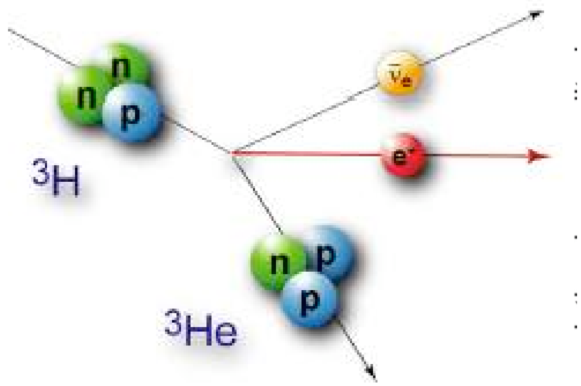
More ν's: Nu Worlds



Stephen Parke
Fermilab

March 2, 2006

http://theory.fnal.gov/people/parke/TALKS/2006/

Hierarchy from ν_μ Disappearance:

$$1 - P(\nu_\mu \to \nu_\mu) = P(\nu_\mu \to \nu_\tau) + P(\nu_\mu \to \nu_e)$$

$\Uparrow$ sub leading matter effect

$\Uparrow$ leading matter effect from $\sin^2 2\theta_{13}$

$$\sin^2 2\theta_{13} = 0.1$$

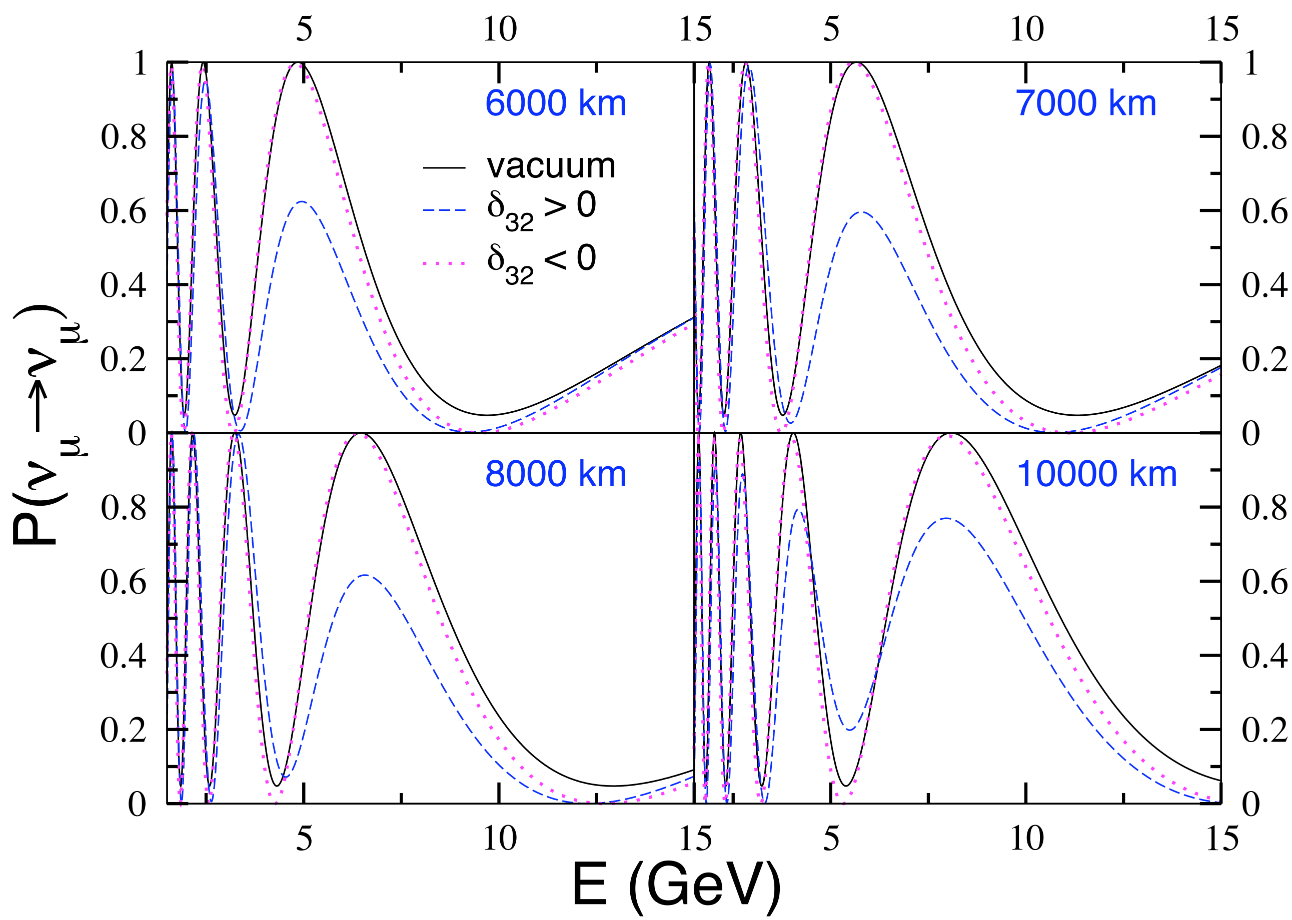
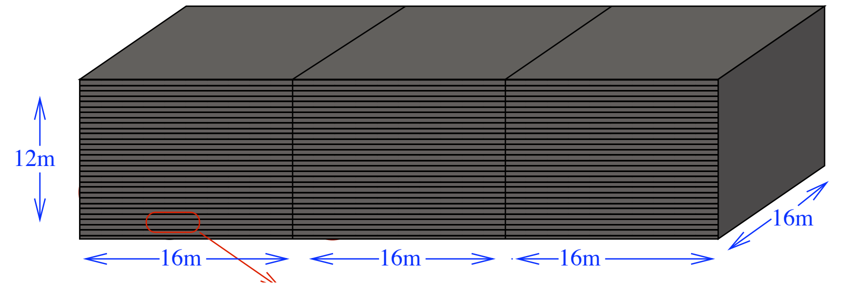


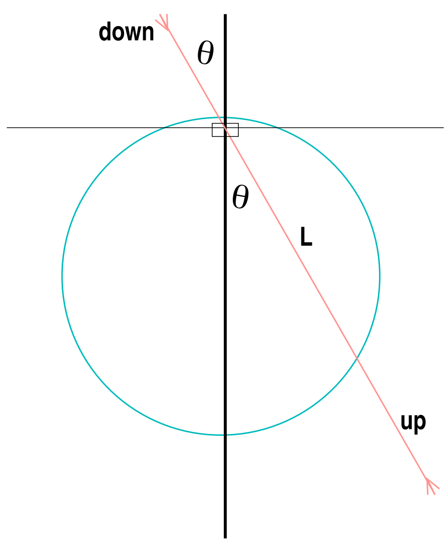
Figure 3.5: The muon survival probability in vacuum and in matter for both signs of δ_{32} plotted against the neutrino energy for different values of baseline lengths, L (in km). The oscillation parameters used in all the plots are : $\delta_{32} = 2 \times 10^{-3} eV^2$ and $\sin^2 2\theta_{23} = 1$.

