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Sterile Neutrinos & Other Exotic Properties

Constraints and Searches in Reactor Experiments

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Outline

1. Introduction
2. Theoretical digression on sterile neutrinos
3. Present knowledge in sterile neutrinos from oscillation experiments, assuming LSND
4. Bounds on sterile neutrinos from laboratory and cosmological data
5. Search for sterile neutrinos in reactor experiments
6. Potential of sterile neutrino search at Daya Bay
7. Other possible programs for reactor experiments with θ_{13} setup

I. Introdution

- Several important topics in neutrino physics can be clarified by oscillation experiments
  - Measuring θ_{13} , how small is it?
  - Does sterile neutrino exist?
  - Matter effects and CP violation.
  - More accurately determined mixing parameters
- The first two can be done in reactor experiments
- Reactor experiment can also address questions on exotic neutrino properties/applications.

Sterile Neutrinos

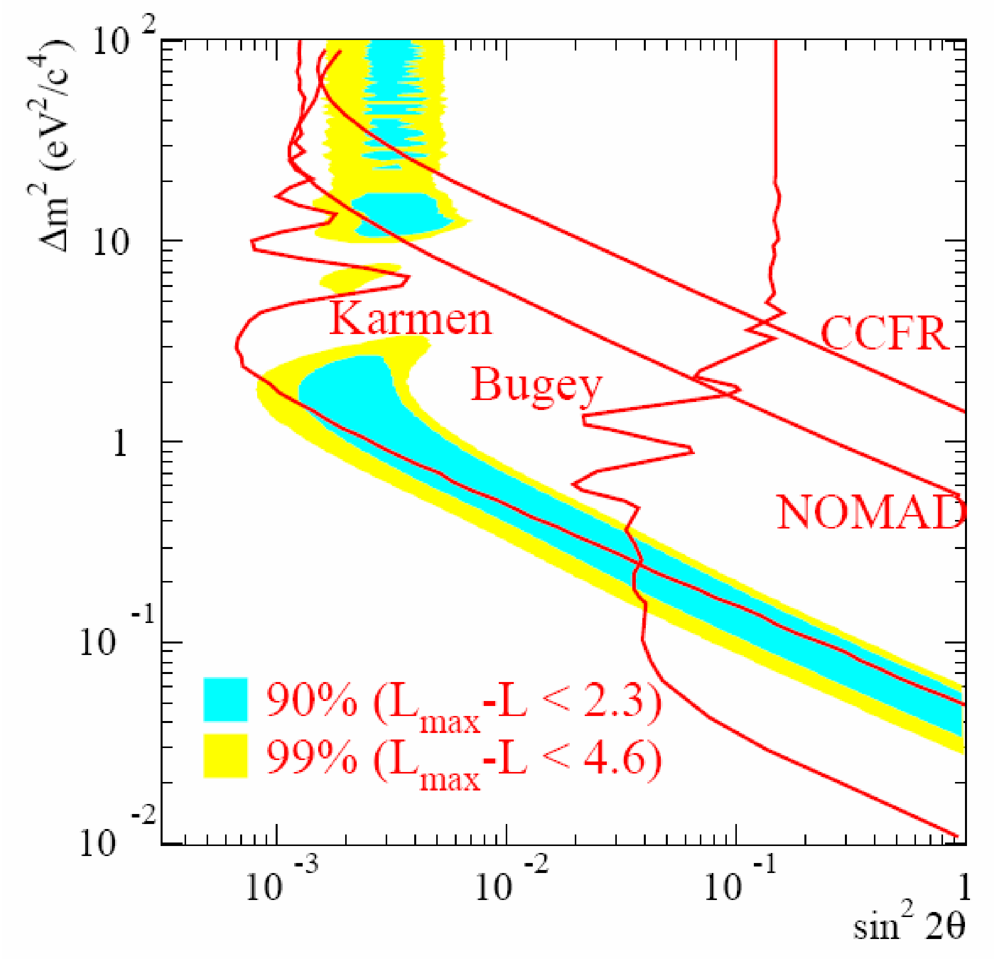
- LSND announced in 1995 a 3.8σ evidence of Oscillation in $\bar{\nu}_\mu \to \bar{\nu}_{\rm e}$ (Aguilar *et al*, 2001)

$$P(\bar{\nu}_\mu \to \bar{\nu}_{\rm e}) = (0.246 \pm 0.067 \pm 0.045)\%$$

$$\Delta m^2 = (0.2 - 10)\ {\rm eV}^2 \text{ and } m_{\rm s} > 0.4\ {\rm eV}$$

- The best fit: $(\sin^2 2\theta,\ \Delta m^2) = (0.003,\ 1.2{\rm eV}^2)$
- Explained as a 2-step process: $\bar{\nu}_\mu \to \bar{\nu}_{\rm s} \to \bar{\nu}_{\rm e}$
  So the sterile neutrino $\bar{\nu}_{\rm s}$ has to have couplings to both $\bar{\nu}_{\rm e}$ and $\bar{\nu}_\mu$.
- LSND also saw a 2σ effect in $\nu_\mu \to \nu_{\rm e}$

To date no other experiments have seen a convincing signal of sterile neutrinos. All oscillation data, other than LSND, can be explained by the SM 3 flavors of active neutrinos.

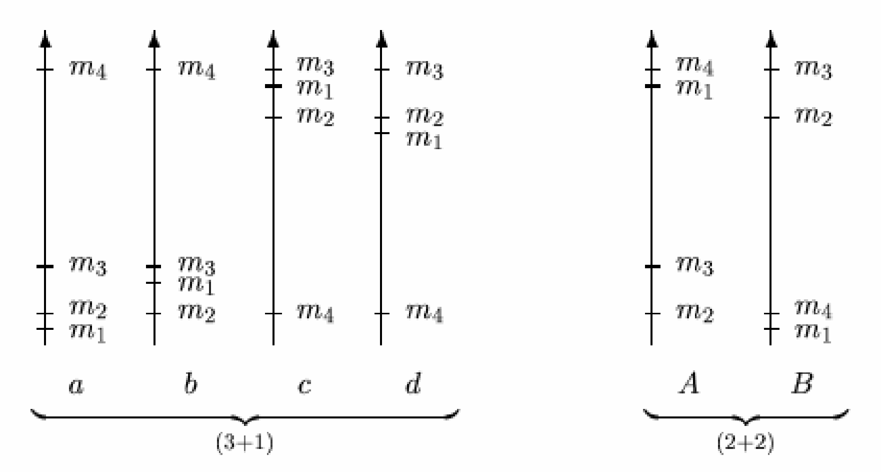


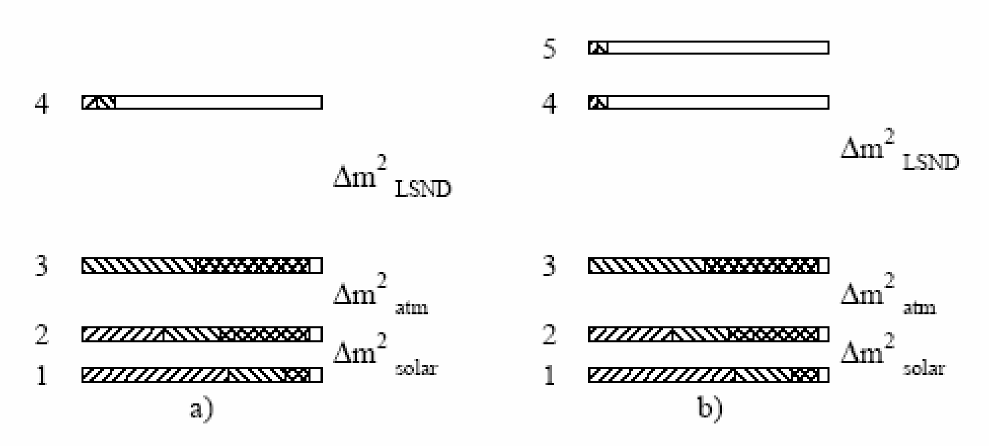
LSND
Aguilar *et al*, 2001

II. Theoretical digressions on sterile neutrinos

- The LSND data require the existence of one or more neutrinos beyond the active ones. They are usually said to be right-handed.
- Sterile neutrinos are natural. Many extensions of SM have neutral fermions like sterile neutrinos which do not interact with the SM gauge bosons. But they may (weakly sterile) or may not (fully sterile) interact with gauge bosons beyond the SM. They should interact with Higgs boson.
- Oscillation phenomenology does not concern with the origin of the sterile neutrinos. It is sufficient to deal with the mixing parameters: For n neutrinos, there are n-1 mass square difference, n(n-1)/2 mixing angle, and (n-1)(n-2)/2 Dirac CP phases.
- Models include 3+1 and 2+2 model for 1 sterile neutrino and 3+2, etc., for 2 or more sterile neutrinos with/out CP.

