Neutrinoless Double beta decay and new physics

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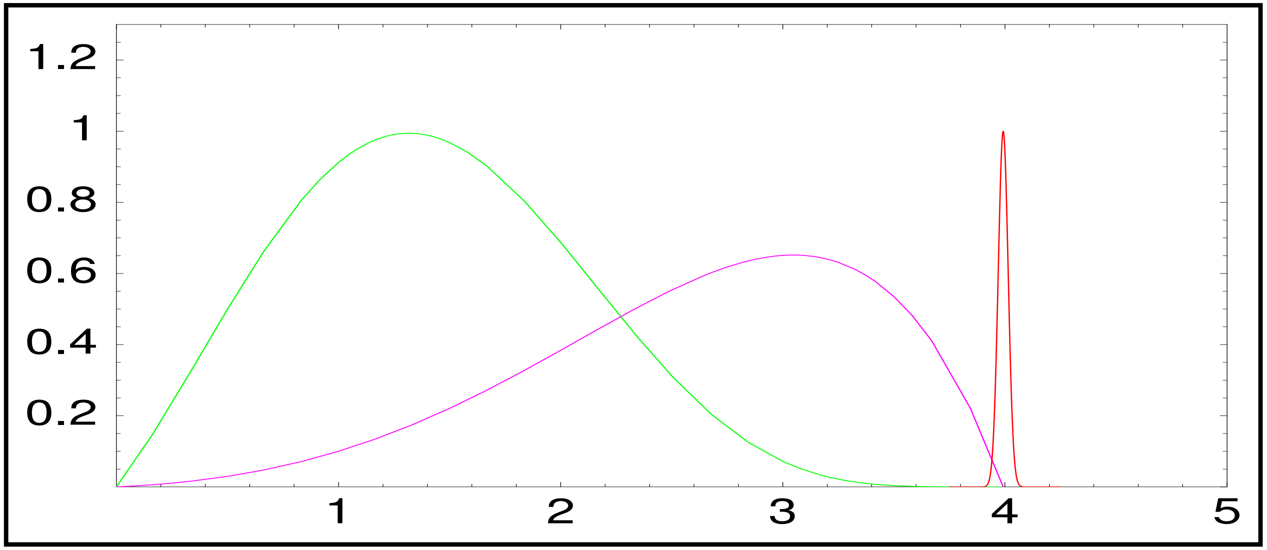
thanks to Martin Hirsch

Nuclear double beta decay

$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

- $2\nu\beta\beta$ decay: $X = 2\nu$, allowed within Standard Model observed for 9 isotopes, half-lives $10^{(19-25)}$ ys
- $0\nu\beta\beta$ decay: $X = 0\nu$, violates lepton number by 2 units, experimentally not observed, lower limits on half-lives of the order of $\mathcal{O}(10^{25})$ ys
- extra scalars, such as the Majoron, $X = J$
- How to differentiate between decay modes?



Experimentally measurable is the summed electron spectrum

Mass mechanism for $\beta\beta_{0\nu}$ decay

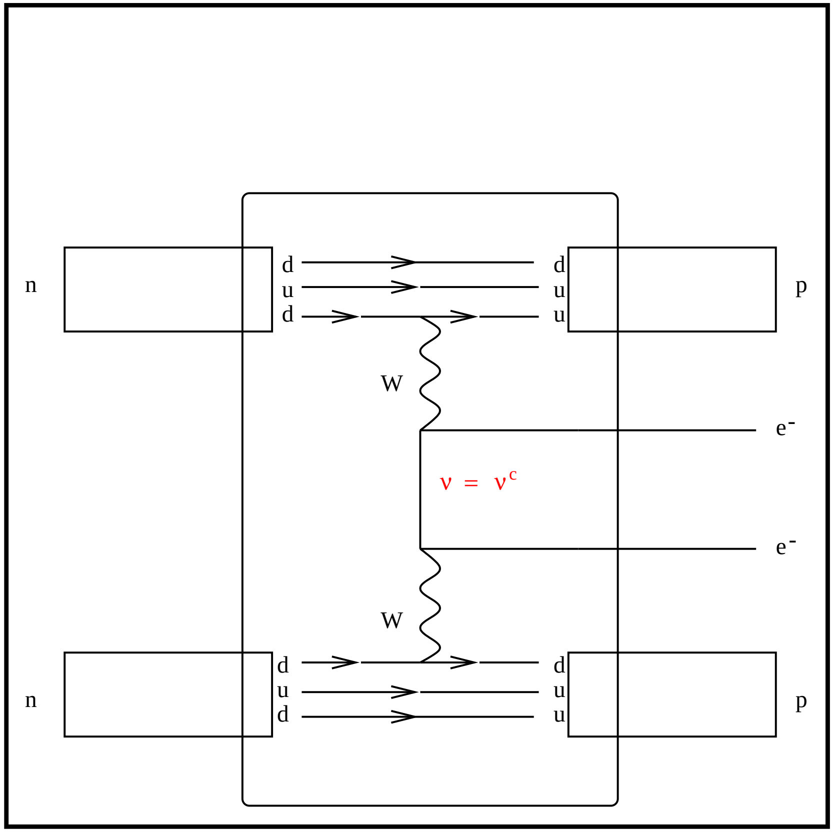
Simplest possibility for $\beta\beta_{0\nu}$ diagram: Majorana neutrino mass term

Neutrino propagator:

$\Rightarrow$ Requires neutrino to be its own antiparticle: $\boxed{\nu = \nu^c}$

$\Rightarrow$ "Mass mechanism" because weak interaction is left-handed

$\Rightarrow$ Propagator has 2 interesting limits, depending on whether $\boxed{m_\nu \ll p}$ or $\gg$

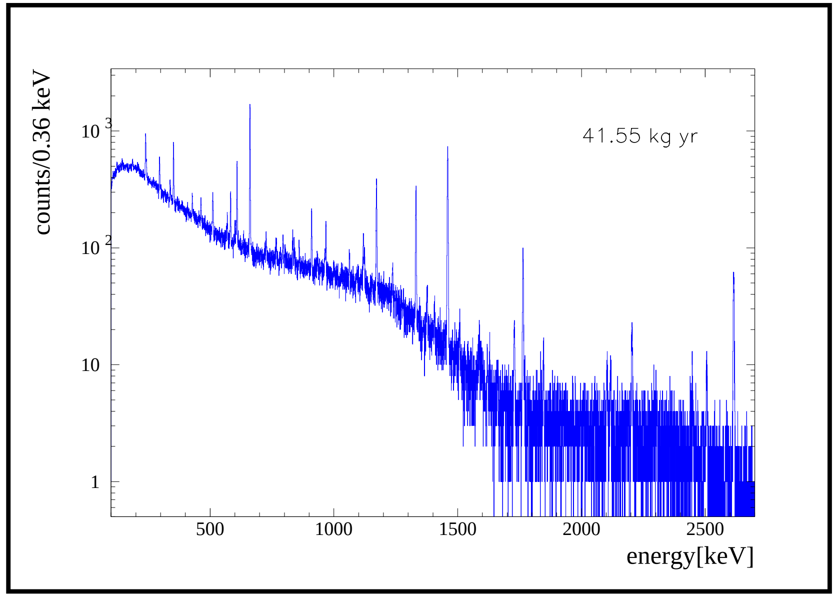


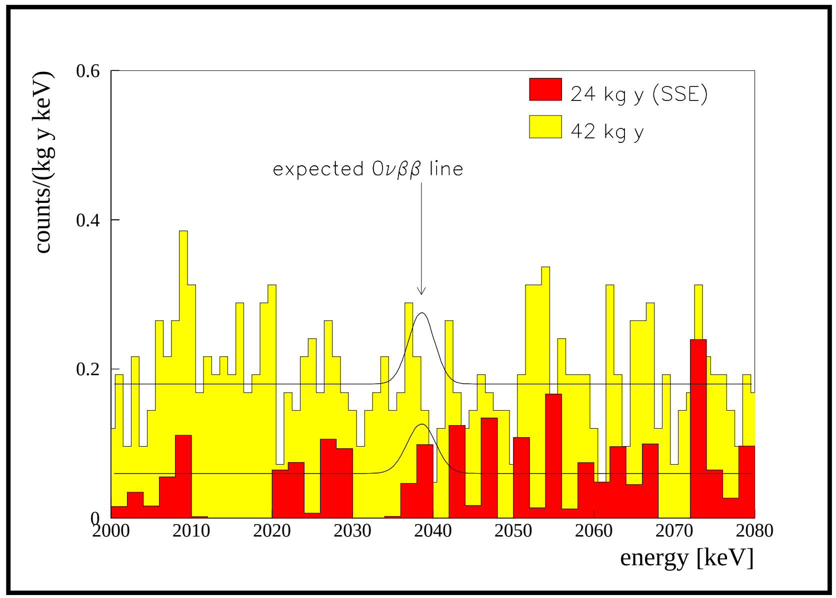
Current limit on $\beta\beta_{0\nu}$ decay

