4]$

But what about other contributions to Λ??

If small mixing of the light sterile to flavor ν, δm^2 changes with z. Hence at some z there will be MSW-like resonance and level crossing & large conversion into ν_{st}.

Depending on details there may be one, two or three such resonances

For example,

$$1 : 1 : 1 \longrightarrow 1/4 : 7/8 : 7/8$$

if ν_s lightest (at 10^{-3}eV) at beginning
& heaviest in vacuum (now)

$\longrightarrow$ lose ν_1

$[2/7 : 1 : 1]$

etc.

[P.Q. Hung & H. Päs (2003)]

Detection of flavors

ν_μ's : μ Tracks thru the Detector with long range.

ν_e's : E.M. Showers [competetion with hadronic showers from N.C. showers events from all flavors. ν_e, ν_μ, ν_τ]

ν_τ's : "Double Bang" events.

Learned & S.P. (1995)

At $E_\nu \sim$ PeV, $L_{abs} \sim D_\oplus$, so only downgoing events.

Idea of Double Bang

for E > 10 PeV
L > 1 km
need other techniques
Air Showers

Decay Length of τ

$$L \sim \gamma c \tau_0$$

$$\sim 100 \text{ m} @ E_\tau \sim 1 \text{ PeV}.$$

CC interaction $\nu_\tau \rightarrow \tau + x.$ (E_1)

↳ hadron shower

$\rightarrow$ # photons in $\hat{c}$ $\sim 10^{11}$

$\tau \longrightarrow$ 100 m Track
minimum ionizing
phot $\sim 10^6$

τ decay (E_2) $\tau \rightarrow h\nu$, $\rightarrow e\nu$ } 80 % B.R.

$\rightarrow$ second shower
$\gamma \sim 2 \cdot 10^{11}$.

· The Distance Bet. showers = c × Time Delay.

Event Classification

[Lollipop also good signature for ν_τ.]

- Double Bang / single bang (Lollipop) $\longrightarrow$ $\nu_\tau + \bar{\nu}_\tau$
- μ Tracks $\longrightarrow$ $\nu_\mu + \bar{\nu}_\mu$
- cascades $\longrightarrow$ $\nu_e + \bar{\nu}_e$ (CC+NC)

  $\left.\begin{matrix}\nu_\mu + \bar{\nu}_\mu \\ \nu_\tau + \bar{\nu}_\tau\end{matrix}\right\}$ NC

- Glashow Resonance events $\bar{\nu}_e$

$\bar{\nu}_e + e^- \rightarrow W^- \longrightarrow X$
(on shell)

$E_{\bar{\nu}_e} \sim 6.4$ PeV

From these determine relative fluxes of

ν_e, ν_μ, ν_τ.

Event types

☐ Muon tracks

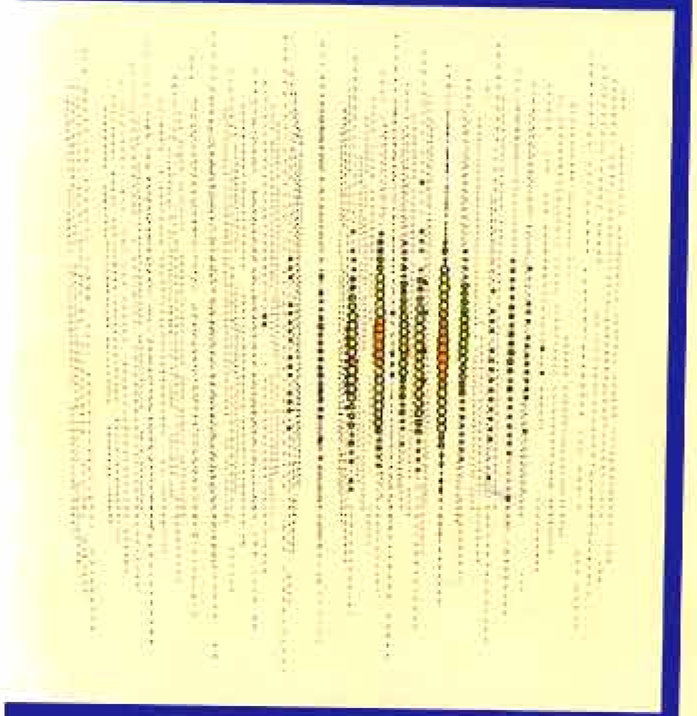
☐ Showers – neutral current interactions of all three flavors, plus CC interactions of ν_e and ν_{τ}.