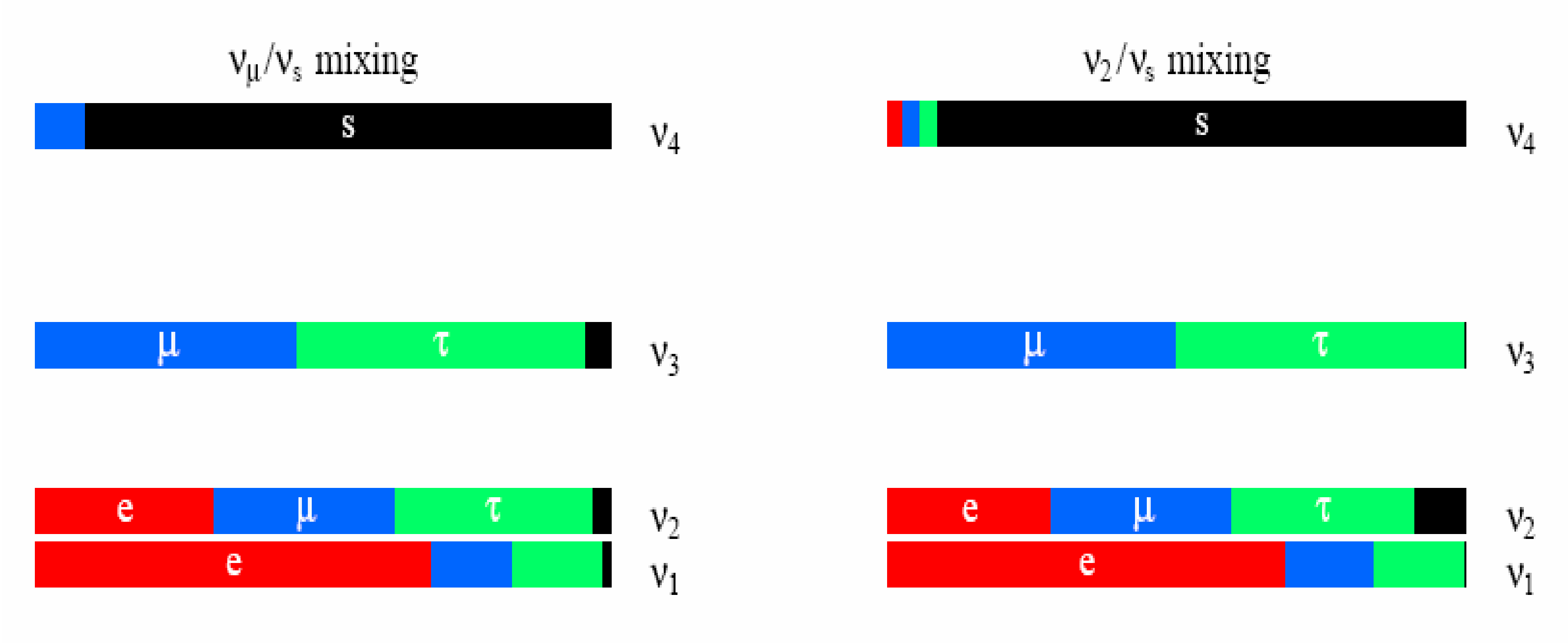
3+1, 2+2, and 3+2 models





Data indicate
Small mixing
among sterile
And active
neutrinos

For specific physics analyses the sterile neutrino can be assumed to mix with a definite flavor state or a definite mass eigenstate, e.g.,



III. Present knowledge in sterile neutrino from oscillation exps., assuming LSND

- Sterile neutrino cannot be a leading effect.
- 2+2 model ruled out by the combined analysis of solar + atmospheric neutrinos.
- 3+1 model is allowed marginally by combined analysis of Bugey + CDHSW (ruled out by 2σ).
- 3+2 model is allowed at the 70% level.
- 3+2 with CP violation is not much constrained.
- Sterile neutrinos are very robust in theoretical considerations and cosmological data analyses.

Why is sterile neutrino so interesting?

- Most of extensions of the SM contain right-handed neutrino and/or neutral fermions (GUT, SUSY breaking, extra dim) which can be manifested as sterile neutrinos.
- Light sterile neutrinos is a challenge to theoretical construction and can have far reaching implications in particle physics and cosmology (quark-lepton symmetry, unification, evolution of early univ, structure formation).
- Heavier sterile neutrinos (~ KeV) are a candidate of warm dark matter (WDM).
- Sterile neutrinos may provide an explanation to anomalies of a number of current laboratory data and cosmological observations.

Why are sterile neutrinos so interesting? -continued

- Most general sterile neutrinos may not be LSND-like, may be connected to electron neutrino but not to muon neutrinos, or vice versa. Then wider searches for sterile neutrinos are possible.
- The discovery of a sterile is no less important than the discovery of the charm quark, opening a new world of fundamental science, to both particle physics and cosmology.

IV. Bounds on sterile neutrinos from lab data and cosmological observations

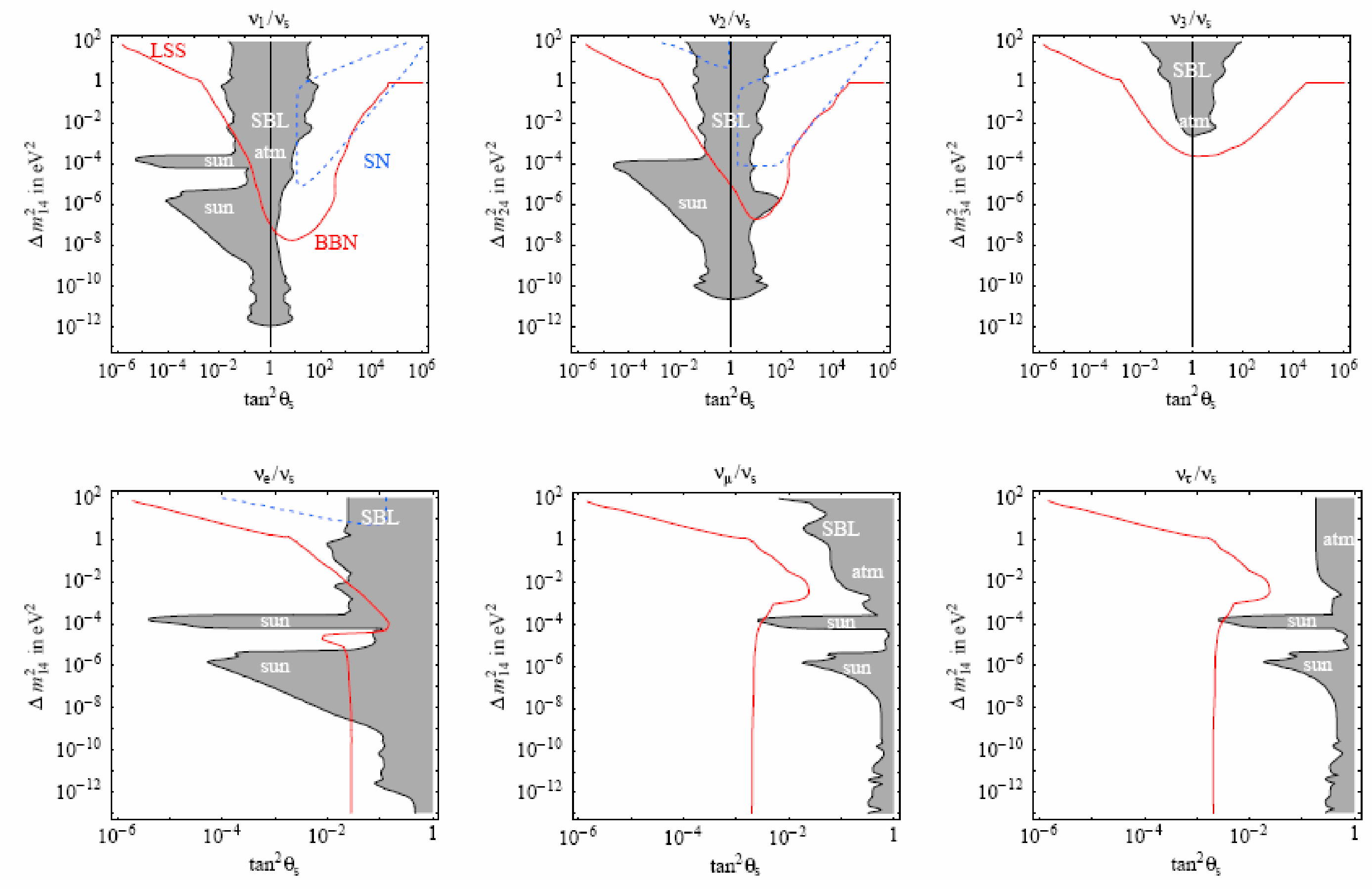
- The six-parameter power-law $\Lambda\mathrm{CDM}$ cosmology based on primordial adiabatic inflation and a cosmological constant is in excellent agreement with precision cosmological observational data. Hence it is meaningful to use cosmological date to test properties of fundamental science.
- An example of the sensitivity of cosmological data is its bound on the absolute mass of neutrino: $\sum m_\nu < 0.76 \text{ eV}$ (Zhang et at; Dodelson et al). The best upper bound in laboratory beta decay measurement (Mainz + Troitsk) gives 1.8 eV.
- Goal of sterile neutrino search: search for effects of sterile neutrinos and identify the $(\sin^2 2\theta_{\alpha \mathrm{s}},\ \Delta M^2_{\mathrm{s}\alpha})$ parameter space allowed.

