ARGONNE THEORY INSTITUTE
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LOOKING FOR NEW

NEW PHYSICS IN NEUTRINO OSCILLATIONS

- PRELUDE: THE MINIMAL NEW STANDARD MODEL © ⇝
  - NEUTRINOS HAVE MASS + MIX
  - NOTHING ELSE EXCEPT (MAYBE) $0\nu\beta\beta$
- NOT THIS TALK: THE NON-MINIMAL NEW S.M. ©
  - THE LSND ANOMALY
  - WHAT IS GOING ON? ⇒ WAIT FOR MINIBOONE!
- NEW PHYSICS IN ν-OSCILLATIONS:
  - HOW DOES IT SHOW UP
  - (NEAR FUTURE) EXAMPLE: KAMLAND VS. SOLAR

MINIMAL NEW STANDARD MODEL

IT IS EXPERIMENTALLY ESTABLISHED THAT NEUTRINOS CHANGE FLAVOR

- SOLAR NEUTRINO "DEFICIT"
- ATM NEUTRINO "DEFICIT"
- K2K LONG BASELINE ν_μ EXPERIMENT
- KAMLAND REACTOR $\bar{\nu}_e$ EXPERIMENT

THE ONLY COHERENT, UNIVERSAL INTERPRETATION OF ALL THESE PHENOMENA IS THAT

$$\boxed{\begin{array}{l}\text{NEUTRINOS HAVE MASS}\\ \text{NEUTRINOS MIX}\end{array}}$$

$\Rightarrow$ TO MEASURE

3 MASSES

3 MIXING ANGLES

1(+2) COMPLEX PHASES

$$\mathcal{L}_{MNSM^{\odot}} = \mathcal{L}_{LSM} + \bar{N}\not{\partial}N + \lambda\, L H N + h.c.$$

⇝ DIRAC NEUTRINOS (1+1 NEW D.O.F PER FAMILY)

⇝ WHY IS LEPTON NUMBER CONSERVED ?

— OR —

$$\mathcal{L}_{MNSM^{\odot}} = \mathcal{L}_{LSM} + \lambda \frac{(L H)^2}{\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

⇝ MAJORANA NEUTRINOS (ϕ NEW D.O.F.)

⇝ Λ IS NEW PHYSICS SCALE

— EITHER WAY —

EXCEPT FOR $0\nu\beta\beta$ NO OTHER (OBSERVABLE IN HEP EXPERIMENTS) PHENOMENA ARE PREDICTED ν

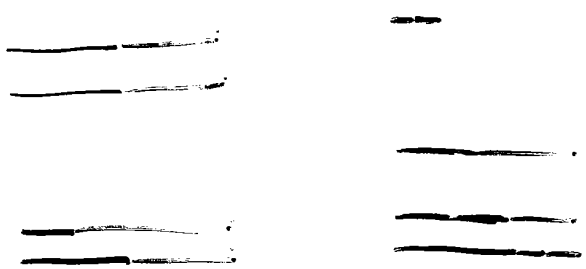
(EMBARASSING OMISSION ⇒ PROTON DECAY!)

THE NON-MINIMAL NEW S.M.©

→ WHAT ABOUT THE LSND ANOMALY ?

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \text{FEW} \times 10^{-3} \quad @\ L = 30\,\text{m}.$$

- ADD STERILE NEUTRINOS



2+2

- RULED OUT BY SOLAR + ATM DATA

3+1

- DISFAVORED BY "OLD" $\nu_\mu \not\to \nu_\mu$ AND $\nu_e \not\to \nu_e$ DATA

$3+2 = (3+1)+1$

$3+N$

- SOMEWHAT BETTER FIT, SOMEWHAT CONTRIVED

- OTHERS

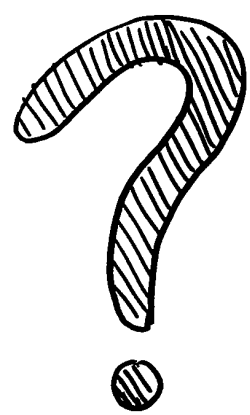
$\mu^+ \to e^+ \nu_e \bar{\nu}_e$

- RULED OUT BY KARMEN II

$\cancel{CPT}$

- STRONGLY DISFAVORED BY ATM. DATA

. . .



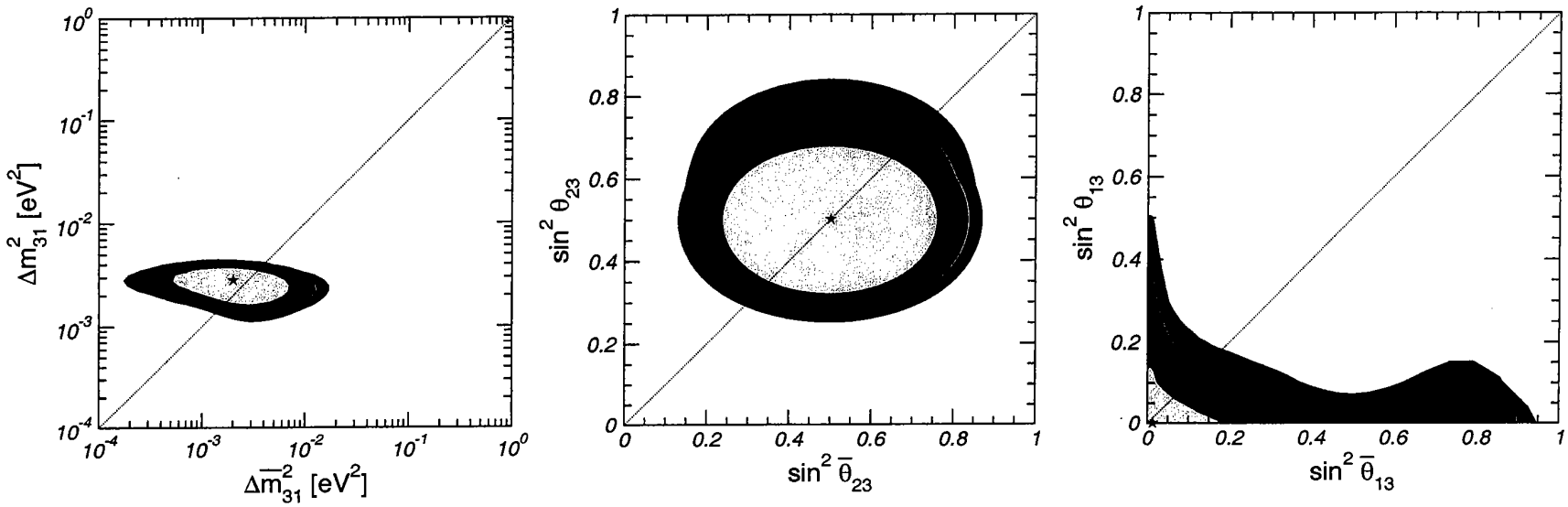


Figure 2: Allowed regions for the largest neutrino and anti-neutrino mass splittings Δm^2_{31} and $\Delta\overline{m}^2_{31}$ and the mixing angles θ_{23} and $\overline{\theta}_{23}$, and θ_{13} and $\overline{\theta}_{13}$ (after marginalization with respect to the undisplayed parameters) for $\Delta m^2_{21}, \Delta\overline{m}^2_{21} \leq 10^{-4}$ eV^2 (see text for details). The different contours correspond to the two-dimensional allowed regions at 90%, 95%, 99% and 3σ CL from all-but-LSND data. The best fit point is marked with a star.

