Summary – Neutrino Theory

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WIN 2005, $\Delta\varepsilon\lambda\varphi o\acute{\iota}$

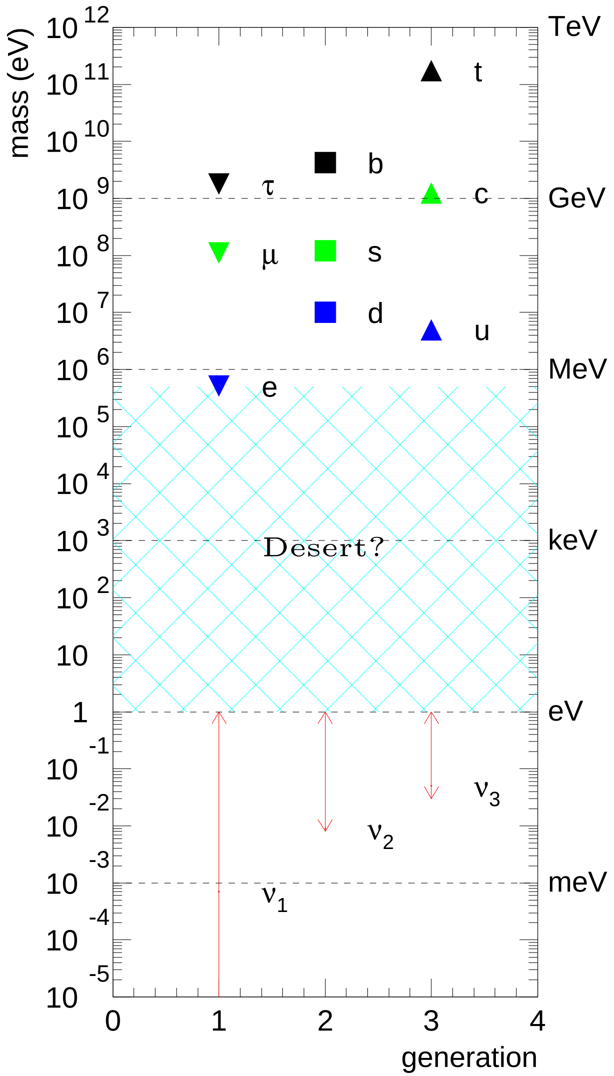
May 6–11, 2005

Outline

1. Neutrinos Have Mass!;
2. What is the New Physics Behind Neutrino Masses?;
3. What We Know We Don't Know;
4. Now That Neutrinos Have Mass. . . – Possible New Surprises;
5. Don't Forget the LSND Anomaly;
6. Concluding Remarks.

[I apologize in advance to all our excellent neutrino theory speakers for omitting, oversimplifying, or misrepresenting their results]

First Evidence of Physics Beyond the Standard Model:



NEUTRINOS HAVE MASS

albeit very tiny ones...

We don't know why that is, but we have a "gut feeling" it means something important.

Are neutrinos fundamentally different?

Are neutrino masses generated by a distinct dynamical mechanism?

Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \qquad \boxed{\text{WHY?}}$$

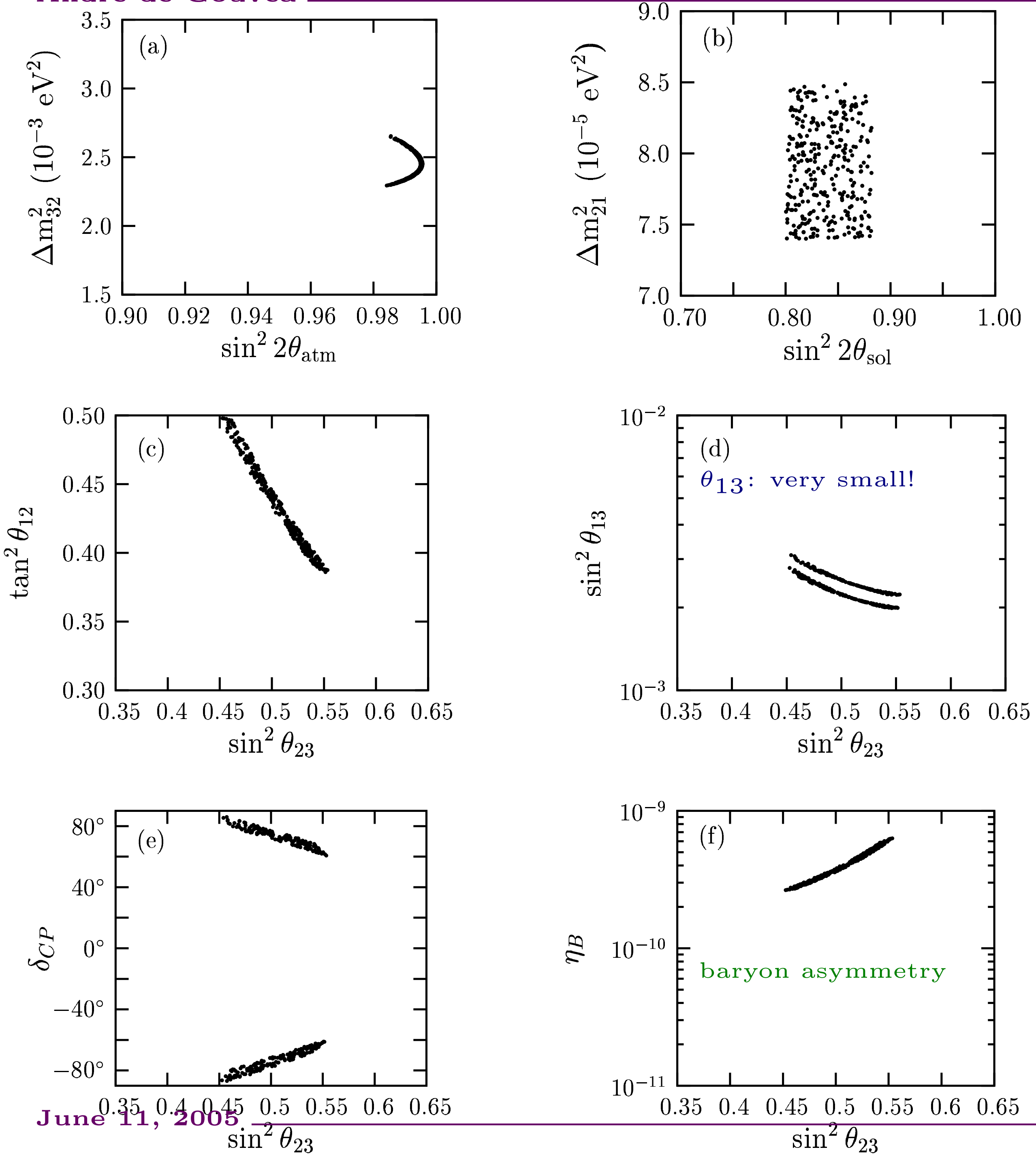
$[|(V_{MNS})_{e3}| < 0.2]$

(they certainly look VERY different, but which one would you label as "strange"?)

Origin of the Neutrino Masses [Albright]

Everyone's Favorite Solution – the SeeSaw Model

- Neutrino Masses are Small $\rightarrow$ $m_\nu = \frac{m^2_{EW}}{M}$, where M are the right-handed neutrino masses;
- Connection to GUT's
  - Right-handed neutrinos are required in $SO(10)$;
  - M related to physics of SO(10) breaking;
  - Connection to Quark Masses and Mixing – flavor symmetry;
  - Predictive?



[Albright]

Fully Loaded SUSY SO(10) Model

$\Rightarrow$ Very Predictive!