L. Baudis et al., PRL 83 (1999) 41-44

Depending on analysis and Matrix elements one finds

$$\langle m_\nu \rangle \leq (0.2 - 0.6)\ \mathrm{eV}$$





A summary of current $\beta\beta(0\nu)$ limits

For references see: S.R. Elliott and P. Vogel, hep-ph/0202264

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21} (76\%)$	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
^{82}Se	$> 2.7 \times 10^{22} (68\%)$	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
^{128,130}Te	$\frac{T_{1/2}(130)}{T_{1/2}(128)} = (3.52 \pm 0.11) \times 10^{-4}$	$< 1.1 - 1.5$
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

Uncertainty in $\beta\beta(0\nu)$ matrix elements

1) Haxton & Stephenson,
PPNP 12 (1984) 409
2) Caurier et al, NPA654 (1999) 973c
3) Engel, Vogel, Zirnbauer,
PRC 37 (1988) 731
4) Staudt, Muto & Klapdor,
EPL 13 (1990) 31
5) Faessler & Šimkovic,
JPG24 (1998) 2139
6) Pantis, Šimkovic, Vergados,
Faessler PRC 53 (1996) 695

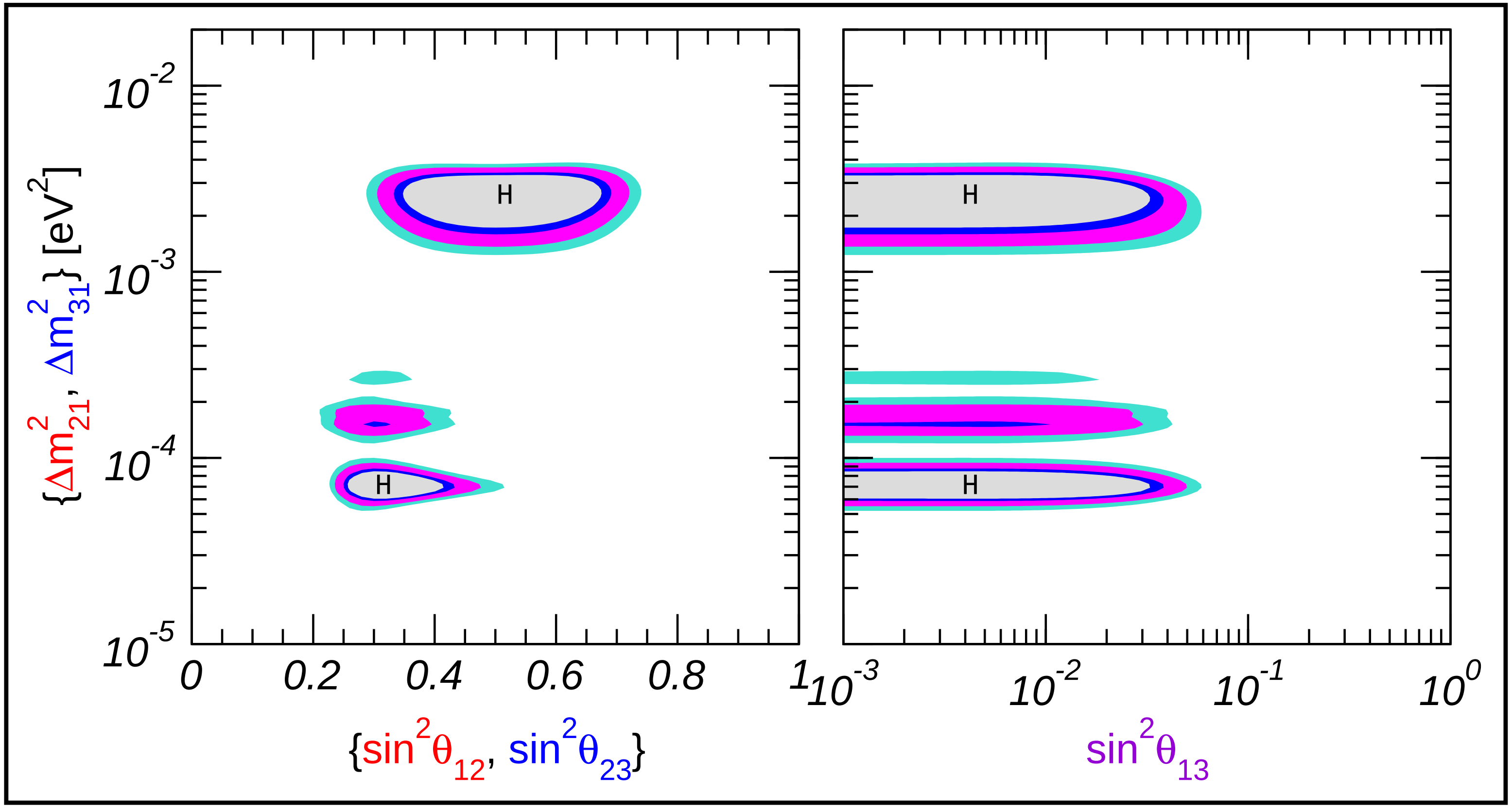
From S.R. Elliott and P. Vogel, hep-ph/0202264

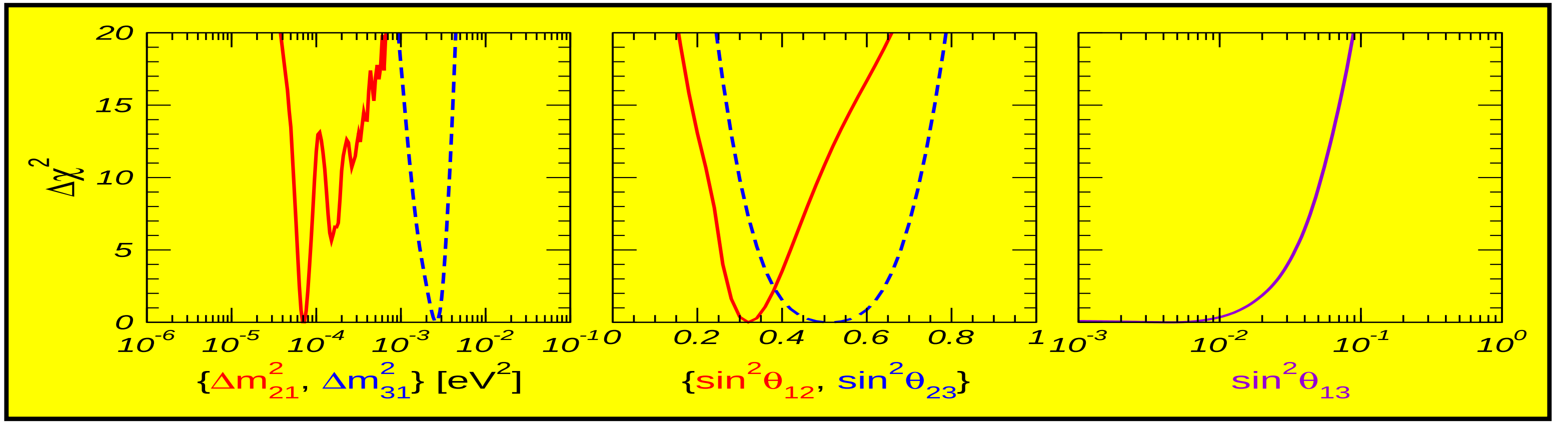
$\beta\beta(0\nu)$ half-lives in units of 10^{26} years for $\langle m_\nu \rangle$ = 50 meV and nuclear matrix elements given in the indicated references

Nucleus	Ref: 1)	2)	3)	4)	5)	6)
^{48}Ca	12.7	35.3	-	-	-	10.0
^{76}Ge	6.8	70.8	56.0	9.3	12.8	14.4
^{82}Se	2.3	9.6	22.4	2.4	3.2	6.0
^{100}Mo	-	-	4.0	5.1	1.2	15.6
^{116}Cd	-	-	-	1.9	3.1	18.8
^{130}Te	0.6	23.2	2.8	2.0	3.6	3.4
^{136}Xe	-	48.4	13.2	8.8	21.2	7.2
^{150}Nd	-	-	-	0.1	0.2	-
^{160}Gd	-	-	-	3.4	-	-

