Physics of Massive Neutrinos

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NuFact 03

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Apologies
to the many contributors to this science
for the omission of references in my talk

1998–2003 : The Neutrino Revolution

Neutrino flavors oscillate □ Neutrinos have mass

Post 2003

Era of further discovery and precision lies ahead

Fundamental properties of neutrinos within reach

Experimental pathways falling in place
- Reactors
- Off-axis beams
- Superbeams
- New detector technologies

Ultimately and inevitably lead to neutrino factories

Goal: unravel the enigma of flavor physics

Neutrino Oscillations

flavor states : ν_α $\alpha = e, \mu, \tau, \ldots$

mass states : ν_i $i = 1, 2, 3, \ldots$

Vacuum oscillations: $P(\nu_\alpha \to \nu_\beta) = \left| \sum_{j=1}^{n} V_{\alpha j} e^{-i\frac{m_j^2}{2E}L} V_{\beta j}^* \right|^2$

For 3 Neutrino Mixing

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

$c \equiv \cos\theta \quad s \equiv \sin\theta$

- 3 mixing angles $\theta_a, \theta_s, \theta_x$
- 3 complex phases δ, ϕ_2, ϕ_3 (CP)

Oscillation probabilities do not depend on ϕ_2, ϕ_3

Empirically, the observed oscillations have very different Δm^2 scales and are nearly decoupled

Useful effective 2-neutrino approximation when one Δm^2 is dominant

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

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2 2\theta \sin^2 \Delta$$

$$P(\nu_\alpha \rightarrow \nu_a) \approx 1 - \sin^2 2\theta \sin^2 \Delta$$

independent $\Delta m^2 = N_\nu - 1$

Matter effects on ν_e oscillations

ν_e scattering on electrons modifies ν_e oscillation amplitudes and wavelengths in matter

$$\sin^2 2\theta^m = \frac{\sin^2 2\theta}{\left(\frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

Enhancement for $\Delta m^2 > 0$

Suppression for $\Delta m^2 < 0$

Crucial for:

- solar neutrinos (N_e varies)
- long-baselines through Earth (E_ν varies)

Analogous matter effects on oscillations to steriles ($N_e \rightarrow N_e/2$)

Where we stand today: Evidence of oscillations

Atmospheric neutrinos

SuperKamiokande, Macro, Soudan, …

ν_μ and $\bar{\nu}_\mu$ disappear

ν_e and $\bar{\nu}_e$ do not

$\theta_a \sim 45°, \quad \theta_x$ small

$\Delta m_a^2 \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

Solar neutrinos

SNO, SuperK, Gallium, Chlorine

ν_e disappear

$\theta_s \sim 33°$

$\Delta m_s^2 \sim 6 \times 10^{-5}\ \mathrm{eV}^2$

LMA solution ($\Delta m_s^2 > 0$)

