"Neutrino physics after KamLAND"

J. W. F. Valle

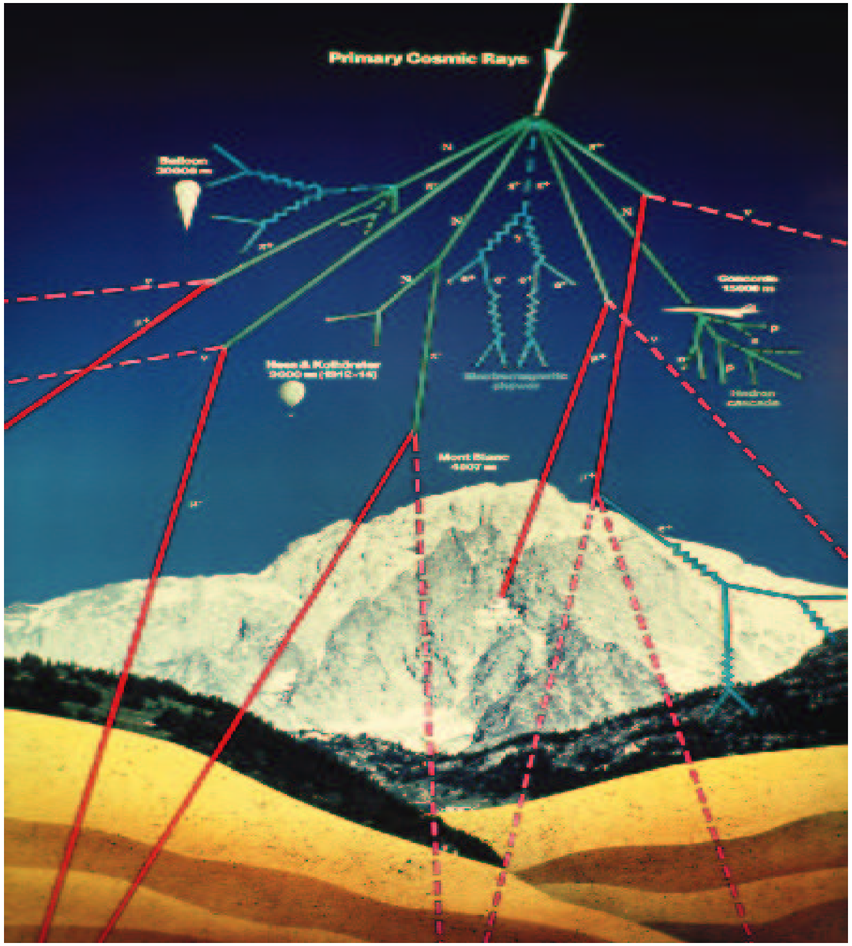
IFIC-CSIC/U. Valencia

Based on review
Neutrino properties before and after KamLAND
S. Pakvasa and JV hep-ph/0301061

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



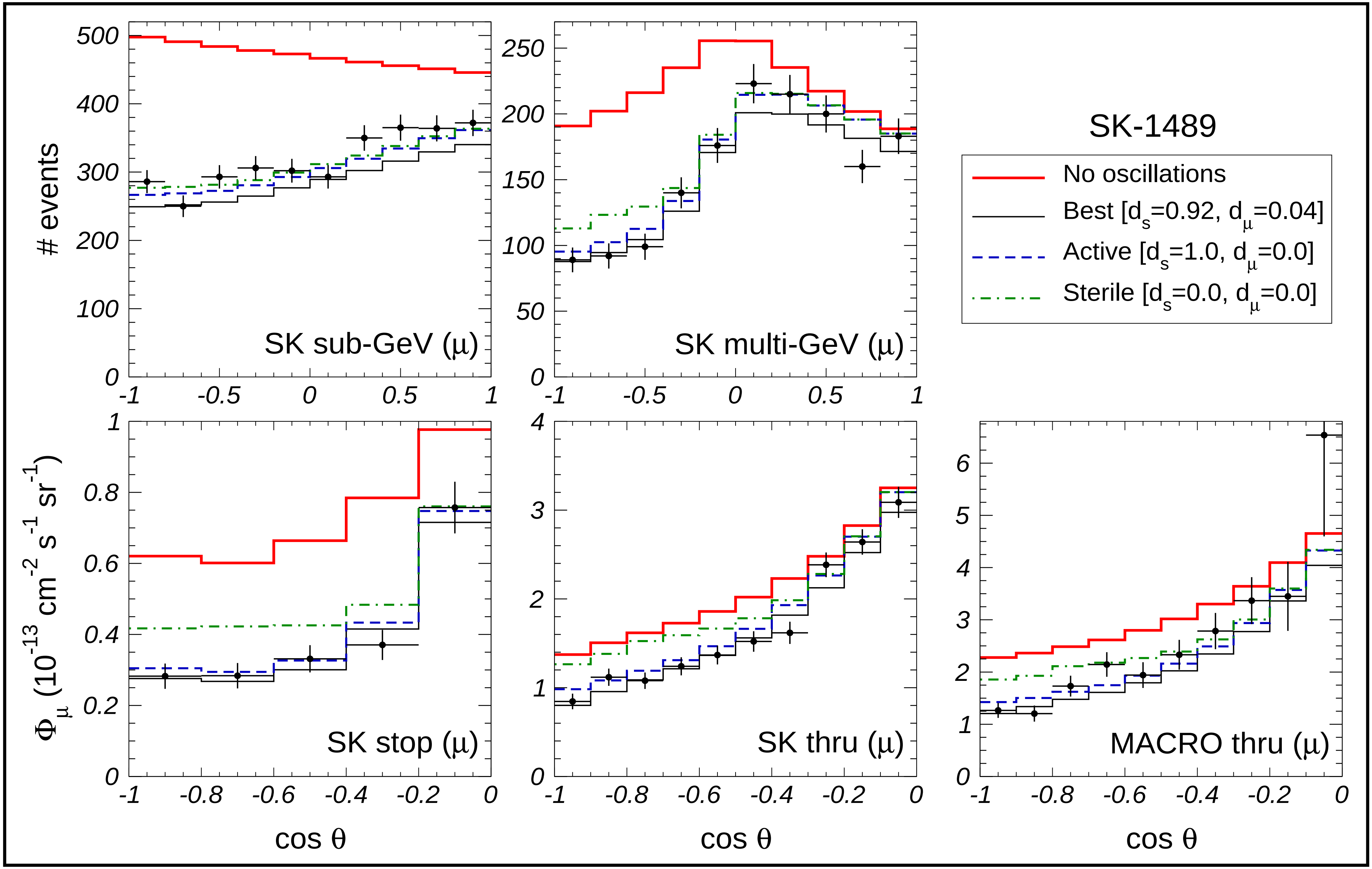
The ν_e flux measured by underground experiments is in agreement with the predictions.

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

deficit is very well explained by the $\nu_\mu \to \nu_\tau$ OSCILLLATION hypothesis