Majorana masses

[νs and Super Strings]

- Can one generate large effective m_S from

$$W_\nu \sim c_{ij}\frac{S^{q+1}}{M_{Pl}^q}N_iN_j \quad \Rightarrow (m_S)_{ij} \sim c_{ij}\frac{\langle S\rangle^{q+1}}{M_{Pl}^q},$$

  consistent with D and F flatness?

- Can one have such terms simultaneously with Dirac couplings, consistent with flatness and other constraints?

- Are bottom-up model assumptions for relations to quark, charged lepton masses maintained?

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Outlook

[νs and Super Strings]

- Neutrino mass likely due to large or Planck scale effects, but little previous work in string context

- *No* viable examples of minimal seesaw in huge class of Z_3 orbifold vacua
  - Could consider more general vacua (two independent VEVs, cancellations of F terms)
  - Other types of orbifolds and heterotic constructions? Will also have strong gauge and stringy constraints. (L conserved in existing intersecting brane)

- Even if a few examples are found, they don't appear generic

WIN 05 (June 10, 2005) *Paul Langacker (Penn)*

- Consider alternatives seriously

[νs and Super Strings]

  - Small Dirac masses from high degree terms (very common in constructions) (could also give light sterile ν's and mixing)
  - Extended seesaws, $m_\nu \sim m_D^{2+k}/M^{1+k}$, with $k \geq 1$ and low (e.g., TeV) scale M
  - Higgs triplet models: non-trivial to embed in strings (higher level), but very predictive (e.g., inverted hierarchy with nearly bi-maximal mixing) (B. Nelson, PL)

Protecting $(B,\ L)$

[Davoudiasl]

H.D., R. Kitano, G. Kribs, H. Murayama, hep-ph/0502176.

- Quarks: Z_A^q ; Leptons: Z_B^ℓ.

Higgs uncharged under $Z_A^q \times Z_B^\ell$ (IR symmetries).

- Anomaly cancellation:

$9a = 0$, mod A $\quad SU(2)$

$3b = 0$, mod B $\quad SU(2)$, gravity

	Q	u^c	d^c	L	e^c
Z_A^q	a	$-a$	$-a$	0	0
Z_B^ℓ	0	0	0	b	$-b$

Choose (a, b) = (1, 1); $Z_9^q \times Z_3^\ell$.

$\not{B},\ \not{L}$: $\quad O \sim Q^9 L^3/\Lambda^{14}$

Multi-nucleon $\tau > \tau_p \Rightarrow \Lambda \gtrsim 200$ *GeV.* *Safe!*

Majorana Neutrinos

[Davoudiasl]

★ $m_\nu \, \nu_L \nu_L \quad \rightarrow \not{Z}_3^\ell$ *spontaneously.*

★ Scalar χ , $Z_3^\ell(\chi) = +1$, $\langle \chi \rangle \neq 0$:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + c\,\chi(LH)^2/\Lambda^2 + \ldots, \quad (c \sim 1)$$

$$\langle H \rangle = v \rightarrow y_\chi \, \chi \, \nu \, \nu \quad ; \quad y_\chi \equiv c(v/\Lambda)^2.$$

★ Important Constraint: $0\nu\beta\beta \oplus \chi \rightarrow y_\chi < 3 \times 10^{-5} \Rightarrow \Lambda > 30$ TeV.

PDG 2004

$$m_\nu = y_\chi \langle \chi \rangle = c\,(0.06 \text{ eV}) \left(\frac{\langle \chi \rangle}{2 \text{ keV}} \right) \left(\frac{30 \text{ TeV}}{\Lambda} \right)^2$$

$[\Delta m^2_{\text{atm}} \simeq (0.06)^2 \, \text{eV}^2]$

Supernova Signatures

[Davoudiasl]

★ SN: $\Delta t_{\rm cool} \sim 10$ s; $R_{\nu-{\rm sphere}} \simeq 50$ km; $n_\nu \sim T_{\rm SN}^3 \sim (30\,{\rm MeV})^3$.

H.D., P. Huber, hep-ph/0504265

★ $\chi \leftrightarrow \nu\,\nu$: $\Gamma_\chi \sim y_\chi^2 T_{\rm SN} \gtrsim (10^{-8}\ {\rm s})^{-1} \Rightarrow \Gamma_\chi^{-1} \lesssim 1$ m.

★ *Thermal Bose-Einstein* χ-gas inside ν-sphere: $n_\chi \sim n_\nu \sim T_{\rm SN}^3$.

★ $T_{\rm SN} \gg \langle\chi\rangle \rightarrow$ Symmetry restoration; $\langle\chi\rangle = 0$: Phase transition at $T_c \sim \langle\chi\rangle$.

★ ν's and χ's radiated from surface of ν-sphere.

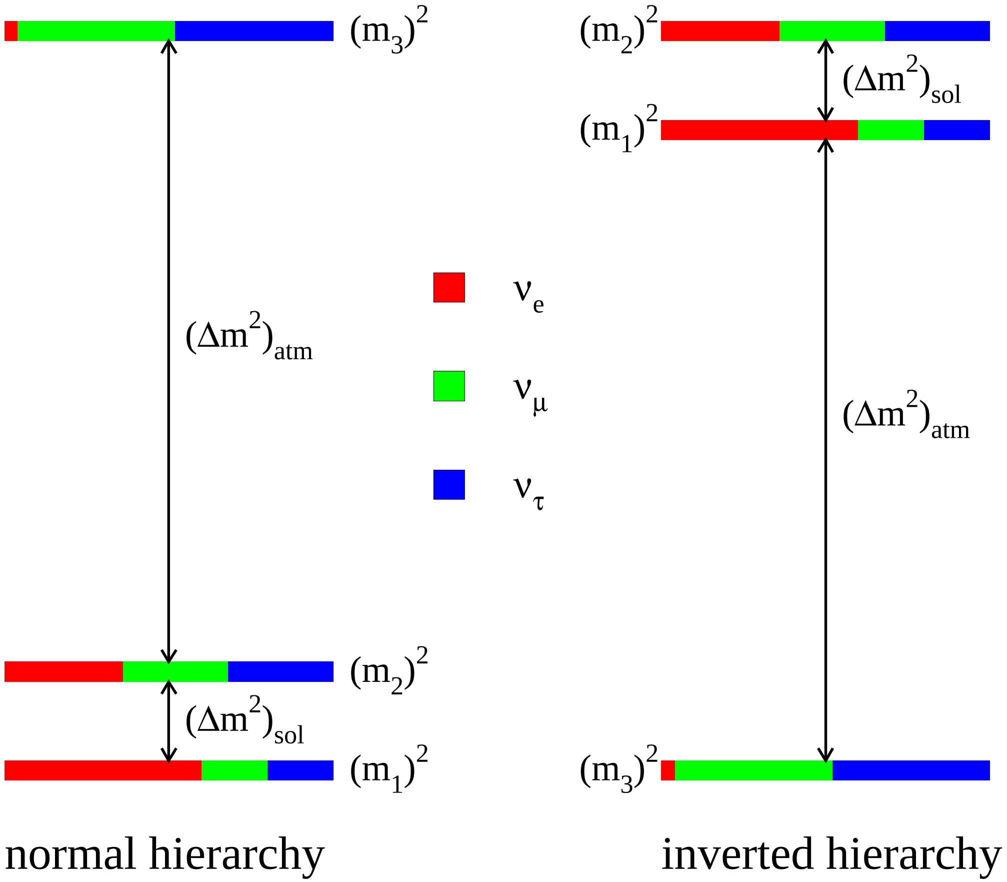
$\therefore$ *SN core radiates a two-component ν-flux:*

(1) Thermal Fermi-Dirac ν's.

(2) From χ-gas decays, $\langle E\rangle \approx \langle E_{\rm thermal}\rangle/2$.

