understanding neutrino oscillations

José W. F. Valle

NNN07 workshop, Hamamatsu, Oct 2007

AHEP Group, IFIC, Valencia

http://ahep.uv.es/

BASIC SETUP

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

Schechter and JV, PRD22(1980)2227 & PDG06

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

23=atm+acc

13=reactor + ..

12=solar+KL

BASIC SETUP

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

Schechter and JV, PRD22(1980)2227 & PDG06

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

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

- **the basic phases are Majorana appearing e. g. in** $\beta\beta_{0\nu}$ at $n \geq 2$

Schechter & JV, PRD23(80)1666, Bilenky etal 80, Doi etal 81

BASIC SETUP

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

Schechter and JV, PRD22(1980)2227 & PDG06

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

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

- **the basic phases are Majorana appearing e. g. in** $\beta\beta_{0\nu}$ at $n \geq 2$

Schechter & JV, PRD23(80)1666, Bilenky etal 80, Doi etal 81

- **what oscillations can probe is the Dirac phase** (2 co-cycle) $n \geq 3$

BASIC SETUP

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

Schechter and JV, PRD22(1980)2227 & PDG06

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

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

- **the basic phases are Majorana appearing e. g. in** $\beta\beta_{0\nu}$ at $n \geq 2$

Schechter & JV, PRD23(80)1666, Bilenky etal 80, Doi etal 81

- **what oscillations can probe is the Dirac phase** (2 co-cycle) $n \geq 3$
- **in general K is NOT unitary eg in SEESAW hep-ph/0608101** $\Rightarrow$ NSI

BASIC SETUP

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

Schechter and JV, PRD22(1980)2227 & PDG06

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

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

- **the basic phases are Majorana appearing e. g. in** $\beta\beta_{0\nu}$ at $n \geq 2$

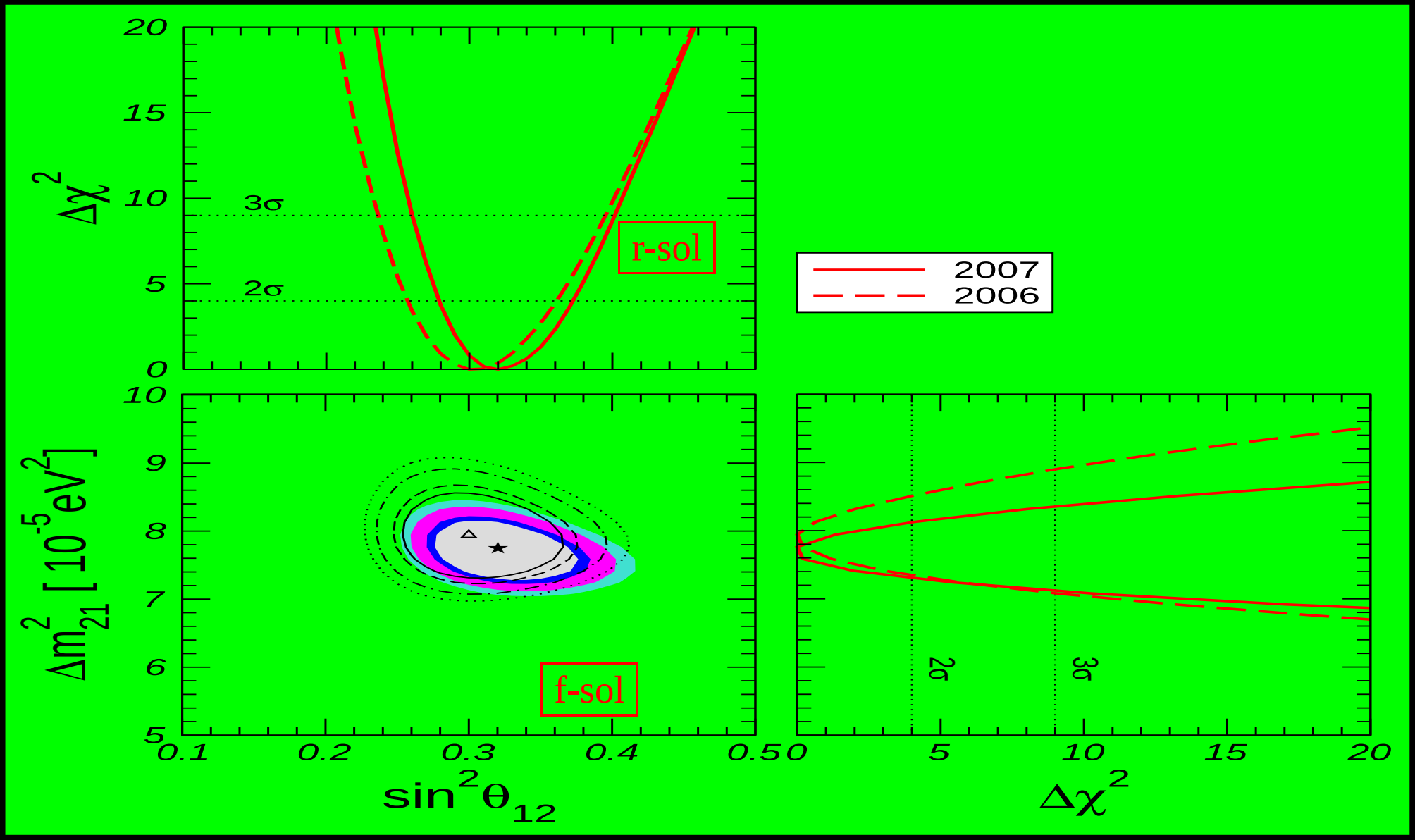
Schechter & JV, PRD23(80)1666, Bilenky etal 80, Doi etal 81

- **what oscillations can probe is the Dirac phase** (2 co-cycle) $n \geq 3$
- **in general K is NOT unitary eg in SEESAW hep-ph/0608101** $\Rightarrow$ NSI
- currently no expt is sensitive to CPV $\Rightarrow$ drop all ϕ_{ij}

5 oscil. parameters

SOLAR OSCILLATION PARAMETERS 2007

Maltoni et al, NJP 6 (2004) 122 **hep-ph/0405172** **version 6**

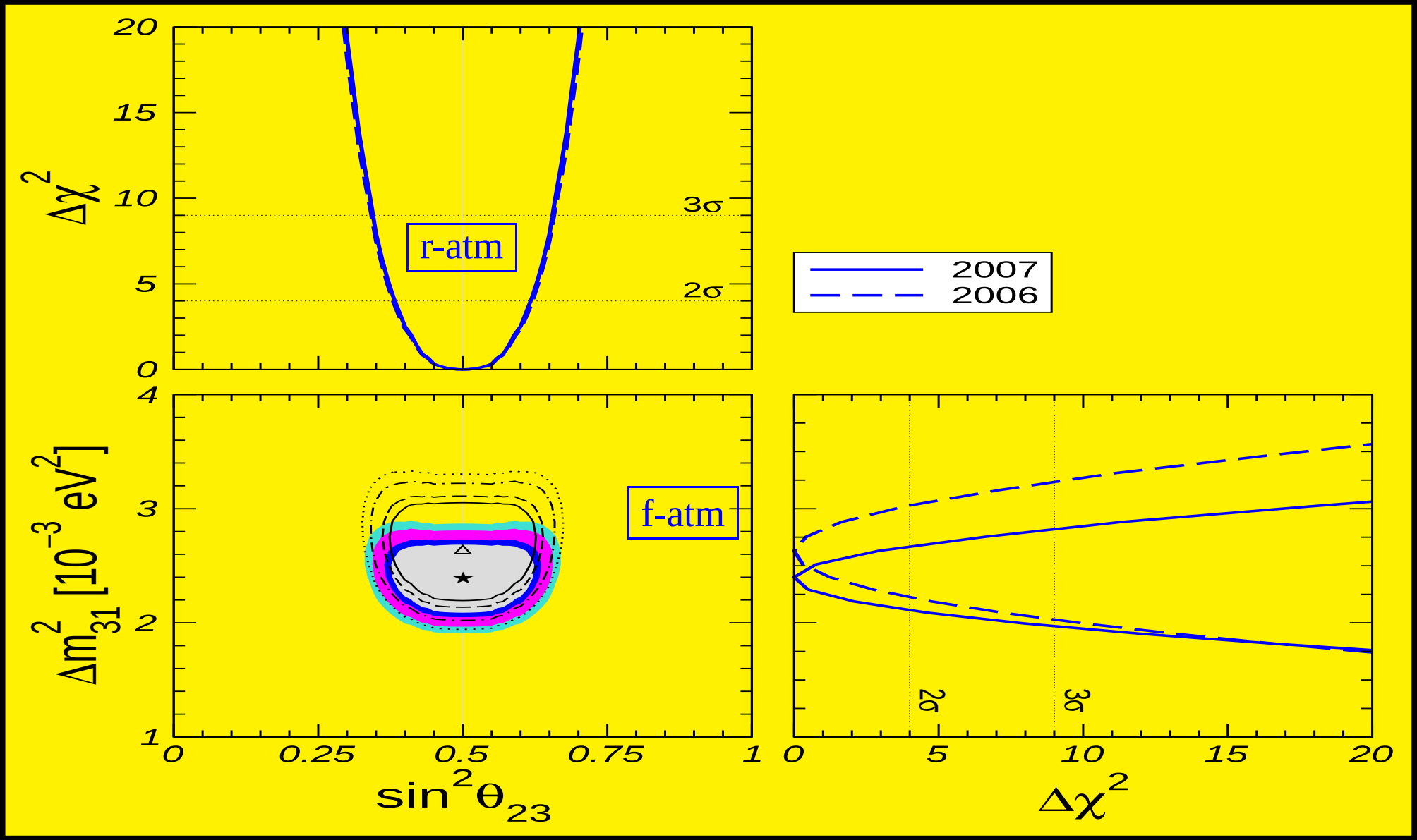


news from KamLAND/Borexino

http://ahep.uv.es/

ATM OSCILLATION PARAMETERS 2007

Maltoni et al, NJP 6 (2004) 122 **hep-ph/0405172** **version 6**

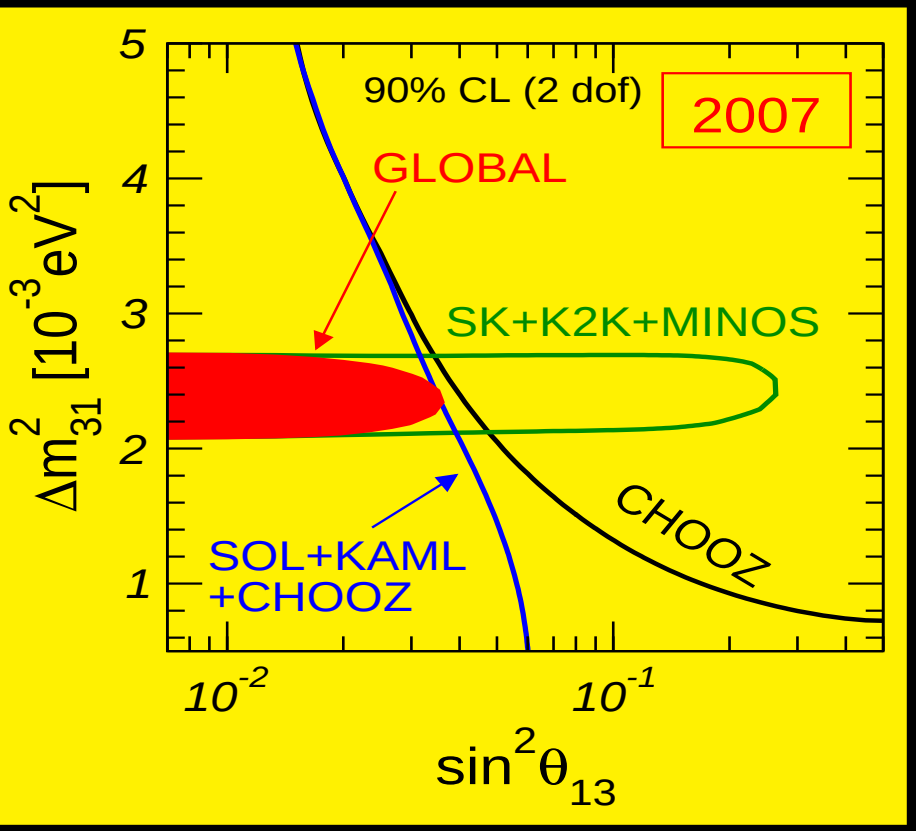


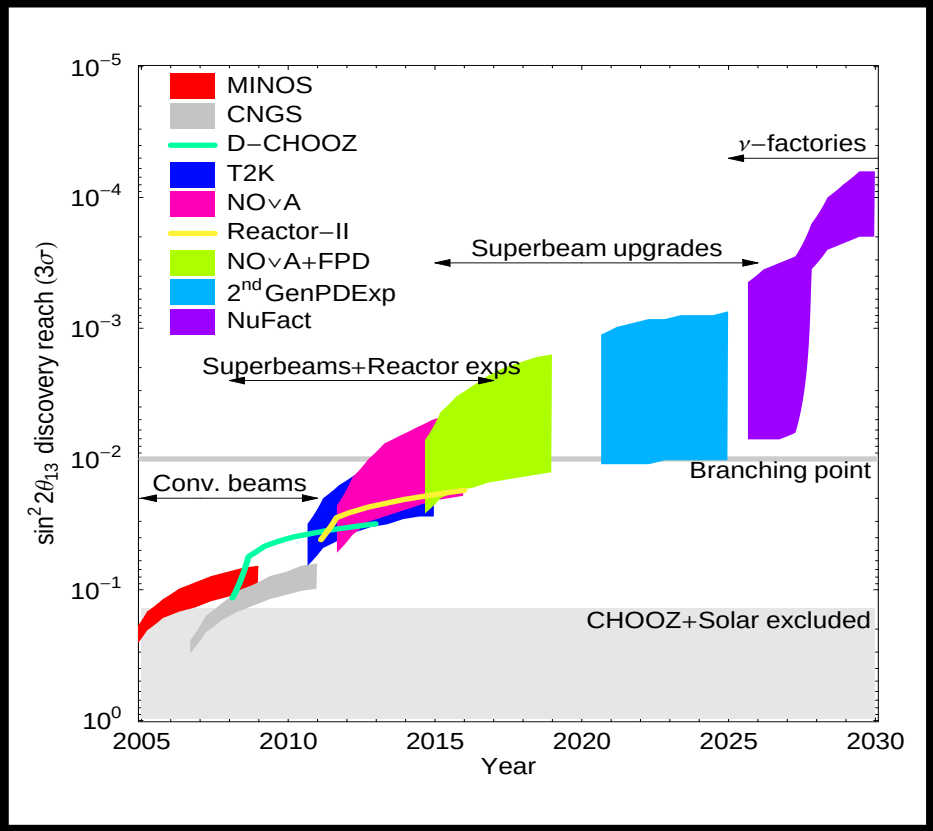
news from MINOS07

http://ahep.uv.es/

THETA13 ROADMAP

M. Maltoni et al, NJP 6 (2004) 122 hep-ph/0405172 version 6 2007-UPDATED Lindner et al





LS : LENA, **LAr** : GLACIER, **WC** : MEMPHYS, UNO, HS, HK ...

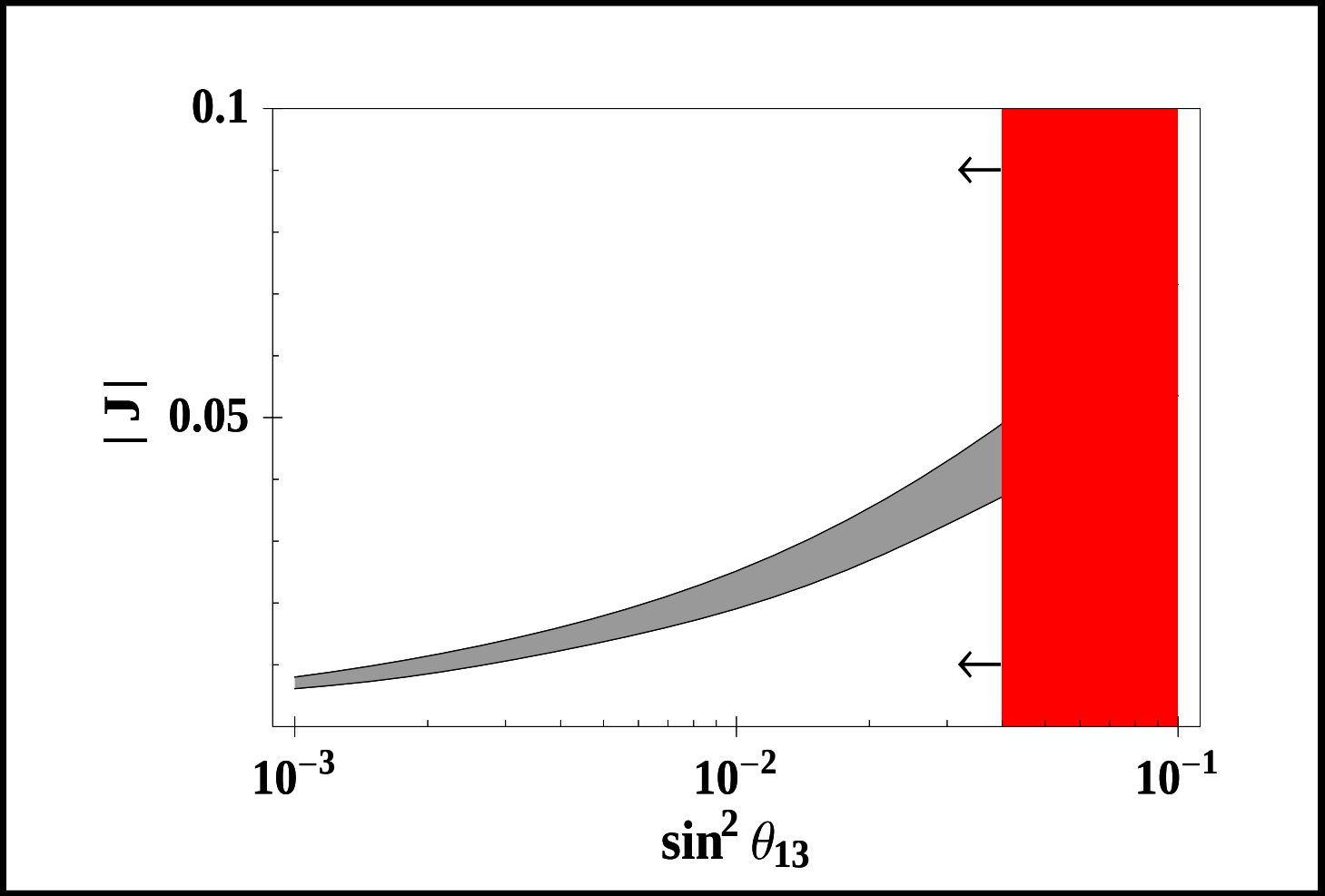
other ways? D/N solar-nu studies Akhmedov et al JHEP05 (2004) 057

if no NSI Huber et al PRL88 (2002) 101804, PRD66, 013006 (2002)

http://ahep.uv.es/

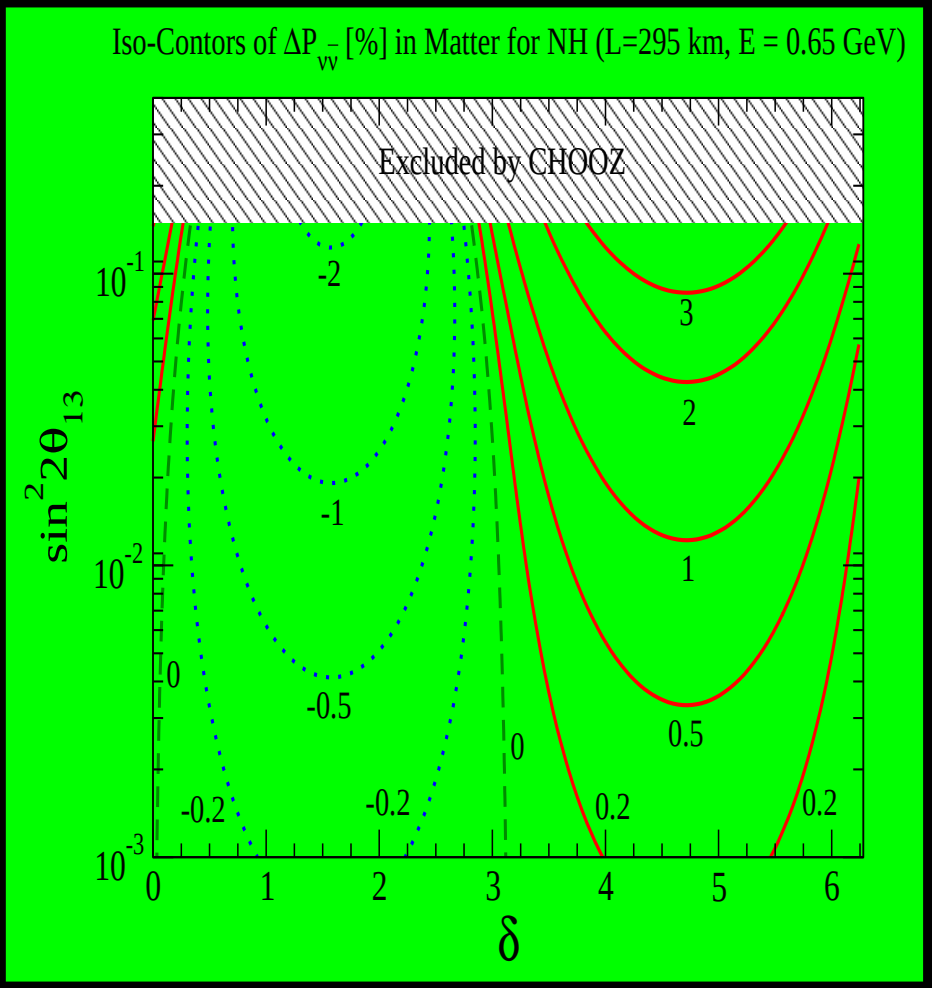
MAXIMAL CPV from THEORY?

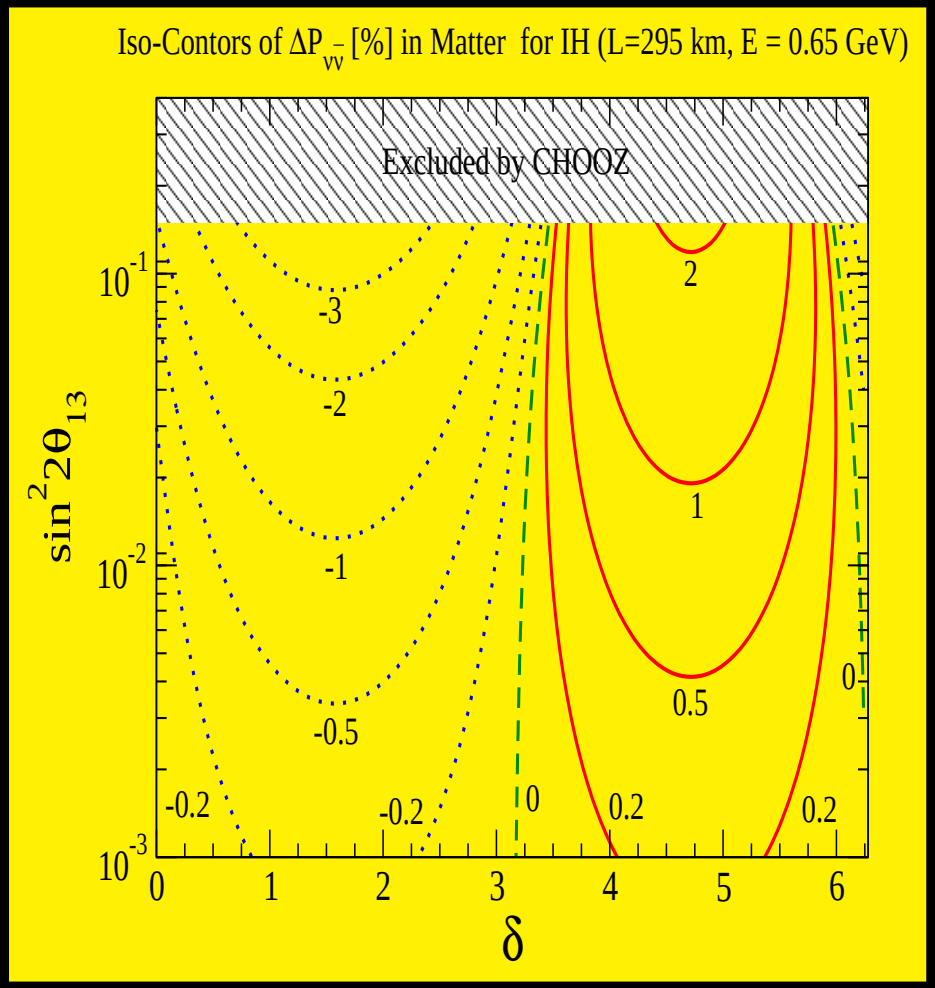
Hirsch et al hep-ph/0703046 PRL



but remember ... **double price for CPV**

CPV in LBL oscillations





Iso-contours of $\Delta P_{\nu\bar{\nu}} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for T2K w/ matter for **normal** & **inverse**

challenge for T2K, NOvA, T2KK, ...