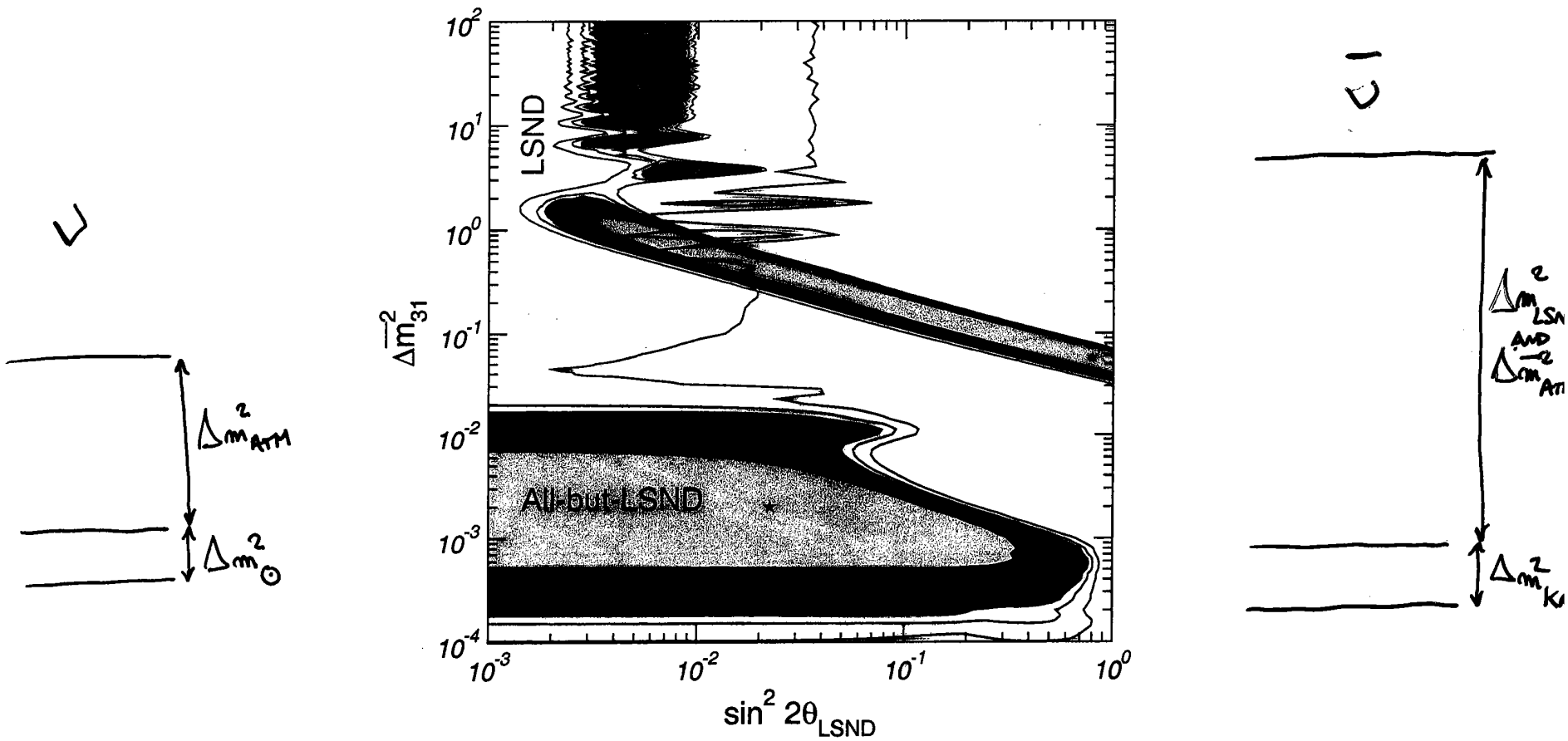
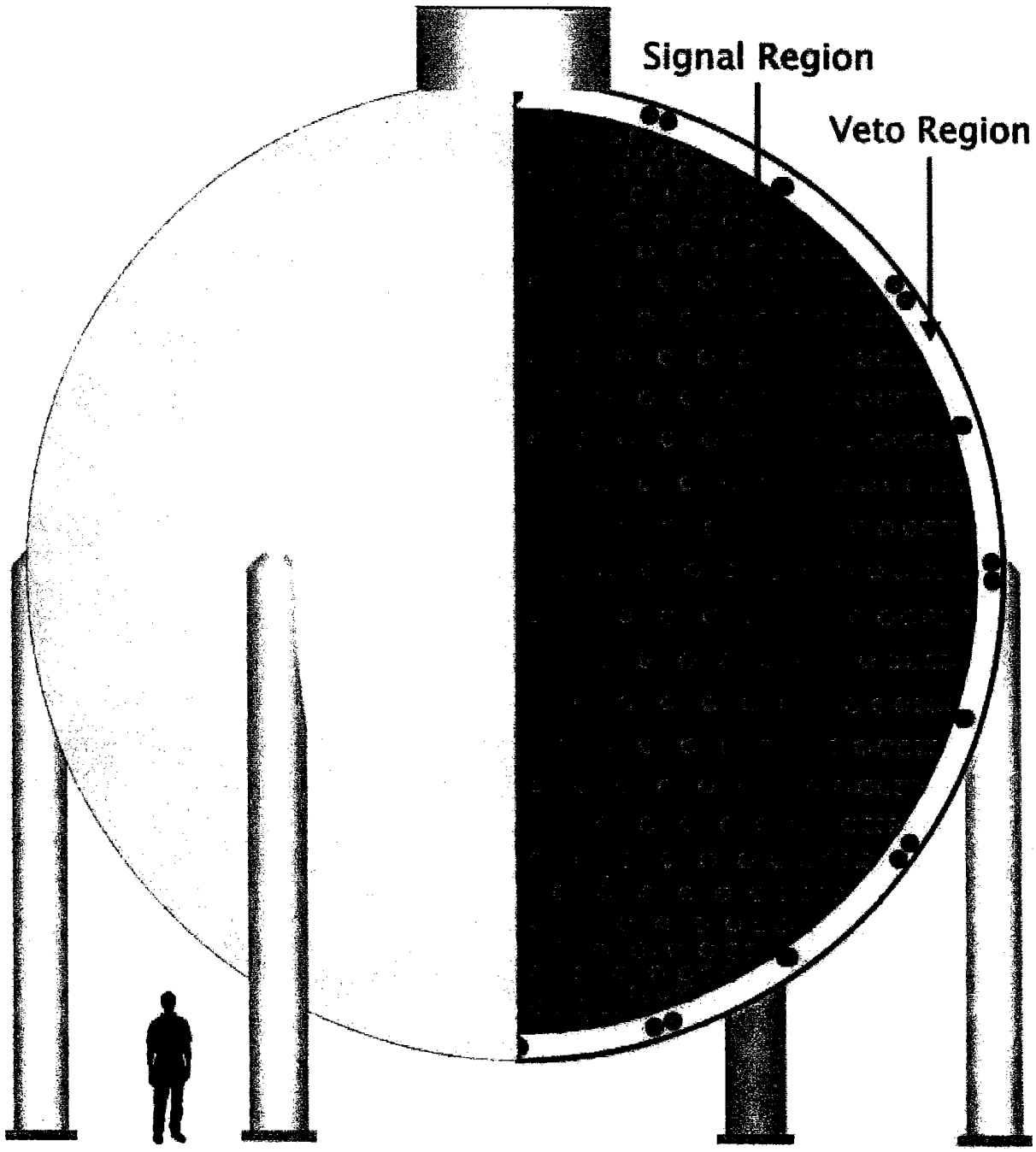
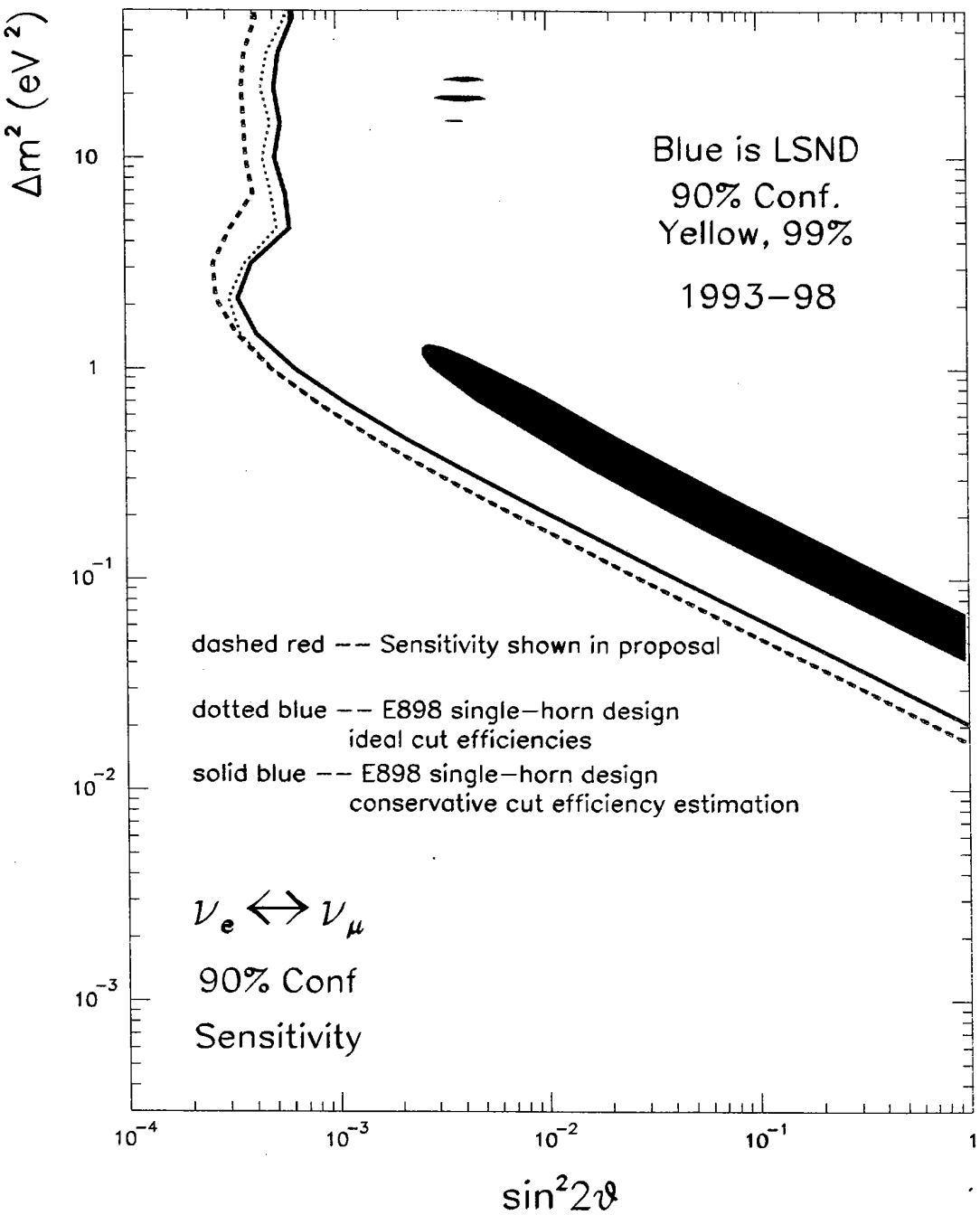