Current status of neutrino parameters

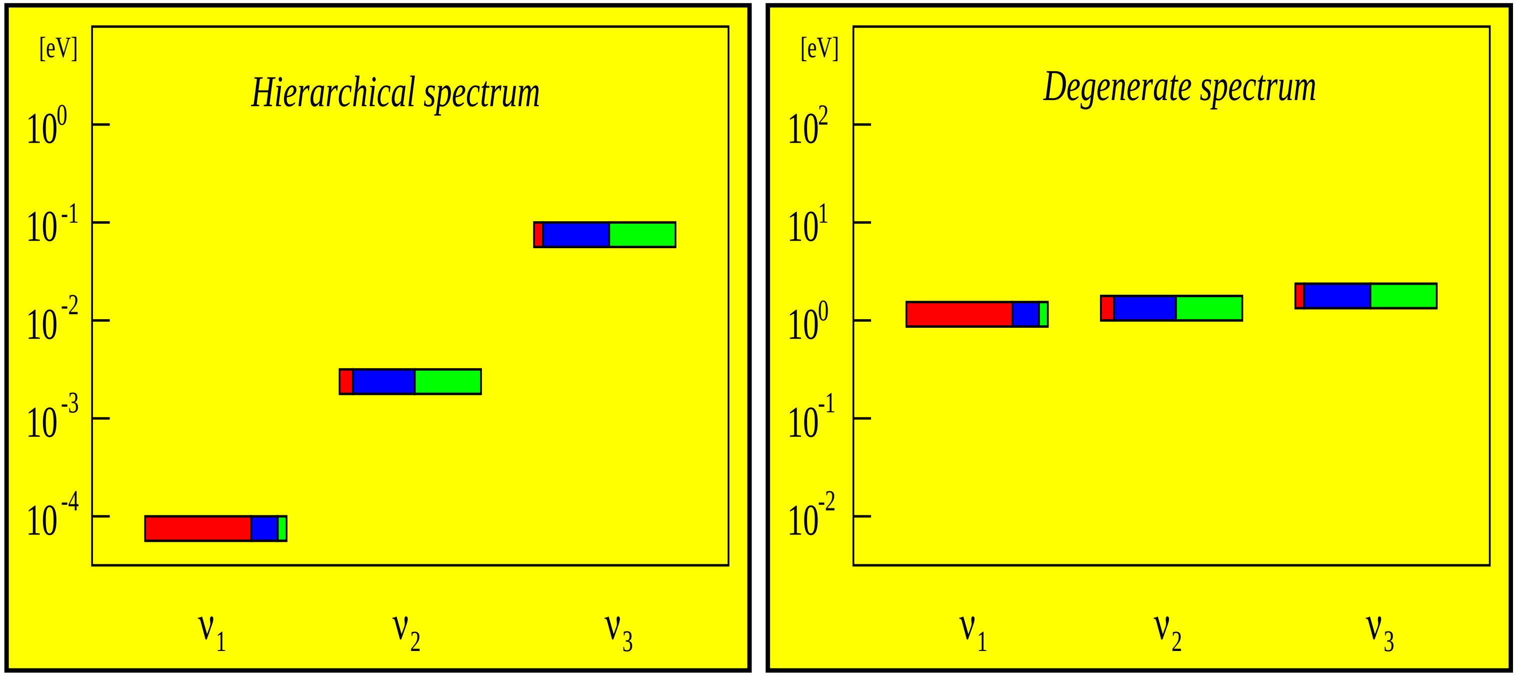
upg of Maltoni et al, PRD67 (2003) 013011 & PRD 67 (2003) 093003, upd of PRD63 (2001) 033005





Which neutrino spectrum?

any of the following can solve solar and atmospheric neutrino problems:



Colour coding for flavour composition: ν_e, ν_μ, ν_τ

cosmological relevance of neutrinos?

simplest gauge theory mixing matrix

- 3 angles θ_{ij} 23=atm 12=sol 13=reac

  1 KM-like phase oscill δ

  2 Majorana phases $\beta\beta_{0\nu}$ $\alpha,\ \beta$

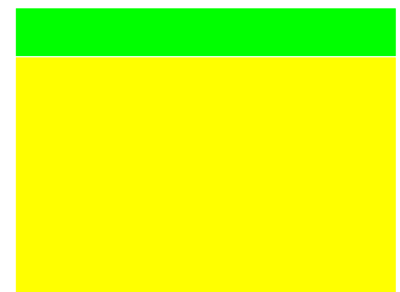
Schechter and JV, PRD22 (1980) 2227

both affect leptogenesis

- max θ_{23}, large θ_{12} & small θ_{13} hierarchical splittings

normal

inverse



quasi-degenerate

$\beta\beta_{0\nu}$ and the neutrino spectra (mass mechanism)

the double beta decay $\beta\beta_{0\nu}$ amplitude is governed by the average mass parameter

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

parametrizing K in terms of angles we get   Schechter and JV, PRD22 (1980) 2227

$$\boxed{\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3}$$

- 3 masses: $\boxed{m_i}$
- 2 angles: $\boxed{\theta_{12}}$ and $\boxed{\theta_{13}}$
- 2 CP violating phases: $\boxed{\alpha, \beta}$

three possibilities

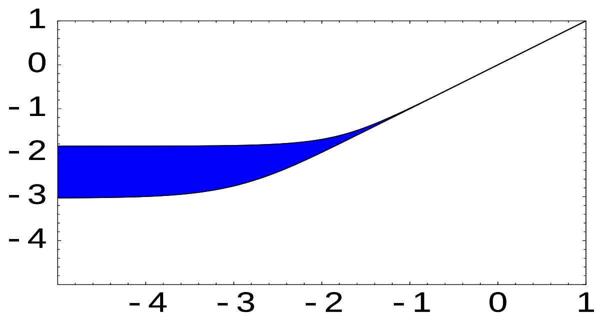
Normal Hierarchy	$m_i \ll m_j \ll m_k$
Inverse Hierarchy	$m_i \ll m_j \approx m_k$
Quasi-Degeneracy	$m_i \approx m_j \approx m_k$

$\langle m_\nu \rangle$ & neutrino oscillation data: Normal hierarchy

Log $\langle m_\nu \rangle$/eV vs Log m_1/eV

$$\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

plots from Martin Hirsch



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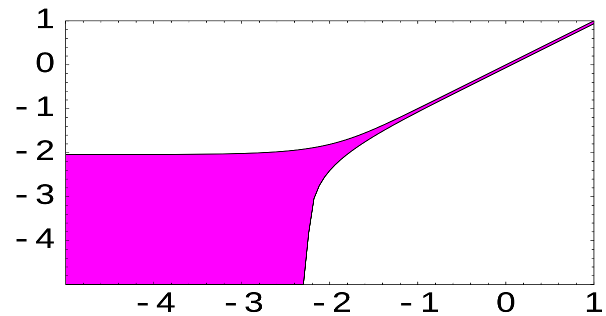

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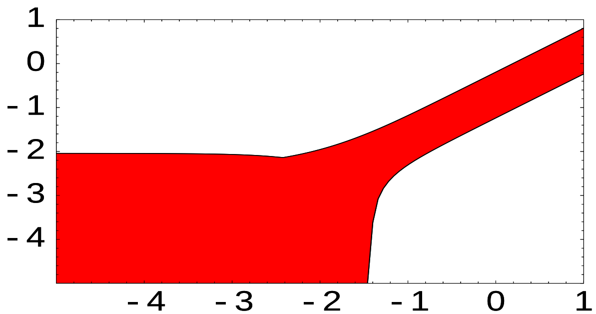

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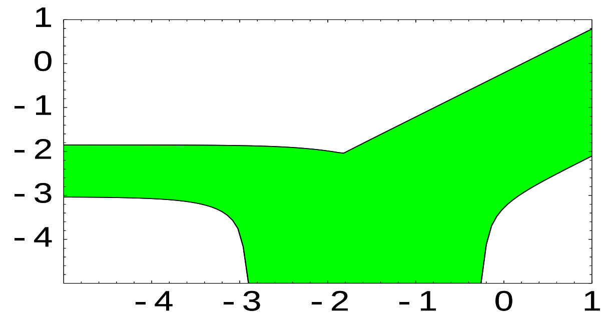

