Overview of mass hierarchy, CP violation and leptogenesis.

(Theory and Phenomenology)

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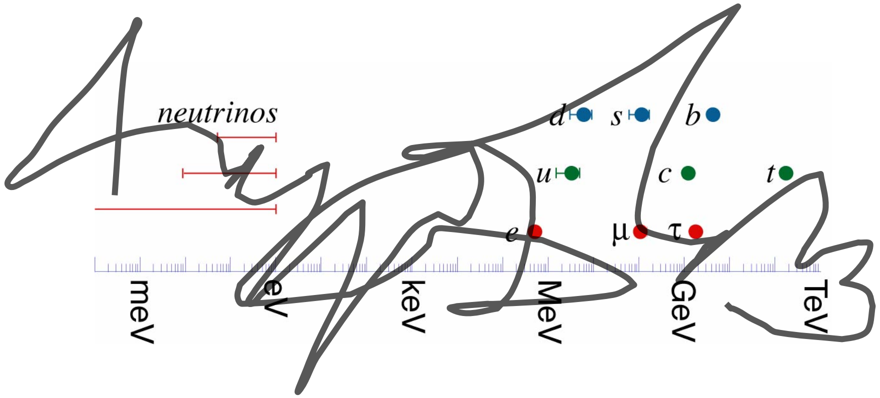
Questions - instead of contents

- Where do neutrino masses come from?
- Where and how do mass ordering and CP phase enter?
- Why are these parameters relevant?
- Is there a connection with baryogenesis?
- What is the role of $0\nu\beta\beta$?
- How can one measure MH and CP (phenomenology)?

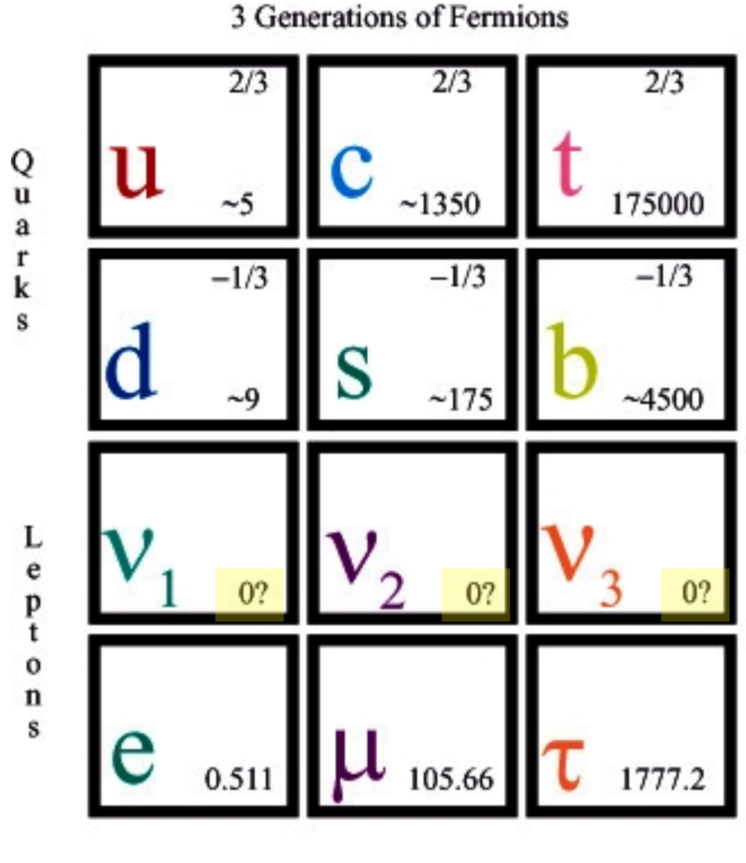
Origin of neutrino mass: physics beyond the SM?

- Neutrinos in the Standard Model are massless
- So what?

Introduce right-handed neutrino field ν^c,
Yukawa interaction ~ Y l H ν^c
forget about fine-tuning (Y)



Problem fixed!!!!!?



Masses are in MeV

Caveat: Neutrinos are electrically neutral …

- **Reminder from "model building 101", rule 1:**
  If I introduce new fields, I have to write down all possible interactions allowed by the gauge symmetries given the field content
- I can write a Majorana mass term ~ $M_R\ \nu^c\ \nu^c$ with the new field ν^c because the neutrino is electrically neutral
- Violates lepton number by two units
- Problem solution (1): get rid off this Majorana mass term

Scenario "ν-simple"

- **Reminder from "model building 101", rule 2:**
  If I want to forbid some interactions, I introduce/invent a (new) discrete symmetry and charge the fields under it
- Here we have such a symmetry already: lepton number is *accidentally* conserved in the Standard Model
- Promote lepton number from an accidental to a fundamental symmetry
- Physics BSM (kind of), but no leptogenesis

What if there is a Majorana mass term?

