Neutrino Properties and Tests of Symmetries

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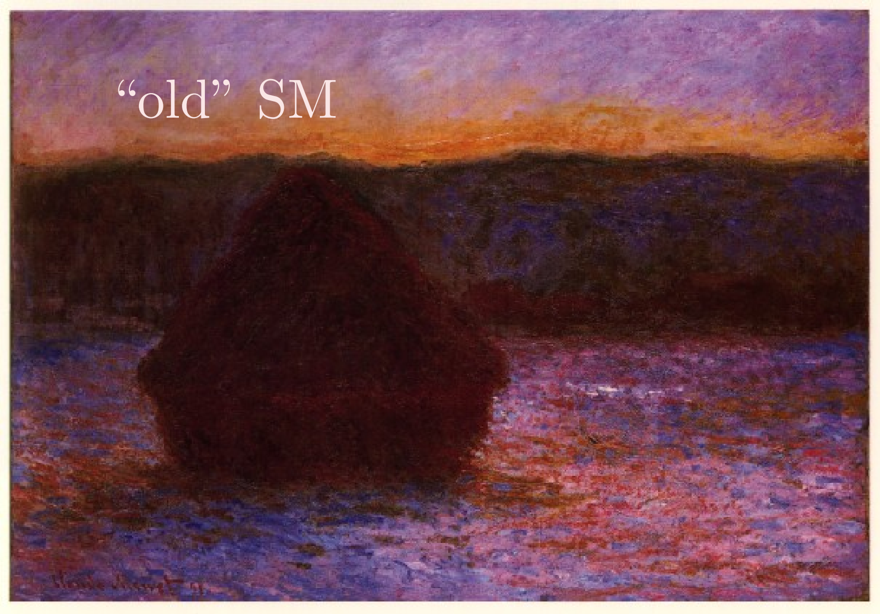


Massless Neutrinos:

- gauged $SU(3)_c \times SU(2)_L \times U(1)_Y$
- global $U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
- No “leptonic” CP-invariance violation

(with apologies to C. Monet)

Massive Neutrinos:

- gauged $SU(3)_c \times SU(2)_L \times U(1)_Y$
- global $U(1)_B$ $(\times U(1)_L)$
- Leptonic CP-invariance violated (?)

$(\star) \Rightarrow$ to be determined experimentally!

There are two "minimal" guesses for the New Standard Model Lagrangian:

(a) $\mathcal{L} = \mathcal{L}_{\text{old SM}} - \lambda^{ij}\frac{L_i H L_j H}{2M} + h.c.$

- $m_\nu = \frac{\lambda v^2}{M}$ – Tiny neutrino masses: $M \gg v \Rightarrow m_\nu \ll m_{\ell,q}$,
- Higher Dimensional Operator – SM no longer works above scale M,
- Neutrinos are Majorana Fermions – lepton number violated

(b) $\mathcal{L} = \mathcal{L}_{\text{old SM}} + i\bar{N}_i \partial\!\!\!/ N_i - \lambda^{\alpha i}\bar{L}_\alpha H N_i + H.c.$

- $m_\nu = \lambda v$ – neutrino masses require $\lambda < 10^{-11}$
- Renormalizable Lagrangian – like the old SM
- New degrees of freedom – standard model gauge singlets N
- Neutrinos are Dirac Fermions – lepton number conserved — WHY?

Neither (a) nor (b) yield other observable new physical effects, except for the faith of lepton number violation YES/NO. [$\Rightarrow$ see talks on $0\nu\beta\beta$]

—

(L = lepton doublets, H = Higgs doublet, λ = dimensionless couplings, M = "seesaw" scale)

However, the fact that neutrinos have mass and given the unprecedented abundance of neutrino data we are in position to probe whether neutrino are endowed with other "unexpected" properties, including,

- a magnetic moment; [⇒ see talk by Wong]
- a finite lifetime;

and whether the leptonic sector respects a variety of fundamental symmetries, including

- CP, T invariance; [⇒ see talk by Petcov]
- Lorentz invariance;
- CPT invariance.

NEUTRINO MAGNETIC MOMENTS

Now that neutrinos have mass, they are "allowed" to have a nonzero magnetic moment μ_ν.

The nature of μ_ν will depend on whether the neutrino is its own antiparticle:

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + H.c.,$$

$$\mu_\nu^{ij} = -\mu_\nu^{ji}, \quad i,j = 1,2,3 \ \rightarrow \ \text{Majorana Magnetic Moment}$$

or

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} N F^{\mu\nu}) + H.c.,$$

$$i,j = 1,2,3 \ \rightarrow \ \text{Dirac Magnetic Moment}$$

In either version of the new SM, μ is really small:

$$\mu \leq \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu = 3\times 10^{-20}\mu_B \left(\frac{m_\nu}{10^{-1}\ \text{eV}}\right); \qquad \mu_B = \frac{e}{2m_e}$$

Bounds come from a variety of sources and constrain different linear combination of elements of μ. $\Rightarrow$ next talk

- $\bar{\nu}_e e^- \to \nu_\beta\ (\bar{\nu}_\beta)\ e^-$, $\forall\beta\ (\beta = e,\mu,\tau)$ TEXONO, MUNU reactor expt's, SuperK solar
- searches for electron antineutrinos from the Sun $(\nu_e \stackrel{(m.m.)}{\longrightarrow} \bar{\nu}_\beta \stackrel{(\text{osc})}{\longrightarrow} \bar{\nu}_e)$ $\vec{B}$ in the Sun?, how well oscillation parameters are known? (KamLAND!) $\Rightarrow$ posters
- astrophysics red giants, SN1987A, ...

$$\Rightarrow \boxed{\boxed{\mu_\nu < 1.5\times 10^{-10}\mu_B}} \quad \text{(PDG accepted bound);}$$

also $O(10^{-[12\div 11]})$ bounds from astrophysics and solar neutrinos.

