What have we learned about neutrinos??

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`http://neutrinos.uv.es`

- **Solar neutrino anomaly**
- **Atmospheric neutrino anomaly**
- **Reconciling Solar + atmospheric**
- oscillation interpretation $\Rightarrow$ ν & Quark Mixings differ radically
- **how far can theory go?**
- **bottom-up**: **hierarchical neutrino masses**
- **top-bottom**: **do ν masses unify ??**
- **Testing ν mixings at High Energy Accelerators**
- **Adding Accelerator ν results (LSND) $\Rightarrow$ 4ν models**
- Exotic Neutrino Conversion Mechanisms:
  ν oscillations vs resonant ν spin flavor conversions
- **Open issues**

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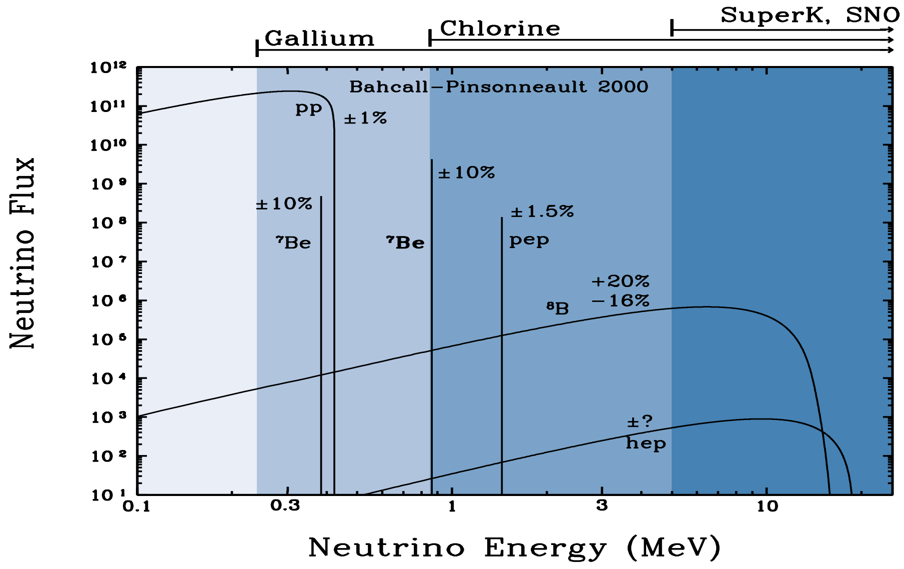
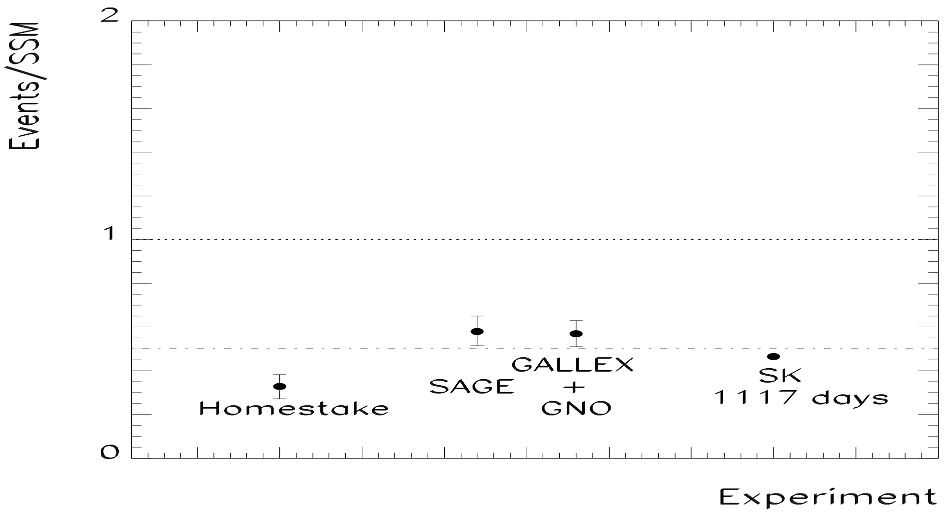
*9th Internat. Workshop on: Neutrino Telescopes, Venice, march 2001
†Supported by TMR project HPRN-CT-2000-00148, ESF network 86 and PB98-0693

Solar-ν fluxes



Solar-ν Rates

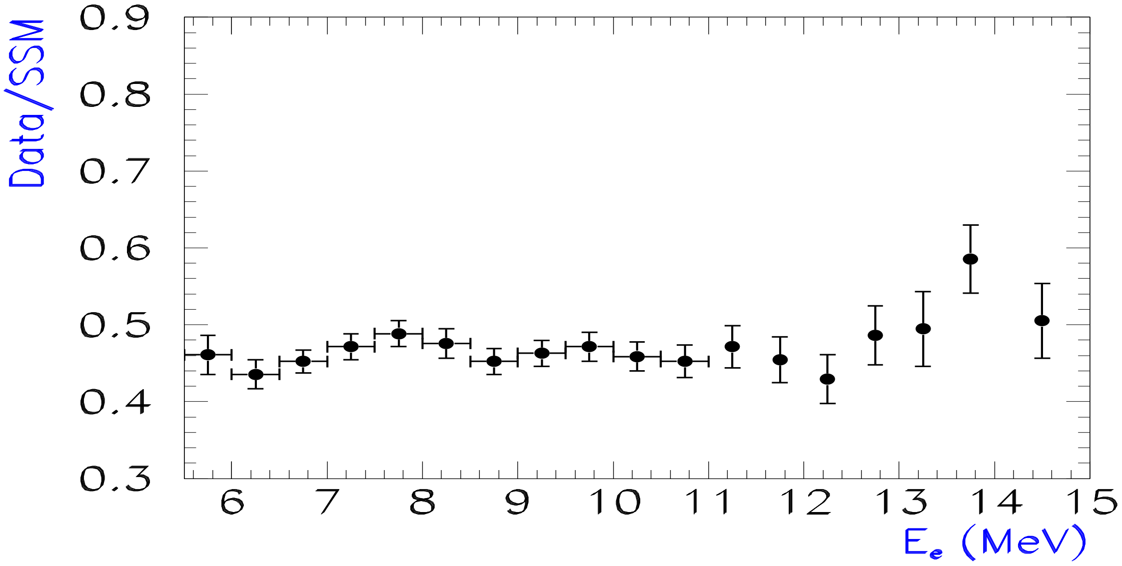


latest results from SK, SAGE & GNO presented at ν2000

first results from SNO from ν2000 not included

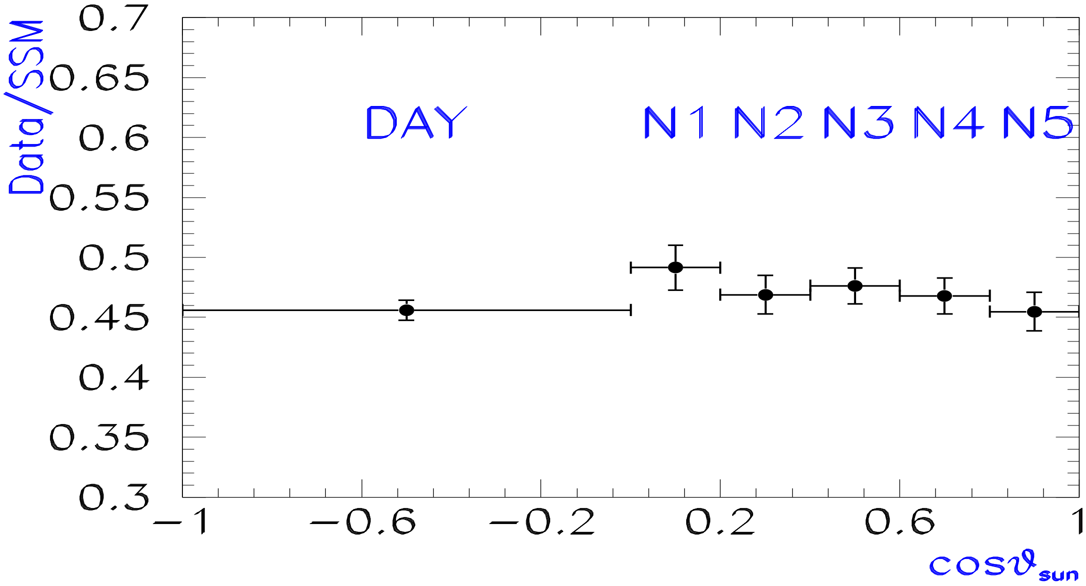
Rate-independent solar-ν observables

recoil electron energy spectrum normalized to SSM



substantially flatter (no hep-crisis)

