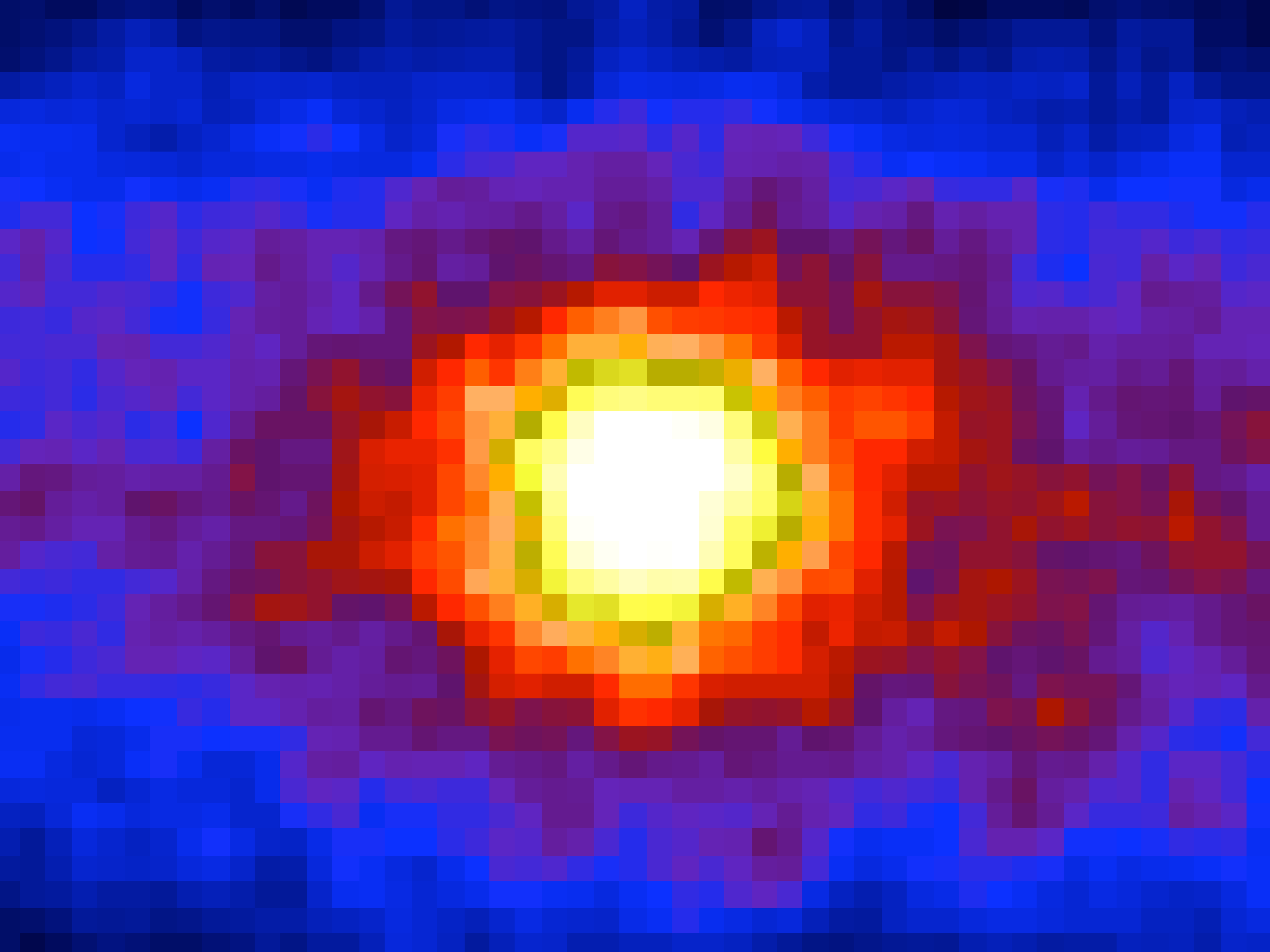


Neutrinos:

In and Out of the Standard Model:

Stephen Parke
Fermilab

- Standard Model Neutrinos
- Flavor Change & Neutrino Mass
- Implications

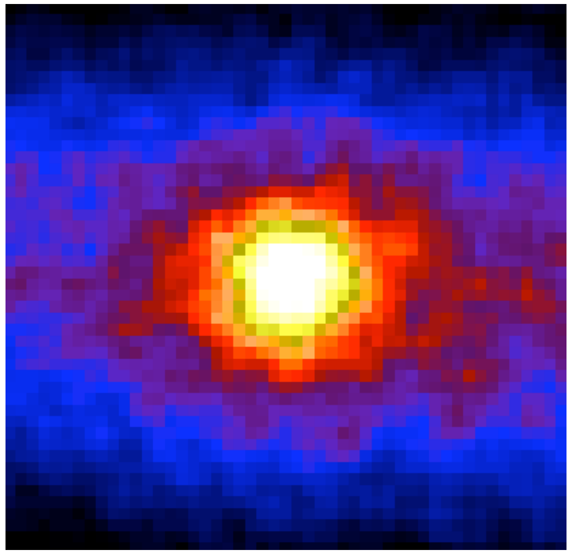
Neutrino Tasting !

Neutron Decay:

$$n \to p + e^- + \bar{\nu}_e$$

Solar Engine:

$$p + p \to d + e^+ + \nu_e$$



SuperNova Cooling:

$$e^+ + e^- \to \nu + \bar{\nu}$$

Leptogenesis:

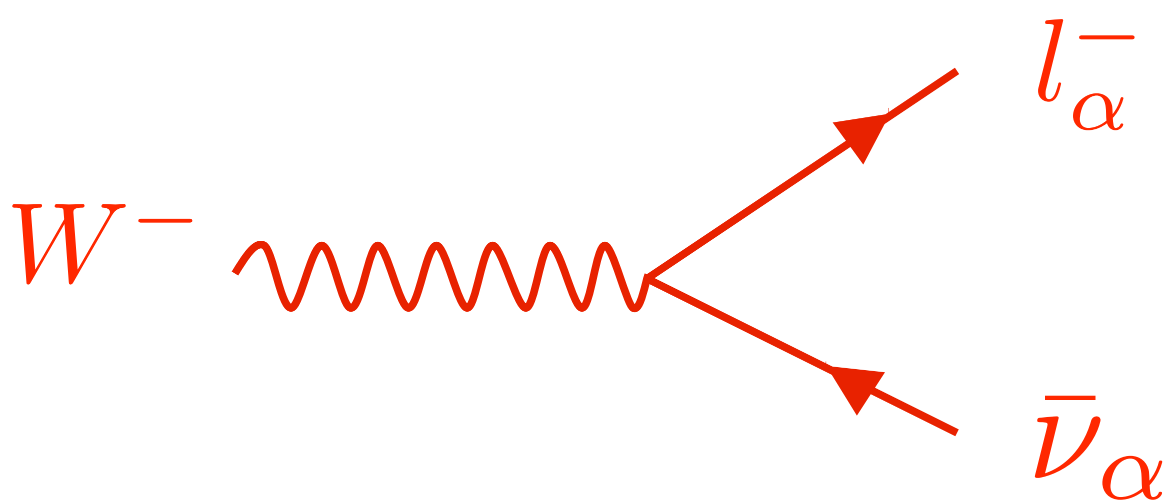
???

Interactions:

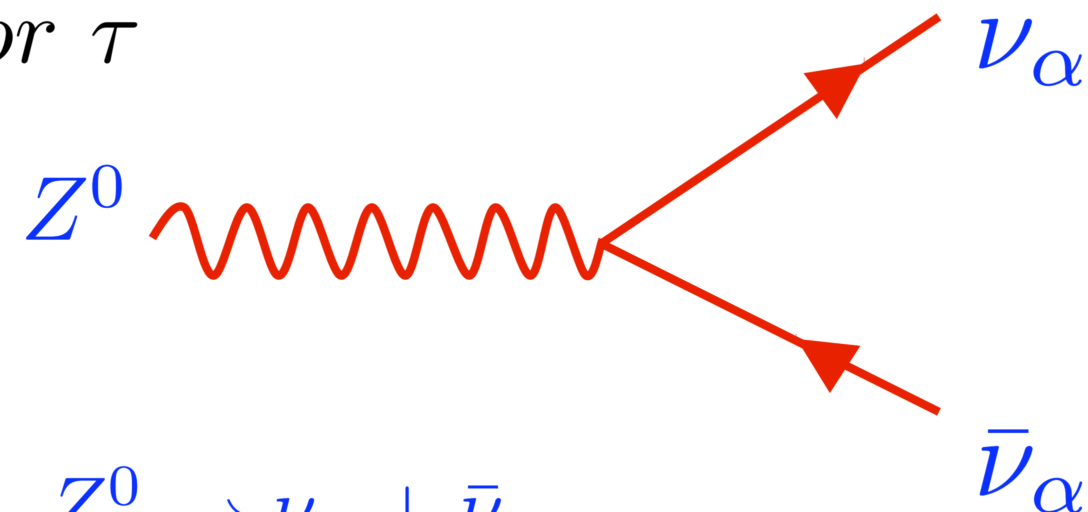
Charge Current (CC)

Neutral Current (NC)

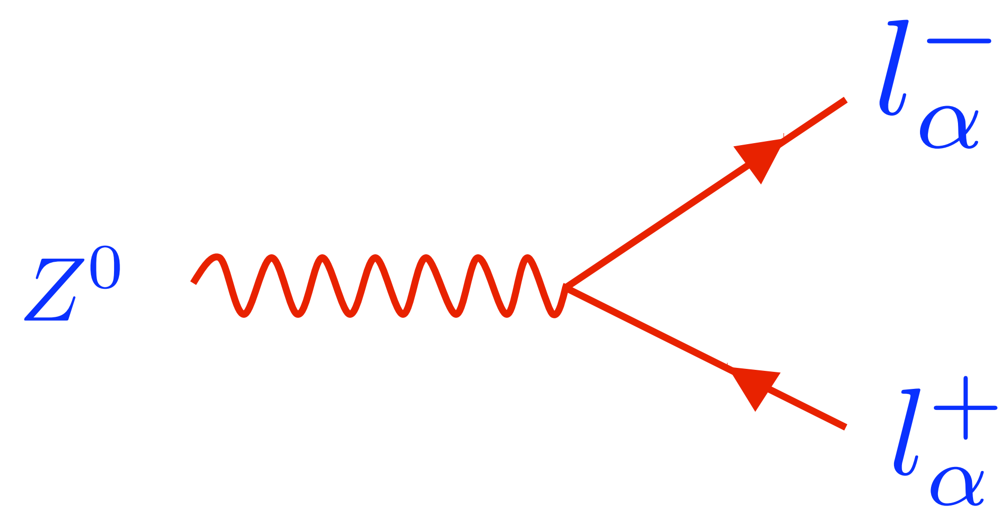
$$\alpha = e, \mu, \ or \ \tau$$



$$W^- \rightarrow l_\alpha^- + \bar{\nu}_\alpha$$



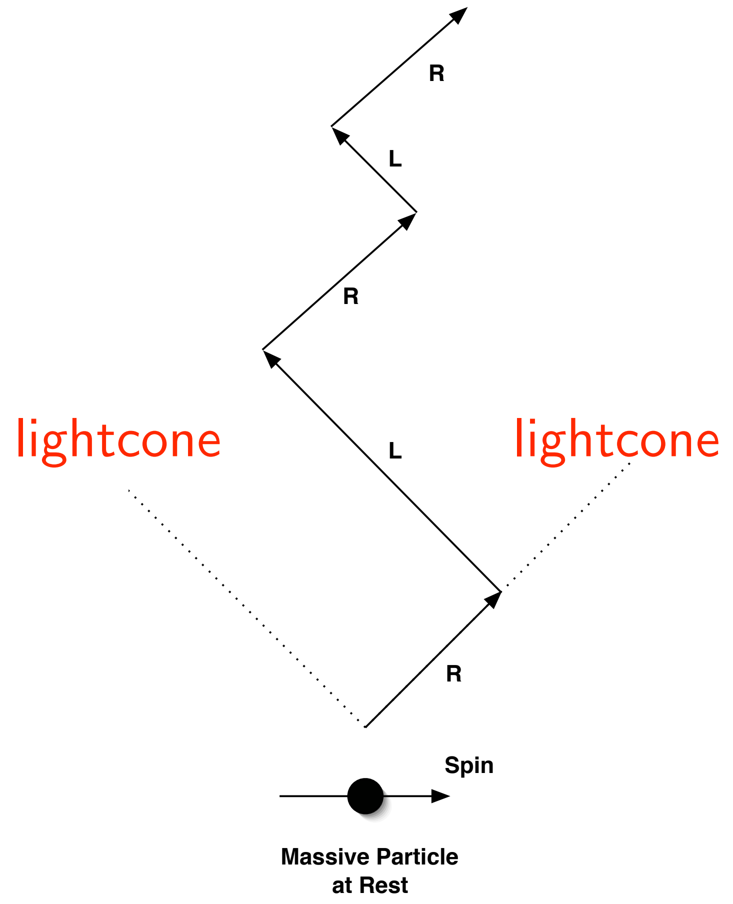
$$Z^0 \rightarrow \nu_\alpha + \bar{\nu}_\alpha$$



$$Z^0 \rightarrow l_\alpha^- + l_\alpha^+$$

ν Left Handed (spin oppose motion)

$\bar{\nu}$ Right Handed (spin along motion)



Absence of ν_R

forbids such a mass term (dim 4)

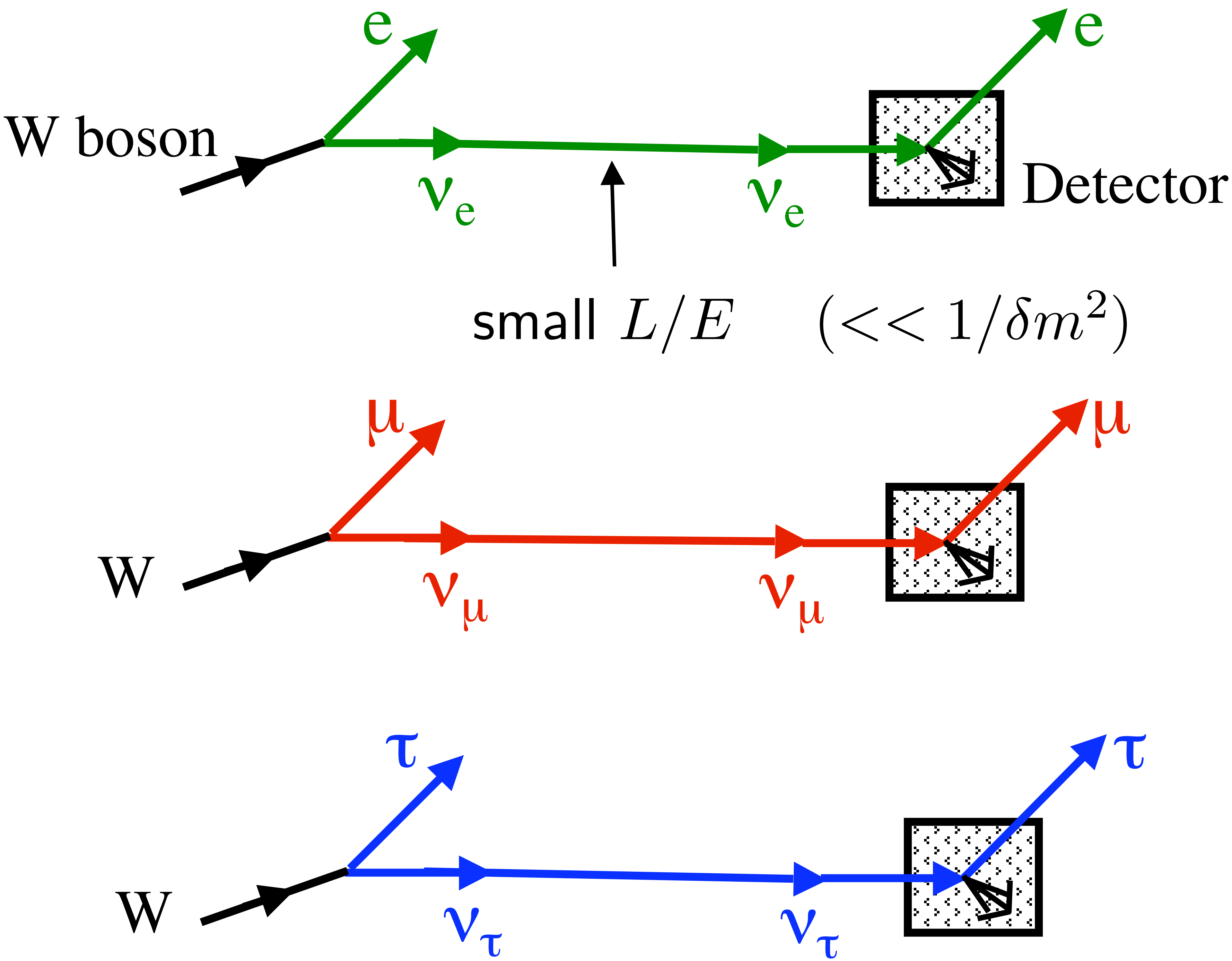
for the Neutrino

Therefore in the SM neutrinos are massless

and hence travel at speed of light.