Atmospheric zenith distribution

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

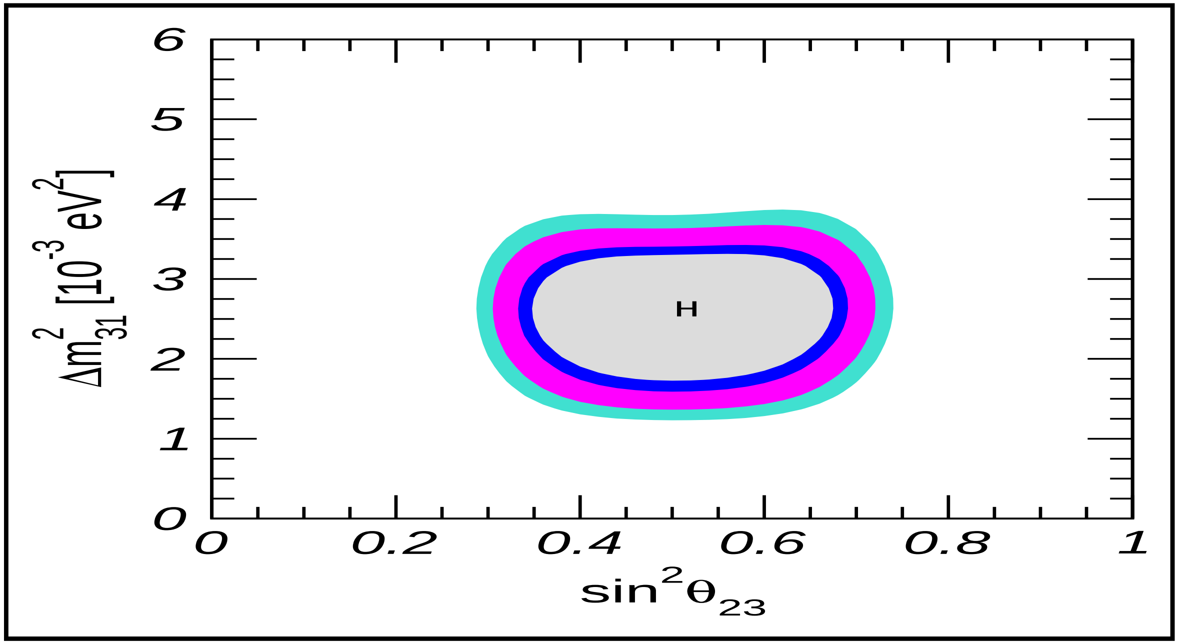


atmospheric neutrinos

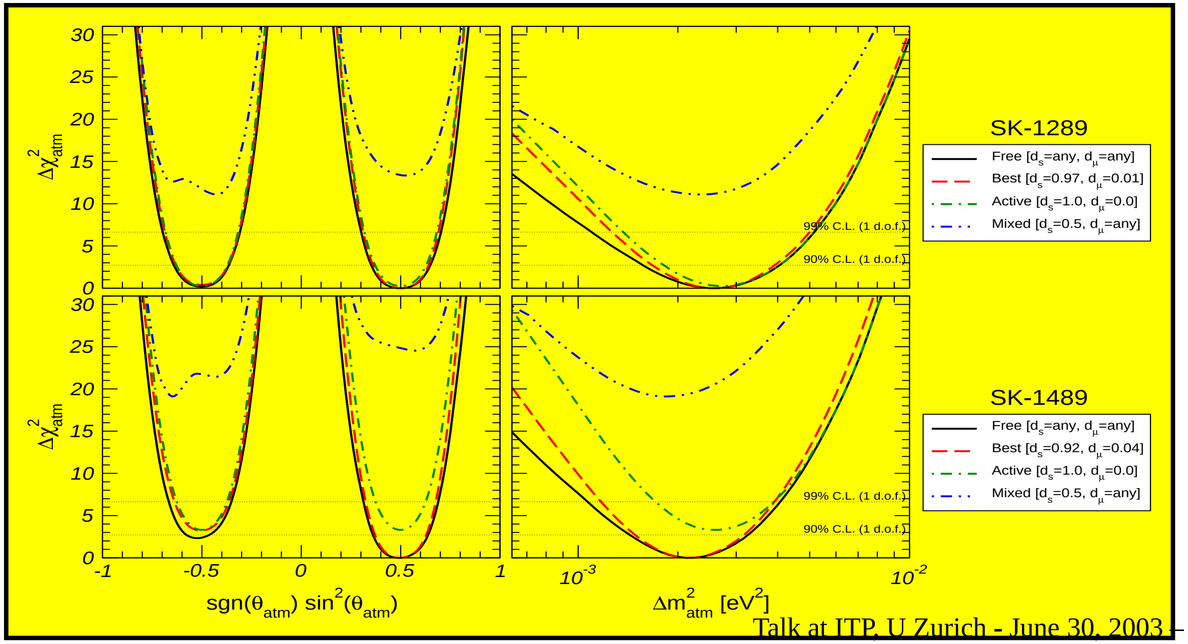
Maltoni et al PRD67 (2003) 013011

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

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

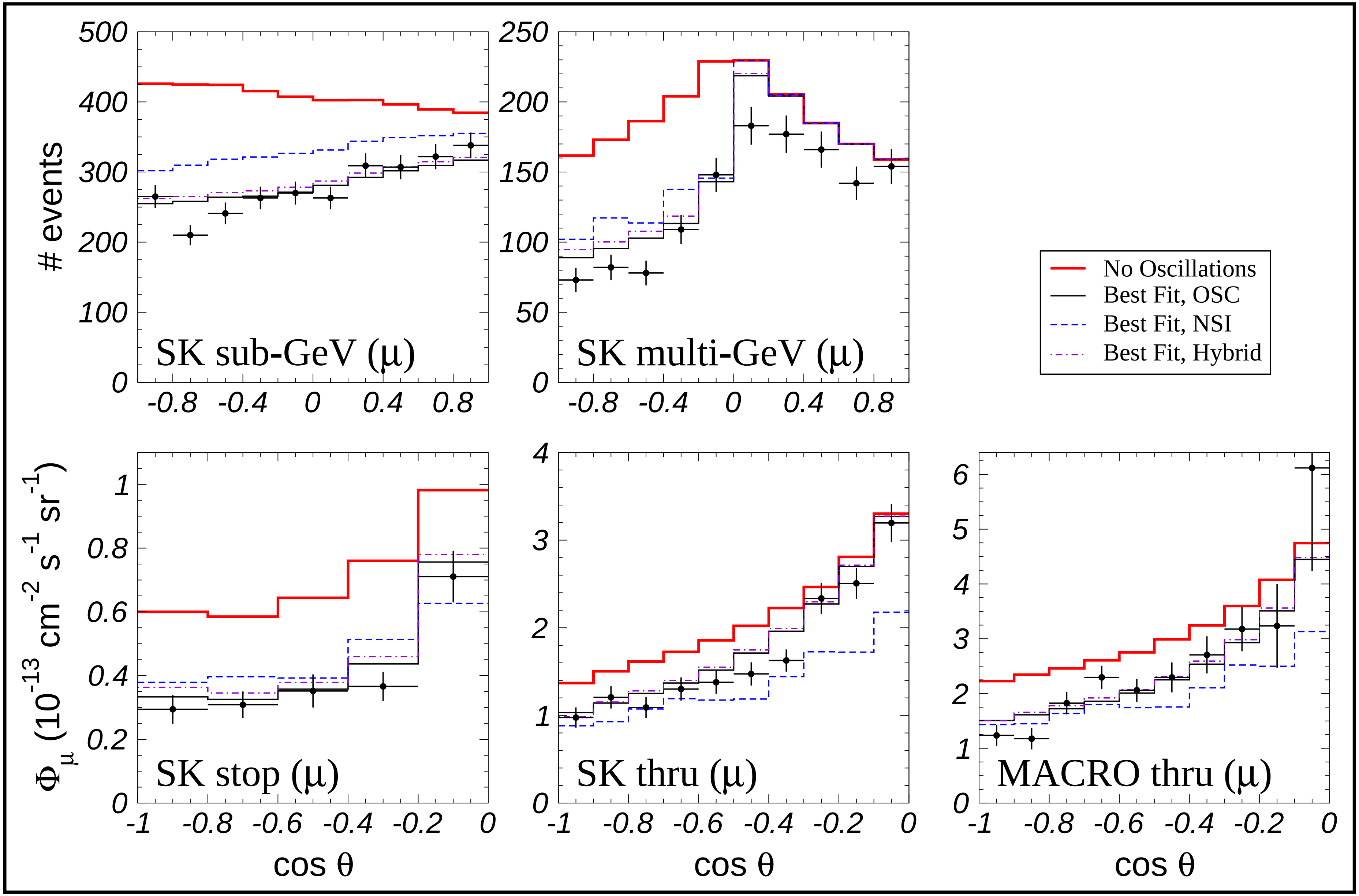


higher sterility rejection



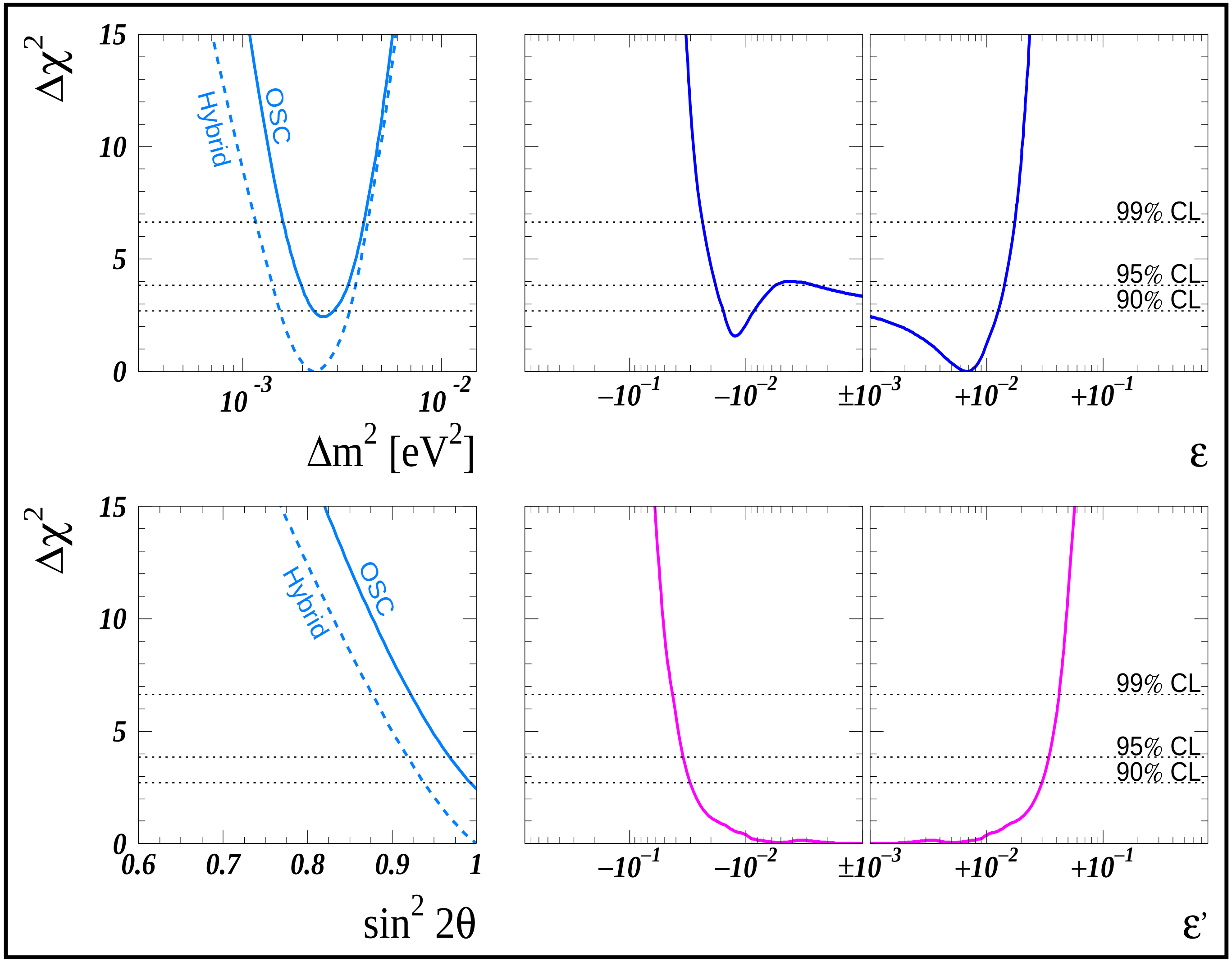
How robust are atmospheric oscillations?

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



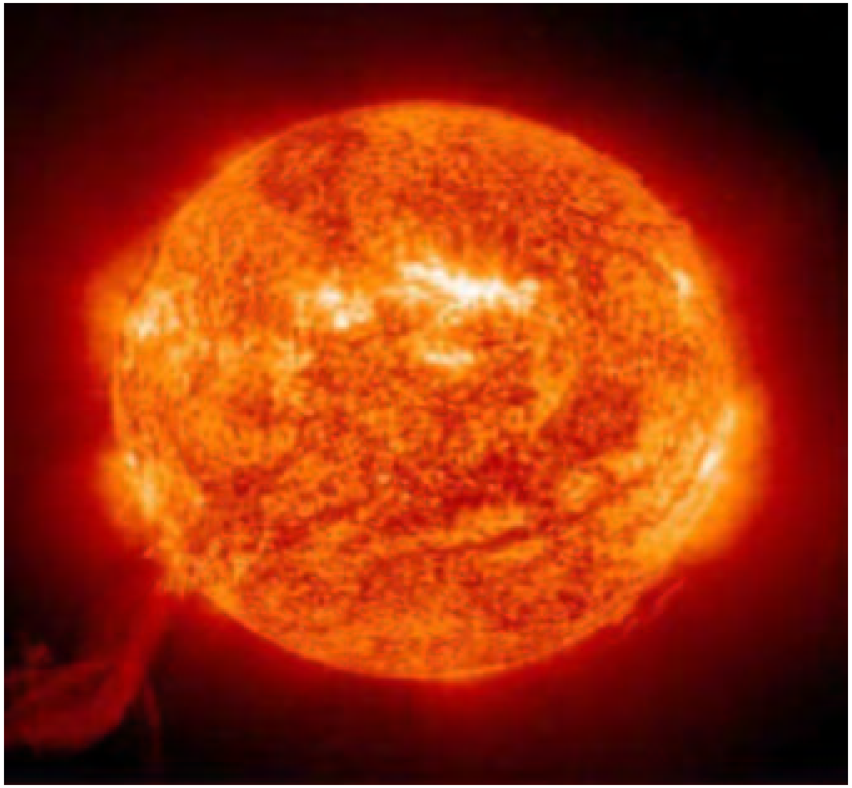
atm bounds on FC and NU nu-interactions

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:
$4p \to {}^4\text{He} + 2e^+ + \gamma + 2\nu_e$

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



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

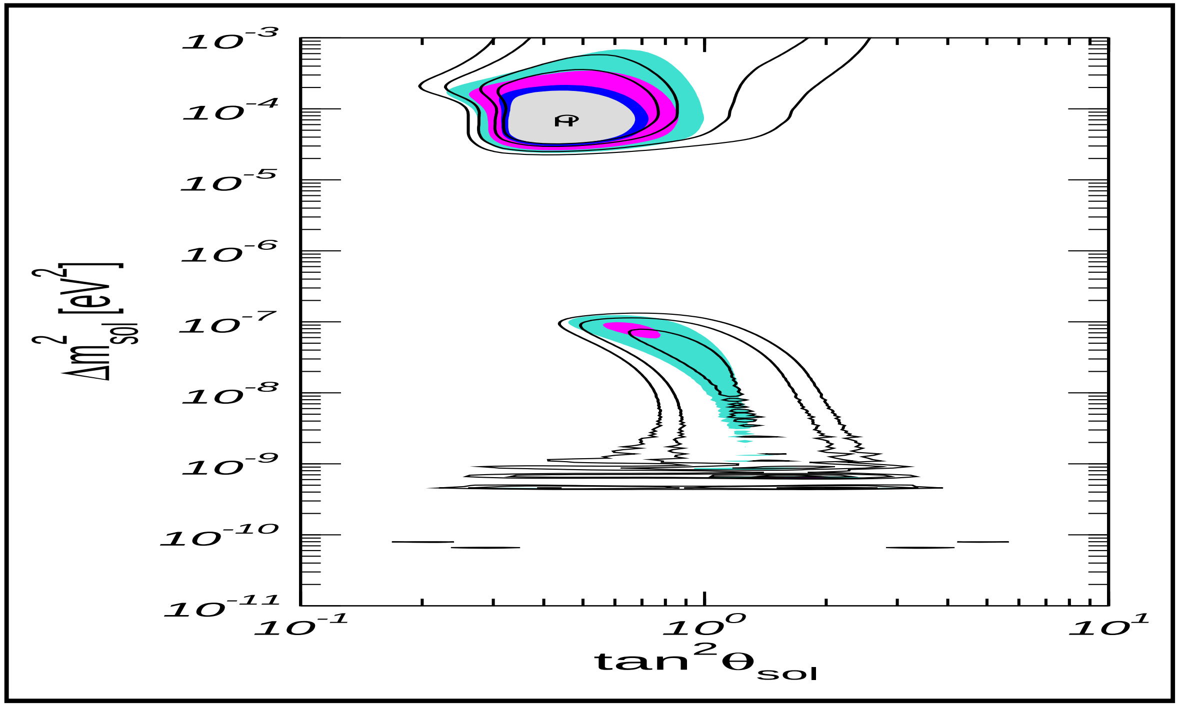
early 2002

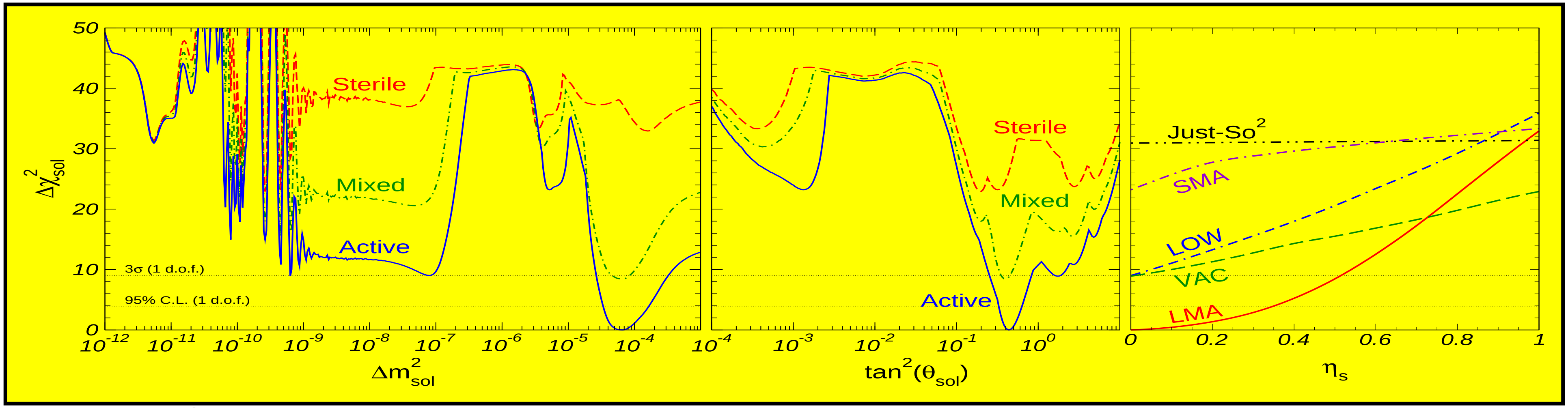
SNO showed that ν_e converts to an active flavour $\nu_e \to \nu_{\mu/\tau}$

