Standard and Non-Standard Neutrinos

J. W. F. Valle

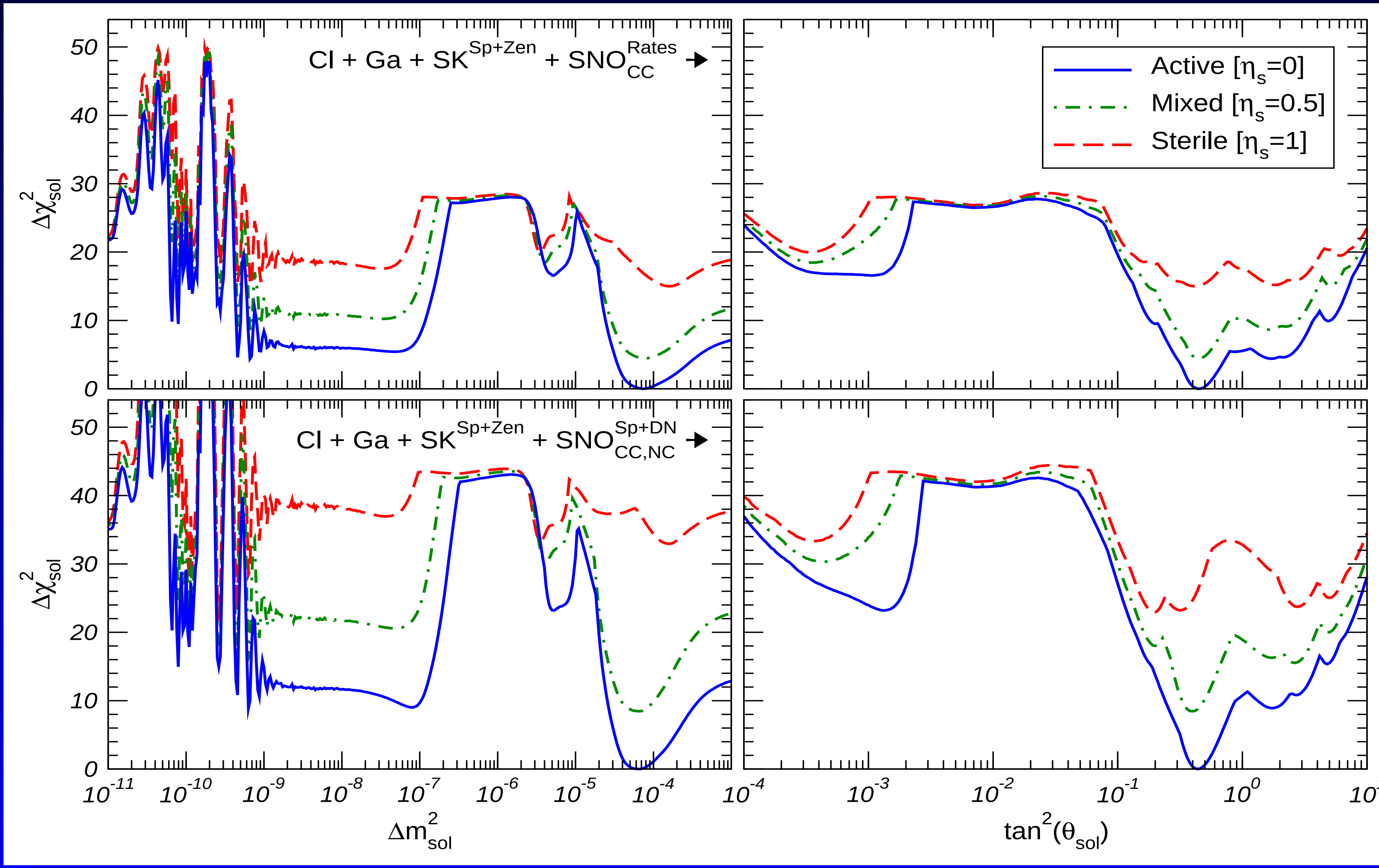
http://ific.uv.es/˜ahep.

Outline

- masses and mixings
- from current oscillation experiments
- neutrinos as astrophysics probe
- ... from first principles ...
- Non-Standard nu-Interactions
- robustness of atmospheric oscillations
- other solar neutrino solutions: NSI ...
- The future

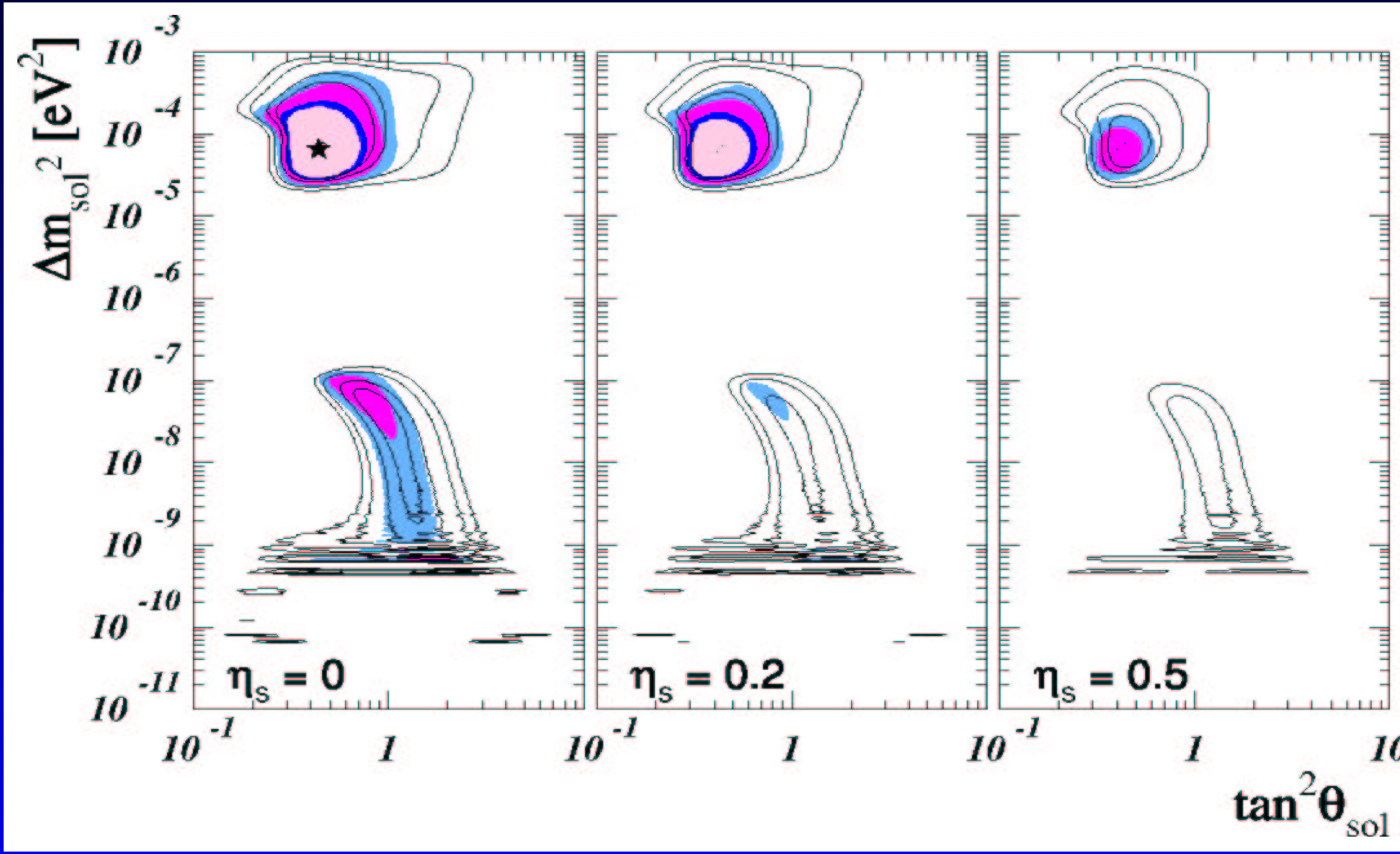
solar nu's before & after SNO-NC

Maltoni et al, hep-ph/0207



solar-nu oscillations

Maltoni et al hep-ph/0207



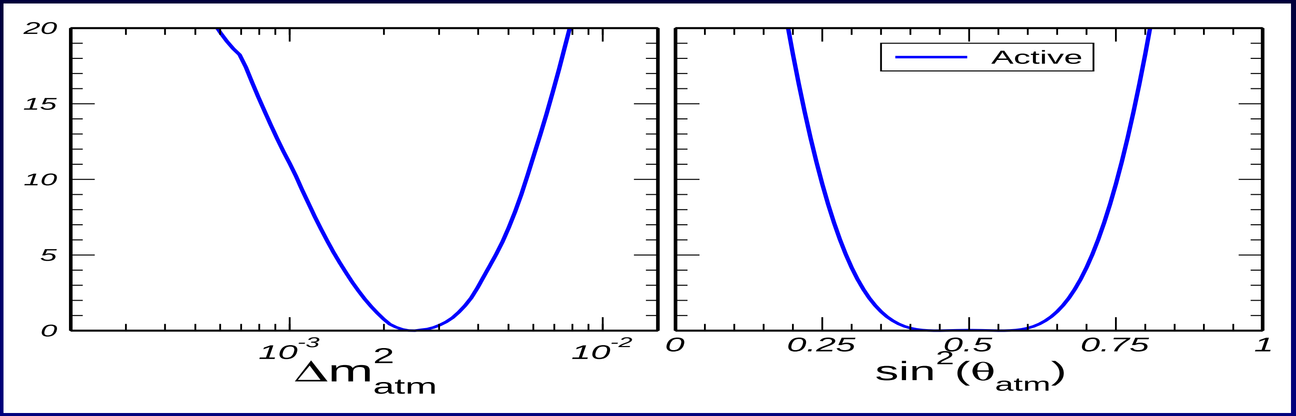
Solar update

Maltoni et al 2002

Region	$\tan^2\theta_{\rm sol}$	$\Delta m^2_{\rm sol}$	$\chi^2_{\rm sol}$	g.o.f.
LMA	0.44	6.6×10^{-5}	66.1	83%
LOW	0.66	7.9×10^{-8}	75.1	57%
VAC	1.7	6.3×10^{-10}	75.0	57%
SMA	1.3×10^{-3}	5.2×10^{-6}	89.3	18%

reactor + atmo oscillations **Maltoni et al 2002**

upd of Fornengo et al PRD65 (2002) 013010



$\sin^2\theta_R \leq 0.045$ at 99% CL 1dof

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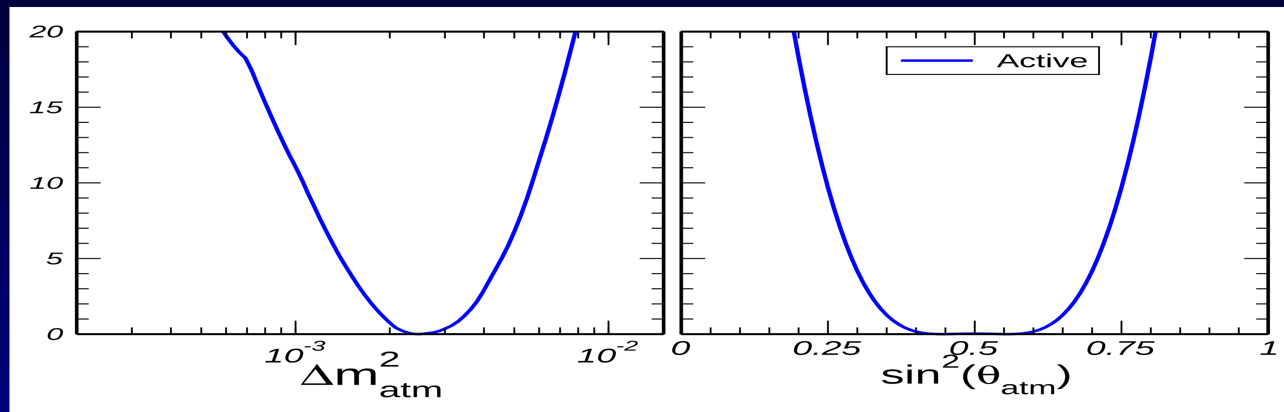

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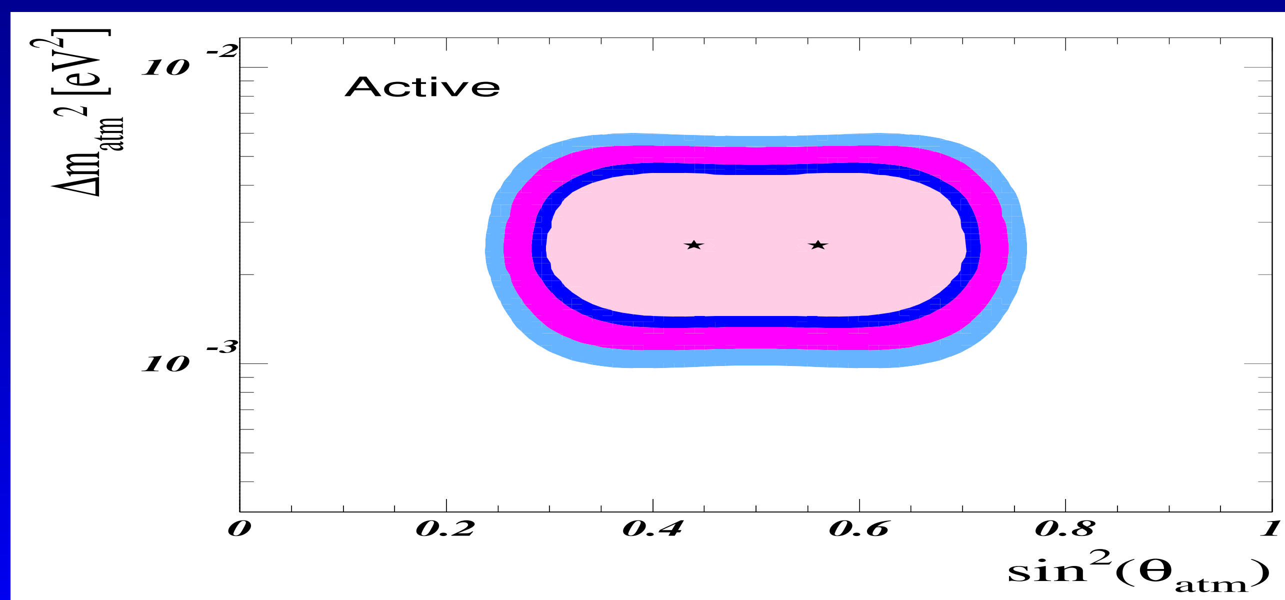

neutrinos as astro probe

- large angle oscillations affect $\bar{\nu}_e$ SN-signal

  Smirnov, Spergel, Bahcall 94; Raffelt et al 96, Kachelriess et al JHEP 0101 (2001) 030

