Standard scenario: solar $\oplus$ atmos. with 3-ν

Let us assign:

$\Delta m^2_{23} = m^2_3 - m^2_2 = \Delta m^2_{atmos}$, $\Delta m^2_{12} = m^2_2 - m^2_1 = \Delta m^2_{solar}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ — 500km/GeV — Atmos. L/E $\mu \leftrightarrow e$ — Solar L/E $e \to \mu, \tau$ — 15km/MeV — $\beta\beta 0\nu$ decay

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

Solar and atmospheric anomalies approximately decouple as independent 2-by-2 mixing phenomena because

- Hierarchy between the two mass splittings: $|\Delta m^2_{atmos}| \gg |\Delta m^2_{solar}|$
- Small θ_{13}: $\sin\theta_{13} = V_{e3} \quad \leftrightarrow V_{ub}$

I. $E/L \sim \Delta m^2_{23}$:

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \\ P(\nu_e \to \nu_\tau) &= c^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \\ P(\nu_\mu \to \nu_\tau) &= c^4_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \end{aligned}$$

Daya Bay θ_{13} miserably small !!!

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atmos}, \theta_{\rm atmos}),$$

II. $E/L \sim \Delta m^2_{12}$:

$$P(\nu_e \to \nu_e) \simeq c^4_{13} \left(1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12}}{4E} L\right)\right) + s^4_{13}$$

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\rm solar}, \theta_{\rm solar})$$

When solar and atmospheric fits are done in the context of three families nothing changes too much

CP violation in neutrino oscillations

Can I have it ?

Vacuum oscillations ($W^{jk}_{\alpha\beta} \equiv [U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}]$)

$$\begin{aligned} P(\nu_\alpha \quad \to \quad \nu_\beta) &= -4 \sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{4\mathrm{E}_\nu}\right) \\ &\pm \quad 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{2\mathrm{E}_\nu}\right) \end{aligned}$$

CP violation shows up as a difference between $P(\nu_\alpha \to \nu_\beta)$ and $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

By CPT:

$$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

CP and T-odd terms cancel in survival probabilities → need appearance measurements: $\alpha \neq \beta$

Observability of CP-violation ↔ measurable CP-asymmetries:

$$A^{CP}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \quad A^{T}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha)}{P(\nu_\alpha \to \nu_\beta) + P(\nu_\beta \to \nu_\alpha)}$$

$$\begin{aligned} P(\nu_i \to \nu_j) &= P_{CP}(\nu_i \to \nu_j) + P_{\not{CP}}(\nu_i \to \nu_j) \\ P(\bar{\nu}_i \to \bar{\nu}_j) &= P_{CP}(\nu_i \to \nu_j) - P_{\not{CP}}(\nu_i \to \nu_j) \end{aligned}$$

$$P_{CP}(\nu_i \to \nu_j) = \delta_{ij} - 4\mathrm{Re}J^{ji}_{12}\sin^2\Delta_{12} - 4\mathrm{Re}J^{ji}_{23}\sin^2\Delta_{23} - 4\mathrm{Re}J^{ji}_{31}\sin^2\Delta_{31}$$

$$P_{\not{CP}}(\nu_i \to \nu_j) = -8\sigma_{ij} J \sin\Delta_{12}\sin\Delta_{23}\sin\Delta_{31},$$

J → $s_{12}\, c_{12}\, s_{13}\, c^2_{13}\, s_{23}\, c_{23}\, \sin\delta_{\mathrm{CP}}$

$$\begin{aligned} J^{ij}_{kh} &\equiv U_{ik}U^\dagger_{kj}U_{jh}U^\dagger_{hi} \\ \Delta_{ij} &\equiv \Delta m^2_{ij} L/4E \\ \sigma_{ij} &\equiv \sum_k \varepsilon_{ijk} \end{aligned}$$

CP(T)-odd terms the same for all $\alpha \neq \beta$:

$$A^{\mathrm{CP(T)-odd}}_{\nu_\alpha \nu_\beta} = \frac{2 \sin\delta c_{13} \sin 2\theta_{13} \overbrace{\sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E_\nu}}^{\mathrm{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E_\nu}}^{atmos}}{P^{\mathrm{CP-even}}_{\nu_\alpha \nu_\beta}}$$

GIM suppressed in all the Δm^2 and all the angles, because if any of them is zero, the CP-odd phase is unphysical

- Minimize GIM suppression: $E/L \sim \Delta m^2_{atmos}$
- Effects of δ are more significant in subleading transitions: $\nu_e \rightarrow \nu_\mu(\nu_\tau)$:

$$P^{\mathrm{CP-even}}_{\nu_\mu \nu_\tau} = \text{unsuppressed in } \theta_{13} \text{ or } \frac{\Delta m^2_{12} L}{E_\nu}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23}}{4E} L \right)$$

$$A^{\mathrm{CP(T)-odd}}_{\nu_\mu \nu_\tau} \sim \sin 2\,\theta_{13} \frac{\Delta m^2_{12} L}{E_\nu}$$

$$P^{\mathrm{CP-even}}_{\nu_e \nu_\mu(\nu_\tau)} = \text{suppressed in } \theta^2_{13} \text{ or } \left(\frac{\Delta m^2_{12} L}{E_\nu} \right)^2$$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{12}}{4E} L \right)$$

$$A^{\mathrm{CP(T)-odd}}_{\nu_e \nu_\mu(\nu_\tau)} \sim \frac{\Delta m^2_{12} L/E_\nu}{\sin 2\theta_{13}} \text{ or } \frac{\sin 2\theta_{13}}{\Delta m^2_{12} L/E_\nu}$$

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\,L}{2}\right) &&\equiv P^{atmos} \\
&+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\,L}{2}\right) &&\equiv P^{solar} \\
+\tilde{J} \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right) \frac{\Delta_{12}\,L}{2} \sin\left(\frac{\Delta_{23}\,L}{2}\right) &&\equiv P^{inter}
\end{aligned}
$$

$$(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu} \ )$$

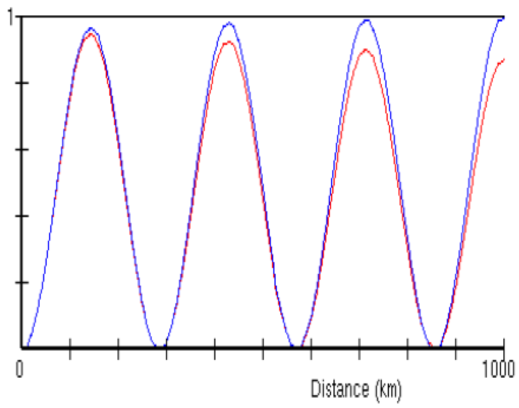
$$P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12} L}{\sin 2\theta_{13}}$$

$$P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12} L}$$

$$P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)$$

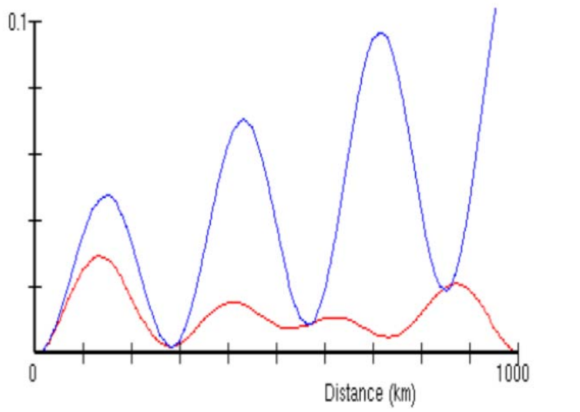
$E_\nu = 500$ MeV $\quad \theta_{13} = 8^\circ \quad \delta = 90^\circ$

