Neutrino Properties: Analysis and Theory

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will follow recent review

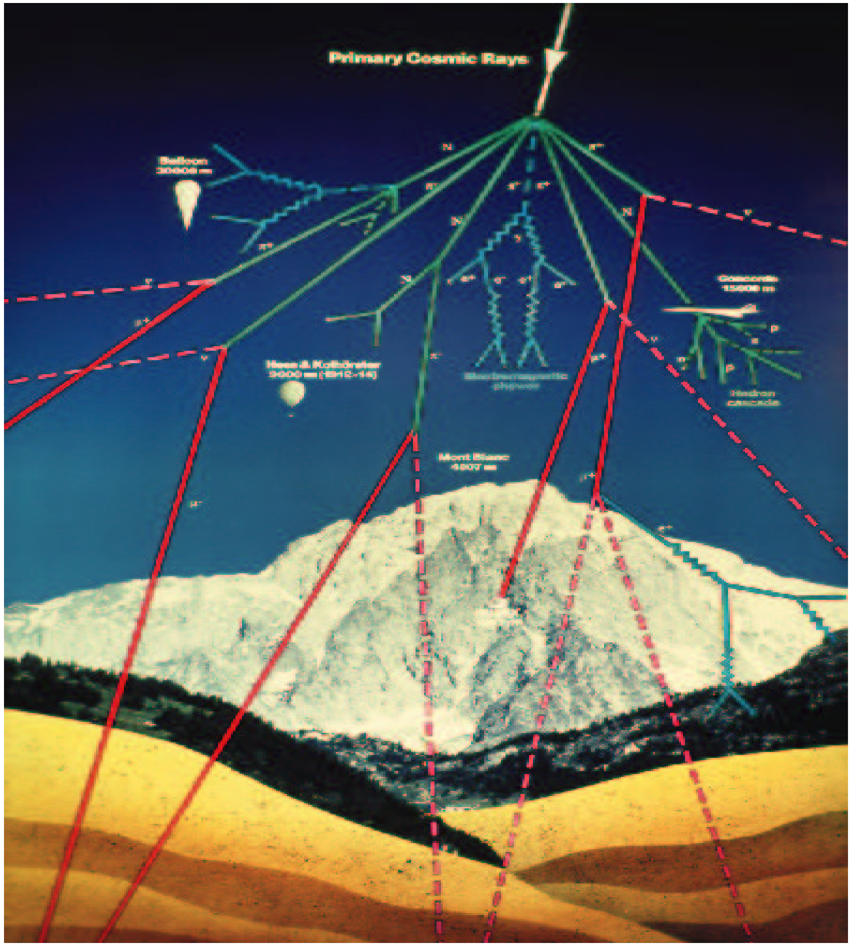
S. Pakvasa and JV "Neutrino properties before and after KamLAND"

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



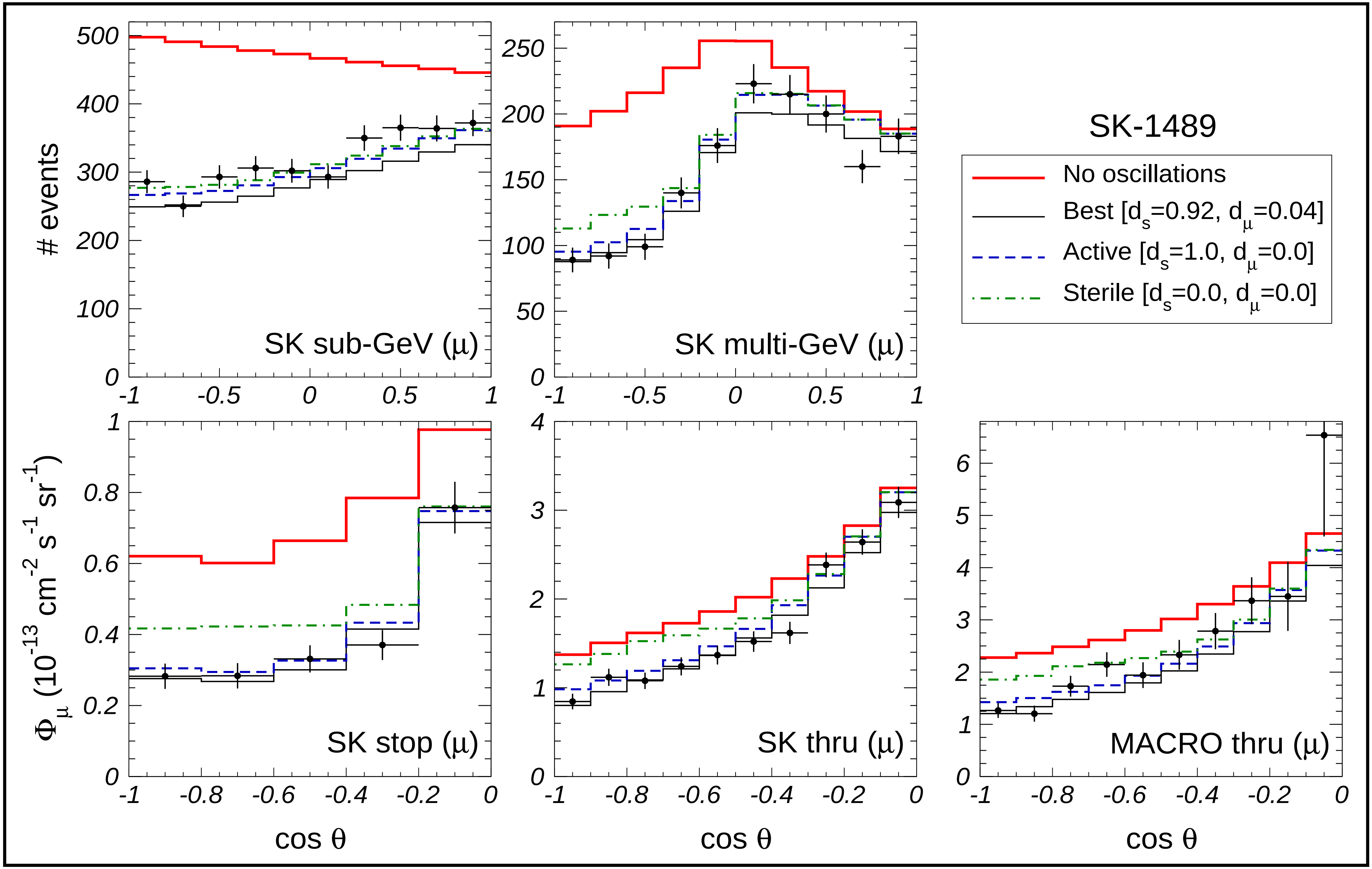
The ν_e flux measured by underground experiments is in agreement with the predictions.

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 Valle Phys. Rev. D 67 (2003) 013011 [hep-ph/0207227]



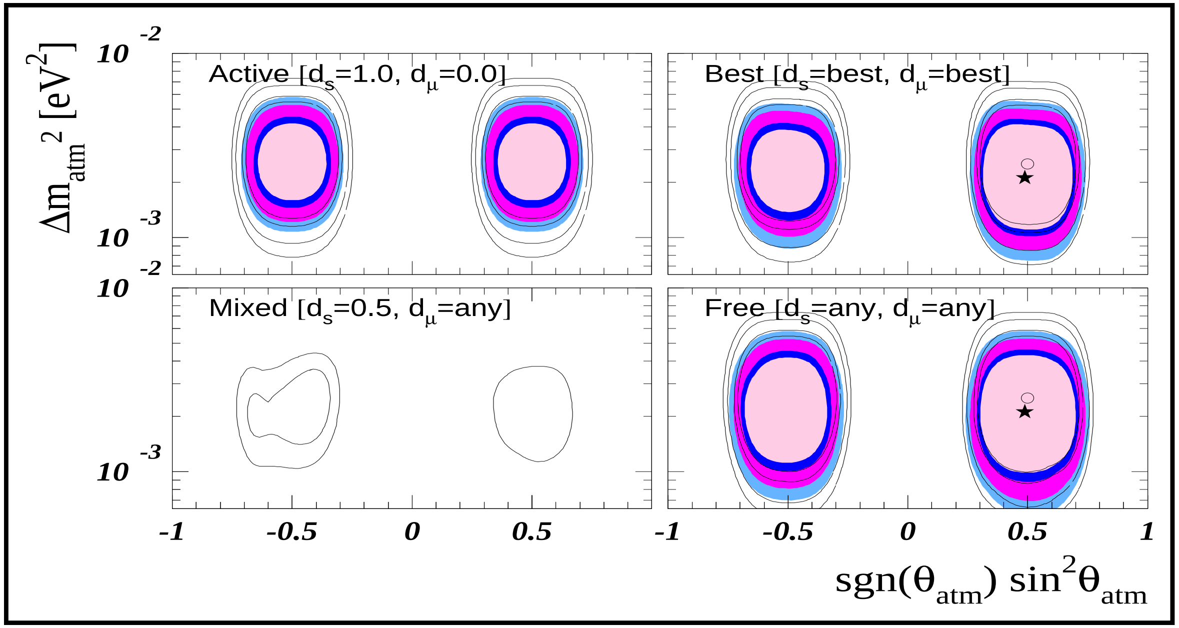
atmospheric neutrinos

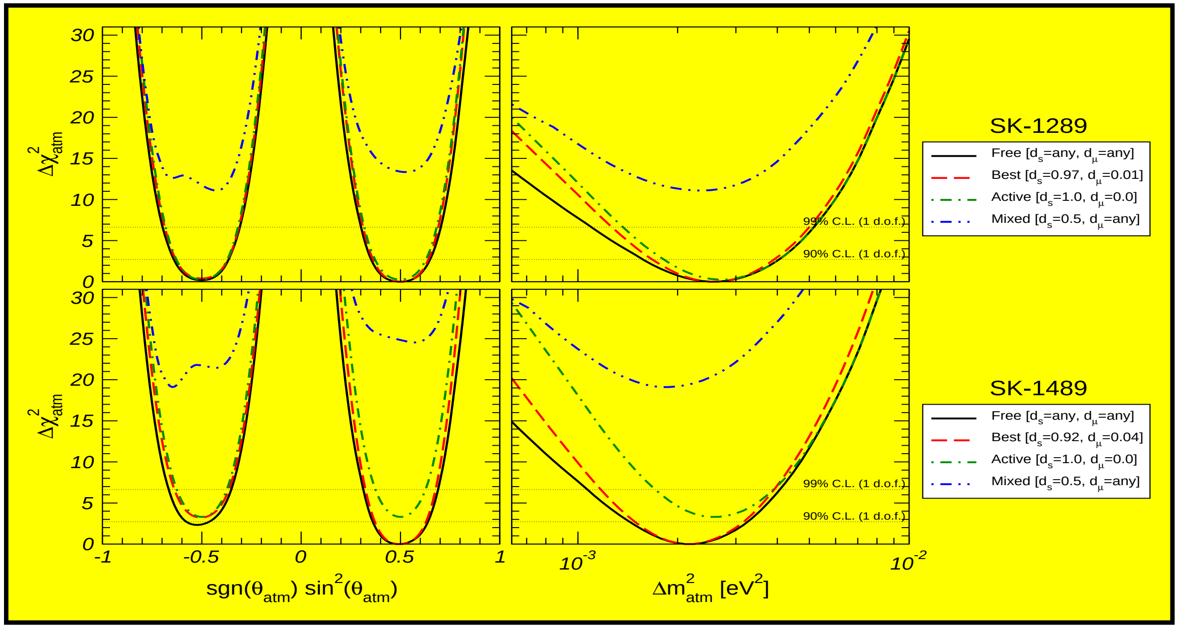
1289 vs 1489-day samples

Maltoni et al

Phys. Rev. D 67 (2003) 013011

hep-ph/0207227



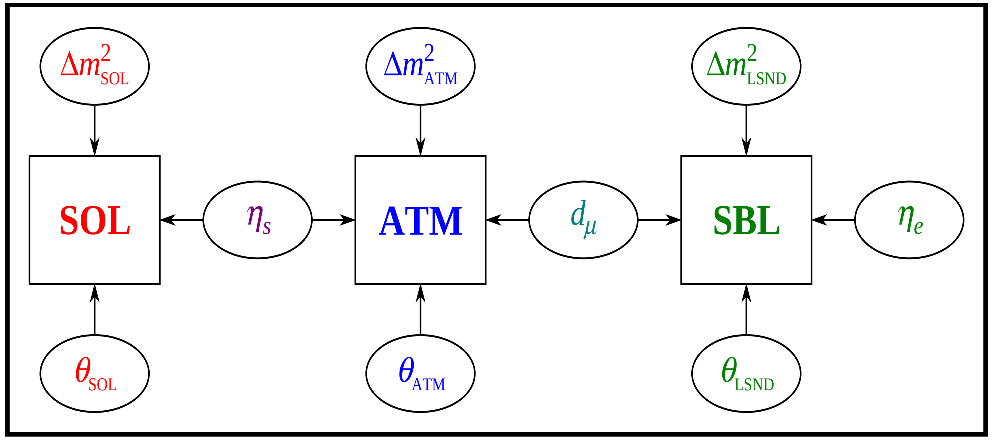


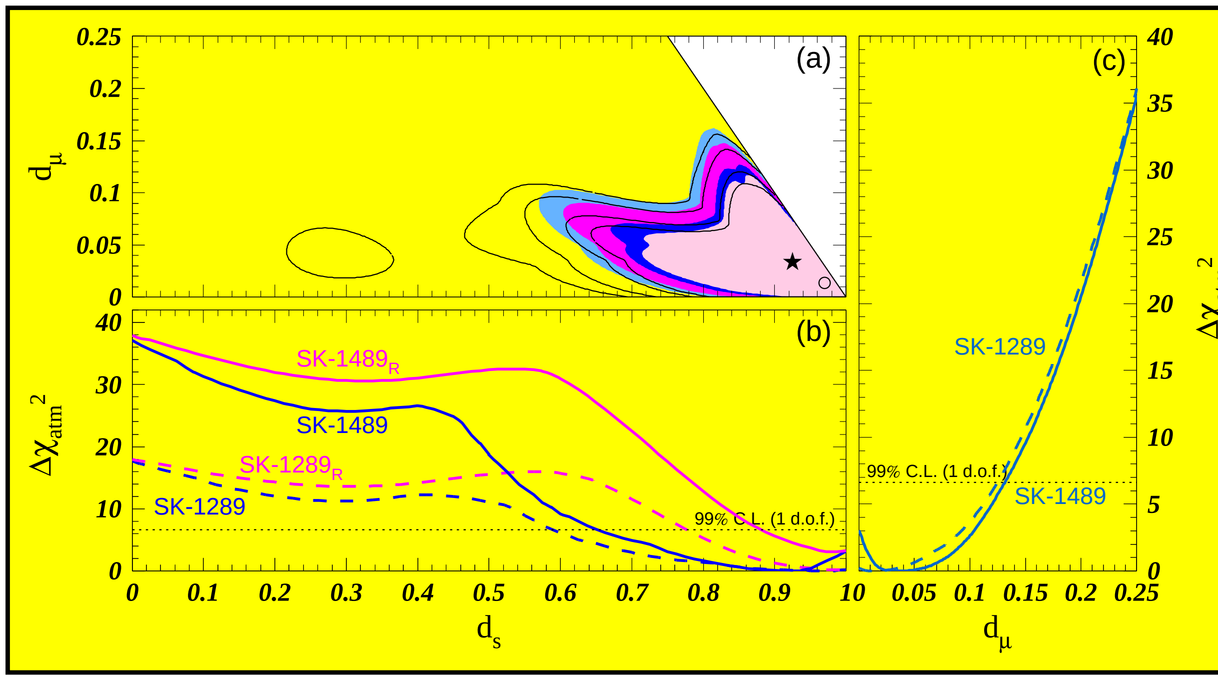
higher sterility rejection

new parameters in atmospheric analysis

sterile as 4th, not 2nd

neglecting CP phases there are 6 angles in the lepton mixing matrix





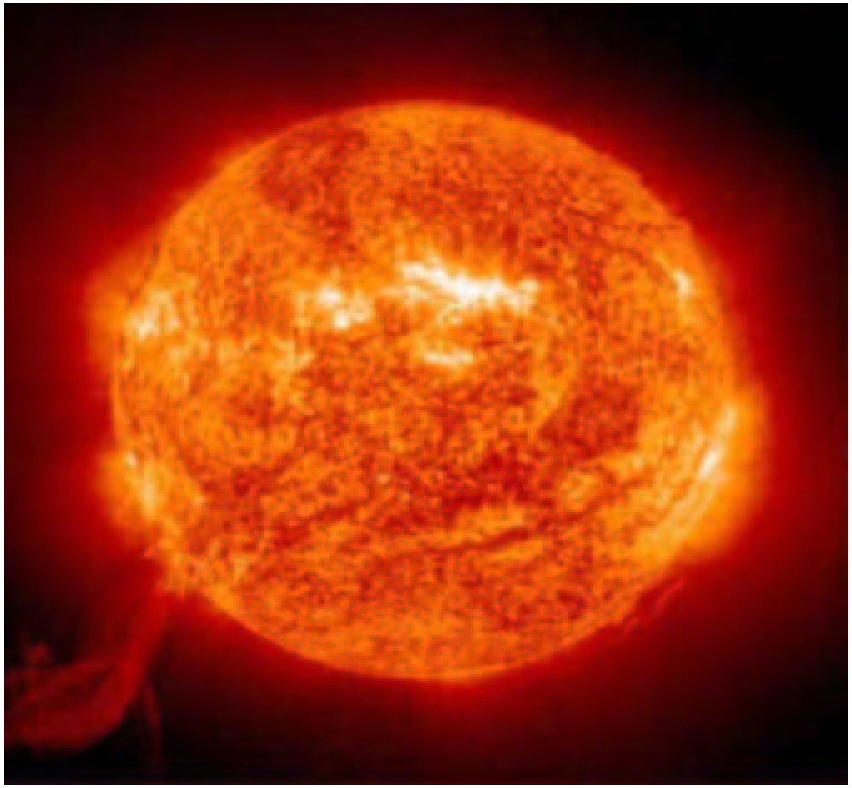
sterility rejection depends on new parameters

