Neutrinos:
NOT just missing ET !

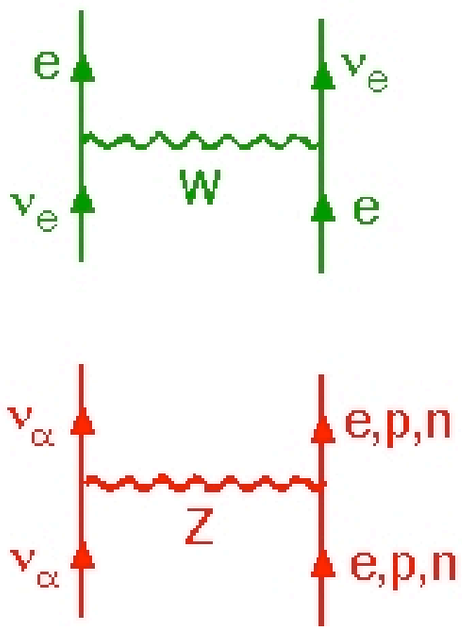
Neutrinos:
NOT just missing ET !

Neutrinos:
NOT just missing ET !

What happens to
Neutrino Oscillations,
e.g. oscillation length,
if $\hbar \rightarrow 0$?

Matter Effects:

Coherent Forward Scattering:

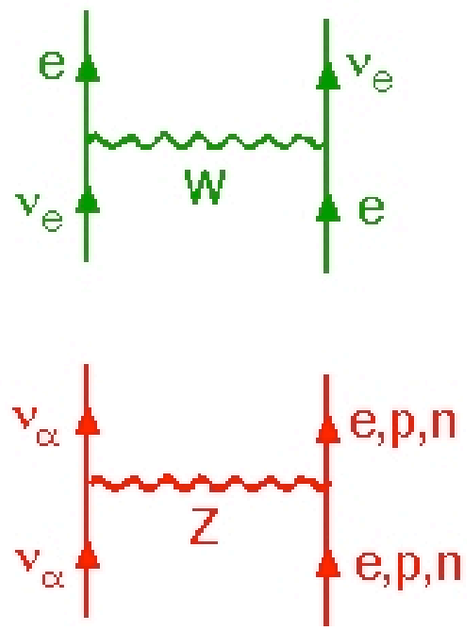


Wolfenstein '78

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

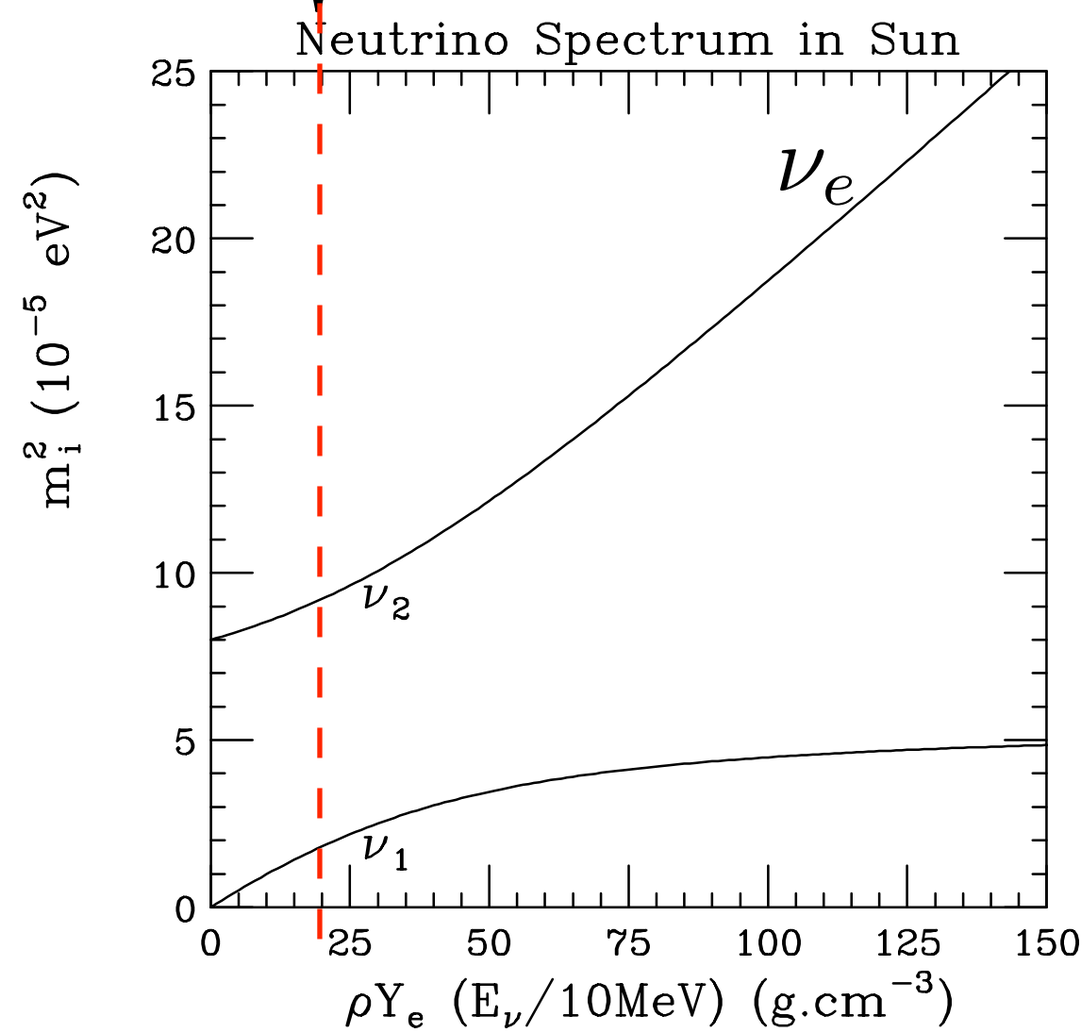
MSW

Coherent Forward Scattering:



Wolfenstein '78

Mikheyev + Smirnov Resonance WIN '85



MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

$$\sim G_F N_e E_\nu$$

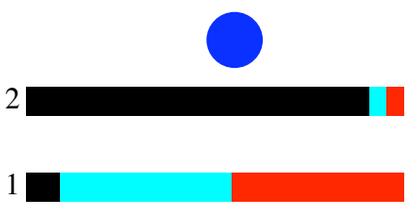
MSW

Life of a Boron-8 Solar Neutrino:

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B



at birth

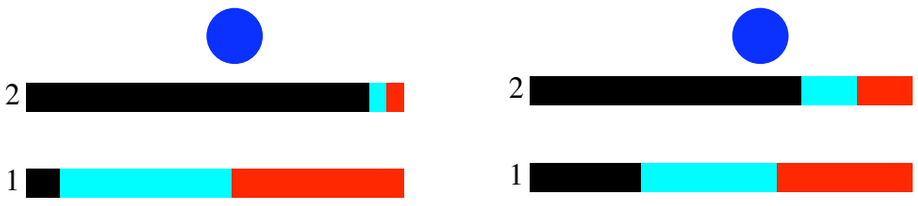
Solar Center

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!



at birth toddler

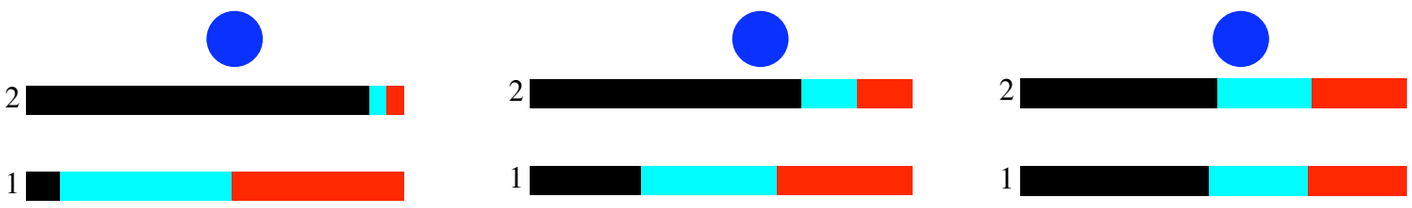
Solar Center

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!



