← *Collège de France / Neutrino 2004 / Alessandro Strumia*

Search for $\nu_{\rm S}$

Cosmology and neutrino experiments discovered something new.
New experiments will test minimal theories and search for the
unseen effects that they suggest: $\theta_{13}, \not{C}P\,, m_\nu;\ n-1, r,$ CDM...

What else could these experiments discover?

They are good probes of...

New light particles

ν are not the best probe of heavy particles: high energy is $\mathrm{SU}(2)_L$ invariant and it is easier to deal with e. Being light, γ, ν, $g_{\mu\nu}$ are sensitive to light particles, which can be searched for with **cosmology, astrophysics, ν experiments**.

Colliders search for new heavy particles. Better if they have fundamental importance for theory or cosmo or astro or. . . E.g. neutralino: SUSY + CDM

Any **light** new particle would be a key discovery:

- Presumably lightness follows from some Deep Principle.
- Presumably a light particle is stable enough for affecting cosmo, astro.

(True for known light particles: γ, $g_{\mu\nu}$, ν).

Which spin?

ν interact with new light particles in different ways, according to their spin:

$$\underbrace{g\ \nu\nu\varphi}_{0,\ \text{minimal}} \qquad \underbrace{\bar\nu\gamma_\mu\nu\partial_\mu\varphi}_{0,\text{Goldstone}} \qquad \underbrace{m\ \nu\nu_{\rm s}}_{1/2,\ \text{minimal}} \qquad \underbrace{(\nu\partial_\mu\nu_{\rm s})Z_\mu v/M^2}_{1/2,\ \text{Goldstino}} \qquad \underbrace{g\bar\nu A_\mu\nu}_{1}$$

Couplings give extra MSW effects (g^2/m^2 even if $m < E_\nu$), ν-decay, reduced free-streaming. In some m, g range this is compatible with star/SN/universe cooling. Mixing with existing light particles does not need couplings:

photon/axion, graviton/..., $\nu/\nu_{\rm s}$

Adding neutral fermions is the simplest extenstion of the massive ν scenario.

$\nu_{\rm s}$ are the standard ‘emergency exit’ from anomalies (solar, atmospheric, LSND, NuTeV, pulsar kicks, r-nucleosynthesys, Karmen, low Chlorine rate, upturn in solar spectrum, solar time dependence, warm dark matter, reionization, galactic $\bar e$, lower Gallium rates,. . .).

But so far the idea remained sterile...

Why $\nu_{\rm s}$ should be light?

¿Why $\nu_{\rm s}$ is not very heavy (Planck or Fermi scale)?

Maybe for the same reason why ν are light: chiral symmetry (new gauge group).
Taken to the exteme suggests 'mirror matter': a sector identical to the SM.

Flavour symmetries of ν, such as $L_e - L_\mu - L_\tau$ could act at low energy.

A plethora of candidates from SUSY, extra dimensions, strings, M-theory
(**A**xino, **B**ranino, **C**omposite, **D**ilatino, **E**xtra-d ν_R, **F**amilino, **G**oldstino, ...).

In any case, light *fermions* are stable under quantum corrections.

¿Why $\nu_{\rm s}$ is not massless (eV-scale masses and mixings)?

Maybe Planck-suppressed corrections $m_{\rm s} \sim v^2/M_{\rm Pl} \gtrsim \mu{\rm eV}$.
Many other model-dependent mechanisms can be introduced.

These would be main questions, if $\nu_{\rm s}$ were found. Now main issue is searching.
Theory does not help: too many answers = no answer...

Predictions

for the number n_{s} of ν_{s} with masses m_{s} and mixings θ_{s} are not very restrictive

$$0 \le n_{\text{s}} < \infty \qquad 0 \le m_{\text{s}} < \infty \qquad 0 \le \theta_{\text{s}} < 360^\circ$$

because theorists worked a lot, but flavour remains not understood.

Good taste allows to guess some patterns:

Small m_{LL}: : $\theta_{\text{s}} \simeq \sqrt{m_{\text{active}}/m_{\text{s}}}$

Small m_{RR}: : $\theta_{\text{s}} \simeq \sqrt{m_{\text{s}}/m_{\text{active}}}$

Dominant m_{LR}: : $\theta_{\text{s}} \simeq \pi/4$

where

$$m = \begin{array}{c c} & \begin{array}{cc} \nu_L & \nu_R \end{array} \\ \begin{array}{c} \nu_L \\ \nu_R \end{array} & \begin{pmatrix} m_{LL} & m_{LR} \\ m_{LR} & m_{RR} \end{pmatrix} \end{array}$$

In general these hold as estimates, vaild up to fine-tunings or up to specific structures. No particular implications. Better to perfom 360° searches.

Signals of 1 ν_S

4 ν mixing

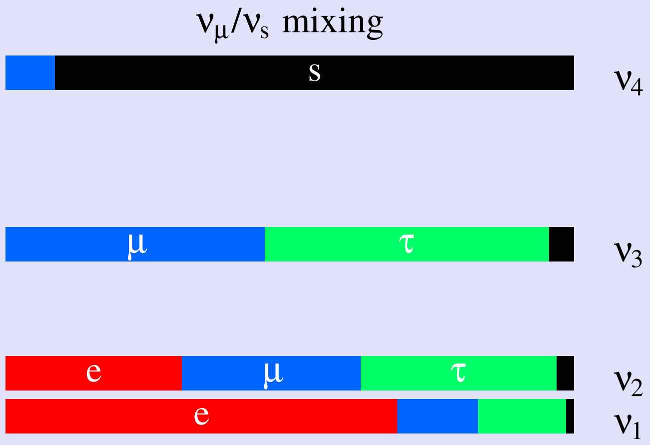
Add 1 ν_s. Neutrino mixing now described by 3 extra parameters: convenient to use a mixing angle θ_s and a versor $\vec{n}$ that tells which active ν mixes with ν_s.

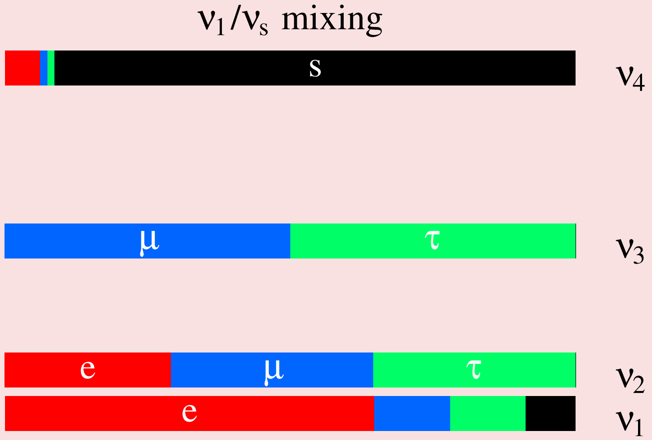
6 representative cases:

Mixing with a flavour eigenstate

$$\vec{n}\cdot\vec{\nu} = \nu_e \quad \text{or} \quad \nu_\mu \quad \text{or} \quad \nu_\tau$$

ν_s oscillates at 3 different Δm^2, two of them known: $\Delta m^2_{\text{sun,atm}}$





Mixing with a mass eigenstate

$$\vec{n}\cdot\vec{\nu} = \nu_1 \quad \text{or} \quad \nu_2 \quad \text{or} \quad \nu_3$$