☐ Double bang and lollipop events for ν_{τ}

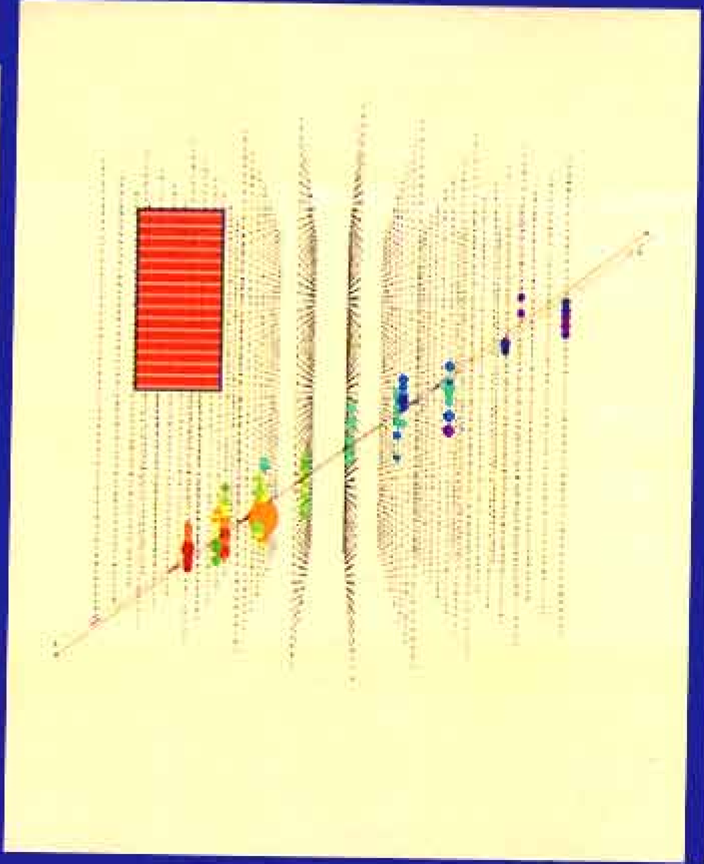
To determine the ν_e / ν_{μ} ratio, we can compare the number of muon tracks to showers. The observation of double-bangs/lollipops would provide additional information.