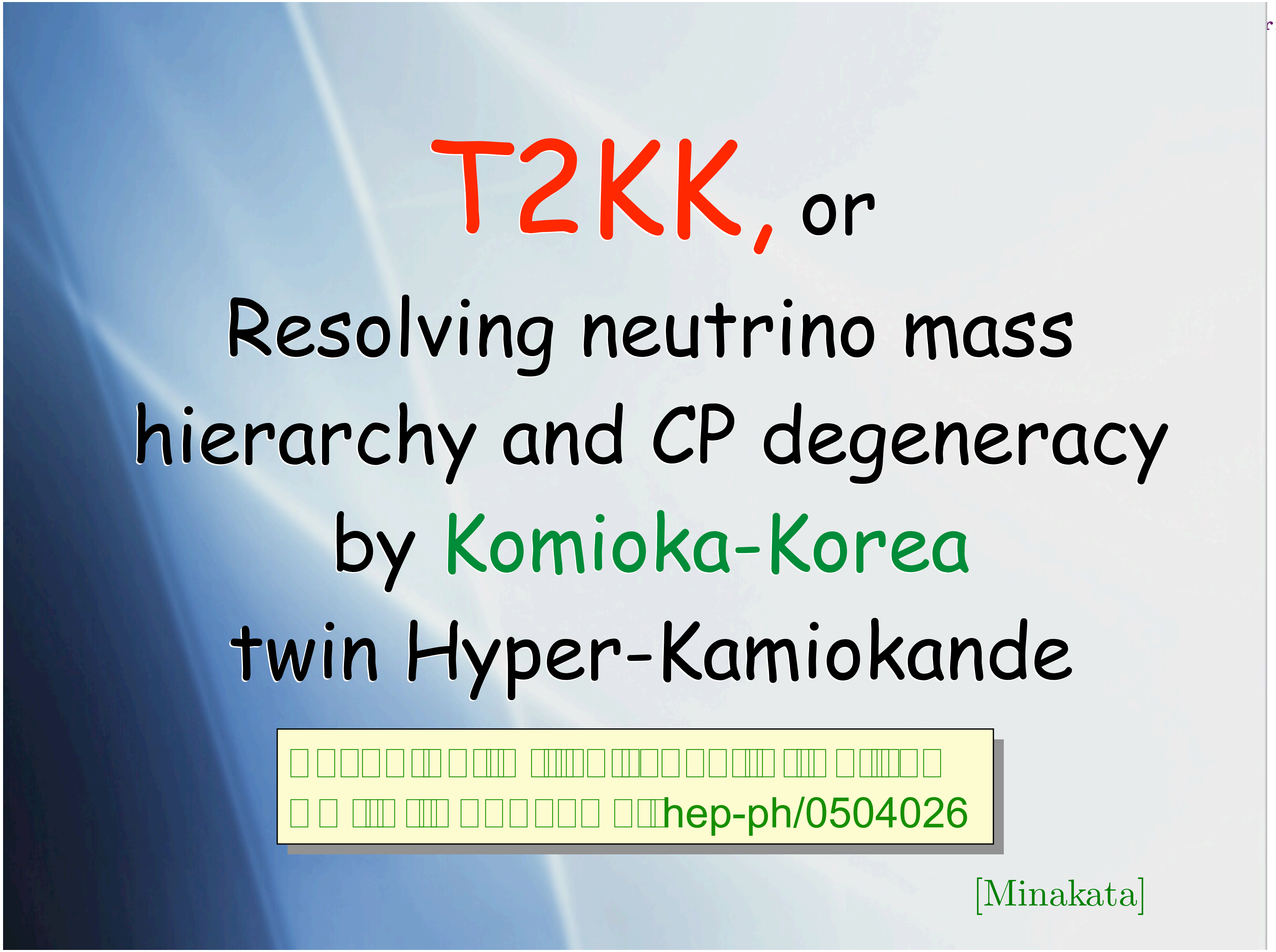
Additional astrophysical signatures:
H. Goldberg, G. Perez, I. Sarcevic,
hep-ph/0505221.

What We Know We Don't Know (1)

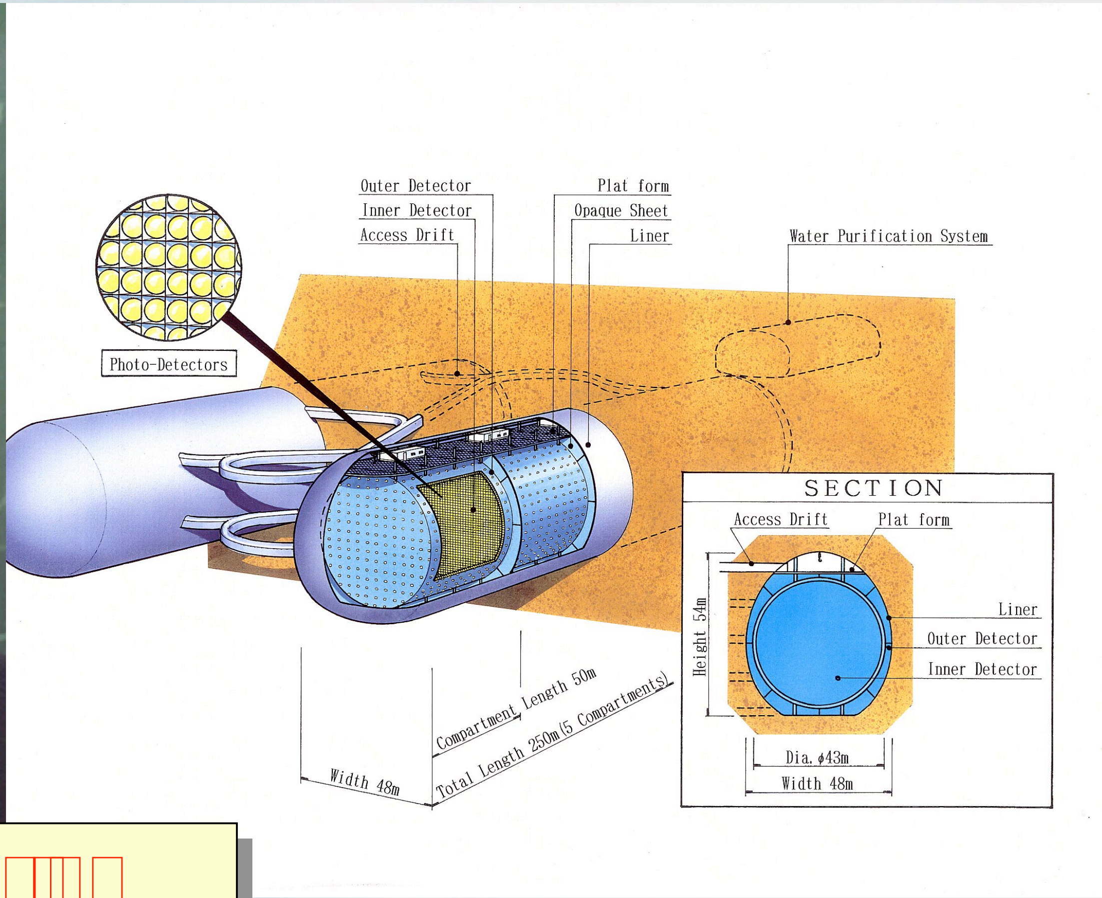


- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of these can be addressed in neutrino oscillation experiments **if** θ_{13} is large enough.


