Neutrinos:
NOT just missing ET !

Neutrinos:
NOT just missing ET !

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

15+ Years ago

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 — Copyright © 1998 The New York Times — FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

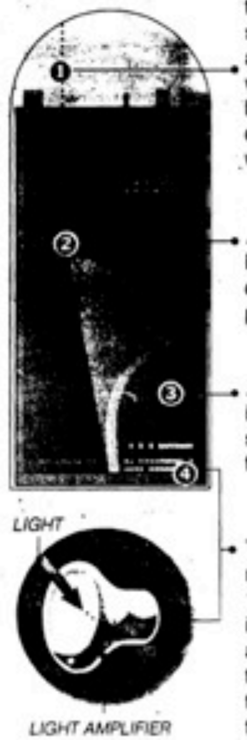
Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos



Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

ν98, @Takayam
June 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo

for the {Kamiokande / Super-Kamiokande} Collaborations

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

Neutrino Mass:

postpone for later whether:

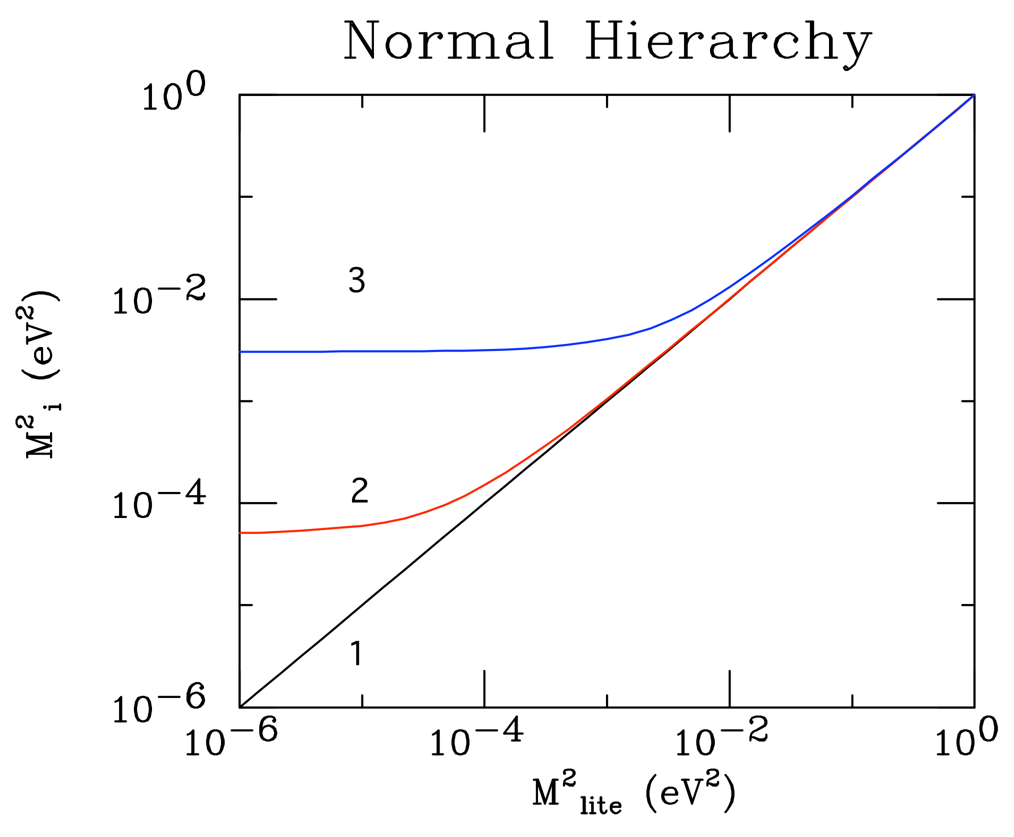
Majorana (2 component) or Dirac (4 component)

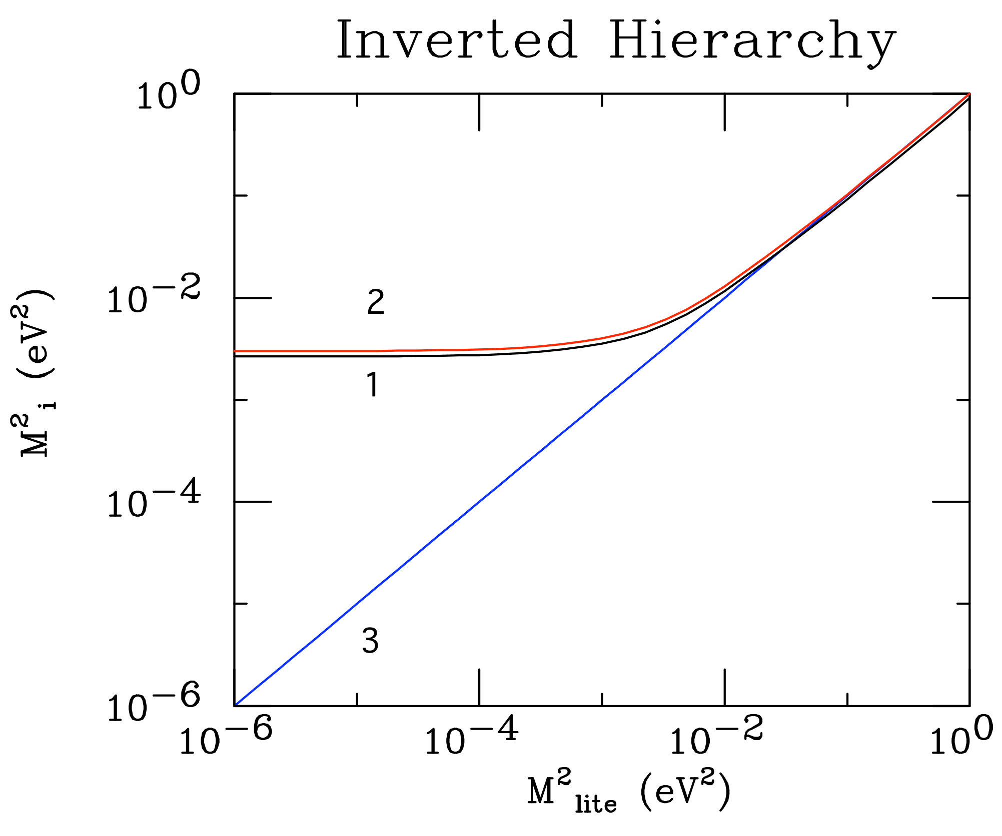
Two different L/E scales have been observed:

- Atmospheric $L/E = 500\, km/GeV$ and Solar $L/E = 15,000\, km/GeV$

Except: LSND, miniBooNE, reactor anomaly, gallium anomaly.