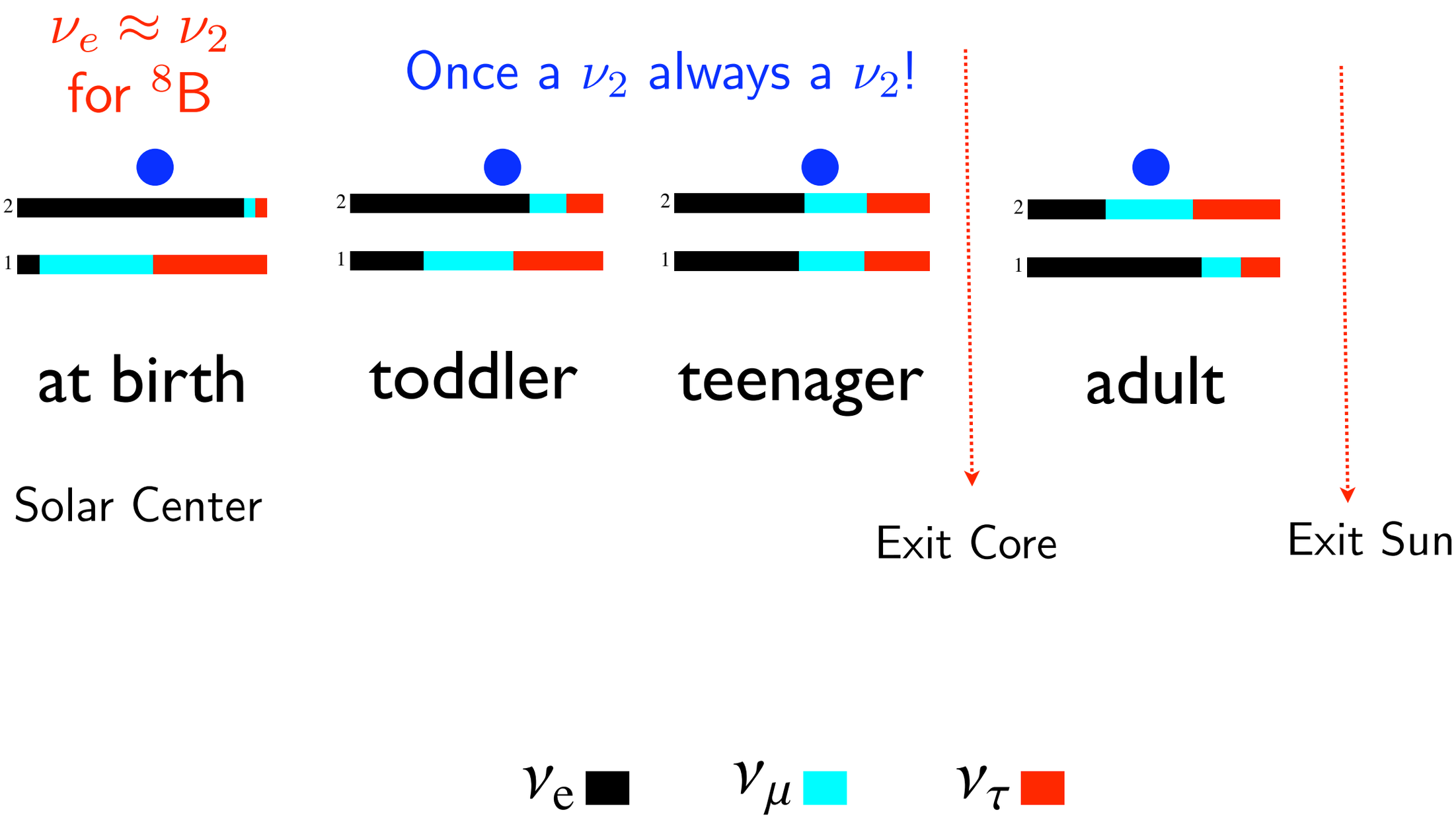
at birth toddler teenager

Solar Center

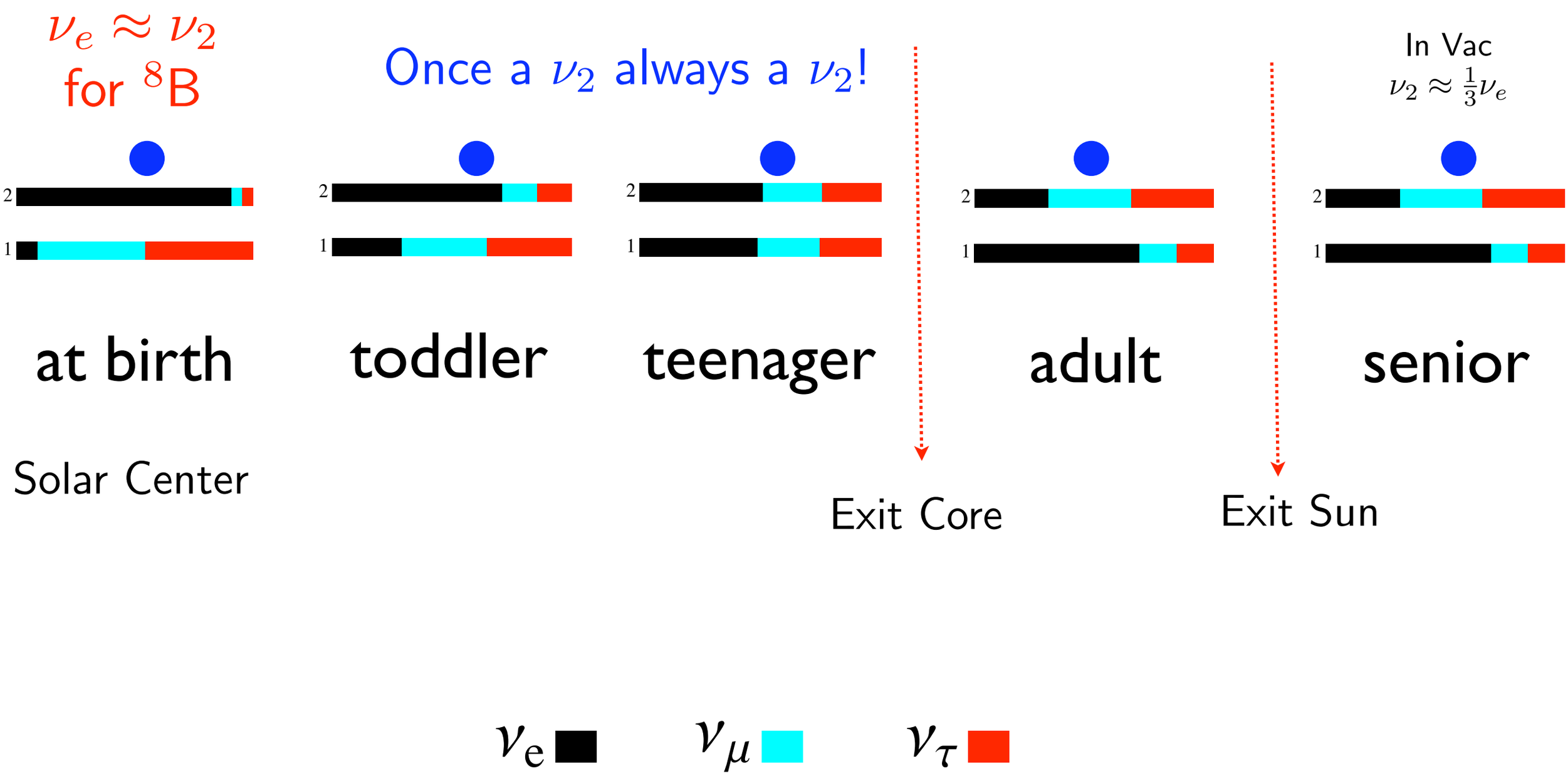
Exit Core

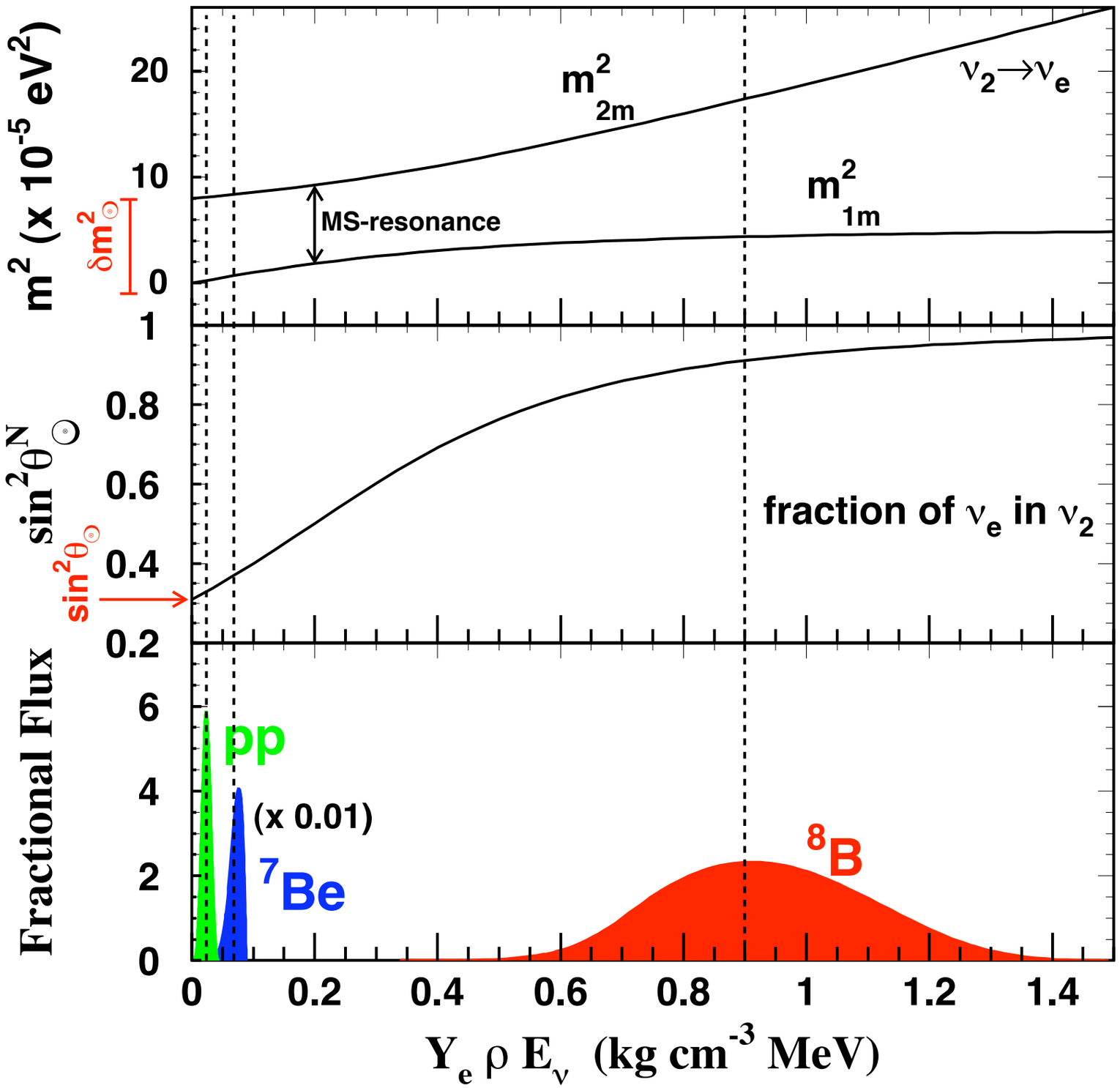
ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:



Life of a Boron-8 Solar Neutrino:





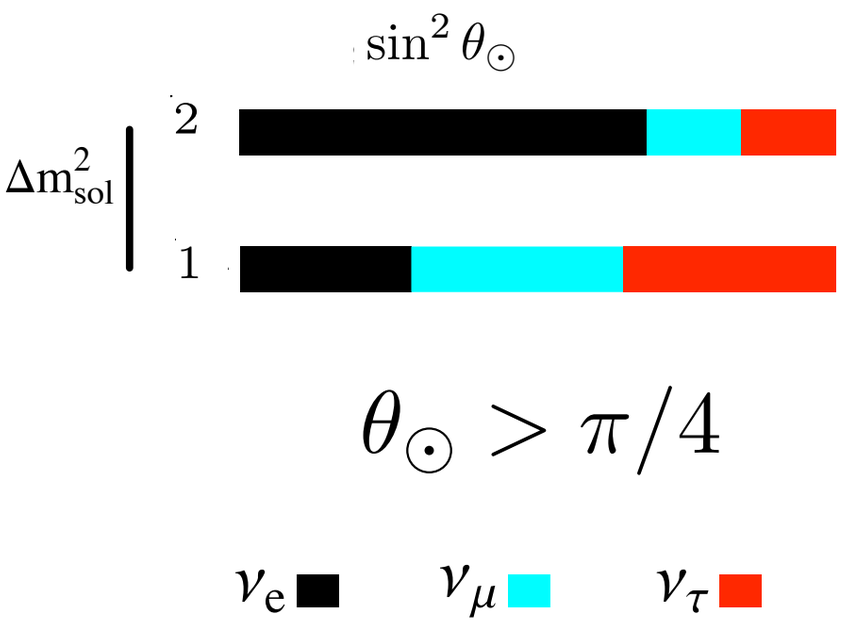
In Vacuum

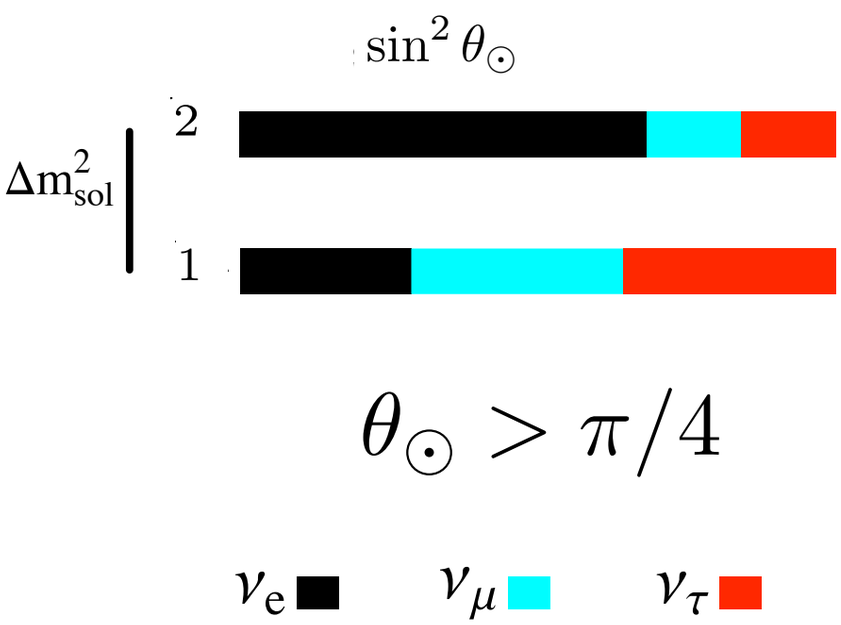
$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$
$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

Whereas for ^{8}B at center of Sun

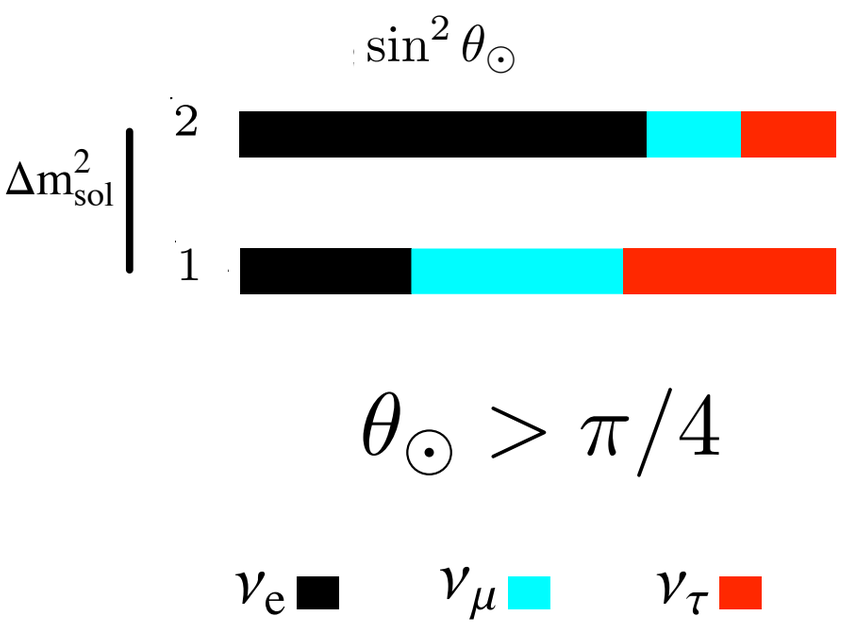
$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$
$$\sin^2\theta^N_\odot = 0.91$$

hep-ph/0601198


$\sin^2\theta_\odot$
2
1
Δm^2_{sol}
$\theta_\odot > \pi/4$
ν_e
ν_μ
ν_τ



Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is $1/2$.



