INTRO TO PHENOMENOLOGY WITH MASSIVE NEUTRINOS IN 2022

Concha Gonzalez-Garcia

(YITP-Stony Brook & ICREA-University of Barcelona)

58th International School of Subnuclear Physics

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Intro to Phenomenology with Massive Neutrinos in 2022

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OUTLINE

- Historic Introduction to the SM of Massless Neutrinos
- Introducing ν mass: Dirac vs Majorana, Lepton mixing, Flavour Oscillations
- Summary of Flavour Oscillation Observations
- Status of 3ν global description
- Explorations beyond 3ν's: steriles,NSI's,Z's…

Discovery of ν's

- At end of 1800's radioactivity was discovered and three types identified: α, β, γ

  β : an electron comes out of the radioactive nucleus.

- Energy conservation $\Rightarrow$ e^- should have had a fixed energy

$$(A, Z) \rightarrow (A, Z+1) + e^- \;\Rightarrow\; E_e = M(A, Z+1) - M(A, Z)$$

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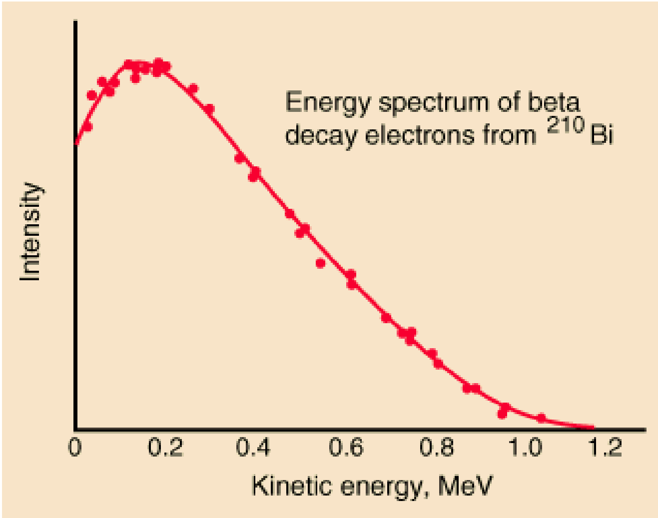
But 1914 James Chadwick showed that the electron energy spectrum is continuous



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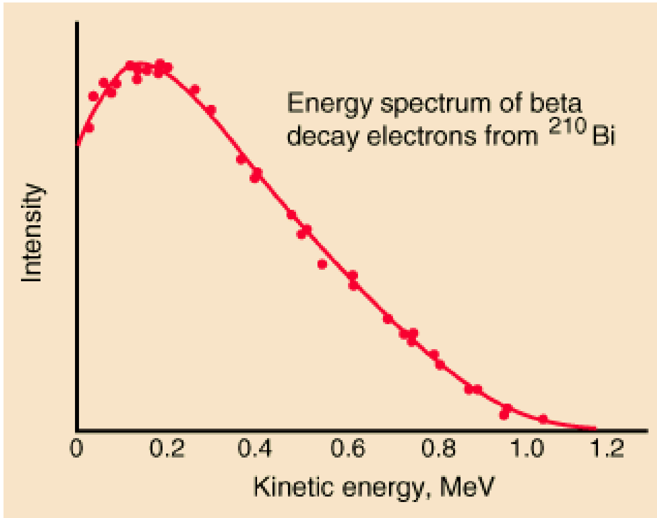

Do we throw away the energy conservation?

Bohr: *we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β ray disintegrations*

Discovery of ν's

• The idea of the neutrino came in 1930, when W. Pauli tried a desperate saving operation of "the energy conservation principle".

In his letter addressed to the *Liebe Radioaktive Damen und Herren* (Dear Radioactive Ladies and Gentlemen), the participants of a meeting in Tubingen. He put forward the hypothesis that a new particle exists as *constituent of nuclei, the neutron* ν, able to explain the continuous spectrum of nuclear beta decay

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$$(A, Z) \to (A, Z+1) + e^- + \nu$$

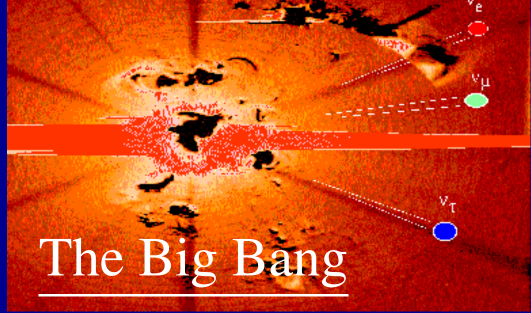
• The ν is light (in Pauli's words: m_ν *should be of the same order as the* m_e), neutral and has spin 1/2

Neutrino Detection

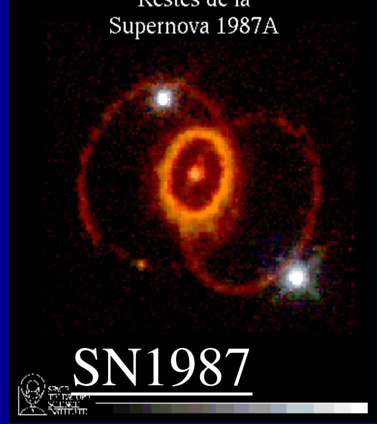
Fighting Pauli's "Curse":

I have done a terrible thing, I have postulated a particle that cannot be detected.

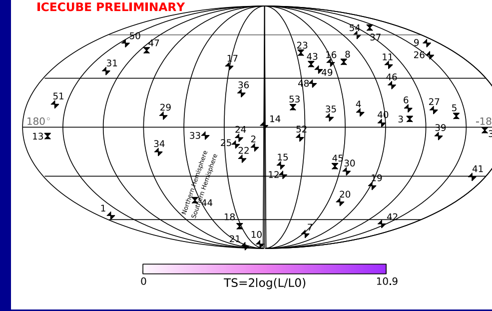
Sources of ν's



$\rho_\nu = 330/\text{cm}^3$
$p_\nu = 0.0004$ eV



$E_\nu \sim$ MeV



ExtraGalactic

$E_\nu \gtrsim 30$ TeV

The Sun

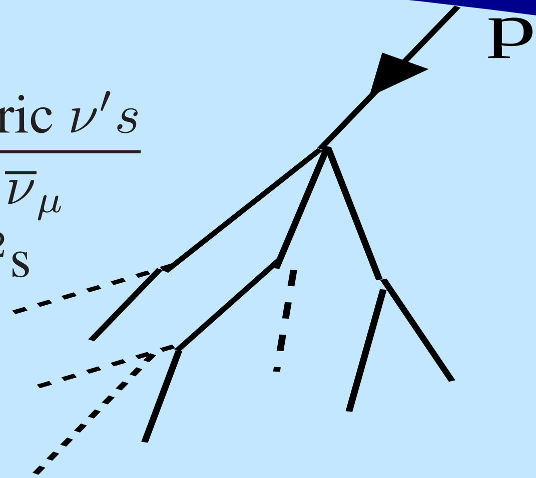
ν_e

$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$
$E_\nu \sim 0.1\text{–}20$ MeV

Atmospheric $\nu's$

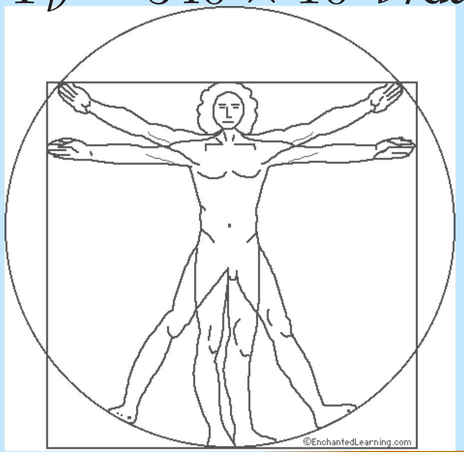
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1 \nu/\text{cm}^2\text{s}$



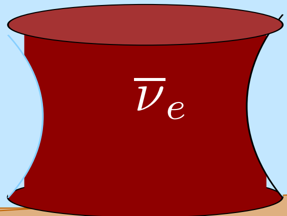
Human Body

$\Phi_\nu = 340 \times 10^6 \nu/\text{day}$



Nuclear Reactors

$E_\nu \sim$ few MeV



Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s}$

Accelerators

$E_\nu \simeq 0.3\text{–}30$ GeV

Fermilab
Discovering the Nature of Nature
CERN
KEK
～宇宙と物質の
起源と構造を探る～

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Neutrino Detection

Problem: Quantitatively: a ν sees a proton of area:

$$\sigma^{\nu p} \sim 10^{-38}\mathrm{cm}^2 \frac{E_\nu}{\mathrm{GeV}}$$

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$$\Phi_\nu^{\text{ATM}} = 1\,\nu/(\,\text{cm}^2\ \text{second})\ \ \text{y}\quad \langle E_\nu \rangle = 1\ \text{GeV}$$

- How many interact?

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$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu p} \times N_{\text{prot}}^{\text{human}} \times T_{\text{life}}^{\text{human}}$$

$$N_{\text{protons}}^{\text{human}} = \frac{M^{\text{human}}}{gr} \times N_A = 80\text{kg} \times N_A \sim 5 \times 10^{28}\text{protons}$$

$$T^{\text{human}} = 80\,\text{years} = 2 \times 10^9\ \text{sec}$$

$(M \times T \equiv \text{Exposure})$

$\text{Exposure}_{\text{human}}$

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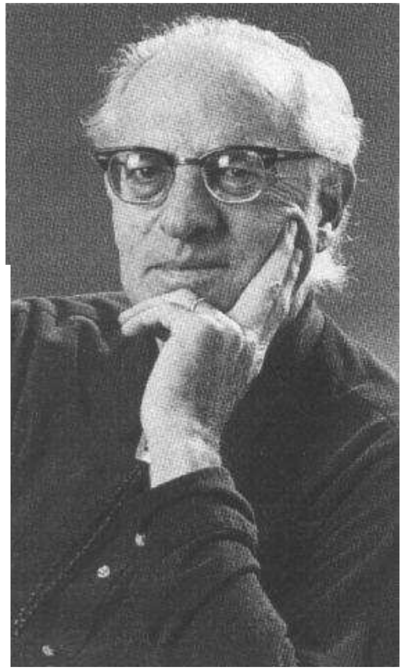
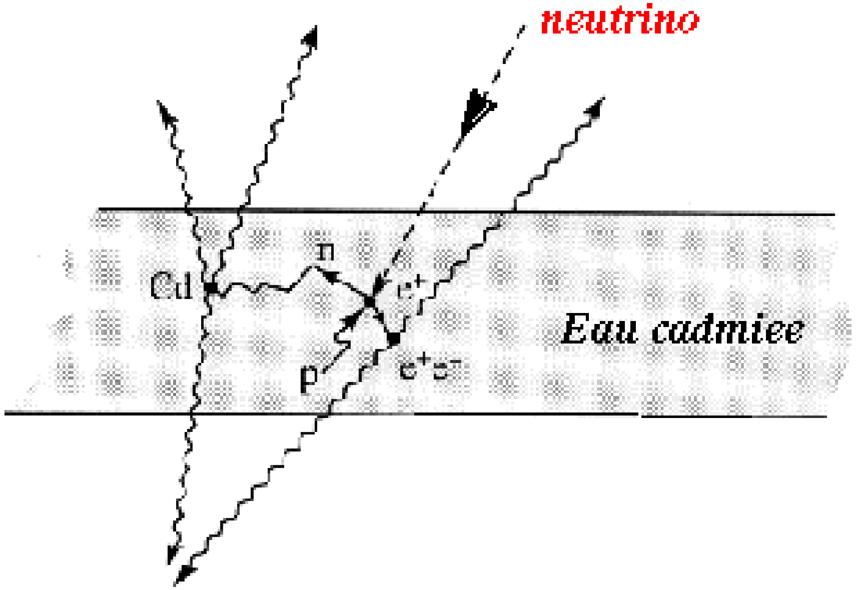
To detect neutrinos we need very intense source and/or
a hugh detector with Exposure $\sim$ KTon $\times$ year

First Neutrino Detection

In 1953 Frederick Reines and Clyde Cowan put a detector near a nuclear reactor (the most intense source available)



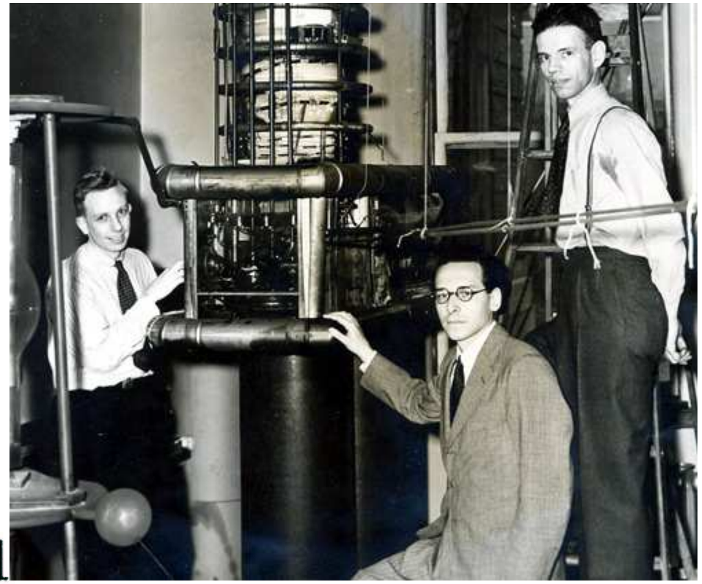
400 l of water
and Cadmium Chloride.



e^+ annihilates with e^- in the water and produces two γ's simultaneouoly.
neutron is captured by por the cadmium and a γ's is emitted 15 msec latter

Reines y Clyde saw clearly this signature: the first neutrino had been detected

Neutrinos = “Left-handed”



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is “left-handed,” i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

WARNING: Helicity versus Chirality

- We define the chiral projections $P_{R,L} = \dfrac{1 \pm \gamma_5}{2}$ $\Rightarrow$ $\psi_L = \frac{1-\gamma_5}{2}\psi$ $\quad$ $\psi_R = \frac{1+\gamma_5}{2}\psi$

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- The Lagrangian of a massive free fermion ψ is $\mathcal{L} = \overline{\psi}(x)(i\gamma \cdot \partial - m)\psi(x)$
- 4 independent states with $(E, \vec{p})$ $(\gamma \cdot p - m)u_s(\vec{p}) = 0$ $\quad (\gamma \cdot p + m)v_s(\vec{p}) = 0$ $\quad s = 1, 2$

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$$P_{\pm} = \frac{1}{2}\left(1 \pm 2\vec{J}\frac{\vec{p}}{|p|}\right) = \frac{1}{2}\left(1 \pm \vec{\Sigma}\frac{\vec{p}}{|p|}\right)$$

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Only for massless fermions Helicity and chirality states are the same.

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ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- 3 Generations of Fermions:

$(1,2,-\frac{1}{2})$ L_L	$(3,2,\frac{1}{6})$ Q^i_L	$(1,1,-1)$ E_R	$(3,1,\frac{2}{3})$ U^i_R	$(3,1,-\frac{1}{3})$ D^i_R
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

- Spin-0 particle ϕ: $(1,2,\frac{1}{2})$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \stackrel{SSB}{\rightarrow} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

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$$Q_{EM} = T_{L3} + Y$$

- ν's are $T_{L3} = \frac{1}{2}$ components of L_L
- ν's have no strong or EM interactions
- No ν_R ($\equiv$ singlets of gauge group)

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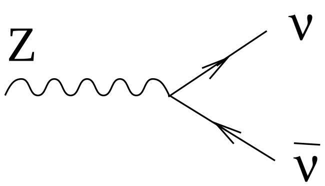
Number of Neutrinos

• The counting of light left-handed neutrinos is based on the family structure of the SM assuming a universal diagonal NC coupling:



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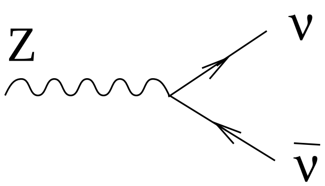

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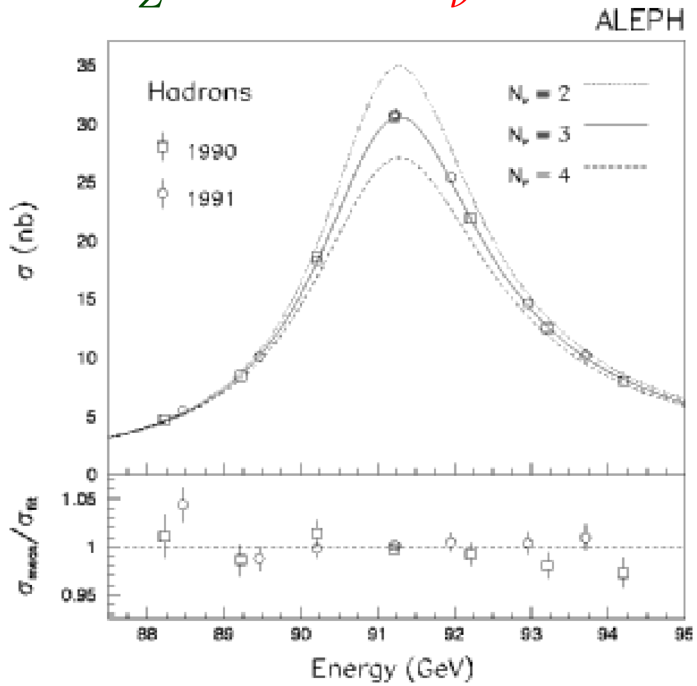
• For $m_{\nu_i} < m_Z/2$ one can use the total Z-width Γ_Z to extract N_ν

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\nu} \equiv \frac{1}{\Gamma_\nu}(\Gamma_Z - \Gamma_h - 3\Gamma_\ell)$$
$$= \frac{\Gamma_\ell}{\Gamma_\nu}\left[\sqrt{\frac{12\pi R_{h\ell}}{\sigma_h^0 m_Z^2}} - R_{h\ell} - 3\right]$$



Γ_{inv}= the invisible width

Γ_h= the total hadronic width

Γ_l= width to charged lepton

Leads $N_\nu = 2.9840 \pm 0.0082$

SM Fermion Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\; & \sum_{k=1}^{3}\sum_{i,j=1}^{3} \overline{Q^i_{L,k}}\gamma^\mu \left(i\partial_\mu - g_s\frac{\lambda_{a,ij}}{2}G^a_\mu - g\frac{\tau_a}{2}\delta_{ij}W^a_\mu - g'\frac{1}{6}\delta_{ij}B_\mu\right) Q^j_{L,k} \\
& \sum_{k=1}^{3}\sum_{i,j=1}^{3} +\overline{U^i_{R,k}}\gamma^\mu \left(i\partial_\mu - g_s\frac{\lambda_{a,ij}}{2}G^a_\mu - g'\frac{2}{3}\delta_{ij}B_\mu\right) U^j_{R,k} \\
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& \sum_{k=1}^{3} +\overline{L_{L,k}}\gamma^\mu \left(i\partial_\mu - g\frac{\tau_i}{2}W^i_\mu + g'\frac{1}{2}B_\mu\right) L_{L,k} + \overline{E_{R,k}}\gamma^\mu \left(i\partial_\mu + g' B_\mu\right) E_{R,k} \\
& -\sum_{k,k'=1}^{3}\left(\lambda^u_{kk'}\overline{Q}_{L,k}(i\tau_2)\phi^* U_{R,k'} + \lambda^d_{kk'}\overline{Q}_{L,k}\phi D_{R,k'} + \lambda^l_{kk'}\overline{L}_{L,k}\phi E_{R,k'} + h.c.\right)
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& \sum_{k=1}^{3}\sum_{i,j=1}^{3} + \overline{U^i_{R,k}}\gamma^\mu \left(i\partial_\mu - g_s\frac{\lambda_{a,ij}}{2}G^a_\mu - g'\frac{2}{3}\delta_{ij}B_\mu\right) U^j_{R,k} \\
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& - \sum_{k,k'=1}^{3}\left(\lambda^u_{kk'}\overline{Q}_{L,k}(i\tau_2)\phi^* U_{R,k'} + \lambda^d_{kk'}\overline{Q}_{L,k}\phi D_{R,k'} + \lambda^l_{kk'}\overline{L}_{L,k}\phi E_{R,k'} + h.c.\right)
\end{aligned}
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- Invariant under global rotations

$Q_{L,k} \to e^{i\alpha_B/3}Q_{L,k}$ $\quad U_{R,k} \to e^{i\alpha_B/3}U_{R,k}$ $\quad D_{R,k} \to e^{i\alpha_B/3}D_{R,k}$ $\quad L_{L,i} \to e^{i\alpha_{L_k}/3}L_{L,k}$ $\quad E_{R,k} \to e^{i\alpha_{L_k}/3}E_{R,k}$

SM Fermion Lagrangian

Concha Gonzalez-Garcia

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$\Rightarrow$ *Accidental ($\equiv$ not imposed)* global symmetry: $B \times L_e \times L_\mu \times L_\tau$

$\Rightarrow$ Each lepton flavour, L_i, is conserved

$\Rightarrow$ Total lepton number $L = L_e + L_\mu + L_\tau$ is conserved

SM = massless $\nu's$ and LFC

- A fermion mass can be seen as at a Left-Right transition

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In SM ν's are *Strictly* Massless & Lepton Flavours are *Strictly* Conserved

- We have observed with high (or good) precision:
  - ∗ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)
  - ∗ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
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  - ∗ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
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All this implies that L_α are violated

and There is Physics Beyond SM

Dirac versus Majorana Neutrinos

- In the SM neutral bosons can be of two type:
  - Their own antiparticle such as γ, π^0 ...
  - Different from their antiparticle such as K^0, $\bar{K}^0$...
- In the SM ν are the only *neutral fermions*

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⇒ And the charged conjugate neutrino field ≡ the antineutrino field

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$\Rightarrow$ These two fields can rewritten in terms of 4 chiral fields

$$\nu_L\ ,\ \nu_R\ ,\ (\nu_L)^C\ ,\ (\nu_R)^C \quad \text{with}\ \ \nu = \nu_L + \nu_R\ \ \text{and}\ \ \nu^C = (\nu_L)^C + (\nu_R)^C$$

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The difference arises when including *a neutrino mass*

Adding ν Mass: Dirac Mass

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- Under spontaneous symmetry-breaking $\mathcal{L}_Y^{(\nu)} \Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})}$

$$\mathcal{L}_{\text{mass}}^{(\text{Dirac})} = -\overline{\nu_R} M_D^\nu \nu_L + \text{h.c.} \equiv -\frac{1}{2}(\overline{\nu}_R M_D^\nu \nu_L + \overline{(\nu_L)^c} {M_D^\nu}^T (\nu_R)^c) + \text{h.c.} \equiv -\sum_k m_k \overline{\nu}_k^D \nu_k^D$$

$M_D^\nu = \frac{1}{\sqrt{2}} \lambda^\nu \, v$ =Dirac mass for neutrinos

${V_R^\nu}^\dagger M_D V^\nu = \text{diag}(m_1, m_2, m_3)$

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$V^{\nu\,\dagger}_R M_D V^\nu = \text{diag}(m_1, m_2, m_3)$

$\Rightarrow$ The eigenstates of M^ν_D are Dirac fermions (same as quarks and charged leptons)

$$\nu^D = V^{\nu\,\dagger}\nu_L + V^{\nu\,\dagger}_R \nu_R$$

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$$\mathcal{L}^{(\text{Dirac})}_{\text{mass}} = -\overline{\nu_R} M_D^\nu \nu_L + \text{h.c.} \equiv -\frac{1}{2}(\overline{\nu}_R M_D^\nu \nu_L + \overline{(\nu_L)^c} M_D^{\nu\,T} (\nu_R)^c) + \text{h.c.} \equiv -\sum_k m_k \overline{\nu}_k^D \nu_k^D$$

$M_D^\nu = \frac{1}{\sqrt{2}} \lambda^\nu \, v$ =Dirac mass for neutrinos

$V_R^{\nu\,\dagger} M_D V^\nu = \text{diag}(m_1, m_2, m_3)$

$\Rightarrow$ The eigenstates of M_D^ν are Dirac fermions (same as quarks and charged leptons)

$$\nu^D = V^{\nu\,\dagger} \nu_L + V_R^{\nu\,\dagger} \nu_R$$

- $\mathcal{L}^{(\text{Dirac})}_{\text{mass}}$ involves the four chiral fields ν_L , ν_R , $(\nu_L)^C$, $(\nu_R)^C$

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Adding ν Mass: Dirac Mass

- A fermion mass is a Left-Right operator : $\mathcal{L}_{m_f} = -m_f \overline{\psi_L} \psi_R + h.c.$
- One introduces ν_R which can couple to the lepton doublet by Yukawa interaction

$$\mathcal{L}_Y^{(\nu)} = -\lambda^\nu_{ij} \overline{\nu_{Ri}} L_{Lj} \tilde{\phi}^\dagger + \text{h.c.} \qquad (\tilde{\phi} = i\tau_2 \phi^*)$$

- Under spontaneous symmetry-breaking $\mathcal{L}_Y^{(\nu)} \Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})}$

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- $\mathcal{L}_{\text{mass}}^{(\text{Dirac})}$ involves the four chiral fields ν_L , ν_R , $(\nu_L)^C$, $(\nu_R)^C$

$\Rightarrow$ Total Lepton number is conserved *by construction* (not *accidentally*):

$$\left.\begin{array}{ll} U(1)_L : \ \nu \to e^{i\alpha}\, \nu \quad \text{and} \quad \overline{\nu} \to e^{-i\alpha}\, \overline{\nu} \\ U(1)_L : \ \nu^C \to e^{-i\alpha}\, \nu^C \quad \text{and} \quad \overline{\nu^C} \to e^{i\alpha}\, \overline{\nu^C} \end{array}\right\} \Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})} \to \mathcal{L}_{\text{mass}}^{(\text{Dirac})}$$

Adding ν Mass: Majorana Mass

• One does not introduce ν_R but uses that the field $(\nu_L)^c$ is right-handed, so that one can write a Lorentz-invariant mass term

$$\mathcal{L}_{\text{mass}}^{(\text{Maj})} = -\frac{1}{2}\overline{\nu_L^c} M_M^\nu \nu_L + \text{h.c.} \equiv -\frac{1}{2}\sum_k m_k \overline{\nu}_i^M \nu_i^M$$

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M^ν_M =Majorana mass for ν's is *symmetric* $V^{\nu T} M_M V^\nu = \mathrm{diag}(m_1, m_2, m_3)$

$\Rightarrow$ The eigenstates of M^ν_M are Majorana particles

$\nu^M = V^{\nu\dagger}\nu_L + (V^{\nu\dagger}\nu_L)^c$ (verify $\nu^{M\,c}_i = \nu^M_i$)

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$\Rightarrow$ But $SU(2)_L$ gauge inv is broken $\Rightarrow \mathcal{L}_{\rm mass}^{\rm (Maj)}$ not possible at tree-level in the SM

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• Moreover under any $U(1)$ symmetry with $U(1)\ :\ \nu \to e^{i\alpha}\,\nu$

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$\mathcal{L}_{\rm mass}^{\rm (Maj)}$ breaks $U(1) \Rightarrow$ only possible for particles without electric charge

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$\Rightarrow$ Breaks Total Lepton Number $\Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Maj})}$ not generated at any loop level in the SM

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• in SM $B - L$ is non anomalous $\Rightarrow \mathcal{L}_{\rm mass}^{\rm (Maj)}$ not generated non-perturbatively in SM

ν Mass $\Rightarrow$ Lepton Mixing

• CC and mass for 3 charged leptons ℓ_i and N neutrinos in weak basis $\nu^W \equiv \begin{pmatrix} \nu_{L,e} \\ \nu_{L,\mu} \\ \nu_{L,\tau} \\ (\nu_{R,1})^C \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}$

$$\mathcal{L}_{CC}+\mathcal{L}_M = -\frac{g}{\sqrt{2}} \sum_{i=1}^{3} \overline{\ell^W_{L,i}} \gamma^\mu \nu_i^W W_\mu^+ - \sum_{i,j=1}^{3} \overline{\ell^W_{L,i}} M_{\ell\, ij} \ell^W_{R,j} - \frac{1}{2} \sum_{i,j=1}^{N} \overline{\nu_i^{c\,W}} M_{\nu\, ij} \nu_j^W + \text{h.c.}$$

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• Change to mass basis : $\ell^W_{L,i} = V^\ell_{L\,ij}\ell_{L,j}$ $\quad \ell^W_{R,i} = V^\ell_{R\,ij}\ell_{R,j}$ $\quad \nu^W_i = V^\nu_{ij}\nu_j$

$$V_L^{\ell\,\dagger} M_\ell V^\ell_R = \text{diag}(m_e, m_\mu, m_\tau)$$

$V^\ell_{L,R} \equiv$ Unitary 3×3 matrices

$$V^{\nu\,T} M_\nu V^\nu = \text{diag}(m_1^2, m_2^2, m_3^2, \ldots, m_N^2)$$

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$$U^{ij}_{\text{LEP}} = \sum_{k=1}^{3} P^\ell_{ii} V_L^{\ell\,\dagger\, ik}\, V^{\nu\, kj} P^\nu_{jj}$$

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- $P^{\nu}_{kk} \supset$ N-1 phases absorbed in ν_i (only possible if ν_i is Dirac)
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- For example for 3 Dirac ν's : 3 Mixing angles + 1 Dirac Phase

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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- For 3 Majorana ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

  $*$ Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

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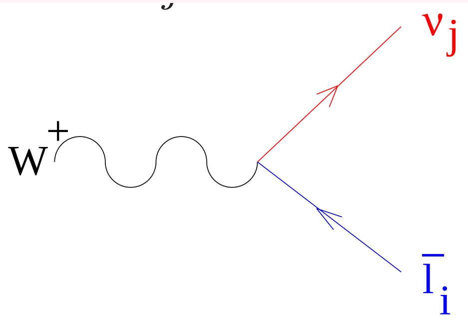
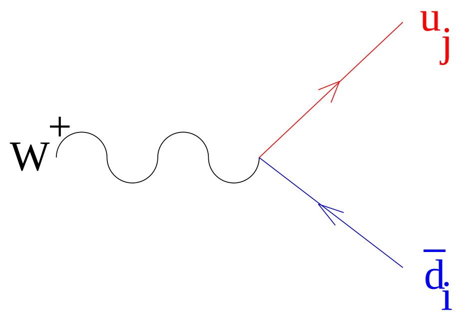
- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\mathrm{LEP}}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{\mathrm{CKM}}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$





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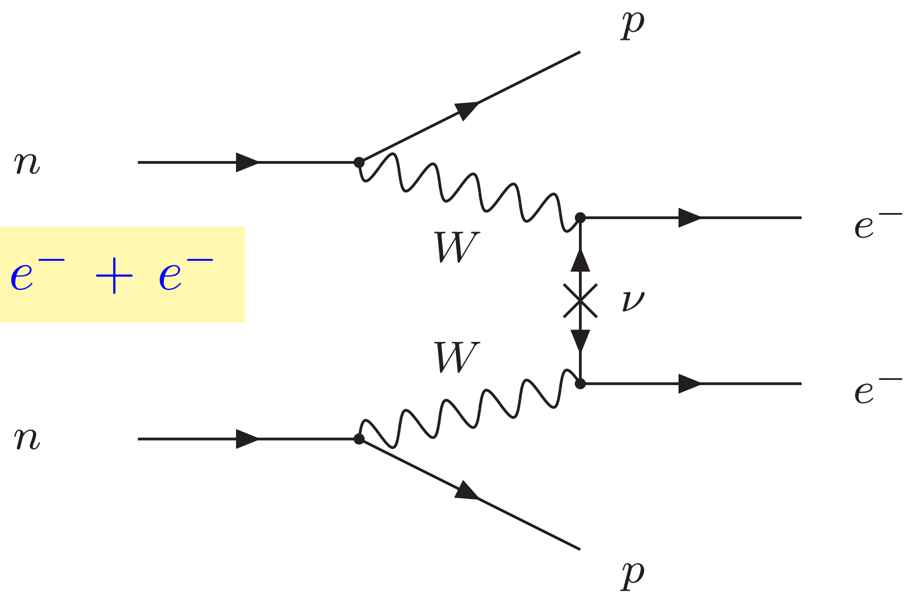
Dirac or Majorana? ν-less Double-β Decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



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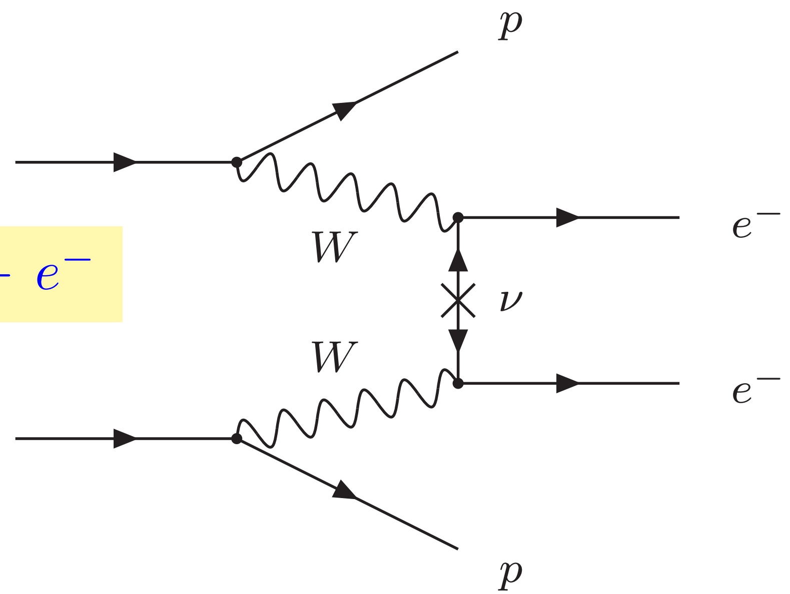

- Amplitude involves the product of two leptonic currents: $\left[\overline{e}\gamma^\mu L\nu\right]\left[\overline{e}\gamma^\mu L\nu\right]$
  - If ν Dirac $\Rightarrow$ ν *annihilates* a *neutrino* and *creates* an *antineutrino*

    $\Rightarrow$ no same state $\Rightarrow$ Amplitude = 0
  - If ν Majorana $\Rightarrow$ $\nu = \nu^c$ *annihilates and creates* a *neutrino=antineutrino*

    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto \overline{\nu\ (\nu)}^T \neq 0$