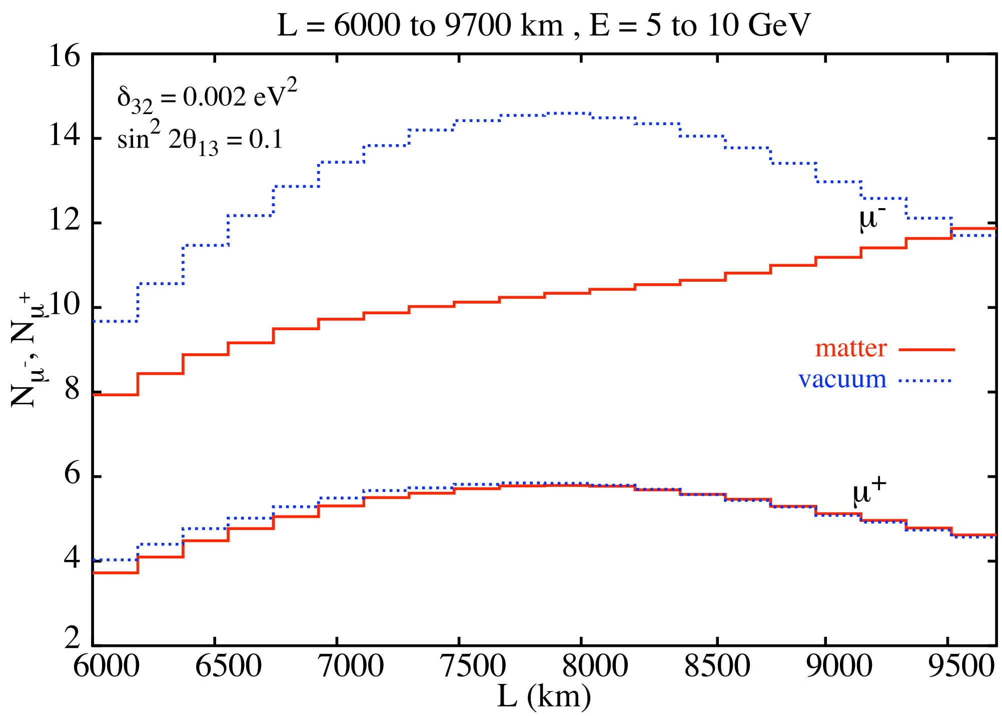
energy range 5–10 GeV and L range 6,000–9,700 km.

INO:

Magnetised Iron Calorimeter







4σ signal at $\sin^2 2\theta_{13} = 0.1$ with 1000 kton-yrs

Absolute Neutrino Mass:

Cosmology: $\sum m_k < \ \sim 1$ eV

Tritium: $m_k < \ \sim 1$ eV

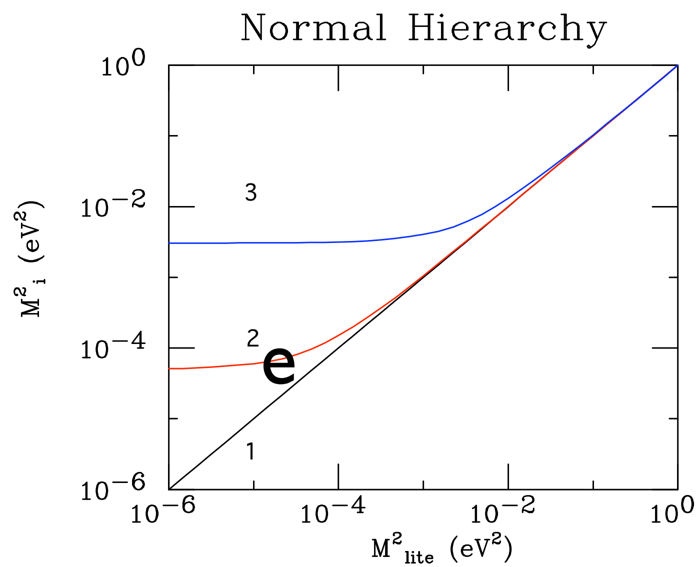
SN1987a: $m_k < \ \sim 10$ eV

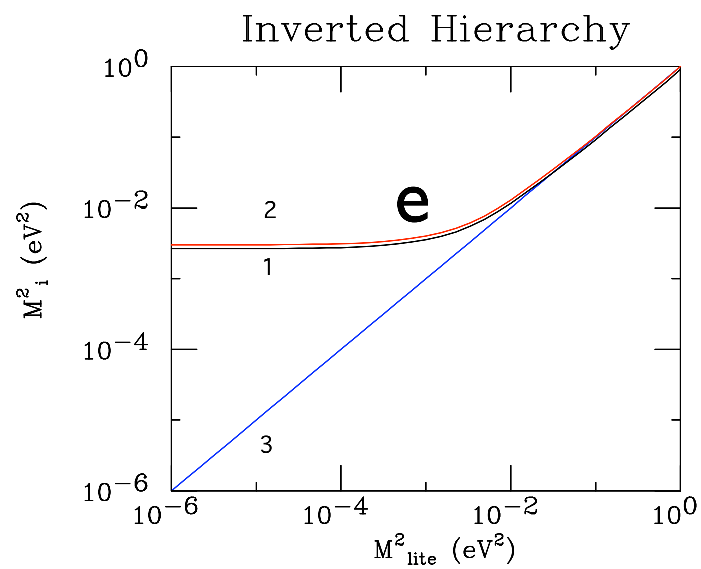
at least one neutrino: $m_H > \sqrt{\delta m^2_{atm}} \approx 0.05$ eV