Generic new, electroweak-scale physics effects yield much larger neutrino magnetic moments. *E.g.*,

$$\mu \sim \frac{e\lambda^2}{M_{\rm new}} m_f \qquad\qquad f = e, \mu, \tau, \ldots$$

Searches for neutrino magnetic moments constrain the new physics scale (M) and coupling (λ) like searches for new physics in the charged-lepton sector: $\mu \to e\gamma$, $(g-2)_\mu$, muon and electron electric dipole moments, etc. After all, they all come from the same effective operator!

One can place bounds on (or find "evidence" for)

- SUSY,
- large extra dimensions ($\bar{\nu}_e e^- \to \sum_{\rm kk} \bar{\nu}_{\rm kk} e^-$),
- $\ldots$ (the usual suspects).

THE NEUTRINO LIFETIME

Now that neutrinos have mass, the heavier neutrino mass eigenstates are unstable and will eventually decay into the lightest mass eigenstates plus X. In the new SM, X are photons and other light (anti)neutrinos.

$\nu_i \to \nu_j \gamma$ is governed by the same type of operators as magnetic moments, and expectations for τ are absurdly long: $\boxed{\tau > 10^{38} \text{ years,}}$ for $m_\nu \sim 1$ eV (GIM suppressed).

Other new SM induced decays are also rare beyond all reason:

$$\tau_{\nu \to 3\nu} > 10^{39} \text{ years}$$

Constraints on μ severely constrain neutrino lifetimes already *e.g.*,

$$\tau > 5 \times 10^{11} \left(\frac{10^{-10} \mu_B}{\mu_\nu} \right)^2 \text{ years} \qquad\qquad m_\nu \sim 1 \text{ eV}$$

Similar to magnetic moments, observable neutrino decays are a sign for physics beyond the new SM. The new physics effects are either of the "bread and butter" $1/M_{\rm new}$-type, or involve the presence of very light, yet to be observed degrees of freedom (say, (quasi-)massless (pseudo)scalars, like "Majorons").

Experimental bounds are very dependent on the decay mode (and the kinematics of the decay) and vary from the billion of years scale (bounds on UV light) to the hundreds of microseconds scale (model independent bounds from the sun).

Best model independent bound comes from solar neutrinos. In order to disentangle the oscillation effects from the decay effects we profit from a combination of solar and KamLAND data. It is easy to see that the constraints are very mild [*e.g.*, Beacom+Bell 2002]:

$$\gamma\tau > 500 \text{ s} \Rightarrow \tau > 500\ s\frac{m}{E} \sim 10^{-4} \text{ s} \left(\frac{m}{\text{eV}}\right)\left(\frac{5 \text{ MeV}}{E}\right)$$

Much better (many orders of magnitude) constraints are expected

- high energy cosmic neutrinos at Ice-Cube (*e.g.*, large violations of 1:1:1 flavor ratios [Beacom *et al.* 2003] with dependency on mixing parameters),
- relic supernova neutrinos [Fogli *et al.* 2004] $\Rightarrow$ poster,
- …

TESTS of CP-INVARIANCE and T-INVARIANCE ⇒Petcov

Given that there are three lepton families and that the neutrinos have distinguishable masses, CP-invariance violation and T-invariance violation are expected in the new SM. They can be probed by

- $P(\nu_\alpha \to \nu_\beta) \times P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$, "Dirac" CP-violation; beware of matter effects; requires $|U_{e3}|^2 \neq 0$
- $P(\nu_\alpha \to \nu_\beta) \times P(\nu_\beta \to \nu_\alpha)$, "Dirac" T-violation; "no" matter effects on Earth-based experiments; requires $|U_{e3}|^2 \neq 0$
- Rate for $0\nu\beta\beta$, CP-even effect, sensitive to Majorana CP-odd phases; can we really observed the effect of the phases?
- CP-odd observables in L-violating processes; "Majorana" CP-violation; we can't measure this in the real world! [AdG, Kayser, Mohapatra 2002]
- Leptogenesis; Other "Majorana" CP-violation; how do we learn about this?
- ...

(Apologies to A. Rodin)

TESTS OF CPT-INVARIANCE and/or LORENTZ-INVARIANCE

"Abandon Every Hope, Ye Who Enters"

TESTS OF LORENTZ-INVARIANCE VIOLATION

Violation of Lorentz-invariance would lead to a modified neutrino dispersion relation ($E^2 - |\vec{p}|^2 \neq m^2$) in a CPT-invariant or violating way.

Modified dispersion relations for the neutrino lead to deviations from the characteristic L/E–oscillatory behavior, which means that precision oscillation measurements can set unprecedented bounds on such effects!

One example ⇒ see poster

Spontaneous breaking of Lorentz invariance [Coleman+Glashow 1997, Colladay+Kostelecký 1997, Barger *et al.* 1998, also Bahcall, Barger, Marfatia 2002, AdG 2002]

$$\mathcal{L}_{\rm CPTV} \supset A_\mu^{ij}\bar{\nu}_i\gamma^\mu\nu_j + B_{\mu\nu}\bar{\nu}\sigma^{\mu\nu}\nu + H.c. + \dots$$

where A_μ is interpreted as having a vacuum expectation value in the "time" direction $A^\mu_{ij} = (V_{ij}/2, \vec{0})$, (in the reference frame where we perform experiments), $B_{\mu\nu}$ can have a vev in some ij direction, etc...

In the limit $E, |\vec{P}| \gg m, V$,

$$E = |\vec{p}| + \frac{m^2}{2|\vec{p}|} \pm \frac{V}{2}$$

This looks just like matter effects!

$\pm$ refers to neutrinos/antineutrinos $\rightarrow$ CPT violation (Does NOT fit LSND + ATM + SOL).

