NEUTRINOS IN ASTROPARTICLE PHYSICS

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Central role in Astroparticle Physics

study tools include

- accelerators: LHC, ILC, ...

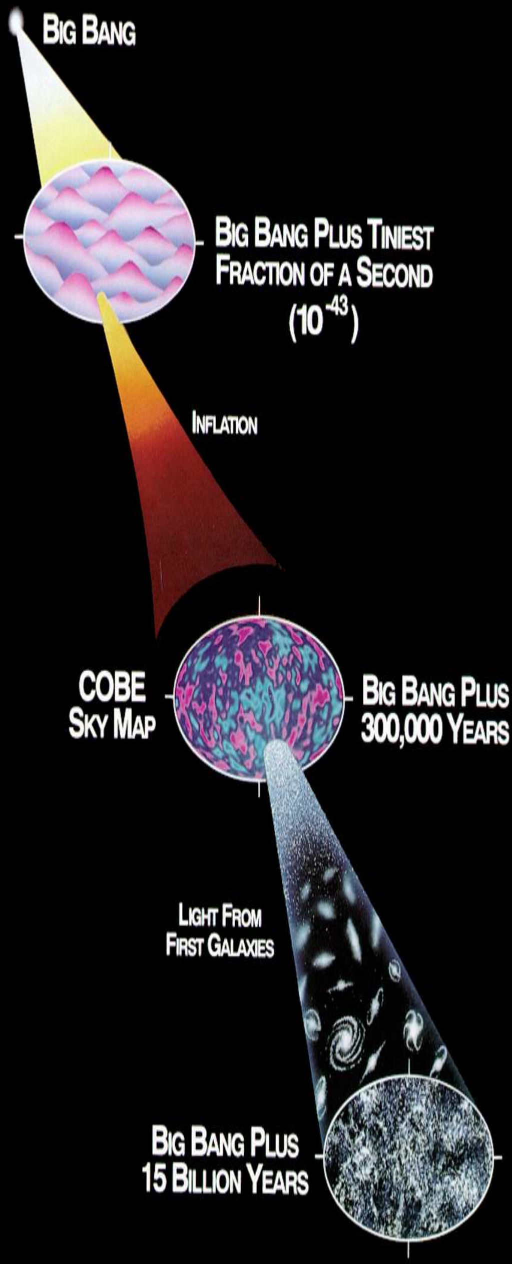
- γ & ν-telescopes:

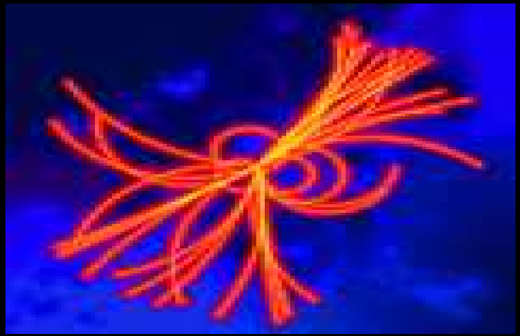
COBE, WMAP, PLANCK, ...
underground/water/ice+surface

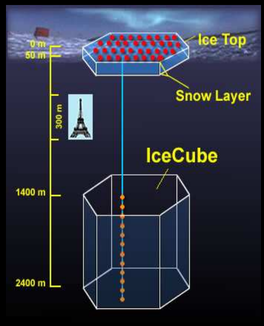
- hybrid expts,
e.g. K2K, MINOS, CNGS ...

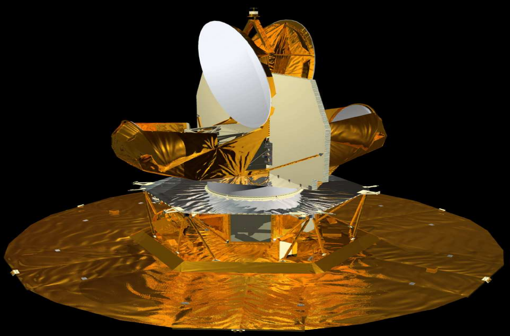
will focus on

- recent data analysis
- impact on basic ideas
- prospects









solar neutrinos

- neutrinos produced in the solar core in thermonuclear reactions which result in the overall fusion of protons into helium:

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

- SSM predicts more neutrinos

than detected in underground experiments

solar neutrino deficit

well explained by $\nu_e \to \nu_{\mu/\tau}$ oscilllation hypothesis

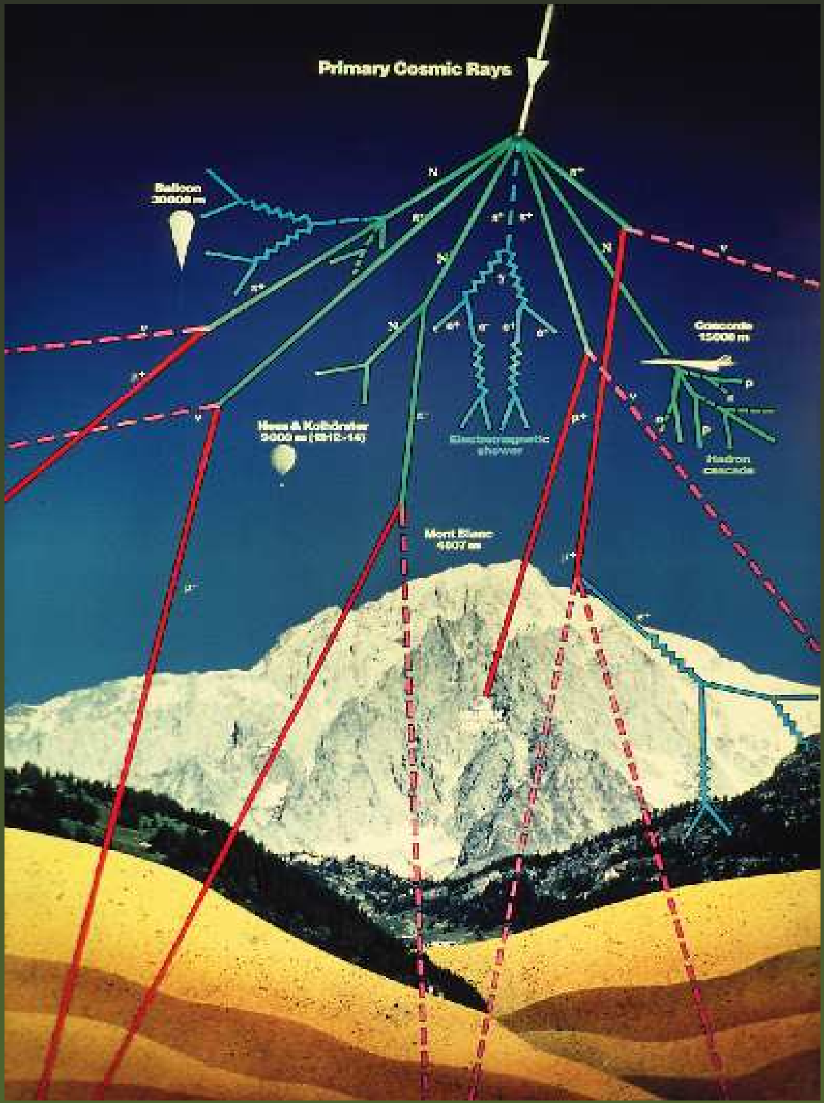
Atmospheric Neutrinos

from cascades initiated by collisions of cosmic rays with the earth's atmosphere

pion & muon decays

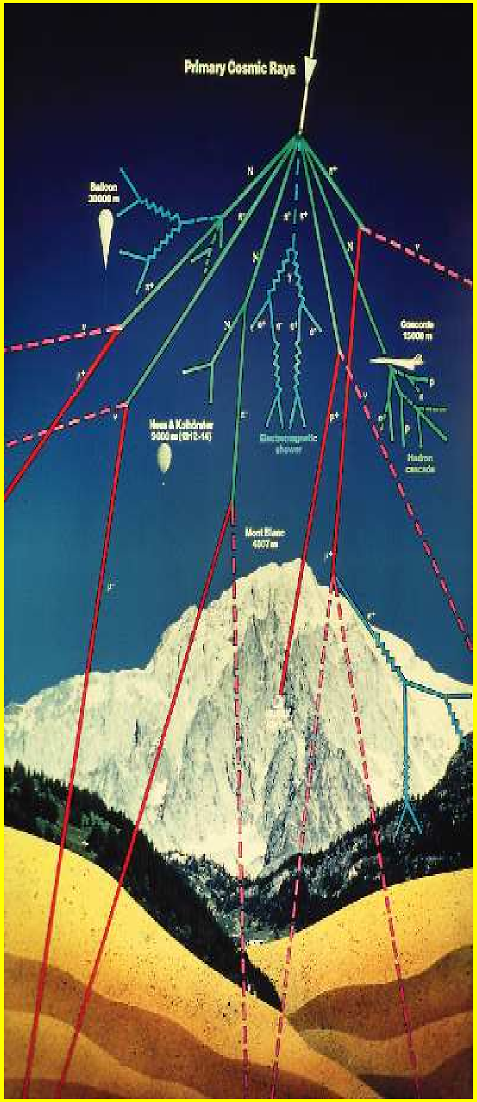
deficit of earth-crossing ν_μ

$\nu_\mu \rightarrow \nu_\tau$ oscillations (1998)

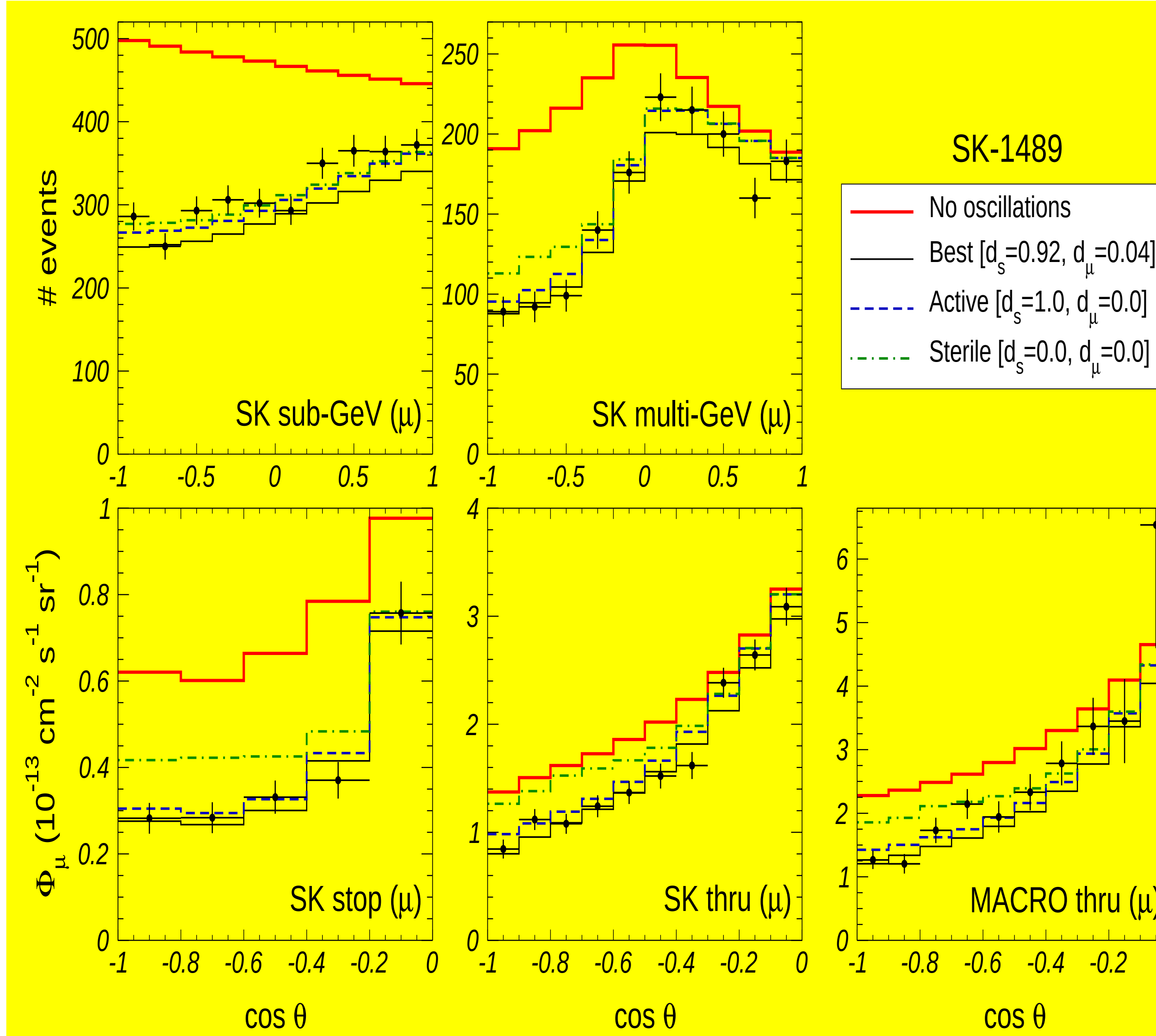


Atmospheric zenith distribution

Maltoni et al, PRD67 (2003) 013011 sterility rejection



Bartol

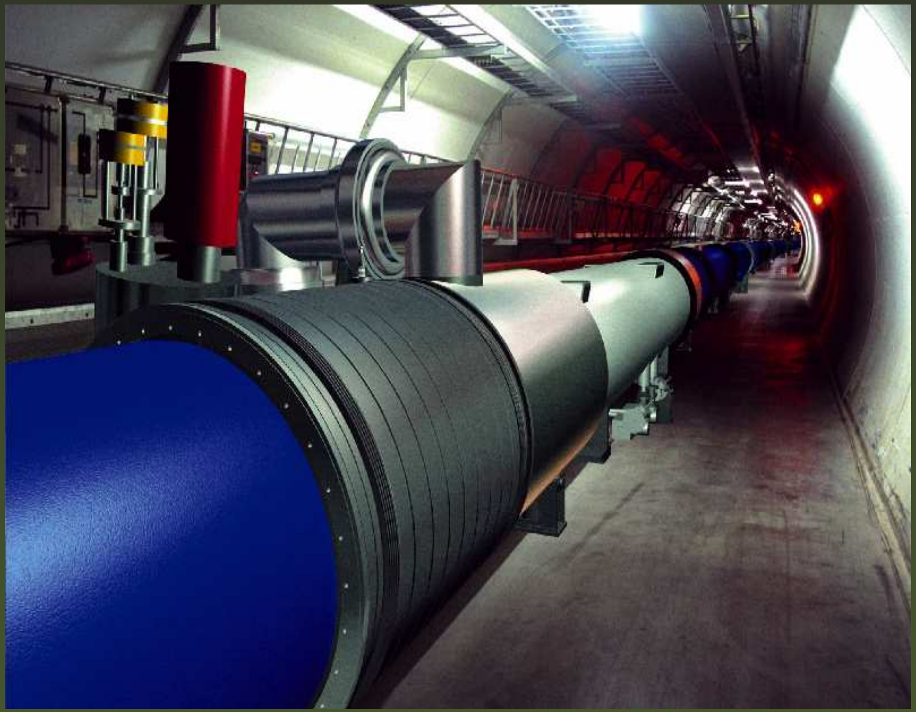


Accelerator Neutrinos

well controlled source

checks atm ν_μ oscill hypothesis

K2K & MINOS confirm the atm ν_μ deficit and observe a distortion of the energy spectrum consistent with oscillation interpretation



neutrinos from nuclear reactors

KamLAND has solved the solar neutrino problem...

rejecting non-standard mechanisms as leading solns

lepton mixing matrix

- $K = \omega_{23} \,.\, \omega_{13} \,.\, \omega_{12}$

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

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & e^{i\phi_{23}} s_{23} \\ 0 & -e^{-i\phi_{23}} s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & e^{i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\phi_{13}} s_{13} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & e^{i\phi_{12}} s_{12} & 0 \\ -e^{-i\phi_{12}} s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

23=atm+acc

13=reactor + ..

