Status of Neutrino Physics

Vernon Barger

SLAC Summer Institute
July 27, 2006

Outline

- The 3ν paradigm
- Neutrino oscillations
  - ATM, solar, reactor, future

- Absolute m_ν
- Neutrino cosmology
  - BBN, CMB, galaxy surveys
- New ideas
  - MaVaNs

Pre 1998: Standard Model $m_\nu = 0$

1998-present: The Neutrino Revolution

Neutrino flavors oscillate ⇒ neutrinos have mass

New SM: minimal SM extensions

With L-conservation add ν_R: Dirac ν ($\nu \neq \nu^c$)

$$L = L_{SM} - m_\nu \overline{\nu}_L \nu_R + \text{ h.c.}$$

With L not conserved: Majorana ν ($\nu = \nu^c$)

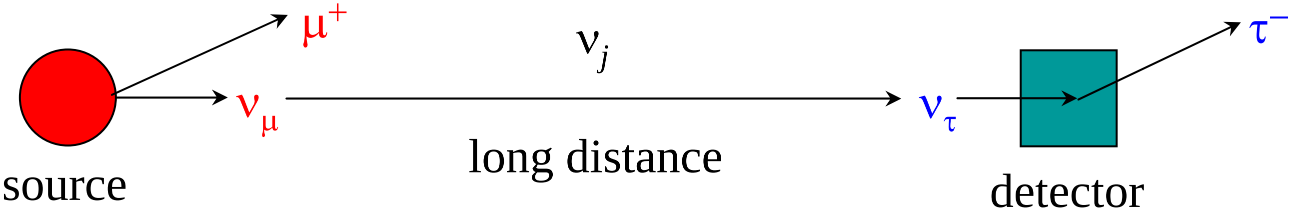
$$L = L_{SM} - \frac{1}{2} m_\nu \overline{\nu}_L \nu_L^c + \text{ h.c.}$$

Note: oscillations give no information on:

Dirac vs. Majorana

absolute ν-mass (only probe $m_i^2 - m_j^2$)

How do oscillations occur?



$$\mathrm{QM}: \; e^{-i(E_j - pL)} \cong e^{-i\frac{m_j^2}{2E}L} \qquad (L \cong ct)$$

Lifestyle of a muon neutrino

PRODUCTION: born as a flavor (e.g. ν_μ)

PROPAGATION: travels as mass eigenstates

$$\nu_\mu(L) = \cos\theta_a \nu_2 e^{-i\frac{m_2^2}{2E}L} + \sin\theta_a \nu_3 e^{-i\frac{m_3^2}{2E}L}$$

DETECTION: dies as a flavor (ν_μ or ν_τ)

Weak charged currents connect flavor eigenstates

$$|\nu_\alpha\rangle \qquad \alpha = e, \mu, \tau$$

The flavor eigenstates are mixtures of mass eigenstates

$$|\nu_i\rangle \qquad i = 1, 2, 3$$

The mixing is described by a unitary matrix V

$$|\nu_\alpha\rangle = V^*_{\alpha j} |\nu_j\rangle$$

Probability of detecting flavor β at a discrete distance L from a source that produced flavor α

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{ab} - 4\sum_{j \neq i}^{n} \mathrm{Re}[V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*}] \sin^2 \Delta_{ij}$$

$$+ 2\sum_{j \neq i}^{n} \mathrm{Im}[V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*}] \sin(2\Delta_{ij})$$

Oscillation argument

$$\Delta_{ij} = 1.27 \frac{\delta m_{ij}^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{km/GeV}}$$

$$\delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Data have probed sub-eV^2 neutrino mass-squared differences

Three Neutrino Paradigm

The 3ν mixing matrix

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix} \begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix} \begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\left(\frac{1}{2}\phi_2\right)} & 0 \\ 0 & 0 & e^{i\left(\frac{1}{2}\phi_3+\delta\right)} \end{bmatrix}$$

atm unknown solar 0νββ

(Majorana phases)

3 angles (θ_a, θ_s, θ_x)

1 Dirac phase (δ)

2 Majorana phases (ϕ_2, ϕ_3)

$\delta \neq 0$ and $s_x \neq 0 \Rightarrow$

$P(\overline{\nu}_\alpha \leftrightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \leftrightarrow \nu_\beta)$ CP-violation

Empirically, δm_a^2 and δm_s^2 are very different and their oscillations are nearly decoupled (θ_x small)

Effective 2-neutrino oscillations good first approximation with one δm^2 is dominant

$$P(\nu_\alpha \to \nu_\beta) \cong \sin^2 2\theta \sin^2 \Delta$$

$$P(\nu_\alpha \to \nu_\alpha) \cong 1 - \sin^2 2\theta \sin^2 \Delta$$

$$\Delta = \frac{\delta m^2 L}{4E}$$

Recap of the evidence for neutrino oscillations

Atmospheric neutrinos

$\nu_\mu \leftrightarrow \nu_\mu$	depletion observed (> 15σ)
$\nu_\mu \leftrightarrow \nu_e$	excluded (> 5σ)*
$\nu_\mu \leftrightarrow \nu_\tau$	inferred

Vacuum oscillations

$$P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 2\theta_a \sin^2 \frac{\delta m_a^2 L}{4E_\nu}$$

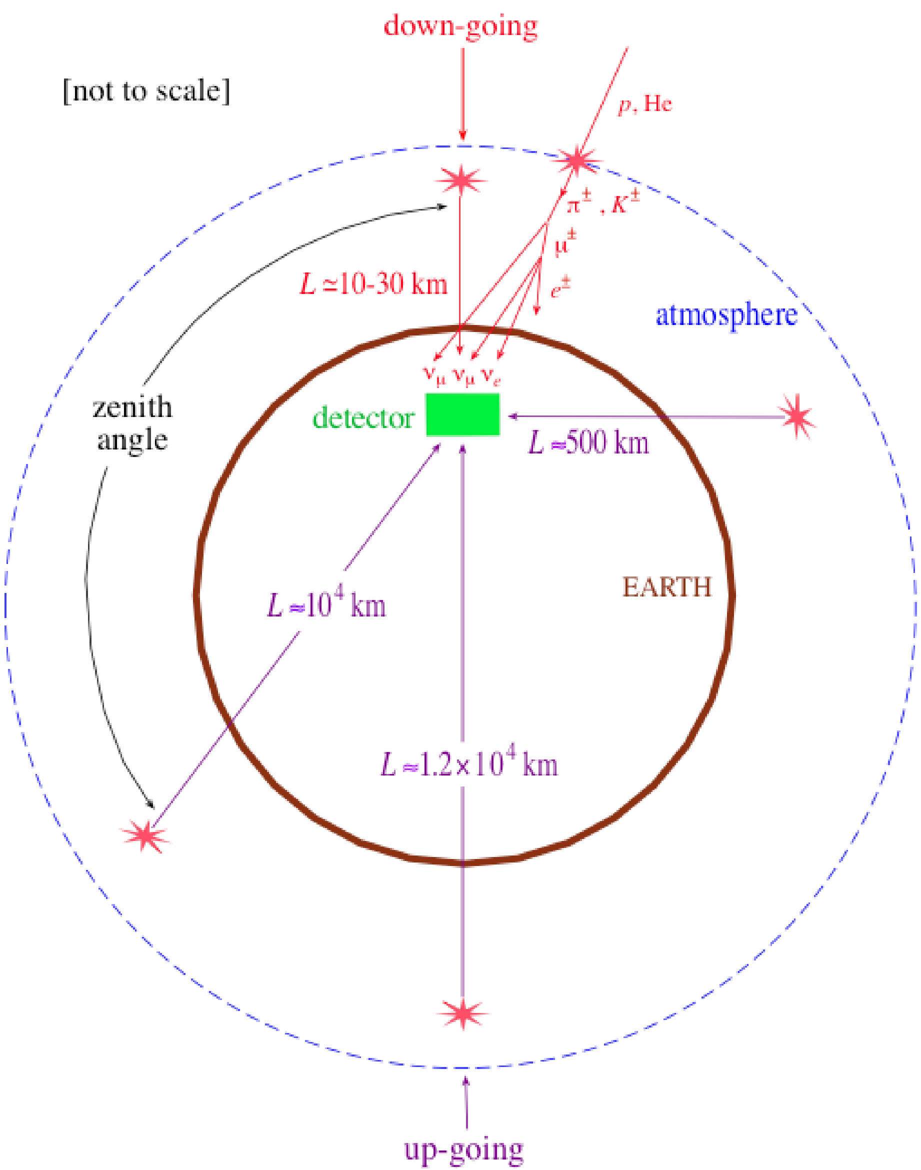
$$\delta m_a^2 \approx 2 \times 10^{-3}\ \text{eV}^2$$

Large mixing $\theta_a = 45 \pm 10^{\circ}$ 95% C.L.

