The uses of flavor detection of high energy astrophysical Neutrinos

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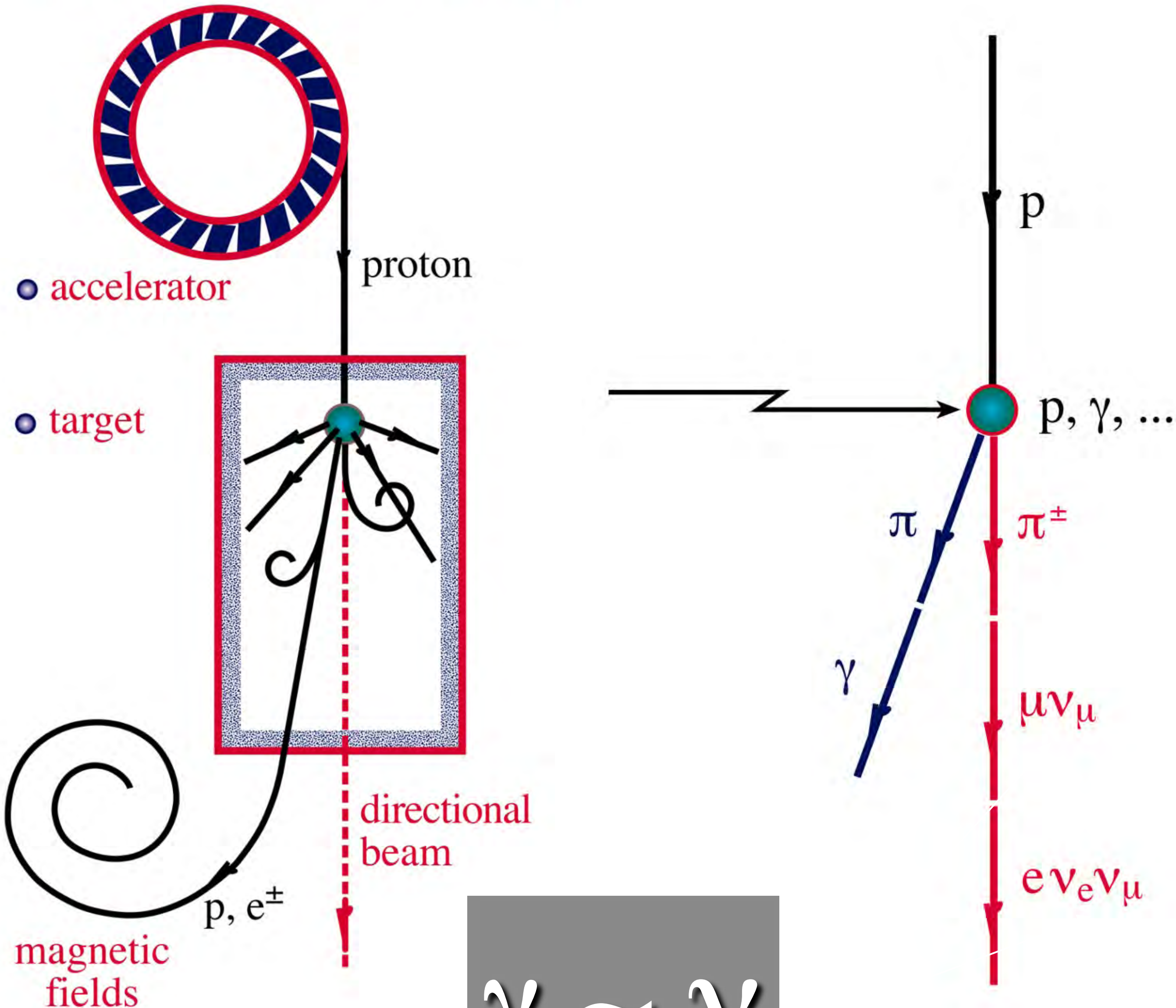
We make as many assumptions as we please:

- Assume that ν sources with energies upto and beyond PeV exist and that the ν's reach us.
- Assume that ν detectors large enuf will exist (Icecube, KM3 etc.....multi KM3)
- Assume a ν signal WILL be seen (with significant rates)
- Assume that ν flavors (e,μ,τ) CAN be distinguished

- Existence of High Energy Gammas suggests that High energy accelerators in space EXIST
- P+P and P+γ collisions produce π^0's and π^+ 's
- $\pi^0 \rightarrow \gamma$'s $\rightarrow$ observed.....(?)
- $\pi^+ \rightarrow \nu$'s.......hence high energy ν 's must exist!
- At detectable, useful fluxes?
- Maybe YES?

Work in Collaboration with:
John Learned, Tom Weiler, John Beacom, Nicole Bell, Dan Hooper, Werner Rodejohann
and more recently Anjan Joshipura and Subhendra Mohanty

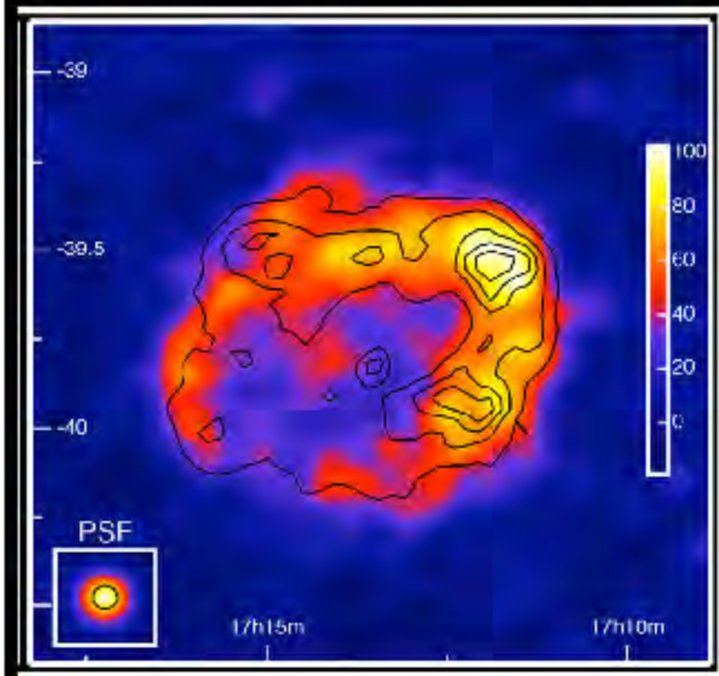
Neutrino Beams: Heaven

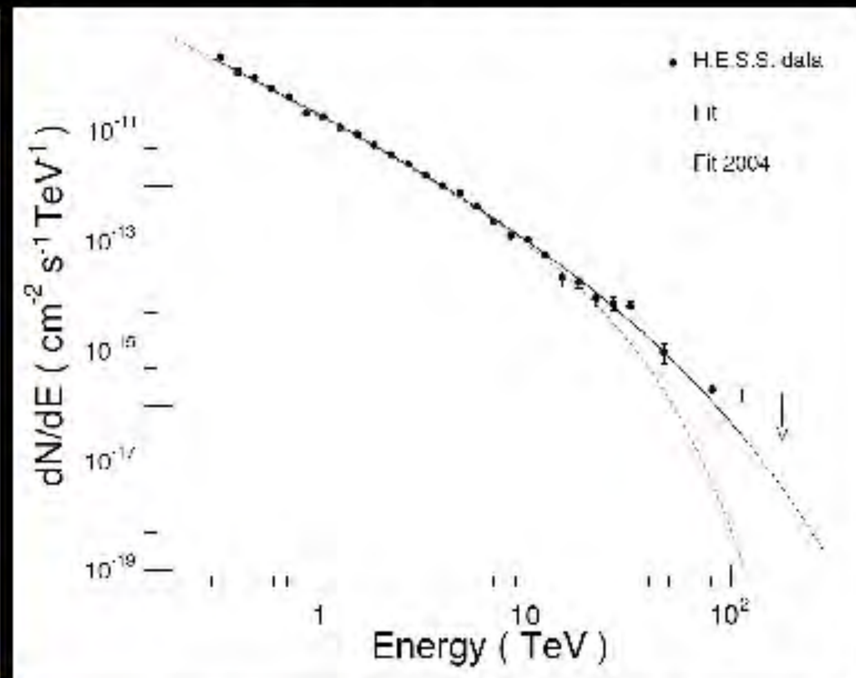


$\gamma \sim \nu$

Sources are High-Energy and Luminous

supernova remnant RX J1713.7-3946





HESS Collaboration (2006)

Detectors:

Neutrino events

- Ice-Cube 0 (non-atmospheric)
- ANTARES
- ANITA 1 (2 candidates became 1)
- AUGER
- PAMELA
- FERMI
- TA
- HESS
- KASCADE-GRANDE

Near Future:

ANITA III will take data in Nov.2013- Jan 2014

ARA-I will be ready by 2012 and may see 3-5 GZK-BZ events per yr

- FUTURE:

- CTA
- ARA
- KM3NET
- DEEPCORE
- AMS

Current Status:

- No (non-atmospheric) neutrino events yet……….
- Implications for source models………….
- Check : Talks at NUSKY 2011(June 2011)

http://cdsagenda5.ictp.trieste.it/full_display.php?email=0&ida=a10149

Because the W-B bound is violated, simple picture of fireballs/jets in AGN/GRB giving UHECR and neutrinos at comparable fluxes in trouble. May need mixed (p+nuclei) beams giving lower neutrino fluxes, SNR, slow jet SN etc……

Also not clear whether the HE gamma rays explained by leptonic or hadronic models, both work for now……

FLAVORS at the Source: The variety of initial flavor mixes

- **Conventional: P +P $\rightarrow$ π + X, π $\rightarrow$ ν_μ + μ, μ $\rightarrow$ ν_μ + ν_e hence: ν_e / ν_μ = 1/2**
- **Same for P + γ, except no anti-ν_e.**
- **Damped muon sources: if μ does not decay or loses energy: No ν_e 's, and hence ν_e / ν_μ = 0/1**
- **Pure Neutron Decay or Beta-Beam sources: n $\rightarrow$ anti-ν_e, hence ν_e/ν_μ = 1/0**
- **Prompt sources, when π's absorbed and only heavy flavors contribute and ν_e/ν_μ = 1, such a flavor mix also occurs in muon damped sources at lower energies from μ decays. (Winter et al,2010)**
- **In general, flavor mix will be energy dependent…….**

Types of sources and initial flavor mixes

Most conventional sources are expected to make neutrinos via π/K decays which leads via the decay chain $\pi/K \rightarrow \mu$ to an approx. flavor mix:

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

Sometimes μ's lose energy or do not decay, in either case the effective flavor mixed becomes:

$e:\mu:\tau = 0:1:0$

In some sources this can happen at higher energies and then the flavor mix can be energy dependent.

