What can DBD experiments do?

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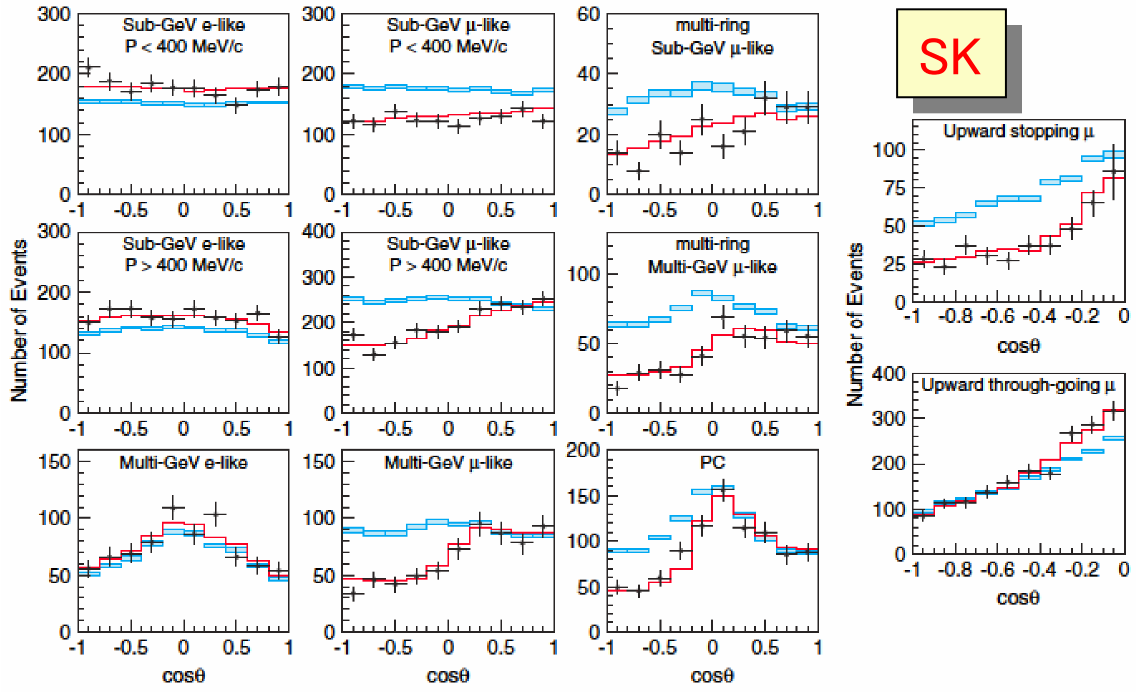
The question

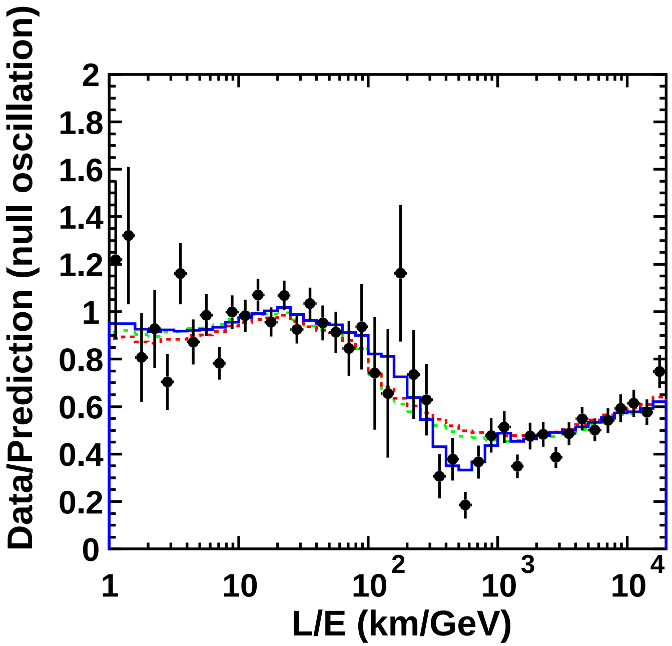
- The question I want to address in this talk is ``what can you do and what would be the implications of DBD experiments?''

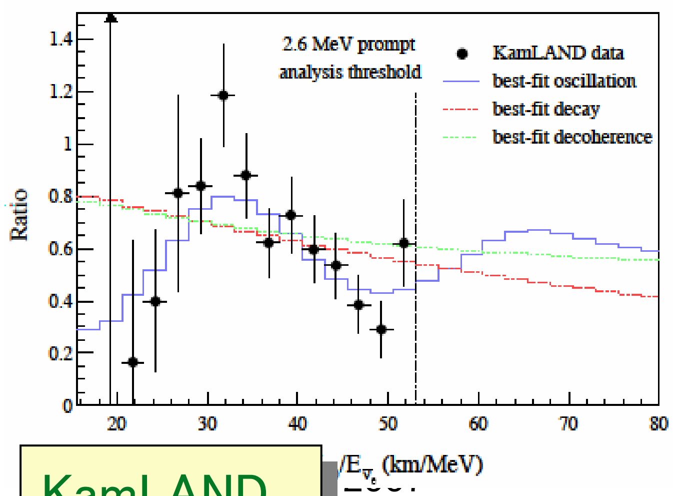
- One of the most important experiments in particle physics

ν oscillation has been seen!