Day/Night Effect

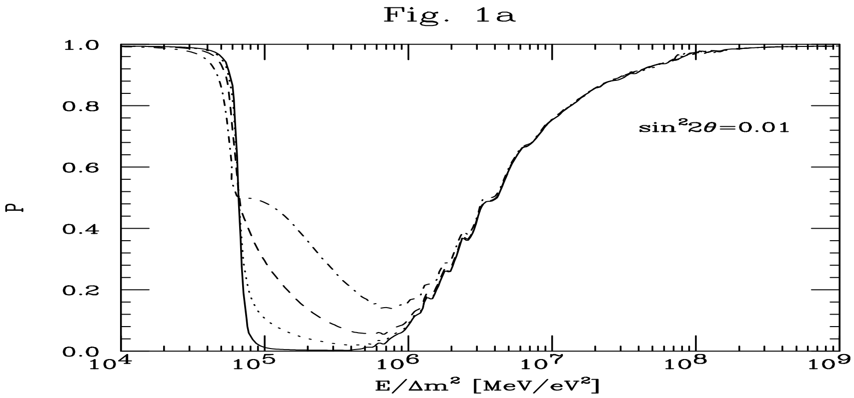


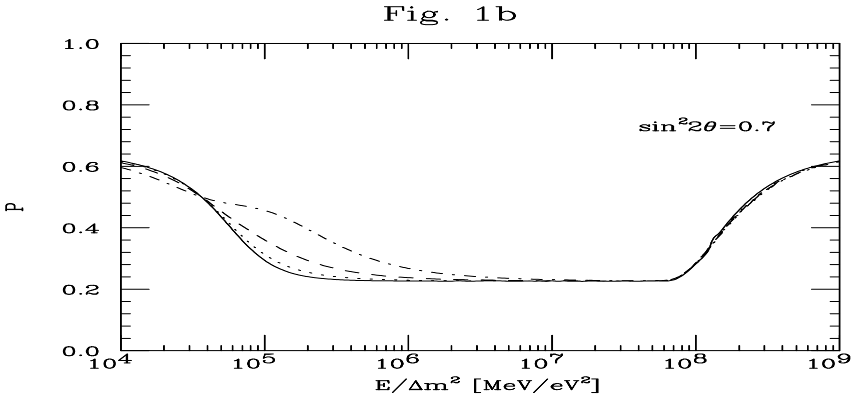
SK Zenith-Angle Distributions

Present data consistent with pure geometric seasonal Effect

oscillation solution of Solar ν problem

large vs small mixing MSW survival probabilities





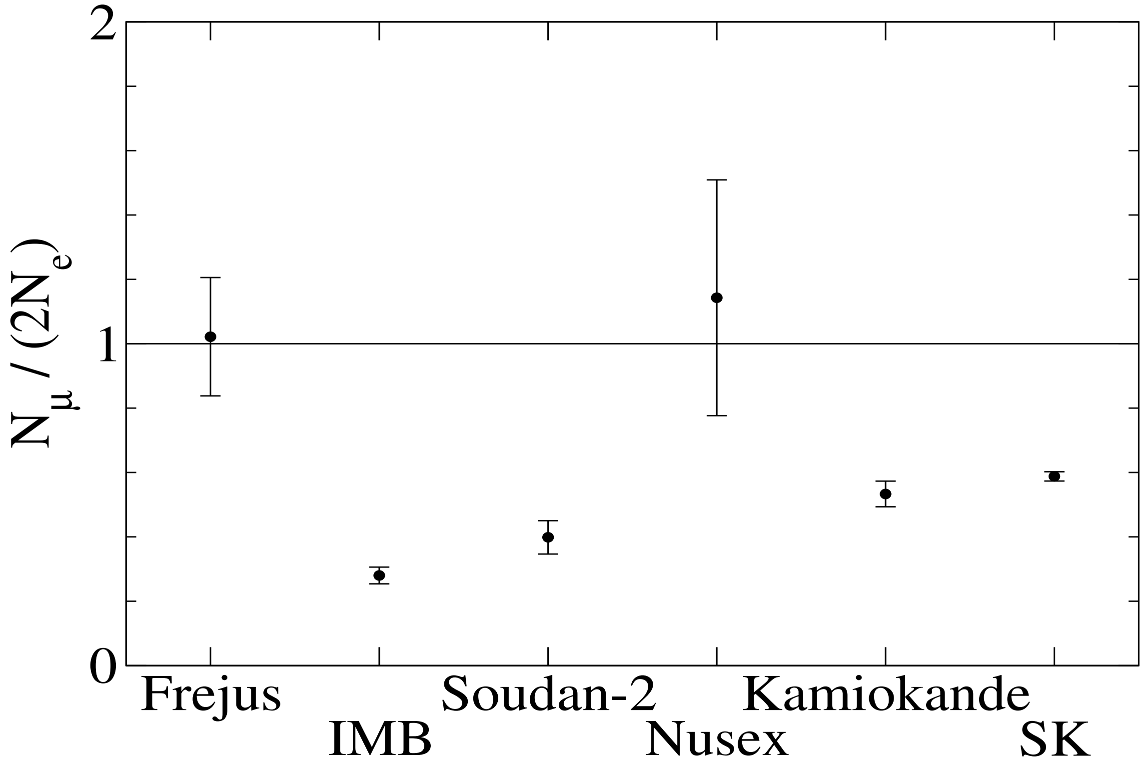
test of solar matter density fluctuations at Borexino

H. Nunokawa et al NP **B472** (1996) 495

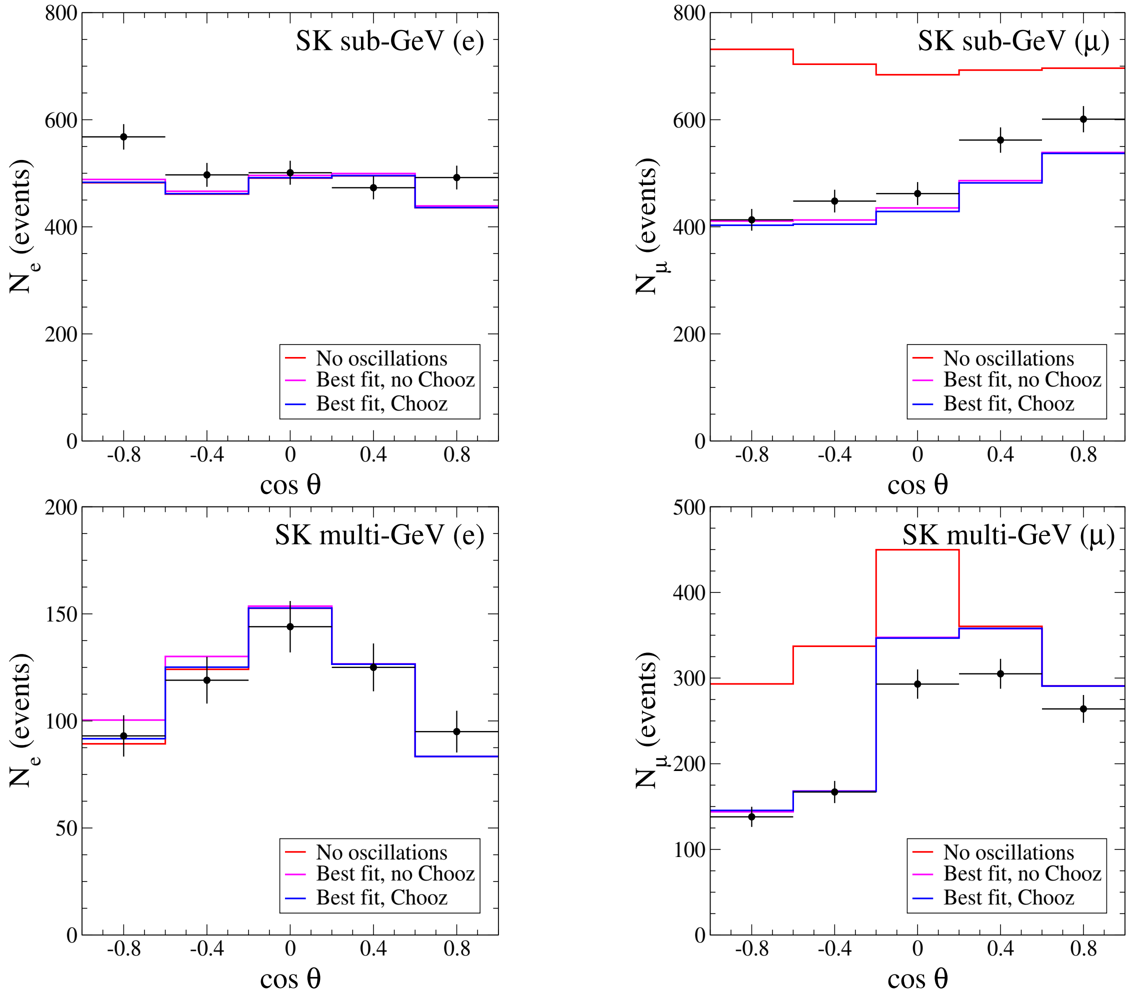
atmospheric ν data

Fréjus	Kamiokande sub-GeV	Soudan-2
IMB	*Kamiokande multi-GeV*	NUSEX
SK sub-GeV	*SK multi-GeV*	*Macro*
SK stopping μ	*SK thru-going μ*	