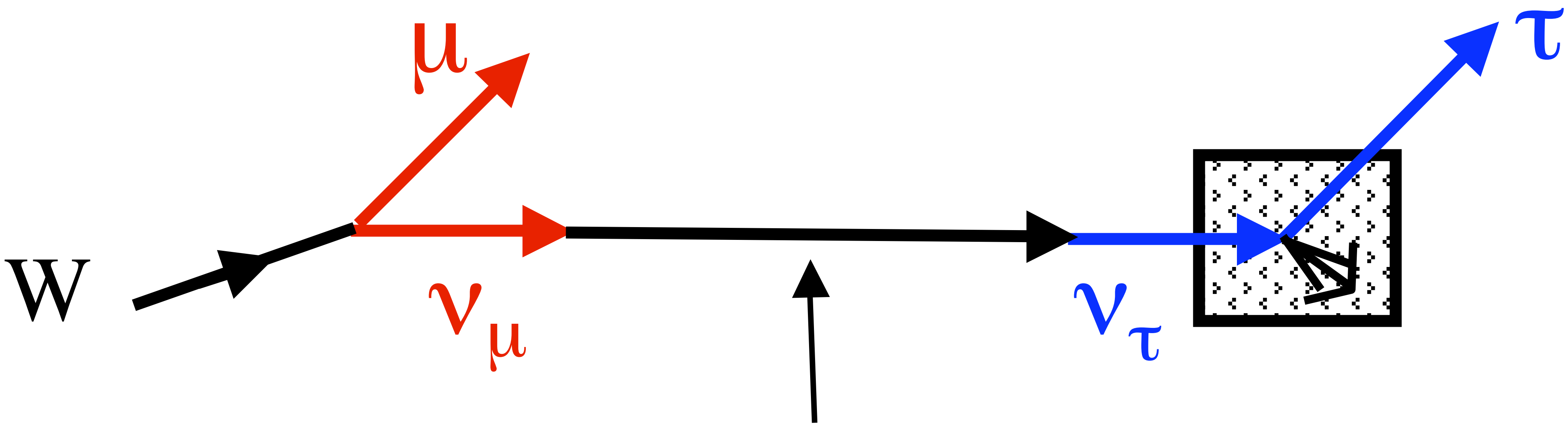
$\Rightarrow$ No Change

Observed



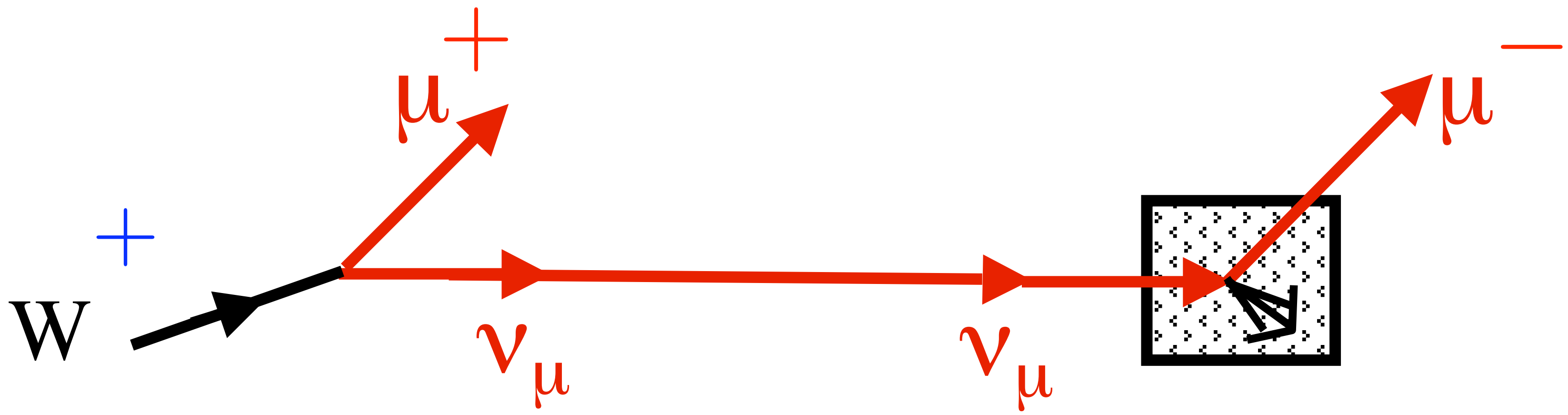
e
e
W boson
ν_e
ν_e
Detector
small L/E $(<< 1/\delta m^2)$
μ
μ
W
ν_μ
ν_μ
τ
τ
W
ν_τ
ν_τ

Not Observed



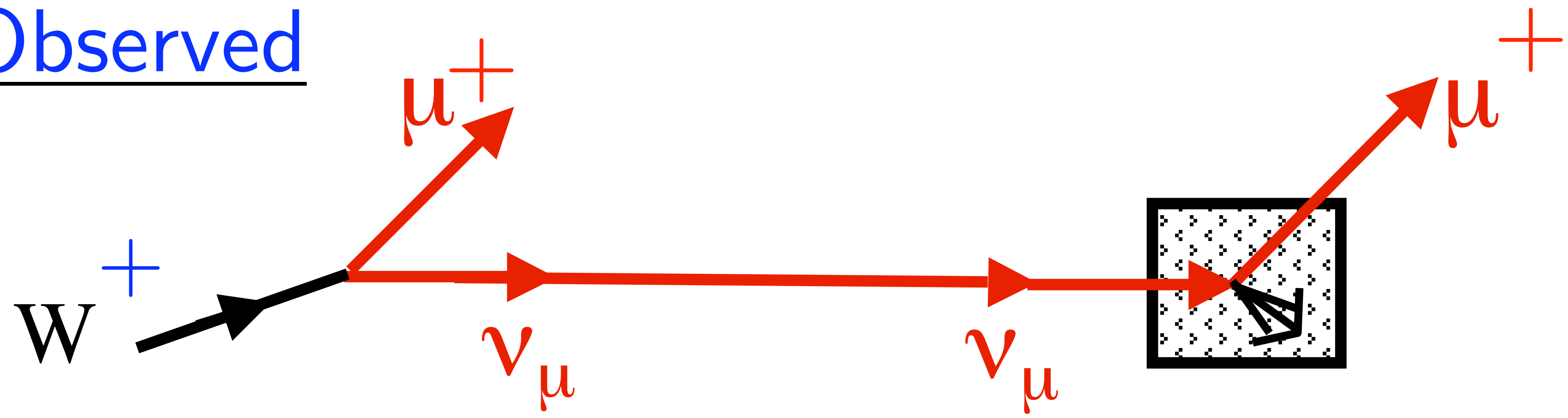
small $L/E \quad (<< 1/\delta m^2)$

Observed



neutrino beam (not anti-neutrino beam)

Not Observed

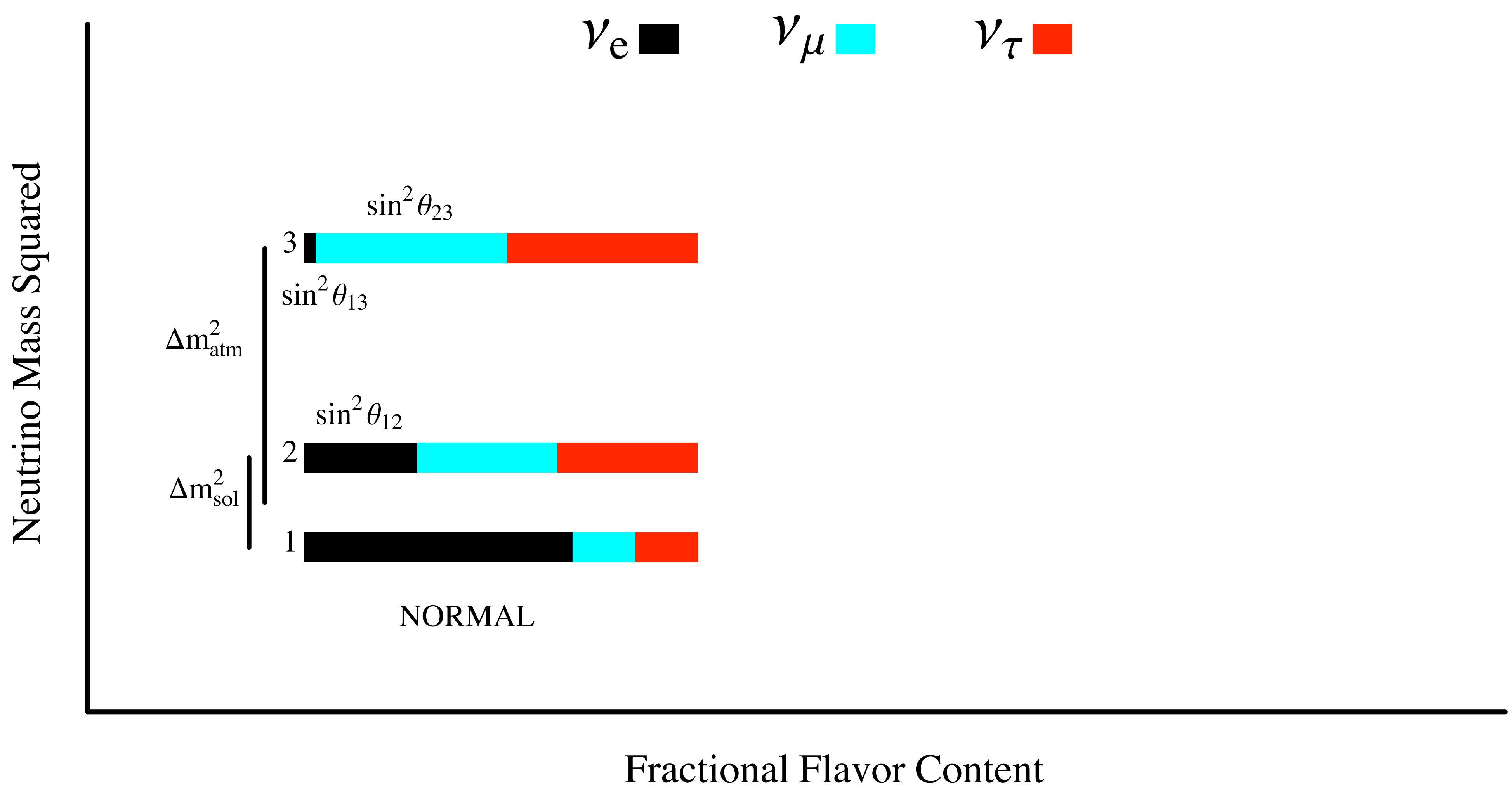


large E ($>> m_\nu$)

Neutrino Flavor Change

implies

Neutrino Mass



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

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

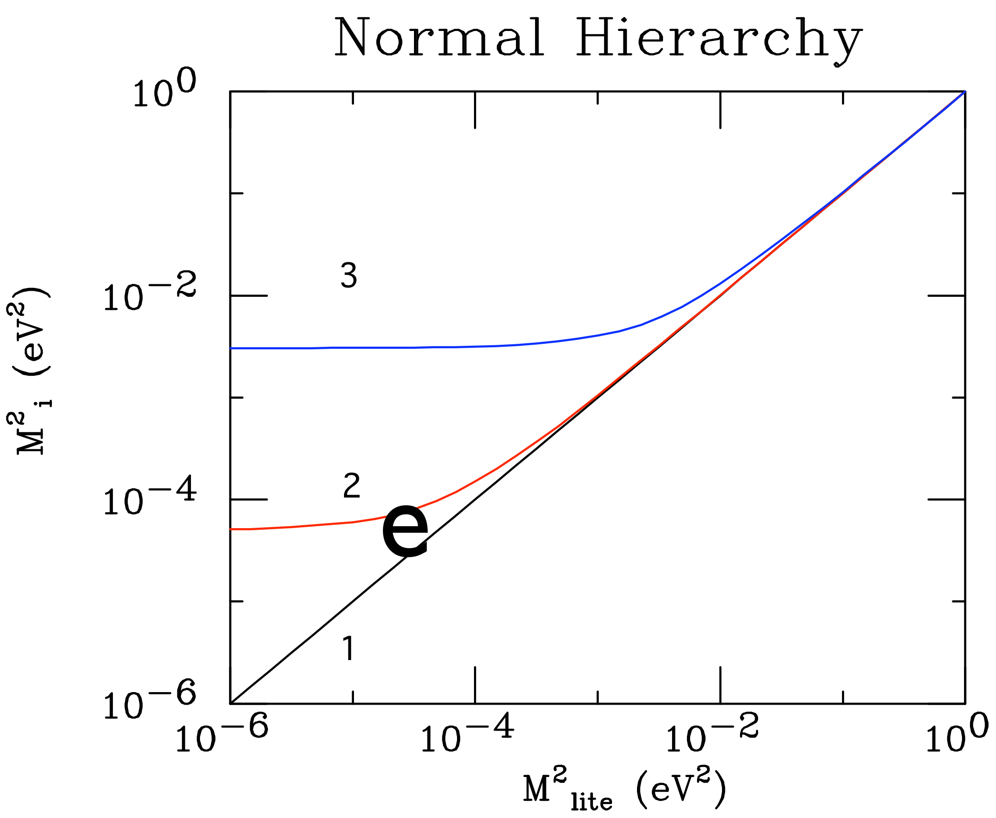
$$\mathsf{L/E = 15\ km/MeV}$$

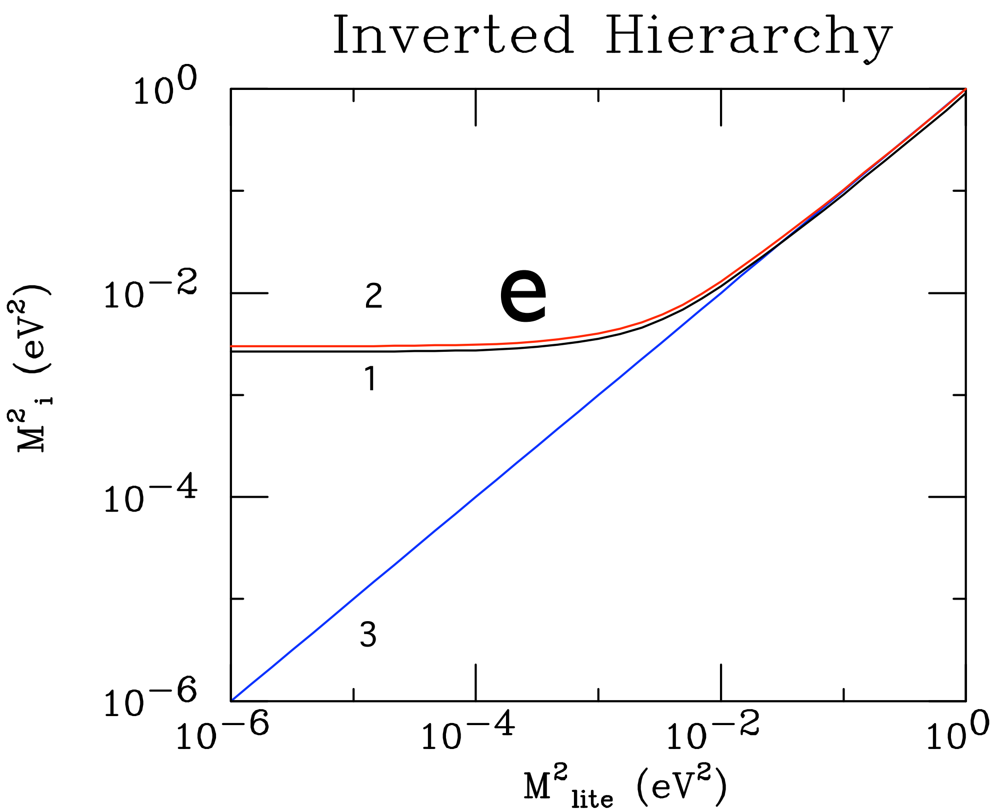
$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2$$

$$L/E = 500\ km/GeV$$

$$\sin^2 2\theta_{atm} > 0.92 \qquad \Rightarrow 0.35 < \sin^2\theta_{atm} < 0.65$$

Masses:





States 1 and 2 are ν_e rich.

NEUTRINO OSCILLATIONS:

Two Flavors

flavor eigenstates $\neq$ mass eigenestates

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

W's produce ν_μ and/or ν_τ's

but ν_1 and ν_2 are the states

that change by a phase over time, mass eigenstates.

$$|\nu_j\rangle \rightarrow e^{-ip_j \cdot x}|\nu_j\rangle \qquad p_j^2 = m_j^2$$

$\alpha, \beta \ldots$ flavor index $\qquad$ $i, j \ldots$ mass index

Production:

$$|\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Propogation:

$$\cos\theta e^{-ip_1\cdot x}|\nu_1\rangle + \sin\theta e^{-ip_2\cdot x}|\nu_2\rangle$$

Detection:

$$|\nu_1\rangle = \cos\theta|\nu_\mu\rangle - \sin\theta|\nu_\tau\rangle$$

$$|\nu_2\rangle = \sin\theta|\nu_\mu\rangle + \cos\theta|\nu_\tau\rangle$$

$$P(\nu_\mu \to \nu_\tau) = |\cos\theta(e^{-ip_1\cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2\cdot x})\cos\theta|^2$$

Same E, therefore $p_j = \sqrt{E^2 - m_j^2} \approx E - \frac{m_j^2}{2E}$

$$e^{-ip_j\cdot x} = e^{-iEt}e^{-ip_jL} \approx e^{-i(Et-EL)} \quad e^{-im_j^2L/2E}$$

Appearance:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

Disappearance:

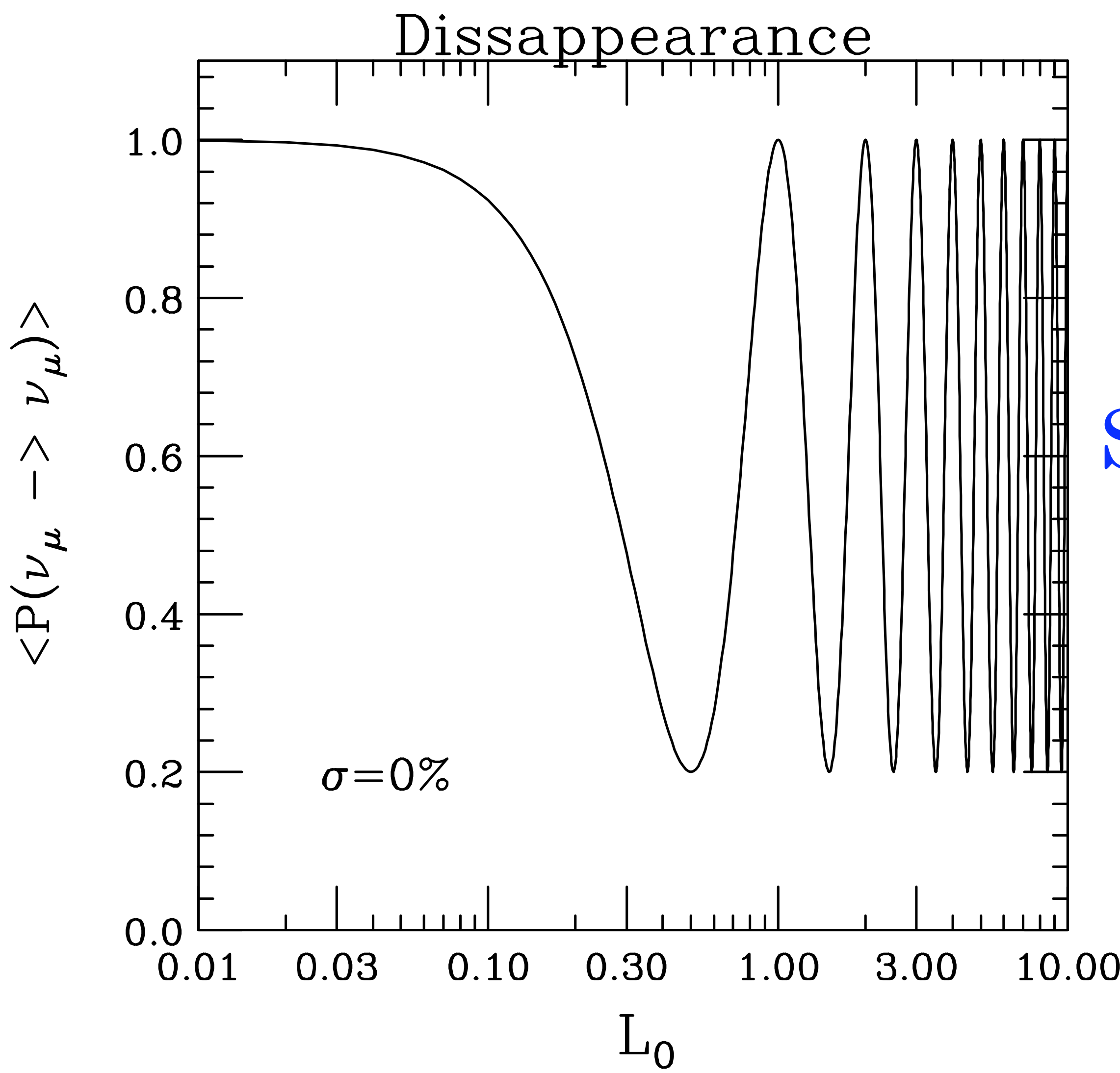
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

$\delta m^2 = m_2^2 - m_1^2$ and $\frac{\delta m^2 L}{4E} \equiv \Delta$ kinematic phase:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

small L/E: $P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \; (\frac{\delta m^2 L}{4E})^2$

