"Neutrinos: a Probe for New Physics"

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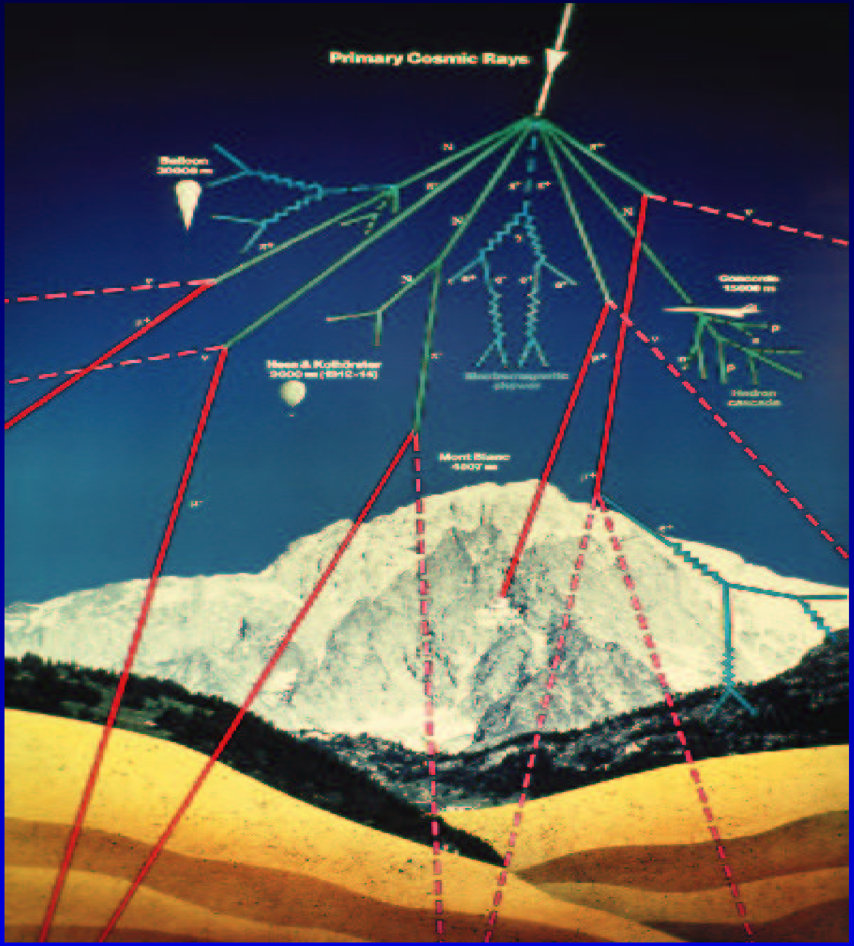
Based on review
Neutrino properties before and after KamLAND
S. Pakvasa and JV hep-ph/0301061

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



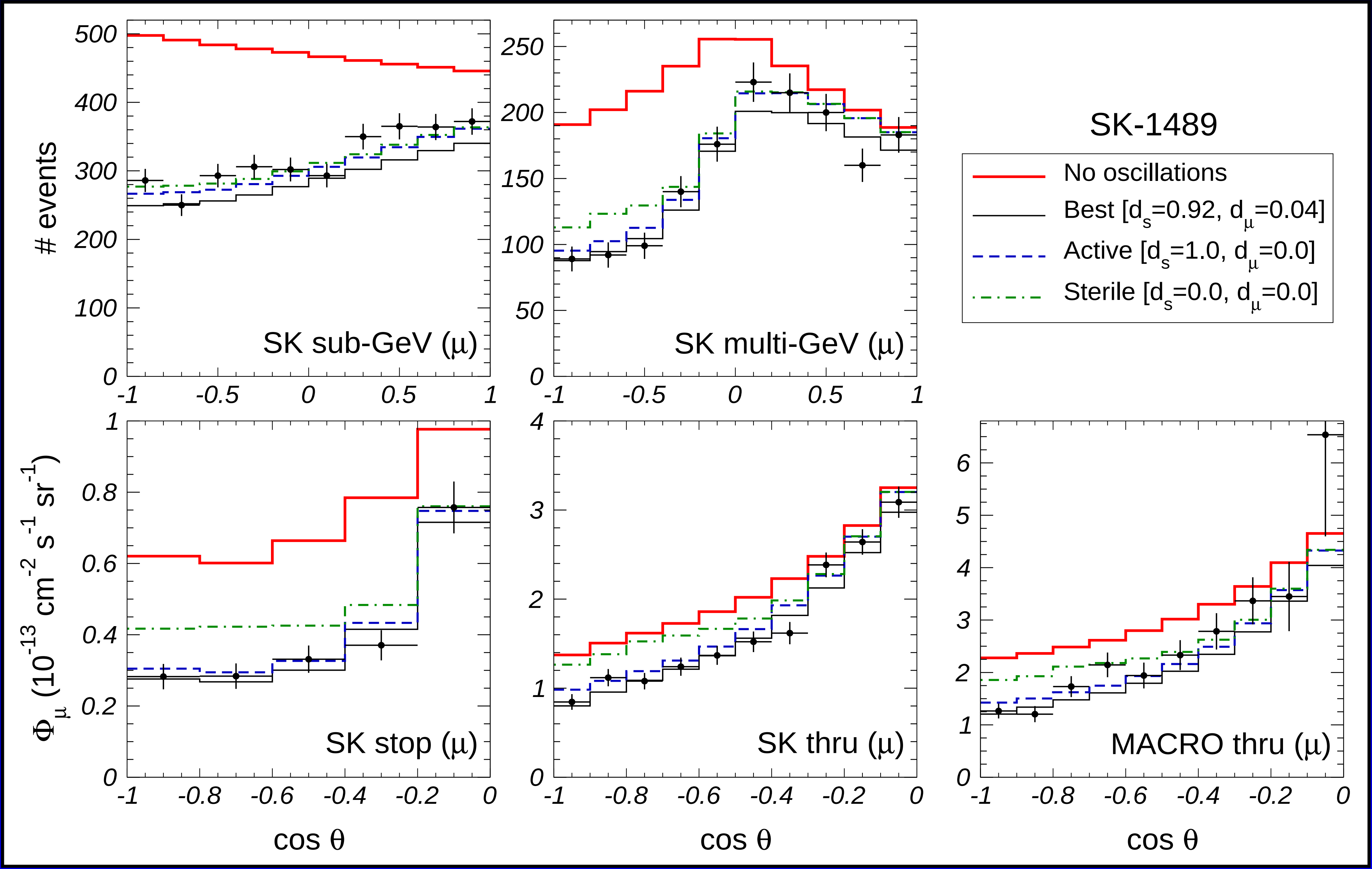
The ν_e flux measured by underground experiments is in agreement with the predictions.

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



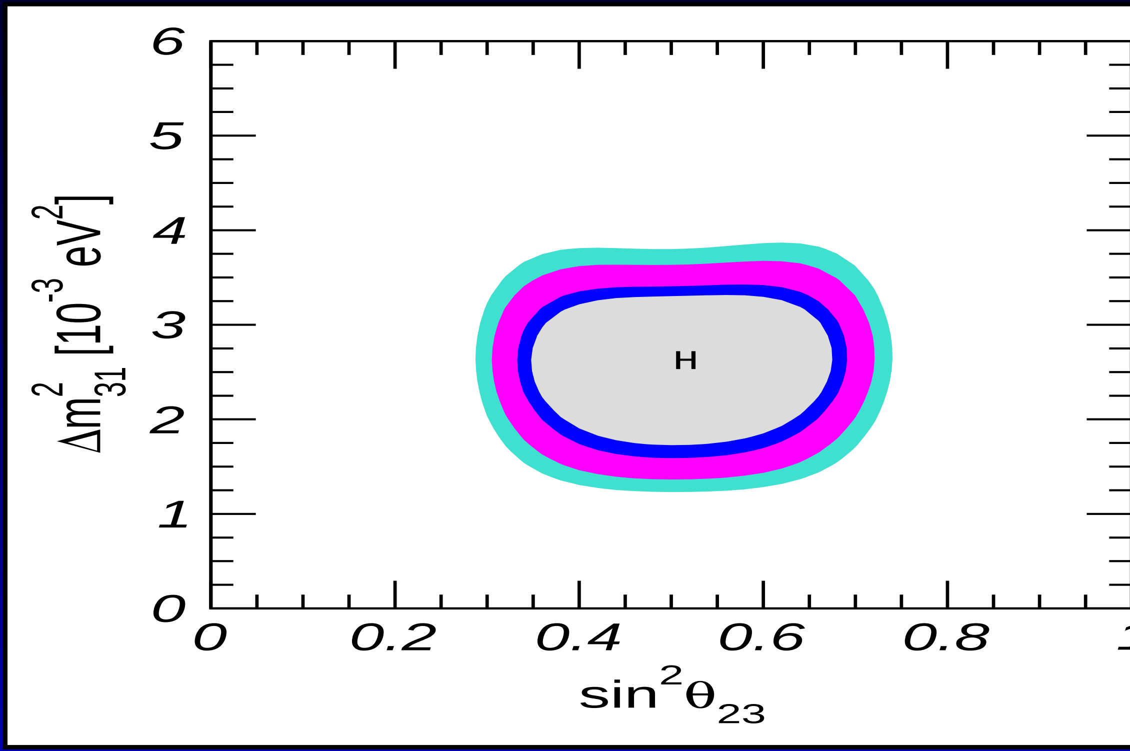
atmospheric neutrino parameters-1

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

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

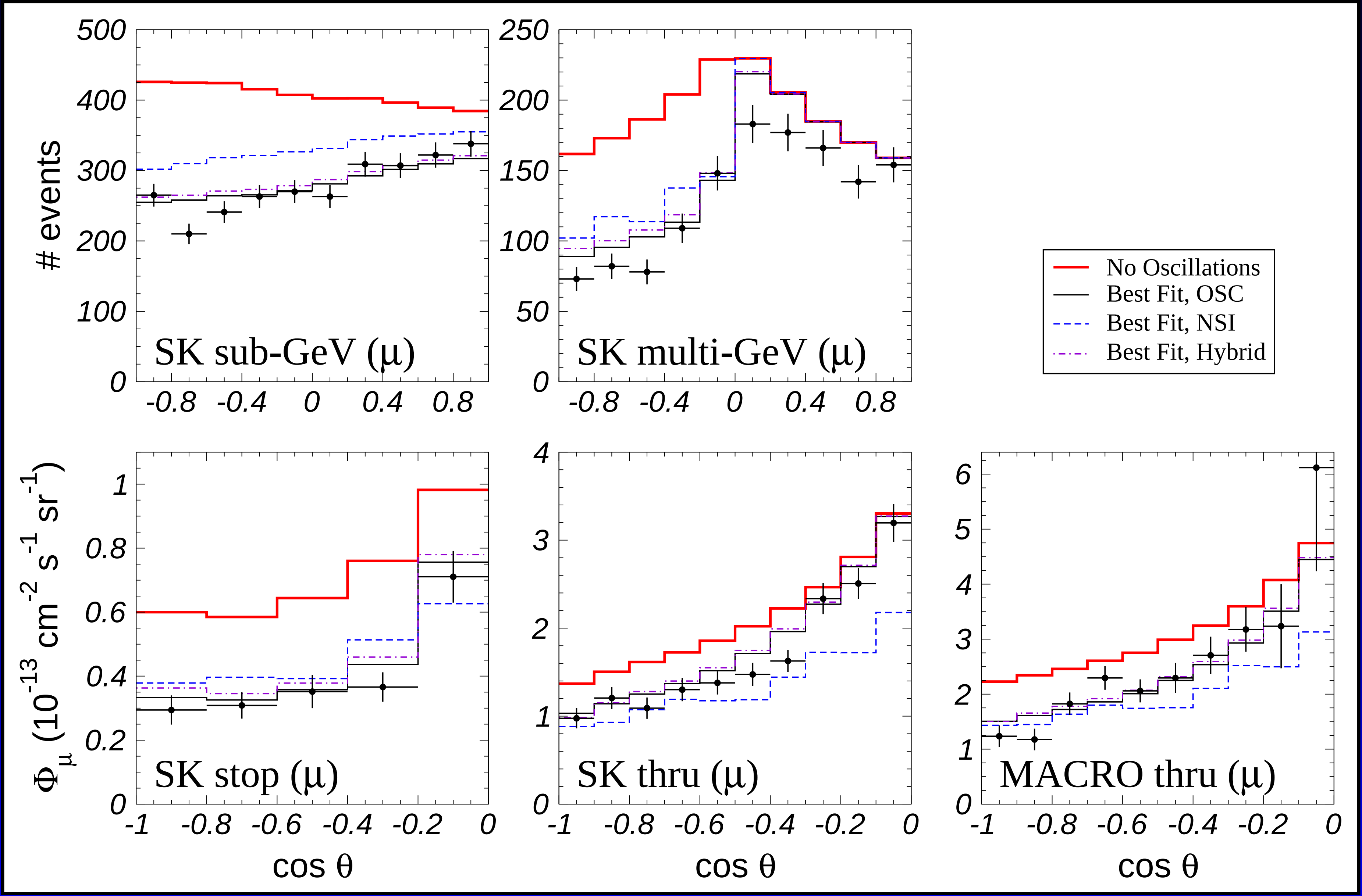
$\Delta m^2_{\rm ATM} = 2.5 \times 10^{-3}\ {\rm eV}^2$