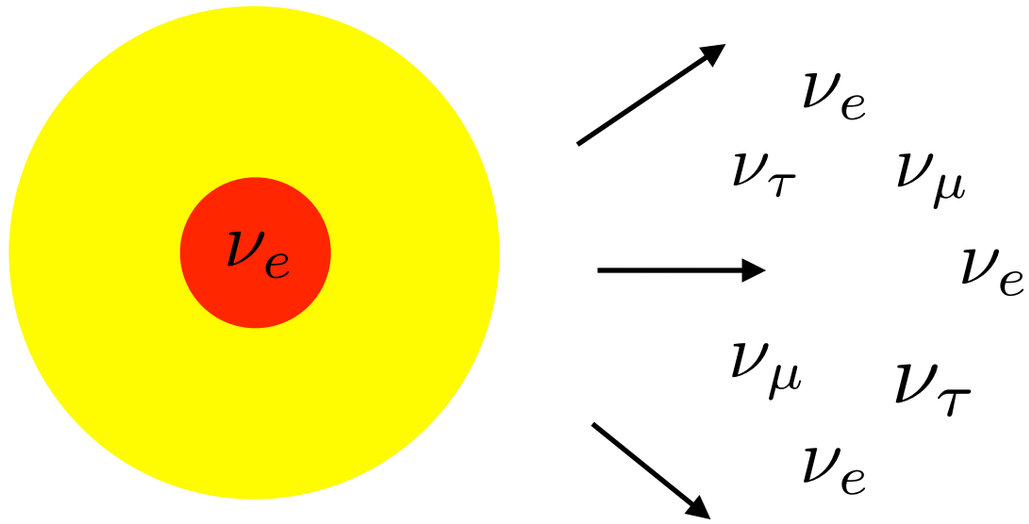
Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is 1/2.

For this hierarchy $\boldsymbol{P_{ee}^{matter} \geq P_{ee}^{vac} \geq 1/2}$

But $\boldsymbol{P_{ee}^{SNO} = 0.347 \pm 0.038 < 1/2}$

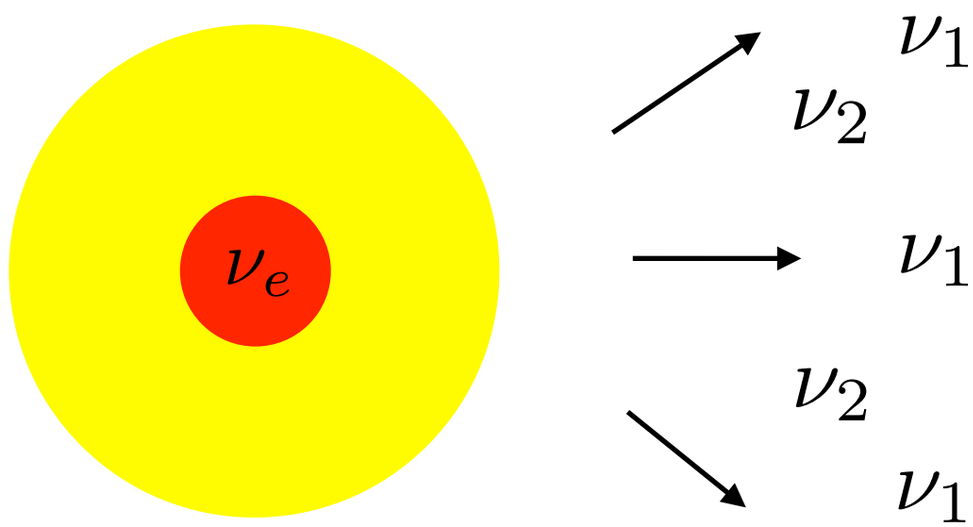
This solar hierarchy EXCLUDED !!!.

Identical Solar Twins:



flavor eigenstates

?????



mass eigenstates

Kinematical Phase:

$$\delta m^2_\odot = 8.0 \times 10^{-5} eV^2$$

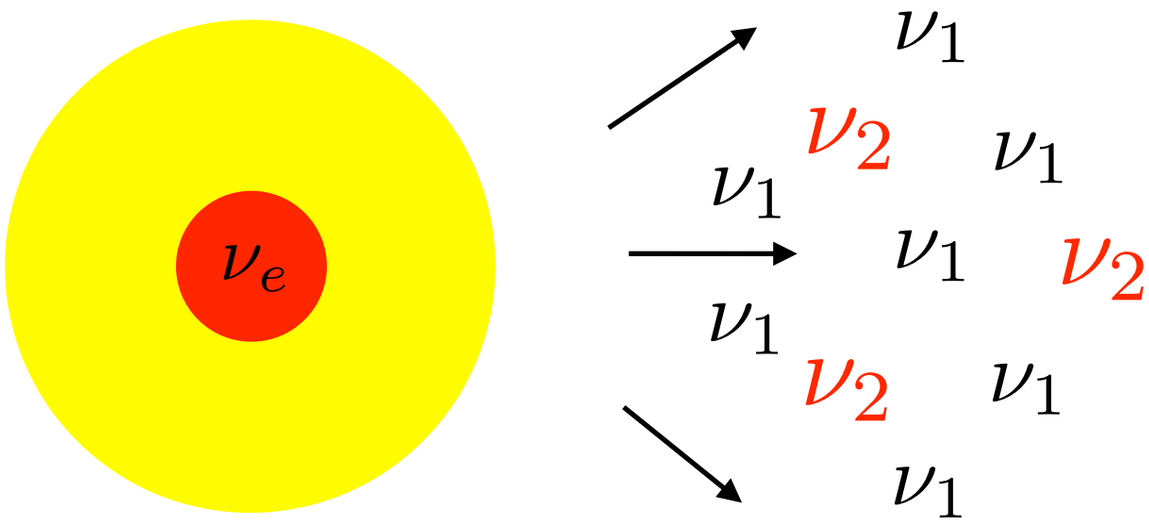
$$\sin^2\theta_\odot = 0.31$$

$$\Delta_\odot = \frac{\delta m^2_\odot L}{4E} = 1.27 \quad \frac{8\times10^{-5}\ eV^2\ \cdot\ 1.5\times10^{11}\ m}{0.1-10\ MeV}$$

$$\Delta_\odot \approx 10^{7\pm1}$$

Effectively Incoherent !!!

pp and ^{7}Be



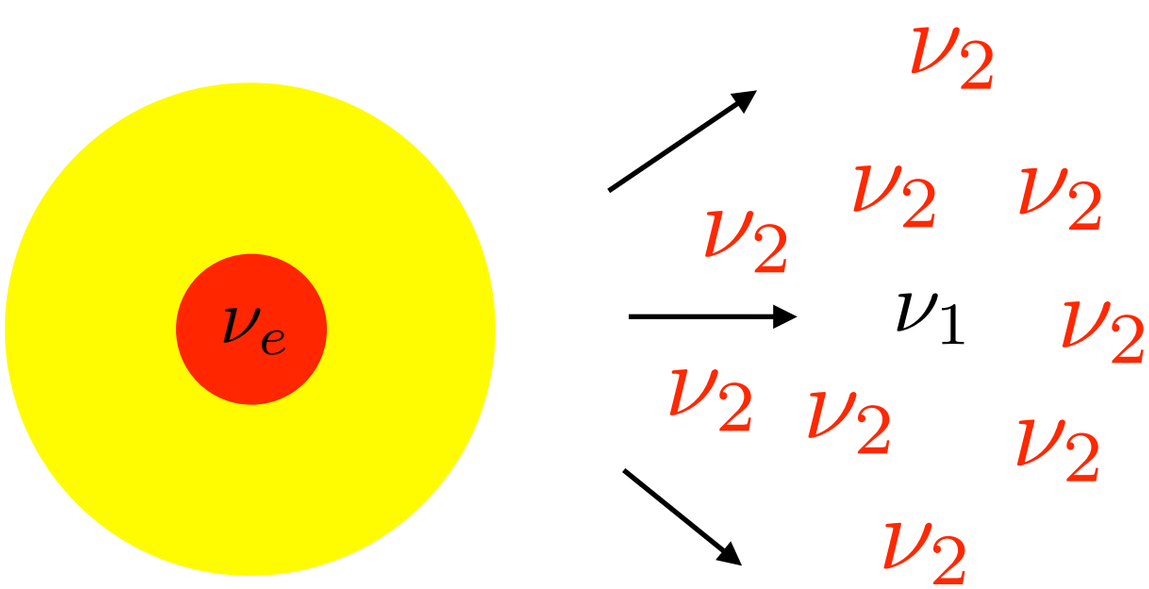
$f_1 \sim 69\%$

$f_2 \sim 31\%$

$$\langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot \approx 0.6$$

$f_3 = \sin^2\theta_{13} < 4\%$

^8B



$f_2 \sim 90\%$

$f_1 \sim 10\%$

$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!

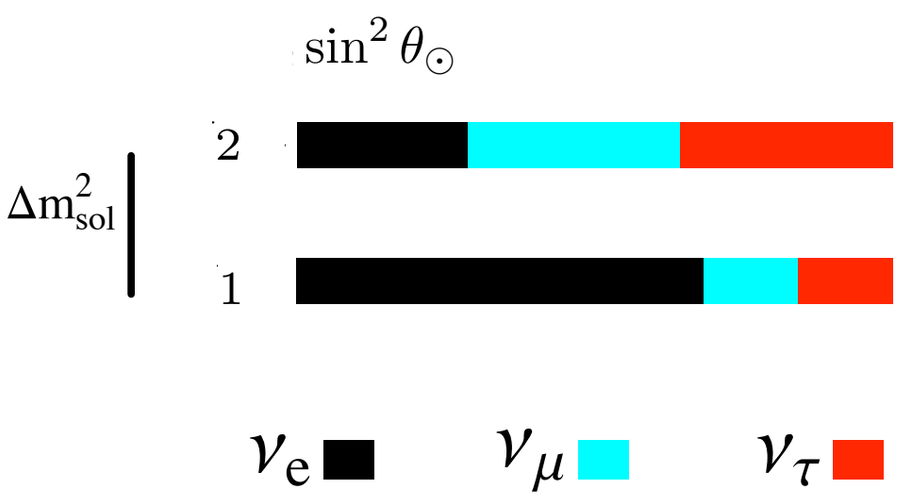
Summary:

The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

$$f_1 = 65 \pm 2\%,\ f_2 = 35 \mp 2\% \text{ with } P_{ee} \approx 0.56$$

The high energy ^{8}B Solar Neutrinos exit the sun as "PURE" ν_2 mass eigenstates due to matter effects.

$$f_2 = 91 \pm 2\% \text{ and } f_1 = 9 \mp 2\% \text{ with } P_{ee} \approx 0.35.$$

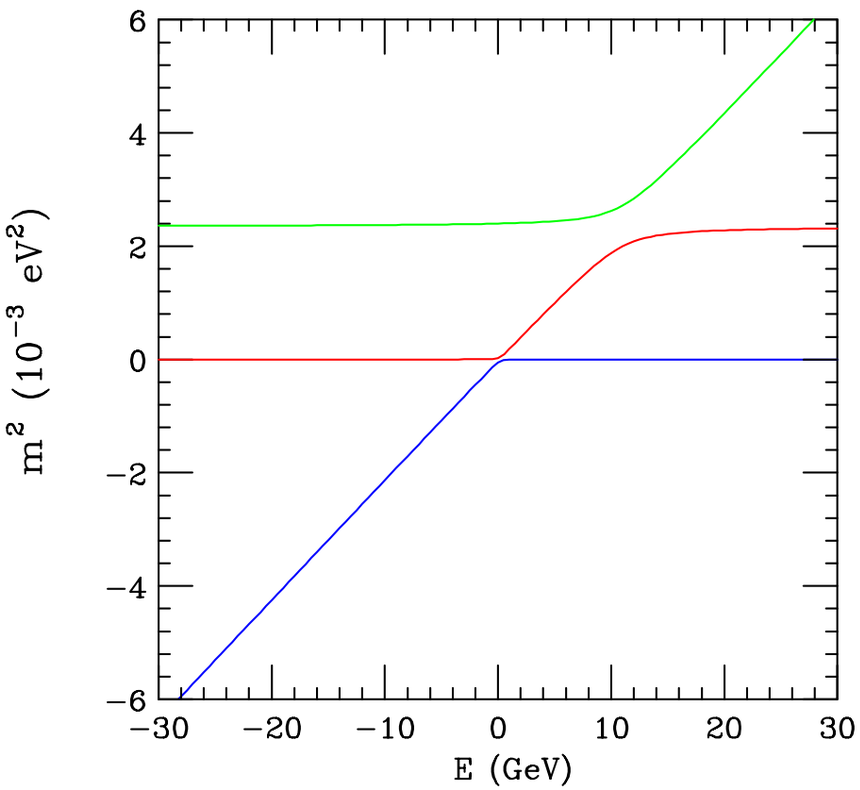


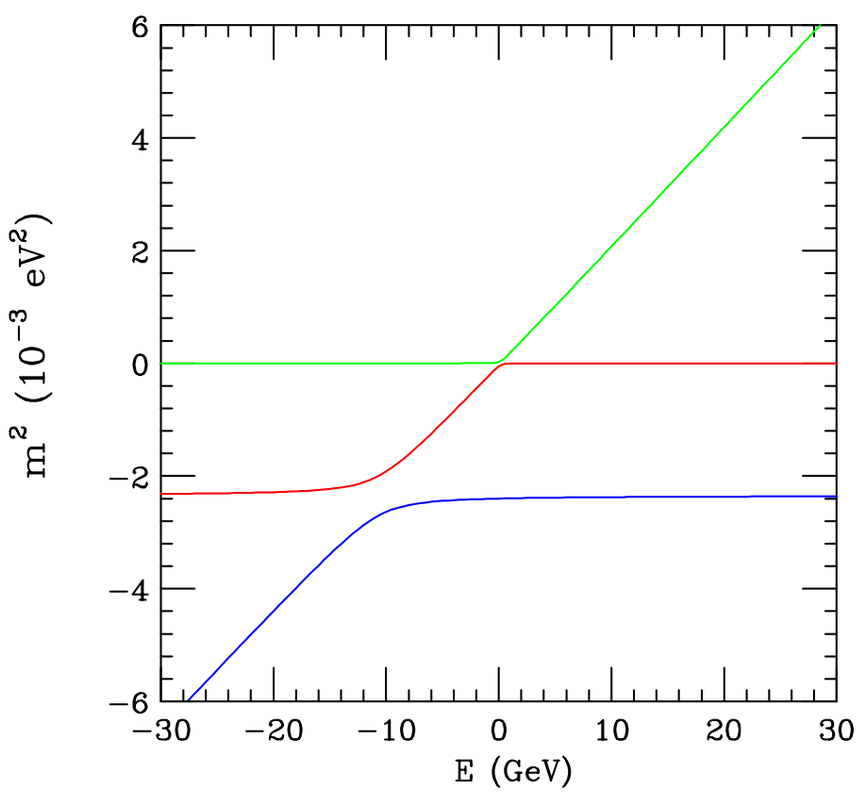
$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5} eV^2$$

