Neutrino Oscillations and New Physics

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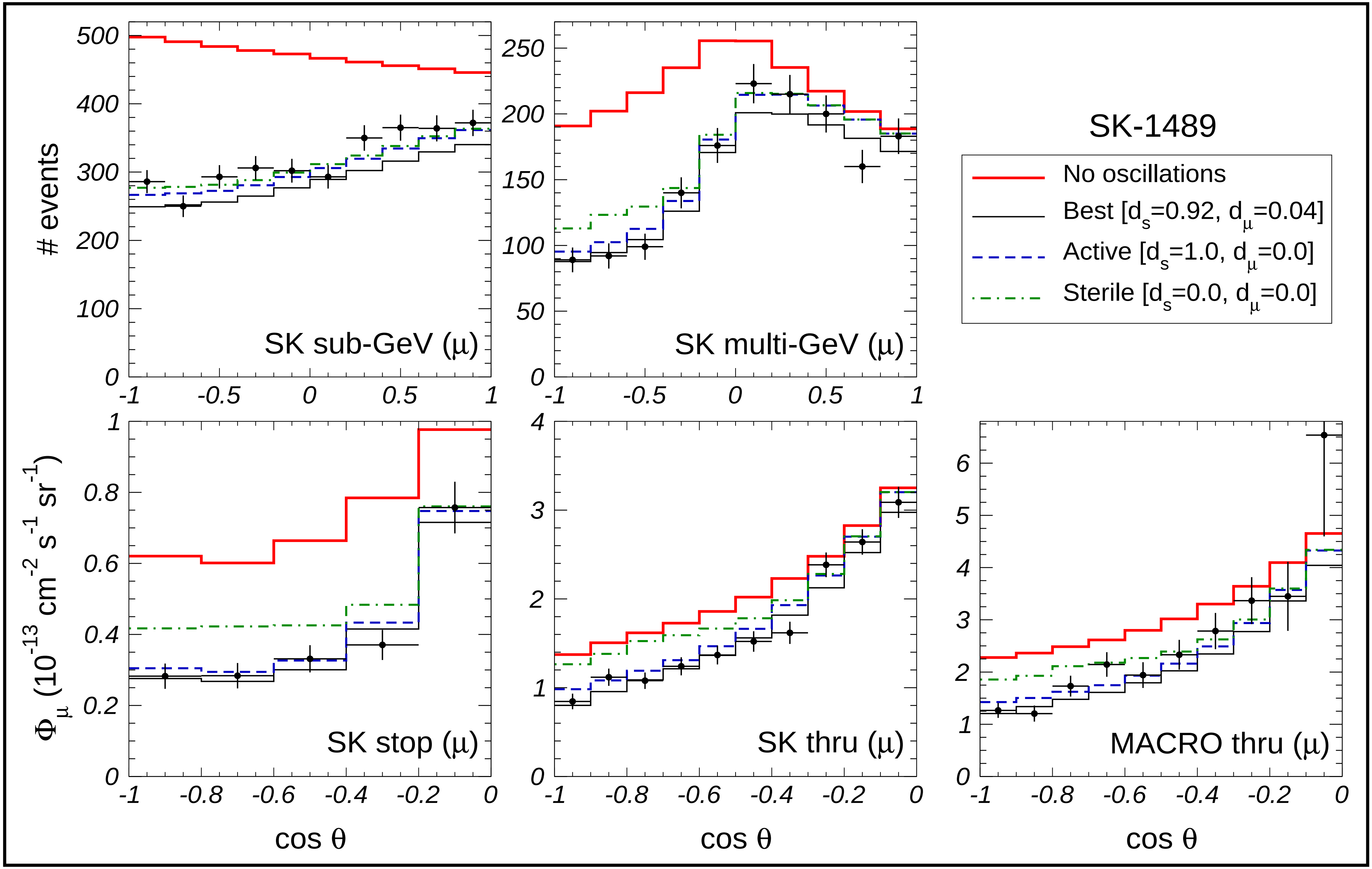
Based on hep-ph/0301061 and hep-ph/0307192
upd to include salt phase data from the SNO experiment

Maltoni, Tortola, Schwetz, JV, hep-ph/0309130, v2 (PRD, in press)

Atmospheric zenith distribution

Maltoni et al, PRD67 (2003) 013011



atmospheric neutrino parameters-1

- sterility rejection

hep-ph/0309130

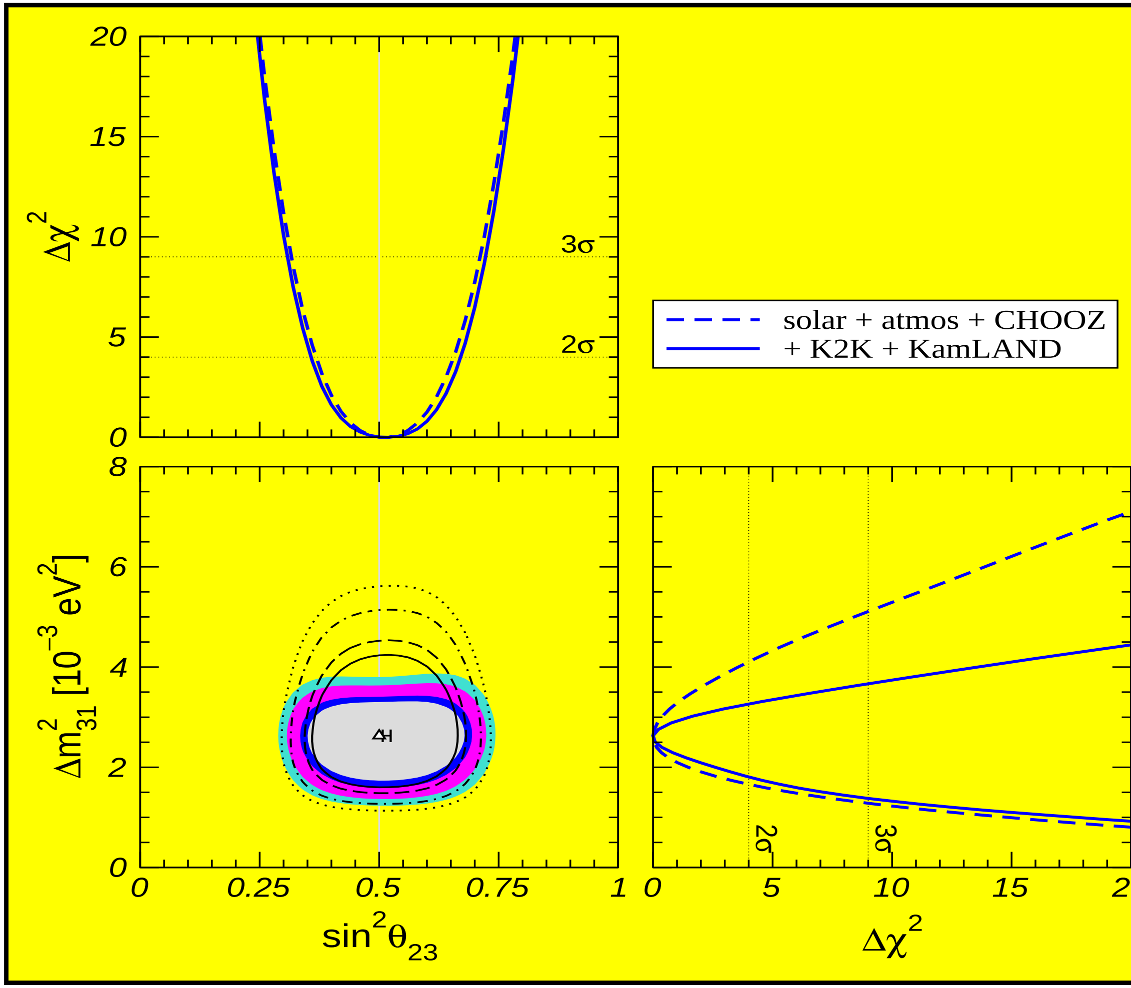
Maltoni et al, PRD, in press

upd of PRD67 (2003) 013011

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

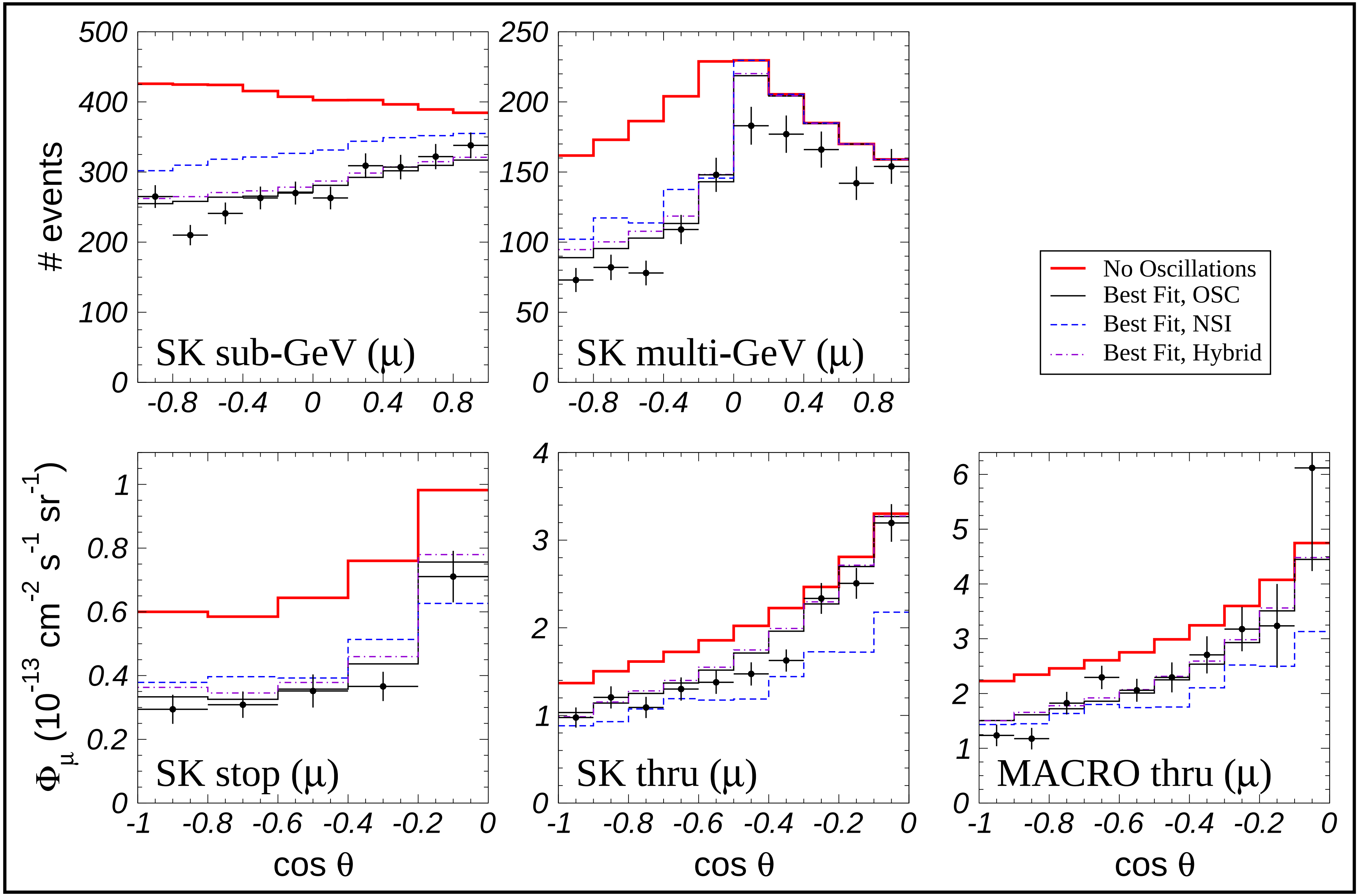
$\Delta m^2_{\rm ATM} = 2.6 \times 10^{-3}$ eV^2

K2K & $\Delta m^2_{\rm ATM}$ upper bound



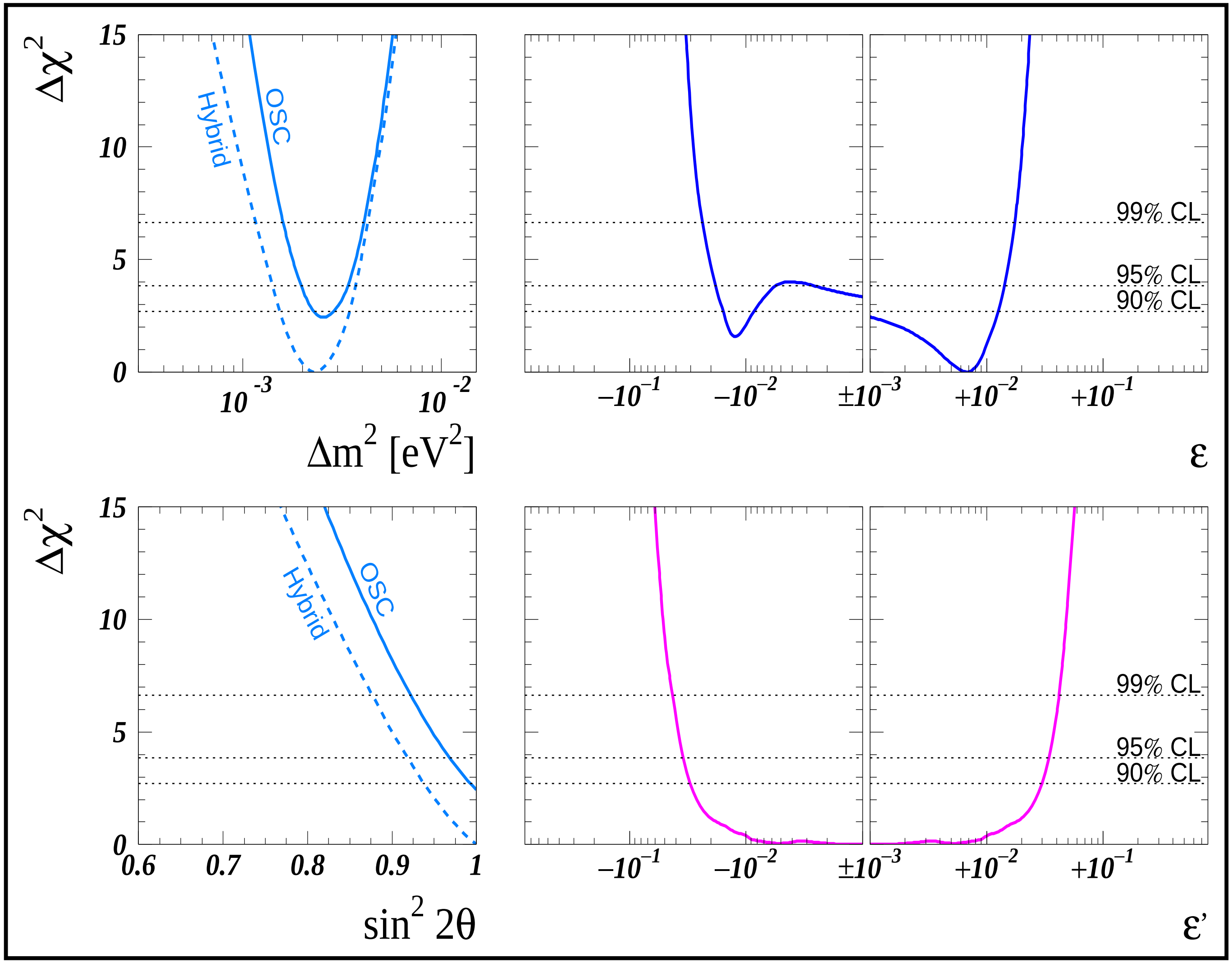
How robust are atmospheric oscillations?

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].

