STERILE NEUTRINOS COSMOLOGICAL, ASTROPHYSICAL AND EXPERIMENTAL PROBES

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The existence of sterile neutrinos is widely believed to be ruled out as a main phenomenon in solar, reactor and atmospheric oscillations

How large can be the subdominant sterile component possibly present in solar or atmospheric oscillations?

How can we detect it?

We study probes of oscillations into sterile neutrinos coming from

- Cosmology (BBN, LSS, CMB)
- Solar experiments
- Atmospheric experiments
- Reactor and beam experiments
- Supernovæ

Active/sterile neutrino mixing

- Present bounds are computed assuming oscillations $|\nu_{\rm a}\rangle \to \cos\theta_s|\nu'_{\rm a}\rangle + \sin\theta_s|\nu_{\rm s}\rangle$ and a single Δm^2 (A. Bandyopadhyay et al. 2003 T. Schwetz 2003, K. Okumura 2003)
- We relax these simplifying assumption and study the more general 4-neutrino context
- For the 3 active neutrinos $\nu_\ell = U_{\ell i}\nu_i^{\rm a}\ \ (i = \{1,2,3\},\ \ell = \{e,\mu,\tau\})$
- The extra sterile neutrino mixes with an arbitrary combination of active neutrinos

$$\vec{n}\cdot\vec{\nu} = n_e\nu_e + n_\mu\nu_\mu + n_\tau\nu_\tau = n_1\nu_1^{\rm a} + n_2\nu_2^{\rm a} + n_3\nu_3^{\rm a}$$

$$\begin{cases} \nu_4 = \nu_{\rm s}\ \cos\theta_{\rm s} + n_\ell\nu_\ell\ \sin\theta_{\rm s} \\ \nu_i = U^*_{\ell i}[\delta_{\ell\ell'} - n^*_\ell n_{\ell'}(1-\cos\theta_{\rm s})]\nu_{\ell'} - \sin\theta_{\rm s} n^*_\ell U^*_{\ell i}\nu_{\rm s} \end{cases}$$

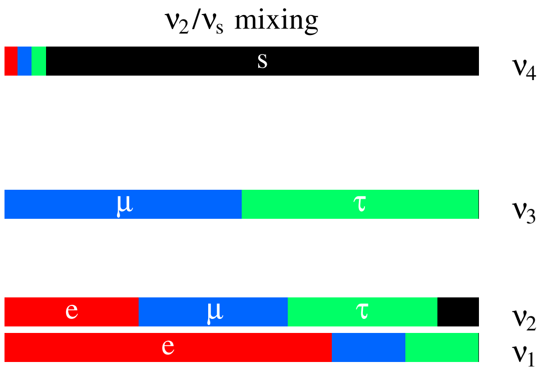
Two interesting cases

(3 + 1 scheme, normal hierarchy, $\theta_{13} = 0$)