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

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

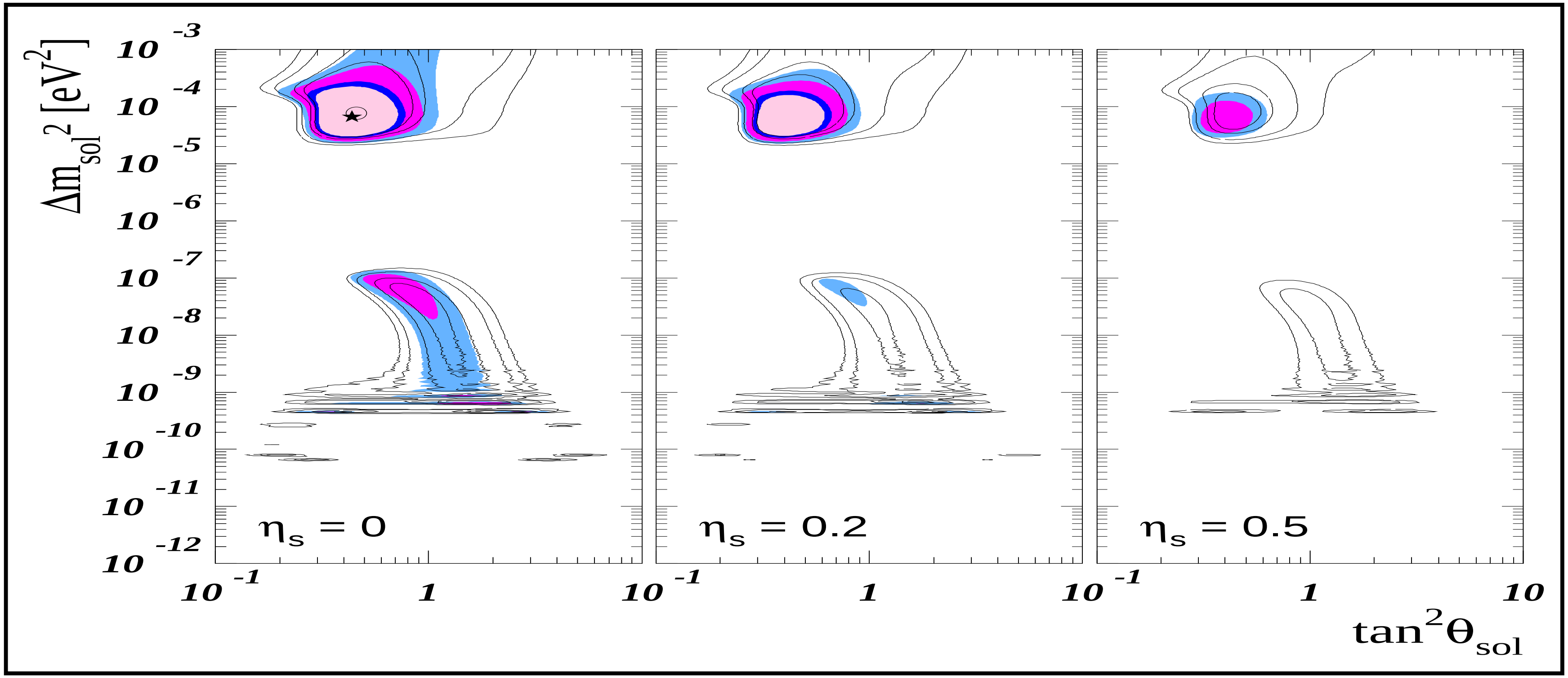


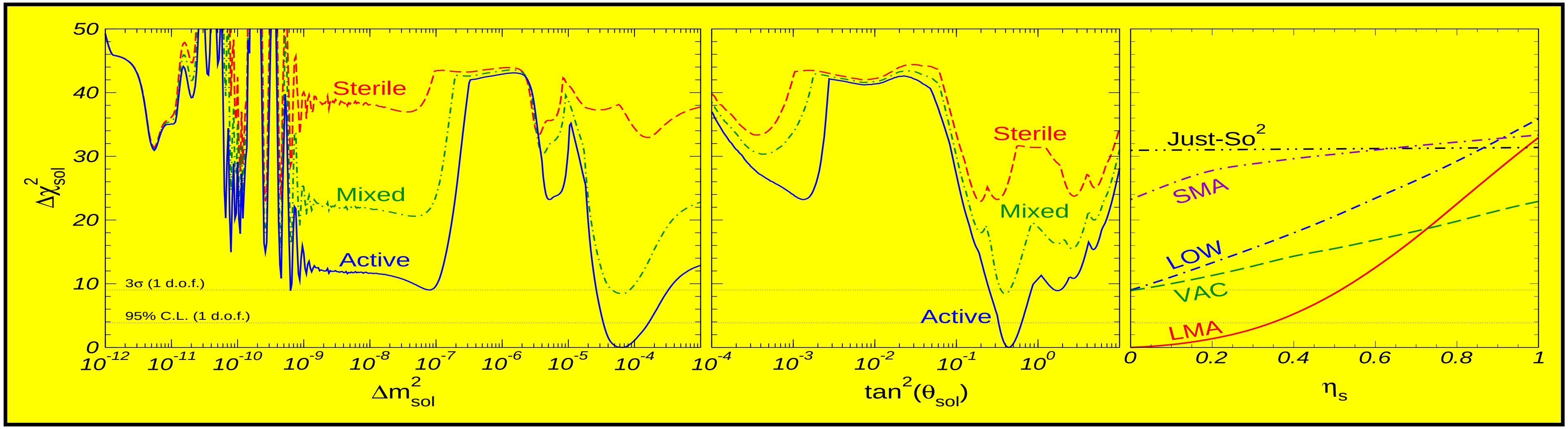
Since 1968 many experiments have measured the flux of electron neutrinos arriving at the Earth, and found they are much less than expected. This has been the Solar Neutrino Problem

early 2002

the SNO experiment showed that ν_e changes flavour due to $\nu_e \rightarrow \nu_{\mu/\tau}$ oscillation

solar-only regions **Maltoni, Schwetz, Tortola and Valle, hep-ph/0207227**





Reactor Neutrinos

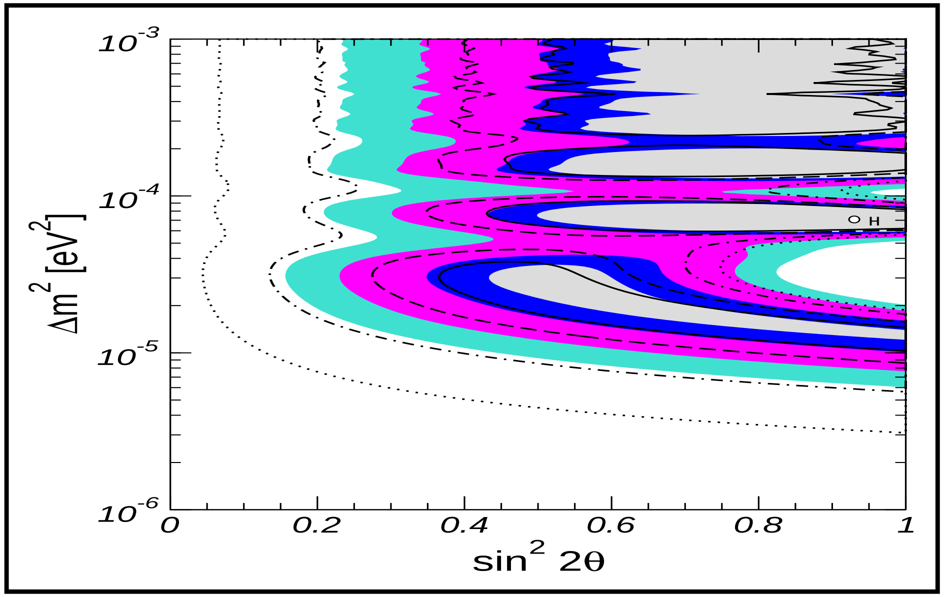
Neutrinos are also produced in nuclear power plants

reactor neutrino experiments have a **well known & controlled** neutrino source

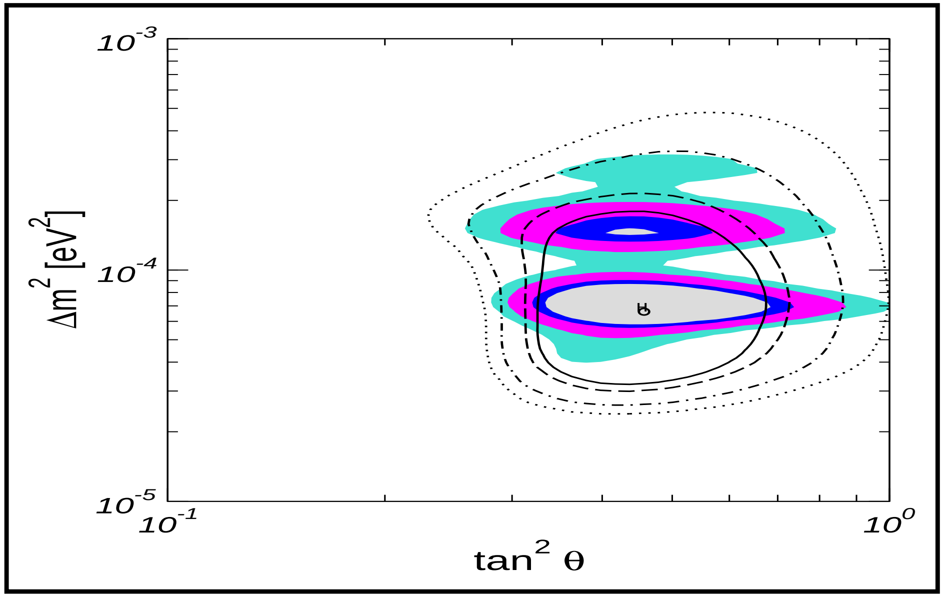
check of the solar neutrino oscillation hypothesis

KamLAND has just announced its first results, providing for a confirmation of the solar neutrino oscillation hypothesis.

Implications of first KamLAND reactor results



Maltoni, Schwetz & Valle, hep-ph/0212129



first terrestrial neutrino experiment probing the solar neutrino anomaly

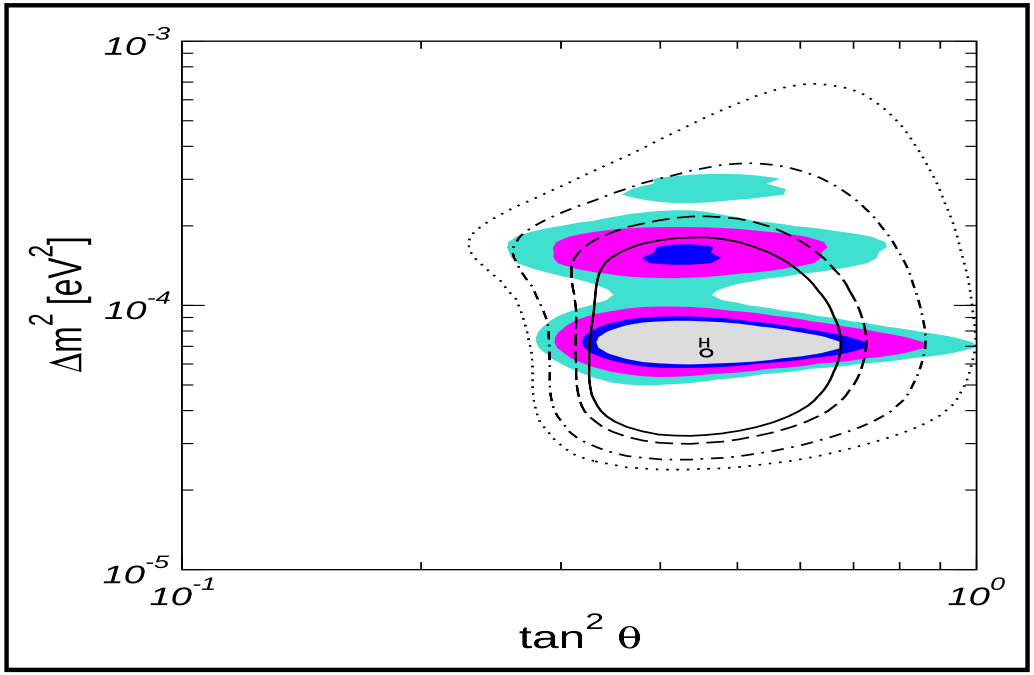
positive oscillation signal from first 145 days of data

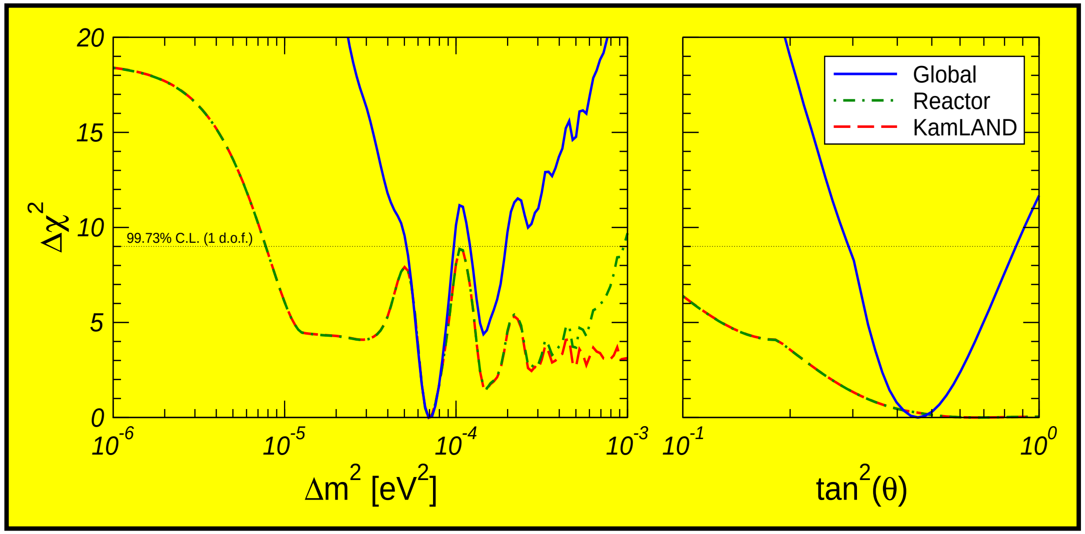
combining with full solar neutrino data sample rules out non-LMA oscillations $\Rightarrow$ **oscilllations happen inside the sun!**

data narrow down allowed $\Delta m^2_{\mathrm{SOL}}$ range inside the LMA-MSW region, but have little impact on best fit point

in contrast to atmospheric, solar mixing remains non-maximal

Implications of first KamLAND results-2





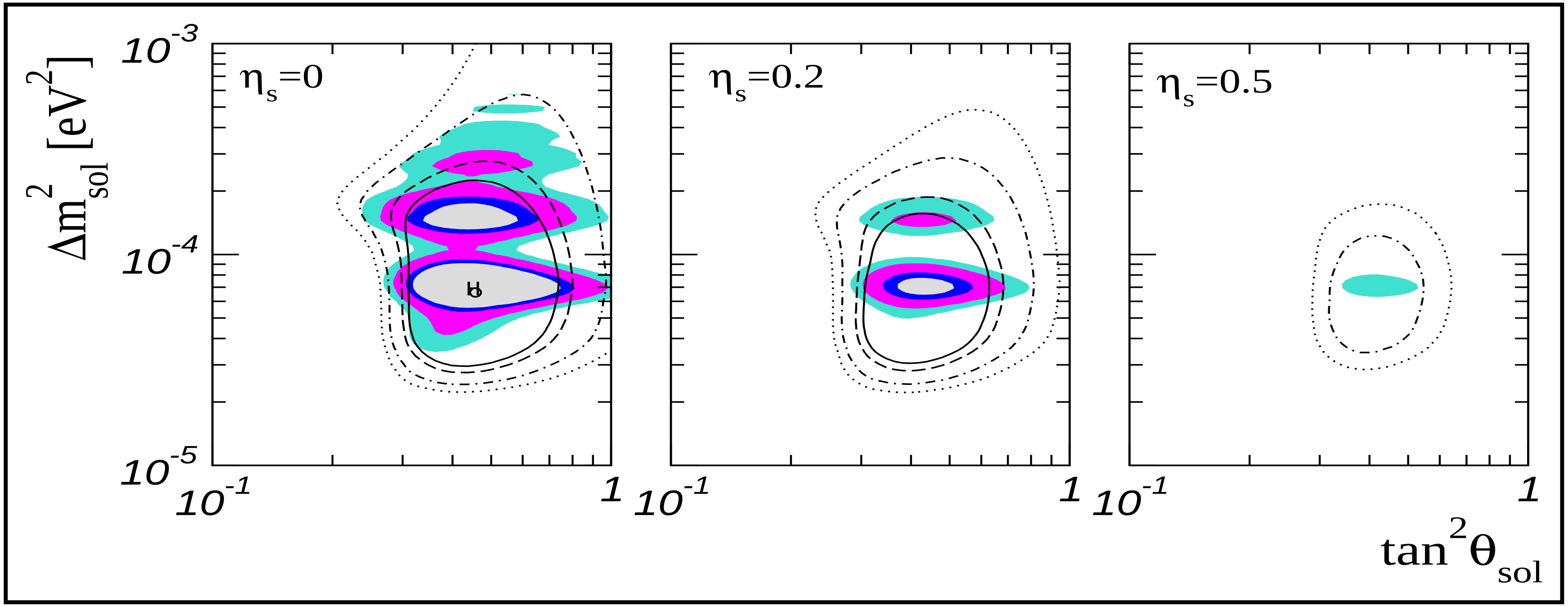
consistent results using Poison method

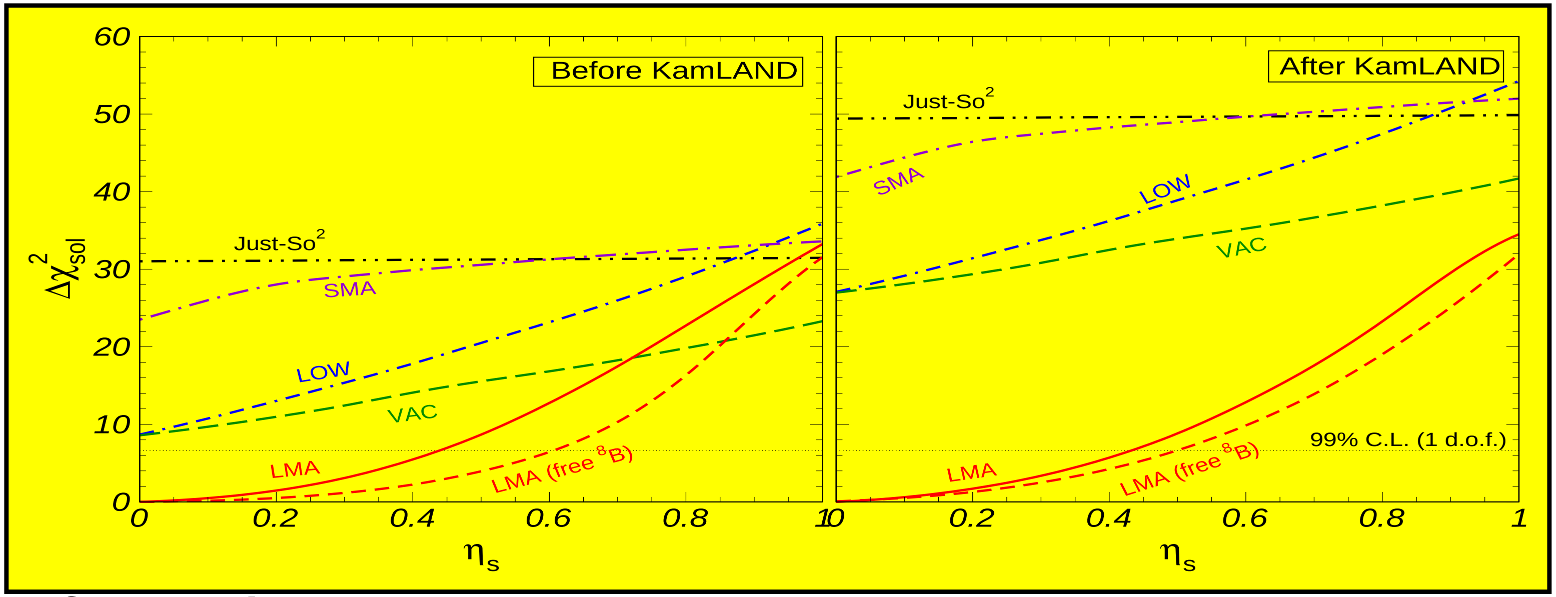
data narrow down allowed $\Delta m^2_{\rm SOL}$ range, with little impact on mixing, nor best fit point location

in contrast to atmospheric, solar mixing remains significantly non-maximal, strongly disfavoring bi-maximal models

