Predictions for and Implications of $0\nu\beta\beta$

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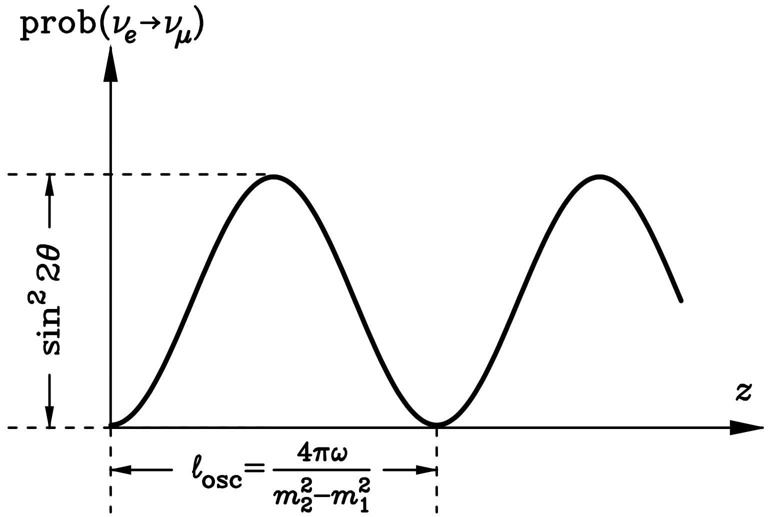
- Neutrino Mixing and $0\nu\beta\beta$
- $|m_{ee}|$ and NH vs. IH
- $|m_{ee}|$ and $|U_{e3}|$
- What's more to $0\nu\beta\beta$
- If we don't observe $0\nu\beta\beta$: vanishing effective mass
- If we observe $0\nu\beta\beta$ ...

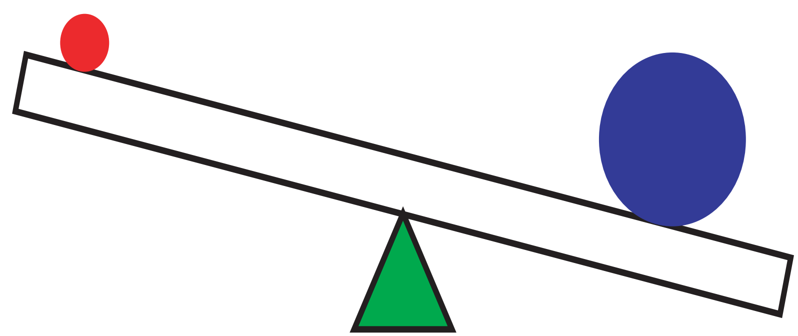
Status and goal of neutrino physics

understand form and origin of

fundamental object in low energy Lagrangian:

$$\mathcal{L} = \frac{1}{2}\,\overline{\nu^c_\alpha}\,(m_\nu)_{\alpha\beta}\,\nu_\beta + h.c. \text{ with } m_\nu = U^T\,\mathrm{diag}(m_1, m_2, m_3)\,U$$





$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta\,\sin^2 \tfrac{\Delta m^2}{4E}\,L$$

Oscillations!

Masses?

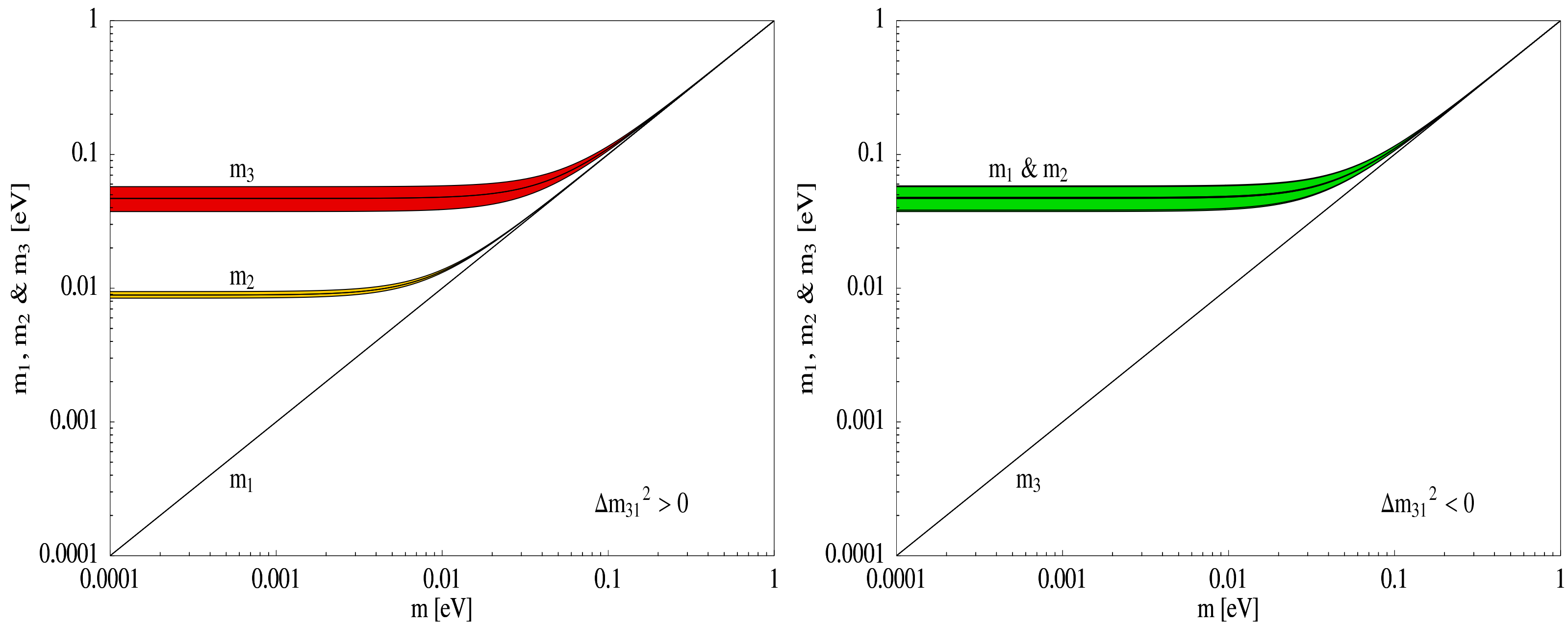
$$m_\nu = -m_D^T\,M_R^{-1}\,m_D$$

See-saw!

Lepton Number Violation?

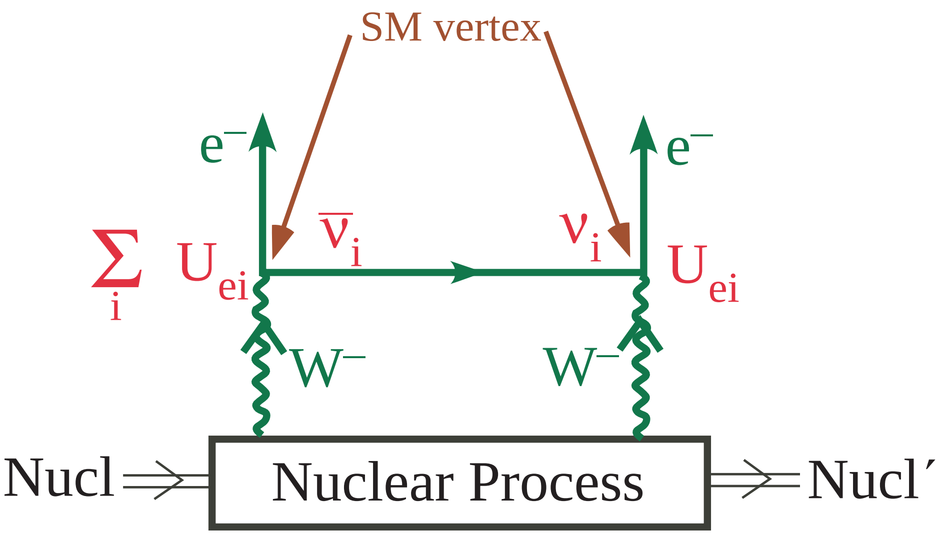
Neutrino masses

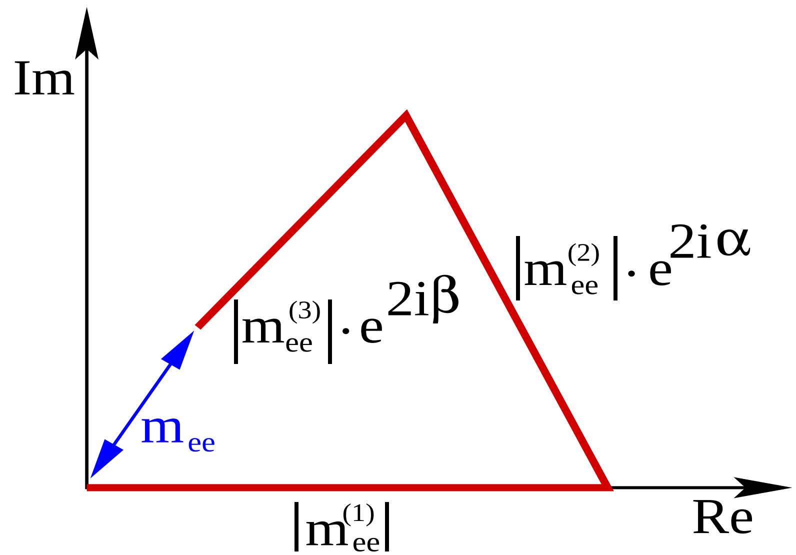
- 9 parameters in m_ν; we only know θ_{12} and θ_{23}
- neutrino masses $\leftrightarrow$ scale of their origin
- neutrino mass ordering $\leftrightarrow$ form of m_ν