Mixing with a

mass eigenstate

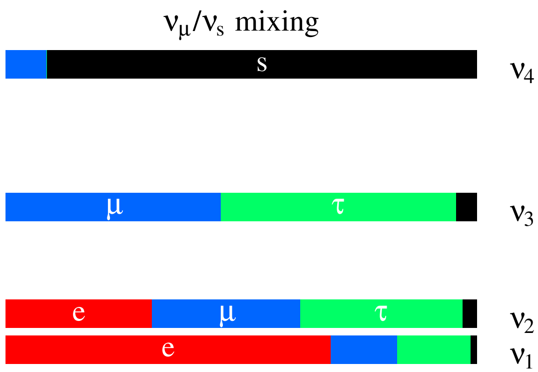
$\vec{n} \cdot \vec{\nu} = \nu_2$



Mixing with a

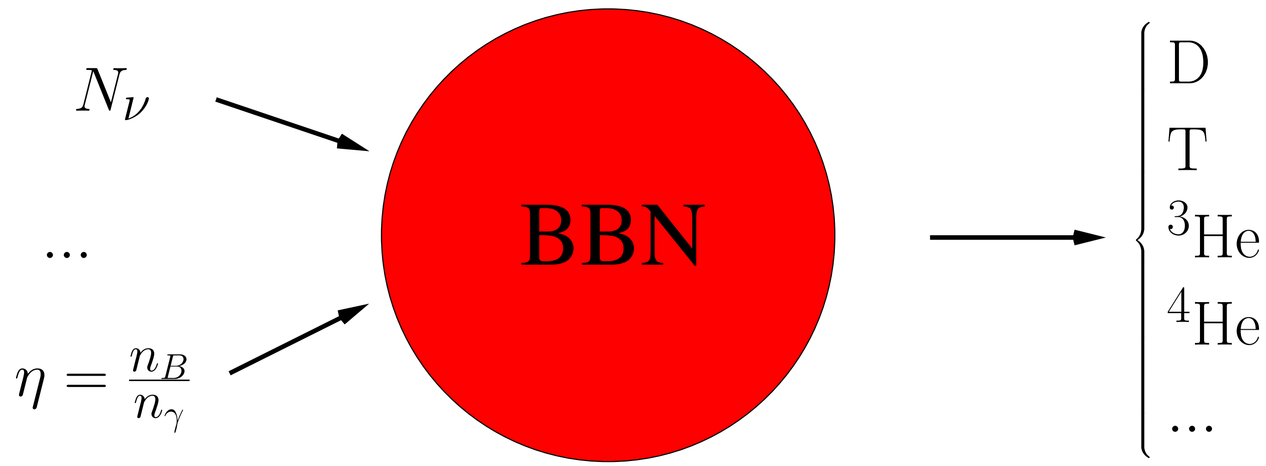
flavor eigenstate

$\vec{n} \cdot \vec{\nu} = \nu_\mu$



Sterile neutrinos and Cosmology

Big Bang Nucleosynthesis



From WMAP : $\eta = (6.15 \pm 0.25) \cdot 10^{-10}$

$\Longrightarrow$ Use primordial abundances to constrain N_ν

- $\nu_{\mu,\tau} - \nu_s$ mixing increases the total energy density of the universe at $T \sim$ MeV

- $\nu_e - \nu_s$ mixing also affects $pe\bar{\nu}_e \leftrightarrow n$, $pe \leftrightarrow n\nu_e$ and $p\bar{\nu}_e \leftrightarrow n\bar{e}$ reactions and then the n/p ratio at freeze-out

- Non standard scenarios (large neutrino asymmetry, low reheating temperature) can weaken the bound

Standard BBN predicts

D.A. Dicus et al. 1982, R.E. Lopez & M.S. Turner 1998

$$Y_p \simeq 0.248 + 0.0096 \ln \frac{\eta}{6.15\ 10^{-10}} + 0.013(N_\nu^{^4\mathrm{He}} - 3)$$

$$D/H \simeq (2.75 \pm 0.13)\ 10^{-5}\ \frac{1 + 0.11\ (N_\nu^{\mathrm{D}} - 3)}{(\eta/6.15\ 10^{-10})^{1.6}}$$

Experimental (very conservative) values

Y.I. Izotov & T.X. Thuan 2003, K. Olive et al. 1997, D. Kirkman et al. 2003

$$Y_p = 0.24 \pm 0.01 \quad \Rightarrow \quad N_\nu^{^4\mathrm{He}} \simeq 2.4 \pm 0.7$$

$$D/H = (2.8 \pm 0.5)\,10^{-5} \quad \Rightarrow \quad N_\nu^{\mathrm{D}} \simeq 3 \pm 2$$

A better determination of Y_p and D/H could lead to stronger bounds

CMB and Large Scale Structure

- Massive neutrino free streaming shifts the acoustic peaks of CMB
  Present fits: $N_\nu^{\rm CMB} \approx 3 \pm 2$ (P. Crotty et al. 2003, Barger et al. 2003)
  Future experiments could discriminate $N_\nu^{\rm CMB} = 3$ from $N_\nu^{\rm CMB} = 4$