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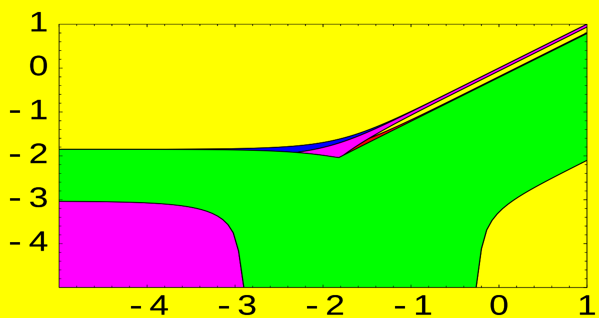
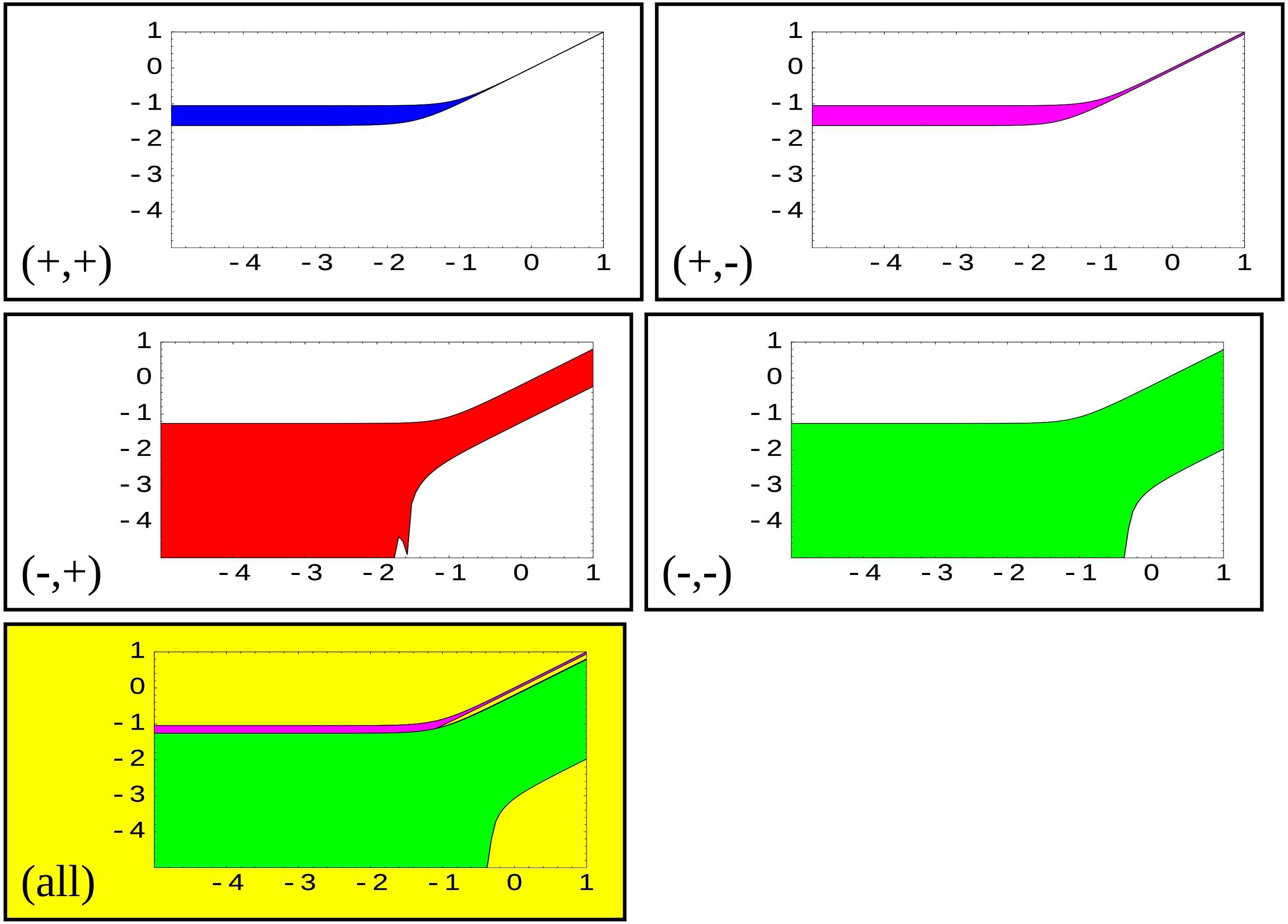


(all)

$\langle m_\nu \rangle$ & neutrino oscillation data: Inverse hierarchy

Log $\langle m_\nu \rangle$/eV vs Log m_1/eV

$$\langle m_\nu \rangle = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$



like cosmology, $\beta\beta_{0\nu}$ probes absolute m-nu scale

in contrast to oscillations

CMB bound on hot dark matter component (2DF, WMAP, ...)

Barger, Glashow, Marfatia and Whisnant, PLB532 (2002) 15 Vissani, JHEP **9906**, 022 (1999)

as other L- violating processes

neutrinoless double beta decay

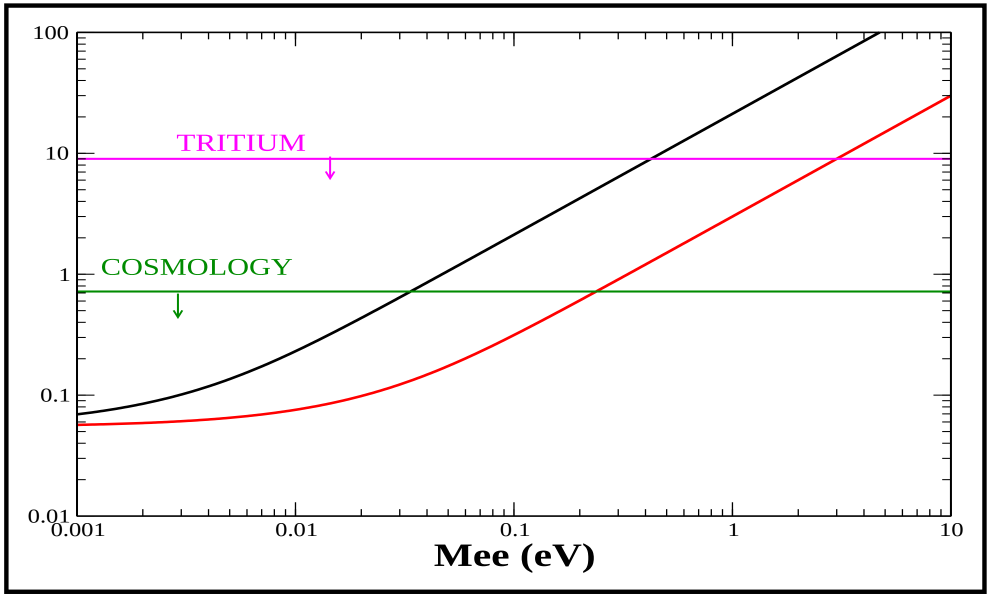
is sensitive to Majorana phases

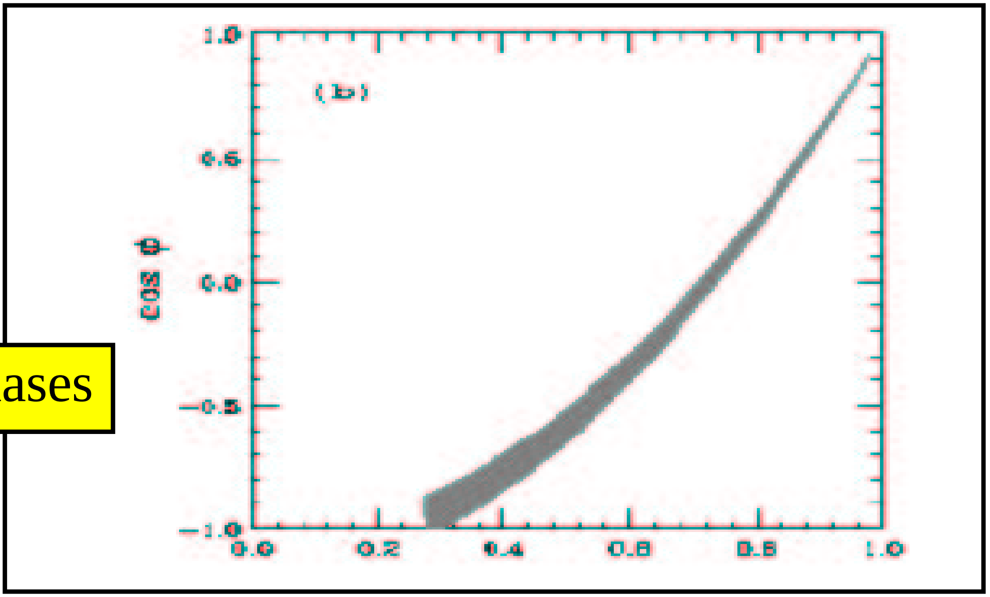
Schechter and JV, PRD22 (1980) 2227, D23 (1981) 1666 Wolfenstein PLB107 (1981) 77; Doi et al