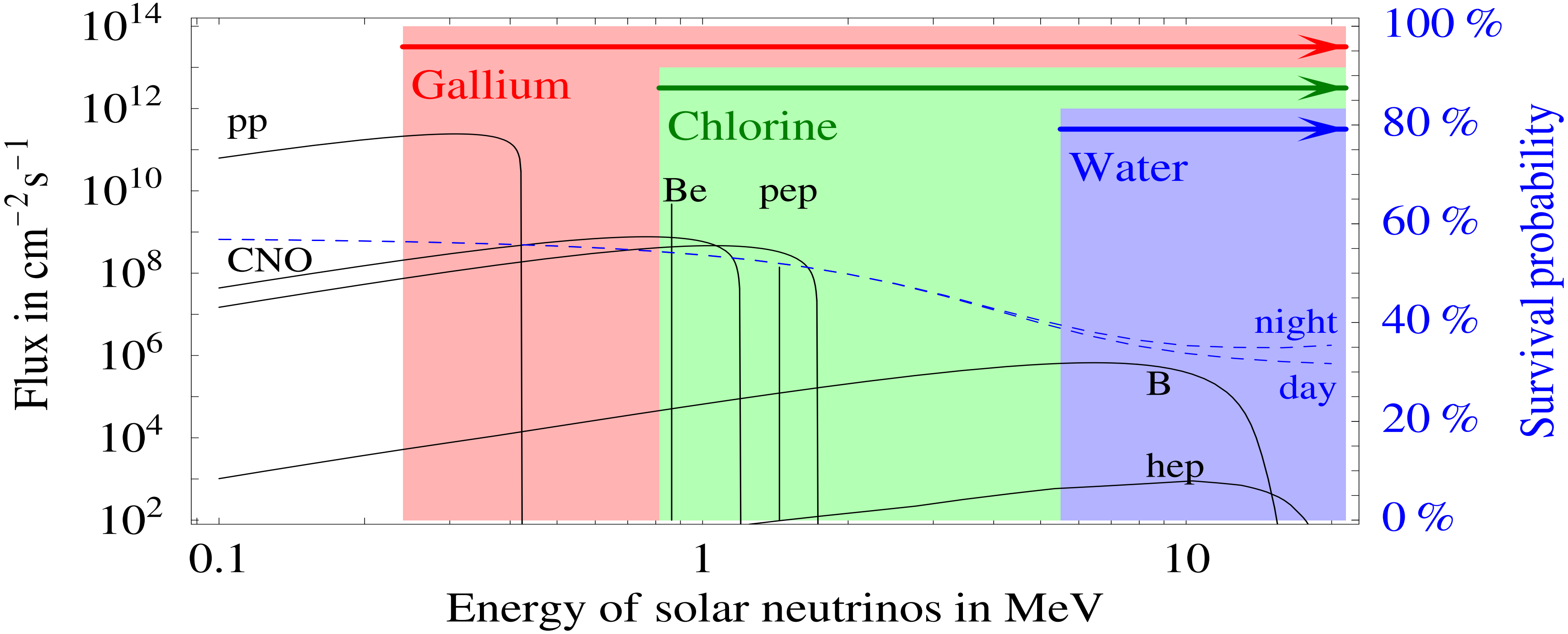
ν_s mixes with a neutrino of mixed flavour at 1 Δm^2_{4i} which can be arbitrarily small.

Usual ‘bounds’ on ν_s from sun or atm correspond to $\nu_s/\nu_{\mu,\tau}$ and large Δm^2 which is not representative

Solar neutrinos

Usual analysis: $\nu_e \to \eta\ \nu_{\rm s} + \sqrt{1-\eta^2}\ \nu_{\mu,\tau}$ gives $\eta = 0 \pm 0.1$ dominated by SNO.
Such energy-independent η is obtained for $\nu_{\rm s}/\nu_\mu$ mixing with large Δm^2.

But things can be qualitatively different:



Averaged vacuum oscillations

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta$$

Sun emits ν_1 ($\propto \cos^2\theta_{\rm sun}$), ν_2

Critical energy

$$\frac{\Delta m^2_{\rm sun}}{G_{\rm F} N_e} \sim \text{few MeV}$$

Adiabatic MSW resonance

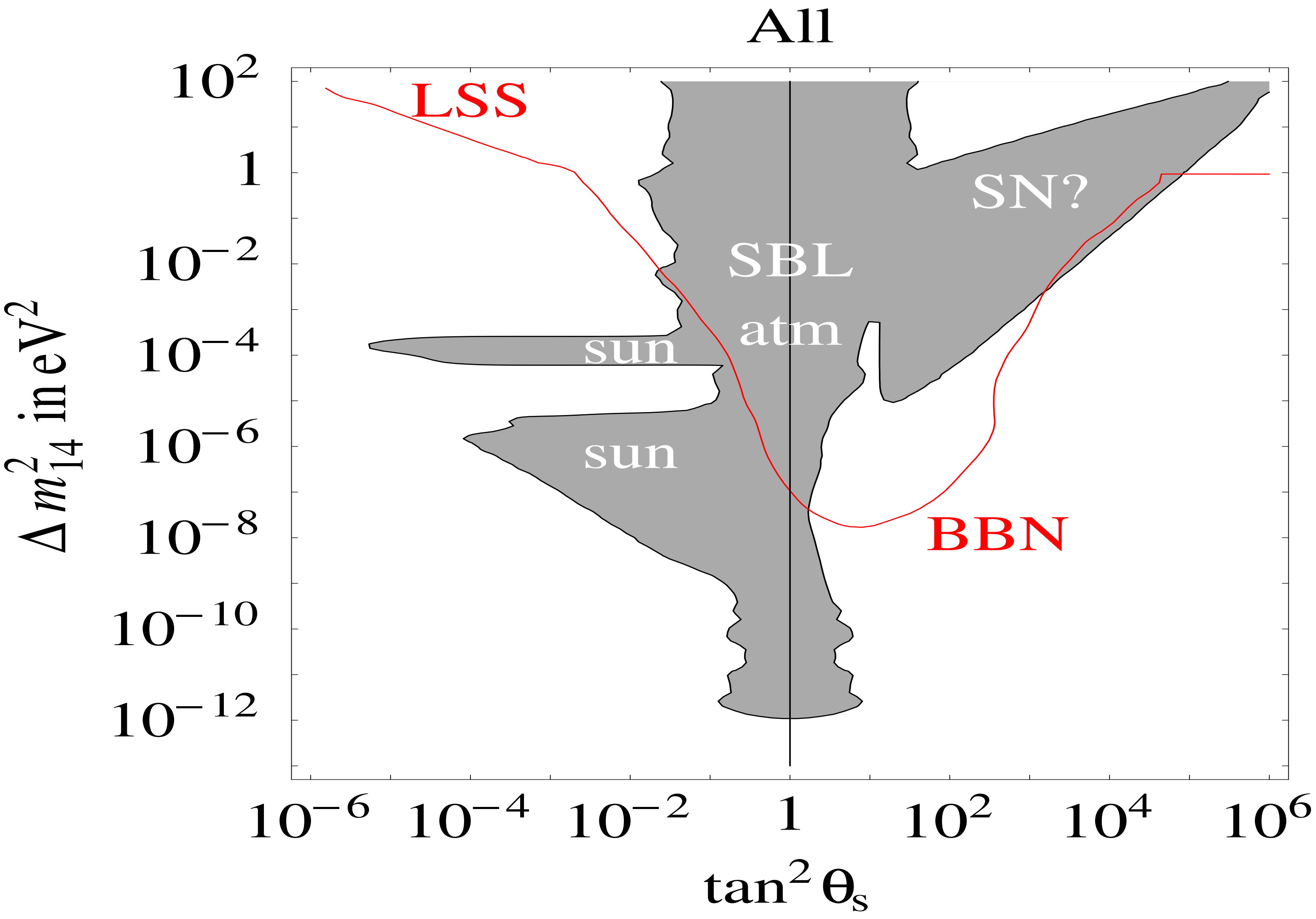
$$P(\nu_e \to \nu_e) = \sin^2\theta$$

Sun emits only ν_2

A $\nu_{\rm s}$ that mixes or MSW-crosses with ν_1 dominantly affects sub-MeV solar ν