- $m_3^2 \simeq \Delta m_{\rm A}^2 \gg m_2^2 \simeq \Delta m_\odot^2 \gg m_1^2$: normal hierarchy (NH)
- $m_2^2 \simeq |\Delta m_{\rm A}^2| \simeq m_1^2 \gg m_3^2$: inverted hierarchy (IH)
- $m_3 \simeq m_2 \simeq m_1 \equiv m_0 \gg \sqrt{\Delta m_{\rm A}^2}$: quasi–degeneracy (QD)

$\Delta L \neq 0$: Neutrinoless Double Beta Decay





- only works when $\nu = \nu^c$ **and** $m_\nu \neq 0 \Leftrightarrow$ See–saw mechanism
- Nuclear Matrix Elements: Uncertainty $\zeta = \mathcal{O}(1)$!?

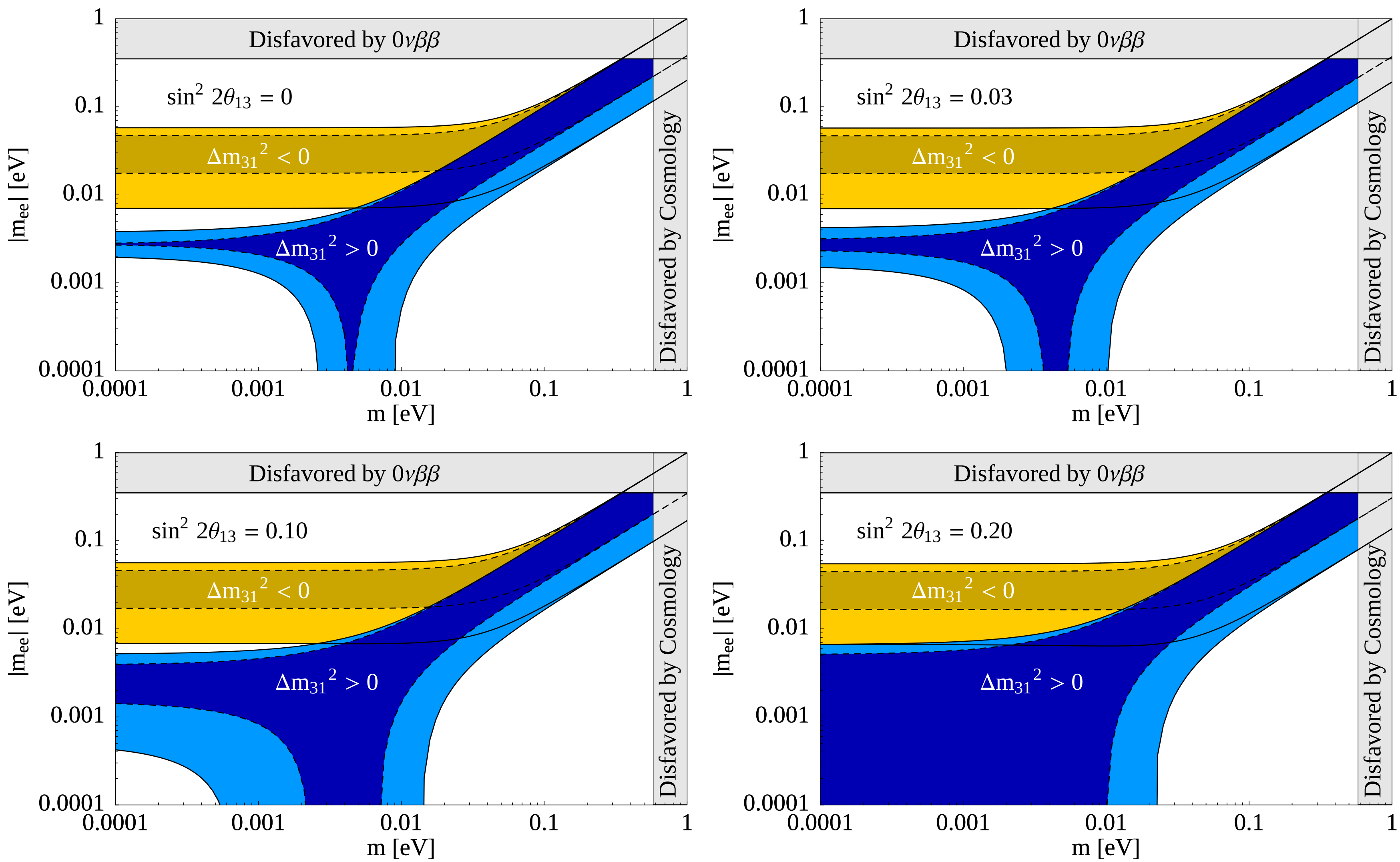
Amplitude proportional to coherent sum (“Effective mass” $|m_{ee}|$):

$$|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{2i\alpha} + s_{13}^2\, m_3\, e^{2i\beta}\right|$$

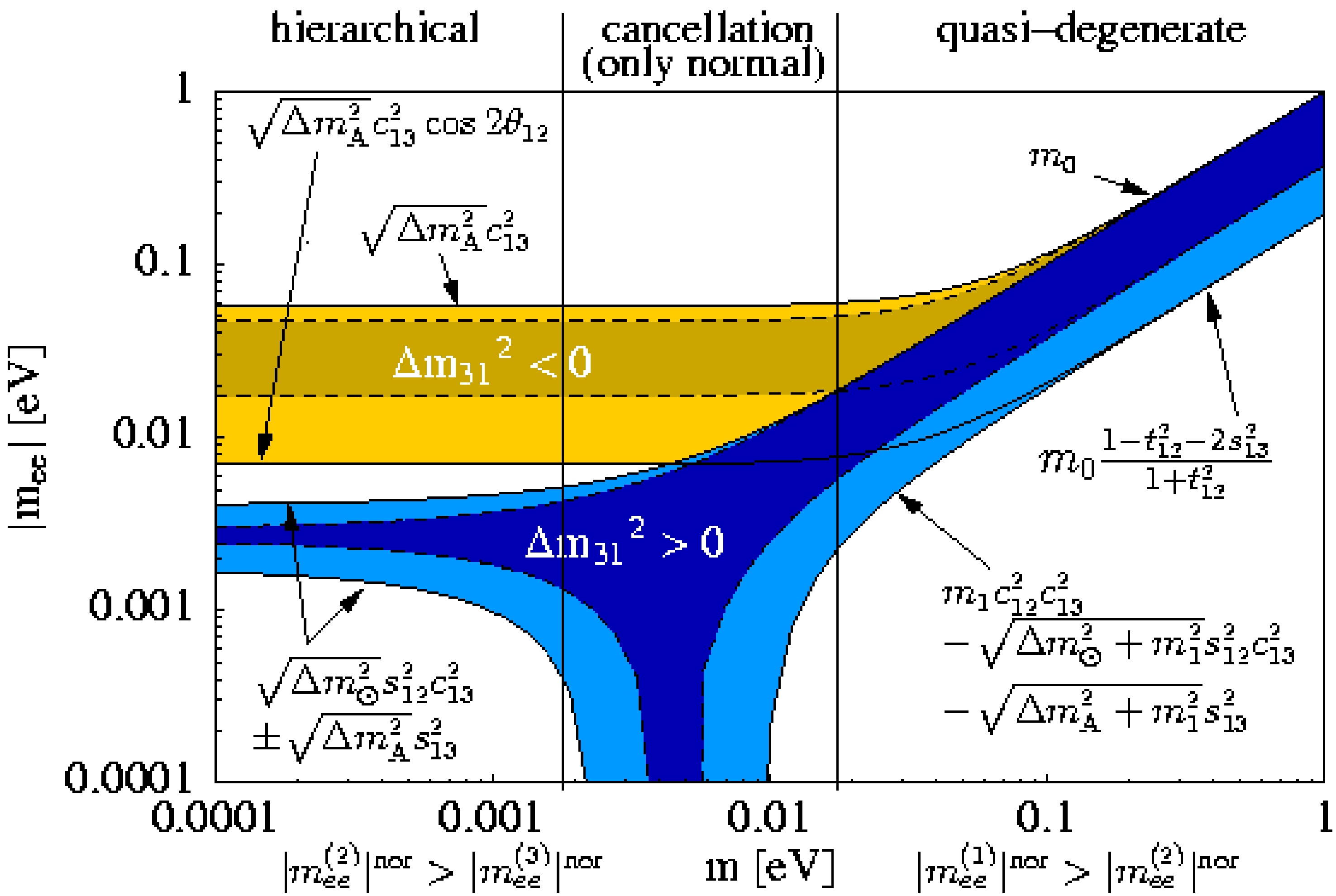
$$= \left||m_{ee}^{(1)}| + |m_{ee}^{(3)}|\, e^{2i\alpha} + |m_{ee}^{(3)}|\, e^{2i\beta}\right| = f\left(\theta_{12}, m_i, |U_{e3}|, \mathrm{sgn}(\Delta m_\mathrm{A}^2), \alpha, \beta\right)$$