unfortunately

currently can not reconstruct majorana phases

Barger, Glashow, Langacker, Marfatia, PLB B540 (2002) 247

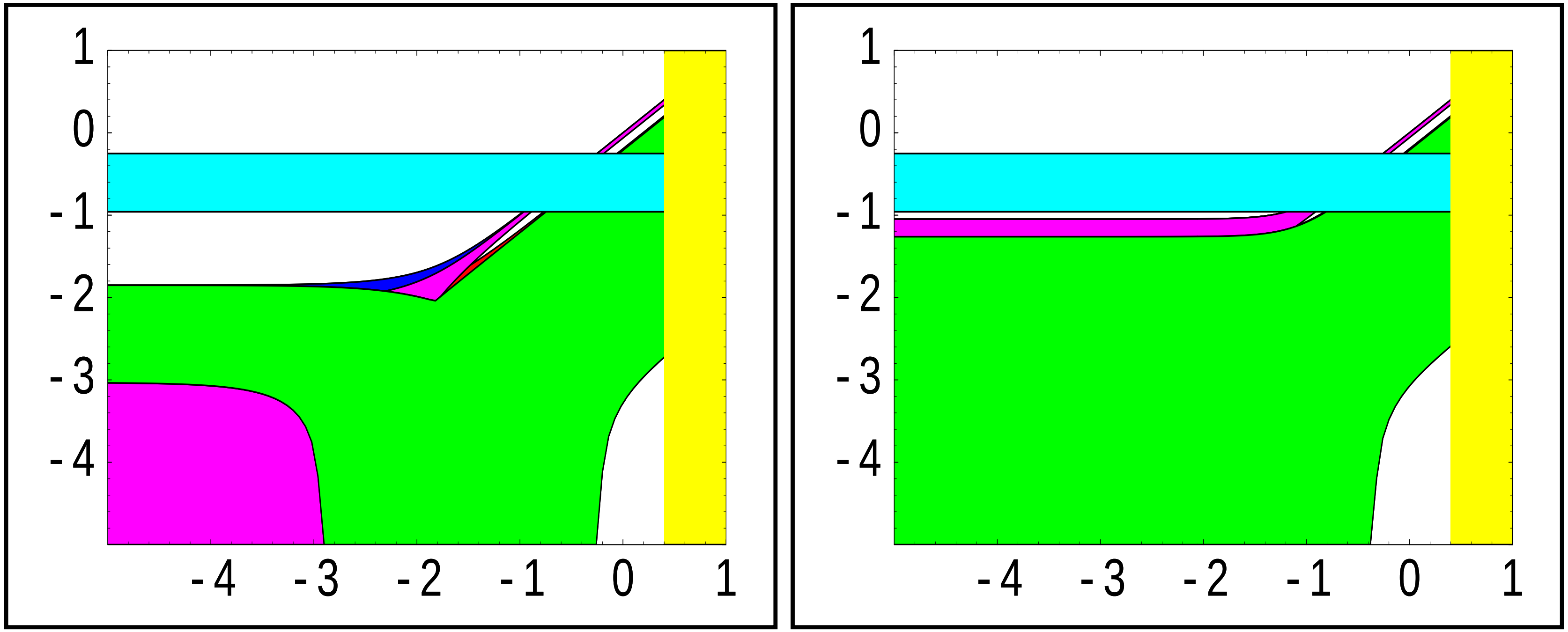




Current sol-atm, $\beta\beta_{0\nu}$ and Tritium sensitivities

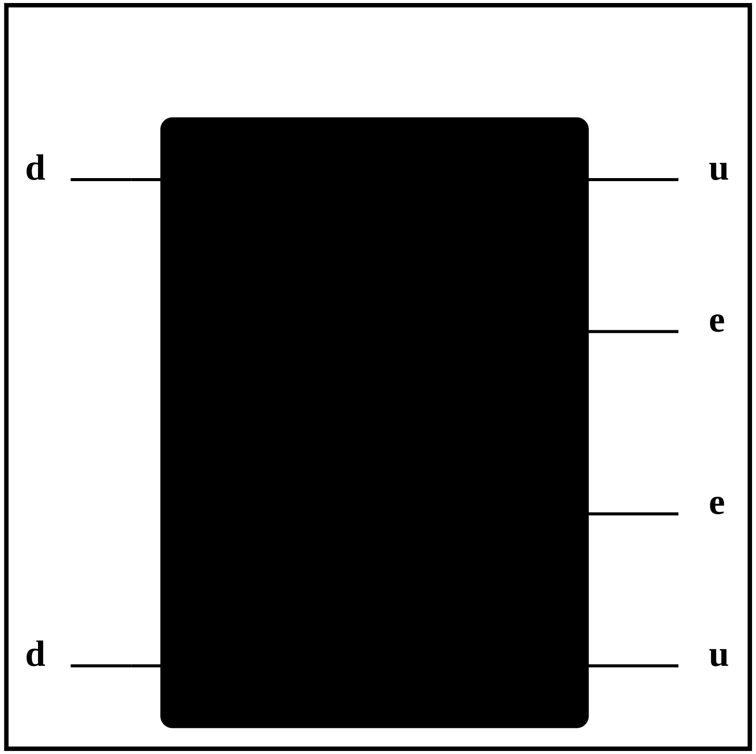
- Current neutrino oscillation data
- Upper limit for $\langle m_\nu \rangle \leq 0.3$ [eV] with factor ~ 2 uncertainty band
- Upper limit from Tritium experiments: $m_1 \leq 2.5$ [eV]

normal versus inverse hierarchy Log $\langle m_\nu \rangle$/eV vs Log m_1/eV



Beyond the mass mechanism

Neutrinoless double beta decay violates lepton number



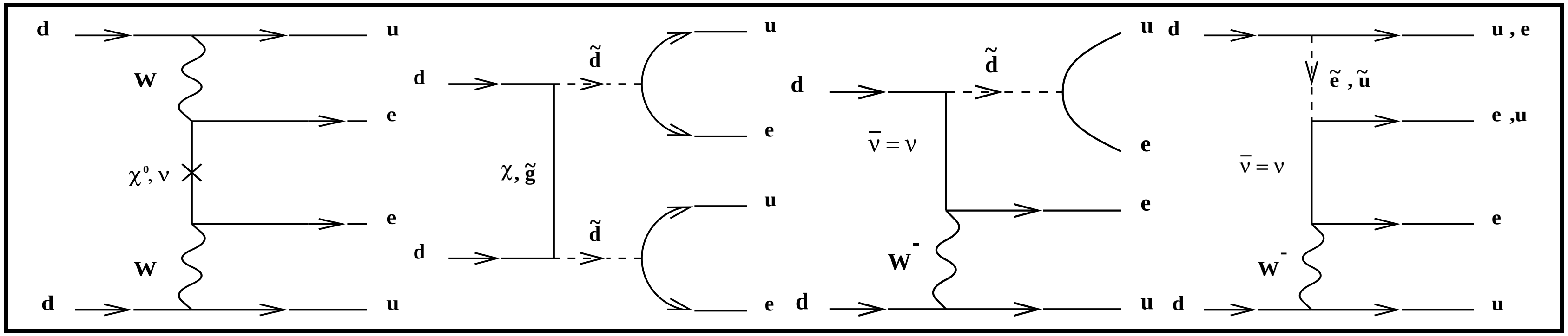
Any model beyond SM with lepton number violation can contribute!

