Status and Consequences of Neutrino Mass

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Based on

Neutrino properties before and after KamLAND

S. Pakvasa and JV hep-ph/0301061

and

Neutrino masses twenty–five years later

J. V. hep-ph/0307192

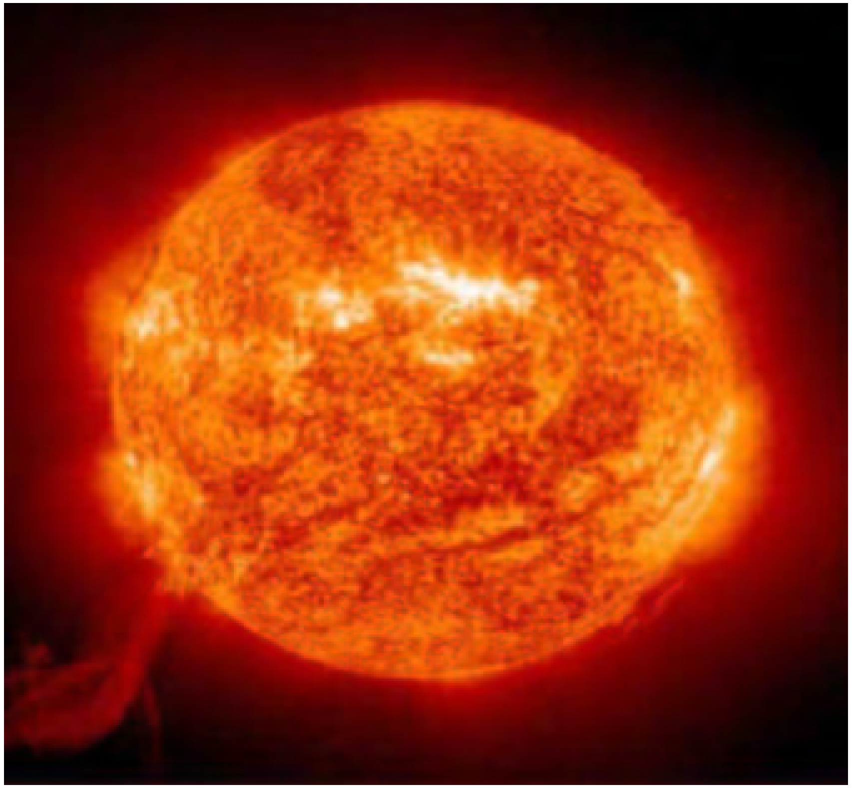
writeup of my talk at Joe Schechter's Fest

Solar Neutrinos

are electron neutrinos produced in the core of our Sun by thermonuclear reactions, which generate the solar energy

All reactions result in the overall fusion of protons into helium:
$4p \to {}^4\mathrm{He} + 2e^+ + \gamma + 2\nu_e$

The Standard Solar Model predicts the total amount of neutrinos produced in terms of solar parameters (surface luminosity, age, radius, mass)



Since 1968 many experiments have measured the flux of electron neutrinos arriving at the Earth, and found they are much less than expected. This has been the Solar Neutrino Problem

Reactor Neutrinos

Neutrinos are also produced in nuclear power plants

controlled source

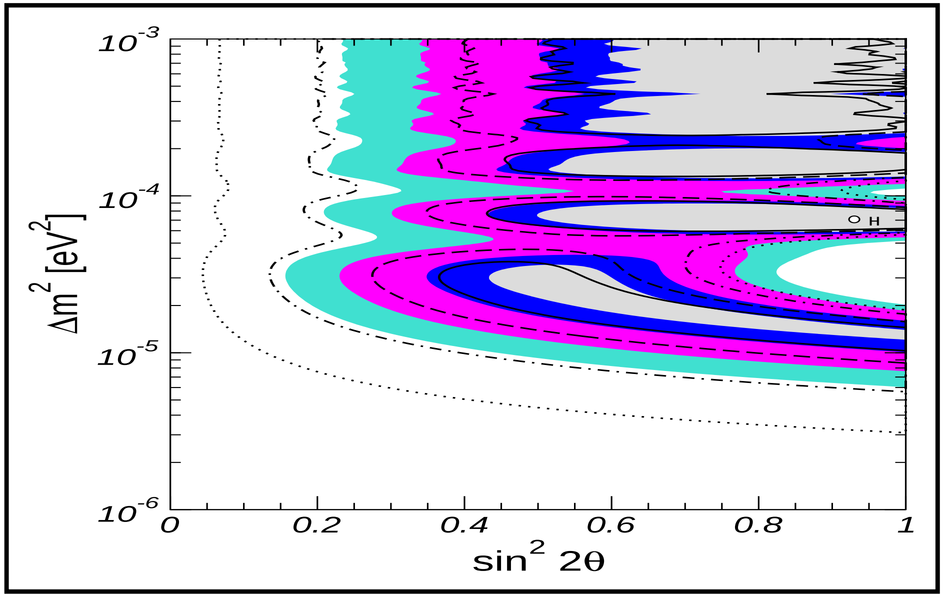
KamLAND rules out non-LMA oscillation descriptions

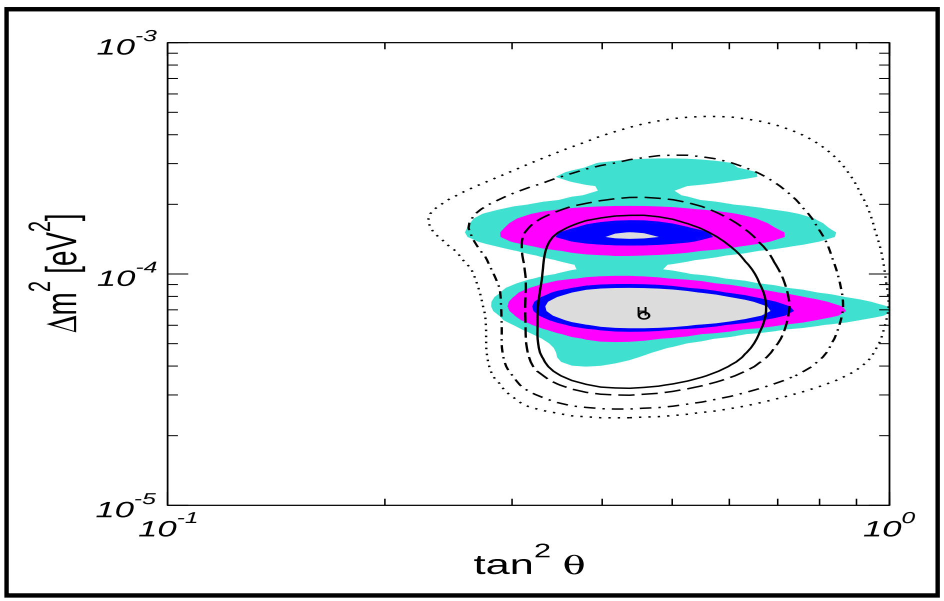
KamLAND rules out non oscillation descriptions

Barranco et al hep-ph/0207326 v3

Guzzo et al hep-ph/0112310 v3

Solar + KamLAND reactor results





Maltoni, Schwetz & JV, PRD67 (2003) 093003

hep-ph/0212129

first 145-days data support oscillation hypothesis

critique of various analyses

S. Pakvasa and JV hep-ph/0301061

combining with solar neutrino data sample rules out non-LMA-MSW solutions

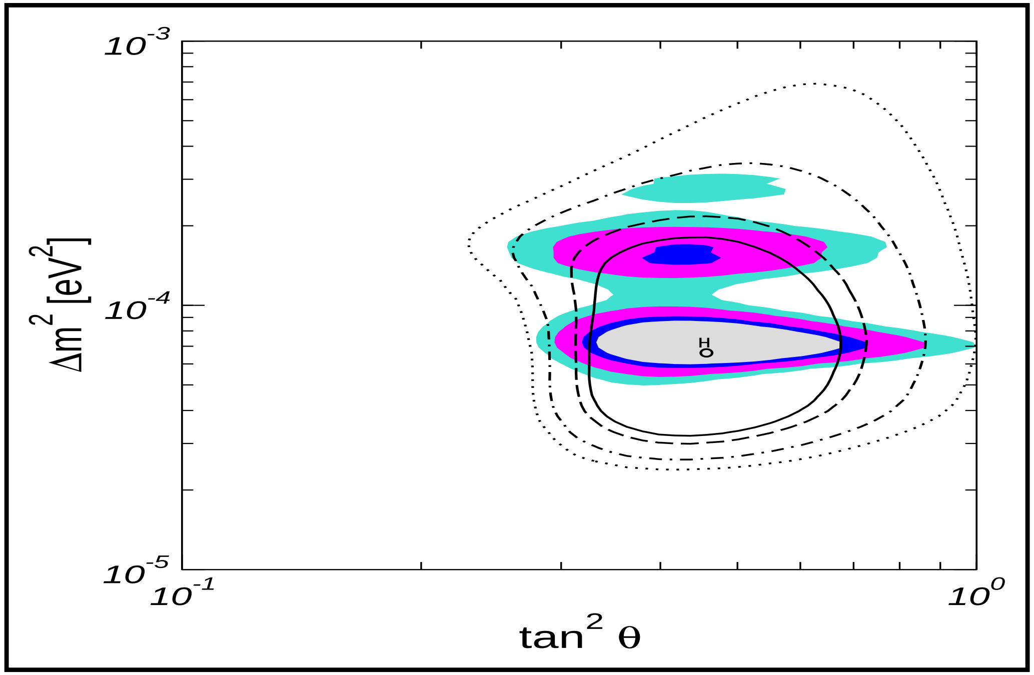
oscilllations happen inside the sun!

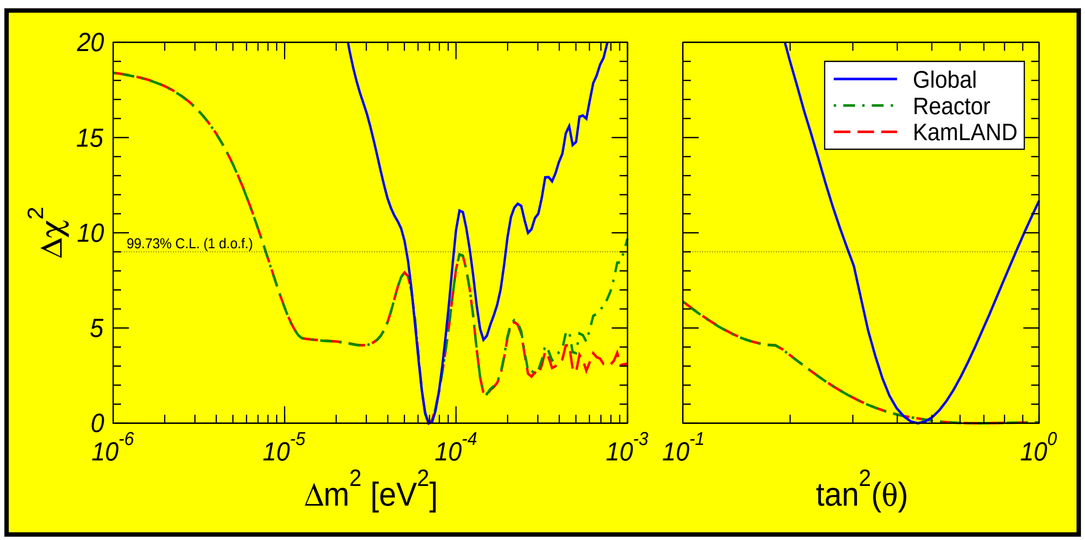
$0.29 \leq \tan^2\theta \leq 0.86$

$5.1 \times 10^{-5}\ \mathrm{eV}^2 \leq \Delta m^2_{\mathrm{SOL}} \leq 9.7 \times 10^{-5}\ \mathrm{eV}^2$

$1.2 \times 10^{-4}\ \mathrm{eV}^2 \leq \Delta m^2_{\mathrm{SOL}} \leq 1.9 \times 10^{-4}\ \mathrm{eV}^2$

Solar + KamLAND results ⊙





Maltoni, Schwetz, JV, PRD67 (2003) 093003

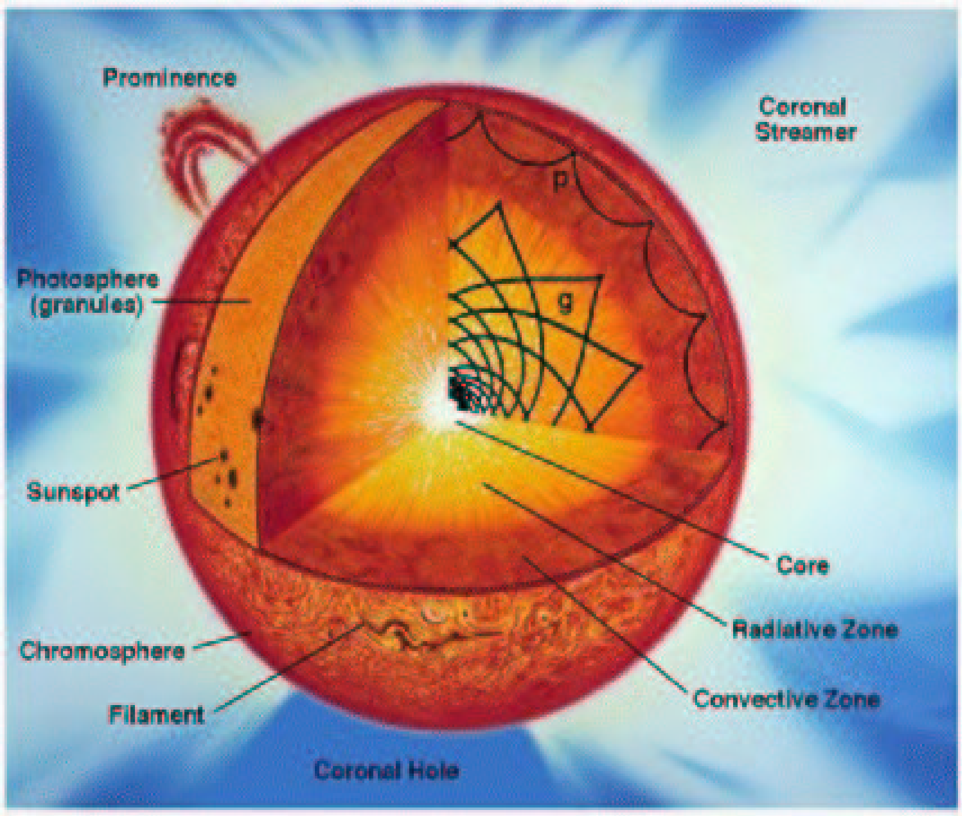
consistency with Poisson method

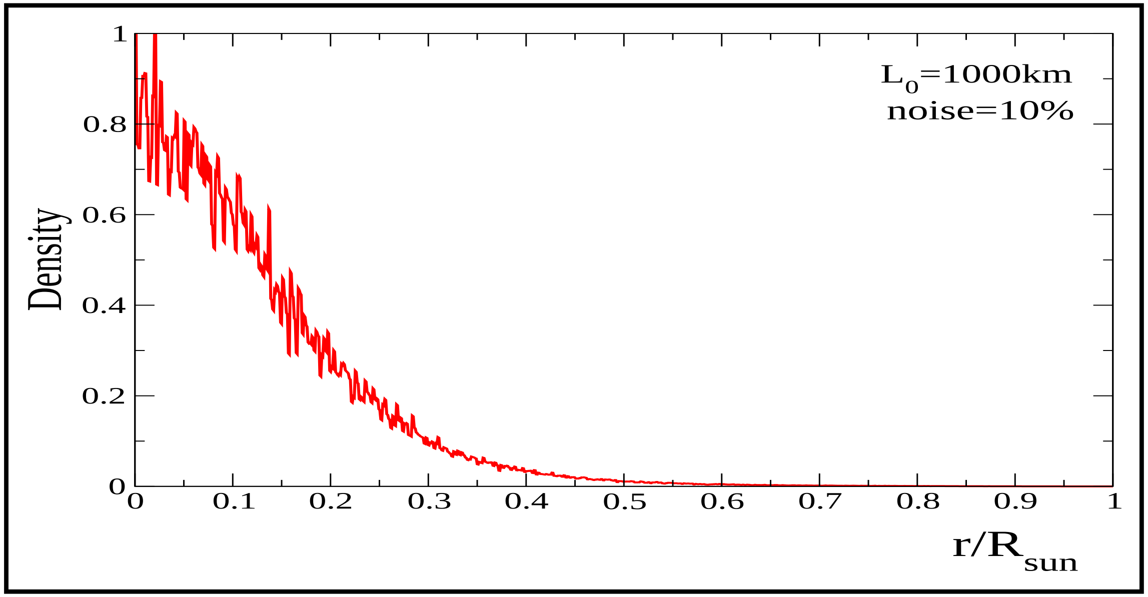
enormous progress wrt pre-KamLAND

in contrast to atmospheric, solar mixing significantly non-maximal

bi-maximal models rejected

do we understand the Sun?