---

* θ_x small
Also from CHOOZ reactor experiment for $\bar{\nu}_e \leftrightarrow \bar{\nu}_e$
disappearance $\sin^2\theta_x < 0.05$

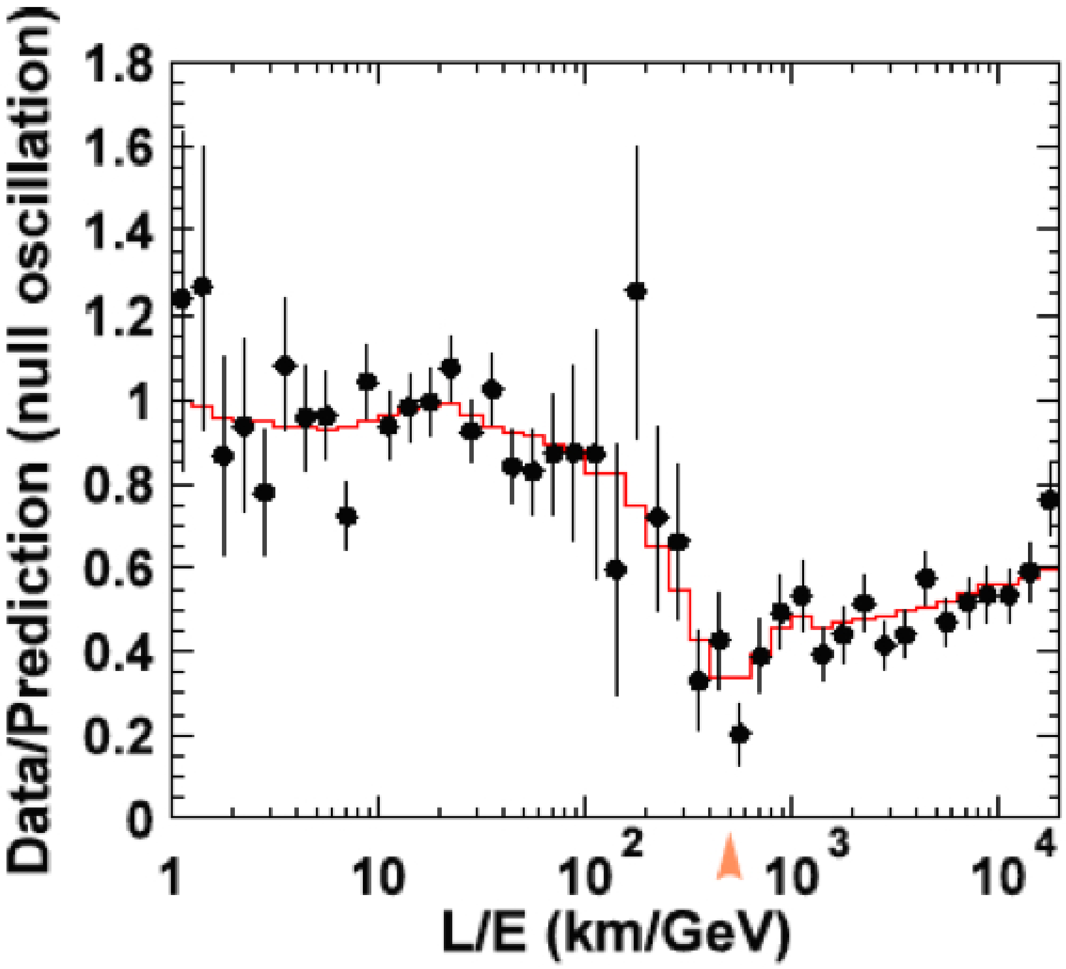
Atmospheric Neutrinos



Atmospheric ν oscillations

$$\nu_\mu \leftrightarrow \nu_\mu, \bar{\nu}_\mu \leftrightarrow \bar{\nu}_\mu$$

SuperK data

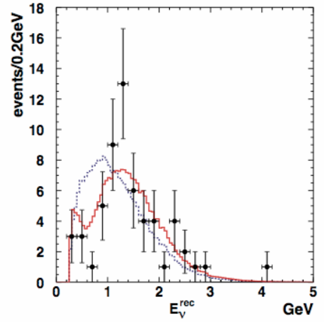


Accelerator Confirmation of ATM oscillations

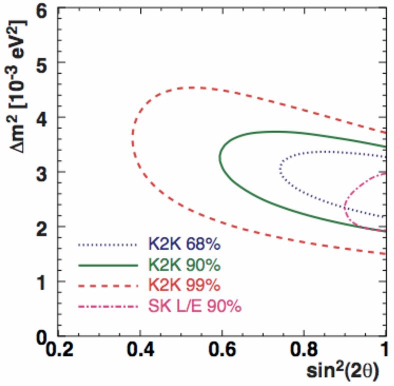
K2K: ν_μ beam from KEK to Kamiokande
L = 250 km

MINOS: ν_μ beam from Fermilab to Soudan
L = 735 km

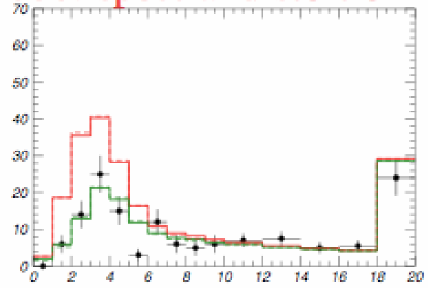
K2K 2006: spectral distortion



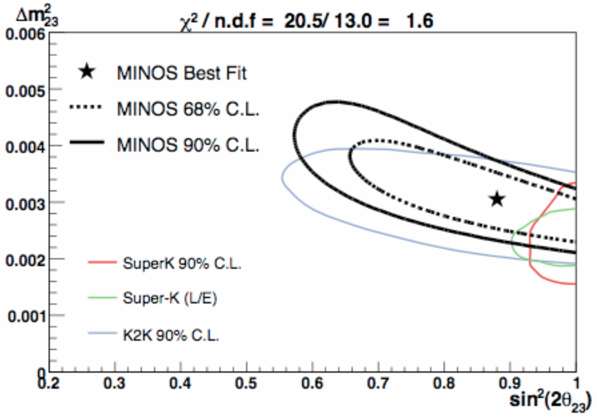
Confirmation of ATM oscillations



MINOS 2006: spectral distortion



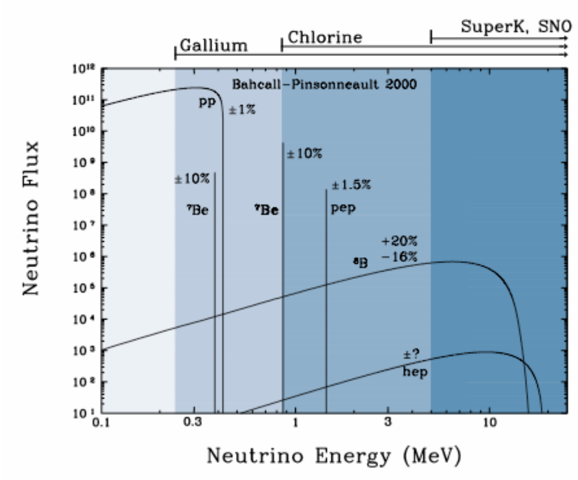
Confirmation of ATM oscillations



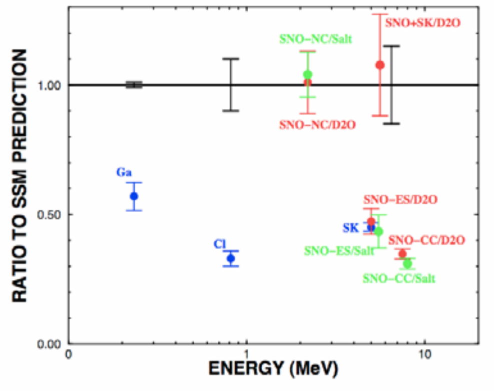
Solar neutrinos

Interior of sun well-modeled and ν_e flux predicted

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$ $\quad {}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$ $\quad {}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

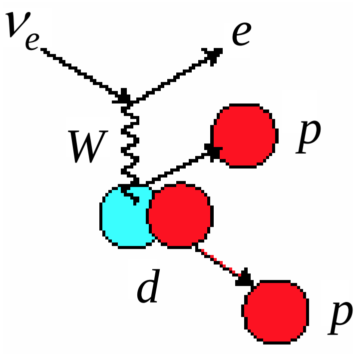


$\nu_e \leftrightarrow \nu_e$ depletion observed ($> 7\sigma$)



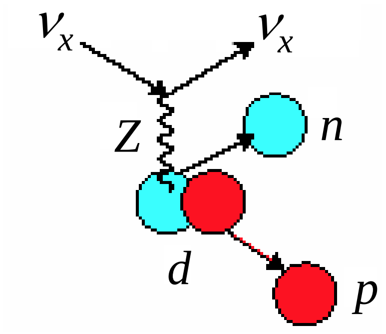
Experimental proof of solar ν_e oscillations from the Sudbury Neutrino Observatory (SNO)

Measured CC



SNO sees ν_e depletion

Measured NC



$\nu_x = \nu_e, \nu_\mu, \nu_\tau$

SNO sees predicted solar neutrino flux

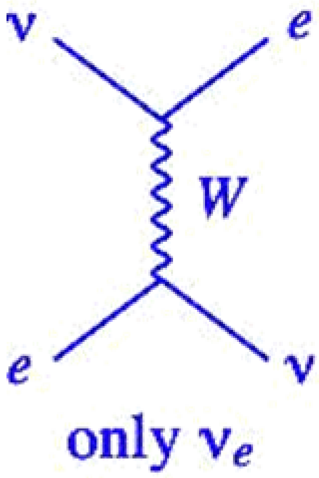
So the "missing" ν_e were converted to ν_μ and ν_τ by oscillations!

Essential Wrinkle

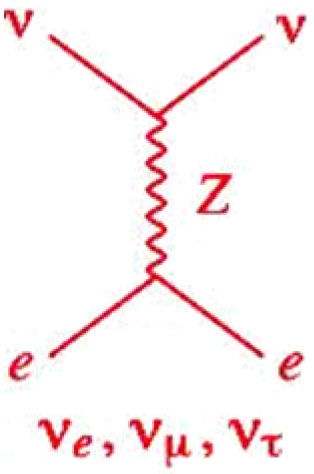
Neutrinos created in the solar core
travel through dense matter to get out

The ν_e scatter from electrons in the matter differently from other neutrinos, creating a different index of refraction for ν_e

Wolfenstein (1976)



(charged current)



(neutral current)

Resonance can occur in ν_e oscillations!

$$\tan 2\theta_s^m = \frac{\tan 2\theta_s}{1-\beta/\cos 2\theta_s} \quad ; \quad \beta = \frac{\lambda_m}{\lambda_{\text{vac}}} = \frac{2\sqrt{2}G_F n_e E_\nu}{\delta m_s^2}$$

$$A = 2\sqrt{2}G_F N_e E_\nu$$

Barger,Pakvasa,Phillips,Whisnant (1980)

$\sin^2 2\theta^m$ enhancement for $\delta m^2 > 0$

Matter resonance proposed as explanation of the solar neutrino deficit (MSW)

Natural: small θ_s amplified by resonance (SMA solution)

Mikheyev-Smirnov (1985)