There are sources in which the dominant component is from neutron decays, and then resulting (beta)beam has:

$e:\mu:\tau = 1:0:0$

Recently, sources called slow-jet supernova have been discussed, where the π's interact rather than decay, then the ν flux

is dominated by short-lived heavy flavor decays, with resulting mix (so-called prompt, due to short-lived heavy flavors):

$e:\mu:\tau = 1:1:0$

Here the very small ν_τ component from heavy flavors has been ignored.

References for source types:

- Damped muon sources: Rachen and Meszaros, PRD 58(1998), Kashti and Waxman, astro-ph/057599(2005).
- Beta-Beam sources: Anchordoqui et al, PLB793 (2004).
- Prompt sources: Razzaque et al., PRD73(2006), Gandhi et al., arXiv:0905.2483.
- Hidden sources: Mena et al., astro-ph/061235 (2006) optically thick sources.
- Interesting new paper: Hummer et al.:arXiv: 1007.0006

  Generic accelerators on Hillas Plot

It is understood that most sources yield equal fluxes of neutrinos and anti-neutrinos with the exception of beta-beam which is a pure anti-ν_e beam.

Neutrinos from "GZK" process: BZ neutrinos:

- Berezinsky and Zatsepin pointed out the existence/inevitability of neutrinos from :
- $P_{CR} + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$
- Flavor Mix: below 10 Pev: (n decays)pure Beta-Beam: $e:\mu:\tau = 1:0:0$
- Above 10 PeV: conventional(π decays) :$e:\mu:\tau = 1:2:0$

(due to Engel et al. PRD64,(2001))

Current Knowledge of Neutrino Mixing and Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \begin{pmatrix} \nu \\ \nu \\ \nu \end{pmatrix}$$

$\delta m_{32}^2 \sim 2.5 \cdot 10^{-3}\, eV^2$, $\delta m_{21}^2 \sim 8 \cdot 10^{-5}\, eV^2$

$$U_{MNSP} \sim U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/} \end{pmatrix}$$

TBM is good to about one sigma.

Unkown:

Mass Pattern: Normal or Inverted:

3 _________ 2_________

1 _________

Also: U_{e3}, phase δ

2__________

1__________ 3_________

Effects of oscillations on the flavor mix are very simple:

- $\delta m^2 > 10^{-5}\ eV^2$, hence $(\delta m^2 L)/4E >> 1$ for all relevant L/E, and
- $\rightarrow \sin^2(\delta m^2 L/4E)$ averages to ½
- survival and transition probablities depend only on mixing:
- $P_{\alpha\alpha} = \sum_i |U_{\alpha i}|^4$
- $P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$

In this tri-bi-maximal approximation, the propagation matrix P is:

$$P = 1/18 \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{earth}} = \mathbf{P} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{source}}$$

Flavor Mix at Earth:

Beam type	Initial	Final
Conventional (pp,pγ)	1:2:0	1:1:1
Damped Muon	0:1:0	4:7:7
Beta Beam(n decay)	1:0:0	5:2:2
Prompt	1:1:0	1.2:1:1

Damped Muon produces a pure muon decay beam at lower energies with same flavor mix as the Prompt beam!

Discriminating flavors

- The ratios used to distinguish various flavor mixes are e.g. f_e (e/(e+μ+τ) and R(μ/[e+τ])

Source type	f_e	R
Pionic	0.33	0.5
Damped-μ	0.22	0.64
Beta-beam	0.55	0.29
Prompt	0.39	0.44

- It has been shown that R and/or f_e can be determined upto 0.07 in an ice-cube type detector. Hence pionic, damped μ, and Beta-beam can be distinguished but probably not the prompt
- (Beacom et al. PRD69(2003).{Esmaili(2009).Choubey(2009).}

Can small deviations from TBM be measured in the flavor mixes?

- E.g. deviation of U_{e3} from zero, or value of δ….as proposed in several papers: Blum et al., Kacherlis and Serpico, Xing, Choubey et al, Rodejohann, Athar et al.,Liu et al……
- E.g. R would deviate from the TBM expected value by amounts proportional to a fraction of $|U_{e3}|\cos(\delta)$, resulting in corrections to the TBM values of less than 10% at best.
- Measuring Such small deviations remain impractical for the foreseeable future

In addition, sources are never "pure" meaning:

- Conventional/pp: after including μ polarization and effects due to K, D etc decays, the mix changes from1:2:0 to approx. 1:1.85:ε, (ε < 0.01)
- Damped μ sources do not have exactly 0:1:0 but probably more like δ:1:0 with δ of a few %.......and similarly for Beta-beam.

Lipari et al(2007), Rodejohann,
Weiler, SP(2008)

A comparison of effects of non-zero θ_{13} and δ with uncertainties in initial fluxes:ΔR

Source	Effect of CPV	Effect of flux
Pionic	<0.022	0.01
Damped μ	<0.07	0.066
Beta-Beam	<0.025	0.01
Prompt	<0.023	0.01

Since R can only be measured at a level of 0.07, a measurement of small mixing angles and small CPV seems precluded in foreseeable future(except for damped mu) Maybe with much bigger detectors…..?

e.g. Serpico and Kacherliess(2005), Blum, Nir and Waxman (2008),Serpico(2005), Choubey et al((2008),Liu et al(2010)

To summarise, small deviations in flavor content NOT easy to measure in near future.

But it should be possible to measure LARGE deviations from the canonical flavor mix.

For our purposes here, let us agree to use the conventional flavor mix as canonical.

In this case the initial mix of 1:2:0 is expected to become 1:1:1; at earth.

So we look for large deviations from this.

Large deviations:

Deviations from 1:1:1
- Particle Physics

Exotic neutrino properties

- Neutrino decay (Beacom, Bell, Hooper, Pakvasa, & Weiler)
- CPT violation (Barenboim & Quigg)
- Oscillation to steriles (Dutta, Reno and Sarcevic)
- Oscillations with tiny delta δm^2 (Crocker, Melia, & Volkas; Berezinsky et al.)
- Pseudo-Dirac mixing (Beacom, Bell, Hooper, Learned, Pakvasa, & Weiler)
- Magnetic moment transitions (Enqvist, Keränen, Maalampi)
- Mass varying neutrinos (Fardon, Nelson & Weiner; Hung & Pas)
- ...

How many ways can the flavor mix deviate from 1:1:1 ?

1. Initial flux different from canonical: e.g. the damped muon scenario. In this case the flavor mix will be:

   4:7:7

   similarly for the beta beam source, the flavor mix will be:

   5:2:2

   instead of 1:1:1

2. Neutrino Decay:

Do neutrinos decay?

Since δm's $\neq 0$, and flavor is not conserved, in general ν's will decay. The only question is whether the lifetimes are short enuf to be interesting and what are the dominant decay modes.

What do we know?

- Radiative decays: $\nu_i \rightarrow \nu_j + \gamma$:

  m.e.: $\Psi_j(C + D\gamma_5)\sigma_{\mu\nu}\,\Psi_i\,F_{\mu\nu}$

SM: $1/\tau = (9/16)(\alpha/\pi)G_F^2/\{128\pi^3\}(\delta m_{ij}^2)^3/m_i\,|$

$\Sigma_\alpha m^2_\alpha/m_W^2(U_{i\alpha}U_{j\alpha}^*)|^2 \quad \rightarrow \tau_{SM} > 10^{45}$ s

(Petcov, Marciano-Sanda)(1977)

Exptl. Bounds on $\kappa = e/m_i[\,|C|+|D|^2]^{1/2} = \kappa_0\mu_B$

From $\nu_e + e \rightarrow e + \nu'$: $\kappa_0 < 10^{-10}$ (PDG2010),

this corresponds to: $\tau > 10^{18}$ s.

Invisible Decays:

- $\nu_i \rightarrow \nu_j + \nu + \nu$: Exptl Bounds:

  $F < \varepsilon G_F$, $\varepsilon < O(1)$, from invisible width of Z

  Bilenky and Santamaria(1999):

$\tau > 10^{34}$ s

$\nu_{iL} \rightarrow \nu_{jL} + \varphi$: $\quad g_{ij}\, \Psi_{jL}\, \gamma_\mu\, \Psi_{jL}\, d_\mu \varphi$

If isospin conserved: invisible decays of charged leptons governed by the same g_{ij}, and bounds on $\mu \rightarrow e + \varphi$, and $\tau \rightarrow \mu/e + \varphi$ yield bounds such as: $\tau > 10^{24}$ s.