$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

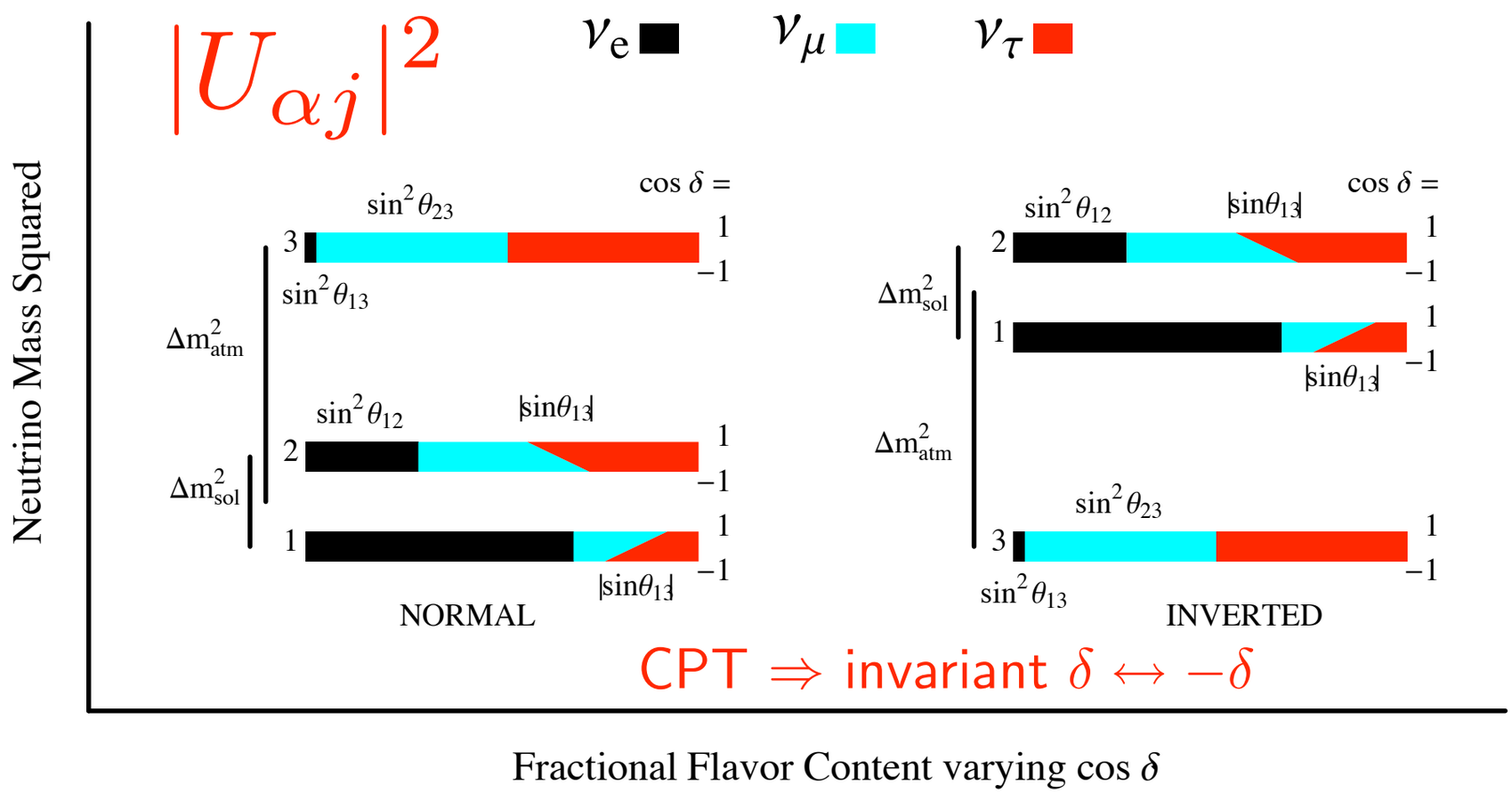
SNO, KamLAND, SK/K, GNO/Gallex, SAGE, Cl


NH
6
4
2
0
−2
−4
−6
−30
−20
−10
0
10
20
30
E (GeV)
m² (10⁻³ eV²)


IH
6
4
2
0
−2
−4
−6
−30
−20
−10
0
10
20
30
E (GeV)
m² (10⁻³ eV²)

Variation of Flavor Content & CPV:

$$0 \leq \delta < 2\pi$$



Appearance Experiments:

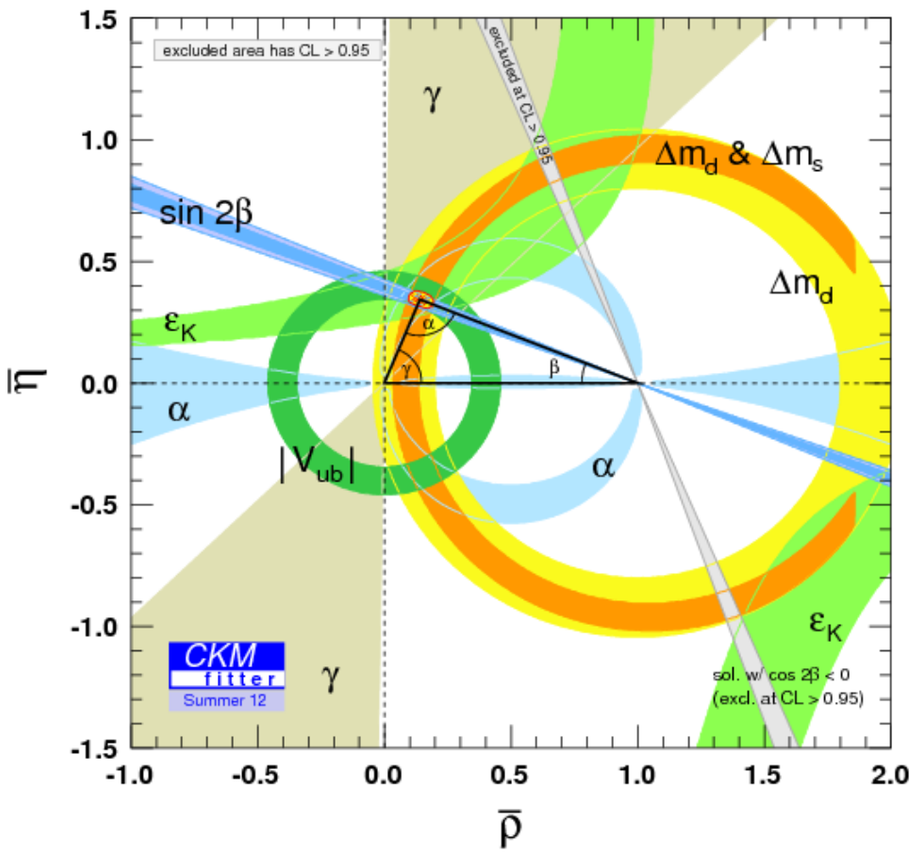
$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

ν_τ at Neutrino Factory

Quark & lepton Unitarity Triangles:

Quark Triangle:

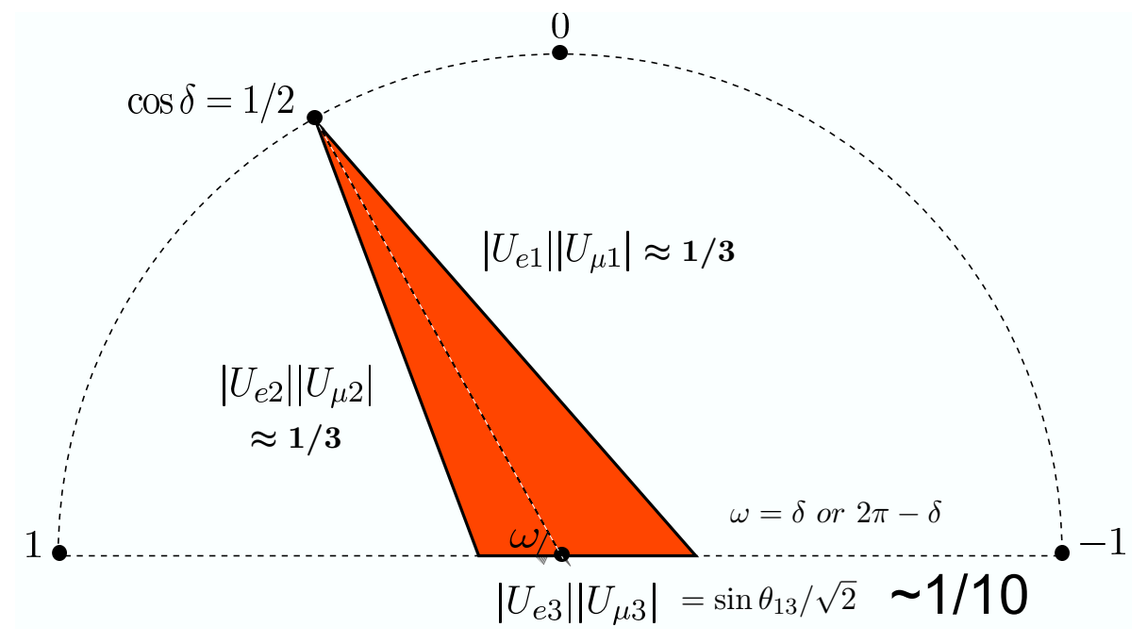


Neutrino Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$

only Unitarity triangle that doesn't involve ν_τ !

$$|J| = 2 \times \mathcal{A}rea$$



$$|U_{e1}||U_{\mu 1}| = 0.0-0.5;\ |U_{e2}||U_{\mu 2}| = 0.2-0.4;\ |U_{e3}||U_{\mu 3}| = 0.1(1\pm 0.2)$$

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}}$$

only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta$$

$$\Delta P_{cp} = 2 \sin\delta \sin 2\theta_{13} \ \sin 2\theta_{23} \sin 2\theta_{12} \cos\theta_{13} \ \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

$\nu_\mu \longrightarrow \nu_e$

In Matter:

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

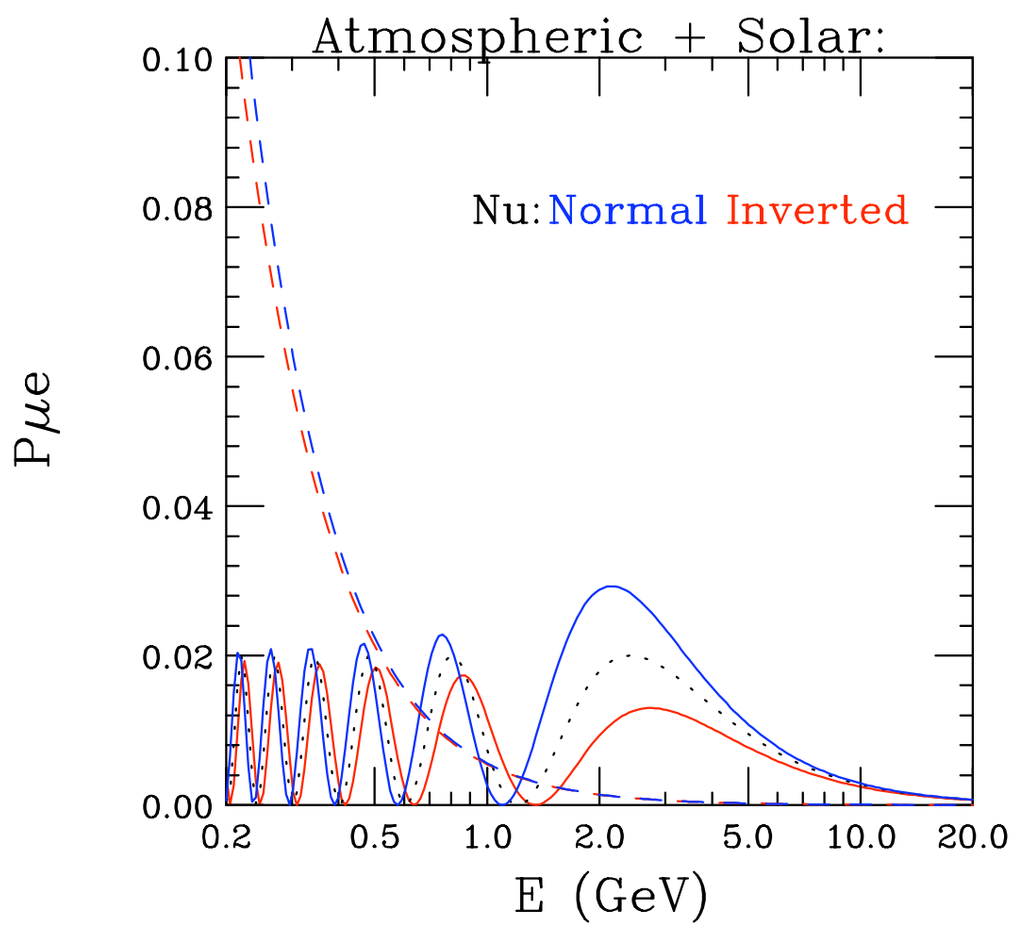
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