We can use intuition of matter effects to understand what is going on (V_{ij} are "ether" potentials). *E.g.*, two-flavor "ether" oscillations

$$P_{ex} = \sin^2\theta_{\rm eff}\sin^2\left(\frac{\Delta_{\rm eff}}{2}L\right)$$

$$\Delta_{\rm eff} = \sqrt{(\Delta\cos 2\theta - V)^2 + (\Delta\sin 2\theta + V_{ex})^2}$$

$$\Delta_{\rm eff}\sin 2\theta_{eff} = \Delta\sin 2\theta + V_{ex}$$

$$\Delta_{\rm eff}\cos 2\theta_{eff} = \Delta\cos 2\theta - V_{ex}$$

where $\Delta = \Delta m^2/(2E)$, $V = 2(V_{ee} - V_{xx})$, and for antineutrinos $V_{ij} \to -V_{ij}$

$\Rightarrow$ neutrinos and antineutrinos have different effective mixing angles (which are energy dependent), and the L/E oscillatory behavior is violated!)

One can probe these "ether effects" through several oscillation measurements. Order of magnitude estimates bounds are easy to estimate $\Delta m^2/(2E) > V_{ij}$ (conservative!, read "certainly bigger/less than"):

- Atmospheric: $V_{\mu\tau,\mu\mu,\tau\tau} < 10^{-3}$ eV^2/GeV$\rightarrow < 10^{-21}$ GeV $\Rightarrow$ poster
- Solar + KamLAND: $V_{e\mu,e\tau} < 10^{-6}$ eV^2/MeV$\rightarrow < 10^{-21}$ GeV

This is a MUCH richer phenomenon. There are even studies of whether you can explain all the neutrino data with Lorentz invariance violation (and no neutrino masses)! Keep in mind that there are MANY free parameter you can tune. [Kostelecký+Mewes, 2003]

(SPECIFIC) TEST OF CPT-INVARIANCE: $m_\nu = m_{\bar{\nu}}$?

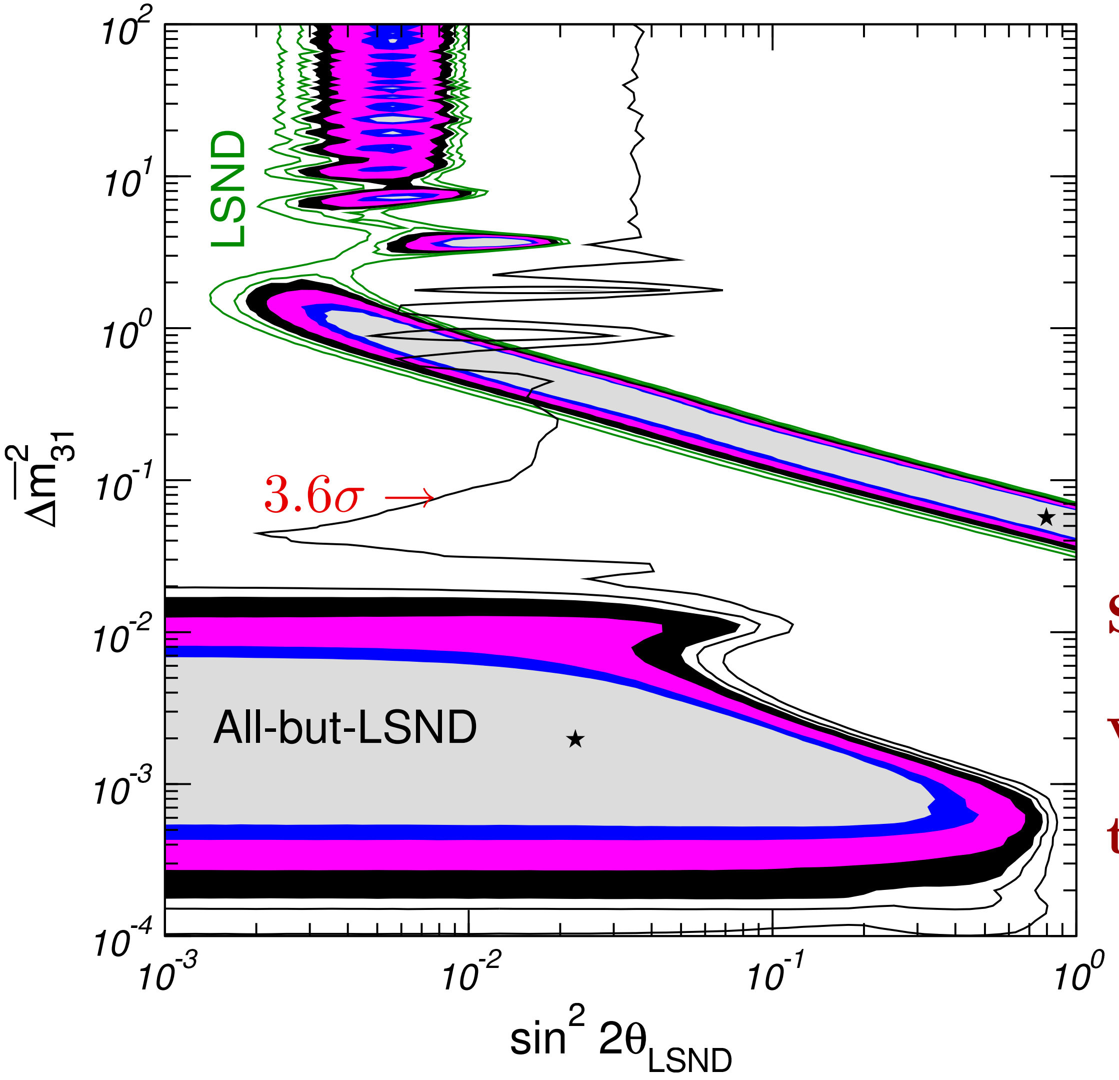
Different masses for neutrinos and antineutrinos were postulated as a potential solution to the LSND anomaly (and also helped address a small problem with SN1987A data) in Murayama+Yanagida (2001), and further pursued in Barenboim *et al.*(2001–2003).