contained event Rates



Contained Atmospheric ν distributions



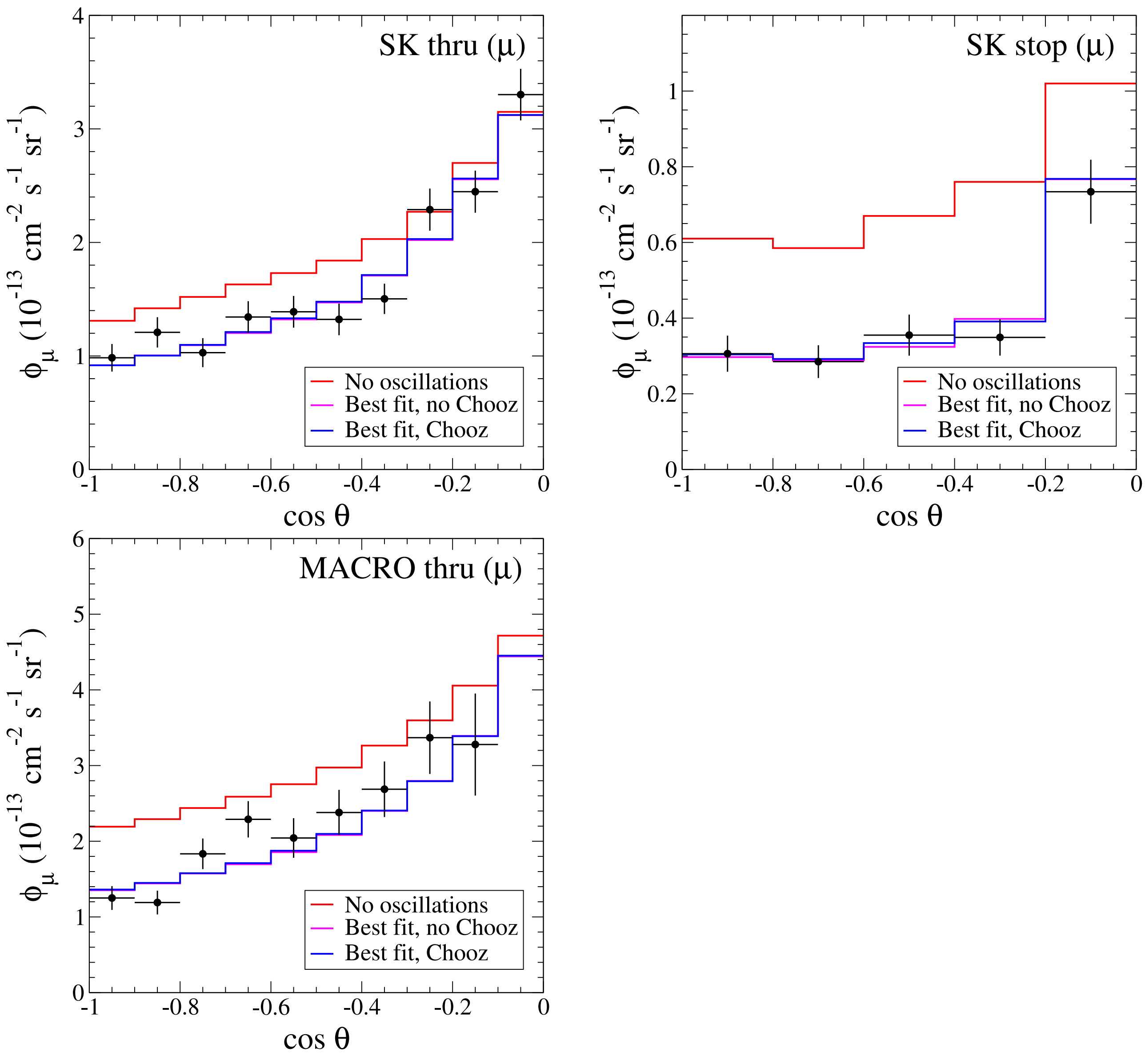
SK data show deficit in μ-like (right-panels) event rates

e-like (left panels) rates agree with SM.

Best fit predictions refer to all atmospheric data

from hep-ph/0009350

Up-going Atmospheric muon fluxes



SK and Macro show deficits in the up-going μ-like event rates

`Best fit predictions from hep-ph/0009350`

oscil. intrepr. of sol + atm $\Rightarrow$ Δm^2_{12} & Δm^2_{23} $\Rightarrow$ 3 ν's

simplest 3-ν CC weak interaction mixing matrix

$$\mathbf{K} = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}$$

where $\vec{\nu} \equiv (\nu_e, \nu_\mu, \nu_\tau)$, $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

$$\mathbf{H_{VAC}} = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m^2_{12}, 0, \Delta m^2_{23}\right)$$

$$\mathbf{V_{MAT}} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right)$$

to first approximation

solar $\Rightarrow$ Δm^2_{12}, θ_{12}, θ_{13} since we can set $\Delta m^2_{23} \to \infty$

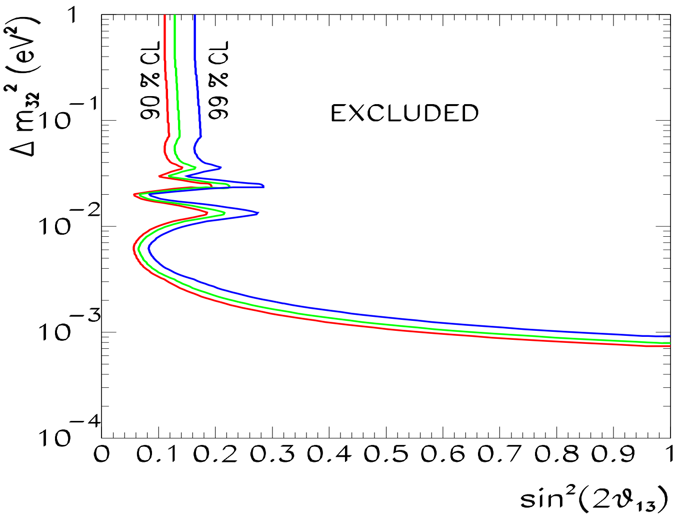
atm $\Rightarrow$ Δm^2_{23}, θ_{23}, θ_{13} since we can set $\Delta m^2_{12} \to 0$

$$\mathbf{K_{atm}} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{13}s_{23} & c_{23} & s_{23}c_{13} \\ -s_{13}c_{23} & -s_{23} & c_{23}c_{13} \end{pmatrix}$$

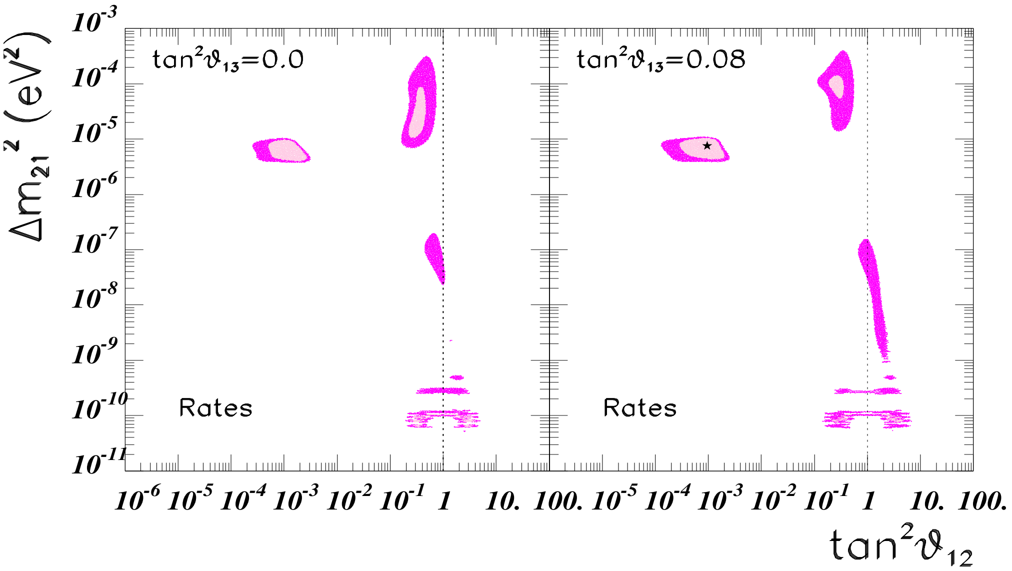
$$\mathbf{H^{atm}_{VAC}} = \frac{1}{2E_\nu}\mathbf{diag}\left(0, 0, \Delta m^2_{23}\right)$$

