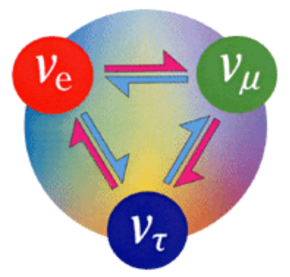
# Neutrino oscillations and beyond

**J W F Valle**
**IFIC/CSIC – U Valencia**

**http://astroparticles.es/**

Mini Workshop on Neutrinos, IPMU, Nov 8-11, 2010

# LEPTON MIXING MATRIX



$$K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$$

Schechter & JV PRD22 (1980) 2227, PRD23 (1981) 1666
PDG

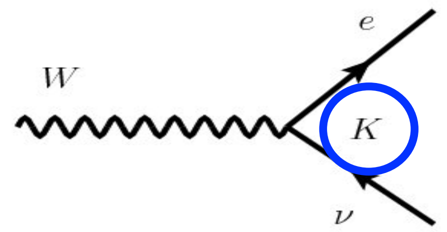
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & e^{i\phi_{23}} s_{23} \\ 0 & -e^{-i\phi_{23}} s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & e^{i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\phi_{13}} s_{13} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & e^{i\phi_{12}} s_{12} & 0 \\ -e^{-i\phi_{12}}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

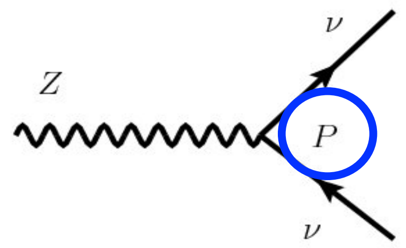
23=atm+acc

13=reactor + ..

12=solar+KL

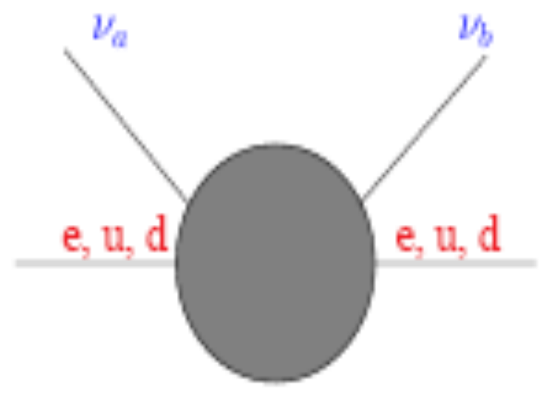
- Even in such simplest unitary form K differs from quark mixing matrix, with two extra (Majorana) phases





- Nontrivial structure of CC & NC in seesaw implies new phases & angles affecting neutrino propagation & inducing LFV

# NONSTANDARD NEUTRINO INTERACTIONS



## from non-trivial seesaw mixing matrix

Schechter & JV PRD22 (1980) 2227

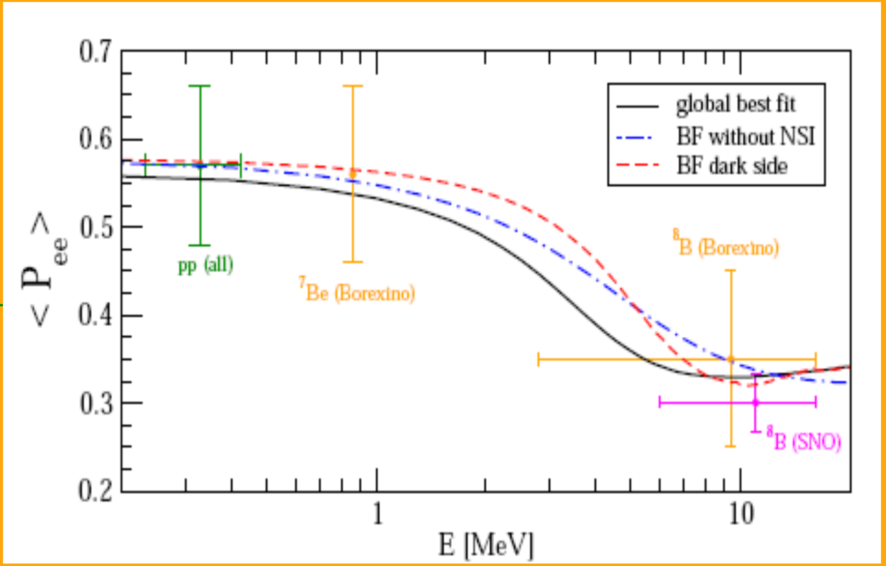
**effective non-unitarity affects propagation, source and detection**, e.g.

Resonant Oscillations Of Massless Neutrinos In Matter. Valle PLB199 (1987) 432

## NSI-OSCILLATION INTERPLAY

manifest @ Long-baseline studies

propagation

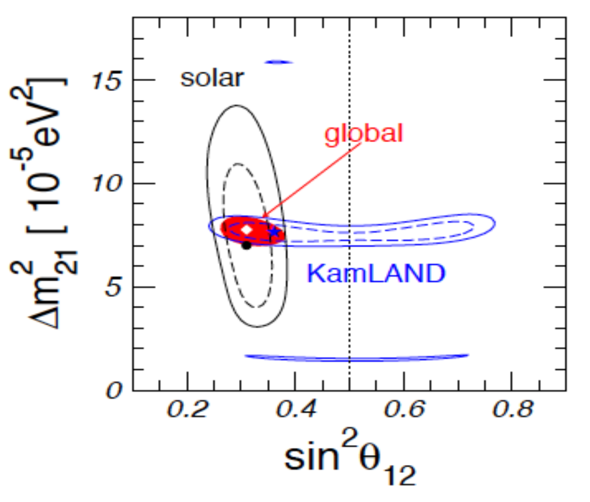


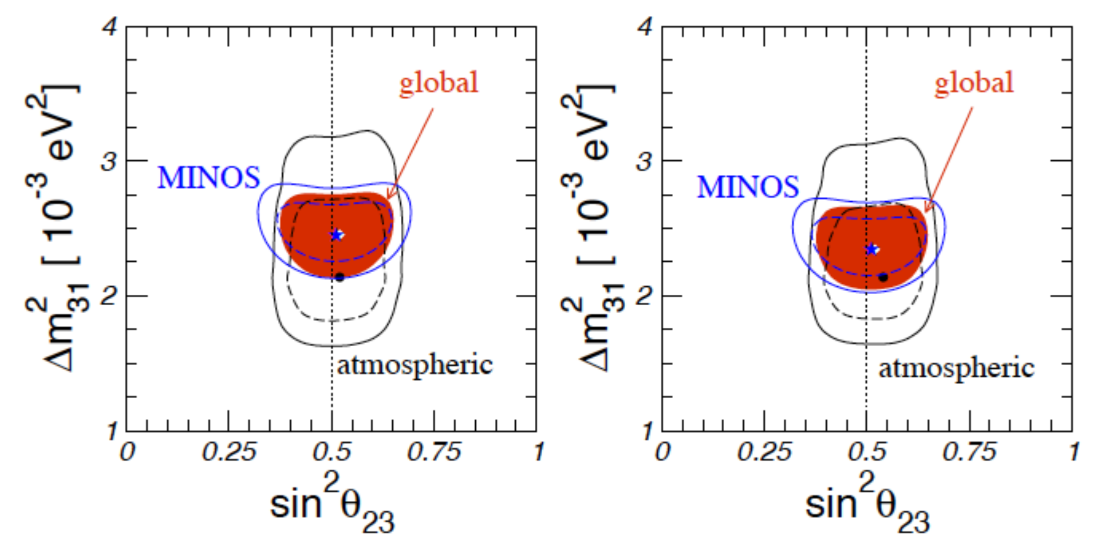
Fornengo et al, PRD65:013010,2002
Huber, Schwetz, JV PRL88:101804,2002
PRD66 013006, 2002
Davidson et al JHEP (2003) 0303:011
Barranco, et al , D73 (2006) 113001, D77 (2008) 093014
Abada, Biggio Bonnet, Gavela, Hambye PRD78
Esteban Huber JV PLB668:197201,2008
Gavela, Hernandez, Ota, Winter, PRD79
Escrihuela et al PRD80:105009,2009; Err-D80:129908,2009
Malinsky et el, arXiv:0905.2889 [hep-ph]
Bolaños et al PRD79 (2009) 113012
Kopp, Machado, Parke, arXiv:1009.0014

**IN ANALYSIS OF CURRENT OSCILLATION DATA WE NEGLECT NSI**

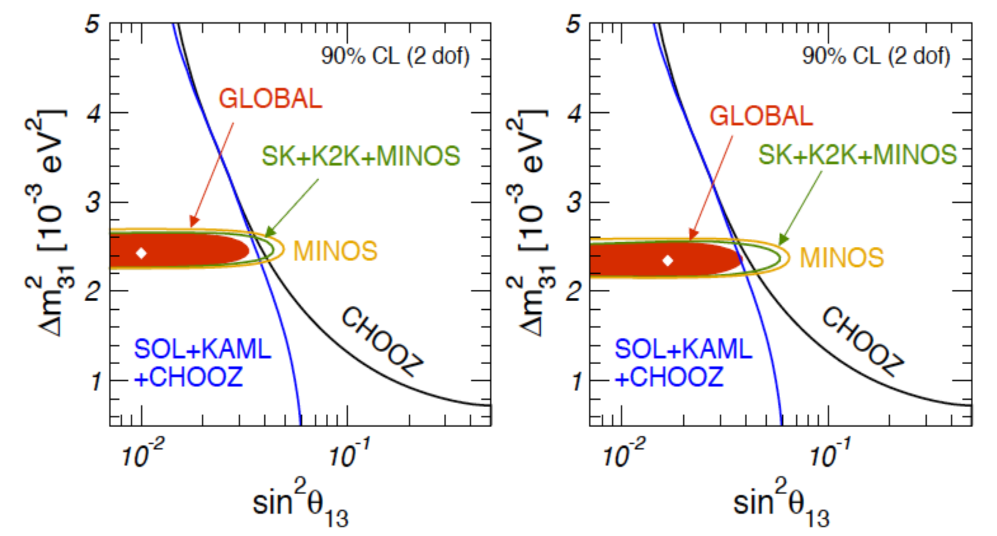
# NEUTRINO OSCILLATIONS STATUS @ NUFACT2010

Update of Schwetz et al, NJP 10 (2008) 113011





**Homestake, SAGE**
**GALLEX/GNO,**
**SK-III**
**SNO-leta, SSM**
**Borexino**
**KamLAND (180 Km)**



**… SK-III**

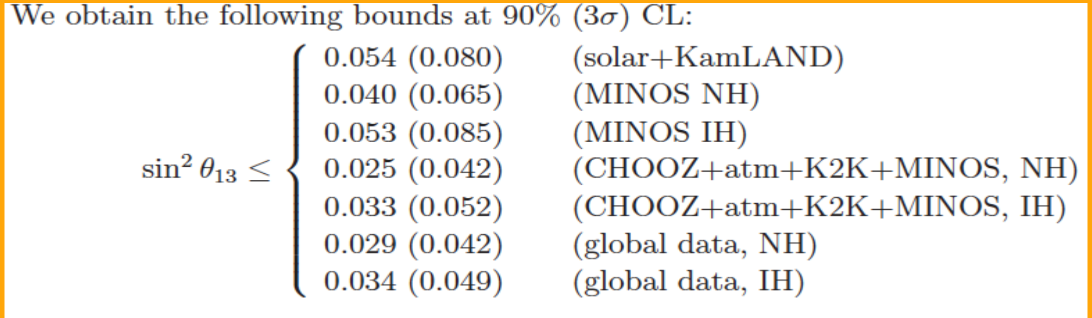
**thanks to SK … E. Kearns**

**K2K (250 Km)**
**MINOS latest**
**(735 Km)**

# UPDATED THETA13

## FUTURE

### Update of NJP 10 (2008) 113011

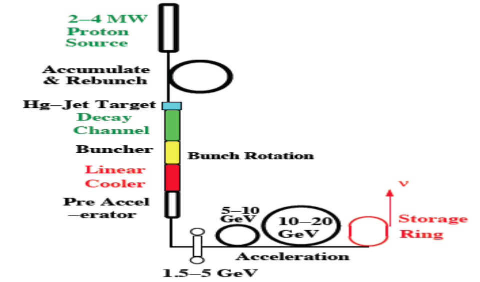


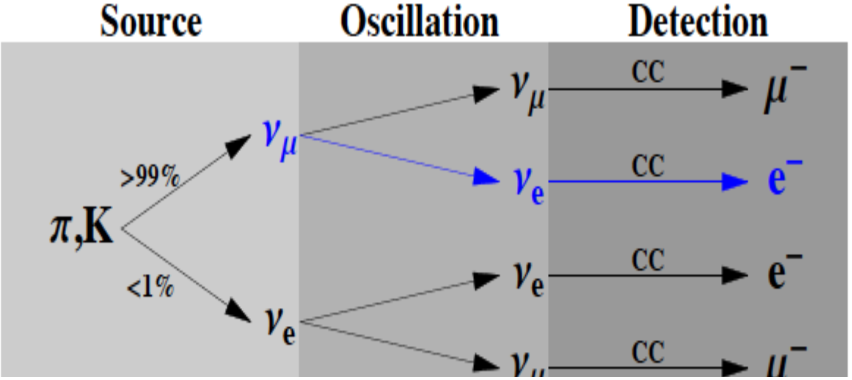
We obtain the following bounds at 90% ($3\sigma$) CL:

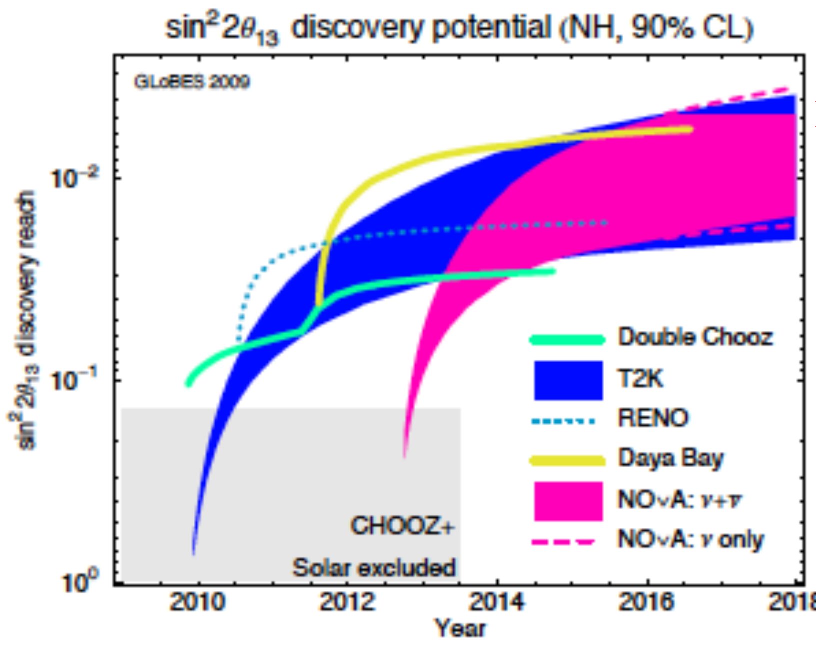
$$\sin^2\theta_{13} \le \begin{cases} 0.054\ (0.080) & \text{(solar+KamLAND)} \\ 0.040\ (0.065) & \text{(MINOS NH)} \\ 0.053\ (0.085) & \text{(MINOS IH)} \\ 0.025\ (0.042) & \text{(CHOOZ+atm+K2K+MINOS, NH)} \\ 0.033\ (0.052) & \text{(CHOOZ+atm+K2K+MINOS, IH)} \\ 0.029\ (0.042) & \text{(global data, NH)} \\ 0.034\ (0.049) & \text{(global data, IH)} \end{cases}$$

IH $\sin^2\theta_{13} = 0.017 \pm 0.010$

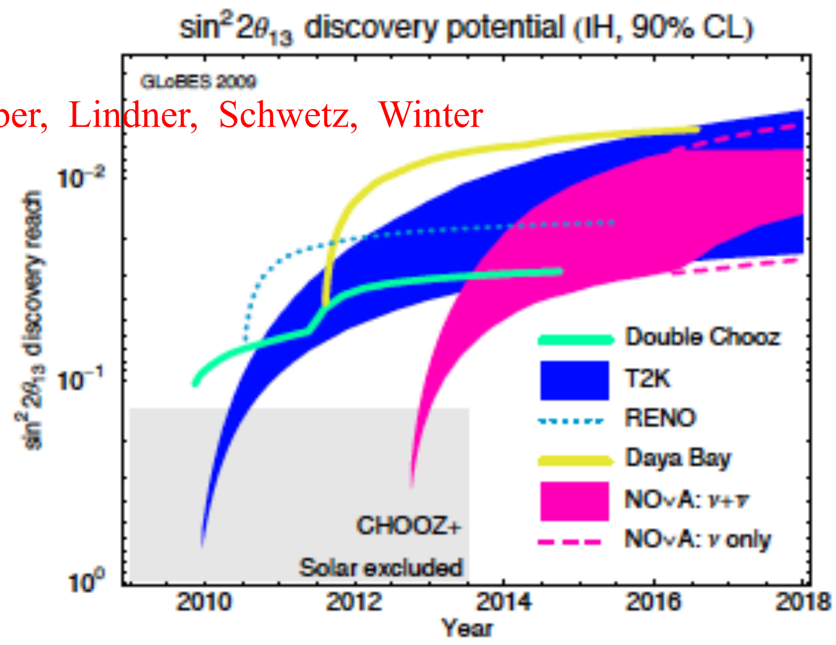
NH $\sin^2\theta_{13} = 0.011^{+0.011}_{-0.007}$