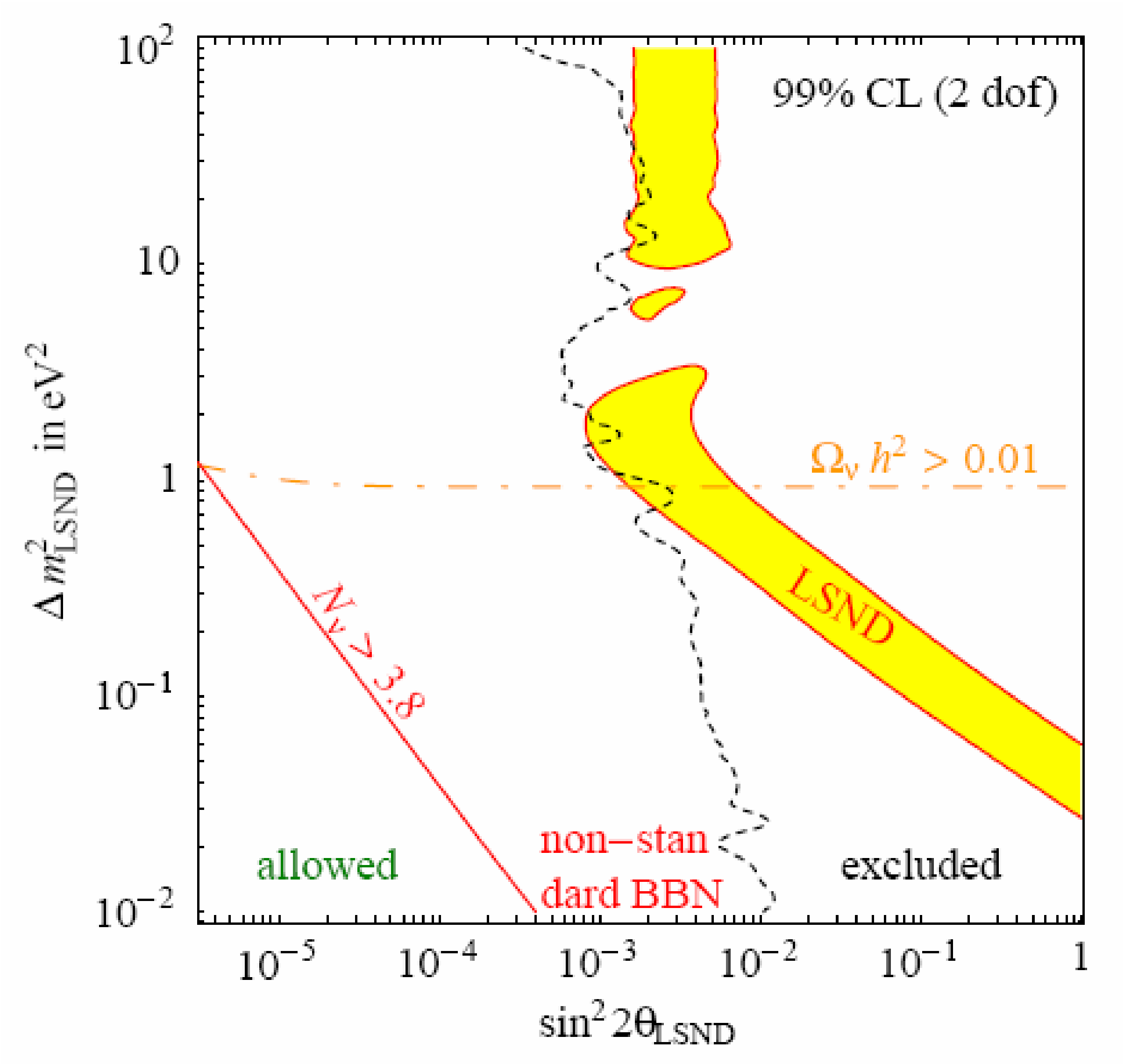
Bounds on sterile neutrinos-continued

- Two large reports (Caveat: analyses not completely inclusive)
  - Cirelli, Marandella, Srtumia, and Vissani hep-ph/0405090.
  - Smirnov and Funchal: hep-ph/0603009
- Laboratory experiments: data in meson decay; beta decay; neutrinoless beta decay; atmospheric, solar, accelerator, and reactor neutrinos
- Cosmological observations: sterile neutrino production, thermalization, and decay, CMB anisotropy, LSS, BBN, x-ray radiation, supernova.
- Conclusion: no compelling evidence for sterile neutrinos other than LSND, but tantalizing hints of sterile neutrinos exist.
- Smirnov: Light sterile substantial effects possible for $\mathrm{m_s} \sim (0.1-1)\mathrm{eV},\ \sin^2\theta_{\alpha\mathrm{s}} \sim (0.001-0.01)$.