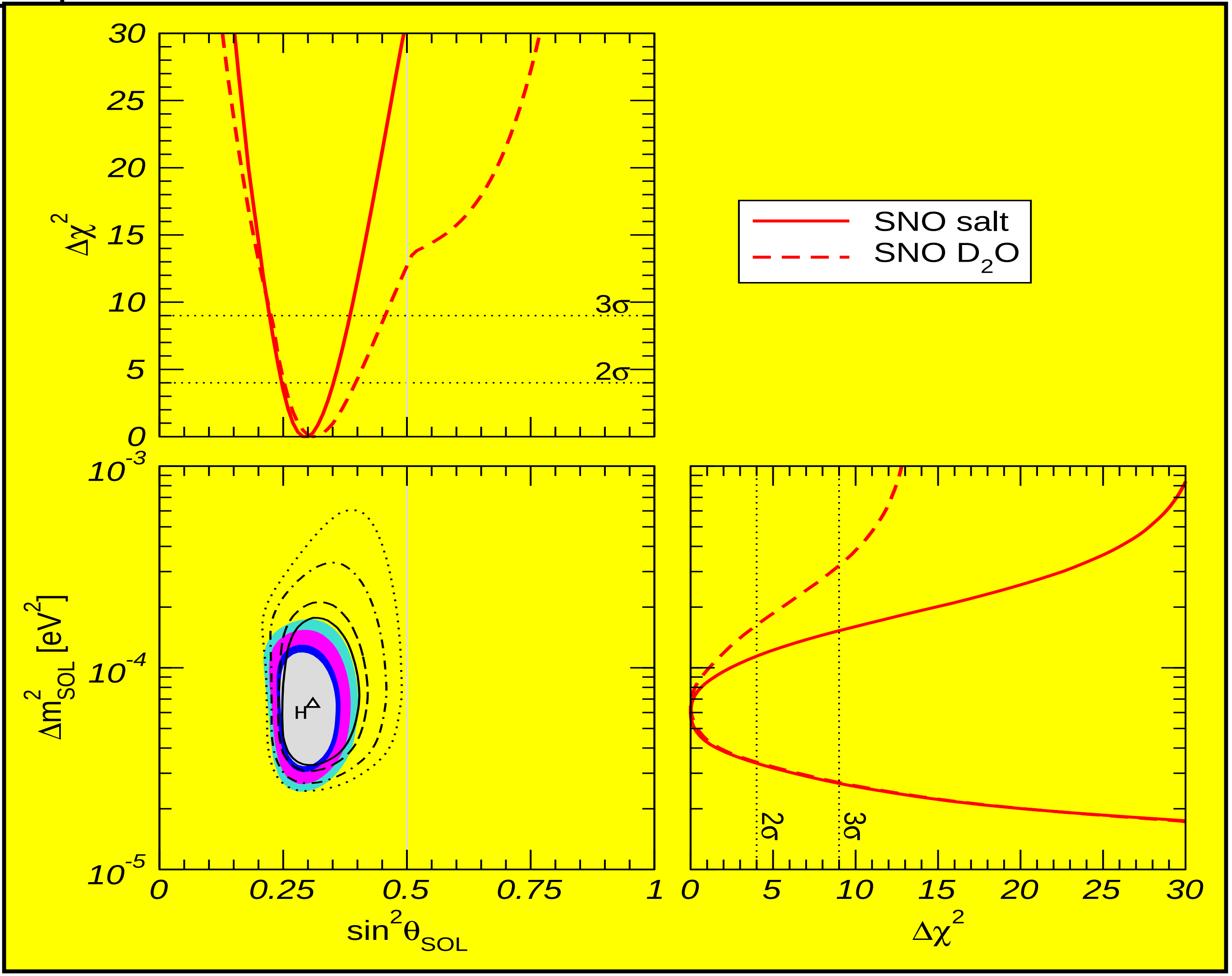


atm bounds on FC and NU nu-interactions

Solar neutrino parameters

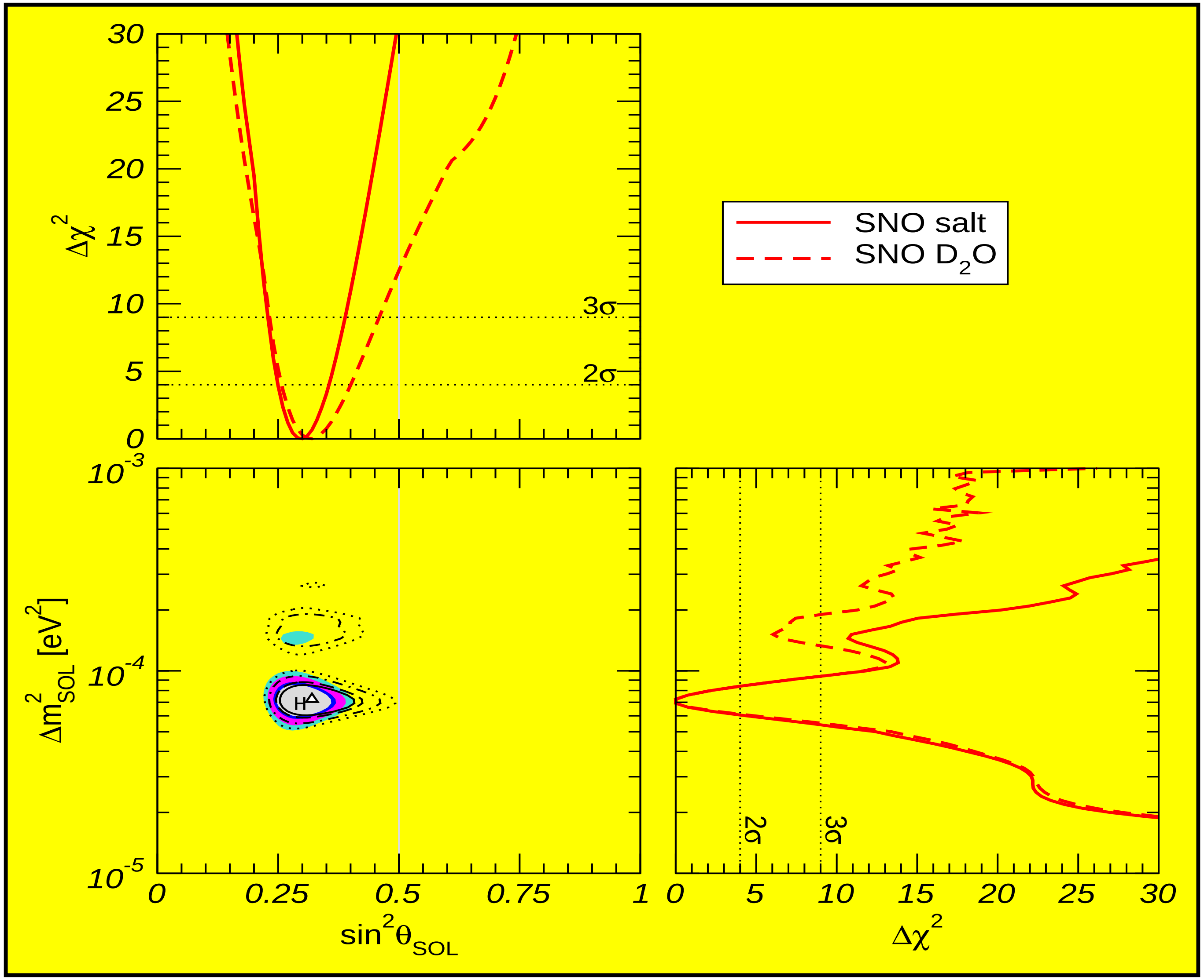
oscilllations happen inside the sun ! MSW

Maltoni et al, hep-ph/0309130 v2



Bandyopadhyay et al, Fogli et al, Balantekin et al

Solar + KamLAND results ● 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

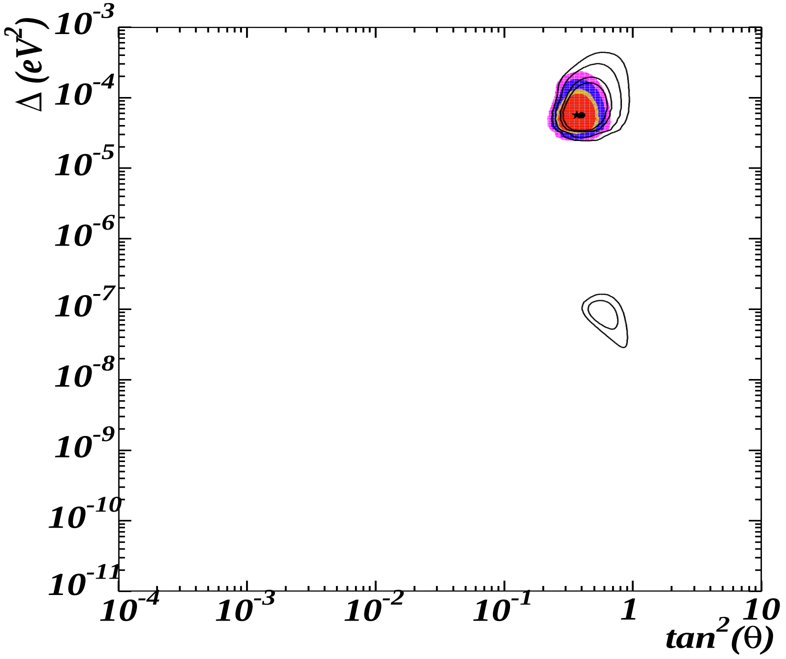
bi-maximal models rejecte

LMA-MSW status wrt SN1987A

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

pre-KamLAND/pre-salt

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,

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

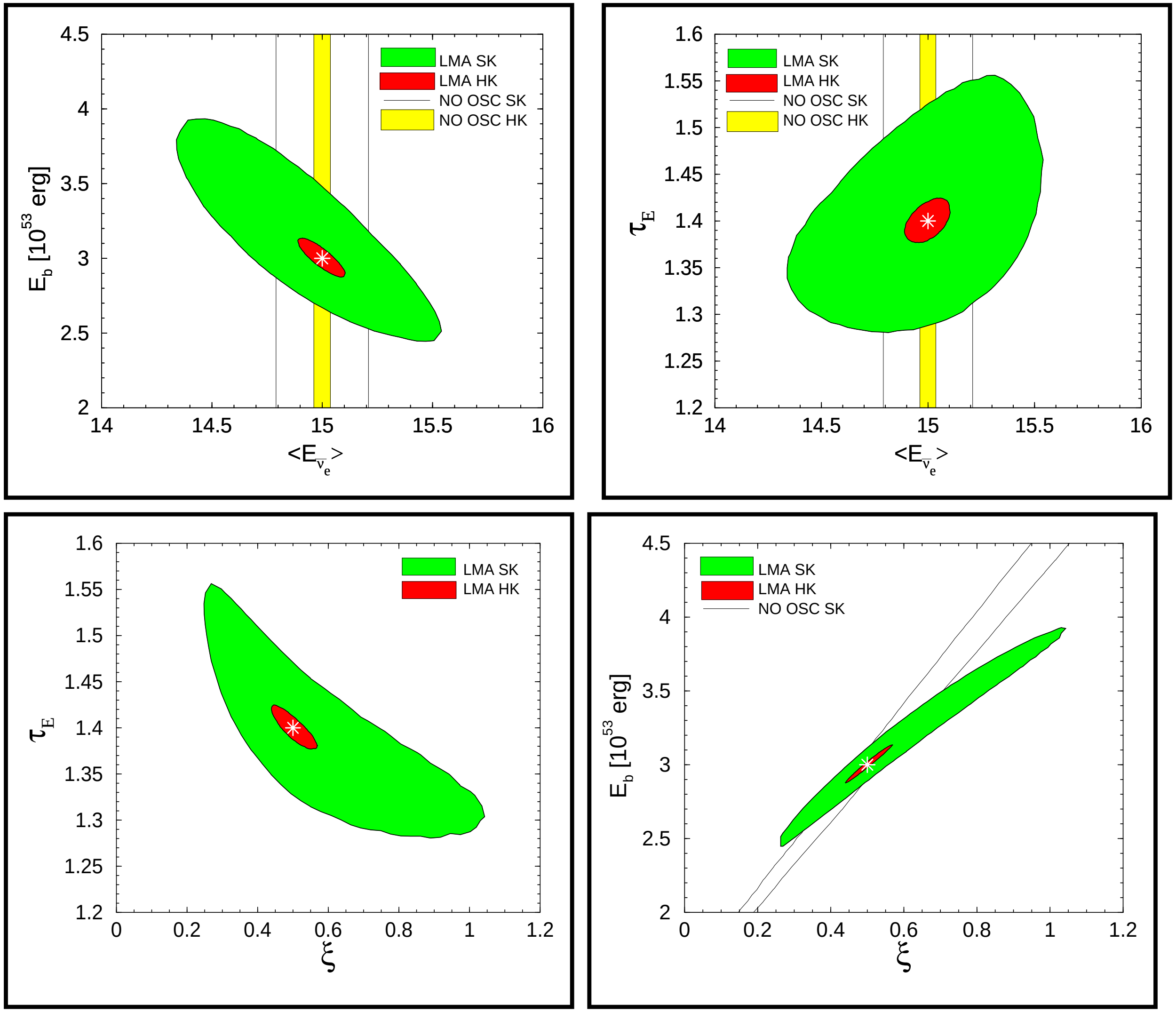
neutrinos as future Supernova probe

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

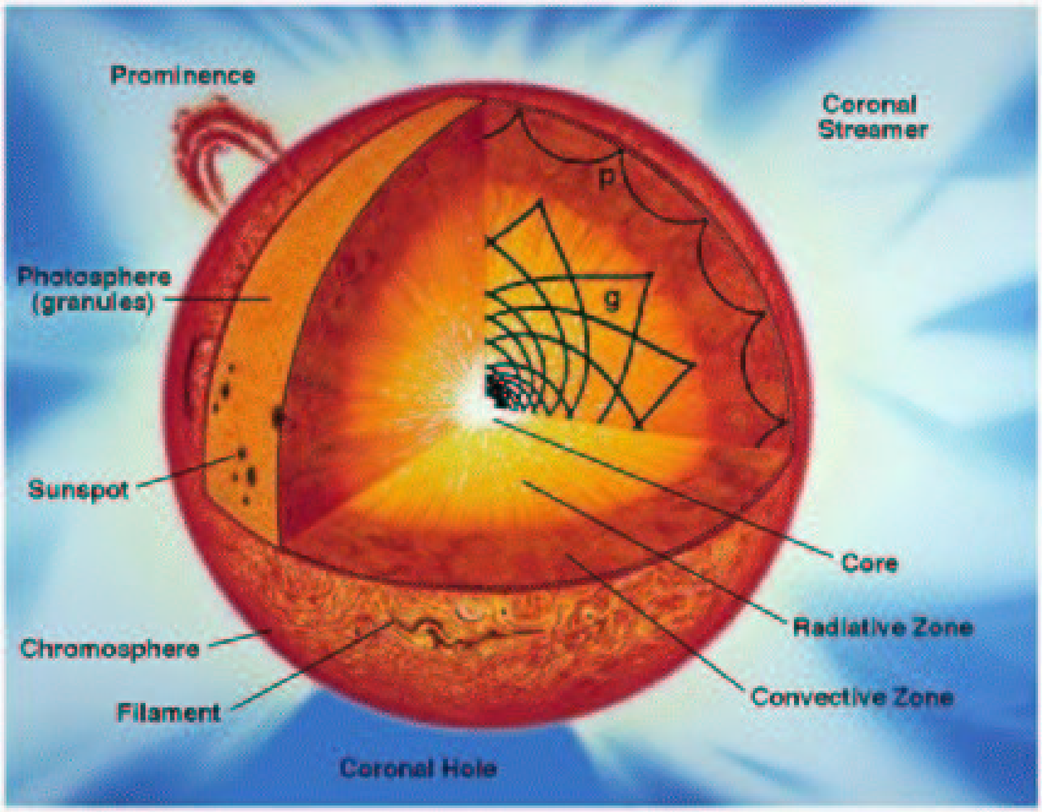
assume 10 kpc galactic SN, simulate data with given astro param

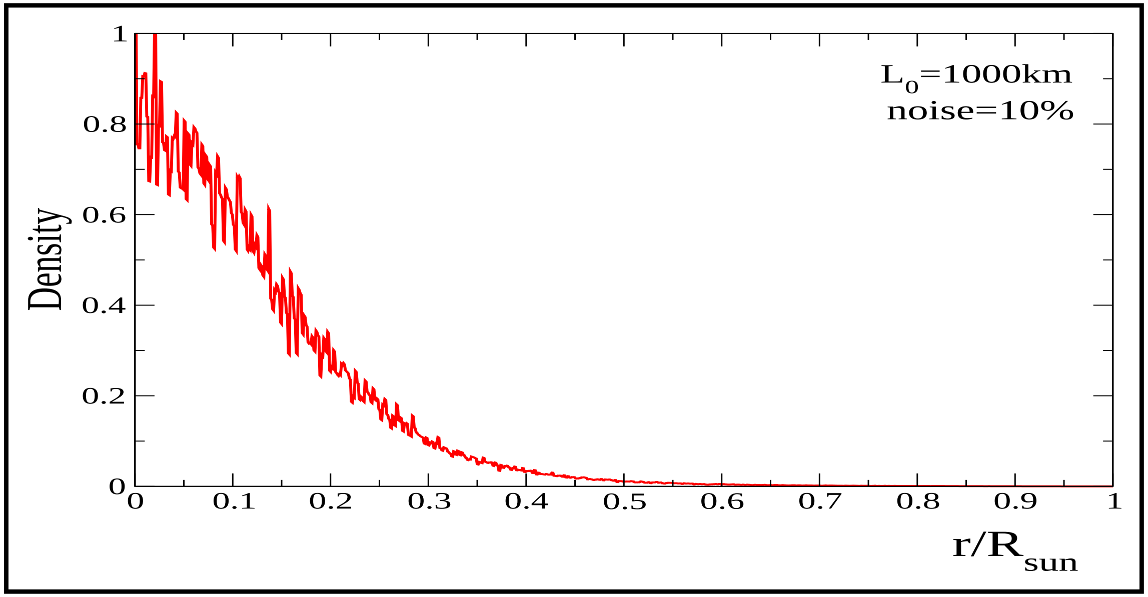
see also Barger, Marfatia & Wood



improved supernova parameter determination

do we understand the Sun?