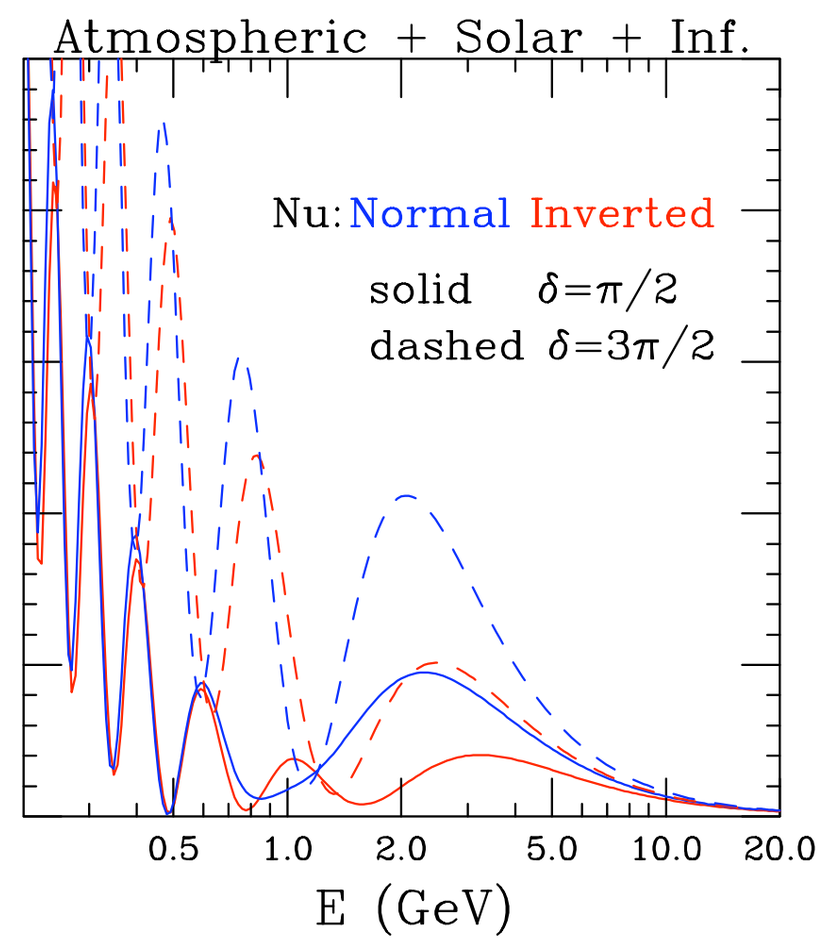
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





Neutrino Energy and Baselines:

- Near 1st Oscillation Maximum: L/E= 500 km/GeV

T2K, NOνA and T2HyperK using Off Axis beams

LBNE (1300km) and T2Okinoshima (658km) –broad band beams

- Near the 2nd Oscillation Maximum: L/E= 1500 km/GeV

ESS to Garpenburg (540km) –broad band beam

- In between these Two: L/E $\approx$ 1000 km/GeV

LBNO near the "bi-magic" baseline: 2300km –broad band beam

1st Oscillation Maxima:

- Near 1st Oscillation Maximum: $\Delta_{31} \approx \pi/2$

T2K, NOνA and T2HyperK using Off Axis beams

LBNE (1300km) and T2Okinoshima (658km) broad band beams

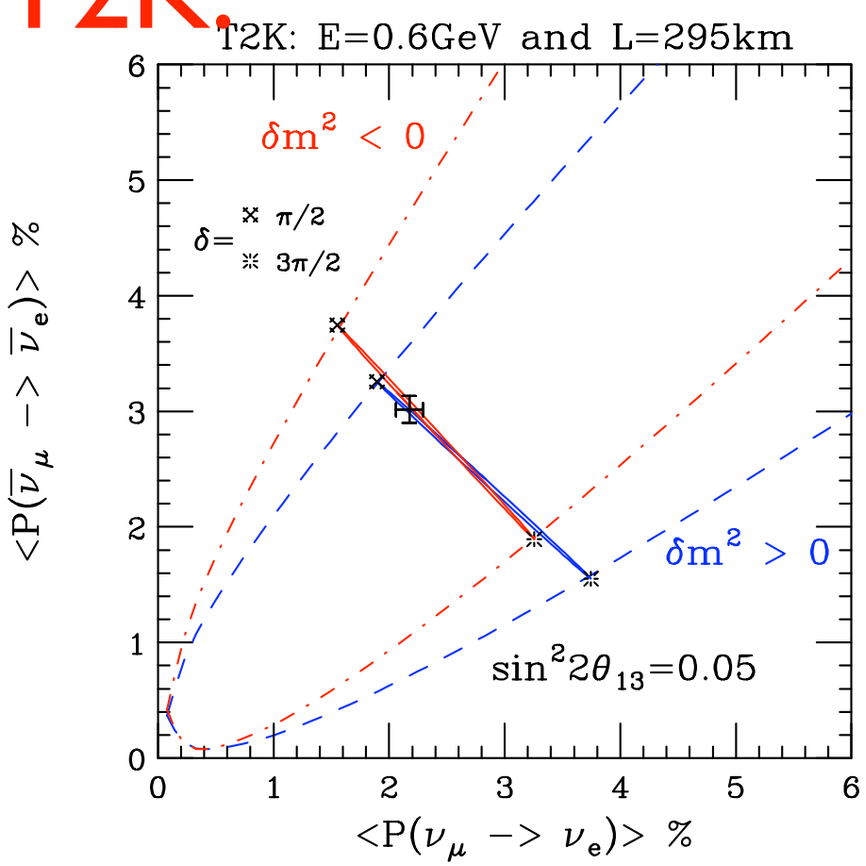
1st Oscillation Maxima:

- Near 1st Oscillation Maximum: $\Delta_{31} \approx \pi/2$

T2K, NOνA and T2HyperK using Off Axis beams

LBNE (1300km) and T2Okinoshima (658km) broad band beams

T2K:



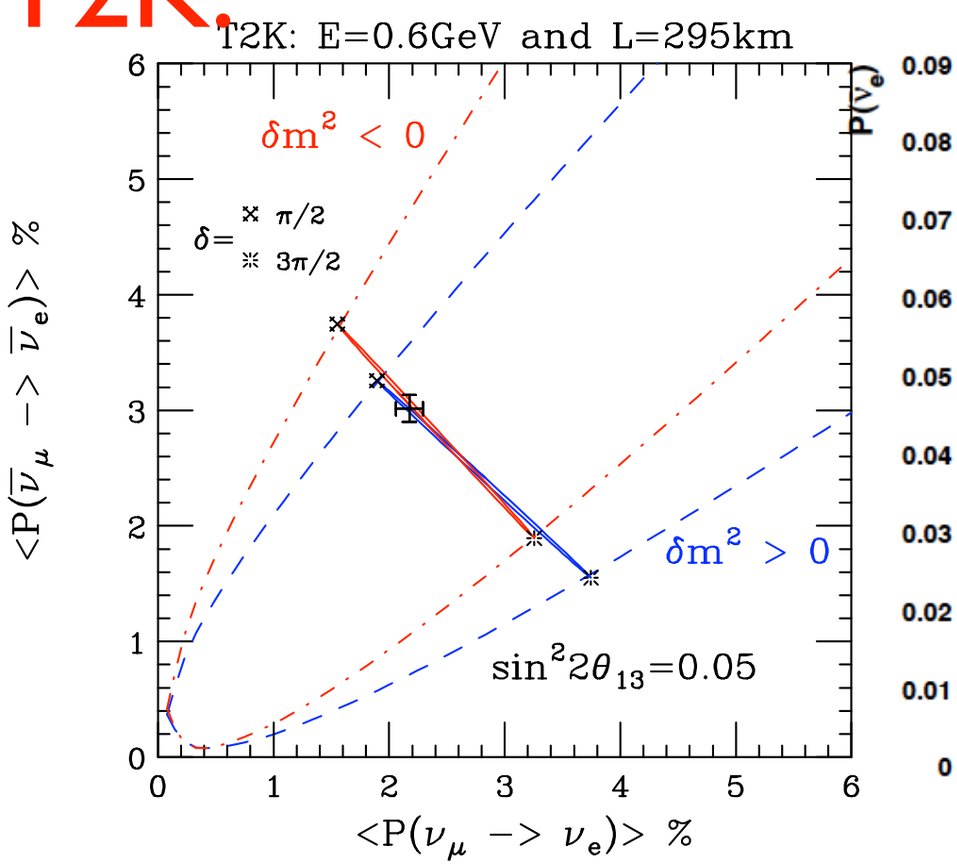
1st Oscillation Maxima:

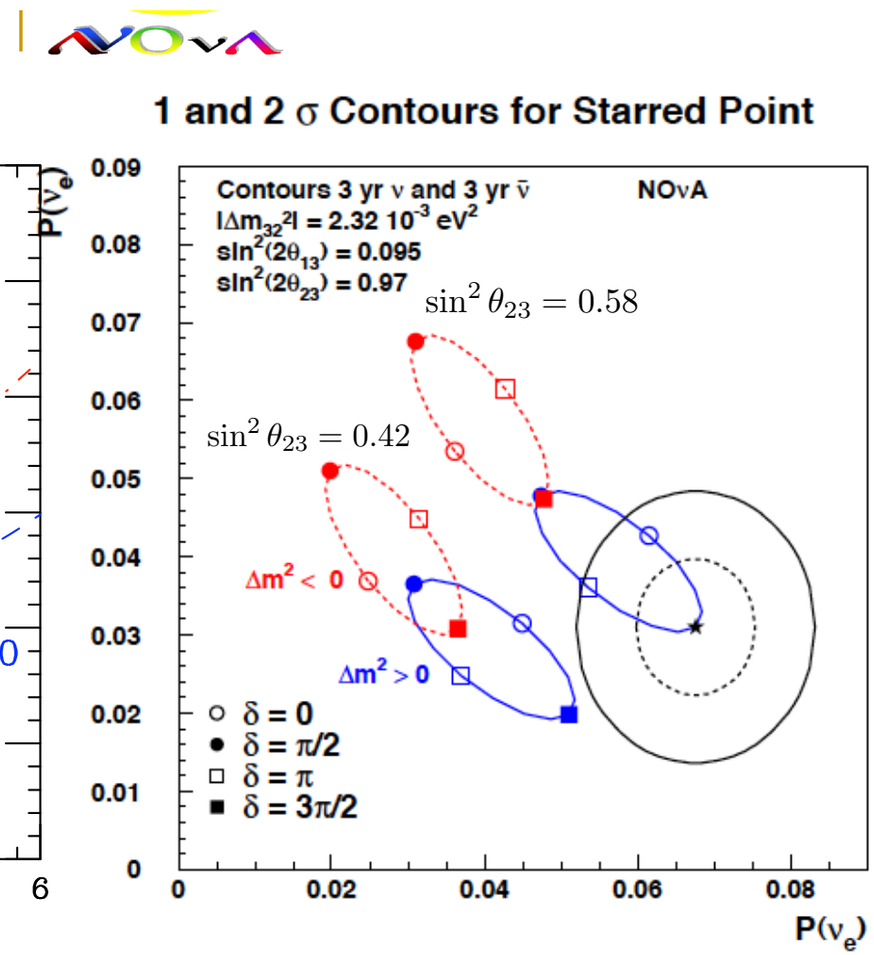
- Near 1st Oscillation Maximum: $\Delta_{31} \approx \pi/2$

T2K, NOνA and T2HyperK using Off Axis beams

LBNE (1300km) and T2Okinoshima (658km) broad band beams

T2K:





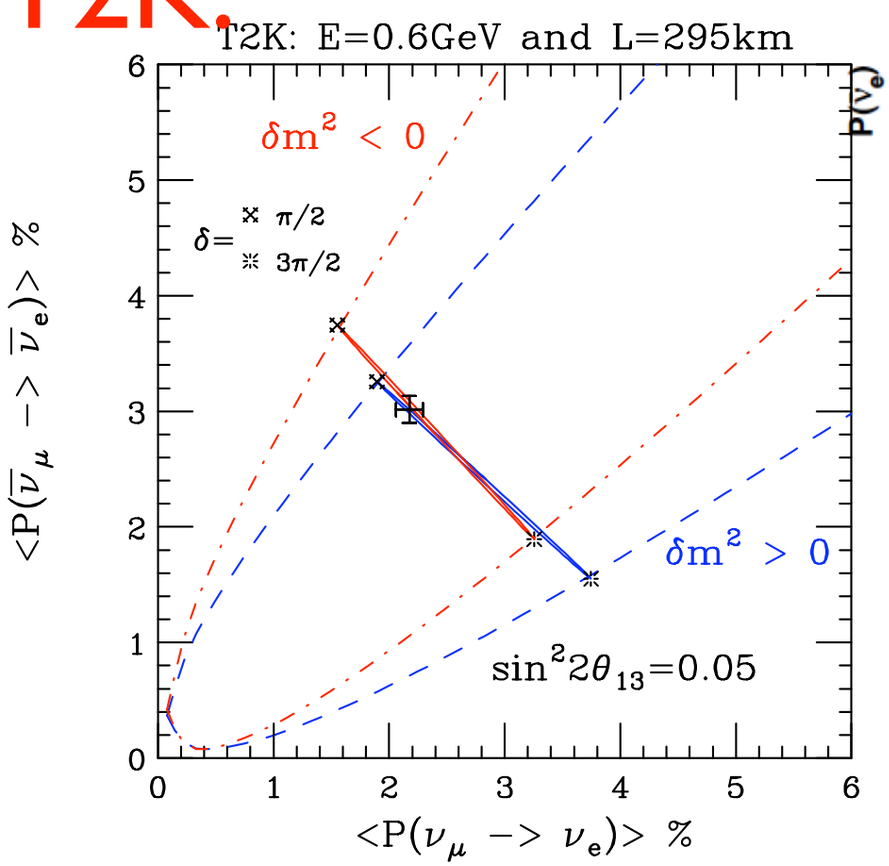
1st Oscillation Maxima:

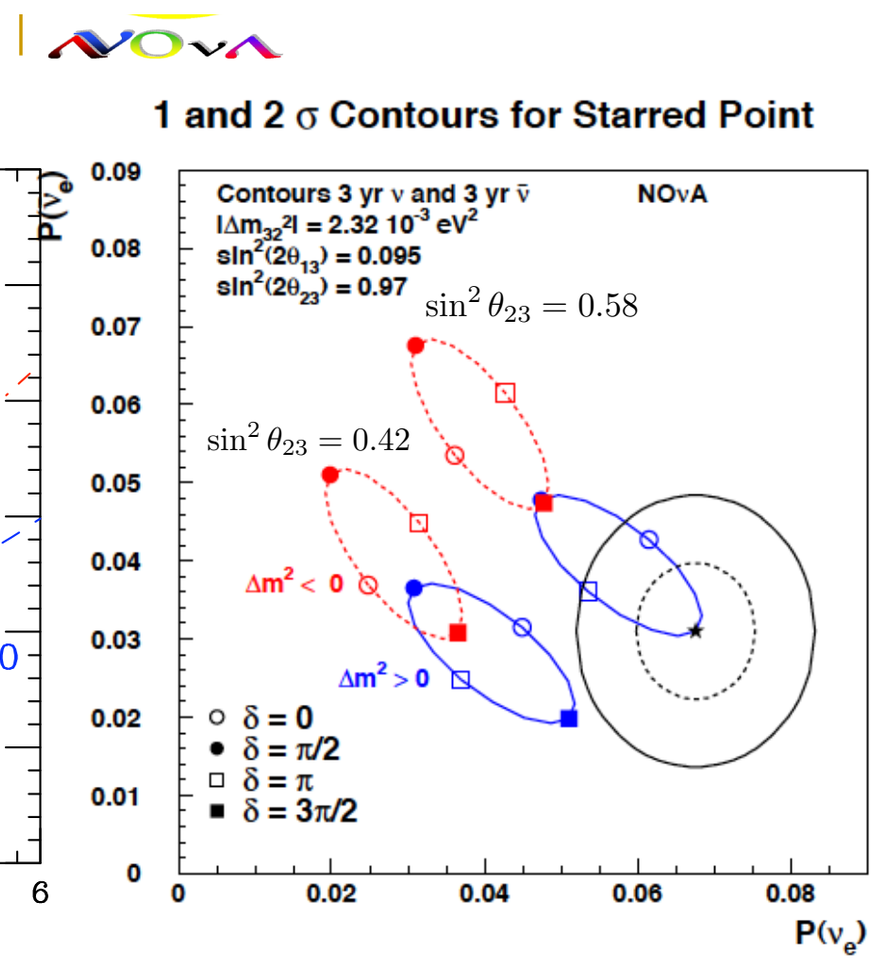
- Near 1st Oscillation Maximum: $\Delta_{31} \approx \pi/2$

T2K, NOνA and T2HyperK using Off Axis beams

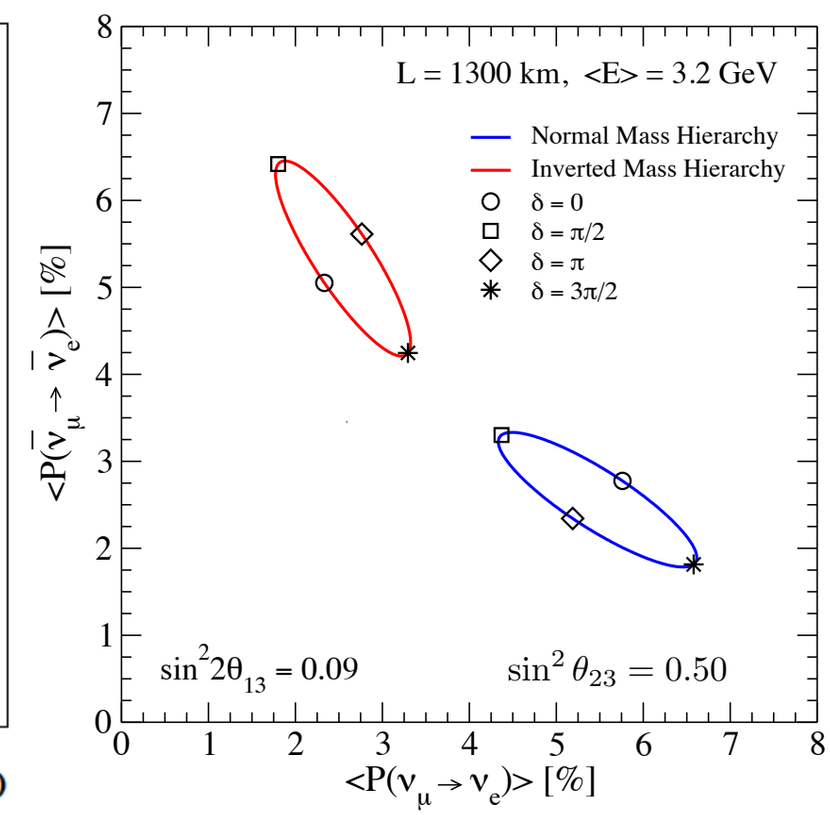
LBNE (1300km) and T2Okinoshima (658km) broad band beams

T2K:





LBNE:
@ same L/E as NOvA

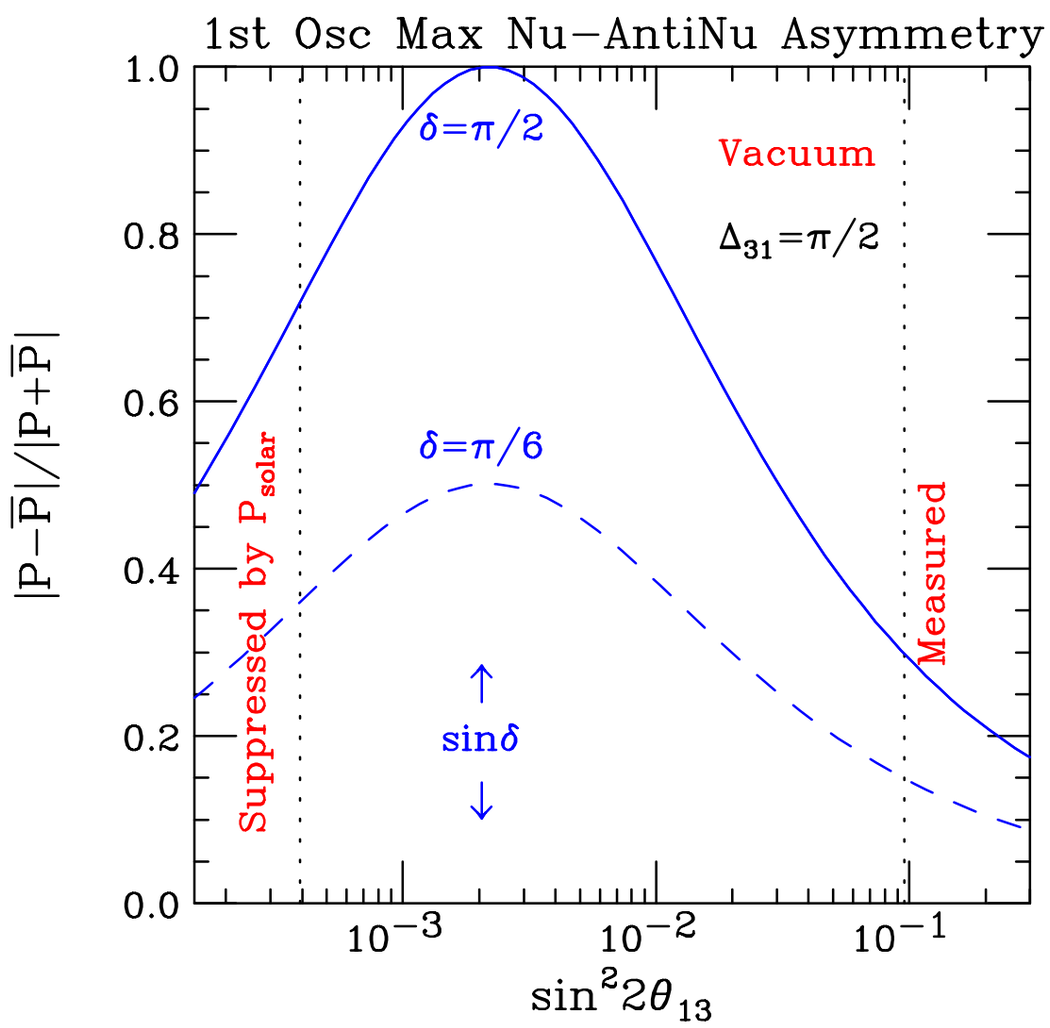


CPV & Neutrino Anti-Neutrino Asymmetry:

In Vacuum, at 1st Oscillation Maximum:

$$A_{vac} \equiv \frac{|P-\bar{P}|}{|P+\bar{P}|} \approx \frac{1}{11}\frac{\sin 2\theta_{13}\sin\delta}{(\sin^2 2\theta_{13}+0.002)} = 0.3\ \sin\delta$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ranges is between $\frac{1}{2}$ and 2 times $P(\nu_\mu \to \nu_e)$!!!