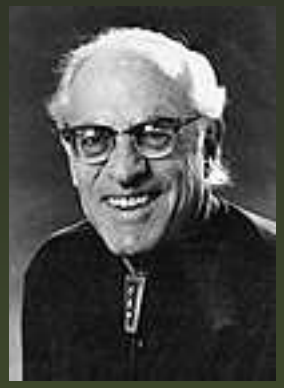
http://ahep.uv.es/

robustness: atm ok, solar NOT

role of reactors ...

KamLAND has solved SNP

identifying oscillation as “the” soln



- noisy Sun robust

Burgess et al JCAP0401 (2004) 007

- SFP robust

Guzzo et al, NPB629 (2002) 479 Barranco et al, PRD66 (2002) 093009

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

- NSI not quite robust yet

Miranda etal JHEP **0610** (2006) 008

LEPTON FLAVOR VIOLATION

NHL

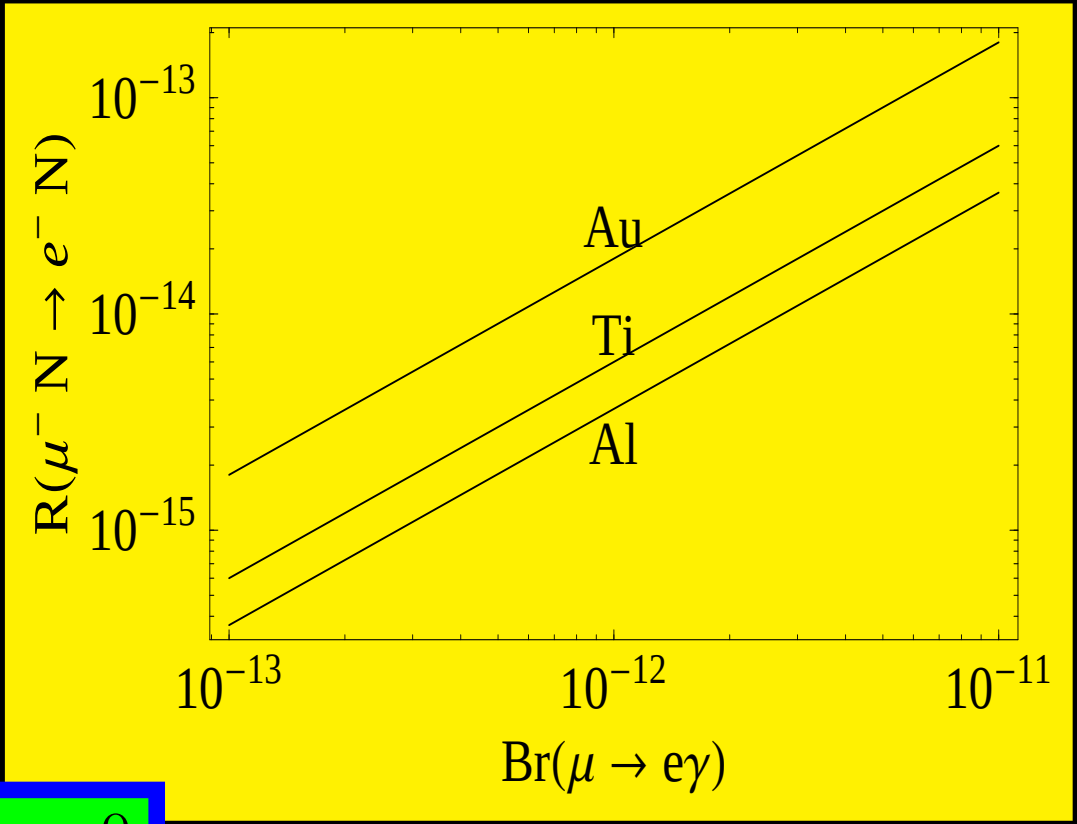
Bernabeu et al, Branco, Rebelo and JV,
Rius & JV, Gonzalez-Garcia & JV
Ilakovac & Pilaftsis...

SUSY

Hall, Kostelecky & Raby
Borzumati & Masiero
Hisano & Tobe, Casas & Ibarra;
Antusch, Arganda, Herrero, Teixeira,
Joaquim & Rossi ...

$\Rightarrow$

$M = 1$ TeV, best-fit oscil param



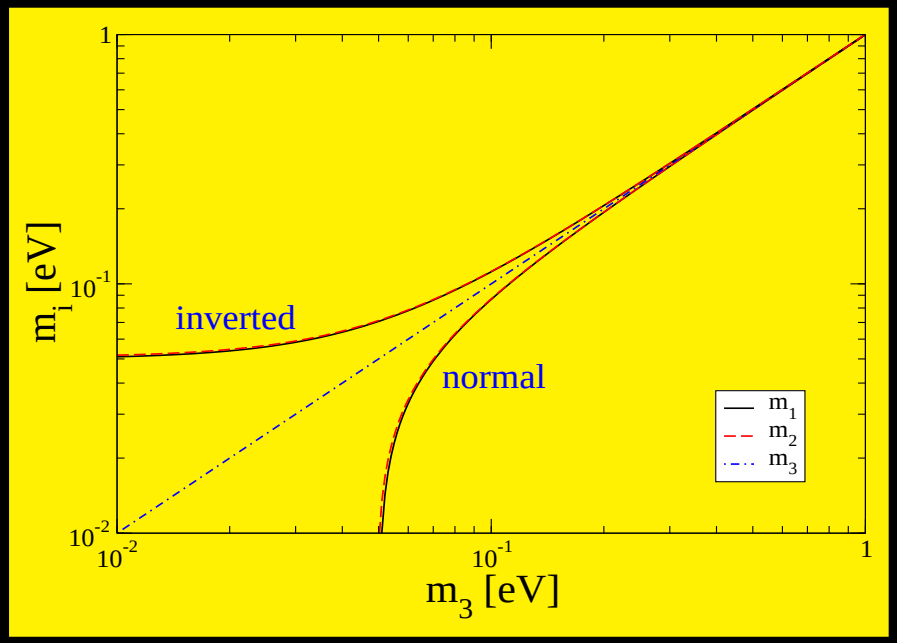
LFV & CPV can exist as $m_\nu \to 0$

from Deppisch & JV, PRD72 (2005) 036001
Deppisch, Kosmas & JV NPB752 (2006) 80

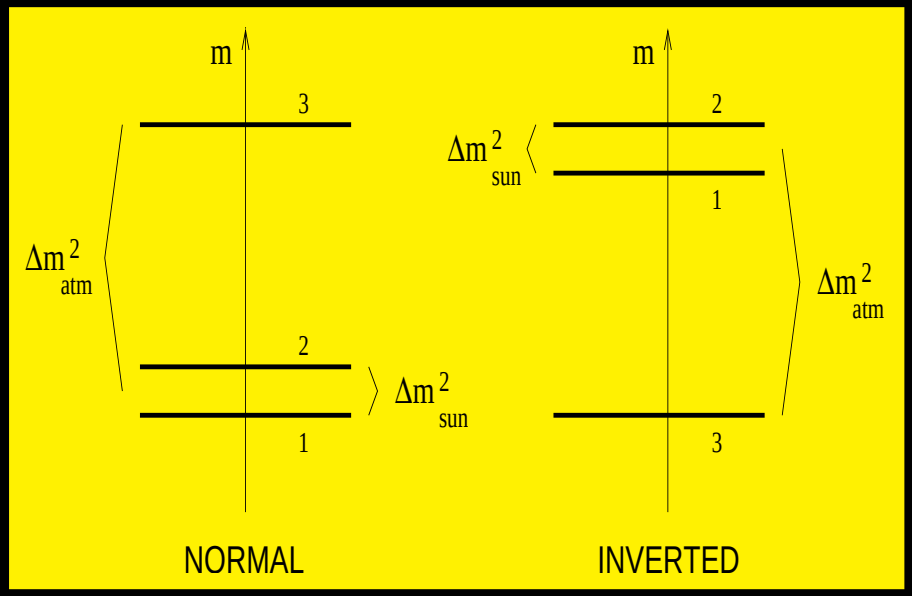
hope for MEG 10^{-13} & PRISM 10^{-18}

WHICH SPECTRUM?

oscil do not probe absolute masses



can not choose spectrum



need for kinematical tests !

http://ahep.uv.es/

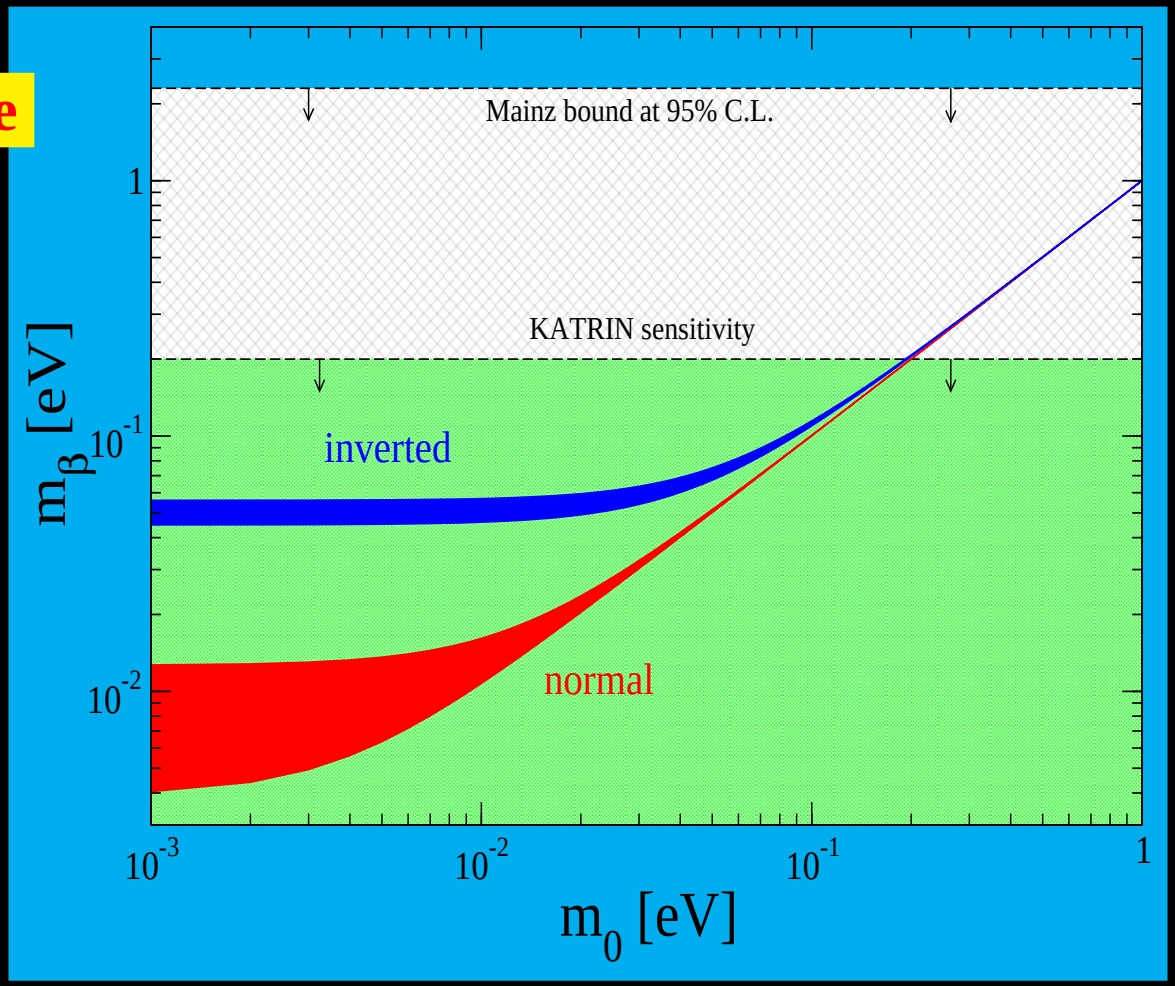
TRITIUM BETA DECAY

test absolute nu-mass scale

Katrin will be next high precision nu-mass expt

scales up size & source intensity

great challenge !!



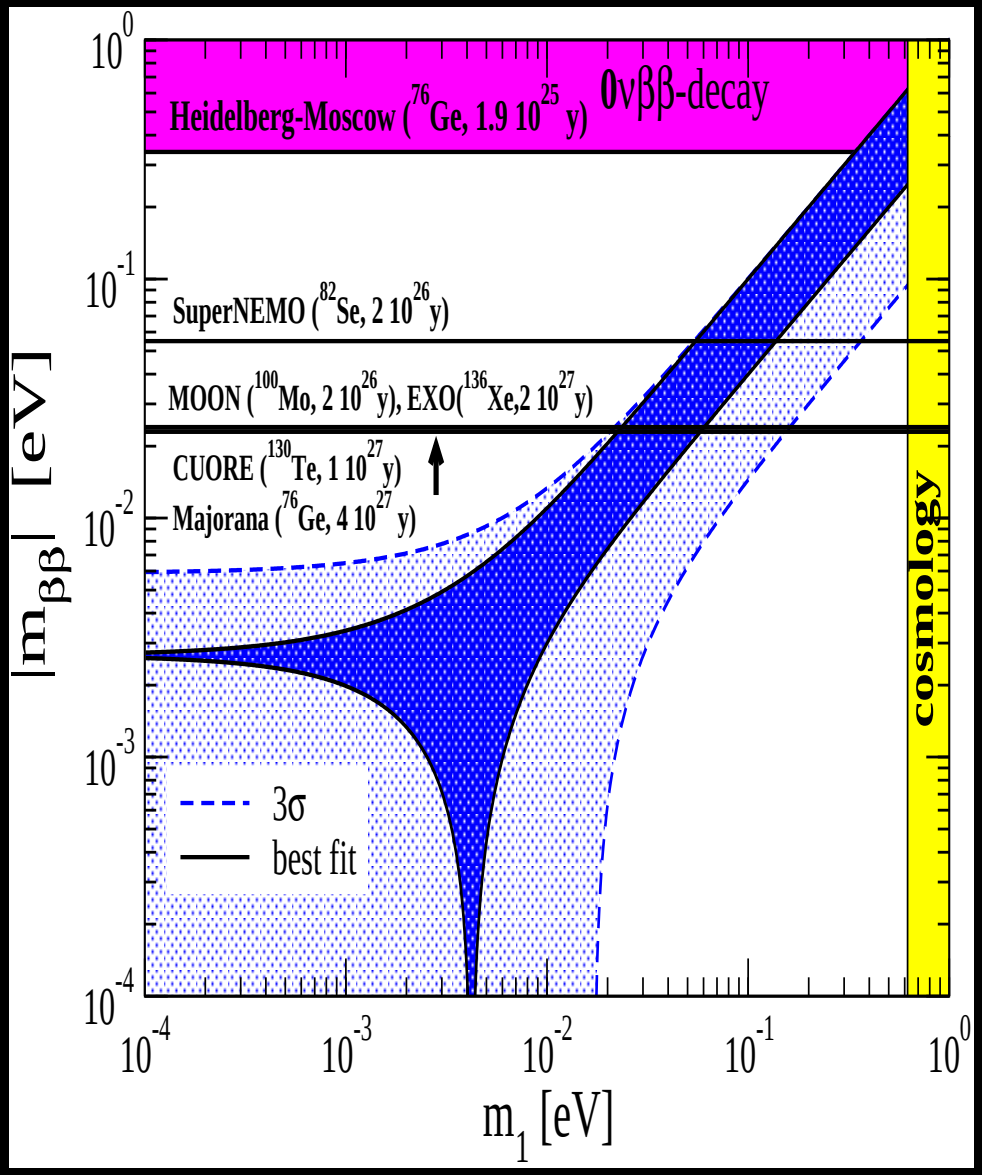
first exact relativistic beta decay endpoint spectrum

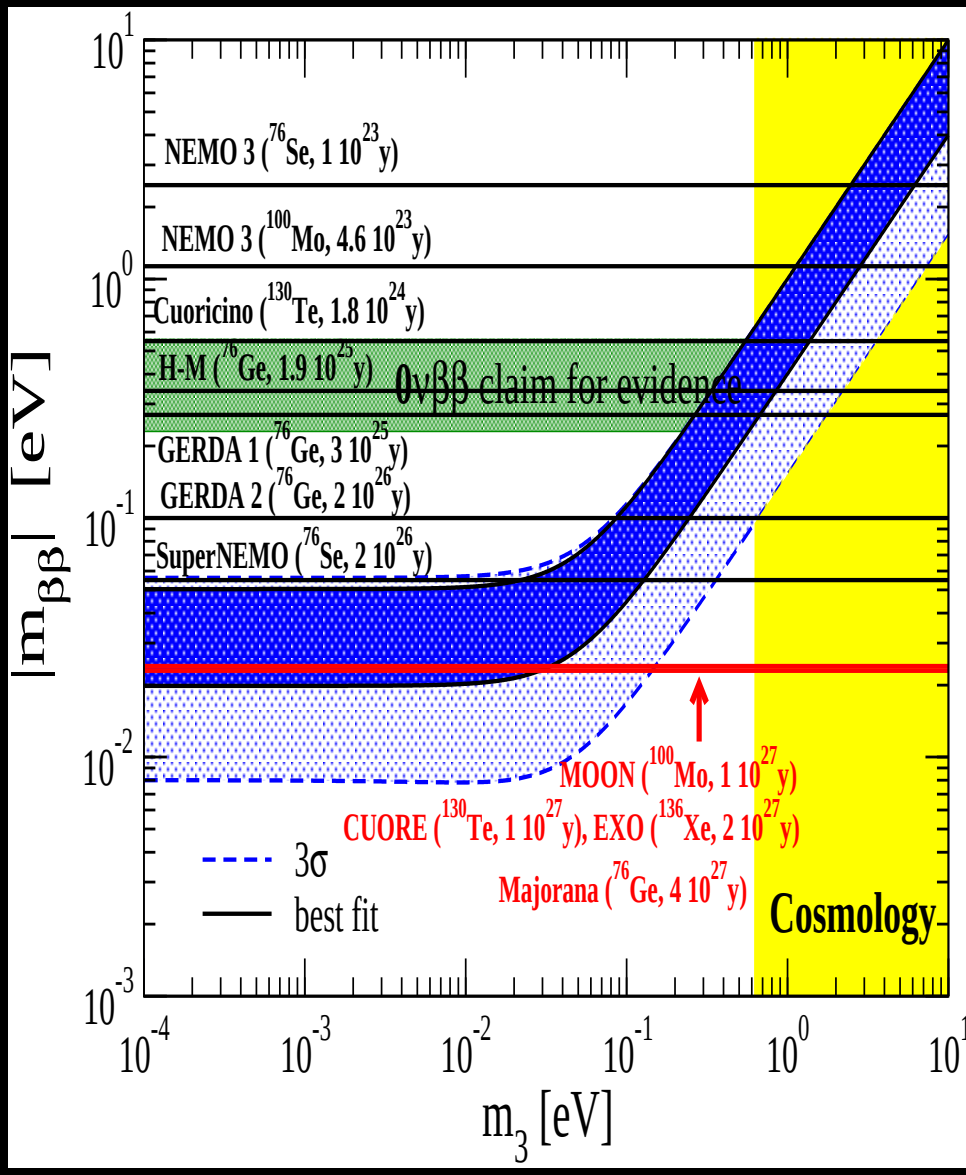
Masood et al 0706.0897 [hep-ph] PhysRevC

VERY FAR FROM PROBING NH/IH

http://ahep.uv.es/

0-nu DBD





NME from Rodin, Faessler, Simkovic, Vogel

SPECTRUM + ABSOLUTE SCALE + MAJ. PHASE

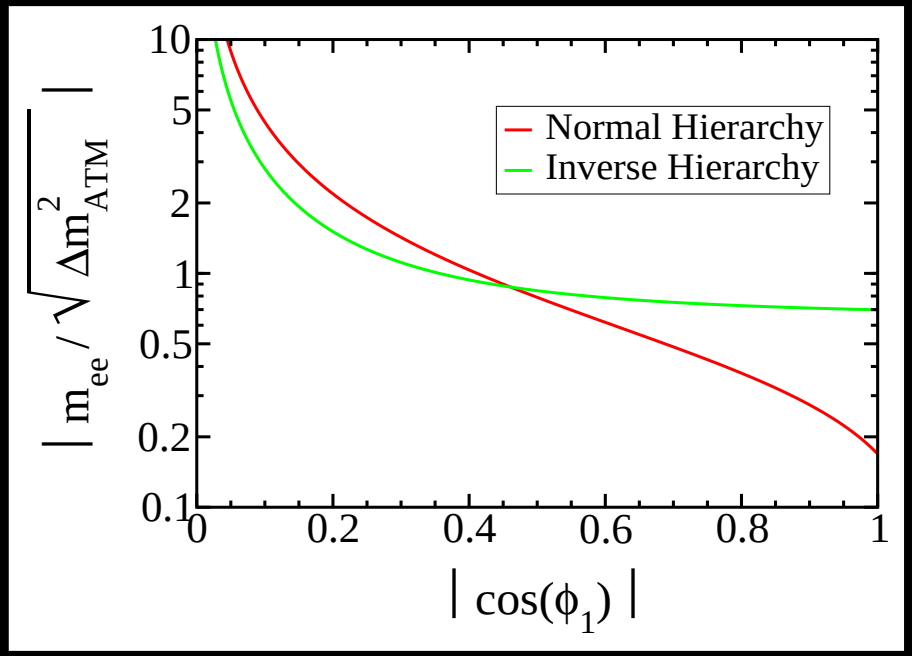
http://ahep.uv.es/

TH DBD LOWER BOUND?

