Interpreting Neutrino Data

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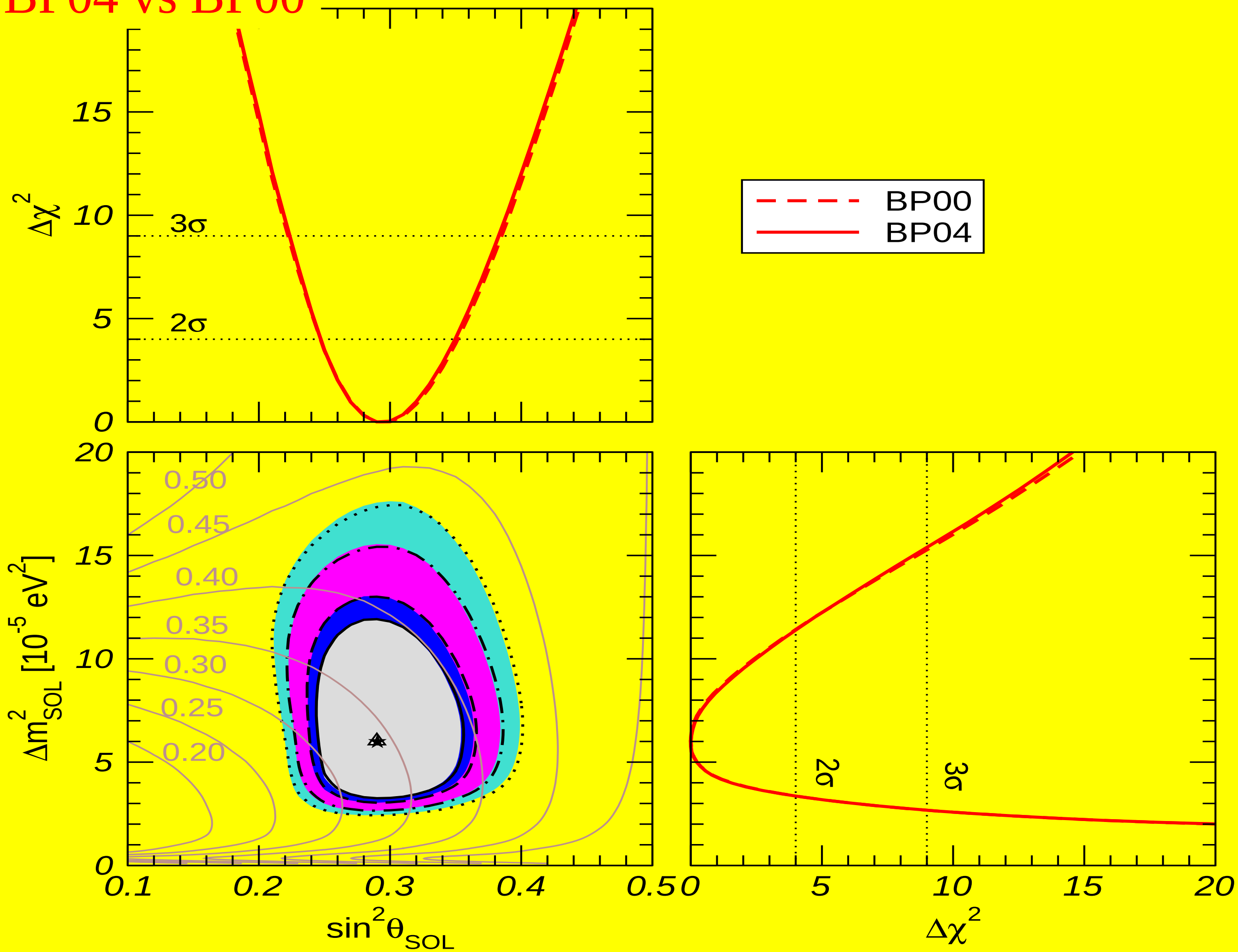
AHEP-IFIC-CSIC/U. Valencia

Solar neutrino oscillations

Maltoni et al, hep-ph 0405172 vs PRD68 (2003) 113010

BP04 vs BP00



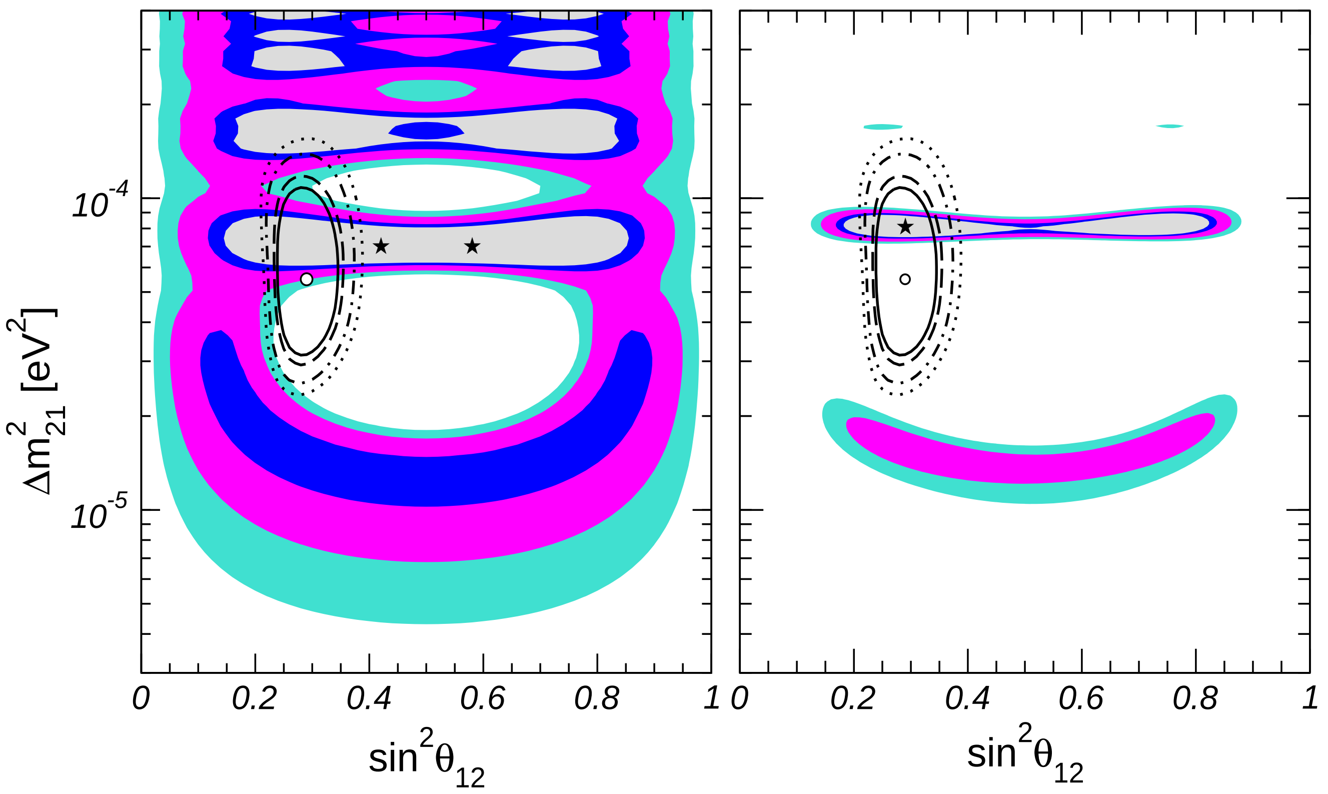
similar analyses by Bahcall et al, Bandyopadhyay et al, Balantekin et al, Fogli et al, ...

Reactor Neutrinos: KamLAND02 vs KamLAND04

Chooz-Palo Verde see no oscillations on $\sim$ 1 Km baseline

defi cit +spectrum distortion over $\lesssim$ 200 Km baseline

confi rms solar-nu oscillation hypothesis and gives tighter $\Delta m^2_{\mathrm{SOL}}$



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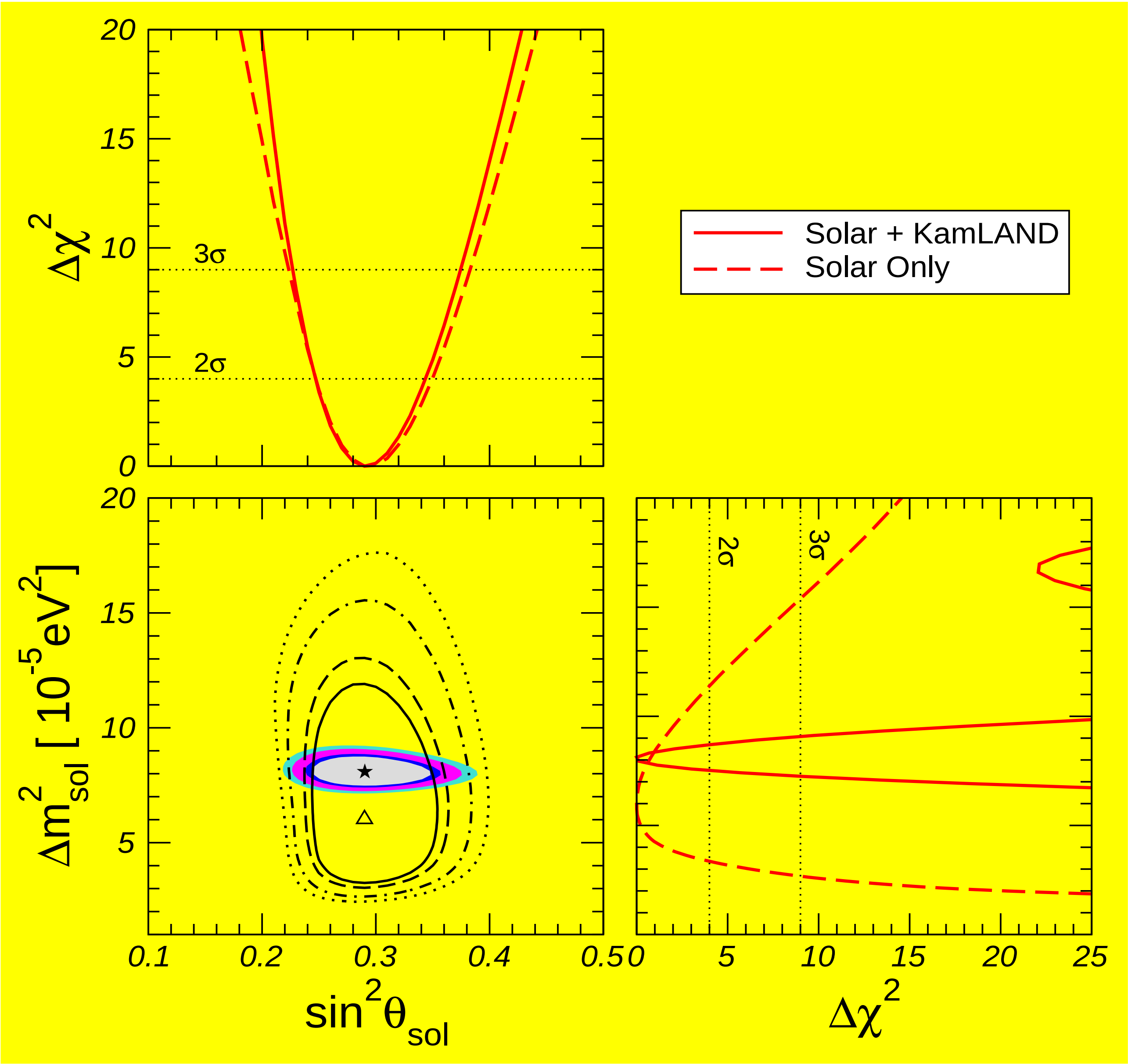
Solar + reactor, after Nu04



Maltoni et al, hep-ph 040517

enormous progress

in contrast to atm, solar mixing is non-maximal

bi-maximal out at 5.6σ

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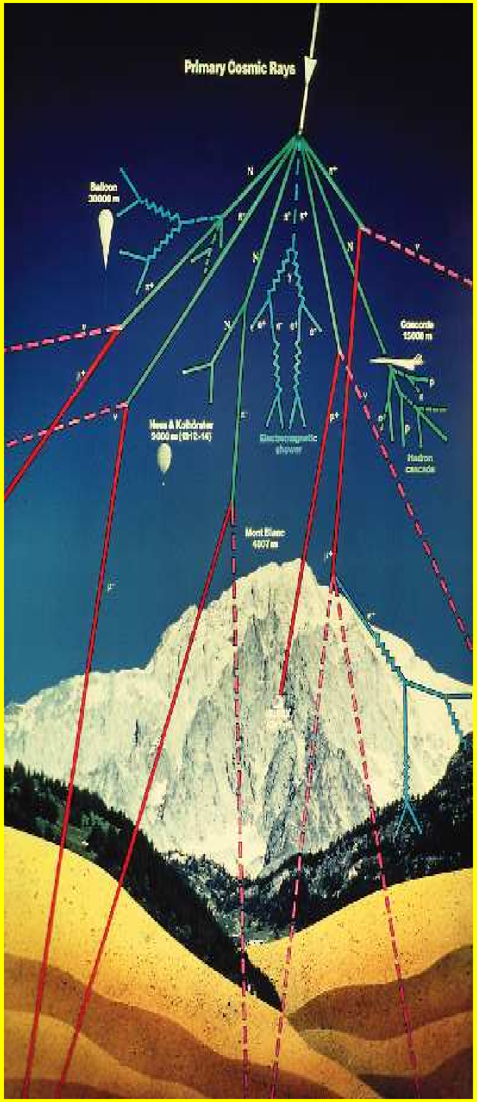
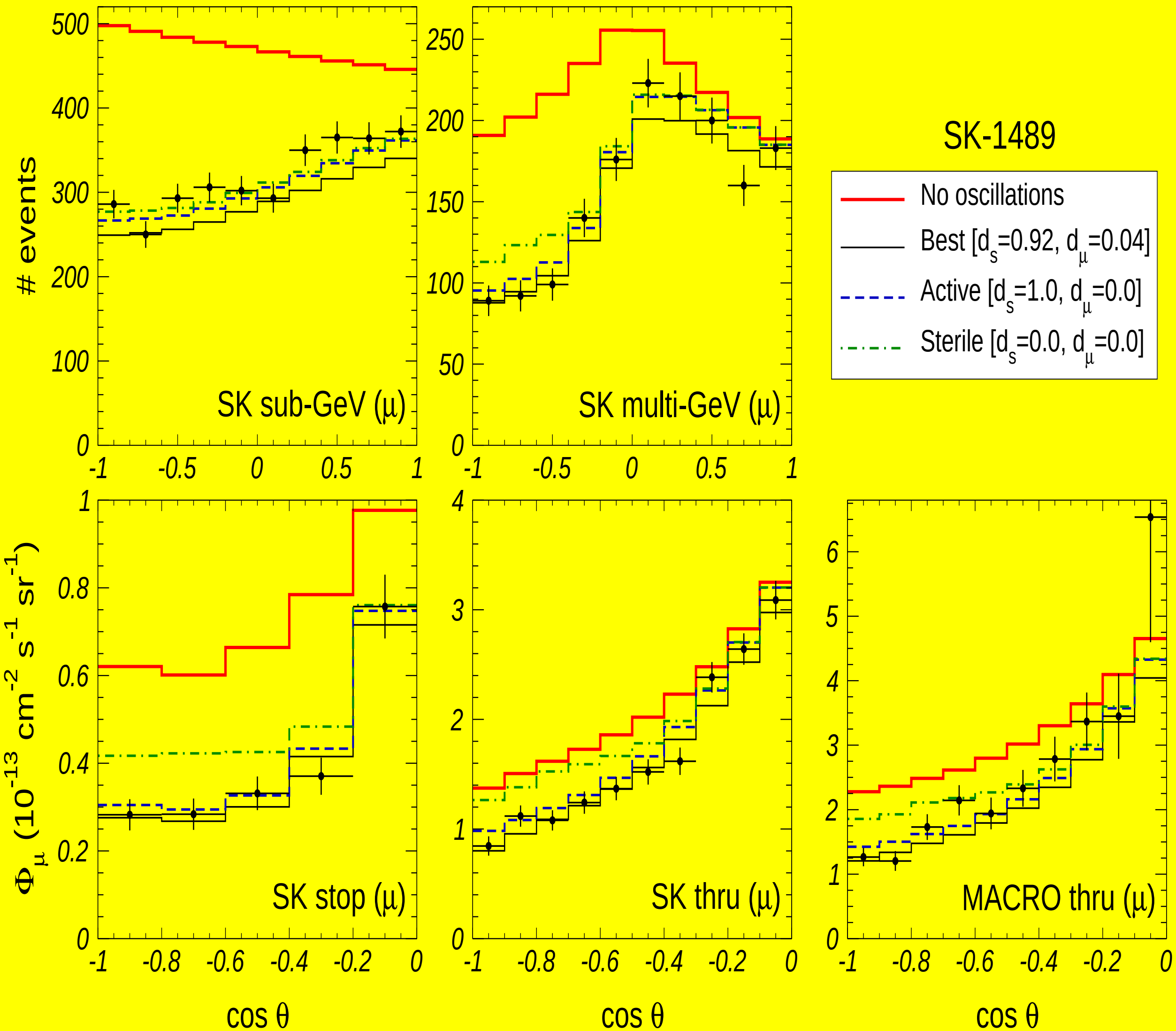
atm neutrinos

the discovery of neutrino mass

Atmospheric zenith distribution

Maltoni et al, PRD67 (2003) 013011 sterility rejection (1-d Bartol)