see PR **D22** (1980) 2227 & **D21** (1980) 309

Reactor bounds



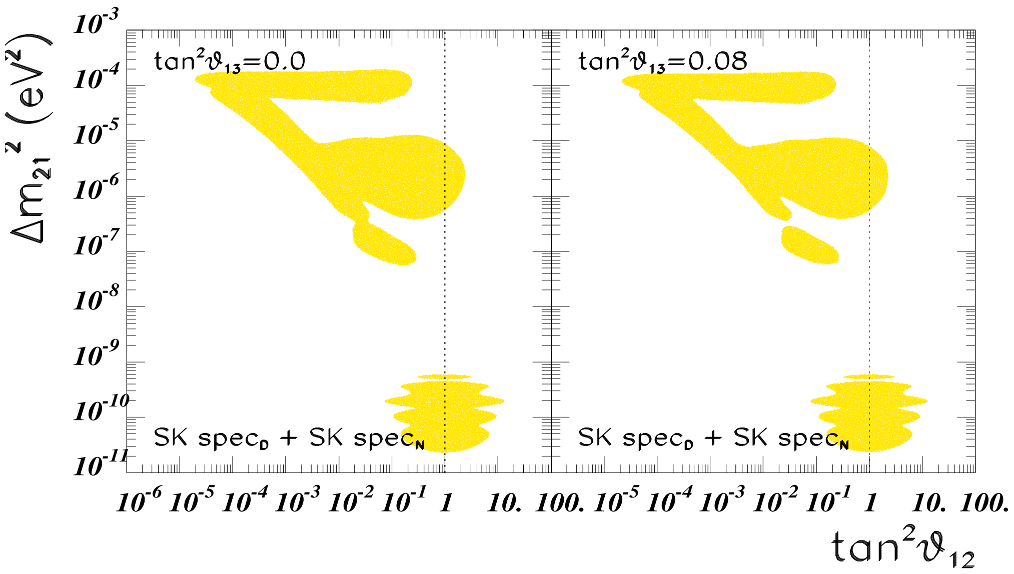
Global fit of solar ν rates



- **unified description**: from MSW to VAC..., from normal to "dark" side
- various solutions: SMA, LMA, LOW, VAC & QVAC
- SMA is best, due to ν_7 suppression

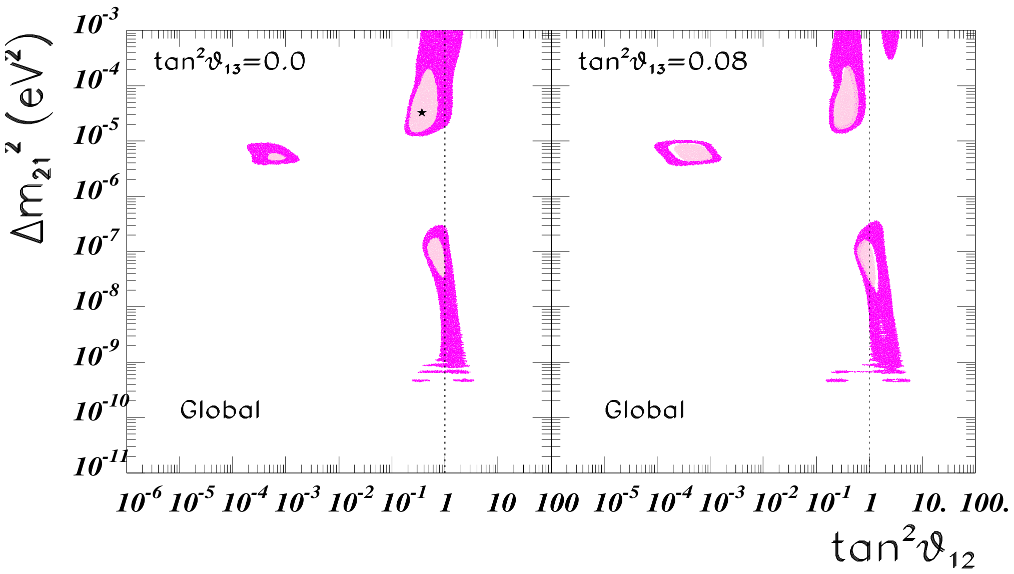
Gonzalez-Garcia et al, PRD **63** (2001) 033005

solar day–night spectra



3-ν regions `excluded` at 99% CL by the D-N spectra

Gonzalez-Garcia et al, PRD **63** (2001) 033005



- **LMA as best global fit was already in 825-d spectrum NP B573, 3 (2000) flatter 1117-d spectrum $\Rightarrow$ SMA more strongly disfavored**
- LMA and LOW allow for seasonality arising from matter effects de Holanda, et al PR **D60** 093010 (1999)
- ... detectable at GNO (Lisi et al PR **D61** 073009 (2000)), Kamland... ??

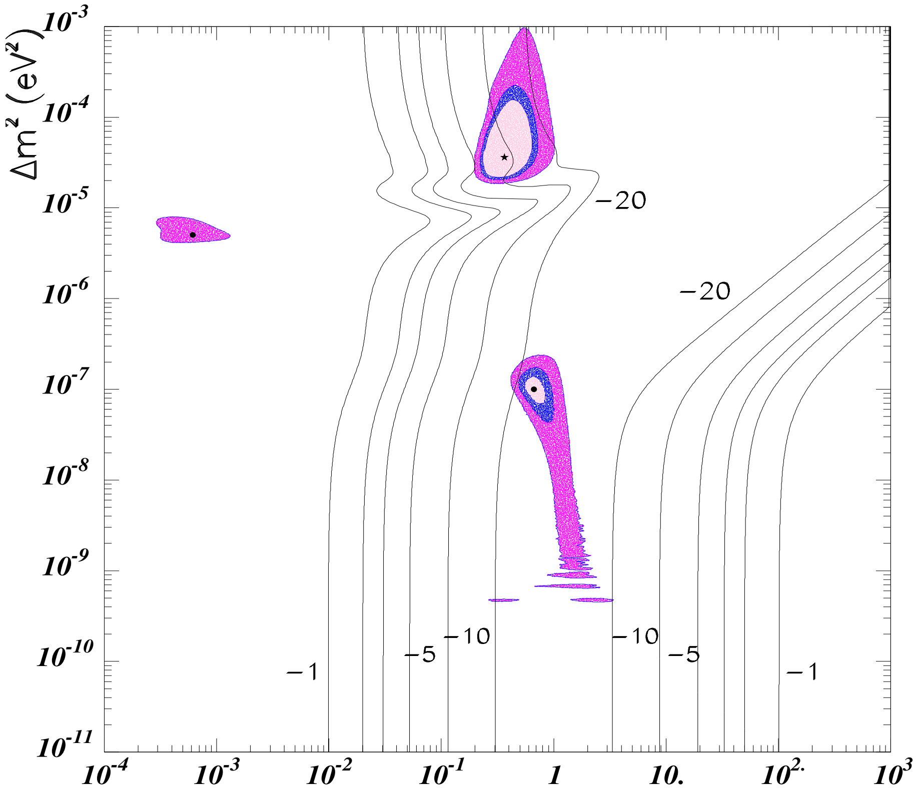
Large mixing disfavored by SN87A...

permutation of the ν spectra... Smirnov et al 94

Jegerlehner et al 96

but...

LMA acceptable and preferred to LOW & QVAC–VAC...



Kachelriess et al, JHEP0101 (2001) 030

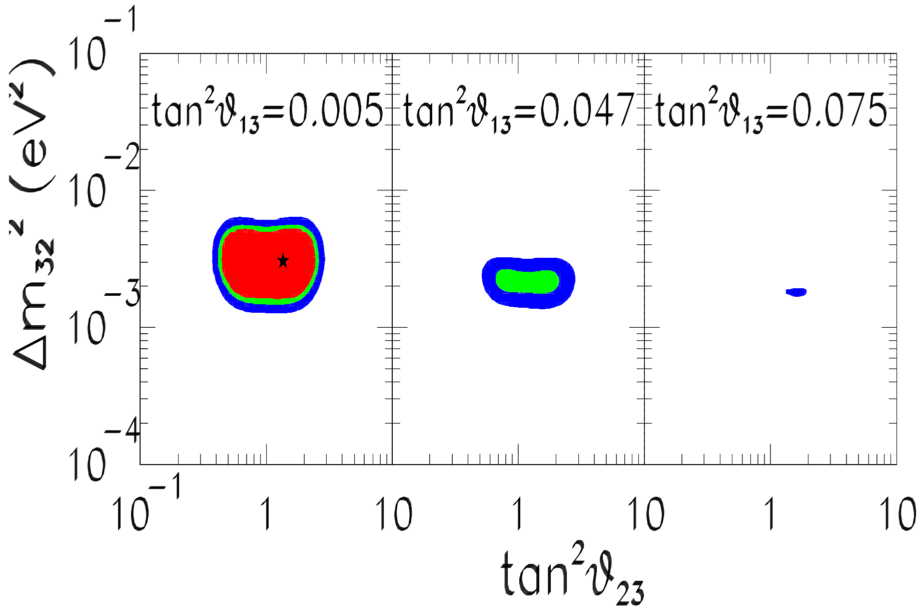
Curves of constant $\log R \equiv \log \mathcal{L}(\alpha) - \log \mathcal{L}_{\rm SMA}$

$$\alpha = \{\tan^2\theta, \Delta m^2, E_b, \langle E_{\bar\nu_e}\rangle, \tau\}$$