light-dark symmetry



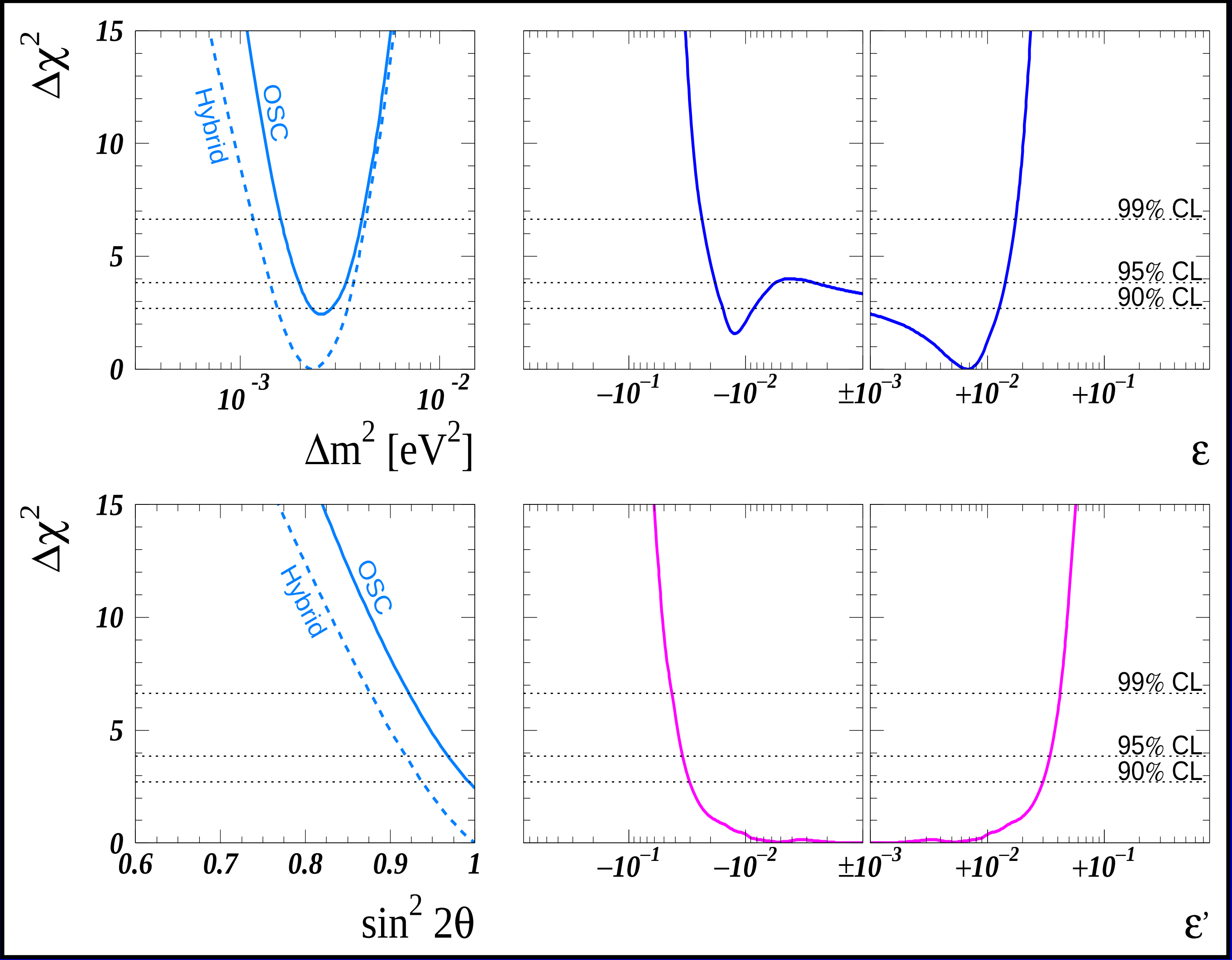
How robust are atmospheric oscillations?

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].



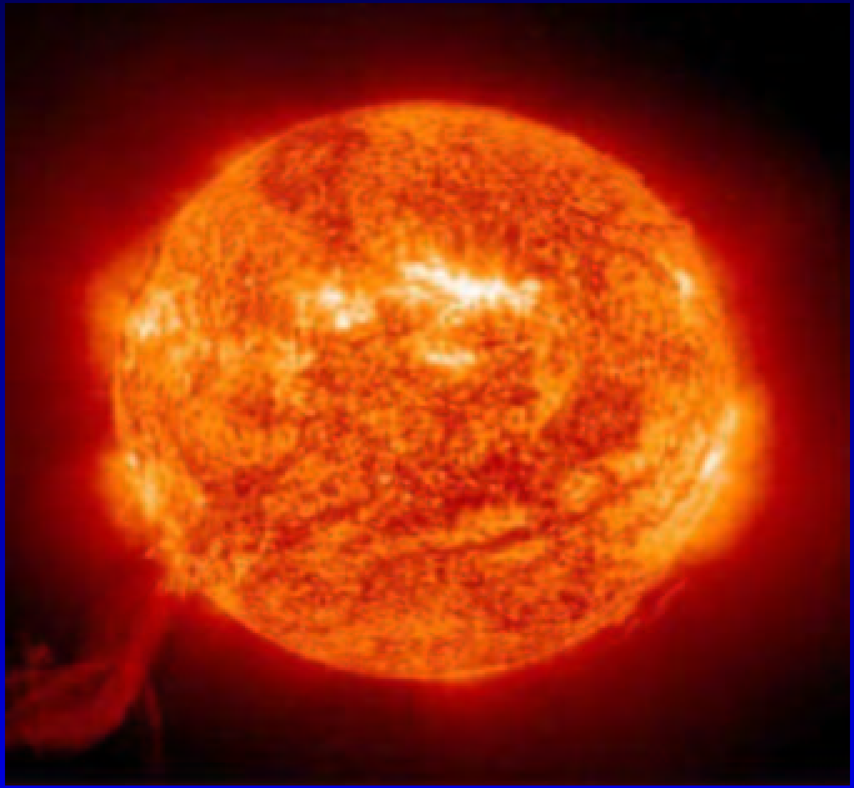
atm bounds on FC and NU nu-interactions

Solar Neutrinos

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

early 2002

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

Reactor Neutrinos

Neutrinos are also produced in nuclear power plants

controlled source

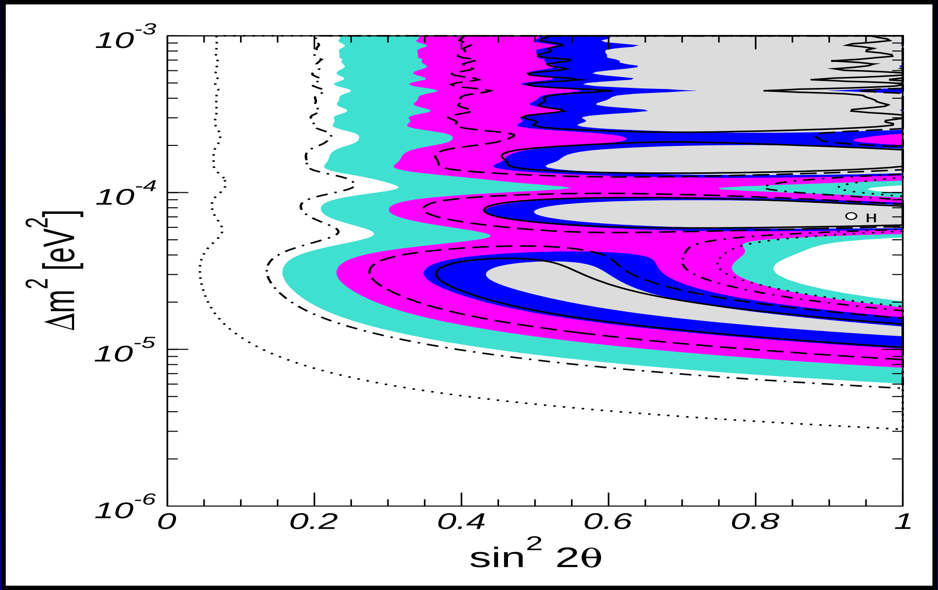
KamLAND rules out non-oscillation descriptions

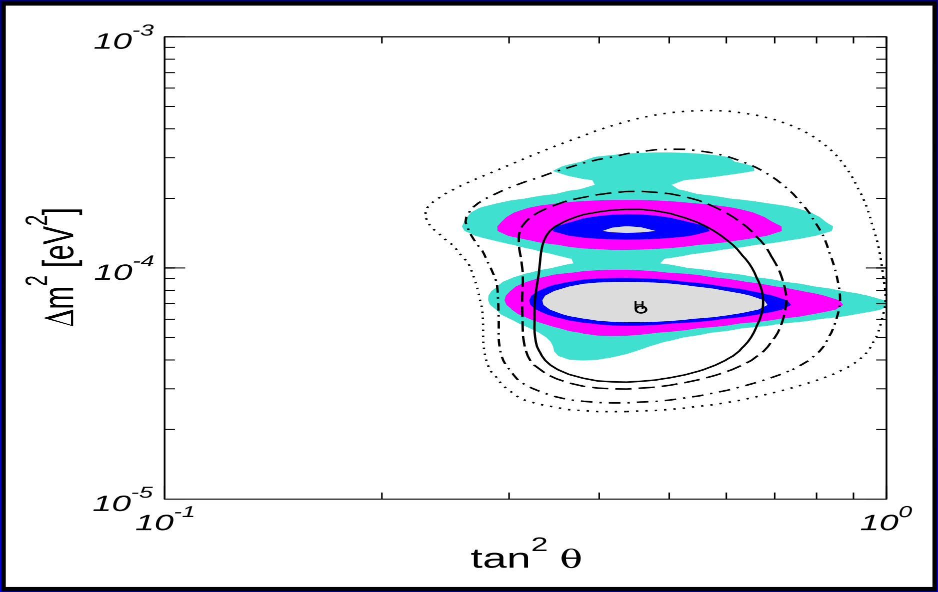
Barranco et al PRD66 (2002) 093009 [hep-ph/0207326]

Guzzo et al NPB629 (2002) 479

KamLAND confirms the oscillation hypothesis

Implications of first 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

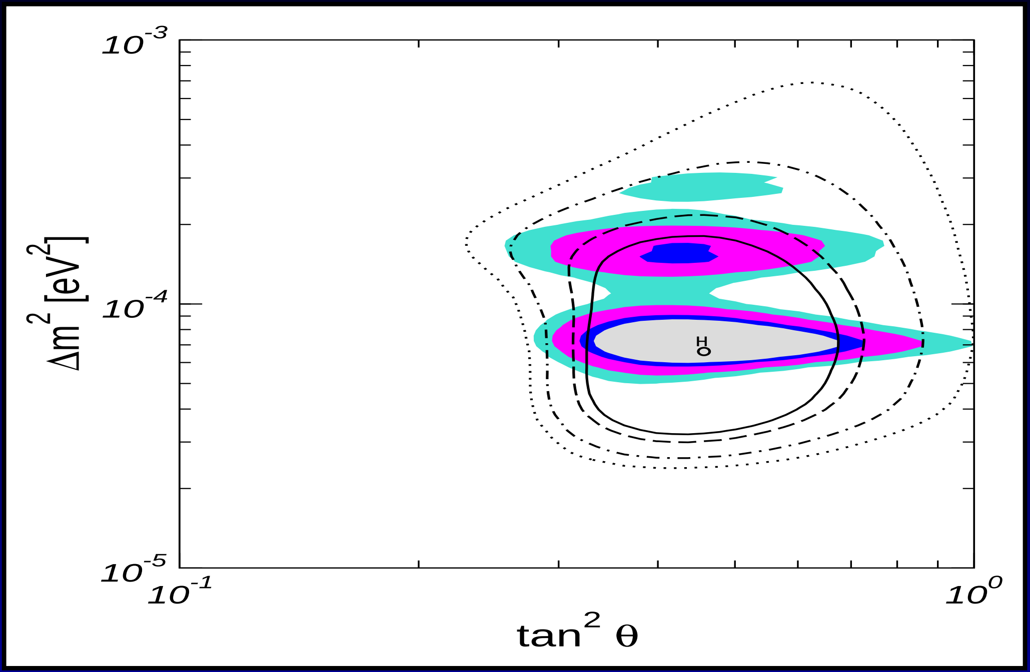
oscilllations happen inside the sun!