Robustness of MSW plot

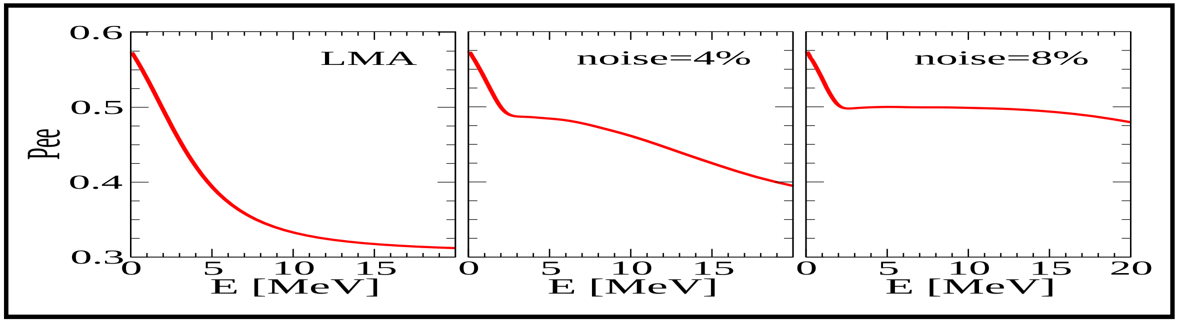
neutrino propagation strongly affected by density noise

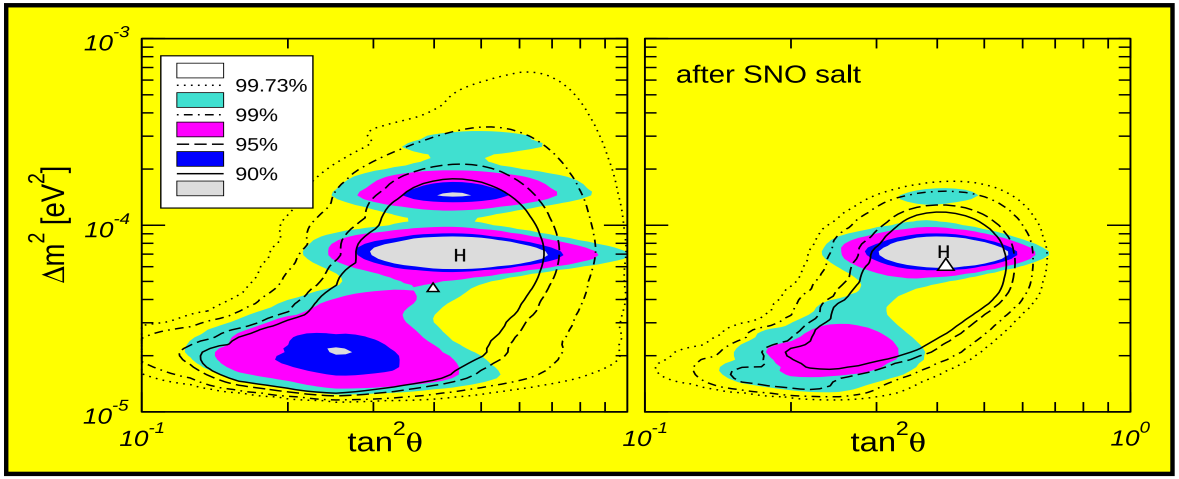
Balantekin et al 95

Nunokawa et al NPB472 (1996) 495

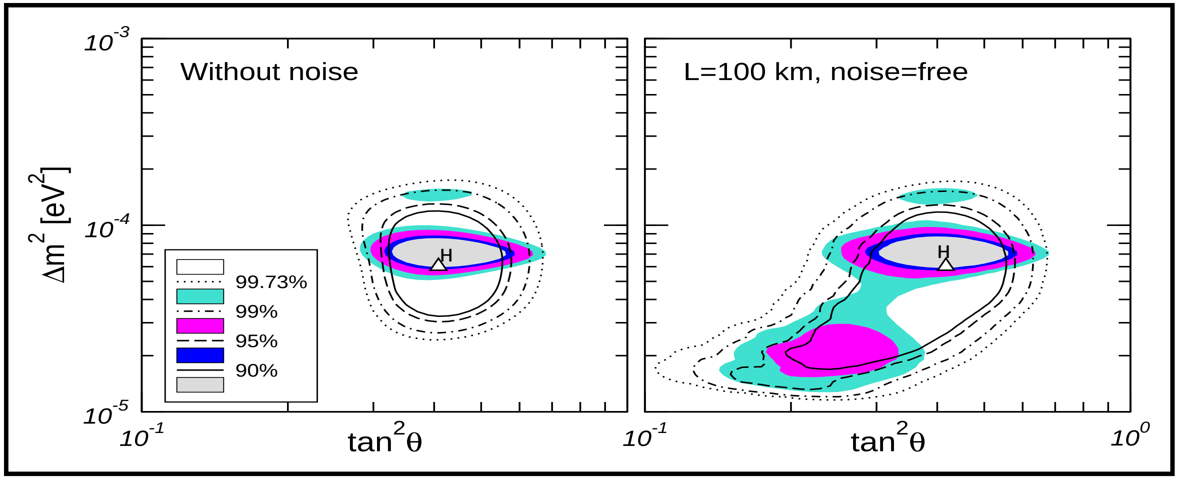
Burgess et al 97

Burgess et al, Ap.J.588:L65 ,2003





despite substantial distortion



robust determination

Burgess et al, hep-ph 0310366

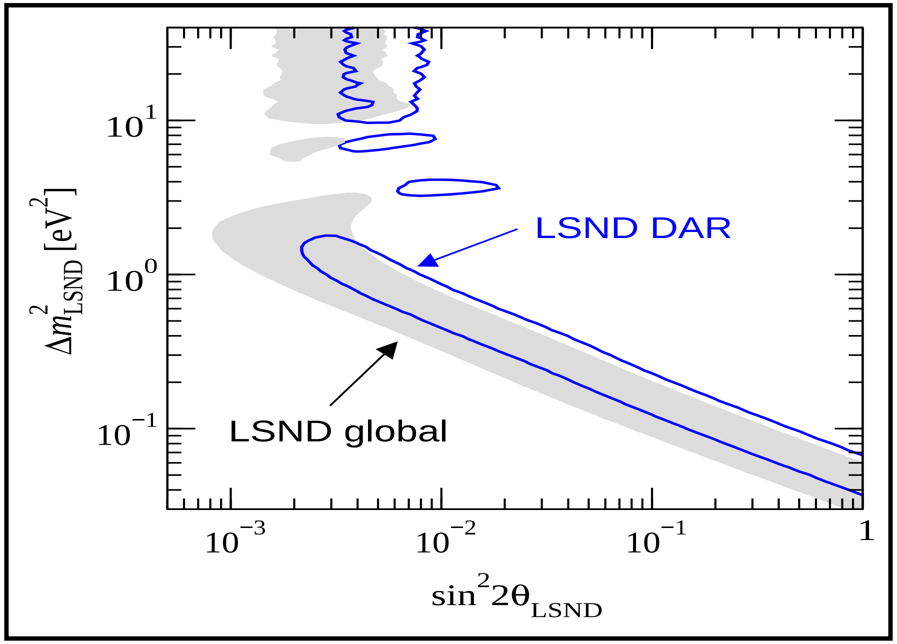
LSND

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 3.2 σ if 3+1

Maltoni et al NPB643 (2002) 321

upd of PRD65 (2002) 093004

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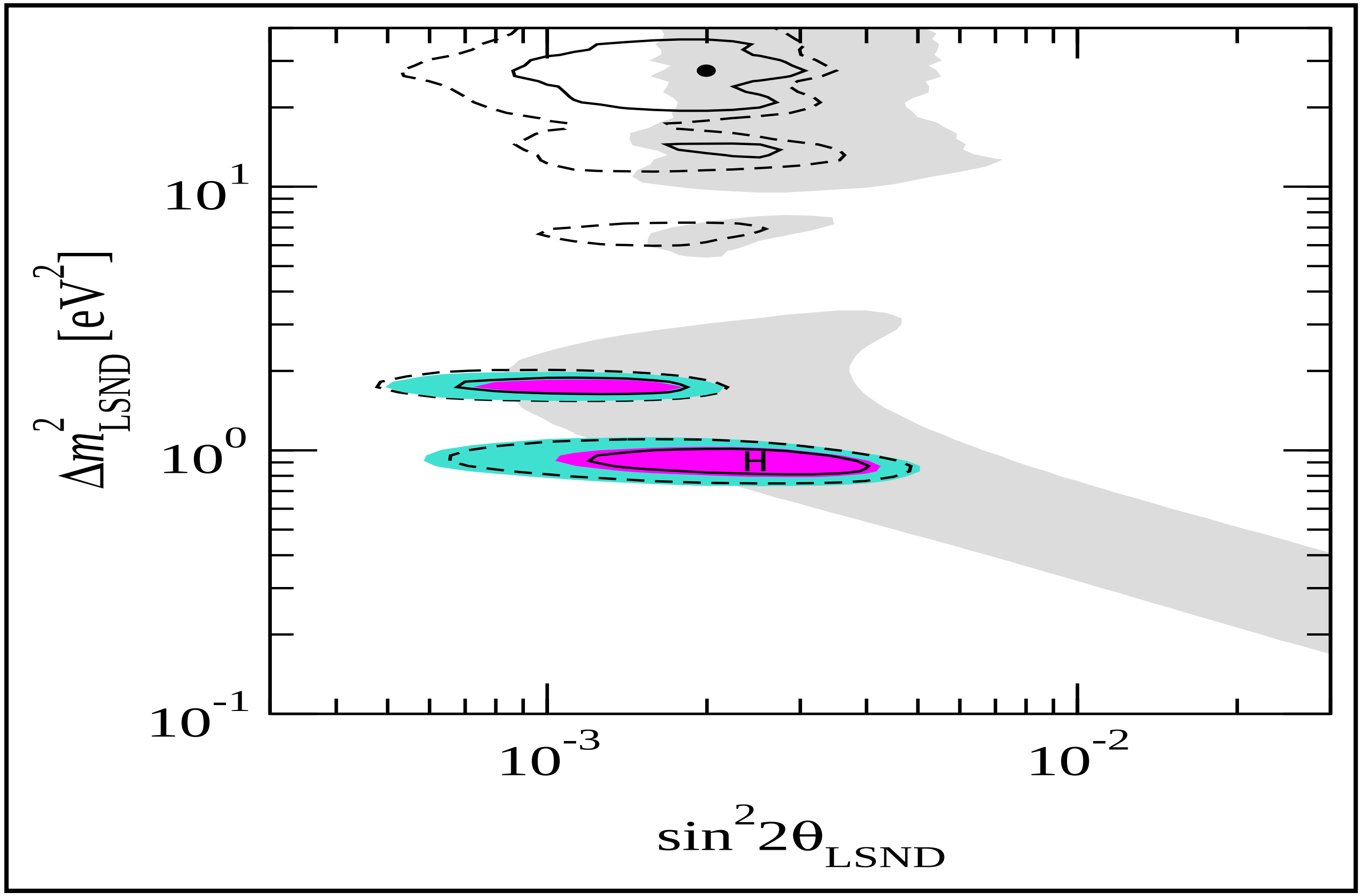
Cosmology closes in on LSND

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



2df + WMAP + HST + SNIa

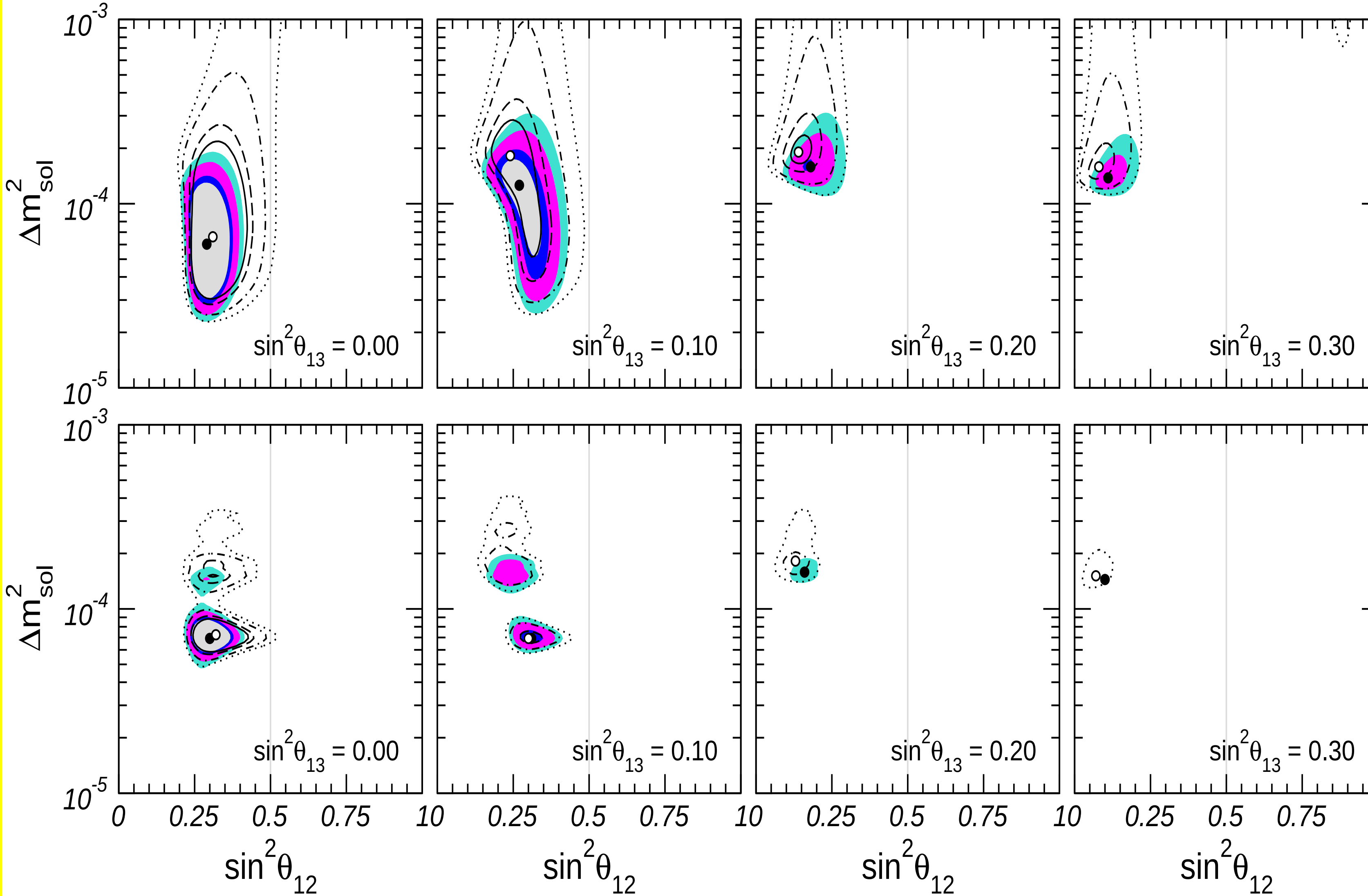
Schwetz et al hep-ph/0305312

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

Crotty, Lesgourgues & Pastor PRD67 (2003) 123005

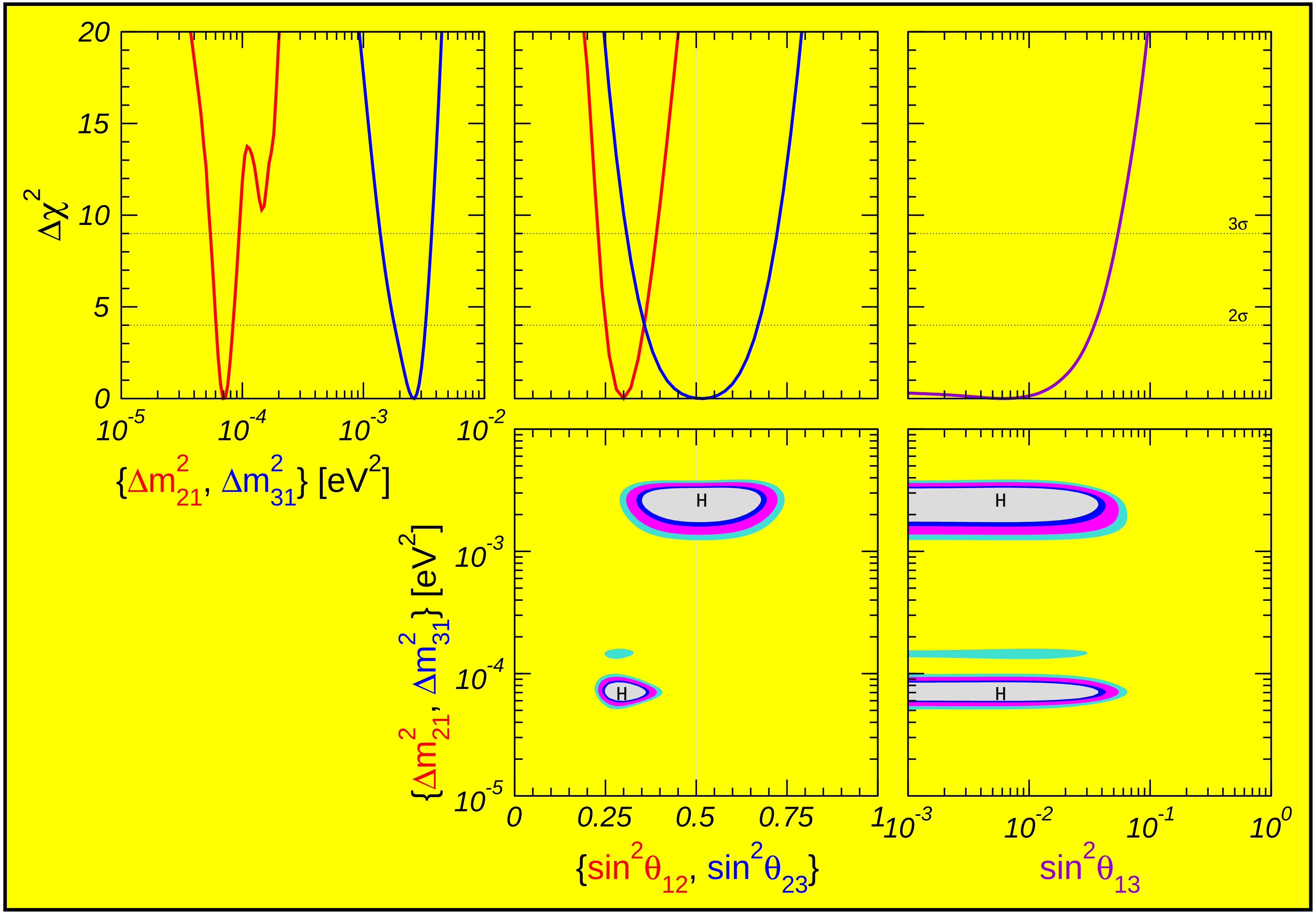
3-nu regions: before and after salt

- Maltoni et al, hep-ph/0309130 v2 without KamLAND (top), with KamLAND (bottom)