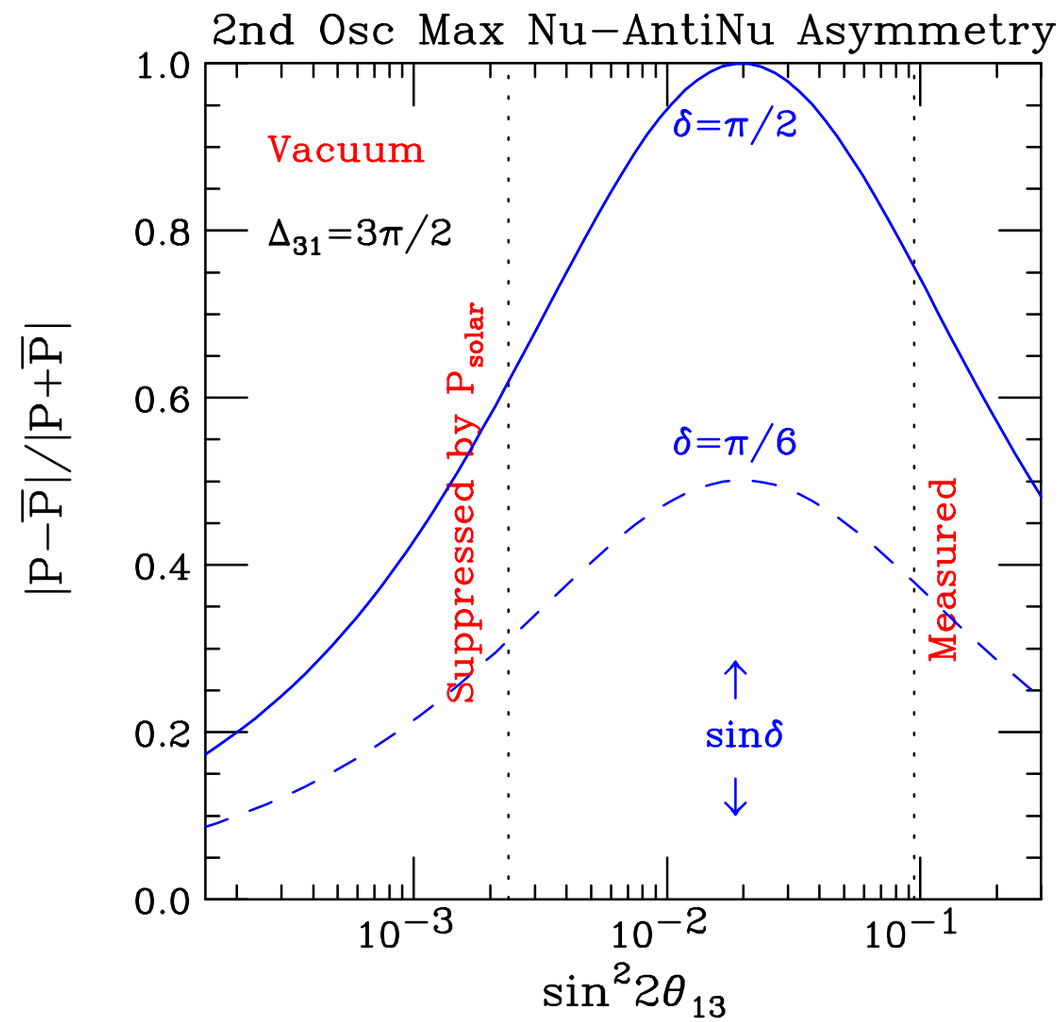


2nd Oscillation Max:

ESS to Garpenburg (540km)

$$A_{vac} \approx 0.75 \sin\delta$$

$$A_{vac}(2^{nd}\ \mathrm{OM}) \approx 2.5\ \ A_{vac}(1^{st}\ \mathrm{OM})$$



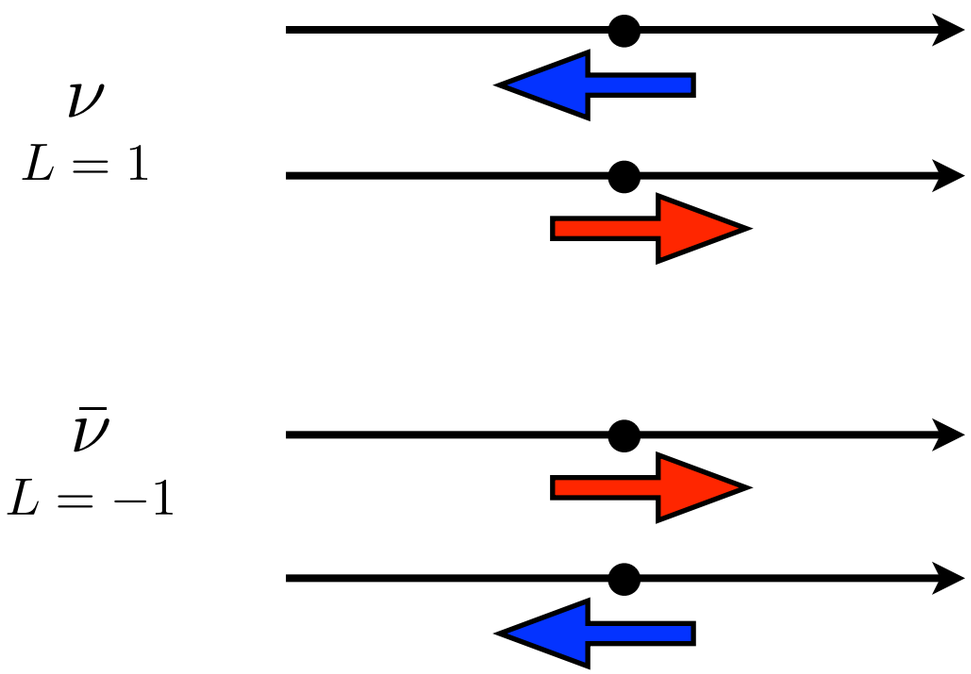
(9/11 of 3)

Appearance Probabilities more dynamic near 2nd Osc. Max. than 1st. OM

Majorana ν Dirac Neutrinos:

Dirac v Majorana

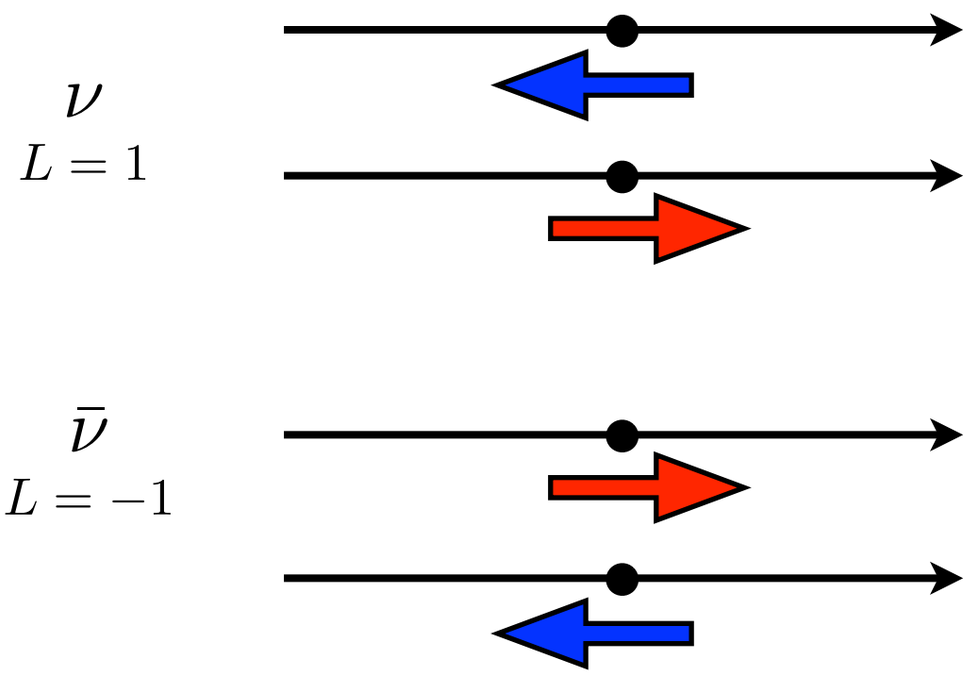
Dirac



helicity	l^-	l^+
L	1	0
R	$(\frac{m_\nu}{E})^2$	0
R	0	1
L	0	$(\frac{m_\nu}{E})^2$

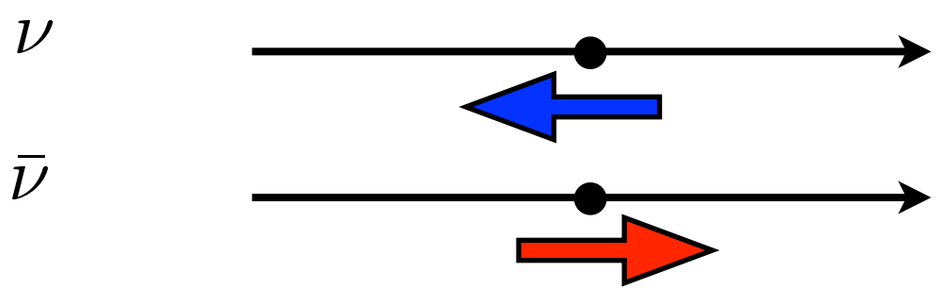
Dirac v Majorana

Dirac



helicity	l^-	l^+
L	1	0
R	$(\frac{m_\nu}{E})^2$	0
R	0	1
L	0	$(\frac{m_\nu}{E})^2$

Majorana



helicity	l^-	l^+
L	1	$(\frac{m_\nu}{E})^2$
R	$(\frac{m_\nu}{E})^2$	1

$$\boldsymbol{\nu = \bar{\nu}}$$

$$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$$

Fermion Mass

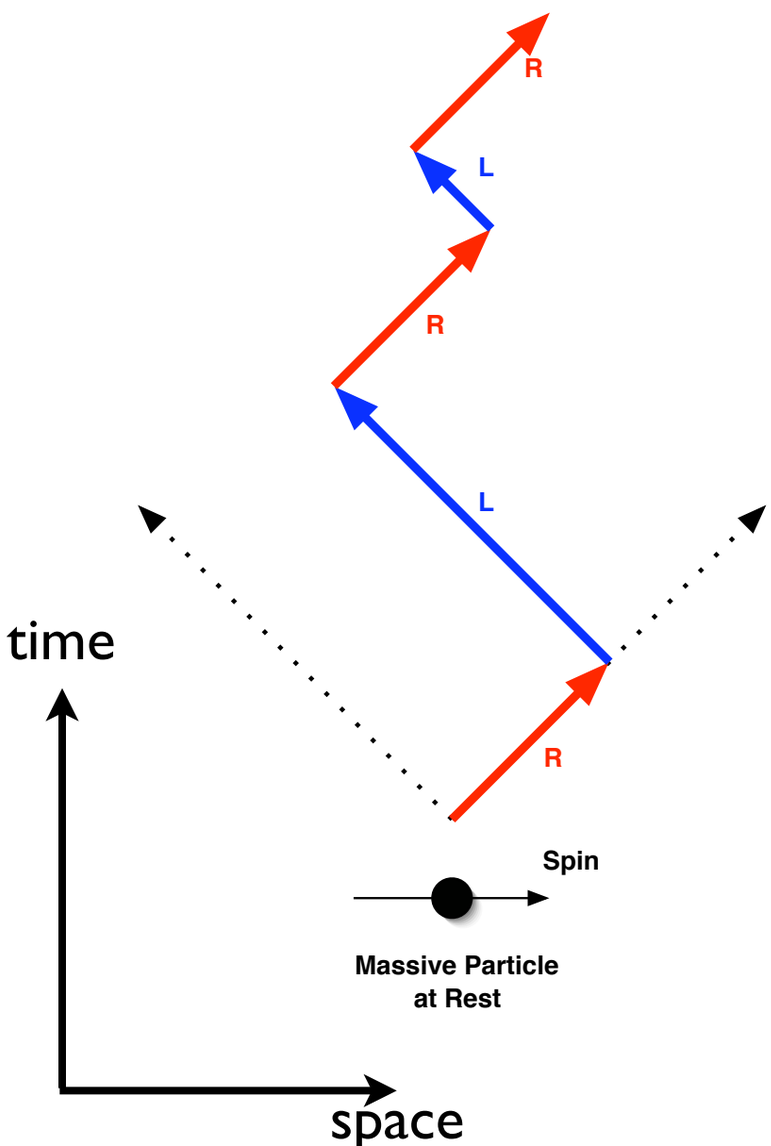
(Neutrino Mass)

Mass is a coupling between the
RIGHT and the LEFT
components of the Fermion Field.

Fermion Mass

(Neutrino Mass)

Mass is a coupling between the RIGHT and the LEFT components of the Fermion Field.



Fermion Mass

(Neutrino Mass)

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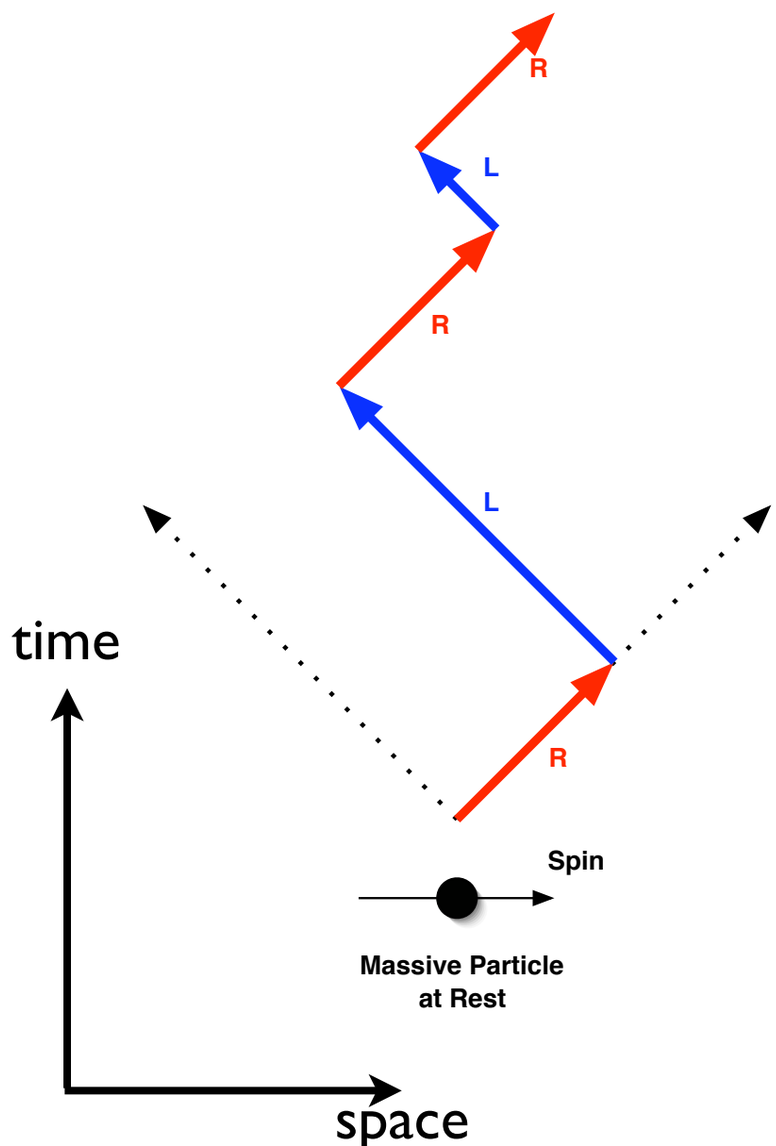


$$P^2 = M^2, \quad S^2 = -1, \quad \text{and} \quad P \cdot S = 0$$

$$\text{then} \quad (P \pm MS)^2 = 0$$

Dirac spinor:

$$U(P,S) = \frac{(1+\gamma_5)}{2}\, U\left(\frac{P+MS}{2}\right) + e^{i\Omega}\, \frac{(1-\gamma_5)}{2}\, U\left(\frac{P-MS}{2}\right)$$