7 out of 9 parameters of $m_\nu \ldots$

Kim, 1996; Minakata & Yasuda, 1996; Hirsch & Klapdor-Kleingrothaus, 1997; Bilenky, Giunti & Monteno, 1997; Fukuyama, Matsuda & Nishiura, 1997; Bilenky, Giunti, Kim & Monteno, 1998; Fukuyama, Matsuda & Nishiura, 1998; Vissani, 1999; Giunti, 1999; Bilenky, Giunti, Grimus, Kayser & Petcov, 1999; Ma, 1999; Wodecki & Kaminsky, 2000; Kalliomaki & Maalampi, 2000; Rodejohann, 2000; Matsuda, Takeda, Fukuyama & Nishiura, 2000; Klapdor-Kleingrothaus, Päs & Smirnov, 2001; Falcone & Tramontano, 2001; Bilenky, Pascoli & Petcov, 2001; Xing, 2001; Osland & Vigdel, 2001; Pascoli & Petcov, 2001; Barger, Glashow, Marfatia & Whisnant, 2002; Hambye, 2002; Minakata & Sugiyama, 2002; Klapdor-Kleingrothaus & Sarkar, 2002; Xing, 2002; Haba & Suzuki, 2002; Pakvasa & Roy, 2002; Rodejohann, 2002; Haba, Nakamura & Suzuki, 2002; Päs & Weiler, 2002; Barger, Glashow , Langacker, Marfatia, 2002; Civitarese & Suhonen, 2002; Pascoli, Petcov & Rodejohann, 2002; Sugiyama, 2002; Avignone & King, 2002; Minakata & Sugiyama, 2002; Cheung, 2003; Abada & Bhattacharyya, 2003; Giunti, 2003; Pascoli & Petcov, 2003; Elliott, 2003; Stoica, 2004; Brahmachari, 2004; Bilenky, Fäßler & Simkovic, 2004; Pascoli & Petcov; 2004; Deppisch, Päs & Suhonen, 2004; Joniec & Zralek, 2004; Pascoli & Petcov, 2005; Pascoli, Petcov & Schwetz, 2005; Goswami & Rodejohann, 2005; Choubey & Rodejohann, 2005; Bilenky, Fäßler, Gutsche, & Simkovic, 2005; Lindner, Merle & Rodejohann, 2005;



Our plots are blue and yellow. . .



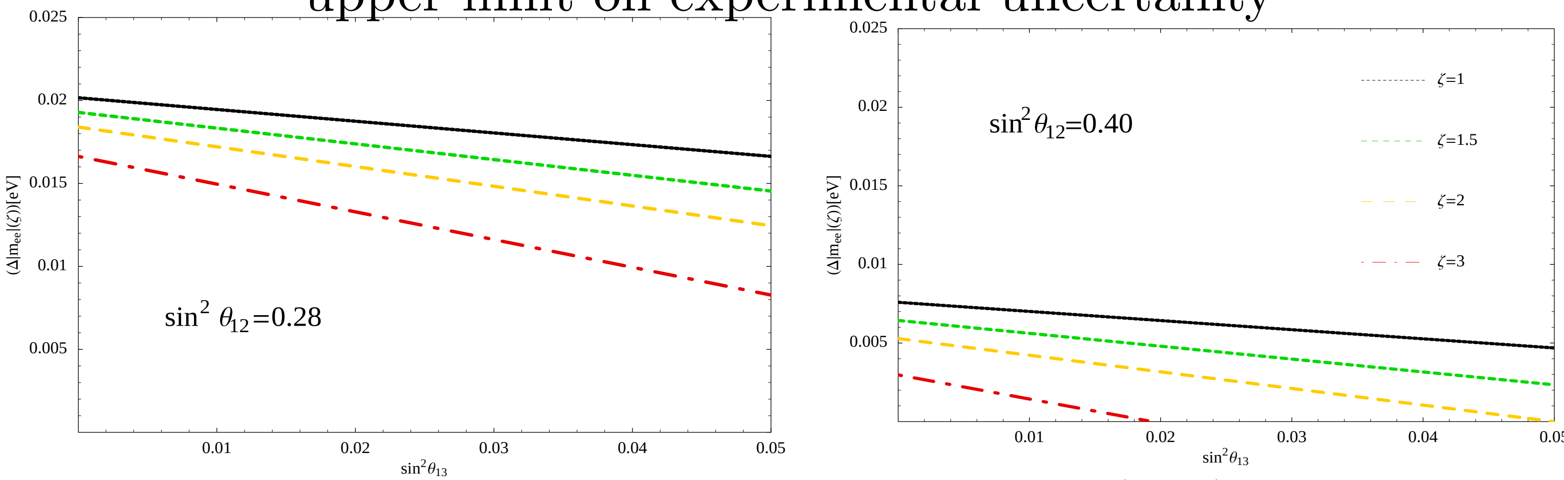
Lindner, Merle, W.R., Phys. Rev. D **73**, 053005 (2006)

Distinguish NH from IH?!

Normal vs. Inverted Hierarchy vs. Nuclear Physics

$$\Delta|m_{ee}| \equiv |m_{ee}|^{\rm IH}_{\rm MIN} - \zeta \, |m_{ee}|^{\rm NH}_{\rm MAX} \stackrel{!}{>} 0$$

upper limit on experimental uncertainty



Lindner, Merle, W.R., PRD **73**, 053005 (2006);

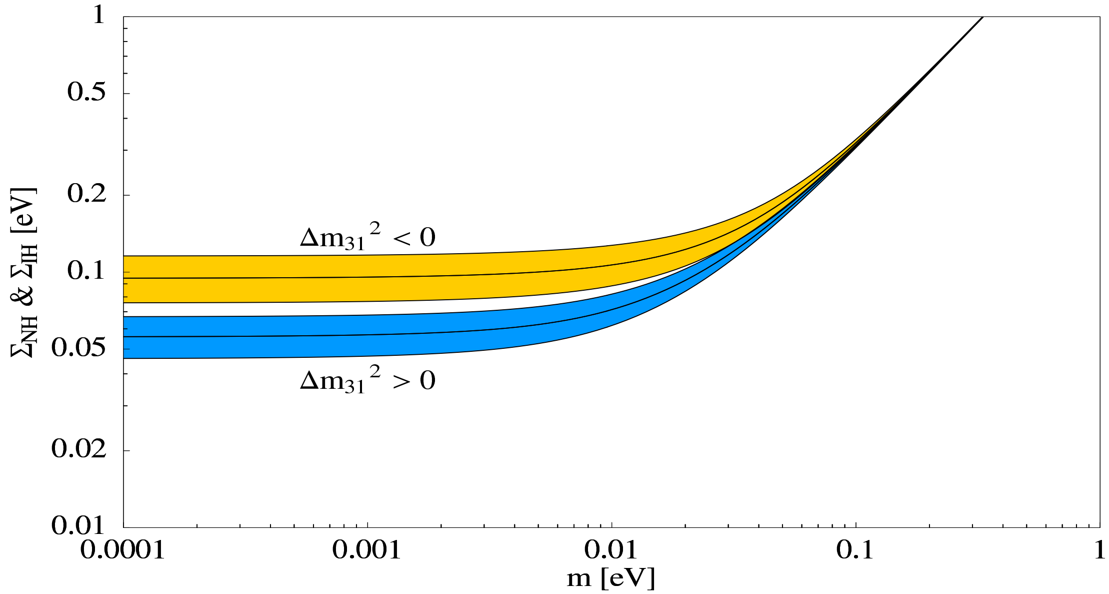
S. Choubey, W.R.; Pascoli, Petcov, Schwetz; de Gouvea, Jenkins