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

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

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

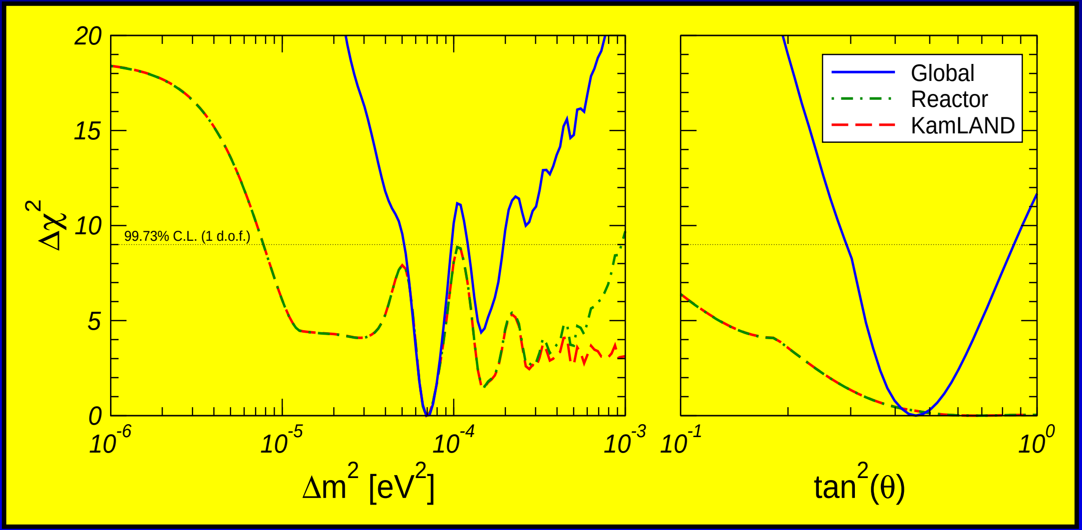
Solar + KamLAND results



Maltoni, Schwetz, JV, PRD67 (2003) 093003

consistency with Poisson method

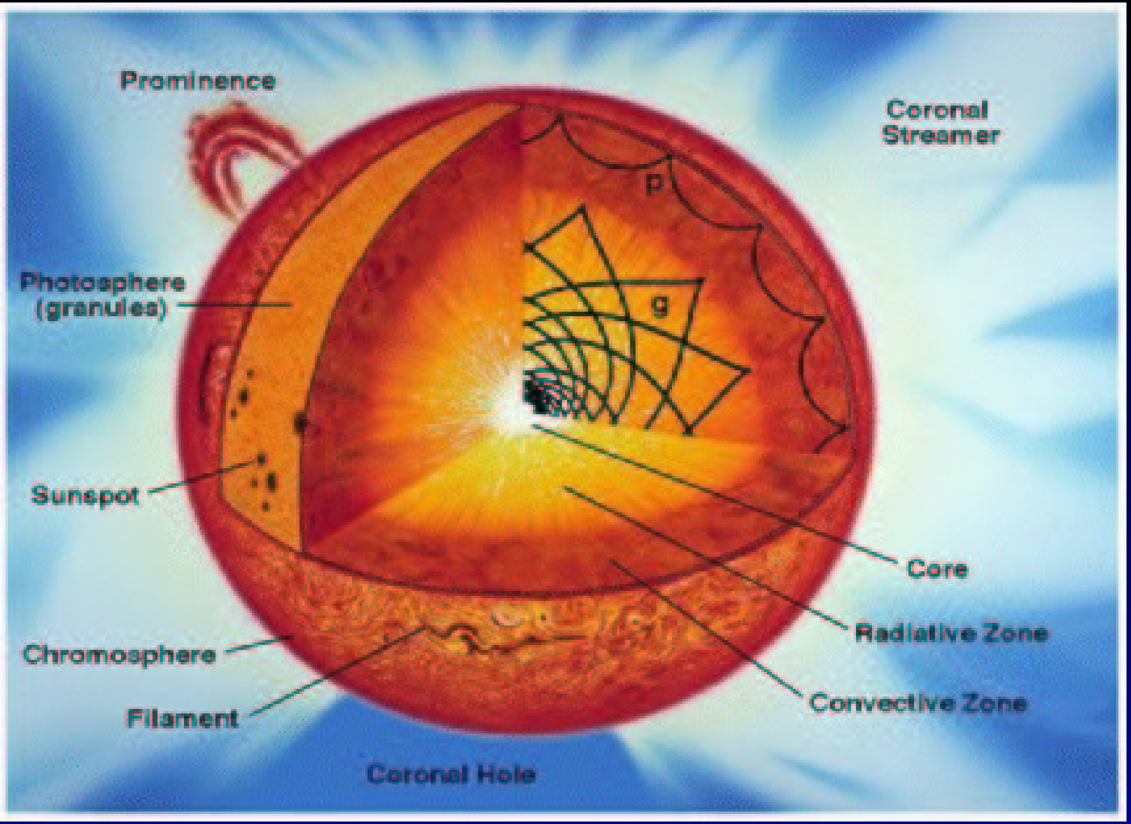
enormous progress wrt pre-KamLAND

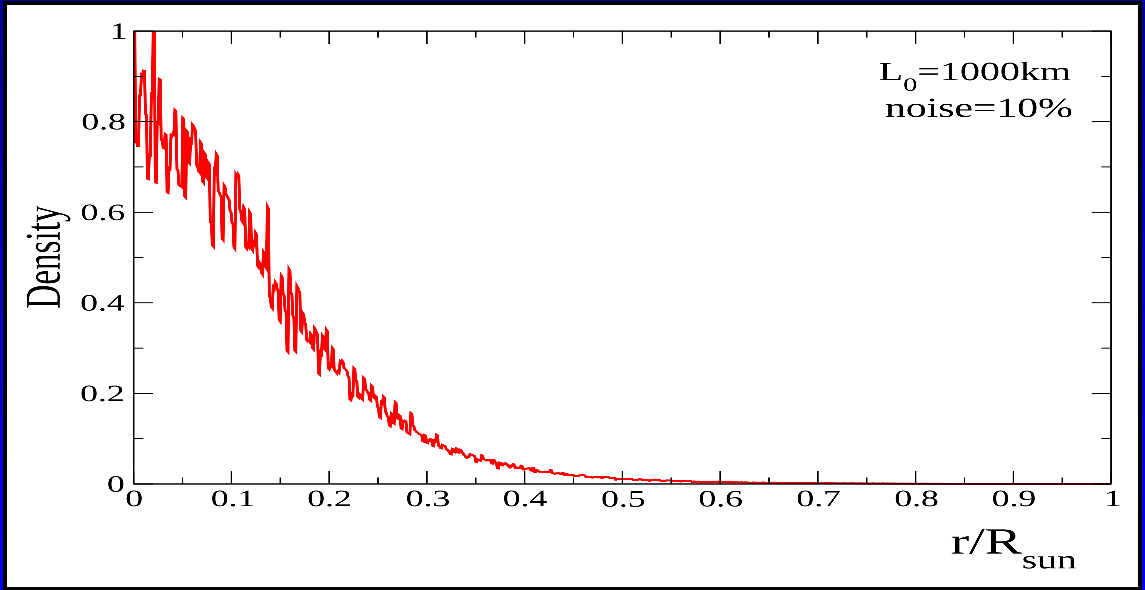


in contrast to atmospheric, solar mixing significantly non-maximal

bi-maximal models rejected

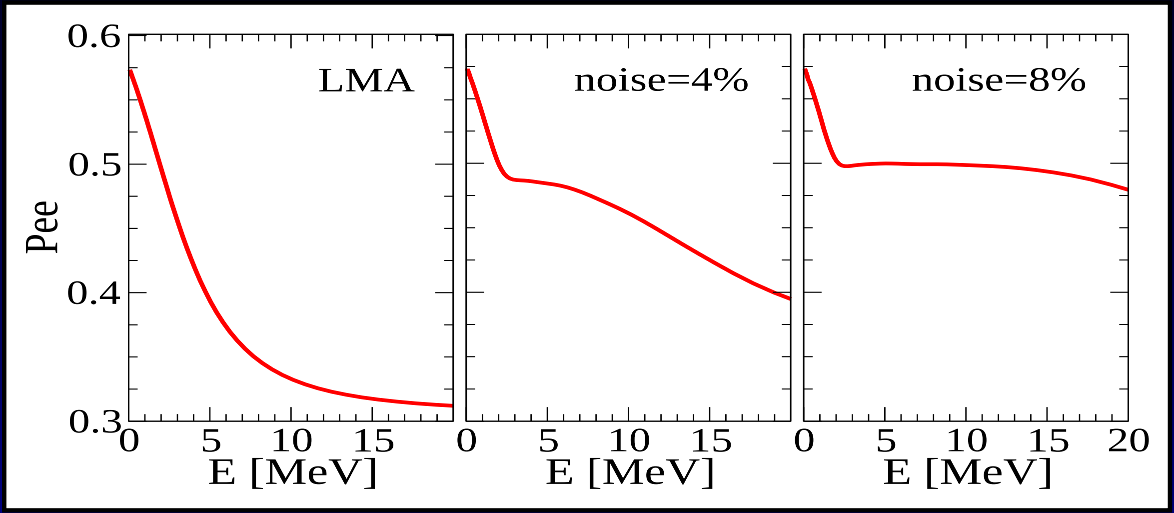
Noisy Sun ?

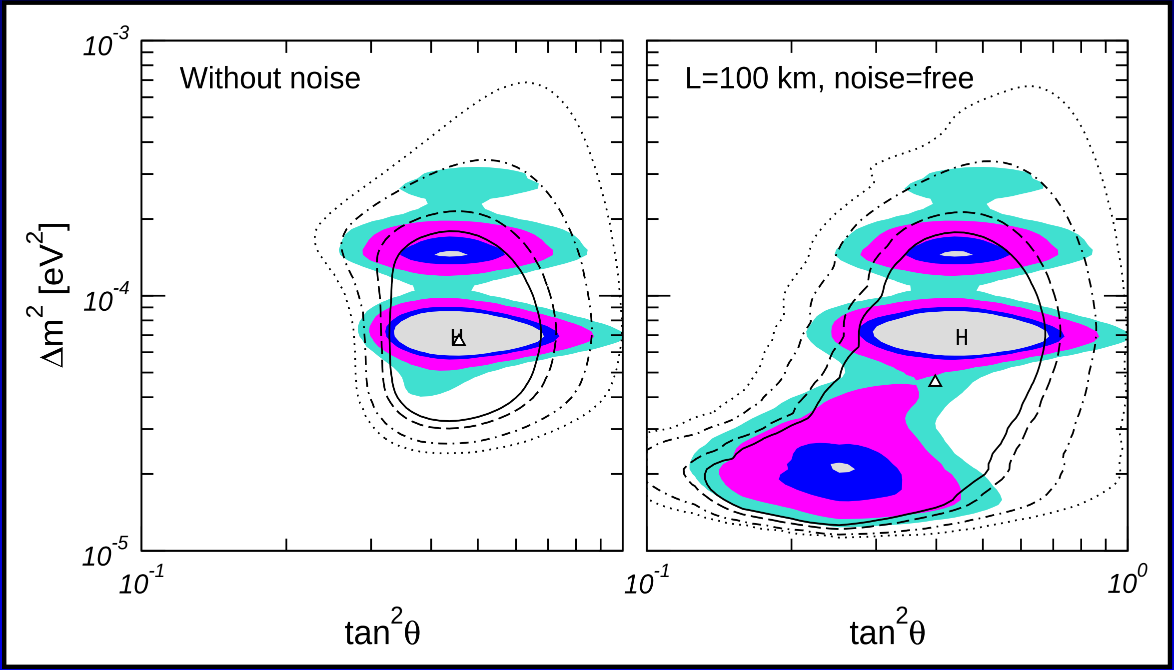

Prominence
Coronal Streamer
p
g
Photosphere (granules)
Sunspot
Core
Radiative Zone
Chromosphere
Filament
Convective Zone
Coronal Hole