3-nu parameters

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



3-nu Oscillation Parameters

hep-ph/0309130 v2 PRD

parameter	best fit	2σ	3σ	5σ
Δm^2_{21} [10^{-5}eV^2]	6.9	6.0–8.4	5.4–9.5	2.1–28
Δm^2_{31} [10^{-3}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

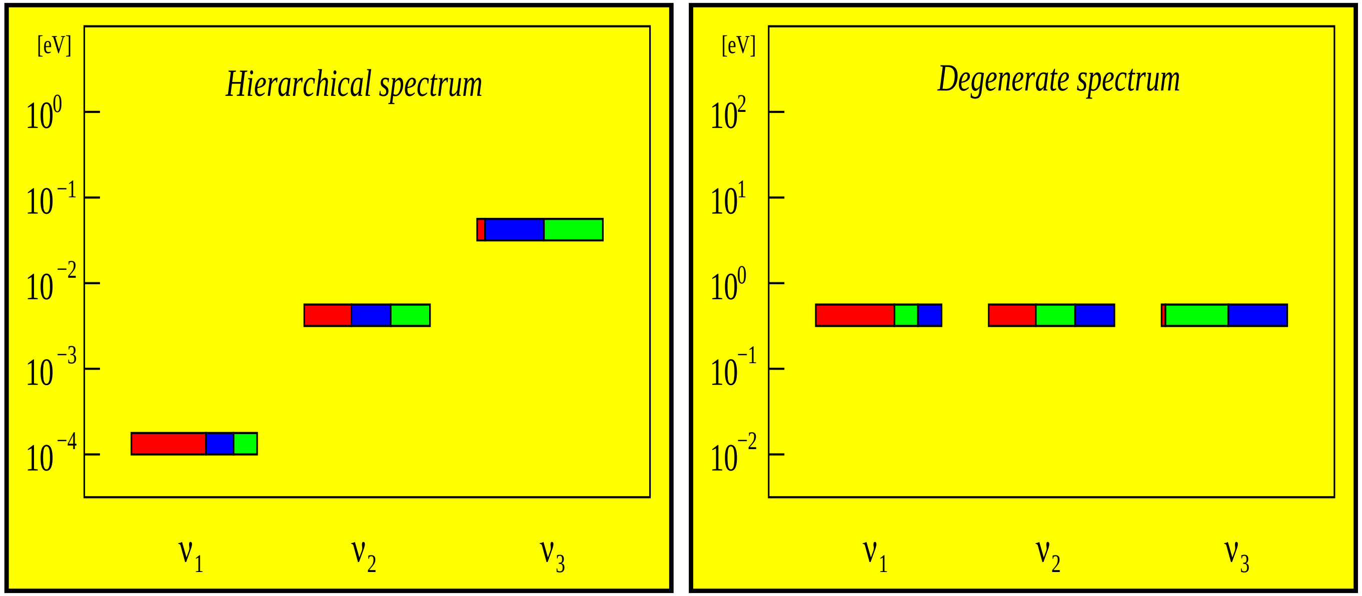
- 3 angles θ_{ij} | 23=atm 12=sol 13=reac |

  1 KM-like phase | oscillations | δ

  2 Majorana phases | $\beta\beta_{0\nu}$ | $\alpha\ ,\beta$

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

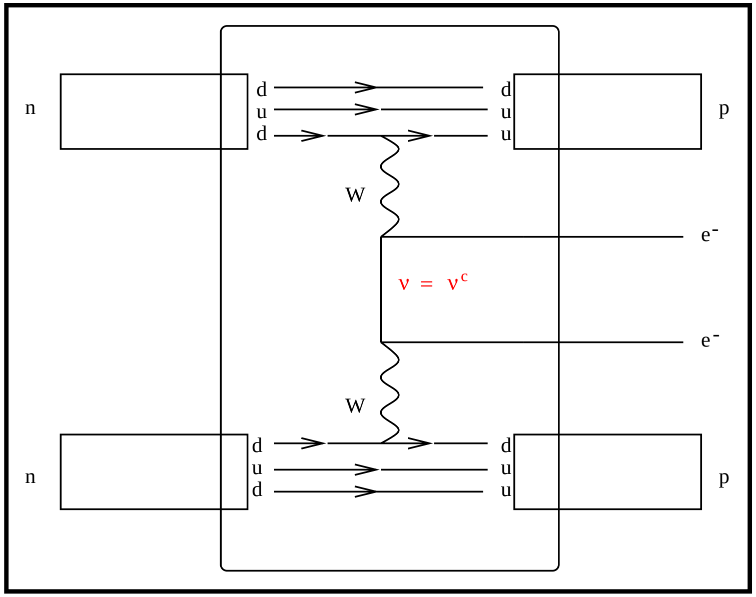
- $\nu_e\ \nu_\mu\ \nu_\tau$



0-nu double beta decay and the neutrino spectra

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

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



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

- 3 masses: m_i
- 2 angles: θ_{12} and θ_{13}
- 2 CP violating phases: α, β

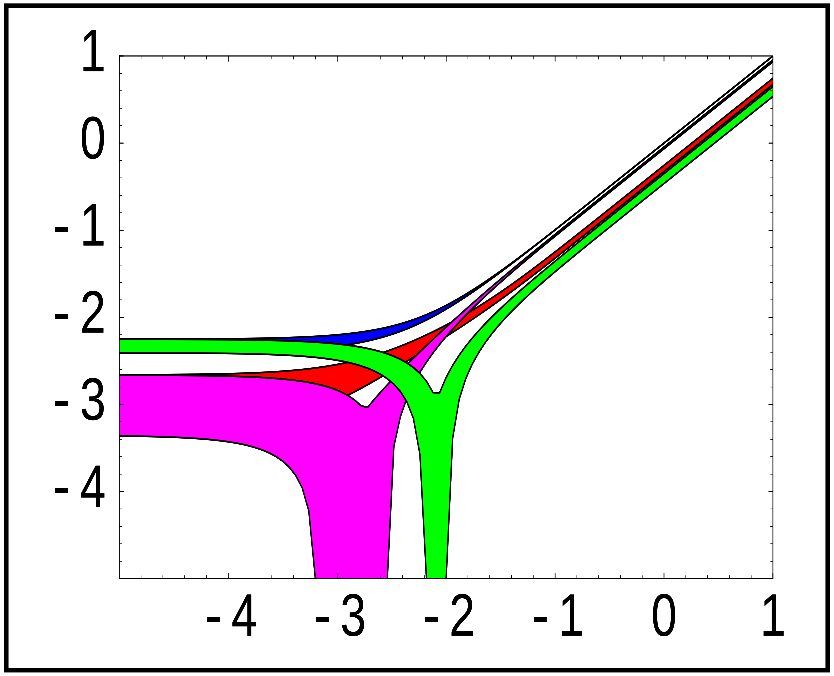
current laboratory tests of absolute neutrino mass

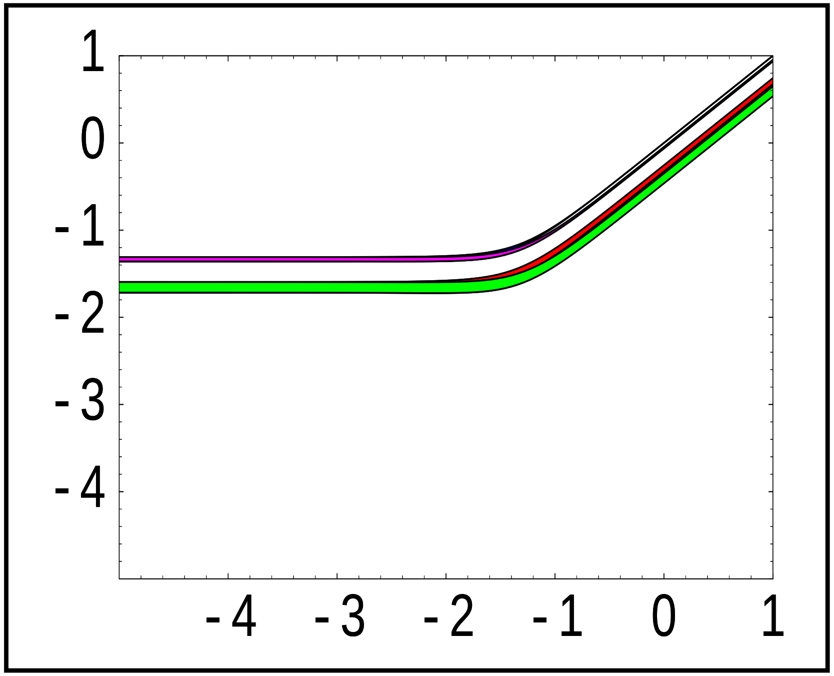
Current sol-atm, $\beta\beta_{0\nu}$ and Tritium sensitivities

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





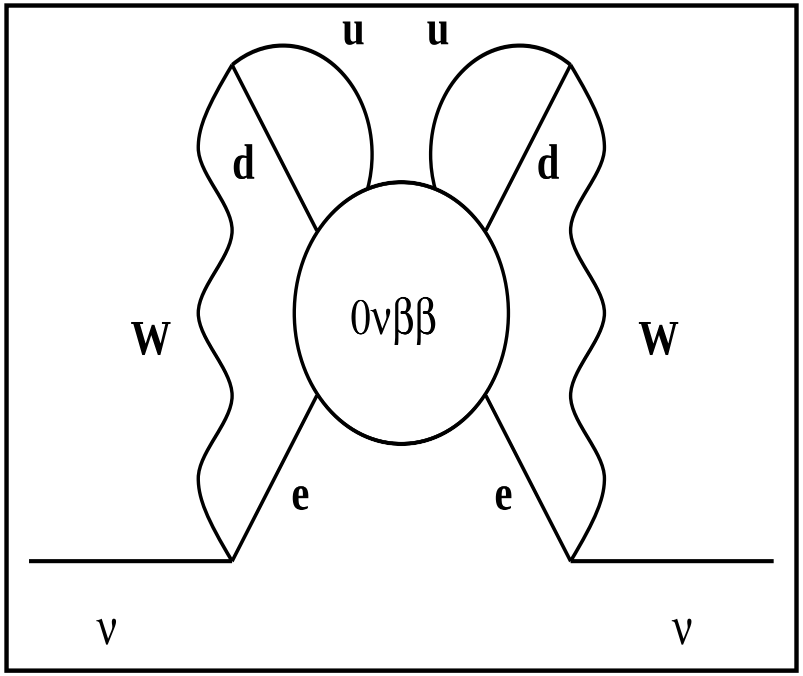
Relevance of 0-nu double beta decay

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

In any gauge theory of the weak interaction a non-zero $\beta\beta_{0\nu}$ rate implies at least one neutrino is a Majorana particle

Schechter and JV, PRD25 (1982) 2951

no such theorem for flavor violation!



probing 3-nu oscillation effects

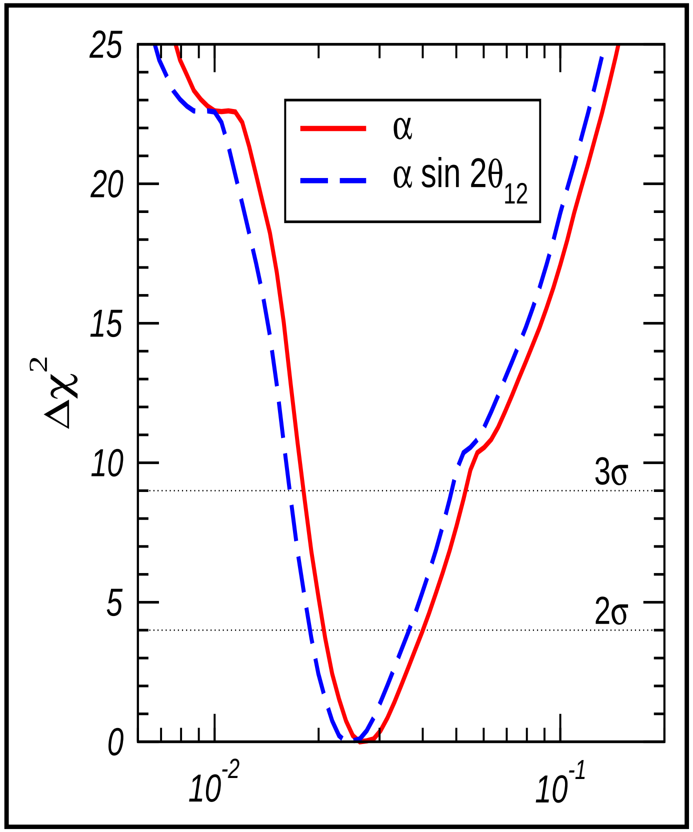
Leptonic CP Violation

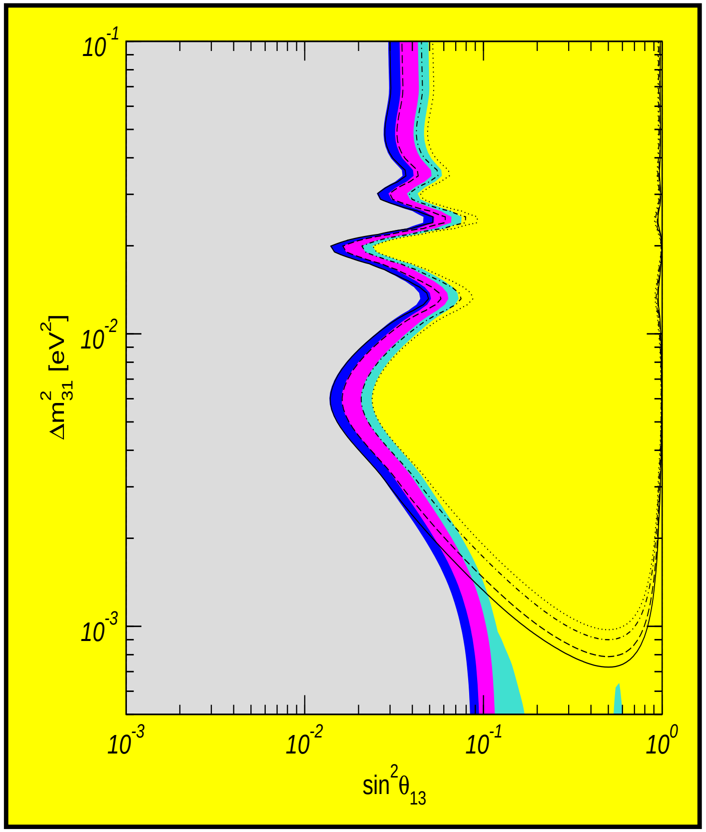
"Dirac" CPV suppressed, since δ disappears when any $\Delta_{ij} \to 0$

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

correlation with $\Delta m^2_{\rm SOL}$ and θ_{13}

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



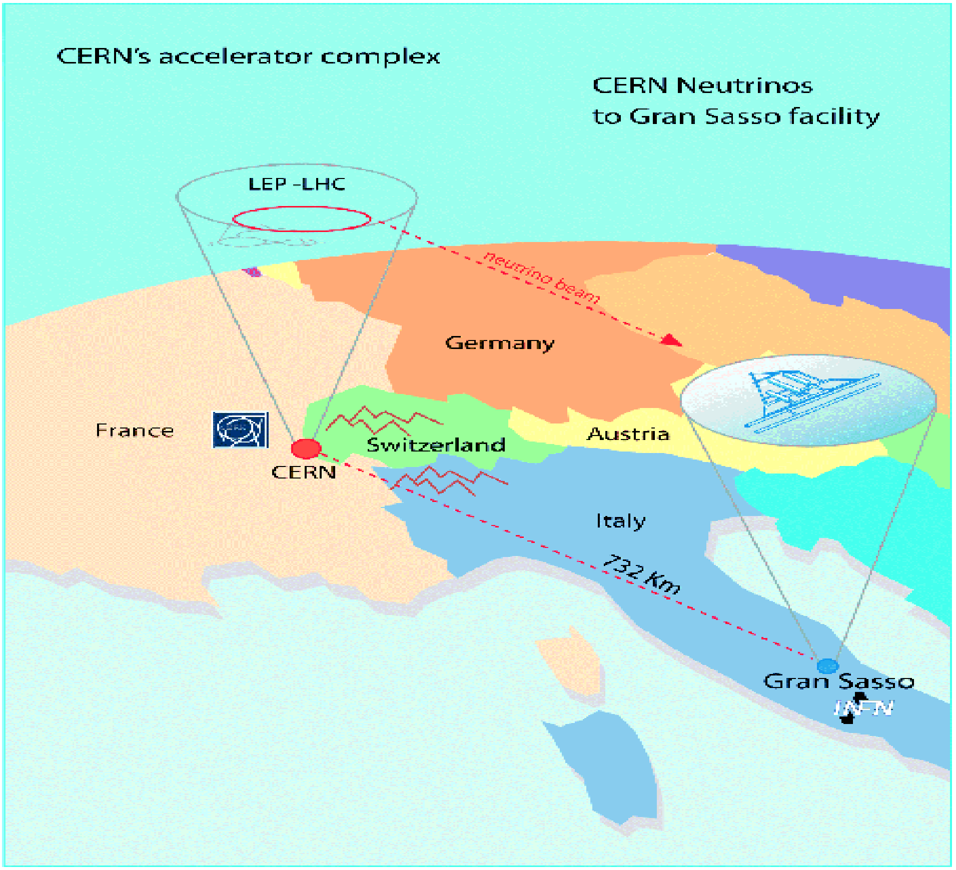


for low $\Delta m^2_{\rm ATM}$ the solar SNO-salt bound becomes relevant

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...