Nu Masses:





1 and 2 are Nu rich:

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

Parametrization of PMNS:

Atmospheric/Accelerator ν's

$0\nu\beta\beta$ decay

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Reactor/Solar ν's

$\boldsymbol{L/E = 500}$ km/GeV $\quad$ **500** km/GeV $\quad$ **15** km/MeV

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Neutrino Mixing Matrix: PMNS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

smaller ν_e content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

Neutrino Mixing Matrix: PMNS

SNO CC
KamLAND
$|U_{e2}|^2$

Reactor/LBL
$|U_{e3}|^2(1-|U_{e3}|^2)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS

KamLAND wiggles
$|U_{e1}|^2$

SNO CC
KamLAND
$|U_{e2}|^2$

Reactor/LBL
$|U_{e3}|^2(1-|U_{e3}|^2)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

smaller ν_e content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

SK & OPERA Tau's
$|U_{\tau 3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS

KamLAND wiggles
$|U_{e1}|^2$

SNO CC
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smaller ν_e content

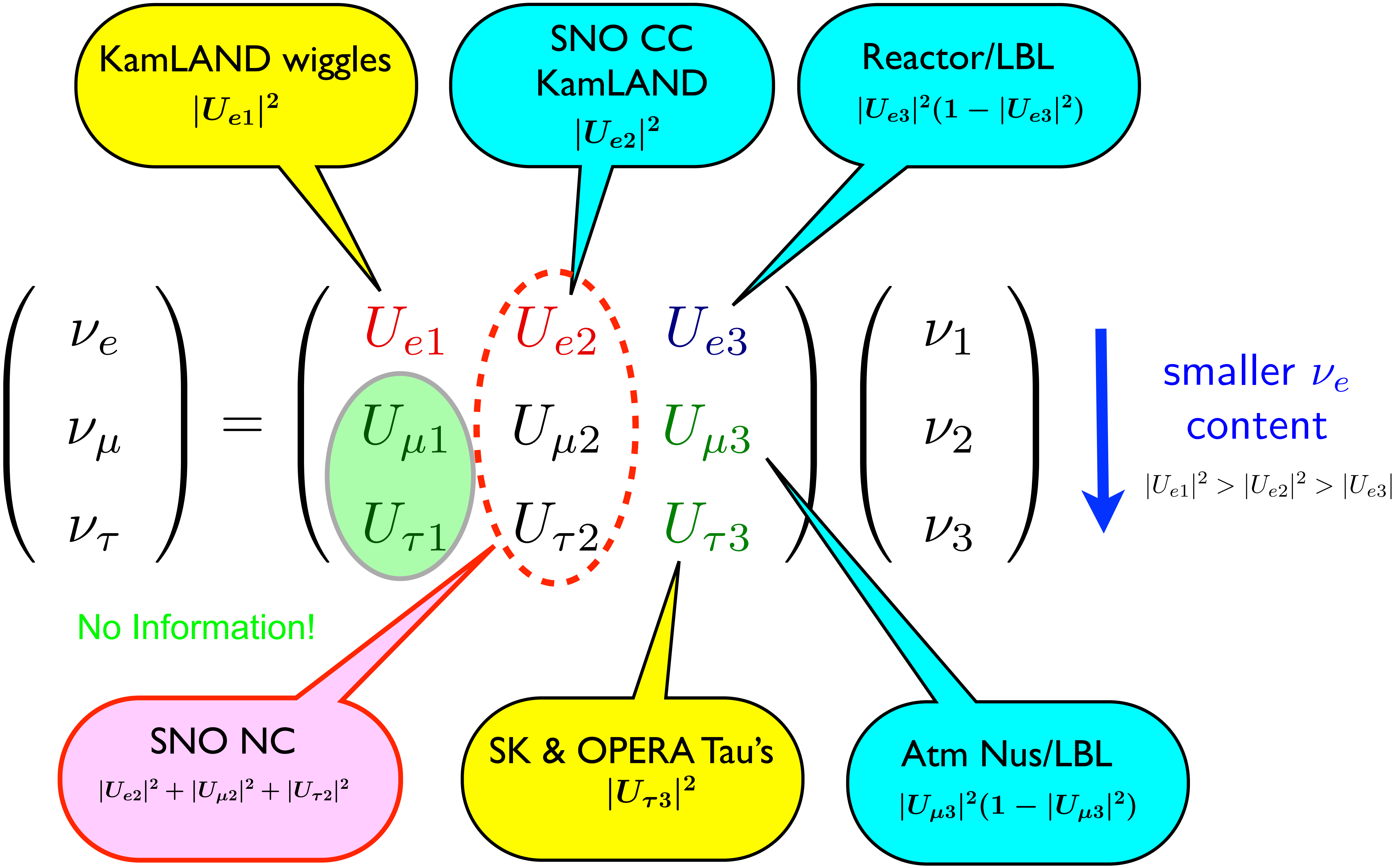
$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

