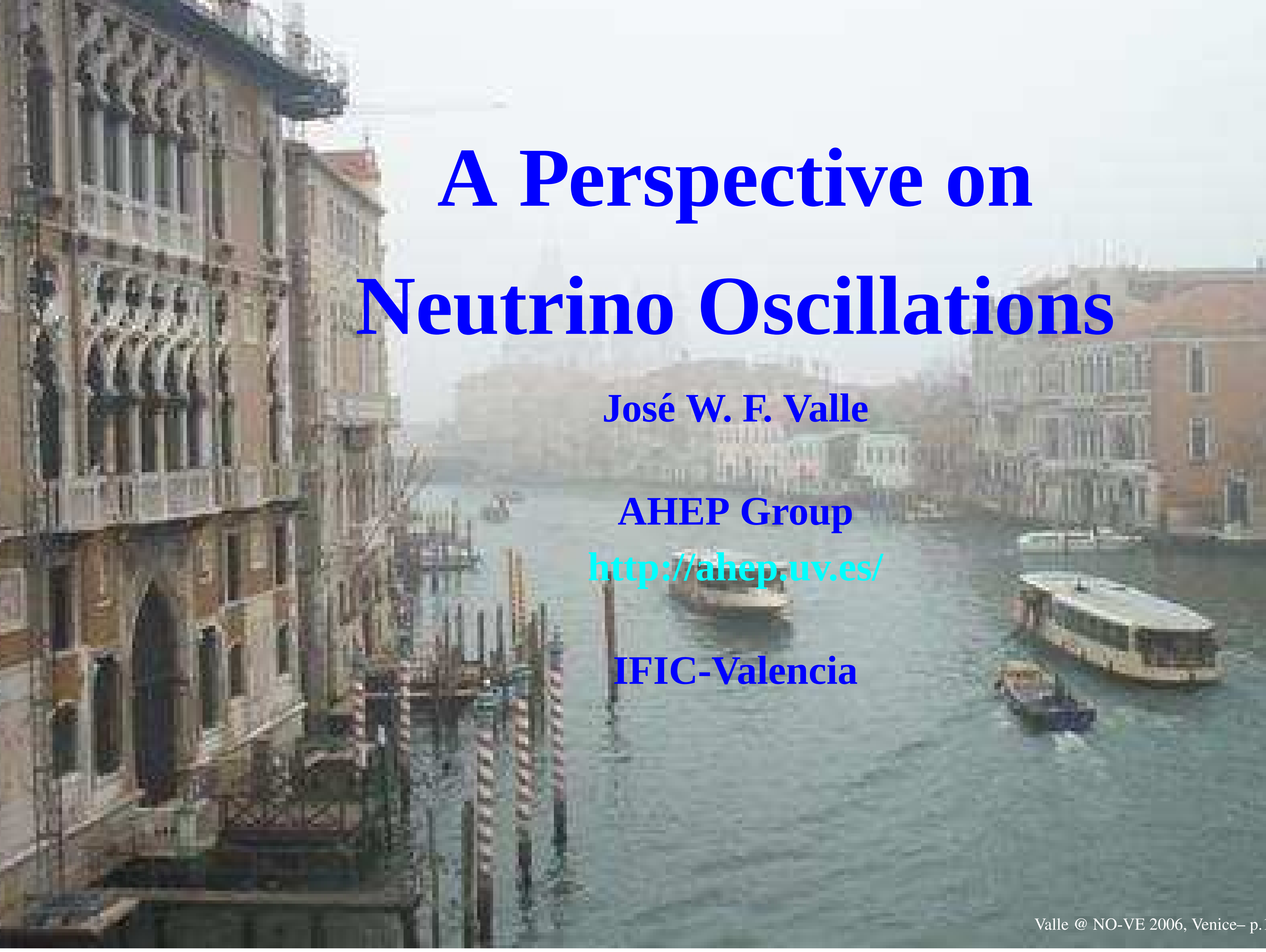


A Perspective on Neutrino Oscillations

José W. F. Valle

AHEP Group
http://ahep.uv.es/

IFIC-Valencia

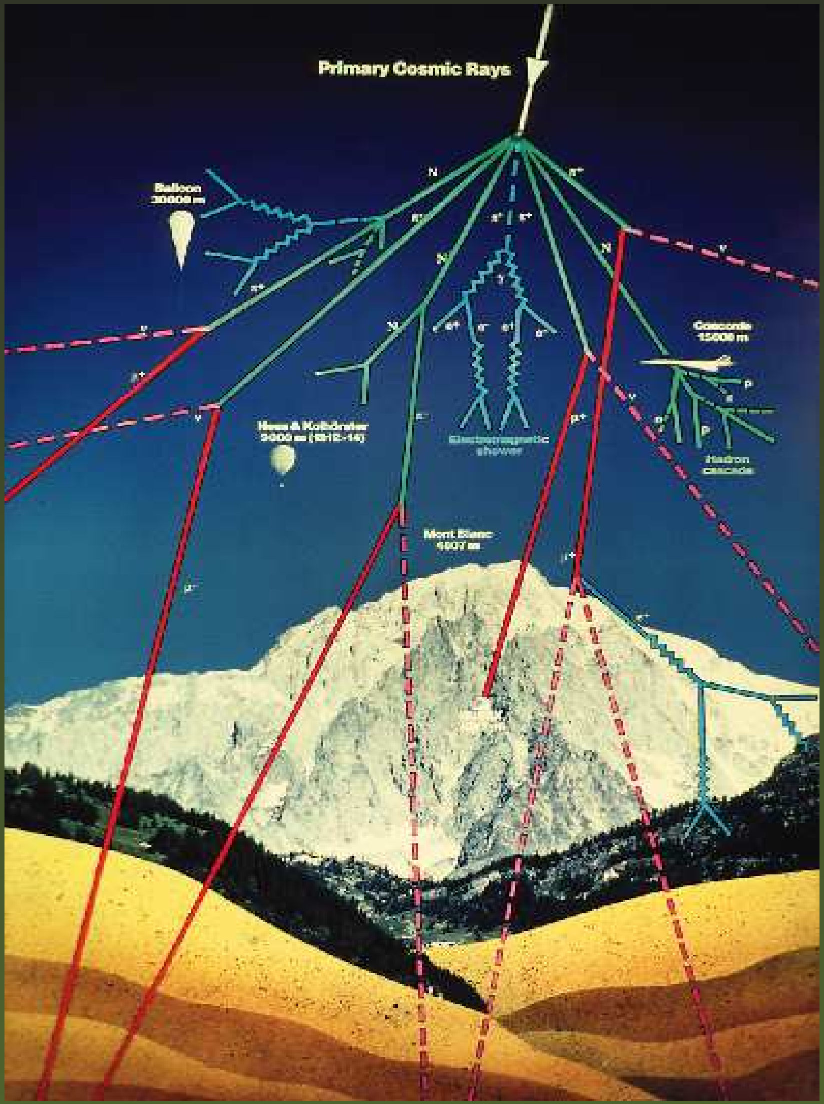
Atmospheric Neutrinos

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

pion & muon decays

deficit of ν_μ

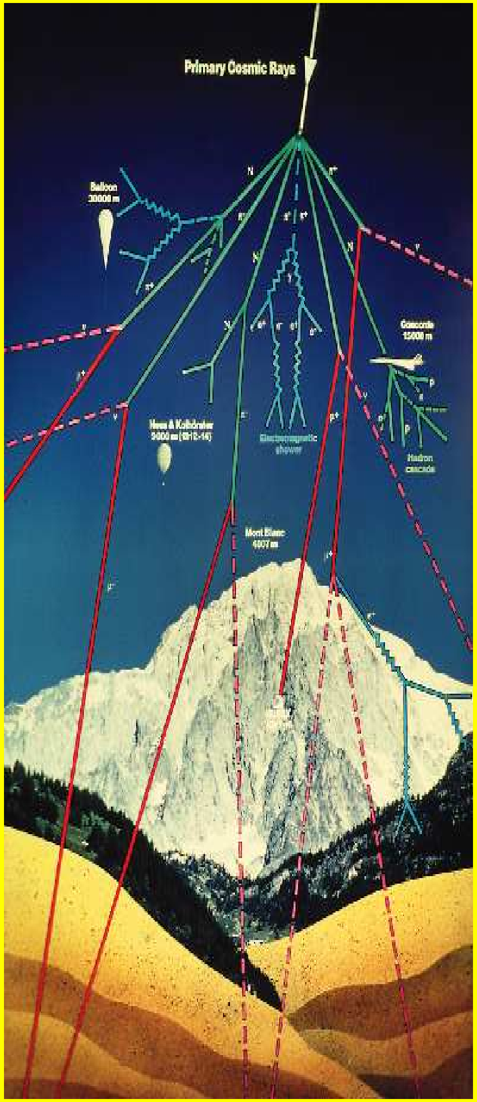
that cross the earth (1998)

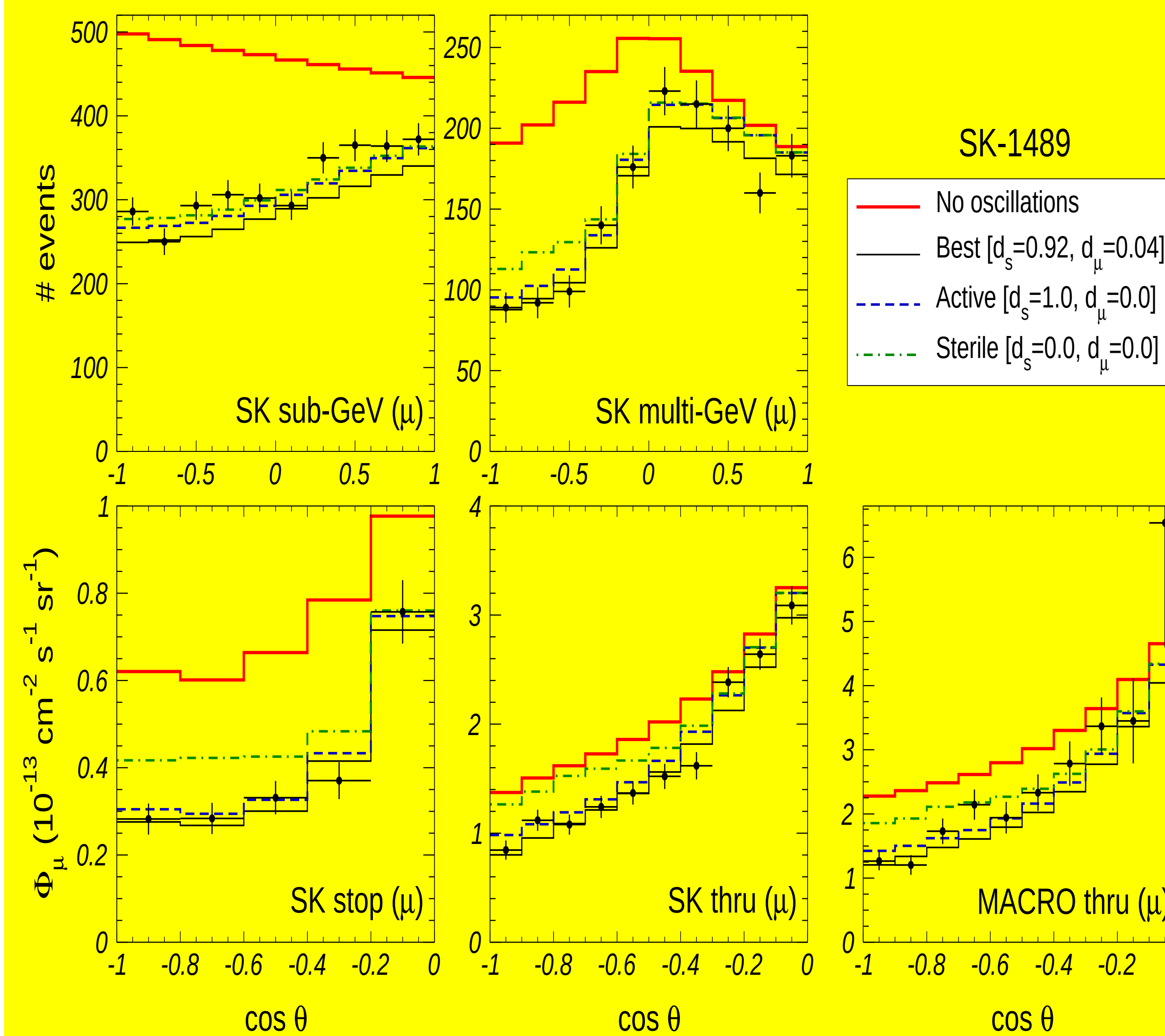


Atmospheric zenith distribution

Maltoni et al, PRD67 (2003) 013011 rejects "sterility"

