Neutrino Physics: Lecture 12

Sterile neutrinos

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Outline

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SBLs: When only one Δm^2 matters

No CP violation, any number of neutrinos:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - \sum_{i<j} 4\mathrm{Re}(\square_{\alpha\beta ij}) \sin^2(\Delta_{ji})$$

$$\square_{\alpha\beta ij} \equiv U_{\alpha_i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i}$$

Approximation of single mass-squared dominance

- All significant Δ_{ji} nearly equal, $\approx \Delta$
- All other Δ_{ji} negligible, ≈ 0

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{eff} \sin^2(\Delta)$$

$$P_{\alpha\beta} = \sin^2 2\theta_{eff} \sin^2(\Delta) \qquad (\alpha \neq \beta)$$

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Equi-probabilty contours

$$\sin^2 2\theta_{eff} \sin^2(\Delta) = \text{ Constant}$$

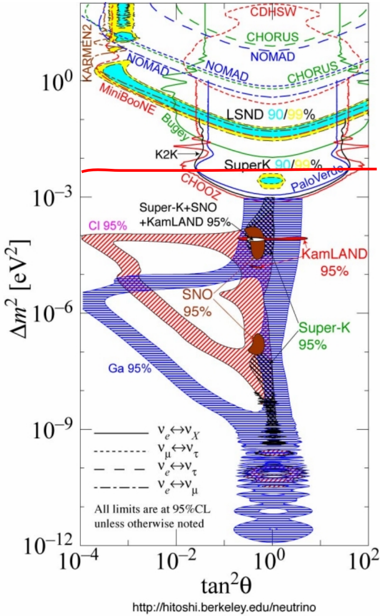
Short baseline and sensitivity to Δm^2

$\Delta \sim 1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)}$

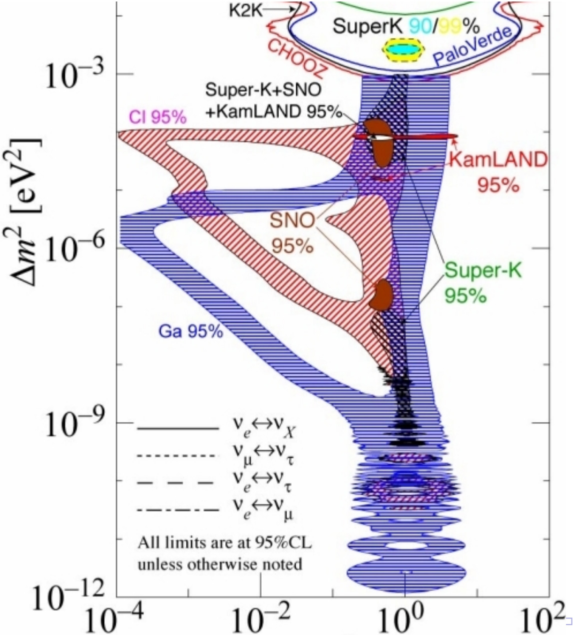
Nontrivial $P_{\alpha\alpha}$ or $P_{\alpha\beta}$ only when $\Delta \gtrsim 1$

- Atmospheric neutrinos:
  $E \sim 1$ GeV, $L \sim 10^3$ km $\Rightarrow \Delta m^2 \gtrsim 10^{-3}$ eV^2
- Reactor neutrinos:
  $E \sim 1$ MeV, $L \sim 1$ km $\Rightarrow \Delta m^2 \gtrsim 10^{-3}$ eV^2
- Long baseline experiments:
  $E \sim 1$–10 GeV, $L \sim 10^3$–10^4 km $\Rightarrow \Delta m^2 \gtrsim 10^{-3}$ eV^2
- Accelerator (short baseline) experiments:
  $E \sim 10$–100 MeV, $L \sim 1$ km $\Rightarrow \Delta m^2 \gtrsim 10^{-2}$–$10^{-1}$ eV^2