SNO NC
$|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2$

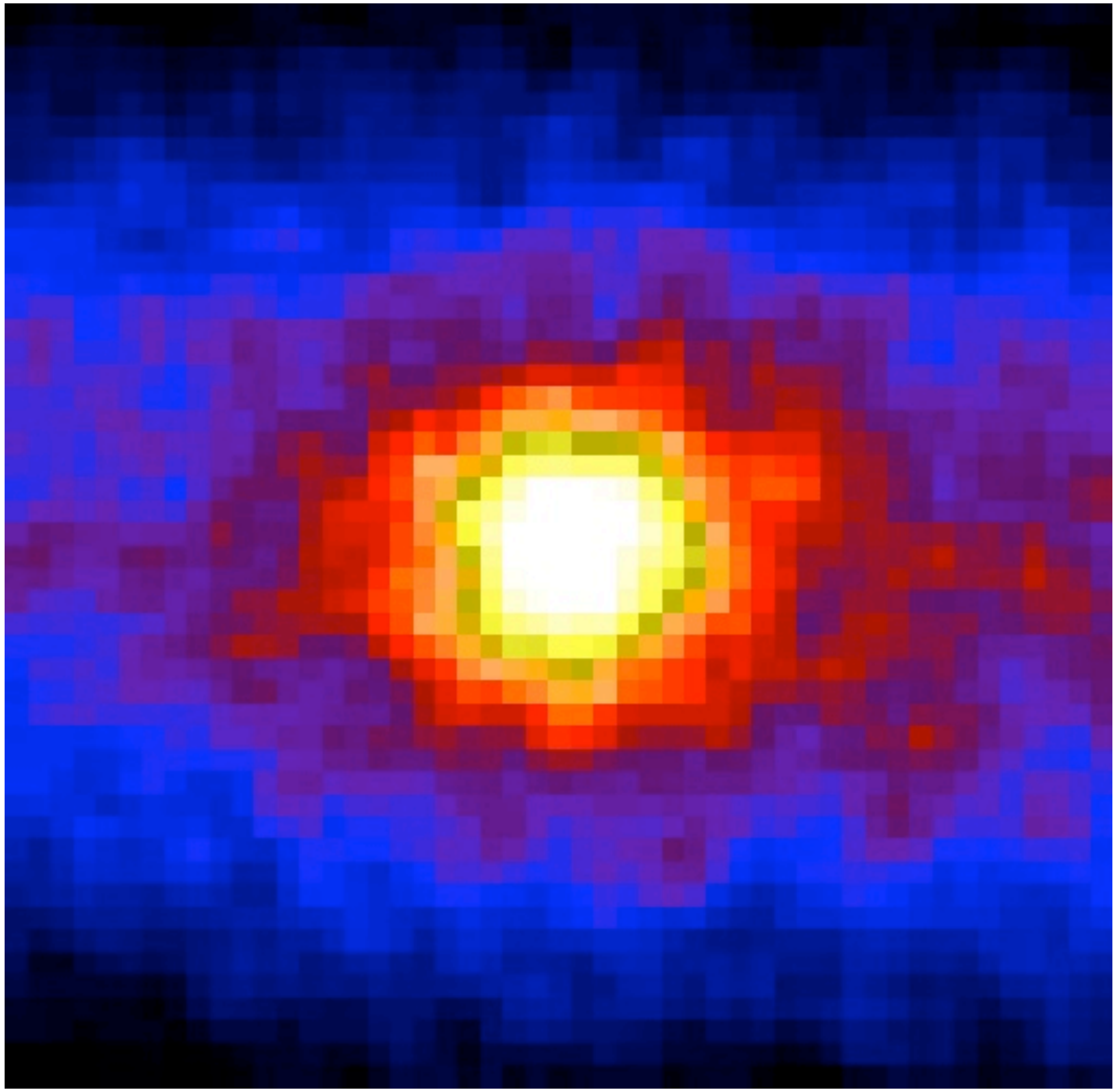
SK & OPERA Tau's
$|U_{\tau 3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS



SuperK

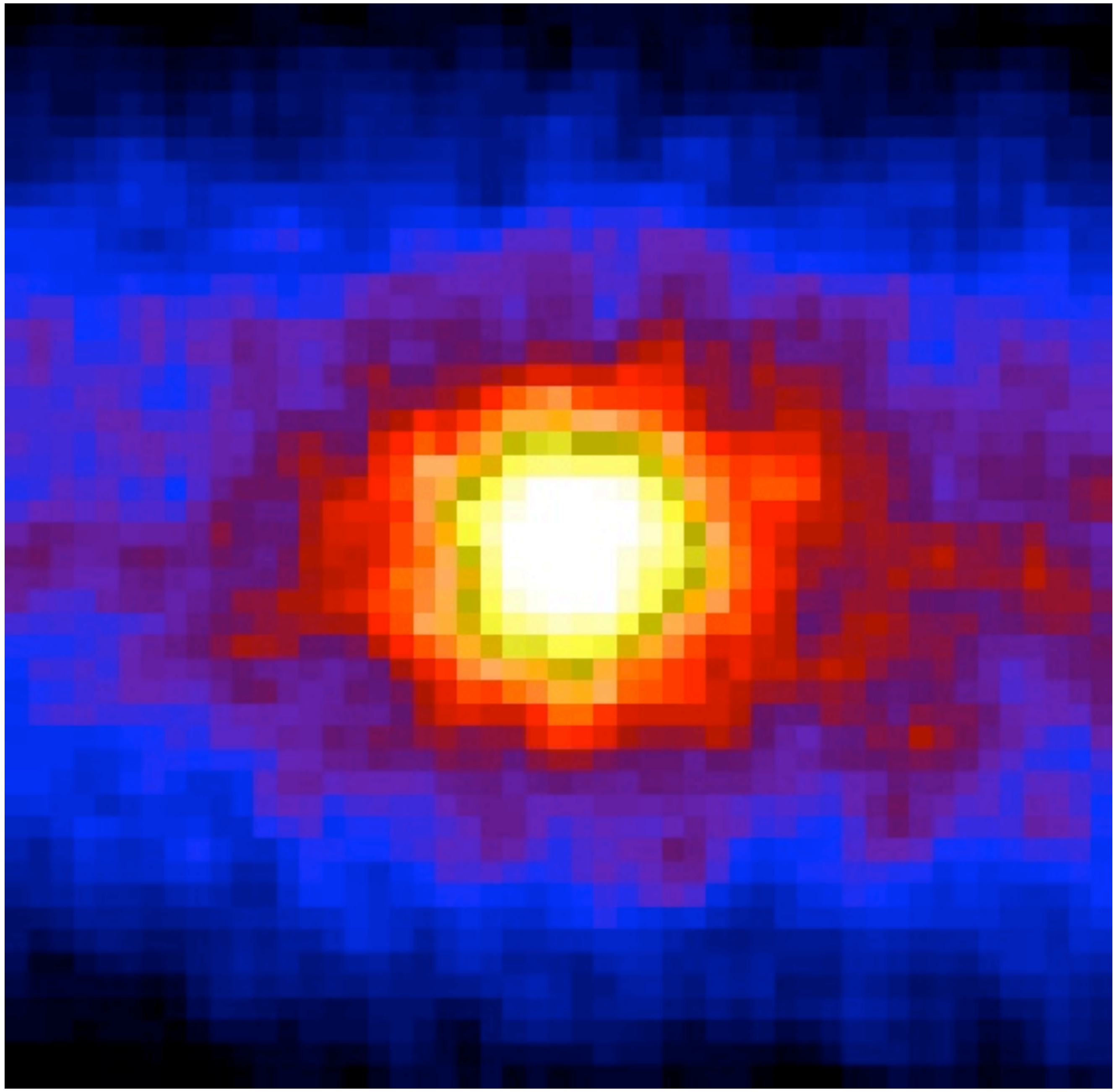


$$\nu_? + e \longrightarrow \nu + e$$

Which Neutrinos ?

SuperK

Flavor
Fraction
76% ν_e's



$$\nu_? + e \longrightarrow \nu + e$$

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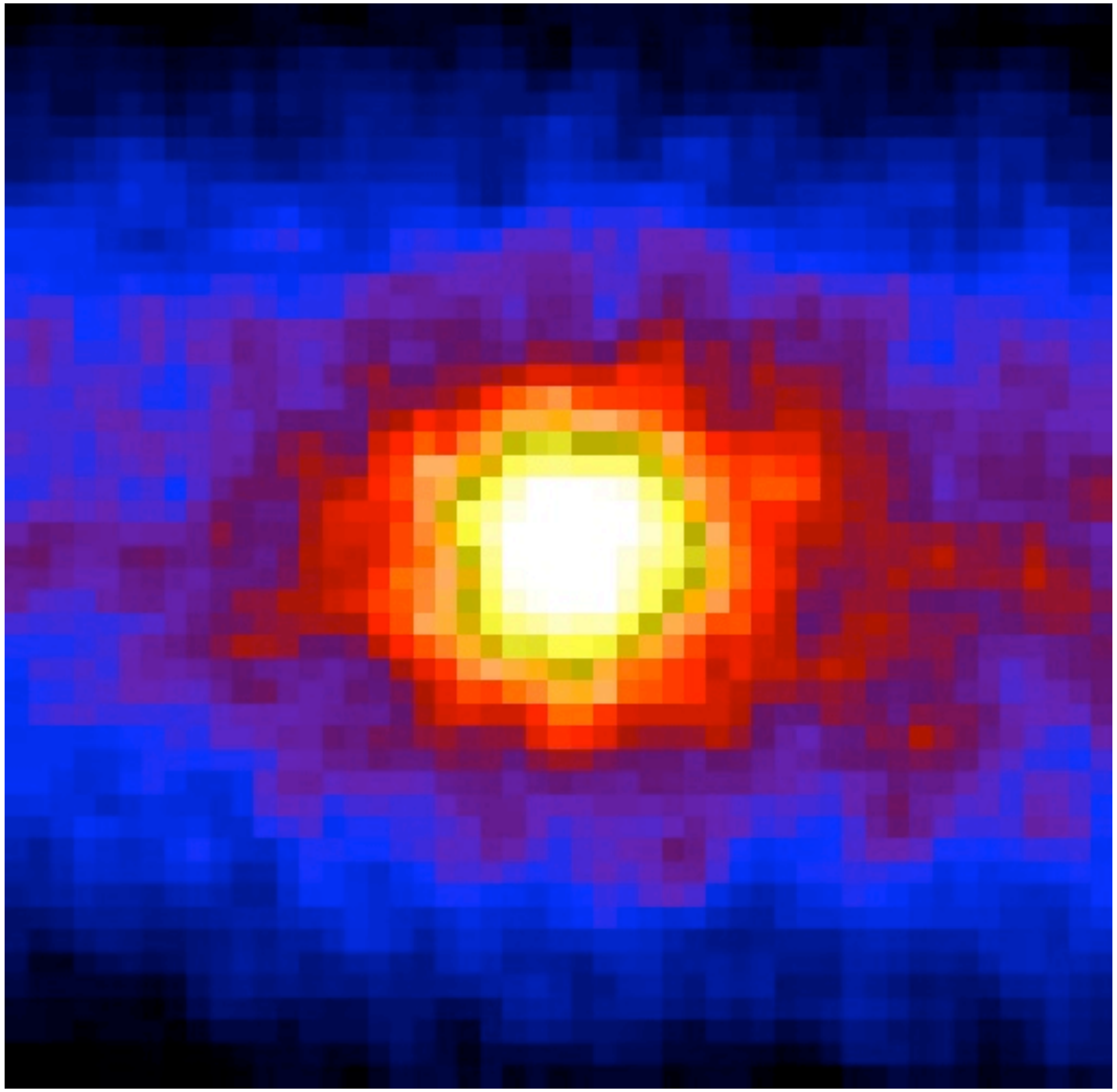
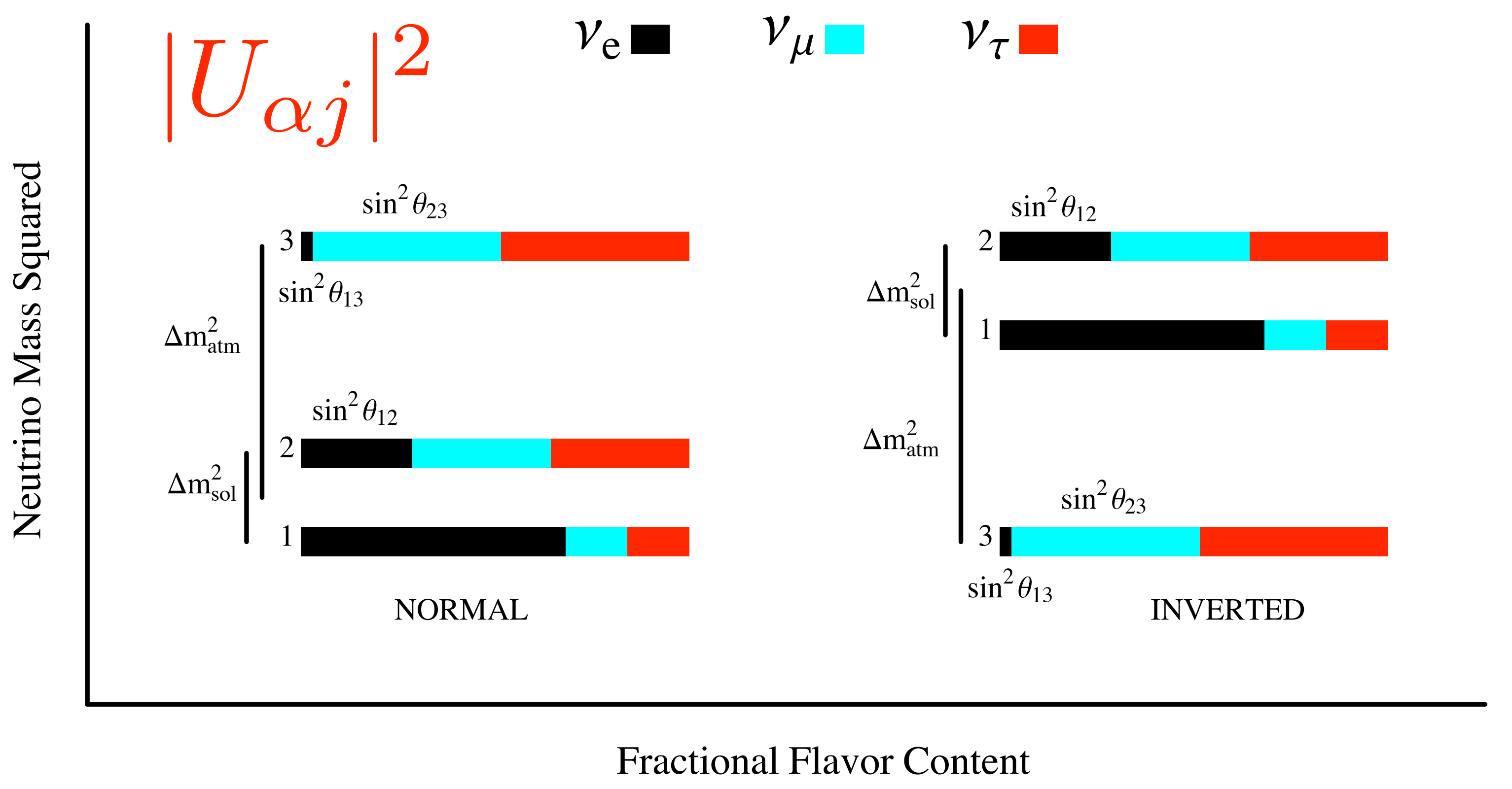