Fixed E_ν



Amplitude of Oscillation

$\Uparrow$

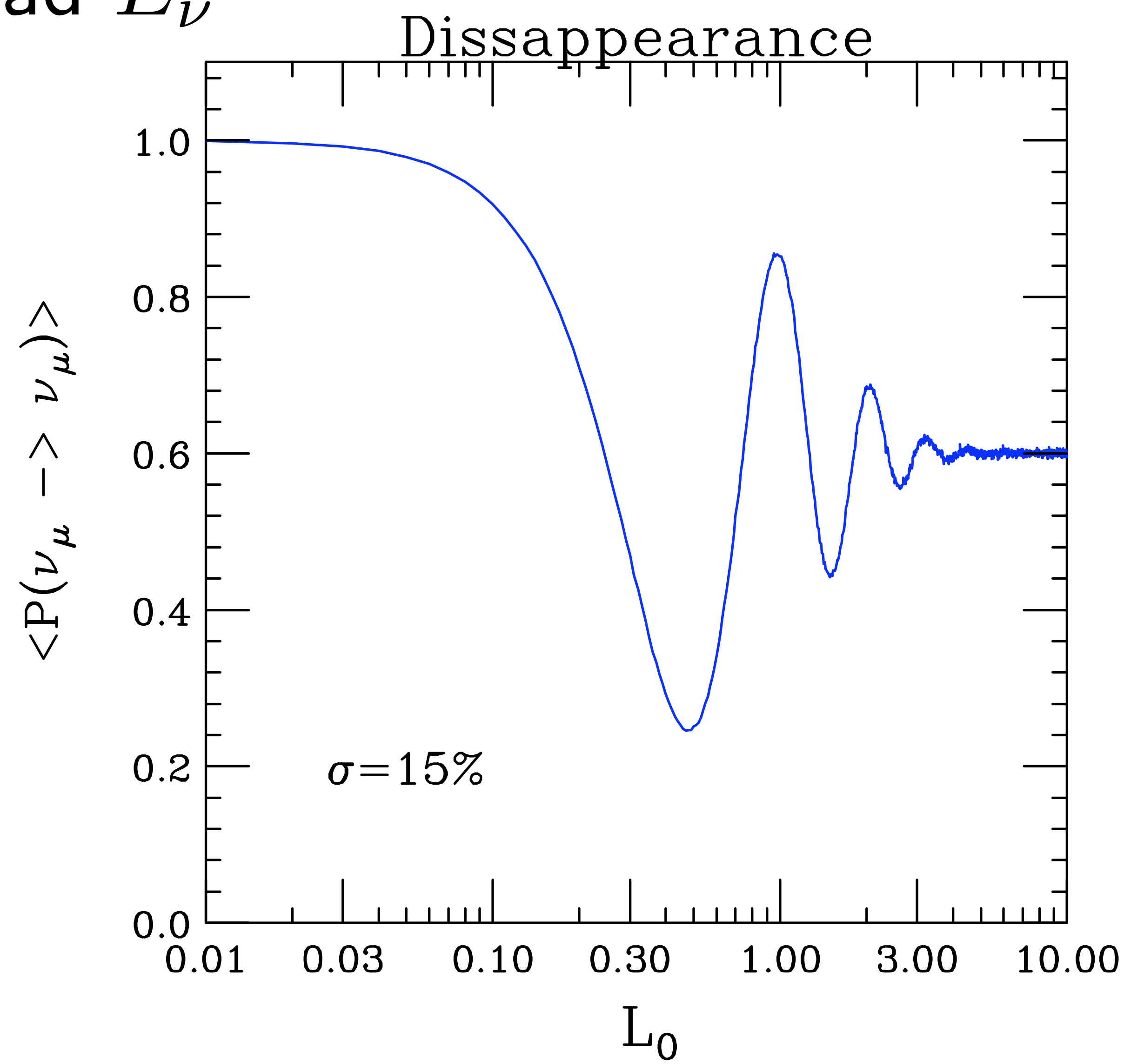
$\sin^2 2\theta$

$\Downarrow$

Oscillation Length $L_0 = 4\pi E/\delta m^2$

$$\langle P(\nu_\mu \to \nu_\mu)\rangle = 1 - \sin^2 2\theta \left\langle \sin^2 \frac{\delta m^2 L}{4E} \right\rangle$$

Spread E_ν



$$1 - \sin^2 2\theta(\tfrac{1}{2}) = \cos^4\theta + \sin^4\theta$$

Understood in terms of probability

$W^+ \to \mu^+ + \nu_1$ probability $\cos^2\theta$

$W^+ \to \mu^+ + \nu_2$ probability $\sin^2\theta$

probability ν_1 contains ν_μ is $\cos^2\theta$

probability ν_2 contains ν_μ is $\sin^2\theta$

flavor

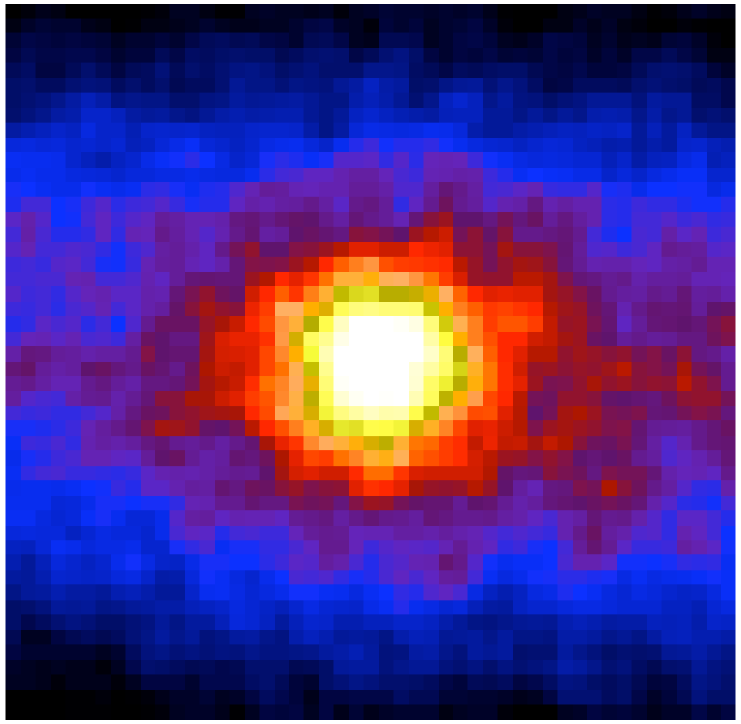
flavor oscillations

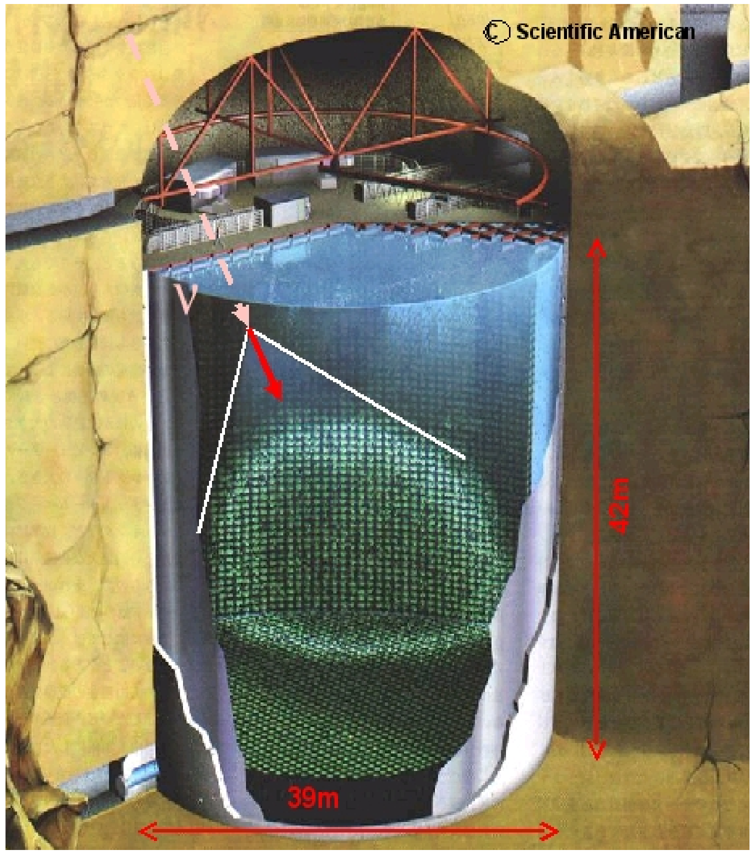
effectively incoherent
mass eigenstates

What happens to the neutrino oscillation length in the semi-classical limit, $\hbar \to 0$?

- $L_{osc} \to \infty$
- $L_{osc} \to 0$
- Other

Solar δm^2





Solar Engine:

$$4p + 2e^- \rightarrow {}^4 He + 2\nu_e + 26.7 MeV$$

$$E = mc^2$$

1 ν_e for every 13.4 MeV ($=2.1 \times 10^{-12}$ J)

$\mathcal{L}_\odot$ at earth's surface 0.13 watts/cm^2

$$\phi_\nu = \frac{0.13}{2.1 \times 10^{-12}} = 6 \times 10^{10}/cm^2/sec$$

This corresponds to an average of 2 ν's per cm^3
since they are going at speed c.

Solar Spectrum:

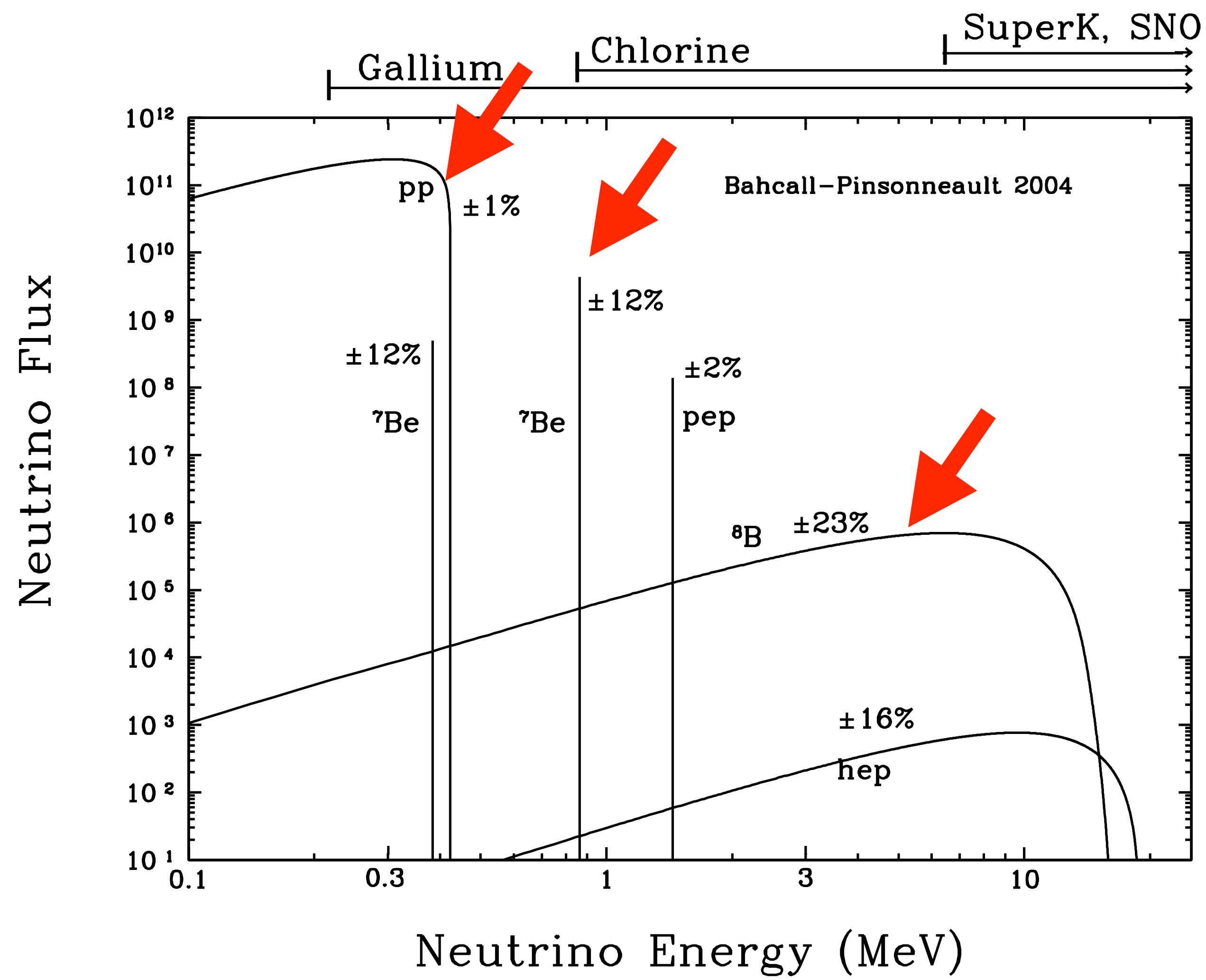


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2}\,s^{-1}$. Total theoretical uncertainties taken from column 2 of table 1 are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes (see table 1).

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

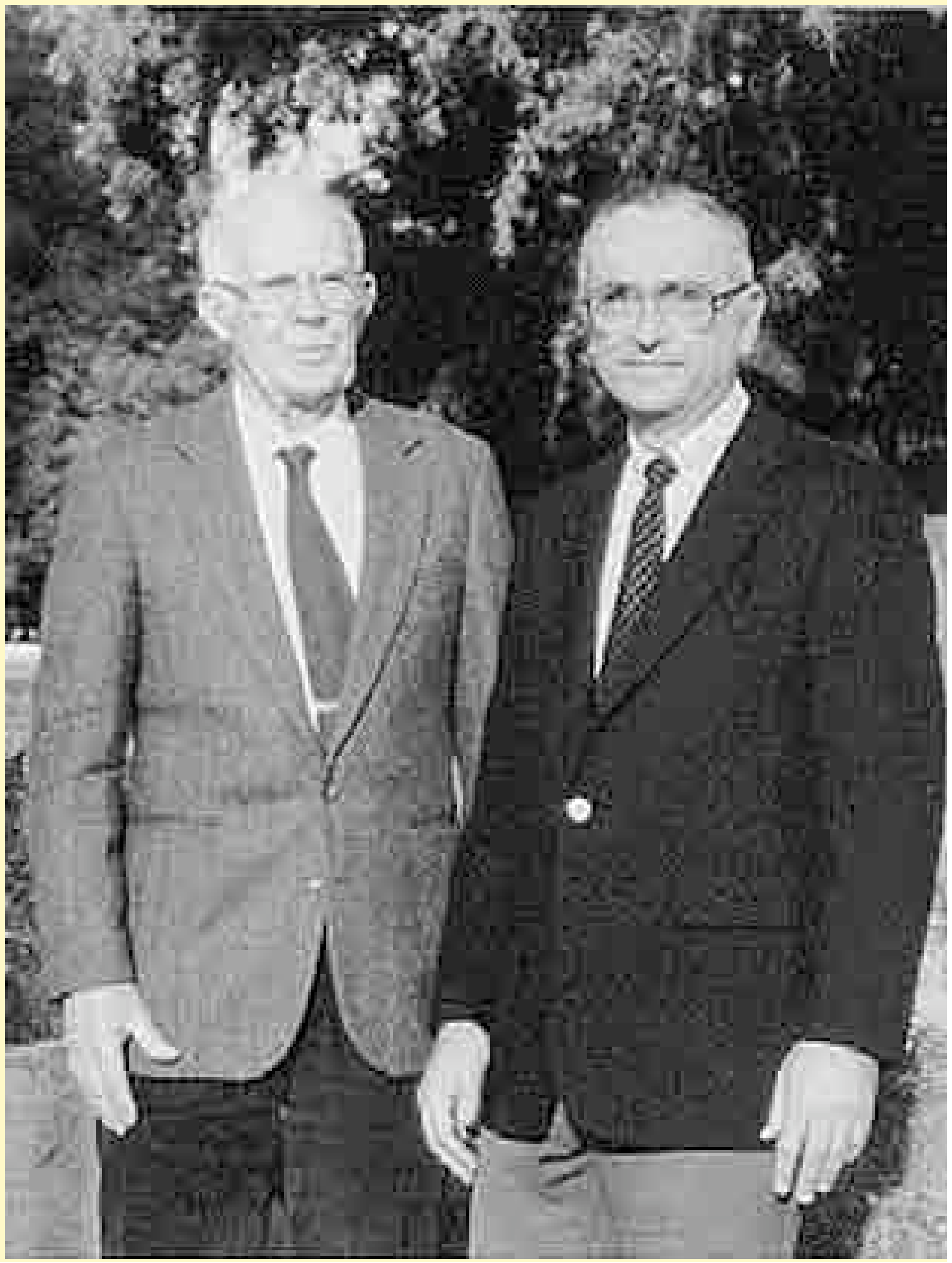
$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

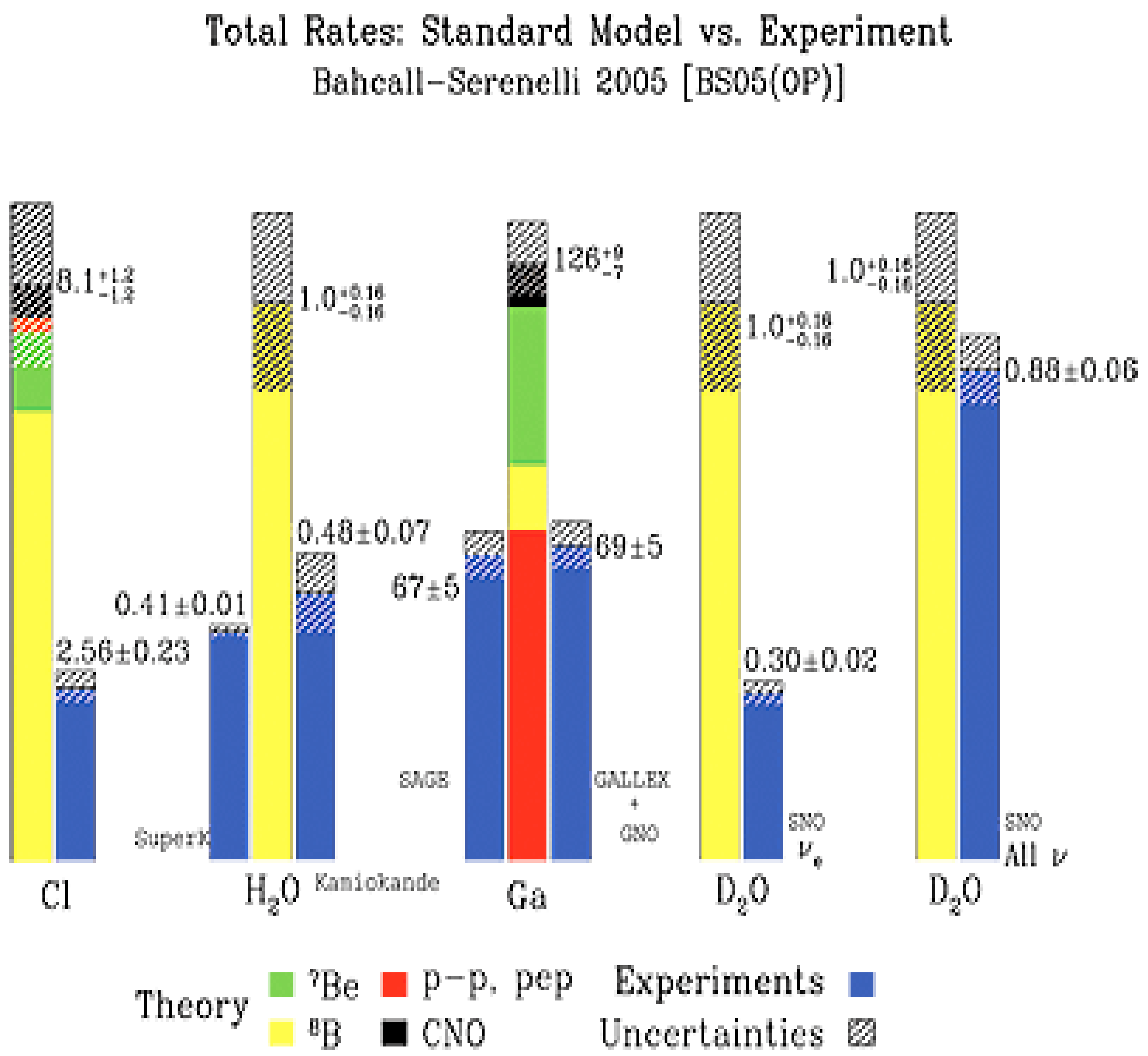
$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^{9} cm^{-2} sec^{-1}$$