- likes $\zeta \lesssim 2$
- strong dependence on θ_{12}: likes small $\sin^2\theta_{12} \lesssim 0.35$
- some dependence on U_{e3}: prefers small U_{e3} ($\leftrightarrow$ oscillations)

Other (non-oscillation) probes of NH vs. IH

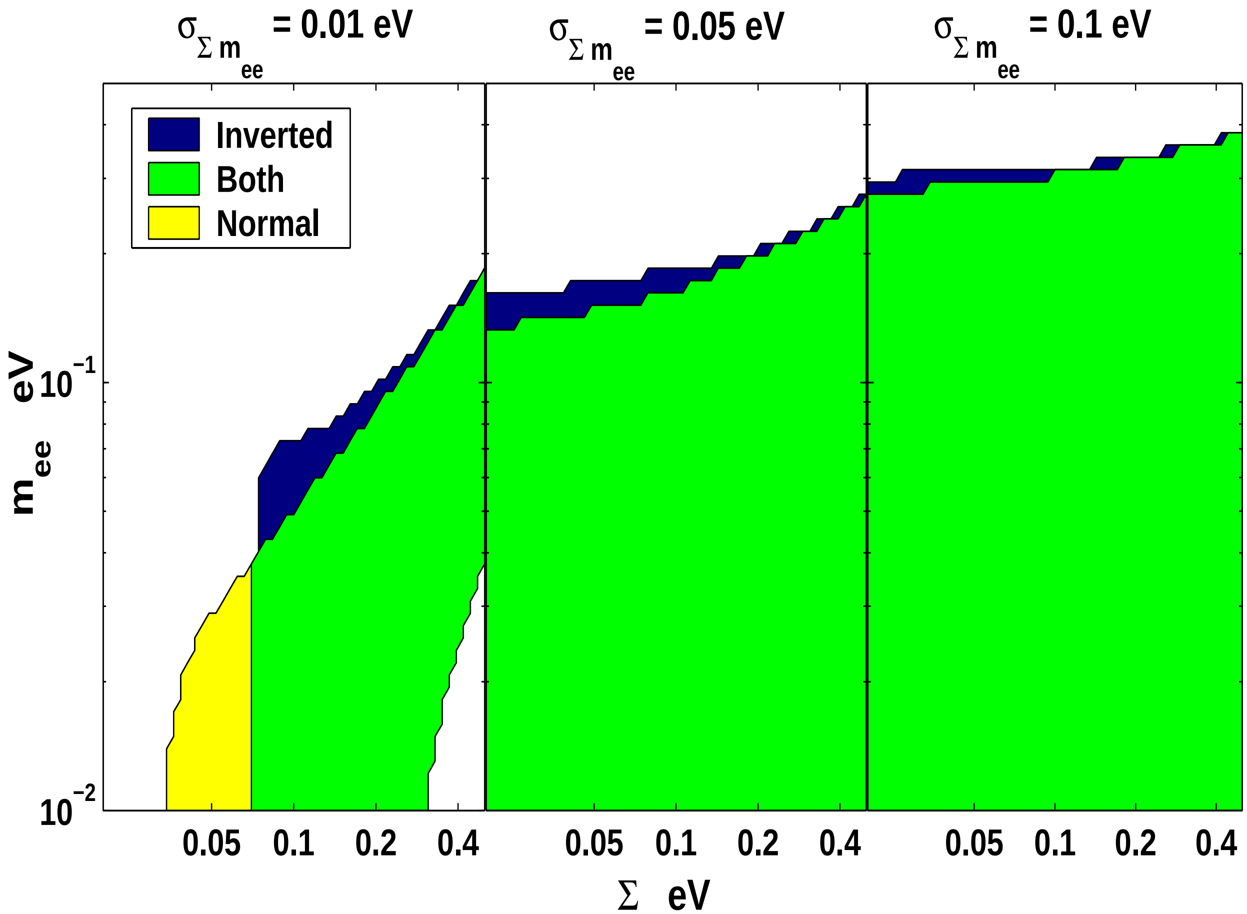
1) Cosmology: $\Sigma = \sum m_i$

$$\Sigma^{\rm NH} \simeq \sqrt{\Delta m^2_{\rm A}} < \Sigma^{\rm IH} \simeq 2\sqrt{\Delta m^2_{\rm A}}$$



- independent on mixing angles
- systematics?

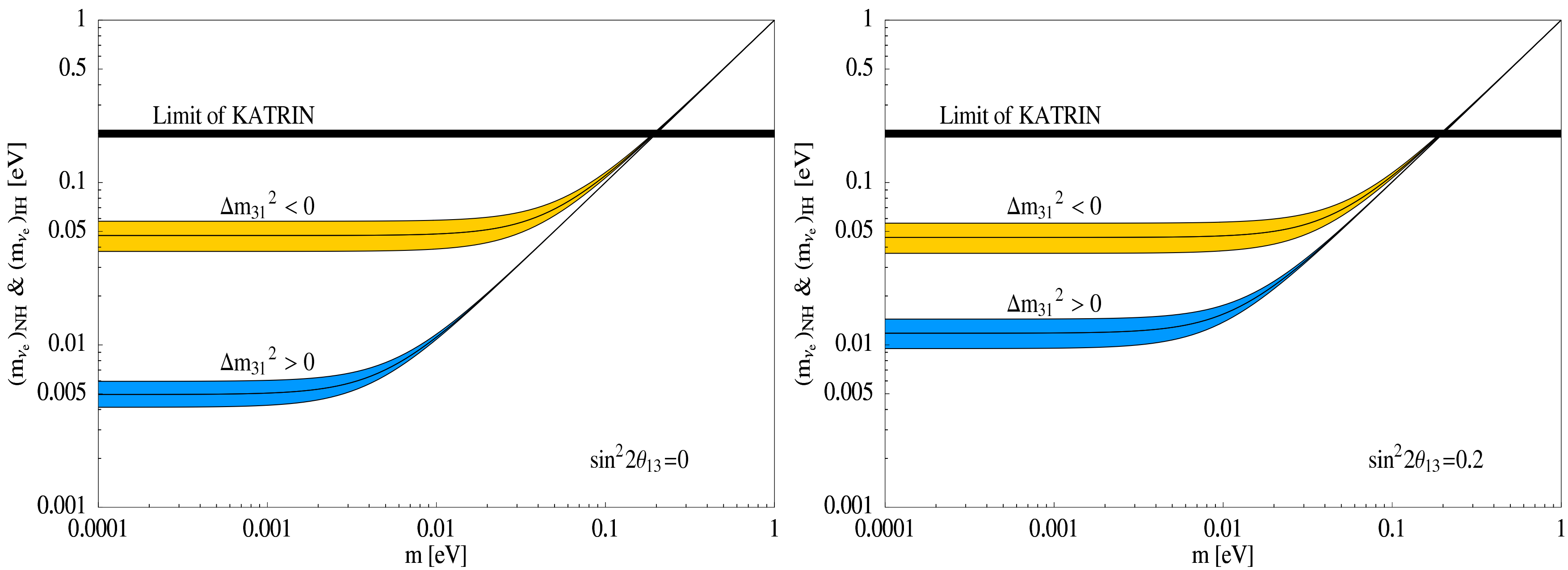
Cosmology and $0\nu\beta\beta$



Jenkins, de Gouvea, hep-ph/0507021

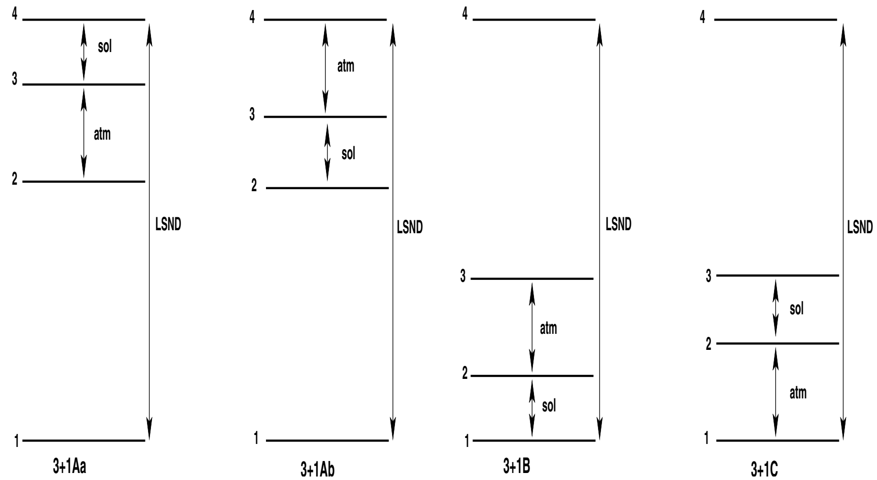
2) β-decay: $m_{\nu_e} = \sqrt{\sum |U_{ei}|^2 \, m_i^2}$