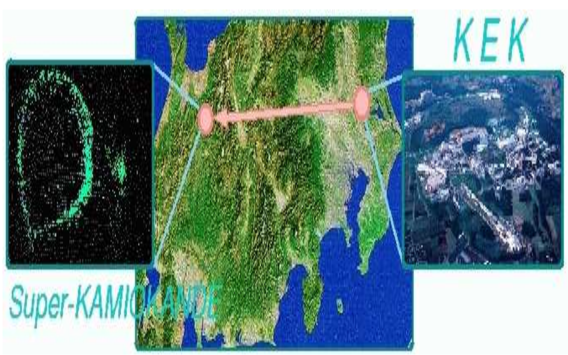
accelerator neutrinos: K2K

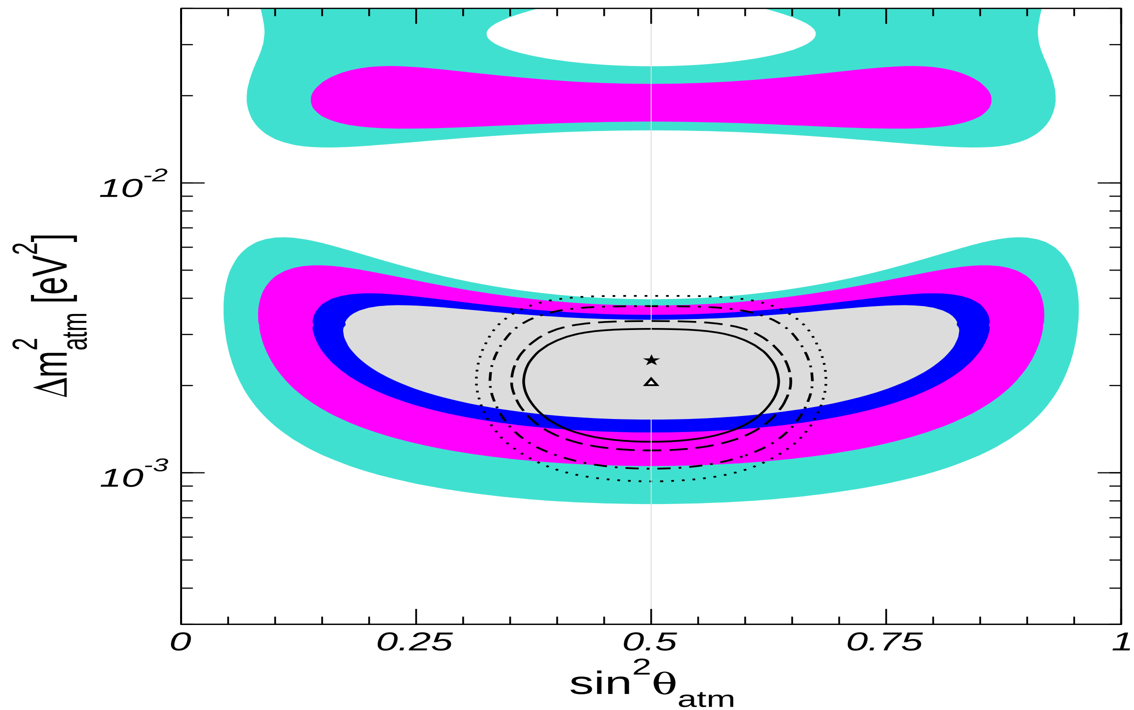
Maltoni et al, hep-ph 0405172

ν_μ defi cit+ distortion of the energy spectrum over 250 km baseline

neutrino oscillation signal

spectrum distortion improves $\Delta m^2_{\rm ATM}$





atmospheric + K2K (3d)

Maltoni et al, hep-ph 0405172 (3-d from Honda et al astro-ph/0404457) earlier 1-d Bartol flux used in PRD68 (2003) 113010

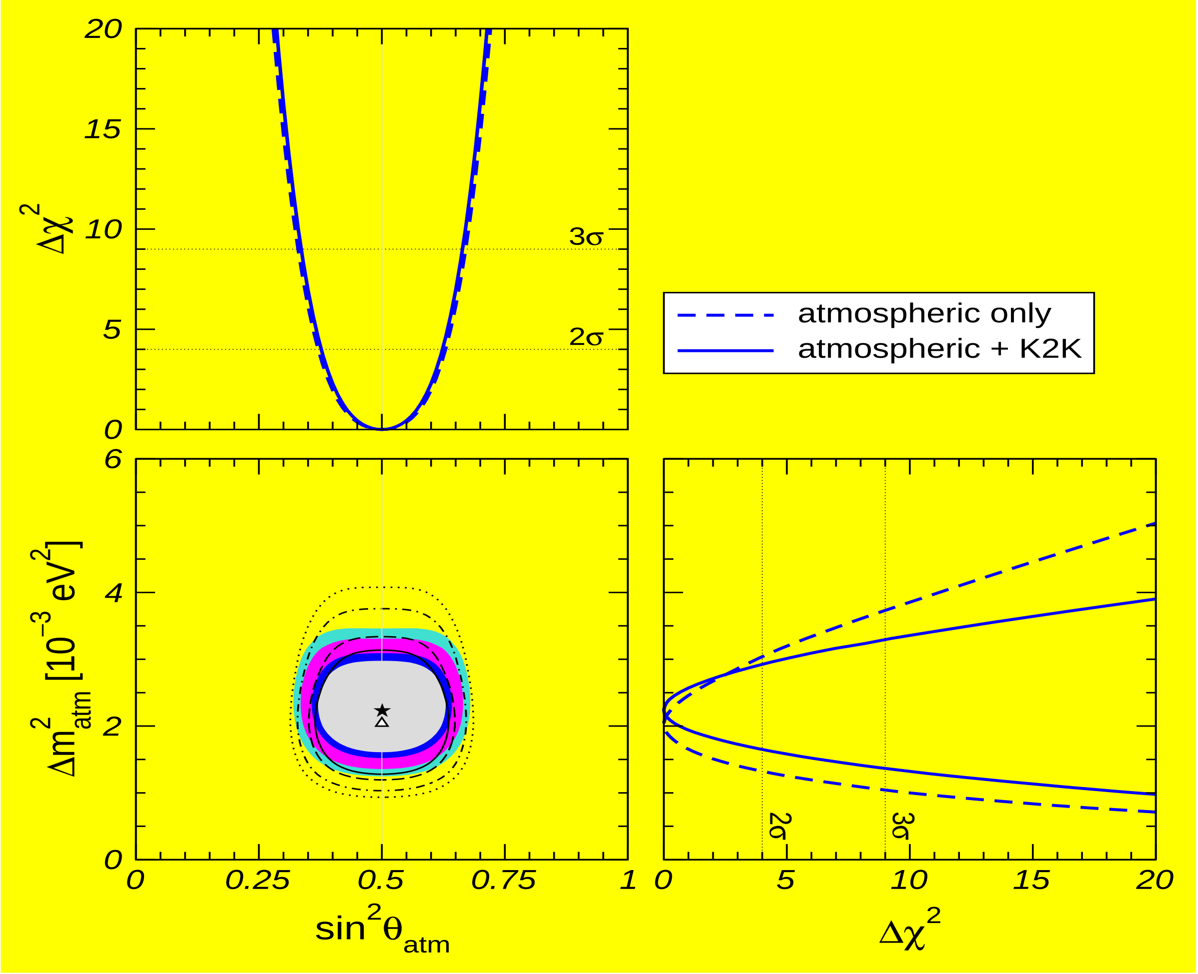
$$\sin^2\theta_{\rm ATM} = 0.50$$

atm

$$\Delta m^2_{\rm ATM} = 2.0 \times 10^{-3}\ {\rm eV}^2$$

atm+k2k

$$\Delta m^2_{\rm ATM} = 2.2 \times 10^{-3}\ {\rm eV}^2$$



3-nu oscillation parameters

minimal set of basic parameters

- 3 masses

minimal set of basic parameters

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

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minimal set of basic parameters

- 3 masses
- 3 angles θ_{ij} 23=atm 12=sol 13=reac
- 3 phases 1 KM-like phase oscillations δ

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

minimal set of basic parameters

- 3 masses
- 3 angles θ_{ij} 23=atm 12=sol 13=reac
- 3 phases 1 KM-like phase oscillations δ

  2 Majorana phases $\beta\beta_{0\nu}$ $\alpha\,,\beta$
- simplest form of 3-f lepton mixing $K = \omega_{23}\omega_{13}\omega_{12}$

  with each factor $\begin{pmatrix} c_{12} & e^{i\phi_{12}} s_{12} \\ -e^{-i\phi_{12}} s_{12} & c_{12} \end{pmatrix}$

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

minimal set of basic parameters

- 3 masses
- 3 angles θ_{ij} — 23=atm 12=sol 13=reac
- 3 phases — 1 KM-like phase — oscillations — δ

  2 Majorana phases — $\beta\beta_{0\nu}$ — $\alpha\ ,\beta$
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  Schechter and JV, PRD22 (1980) 2227, D23(1980) 1666
- for $\Delta L = 0$ oscillations we can drop Maj phases & take KM-like form

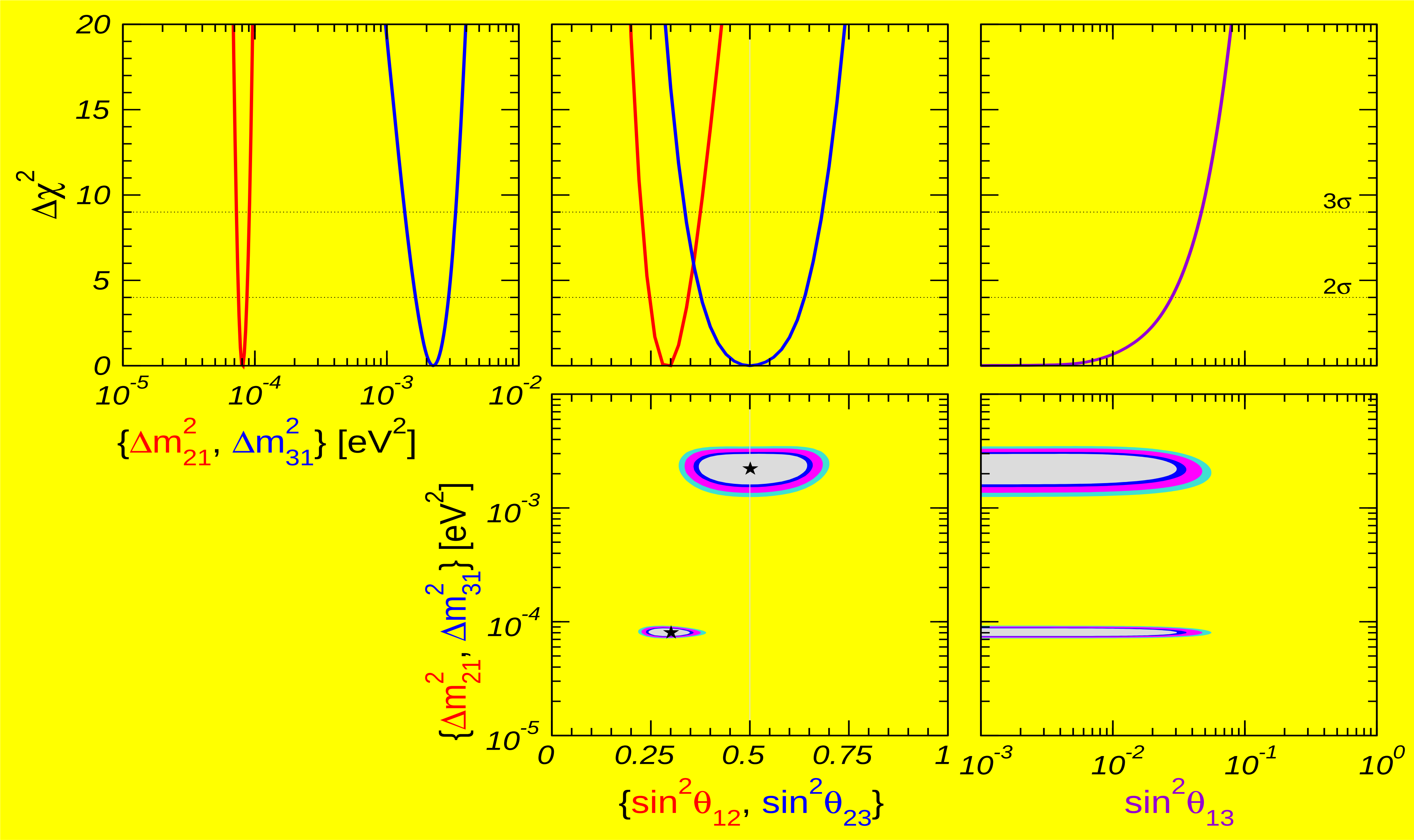
$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-\mathrm{i}\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}\mathrm{e}^{\mathrm{i}\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}\mathrm{e}^{\mathrm{i}\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}\mathrm{e}^{\mathrm{i}\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}\mathrm{e}^{\mathrm{i}\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix}$$

oscil currently not sensitive to δ_{CP} so we also drop it — 5 parameter 3-f oscillation analysis

3-nu Oscillations, after Nu04

M. Maltoni et al, hep-ph/0405172

θ_{13}



3-nu Oscillation Parameters, after Nu04

M. Maltoni et al, hep-ph/0405172

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	8.1	7.3–8.7	7.2–9.1
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.3	1.7–2.9	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68
$\sin^2\theta_{13}$	0.00	≤ 0.028	≤ 0.047

Table I: Best-fit values, 2σ and 3σ intervals (1 d.o.f.) for the three-flavour neutrino oscillation parameters from global data including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K) experiments.

probing 3-nu oscillation effects

tough challenge

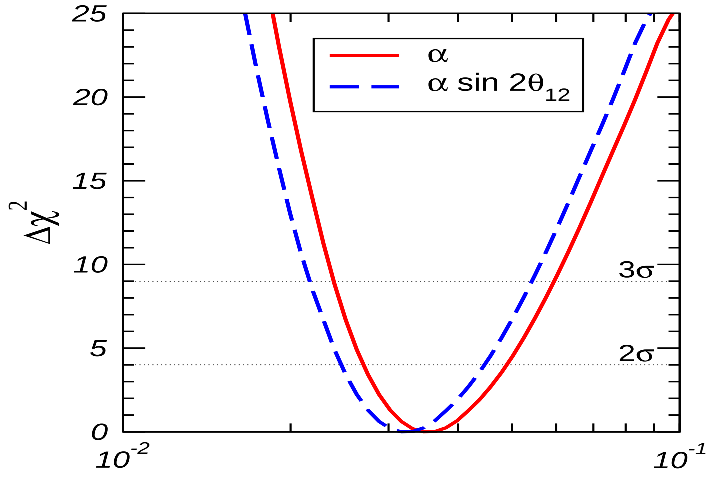
“Dirac” CPV disappears when any $\Delta_{ij} \to 0$, e. g. $\Delta m^2_{\rm SOL}$

Schechter and JV, PRD21 (1980) 309

and when $\theta_{13} \to 0$

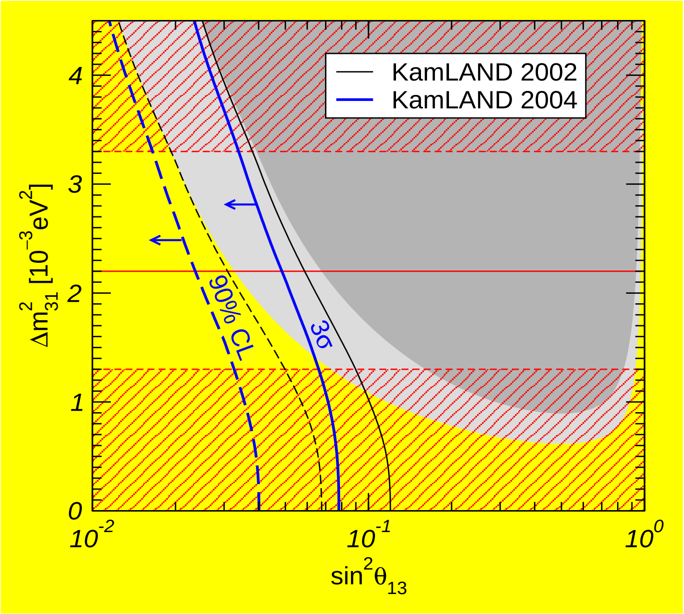
$\Delta m^2_{\rm SOL}$-θ_{13} correlation...

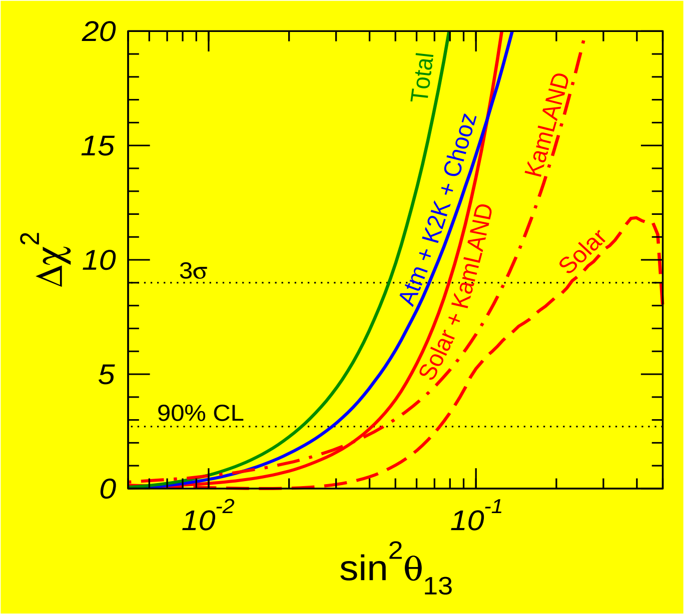
$\alpha = \Delta m^2_{\rm SOL}/\Delta m^2_{\rm ATM}$ and θ_{13} after Nu04



improvements
will come from LBL
reactor/accel expts

as well as solar
(Akhmedov etal)





for low $\Delta m^2_{\rm ATM}$ solar+KamLAND both contribute

are oscillations robust ?