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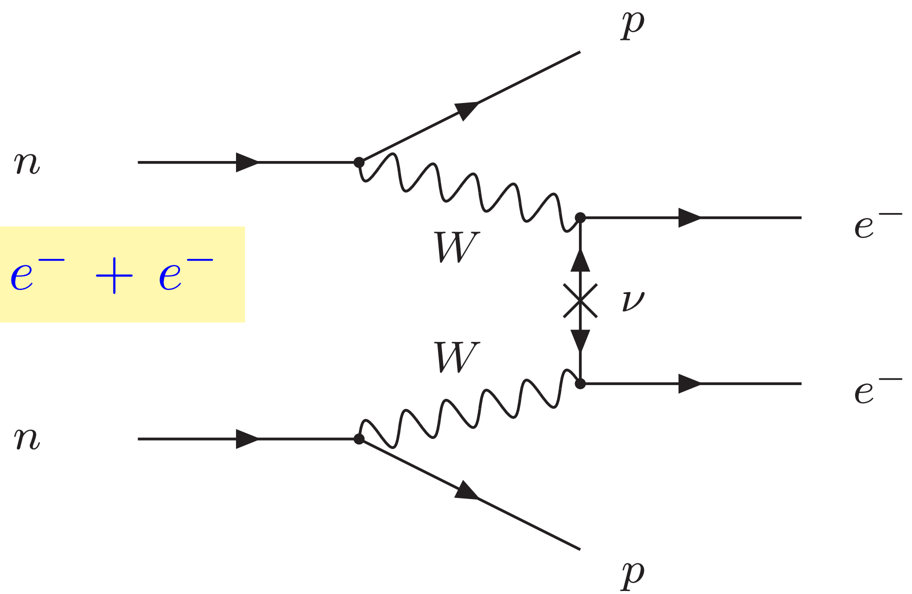

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  - If ν Dirac $\Rightarrow$ ν *annihilates* a *neutrino* and *creates* an *antineutrino*

    $\Rightarrow$ no same state $\Rightarrow$ Amplitude = 0
  - If ν Majorana $\Rightarrow$ $\nu = \nu^c$ *annihilates and creates* a *neutrino=antineutrino*

    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto \overbrace{\nu\ (\nu)}^{}{}^T \neq 0$
- If Majorana m_ν only source of L-violation

$\Rightarrow$ Amplitude of ν-less-$\beta\beta$ decay is proportional to $\langle m_{\beta\beta}\rangle = \sum U_{ej}^2 m_j$

Neutrino Mass Scale: Tritium β Decay

- Fermi proposed a kinematic search of ν_e mass from beta spectra in ${}^3H$ beta decay

$$^3H \rightarrow ^3 He + e + \overline{\nu}_e$$

- For "allowed" nuclear transitions, the electron spectrum is given by phase space alone

$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{Cp\,E\,F(E)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}}$$

$T = E_e - m_e$, Q= maximum kinetic energy, (for ${}^3H$ beta decay $Q = 18.6$ KeV)

Taking into account mixing $m_{\nu_e}^{\text{eff}} \equiv \sqrt{\sum m_{\nu_j}^2 |U_{ej}|^2}$

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$$m_\nu = 0 \;\Rightarrow\; T_{\max} = Q$$
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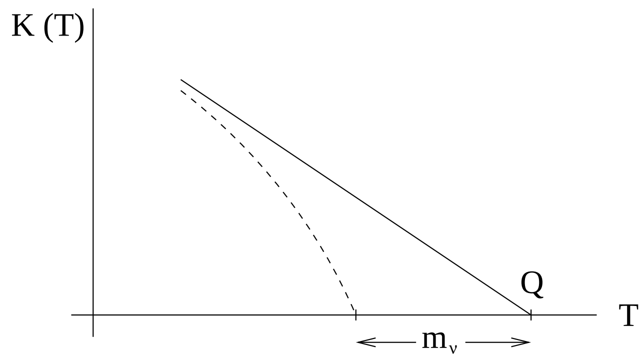

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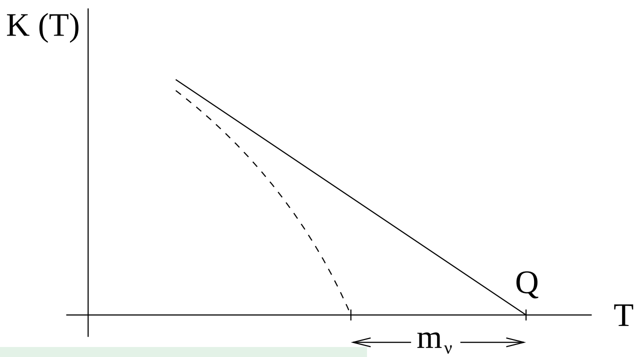

  - At present only a bound: $m_{\nu_e}^{\rm eff} < 0.8$ eV (at 90 % CL) (Katrin)
  - Katrin operating can improve present sensitivity to $m_{\nu_e}^{\rm eff} \sim 0.3\,$eV

Effects of ν Mass: Flavour Transitions

- Flavour ($\equiv$ Interaction) basis (production and detection): ν_e, ν_μ and ν_τ
- Mass basis (free propagation in space-time): ν_1, ν_2 and ν_3 $\ldots$

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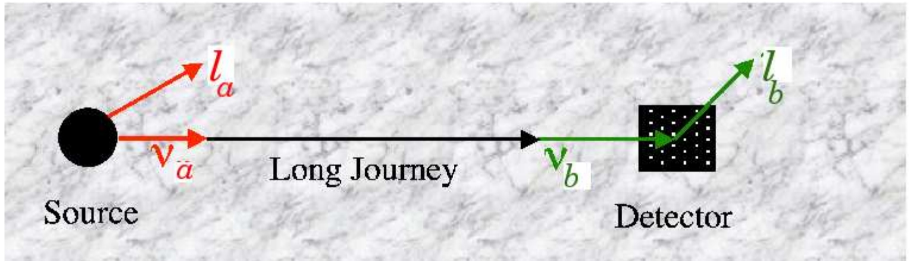
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm LEP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \dots \end{pmatrix} \Rightarrow$$

Flavour not conserved in propagation



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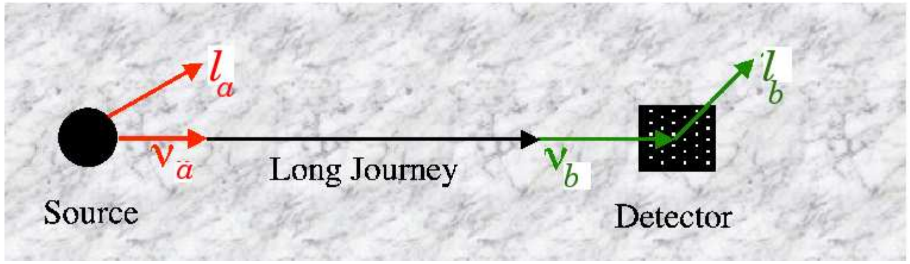

- The probability $P_{\alpha\beta}$ of producing neutrino with flavour α and detecting with flavour β has to depend on:
  - Misalignment between interaction and propagation states ($\equiv U$)
  - Difference between propagation eigenvalues
  - Propagation distance

Mass Induced Flavour Oscillations in Vacuum

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$ is a linear combination of the mass eigenstates ($|\nu_i\rangle$)

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\, |\nu_i\rangle$$

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- it can be detected with flavour β with probability

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- We call E_i the neutrino energy and m_i the neutrino mass

- Under the approximations:

  $(\mathbf{1})$ $|\nu\rangle$ is a *plane wave* $\Rightarrow$ $|\nu_i(t)\rangle = \mathrm{e}^{\,-i\,E_i t}|\nu_i(0)\rangle$ and using $\langle\nu_j|\nu_i\rangle = \delta_{ij}$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n}\mathrm{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{i<j}\mathrm{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin\left(\Delta_{ij}\right)$$

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(**2**) *relativistic* ν

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2E_i}$$

(**3**) Lowest order in mass $p_i \simeq p_j = p \simeq E$

$$\frac{\Delta_{ij}}{2} = 1.27 \frac{m_i^2 - m_j^2}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$

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– If $\alpha = \beta \Rightarrow$ $\mathrm{Im}[U_{\alpha i}U^*_{\alpha i}U^*_{\alpha j}U_{\alpha j}] = \mathrm{Im}[|U^\star_{\alpha i}|^2|U_{\alpha j}|^2] = 0$

$\Rightarrow$ CP violation observable only for $\beta \neq \alpha$

Flavour Oscillations in Vacuum

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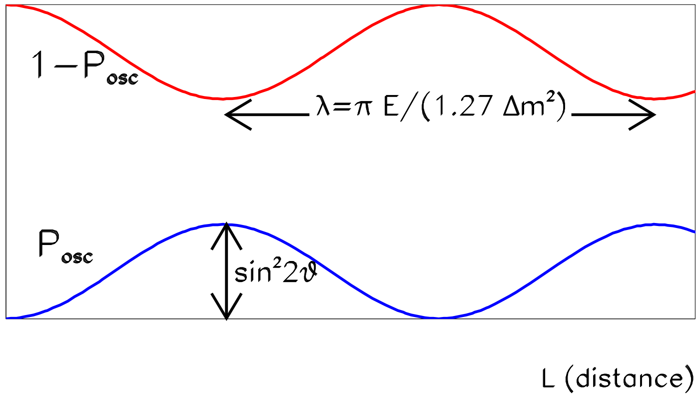
- No information on mass scale nor Majorana phases

2-ν Oscillations

- When oscillations between 2-ν dominate: $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

$$P_{osc} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \text{Appear}$$

$$P_{\alpha\alpha} = 1 - P_{osc} \quad \text{Disappear}$$



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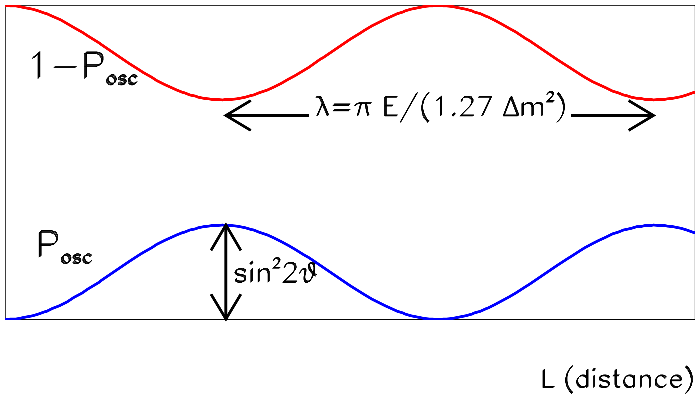

- P_{osc} is symmetric *independently* under $\Delta m^2 \to -\Delta m^2$ **or** $\theta \to -\theta + \frac{\pi}{2}$
  $\Rightarrow$ No information on ordering ($\equiv$ signΔm^2) nor octant of θ
- U is real $\Rightarrow$ no CP violation

This only happens for 2ν vacuum oscillations

ν Oscillations: Experimental Probes

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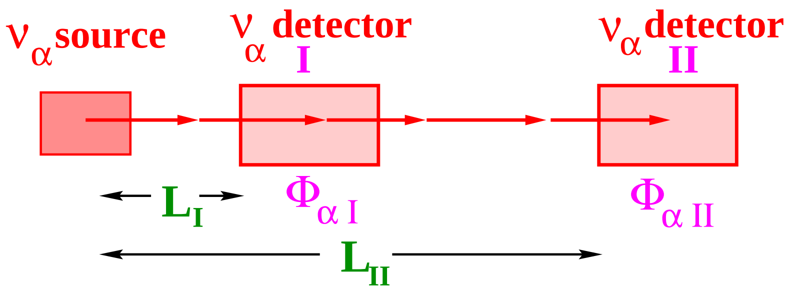
Disappearance Experiment



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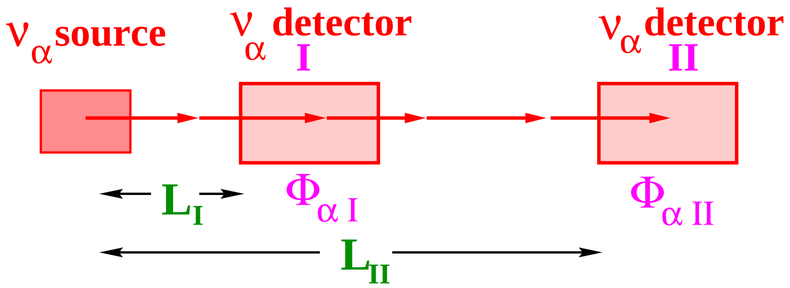

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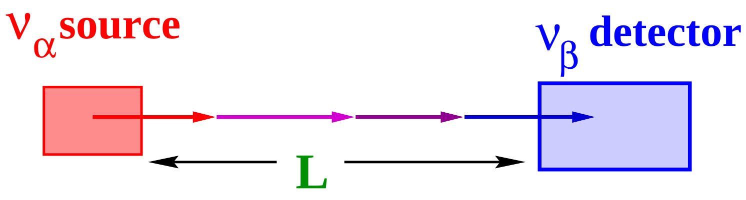

Searches for β diff α

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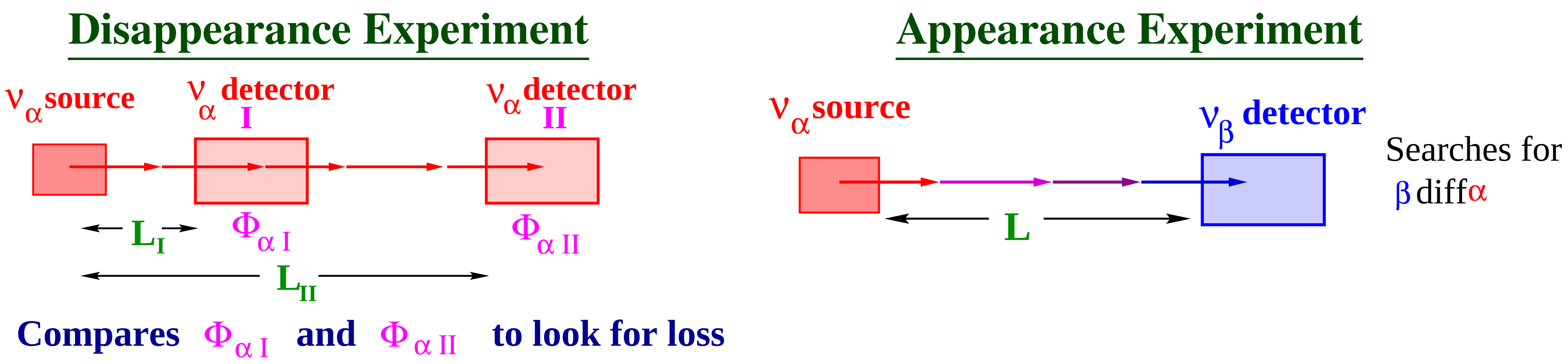

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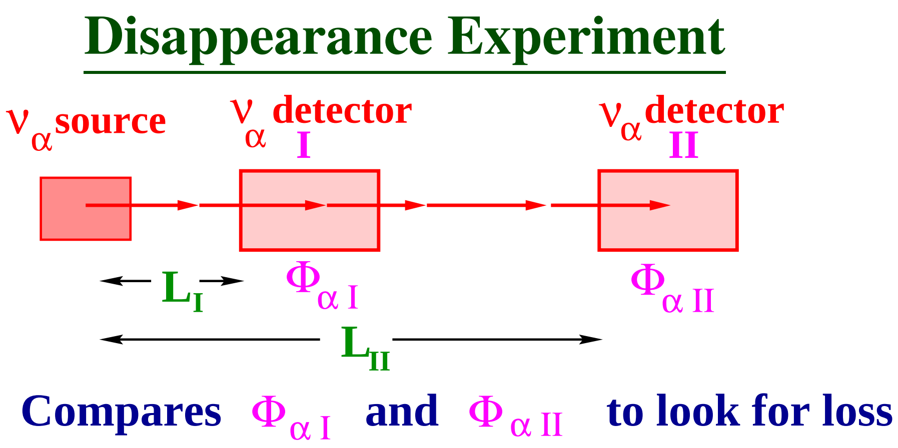
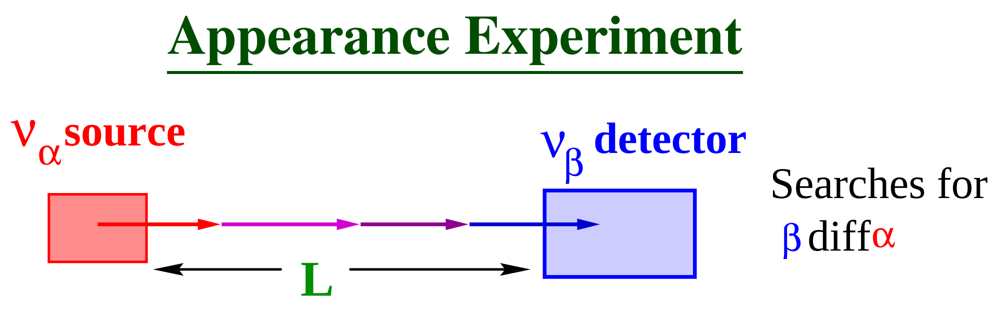
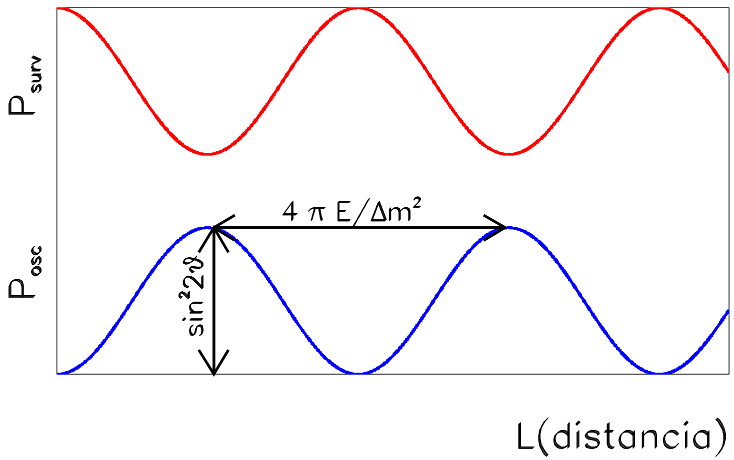




- To detect oscillations we can study the neutrino flavour as function of the Distance to the source



Concha Gonzalez-Garcia

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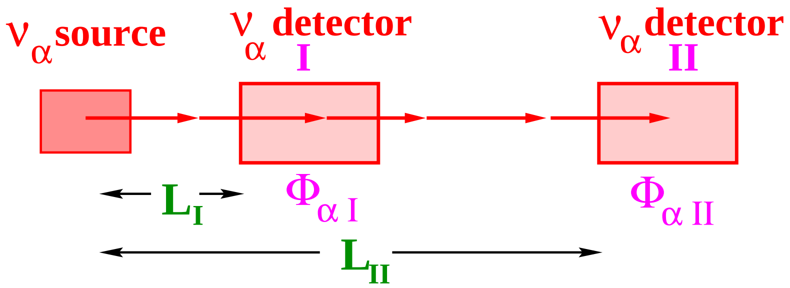

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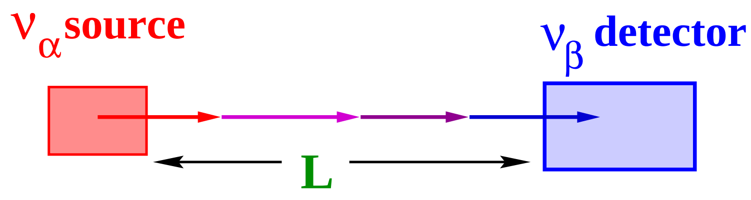

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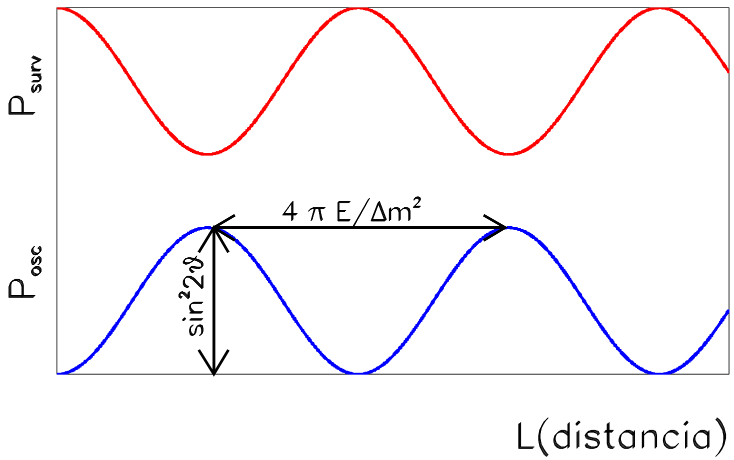
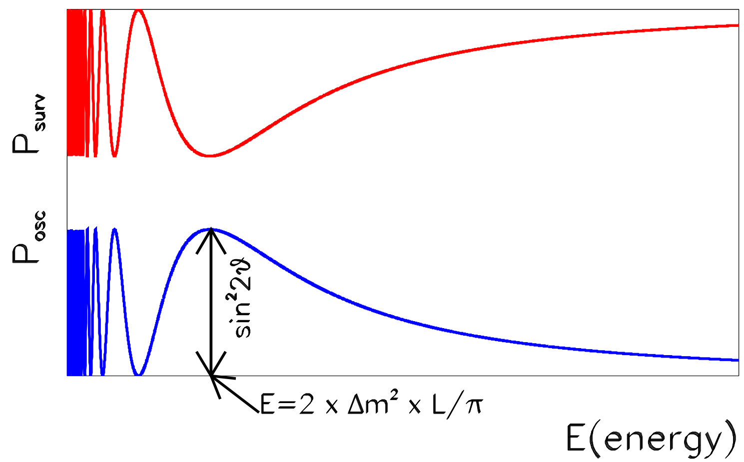


As function of the neutrino Energy



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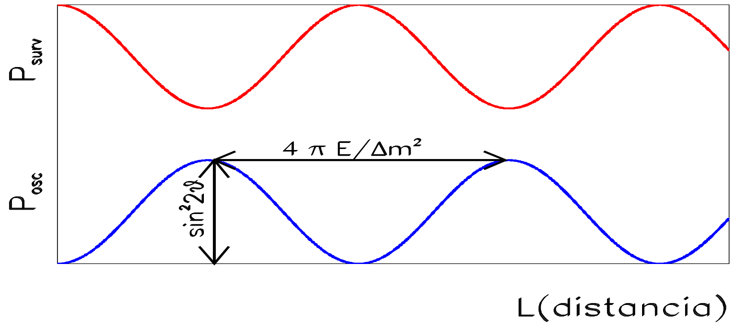

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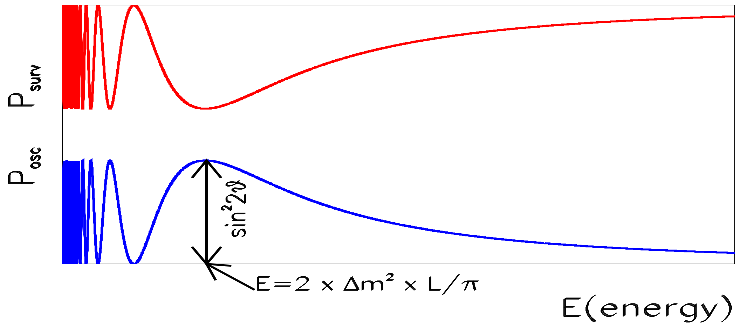

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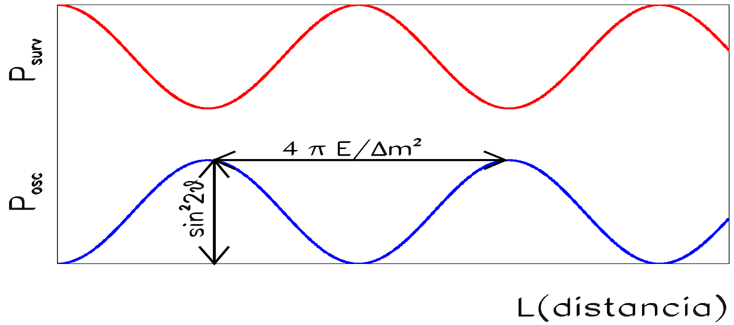

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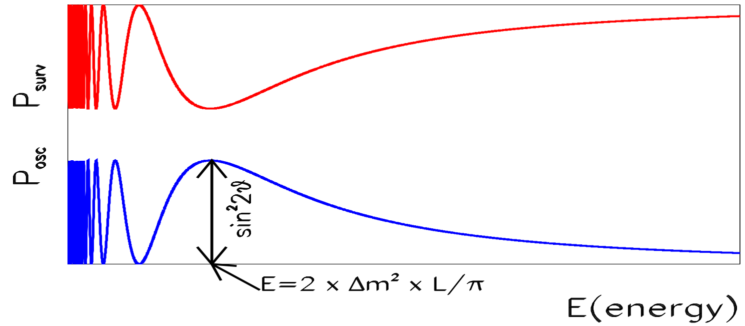
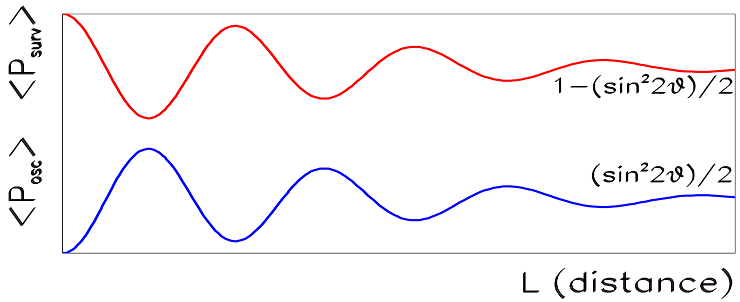
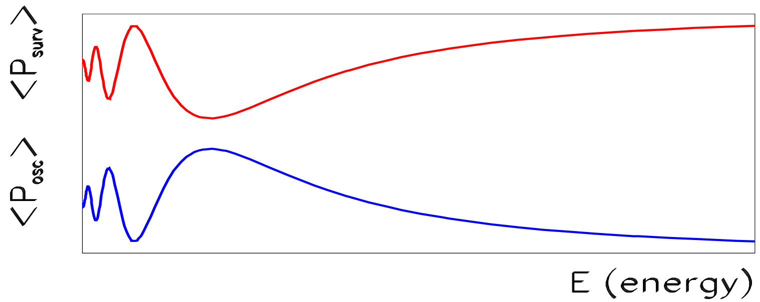


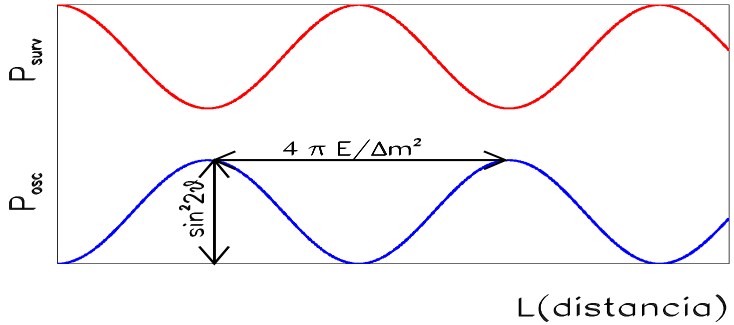
- In real experiments $\Rightarrow$ $\langle P_{\alpha\beta}\rangle = \int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu) P_{\alpha\beta}(E_\nu)$



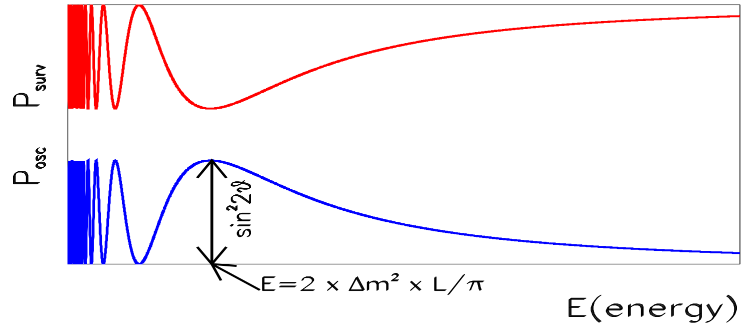


- To detect oscillations we can study the neutrino flavour

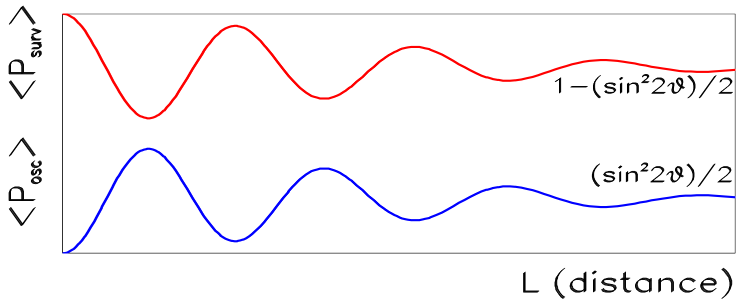
as function of the Distance to the source

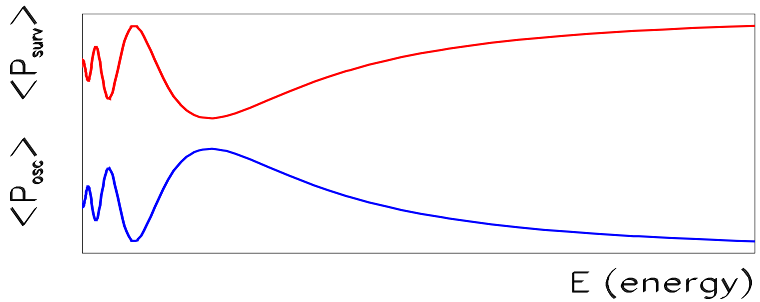


As function of the neutrino Energy



- In real experiments $\Rightarrow$ $\langle P_{\alpha\beta}\rangle = \int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu) P_{\alpha\beta}(E_\nu)$





- Maximal sensitivity for $\Delta m^2 \sim E/L$

– $\Delta m^2 \ll E/L \Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq 0 \rightarrow \langle P_{\alpha\neq\beta}\rangle \simeq 0$ & $\langle P_{\alpha\alpha}\rangle \simeq 1$

– $\Delta m^2 \gg E/L \Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq \frac{1}{2} \rightarrow \langle P_{\alpha\neq\beta}\rangle \simeq \frac{\sin^2(2\theta)}{2} \leq \frac{1}{2}$ & $\langle P_{\alpha\alpha}\rangle \geq \frac{1}{2}$

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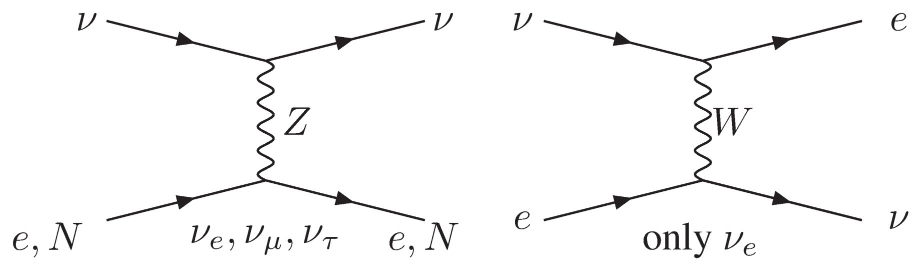
Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently* with the matter fermions

  – But Different flavours have different interactions :



$\Rightarrow$ Effective potential in ν evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^{\nu} = -\Delta V^{\bar{\nu}} = \sqrt{2} G_F N_e$

$$-i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e \\ \nu_X\end{pmatrix} = \Big[\,\big[-\begin{pmatrix} V_e - V_X - \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\Big]\begin{pmatrix}\nu_e \\ \nu_X\end{pmatrix}$$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

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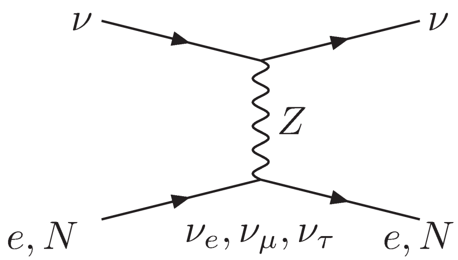

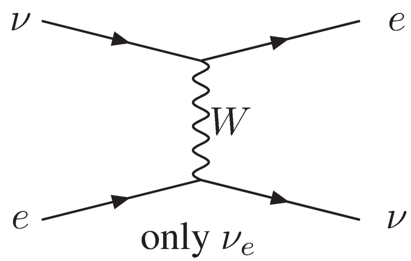

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- Mass difference and mixing in matter:

$$\Delta m^2_{mat} = \sqrt{(\Delta m^2 \cos 2\theta - 2E\Delta V)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin(2\theta_{mat}) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2_{mat}}$$

$\Rightarrow$ For solar $\nu' s$ in adiabatic regime

$$P_{ee} = \frac{1}{2}\left[1 + \cos(2\theta_m)\cos(2\theta)\right]$$

Dependence on θ octant

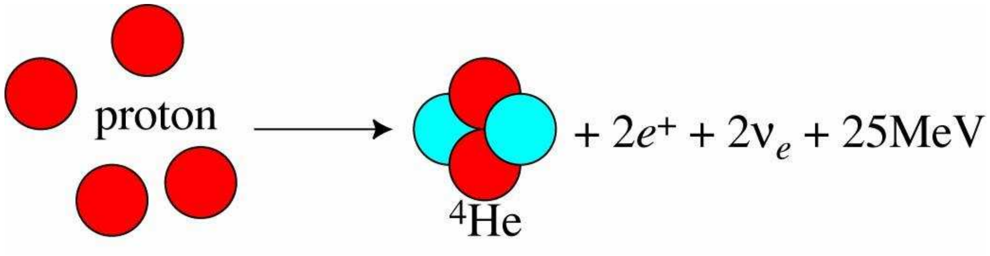
$\Rightarrow$ In LBL terrestrial experiments

Dependence on sign of Δm^2

and θ octant

Solar Neutrinos

- Sun shines by nuclear fusion of protons into He



And only ν_e are produced

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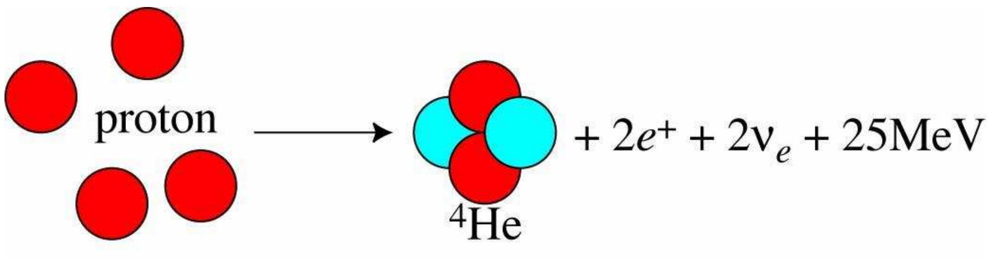
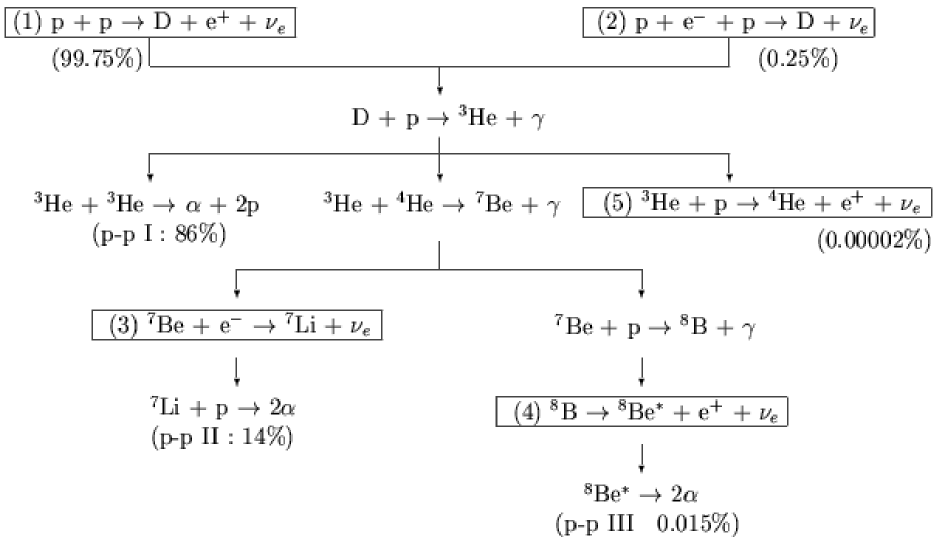