TWO A_4 MODELS

Hirsch, et al, PRD72 (2005) 091301

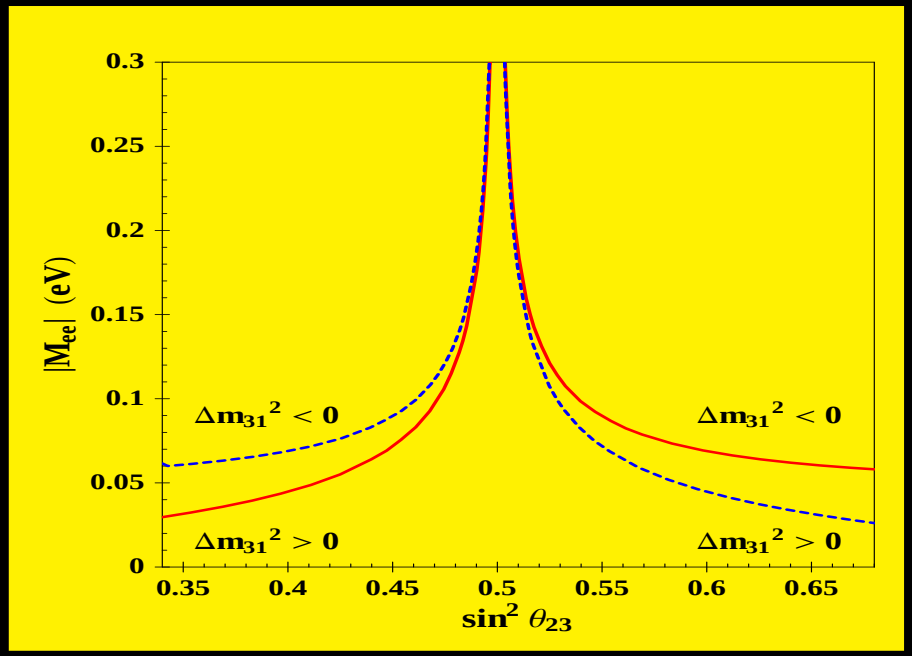
sensitive to Majorana phase



Hirsch et al hep-ph/0703046 PRL

DBD limit depends on ATM angle

deviation from $\pi/4$



http://ahep.uv.es/

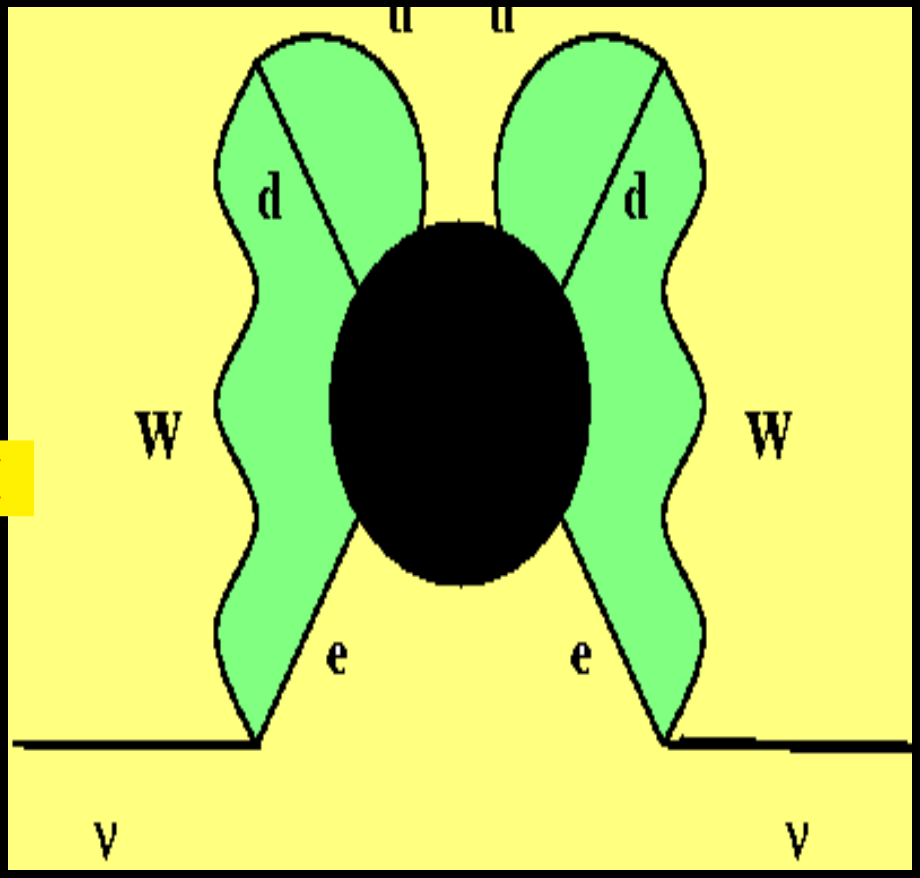
SIGNIFICANCE of 0-nu DBD

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

tests majorana nature

IRRESPECTIVE OF MECHANISM

no such theorem for flavor violation

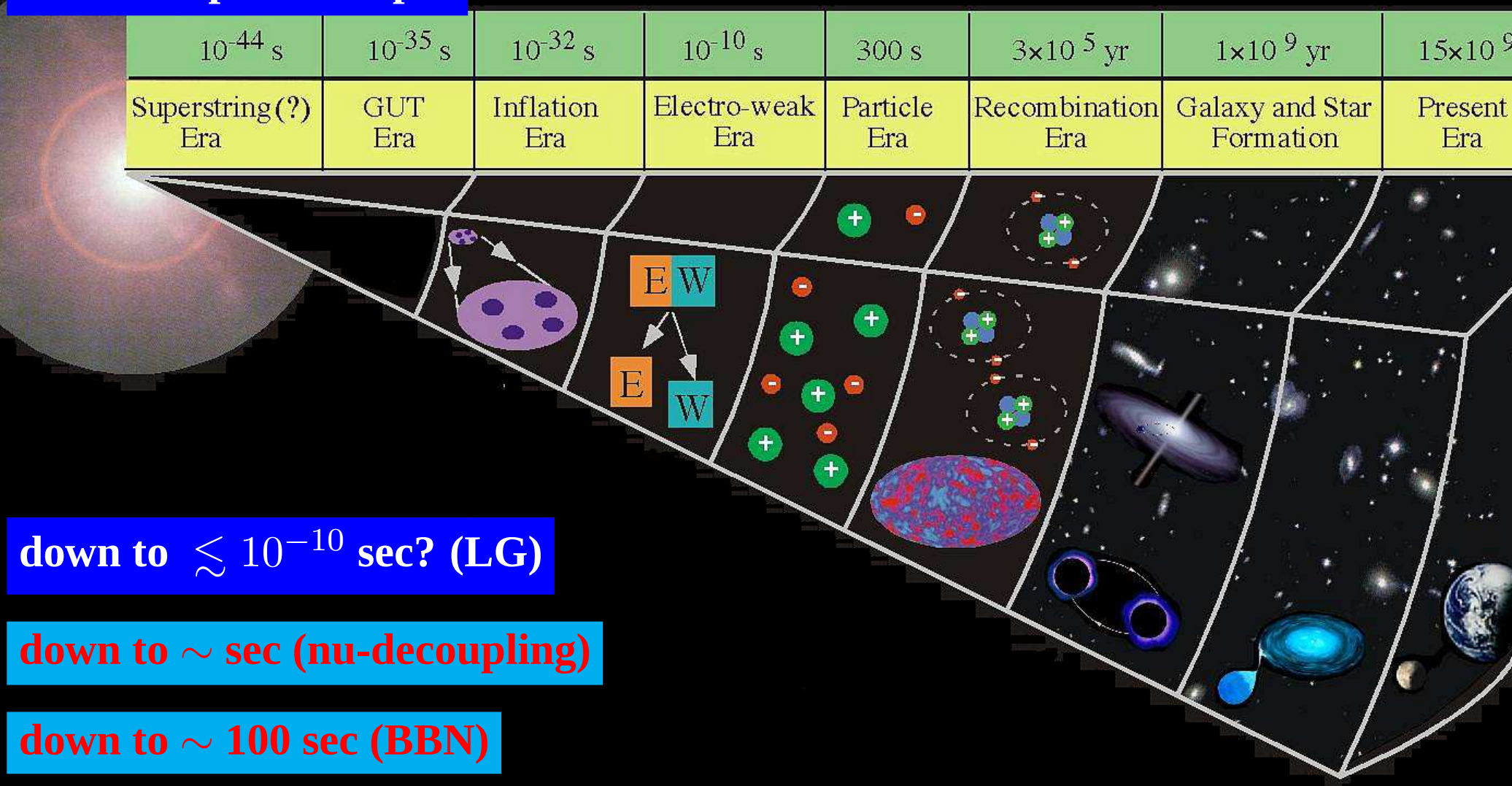


Schechter and JV, PRD25 (1982) 2951

neutrinos as cosmo probes

time

neutrinos probe deeper



down to $\lesssim 10^{-10}$ sec? (LG)

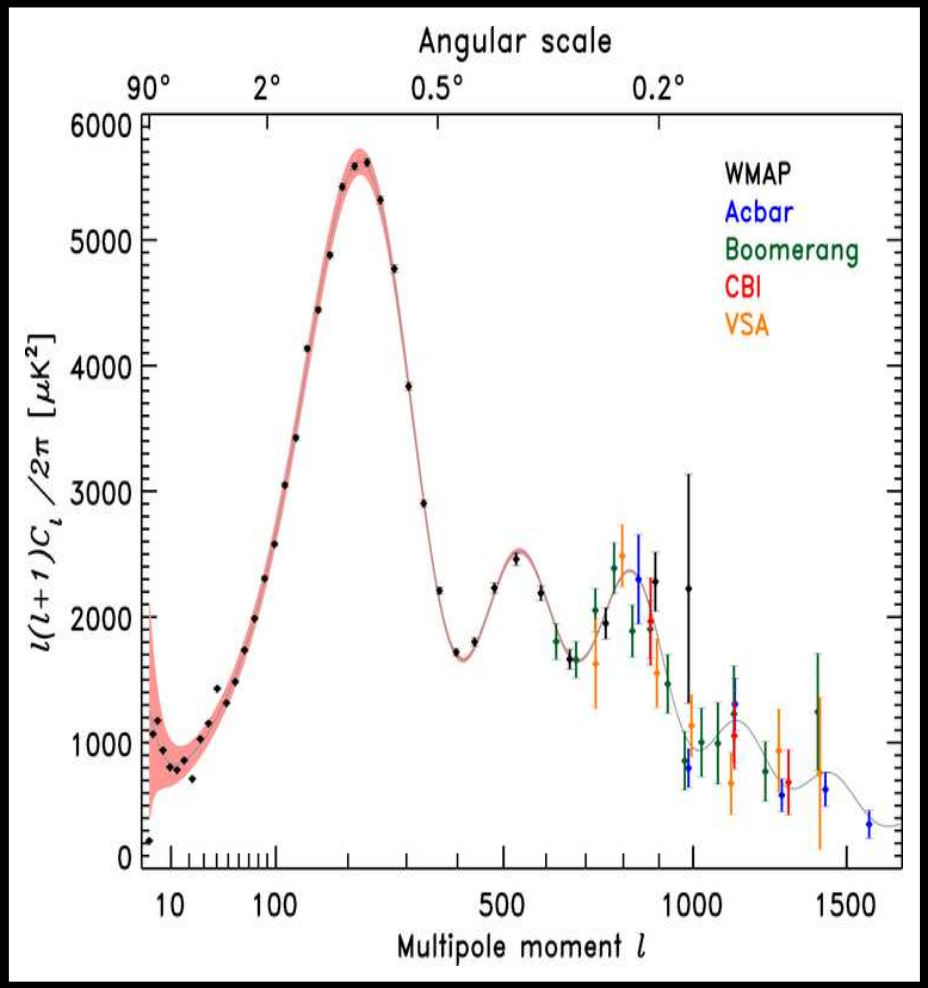
down to $\sim$ sec (nu-decoupling)

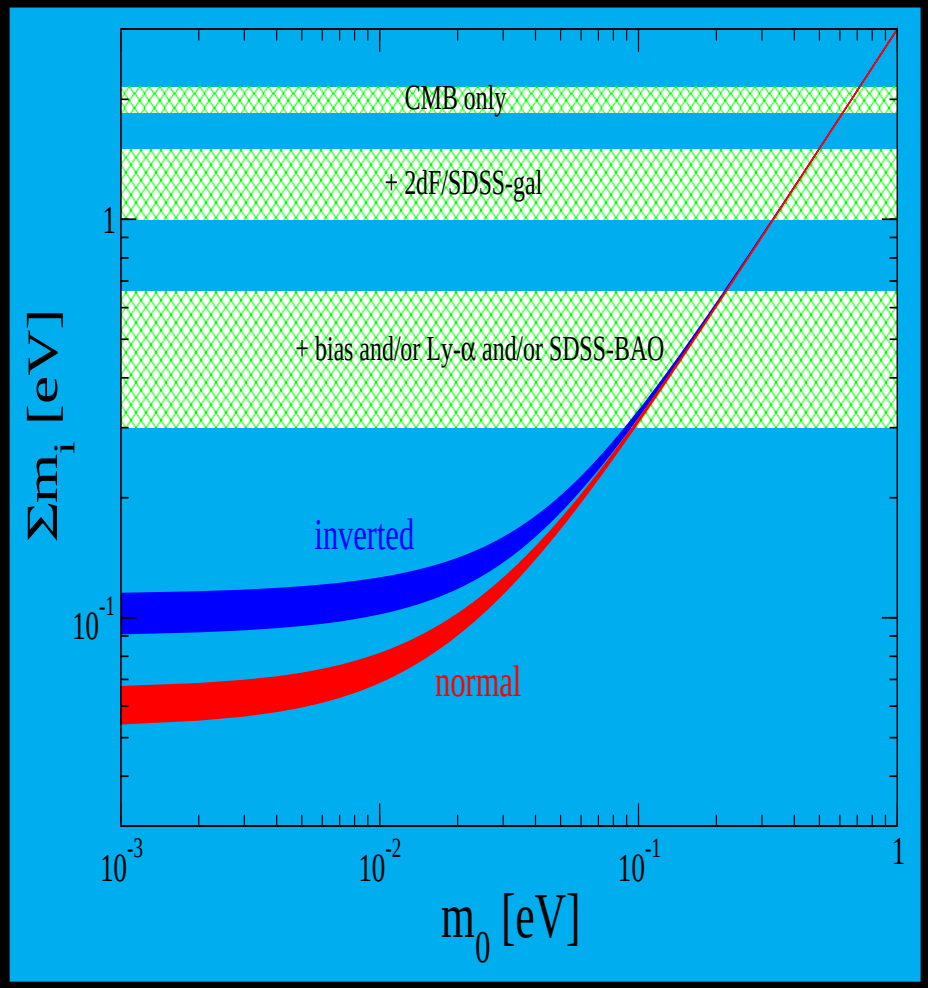
down to $\sim$ 100 sec (BBN)

CMB & LSS

http://ahep.uv.es/

CMB, LSS ... & M-nu SCALE





Fogli et al, Hannestad, ...

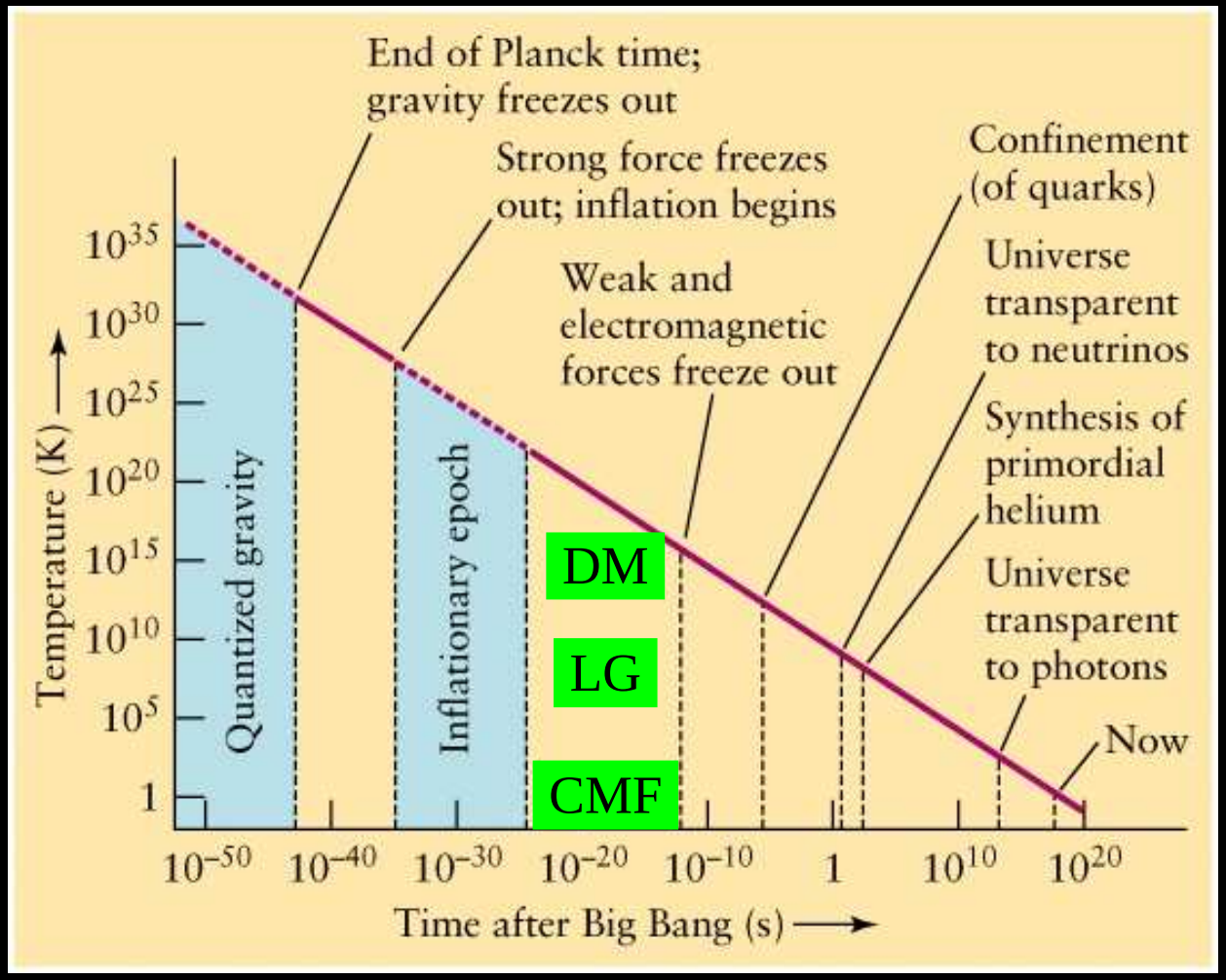
Lesgourgues & Pastor ⇒

STILL FAR FROM PROBING NH/IH

http://ahep.uv.es/

NEUTRINOS BEFORE EWPT

spontaneous L-violation a la seesaw may explain BAU & DM $\Rightarrow$ **CMF**



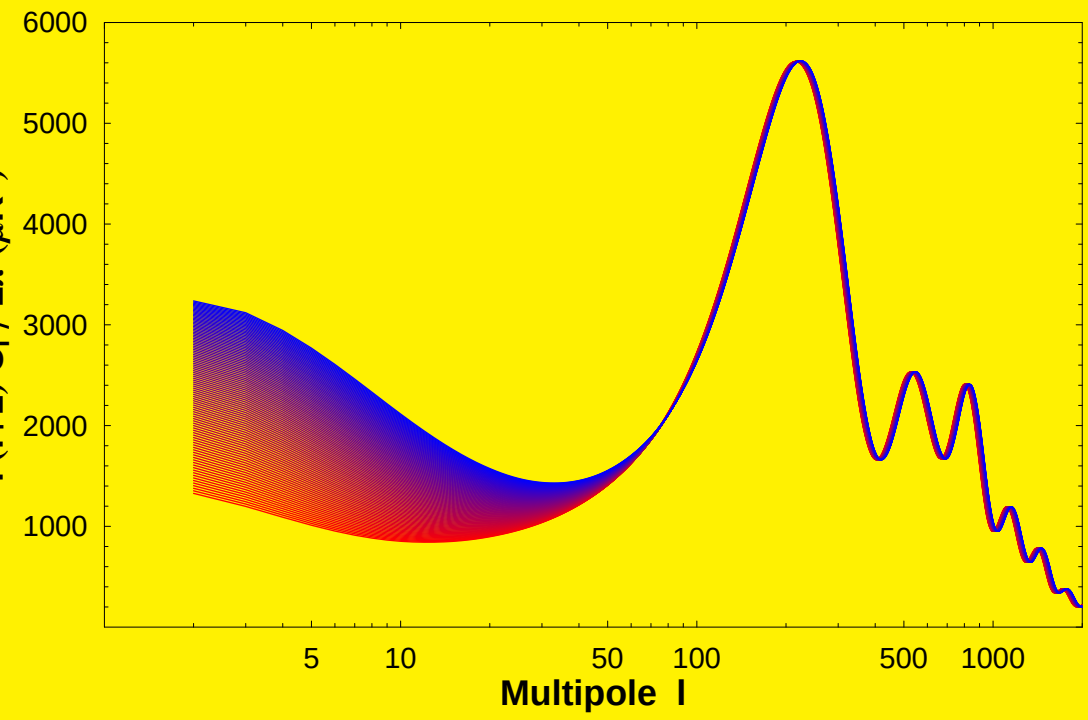
http://ahep.uv.es/

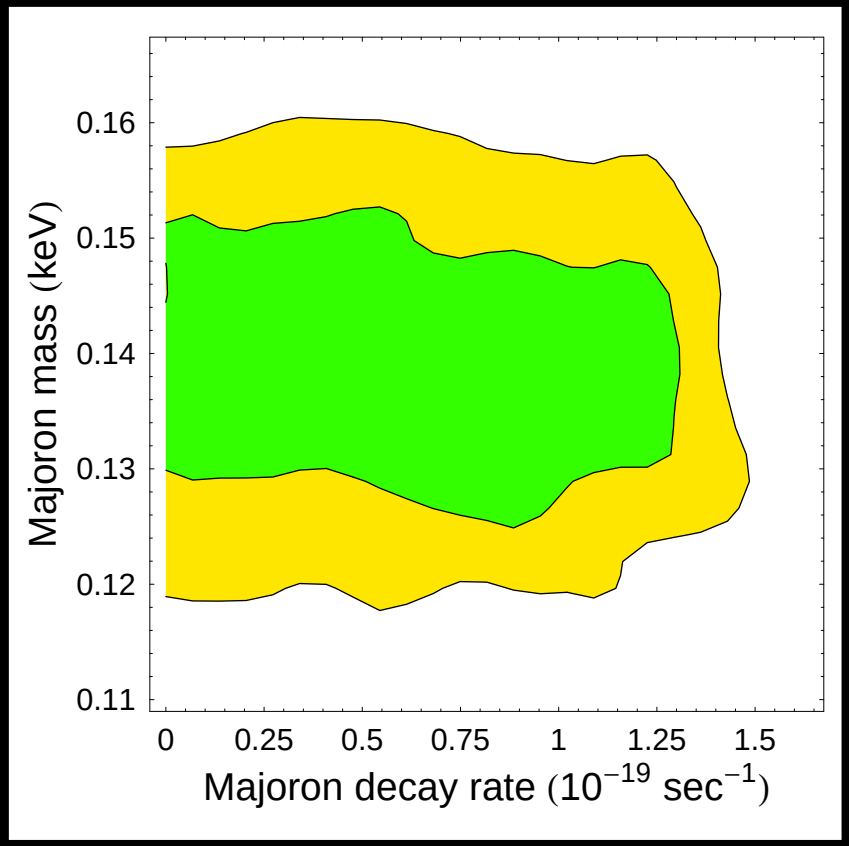
CMB & Decaying DARK MATTER

- ⇒

Lattanzi & Valle 0705.2406 [astro-ph] PRL 99, 121301 (2007)