Status of ν_s/ν_1 mixing

Active/active effects fully included assuming normal hierarchy and $\theta_{13} = 0$



ν_s heavier than ν_1 ν_s lighter than ν_1*

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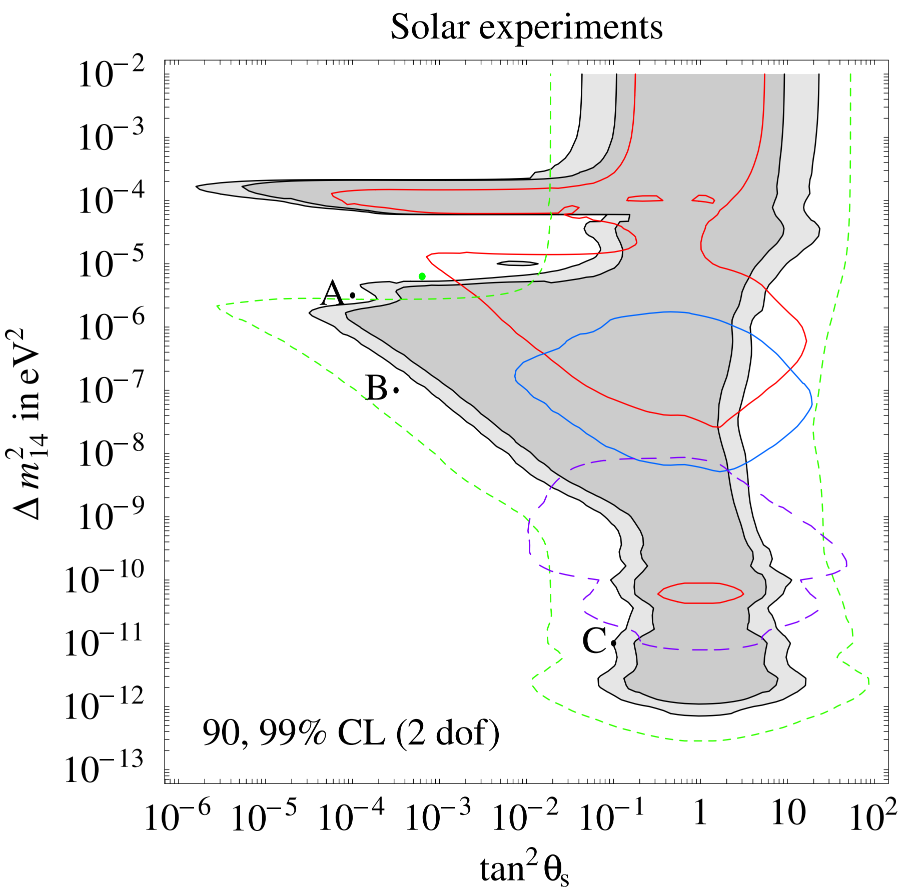
* This sentence correctly summarizes the result of a hidden trick. Large active/sterile mixing is already excluded if their mass splitting is too large: we swap their masses above maximal mixing in order to cover a more intersting slice of the parameter space. Details in hep-ph/0403158.

ν_s/ν_1: solar neutrinos



distorted MSW triangle at

$\Delta m^2_{41} \lesssim \Delta m^2_{\rm sun}$ $\qquad \tan\theta_s < 1$

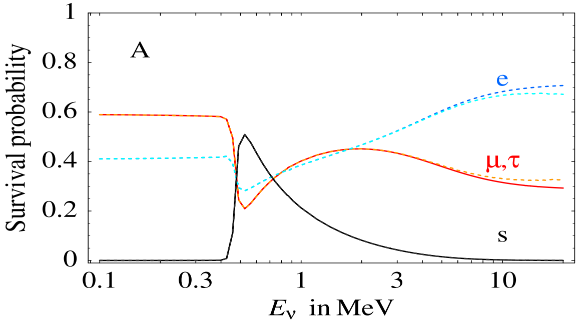
Gallium experiments are crucial.

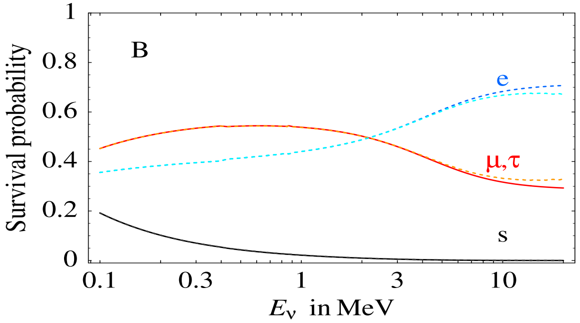
Measure *pp* rate at 2%!

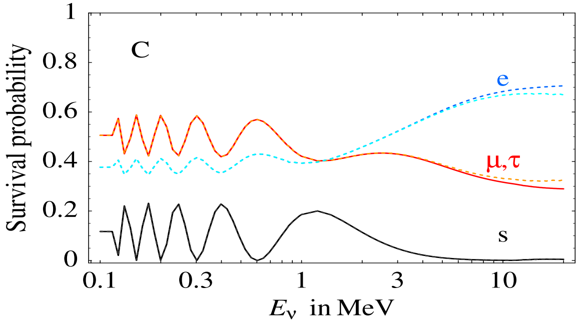
Borexino day/night at 2%

Borexino seasonal at 2%

Mton WČ: $A^{\rm ES}_{\rm d/n}$ at 0.005.