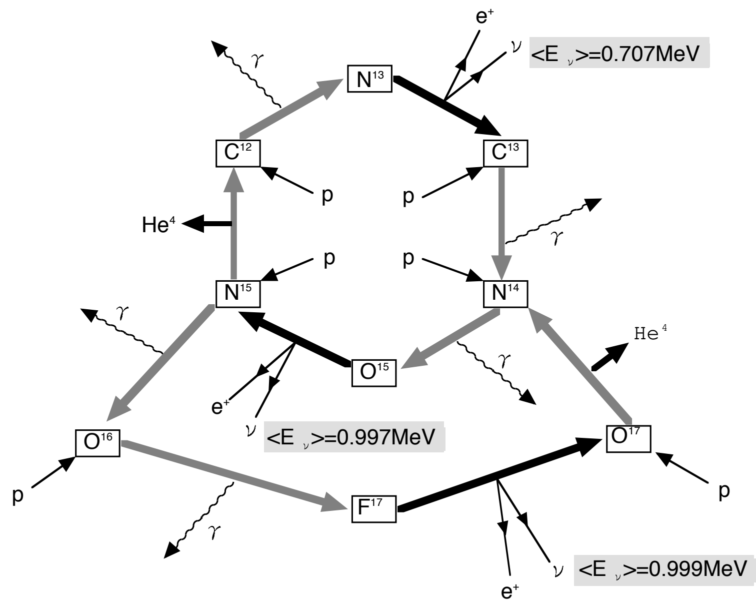
And only ν_e are produced

- Two main chains of nuclear reactions

pp Chain :



CNO cycle:



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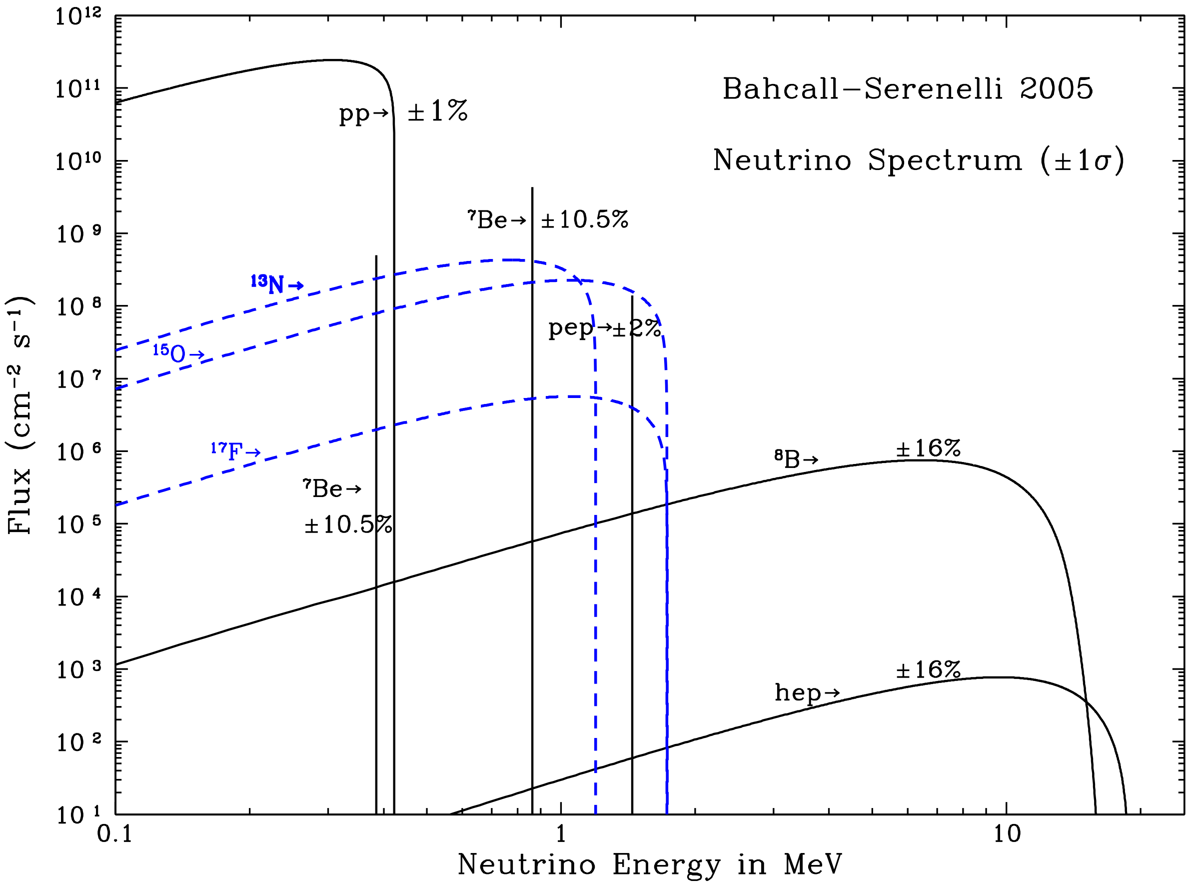
Solar Neutrinos: Fluxes



PP CHAIN	E_ν (MeV)
(pp)	
$p + p \to^2 H + e^+ + \nu_e$	≤ 0.42
(pep)	
$p + e^- + p \to^2 H + \nu_e$	1.552
(^{7}Be)	
$^7Be + e^- \to^7 Li + \nu_e$	$0.862(90\%)$
	0.384 (10%)
(hep)	
$^2He + p \to^4 He + e^+ + \nu_e$	≤ 18.77
(^{8}B)	
$^8B \to^8 Be^* + e^+ + \nu_e$	≤ 15
CNO CHAIN	E_ν (MeV)
(^{13}N)	
$^{13}N \to^{13} C + e^+ + \nu_e$	≤ 1.199
(^{15}O)	
$^{15}O \to^{15} N + e^+ + \nu_e$	≤ 1.732
(^{17}F)	
$^{17}F \to^{17} O + e^+ + \nu_e$	≤ 1.74

Solar Neutrinos: Results

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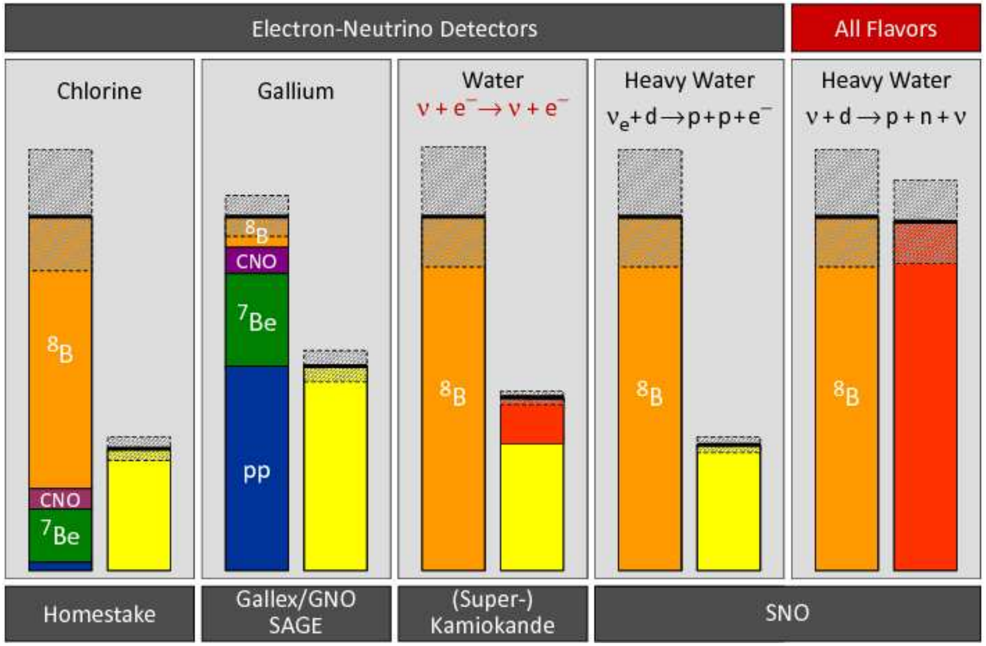


Experiments measuring ν_e observe a deficit

Deficit disappears in NC

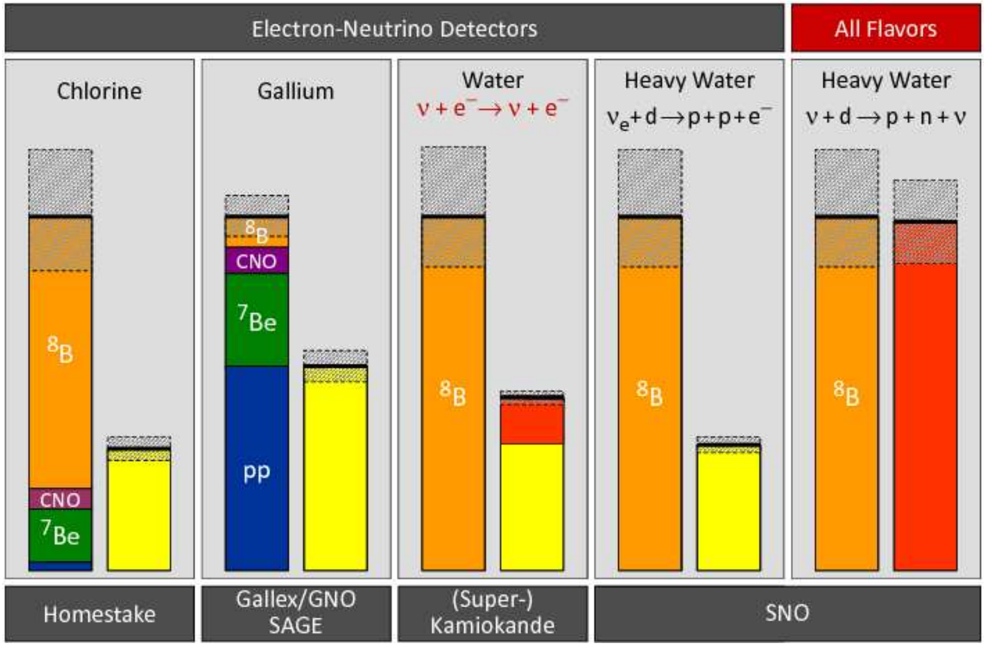
$\Rightarrow$ Solar Model Independent Effect

Deficit is energy dependent

Deficit $\Rightarrow P_{ee} \sim 30\% \; (< 0.5)$ for $E_\nu \gtrsim 0.8$ MeV

Solar Neutrinos: Results

Concha Gonzalez-Garcia



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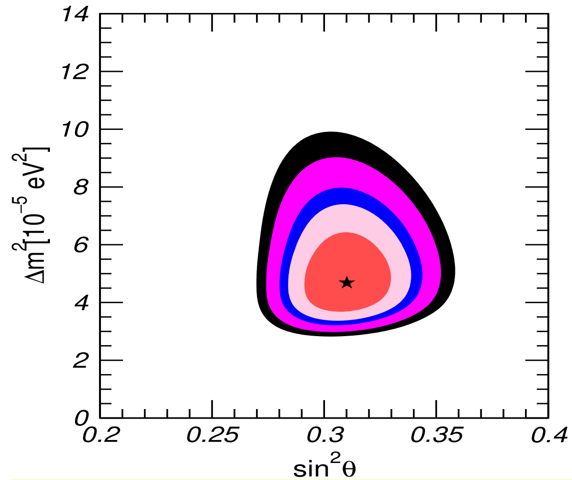
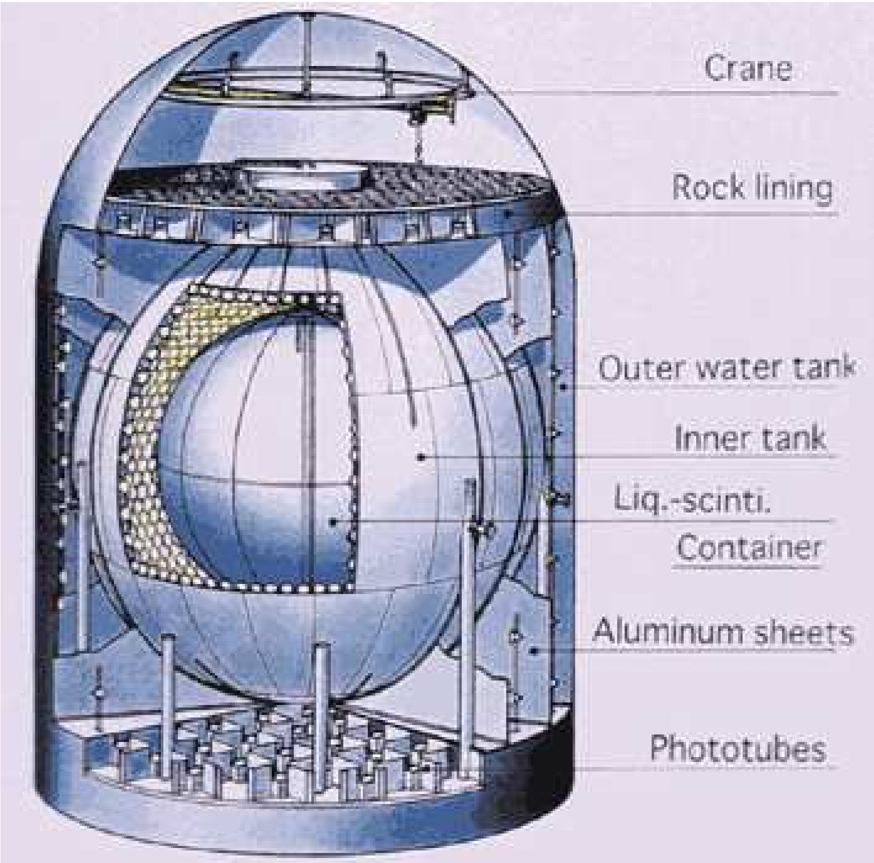
Best explained by MSW $\nu_e \to \nu_{\mu,\tau}$

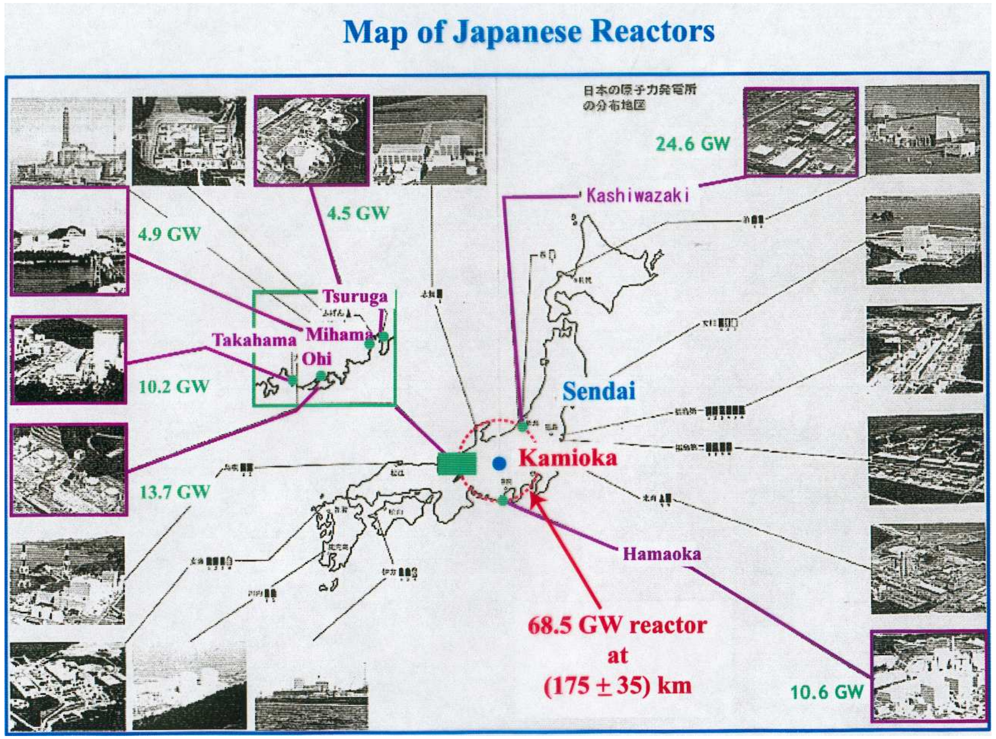


$\Delta m^2 \sim 5 \times 10^{-5}\ \mathrm{eV}^2, \theta \sim \frac{\pi}{6}$

Terrestrial test: KamLAND

KamLAND: Detector of $\bar{\nu}_e$ produced in nuclear reactors in Japan at an average distance of 180 Km





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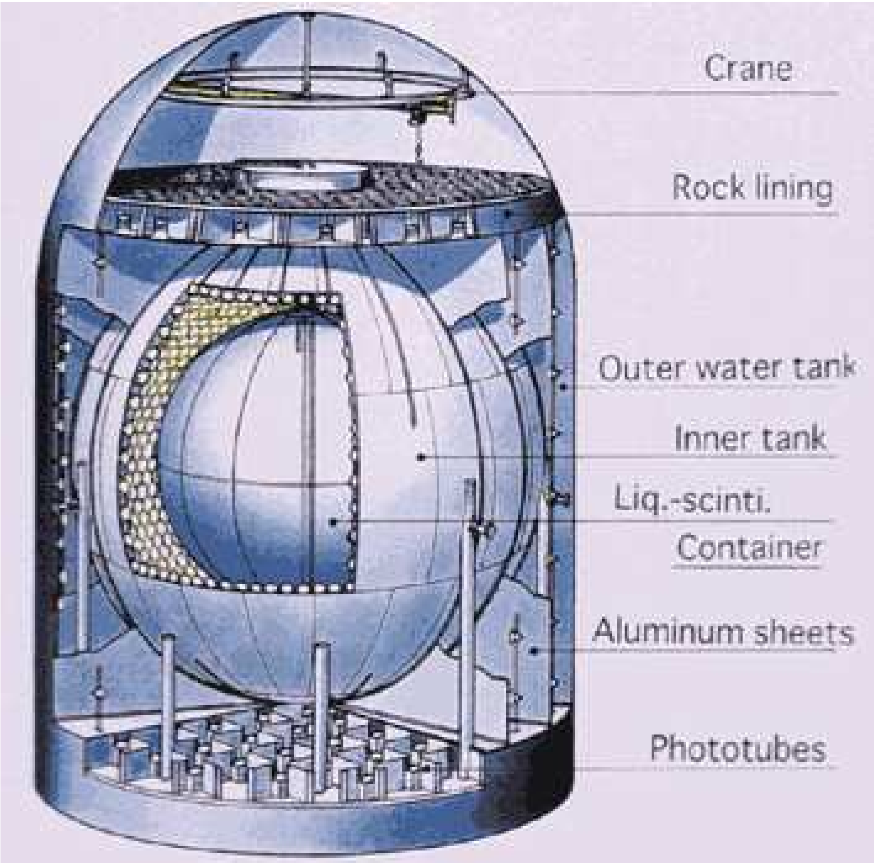
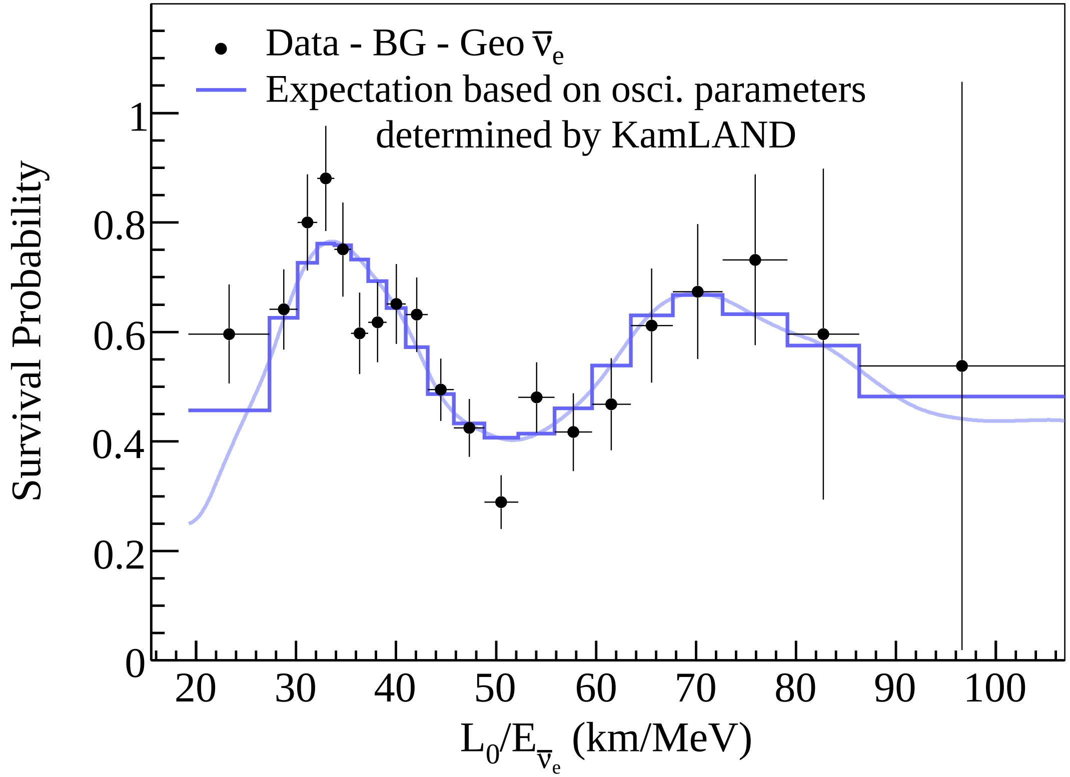


Results of KamLAND

compared with P_{ee} for

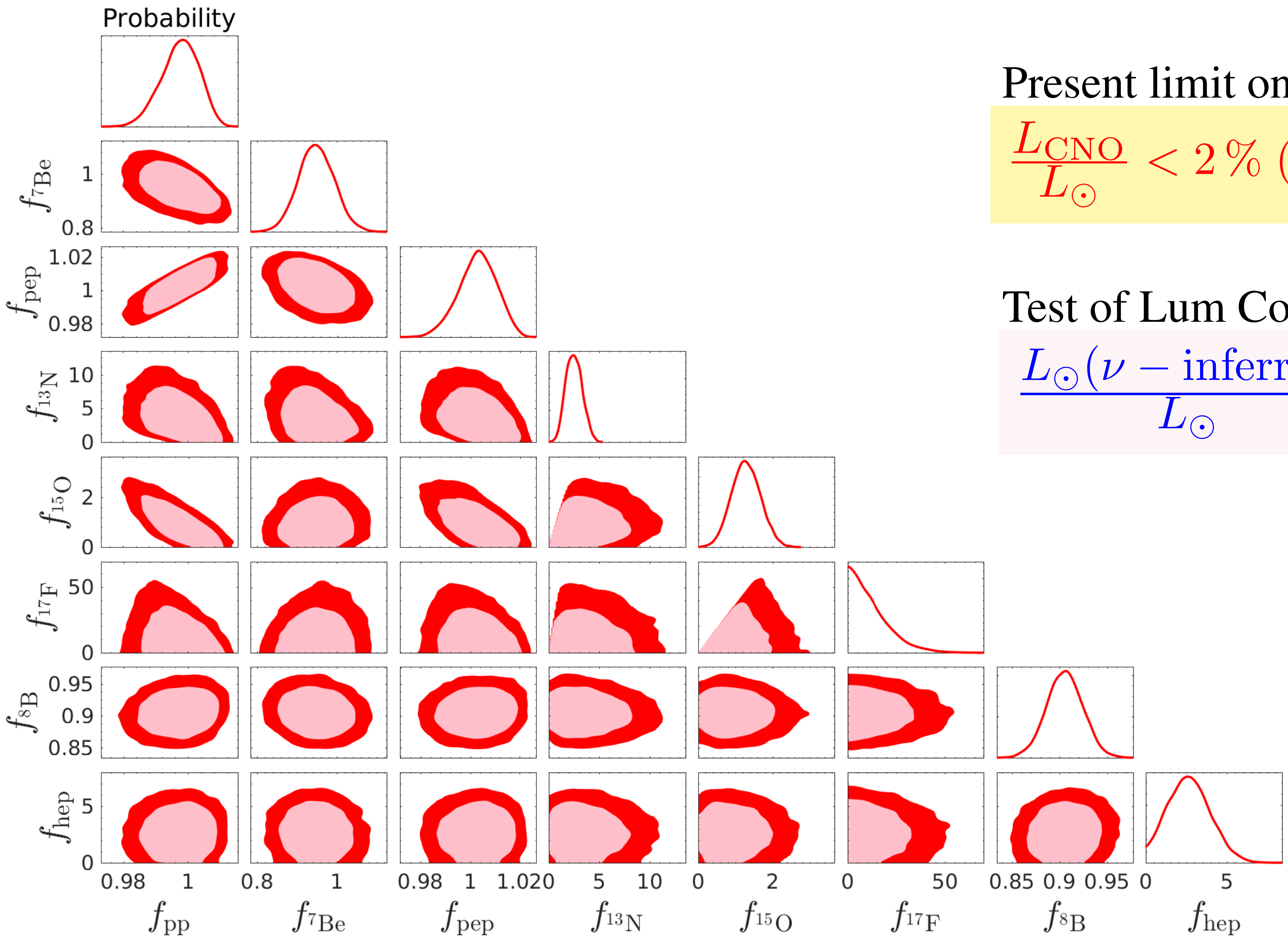
$\theta = 35^\circ$ y $\Delta m^2 = 7.5 \times 10^{-5}$ $(\mathrm{eV/c^2})^2$



Byproduct: Testing How the Sun Shines with $\nu's$

Fitting together Δm^2, θ and normalization of ν-producing reactions: $f_i = \frac{\Phi_i}{\Phi_i^{SSM}}$

$\Rightarrow$ Constraint on solar energy produced by nuclear



Present limit on CNO:

$$\frac{L_{\mathrm{CNO}}}{L_\odot} < 2\,\%\ (3\sigma)$$

Test of Lum Constraint:

$$\frac{L_\odot(\nu - \mathrm{inferred})}{L_\odot} = 1.04 \pm 0.07$$

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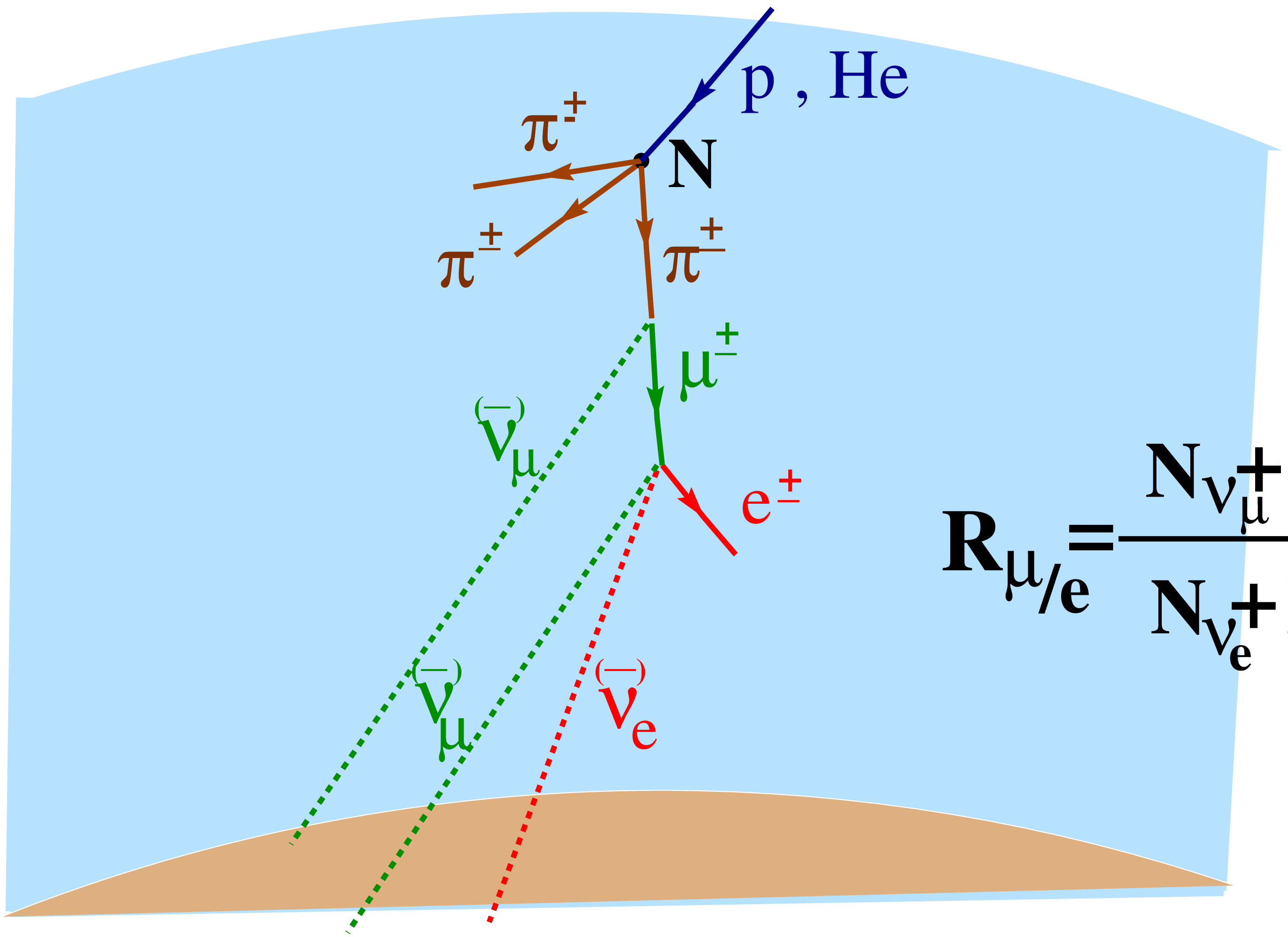
Atmospheric Neutrinos

Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He . . .) with the atmosphere

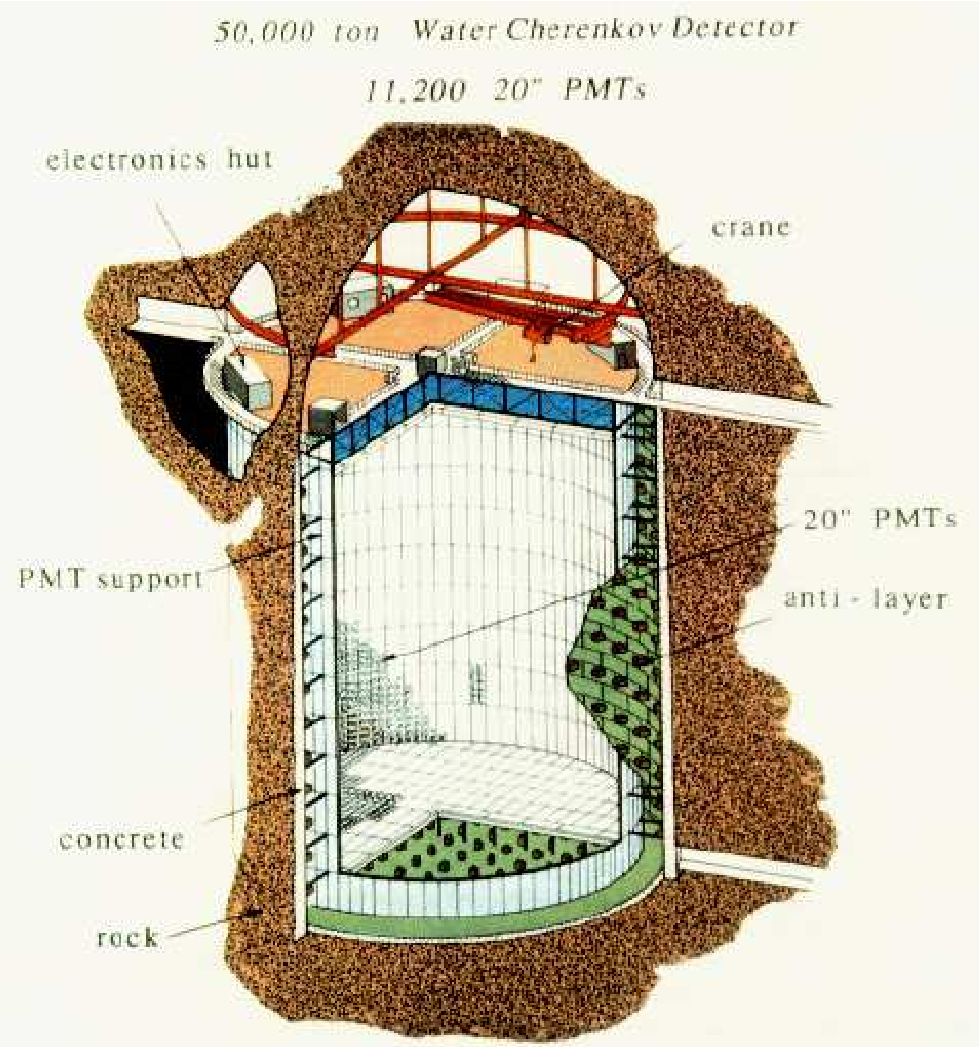


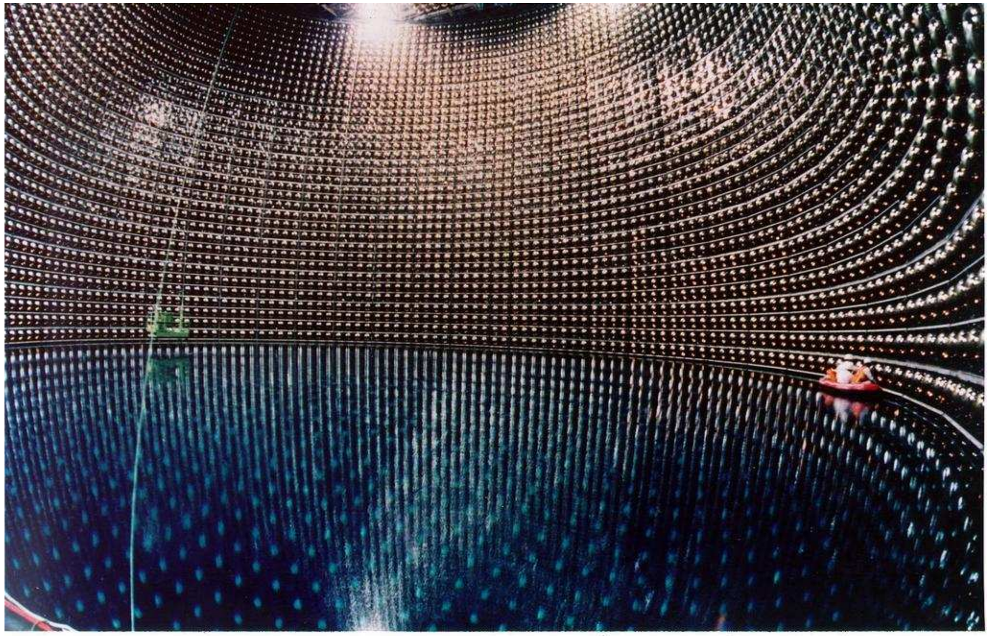
$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