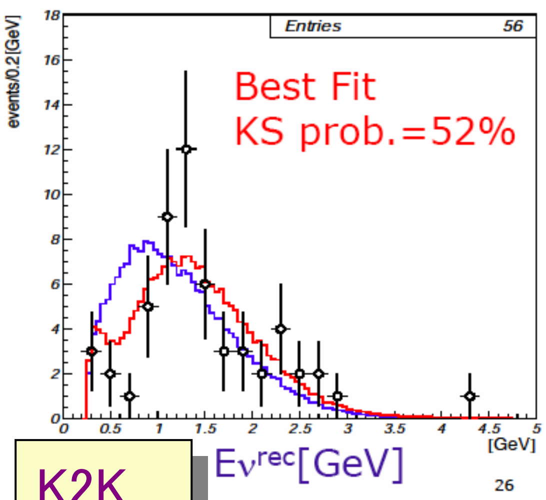


SK

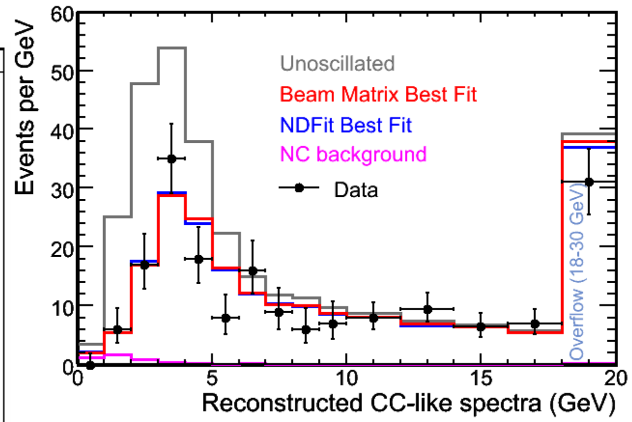




KamLAND

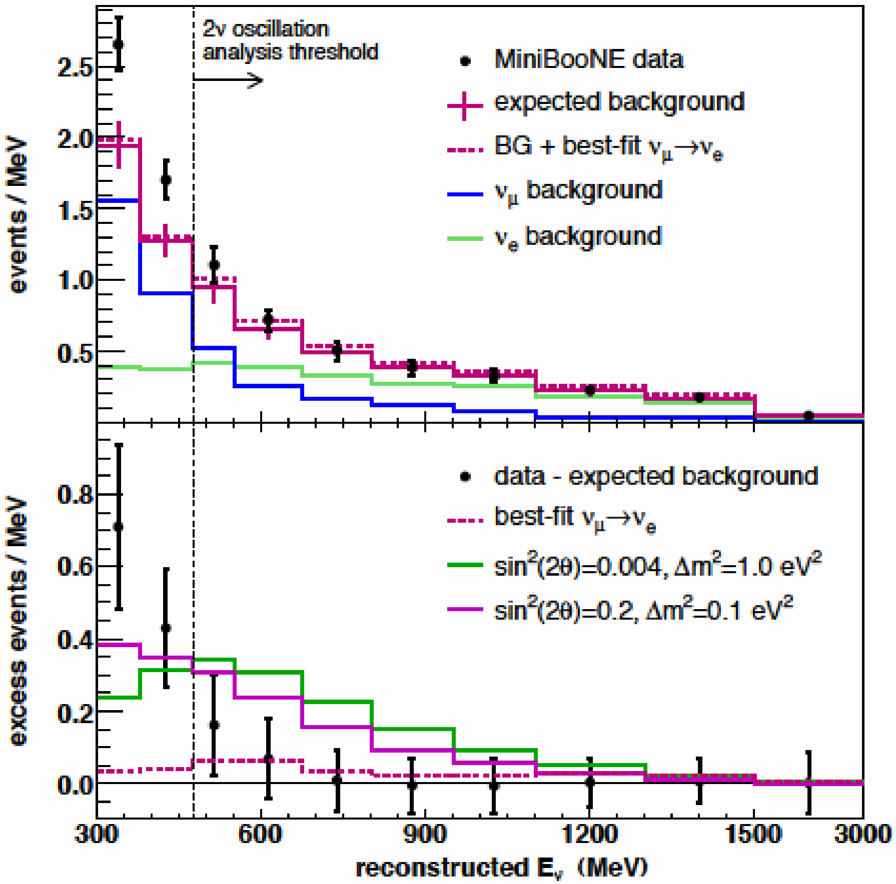


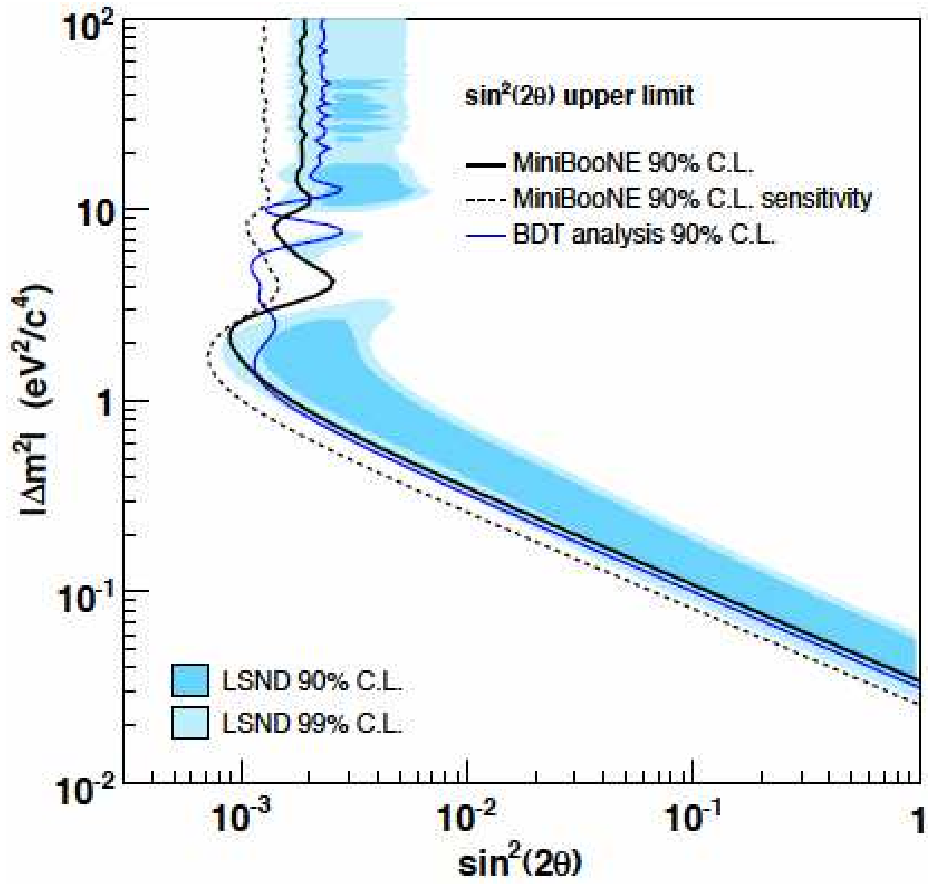
K2K



MINOS

Mini-BooNE did NOT confirm LSND data





No strong motivation for structure beyond 3 generation mixing

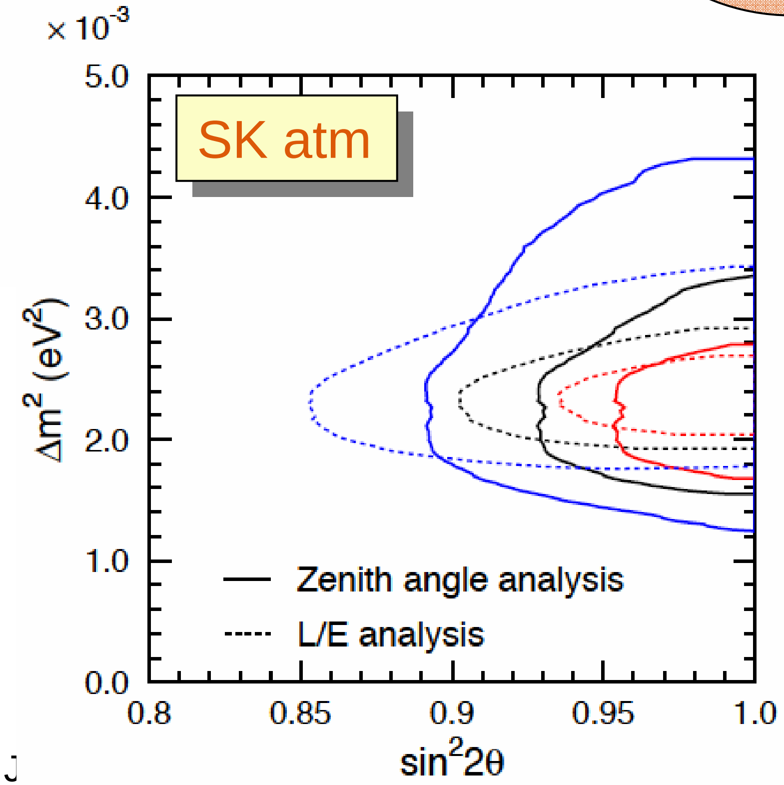
MNS matrix and ν mass pattern

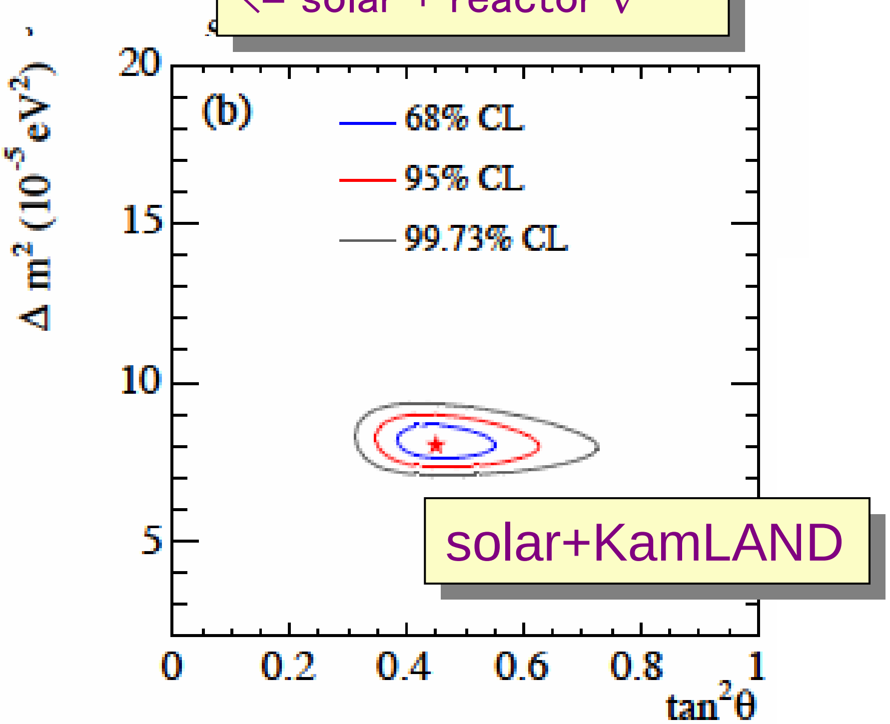
$\nu_\alpha = U_{\alpha i}\, \nu_i$

Atm + accel ν =>

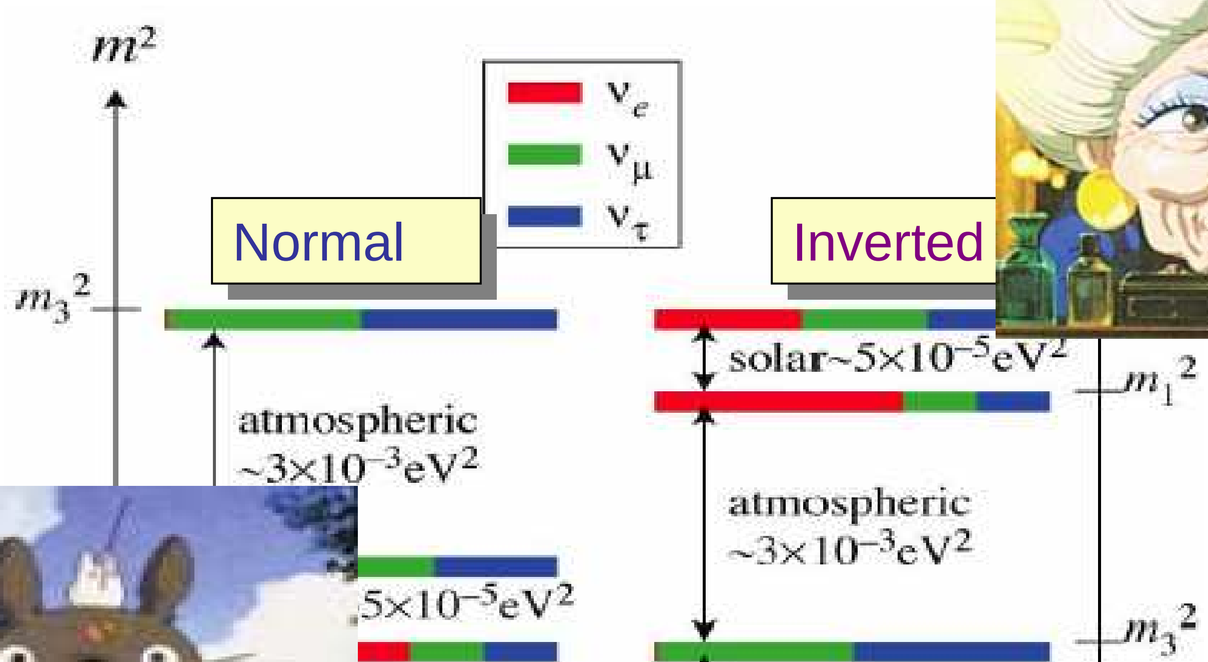
$$U \equiv U_{\rm MNS} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \mathrm{diag}(1, e^{i\beta}, e^{i\gamma})$$

<= solar + reactor ν





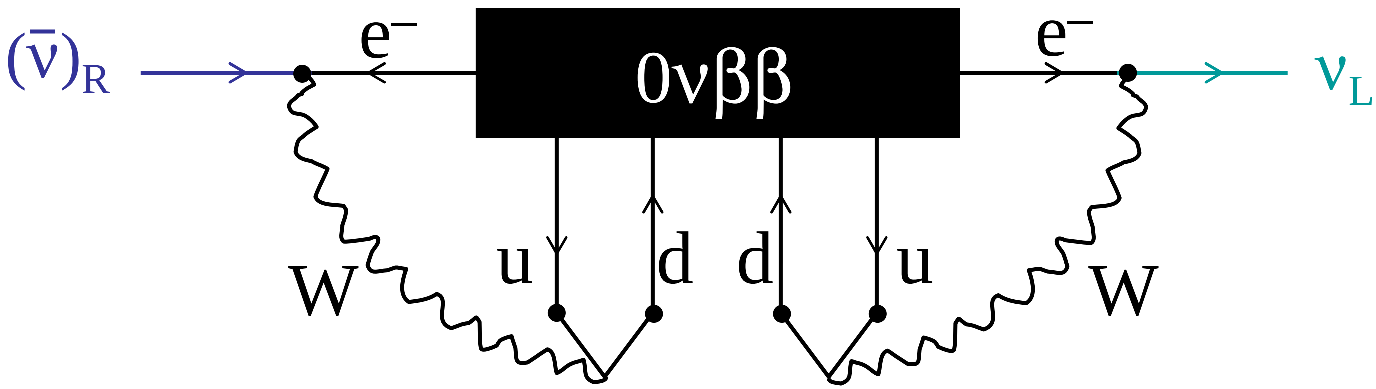
ν mass hierarchy & absolute mass scale



General statement

Whatever diagrams cause 0νββ, its observation would imply the existence of a Majorana mass term

Schechter and Valle



$(\bar{\nu})_R \rightarrow \nu_L$: A Majorana mass term

Borrowed from Boris

Why don’t want to know the nature of neutrinos

- Many theorists say it is ``Majorana’’ because it is the case in my model(s)
- … in most models

→

- We need less model dependent argument

Yanagida's argument

Delivered at DBD05 in Hawaii

- There is a strong argument which says that ν must be Majorana particle
- We know that our universe is asymmetric to baryon number
- We know that above 1 TeV, only meaningful quantum number is B-L, not B or L separately, because of anomaly ("sphaleron")
- Therefore, we must have B+L generation to have nonzero baryon number

Yanagida's argument (continued)

- Let us assume SM of particle physics => no operator which violates B+L
- The lowest dimension operator which violate B-L is

$(1/M)\ \phi\phi\nu\nu$ ⇐ which must exists

- This is consistent with the neutrino mass operator required by SK, SNO, KamLAND, and K2K, and others (confirmed to exists!)
- Therefore, ν Majorana mass must exist (otherwise, we do not have baryon # excess)

Success guaranteed

- There is a well defined model of baryon number generation embodying this idea

⇨ leptogenesis

- Double beta decay experiments are guaranteed to have a success !
- Practically, ???

Rest of my talk

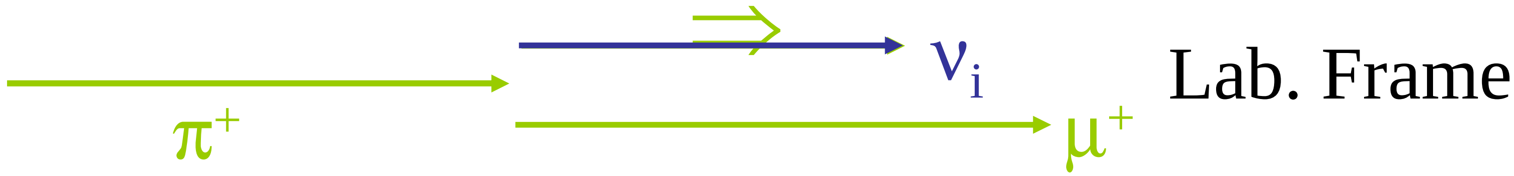
- What quantities can DBD experiments determine ?
- What would be implications of successful DBD experiments, in particular
- Absolute ν mass
- Majorana phase

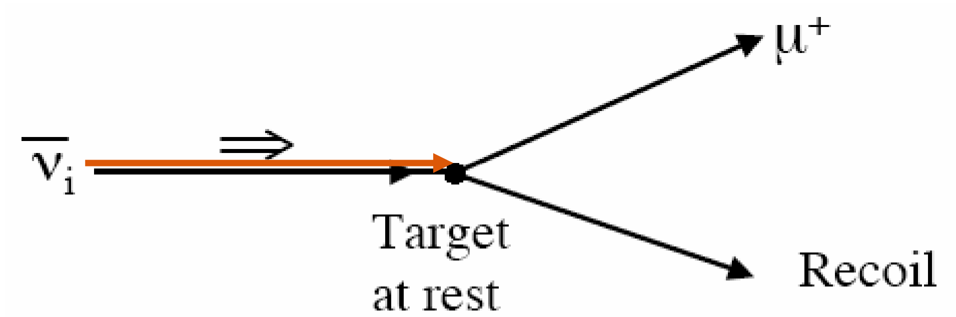
Looking for experiments for proving Majorana ν