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

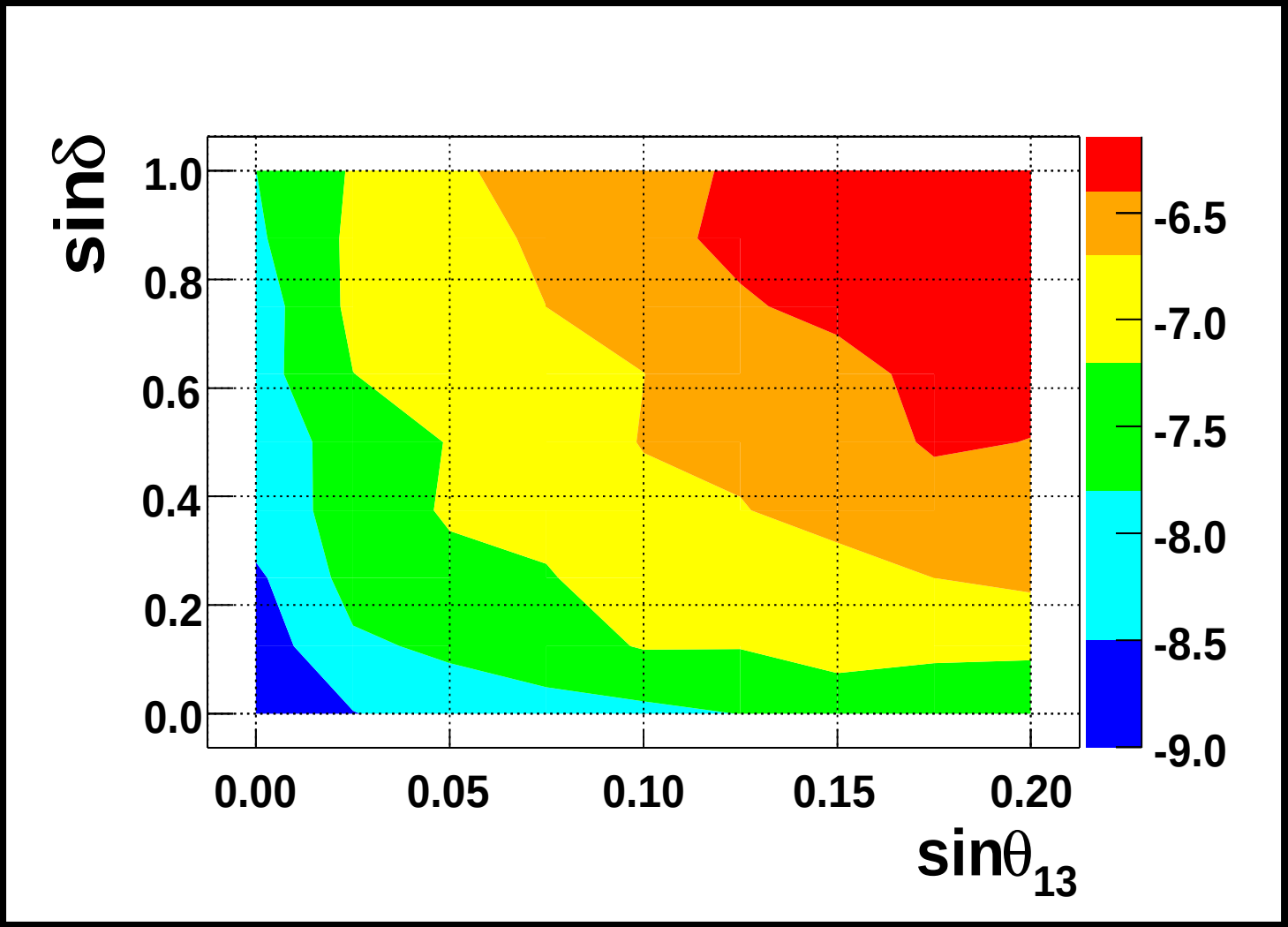




Thermal seesaw leptogenesis & oscill phase

Fukugita, Yanagida 86

Romao, Tortola, Hirsch, Valle **arXiv:0707.2942**



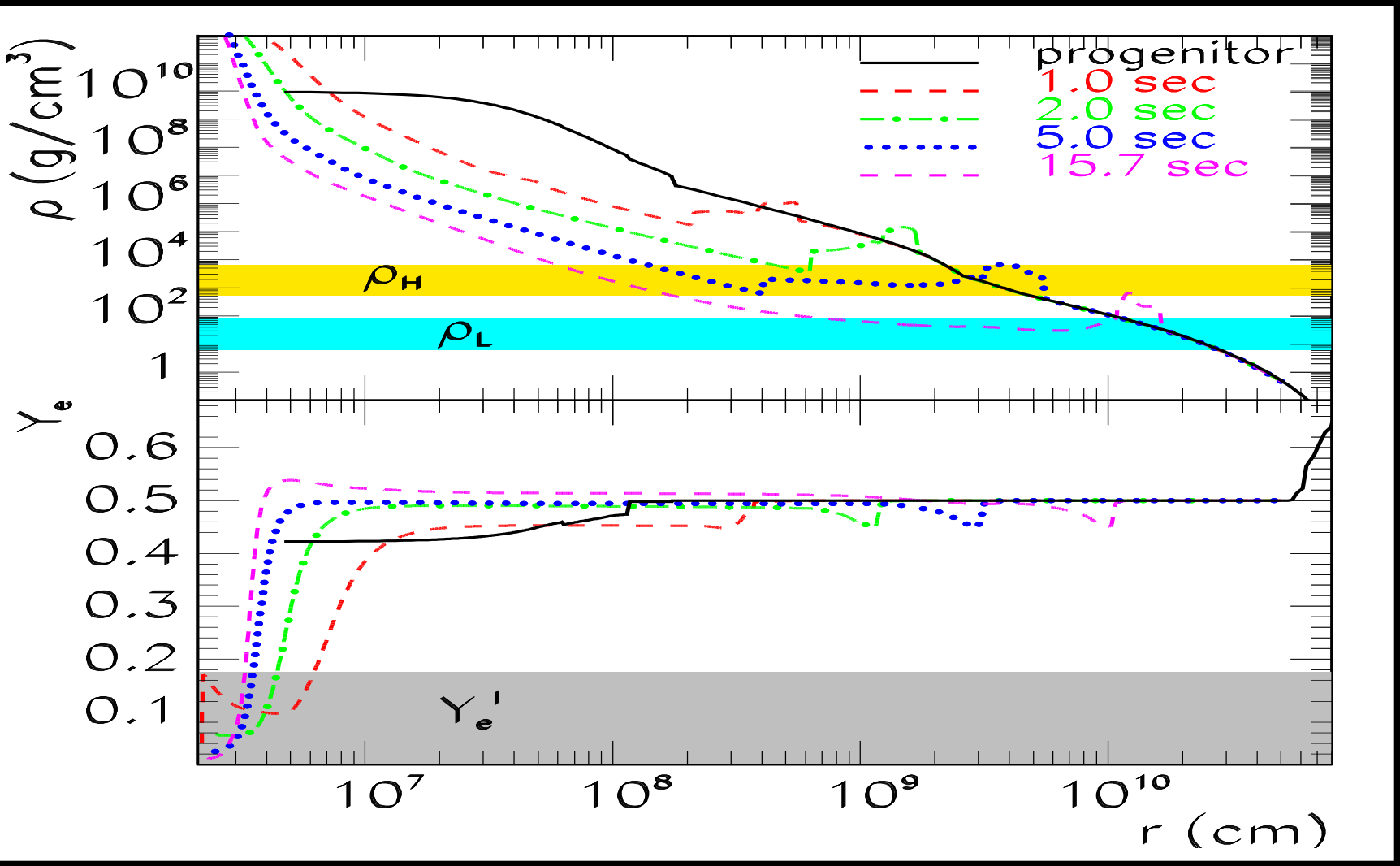
DIRAC NU-OSCILLATIONS PHASE IS ENOUGH

SCALE CAN BE LOW

Hirsch et al PRD75 (2007) 011701

http://ahep.uv.es/

NEUTRINOS AS SNOVA-PROBE



OUTER H/L OSCILLS **ATM** **SOL**

e.g MINAKATA et al

NSI-INDUCED INNER RESONANCE

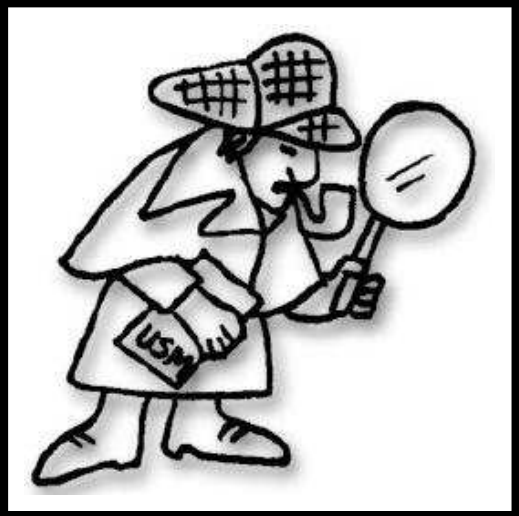
Valle PLB199 (1987) 432

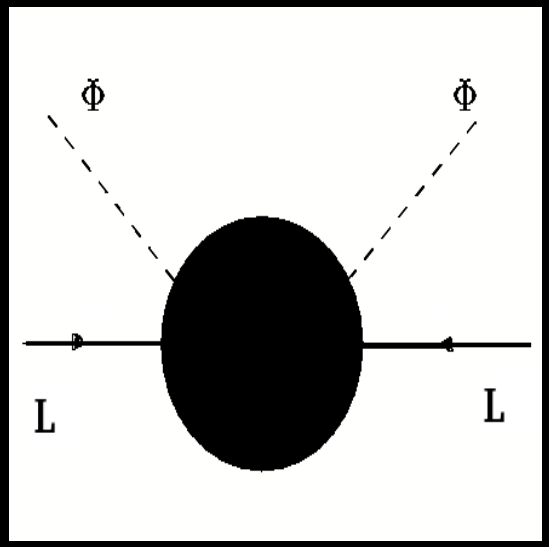
Nunokawa et al 96

http://ahep.uv.es/

Esteban-Pretel, Tomas, Valle arXiv:0704.0032 PRD76:053001,2007

MYSTERY REMAINS





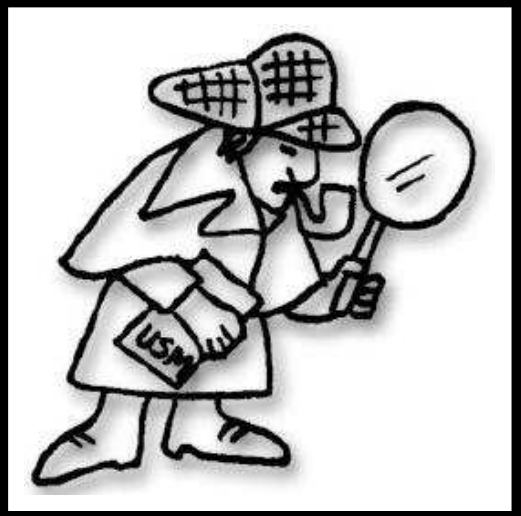
PATHWAYS

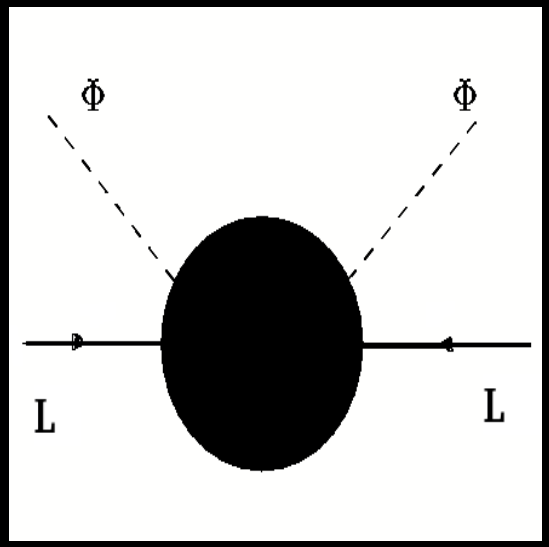
Weinberg PRD22 (1980) 1694

SEESAW

hep-ph/0608101

MYSTERY REMAINS





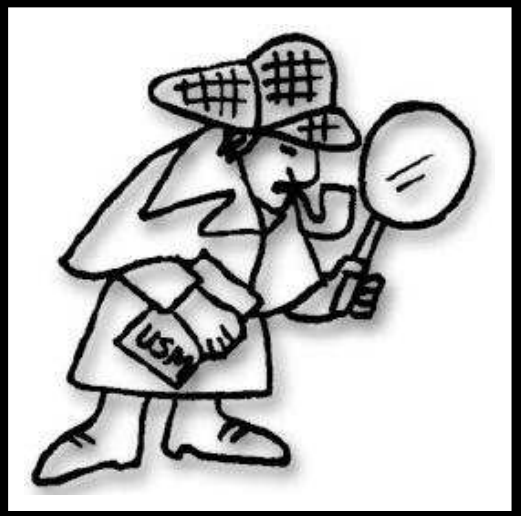
PATHWAYS

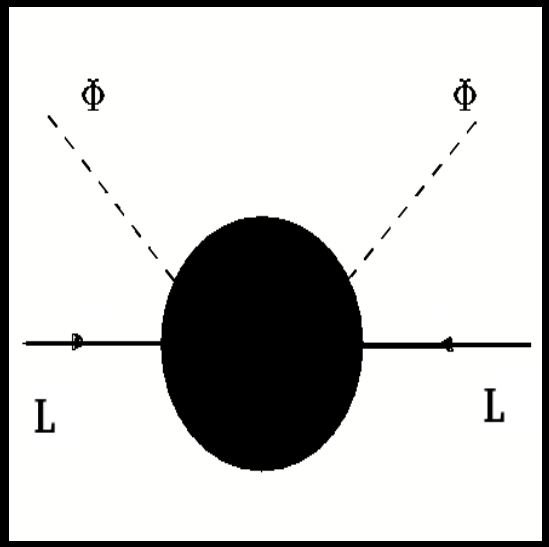
- Weinberg PRD22 (1980) 1694

SEESAW hep-ph/0608101

- which scale $\Rightarrow$ ew-J

MYSTERY REMAINS





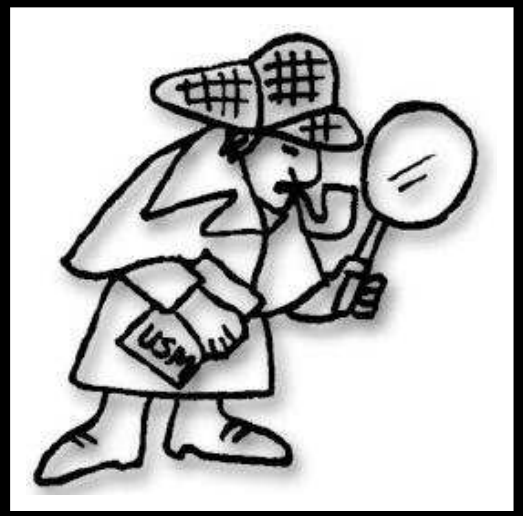
PATHWAYS

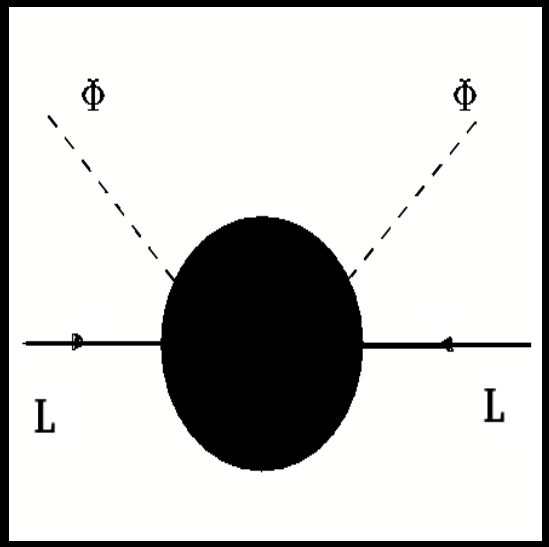
- Weinberg PRD22 (1980) 1694

SEESAW hep-ph/0608101

- which scale ⇒ ew-J
- which flavour structure

MYSTERY REMAINS





PATHWAYS

- Weinberg PRD22 (1980) 1694

SEESAW hep-ph/0608101

- which scale ⇒ ew-J
- which flavour structure
- which mechanism

many realizations

FIN

END: BACKUP SLIDES

from here on there is no logical order among slides

Cosmological magnetic fields

$$B_Y(x) = B_0^Y \exp\left[10^2 \int_x^{x_0} \frac{\mathrm{d}x'}{x'^2}\left(\frac{\xi_\nu(x')}{0.001}\right)^2\right]$$

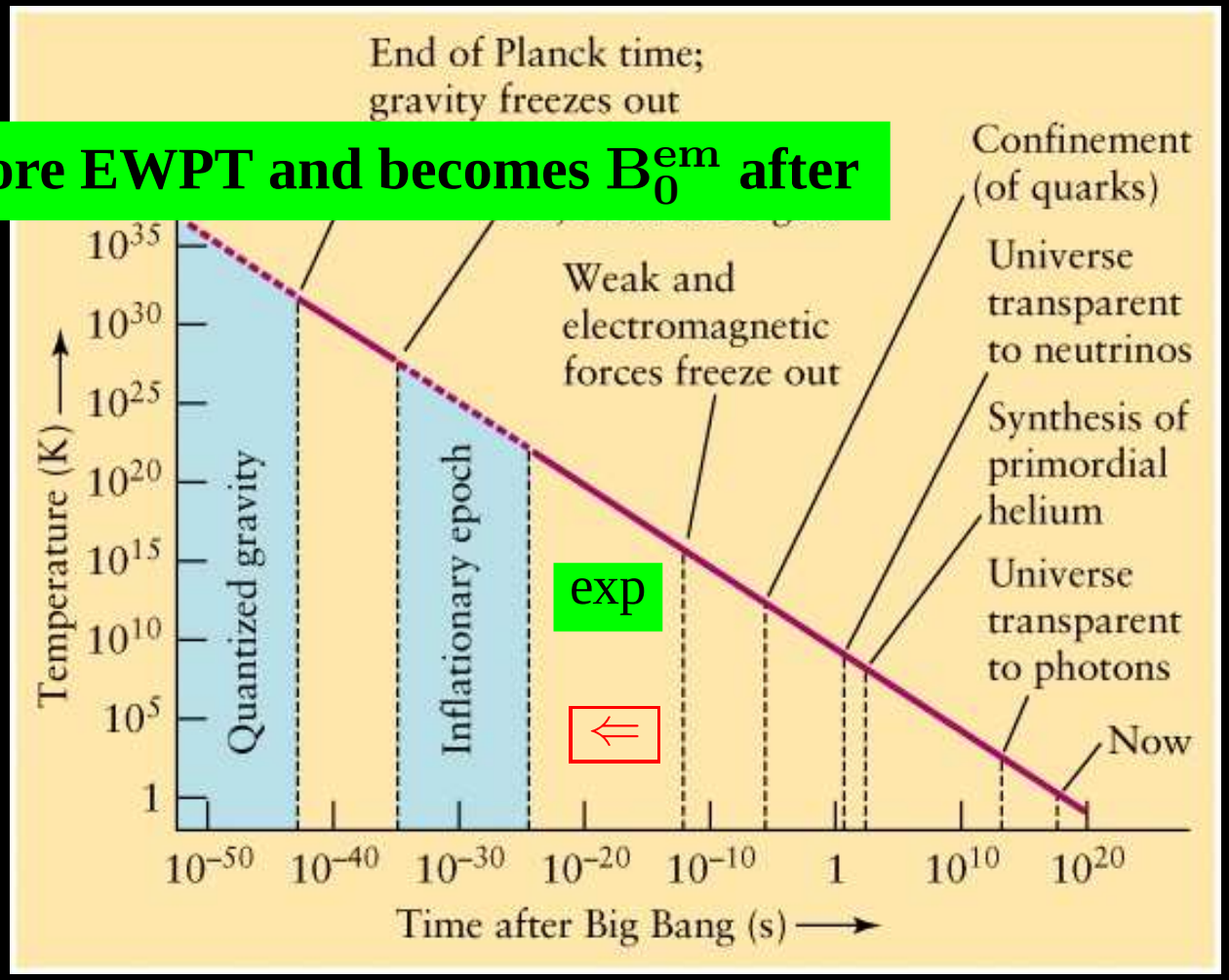
P-violation before EWPT

Semikoz & Valle 0704.3978 [hep-p

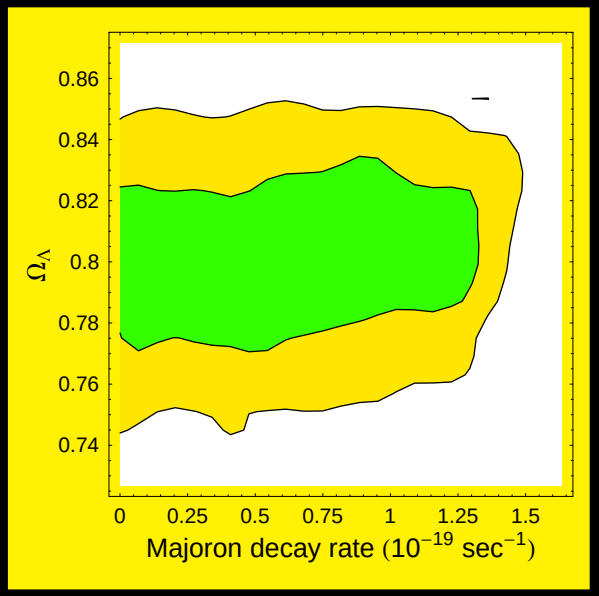
B_0^Y grows before EWPT and becomes B_0^{em} after