12=solar+KL

)

lepton mixing matrix

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23=atm+acc 13=reactor + .. 12=solar+KL

- **oscillations depend only on the KM-like phase ($n \geq 3$)**

lepton mixing matrix

- $K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$ Schechter and JV, PRD22 (1980) 2227, D23(1980) 1666

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- **oscillations depend only on the KM-like phase ($n \geq 3$)**
- **the 2 new phases ($n \geq 2$) appear in L-violating processes eg $\beta\beta_{0\nu}$**

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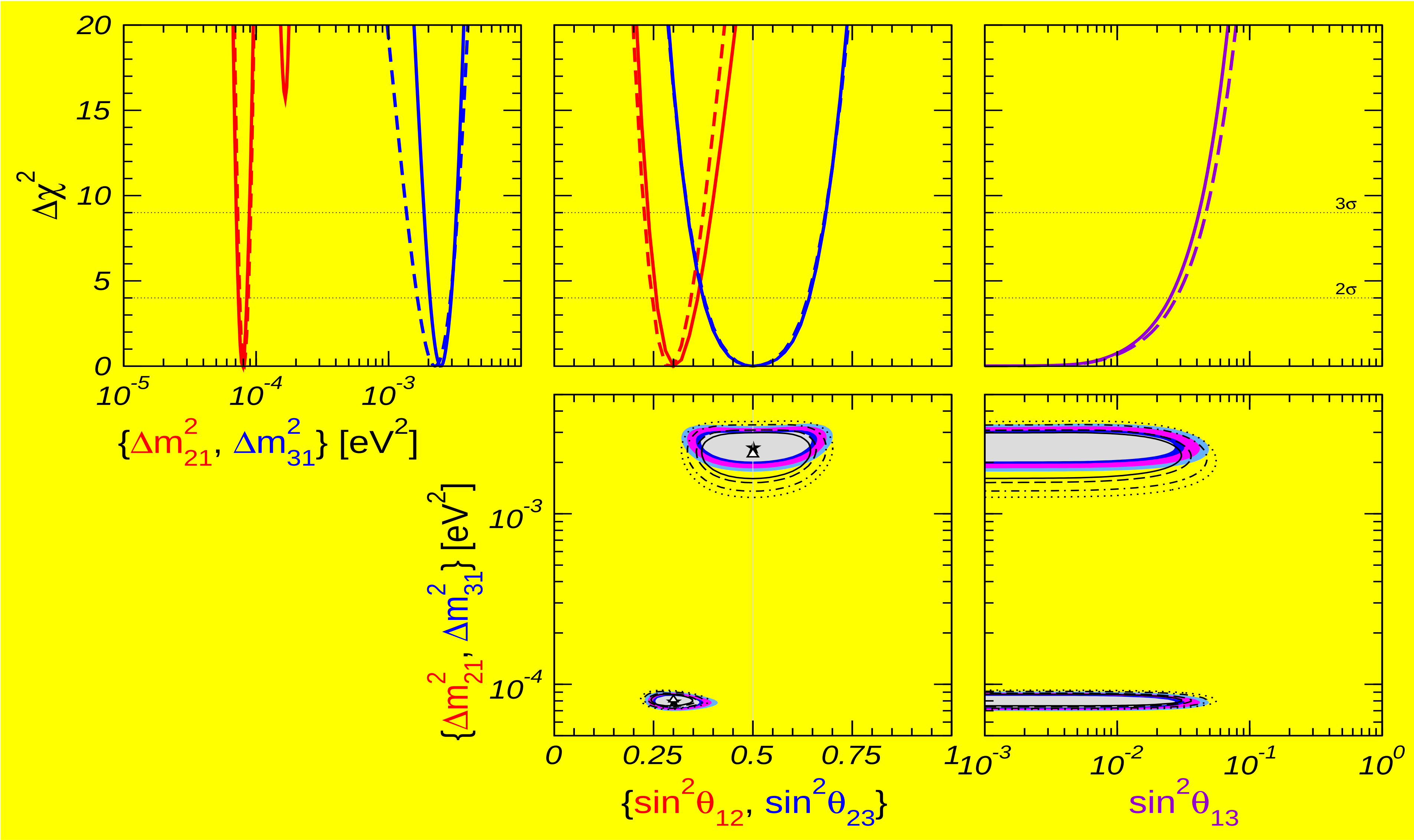
23=atm+acc 13=reactor + .. 12=solar+KL

- **oscillations depend only on the KM-like phase ($n \geq 3$)**
- **the 2 new phases ($n \geq 2$) appear in L-violating processes eg $\beta\beta_{0\nu}$**
- **currently no expt is sensitive to CPV, so we also drop all ϕ_{ij}**

5 parameter 3-nu oscillation analysis

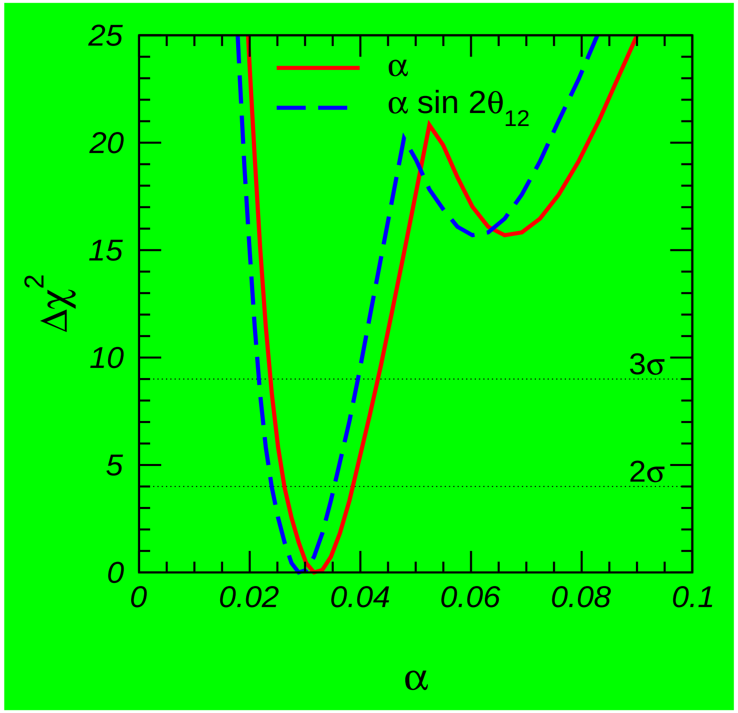
GLOBAL STATUS OF OSCILLATIONS

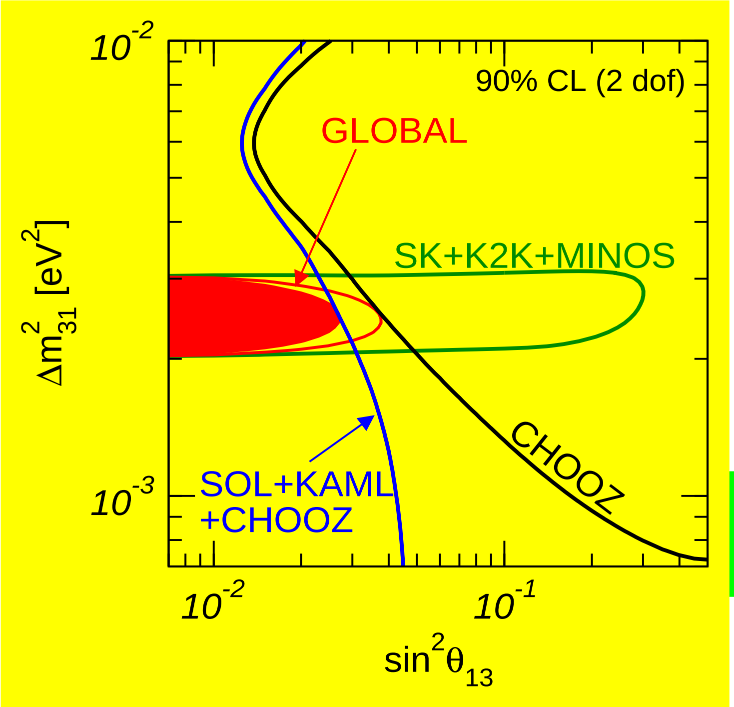
M. Maltoni et al, NJP 6 (2004) 122 = hep-ph/0405172v5 MINOS, SNO06, SSM06 Tab t13



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

TWO SMALL PARAMETERS





$\frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}}$ and θ_{13}

solar+KamLAND contribute to improve upon Chooz

further improvements will come from LBL reactor/accel expts

as well as D/N solar-nu studies (Akhmedov etal)

ARE OSCILLATIONS ROBUST ?

Do we understand

... the Sun?

... neutrino propagation ?

... neutrino interactions ?

the importance of reactors

KamLAND has solved the solar neutrino problem...

rejecting non-standard mechanisms as leading solns

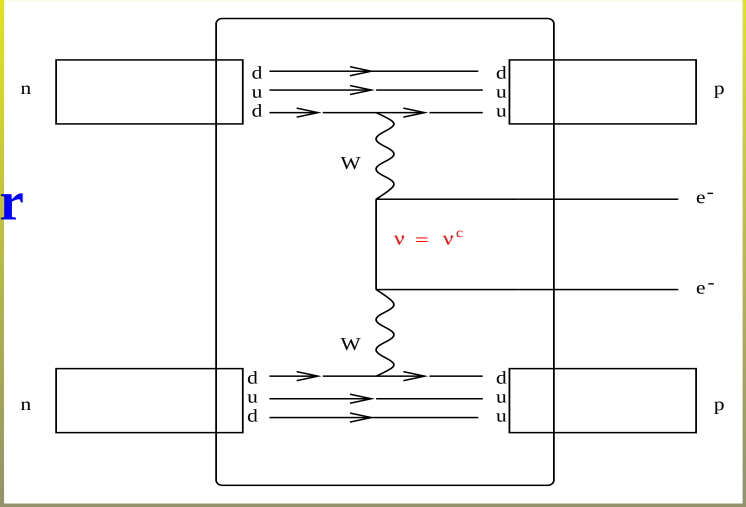
noisy Sun robust Burgess et al JCAP0401 (2004) 007

SFP robust Miranda et al PRL93 (2004) 051304 & PRD70 (2004) 113002

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

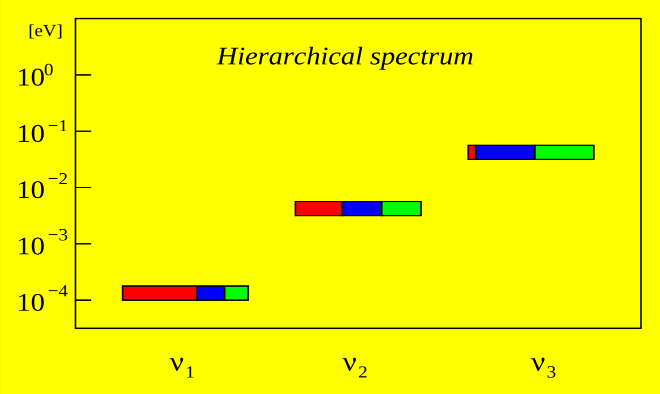
0-nu DOUBLE BETA DECAY

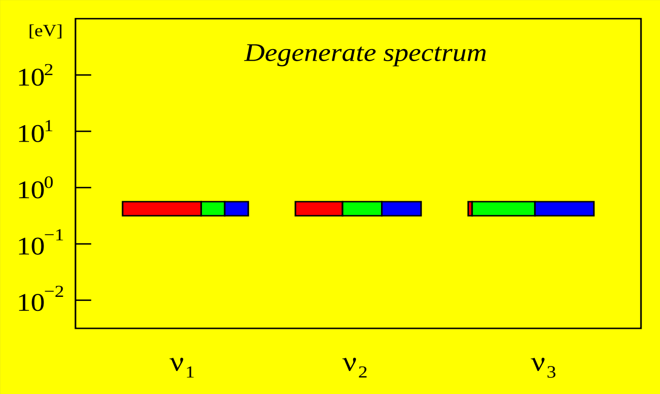
- **given that neutrinos are massive, $\beta\beta_{0\nu}$ should occur with an amplitude governed by the average mass parameter**