But global fits select LMA solution

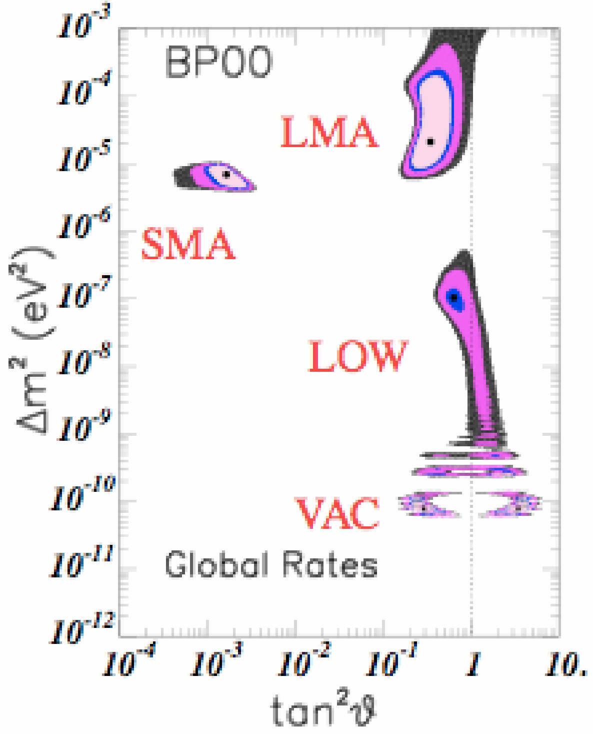
Neutrinos propagate adiabatically through the matter resonance
 - no level crossing

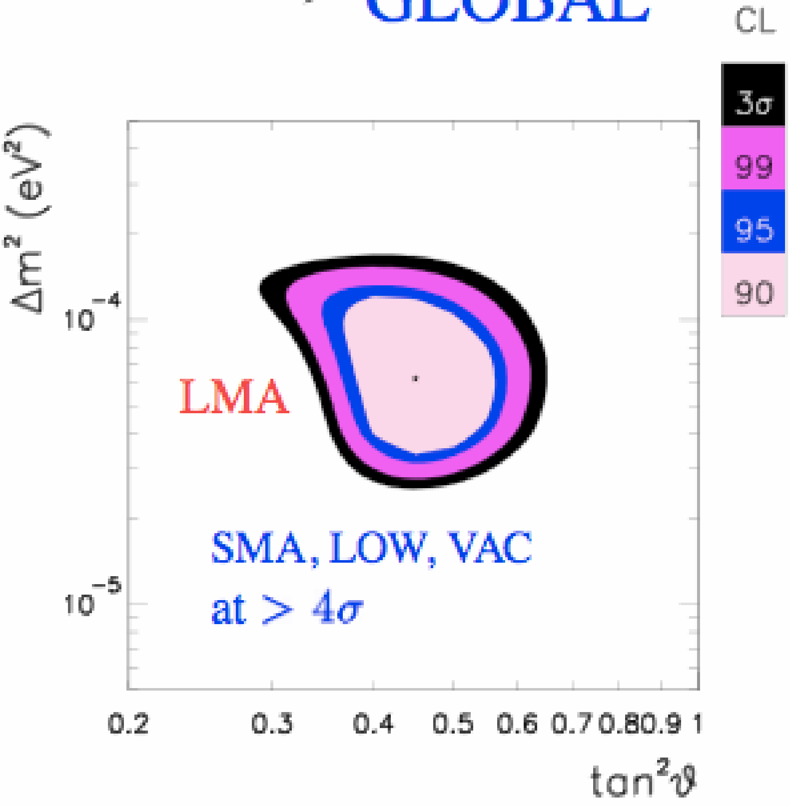
$$\delta m_s^2 \approx 6 \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_s \approx 33^o$$

Solar Neutrinos: Oscillation Solutions

RATES ONLY $\xrightarrow{\text{SK and SNO E and t dependence}}$ GLOBAL



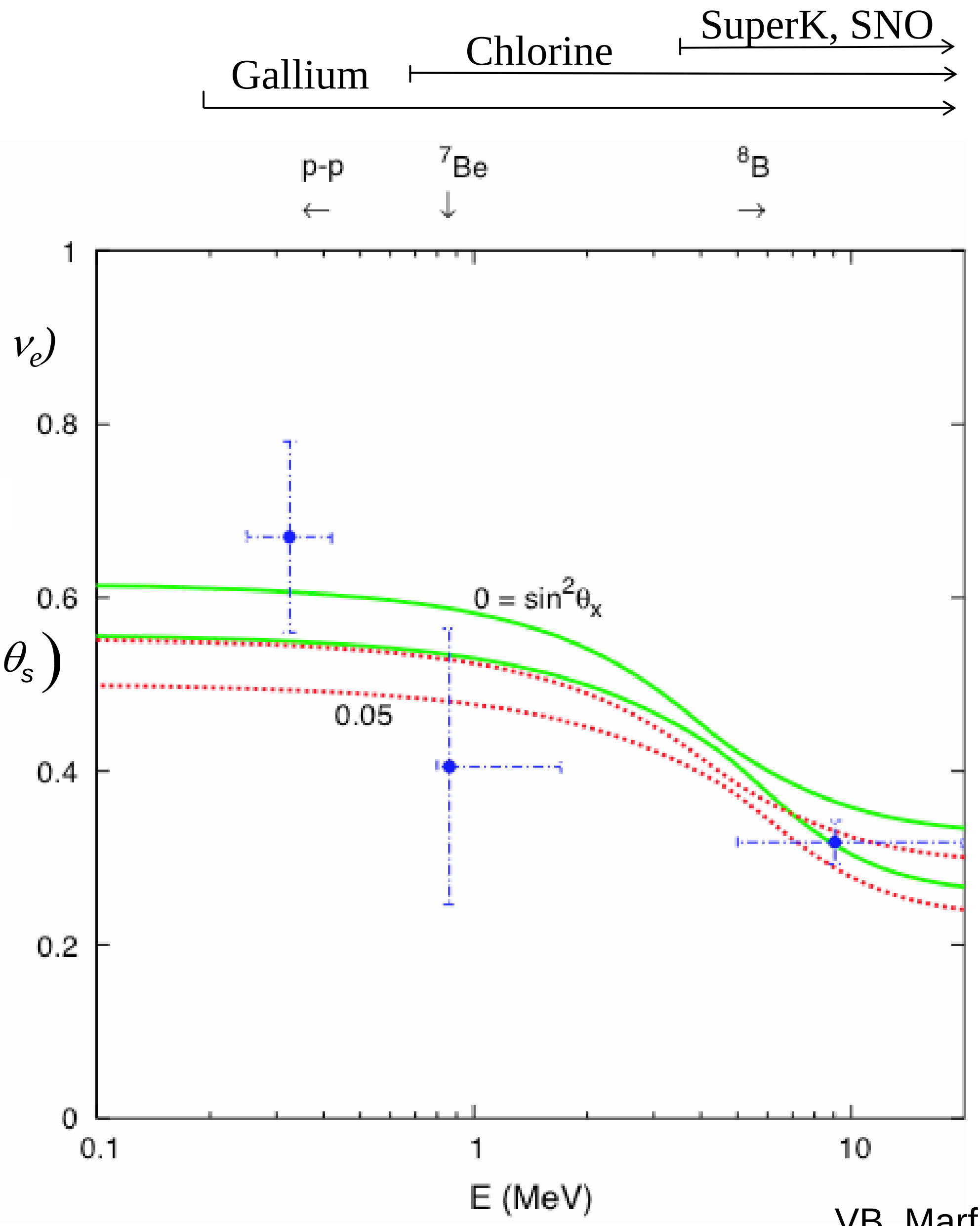


$$\Delta m^2 = (6.3^{+2.3}_{-1.9}) \times 10^{-5}\ \mathrm{eV}^2\ (1\sigma)$$

$$\tan^2\theta = 0.45^{+0.05}_{-0.04}$$

C. Gonzalez-Garcia et al.

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$ $\quad$ ${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$ $\quad$ ${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$



data points assume SSM fluxes for Low, Intermediate energies

$$P_L = \cos^4\theta_x \left(1 - \tfrac{1}{2}\sin^2 2\theta_s\right)$$

vacuum average

$$P_H = \cos^4\theta_x \sin^2\theta_s + \sin^4\theta_x$$

matter dominated

VB, Marfatia, Whisnant, 2005

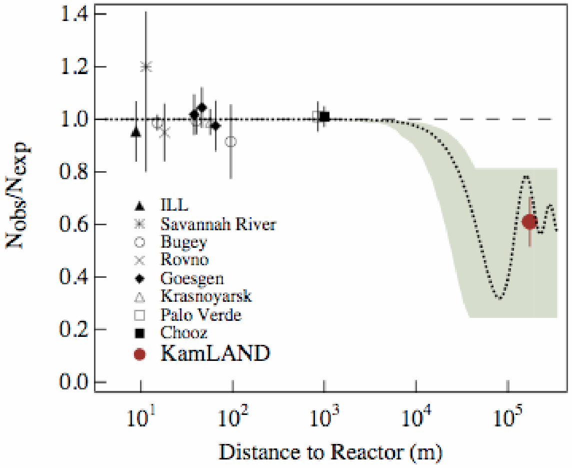
KamLAND reactor confirmation of LMA

$$\overline{\nu}_e \leftrightarrow \overline{\nu}_e \text{ at L } \sim \text{ 180 km, } E_{\overline{\nu}} \sim \text{ few MeV}$$

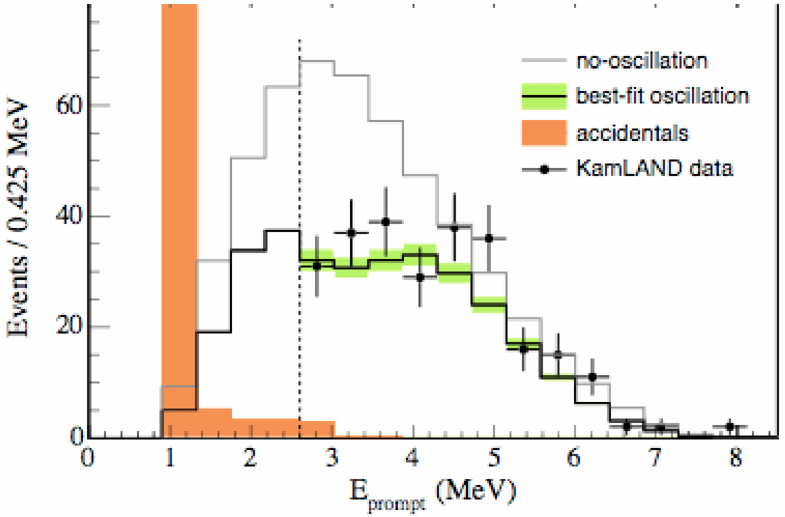
$$\overline{\nu}_e + p \rightarrow n + e^+$$

$$\left[\text{assume CPT : } \quad P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = P(\nu_e \rightarrow \nu_e)\right]$$