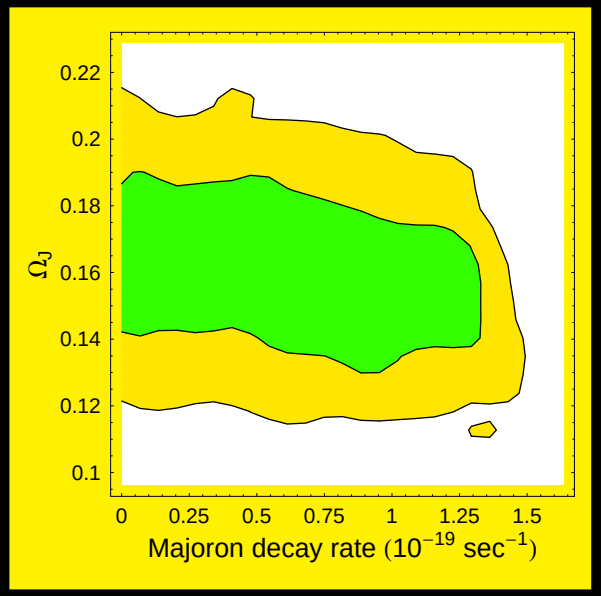
B_0^Y polarize the EU

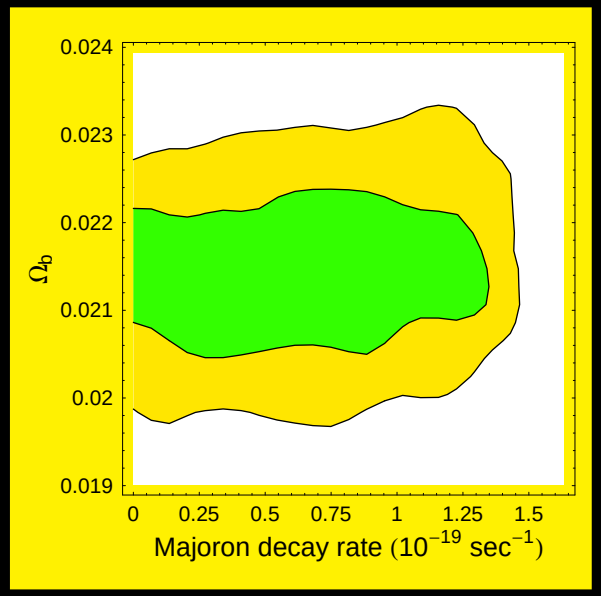
plasma before EWPT

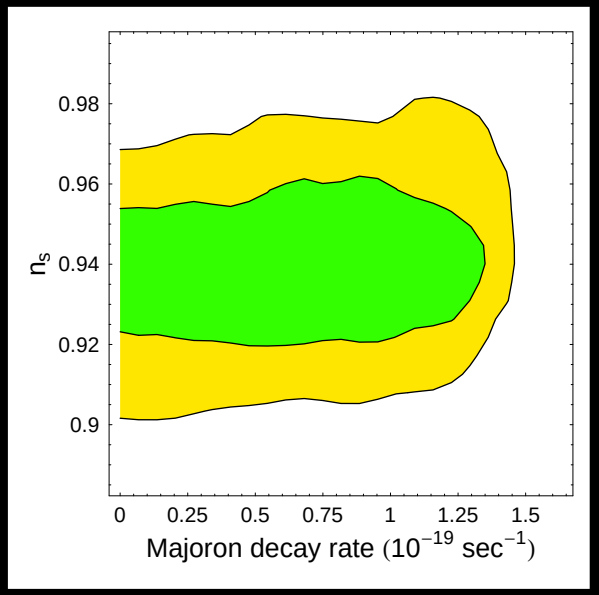


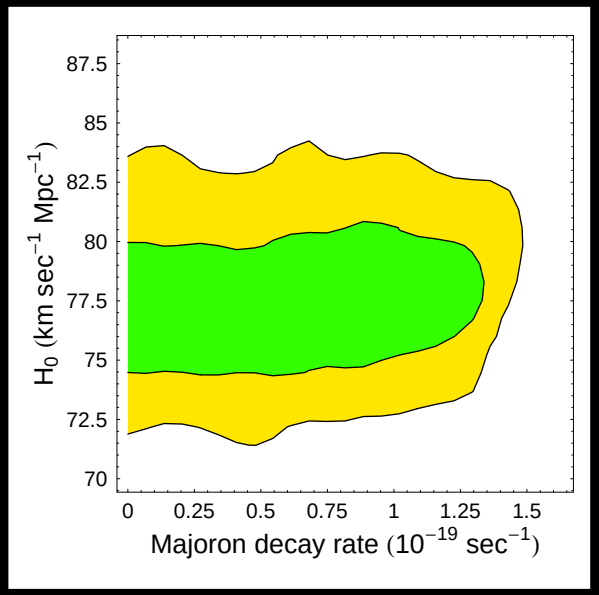
CMB & DDM











Lattanzi & Valle PRL99, 121301 (20

⇐

NEUTRINOS AS MESSENGERS

neutrinos ideal to monitor the Universe, the interior of the sun, stars, etc

- Big Bang probes
- astro-probes
  - Sun ⇒
  - SN neutrinos
  - HE neutrinos
- geo-probes ⇒

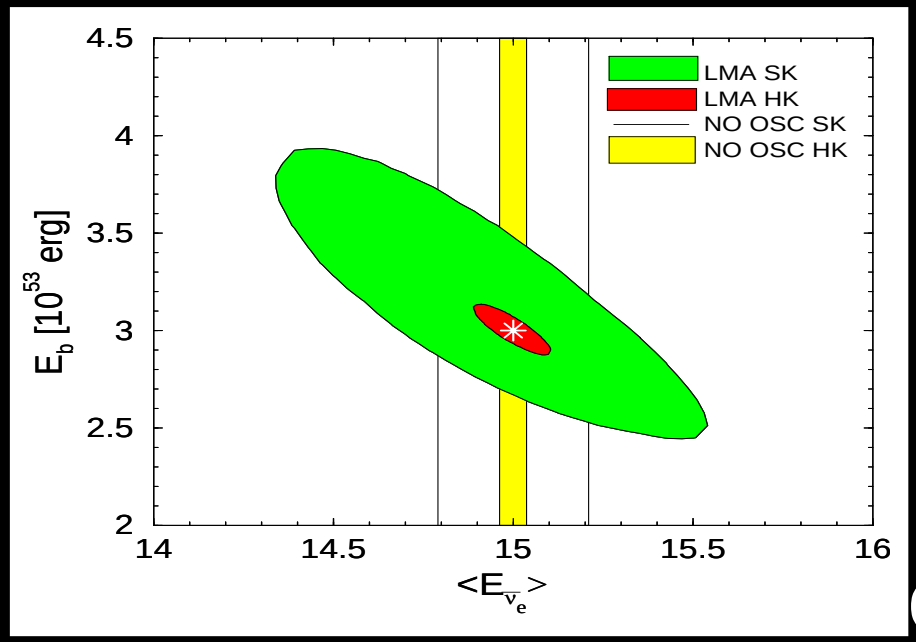
http://ahep.uv.es/

NEUTRINOS AS SN-PROBE-osc

Minakata et al, PLB542 (2002) 239

SN parameters from precise nu-properties

simulate nu-signal from 10 kpc galactic SN



(small θ_{13} approx)

improved SN-parameter determination

new effects in nu-conversions at SN-core (neutron-rich regime)

http://ahep.uv.es/

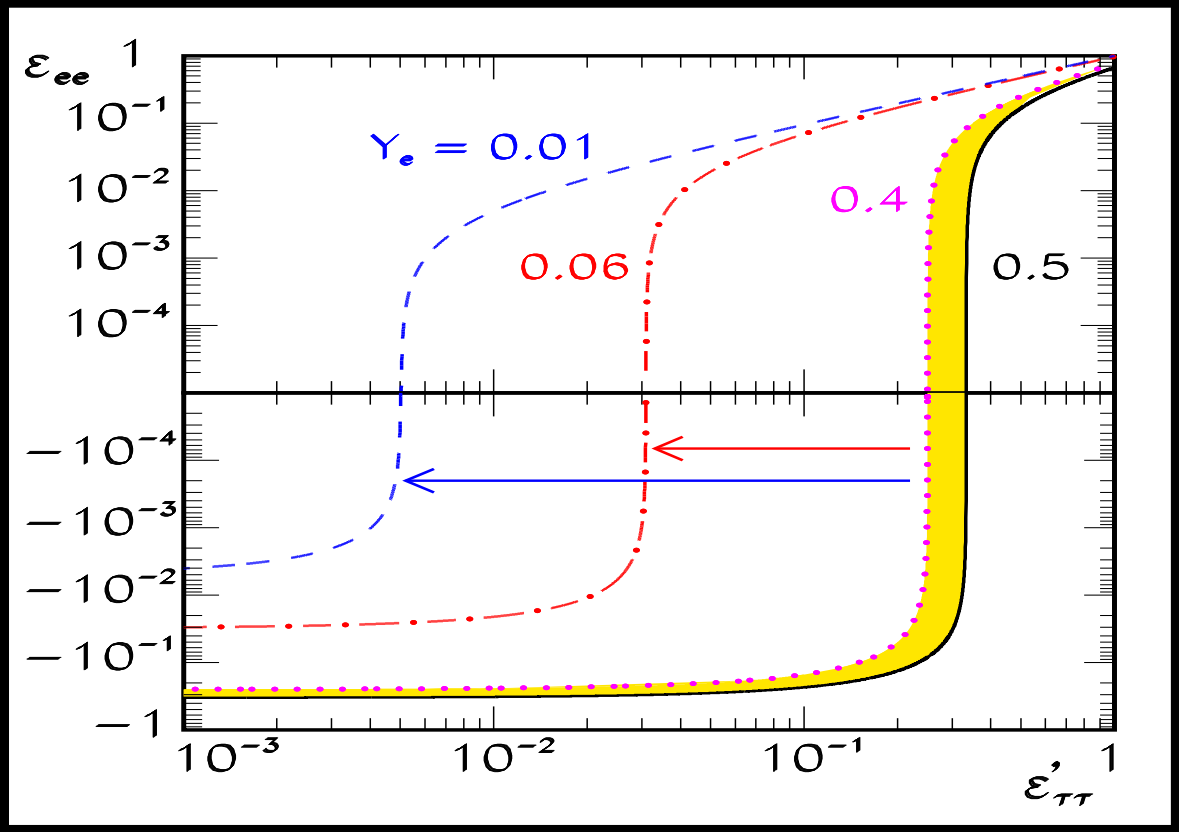
NEUTRINOS AS SN-PROBE-nsi

probing non-standard neutrino interactions with supernova neutrinos

Esteban-Pretel,Tomas, Valle arXiv:0704.0032

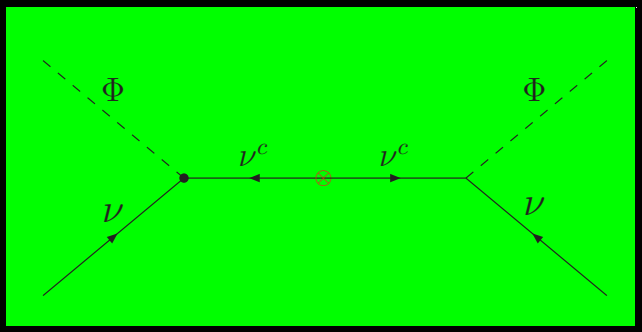
simulate nu-signal from 10 kpc galactic SN

new effects in nu-conversions in neutron-rich regime



a future galactic nu-signal will give us good info on nu-properties

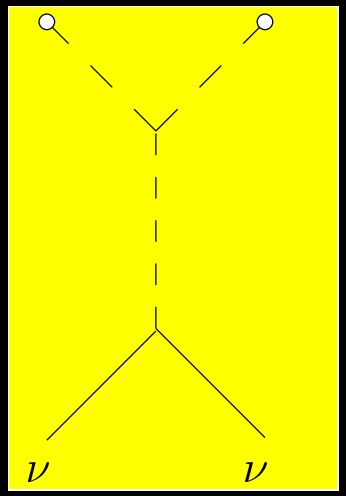
SEESAW & LEPTOGENESIS



why nu-masses small?

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

many realizations



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

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

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

both suppressed by new scale

more to seesaw than meets the eye... seesaw KS $\Rightarrow$ **hep-ph/0608101**

PREDICTING NU-MASSES & MIXINGS

neutrino unification "top-down"

Chankowski et al PRL86 (2001) 3488

due to A4 Babu, Ma & JV, PLB552 (2003) 207
Hirsch et al, PRD69 (2004) 093006

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

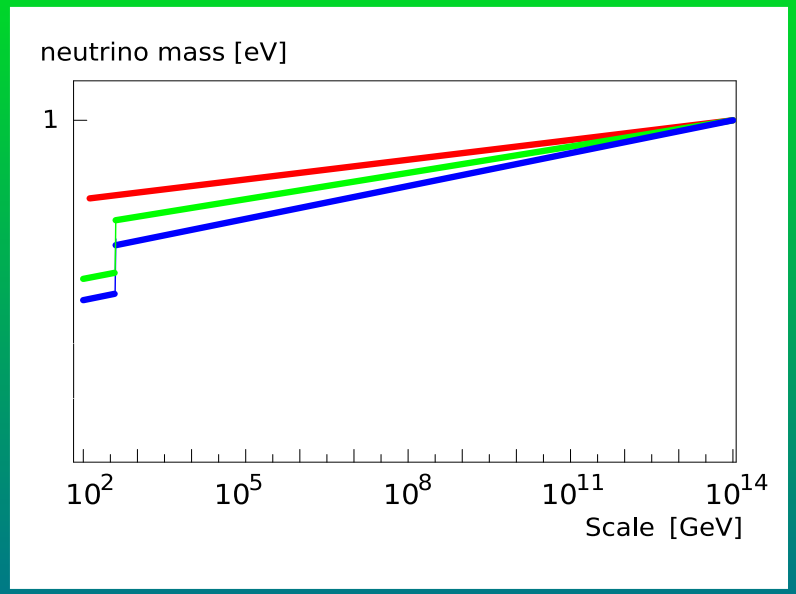
[when $\theta_{13} \neq 0$ CPV is maximal]

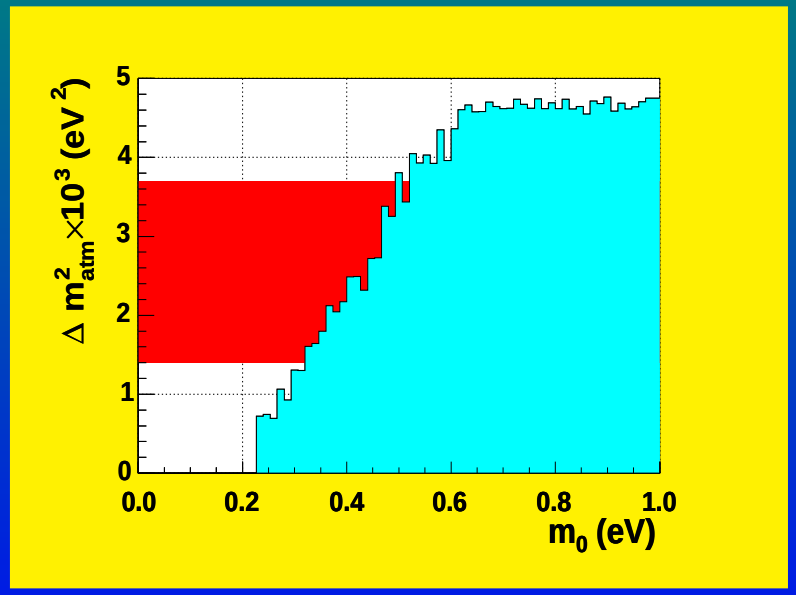
minimal nu-mass $m \gtrsim 0.3$ eV

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

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

light slepton





PREDICTING NU-ANGLES-2

tri-bimaximal mixing at high energies

Harrison, Perkins & Scott

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

gives

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

mainly $\theta_{\rm SOL}$ modified at low energies by radiative corrections

Hirsch, et al hep-ph/0606082 (mSUGRA)

related work by

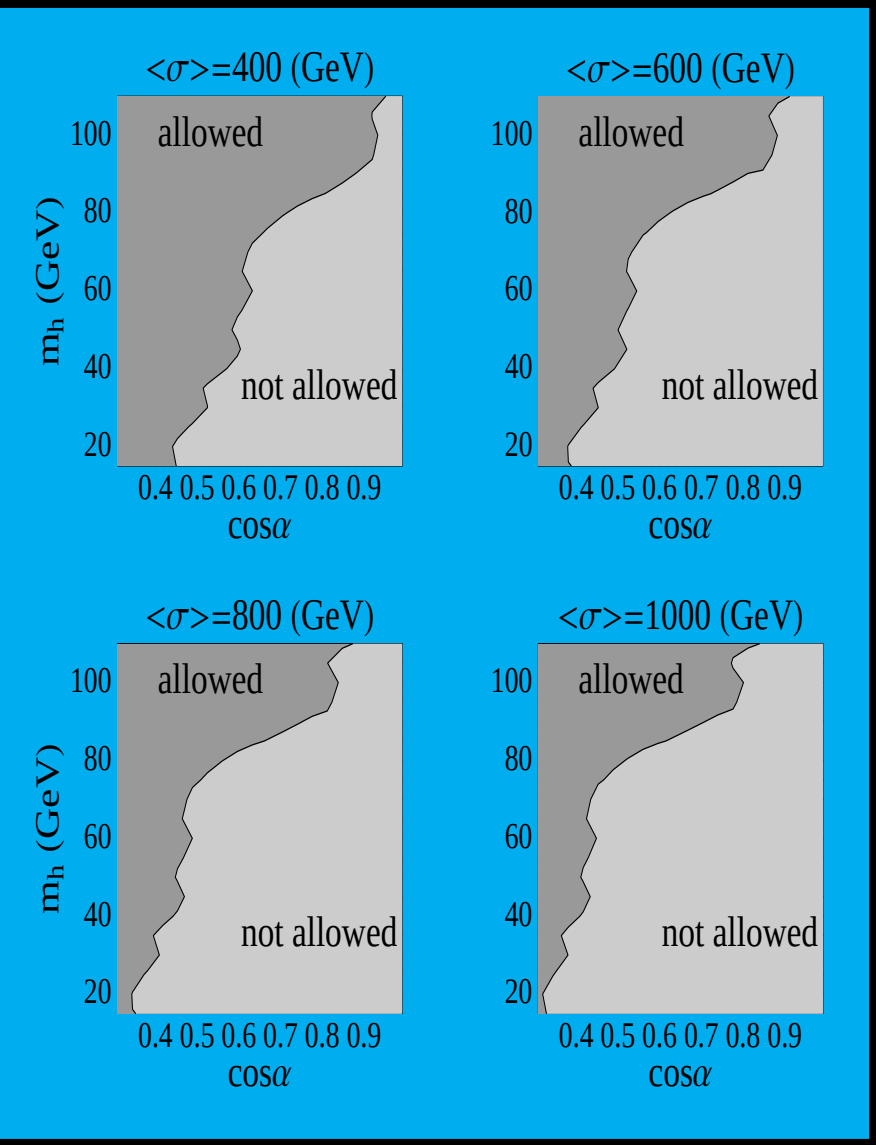
also Altarelli & Feruglio 06, He & Zee 06, Z Z Xing, ...

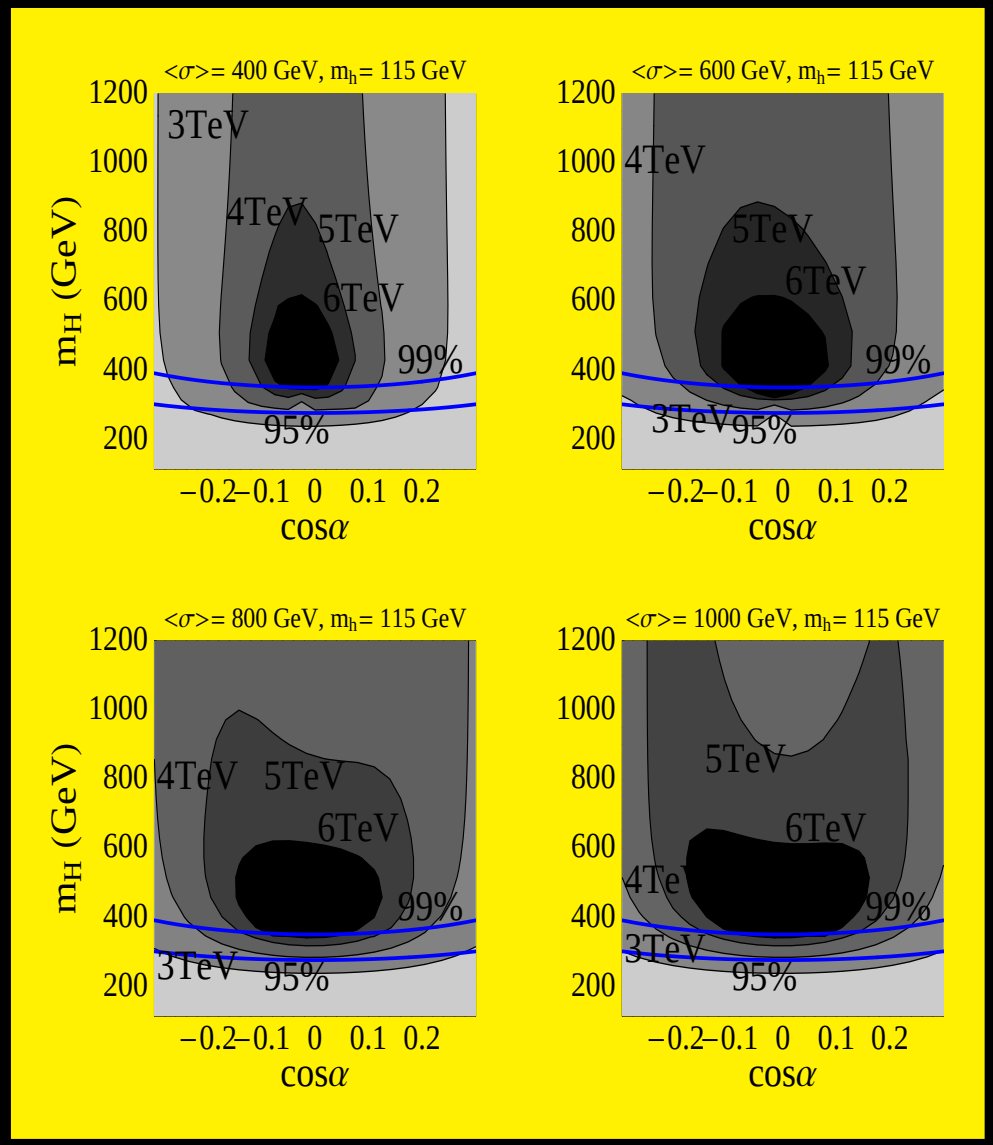
NU-MASSES AND EW SYMMETRY BREAKING

Joshipura & JV, NPB397 (1993) 105

Bazzochi & JV hep-ph/0609093

⇐ FIN



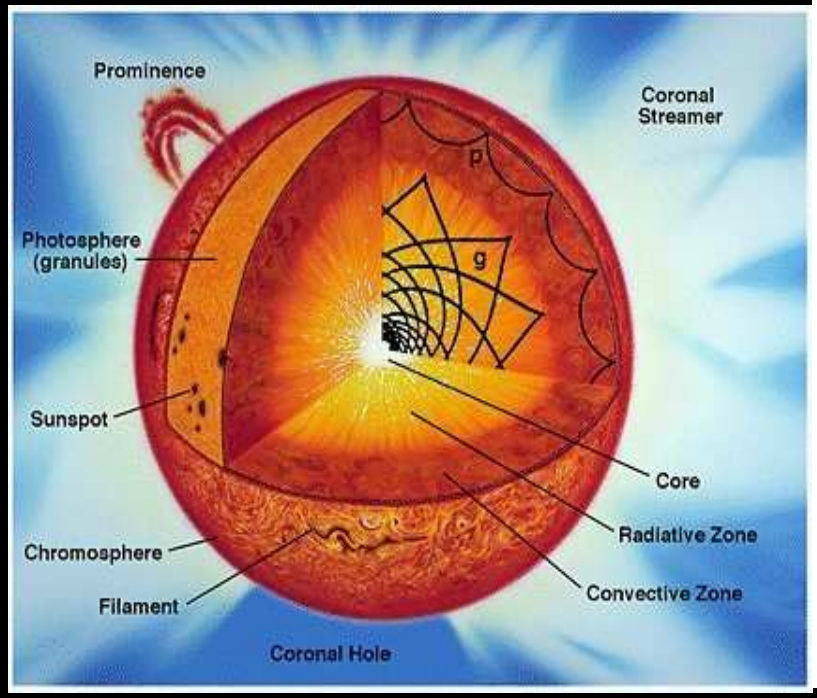


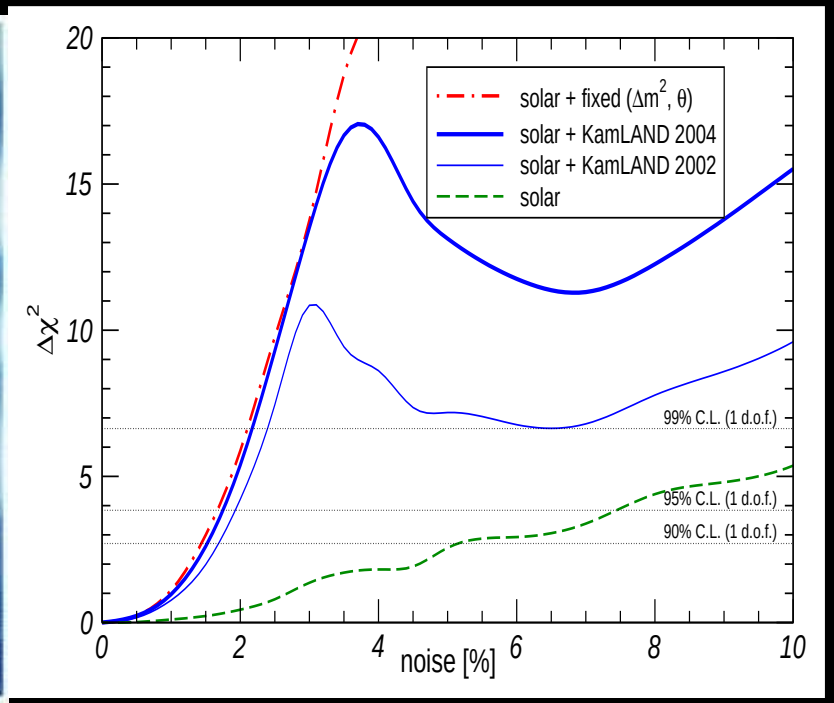
http://ahep.uv.es/

nu-OSCILLATIONS AS DEEP SOLAR PROBE

- e.g. R-zone MHD leads to density fluctuations

Burgess et al, Mon. Not. Roy. Astron.Soc. 348 (2004) 609





- use precision solar-nu data to probe the sun beyond helioseismology contraints ⇐ Burgess et al, Astrophys.J.588 (2003) L65 & JCAP 0401 (2004) 007