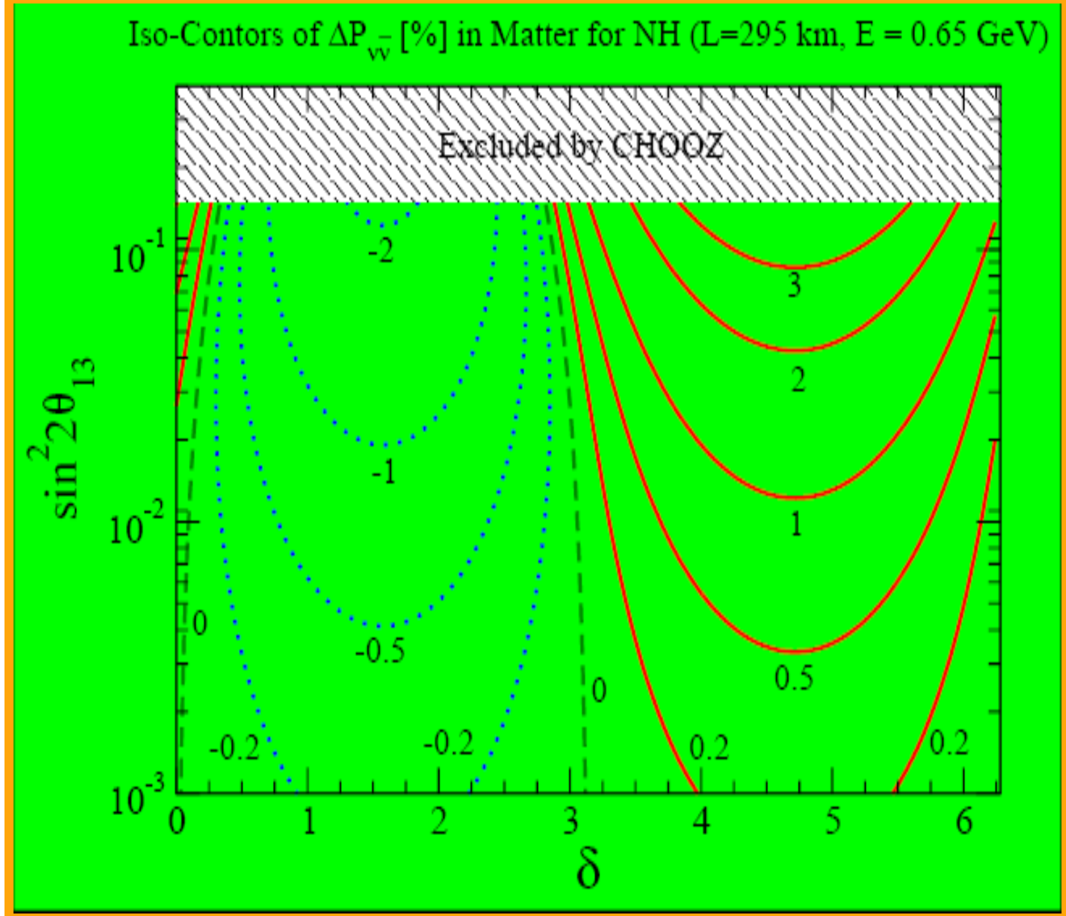
Huber, Lindner, Schwetz, Winter



# CPV & NU-OSCILLATIONS AT LONG BASELINES

**aymmetries at % level**

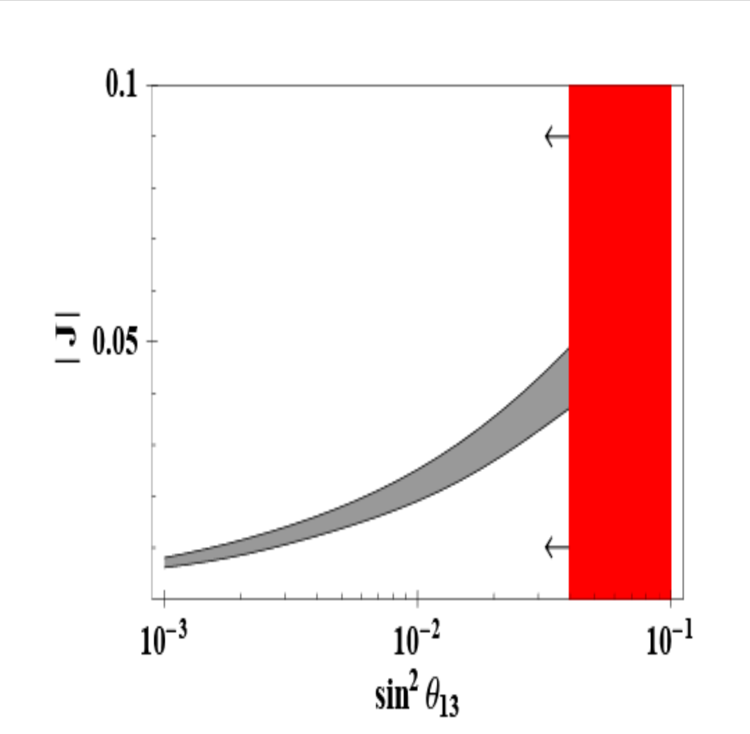
**maximal CPV**



**Nunokawa et al**
**Prog.Part.Nuc.Phys. 60 (2008) 338**

**ISS report S. King et al Rep. Prog. Phys.**

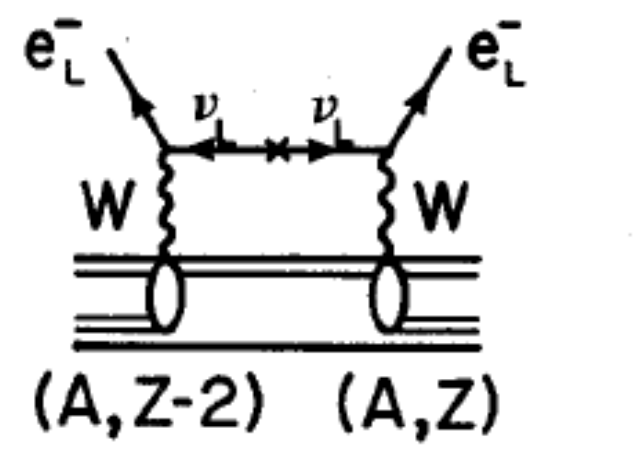
**Hirsch et al PRL99(2007)151802**

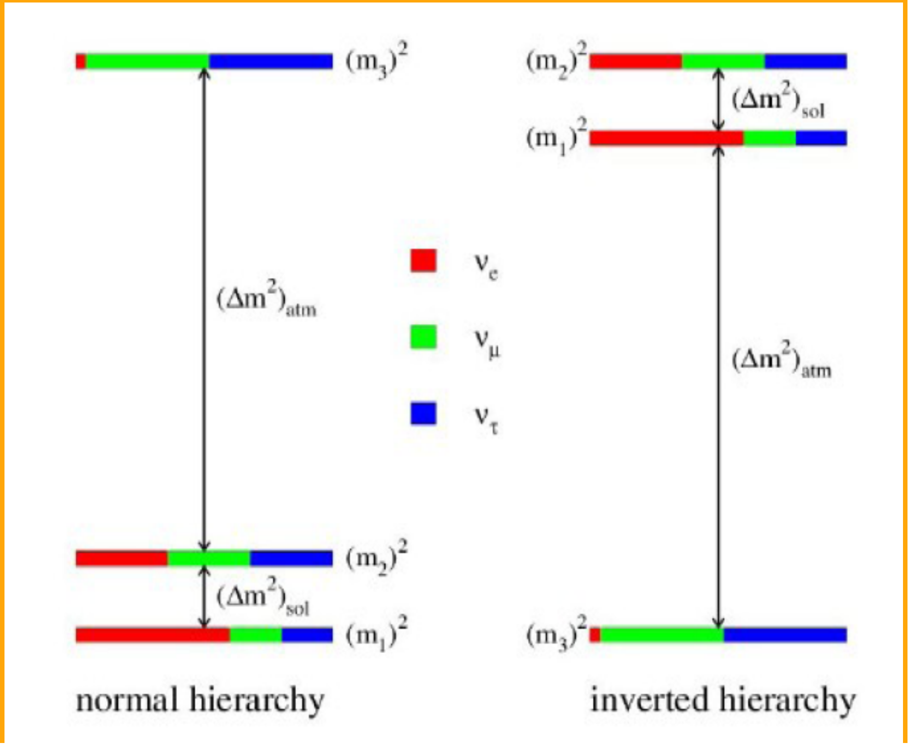


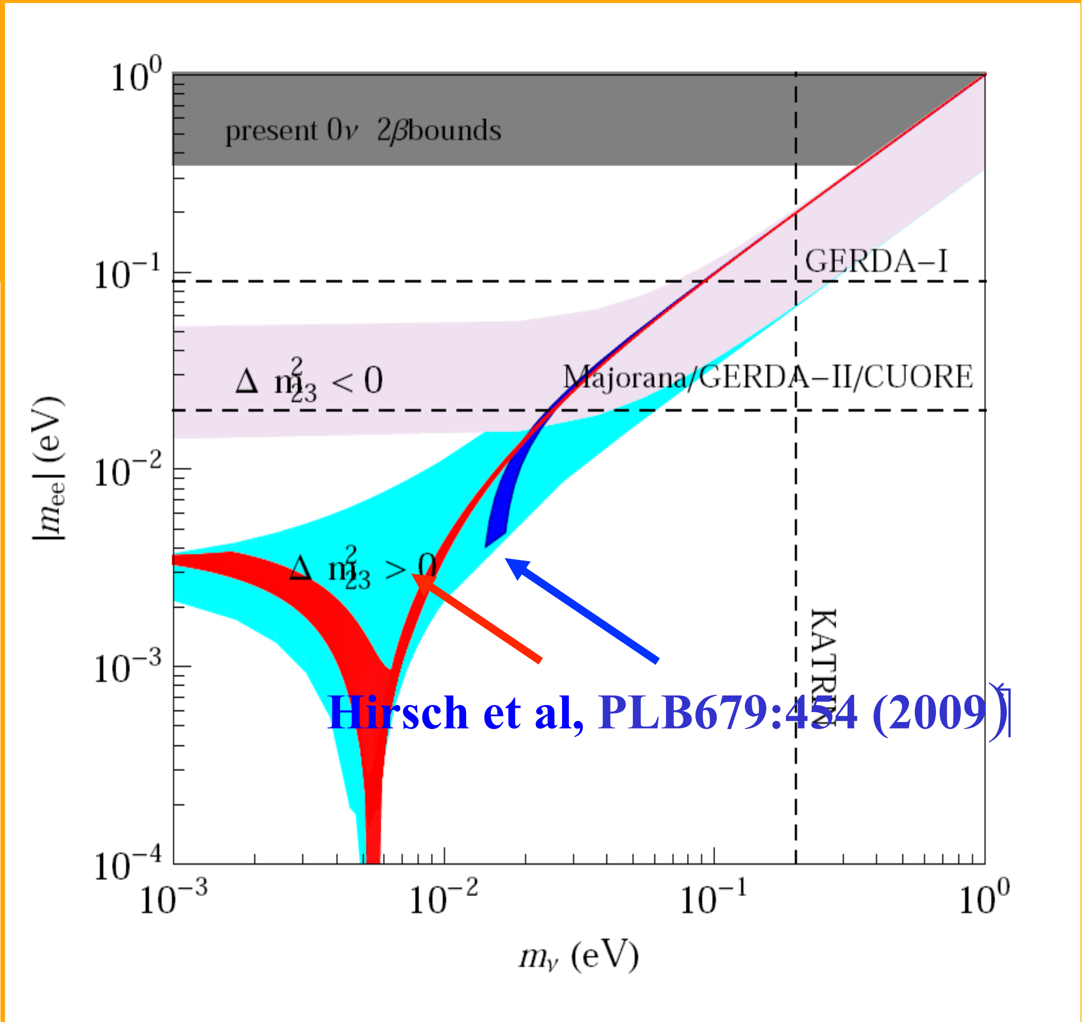
# TESTING NEUTRINO SPECTRA WITH DBD

## NH VERSUS IH

- **SBD & Cosmology …**
- **Flavor sensitivity**



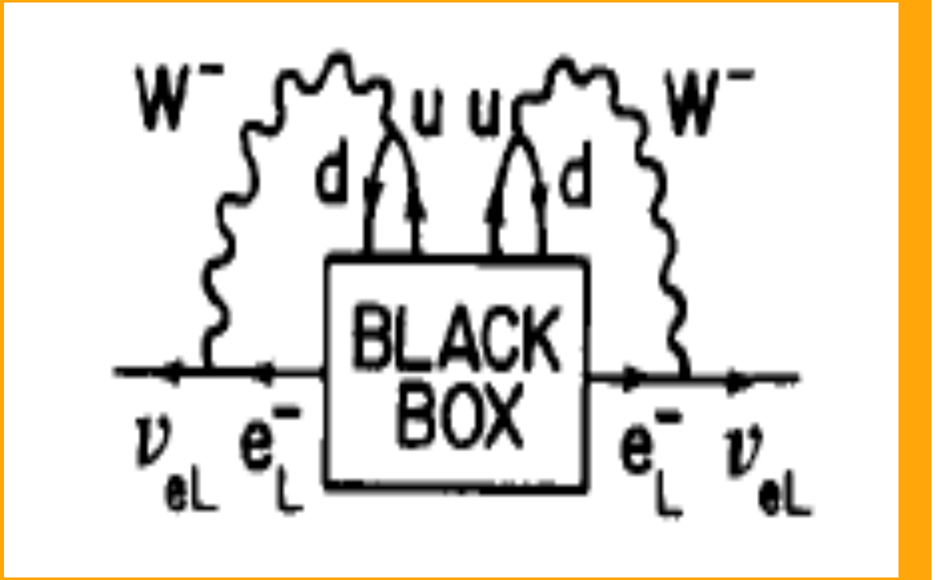




Hirsch et al, PLB679:454 (2009)

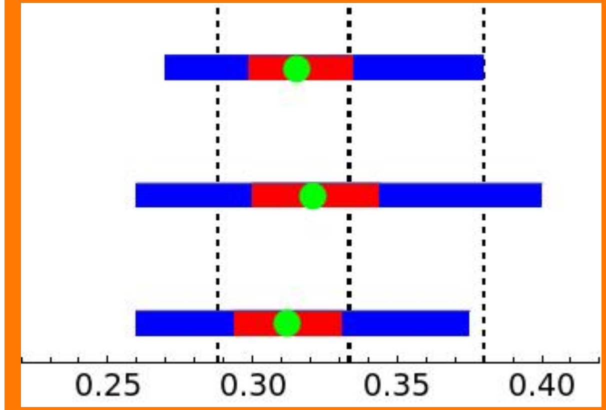
# NEUTRINOLESS DOUBLE BETA DECAY

0-nu DBD ⇄ majorana

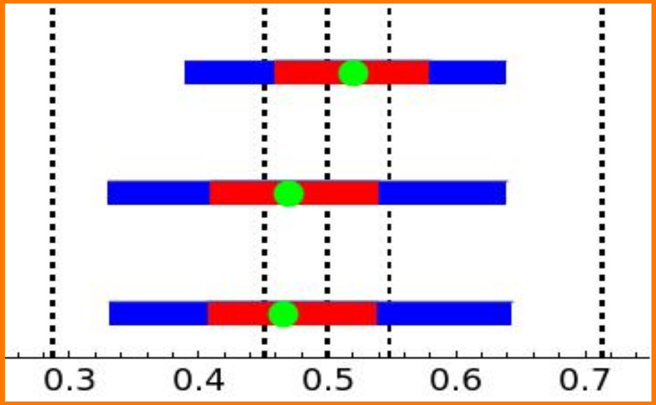


Schechter, JV PRD25 (1982) 2951

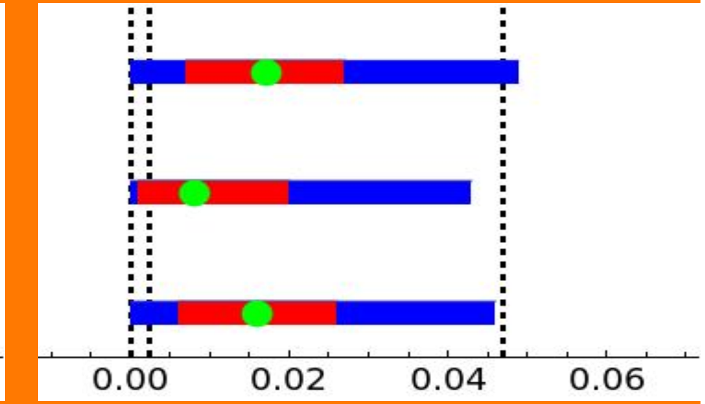
# IN SHORT: OSCILLATION ANALYSES CONVERGE …



$\sin^2\theta_{12} = 1/3$



$\sin^2\theta_{23} = 0.5$



$\sin^2\theta_{13} = 0$

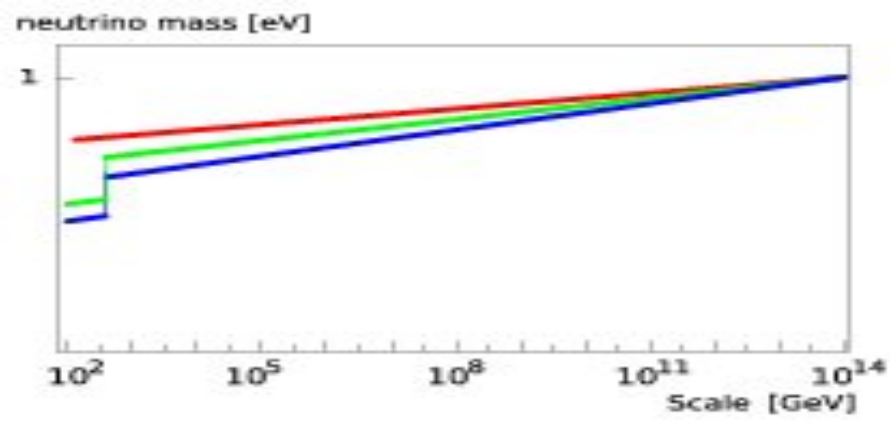
## TRI-BIMAXIMAL MIXING

**Harrison, Perkins & Scott**

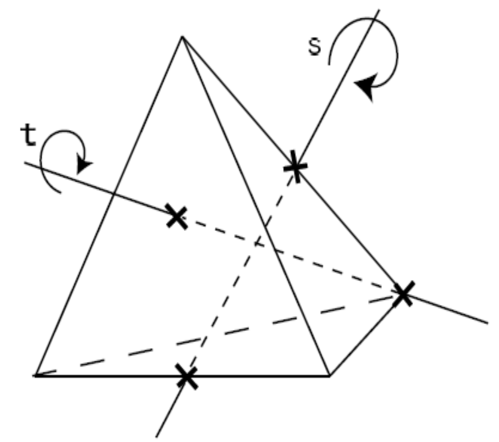
$$U_{\text{HPS}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

**various other ansatze were proposed:** mu-tau, bi-maximal, tri-maximal, tetra-maximal, symmetric mixing, hexagon mixing, golden mixing, QLC ...

Albright, Dueck, Rodejohann 1004.2798



Babu et al PLB552 (2003) 207
Hirsch et al PRD69 (2004) 093006



# ORIGIN OF TBM

**A4**

$Z_3$

$\langle\phi\rangle \sim (1,1,1)$

**CHARGED LEPTONS**

**Sectors are separated by an extra Abelian Zn**

$Z_2$

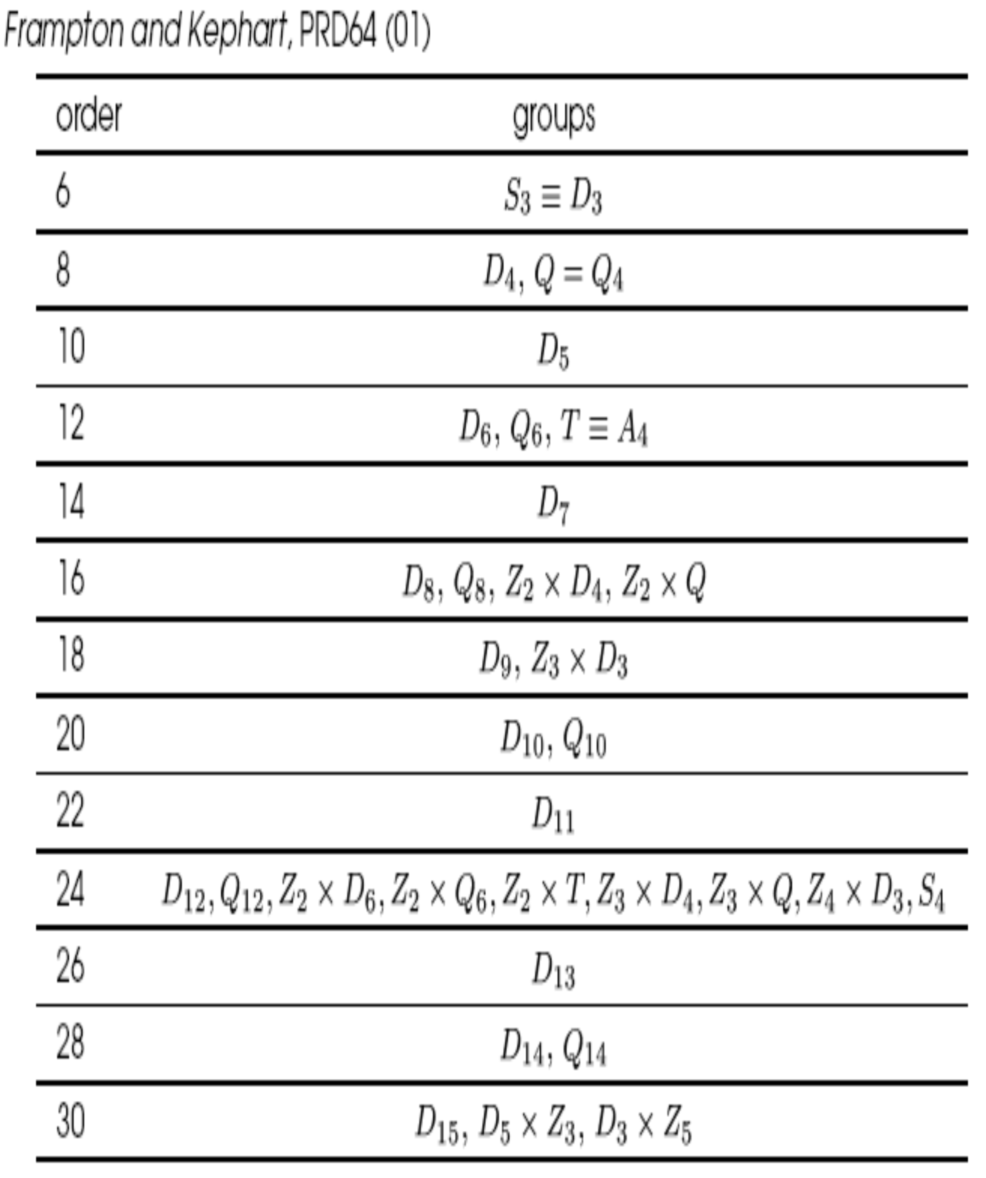
$\langle\phi'\rangle \sim (1,0,0)$

**NEUTRINOS**

$$U^\dagger_{lep} U_\nu = V_{TBM}$$

# FLAVOR SYMMETRIES

Ishimori, Kobayashi, Ohki, Okada, Shimizu & Tanimoto arXiv:1003.3552



Frampton and Kephart, PRD64 (01)

| order | groups |
|---|---|
| 6 | $S_3 \equiv D_3$ |
| 8 | $D_4, Q = Q_4$ |
| 10 | $D_5$ |
| 12 | $D_6, Q_6, T \equiv A_4$ |
| 14 | $D_7$ |
| 16 | $D_8, Q_8, Z_2 \times D_4, Z_2 \times Q$ |
| 18 | $D_9, Z_3 \times D_3$ |
| 20 | $D_{10}, Q_{10}$ |
| 22 | $D_{11}$ |
| 24 | $D_{12}, Q_{12}, Z_2 \times D_6, Z_2 \times Q_6, Z_2 \times T, Z_3 \times D_4, Z_3 \times Q, Z_4 \times D_3, S_4$ |
| 26 | $D_{13}$ |
| 28 | $D_{14}, Q_{14}$ |
| 30 | $D_{15}, D_5 \times Z_3, D_3 \times Z_5$ |