matter enhancement,
but not resonant

Reactor antineutrinos

KamLAND, $L \approx 175$ km

$\bar{\nu}_e$ disappear

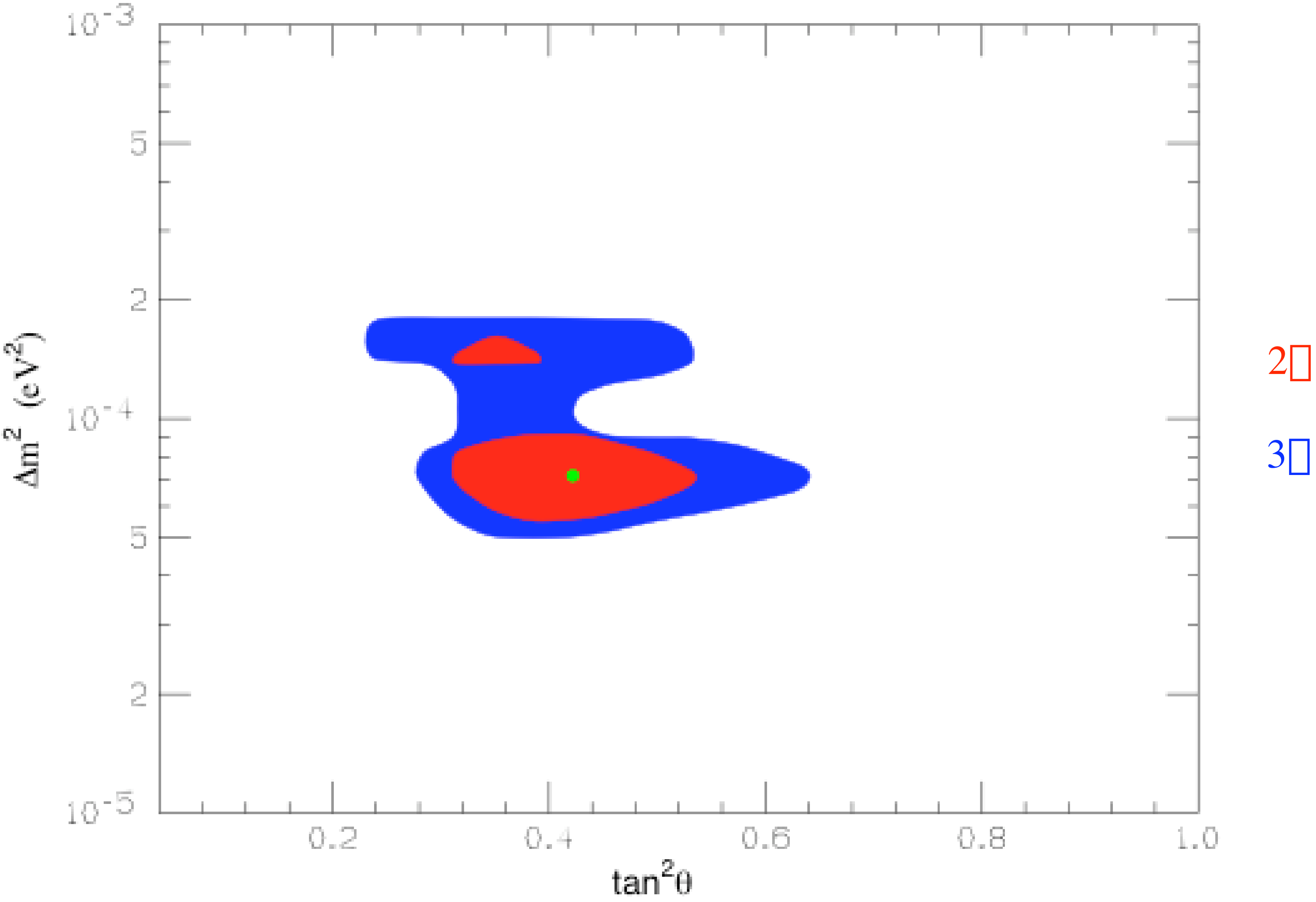
$\Delta m_s^2 \sim 7 \times 10^{-5}\ \mathrm{eV}^2$

Confirms LMA

KamLAND + Solar further constrains Δm_s^2

KamLAND massacre: all other solar solutions killed

Solar + KamLAND



Reactor antineutrinos   CHOOZ, $L \approx 1$ km

$\bar{\nu}_e$ do not disappear

$\theta_x \leq 9°$

Accelerator antineutrinos   LSND, KARMEN

$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance $\Delta m^2_{\mathrm{LSND}} \sim 0.1 - 1\ \mathrm{eV}^2$

$\theta_{\mathrm{LSND}} \sim 0.5°$

Limits on

$\nu_\mu \to \nu_s$ atm

$\nu_e \to \nu_s$ solar

$\nu_\mu \to \nu_\mu$ accelerator/reactor at short baselines

Barely acceptable global fits in models with sterile neutrinos
(tension between atm/solar and SBL)

Is cosmology consistent with steriles?

Neutrino Counting in the Early Universe

Photons and light neutrinos dominate the relativistic energy density at very early epochs

Extra neutrinos speed up the expansion of the Universe

Cosmic Microwave Background (TT power spectrum)

age ≈ 380,000 years

$N_\nu = 0.9–8.3$ (2σ range)

Big Bang Nucleosynthesis (D and ^{4}He)

age ≈ few minutes

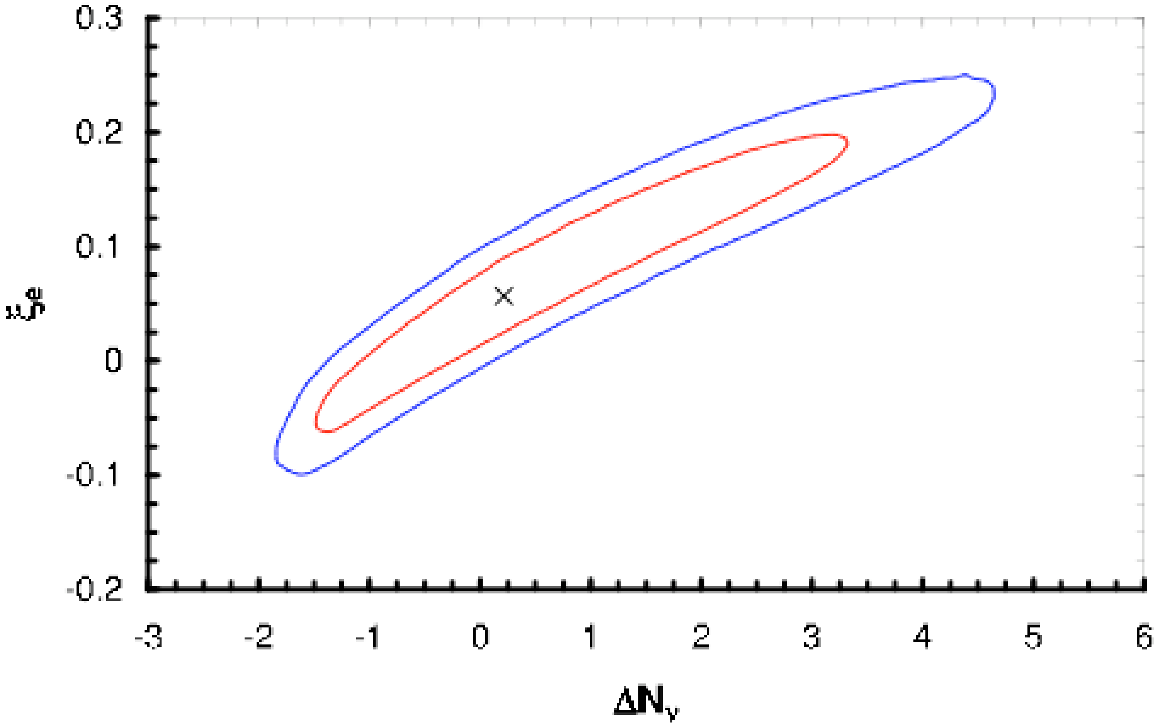
$N_\nu = 1.7–3.0$ (2σ range)