{Jodidio et al. (1986), PDG(1996)}

Conclusion: Only "fast" invisible decays are Majoron type couplings

- $g\ \nu^C_{jR} \nu_{iL}\ X$:
- I can be a mixture of 0 and 1(G-R, CMP)
- The ν's can be mixture of flavor/sterile states………
- Bounds on g from π & K decays
  - Barger,Keung,SP(1982),Lessa,Peres(2007), $g^2 < 5.10^{-6}$
  - SN energy loss bounds: Farzan(2003): $g < 5.10^{-7}$
- $g^2 < 5.10^{-6}$ corresp. to $\tau > 10^{-8}$ s/eV
- $g < 5.\ 10^{-7}$ corresp. to $\tau > 0.1$ s/ev

Current experimental limits on τ_i:

- $\tau_1 > 10^5$ s/eV SN 1987A

B. o. E. Careful analysis.

- $\tau_2 > 10^{-4}$ s/eV (Solar) 10^{-4}-10^{-2} s/eV

Beacom-Bell(2003),KamLand(2004)

$\tau_3 > 3.10^{-11}$ s/eV (Atm) 9.10^{-11} s/eV

Gonzalez-Garcia-Maltoni(2008)

Cosmology: WMAP→free-streaming ν's→

$\tau > 10^{10}$ s/eV at least for one ν...

Hannestad-Raffelt(2005), Bell et al.(2005)

With L/E of TeV/Mpsc, can reach τ of 10^4 s/eV

When ν_i decays, $U_{\alpha i}^2$ gets multiplied by the factor $\exp(-L/\gamma c \tau)$ and goes to 0 for sufficiently long L. For normal hierarchy, only ν_1 survives,

and the final flavor mix is simply (SP 1981):

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

$$\sim 4:1:1$$

These flavor mixes are drastically different from canonical 1:1:1 and easily distinguishable.

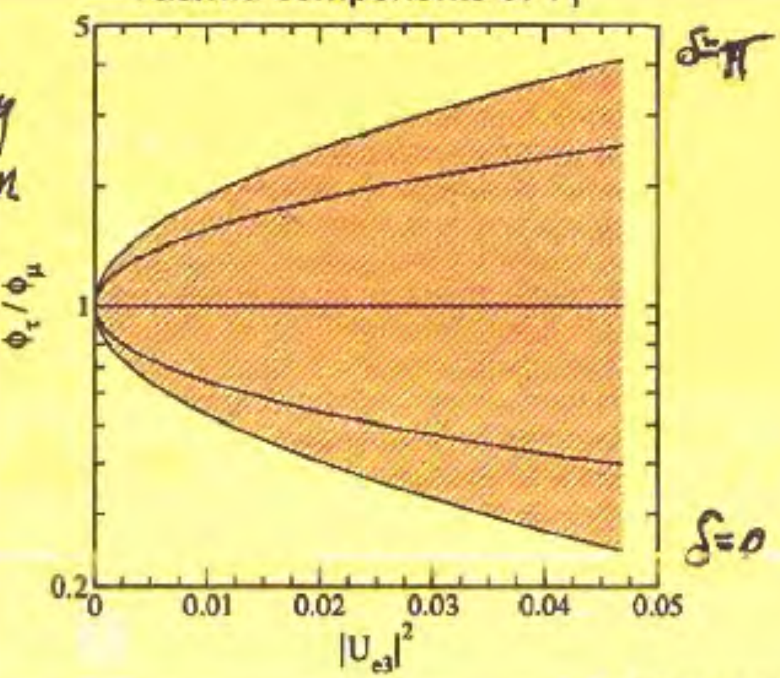
Beacom et al(2003)

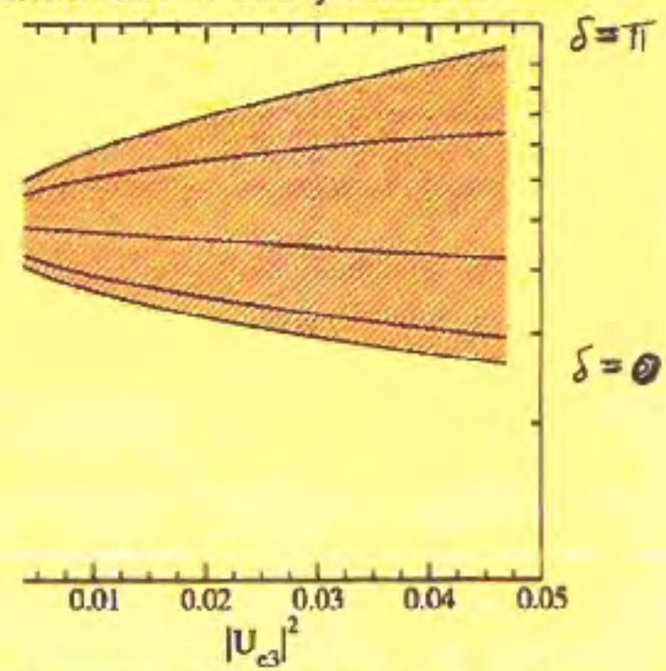
Measuring U_{e3} & δ ($\cos\delta$)

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

Nonzero θ_{13} breaks mu-tau symmetry

τ/μ Symmetry broken





Beacom, Bell, Hooper, Pakvasa & Weiler 13

Normal Hierarchy

τ/μ can be between 5 & 0.2
e/μ " " 5 & 1.

Caveat about inverted hierarchy and decay:

In this case things are a bit more subtle:

Since the limit on lifetime of ν_1 is 10^5 s/eV and we are unlikely to probe beyond 10^4 s/eV (this way); ν_1's will not have had enuf time to decay and so both ν_1 and ν_3 will survive with only ν_2 having decayed, leads to a final flavor mix of 1:1:1…. !

Of course the net flux will have decreased by 2/3.

More complex decay scenarios in e.g.

Bhattacharya et al.arXiv:1006.3082, Meloni and Ohlsson, hep-ph/0612279, Maltoni and Winter, arXiv;0803.2050….

Comments about decay scenario

- **With many sources at various L and E, it would be possible to make a L/E plot and actually measure lifetime. E.g. one can see the e/μ ratio go from 1 to 4 for the NH case.**

For relic SN signal, NH enhances the rate by about a factor of 2, whereas IH would make the signal vanish (for complete decay)! Relic SN can probe τ beyond 10^4 s/eV.

Barenboim-Quigg, Fogli et al(2004)

3. Flavor Violating Gravity;

- Violation of Equivalence Principle
- Different flavor states have slightly different couplings to gravity: f_e , f_μ , f_τ
- Current Bounds: $\delta f/f < 10^{-24}$
- Suppose neutrinos travel thru region of varying gravitational field, they could pass thru a MSW-type resonance and deplete one flavor and we get anisotropy. For example $\nu_\mu/\nu_\tau << 1$ from direction of Great Attractor but $= 1$ from all other directions!

Minakata-Smirnov(1996)

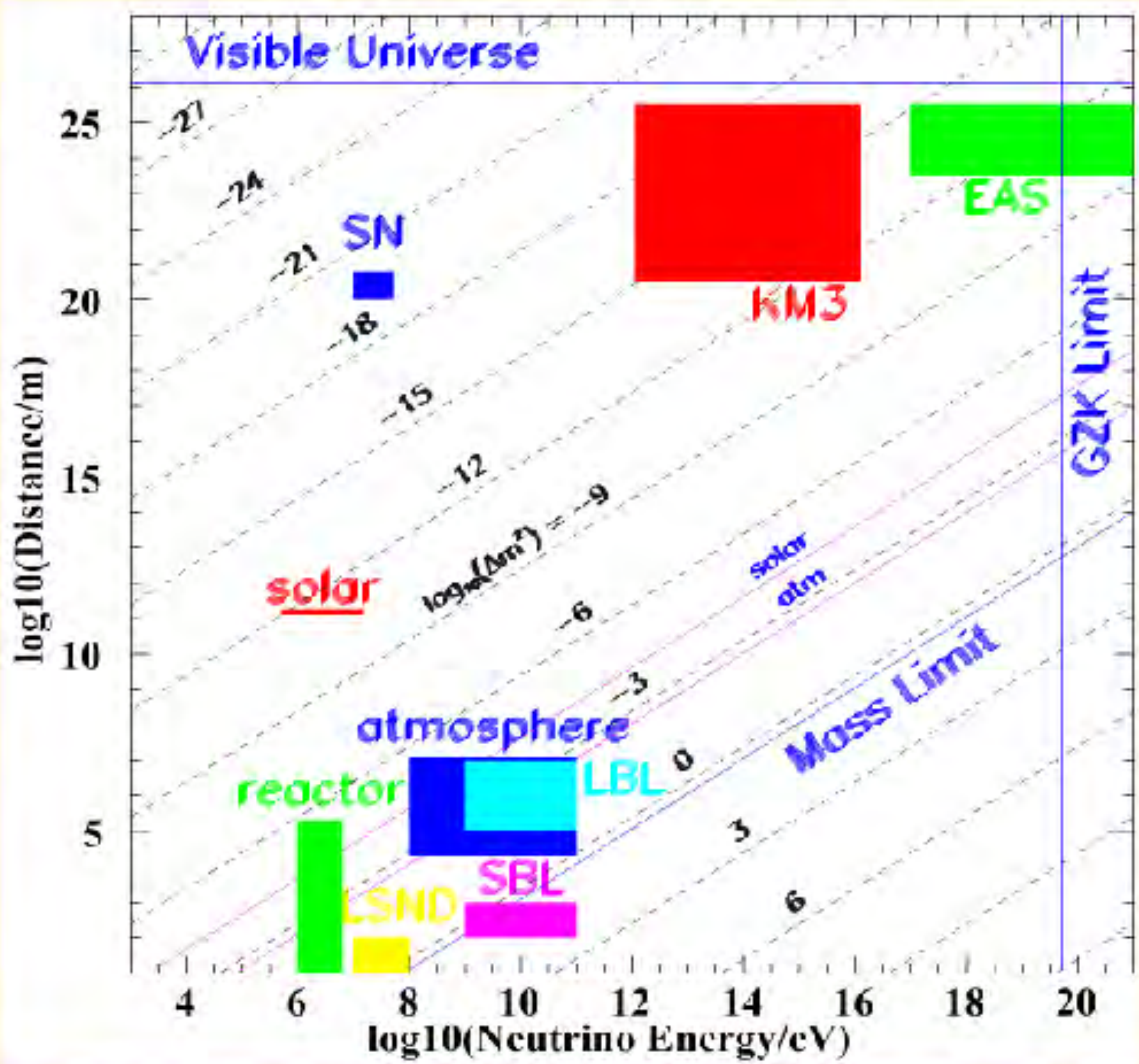
Ultimate long-baseline experiment

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

This allows a sensitivity to oscillations with tiny $\delta\mathbf{m}^2$

Eg. 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)
Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004)



Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004) PRL, 92, 011101 (2004)

4. Pseudo-Dirac Neutrinos: (Sometimes called Quasi-Dirac)

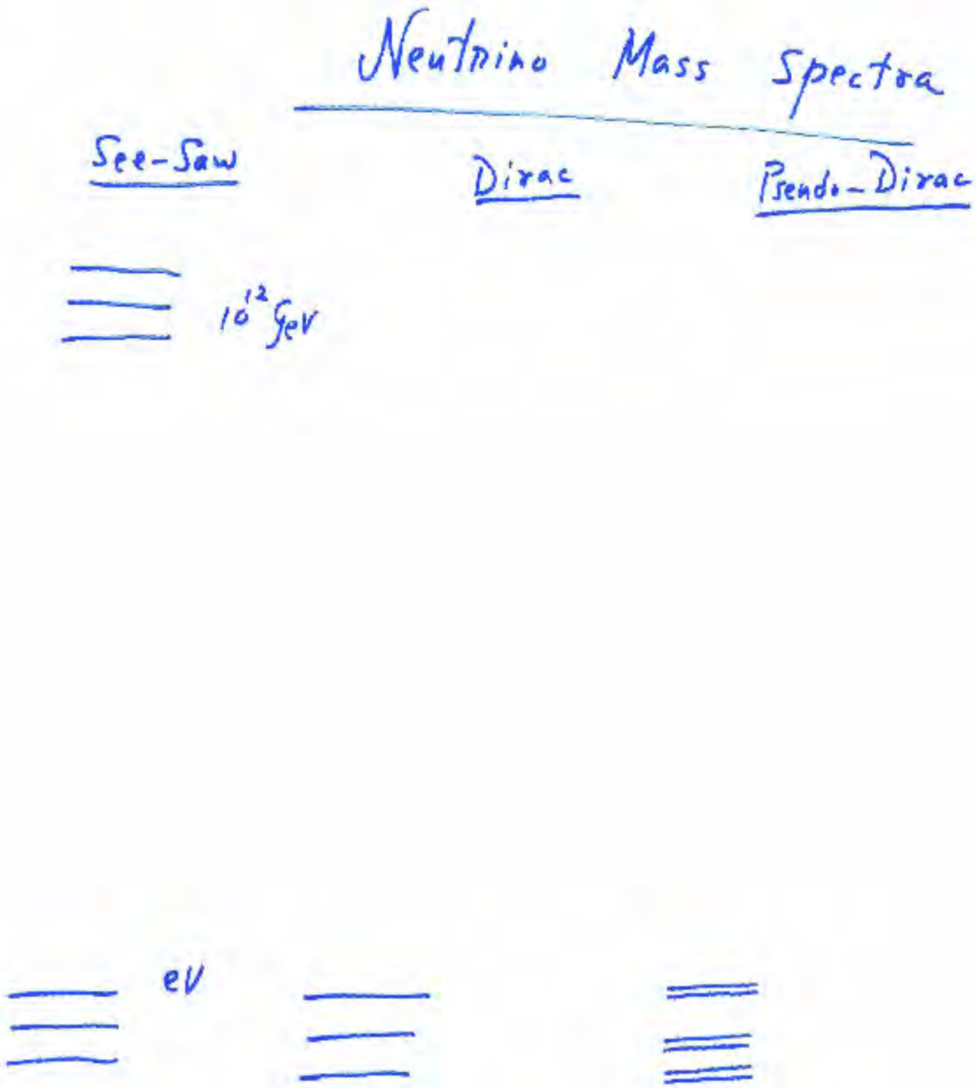
If no positive results are found in neutrino-less double-beta-decay experiments, it may mean that neutrinos are Dirac or Pseudo-Dirac(type I)

Idea of pseudo-Dirac neutrinos goes back to Wolfenstein, Petcov and Bilenky - Pontecorvo (1981-2).

Also clear discussion in Kobayashi-Lim (2001).

These arise when there are sub-dominant Majorana mass terms present along with dominant Dirac mass terms.

There is a somewhat different realisation, type II which allows double beta decay.....



The three δm^2's will be different, in general.

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)

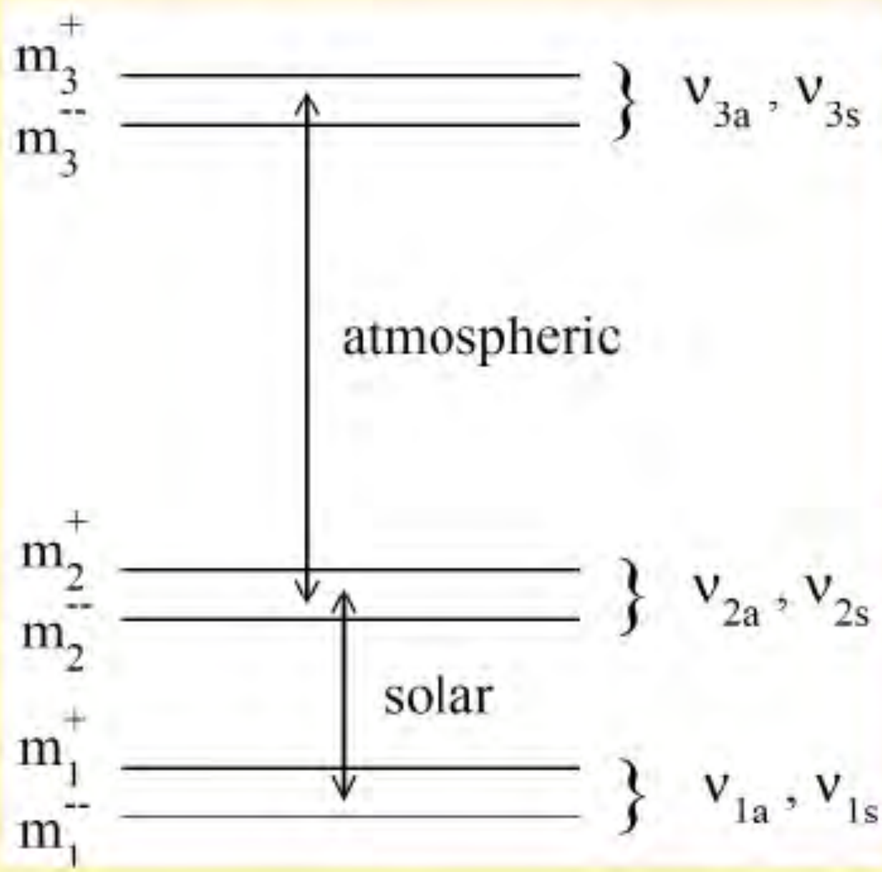
$$\nu_\alpha = \frac{1}{\sqrt{2}}\left(\nu^+ + i\nu^-\right) \qquad \nu_s = \frac{1}{\sqrt{2}}\left(\nu^+ - i\nu^-\right)$$

