Neutrino Oscillations and Implications for New Physics

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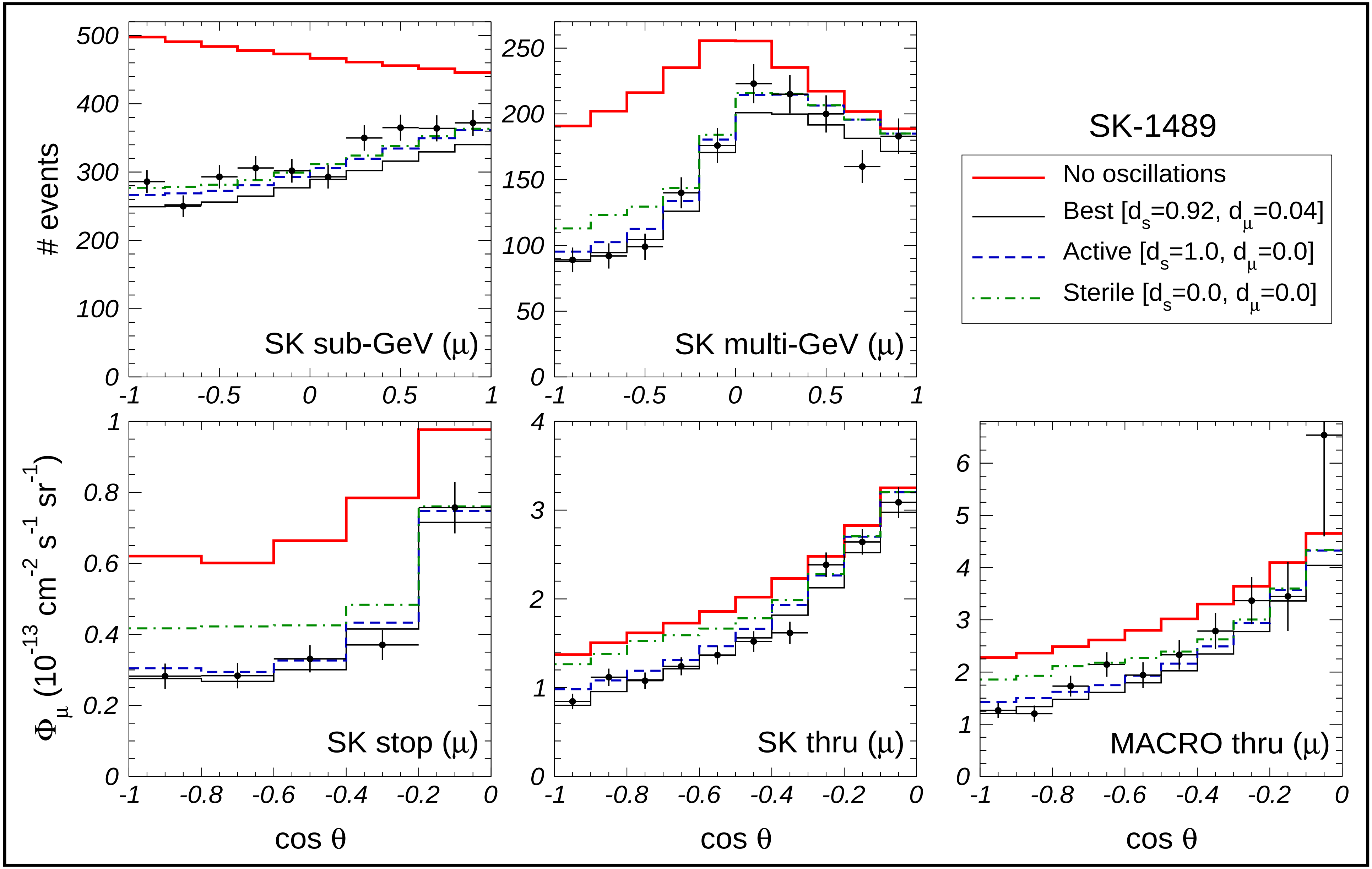
Based on hep-ph/0301061 and hep-ph/0307192
upd to include salt phase data from the SNO experiment

Maltoni, Tortola, Schwetz, JV, hep-ph/0309130

Atmospheric zenith distribution

Maltoni et al, PRD67 (2003) 013011



atmospheric neutrino parameters-1

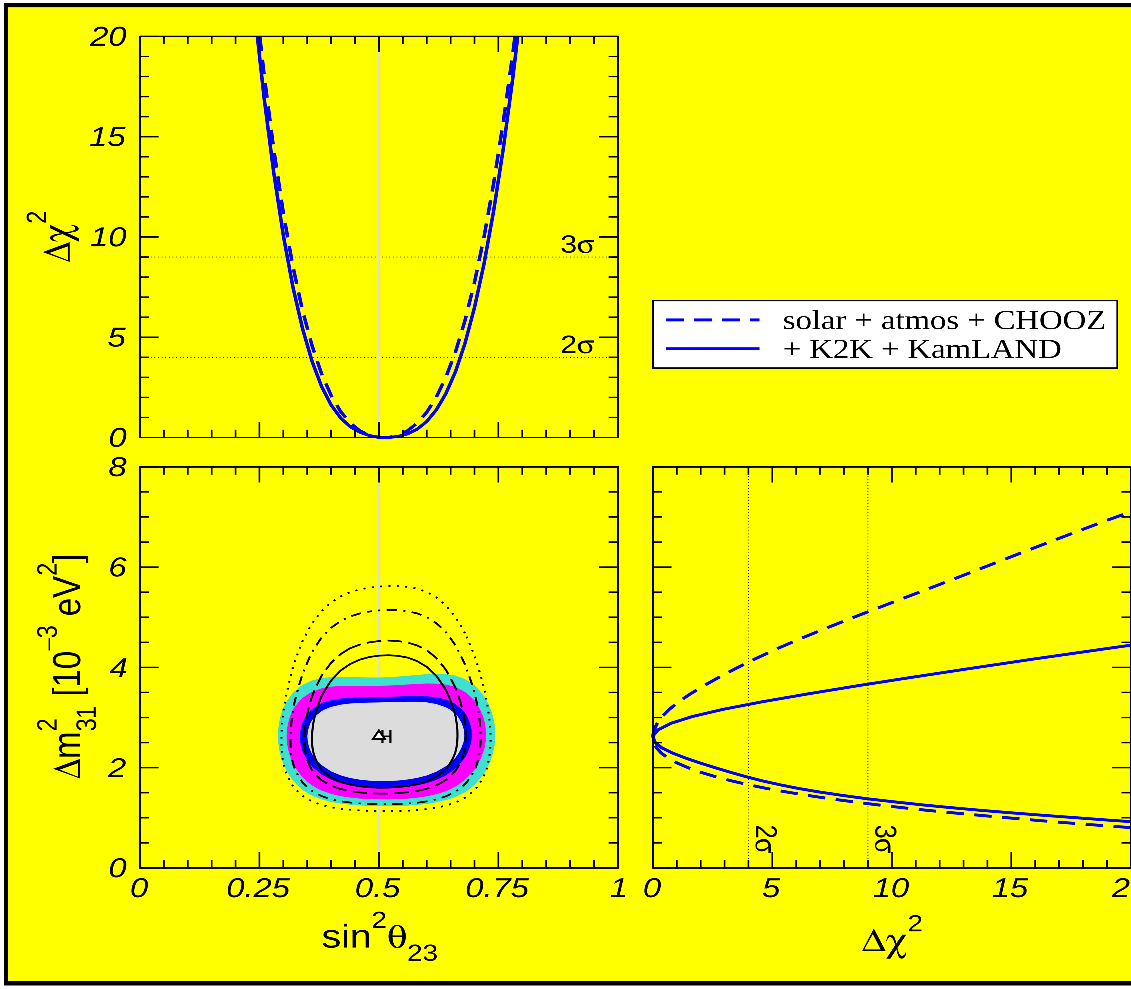
- sterility rejection

Maltoni et al, hep-ph/0309130 v2

upd of PRD67 (2003) 013011

$$\sin^2\theta_{\mathrm{ATM}} = 0.5$$

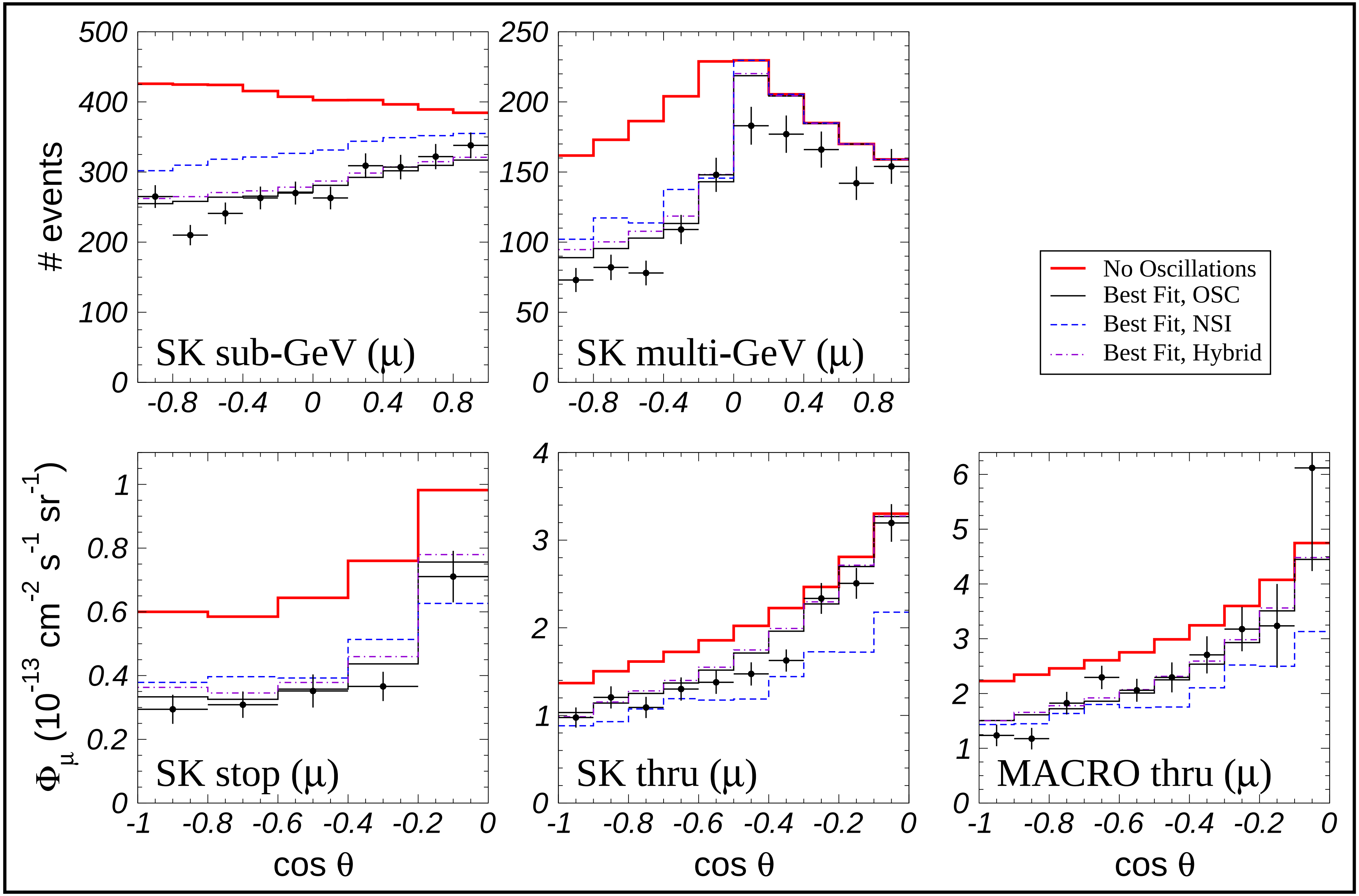
$$\Delta m^2_{\mathrm{ATM}} = 2.6 \times 10^{-3}\ \mathrm{eV}^2$$