Bartol





Accelerator Neutrinos

well controlled source

checks atm ν_μ oscill hypothesis

K2K confirms the atm neutrino oscillation interpretation: both by ν_μ deficit and by obs a distortion of the energy spectrum

solar neutrinos

- neutrinos produced in the solar core in thermonuclear reactions
- these result in the overall fusion of protons into helium: $4p \rightarrow {}^{4}\textbf{He} + 2e^{+} + \gamma + 2\nu_e$
- SSM predicts more neutrinos
- than detected in underground experiments

solar neutrino defi cit

neutrinos from reactors

KamLAND has solved the solar neutrino problem...

rejecting non-standard mechanisms as leading solns

simplest lepton mixing matrix

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

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

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

)

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

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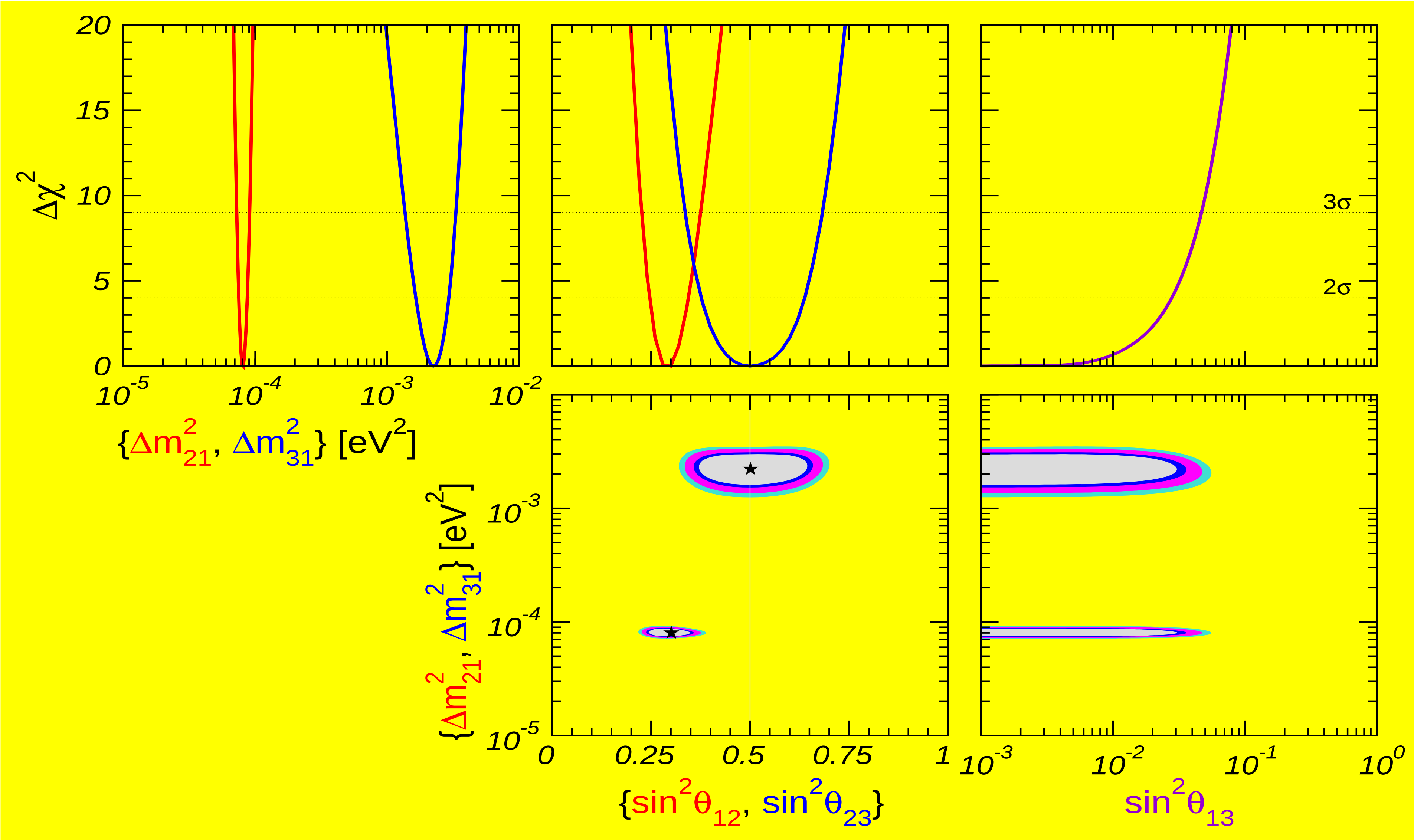
- **oscillations depend only on the KM-like phase ($n \geq 3$)**
- **the 2 new phases ($n \geq 2$) appear in L-violating processes eg $\beta\beta_{0\nu}$**
- **currently no expt is sensitive to CPV, so we also drop all** ϕ_{ij}

5 parameter 3-nu oscillation analysis

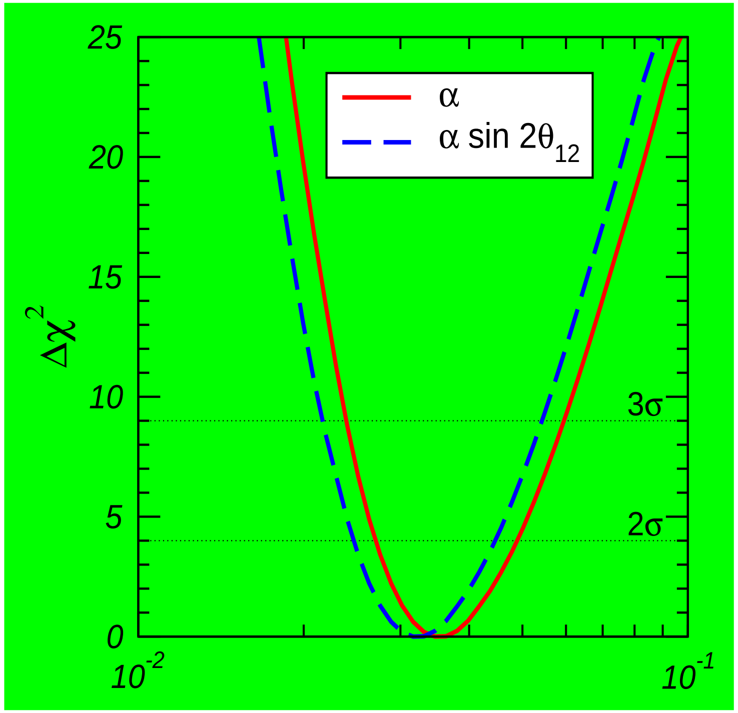
LATEST GLOBAL STATUS OF OSCILLATIONS

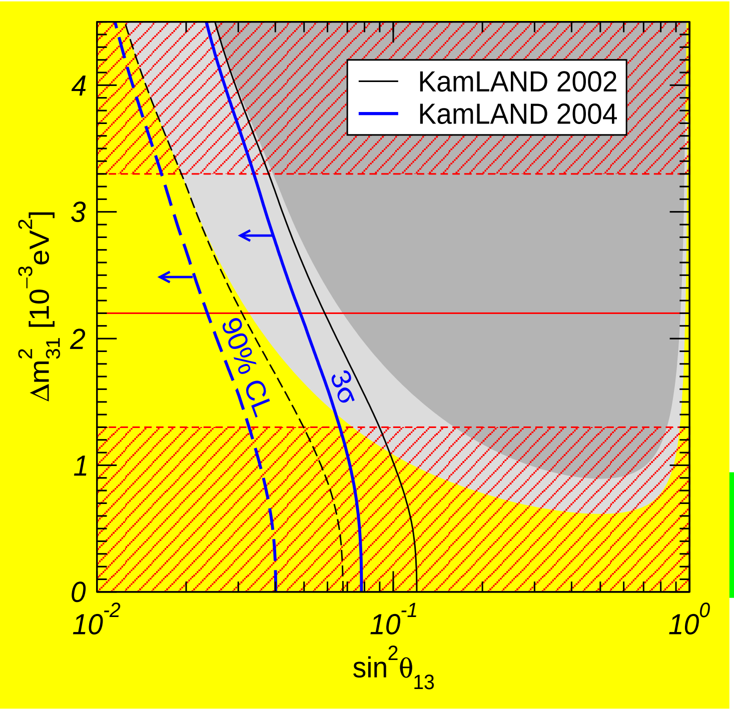
M. Maltoni et al, NJP 6 (2004) 122 nu-phys enter precision era Tab t13



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}

for low $\Delta m^2_{\rm ATM}$ solar+KamLAND contribute to improve upon Chooz

closeup

further improvements will come from LBL reactor/accel expts

as well as D/N solar-nu studies (Akhmedov etal JHEP05 (2004) 057)

are oscillations robust ?

how well do we understand

... the Sun?

... neutrino propagation ?

... neutrino interactions ?

the importance of reactors

KamLAND has solved the solar neutrino problem...

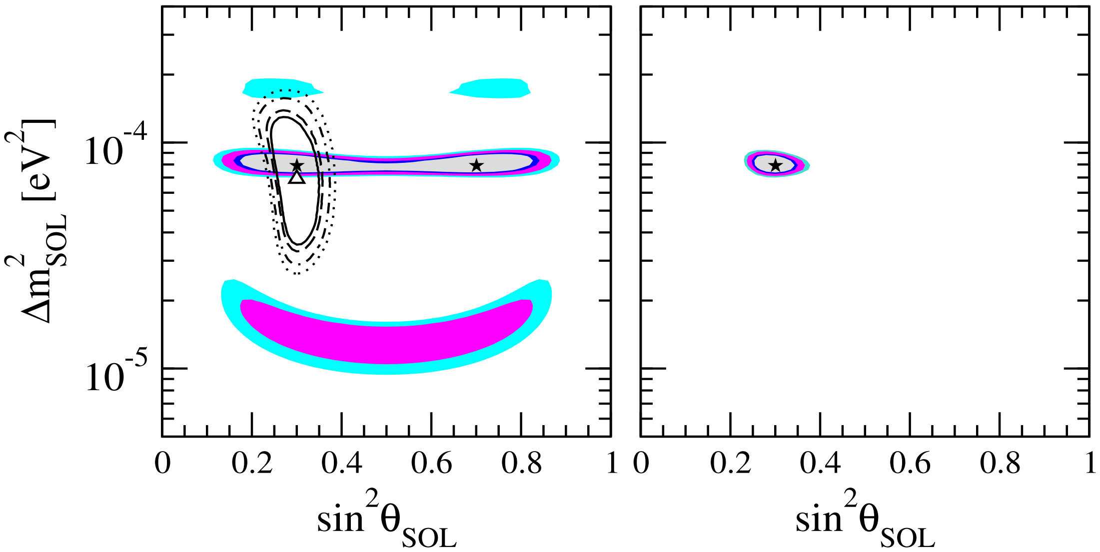
rejecting non-standard mechanisms as leading solns

- **noisy Sun** robust — Burgess et al JCAP0401 (2004) 007
- **SFP** robust — Miranda et al PRL93 (2004) 051304 & PRD70 (2004) 113002
- **NSI** almost robust ...

FRAGILITY OF SOLAR-NU?