at least two neutrinos: $m_H \ \& \ m_M > \sqrt{\delta m^2_{sol}} \approx 0.01$ eV

sum neutrino masses: $\sum_k m_k > \sqrt{\delta m^2_{atm}} \approx 0.05$ eV

lightest neutrino: m_{lite}





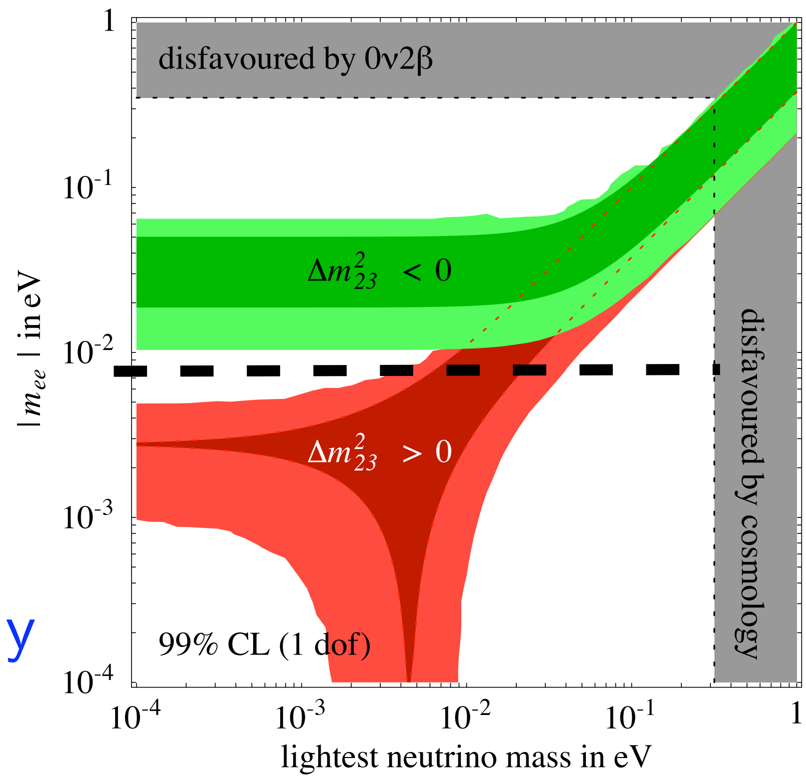
States 1 and 2 are ν_e rich.

Neutrinoless double beta decay

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

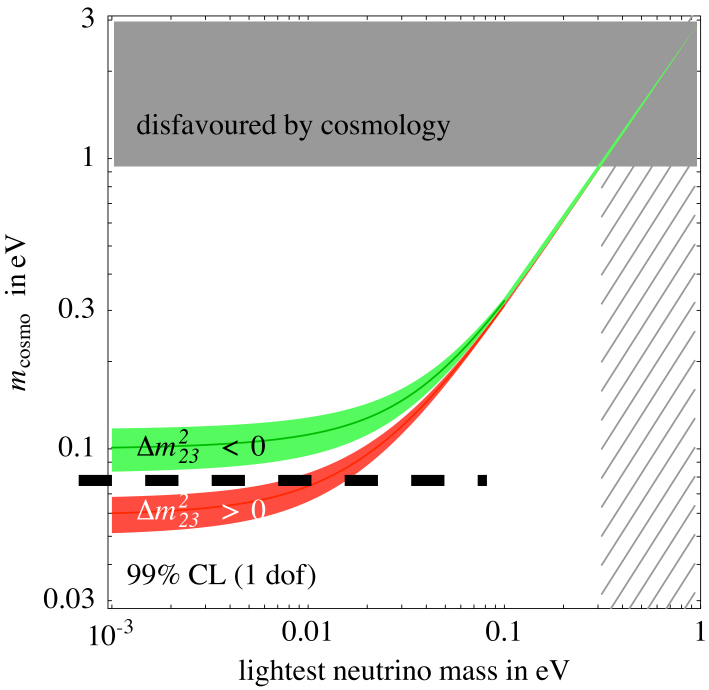
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

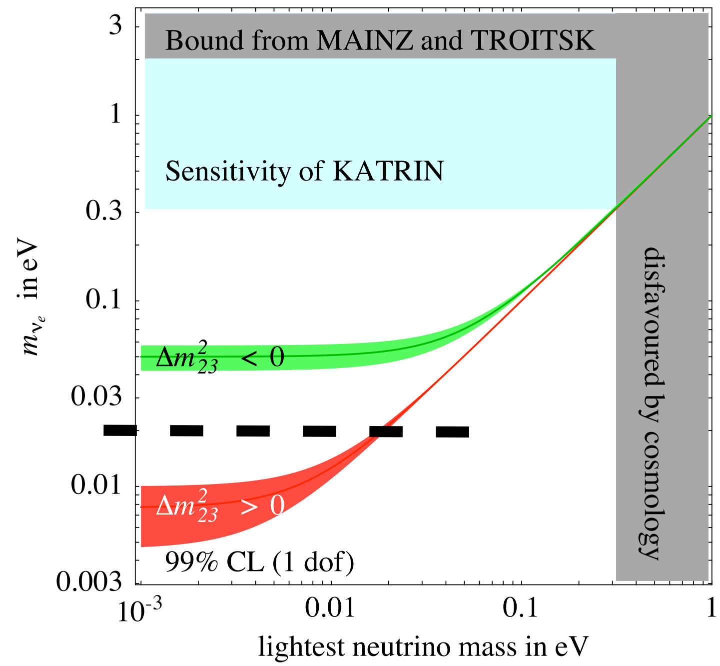
dividing point $m_{\beta\beta} \approx 10meV$ $\Rightarrow\Rightarrow$