Regions of exclusion

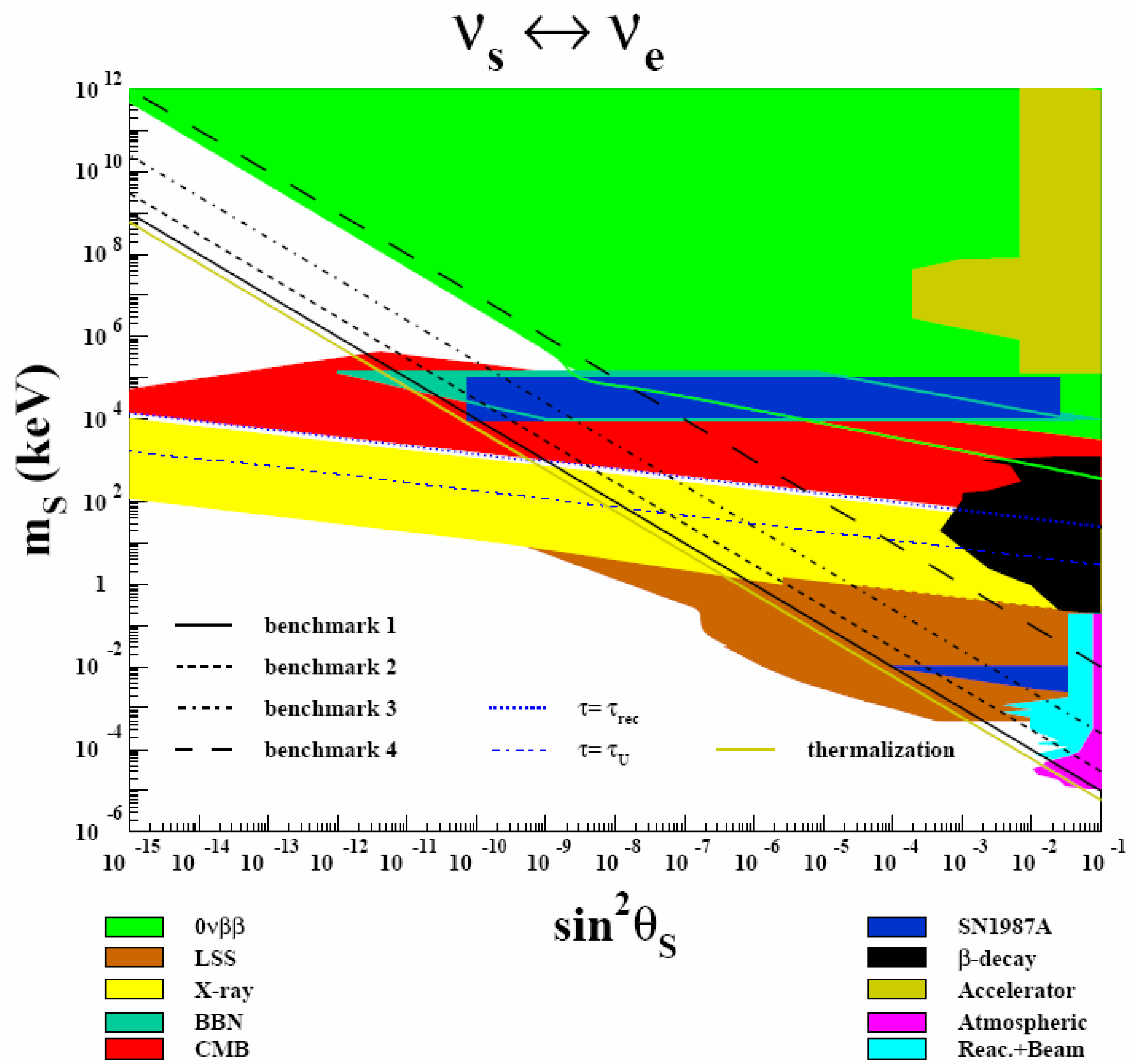
Cirelli *et al*, hep-ph/0403158





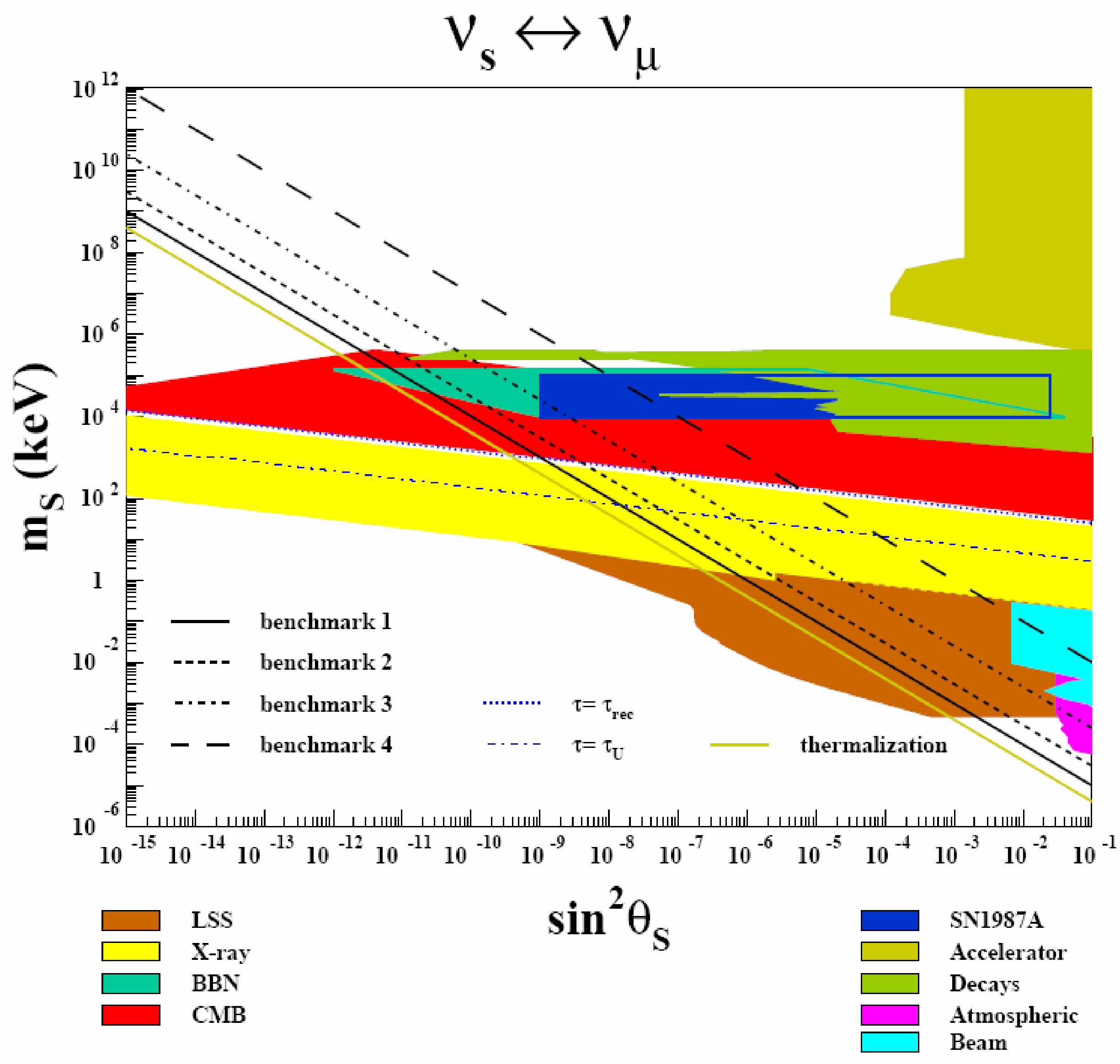
Regions of Exclusion

Cirelli *et al*, hep-ph/ 0503158



Regions of exclusion

Smirnov & Funchal, hep-ph/ 0603090



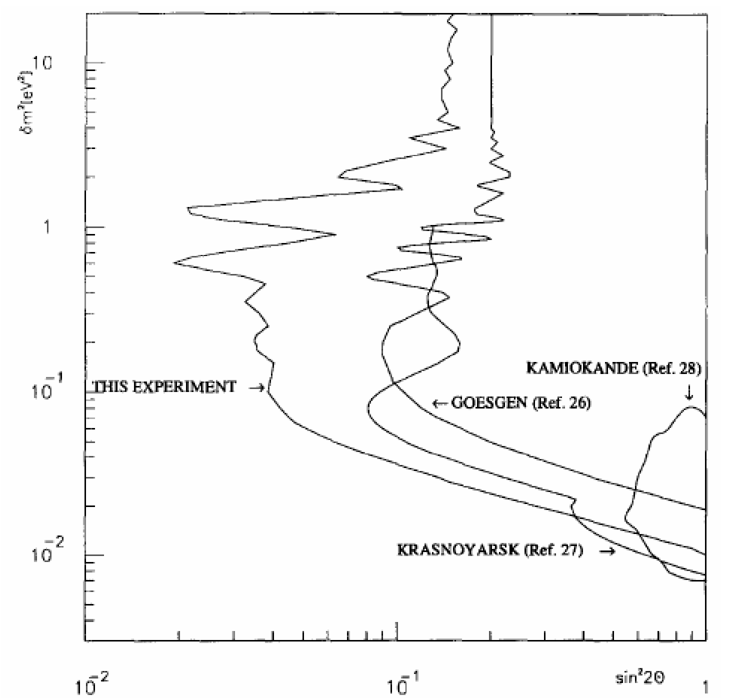
Regions of exclusion

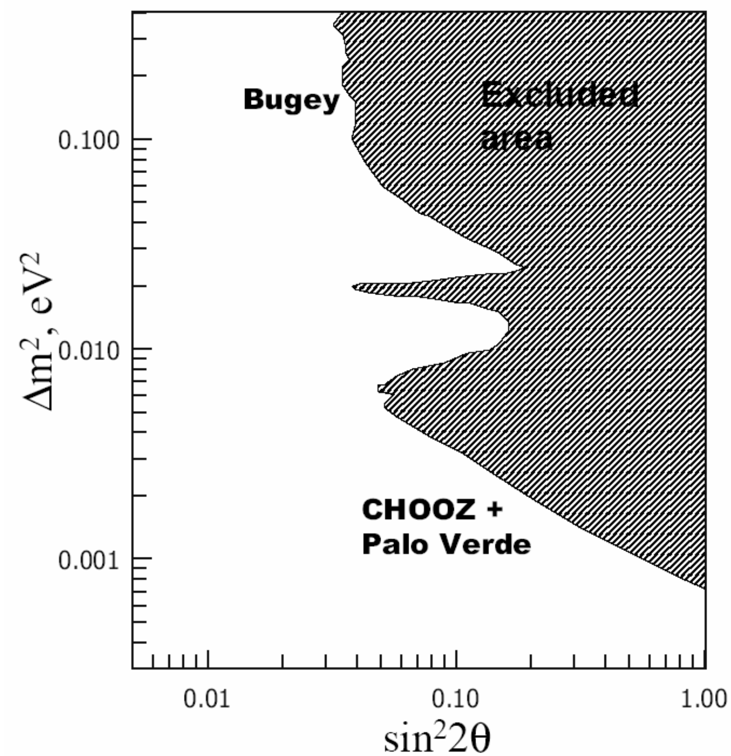
Smirnov & Funchal, hep-ph/ 0603090

V. Search for sterile neutrino in reactor experiments

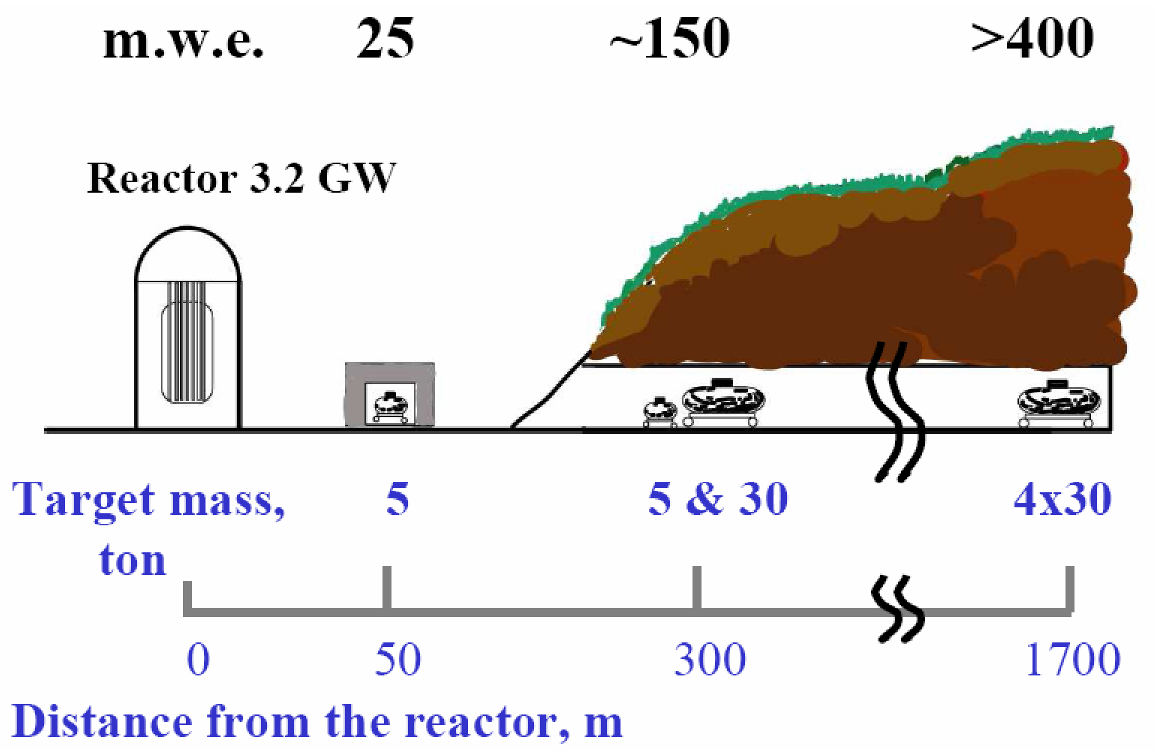
- If the LSND effect is real, a sterile neutrino signal at some level should be visible in reactor experiments.
- Reactor experiment can also search for non-LSND like sterile neutrino-couplings to electron anti-neutrino, not other flavors.
- The best existing reactor bound is given by Bugey: detectors at 15, 40, and 95 meters.