Robustness of MSW plot

neutrino propagation strongly affected by density noise

Balantekin et al 95

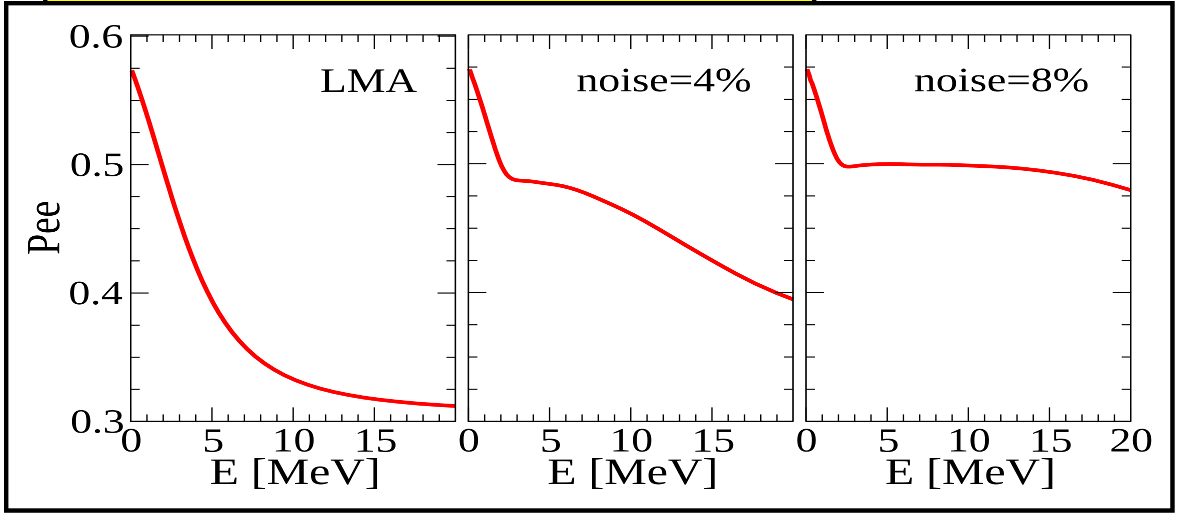
Nunokawa et al NPB472 (1996) 495

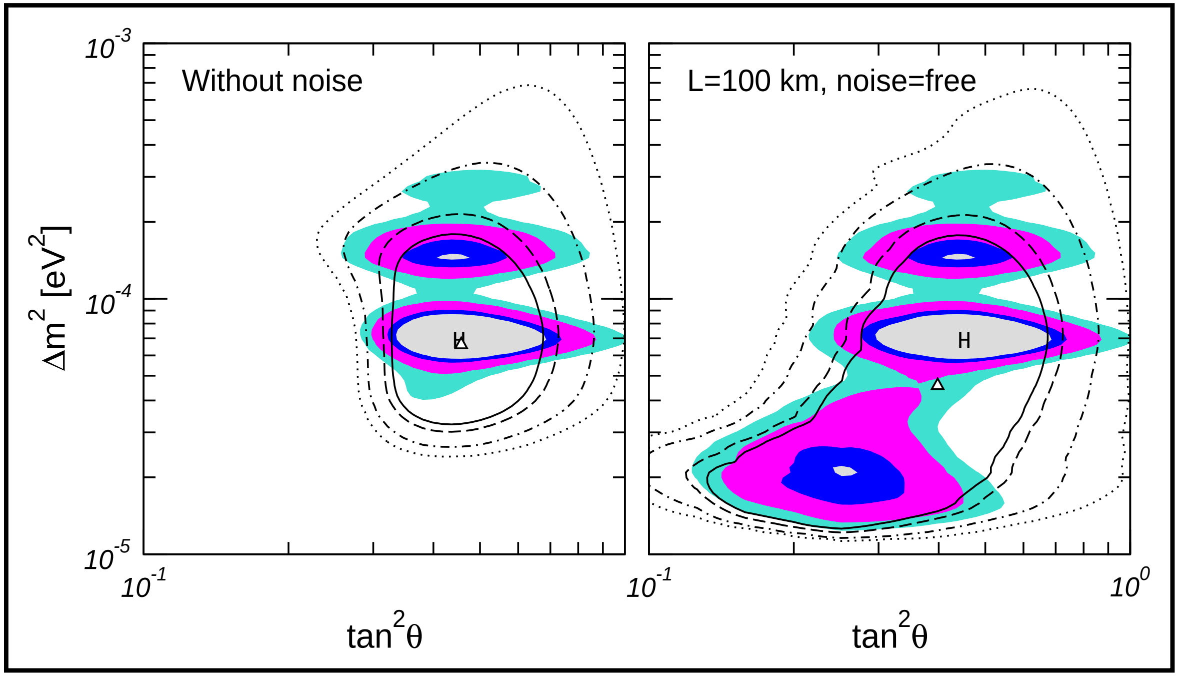
Burgess et al 97

substantial distortion implies that lower $\Delta m^2_{\rm SOL}$ possible but

mixing remains large

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





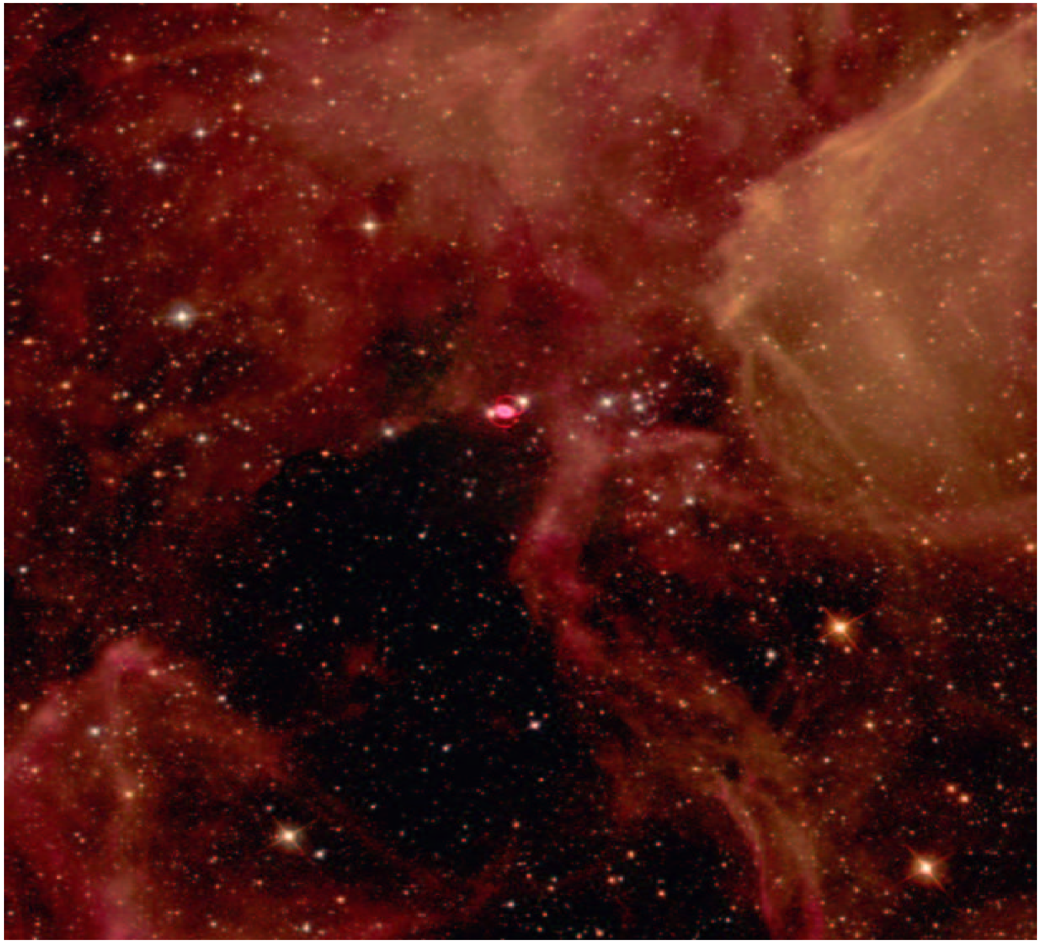
Supernova neutrinos

Supernovae end their lives in an extremely violent explosion in which the maximal optical luminosity can be as great as that of a small galaxy

99% of the total gravitational binding energy is emitted in the form of neutrinos of all flavours $\nu_e\ \nu_\mu\ \nu_\tau$

this huge flux can transverse large distances and be detected in underground experiments before the corresponding optical signal

SN1987A



LMA-MSW status wrt SN1987A

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

large angle 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

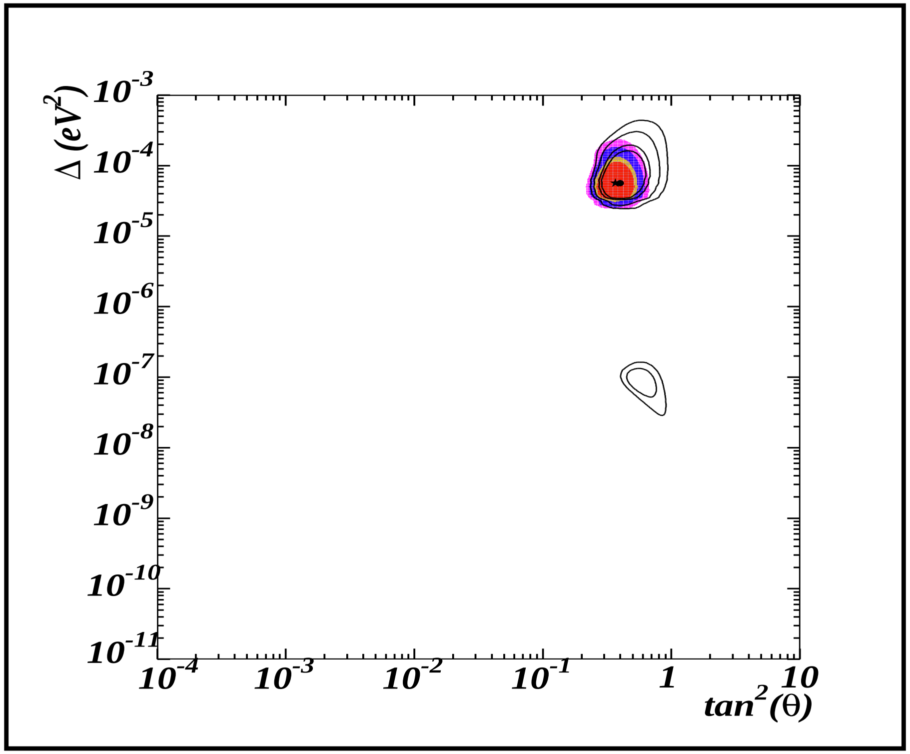
$E_{\bar{\nu}_e}$ =14 MeV,

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

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

solar+SN1987A analysis

LMA-MSW may remain best



Kachelriess et al PRD65 (2002) 073016

Oscillation vs Non-Standard Interactions

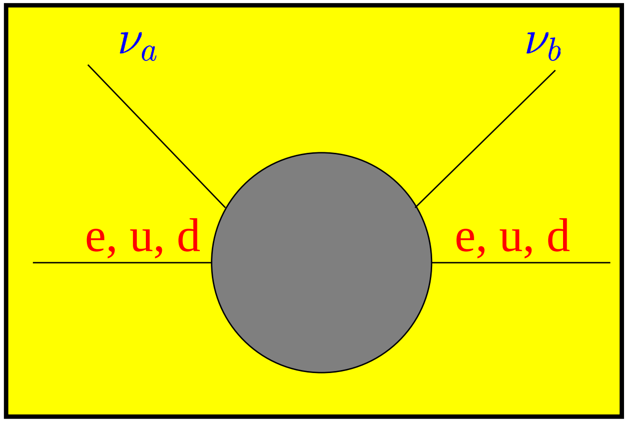
- NSI are FC or NU sub-weak strength dim-6 terms εG_F
- theoretically attractive
  by-product of nu-masses in most models, like seesaw, where CC and NC are "non-standard" (rectangular and projective)

  Schechter, JV PRD22 (1980) 2227

  independent, sometimes **leading** source of LFV

  Lee & Shrock, 1978

  J. V. Prog. Part. Nucl. Phys. 26 (1991) 91

- 

  affect neutrino propagation and may induce (E-independent) oscillations of massless neutrinos in matter, which may be important in SNovae/pulsars since they may be resonant and convert both neutrinos & anti-nu's

  Valle PLB199 (1987) 432, Nunokawa et al, PRD54 (1996) 4356, Grasso et al, PRL81 (1998) 2412

Oscillation vs Spin Flavor Precession

Schechter, JV PRD24 (1981) 1883; Akhmedov PLB213 (1988) 64; Lim-Marciano PRD37 (1988) 1368

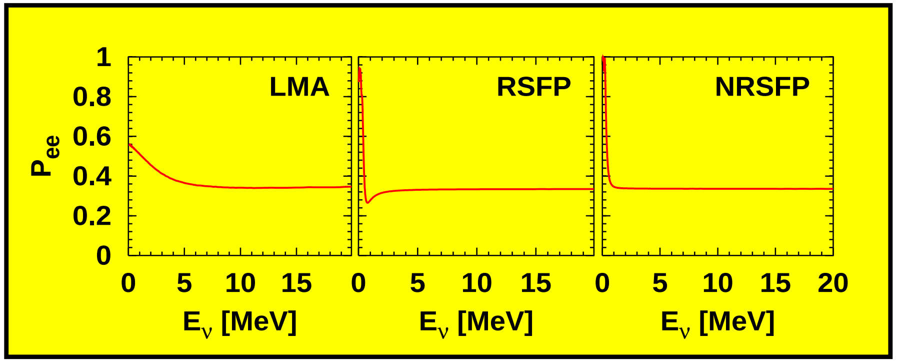
"fixed" B(r)

Miranda et al NPB595 (2001) 360, PLB521 (2001) 299

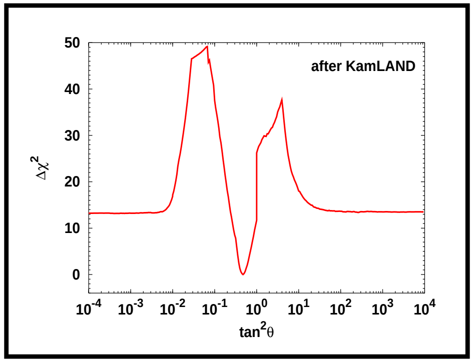
current solar data alone do not allow the reconstruction of the profile of ν_e - conversion probability

Barranco et al PRD66 (2002) 093009

hep-ph/0207326

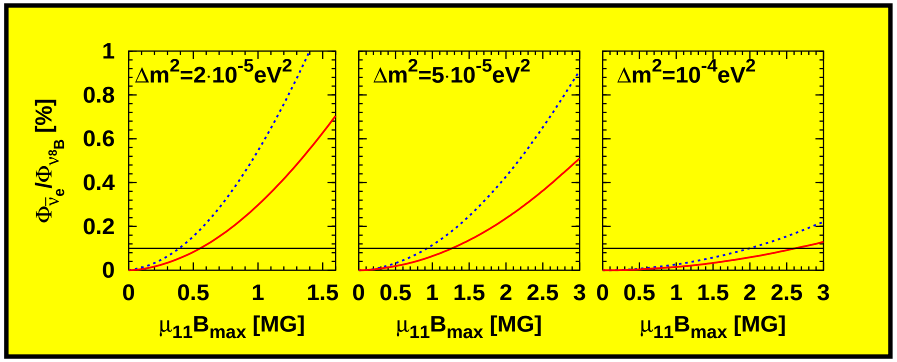


LMA-MSW, RSFP, NRSFP equivalent



KamLAND lifts degeneracy

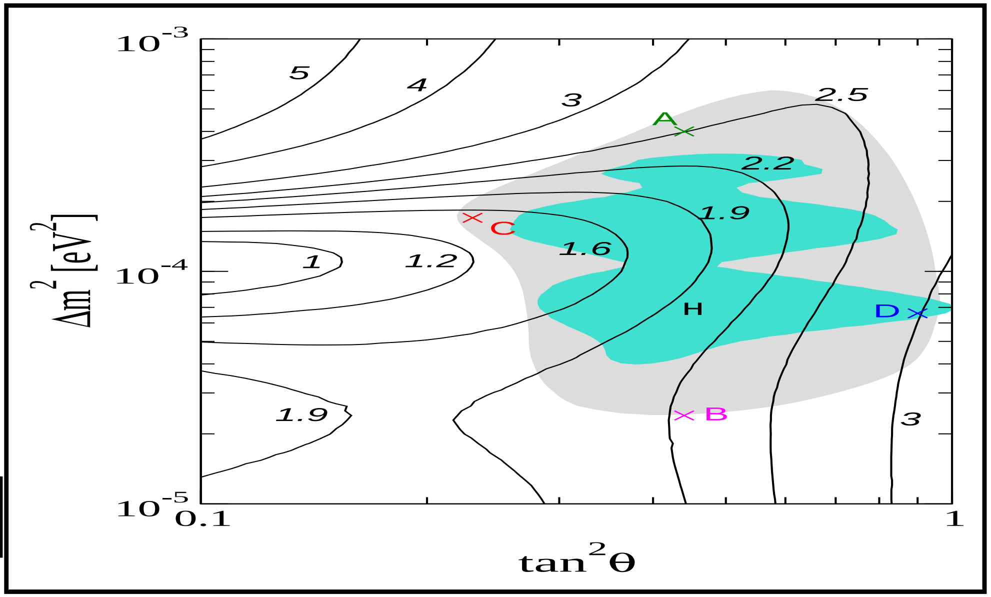
ruling out SFP as solution ($\gtrsim 3\ \sigma$)