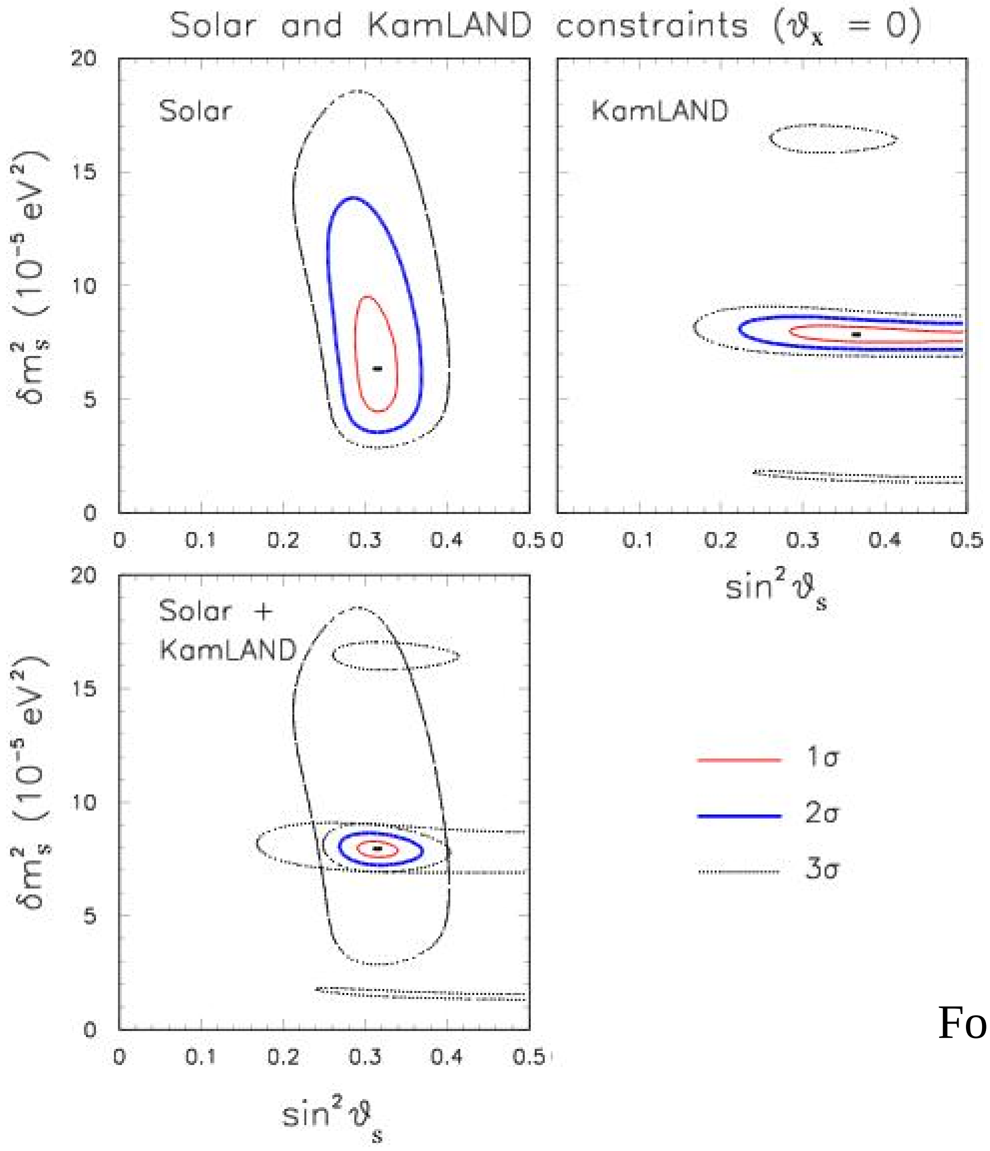
2002: Deficit $R_{\mathrm{KLAND}} = 0.611 \pm 0.094$



2004: Energy Distortion



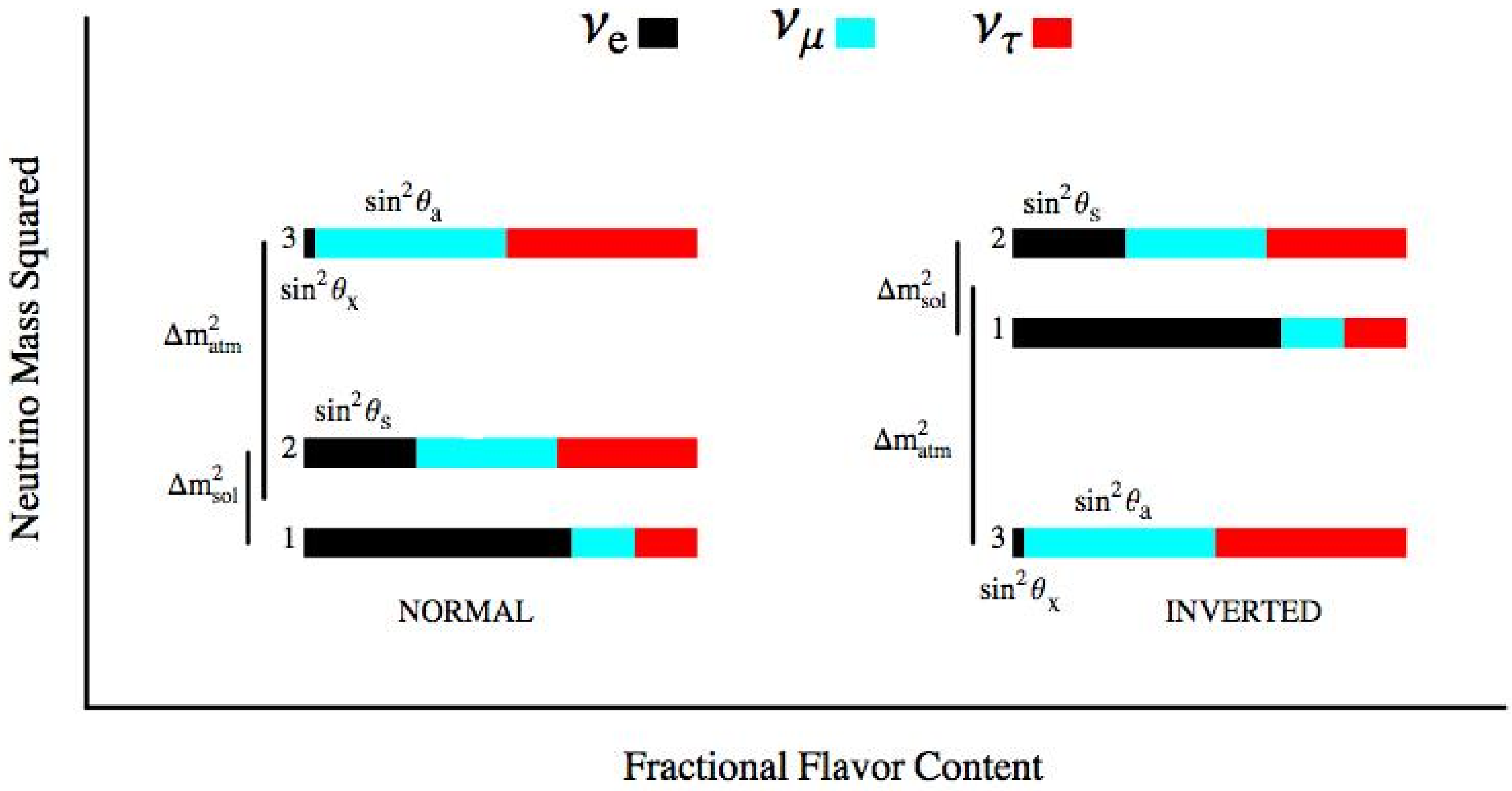
Solar + KamLAND



Fogli et al. (2005)

State composition for two possible mass orderings

NH IH



Still Unknown

θ_x	$\nu_\mu \to \nu_e$ oscillations at δm_a^2 scale not seen; θ_x small for unknown reason
sign(δm_a^2)	Can be resolved by earth matter Effects on $\nu_\mu \to \nu_e$ oscillations in Earth provided that $\theta_x \neq 0$

Enhance $P(\nu_\mu \to \nu_e)$ and suppress $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or vice versa depending on sign(δm_a^2)

Summary of knowns and unknowns

3ν observable	Present knowledge (1σ)
$\lvert \delta m_a^2 \rvert$	$(2.05 \pm^{0.4}_{0.4}) \times 10^{-3}\ \mathrm{eV}^2$
$sign(\delta m_a^2)$	unknown
$\lvert \delta m_s^2 \rvert$	$(8.0 \pm^{0.4}_{0.5}) \times 10^{-5}\ \mathrm{eV}^2$
$sign(\delta m_s^2)$	$+$
$\tan^2 \theta_a$	$1.00^{+0.38}_{-0.27}$
$\tan^2 \theta_s$	$0.45^{+0.05}_{-0.05}$
$\sin^2 \theta_x$	< 0.045
δ	unknown
Majorana/Dirac	unknown
ϕ_2, ϕ_3	unknown
m_ν	$\sum m_\nu \leq 0.6\ \mathrm{eV}$ (cosmology)

The ultimate goal of long-baseline experiments is to determine the CP-violating phase δ

$\boxed{\delta}$

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

$$\Delta P \propto \left(\frac{\delta m_s^2}{\delta m_a^2}\right) \sin 2\theta_x \sin \delta$$