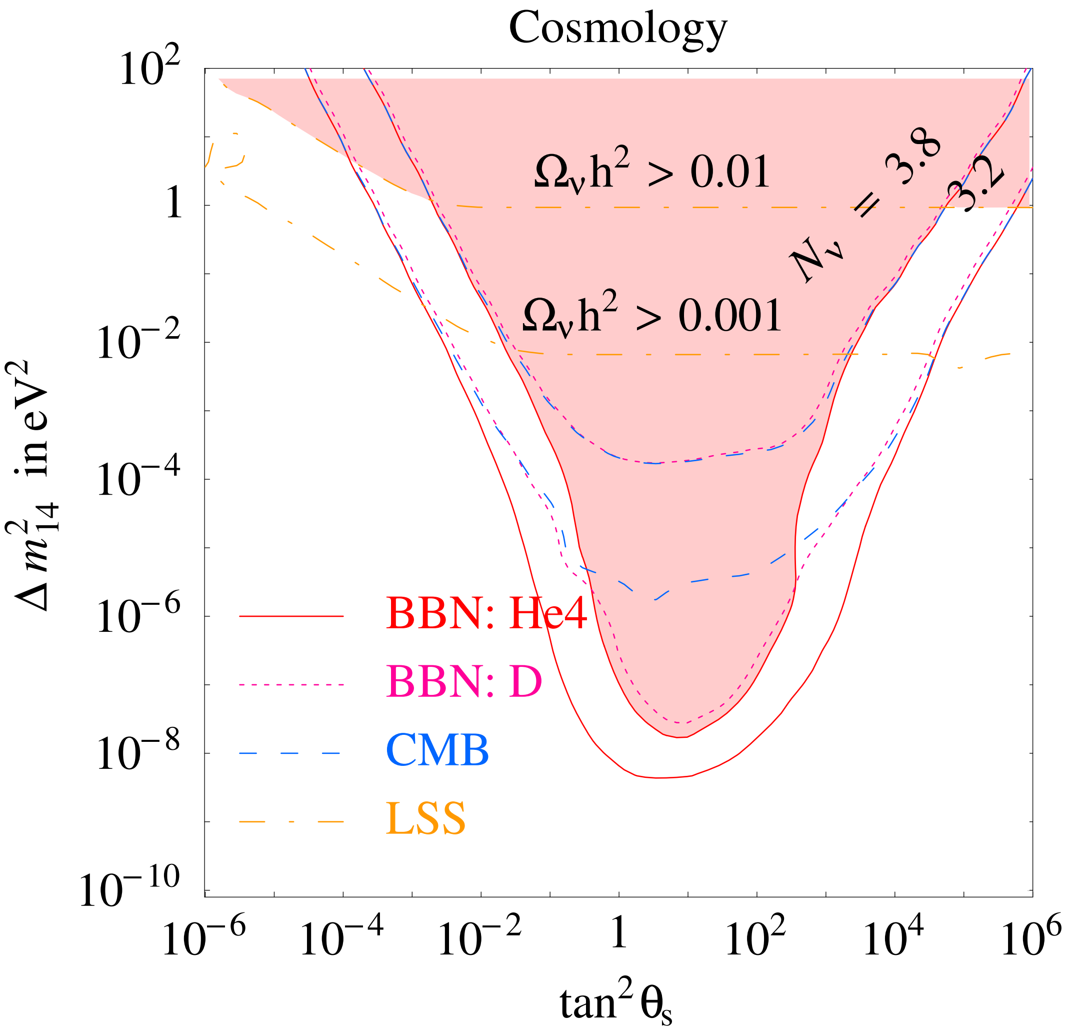






ν_s/ν_1: cosmology

If $\Delta m^2 \gtrsim 10^{-5}\,\text{eV}^2$ ν_s produced before T_ν decoupling $\sim$MeV. Below $\nu_{e,\mu,\tau}$ depleted.



Compatibility with minimal cosmology: ΛCDM, flat n.

5 N_ν observables: **redundant?**

BBN ^{4}He: $N_\nu^{^4\text{He}} = 4$ disfavored?

$$N_\nu^{^4\text{He}} = \overset{?}{2}.7 \pm \overset{?}{0}.7$$

^{4}He affected by ν_e, depleted before BBN if $\Delta m^2 \gtrsim 10^{-8}\,\text{eV}^2$.

Deuterium and CMB now

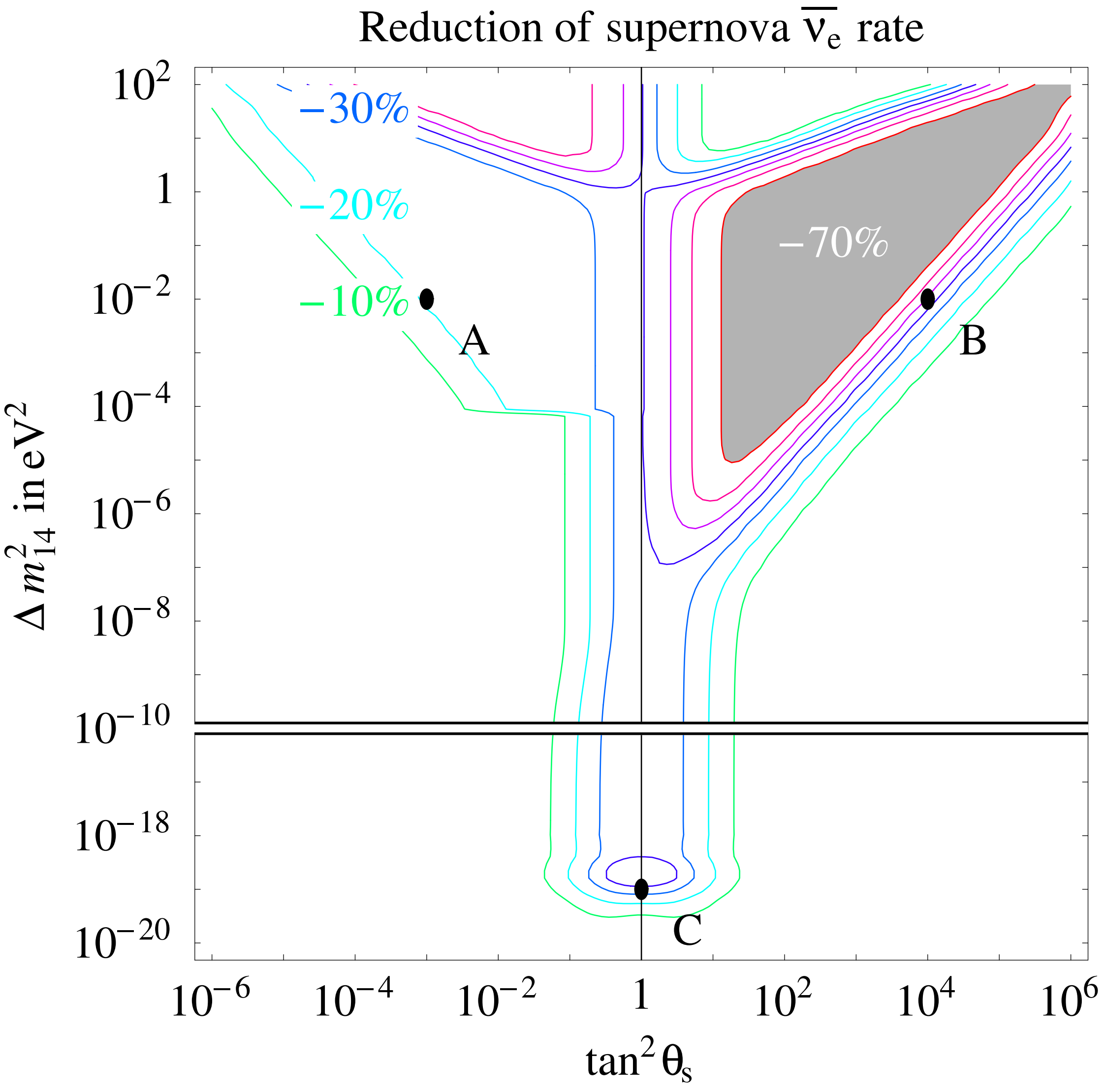
$$N_\nu^{\text{D}} \approx N_\nu^{\text{CMB}} \approx 3 \pm 2$$

but can/will improve (± 0.2)

LSS sensitive to m_ν (i.e. Ω_ν?)