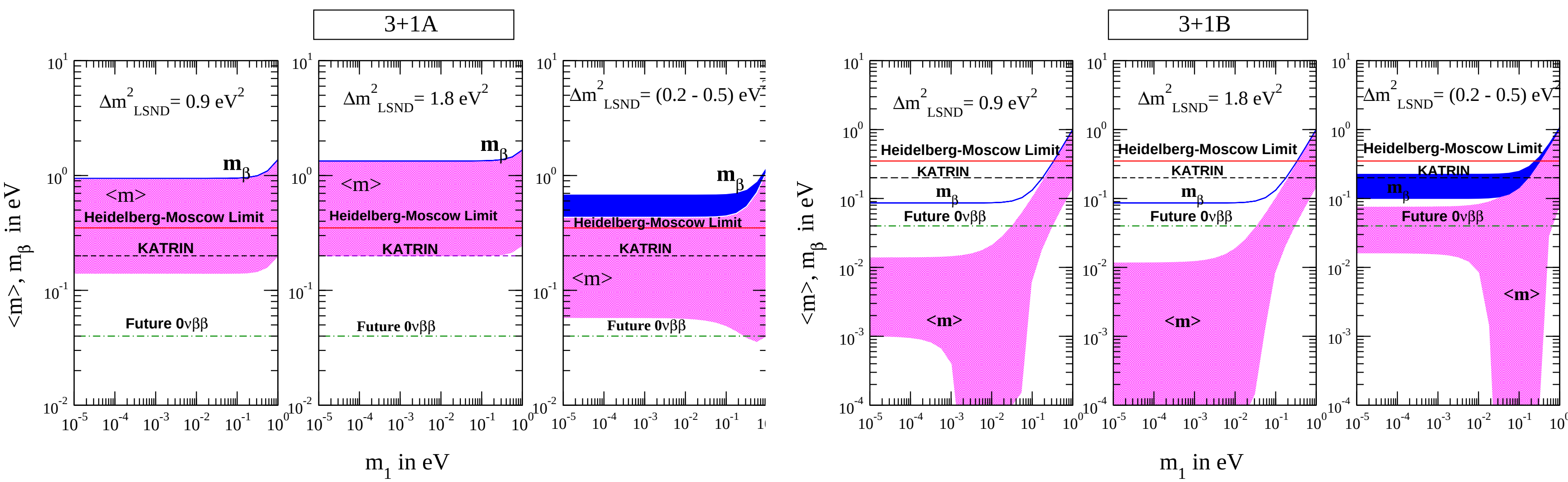
$$m_{\nu_e}^{\rm NH} \simeq \sqrt{s_{12}^2 \, c_{13}^2 \, \Delta m_\odot^2 + s_{13}^2 \, \Delta m_{\rm A}^2} \ll m_{\nu_e}^{\rm IH} \simeq \sqrt{c_{13}^2 \, \Delta m_{\rm A}^2}$$



- almost independent on mixing angles
- difference of normal and inverted shows up well below KATRIN limit
- different for sterile (LSND/MiniBoone!!) neutrinos

LSND AND $|m_{ee}|$ (Goswami, W.R., Phys. Rev. D **73**, 113003 (2006))





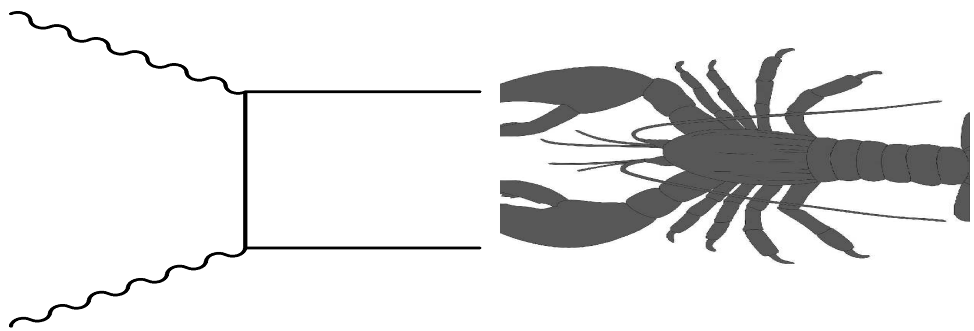
KATRIN AND $0\nu\beta\beta$

$0\nu\beta\beta$	Δm^2_{A}	KATRIN	Conclusion
yes	> 0	yes	QD, Majorana
yes	> 0	no	QD, Majorana or
			NH, Majorana + heavy particles
yes	< 0	no	IH, Majorana
yes	< 0	yes	QD, Majorana
no	> 0	no	NH, Dirac or Majorana
no	< 0	no	Dirac
no	< 0	yes	Dirac
no	> 0	yes	Dirac

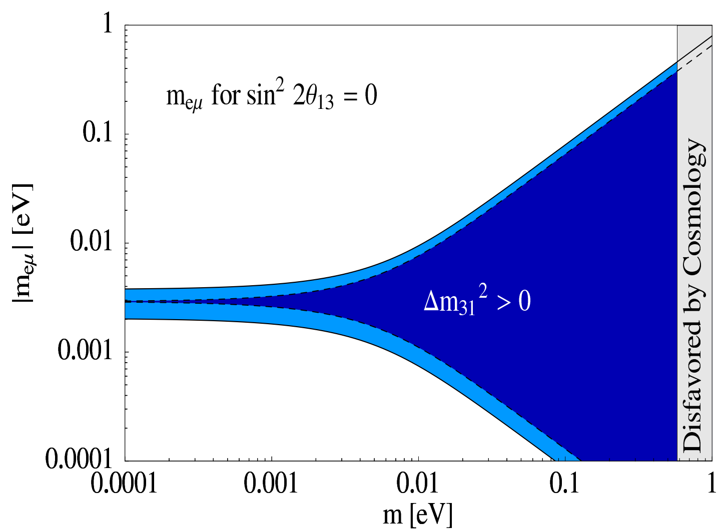
APS study, Mohapatra *et al.*, hep-ph/0510213

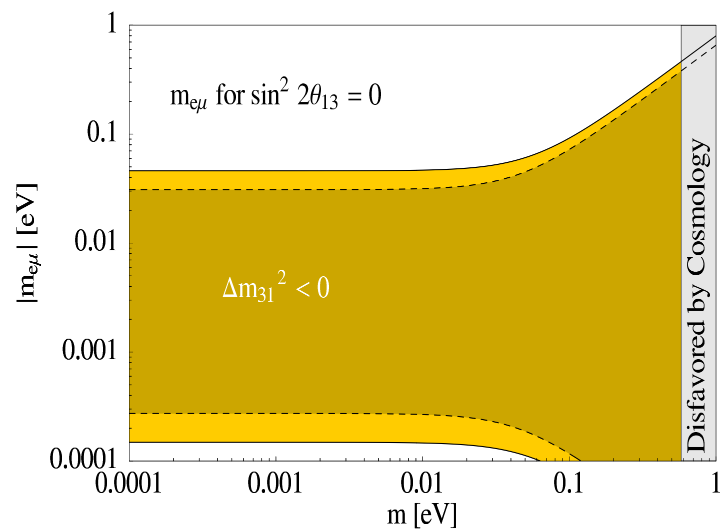
Other (non-oscillation) probes of NH vs. IH

3) Other elements of m_ν: "the lobster"