Detection of Atmpospheric Neutrinos: SuperKamiokande

Located in the Kamiokande mine in the center of Japan at $\sim$ 1Km deep

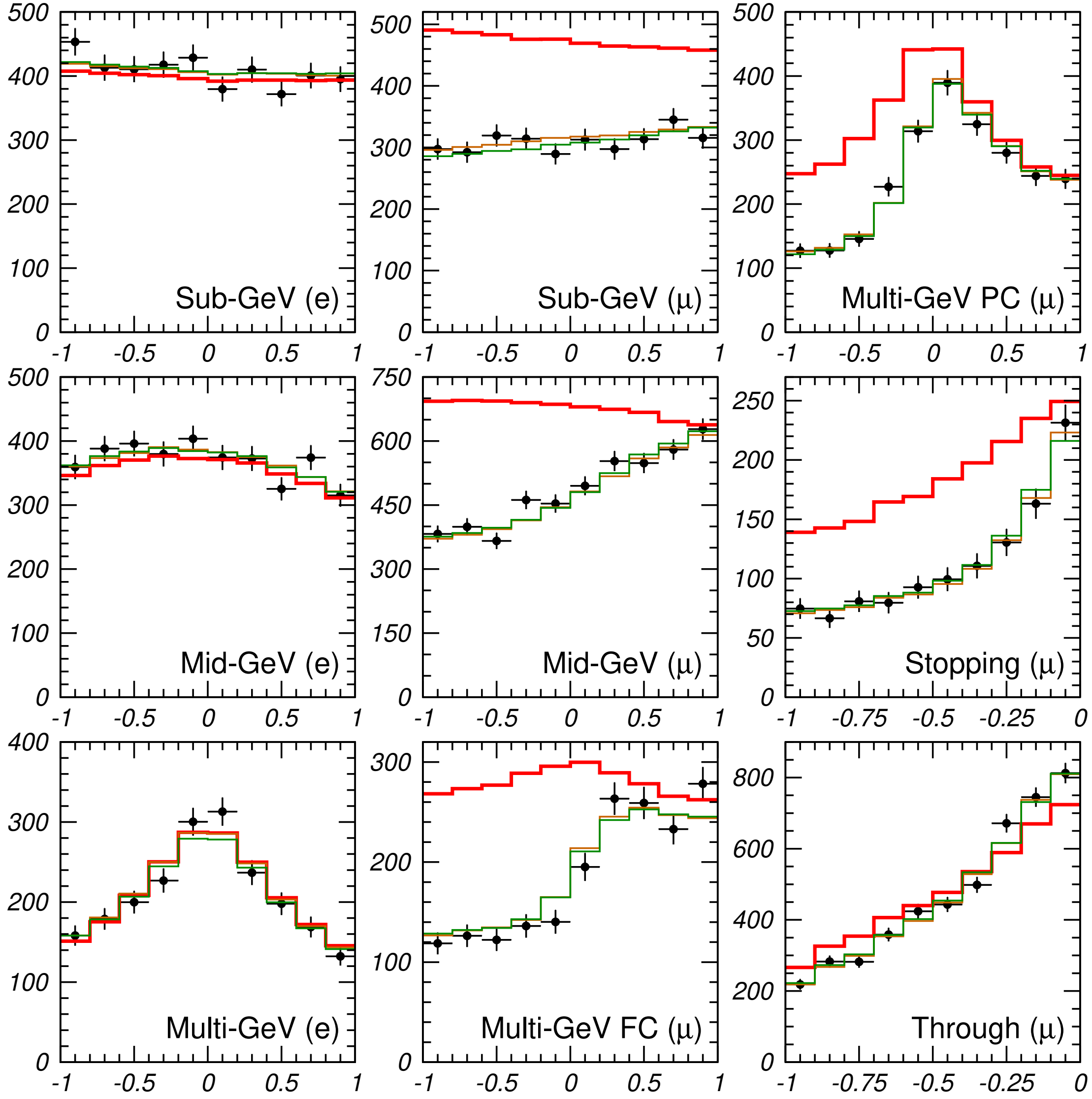
50 Kton of water surounded by $\sim$ 12000 photomultipliers

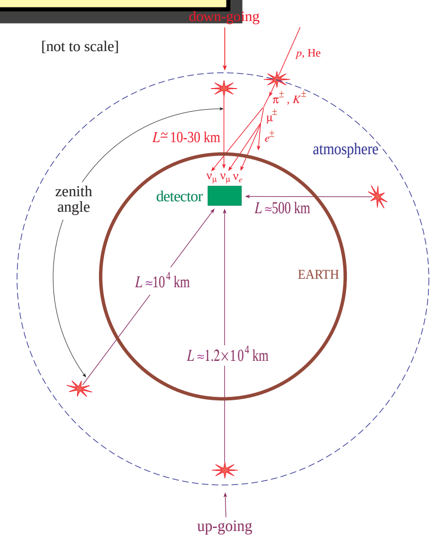


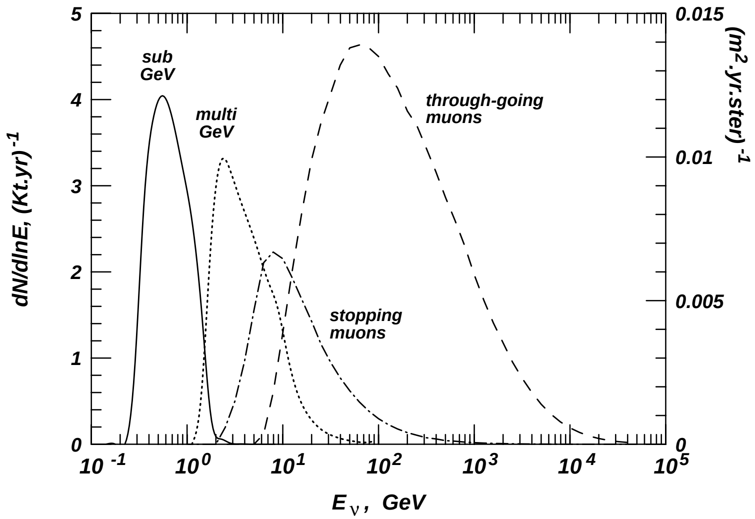


Atmospheric Neutrinos:Results

- SKI+II+III+IV data:







Atmospheric Neutrinos:Results

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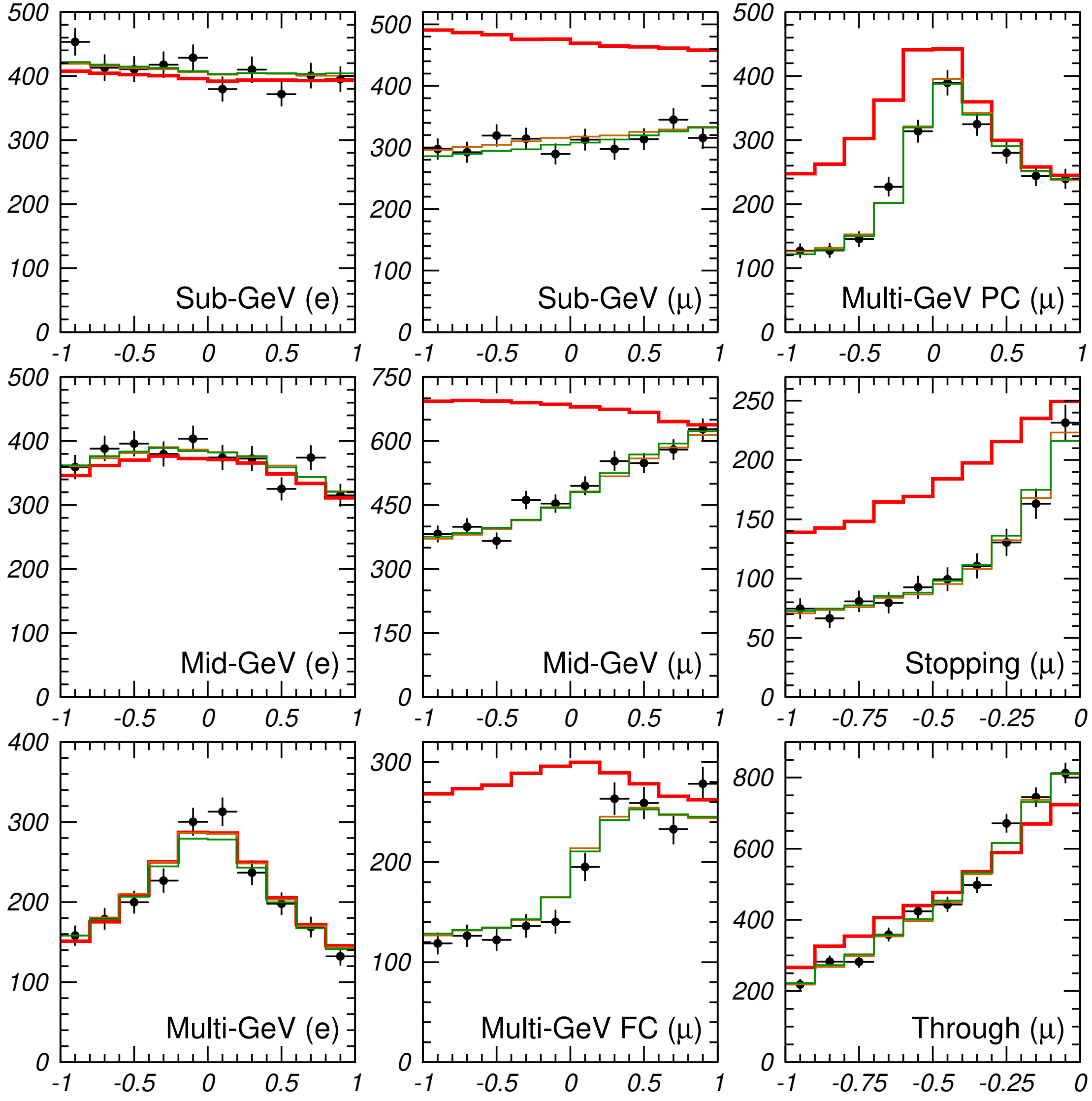
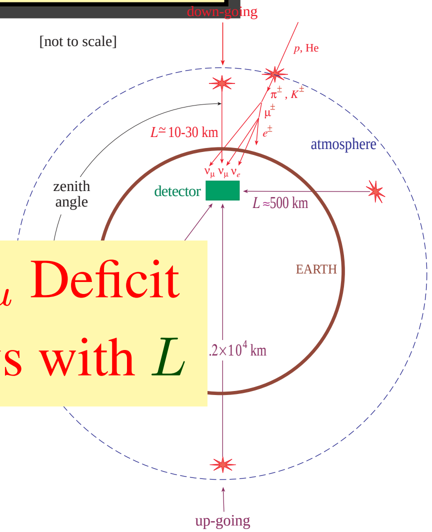
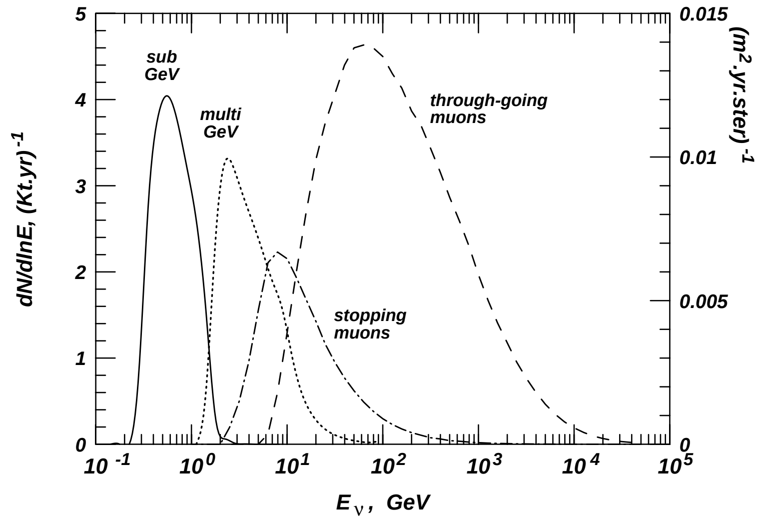
- SKI+II+III+IV data:

ν_e in agreement with SM





$\rightarrow \nu_\mu$ Deficit grows with L



$\rightarrow \nu_\mu$ Deficit decreases with E

Atmospheric Neutrinos: Results

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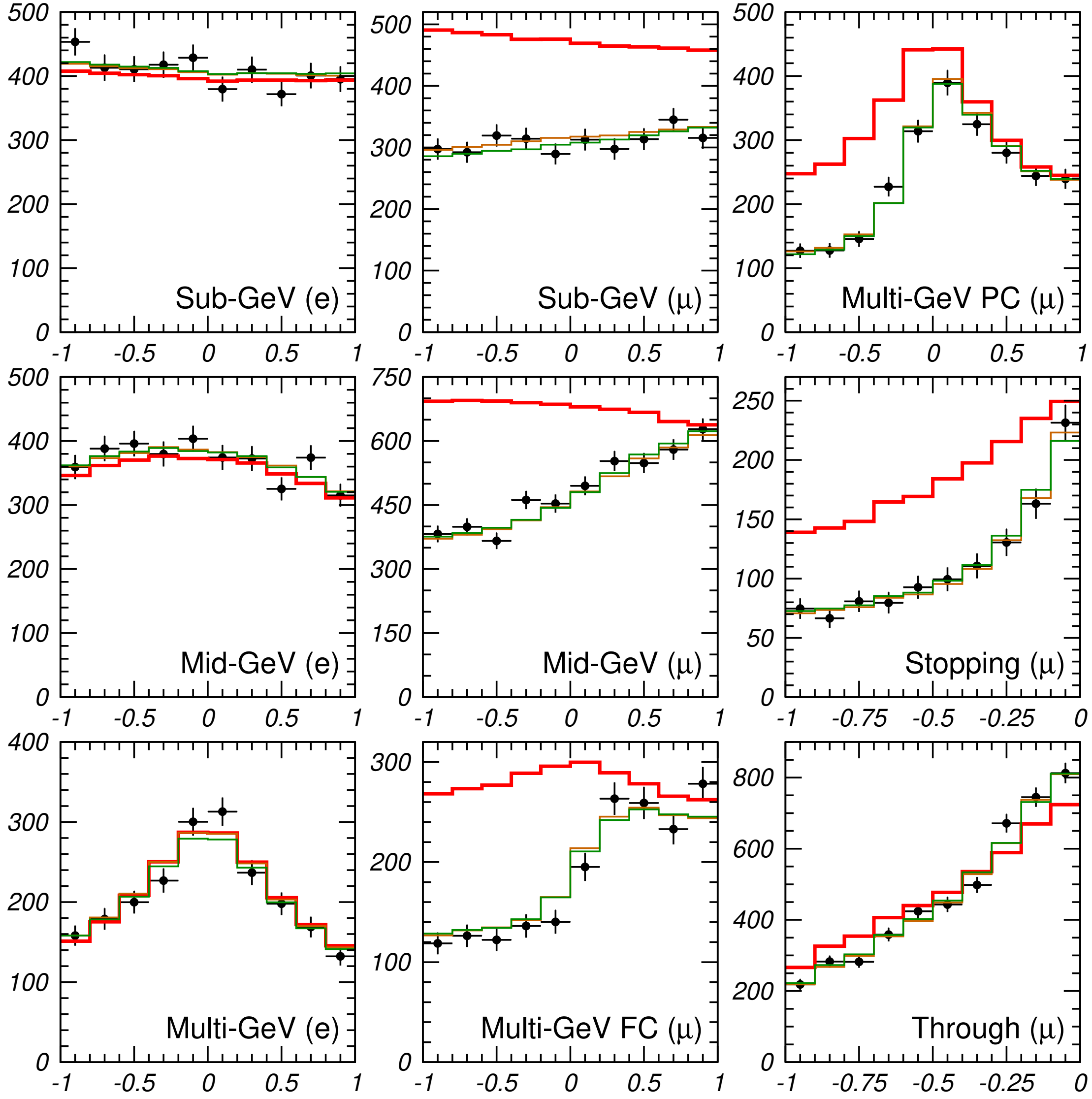
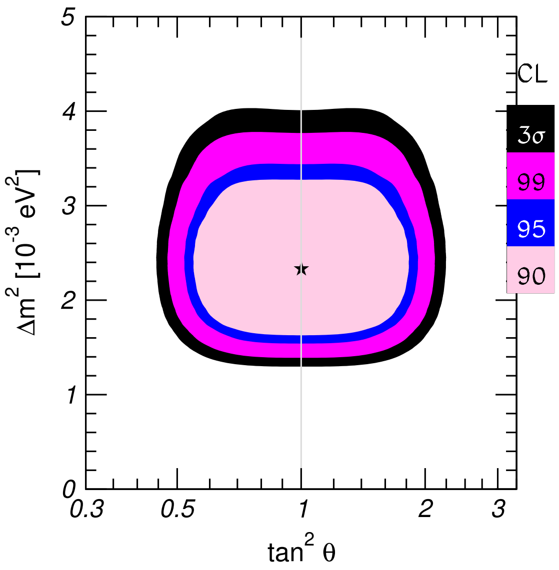
- SKI+II+III+IV data:



Best explained by $\nu_\mu \to \nu_\tau$



$\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2

$\tan^2\theta \sim 1 \Rightarrow \theta \sim \frac{\pi}{4}$

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

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- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

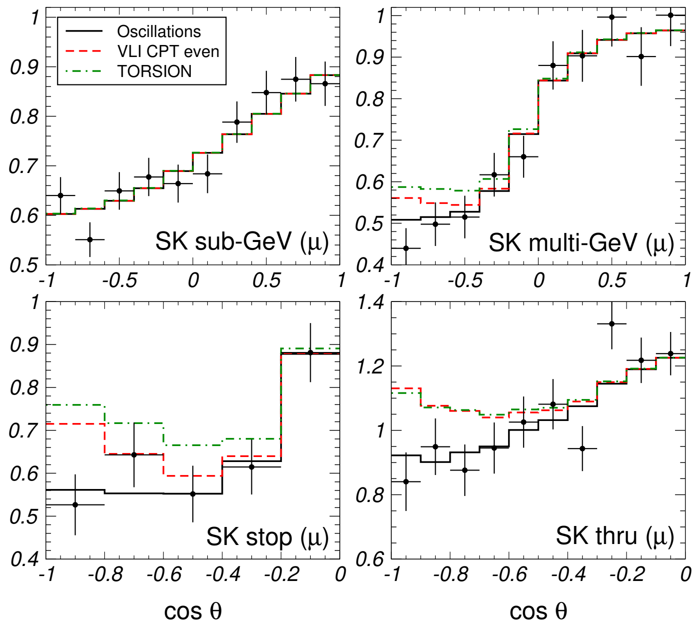
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar{\nu}_L^\alpha b_\mu^{\alpha\beta}\gamma_\mu\nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

Alternative Mechanisms vs ATM ν's

- Strongly constrained with ATM data (MCG-G, M. Maltoni PRD 04,07)



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\,\Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|Q\,\Delta k| \leq 4.8 \times 10^{-23}\ \text{GeV}$$

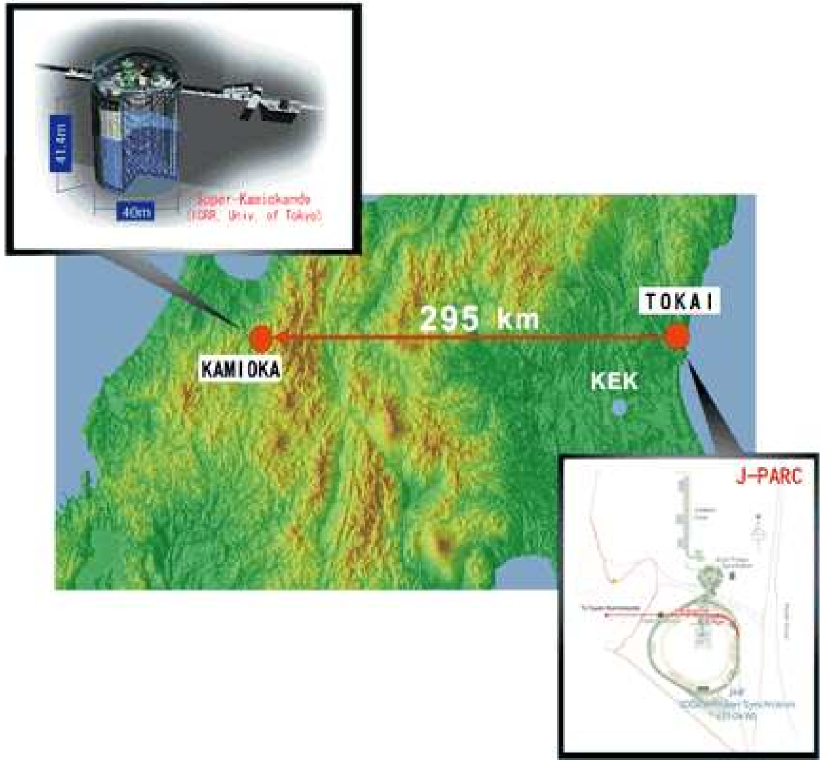
$$|\Delta b| \leq 3.0 \times 10^{-23}\ \text{GeV}$$

ν_μ Disappearance in Accelerator ν Fluxes

T2K:

ν_μ produced in Tokai (Japan)

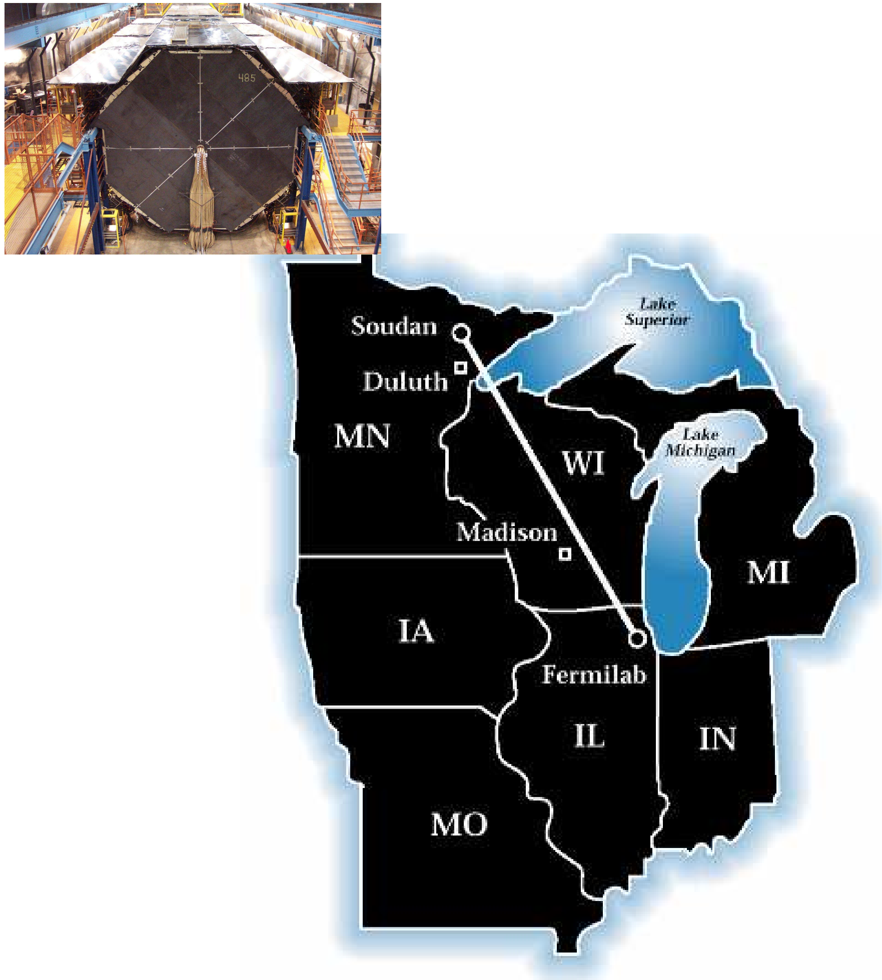
detected in SK at $\sim$ 250 Km



MINOS, NOνA

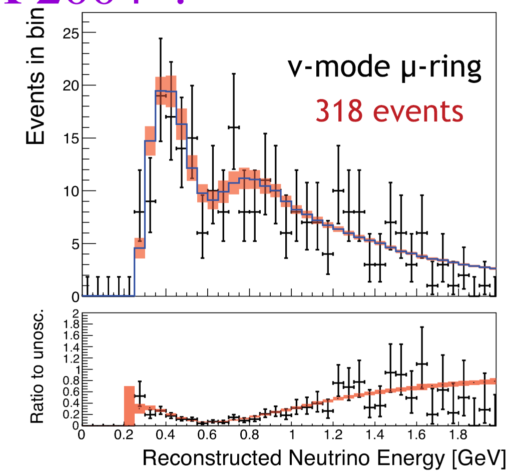
ν_μ produced en Fermilab (Illinois)

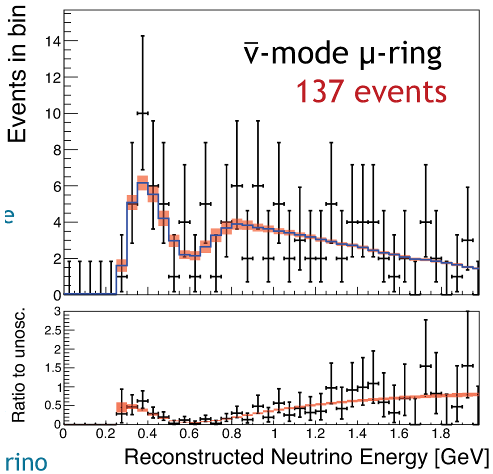
detected in Minnesota at $\sim$ 800 Km



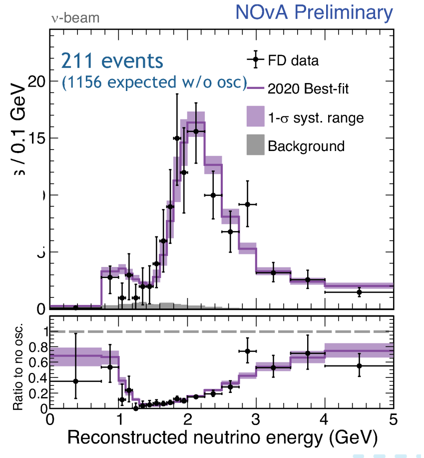
Long Baseline Experiments: ν_μ Disappearance

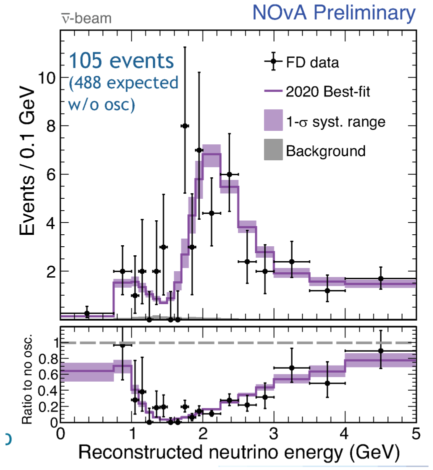
K2K/T2K 2004–:





NOνA: 2015–





ν_μ oscillations with $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2 and mixing compatible with $\frac{\pi}{4}$

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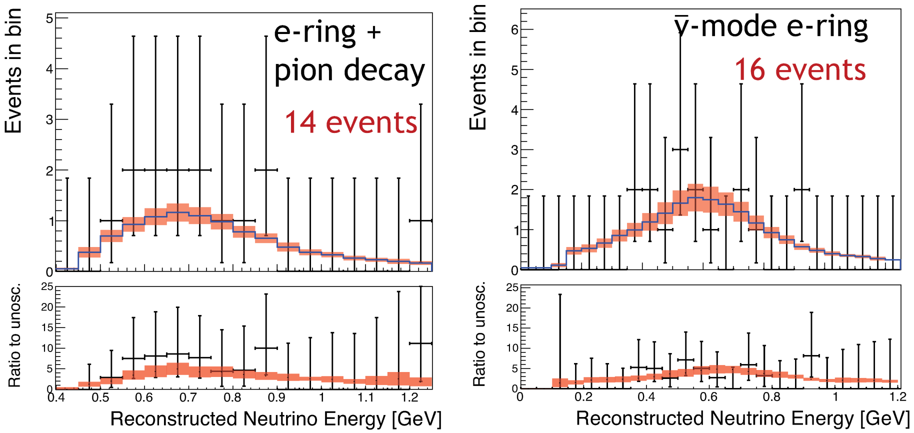
Long Baseline Experiments: ν_e Appearance

- Observation of $\nu_\mu \to \nu_e$ transitions with $E/L \sim 10^{-3}$ eV^2

T2K

$\nu_\mu \to \nu_e$ $\qquad$ $\bar\nu_\mu \to \bar\nu_e$



NOνA

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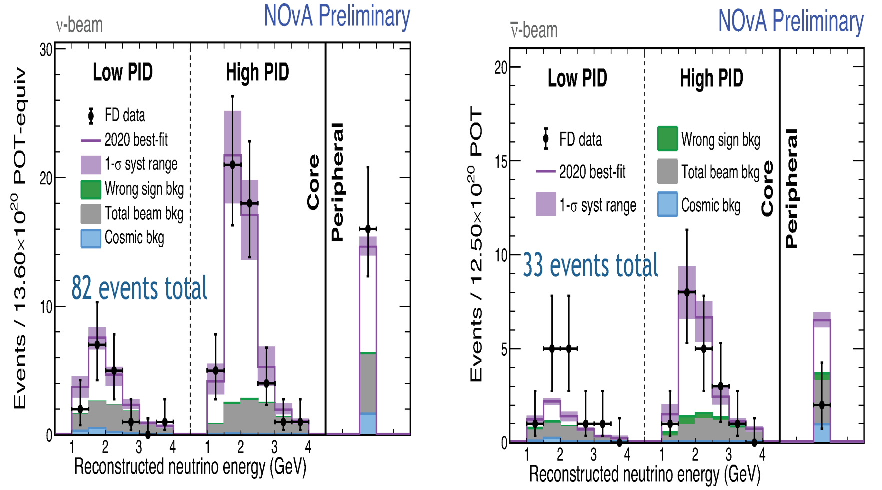
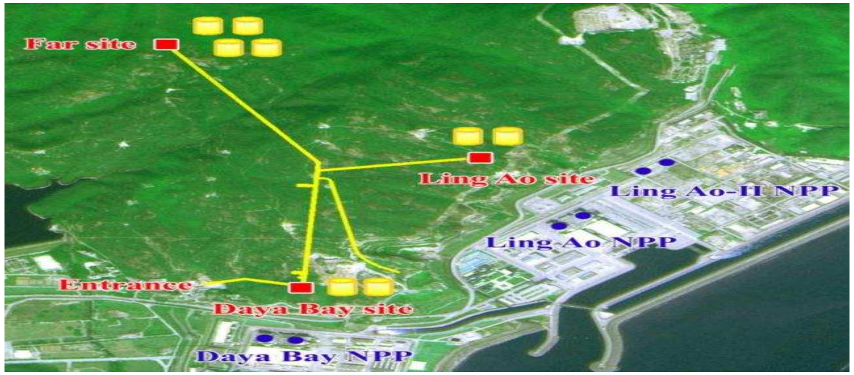


- Test of $P(\nu_\mu \to \nu_e)$ vs $P(\bar\nu_\mu \to \bar\nu_e) \Rightarrow$ Leptonic CP violation

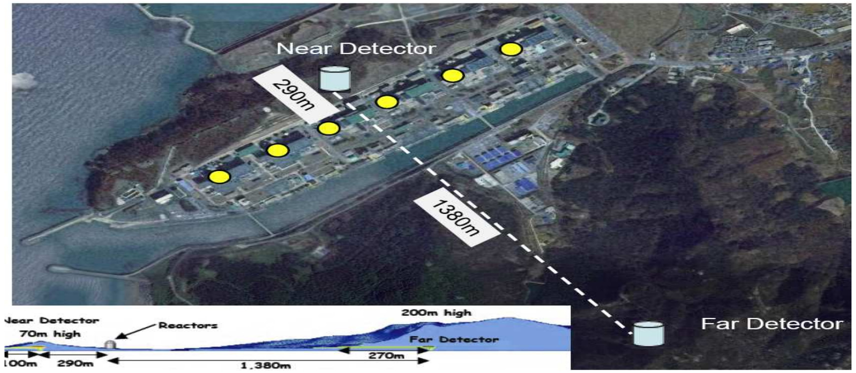
Medium Baseline Reactor Experiments

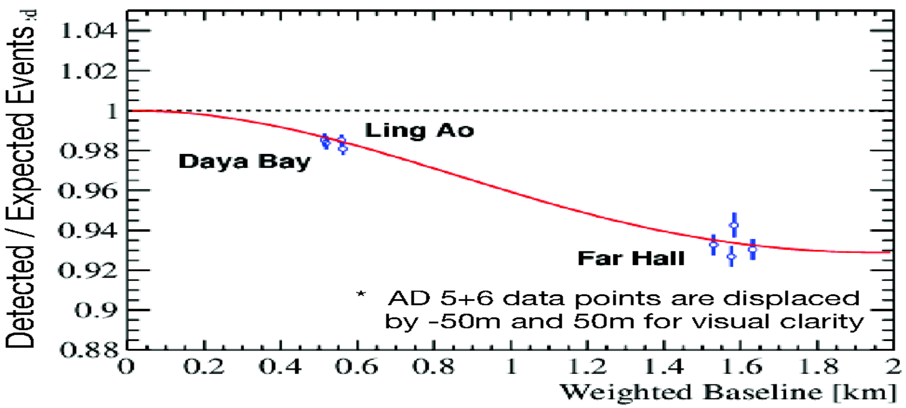
- Searches for $\bar\nu_e \to \bar\nu_e$ disapperance at $L \sim$ Km ($E/L \sim 10^{-3}$ eV^2)
- Relative measurement: near and far detectors