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

Robustness of MSW plot

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





neutrino propagation strongly affected by density noise

Balantekin et al 95

Nunokawa et al NPB472 (1996) 495

Burgess et al 97

substantial distortion

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

Accelerator Neutrinos

Neutrinos are also produced in particle accelerators

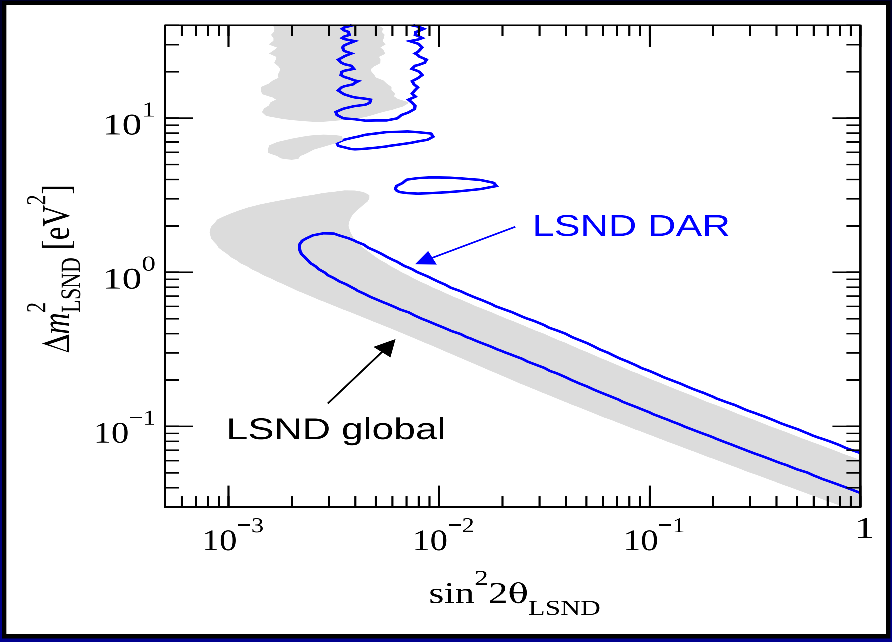
well controlled neutrino source

check 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

LSND

SOL

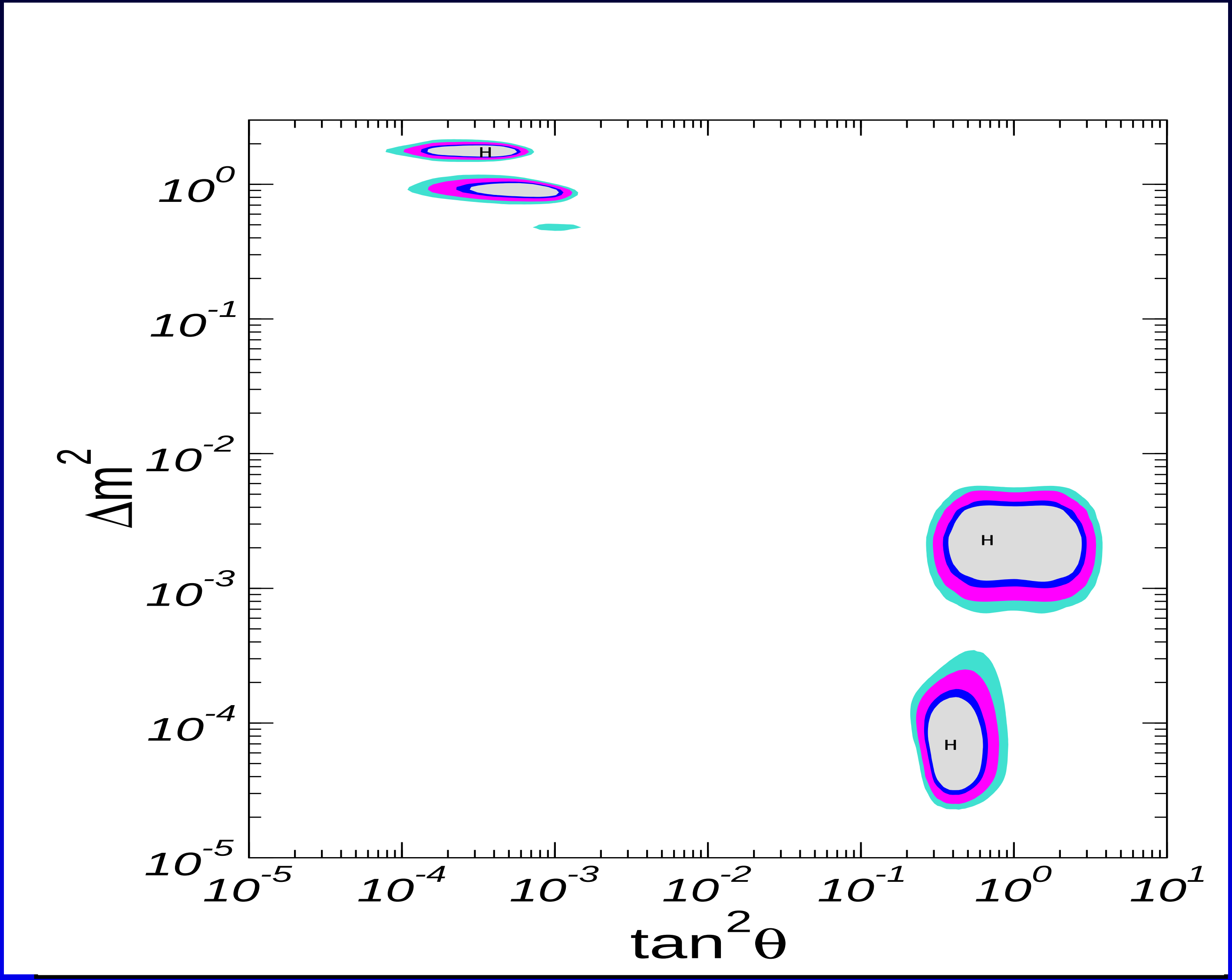
Peltoniemi, JV, NPB **406**, 409 (1993)
Peltoniemi, Tommasini and JV, PLB **298** (1993) 383

Caldwell-Mohapatra PRD48 (1993) 325

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

Grand Unified oscillation plot ?

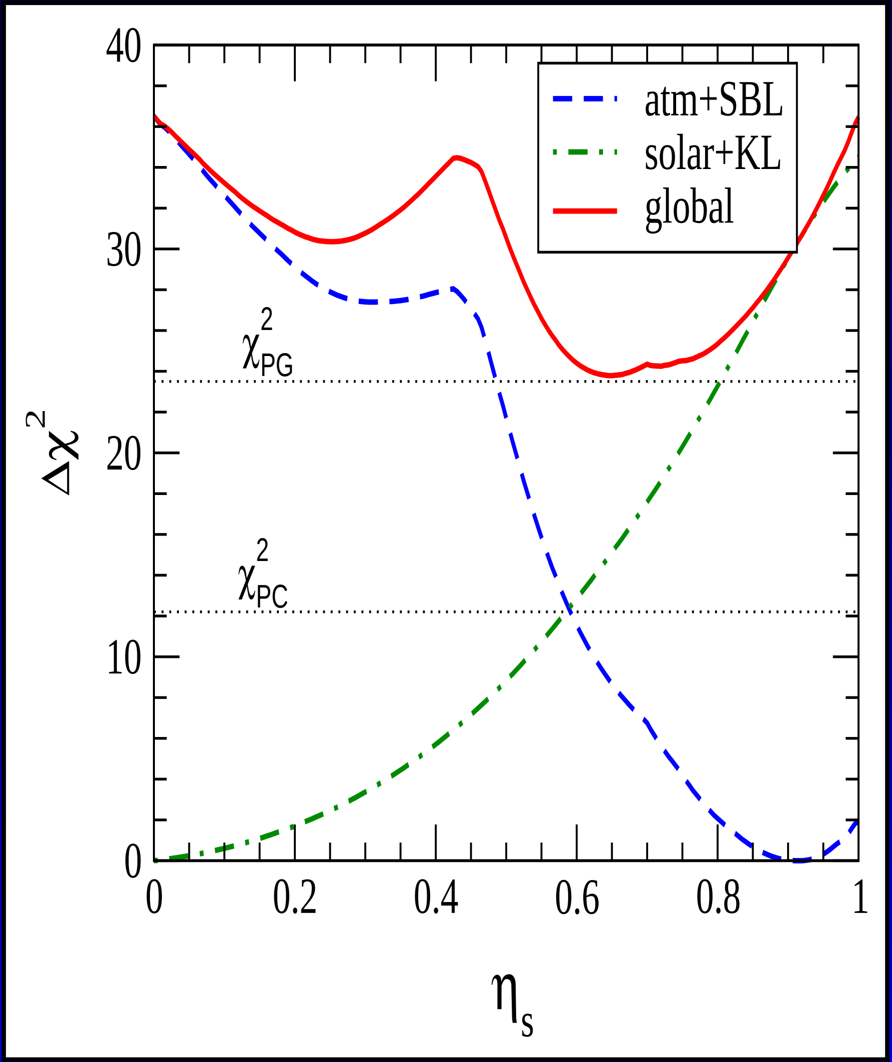
can oscillations fit all current nu-data | sol+atm+reac+**sbl/lsnd**