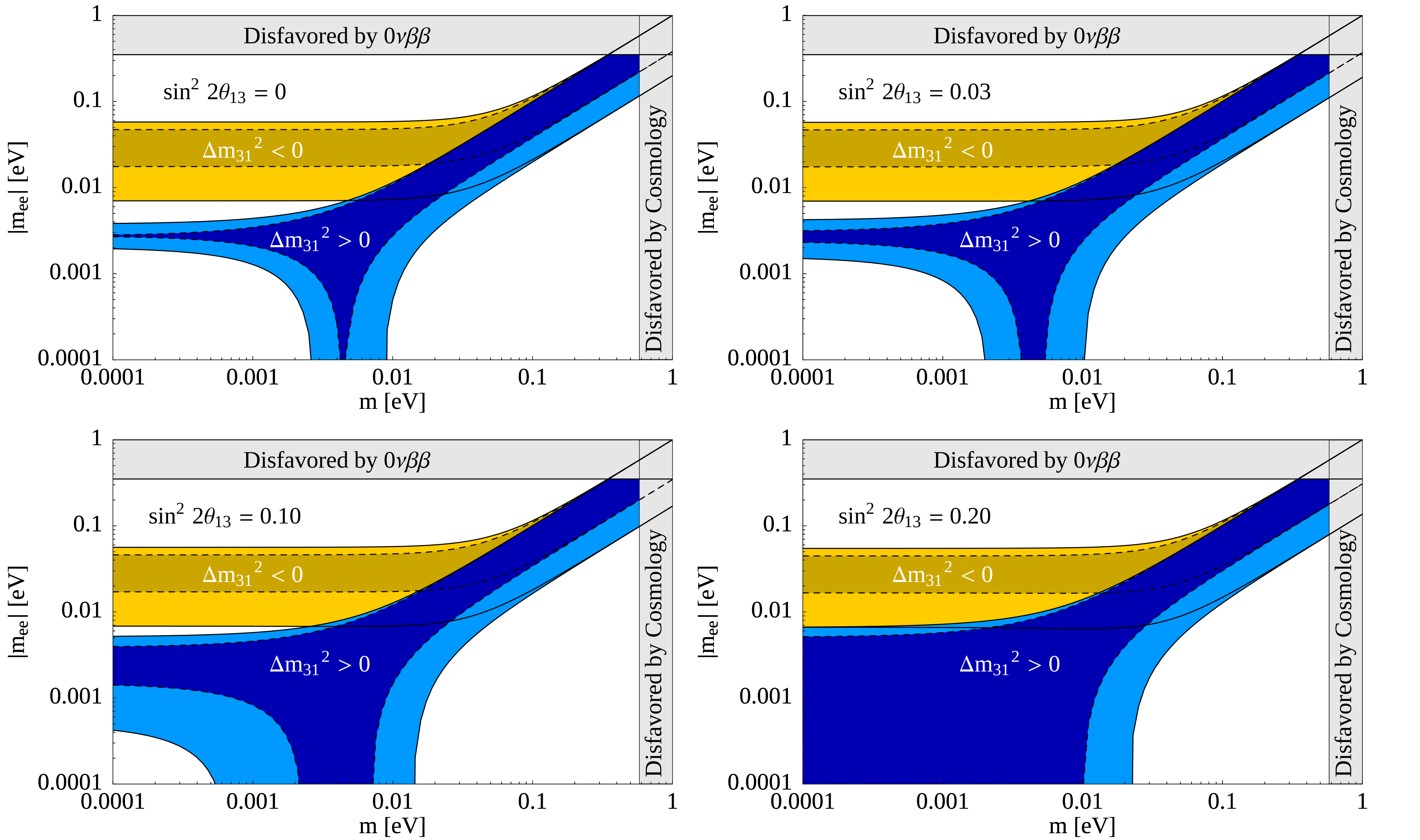
$$\mathrm{BR}(K^+ \to \pi^- \, e^+ \, \mu^+) \propto |m_{e\mu}|^2 = \left| \sum U_{ei} \, U_{\mu i} \, m_i \right|^2 \sim 10^{-30} \left(\frac{|m_{e\mu}|}{\mathrm{eV}} \right)^2$$





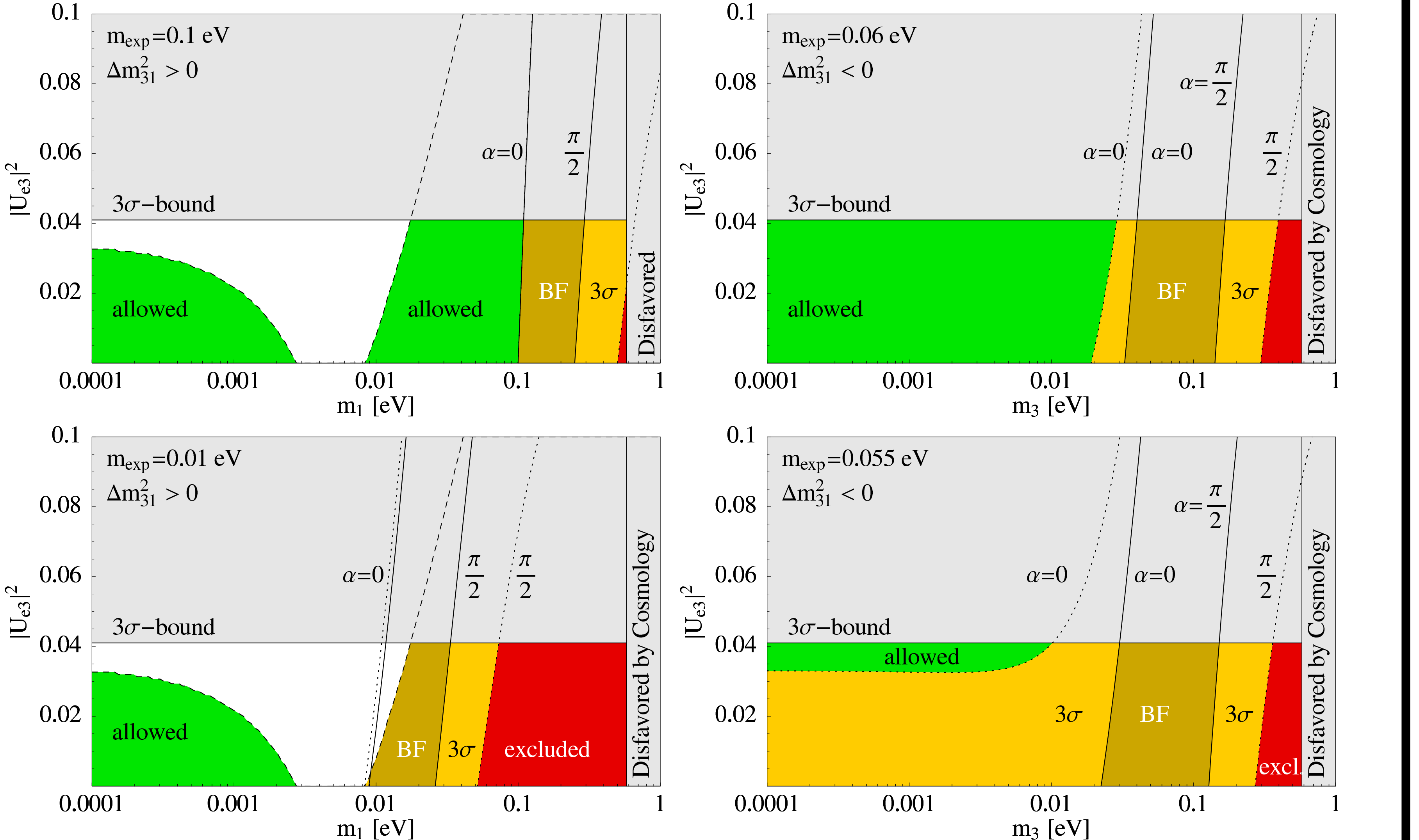
Merle, W.R., Phys. Rev. D **74**, 017701 (2006)

$|U_{e3}|$ AND $0\nu\beta\beta$



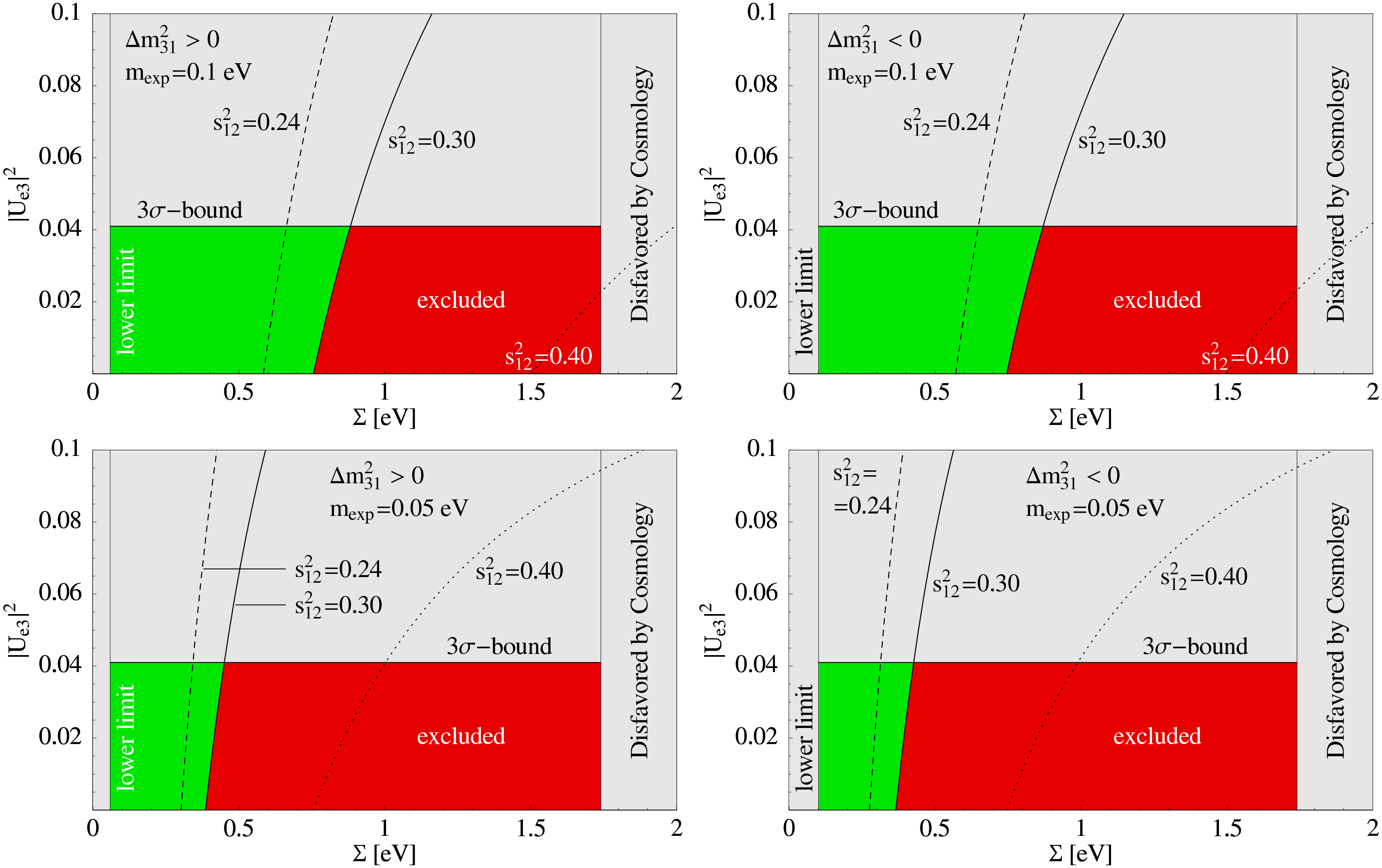
$\Rightarrow$ Value of U_{e3} influences $|m_{ee}|$, in particular NH vs. IH