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  Kachelriess et al PRD65 (2002) 073016

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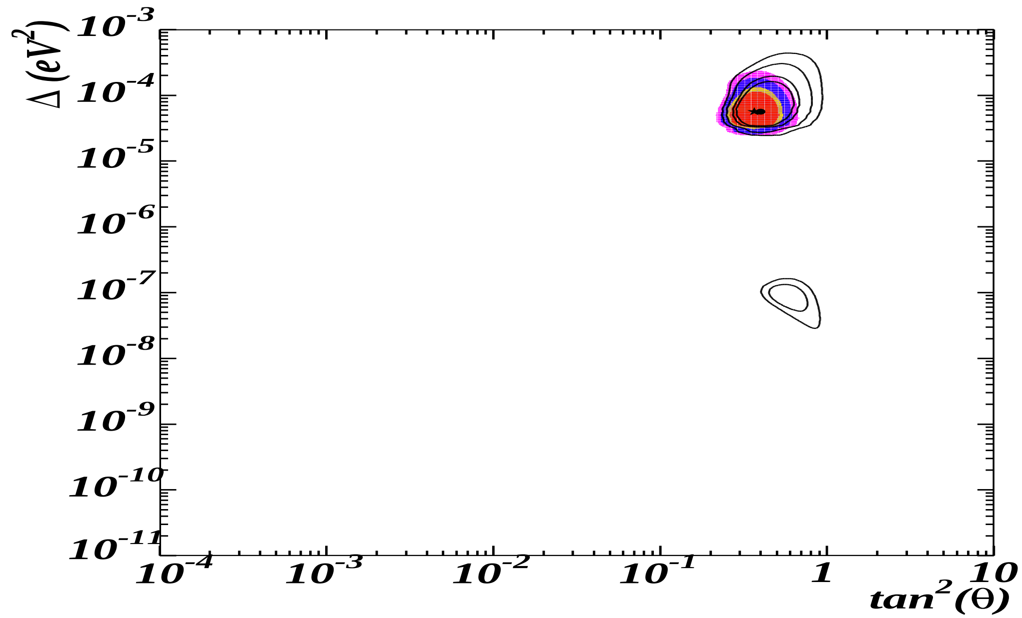
- "standard" SN input, $E_{\bar{\nu}_e}$=14, $E_{\rm bind}$=3, $\tau \equiv T_{\nu_h}/T_{\bar{\nu}_e}$=1.4



thanks to Strumia

LMA may remain best

neutrinos as astro probe future SN

use effect of large mixing on $\bar{\nu}_e$ signal to probe $\tau \equiv T_{\nu_h}/T_{\bar{\nu}_e}$

Minakata, Nunokawa, Tomàs, J. V. hep-ph 0112160

assume 10 kpc gal SN, simulate data with given $\langle E^0_{\bar{\nu}_e} \rangle,\ \tau^0,\ E^0_b$

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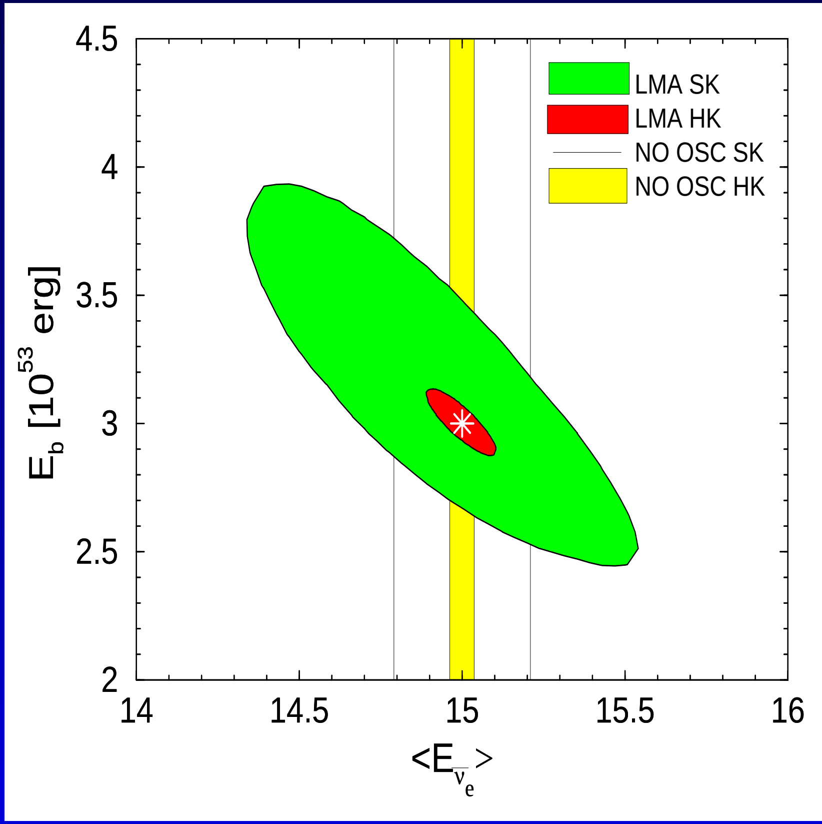

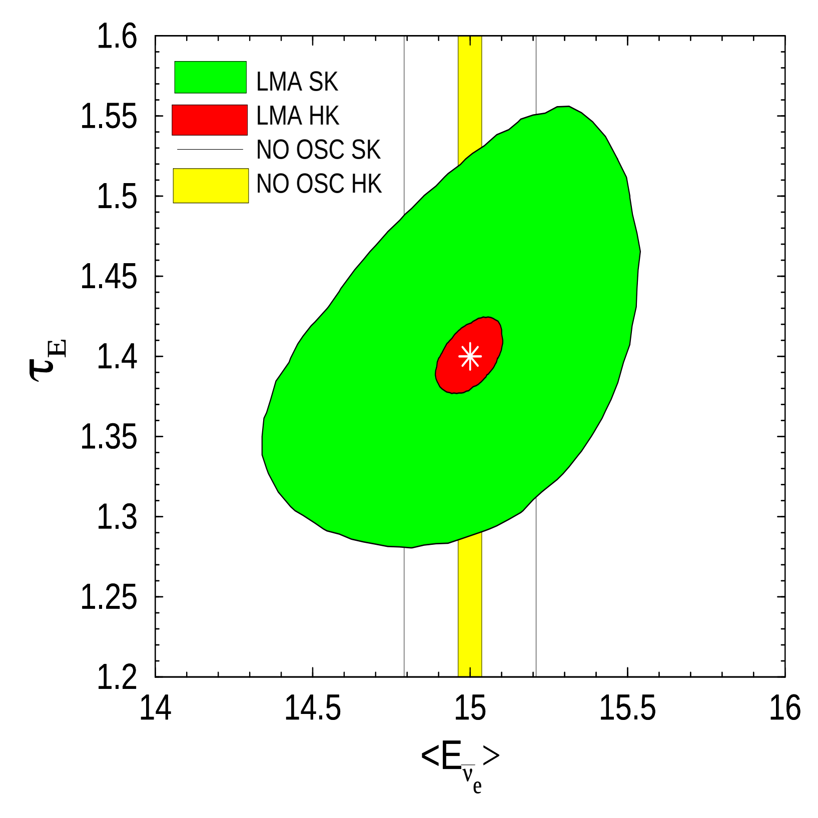

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simplest gauge theory mixing matrix

- 3 angles θ

  1 KM-like

  + 2 extra phases + ... $\beta\beta_{0\nu}$

23=A 12=S 13=R

ϕ_R

ϕ_1 , ϕ_2

Schechter, JV PRD22 (1980) 2227

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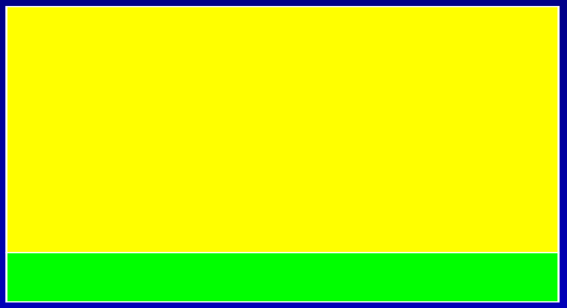
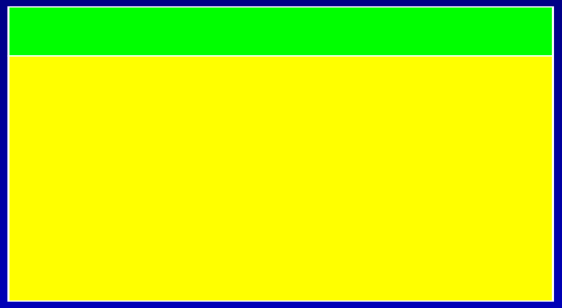
  Schechter, JV PRD22 (1980) 2227

- max θ_A, large θ_S & small θ_R — hierarchical splittings

N 

I 

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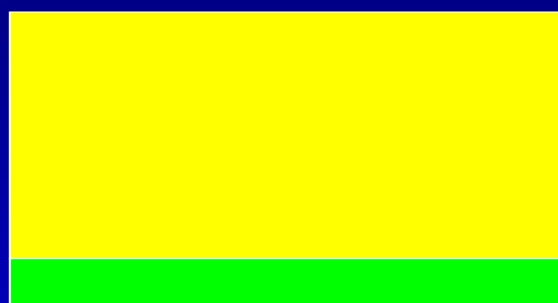
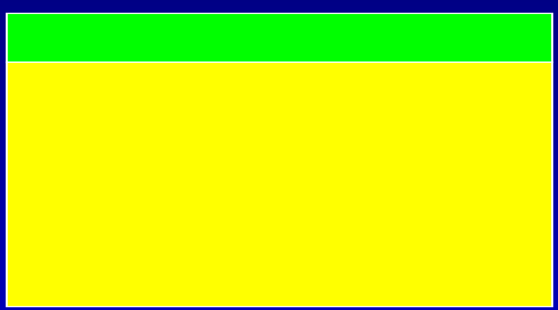
N 

I 

- leptonic CPV will be a challenge !

  "Dirac" CPV disappears when $\Delta_S \to 0$ PRD21 (1980) 309

  "Majorana" CPV is V-A suppressed PRD23 (1981) 1666

oscillations from first principles

predicting nu-mass and mixing?

- 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

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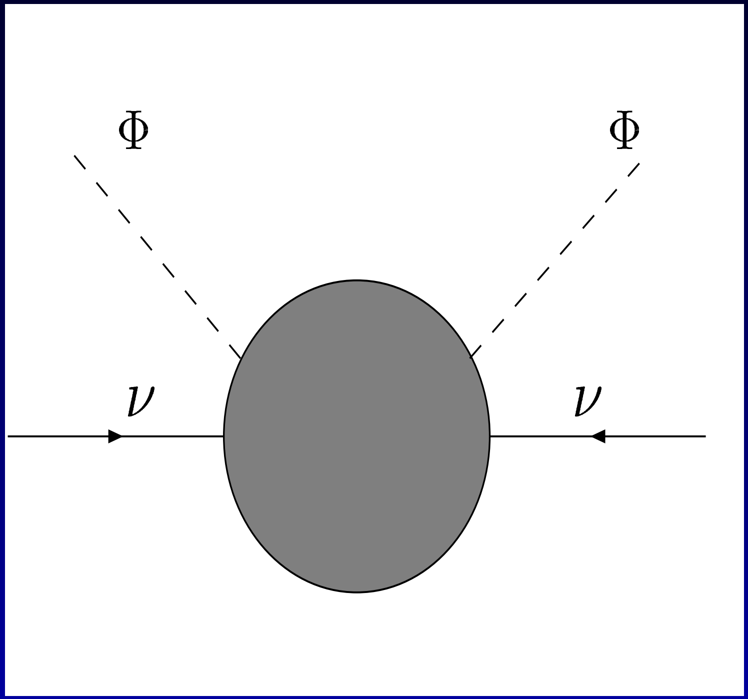
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- no theory of flavour

neutrino mass theories

2 approaches: top-down and bottom-up

hierarchical vs quasi-degenerate spectra

basic dim-5 operator



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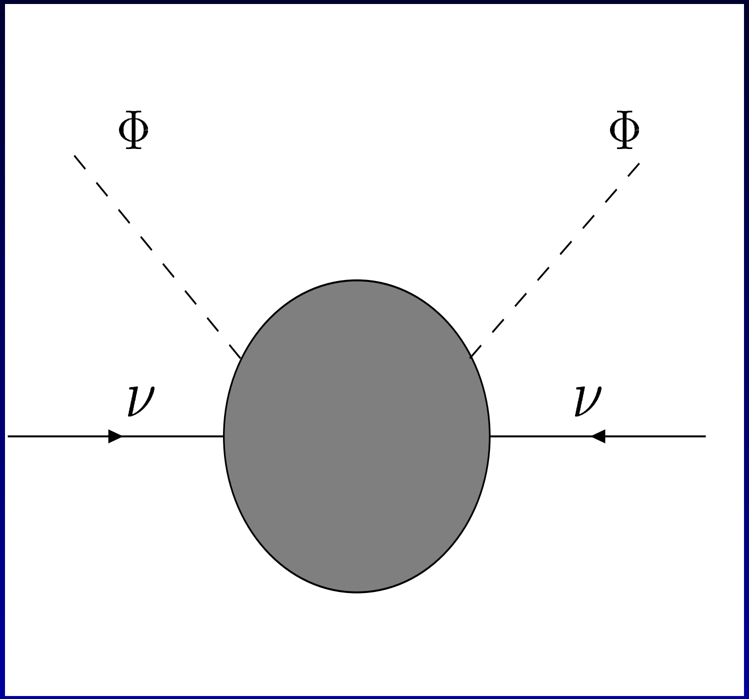
- 

- from Gravity

Weinberg; Barbieri, Ellis, Gaillard; Akhmedov et al

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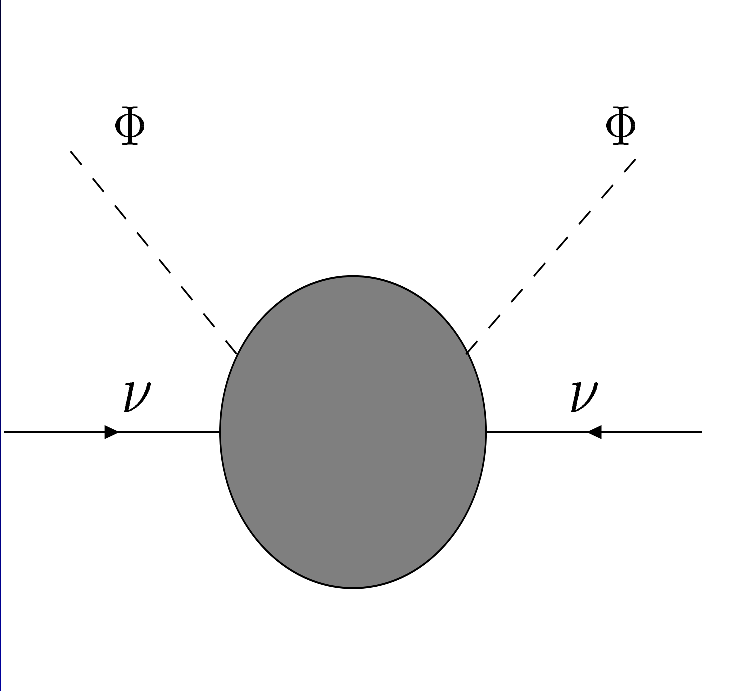
- 