**A4**

Babu, Ma, Valle PLB552 (2003)
Altarelli, Feruglio NPB72 (2005)
Hirsch, Morisi, Valle PRD78 & D79 (2008) & PLB679 (2009) 454
Hagedorn, Molinaro, Petcov (2009)
Ibanez, Morisi, Valle, PRD80 (2009)

**S3**

Grimus, Lavoura, JHEP0904
Mohapatra, Nasri, Yu, PLB627
Mondragón, Mondragón, Peinado

**S4**

Lam PRL101
Bazzocchi, Morisi, PRD80

**T'**

Feruglio, Hagedorn, Lin, Merlo (2007)
Carr, Frampton (2007)
Aranda, Carone, Lebed PLB474

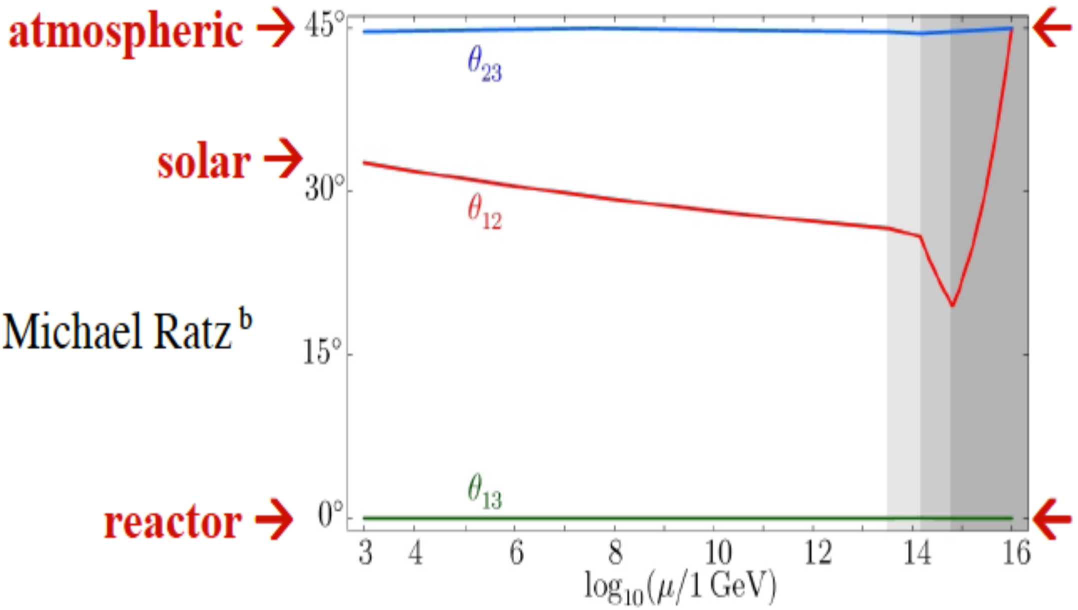
**D(27)**

Medeiros, King, Ross PLB648

....

# TBM DEVIATIONS

Stefan Antusch [a], Jörn Kersten [a], Manfred Lindner [a], Michael Ratz [b]

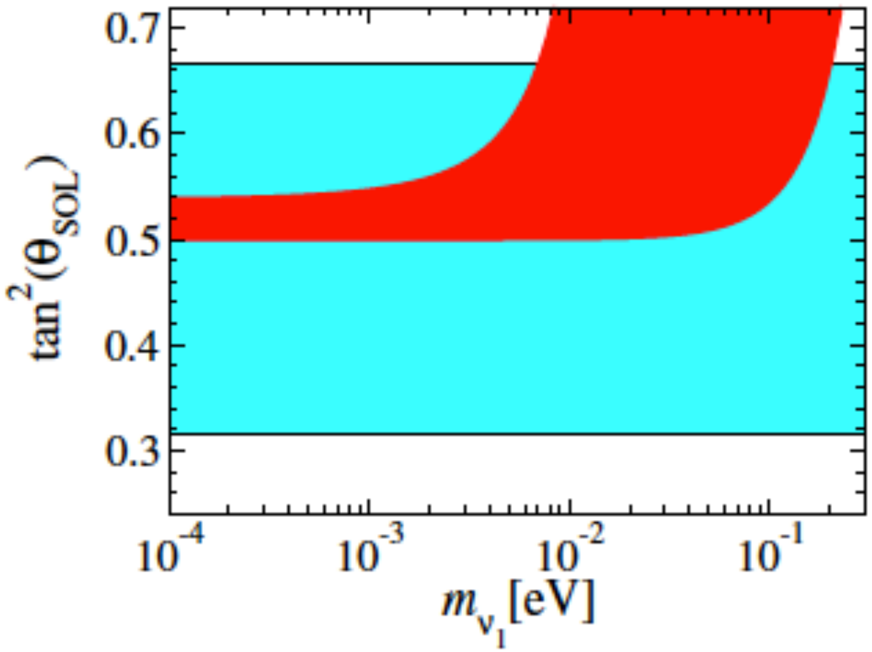


**Hirsch et al**

PHYSICAL REVIEW D **75,** 053006 (2007)

Luo, Xing, Plentinger, Rodejohann, …

## Minimal supergravity radiative effects on the tribimaximal neutrino mixing pattern



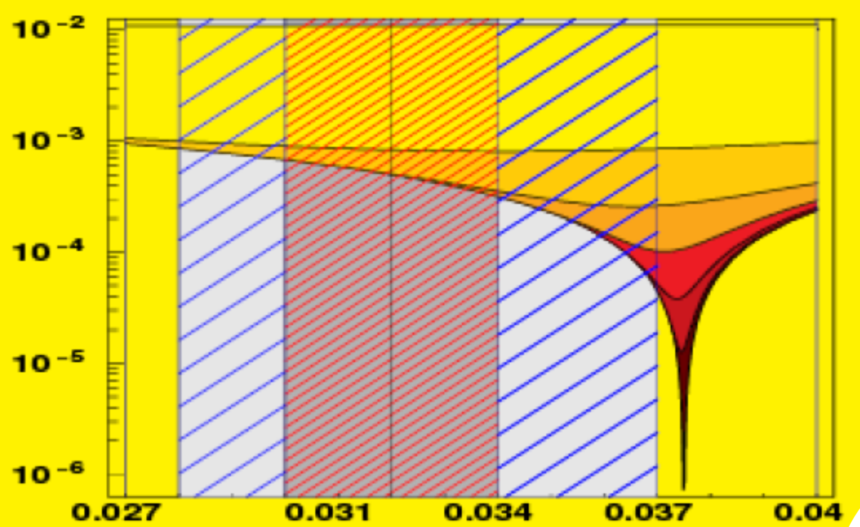
$$\epsilon_{23} = \frac{\delta^0_{23}(m_2 + m_3)}{(-1 - \delta^0_{22})m_2 + (1 + \delta^0_{33})m_3},$$

$$\epsilon_{13} = \frac{\delta^0_{13}(m_1 + m_3)}{(-1 - \delta^0_{11})m_1 + (1 + \delta^0_{33})m_3},$$

$$\epsilon_{12} = \frac{\delta^0_{12}(m_1 + m_2)}{(-1 - \delta^0_{11})m_1 + (1 + \delta^0_{22})m_2}.$$

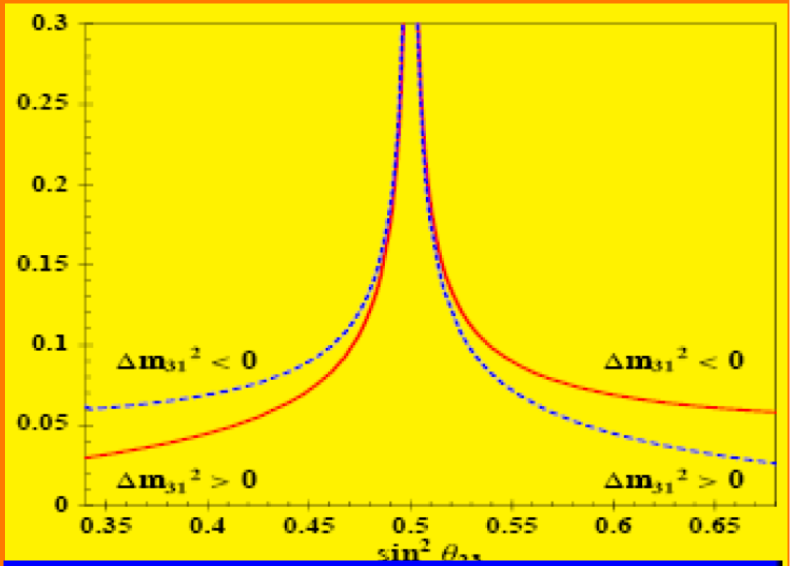
# 0-nu DBD & FLAVOR

PRD78:093007 (2008)



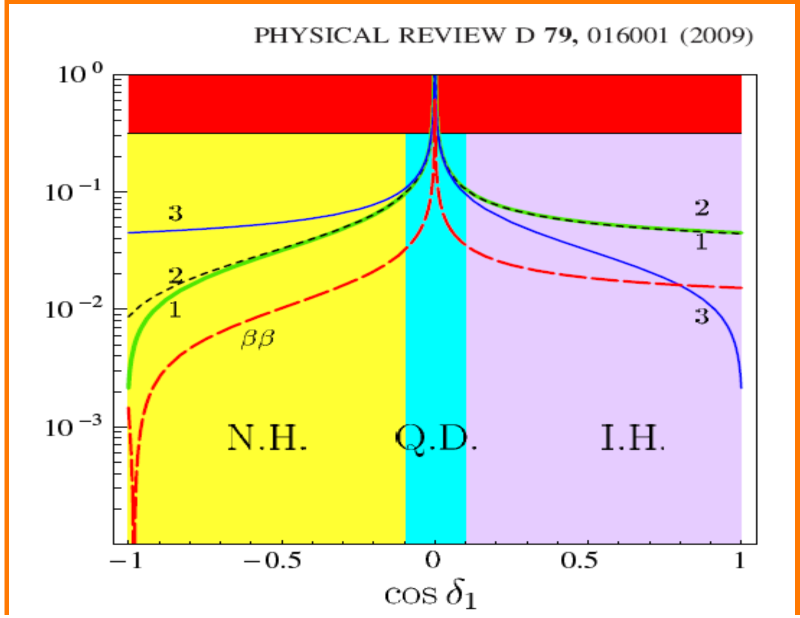
correlates with $\alpha = \frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}}$

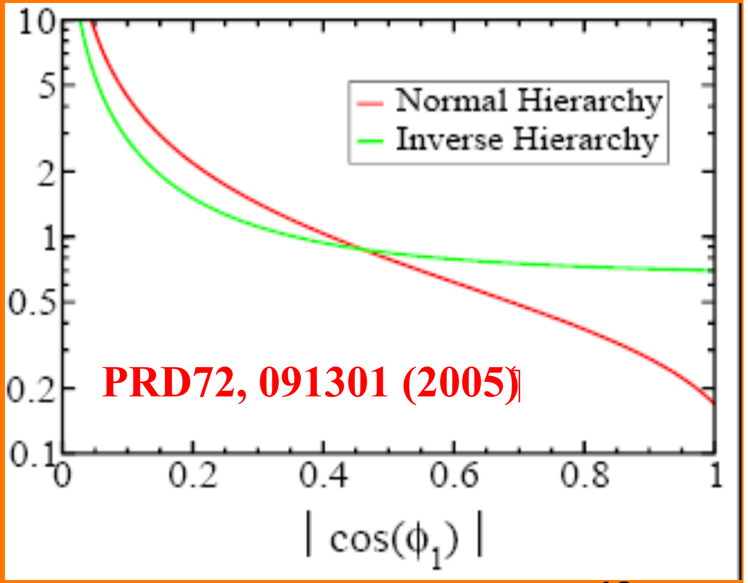
PRL 99 (2007) 151802, PRD82 (2010) 073008



correlates with ATM angle

A4

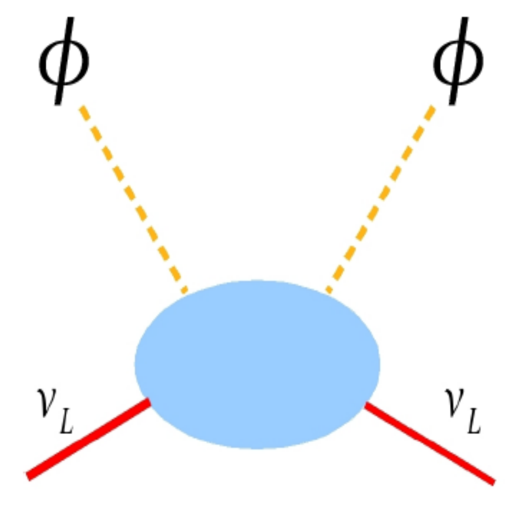

PHYSICAL REVIEW D **79**, 016001 (2009)



PRD72, 091301 (2005)

correlates with Majorana phase

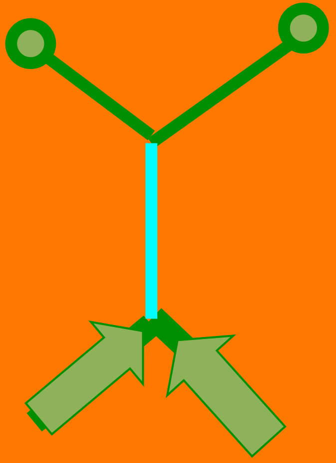
# ORIGIN OF NU-MASSES & MIXINGS



**Fermion exchange**

**Type I & III**

Minkowski 77
Gellman Ramond Slansky 80
Glashow, Yanagida 79
Mohapatra Senjanovic 80
Schechter-Valle, 80 & 82
Lazarides Shafi Weterrich 81
Foot et al 89



**Scalar exchange**

**type II**

Schechter-Valle 80/82

**scale**

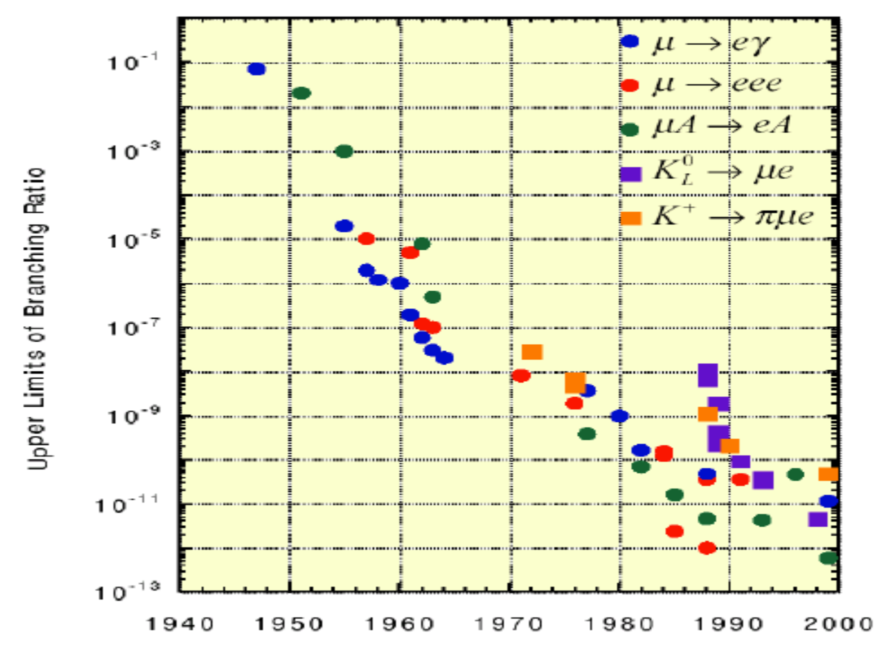
**mechanism**

**flavor structure**

**LOW-SCALE SEESAW** Mohapatra-Valle 86

# LFV & neutrino oscillations

Flavor is violated in neutrino Propagation !!



Okada@NuFact2010

- **HEAVY** vs **LIGHT** MESSENGERS
- **VIRTUAL** vs **DIRECT EFFECTS**

F. del Aguila et al. Eur.Phys.J.C57:183-308,2008
Hall, Kostelecky, Raby 86, Borzumati, Masiero, 86, ..

# LOW-SCALE SEESAW

## INVERSE SEESAW

Mohapatra-Valle, 86
Ibanez Morisi JV, PRD80 (2009) 053015
Bazzocchi, et al, PRD81 (2010) 051701

## LINEAR SEESAW

Malinsky et al PRL95(2005)161801
Hirsch, et al PLB679:454,2009

- **LFV & CPV survive in massless neutrino limit**
- **hence unsuppressed by m-nu**

Bernabeu et al 87, Branco et al 89, Rius JV 90,
Gonzalez-Garcia, JV, Mod.Phys.Lett.A7:477,1992
Ilakovac Kniehl Pilaftsis 95,
Deppish et al PRD72:036001,2005 & NPB752 (2006) 80
Deppish, Kosmas & JV 2006,
Malinsky, Ohlsson, Zhang, PRD79, 073009
Gavela, Hambye, Hernández, Hernández…
Okada, et al

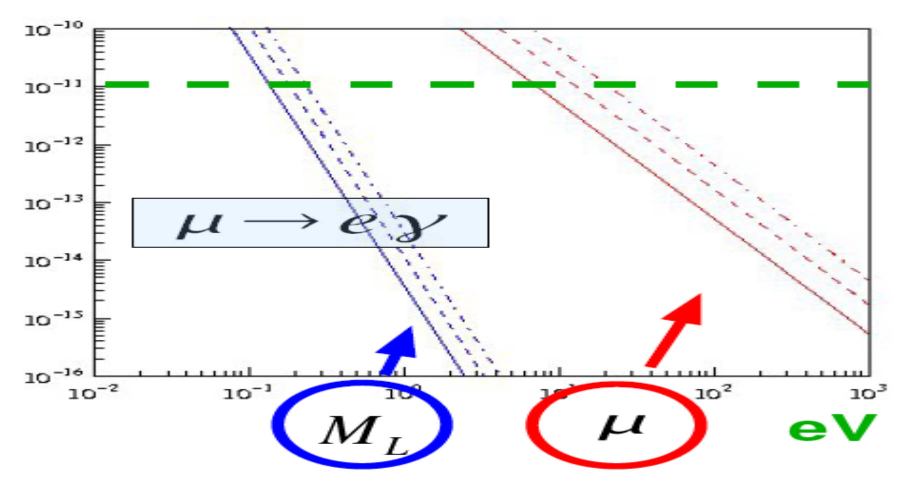
## LFV from NHL exchange

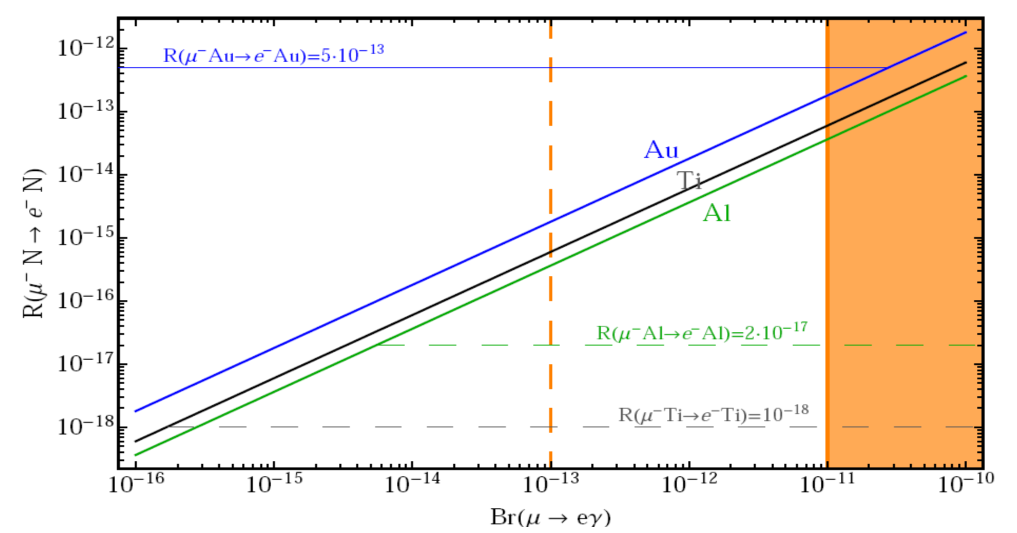
**M=0.2-1 TeV**

$$\begin{pmatrix} 0 & M_D & M_L \\ M_D^T & 0 & M \\ M_L^T & M^T & 0 \end{pmatrix}$$