The Bugey + other experiments

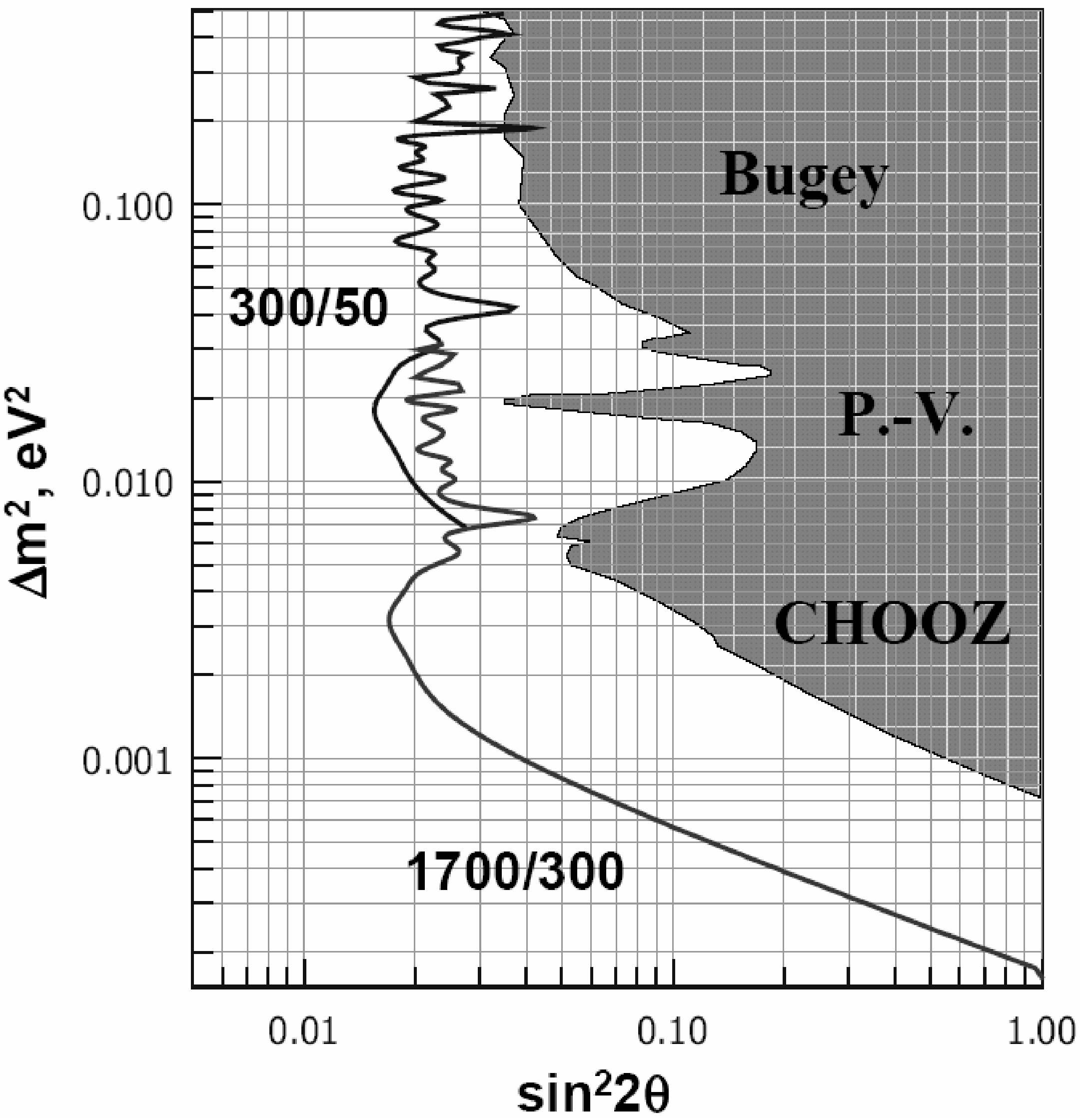




A proposed sterile neutrino search in conjunction with θ_{13}-Kurchatov, Kr2Det



1700 m: 4 detectors, total target mass ~120 t
300 m: 1 det. 30 t target + 1 small det. of 5 t targets
50 m: 1 small detector 5 t target mass



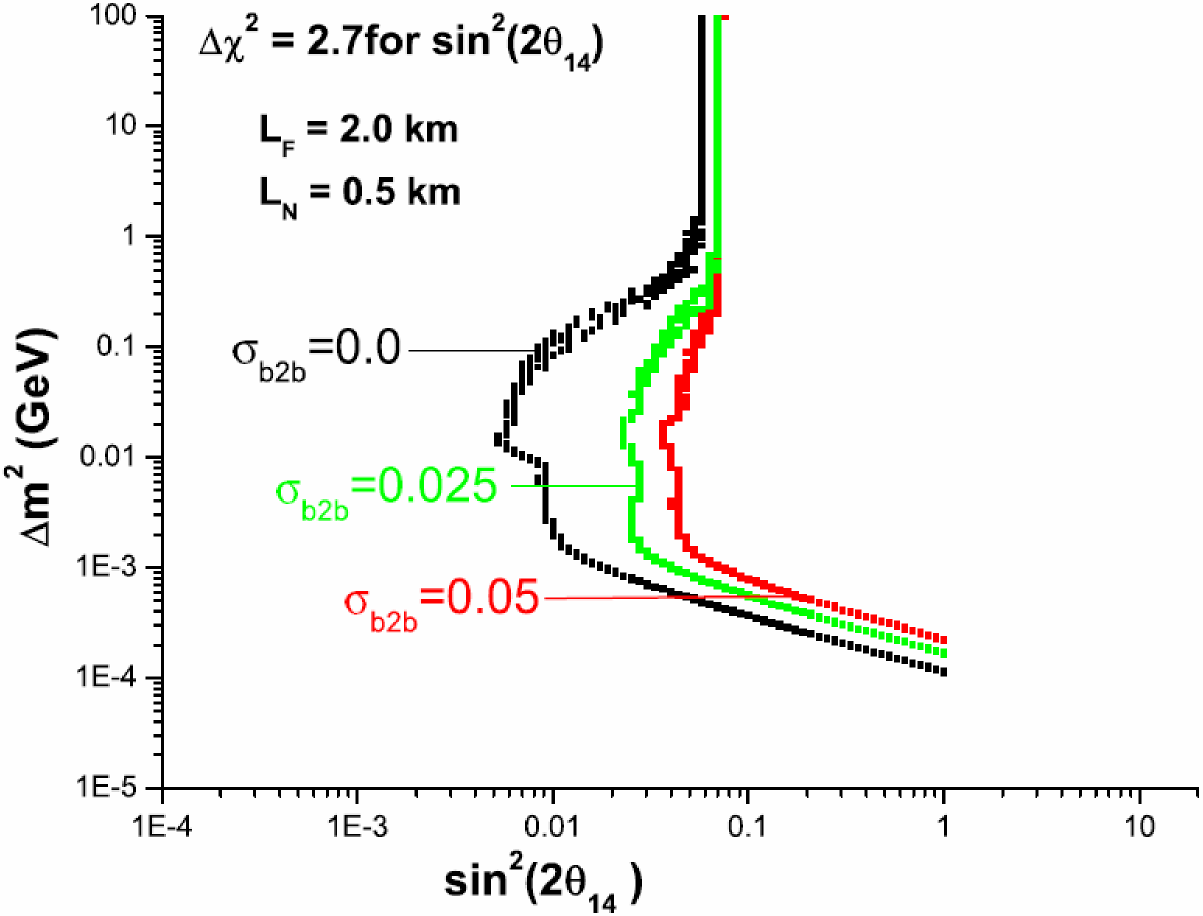
Kr2Det: expected bound on the sterile neutrino

VI. Potential of sterile neutrino search at Daya Bay

- Two possible approaches
  - Use the proposed Near + Far detector sets
  - Add a 3rd set of detector very close to reactor

    Close + Near + Far detector sets
- For the Near + Far sets, it is very difficult to extra useful information on sterile neutrinos if a θ_{13} signal is found.
- Information on both sterile neutrino and θ_{13} can be obtained for the Close + Near + Far detector sets.