$$^7Be + p \rightarrow {}^8B \rightarrow {}^8Be^* + e^- + \nu_e$$

$$\phi_{^8B} = 5.82(1 \pm 0.23) \times 10^{6} cm^{-2} sec^{-1}$$



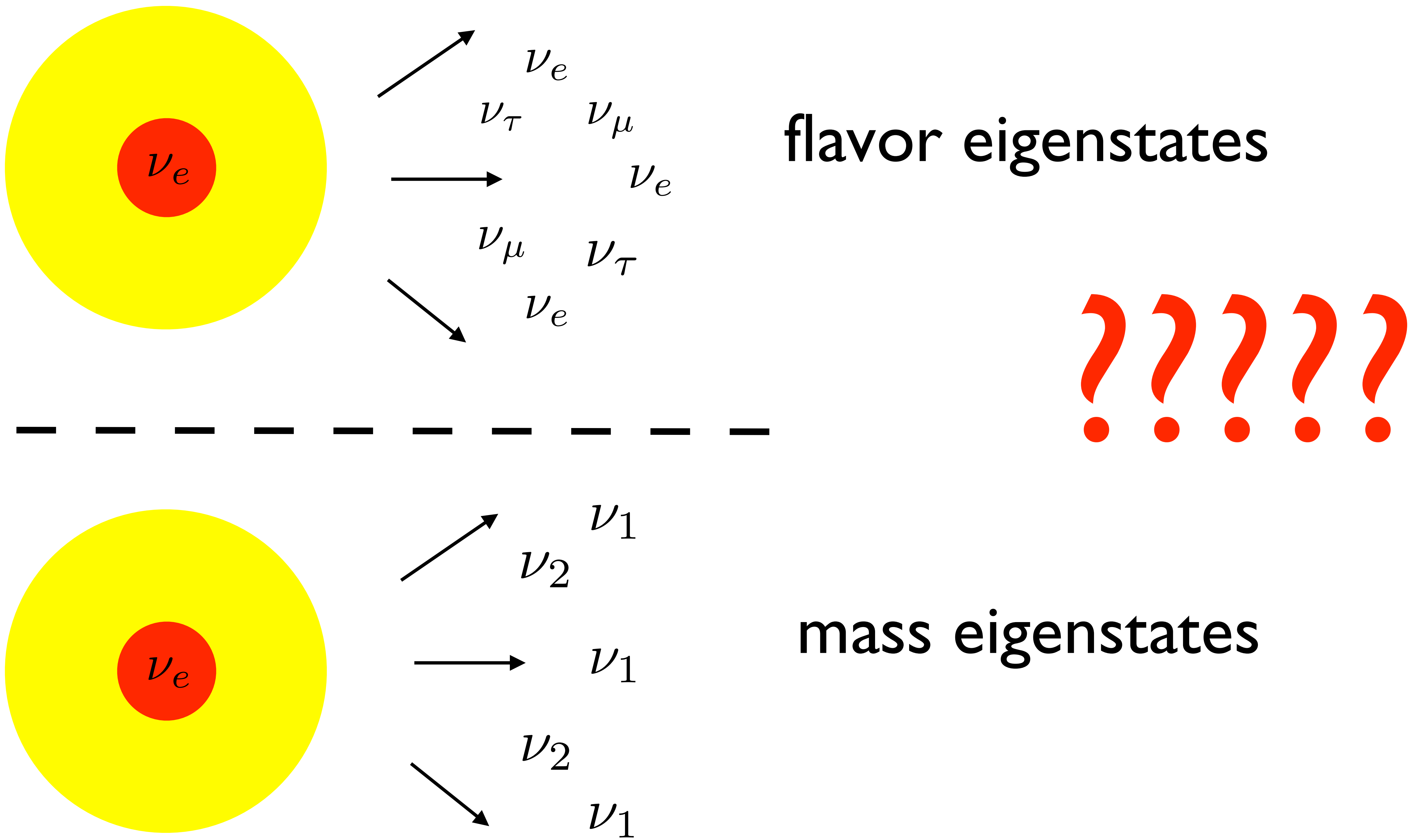
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Identical Solar Twins:



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 !!!

Vacuum ν_e Survival Probability:

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

where f_1 and f_2 are the fraction of ν_1 and ν_2 at production.

In vacuum $f_1 = \cos^2\theta_\odot$ and $f_2 = \sin^2\theta_\odot$.

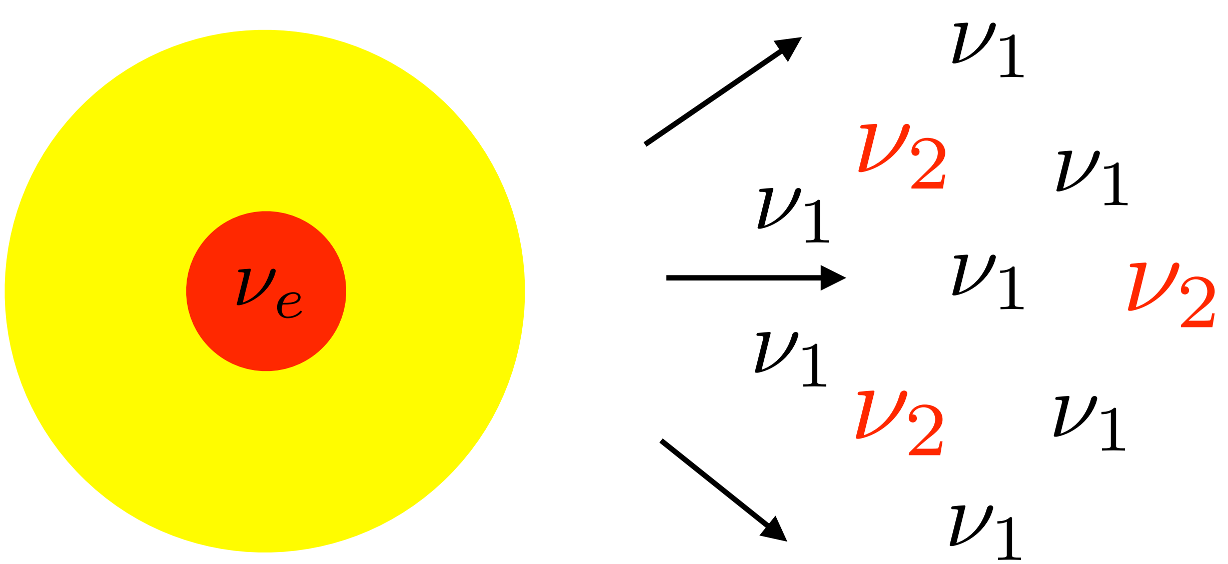
Note energy independence.

$$\langle P_{ee} \rangle = \cos^4\theta_\odot + \sin^4\theta_\odot = 1 - \frac{1}{2}\sin^2 2\theta_\odot$$

for pp and ^{7}Be this is approximately THE ANSWER.

$f_1 \sim 69\%$ and $f_2 \sim 31\%$ and $\langle P_{ee} \rangle \approx 0.6$

pp and ^{7}Be



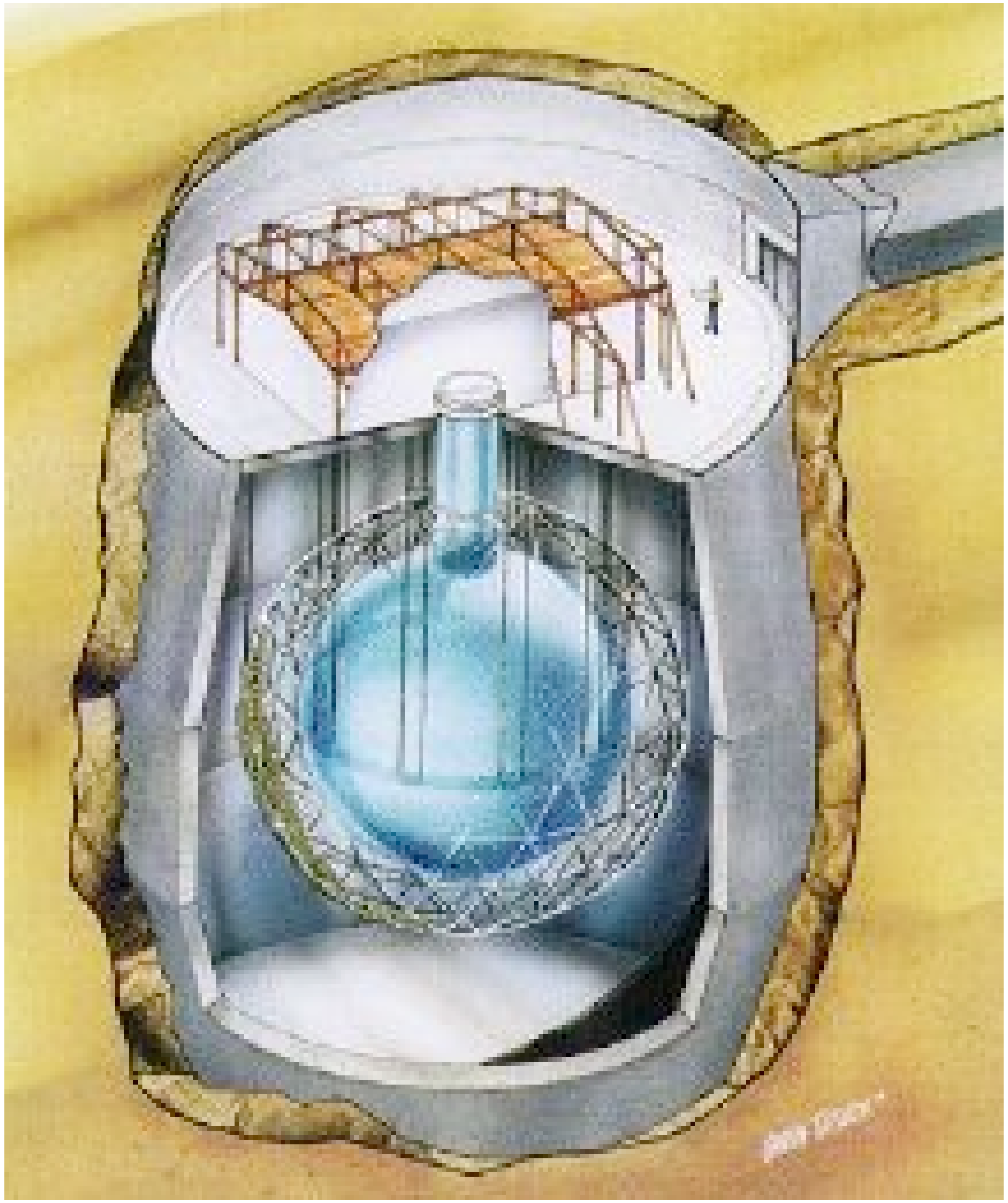
$f_1 \sim 69\%$

$f_2 \sim 31\%$

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

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

SNO's CC/NC



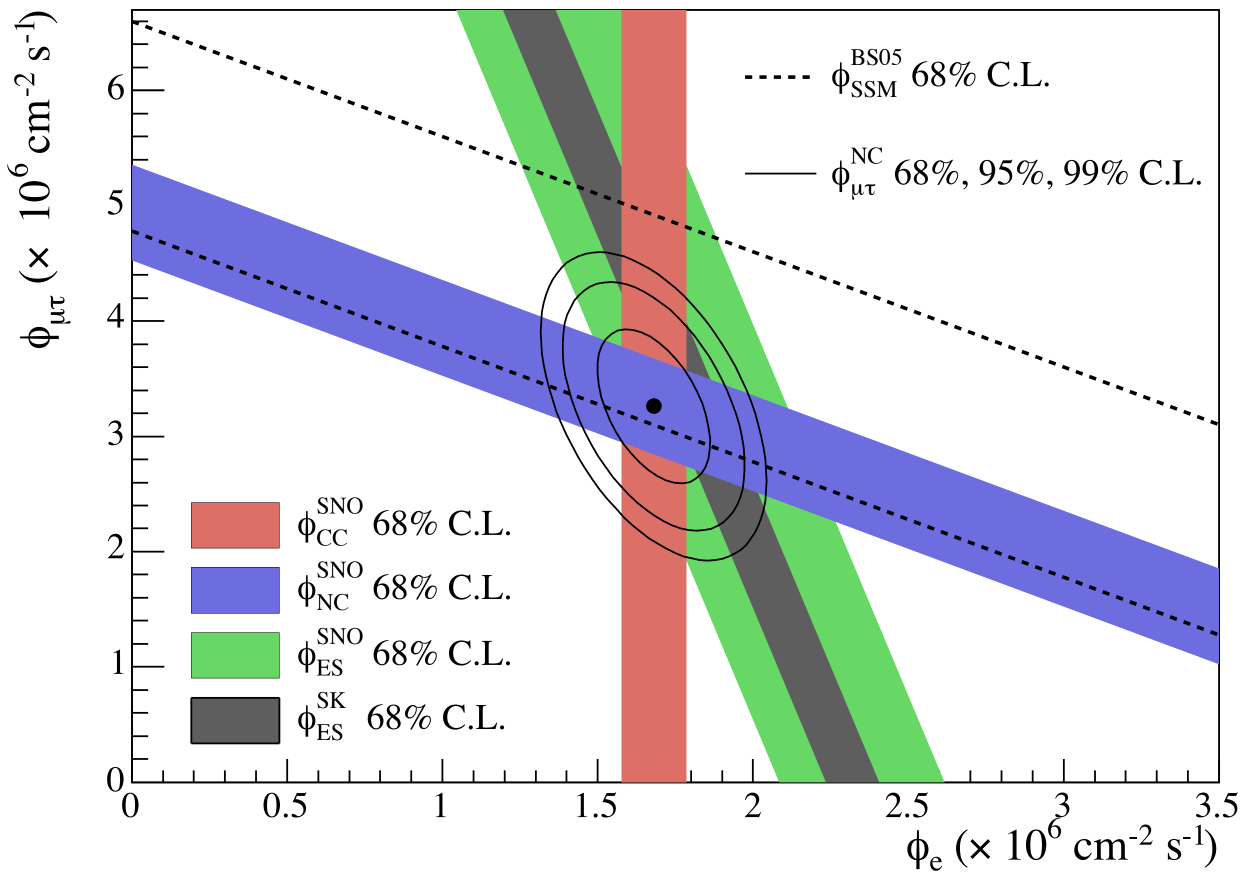
D2O
<1% DHO

What about ^8B ?

CC: $\nu_e + d \rightarrow e^- + p + p$

NC : $\nu_x + d \rightarrow \nu_x + p + n$

ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$



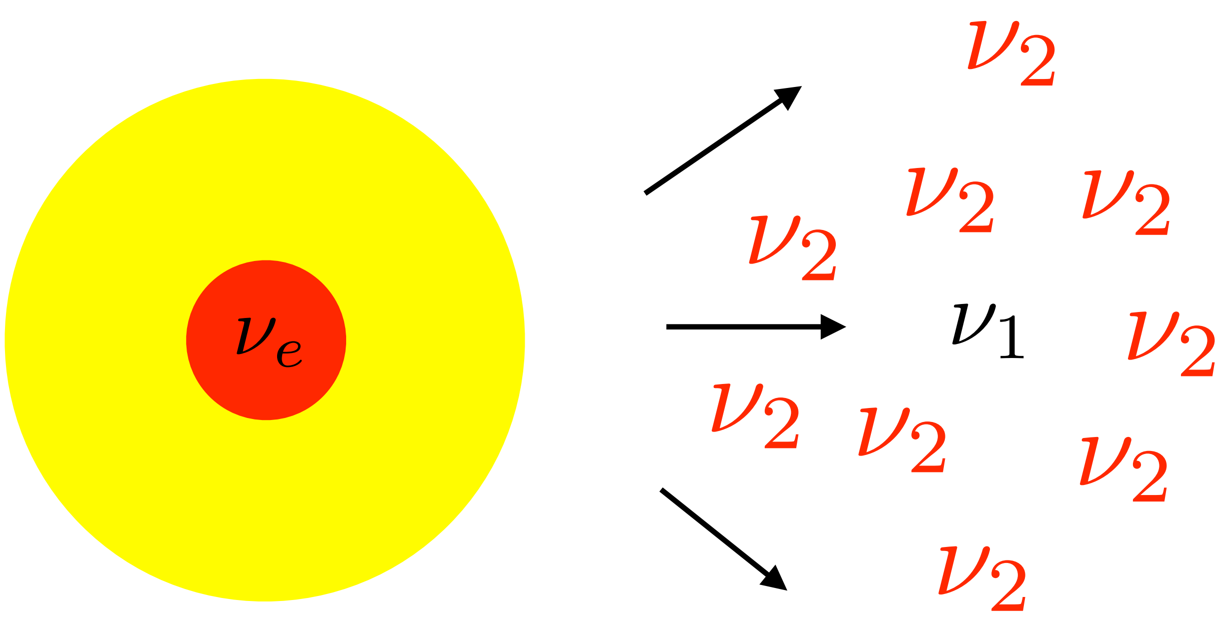
SNO's CC/NC

$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = \left(\frac{CC}{NC} - \sin^2\theta_\odot\right) / \cos 2\theta_\odot$$

$$= (0.35 - 0.31)/0.4 \approx 10 \;\pm\; ???\%$$

^8B



$$f_2 \sim 90\%$$

$$f_1 \sim 10\%$$

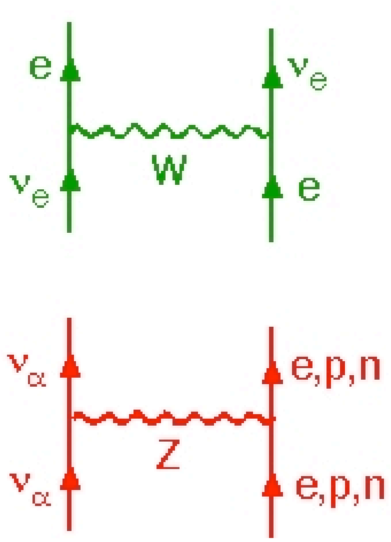
$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!