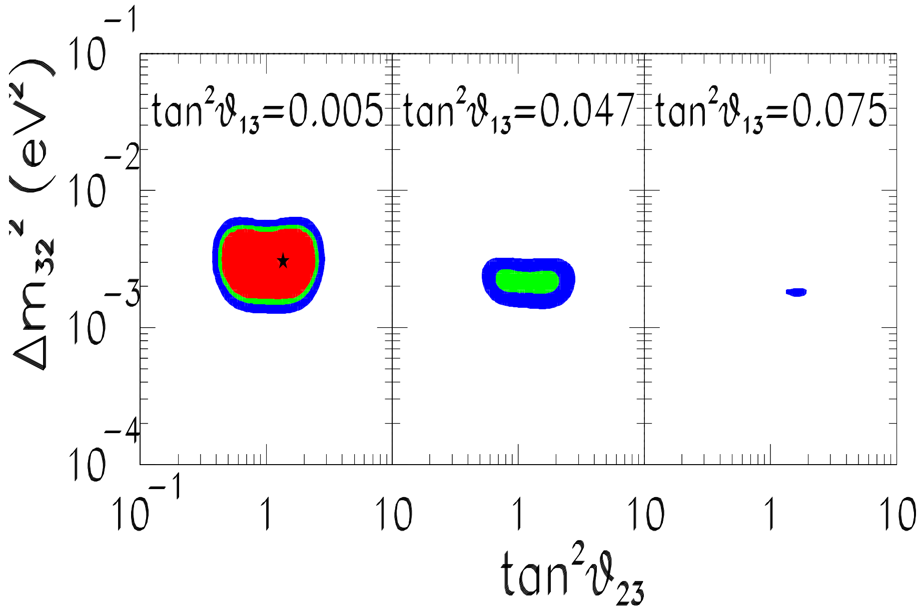
$E_b = 3\times 10^{53}$ **erg,** $\langle E_{\bar\nu_e}\rangle = 14$ **MeV and** $\tau \equiv \langle E_{\bar\nu_\mu}\rangle/\langle E_{\bar\nu_e}\rangle = 1.7$

$$\mathcal{L}(\alpha) \propto \exp\left(-\int n(E,\alpha)\,dE\right) \prod_{i=1}^{N_{\rm obsevents}} n(E_i,\alpha)$$

Unified 3-ν atmospheric oscillations Global Fit



90, 95 and 99% 3–ν regions allowed by combining all atm data

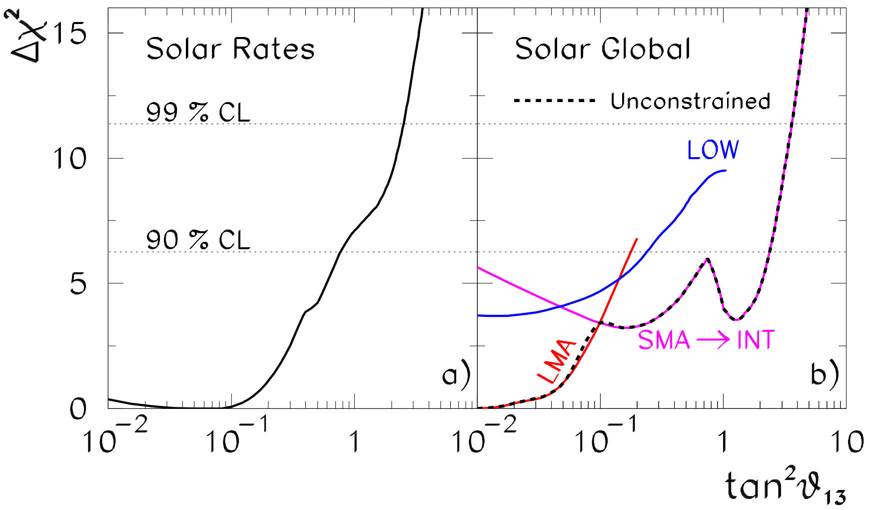


90, 95 and 99% 3–ν regions allowed by combining all neutrino data

includes 1144-day SK data + new Soudan-2 5.1 kton data + new Macro data + reactor results (Chooz+Palo Verde)

Gonzalez-Garcia et al PRD 63 (2001) 033005

Relative quality of 3-ν solutions to the solar ν problem



Minimum χ^2_{atm} and best fit points

Without reactor data

Data sets	d.o.f.	$\sin^2\theta_{13}$	$\tan^2\theta_{23}$	Δm^2_{23} [eV^2]	$\chi^2_{\rm SM}$	$\chi^2_{\rm min}$
FINKS	**7**	**0.5**	> 100	$0.9 \cdot 10^{-3}$	**29.9**	**14.8**
Super-Kamiokande	**32**	**0.01**	**1.3**	$2.8 \cdot 10^{-3}$	**131.4**	**27.8**
Contained events	**37**	**0.02**	**1.6**	$2.5 \cdot 10^{-3}$	**115.1**	**41.3**
Upgoing events	**22**	**0.2**	**3.3**	$7.1 \cdot 10^{-3}$	**50.3**	**25.1**
All experiments	**62**	**0.02**	**1.6**	$3.3 \cdot 10^{-3}$	**191.7**	**61.7**

With reactor data

Data sets	d.o.f.	$\sin^2\theta_{13}$	$\tan^2\theta_{23}$	Δm^2_{23} [eV^2]	$\chi^2_{\rm SM}$	$\chi^2_{\rm min}$
FINKS	**8**	**0.4**	**12.9**	$0.3 \cdot 10^{-3}$	**30.0**	**16.1**
Super-Kamiokande	**33**	**0.00**	**1.2**	$3.1 \cdot 10^{-3}$	**131.5**	**28.0**
Contained events	**38**	**0.01**	**1.4**	$2.3 \cdot 10^{-3}$	**115.2**	**42.5**
Upgoing events	**23**	**0.00**	**1.2**	$4.0 \cdot 10^{-3}$	**50.4**	**25.9**
All experiments	**63**	**0.00**	**1.4**	$3.1 \cdot 10^{-3}$	**191.8**	**62.5**

What have we learned??

how to reconstruct...

basic ν parameters

Bilenky, Giunti & Grimus , Barger, Pakvasa & Weiler, Klapdor, Smirnov, Paes, ...

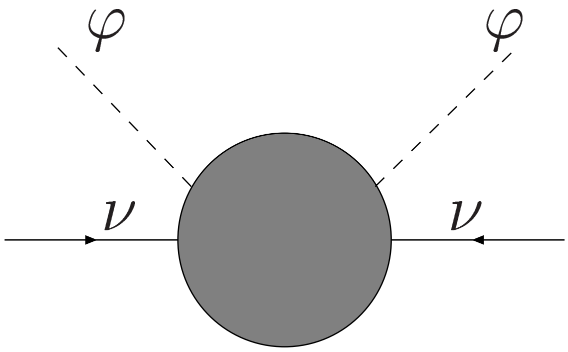
versus

basic ν Theory

$\Rightarrow$ **caveat: this pre-supposes that ν–oscillations is the expanation of both solar & atm data...**

Fundamental dim 5 operator

may arise from gravity...



Weinberg
Barbieri, Ellis & Gaillard
Akhmedov et al

or from lower scale physics

$\mathbf{SO(10)}$

Gell-Mann-Ramond-Slansky, Yanagida

$$\begin{pmatrix} u & \nu & u^c & \nu^c \\ d & e & d^c & e^c \end{pmatrix}$$

$$\Downarrow$$

$\mathbf{SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)}$

Mohapatra-Senjanovic

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} u^c \\ d^c \end{pmatrix} \begin{pmatrix} \nu \\ e \end{pmatrix} \begin{pmatrix} \nu^c \\ e^c \end{pmatrix}$$

$$\Downarrow$$

$\mathbf{SU(3)_C \otimes SU(2)_L \otimes U(1)}$

Schechter & J.V...