T2KK, or
Resolving neutrino mass hierarchy and CP degeneracy
by Komioka-Korea
twin Hyper-Kamiokande
hep-ph/0504026
[Minakata]

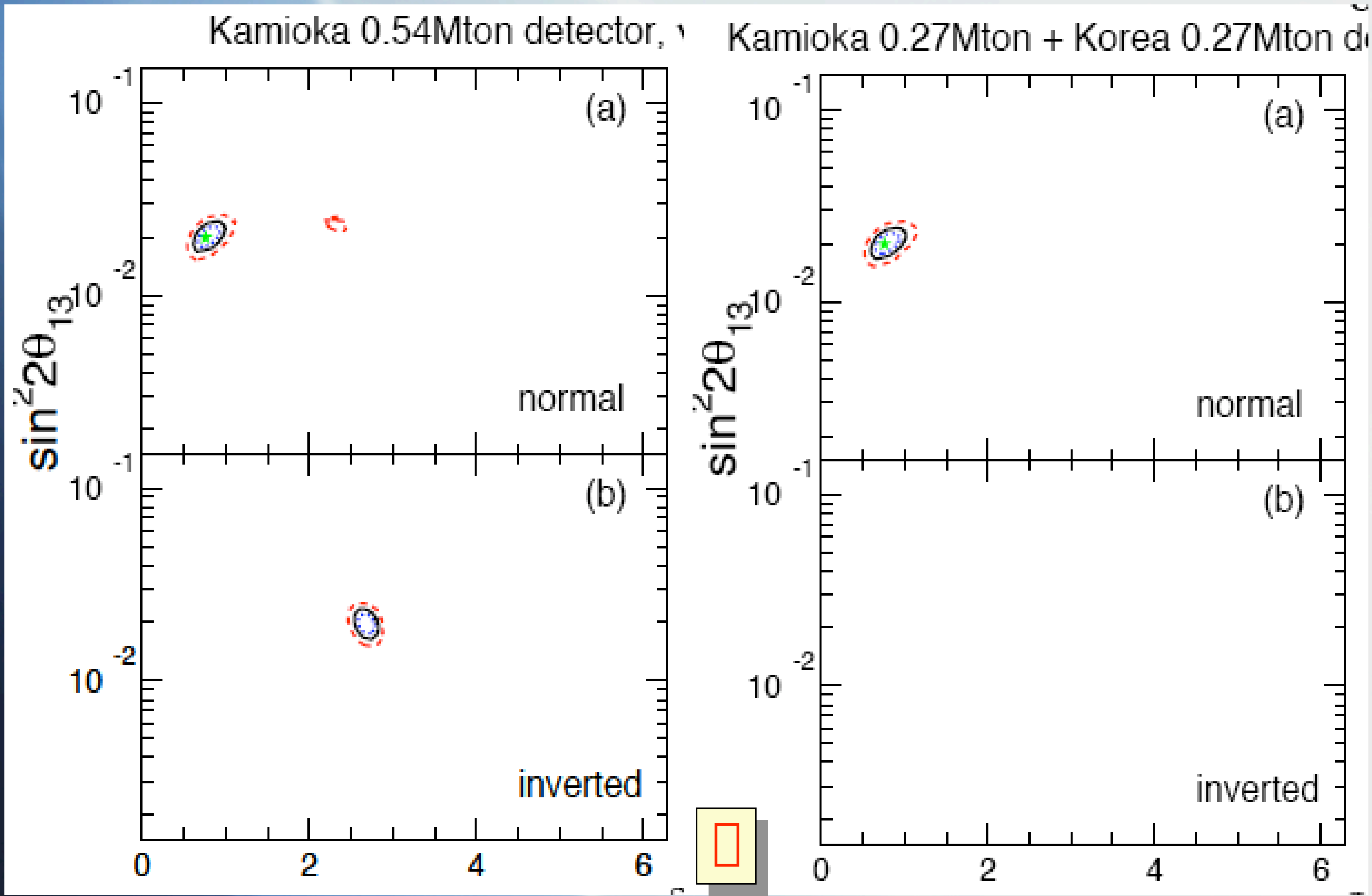
Current design of Hyper-Kamiokande contains 2 tanks !



u Minakata

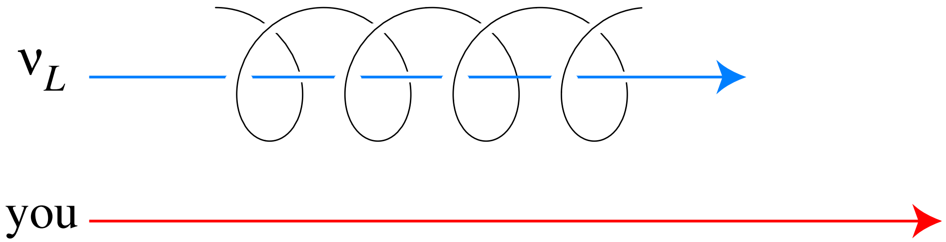
[Resolving Degeneracies]

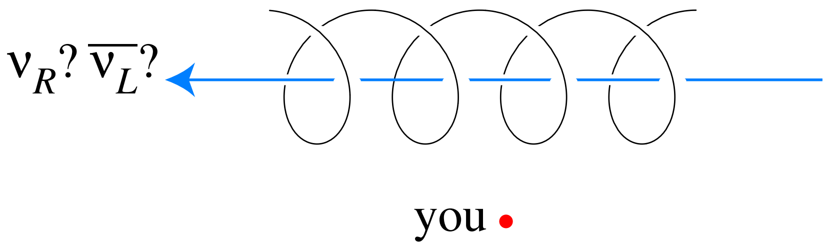
T2K(0.54 Mt) vs. T2KK(0.27+0.27 Mt)



WIN05, June 6-11 Hisakazu Minakata [Resolving Degeneracies]

What We Know We Don't Know (2) – Are Neutrinos Majorana Fermions?





The neutrino is the only neutral elementary fermion. There is a left-handed one and a right-handed one.

the left-handed has lepton number $L = +1$, while the right-handed one has $L = -1$:

$(\nu_\ell)_L + X \to \ell^- + X'$, while
$(\nu_\ell)_R + X \to \ell^+ + X'$, so we call $(\nu_\ell)_R \equiv \bar{\nu}_\ell$

If the neutrino is its own antiparticle (Majorana fermion), then the lepton number conservation law must not be exact $\to$ look for L-violation.

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2\, e^{i\alpha_{21}} + m_3|U_{e3}|^2\, e^{i\alpha_{31}}|,$$

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix.

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;
S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;
B. Kayser, 1984.

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.

Claim for a positive signal at $> 3\sigma$:
H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|<m>| = (0.1 - 0.9)$ eV (99.73% C.L.).