solar+KamLAND regions: sterility rejection

Maltoni et al Phys. Rev. D 67 (2003) 013011





Stability of MSW plot

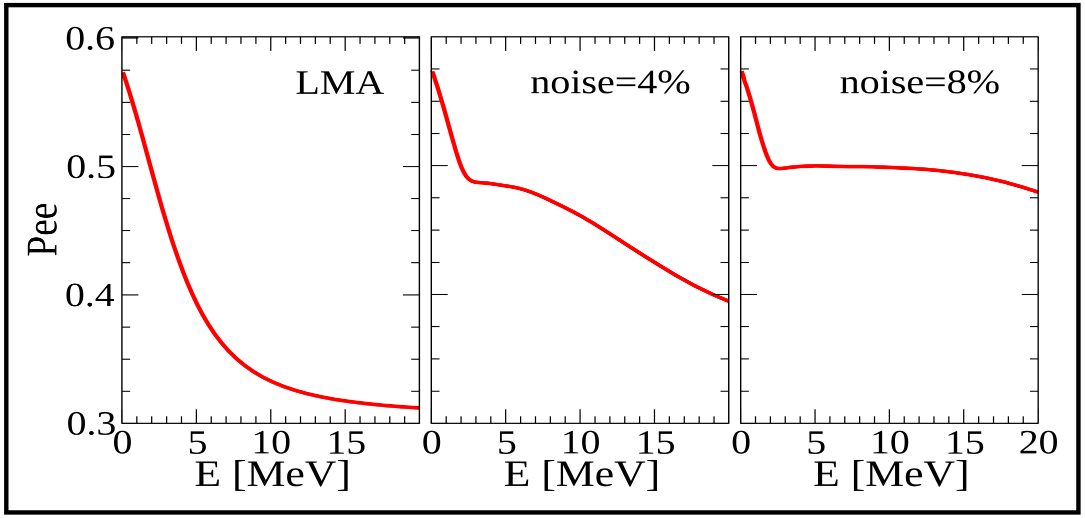
Burgess etal, hep-ph/0209094

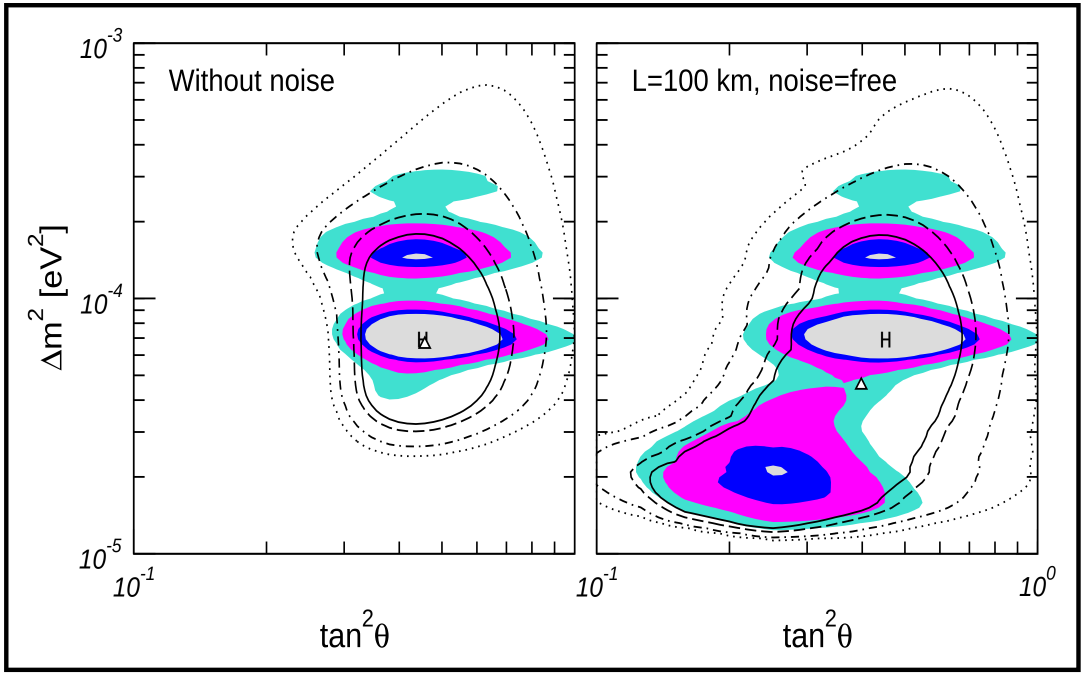
neutrino propagation affected by noise

Balantekin et al 95

Nunokawa et al NPB472 (1996) 495

Burgess etal 97

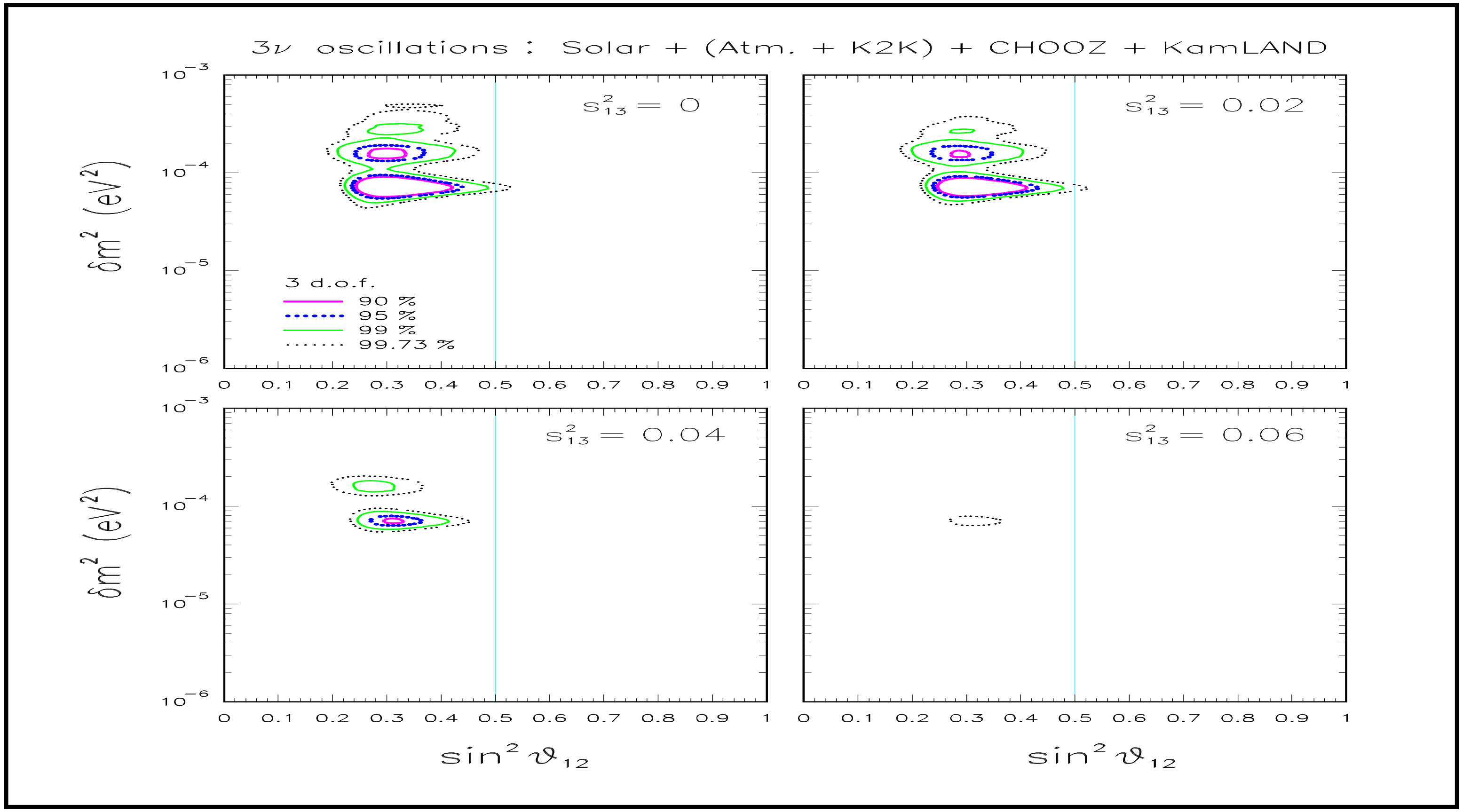


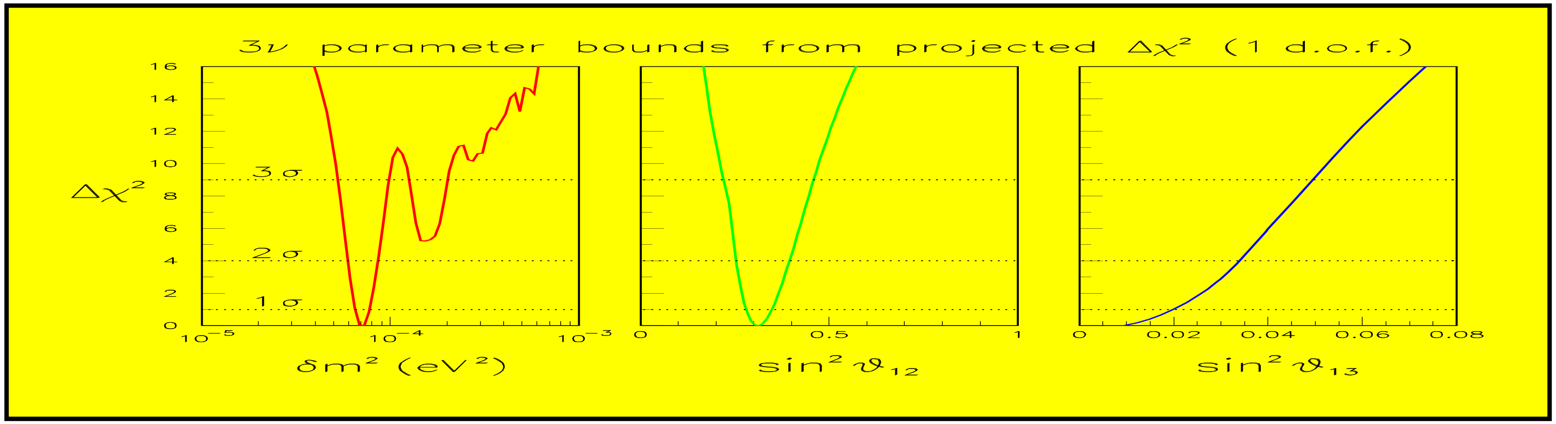


regions are substantially distorted, lower $\Delta m^2_{\rm SOL}$ possible

Constraining θ_{13}

Fogli, Lisi et al, hep-ph/0212127





Accelerator Neutrinos

Neutrinos are also produced in particle accelerators

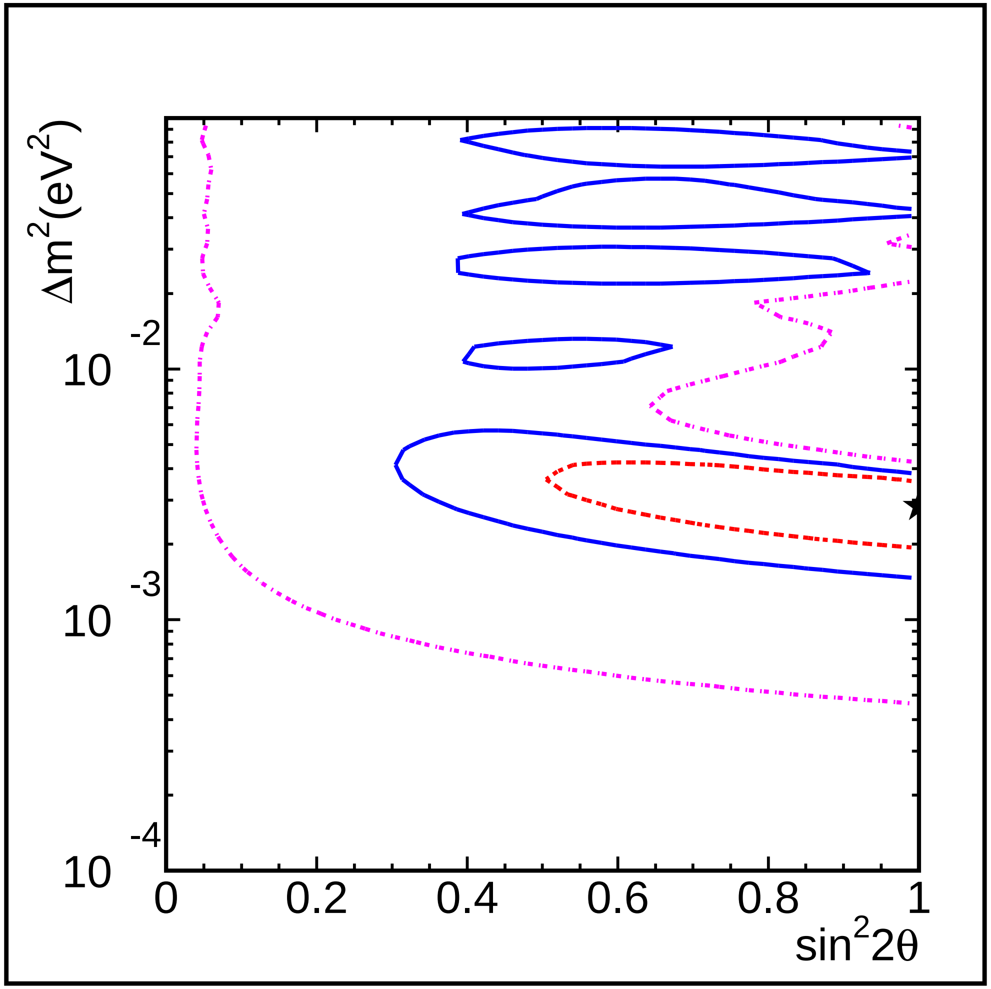
Experiments which measure the flux of neutrinos coming from accelerators have the advantage that the **neutrino source is well known/controlled**

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.

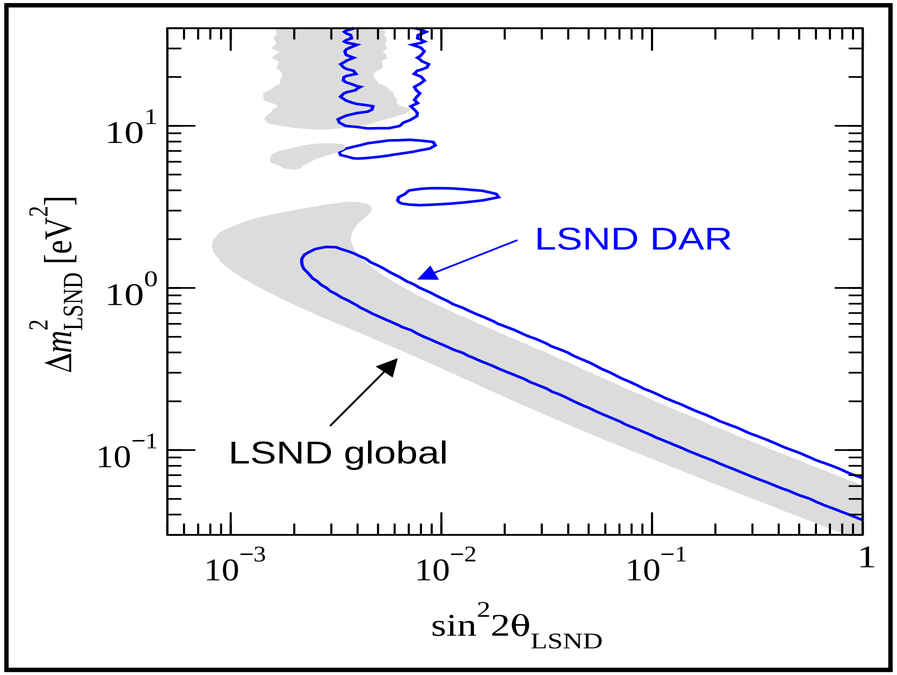
K2K agrees with atm results

hints of neutrino conversions also exist from the detection of accelerator-produced neutrinos in the K2K experiment



LSND

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



ATM

SOL

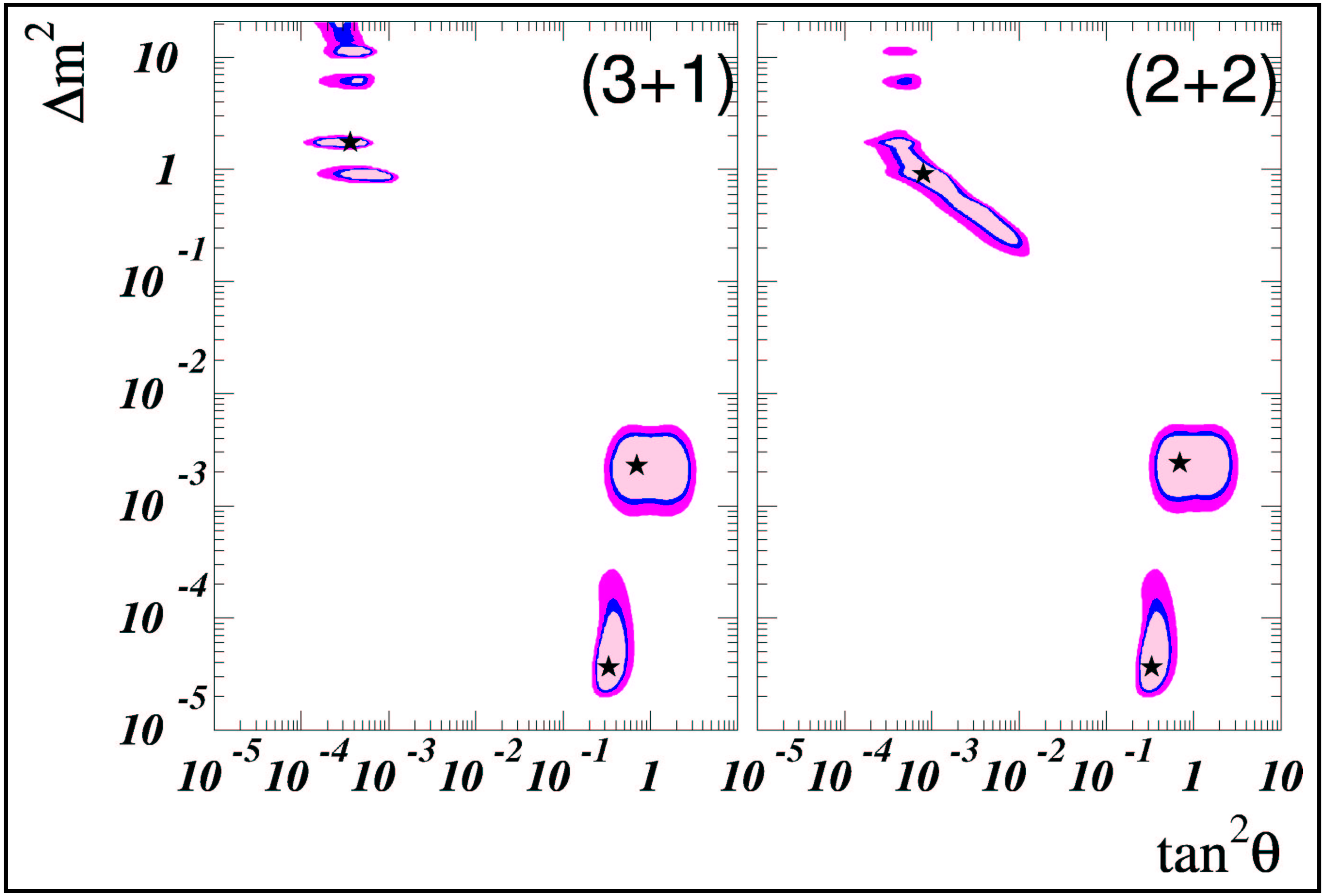
Peltoniemi, Valle, Nucl. Phys. B 406, 409 (1993); Peltoniemi, Tommasini and Valle, Phys. Lett. B 298 (1993) 383

Caldwell-Mohapatra PRD48 (1993) 325

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

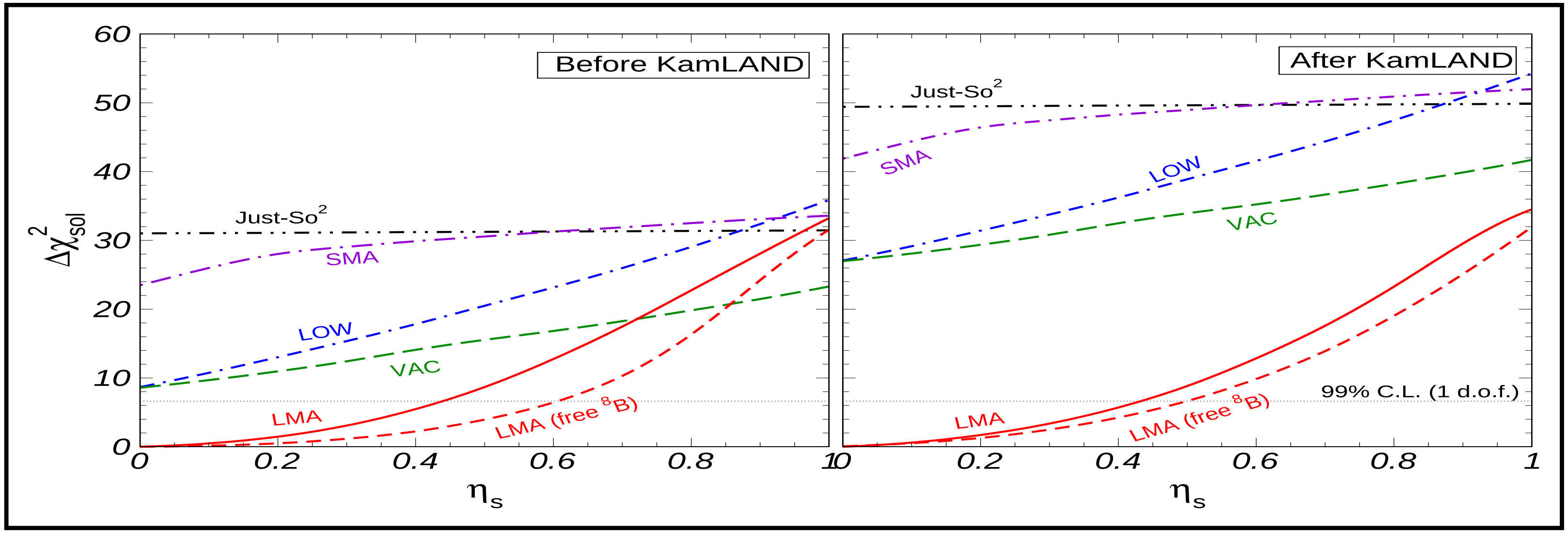
can one fit all current nu-data with oscillations ?