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

## t'Hooft naturalness





# PROBING LFV IN SUSY DECAYS AT LHC

**Hirsch et al PRD 78 (2008) 013006**
**Esteves et al JHEP05 (2009) 3**

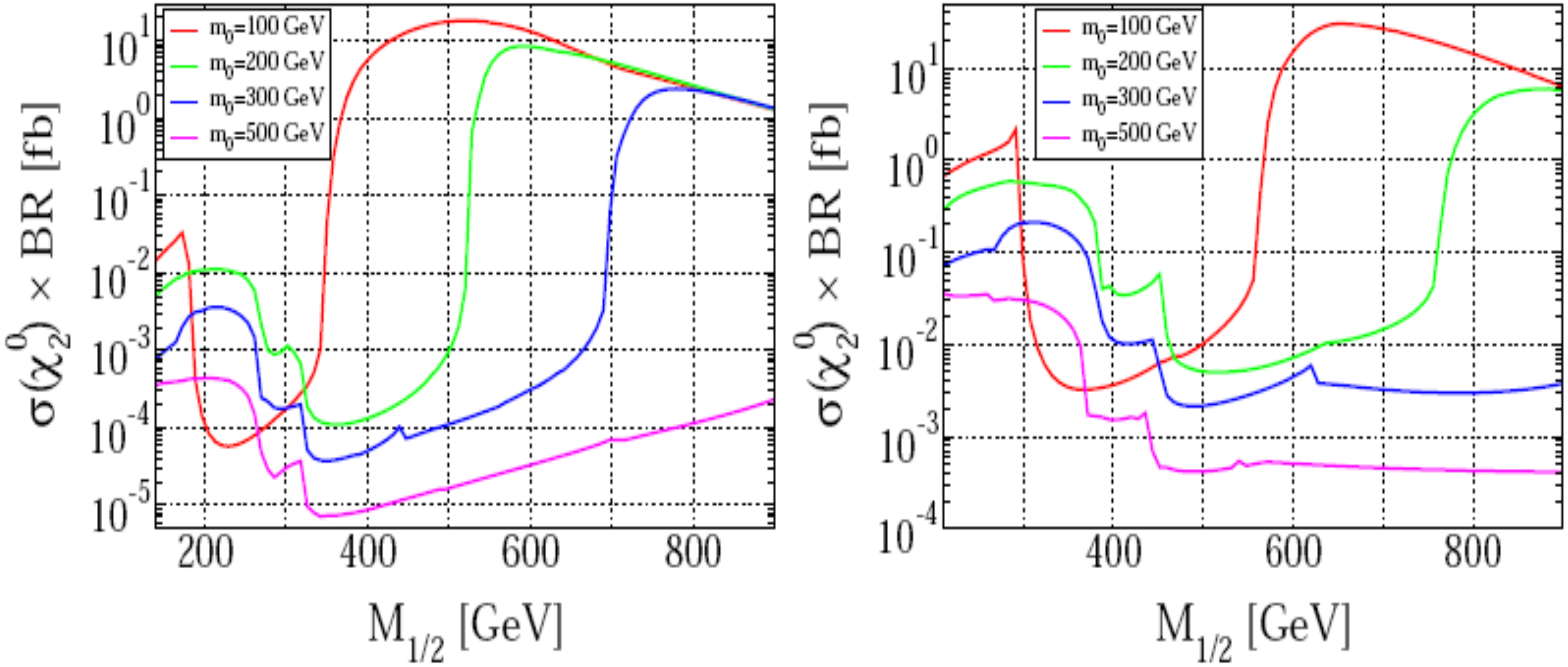
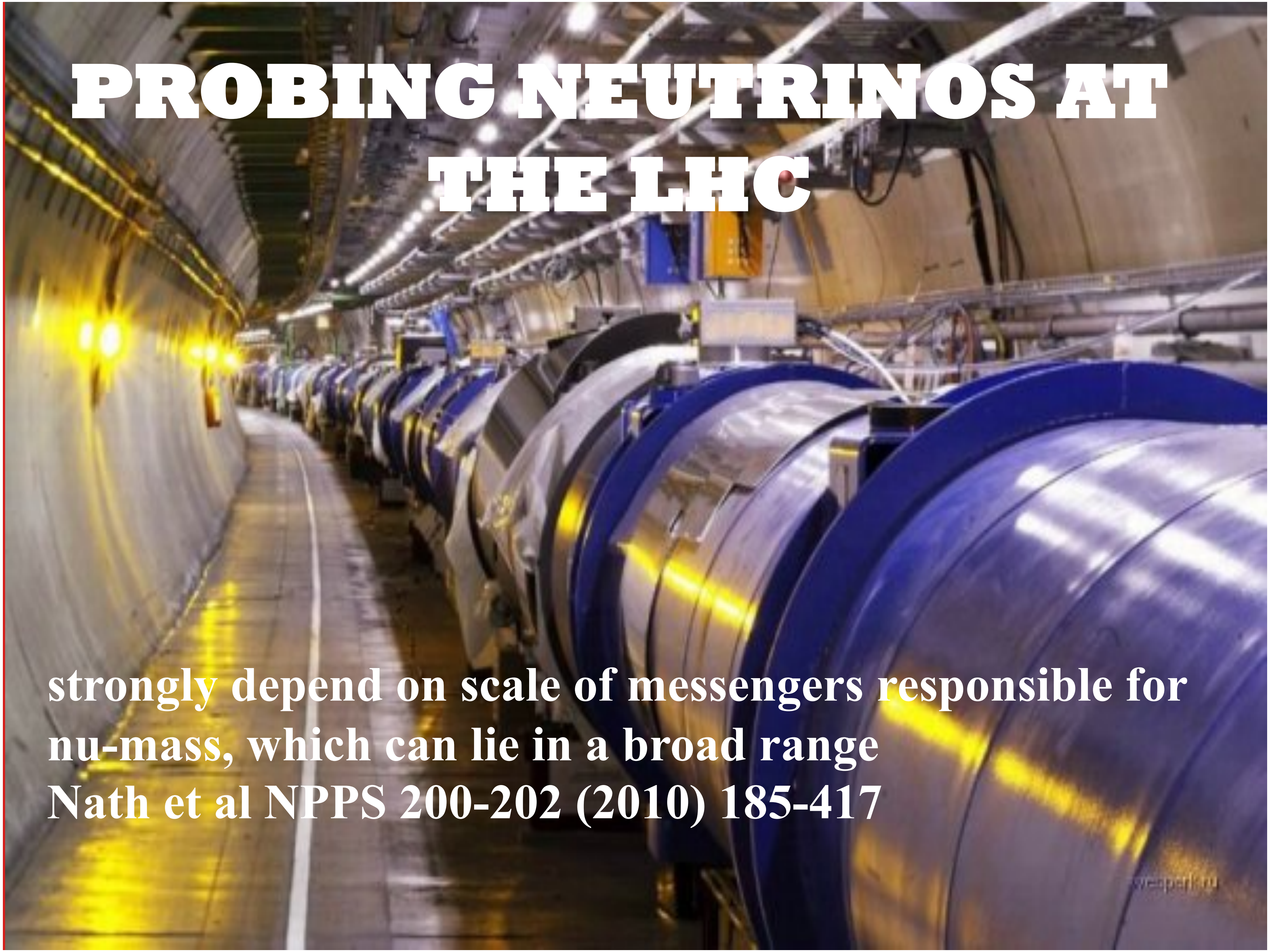


FIG. 12: Production cross section (at leading order) of $\chi_2^0$ times BR of $\chi_2^0$ going to $\mu$-$\tau$ lepton pair versus $M_{1/2}$ for $m_0 = 100$ GeV (red), 200 GeV (green), 300 GeV (blue) and 500 GeV (magenta), and for our standard choice of parameters: $\mu > 0$, $\tan\beta = 10$ and $A_0 = 0$ GeV, for type-I (left panel) and for type-II seesaw (right panel) with $\lambda_1 = 0.02$ and $\lambda_2 = 0.5$, imposing $\mathrm{Br}(\mu \to e + \gamma) \leq 1.2 \cdot 10^{-11}$.

# PROBING NEUTRINOS AT THE LHC



strongly depend on scale of messengers responsible for nu-mass, which can lie in a broad range
Nath et al NPPS 200-202 (2010) 185-417

# SPONTANEOUS/BILINEAR R-PARITY VIOLATION

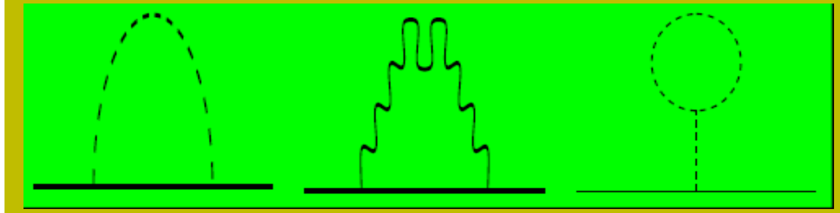
**Masiero & Valle, PLB251 (1990) 273**

**Bhattacharyya & Pal, PRD82 (2010) 055013**

**ATM SCALE**

**SUSY-SEESAW**

Hall & Suzuki, Ross & JV 85,
Ellis et al, 85, Santamaria JV, ...



**SOLAR SCALE**

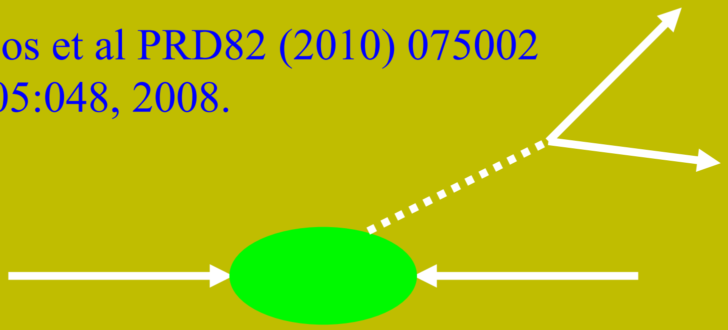
RADIATIVE

Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008
PRD65 (2002) 119901; PRD61 (2000) 071703

**LSP decay**

# DISPLACED VERTICES

De Campos et al PRD82 (2010) 075002
JHEP 0805:048, 2008.

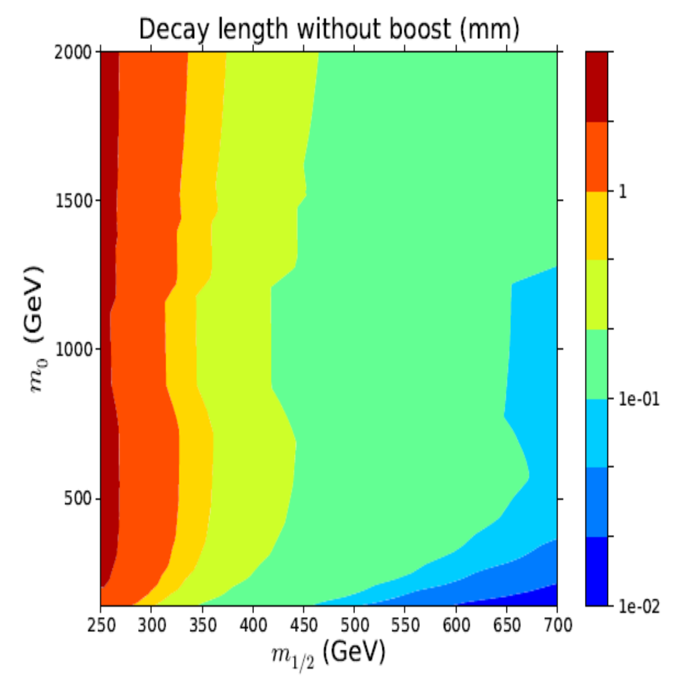


$$\chi_1^0 \longrightarrow \nu\, l^+\, l^-$$
$$\chi_1^0 \longrightarrow \nu\, \tau^+\, \tau^-$$
$$\chi_1^0 \longrightarrow \nu\, \tau\, l$$

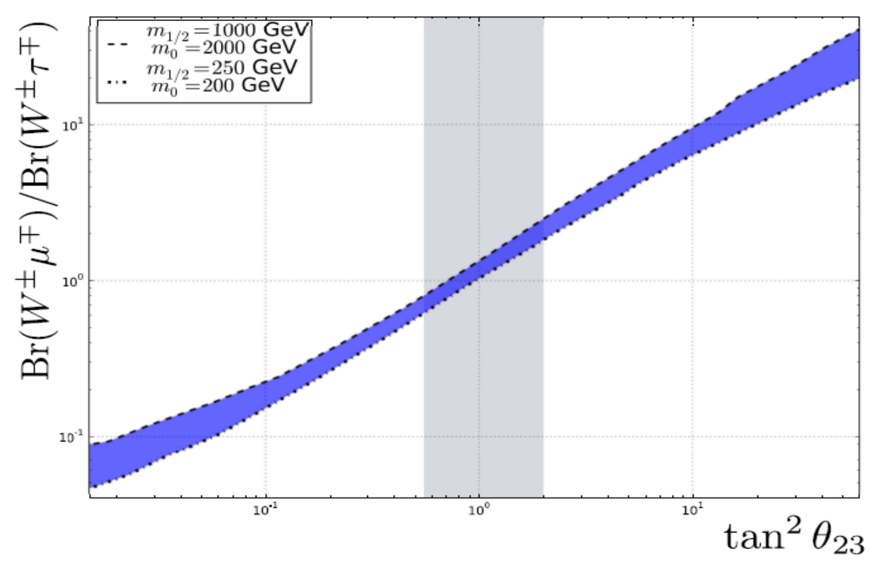
$$\chi_1^0 \longrightarrow \nu\, q\, \bar{q}$$
$$\chi_1^0 \longrightarrow \tau\, q'\, \bar{q}$$
$$\chi_1^0 \longrightarrow l\, q'\, \bar{q}$$
$$\chi_1^0 \longrightarrow \nu\, b\, \bar{b}$$

$$\chi_1^0 \longrightarrow \nu\, \nu\, \nu$$

The LSP can live long enough to
leave a **displaced vertex** in the detector



$\tilde{\chi}_1^0$ decay length in the plane $m_0, m_{1/2}$ for $A_0 = -100$ GeV, $\tan\beta = 10$ and $\mu > 0$.



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

# PROBING OSCILLATION PARAMETERS @ LHC

- LSP decays deplete pT-miss, increasing multiplicities
- leaving displaced vertices
- decay pattern correlates with oscillation angles

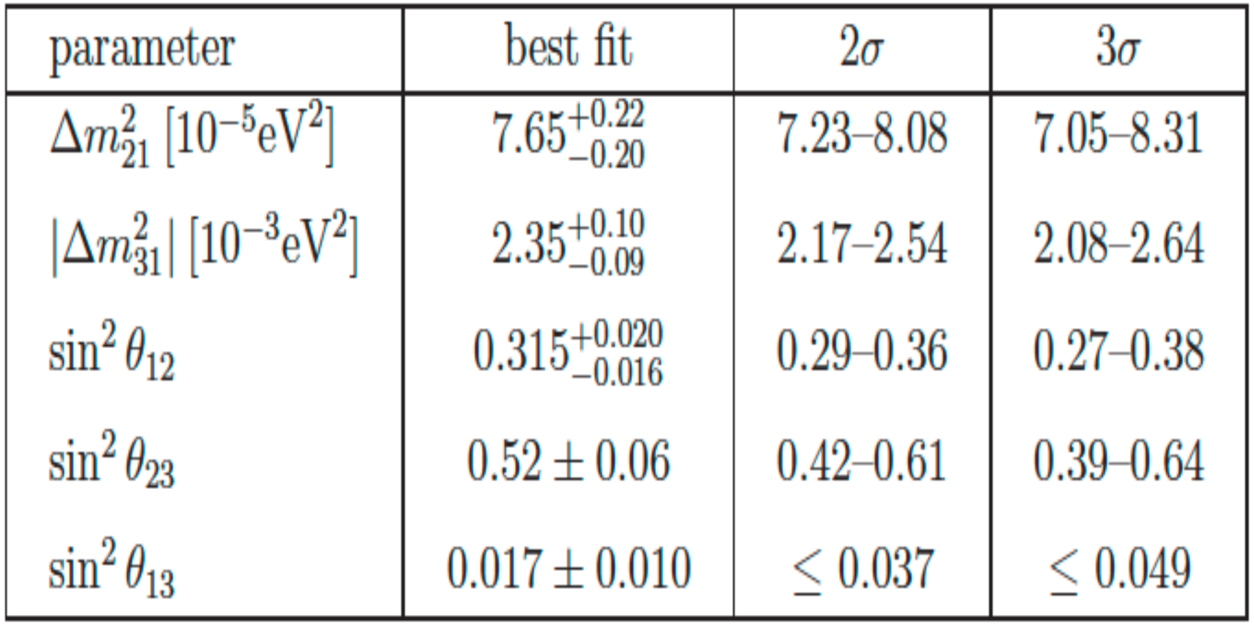
**Simulation reveals that 23-mixing angle can be extracted competitive with Super-K**

**work needed …**
**12 & 13-angles, magnitude of nu-mass …**

**ROBUST:**
**similar features in any SUSY breaking scenario & hence with any LSP profile**

stop Restrepo et al, PRD64 (2001) 055011
stau Hirsch et al, PRD66 (2002) 095006
others D68 (2003) 115007