Figure 4: 90%, 95%, 99%, and 3σ CL allowed regions (filled) in the $(\Delta\overline{m}^2_{31} = \Delta m^2_{\rm LSND}, \sin^2 2\theta_{\rm LSND})$ plane required to explain the LSND signal together with the corresponding allowed regions from our global analysis of all-but-LSND data. The contour lines correspond to $\Delta\chi^2 = 13$ and 16 (3.2σ and 3.6σ, respectively).

MiniBooNE Detector



SENSITIVITY OF THE MINIBOONE EXPERIMENT



START OF DATA TAKING → END OF [illegible]

NEW PHYSICS IN ν-OSCILLATIONS

NEUTRINO OSCILLATIONS $\Rightarrow$ QUANTUM INTERFERENCE AT MACROSCOPIC DISTANCES.

$\Rightarrow$ SENSITIVE TO VERY SMALL EFFECTS ?

E.G. IS "SEESAW", $\Lambda \sim 10^{14}$ GeV $\Rightarrow$ $10^{11} M_{WEAK}$!

ALSO, NEUTRINO INTERACTIONS ARE $\frac{1}{M_W}$ SO

PRECISION OSCILLATION EXPERIMENTS ALSO PROBE "BREAD AND BUTTER" NEW PHYSICS AT (OR SLIGHTLY ABOVE) THE ELECTROWEAK SCALE.

(LIKE LEP, $g-2$, e^-e^- SCATTERING, $B \to S\gamma$, ETC.)