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

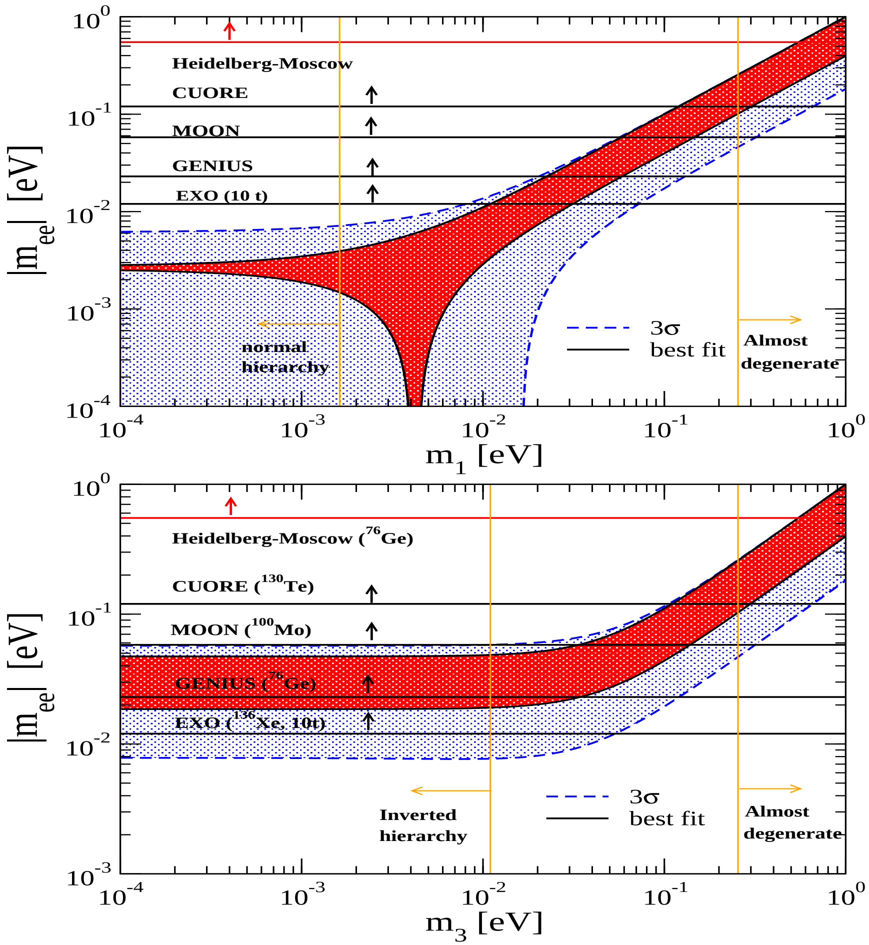
- **3 masses:** m_i
- **2 angles:** θ_{12} **and** θ_{13}
- **2 CP phases:** ϕ_{12}, ϕ_{13}





NEW: sensitivity to abs m-nu scale & Majorana phase

PROBING ABSOLUTE M-NU SCALE



Bilenky, Faessler, Simkovic PRD70 (2004) 033003 **can not yet reconstruct majorana phases** Barger, Glashow, Langacker, Marfatia, PLB540 (2002) 247

Hirsch's talk at Nu-2006

predicting 0-nu double beta decay

A_4 triplet model of nu-masses

Hirsch, et al: PRD72: 091301, 2005

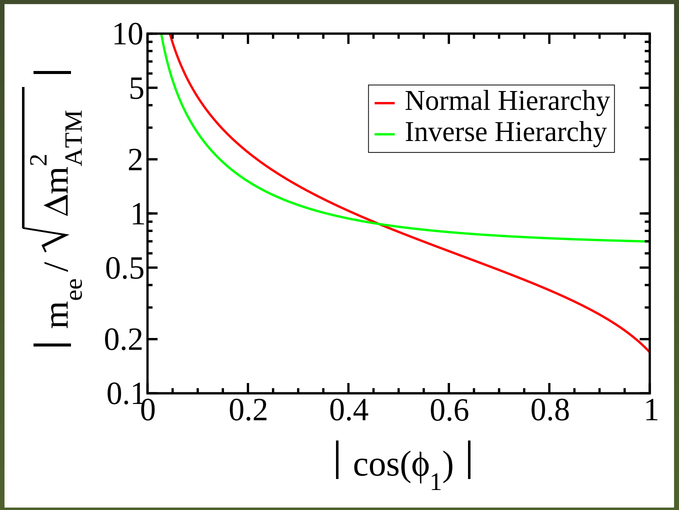
$$M_\nu = \begin{pmatrix} a+2b & d & d \\ f & a-b & d \\ e & d & a-b \end{pmatrix}$$

gives $\theta_{23} = 45 \; \tan^2\theta_{12} = 1/2$

and implies a lower bound

$|\langle m_{ee}\rangle| \geq 0{,}17\sqrt{\Delta m^2_{\rm ATM}}$

also for normal hierarchy $\longrightarrow$



SIGNIFICANCE of 0-nu DOUBLE BETA DECAY

- tests **absolute nu-mass scale**

cf cosmology CMB/LSS ☐

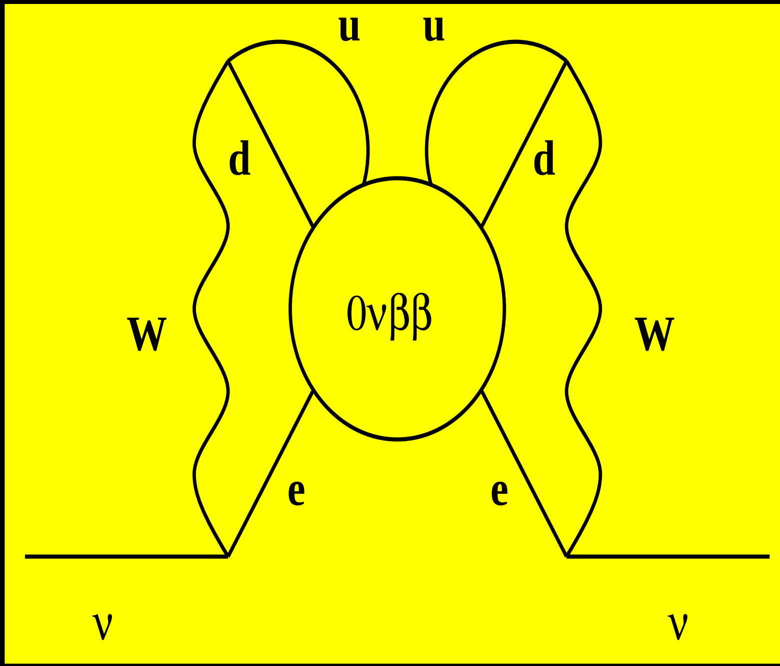
& tritium beta decays ...

- tests **majorana nature**

irrespective of mechanism

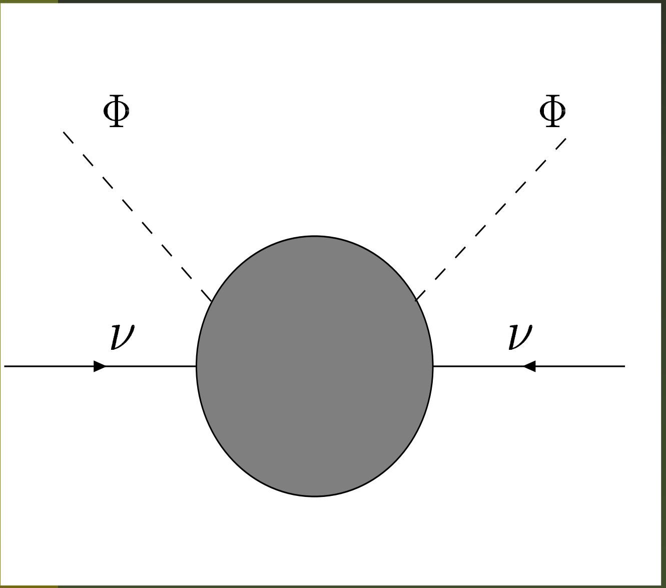
- in a weak interaction gauge theory non-zero $\beta\beta_{0\nu}$ implies at least one neutrino is Majorana

no such theorem for flavor violation



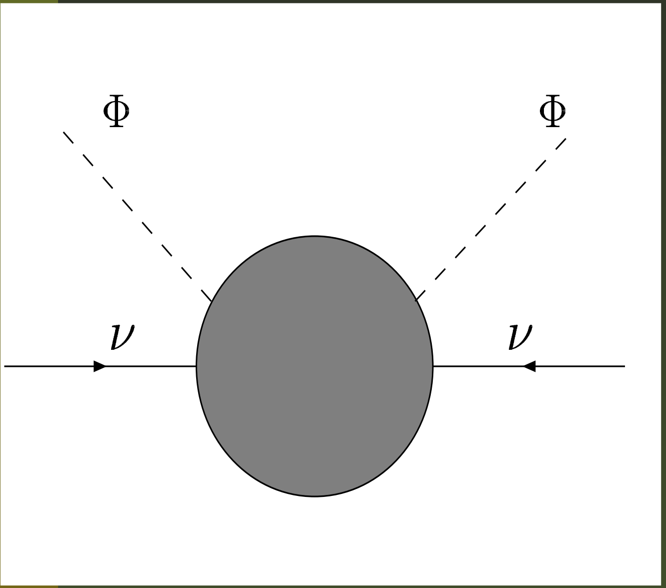
Schechter and JV, PRD25 (1982) 2951

the origin of neutrino mass



Weinberg PRD22 (1980) 1694

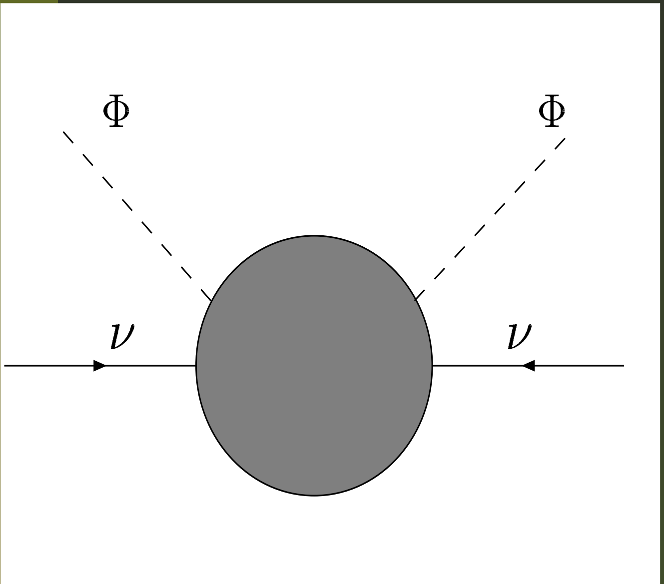
the origin of neutrino mass

- 

Weinberg PRD22 (1980) 1694

- unknown scale

the origin of neutrino mass

- 

Weinberg PRD22 (1980) 1694

- unknown scale
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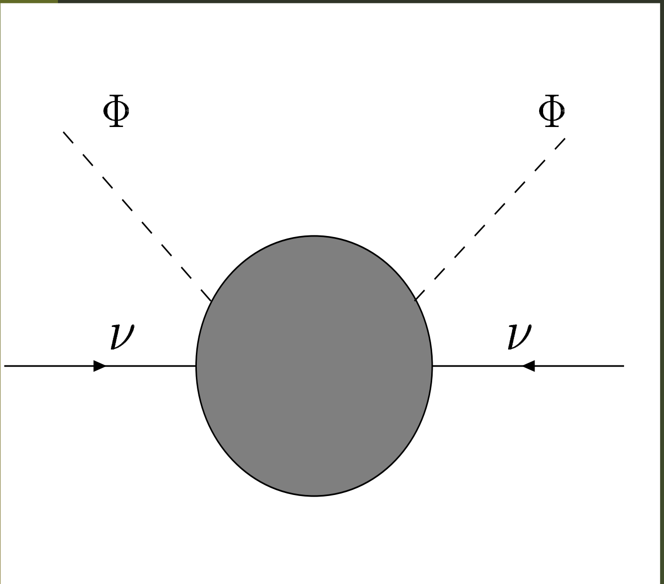
the origin of neutrino mass



Weinberg PRD22 (1980) 1694

- unknown scale
- unknown flavour structure
- unknown mechanism

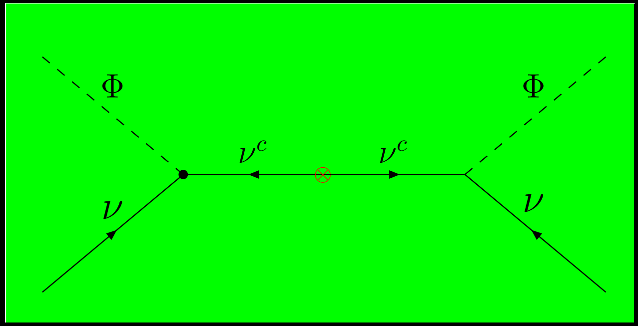
pathways **many realizations**

The SEESAW PARADIGM

Minkowski 77, GRS-Y-G 79, Mohapatra, Senjanovic, Lazarides, Shafi, Wetterich | Schechter, Valle

nu-masses follow from

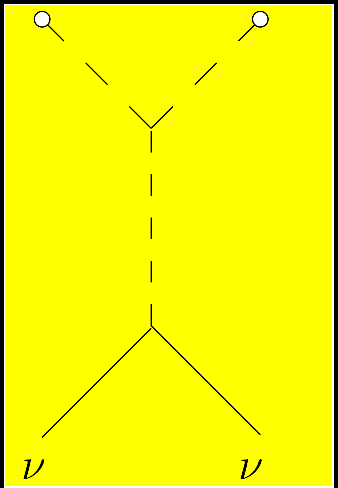
- $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ **singlet exchange: type I**
- **heavy 3-plet scalar boson exchange: type II**



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

first gives $M_{\nu\,\mathrm{eff}} = M_L - D M_R^{-1} D^T$ **where**

D **is an** $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ **breaking Dirac mass**



both suppressed by new scale

SO10 SEESAW: GAUGED B-L

$$\mathrm{M}_{\nu\nu^c\mathrm{S}} = \begin{bmatrix} 0 & Y_\nu \langle\Phi\rangle & F\langle\chi_L\rangle \\ Y_\nu^T\langle\Phi\rangle & 0 & \tilde{F}\langle\chi_R\rangle \\ F^T\langle\chi_L\rangle & \tilde{F}^T\langle\chi_R\rangle & 0 \end{bmatrix}$$