- from Gravity

Weinberg; Barbieri, Ellis, Gaillard; Akhmedov et al

- from seesaw schemes

Gell-Mann, Ramond, Slansky; Yanagida;

Mohapatra, Senjanovic; Schechter, Valle

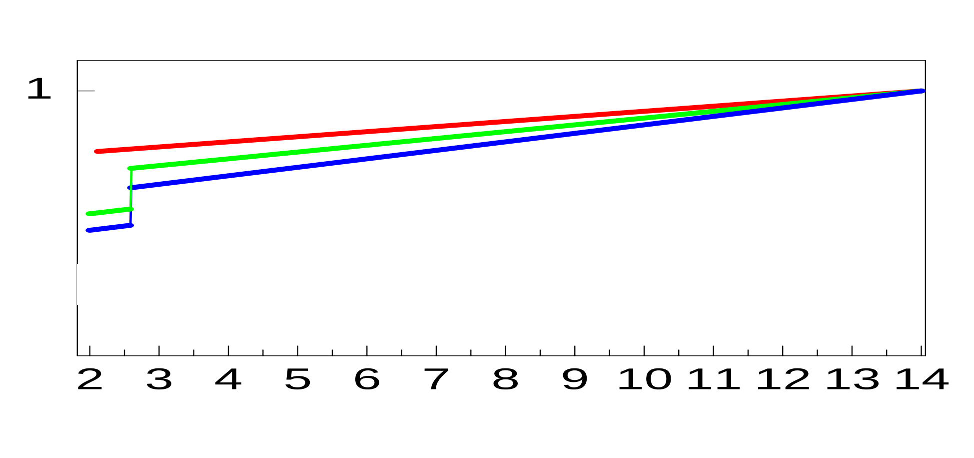
King's talk @ Nu2002 here I consider at an effective level

neutrino unification

Babu, Ma & JV hep-ph/0206292

- due to symmetry (A_4) nu-masses unify when they run up

Chankowski, Ioannisian, Pokorski & JV PRL 86 (2001) 3488



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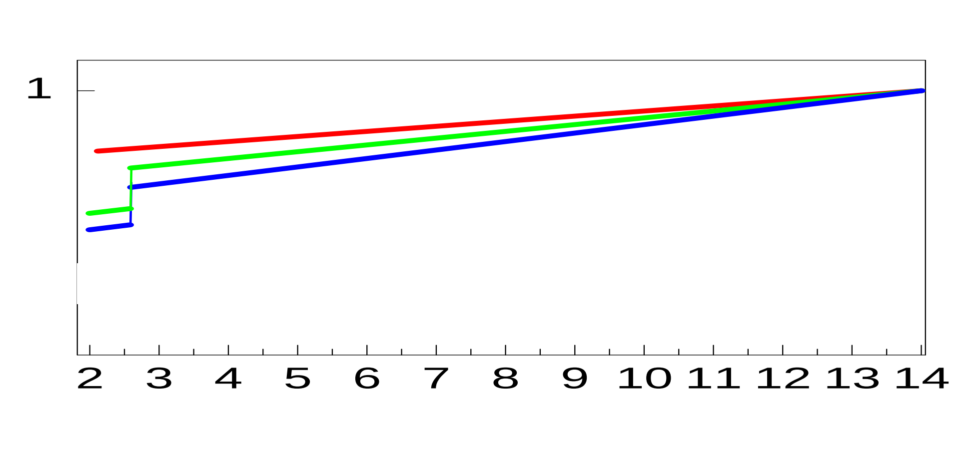

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effects in cosmology, β and $\beta\beta_{0\nu}$ decays

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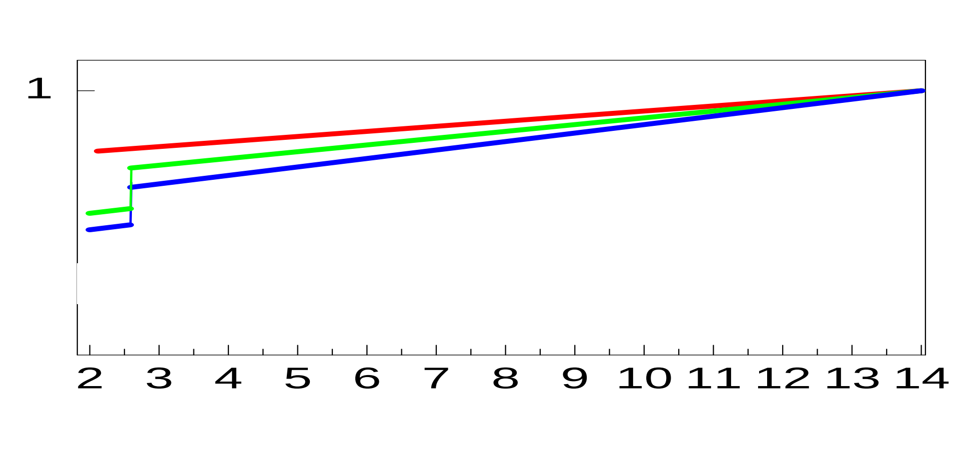

- nu-splittings and KM mixing from RGE + thr effects in cosmology, β and $\beta\beta_{0\nu}$ decays

- $B(\tau \to \mu\gamma) \gtrsim 10^{-6}$

minimalism

Gouvea & JV PLB501 (2001) 115

- based on 3 + 1 scheme

S & V PRD21 (1980) 309

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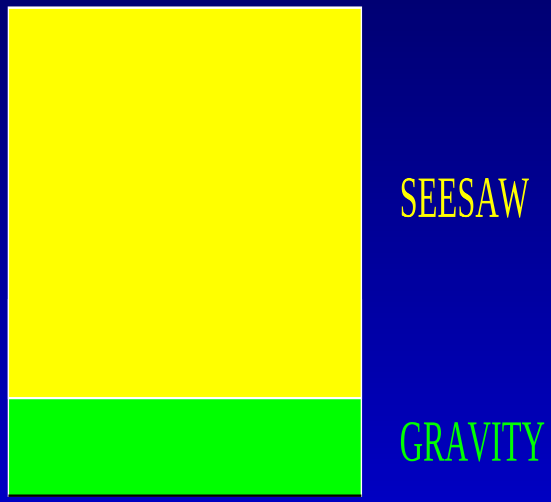

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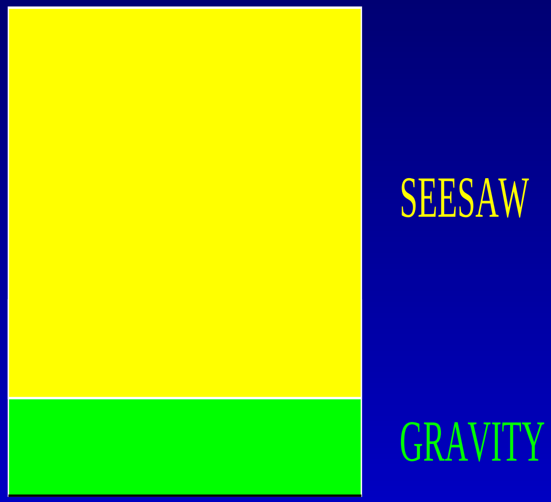

-
- $\rightarrow$ **seasonal effects**

U(1) family symmetries

Nardi et al PLB492 (2000) 81

quark and lepton mixing from textures

U(1) symmetry gives simplest bi-linear RPV SUSY model:

$W = W_{MSSM} + \mu_\alpha \ell_\alpha H_u$

giving common origin for μ-problem & nu-anomalies

$\mu_0 \sim m_{3/2}\theta$ Giudice-Masiero

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2 massless nu's after RPV-seesaw degeneracy lifted by loops

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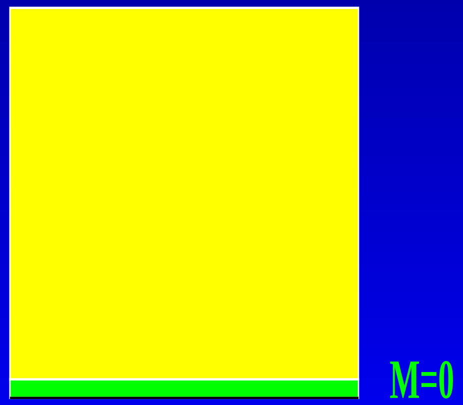

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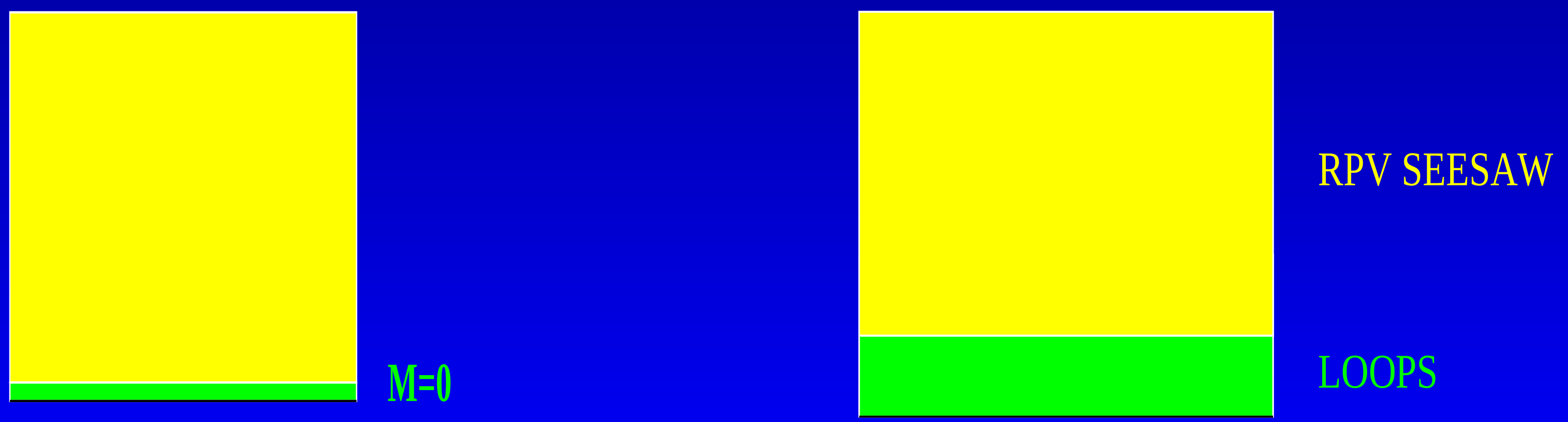

RPV as origin of neutrino masses

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

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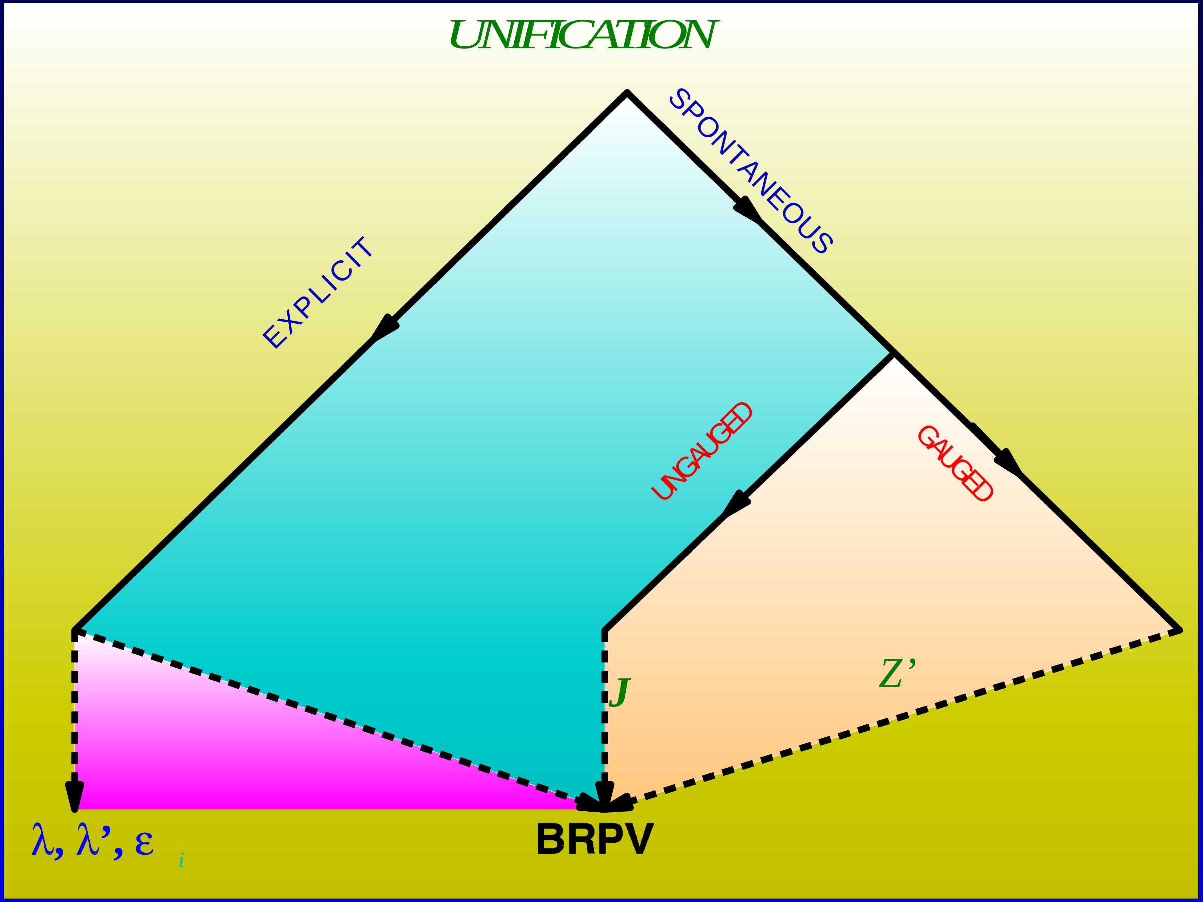