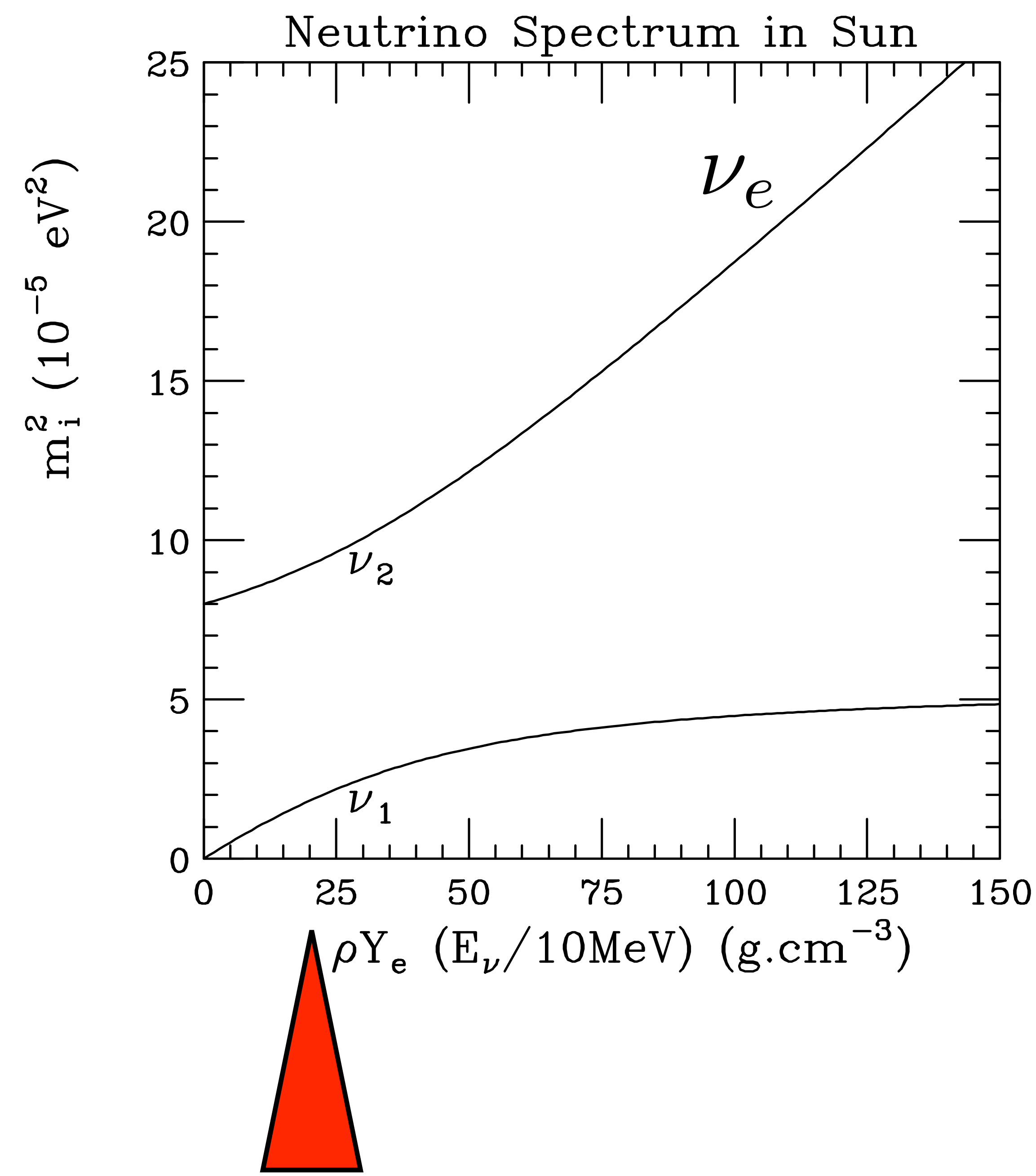
MSW

Coherent Forward Scattering:



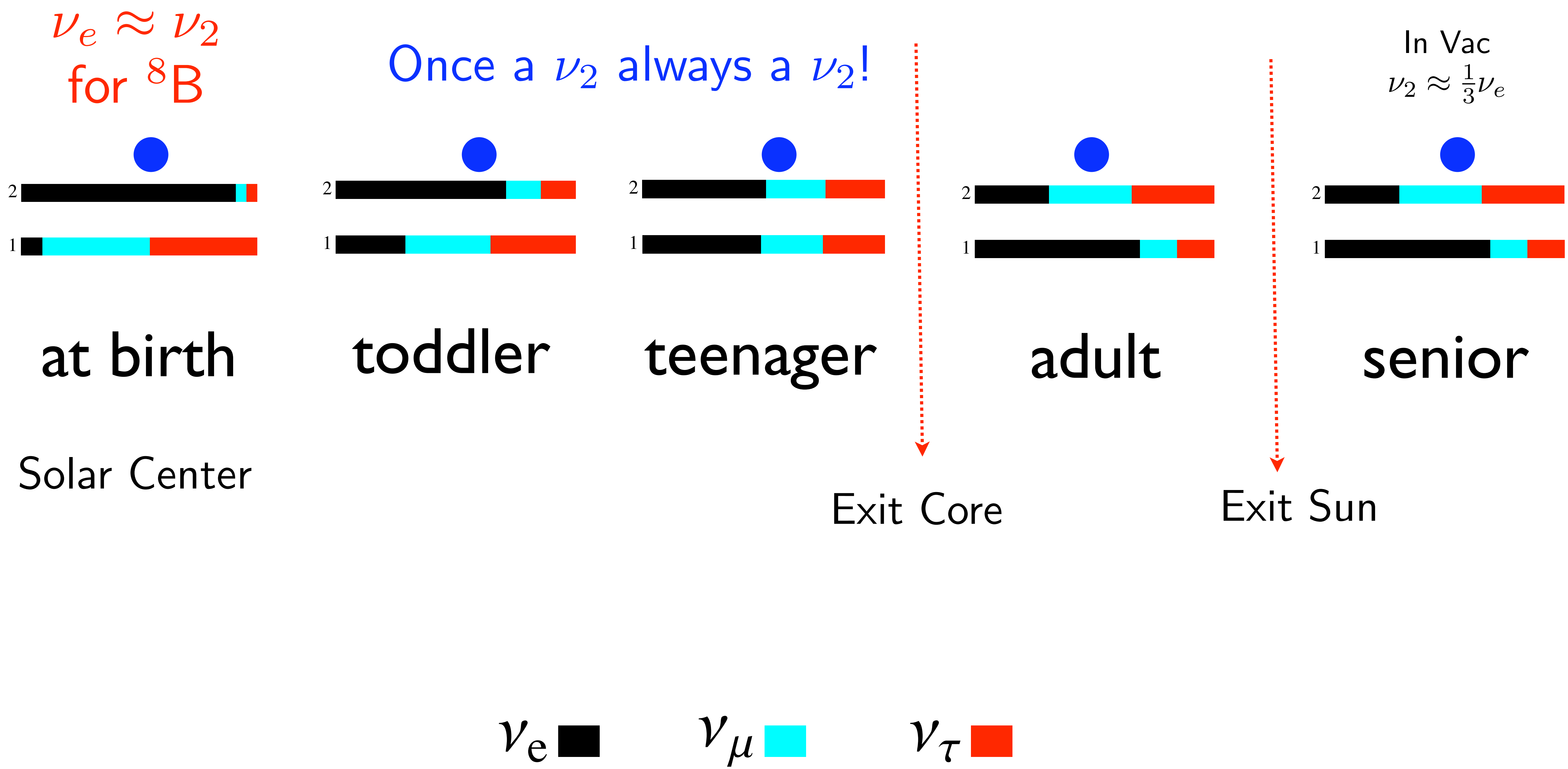
Wolfenstein '78

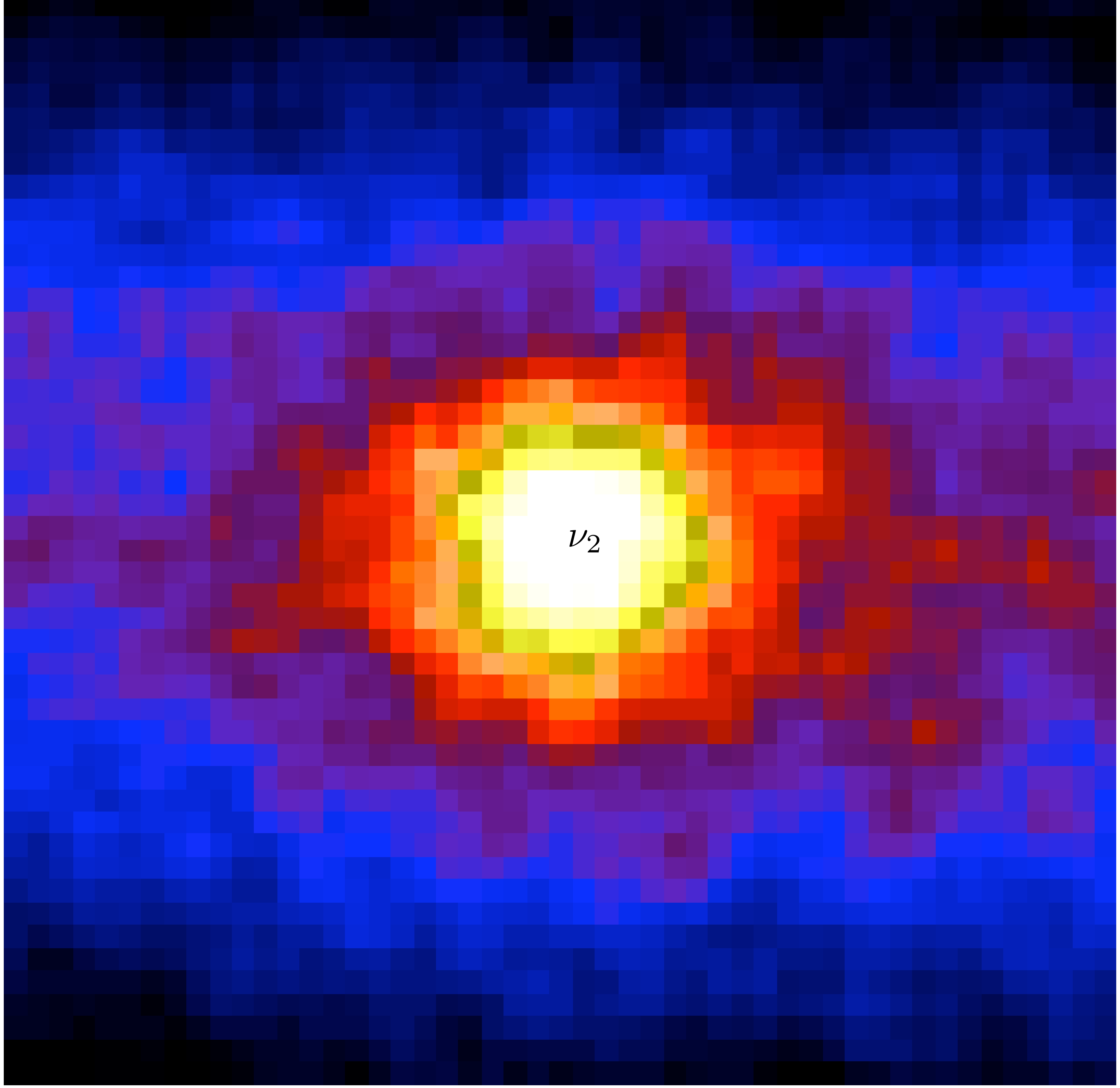
MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS



Mikheyev + Smirnov Resonance WIN '85

Life of a Boron-8 Solar Neutrino:





These are ν_2 Neutrinos !!!

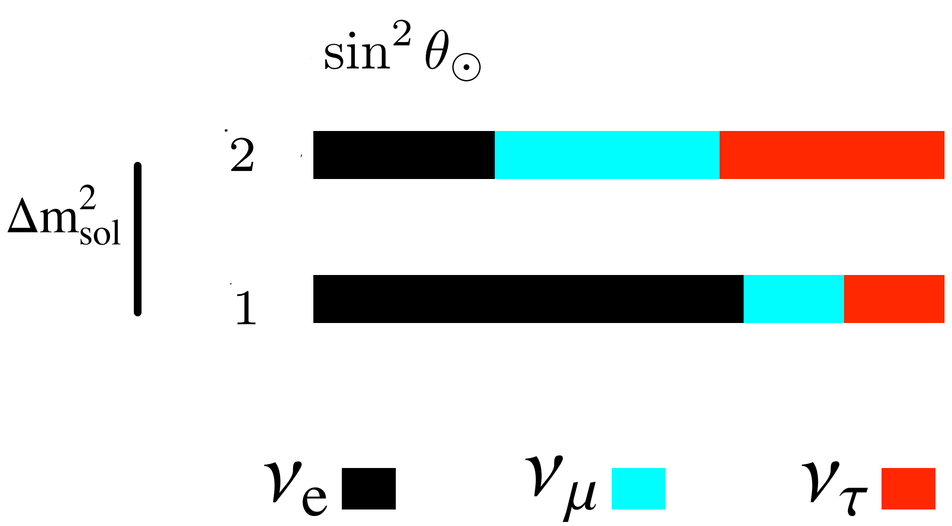
Solar Summary

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.

$f_1 = 65 \pm 2\%,\ f_2 = 35 \mp 2\%$ 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.

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



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

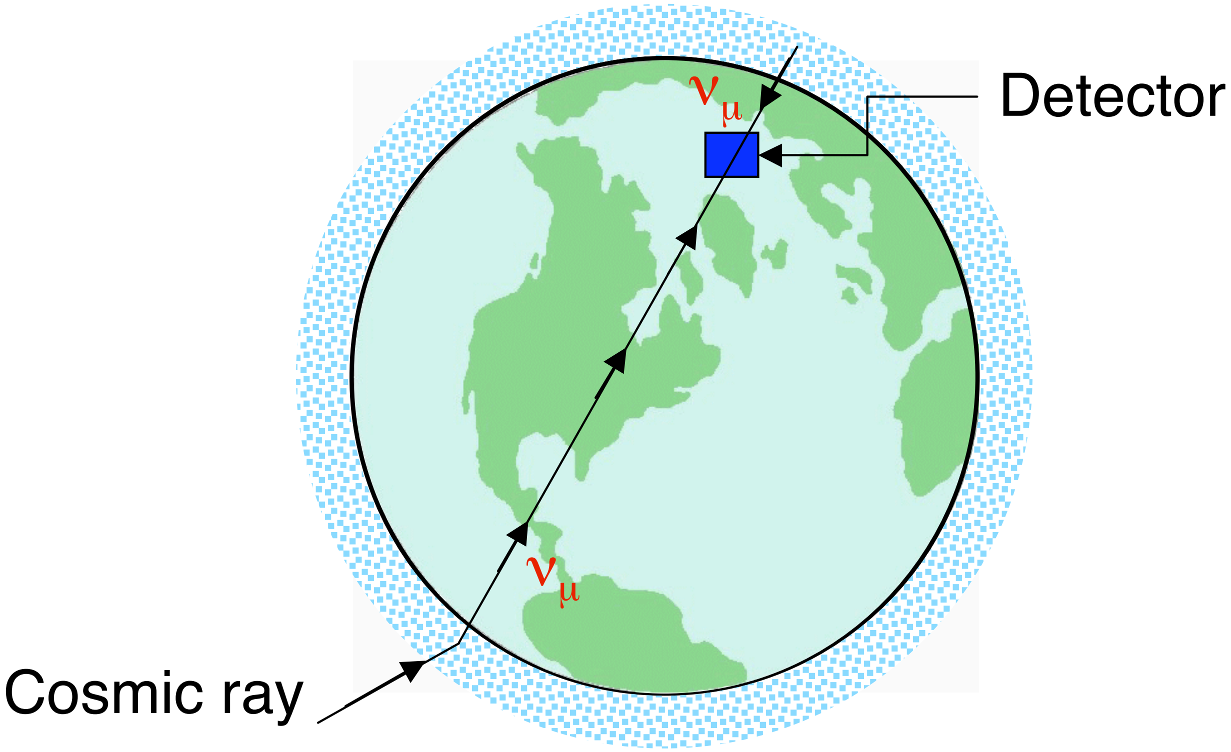
$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

L/E = 15 km/MeV

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

Atmospheric Neutrinos

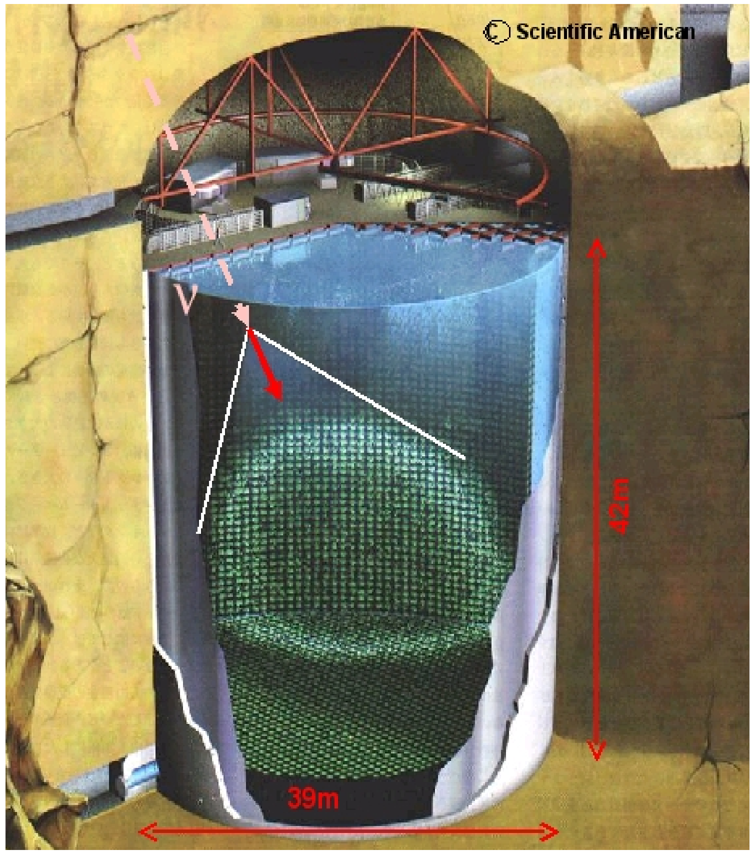


Isotropy of the $\gtrsim$ 2 GeV cosmic rays + Gauss' Law + No ν_μ disappearance

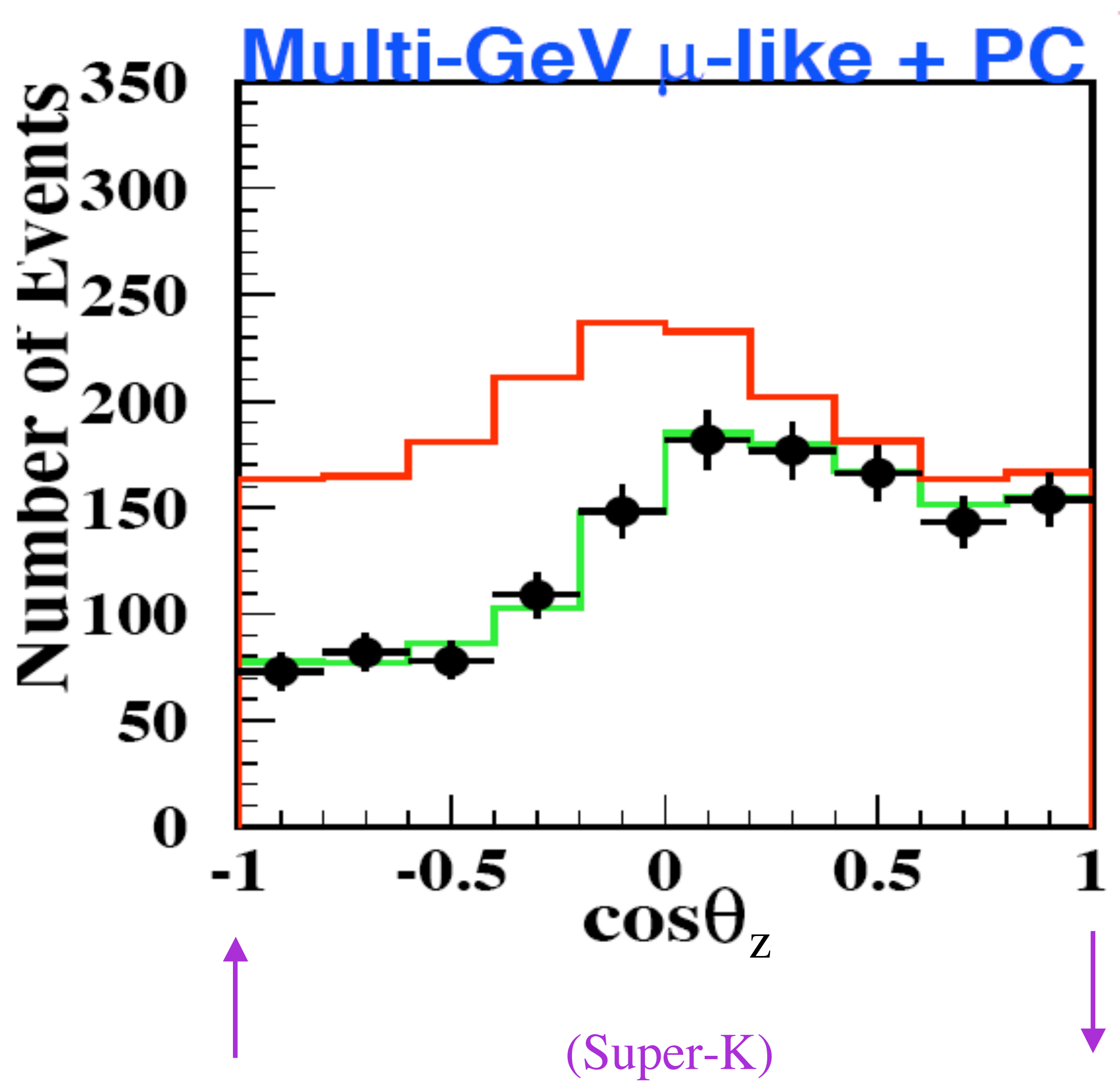
$$\Rightarrow \quad \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 \ .$$