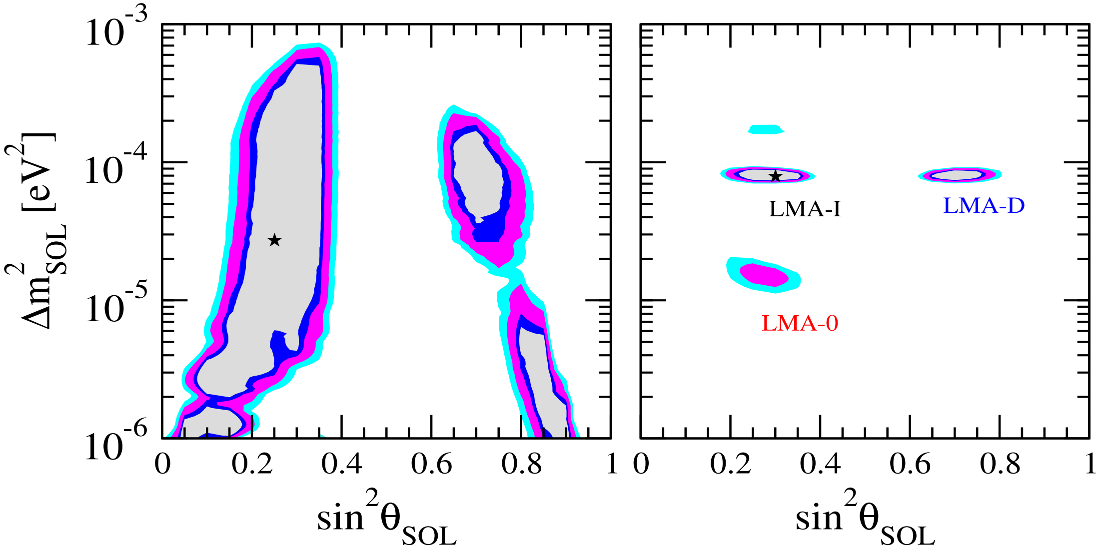
wrt NSI

Miranda etal, hep-ph/0406280



resolve NF

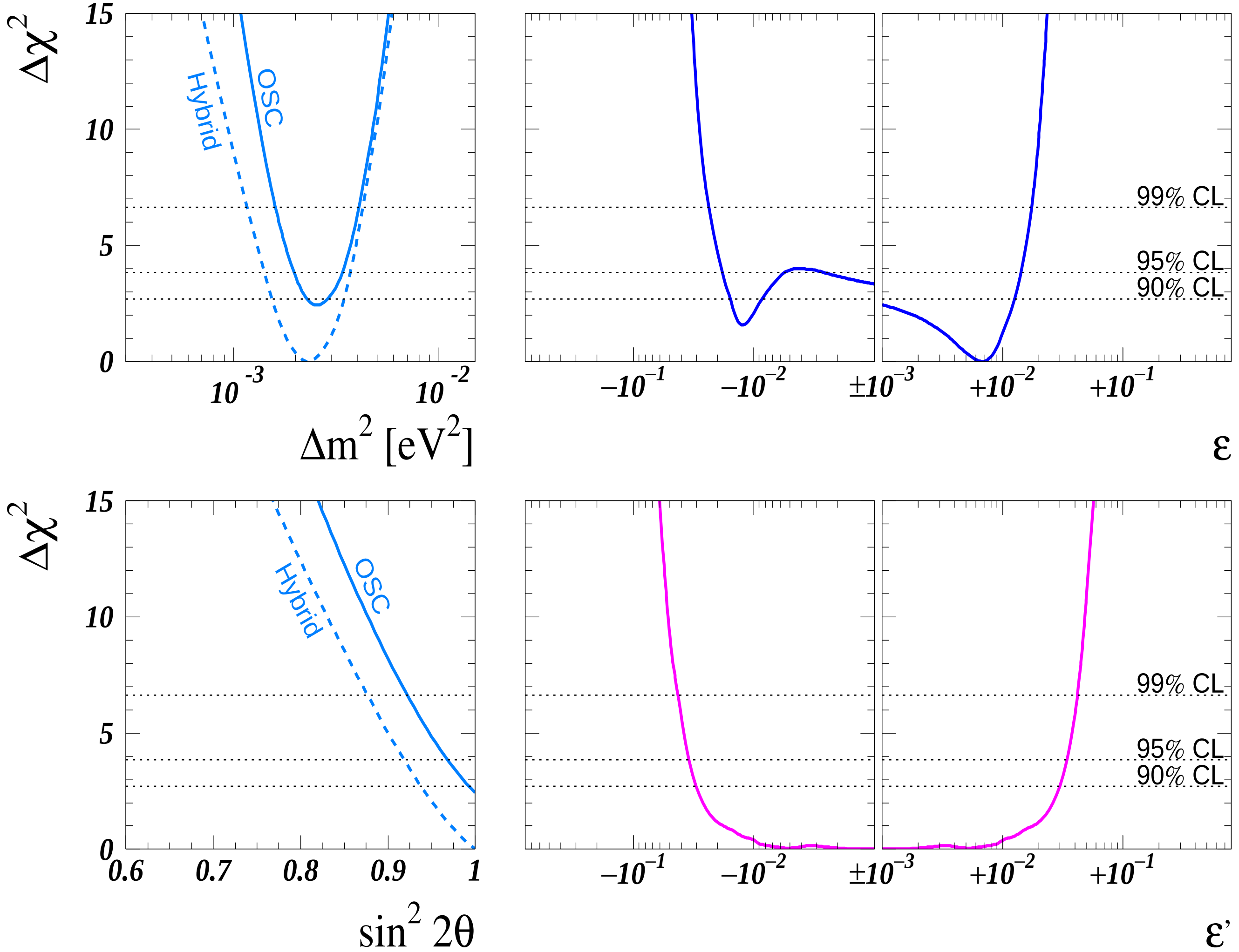
degenerate dark-side soln, not resolved by KamLAND



ROBUSTNESS OF ATM-NU

atm bounds on FC and NU nu-interactions

upd of Fornengo et al, PRD65 (2002) 013010



(1-d Bartol)

will improve at NuFact

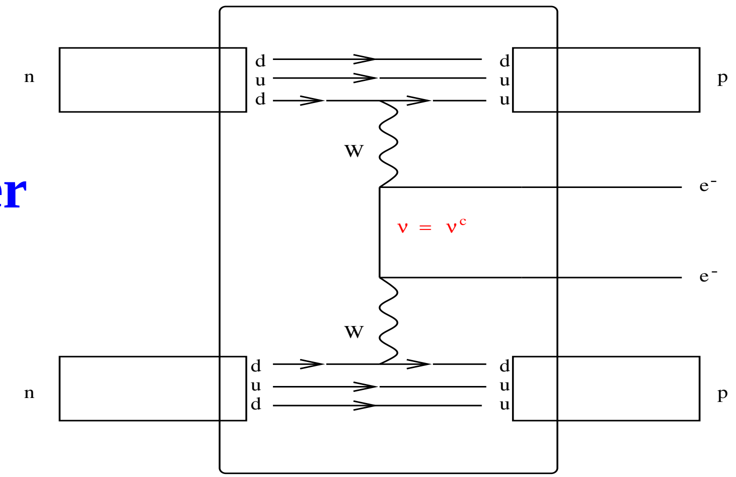
(3-g) Friedland, Lunardini, Maltoni PRD70 (2004)

non-oscillation physics

the next challenge

0-nu DOUBLE BETA DECAY AND NU-SPECTRA

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

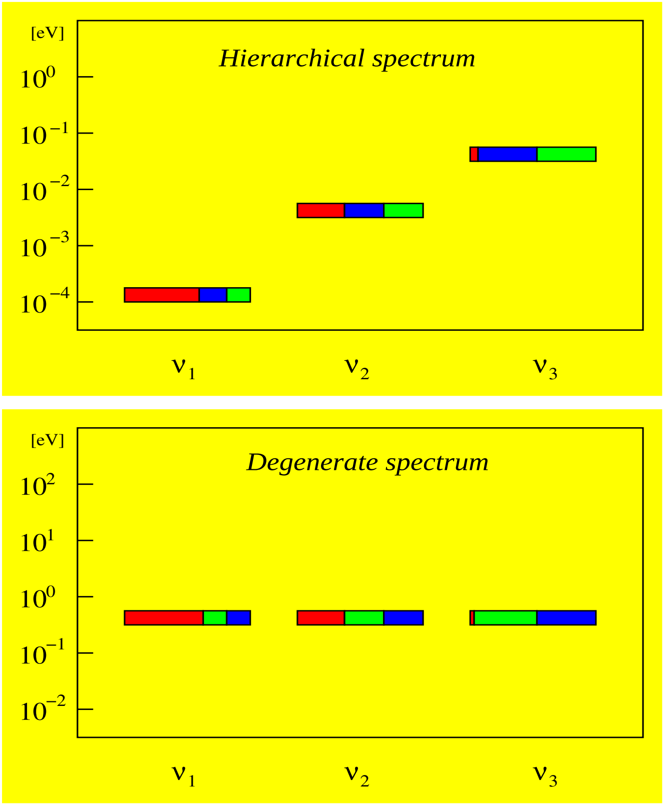


$$\langle m_\nu \rangle = \sum_j K_{ej}^2 m_j$$

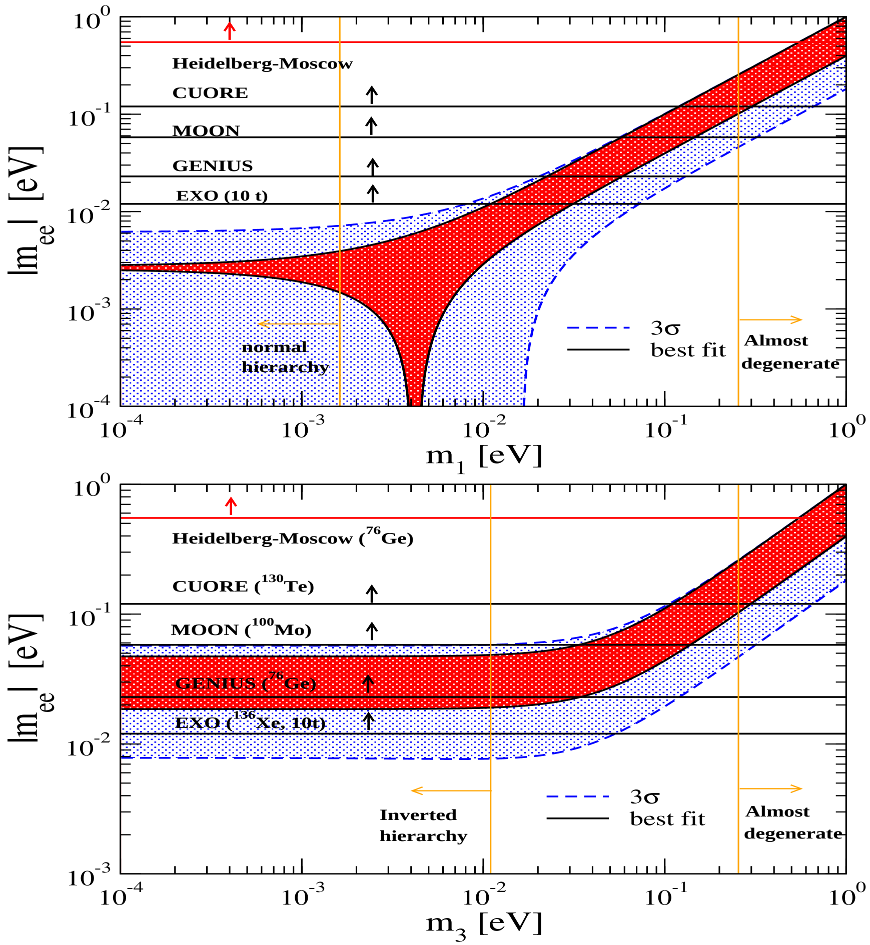
- **3 masses:** m_i **NEW**
- **2 angles:** θ_{12} **and** θ_{13}
- **2 CP phases: NEW** ϕ_{12}, ϕ_{13}

with $S_{ij} \equiv \sin 2\phi_{ij}$

$C_{ij} \equiv \cos 2\phi_{ij}$



PROBING ABSOLUTE M-NU SCALE



Bilenky, Faessler, Simkovic PRD70 (2004) 033003

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

predicting 0-nu double beta decay

A_4 triplet model of nu-masses

Hirsch et al, PRD72 (2005) 091301

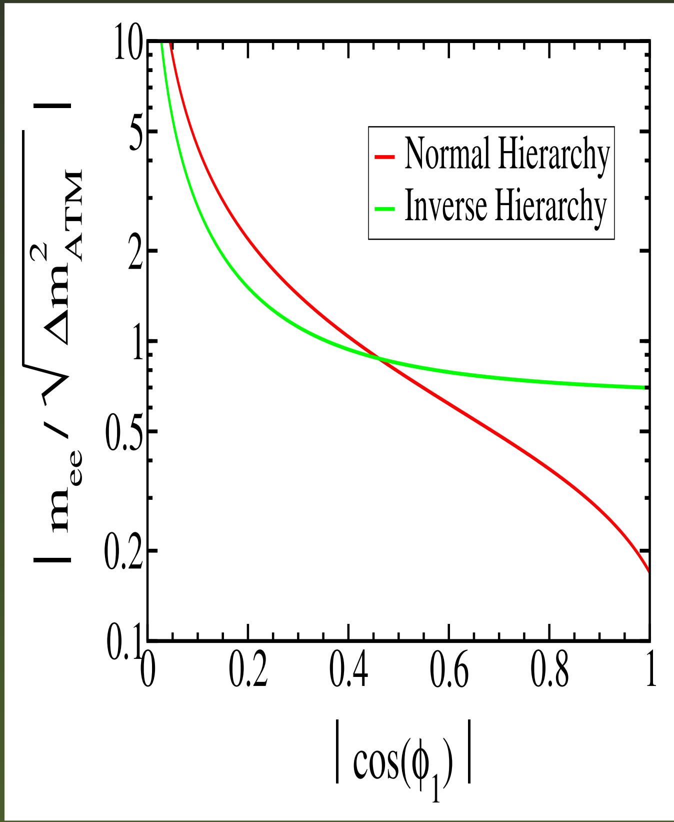
$$M_\nu = \begin{pmatrix} a+2b & d & d \\ f & a-b & d \\ e & d & a-b \end{pmatrix}$$