BRPV soln to nu-anomalies

Hirsch et al PRD62 (2000) 113008 & PRD61 (2000) 071703

- arises automatically if RPV spontaneous

  Masiero, JV PLB251 (1990) 273

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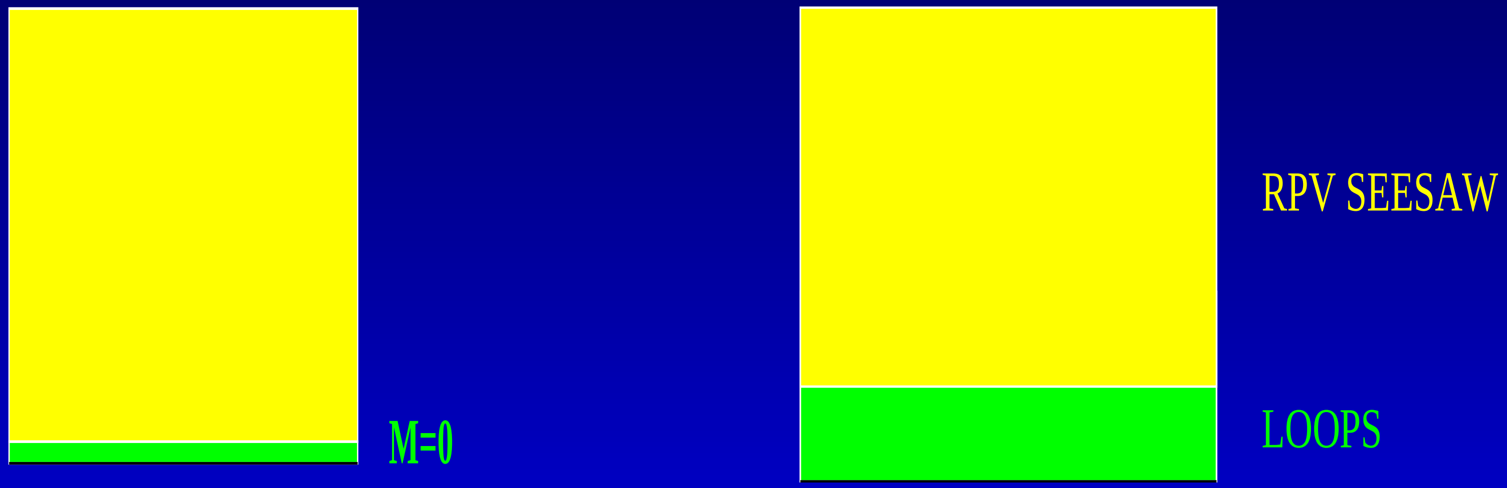
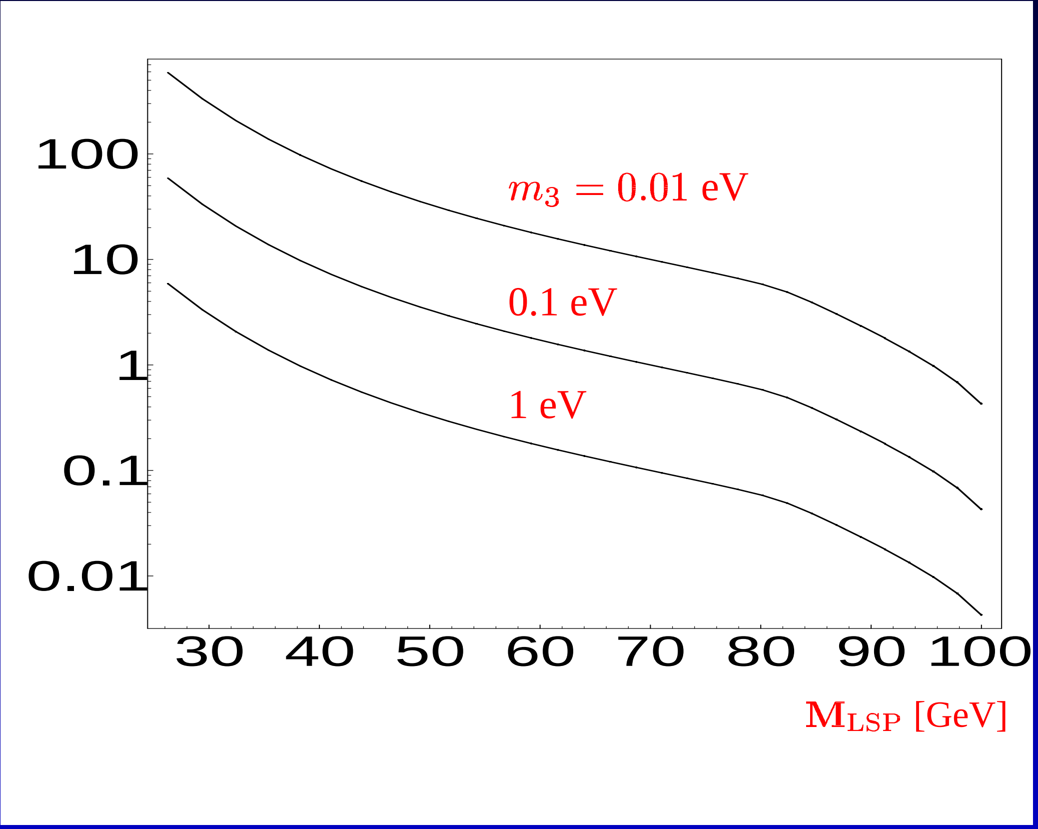
- hierarchical nu-masses



LSP decay length [cm]: BRPV

from Bartl et al NPB 600 (2001) 39

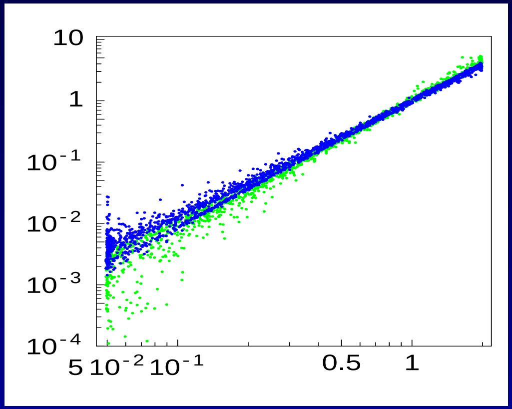


Mukhopadhyaya, Roy & Vissani; Chun & Lee; Choi et al; Datta et al

neutrino mixing angles in BRPV

Hirsch et al PRD62 (2000) 113008

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



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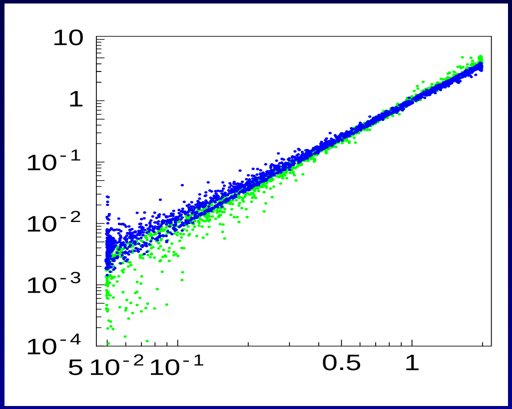
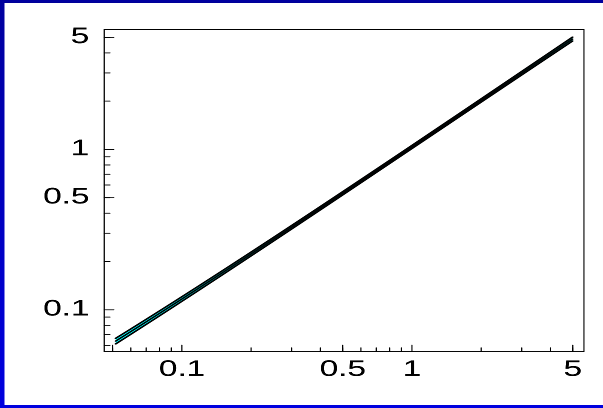


tested in Sparticle decays

LSP decays probe ATM $\frac{\chi\to\mu qq}{\chi\to\tau qq}$ Porod etal PRD63 (2001) 115004



Stop decays trace SOL Restrepo et al PRD64 (2001) 055011

Life beyond oscillations ??

Non-standard interactions more

- dim-4 renormalizable (eg CC & NC)

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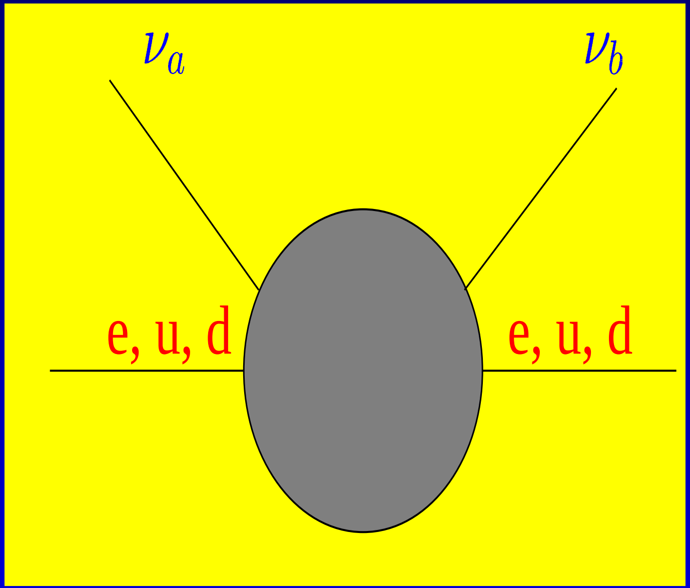


- affect nu-propagation

good atm-contained fit, G-G et al PRL82 (1999) 3202

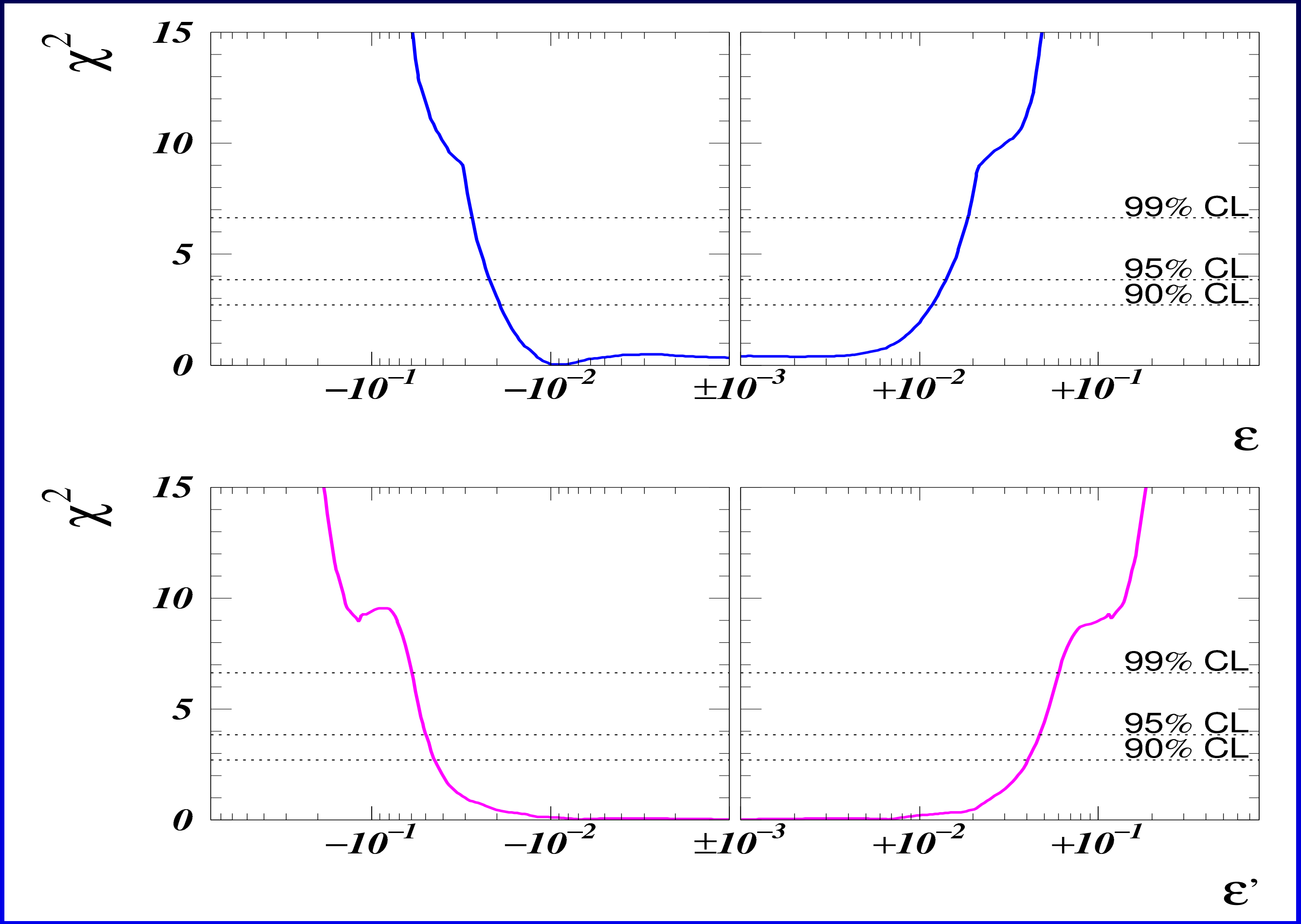
more...