LSND sterile neutrino would be fully thermalized by BBN era.

Standard BBN cosmology rejects it.

Houdini's escape from the BBN constraints

A large asymmetry between numbers of ν_e and $\bar{\nu}_e$ in the early universe allows extra neutrinos



$$L_e = \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \approx 0.7\,\xi_e$$

degeneracy parameter

$$\xi_e \equiv \frac{\mu_e}{T}$$

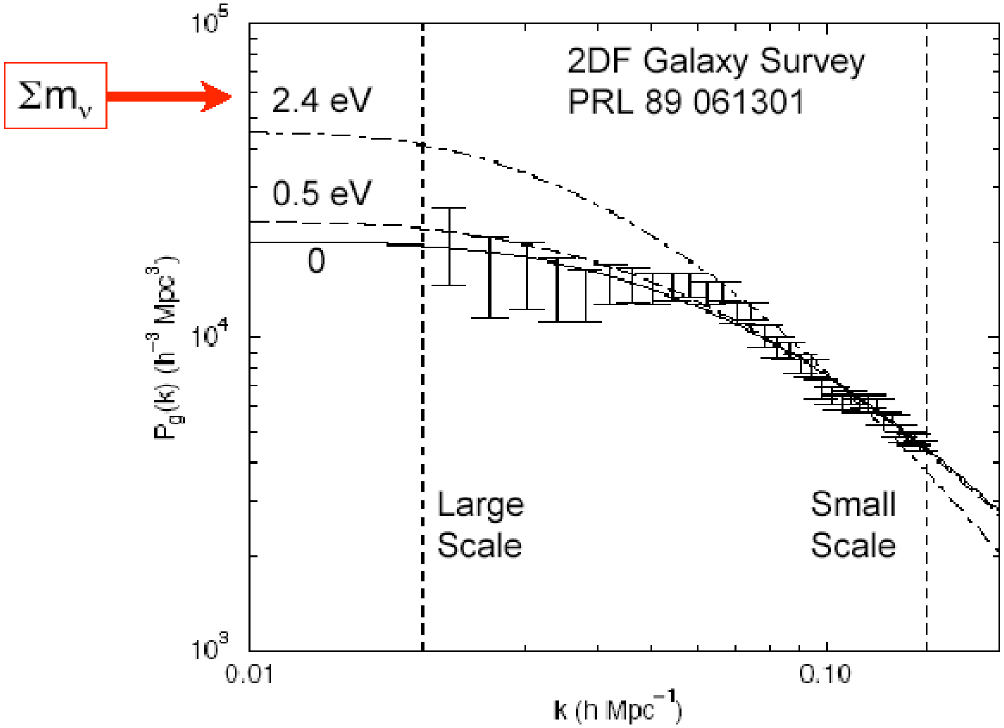
$$\left(\frac{n}{p}\right)_{equil} = \exp\left[-\frac{\Delta m_{np}}{T} - \xi_e\right]$$

ξ_e reconciles LSND neutrino with BBN by suppressing its thermalization prior to BBN

LSND sterile neutrino implies $\dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \sim 0.01 - 0.1$