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

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

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

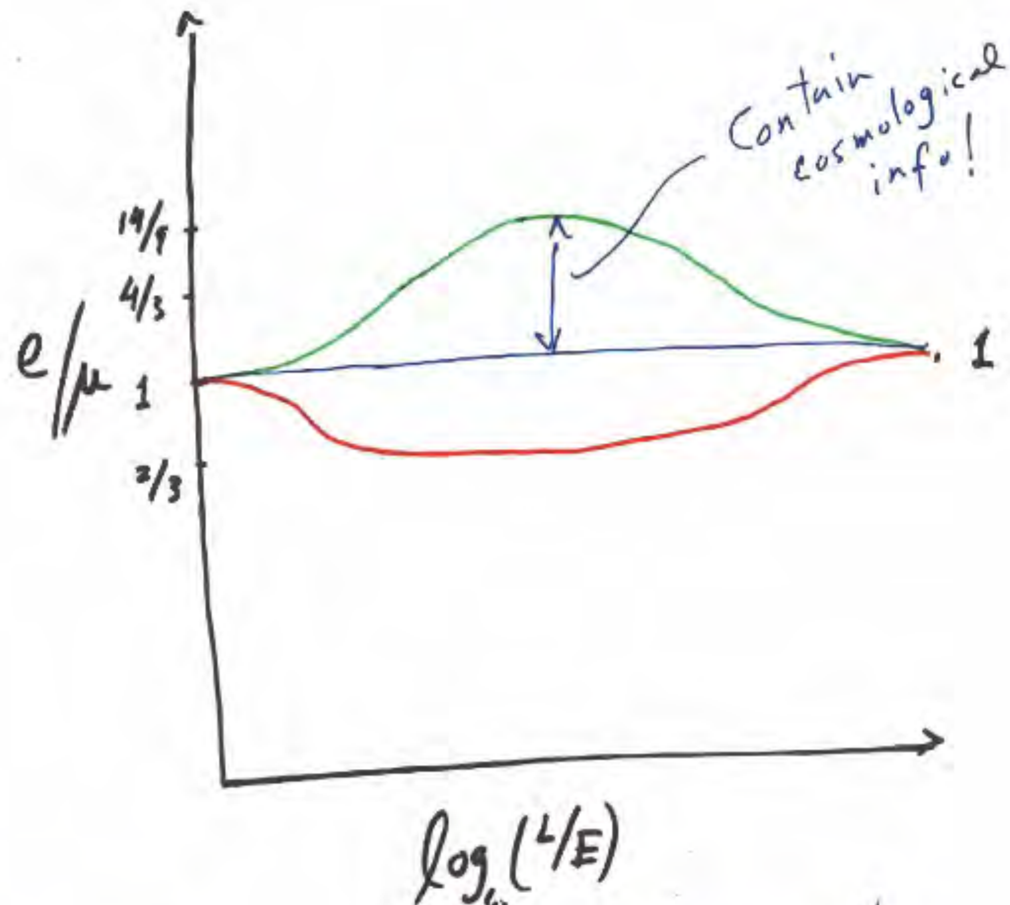
Pseudo-Dirac Neutrinos



Neutrinos appear to be Dirac, but in fact have subdominant Majorana mass terms.

→Oscillations driven by tiny mass differences.

→ Would show up in astro-nu flavor ratios.



Probing Pseudo-Dirac ν's

with $10^{-16}\,eV^2 \lesssim \delta m^2 \lesssim 10^{-12}\,eV^2$

In this case when δm^2 are as small or smaller than 10^{-12} eV^2, it is possible to do cosmology!

- **The transition probability $P_{\alpha\beta}$ becomes:**

$P_{\alpha\beta} = \Sigma_j |U_{\alpha j}|^2 |U_{\beta j}|^2 (1 - \sin^2(\varphi_j))$, where
$\varphi_j = \{\delta m_j^2/4E\}f$, and f, the lookback distance is:
$f = (z/H)[1 - (3+q)/z.........]$ and z is red shift and H is Hubble parameter, q is de-acceleration etc............

And thus f contains cosmological information but measured by neutrinos. If enuf data is available, one can check whether red shift in neutrinos is identical to red shift in photons!

Recent proposals:

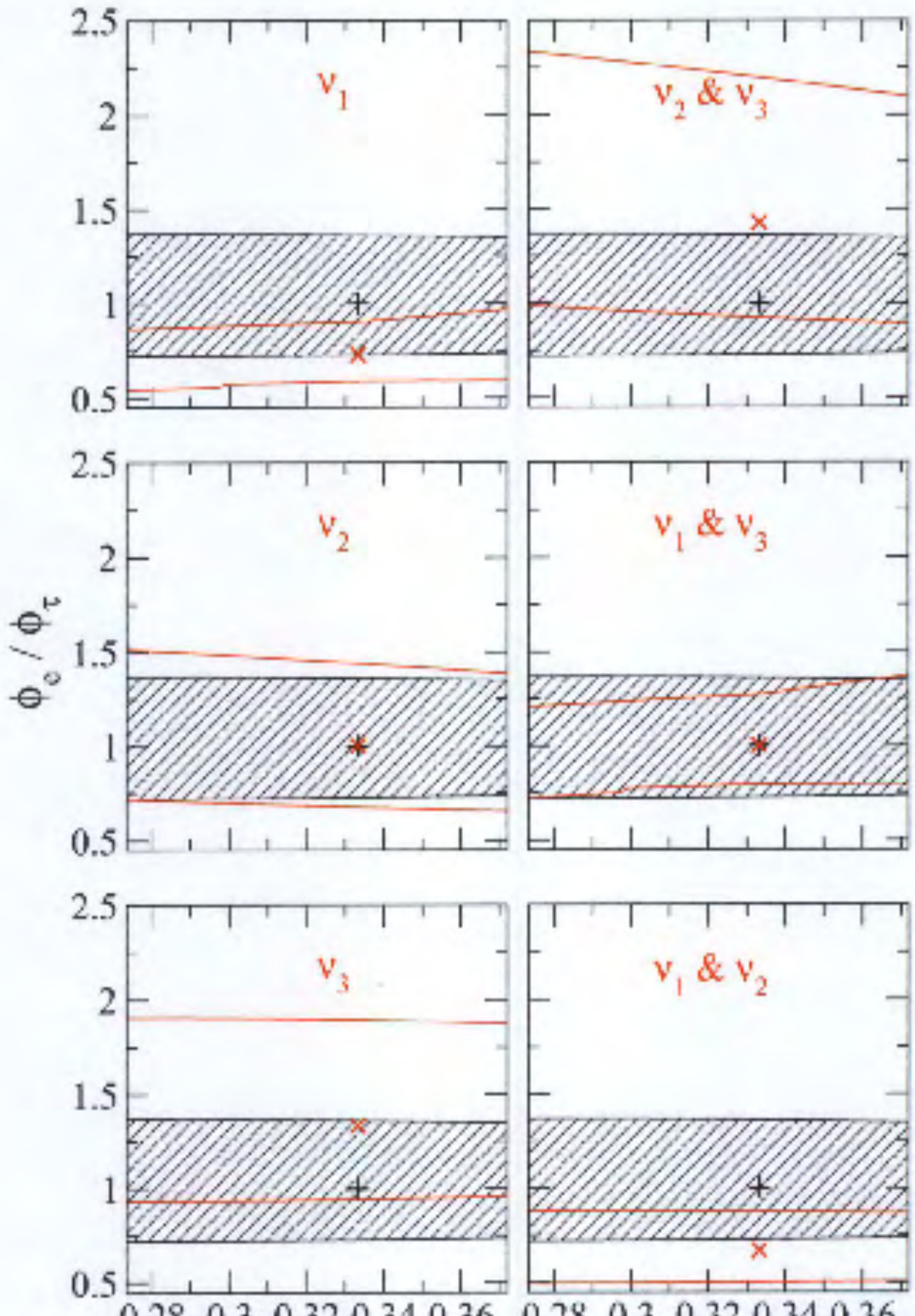
- Mohapatra et al(2010): Main idea: Not all three are pseudo-Dirac, only one(or two) are pseudo-Dirac (the small mass difference generated radiatively) and the other remains Majorana

(Fancy new names:Bimodal, schizophrenic)

Phenomenology essentially same as pseudo-Dirac case……for one or two flavors…..

To be fair, these models were invented for other purposes…..

Barry et al



5. A different realisation of pseudo-Dirac states(pseudo-Dirac type II)

- **Discussed by Wolfenstein and Petcov in 1981/2**
- **If mass matrix for a single flavor looks like**

$$\begin{matrix} a & b \\ b & -a+\delta \end{matrix}$$

When $\delta=0$ and a=b, get exact degeneracy and a Dirac state.
But when δ is not 0, the mass difference is governed by δ,(may need fine tuning
to keep mass difference small)
And the mixing angle is NOT maximal but can be arbitrary:
$\tan(2\theta) = b/a$.....
Recently revived by Joshipura et al.........
Why is this interesting?
For small mixing angle it may be possible to get MSW
resonance effect and get a flavor convert almost completely to
Steriles! For example, in passage thru neutrino background etc.....
In this case only steriles arrive at earth! (Mohanty, Joshipura,SP)
For example: Lunardini-Smirnov(2001) showed that for large lepton asymmetries,
for δm^2 of 10^{-15} eV^2, E of a PeV, large conversion to sterile can happen......

For E/δm^2 > 10^{31} eV^{-1}, MSW resonance can happen after production and give large conversion to sterile

Lunardini & Smirnov
hep-ph/009356

Lunardini & Smirnov hep-ph/0009356

$$\left\{ 10^{31} = \frac{1\ P_0 V}{10^{-16}\ eV^2} \right\}$$

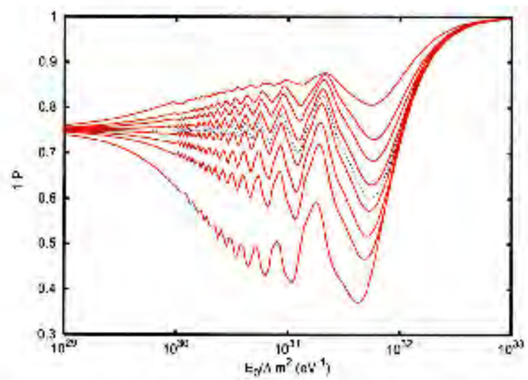


FIG. 9. The survival probability $1 - P(\nu_a - \nu_s)$ as a function of the ratio $E_0/\Delta m^2$ for various values of $F\eta$. From the upper to the lower curve: $F\eta = -20, -10, -6, -2, 0, 2, 6, 10, 20$; the dotted line represents the effect of vacuum oscillations ($F\eta = 0$). We have taken $\sin^2 2\theta = 0.5$ and production epoch $z = 3$.