Do we really understand

... the Sun?

... neutrino propagation ?

... neutrino interactions ?

more than constraining oscillations ...

KamLAND has solved the solar neutrino problem...

rejecting non-standard mechanisms as leading solns

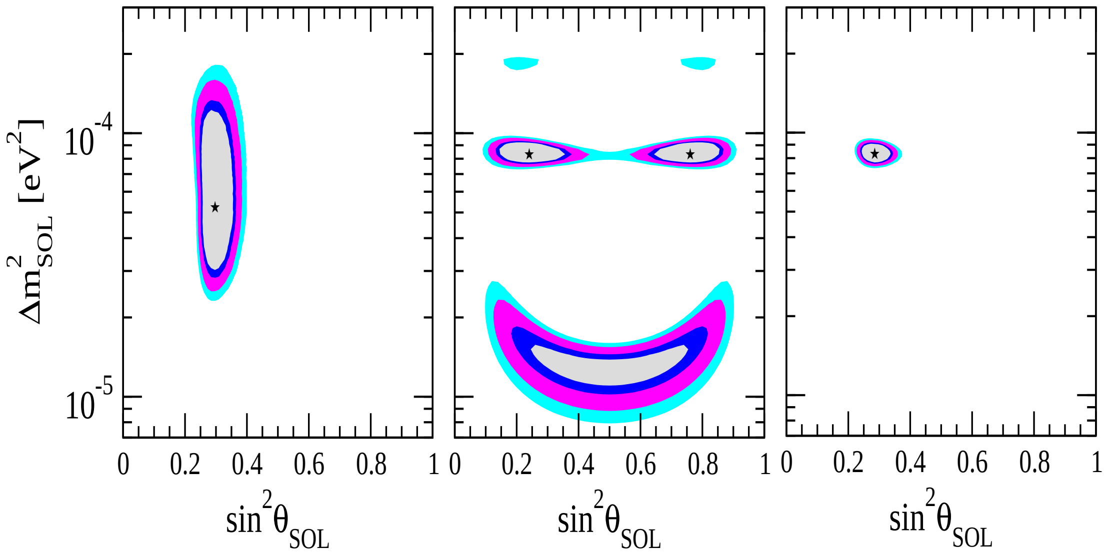
Burgess et al JCAP 0401 (2004) 007, MNRAS 348 (2004) 609 robust **noisy Sun**

Miranda et al PRL 93, 051304 (2004) & hep-ph/0406066 robust **SFP**

Miranda etal hep-ph/0406280 almost robust ... **NSI**

fragility of solar-nu oscillations?

unfortunately yes, wrt NSI



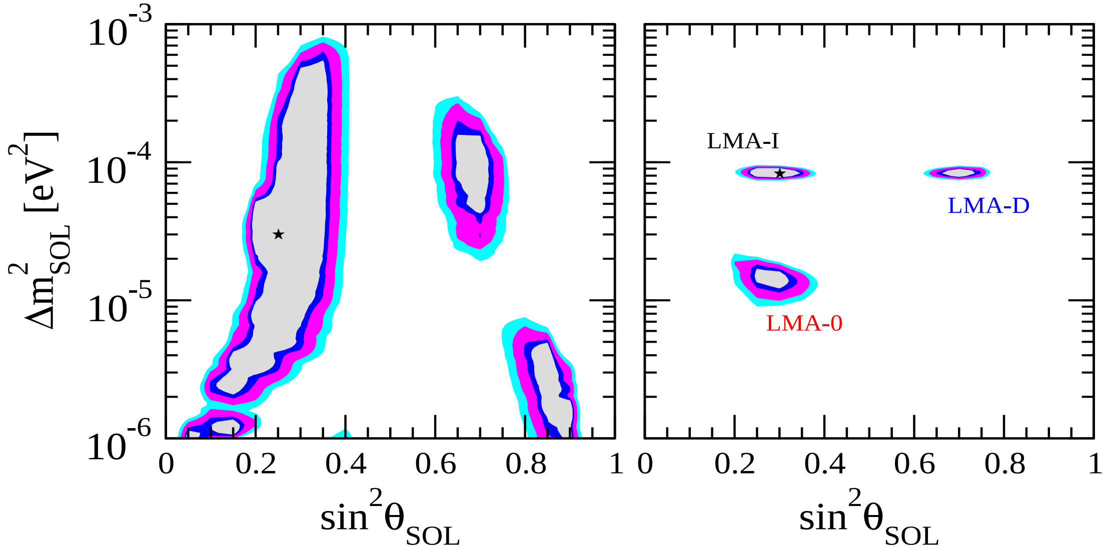
Miranda etal, hep-ph/0406280

KamLAND04

degenerate dark-side soln, not resolved by KamLAND

LMA-0 also noted in
Guzzo, de Holanda, Peres,
Friedland, Lunardini, Pena-Garay

LMA-D new



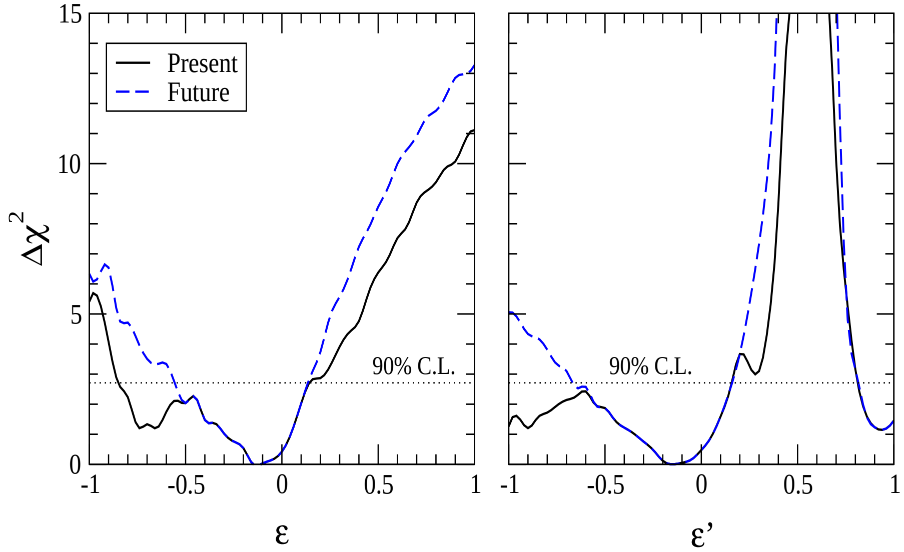
probing non-standard interactions with solar-nu's

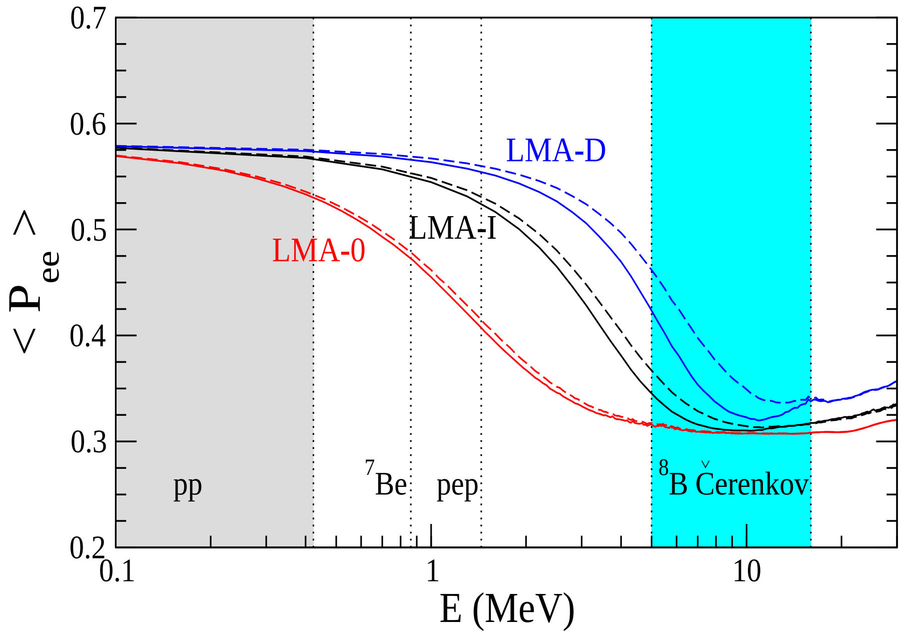
O. Miranda et al, hep-ph/0406280

KamLAND can not resolve

need for new solar expts...

a chance for Hiper-K and Borexino?

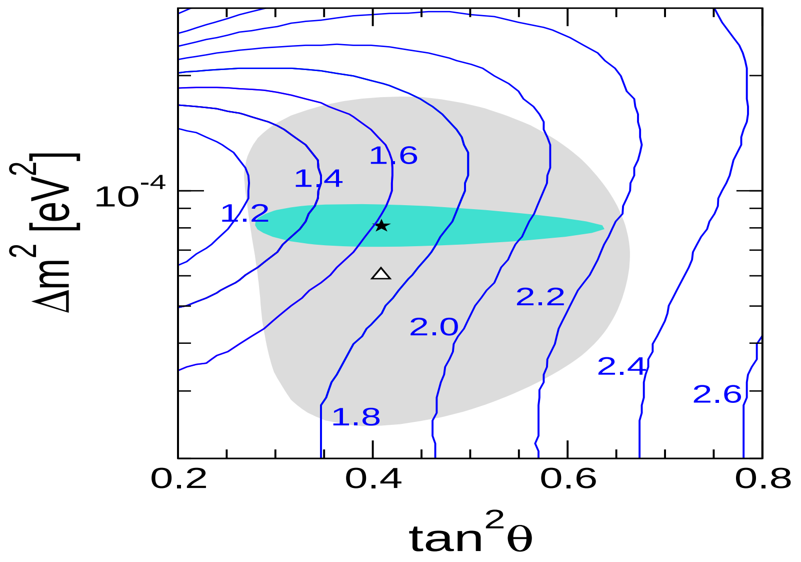




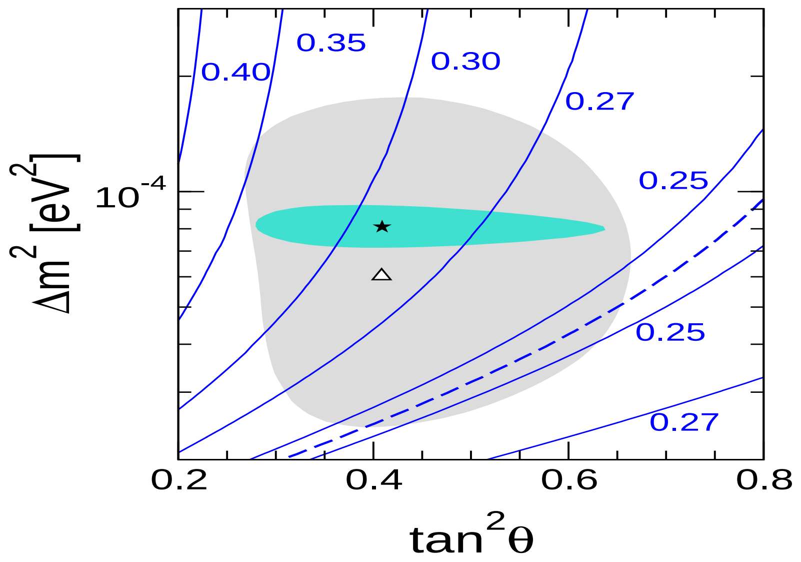
probing neutrino magnetic moments at LMA-MSW

present sensitivity

$$|\mathbf{\Lambda}| < \begin{cases} 3.4 \times 10^{-10}\mu_B & \text{sol + KL04} \\ 1.7 \times 10^{-10}\mu_B & \text{sol + KL04 + reac} \end{cases}$$



upd of Grimus et al, NPB648, 376 (2003)



projected Borexino sensitivity

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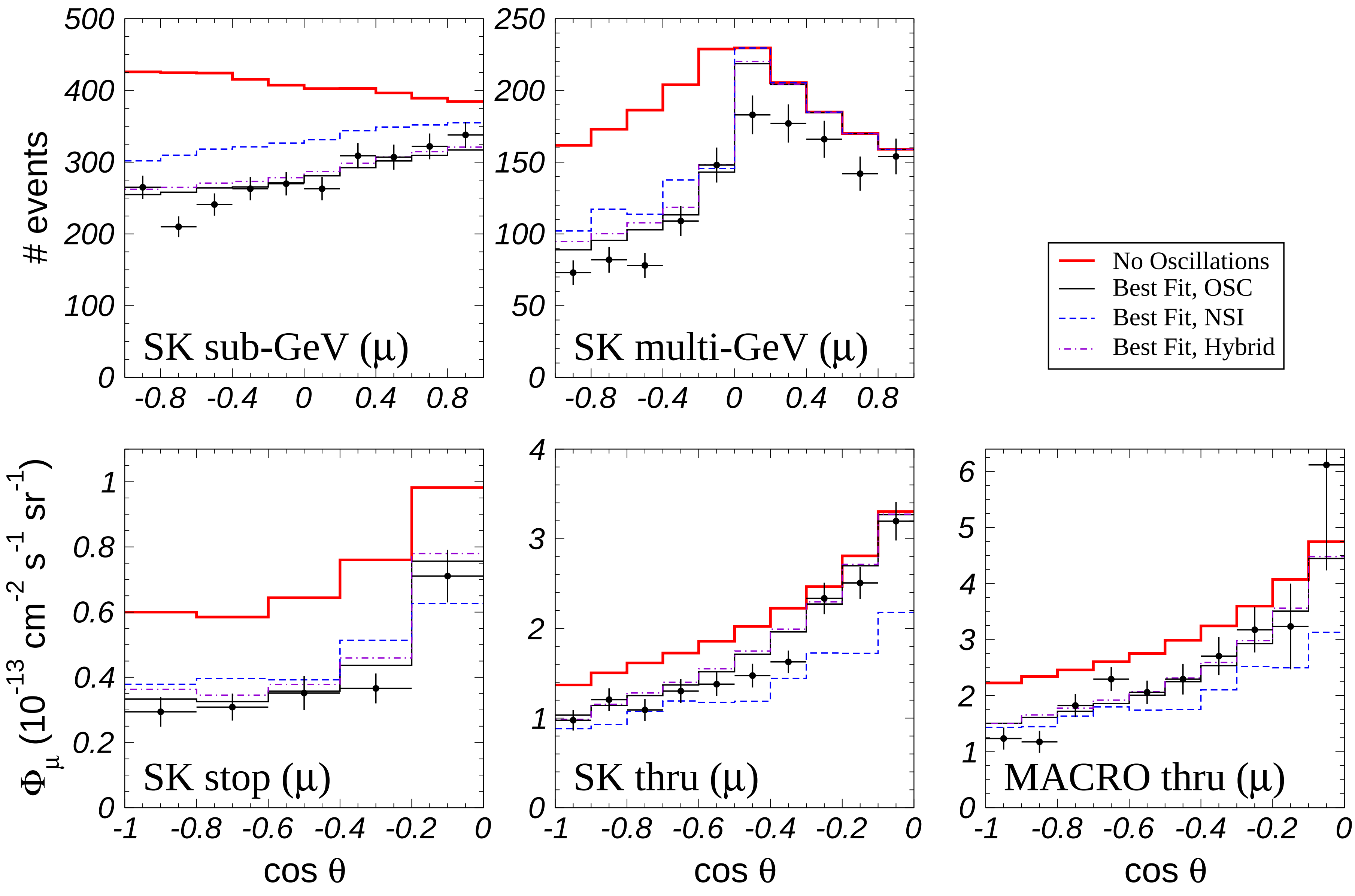
How robust are atmospheric oscillations?