# ROBUSTNESS OF OSCILLATIONS



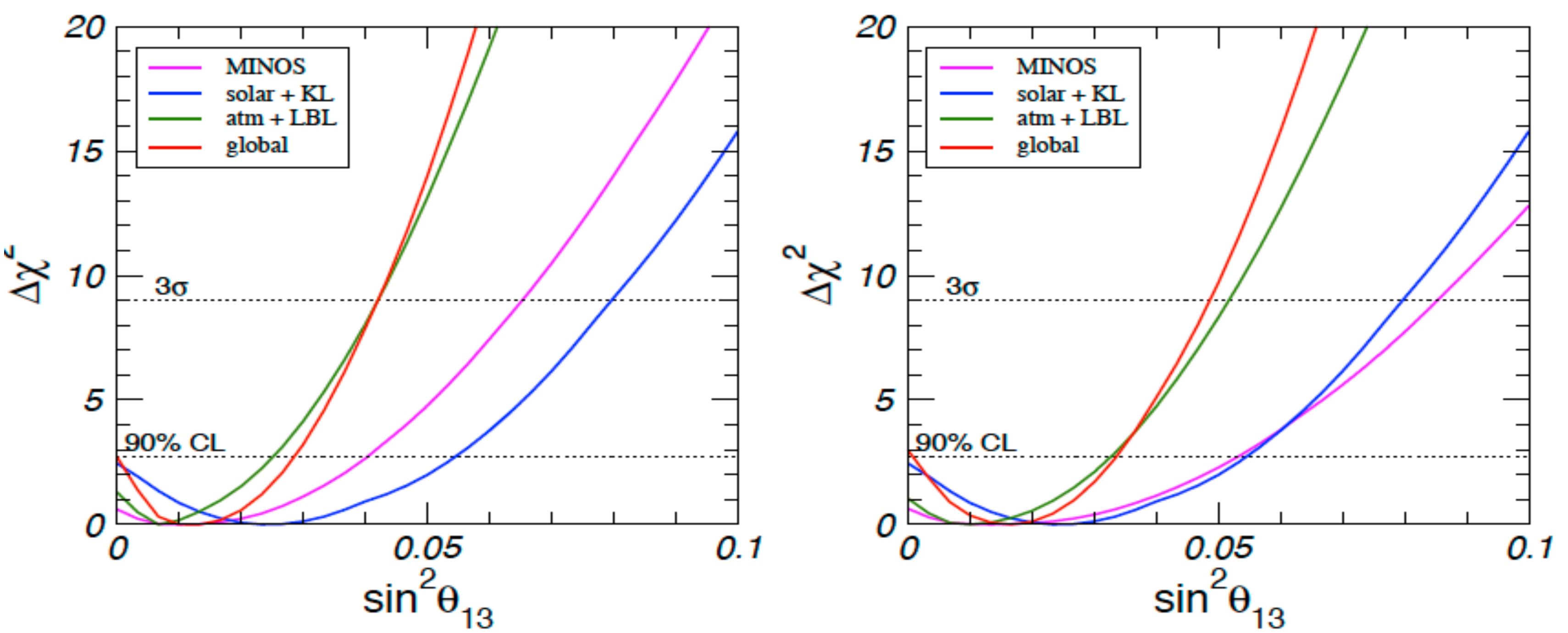
| parameter | best fit | $2\sigma$ | $3\sigma$ |
|---|---|---|---|
| $\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$ | $7.65^{+0.22}_{-0.20}$ | 7.23–8.08 | 7.05–8.31 |
| $\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ | $2.35^{+0.10}_{-0.09}$ | 2.17–2.54 | 2.08–2.64 |
| $\sin^2\theta_{12}$ | $0.315^{+0.020}_{-0.016}$ | 0.29–0.36 | 0.27–0.38 |
| $\sin^2\theta_{23}$ | $0.52 \pm 0.06$ | 0.42–0.61 | 0.39–0.64 |
| $\sin^2\theta_{13}$ | $0.017 \pm 0.010$ | $\leq 0.037$ | $\leq 0.049$ |

**NEUTRINO OSCILLATIONS STATUS @ NUFACT2010**

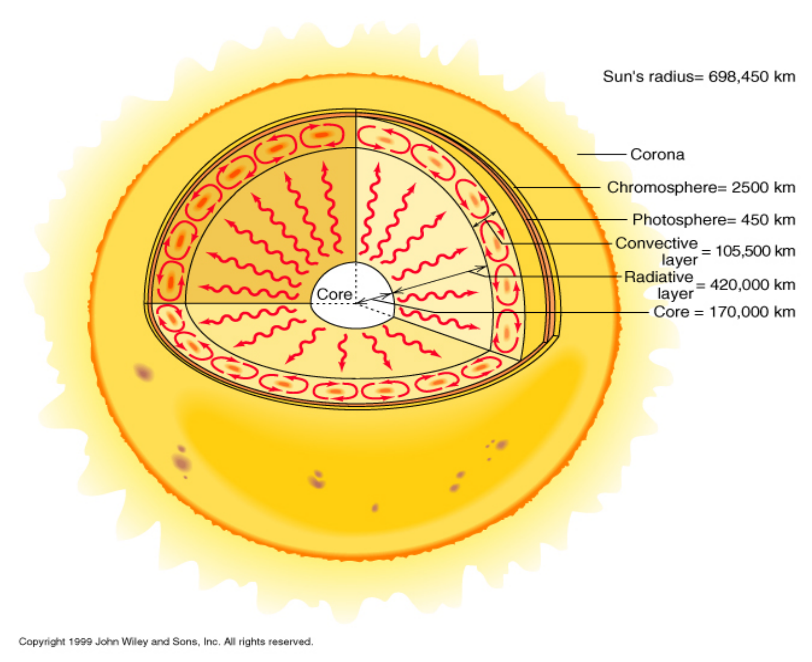
upd Schwetz et al,

NJP 10 (2008) 113011

Maltoni et al, NJP 6 (2004) 122



# HOW ROBUST ARE SOLAR NU-OSCILLATIONS



RZ magn fields Burgess et al JCAP0401 (2004) 007

CZ magn fields Miranda et al

Both strongly disfavored by KamLAND

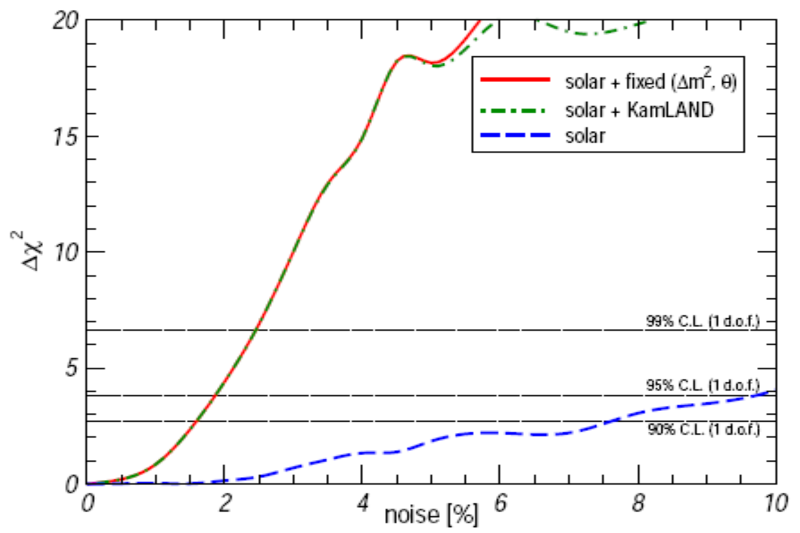
## FROM NEUTRINO PROPERTIES TO SOLAR PHYSICS

Test SSM fluxes

Probe RZ mag-fields & RZ-density fluctuations

helioseismology & magneto-gravity waves ...

Burgess et al MNRAS.348 (2004) 609



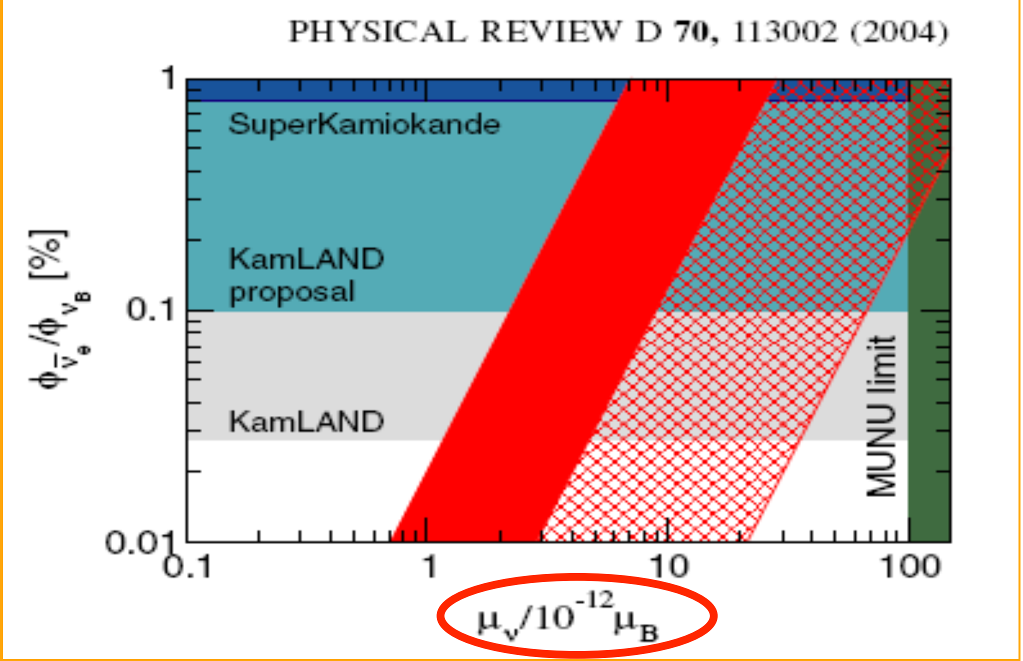
# TRANSITION MAGNETIC MOMENTS

## AFFECT NU-PROPAGATION

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

**KamLAND anti-nu-e flux limit**

SFP must be sub-leading w.r.t. oscillations

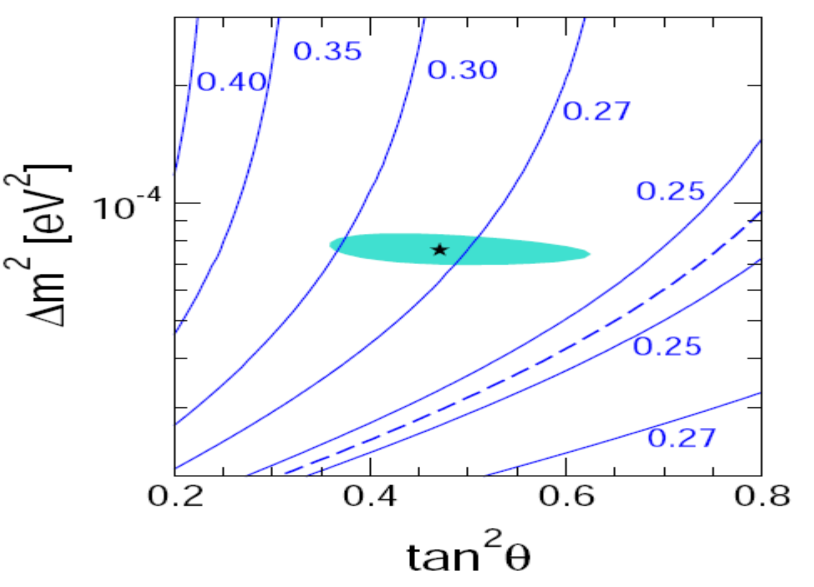

PHYSICAL REVIEW D **70**, 113002 (2004)

**bounds on transition mag-moment in a turbulent magnetic field**

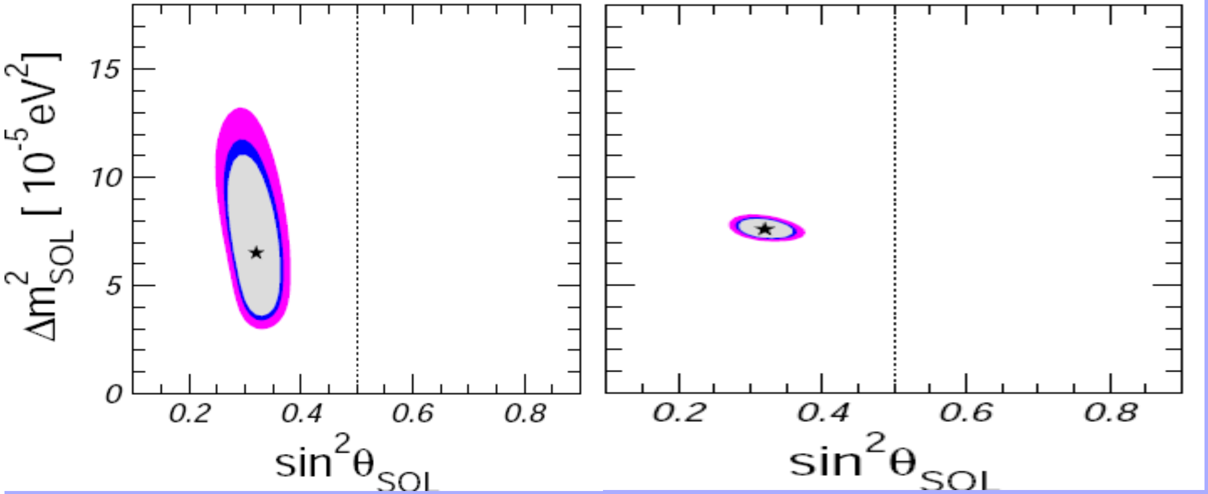
## AFFECT DETECTION NEUTRINO-ELECTRON SCATTERING X-SECTION

Grimus et al, NPB648, 376 (2003)

cf. Borexino sensitivities



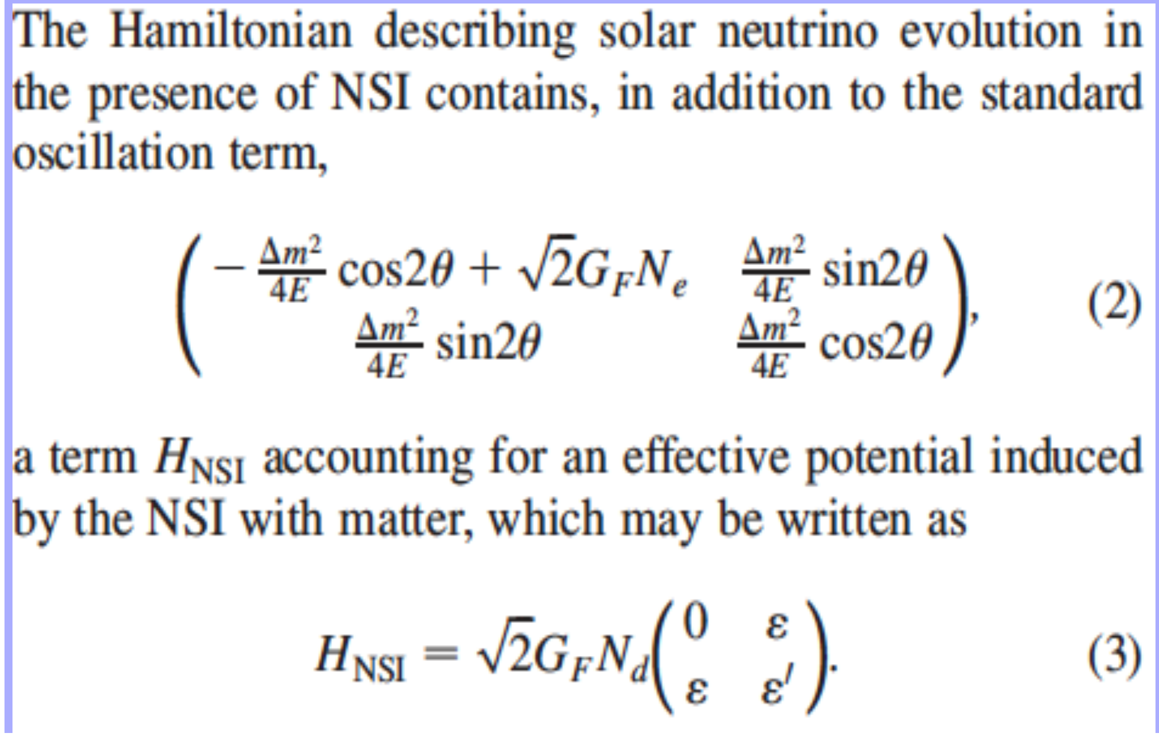
Miranda, Tortola & Valle JHEP 0610:008,2006.



**SOL**

**SOL+KAML**

pure oscillation



The Hamiltonian describing solar neutrino evolution in the presence of NSI contains, in addition to the standard oscillation term,

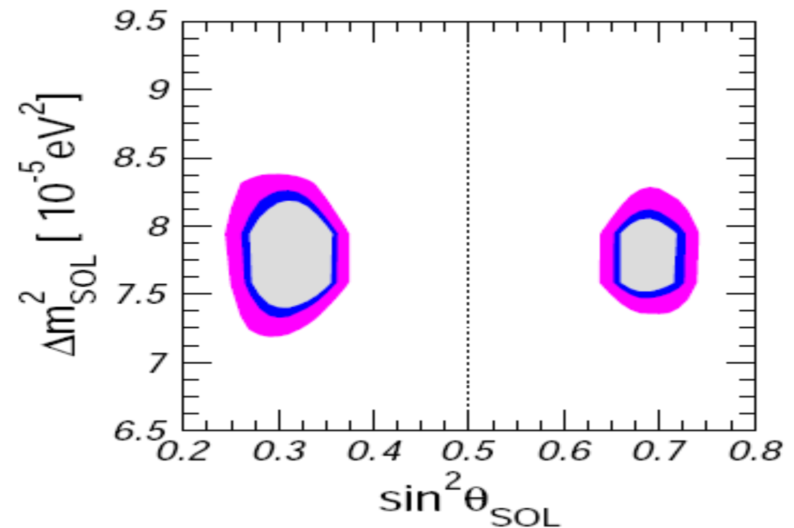
$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}, \qquad (2)$$

a term $H_{\rm NSI}$ accounting for an effective potential induced by the NSI with matter, which may be written as

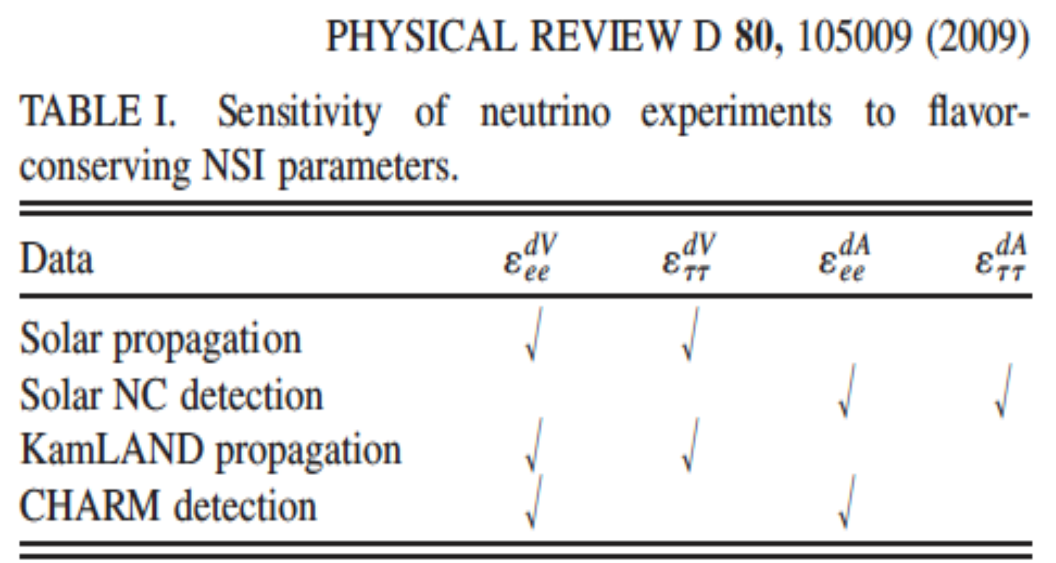
$$H_{\rm NSI} = \sqrt{2}G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}. \qquad (3)$$

**OSC+NSI**

**SOL+KAML**



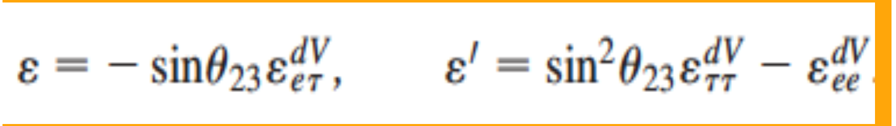
# Combining with accelerator data: tau-neutrino NSI parameters



PHYSICAL REVIEW D **80**, 105009 (2009)

TABLE I. Sensitivity of neutrino experiments to flavor-conserving NSI parameters.

| Data | $\varepsilon_{ee}^{dV}$ | $\varepsilon_{\tau\tau}^{dV}$ | $\varepsilon_{ee}^{dA}$ | $\varepsilon_{\tau\tau}^{dA}$ |
|---|---|---|---|---|
| Solar propagation | √ | √ | | |
| Solar NC detection | | | √ | √ |
| KamLAND propagation | √ | √ | | |
| CHARM detection | √ | | √ | |



$$\varepsilon = -\sin\theta_{23}\varepsilon_{e\tau}^{dV}, \qquad \varepsilon' = \sin^2\theta_{23}\varepsilon_{\tau\tau}^{dV} - \varepsilon_{ee}^{dV}$$

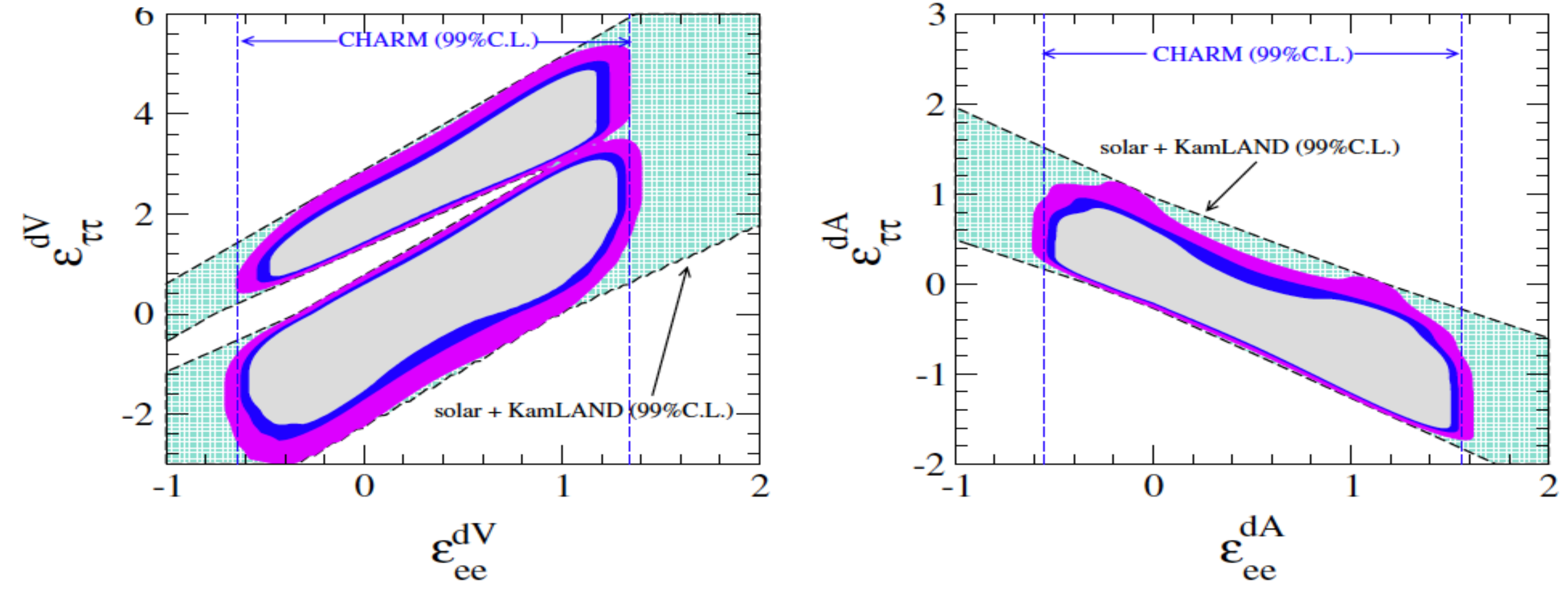


FIG. 6 (color online). Constraints on the vector (left panel) and axial-vector (right panel) NSI couplings from our global analysis at 90%, 95%, and 99% C.L., and from the separate solar + KamLAND and CHARM data sets (dashed lines).