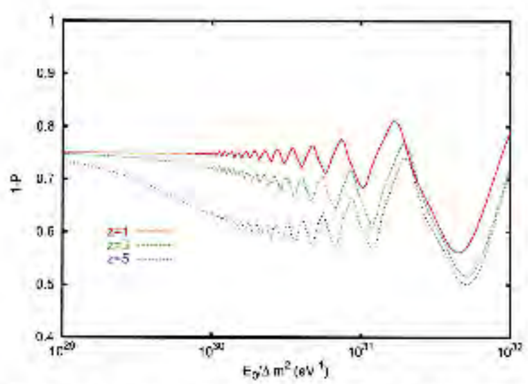


FIG. 10. The survival probability $1 - P(\nu_a - \nu_s)$ as a function of the ratio $E_0/\Delta m^2$ for various values of the production epoch z. We have taken $\sin^2 2\theta = 0.5$ and $F\eta = 6$.

Lunardini & Smirnov hep-ph/0009356

that the vacuum oscillation probability converges to $\sin^2 2\theta/2$ [7]. A substantial ($\sim 10\%$) deviation from the vacuum oscillation probability due to matter effect starts at $z \simeq 1$ for $F\eta \simeq 10$ and at $z \simeq 3$ for $F\eta \simeq 2$.

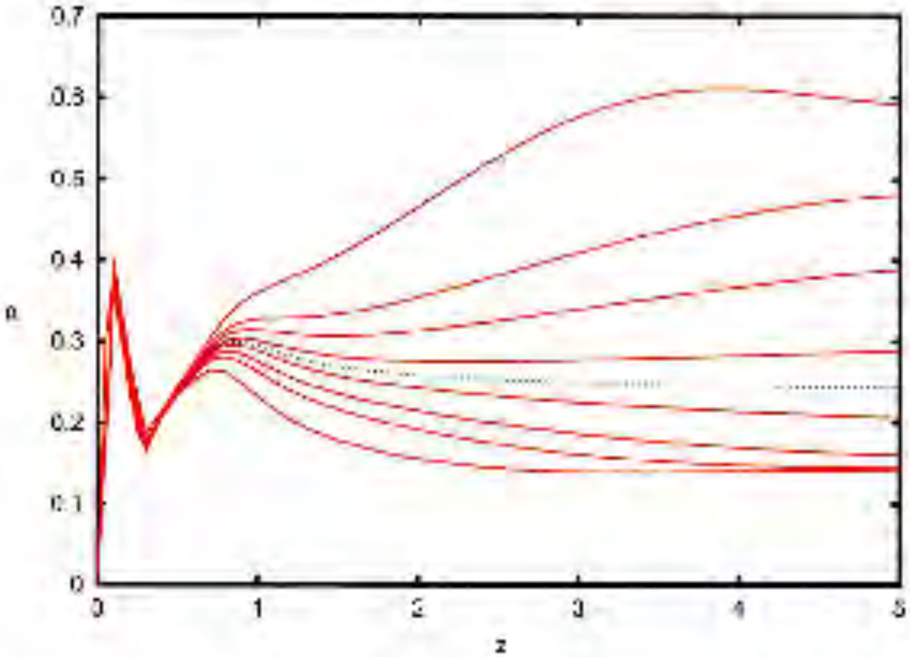


FIG. 8. The $\nu_s - \nu_e$ conversion probability P as a function of the production epoch z for various values of $F\eta$. From the upper to the lower curve: $F\eta = 20, 10, 6, 2, 0, -2, -6, -10, -20$, the dotted line represents the vacuum oscillations probability ($F\eta = 0$). We have taken $\sin^2 2\theta = 0.5$ and $E_0/\Delta m^2 = 10^{21}$ eV^{-1}.

6. Effects of Magnetic Fields

- In regions with large magnetic fields, neutrino magnetic transitions can modify the flavor mix.
- However, for Majorana neutrinos, the magnetic moment matrix is antisymmetric and hence, a flavor mix of 1:1:1 remains 1:1:1
- For Dirac case, possible interesting effects via RSFP (Akhmedov and Lim-Marciano) for μ_ν at the maximum allowed values of about $10^{-14}\mu_B$ and B of order of a Gauss

  In this case also, large conversion from flavor to sterile state can occur.

Other possibilities

- 7. Lorentz Invariance Violation
- 8. CPT Violation
- 9. Decoherence
- 10. Mass varying Neutrinos
- 11. etc.....

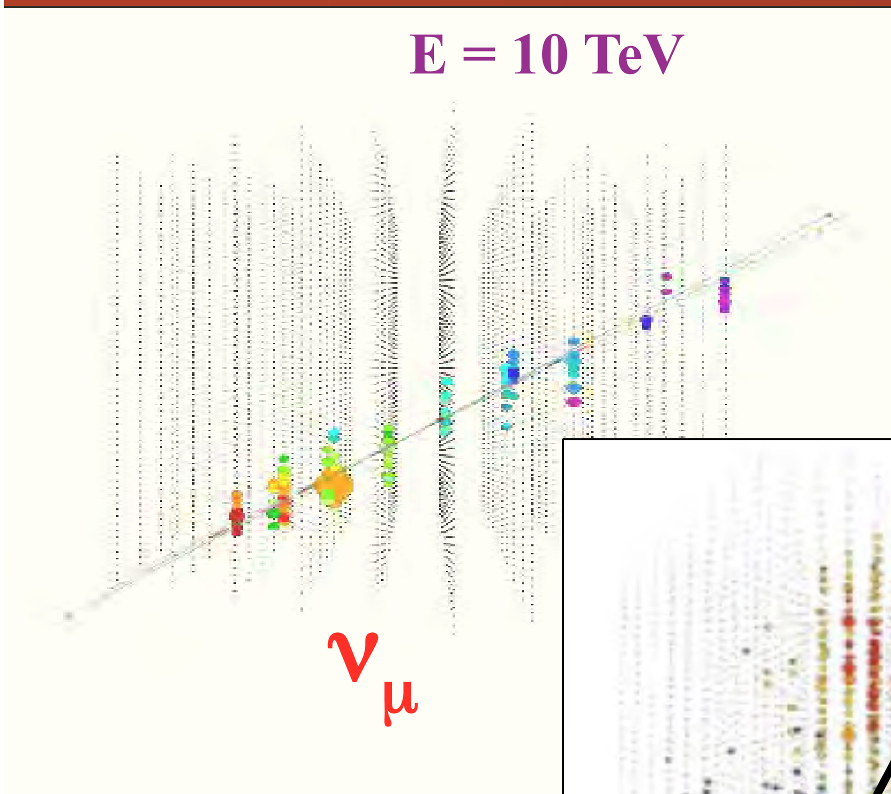
Can we measure it?

FLAVOR INFORMATION

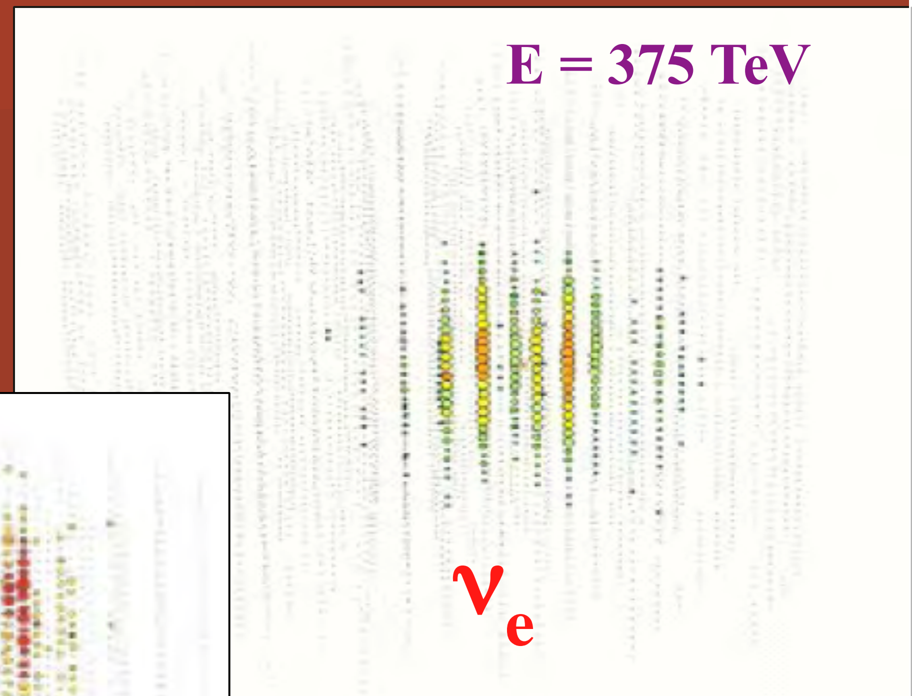
- Muon tracks – CC interactions of ν_μ
- Showers – neutral current interactions of all flavors, plus CC interactions of ν_e and ν_τ.
- Double bang and lollipop events - only ν_τ
- Glashow resonance – only $\bar{\nu}_e$, at E=6.3PeV.

To determine the ν_e/ν_μ ratio
→ compare muon tracks to showers.