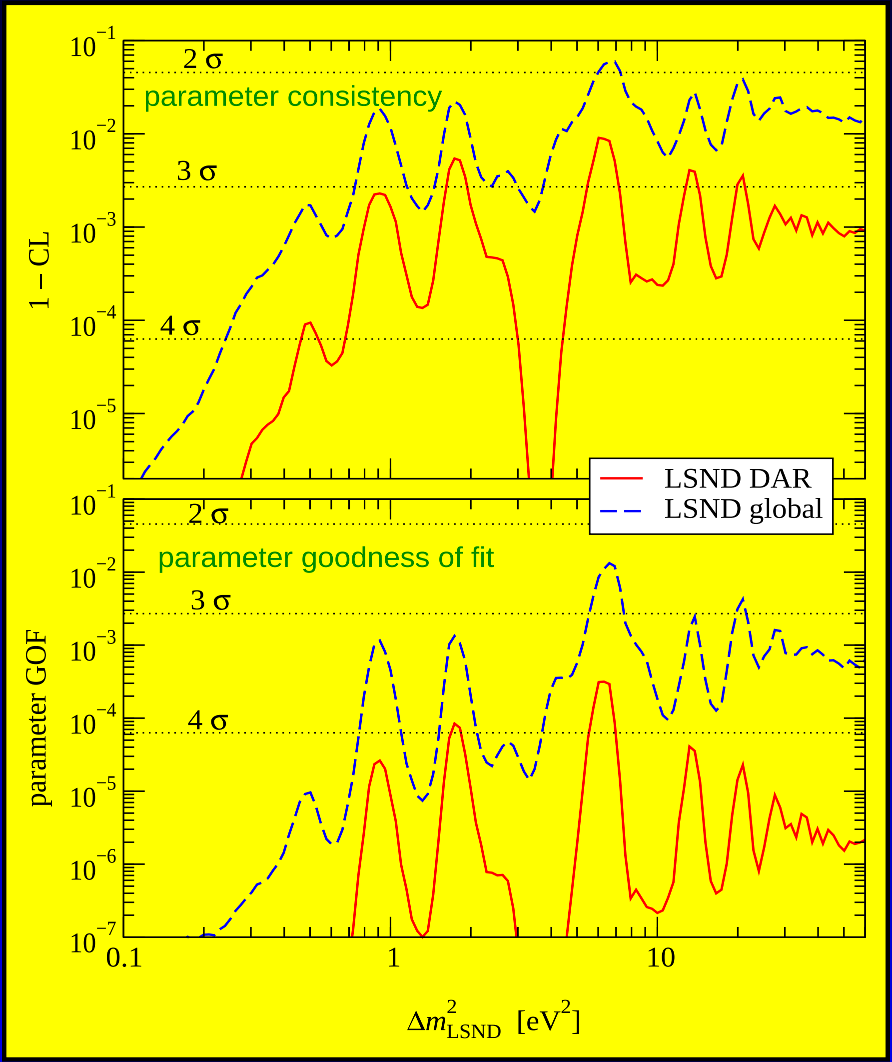


4-nus do not really fit LSND with the rest

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

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





Pas & Weiler

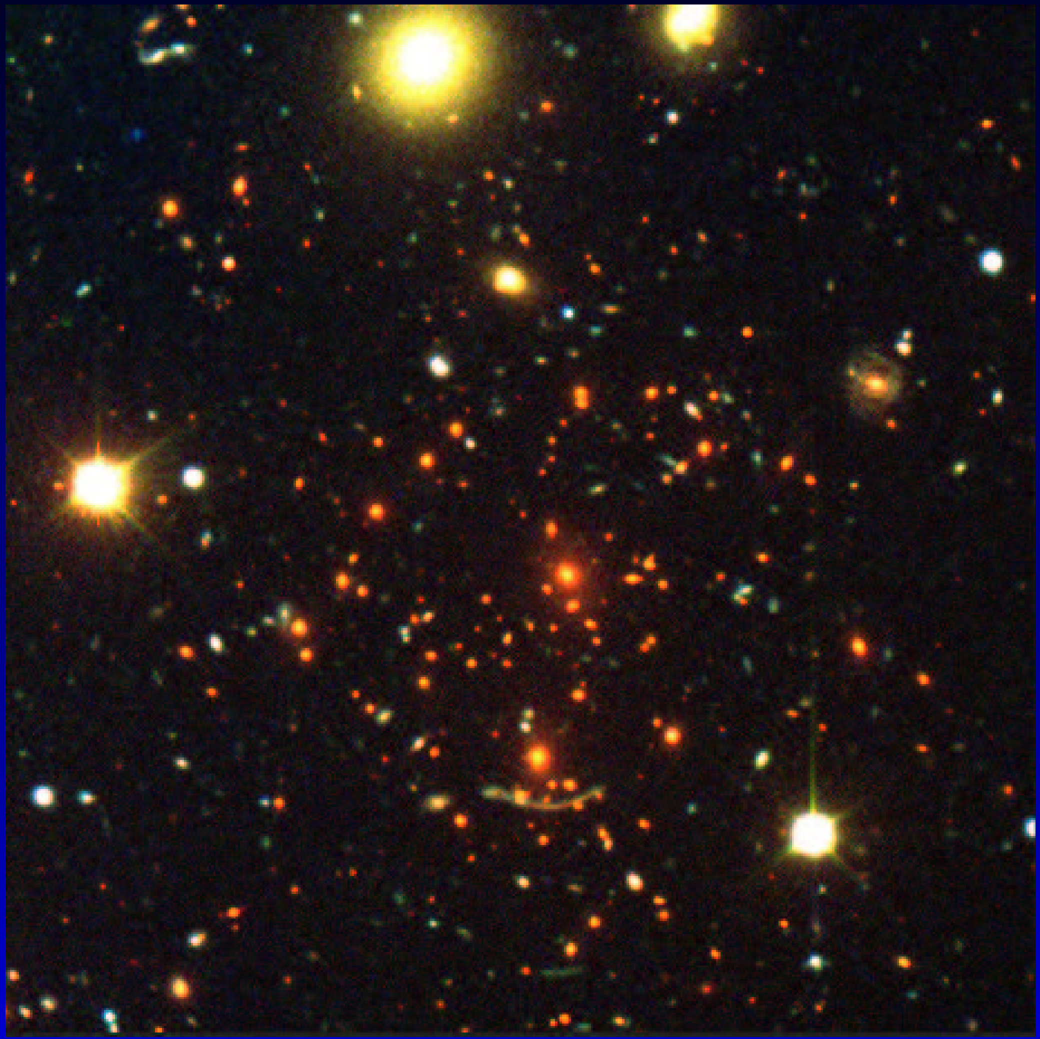
Cosmological Neutrinos

Neutrinos were copiously produced in the early hot and dense universe

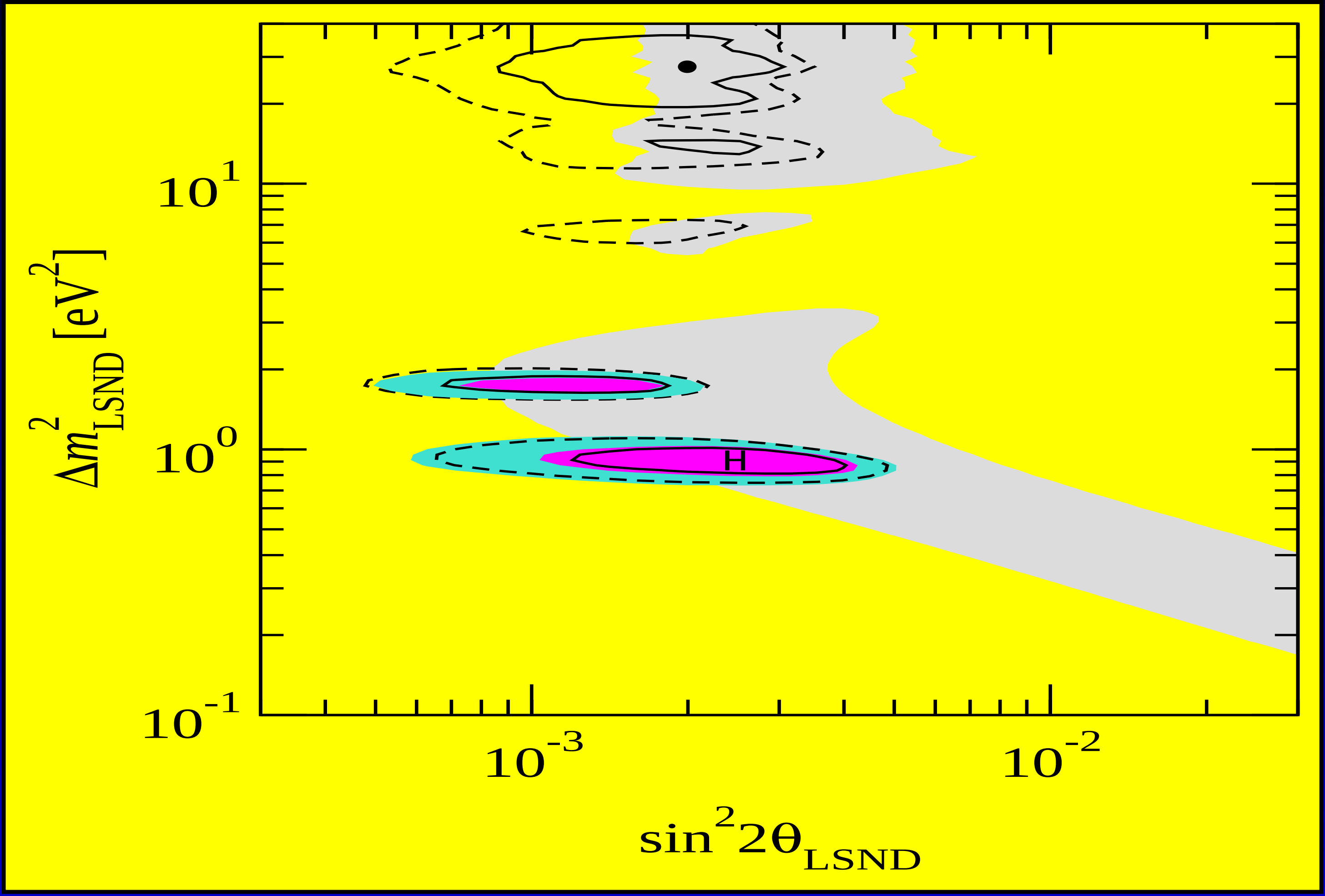
there are 336 neutrinos of the three flavours per cm^3, a bit more than the CMB photons

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



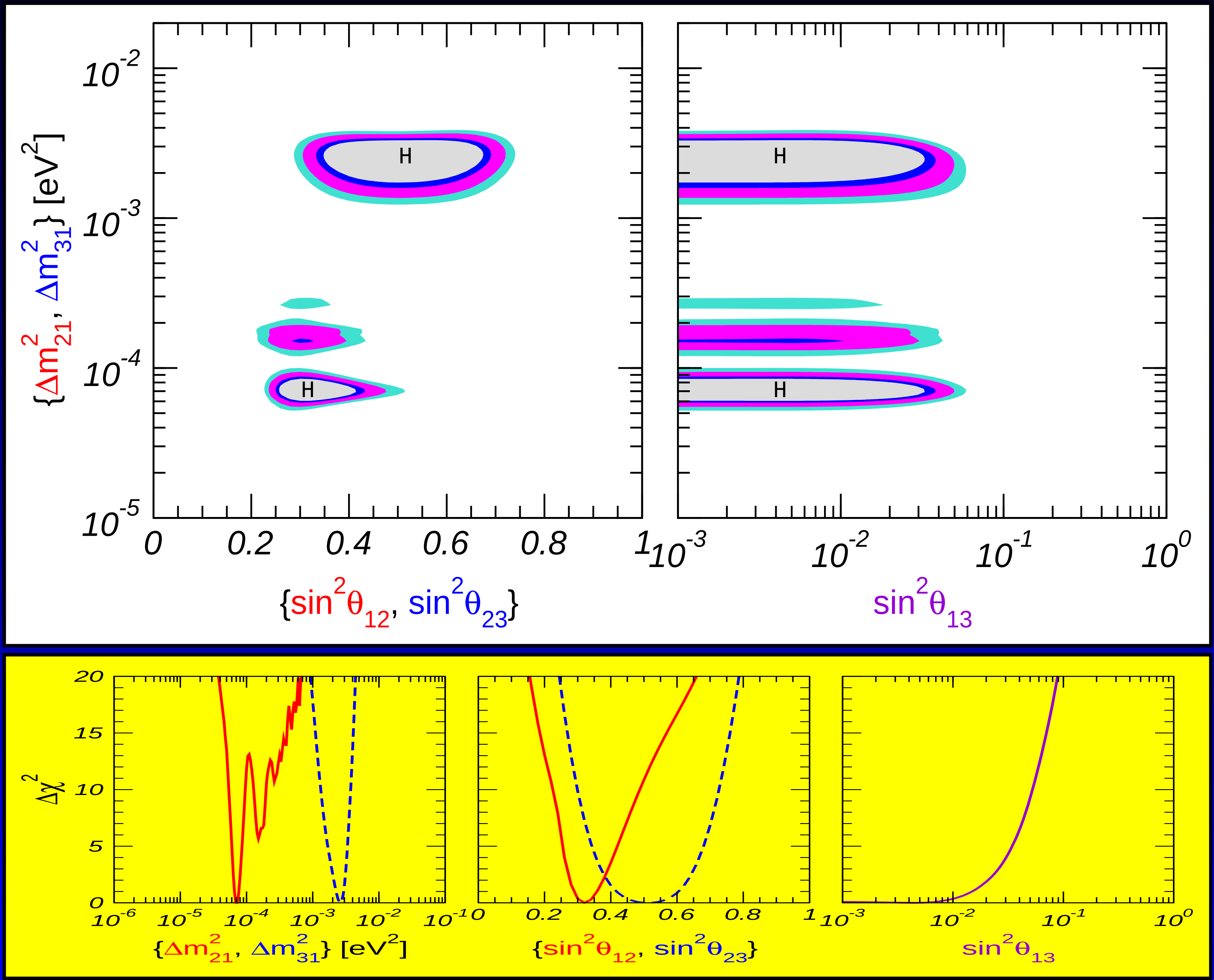
2df + WMAP + HST + SNIa

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

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

both appear in leptogenesis

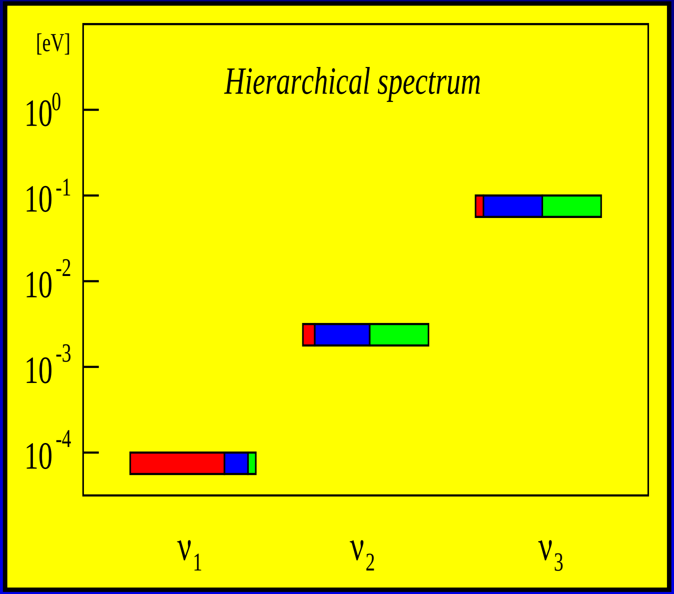
minimal set of basic parameters

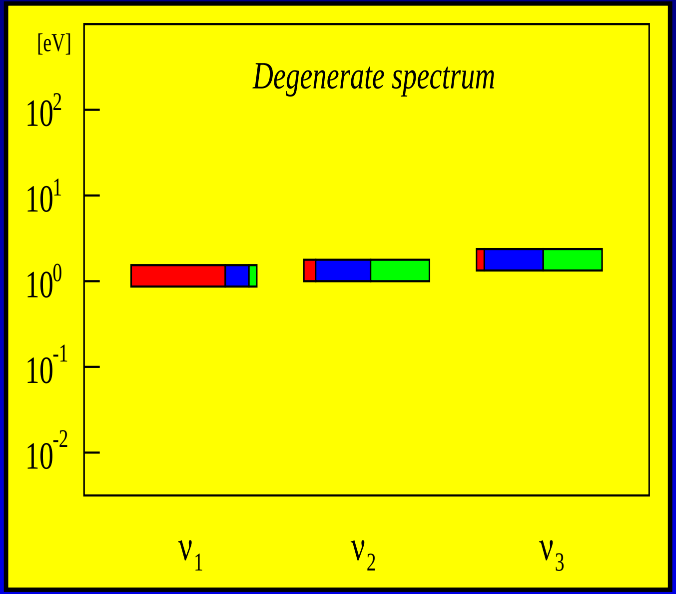
- 3 angles θ_{ij} — 23=atm 12=sol 13=reac
  1 KM-like phase — oscillations — δ
  2 Majorana phases — $\beta\beta_{0\nu}$ — $\alpha\ ,\beta$