$P_{\nu_\mu \to \nu_\tau}$ vs. $P_{\bar\nu_\mu \to \bar\tau_\mu}$



$E_\nu = 500$ MeV $\quad \theta_{13} = 8^\circ \quad \delta = 90^\circ$

$P_{\nu_e \to \nu_\mu}$ vs. $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$



The challenge

We need to measure for the first time small oscillation probabilities: need more intense and purer ν sources

- **Superbeams** ν from K, π decay

$$\pi, K \to \quad \nu_\mu \quad O(1\%)\, \nu_e\ \bar{\nu}_\mu;$$
$$\nu_\mu \quad \to \nu_e \to e^-$$
$$\nu_e \to \nu_e \to e^-$$

- **Neutrino factory** ν from muon decay

$$\mu^- \to e^- \quad \nu_\mu \quad \bar{\nu}_e\,;$$
$$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$$
$$\nu_\mu \quad \to \nu_\mu \to \mu^-$$

- **β-beams** from boosted heavy ions decays

$$^6He^{++} \to^6_3 Li^{+++}\ e^- \qquad \bar{\nu}_e$$
$$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$$

Matter Effects

The oscillation probabilities for three neutrino mixing in matter are not very illuminating. A particularly useful approximation is obtained for $E/L \sim \Delta m^2_{23}$ and to second order in the two small parameters: θ_{13} and Δm^2_{12} :

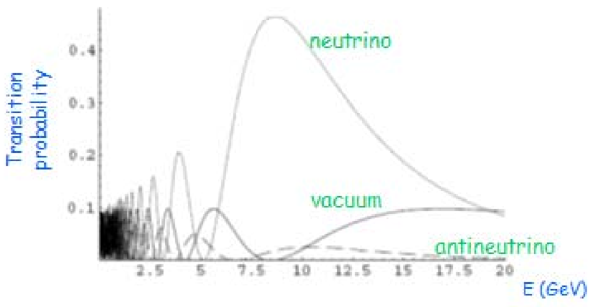
$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\,\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\ \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+c^2_{23}\,\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin(\frac{AL}{2})\,\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\ \cos\left(\pm\delta - \frac{\Delta_{13}L}{2}\right)$$

$$B_\pm = |A \pm \Delta_{13}| \qquad \Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

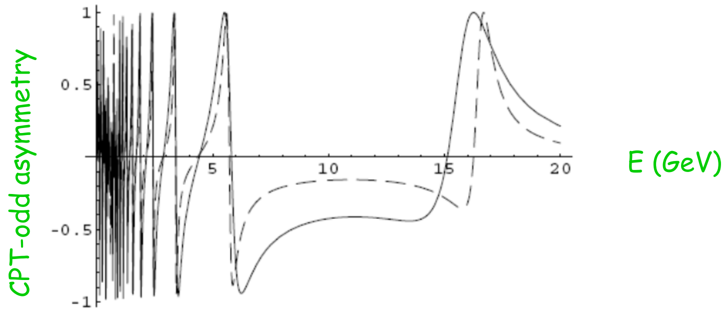
There is an MSW effect in θ_{13}! There is a huge enhancement of the ν or $\bar{\nu}$ (depending on the sign of Δm^2_{23}) channel if:

$$2E_\nu A \sim |\Delta m^2_{13}|, \qquad E_\nu \sim 10 - 20GeV$$

$$\sin^2(2\tilde{\theta}_{13}) \;=\; \frac{4s^2_{13}c^2_{13}\left(\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2}{\left(E - \cos 2\theta_{13}\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2 + 4s^2_{13}c^2_{13}\left(\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2}$$



For very long baselines and atmospheric neutrinos...

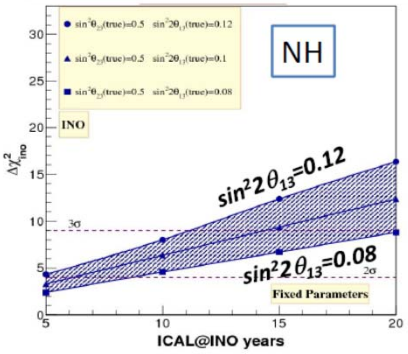


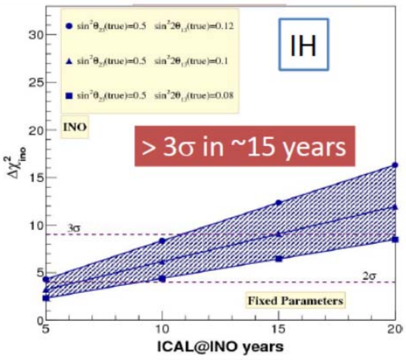
INO

The detector

- Magnetised iron calorimeter (~ 50kT)
- 140 horizontal (vertical) iron layers interspersed with Glass RPC
- Modular structure

- Sensitive to muons
- Energy determination from
  - Track length
  - Track curvature in a magentic field
- Direction of parent neutrino from the track





To disentangle fundamental $\not{CP}$ from the matter induced one in LBL experiments – need to measure energy dependence of oscillated signal or signal at two baselines

Alternatives:

- Low-E experiments ($E \sim$ 0.1 – 1 GeV) with $L \sim$ 100 – 1000 km
- Indirect measurements: CP-even terms $\sim \cos\delta_{\rm CP}$ or area of leptonic unitarity triangle

Neutrinos,

In and Beyond the Standard Model:

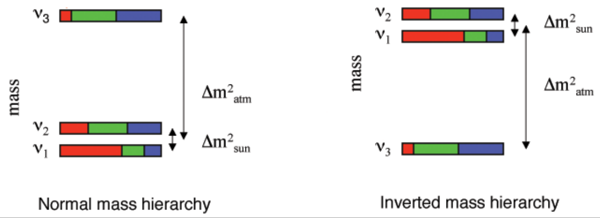
NEUTRINO MASS:

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

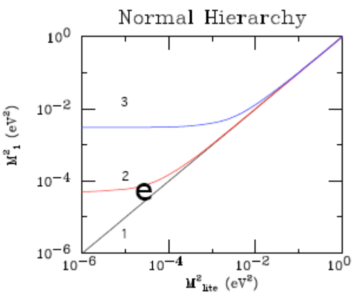
$$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2 \qquad L/E = 15\ km/MeV$$