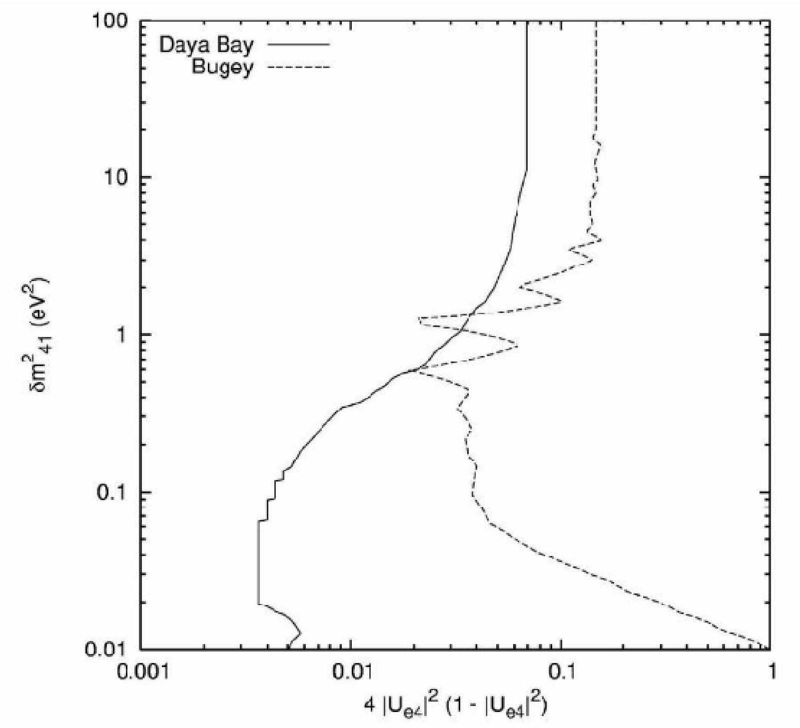
Near + Far detector sets
(when no θ_{13} signals found)

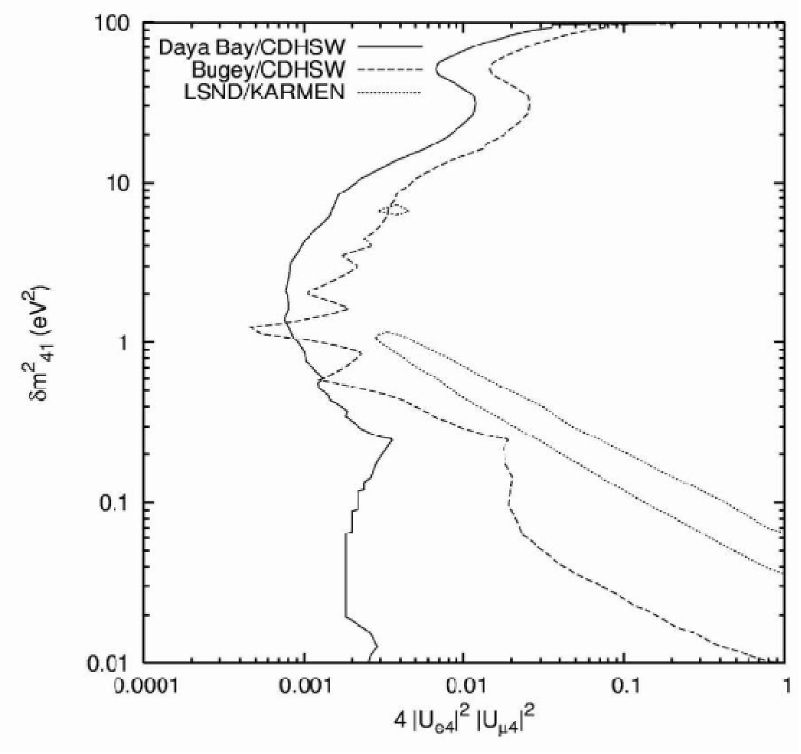


The error should be 0.005. The Currect curve lies between those of 0.0 and 0.025

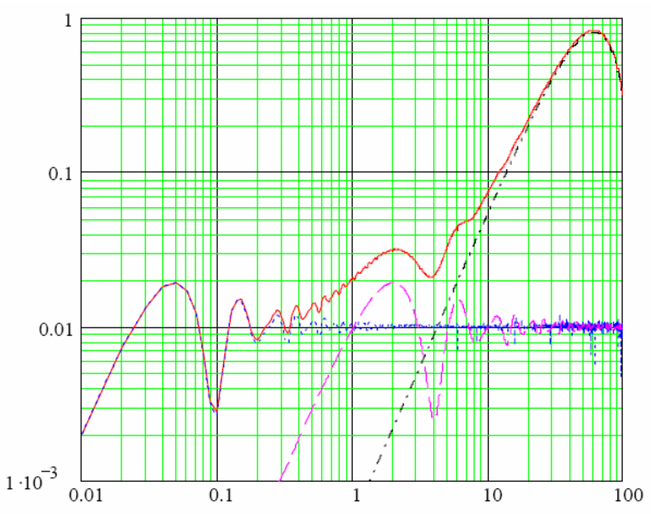
Daya Bay exclusion region for $\Delta m^2 > 0.01\ \mathrm{eV}^2$

Near + Far detector set, without a θ_{13} signal, bounds deteriorate somewhat when a 0.5% error is included





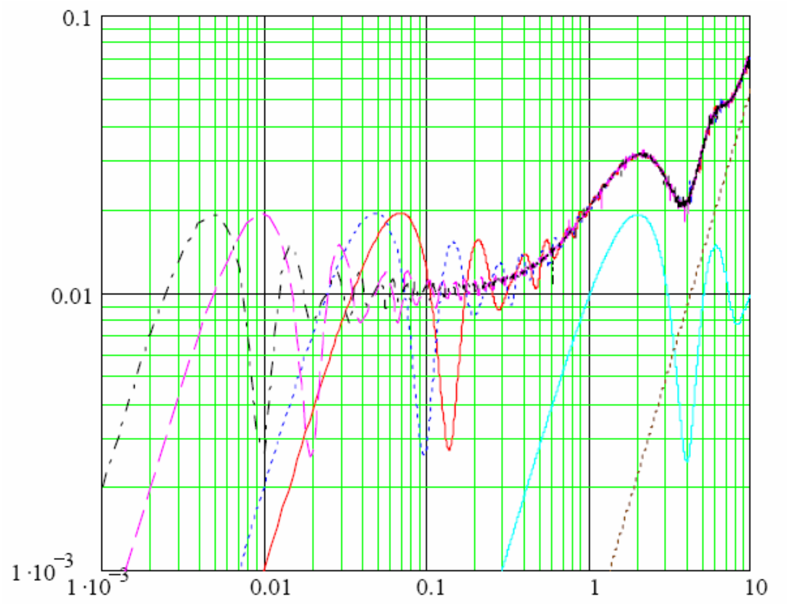
Oscillation character of a sterile neutrino ν_e disappearance probability of



Sterile neutrino
Mass scale
Blue: 0.1

Input:
$\sin^2 2\theta_{13} = 0.02$
$\sin^2 2\theta_{14} = 0.02$

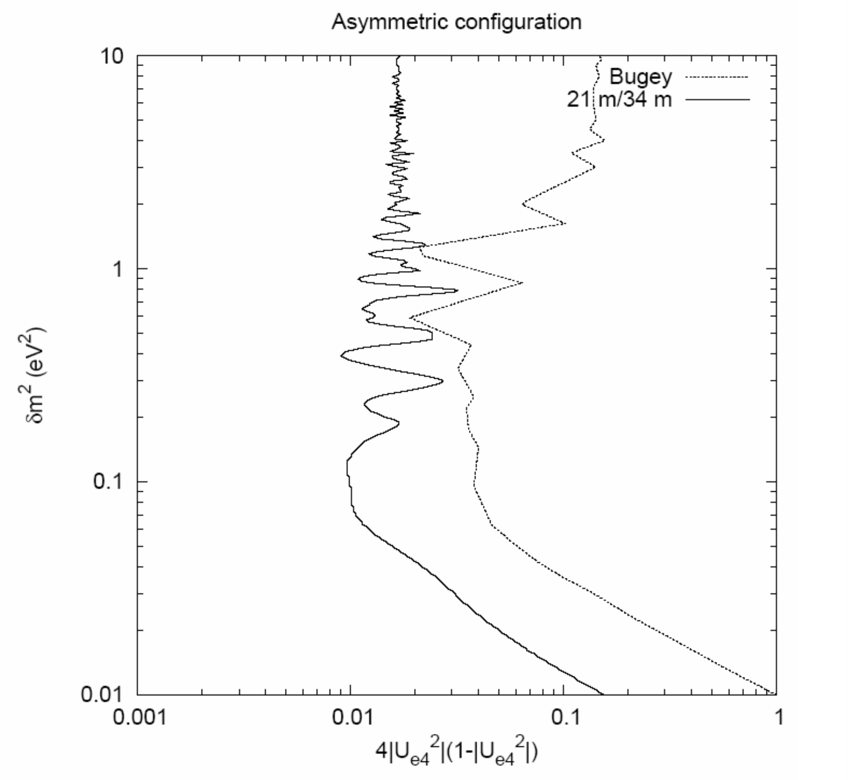
Sterile neutrino of different masses scale
Black ddotted: 1.0
Purple dashed: 0.5
Dashed blue: 0.1
Solid red: 0.07