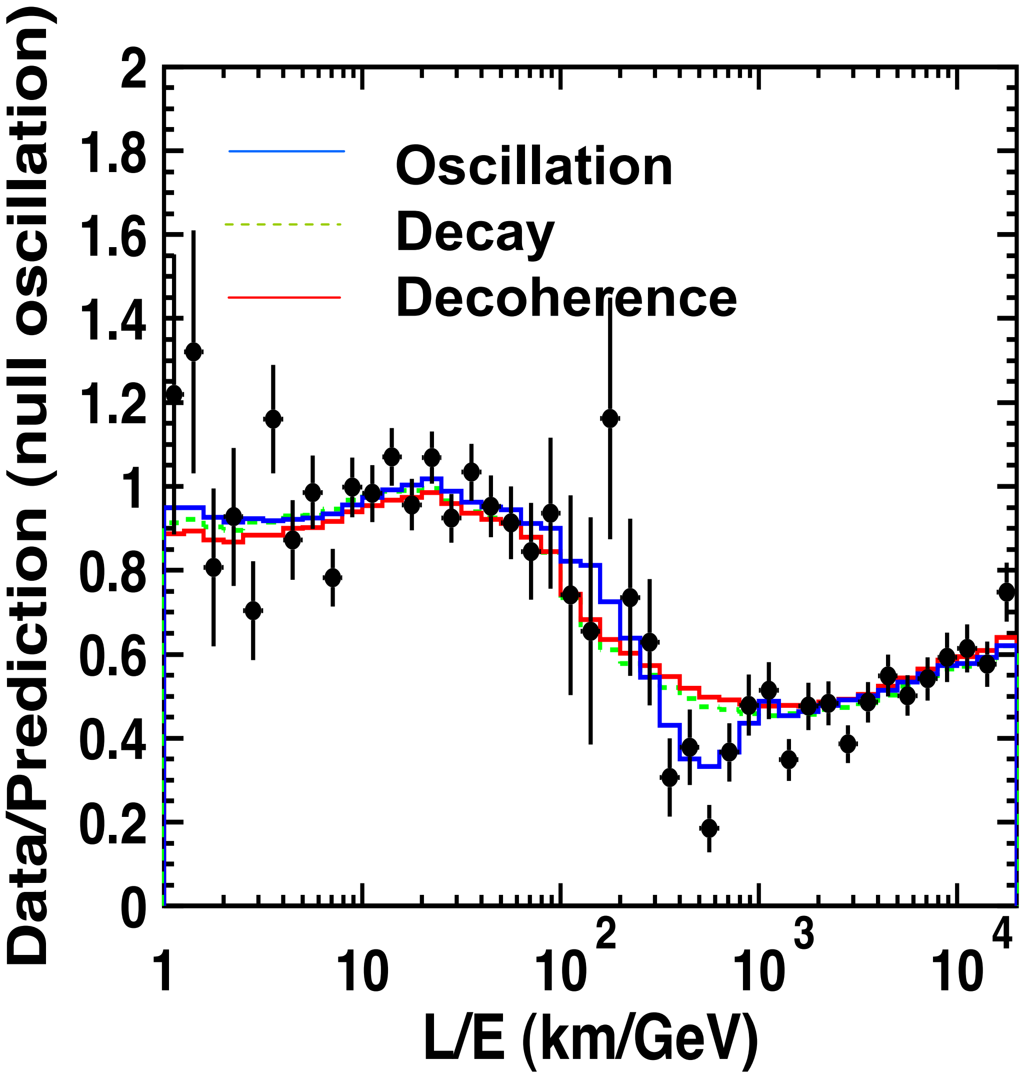
But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 \ .$$



L/E Analysis

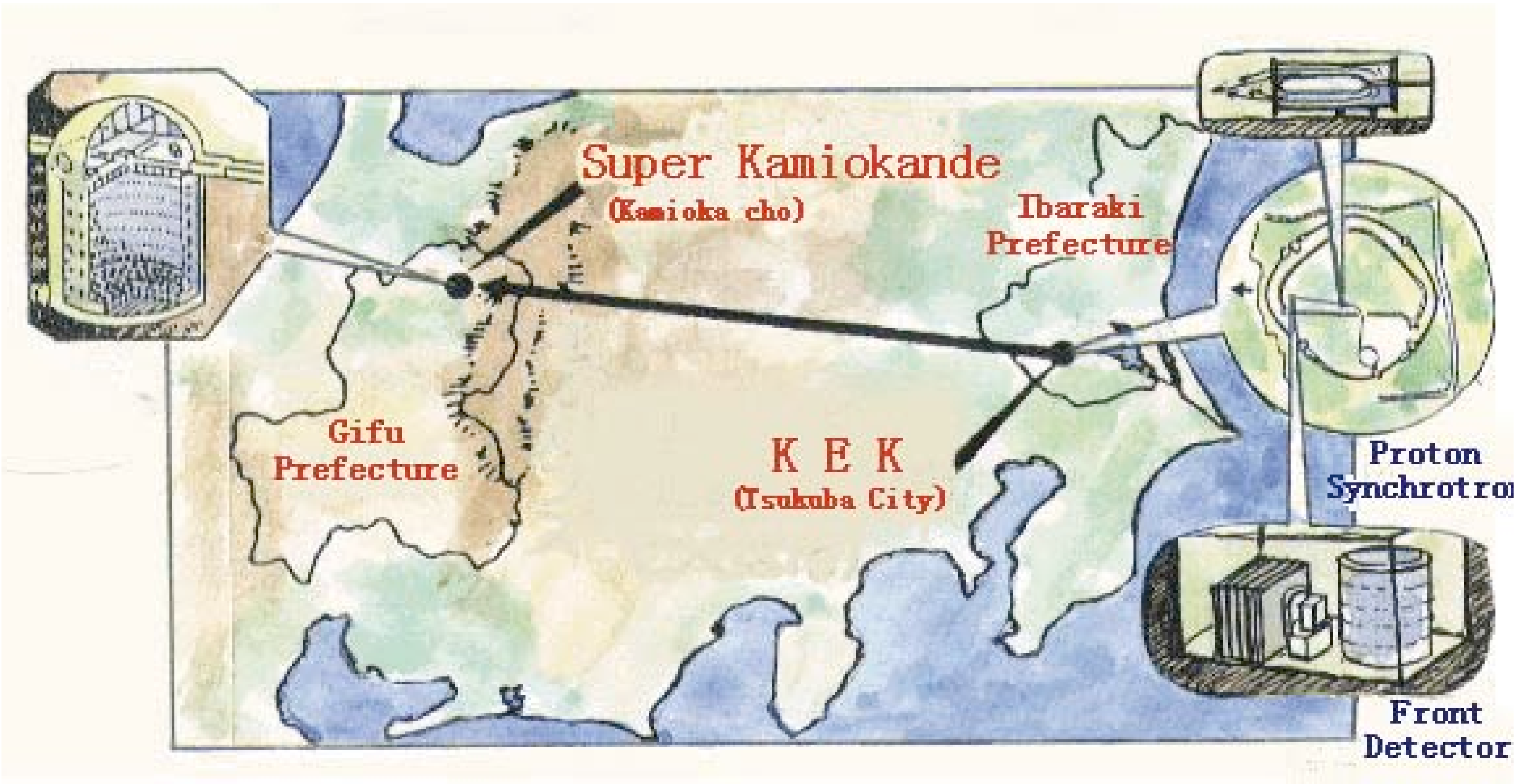


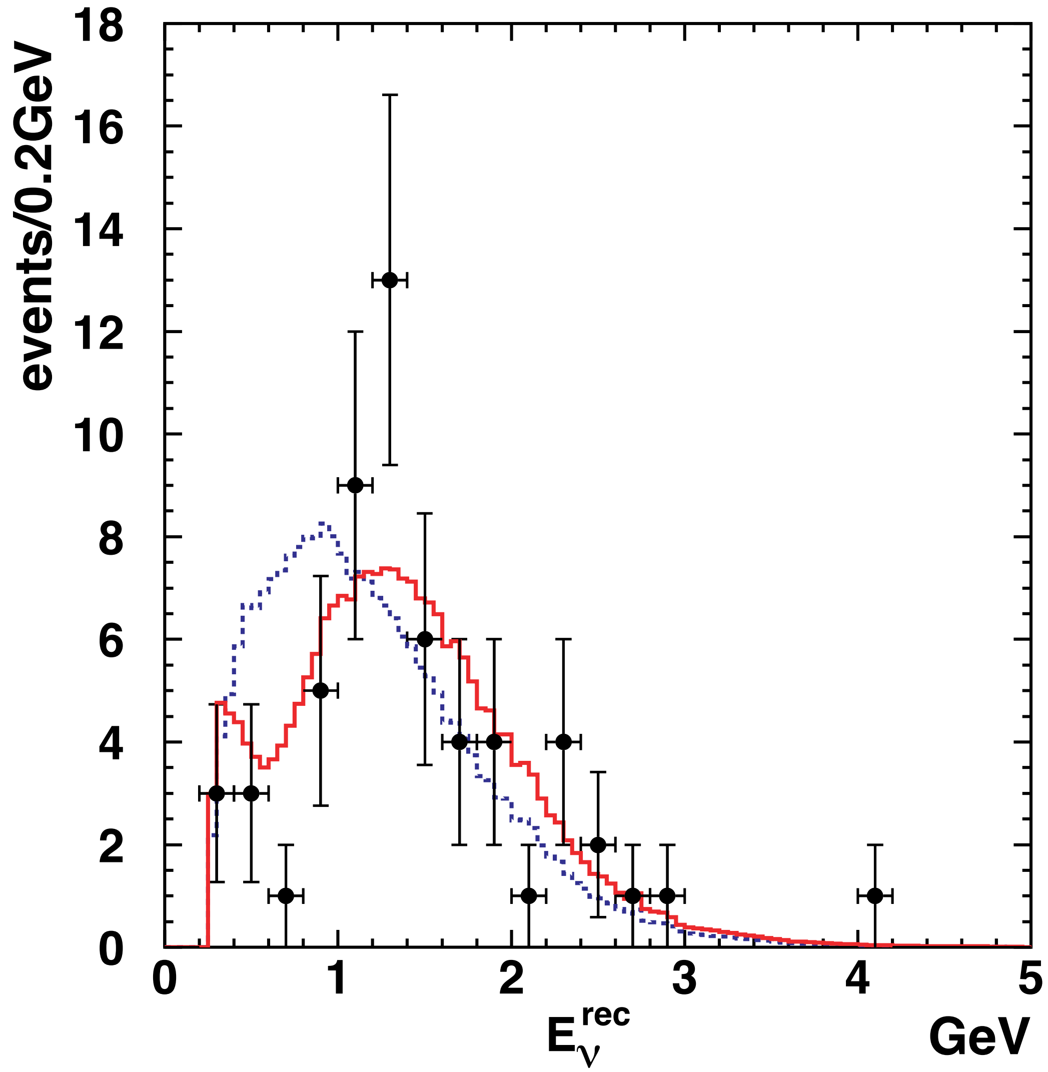


❖Oscillation, decay and decoherence models tested

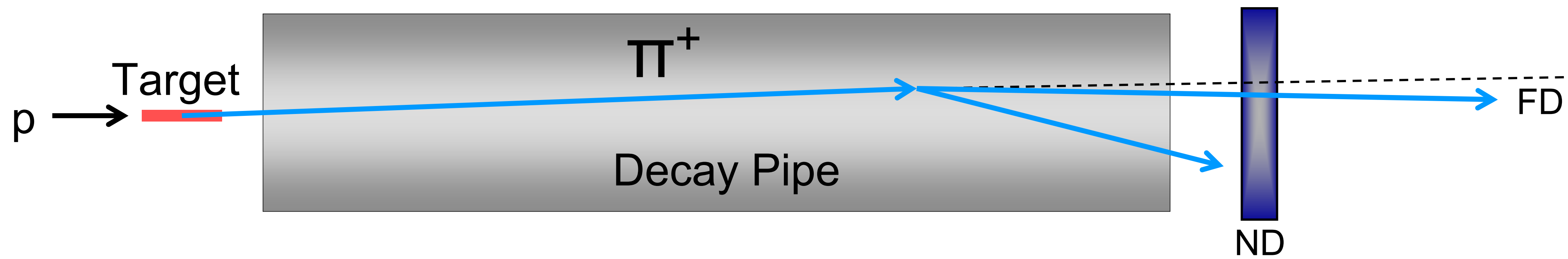
χ^2_{osc} = 83.9/83
χ^2_{dcy} = 107.1/83, $\Delta\chi^2$ = 23.2(**4.8σ**)
χ^2_{dec} = 112.5/83, $\Delta\chi^2$ = 27.6(**5.3σ**)

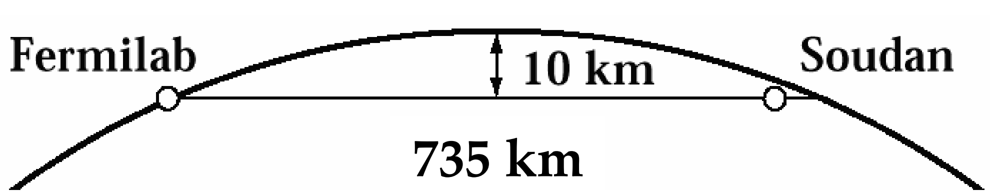
K2K


Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotro
Front
Detector


events/0.2GeV
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
E_ν^{rec}
GeV