GUT-suppressed & linear in Y_ν

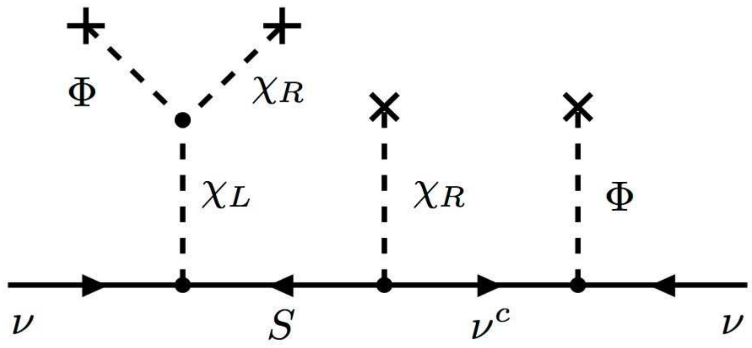
$$\mathrm{M}_{\nu-\mathrm{eff}} \simeq \frac{\rho\langle\Phi\rangle^2}{M_X}\left[Y(F\tilde{F}^{-1})^T + \mathrm{tr}\right]$$

seesaw & g_i-unification consistent with low B-L scale & SUSY

Malinsky, Romao, JV, PRL95,161801

Akhmedov et al PLB368 (1996) 270, PRD53 (1996) 2752

Barr & Dorsner, Fukuyama et al 05



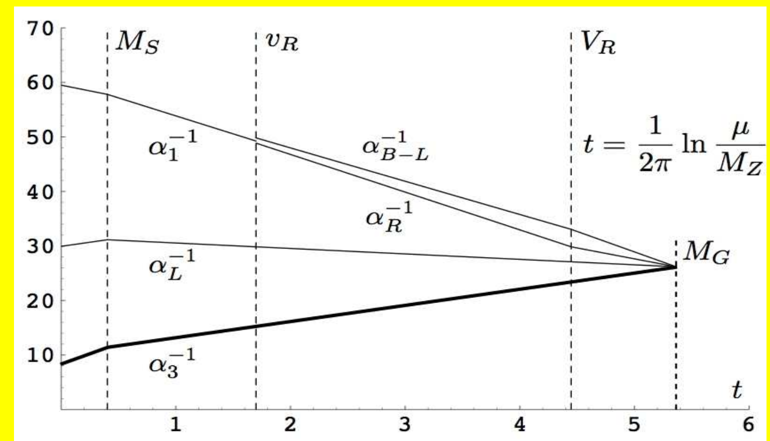
$$\mathrm{SO(10)} \xrightarrow[\mathrm{DpV@V_X}]{210,45} \mathrm{SU(3)\otimes SU(2)_L\otimes SU(2)_R\otimes U(1)_{B-L}}$$

$$\xrightarrow[\mathbf{V_R}]{16\overline{16}} \mathrm{SU(3)\otimes SU(2)_L\otimes U(1)_R\otimes U(1)_{B-L}} \xrightarrow[\mathbf{v_R}]{16\overline{16}}$$

$$\mathrm{SU(3)\otimes SU(2)_L\otimes U(1)_Y}$$

$$\xrightarrow[\mathbf{v_u,v_d,v_L}]{16\overline{16}} \mathrm{SU(3)\otimes U(1)_Q}$$

$\mathrm{v}_R \ll V_R$

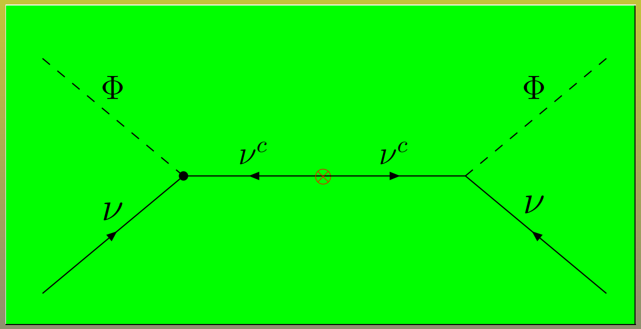


UNGAUGED B-L SEESAW

neutrino mass follows in the same way

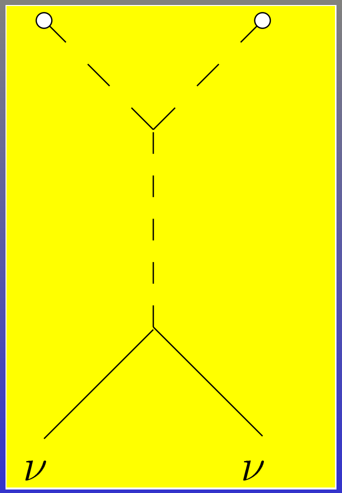
B-L violation is spont $\rightarrow$ majoron

Chikashige, Mohapatra, Peccei



opens $\nu_h \rightarrow \nu_l$ + majoron decay

Schechter, JV, PRD25, 774 (1982)



detectable at SNO with a future SNova

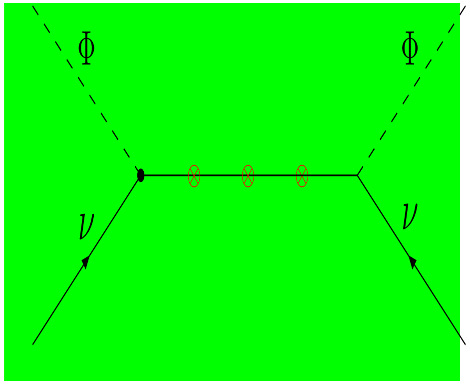
Kachelriess et al PRD62 (2000) 023004

INVERSE & DOUBLE SEESAW

Mohapatra & JV, PRD34 (1986) 1642

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

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



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

NHL exchange

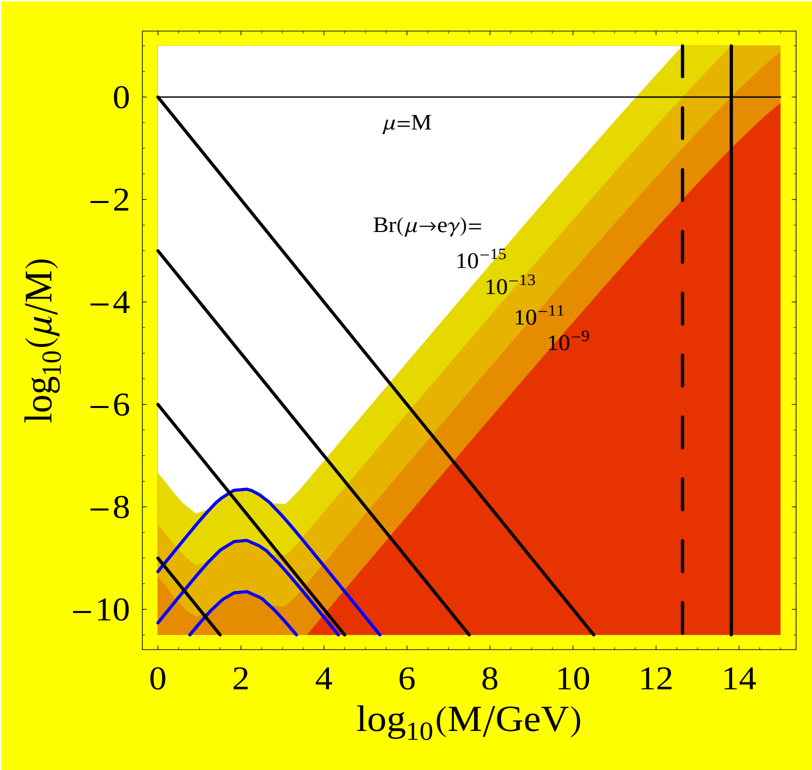
Bernabeu et al, Branco, Rebelo and JV, Rius & JV, Gonzalez-Garcia & JV

SUSY loops

Hall, Kostelecky & Raby

Borzumati & Masiero

Barbieri & Hall, Casas & Ibarra, ...



Deppisch & JV, PRD72 (2005) 036001 & hep-ph/0512360

MODEL–INDEPENDENT SEESAW

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

- **scale need not be high** **since # of $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ singlets is arbitrary**
- **far more angles and phases** **in lepton mixing than for quarks**

  (i) Majorana phases

  (ii) isodoublet-isosinglet neutrino mixings
- **non-unitary eff. lepton mixing matrix K_L**
- **explicit parametrization in terms of θ_{ij} and CP violating phases ϕ_{ij}**
- **sizeable gauge-induced NSI** **from charged and neutral currents**

PREDICTING NU-PROPERTIES

tri-bimaximal mixing

Harrison, Perkins & Scott

$$U_{\rm HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

which corresponds, at high energies, to

$\tan^2\theta_{\rm ATM} = \tan^2\theta^0_{23} = 1$ $\sin^2\theta_{\rm Chooz} = \sin^2\theta^0_{13} = 0$ $\tan^2\theta_{\rm SOL} = \tan^2\theta^0_{12} = \frac{1}{2}$

$$\begin{pmatrix} \frac{2}{3}m_1 + \frac{1}{3}m_2 & -\frac{1}{3}m_1 + \frac{1}{3}m_2 & -\frac{1}{3}m_1 + \frac{1}{3}m_2 \\ -\frac{1}{3}m_1 + \frac{1}{3}m_2 & \frac{1}{6}m_1 + \frac{1}{3}m_2 + \frac{1}{2}m_3 & \frac{1}{6}m_1 + \frac{1}{3}m_2 - \frac{1}{2}m_3 \\ -\frac{1}{3}m_1 + \frac{1}{3}m_2 & \frac{1}{6}m_1 + \frac{1}{3}m_2 - \frac{1}{2}m_3 & \frac{1}{6}m_1 + \frac{1}{3}m_2 + \frac{1}{2}m_3 \end{pmatrix}$$

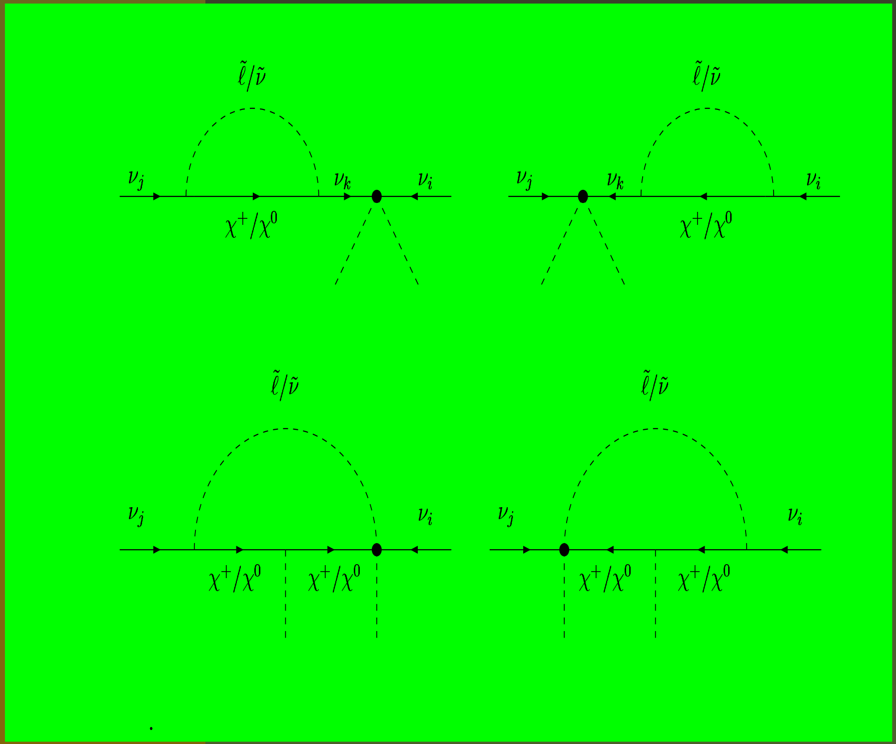
this can arise from a suitable flavor symmetry, such as A_4 Ma et al, Altarelli & Feruglio

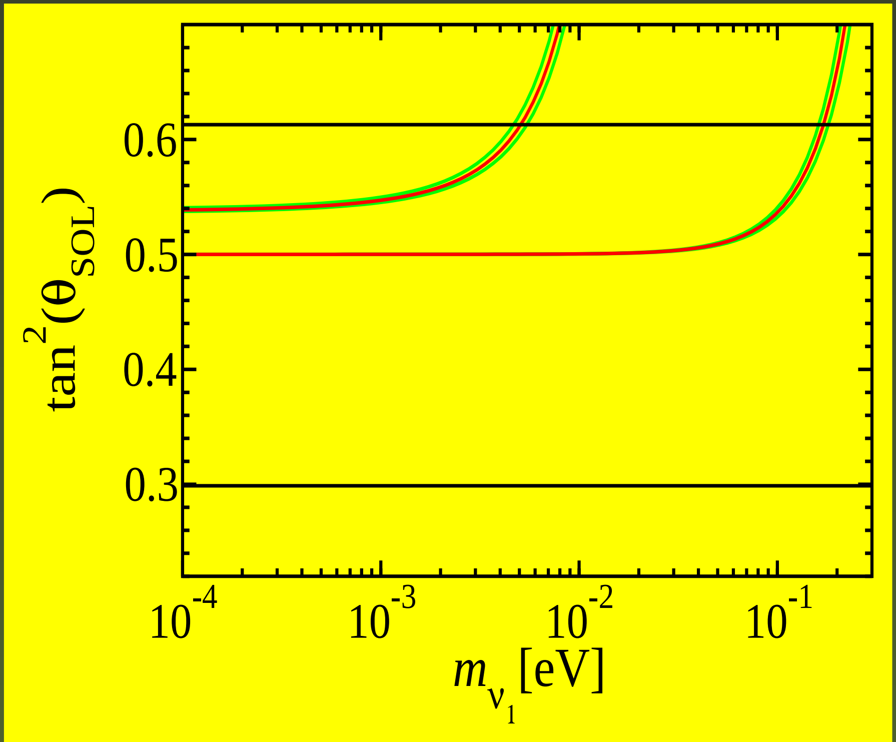
must be corrected eg Casas et al, Antusch et al, Frigerio & Smirnov, Luo & Xing, Plentinger & Rodejohann

can we lower the solar angle?