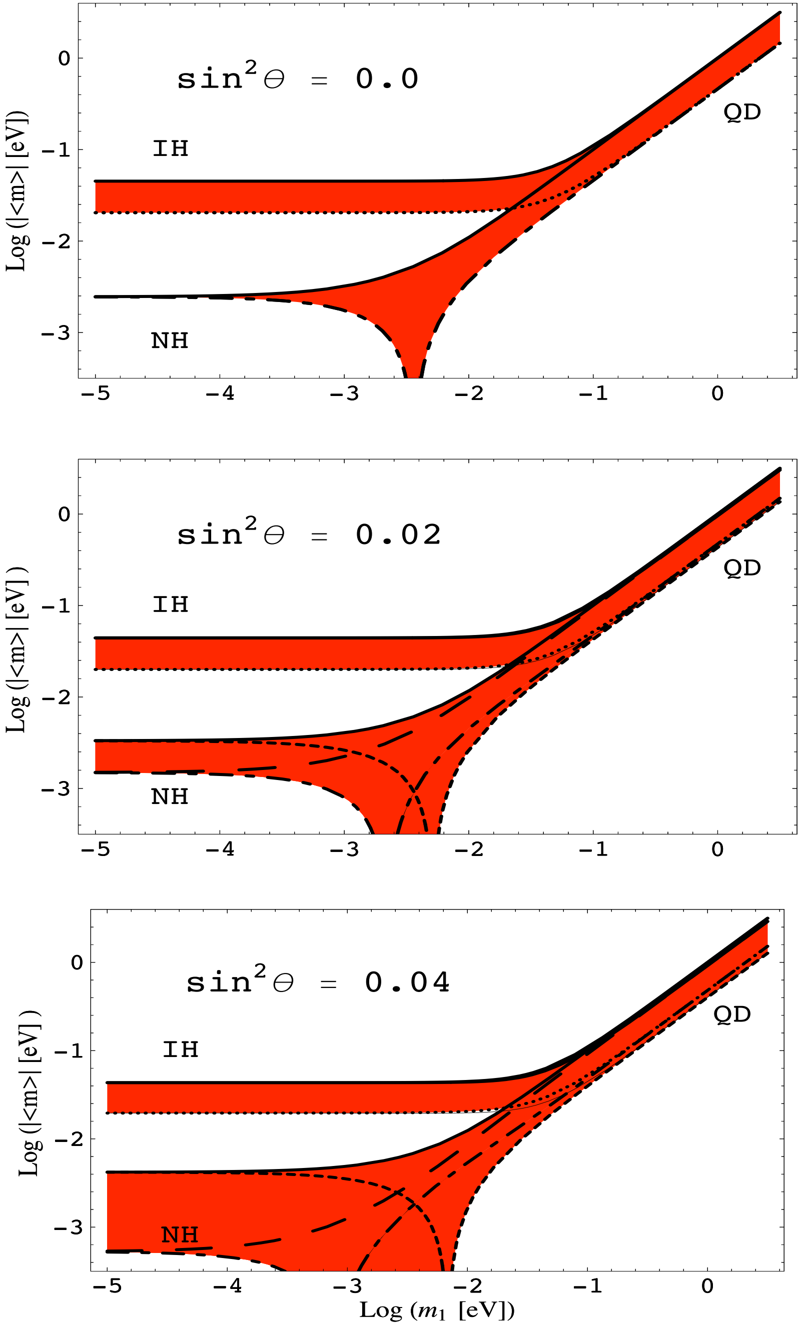
IGEX ^{76}Ge: $|<m>| < (0.33 - 1.35)$ eV (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|<m>| <(0.7–1.2)$ eV, $|<m>| <(0.2–1.1)$ eV (90% C.L.).

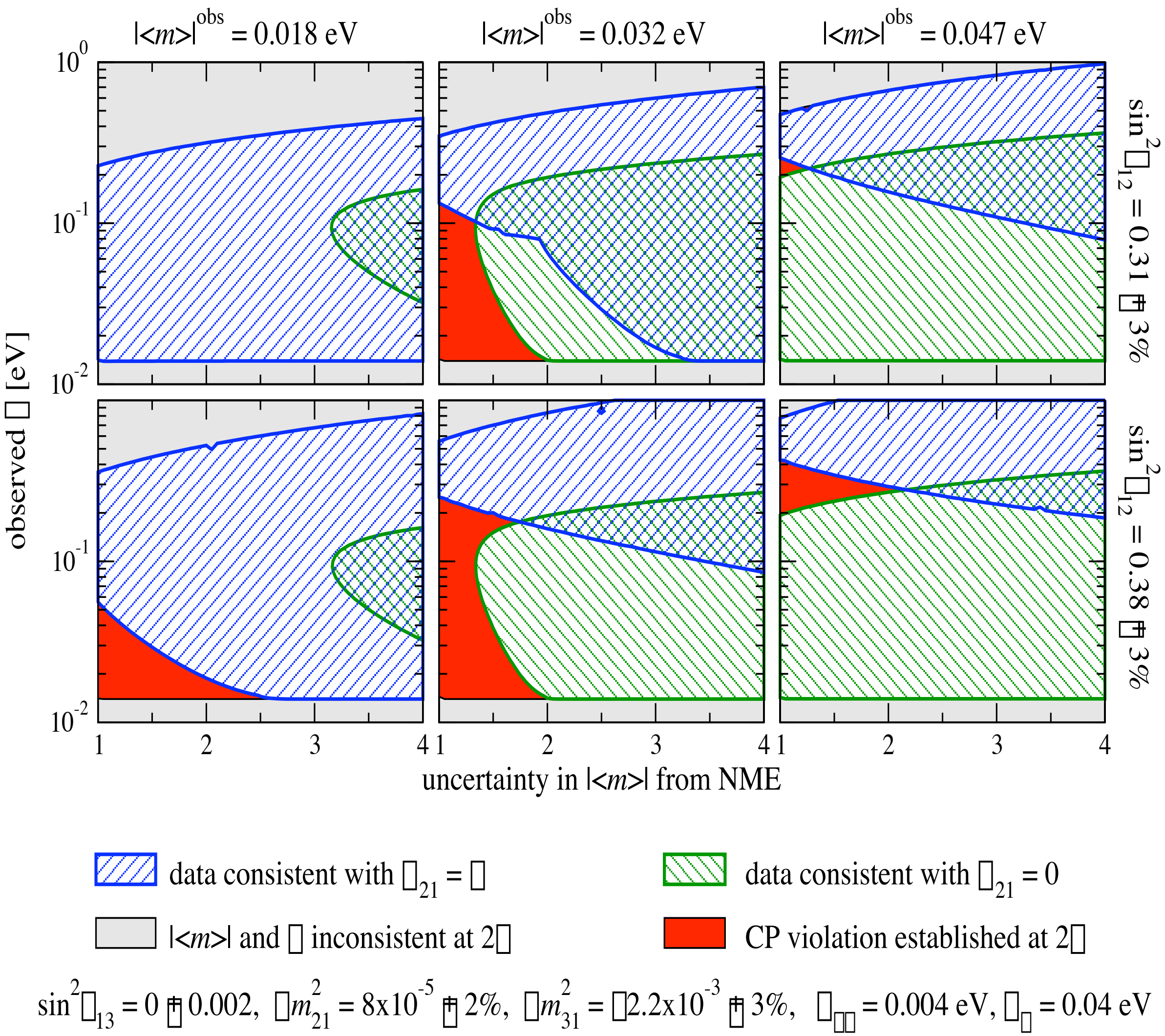
Large number of projects: $|<m>| \sim (0.01 - 0.05)$ eV
CUORE - ^{130}Te,
GERDA - ^{76}Ge,
EXO - ^{136}Xe,
MAJORANA - ^{76}Ge,
MOON - ^{100}Mo,
CANDLES - ^{48}Ca,
XMASS - ^{136}Xe.

[Petcov – 0ν Double-Beta Decay]



[Petcov – 0ν Double-Beta Decay]

S. Pascoli, S.T.P., 2004



S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

[Petcov – 0ν Double-Beta Decay]

ν electromagnetic properties: theoretical grounds

Standard Model with $m_\nu \neq 0$

- SM with right handed neutrino singlet [Lee & Shrock'77]

$$\mu_\nu = 3.2 \times 10^{-19} \mu_B \frac{m_\nu}{1\ \mathrm{eV}}$$

Extensions beyond the Standard Model

- However in extended electroweak models there are no direct relations between μ_ν and m_ν and, e.g., μ_ν might be proportional to the mass of heavy charge lepton interacting with charge scalar
- e.g. in MSSM with horizontal symmetry between e and μ transition magnetic moments might be up to

$$\mu_\nu \sim 10^{-11} - 10^{-10} \mu_B$$

keeping neutrino masses and splittings small

[Babu & Mohapatra'89, Leurer & Marcus'90,...]