The MINOS Experiment





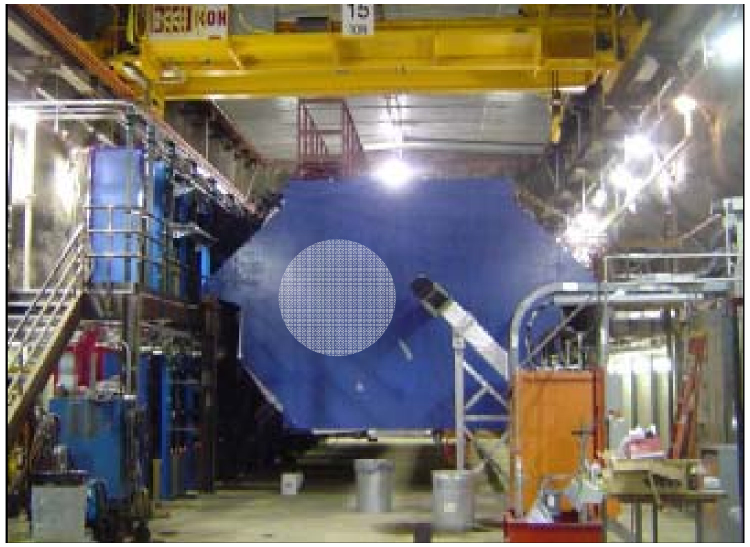
Near Detector

1 kton

$3.8 \times 4.8 \times 15$ m^3

282 steel planes

153 scintillator planes

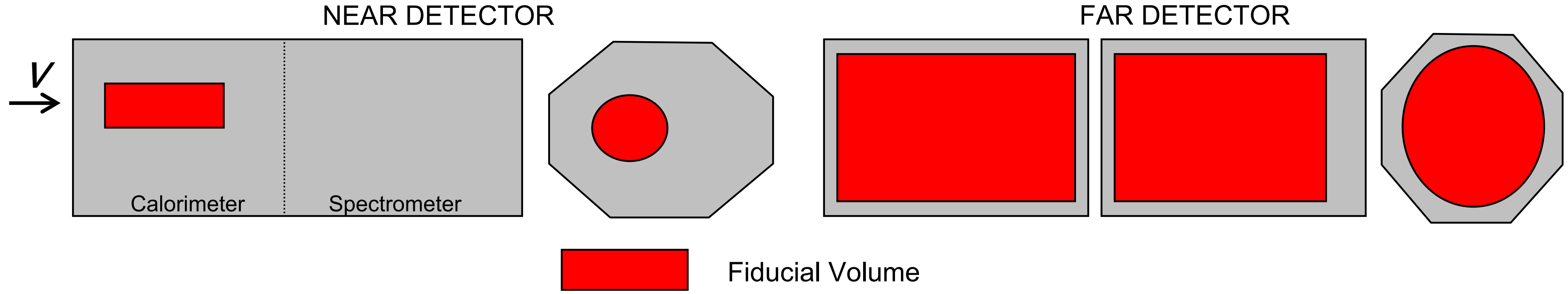


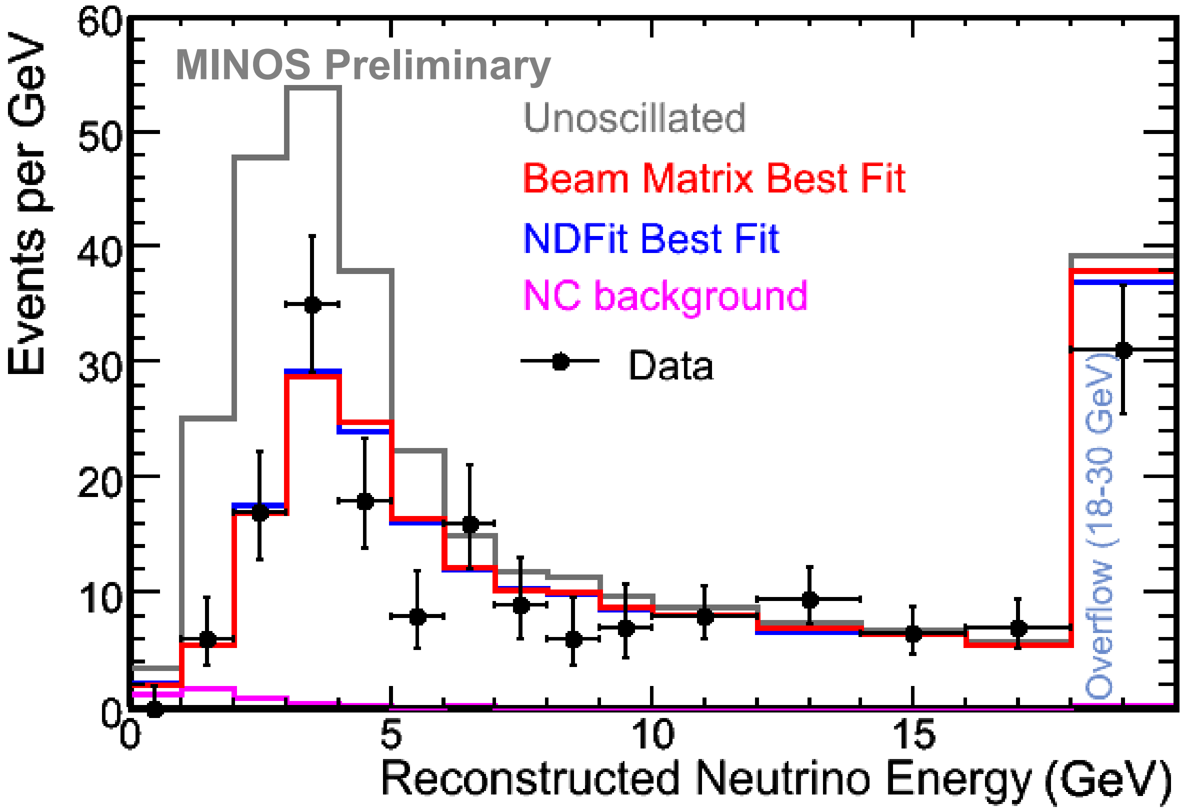
Far Detector

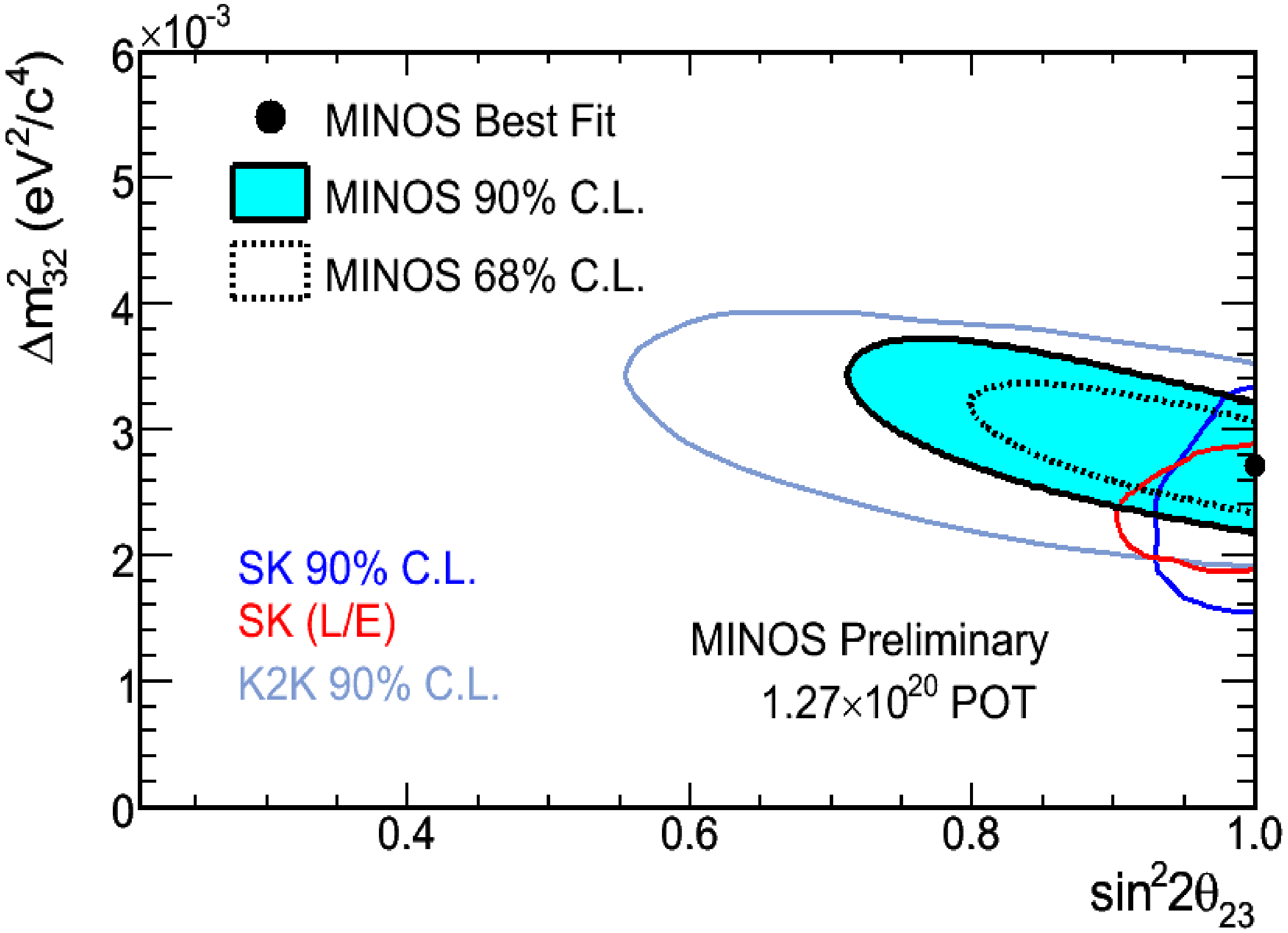
5.4 kton

$8 \times 8 \times 30$ m^3

484 planes







$|\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25}\,(\mathrm{stat}) \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2 2\theta_{23} = 1.00_{-0.13}\,(\mathrm{stat})$

Normalization = 0.98

$|\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25}\,(\mathrm{stat}) \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2 2\theta_{23} = 1.00_{-0.13}\,(\mathrm{stat})$

Constrained to $\sin^2(2\theta_{23}) \leq 1$

Statistical errors

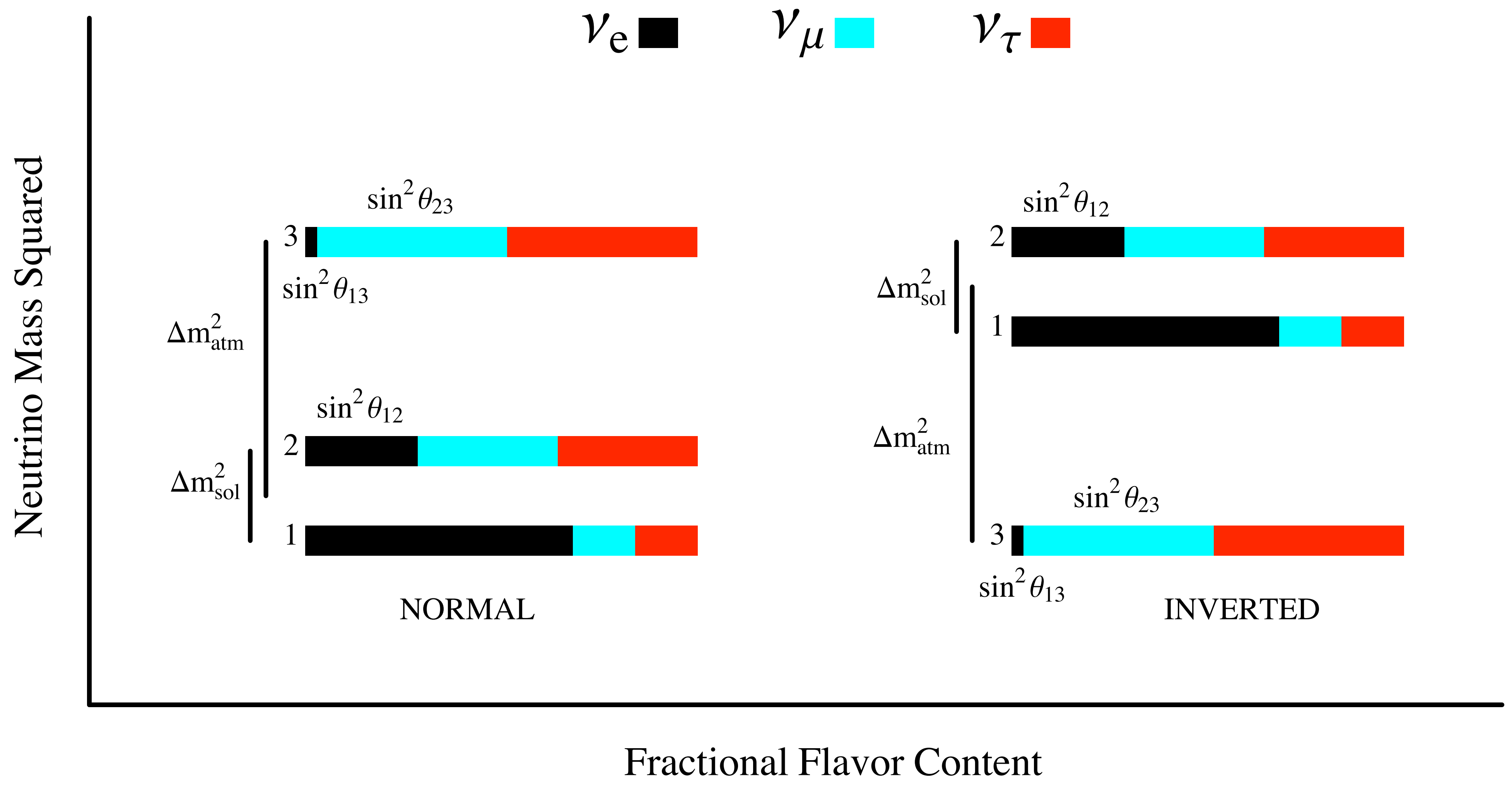
"Atmospheric" Neutrino Summary

$$\nu_\mu \longrightarrow \nu_\tau$$

no evidence of ν_e involvement:

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad L/E = 500\ km/GeV$$

$$\sin^2 2\theta_{atm} > 0.92 \qquad \Rightarrow 0.35 < \sin^2\theta_{atm} < 0.65$$

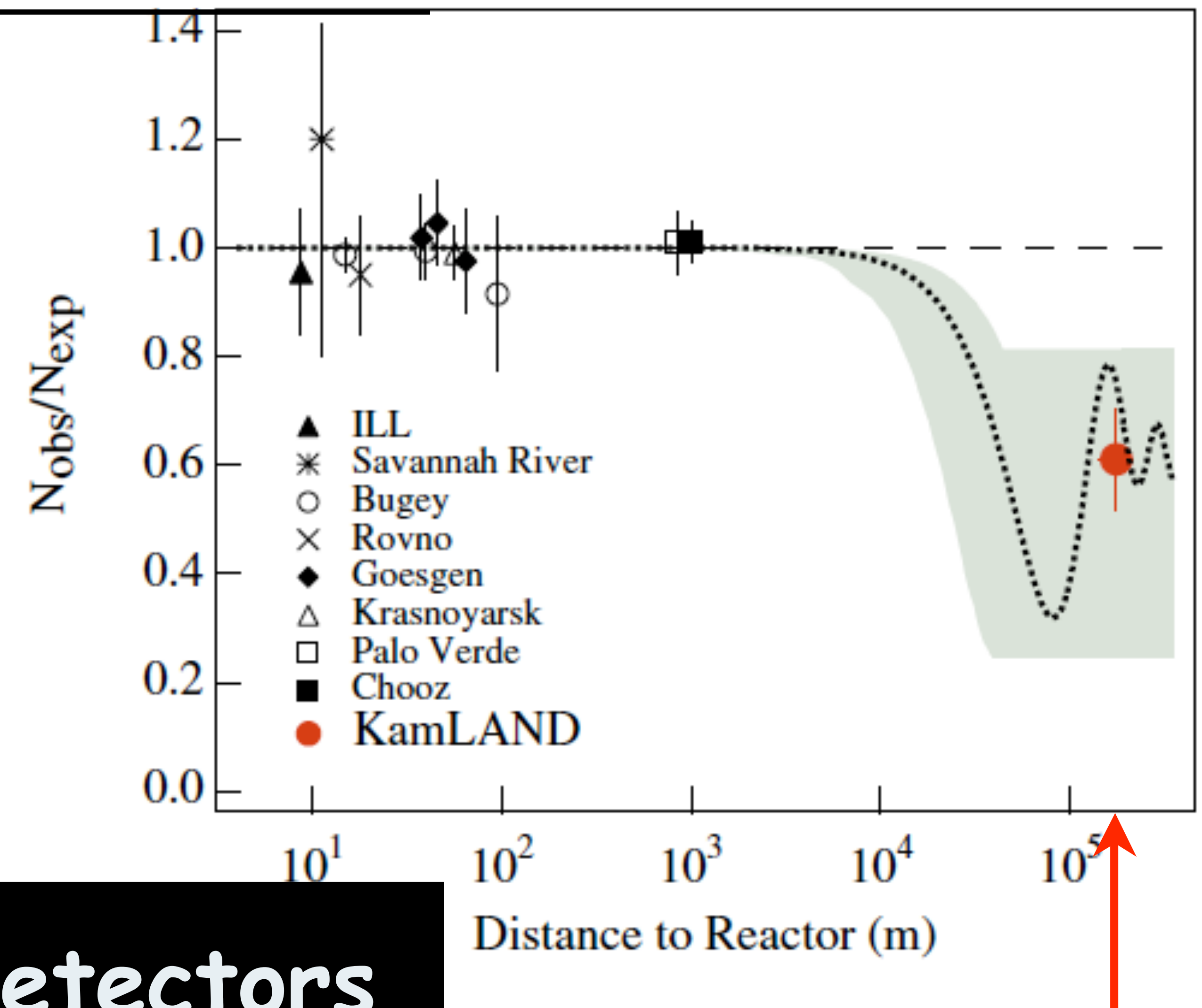


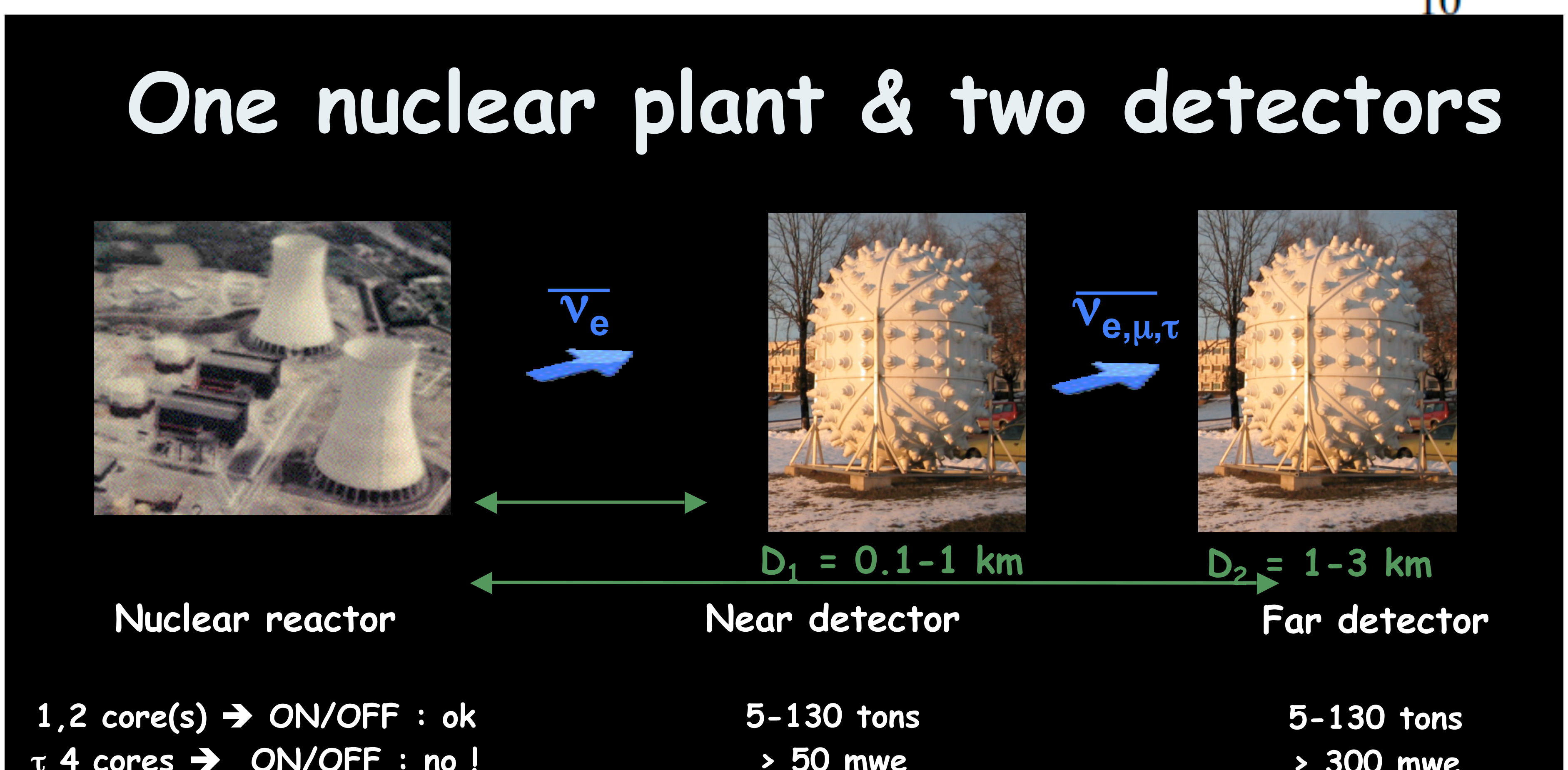
ν_e
ν_μ
ν_τ
Neutrino Mass Squared
$\sin^2\theta_{23}$
3
$\sin^2\theta_{13}$
Δm^2_{atm}
$\sin^2\theta_{12}$
2
Δm^2_{sol}
1
NORMAL
$\sin^2\theta_{12}$
2
Δm^2_{sol}
1
Δm^2_{atm}
$\sin^2\theta_{23}$
3
$\sin^2\theta_{13}$
INVERTED
Fractional Flavor Content

θ_{13} from Reactor Disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{atm}$$

$<10\%$





- Double Chooz
- Daya Bay
- ...

Long BaseLine:

$$\nu_\mu \longrightarrow \nu_e$$

Vacuum LBL:

$$\nu_\mu \longrightarrow \nu_e$$

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

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

CP violation !!!

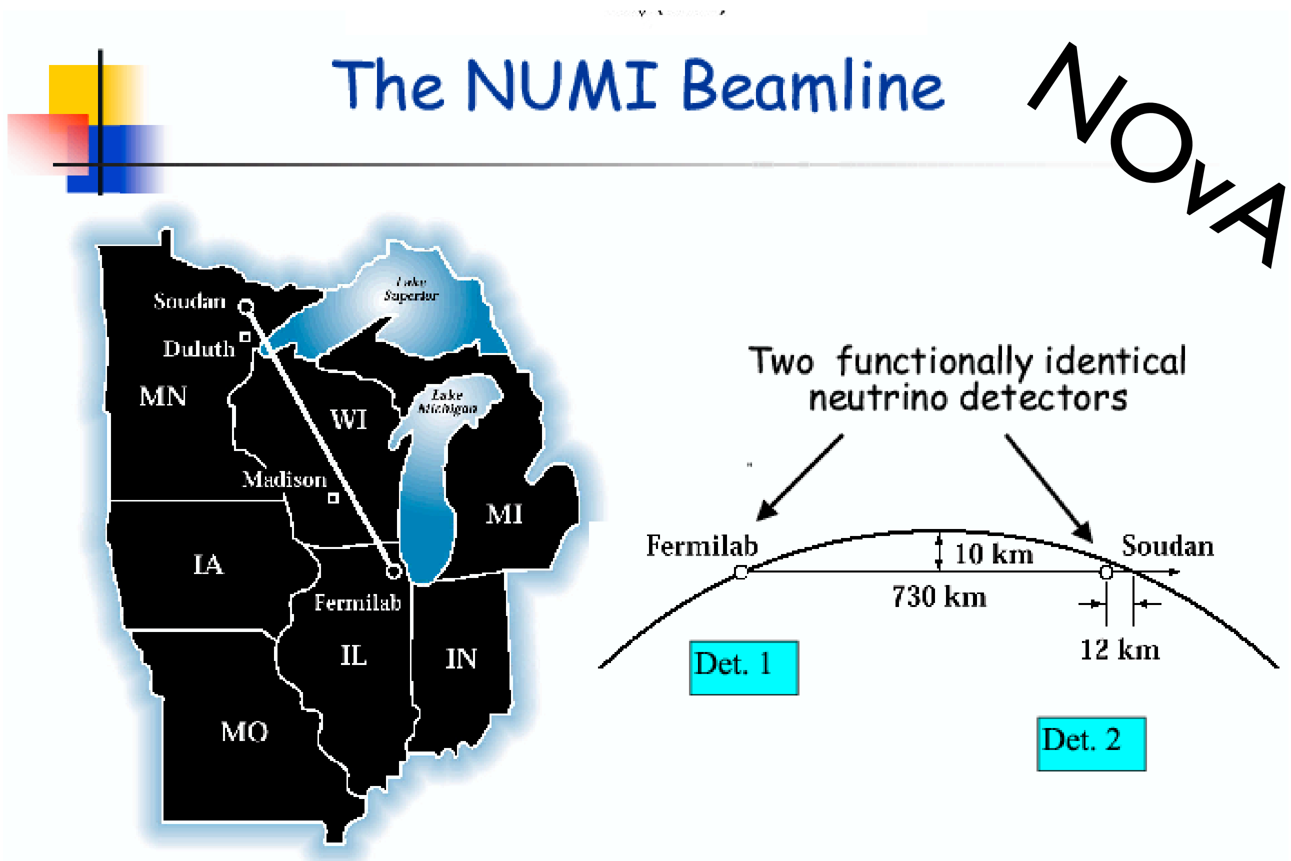
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \sin\Delta_{31}$