very good contained atm-fi t

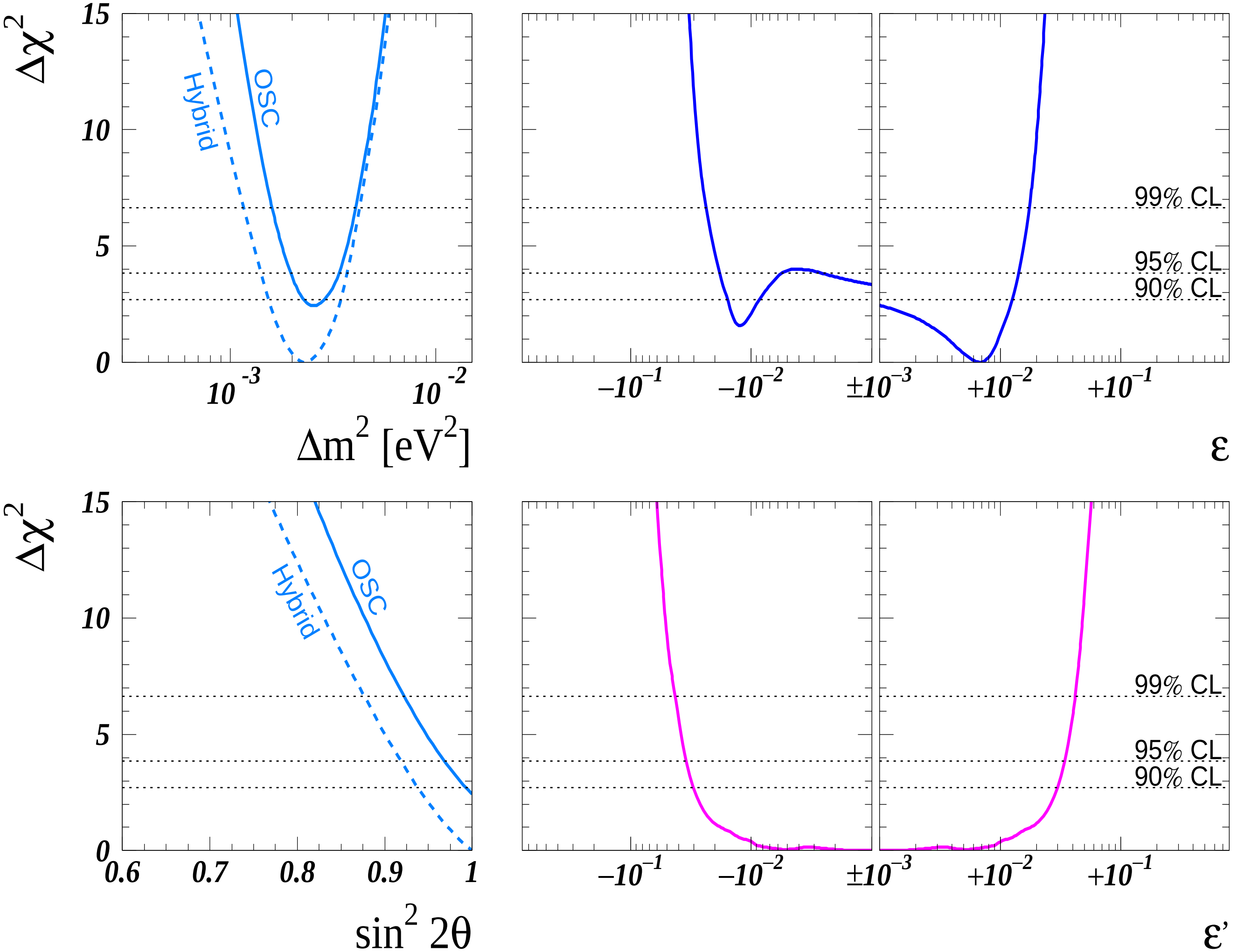
Gonzalez-Garcia et al, PRL82 (1999) 3202



probing non-standard interactions with atm data

atm bounds on FC and NU nu-interactions

upd of Fornengo et al, PRD65 (2002) 013



(1-d Bartol)

will improve at NuFact

(3-g) Friedland, Lunardini & Maltoni hep-ph/0408264

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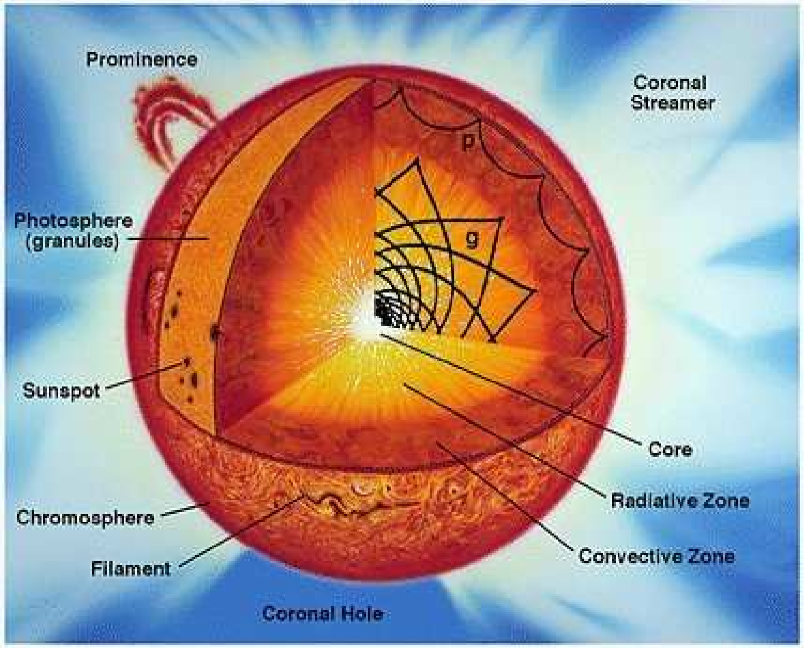
Neutrinos from Heavens

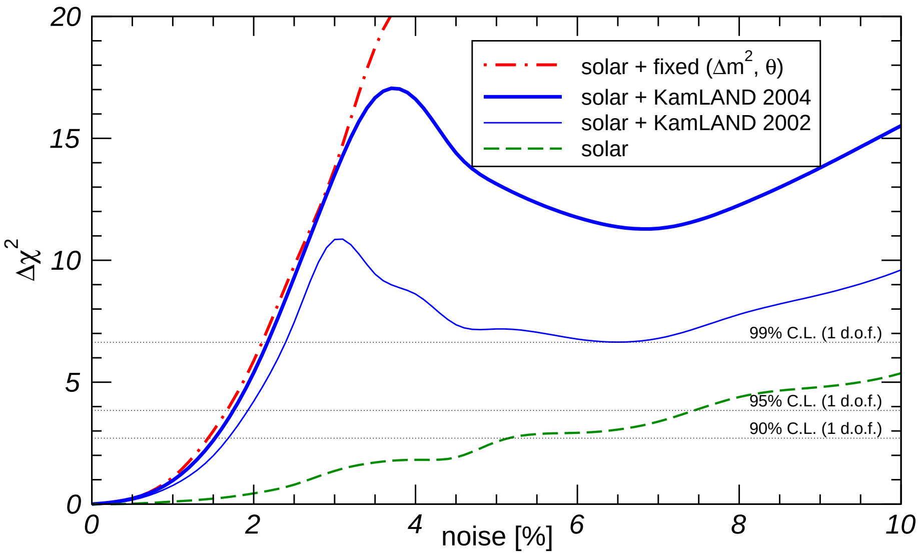
nu's as astro probe

Neutrinos as deep solar probe

use precision solar-nu data to probe the sun beyond helioseismology ... e.g. R-zone MHD physics leading to density fluctuations

Burgess et al, MNRAS 348 (2004) 609





neutrinos as future Supernova probe

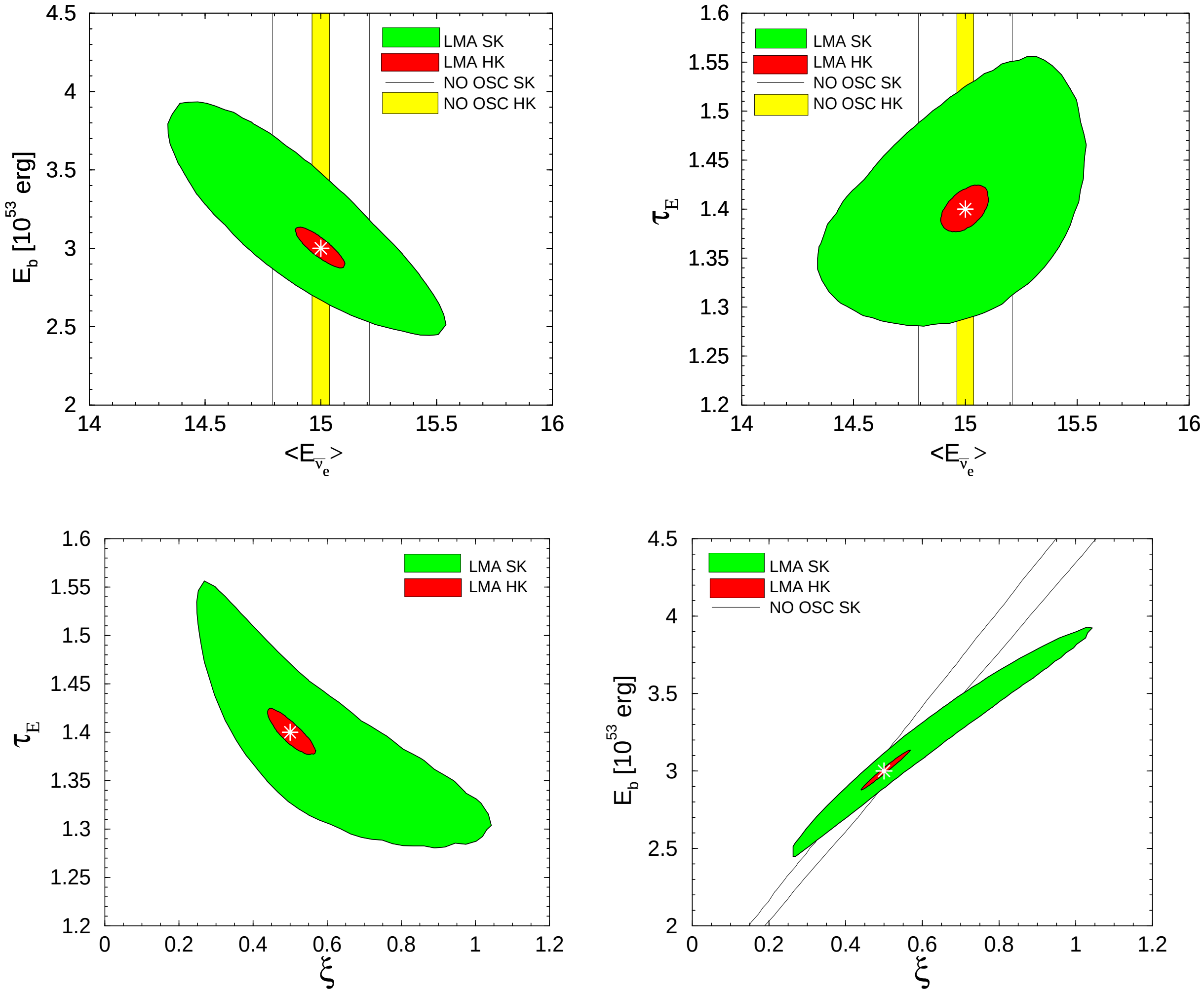
though OK with SN1987A

Kachelriess et al PRD65 (2002) 073016

LMA may clash with future SNovae

Minakata et al, PLB542 (2002) 239

The measurement of a large number of neutrinos from a future galactic supernova will give us important astro information



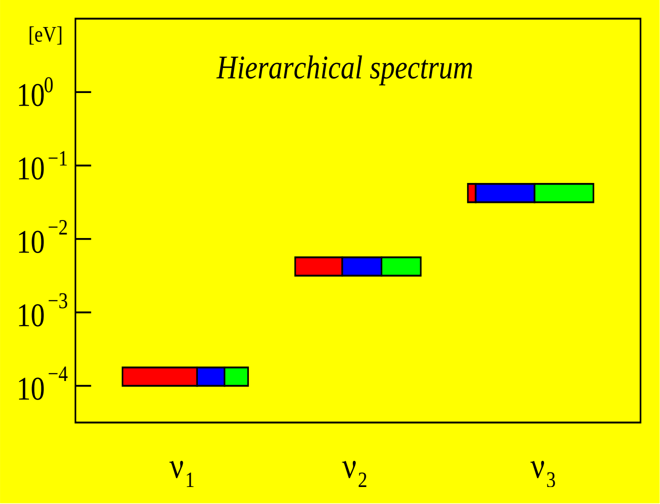
simulate nu-signal from 10 kpc galactic SN with given astro param...

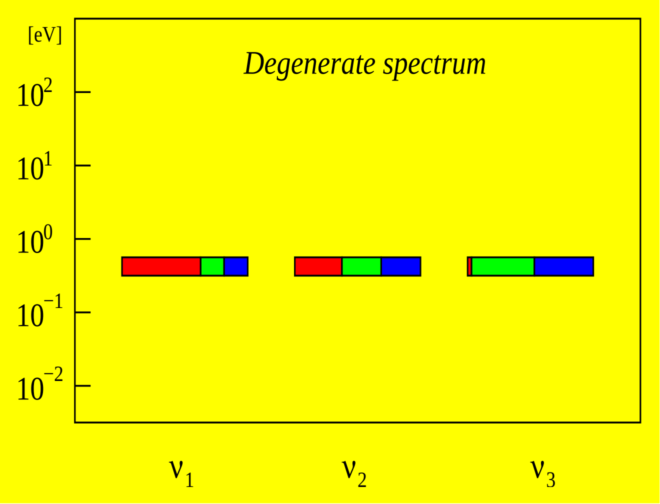
see also Barger, Marfatia & Wood

improved supernova parameter determination

hierarchical or (quasi)-degenerate

ν_e ν_μ ν_τ

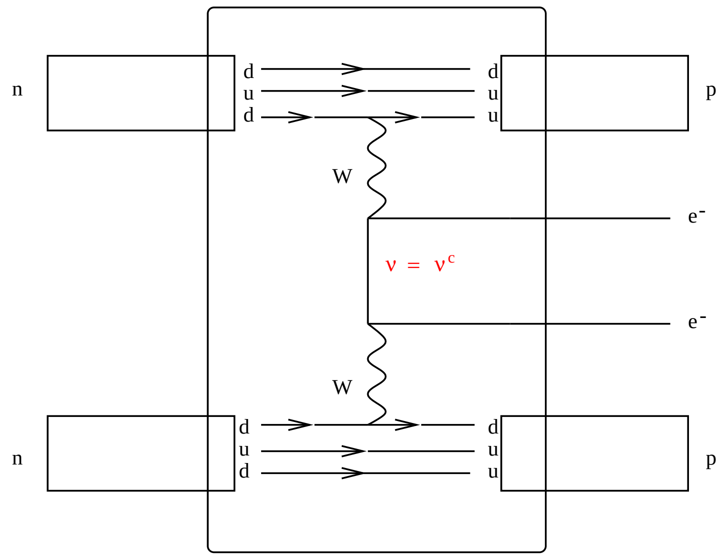




oscillations can not resolve ...

0-nu double beta decay and the neutrino spectra

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

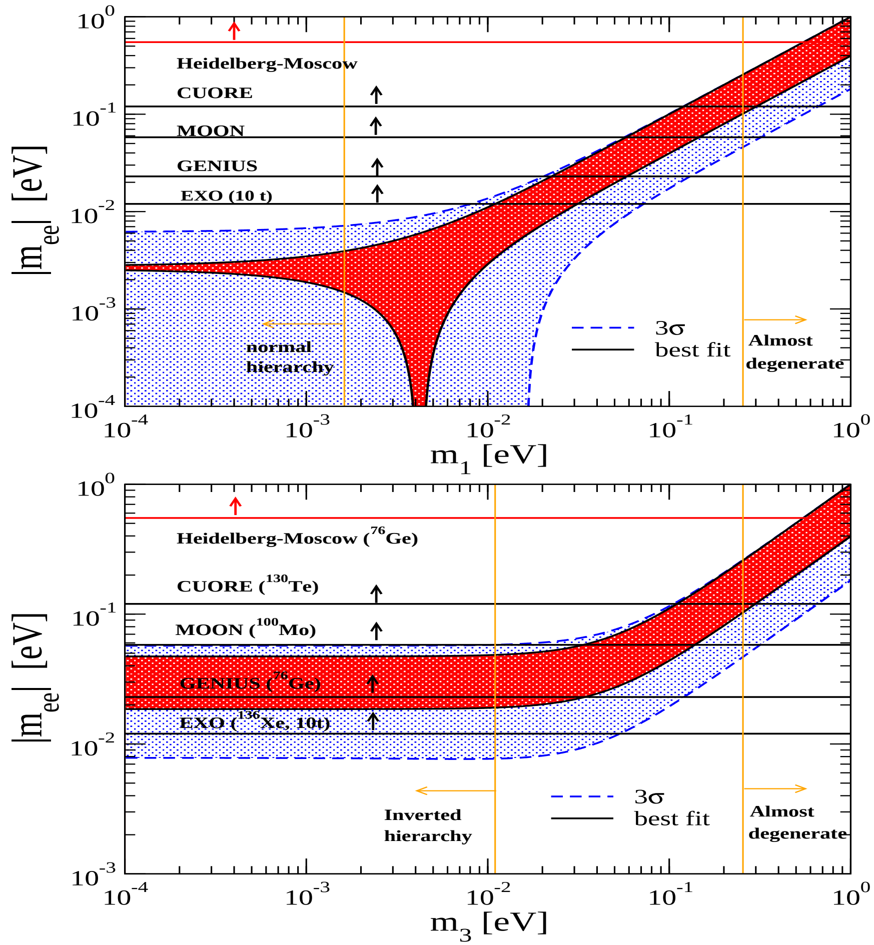


$$\langle m_\nu \rangle = \sum_j K_{ej}^2 m_j$$

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

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

$\beta\beta_{0\nu}$ decay sensitivities cf tritium & cosmo



Klapdor, Paes, Smirnov, ... Bilenky, Faessler, Simkovic hep-ph/0402250

can not yet reconstruct majorana phases Barger, Glashow, Langacker, Marfatia, PLB540 (2002) 247