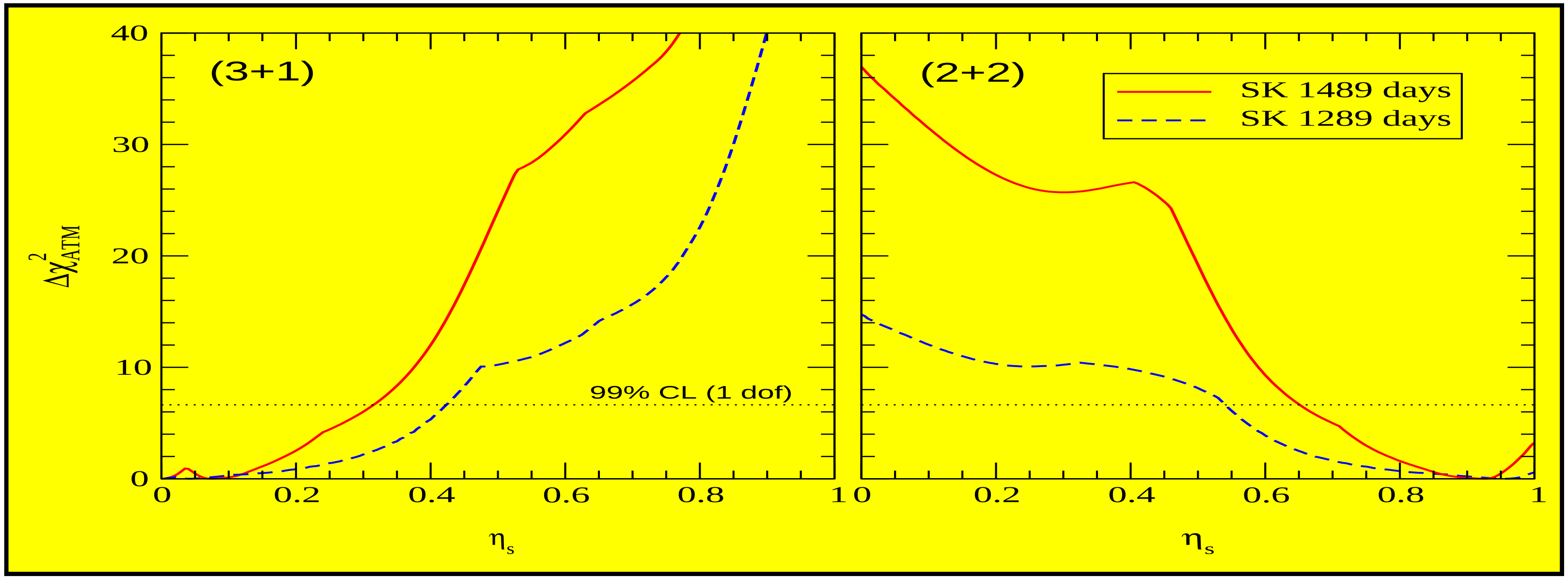
sol+atm+reac+**sbl/lsnd**



stronger sterility rejection by solar & atm data

from SK-1496d-sol + SNO-NC: **Maltoni et al Phys. Rev. D 67 (2003) 013011 [hep-ph/0207227]**

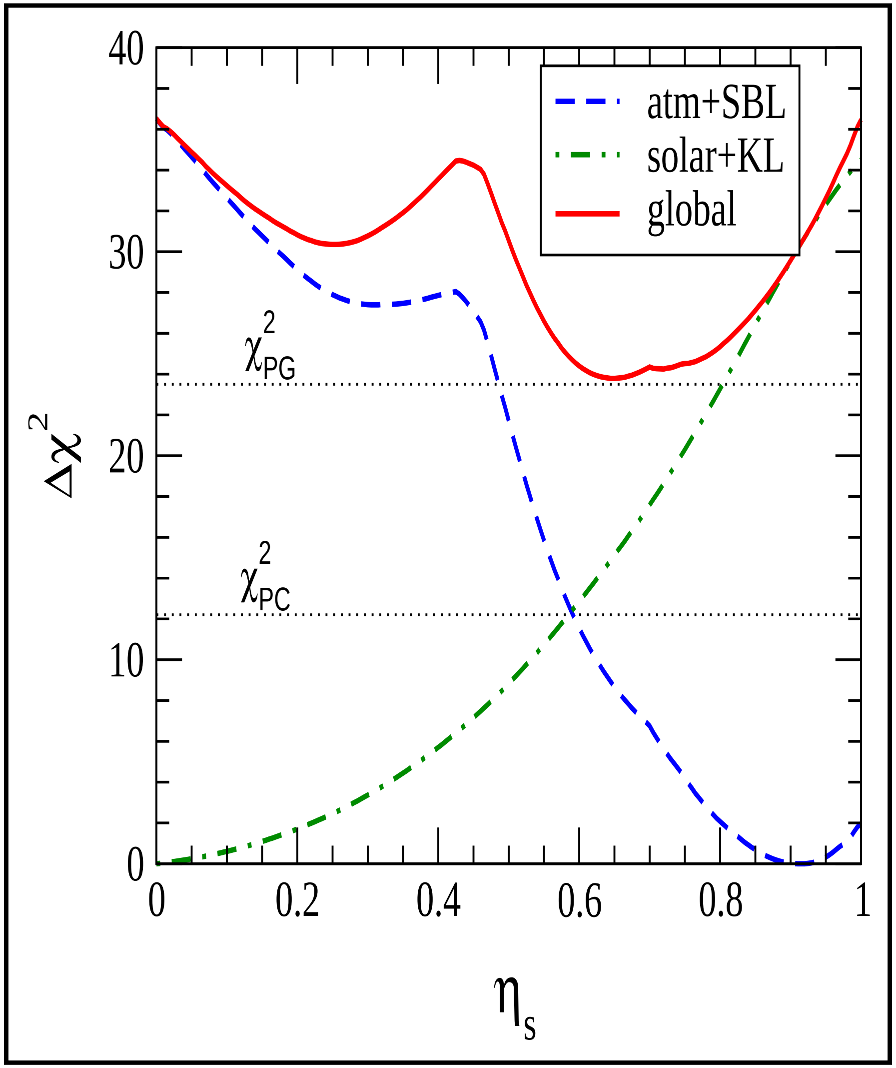


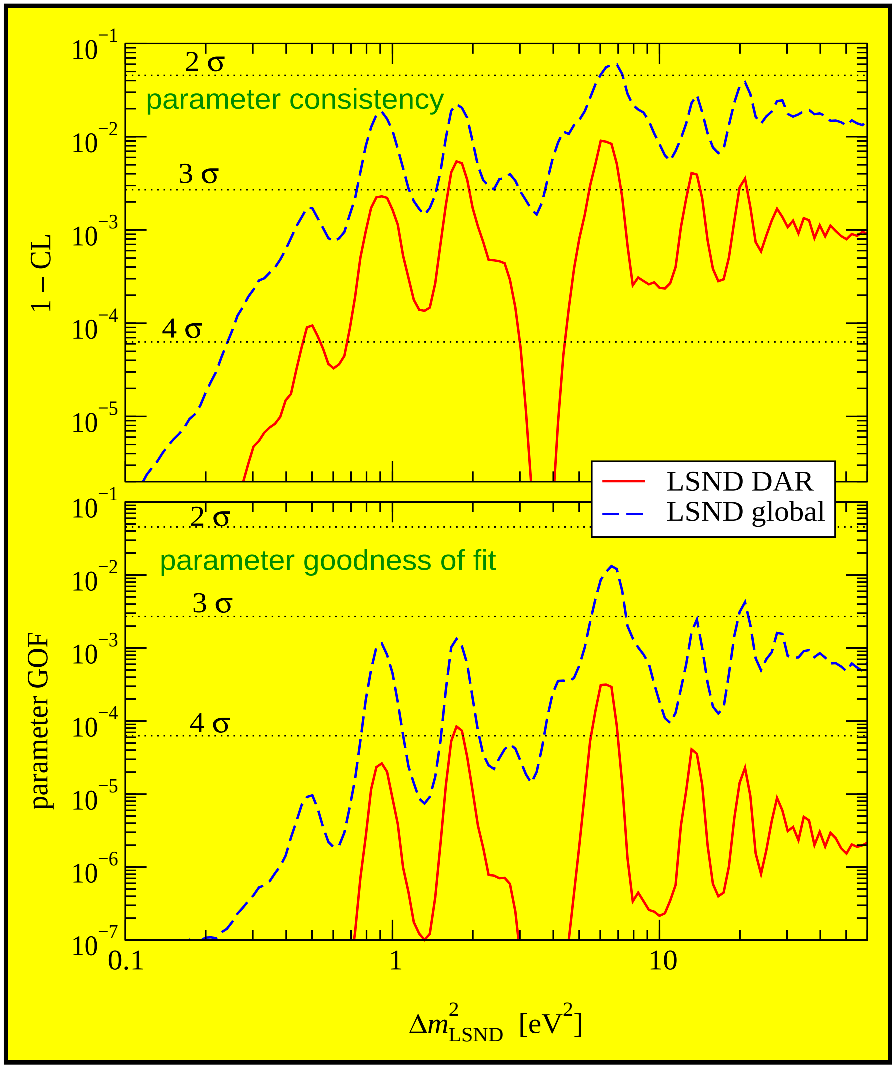


4-nus do not fit LSND with sol+atm

Maltoni etal NPB643 (2002) 321; upd of PRD65 (2002) 093004

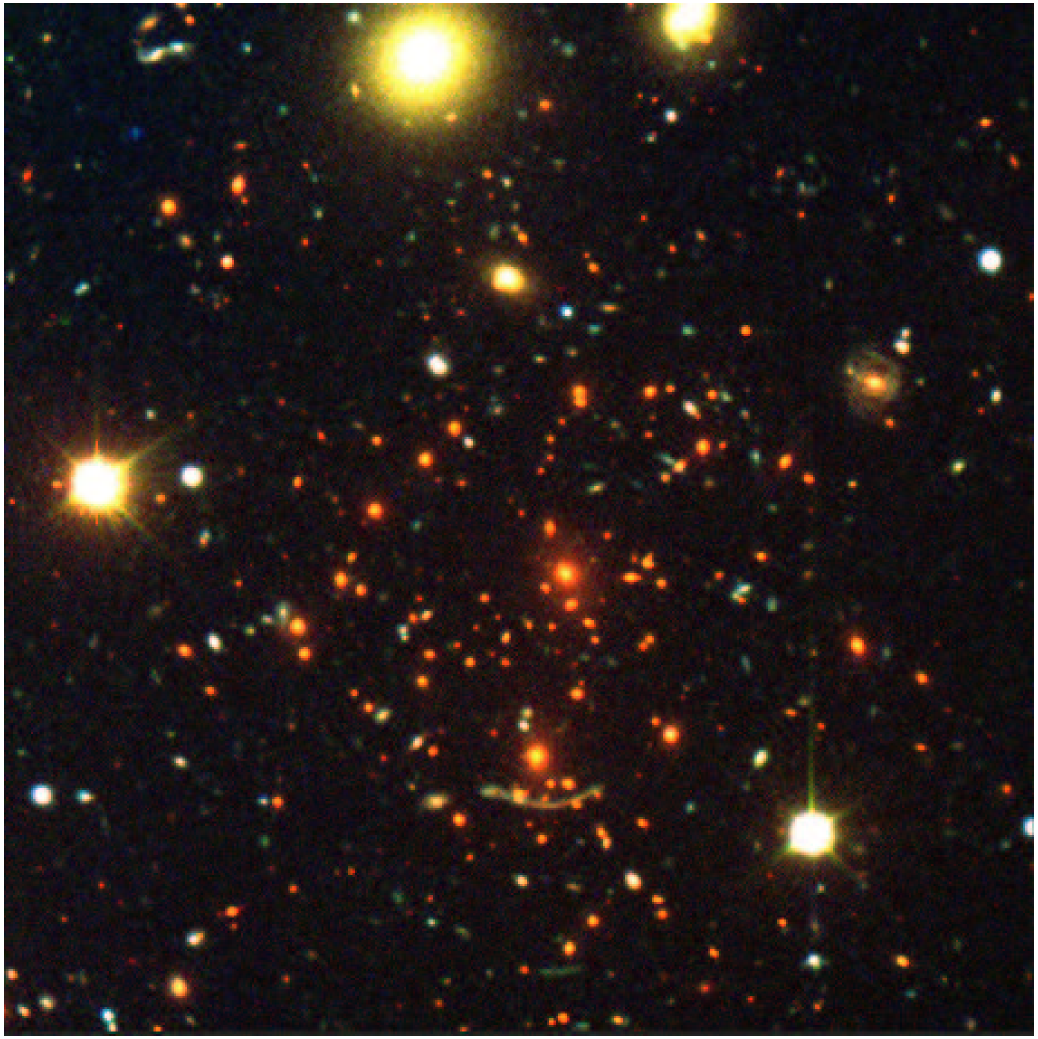
stronger rejection by solar & atm in 2+2 than 3+1





Cosmological Neutrinos

- Neutrinos were copiously produced in the early universe, when our Cosmos was hot and dense
- there are 336 neutrinos of the three flavours per cm^3, a bit more than the number of photons of the Cosmic Microwave Background
- Neutrinos could have been important in the production of the relic abundances of light elements
- Their tiny mass but huge number might contribute to total mass of the universe and affect its expansion
- Although too light to be the main component of the dark matter, neutrinos could have played an important role in the formation of large-scale structure



Absolute neutrino mass scale

back

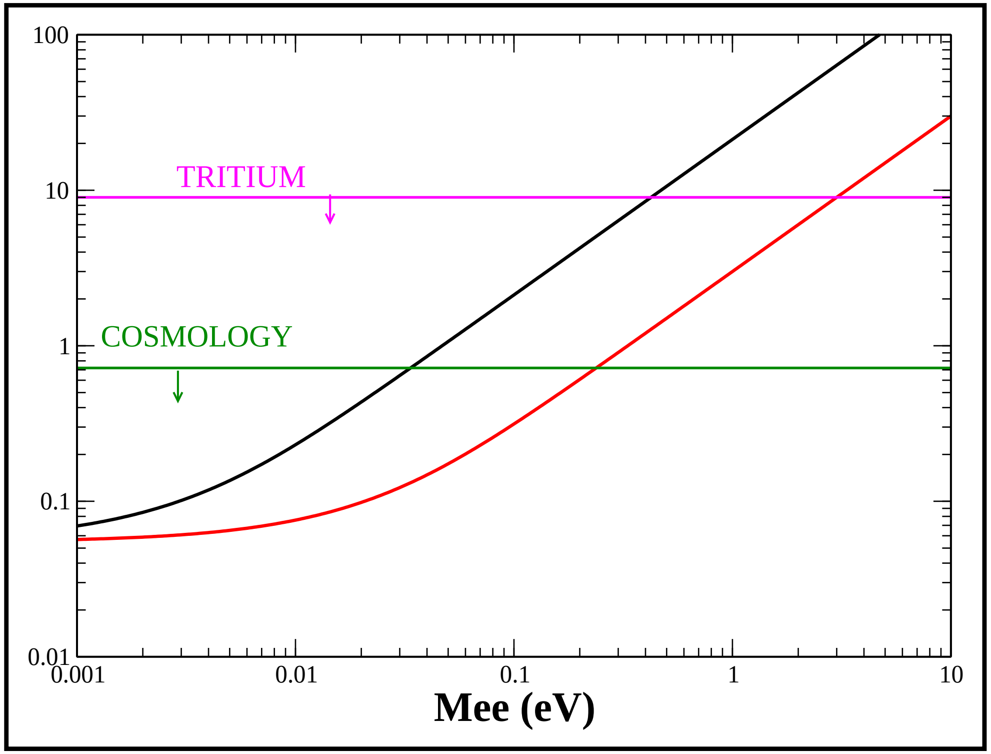
in contrast to oscillations

cosmology can probe absolute m-nu scale

tritium beta decay experiments

CMB bound on hot dark matter component (2DF, WMAP, ...)

neutrinoless double beta decay



Barger, Glashow, Marfatia and Whisnant, Phys. Lett. B **532** (2002) 15 [hep-ph/0201262]

Vissani, JHEP **9906**, 022 (1999) [hep-ph/9906525]

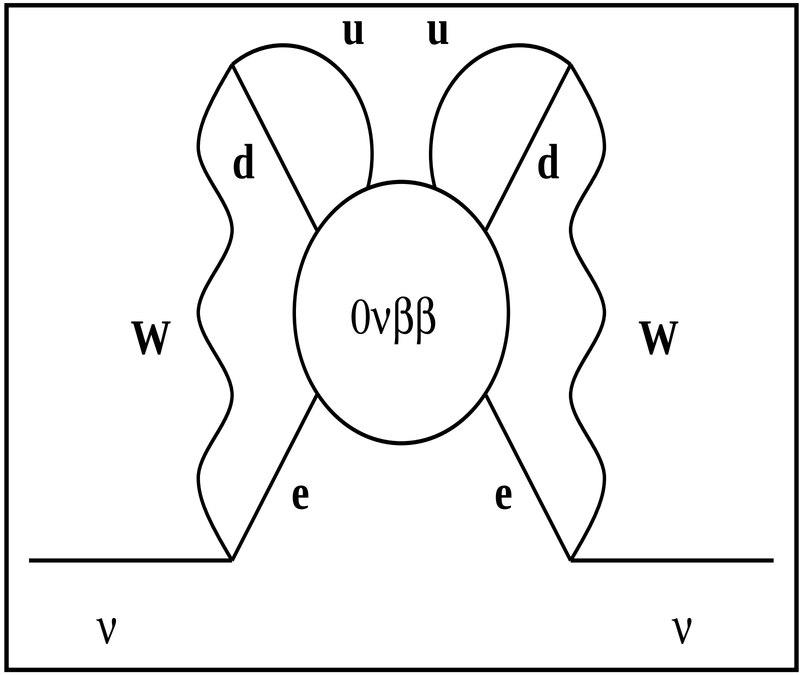
Dirac or Majorana?

back

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

Schechter and Valle, Phys. Rev. D **25** (1982) 2951

Hirsch's talk



like other L violating processes (e.g. nu-transition magnetic moments) $\beta\beta_{0\nu}$ is sensitive to Majorana phases

Wolfenstein PLB107 (1981) 77; Doi et al; Bilenky et al

no such theorem for flavor violation!