# Interplay of nonstandard neutrino interactions with oscillations

Palazzo & JV PRD80:091301,2009

**similar confusion as in LBL neutrino oscillations**

Huber, Schwetz, JV PRL88:101804,2002 & PRD66:013006,2002

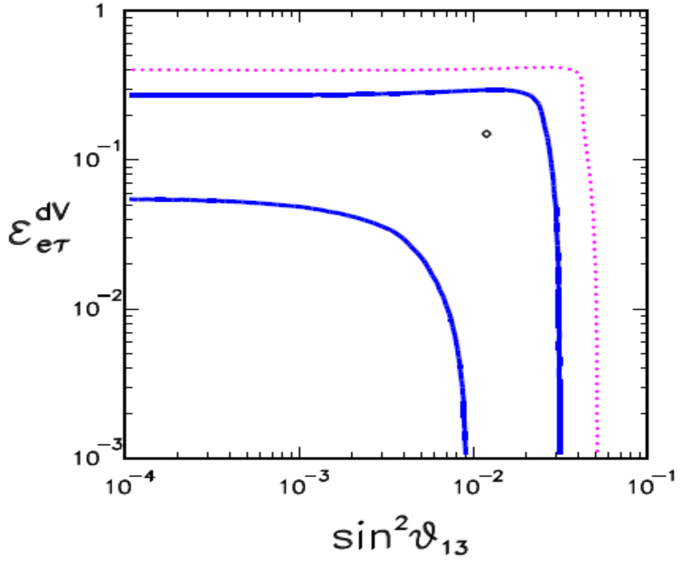
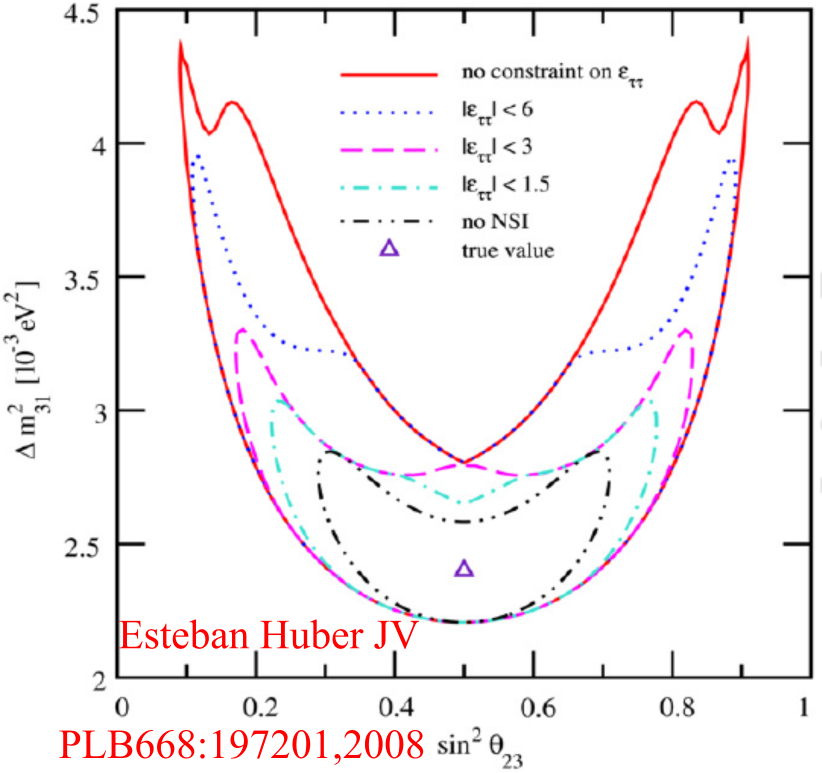


FIG. 2: Region allowed by the combination of solar and KamLAND data at two C.L's [$\Delta\chi^2 = 1$ (solid line) and $\Delta\chi^2 = 4$ (dashed line)] after marginalization of $\delta m^2$ and $\theta_{12}$.



Esteban Huber JV

PLB668:197201,2008

## NSI in MINOS

Parke et al, Akhmedov et al

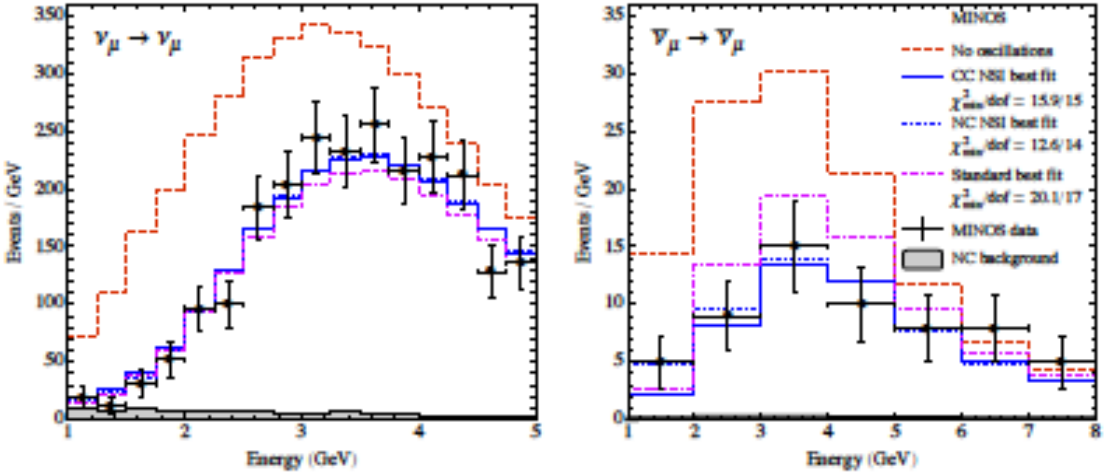
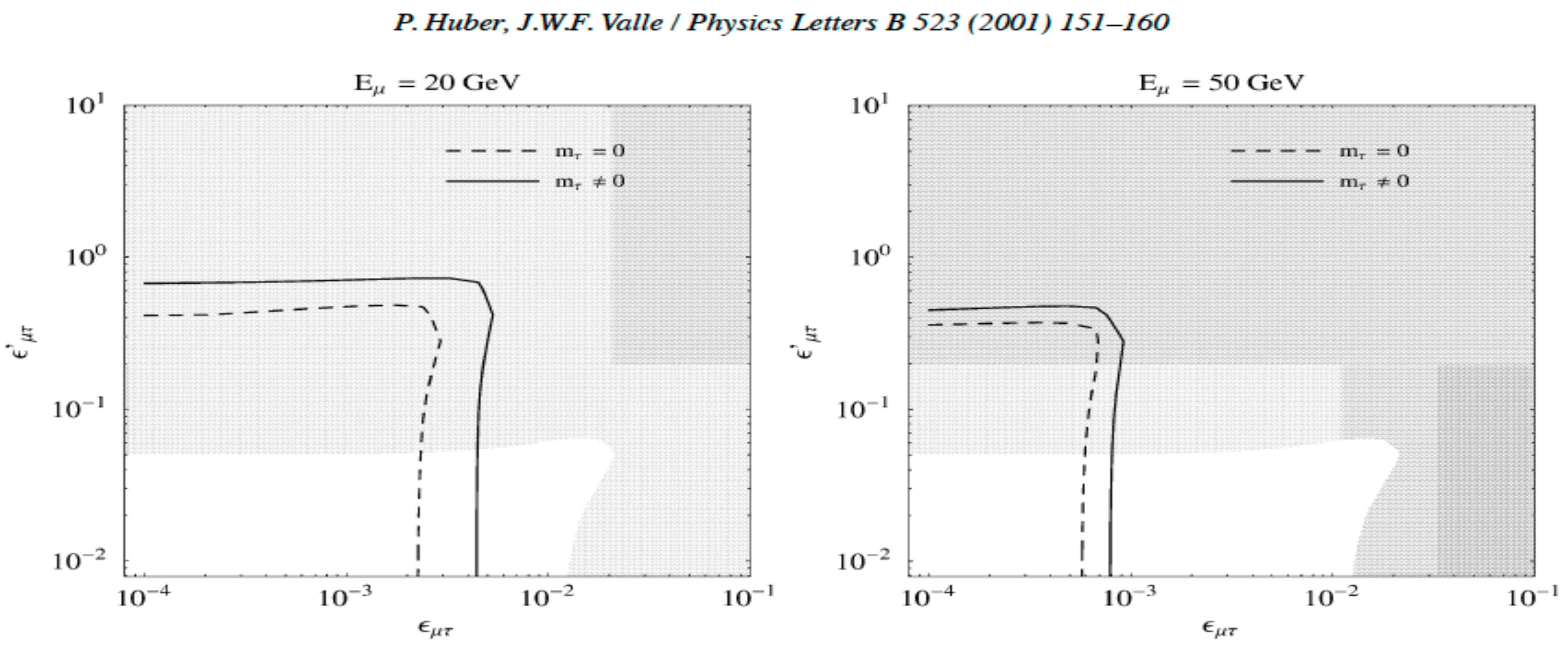


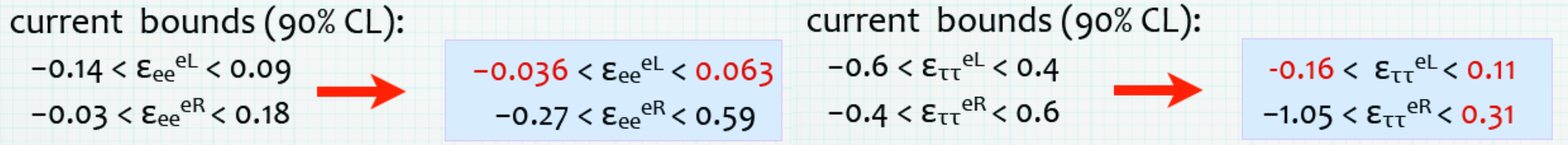
Figure 3: Comparison of MINOS data (black dots and error bars) to theoretical predictions including neutral-current NSI parameterized by the best fit point eq. (20) (blue dotted histograms) and charged current NSI parameterized by the best fit point eq. (21) (blue solid histograms). For comparison, the red dashed histograms show the theoretical prediction in the absence of neutrino oscillations, and the pink dash-dotted histograms represent the results of a two-flavor standard oscillation fit to the combined $\nu_\mu$ and $\bar{\nu}_\mu$ data.

# improving FC NSI sensitivity @ future NuFact



P. Huber, J.W.F. Valle / Physics Letters B 523 (2001) 151–160

# PROBING NSI WITH ELECTRONS



current bounds (90% CL):

$-0.14 < \varepsilon_{ee}^{eL} < 0.09$

$-0.03 < \varepsilon_{ee}^{eR} < 0.18$

→

$-0.036 < \varepsilon_{ee}^{eL} < 0.063$

$-0.27 < \varepsilon_{ee}^{eR} < 0.59$

current bounds (90% CL):

$-0.6 < \varepsilon_{\tau\tau}^{eL} < 0.4$

$-0.4 < \varepsilon_{\tau\tau}^{eR} < 0.6$

→

$-0.16 < \varepsilon_{\tau\tau}^{eL} < 0.11$

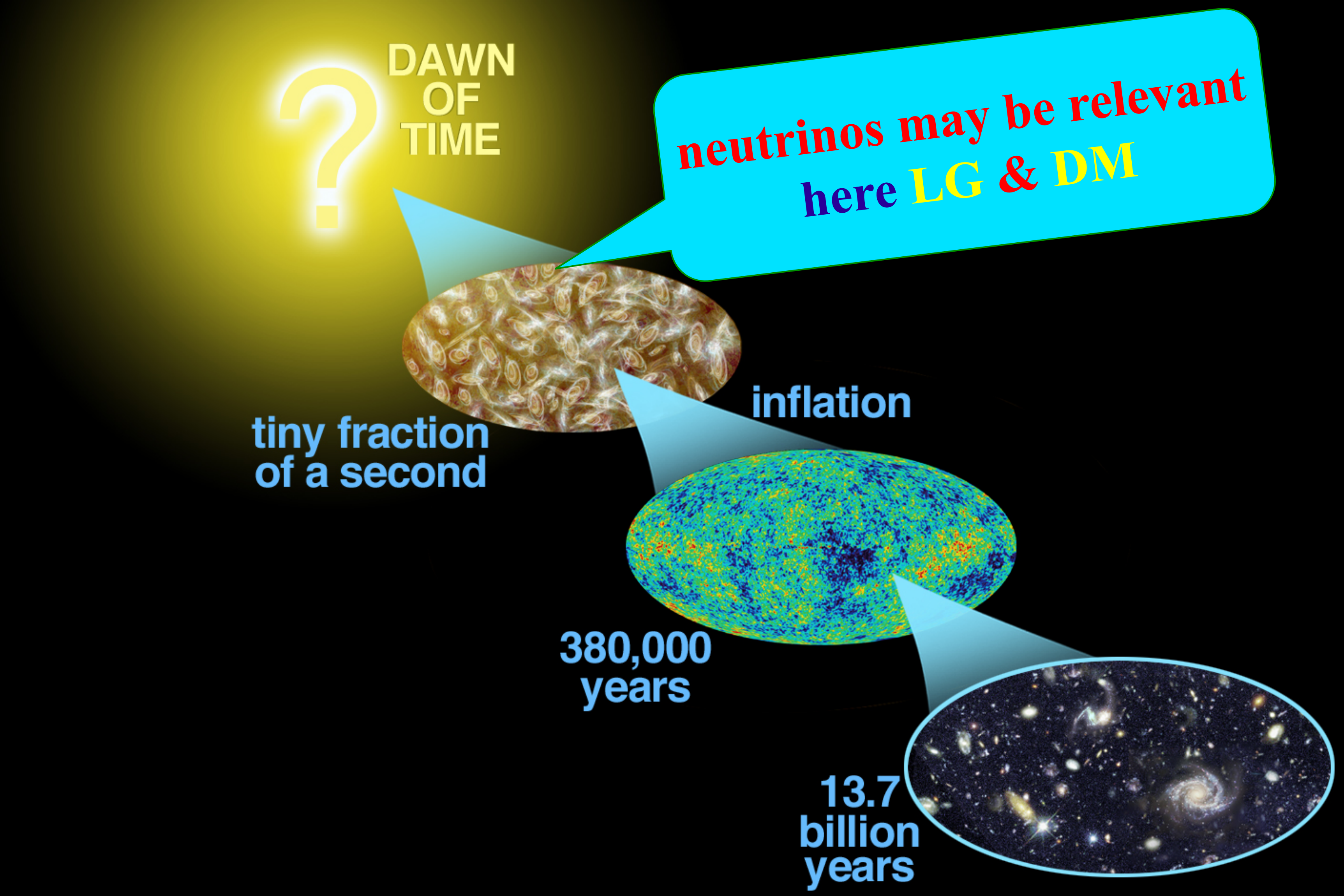
$-1.05 < \varepsilon_{\tau\tau}^{eR} < 0.31$

Bolaños et al PRD79 (2009) 113012 improves LL.