light-dark or normal/inverted symmetry

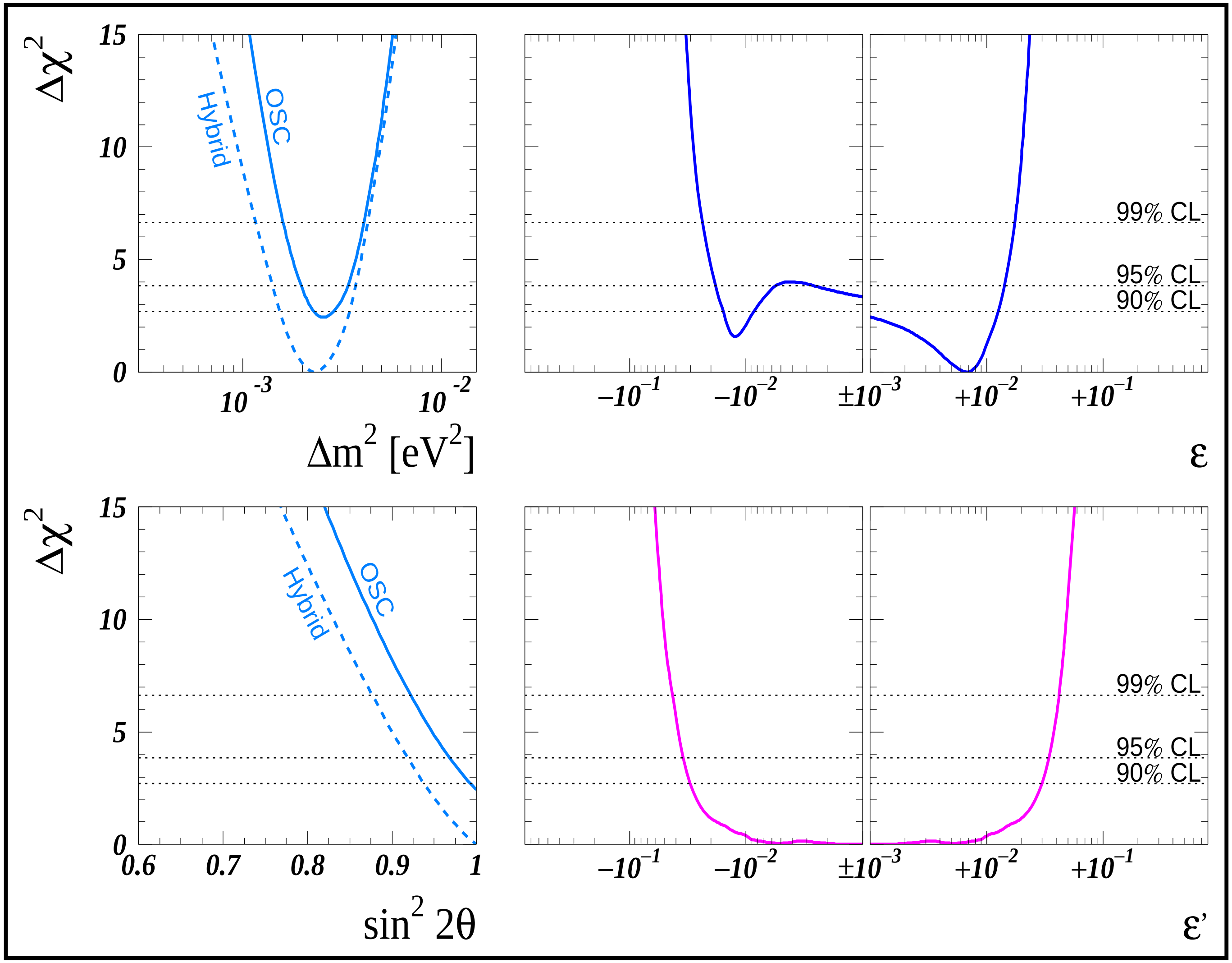
How robust are atmospheric oscillations?

very good contained atm-fit, Gonzalez-Garcia et al, PRL **82** (1999) 3202



non-standard interactions vs atm data

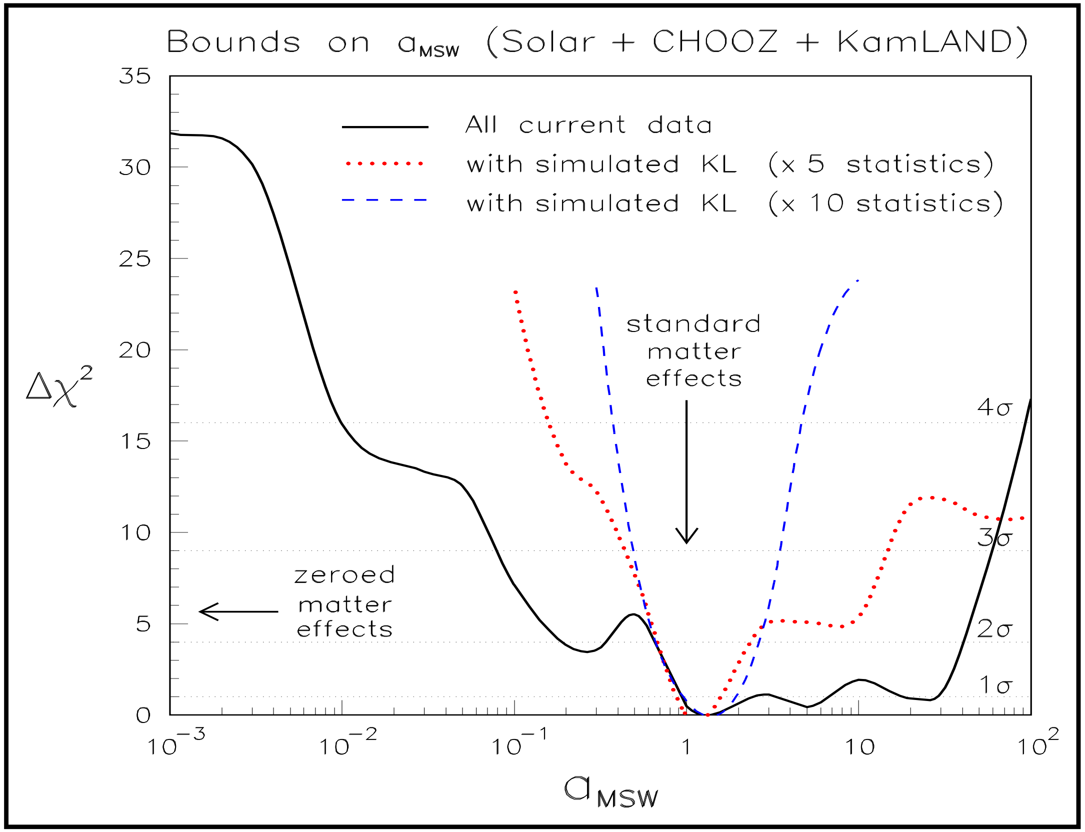
Fornengo et al,
PRD **65** (2002) 013010
[hep-ph/0108043].



atm bounds on FC and NU nu-interactions

Solar neutrinos

matter effects confirmed !