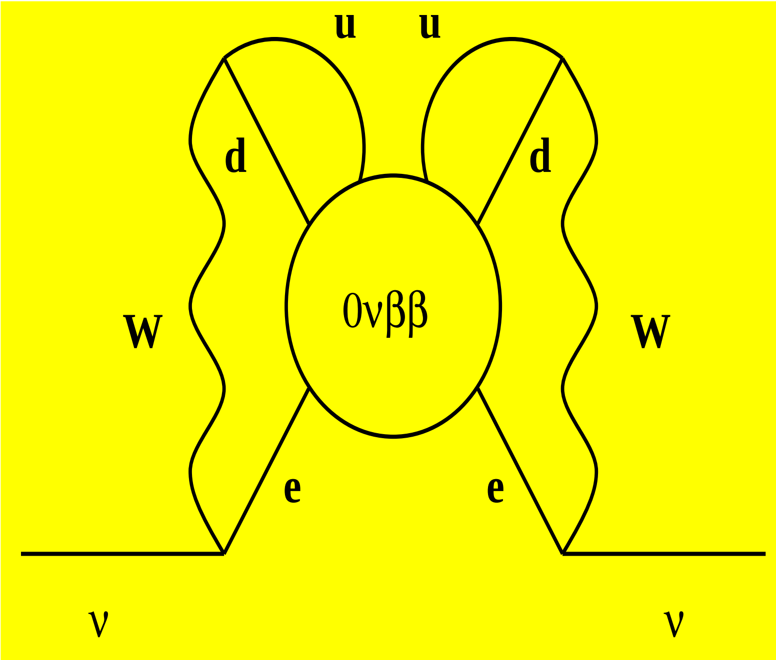
Relevance of 0-nu double beta decay

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

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

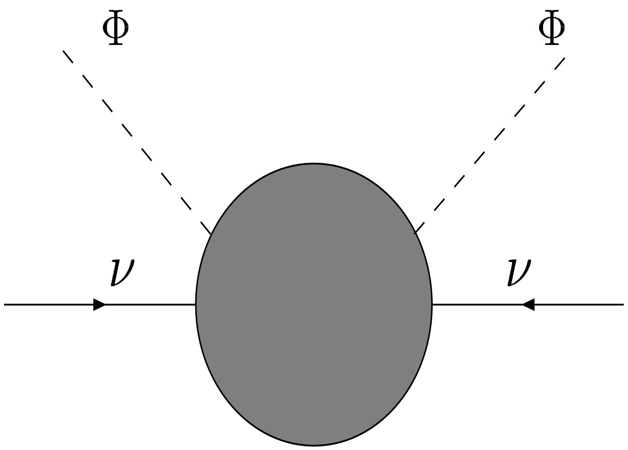
Schechter and JV, PRD25 (1982) 2951

no such theorem for flavor violation



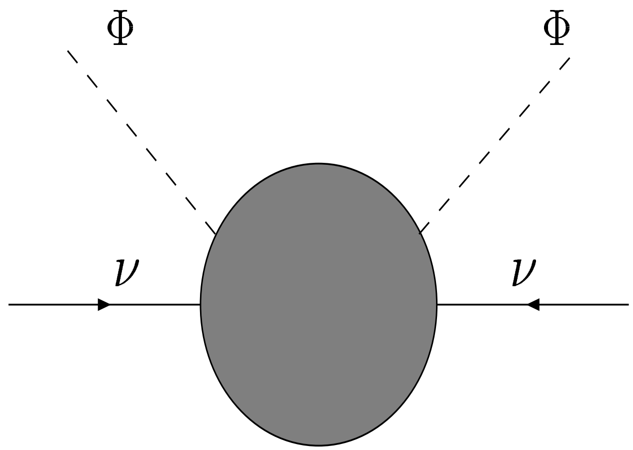
the origin of neutrino mass

basic dim-5 operator



Weinberg PRD22 (1980) 1694

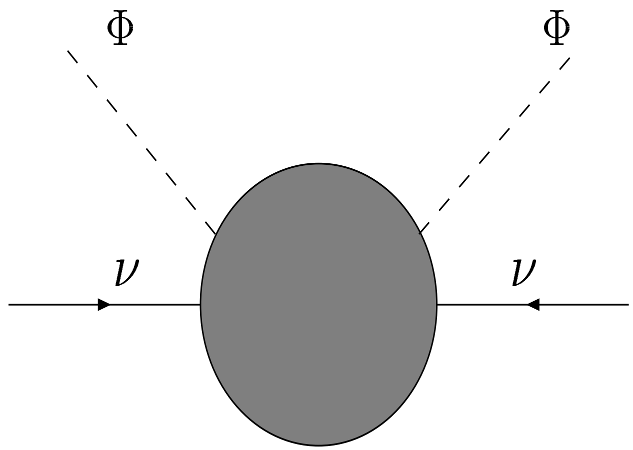
basic dim-5 operator



- Weinberg PRD22 (1980) 1694
- **unknown scale and flavour structure**

many possible realizations, eg seesaw **just A MECHANISM**

basic dim-5 operator



- Weinberg PRD22 (1980) 1694
- **unknown scale and flavour structure**

  many possible realizations, eg seesaw **just A MECHANISM**

- whatever one does ... one must come down to **the effective seesaw**

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

  is in terms of $SU(2) \otimes U(1)$ and contains a Higgs triplet (type-II seesaw)

  contains a large number of parameters, angles, D & M-phases

top-bottom neutrino masses

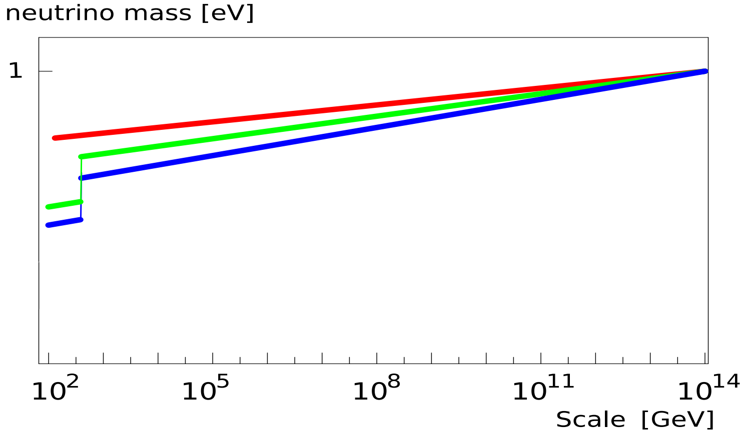
neutrino unification?

Babu, Ma & JV, PLB552 (2003) 207

Hirsch et al, PRD69 (2004) 093006

neutrino masses unify as they run up

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

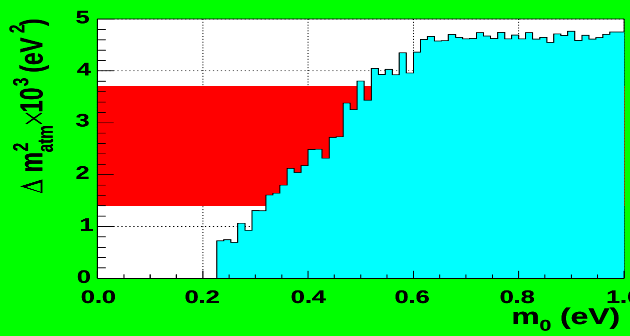


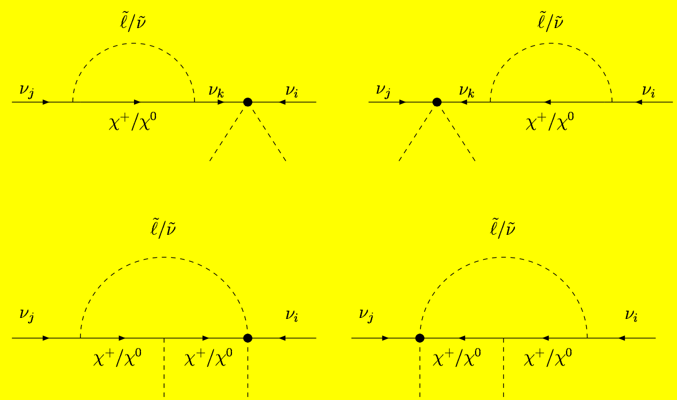
$\theta_{23} = \pi/4$; $\theta_{13} = 0$ or maximal CPV & large, unpredicted θ_{12} also Grimus & Lavoura

min nu-mass solar & atm splittings calculable

lepton mixing large wrt quark

large LFV





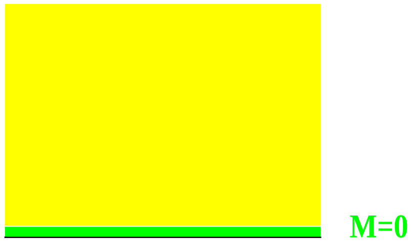
bottom-up neutrino masses

SUSY as origin of neutrino mass

M. Hirsch, JV, hep-ph 0405015 NJP

SUSY origin for neutrino masses?

- weak-scale seesaw atm scale

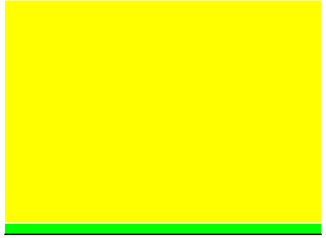


0-0

Diaz etal PRD68 (2003) 013009, PRD62 (2000) 113008; D65 (2002) 119901; PRD61 (2000) 071703

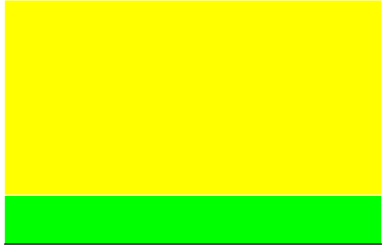
SUSY origin for neutrino masses?

- weak-scale seesaw atm scale



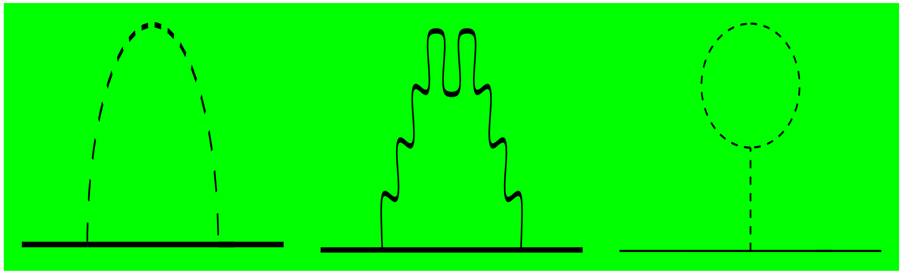
M=0

- radiative nu-masses solar scale



"TREE"

LOOPS



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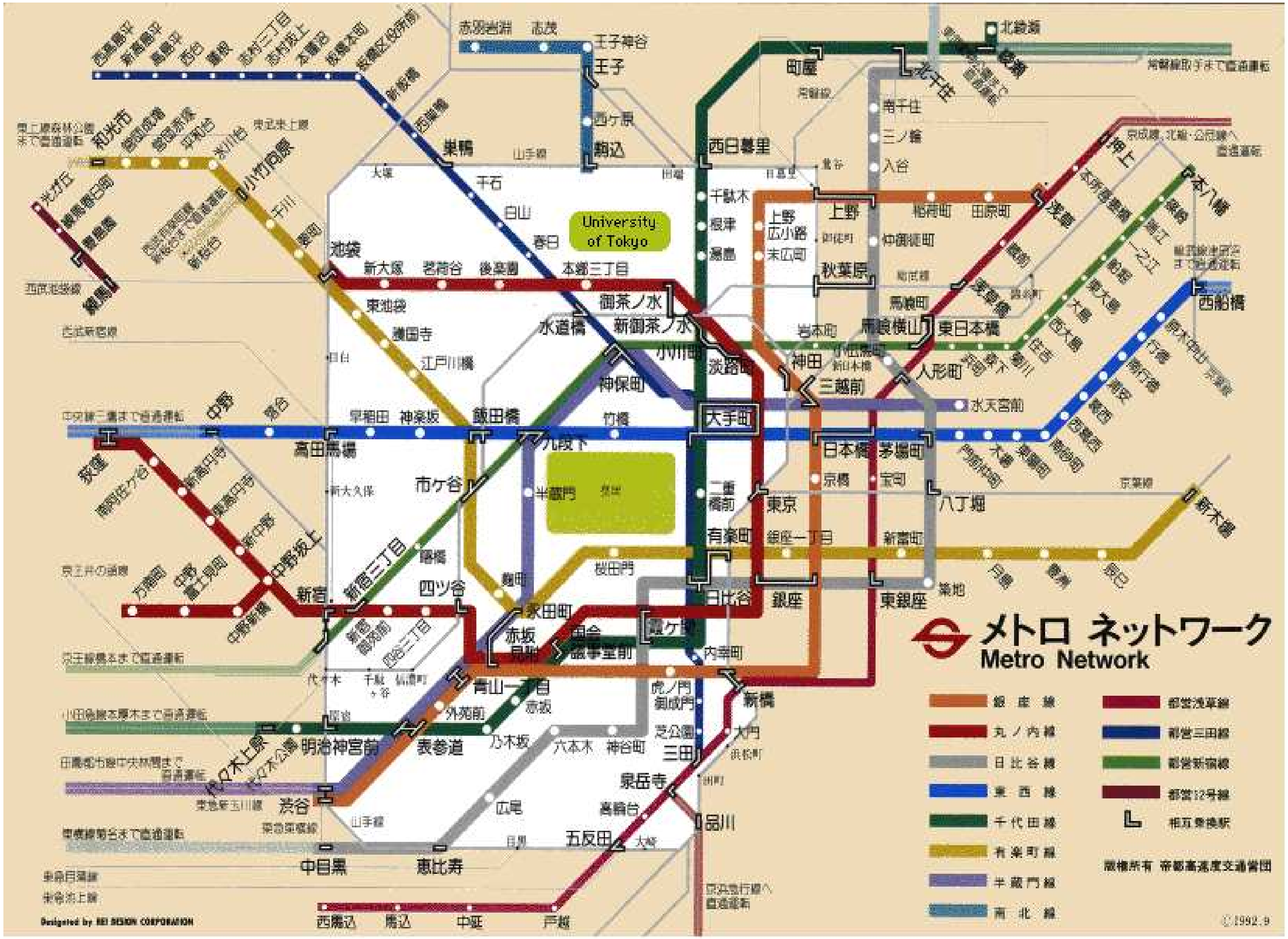
Diaz etal PRD68 (2003) 013009, PRD62 (2000) 113008; D65 (2002) 119901; PRD61 (2000) 071703

probing nu-mixing at LHC/NLC?

-

the road to nu-mass Theory



theory pathways to nu-mass

- top-bottom vs bottom-up

theory pathways to nu-mass

- top-bottom vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...

theory pathways to nu-mass

- top-bottom vs bottom-up
- what is the mechanism?
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  - 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

theory pathways to nu-mass

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theory pathways to nu-mass

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  - Weak SU(3) $\otimes$ SU(2) $\otimes$ U(1) scale
- **no theory of flavour** LSND?
- not the end, much more to come!!

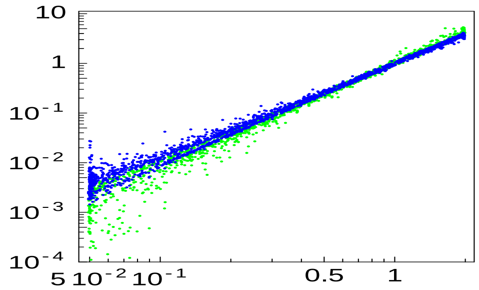
end of the talk

testing neutrino mixing angles at LHC

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

- mixings given as RPV ratios, e,g, atm mixing

$\tan^2_{23}$ vs (Λ_2/Λ_3)

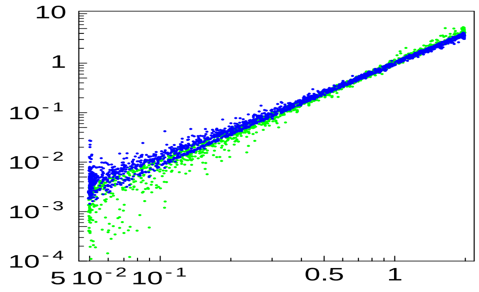


testing neutrino mixing angles at LHC

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

- mixings given as RPV ratios, e,g, atm mixing

$\tan^2_{23}$ vs (Λ_2/Λ_3)

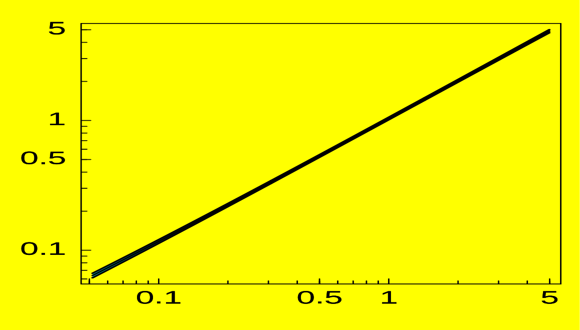


- LSP decay properties correlate with angles

neutralino

Porod et al PRD63 (2001) 115004

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



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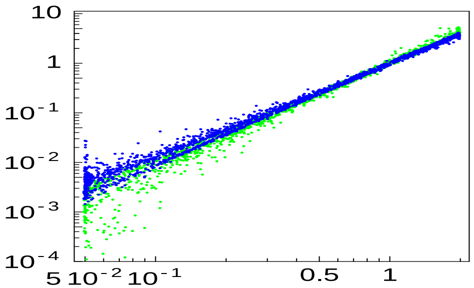

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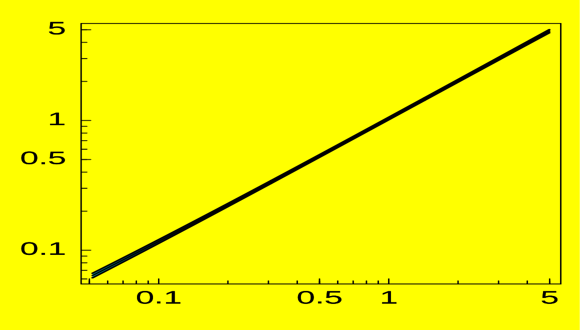

- irrespective of the LSP nature
  stop
  slepton ...