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{matrix} u^c \\ d^c \end{matrix} \begin{pmatrix} \nu \\ e \end{pmatrix} \begin{matrix} \\ e^c \end{matrix}$$

Uncertainties in predicting ν-properties from first principles

- **the basic scale is unknown**
  - **Planck scale**
  - **GUT scale** $E(6)$, $SO(10)$,...
  - **intermediate left-right or P-Q scale**

    $SU(4) \otimes SU(2)_L \otimes SU(2)_R$, $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$
  - **weak** $SU(3) \otimes SU(2) \otimes U(1)$ **scale**

- **mechanism is unknown**: **tree** vs **radiative**

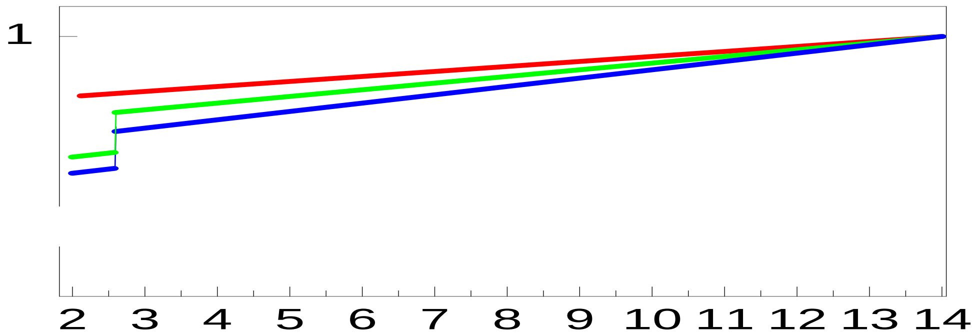
- **the theory of flavour is unknown**:

  Yukawa textures from family symmetries?? ...

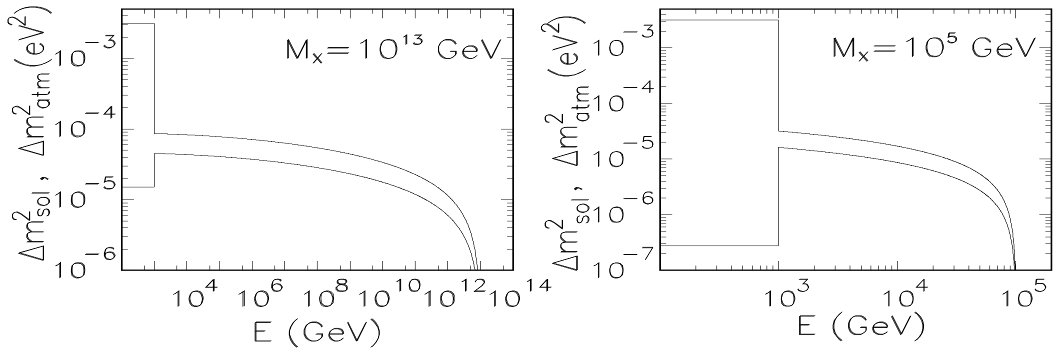
three examples of predictive 3-ν theories of sol + atm

- **minimalism gravity + int. scale** $\Rightarrow$ **bi-max QVAC**
- **top-bottom neutrino unification** $\Rightarrow$ **bi-max LMA/LOW**
- **bottom-up** $R\!\!\!/_p$ **supersymmetry** $\Rightarrow$ **accelerator tests**

top-bottom approach: neutrino unification



$$\Downarrow$$



one prediction for the neutrino oscillation parameters

$$\Delta m^2_\odot \approx 2\Delta m^2_{atm}\left[\cos 2\theta_{12} + 2\sin^2\theta_{13}\right]$$

$$\Downarrow$$

SMA ruled out

Chankowski, Ioannisian, Pokorski & J.V. hep-ph/0011150, PRL

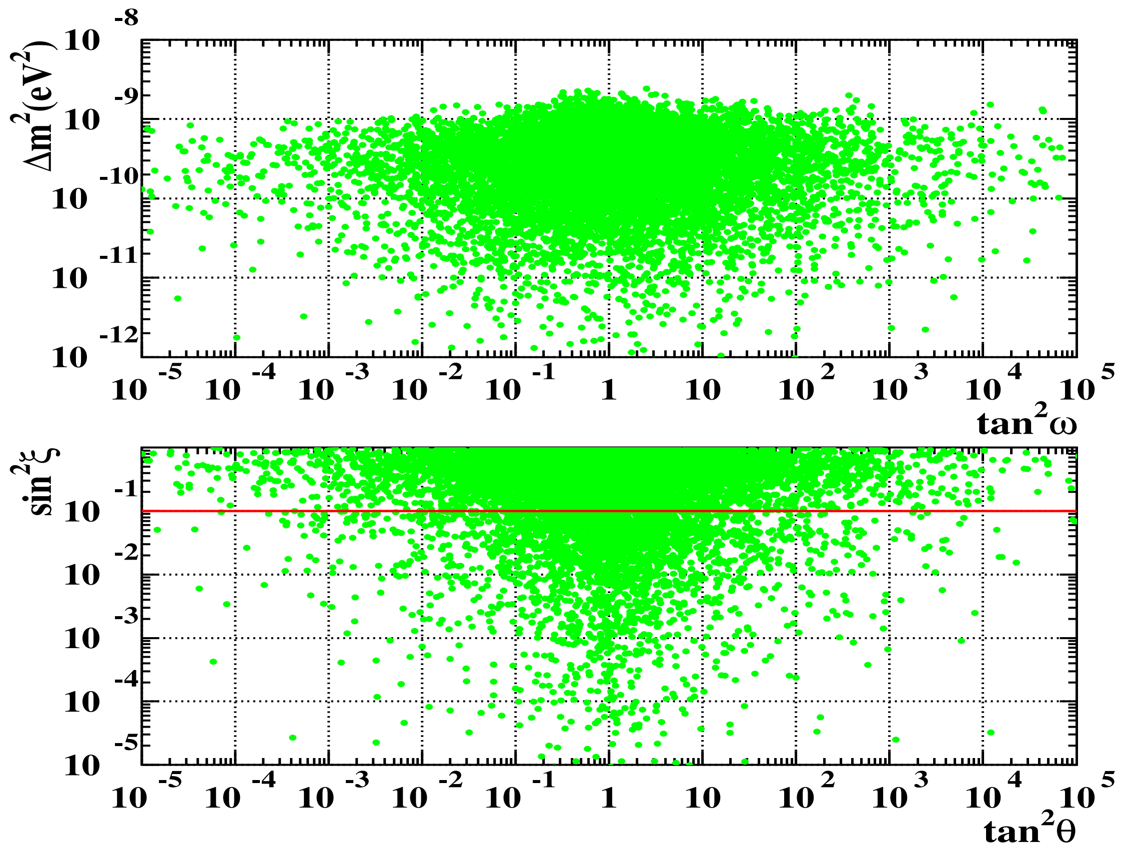
- **no stability problem** (Ellis & Lola, Ma, Casas et al, Haba et al, ...)
- **many other quasi-degenerate ν models**:

  Caldwell & Mohapatra, PR D48 (1993) 329; Ioannisian & J. V. PL B332 (1994) 93; Albright, Babu & Barr, Altarelli & Feruglio; Balaji et al...

Minimalistic approach

3+1 model $\Rightarrow$

- SM (gravity) $\Rightarrow$ solar scale $\Delta m^2_{\odot}$ in VAC or QVAC regime
- BSM (intermediate scale) $\Rightarrow$ atm scale $\Delta m^2_{atm} \approx m_3^2$(projectivity)



no real mixing predictions but acceptable angles $\tan^2\omega$ (top), and $\sin^2\xi$ $\tan^2\theta$ (bottom) arise randomly

Gouvea & J.V. PL B501 (2001) 115 [hep-ph/0010299]

SUSY solution to ν anomalies

- based on low energy SUSY with bilinear $\not{R}_p$

  Diaz, Romão, J. V. NP B524 (1998) 23

- motivated by spontaneous $\not{R}_p$ models

  A. Masiero & J. V. PL B251 (1990) 273

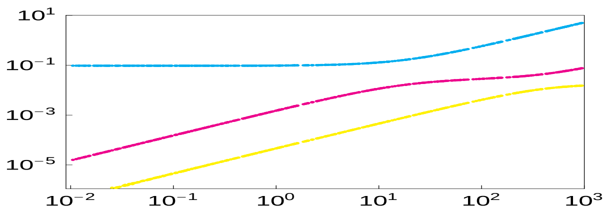
- ... and/or higher symmetries e. g. U(1) flavor symmetry model:

  Mira et al PL B492 (2000) 81

- ... closed, unlike 3-linear...