Interacting ν or ν_s reduce free-streaming (CMB ‘peaks’ shifted, clusterings)

ν_s/ν_1: core collapse supernovæ

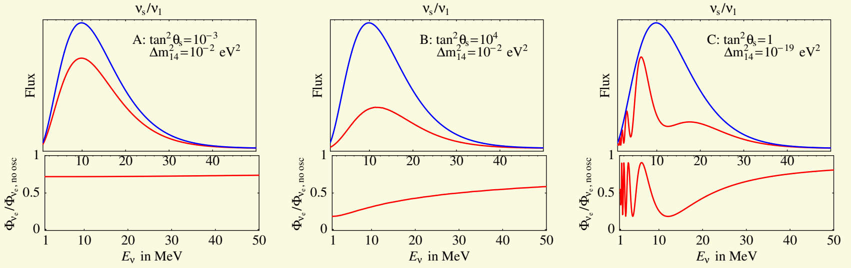

Reduction of supernova $\overline{\nu}_e$ rate

MSW resonance mostly for $\tan\theta_s > 1$ (but peculiar Y_e profile)

Need a exp/th compromise: $\bar{\nu}_e$ rate will be the main observable?

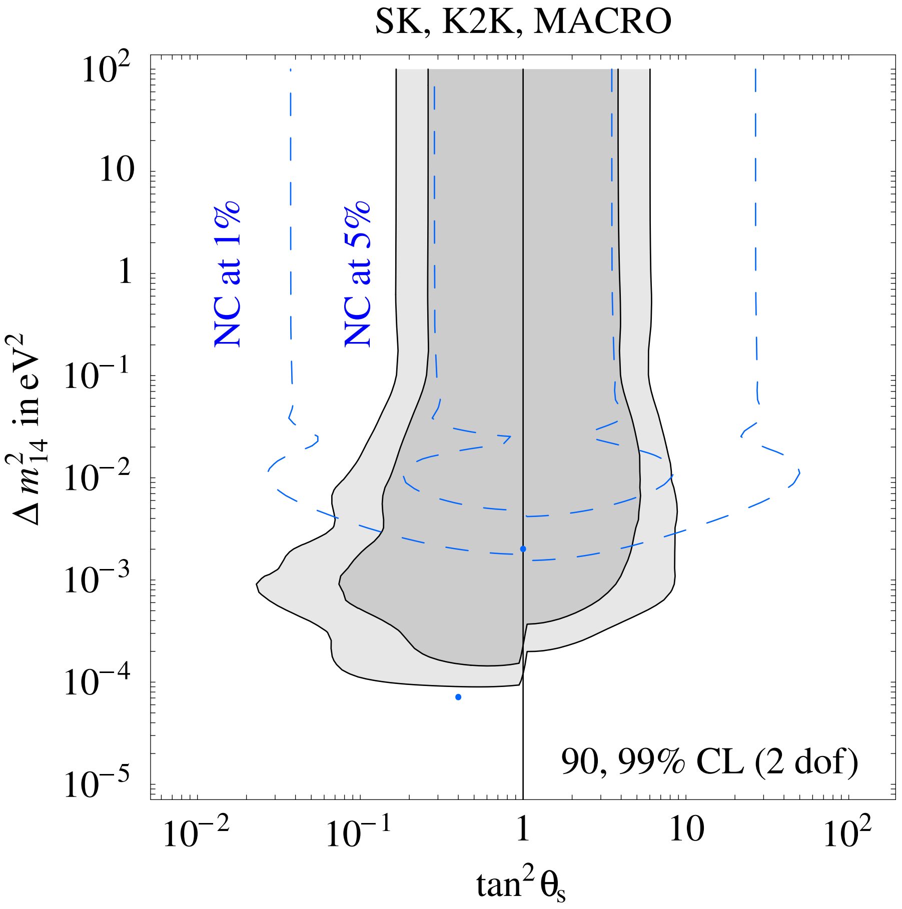
Max effect: $\Phi_{\bar{\nu}_e} = \sin^2\theta_{\text{sun}}\Phi_{\bar{\nu}_{\mu,\tau}}$: 70% deficit excluded by SN1987?

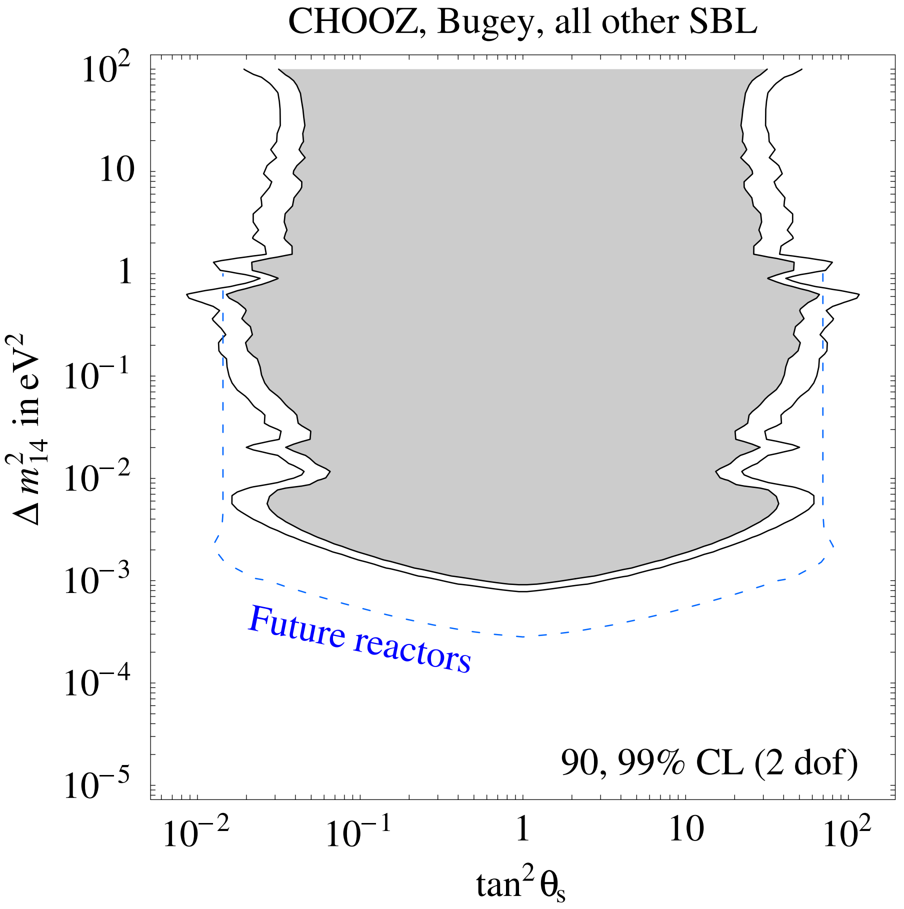
Spectral distortions around sides of MSW triangles