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

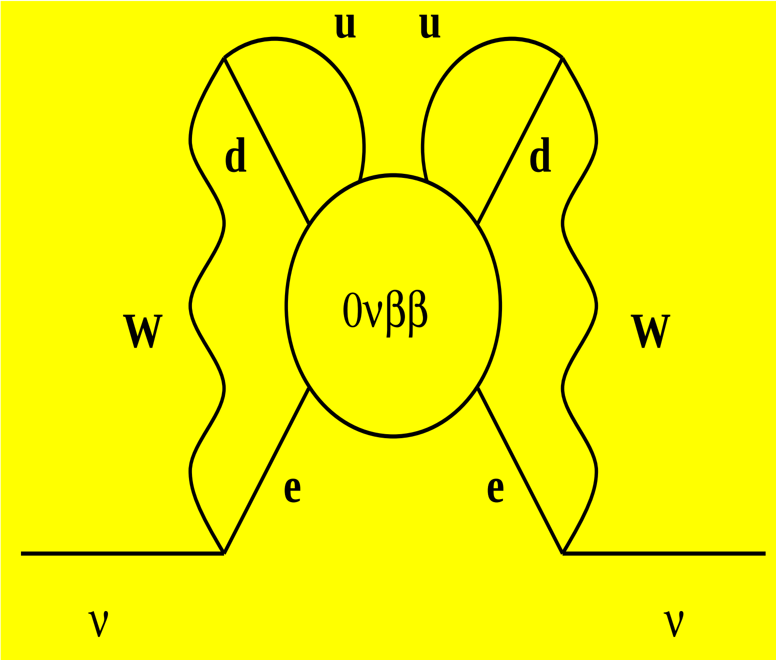
$|\langle m_{ee}\rangle| \geq 0{,}17\sqrt{\Delta m^2_{\mathrm{ATM}}}$

also for normal hierarchy

sensitive to Majorana phase



SIGNIFICANCE of 0-nu DOUBLE BETA DECAY



- tests **absolute nu-mass scale**

just as **cosmology CMB/LSS** •

tritium beta decays ...

- tests **majorana nature**

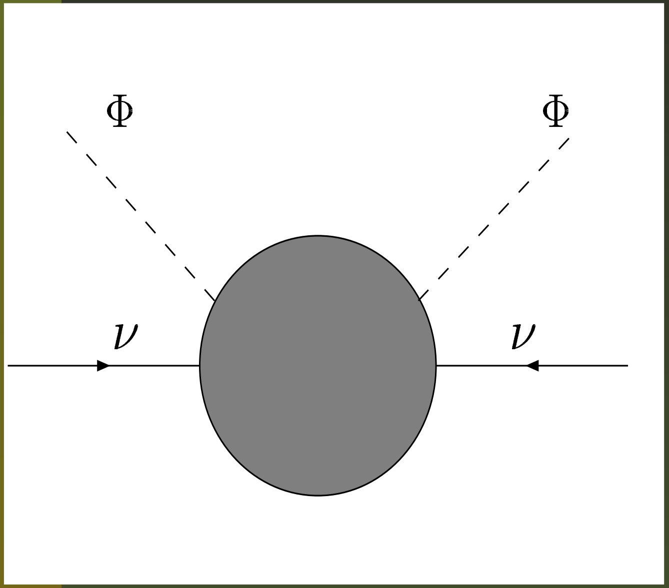
irrespective of mechanism

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

Schechter and JV, PRD25 (1982) 2951

no such theorem for flavor violation

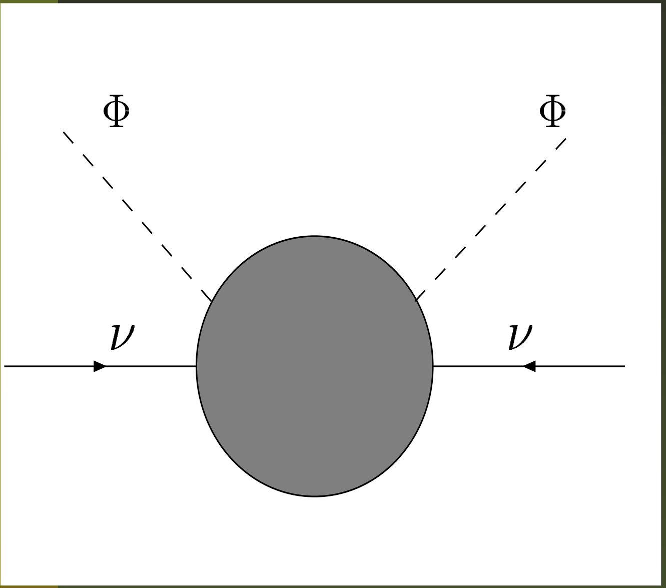
the origin of neutrino mass



- most basic nu-mass definition

Weinberg PRD22 (1980) 1694

the origin of neutrino mass

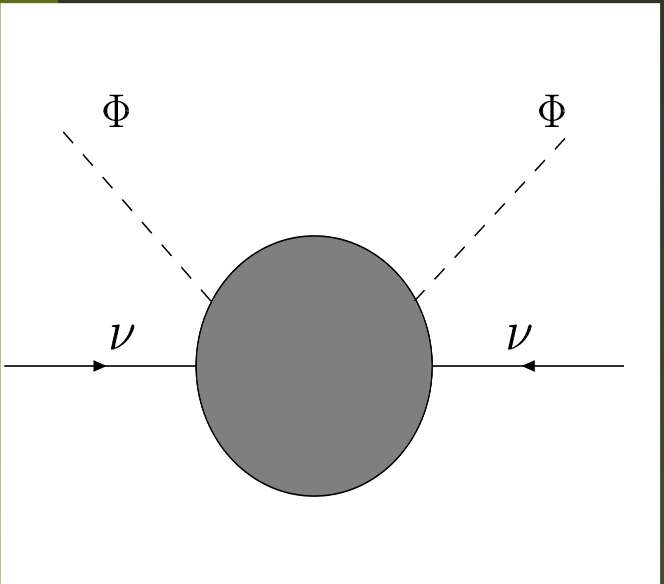


- most basic nu-mass definition

Weinberg PRD22 (1980) 1694

- unknown scale

the origin of neutrino mass

- 

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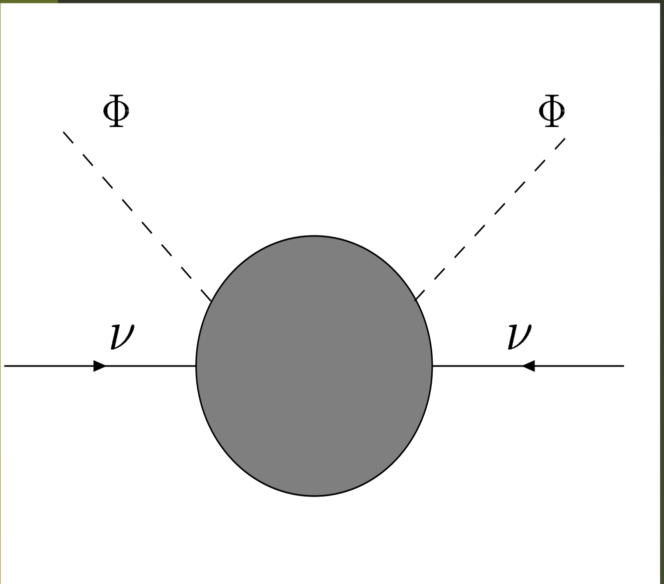
- unknown scale
- unknown flavour structure

the origin of neutrino mass

- 

  most basic nu-mass definition

  Weinberg PRD22 (1980) 1694

- unknown scale
- unknown flavour structure
- unknown mechanism

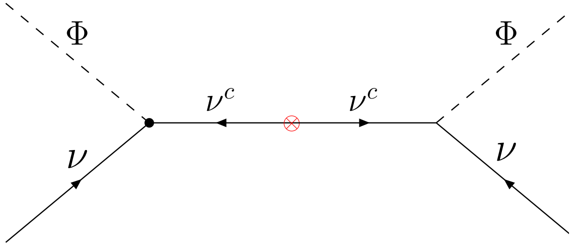
many pathways

The SEESAW PARADIGM

Minkowski 77, GRS-Y 79, Schechter, Valle 80 & 82, Mohapatra, Senjanovic 80, Lazarides, Shafi, Wetterich

nu-masses follow from

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

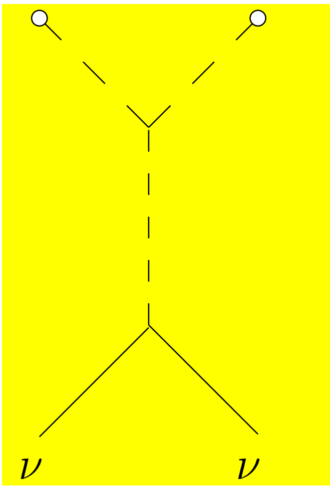


$$\begin{pmatrix} M_L & D \\ D^T & M_R \end{pmatrix}$$

first gives $M_{\nu\,\mathrm{eff}} \simeq -D M_R^{-1} D^T$

both suppressed by new scale

simplest seesaw possibly out ...



thermal leptogenesis

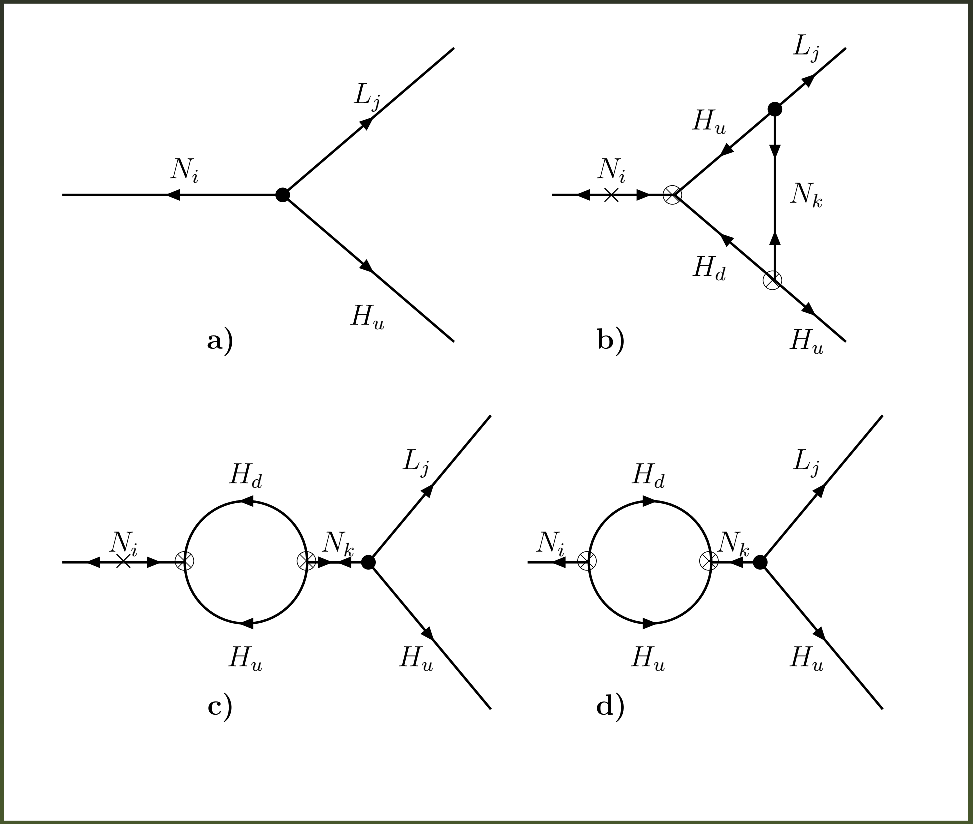
seesaw offers a way to generate cosmic baryon asymmetry from out-of-equilibrium decay of heavy singlet neutrinos

Fukugita, Yanagida 86

simplest (type-I) supersymmetric seesaw requires the lightest of the three right-handed neutrinos $\gtrsim 10^9$ GeV Their thermal production requires very high reheating temperatures