Hirsch, et al hep-ph/0606082

mSUGRA radiative corrections





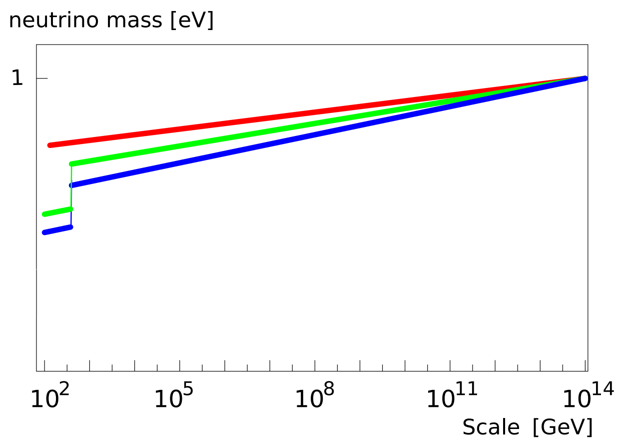
PREDICTING NU-PROPERTIES IN SEESAW

neutrino masses unify

Chankowski et al PRL86 (2001) 3488

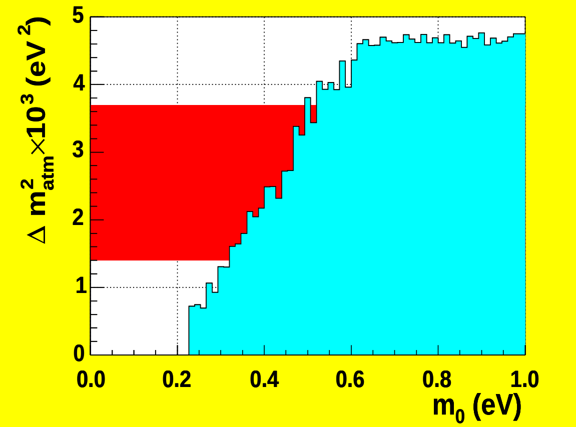
due to A4 Babu, Ma & JV, PLB552 (2003) 207

Hirsch et al, PRD69 (2004) 093006



$\theta_{23} = \pi/4$ $\theta_{13} = 0$ $\theta_{12} = \mathcal{O}(1)$

if $\theta_{13} \neq 0$ then CPV is maximal



Grimus, Lavoura; Kitabayashi, Yasue; Ma et al; Altarelli, Feruglio

$B(\mu \to e\gamma) \gtrsim 10^{-15}, B(\tau \to \mu\gamma) \gtrsim 10^{-9}$

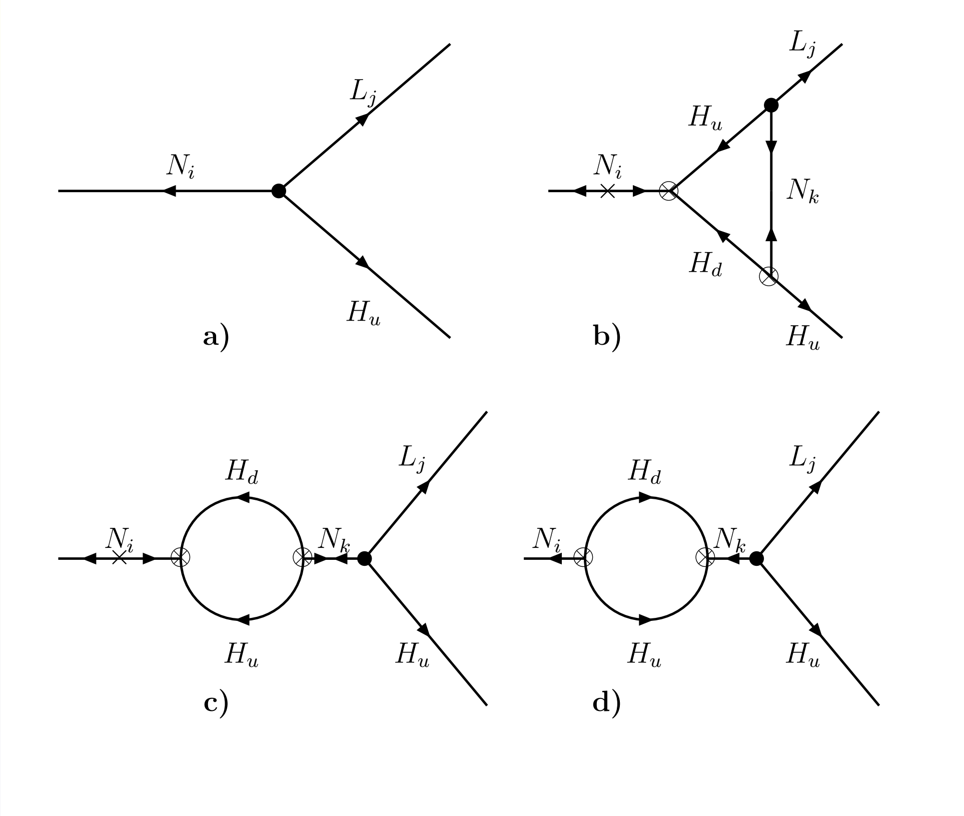
minimal nu-mass $m \gtrsim 0.3$ e

light slepton

THERMAL SEESAW LEPTOGENESIS

cosmic baryon asymmetry from out-of-equilibrium decay of heavy $\mathrm{SU(2)} \otimes \mathrm{U(1)}$ singlets

Fukugita, Yanagida 86



simplest (type-I) supersymmetric seesaw requires lightest singlet above $\gtrsim 10^9$ GeV in conflict with reheat temperature limit to prevent gravitino crisis

Small R-p violation $\lambda_i \hat{N}_i \hat{H}_u \hat{H}_d$ cures the problem •

Farzan & Valle PRL (2006) 011601

same term for different parameter choice advocated by Lopez-Fogliani, Munoz to solve μ problem [hep-ph/0508297]

SUSY origin of neutrino mass

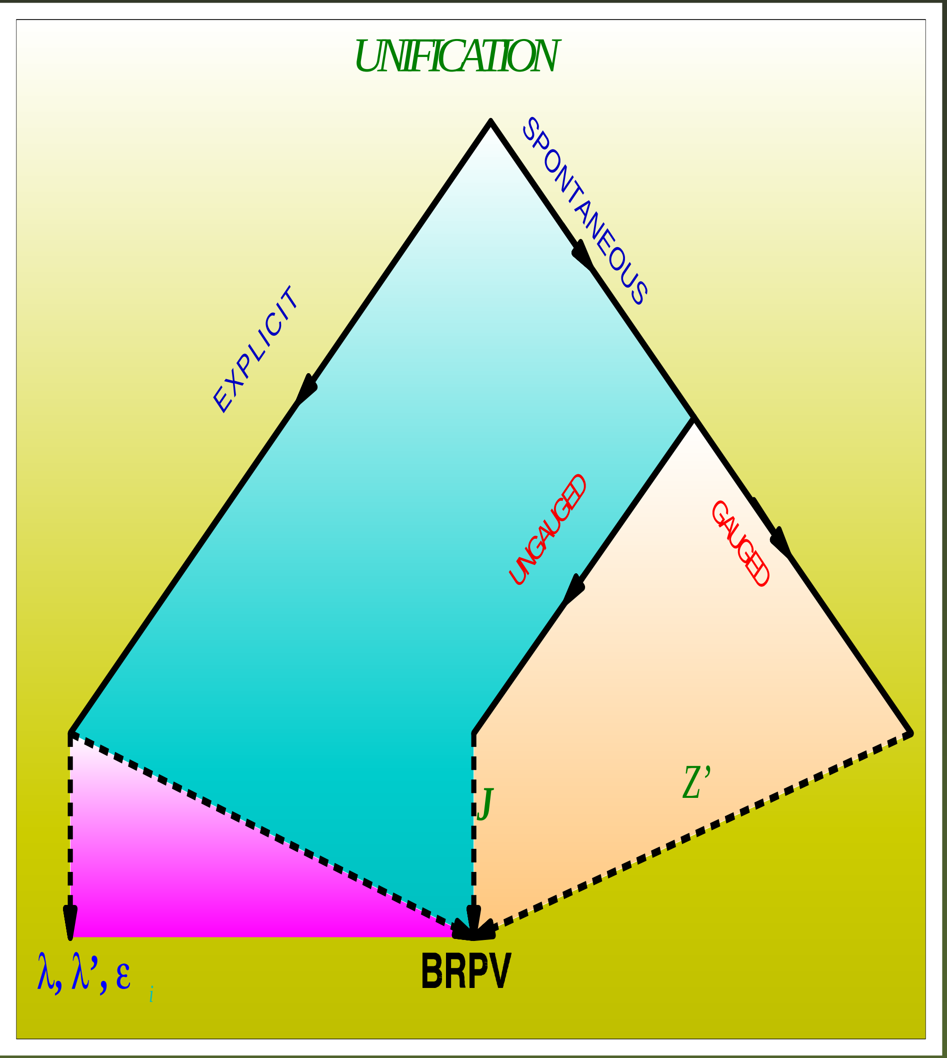
spontaneous R parity violation

gauge singlet sneutrino vev

Masiero and Valle, PLB251 (1990) 273

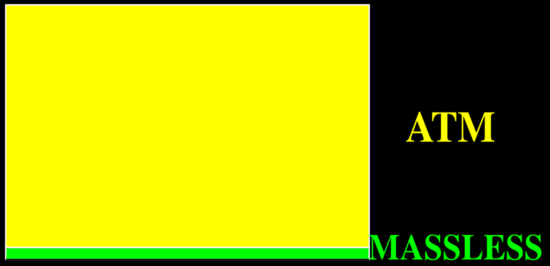
→ effective bilinear RPV

M. Hirsch, JV, NJP 6 (2004) 76



NU–MASSES FROM LOW–ENERGY SUSY?

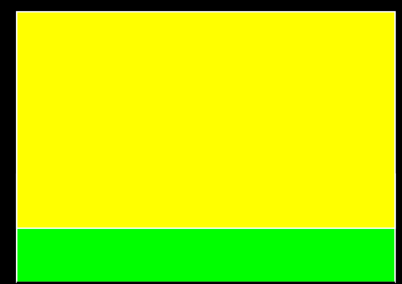
- **weak-scale seesaw** **atm scale**



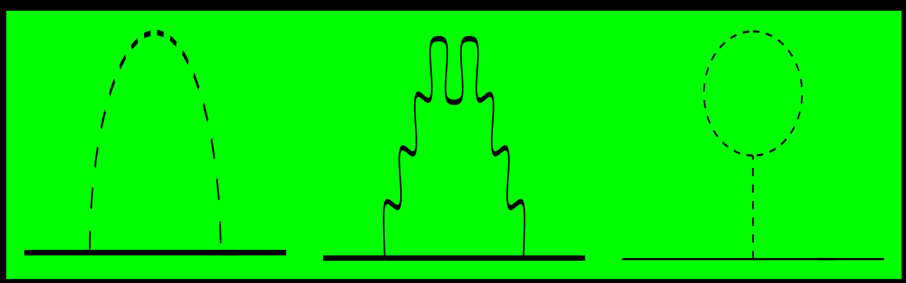
Diaz etal PRD68 (2003) 013009, PRD62 (2000) 113008; D65 (2002) 119901; PRD61 (2000) 071703

NU–MASSES FROM LOW–ENERGY SUSY?

- **weak-scale seesaw atm scale**



- **radiative solar mass scale**



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

TESTING NU-PROPERTIES

AT HE ACCELERATORS, eg LHC

TESTING NU–MIXING ANGLES at LHC/ILC

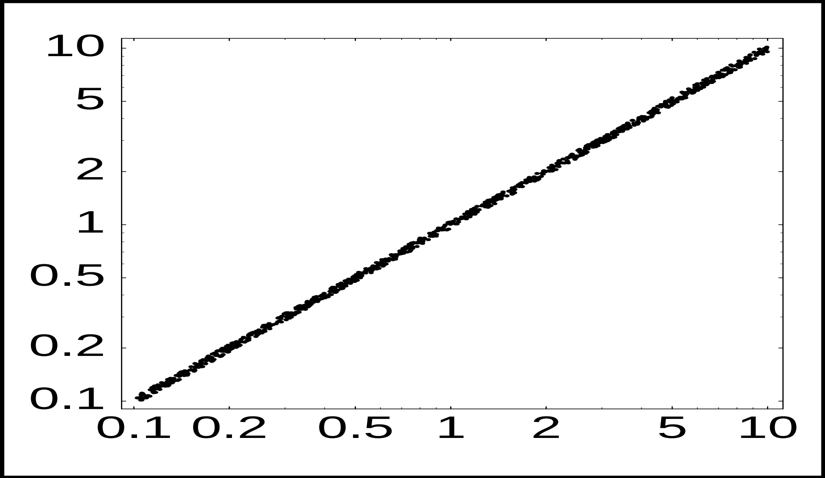
- LSP decays lead to **double vertices**, e.g. at Tevatron

de Campos et al, PRD71 (2005) 075001

  - LSP decay properties correlate with nu-mixing angles

    LHC will provide enough luminosity for detailed **correlation studies**

    smoking gun test of SUSY origin of nu-mass   Porod et al PRD63 (2001) 115004



$\frac{BR(\chi \to \mu W)}{BR(\chi \to \tau W)}$ **vs** $\tan^2_{\rm atm}$

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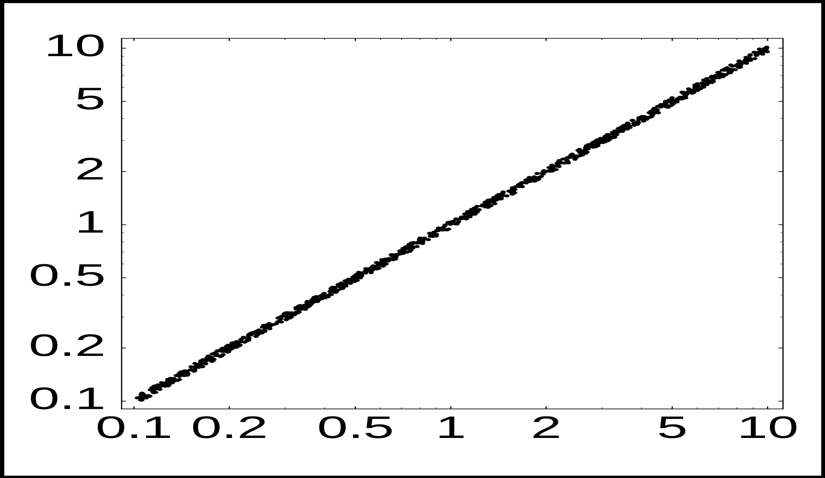