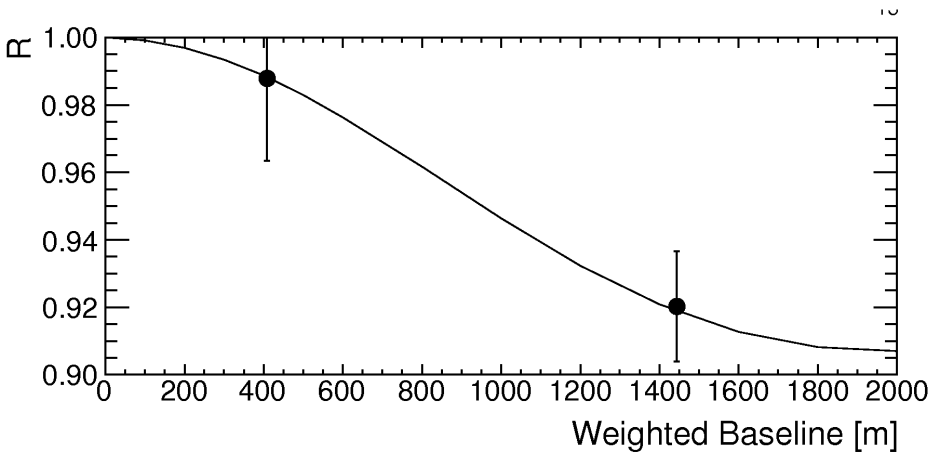
Daya-Bay



Reno







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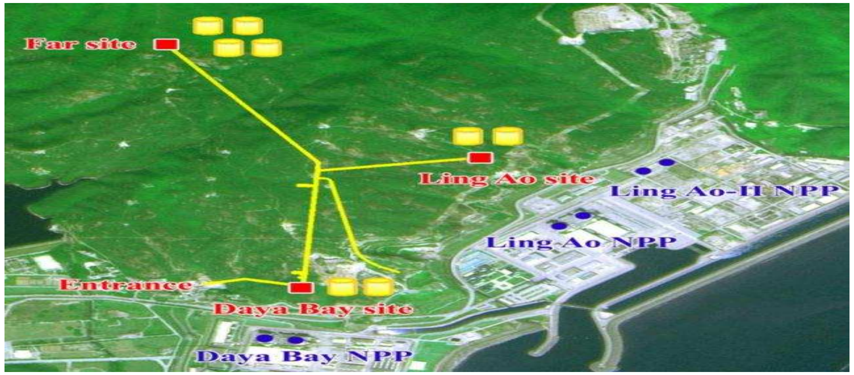

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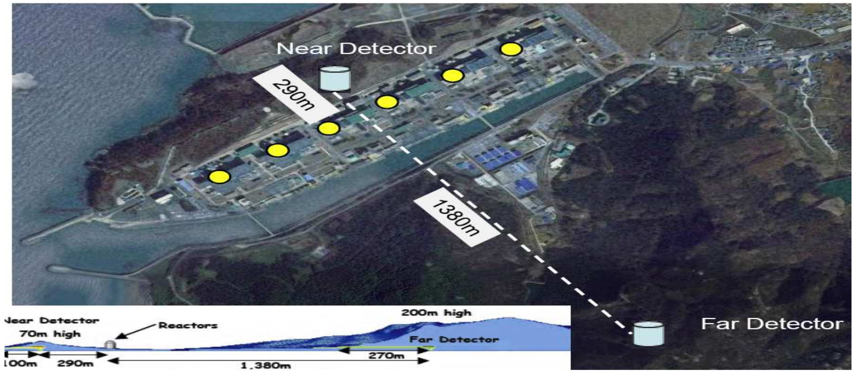
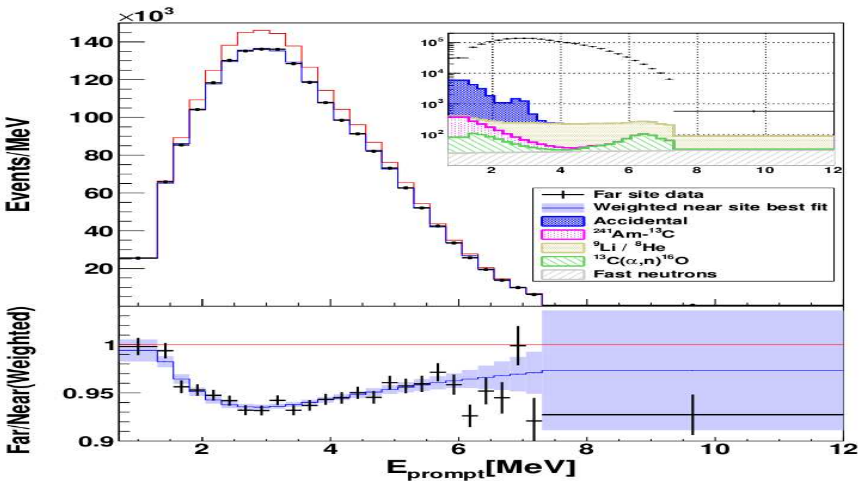
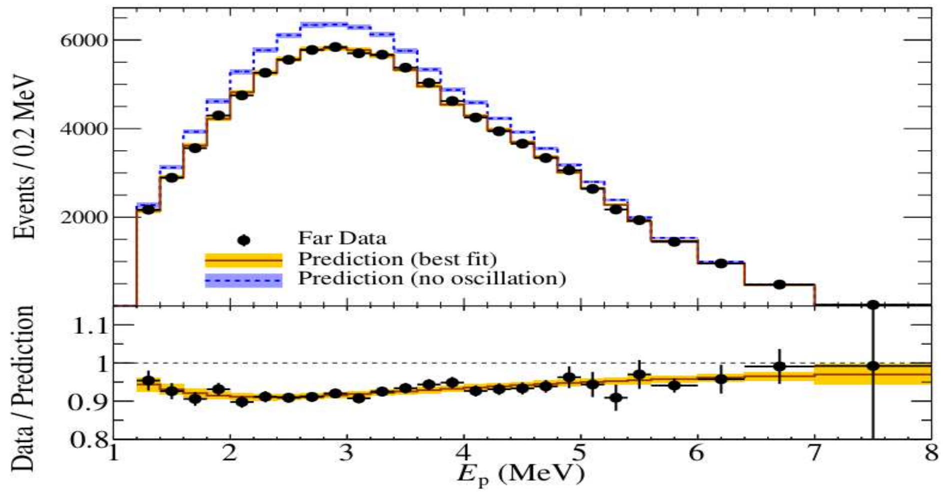


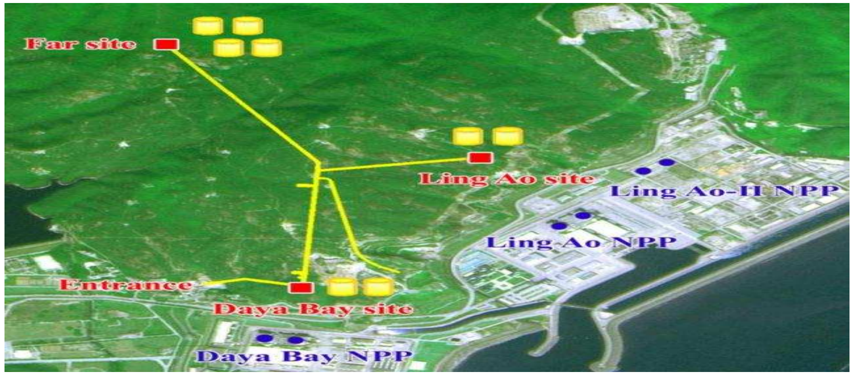




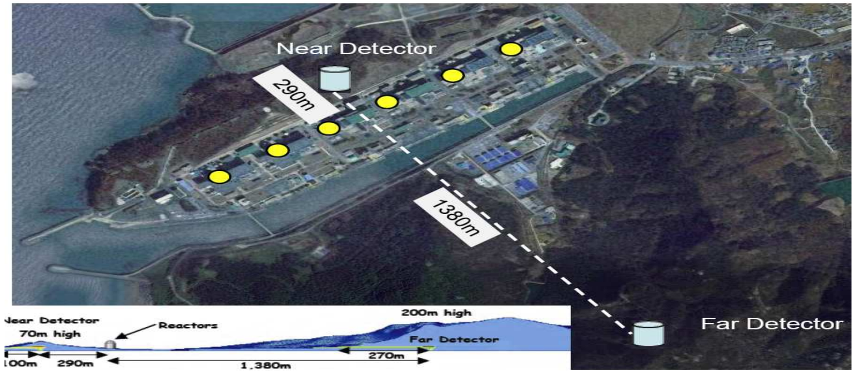
Medium Baseline Reactor Experiments

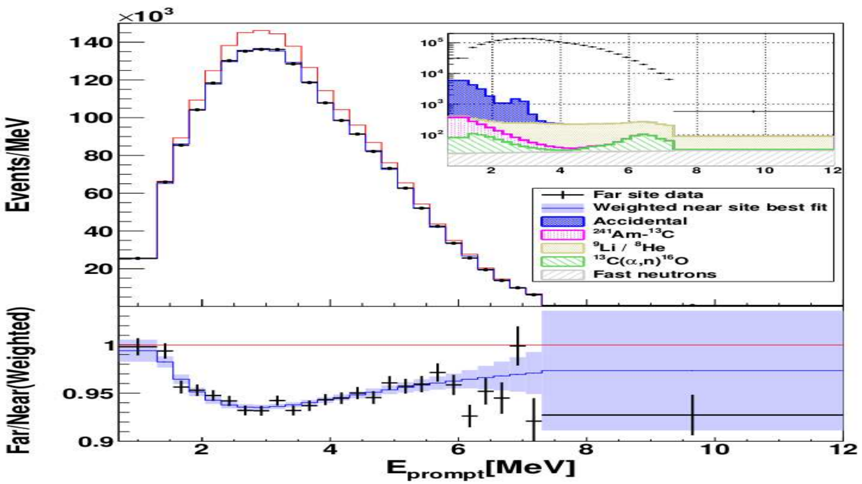
- Searches for $\bar{\nu}_e \to \bar{\nu}_e$ disapperance at $L \sim$ Km ($E/L \sim 10^{-3}$ eV^2)
- Relative measurement: near and far detectors

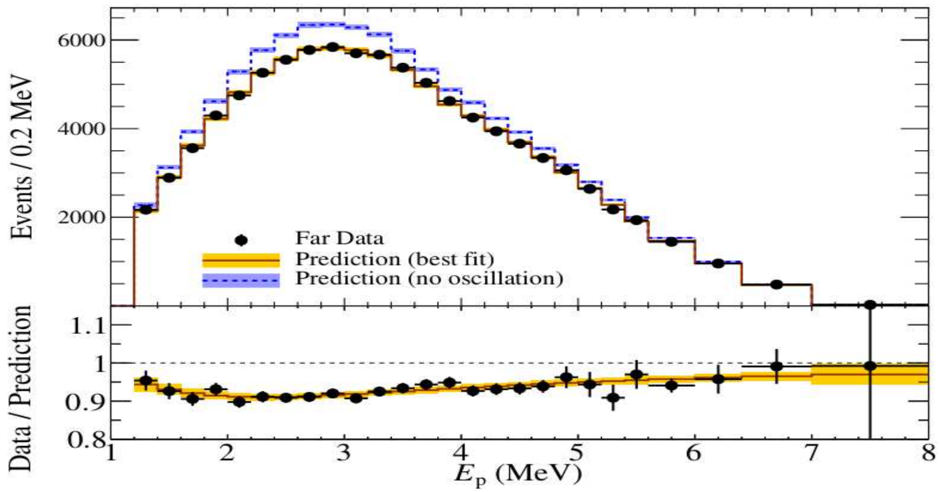
Daya-Bay



Reno





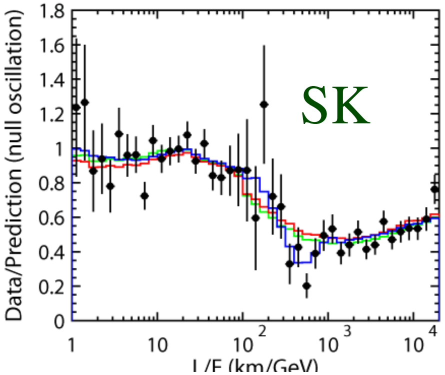


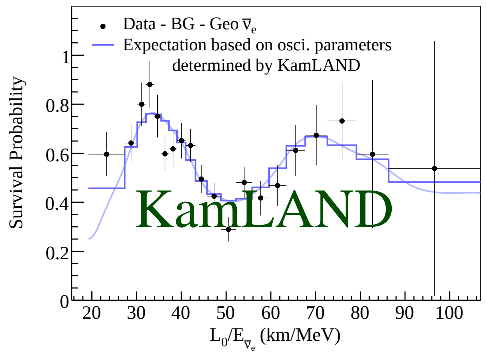
Described with $\Delta m^2 \sim 2.5 \times 10^{-3}$eV^2 (as ν_μ ATM and LBL acc but for ν_e) and $\theta \sim 9^\circ$

- We have observed with high (or good) precision:

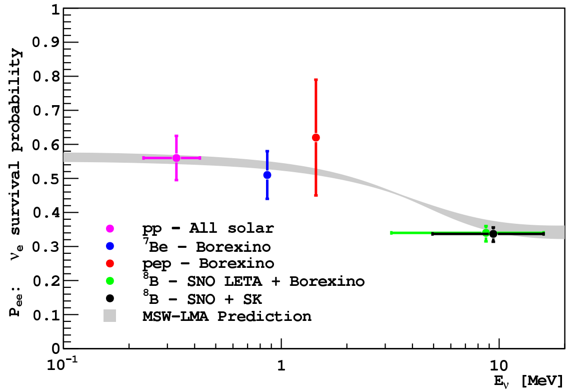
  - $*$ Atmospheric ν_μ & $\bar\nu_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE) $\frac{\Delta m^2}{\text{eV}^2} \sim 2\,10^{-3}$
  - $*$ Accel. ν_μ & $\bar\nu_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**) $\theta \sim 45^\circ$
  - $*$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA) $\theta \sim 8^\circ$
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**) $\frac{\Delta m^2}{\text{eV}^2} \sim 10^{-5}, \theta \sim 30^\circ$
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (D-Chooz, **Daya Bay, Reno**) $\frac{\Delta m^2}{\text{eV}^2} \sim 2\,10^{-3}, \theta \sim 8^\circ$

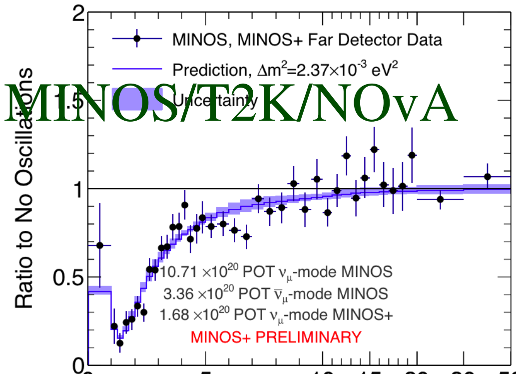
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

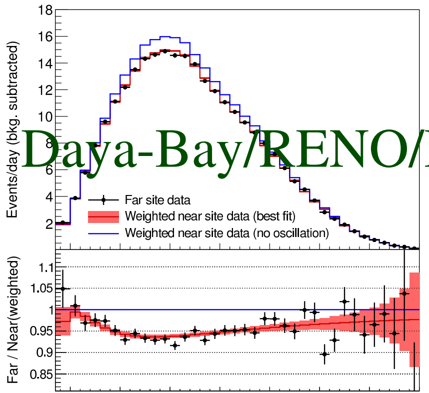




MSW conversion in Sun







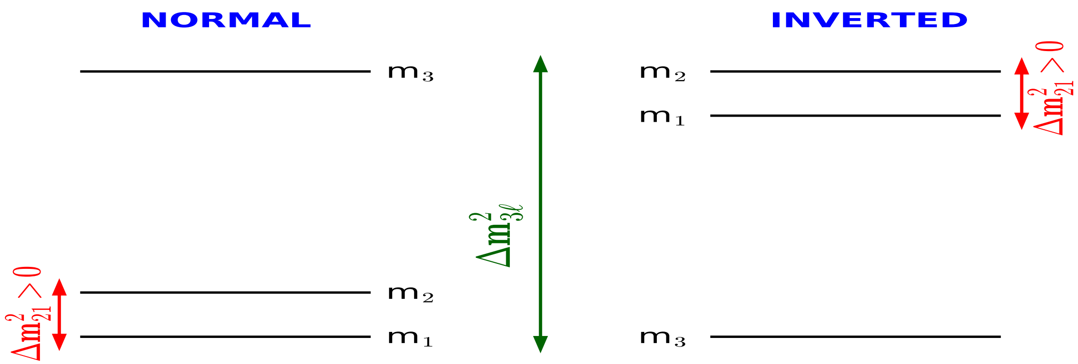
3ν Flavour Parameters

Concha Gonzalez-Garcia

- For **for 3 ν's** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Convention: $0 \le \theta_{ij} \le 90^\circ$ $\quad 0 \le \delta \le 360^\circ$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

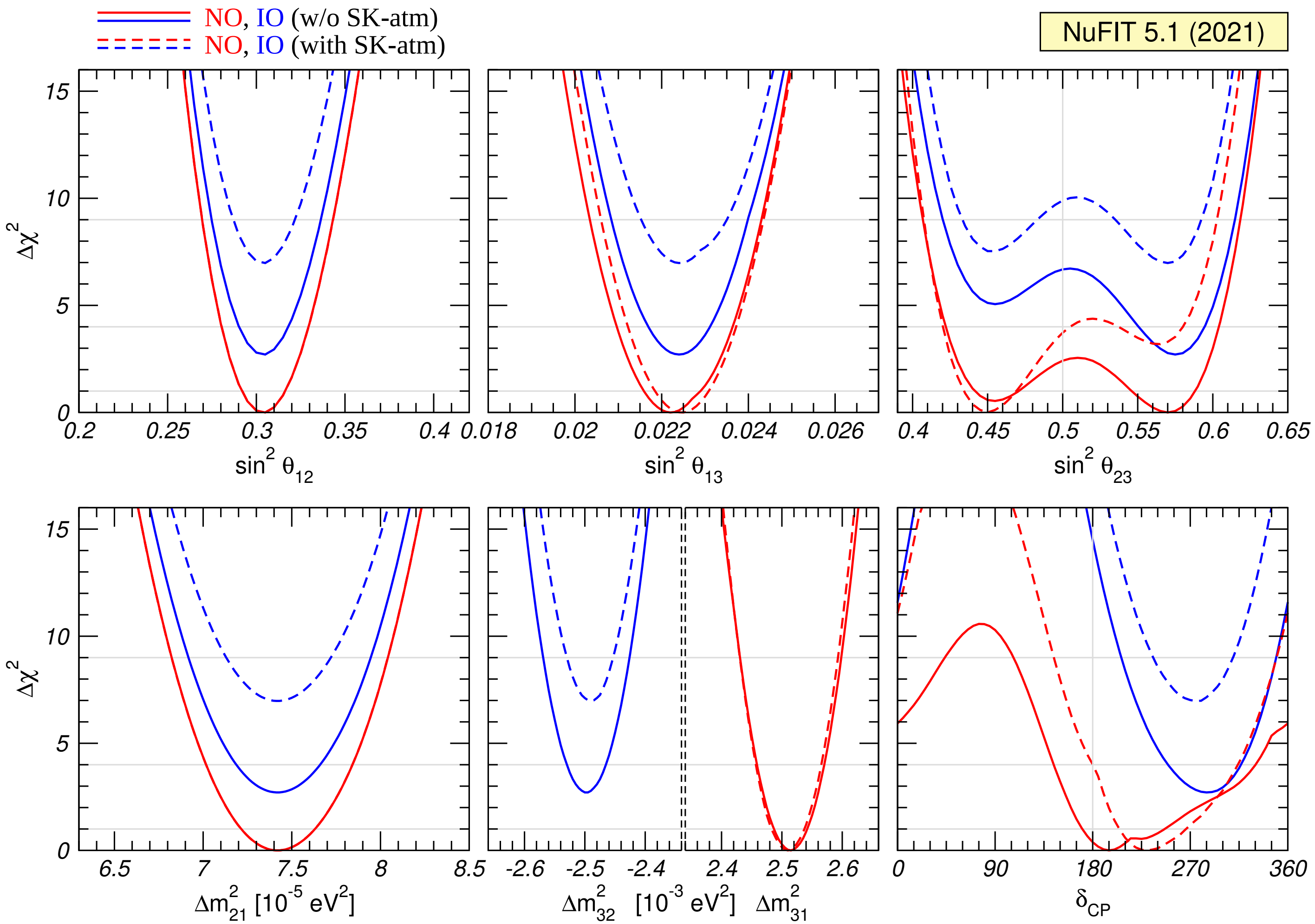
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

Experiment	Dominant Dependence	Important Dependence
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13} $\Delta m^2_{3\ell}$	
Atmospheric Experiments (SK,IC)		θ_{23}, $\Delta m^2_{3\ell}$, θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$ θ_{23}	
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}, θ_{23}

Summary: Global 3 ν Flavour Parameters

Global 6-parameter fit http://www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]



SK-atm $\equiv$ χ^2 table from SK1-4 for 372 kton-years

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Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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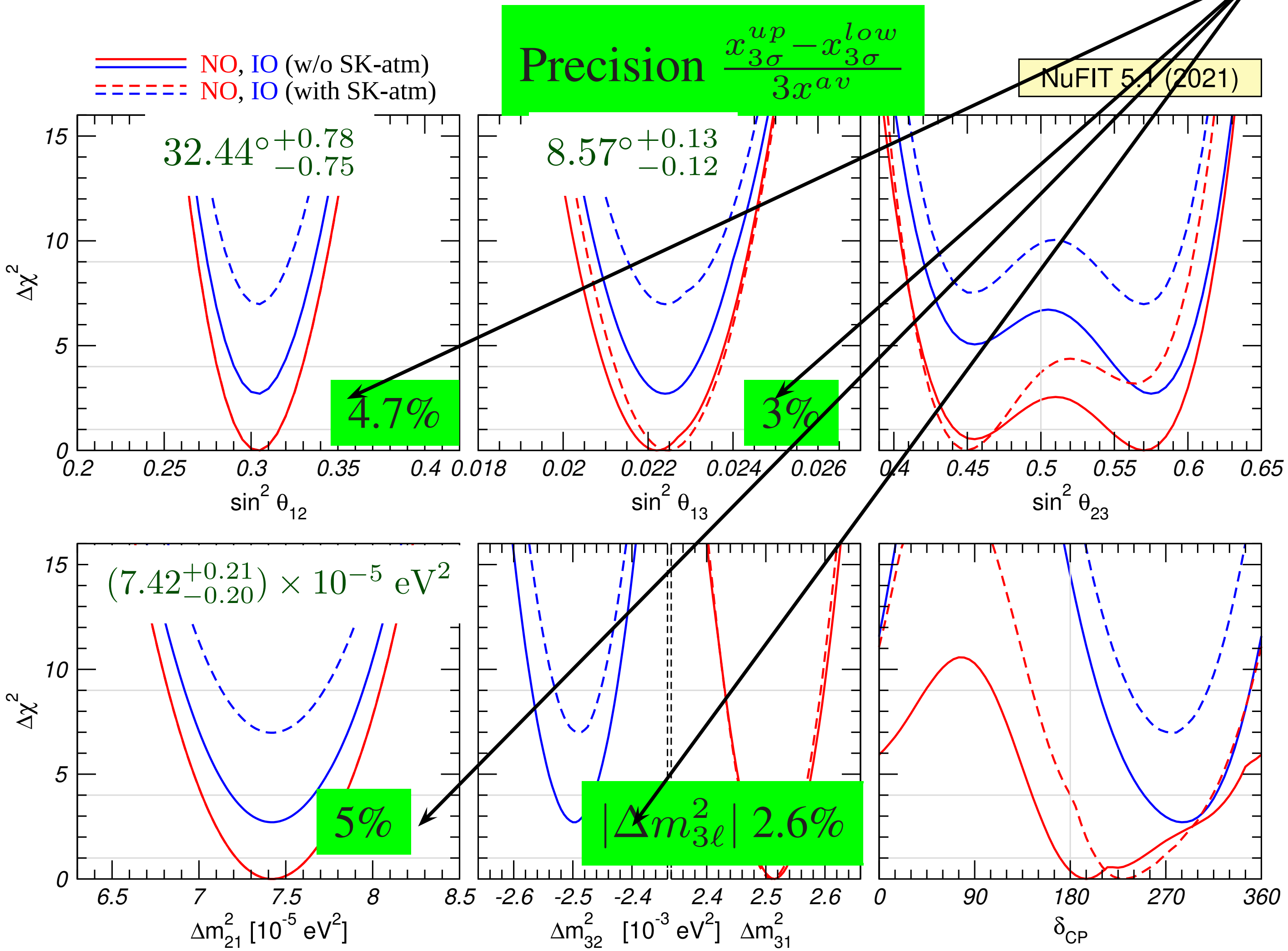

Summary: Global 3 ν Flavour Parameters

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1	
θ_{12}	15%	14%	14%	14%	14%	**1.07**
θ_{13}	30%	15%	11%	8.9%	9.0%	**3.3**
θ_{23}	43%	32%	32%	27%	27%	**1.6**
Δm^2_{21}	14%	14%	14%	16%	16%	**0.88**
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]	**2.5**
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	**1 [1.2]**
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

w/o [w] SK atm data

relat. precision at 3σ : $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

improvement factor from 2012 to 2021

Summary: Global 3 ν Flavour Parameters

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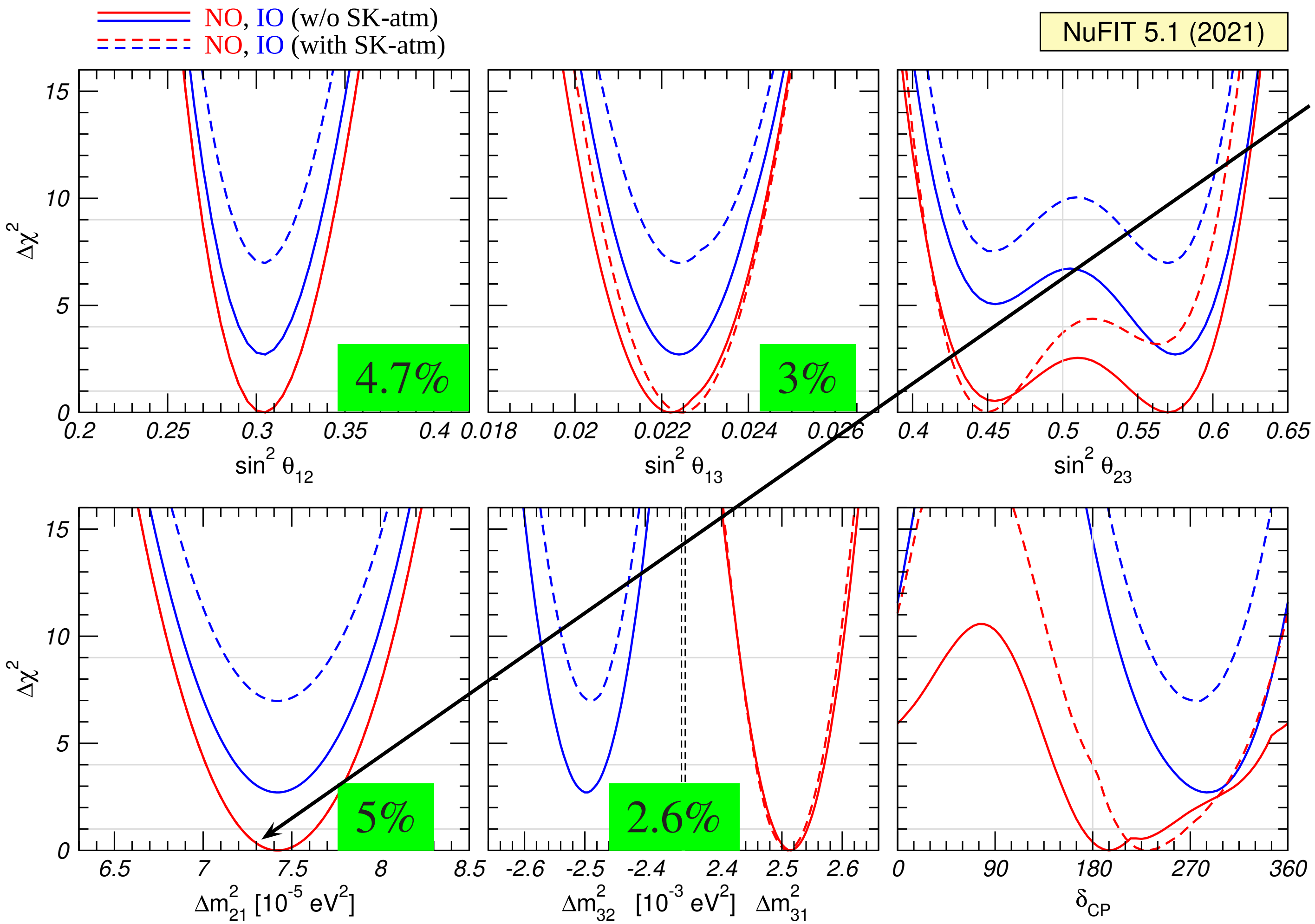
Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]



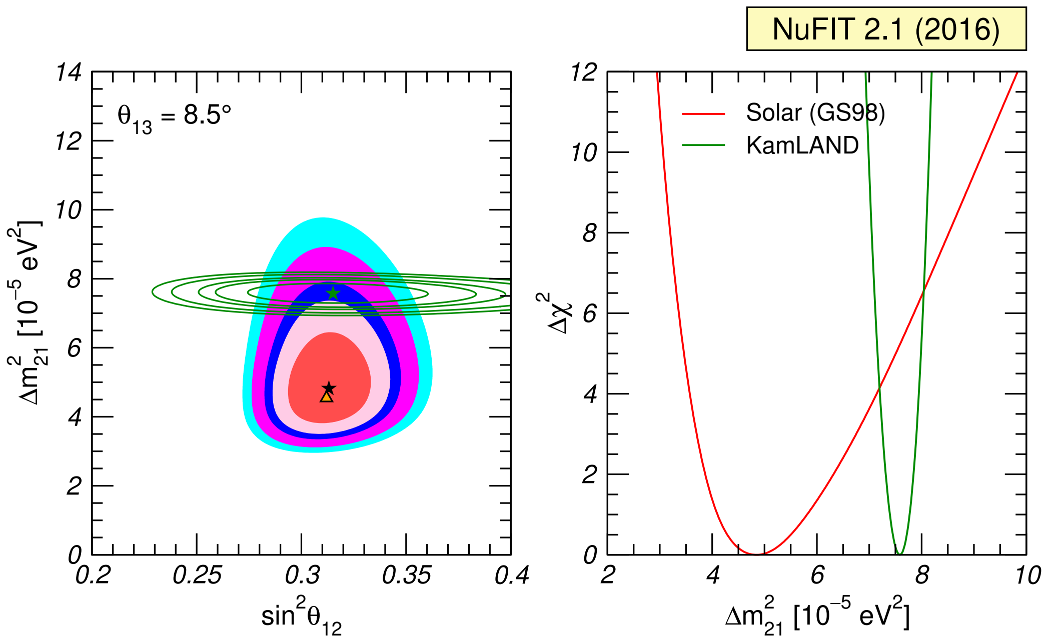
- 4 well-known parameters:

  θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$

  Δm^2_{21} Solar vs KLAND

  Tension Resolved

- Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar



θ_{12} better than 1σ agreement

But $\sim 2\sigma$ tension on Δm^2_{12}

Concha Gonzalez-Garcia

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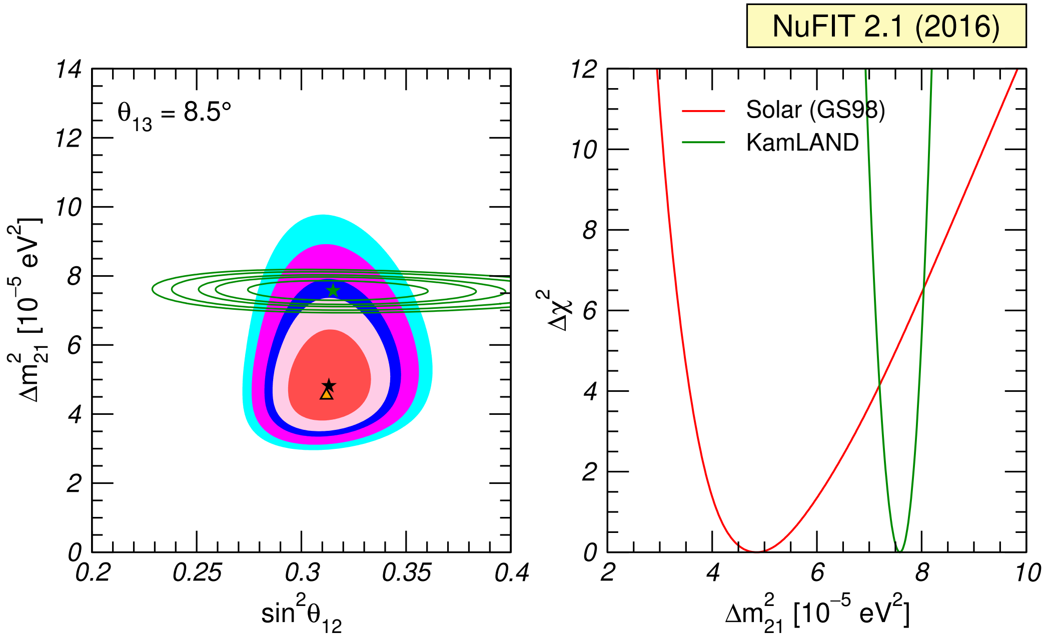

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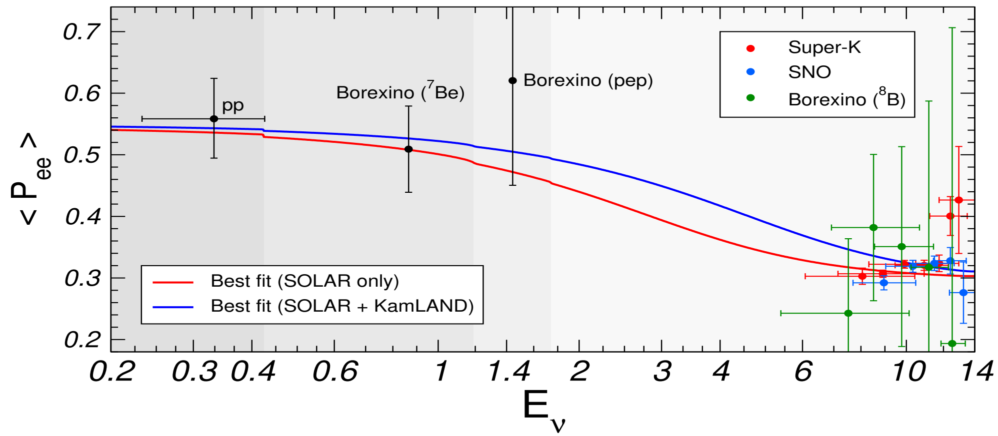
But $\sim 2\sigma$ tension on Δm^2_{12}

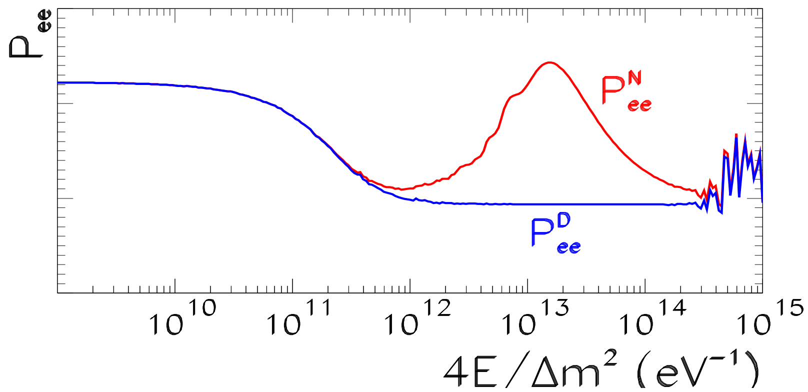
- Tension arising from:

Smaller-than-expected MSW low-E turn-up in SK/SNO spectrum at global b.f.