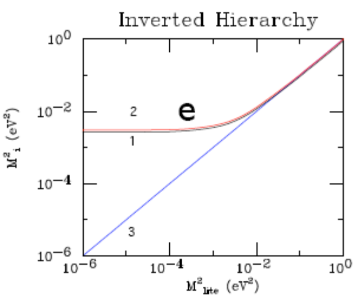
$$\Downarrow$$

$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$

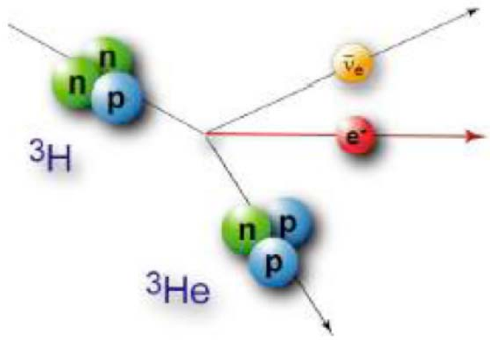


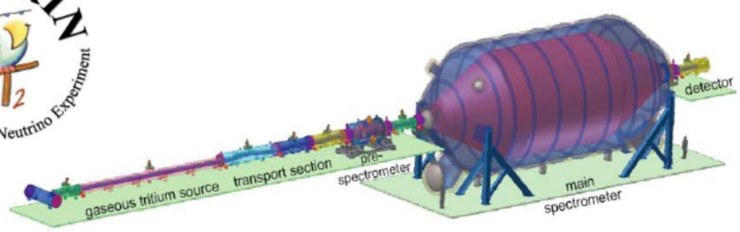
Masses:

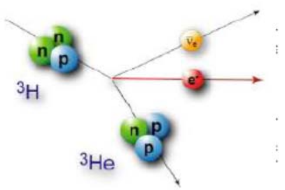




States 1 and 2 are ν_e rich.





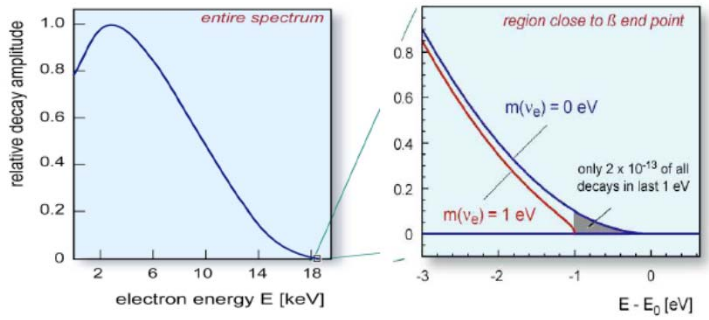


Requirements:

- 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:

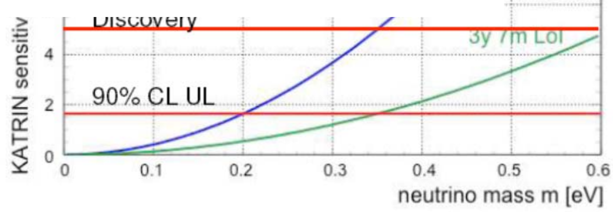
$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

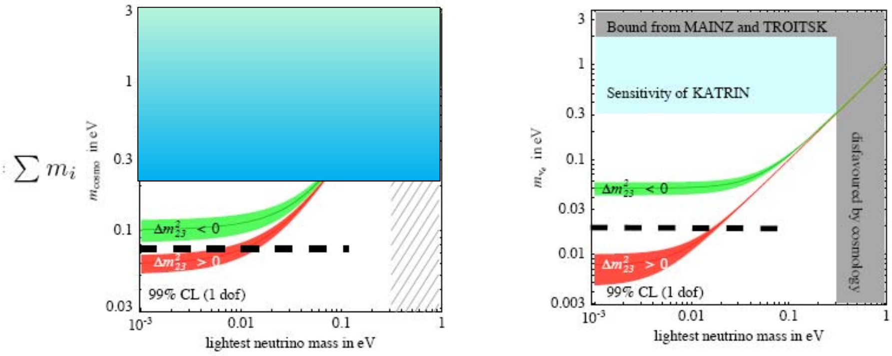
if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

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

KATRIN

- March: Connect main spectrometer and detector system
- April: Begin commissioning main spectrometer
  - Transmission measurement with electron gun
- 2014: Completion of tritium sections
- Late 2015: Begin data-taking for neutrino mass





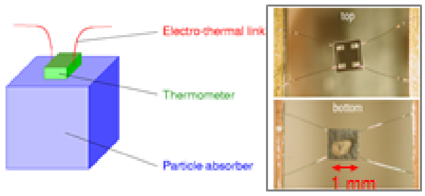
$\sum m_i \approx 2\ eV$ closes the Universe. Limit a few % of this number.

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

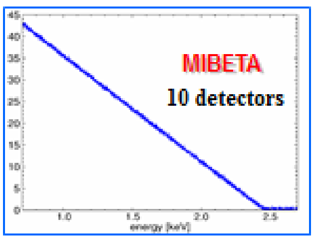
Beta decay: MARE experiment

MicroBolometers of ArReO4

^{187}Re Q_β = 2.47 keV



Full energy measurement
No systematic from source
But time response of sensor → pile-up



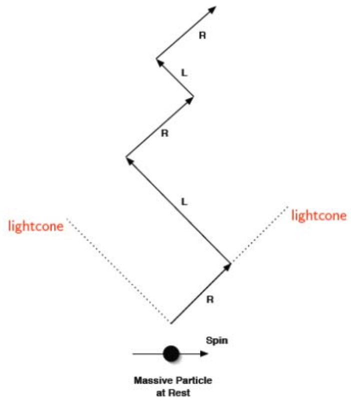
$\langle m_\nu \rangle^2 = -141 \pm 211_{stat} \pm 90_{sys}\ eV^2$

$\langle m_\nu \rangle < 15$ eV (90% c.l.)

MARE-I: 300 detectors
FWHM ~20 eV
τ ~100 – 500 µs
$\langle m_\nu \rangle < 2 – 4$ eV (5 years)

MARE – II : 5000 detectors (~2018)
FWHM ~20 eV
τ ~1 – 5 µs
$\langle m_\nu \rangle < 0.2$ eV (10 years)

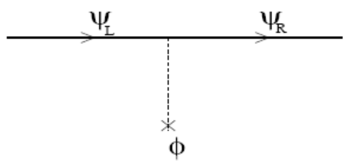
What is Fermion Mass ???



A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m\,\overline{\psi_L}\psi_R + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



$$\lambda_f\;\overline{\psi_L}\;\Phi\;\psi_R + h.c. \rightarrow m_f = \lambda_f\;v$$

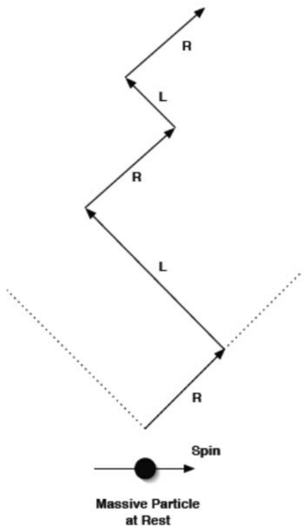
Fermion Masses:

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.