Both δm_s^2 and δm_a^2 oscillations must contribute to have CP violation

Must distinguish intrinsic CP-violation from fake CP-violation due to matter effects

8-fold parameter degeneracy

$sign(\delta m_a^2)$

(δ, θ_x)

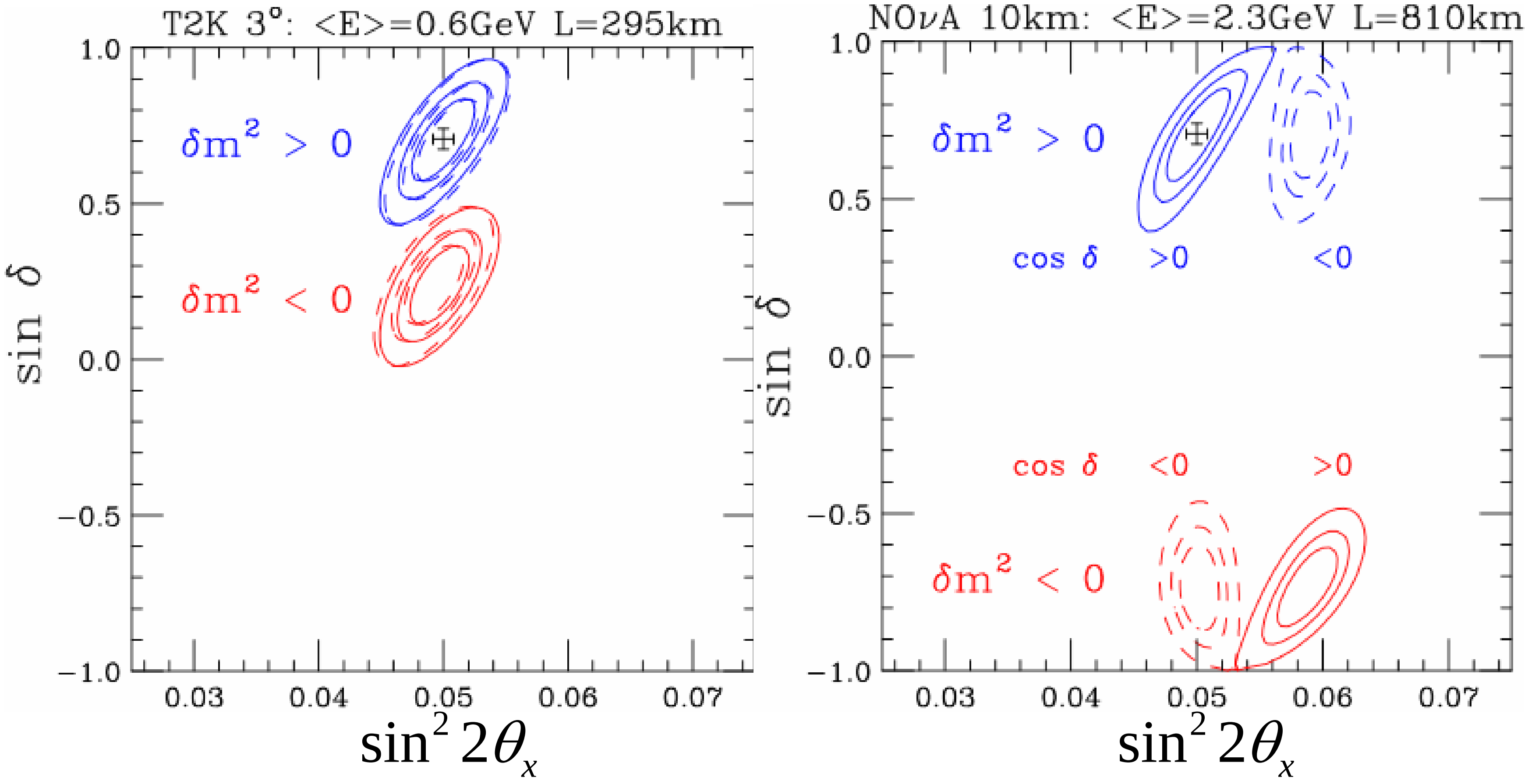
$(\theta_a, \frac{\pi}{2} - \theta_a)$

Can be resolved with long baseline experiments

Barger, Marfatia, Whisnant

T2HK and NOνA are complementary

Combining results from 2 long-baseline experiments
eliminates fake solutions caused by matter effects



Mena and Parke

Tri-bi maximal mixing
($\theta_a = \pi/4$, $\theta_s = \pi/6$, $\theta_x = 0$)

$$V = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Harrison, Perkins, Scott

Theoretical basis uncertain: models proposed

Consistent with all present data

Alas, if true,

- No δm_a^2 dependent Earth matter effects
- No CP violation

3 neutrino paradigm in great shape with one possible exception:

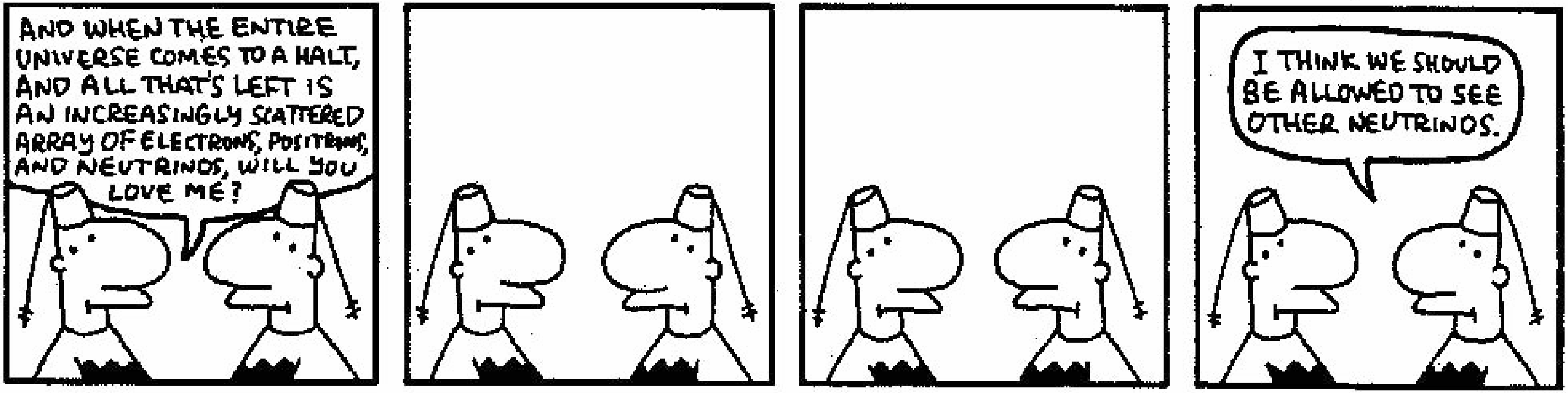
LSND evidence for $\overline{\nu}_\mu \leftrightarrow \overline{\nu}_e$ oscillations with

$$\delta m^2_{\text{LSND}} \sim 1\ \text{eV}^2 \text{ and } \theta_{\text{LSND}} \sim 10^{-2}$$

Oscillations to sterile neutrinos invoked:

Active	Sterile	extra
3	2	-
3	1	CPT violation
3	1	MaVaNs
3	1	Sterile decay
3	1	Extra dim
3	-	Quantum decoherence

Fermilab MiniBooNE experiment will
test these speculative models



Life in Hell
by Matt Groening

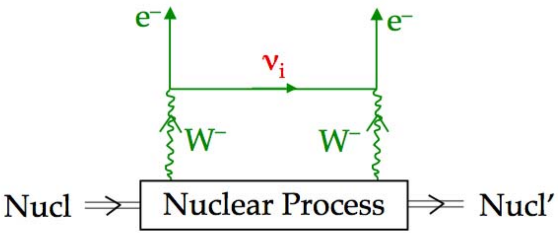
Absolute neutrino mass

- ^{3}H beta decay: Mainz experiment

$$m_\beta = \left(\sum |V_{ei}|^2 m_{\nu_i}^2\right)^{1/2} < 2.2\ \mathrm{eV}$$

Future: KATRIN sensitivity down to 0.3 eV

- Neutrinoless nuclear double beta decay

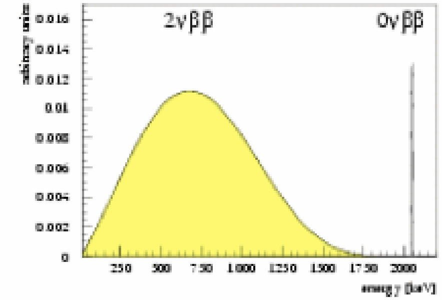


$$N(n,p) \rightarrow N(n-2,p+2)+2e^-$$

Occurs only if neutrinos are Majorana $\overline{\nu}_i = \nu_i$

(usual theoretical prejudice)