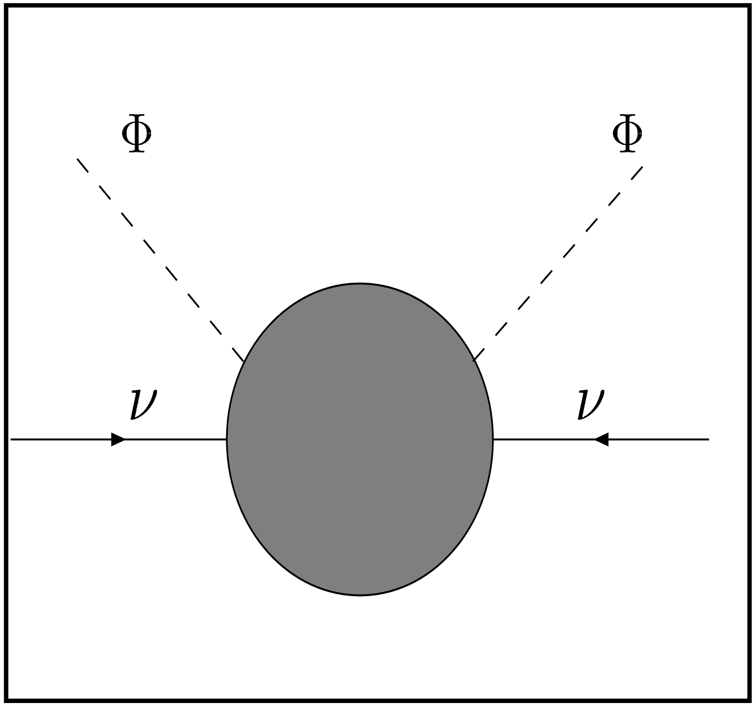
provided Non-Standard nu-Intercations (NSI) can be rejected ...

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

Huber & JV PLB523 (2001) 151 •

Theory ideas

basic dim-5 operator



- 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

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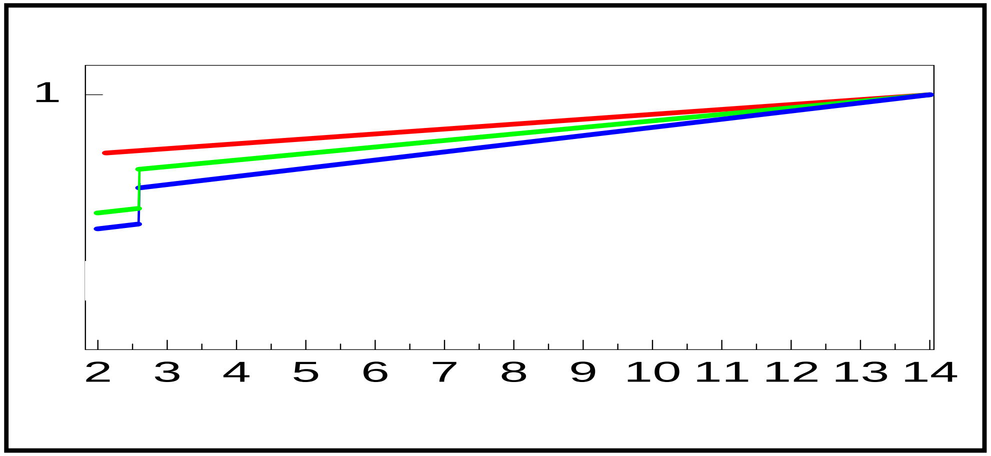
Babu, Ma and Valle, PLB552 (2003) 207

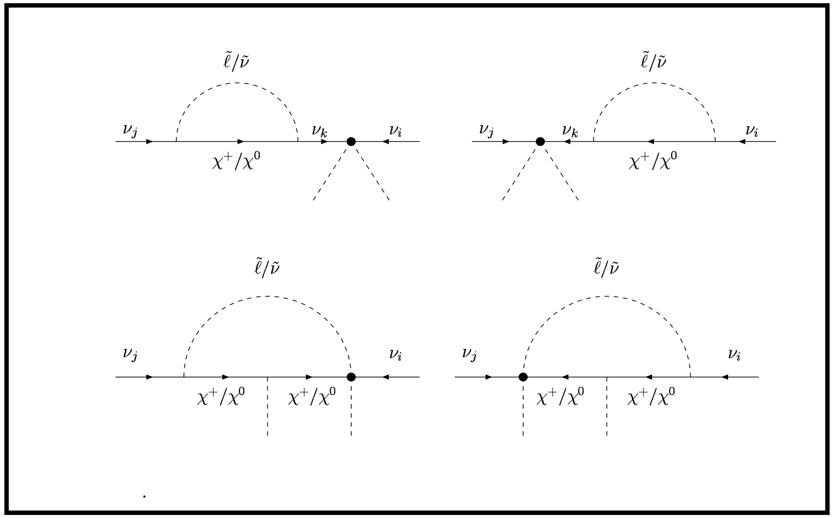
neutrino masses unify as they run up

m_ν/eV vs. Log M_X/GeV



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

solar & atm splittings from RGE



A4 model of neutrino mass

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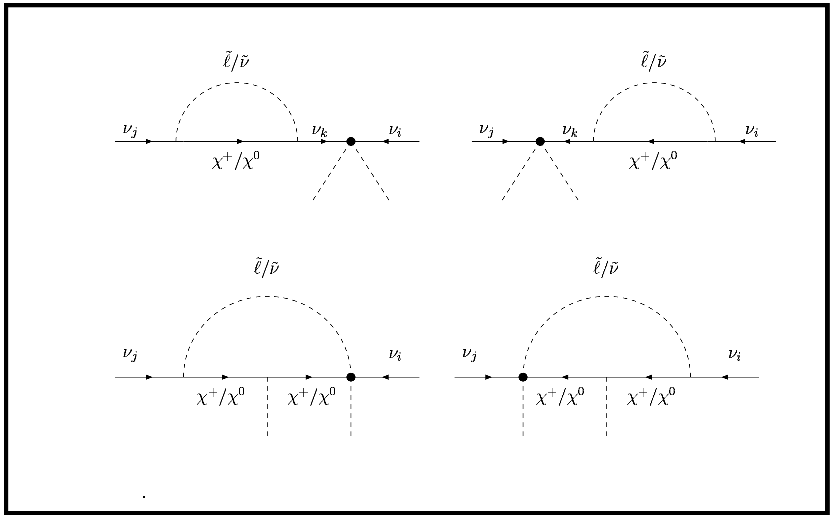
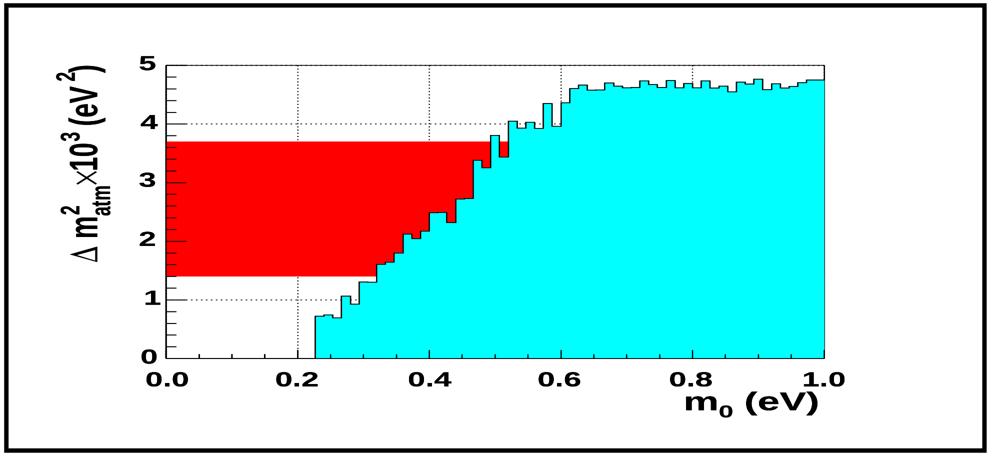


neutrino masses unify due to A4

same origin for lepton and KM mixing

atm splitting vs neutrino mass



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

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

[1] see also Grimus & Lavoura

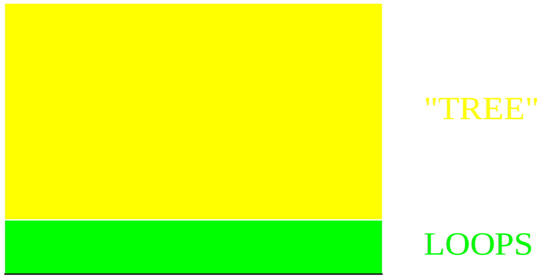
observable Lepton Flavor Violation

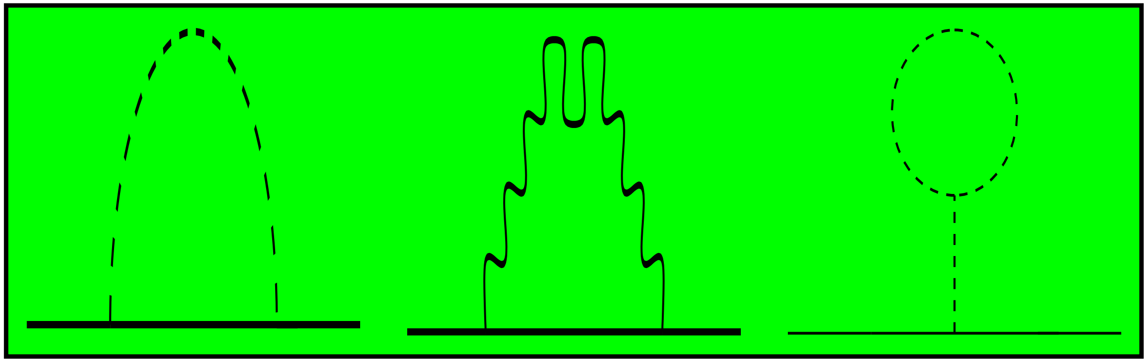
bilinear R parity violation: weak-scale seesaw

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

- weak-scale seesaw atm scale

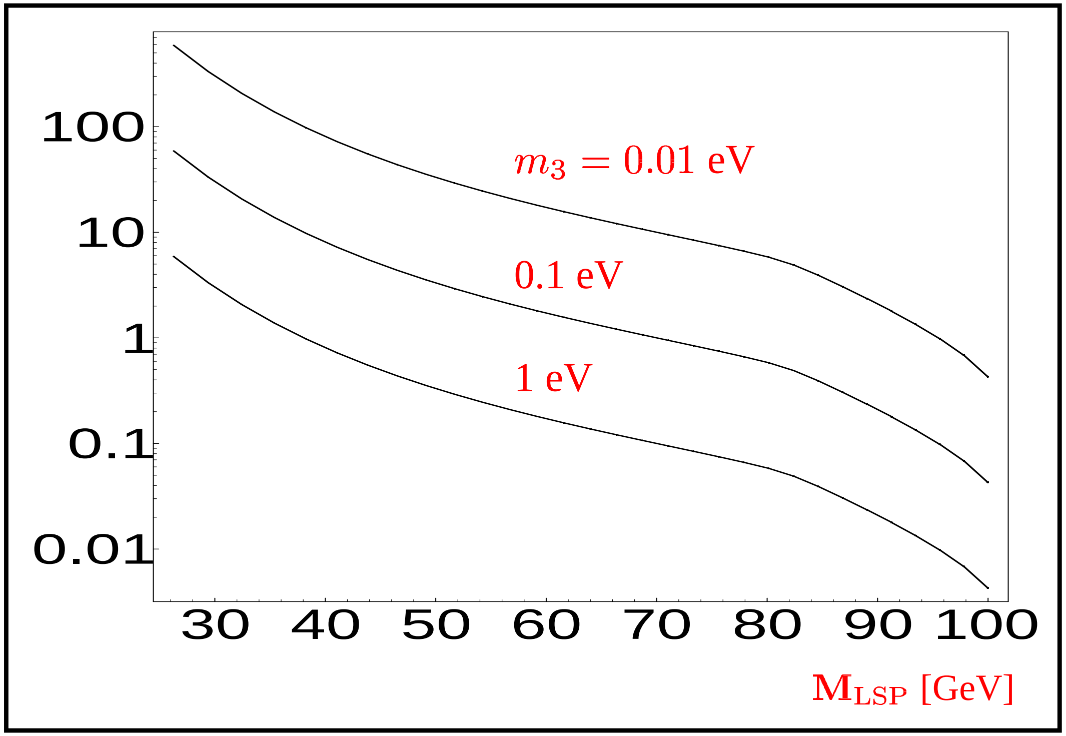
- radiative nu-masses solar scale





LSP decay length [cm]: BRPV

from Bartl et al NPB 600 (2001) 39



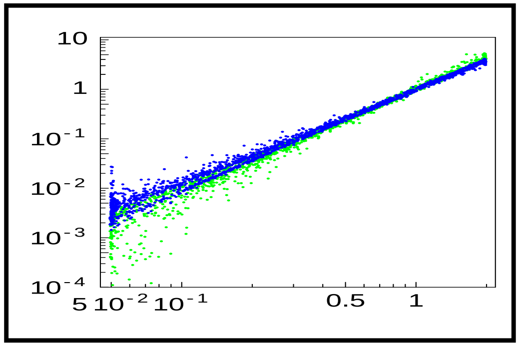
Mukhopadhyaya, Roy & Vissani; Chun & Lee; Choi et al; Datta et al

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 given as RPV ratios, e,g, atm mixing

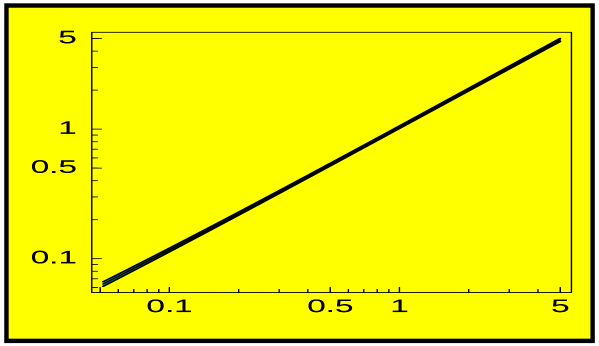


$\tan^2_{23}$ vs (Λ_2/Λ_3)

- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004



$\chi \to \mu qq / \chi \to \tau qq$ 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

nu-mass from BRPV + triplets

Aristizabal et al PRD68 (2003) 033006

- $$W = W_{MSSM} + W_{BRpV} + W_{\Delta} \qquad \widehat{\Delta}_u = \begin{pmatrix} \widehat{\Delta}_u^{++} \\ \widehat{\Delta}_u^{+} \\ \widehat{\Delta}_u^{0} \end{pmatrix} \qquad \widehat{\Delta}_d = \begin{pmatrix} \widehat{\Delta}_d^{0} \\ \widehat{\Delta}_d^{-} \\ \widehat{\Delta}_d^{--} \end{pmatrix}$$
- induced triplet vevs (weak-scale type-II seesaw) E. Ma

$$\langle \Delta^0_{u,d} \rangle \simeq \frac{1}{\sqrt{2}} h^{ij} \frac{\xi_i \xi_j}{M^2_{susy}} \qquad \xi_j \equiv v_i \text{ or } \epsilon_j$$

- atm scale from bilinear R-parity breaking, solar scale from small Higgs triplet
- LSP decay properties correlate with atm & reactor (ratios as RPV)

  Higgs$^{\pm\pm}$ decay BR ratios correlate with solar mixing (triplet Yukawa ratios)

No Road Map to ultimate 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**
- 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

beyond oscillations?