solar-only 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





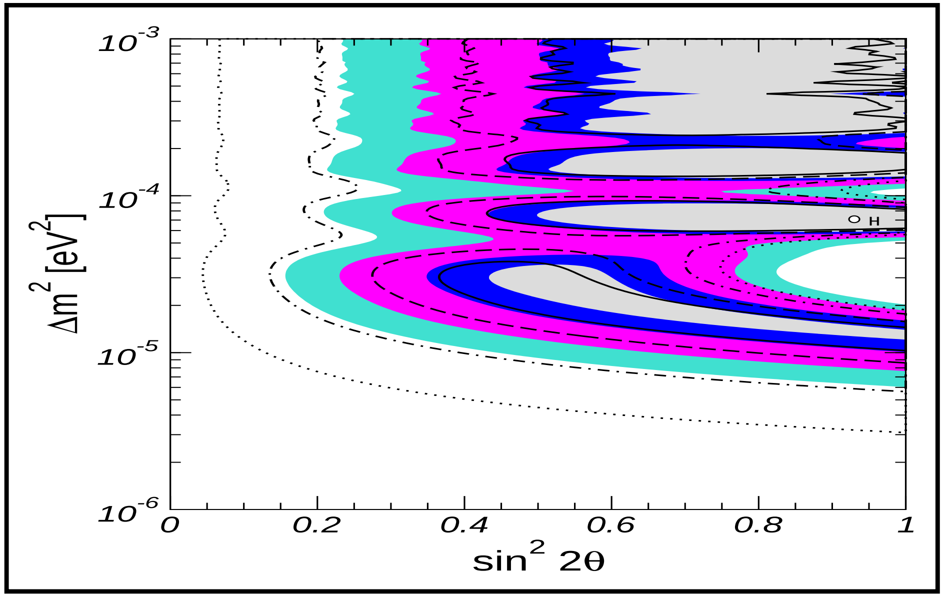
Reactor Neutrinos

Neutrinos are also produced in nuclear power plants

reactor neutrino experiments have a **controlled** source

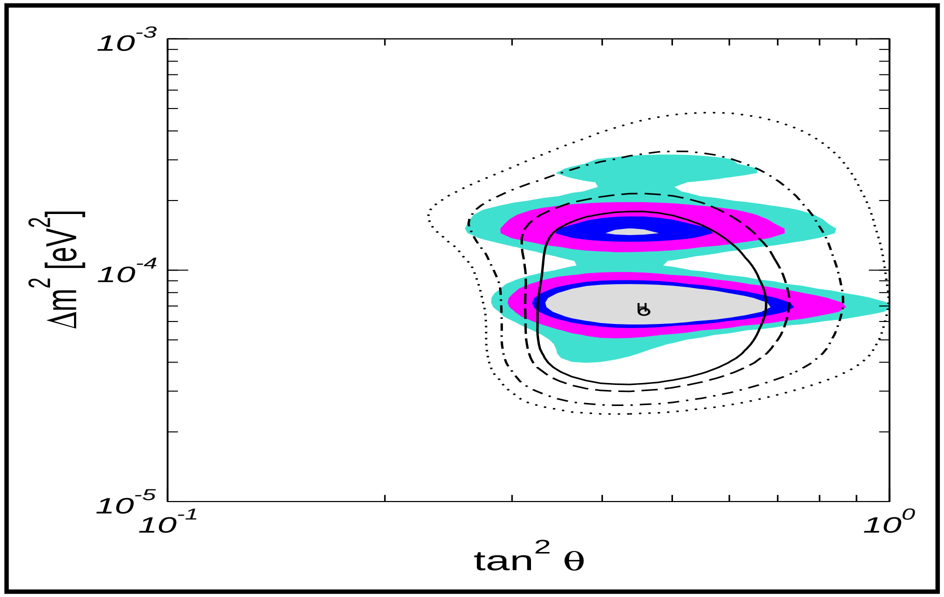
KamLAND first results provide (indirect) confirmation of the solar neutrino OSCILLATION hypothesis.

Implications of first KamLAND reactor results



Maltoni, Schwetz & JV, PRD67 (2003) 093003

first 145-days data support oscillation hypothesis



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

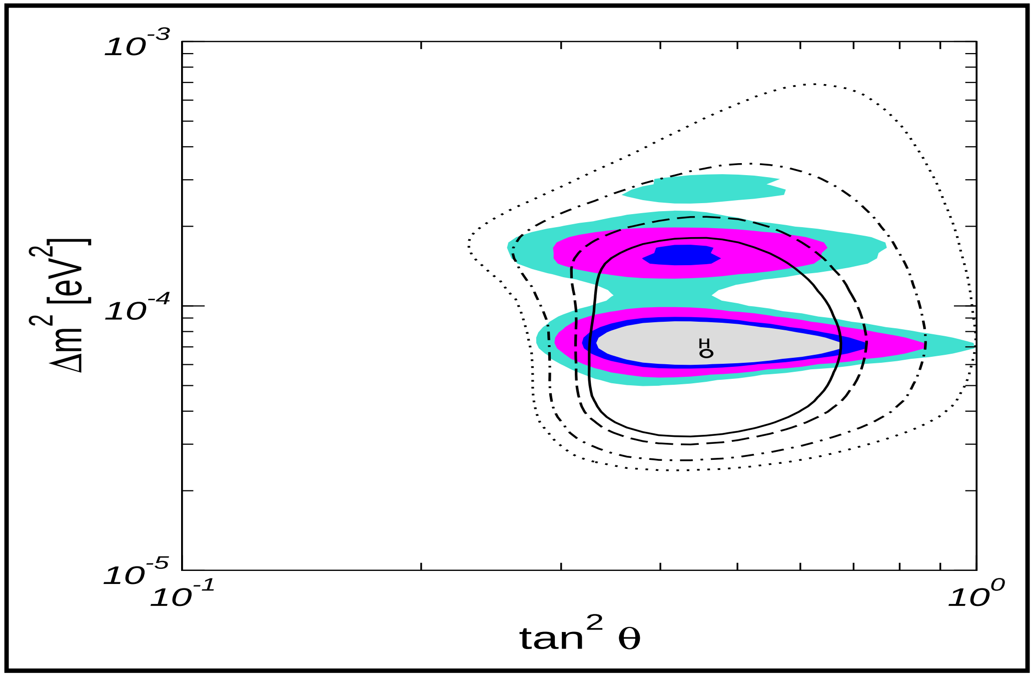
⇒ **oscilllations happen inside the sun!**

$$0.29 \le \tan^2\theta \le 0.86,$$

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

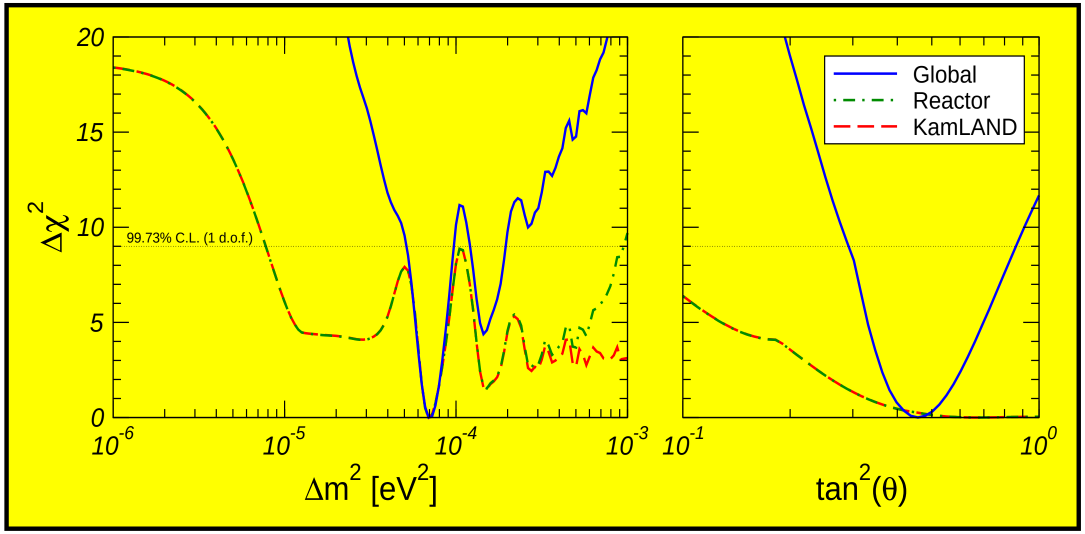
$$1.2 \times 10^{-4}\ \mathrm{eV}^2 \le \Delta m^2_{\rm SOL} \le 1.9 \times 10^{-4}\ \mathrm{eV}^2.$$

Solar + KamLAND results



Maltoni, Schwetz, JV, PRD67 (2003) 093003

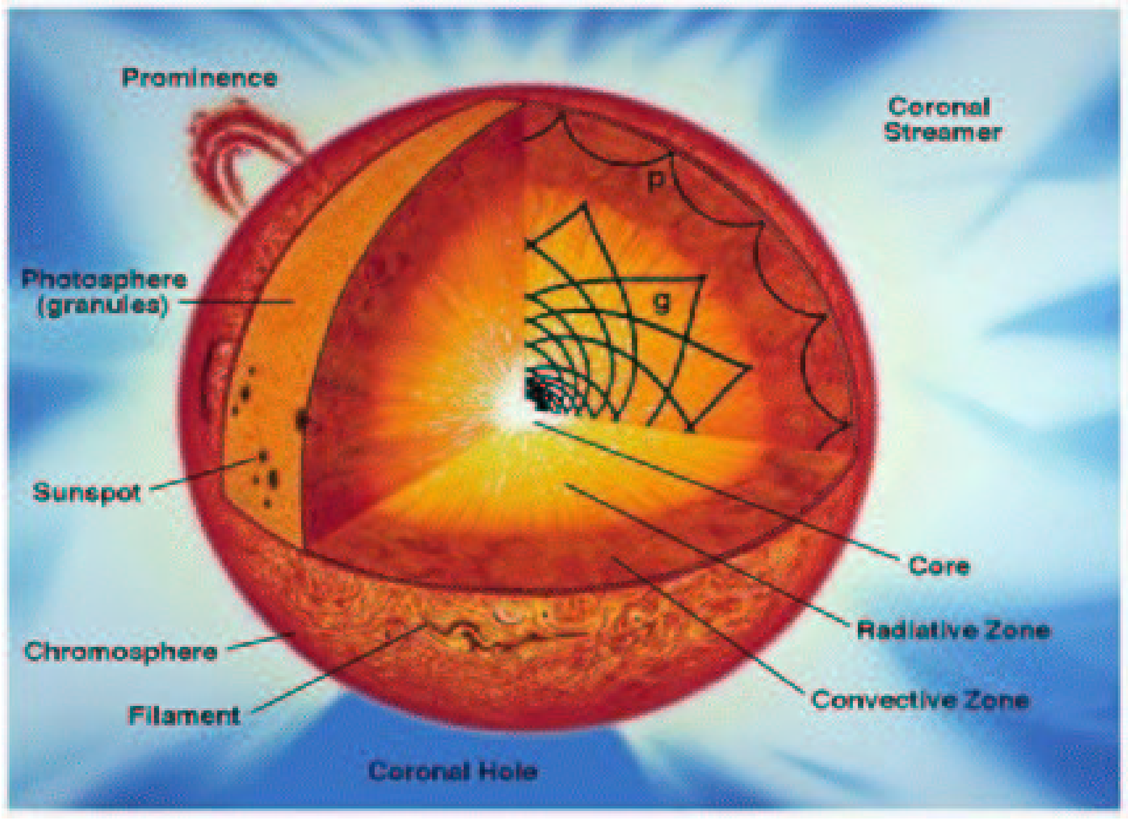
consistency with Poisson method

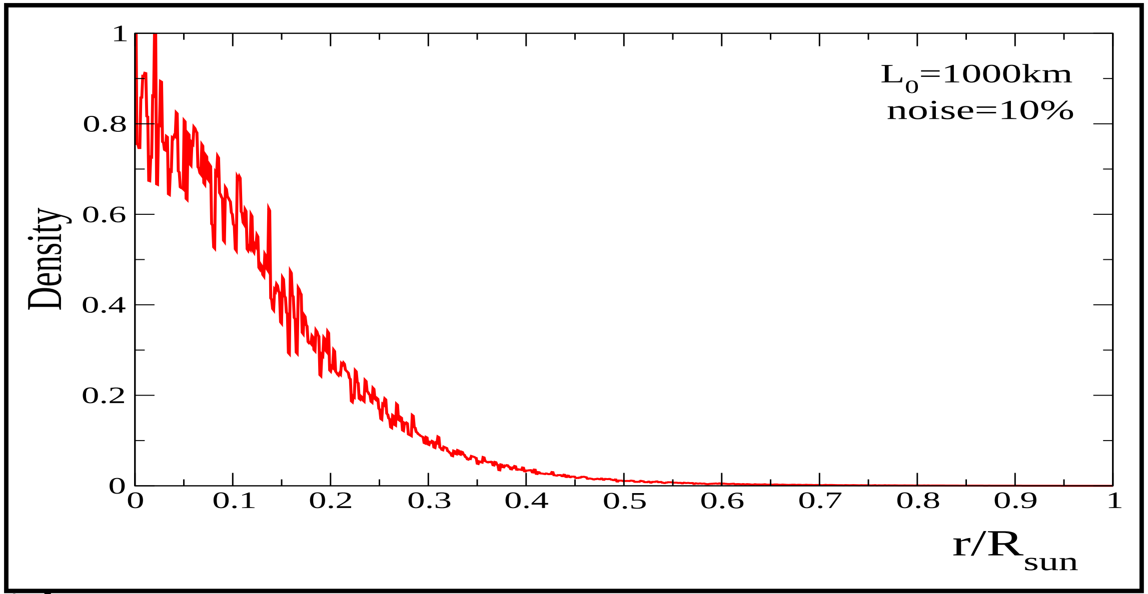


in contrast to atmospheric, solar mixing remains significantly non-maximal

bi-maximal models rejected

Noisy Sun ?