RANDOM LIST OF EXAMPLES

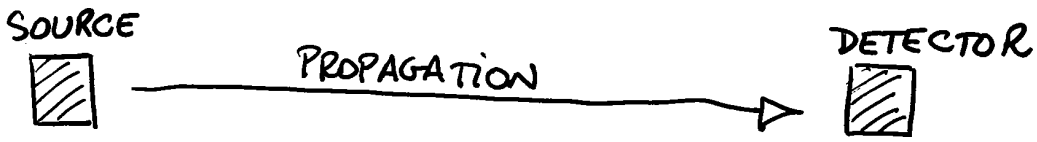
"BREAD + BUTTER"

- → NEUTRINO MAGNETIC MOMENTS
- → ANOMALOUS μ, π DECAYS
- → MODIFIED CHARGED AND/OR NEUTRAL CURRENT COUPLINGS
- → FCNC
- → ...

"EXOTICA"

- → NEUTRINO DECAYS
- → VIOLATIONS OF LORENTZ INVARIANCE W/ CPT
- → " " " " W/ $\not{CPT}$
- → MODIFICATIONS TO QUANTUM MECHANICS
- → "QUANTUM GRAVITY"

HOW DOES IT "WORK"?



ALL 3 CAN BE MODIFIED BY NEW PHYSICS

e.g. SOURCE ⇒ ANOMALOUS π^+ DECAY

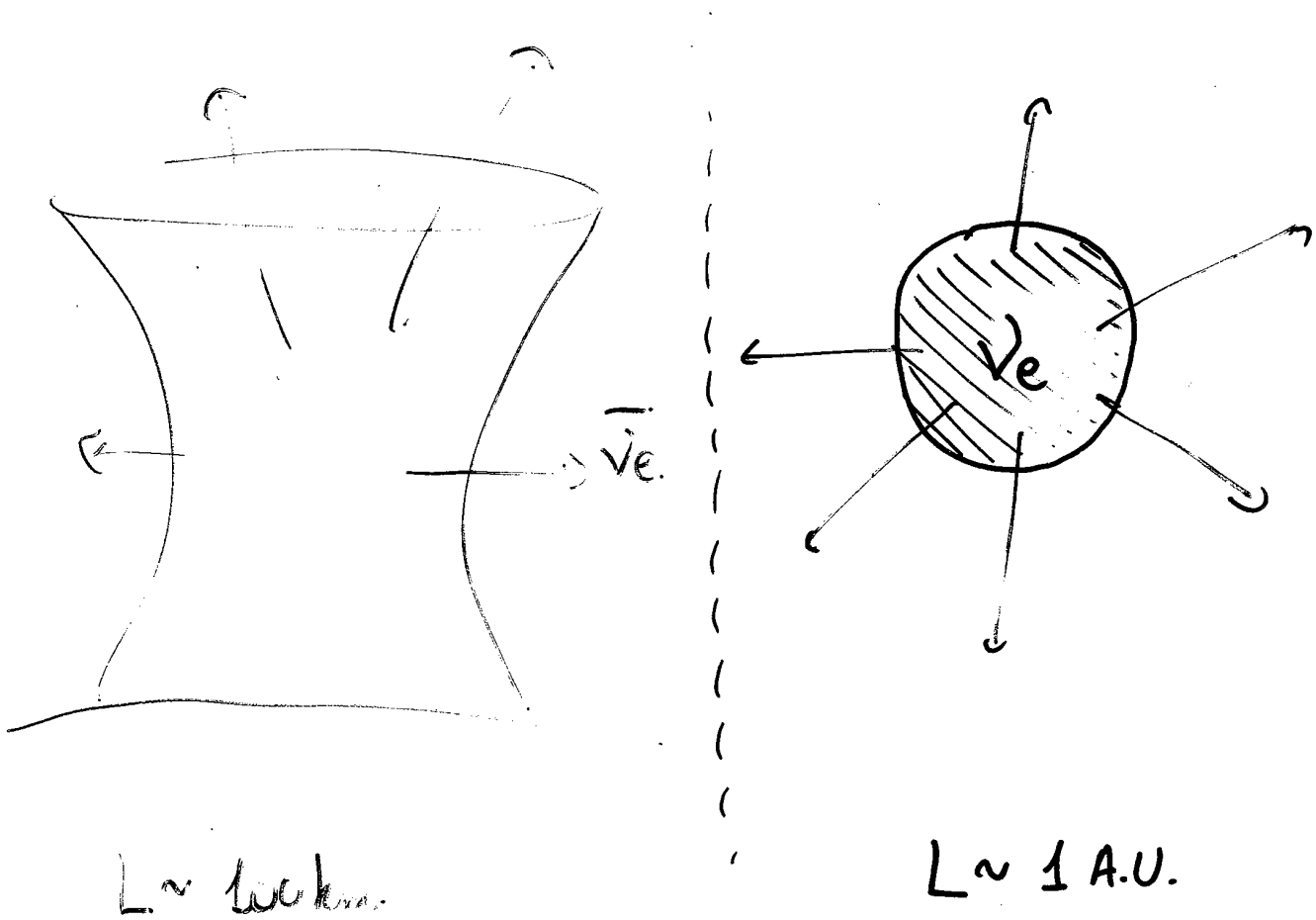
DETECTOR ⇒ MODIFIED ν-Z COUPLINGS

PROPAGATION ⇒ VIOLATION OF "QUANTUM MECHANICS"

THE HARD PART IS SEPARATING THESE EFFECTS FROM THE ORDINARY ν-OSCILLATIONS INDUCED BY MASSES + MIXING ANGLES!