LOWER LIMIT ON $|U_{e3}|^2$



Merle, W.R., hep-ph/0703135

Cosmology and $|U_{e3}|^2$

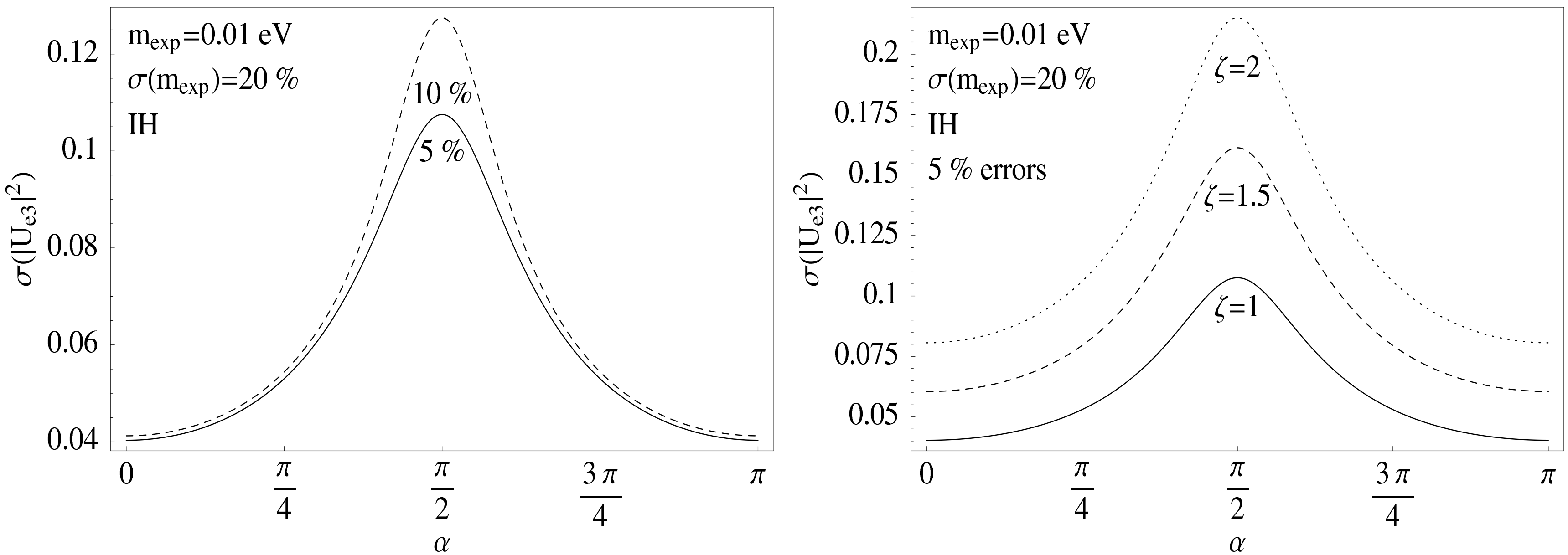


Merle, W.R., hep-ph/0703135

Measuring $|U_{e3}|^2$ with Neutrino-less Double Beta Decay?

Example inverted hierarchy:

$$|U_{e3}|^2 = 1 - \frac{|m_{ee}|}{\sqrt{\Delta m_A^2}\,\sqrt{1-\sin^2 2\theta_{12}\,\sin^2\alpha}}$$



Merle, W.R., hep-ph/0703135

What's more to $0\nu\beta\beta$?

* Mass scale: consider QD spectrum

$$m_0 \leq \frac{1+\tan^2\theta_{12}}{1-\tan^2\theta_{12}-2\,|U_{e3}|^2}\,|m_{ee}|_{\rm exp} \lesssim 5 \text{ eV}$$

* Majorana phases: consider IH spectrum

$$\sin^2\alpha = \left(1-\frac{|m_{ee}|}{\sqrt{|\Delta m^2_{\rm A}|}\,(1-|U_{e3}|^2)}\right)^2 \frac{1}{\sin^2 2\theta_{12}}$$

measurement requires $\zeta \lesssim 1.5$ and

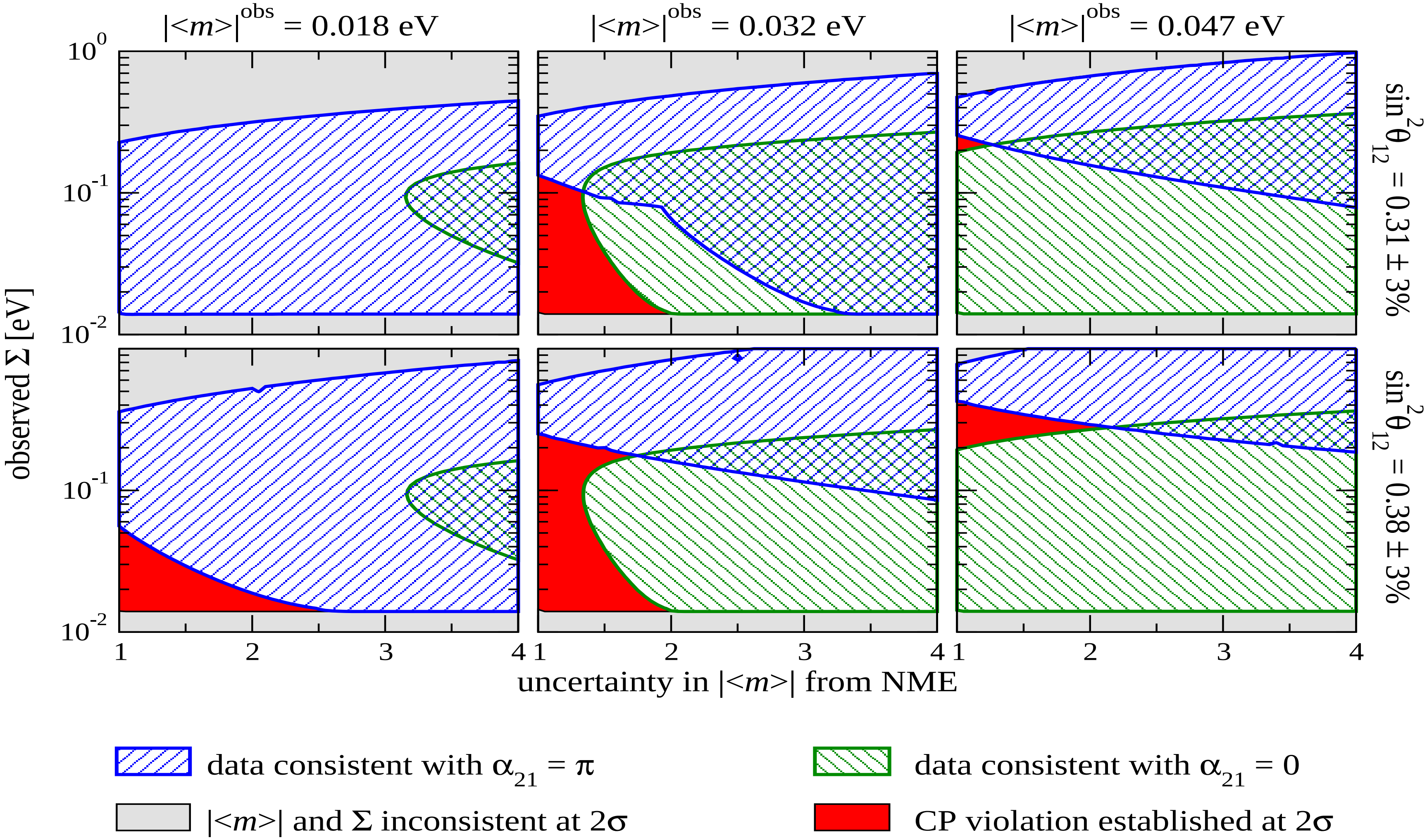
- $\sigma(|m_{ee}|) \lesssim 15\%$
- $\sigma(\Delta m^2_{\rm A}) \lesssim 10\%$ (IH) or $\sigma(m_0) \lesssim 10\%$ (QD)
- $\sin^2\theta_{12} \gtrsim 0.29$
- $2\alpha \in [\pi/4, 3\pi/4]$ or $[5\pi/4, 7\pi/4]$