Prominence
Coronal Streamer
p
g
Photosphere (granules)
Sunspot
Core
Radiative Zone
Chromosphere
Filament
Convective Zone
Coronal Hole


L_0=1000km
noise=10%
Density
r/R_{sun}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Robustness of MSW plot

neutrino propagation strongly affected by density noise

Balantekin et al 95

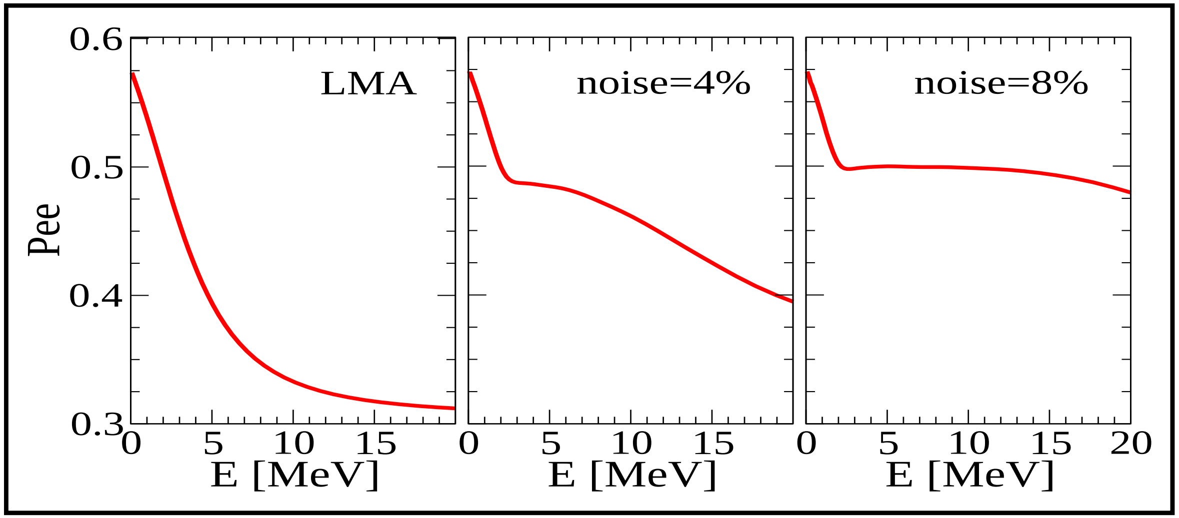
Nunokawa et al NPB472 (1996) 495

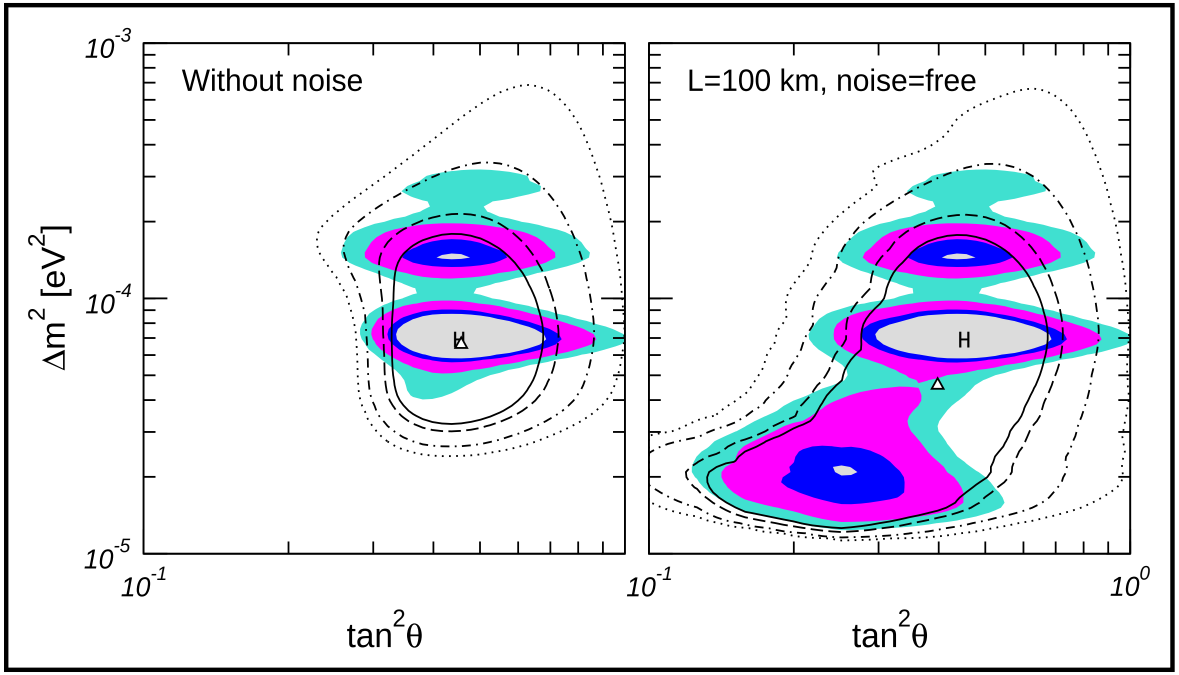
Burgess et al 97

substantial distortion

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

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





Accelerator Neutrinos

Neutrinos are also produced in particle accelerators

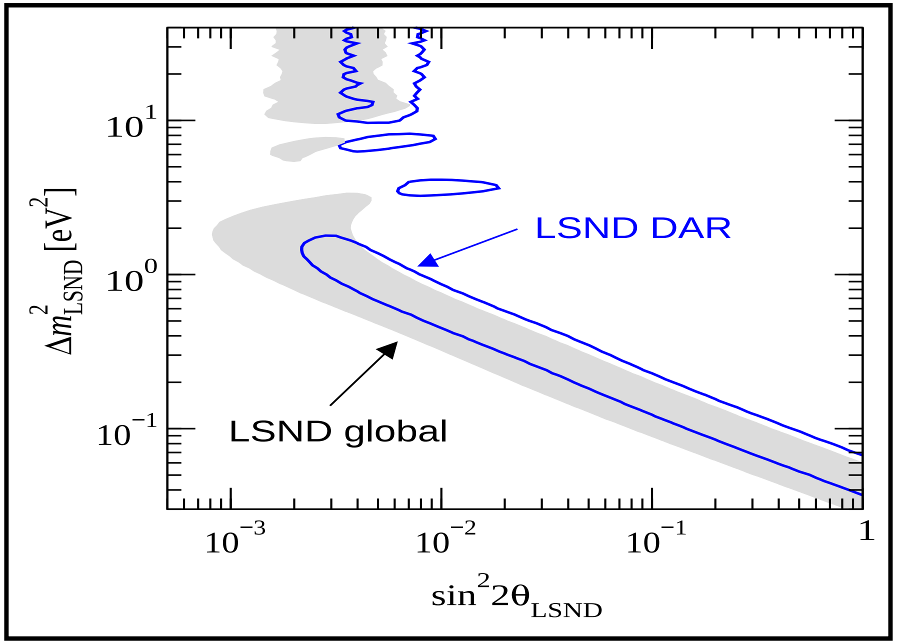
Experiments which measure the flux of neutrinos coming from accelerators have the advantage that the **neutrino source is well controlled**

check of the atmospheric neutrino oscillation hypothesis

The K2K accelerator experiment is observing a small deficit in the flux of muon neutrino arriving at the detector, thus confirming atmospheric neutrino oscillations.

LSND

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



ATM

SOL

Peltoniemi, JV, NPB **406**, 409 (1993)
Peltoniemi, Tommasini and JV, PLB **298** (1993) 383

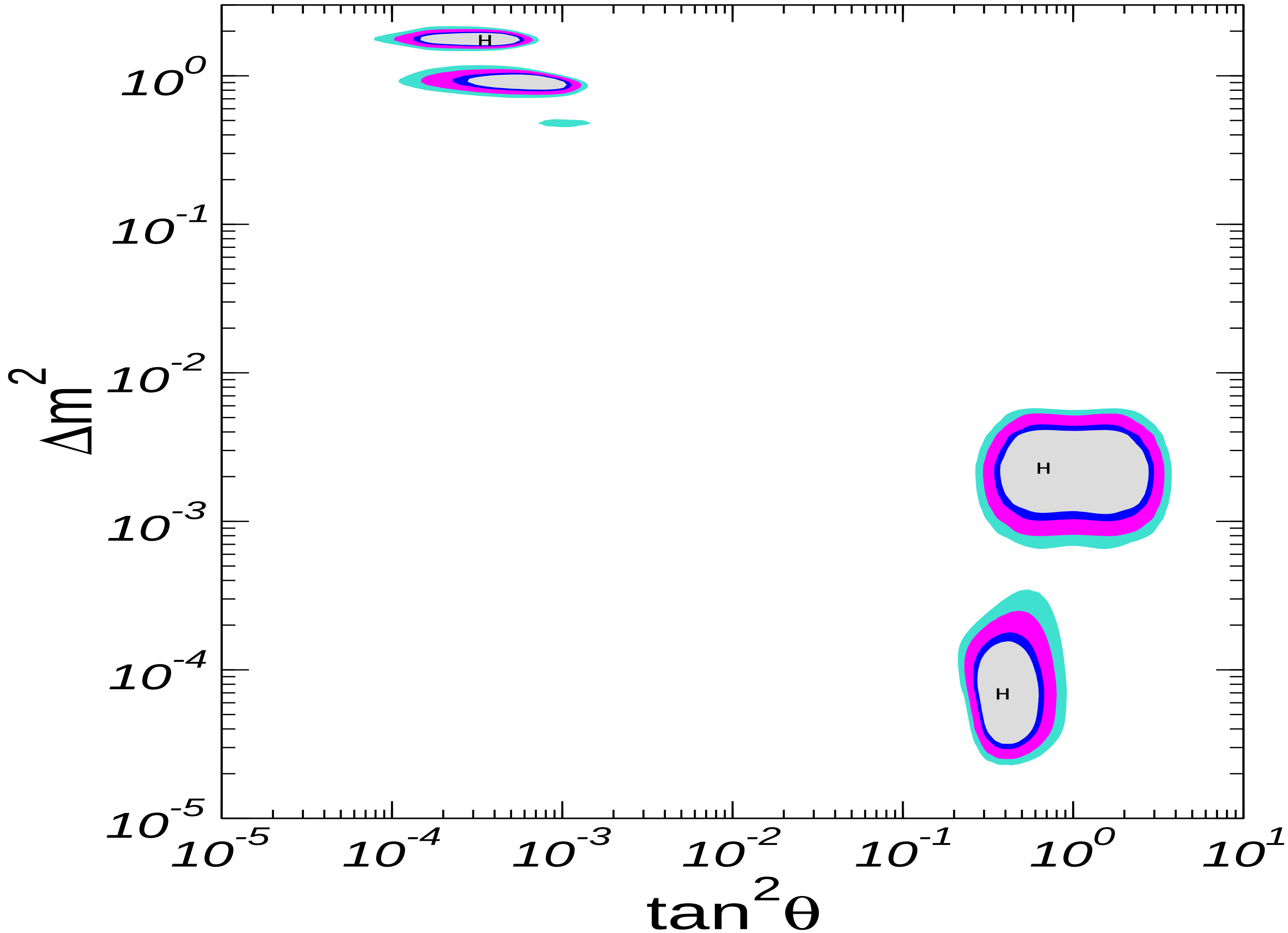
Caldwell-Mohapatra PRD48 (1993) 325

http://www.to.infn.it/~giunti/neutrino/

Grand oscillation plot ?