Restrepo, Porod & JV, PRD64 (2001) 055011

Hirsch et al, PRD66 (2002) 095006 & hep-ph/0307364

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variations over a theme ... susy + triplets

Aristizabal et al PRD68 (2003) 033006

$$W = W_{MSSM} + W_{BRpV} + W_{\Delta} \qquad \widehat{\Delta}_u = \begin{pmatrix} \widehat{\Delta}_u^{++} \\ \widehat{\Delta}_u^{+} \\ \widehat{\Delta}_u^{0} \end{pmatrix} \qquad \widehat{\Delta}_d = \begin{pmatrix} \widehat{\Delta}_d^{0} \\ \widehat{\Delta}_d^{-} \\ \widehat{\Delta}_d^{--} \end{pmatrix}$$

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- solar scale from small induced Higgs triplet vevs
(weak-scale type-II seesaw) E. Ma

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

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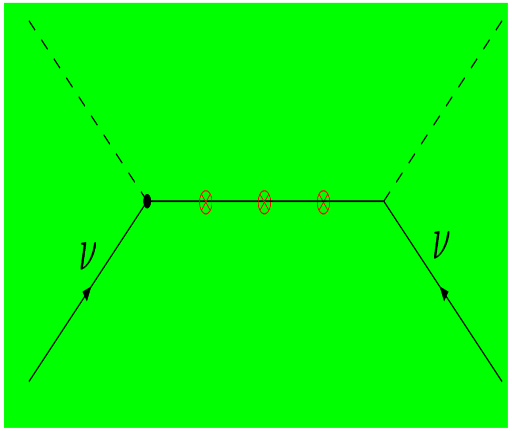
- atm scale from susy
- LSP decay properties correlate with atm & reactor (ratios as RPV)

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

inverse seesaw with low-scale origin for nu-mass

Mohapatra & JV, PRD34 (1986) 1642



"inverse seesaw" $m_\nu \to 0$ as $\mu \to 0$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix},$$

LFV & CPV persist as $m_\nu \& \mu \to 0$

NHL exchange

Bernabeu et al, Branco, Rebelo and JV,

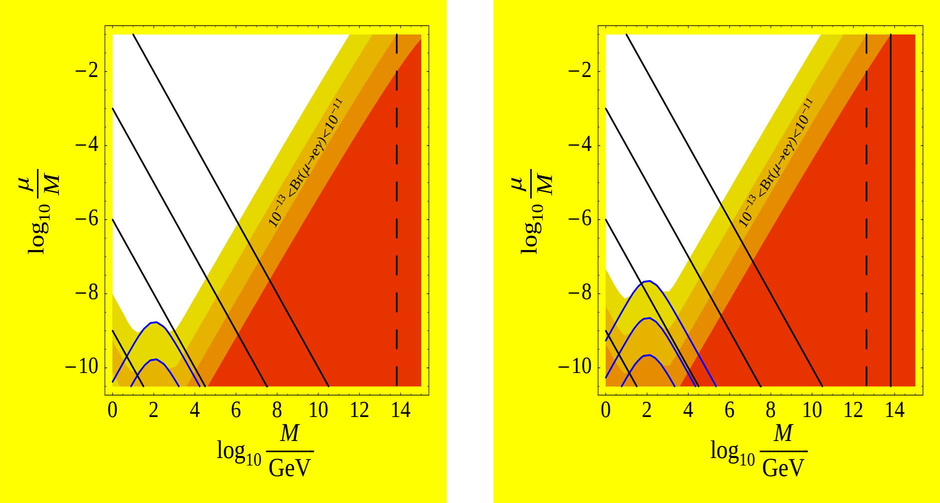
Rius & JV, Gonzalez-Garcia & JV

susy loops

Hall, Kostelecky & Raby

Borzumati & Masiero

Barbieri & Hall, Casas & Ibarra, ...



Deppisch & JV, hep-ph 0406040

0-0

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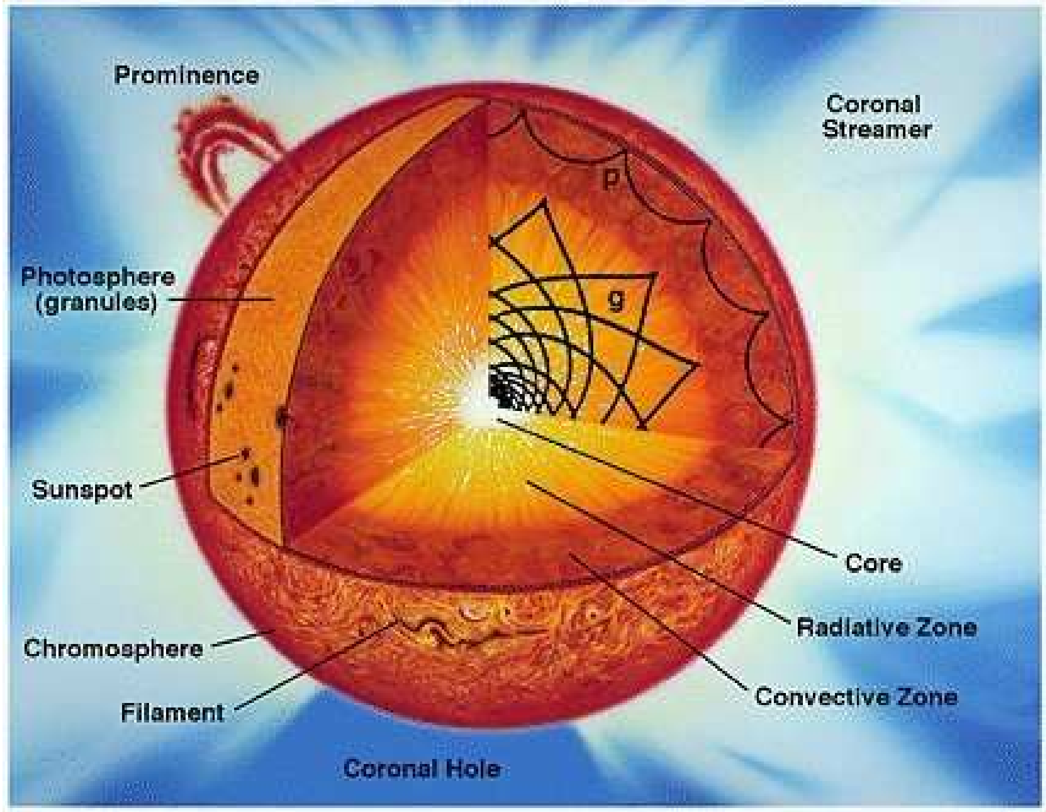
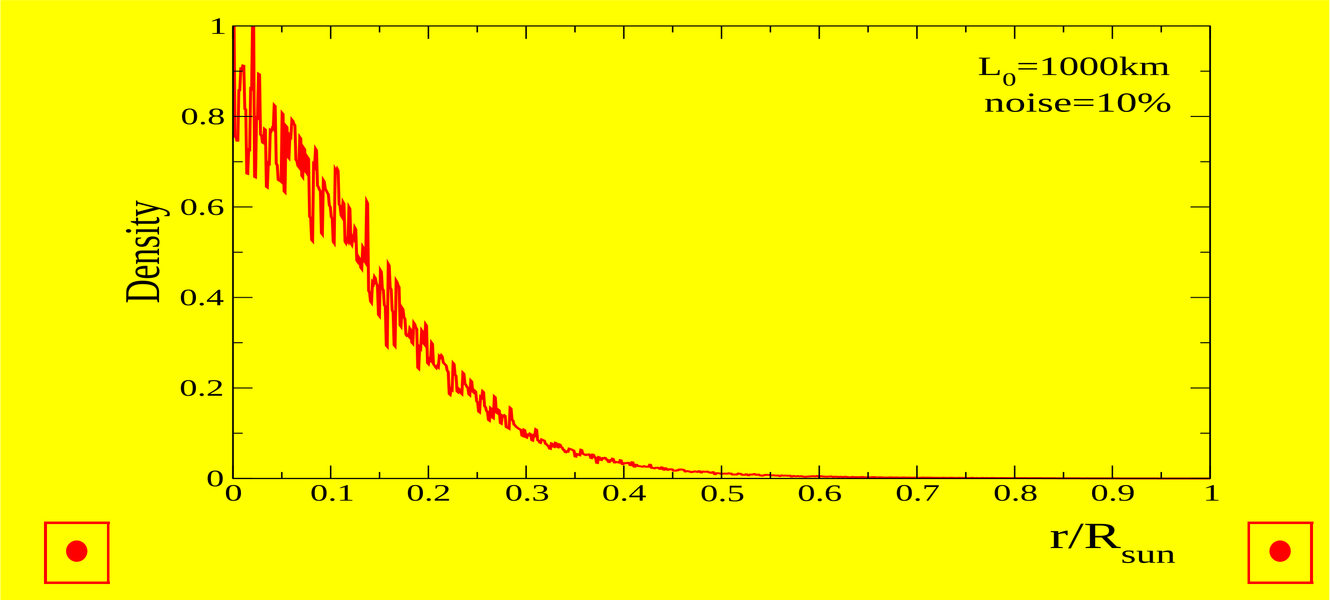
fragility of solar-nu oscillations against NSI

	$\sin^2\theta_{\rm SOL}$	$\Delta m^2_{\rm SOL}$ [eV^2]	ε	ε'	χ^2
OSC analysis					
LMA-I	0.30	8.3×10^{-5}	–	–	83.0
OSC+NSI analysis					
LMA-I	0.30	8.3×10^{-5}	-0.15	-0.15	81.9
LMA-D	0.70	8.3×10^{-5}	-0.15	0.95	83.1
LMA-0	0.30	1.4×10^{-5}	0.00	0.30	85.0

Best fi t solar neutrino oscillation points with and without non-standard interactions

is the Sun noisy?





Robustness of solar-nu oscillations wrt noise-KL04

neutrino propagation strongly affected by solar density noise

Balantekin et al 95

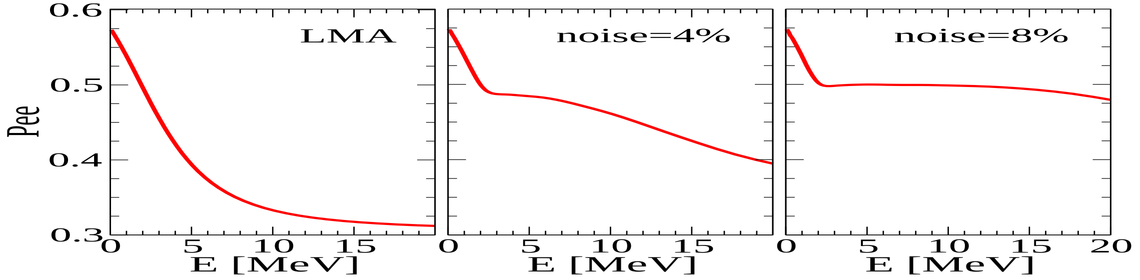
Nunokawa et al NPB472 (1996) 495

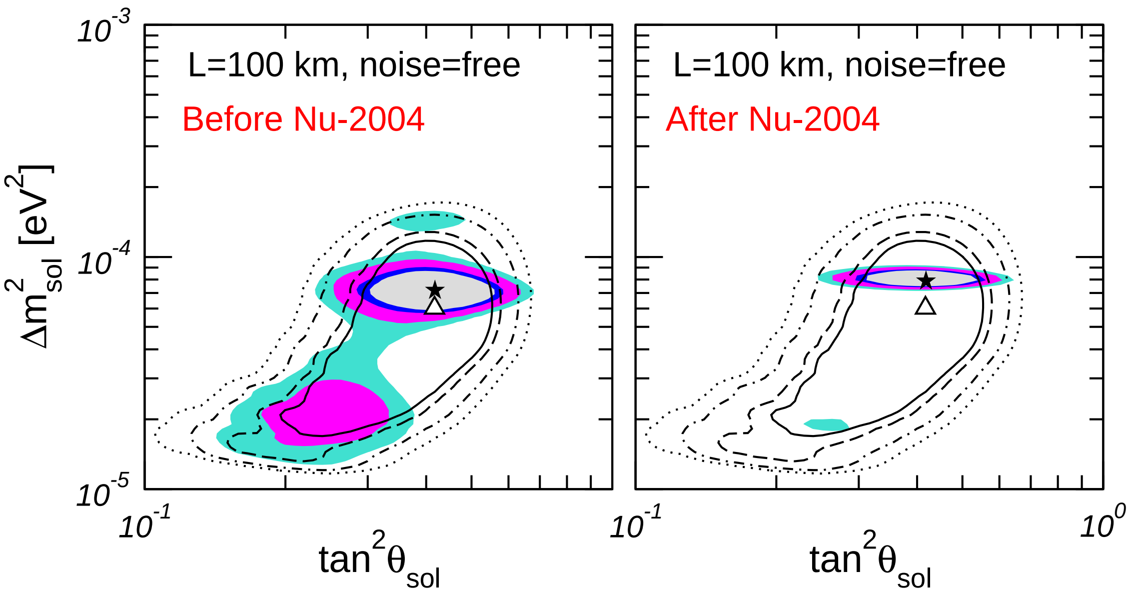
Burgess et al 97

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

& JCAP 0401 (2004) 007

Guzzo et al, Balantekin et al





despite such large distortion

determination is robust

cf salt

Maltoni et al, hep-ph 0405172

Robustness of solar-nu oscillations against SFP

minima shifted by huge fields

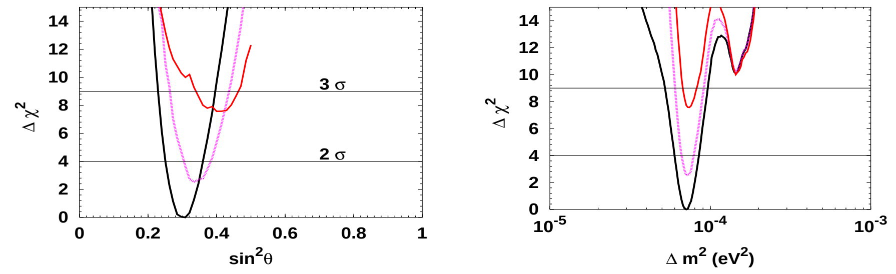
prevented by solar anti-nu limit

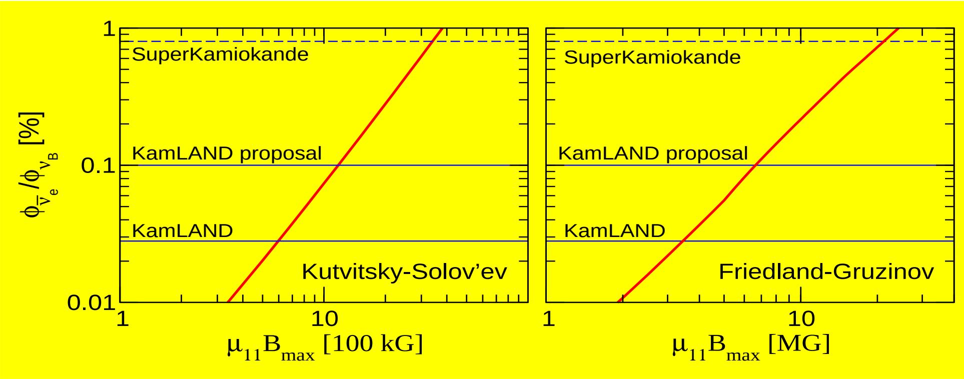
anti-nu limit implies robustness

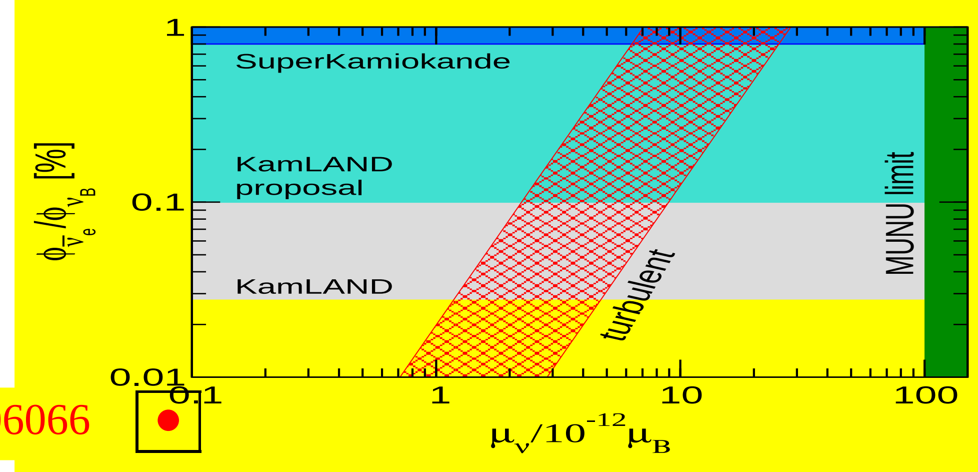
regular versus random mag field

isolating μ_ν from $\mu_\nu B$?