Huge compared to baryon asymmetry $\dfrac{n_B}{n_\gamma} \sim 10^{-9}$

Neutrino mass and Large Scale Structure in the Universe



Even small $\sum m_\nu$ influences power spectrum of galaxy correlations

Neutrinos that are more massive cluster more on large scales

$\sum m_\nu < 0.7$ eV 2dF + Lyα Forest + WMAP

$\sum m_\nu < 1$ eV 2dF + WMAP

LSND $\Delta m_\nu \geq \sqrt{\Delta m^2_{LSND}} \geq 0.3$ eV

Just escapes LSS bounds

Final resolution of LSND sterile neutrino awaits miniBooNE

3 neutrino observables	Present knowledge	Near Future
θ_a	45° ± 9°	$P(\nu_\mu \to \nu_\mu)$ MINOS , CNGS
θ_s	33° ± 3°	$P(\nu_e \to \nu_e)$ SNO
θ_x	≤ 9°	$P(\bar\nu_e \to \bar\nu_e)$Reactor, $P(\nu_\mu \to \nu_e)$LBL
Δm_a^2	$(2.5^{+2}_{-1}) \times 10^{-3}\,\mathrm{eV}^2$	$P(\nu_\mu \to \nu_\mu)$ MINOS , CNGS
sign(Δm_a^2)	unknown	$P(\nu_\mu \to \nu_e)$, $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
Δm_s^2	$(7.\pm 2.) \times 10^{-5}\,\mathrm{eV}^2$	$P(\bar\nu_e \to \bar\nu_e)$ KamLAND
sign(Δm_s^2)	+ (MSW)	done
δ	unknown	$P(\nu_\mu \to \nu_e)$, $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
Majorana	unknown	0$\nu\beta\beta$
□$_2$	unknown	0$\nu\beta\beta$ (if ≈ 0, □)
□$_3$	unknown	hopeless
m_ν	$\Sigma m_\nu < 1$ eV	LSS, 0$\nu\beta\beta$, β-decay

Key Neutrino Issues
and how they are being/can be solved

Key issue #1: VERIFY OSCILLATIONS / PRECISION

“See” the oscillation wiggles versus energy, not just average suppressions

$$\boxed{P(\bar{\nu}_e \to \bar{\nu}_e) \qquad \Delta m_s^2}$$

KamLAND

$$\boxed{P(\nu_\mu \to \nu_\mu) \qquad \Delta m_a^2}$$

K2K (250 km) MINOS (730 km) CNGS (730 km)

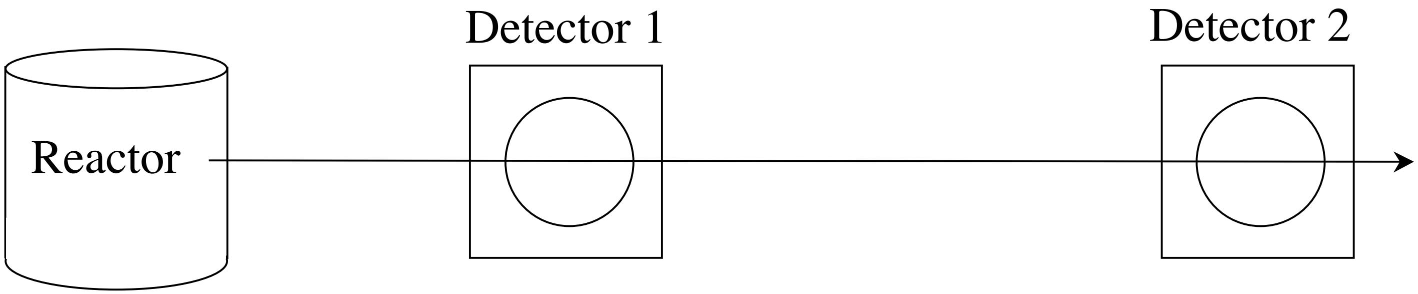
Observe ν_τ appearance

$$\boxed{P(\nu_\mu \to \nu_\tau) \qquad \Delta m_a^2}$$

CNGS (OPERA)

KEY ISSUE #2: HOW SMALL IS θ_x?

Proposed reactor experiments with two detectors
Short L (< few km)



Measure θ_x from wiggles in $P(\bar{\nu}_e \to \bar{\nu}_e)$ vs. energy

Sensitivity limit: $\sin^2 2\theta_x \approx 0.01$

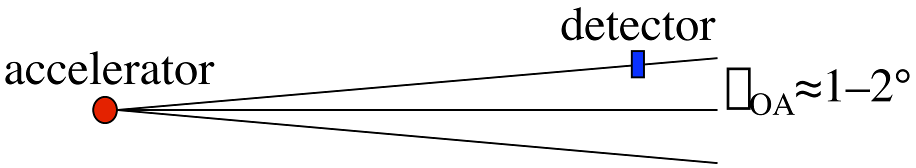
	L_1	L_2
Krasnoyarsk	0.1 km	1 km
Kashiwazaki	0.3 km	1.7 km
LBNL	1 km 6 km	3 km 7.8 km

Future accelerator experiments

Measure θ_x via appearance:

$P(\nu_\mu \to \nu_e)$ or $P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_x \sin^2\theta_a$

- Off-axis "magic" (JHF, FNAL)