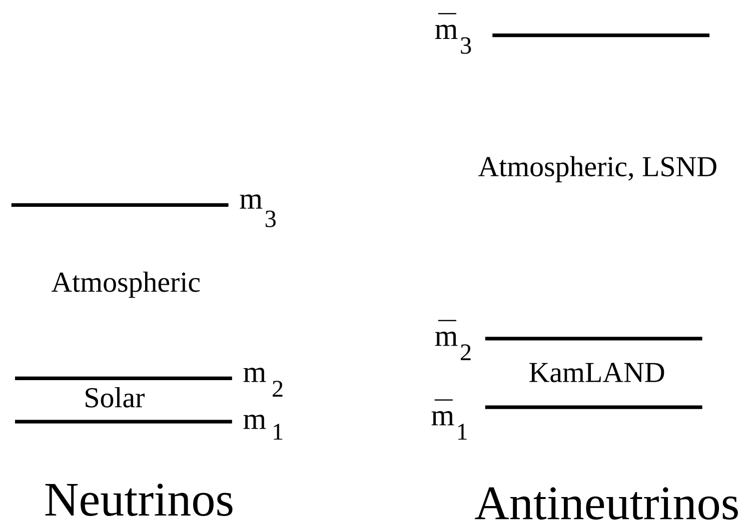
Currently, this form of CPT-violating solution to all neutrino puzzles plus LSND (and only active (anti)neutrinos) is experimentally disfavored

- KamLAND and solar data “agree” ($\Delta m^2_{\rm sol} = \Delta \bar{m}^2_{\rm Kam}$)
- $\Delta \bar{m}^2_{\rm atm} \ll \Delta \bar{m}^2_{\rm LSND}$

+ Given that there is no evidence for CPT violation, these (and other) “precision neutrino oscillation experiments” allows one to bind how much CPT can be violated in the neutrino sector.

[Gonzalez-Garcia+Maltoni (2003)]





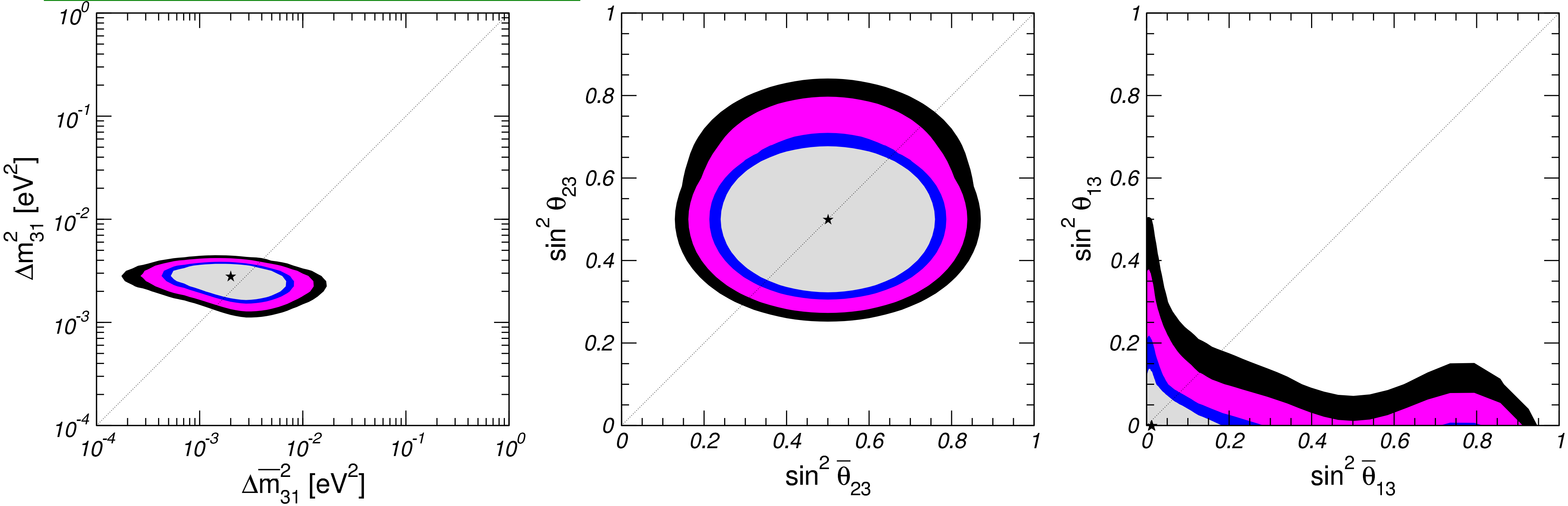
SuperK atmospheric data exclude values of $\Delta\bar{m}^2_{13}$ required to address the LSND anomaly at 3σ

Assuming CPT-invariance, we can bind CPT-violating observables

$$\Delta(\Delta m^2) \equiv |\Delta m^2 - \Delta \bar{m}^2| \qquad \Delta(\sin^2\theta) \equiv |\sin^2\theta - \sin^2\bar{\theta}|$$

$\Rightarrow$ [see Kearns, "δ"]

$$\boxed{\Delta(\Delta m^2_{13}) < 1.9 \times 10^{-2}\ \mathrm{eV}^2} \qquad \boxed{\Delta \sin^2\theta_{23} < 0.5}$$