**Texono 1006.1947 improves ee-RR**

Wrt. Barranco et al PRD77:093014,2008 & PRD73:113001,2006

# COSMO-CONNECTION



DAWN
OF
TIME

neutrinos may be relevant
here LG & DM

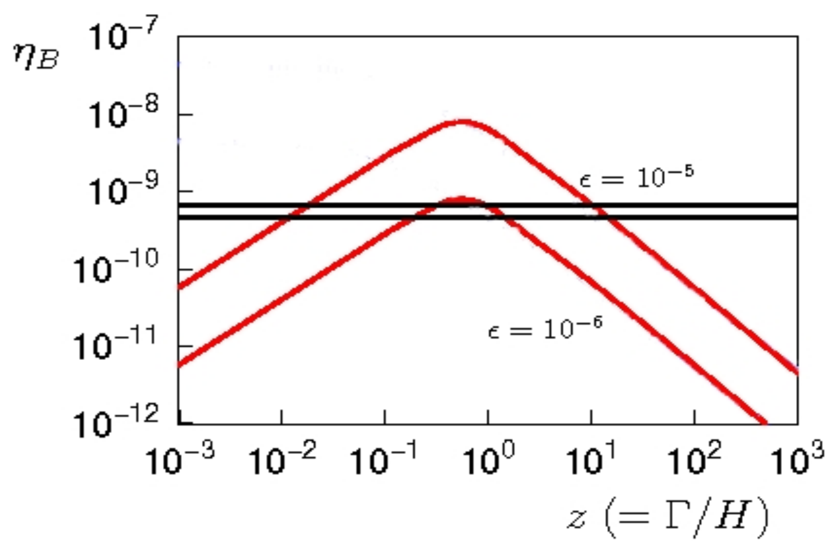
inflation

tiny fraction
of a second

380,000
years

13.7
billion
years

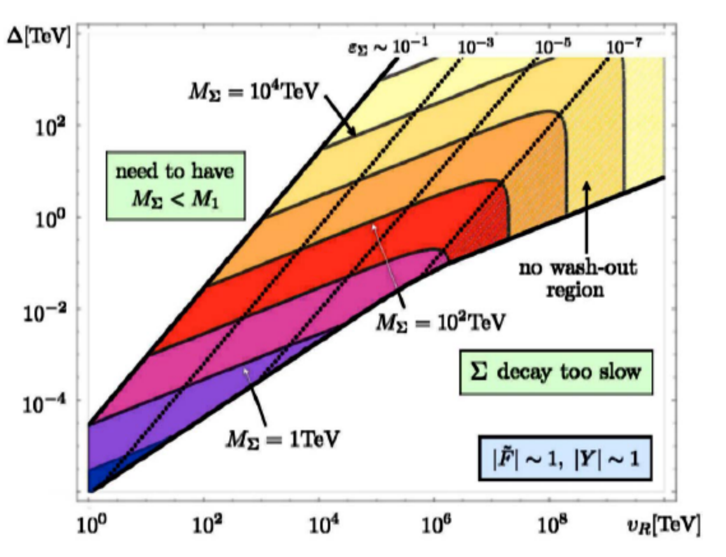
# THERMAL SEESAW LEPTOGENESIS



From PRD77 (2008) 055002

**Sakharov, KRS,Fukugita,Yanagida**

Low-scale LG in non-minimal seesaw

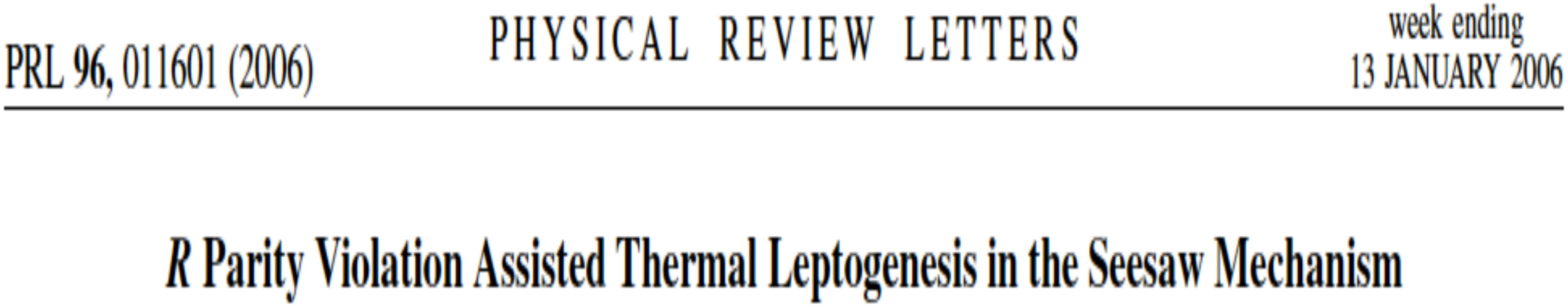


**BUT inconsistency with BBN**

Kawasaki, Kohri & Moroi, PRD71 (2005) 083502

**Gives lower bound on M1**

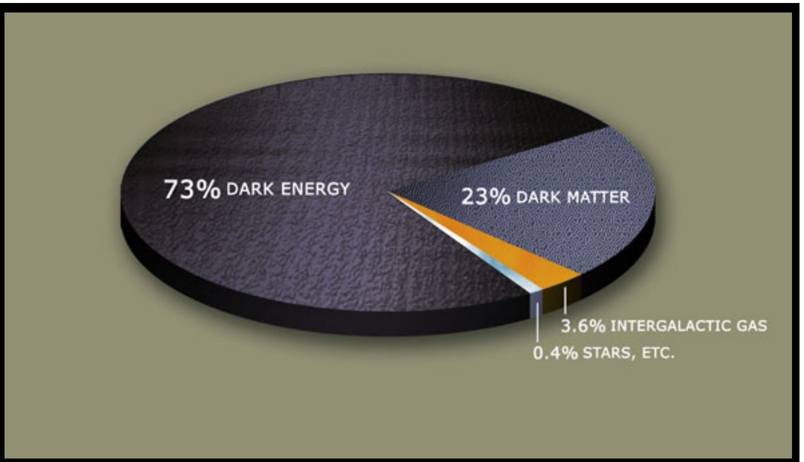
Dirac phase suffices



PRL 96, 011601 (2006) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2006

## *R* Parity Violation Assisted Thermal Leptogenesis in the Seesaw Mechanism

# Even if not the source neutrinos may give the clue to DM

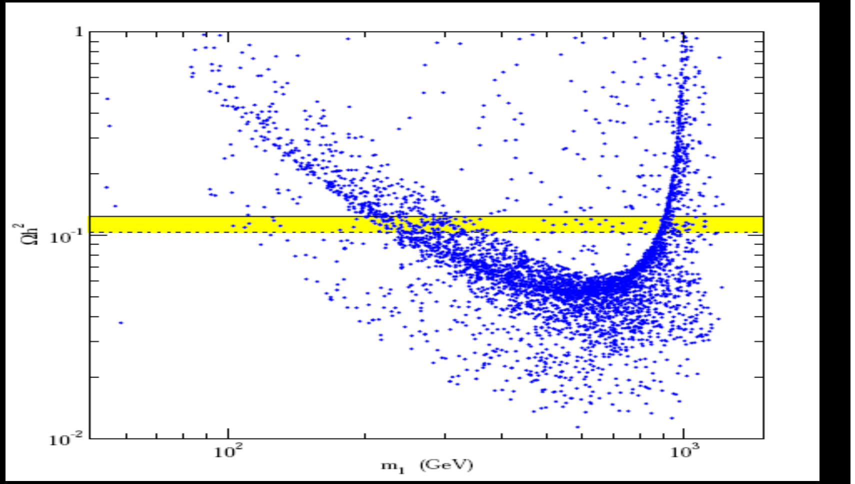


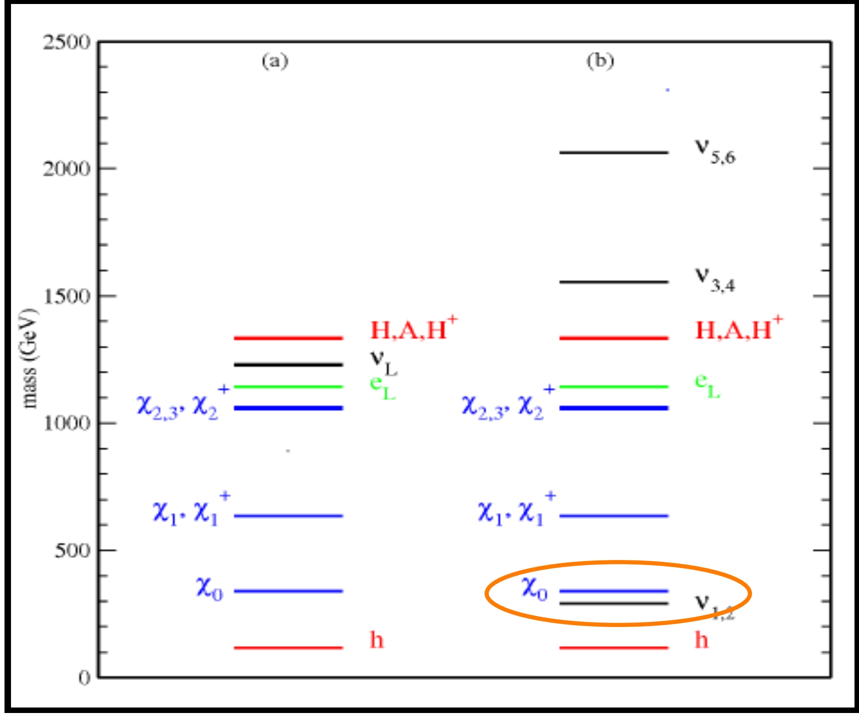
**Neutrinos masses may change the SUSY spectrum : e.g. in inverse seesaw**

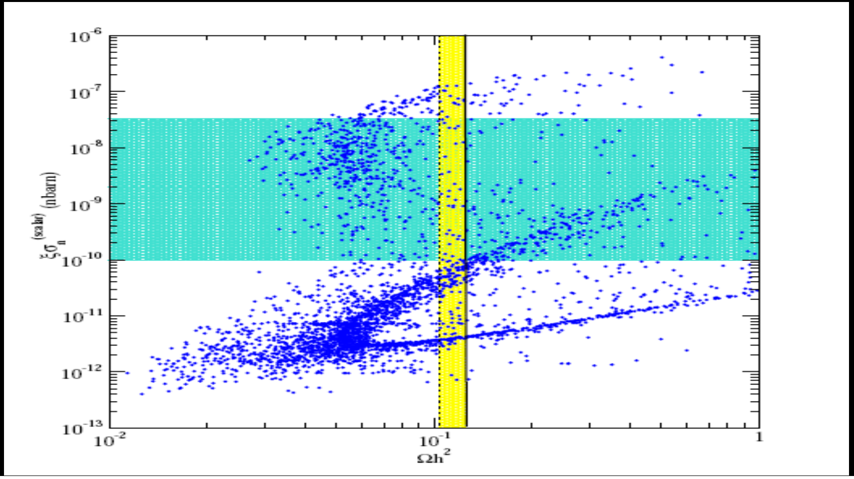
**one may have SNEUTRINO-like DM**

Arina & al PRL101 (2008) 161802

Bazzocchi, Cerdeno, Munoz, Valle, PRD81:051701,2010







# Gravity → No DM strictly stable

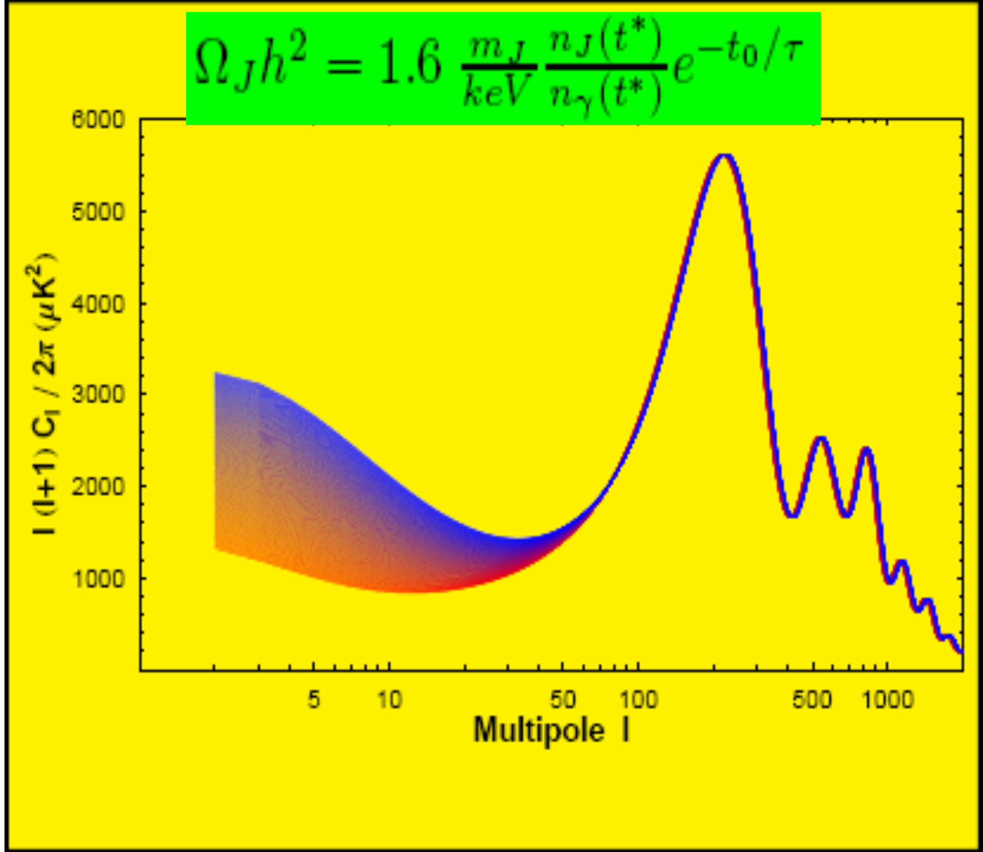
Coleman 88, Kallosh, Linde, Susskind, Nelson, Seiberg, ...

**Majoron decaying dark matter**

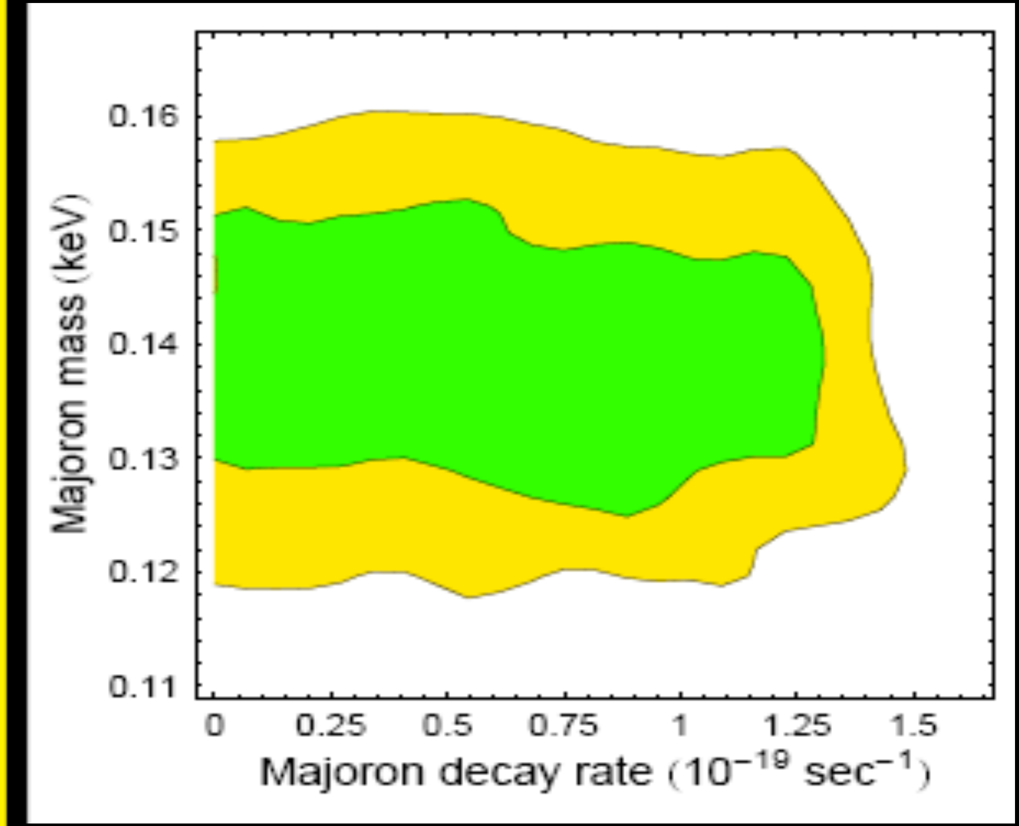
Berezinsky et al PLB318 (1993) 360, PRD57( 1998) 147

**Consistency with CMB**

**Lattanzi & Valle, PRL99 (2007) 121301**



$$\Omega_J h^2 = 1.6\,\frac{m_J}{keV}\,\frac{n_J(t^*)}{n_\gamma(t^*)}\,e^{-t_0/\tau}$$

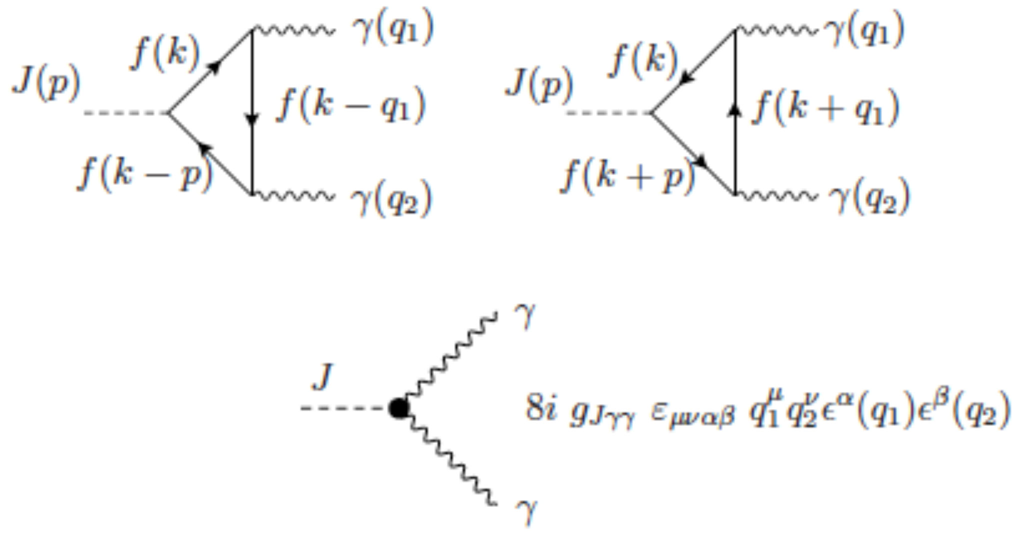


**Bazzocchi & al JCAP 0808 (2008) 013**

**XENIA arXiv:0906.1788**

# TYPE-II SEESAW MAJORON DECAYING-DM

$g_{J\gamma\gamma} J \epsilon^{\nu\mu\rho\sigma} F_{\nu\mu} F_{\rho\sigma}$



**Esteves et al, PRD 82, 073008 (2010)**

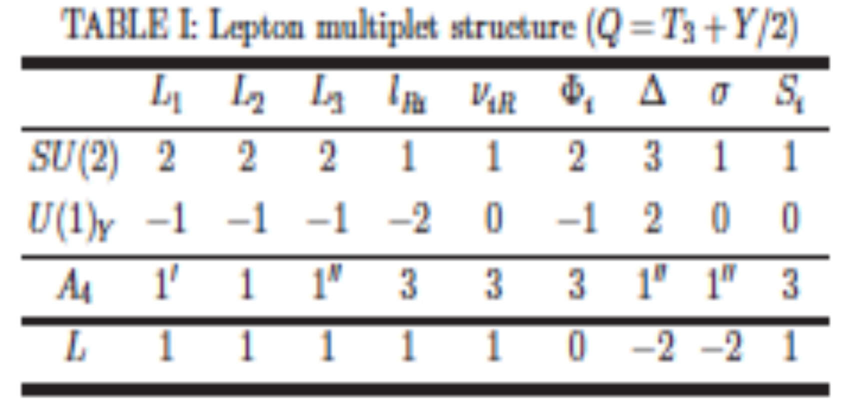
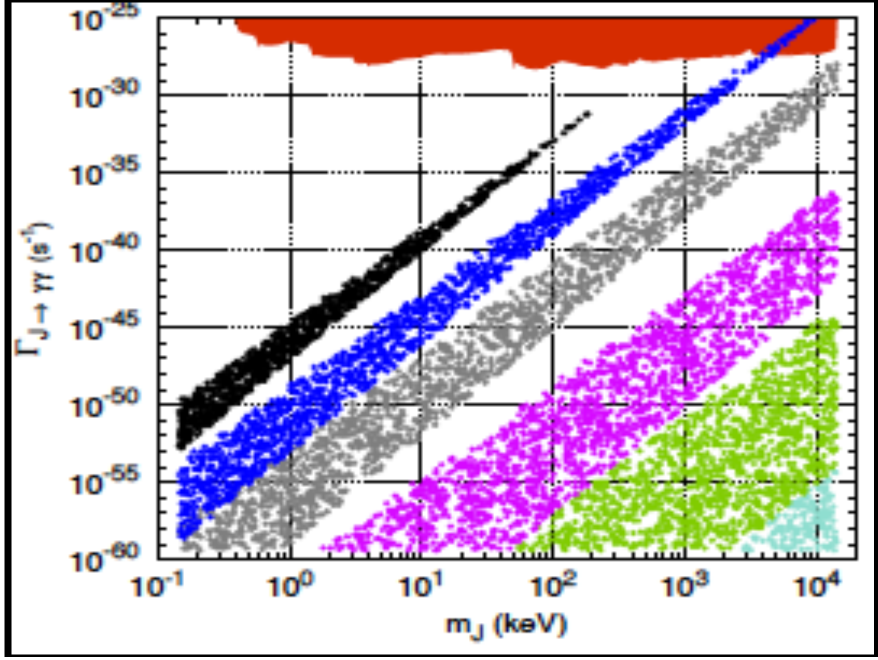
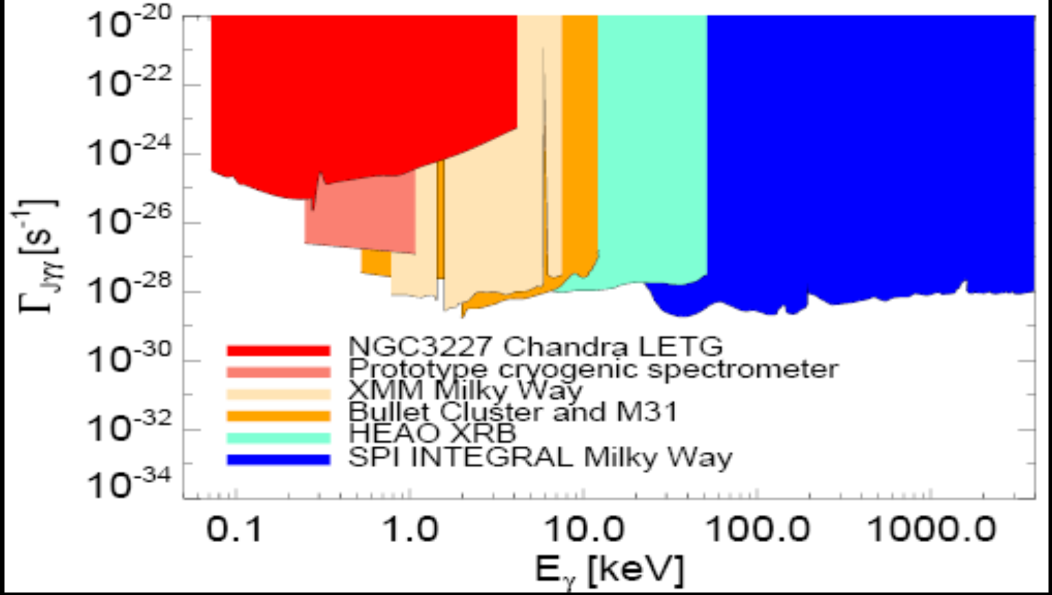