testing SFP as sub-leading

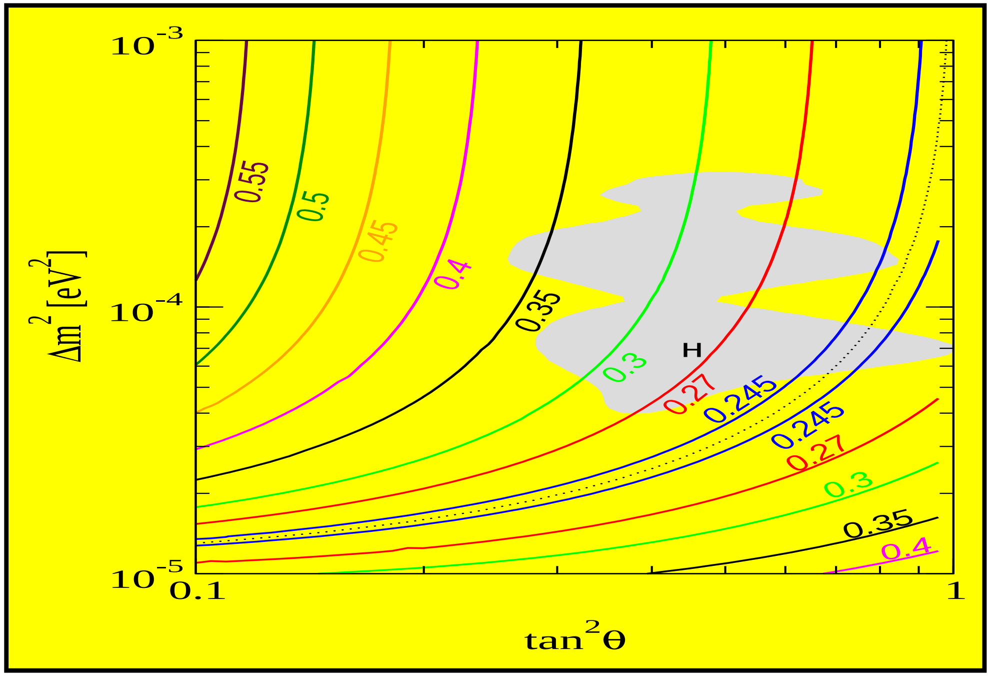
probing neutrino magnetic moments at LMA-MSW

present sensitivity



Grimus et al NPB648 (2003) 376, hep-ph/0208132

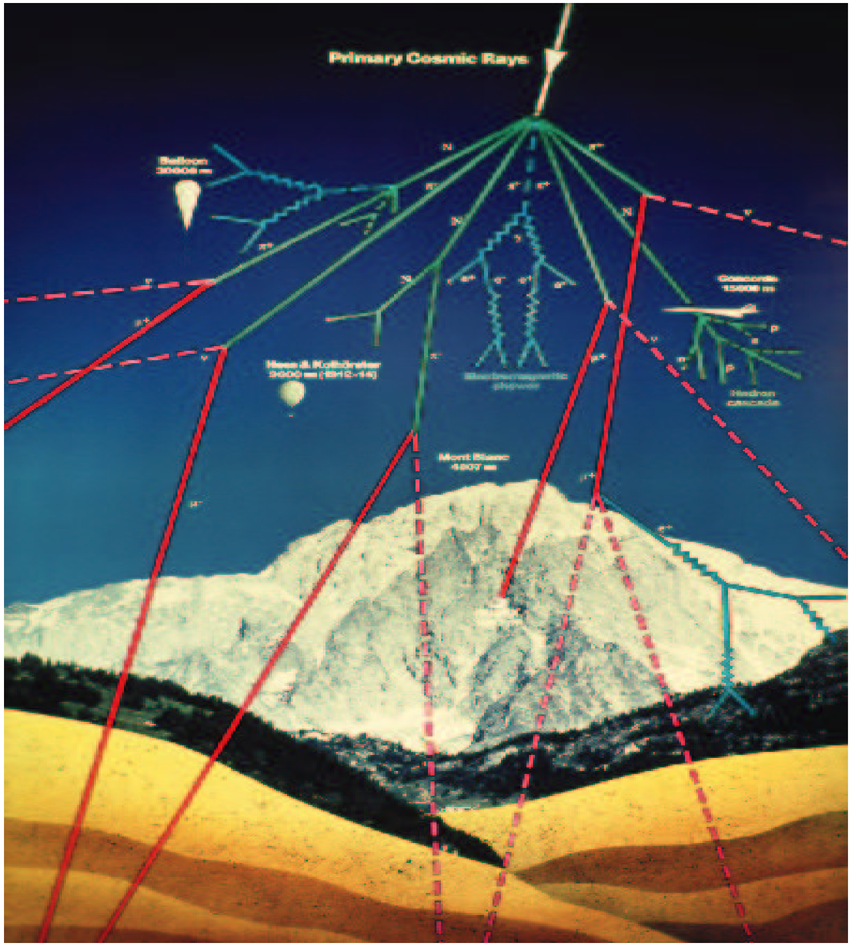
expected Borexino sensitivity



Atmospheric Neutrinos

are produced in decay cascades initiated by collisions of cosmic rays (p, He, ...) with the Earth's atmosphere

arise mainly from pion decay, and the subsequent muon decay
$\pi \to \mu + \nu_\mu$ and $\mu \to e + \nu_e + \nu_\mu$
one expects roughly two ν_μ per ν_e

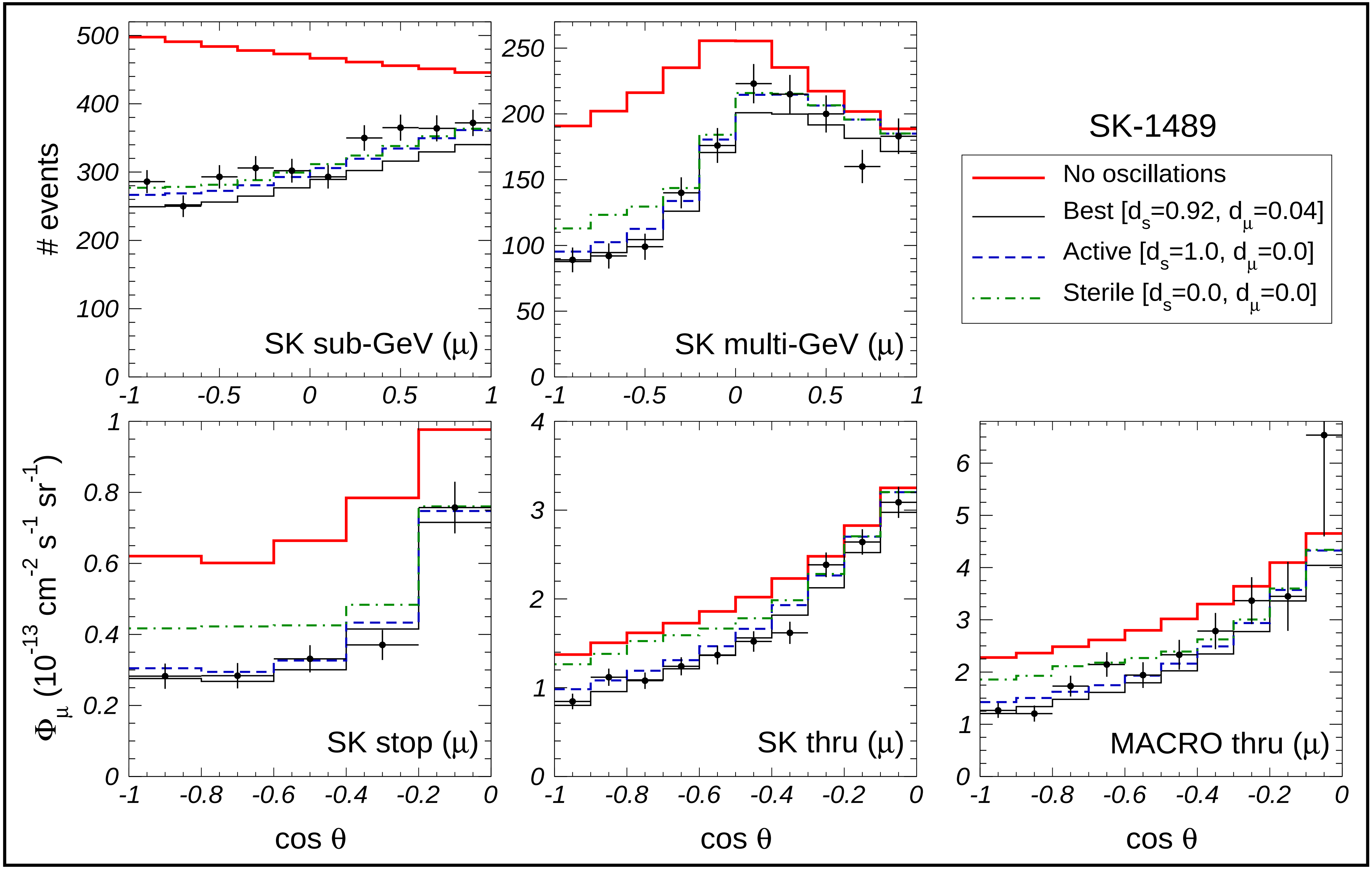


The ν_e flux measured by underground experiments is in agreement with the predictions.

However, these experiments observe a strong deficit of ν_μ's, especially of those coming from "below"

Atmospheric zenith distribution

Maltoni, Schwetz, Tortola and JV PRD67 (2003) 013011



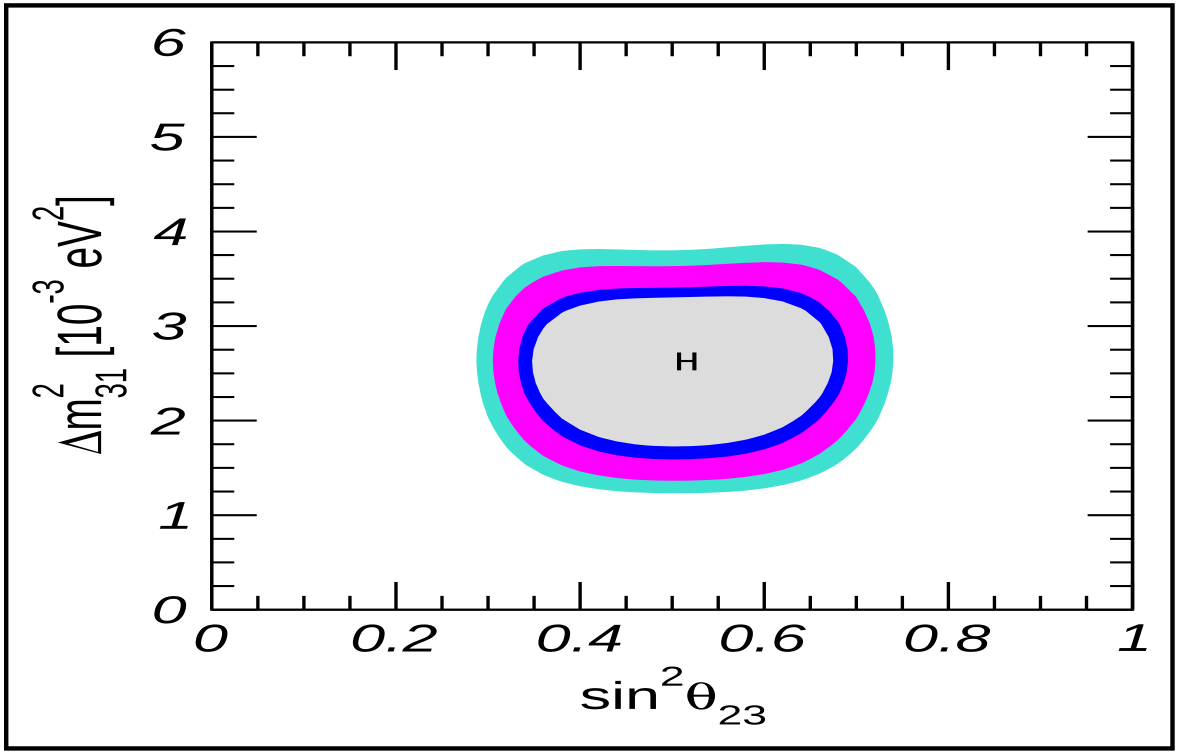
atmospheric neutrino parameters-1

- sterility rejection

Maltoni et al PRD67 (2003) 013011
hep-ph/0207227

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

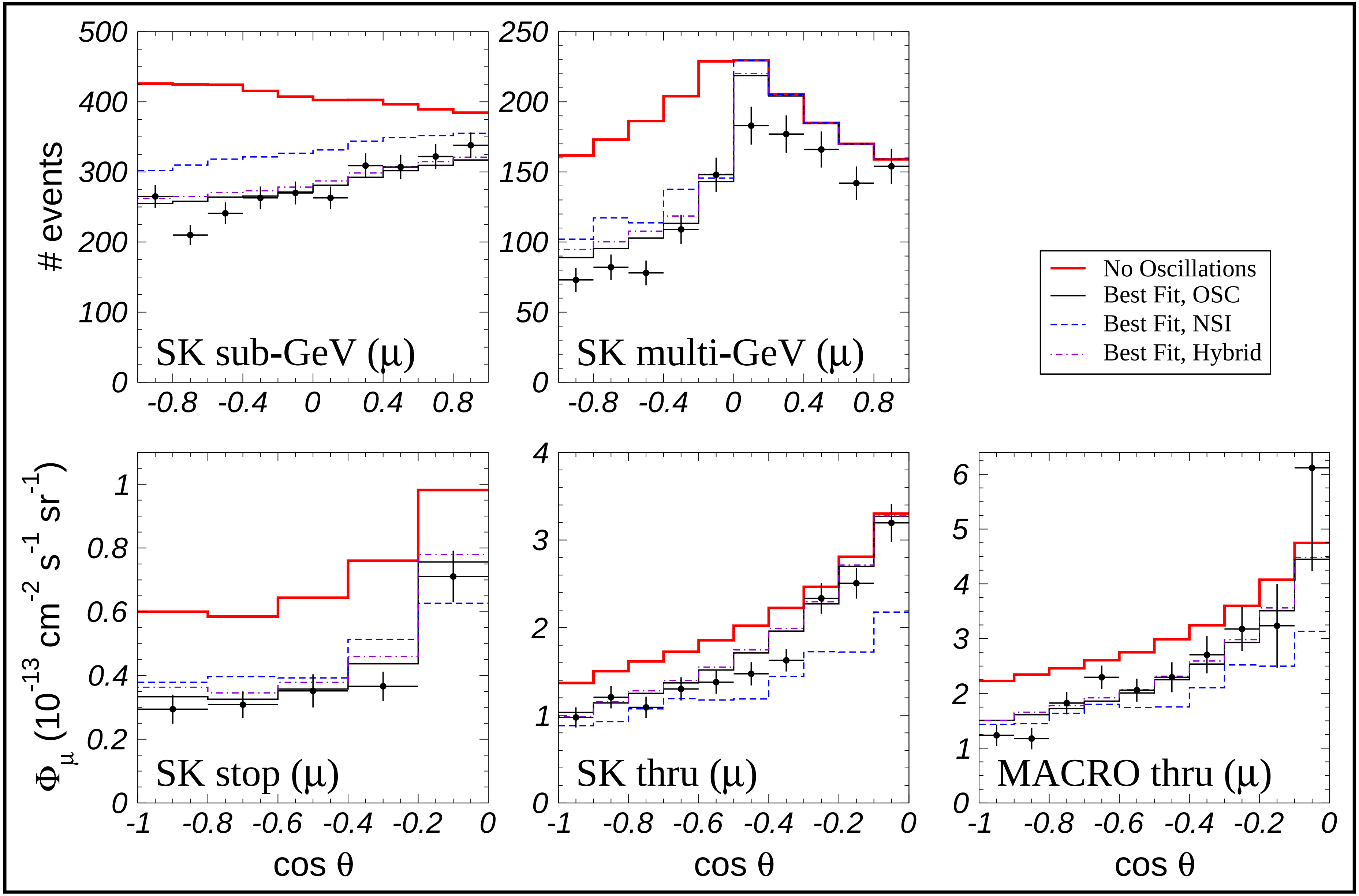
$\Delta m^2_{\rm ATM} = 2.5 \times 10^{-3}\ {\rm eV}^2$