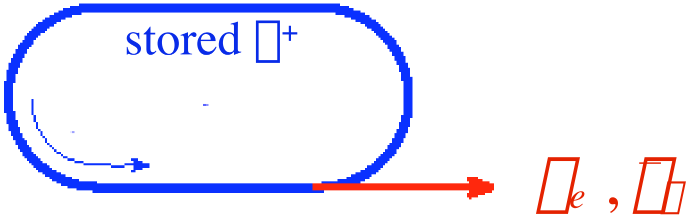
~ monochromatic E_ν, lower backgrounds

- Superbeams (upgrades ×4–5)

  Off-axis or Wide-band* (BNL)

  *binning quasi-elastic events gives equivalent of many narrow-band beams

- Neutrino factory



Golden channel: $\nu_e \to \nu_\mu$

- New detector technologies with 50–500 kton sizes
  - low-*Z* calorimeter
  - liquid Argon
  - water Cherenkov
  - iron scintillator

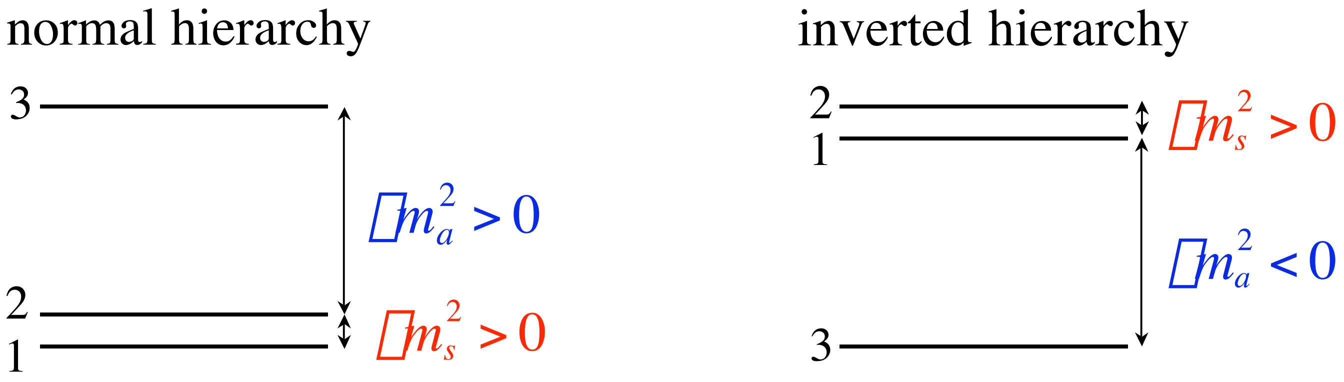
Approximate discovery reaches in $\sin^2 2\theta_x$

Current limit	**10^{-1}**
Reactor	**10^{-2}**
Conventional ν-beam	**10^{-2}**
Superbeam	**3×10^{-3}**
NuFact (entry level)	**5×10^{-4}**
NuFact (high performance)	**5×10^{-5}**

How low in $\sin^2 2\theta_x$ will we need to go?

KEY ISSUE #3: MASS HIERARCHY?