Mass couples L to R:

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

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless   left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	ν_L	$\Leftrightarrow$	$\bar{\nu}_R$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	ν_R	$\Leftrightarrow$	$\bar{\nu}_L$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

ν_L to $\bar{\nu}_R$ → 0

ν_L to ν_R → m_D

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$\bar{\nu}_R$ to $\bar{\nu}_L$ → m_D

ν_R to $\bar{\nu}_L$ → M

Two Majorana neutrinos with masses m_D^2/M and M

Seesaw: Yanagida, Gell-man-Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

The consequences of this alternative are profound:

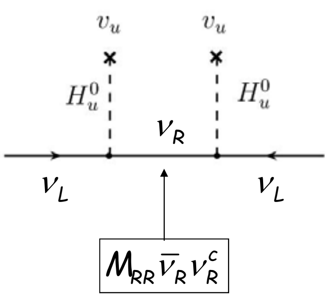
- Physics beyond the SM at a scale M!
- Majorana fermions carry no conserved charge: L is violated !

$$\nu_L \to e^{i\alpha}\nu_L$$

does not leave the Majorana mass term invariant.
→ Most welcome for baryogenesis: a mechanism to understand the matter-antimatter asymmetry in the Universe emerges naturally
→ Most welcome by string theory: it is difficult to get global $U(1)$ charges conserved

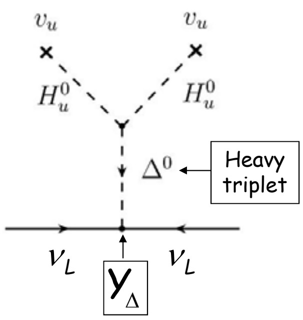
Types of see-saw mechanism

Type I see-saw mechanism



$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Type II see-saw mechanism



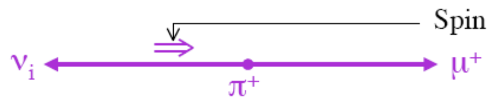
$$m_{LL}^{II}\,\bar{\nu}_L\nu_L^c \approx Y_\Delta \frac{v_u^2}{M_\Delta}$$

How Can We Demonstrate That $\overline{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \to \ell^-$; $\overline{\nu} \to \ell^+$).

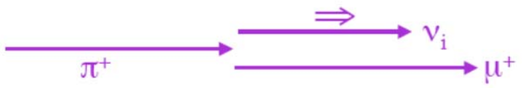
An Idea that Does Not Work
[and illustrates why most ideas do not work]

Produce a ν_i via—

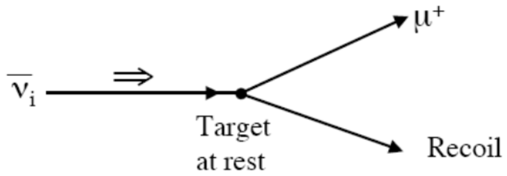


Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$



The SM weak interaction causes—



$\nu_i = \overline{\nu}_i$ means that $\nu_i(h) = \overline{\nu}_i(h)$.

helicity

If $\nu_i \xrightarrow{\Rightarrow}$ = $\overline{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

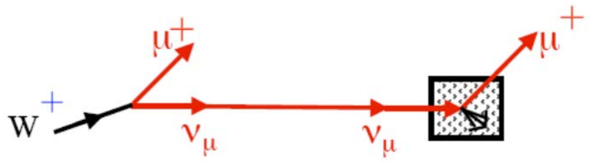
$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi \ (\text{Lab}) > 10^4 \ \text{TeV} \quad \text{if} \ \ m_\nu \sim 1 \text{ eV}$$

Fraction of all π–decay that get helicity flipped

$$\approx \left(\frac{m_\nu}{E_\nu \ (\pi \text{ Rest Frame})} \right)^2 \sim 10^{-16} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

For Majorana Neutrinos

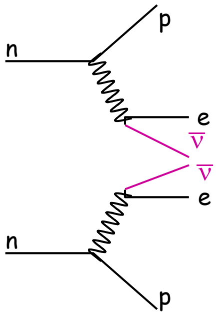


Not Observed

Allowed

BUT Suppressed by $\frac{m_\nu^2}{E^2} \sim 10^{-20}$!!!

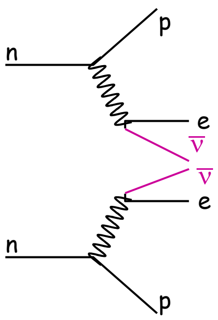
➢ How we can find out ?



SM double weak process

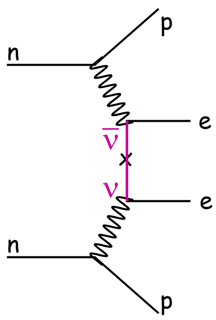
4 body decay: continuos spectrum for the e energy sum

➢ How we can find out ?



SM double weak process

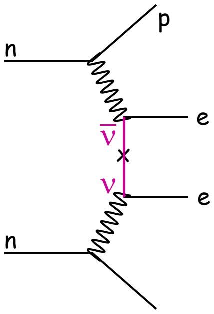
4 body decay: continuos spectrum for the e energy sum



Only allowed for Majorana ν

2 body decay: e energy sum is a delta

$\overline{\nu}_i$ is emitted (RH + O(m_i/E) LH)