can oscillations fit all current nu-data

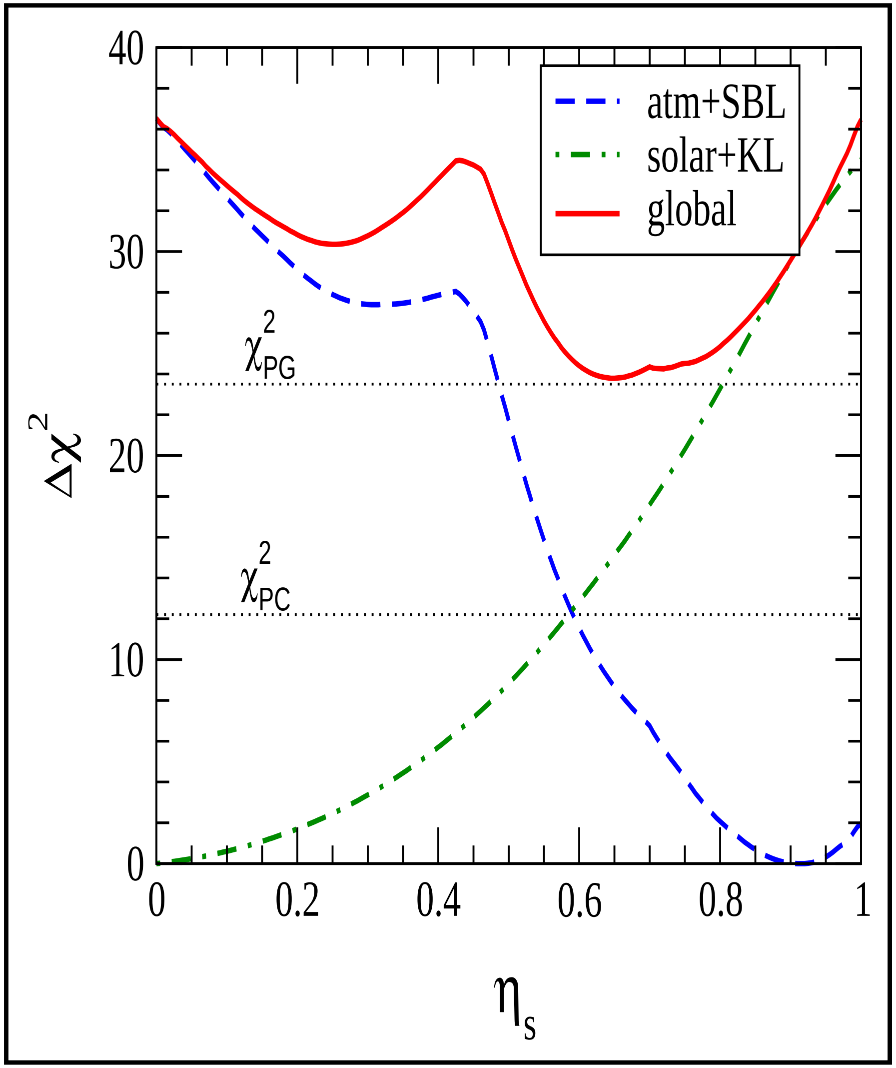
sol+atm+reac+**sbl/lsnd**

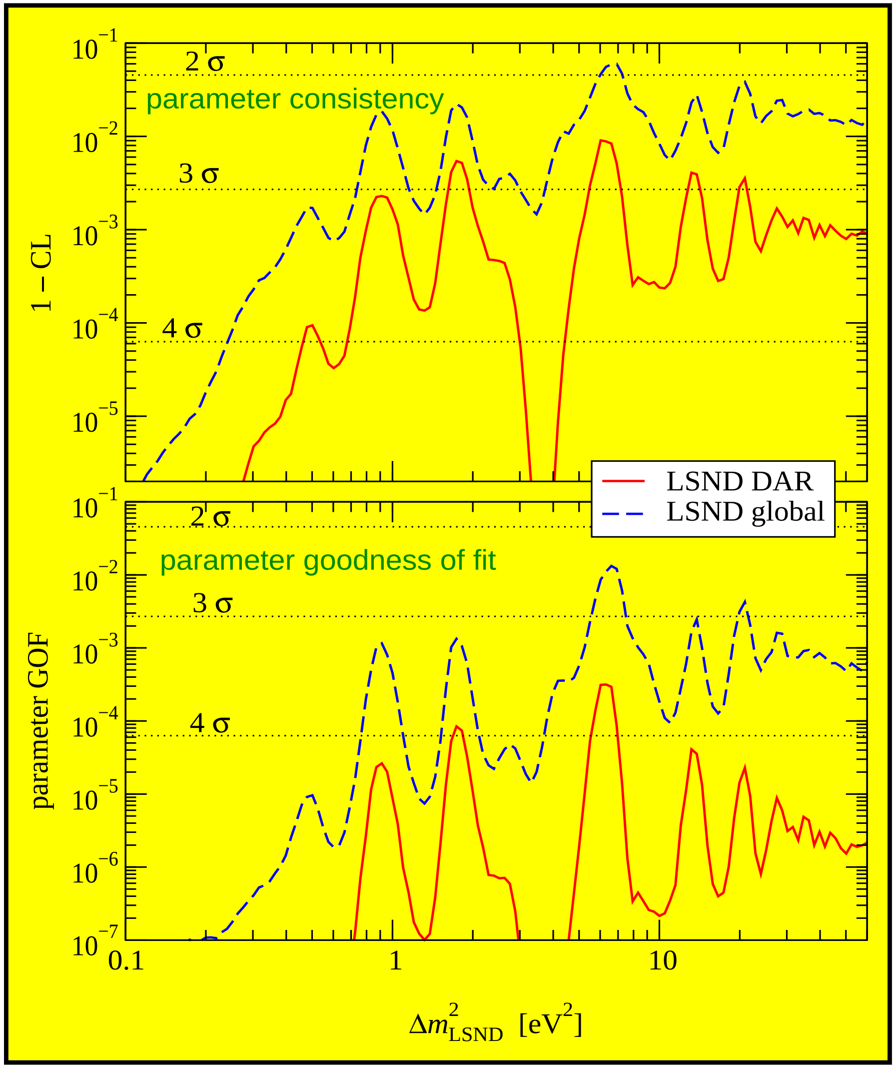


4-nus do not really fit LSND with the rest

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

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





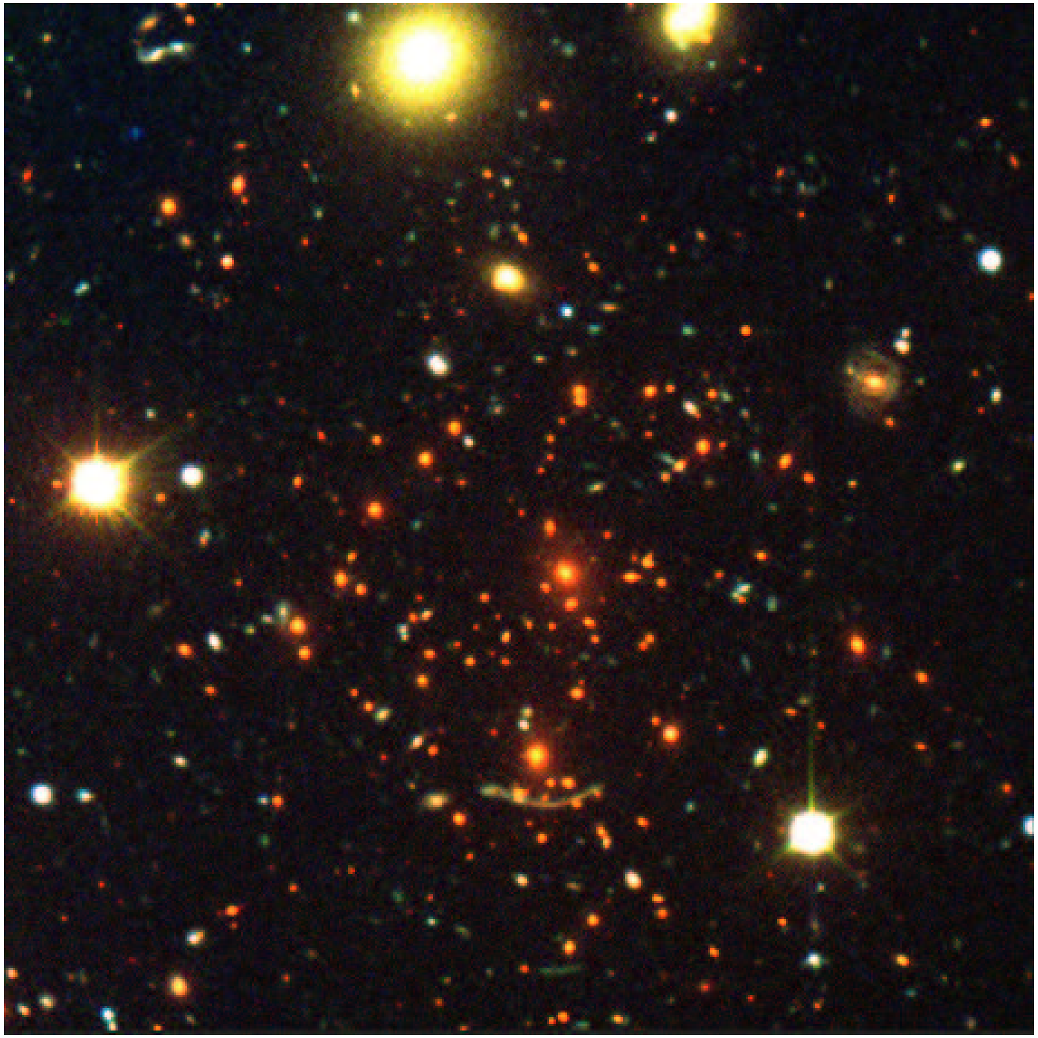
Cosmological Neutrinos

Neutrinos were copiously produced in the early hot and dense universe

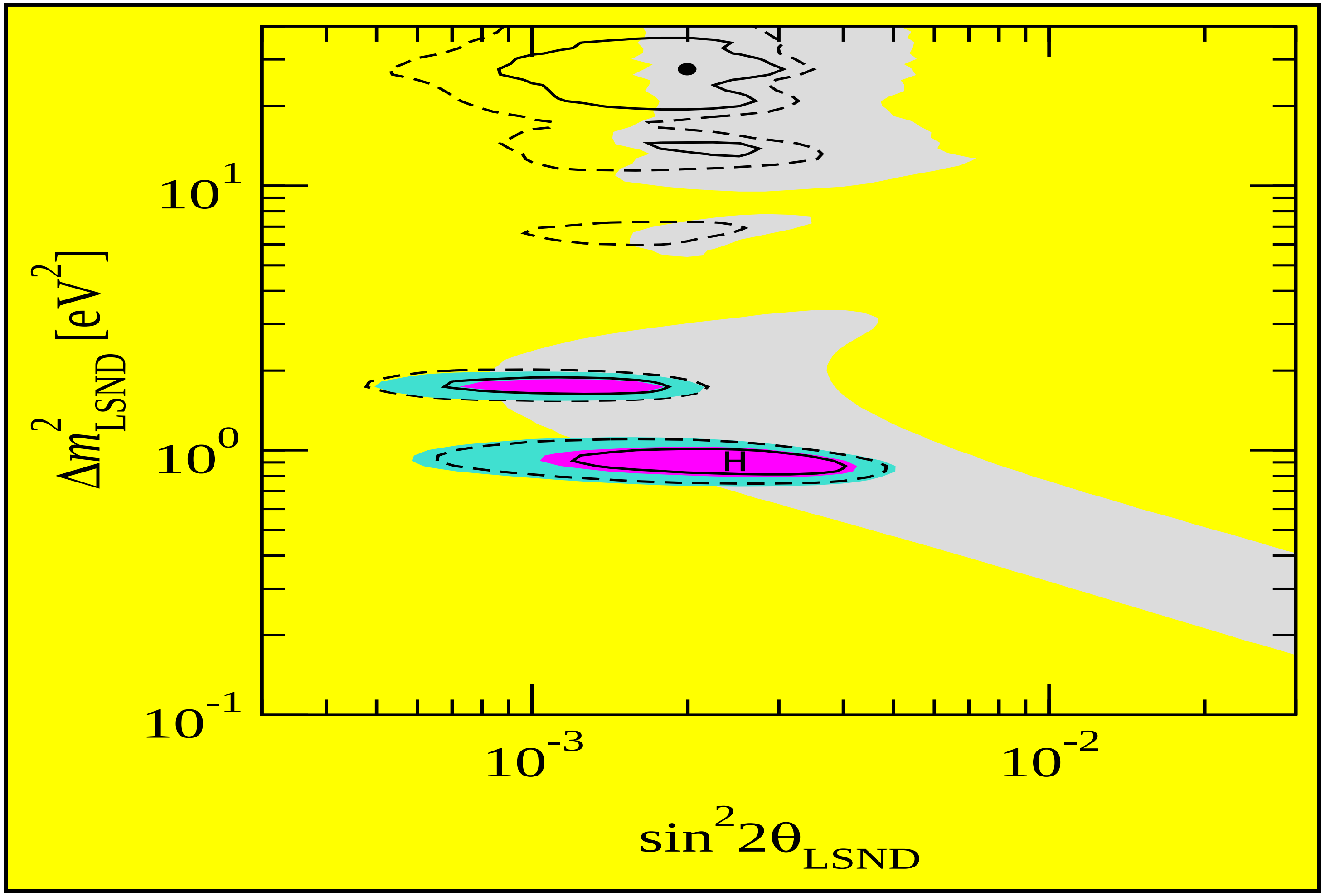
there are 336 neutrinos of the three flavours per cm^3, a bit more than the CMB photons