Kayser's $\pi + N \rightarrow 2\mu^+ + X$ experiment

Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$





Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi(\text{Lab}) \gtrsim 10^5 \text{ TeV if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Fraction of all π – decay ν_i that get helicity flipped

$$\approx \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})} \right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{ eV}$$

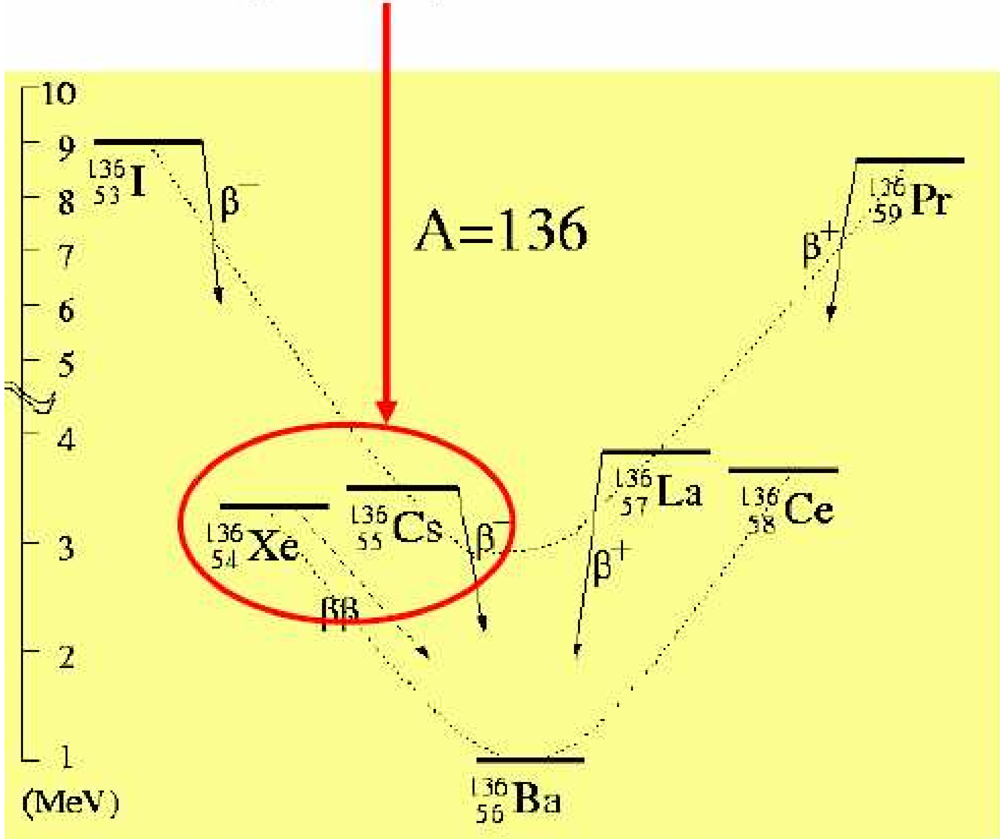
Since L-violation comes only from Majorana neutrino *masses*, any attempt to observe it will be at the mercy of the neutrino masses.

(BK & Stodolsky)

Double beta decay; an ingenious way

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Lifetime of 0νββ decay

Phase space factor

nuclear matrix element

uncertainties

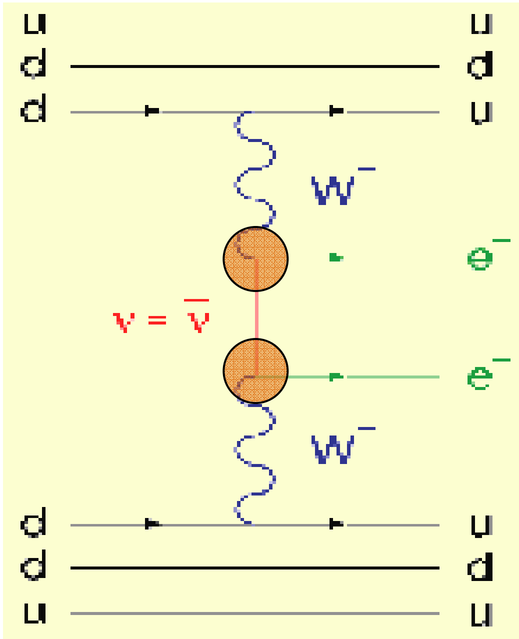
$$\tau^{-1} = G_{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2$$

Effective neutrino mass

Effective mass parameter =

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

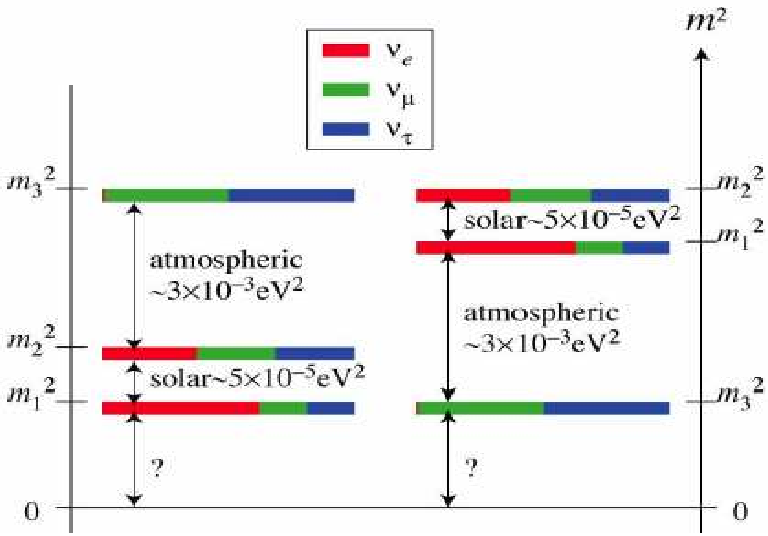
$$= \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$



<m> or lowest (highest) neutrino mass as the unique parameter

$$m_3 = \sqrt{\Delta m^2_{atm} + \Delta m^2_{\odot} + m^2_{lowest}}$$
$$m_2 = \sqrt{\Delta m^2_{\odot} + m^2_{lowest}}$$
$$m_1 = m_{lowest}$$

Normal



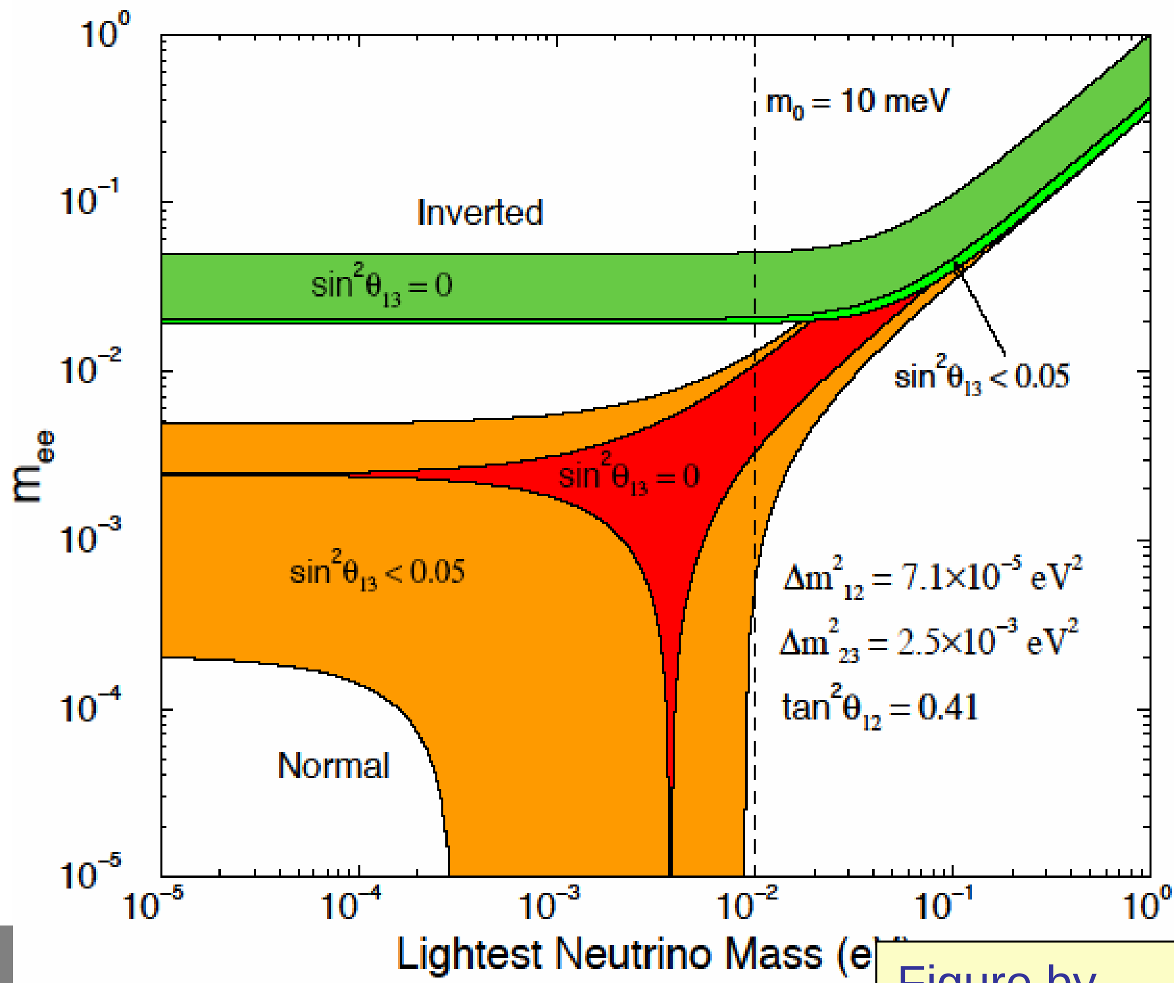
Inverted

$$m_2 = \sqrt{\Delta m^2_{atm} + \Delta m^2_{\odot} + m^2_{lowest}}$$
$$m_1 = \sqrt{\Delta m^2_{atm} + m^2_{lowest}}$$
$$m_3 = m_{lowest}$$

m_{ee} vs. lowest ν mass

$$\langle m \rangle_{ee} = \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Minimum m_{ee} in inverted mass hierarchy NH & IH look so different



If θ_{13}=0, $<m_{ee}>$=0,
=> m_1=4x10^{-3} eV^2

Figure by H.Nunokawa

Why minimum m_{ee} in inverted hierarchy?

$$\langle m \rangle_{\beta\beta} = \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$
$$= \left| m_1 c_{12}^2 c_{13}^2 e^{-i\beta} + m_2 s_{12}^2 c_{13}^2 e^{+i\beta} + m_3 s_{13}^2 e^{i(3\gamma - 2\delta)} \right|$$

Inverted hierarchy => minimum at $\cos 2\beta = -1$

$$\langle m \rangle_{\beta\beta} \geq c_{13}^2 \left| m_1 c_{12}^2 - m_2 s_{12}^2 \right| - m_3 s_{13}^2.$$