- Massive neutrino free streaming affects LSS making galaxies less clustered
  Present bound: $\Omega_\nu h^2 \lesssim 0.01$ (D.N. Spergel et al. 2003)

What we have done

Fixing the active-active mixing to the experimental value and given active-sterile mixing parameters

- We solved the kinetic equations for the neutrino density matrix (neglecting spectral distortions)

$$\dot{\rho} = -HT\frac{\mathrm{d}\rho}{\mathrm{d}T} = i[\mathscr{H}, \rho] - \{\Gamma, (\rho - \rho^{\mathrm{eq}})\}$$

  assuming $\rho_{ss}(T \gg \text{ MeV}) = 0$

- We followed the relative n/p abundance

$$\dot{r} = -HT\frac{\mathrm{d}r}{\mathrm{d}T} = \Gamma_{p\to n}(1-r) - r\Gamma_{n\to p} \qquad r = \frac{n_n}{n_n + n_p}$$

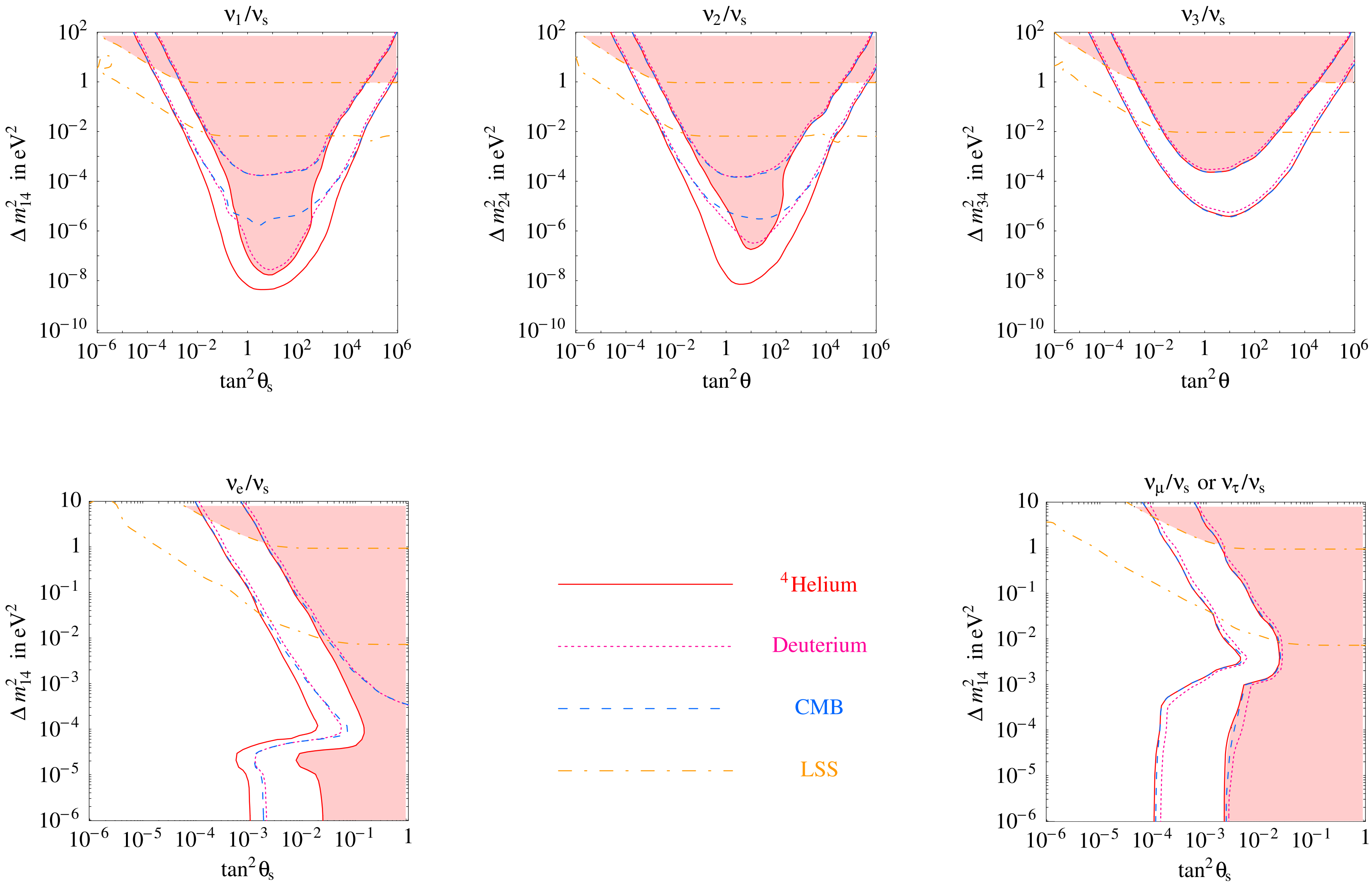
  where $N_\nu \neq 3$ enters in the Hubble constant H and/or $\Gamma_{p\leftrightarrow n}$