Neutrinos important in the production of the relic abundances of light elements: BBN

Although too light to be a significant component of the dark matter, neutrinos might still have played a role in the formation of large-scale structure: LSS



Cosmology closes in on LSND



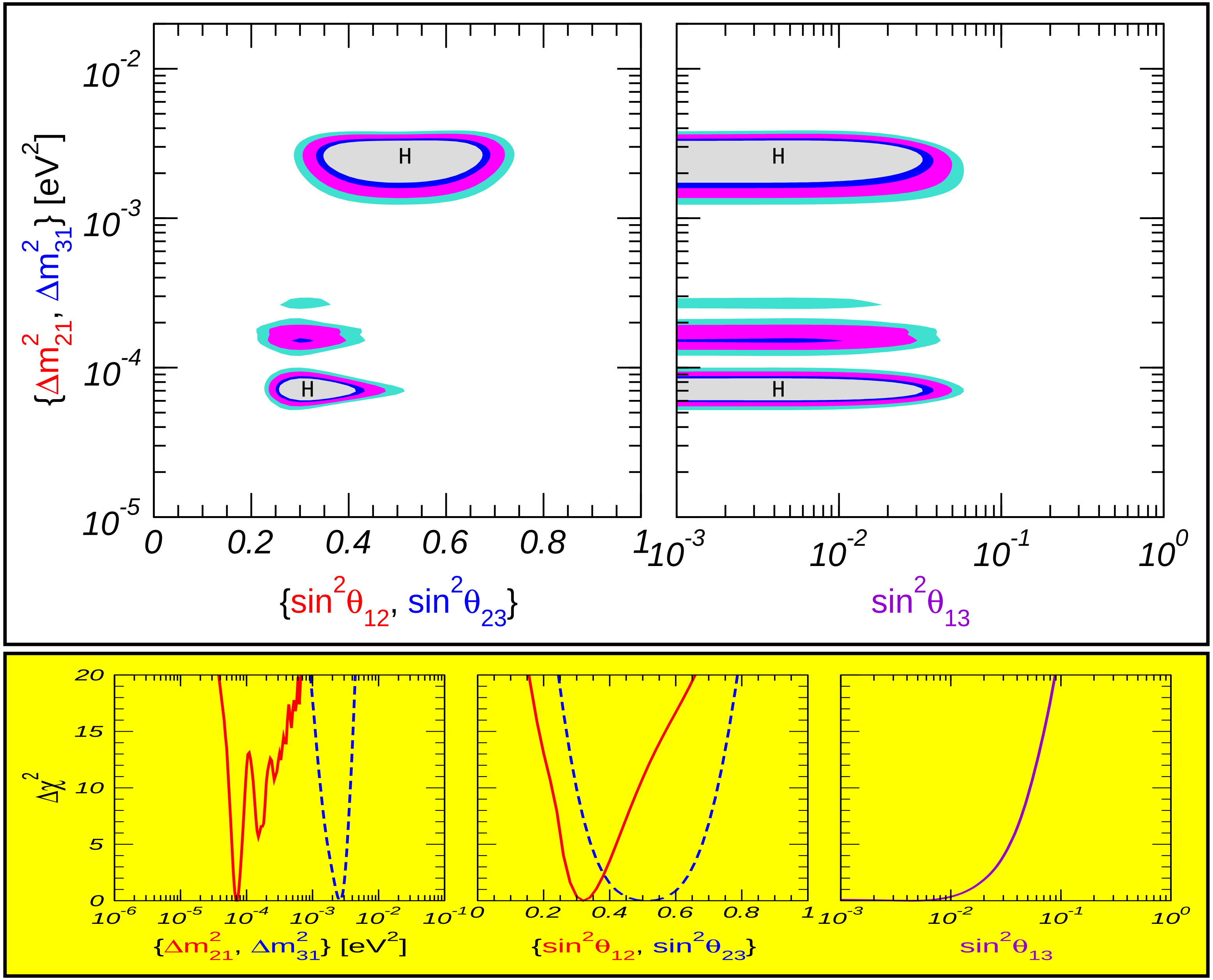
2df + WMAP

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



simplest picture

- 3 angles θ_{ij}

  1 KM-like phase [oscillations]

  2 Majorana phases [$\beta\beta_{0\nu}$]

[23=atm 12=sol 13=reac]

[ϕ]

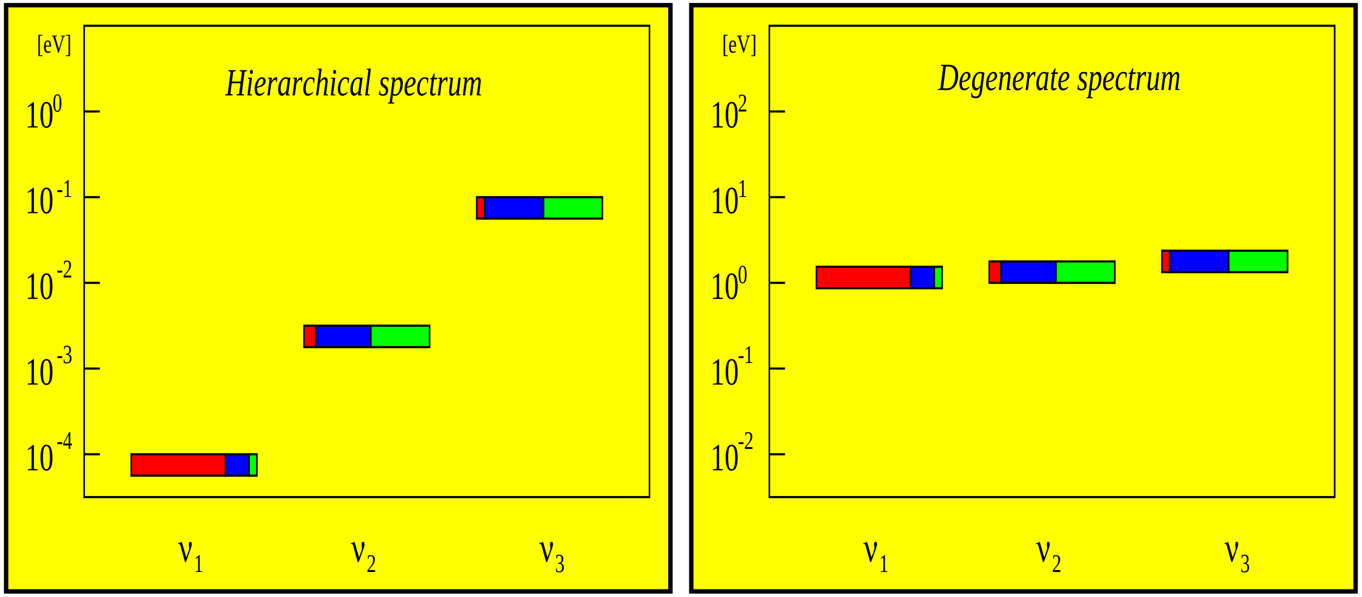
[ϕ_1 , ϕ_2]

Schechter and JV, PRD22 (1980) 2227

[both appear in leptogenesis]

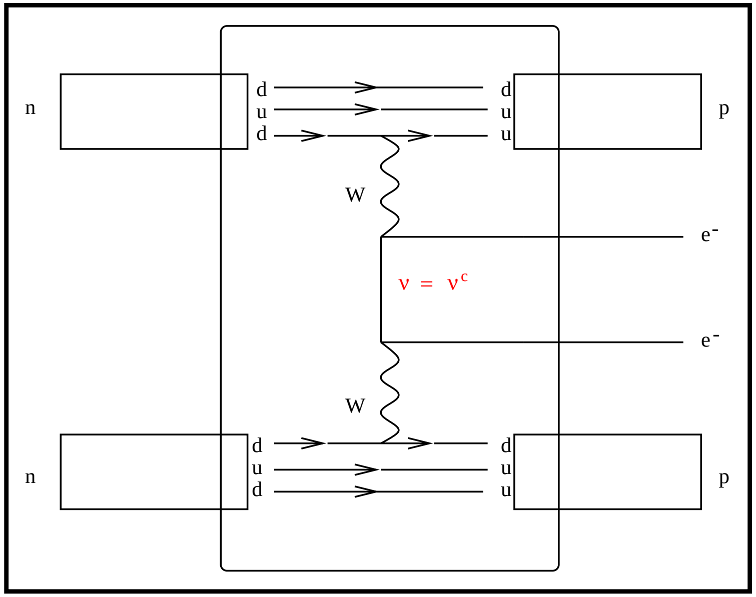
- max θ_{23}, large θ_{12} & small θ_{13}

[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



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

parametrizing K as in

Schechter and JV, PRD22 (1980) 2227

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

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

three possibilities

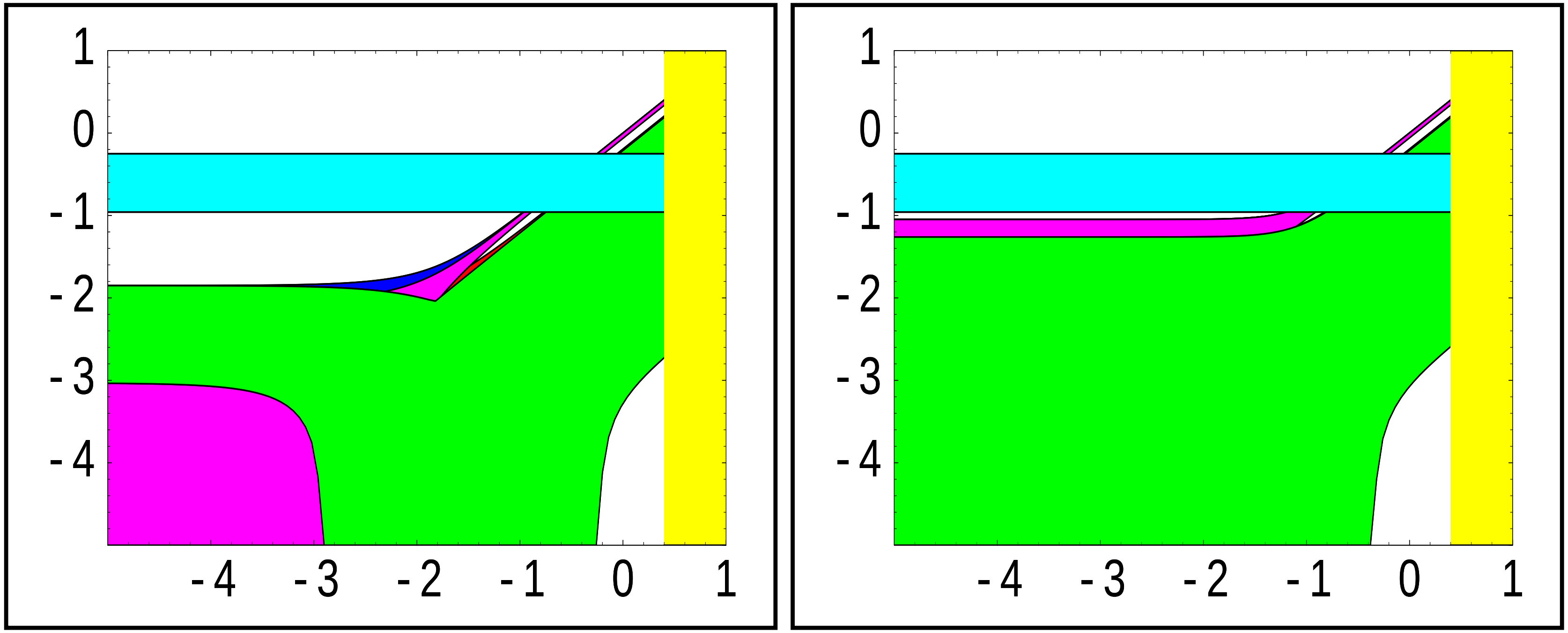
Absolute neutrino mass scale

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: $m_1 \leq 2.5$ [eV]