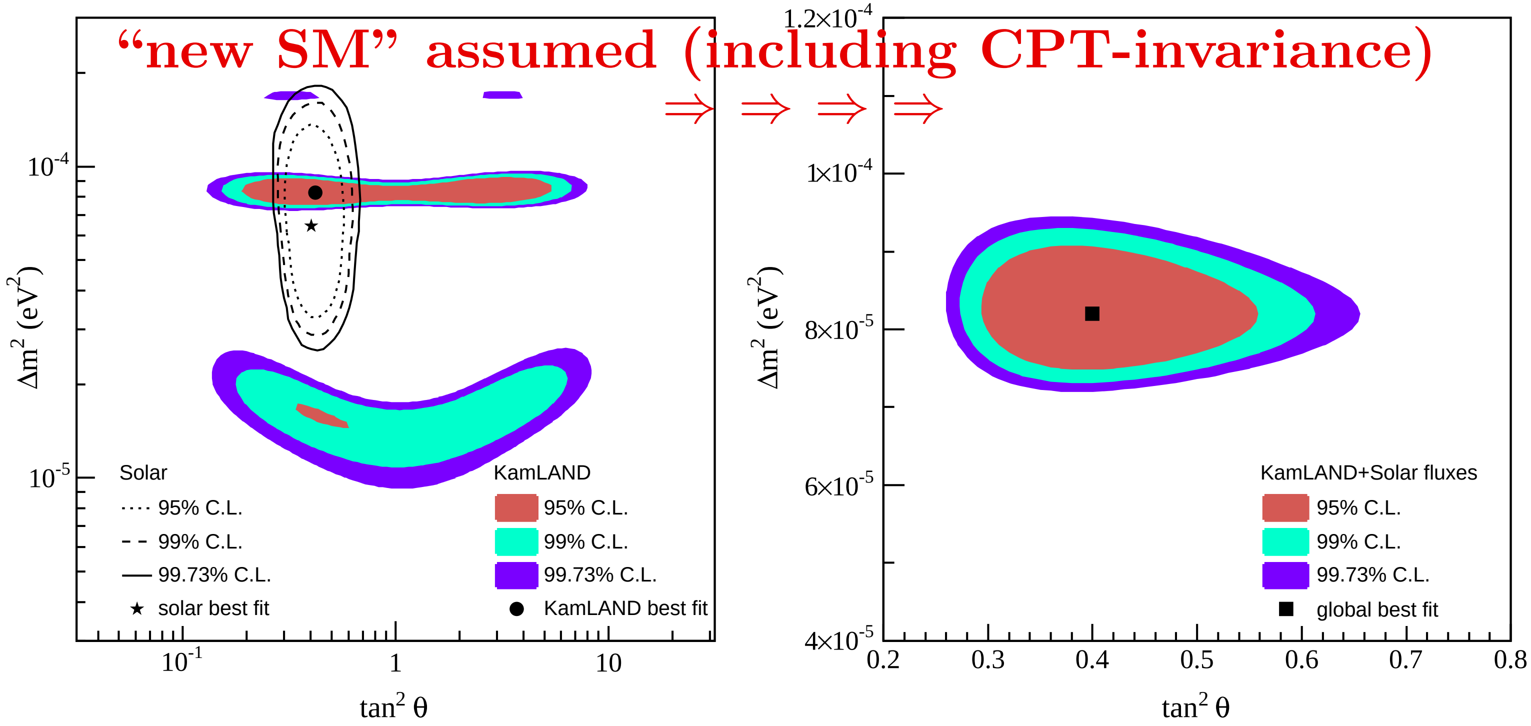


[Gonzalez-Garcia+Maltoni (2003)]

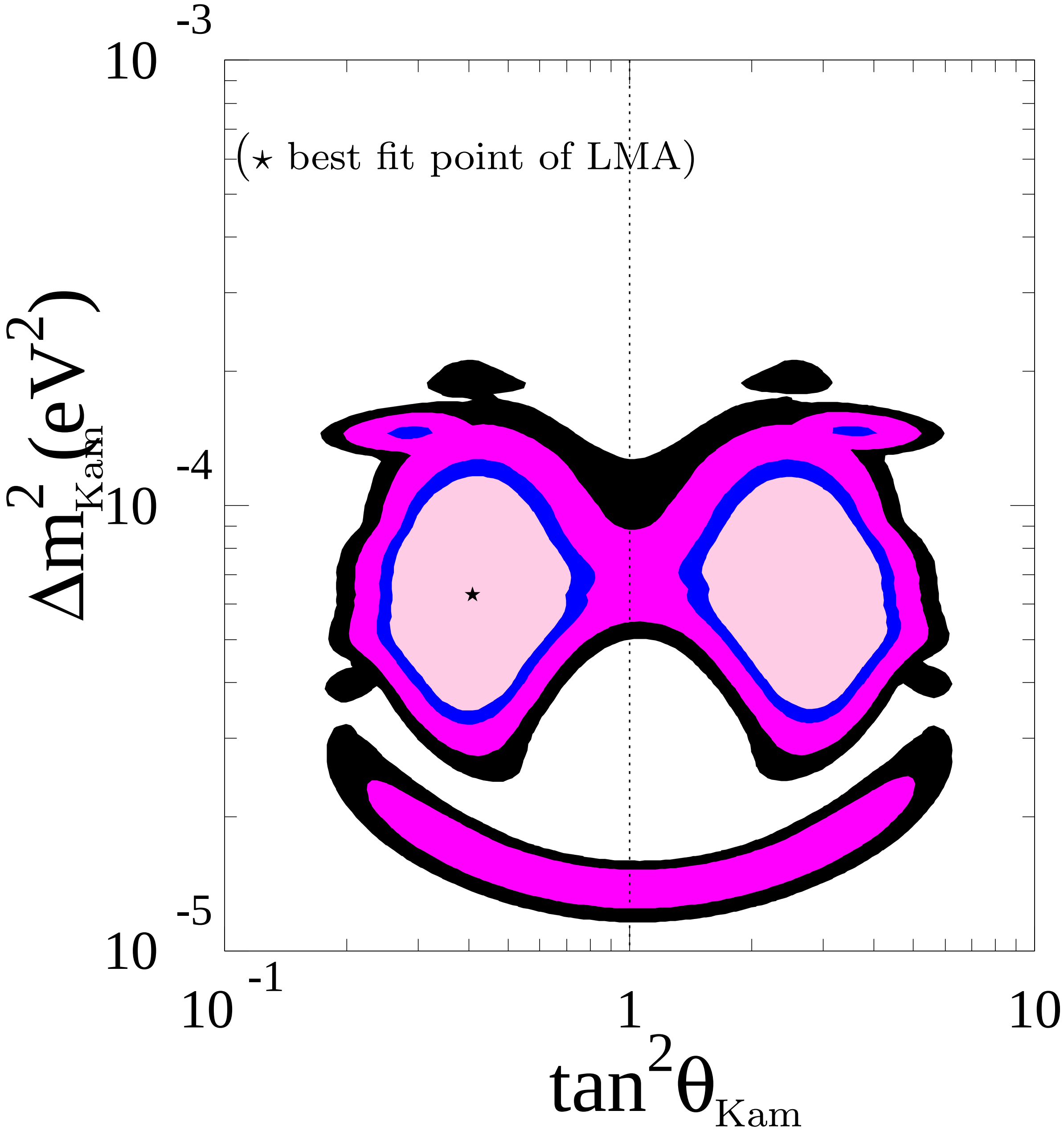
Solar and KamLAND data, interpreted in terms of two-flavor neutrino oscillations, agree!!!!! This is a remarkable achievement of Physics.