Miranda et al hep-ph/0311014 (PRL) & hep-ph/0406066







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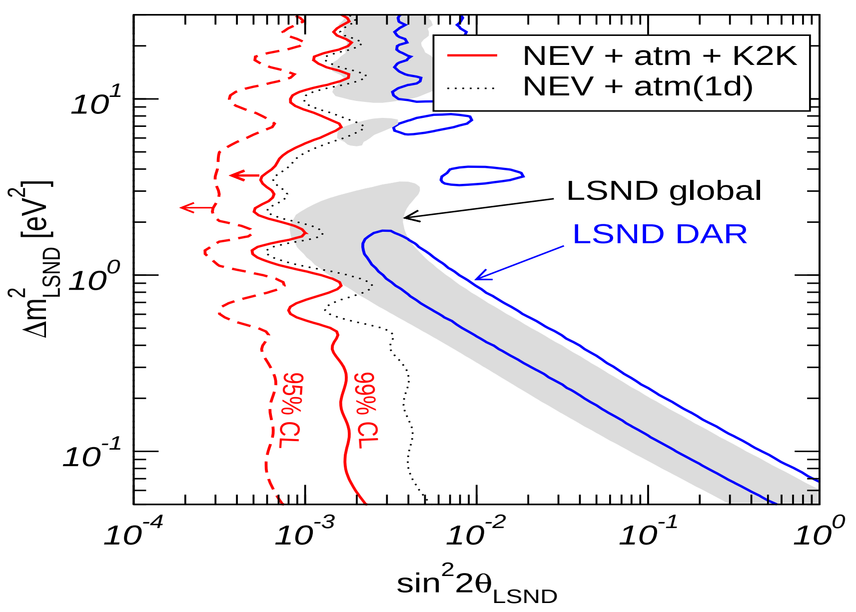
LSND

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



3+1 disfavored at 3.1 σ

2+2 excluded at 4.7 σ

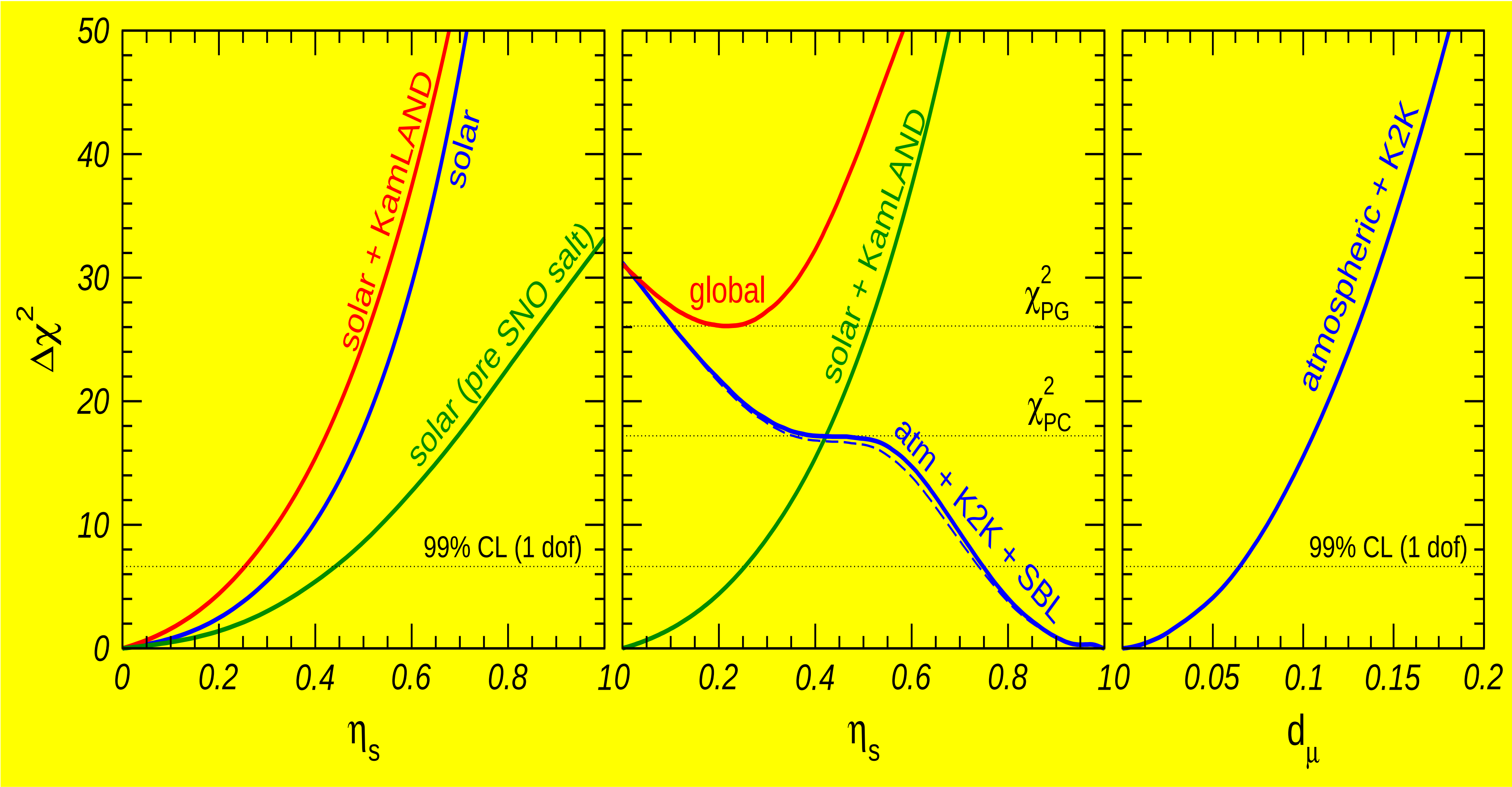
Maltoni et al NPB643 (2002) 321
upd of PRD65 (2002) 093004

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

4-nus do not really fit LSND with the rest

- M. Maltoni et al, hep-ph/0405172; NPB643 (2002) 321

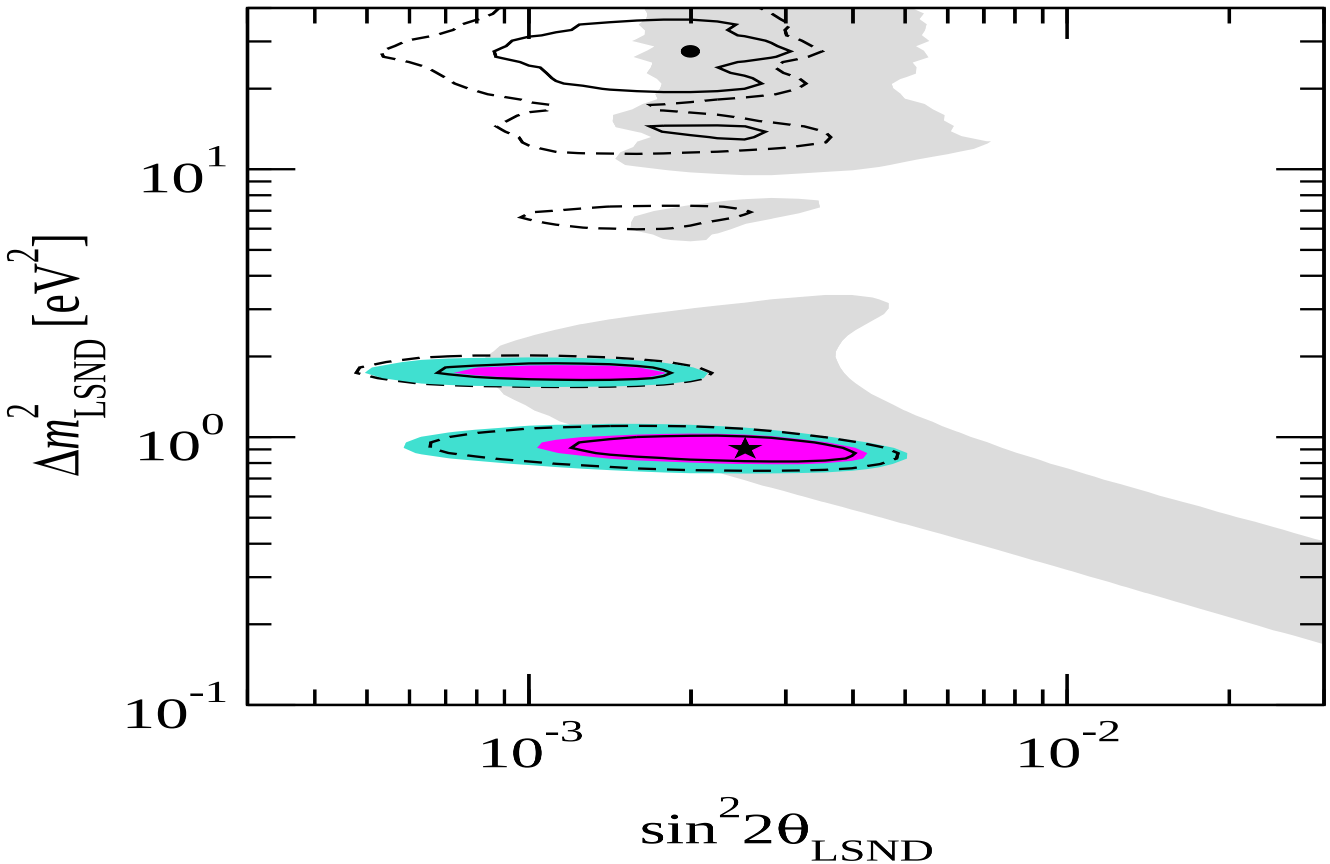
stronger rejection by solar & atm in 2+2 than 3+1



Pas & Weiler

Cosmology closes in on LSND

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



2df + WMAP + HST + SNIa

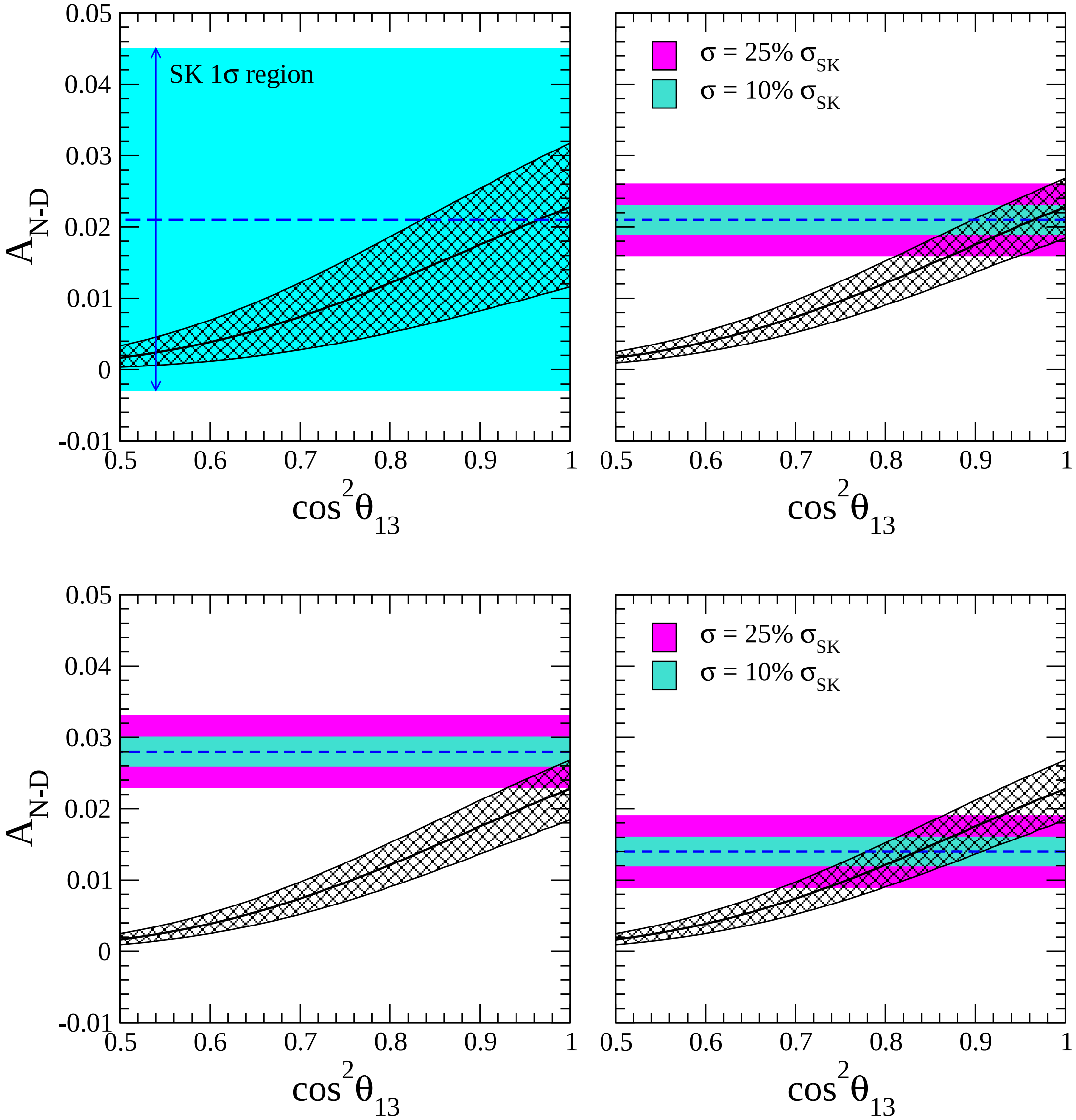
Schwetz et al hep-ph/0305312

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

Crotty, Lesgourgues & Pastor PRD67 (2003) 123005

day-night effect as a probe of θ_{13}

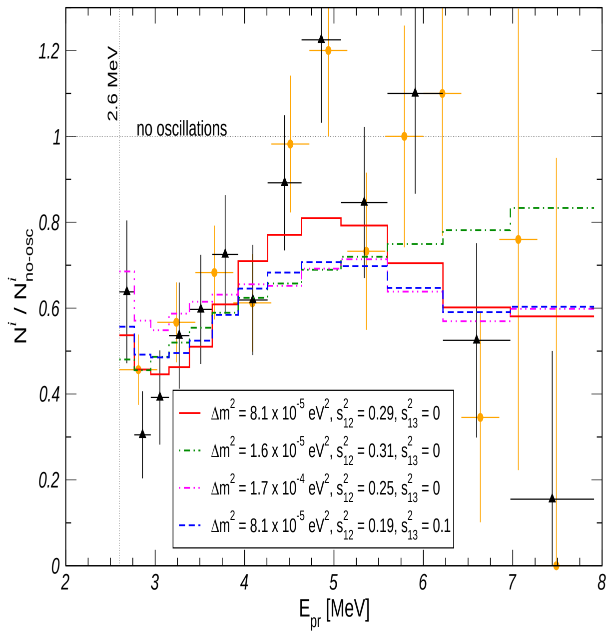
Akhmedov, Tortola, JV, JHEP05 (2004) 057 relevance of central value