Present data allow 2 mass orderings

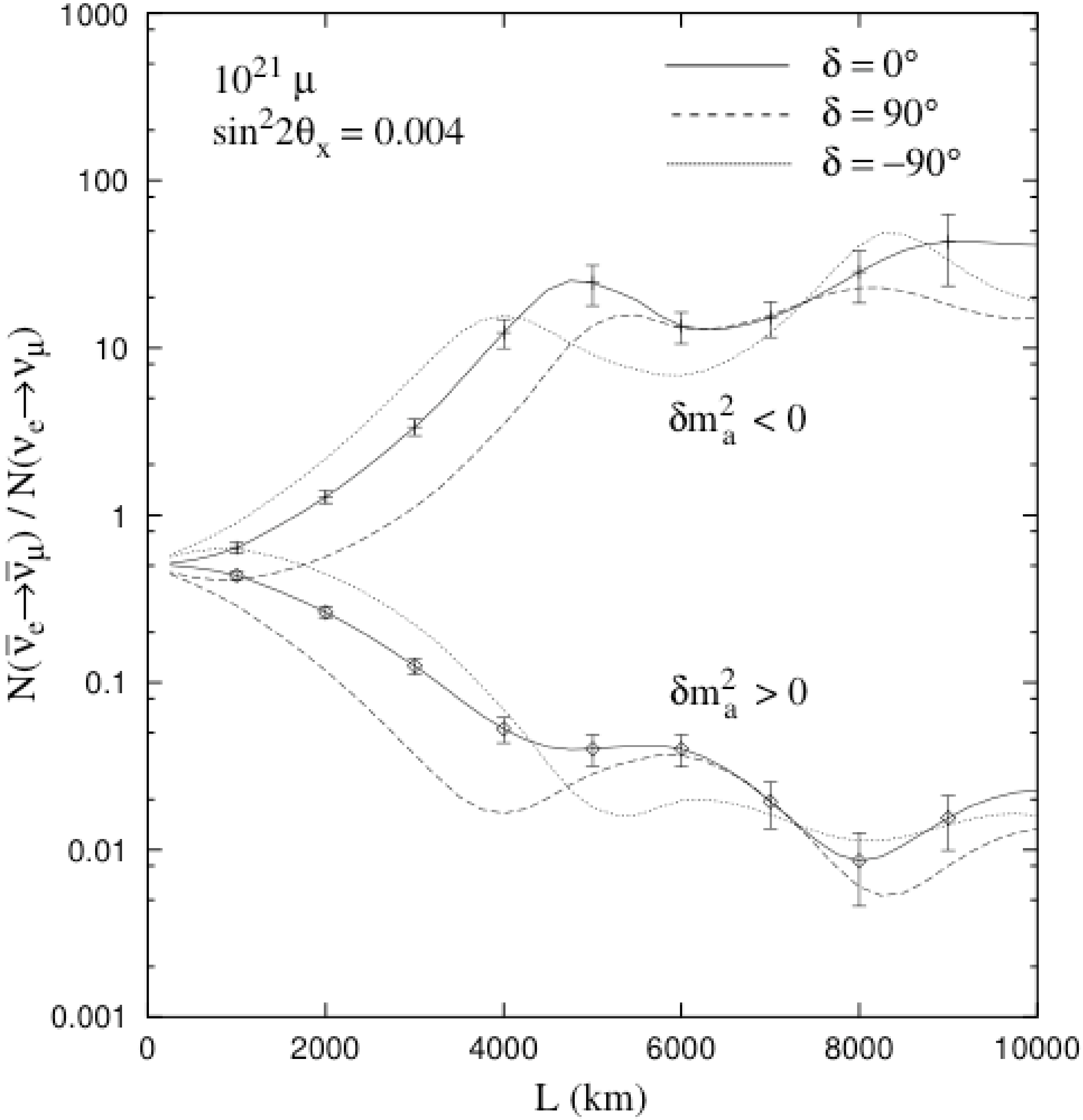


Grand Unified Theories
predict normal hierarchy

Earth matter effects

- enhance $P(\nu_\mu \to \nu_e)$ and suppress $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or vice-versa, depending on sign of Δm_a^2
- increase with distance
- long baselines needed ($L > 900$ km) to determine hierarchy

Neutrino factory: Hairpin prediction



Error bars:
2□10^{20} decays/yr
for 5 years

KEY ISSUE #4: CP VIOLATION?

Is $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$? (intrinsic)

$$\Delta P \approx \left(\frac{\Delta m_s^2}{\Delta m_a^2}\right) \sin\delta \sin^2 2\theta_x \qquad \frac{\Delta P}{P} \sim \frac{\sin\delta\,\theta_s}{\theta_x}$$

- δ measurement depends on θ_x ($\sin\theta_x e^{-i\delta}$ in **V**)
- Both Δm_s^2 *and* Δm_a^2 oscillations must contribute
- Must distinguish intrinsic CP-violation from fake CP-violation due to matter effects

Magic baselines $P(\nu_\mu \rightarrow \nu_e)$

$L/E_\nu \approx 500$ km depends only on $\sin\delta$ (not $\cos\delta$)

$L \approx 7600$ km no δ-dependence (no CP-violation)
— matter oscillation wavelength

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

	$\mathrm{sign}(\Delta m_a^2)$	CP-violation
Superbeam	3×10^{-3}	3×10^{-2}
NuFact (entry level)	3×10^{-4}	2×10^{-3}
NuFact (high performance)	1×10^{-4}	5×10^{-4}

Must resolve degeneracies that can confuse CP-violating and CP-conserving solutions

Parameter sets that give same

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at one L

Eight-fold degeneracy

(δ, θ_x)

$\mathrm{sign}(\delta m_a^2) = \pm$

$\left(\theta_a, \frac{\pi}{2} - \theta_a\right)$ if $\theta_a \neq \frac{\pi}{4}$

Best strategies:

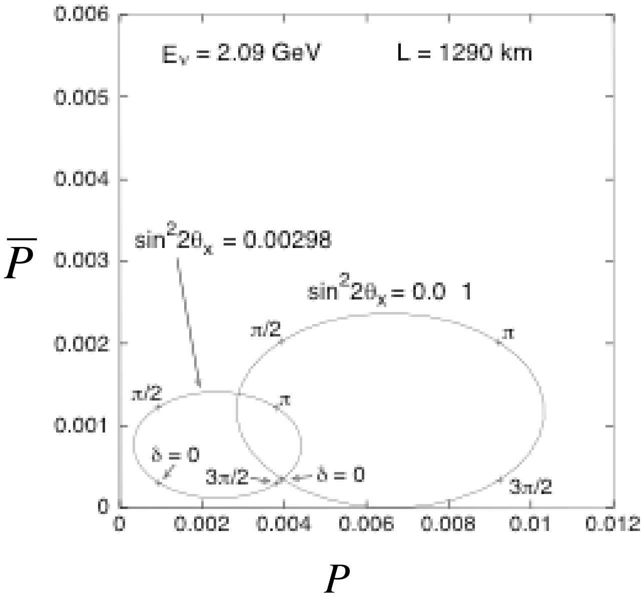
1) detector at first oscillation peak
2) long L (>1000 km)
3) 2 distances