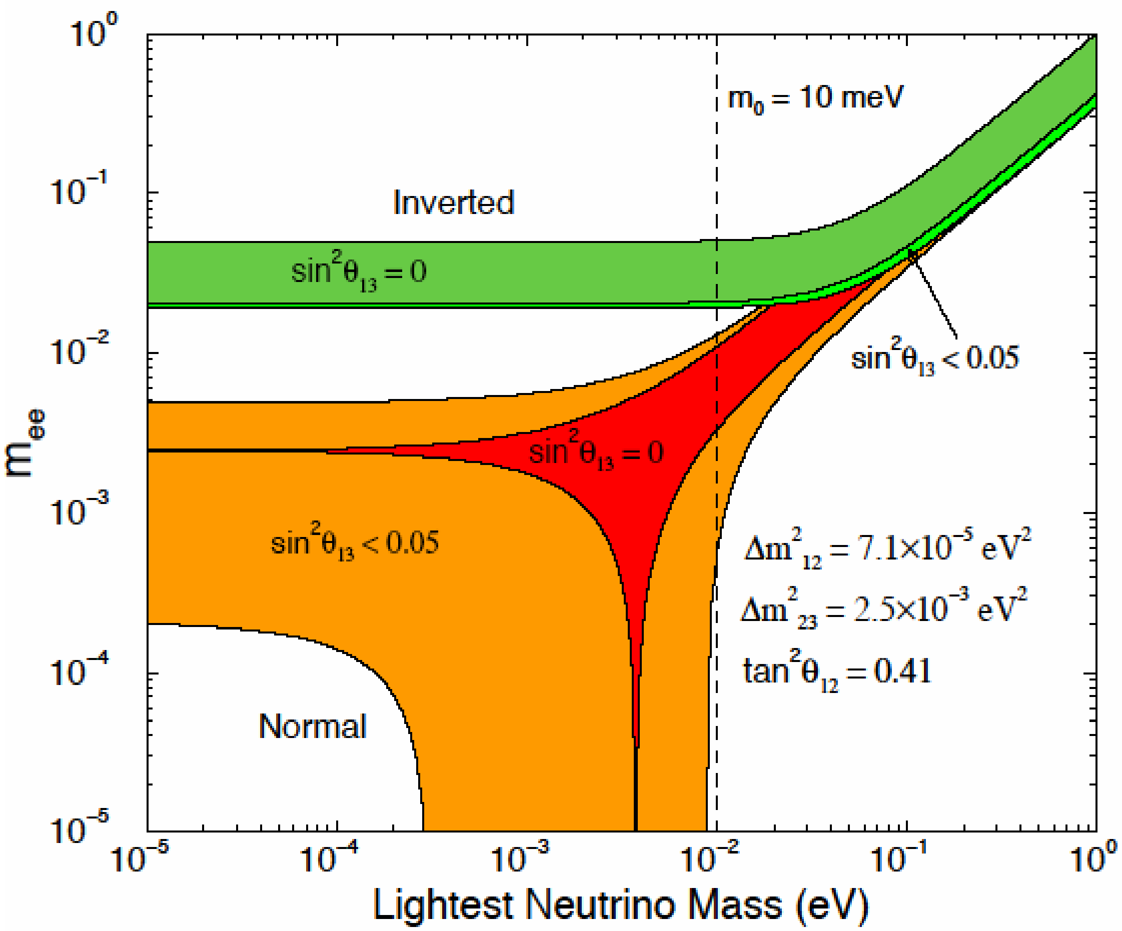
<== Cannot cancel out for nonmax. θ_{12}

Case of inverted mass hierarchy

Majorana phase?

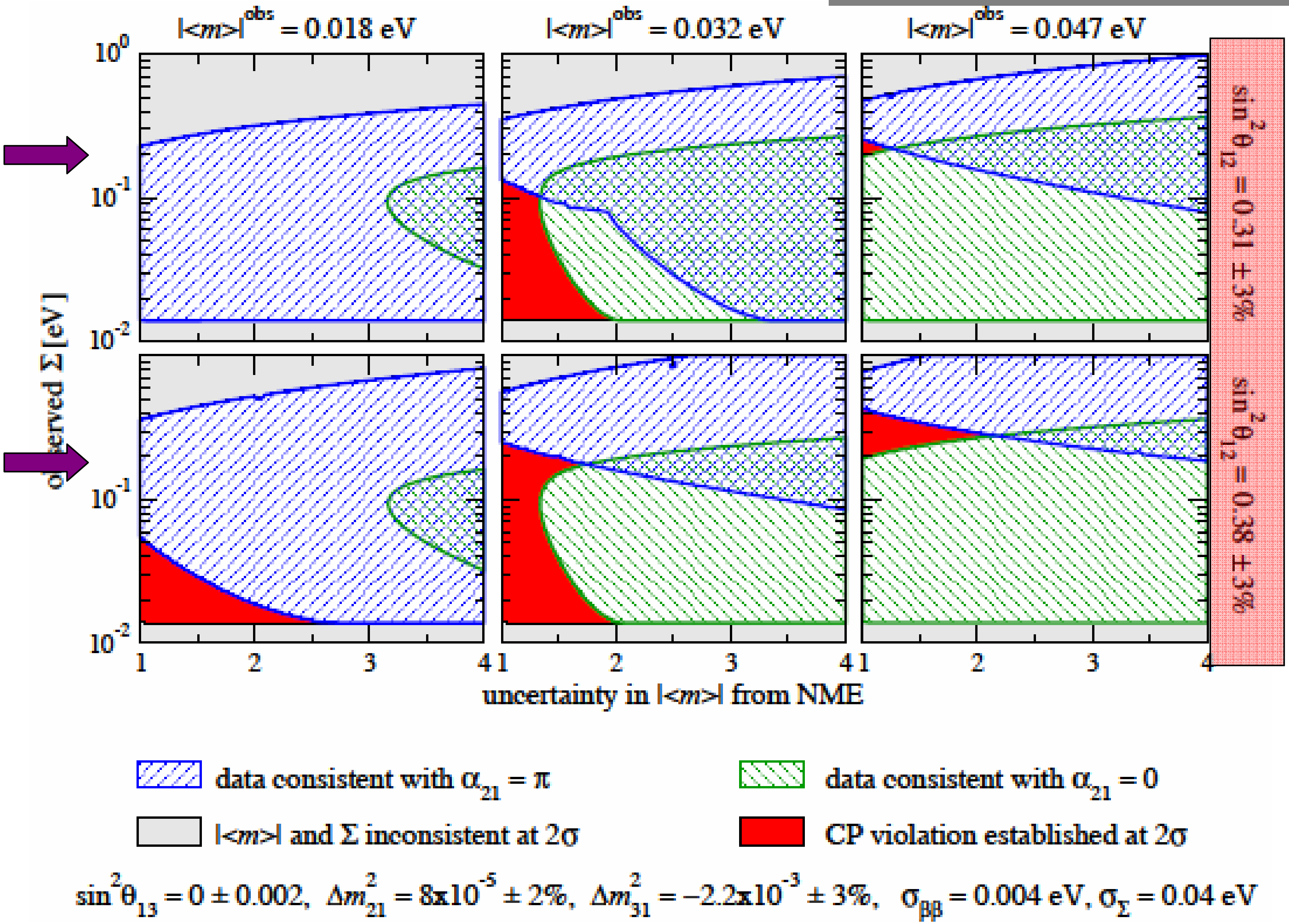
$$\langle m \rangle_{ee} = \left| c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Basics: Width of the band represents effect of CP phases

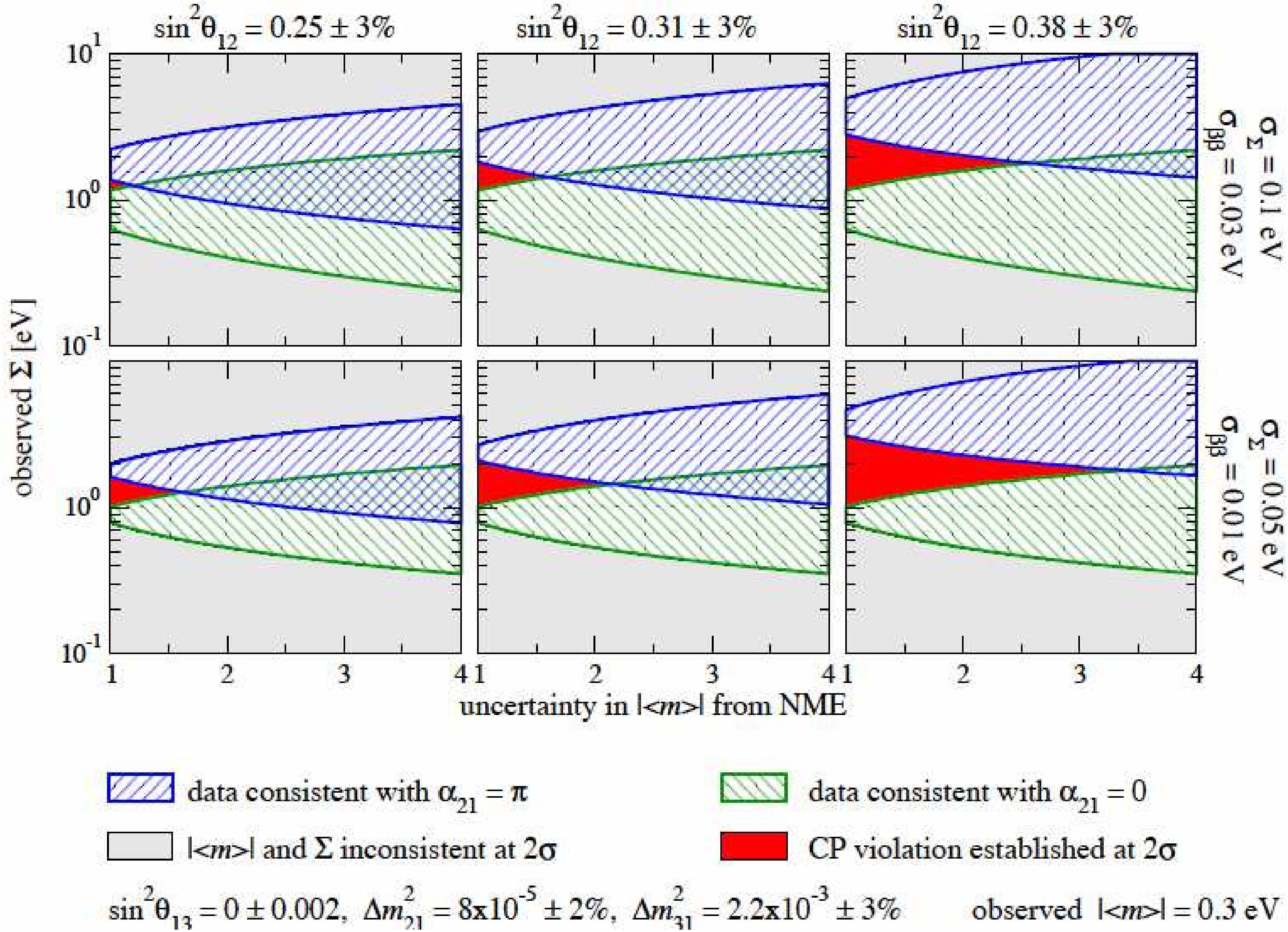


In real life, however, …

Pascoli-Petcov-Schwetz (PPS) hep-ph/0505226



Quasi degenerate case



What Majorana phase tell us; simple example

Leading-order neutrino mass matrix

Normal

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m3 \end{pmatrix} \Longleftrightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{m3}{2} & -\frac{m3}{2} \\ 0 & -\frac{m3}{2} & \frac{m3}{2} \end{pmatrix}$$

Inverted1

$$\begin{pmatrix} m2 & 0 & 0 \\ 0 & m2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Longleftrightarrow \begin{pmatrix} m2 & 0 & 0 \\ 0 & \frac{m2}{2} & \frac{m2}{2} \\ 0 & \frac{m2}{2} & \frac{m2}{2} \end{pmatrix}$$

Inverted2

$$\begin{pmatrix} m2 & 0 & 0 \\ 0 & -m2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Longleftrightarrow \begin{pmatrix} 0 & \frac{m2}{\sqrt{2}} & \frac{m2}{\sqrt{2}} \\ \frac{m2}{\sqrt{2}} & 0 & 0 \\ \frac{m2}{\sqrt{2}} & 0 & 0 \end{pmatrix}$$

$L_e - L_\mu - L_\tau$ symmetry!