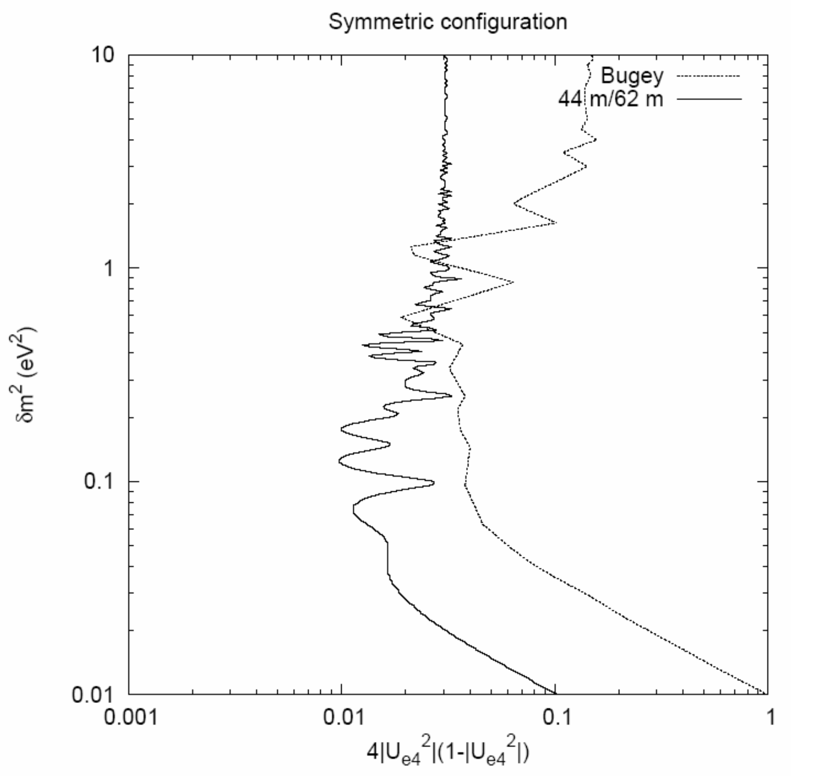


3 sets of detectors: Close +Near + Far adding a "close detector"

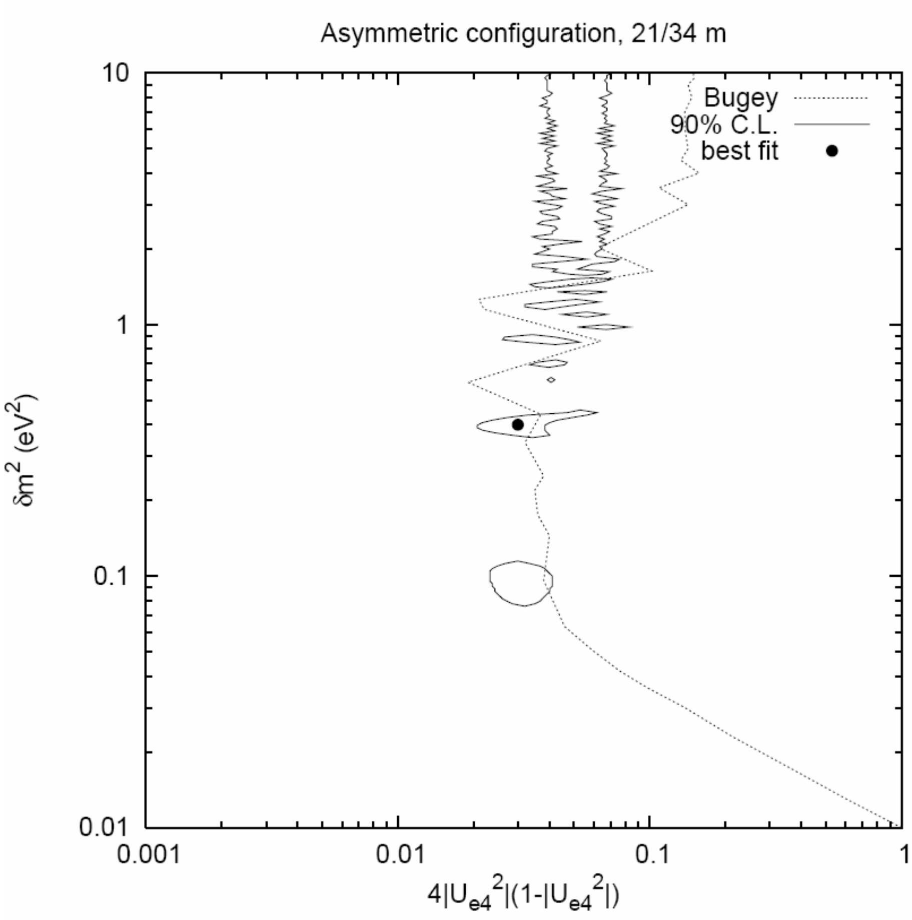
- Two movable "close detector" (CD) configurations
  - **Asymmetric: CD along line joining cores, baselines L and 88+L.**
  - **Symmetric: CD along perpendicular bisector of cores, baselines L.**
- Comparing data in rate & shape at two L's in.
  - **5 t-y total exposure of data**
  - **0.25 MeV energy bins from 1.8 to 7.8 MeV plus a high energy bin covering 7.8 o 15 MeV.**
- Errors included:
  - **2% systematic error due to possible time variation of flux**
  - **0.5% uncorrelated systematic error**
  - **Neglect all distance independent errors**

Close + Near + Far
results using close detector only



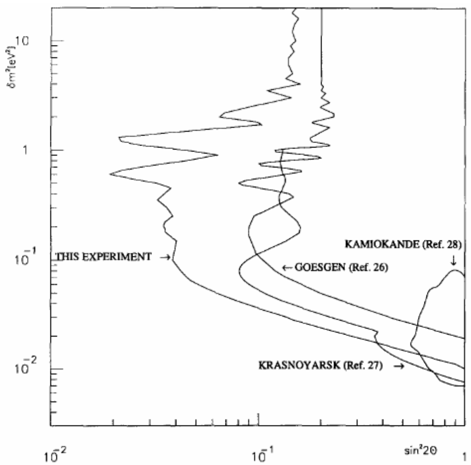


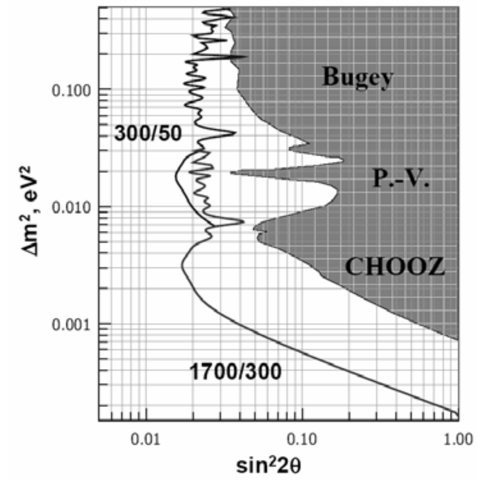
A “gedanken experiment”

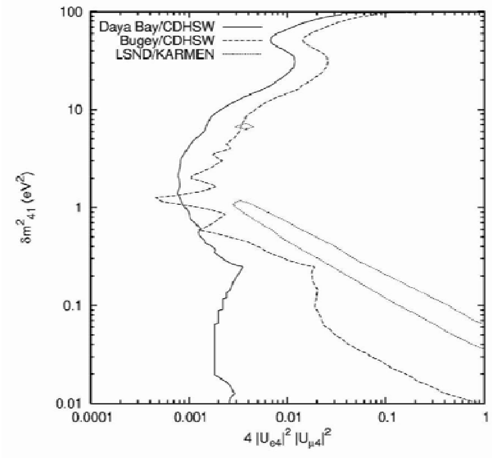


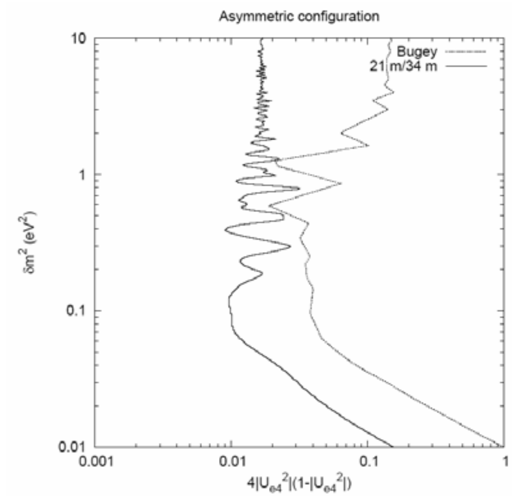
- Assuming a sterile neutrino is just below the LSND bound.
- 90% allowed region
- Infornation in $\Delta M^2_{\rm se}$ is poor.