- We followed a network of Boltzmann equations and to computed the abundances of the various nuclei: p, n, D, T, ^{3}He, ^{4}He,...

- At the end we compute four relevant quantities:

$$
\begin{aligned}
Y_p &\implies N_\nu^{^4\mathrm{He}} \\
D/H &\implies N_\nu^{\mathrm{D}} \\
& \quad\; N_\nu^{\mathrm{CMB}} = \mathrm{Tr}\ \rho \\
& \quad\; \Omega_\nu h^2 = \mathrm{Tr}[m \cdot \rho]/(93.5\,\mathrm{eV})
\end{aligned}
$$

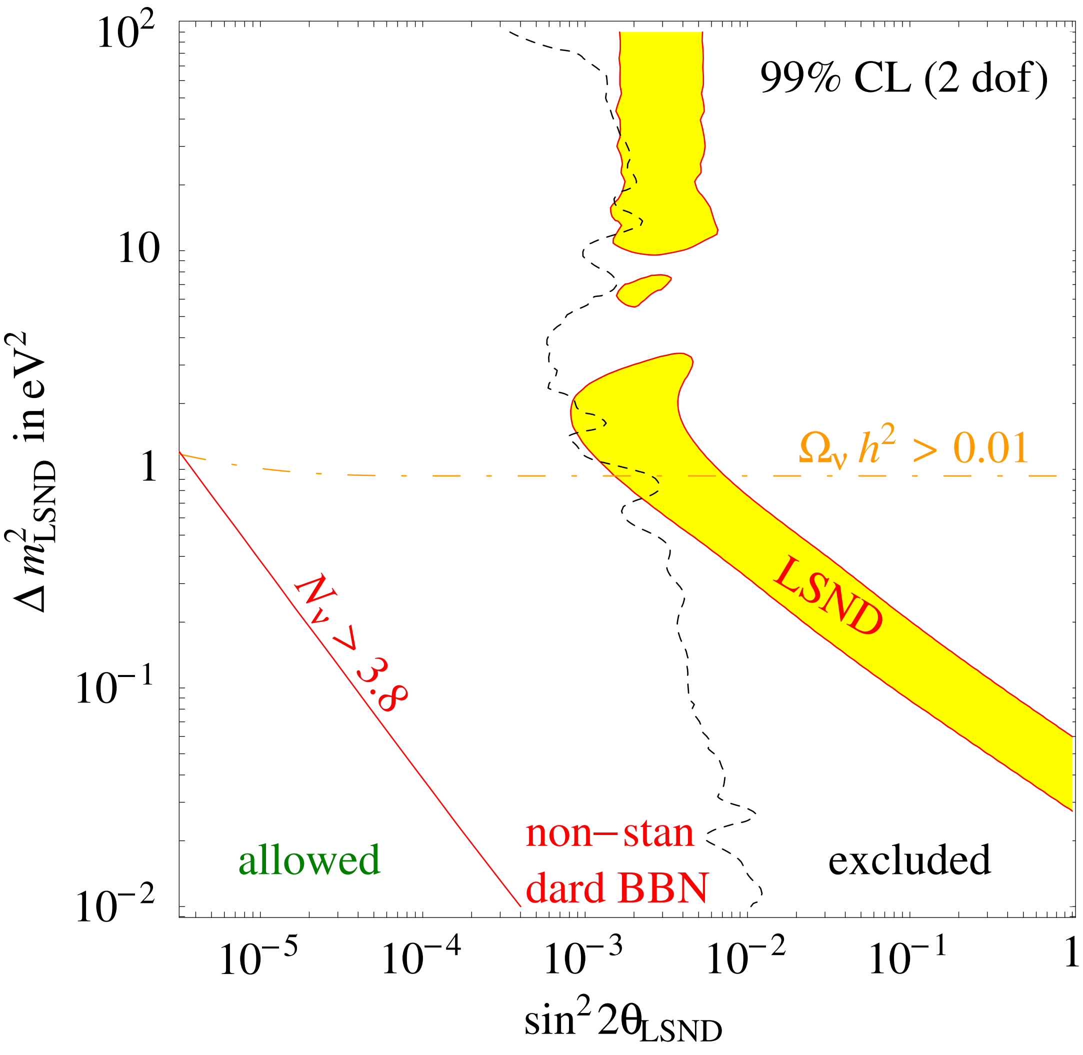
In presence of active-active mixing



BBN, LSS and the LSND anomaly

- LSND finds an evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$, that ranges between 3 to 7σ
- Among possible explanations there is a sterile neutrino with eV-scale mass $\nu_\mu \to \nu_{\rm s} \to \nu_e$ with a mixing angle $\theta_{\rm LSND} \approx \theta_{es} \cdot \theta_{\mu s}$ (for small angles)
- Previous analysis of the BBN bounds were done assuming only $\nu_{\rm a} - \nu_s$ mixing
- We extend usual analysis to a general 4 neutrinos context