light-dark or normal/inverted symmetry

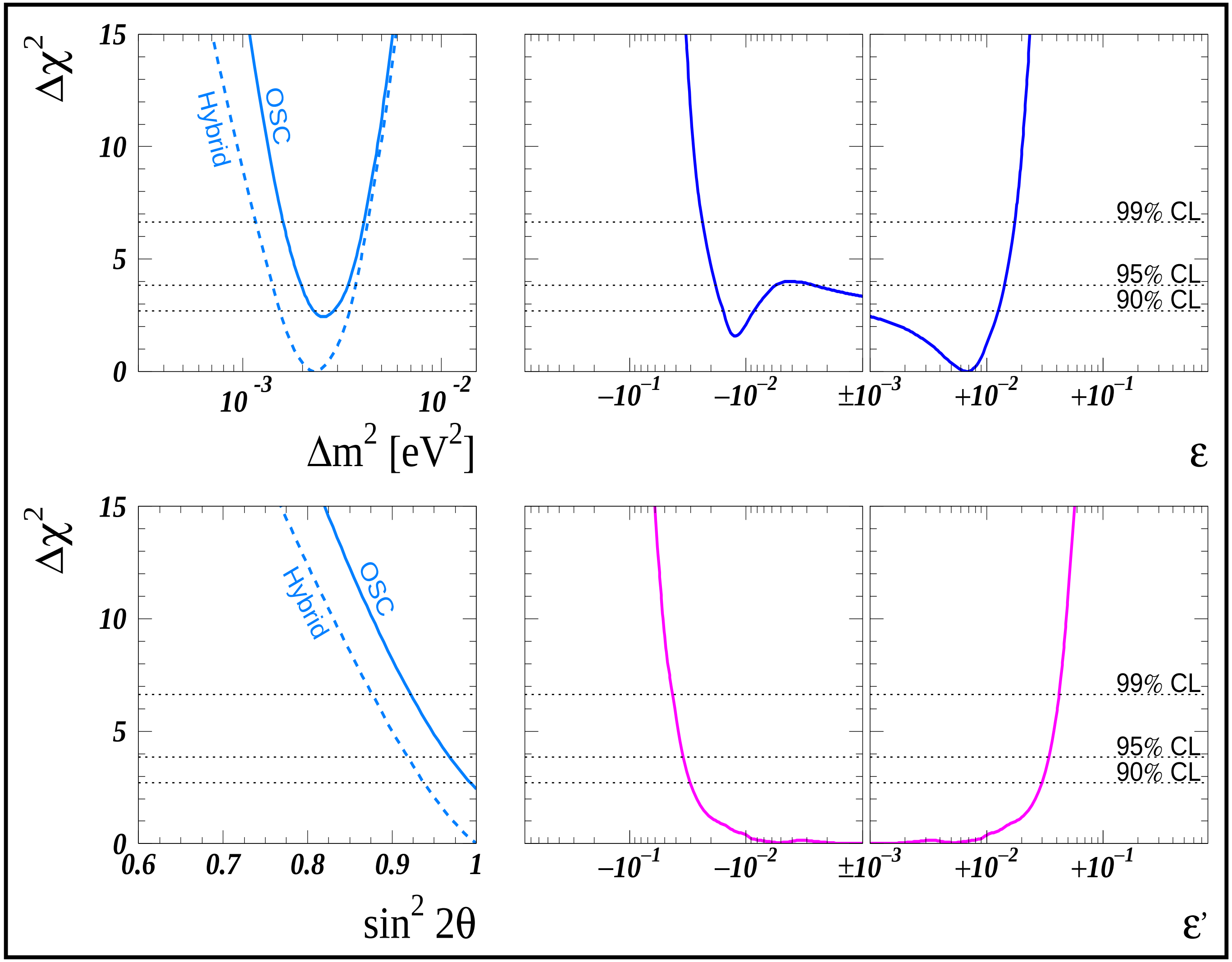
How robust are atmospheric oscillations?

NSI give excellent CONTAINED atm-fit, Gonzalez-Garcia et al, PRL82 (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

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)

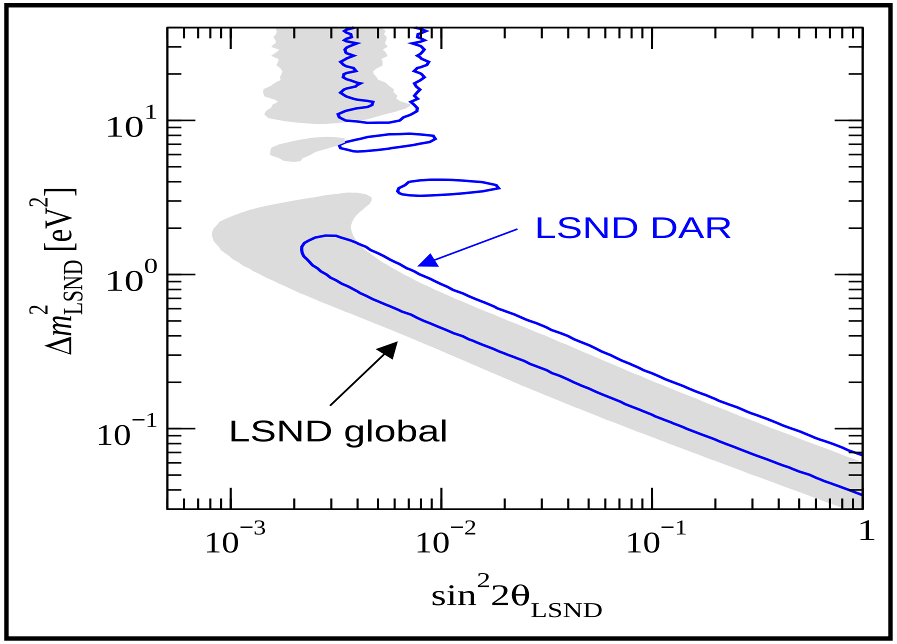
Peltoniemi, Tommasini and JV, PLB298 (1993) 383

Caldwell-Mohapatra PRD48 (1993) 325

barely possible at 3 σ

Maltoni et al NPB643 (2002) 321

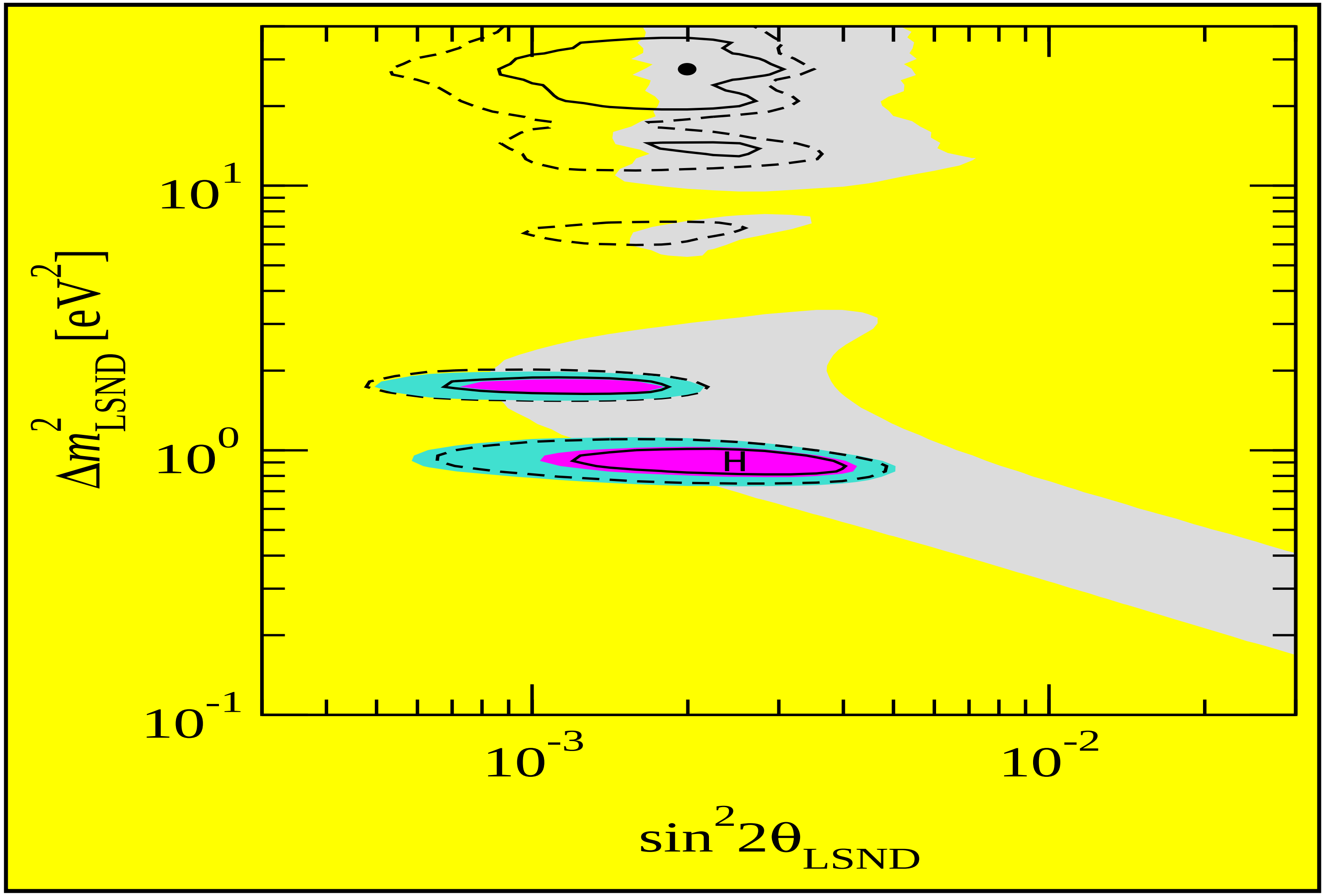
upd of PRD65 (2002) 093004



ATM

SOL

Cosmology closes in on 4-nu LSND interpretations



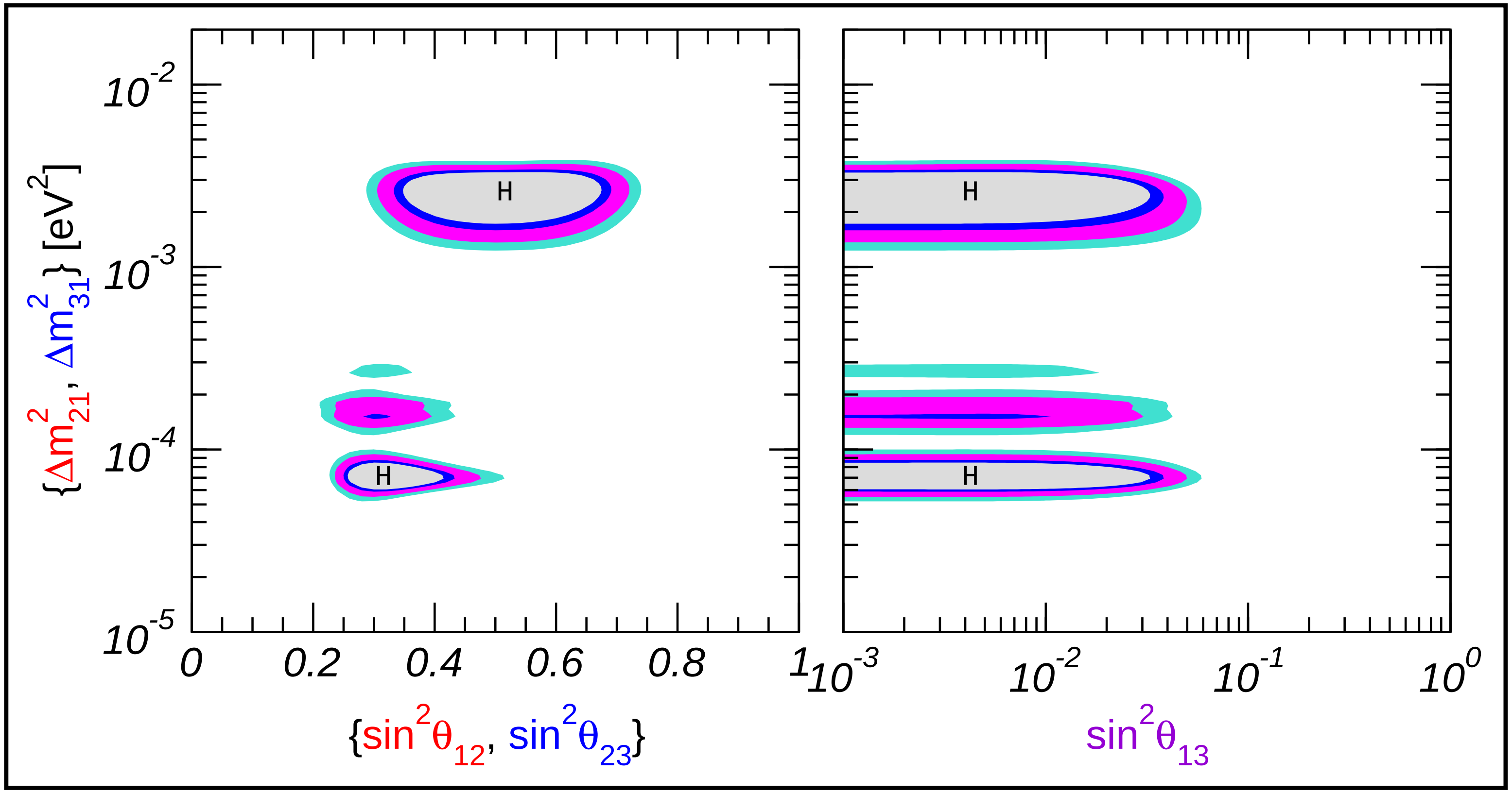
2df + WMAP + HST + SNIa

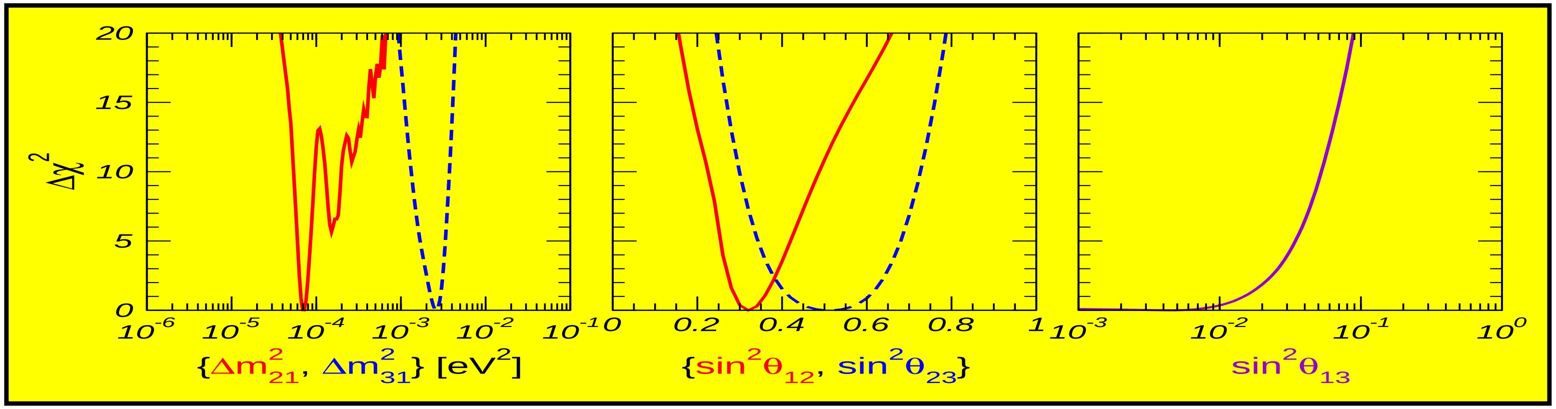
Schwetz et al hep-ph/0305312

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

Three neutrino parameters in a nut shell

upg of Maltoni et al, PRD67 (2003) 013011 & PRD 67 (2003) 093003, upd of PRD63 (2001) 033005





minimal set of basic parameters

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

  1 KM-like phase oscillations δ

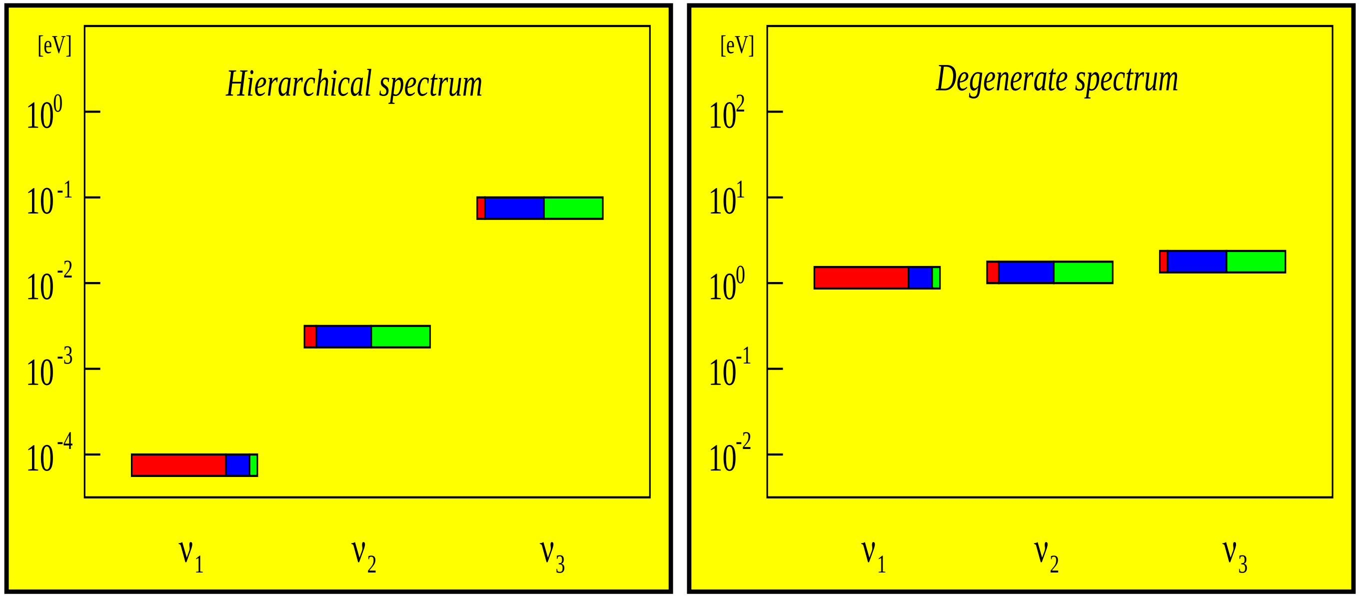
  2 new phases since Majorana mass terms not invariant under rephasings