$$m_{ee} = \left|\sum V_{ej}^2 m_{\nu_j}\right|$$

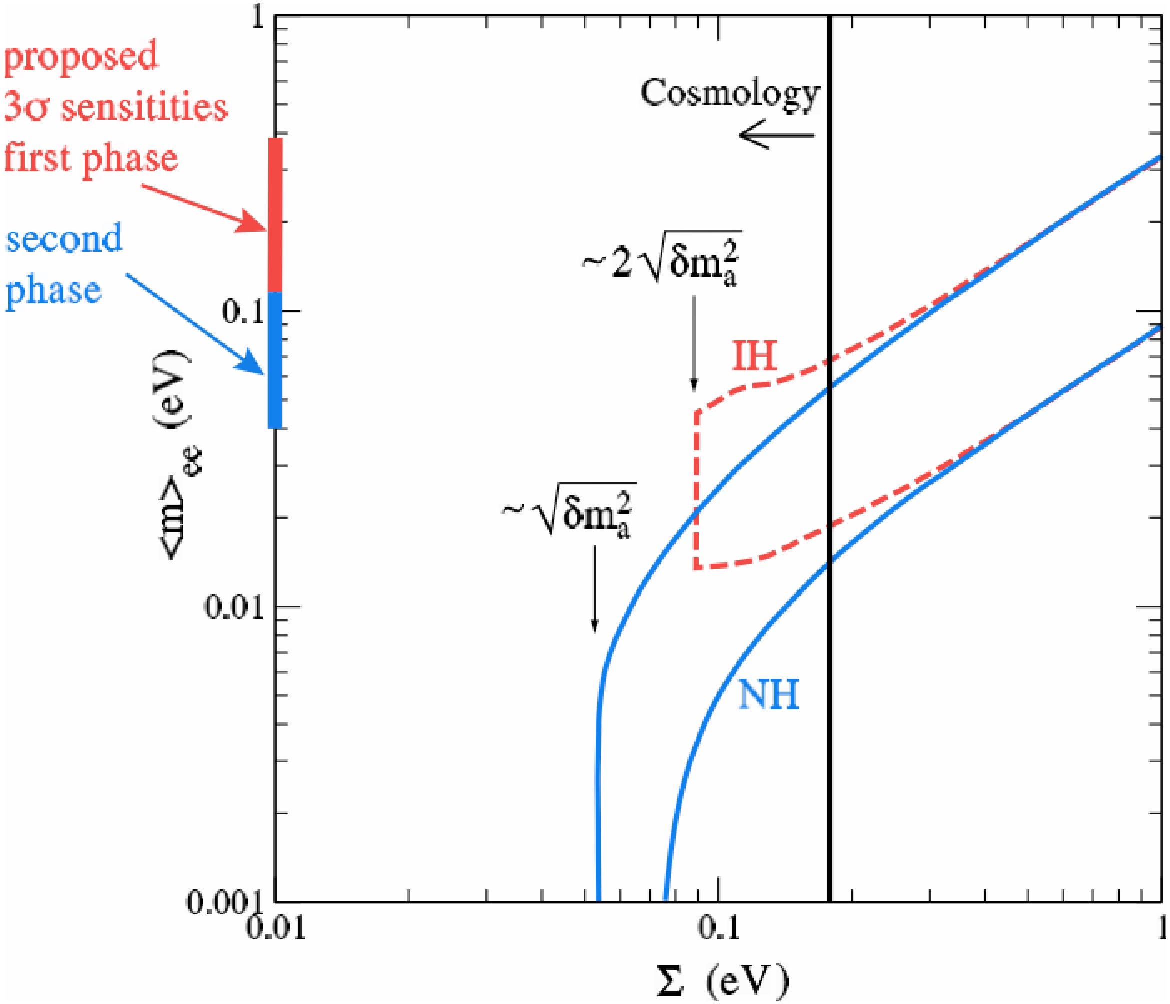


Heidelberg-Moscow experiment:

Upper limit: $m_{ee} < 0.35$ eV at 95% C.L.

$m_{ee} = 0.1 - 0.9$ eV controversial detection

IH predicts lower limit on m_{ee}



Atre et al. (2005)

Future U.S. neutrino program goals

Nu-SAG charges (2006)
[Neutrino Scientific Assesment Group]

1. Reactor experiment with θ_x sensitivity down to

$$\sin^2 2\theta_x = 0.01 \qquad (\text{now } \sin^2 2\theta_x < 0.19)$$

Daya Bay (Double Chooz)

2. Neutrinoless nuclear double beta decay experiments (different nuclei)
   CUORE, EXO, Majorana
   GERDA, Super Nemo, Moon

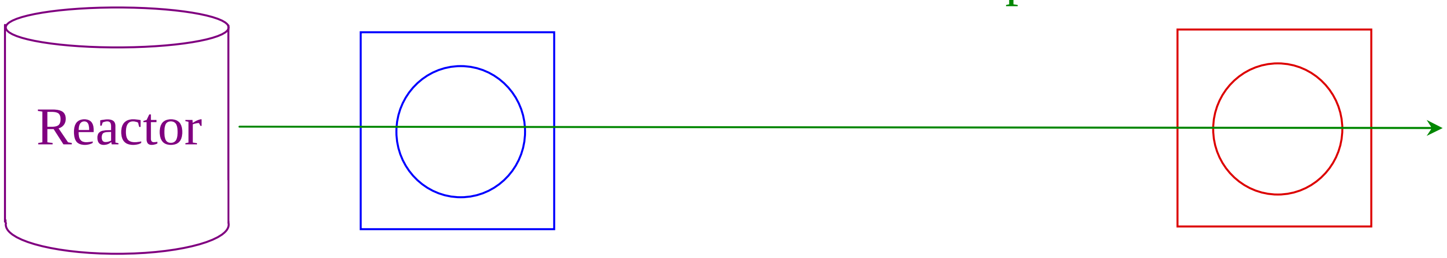
3. Accelerator experiment with θ_x sensitivity down to

$$\sin^2 2\theta_x = 0.01$$

and sensitivity to the mass-hierarchy through matter effects
T2K (Japan), NOVA (US)

Reactor experiments

Measure θ_x via disappearance with two detectors



optimal distance ~1.7 km

Reactor

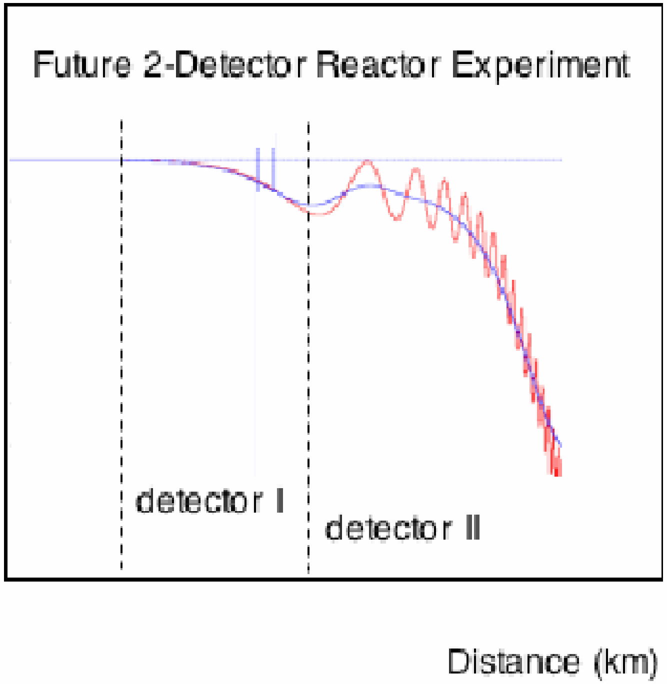
monitor flux

measure $P(\bar{\nu}_e \to \bar{\nu}_e)$
at δm_a^2 osc minimum

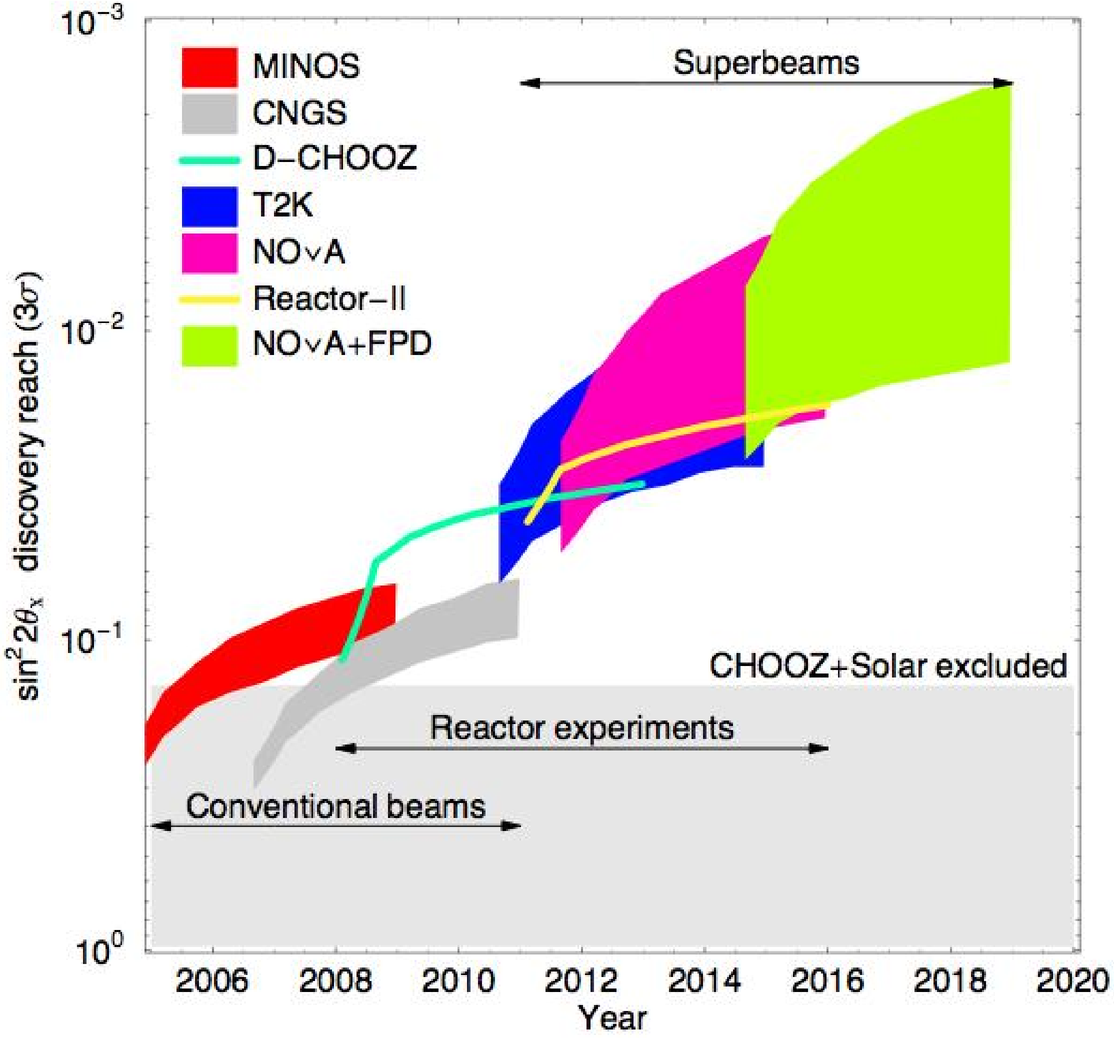
Double Chooz (approved)

$\sin^2 2\theta_x$ sensitivity:

0.02 at 90% C.L.