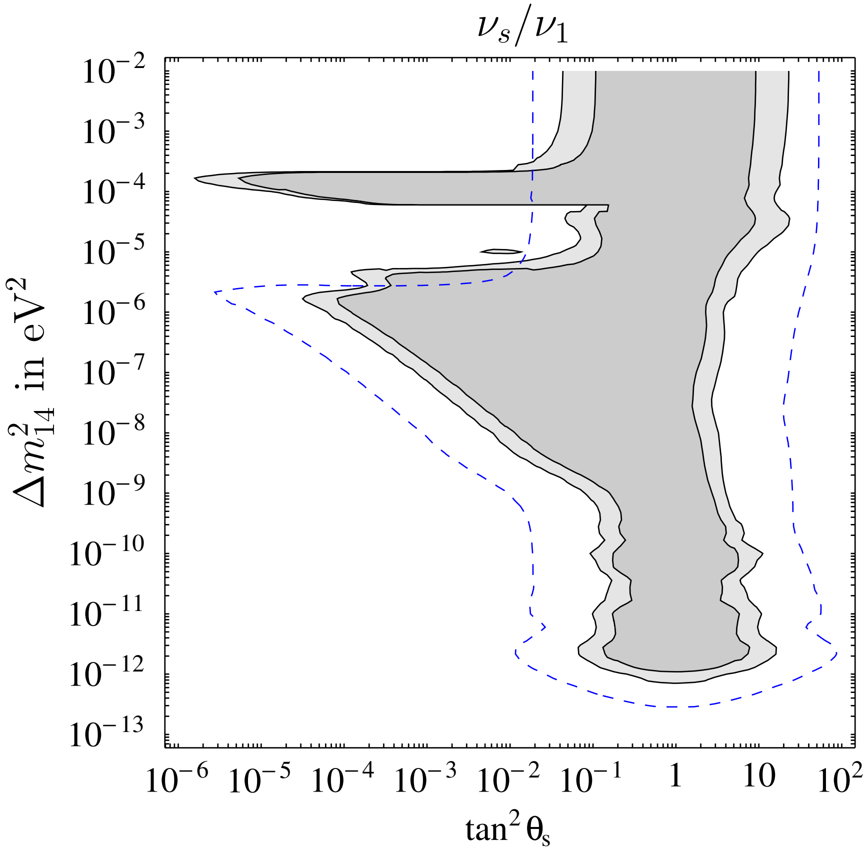
Results

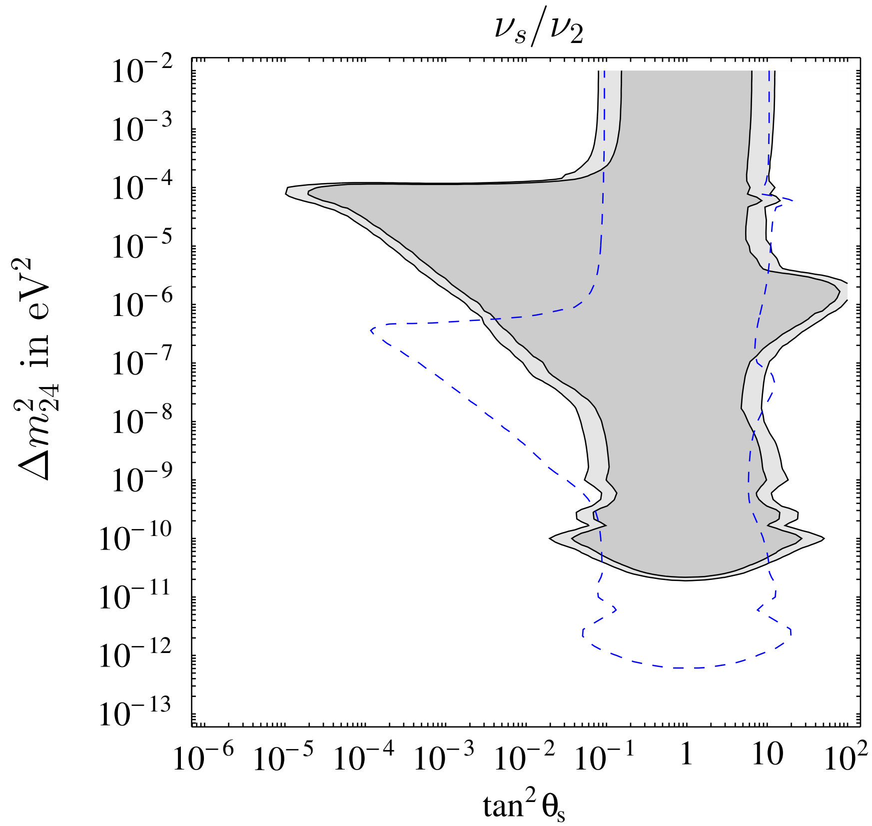


99% CL (2 dof)
$\Omega_\nu h^2 > 0.01$
LSND
$N_\nu > 3.8$
allowed
non−stan
dard BBN
excluded
$\Delta m^2_{\rm LSND}$ in eV^2
$\sin^2 2\theta_{\rm LSND}$
10^2
10
1
10^{-1}
10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

SOLAR NEUTRINOS

Looking for subdominant effects around the LMA region





Shaded region: excluded at $90, 99\%$ C.L.