ν electromagnetic interactions

Effective hamiltonians

$$H_{em}^{Dirac} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\mu\nu} \nu_L F_{\mu\nu} + \text{H.c.}$$

$$H_{em}^{Majorana} = -\frac{1}{4}\nu_L^T C^{-1} \lambda \sigma^{\mu\nu} \nu_L F_{\mu\nu} + \text{H.c.}$$

In Dirac case: λ is an arbitrary matrix

In Majorana case: $\lambda^T = \lambda$, only transition moments are non-zero, may be parametrized as $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$

$\lambda = \mu - id$, $\quad \mu$ – magnetic moment matrix, d – electric dipole moment matrix

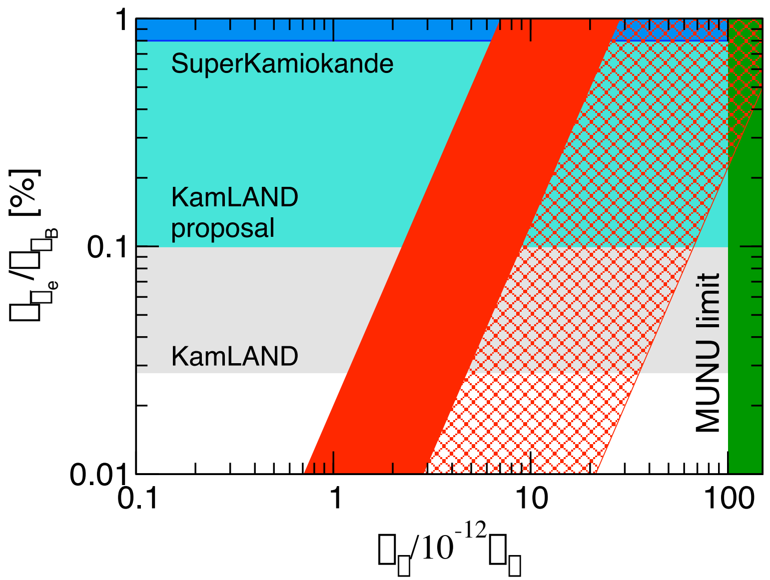
Majorana μ_ν bound in solar turbulent magnetic field

KamLAND bound on $\bar{\nu}_e$ flux

$$\Phi_{\bar{\nu}_e} < 2.8 \times 10^{-4} \Phi_{\nu_e}^{^8B}$$

Majorana $\bar{\nu}_e$ appearance in solar turbulent field

[*Miranda et al'04*]



$$P(\bar{\nu}_e)_{Earth} \sim \mu_{12}^2 \frac{b_{max}^2}{L_{max}^{2/p}}$$

Turbulent field scales as $b \sim L^{1/p}$

"Realistic" bound: $\mu_{12}^{(M)} < 5 \times 10^{-12} \mu_B$

"Conservative": $\mu_{12}^{(M)} < 4 \times 10^{-11} \mu_B$

[*For discussion see also Friedland'05*]

The Lagrangian

$$L^{NSI} = -2\sqrt{2}G_F\left(\bar{\nu}_\alpha\gamma_\mu\nu_\beta\right)\left(\epsilon_{\alpha\beta}^{f\tilde{f}L}\bar{f}_L\gamma^\mu\tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R}\bar{f}_R\gamma^\mu\tilde{f}_R\right) + h.c.$$

vertex	Current bound
$(\bar{e}\gamma^\rho Pe)(\bar{\nu}_\tau\gamma_\rho L\nu_\tau)$	$\lvert\epsilon^{eP}_{\tau\tau}\rvert<0.5$ LEP
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\tau\gamma_\rho L\nu_e)$	$\lvert\epsilon^{dP}_{\tau e}\rvert<1.6$ CHARM
$(\bar{u}\gamma^\rho Ru)(\bar{\nu}_e\gamma_\rho L\nu_e)$	$-0.4<\epsilon^{uR}_{ee}<0.7$ CHARM

From: S.Davidson, C.Pena-Garay and N.Rius, JHEP 0303:011,2003

[Lunardini – NSνI]

Phenomenological approach...

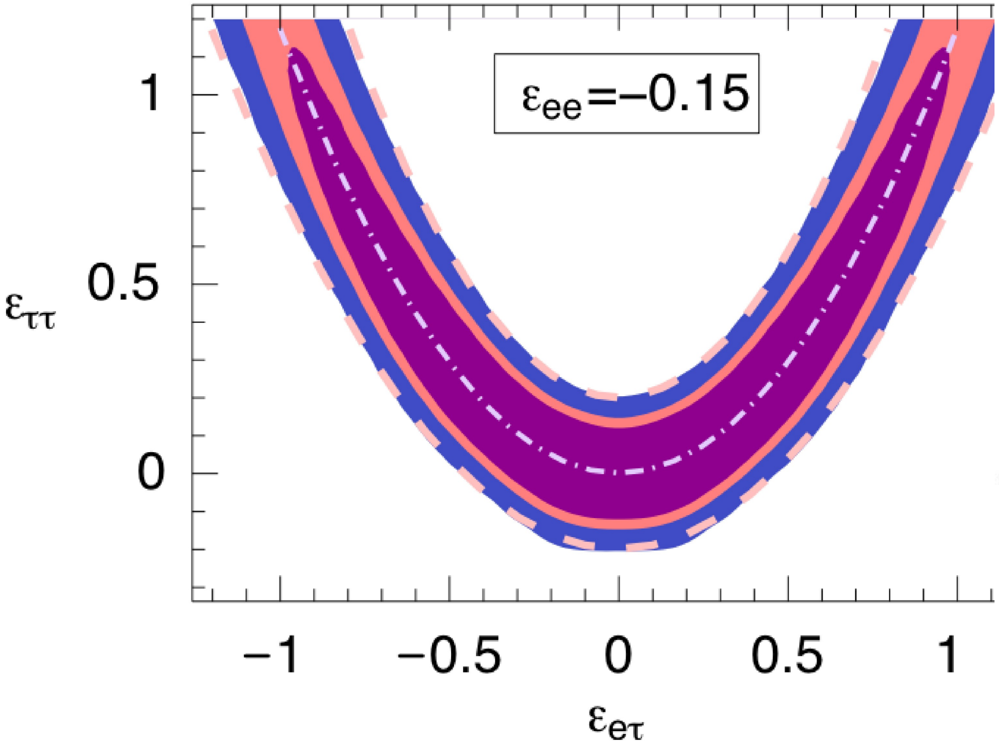
- We want to test NSI in a 3-flavor context, with NSI in e,□ sector
- The oscillation Hamiltonian

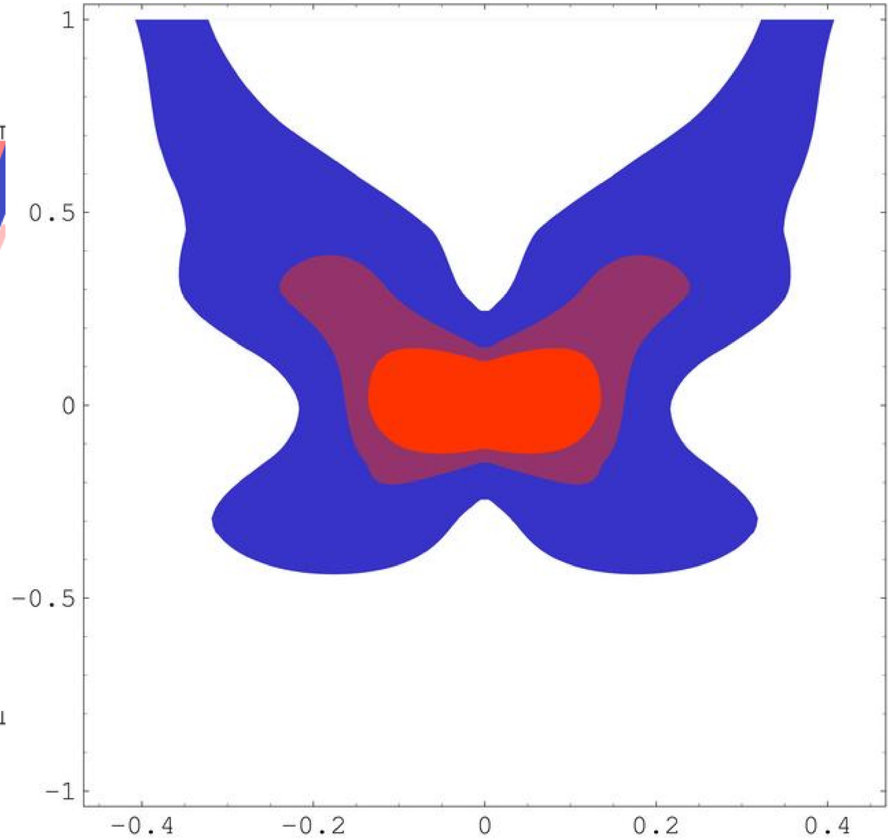
$$H_{\text{eff}} = \frac{\Delta m^2_{13}}{4E} \begin{pmatrix} -1 + .. & .. & .. \\ .. & -\cos 2\theta_{23} & \sin 2\theta_{23} \\ .. & \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} +$$