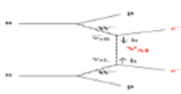
Amp[ν_i contribution] $\propto$ m_i

Amp[0νββ] $\propto$ $\left| \sum m_i U_{ei}^2 \right|$

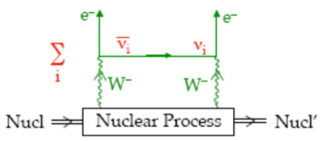
effective mass

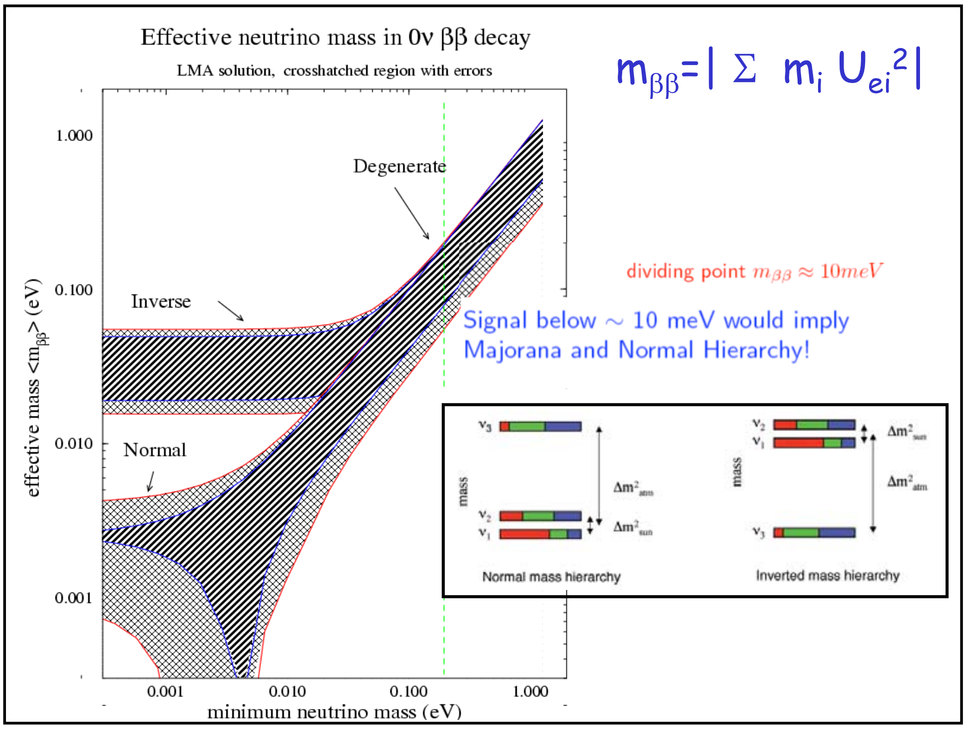
Neutrinoless double beta decay

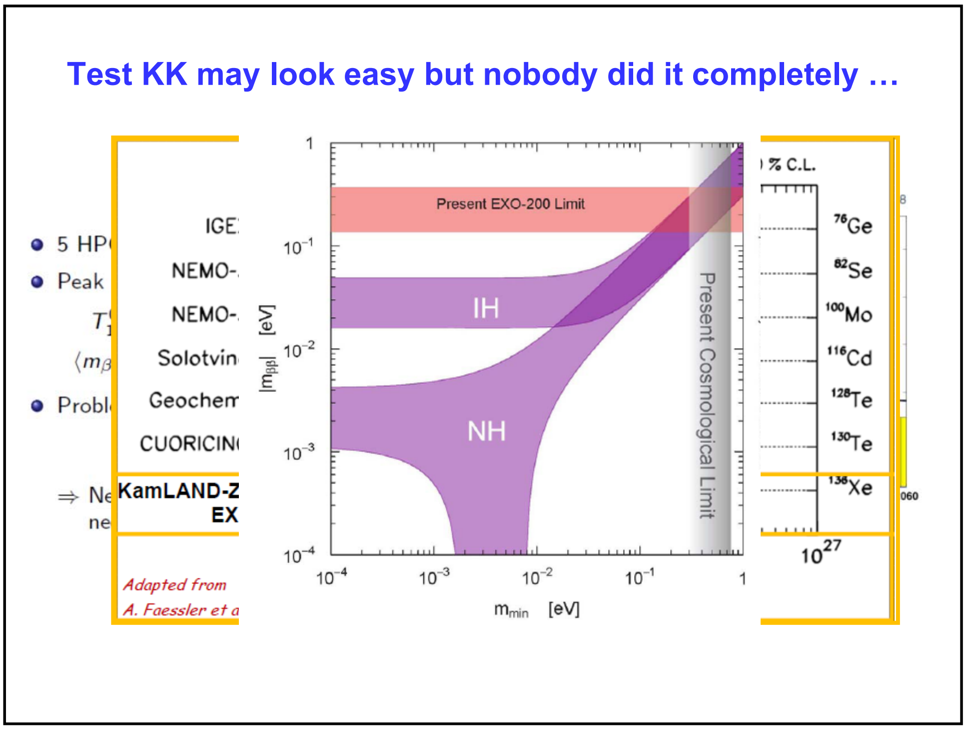
- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$




Effective neutrino mass in 0ν ββ decay
LMA solution, crosshatched region with errors
$m_{\beta\beta}=|\Sigma\ m_i\ U_{ei}^2|$
Degenerate
Inverse
Normal
1.000
0.100
0.010
0.001
effective mass <$m_{\beta\beta}$> (eV)
0.001
0.010
0.100
1.000
minimum neutrino mass (eV)
dividing point $m_{\beta\beta} \approx 10meV$
Signal below ~ 10 meV would imply
Majorana and Normal Hierarchy!
ν_3
ν_2
ν_1
Δm^2_{atm}
Δm^2_{sun}
mass
Normal mass hierarchy
Inverted mass hierarchy


Test KK may look easy but nobody did it completely …
5 HP
Peak
Probl
⇒ Ne
ne
IGE
NEMO-
NEMO-
Solotvin
Geochem
CUORICIN
KamLAND-Z
EX
Adapted from
A. Faessler et a
Present EXO-200 Limit
IH
NH
Present Cosmological Limit
$|m_{\beta\beta}|$ [eV]
m_{min} [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
% C.L.
^{76}Ge
^{82}Se
^{100}Mo
^{116}Cd
^{128}Te
^{130}Te
^{136}Xe
10^{27}

Leptogenesis

The Universe is made of matter:

$$\eta_B \equiv \frac{N_b - N_{\bar{b}}}{N_\gamma} \sim 6 \times 10^{-10}$$

The hope is that this asymmetry might have been produced dynamically from a symmetric initial state:

- Baryon number violation
- Deviation from thermal equilibrium
- C and CP violation

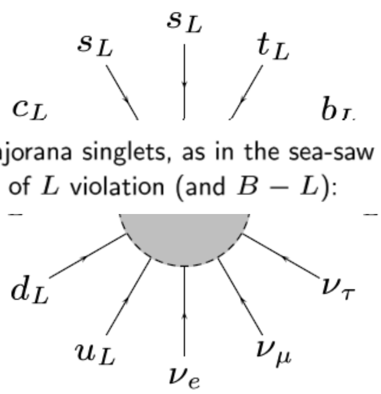
Sakharov

All these conditions are present in the SM !

Baryon number violation:

$B + L$ is anomalous in the SM both with and without massive neutrinos, while $B - L$ is preserved

At high T in the early Universe, $B + L$ violating transitions could be in thermal equilibrium due to the thermal excitation of configurations with topological charge called sphalerons :



If there are heavy Majorana singlets, as in the sea-saw mechanism, there is a additional source of L violation (and $B - L$):

$\Delta B = \Delta L$

Deviation from equilibrium:

Sphalerons are in equilibrium for $T \geq 100$ GeV: to get these processes out-of-equilibrium we need to go to the EW phase transition.