EXAMPLE: KAMLAND VERSUS SUN

⇒ IT IS FUNDAMENTAL TO COMPARE EXPERIMENTS W/ DIFFERENT SOURCES, AND/OR PROPAGATION CONDITIONS, AND/OR DETECTORS



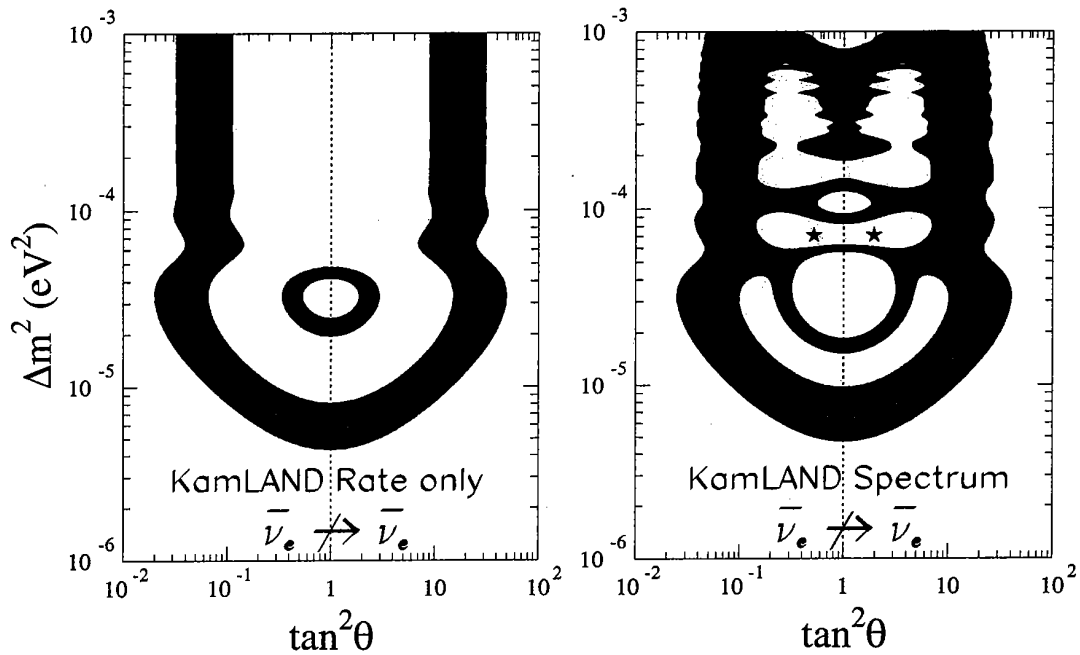


Figure 1: Anti-neutrino oscillation parameters regions allowed by KamLAND. The figure shows the allowed regions for anti-neutrino oscillation, $\bar{\nu}_e \not\rightarrow \bar{\nu}_e$, as implied by the first KamLAND results [1]. The contours shown in the left hand panel were calculated using only the total rate observed in the KamLAND experiment; the contours in the right hand panel were calculated using the measured KamLAND energy spectrum. The contours shown in figure 1 are 90%, 95%, 99%, and 99.73% (3σ)confidence limits. The dark crosses mark the best-fit values for the energy spectrum. The non-observation of anti-neutrino oscillations in the CHOOZ [21] reactor experiment rules out solutions with Δm^2 greater than $\sim 1 \times 10^{-3}\text{eV}^2$ at 3σ or $\sim 8 \times 10^{-4}\text{eV}^2$ at 99% CL.

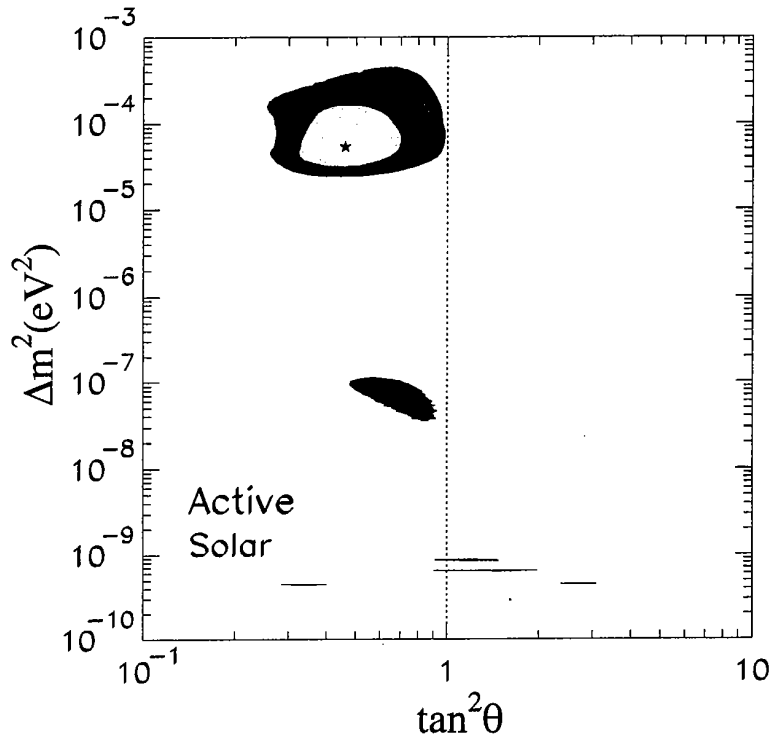


Figure 3: Before: Solar neutrino oscillations before KamLAND. The contours shown in figure 3 are 90%, 95%, 99%, and 99.73% (3σ)confidence limits. The global best-fit points are marked by a star.The input data used in constructing the figure include all the available solar neutrino measurements [13, 18, 19, 14, 15, 16, 17] and the neutrino fluxes and uncertainties predicted by the BP00 solar model [29] for all but the ^{8}B flux. The ^{8}B neutrino flux is treated as a free parameter.