  $\beta\beta_{0\nu}$ α , β

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

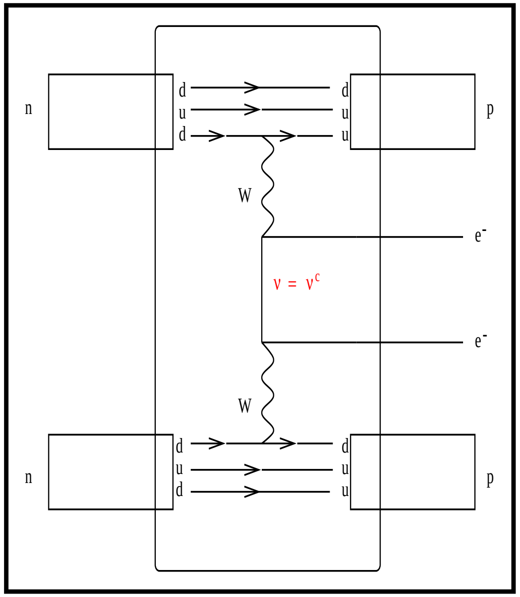
  both appear in leptogenesis

- 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



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

or

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

Schechter and JV, PRD22 (1980) 2227

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

far more angles θ_{ij} and phases ϕ_{ij} in seesaw schemes

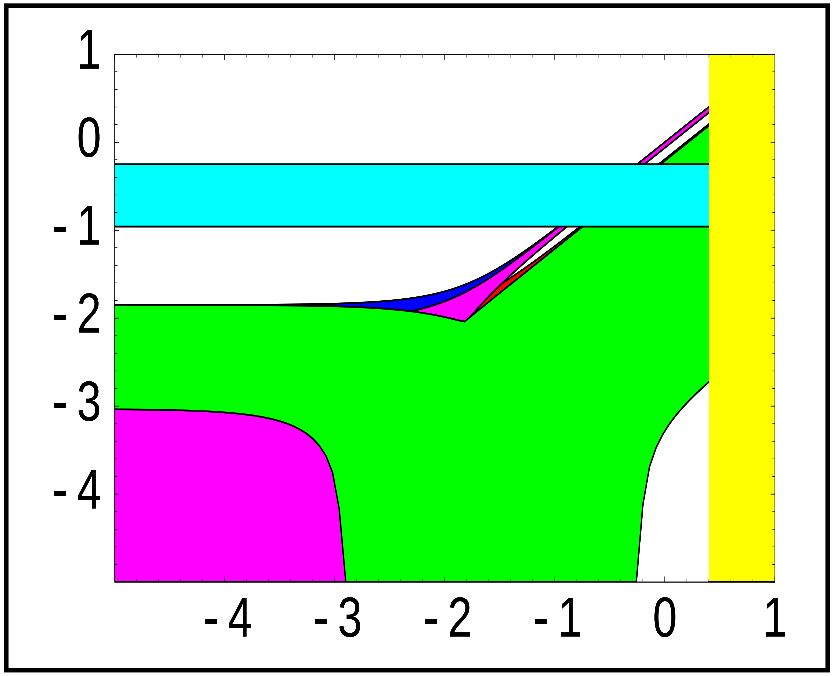
current laboratory tests of absolute neutrino mass

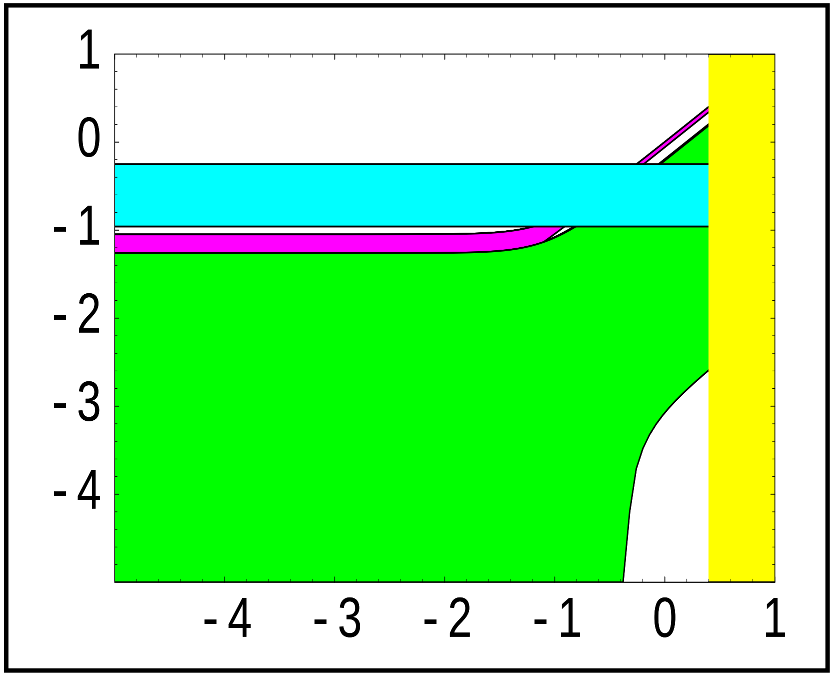
Current sol-atm, $\beta\beta_{0\nu}$ and Tritium sensitivities

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



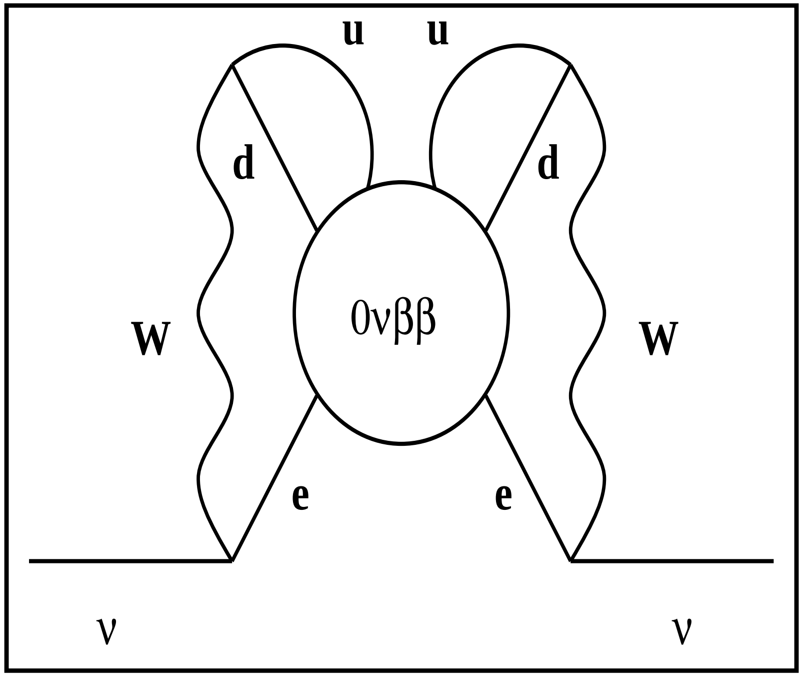


Relevance of $\beta\beta_{0\nu}$

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

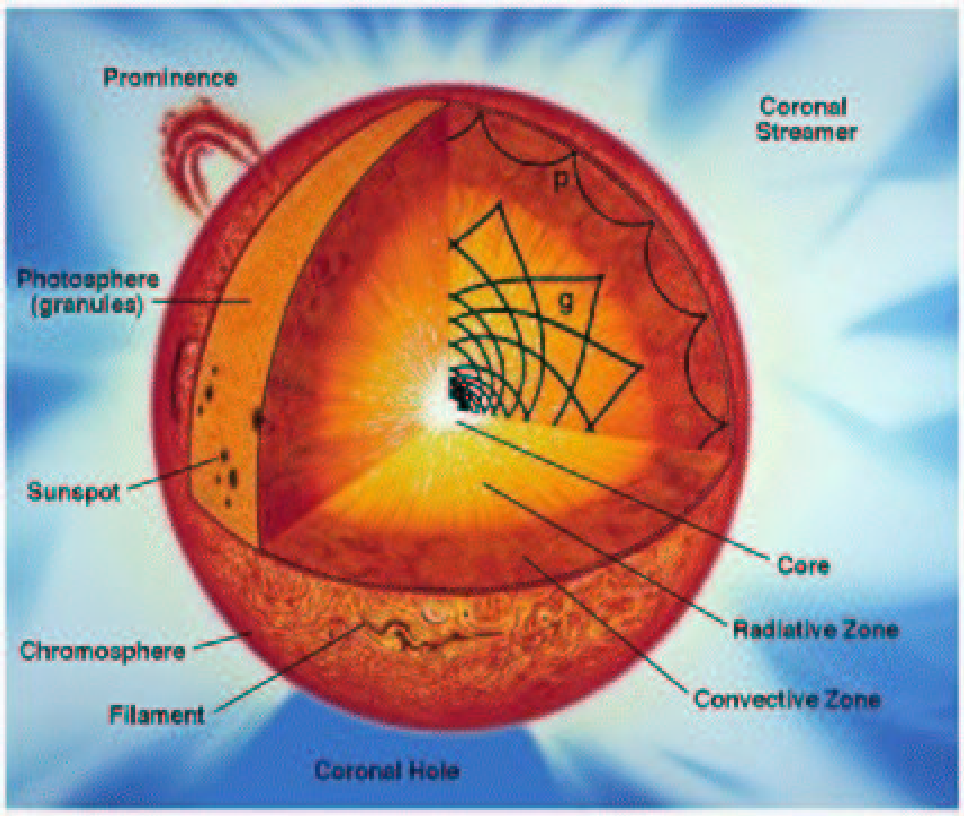
Schechter and JV, PRD **25** (1982) 2951

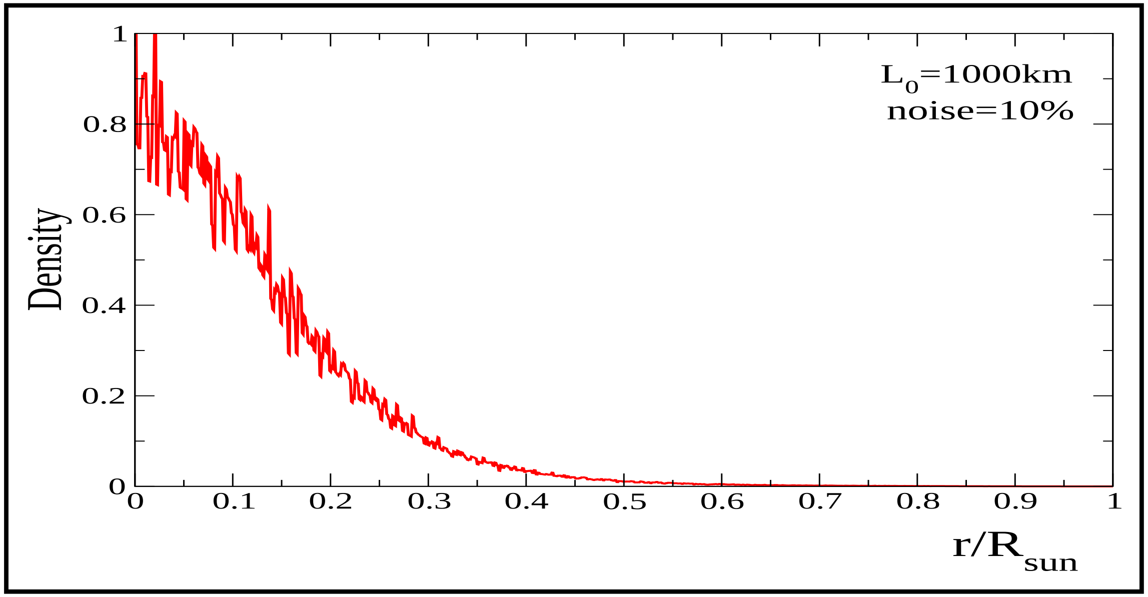
no such theorem for flavor violation!



Neutrinos as astro probe

neutrinos as a solar probe

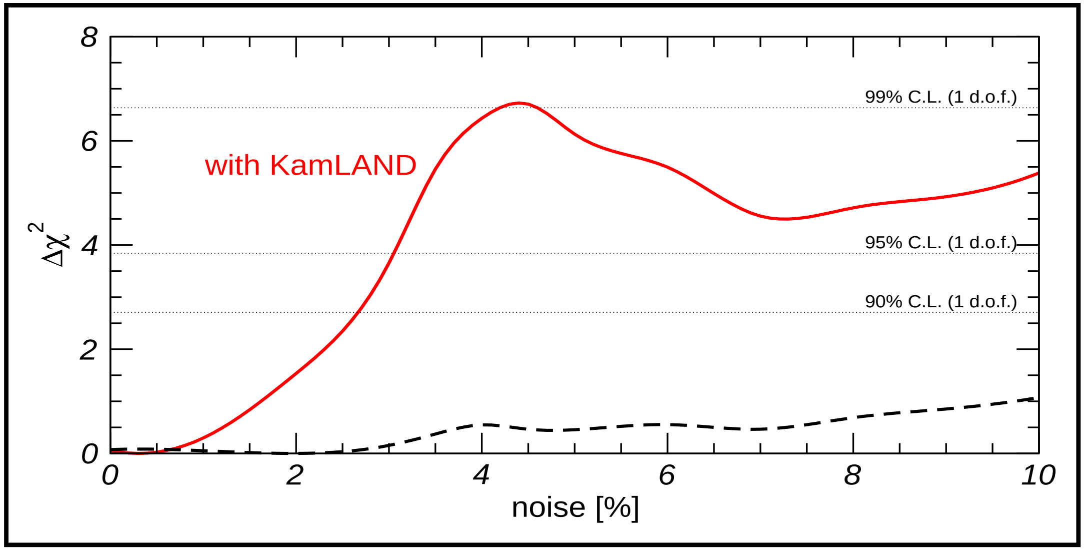




neutrinos as deep solar probe

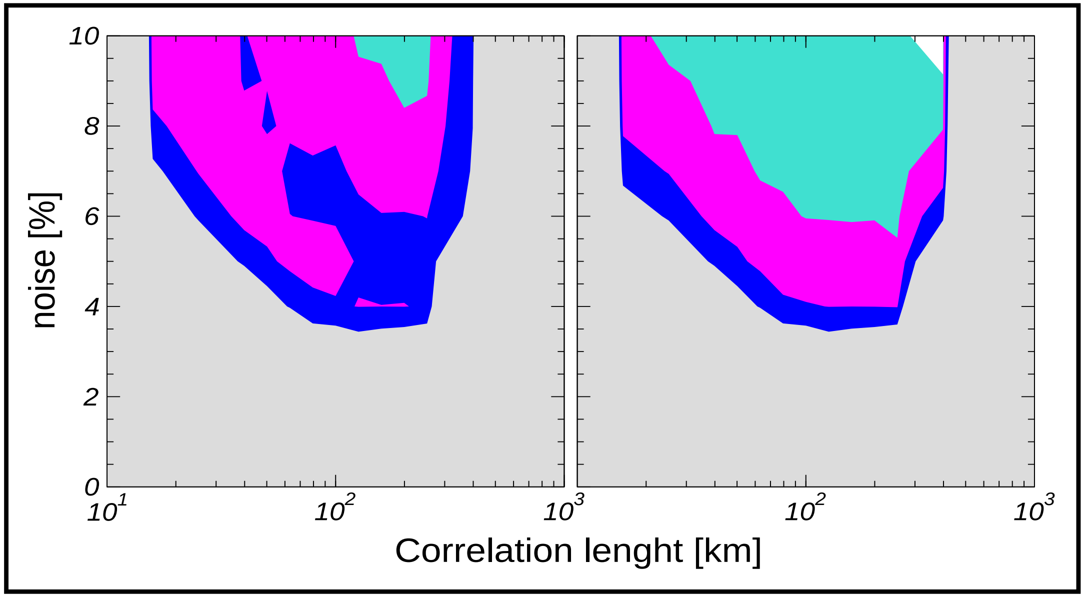
Burgess et al, Astrop. J. 588:L65,2003 hep-ph/0209094