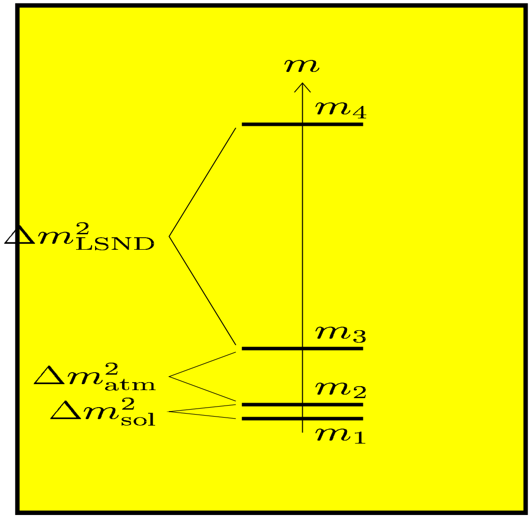
WMAP bound on hot dark matter component

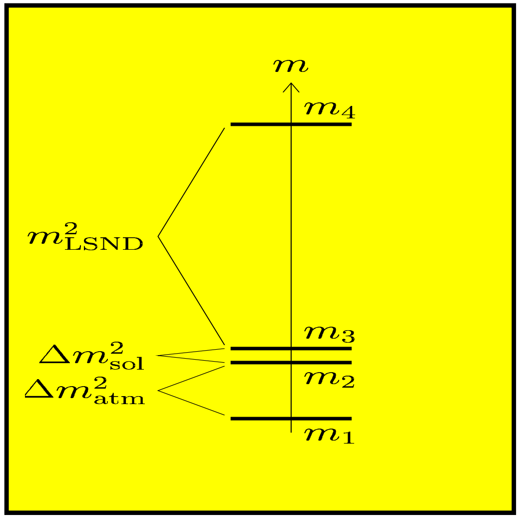
astro-ph/0302207

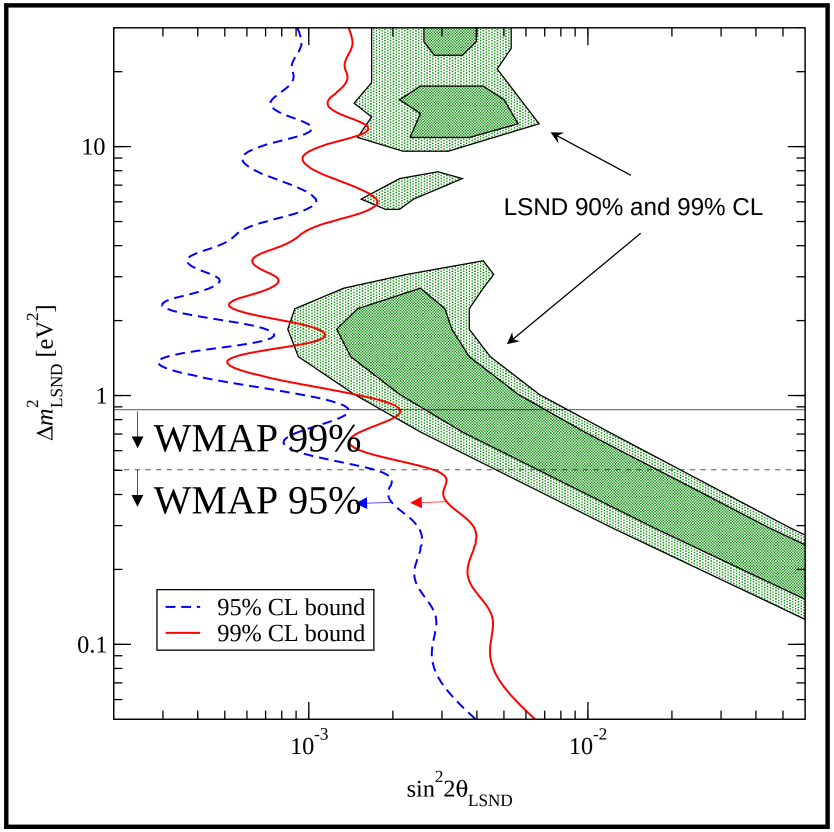
tightens even more 3+1 LSND models

Maltoni etal NPB643 (2002) 321; upd of PRD65 (2002) 093004

Giunti hep-ph/0302173 adds WMAP line







Neutrinos as astro probe

neutrinos as deep solar probe

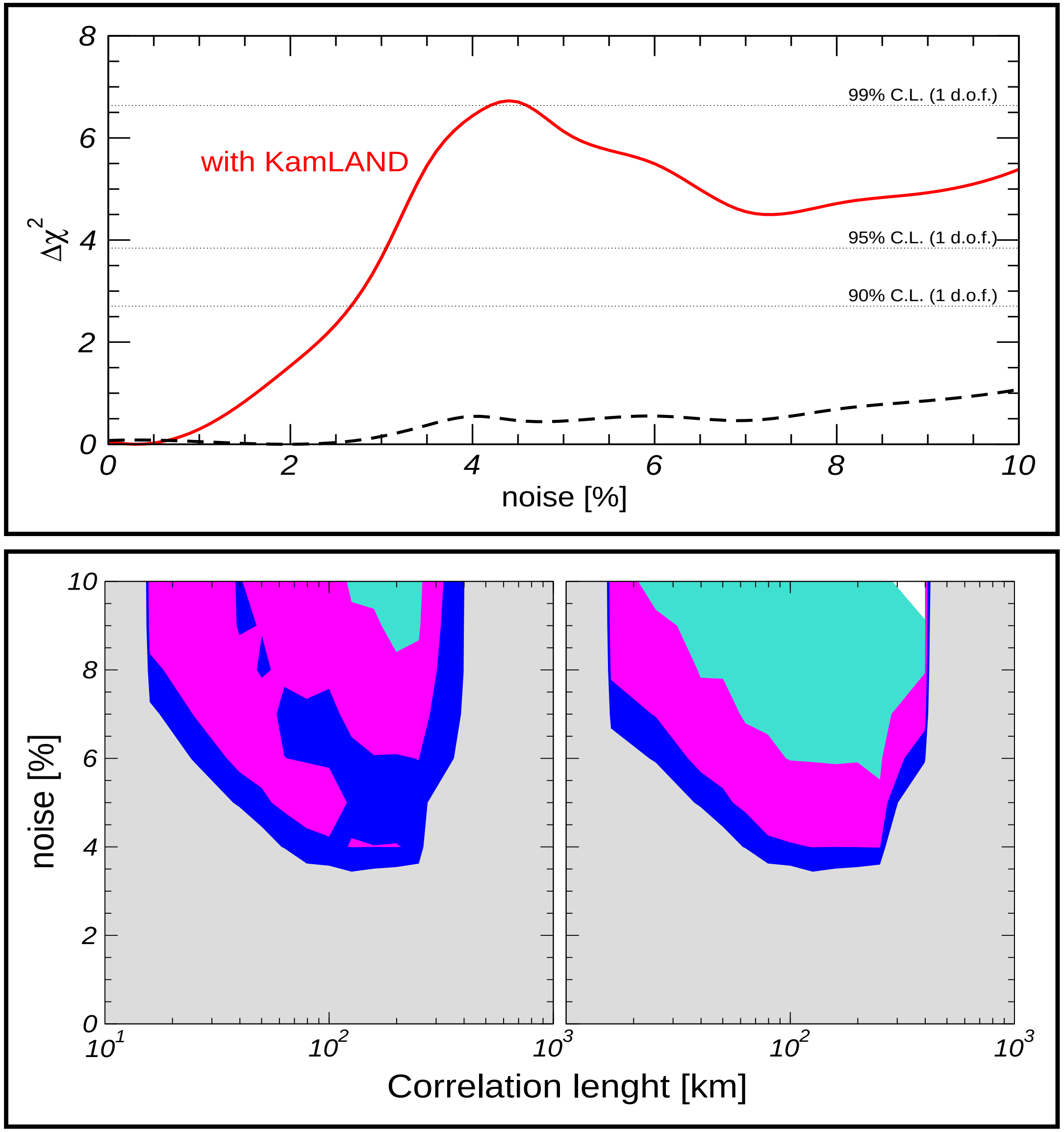
Burgess etal, hep-ph/0209094

$L_0 = 100\text{Km}$

KamLAND as solar probe

beyond helioseismology

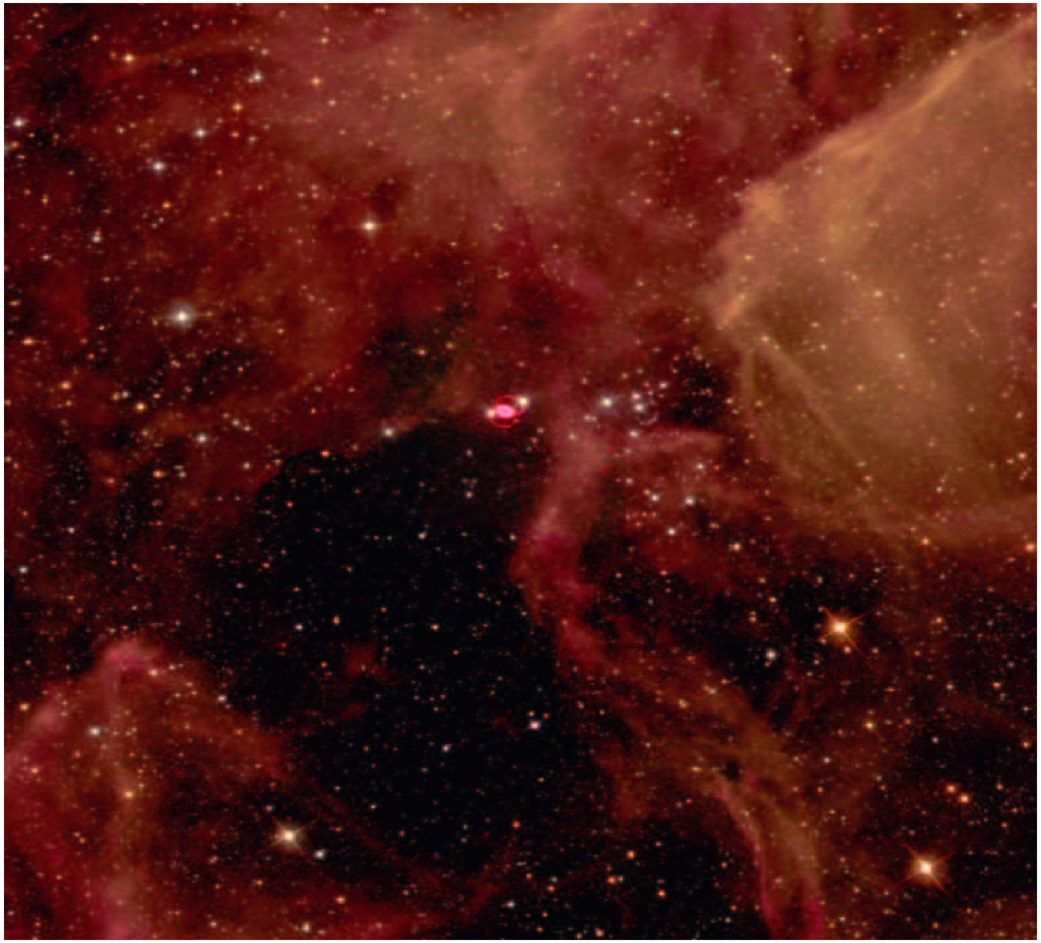
free vs BFP



Supernova neutrinos

Supernovae are massive stars that end their lives in an extremely violent and luminous explosion in which the optical luminosity of the star at maximum 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. This huge flux can transverse large distances and be detected in underground experiments before the corresponding optical signal, thus providing an early warning for astronomers



neutrinos and SN1987A

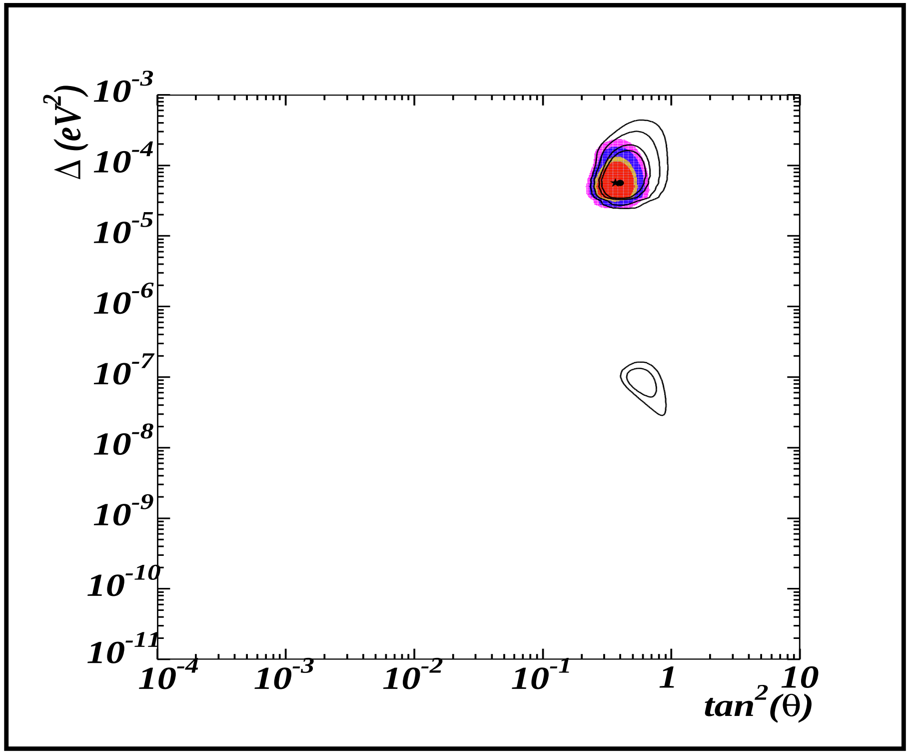
In 1987, a few neutrinos were detected from the nearby supernova 1987A that exploded in the Large Magellanic Cloud, a companion to our galaxy about 170,000 light-years away

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,
$\mathrm{E_{bind}} = 3 \times 10^3$ erg
$\tau \equiv T_{\nu_h}/T_{\bar{\nu}_e}$=1.4

pre-KamLAND

solar+SN1987A analysis



Kachelriess et al PRD65 (2002) 073016

LMA-MSW may remain best

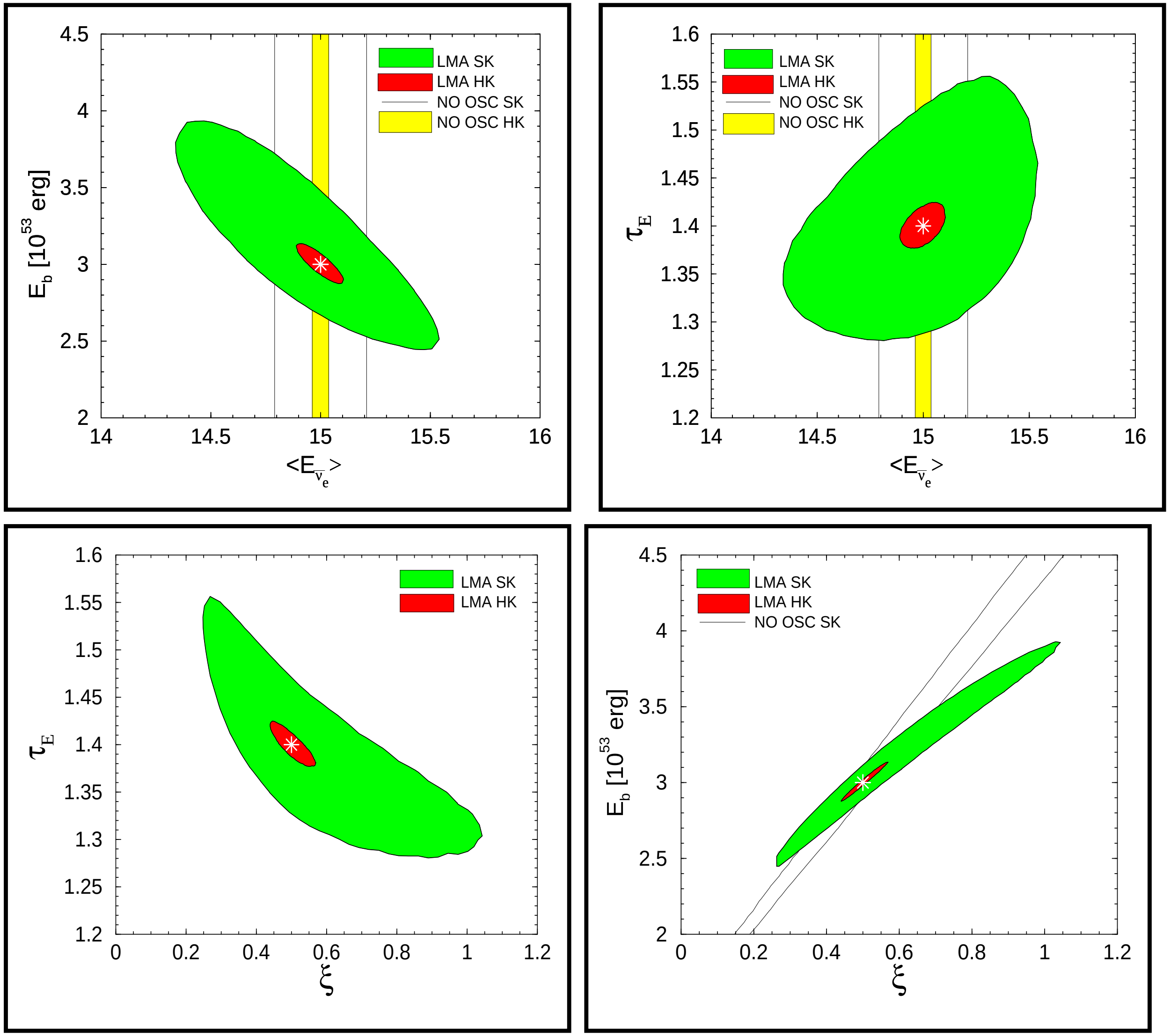
neutrinos as future Supernova probe

Minakata et al, PLB542 (2002) 239

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

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

see also Barger, Marfatia & Wood



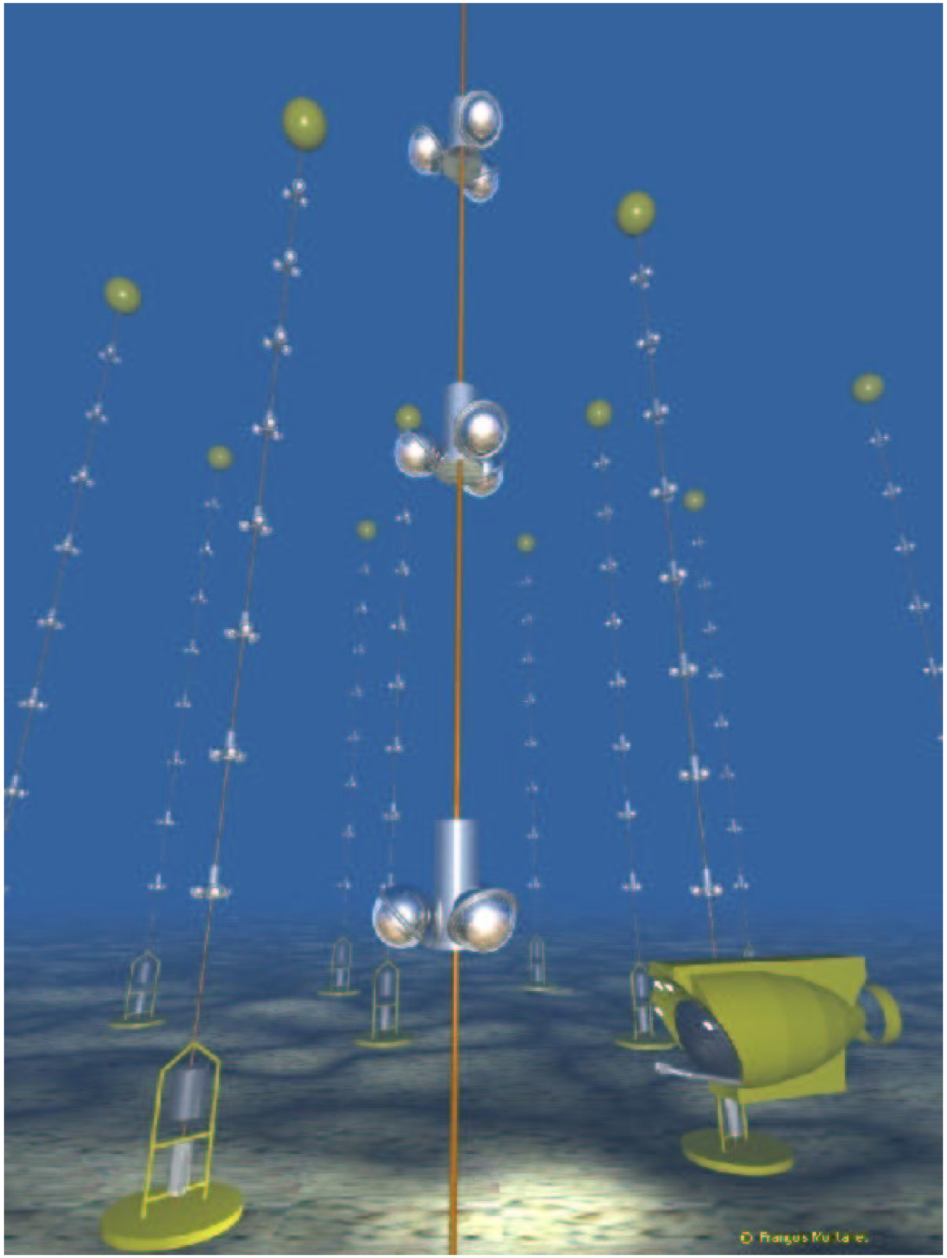
improved determination of supernova parameters

High-energy astrophysical neutrinos

Neutrino astronomy can provide new information complementary to the more traditional detection of photons and cosmic rays.

Neutrinos can escape from very dense astrophysical sources and travel long distances. Therefore, they are unique candidates for the study the very high-energy Universe.

Today there are several projects of neutrino telescopes, under water or ice, which aim at detecting the Cerenkov light produced by the charged leptons originated from the interaction of upgoing high-energy neutrinos with the surrounding matter.



alternatives to oscillations?