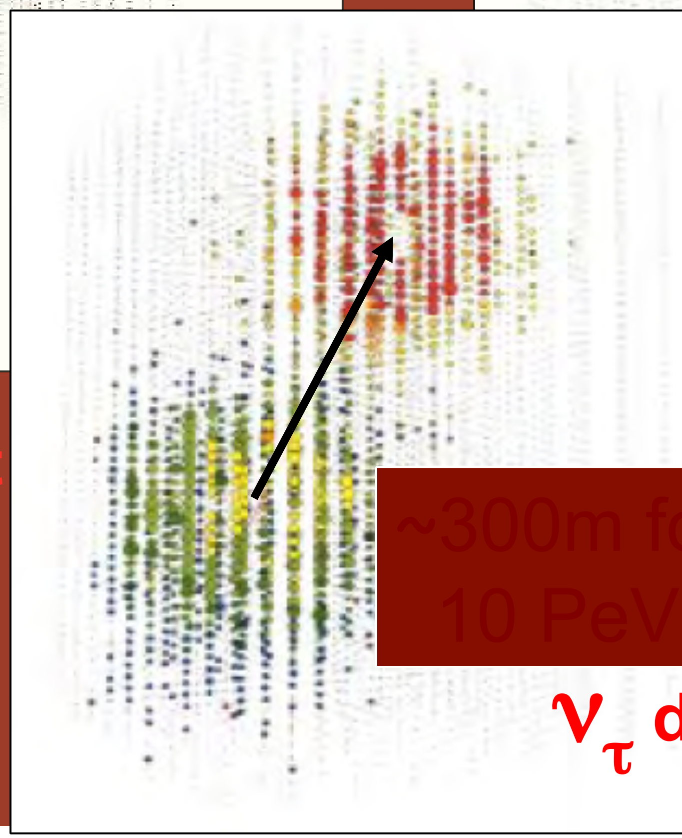
Event Simulation in IceCube



muon event

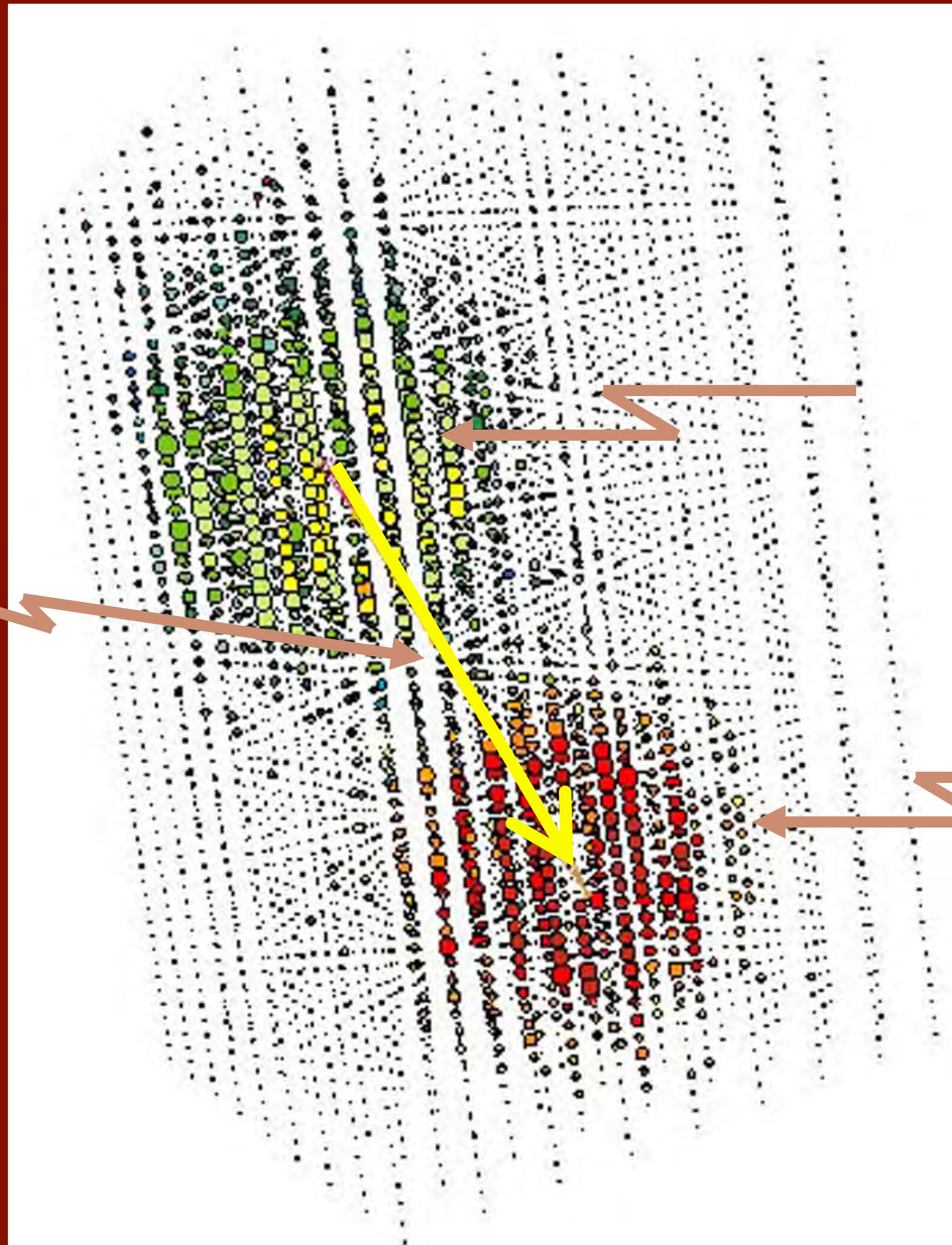


shower event



~300m for 10 PeV ν_τ

ν_τ double bang event



$\nu_\tau \rightarrow \tau$

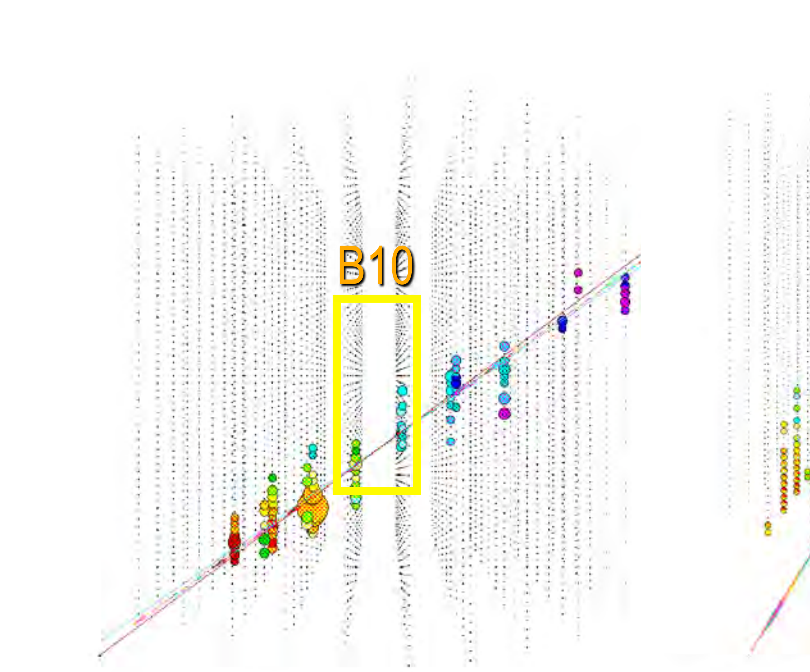
PeV
τ
(300m)

τ decays

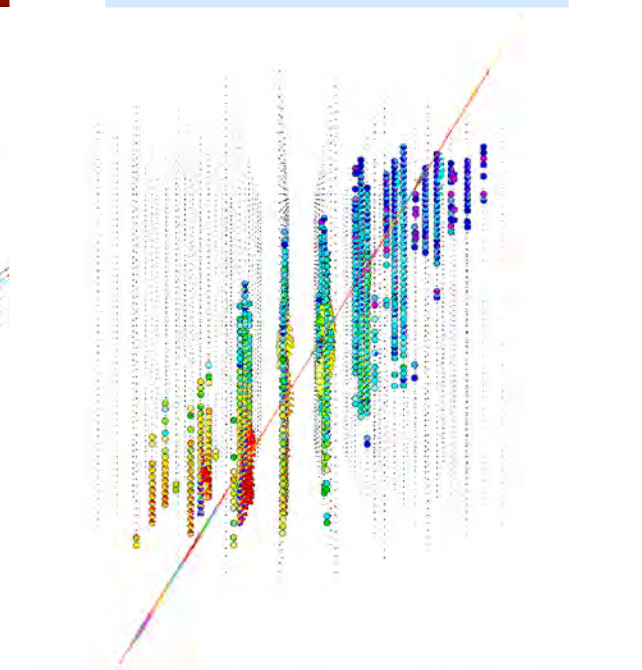
Dounble Bang signature: Learned and SP(1995)

Signatures in IceCube ...