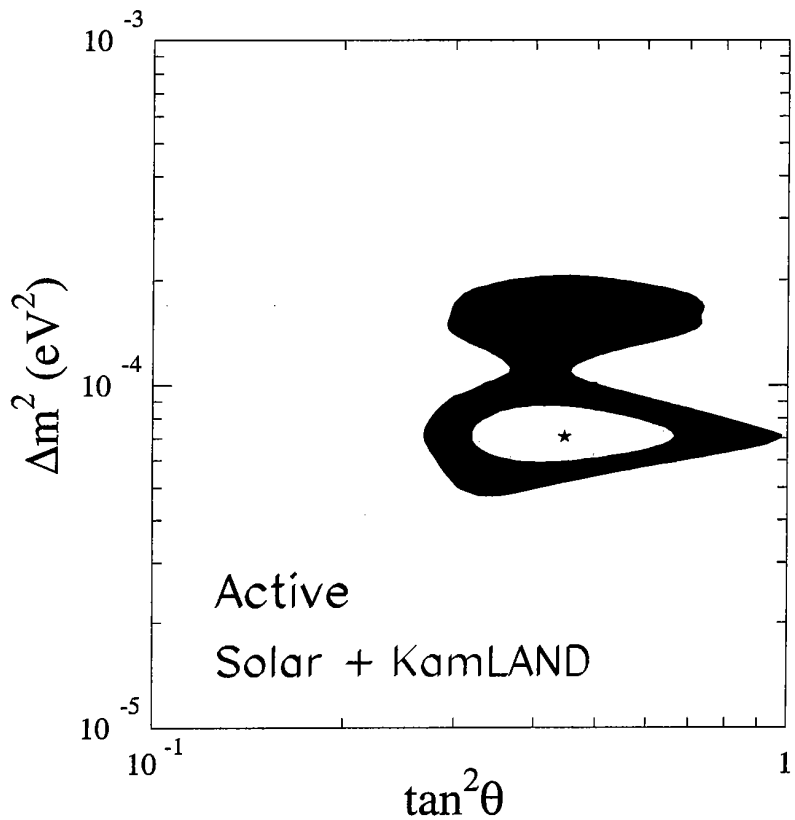
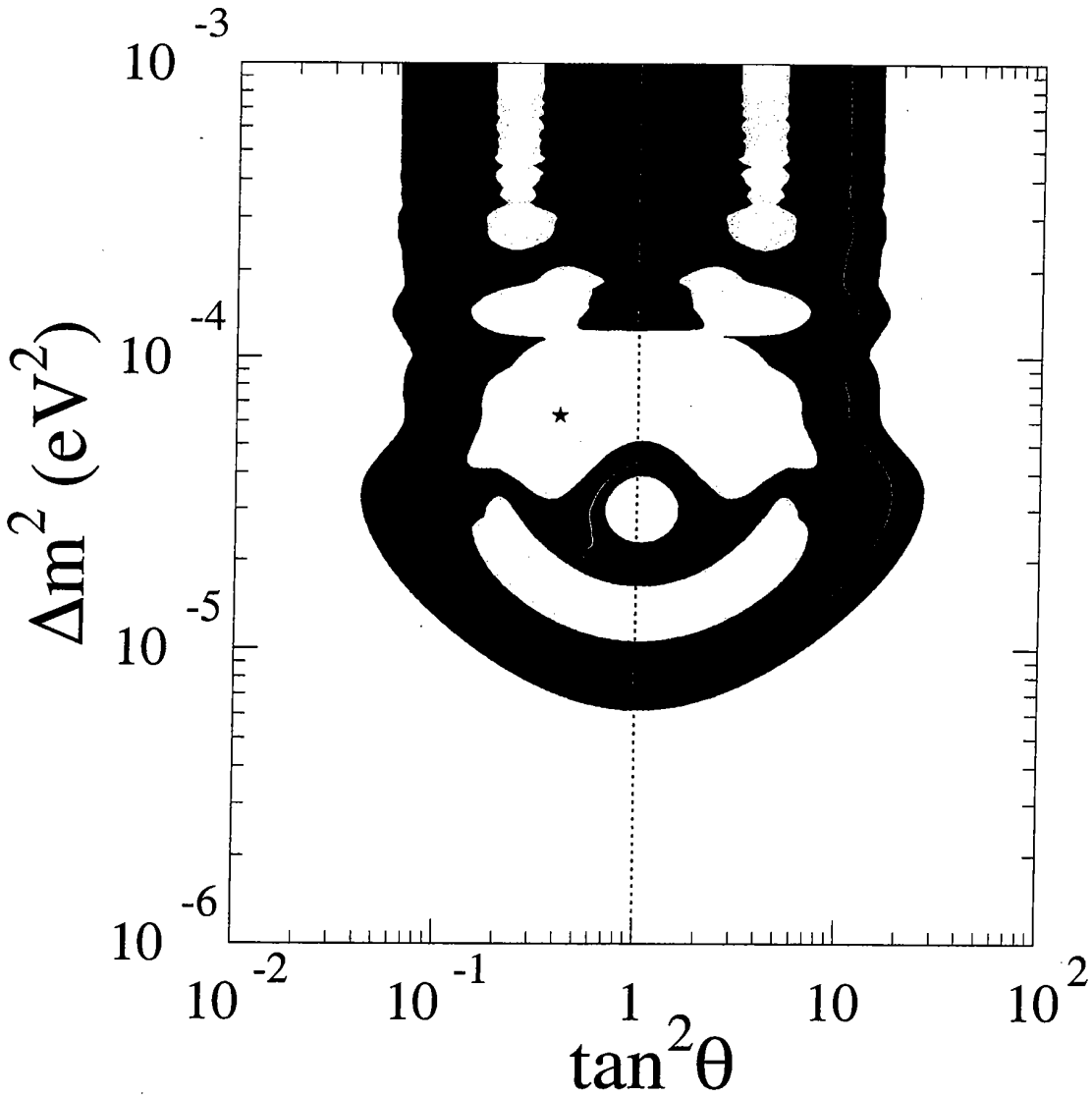


Figure 4: After: Solar neutrino oscillations after KamLAND. The allowed contours shown in figure 3 include the recent KamLAND measurements and all the available solar neutrino data [13, 14, 15, 16, 17, 18, 19]. The contour limits are the same as in figure 1 and figure 3.



KamLAND versus Solar Data

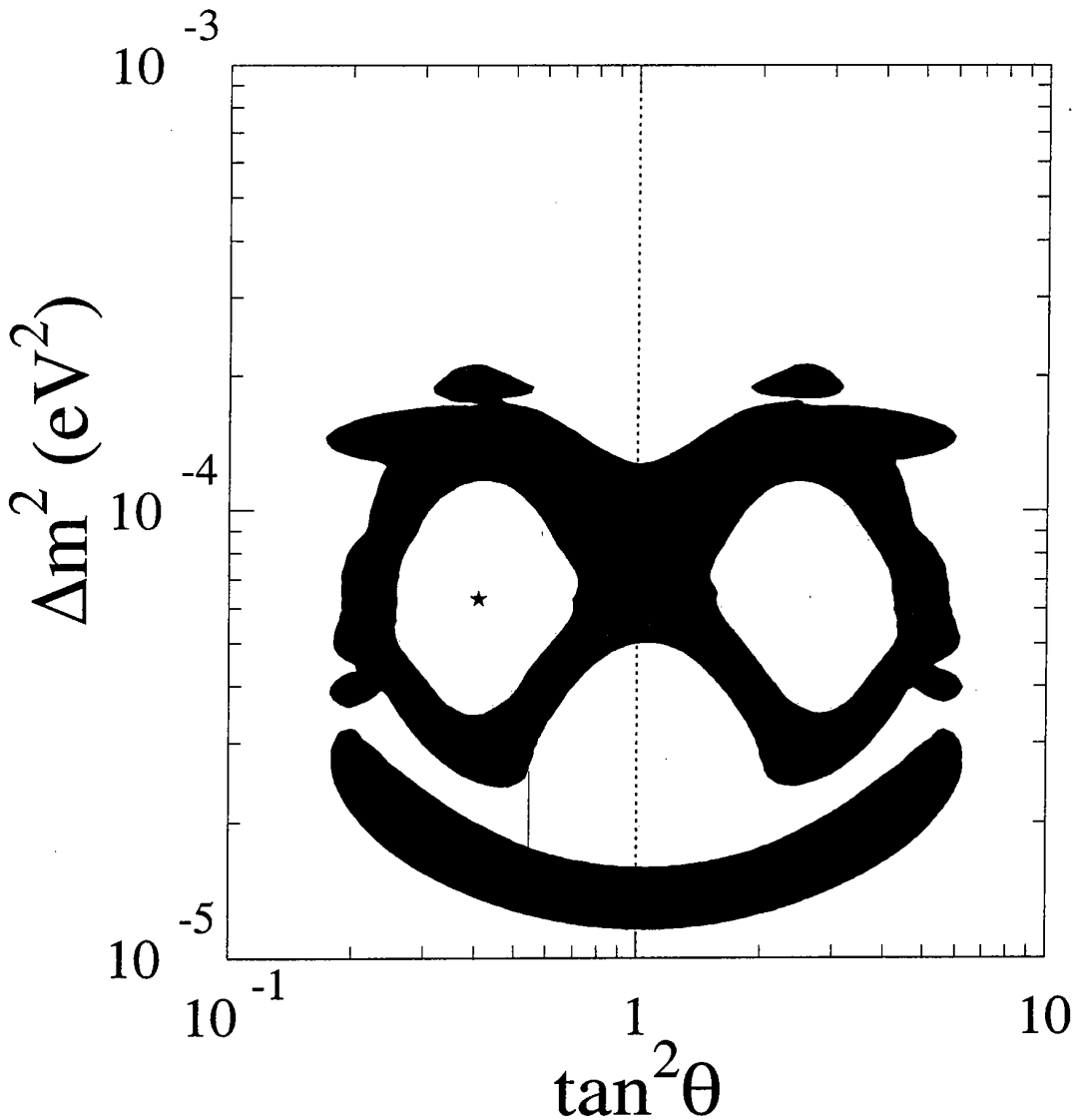
$\Rightarrow$ 2 $\times$ current KamLAND sample (2$\times$162 ton-years)