"too large" of Day/Night at SK

$A_{\rm D/N,SK4-2055} = [-3.1 \pm 1.6({\rm stat.}) \pm 1.4({\rm sys.})]\%$





Concha Gonzalez-Garcia

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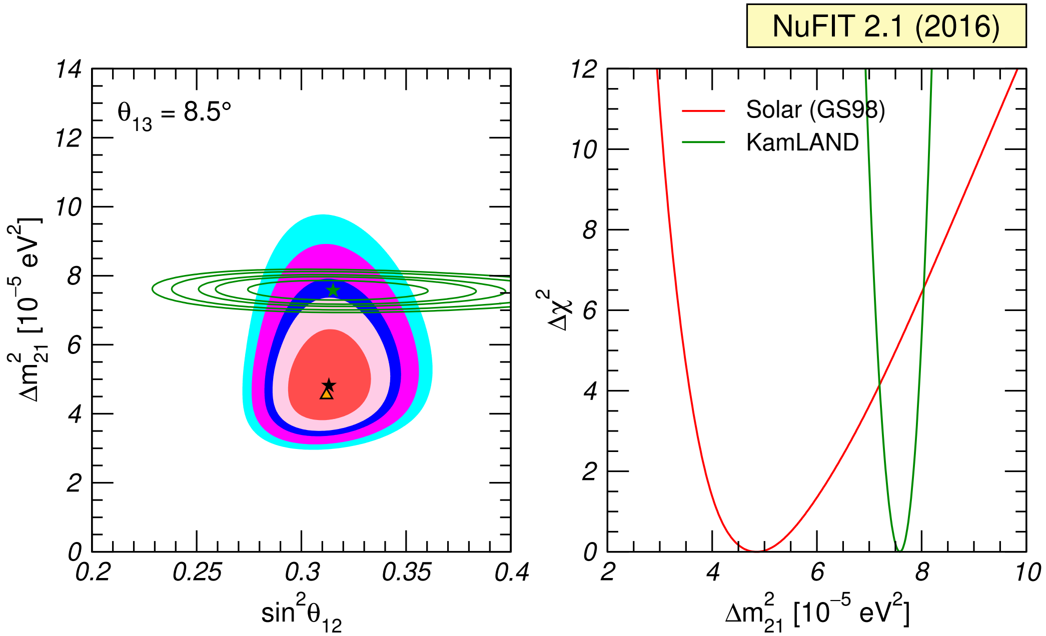

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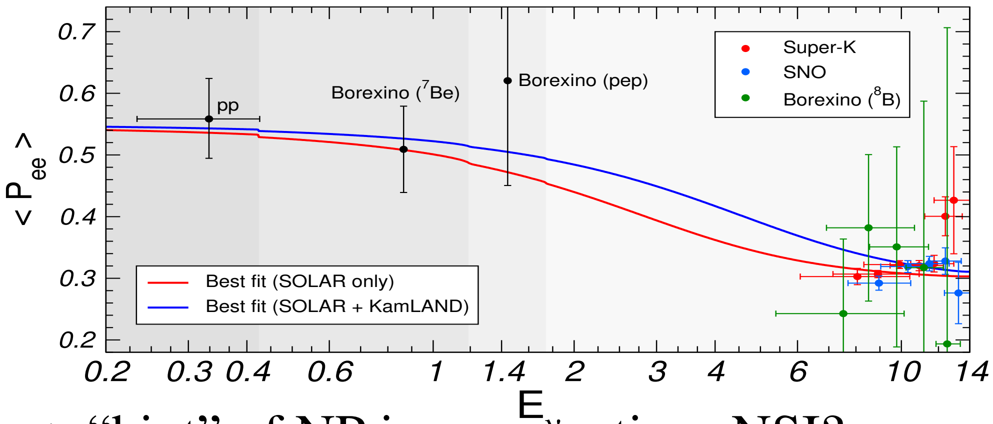
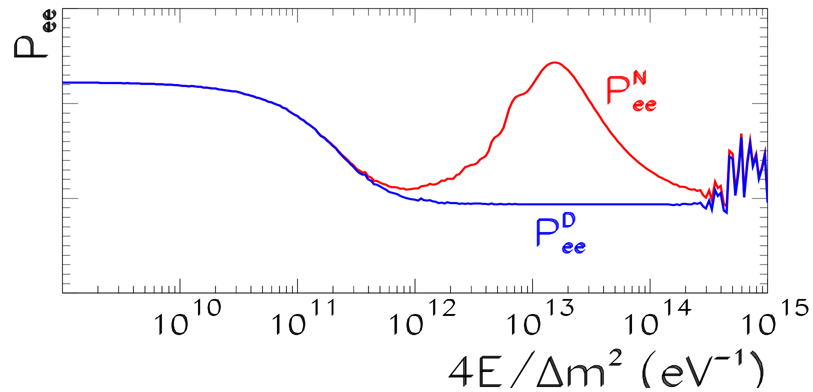
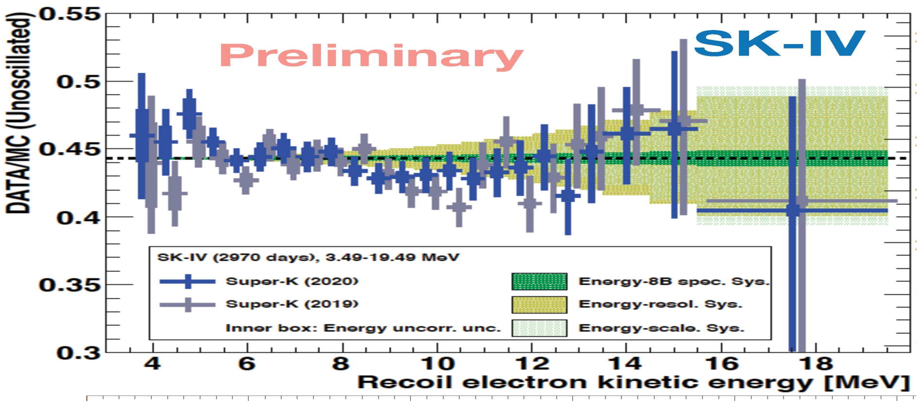




$\Rightarrow$ "hint" of NP in propagation: NSI?

• AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up

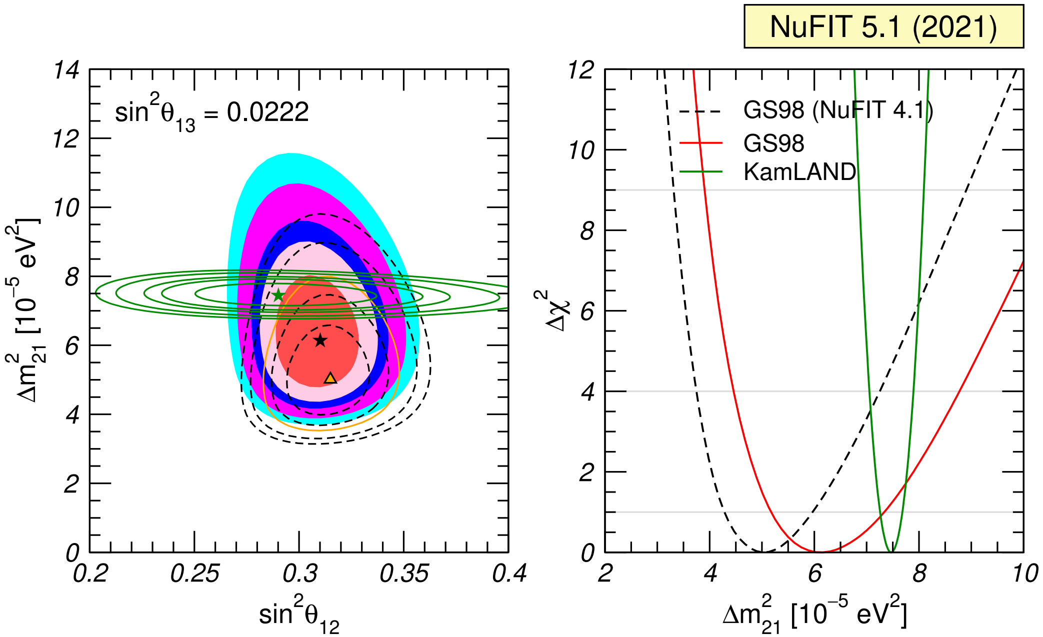


Smaller of Day/Night at

$A_{\rm D/N,SK4-2055} = [-3.1 \pm 1.6({\rm stat.}) \pm 1.4({\rm sys.})]\%$

$A_{\rm D/N,SK4-2970} = [-2.1 \pm 1.1]\%$

• In NuFIT 5.1

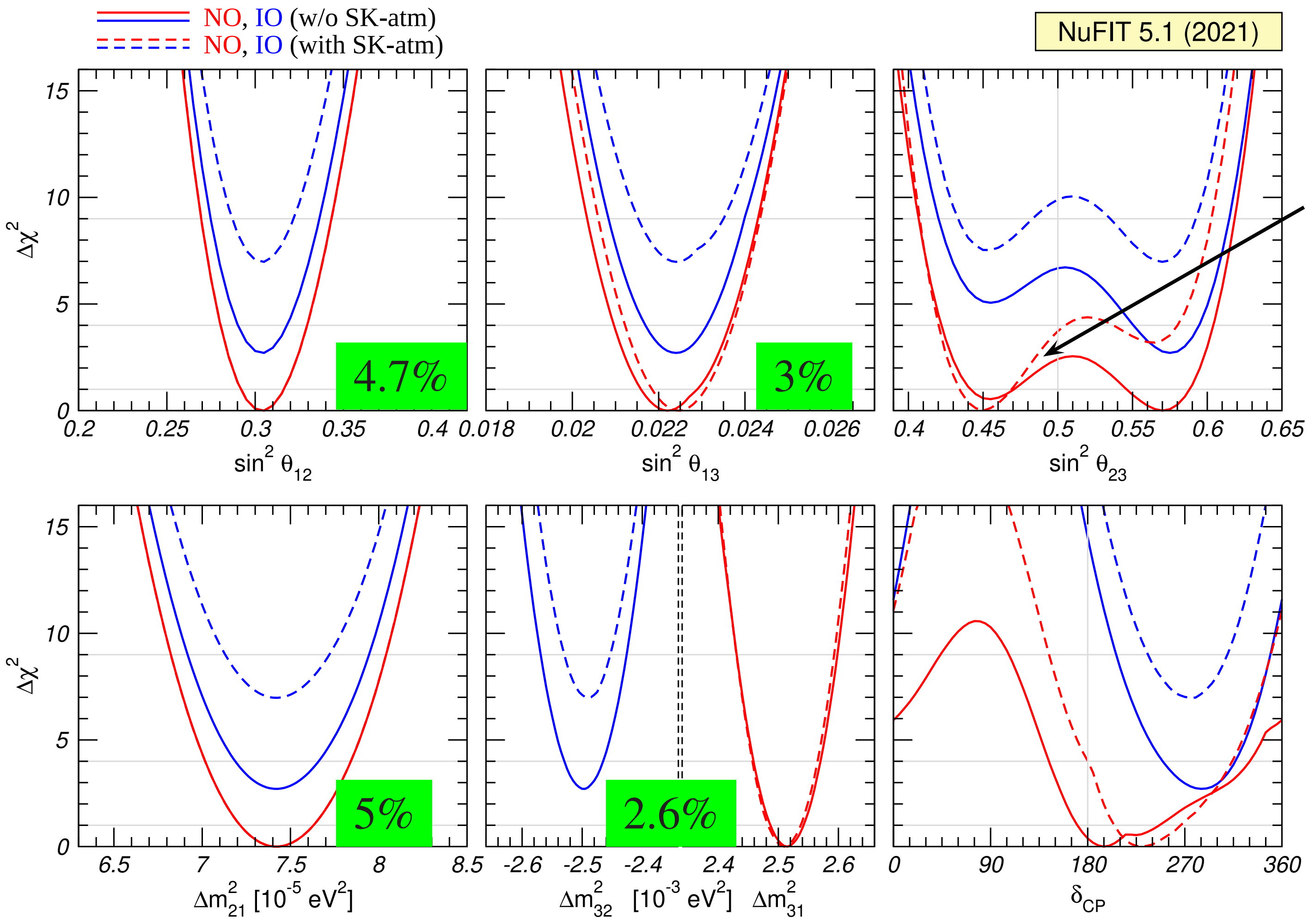


$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ

Summary: Global 3 ν Flavour Parameters

Global 6-parameter fit http://www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]



- 4 well-known parameters: $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$

Δm^2_{21} Solar vs KLAND

Tension Resolved

- θ_{23}: Least known angle

Maximal? Octant?

non-robust wrt ATM

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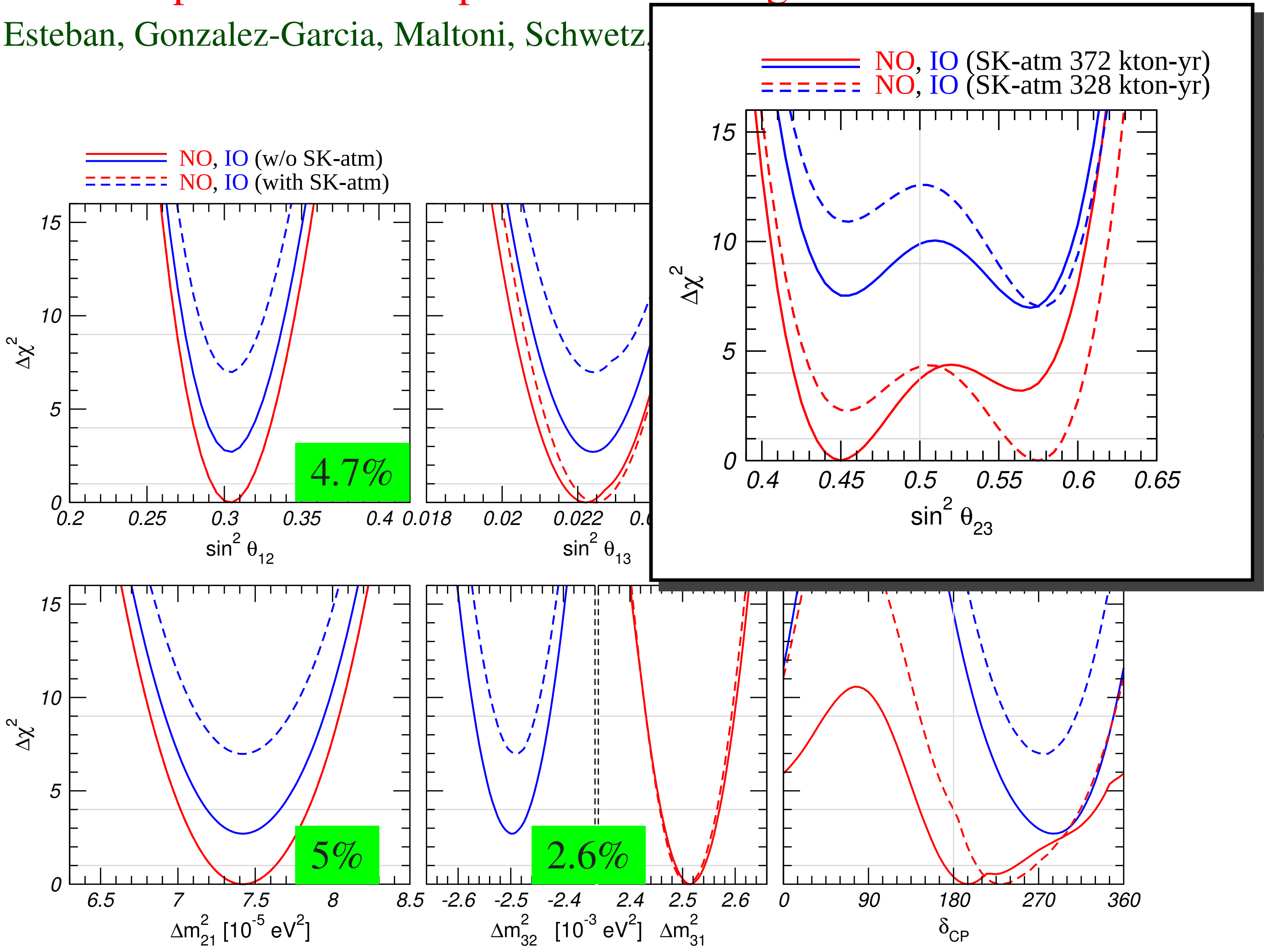
Esteban, Gonzalez-Garcia, Maltoni, Schwetz,



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Solar vs KLAND

on Resolved

Least known angle

mal? Octant?

obust wrt ATM

Flavour Parameters: Mixing Matrix

- We have the three leptonic mixing angles determined (at $\pm\,3\sigma/6$)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.844 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.639 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

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- Good progress but still precision very far from:

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

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- Also very different flavour mixing of leptons vs quarks

Leptonic CPV in 3ν Mixing: Jarlskog Invariant

- Leptonic $\not{C}$P $\Rightarrow P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$
- In 3ν always

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J \quad \text{with} \quad J = \text{Im}(U_{\alpha 1} U^*_{\alpha_2} U_{\beta 2} U^*_{\beta_1}) = J^{\text{max}}_{\text{LEP,CP}} \sin \delta_{\text{CP}}$$

$$J^{\text{max}}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

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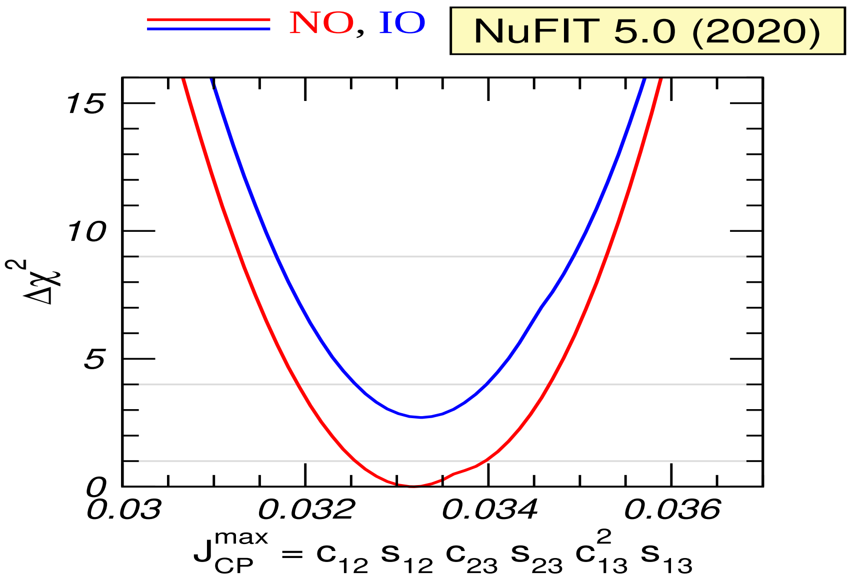
$$J^{\max}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

- Maximum Allowed Leptonic CPV:



$$J^{\max}_{\text{LEP,CP}} = (3.29 \pm 0.07) \times 10^{-2}$$

to compare with

$$J_{\text{CKM,CP}} = (3.04 \pm 0.21) \times 10^{-5}$$

$\Rightarrow$ Leptonic CPV may be largest CPV in New Minimal SM

if $\sin\delta_{\text{CP}}$ not too small

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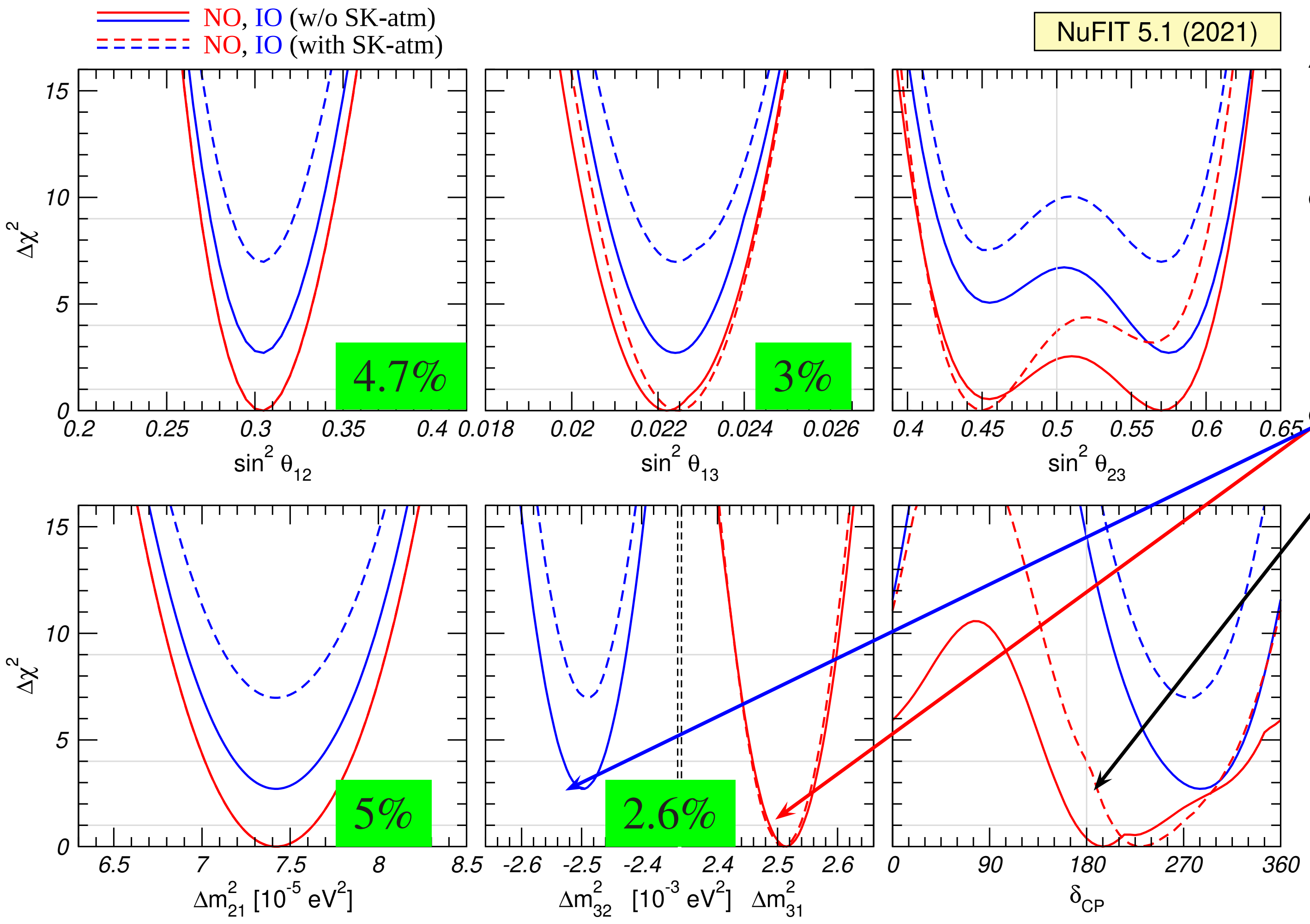
Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]



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  Tension Resolved

- θ_{23}: Least known angle

  Maximal? Octant?

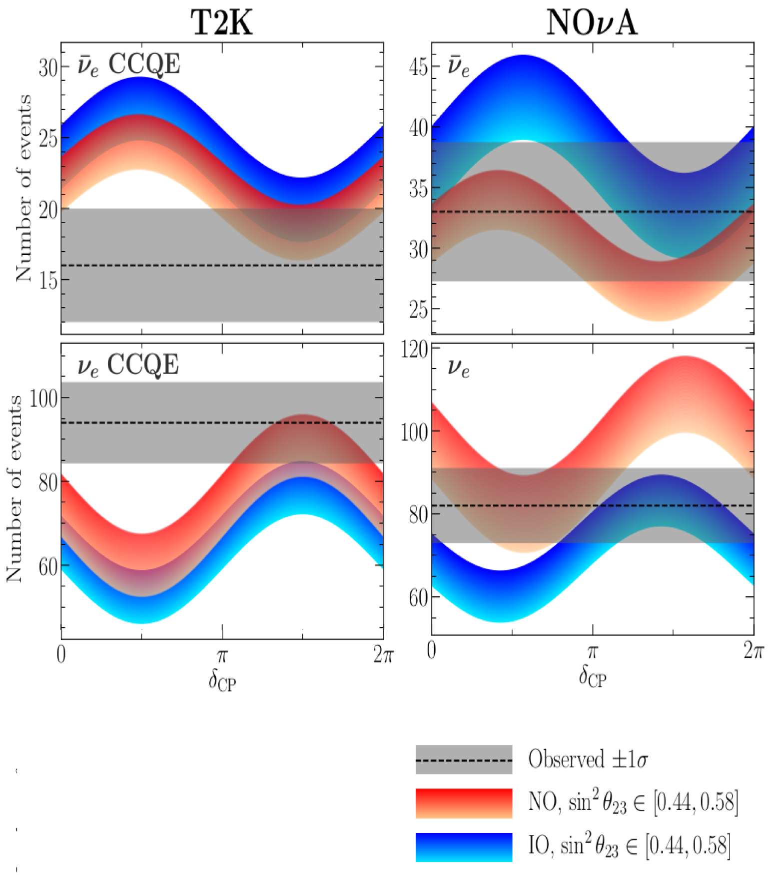
  non-robust wrt ATM

- Ordering NO or IO?

  CPV?:

CPV and Ordering in LBL: ν_e appearace

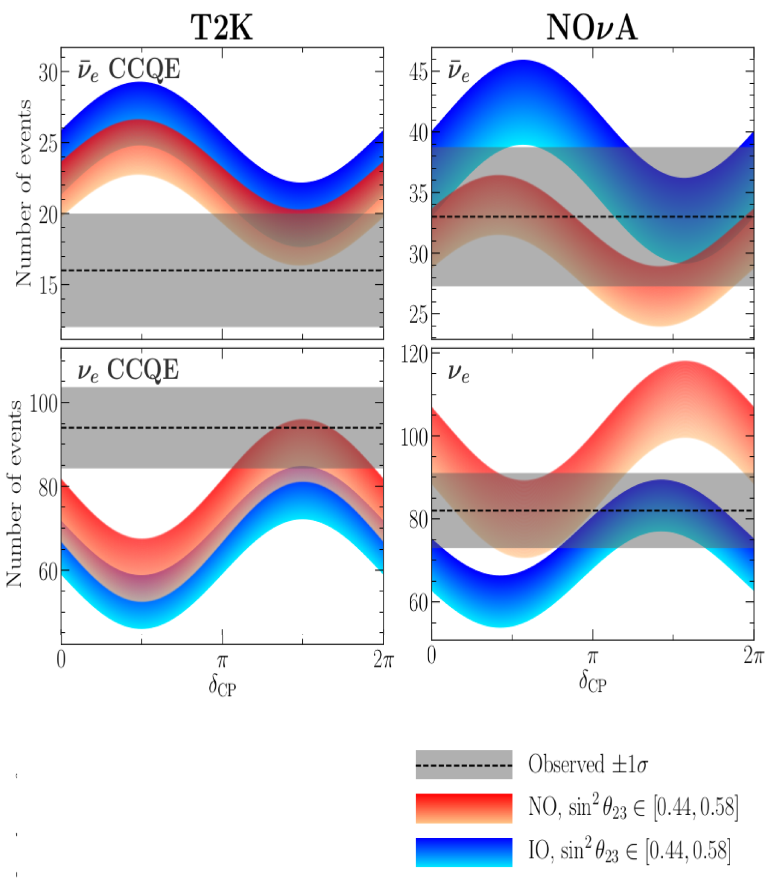
ν_e and $\overline{\nu}_e$ apperance events



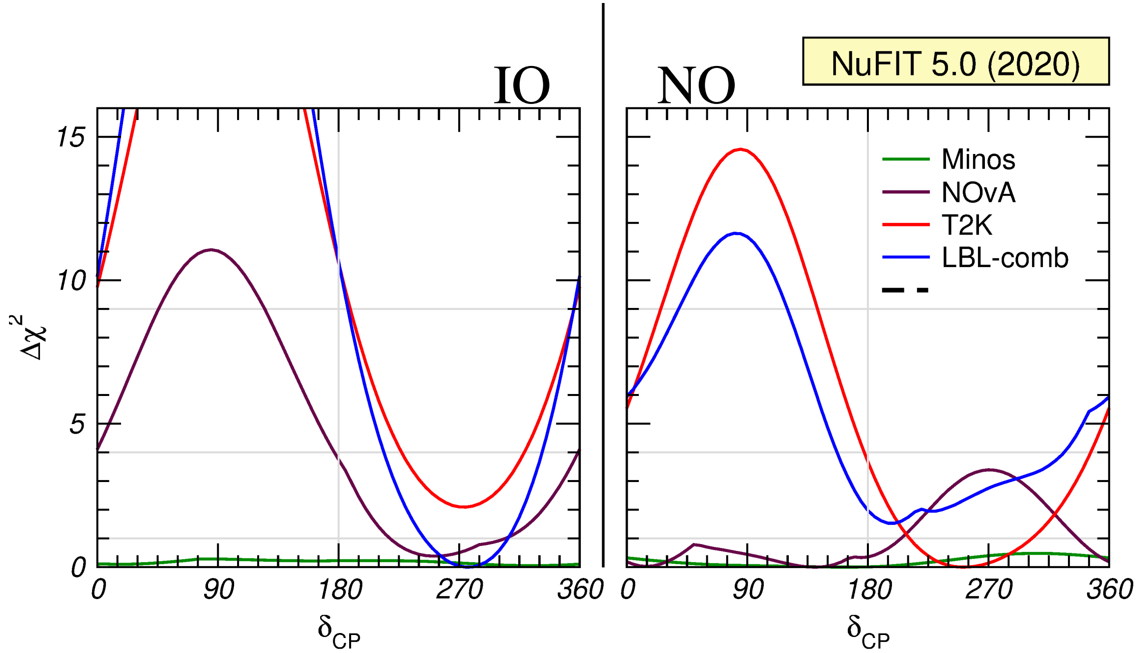
$\Rightarrow$ Each T2K and NOνA favour NO

CPV and Ordering in LBL: ν_e appearace

ν_e and $\overline{\nu}_e$ apperance events



But tension in favoured values of δ_{CP} in NO



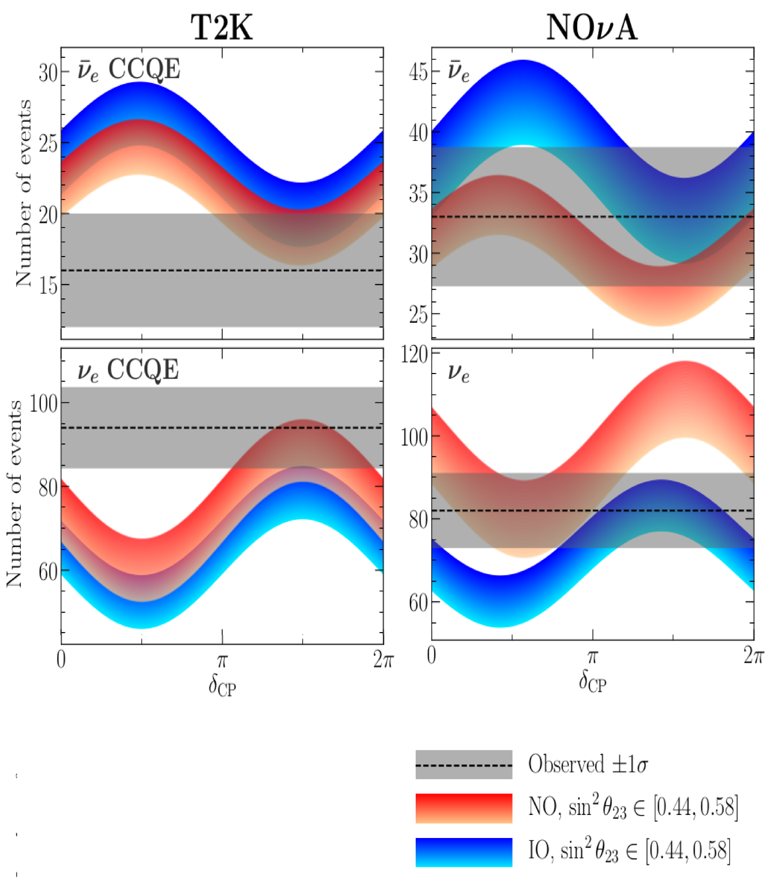
$\Rightarrow$ IO best fit in LBL combination