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

: $\sum m_i$



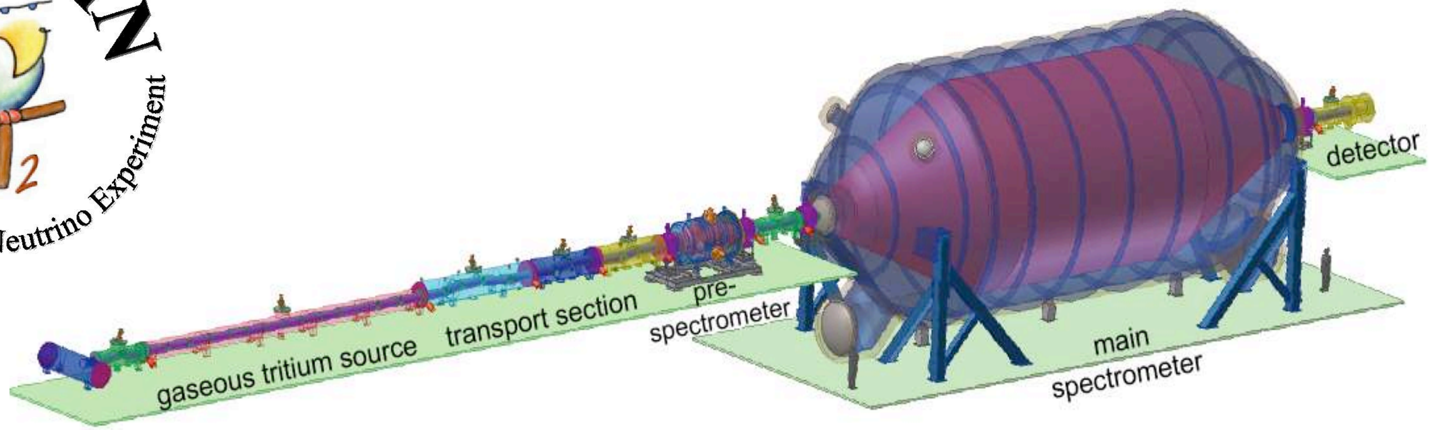


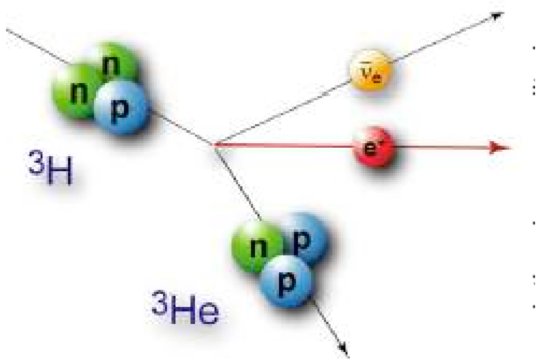
Similarly, if Tritium decay exp. (Hyper-Katrin) could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, then Normal Hierarchy.

these 3 figs from Strummia and Vissani hep-ph/0503246

KATRIN

Karlsruhe Tritium Neutrino Experiment



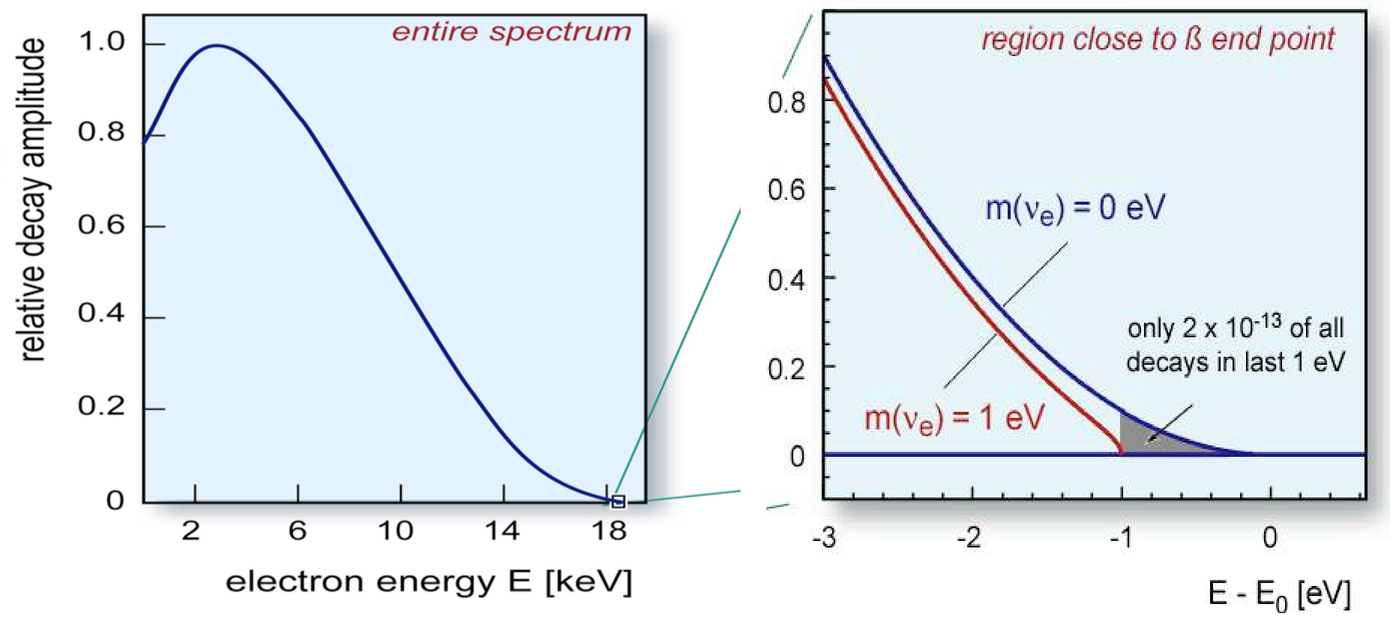


Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)