Mass E-state
Fraction
84% ν_2's

$$\nu_? + e \rightarrow \nu + e$$

Which Neutrinos ?

Neutrino Standard Model:



$$\sin^2\theta_{12} \sim \frac{1}{3}$$

$$\sin^2\theta_{23} \sim \frac{1}{2}$$

$$\sin^2\theta_{13} \sim 0.02$$

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

Disappearance Experiments: δm^2_{eff} and $\sin^2 2\theta_{eff}$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2\Delta_{21}$$
$$-4|U_{\alpha 3}|^2(1-|U_{\alpha 3}|^2)\left\{r_a \sin^2\Delta_{31} + (1-r_\alpha)\sin^2\Delta_{32}\right\}$$

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

$$\text{where } \; r_\alpha = \frac{|U_{\alpha 1}|^2}{(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2)}$$

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$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E} \qquad \text{where} \;\; r_\alpha = \frac{|U_{\alpha 1}|^2}{(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2)}$$

For $\Delta_{31} - \Delta_{32} = \Delta_{21} \ll 1$ Trig. ID

$$r_\alpha \sin^2\Delta_{31} + (1-r_\alpha)\sin^2\Delta_{32} = \sin^2(r_\alpha\Delta_{31} + (1-r_\alpha)\Delta_{32}) + \mathcal{O}(\Delta^2_{21})$$

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$$= \sin^2(x\Delta_{31} + (1 - x)\Delta_{32}) + \mathcal{O}(\Delta_{21}) \text{ for } x \neq r_\alpha$$

Disappearance Experiments: δm^2_{eff} and $\sin^2 2\theta_{eff}$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2\Delta_{21}$$
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$$= \sin^2(x\Delta_{31} + (1-x)\Delta_{32}) + \mathcal{O}(\Delta_{21}) \text{ for } x \neq r_\alpha$$

Daya Bay: $\sin^2\Delta_{ee} \equiv c^2_{12}\sin^2\Delta_{31} + s^2_{12}\sin^2\Delta_{32}$, Which L/E ?

Disappearance:

$\Longrightarrow$ near the 1st Oscillation Minimum,

where $\Delta_{31} \approx \pi/2$ and therefore $\Delta_{21}^2 \approx 3 \times 10^{-3}$

- Three flavor effects are invisible until $\Delta P < 0.003$

  Use: $P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\delta m^2_{\alpha\alpha} L}{4E} + \mathcal{O}(\Delta_{21}^2)$

  - where the effective δm^2 measured is

    $\delta m^2_{\alpha\alpha} \equiv r_\alpha |\delta m^2_{31}| + (1 - r_\alpha)|\delta m^2_{32}|$

    ν_α weighted average of $|\delta m^2_{31}|$ and $|\delta m^2_{32}|$

  - and the effective mixing angle, $\theta_{\alpha\alpha}$ is given by

    $\sin^2 2\theta_{\alpha\alpha} \equiv 4|U_{\alpha 3}|^2(1 - |U_{\alpha 3}|^2)$

defined in Nunokawa, Zukanovich Funchal and SP: hep-ph/0503283

Disappearance Experiments:

$\boldsymbol{\nu_\mu \longrightarrow \nu_\mu}$

$\mathbf{4|\boldsymbol{U_{\mu 3}}|^2(1 - |\boldsymbol{U_{\mu 3}}|^2)}$: hard to get precision on $|U_{\mu 3}|^2$ near 1/2

the Δm^2 measured is ν_μ weighted average of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$