The race for θ_x discovery



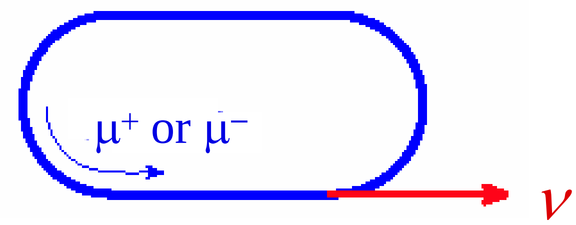
Geer (2006)

Off-axis neutrino beams

Superbeams

Neutrino Factory

β-beams



+ new detector technologies

Approximate discovery reaches in $\sin^2 2\theta_x$

Current limit	10^{-1}
Reactor	10^{-2}
Conventional π-beam	10^{-2}
Superbeam	3×10^{-3}
NuFact (entry level)	5×10^{-4}
NuFact (high performance)	5×10^{-5}
β-beams	comparable to NuFact (10^{-3} -10^{-4})

Pursue θ_x as small as we need to go!

Primordial Neutrinos

^{4}He primordial abundance in BBN

$$Y_p \cong \left. \frac{2n_n/n_p}{1+n_n/n_p} \right|_{T_{freeze}} \qquad n_n/n_p \sim e^{-(m_n-m_p)/T_{freeze}}, \quad T_{freeze} \sim 1\ \mathrm{MeV}$$

Extra light neutrinos

$$\Delta N_\nu = N_\nu - 3$$

would speed up expansion

$$\frac{H_{new}}{H_{std}} = \left(1+\frac{7}{43}\Delta N_\nu\right)^{1/2} \qquad \mathrm{H} = \dot{a}/a$$

giving earlier n/p freeze-out and higher ^{4}He abundance for $\Delta N_\nu > 0$

Revised estimates of primordial helium abundance

$Y_p = 0.249 \pm 0.009$ Olive-Skillman (2004)

$Y_p = 0.250 \pm 0.004$ Fukugita-Kawasaki (2006)

BBN + Y_p + η_{CMB} (baryon / photon ratio):

$$\boxed{1.7 \leq N_\nu \leq 4.5 \text{ at 95\% C.L.}}$$

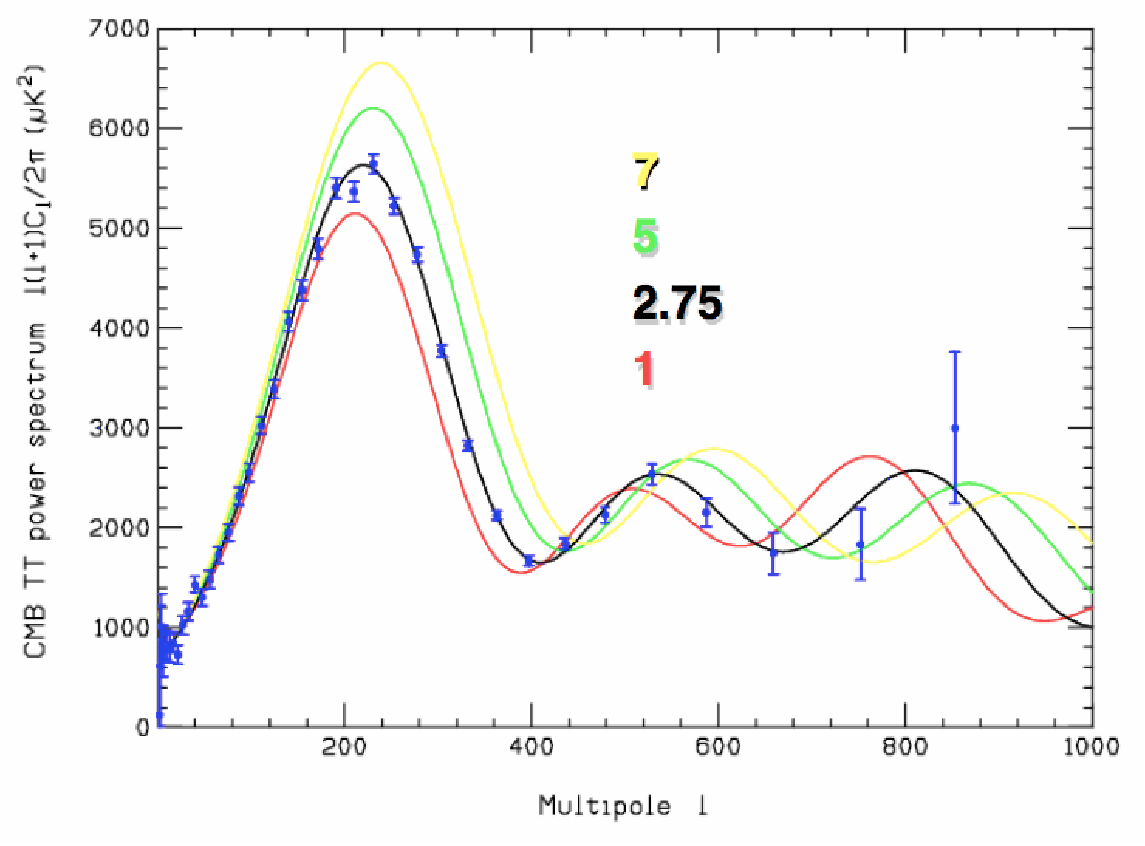
Cyburt et al. (2004)

- Preferred N_ν consistent with 3
- Neutrino contribution to radiation density established (lower bound on N_ν)
- $N_\nu = 4$ allowed

  LSND neutrino thermalizes giving $N_\nu = 4$

Neutrino counting with CMB

Power spectrum is sensitive to N_ν



But N_ν correlated with $\Omega_M h^2$

Analyze CMB data along with data that constrain Ω_M

CMB	WMAP 3-year + other CMB	$(\Omega_\Lambda + \Omega_M)h^2$
SN	Supernova gold + SNLS	$(\Omega_\Lambda - \Omega_M)h^2$
LSS	Galaxy clustering SDSS & 2dF	$(\Omega_\Lambda, \Omega_M)h$
BAO	Luminous red galaxies	$\Omega_M h^2$
LYA	Lyman-α forest	$\Omega_M h$

N_ν (with $\Sigma m_\nu = 0$) at 2σ

- Barger et al (2003)

WMAP-1 + H_0

$$0.9 < N_\nu < 8.3$$

- Spergel et al (2006)

WMAP-3 + other CMB
+ SN + LSS

$$N_\nu = 3.29^{+0.45}_{-2.18}$$

- Seljak et al (2006)

… + LYA + BAO

$$N_\nu = 5.1^{+2.1}_{-1.7}$$

(N_ν=3 allowed only at 3σ)

- Hannestad et al (2006)

CMB + LSS

$$2.7 < N_\nu < 4.6$$

Excellent accord of BBN (20 min), CMB (380,000 years) and LSS (10 Gyr)

N_ν = 4 OK

Neutrino Mass from the CMB

Massive neutrinos slow the growth of small scale structure

Joint analyses of CMB and LSS data constrains Σm_ν

	Σm_ν (for $N_\nu = 3$)	
• Barger et al (2004) WMAP-1 + LSS + H_0 + other CMB	< 0.75 eV	(2σ)
• Spergel et al (2006)	< 0.68 eV	(1σ)
• Seljak et al (2006)	< 0.17 eV	(2σ)
• Hannestad et al (2006)	< 0.62 eV	(2σ)

New Ideas:

Mass varying Neutrinos (MaVaNs)

Motivation: dark energy density (2x10^{-3} eV)^4 is comparable to neutrino mass splitting scale

$$\delta m_\nu^2 \sim (10^{-2}\ \mathrm{eV})^2$$

Proposal: relic neutrinos interact via a new scalar field ϕ (the "acceleron") and form a negative pressure fluid that causes the cosmic acceleration. Fardon, Nelson, Weiner (2005)

Very speculative, but very interesting!

Mechanism: sterile neutrino interacts through Yukawa couplings to the acceleron ϕ

A prototype low energy effective Lagrangian

$$L = m_D \nu N + \kappa\phi NN + \text{h.c.} + V(\phi)$$

$\nu =$ left-handed active neutrino
$N =$ right-handed sterile neutrino
$\kappa =$ Yukawa coupling

If $\kappa\phi >> m_D$ see-saw gives

$$L = \frac{m_D^2}{\kappa\phi}\nu^2 + \text{h.c.} + V(\phi)$$

Effective ϕ-dependent neutrino mass at late times:

$$m_\nu(\phi) = m_D^2 / |\kappa\phi|$$

FNW Dark Energy Scenario

- Neutrino mass a dynamical field which is a function of the acceleron field: $m_\nu(\phi)$
- Dark energy is the sum of the neutrino energy density and the scalar potential of the acceleron