typical ν masses are hierarchical

ν masses in eV

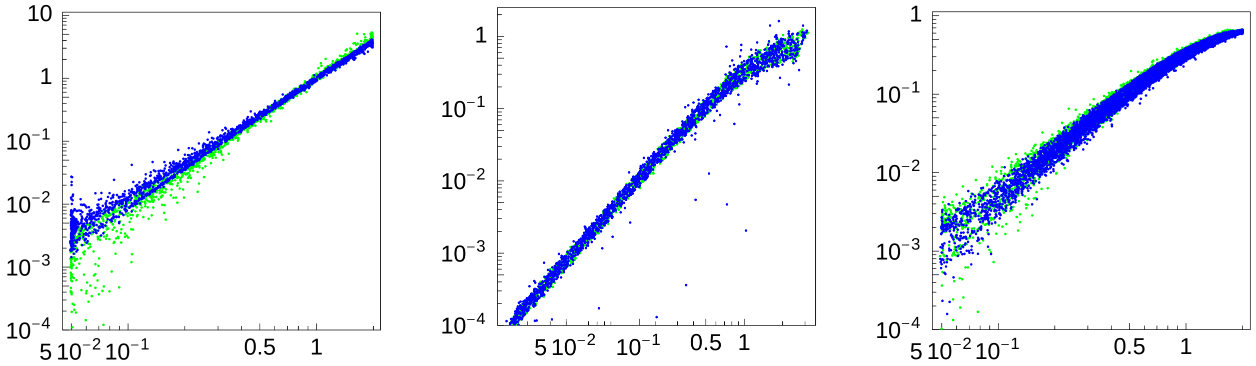


ϵ^2/Λ

3 basic $\not{R}_p$ MSSM parameters $\Rightarrow$ 3 masses + 3 angles

$\Downarrow$

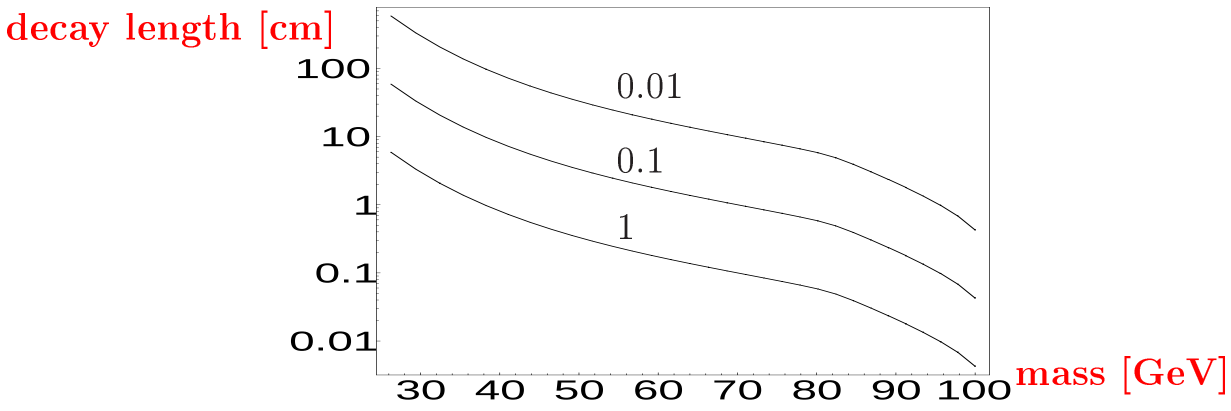
ν mixing predictions...

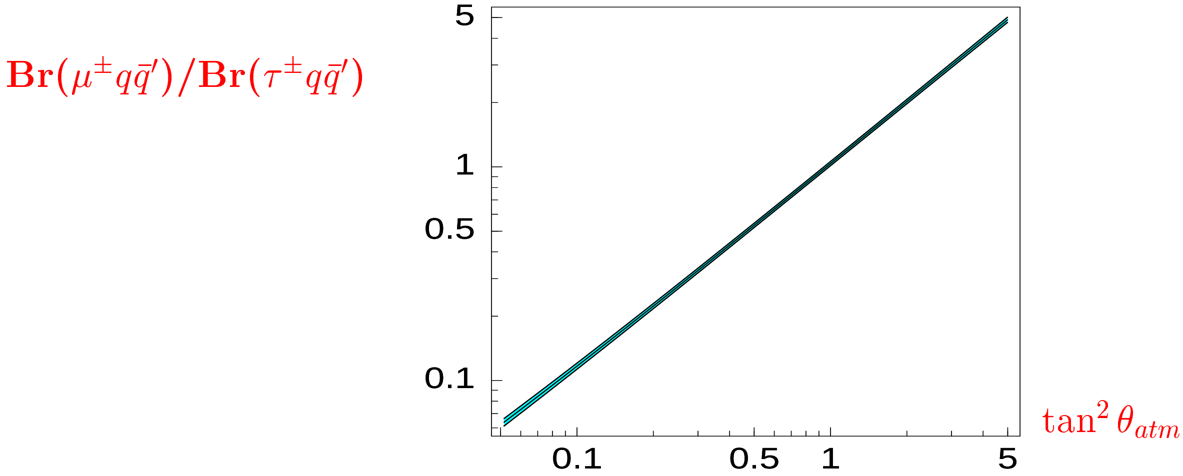


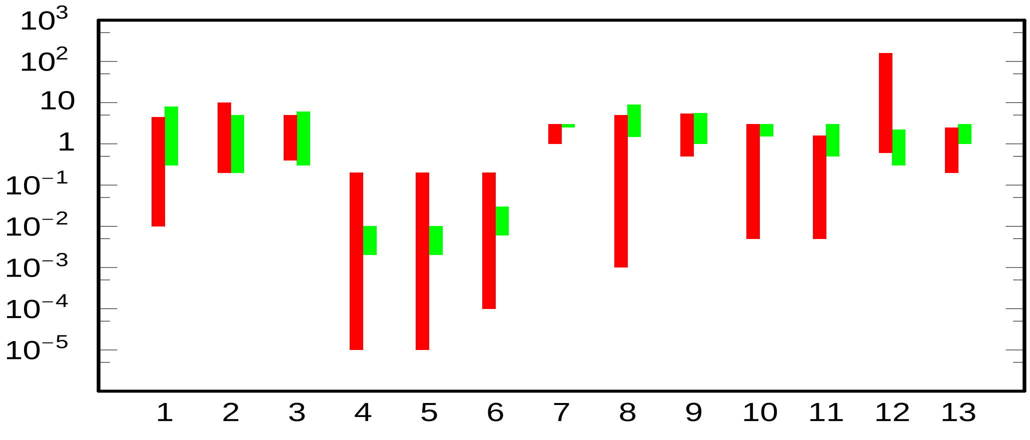
... expressed as correlations with $\not{R}_p$ parameter ratios...

Hirsch et al PR D 62 (2000) 113008 & D61 (2000) 071703

Neutralino decay properties in $\not{R}_p$ MSSM







Predicted ranges for the ratios of various LSP branching ratios for large mixing solar-ν solutions (LMA, LOW or VAC-QVAC) and for SMA

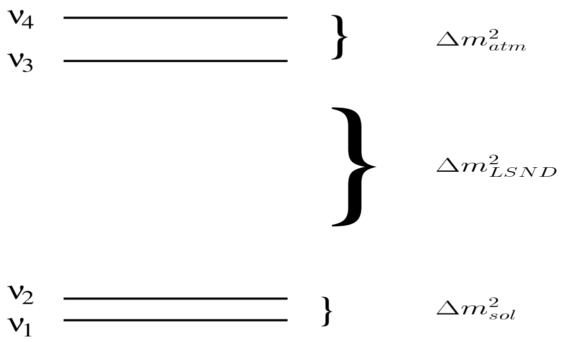
Porod et al, hep-ph/0011248, PRD in press

Adding LSND to sol + atm

3 splittings $\Rightarrow$ 4-νs: 3 active ν_i + 1 sterile ν_s

Peltoniemi, Tommasini & J.V. PL **B298** (1993) 383 : PTV, Peltoniemi & J.V. NP **B406** (1993) 409 [hep-ph/9302316] : PV, Caldwell-Mohapatra, PR **D48** (1993) 3259 : CM, Ioannissian & J. V. PR **D63** (2001) 073002 : IV, Hirsch & J.V. PL **B495** (2000) 121 HV

maximally symmetric (2,2) models



- 2 neutrinos degenerate and 2 massless, to first approximation
- Δm^2_{LSND} small due to 1-loop (PTV & PV) or volume suppression in models with extra-dim(IV, HV)
- Δm^2_{atm} and Δm^2_{sol} small w. r. t. Δm^2_{LSND} due to 2-loop (PTV & PV) or $R\!\!\!/_p$ suppression (HV)
- tests in NC-sensitive experiments SK & SNO since solar & atm conversions can involve a mixture of ν_s

  Smirnov et al, Yasuda, Giunti et al, Grimus & Schwetz...
- tests in cosmology CMBR (MAP & Planck): Hannestad & Raffelt

  BBN: Dolgov et al, Kainulainen et al, Volkas et al, Kirilova, ...

MHD-Spin Flavour Solar ν Conversion

Unless dictated by speacial symmetries...