$\boldsymbol{\bar{\nu}_e \longrightarrow \bar{\nu}_e}$

precision measurement of $|U_{e3}|^2$ and $|U_{e2}|^2$

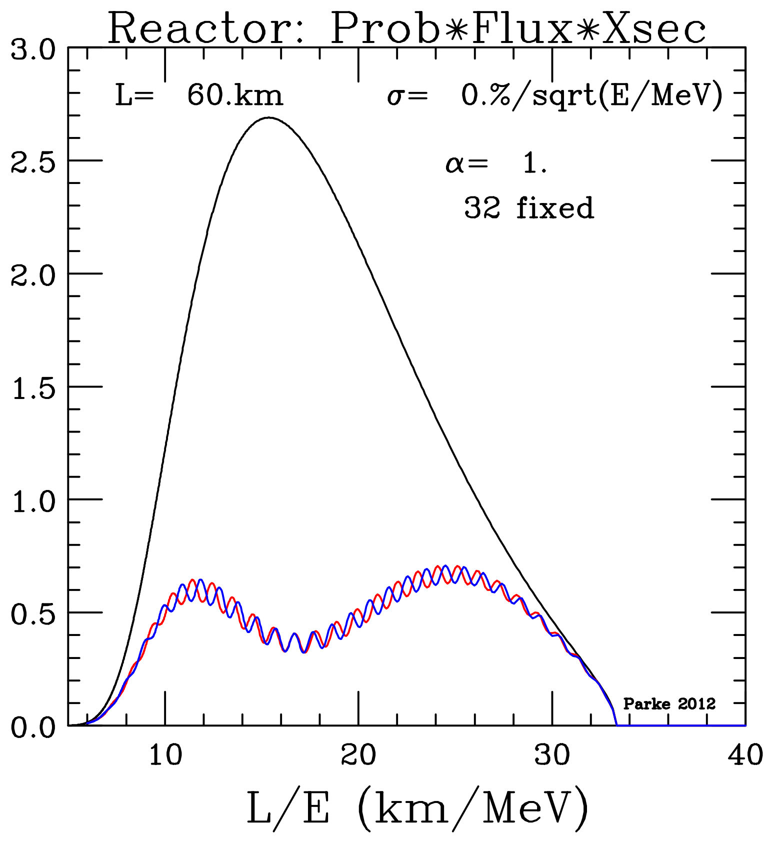
Mass Hierarchy is very challenging!!!

Reactors Experiments at 50-60km

- Precision measurement of $\sin^2\theta_{12}$
- Mass Hiearchy?

Reactors Experiments at 50-60km

- Precision measurement of $\sin^2\theta_{12}$
- Mass Hiearchy?



Reactors Experiments at 50-60km

- Precision measurement of $\sin^2 \theta_{12}$
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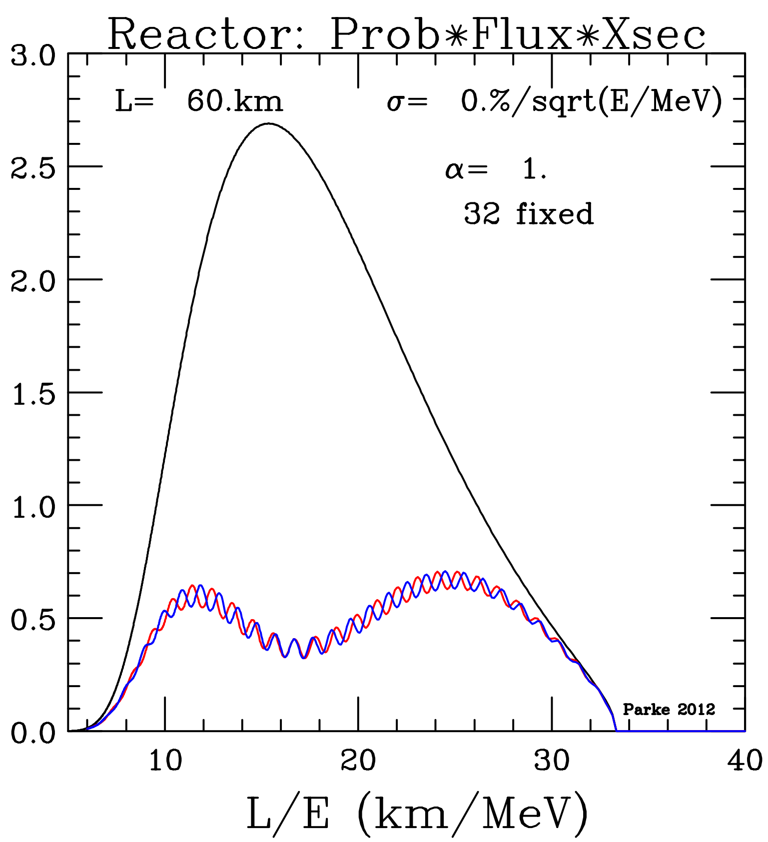
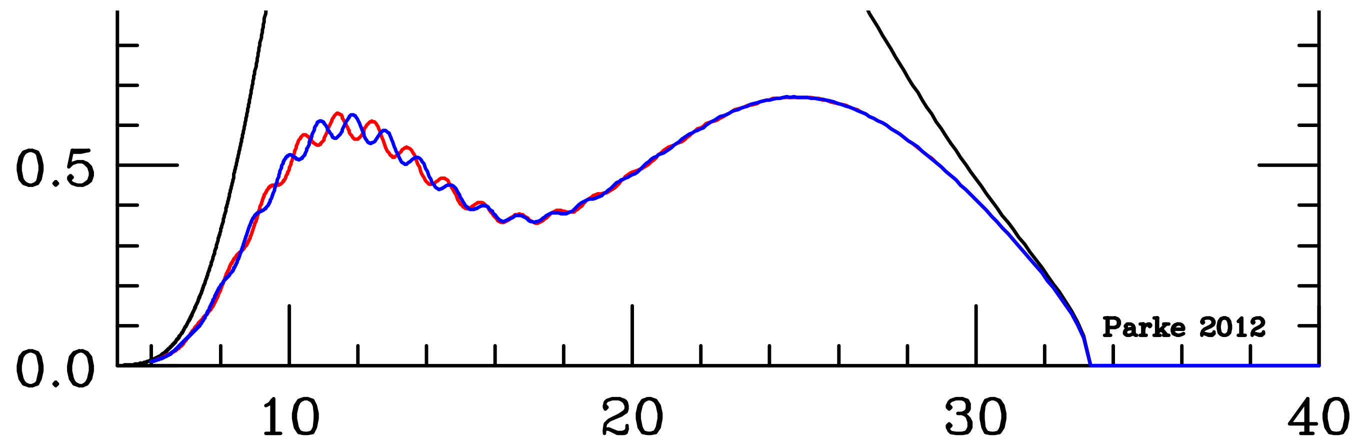
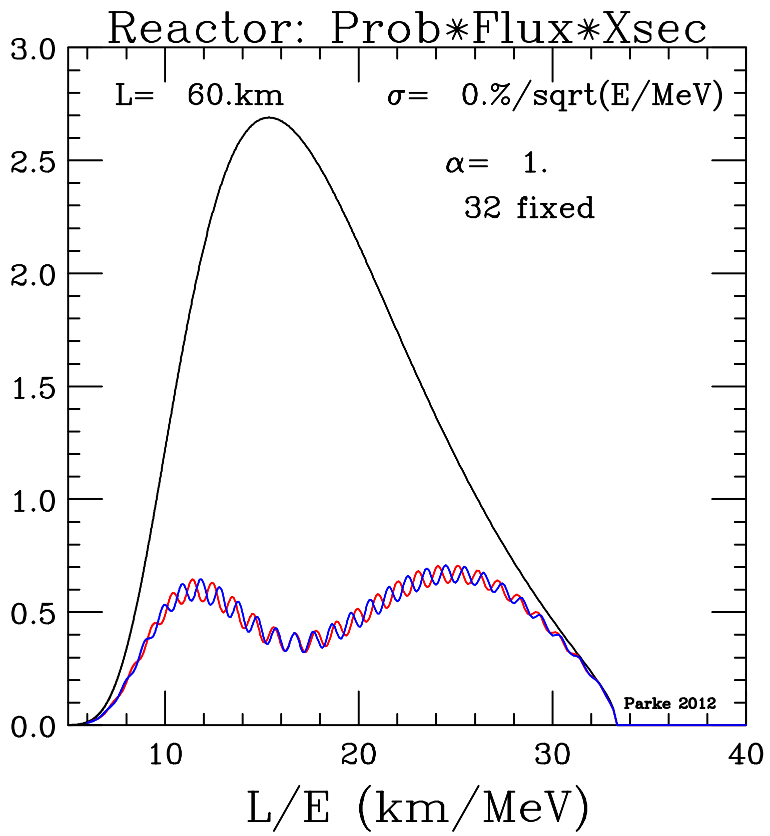