$\frac{BR(\chi\to\mu W)}{BR(\chi\to\tau W)}$ **vs** $\tan^2_{\rm atm}$

  - irrespective of the nature of the LSP

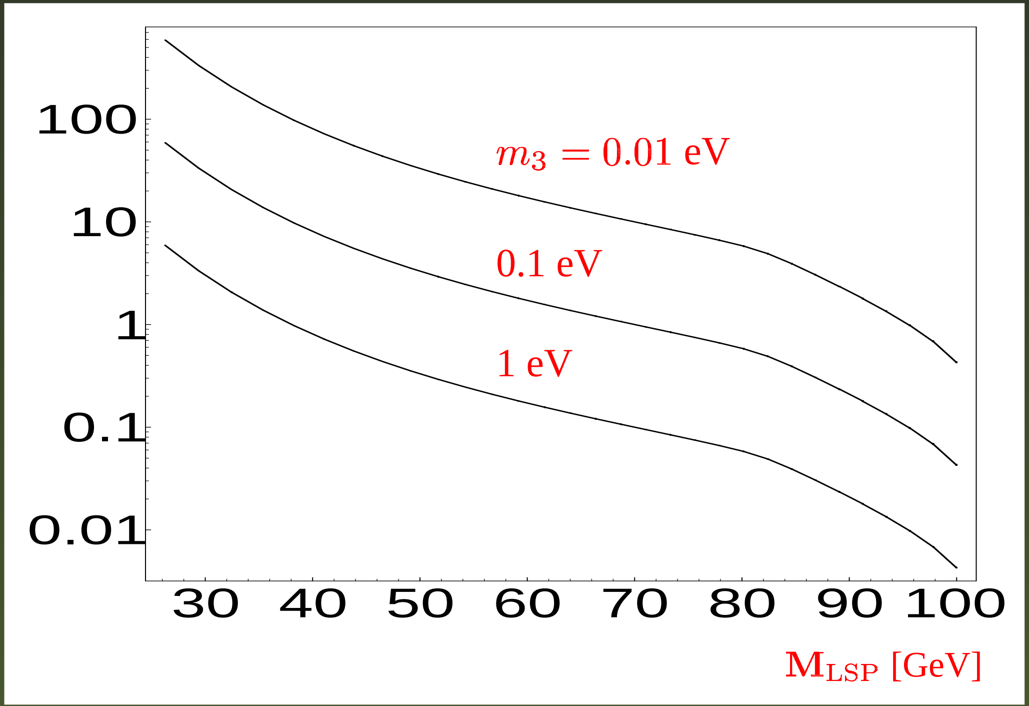
stop Restrepo et al, PRD64 (2001) 055011

stau Hirsch et al, PRD66 (2002) 095006

others D68 (2003) 115007

LSP DECAY length [cm]: BRPV

Bartl et al NPB 600 (2001) 39



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

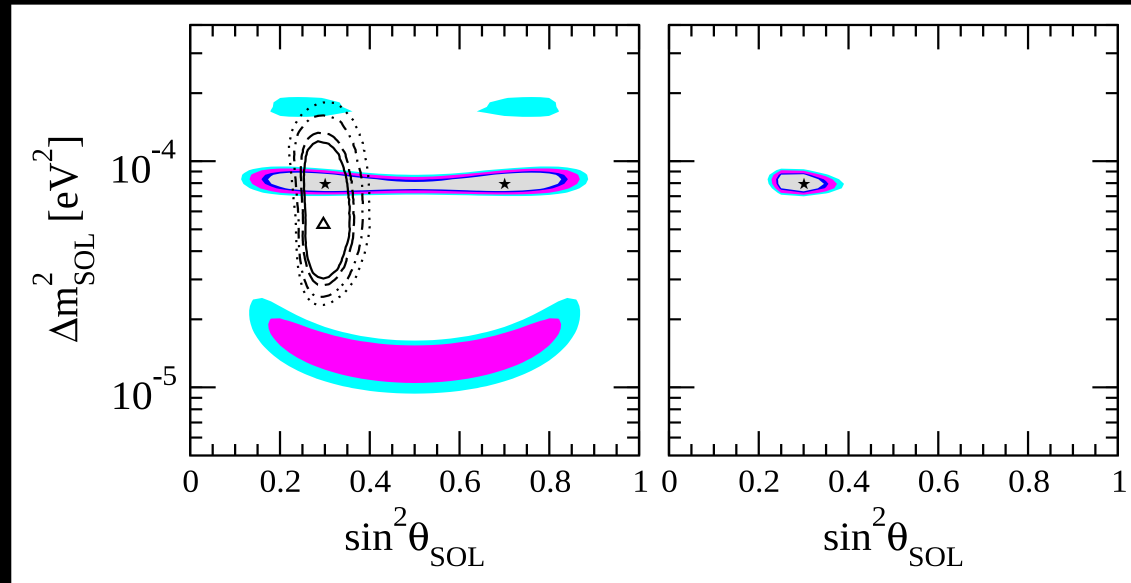
decays in detector

END

FRAGILITY OF SOLAR-NU?

wrt NSI

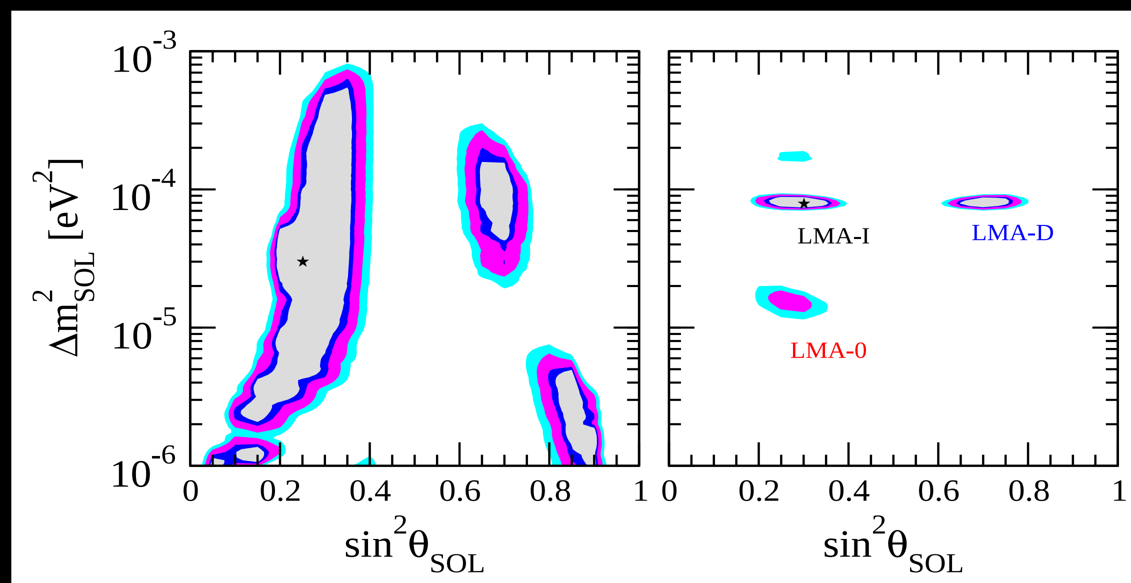
Miranda etal, hep-ph/0406280



NSI

degenerate dark-side soln, not resolved by KamLAND

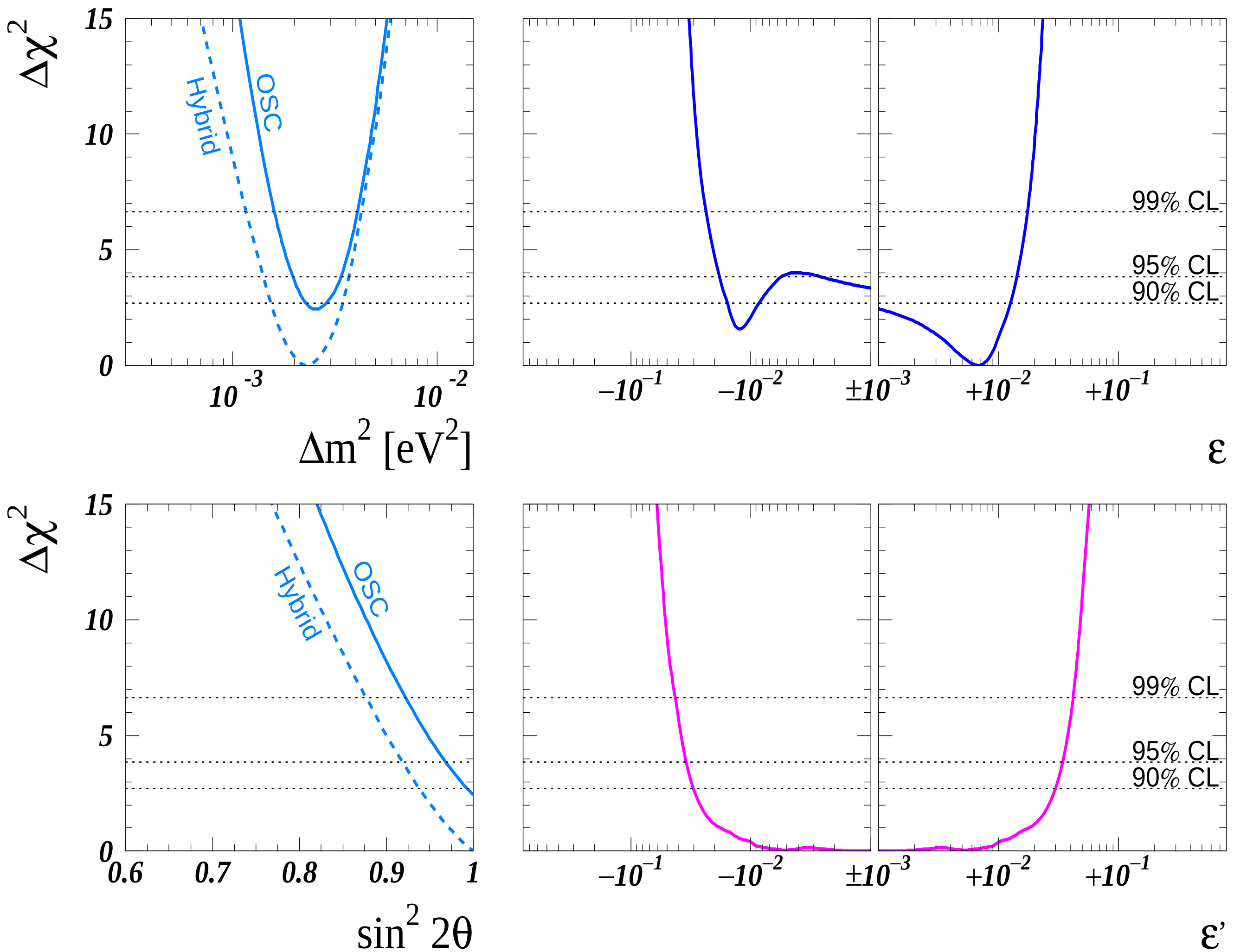
resolve NF



ROBUSTNESS OF ATM-NU

atm bounds on FC and NU nu-interactions

upd of Fornengo et al, PRD65 (2002) 01

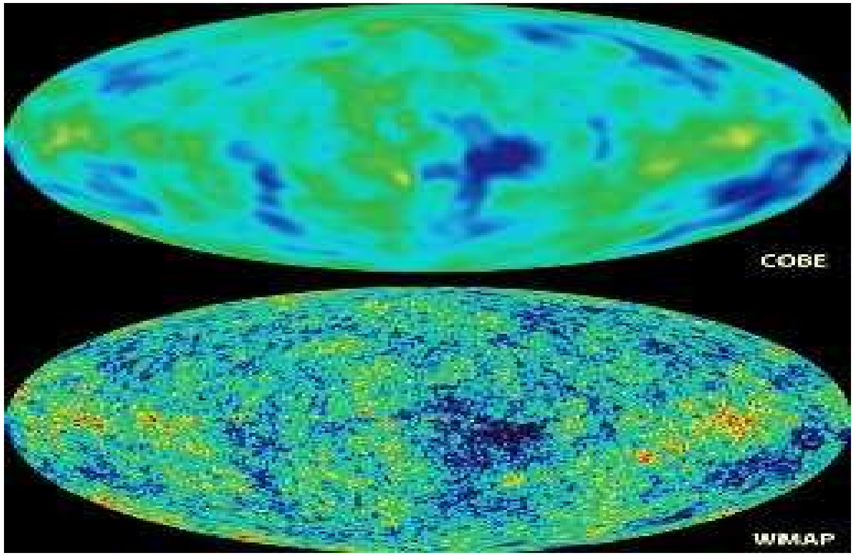


(1-d Bartol)