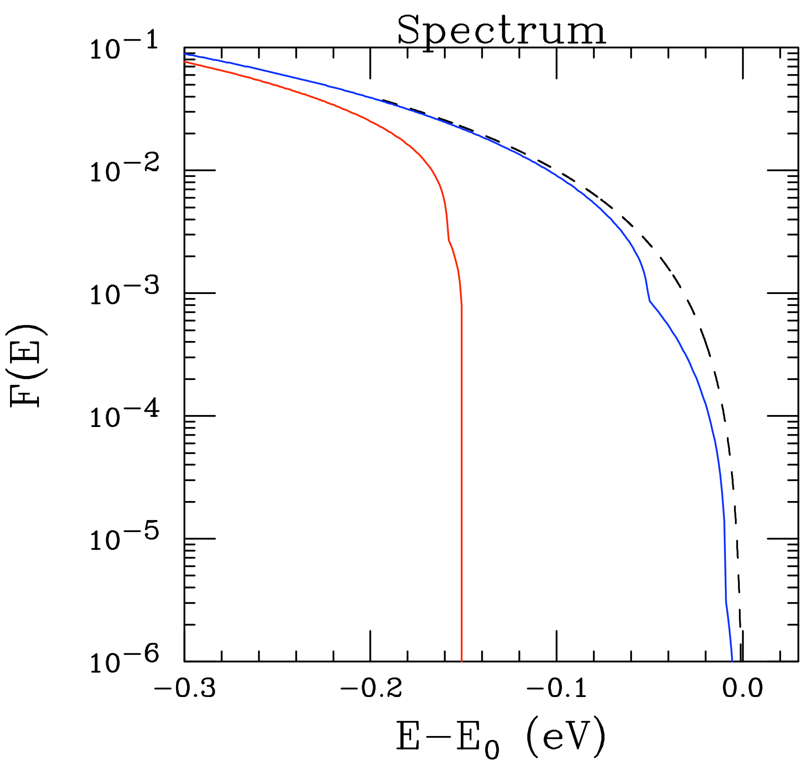


Decay Rate:

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$



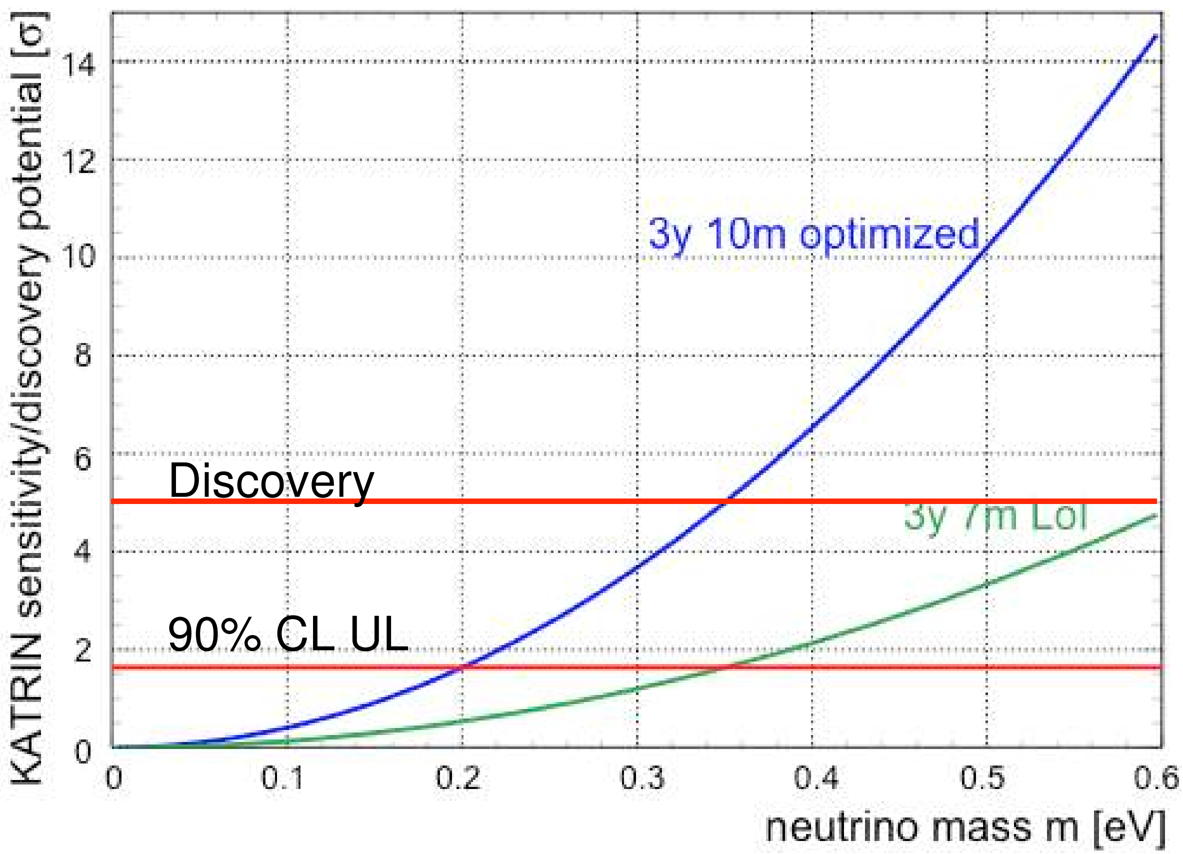
E_0=18 KeV

Decay Rate:

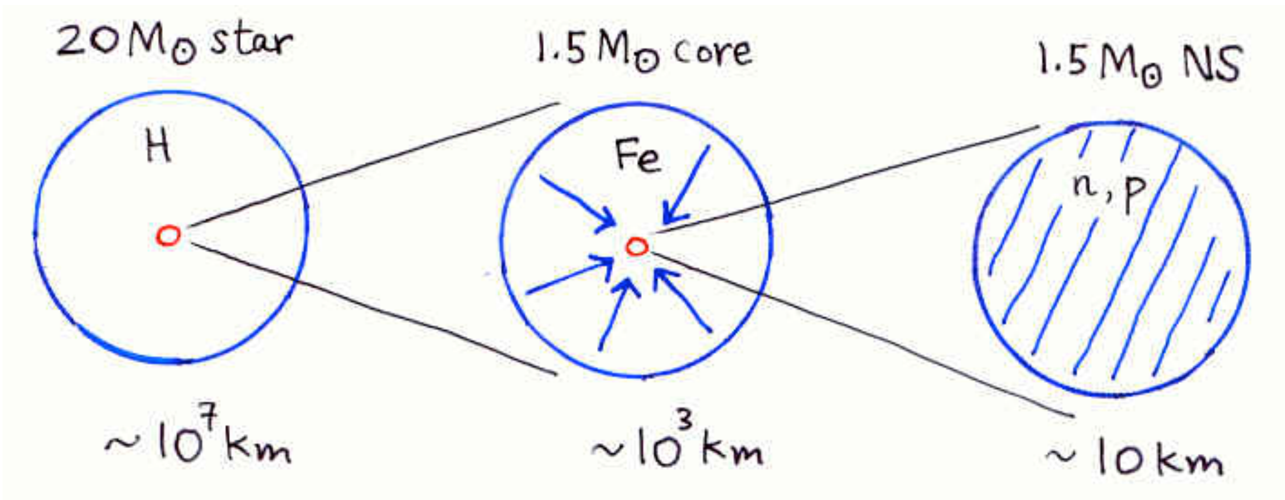
$$|\langle ^3He + e^- + \bar{\nu}|T|^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle ^3He + e^- + \bar{\nu}|T|^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$