GEO-NEUTRINOS

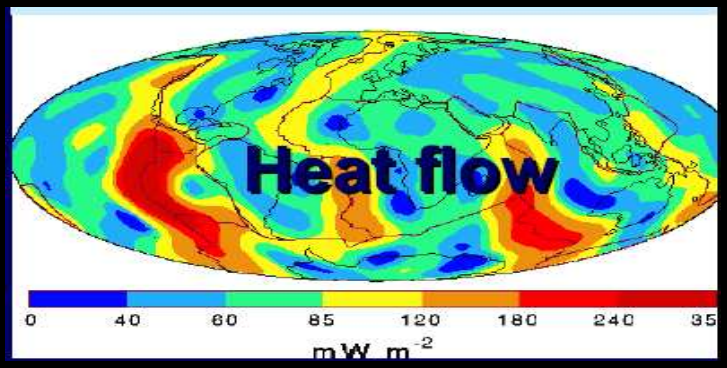
- neutrinos from natural radioactive decays in the Earth's interior give a 3d map

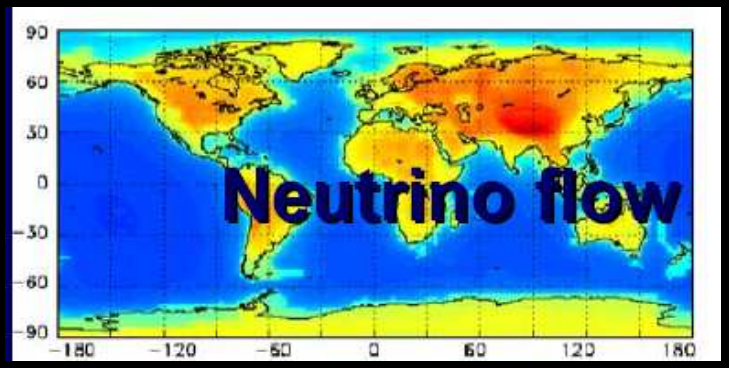
Fiorentini et al ⇐

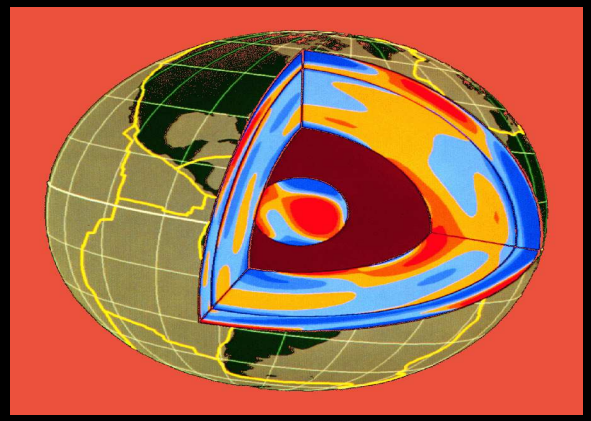
- also, Earth matter effect on solar and supernova neutrino oscillations inside the Earth enable in principle reconstruct the Earth's electron number density profile.

GEOTOMOGRAPHY W/
SOLAR & SUPERNOVA NEUTRINOS

Akhmedov et al JHEP06 (2005) 053







WHERE WE ARE 2007

glob ⇐

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.6	7.3–8.1	7.1–8.3
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.4	2.1–2.7	2.0–2.8
$\sin^2\theta_{12}$	0.32	0.28–0.37	0.26–0.40
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.67
$\sin^2\theta_{13}$	0.007	≤ 0.033	≤ 0.050

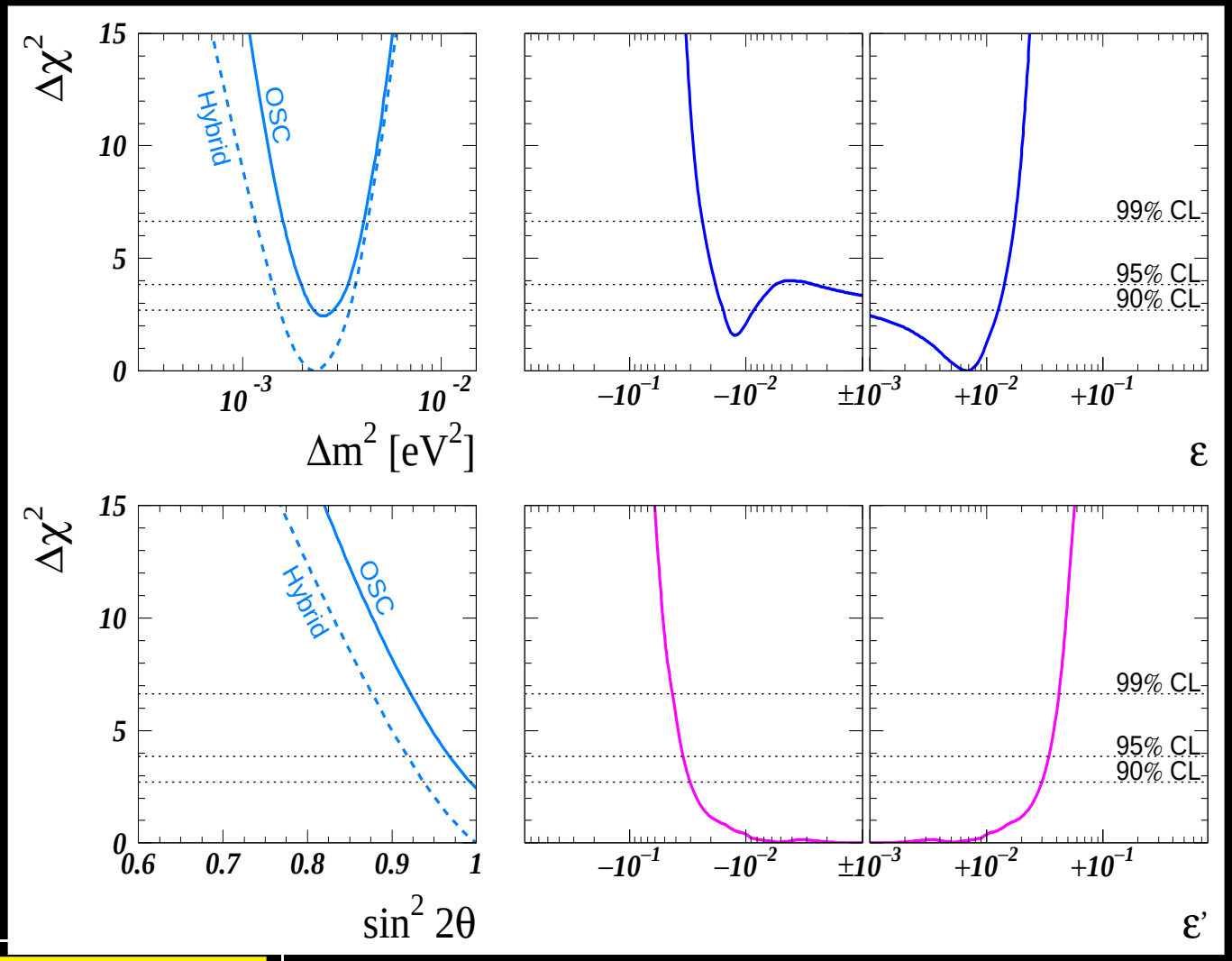
Table I: Best-fit values, 2σ and 3σ intervals (1 d.o.f.) for the three–flavour neutrino oscillation parameters from global data including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K and MINOS) experiments.

http://ahep.uv.es/ **M. Maltoni et al, NJP 6 (2004) 122 = hep-ph/0405172** **v6**

ROBUSTNESS OF ATM-NU global view

atm bounds on FC and NU nu-interactions

upd of Fornengo et al, PRD65 (2002) 013010



(1-d Bartol) will improve at NuFact

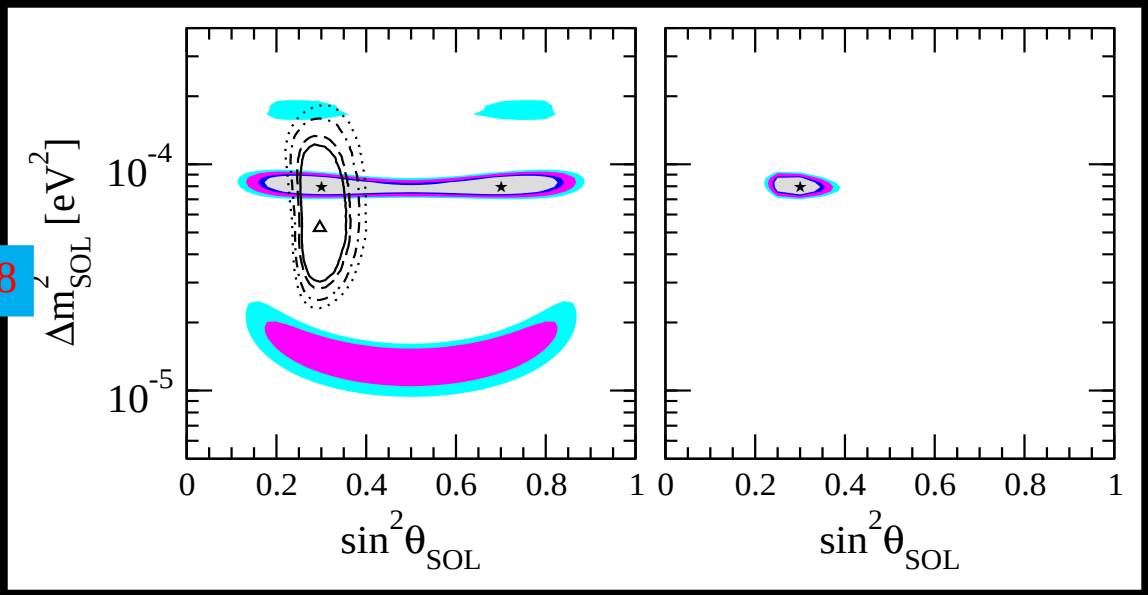
(3-g) Friedland, Lunardini & Maltoni hep-ph/0408264

FRAGILITY OF SOLAR-NU?

wrt NSI

Miranda etal, JHEP **0610** (2006) 008

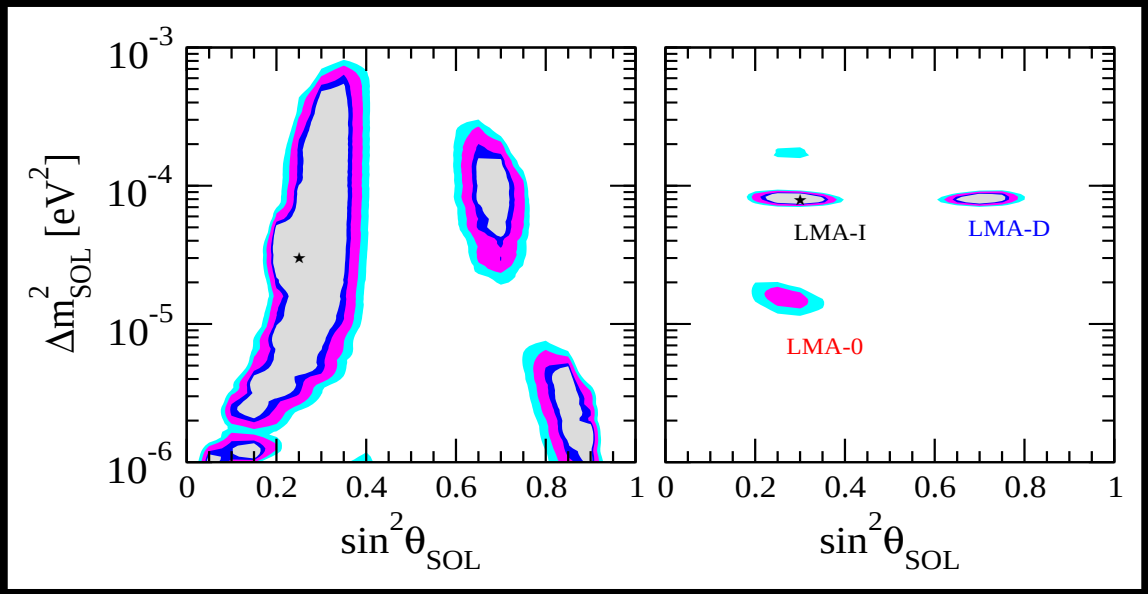
Glbview



degenerate dark-side soln, unresolved by KamLAND

NSI

resolve



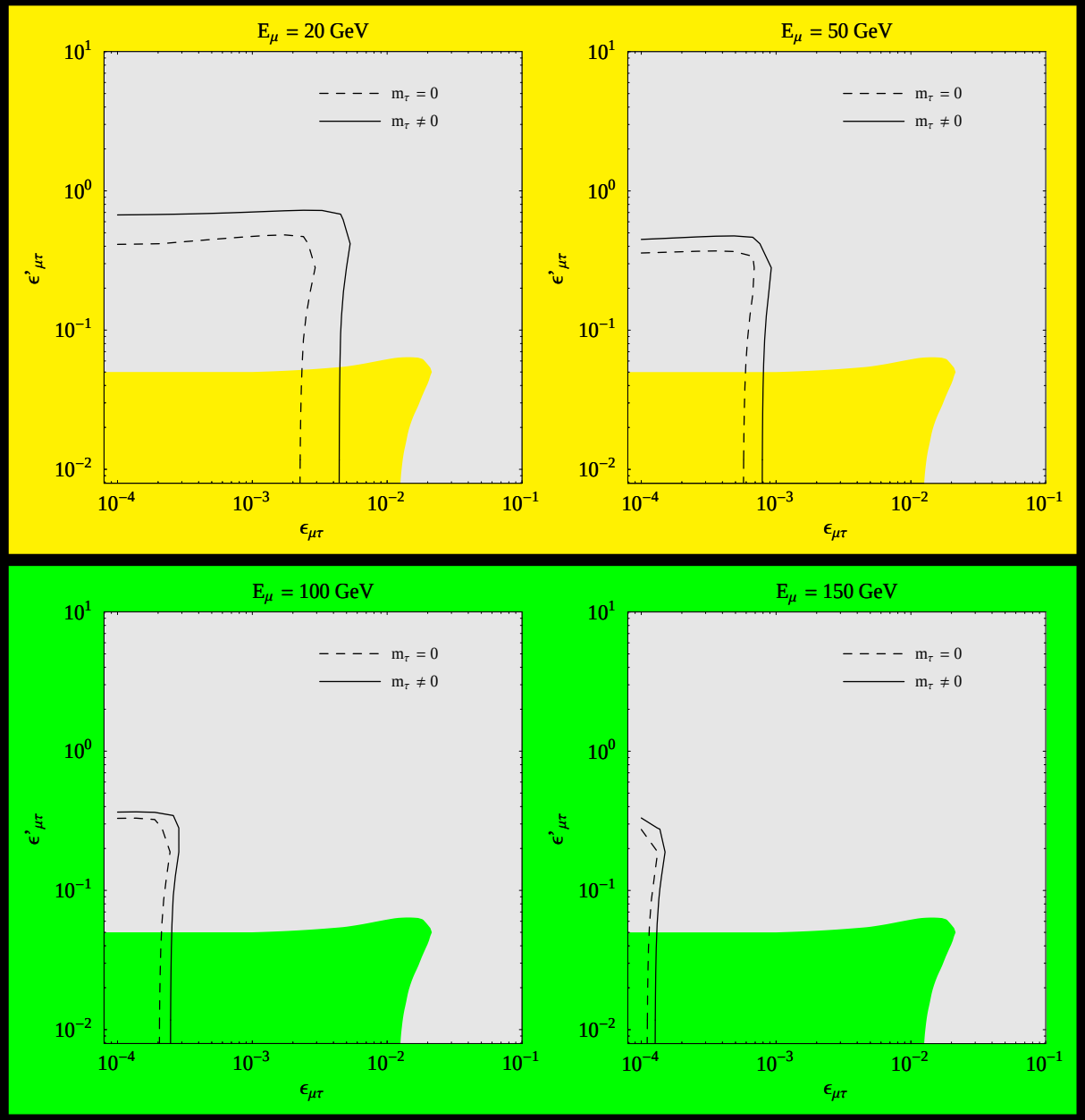
http://ahep.uv.es/

FC-NSI-tests at generic NuFact

10 kt detector,
0.33 ν_τ detection eff above
4 GeV; no tau charge id
needed

improved FC test

Huber & JV PLB523 (2001) 151



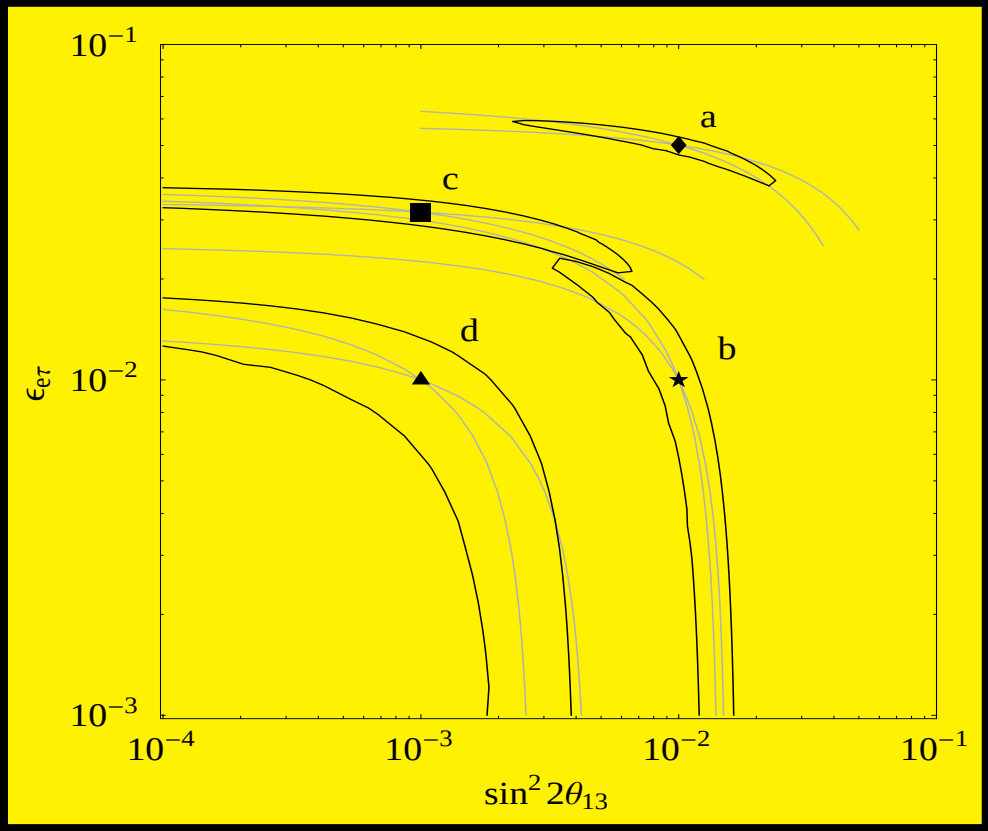
http://ahep.uv.es/

FCI-OSC CONFUSION THEOREM

a neutrino factory is less sensitive to θ_{13} because non-standard neutrino interactions are confused with oscillations

Huber et al, PRL88 (2002) 101804

& PRD66 (2002) 013006



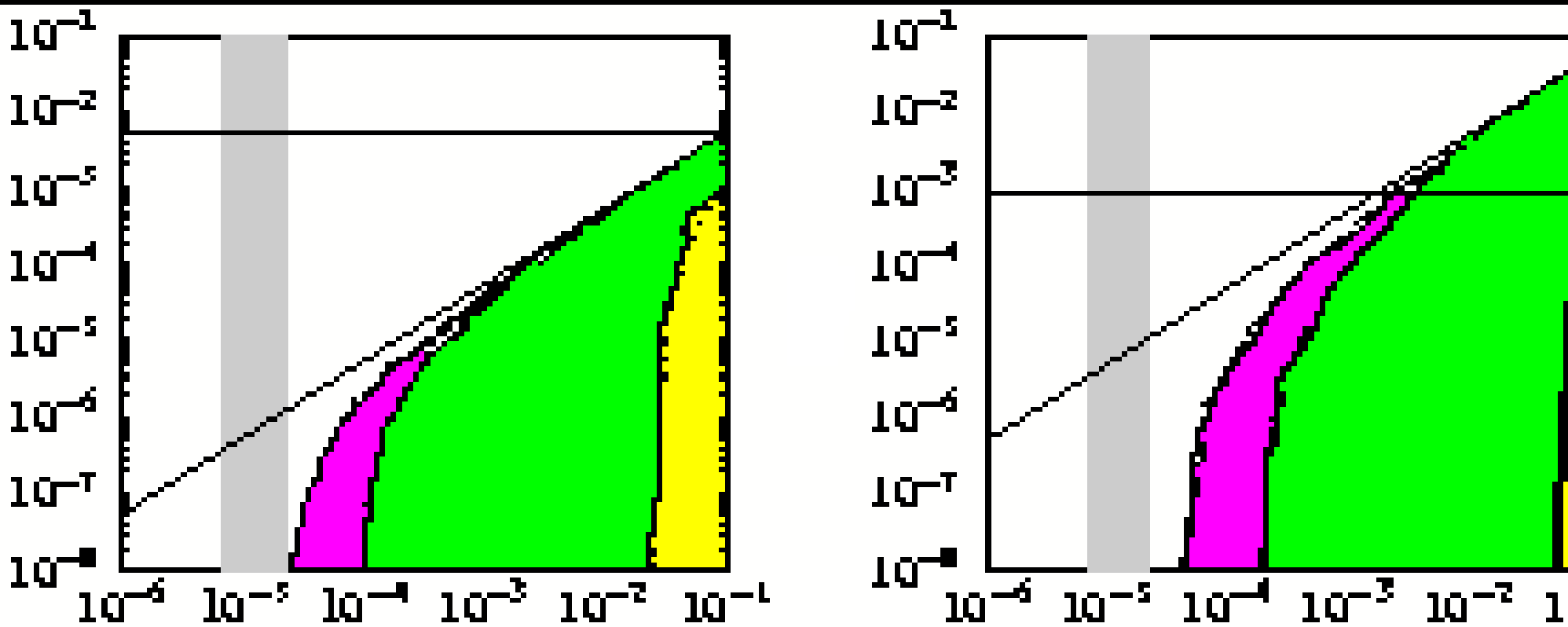
near-site programme essential

2×10^{20} mu/yr/polarity $\times$ 5 yr, 40 kt magn iron calorim, 10% muon E-resoln above 4 GeV

FCI-OSC CONFUSION THEOREM-2

Huber et al, PRD66, 013006 (2002)

90% CL reach on $\sin^2 2\theta_{13}$ (horizontal) vs NSI bounds (vertical)



baselines 700 km 3 000 km 7 000 km

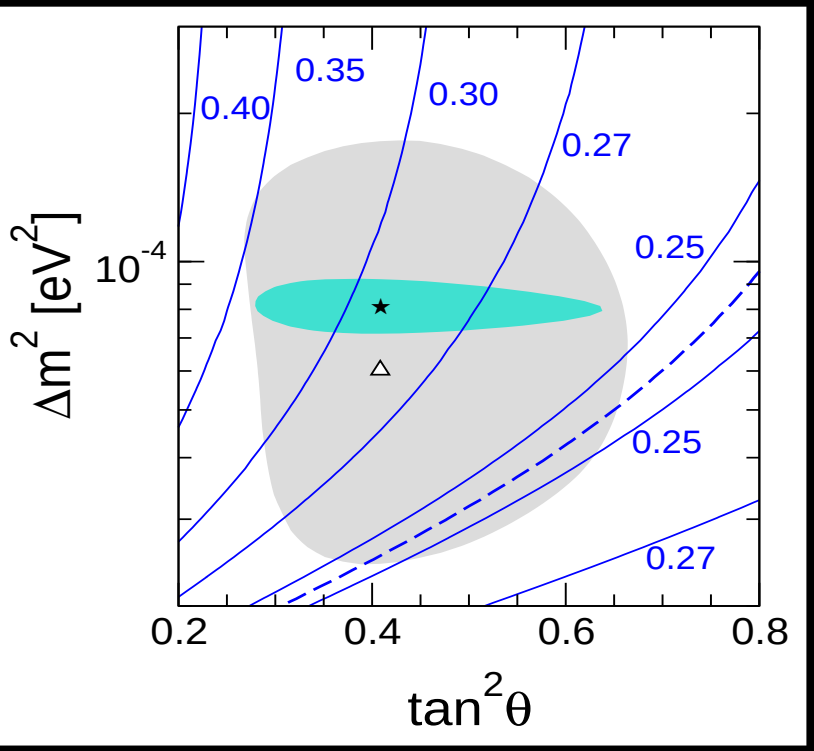
horizontal black line is current NSI limit vertical grey band: sensitivity without NSI

LOW ENERGY SOLAR NEUTRINOS

two tasks for Borexino? KamLAND?