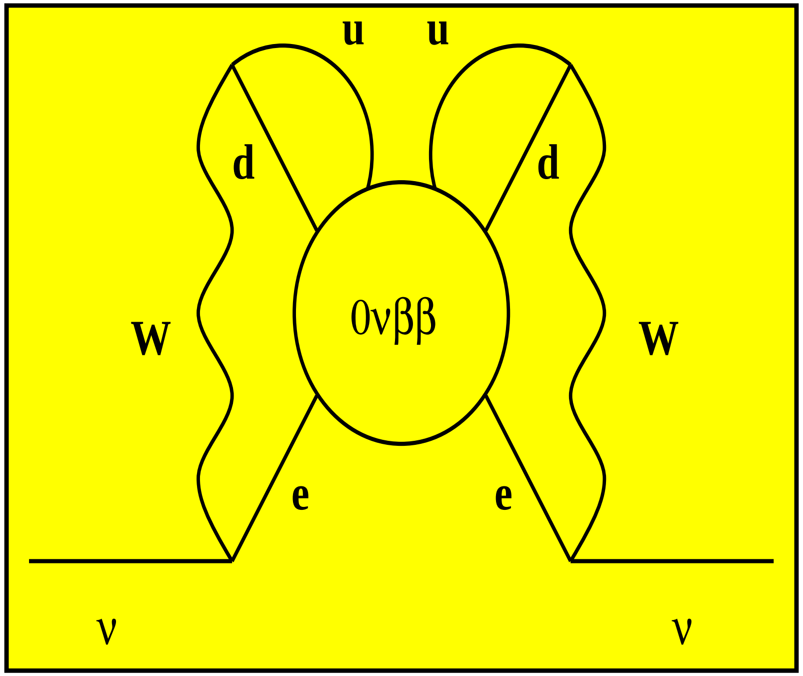
normal versus inverse hierarchy Log $\langle m_\nu \rangle$/eV vs Log m_1/eV



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

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

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



like other L violating processes
$\beta\beta_{0\nu}$ is sensitive to Majorana phases

Schechter and JV, PRD22 (1980) 2227, D23 (1981) 1666

Wolfenstein PLB107 (1981) 77; Doi et al

can not reconstruct majorana phases

Barger, Glashow, Langacker, Marfatia, PLB B540 (2002) 247

a pity for leptogenesis

θ_{13} and Leptonic CP Violation

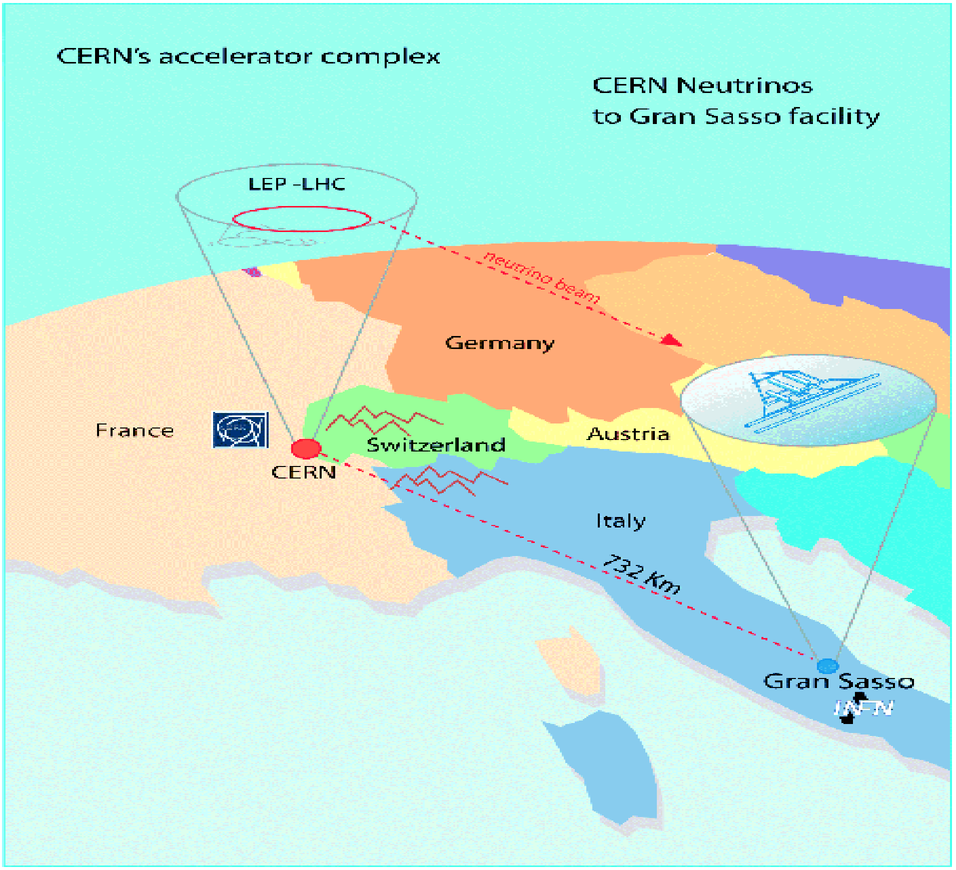
"Dirac" CPV suppressed, since δ disappears when any $\Delta_{ij} \to 0$

Schechter and J. V., PRD **21** (1980) 309

Neutrino Factories

apart from probing s_{13} and δ ... Cervera et al, De Rujula, Gavela, Hernandez, Freund, Huber, Lindner, Albright et al, Barger et al...

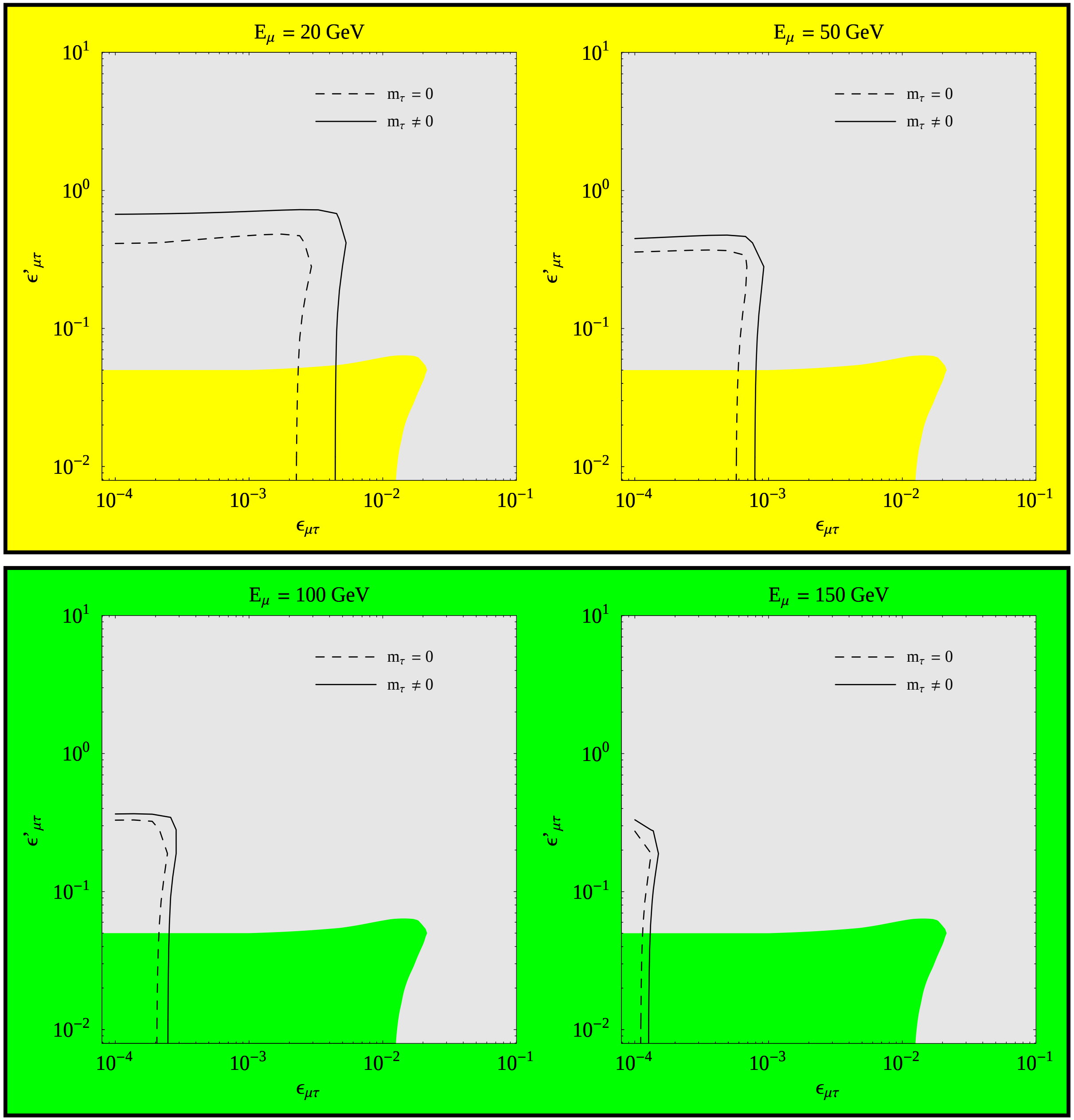
they can probe Non-Standar nu-Intercations (NSI)



Improved FC-tests at NuFact

Huber & JV PLB **523** (2001) 151

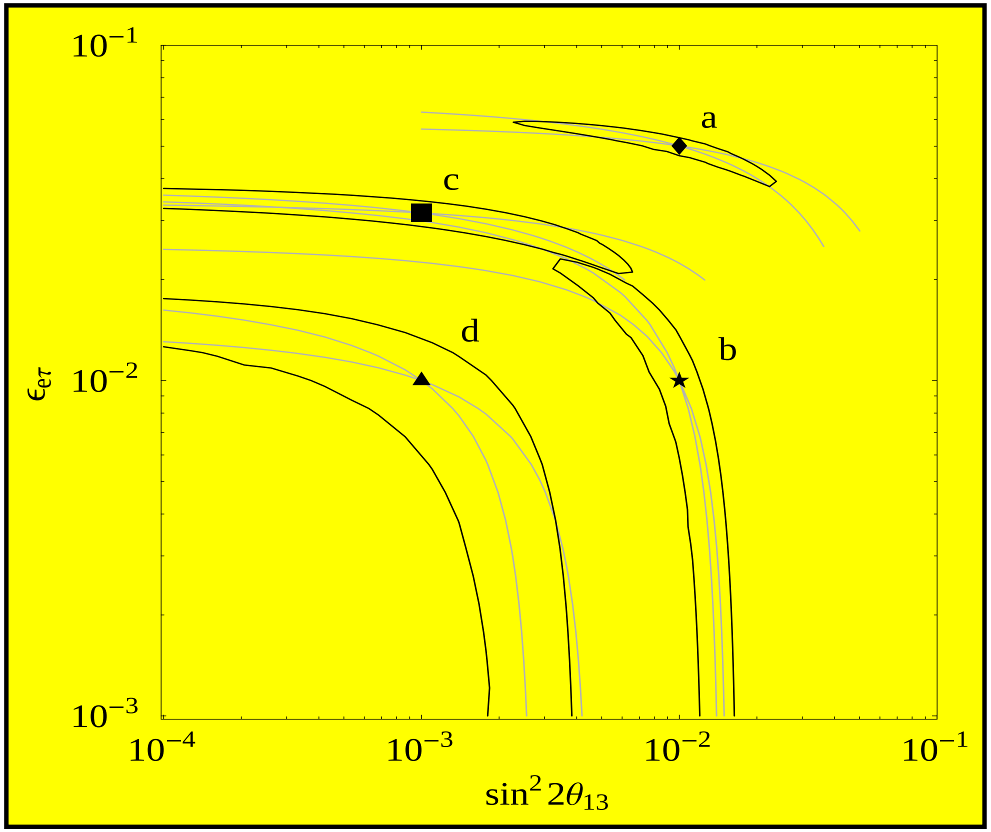
10 kt detector, 0.33 ν_τ detection eff above 4 GeV; need no tau charge id



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)

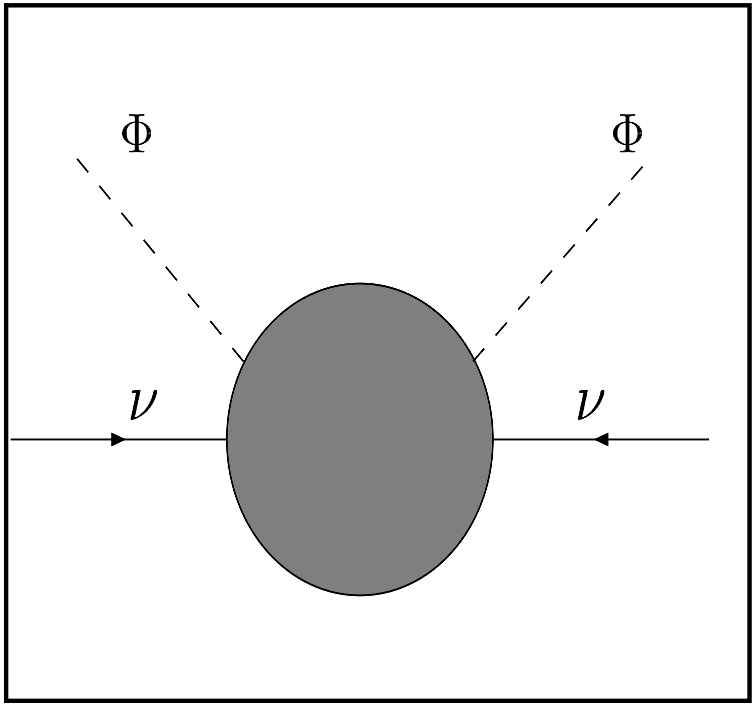


near-site programme essential

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

Theory ideas

basic dim-5 operator

- 

- from Gravity

  Weinberg; Barbieri, Ellis, Gaillard; Zee & Weldon

- from seesaw schemes

  Gell-Mann, Ramond, Slansky; Yanagida;
  Mohapatra, Senjanovic PRL **44** (1980) 91
  Schechter, JV PRD **22** (1980) 2227