$\rightarrow$ gravitino crisis

tiny RPV $\lambda_i \hat{N}_i \hat{H}_u \hat{H}_d$ helps

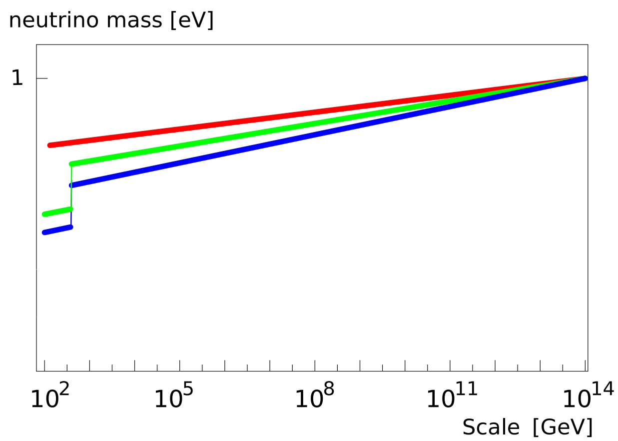


Farzan & Valle PRL 96 (2006) 011601

SEESAW UNIFICATION AT HIGH SCALE

neutrino masses unify as they run up

Chankowski et al PRL86 (2001) 3488



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

Hirsch et al, PRD69 (2004) 093006

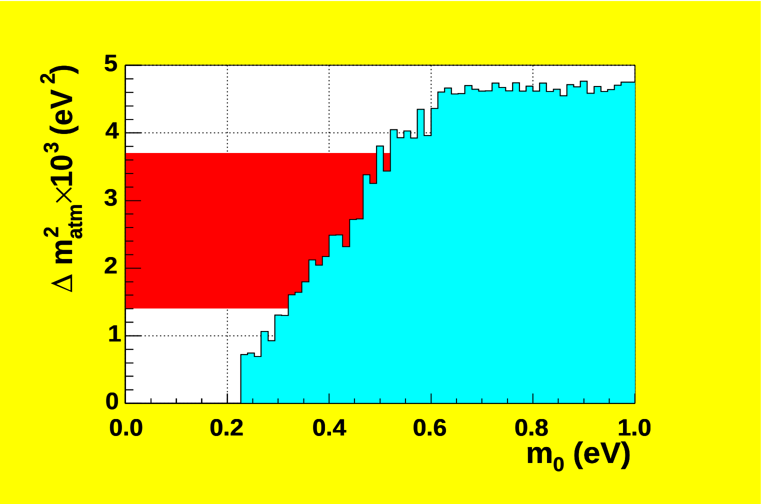
$\theta_{23} = \pi/4$; $\theta_{13} = 0$; θ_{12} large wrt Cabibbo

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

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

minimal nu-mass $m \gtrsim 0.3$ eV

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



light slepton

UNIFIED SEESAW w/ LOW SCALE

$$\mathrm{M}_{\nu\nu^c\mathrm{S}} = \begin{pmatrix} 0 & Y v_u & F v_L \\ Y^T v_u & 0 & \tilde{F} v_R \\ F^T v_L & \tilde{F}^T v_R & 0 \end{pmatrix}$$

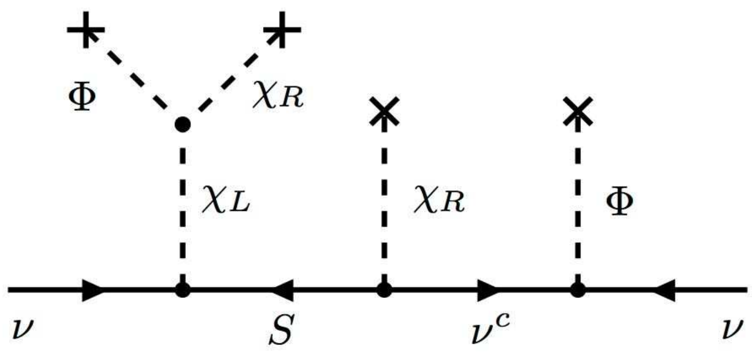
$$\mathrm{M}_{\nu-\mathrm{eff}} \simeq \frac{\rho v^2}{M_X}\left[Y(F\tilde{F}^{-1})^T + \mathrm{tr}\right]$$

Malinsky, Romao, JV, PRL95 (2005) 161801

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

Albright & Barr, Fukuyama, ... 2005

SUSY SO(10) with low B-L scale



$\mathrm{SO}(10)$

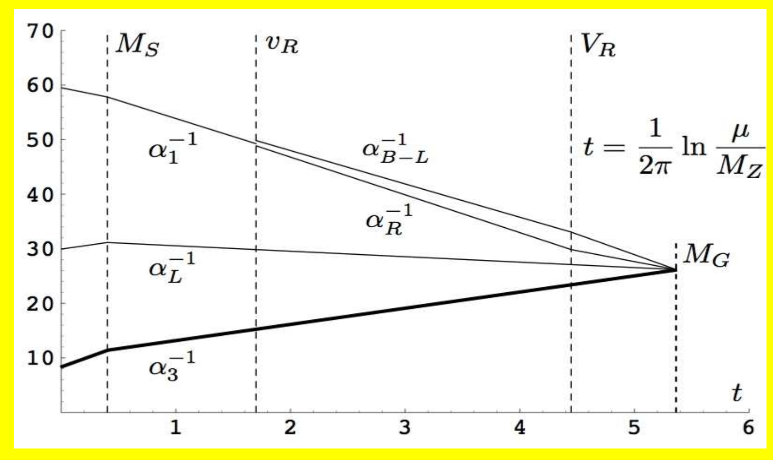
$\xrightarrow[\mathbf{V_X}]{210,45}$ $\mathrm{SU}(3) \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}} \otimes \mathrm{U}(1)_{\mathrm{B-L}}$

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

$\xrightarrow[\mathbf{v_R}]{16\overline{16}}$ $\mathrm{SU}(3) \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{\mathrm{Y}}$

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

$\mathrm{v}_R \ll V_R$



gauge couplings unify D_p **breaks at** $\mathrm{M_X}$

MODEL-INDEPENDENT SEESAW

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

- scale need not be high (any # of $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ singlets)
- doublet-singlet mixing implies effectively
  non-unitary lepton mixing matrix K_L
- seesaw mixing matrix contains
  far more angles θ_{ij} and phases ϕ_{ij} than for quarks
  (i) Majorana phases
  (ii) isodoublet-isosinglet neutrino mixings
- charged and neutral currents may produce sizeable gauge-induced NSI
- The (3, 1) model as basis for hybrid models of nu-mass

SEESAW and LFV

missing partner
or inverse seesaw
Mohapatra & Valle 86

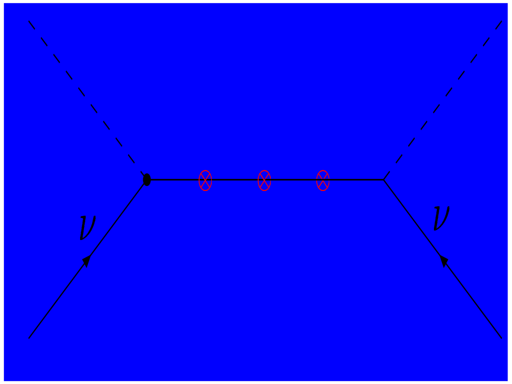
$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix}$$

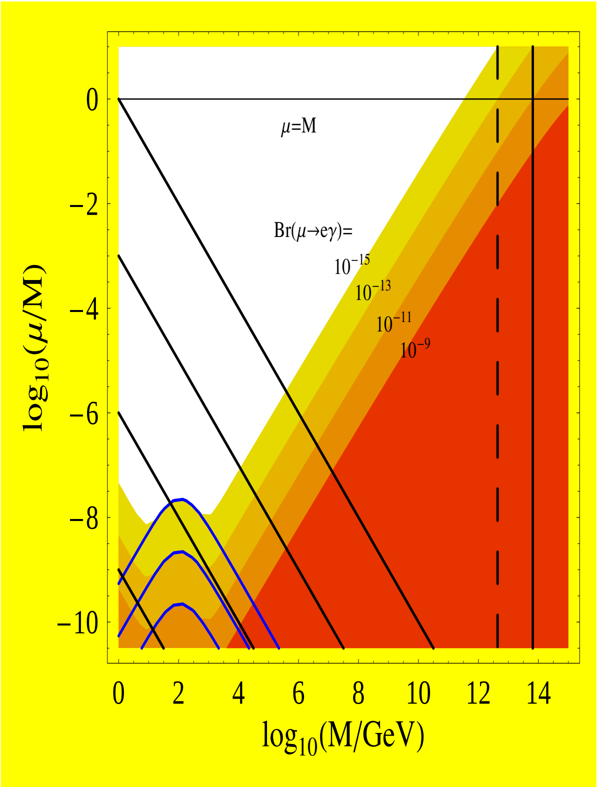
LFV & CPV

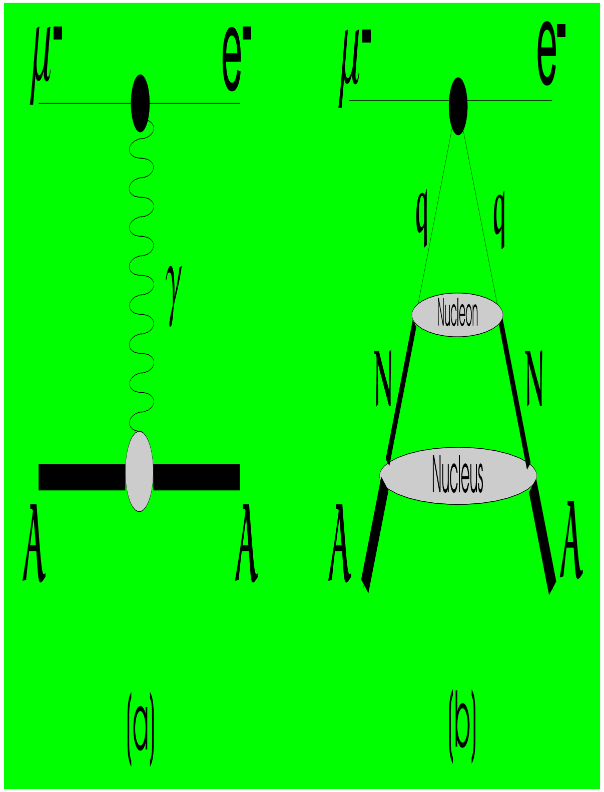
(even as $m_\nu \to 0$)

NHL exchange

SUSY loops







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

SUSY ORIGIN OF NU-MASS

spontaneous RPV

singlet sneutrino vev

Masiero and JV, PLB251 (1990) 273

→ effective bilinear RPV

NU-MASSES FROM LOW–ENDERGY SUSY?

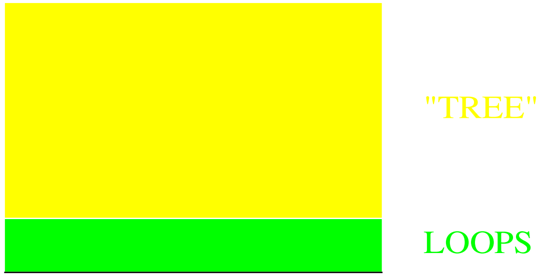
- **weak-scale seesaw atm scale**

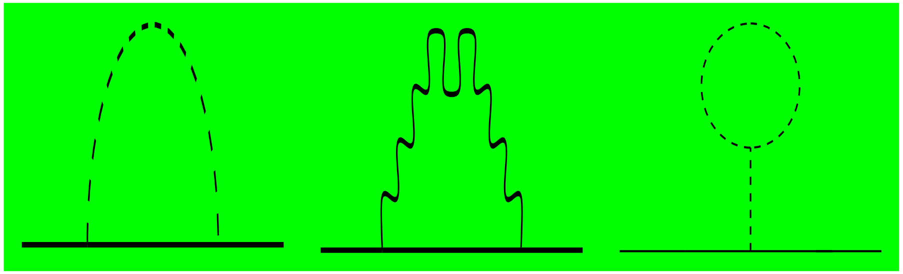
for a review see M. Hirsch, JV, NJP 6 (2004) 76

NU-MASSES FROM LOW–ENERGY SUSY?