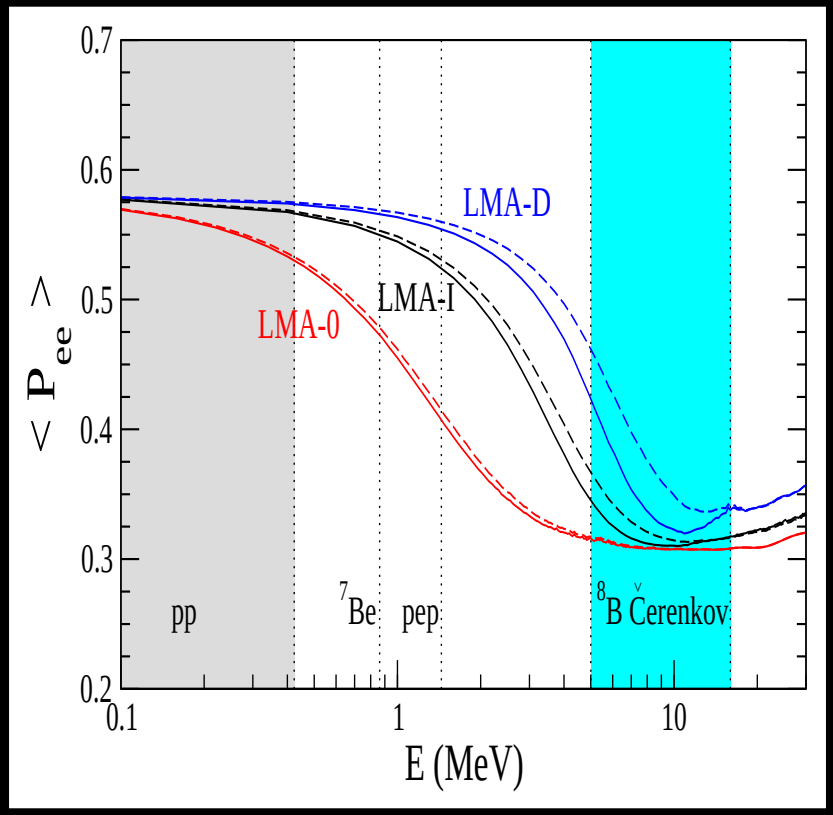
- **probe nu-magn moment**

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



- **probe NSI**

Miranda et al hep-ph/0406280 JHEP



NSI-frag

new frontier ... θ_{13}, new neutral gauge bosons, etc ⇐

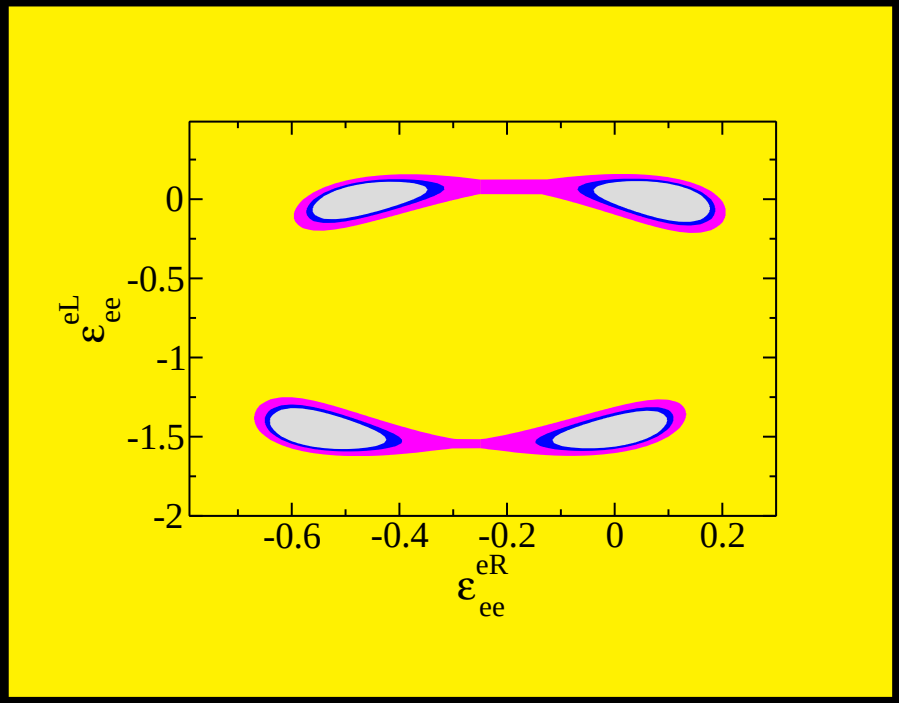
http://ahep.uv.es/

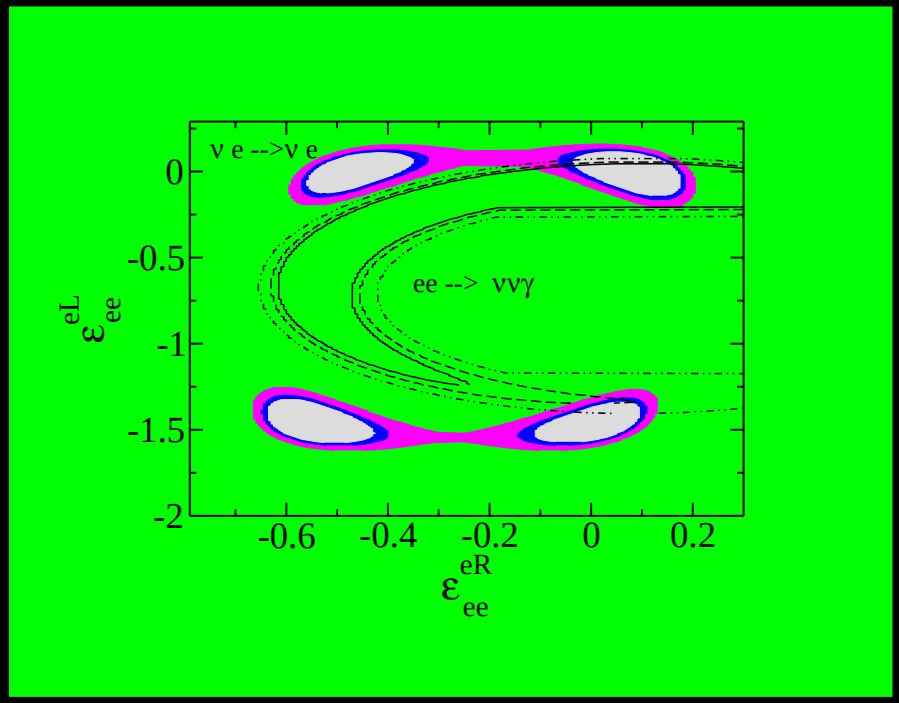
NSI with ELECTRONS

$\nu - e$ scattering data constrain NSI parameters up to four-fold degeneracy (even with just two NU free parameters) Barranco et. al. PRD73 (2006) 113001

can $ee \to \nu\nu\gamma$ from LEP help?

$\Rightarrow$

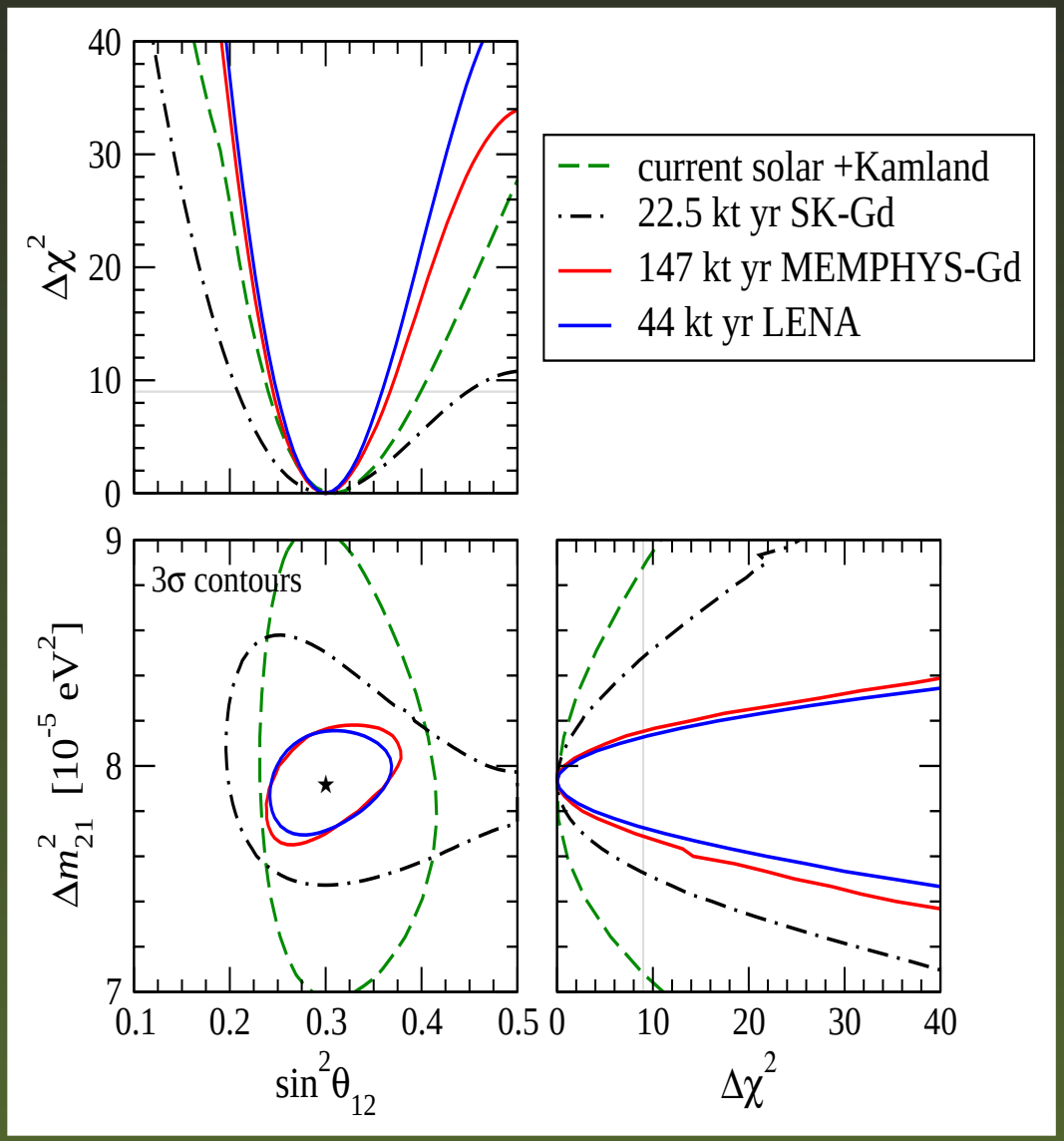




IMPROVING ON SOLAR

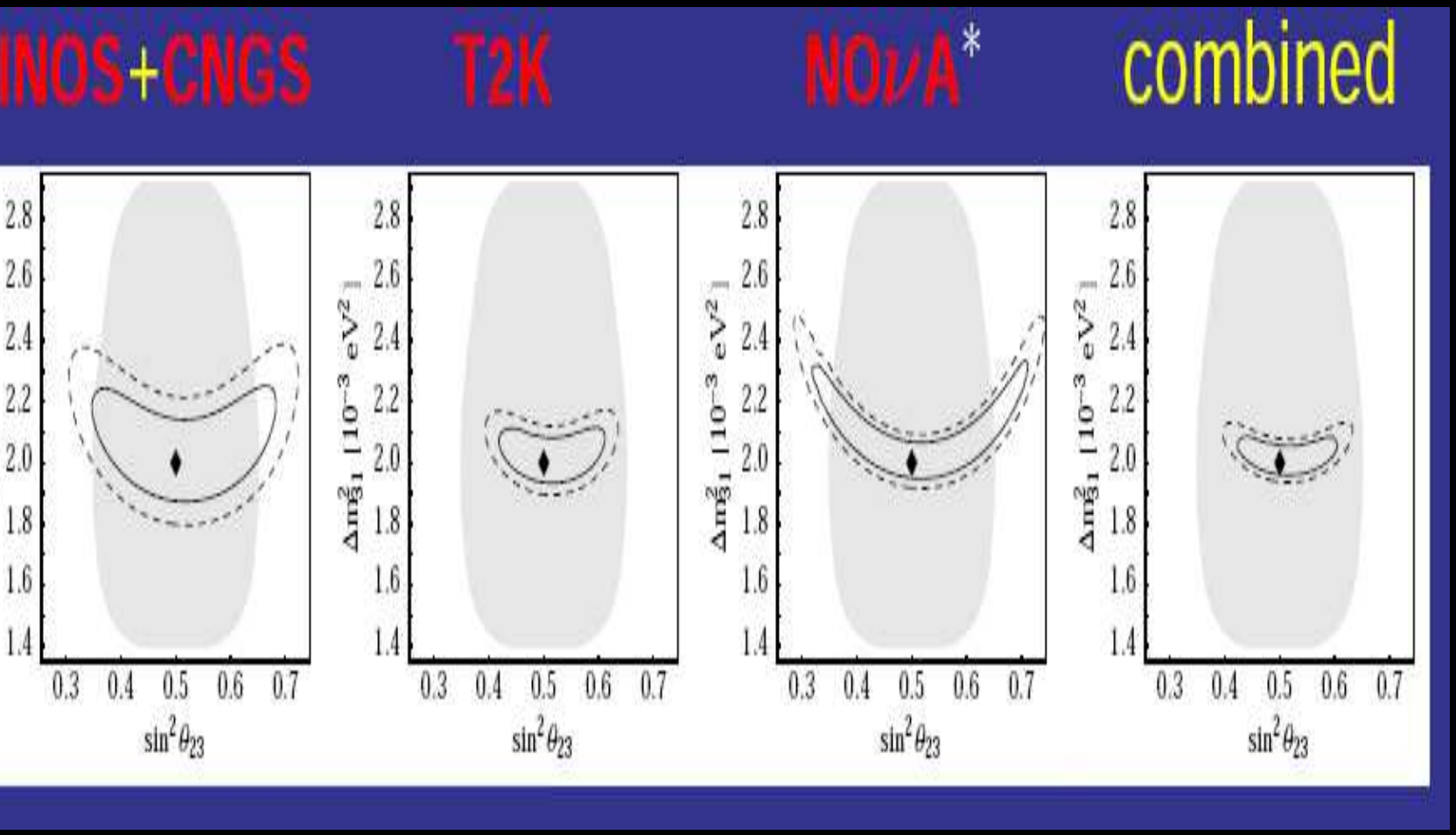
long-baseline expt using french reactors & a detector in Frejus underground lab

courtesy of T. Schwetz **Global**



http://ahep.uv.es/

IMPROVING ON ATM PARAMETERS



Huber et al PRD70 (2004) 073014 also CERN-MEMPHYS Campagne et al hep-ph/0603172

need long-baseline accelerator expts eg T2K Global

PATHWAYS TO NU-MASS $\Rightarrow$ FIN

- **top-down** vs **bottom-up**

PATHWAYS TO NU-MASS $\Rightarrow$ FIN

- top-down vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...

PATHWAYS TO NU-MASS $\Rightarrow$ FIN

- top-down vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- what is the scale ?
  - GUT scale seesaw with low B-L scale
  - Intermediate scale seesaw: P-Q, L-R ...
  - Weak scale (inverse) seesaw

PATHWAYS TO NU-MASS ⇒ FIN

- top-down vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- what is the scale ?
  - GUT scale seesaw with low B-L scale
  - Intermediate scale seesaw: P-Q, L-R ...
  - Weak scale (inverse) seesaw
- a theory of flavour?

PATHWAYS TO NU-MASS $\Rightarrow$ FIN

- top-down vs bottom-up
- what is the mechanism?
  - tree vs radiative
  - B-L gauged vs ungauged...
- what is the scale ?
  - GUT scale seesaw with low B-L scale
  - Intermediate scale seesaw: P-Q, L-R ...
  - Weak scale (inverse) seesaw
- a theory of flavour?
- implications other than oscillations?

  "generic": LFV $\mu \to e\gamma$, $\tau \to \mu\gamma$, mu-e conversion in nuclei, ...

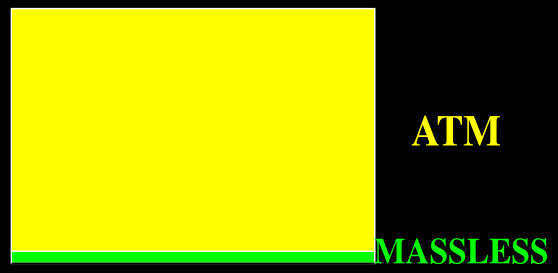
  quasidegenerate nu-models $\Rightarrow$ DBD, cosmo & tritium expts

  "smoking gun": testing nu-mixing at LHC?

MNU FROM LOW–ENERGY SUSY

$\Rightarrow$ paths

- **weak-scale seesaw** atm scale



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

theoretical origin

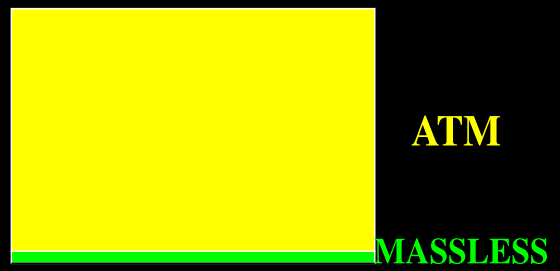
models with spont RPV: Masiero and Valle, PLB251 (1990) 273