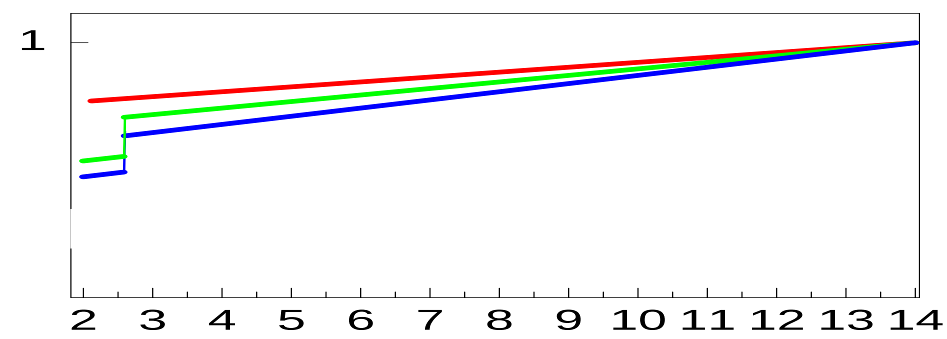
neutrino unification: large-scale seesaw

-

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 Valle, PRL86 (2001) 3488

solar & atm splittings from RGE

common origin for neutrino and KM mixing

maximal θ_{23}; large θ_{12} & small θ_{13}

see also Grimus & Lavoura

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

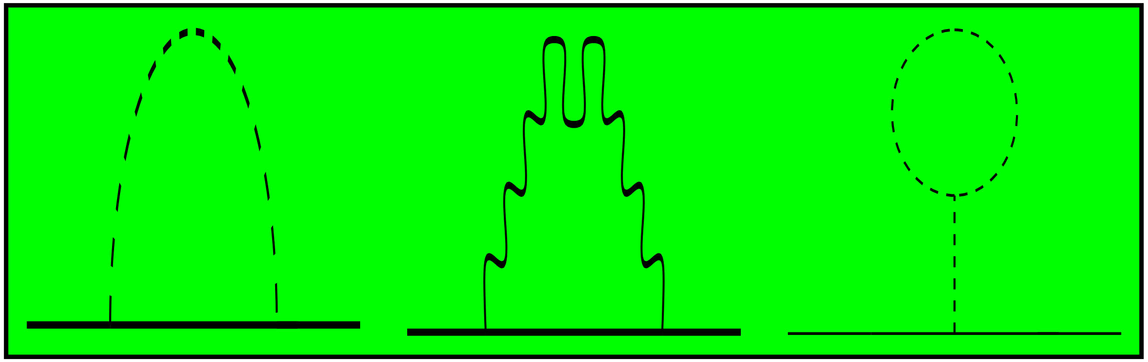
observable Lepton Flavor Violation $B(\tau \to \mu\gamma) \sim 10^{-6}$

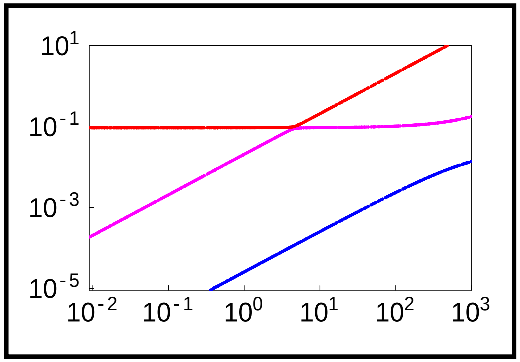
bilinear R parity violation: weak-scale seesaw

Diaz, Hirsch, Porod, Romao and Valle, hep-ph/0302021 PRD in press;
PRD **62** (2000) 113008 [Err-ibid. D **65** (2002) 119901]; PRD **61** (2000) 071703

- weak-scale seesaw atm scale

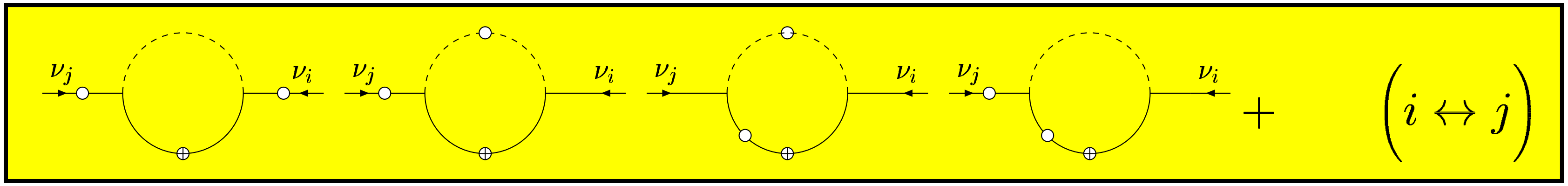
- radiative nu-masses solar scale

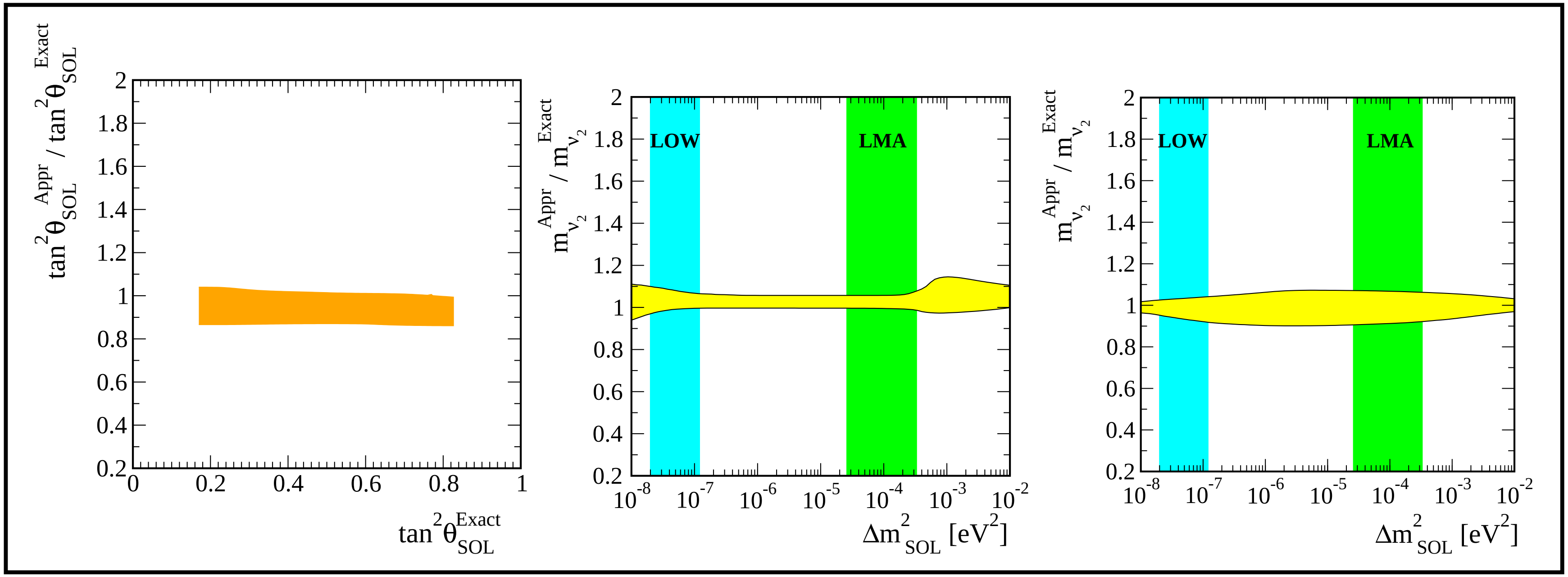




solar mass scale loops: analytical vs numerical

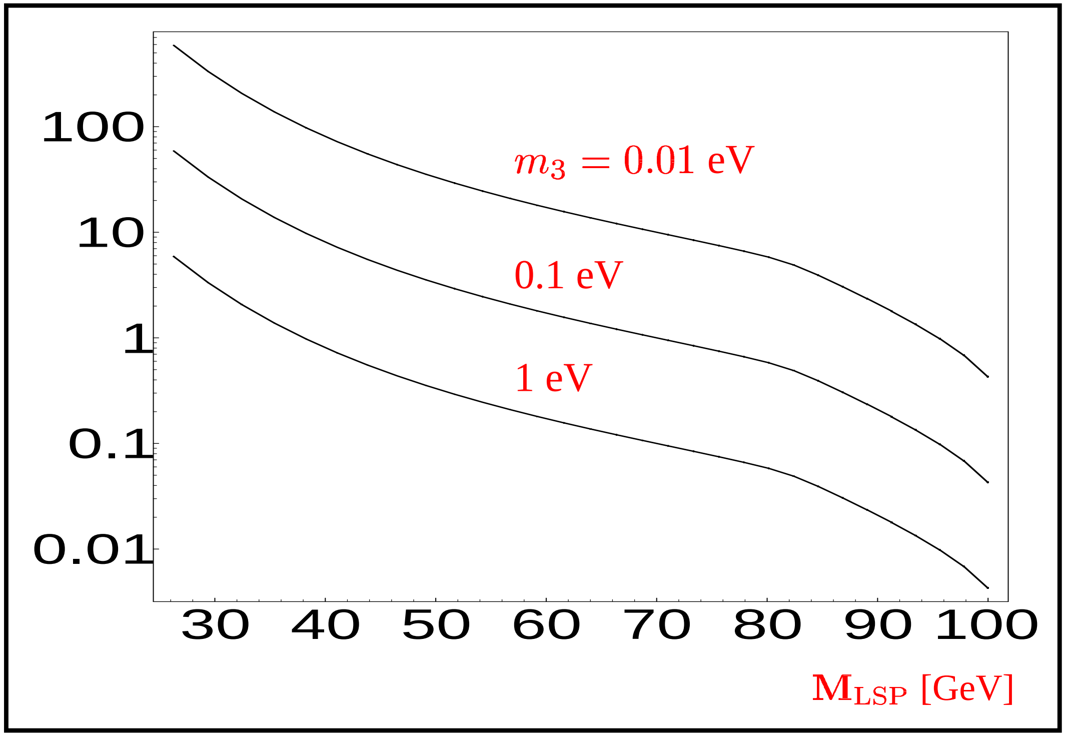
M. A. Diaz et al hep-ph/0302021





LSP decay length [cm]: BRPV

from Bartl et al NPB 600 (2001) 39



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

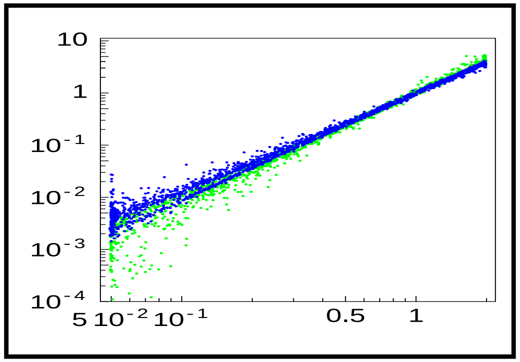
any charged SUSY particles can be the LSP

neutrino mixing angles 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)

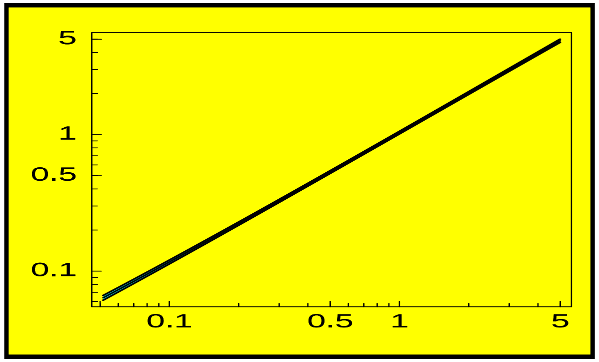


- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004

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



- stop decays
  slepton decays

Restrepo, Porod & Valle, PRD64 (2001) 055011

M. Hirsch et al, PRD66 (2002) 095006

All Pathways to Neutrino Mass are Open

- top-bottom vs bottom-up
- hierarchical vs quasi-degenerate, sterile-nus?
- 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
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- **no theory of flavour**