8-fold parameter degeneracy

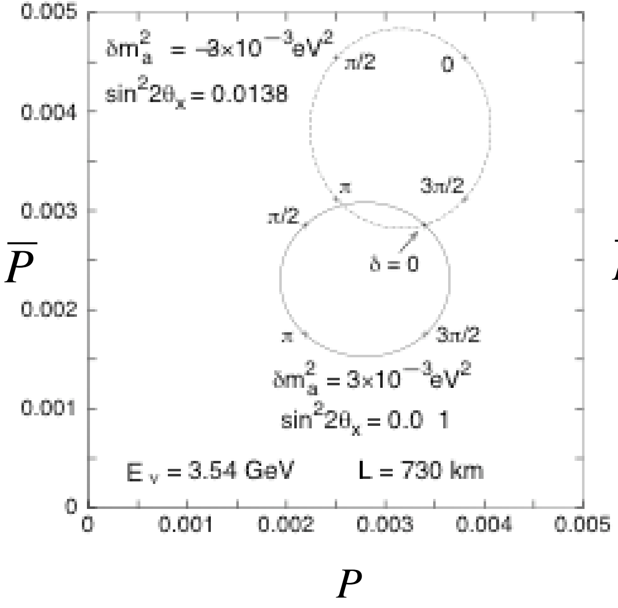
$P(\nu_\mu \to \nu_e)$ vs. $\bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)$

θ_x fixed, δ varied

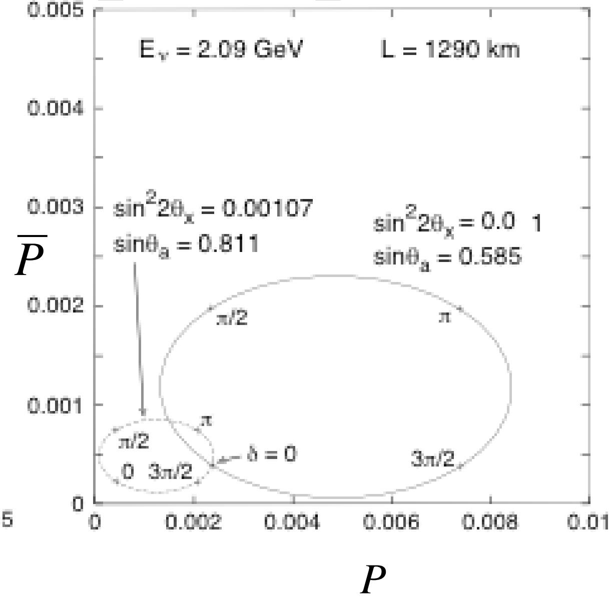
(δ, θ_x) degeneracy



sign(δm_a^2) degeneracy



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



KEY ISSUE #5: 3×3 MIXING MATRIX UNITARITY?

Need to measure all elements

ν_e beams required: only at a neutrino factory

channel	detect
$\nu_\mu \to \nu_\mu$	μ^-
$\nu_\mu \to \nu_e$	e^-
$\nu_\mu \to \nu_\tau$	τ^-
$\bar{\nu}_e \to \bar{\nu}_e$	e^+
$\bar{\nu}_e \to \bar{\nu}_\mu$	μ^+
$\bar{\nu}_e \to \bar{\nu}_\tau$	τ^+