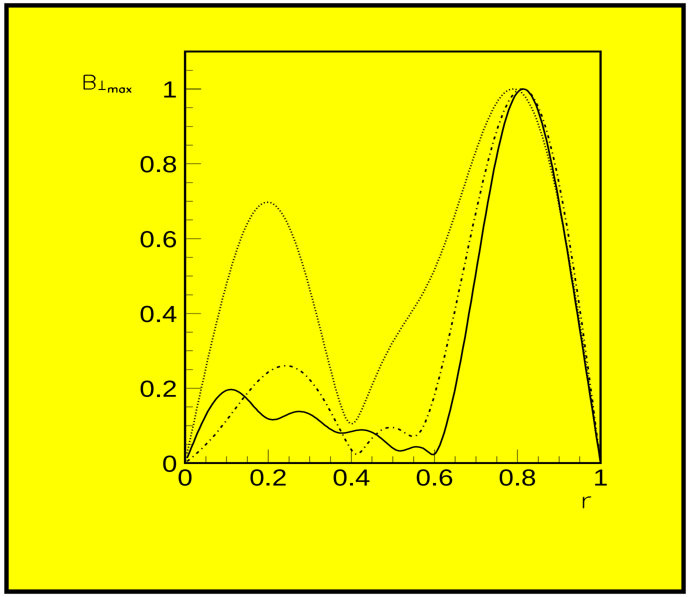
Oscillation vs Spin Flavor Precession

Spin Flavor Precession

Schechter, Valle PRD24 (1981) 1883 & D25, 283

Akhmedov PLB213 (1988) 64

Lim-Marciano PRD37 (1988) 1368

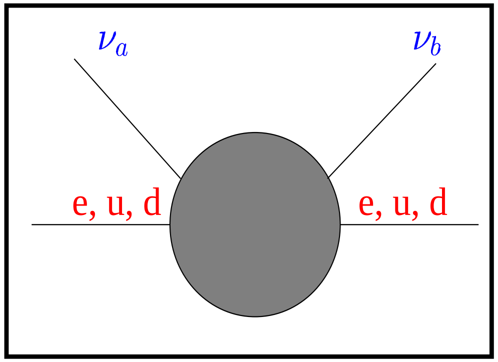


MHD fixes B-profile

Miranda etal NPB595 (2001) 360, PLB521 (2001) 299

Non-standard interactions

consider FC/NU sub-weak strength terms εG_F

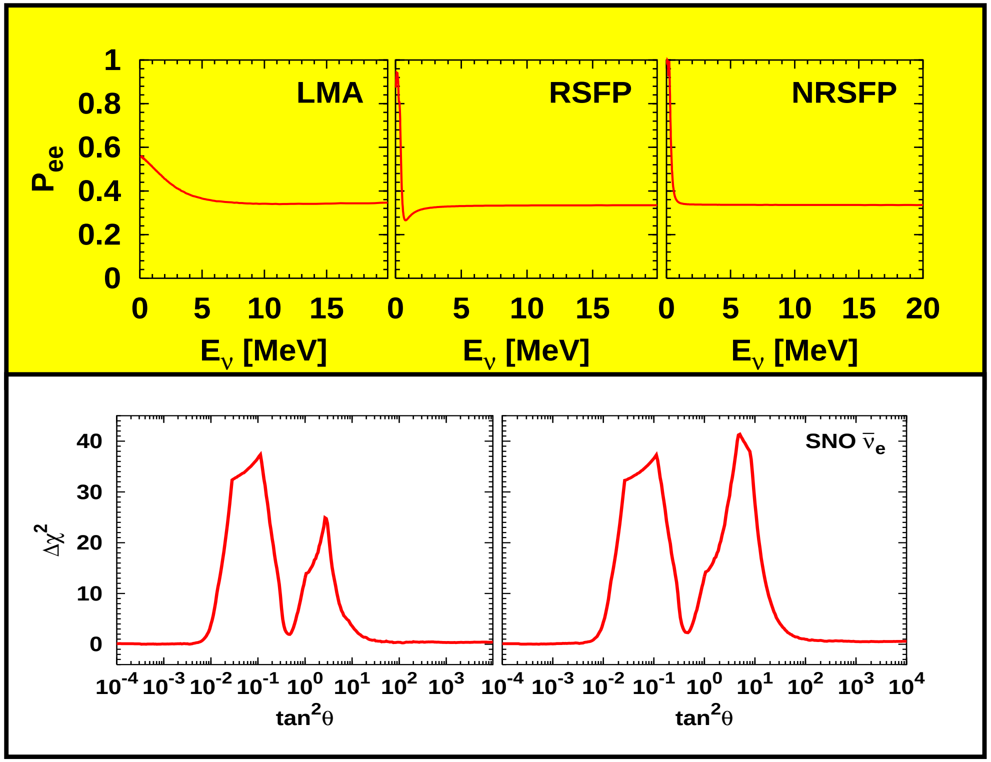


can induce oscillations of massless neutrinos in matter, which are E-independent, converting both neutrinos & anti-nu's, can be resonant in SNovae Valle PLB199 (1987) 432, Roulet 91; Guzzo etal 91; Barger etal 91

global analysis in Guzzo et al NPB629 (2002) 479 more

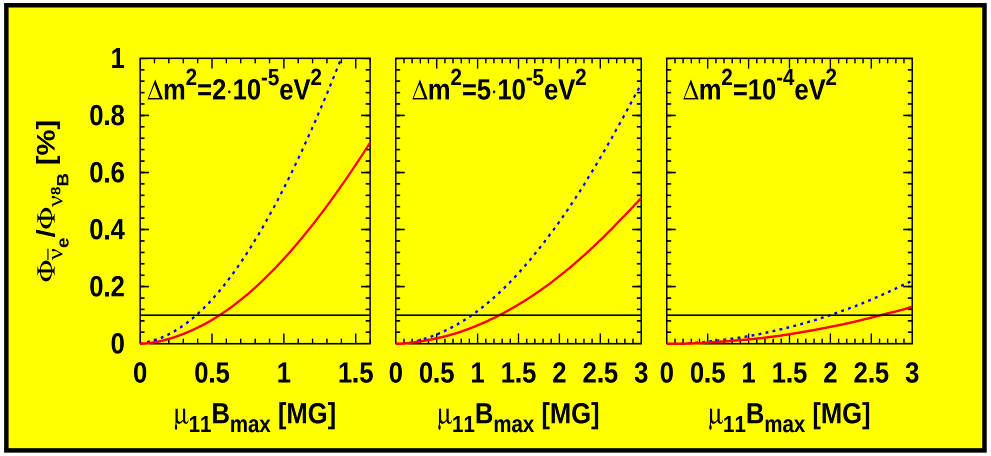
Oscillation vs Spin Flavor Precession

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



current solar data still do not allow the recosntruction of the profile of ν_e -conversion probability

LMA-MSW, RSFP, NRSFP equivalent



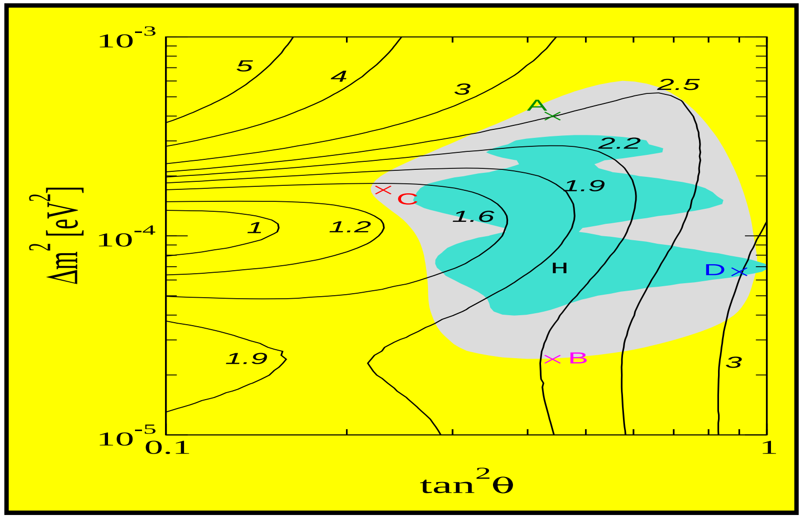
KamLAND lifts degeneracy

ruling out SFP as main solution

testing SFP as sub-leading

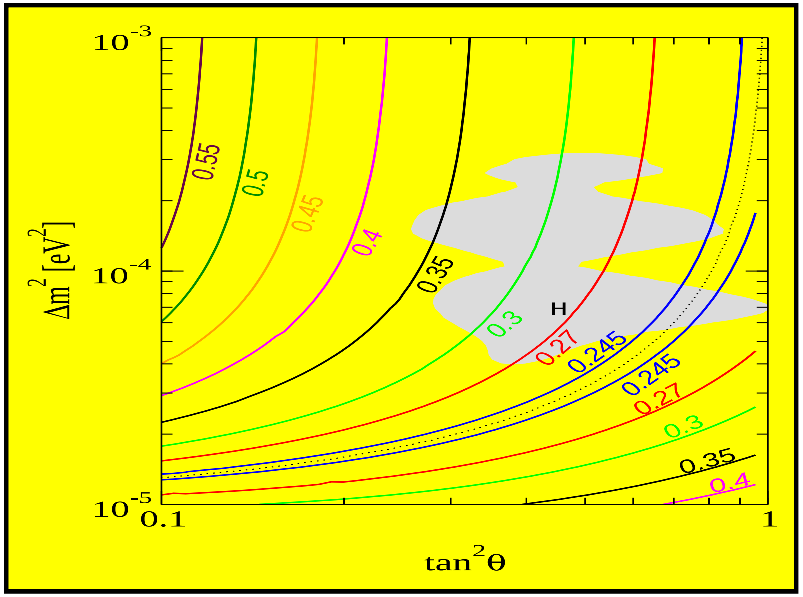
probing neutrino magnetic moments at LMA-MSW

present solar data sensitivity



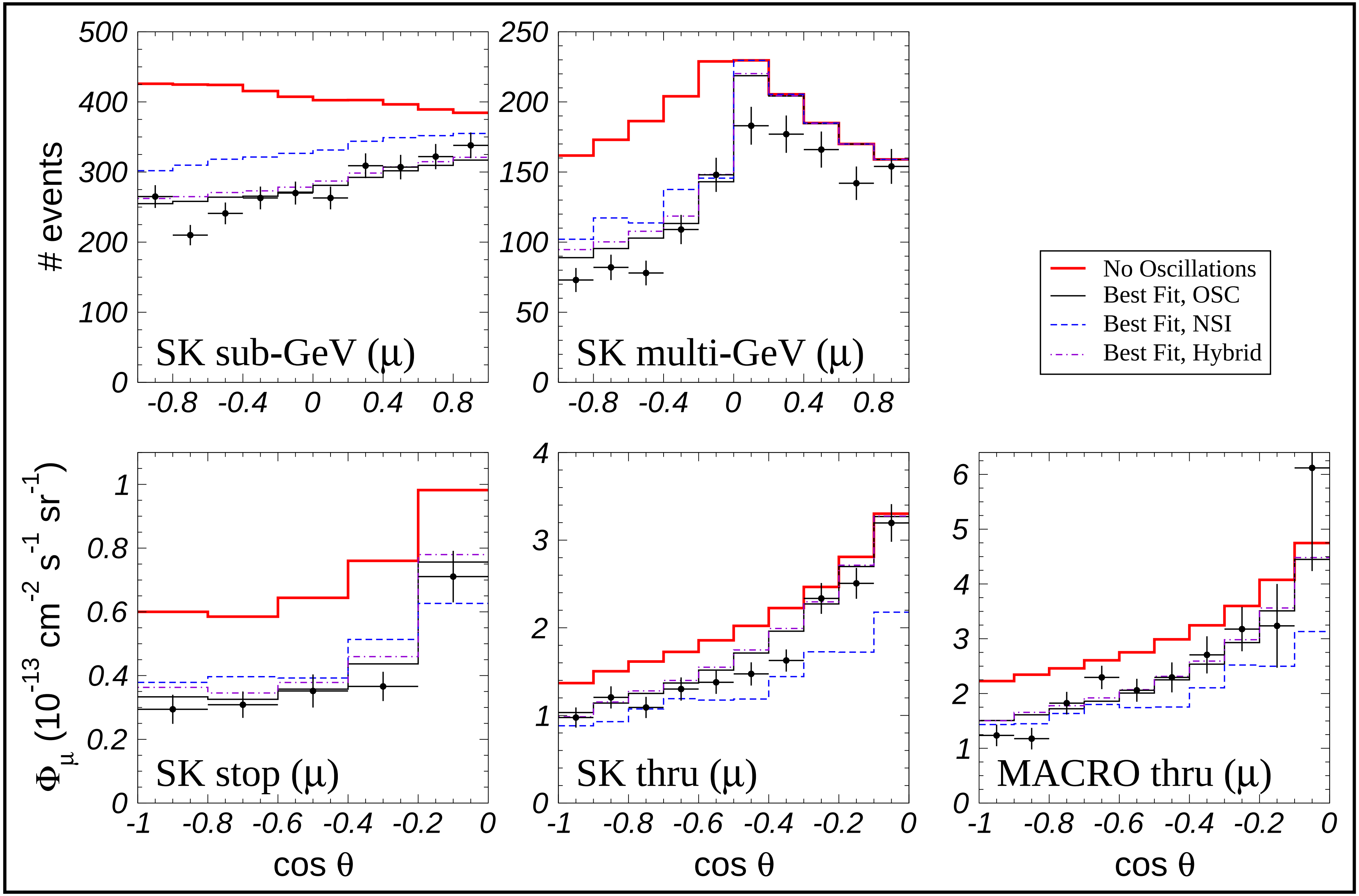
Grimus, Maltoni, Schwetz, Tortola and Valle, Nucl. Phys. B 648, 376 (2003) [hep-ph/0208132]

expected Borexino sensitivity



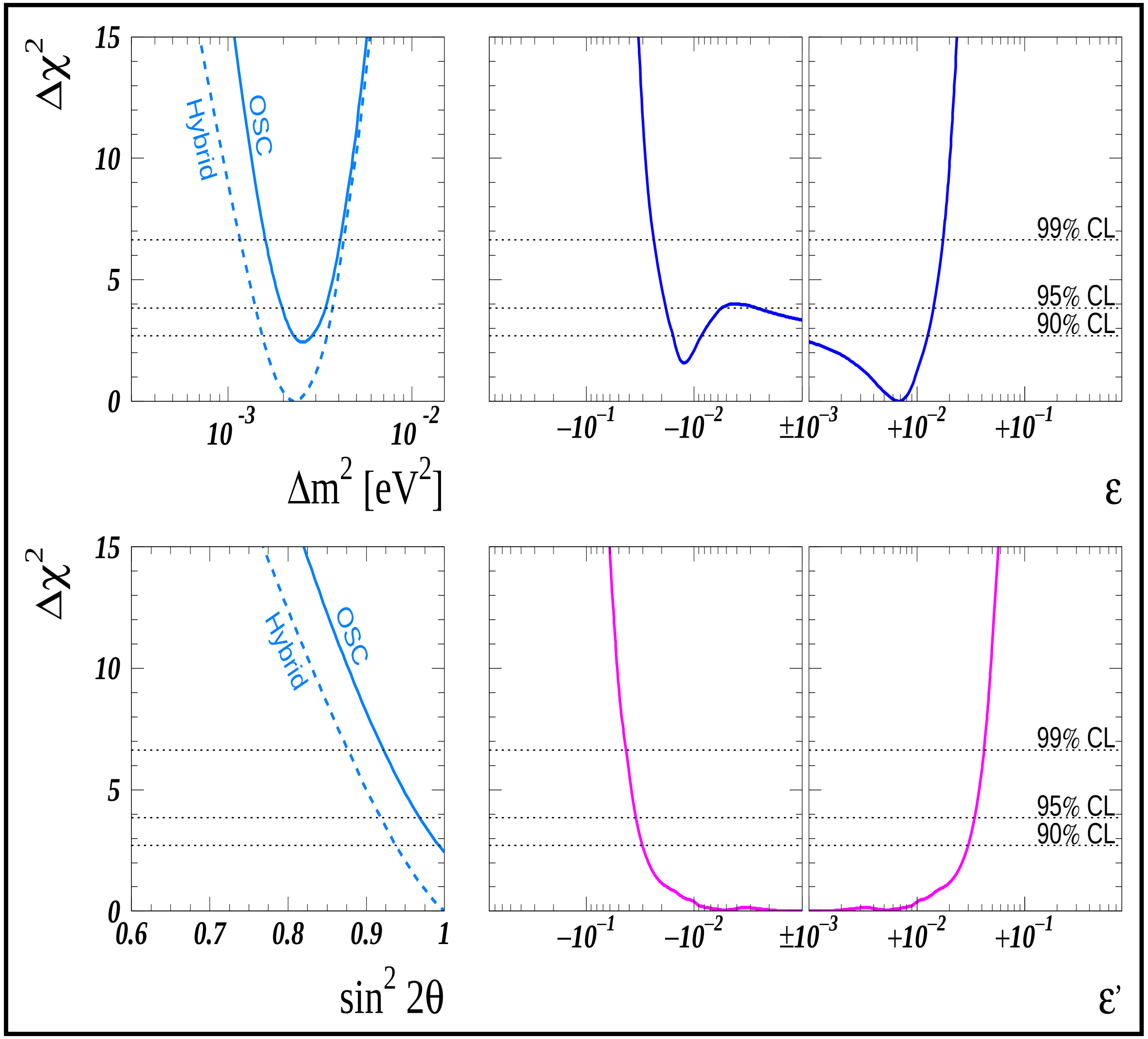
How robust are atmospheric oscillations?

very good contained atm-fit, Gonzalez-Garcia etal, Phys. Rev. Lett. **82** (1999) 3202 [hep-ph/9809531]



probing NSI with atmospheric data

Fornengo et al,
Phys. Rev. D 65 (2002) 013010
[hep-ph/0108043].



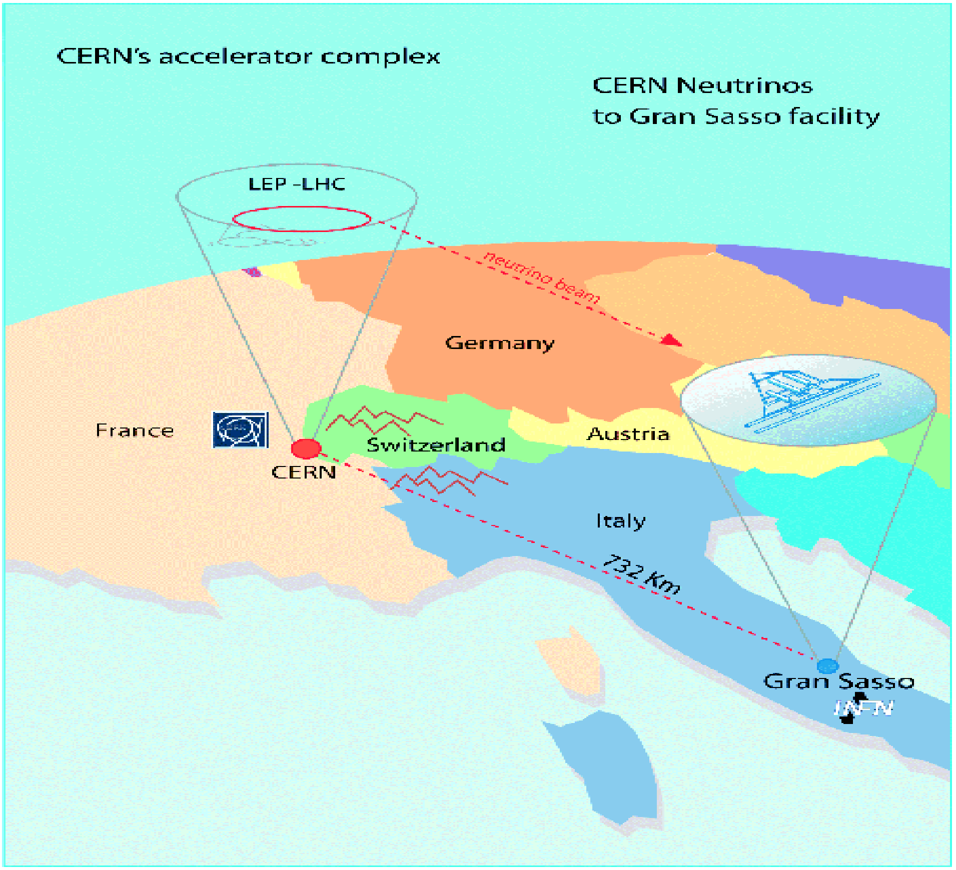
atm bounds on FC and NU nu-interactions

back

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...