Oscillation vs Spin Flavor Precession

Schechter, JV PRD24 (1981) 1883 & D25, 283
Akhmedov PLB213 (1988) 64
Lim-Marciano PRD37 (1988) 1368
Miranda et al NPB595 (2001) 360
PLB521 (2001) 299

Barranco et al PRD66 (2002) 093009

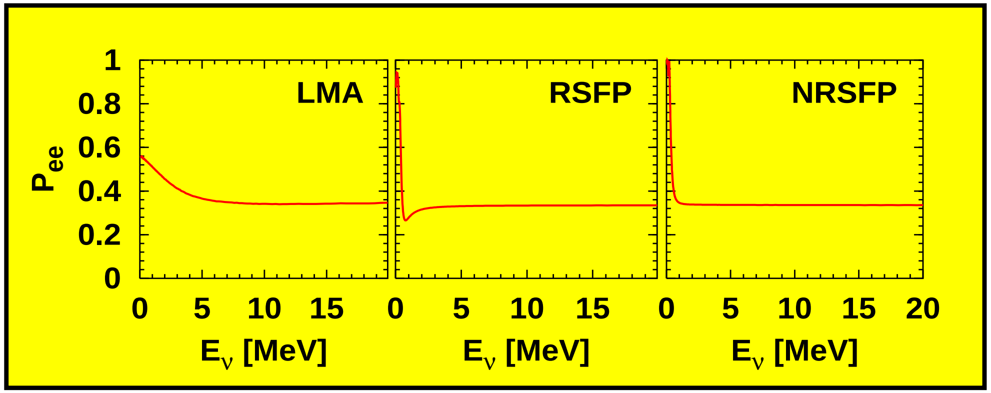
current solar data still do not allow the reconstruction of the of ν_e -survival probability profile

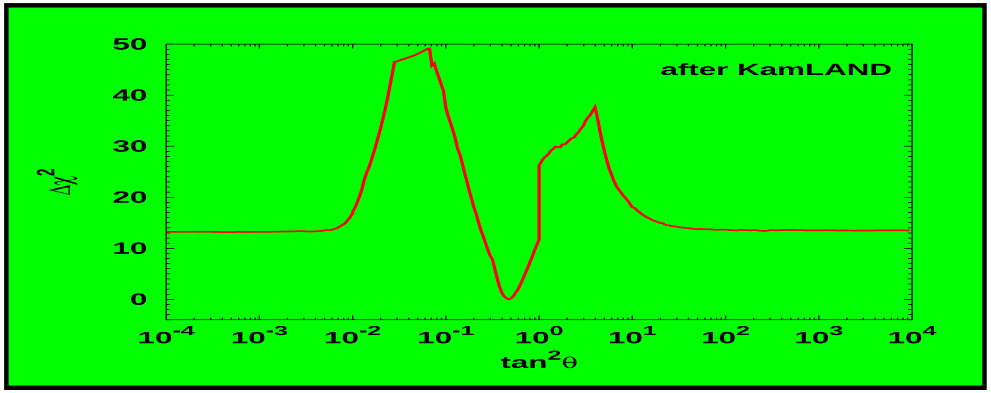
LMA-MSW, RSFP, NRSFP equivalent

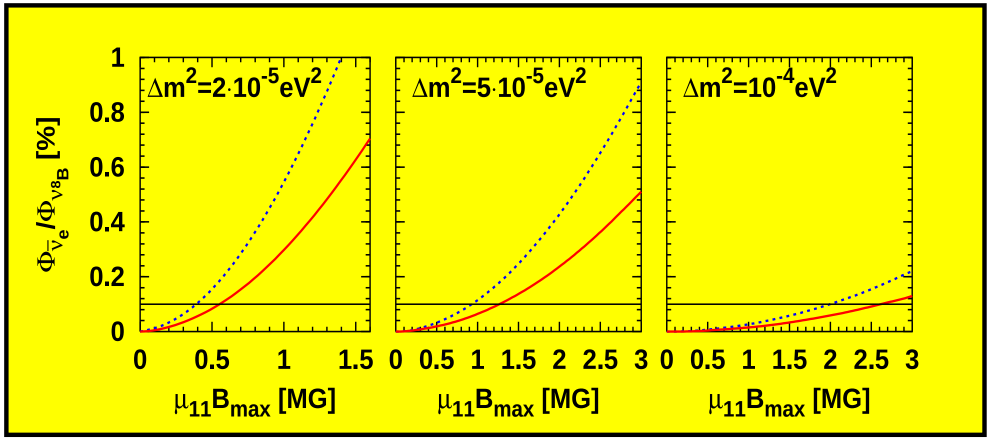
KamLAND lifts degeneracy

ruling out SFP as main solution

testing SFP as sub-leading



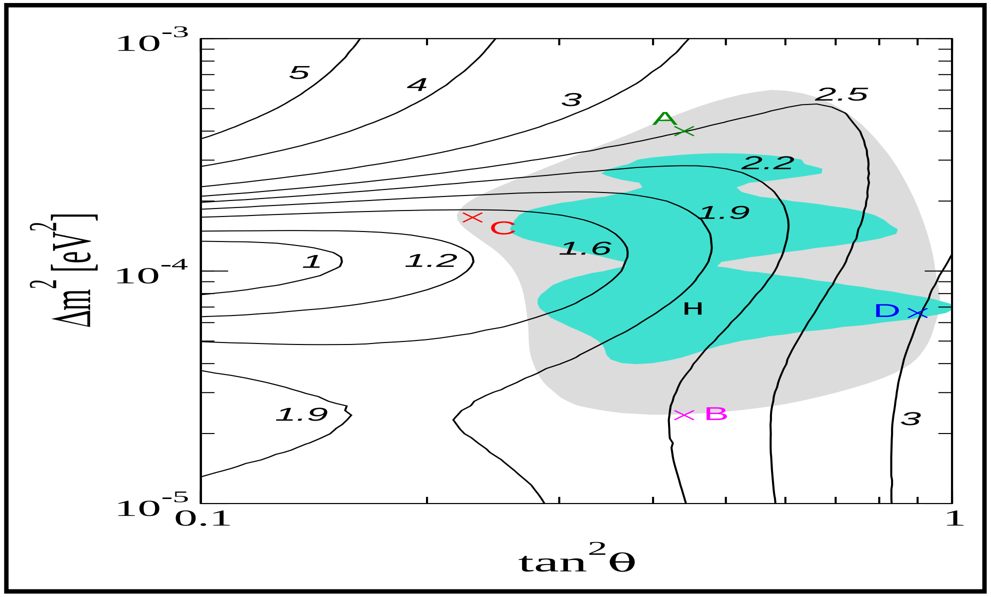




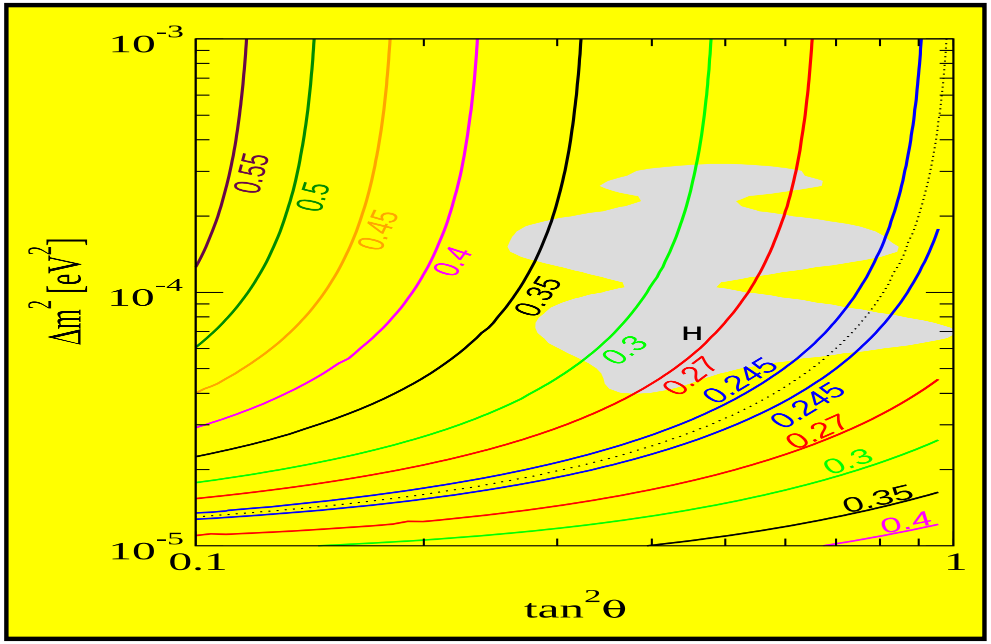
probing neutrino magnetic moments at LMA-MSW

present sensitivity

Grimus, et al , NPB648, 376 (2003)



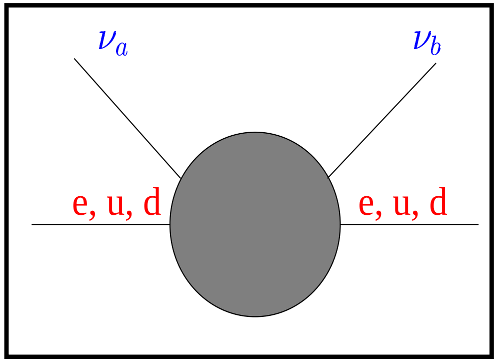
expected Borexino sensitivity



Oscillation vs NSI

Non-standard interactions

FC or NU sub-weak strength dim-6 terms εG_F



can induce oscillations of massless neutrinos in matter, which are E-independent, converting both neutrinos & anti-nu's, can be resonant in SNovae

Valle PLB199 (1987) 432,

Roulet 91; Guzzo et al 91; Barger et al 91

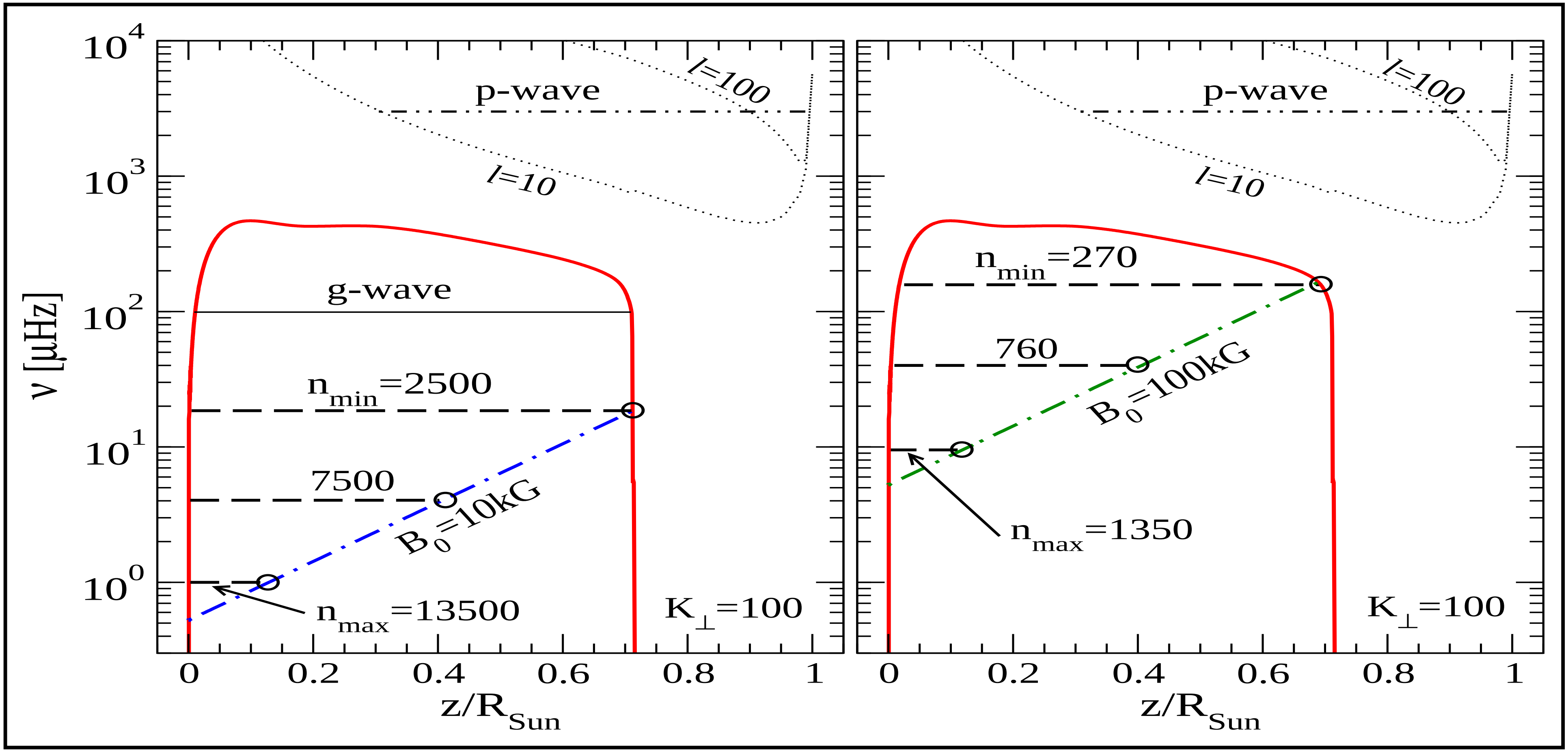
excellent description of solar data

Guzzo et al NPB629 (2002) 479

KamLAND implies not the leading mechanism

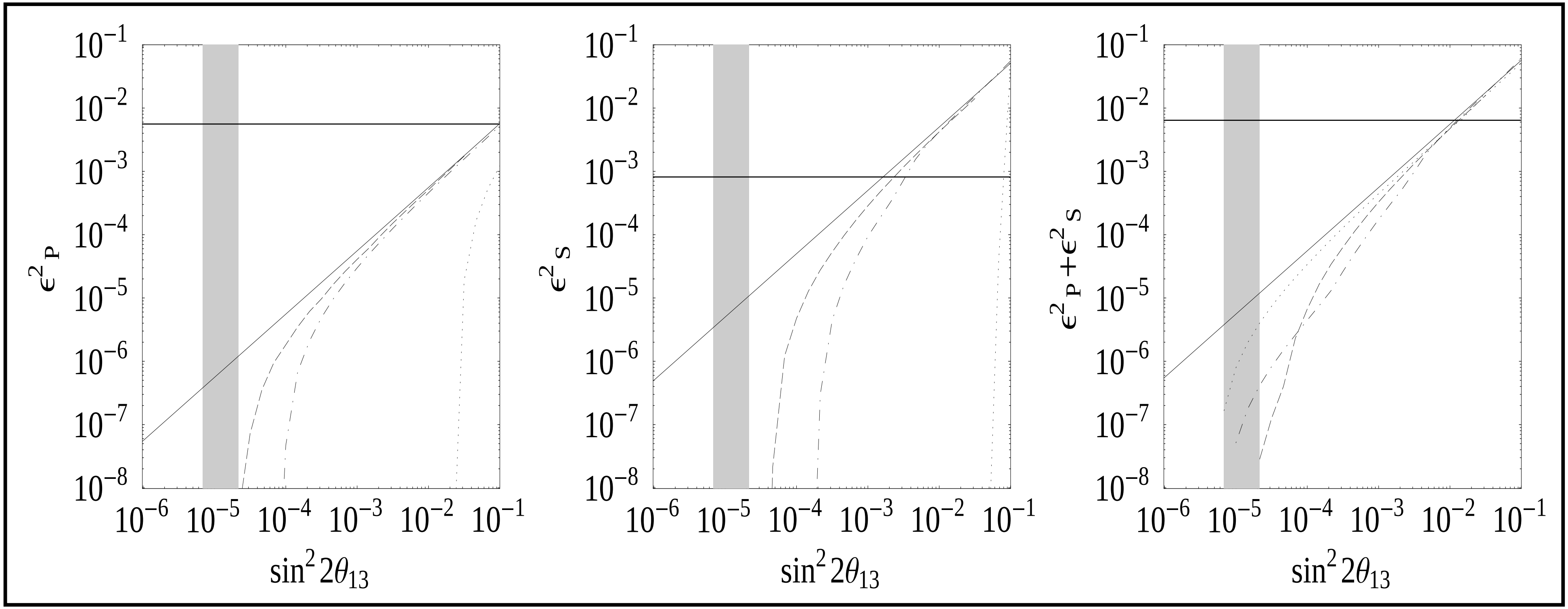
origin for density fluctuations deep in the sun

Burgess et al, astro-ph/0304462



FCI-oscillation confusion theorem-2

Huber, Schwetz and J. V. PRD66, 013006 (2002)



2×10^{20} mu/yr/polarity $\times$ 5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