Neutrino experiments with 2ν approximation

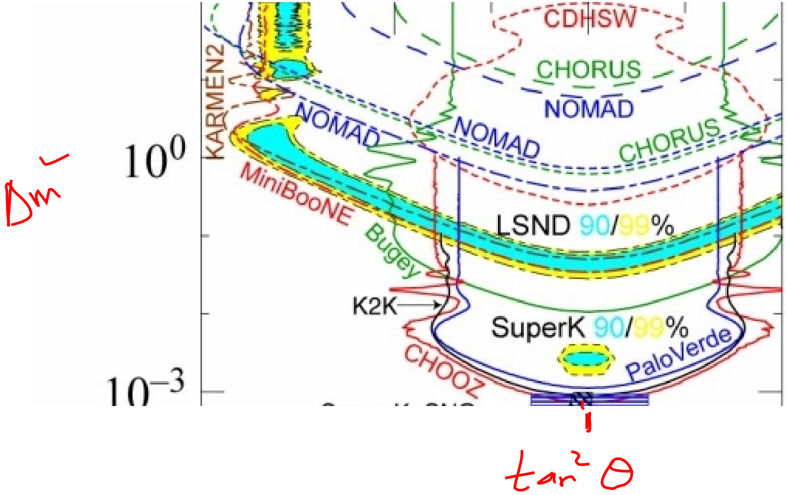


Solar and atmospheric experiments

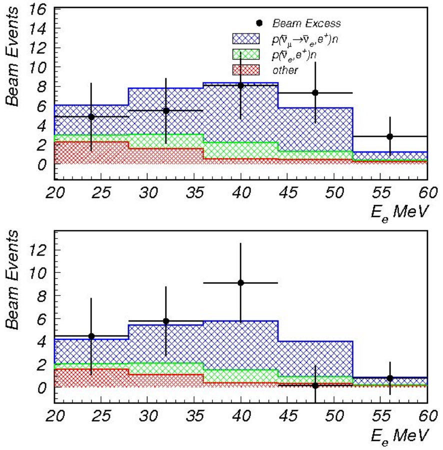


$\tan^2\theta$

Results from short baseline experiments

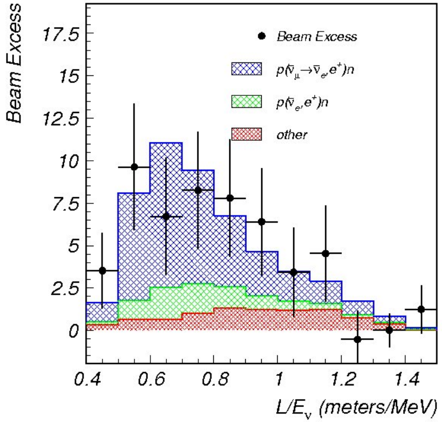


The LSND excess



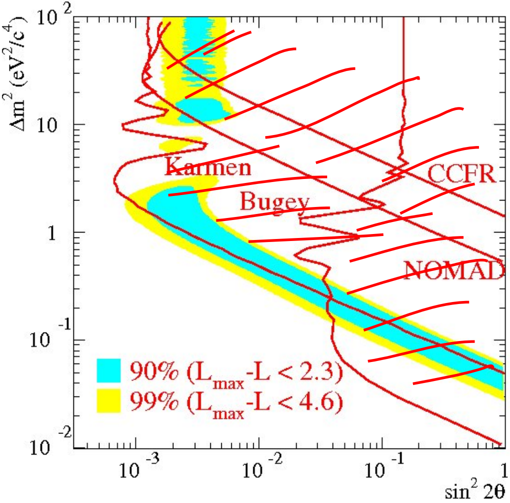
- $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations !
- Excess = $87.9 \pm 22.4 \pm 6.0$ events

L/E oscillations in LSND



- Oscillation probability $0.264 \pm 0.067 \pm 0.045$
- $\Delta m^2 \approx 0.2$–$10\ \text{eV}^2$

The LSND parameter space



$\Delta m^2 \sim 1\ eV^2$

$\sin^2 2\theta \sim 10^{-2}$

hep-ex/0104049

A fourth neutrino ?