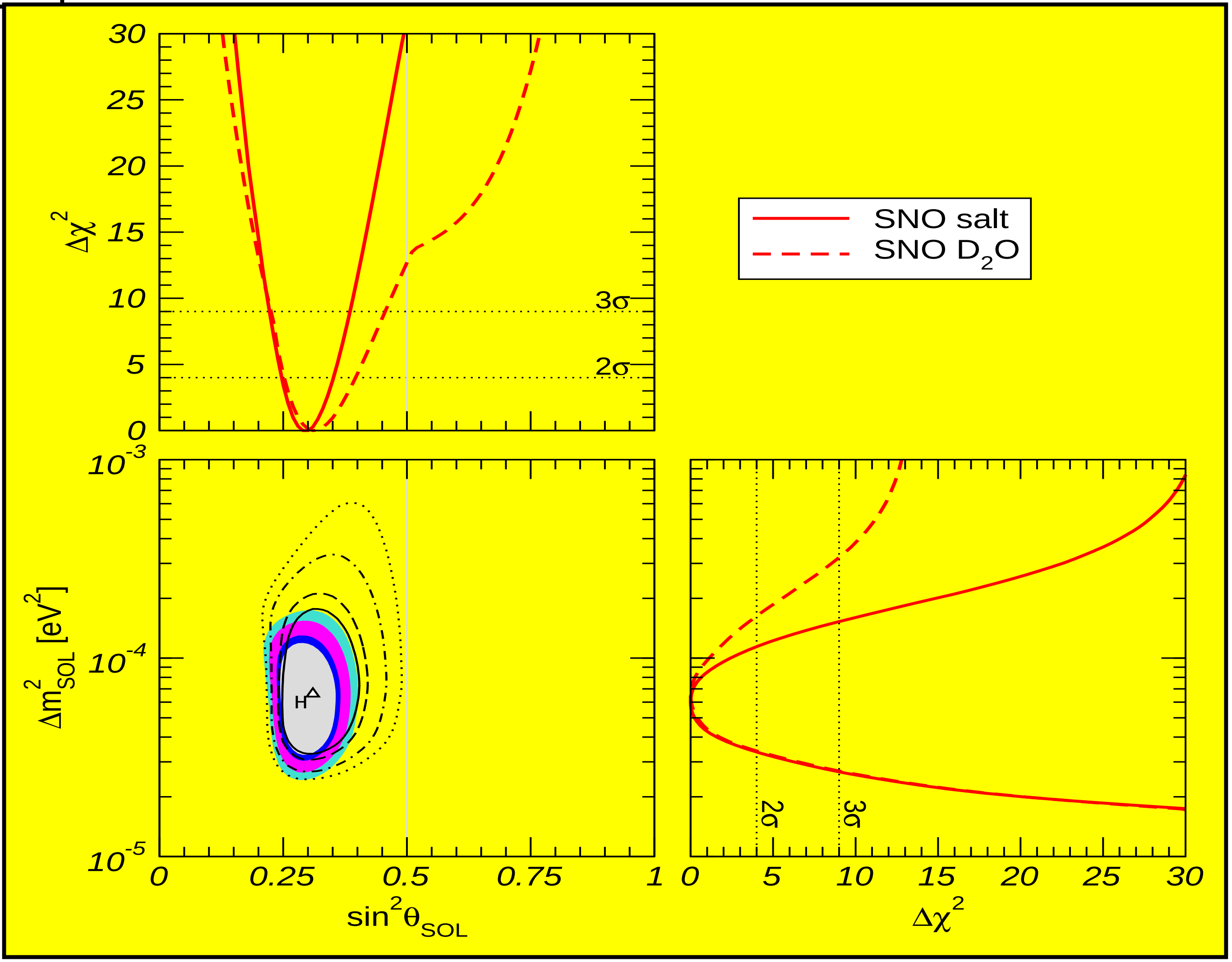


Fogli, Lisi, Marrone, Palazzo, hep-ph/0309100

Solar neutrino parameters

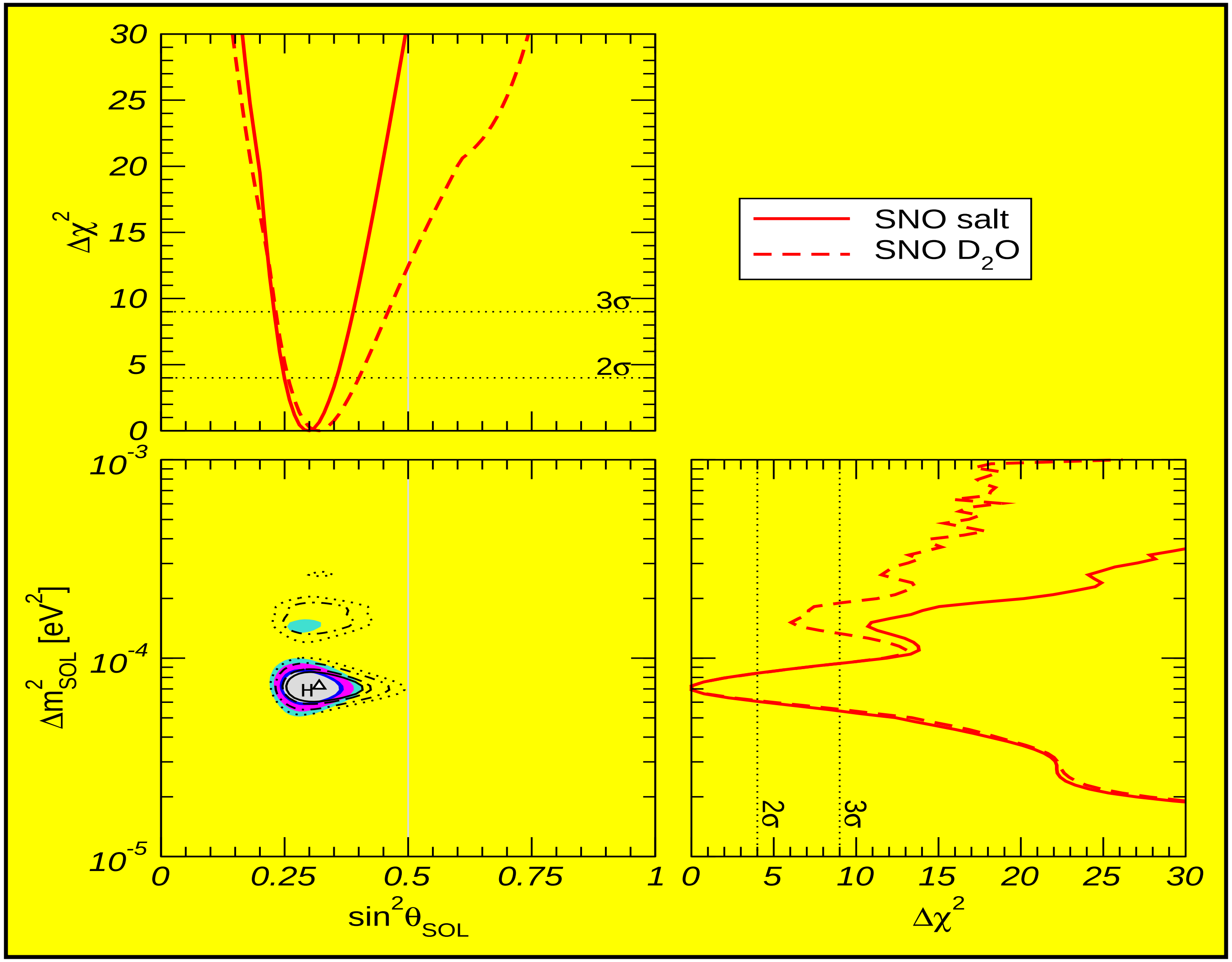
oscilllations happen inside the sun!

Maltoni et al, hep-ph/0309130 v2



Bandyopadhyay et al, Fogli et al, Balantekin et al, Aliani et al

Solar + KamLAND results $\boxed{\bullet}$ $\boxed{\text{3-nu}}$



Maltoni et al, hep-ph/0309130 v2

upd of PRD67 (2003) 013011

and PRD67 (2003) 093003

enormous progress

in contrast to atm,

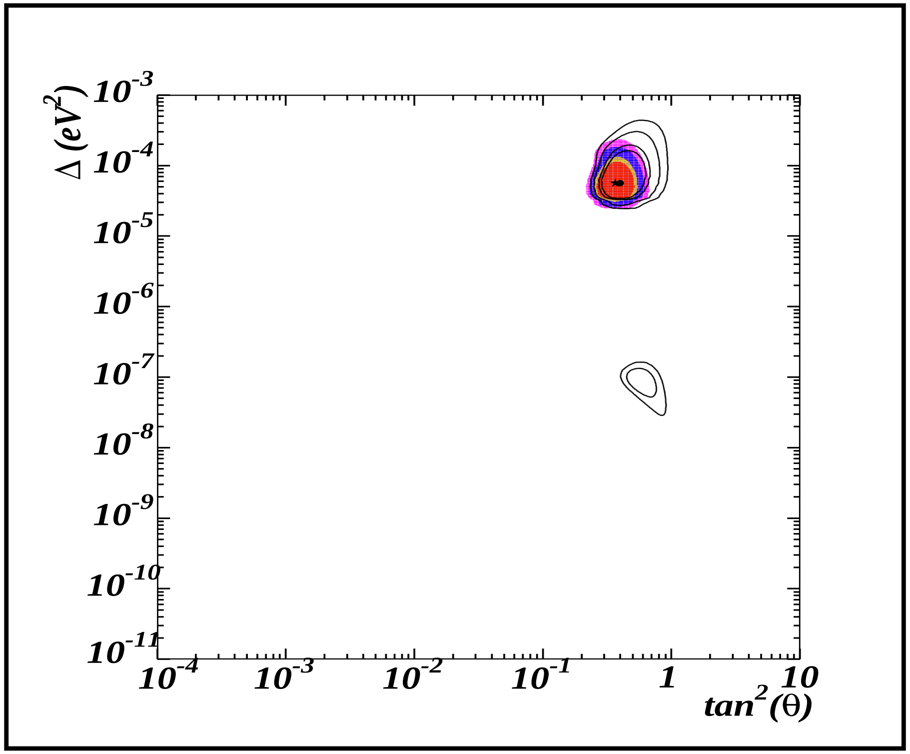
solar mixing is non-maximal

bi-maximal models rejected

LMA-MSW status wrt SN1987A

In 1987, a few neutrinos were detected from the nearby supernova 1987A galaxy about 170,000 light-years away

LMA oscillations may strongly affect $\bar{\nu}_e$ SN-signal Smirnov, Spergel, Bahcall 94; Raffelt et al 96, Kachelriess et al JHEP 0101 (2001) 030, Lunardini & Smirnov



$E_{\bar{\nu}_e}$ =14 MeV,

$E_{\rm bind} = 3 \times 10^{53}$ erg

$\tau \equiv T_{\nu_h}/T_{\bar{\nu}_e}$=1.4

Keil, Raffelt & Janka, APJ590 (2003) 971

solar+SN1987A analysis

Kachelriess et al PRD65 (2002) 073016

LMA-MSW may remain best

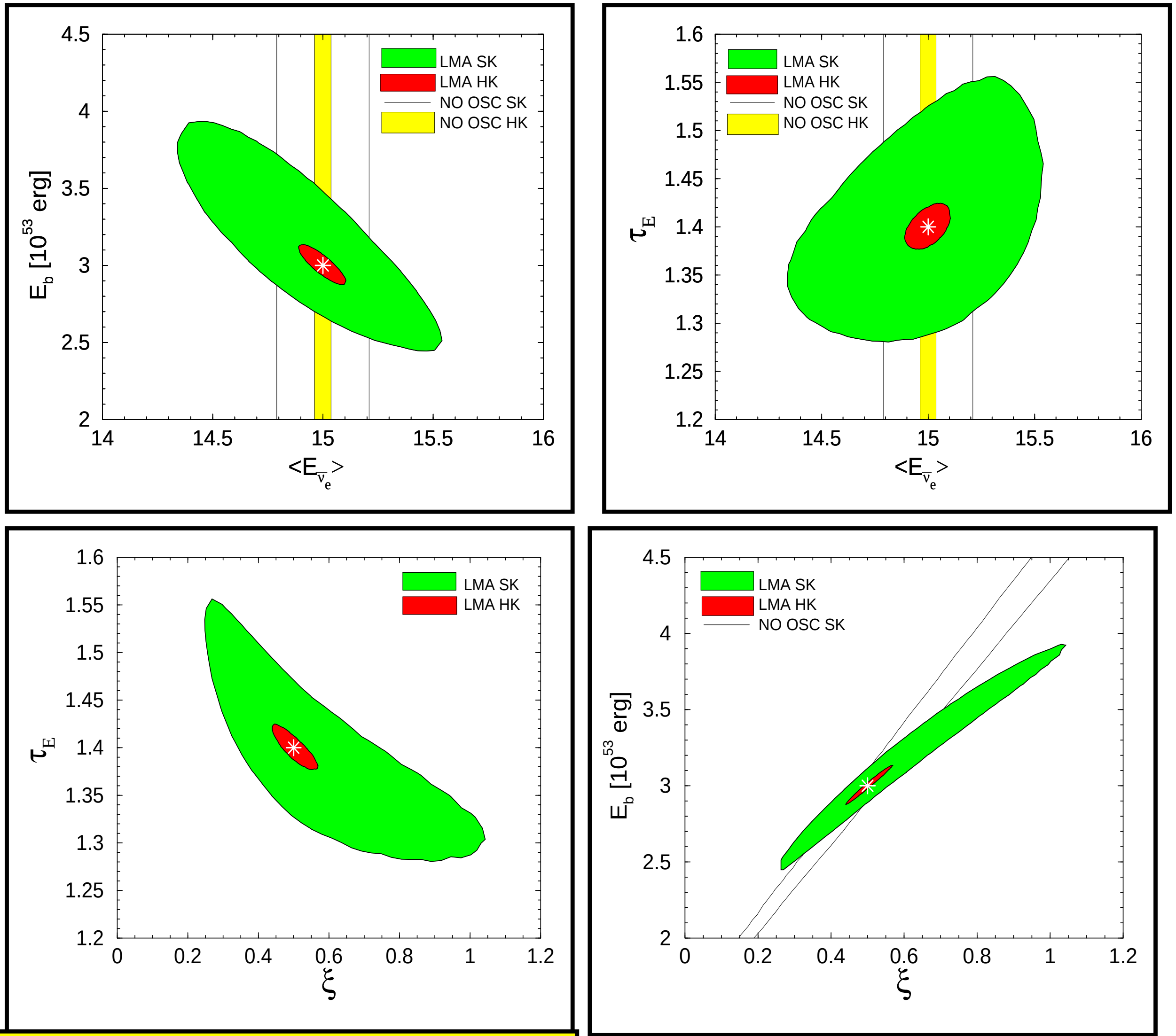
neutrinos as future Supernova probe

Minakata et al, PLB542 (2002) 239

The measurement of a large number of neutrinos from a future galactic supernova will give us important astro information