$\Rightarrow$ Each T2K and NOνA favour NO

CPV and Ordering in LBL: ν_e appearace

nzalez-Garcia

ν_e and $\overline{\nu}_e$ apperance events



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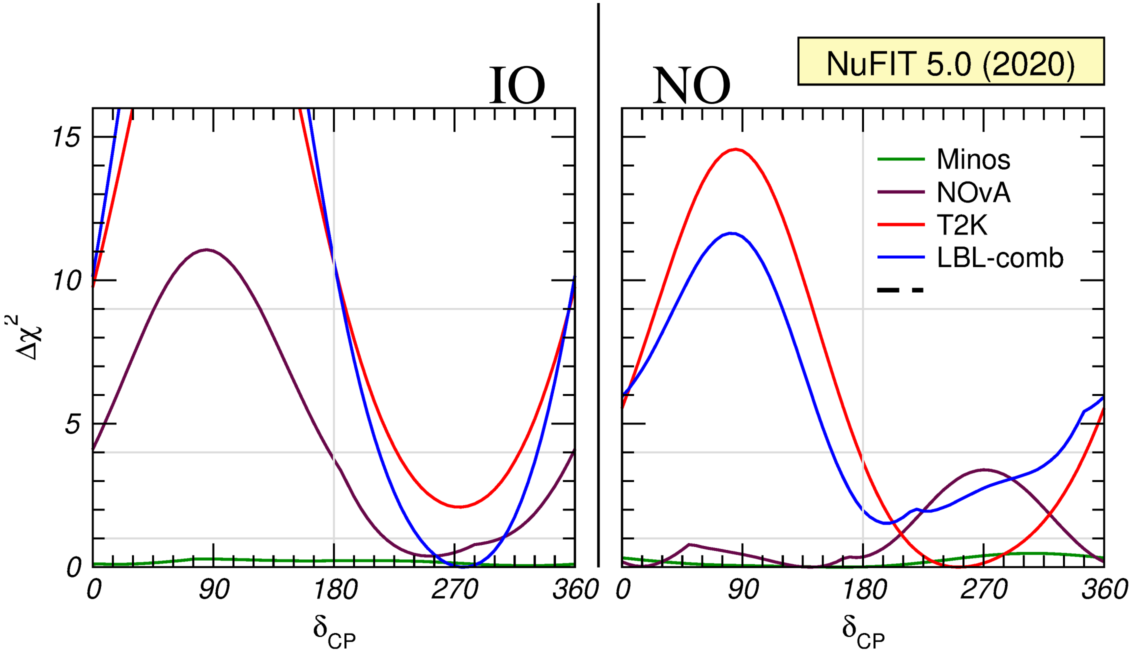


$\Rightarrow$ IO best fit in LBL combination

- Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	χ^2_{PG}/n	p-value	$\#\sigma$	χ^2_{PG}/n	p-value	$\#\sigma$
T2K vs NOvA (θ_{13} free)	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs NOvA (θ_{13} fix)	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ

No significant incompatibility

Δm^2_{3l} in LBL & Reactors

- At LBL determined in ν_μ and $\bar{\nu}_\mu$ disapperance spectrum

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data

Concha Gonzalez-Garcia

Δm^2_{3l} in LBL & Reactors

- At LBL determined in ν_μ and $\bar{\nu}_\mu$ disapperance spectrum

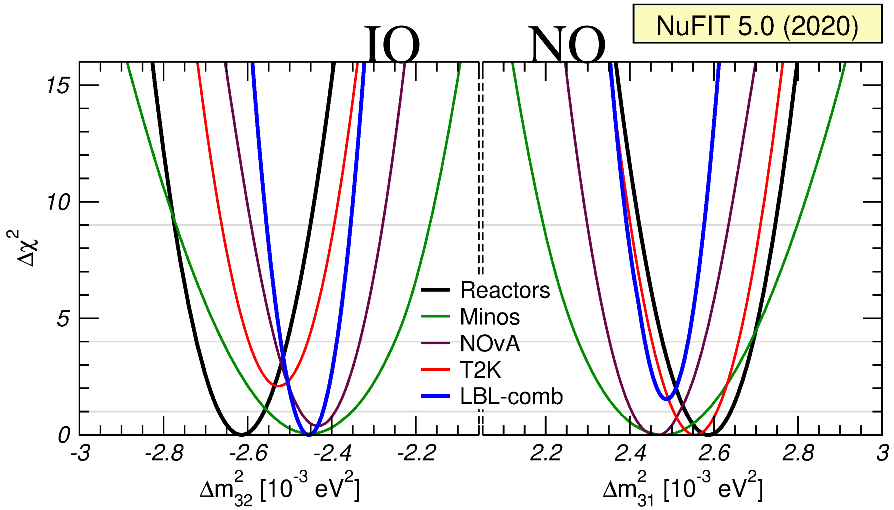
$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \dots$$

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data



- T2K and NOνA more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors

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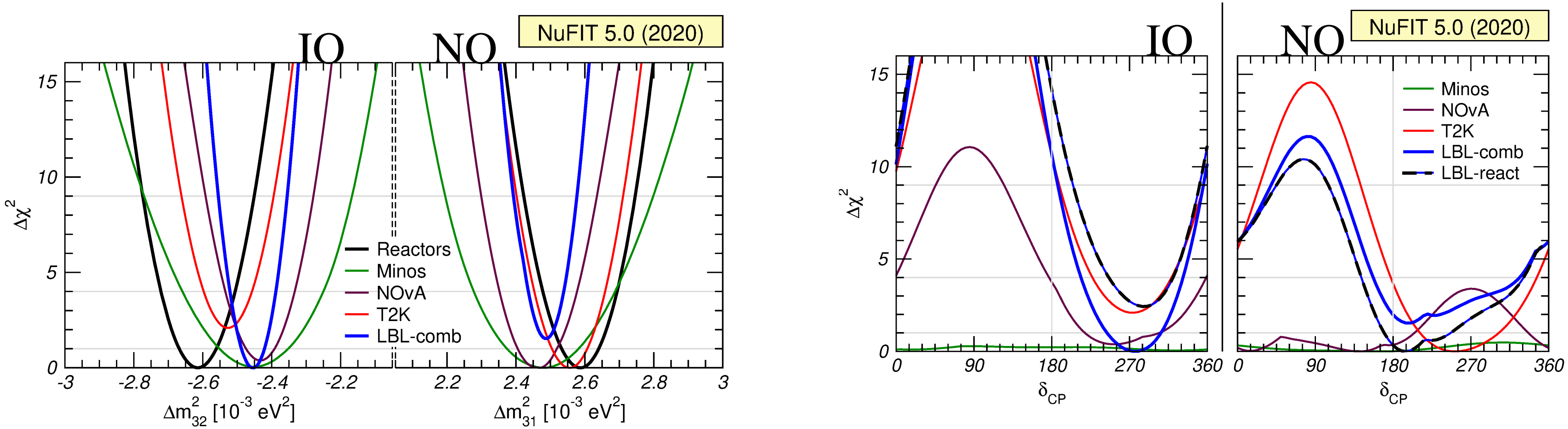

- T2K and NOνA more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors
- in NO: b.f $\delta_{\rm CP} = 195°$ $\Rightarrow$ CPC allowed at 0.6 σ
- in IO: b.f $\delta_{\rm CP} \sim 270°$ $\Rightarrow$ CPC disfavoured at 3 σ

Near Future for CP and Ordering: Strategies

- $\nu/\bar{\nu}$ comparison with or without Earth matter effects in $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ at LBL: DUNE (wide band beam, L=1300 km), HK (narrow band beam, L=300 km)

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31} \pm V}\right)^2 \sin^2\left(\frac{\Delta_{31} \pm V\, L}{2}\right)$$

$$+8\, J_{\rm CP}^{\rm max} \frac{\Delta_{12}}{V} \frac{\Delta_{31}}{\Delta_{31} \pm V} \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31} \pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$J_{\rm CP}^{\rm max} = c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12}$$

– Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

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  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with Δm^2_{31} and Δm^2_{32}: JUNO, RENO-50

$$P_{\nu_e,\nu_e} = 1 - c^4_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \left[c^2_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s^2_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

  – Challenge: Energy resolution

Near Future for CP and Ordering: Strategies

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  – Challenge: Energy resolution

- Earth matter effects in large statistics ATM ν_μ disapp : HK,INO, PINGU,ORCA . . .
  – Challenge: ATM flux contains both ν_μ and $\bar\nu_\mu$, ATM flux uncertainties

Beyond 3ν's: Light Sterile Neutrinos

• Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

LSND &MiniBoone

LSND 2001:

Signal $\nu_\mu \to \nu_e$ (3.8 σ)

MiniBooNE 2020:

$\bar\nu_\mu \to \bar\nu_e$ & $\nu_\mu \to \nu_e$

(639 ± 132.8 events)

Gallium Anomaly

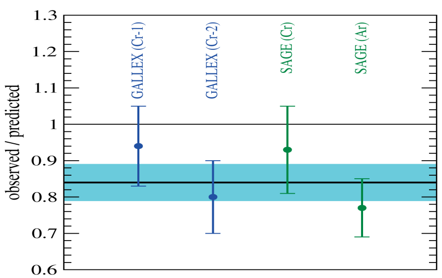
Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder,1006.3244

Radioactive Sources (^{51}Cr, ^{37}Ar)

in calibration of Ga Solar Exp;

$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

Give a rate lower than expected



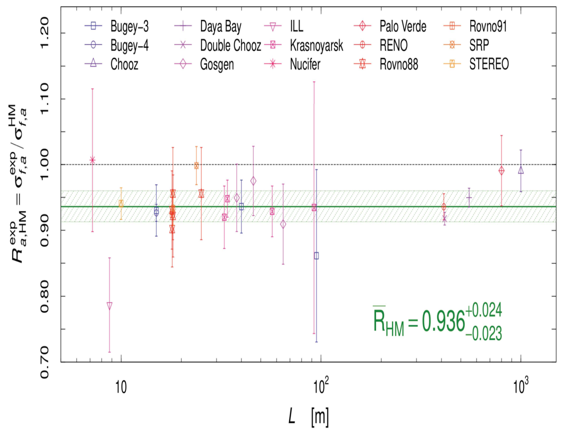
Explained as ν_e disappearance

Reactor Anomaly (2011)

Huber, 1106.0687
Mention *etal* ,1101.2755

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m



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MiniBooNE 20

$\bar{\nu}_\mu \to \bar{\nu}_e$ & ν_μ

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calculation

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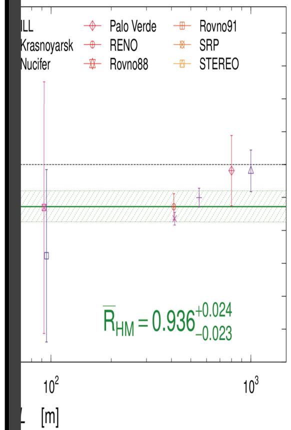
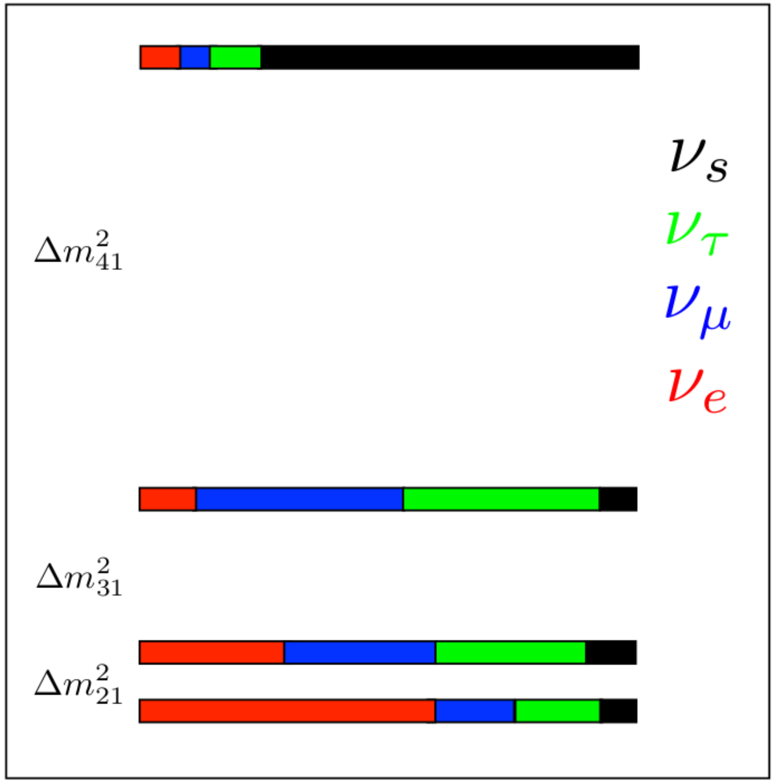


disappearance

Oscillation Interpretation Requires new (sterile) ν's



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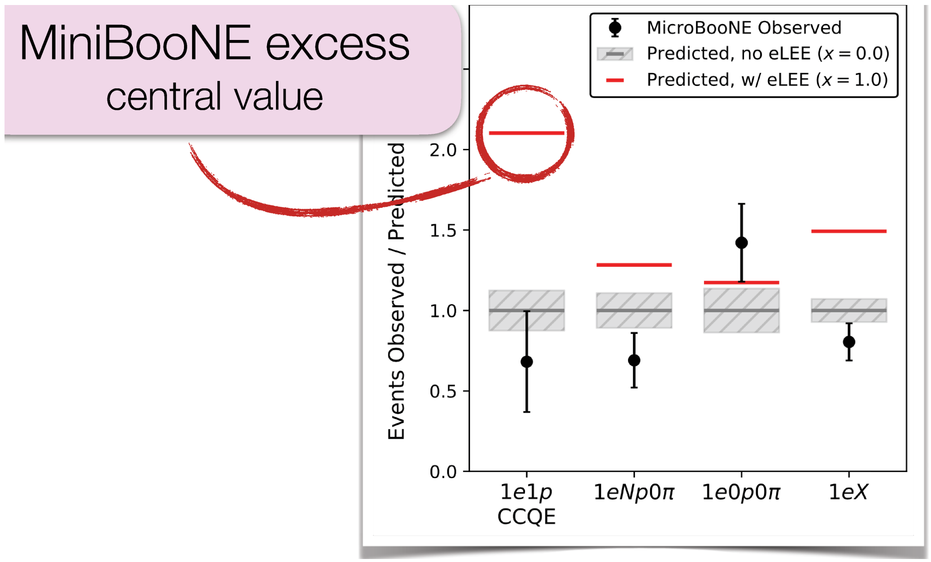
MicroBooNE 2021/2022:



No support for excess ν_e interpretation in MiniBooNE

(Fig from Kopp's ν2022 talk)

MicroBooNE Coll.

2110.14054

Beyond 3ν's: Light Sterile Neutrinos

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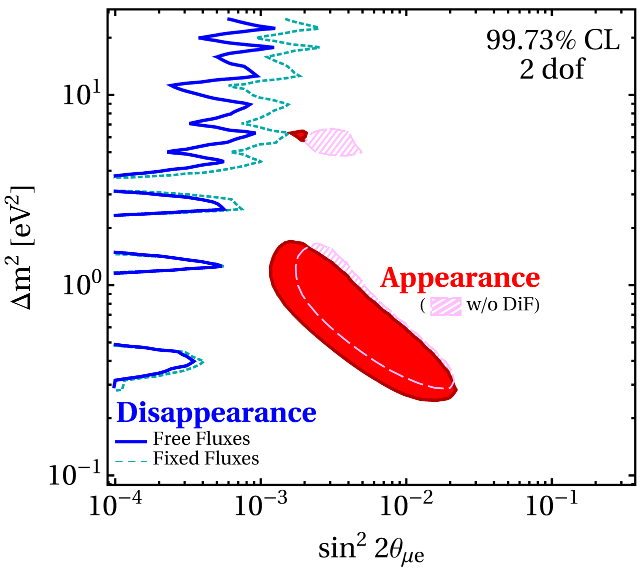
$\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$

Strong tension with
non-obervation of ν_μ dissap



Dentler etal, 1803.10661

Purely sterile oscillation
robustly disfavoured
additional SM or NP effects?

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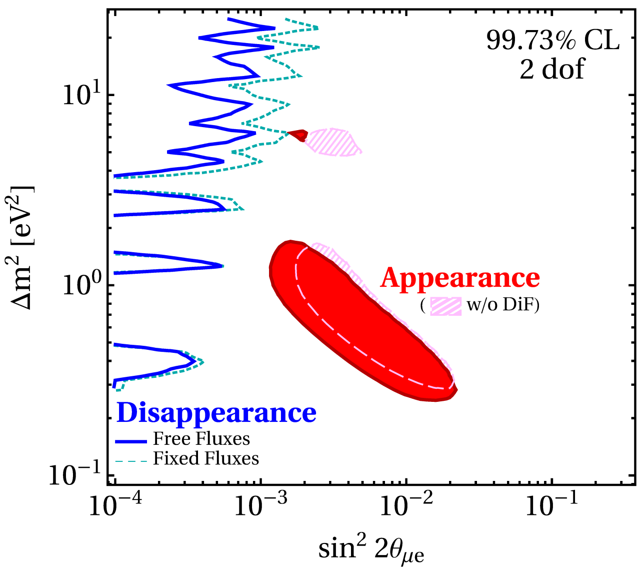

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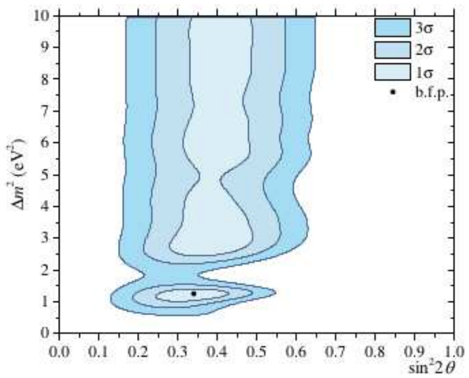
Rate lower than expected

Explained as ν_e disappearance

Confirming results from BEST

2109.11482



Re-quires large mixings

Ruled out/tension by solar $\nu' s$

Goldhagen etal 2109.14898

Berryman etal 2111.12530

Beyond 3ν's: Light Sterile Neutrinos

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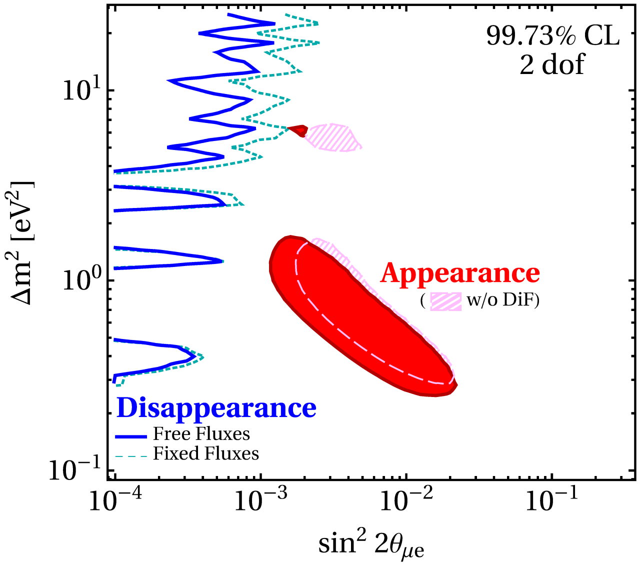

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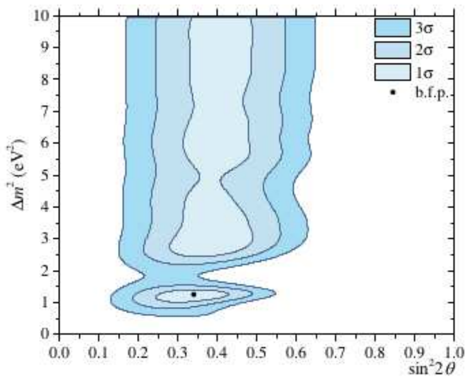

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Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

2011 reactor flux calculation $\Rightarrow$

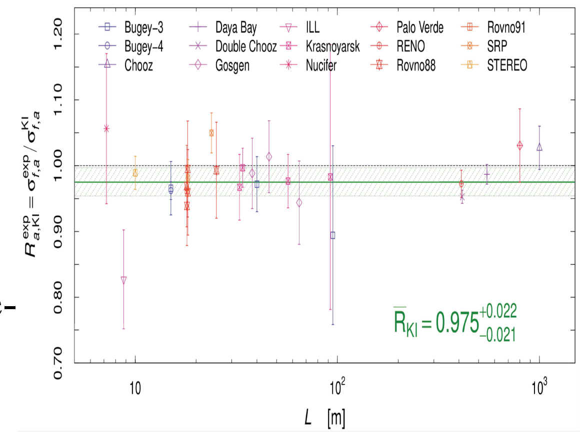
Deficit in $R = \frac{\text{data}}{\text{predict}}$ at $L \lesssim 100$ m

Explained as $\bar\nu_e$ disappearance

2022 with updated inputs (^{235}U)

Berryman Huber, 2005.01756
Kipeikin etal, 2103.01486
Giunti etal, 2110.06820

Re-

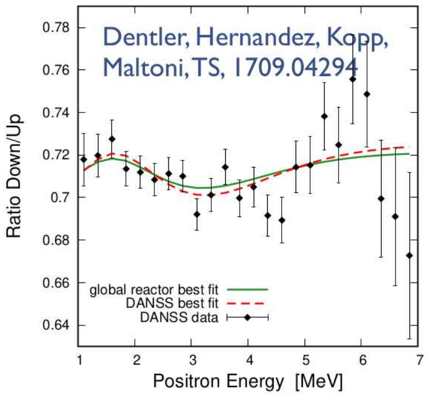


(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

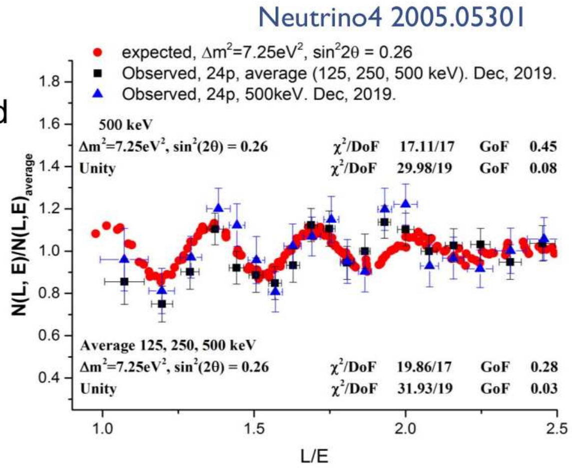
with new fluxes

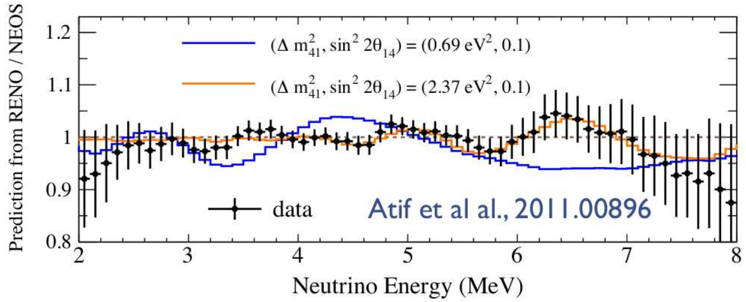
Recent relative spectral measurments



DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)

Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication





segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9
PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m

NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Spectral ratios at different baselines ⇒ Independent of flux normalizations.

But low statistical significance (Wilk's theorem fails) Berryman, etal 2111.12530

MC estimation of prob distribution ⇒ no significant indication of ν_s oscillations

Non Standard ν Interactions (NSI)

At dimension-6 new 4-fermion interactions involving ν's.

Some can afffect CC process in production and detection

$$(\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)(\bar{f}' \gamma^\mu P f)$$

and can be strongly constrained with charged lepton processes

Some affect only NC ν interactions

$$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f)$$

and are more poorely constrained

NC-Non Standard ν Interactions in ν-OSC

Including non-standard neutrino NC interactions with fermion f

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P f)\,, \qquad P = L, R$$

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$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F N_e(r)\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued} \frac{N_f(r)}{N_e(r)}\varepsilon^{fV}_{\alpha\beta}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

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$\Rightarrow$ Parameters degeneracies

In particular $H \to -H^*$ $\Rightarrow$ same Probabilities $\Rightarrow$ invariance under simultaneously:

$$\theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}\,, \qquad (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,,$$

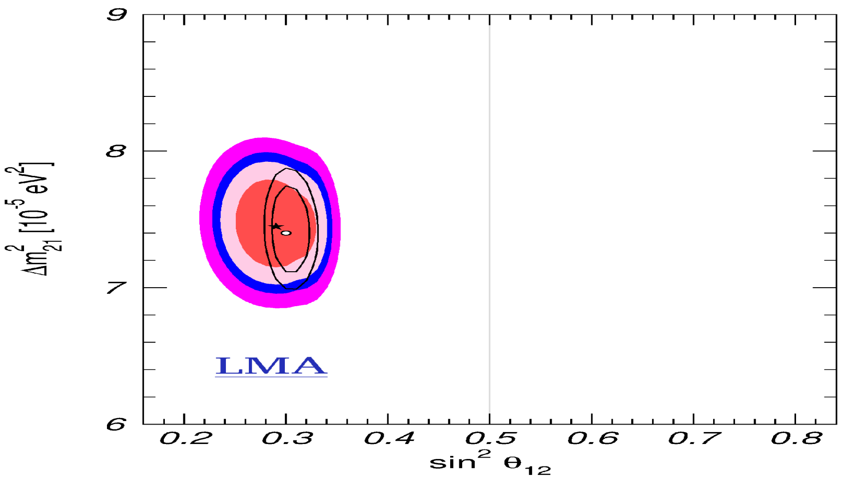
$$\Delta m^2_{31} \to -\Delta m^2_{32}\,, \qquad (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,,$$

$$\delta \to \pi - \delta\,, \qquad \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,,$$

$\Rightarrow$ Degeneracies in θ_{12} octant and mass ordering

NSI: Bounds/Degeneracies from/in Oscillation data

Esteban *etal* JHEP'18[1805.04530] Coloma, Esteban, MCGG, Maltoni, JHEP'19[1911.09109] (updated 2020)



- Standard Solution $\equiv$ LMA $\Rightarrow$ Bounds $\mathcal{O}(1\% - 10\%)$

	LMA
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$

Concha Gonzalez-Garcia

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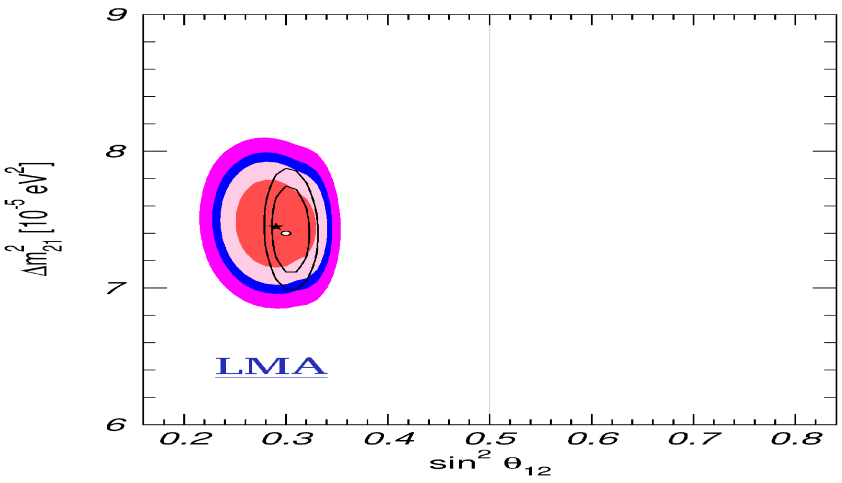

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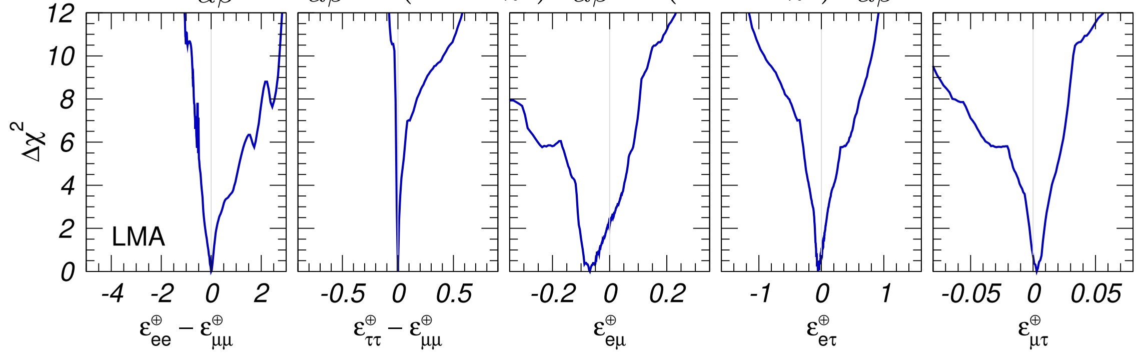
- Standard Solution $\equiv$ LMA $\Rightarrow$ Bounds $\mathcal{O}(1\% - 10\%)$

  $\Rightarrow$ Maximum effect at LBL experiments:

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + \left(2 + Y^{\oplus}_n\right)\varepsilon^{u}_{\alpha\beta} + \left(1 + 2Y^{\oplus}_n\right)\varepsilon^{d}_{\alpha\beta}$$



$\Rightarrow$ To be considered in effects/sensitivity studies at DUNE, HK... (tables available)

Concha Gonzalez-Garcia

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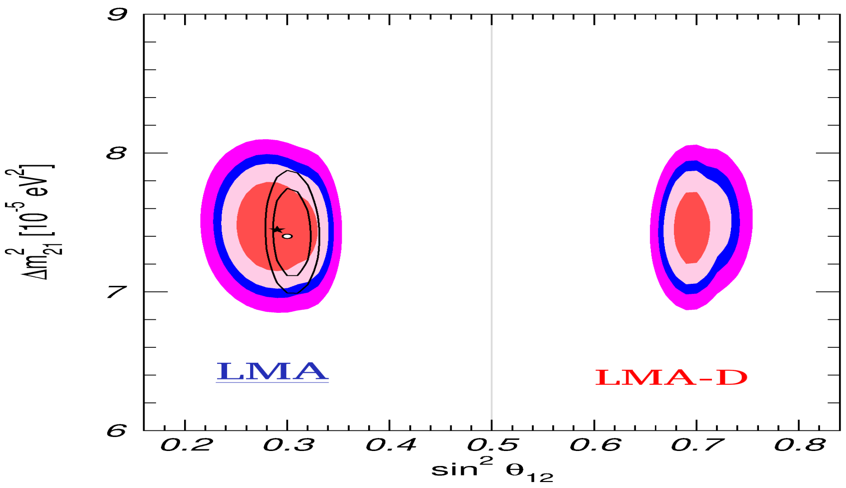

	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$

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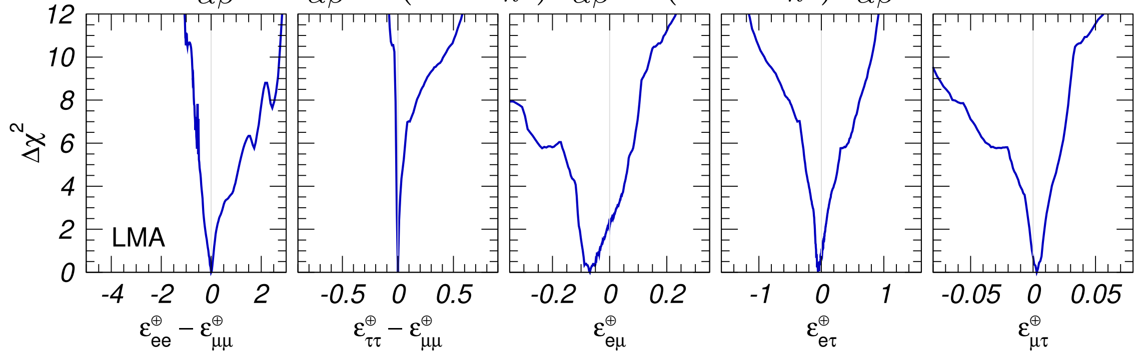


  $\Rightarrow$ To be considered in effects/sensitivity studies at DUNE, HK…(tables available)

- Degenerate solution $\equiv$LMA-D

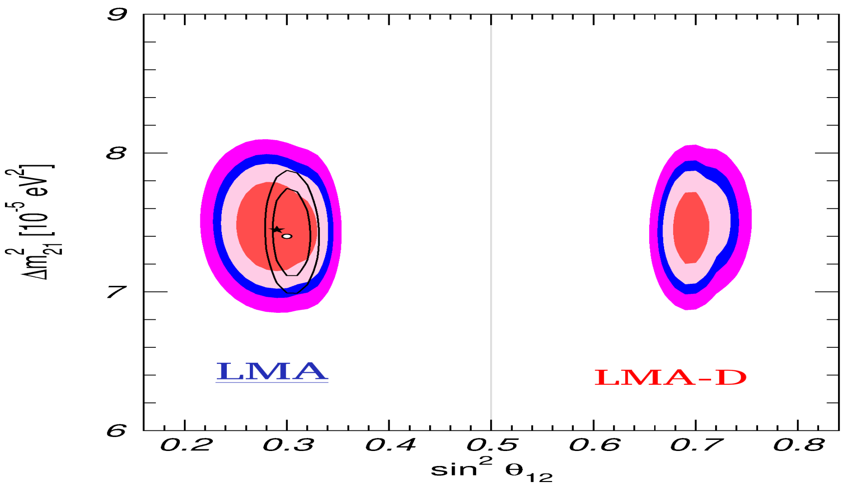
  Miranda,Tortola, Valle, hep-ph/0406280

  $\Rightarrow \theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}$ & $(\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2$

Concha Gonzalez-Garcia

NSI: Bounds/Degeneracies from/in Oscillation data

Esteban *etal* JHEP'18[1805.04530] Coloma, Esteban, MCGG, Maltoni, JHEP'19[1911.09109] (updated 2020)

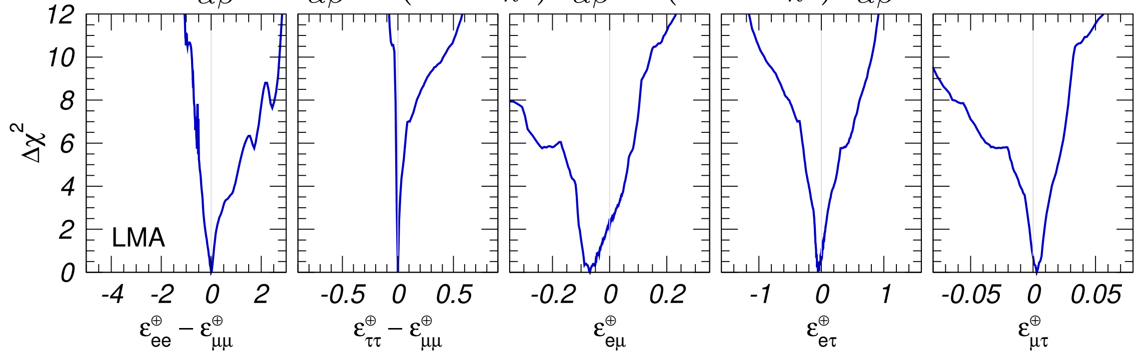


	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$

- Standard Solution ≡ LMA ⇒ Bounds $\mathcal{O}(1\% - 10\%)$

  ⇒ Maximum effect at LBL experiments:

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + \left(2 + Y^{\oplus}_n\right)\varepsilon^u_{\alpha\beta} + \left(1 + 2Y^{\oplus}_n\right)\varepsilon^d_{\alpha\beta}$$



  ⇒ To be considered in effects/sensitivity studies at DUNE, HK. . . (tables available)

- Degenerate solution ≡LMA-D

  Miranda,Tortola, Valle, hep-ph/0406280

  ⇒ $\theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}$ & $(\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2$

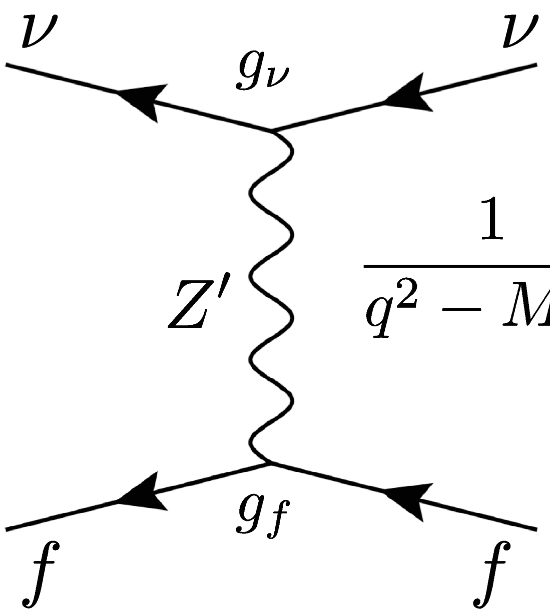
  ⇒ Requires NSI $\sim G_F$ (light mediators?)