ν_s/ν_1: terrestrial exp.s

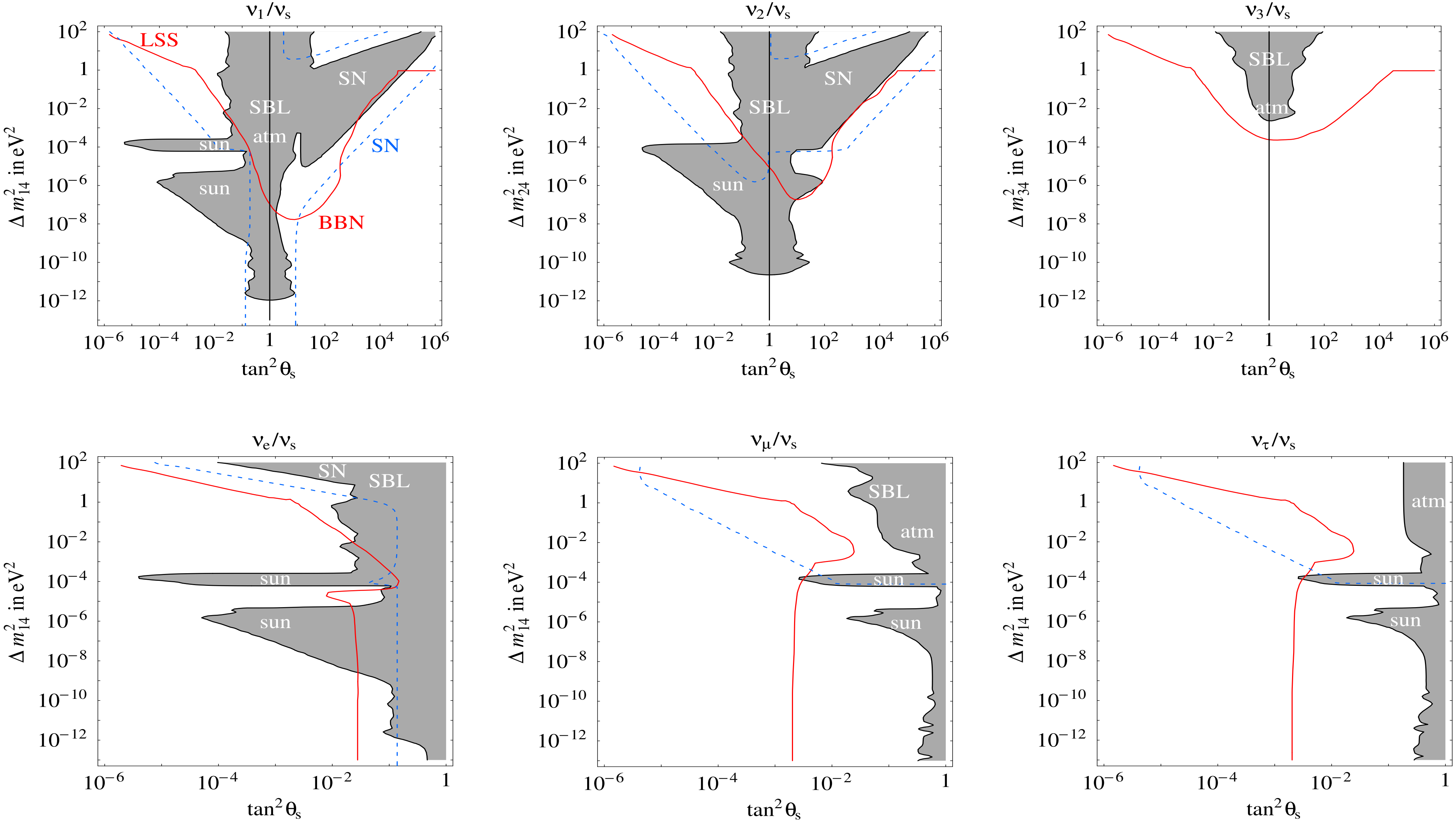
ν_s/ν_1 induces $P(\nu_\ell \to \nu_s) \propto \theta_s^2$ and $P(\nu_\ell \to \nu_\ell') \propto \theta_s^4$ $(\ell = \{e, \mu, \tau\})$.
CHOOZ, Bugey (Karmen, CDHS, CCFR, Nomad, Chorus) better at small θ_s.
Atmospheric experiments SK, K2K, MACRO better at smaller Δm_{14}^2.





- Search non standard sterile signals in atm data.
- Build double-CHOOZ.

$\nu_s/\nu_{\rm other}$



Results similar to ν_s/ν_1 with one qualitative difference: if ν_e is negligibly involved in sterile mixing cosmology becomes the main probe

Other probes?

Other probes are potentially sensitive down to much smaller Δm^2. But...

Relic supernovæ $\bar{\nu}_e$: initial flux uncertain. Energy spectrum unaffected.

Neutrino astrophysics at high energy: intial flux, energy spectrum unknown.
Expected flavour composition: $\Phi_e : \Phi_\mu : \Phi_\tau = r : 1 : 1$ with $r = 1$.
But $r < 1$ if some μ cannot decay. But different spectra.

$\nu_{\rm s}$ negligibly affect Φ_μ/Φ_τ ($\nu_{1,2,3}$ contain roughly equal amounts of μ and τ).

$\nu_{\rm s}$ can modify $\Phi_e/\Phi_{\mu,\tau}$, but hard to measure Φ_e. Could be (?) reconstructed from the shower rate, proportional to $\text{CC}_e + \text{NC}_{e,\mu,\tau}$.

Direct detection of CMB neutrinos: sensitive to $\nu/\nu_{\rm s}$ oscillations after BBN, i.e. $\Delta m^2 \lesssim 10^{-8}\,\text{eV}^2$. Rate well known and ridiculously small: see you at Nu2040 (unless extra interaction could make ν clustered enough)

Signals of ∞ νs

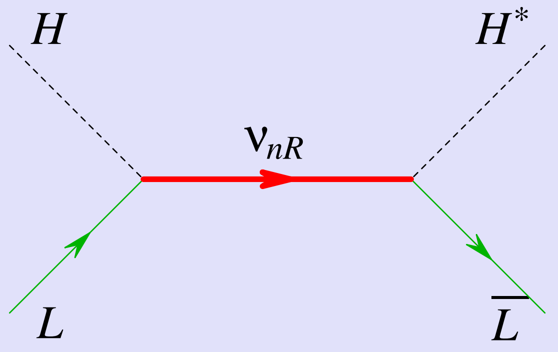
ν_R in flat extra dimensions

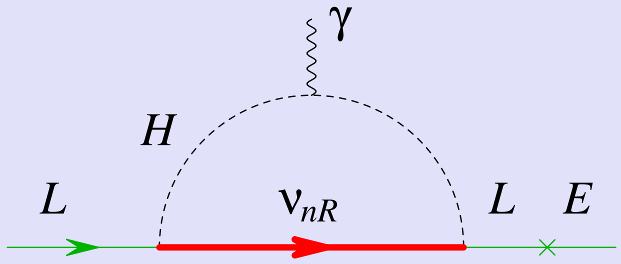
The minimal model predicts, in terms of the radius R, a tower of sterile ν_n with

$$m_n \sim \frac{n}{R}, \qquad \theta_n \sim \frac{m_\nu}{m_n} \qquad n = 1, 2, 3, \ldots$$

Much studied before SNO, SK. Something survives: SN and virtual effects.

$1/R > \sqrt{AE_\nu} \sim 10^3\,$eV (i.e. $R \lesssim$ Å) in order to avoid MSW resonances in supernovæ. Actually $1/R > 10^2\,$eV allowed with a non-standard SN explosion (some energy lost into KK, chemical composition modified such that $A_e = 0$, non standard flavour ratios in ν fluxes). Predictions studied in non minimal models.





$$P(\nu_i \to \nu_j; L \approx 0) \sim |\epsilon^2_{ij}|, \qquad \text{BR}(\ell_i \to \ell_j\gamma) \sim |e\epsilon_{ij}/4\pi|^2$$

$P(\nu_{e,\mu} \to \nu_\tau)$ competitive with charged leptons, suppressed by a loop. $\epsilon_{ij} \sim 10^{-\text{few}}$. Minimal model predicts the flavour structure $\epsilon_{ij} \propto (m_\nu m_\nu^\dagger)_{ij}$.