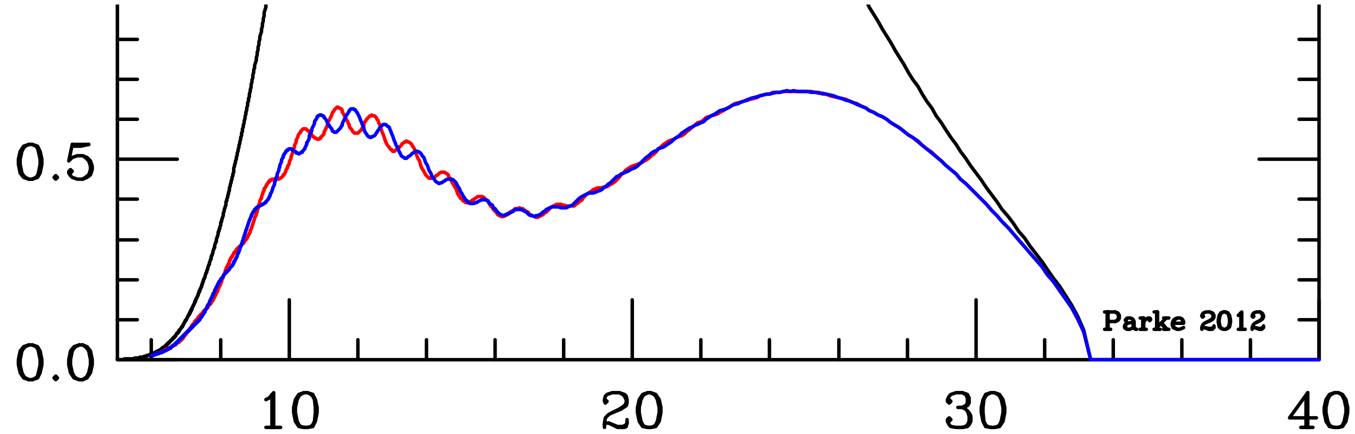


32 fixed

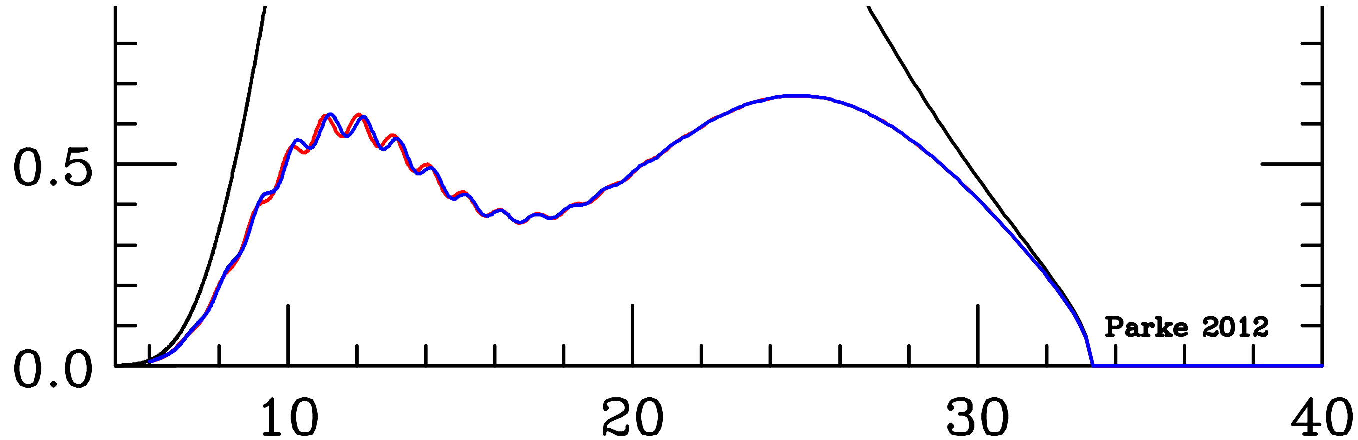
Reactors Experiments at 50-60km

- Precision measurement of $\sin^2\theta_{12}$
- Mass Hiearchy?