EW baryogenesis is disfavoured because:

1. The sources of CP violation involved are too small in the SM
2. The out-of-equilibrium condition is not well met: the EW phase transition is not strongly first order

Majorana singlets are in equilibrium until they decouple: $T \sim M_R$

This happens much earlier then EW transition since $M_R \gg v$ and sphalerons are still in equilibrium:

$$Y_B = aY_{B-L} = \frac{a}{a-1} Y_L \quad a = \frac{28}{79} \quad \text{in SM}$$

Leptogenesis

Baryon Asymmetry is created by a Lepton Asymmetry produced by the decays of super heavy Majorana Neutrinos.

$$\frac{\Gamma(N \to l^+ \phi^-) - \Gamma(N \to l^- \phi^+)}{\Gamma(N \to l^+ \phi^-) + \Gamma(N \to l^- \phi^+)}$$

$\Gamma(N \to l^\pm \phi^\mp)$ depends on the Majorana Phases in the MNS mixing matrix.

$$B_{now} = \tfrac{1}{2}(B-L) + \tfrac{1}{2}(B+L) = \tfrac{1}{2}(B-L)_{ini} = -\tfrac{1}{2}L_{ini}$$

0

Final asymmetry:

$$Y_B = 10^{-2} \overbrace{\epsilon_1}^{\text{CP}-\text{asym}} \overbrace{\kappa}^{\text{eff. factor}}$$

$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

κ efficiency factor which depends on the non-equilibrium dynamics.

A relation between the baryon number of the Universe and the neutrino flavour parameters!

Some exotic (and not so exotic) scenarios

Non standard neutrino interactions

CPT violation

Violations of Lorentz invariance

Non standard neutrino interactions

They can be described by effective four-fermion operators of the form

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R} f'\right)$$

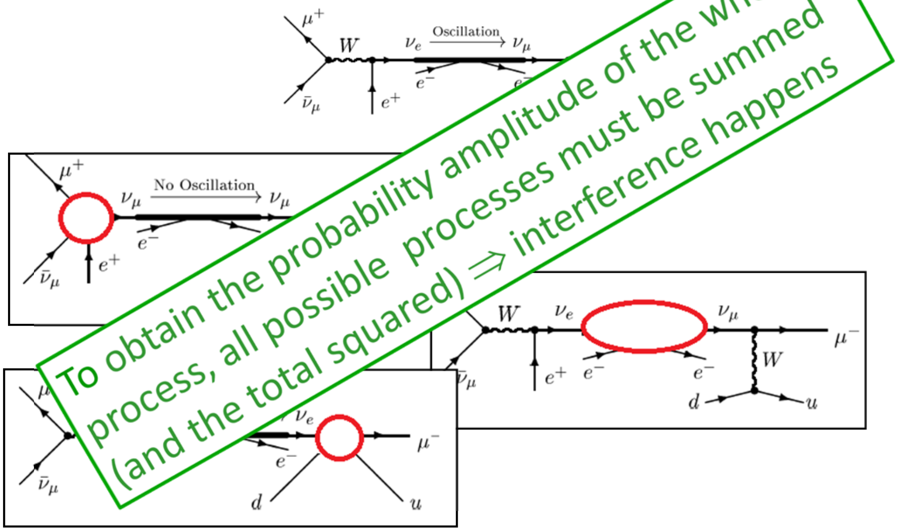
normalizing the operator with the Fermi constant

$$\varepsilon_{\alpha\beta} = \frac{M_W^2}{M_{NSNI}^2}$$

NSNI can appear at every step. It is therefore necessary to break down the analysis in three stages

- the production process
- the time evolution
- the detection process

Lets have a look at what is called the “golden ” channel in a neutrino factory



To obtain the probability amplitude of the whole process, all possible processes must be summed (and the total squared) ⇒ interference happens

---

The system consists of an initial state

state of the parent particle $A + T$ state of the target

and a final state

intermediate state B

state of the particle producing and identifiable event $C + U$ unobserved particles

$$P(A + T \rightarrow C + U) = \left| \sum_B \Phi(A, T; B; C, U) \right|^2$$

The system consists of an initial state

state of the parent particle $A + T$ state of the target

intermediate state B

and a final state

state of the particle producing and identifiable event $C + U$ unobserved particles

$$P(A + T \rightarrow C + U) = |\, \Sigma_B \; \Phi(A, T; B; C, U) \,|^2$$

$$P(A \rightarrow C) = \sum_{T,U} P(A + T \rightarrow C + U)$$

Assuming that the amplitude $\Phi\,(A, T_o\,; B_o; C, U_o\,)$ is dominant

$P\,(A \rightarrow C) \approx P(A + T_o \rightarrow C + U_o)$

$= |\, \Phi\,(A, T_o\,; B_o; C, U_o)|^2$

$+\, 2\,\mathrm{Re}[\, \Phi\,(A, T_o\,; B_o; C, U_o)^* \; \Sigma_{B \neq B_o} \Phi\,(A, T_o\,; B; C, U_o\,)]$

$+\, |\Sigma_{B \neq B_o} \Phi\,(A, T_o\,; B; C, U_o\,)\,|^2$

For a neutrino factory : $A \rightarrow \mu^-$ $C \rightarrow \mu^+$

Production and detection involve charged current NSNI

$\pi \rightarrow \mu + \nu_\alpha$

$\mu^- \rightarrow e^- \, \nu_\mu \, \overline{\nu_\alpha}$

$n + \nu_\alpha \rightarrow p + l_\beta$

$$2\sqrt{2}G_F \varepsilon^{ud}_{\alpha\beta} (\bar{l}_\beta \gamma^\mu P_L \nu_\alpha)(\bar{u}\gamma_\mu P_{L,R} d) \qquad 2\sqrt{2}G_F \varepsilon^{\mu e}_{\alpha\beta} (\bar{\mu}\gamma^\mu P_L \nu_\beta)(\bar{\nu}_\alpha \gamma_\mu P_L e)$$

$$|\varepsilon^{ud}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 2.6\cdot10^{-5} & 0.078 & 0.013 \\ 0.011 & 0.016 & 0.13 \end{pmatrix} \qquad |\varepsilon^{\mu e}| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

bounds are ~ 10^{-2}

We are left "only" with neutral current NSNI

$$2\sqrt{2}G_F \varepsilon_{\alpha\beta} (\overline{\nu}_\beta \gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta\end{pmatrix} \ldots \begin{pmatrix} \ldots & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \ldots & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

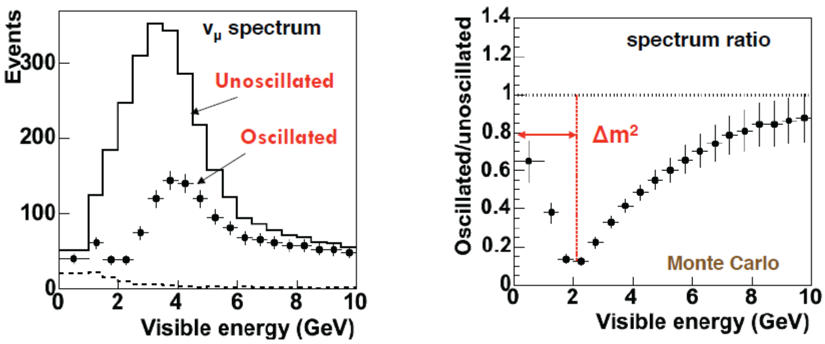
$$a \equiv 2\sqrt{2}G_F n_e E$$

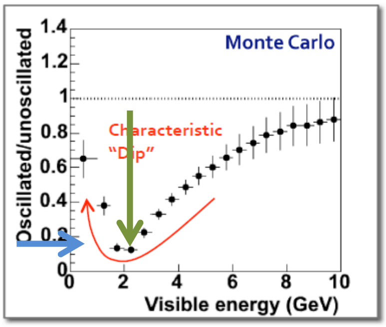
$$H = \ldots m^2_{32}\Big) U^\dagger + a \begin{pmatrix}\epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\Big]$$

Anomalies

the driving force in neutrino physics for 30+ years !!!!!