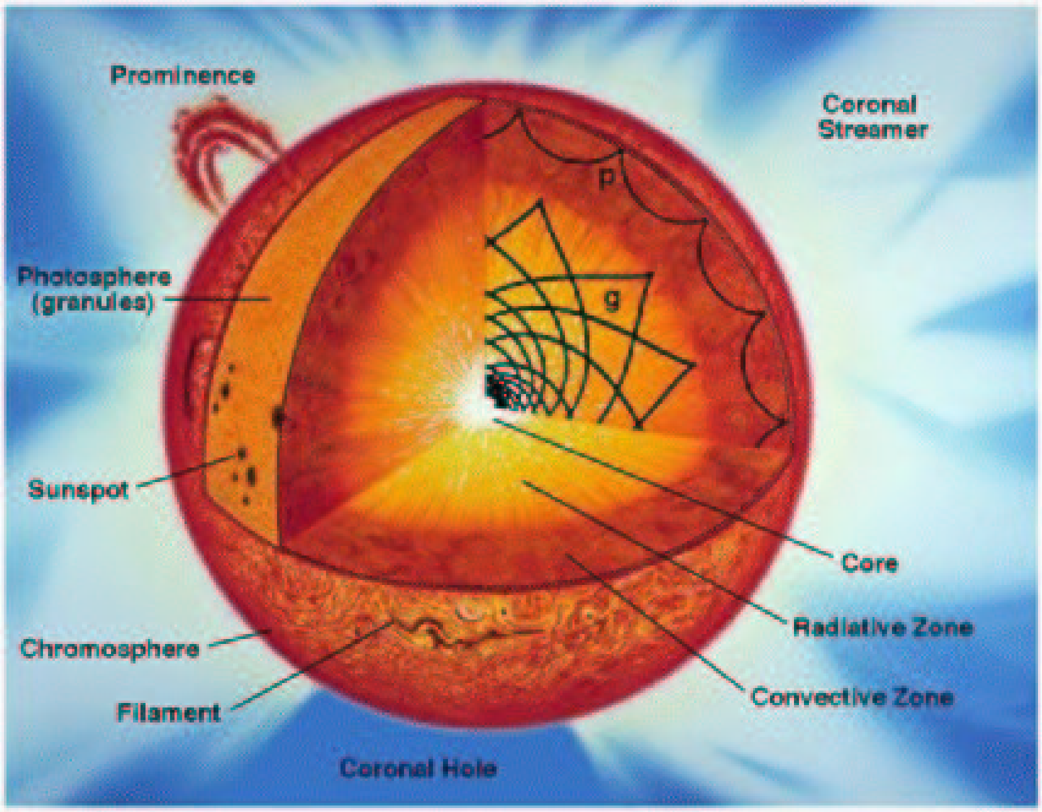
assume 10 kpc galactic SN, simulate data with given astro param

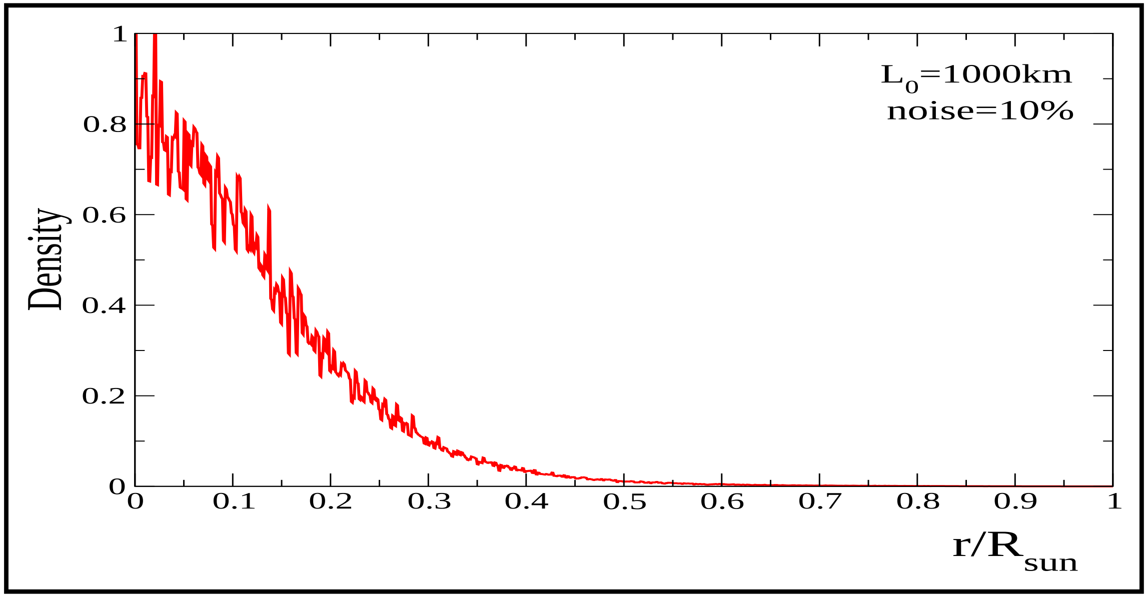
see also Barger, Marfatia & Wood



improved supernova parameter determination

do we understand the Sun?





Robustness of MSW plot

neutrino propagation strongly affected by density noise

Balantekin et al 95

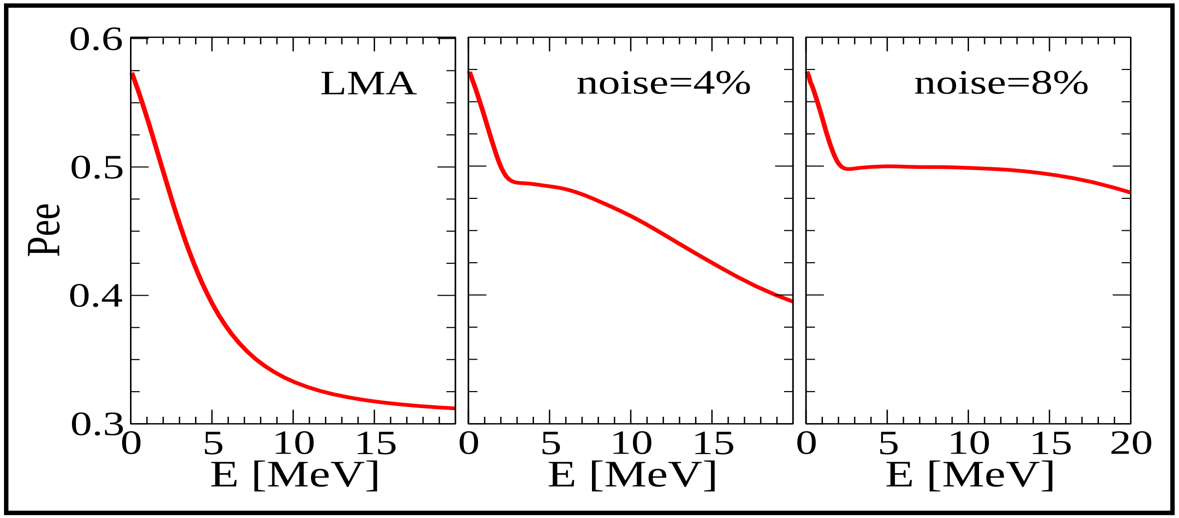
Nunokawa et al NPB472 (1996) 495

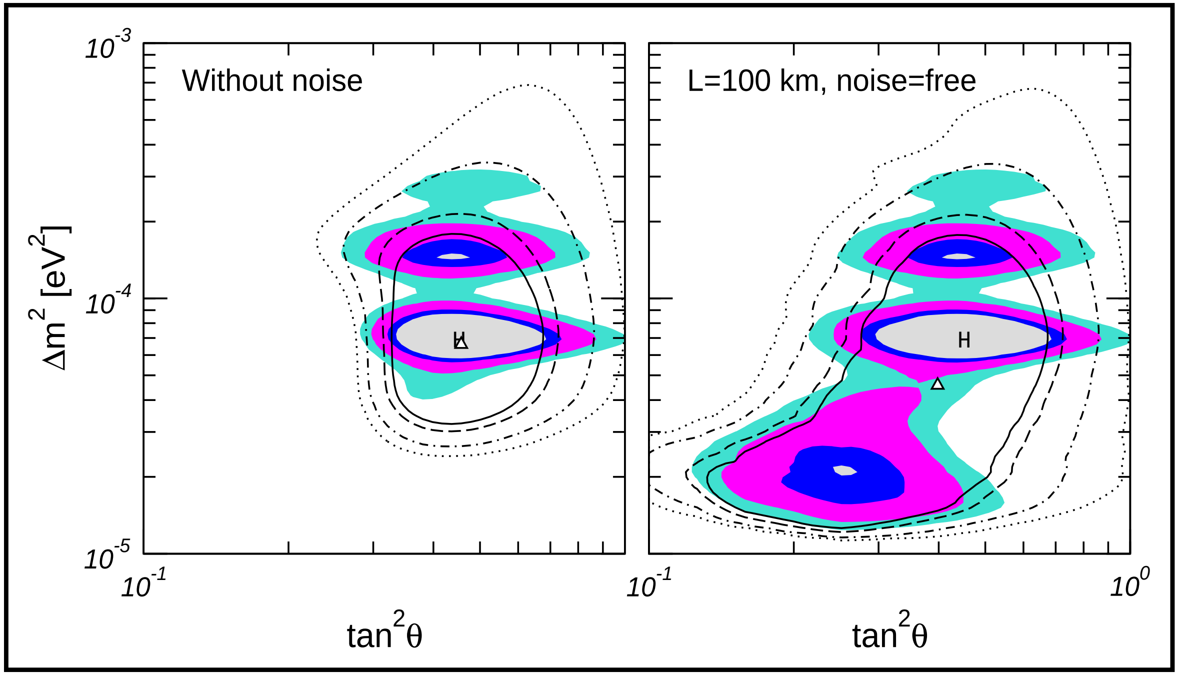
Burgess et al 97

substantial distortion

lower $\Delta m^2_{\mathrm{SOL}}$ possible

Burgess et al, Astrophys.J.588:L65,2003 [hep-ph/0209094]





LSND

hints of neutrino conversions also from the detection of accelerator-produced neutrinos in the LSND experiment