- **weak-scale seesaw atm scale**

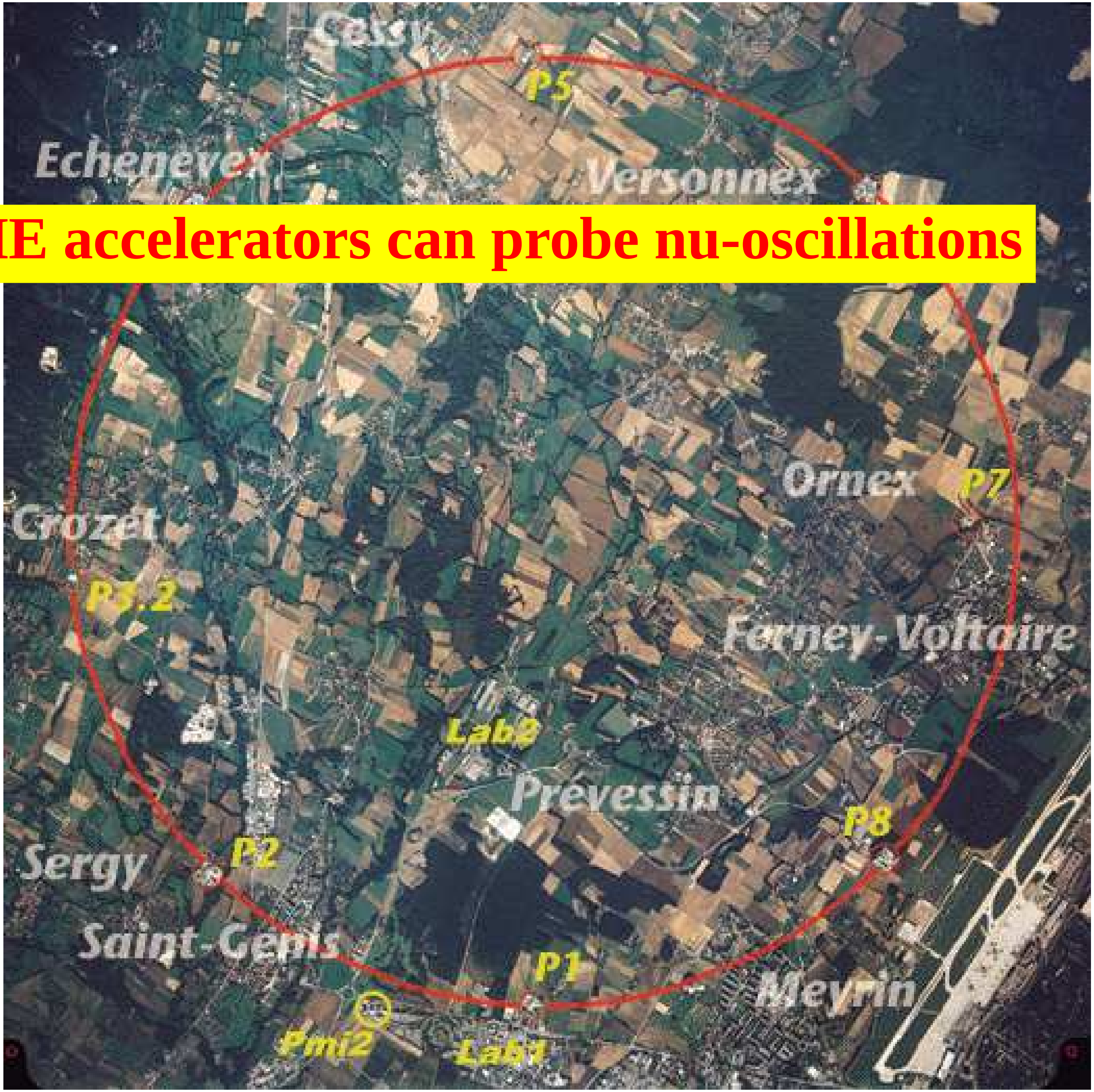
- **radiative solar mass scale**





for a review see M. Hirsch, JV, NJP 6 (2004) 76

HE accelerators can probe nu-oscillations

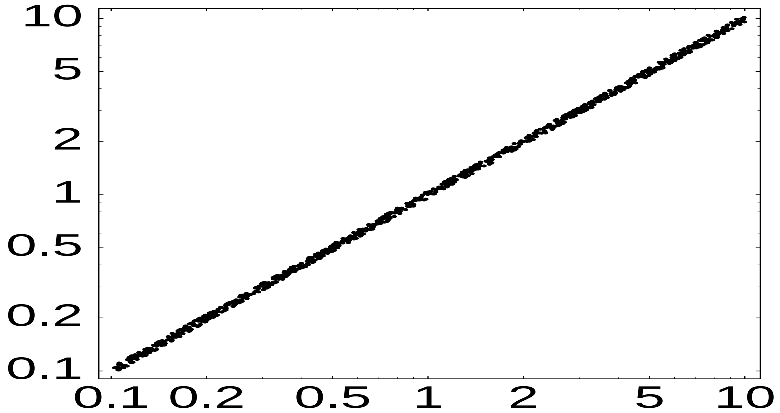


TESTING NU-OSCILLATIONS at LHC/ILC

- LSP decays lead to D-V events   de Campos et al, PRD71 (2005) 075001

TESTING NU-OSCILLATIONS at LHC/ILC

- **LSP decays lead to D-V events** de Campos et al, PRD71 (2005) 075001
- **LSP decay properties correlate with nu-mixing angles**



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

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

LHC will provide enough luminosity for detailed correlation studies

TESTING NU-OSCILLATIONS at LHC/ILC

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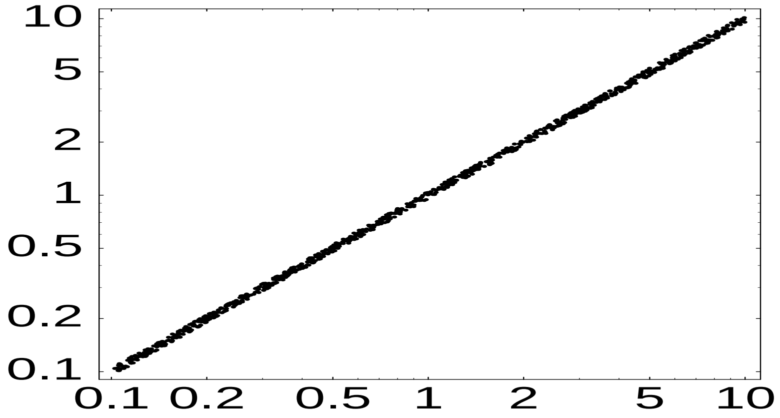

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smoking gun test of SUSY origin of nu-mass — Porod et al PRD63 (2001) 115004

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

- irrespective of the nature of the LSP

stop Restrepo et al, PRD64 (2001) 055011

stau Hirsch et al, PRD66 (2002) 095006

other LSPs D68 (2003) 115007

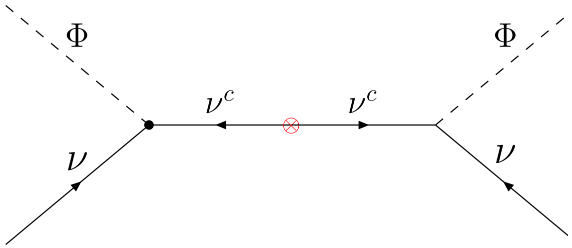
END

GLOBAL REALIZATION OF SEESAW

neutrino mass follows in the same way

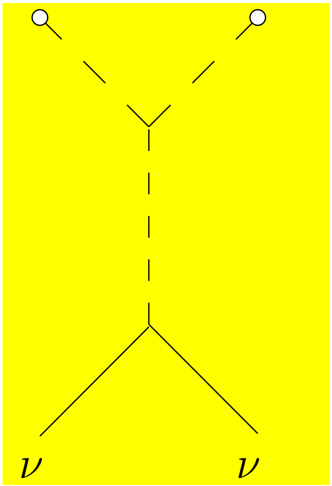
B-L violation is spont $\longrightarrow$ majoron

Chikashige, Mohapatra, Peccei



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

Schechter, JV, PRD25, 774 (1982)



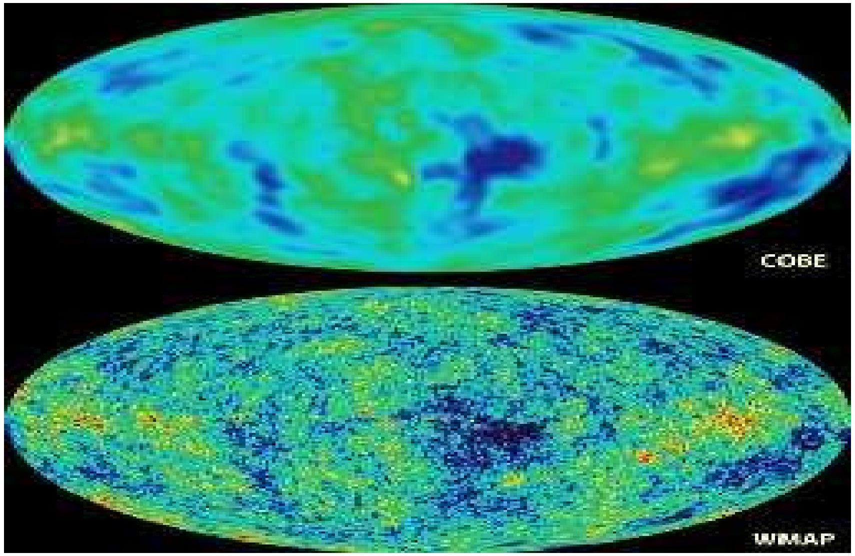
detectable at SNO with a future SNova

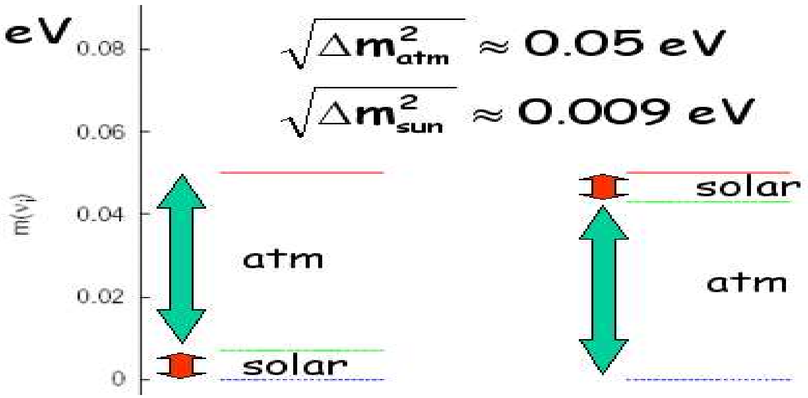
Kachelriess et al PRD62 (2000) 023004

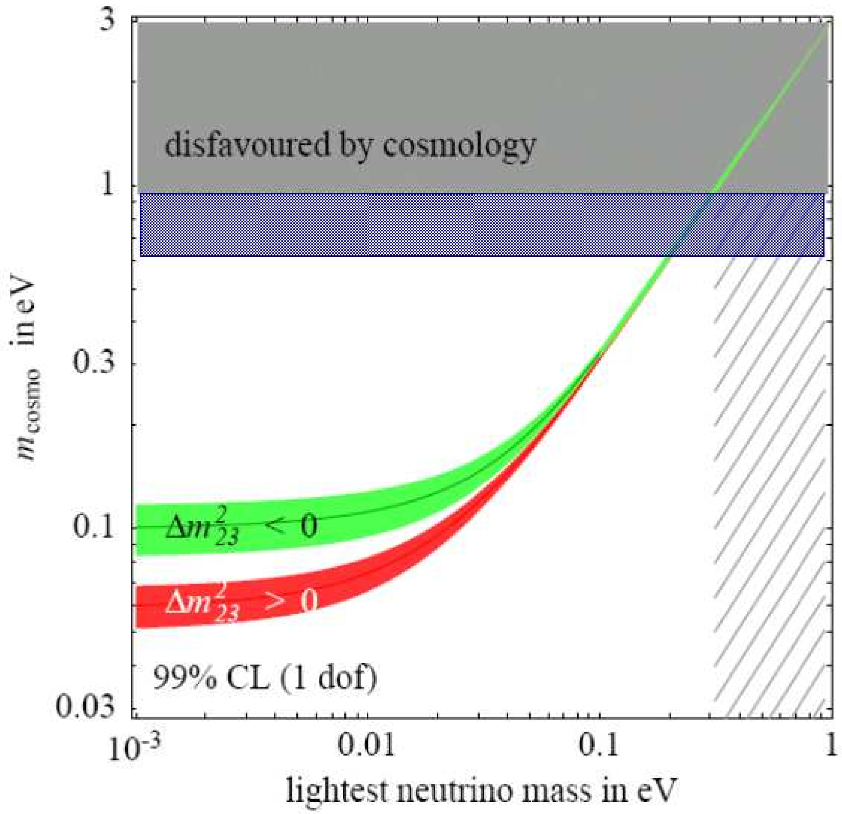
open questions

- what is the absolute scale of neutrino mass?
- are neutrinos Dirac or Majorana?
- is CP violated in the lepton sector?
  does it produce the cosmic baryon asymmetry?
- what is the origin of neutrino mass?
  can it be tested at accelerators?
- can neutrinos have non-standard interactions?
- can neutrinos probe the cosmos?
- can neutrinos probe our earth?