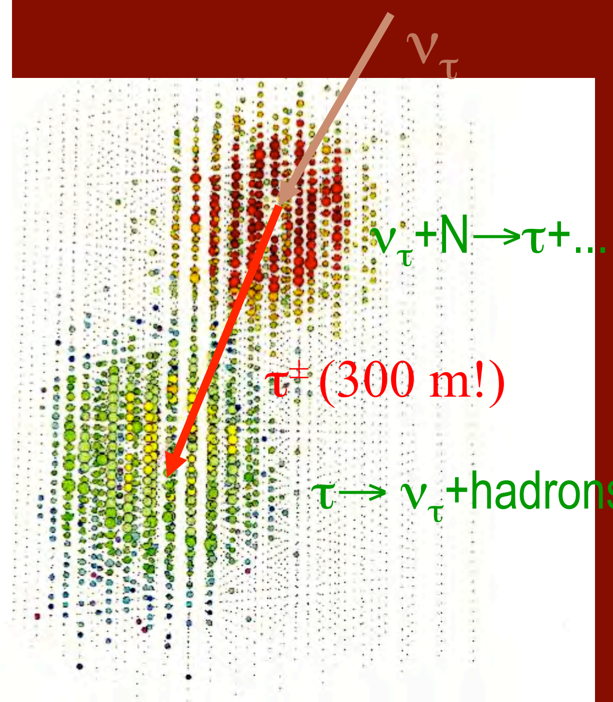
10^{13} eV (10 TeV)



$6x10^{15}$ eV (6 PeV)



Multi-PeV

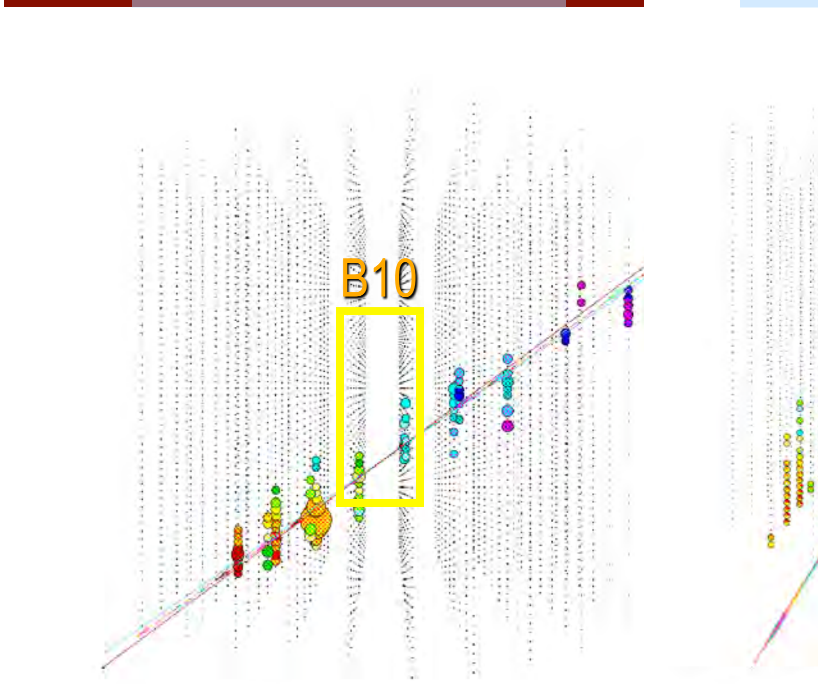


signature of ν_μ

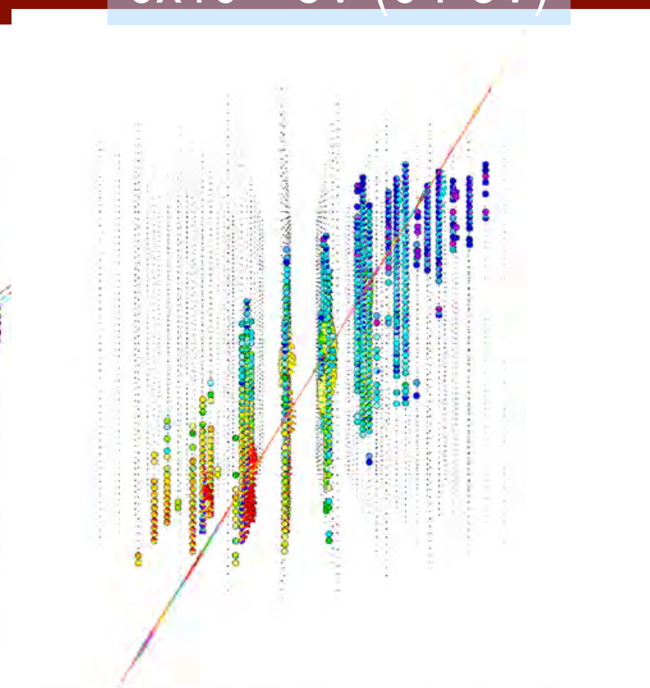
signature of ν_τ

Signatures in IceCube ...

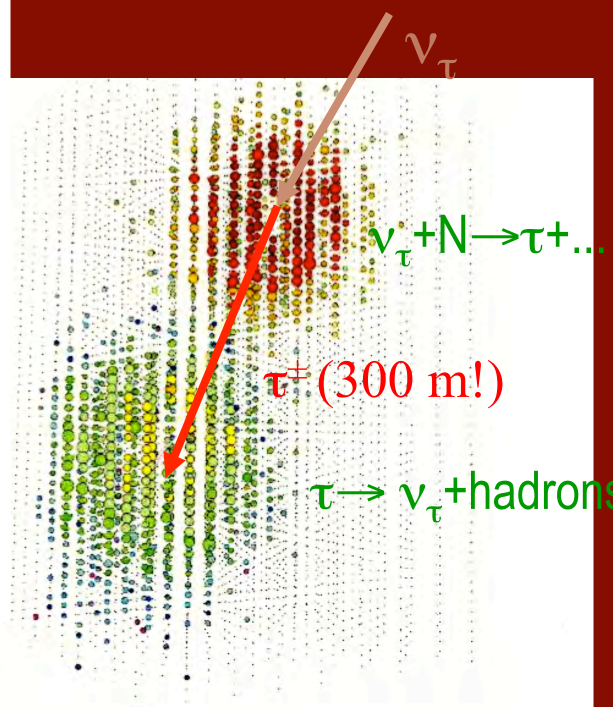
10^{13} eV (10 TeV)



6×10^{15} eV (6 PeV)



Multi-PeV

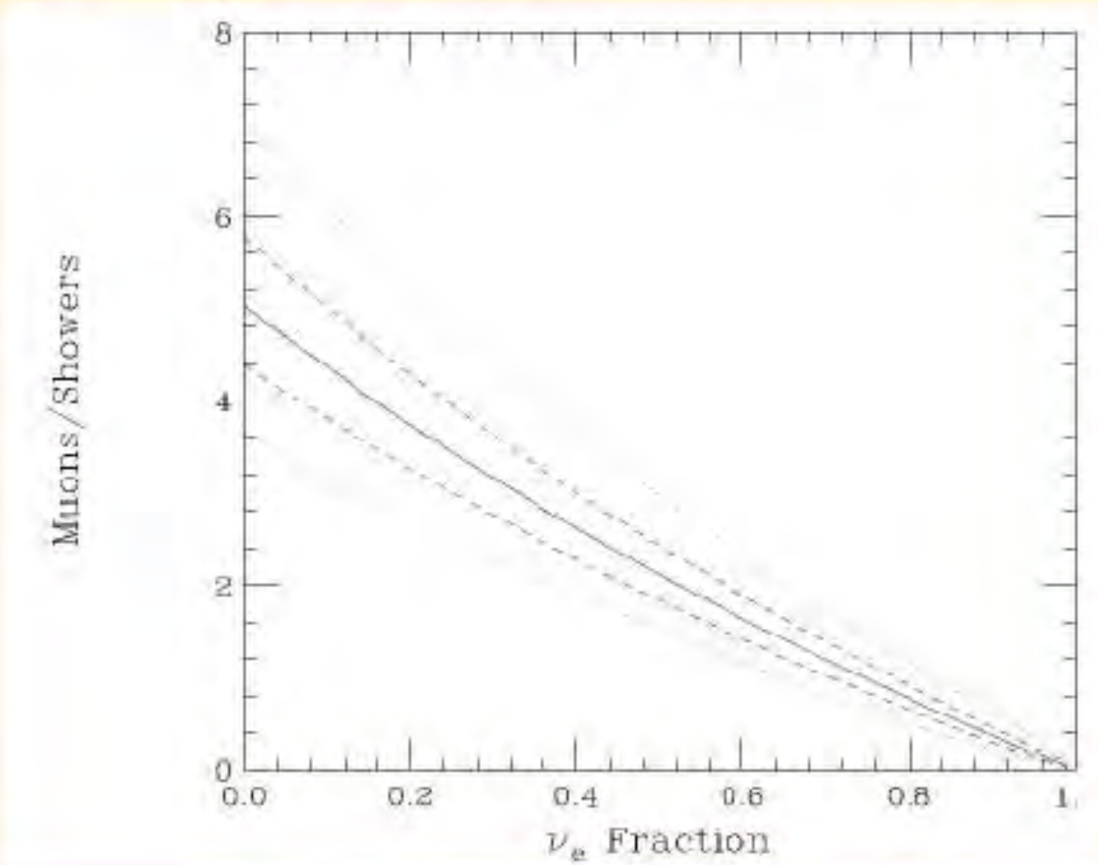


signature of ν_μ

signature of ν_τ

Muons/Showers rate for different electron fractions.

(Waxman-Bahcall flux, 1yr at Icecube)



Beacom, Bell, Hooper, Pakvasa, and Weiler, PRD 68, 093005 (2003)

For other detection techniques, such as air showers, radio cherenkov etc (AUGER, ANITA etc),

it may be possible to determine flavors via

LPM effect etc, or taus showering out of

mountains etc…….probably not as well as H_2O cherenkov…………..much more work needs to be done

Conclusions/summary

- Neutrino Telescopes MUST measure flavors, and need to be v.v.large(Multi-KM), just OBSERVING neutrinos NOT enuf……
- If the flavor mix is found to be 1:1:1, it is BORING and confirms CW, even so can lead to many constraints.
- If it is approx ½:1:1, we have damped muon sources.
- If the mix is a:1:1, then a>1 may mean decays with normal hierarchy and can give info about θ_{13} and δ…..
- If a is <<1, then decays with inverted hierachy may be occuring..
- Can probe v.v. small δm^2 beyond reach of neutrinoless double beta decay….
- Anisotropy can be due to flavor violating gravity?

- ……"although tough to measure, flavor ratios are a very interesting possibility to constrain particle physics properties using astrophysical sources in parameter ranges which would otherwise NOT be accessible"

arXiv:1101.2673(Mehta and Winter)