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

both appear in leptogenesis

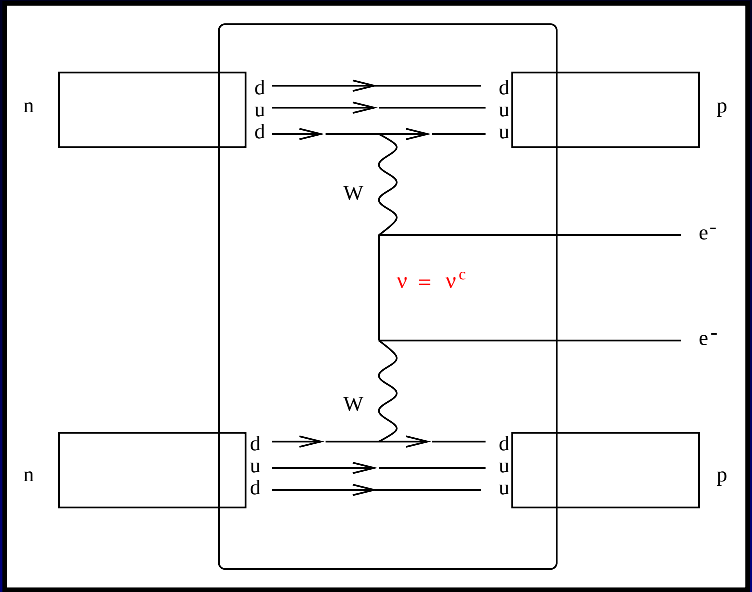
- max θ_{23}, large θ_{12} & small θ_{13} — ν_e ν_μ ν_τ





$\beta\beta_{0\nu}$ 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

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

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

three possibilities

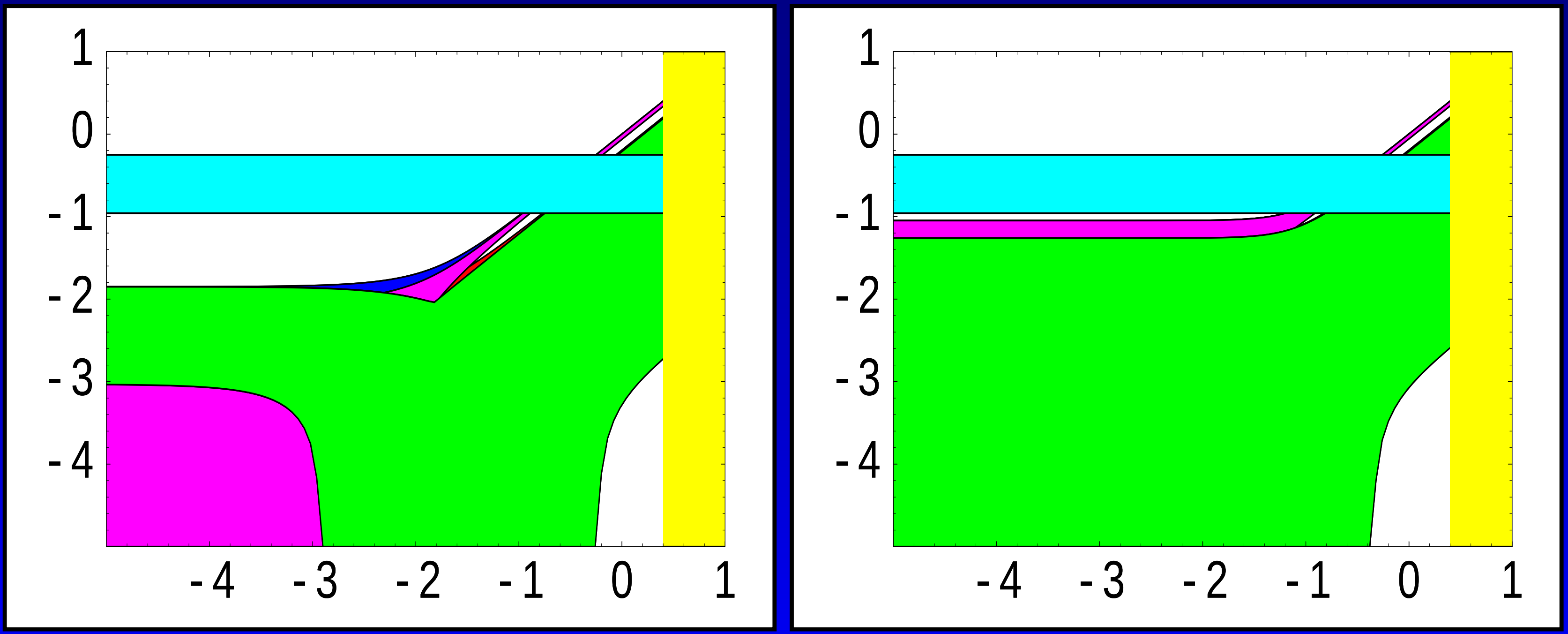
current laboratory tests of absolute neutrino mass

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: $m_1 \leq 2.5$ eV

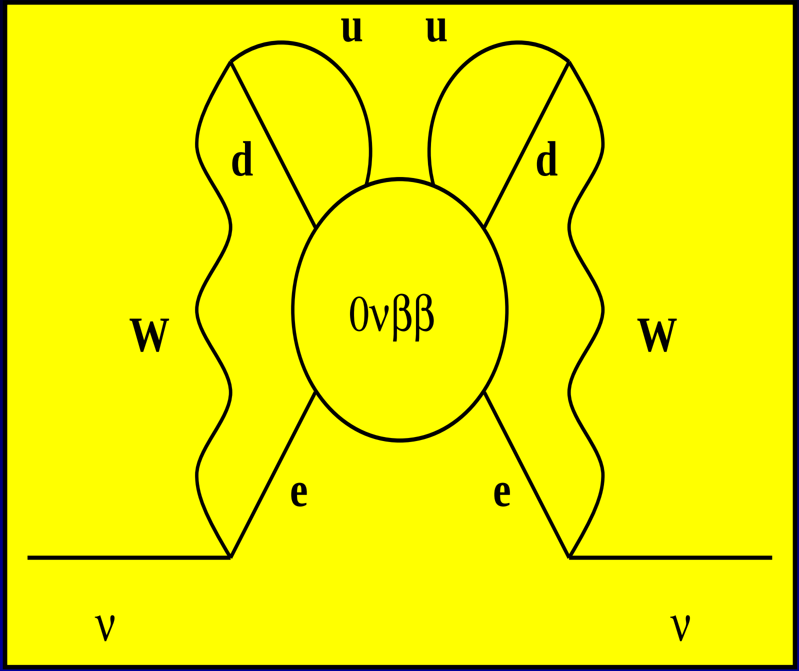
normal versus inverse hierarchy Log $\langle m_\nu \rangle$/eV vs Log m_1/eV



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

Perversity of nature?

θ_{13} and Leptonic CP Violation

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

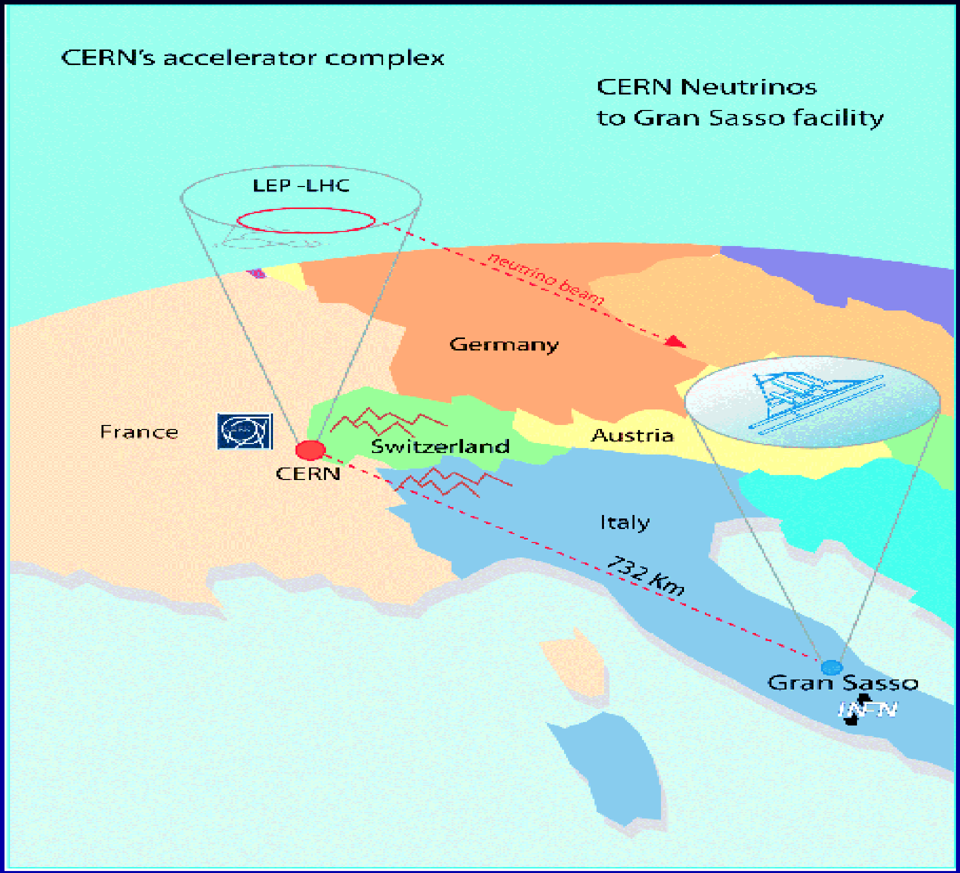
Schechter and J. V., PRD **21** (1980) 309

Try harder

Neutrino Factories

apart from probing s_{13} and δ ...

Cervera et al, De Rujula, Gavela, Hernandez, Fre-und, Huber, Lindner, Albright et al, Barger et al...