  Farzan 1505.06906, and Shoemaker 1512.09147

Oscillation bounds on Z’/Dark Photons

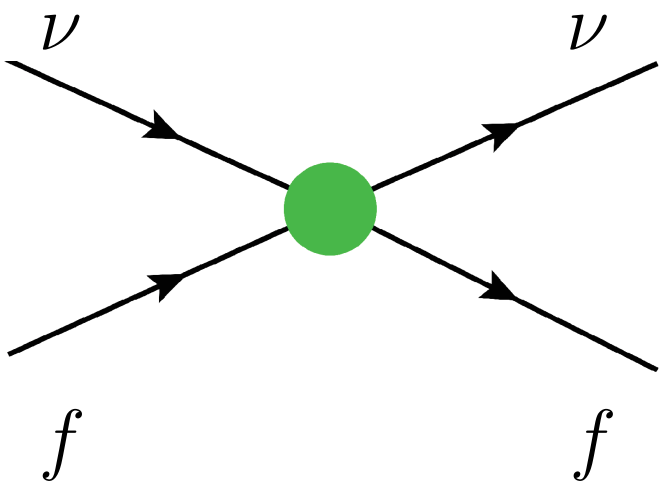
Coloma, MCGG, Maltoni, JHEP’21 [2009.14220]

Interpreting



$$\frac{1}{q^2 - M_{Z'}^2}$$

$$\Longleftarrow$$
$$q^2 \to 0$$

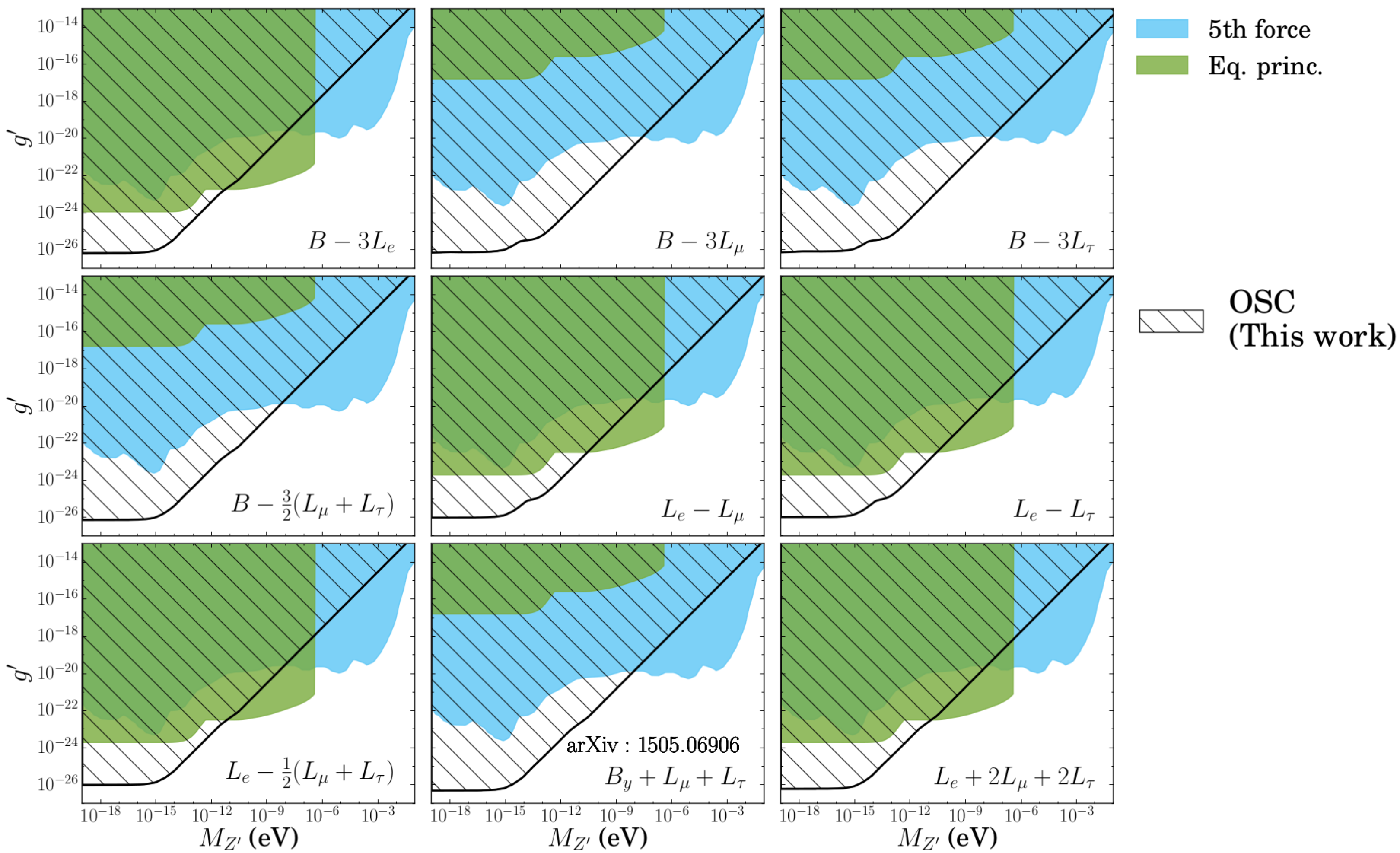


$$\frac{g'^2}{M_{Z'}^2}\, q'_f\, q'_\nu \qquad \Leftarrow \qquad \epsilon^f_{\alpha\beta}$$

Z'/Dark-photon: Bounds from ν Oscillations

Coloma, MCGG, Maltoni, JHEP'21 [2009.14220]

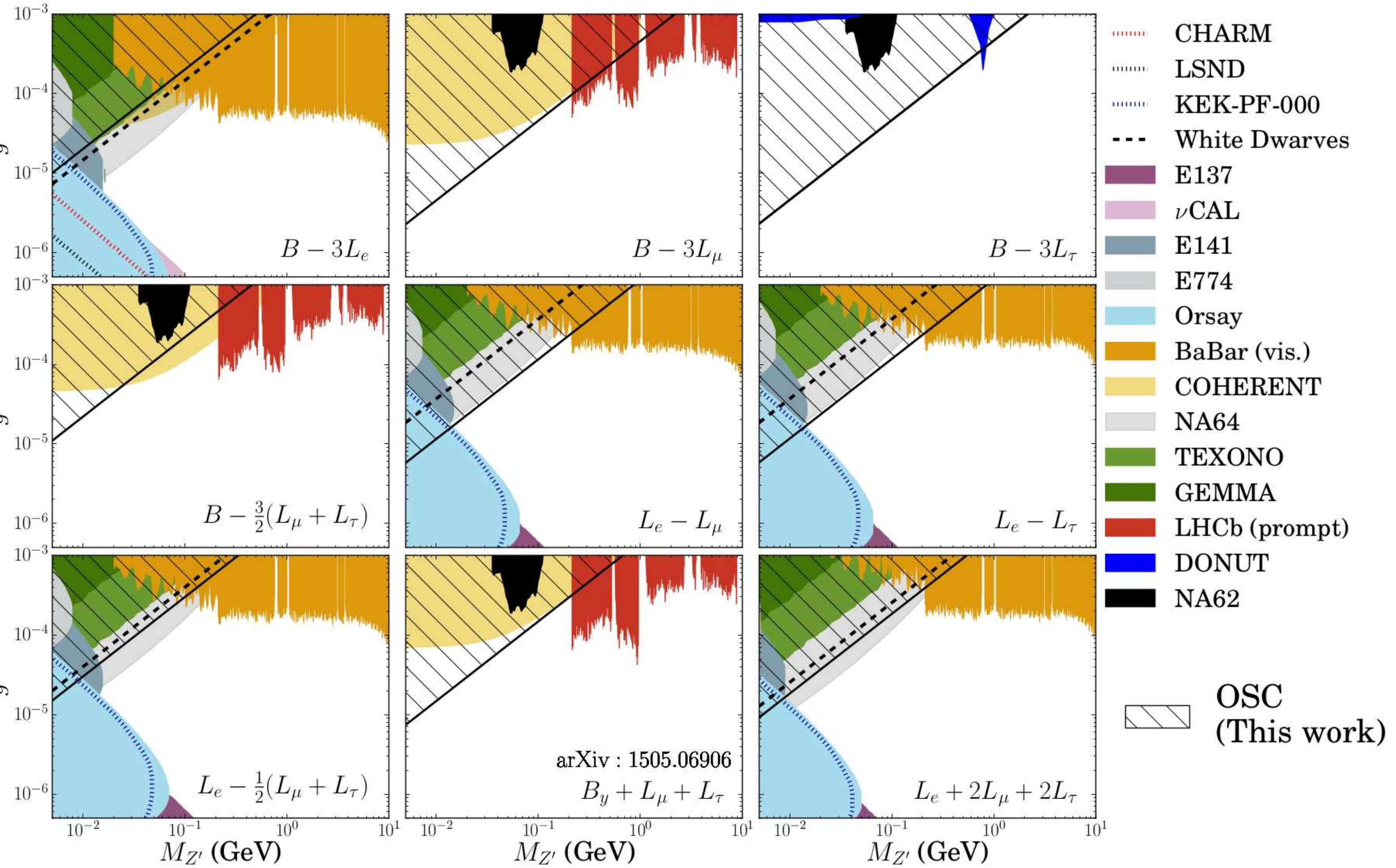
Very light ($M' \lesssim \mathcal{O}(\mathrm{eV})$) mediator $\Rightarrow$ Long Range Force to Contact Interaction in $H_{\rm mat}$



Z' Models: ν Oscillations Bounds

Coloma, MCGG, Maltoni ArXiv:2009.14220

$M_{Z'} \gtrsim \mathcal{O}(\mathrm{MeV}) \Rightarrow$ Contact Interaction in $H_{\rm mat}$



Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive $\Rightarrow$ There is NP
- Oscillations DO NOT determine the lightest mass

  Only model independent probe of m_ν β decay: $\sum m_i^2 |U_{ei}|^2 \leq (0.8\ \text{eV})^2$ Katrin 2021
- Dirac or Majorana?: *Anxiously* waiting for ν-less $\beta\beta$ decay Lecture by S. Bettini
- Three mixing angles are non-zero (and relatively large) $\Rightarrow$ very different from CKM
- Leptonic CP and Ordering: "Hints" but not confirmation

  Definite answer may require new oscillation experiments
- Only three light states? Some old anomalies supporting light sterile neutrinos vanishing, and tensions with new experiments
- Other NP at play in oscillations Interesting effects of NP with light mediators

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- Neutrinos in Cosmology? Lectures by L. Verde
- Astrophysics/Astronomy with Neutrinos? Lecture by F.Halzen

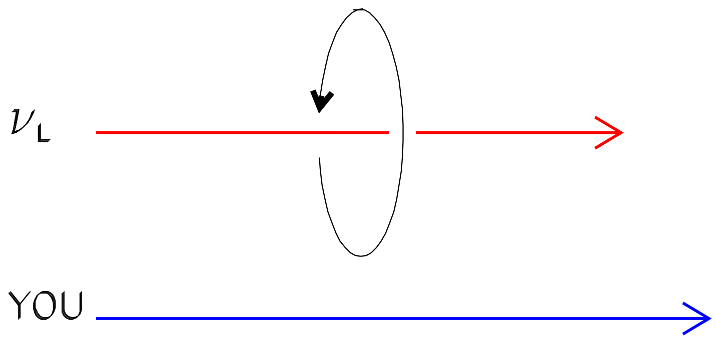
  …

Neutrinos always "Left-Handed" ≡ Massless

- If ν had a mass they would not go to the speed of light:

  $\Rightarrow$ the direction of its momentum depends on the reference frame

  So in one reference frame



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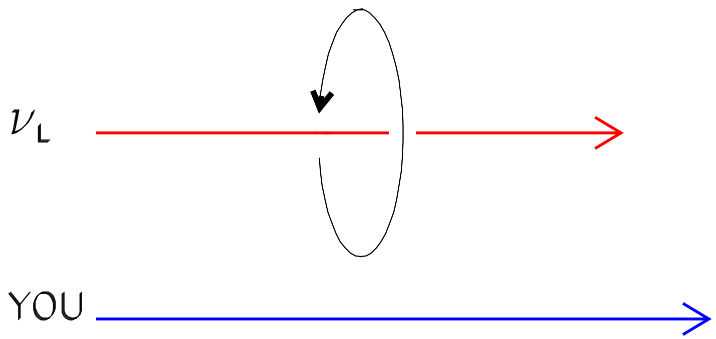
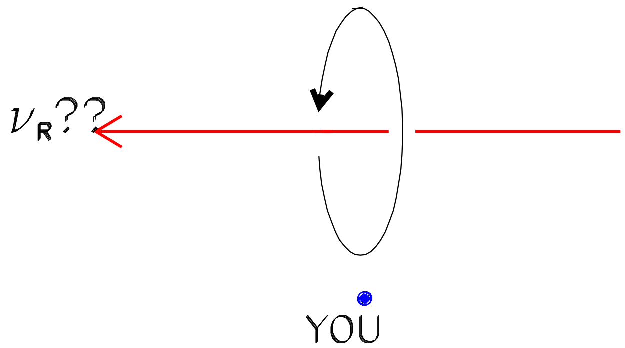


And in another



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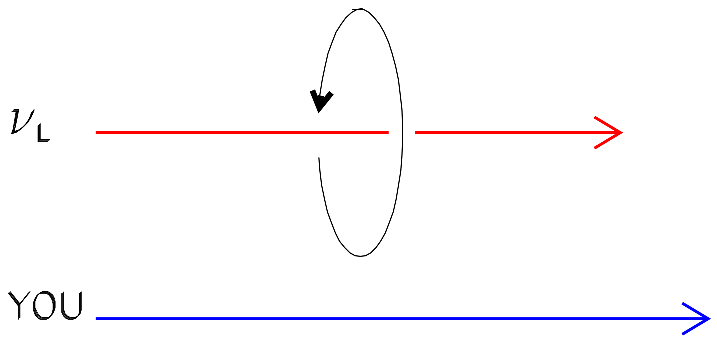

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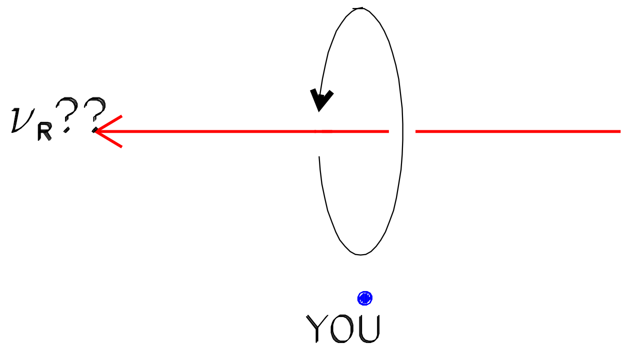

The Other Flavours

ν coming out of a nuclear reactor is $\overline{\nu}_e$ because it is emitted together with an e^-

Question: Is it different from the muon type neutrino ν_μ that could be associated to the muon? Or is this difference a theoretical arbitrary convention?

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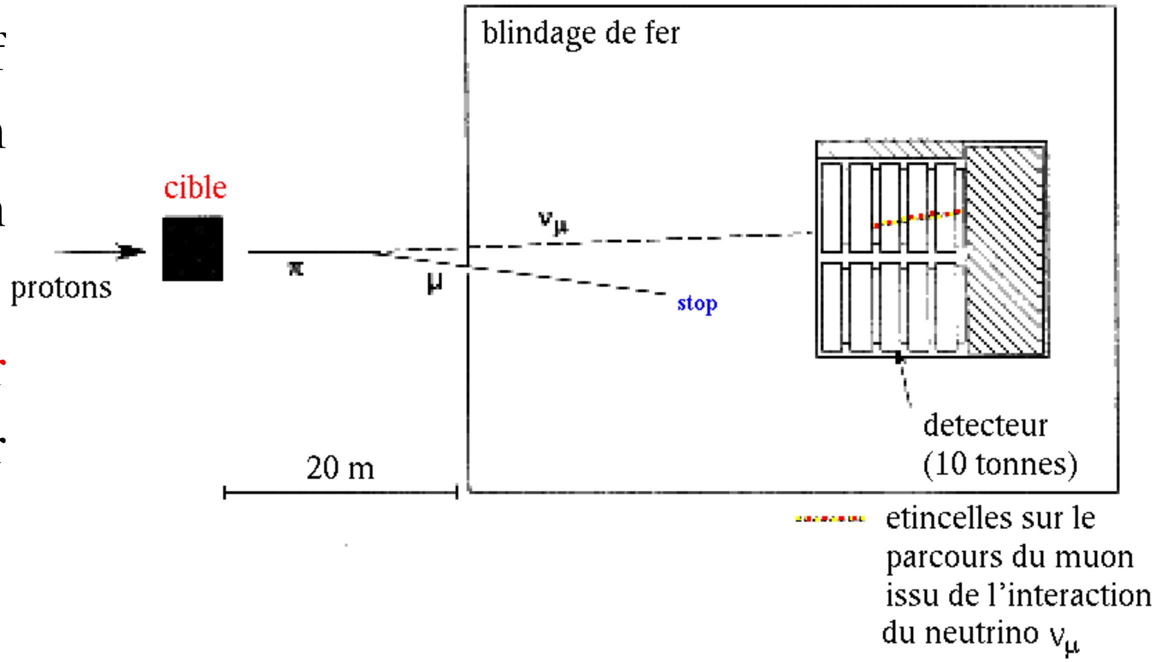
Schwartz, Lederman, Steinberger and Gaillard built a spark chamber (a 10 tons of neon gas) to detect ν_μ



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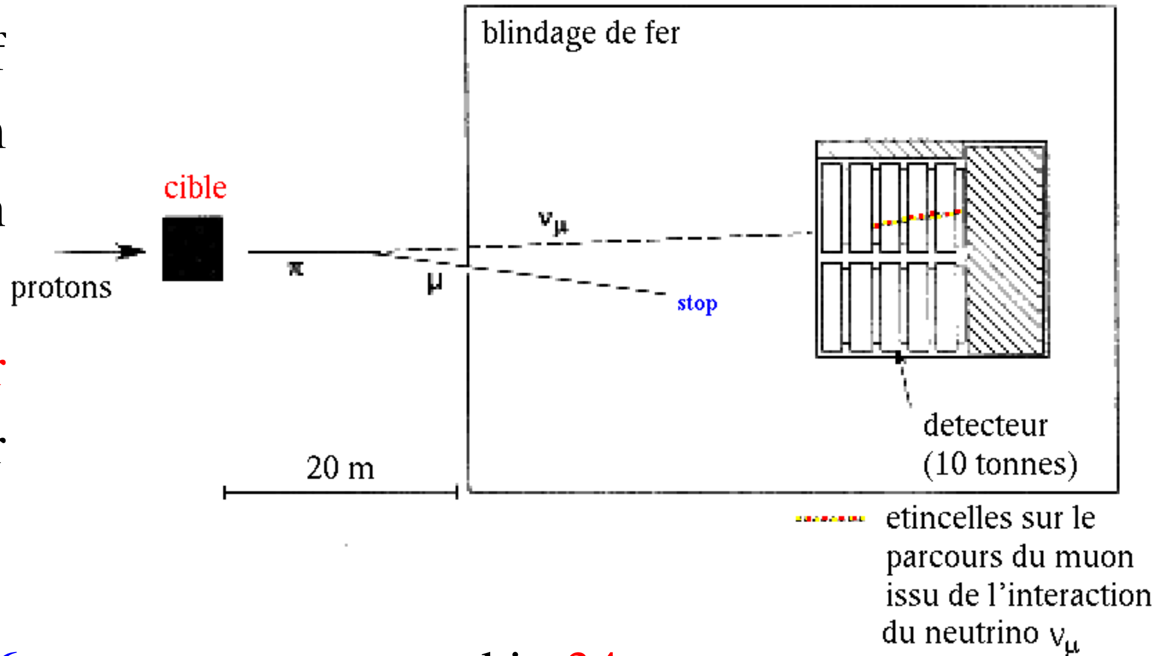

They observe 40 ν interactions: in 6 an e^- comes out and in 34 a μ^- comes out.

If $\nu_\mu \equiv \nu_e \Rightarrow$ equal numbers of μ^- and $e-$

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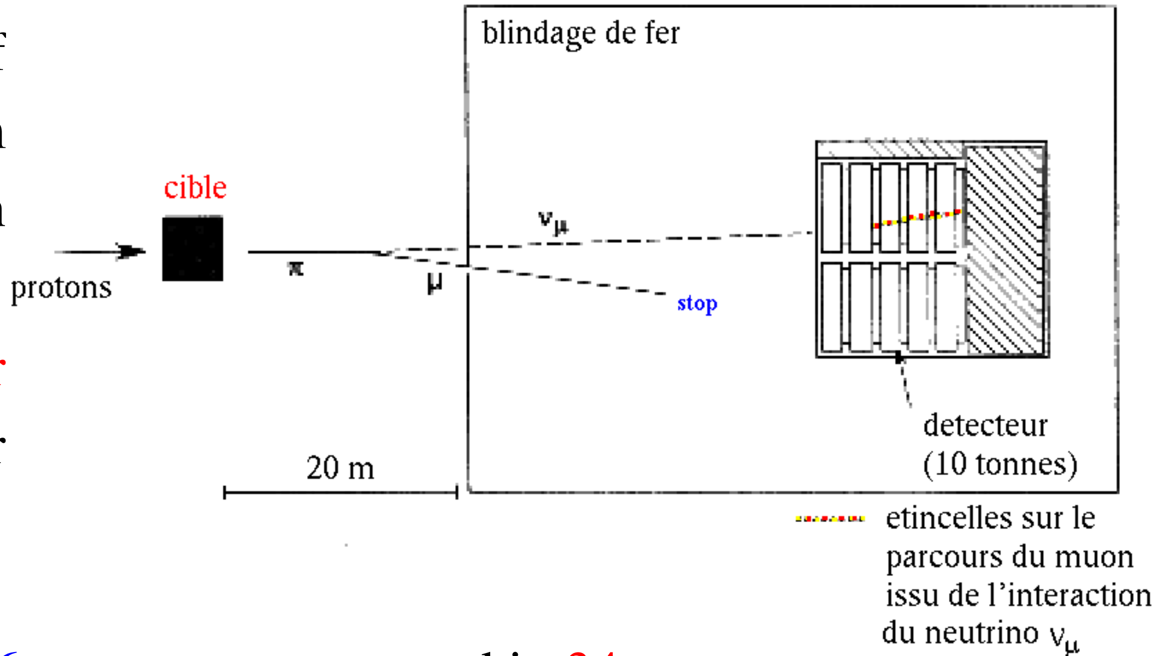

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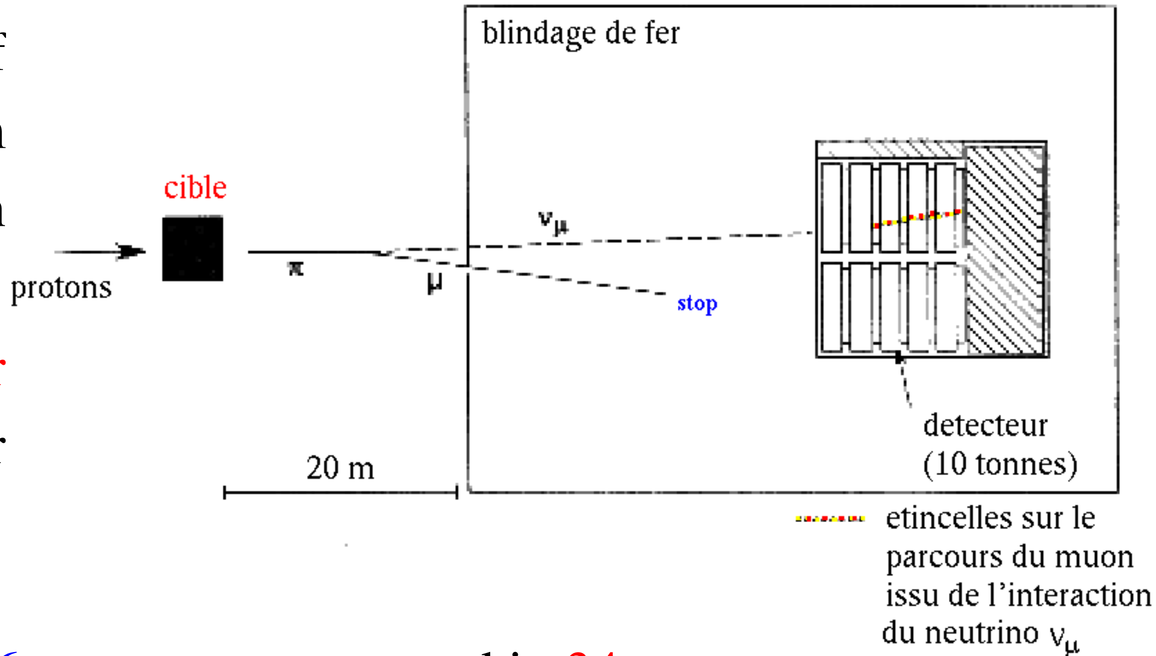

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In 1977 Martin Perl discovers the particle tau $\equiv$ the third lepton family.

The ν_τ was observed by DONUT experiment at FNAL in 1998 (*officially* in Dec. 2000).

ν Mass from Non-Renormalizable Operator

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If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim>4) operators

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First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{L}_5 = \frac{Z^{\nu}_{ij}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}} \tilde{\phi}\right) \left(\tilde{\phi}^T L^C_{L,j}\right)$$

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which after symmetry breaking

induces a ν Majorana mass

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Implications:

– It is natural that ν mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$ if $\Lambda_{\rm NP} >> v$

– See-saw with heavy ν_R integrated out is a particular example of this

Neutrino Mass Scale: Other Channels

Muon neutrino mass

- From the two body decay at rest

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

- Energy momentum conservation:

$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + \sqrt{p_\mu^2 + m_\nu^2}$$

$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 + m_\mu \sqrt{p^2 + m_\pi^2}$$

- Measurement of p_μ plus the precise knowledge of m_π and $m_\mu \Rightarrow m_\nu$
- The present experimental result bound:

$$m_{\nu_\mu}^{eff} \equiv \sqrt{\sum m_j^2 |U_{\mu j}|^2} < 190 \text{ KeV}$$

Tau neutrino mass

- The τ is much heavier $m_\tau = 1.776$ GeV

$\Rightarrow$ Large phase space $\Rightarrow$ difficult precision for m_ν

- The best precision is obtained from hadronic final states

$$\tau \to n\pi + \nu_\tau \quad \text{with } n \geq 3$$

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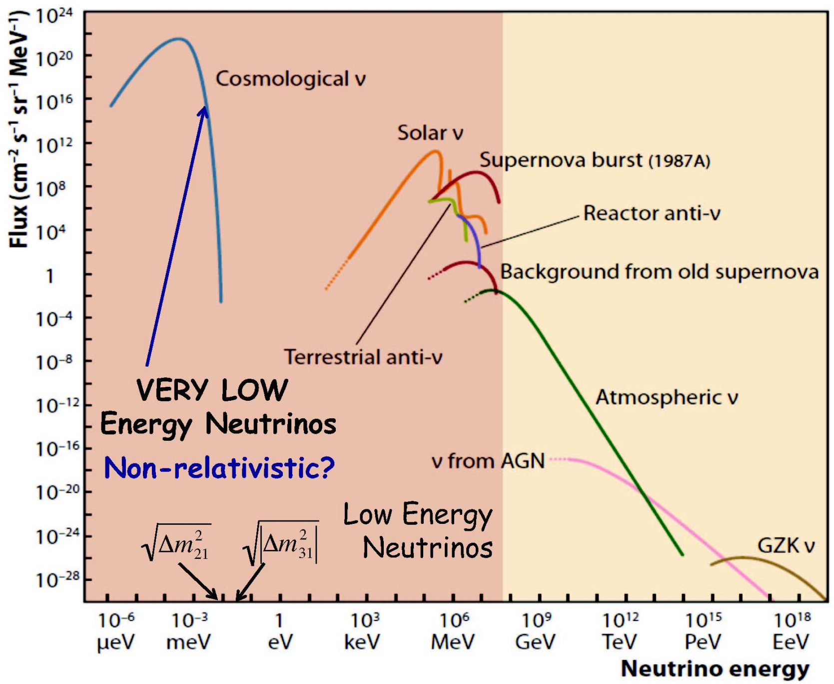
$\Rightarrow$ If mixing angles U_{ej} are not negligible

Best kinematic limit on Neutrino Mass Scale comes from Tritium Beta Decay

To allow observation of neutrino oscillations:

– Nature has to be good: $\theta \not\ll 0$

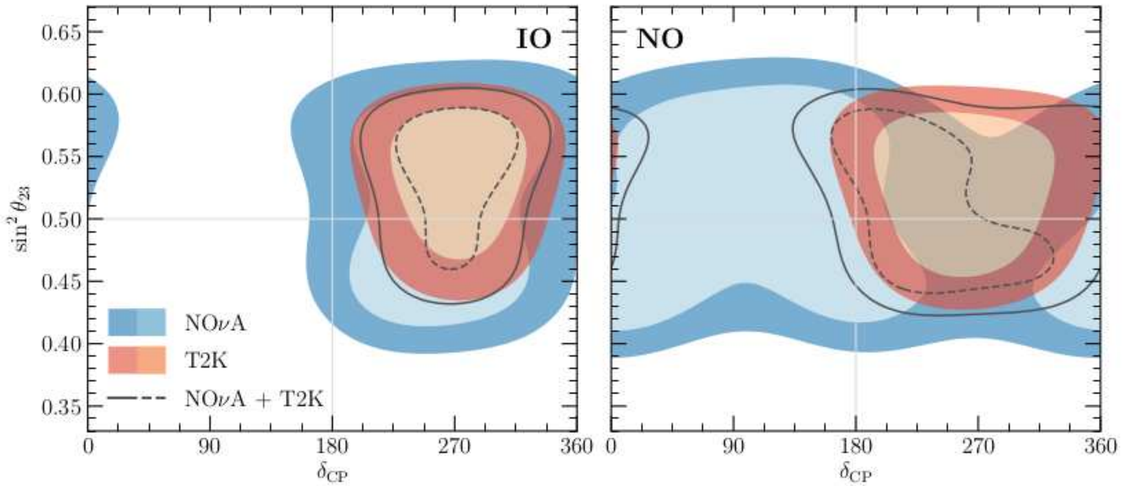
– Need the right set up ($\equiv$right $\langle \frac{L}{E} \rangle$) for Δm^2



Source	E (GeV)	L (Km)	Δm^2 (eV^2)
Solar	10^{-3}	10^7	10^{-10}
Atmos	0.1–10^2	10–10^3	10^{-1}–10^{-4}
Reactor	10^{-3}	SBL: 0.1–1	10^{-2}–10^{-3}
		LBL: 10–10^2	10^{-4}–10^{-5}
Accel	10	SBL: 0.1	$\gtrsim 0.01$
		LBL: 10^2– 10^3	10^{-2}–10^{-3}

Compatibility T2K/NOνA

- 1 and 2 σ (2dof) allowed regions (for $s^2_{13} = 0.0224$, marg over $|\Delta m^2_{3\ell}|$)



$\Rightarrow$ Better agreement in IO but NO 1σ regions "touch"

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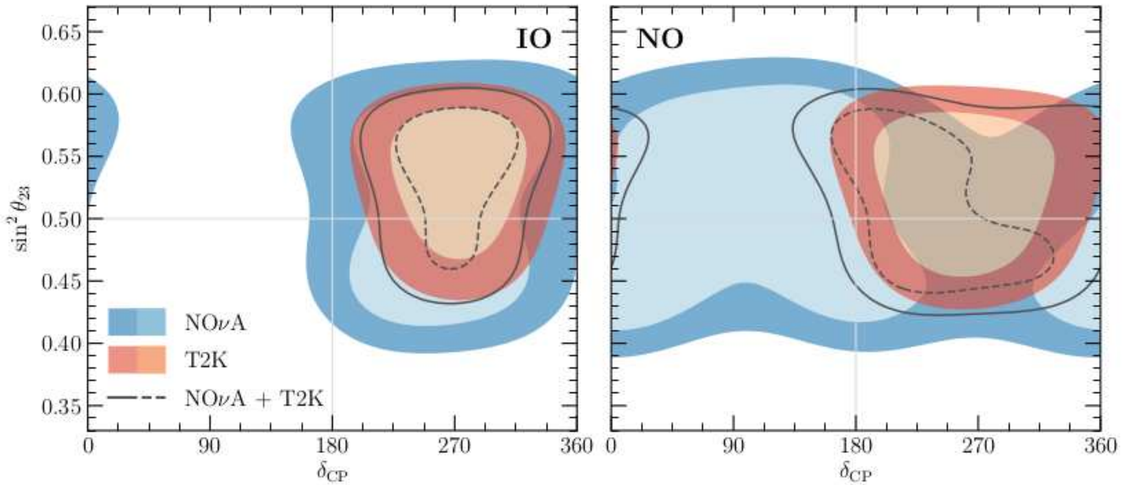

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- Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	χ^2_{PG}/n	p-value	#σ	χ^2_{PG}/n	p-value	#σ
T2K vs NOvA (θ_{13} free)	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs NOvA (θ_{13} fix)	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ

No significant incompatibility

Z' Models: Viable models for LMA-D

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