How robust are Oscillations ??

atmospheric bounds on NSI

Fornengo, Maltoni, Tomàs & J. V. PRD65 (2002) 013010

bounds on FC and NU nu-interactions

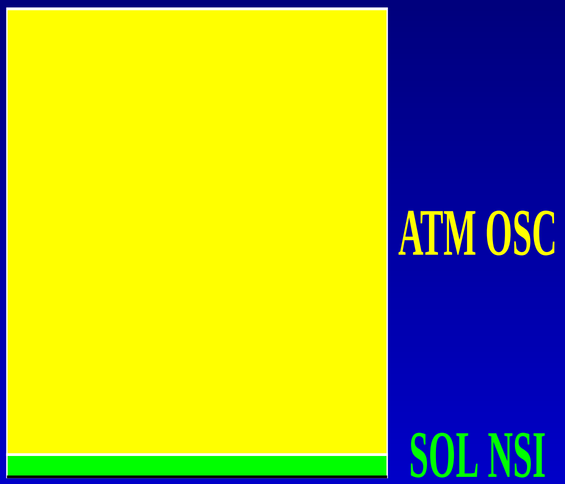


alternatives to oscillations?

at least two viable ones for SNP ... SFP

hybrid NSI soln to nu-anomalies

post-SNO-NC global fit   upd of Guzzo et al NPB629 (2002) 479



no solar splitting nor mixing needed

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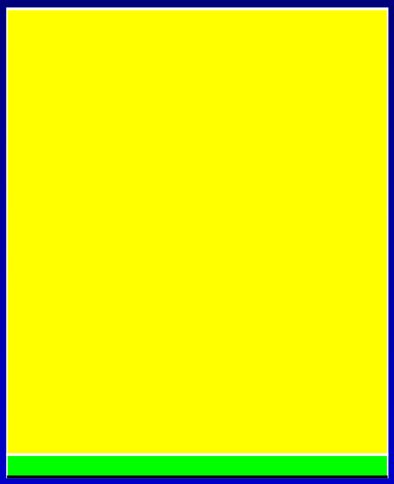

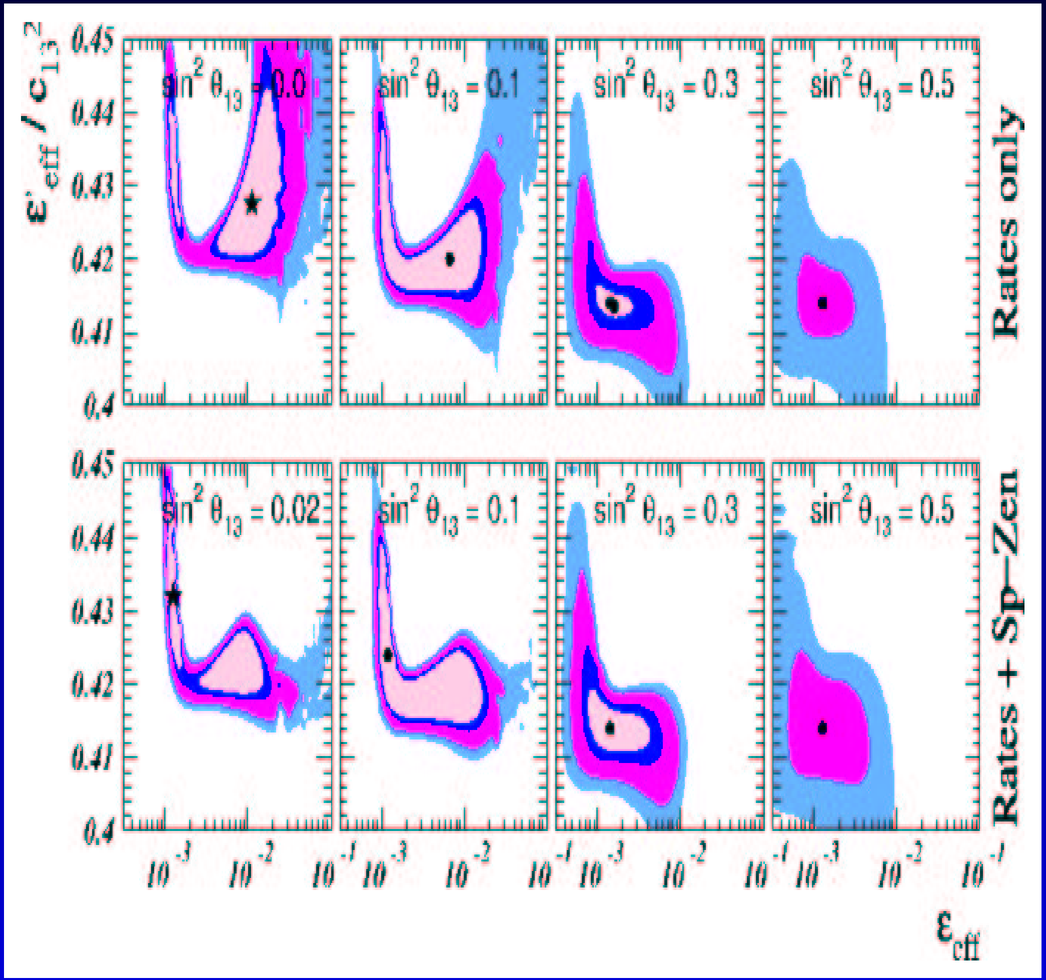

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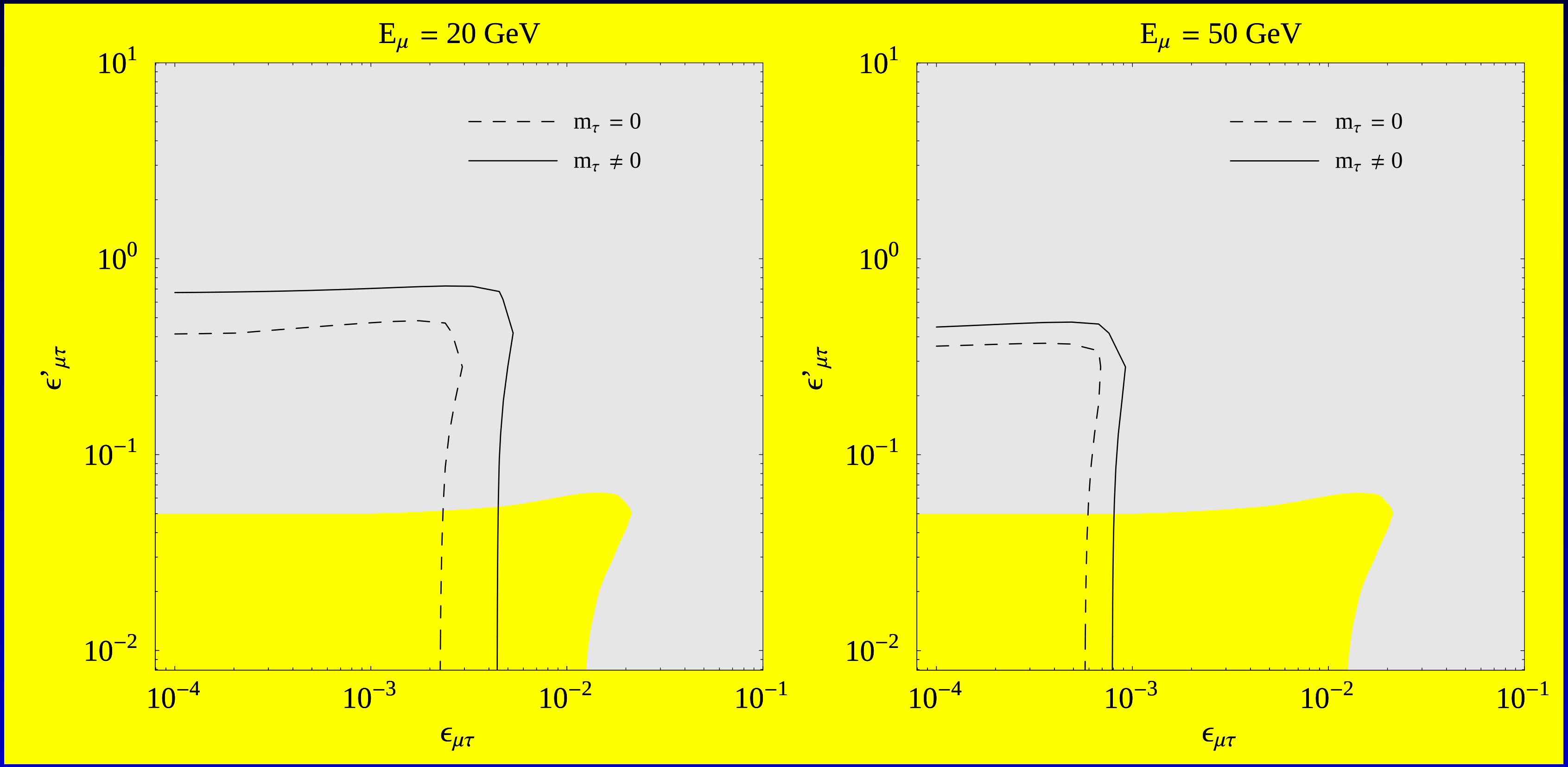
Improved FC-tests at NuFact

from Huber & JV PLB523 (2001) 151



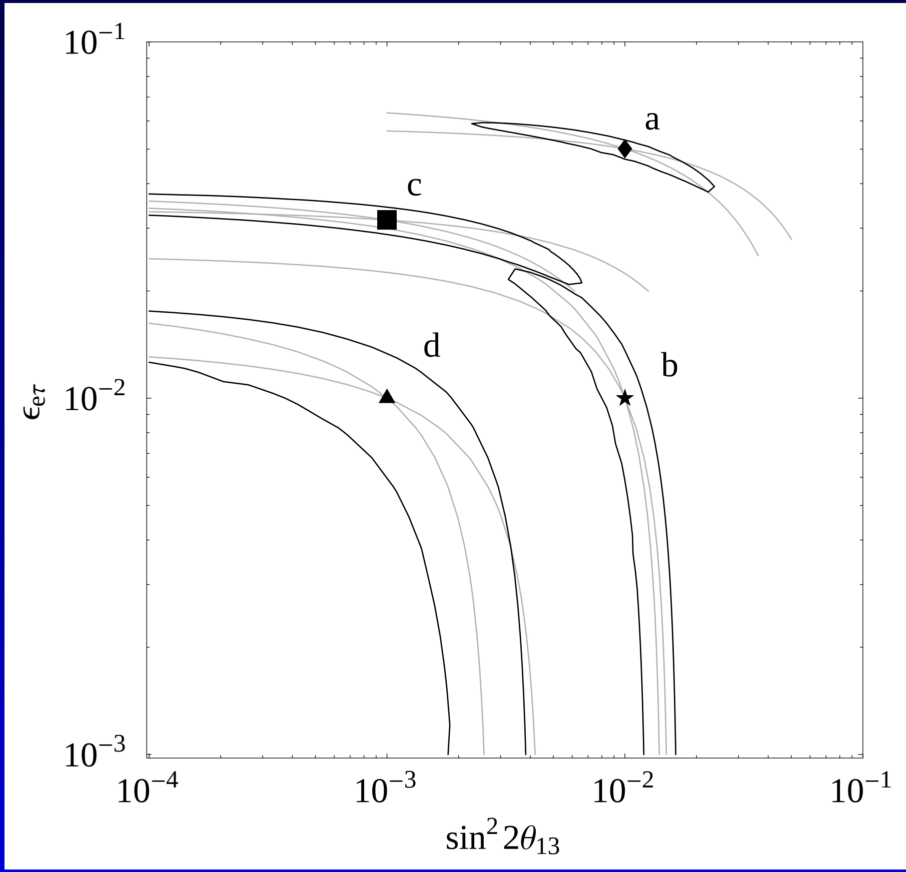
L = 732 km 10 kt detector, .33 ν_τ detection eff above 4 GeV

need no tau charge id

FCI-oscillation confusion

from Huber, Schwetz & J. V. PRL88 (2002) 101804;

for inclusion of NSI in **S** and **D** see hep-ph/0202048



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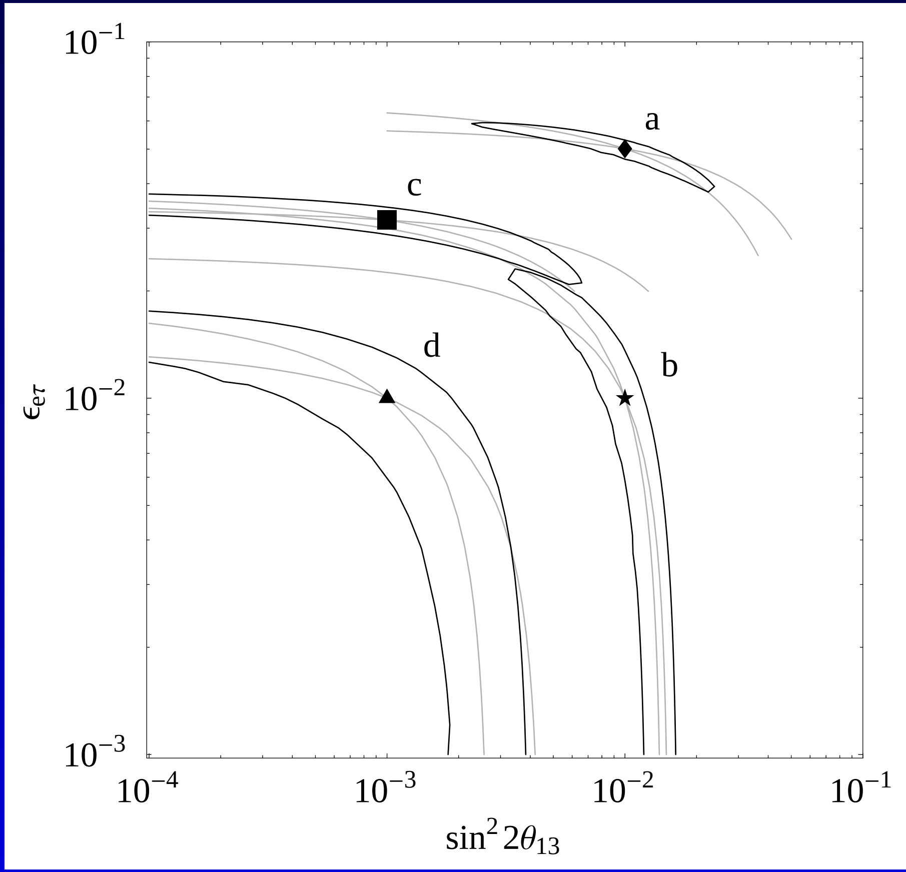

near-site programme essential! 2×10^{20} muons/yr/polarity $\times$ 5 yr,

40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

4-nu models

Peltoniemi, Tommasini & JV PLB298 (1993) 383

Peltoniemi & JV NPB406 (1993) 409

Caldwell-Mohapatra PRD48 (1993) 325

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

light sterile-nus from extra dimensions

Ioannisian, JV PRD63 (2001) 073002

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

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

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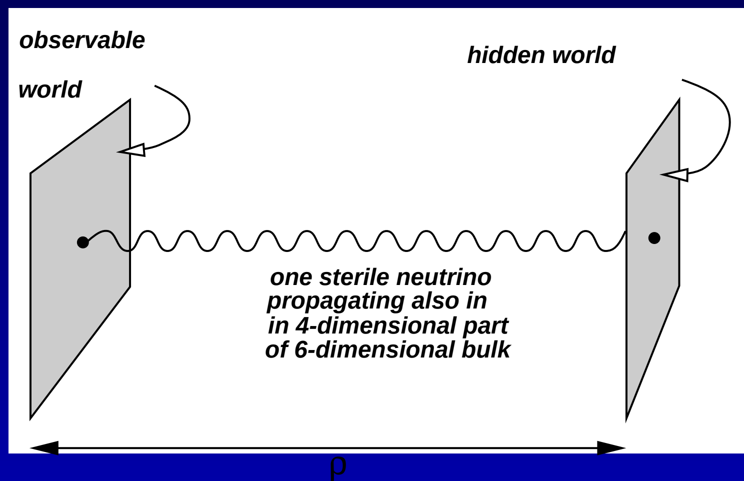