$L_0 = 100\text{Km}$



KamLAND as solar probe

beyond helioseismology



free vs BFP

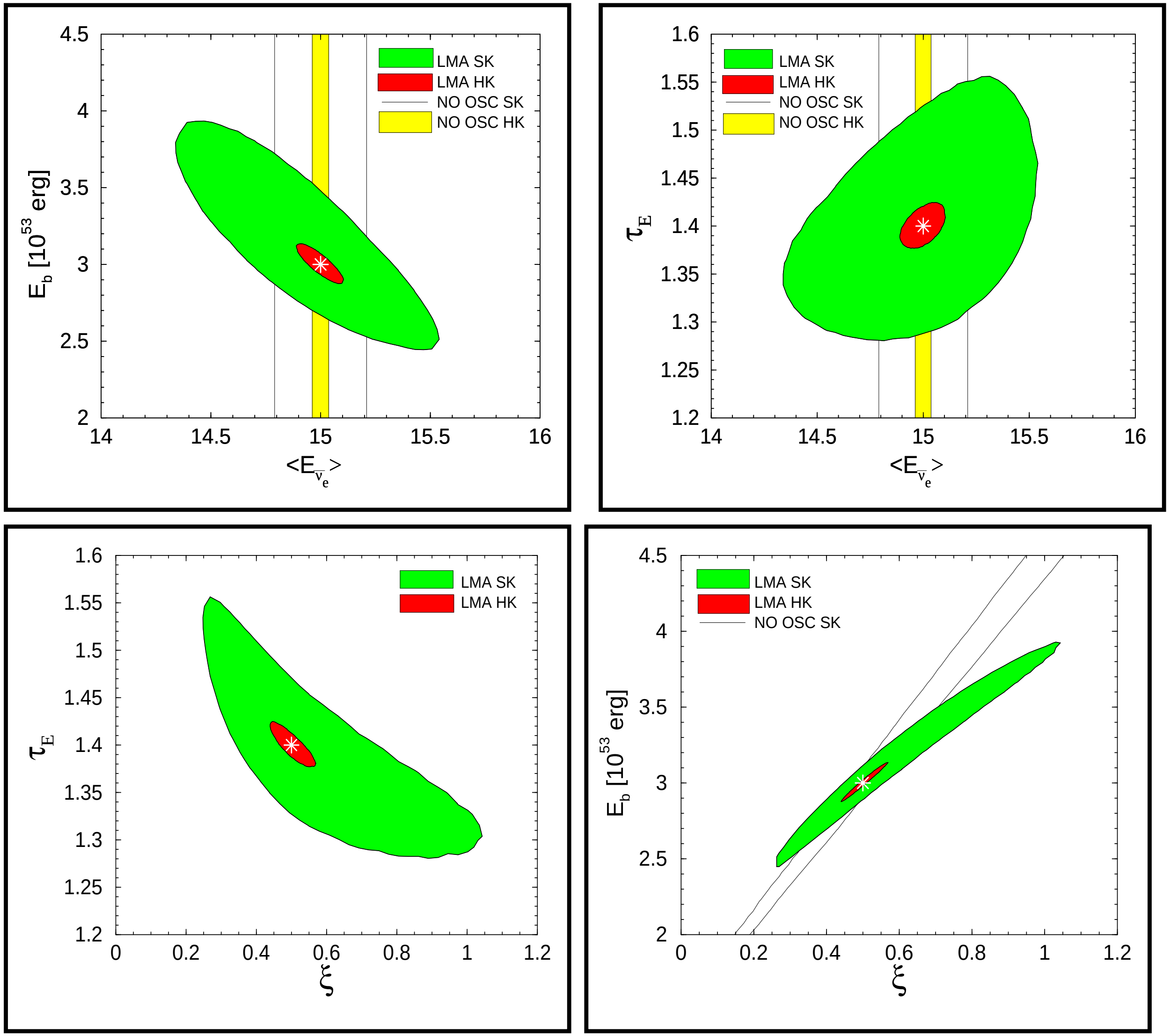
neutrinos as future Supernova probe

Minakata et al, PLB542 (2002) 239

with good info on neutrino properties the measurement of a large number of neutrinos from a future galactic supernova will give us important information the processes that lead to the stellar explosion

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

see also Barger, Marfatia & Wood



improved supernova parameter determination

Probing θ_{13}?

through Leptonic CP Violation

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

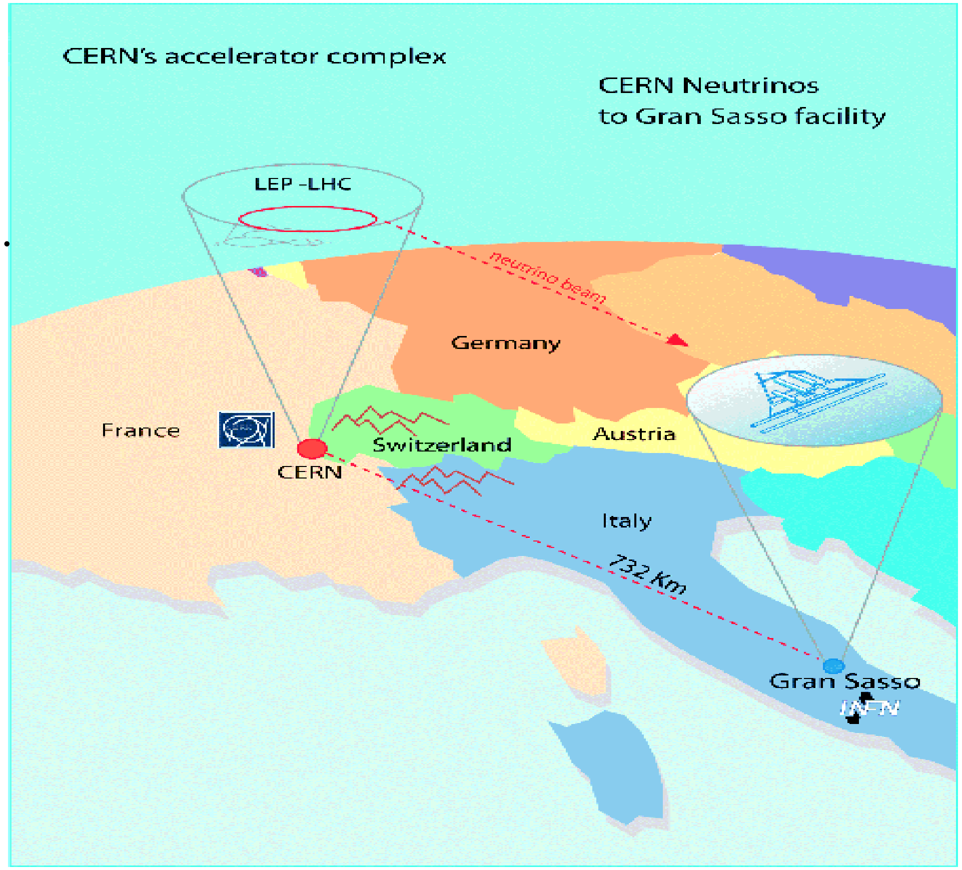
Schechter and JV, PRD **21** (1980) 309

Try harder

Neutrino Factories

will probe s_{13} and δ

Cervera et al, De Rujula, Gavela, Hernandez
Freund, Huber, Lindner, Albright et al, Barger et al, ..



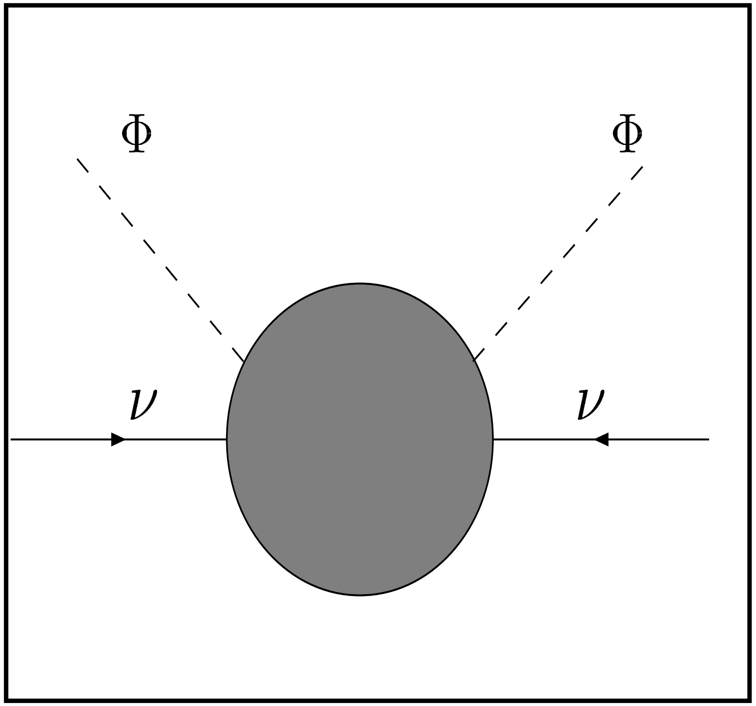
provided Non-Standard nu-Intercations (NSI) can be rejected ...

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

removing seesaw myths...

Schechter, JV, PRD22, 2227 (1980) & D25, 774 (1982)

- B-L scale need not be high, nor gauged
- light nu-masses need not scale as m_f^2
- lepton mixing matrix K need not be unitary

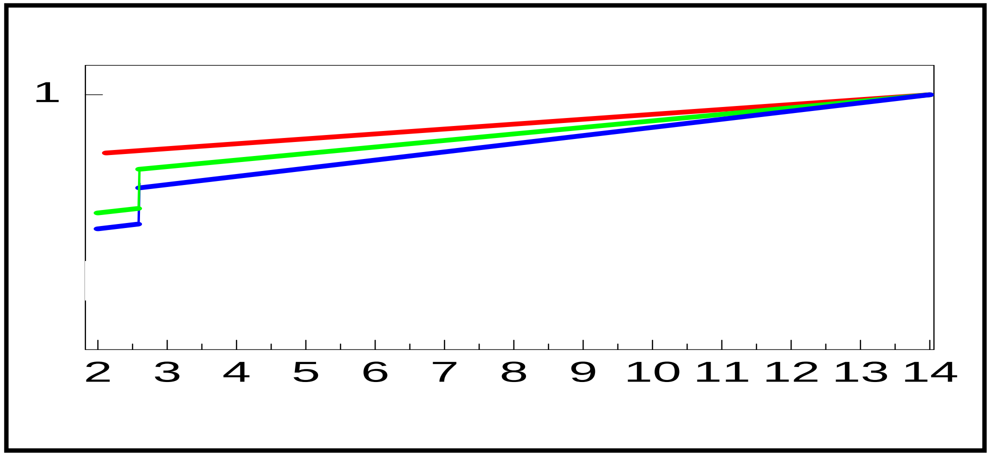
  and may be decomposed as $K = (K_L, K_H)$ where K_L describes the light states while K_H describes doublet-singlet mixing involved in leptogenesis
- $\nu_i \nu_j Z$ vertex need not be diagonal described by $P_{LL} = (K^\dagger K)_{LL}$
- the number of singlet neutrinos need not equal 3

  the (3, 1) model has 2 massless neutrinosand forms a basic starting point for the direct hierarchy spectrum Schechter & JV, PRD21 (1980) 309
- gauge-induced NSI need not have negligible strength

neutrino unification: large-scale seesaw

- Babu, Ma and Valle, PLB552 (2003) 207

m_ν/eV vs. Log M_X/GeV



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 $\delta = \pi/2$ (maximal CP violation) see also Grimus & Lavoura

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

observable Lepton Flavor Violation $B(\tau \to \mu\gamma) \sim 10^{-6}$

SUSY origin for neutrino mass

spontaneous RPV ●

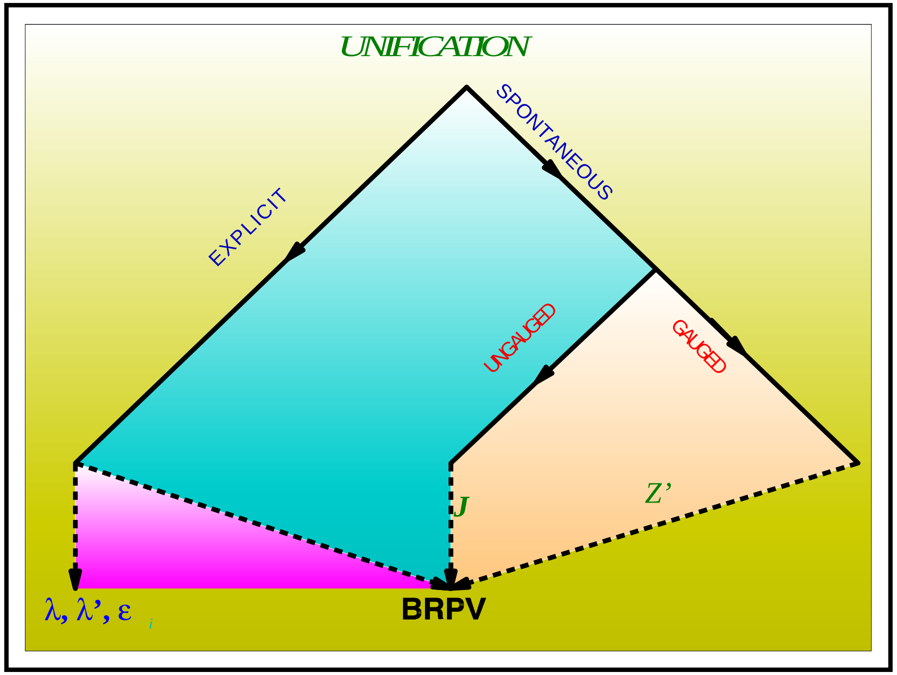
singlet sneutrino vev

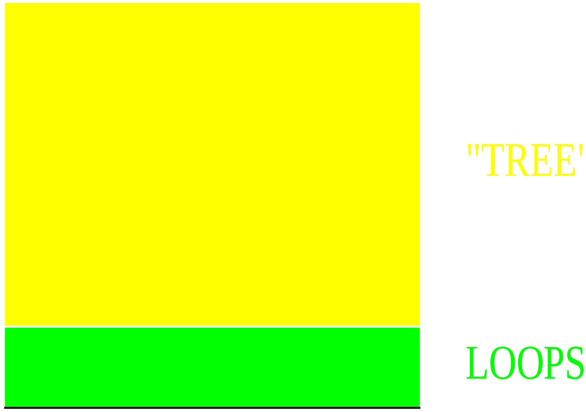
Masiero & JV, PLB251 (1990) 273

attractive dynamics and systematic parametrization of RPV

spontaneous RPV $\to$ effective bilinear RPV

hybrid neutrino masses

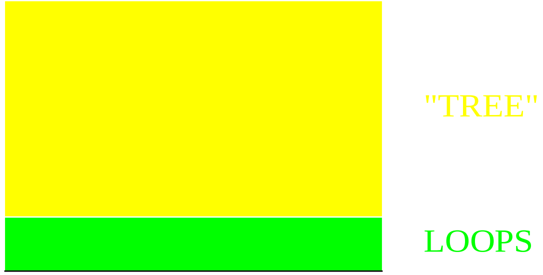




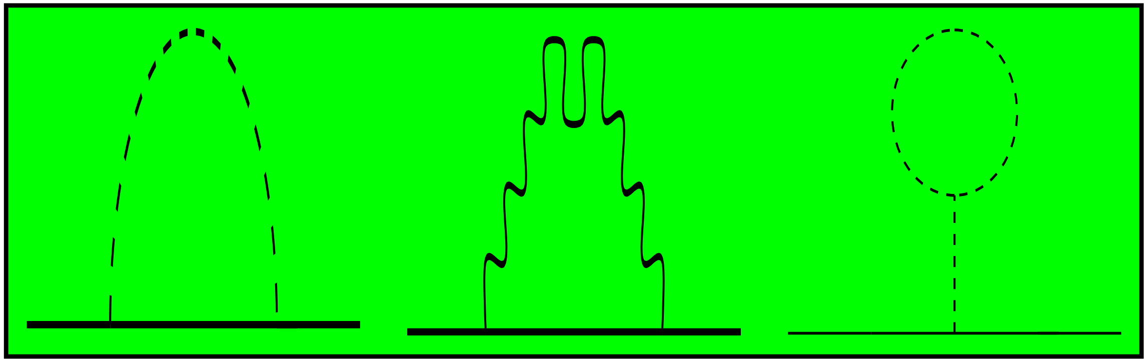
bilinear R parity violation: weak-scale seesaw

- Diaz, Hirsch, Porod, Romao and JV, PRD68 (2003) 013009 [hep-ph/0302021]; PRD62 (2000) 113008 [Err-ibid. D65 (2002) 119901]; PRD61 (2000) 071703