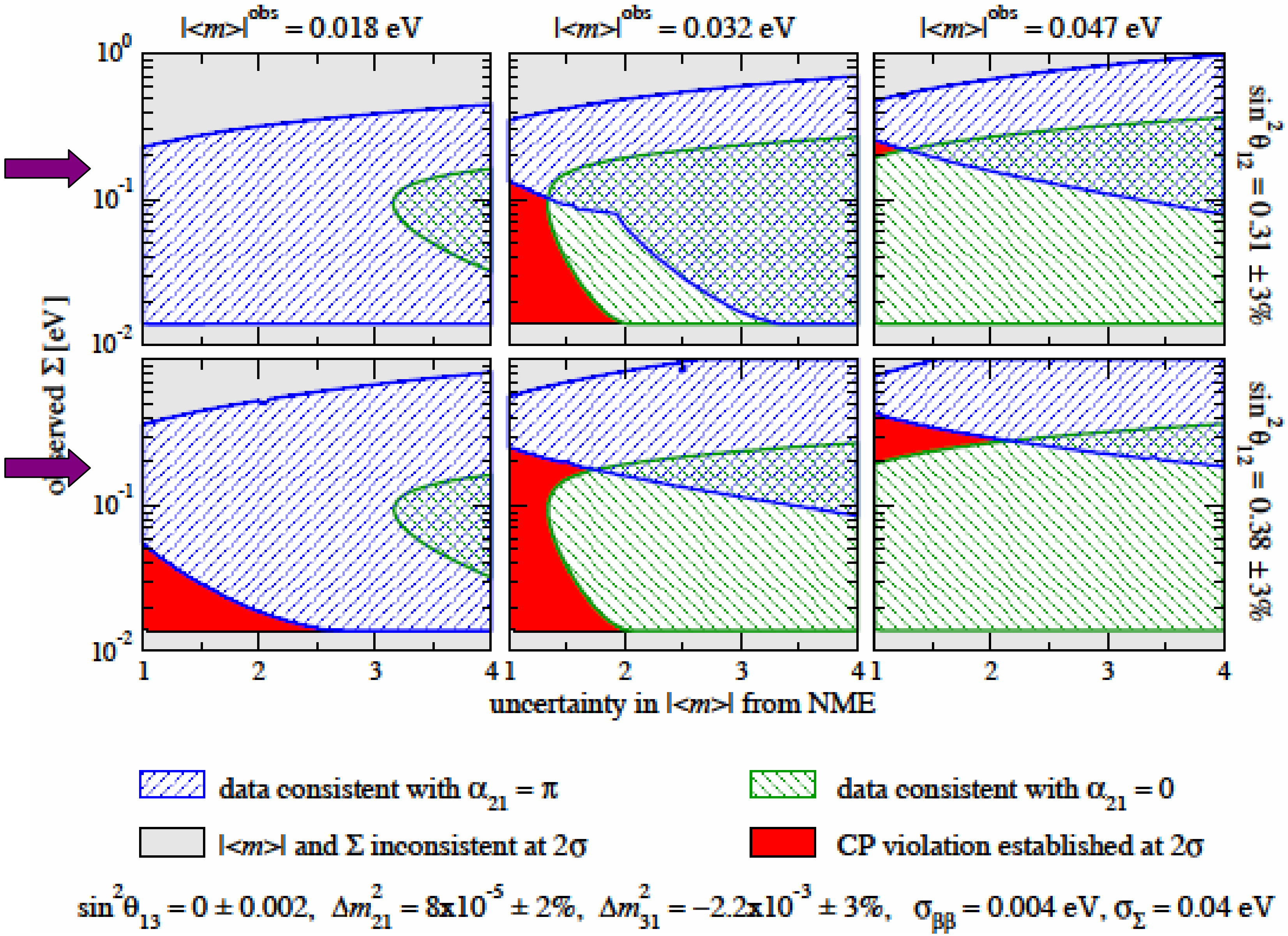
Perturbative correction does not alter CP parities

Normalized mass matrix $\widehat{\mathcal{M}}_\nu$	zero term $\widehat{\mathcal{M}}_\nu^{\rm atm}$	solar mass correction $\widehat{\mathcal{M}}_\nu^{\rm sol}$	QLC correction $\widehat{\mathcal{M}}_\nu^{\rm QLC}$	Eigenvalues
normal hierarchy	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} -4\lambda_\nu & 0 & 0 \\ 0 & \lambda_\nu & \lambda_\nu \\ 0 & \lambda_\nu & \lambda_\nu \end{bmatrix}$	$(0, \gamma, 1)$ $\gamma \approx \lambda$
inverted hierarchy with same CP parities	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} -2\lambda_\nu & 0 & 0 \\ 0 & \lambda_\nu & \lambda_\nu \\ 0 & \lambda_\nu & \lambda_\nu \end{bmatrix}$	$(1, (1+\gamma), 0)$ $\gamma \approx \lambda^2/2$
inverted hierarchy with opposite CP parities	$\begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix}$	$\frac{\gamma}{\sqrt{2}}\begin{bmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} \end{bmatrix}$	$\begin{bmatrix} 2\lambda_\nu & 0 & 0 \\ 0 & -\lambda_\nu & -\lambda_\nu \\ 0 & -\lambda_\nu & -\lambda_\nu \end{bmatrix}$	$(1, -(1+\gamma), 0)$ $\gamma \approx \lambda^2/2$

- Perturbative mass generation:
- $M_\nu = M_\nu^{\rm atm} + M_\nu^{\rm solar} + M_\nu^{\rm QLC}$

Ferrandis–Pakvasa 04

CP parity may be measured …



Lepto-genesis; attractive model for B generation

Leptogenesis

Fukugita-Yanagida 86

- Lepton # asymmetry generated by Majorana ν converted to baryon # asym. by "sphareleon"
- Offers interesting connection between neutrino mass and cosmological baryon number asymmetry
- Can give rise to bound on neutrino mass, $\sqrt{\sum m^2} < 0.3$ eV

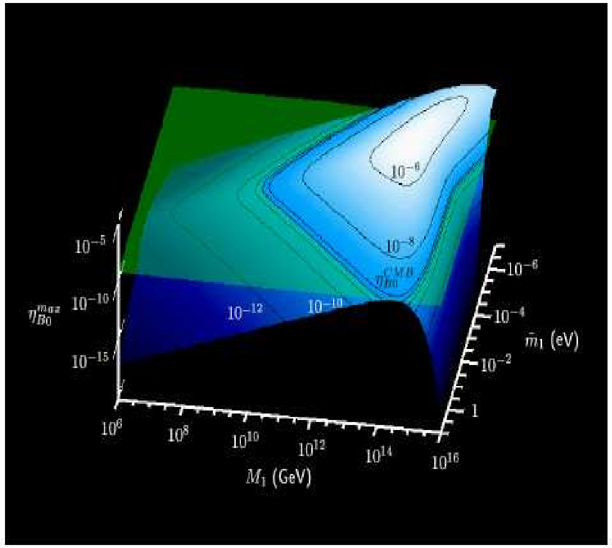
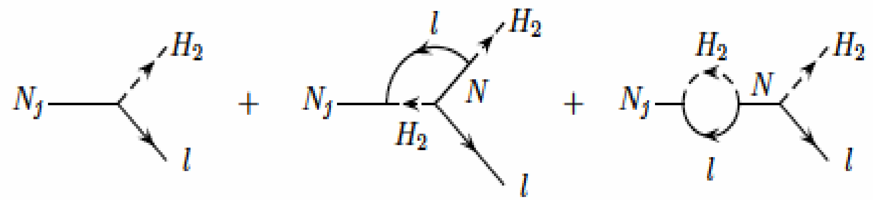


Figure 2: *Maximal baryon asymmetry* $\eta_{B0}^{\max}$ *(blue) as function of* $\tilde{m}_1$ *and* M_1 *for* $\overline{m} =$ 0.05 *eV. The black lines are curves of constant baryon asymmetry with the value indicated. The lines around the intersection with the green plane correspond to the measured value and the upper/lower limits at* 3σ.

(Buchmuller et al.)



Flavored leptogenesis

Abada et al. hep-ph/0605281

$$\epsilon_1 \equiv \frac{\sum_\alpha [\Gamma(N_1 \to H\ell_\alpha) - \Gamma(N_1 \to \bar{H}\bar{\ell}_\alpha)]}{\sum_\alpha [\Gamma(N_1 \to H\ell_\alpha) + \Gamma(N_1 \to \bar{H}\bar{\ell}_\alpha)]}$$

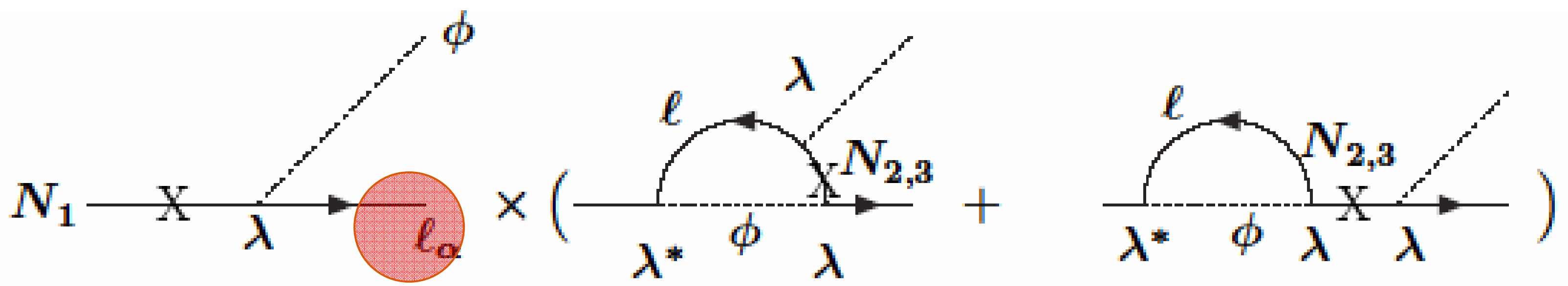
$$= -\frac{3M_1}{16\pi} \sum_{j\neq 1} \frac{\mathrm{Im}[(\lambda\lambda^\dagger)^2_{1j}]}{[\lambda\lambda^\dagger]_{11}} \frac{1}{M_j}.$$

If summed over α

$$= -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}(\sum_\rho m_\rho^2 R_{1\rho}^2)}{\sum_\beta m_\beta |R_{1\beta}|^2}.$$

If not

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$



Connecting low E CPV to leptogenesis

S. PASCOLI, S. T. PETCOV, AND ANTONIO RIOTTO

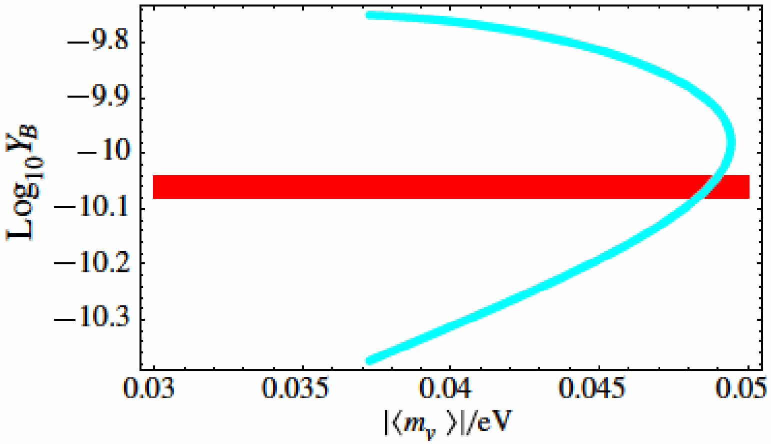


FIG. 2 (color online). The baryon asymmetry $|Y_B|$ versus the effective Majorana mass in neutrinoless double beta decay, $\langle m_\nu \rangle$, in the case of Majorana CP-violation, hierarchical RH neutrinos and IH light neutrino mass spectrum, for $\delta = 0$, $s_{13} = 0$, purely imaginary $R_{11}R_{12}$, $|R_{11}| = 1.05$ and $M_1 = 2 \times 10^{11}$ GeV. The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

- Under some assumptions of Casas-Ibarra matrix R

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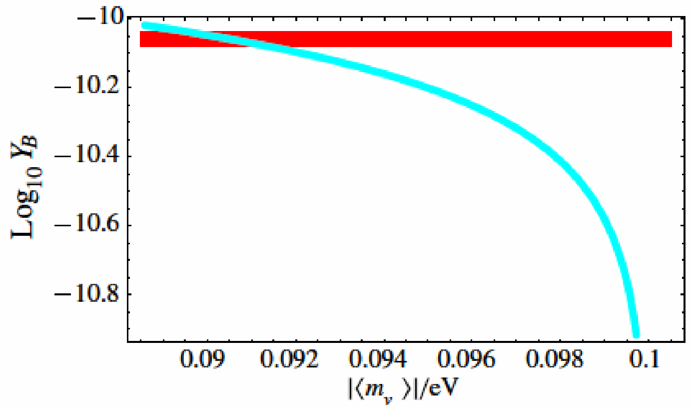