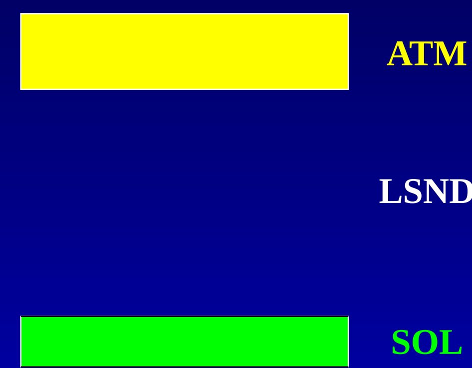

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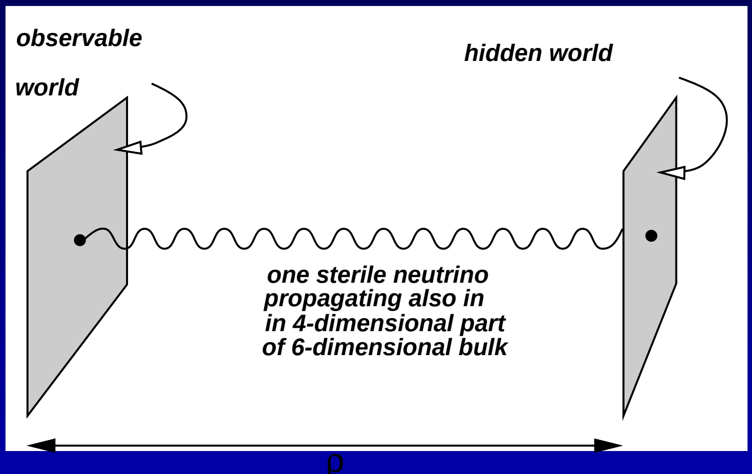

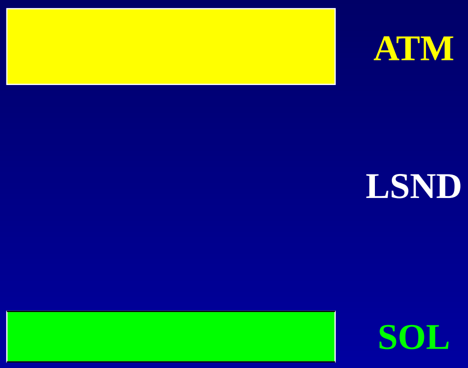

-
- $m_\nu = (\frac{M_F}{M_{\rm P}})^{\frac{\delta}{n}} m_f$ $\quad M_F \sim \text{TeV} \quad \delta = 4 \quad n = 6$

volume suppression vs symmetry protection ...

light sterile-nus from extra dimensions

Ioannisian, JV PRD63 (2001) 073002

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

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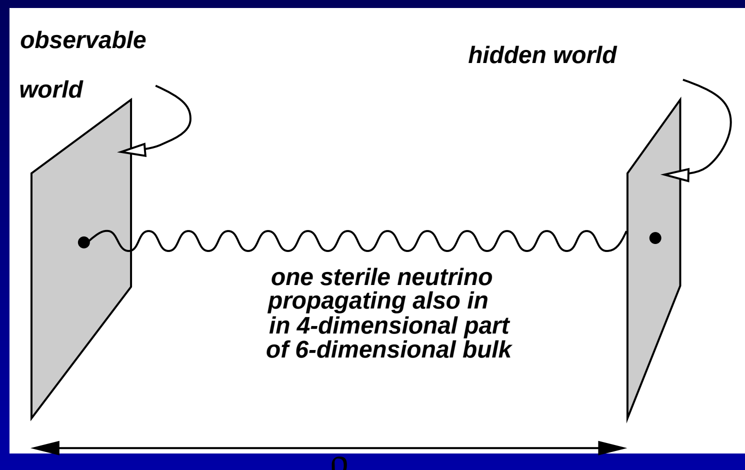

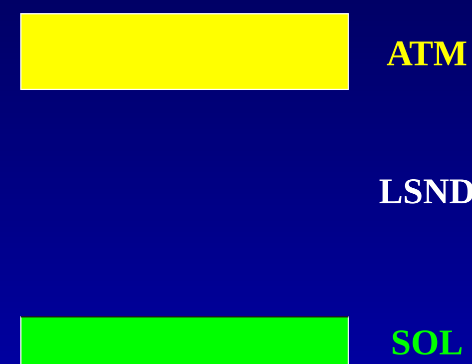

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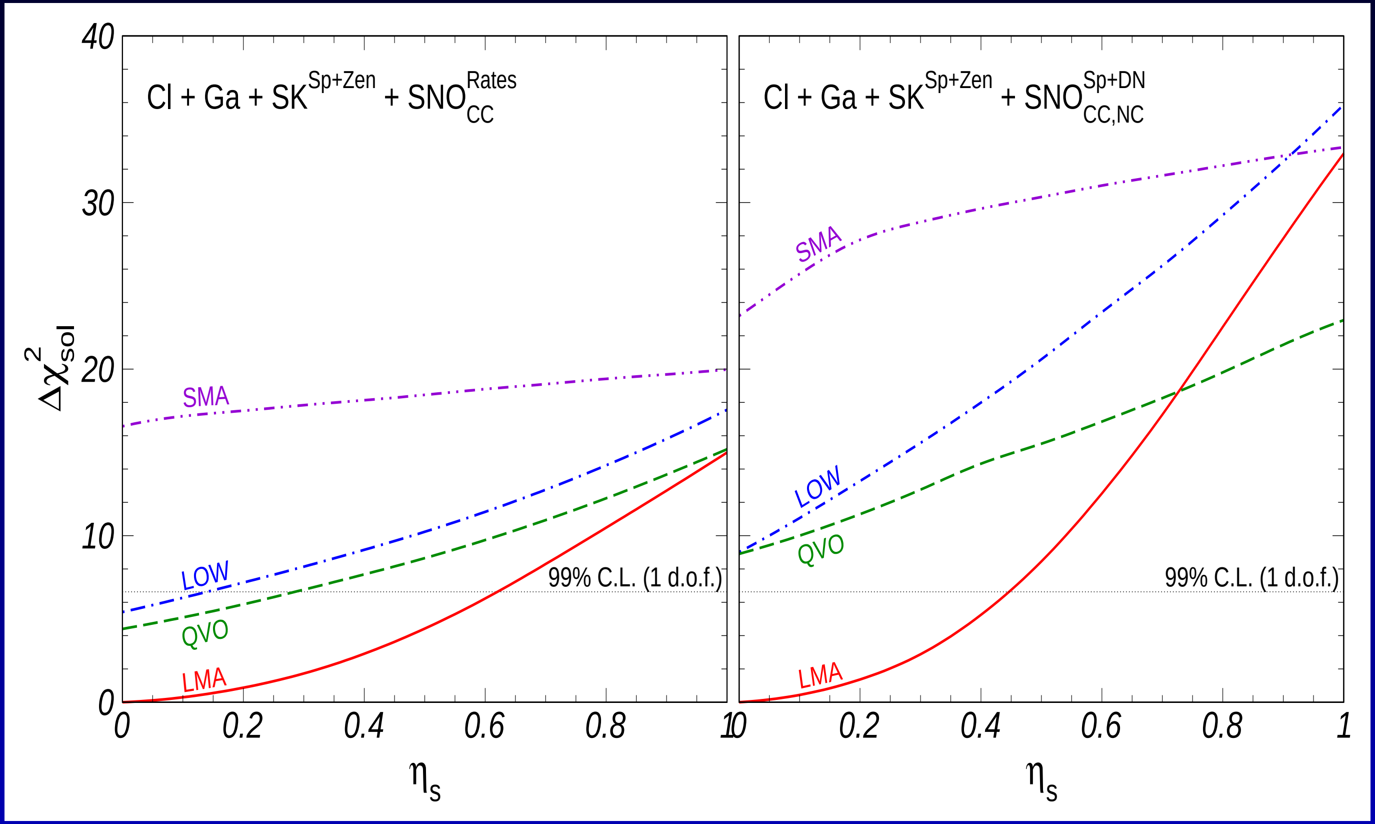
  volume suppression vs symmetry protection ...

- atm & solar scale from RPV Hirsch, JV PLB495 (2000) 121

  or radiative Peltoniemi, Tommasini, JV PLB298 (1993) 383

  $\theta_A \sim \pi/4$ predicted

sterile-nu after SNO-NC Maltoni et al 2002



also strong rejection by atm data

are oscillations the end of it ?

Maltoni, Schwetz, Tórtola & JV 2002; PRD65 (2002) 093004

- oscillations give excellent picture of sol+atm

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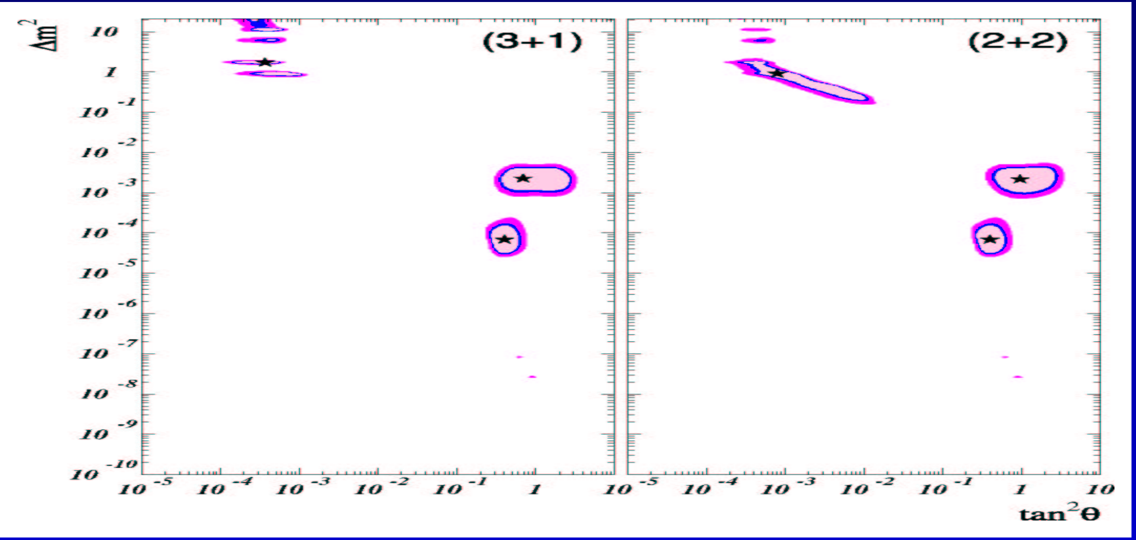
- 

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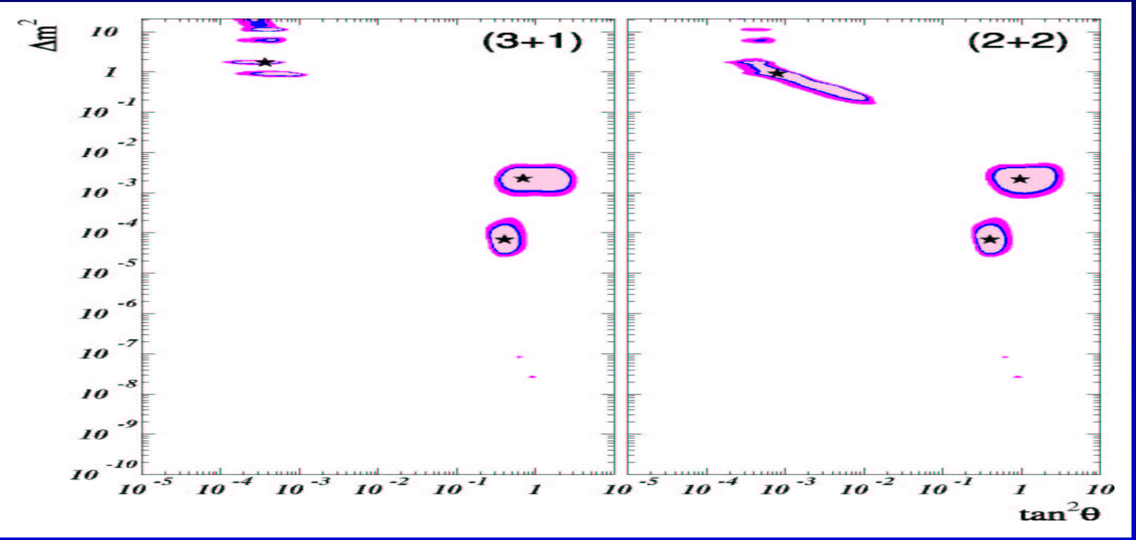

-
- null KamLAND ⟶ NSI solns   testable @ NuFact

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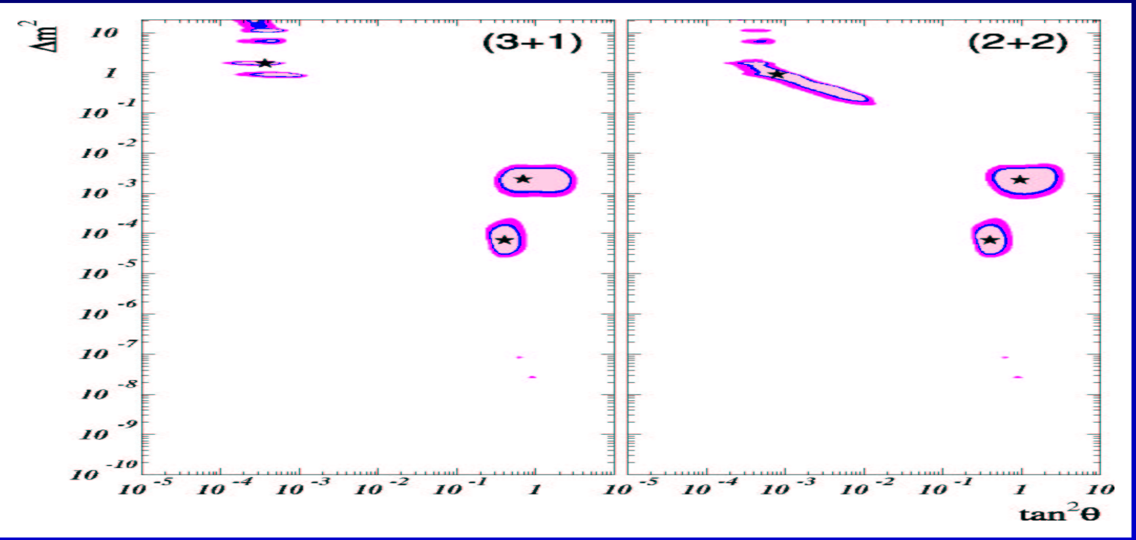
- 

- null KamLAND ⟶ NSI solns testable @ NuFact
- Dirac or Majorana ??