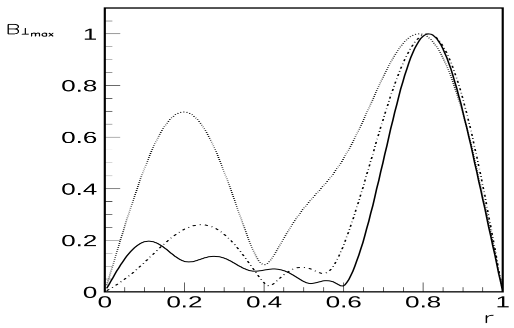
Theory $\Rightarrow$ Majorana ν $\Rightarrow$ Spin Flavour rotation in $\vec{B}$

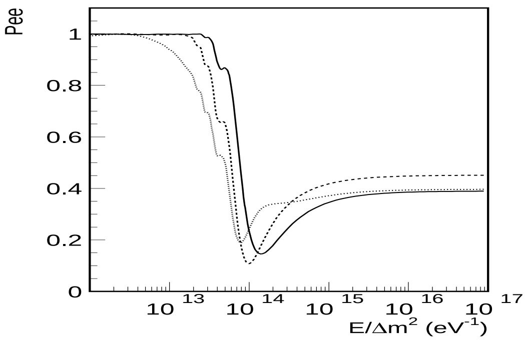
J. Schechter & J. V., PR **D24** (1981) 1883; **D25** (1982) 283

SF conversion can be resonant $\Rightarrow$ RSF

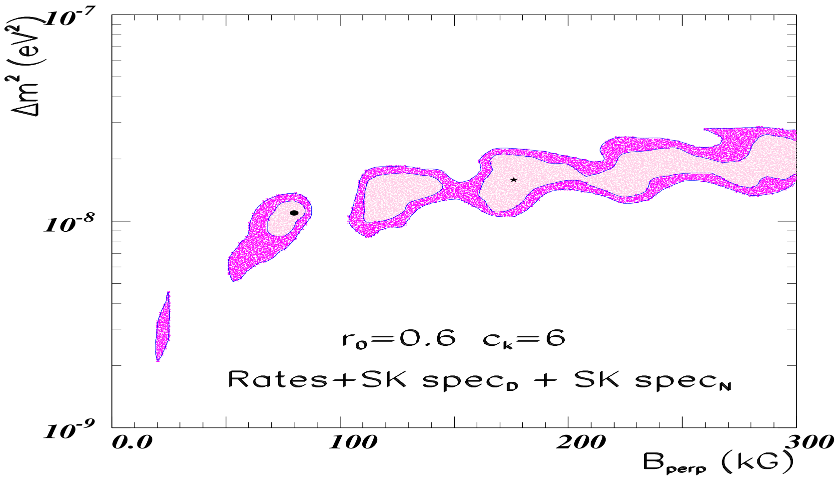
Akhmedov, PL **B213** (1988) 64; Lim & Marciano, PR **D37** (1988) 1368

MHD nearly fixes $\vec{B}^{\perp}_{sol}(r)$ $\Rightarrow$ 2-ν RSF survival probability





MHD-RSF Solar Neutrino Global Fit

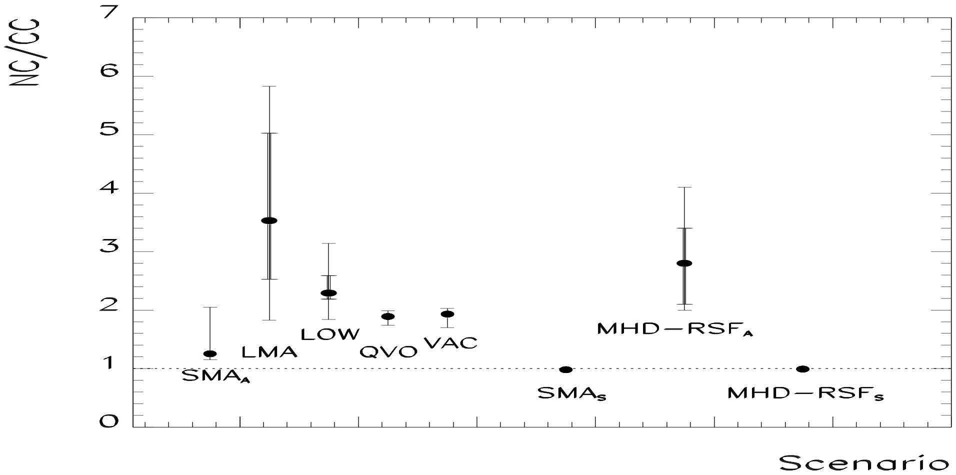


from Miranda et al NP **B595** (2001) 360

Oscillations vs RSF-MHD ν conversions

Oscillation Solution	Δm^2	$\sin^2(2\vartheta)$	χ^2_{min} (Prob %)
LMA	3.2×10^{-5}	0.75	33.4 (59)
LOW	1.0×10^{-7}	0.93	37.4 (40)
SMA_{active}	5.0×10^{-6}	2.2×10^{-3}	38.9 (34)
$SMA_{sterile}$	3.9×10^{-6}	2.4×10^{-3}	39.6 (31)
VAC	6.7×10^{-10}	0.93 (d)	39.3 (32)
QVO	2.3×10^{-9}	0.96 (d)	40.3 (29)
MHD-RSF Solution	Δm^2	$B_{\perp max}$	χ^2_{min} (Prob %)
MHD-RSF$_{active}$	1.1×10^{-8}	80	30.4 (73)
MHD-RSF$_{sterile}$	1.1×10^{-8}	75	34.9 (52)
NO-OSC			91 (3×10^{-4})

Predicting the future from the present



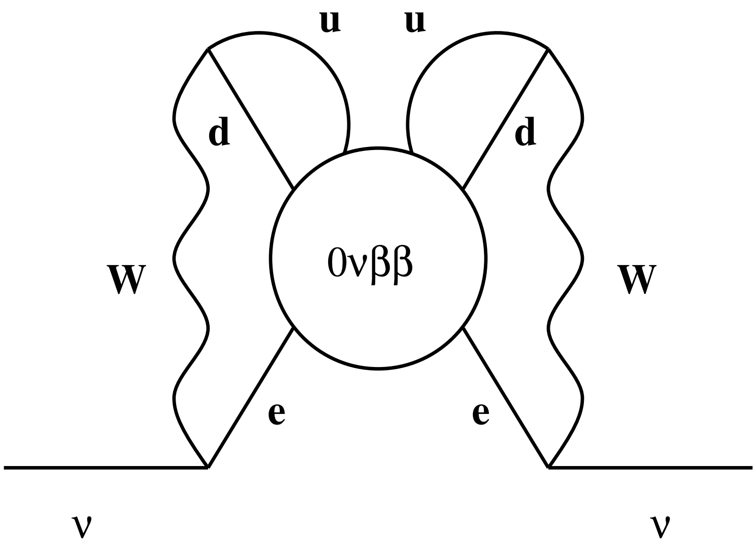
Neutral-to-charged-current event ratio expected at SNO at 90% and 99% CL

`little discriminating power beyond the active-sterile one`

from Miranda et al NP **B 595 (2001) 360** Akhmedov & Pulido, PL **B485** (2000) 178; for SNO observables correlation studies: Bahcall, Krastev & Smirnov

dirac or majorana??

the importance of $\beta\beta_{0\nu}$ decay



- **black box theorem**: whatever induces $\beta\beta_{0\nu}$ $\Rightarrow$ **majorana mass**
  Schechter and J.V. PR **D25** (1982) 2951

- **no such theorem for flavor violation...**

the importance of ν CP properties: Wolfenstein

Additional CP phases in gauge theories of Majorana $\nu's$

Schechter & J. V. PR D22 (1980) 2227 .... may show up in

- $\Delta L = 2$ **neutrino propagation**

  but helicity suppresssed ... J. Schechter & J. V. PR **D23** (1981) 1666

- $\beta\beta_{0\nu}$ **decay**

  same structure as $\Delta L = 2$ ν-propagation but virtual ν's make it better

  Wolfenstein, PL **B107** (1981) 77

- ν **electromagnetic properties**

  Schechter & J. V. PR **D24** (1981) 1883 & **D25** (1982) 283

  more hopeful if use the resonant matter effects: Pastor et al NP **B566** (2000) 92 ...

Conclusions

- Solar neutrino anomaly $\Longrightarrow$ ν_e **conversion**

  osc, RSFP, FC, ...

- Atm neutrino anomaly has $\nu_\mu \to \nu_\tau$ **oscillation** as best solution

- **sol + atm** oscilllation fits $\Longrightarrow$ ν and quark mixings differ radically

- theory can't predict ν properties from first principles

  but may suggest predictive models of neutrino anomalies:

  - **minimalism** $3+1+$ gravity $+$ int. scale $\Longrightarrow$ bi-maximal mixing with QVAC

  - **bottom-up** $R\!\!\!/_p$ MSSM $\Longrightarrow$ hierarchical ν masses with collider tests of ν mixing

  - **top-bottom** ν unification idea $\Longrightarrow$ bi-maximal mixing scheme with LMA or LOW

- Adding Accelerator ν results (LSND) $\Longrightarrow$ 4ν models $\Rightarrow$ atm conversions may be accompanied by sizeable $\nu_\mu \to \nu_s$. Solar conversions may also involve $\nu_e \to \nu_s$ $\Rightarrow$ testable at SK & SNO, as well as cosmology: CMBR & BBN

- room for exotic neutrino conversion mechanisms $\Longrightarrow$

  ν parameters can't be determined reliably, e.g. ν_e mixing can be zero; $\Delta m^2_\odot$ can differ from that required in oscillation fits

- Open: still do not know if Dirac or Majorana