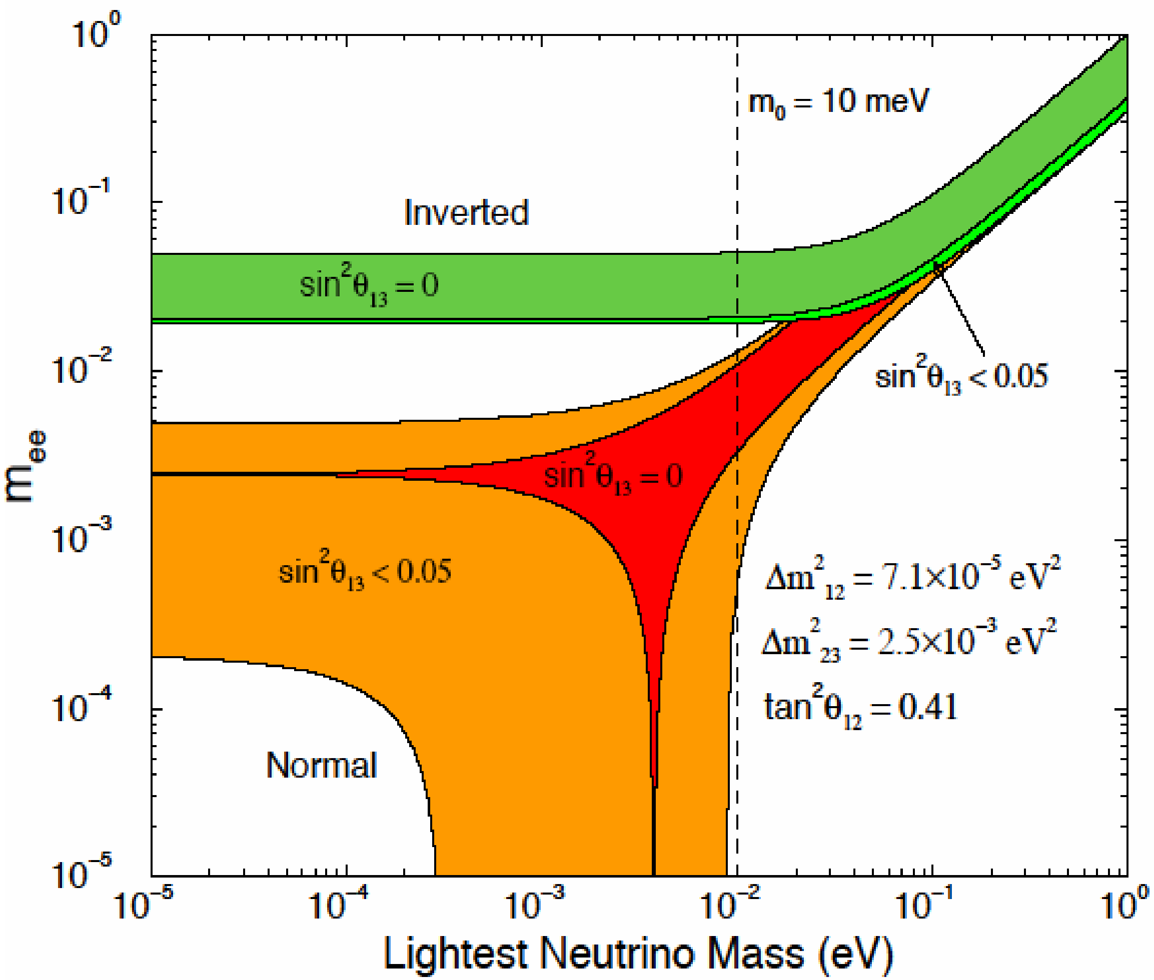
FIG. 3 (color online). The quantity $|\langle m_\nu \rangle|$ versus the baryon asymmetry varying α_{32} between 0 and $\pi/3$ for the case of degenerate RH neutrinos and QD for light neutrinos for $\delta = \pi/3$, $s_{13} = 0.01$, $M_1 = 10^{10}$ GeV and $m = 0.1$ eV.

Is inverted mass hierarchy discriminable?

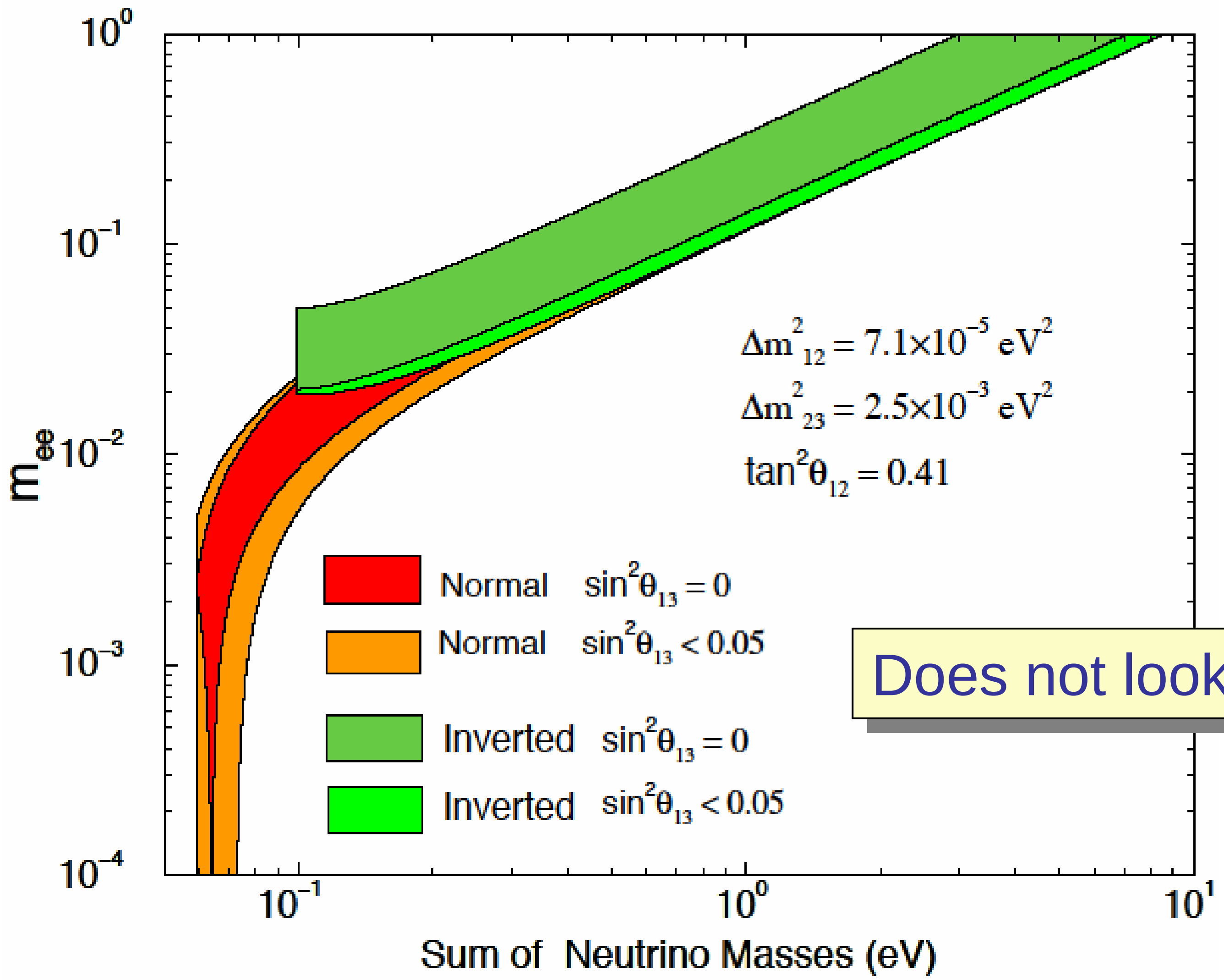
m_{ee} vs. lowest ν mass

$$\langle m\rangle_{ee} = \left|c_{12}^2 c_{13}^2 m_1 e^{i\phi_1} + s_{12}^2 c_{13}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Normal vs. inverted mass hierarchy looks discriminable