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$





$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

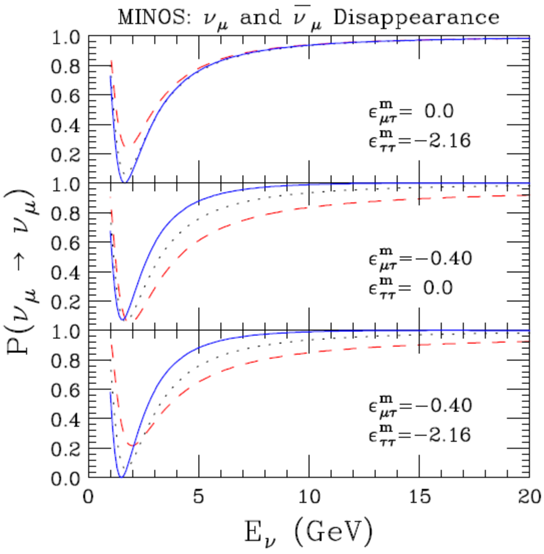
Δm^2

$\varepsilon_{\tau\tau}$ modifies the dissapearence probability near the first oscillation minimum, especially the depth of the minimum

$\sin^2(2\,\theta_{23})$

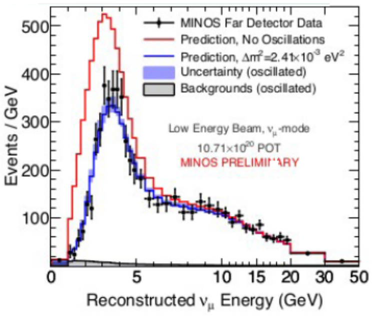
neutrino

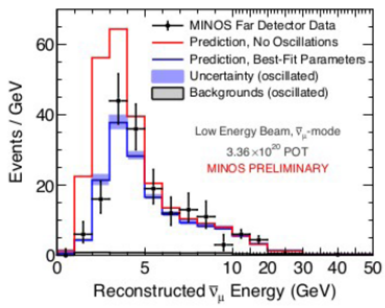
antineutrino



Kopp et al. 1009.0014

Neutrino (2012) Antineutrino





For $0 < E_{reco} < 50$ GeV
Prediction, No Oscillations: **3564 events**
Observed: **2894 events**

For $0 < E_{reco} < 50$ GeV
Prediction, No Oscillations: **312 events**
Observed: **226 events**

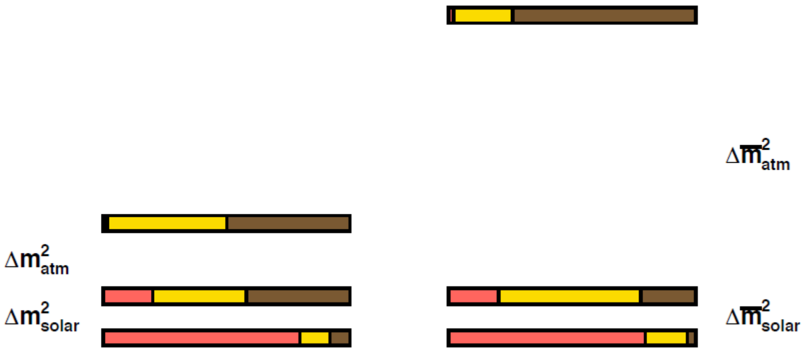
ν_μ Oscillations Best Fit Parameters

$$|\Delta m^2_{atm}| = 2.41^{+0.11}_{-0.10} \times 10^{-3} eV^2$$
$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

$\bar{\nu}_\mu$ Oscillations Best Fit Parameters

$$|\Delta \bar{m}^2_{atm}| = 2.64^{+0.28}_{-0.27} \times 10^{-3} eV^2$$
$$\sin^2(2\bar{\theta}) > 0.78 \ (90\% \ C.L.)$$

CPT violation



$$\frac{|\, m(K_0) \; - m(\overline{K_0}) \,|}{m_{K-av}} < 10^{-18}$$

$$m_{K-av} \approx \frac{1}{2} \; 10^9 \; \text{eV}$$

$$(m(K_0) - m(\overline{K_0}))(m(K_0) + m(\overline{K_0})) < 2 \;\; 10^{-18} \, {m_{K-av}}^2$$

$$|m^2(K_0) \; - m^2(\overline{K_0})| \qquad \approx \frac{1}{2} \; \text{eV}^2$$

$$|\, \Delta m^2 \text{ - } \overline{\Delta m^2} \,| \approx 10^{-6} - \; 10^{-3} \, \text{eV}^2$$

Distinguishing CPT violation from NSNI

The muon neutrino survival probability in matter can be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_\nu \sin^2\left(\frac{\Delta m^2_\nu L}{4E}\right).$$

in matter

$\Delta m^2_\nu \cos 2\theta$ … $- \epsilon_{\tau\tau} A$,

$\Delta m^2_\nu \sin 2\theta$ … $- 2\epsilon_{\mu\tau} A$.

$$4\Delta m^4 = \Delta m^4_\nu + \Delta m^4_{\bar\nu} + 2\Delta m^2_\nu \Delta m^2_{\bar\nu}\cos(2\theta_\nu - 2\theta_{\bar\nu})$$

$$\sin^2(2\theta) = \frac{\left(\Delta m^2_\nu \sin(2\theta_\nu) + \Delta m^2_{\bar\nu}\sin(2\theta_{\bar\nu})\right)^2}{\Delta m^4_\nu + \Delta m^4_{\bar\nu} + 2\Delta m^2_\nu \Delta m^2_{\bar\nu}\cos(2\theta_\nu - 2\theta_{\bar\nu})}$$

$$\begin{aligned} 2\epsilon^m_{\tau\tau} A &= \Delta m^2_\nu \cos(2\theta_\nu) - \Delta m^2_{\bar\nu}\cos(2\theta_{\bar\nu}) \\ 4\epsilon^m_{\mu\tau} A &= \Delta m^2_\nu \sin(2\theta_\nu) - \Delta m^2_{\bar\nu}\sin(2\theta_{\bar\nu}) \end{aligned}$$

Violations of Lorentz invariance

$$(h_{\text{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta\right]_{ab}$$

Violations of Lorentz invariance

Lorentz violation

$$(h_{\text{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta\right]_{ab}$$

standard Lorentz covariant term

violates both CPT and Lorentz invariance

Violations of Lorentz invariance

Lorentz violation

$$(h_{\text{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^\alpha p_\alpha - (c_L)^{\alpha\beta} p_\alpha p_\beta\right]_{ab}$$

standard Lorentz covariant term

violates both CPT and Lorentz invariance

As usual, the oscillation probability is governed by the difference of the eigenvalues of the effective hamiltonian.