KATRIN sensitivity/discovery potential [σ]
neutrino mass m [eV]
3y 10m optimized
3y 7m LoI
Discovery
90% CL UL
0
2
4
6
8
10
12
14
0
0.1
0.2
0.3
0.4
0.5
0.6

Supernova SN1987a:

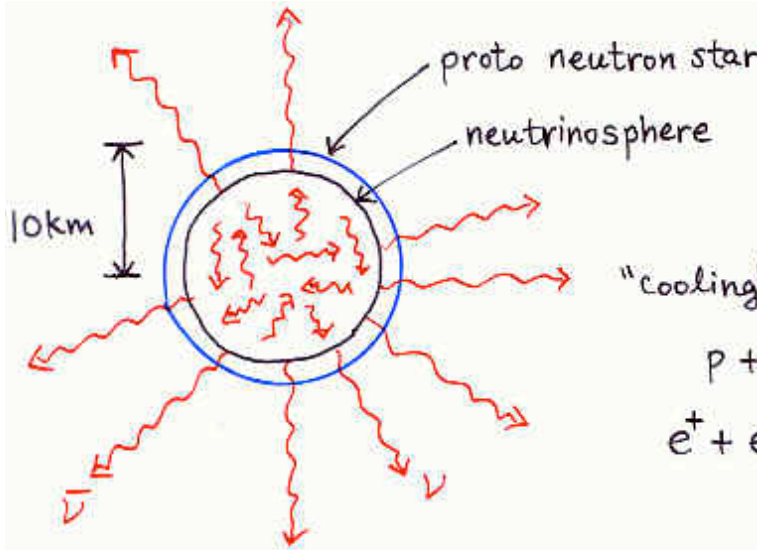


$$\Delta E_B \simeq \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{NS}^2}{R_{core}} \simeq 3\times10^{53}\ \text{ergs} \simeq 2\times10^{59}\ \text{MeV} \sim \frac{1}{10}m_\odot c^2$$

K.E. of explosion $\simeq 10^{-2}\,\Delta E_B$

E.M. radiation $\simeq 10^{-4}\,\Delta E_B$

ν radiation $0.99\Delta E_B$



"cooling" by neutrino emission :

$$p + e^- \longrightarrow n + \nu_e$$

$$e^+ + e^- \longrightarrow \nu_e + \bar{\nu}_e,\ \nu_\mu + \bar{\nu}_\mu,\ \nu_\tau + \bar{\nu}_\tau$$

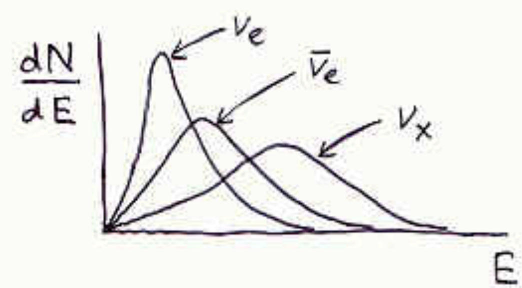
etc.

diffusion until $\lambda = 1/\rho\sigma$ from surface, then escape

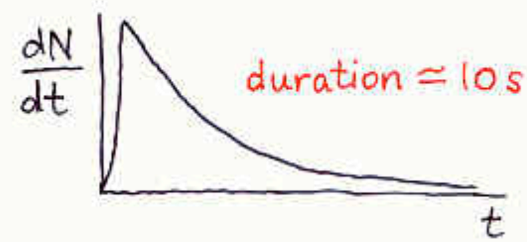
$\langle E_{\nu_e} \rangle \simeq 11$ MeV