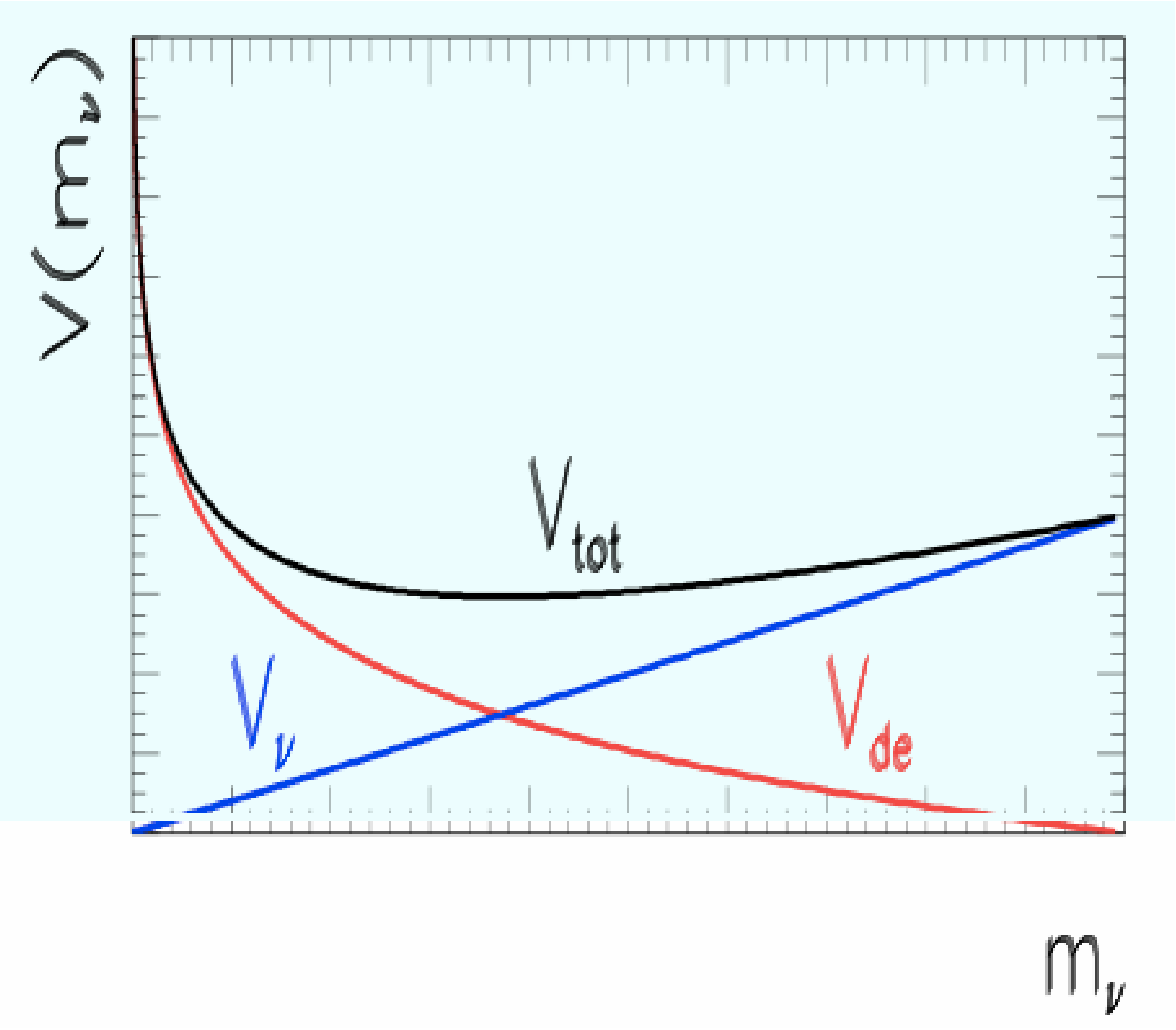
$$\rho_{DE} = \rho_\nu + V(\phi) \qquad \text{Non-Rel}: \ \rho_\nu = m_\nu n_\nu$$

- .ρ_{DE} is stationary with respect to m_ν

$$\frac{\partial \rho_{DE}}{\partial m_\nu} = 0$$

So, m_ν tracks the instantaneous minimum of the DE

Solution of stationary condition gives m_ν as a function of T for a given $V(\phi)$



$V(m_\nu)$
V_{tot}
V_ν
V_{de}
m_ν

MaVaNs implications for neutrino mass in particle physics

Background m_ν declines with redshift

But, a higher vacuum m_ν causes clustering and the corresponding higher neutrino number density lowers the effective neutrino mass

Complicated interplay that remains to be quantitatively explored

Extension: ϕ also couples to matter, then local neutrino mass could vary with local mass density

Neutrinos would be most massive in a vacuum

Phenomenology: MaVaN effects in addition to standard matter effects in neutrino oscillations

Revisit solar neutrinos (high densities)

Two-neutrino framework ($\nu_e, \ \nu_\mu$)

$$H_{\text{MaVaN}} = \frac{1}{2E} V \begin{pmatrix} (m_1 - M_1(r))^2 & M_3(r)^2 \\ M_3(r)^2 & (m_2 - M_2(r))^2 \end{pmatrix} V^+$$

$V = 2 \times 2$ mixing matrix

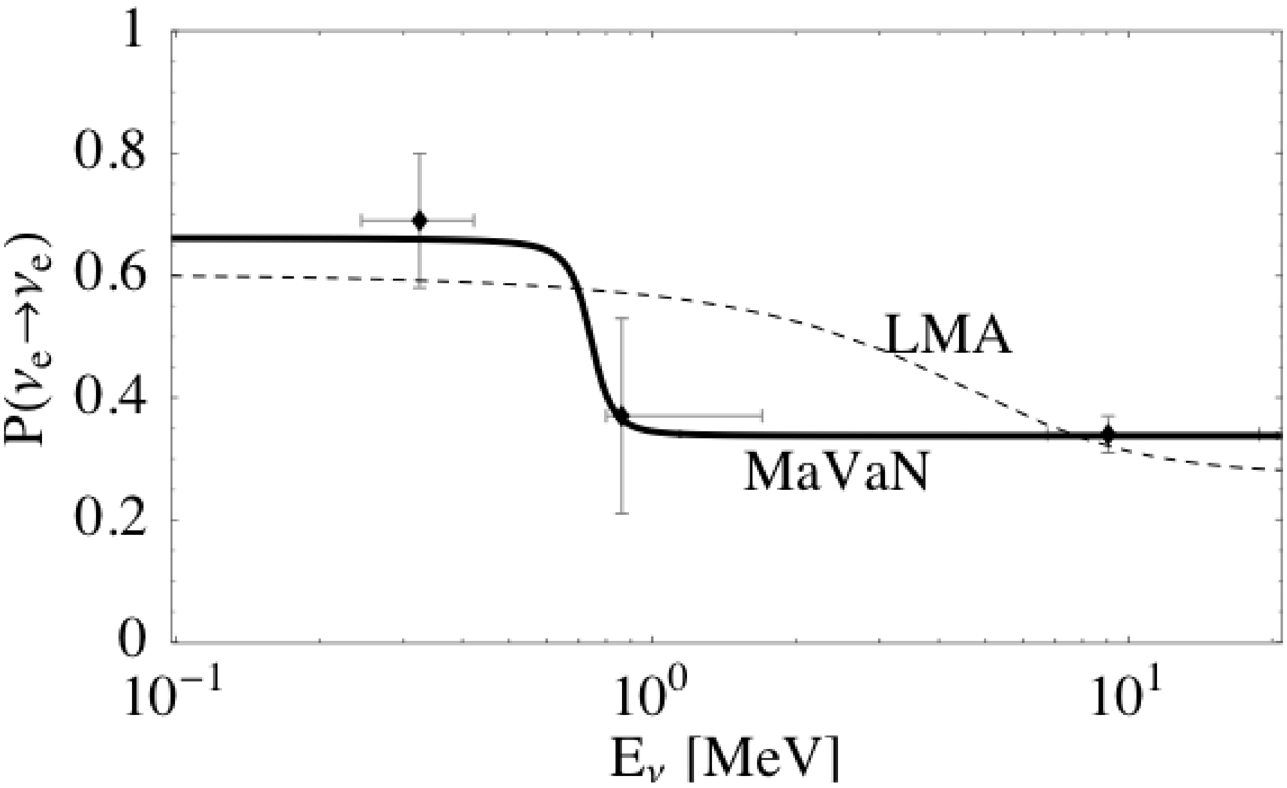
$$H_{\text{matter}} = \frac{1}{2E} \begin{pmatrix} 2\sqrt{2} G_F E_\nu n_e(r) & 0 \\ 0 & 0 \end{pmatrix}, \qquad n_e \propto e^{-r/r_0}$$

$n_e^0 =$ electron density at production point

Introduce parameterization

$$M_i = \mu_i \left(\frac{n_e(r)}{n_e^0} \right)^k$$

μ_i, k free parameters



VB, Huber, Marfatia (2005)

MaVaN oscillations with exotic matter effects comparable to standard matter effects allowed

- propagation inside sun still adiabatic - solar survival probability independent of how the neutrino masses depend on density

- can be tested with MeV and lower energy solar neutrino experiments (KamLAND, Borexino)

- are consistent with other neutrino oscillation experimental data (KamLAND, day night Earth effects, atm neutrino oscillations)

Why are neutrinos so light?

Favored explanation — the light neutrino masses are pushed down by mixing with very heavy neutrinos that are present in Grand Unified Theories

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

$$m_{light} \cong \frac{m^2}{M} \qquad \frac{(100\ \mathrm{GeV})^2}{10^{13}\ \mathrm{GeV}}$$

$$m_{heavy} \cong M$$

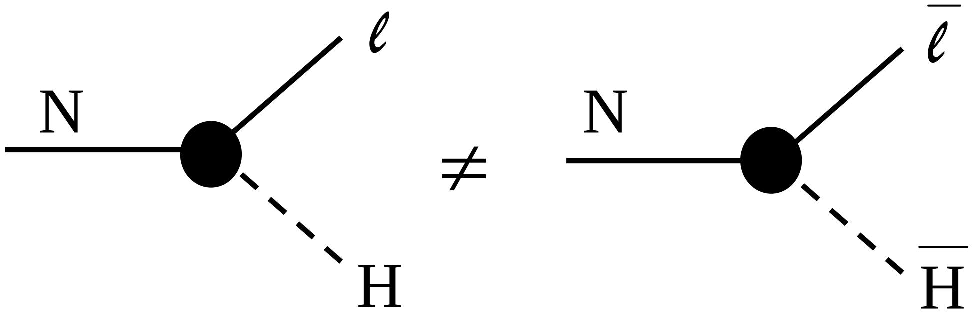
Eigenstates are dominantly Majorana

If so, light neutrinos are a “window” to new physics at energies that are inaccessible in the laboratory

Leptogenesis?

Matter-antimatter asymmetry from processes that violate CP in the early universe

Lepton asymmetry from decays of heavy right-handed neutrinos (CP-violating phase)



Baryon number asymmetry could be associated with lepton number asymmetry through SM sphaleron processes

Outlook

Sensitive new probes coming:

New terrestrial experiments

- β, 0νββ, reactor, long baseline experiments

New cosmology observations

- Planck CMB

New ideas to be explored

Neutrino mass changes with density?
Neutrino connection to dark energy?

The exciting physics of neutrinos is still unfolding.