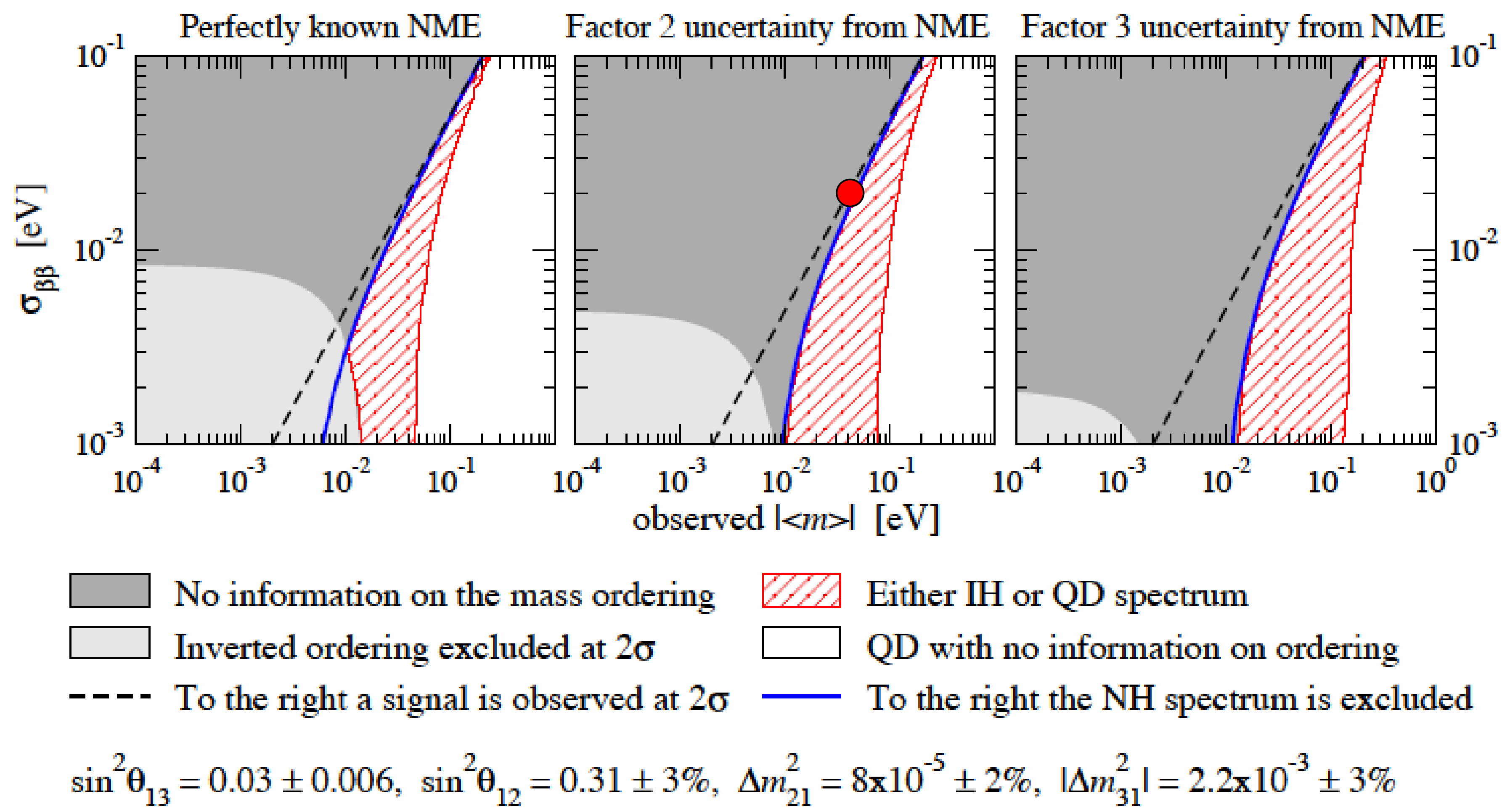


m_{ee} vs. sum of ν masses



Does not look like easy

To distinguish mass hierarchy …

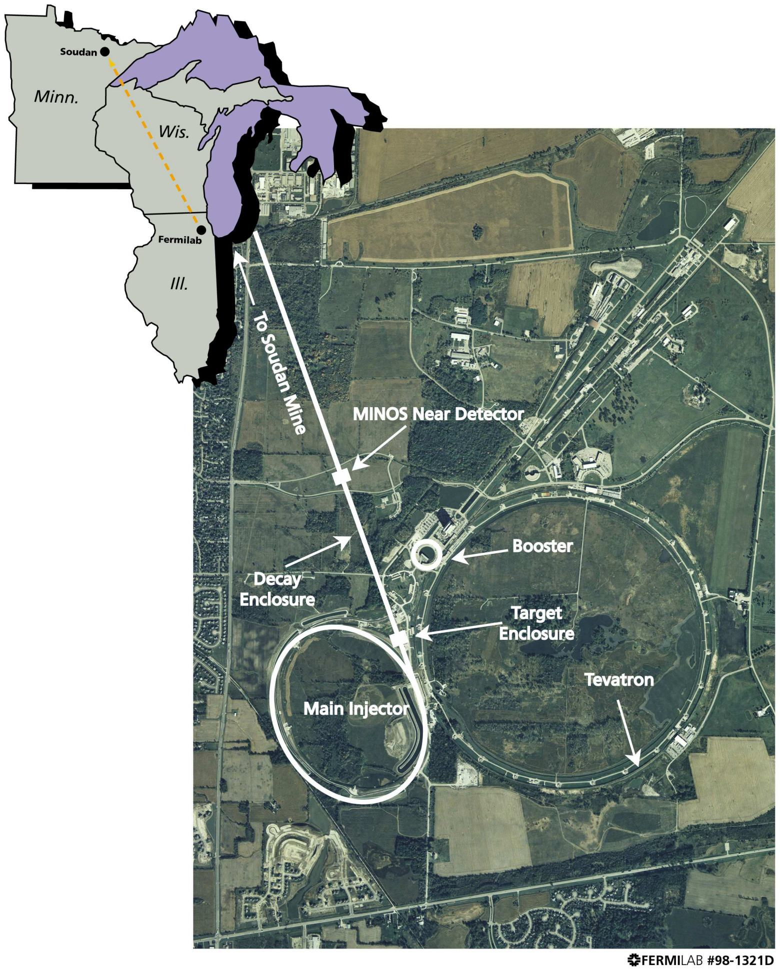


PPS hep-ph/0505226

Possible better strategy

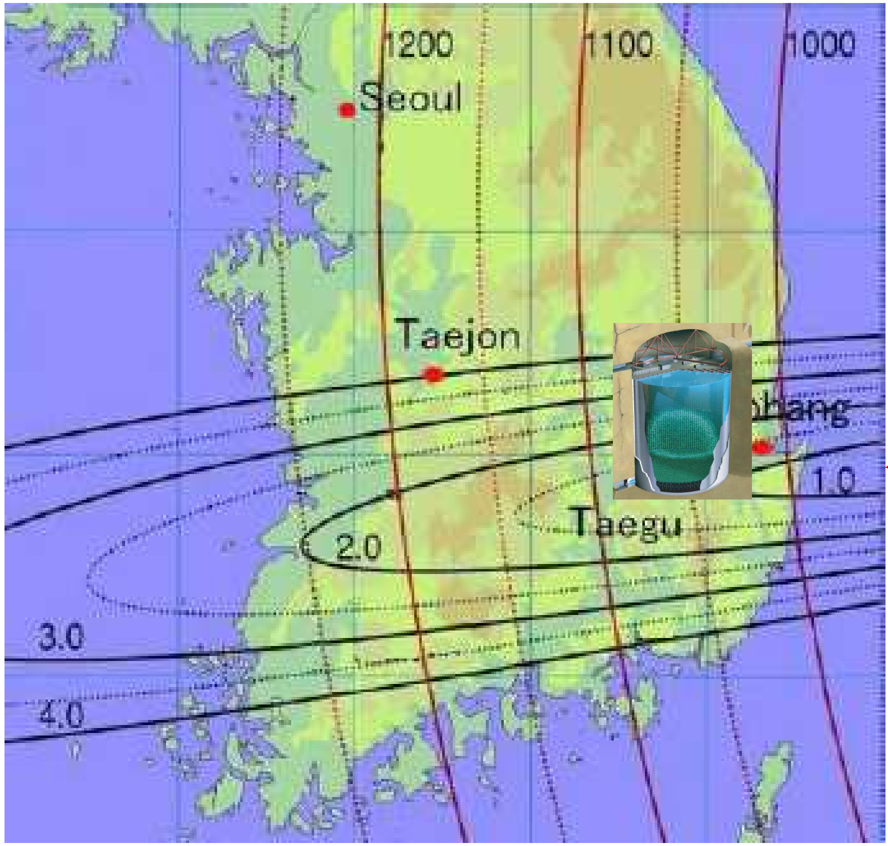
Better strategy (to my opinion)

- Determine hierarchy by some other methods and utilize DBD informations to ``get most''



Ongoing longest-baseline experiment MINOS

An example; T2KK;
Tokai to Kamioka-Korea



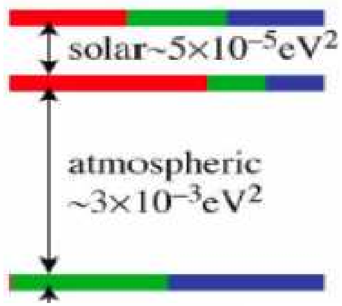
Ishitsuka-Kajita-HM-Nunokawa hep-ph/0504026

Signal at ~50 meV; what does it mean?

Inverted mass hierarchy without extra m_0

- m_0~0 can be inferred, e.g., by Planck satellite

$$\langle m \rangle_{ee} \approx \left| c_{12}^2 m_1 + s_{12}^2 m_2 e^{i(\phi_2 - \phi_1)} \right|$$



$$c_{12}^2 m_1 \simeq c_{12}^2 \sqrt{\Delta m_{atm}^2} \simeq 0.035\ eV$$
$$s_{12}^2 m_2 \simeq s_{12}^2 \sqrt{\Delta m_{atm}^2} \simeq 0.015\ eV$$
$$s_{13}^2 m_3 \simeq s_{13}^2 \sqrt{\Delta m_{\odot}^2} < 0.025 \times 9 \cdot 10^{-3} \simeq 2.2 \times 10^{-4}\ eV$$

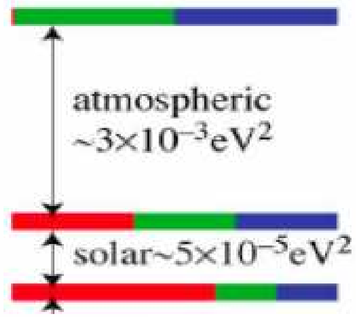
$$0.02\ eV < \sqrt{\Delta m_{atm}^2} \cos 2\theta_{12} < \langle m \rangle_{ee} < \sqrt{\Delta m_{atm}^2} = 0.05\ eV$$

Majorana phase may be measured

Signal at ~50 meV; what does it mean?

Normal mass hierarchy without extra m_0

$$\langle m \rangle_{ee} \approx \left| c_{12}^2 m_1 e^{i\phi_1} + s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$



$$c_{12}^2 m_1 \simeq c_{12}^2 \sqrt{\Delta m_\odot^2} \simeq (6.2 \times 10^{-3} \leftrightarrow 0.0)\ eV$$

$$s_{12}^2 m_2 \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 2.7 \times 10^{-3}\ eV$$

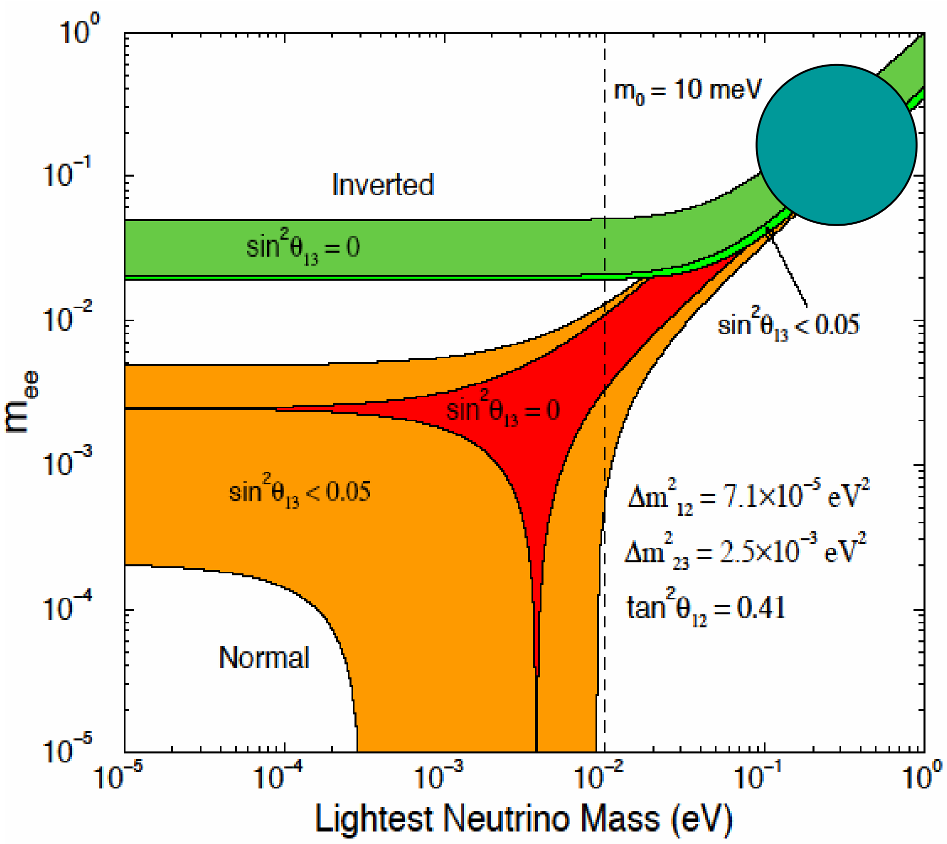
$$s_{13}^2 m_3 \simeq s_{13}^2 \sqrt{\Delta m_{atm}^2} \approx 0.025 \times 0.05\ eV \simeq 1.3 \times 10^{-3}\ eV$$

$$0\ eV < \langle m \rangle_{ee} \sim (\text{a few - several})\ meV < \sqrt{\Delta m_\odot^2} = 0.01\ eV$$

- Definitely implies extra mass scale m_0
- Harder to obtain Majorana phase information

Degenerate ν mass

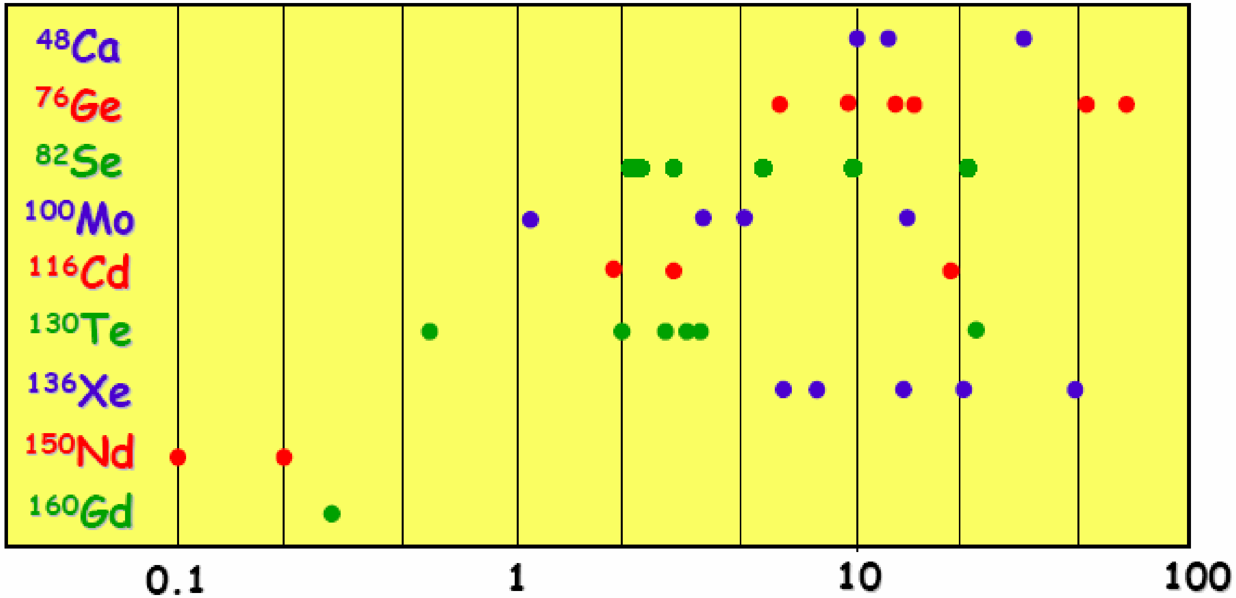
Experimentally the clearest situation !