Derive constraints from absence of $\beta\beta_{0\nu}$

Examples:

⇒ Left-right symmetric models
⇒ R-parity conserving supersymmetry
⇒ R-parity violating supersymmetry

Hirsch, Klapdor, Kovalenko, PRL75 (1995) 17; Faessler, Kovalenko, Simkovic, PRD58 (1998) 055004

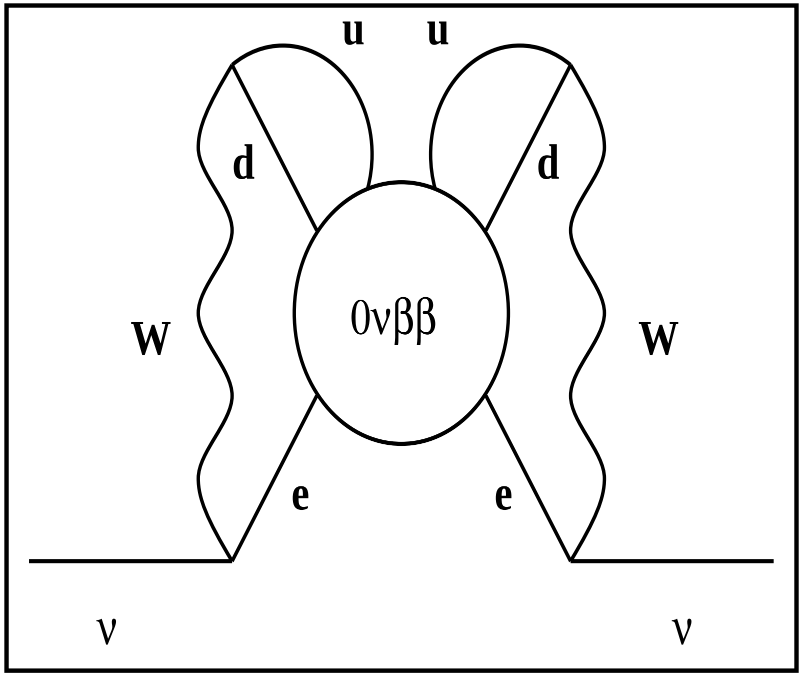


Relevance of $\beta\beta_{0\nu}$

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

Schechter and JV, PRD **25** (1982) 2951

no such theorem for flavor violation!



like other L violating processes
$\beta\beta_{0\nu}$ is potentially sensitive to Majorana phases

Schechter and JV, PRD22 (1980) 2227, D23 (1981) 1666

Wolfenstein PLB107 (1981) 77; Doi et al

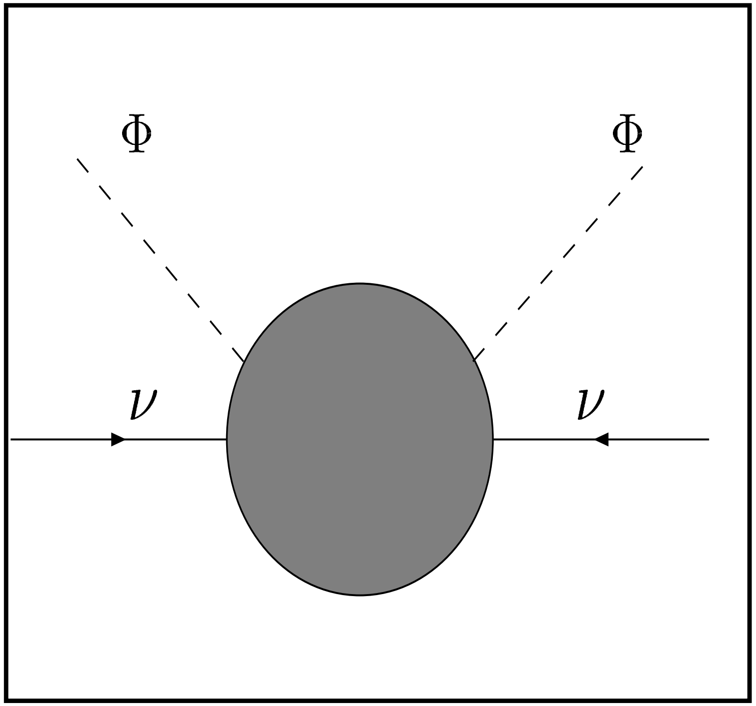
currently can not reconstruct majorana phases

Barger, Glashow, Langacker, Marfatia, PLB B540 (2002) 247

a pity for leptogenesis

Theory of neutrino properties

basic dim-5 operator ⊙

- 

- from Gravity

  Weinberg; Barbieri, Ellis, Gaillard; Zee & Weldon
- from seesaw schemes

  Gell-Mann, Ramond, Slansky; Yanagida;
  Mohapatra, Senjanovic PRL **44** (1980) 91
  Schechter, JV PRD **22** (1980) 2227
- weak-scale seesaw

neutrino unification: GUT-scale seesaw

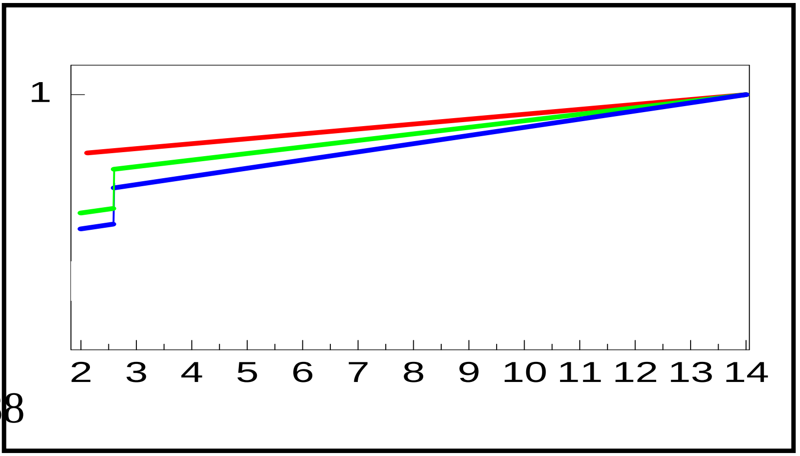
⊙

Babu, Ma and Valle, PLB552 (2003) 207

neutrino masses unify as they run up

Chankowski, Ioannisian, Pokorski and Valle, PRL86 (2001) 3488

m_ν/eV vs. Log M_X/GeV



solar & atm splittings from RGE

common origin for both neutrino and KM mixing

predict maximal θ_{23} & small θ_{13}; θ_{12} can be large

see also Grimus & Lavoura

observable mass in cosmology and β decays

observable $\beta\beta_{0\nu}$ decay rates

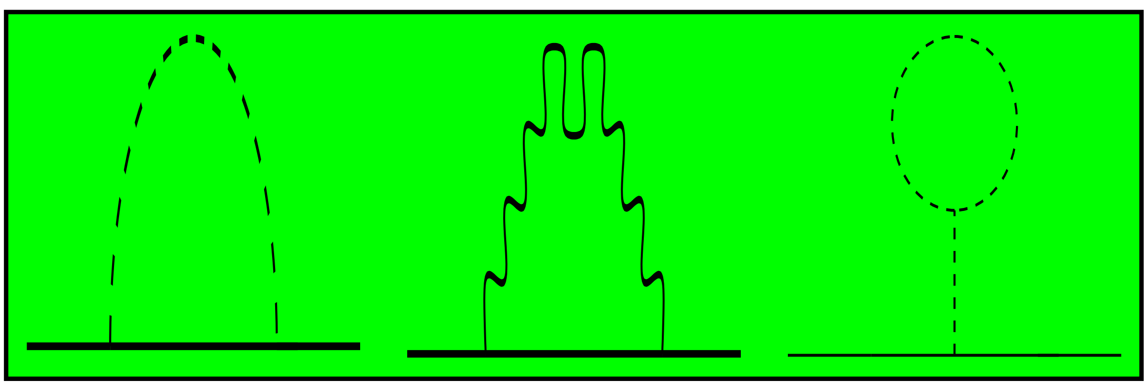
observable Lepton Flavor Violation

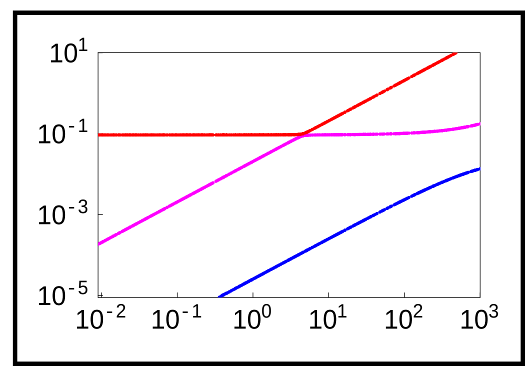
bilinear R parity violation: weak-scale seesaw

⊙ Diaz, Hirsch, Porod, Romao and Valle, hep-ph/0302021 PRD in press; PRD **62** (2000) 113008 [Err-ibid. D **65** (2002) 119901]; PRD **61** (2000) 071703