- weak-scale seesaw atm scale

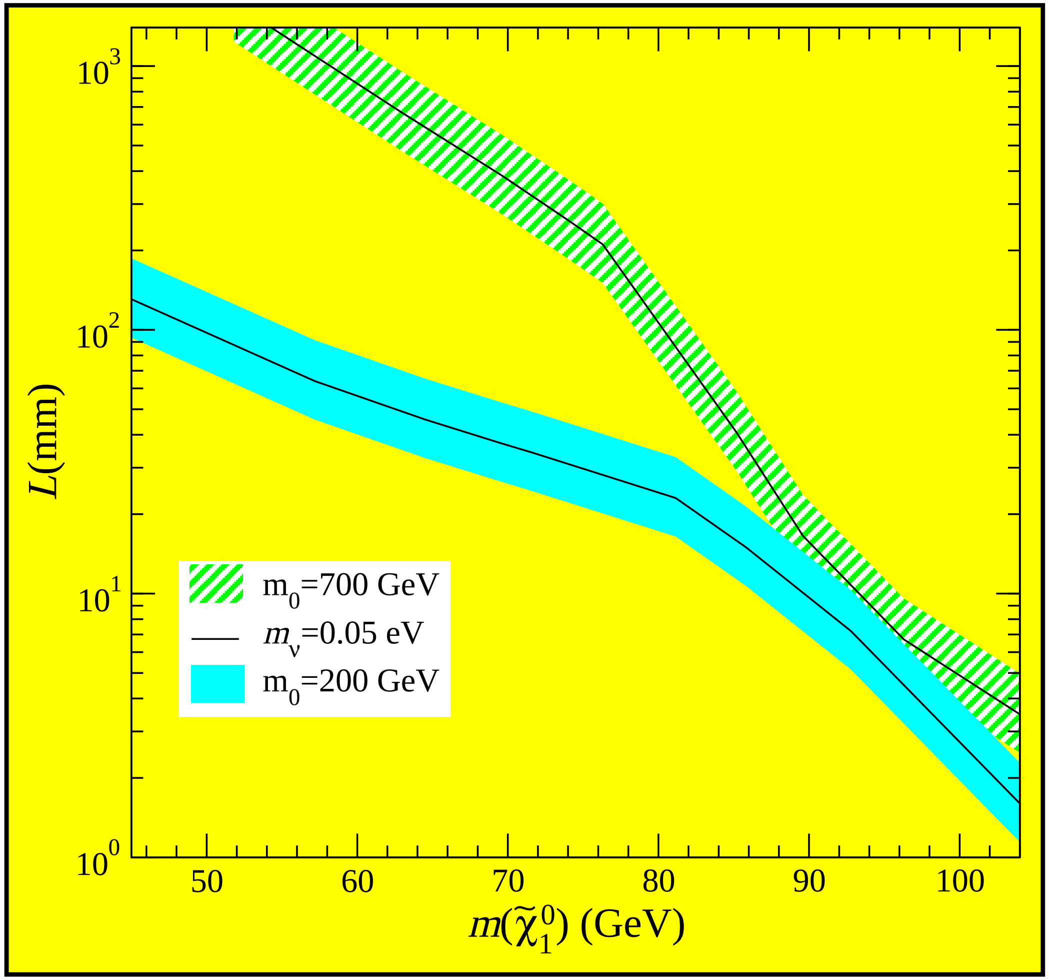


- radiative nu-masses solar scale



LSP decay length [cm]: BRPV

- from Magro et al hep-ph/0304232; Bartl et al NPB 600 (2001) 39



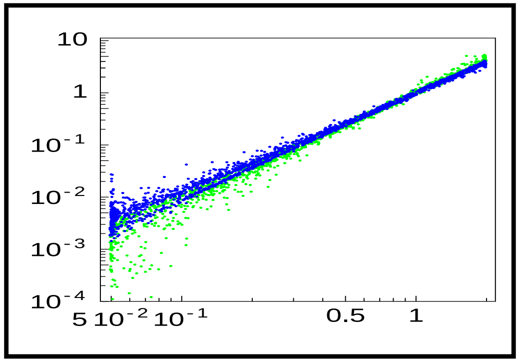
Mukhopadhyaya, Roy & Vissani; Chun & Lee; Choi et al; Datta et al

ANY charged SUSY particles can be the LSP

neutrino mixing angles as RPV ratios

Martin Hirsch's talk

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

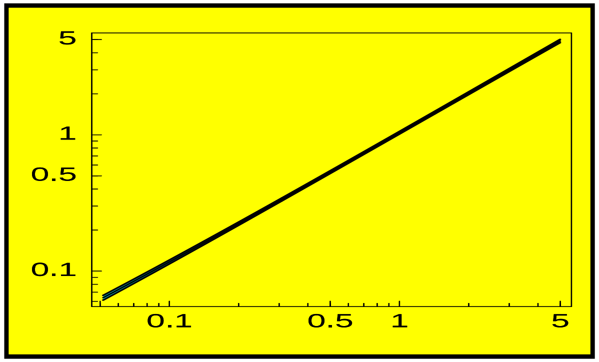


$\tan^2_{23}$ vs (Λ_2/Λ_3)

- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004



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

- stop decays

Restrepo, Porod & Valle, PRD64 (2001) 055011

- slepton decays

M. Hirsch et al, PRD66 (2002) 095006

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?

http://alpha.ific.uv.es/˜valle/talks/talks.html

more refs on spontaneous RPV

- pre-LEP

Aulakh, Mohapatra 83; Hall, Suzuki 84 Ross & JV 85; Ellis et al 85; Santamaria & JV 87 Lee 85 ...

post-LEP

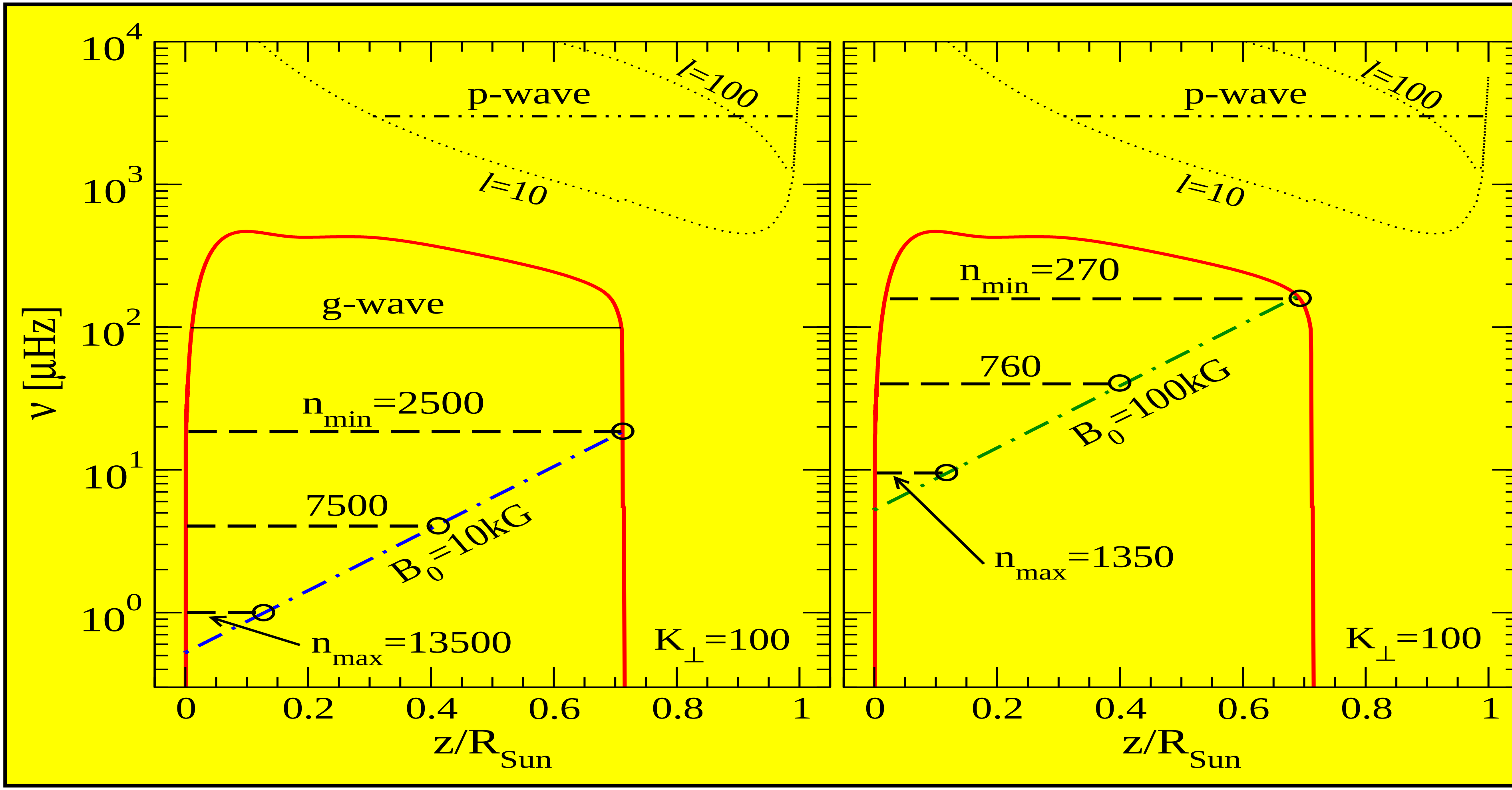
Romão, Santos, JV Phys. Lett. B **288** (1992) 311. M. C. Gonzalez-Garcia, J. C. Romao and J. W. Valle, Nucl. Phys. B **391**, 100 (1993). J. C. Romao, A. Ioannisian and J. W. Valle, Phys. Rev. D **55** (1997) 427 [hep-ph/9607401]. M. Shiraishi, I. Umemura and K. Yamamoto, Phys. Lett. B **313** (1993) 89.

A. S. Joshipura and S. K. Vempati, Phys. Rev. D **60**, 111303 (1999) [hep-ph/9903435]. R. Kitano and K. y. Oda, Phys. Rev. D **61** (2000) 113001 [hep-ph/9911327]. D. Suematsu, Phys. Lett. B **506** (2001) 131

M. Frank and K. Huitu, Phys. Rev. D **64** (2001) 095015

origin for solar density fluctuations

Burgess et al, astro-ph/0304462

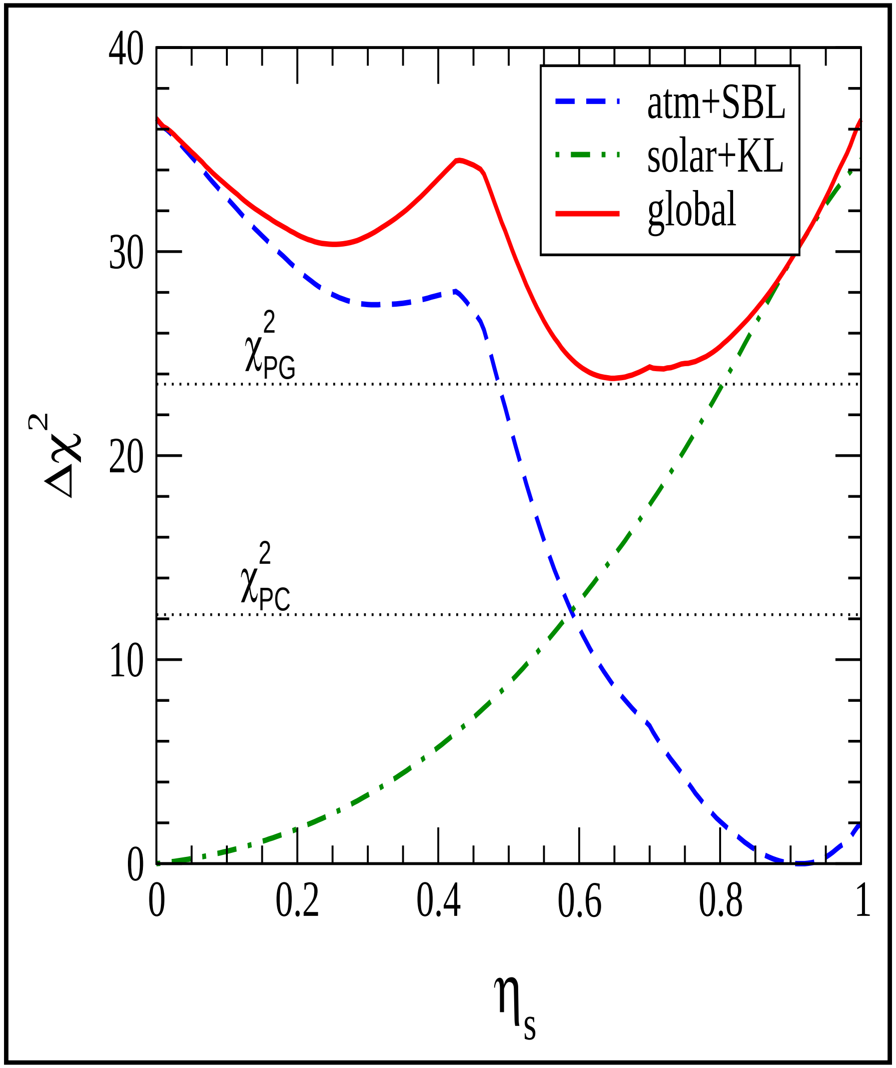


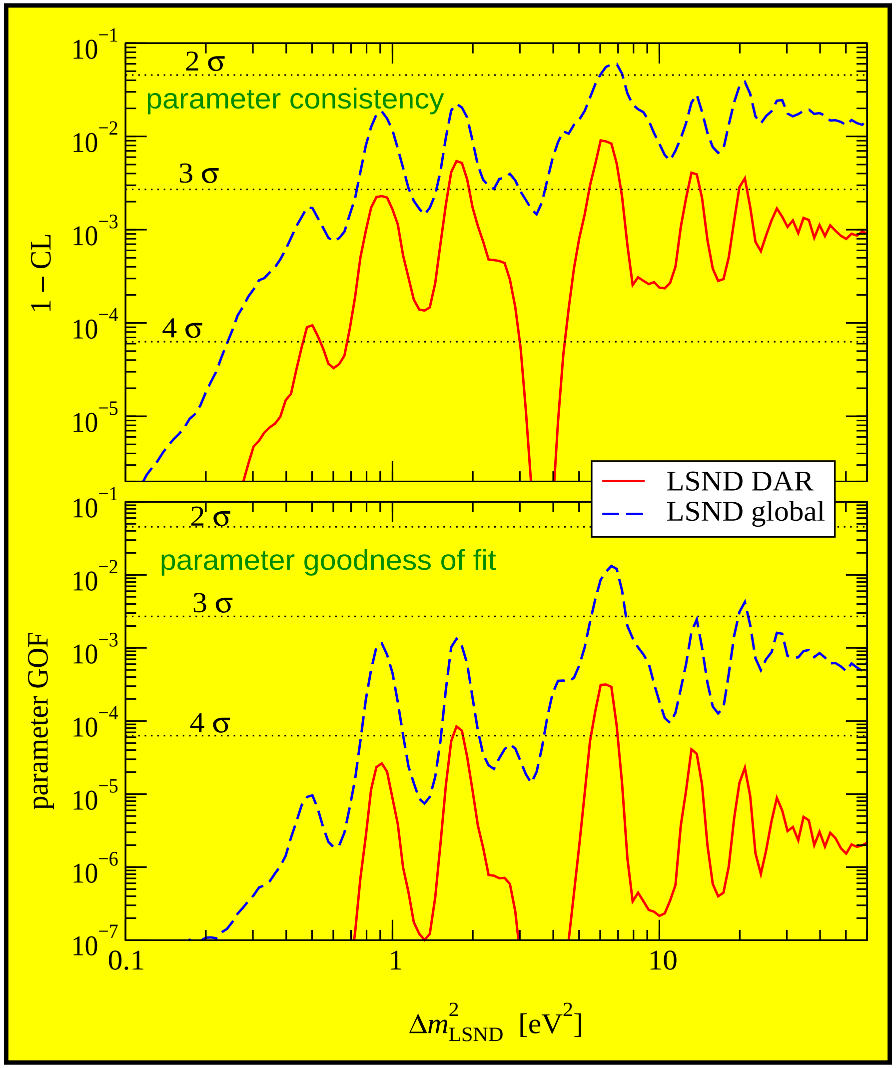
4-nus do not really fit LSND with the rest