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

No Room to Disagree!

($\star$ best fit point of LMA)

AdG and C. Peña-Garay, to appear



KamLAND versus Solar Data

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

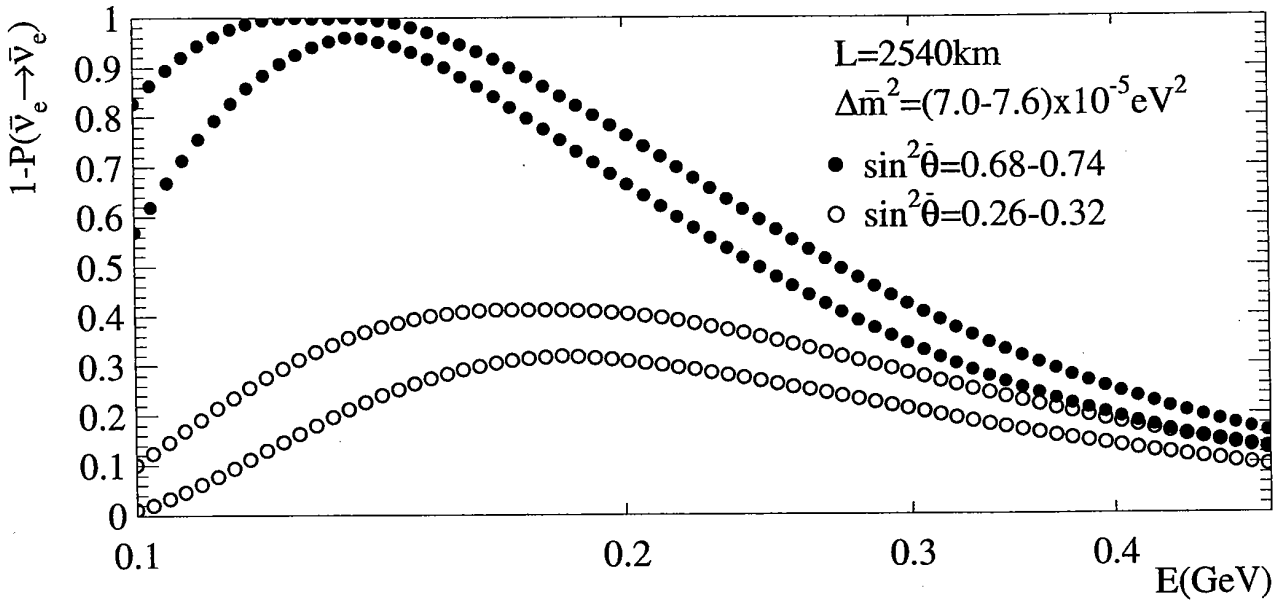
Contours are agreement at 90%,95%, 99%, and 3σ confidence level