$$\sqrt{2} G_f N_e \begin{pmatrix} 1 + \epsilon_{ee} & .. & \epsilon^*_{e\tau} \\ .. & 0 & .. \\ \epsilon_{e\tau} & .. & \epsilon_{\tau\tau} \end{pmatrix}, \qquad \epsilon_{\alpha\beta} = \sum_{P,f} \epsilon^{ffP}_{\alpha\beta}$$

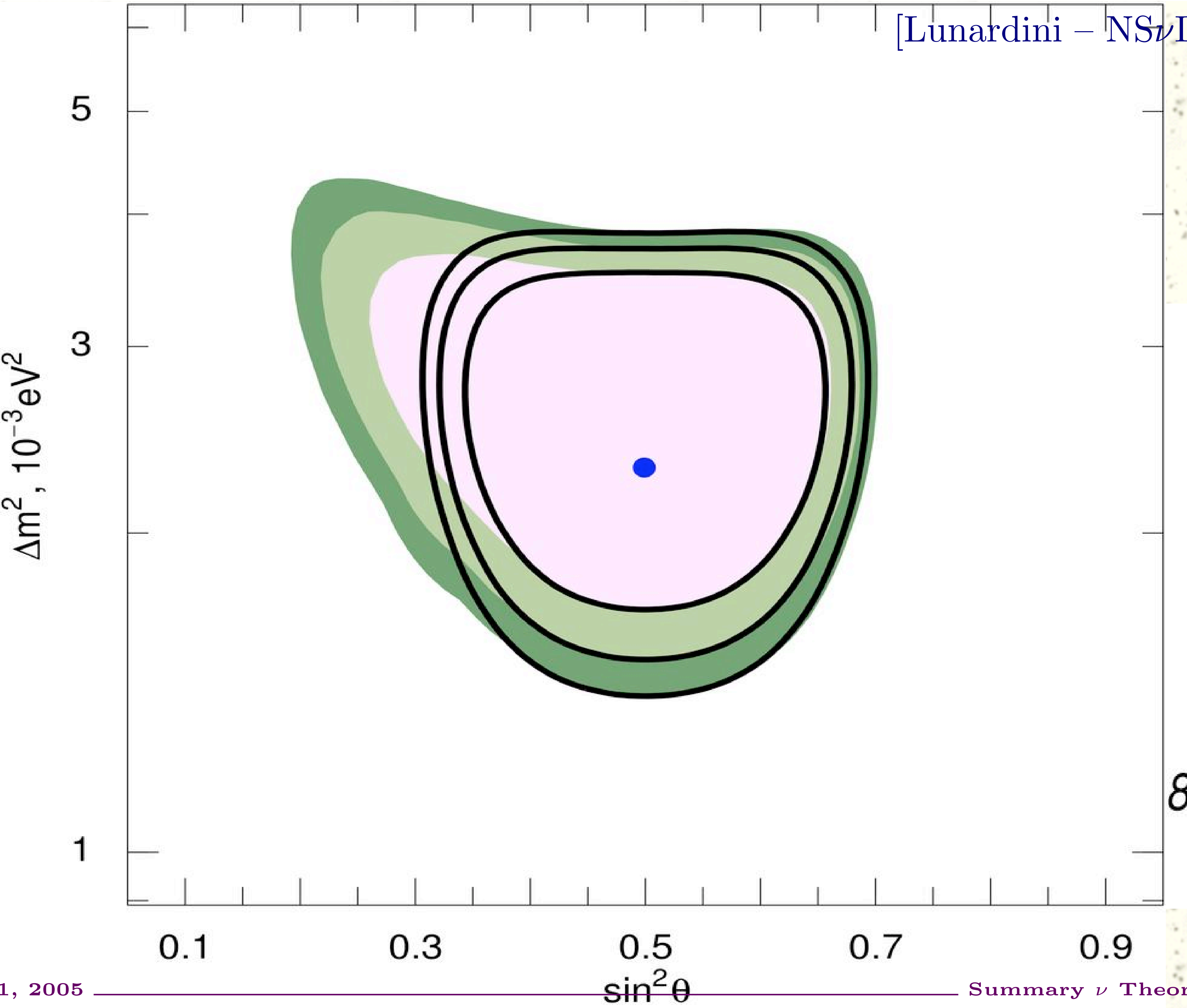
[Lunardini – NSνI]

“smile”





“butterfly”


5
3
1
Δm^2, 10^{-3}eV^2
0.1
0.3
0.5
0.7
0.9
$\sin^2\theta$

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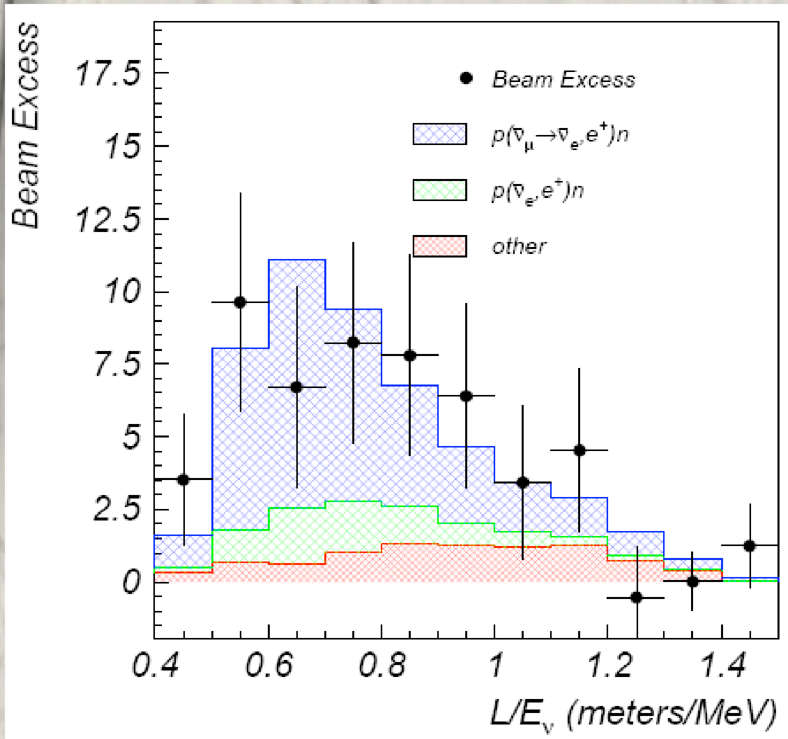
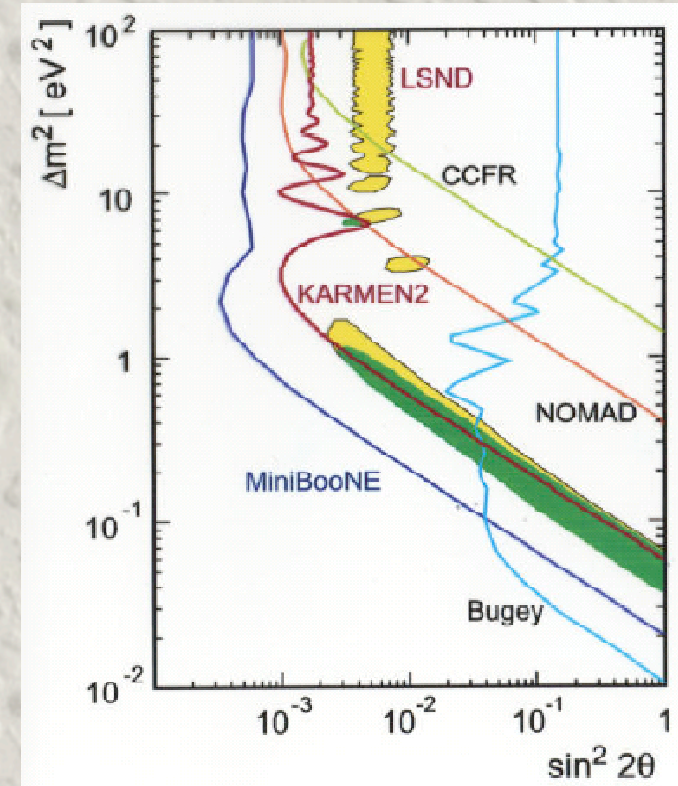
$\bar{\nu}_e$ **excess : 87.9 ± 22.4 ± 6.0** → **3.3 σ effect** (3.8 σ – Shaevitz)