4-nu models Peltoniemi, JV, NPB406, 409 (1993)

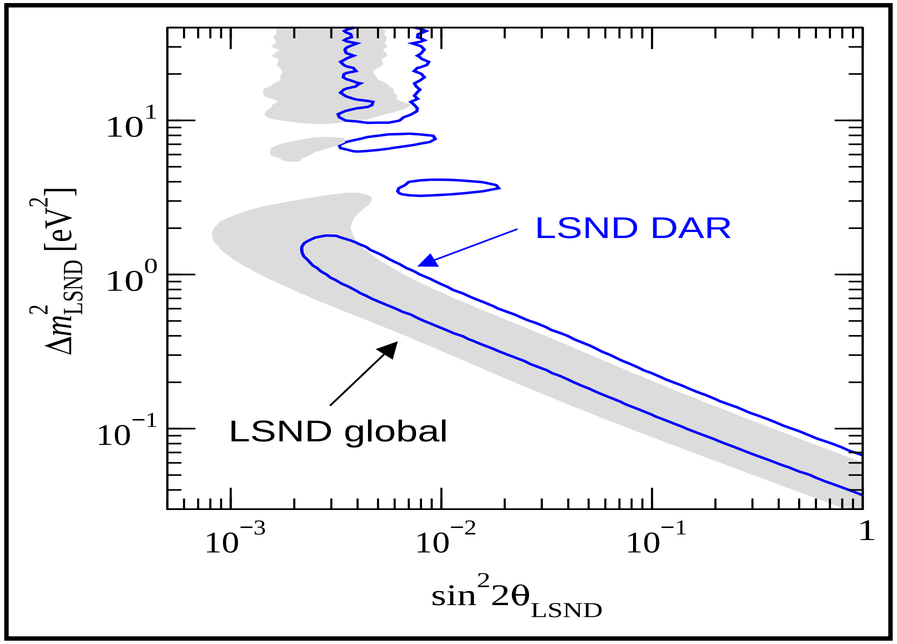
Peltoniemi, Tommasini and JV, PLB298 (1993) 383

Caldwell-Mohapatra PRD48 (1993) 325

barely possible at 3 σ

Maltoni et al NPB643 (2002) 321

upd of PRD65 (2002) 093004

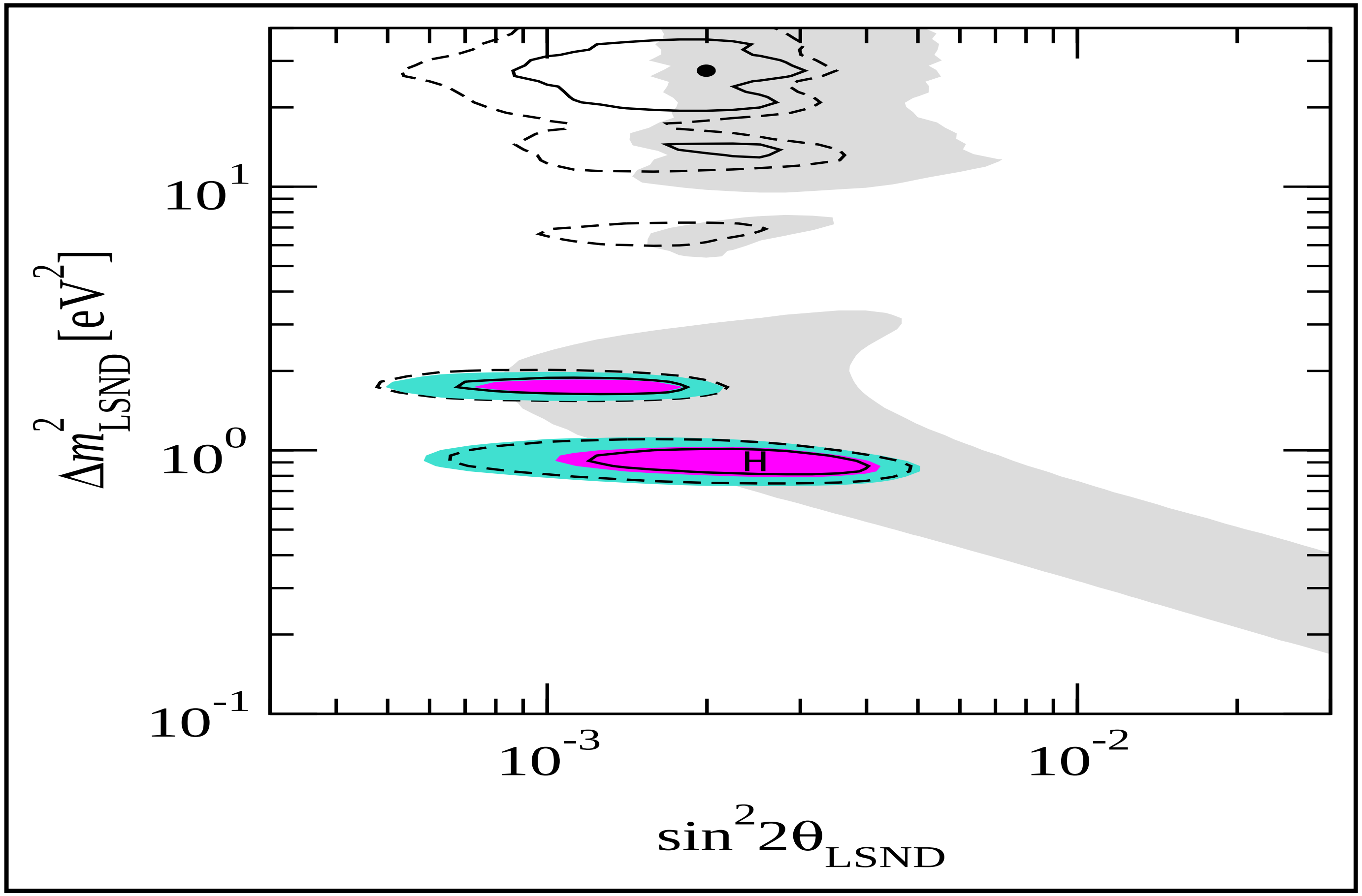


ATM

SOL

Cosmology closes in on LSND

3+1 scheme still OK at 3sigma, higher masses excluded



2df + WMAP + HST + SNIa

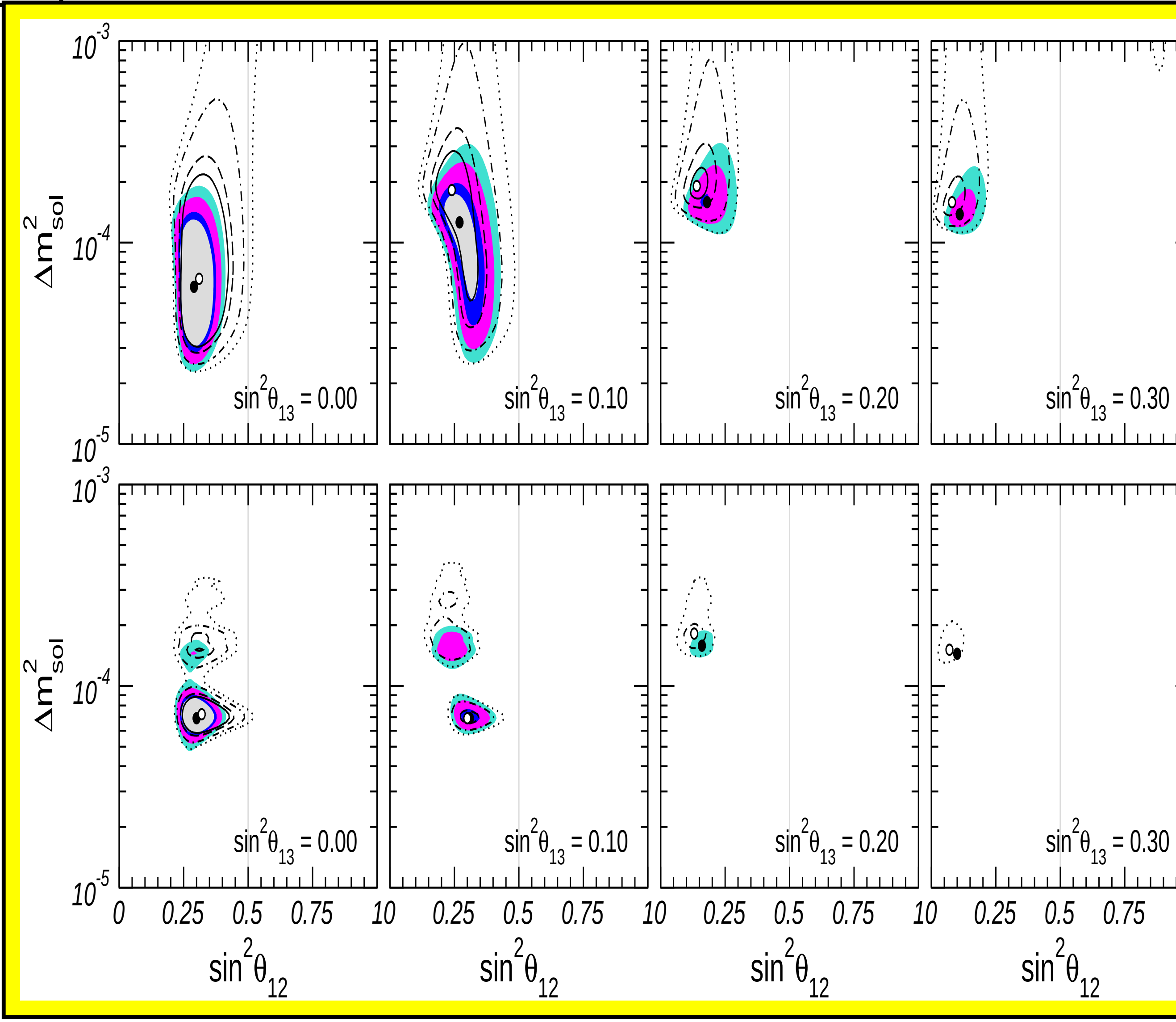
Schwetz et al hep-ph/0305312

Spergel et al, astro-ph/0302209; Hannestad, astro-ph/0303076; Elgaroy & Lahav, astro-ph/0303089,