Right massless spinor Left massless spinor

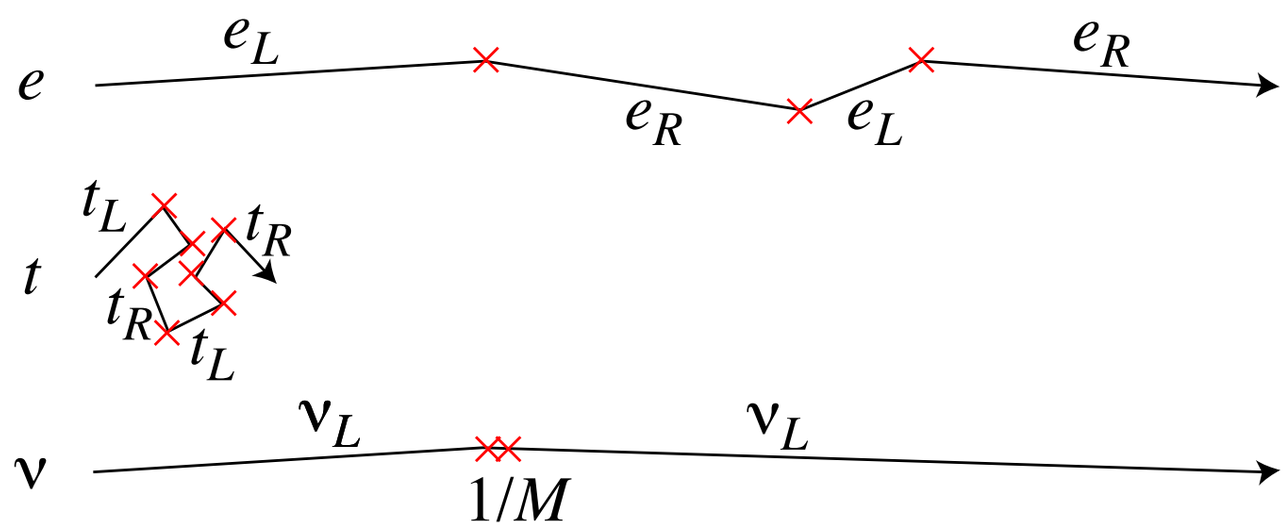
for massless particles chirality and helicity are the identical

How do the Observed Neutrinos Coupling to the Higgs ?

Mass is a coupling between the
RIGHT and the LEFT
components of the Fermion Field.

Weinberg '79

Dirac: $\bar{L}H\nu_R$ OR Majorana: $\frac{1}{M}(\bar{L}H)^2$



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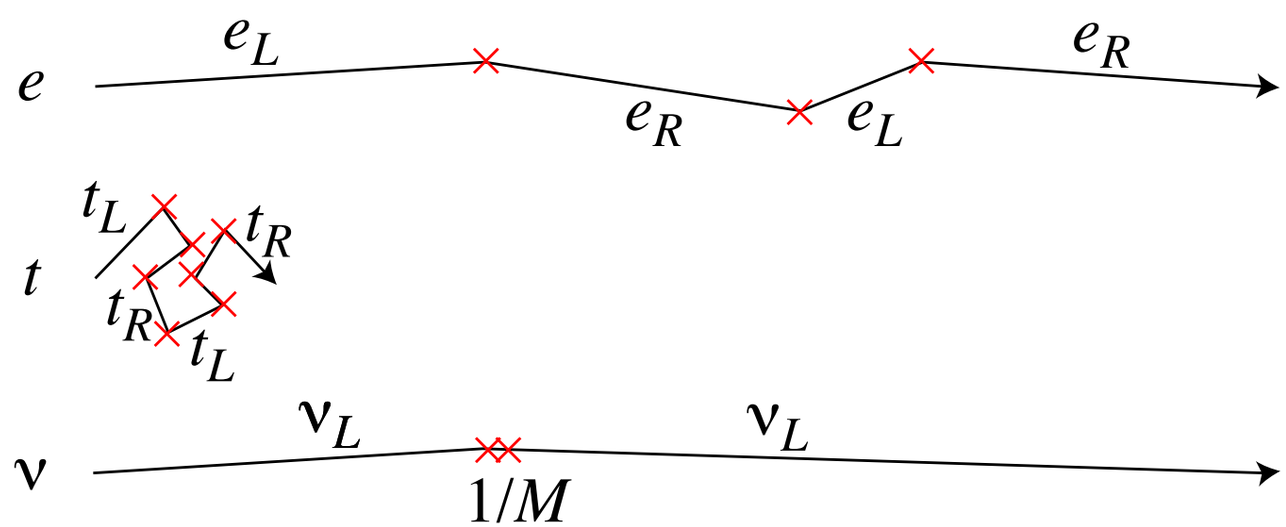
Lepton Number Conservation v. Lepton Number Violation



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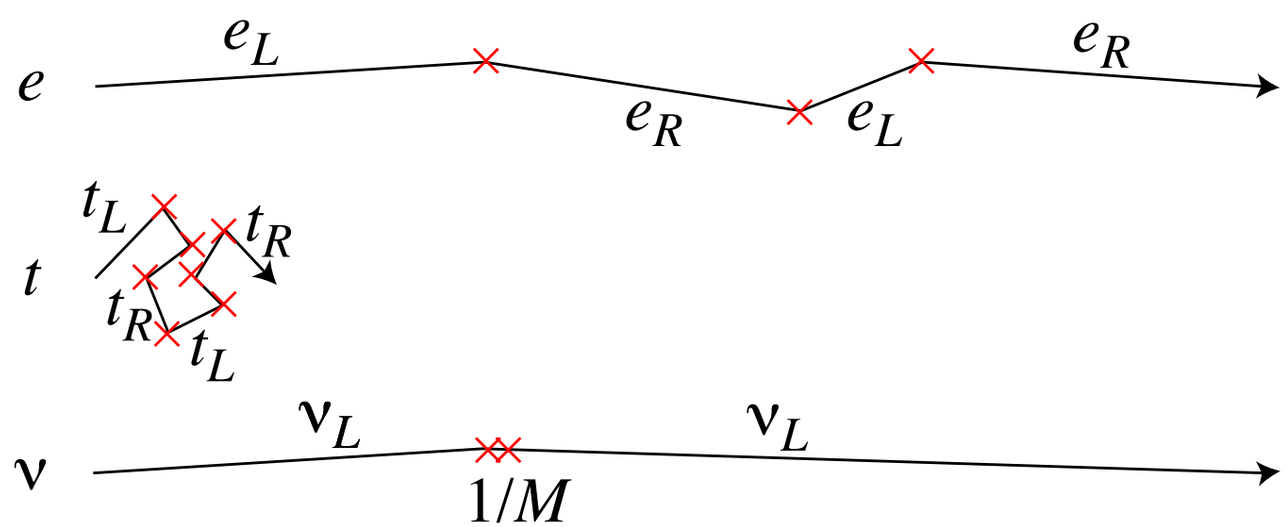
Lepton Number Conservation **v.** **Lepton Number Violation**



$$\Gamma_{\rm tree}(H \to \nu_i\bar{\nu}_i) \approx \left(\frac{m_{\nu i}}{m_b}\right)^2 \Gamma(H \to b\bar{b})$$

Invisible & Impossibly tiny !!!

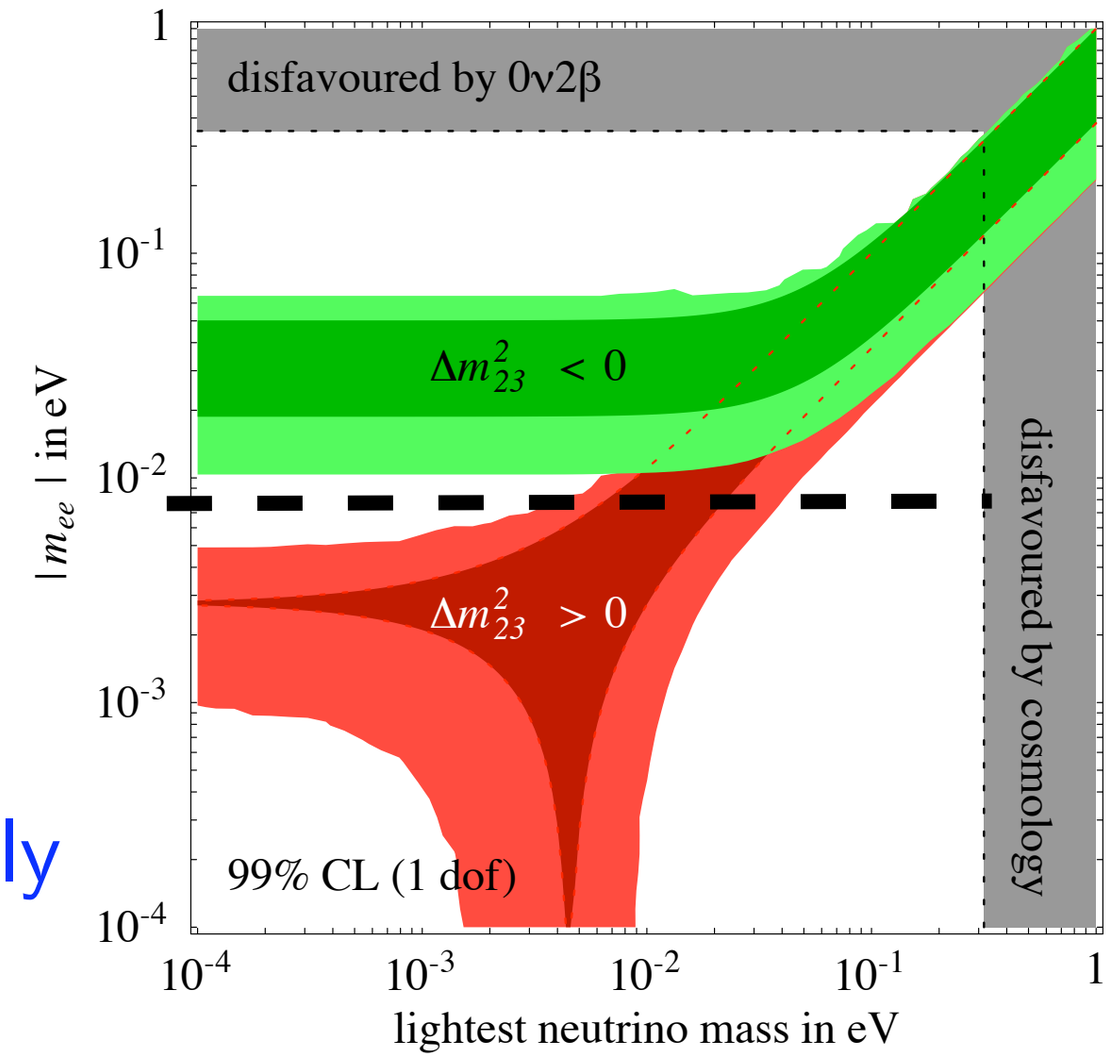
(swamped by loop processes!!)

Neutrinoless double beta decay

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

dividing point $m_{\beta\beta} \approx 10 meV$ $\Rightarrow\Rightarrow$



Signal below $\sim$ 10 meV would imply Majorana and Normal Hierarchy!

SUMMARY:

- To Be Majorana or Not To Be Majorana?

- We know $(|U_{e2}|^2,\ |U_{e3}|^2,\ |U_{\mu 3}|^2)$ with precision of (5,10,15)% but have little information on the other 6 elements of the PMNS matrix without assuming Unitarity.

- Stringent tests of the νSM Paradigm, determining the Mass Hierarchy & measuring CPV are the next steps. Unitarity Triangle? Tau's?

- Are there lite Sterile neutrinos?

Can we exclude $|U_{e4}|^2$ and $|U_{\mu 4}|^2 > 0.01$, say, for $\delta m^2 \sim 1eV^2$

- Solving the Neutrino Masses and Mixing pattern is difficult challenge for Theory!