- Problem solution (2): Accept that there is such a mass term
- Lepton number violation, clearly physics beyond the Standard Model
- Lagrangian for fermion masses after EWSB

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c - \frac{1}{2}(M_R)_{ij} \nu_i^c \nu_j^c + h.c.$$

Scenario "ν-compact"
aka Type-I seesaw

$$\mathcal{L}_{\text{mass}} \sim (\nu \;\; \nu^c) \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}$$

Block diag.

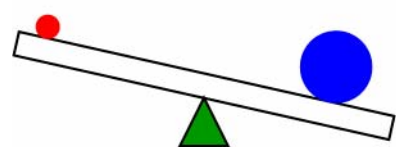
$$M_{\text{eff}}^{\text{Maj}} = -M_D M_R^{-1} M_D^T$$

- Fixes two other problems: smallness of neutrino mass and leptogenesis

$$m_\nu = \frac{m_D^2}{M_R}$$

← Other SM particles

← Heavy partner



Generation of fermion mixings: Standard theory

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c - \frac{1}{2}(M_R)_{ij} \nu_i^c \nu_j^c + h.c.$$

Model-dependent (type-II, III seesaw, radiative generation of neutrino mass, etc)

$$\mathcal{L}_{\text{mass}} \sim (\nu \; \nu^c) \begin{pmatrix} & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}$$

Block diag.

$$M_{\text{eff}}^{\text{Maj}} = -M_D M_R^{-1} M_D^T$$

Scenario "ν-complex"

Charged lepton mass terms

Eff. neutrino mass terms

$$M_\ell = U_\ell M_\ell^{\text{diag}} (U'_\ell)^\dagger \qquad M_{\text{eff}}^{\text{Maj}} = U_\nu M_\nu^{\text{diag}} U_\nu^T$$

Rotates left-handed fields

$$U_{\text{PMNS}} = U_\ell^\dagger U_\nu$$

cf., charged current

$$J^\mu = \bar{l}_L \gamma^\mu (1 - \gamma_5) U_\ell^\dagger U_\nu \nu$$

Origin of MH and CP violation? Leptogenesis?

Structure from flavor model?

Mass hierarchy

CP violation

- Scenario "**ν-simple**"

$$\mathcal{L}_{\rm mass} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c$$

$$M_\ell = U_\ell M_\ell^{\rm diag} (U'_\ell)^\dagger \quad M_\nu = U_\nu M_\nu^{\rm diag} (U'_\nu)^\dagger$$

$$U_{\rm PMNS} = U_\ell^\dagger U_\nu$$

No leptogenesis

- Scenario "**ν-compact**" (aka type-I seesaw)

$$\mathcal{L}_{\rm mass} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c - \frac{1}{2} (M_R)_{ij} \nu_i^c \nu_j^c + h.c.$$

… works even if heavy neutrinos at GeV scale, and together with a keV dark matter candidate
Canetti, Drewes, Shaposhnikov, 2012

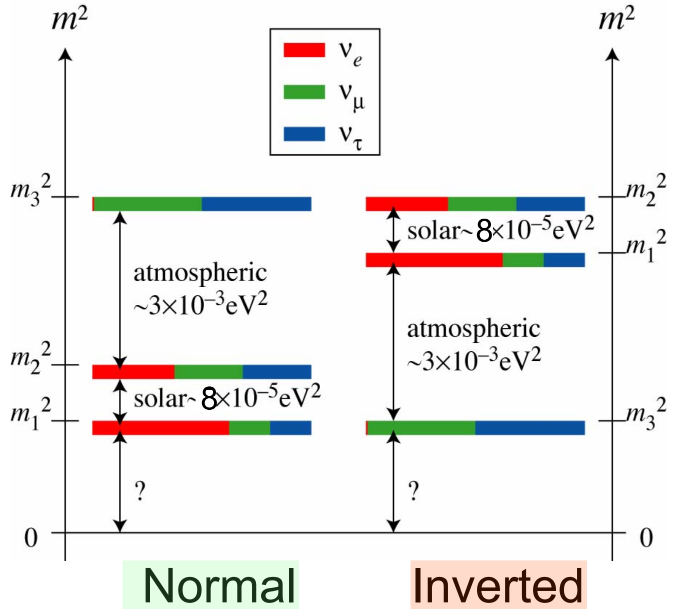
Leptogenesis!