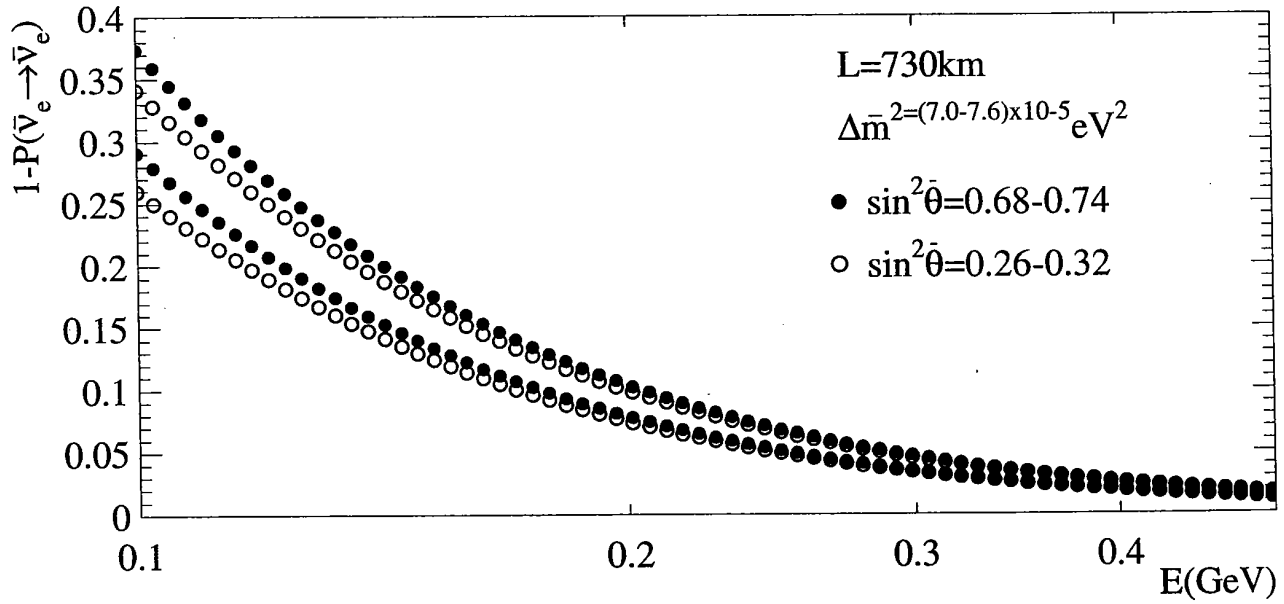
Note Ranges

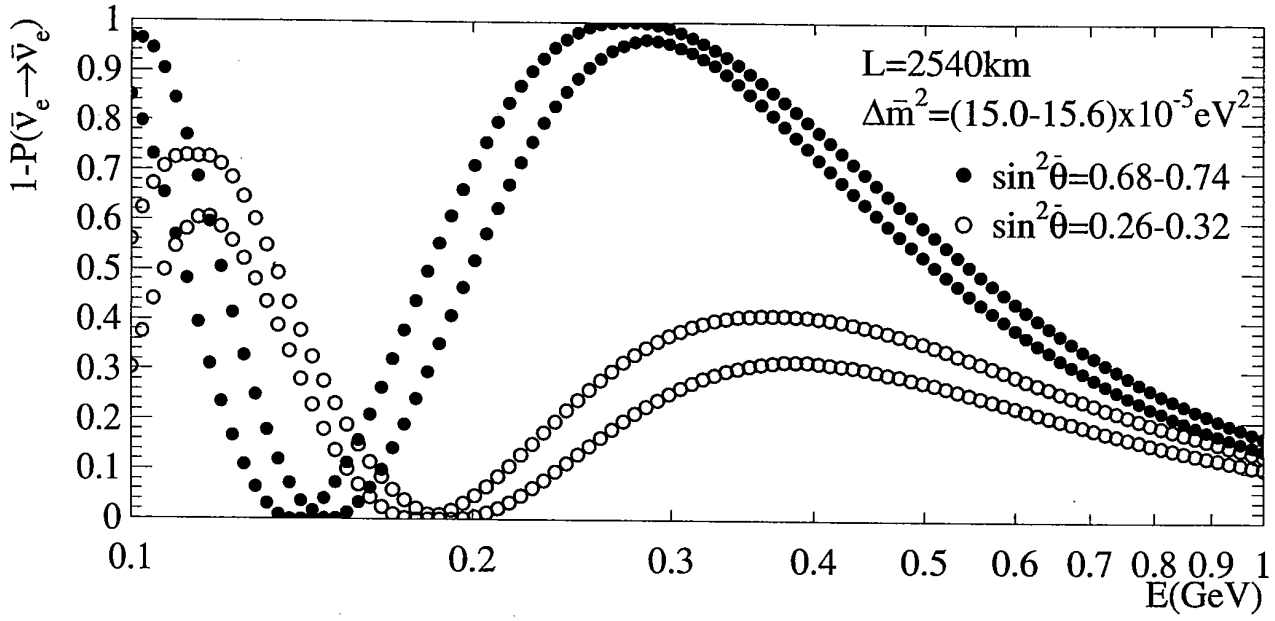
Things Could Get Interesting...

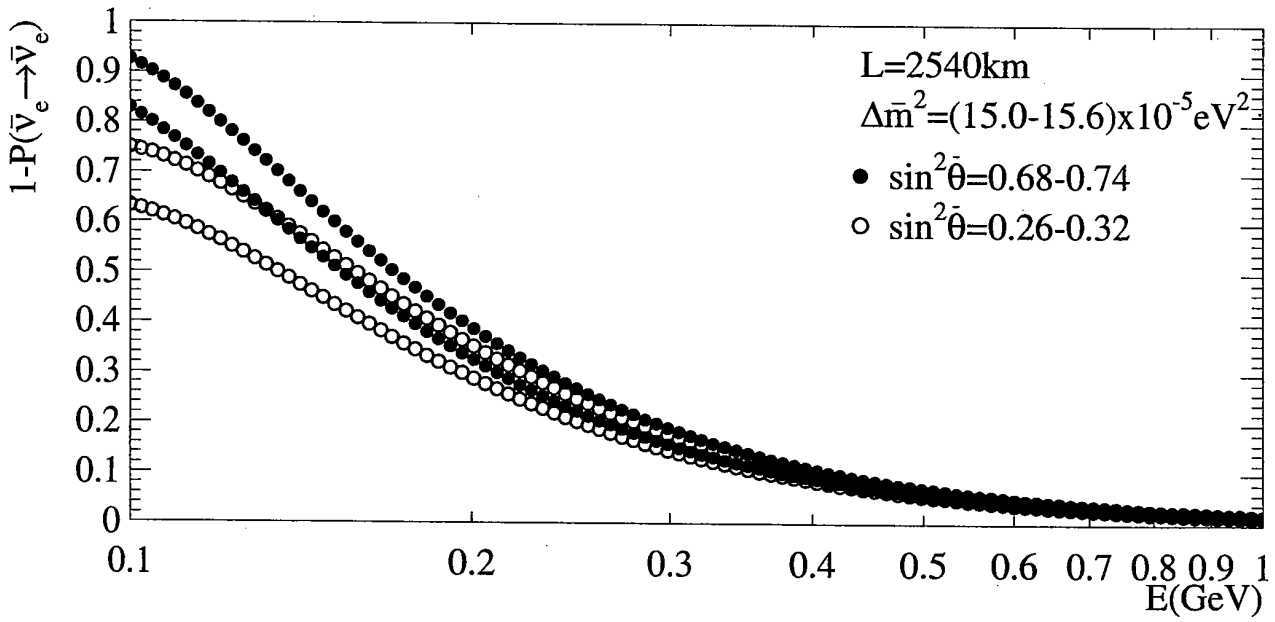
($\star$ best fit point of LMA)

AdG and C. Peña-Garay, to appear


L=2540km
$\Delta\bar{m}^2$=(7.0-7.6)x10^{-5}eV^2
$\sin^2\bar{\theta}$=0.68-0.74
$\sin^2\bar{\theta}$=0.26-0.32
1-P($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
E(GeV)


L=730km
$\Delta\bar{m}^{2=(7.0-7.6)x10-5}$eV^2
$\sin^2\bar{\theta}$=0.68-0.74
$\sin^2\bar{\theta}$=0.26-0.32
1-P($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
E(GeV)


1-P($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
L=2540km
$\Delta\bar{m}^2$=(15.0-15.6)x10^{-5}eV^2
$\sin^2\bar{\theta}$=0.68-0.74
$\sin^2\bar{\theta}$=0.26-0.32
E(GeV)


1-P($\bar{\nu}_e \rightarrow \bar{\nu}_e$)
L=2540km
$\Delta\bar{m}^2$=(15.0-15.6)x10^{-5}eV^2
$\sin^2\bar{\theta}$=0.68-0.74
$\sin^2\bar{\theta}$=0.26-0.32
E(GeV)

CONCLUDING REMARKS

- NEUTRINO OSCILLATIONS PROVIDE THE ONLY "PALPABLE" EVIDENCE FOR PHYSICS BEYOND THE OLD STANDARD MODEL (IGNORE "GRAVITY" STUFF)

- THERE IS A NEW S.M. => OSM + NEUTRINO MASSES, AND WE ARE STARTING TO BECOME SENSITIVE TO PHYSICS BEYOND THE NSM.

- WE STILL NEED TO ADDRESS THE LSND ANOMALY (EXPERIMENTALLY)!

- NEUTRINOS ARE ONE OF THE BEST PROBES OF SPECIFIC EXOTICA, THANKS TO OSCILLATIONS.