CMB and LSS bounds on absolute m-nu scale







- Pastor et al PRD69 (2004) 123007

latest fit of oscillation parameters

M. Maltoni et al

GlobalView

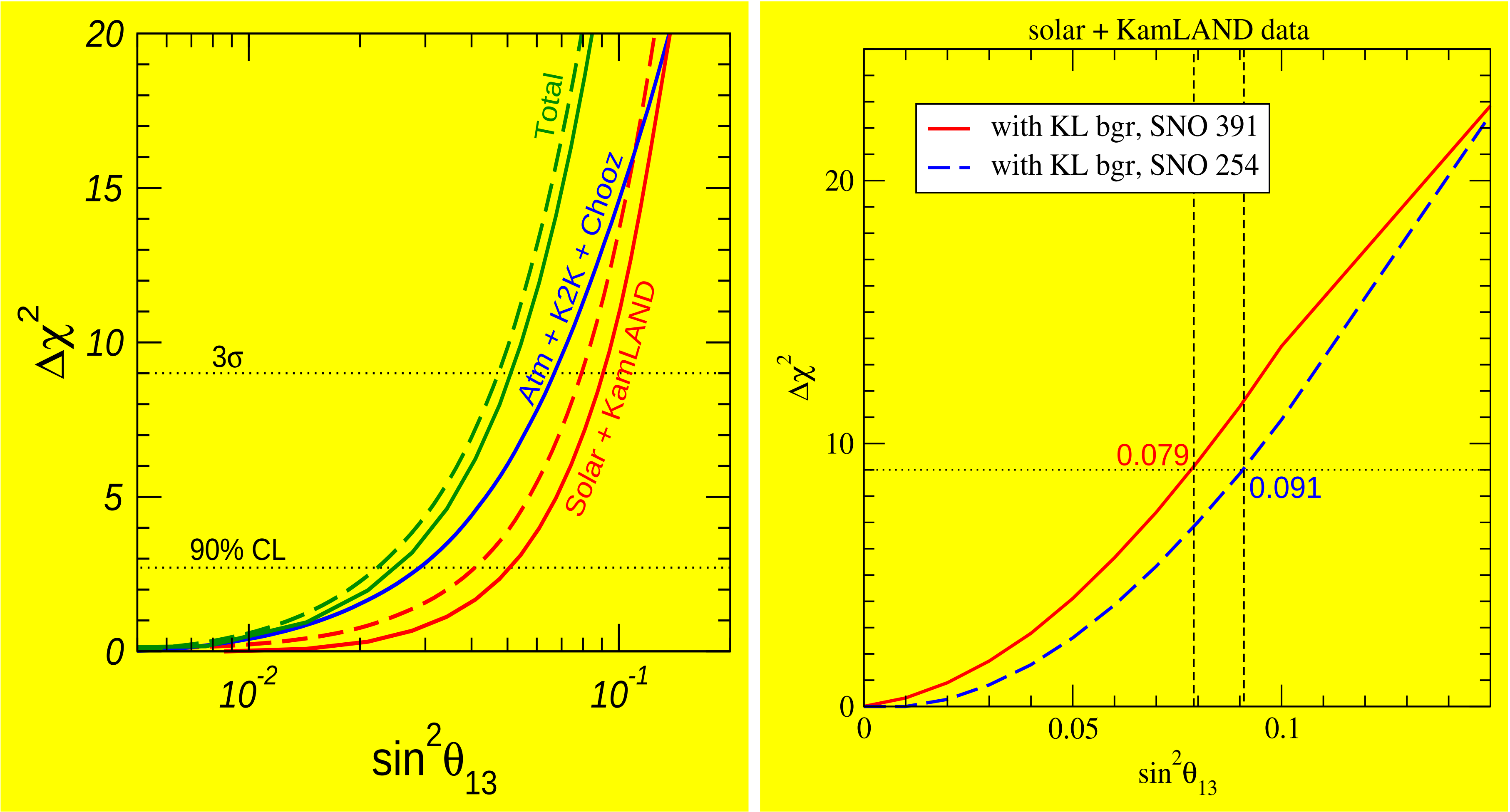
parameter	best fit	2σ	3σ	4σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.9	7.3–8.5	7.1–8.9	6.8–9.3
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.2	1.7–2.9	1.4–3.3	1.1–3.7
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38	0.21–0.41
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68	0.30–0.72
$\sin^2\theta_{13}$	0.00	≤ 0.031	≤ 0.051	≤ 0.073

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.

what constrains θ_{13}

M. Maltoni et al, NJP 6 (2004) 122 = hep-ph 0405172

t13

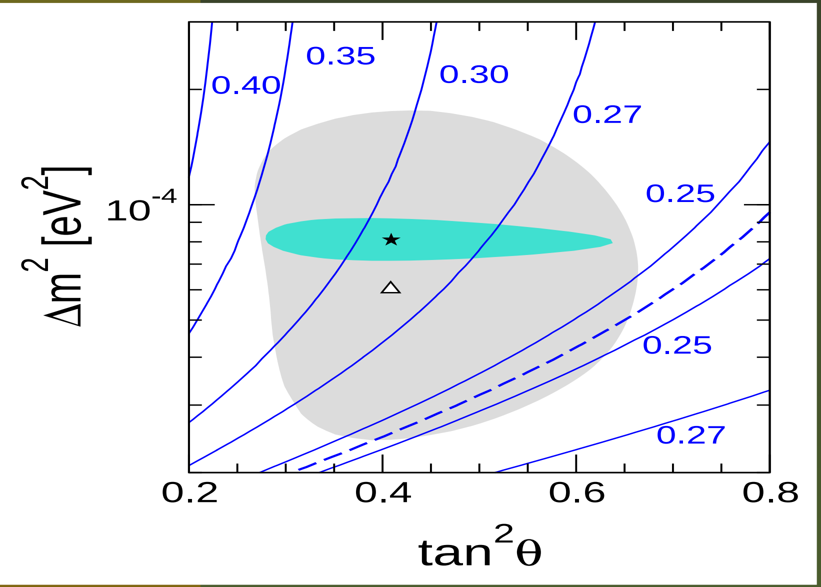


weak interactions at low energies

two tasks for Borexino?

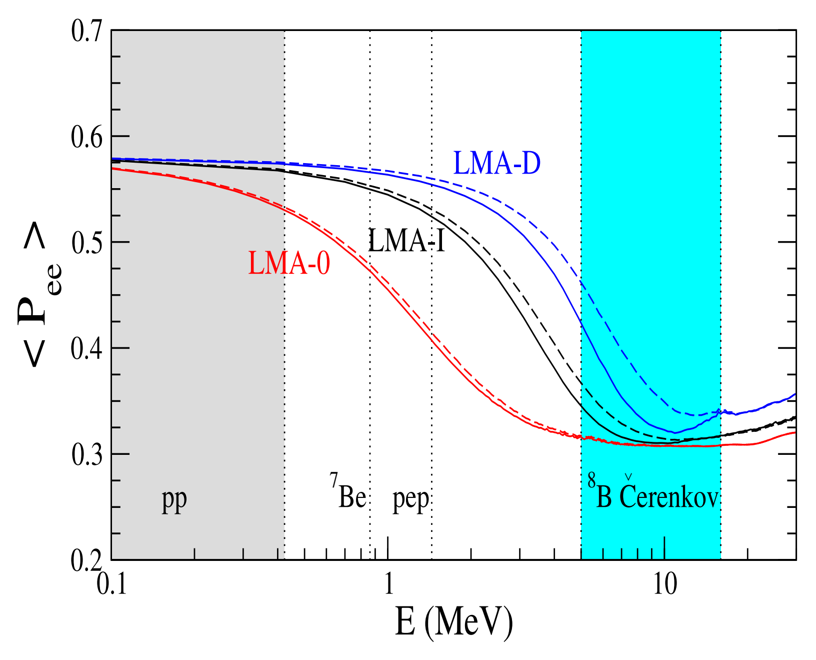
- probe nu-magn moment

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



- probe NSI

Miranda et al hep-ph/0406280

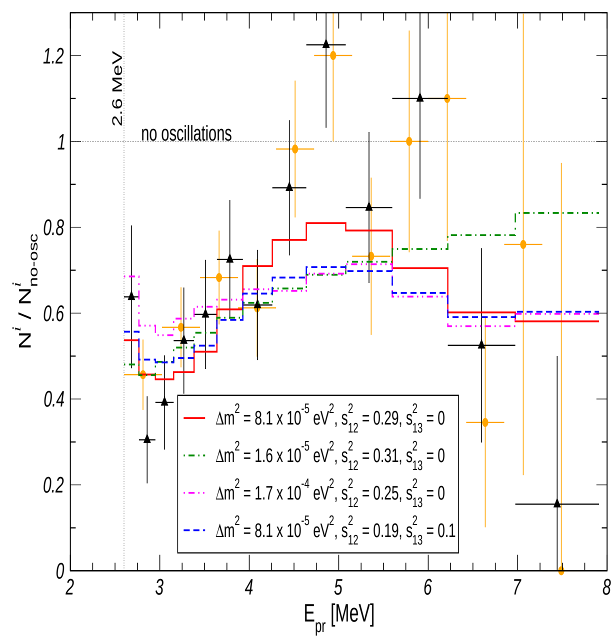


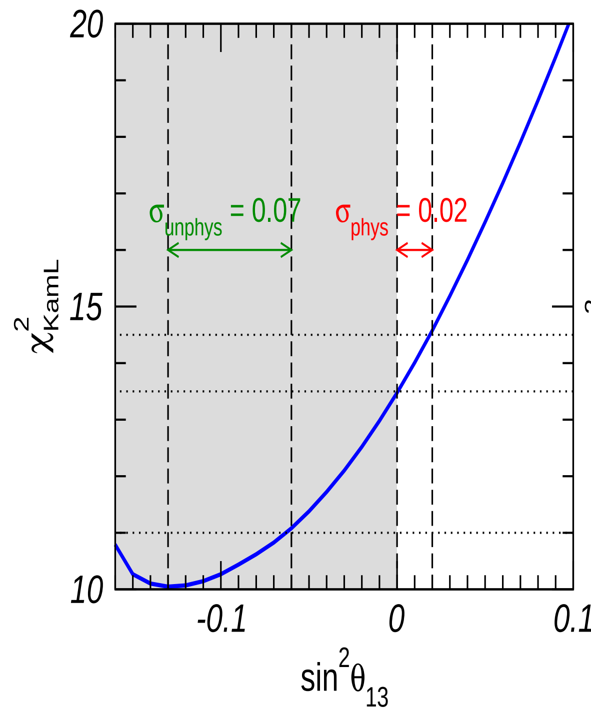
NSI-frag

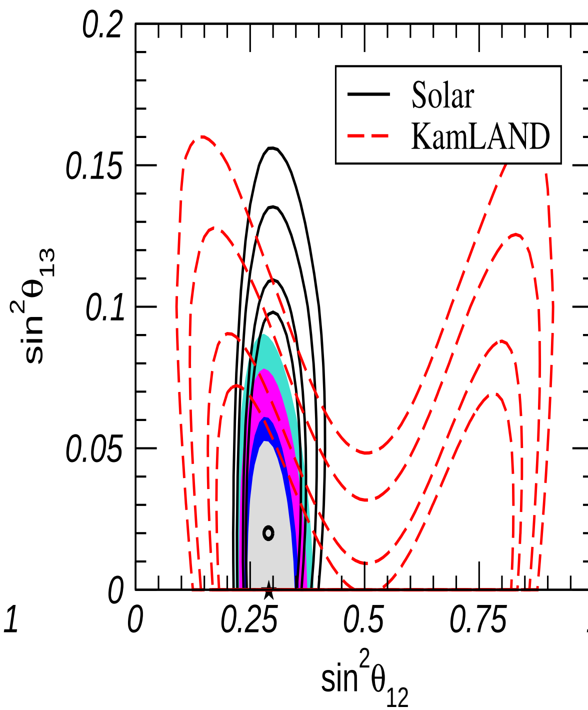
why KamLAND04 improves θ_{13}

- strong spectrum distortion

favors unphysical θ_{13} values







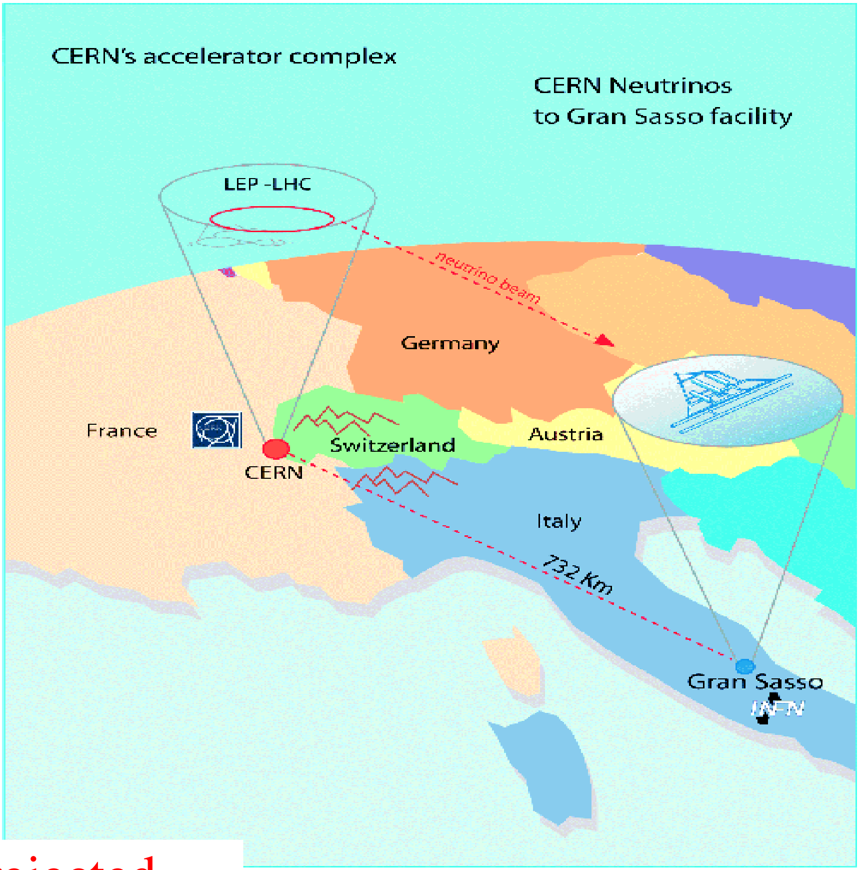
combination with solar further improves ...