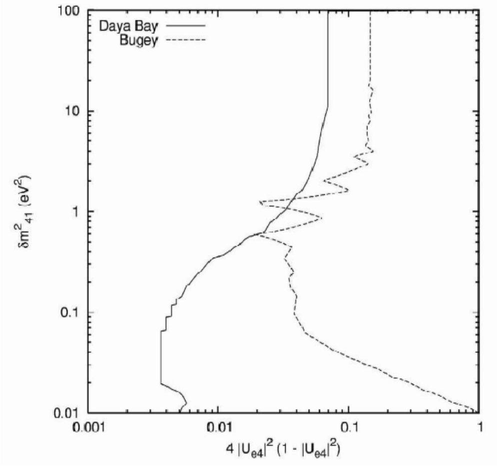
Comparing bounds

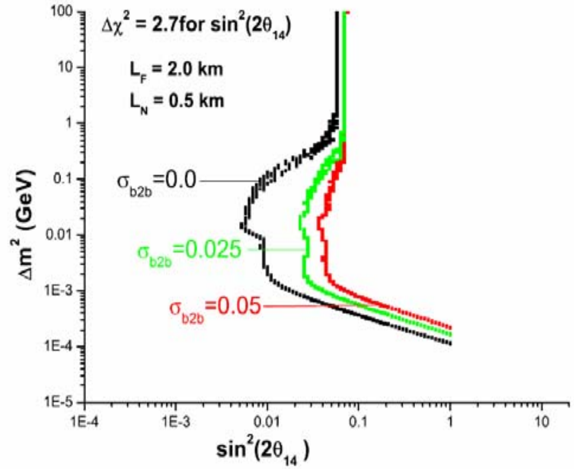












Coomparing bounds

- Antisymmetric configuration (L=21, 34 m):
  - Improves significantly the Bugey bound in the whole range of $\sin^2 2\theta_{14} - \Delta m^2_{41}$.
  - Improves the Kre2Det expectation and that of the Daya Bay Near + Far setup for $\Delta m^2_{41} > 0.2 \text{ eV}^2$.
- Symmetric configuration (L=44, 62 m):
  - Improves Bugey, but not Kr2Det for $\Delta m^2_{41} > 0.4 \text{ eV}^2$.
  - Also improves Daya Bay Near-Far case for $\Delta m^2_{41} > 1 \text{ eV}^2$ but not for $\Delta m^2_{41} < 1 \text{ eV}^2$.

VII. Other possible programs for reactor experiments – with θ_{13} setup some need additional detectors

- Supernova neutrinos-SNEWS

  (Guo & Young, PR D73, 093003 (hep-ph/0605122))

- Precision measurement of Weinberg angle

  θ_{W} (Conrad, Link, & Shaevitz, PR D71, 073013, (hep-ex/0403048))

- Search for Z' and new physics

  (Gouvea & Jenkins, hep-ph/0603036)

Other possible programs

- Property of Z-boson coupling and new physics

  (Gouvea & Jenkins, hep-ph/0603036)
- Neutrino magnetic moment

  (Beacom and Vogel, hep-ph/907383; TEXONO(
- Reactor physics-very low energy neurtrino flux

  (Li & Wong, J. Phys. G: Nucl. Part. Phys., 28 (‘02) 1453)

VII. A Supernova neutrinos: SNEWS

- SN 1987A confirmed existence of cosmic neutrinos, big massive stars can tell us their existence and demise by more ways than EM radiations.
- Studies of SN neutrinos include:
  - Neutrino spectra and core collapsing mechanism.
  - Diagnosing collapse to a black hole.
  - Testing physics under extreme conditions.
  - Study neutrino mass and matter effect.
- Neutrino events forewarn a SN (type II) explosion for optical observation (onset of light curve, etc)-- SNEWS (Supernova Early Warning System)

SNWES-conitnued

- Signals: mostly Inverse Beta Decay with antineutrino energy peaked above 10 MeV.
- Including SN and Earth matter effects, for a SN at $10\ kpc = 3.1 \times 10^{19}\ km$, with 300 t detector mass, depending on the neutrino mass hierarchy
  - 100 to 140 events in $\bar{\nu}_{\mathrm{e}} + p \rightarrow e^{+} + n$
  - 5 events in $\bar{\nu}_{\mathrm{e}} + e^{-} \rightarrow \bar{\nu}_{\mathrm{e}} + e^{-}$
  - 36 to 45 events in $(\bar{\nu}_{\mathrm{e}},{}^{12}C)$ reactions.
- Need to study details of the trigger of SN events.

VII.B Precision measurement of the Weinberg angle θ_{W}

- Motivation:
  - The unprecedented measurement of Weinberg angle by NuTeV found a 3σ deviation from the standard model prediction.
  - Reactor measurements probe very low momentum transfer at $Q^2 \approx 4 \times 10^{-6}\ \mathrm{GeV}^2$, existing measurements are in the range $Q^2 = (0.026\ \mathrm{GeV}^2 - M_Z^2)$.
  - Opportunity for discovering new physics without QCD complications, or subtle effect of systematics.
- Use Close/Near detector to measure $\bar{\nu}_{\mathrm{e}} e^-$ elastic scatterings, Far detector to monitor backgrounds.

Weinberg angle--continued

- Some pertinent questions:
  - Are there sufficient elastic scattering events?
  - Can the background be controlled?
  - Can the elastic scattering events be distinguished from the inverse beta decay events?
  - How well do we have to know the antineutrino flux?
- Another question—Can a close detector be used to alleviate some of the questions?

C. Constraining on extra gauge boson Z'

- Extra gauge bosons which exist in extensions of standard model can couple to leptons and modify the SM neutrino-electron coupling represented by an effective Lagrangian

$$\mathcal{L} = \epsilon(2\sqrt{2}G_F\bar{\nu}_\ell\gamma^\alpha\nu_\ell\bar{e}\gamma_\alpha e + h.c.)$$

- Then the antineutrino-electron scattering cross section is modified of its SM form by a factor $1+\epsilon$.
- From Gouvea and Jenkins (hep-ph/0603036), for a Close detector of baseline 40 m with 5 t-y running, a 68% upper bound of 4×10^{-4} can be reached, comparable to the best limit obtained in a neutrino factor.

VII.D Property of Z coupling and new physics

- In SM the left-handed neutrino-Z coupling at the tree-level is $\rho = 1$, as the coupling is purely left-handed. But this has not been fully checked. The current bound is $\rho > 0.9$ and the right-coupling can be as large as 40% of the left-handed coupling.
- According to SM, $\bar{\nu}_{\mathrm{e}} + e^{-} \rightarrow \bar{\nu}_{\mathrm{e}} + e^{-}$ has both Z and W contributions and is therefore sensitive to ρ.
- Reactor experiment can easily check the sign of ρ and to some accuracy its magnitude. This requires enough statistics and control of uncertainties of the neutrino flux.

VII.E Neutrino magnetic moment

- Massive neutrinos have magnetic dipole moments. In SM they arise from loop corrections and are tiny $\mu_\nu = 3 \times 10^{-19} \mu_{\rm B} (m_\nu / 1{\rm eV})$. ($\mu_{\rm B}$ Bohr magneton)
- Magnetic moment contributes to $\bar{\nu}_{\rm e} e^-$ elastic scattering cross section

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_{\rm e}}{\pi}\left[g_{\rm R}^2 + g_{\rm L}^2 \left(1 - \frac{T}{E_\nu}\right)^2 + g_{\rm L} g_{\rm R} \frac{m_{\rm e} T}{E_\nu^2}\right] + \mu_\nu^2 \frac{\pi \alpha_{\rm EM}^2}{m_{\rm e}^2} \frac{1 - T/E_\nu}{T}$$

$$g_{\rm L} = \sin^2\theta_{\rm W} + \frac{1}{2}, \quad g_{\rm R} = \sin^2\theta_{\rm W}$$

- The current best limit is from TEXONO (Li *et al*, PRL, **90** (04) 131802) $\mu_\nu < 1.3 \times 10^{-10} \mu_{\rm B}$. There is room for significant improvement. The experiment needs a different detector setup.

Reactor physics

- Some miscellaneous topics
  - Precise measurement of neutrino energy spectrum at very low energies below 2.5 MeV has not been made, the uncertainty can be as large as 30%. Low energy neutrinos are used to measure neutrino magnetic moment, very low energy antineutrino-electron scattering, and the study of neutrino-nucleus coherent scattering.

Summary

- In addition to the θ_{13} measurement, a broad range of interesting programs can be constructed at reactor neutrino experiments like Daya Bay, and most of the programs can be done using the Near-Far setup.
- The addition of a small " close detector" may significantly enhance most of the additional programs.