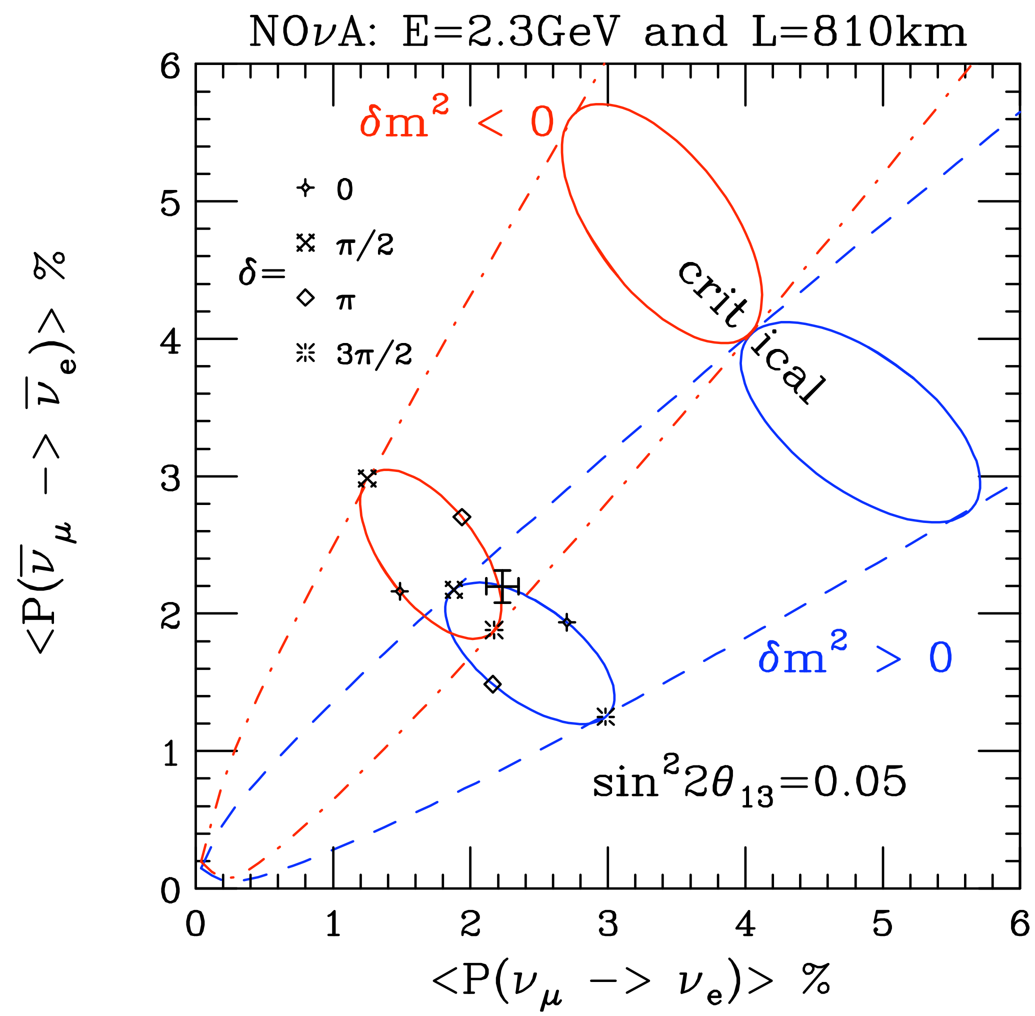
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21}$

- ν_e fraction of ν_3: – $\sin^2\theta_{13}$
- mass hierarchy: – sign of δm^2_{31}
- ^ CP violation: – $\sin\delta \neq 0$

observable

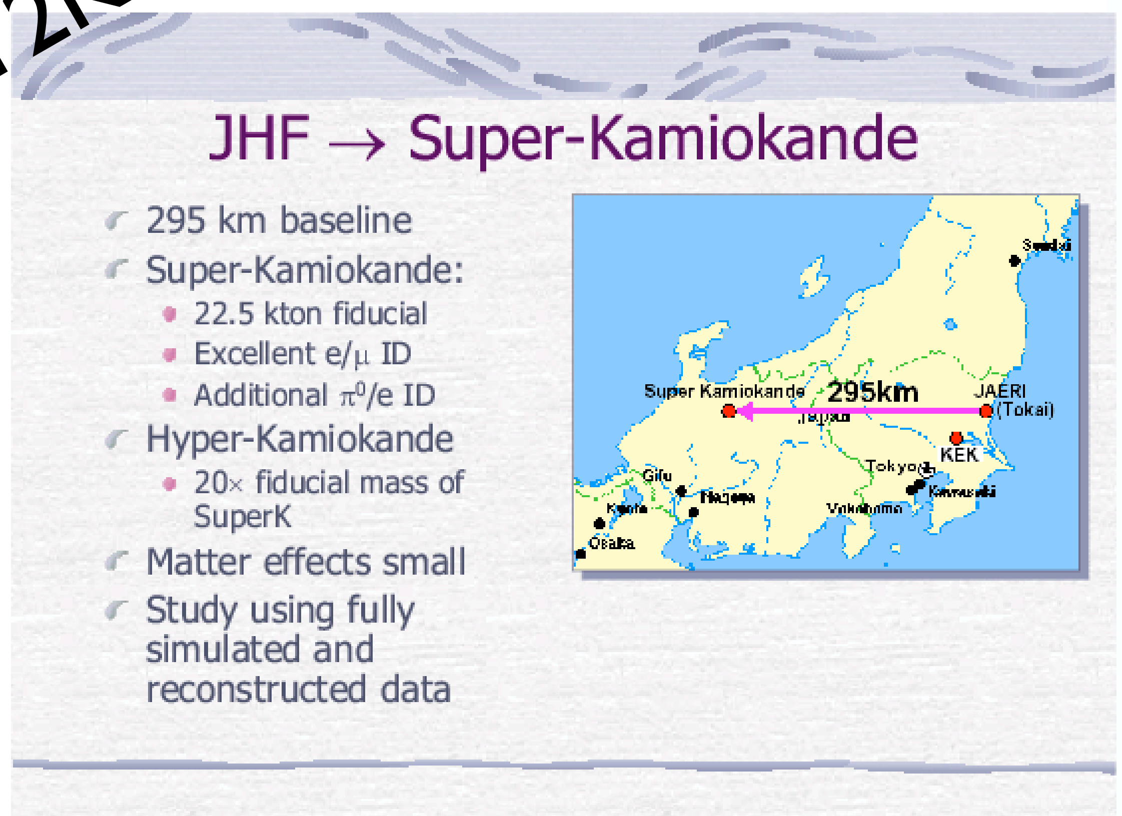
Neutrino v Anti-Neutrino One Expt.

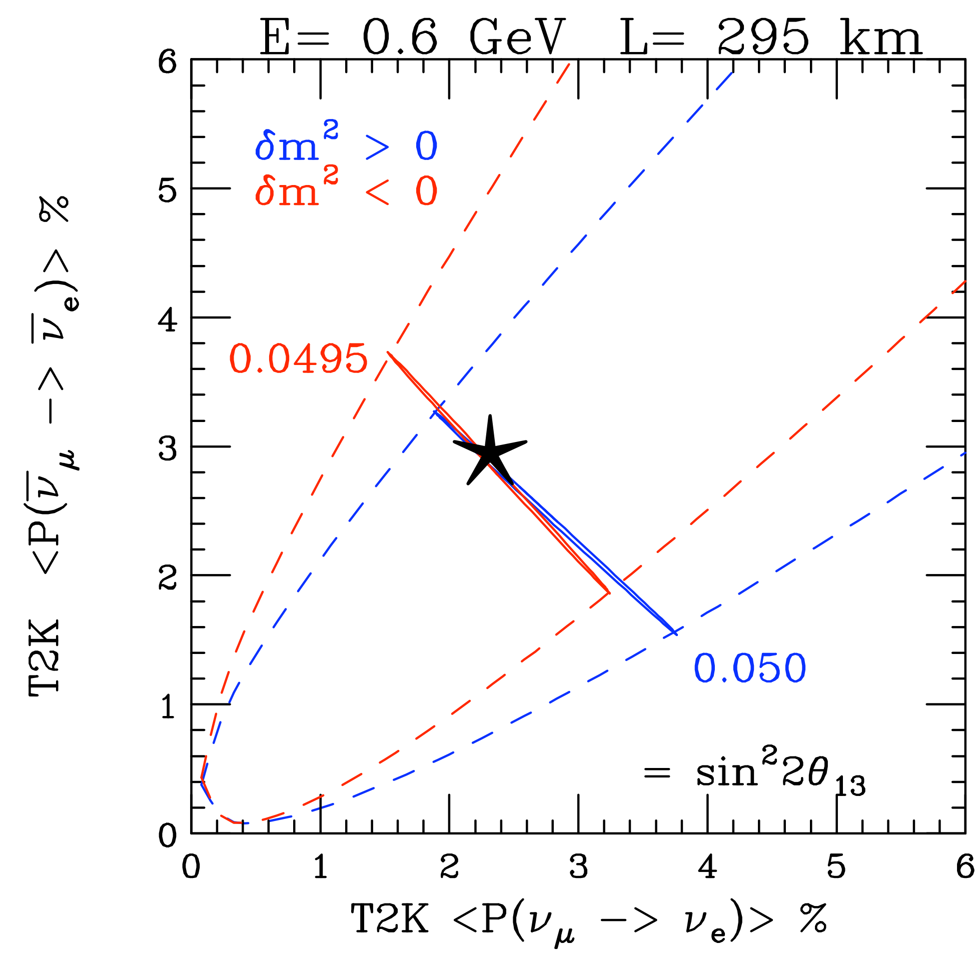




$$\color{blue}{\langle \sin\delta \rangle_+} - \color{red}{\langle \sin\delta \rangle_-} \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

T2K



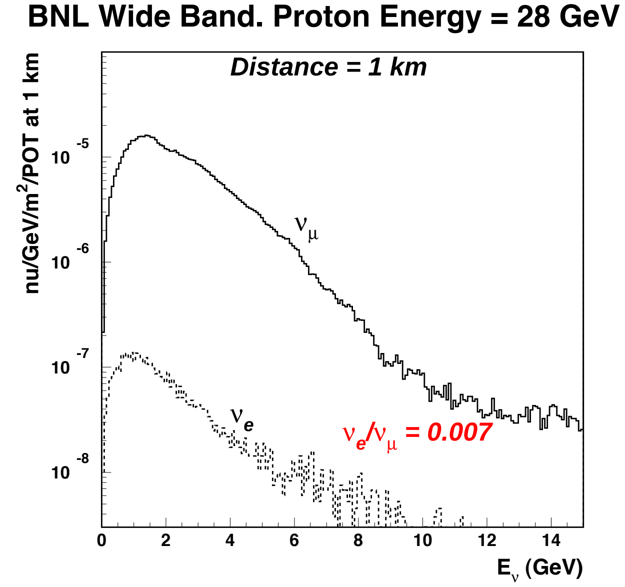


$$\color{blue}{\langle \sin\delta \rangle_+} - \color{red}{\langle \sin\delta \rangle_-} = 2\langle\theta\rangle/\theta_{crit} \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

(ρL) for NOvA <u>three</u> times larger than (ρL) than T2K.

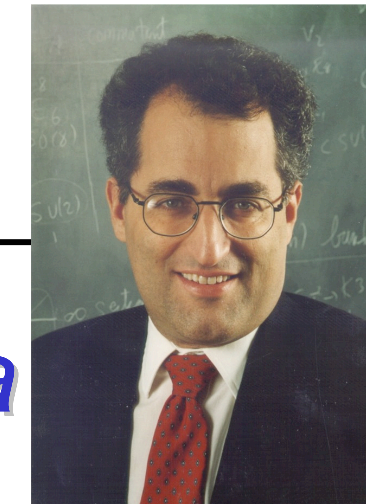
On Axis Beams:

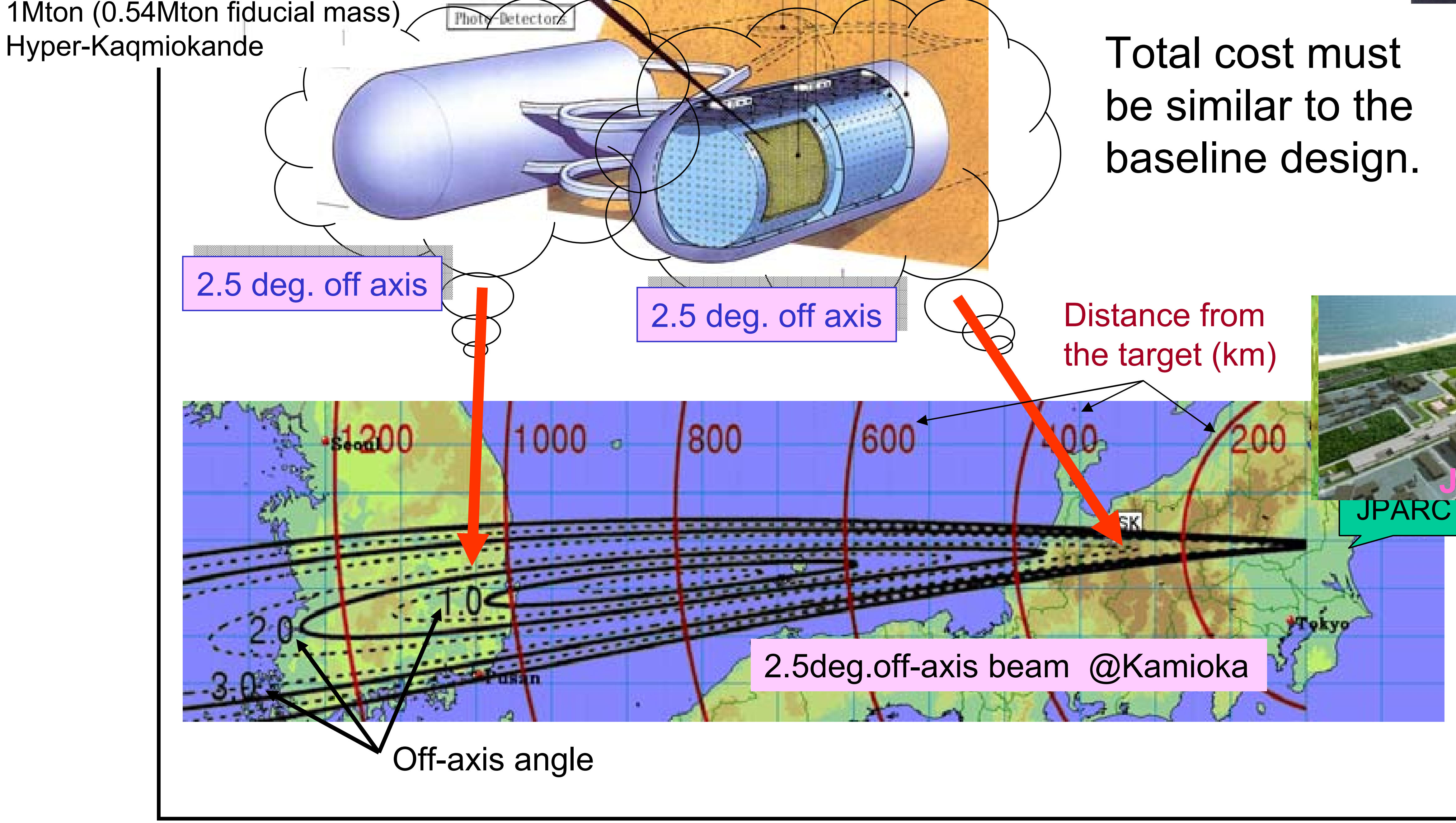
- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake



Brookhaven Proposal

Off Axis:





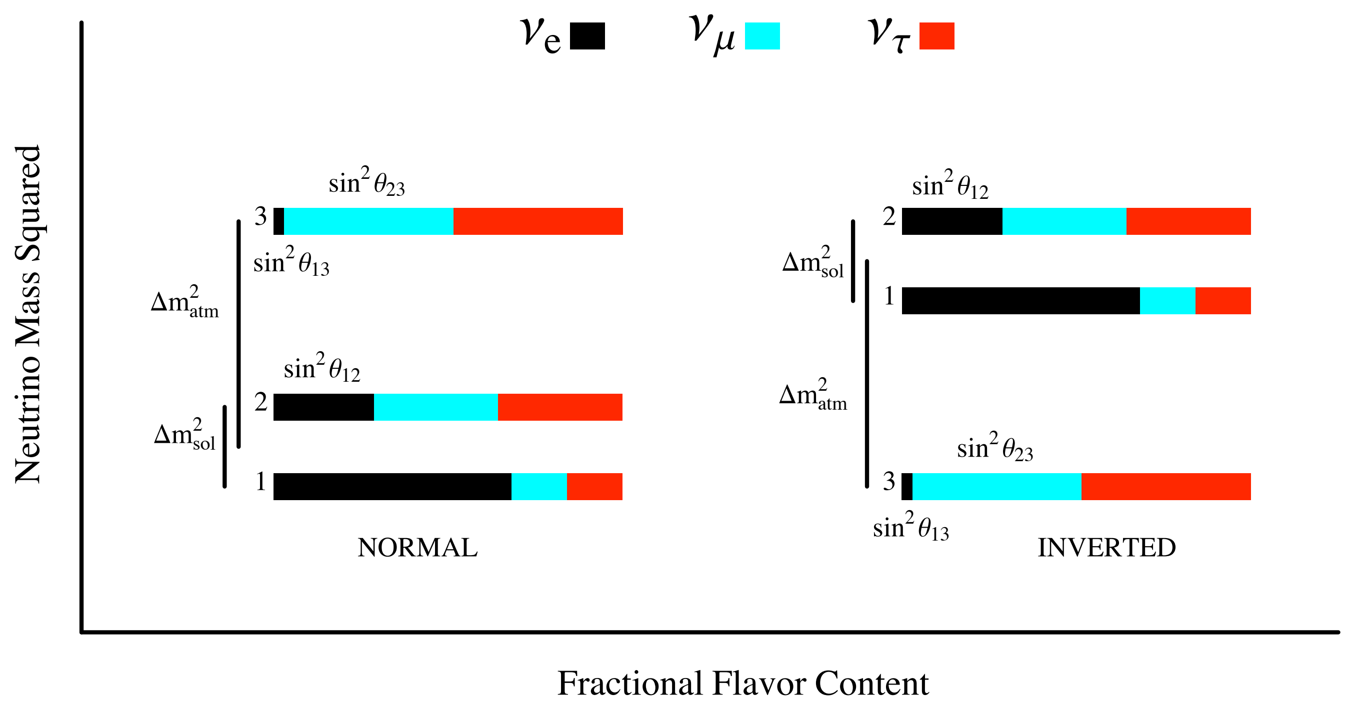
see Kajita talk:

SUMMARY

neutrino mass $\Leftrightarrow$ flavor change

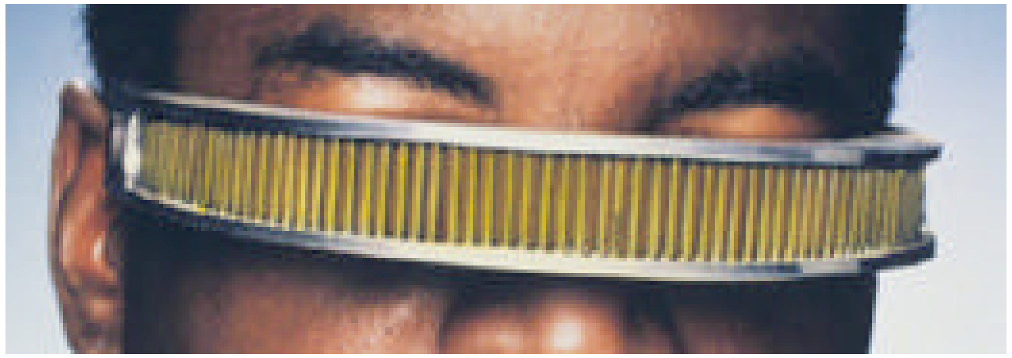
Unknowns:

- Majorana v Dirac
- Light Steriles ???
- Mass Hierarchy $m_3 > m_2 > m_1$ OR $m_2 > m_1 > m_3$
  using $|U_{e3}|^2 < |U_{e2}|^2 < |U_{e1}|^2$
- fraction of ν_e in ν_3 ($< 4\%$)
- Is CP violated ? $\sin\delta \neq 0$
- Mass of Heaviest Neutrino
- Mass of Lightest Neutrino
- New Interactions, Surprises !!!



Star Trek: The Next Generation

Geordi La Forge:
in “The Enemy”



The visor “sees” Neutrinos!!!

... but this requires special New Physics !!!