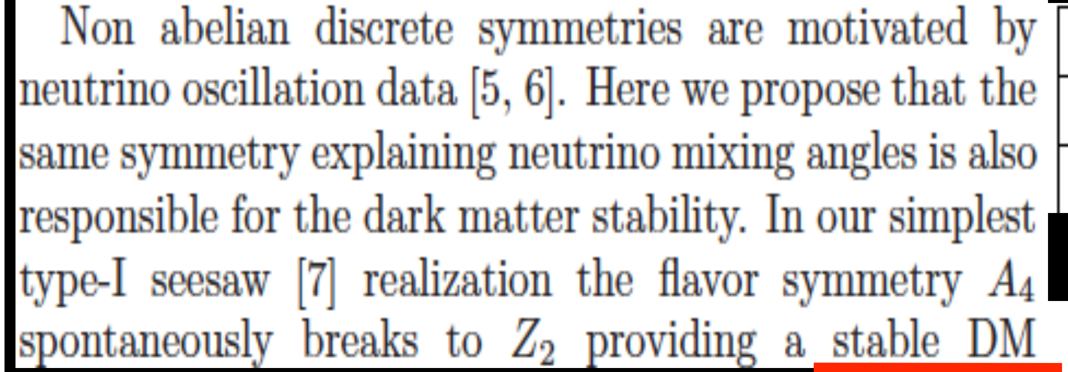
TABLE I: Lepton multiplet structure ($Q = T_3 + Y/2$)

| | $L_1$ | $L_2$ | $L_3$ | $l_{iR}$ | $\nu_{iR}$ | $\Phi_i$ | $\Delta$ | $\sigma$ | $S_i$ |
|---|---|---|---|---|---|---|---|---|---|
| $SU(2)$ | 2 | 2 | 2 | 1 | 1 | 2 | 3 | 1 | 1 |
| $U(1)_Y$ | −1 | −1 | −1 | −2 | 0 | −1 | 2 | 0 | 0 |
| $A_4$ | 1′ | 1 | 1″ | 3 | 3 | 3 | 1″ | 1″ | 3 |
| $L$ | 1 | 1 | 1 | 1 | 1 | 0 | −2 | −2 | 1 |

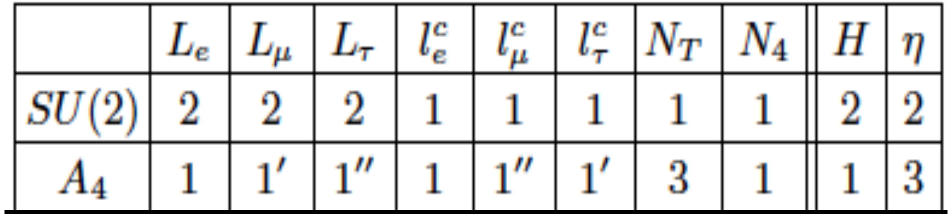




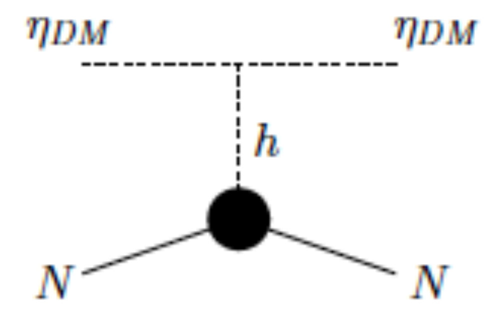
# Discrete dark  matter



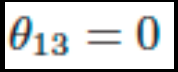
Non abelian discrete symmetries are motivated by neutrino oscillation data [5, 6]. Here we propose that the same symmetry explaining neutrino mixing angles is also responsible for the dark matter stability. In our simplest type-I seesaw [7] realization the flavor symmetry $A_4$ spontaneously breaks to $Z_2$ providing a stable DM



|  | $L_e$ | $L_\mu$ | $L_\tau$ | $l_e^c$ | $l_\mu^c$ | $l_\tau^c$ | $N_T$ | $N_4$ | $H$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $SU(2)$ | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| $A_4$ | 1 | $1'$ | $1''$ | 1 | $1''$ | $1'$ | 3 | 1 | 1 | 3 |



Inverse hierarchy



$\theta_{13} = 0$

**Just an example !!**

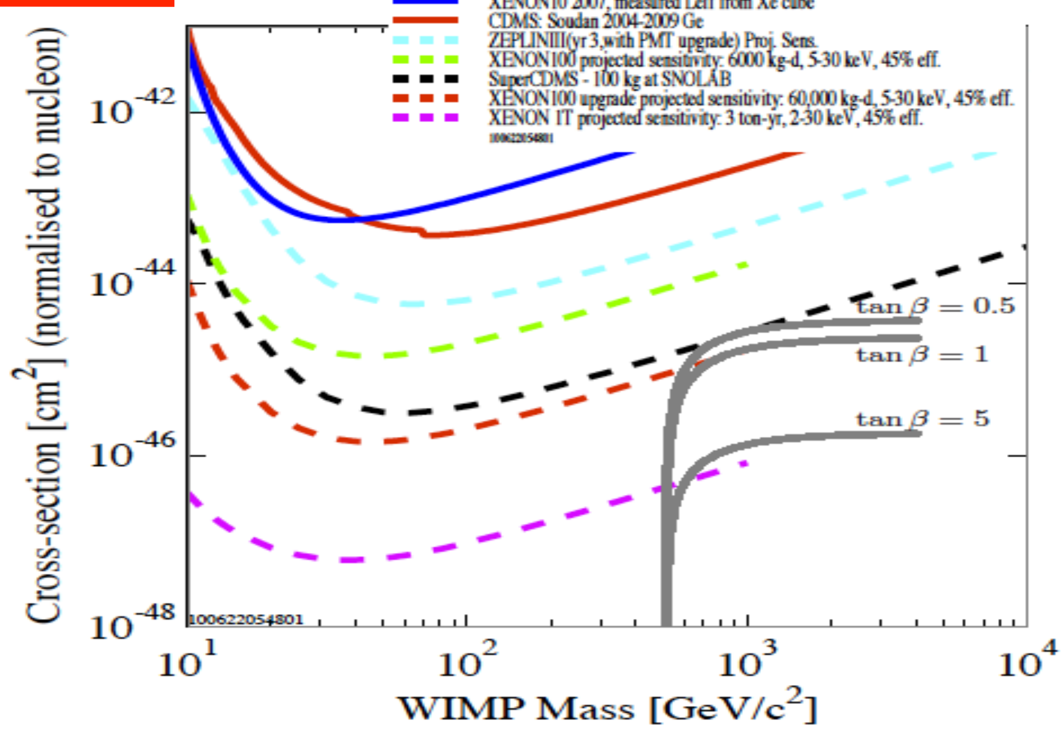
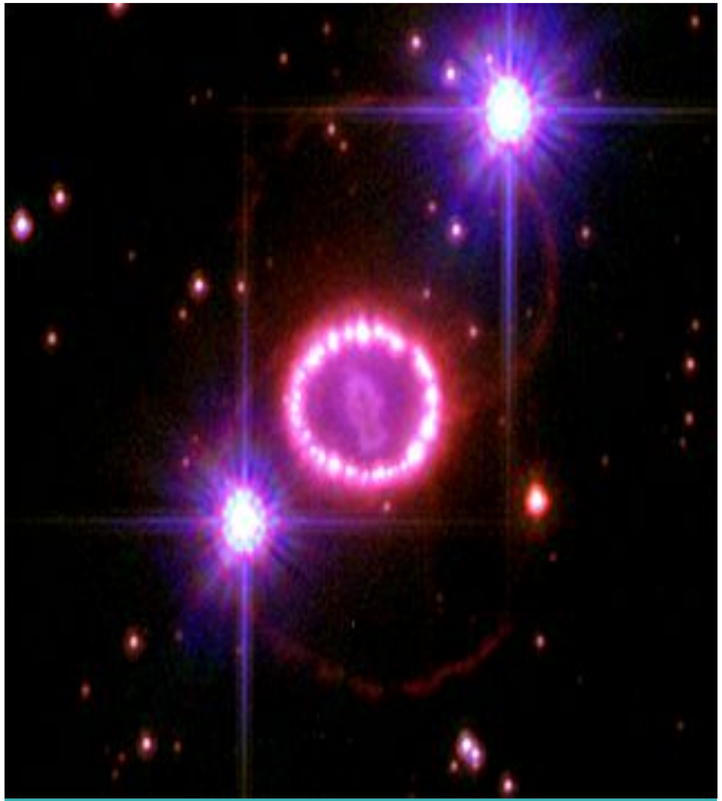
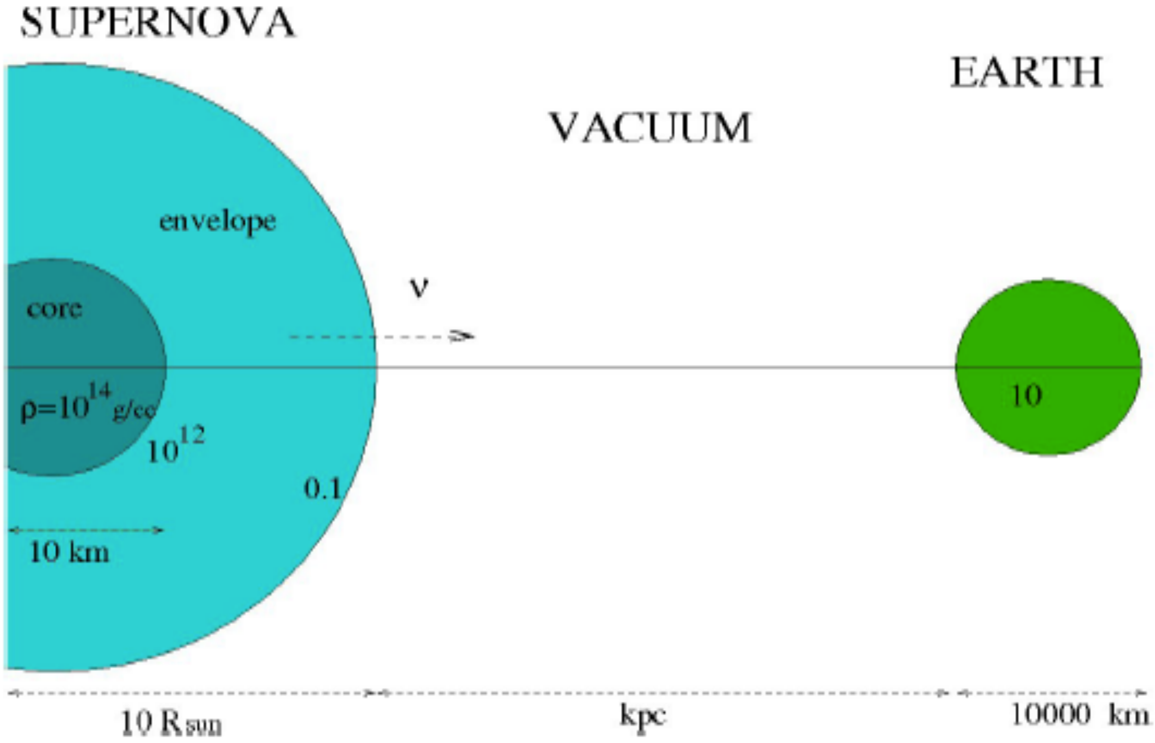
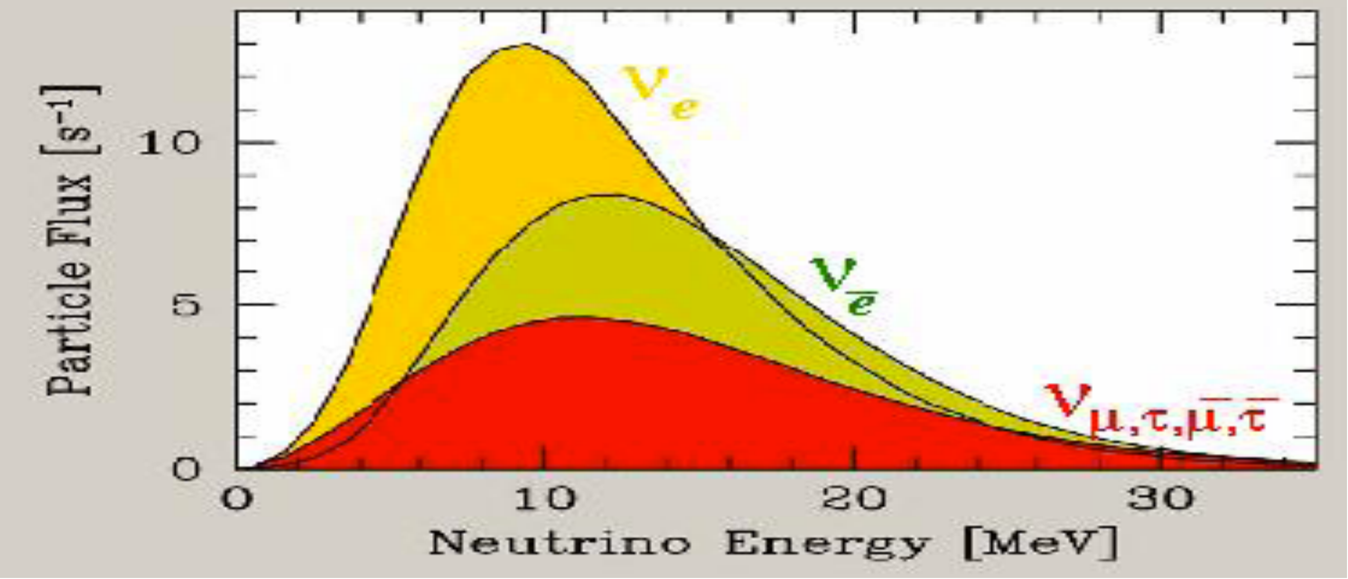


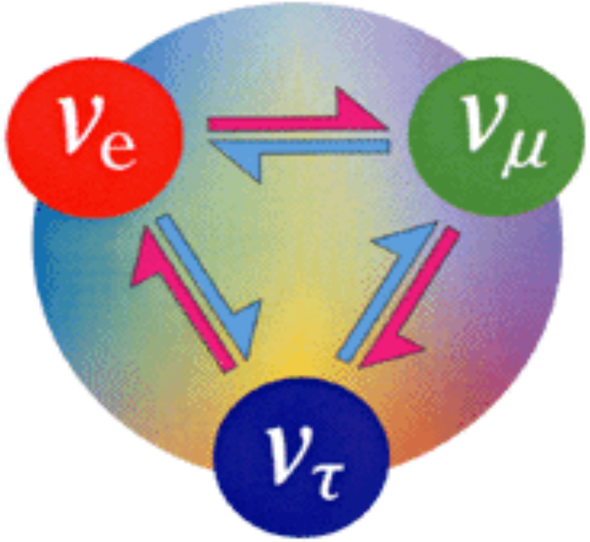
FIG. 2: Elastic DM scattering cross section with a nucleon versus DM mass. We compare present [16, 17] and future [18, 19] sensitivities with our model expectations, for $m_H = 120$ GeV and $\tan\beta = 0.5,\ 1,\ 5$ (grey solid lines).





# NEUTRINO PROPERTIES FROM SUPERNOVAE





# NSI induced flavor conversion near SN-core

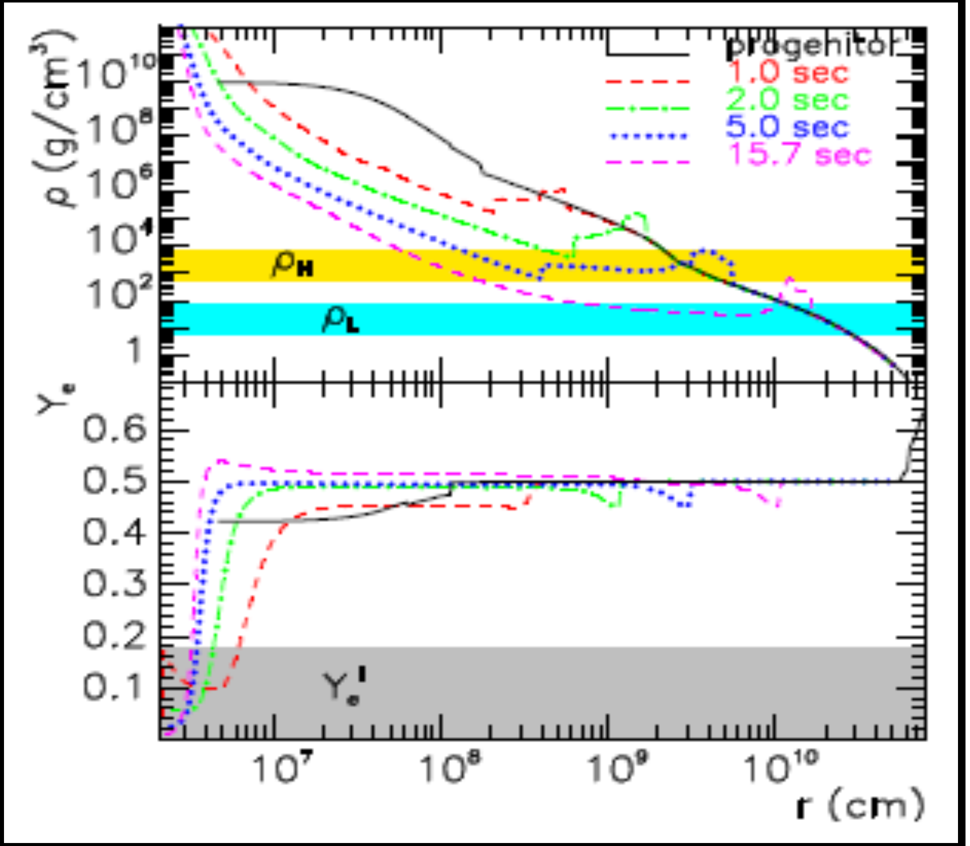
atm

sol

**Interplay between collective effects and non-standard interactions in supernova**

Esteban-Pretel et al PRD76 (2007) 053001 & PRD81 (2010) 063003

NSI



## OSCILLATIONS MAINLY ROBUST but NEED TO GO BEYOND

**THE ORIGIN OF NEUTRINO MASS REMAINS A MYSTERY**

**NSI and LFV searches help distinguish the heavy from light messenger models**

**in low-scale seesaw models, e.g. inverse & linear, messengers may be produced**

**SUSY ORIGIN OF NEUTRINO MASS TESTABLE AT LHC**

**DISPLACED VERTEX searches probe neutrino mass scale**
**LSP DECAY PATTERN probes neutrino mixing**

**STILL DO NOT UNDERSTAND FLAVOR**
**flavor models correlate LFV phenomena & oscillations**
**if flavor is linked to unification, hard to reconcile lepton & quark mixings**

**NEUTRINOS -- COSMO CONNECTION (not covered)**

- **thermal LEPTOGENESIS from low-scale seesaw**
- **sneutrinos as DARK MATTER in inverse seesaw**
- **DARK MATTER stabilized by neutrino flavor symmetry**
- **majoron as Decaying DARK MATTER**

# THANK YOU

next are BACKUP slides