Neutrino Factories

θ_{13} NSI

double price for probing CPV

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



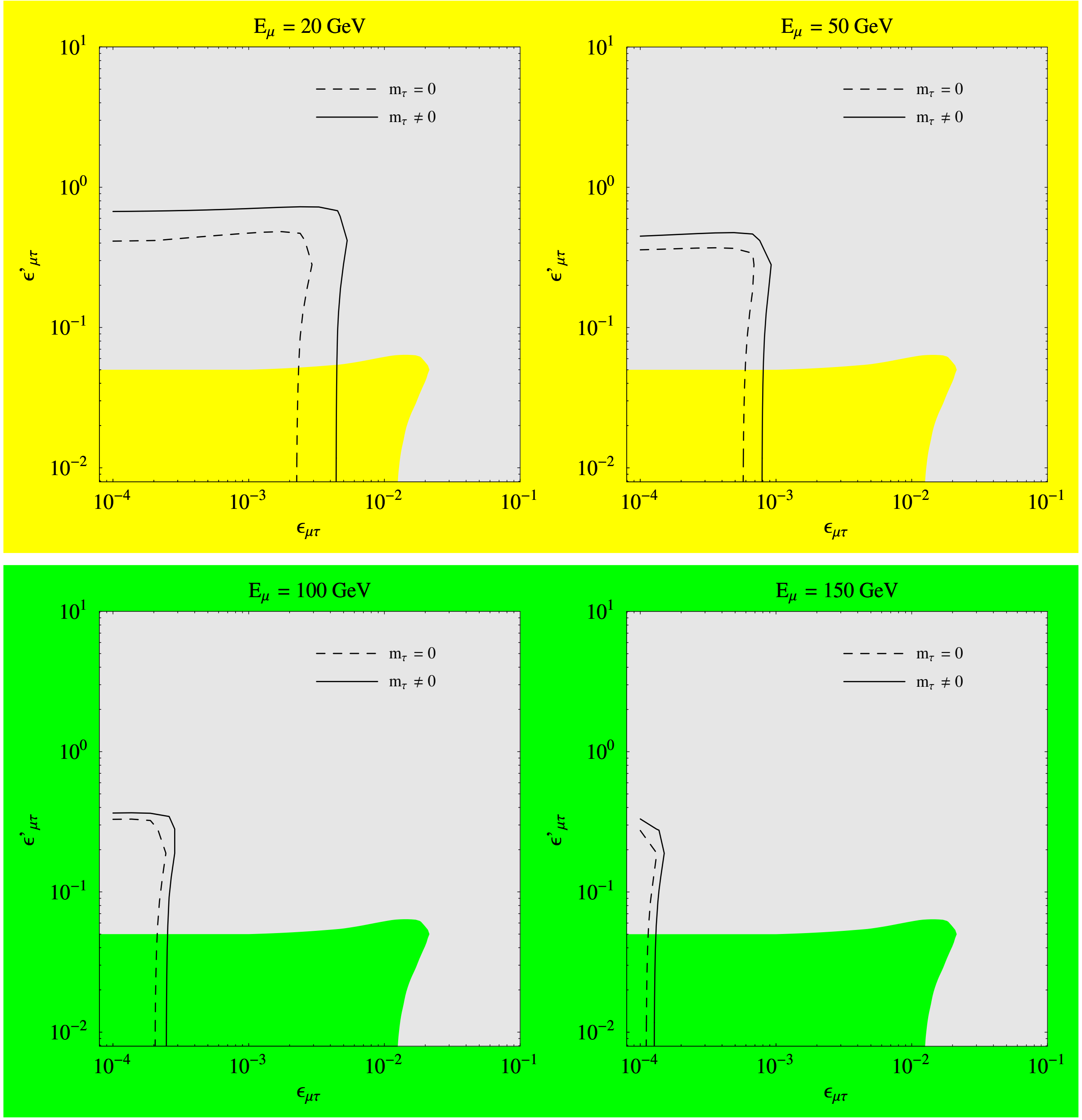
Non-Standard nu-Intercations (NSI) must be rejected ...

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

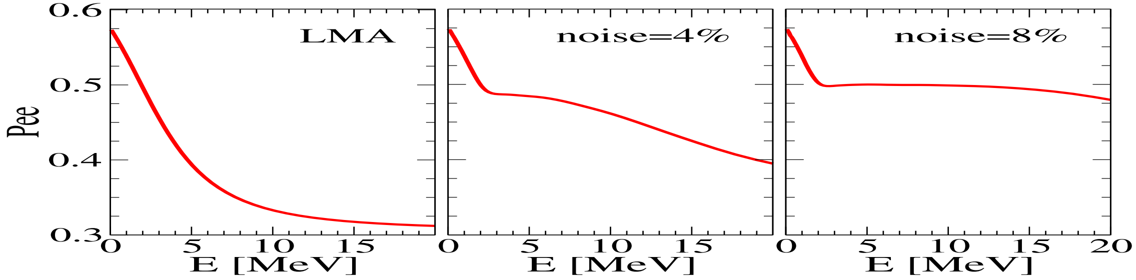
Nunokawa et al NPB472 (1996) 495

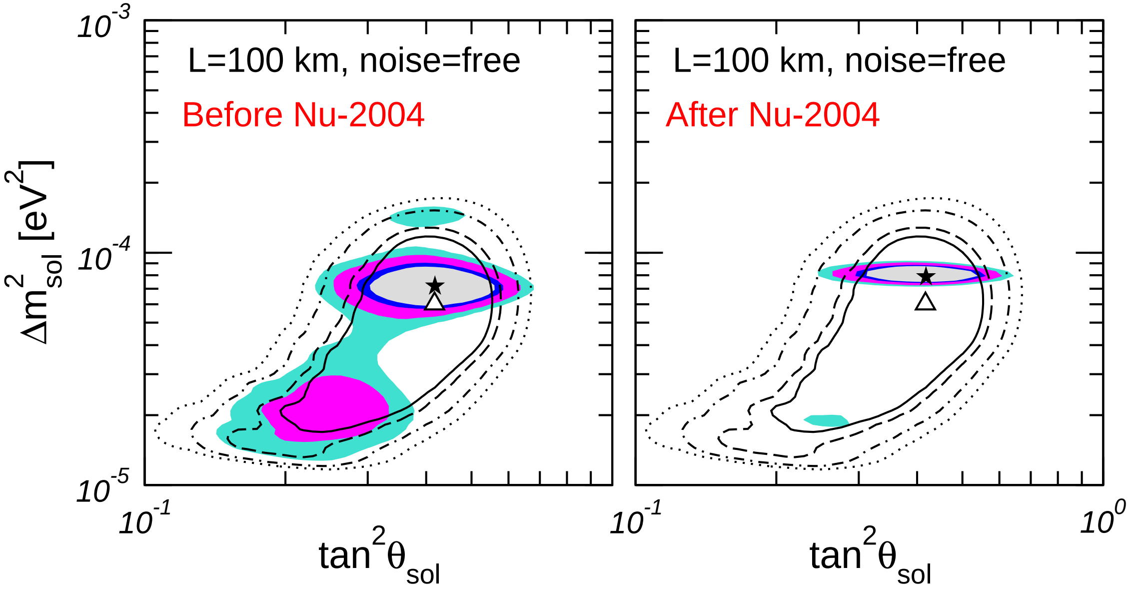
Burgess et al 97

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

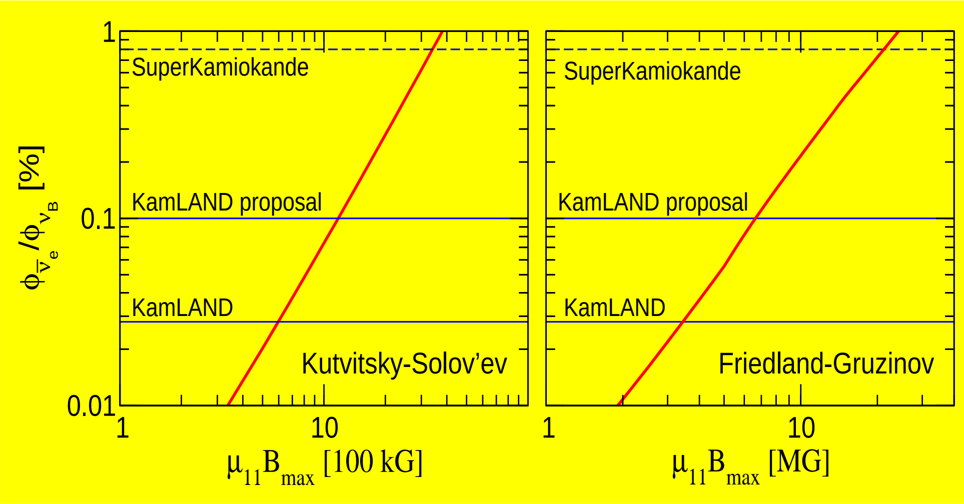
anti-nu limit implies robustness

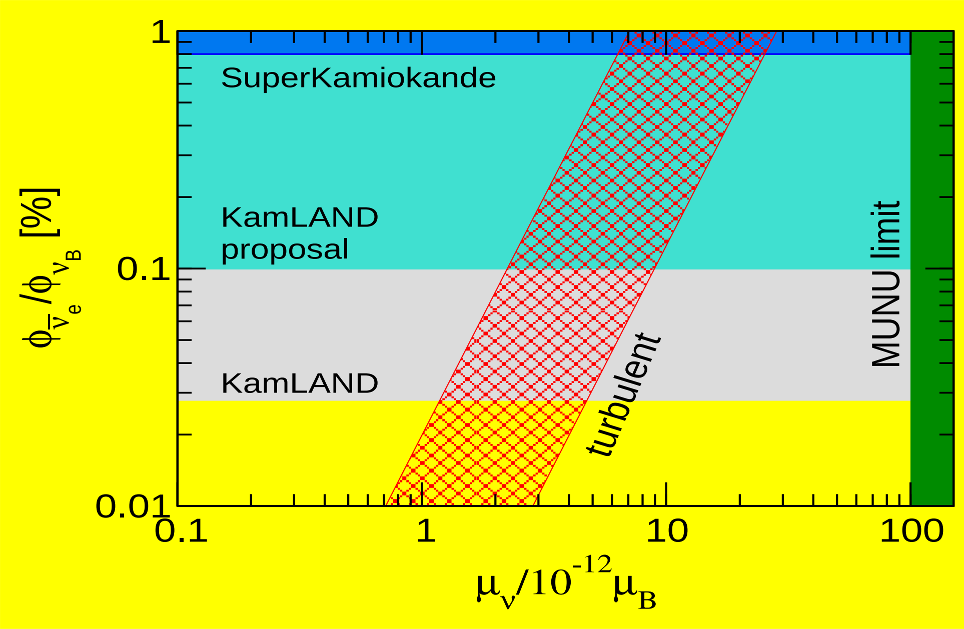
regular versus random mag field

isolating μ_ν from $\mu_\nu B$?

Miranda et al PRL93 (2004) 051304

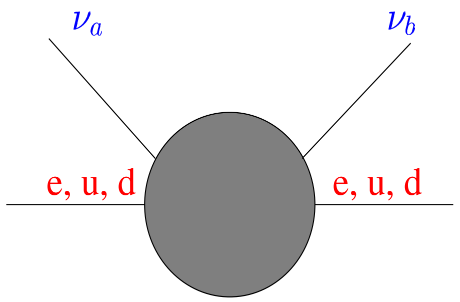
& PRD70 (2004) 113002





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, 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?

day-night effect with 3 neutrinos

Akhmedov, Tortola, JV, JHEP05 (2004) 057