Executive summary /gosplan

(suggesting is always easier than doing)

Astroph/cosmo/ν exps can probe **different** patterns. Main $\nu_{\rm s}$ searches seem

- Measure $N_\nu^{^4{\rm He}}$ **and** $N_\nu^{\rm D}$ **and** $N_\nu^{\rm CMB}$: different physics, different systematics.
  Today none discriminates 3 from 4 (extra $\nu_{\rm s}$) from $3+4/7$ (extra spin 0).
  Minimal subset: test $N_\nu^{^4{\rm He}} \overset{?}{=} 4$ and measure $N_\nu^{\rm CMB}$.

  Large Scale Structures + CMB test $\nu_{\rm s}$ with small abundancy and $m_{\rm s} \sim 10\,{\rm eV}$

- Measure better **low energy solar** ν: $\nu_{\rm s}$ could manifest only there.
  Also DoubleChooz, Mton WČ, Monolith-ino. . .

- Test if the the next **supernova** ν burst is standard.
  If explodes tomorrow, theoretical errors would dominate.

Anomalous ν **couplings** from mixing with extra-d ν_R (or with 4d pseudo-Dirac).

Reduced $N_\nu^{\rm Free\ Stream}$ from new low-energy interactions: test with CMB/LSS.

Thanks to Cirelli, Marandella, Vissani

Backup slides

FAQ:

1) Relate $\vec{n}$ to V
2) What is ν_s/ν_1 level crossing?
3) How computations are done?
4) How fits are done?
5) Relate N_ν to true observables
6) LSND?

Other questions are at the asker's risk

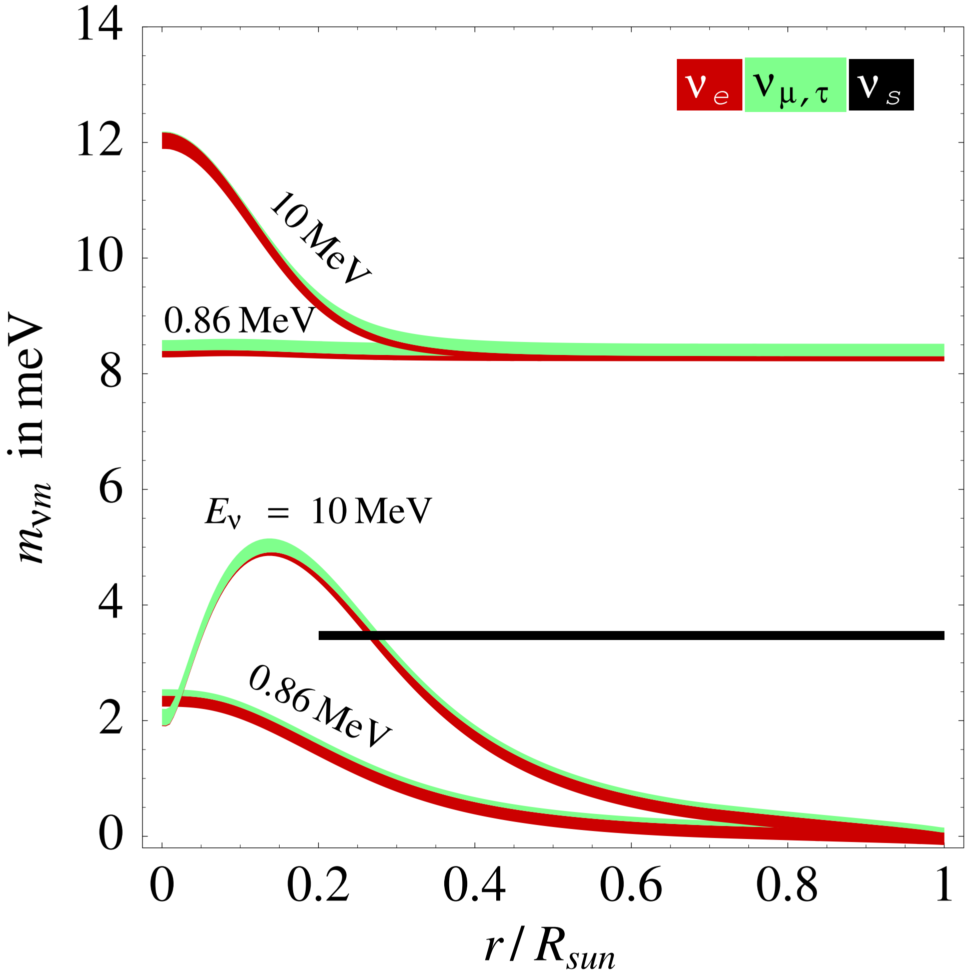
Hidden details

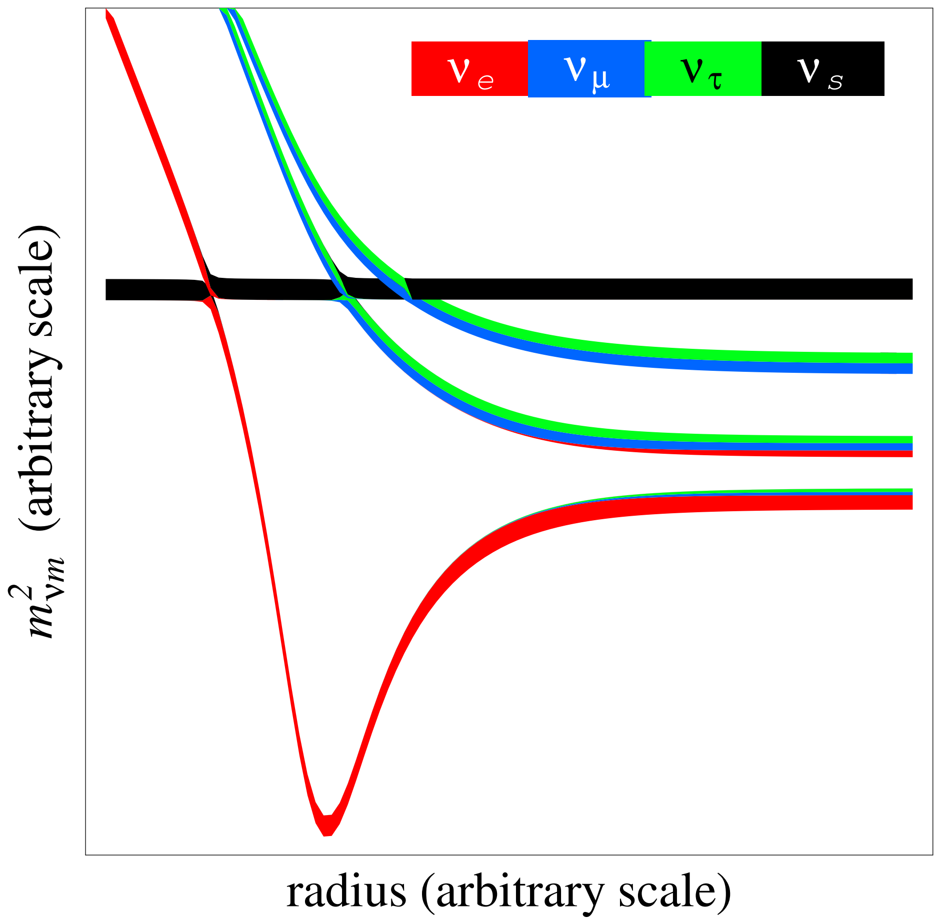
4×4 mixing V in terms of: 3×3 mixing U, a mixing angle θ_s and a versor $\vec{n}$

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

$$V = \begin{array}{c} \\ \nu_\ell \\ \nu_\mathsf{s} \end{array} \!\!\begin{array}{c} \begin{array}{cc} \qquad\qquad \nu_i \qquad\qquad & \qquad \nu_4 \end{array} \\ \begin{pmatrix} U_{\ell i} - n_i n_\ell^* (1 - \cos\theta_\mathsf{s}) & n_\ell^* \sin\theta_\mathsf{s} \\ -n_i \sin\theta_\mathsf{s} & \cos\theta_\mathsf{s} \end{pmatrix} \end{array}.$$

Level crossings in the sun and in a SN





(How to compute

4ν analyses are orders of magnitude more demanding than usual fits.
Compute oscillations using the matrix density in the mass eigenstate bases.