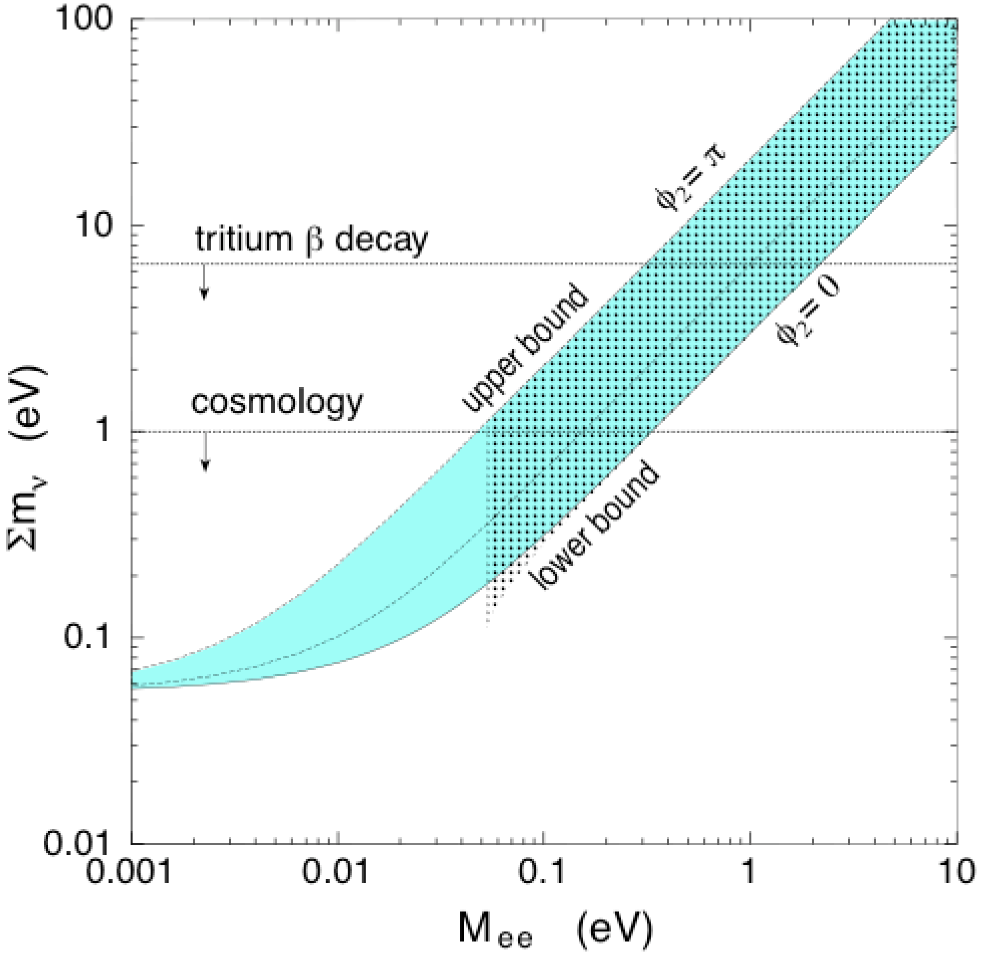
With ν_e beams can also test time reversal violation

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

KEY ISSUE #6: DIRAC OR MAJORANA?

Neutrinoless double-β decay *only if* neutrinos are Majorana

$$\left|M_{ee}\right| = \left\{\tfrac{2}{3}\Sigma \mp \tfrac{1}{3}\left[\Sigma^2 + 3\delta m_a^2\right]^{1/2}\right\}\left|c_s^2 + s_s^2 e^{i\phi_2}\right|$$



Neutrinoless double-β decay can constrain Σm_ν (upper and lower bounds)

KEY ISSUE #7: WHAT THEORY?

See-Saw mechanism favored

$$m_\nu \sim \frac{m_D^2}{M_N}$$

N_R: singlets in GUT representations

GUT models can accommodate all
quark and lepton data

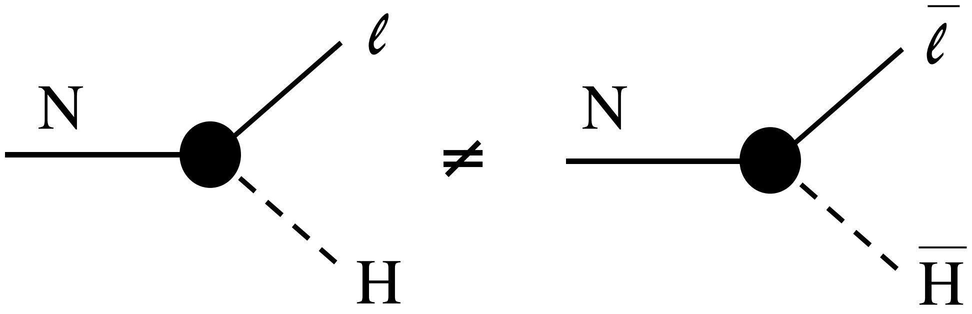
Make differing predictions for θ_x and CP violation

KEY ISSUE #8: LEPTOGENESIS?

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

Baryon number could be associated with violation of lepton number

Lepton asymmetry from decays of heavy right-handed neutrinos



In some models, sign of cosmological baryon number is related to the CP phase in neutrino oscillations

These models make testable low energy predictions

SUMMARY

Neutrino mass is the first discovery of physics beyond the Standard Model.

Oscillation experiments "on the table" have great potential for another breakthrough in measuring θ_x.

The future of oscillation physics is very bright, with Superbeams and longer baselines as the next horizon

Whatever experiments accomplish over the next decade, Neutrino Factories will be essential to reconstruct all neutrino mixings with high precision. Combine Neutrino Factory and Superbeam data.

If theoretical prejudices for Grand Unified Theories are correct, neutrino mass owes its origin to right-handed neutrinos with masses near the GUT scale.

The sign of the baryon asymmetry may be related to the CP phase in neutrino oscillations.

These and other ideas can soon be "put to the test," at least in the context of models, by measuring θ_x, $\text{sign}(\Delta m_a^2)$ and δ.

Neutrino physics has always been full of surprises. There will likely be more surprises to comes!