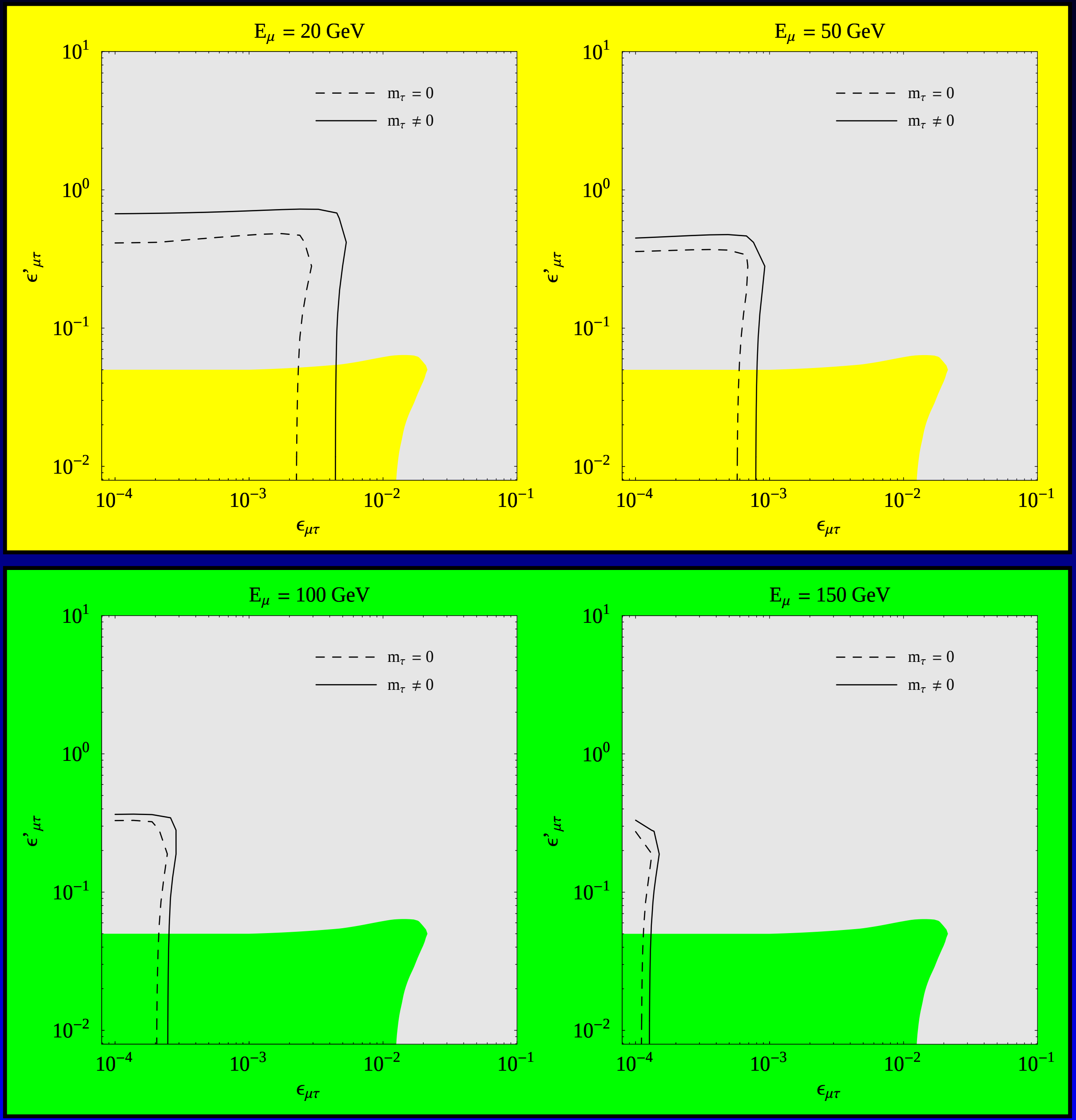


they can probe Non-Standard nu-Intercations (NSI)

Improved FC-tests at NuFact

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

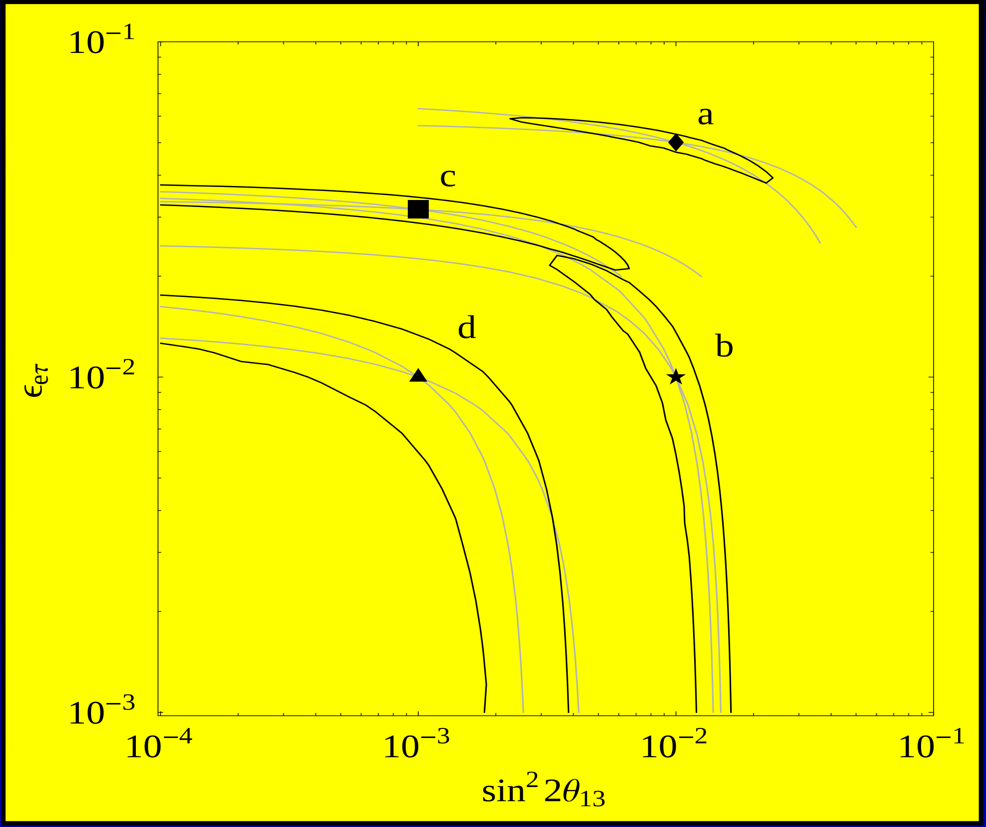
10 kt detector, 0.33 ν_τ detection eff above 4 GeV; need no tau charge id



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)

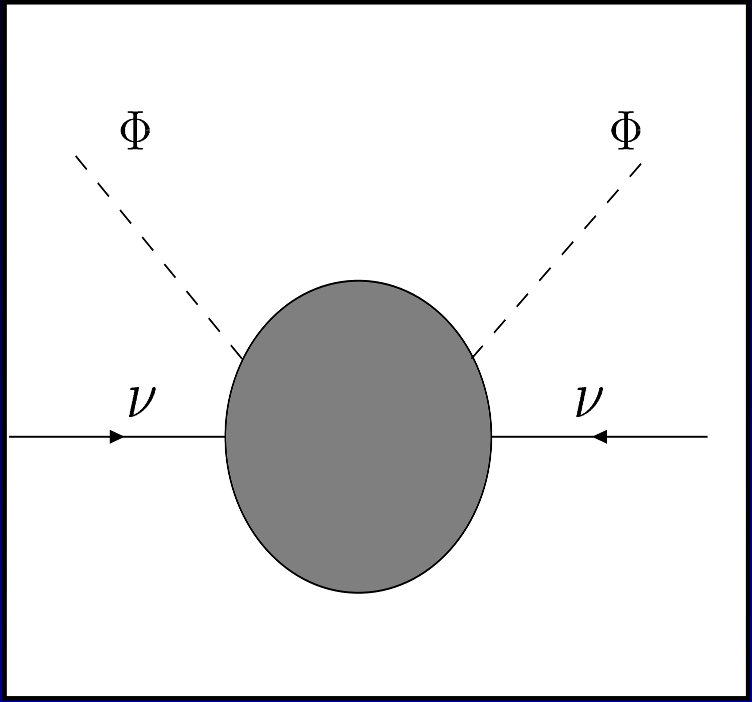


near-site programme essential

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

Theory ideas

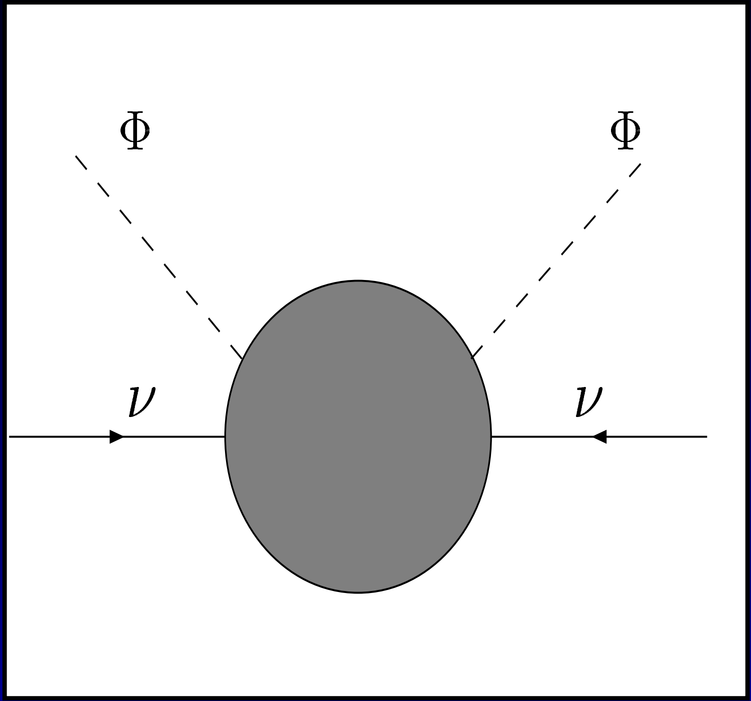
basic dim-5 operator



- from Gravity

Weinberg; Barbieri, Ellis, Gaillard; Zee & Weldon

basic dim-5 operator

- 

  from Gravity

  Weinberg; Barbieri, Ellis, Gaillard; Zee & Weldon

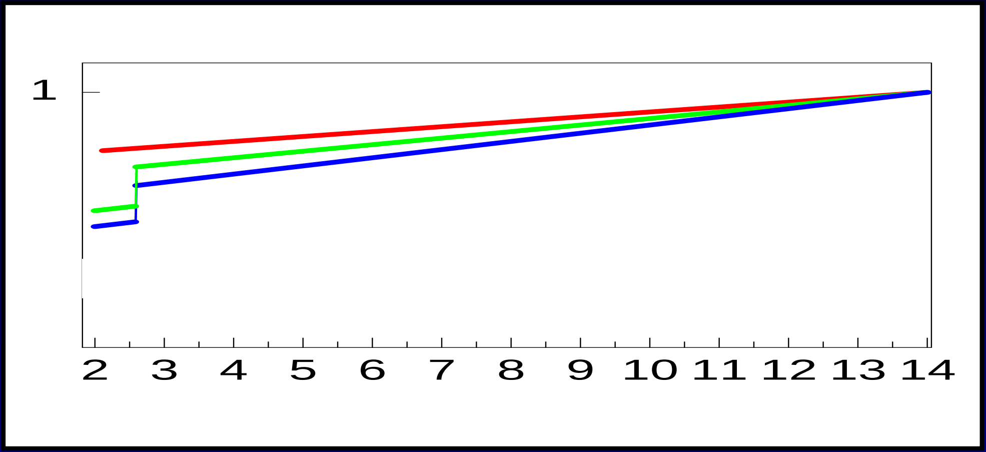
- from seesaw schemes

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

neutrino unification: large-scale seesaw

- 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 Valle, PRL86 (2001) 3488

solar & atm splittings from RGE

common origin for neutrino and KM mixing

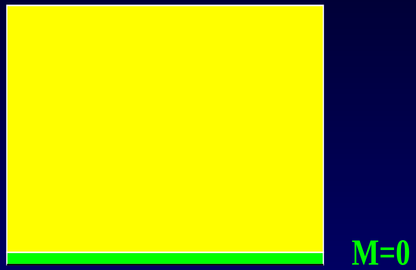
maximal θ_{23}; large θ_{12} & $\theta_{13} = 0$ or maximal CP violation see also Grimus & Lavoura