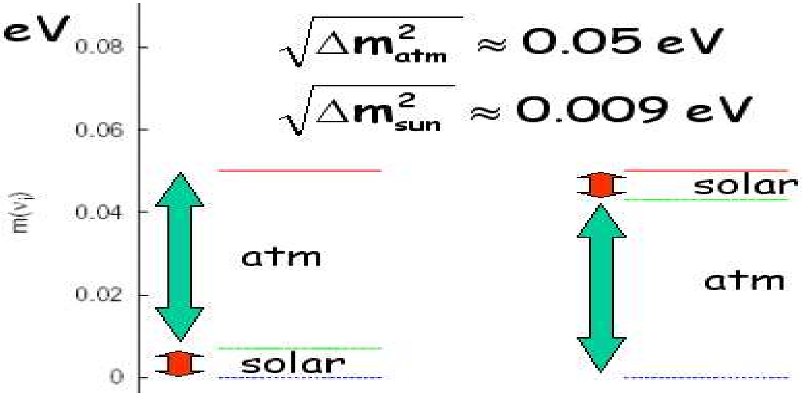
will improve at NuFact

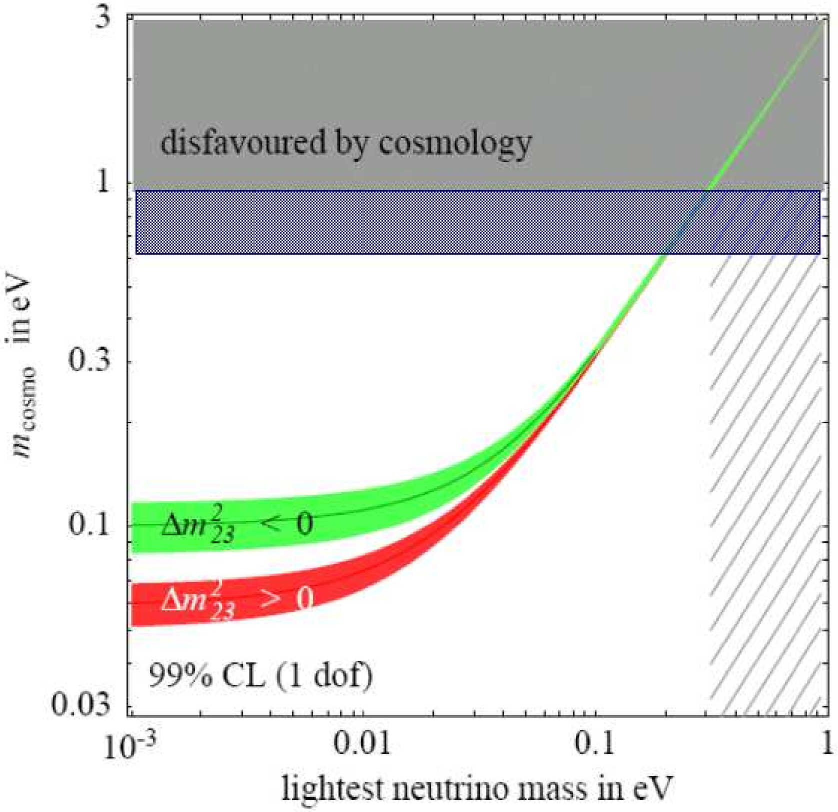
(3-g) Friedland, Lunardini & Maltoni hep-ph/0408264

CMB and LSS bounds on absolute m-nu scale



RL





- Pastor et al PRD69 (2004) 123007

NU-OSCILLATION PARAMETERS-2006

M. Maltoni et al hep-ph/0405172v5

GlobalView

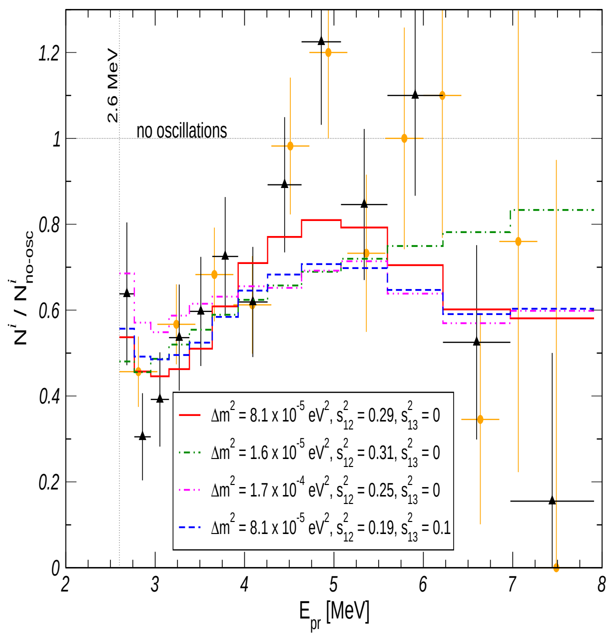
parameter	best fit	2σ	3σ	4σ
$\Delta m^2_{21}\ [10^{-5}\text{eV}^2]$	7.9	7.3–8.5	7.1–8.9	6.8–9.3
$\Delta m^2_{31}\ [10^{-3}\text{eV}^2]$	2.5	2.1–3.0	1.9–3.2	1.7–3.5
$\sin^2\theta_{12}$	0.30	0.26–0.36	0.24–0.40	0.22–0.44
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68	0.30–0.72
$\sin^2\theta_{13}$	0.000	≤ 0.025	≤ 0.041	≤ 0.060

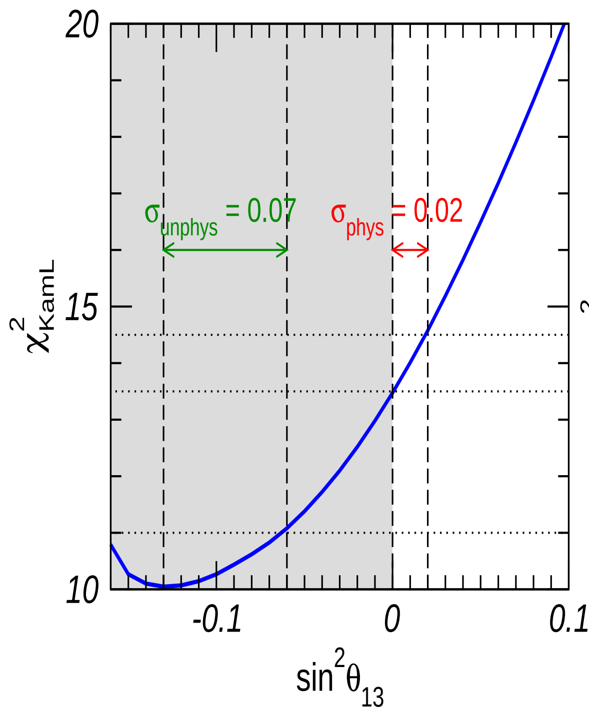
Table I: **THREE–NEUTRINO OSCILLATION PARAMETERS-2006**. Best-fit values, 2σ, 3σ, and 4σ intervals (1 d.o.f.) for the from global data including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K and MINOS) experiments.

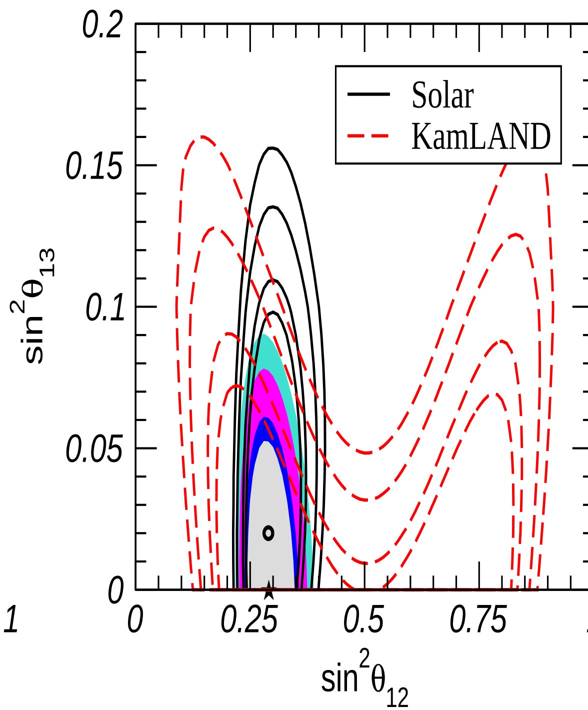
why KamLAND04 improves θ_{13}

- strong spectrum distortion

  favors unphysical θ_{13} values







combination with solar further improves ...

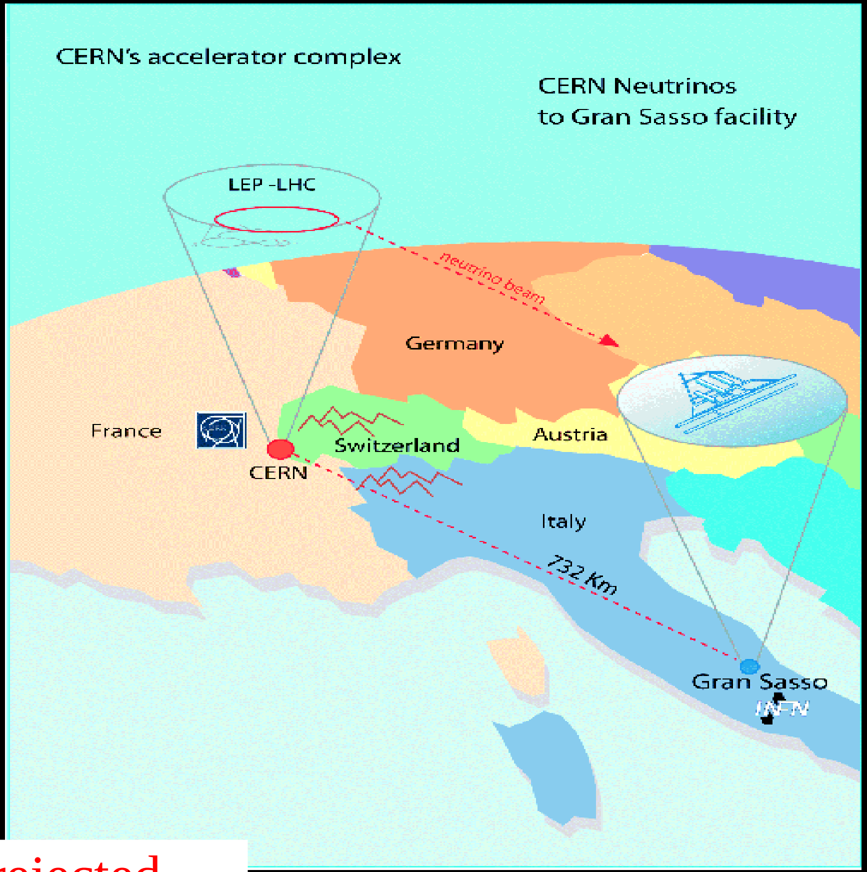
NEUTRINO FACTORIES

θ_{13} NSI

double price for probing CPV

s_{13} & $\frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}}$

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



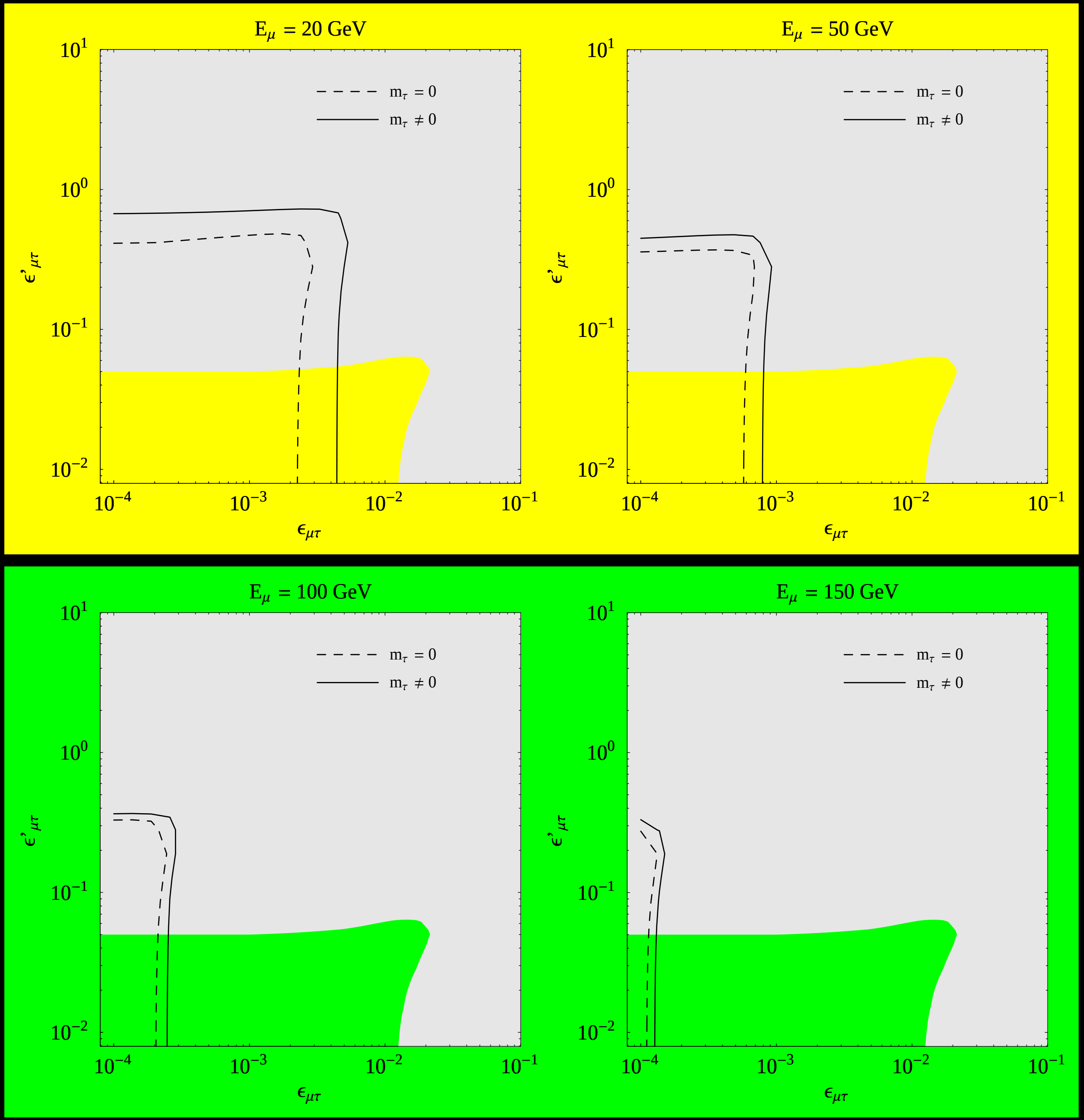
Non-Standard nu-Intercations (NSI) must be rejected ...