Crotty, Lesgourgues & Pastor PRD67 (2003) 123005

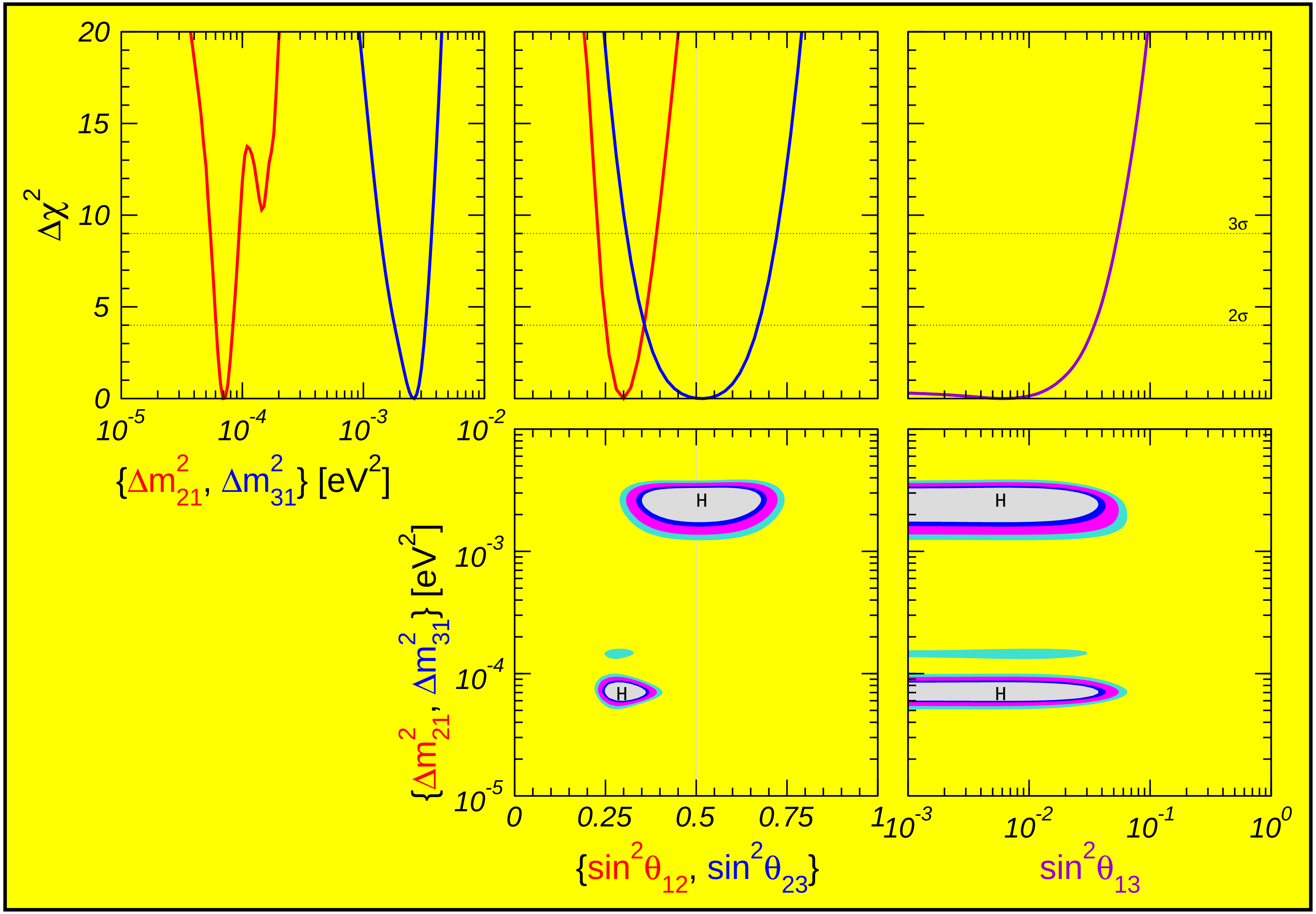
3-nu regions

- Maltoni et al, hep-ph/0309130 v2



In a nut shell

- Maltoni et al, hep-ph/0309130 v2, upd of PRD63 (2001) 033005



3-nu Oscillation Parameters

•

parameter	best fit	2σ	3σ	5σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.6	1.8–3.3	1.4–3.7	0.77–4.8
$\sin^2\theta_{12}$	0.30	0.25–0.36	0.23–0.39	0.17–0.48
$\sin^2\theta_{23}$	0.52	0.36–0.67	0.31–0.72	0.22–0.81
$\sin^2\theta_{13}$	0.006	≤ 0.035	≤ 0.054	≤ 0.11

Table I: Best-fit values, 2σ, 3σ and 5σ intervals (1 d.o.f.) for the three-flavour neutrino oscillation parameters from global data including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K) experiments.

minimal set of basic parameters

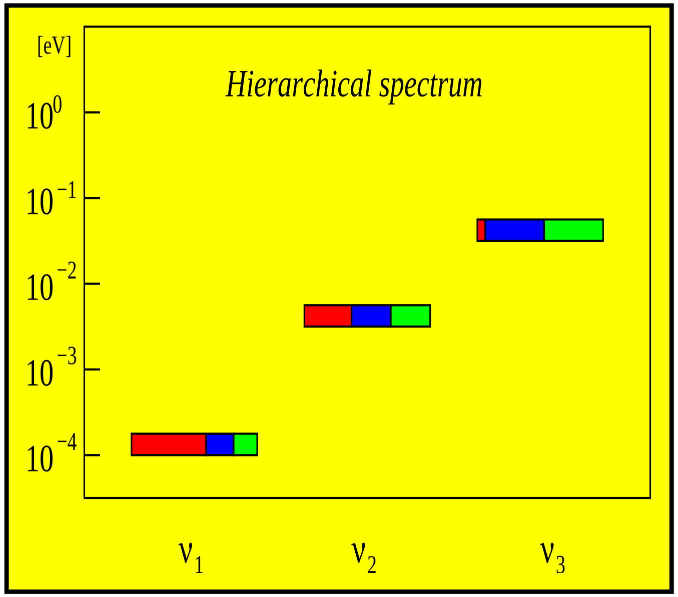
- 3 angles θ_{ij} — 23=atm 12=sol 13=reac

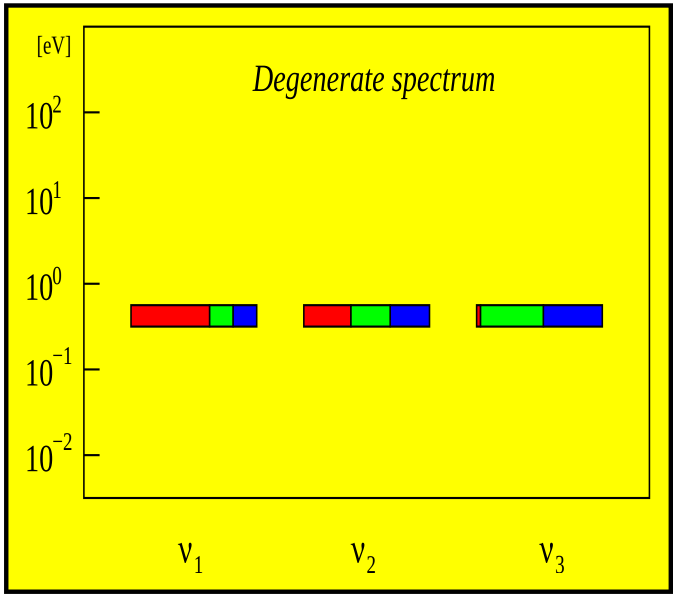
  1 KM-like phase — oscillations — δ

  2 Majorana phases — $\beta\beta_{0\nu}$ — α , β

Schechter and JV, PRD22 (1980) 2227, D23(1980) 1666

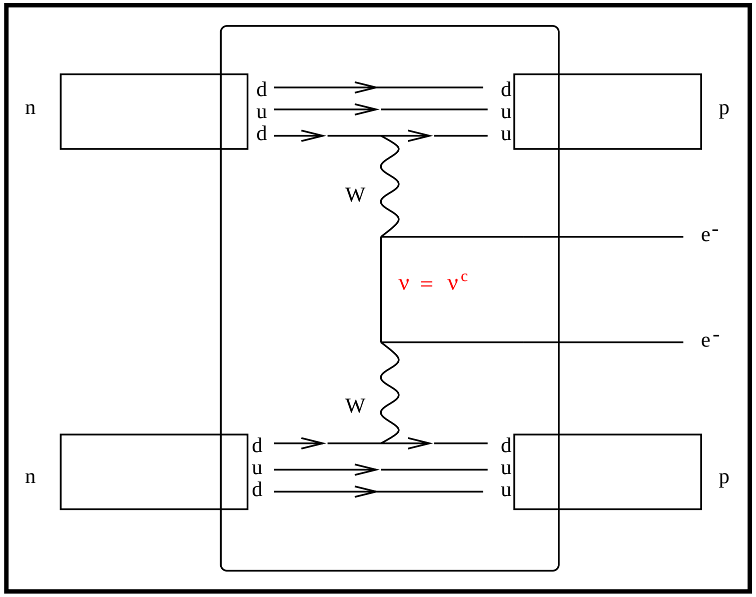
- ν_e ν_μ ν_τ





$\beta\beta_{0\nu}$ and the neutrino spectra (mass mechanism)

given that neutrinos are massive, one expects $\beta\beta_{0\nu}$ to occur with an amplitude governed by the average mass parameter



$$\boxed{\langle m_\nu \rangle = \sum_j K_{ej}^2 m_j}$$

$$\boxed{\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3}$$

- 3 masses: $\boxed{m_i}$
- 2 angles: $\boxed{\theta_{12}}$ and $\boxed{\theta_{13}}$
- 2 CP violating phases: $\boxed{\alpha, \beta}$

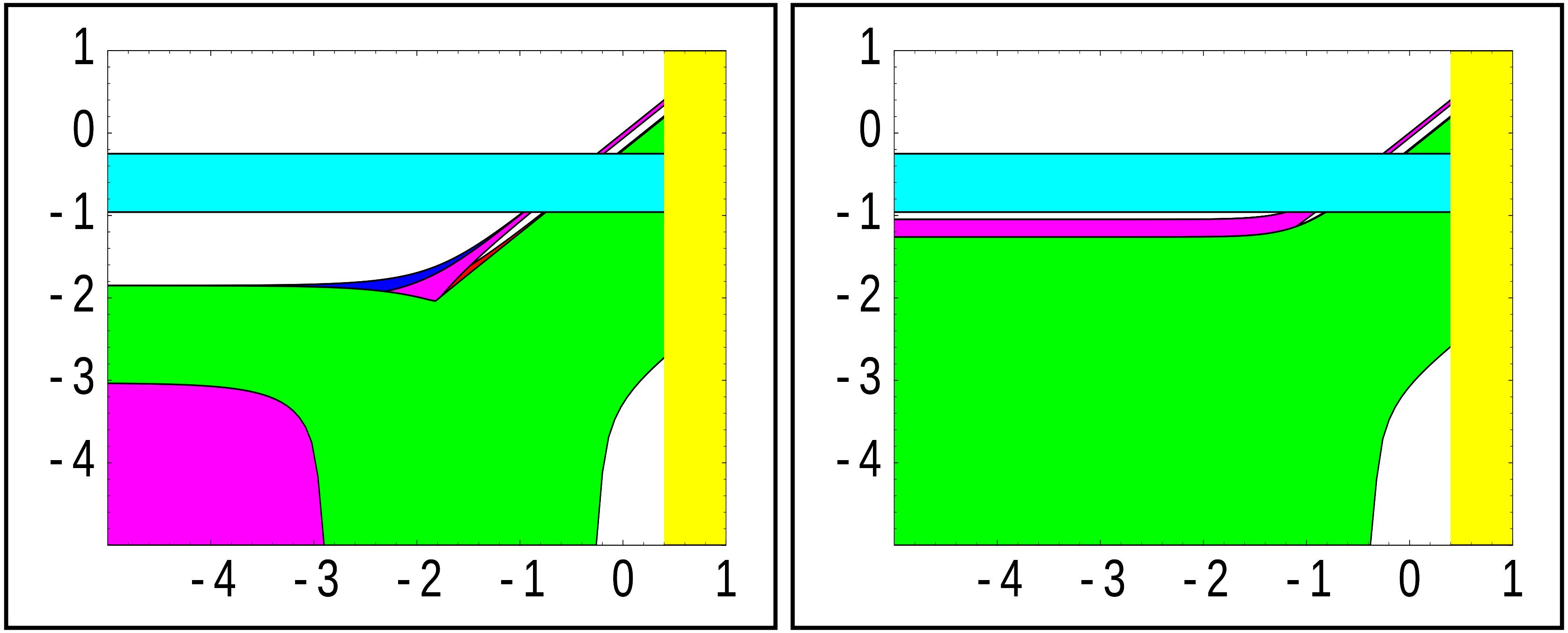
current laboratory tests of absolute neutrino mass