-

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

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

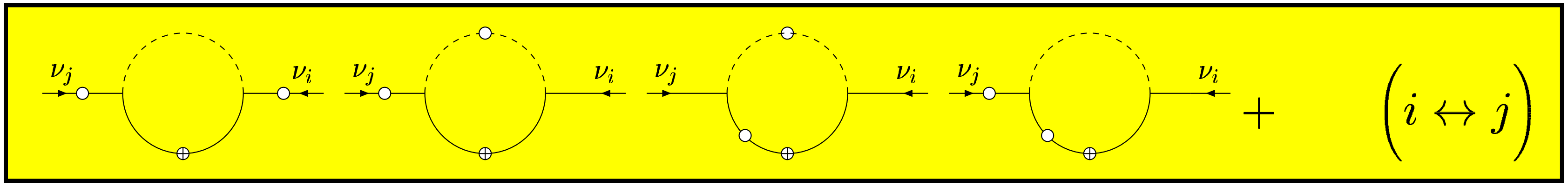


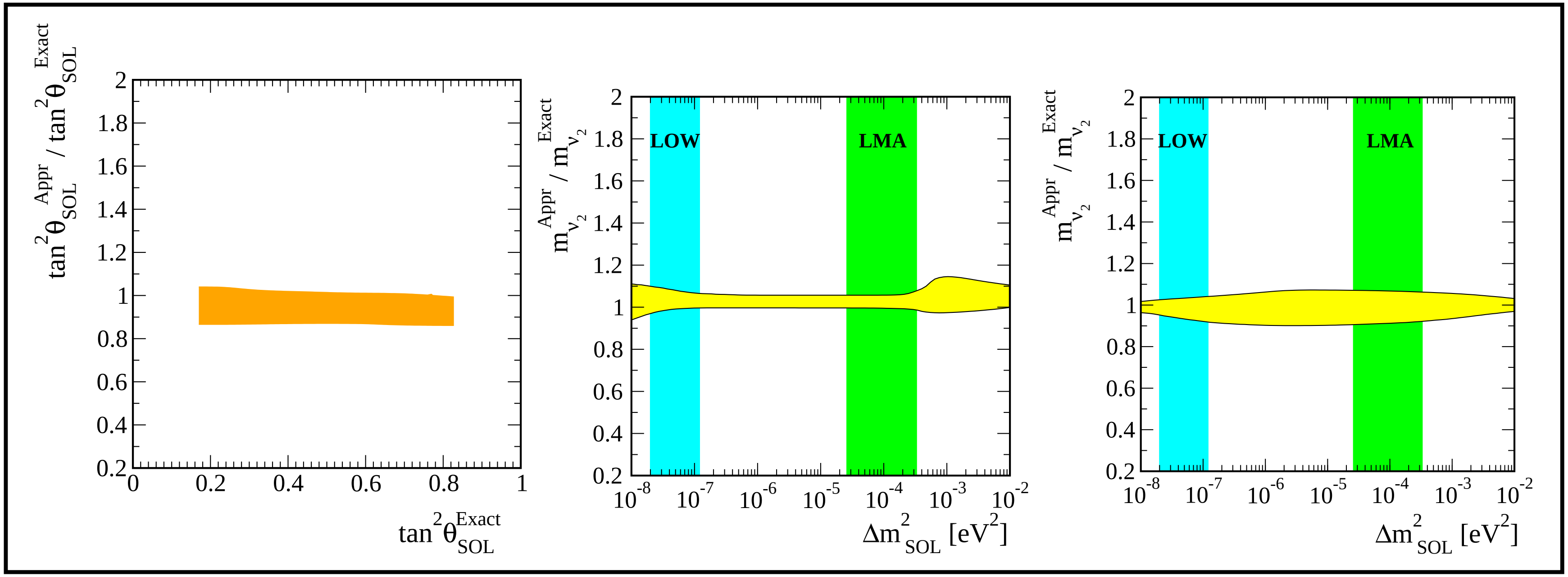


Pas & Weiler

solar mass loops: analytical vs numerical

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

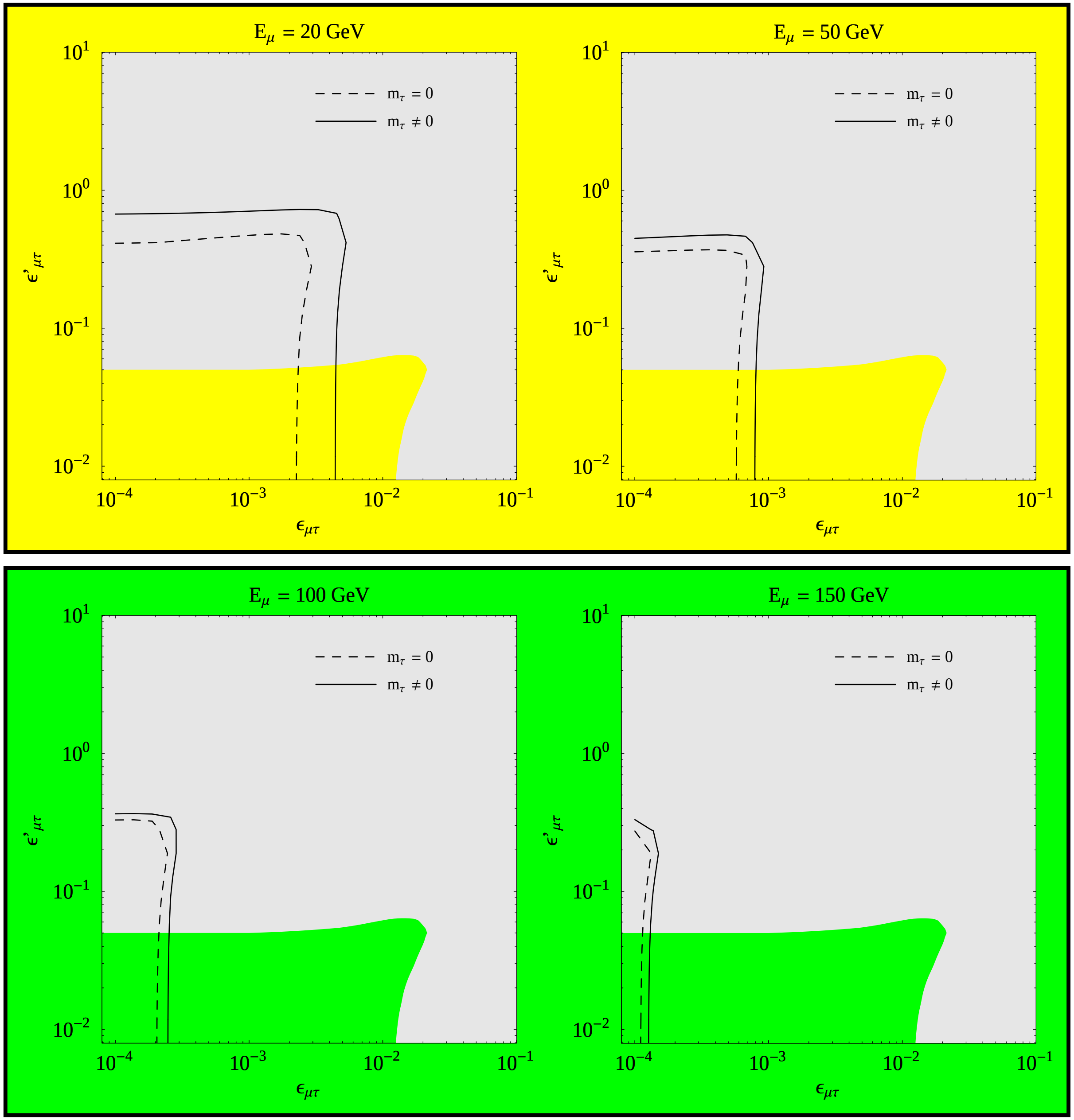




Improved FC-tests at NuFact

Huber & JV PLB523 (2001) 151

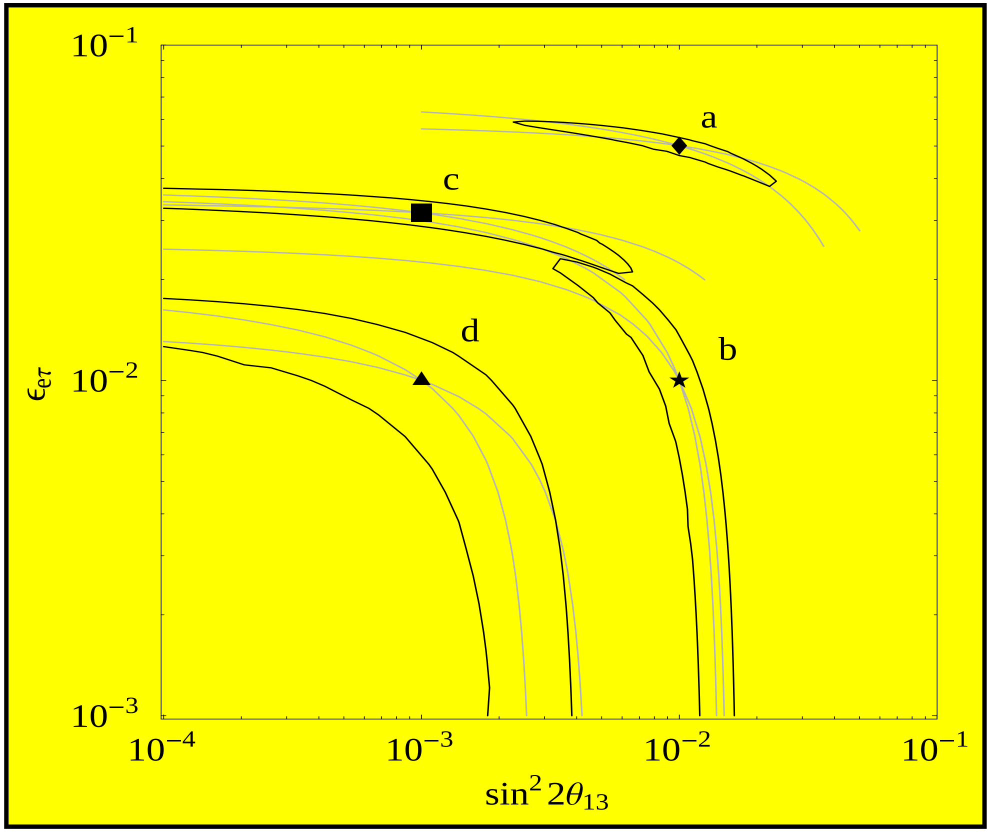
10 kt detector, 0.33 ν_τ detection eff above 4 GeV; need no tau charge id



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)



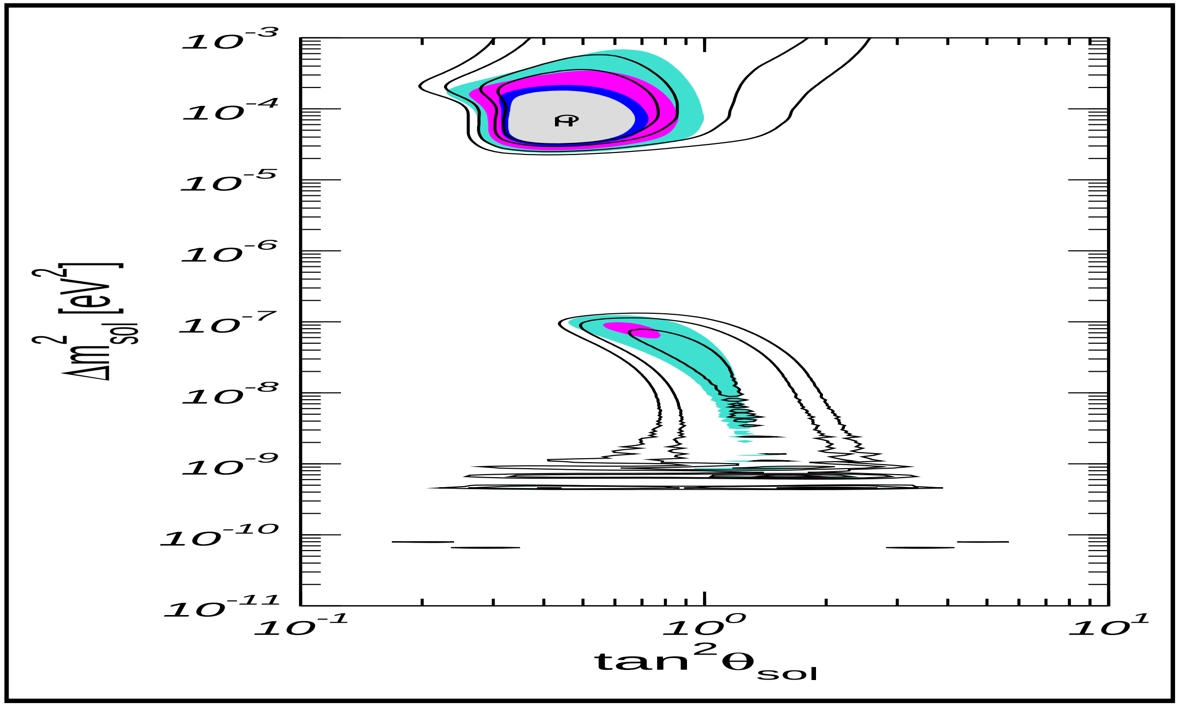
near-site programme essential

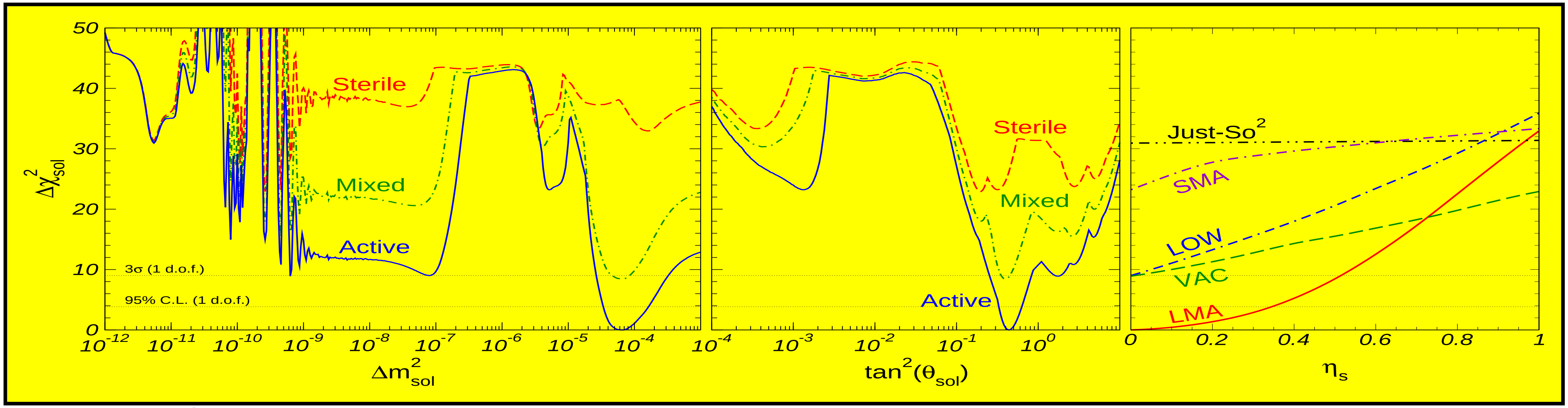
2×10^{20} mu/yr/polarity $\times$ 5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

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

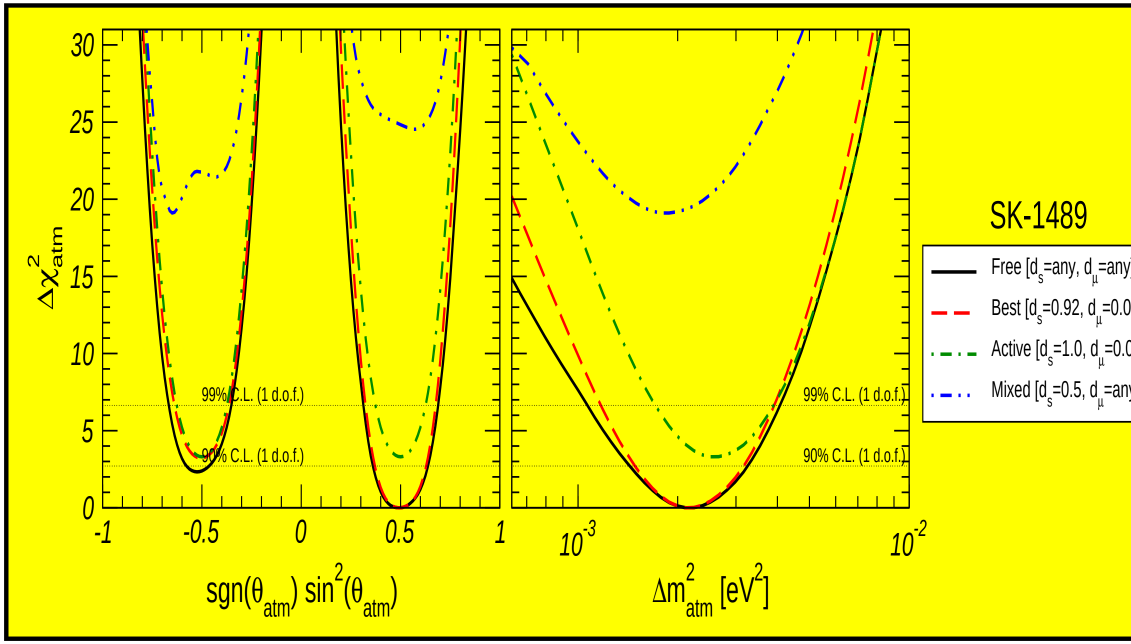




atmospheric neutrino parameters-2

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

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



higher sterility rejection