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

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



Robustness of solar-nu oscillations wrt noise-KL04

neutrino propagation strongly affected by solar density noise

Balantekin et al 95

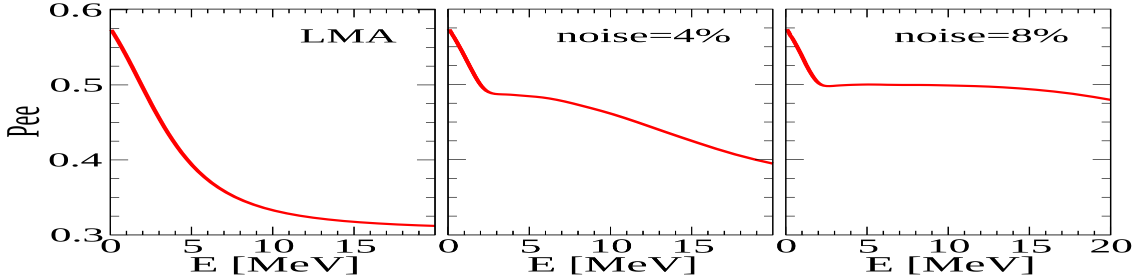
Nunokawa et al NPB472 (1996) 495

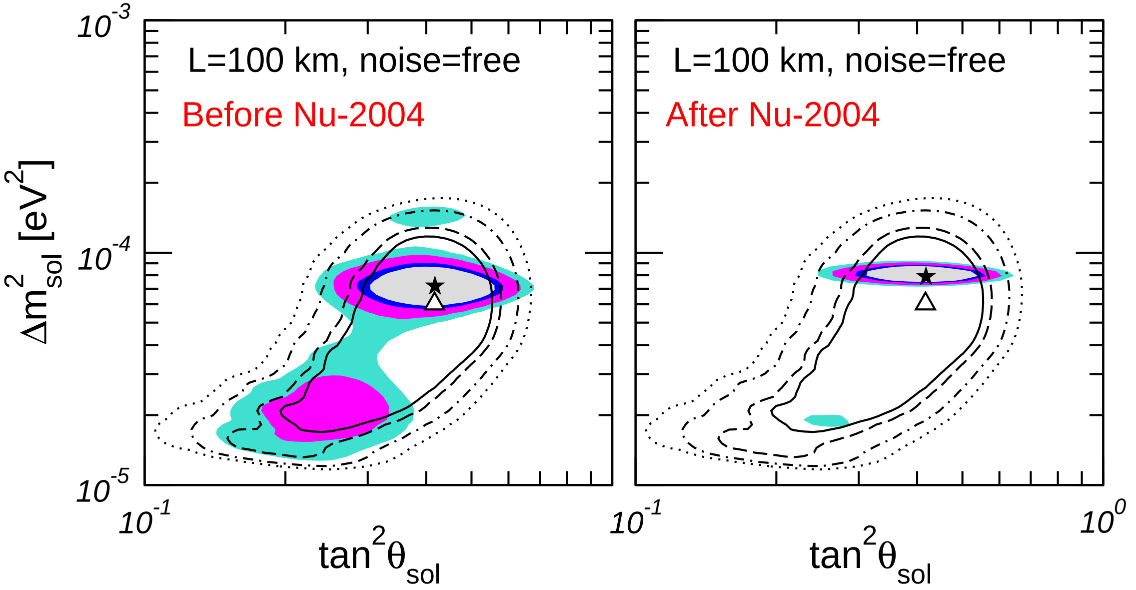
Burgess et al 97

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

Maltoni et al, hep-ph 0405172

noisy Sun

Robustness of solar-nu oscillations against SFP

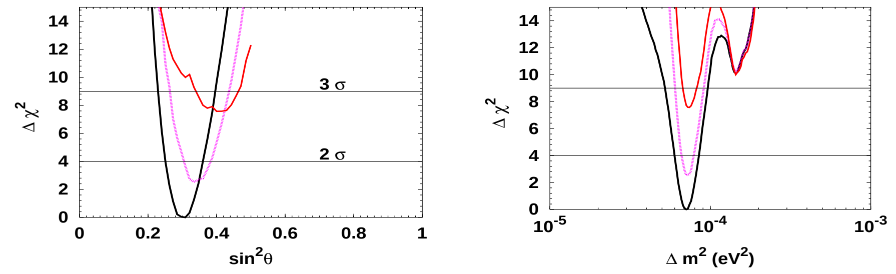
minima shifted by huge fields

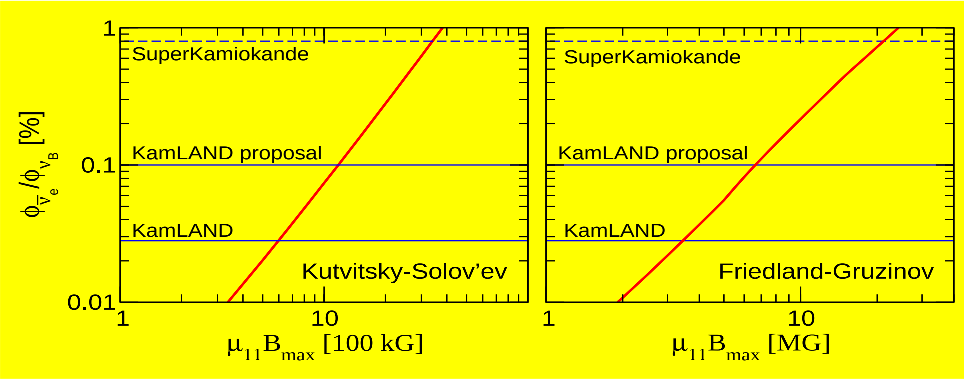
prevented by solar anti-nu limit

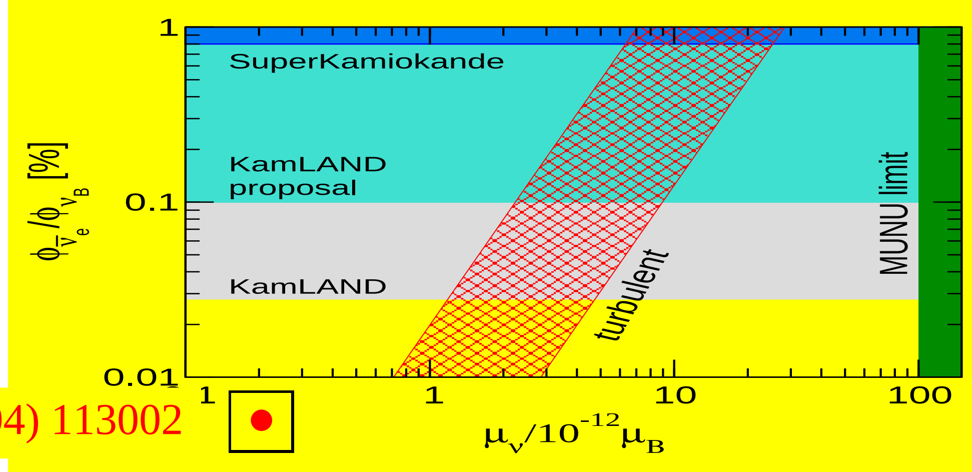
anti-nu limit implies robustness

regular versus random mag field

isolating μ_ν from $\mu_\nu B$?



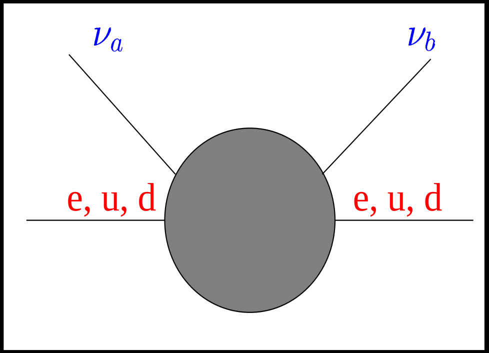




Miranda et al PRL93 (2004) 051304 & PRD70 (2004) 113002

NON-STANDARD INTERACTIONS

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



can induce non-standard interactions

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

Wolfenstein, Valle PLB199 (1987) 432

Roulet 91; Guzzo et al 91; Barger et al 91,...

they give excellent description of solar data

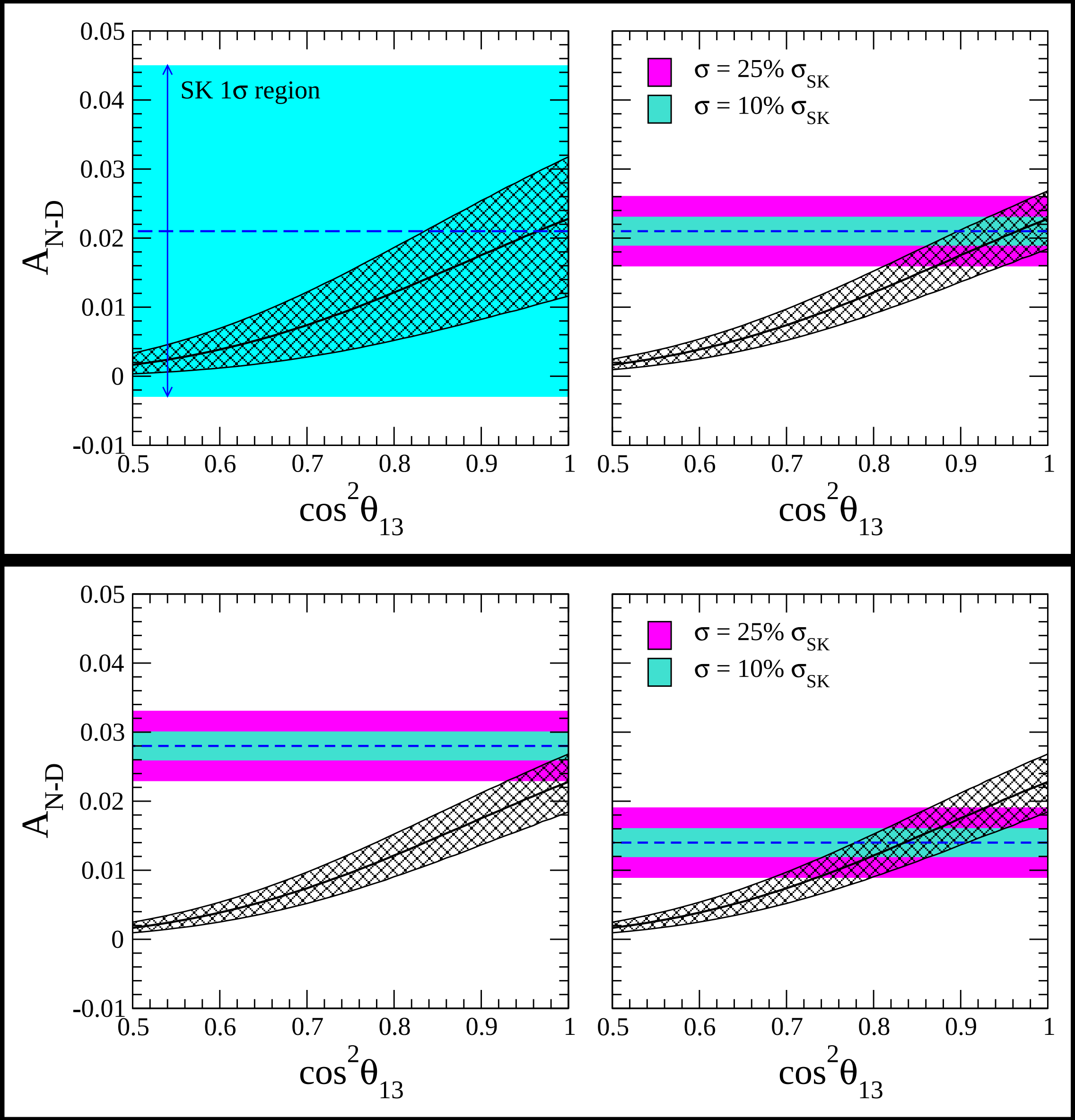
Guzzo et al NPB629 (2002) 479

but can not be the leading mechanism, due to KamLAND

how much can they affect solar neutrino oscill parameters?

DAY-NIGHT EFFECT WITH 3 NEUTRINOS

Akhmedov, Tortola, JV, JHEP05 (2004) 057

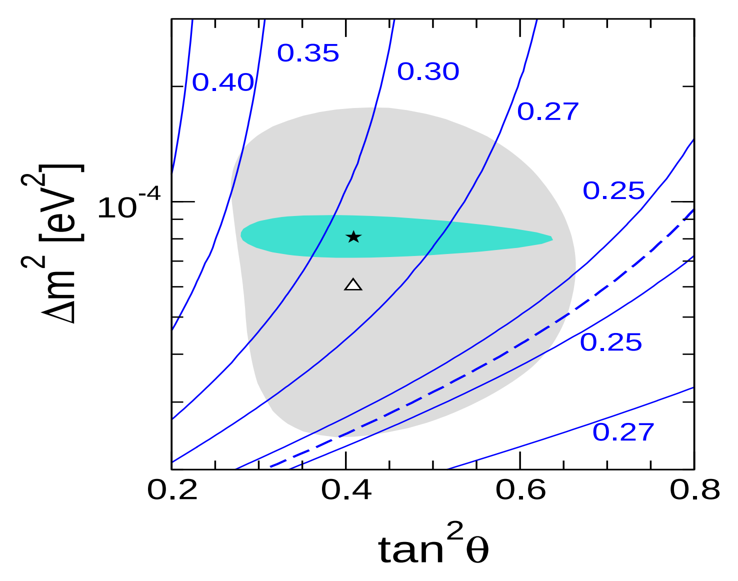


weak interactions at low energies

two tasks for Borexino?

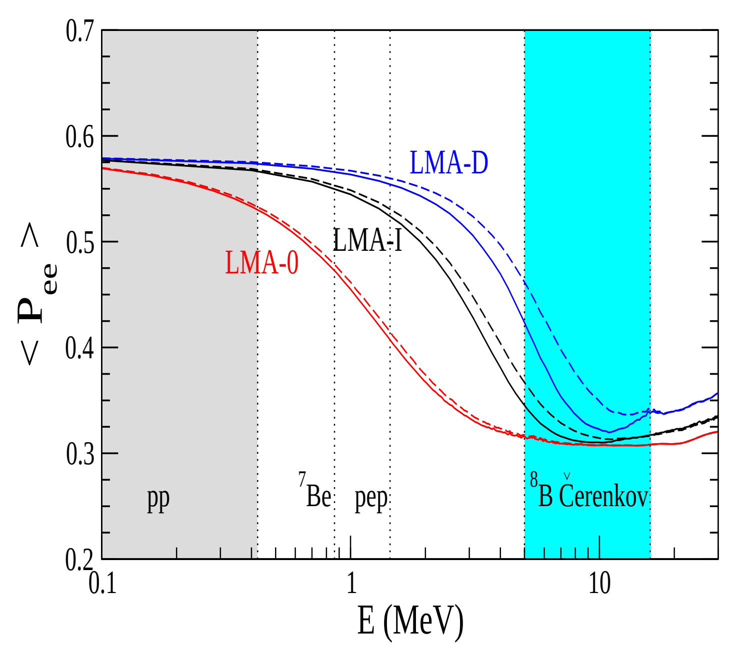
- probe nu-magn moment

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



- probe NSI

Miranda et al hep-ph/0406280



NSI-frag