Short-dashed blue line: P_{ee} at sub-MeV energies differs from LMA by 0.02

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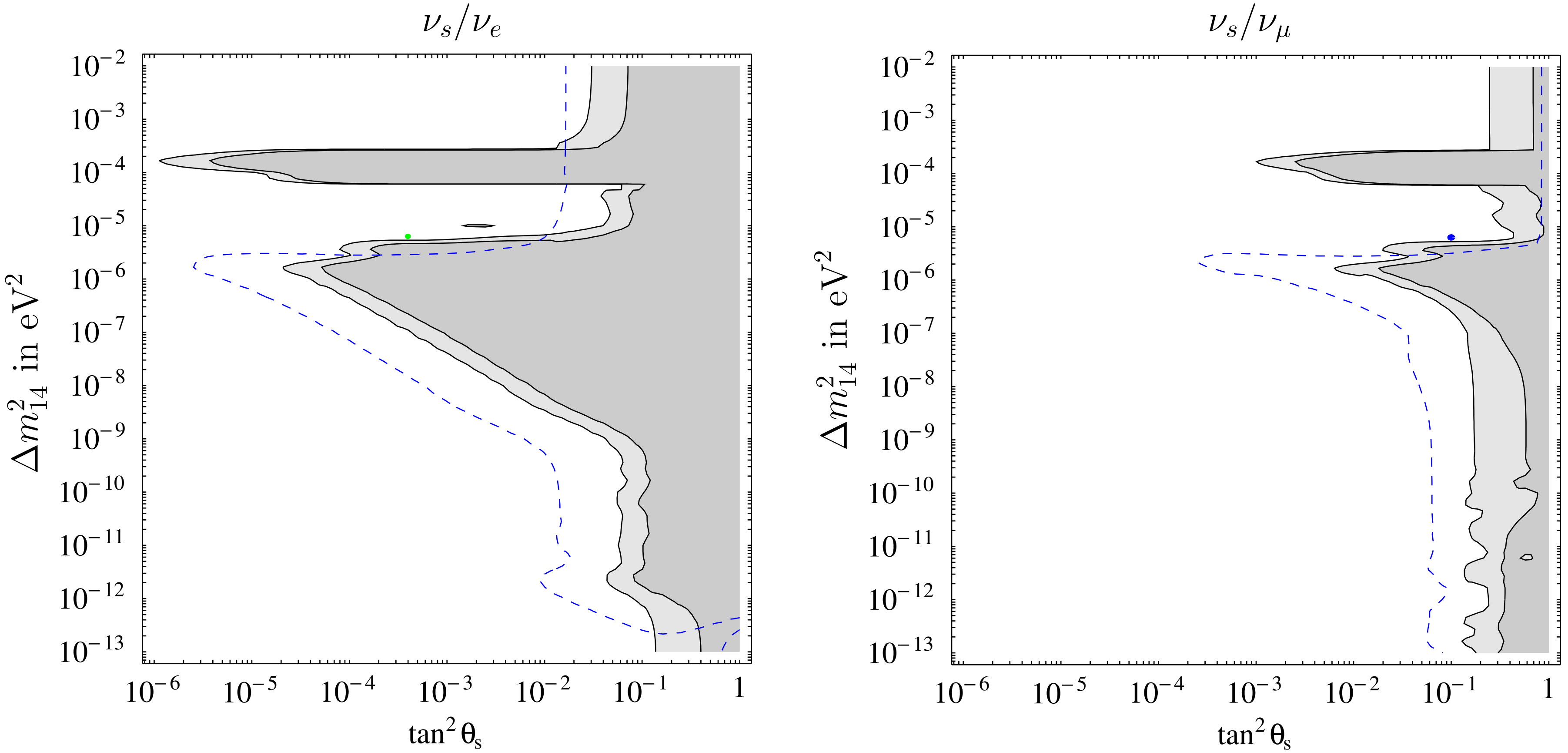


Shaded region: excluded at 90, 99% C.L.