Current sol-atm, $\beta\beta_{0\nu}$ and Tritium sensitivities

thanks to Martin Hirsch

- Current neutrino oscillation data
- Upper limit for $\langle m_\nu \rangle \leq 0.3$ eV with factor ~ 2 uncertainty band
- Upper limit from Tritium experiments: $m_1 \leq 2.2$ eV

normal versus inverse hierarchy Log $\langle m_\nu \rangle$/eV vs Log m_1/eV

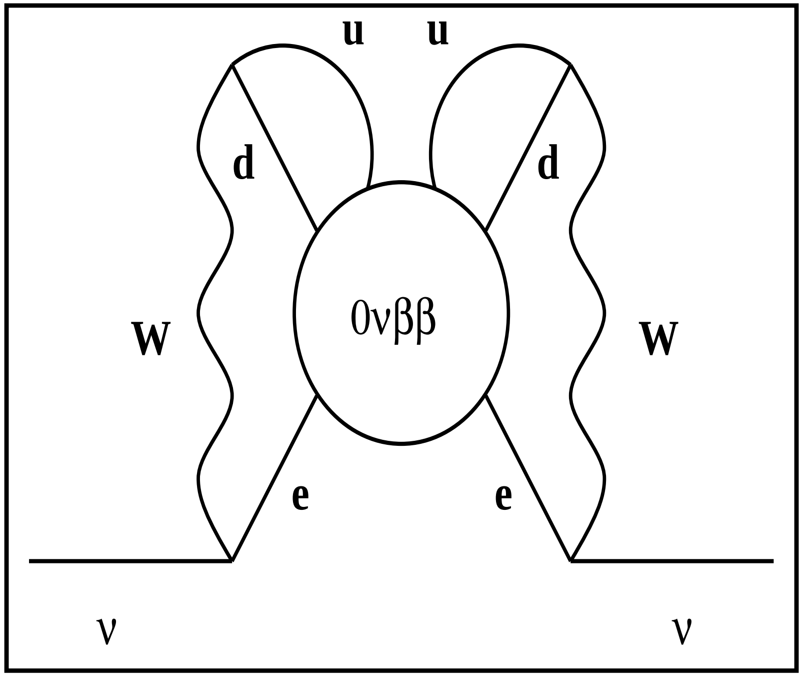


Relevance of $\beta\beta_{0\nu}$

$\boxed{\text{gauge theories } \beta\beta_{0\nu} \leftrightarrow \text{majorana mass}}$

Schechter and JV, PRD25 (1982) 2951

$\boxed{\text{no such theorem for flavor violation!}}$



probing 3-nu oscillation effects

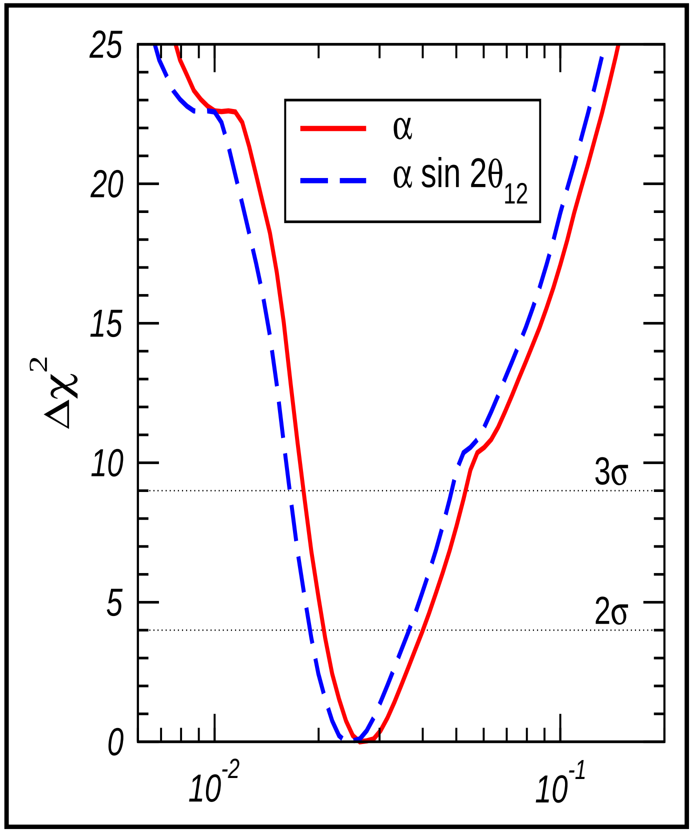
Leptonic CP Violation

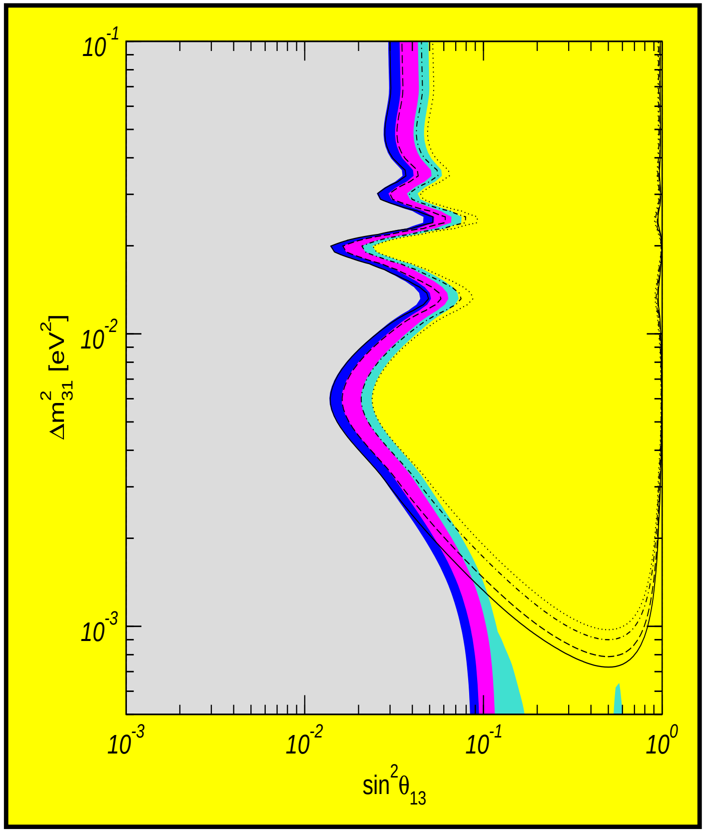
"Dirac" CPV suppressed, since δ disappears when any $\Delta_{ij} \to 0$

Schechter and JV, PRD **21** (1980) 309

Try harder

determining $\alpha = \Delta m^2_{\rm SOL}/\Delta m^2_{\rm ATM}$ and θ_{13}





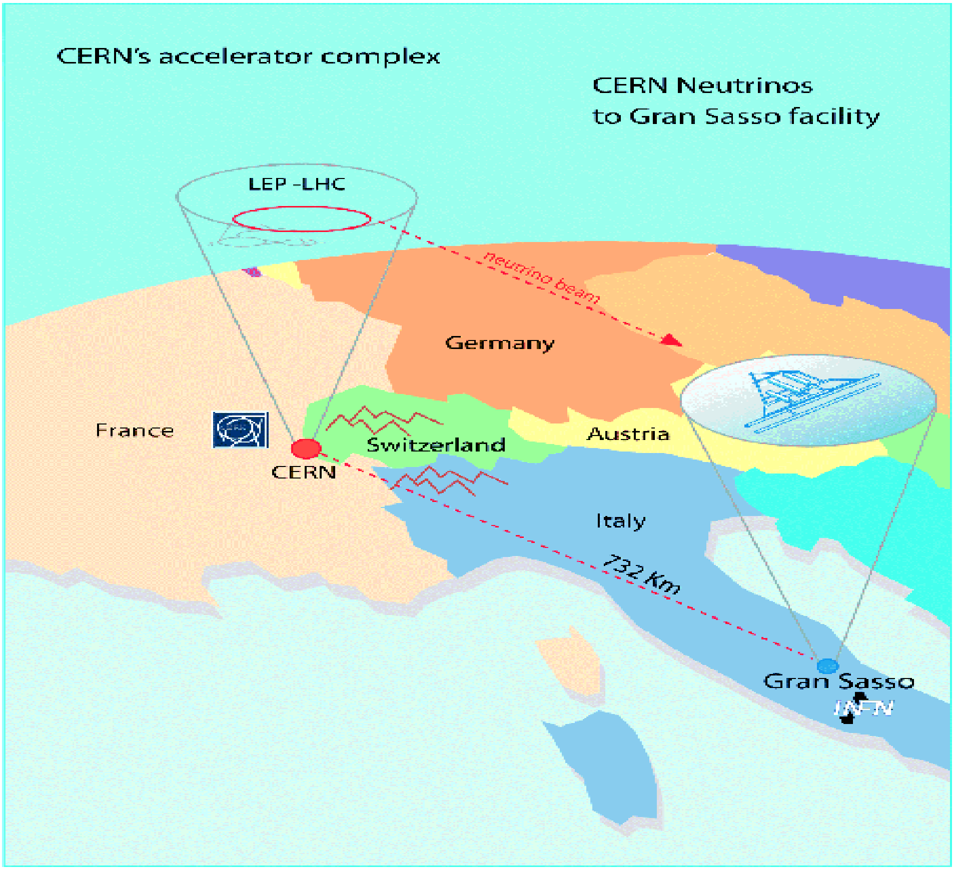
for low $\Delta m^2_{\rm ATM}$ the solar SNO-salt bound becomes relevant

Neutrino Factories

will probe s_{13} and CP phase δ

Cervera et al, De Rujula, Gavela, Hernandez

Freund, Huber, Lindner, Albright et al, Barger et al...