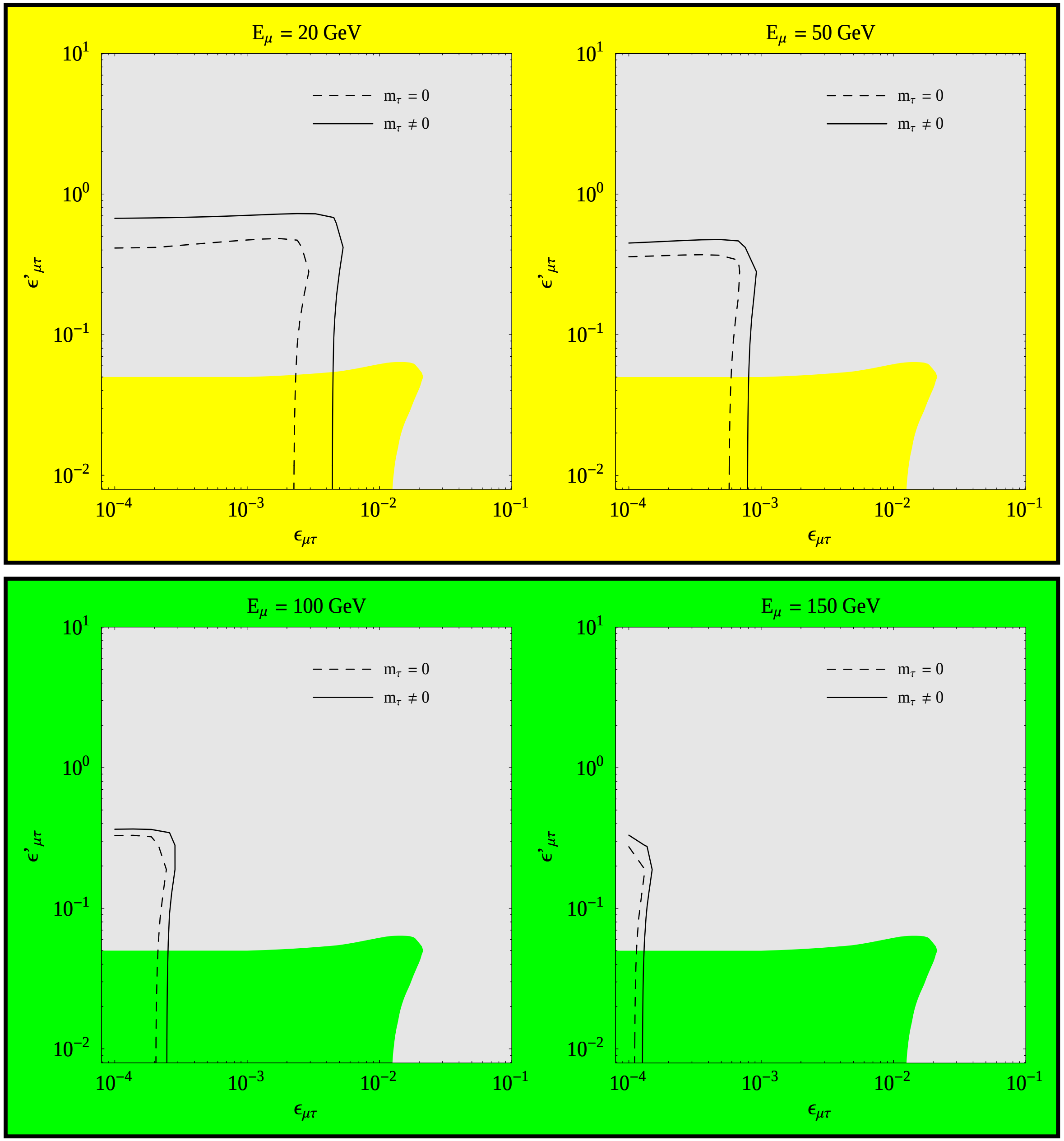
they can probe NSI



Improved FC-tests at NuFact back

Huber & JV Phys. Lett. B 523 (2001) 151 [hep-ph/0108193]

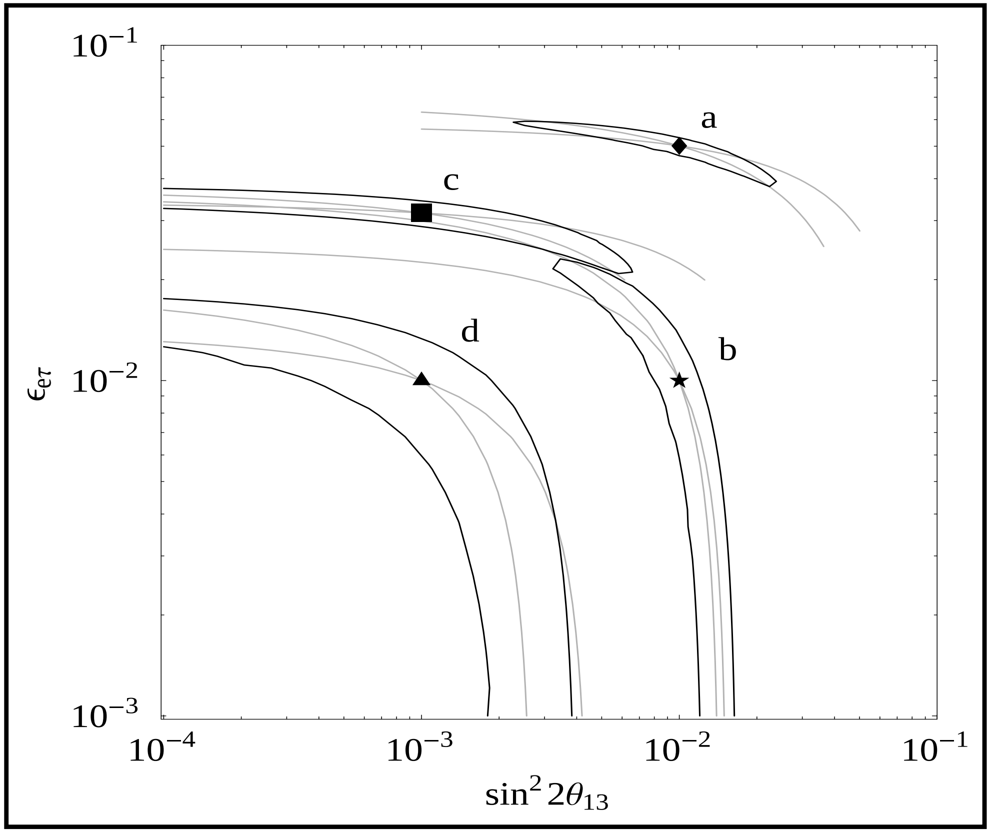
10 kt detector, .33 ν_τ detection eff above 4 GeV; need no tau charge id



FCI-oscillation confusion theorem back

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

Huber, Schwetz & JV Phys. Rev. Lett. 88 (2002) 101804 [hep-ph/0111224]

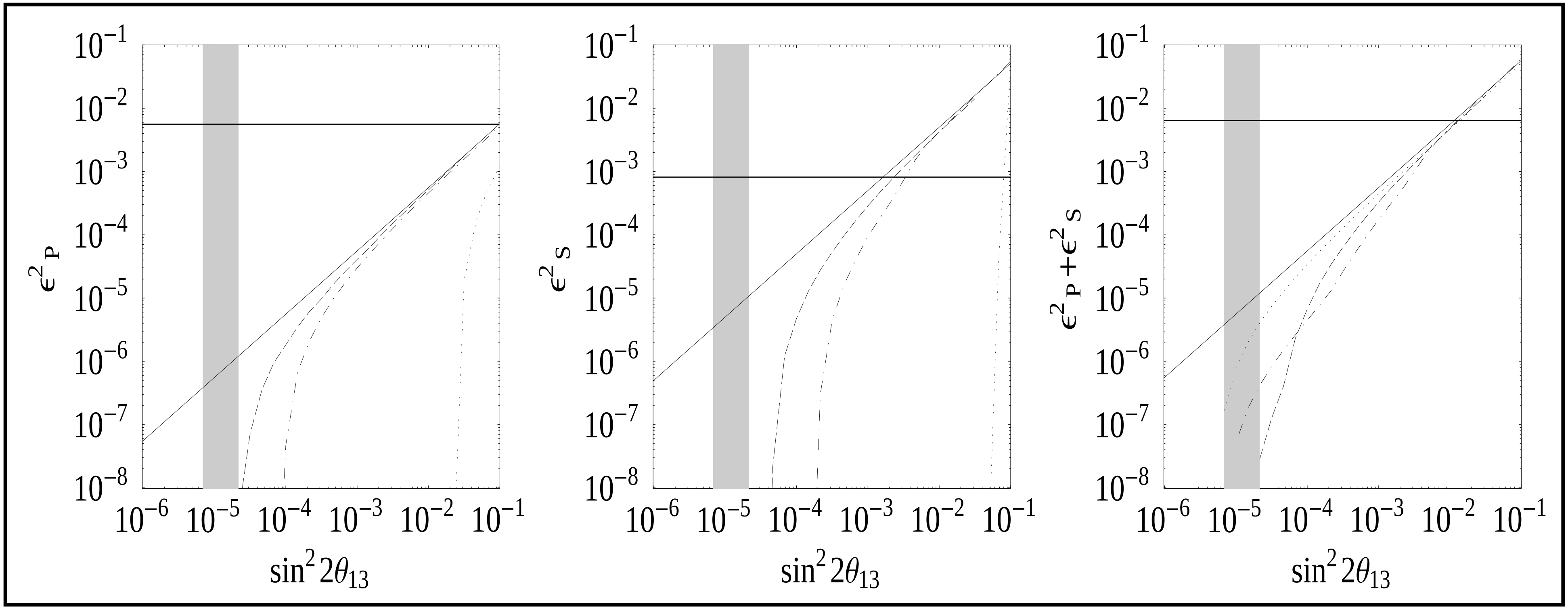


near-site programme essential

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

FCI-oscillation confusion theorem-2 back

Huber, Schwetz and J. V. Phys. Rev. D 66, 013006 (2002) [hep-ph/0202048]



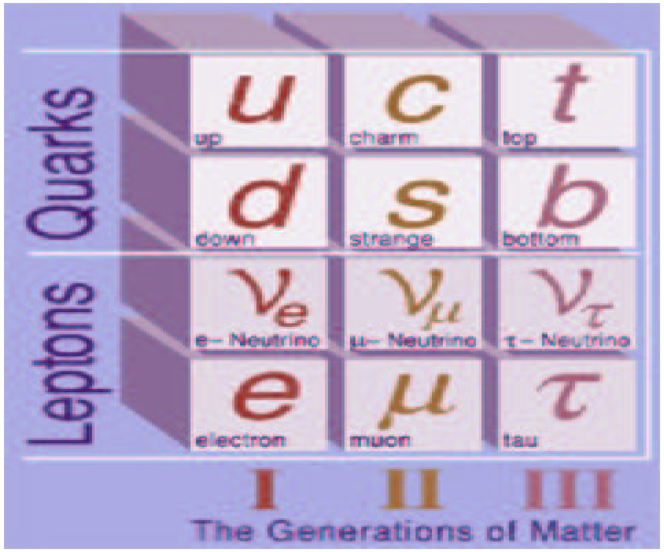
2×10^{20} **mu/yr/polarity** $\times$ **5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV**

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

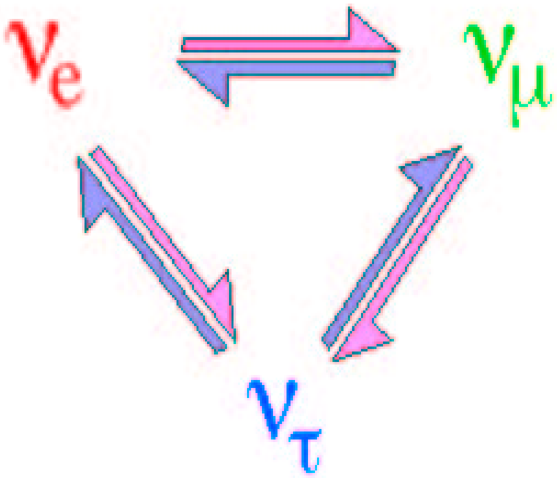
Neutrinos and new physics

massive neutrinos of different flavour $(\nu_e, \nu_\mu, \nu_\tau)$ can mix by quantum mechanics



Since 1998, measurements of the flux of atmospheric neutrinos in the Super-Kamiokande detector have shown evidence for neutrino $\nu_\mu \to \nu_\tau$ oscillations

In April 2002, the SNO collaboration demonstrated that the solar neutrinos were also converted into other flavours before reaching the Earth



study of neutrino properties is the best way

to probe new physics at scales

nu-oscillations first/only evidence for physics beyond the Standard Model

Theory of neutrino properties

how to reconstruct the parameters

how to reconstruct the underlying Theory

simplest gauge theory mixing matrix

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

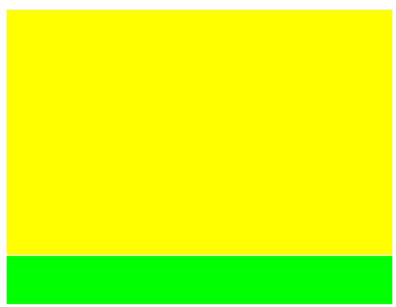
  1 KM-like — ϕ

  2 Majorana phases $\beta\beta_{0\nu}$ — ϕ_1 , ϕ_2

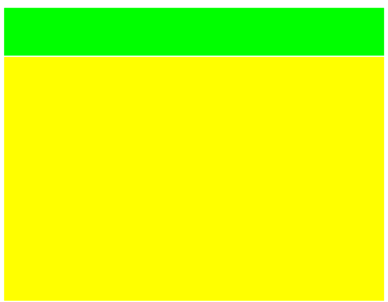
Schechter and Valle, Phys. Rev. D **22** (1980) 2227

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

NORMAL



INVERSE



quasi-degenerate may lead to $\beta\beta_{0\nu}$ rate similar to present hint

Ioannisian & J. V. PL B332 (1994) 93; Caldwell & Mohapatra; Joshipura; Bamert & Burgess; Balaji, Mohapatra, Parida & Paschos, Babu, Ma & Valle, ...

Ellis & Lola, Ma, Casas et al, Haba et al, ... back

leptonic CP violation

- will be a challenge !

  "Dirac" CPV suppressed, since ϕ disappears when $\Delta_{12} \to 0$

  Schechter and Valle, Phys. Rev. D **21** (1980) 309

- "Majorana" CPV absent from conventional $\Delta L = 0$ oscillations

- require L violation and effect is V-A suppressed (Dirac-Majorana confusion theorem) e.g. $\beta\beta_{0\nu}$ (Doi et al 1981) & $\Delta L = 2$ oscillations

  Schechter and Valle, Phys. Rev. D **23** (1981) 1666

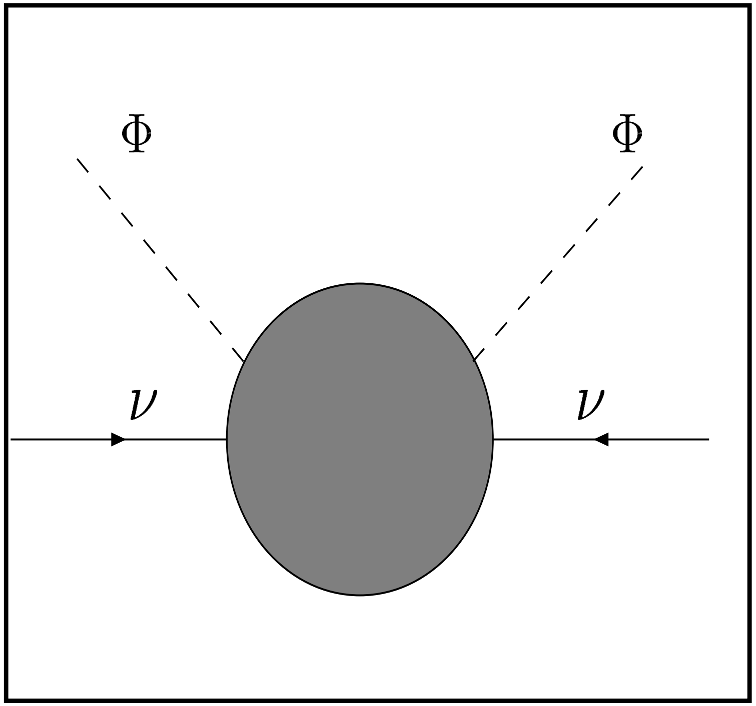
- must look for chirality violating processes, such as neutrino electromagnetic form factors

- **or processes involving large "Majorana"-masses, such as leptogenesis**

- the seesaw connection opens the remarkable possibility that the Majorana phases of the light neutrrinos affect the baryon asymmetry generated in leptogenesis models in an unsuppressed way

Theory ideas

basic dim-5 operator back

- 

- from Gravity

Weinberg; Barbieri, Ellis, Gaillard; Akhmedov et al

- from seesaw schemes

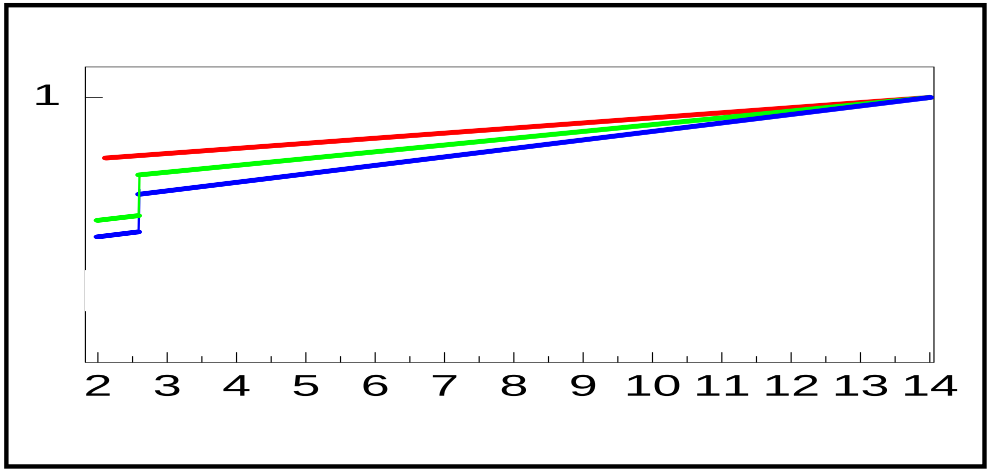
Gell-Mann, Ramond, Slansky; Yanagida;
Mohapatra, Senjanovic Phys. Rev. Lett. **44** (1980) 91
Schechter, Valle Phys. Rev. D **22** (1980) 2227

here I consider at an effective level

neutrino unification

back

Babu, Ma and Valle, Phys. Lett. B 552 (2003) 207 [hep-ph/0206292]



due to A_4 symmetry neutrino masses unify as they run up

Chankowski et al, Phys. Rev. Lett. **86** (2001) 3488 [hep-ph/0011150]

solar & atm splittings arise from RGE + threshold effects

common origin for neutrino and KM mixing

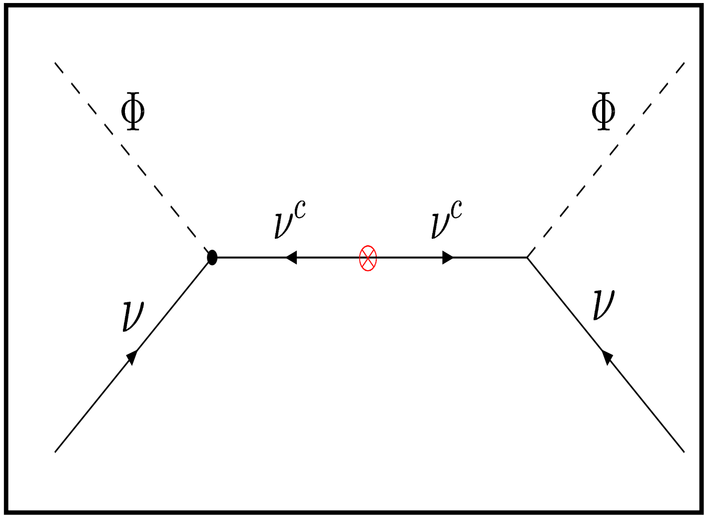
maximal θ_{23}; large θ_{12} & small θ_{13}