- If m_{ee} discovered in "degenerate mass region" (as claimed by Klapdor et al) it implies that there is new mass scale >> sqrt{Δm^2_{atm}}
- => most probably new scale different from GUT

Uncertainty of nuclear matrix elements

0νββ decay half lives in 10^{26} yr units for $\langle m_\nu \rangle$ = 50 meV
according to different nuclear matrix element calculations



[adapted from S.R.Elliott & P.Vogel Ann. Rev. Nucl. Part. Sci. 52 (2002) 115]

Unfortunately it is not trivial to use the 2ν matrix element to normalize the 0ν one:

- $|M_{2\nu}|$ – has stronger dependence on intermediate states
- $|M_{0\nu}|$ – all multipoles contribute
  - – ν propagator results in long range potential

Now, we have hope

Sensitivity to g_{pp} partially cancel if normalized by 2ν decay; Rodin-Faessler-Simkovic-Vogel, nucl-th/0503063

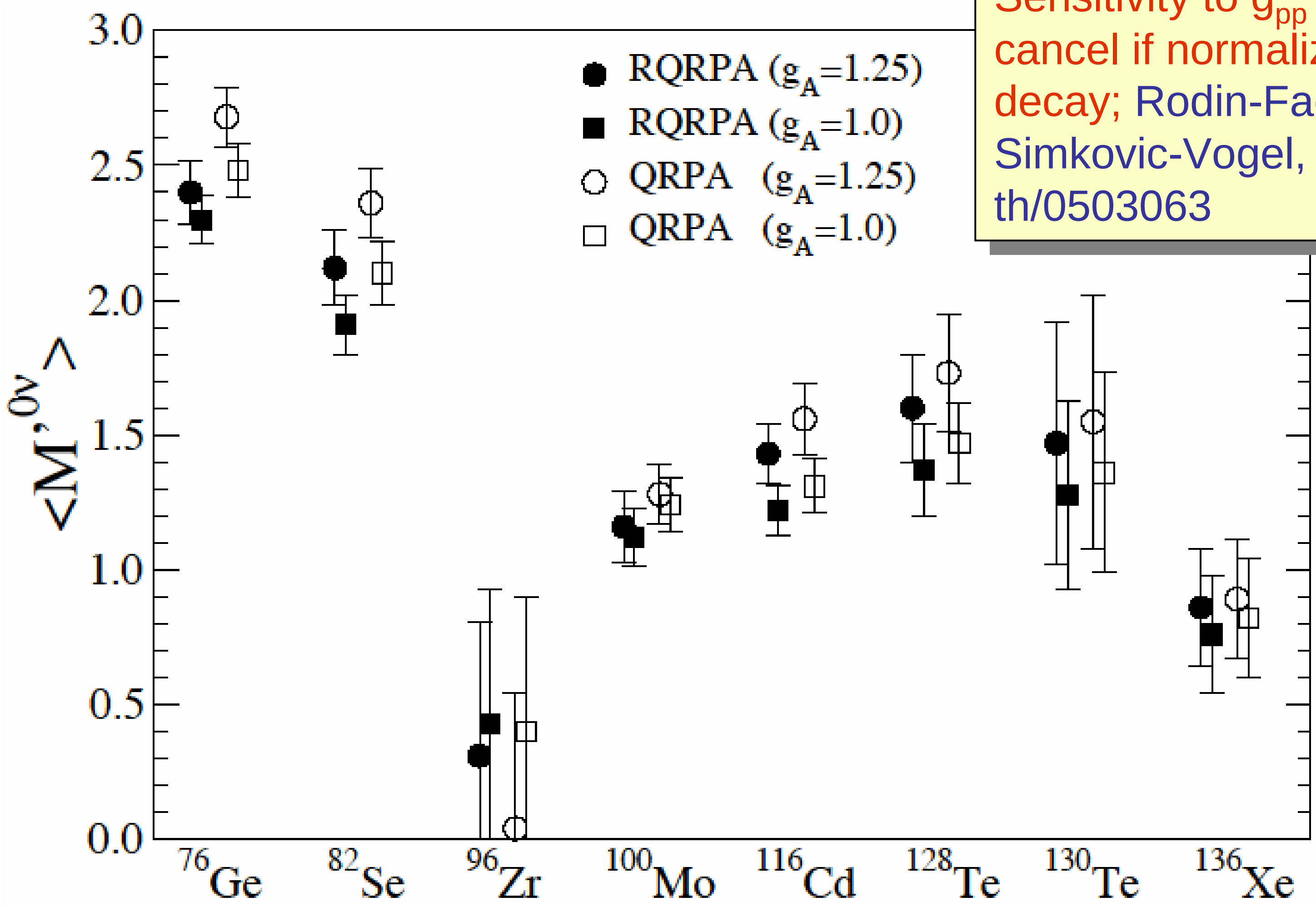
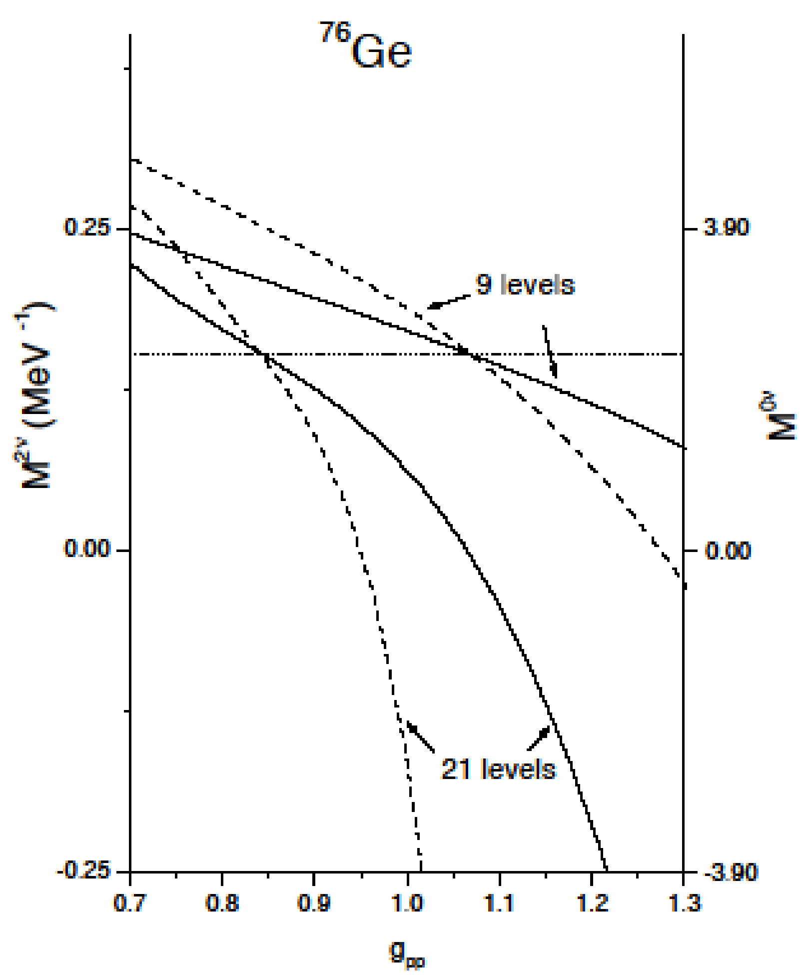
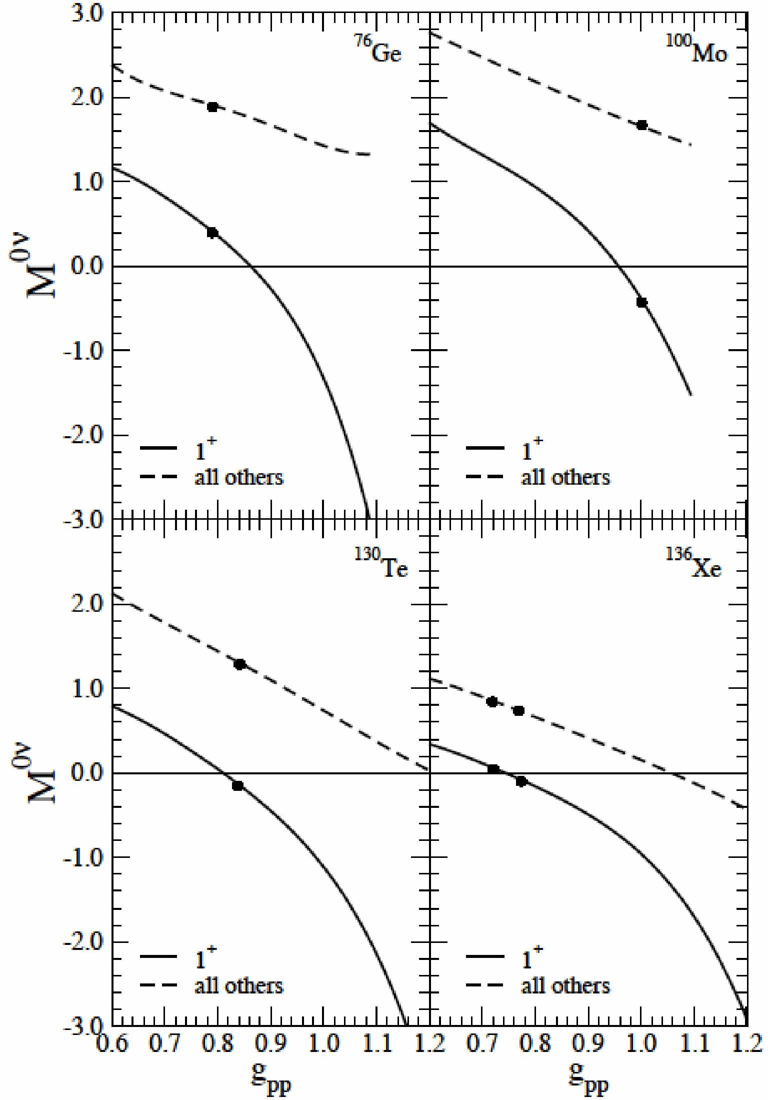


FIG. 2: Average nuclear matrix elements $\langle M'^{0\nu}\rangle$ and their variance (including the error coming from the experimental uncertainty in $M^{2\nu}$) for both methods and for all considered nuclei. For ^{136}Xe the error bars encompass the whole interval related to the unknown rate of the $2\nu\beta\beta$ decay.

Sensitivity to g_{pp} cancel against its 2ν counterpart





Shell model vs. QRPA

TABLE XVII Calculated $T^{2\nu}_{1/2}$ half-lives for several nuclei and $0^+ \to 0^+$ transitions

Parent	^{48}Ca	^{76}Ge	^{82}Se
$T^{2\nu}_{1/2}$ th.(y)	3.7×10^{19}	2.6×10^{21}	3.7×10^{19}
$T^{2\nu}_{1/2}$ exp.(y)	4.3×10^{19}	1.8×10^{21}	8.0×10^{19}

TABLE XVIII 0ν matrix elements and upper bounds on the neutrino mass for $T^{0\nu}_{1/2} \geq 10^{25}$ y. $\langle m_\nu \rangle$ in eV.

Parent	^{48}Ca	^{76}Ge	^{82}Se
$M^{0\nu}_{GT}$	0.63	1.58	1.97
$M^{0\nu}_{F}$	-0.09	0.19	-0.22
$\langle m_\nu \rangle$	0.94	1.33	0.49

Caurier et al., nucl-th/0402046

$M^{0\nu}$: Shell model: 1.5, 2.1, 1.1, and 0.7 for ^{76}Ge, ^{82}Se, ^{130}Te and ^{136}Xe,

$M^{0\nu}$: RQRPA 2.4, 2.1, 1.5, and 0.7-1.0

Conclusion

- $0\nu\beta\beta$ decay: unique for demonstrating Majorana ν + indispensible for absolute mass determination
- Majorana phase or CP parity important for understanding physics
- Uncertainty of nuclear matrix elements = most important problem for interpretation of the results
- Gives great opportunity in the future (with LBL experiments)

Seesaw mechanism as a paradigm of neutrino mass

Minkowski, Yanagida, Gell-Mann-Ramond-Slansky, …

- $W = N^c Y_\nu LH - E^c Y_\nu LH + (1/2) N^c MN$

(N=R-handed Majorana, L=left doublet, E=charged lepton, H=higgs)

- $m_\nu = Y_\nu^T (M_{diag})^{-1} Y_\nu$
- Y_ν has 6 phases
- Leptogenesis is sensitive to $Y_\nu Y_\nu^+$ (3 left phases, independent of low energy CPV phase)
- CP violating LFV appears from $Y_\nu^+ Y_\nu$ (1 right phase)