90% CL reach on $\sin^2 2\theta_{13}$ vs NSI bounds

The dotted line is for $700\,\mathrm{km}$, dash-dotted for $3\,000\,\mathrm{km}$ and dashed is for $7\,000\,\mathrm{km}$ baseline

horizontal black line is the current NSI limit

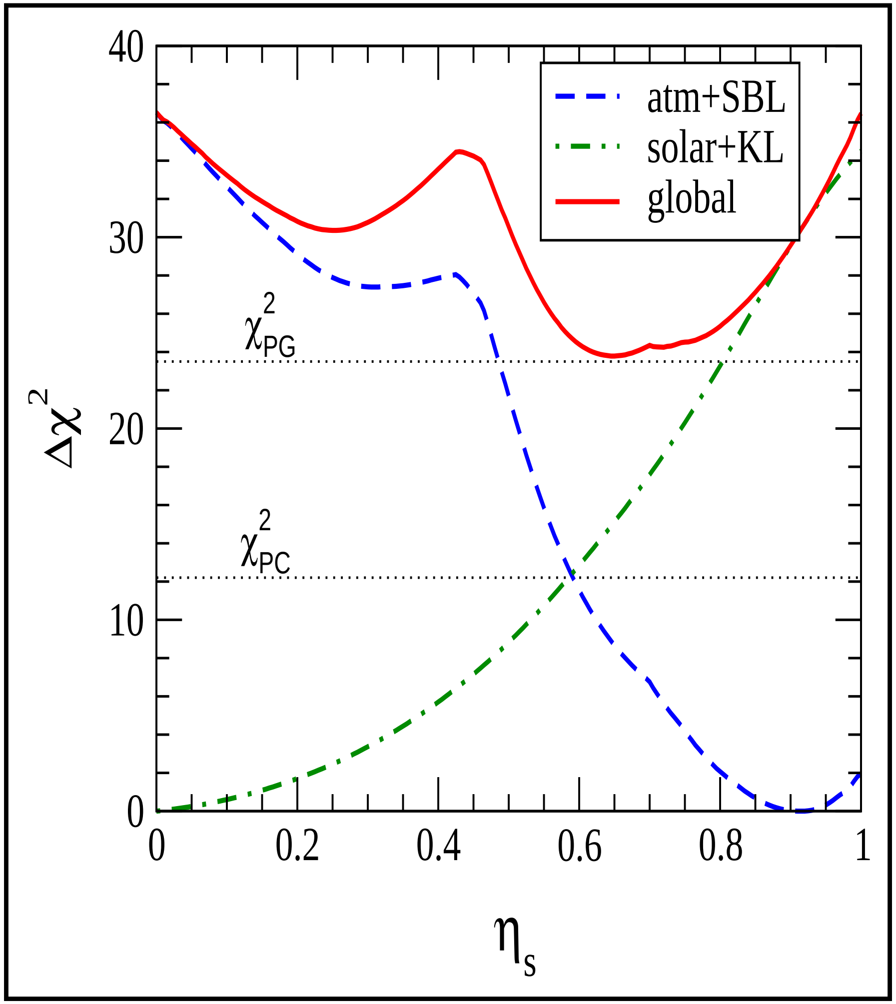
vertical grey band is the sensitivity without NSI

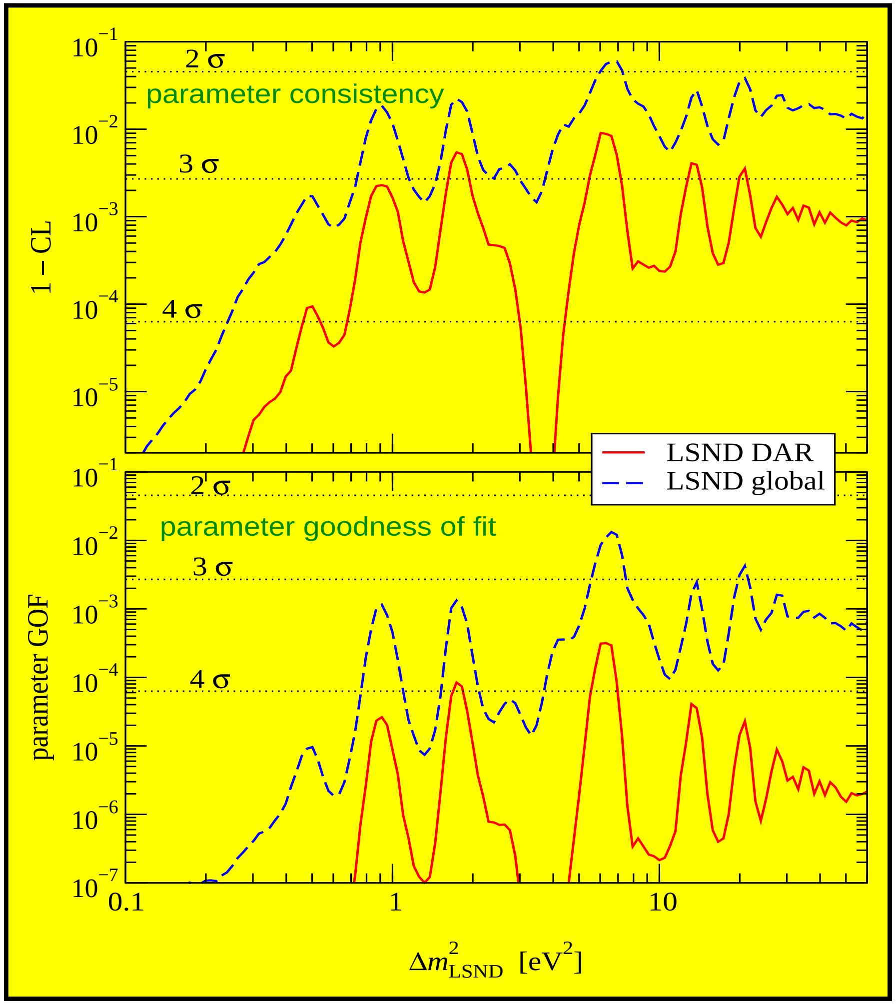
diagonal solid line is the theoretical bound derived from our confusion theorem

4-nus do not really fit LSND with the rest

Maltoni et al NPB643 (2002) 321; upd of PRD65 (2002) 093004

stronger rejection by solar & atm in 2+2 than 3+1



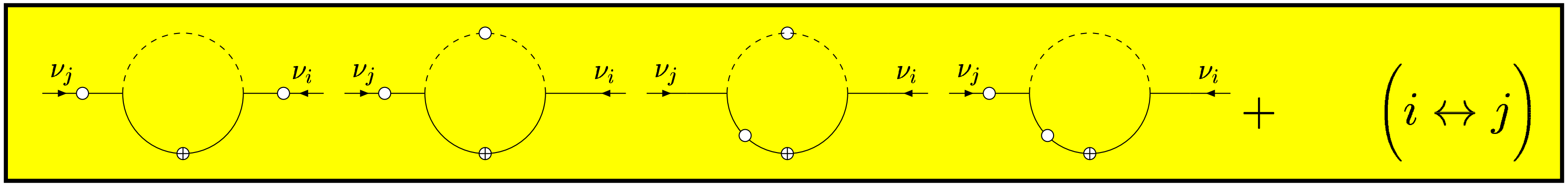


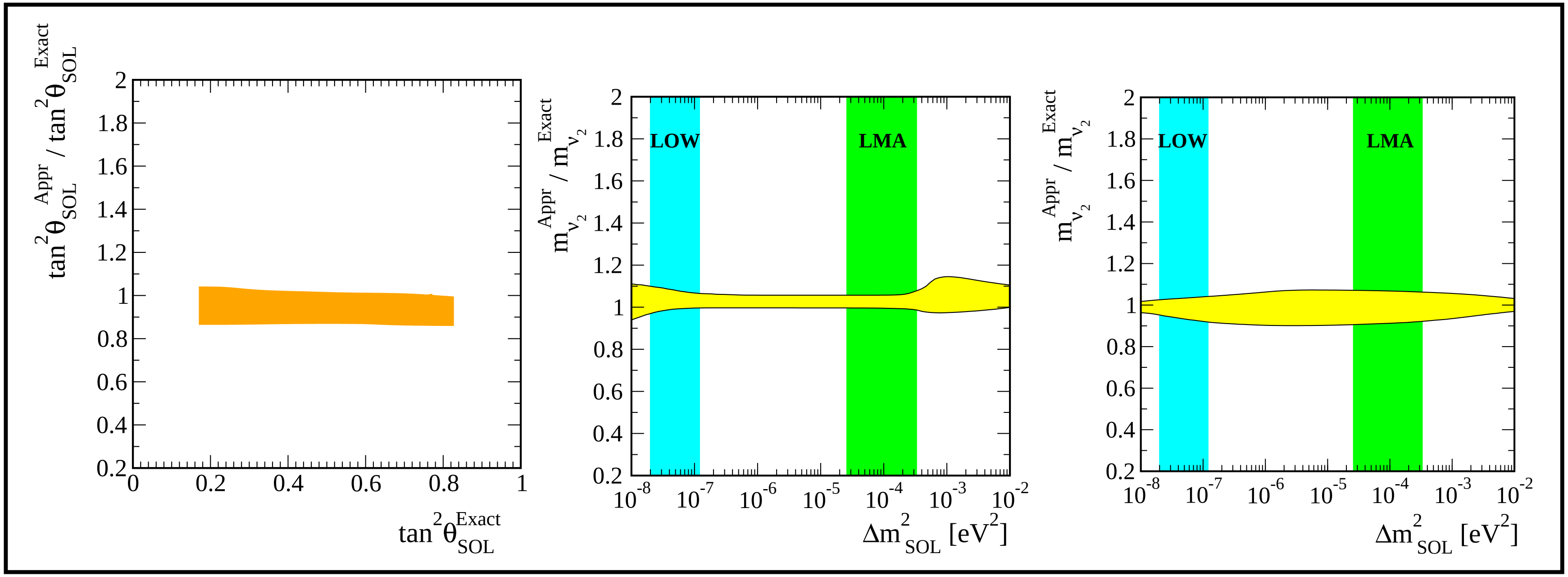
Pas & Weiler

AHEP http://ific.uv.es/~ahep

solar mass loops: analytical vs numerical

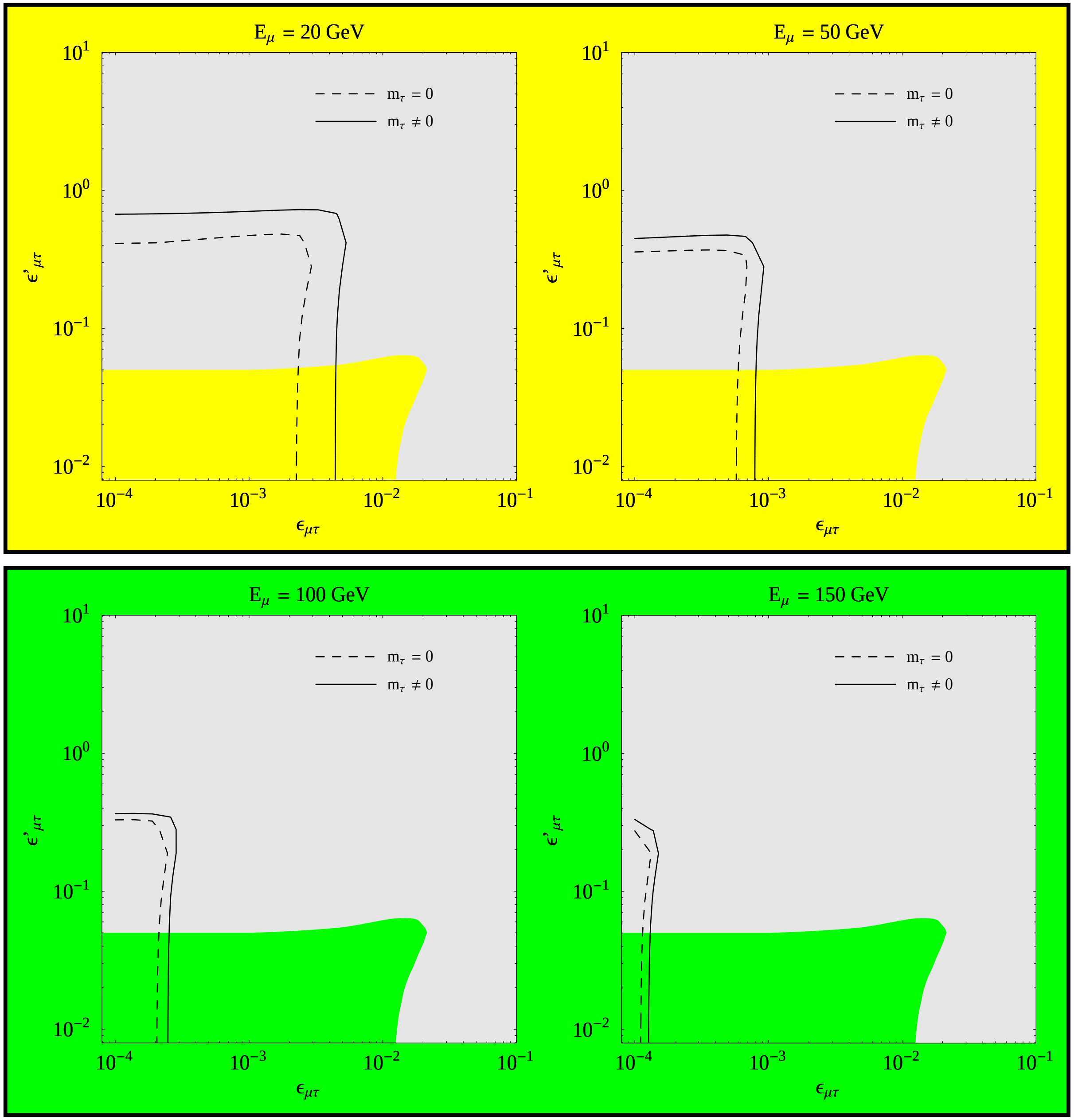
M. A. Diaz et al PRD68 (2003) 013009 [hep-ph/0302021]





Improved FC-tests at NuFact ⊡

10 kt detector, 0.33 ν_τ detection eff above 4 GeV; need no tau charge id

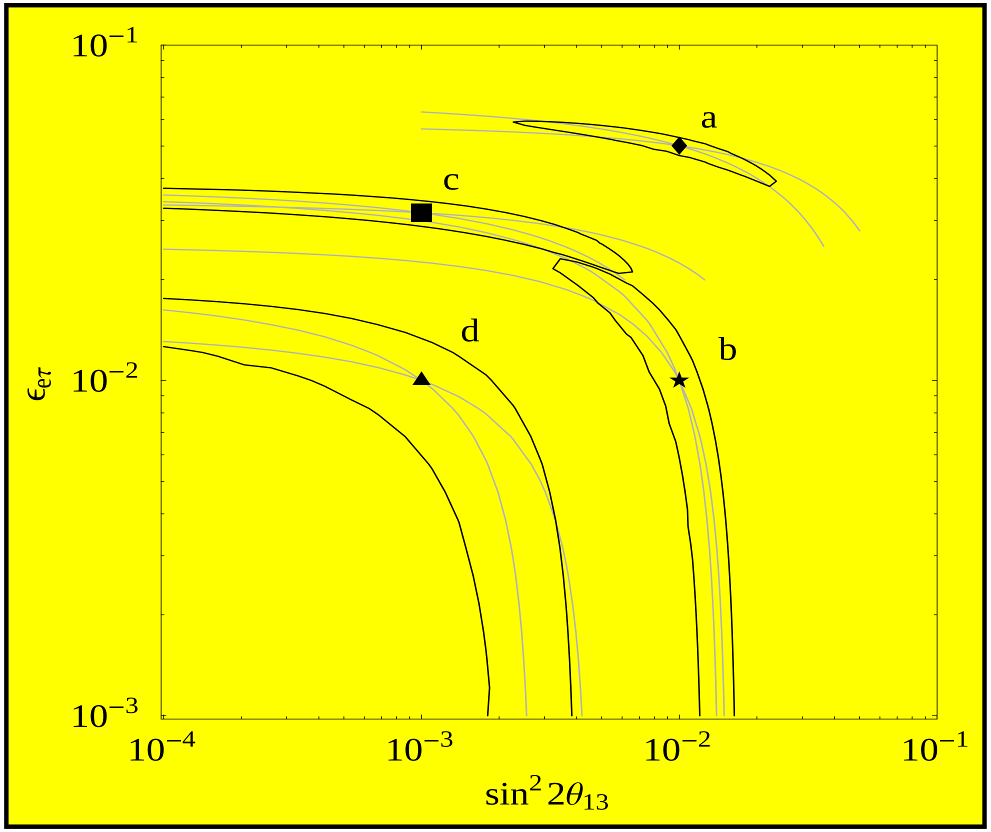


Huber & JV PLB523 (2001) 151

FCI-oscillation confusion theorem

a neutrino factory is less sensitive to θ_{13} because non-standard neutrino interactions are confused with oscillations

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



near-site programme essential

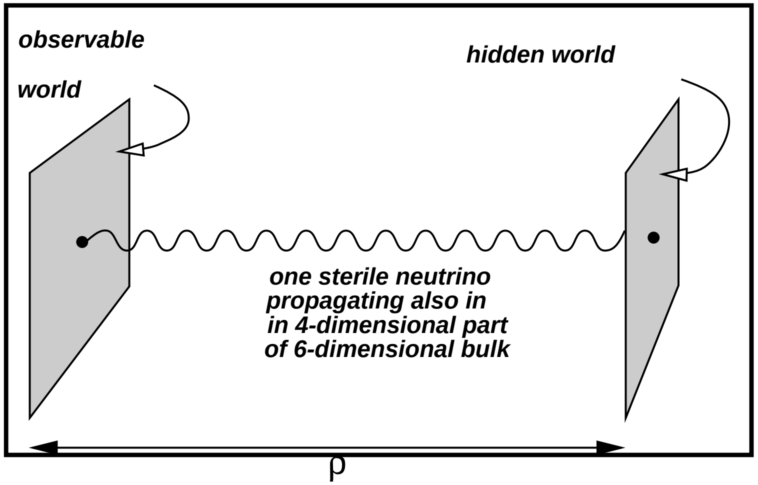
2×10^{20} mu/yr/polarity $\times$ 5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

light sterile-nus from extra dimensions

Ioannisian, JV PRD63 (2001) 073002

Antoniadis, Arkani-Hamed, Dimopoulos, Dvali... Mohapatra, Perez-Lorenzana

- sterile-nu as zero-th mode of the Kaluza-Klein tower



- $m_\nu = (\frac{M_F}{M_\mathrm{P}})^{\frac{\delta}{n}} m_f$ $\quad M_F \sim \mathrm{TeV} \quad \delta = 4 \quad n = 6$

  volume suppression vs symmetry protection ...