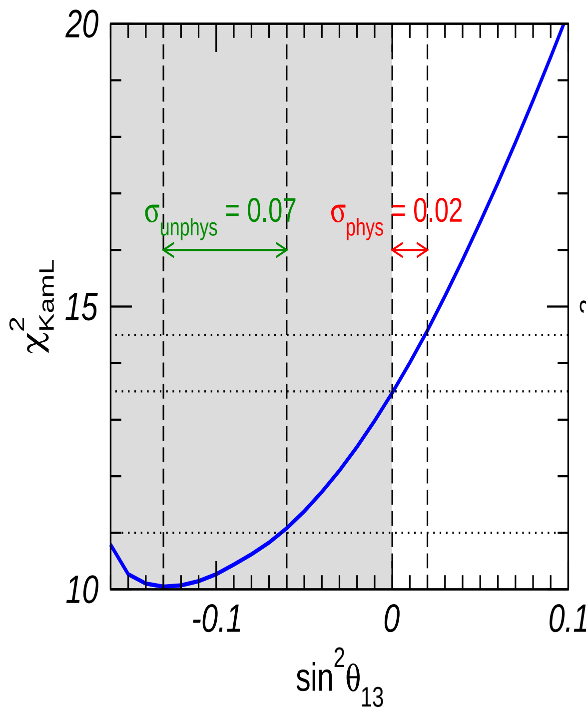


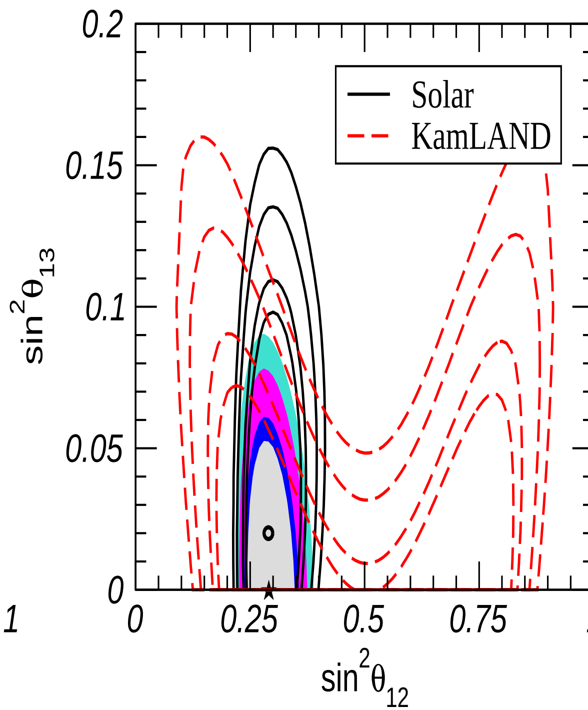
why KamLAND04 improves θ_{13}

- strong spectrum distortion

  favors unphysical θ_{13} values







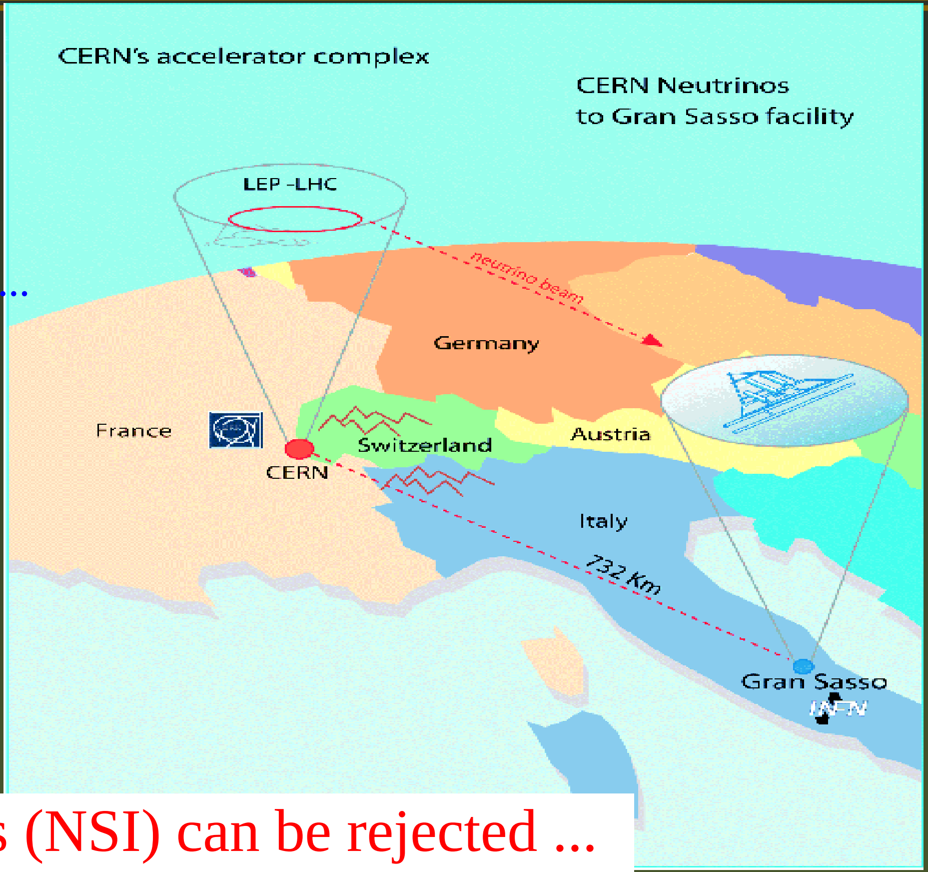
combination with solar further improves ...

Neutrino Factories

will probe s_{13} and CP phase δ

Cervera et al, De Rujula, Gavela, Hernandez

Freund, Huber, Lindner, Albright et al, Barger et al...



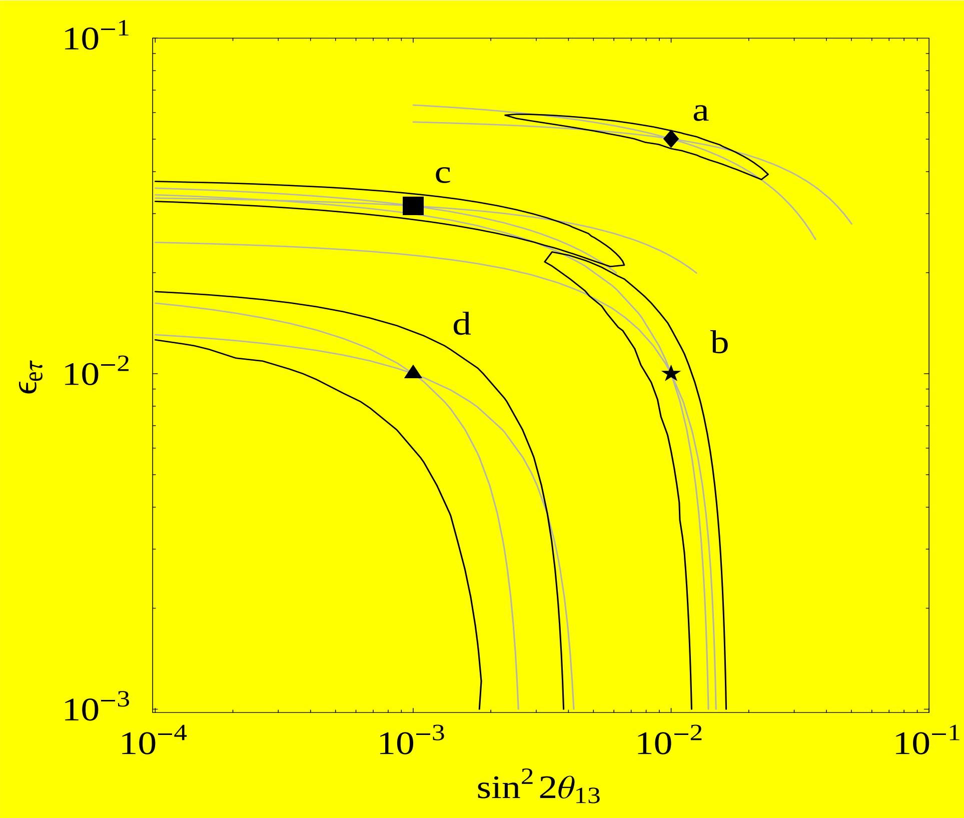
only if Non-Standard nu-Intercations (NSI) can be rejected ...

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

FCI-oscillation confusion theorem

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

Huber et al, PRL88 (2002) 101804

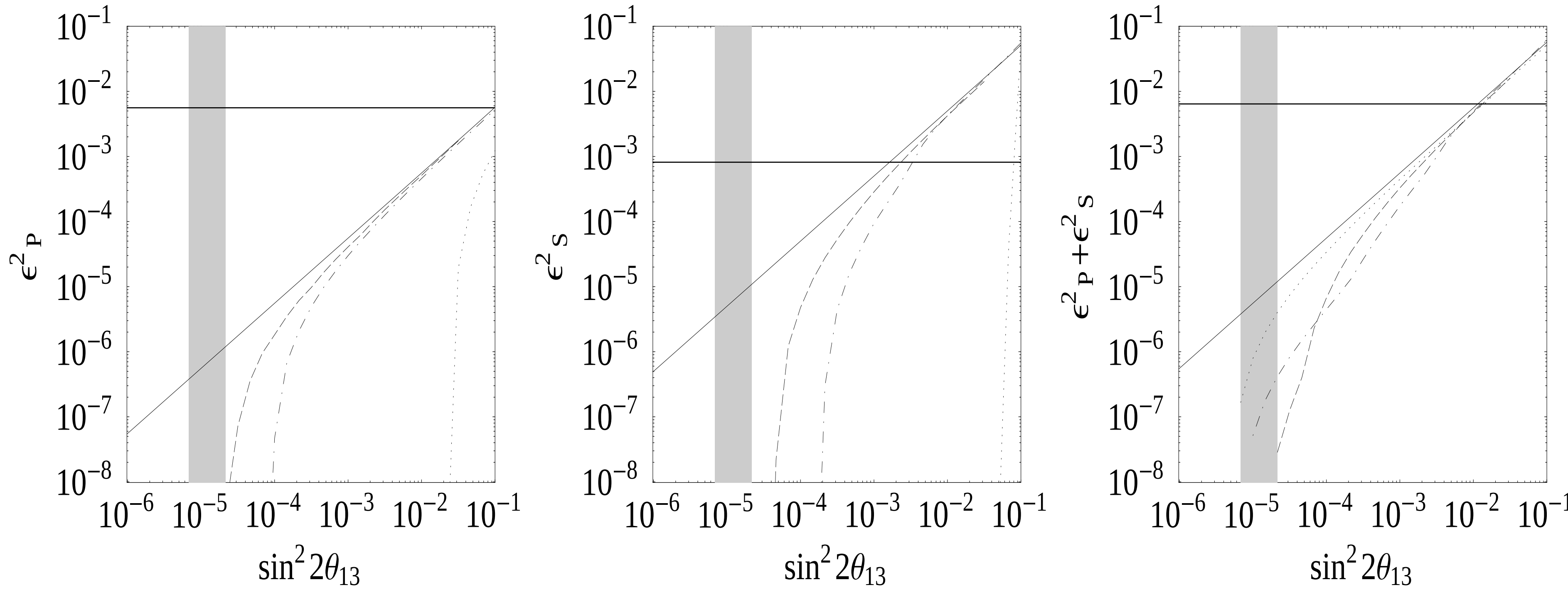


near-site programme essential

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

Huber et al, PRD66, 013006 (2002)



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

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

The dotted line is for 700 km, dash-dotted for 3 000 km and dashed is for 7 000 km baseline

horizontal black line is the current NSI limit

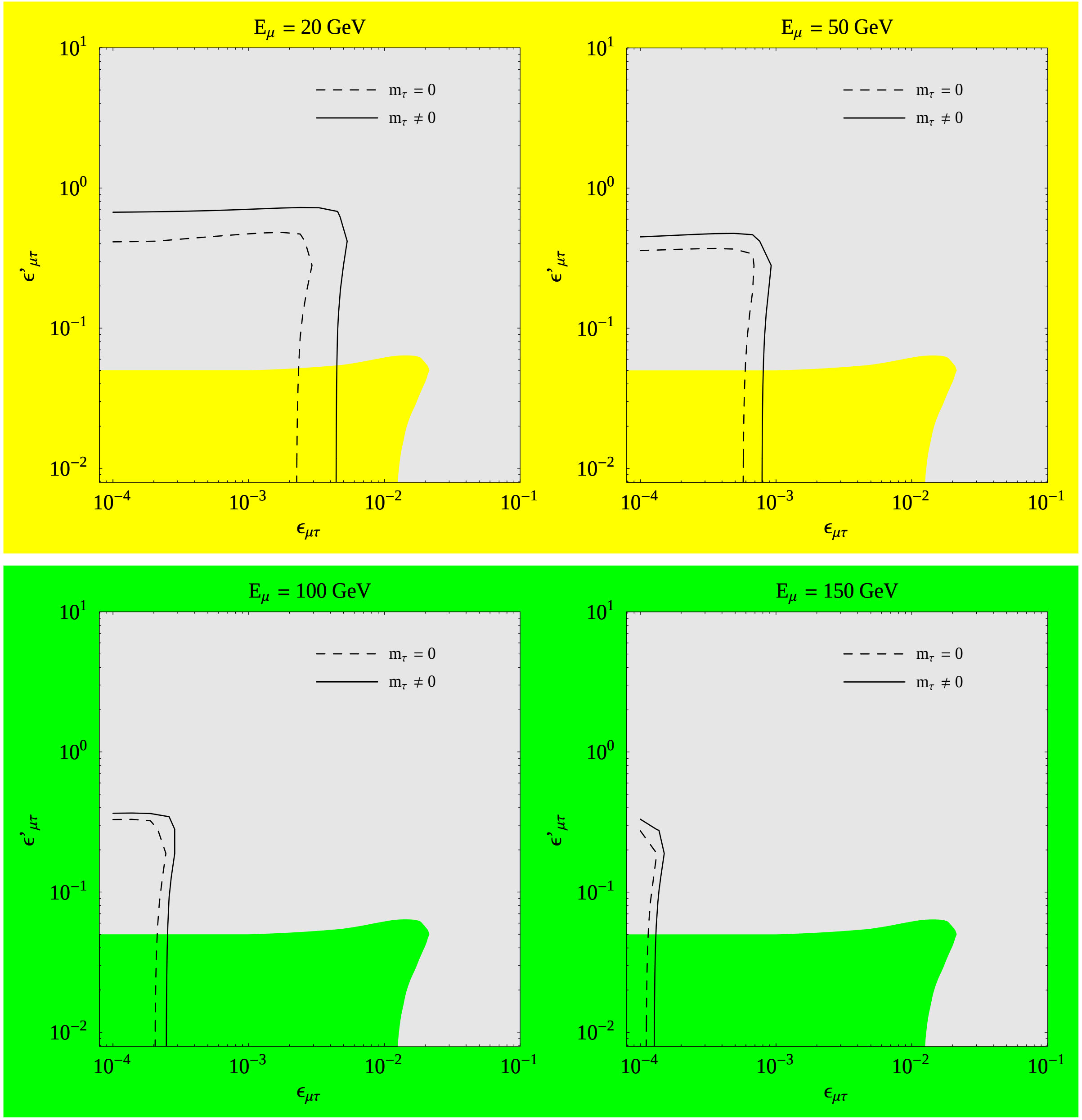
vertical grey band is the sensitivity without NSI

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

Improved FC-NSI-tests at NuFact

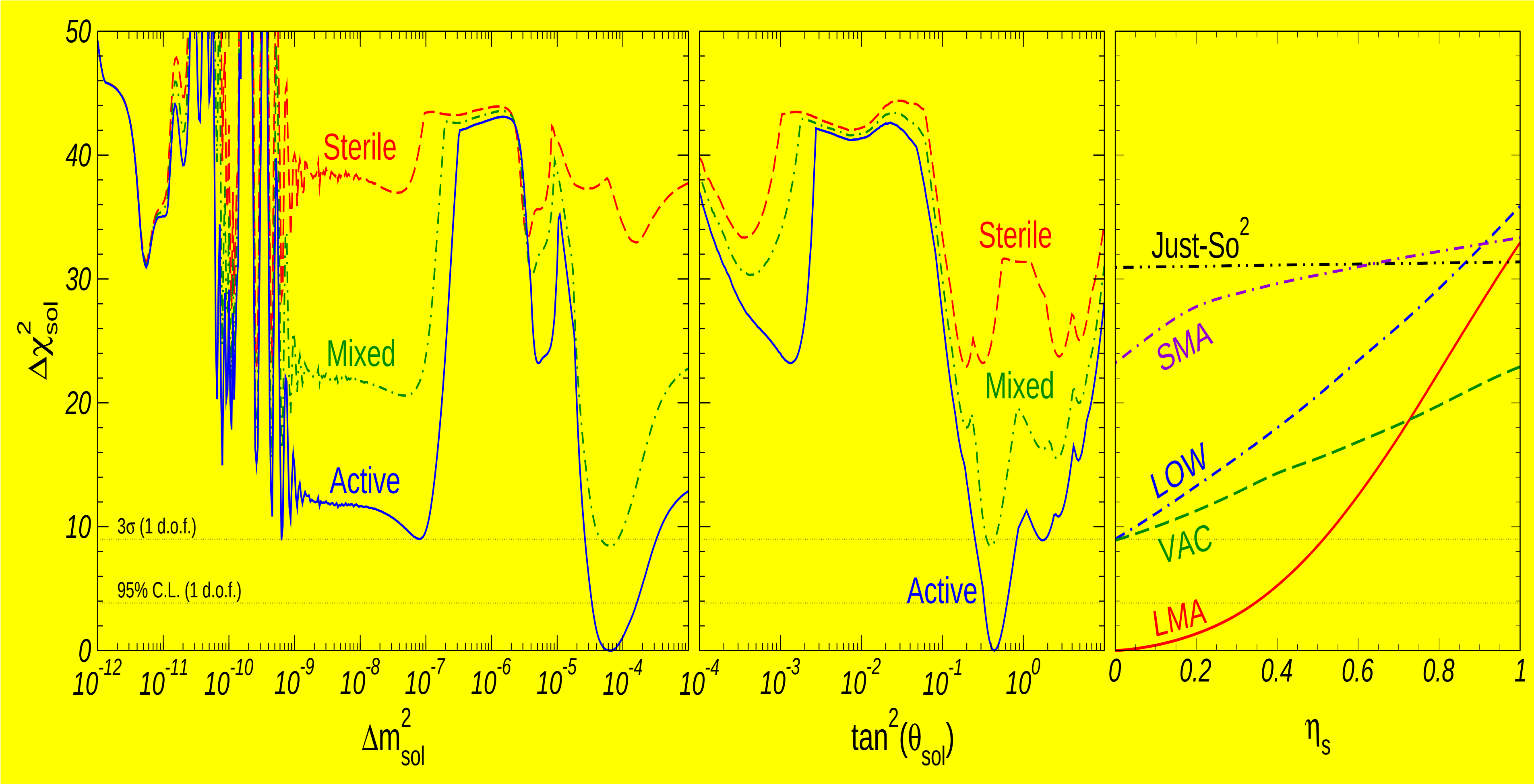
10 kt detector, 0.33 ν_τ detection efficiency above 4 GeV; no tau charge id needed

Huber & JV PLB523 (2001) 151



solar-nu 2002

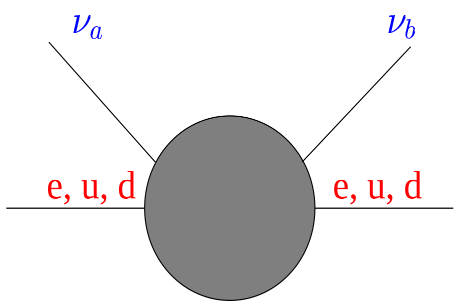
- Maltoni et al, PRD67 (2003) 013011



non-standard neutrino propagation

Non-standard interactions

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



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

Valle PLB199 (1987) 432,

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

they give excellent description of solar data Guzzo et al NPB629 (2002) 479

but can not be the leading mechanism, due to KamLAND

how much can they affect solar neutrino oscill parameters?