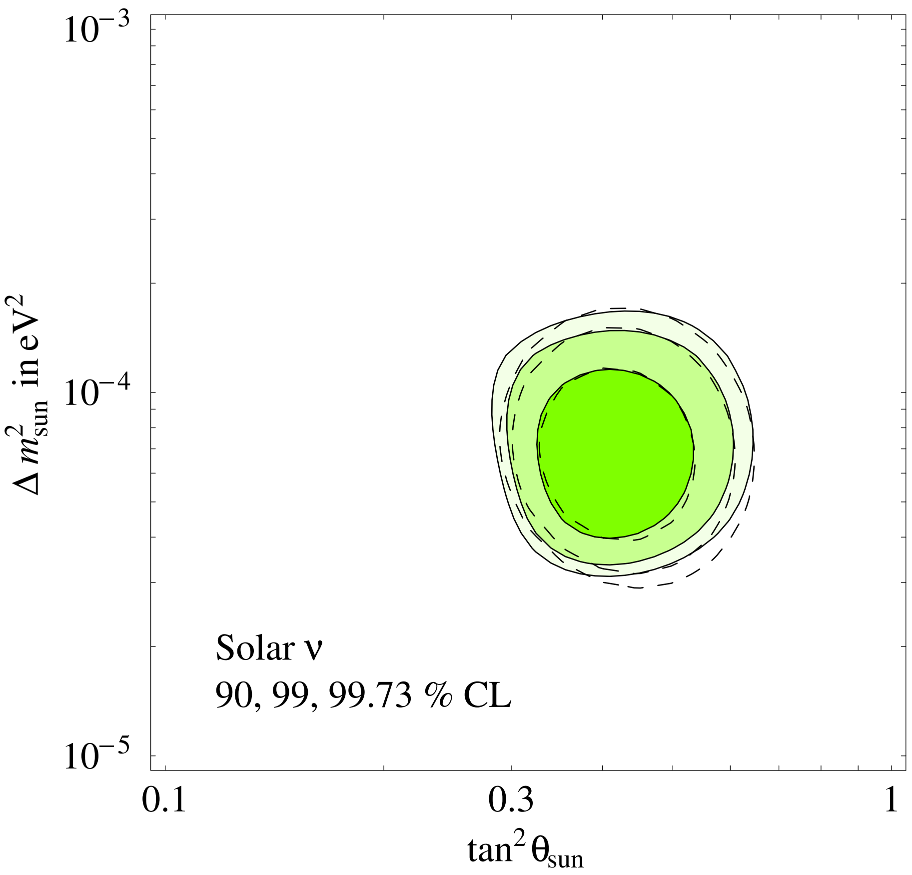
1) When density is constant, this allows to *analytically* average over fast oscillations: give small imaginary parts to oscillation phases.

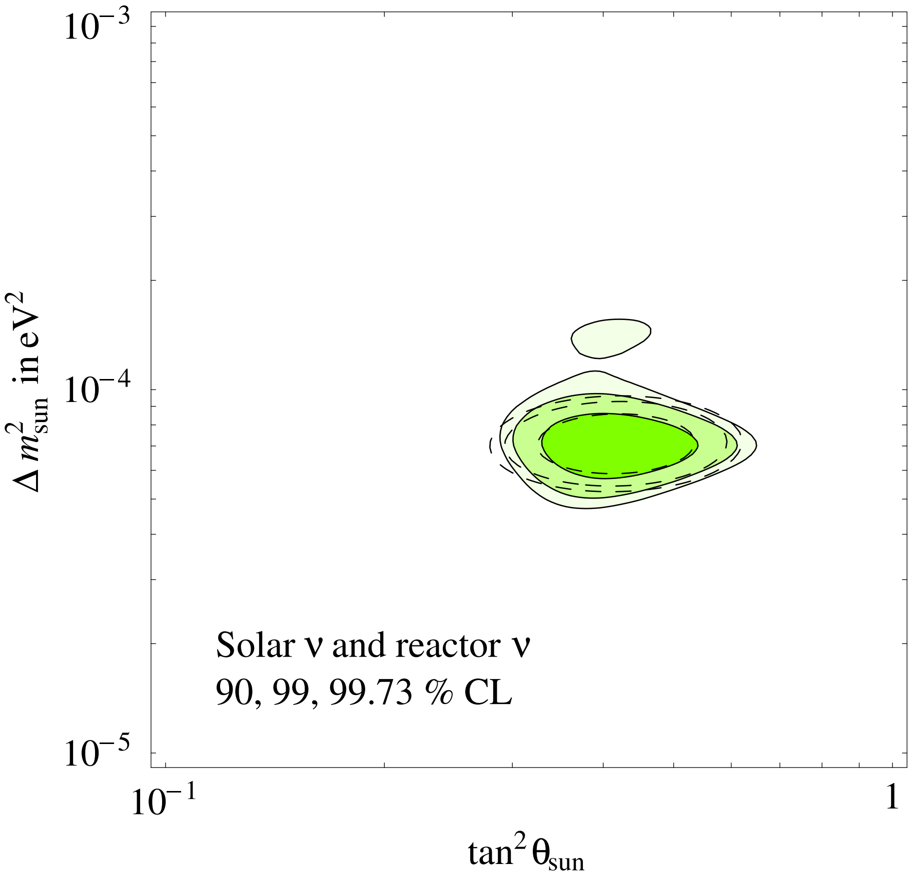
2) When ρ changes in a sharp way $\mathscr{U} = V_m^\dagger(r \lesssim R) \cdot V_m(r \gtrsim R)$
(e.g. air/mantle, mantle/core in the earth; MSW resonances in the sun or SN).
If levels i and j cross, $\mathscr{U}$ is a rotation with angle $\alpha = 90^\circ$ in the (ij) plane.

3) When ρ changes in a not very sharp way the rotation angle is given by $\tan^2\alpha = P_C/(1-P_C)$, where P_C is the level crossing probability.

How to fit)

Include uncertainties on active parameters in Gaussian approximation:





Cosmological observables

parameterized in terms of “effective number of neutrinos”

$$
\begin{aligned}
Y_p &\simeq 0.248 + 0.0096 \ln \frac{\eta}{6.15\ 10^{-10}} + 0.013(N_\nu^{^4\mathrm{He}} - 3), \\
\frac{Y_\mathrm{D}}{Y_\mathrm{H}} &\simeq (2.75 \pm 0.13)\ 10^{-5}\ \frac{1 + 0.11\ (N_\nu^\mathrm{D} - 3)}{(\eta/6.15\ 10^{-10})^{1.6}} \\
\rho_\mathrm{relativistic} &\simeq \rho_\gamma \left[1 + \frac{7}{8} (\frac{4}{11})^{4/3} N_\nu^\mathrm{CMB} \right]
\end{aligned}
$$

LSND

Full computation confirms estimates: 3+1 implies non standard cosmology