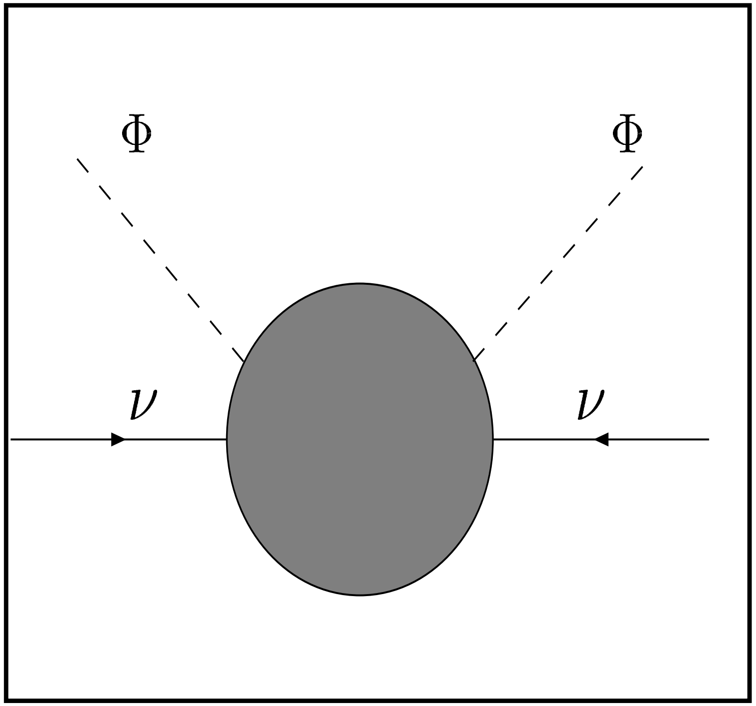
provided Non-Standard nu-Intercations (NSI) can be rejected ...

Huber, Schwetz & JV PRL88 (2002) 101804 & PRD66, 013006 (2002) •

Huber & JV PLB523 (2001) 151 •

Theory ideas

basic dim-5 operator $\boxed{\bullet}$

- 

  from Gravity

  Weinberg ....

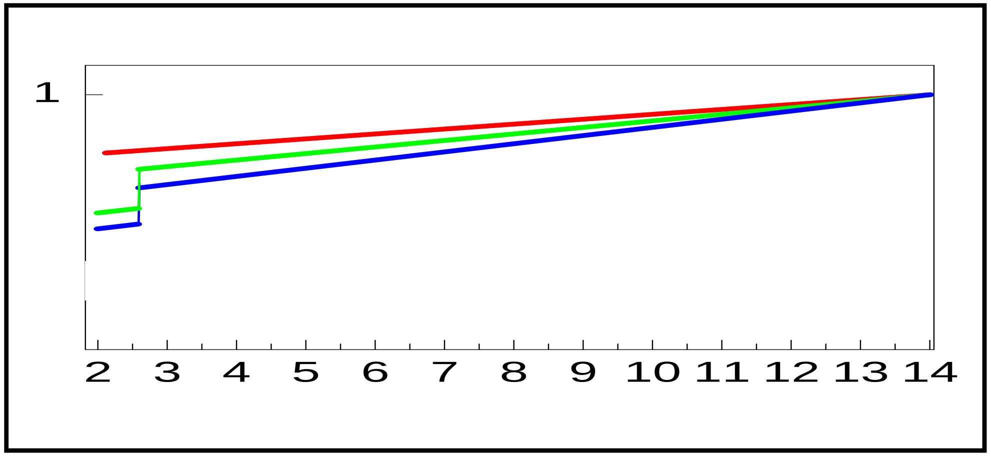
- from seesaw schemes

Gell-Mann, Ramond, Slansky; Yanagida;
Mohapatra, Senjanovic PRL44 (1980) 91
Schechter, JV PRD22 (1980) 2227; PRD25 (1982) 774

neutrino unification: large-scale seesaw

$\boxed{\bullet}$

m_ν/eV vs. Log M_X/GeV



Babu, Ma and Valle, PLB552 (2003) 207

neutrino masses unify as they run up

Chankowski, Ioannisian, Pokorski and JV, PRL86 (2001) 3488

solar & atm splittings from RGE

common origin for neutrino and KM mixing

maximal θ_{23}; large θ_{12} & $\theta_{13} = 0$ or maximal CP violation see also Grimus & Lavoura

observable neutrino mass eg in cosmology, β and $\beta\beta_{0\nu}$ decays

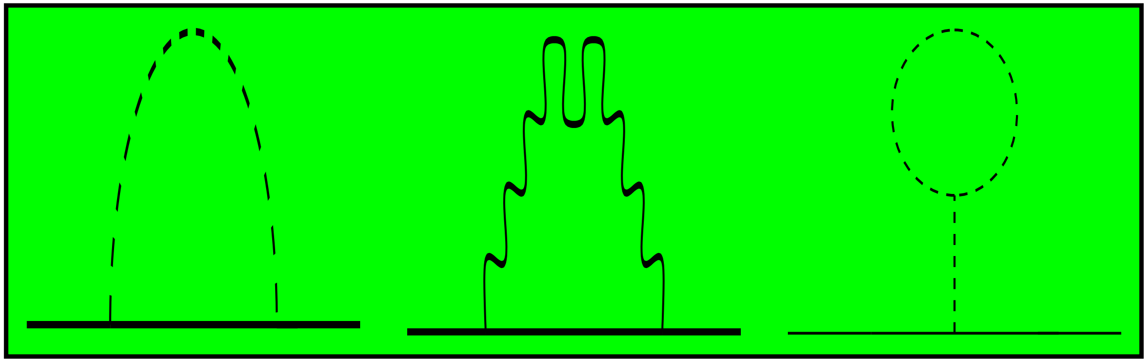
observable Lepton Flavor Violation

bilinear R parity violation: weak-scale seesaw

- Diaz etal PRD68 (2003) 013009 [hep-ph/0302021];
PRD62 (2000) 113008 [Err-ibid. D65 (2002) 119901]; PRD61 (2000) 071703

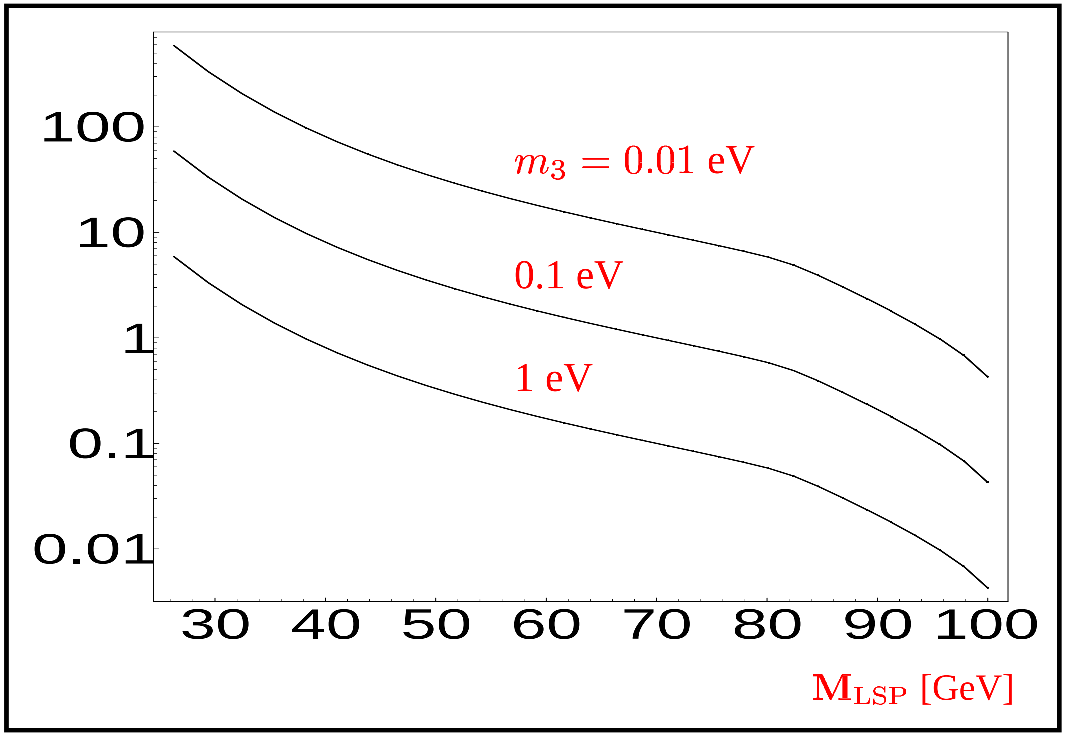
- weak-scale seesaw atm scale

- radiative nu-masses solar scale



LSP decay length [cm]: BRPV

- from Bartl et al NPB 600 (2001) 39



Mukhopadhyaya, Roy & Vissani; Chun & Lee; Choi et al; Datta et al

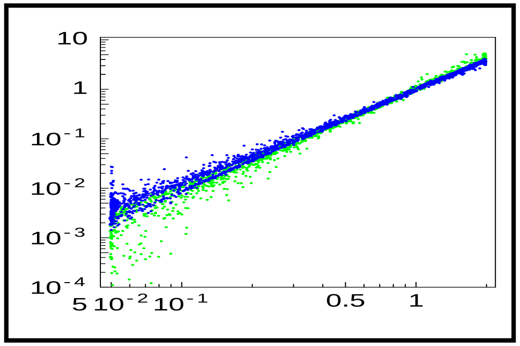
charged SUSY particles can be the LSP

neutrino mixing angles in BRPV

$\tan^2_{23}(\Lambda_2/\Lambda_3)$ $\tan^2_{12}(\epsilon_1/\epsilon_2)$ $U^2_{e3}(\Lambda_1/\Lambda_3)$

- mixings in terms of RPV ratios, e,g, atm mixing

$\tan^2_{23}$ vs (Λ_2/Λ_3)

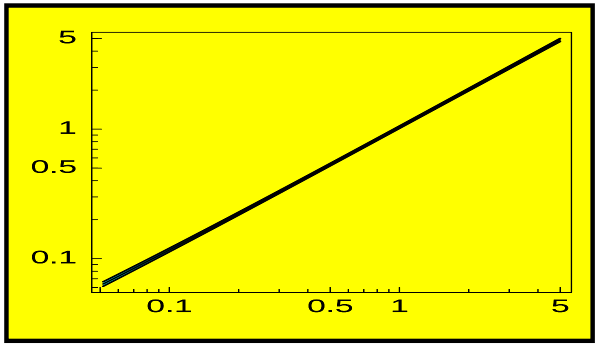


- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004

$\chi \to \mu q q / \chi \to \tau q q$ vs $\tan^2_{23}$



- stop decays
  slepton decays
  any LSP

Restrepo, Porod & Valle, PRD64 (2001) 055011
M. Hirsch et al, PRD66 (2002) 095006
Hirsch & Porod hep-ph/0307364

No Road Map to Theory of Neutrino Mass

- top-bottom vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- what is the scale ?
  - Planck scale: Strings?
  - GUT scale $E(6)$, $SO(10)$,...
  - Intermediate scale: P-Q, L-R ...
  - Weak $SU(3) \otimes SU(2) \otimes U(1)$ scale
- **no theory of flavour**
- are there sterile-nus? Are oscillations the end of the road?
- not the end, nor the beginning of the end, at best the end of the beginning...

http://ific.uv.es/~valle/talks/talks.html