P ($\bar{\nu}_\mu \to \bar{\nu}_e$) = (0.264 ± 0.067 ± 0.045) %





A. Aguilar *et al.*, Phys. Rev. D64:112007, 2001

G. Drexlin, Nucl.Phys.Proc.Suppl.118:146-153,2003

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Classifying solutions

- With and without sterile neutrinos
  - With one and with more than one sterile
- With and without neutrino oscillations
- With and without CPT violation
- With non-standard and with standard processes
- With and without extra dimensions
- With problems and with problems
- Those we like and those we don't like
- Those we have proposed and those we haven't proposed
- No solution

But if LSND is right, all imply NEW PHYSICS!

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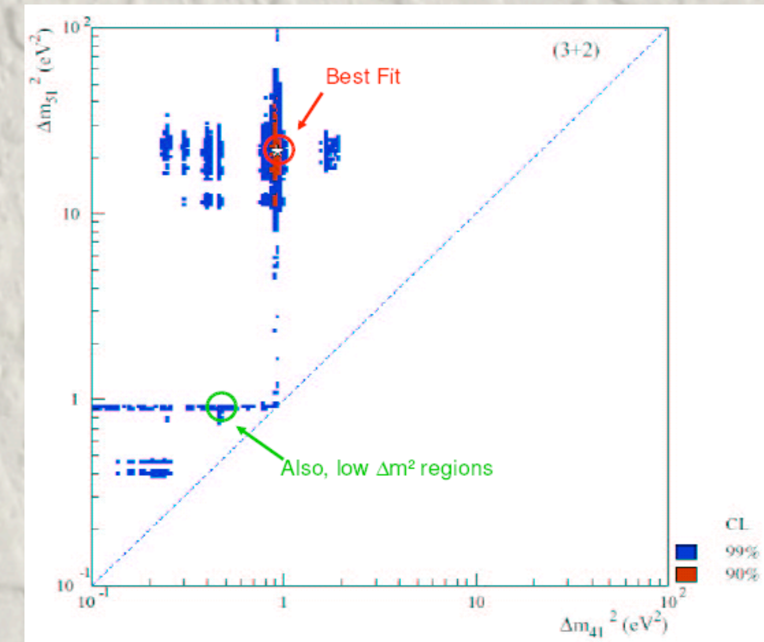
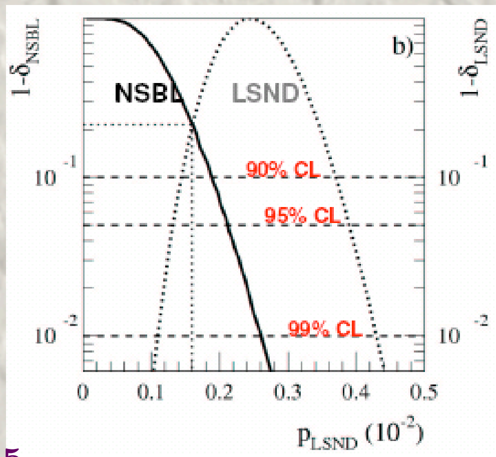
3+2 neutrino models





Compatibility between SBL (including KARMEN) and LSND of 30%, instead of 3.6 % in the standard 3+1 model

M. Sorel, J. M. Conrad and M. H. Shaevitz, Phys. Rev. D66:033009,2002

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Neutrino decay

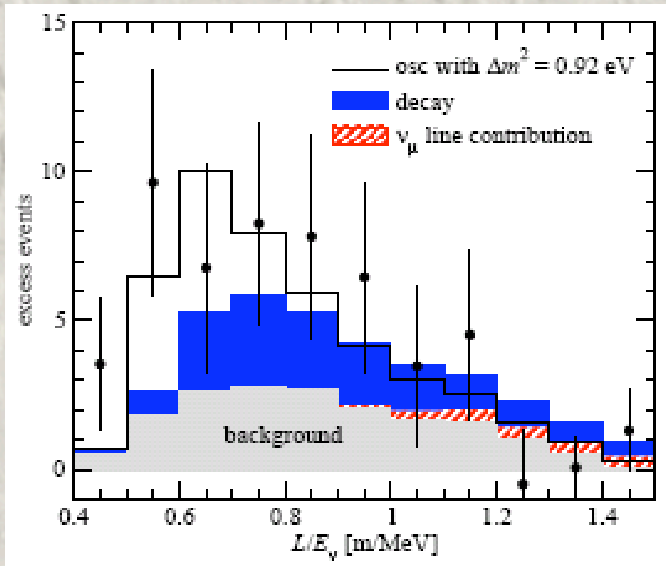
3+1 model with a decay option…

$$L_{\text{int}} = \sum_{l,h} g_{hl}\,\bar{\nu}_{lL}\, n_{hR}\,\phi + h.c. \quad \Rightarrow \quad \nu_4 \to \bar{\nu}_{1,2,3} + \phi \quad \text{and} \quad \bar{\nu}_4 \to \nu_{1,2,3} + \phi$$

…but LSND explained by decay

$$\Gamma(N \to \bar{\nu}_l + \phi) = \Gamma(N \to \nu_l + \phi) = \frac{|g_{hl}|^2\, m_N}{32\pi\, E_N}$$

As far as $g_e' \equiv U_{el}\, g_{hl} \neq 0$, we expect $\bar{\nu}_e$ and ν_e appearance



Good fit to data

SPR, S. Pascoli and T. Schwetz, hep-ph/0505216

CONCLUSIONS

The venerable Standard Model has finally sprung a leak – neutrinos are not massless!

1. we have a very successful parametrization of the neutrino sector, and we have identified what we know we don't know $\rightarrow$ well-defined "no-brainer" experimental program.
2. we are moving from the "discovery phase" to the "precision phase" – probe non-standard neutrino interactions, neutrino electromagnetic moments, etc.
3. neutrino masses are very small – we don't know why, but we think it means something important.
4. lepton mixing is very different from quark mixing – we don't know why, but we think it means something important.

5. We need more experimental input – this is a truly data driven field right now. We only started to figure out what is going on.

6. There is plenty of room for surprises, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that oscillating neutrinos serve as "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $M_{\rm seesaw} \simeq 10^{14}$ GeV).

7. Finally, we need to resolve the LSND anomaly. If MiniBooNE agrees with the LSND result, life will be much more interesting!