Spin Flavor Precession

over 20 years

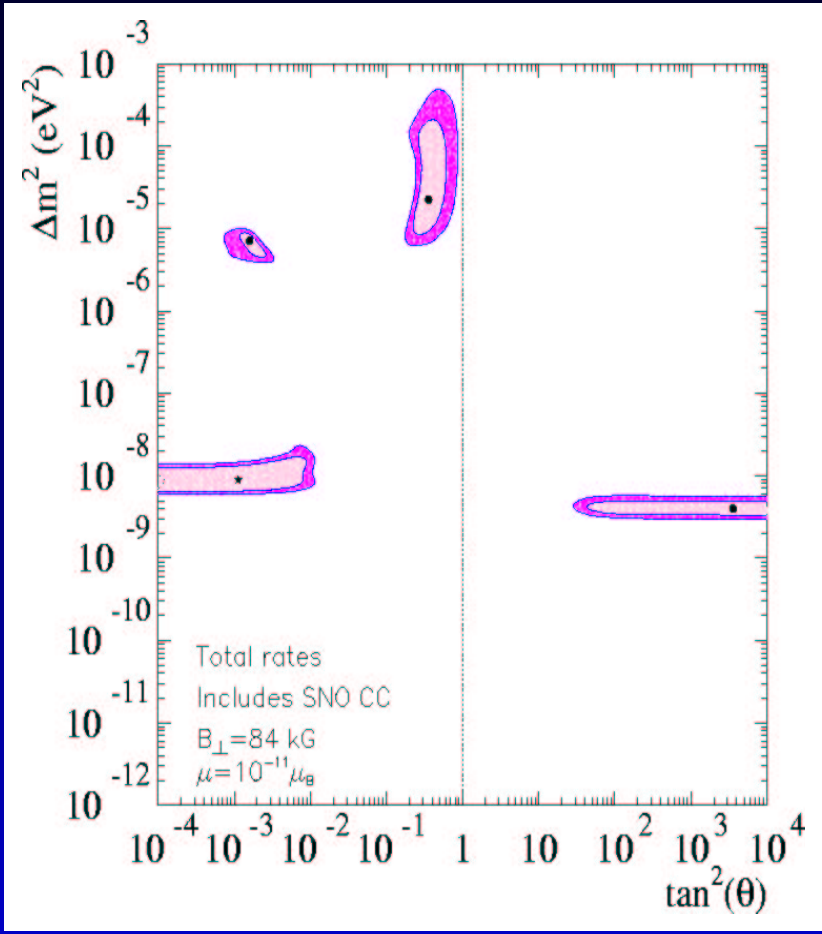
Schechter, Valle PRD24 (1981) 1883 & D25, 283

Akhmedov; Lim-Marciano PRD37 (1988) 1368; PLB213 (1988) 64

back

Oscillation-SFP

Miranda etal PLB521 (2001) 299



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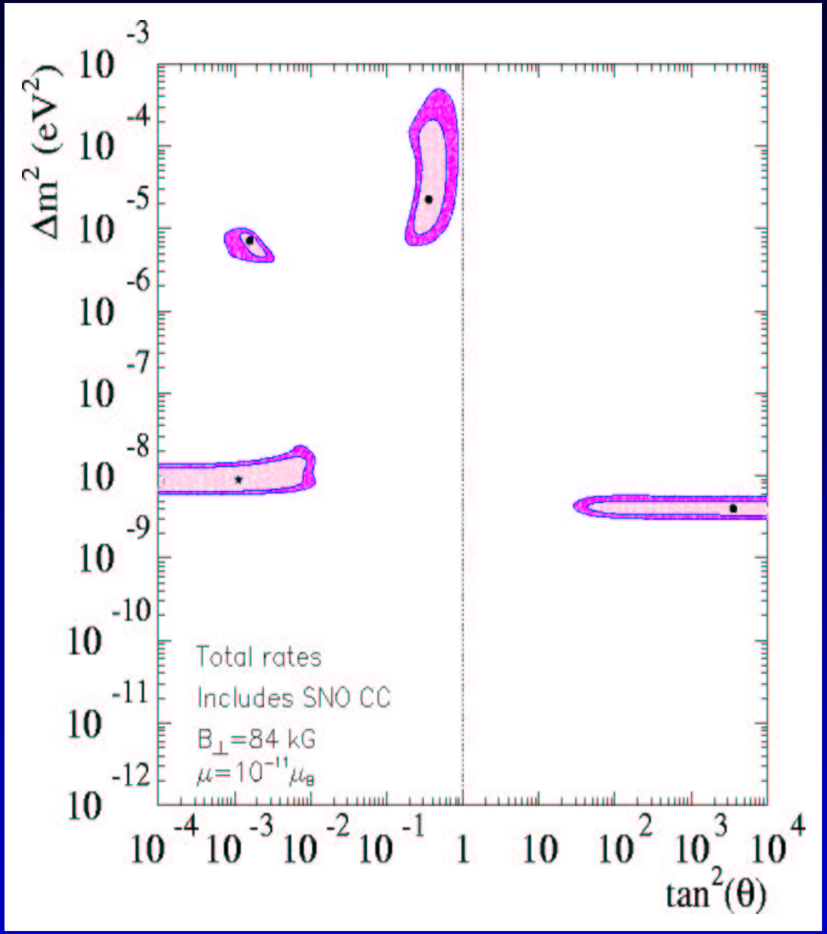
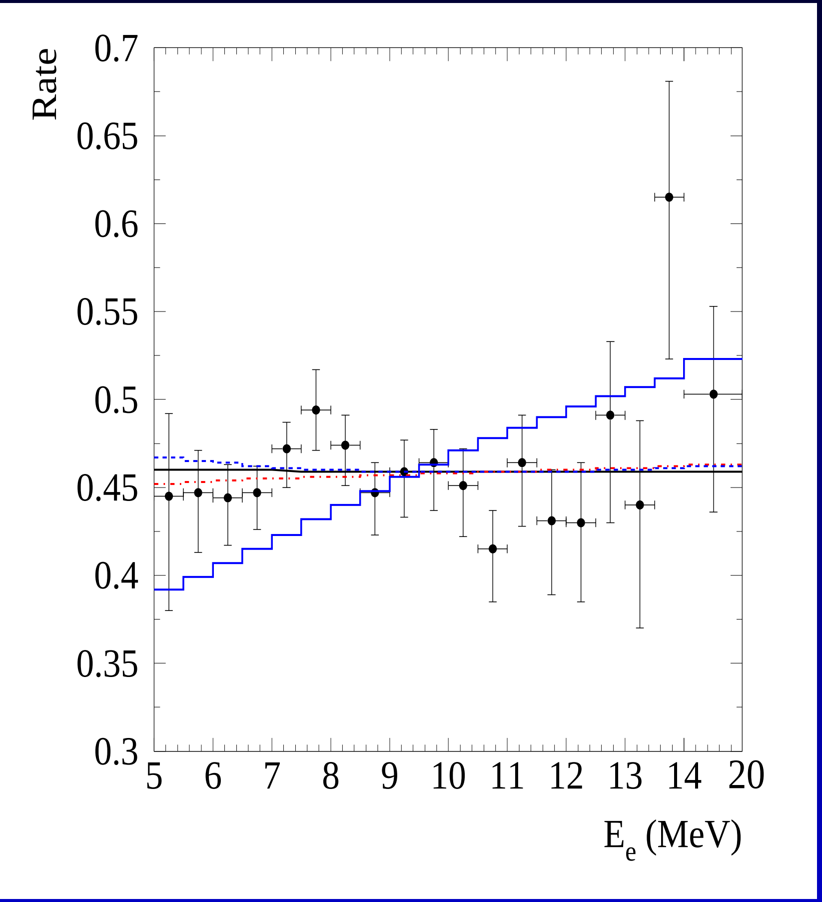
Oscillation-SFP

Miranda etal PLB521 (2001) 299





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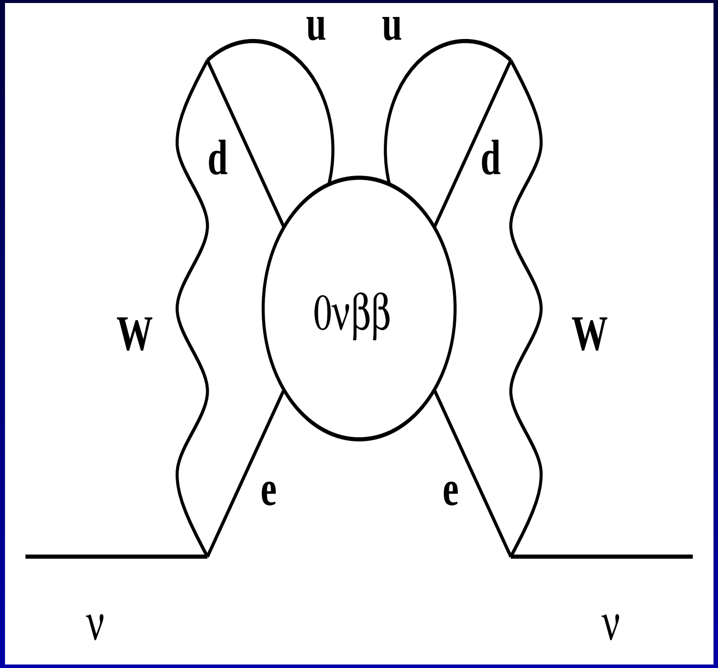
only 3 good solns: RSFP, NRSFP & LMA

expected Borexino signal lower than for LMA Akhmedov & Pulido

Dirac or Majorana?

absolute scale

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



Schechter, JV PRD25 (1982) 2951

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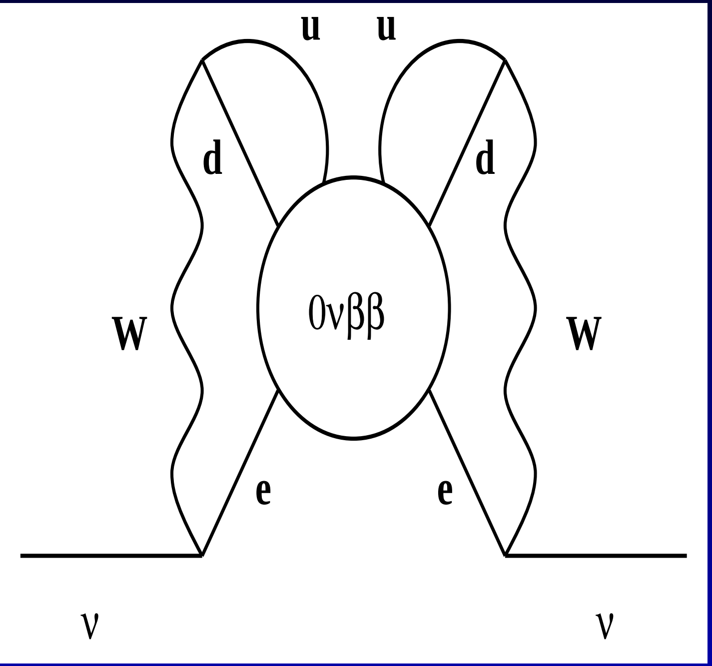
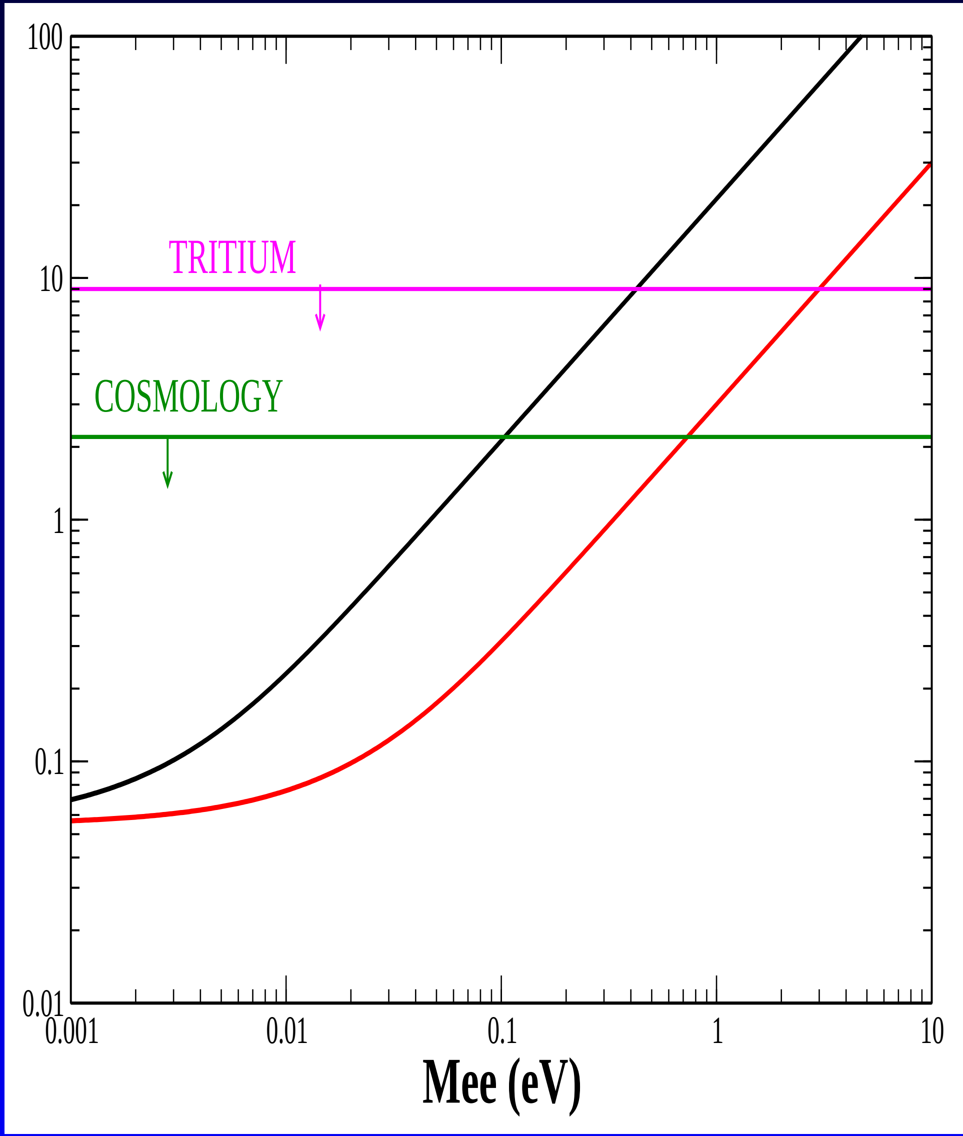


Schechter, JV PRD25 (1982) 2951

- like other $\Delta L = 2$ processes (e.g. nu-transition magnetic moments) $\beta\beta_{0\nu}$ is sensitive to Majorana phases
  Schechter & JV D24 (1981) 1883; Wolfenstein PLB107 (1981) 77; Doi et al; Bilenky et al, Kayser et al