Three independent Δm^2:

- $\Delta m^2_\odot \approx 8 \times 10^{-5}$ eV^2
- $\Delta m^2_{atm} \approx 2.5 \times 10^{-3}$ eV^2
- $\Delta m^2_\odot \approx 0.2$–$10$ eV^2

Not possible with only three neutrino masses !

A fourth neutrino species must be present

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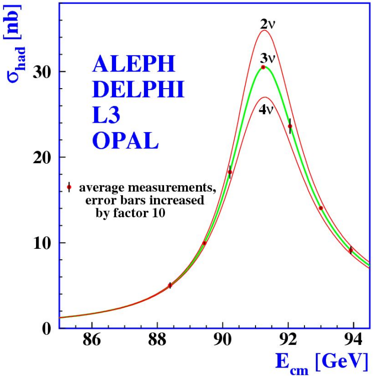
A fourth generation neutrino ?



- LEP: $e^+e^- \to Z \to f\,\bar{f}$
- Effective number of neutrinos: $N_\nu = 2.985 \pm 0.008$
- Only three light neutrinos interact with Z
- The fourth neutrino has to be sterile !

What is a (light) sterile neutrino

- A fermion without electric charge
- Does not have electroweak interactions
  (Does not interact with W, Z, γ)
- Can have interactions beyond the Standard Model (BSM)
- Can mix with “active” neutrinos due to the BSM interactions
- NOT the right-handed partner of active neutrinos

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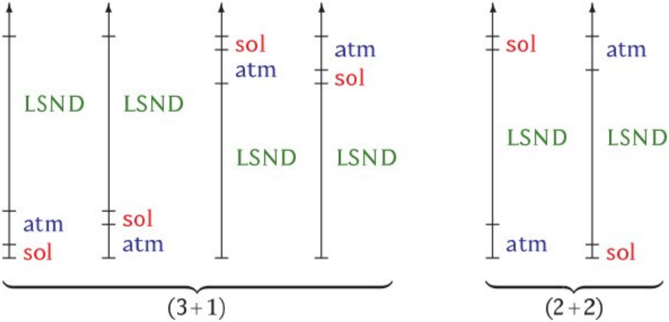
What would the neutrino mass spectrum look like ?

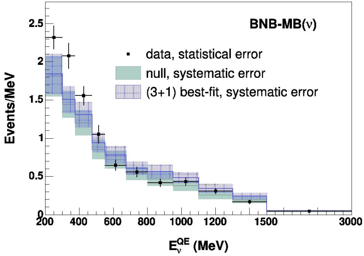


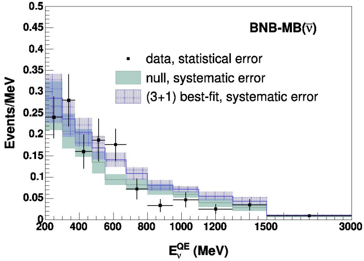
Mixing matrix: 6 angles and 10 phases

$$\mathcal{U} = \Phi(\chi_1, \chi_2, \chi_3, \chi_4)\ U_{14}(\theta_{14}, \delta_{14})\ U_{34}(\theta_{34}, 0)\ U_{24}(\theta_{24}, \delta_{24}) \times U_{23}(\theta_{23}, 0)\ U_{13}(\theta_{13}, \delta_{13})\ U_{12}(\theta_{12}, 0)\ \Phi(\phi_1, \phi_2, \phi_3, 0)$$

Outline

Testing the LSND anomaly

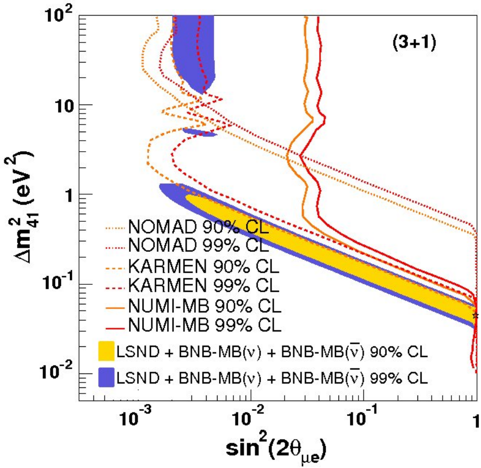




MiniBOONE:

- $E \sim 1$ GeV, $L \sim 1$ km
- ν_μ as well as $\bar{\nu}_\mu$ beams

Constraining sterile ν from appearance experiments



Constraints from disappearance experiments

Solar neutrinos

- SNO indicates that most ν_e go to ν_μ or ν_τ
  $\Rightarrow$ bound on ν_e–ν_s mixing

Atmospheric neutrinos

- Extra contribution to atmospheric oscillations:

$$P_{\mu\mu} \approx P_{\mu\mu}(3\nu) - \frac{1}{2}\sin^2 2\theta_{\mu s}$$

$\Rightarrow$ bound on ν_μ–ν_s mixing

Reactor experiments

- Δm^2_{LSND} would contribute to KamLAND, K2K, MINOS
  $\Rightarrow$ bound on ν_e–ν_s and ν_μ–ν_s mixing
- Δm^2_{LSND} would contribute to CHOOZ
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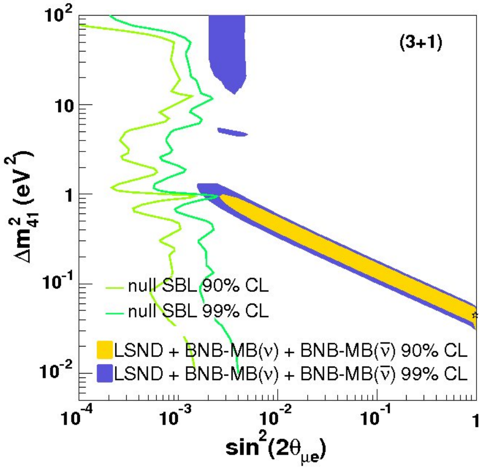
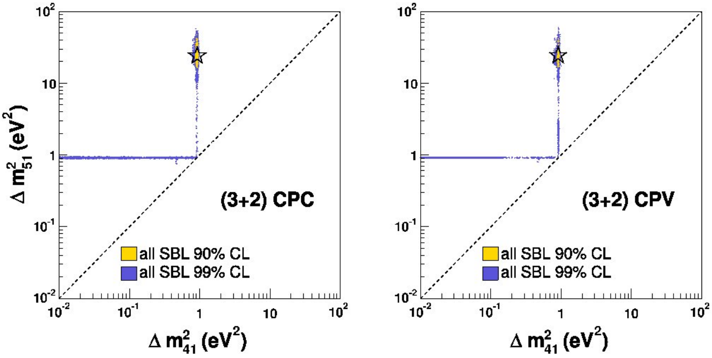
LSND parameter space ruled out



include disappearance expts

ArXiv:0906.1997

Can more than one sterile neutrinos help ?



- Need 2 neutrinos of masses $\gtrsim$ eV
- Constraints from cosmology

Outline

Sterile neutrinos in astrophysics

- Nucleosynthesis of heavy elements (r-process)
  - Heavy elements need more neutrons
  - ν_e tend to reduce number of neutrons: $\nu_e + n \to e^- + p$
  - $\nu_e \to \nu_s$ conversion can allow heavy elements to be formed, if $\Delta m^2 \sim$ 10–100 eV^2

- Supernova explosions
  - Conversions to ν_s carry away energy efficiently $\Rightarrow$ May affect explosion dynamics
  - Can create large asymmetries in ν emission $\Rightarrow$ May explain large pulsar velocities

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Sterile neutrinos in cosmology

- keV neutrinos are viable dark matter candidates
- Can help in producing supermassive black holes
- Predicted by some models (e.g. νMSM) that explain baryon asymmetry

(Not) the last word on sterile neutrinos

- eV-neutrinos not required for explaining oscillation data, Not ruled out either (only mixing constrained)
- Can help some astrophysical phenomena if $\Delta m^2 \sim 10$–$100\ \mathrm{eV}^2$, very small mixing
- keV-neutrinos may play a role in cosmology, structure formation

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