“new SM” assumed (including CPT-invariance)

$\Rightarrow \Rightarrow \Rightarrow \Rightarrow$



Gratta, KamLAND (2004)



KamLAND versus Solar Data

$\Leftarrow$ Could they have disagreed?

$\Rightarrow$ 9 $\times$ "old" KamLAND sample (9$\times$162 ton-years)

Contours are agreement at 90%,95%, 99%, and 3σ confidence level

Things Could Have Gotten

Much More "Interesting"...

[AdG+Peña-Garay, to appear]

Assuming CPT-Invariance, we can bind CPT-violating observables

$$\boxed{\Delta(\Delta m^2) < 1.2 \times 10^{-4}\ \mathrm{eV}^2}$$

From solar data!

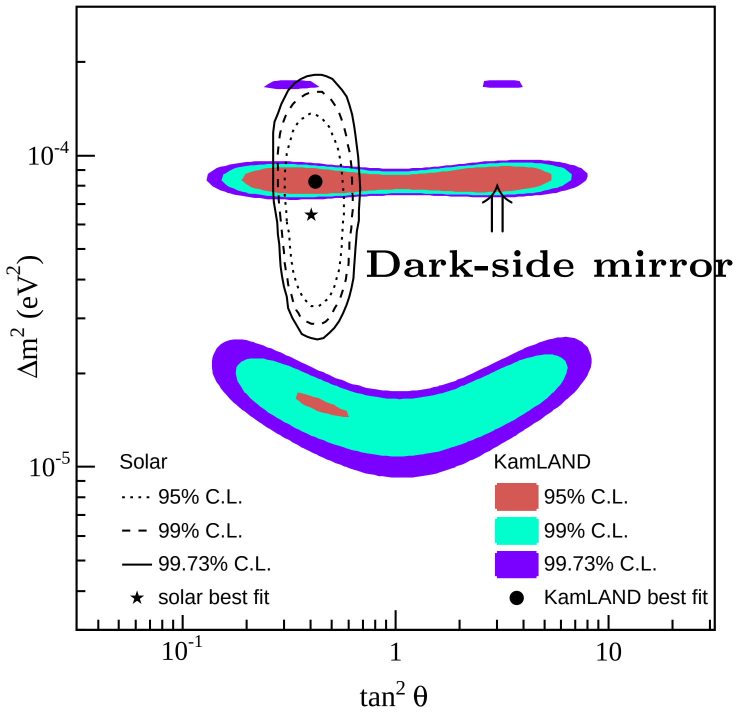
$$\boxed{\Delta(\sin^2\theta) < 0.7}$$

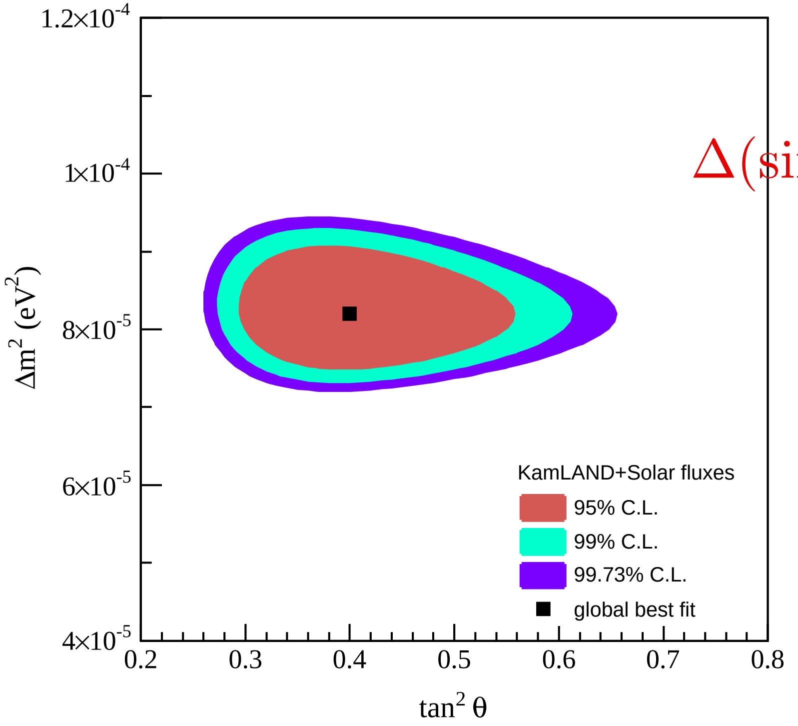
will not improve much – matter efffects do not matter!