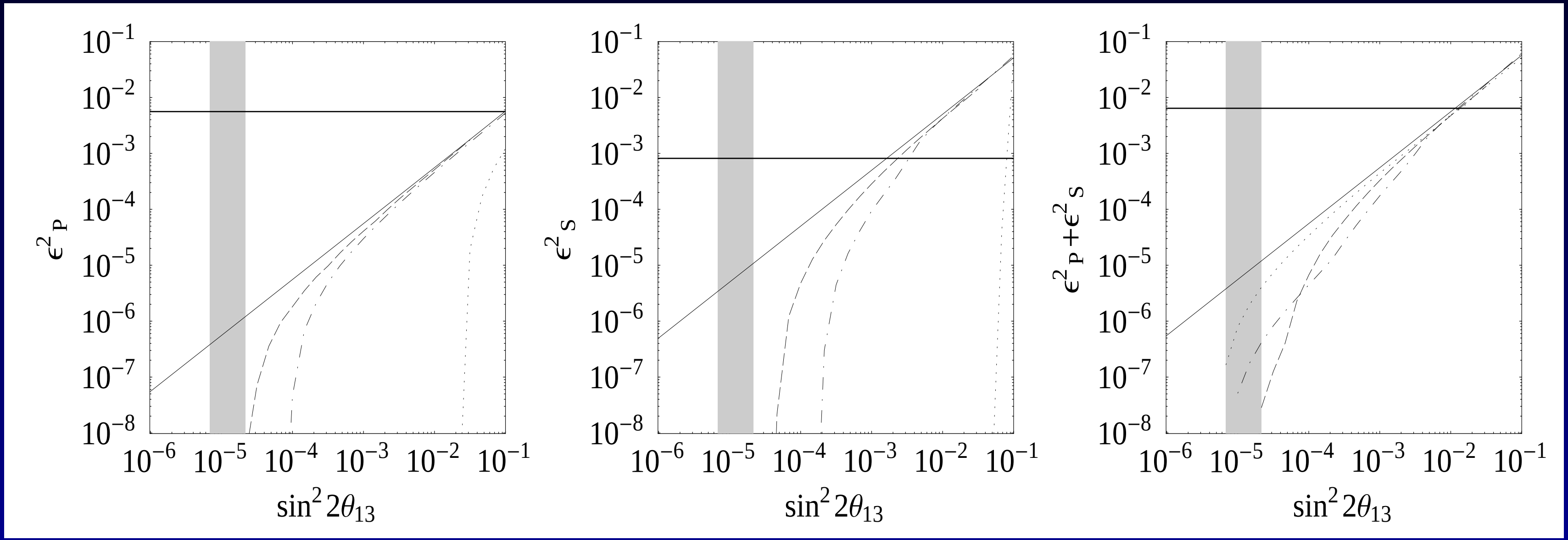
absolute neutrino mass scale

back



Barger et al PLB532 (2002) 15

Nufact θ_{13} sensitivities **back**

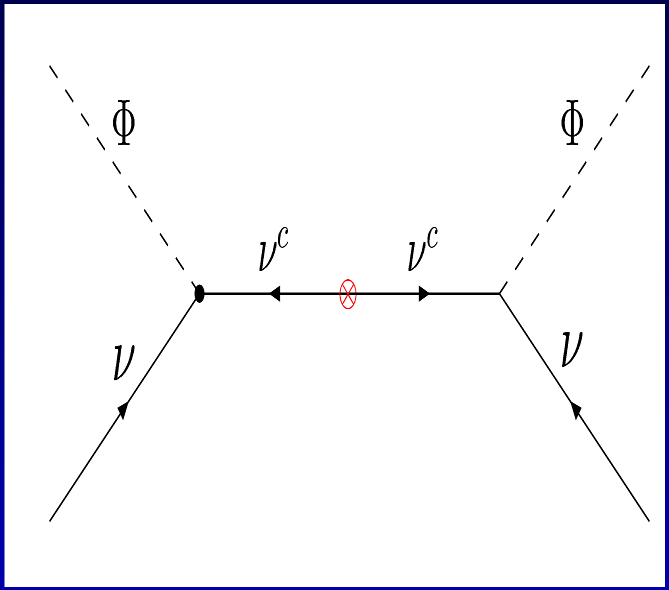


90% CL sensitivity limits on $\sin^2 2\theta_{13}$ if a bound on ϵ_P^2 (left panel), ϵ_S^2 (middle panel) or $\epsilon_P^2 + \epsilon_S^2$ (right panel) is given. The dotted line is for a baseline of 700 km, the dash-dotted for 3 000 km and the dashed line for 7 000 km. **The horizontal black line shows the current estimate of the limit on the NSI parameter**. The vertical grey band shows the range of possible sensitivities without NSI. The diagonal solid line is the theoretical bound derived from our confusion theorem.

m-nu from global B-L violation

- majoron seesaw

Chikashige, Mohapatra, Peccei
Schechter, Valle back



- $\nu_h \to \nu_l$ + majoron PRD25 (1982) 774

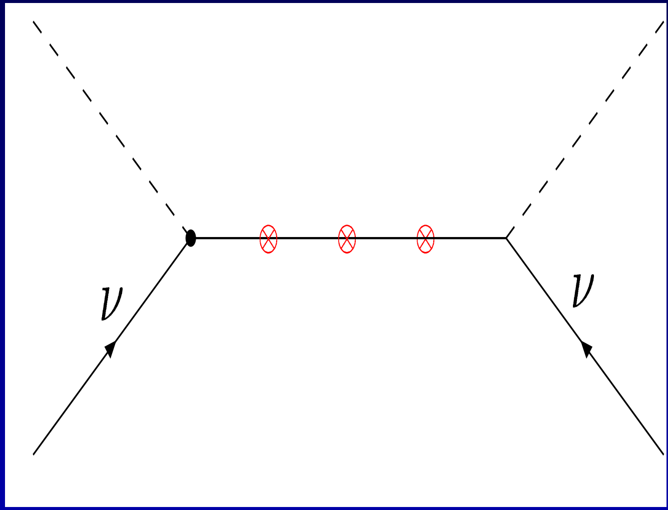
- negligible in vacuo, but important in SNovae Kachelriess et al PRD62 (2000) 023004, Lindner, et al NPB607 (2001) 326

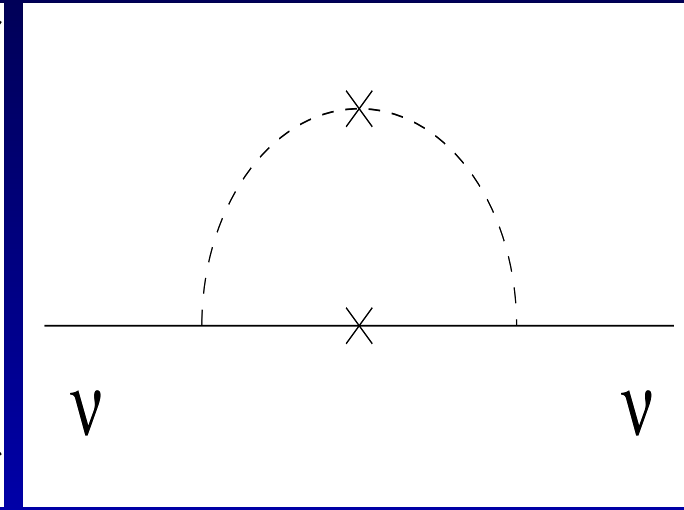
light-nu’s without new scale

- unlike seesaw, m-nu $\to 0$ as LNV scale $\to$ zero

light-nu's without new scale

- unlike seesaw, m-nu $\to$ 0 as LNV scale $\to$ zero
- TREE GG-JV PLB yr 89, JR-JV NPB yr 92... RAD Zee or Babu-type





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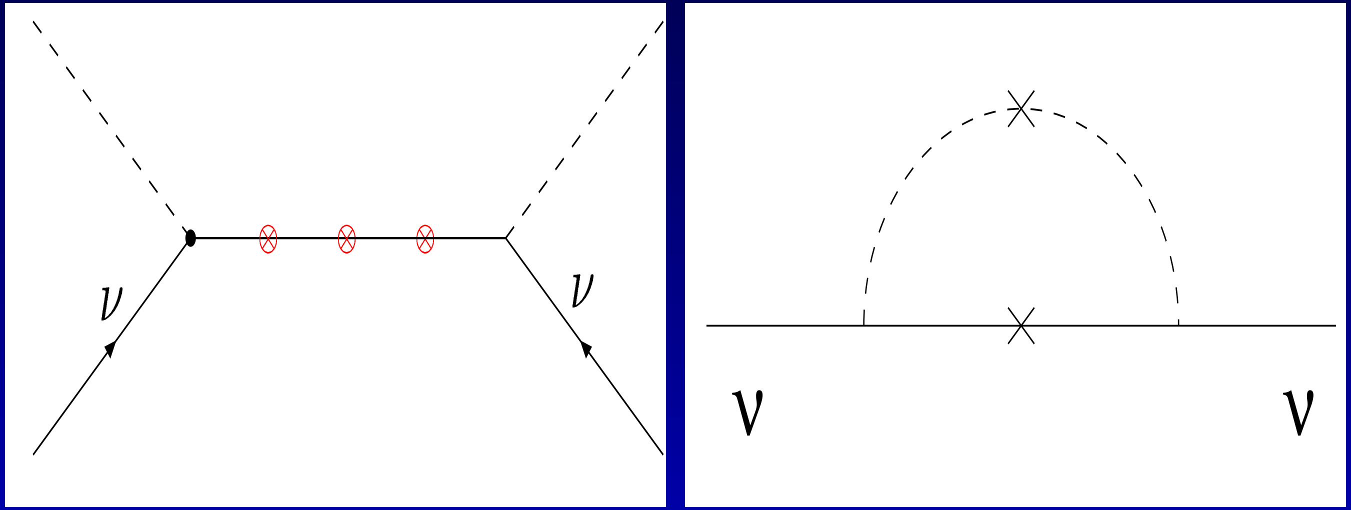

- Higgs $\to$ 2–majoron "invisible" decays

Joshipura, JV NPB397 (1993) 105; Campos et al PRD55 (1997) 1316 back

quasi-degenerate models

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

- may be unstable under RC

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

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

Klapdor et al MPLA **16** (2001) 2409 back

more refs on spontaneous RPV

Romão, Santos, JV Phys. Lett. B **288** (1992) 311. M. C. Gonzalez-Garcia, J. C. Romao and J. W. Valle, Nucl. Phys. B **391**, 100 (1993). J. C. Romao, A. Ioannisian and J. W. Valle, Phys. Rev. D **55** (1997) 427 [arXiv:hep-ph/9607401]. M. Shiraishi, I. Umemura and K. Yamamoto, Phys. Lett. B **313** (1993) 89. A. S. Joshipura and S. K. Vempati, Phys. Rev. D **60**, 111303 (1999) [arXiv:hep-ph/9903435]. R. Kitano and K. y. Oda, Phys. Rev. D **61** (2000) 113001 [arXiv:hep-ph/9911327]. D. Suematsu, Phys. Lett. B **506** (2001) 131 M. Frank and K. Huitu, Phys. Rev. D **64** (2001) 095015 .

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NSI models

back R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D **34** (1986) 1642; L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. B **267** (1986) 415; F. Gabbiani and A. Masiero, Nucl. Phys. B **322** (1989) 235. J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez and J. W. Valle, Phys. Lett. B **187** (1987) 303. N. Rius and J. W. Valle, Phys. Lett. B **246** (1990) 249. M. C. Gonzalez-Garcia and J. W. Valle, Mod. Phys. Lett. A **7** (1992) 477. G. C. Branco, M. N. Rebelo and J. W. Valle, Phys. Lett. B **225** (1989) 385. M. Dittmar et al Nucl. Phys. B **332** (1990) 1

neutrino decay refs

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J. N. Bahcall et al, Phys. Lett. B **181** (1986) 369. S. Pakvasa and K. Tennakone, Phys. Rev. Lett. **28** (1972) 1415. V. D. Barger, J. G. Learned, P. Lipari, M. Lusignoli, S. Pakvasa and T. J. Weiler, Phys. Lett. B **462** (1999) 109 V. D. Barger, J. G. Learned, S. Pakvasa and T. J. Weiler, Phys. Rev. Lett. **82** (1999) 2640 A. Acker and S. Pakvasa, Phys. Lett. B **320** (1994) 320 A. Acker, A. Joshipura and S. Pakvasa, Phys. Lett. B **285** (1992) 371. R. S. Raghavan, X. G. He and S. Pakvasa, Phys. Rev. D **38** (1988) 1317. Z. G. Berezhiani and A. Rossi, Phys. Lett. B **336** (1994) 439 Z. G. Berezhiani et al, Z. Phys. C **54** (1992) 581. A. Bandyopadhyay, S. Choubey and S. Goswami, Phys. Rev. D **63** (2001) 113019 C. Giunti et al, Phys. Rev. D **45** (1992) 1557. J. F. Beacom and N. F. Bell, arXiv:hep-ph/0204111. A. Bandyopadhyay et al, arXiv:hep-ph/0204173

NSI effects in nu-propagation back

L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); S.P. Mikheev and A.Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985). J. W. F. Valle, Phys. Lett. B **199** (1987) 432. M. M. Guzzo *et al.*, Phys. Lett. **B260**, 154 (1991); E. Roulet, Phys. Rev. **D44**, 935 (1991); V. Barger, R. J. N. Phillips and K. Whisnant, Phys. Rev. **D44**, 1629 (1991); S. Bergmann, Nucl. Phys. **B515**, 363 (1998); E. Ma and P. Roy, Phys. Rev. Lett. **80**, 4637 (1998). M.C. Gonzalez-Garcia *et al.*, Phys. Rev. Lett. **82** (1999) 3202; N. Fornengo et al, JHEP **0007** (2000) 006; P. Lipari and M. Lusignoli, Phys. Rev. D **60** (1999) 013003; G.L. Fogli et al, Phys. Rev. D **60** (1999) 053006 M.M. Guzzo et al, Nucl. Phys. Proc. Suppl. **87** (2000) 201. H. Nunokawa et al, Phys. Rev. D **54** (1996) 4356; D. Grasso, H. Nunokawa and J.W.F. Valle, Phys. Rev. Lett. **81** (1998) 2412 Z. Berezhiani et al, arXiv:hep-ph/0111138. Z. Berezhiani and A. Rossi, arXiv:hep-ph/0111137; M.M. Guzzo et al, Phys. Rev. **D** 64 (2001) 097301. T. Ota, J. Sato and N. a. Yamashita, arXiv:hep-ph/0112329.

Non-Standard nu-Interaction Types

back

- arise in most nu-mass models

eg Prog. Part. Nucl. Phys. 26 (1991) 91

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- scalar NSI arise in radiative models
- pseudoscalar NSI arise in majoron models & lead to nu-decays Chikashige, Mohapatra, Peccei; Schechter, JV PRD25 (1982) 774; Gelmini, JV PLB142 (1984) 181 more