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

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

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

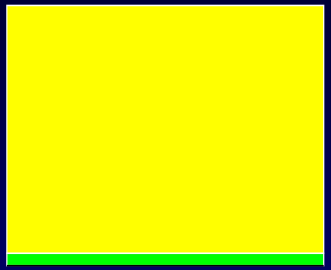


- weak-scale seesaw atm scale

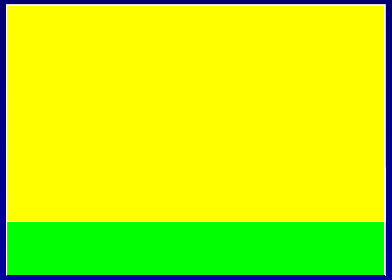
0-0

bilinear R parity violation: weak-scale seesaw

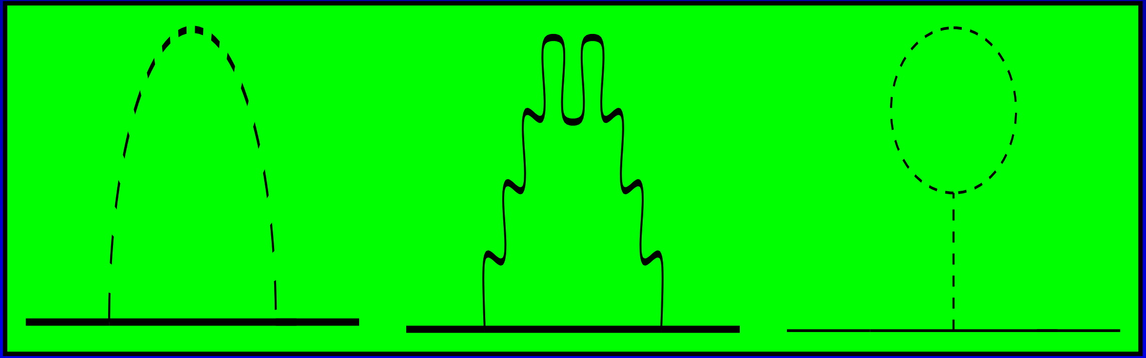
Diaz, Hirsch, Porod, Romao and Valle, hep-ph/0302021 PRD in press;
PRD **62** (2000) 113008 [Err-ibid. D **65** (2002) 119901]; PRD **61** (2000) 071703

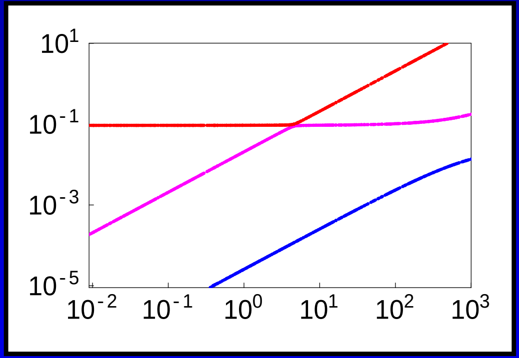


- weak-scale seesaw atm scale



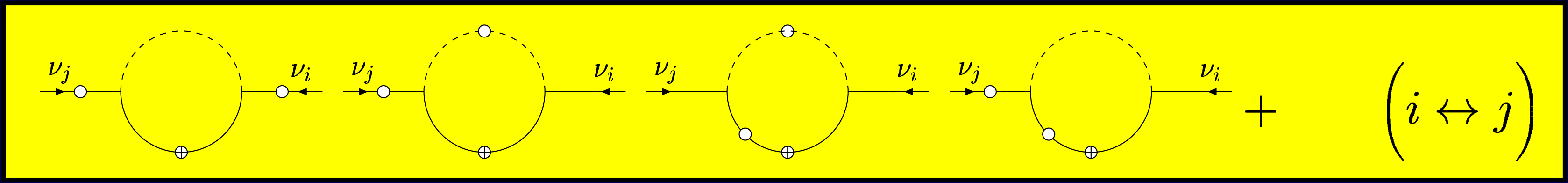
- radiative nu-masses solar scale

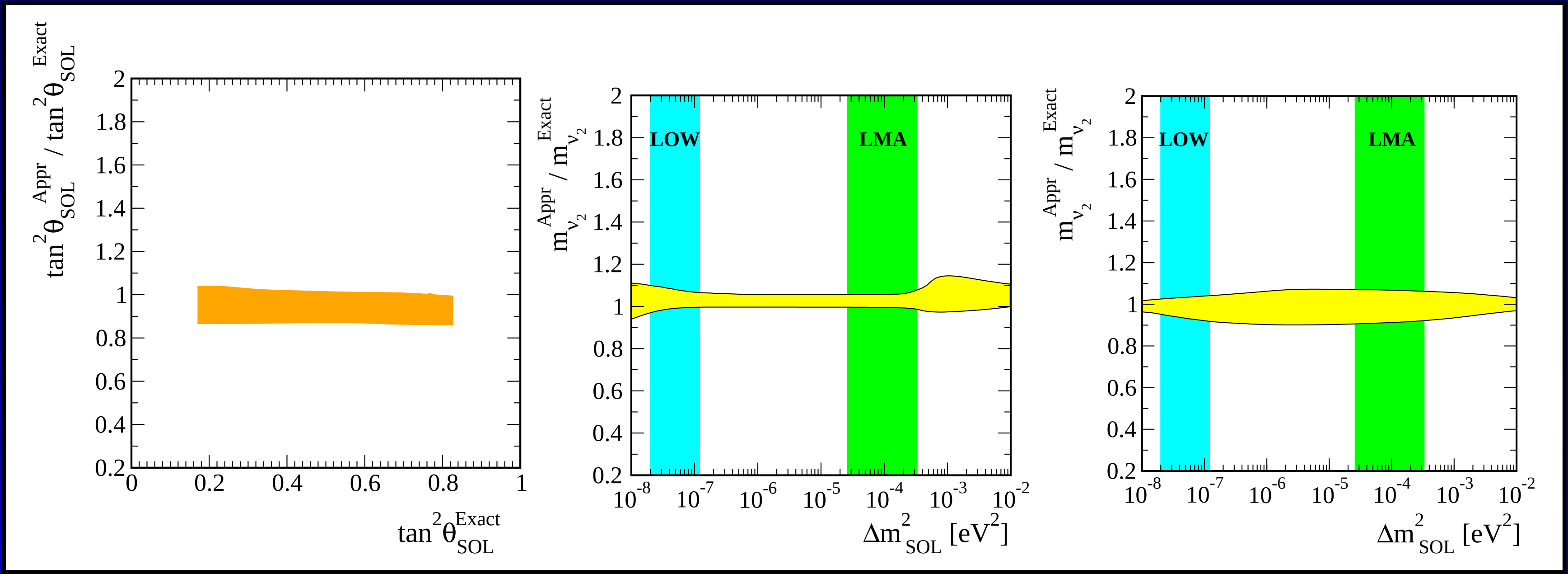




solar mass scale loops: analytical vs numerical

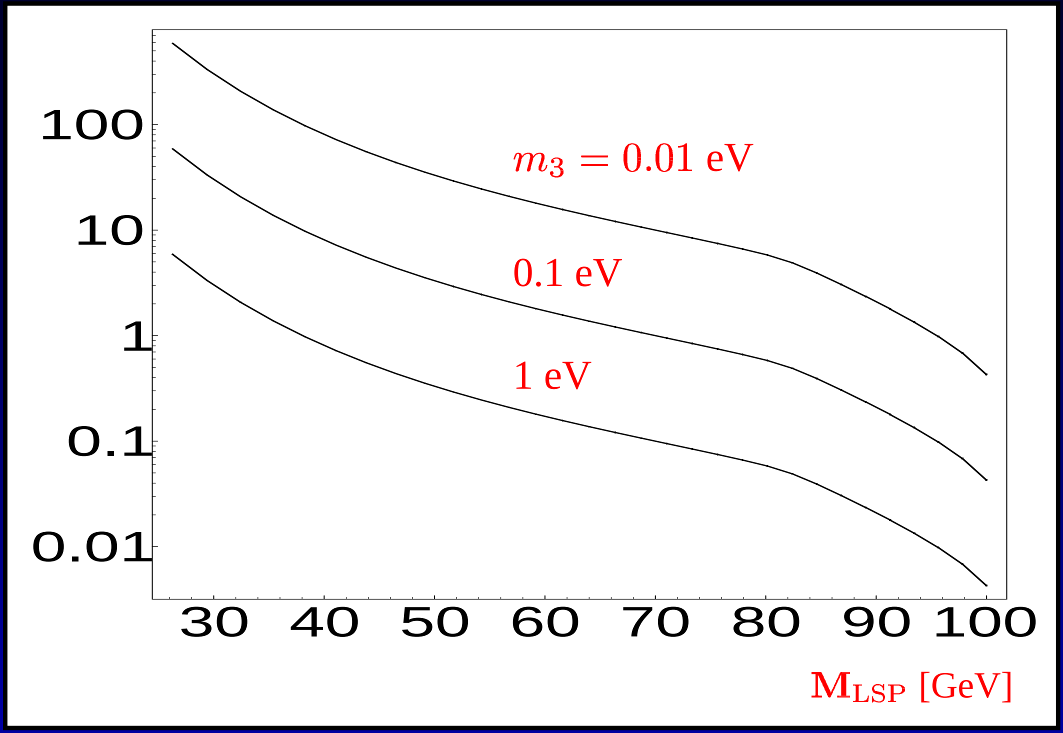
M. A. Diaz et al hep-ph/0302021





LSP decay length [cm]: BRPV

- from Bartl et al NPB 600 (2001) 39



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

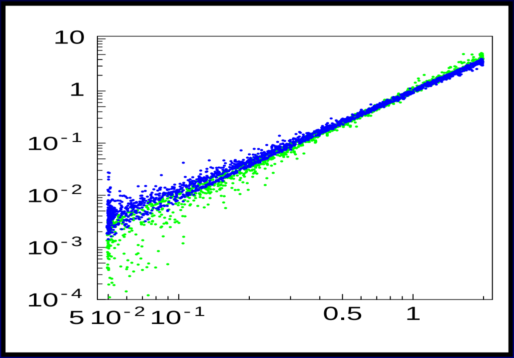
any charged SUSY particles can be the LSP

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)



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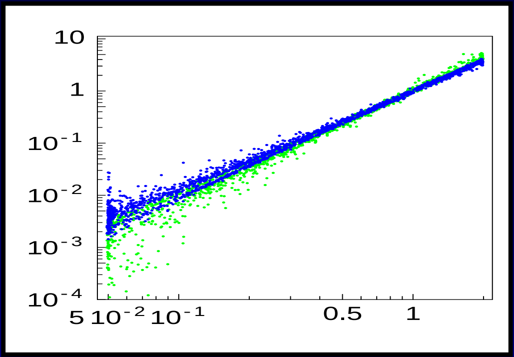
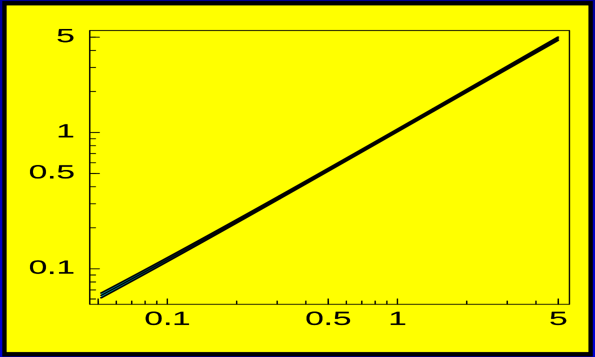


- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004

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



neutrino mixing angles in BRPV

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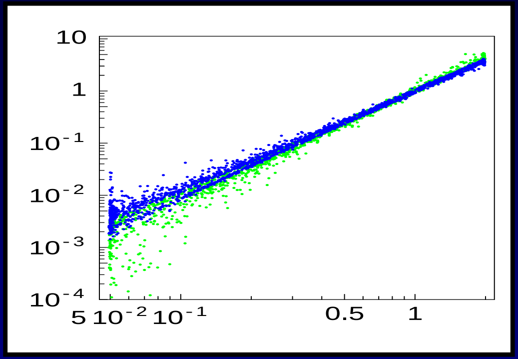
- mixings in terms of RPV ratios, e,g, atm mixing

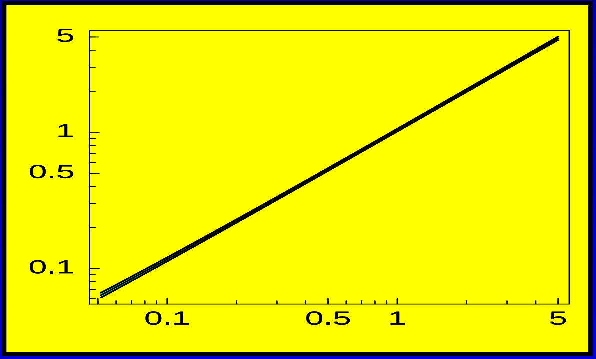


$\tan^2_{23}$ vs (Λ_2/Λ_3)

- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004



$\chi \rightarrow \mu q q / \chi \rightarrow \tau q q$ 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

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

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  - Weak $SU(3) \otimes SU(2) \otimes U(1)$ scale

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