Pascoli, Petcov, W.R., Phys. Lett. B **549**, 177 (2002)

No to "no-go" from Barger *et al.*, Phys. Lett. B **540**, 247 (2002)

Majorana phases

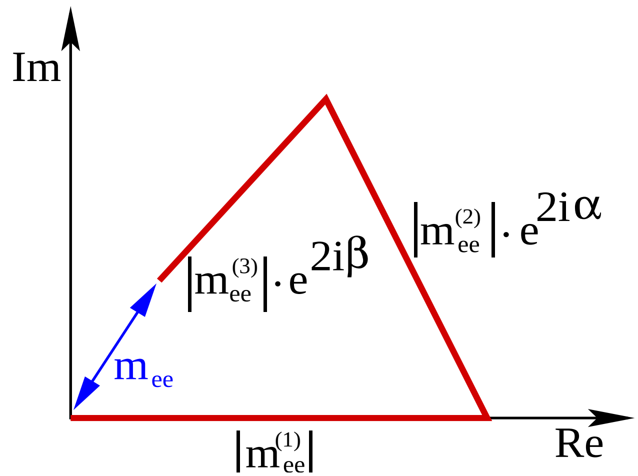
Pascoli, Petcov, Schwetz, Nucl. Phys. B **734**, 24 (2006)



$\sin^2\theta_{13} = 0 \pm 0.002$, $\Delta m^2_{21} = 8\text{x}10^{-5} \pm 2\%$, $\Delta m^2_{31} = -2.2\text{x}10^{-3} \pm 3\%$, $\sigma_{\beta\beta} = 0.004$ eV, $\sigma_\Sigma = 0.04$ eV

IF WE DON'T OBSERVE $0\nu\beta\beta$: VANISHING $|m_{ee}|$

- a triangle can be formed! $\left| |m_{ee}^{(1)}| + |m_{ee}^{(3)}|\, e^{2i\alpha} + |m_{ee}^{(3)}|\, e^{2i\beta} \right|$



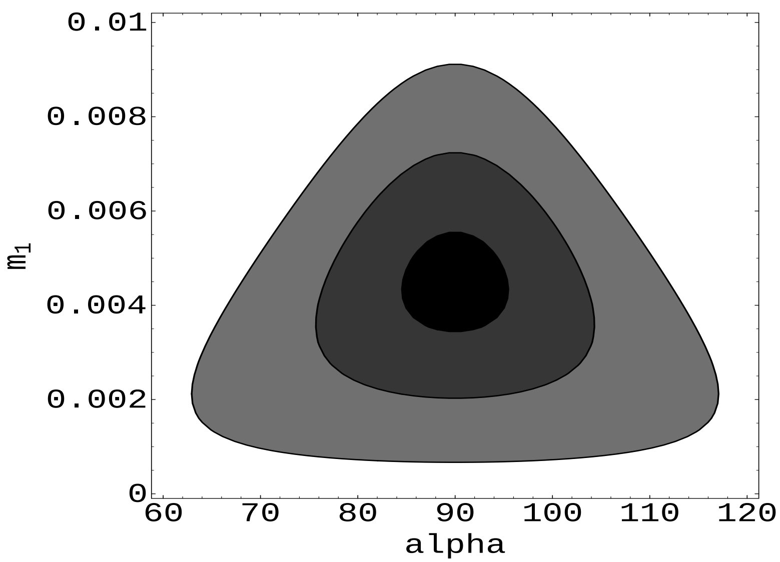
- texture zero in charged lepton basis!

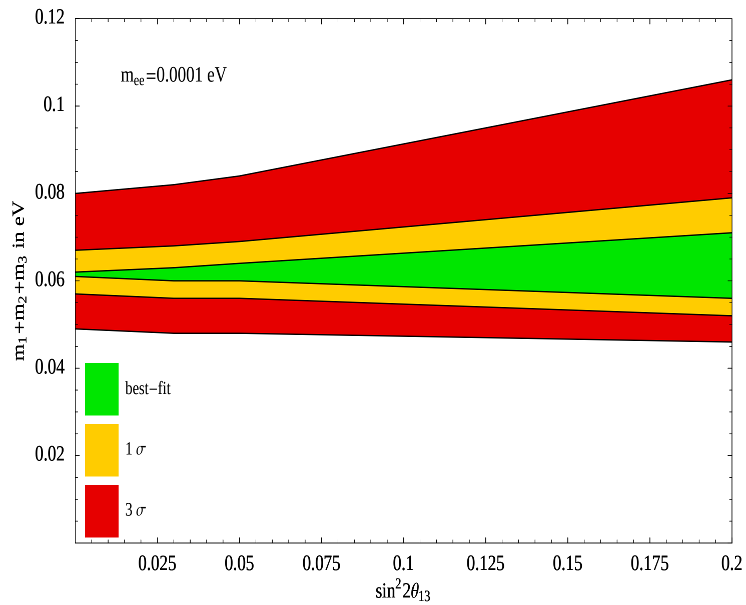
$$\cos 2\alpha = \frac{|m_{ee}^{(1)}|^2 + |m_{ee}^{(2)}|^2 - |m_{ee}^{(3)}|^2}{2|m_{ee}^{(1)}|\,|m_{ee}^{(2)}|} =$$

$$\frac{m_1^2\,\left(c_{13}^4\left(s_{12}^4 + c_{12}^4\right) - s_{13}^4\right) + \Delta m_\odot^2\, s_{12}^4\, c_{13}^4 - \Delta m_{\rm A}^2\, s_{13}^4}{2m_1\,\sqrt{m_1^2 + \Delta m_\odot^2\, s_{12}^2\, c_{12}^2\, c_{13}^4}}$$

IF WE DON'T OBSERVE $0\nu\beta\beta$: VANISHING $|m_{ee}|$

- only possible for NH
- if $\theta_{13} = 0$: $m_1 = \sin^2\theta_{12}\sqrt{\frac{\Delta m^2_\odot}{\cos 2\theta_{12}}} \simeq 4.5\ (2.8 \div 8.4)$ meV
- if $m_1 = 0$: $\sin^2 2\theta_{13} \simeq 4\ \sin^2\theta_{12}\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\mathrm{A}}}} \simeq 0.24\ (0.14 \div 0.40)$

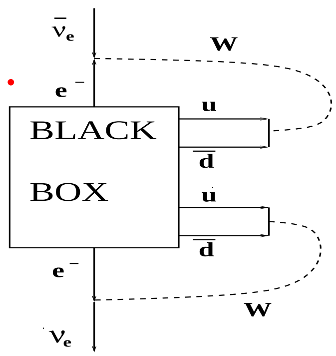




Dev, Kumar, hep-ph/0607048

Lindner, Merle, W.R., PRD **73**, 053005 (2006)

If we observe $0\nu\beta\beta$...



- Neutrinos are Majorana (Schechter-Valle)
- we still need to identify the mechanism of $0\nu\beta\beta$: SUSY, RH currents, heavy Majorana neutrinos,...
  solution: angular distribution, measure $0\nu\beta\beta$ in many different nuclei...
- reduce NME uncertainty: measure $0\nu\beta\beta$ in many different nuclei...
- if non-zero, Majorana phases **do contribute** to Y_B in leptogenesis (flavor effects)
- in general, we will believe much more firmly in leptogenesis
- $|m_{ee}|$ with precision experiments of oscillation parameters fixes structure of m_ν

Summary

- – Oscillations $\Rightarrow m_\nu \neq 0$
  - almost all models explain $m_\nu \neq 0$ in connection with Lepton Number Violation $\Rightarrow 0\nu\beta\beta$
- $0\nu\beta\beta$ can
  - distinguish NH from IH
  - Mass scale (consistency with KATRIN and cosmology)
  - consistency with U_{e3}
  - Majorana phases (Leptogenesis?)
- identify structure of mass matrix

$|m_{ee}|$ + precision data will help