$$\Downarrow$$

$$\Delta(\sin^2\theta) = |\cos 2\theta|?$$

$$(\theta + \bar{\theta} = \pi/2?)$$





Gratta, KamLAND (2004)

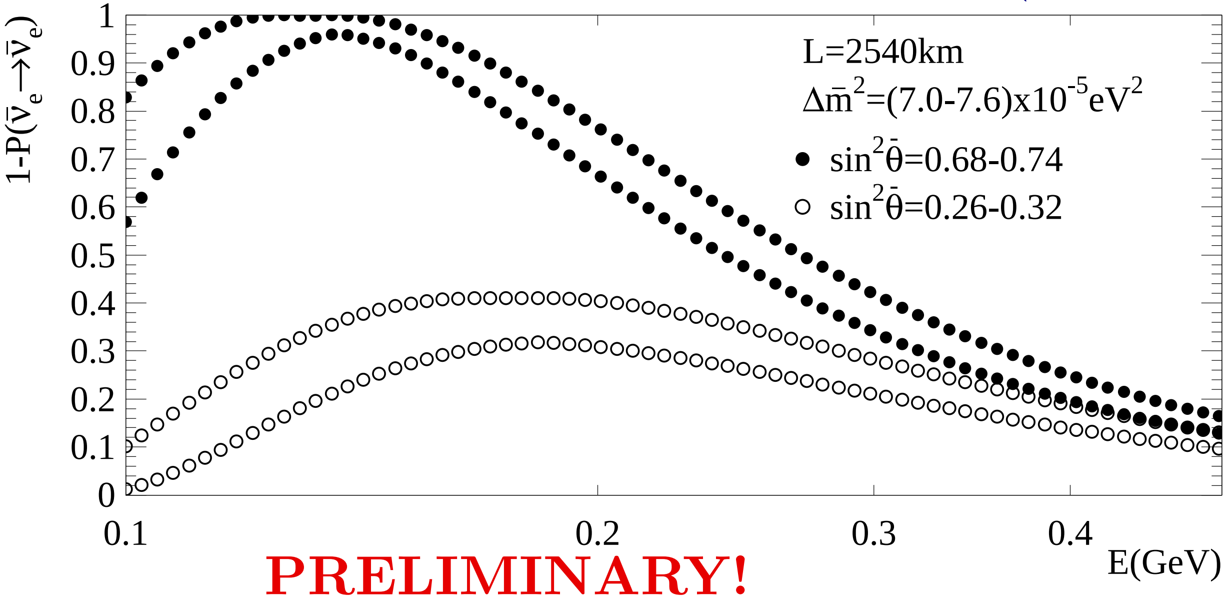
In order to address whether CPT-invariance is "maximally violated" in the solar mixing we need:

- Antineutrinos
- Matter effects

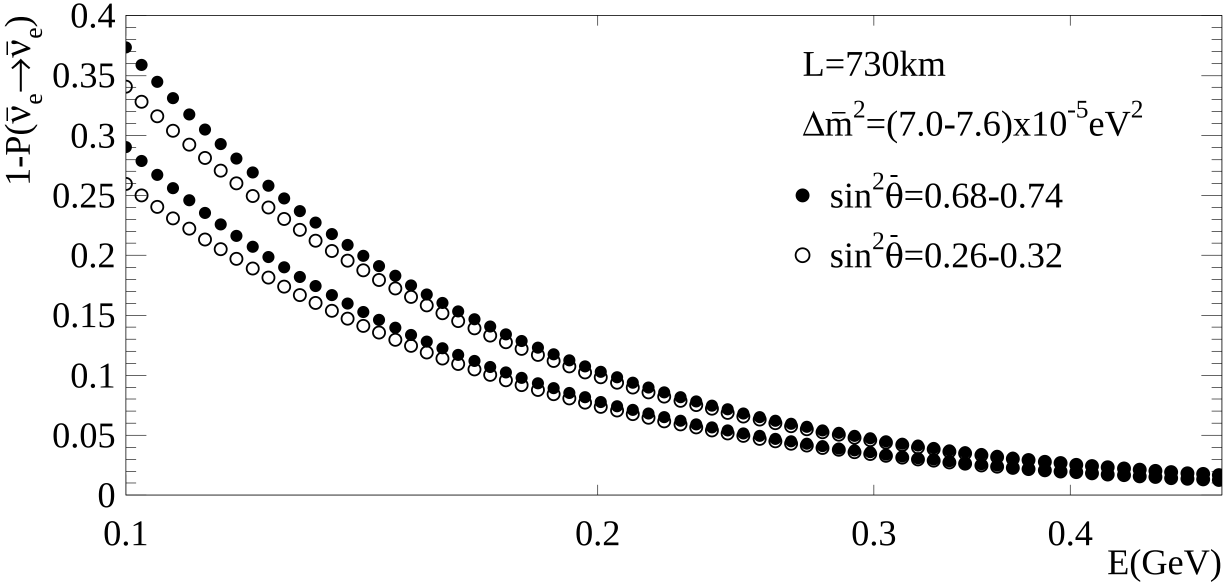
Possible experiments include

- Supernova neutrinos $\Rightarrow P_{\bar{\nu}_e} \simeq \cos^2\theta$; can it really be done?
- Very long baseline $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,e}$ searches with frequency $\Delta\bar{m}^2_{\rm Kam}$ $\Rightarrow$
- ?