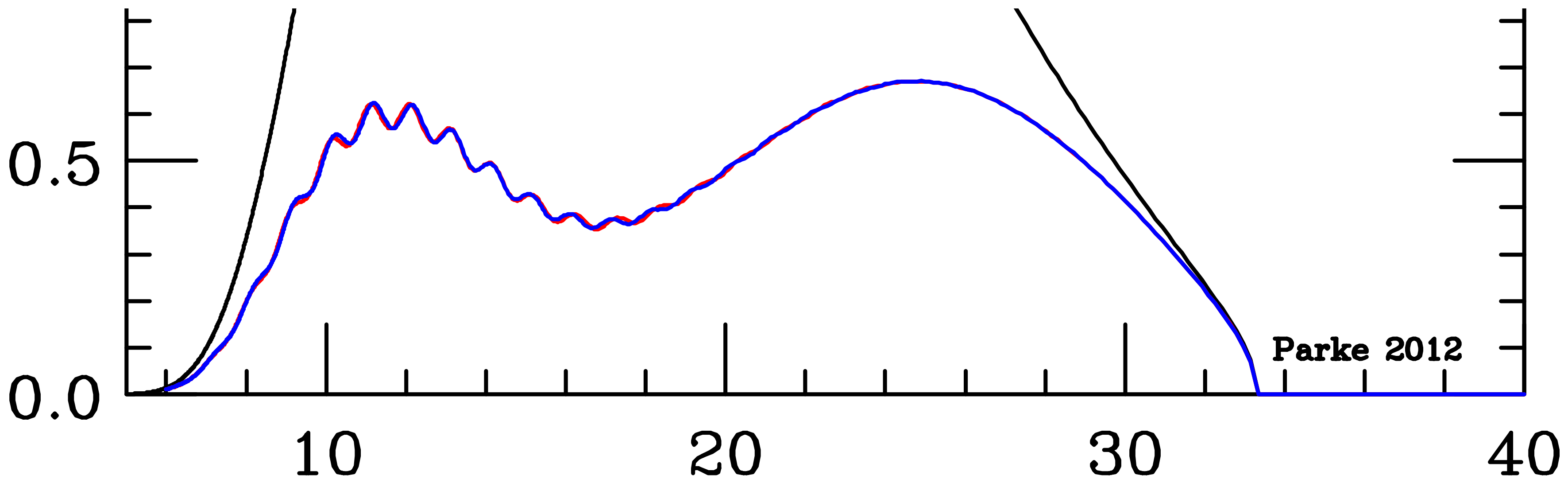


32 fixed



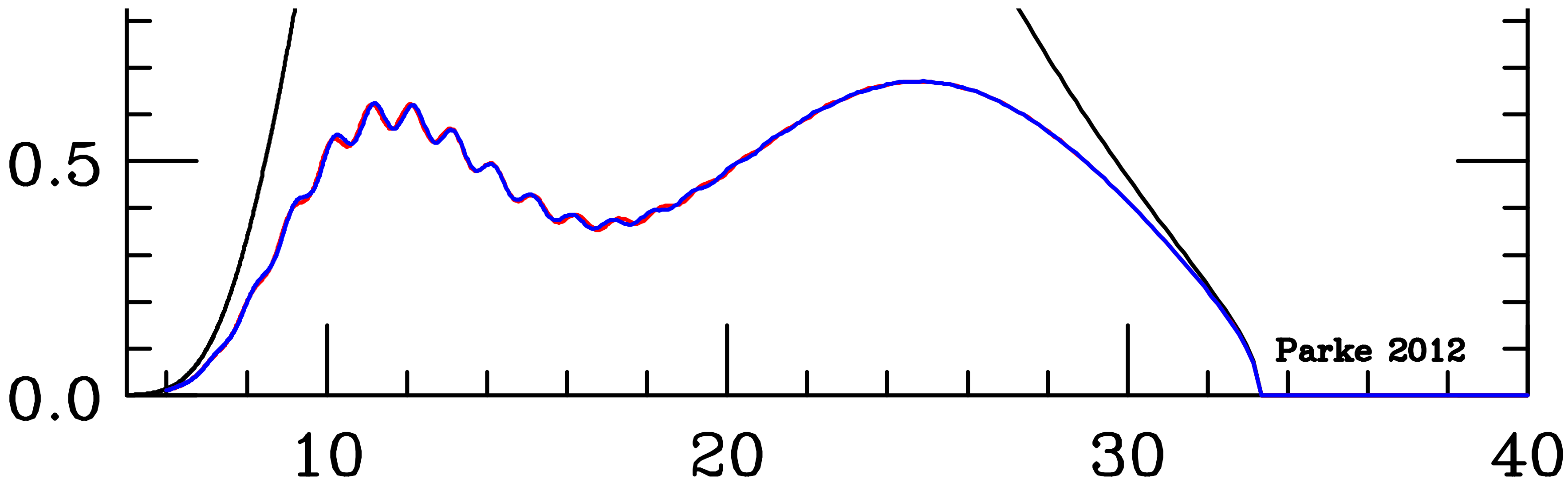
31 fixed

Float between these Two:



float within uncertainities

Float between these Two:



float within
uncertainities

Constraining the non-linearity of the detector energy scale at better than 1% is required!

KamLAND achieved 1.9%

see arXiv:1208.1551

Variation of Flavor Content & CPV:

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