$\langle E_{\bar{\nu}_e} \rangle \simeq 16$ MeV

$\langle E_{\nu_x} \rangle \simeq 25$ MeV

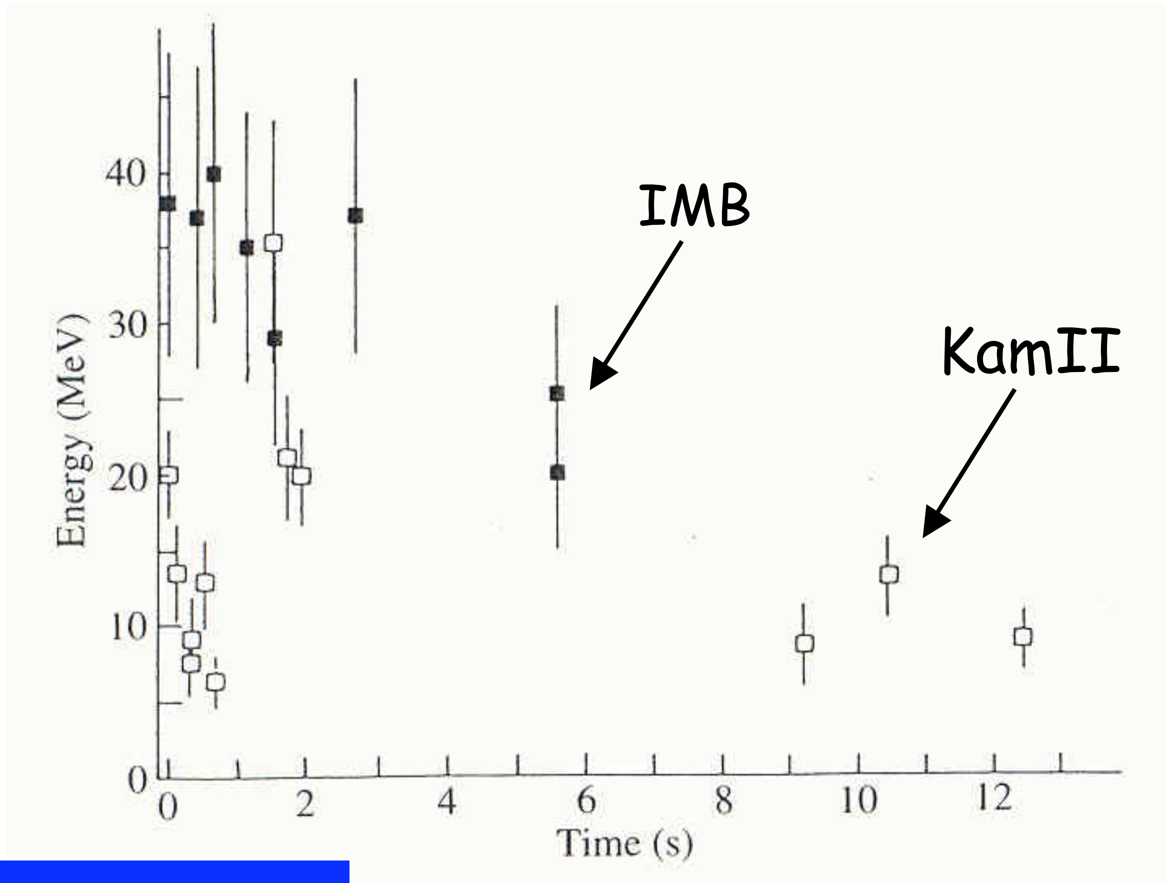


$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t)$



SN1987A :

~ 20 $\bar{\nu}_e p \rightarrow e^+ n$ events



SN200?? :

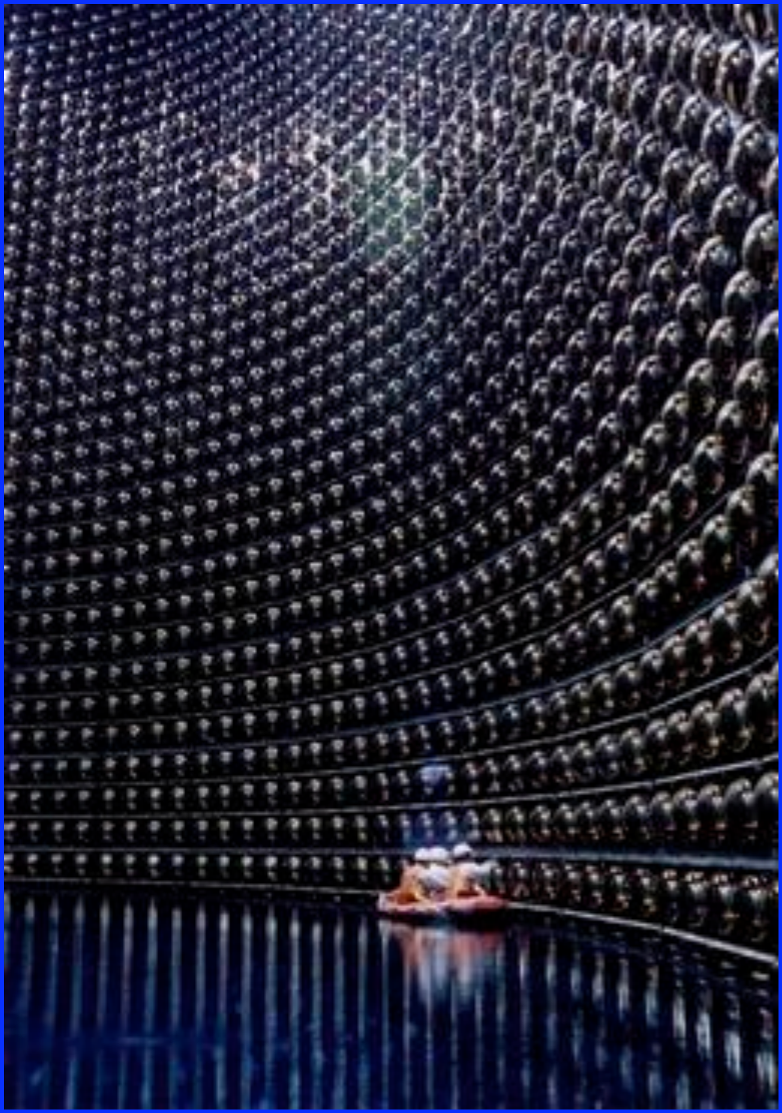
~ 10^4 CC events

~ 10^3 NC events

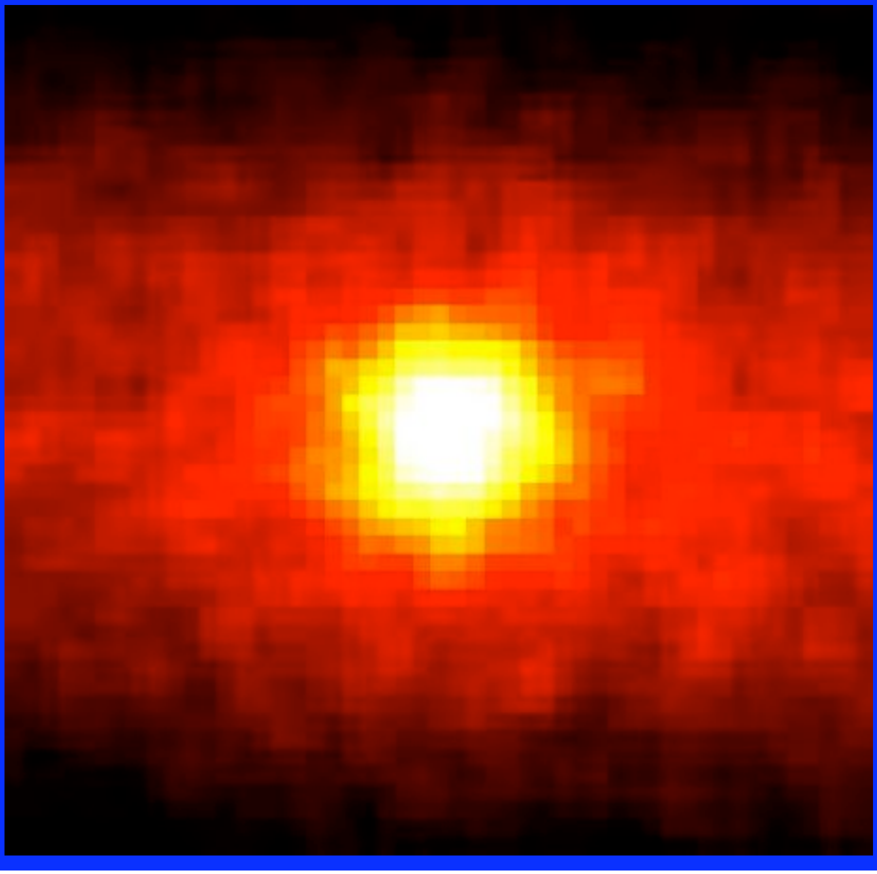
Supernova physics (models, black holes, progenitors…)