$(\bar{U}_{e3} = 0)$



PRELIMINARY!



"KamLAND" LBL Oscillations

- low energies
- very long baselines
- antineutrinos

$\Downarrow$

Small statistics, hard to detect, large backgrounds,...

BNL-setup, β-beams, NuFact ?

[AdG+Peña-Garay, to appear]

In summary (some tests of CPT-invariance)

- "Order one" CPT-violating observables are allowed: improvements expected from more "precision neutrino data" (which we expect to get a hold of in the next several years!)
- $\Delta(\Delta m^2_{12}) \equiv \Delta(m^2_2) - \Delta(m^2_1)$ – Need to ignore "conspiracies" in order to interpret bound
- *cf.* with $|m^2(K^0 - m^2(\bar{K}^0))| < 0.25$ eV^2 – neutrino bounds much better? This is a "model dependent" question.
- Binding CPT-violating leptonic mixing angles may be very challenging – Is this another job for (next-)next-generation LBL experiments?

CONCLUSIONS

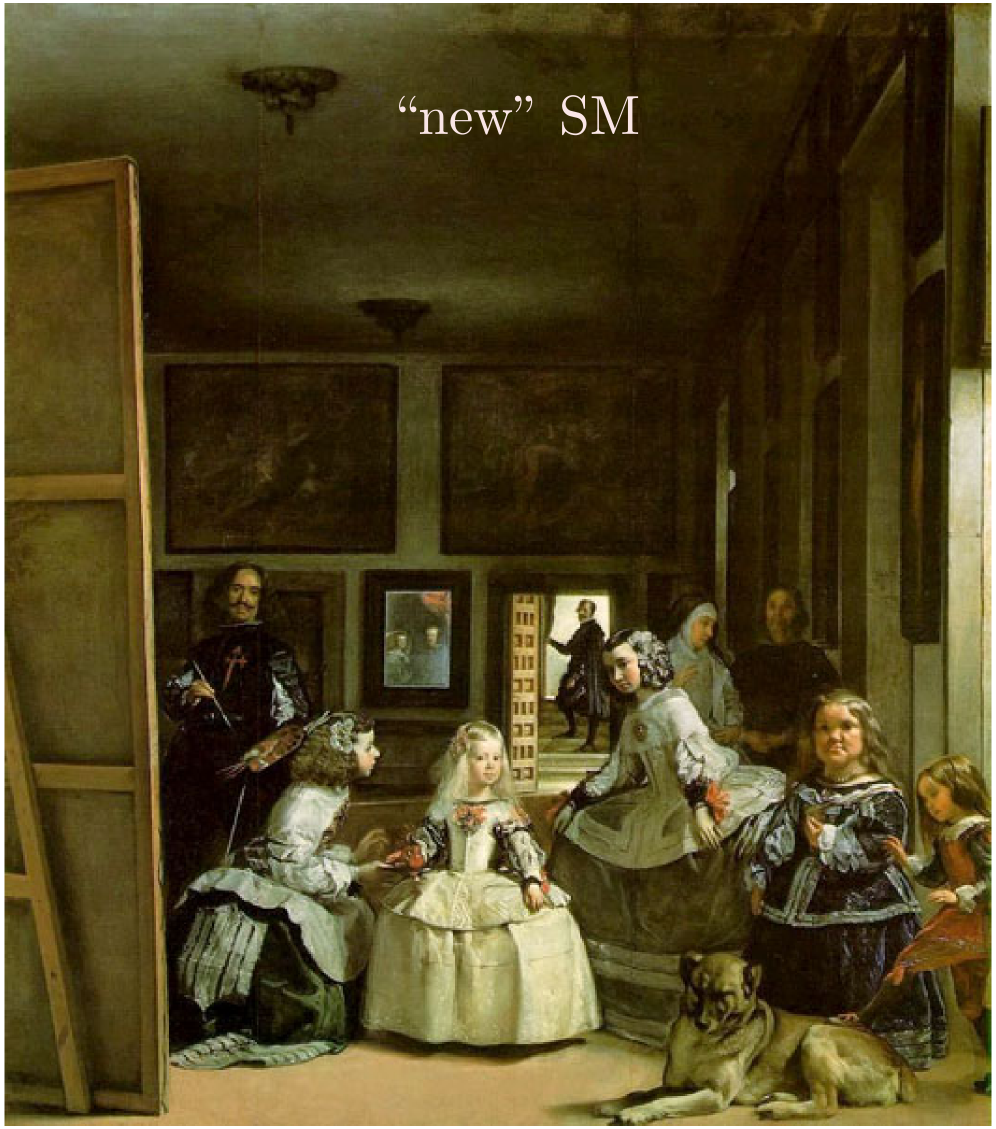
- In the new SM (old SM plus neutrino masses) "other" observable neutrino properties are NOT expected, and one can only verify whether CP-invariance, T-invariance and L-number are conserved. All three are naïvely expected to be violated.

- Nonetheless, massive neutrinos plus precision neutrino data allow one to look for new new-physics. Neutrino experiments are "weaker" but "unique" relatives of charged-lepton experiments like the search for rare muon processes ($e.g.$, $\mu \to e\gamma$), charged-lepton electric dipole moments, and deviations of the anomalous magnetic moment from SM predictions.

- Finally, neutrinos serve as narrow but very deep, unique probes of "Earth-shattering" effects, that if observed would require a long and hard revision of some of the fundamental principles of Physics. This is a consequece of the "quantum interferometry" nature of the oscillation phenomena. Keep in mind that these may have allowed a peek at a very large energy scale, $M_{\rm seesaw} > 10^{10}$ GeV!

$\Rightarrow$

Maybe our next "change of picture" will look something like this: EXCITING!



$\Rightarrow$
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(with apologies to D. Velasquez)

(with apologies to P. Picasso)