- weak-scale seesaw atm scale

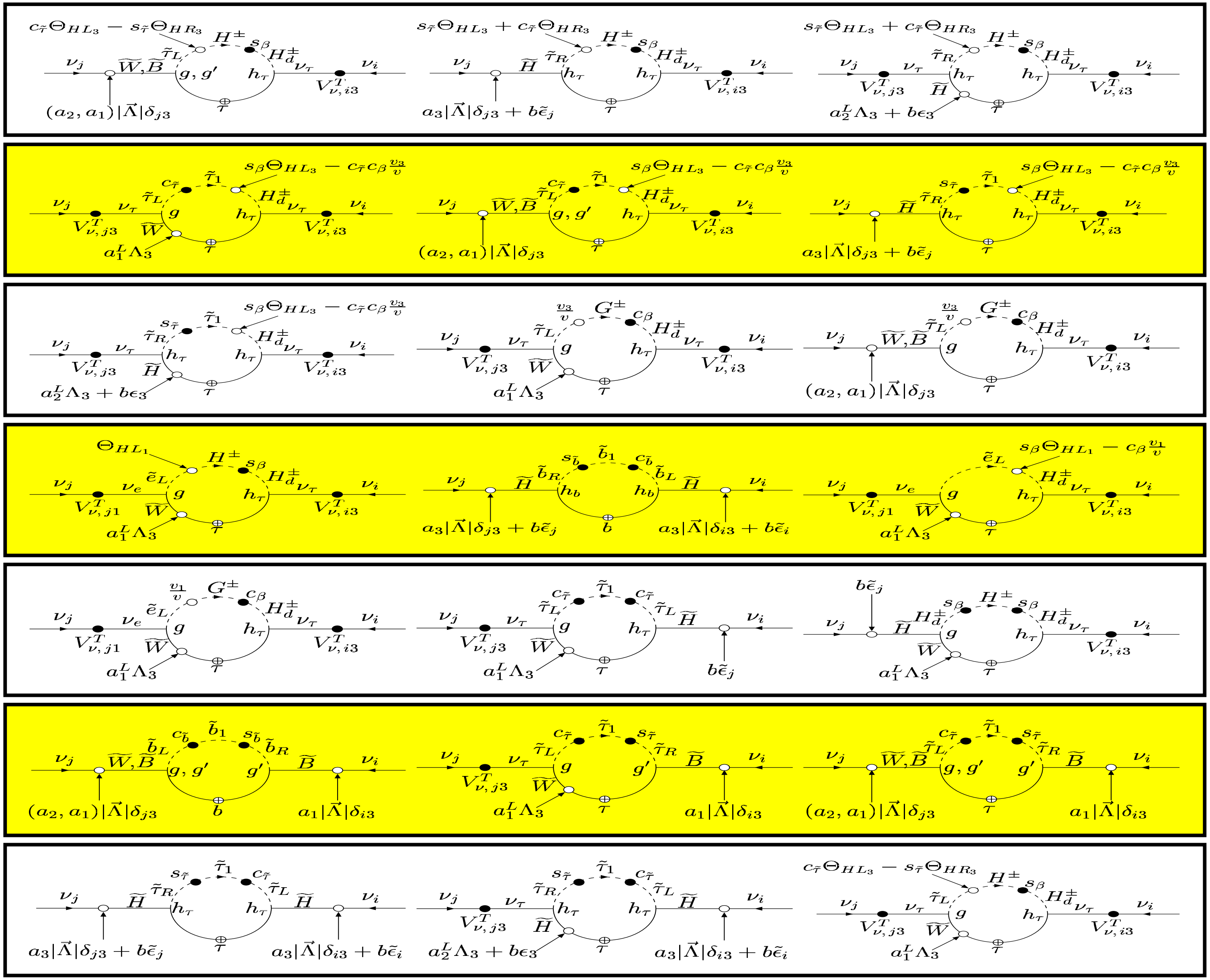
- radiative nu-masses solar scale





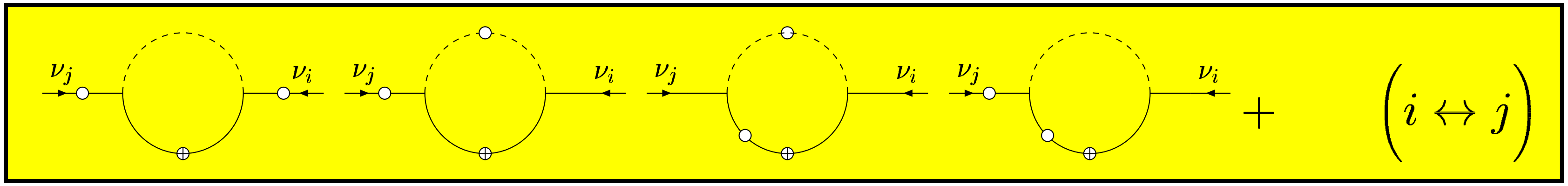
solar mass scale loops in Broken R parity Susy