- atm & solar scale from RPV — Hirsch, JV PLB495 (2000) 121

  or radiative — Peltoniemi, Tommasini, JV PLB298 (1993) 383

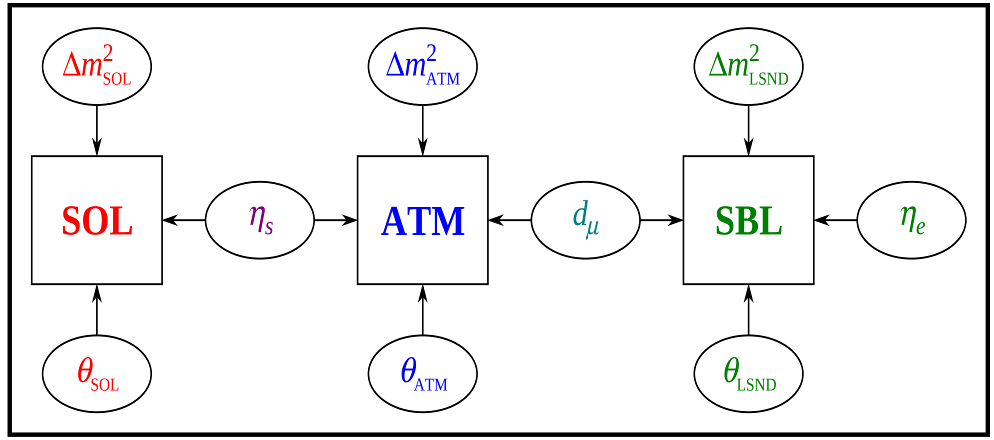
  $\theta_{23} \sim \pi/4$ predicted. But can not reconcile LSND with solar + atm data

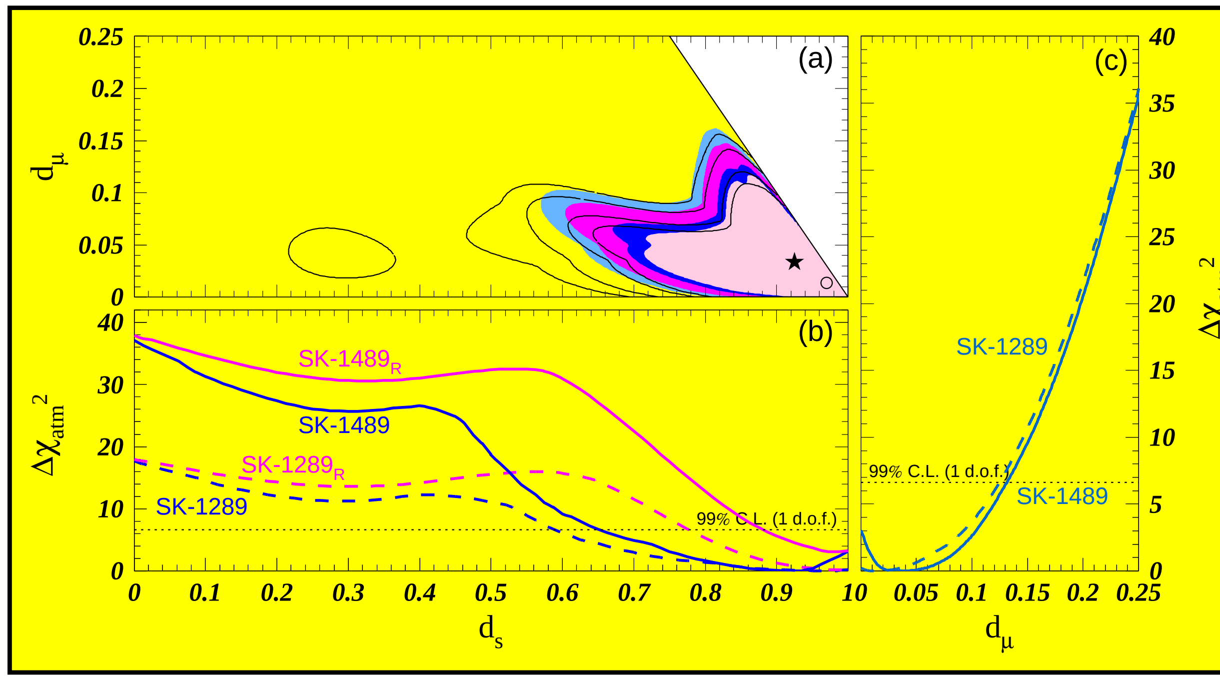
new parameters in atmospheric analysis

sterile as 4th, not 2nd

neglecting CP phases there are 6 angles in lepton mixing matrix
Schechter, JV PRD22 (1980) 2227

Maltoni et al PRD65 (2002) 093004



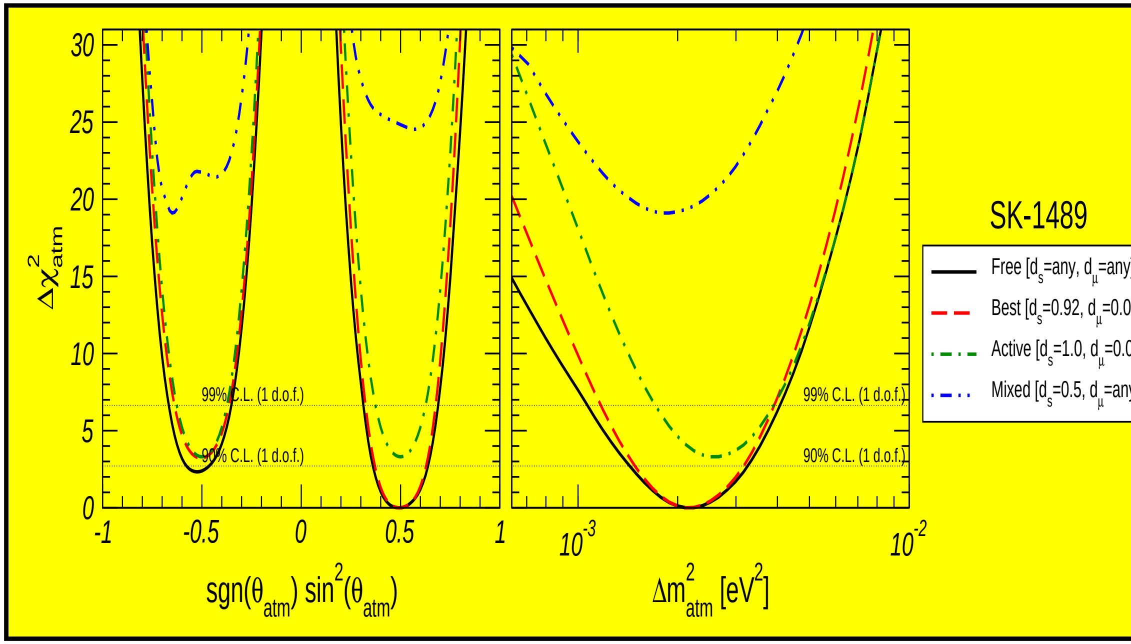


sterility rejection sensitive to new parameters

atmospheric neutrino parameters-2

- $$\sin^2\theta_{\rm ATM} = 0.5$$

$$\Delta m^2_{\rm ATM} = 2.5\times 10^{-3}\ {\rm eV}^2$$

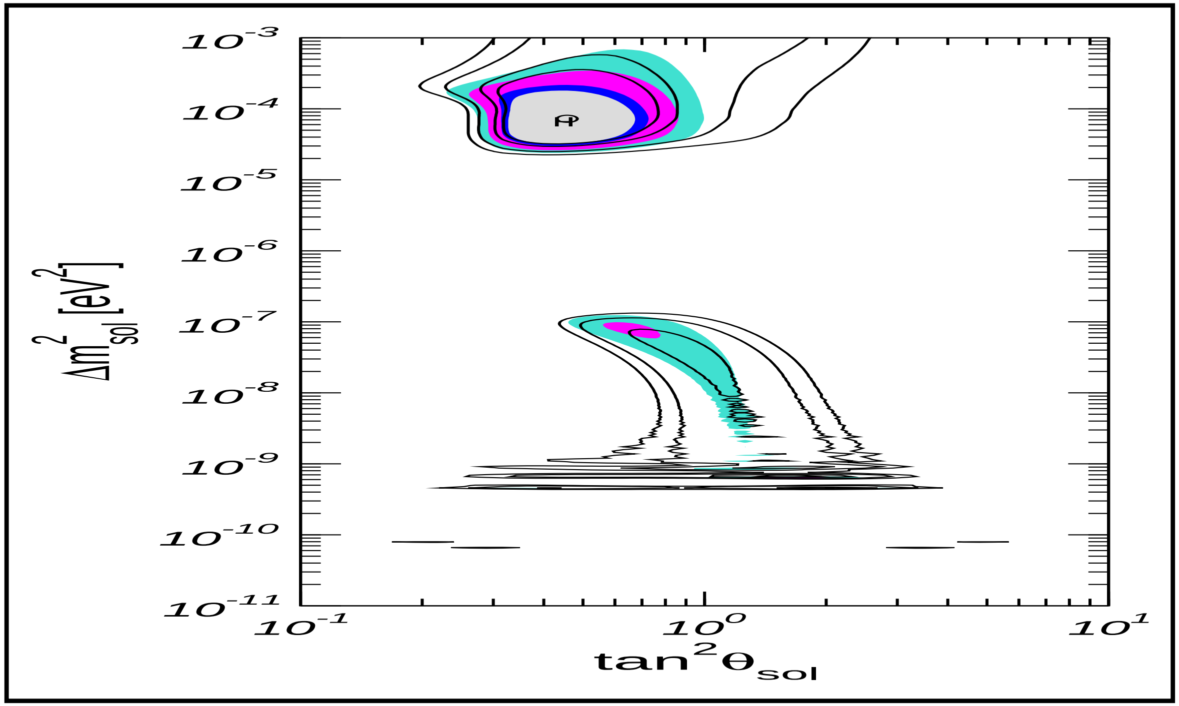


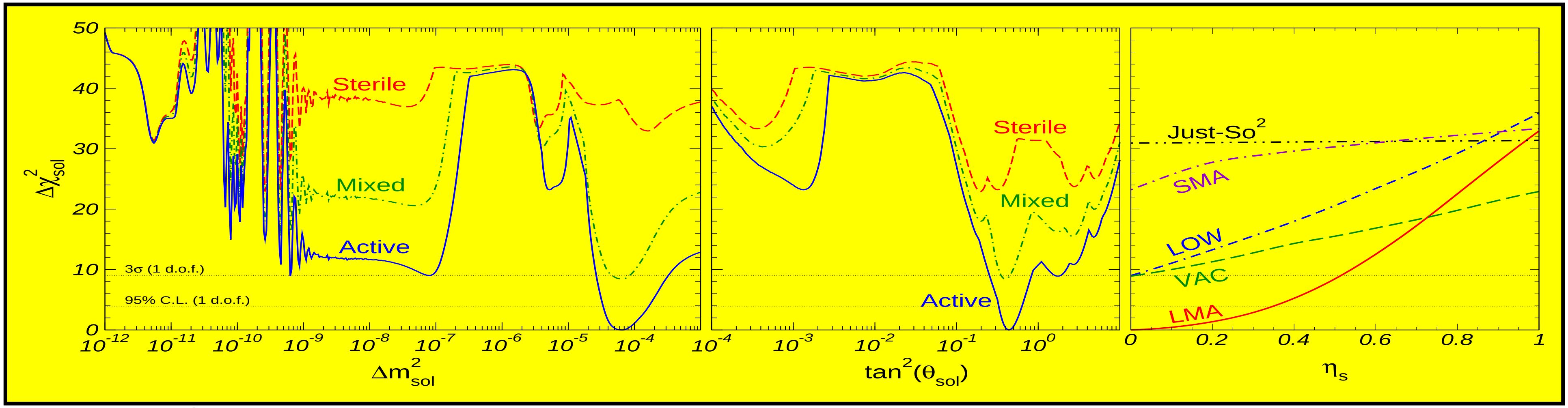
higher sterility rejection

solar neutrino oscillation regions ⊙

Maltoni et al, PRD67 (2003) 013011 (cf different groups)

previous LMA-MSW hint came from spectrum, Gonzalez-Garcia et al, NPB573 (2000)3





light-nu's without new scale

tree

"anti-seesaw" Gonzalez-Garcia, JV, PLB216, 360 (1989) RPV Romao and JV, NPB381 (1992) 87... Hirsch et al;

radiative

Zee or Babu-type

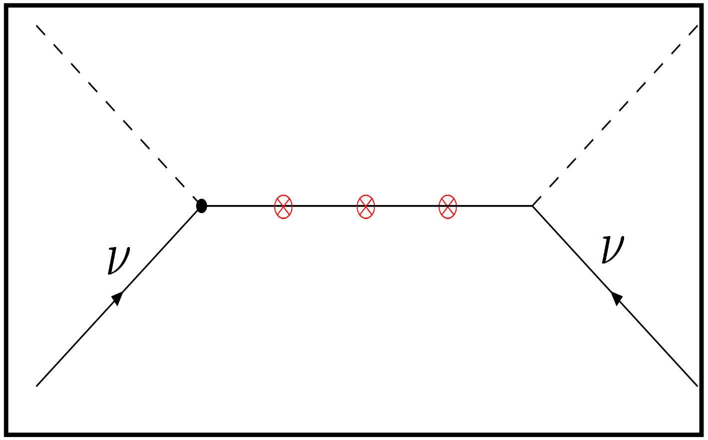
In contrast to seesaw

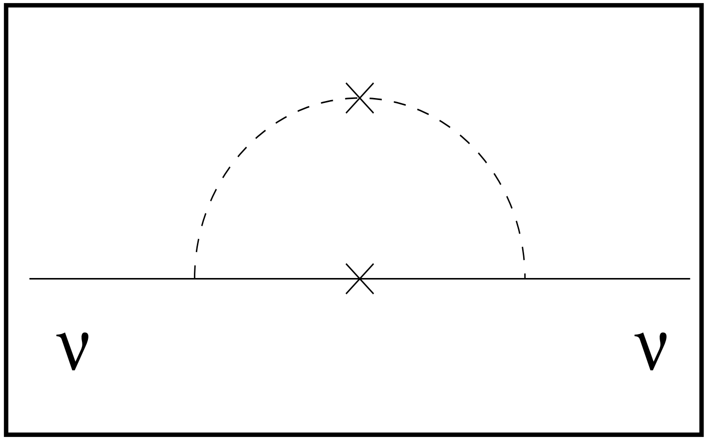
m-nu → 0 as the LNV scale → zero

Higgs → 2–majoron "invisible" decays

Joshipura, JV NPB397 (1993) 105;

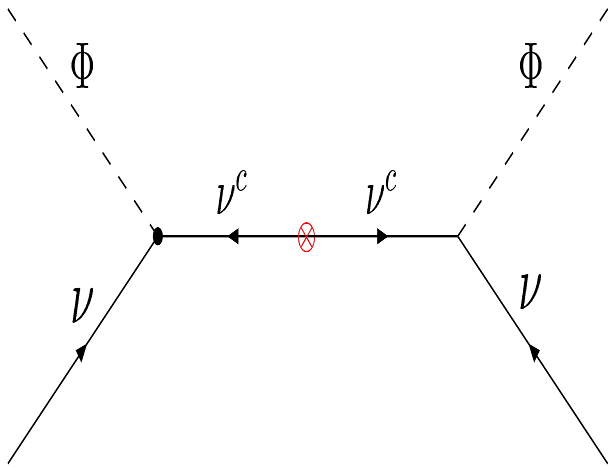
Campos et al PRD55 (1997) 1316 ●





Global realization of seesaw

neutrino mass follows in the same way



spontaneous violation of global B-L implies majoron Chikashige, Mohapatra, Peccei

opens $\nu_h \to \nu_l$ + majoron decay Schechter, Valle, PRD25, 774 (1982)

detectable at SNO with a future SNova Kachelriess et al PRD62 (2000) 023004