http://ahep.uv.es/

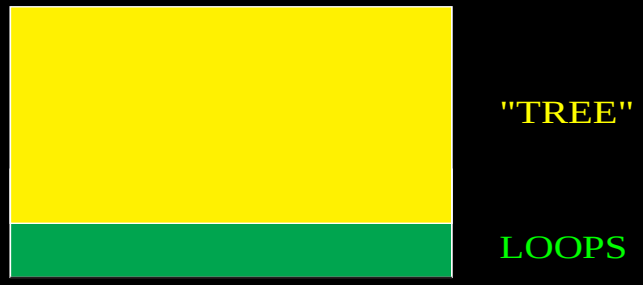
MNU FROM LOW–ENERGY SUSY

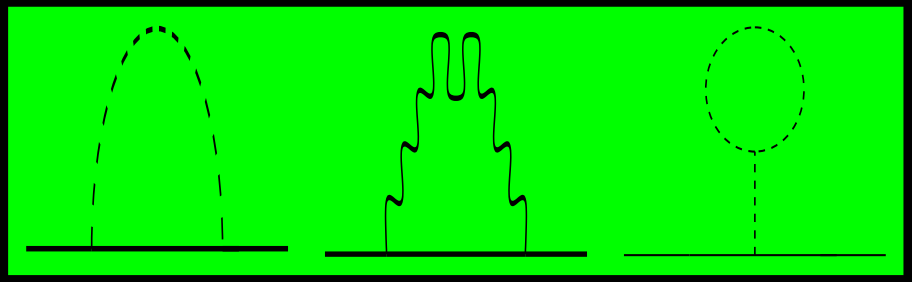
$\Rightarrow$ paths

- **weak-scale seesaw** atm scale



- **radiative** solar mass scale





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

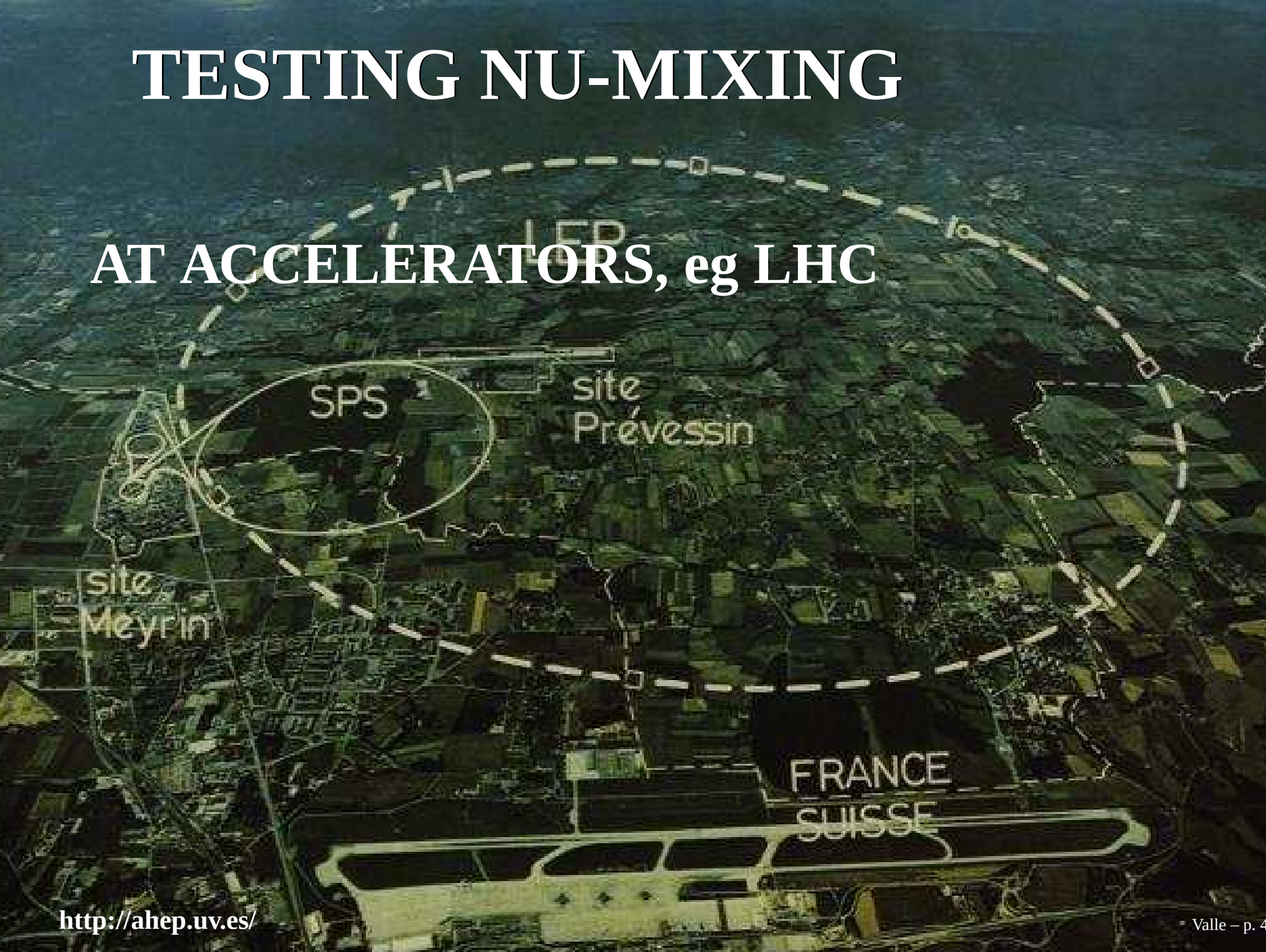
theoretical origin

models with spont RPV: Masiero and Valle, PLB251 (1990) 273

http://ahep.uv.es/

TESTING NU-MIXING

AT ACCELERATORS, eg LHC



http://ahep.uv.es/

TESTING NU–MIXING at LHC/ILC

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

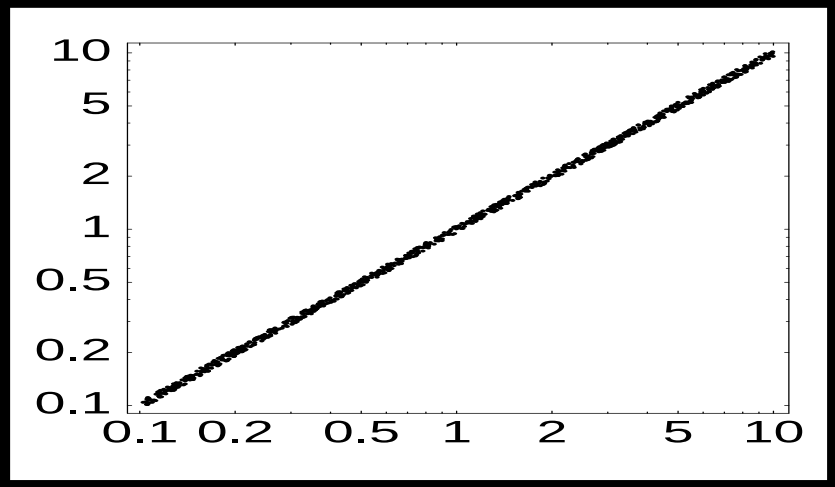
de Campos et al, PRD71 (2005) 075001

- LSP decay properties correlate with nu-mixing angles

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

smoking gun test of SUSY origin of nu-mass

Porod et al PRD63 (2001) 115004



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

TESTING NU–MIXING at LHC/ILC

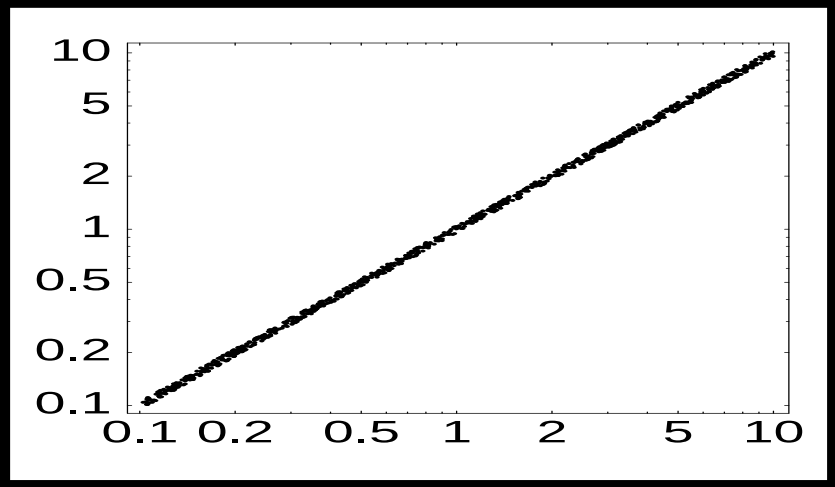
- LSP decays lead to **double vertices**, e.g. at Tevatron

de Campos et al, PRD71 (2005) 075001

- LSP decay properties correlate with nu-mixing angles

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

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



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

- **irrespective of the nature of the LSP**

stop Restrepo et al, PRD64 (2001) 055011

stau Hirsch et al, PRD66 (2002) 095006

others D68 (2003) 115007

http://ahep.uv.es/

SEESAW-TYPE NSI

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

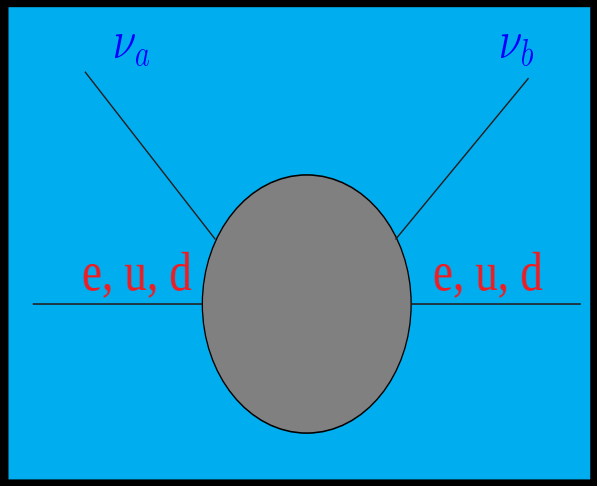
- **seesaw-scale need not be high** as # of $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ singlets is arbitrary

- **far more angles and phases** than for quarks

  (i) Majorana phases

  (ii) isodoublet-isosinglet mixing angles

- **effective deviations from unitarity in lepton mixing**



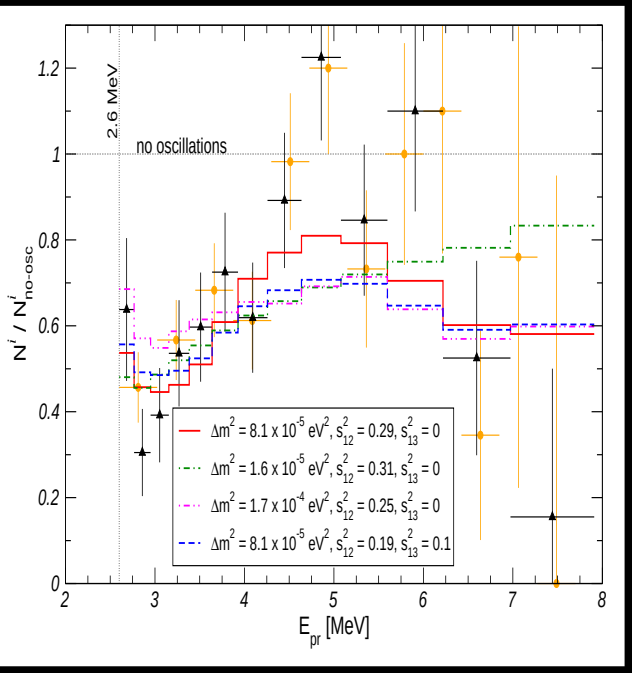
$\Leftarrow$KM SS $\Leftarrow$

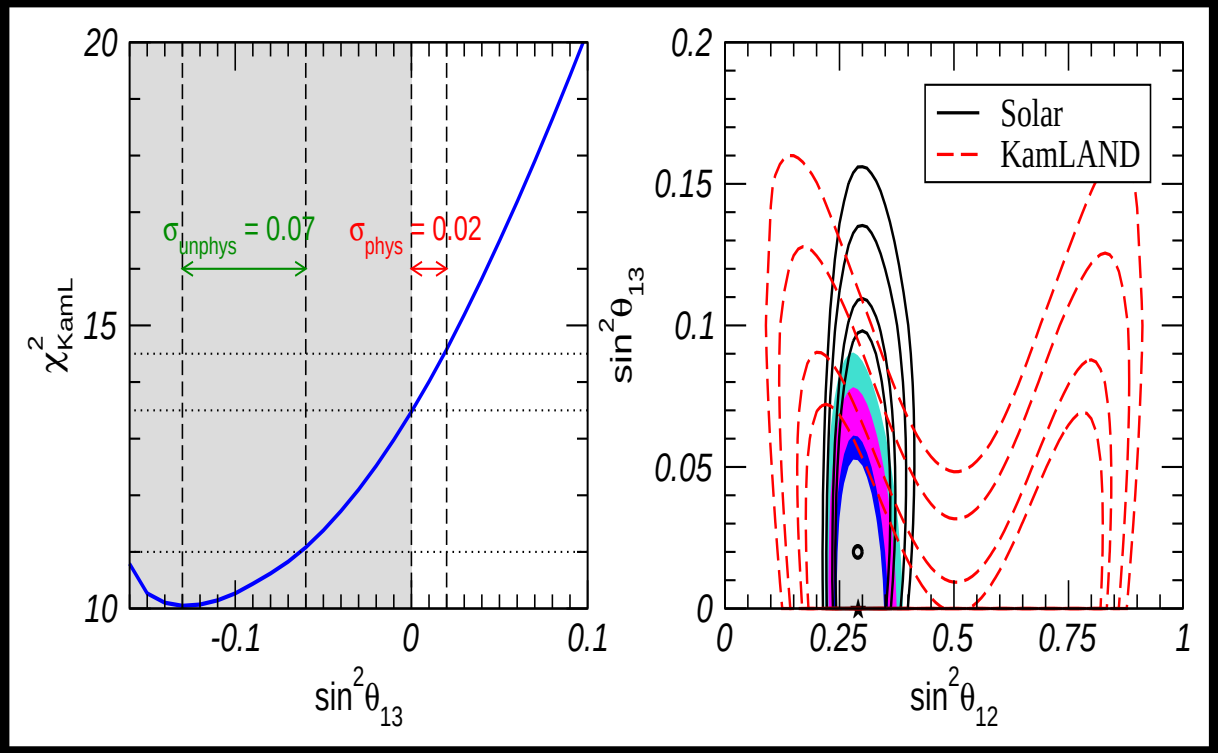
- **CC & NC source of gauge-induced NSI**

THETA13 AND KamLAND

strong spectrum distortion

favors unphysical θ_{13} values





combination with solar further improves ...

NOISE & SOLAR ROBUSTNESS

neutrino propagation strongly affected by solar density noise

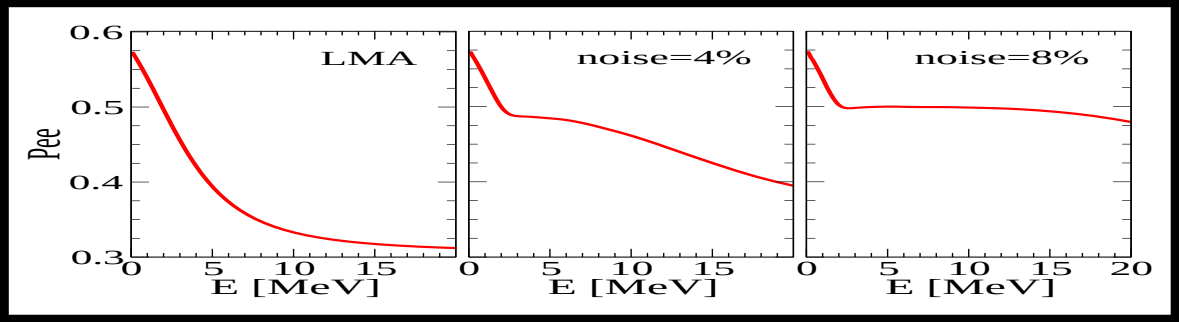
Balantekin et al 95

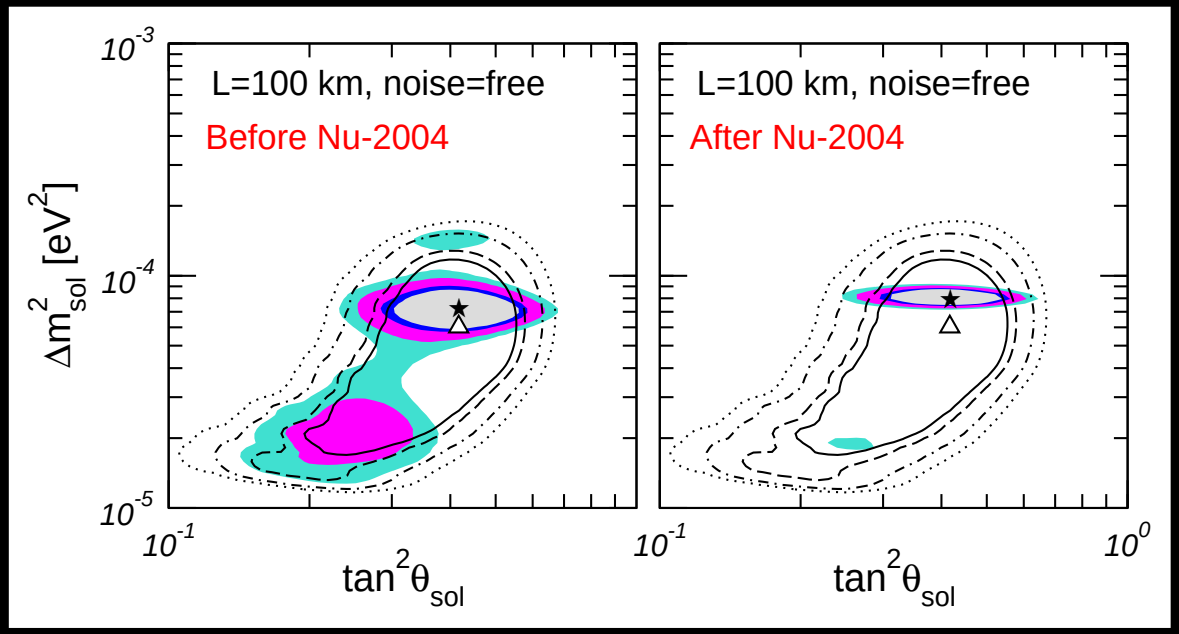
Nunokawa et al NPB472 (1996) 495

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

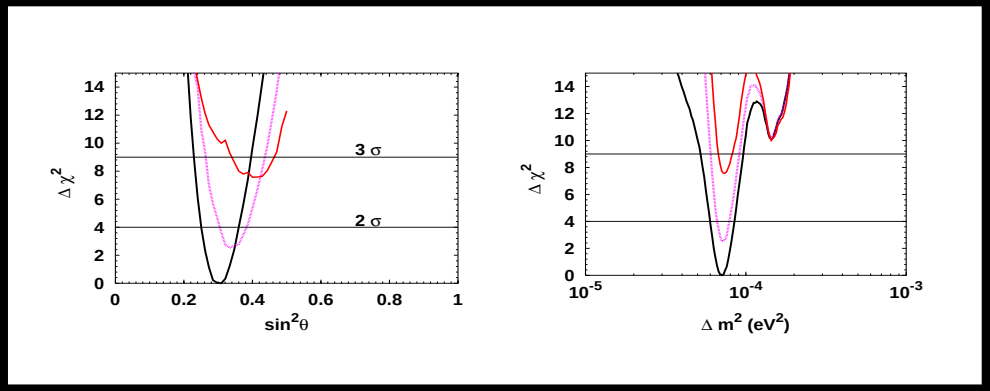
determination is robust

Maltoni et al, hep-ph 0405172

noisy Sun

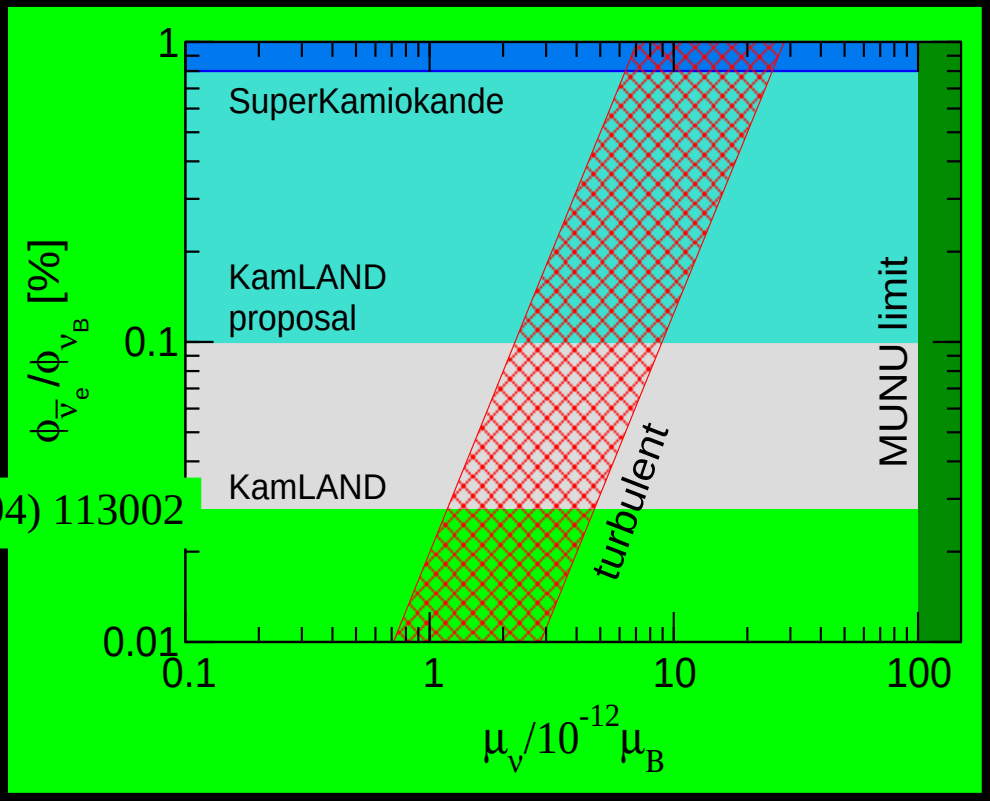
SFP & SOLAR ROBUSTNESS

ensured by absence of solar anti-nu



regular versus random mag field

isolating μ_ν from $\mu_\nu B$?



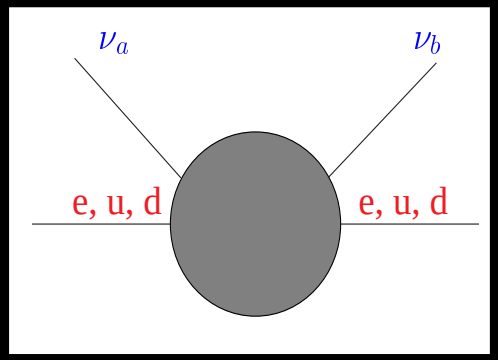
Miranda et al PRL93 (2004) 051304 & PRD70 (2004) 113002

⇐SFP

NON-STANDARD INTERACTIONS

⇐ Frag

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

Wolfenstein; Valle PLB199 (1987) 432

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

they give excellent description of solar data Guzzo et al NPB629 (2002) 479

but can not be the leading mechanism, due to KamLAND

lead to new dark-side solar neutrino oscill solution

NSI TYPES

Non-Standard Interactions arise in most massive neutrino models,
Prog. Part. Nucl. Phys. 26 (1991) 91

gauge NSI arise in seesaw-type models rectangular CC lepton mixing matrix and non-diagonal NC, PRD22 (1980) 2227

may lead to sizeable flavor and CPV even in massless neutrino limit

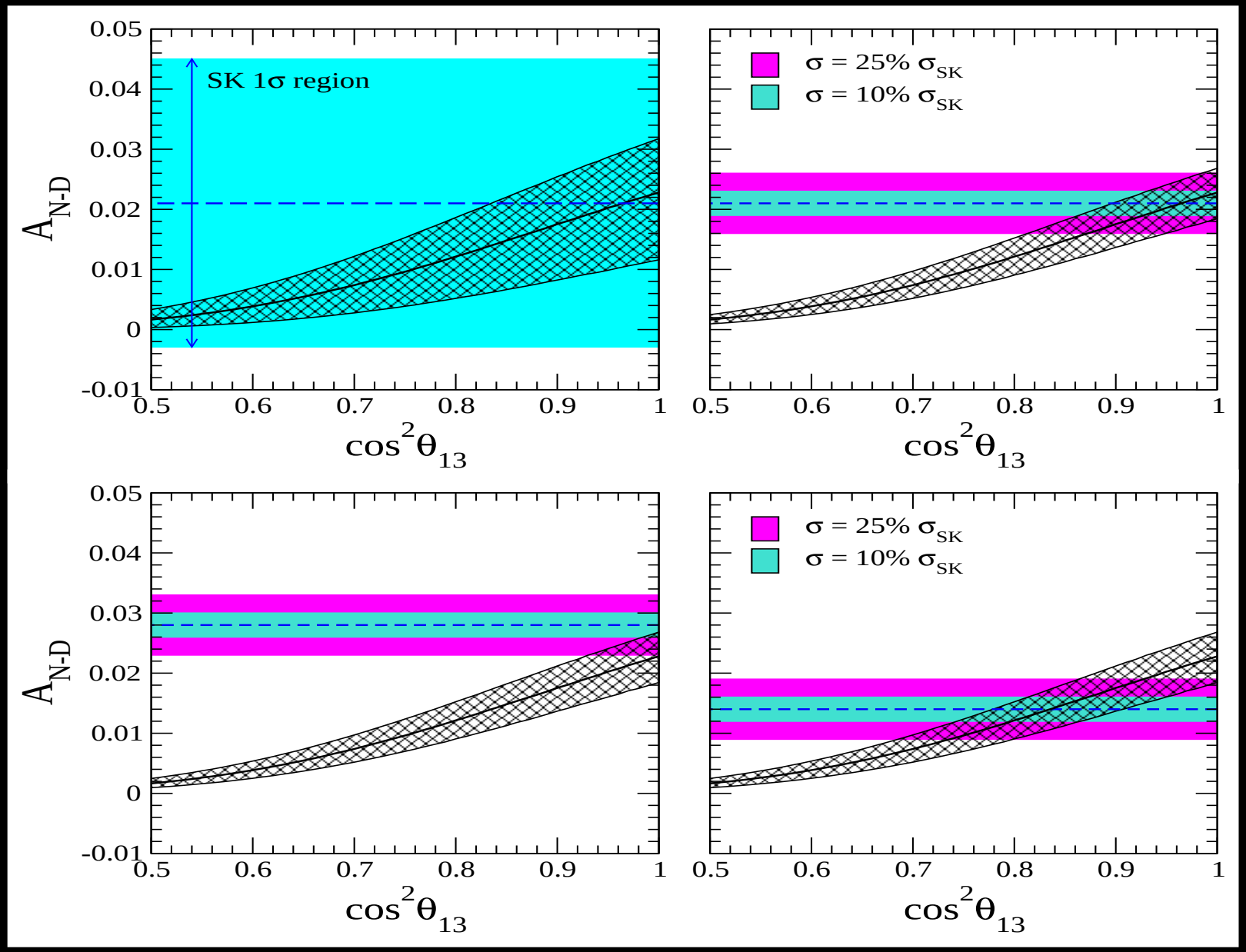
scalar NSI arise in radiative models of neutrino mass, Zee or Babu, etc

majoron emitting neutrino decays

Chikashige, Mohapatra, Peccei
Schechter, JV PR D25 (1982) 774; JV PLB131 (1983) 87; Gelmini, JV, etc

DAY-NIGHT EFF. W/ 3 NEUTRINOS

Akhmedov, Tortola, JV, JHEP05 (2004) 057



http://ahep.uv.es/