Particle physics (neutrino properties, new particles, …)

Super-Kamiokande



e^- , e^+ , γ
convert to Cerenkov light



Detection Yields

Assume a Galactic supernova at 10 kpc

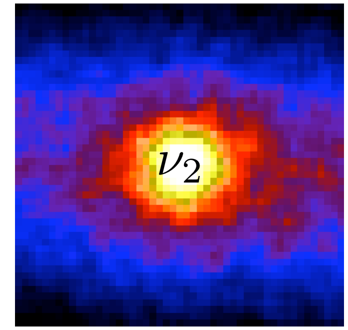
Yields in 22.5 kton Super-Kamiokande:

$\simeq 8000$	$\bar{\nu}_e + p \to e^+ + n$	
$\simeq 700$	$\nu + {}^{16}O \to \nu + \gamma + X$	$(E = 5 - 10\ \mathrm{MeV})$
$\simeq 300$	$\nu + e^- \to \nu + e^-$	(e^- is forward)
~ 100	$\nu_e + {}^{16}O \to e^- + X$	(buried)
	$\bar{\nu}_e + {}^{16}O \to e^+ + X$	

~ 1 kton detectors: SNO, KamLAND, MiniBooNE

~ 1 Gton (but very noisy) detector: IceCube

SOLAR NEUTRINOS:

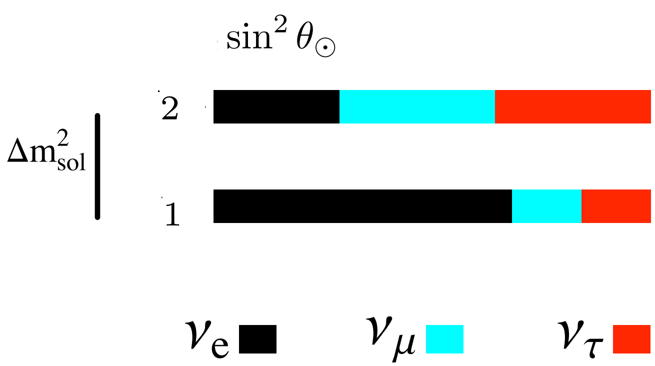


The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

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

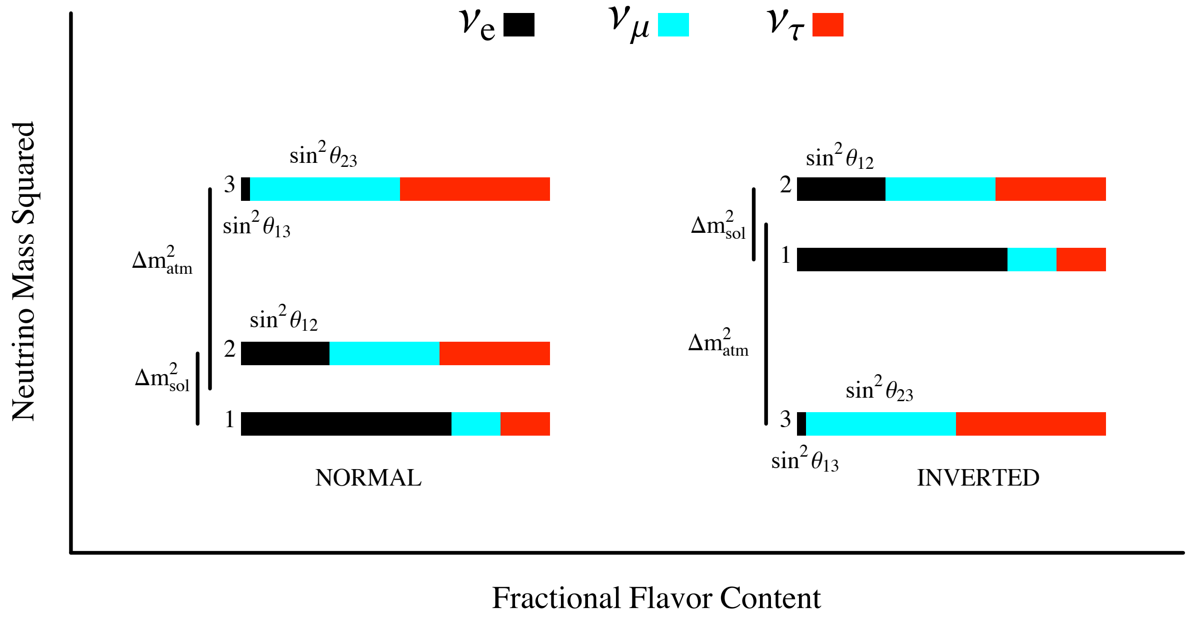
$f_2 = 91 \pm 2\%$ and $f_1 = 9 \mp 2\%$ with $P_{ee} \approx 0.35$.



$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5} eV^2$$
$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

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



- Fraction ν_e in ν_3: $\sin^2\theta_{13}$
- Mass Hierarchy: sign δm^2_{31}
- CP Violation: $\sin\delta_{CP}$

Reactor $(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

- Size $\sin^2\theta_{13}$
- Mass Hierarchy $m_3 > or < m_1, m_2$
- Is $\sin\delta_{CP} \neq 0$??? CP violation !!!

Long Baseline $(\nu_\mu \rightarrow \nu_e)$

$\mathbf{\sin^2\theta_{23}\sin^2 2\theta_{13}}$ verses $\mathbf{\sin^2 2\theta_{13}}$

- Mass Hierarchy $m_3 > or < m_1, m_2$

NOvA or NOvA+T2K or T2KK

- Is $\sin\delta_{CP} \neq 0$??? CP violation !!!

NOvA or T2K

Absolute Neutrino Mass:

- Neutrinoless Double β Decay: $\langle m_{\beta\beta} \rangle$
- Tritium End Point: m_H and $|U_{eH}|^2$
- Cosmology: $\sum_k m_k$
- What about m_{lite} ???

Neutrinos are Full of Surprises!!!