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

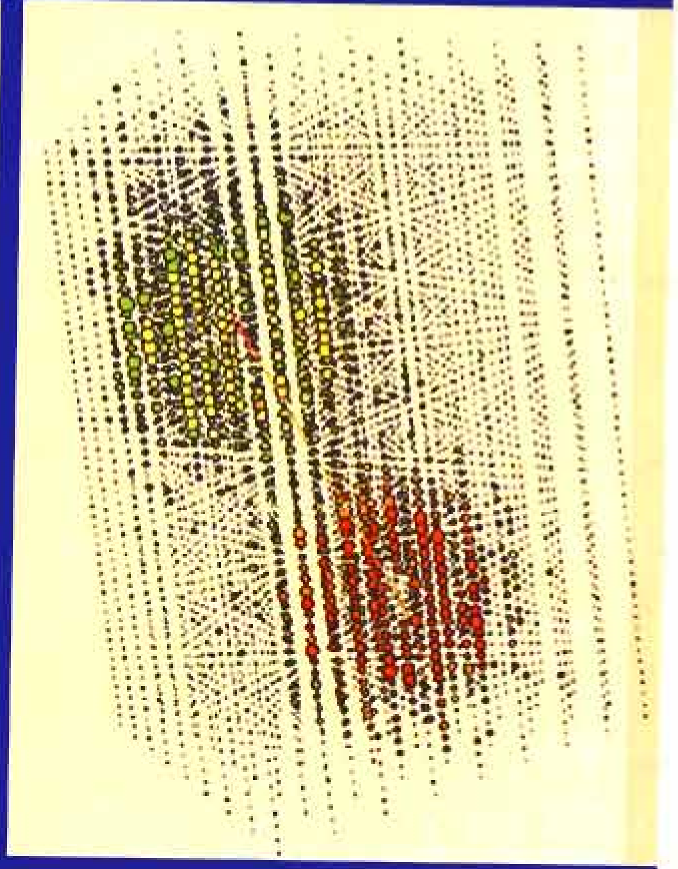
Flavor Identification



~ 100 TeV ν_e



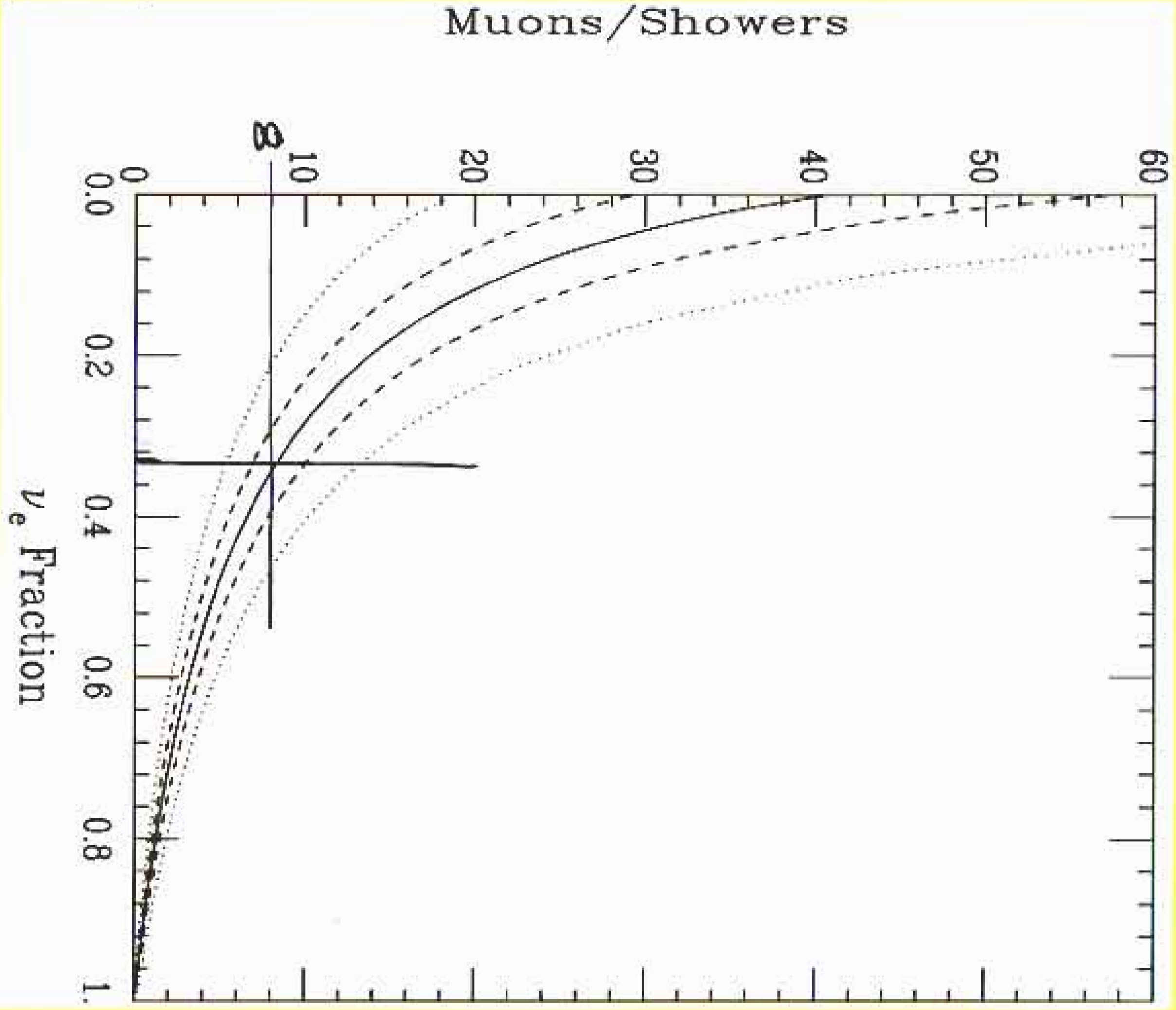
~ 10 TeV ν_μ



~ 10 PeV ν_τ

Muons/Showers rate for different electron fractions.

Mu-tau symmetry assumed



Beacom, Bell, Hooper, Pakvasa & Weiler

CONCLUSIONS

- ν Telescopes MUST MEASURE FLAVORS
- If $e/\mu/\tau$ found to be
- $\alpha/1/1$
    - $\alpha = 1$ → Boring!
        - confirms CW
        - new bounds on ν lifetime
    - $\alpha = 1/2$ → initial mix pure ν_μ
    - $\alpha > 1$ → ν Decays w. normal hierarchy
    - $\alpha < 1/2$ → ν Decays w. Inv. hierarchy.
- $\alpha > 1$, $\mu/\tau \neq 1$

  → Learn about U_{e3}, $\cos\delta$

  Probe pseudo-Dirac δm^2
- Enuf events from Known sources cosmology with ν's.