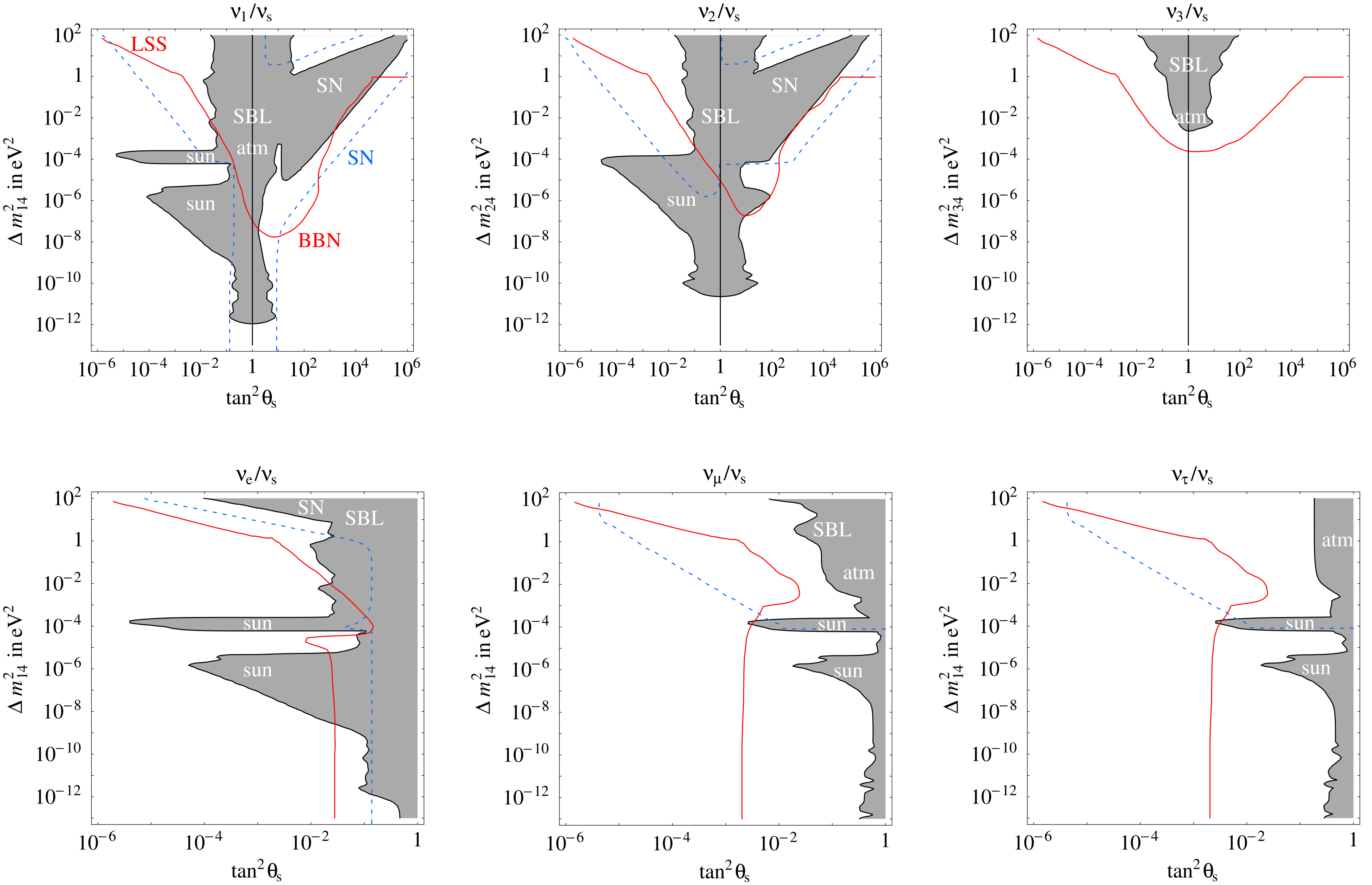
Short-dashed blue line: P_{ee} at sub-MeV energies differs from LMA by 0.02

CONCLUSION

NO statistical evidence of sterile neutrinos is found

Sensible probes are outlined

SUMMARY



ν_1/ν_s
ν_2/ν_s
ν_3/ν_s
ν_e/ν_s
ν_μ/ν_s
ν_τ/ν_s
Δm^2_{14} in eV^2
Δm^2_{24} in eV^2
Δm^2_{34} in eV^2
$\tan^2\theta_s$
LSS
BBN
SN
SBL
atm
sun