$$\sin^2(\Delta_{ab}\ L/2)$$

$m_{ab}{}^2 L/E$

$(a^\alpha)_{ab}\ L$

$(c^{\alpha\beta})_{ab}\ L\,E$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

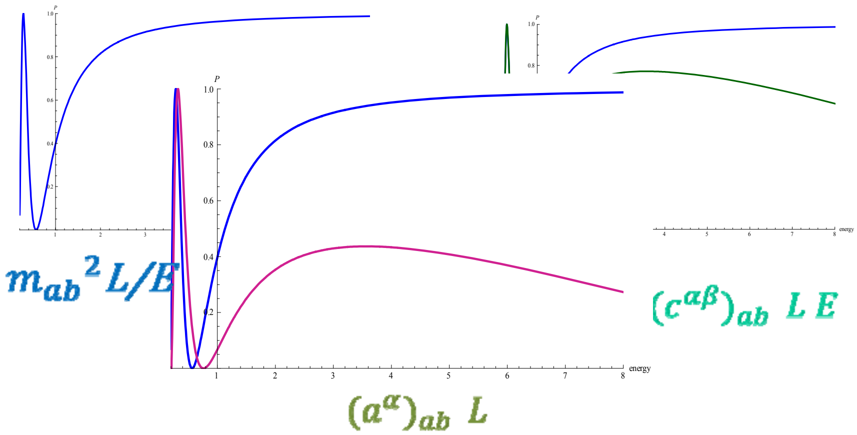


TABLE X: Neutrino sector

Combination	Result	System	Ref.
$(a_L)^T_{e\mu}$	$(-3.1 \pm 0.9) \times 10^{-20}$ GeV	MiniBooNE	[93]
$(a_L)^X_{e\mu}$	$(0.6 \pm 1.9) \times 10^{-20}$ GeV	"	[93]
$(a_L)^Y_{e\mu}$	$(-0.9 \pm 1.8) \times 10^{-20}$ GeV	"	[93]
$(a_L)^Z_{e\mu}$	$(-4.2 \pm 1.2) \times 10^{-20}$ GeV	"	[93]
$(c_L)^{TT}_{e\mu}$	$(7.2 \pm 2.1) \times 10^{-20}$	"	[93]
$(c_L)^{TX}_{e\mu}$	$(-0.9 \pm 2.8) \times 10^{-20}$	"	[93]
$(c_L)^{TY}_{e\mu}$	$(1.3 \pm 2.6) \times 10^{-20}$	"	[93]
$(c_L)^{TZ}_{e\mu}$	$(5.9 \pm 1.7) \times 10^{-20}$	"	[93]
$(c_L)^{XZ}_{e\mu}$	$(-1.1 \pm 3.7) \times 10^{-20}$	"	[93]
$(c_L)^{YZ}_{e\mu}$	$(1.7 \pm 3.4) \times 10^{-20}$	"	[93]
$(c_L)^{ZZ}_{e\mu}$	$(2.6 \pm 0.8) \times 10^{-19}$	"	[93]
$a^X_L,\ a^Y_L$	$< 1.8 \times 10^{-23}$ GeV	IceCube	[94]
$\|(a_L)^X_{\mu\tau}\|$	$< 5.9 \times 10^{-23}$ GeV	MINOS FD	[95]
$\|(a_L)^Y_{\mu\tau}\|$	$< 6.1 \times 10^{-23}$ GeV	"	[95]
$\|a^X_L\|,\ \|a^Y_L\|$	$< 3.0 \times 10^{-20}$ GeV	MINOS ND	[96]
$c^{TX}_L,\ c^{TY}_L$	$< 3.7 \times 10^{-27}$	IceCube	[94]
$\|(c_L)^{TX}_{\mu\tau}\|,\ \|(c_L)^{TY}_{\mu\tau}\|$	$< 0.5 \times 10^{-23}$	MINOS FD	[95]
$\|(c_L)^{XX}_{\mu\tau}\|$	$< 2.5 \times 10^{-23}$	"	[95]
$\|(c_L)^{YY}_{\mu\tau}\|$	$< 2.4 \times 10^{-23}$	"	[95]
$\|(c_L)^{XY}_{\mu\tau}\|$	$< 1.2 \times 10^{-23}$	"	[95]
$\|(c_L)^{YZ}_{\mu\tau}\|,\ \|(c_L)^{XZ}_{\mu\tau}\|$	$< 0.7 \times 10^{-23}$	"	[95]
$\|c^{TX}_L\|,\ \|c^{TY}_L\|$	$< 9 \times 10^{-23}$	MINOS ND	[96]
$\|c^{XX}_L\|$	$< 5.6 \times 10^{-21}$	"	[96]
$\|c^{YY}_L\|$	$< 5.5 \times 10^{-21}$	"	[96]
$\|c^{XY}_L\|$	$< 2.7 \times 10^{-21}$	"	[96]
$\|c^{YZ}_L\|$	$< 1.2 \times 10^{-21}$	"	[96]
$\|c^{XZ}_L\|$	$< 1.3 \times 10^{-21}$	"	[96]

V.Kostelecky and N. Russell
Rev.Mod.Phys. 83 (2011) 11
e-Print: arXiv:0801.0287

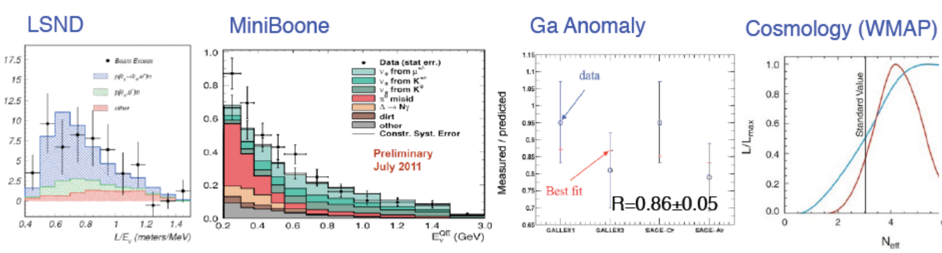
SUMMARY I

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

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

Atmos. δm β decay

parameters	3σ range
$\sin^2\theta_{12}$	0.267 – 0.344
$\sin^2\theta_{23}$	0.342 – 0.667
$\sin^2\theta_{13}$	0.0156 – 0.0299
Δm_{12}^2	$(7.00 – 8.09) \times 10^{-5}$ eV^2
$\lvert\Delta m_{13\ \mathrm{or}\ 23}^2\rvert$	$(2.24 – 2.70) \times 10^{-3}$ eV^2



- Light Steriles ???
- Mass Hierarchy $m_3 > m_2 > m_1$ OR $m_2 > m_1 > m_3$ using $|U_{e3}|^2 < |U_{e2}|^2 < |U_{e1}|^2$
- Is CP violated ? $\sin\delta \neq 0$
- Mass of Heaviest Neutrino
- Mass of Lightest Neutrino
- New Interactions, Surprises !!!