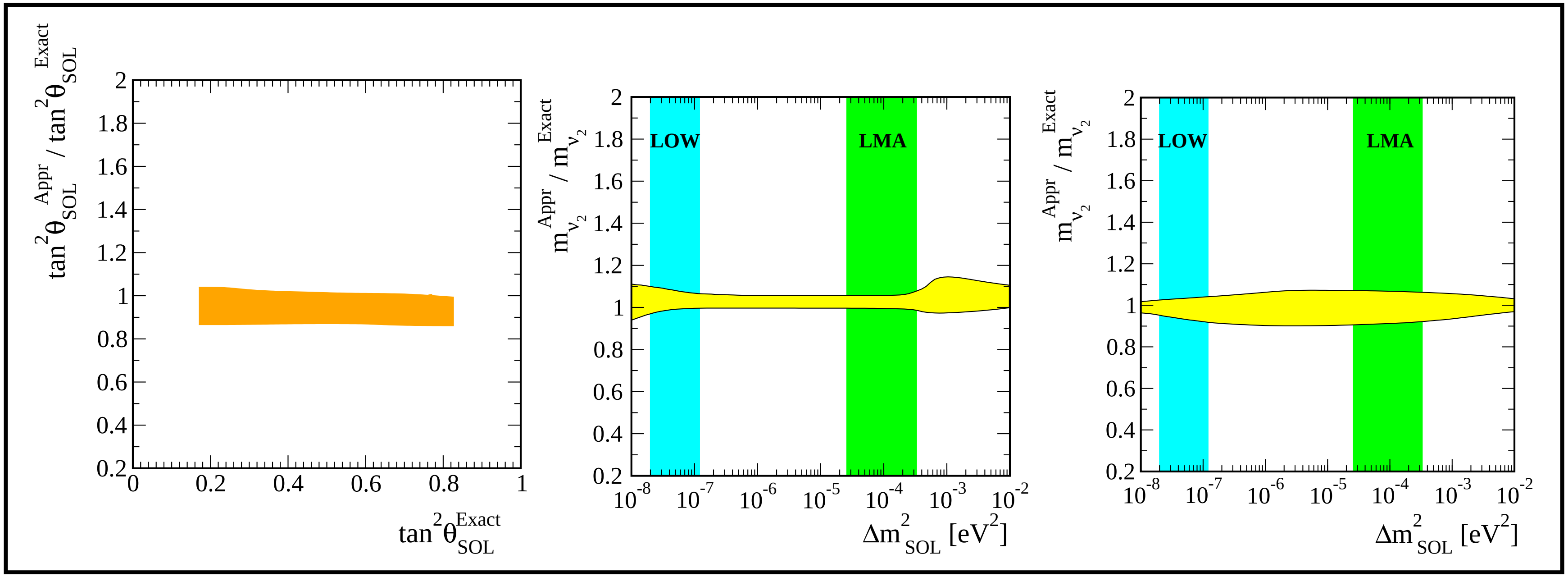
M. A. Diaz et al hep-ph/0302021



solar mass scale loops: analytical vs numerical

M. A. Diaz et al hep-ph/0302021



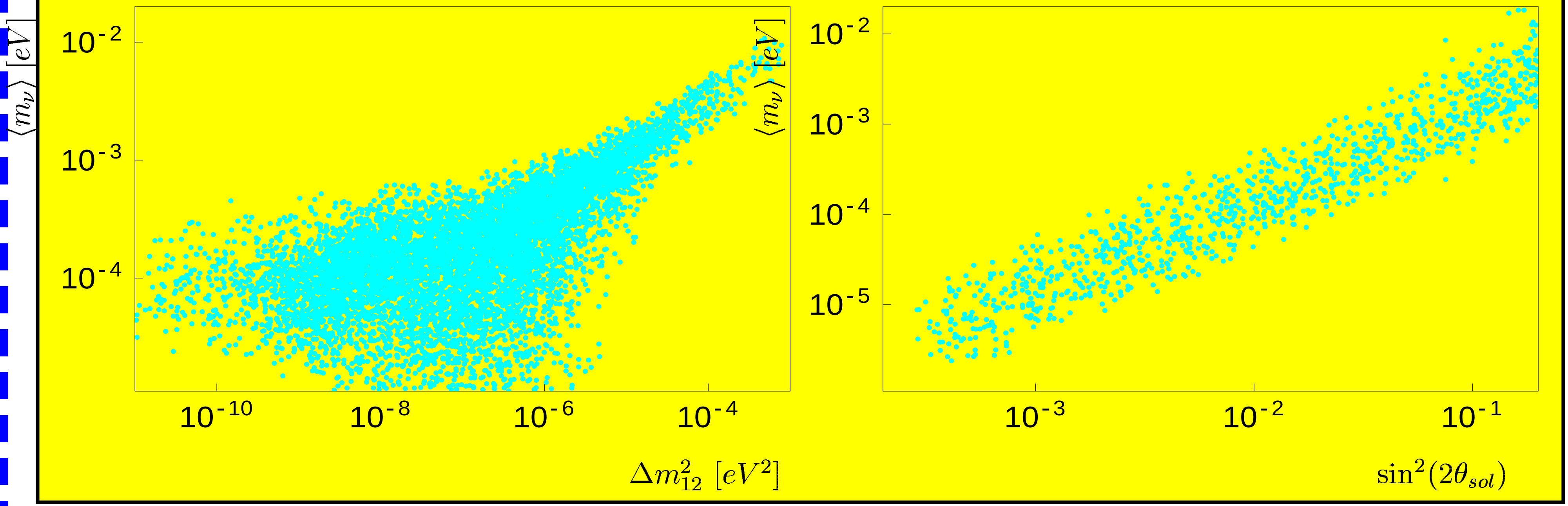


$\beta\beta_{0\nu}$ decay in Bilinear Broken R parity Susy

In bilinear (spontaneous) RP breaking dominated by mass mechanism

$\langle m_\nu \rangle$ vs solar

Hirsch, Romao, Valle PLBB486 (2000) 255, Hirsch & Valle. NPB557 (1999) 60



requires new generation of expts

The future

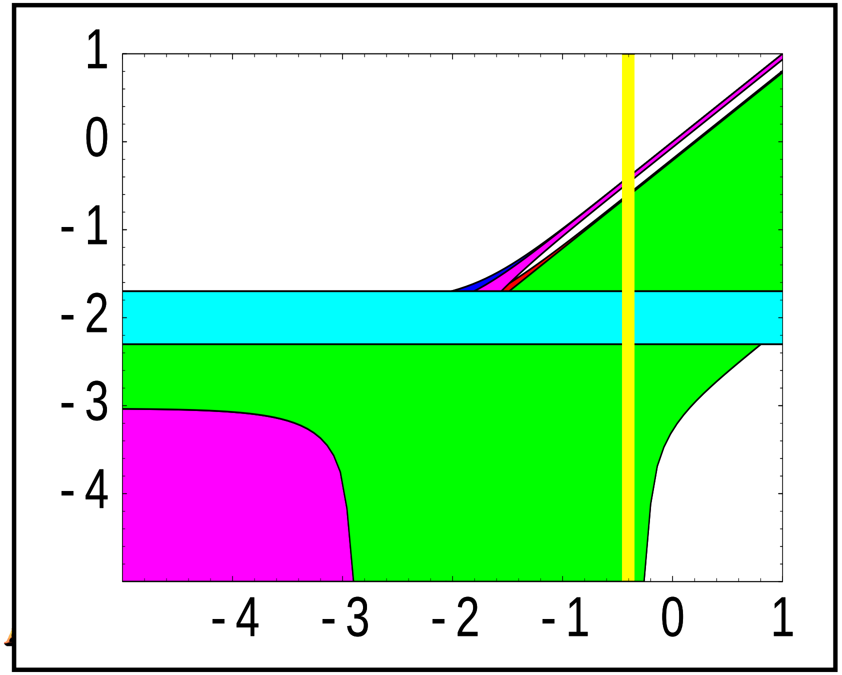
Future $\beta\beta_{0\nu}$ experiments

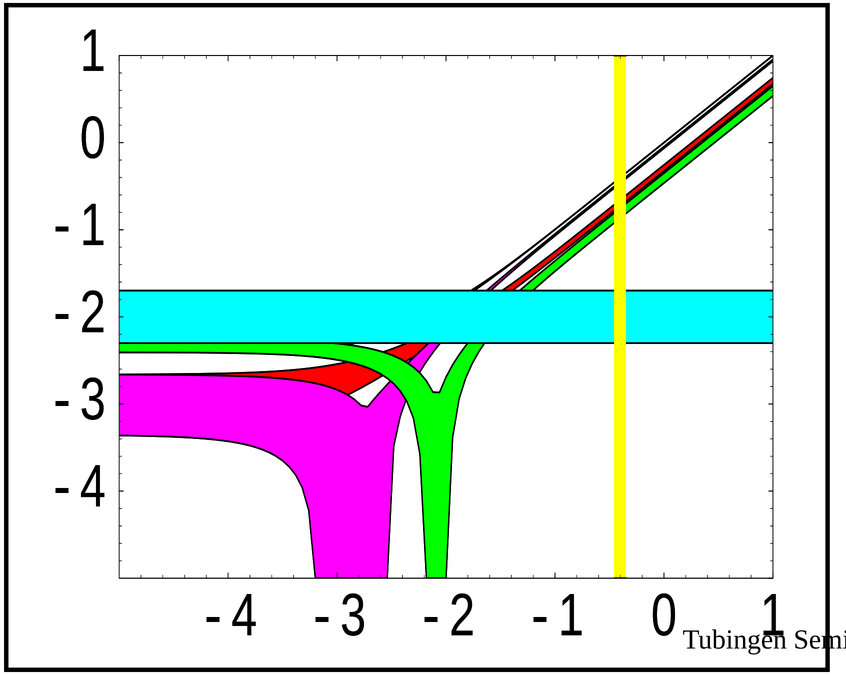
- GENIUS: J. Hellmig and H. V. Klapdor-Kleingrothaus, Z.Phys. A359 (1997) 351-359
  $\Rightarrow$ many ($\sim 300 - 3000$) detectors ($\simeq 1 - 10$ ton)
  $\Rightarrow$ to reduce background operate detectors in liquid nitrogen
  $\Rightarrow$ claims sensitivity of $\langle m_\nu \rangle \sim 0.01(0.002)$ eV
- EXO: M. Danilov et al., hep-ex/0002003
  $\Rightarrow$ (1-10) tons in high pressure TPC
  $\Rightarrow$ to reduce background detect Ba^+ daughter ion by laser tagging
  $\Rightarrow$ claims sensitivity of $\langle m_\nu \rangle \sim 0.02$ (0.0025) eV
- MOON: H. Ejiri et al., nucl-ex/9911008
  $\Rightarrow$ foils of several tons of enriched ^{100}Mo surrounded by plastic scintillators
  $\Rightarrow$ reduce background by ???
  $\Rightarrow$ claims sensitivity of $\langle m_\nu \rangle \sim 0.02 - 0.05$
- CUORE: Avignone FT, *et al.*, hep-ex/0201038
  $\Rightarrow$ 750 kg TeO_2 bolometers
  $\Rightarrow$ claims sensitivity $T_{0\nu\beta\beta} \sim 2 \times 10^{26}$ ($\langle m_\nu \rangle \sim 0.02 - 0.05$ eV)
- ...other expts ... CAMEO, CANDLES, GEM, Majorana ...

current vs future sol-atm, β and $\beta\beta_{0\nu}$ sensitivities

- take current neutrino oscillation data as in Maltoni et al, PRD67 (2003) 013011 & PRD 67 (2003) 093003, vs Δm^2 (best-fit point) data within 10 %
- let the upper limit for (or discovery) be $\langle m_\nu \rangle \leq 0.01$ [eV], with factor ~ 2 uncertainty
- take the upper limit (or discovery) from KATRIN experiment as $m_1 \simeq 0.4$ [eV] $(\pm 10\%)$

current vs future oscillation data: Log $\langle m_\nu \rangle$/eV vs Log m_1/eV





normal versus inverse hierarchy in the future

- assume future LMA-MSW parameters to within 10 %
- Non-zero s_{13}^2 discovered: $0.05 \leq s_{13}^2 \leq 0.07$

Log $\langle m_\nu \rangle$/eV vs Log m_1/eV