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

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

The seesaw

neutrino masses follow from the exchange of heavy isosinglet neutral heavy leptons with mass $M_R = M_R^T \propto \Delta_R$ (**126** of SO(10), type I) or from the exchange of heavy scalar bosons (type II)



$$\begin{pmatrix} M_L & D \\ D^T & M_R \end{pmatrix}$$

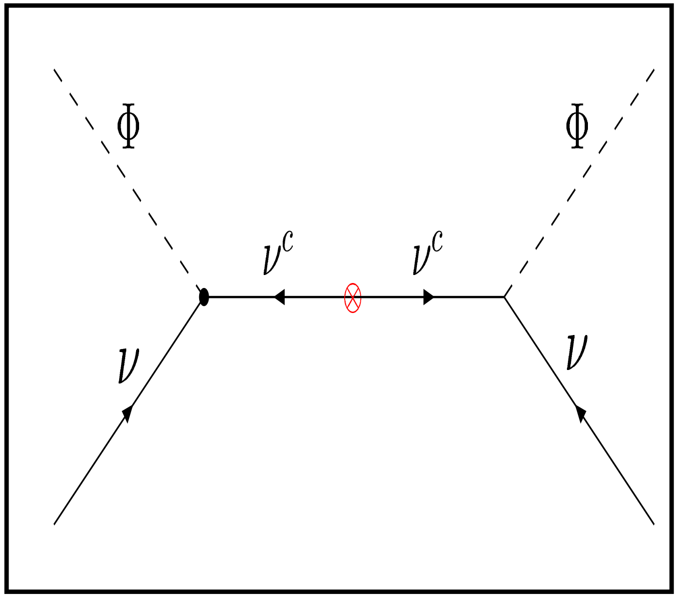
the first gives $M_{\nu\,\mathrm{eff}} = M_L - DM_R^{-1}D^T$ where D is the standard $SU(2) \otimes U(1)$ breaking Dirac mass term

the M_L term is propto an effective iso-triplet vev Schechter, Valle Phys. Rev. D **22** (1980) 2227 also suppressed by the left-right breaking scale, $M_L \propto 1/M_R$ Mohapatra, Senjanovic

hardly any predictivity, unless specific symmetries are assumed

global realization of seesaw mechanism

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, Phys. Rev. D **25**, 774 (1982) back

negligible in vacuo, but important in SNovae Kachelriess et al PRD62 (2000) 023004, Lindner, et al NPB607 (2001) 326

seesaw charged and neutral currents

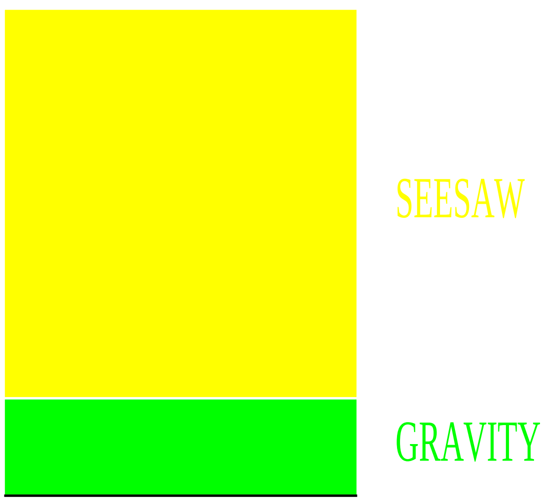
Schechter, Valle, Phys. Rev. D **22**, 2227 (1980) & D **25**, 774 (1982)

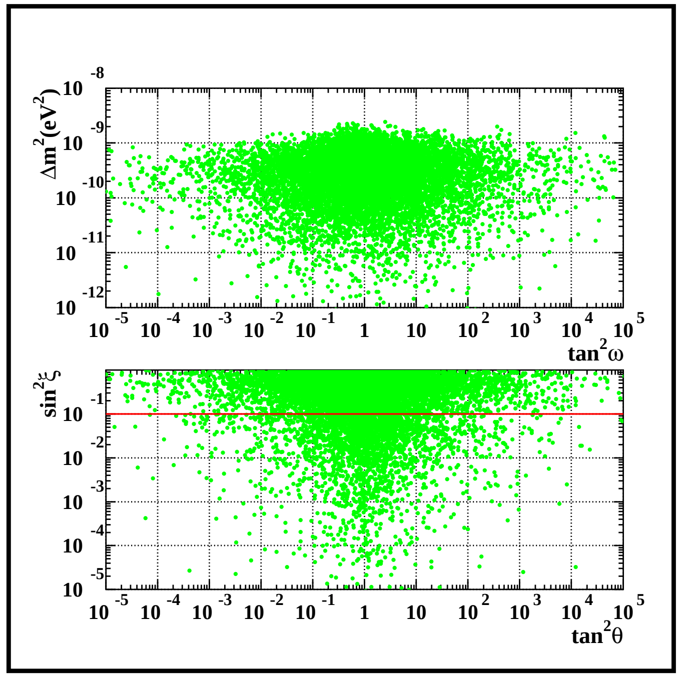
- arbitrary number of $SU(2) \otimes U(1)$ singlets implies that the mixing matrix describing the charged leptonic weak interaction is a rectangular matrix K which may be decomposed as $K = (K_L, K_H)$ where K_L and K_H are 3×3 matrices.
- far more mixing angles θ_{ij} and CP violating phases ϕ_{ij} than needed to describe the charged current weak interaction of quarks, since (i) neutrinos are Majorana particles so that their mass terms are not invariant under rephasings, and (ii) the isodoublet neutrinos mix with the isosinglets.
- The NC weak interactions are described by a non-trivial matrix $P = K^\dagger K$ implies $\nu_h \to 3\nu$
- strength of new couplings maybe sizable in variants of the seesaw: NSI
- The (3, 1) model has 2 massless neutrinos. The other two form a light-heavy Majorana pair or a Dirac pair if lepton number is a good symmetry. If not the massless degeneracy is lifted by radiative corrections.
- forms the basis for hybrid model where atm scale comes from tree, while solar arises from loops

minimalistic neutrino masses?

Gouvea and Valle, Phys. Lett. B **501** (2001) 115 [hep-ph/0010299]

- based on 3 + 1 scheme
- seesaw generates atm scale, leaving 2 neutrinos massless
- degeneracy lifted by gravity-induced dim-5: solar scale

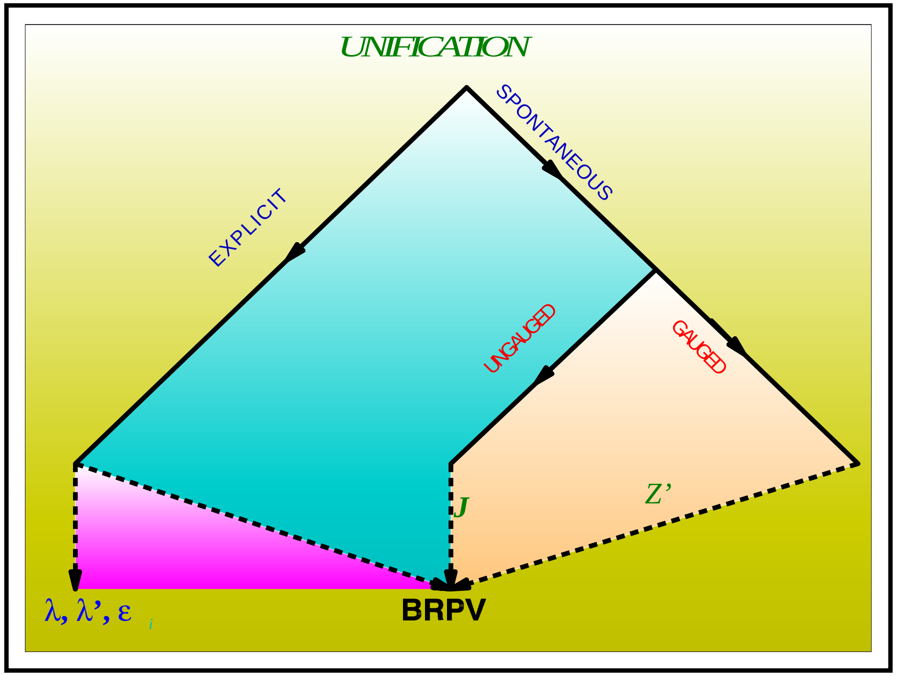




- KamLAND implies need for a non-gravitational mechanism to generate the solar scale

SUSY origin for neutrino mass

back



spontaneous RPV

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

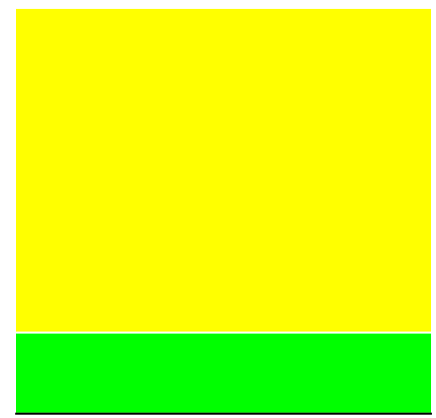
singlet sneutrino vev

Masiero and Valle, Phys. Lett. B 251 (1990) 273

attractive dynamics and systematic parametrization of RPV

spontaneous RPV $\longrightarrow$ effective bilinear RPV

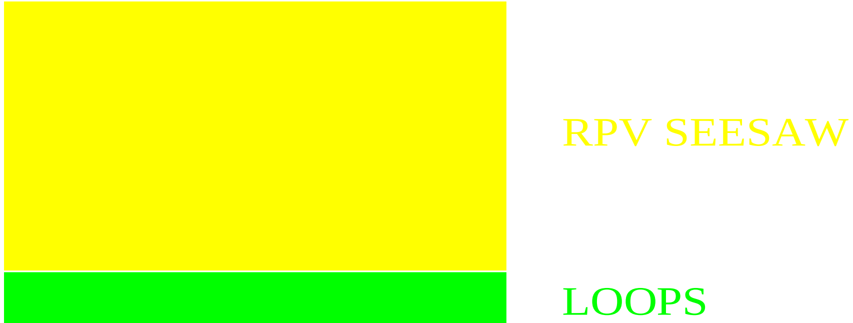
hybrid neutrino masses



U(1) family symmetries

Mira, Nardi, Restrepo and Valle, Phys. Lett. B 492 (2000) [hep-ph/0007266] back

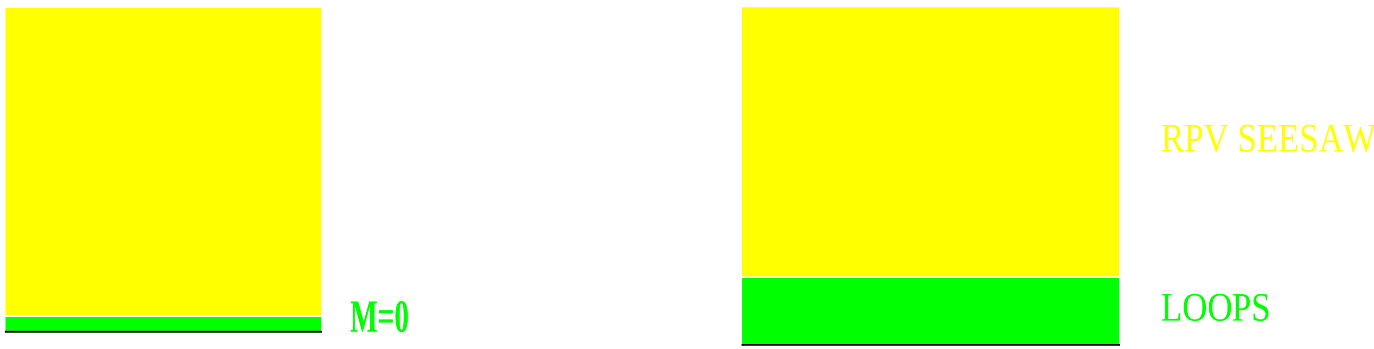
- quark and lepton mixing from textures
- U(1) symmetry $\to$ simplest bilinear RPV SUSY model:
  $W = W_{MSSM} + \mu_\alpha \ell_\alpha H_u$
  common origin for μ-problem & nu-anomalies
- $\mu_0 \sim m_{3/2}\theta$ Giudice-Masiero
  $\mu_i \sim m_{3/2}\theta^{7+x}$ Nilles-Polonsky
- RPV-seesaw gives atm scale, leaving 2 nu's massless
- degeneracy lifted by loops, to give solar scale. Need to change U(1) assignments so as to get hugher Δm^2_{SOL} in agreement with Kamland

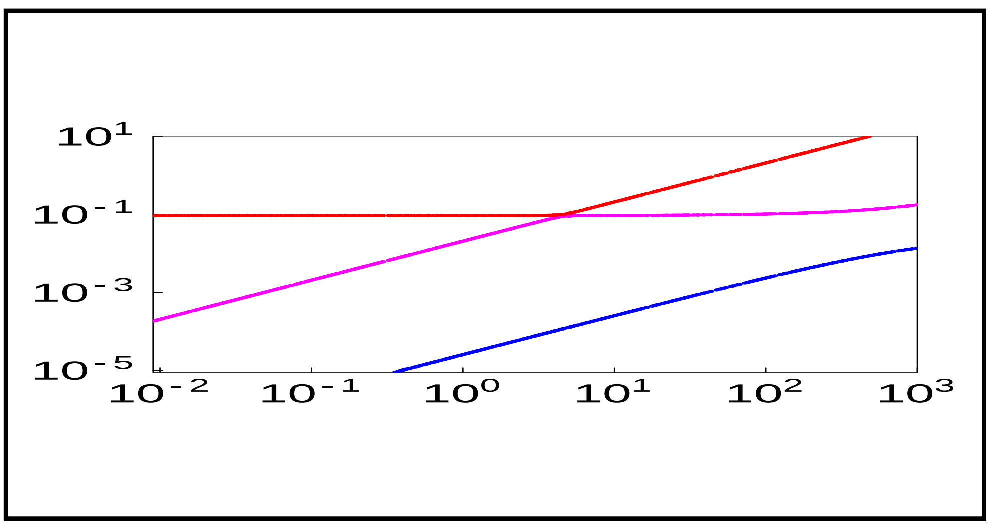


bilinear RPV solution to neutrino anomalies

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

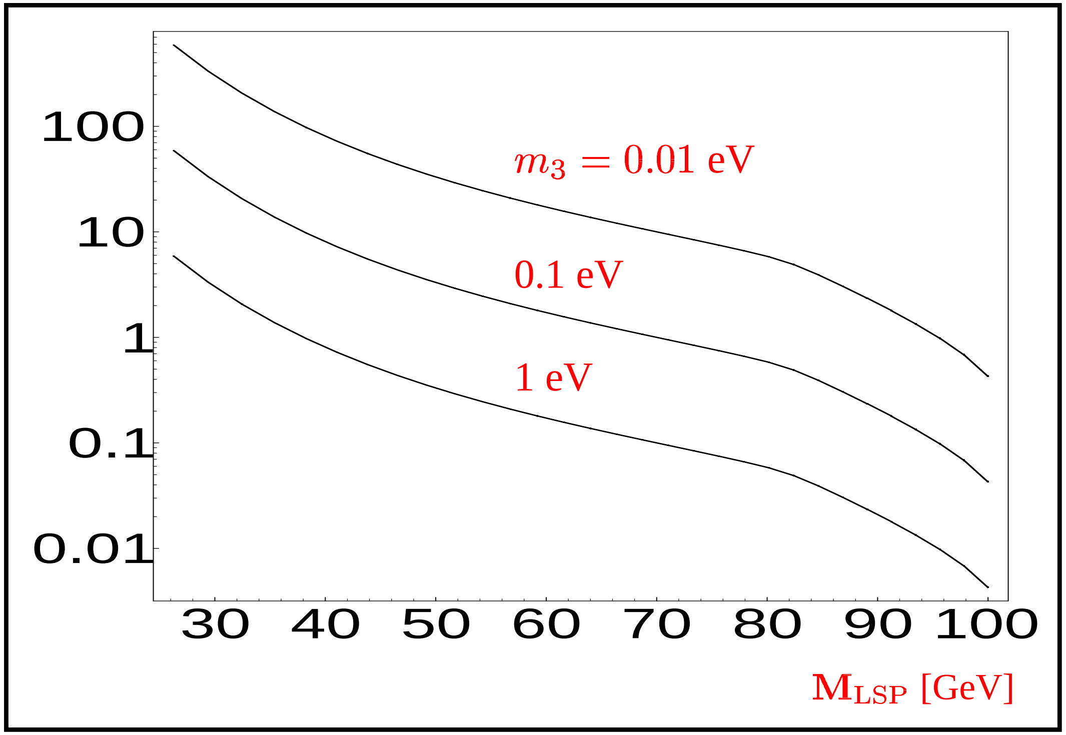
- weak-scale seesaw atm scale
- radiative nu-masses solar scale





LSP decay length [cm]: BRPV

back from Bartl et al NPB 600 (2001) 39



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

no neutralino dark matter

any charged SUSY particles can be the LSP

neutrino mixing angles in BRPV back

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

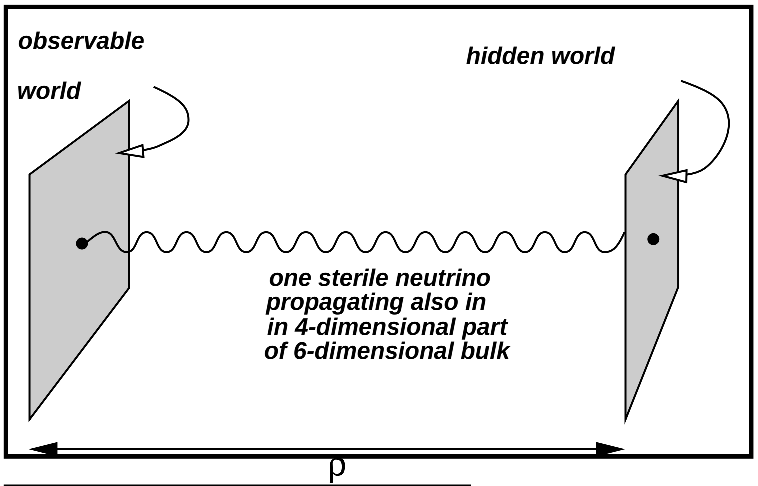
Hirsch's talk

light sterile-nus from extra dimensions

back — Ioannisian, JV PRD63 (2001) 073002

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

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



-

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

  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, as mentioned, can not reconcile LSND and other SBL data with solar + atm data

light-nu's without new scale

tree

Gonzalez-Garcia, JV, Phys. Lett. B **216**, 360 (1989); Romao and JV, Nucl. Phys. B **381** (1992) 87...

vs radiative

Zee or Babu-type

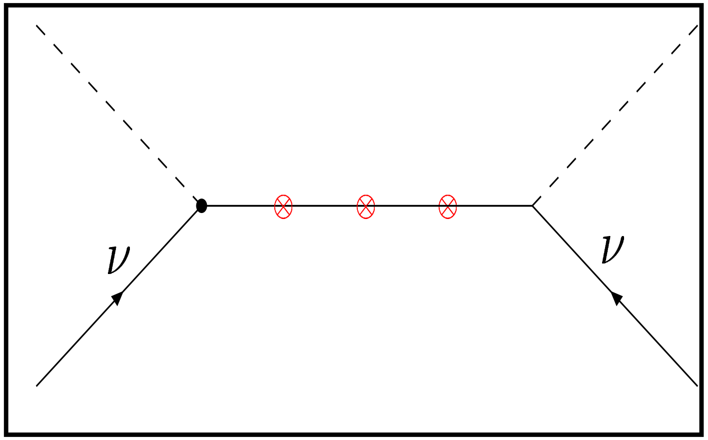
In contrast to seesaw

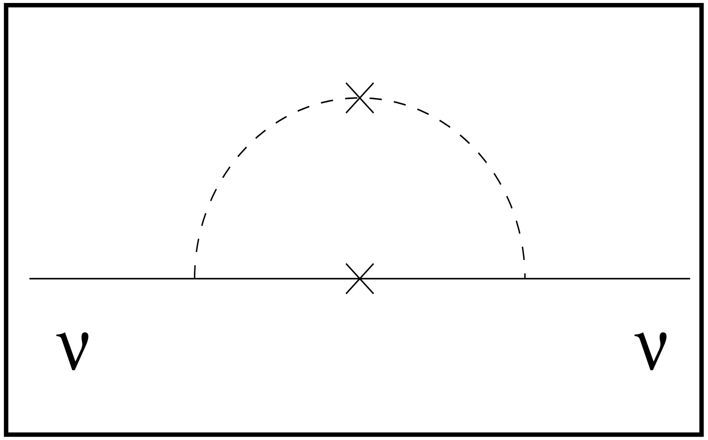
m-nu $\to$ 0 as the LNV scale $\to$ zero

Higgs $\to$ 2–majoron "invisible" decays

Joshipura, JV NPB397 (1993) 105;

Campos et al PRD55 (1997) 1316 back





predicting nu-mass and mixing?

back

- 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

In short

- oscillations fit well sol+atm, but **not LSND**
- LMA-MSW as astro-probe: SuperNovae and Sun

  probing the Sun beyond helioseismology
- **non-standard properties can only play a sub-leading role in solar and atm**

  robustness
- NSI test @ NuFact | e-tau NSI-OSC confusion...
- **no hard theory predictions** | **but suggests Majorana**
- if neutrino masses arise from low energy supersymmetry, neutrino properties may be testable at high energy accelerators