- Scenario "**ν-complex**"
Origin of MH and CP violation depends on specific scenario; no universal discussion of leptogenesis possible

Leptogenesis?

Neutrino masses: Ordering versus Hierarchy

- The (atmospheric) mass **ordering** is unknown (normal or inverted) →



- The absolute neutrino mass scale is unknown (< eV). Often parameterized by lightest neutrino mass: m_1 or m_3
- In theory: three cases
  - Normal **hierarchy**: $m_1 < (\Delta m_{21}^2)^{0.5}$ (**ordering**: normal)
  - Inverted **hierarchy**: $m_3 \ll |\Delta m_{31}^2|^{0.5}$ (**ordering**: inverted)
  - (Quasi-)**Degenerate**: $m_1 \sim m_2 \sim m_3 \gg |\Delta m_{31}^2|^{0.5}$ (**ordering**: normal or inverted)

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

- Lower bound on neutrino neutrino masses from $\Delta m_{31}^2 \sim 0.0024$ eV^2:
  Normal hierarchy: $m_3 \sim 0.05$ eV
  Inverted hierarchy: m_1, $m_2 \sim 0.1$ eV

Why is the mass hierarchy so important?
(simple example: effective Majorana mass, charged leptons diagonal)

- Neutrino masses read, roughly (ε: hierarchy parameter)

$$M_\nu^{\rm diag} \simeq m_3 \begin{pmatrix} \varepsilon^2 & & \\ & \varepsilon & \\ & & 1 \end{pmatrix}$$

Hierarchy: normal

$$M_\nu^{\rm diag} \simeq m_1 \begin{pmatrix} 1 & & \\ & 1 & \\ & & \varepsilon \end{pmatrix}$$

Hierarchy: inverted

$$M_\nu^{\rm diag} \simeq m_3 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

Degenerate case

- Neutrino mixings, roughly (limit $\theta_{13} \sim 0$)

$$U_{\rm PMNS} \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Tri- bi- maximal

- Consequences for $M_\nu = U_{\rm PMNS} \, M_\nu^{\rm diag} \, U_{\rm PMNS}^T$ (to leading order)

$$M_\nu \simeq \begin{pmatrix} \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

Hierarchy: normal

$$M_\nu \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

Hierarchy: inverted

$$M_\nu \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Degenerate case

- **Very different structure of neutrino mass matrix! Model discriminator (flavor models)**

Neutrino mixings and leptonic CP violation

> Use same parameterization as for CKM matrix

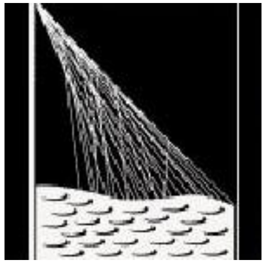
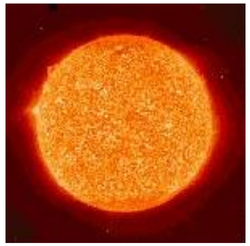
$$U_{\mathrm{PMNS}} = U_\ell^\dagger U_\nu$$

Potential CP violation ~ θ_{13}

Evidence for $\delta \sim 3\pi/2$ from T2K+reactor?

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

($s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$)

= () x () x ()

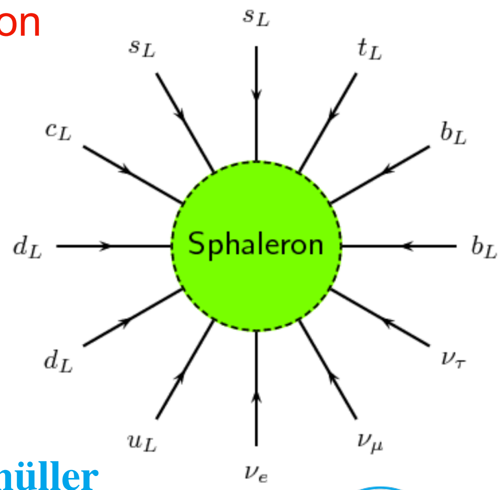
Pontecorvo-Maki-Nakagawa-Sakata matrix

> Neutrinos ⇨ Anti-neutrinos: **U** ⇨ **U*** (neutrino oscillations)

> If neutrinos are their own anti-particles (Majorana neutrinos):
U ⇨ U diag($1, e^{i\alpha}, e^{i\beta}$) – do enter $0\nu\beta\beta$, but not neutrino oscillations

Why would one care about CP violation?

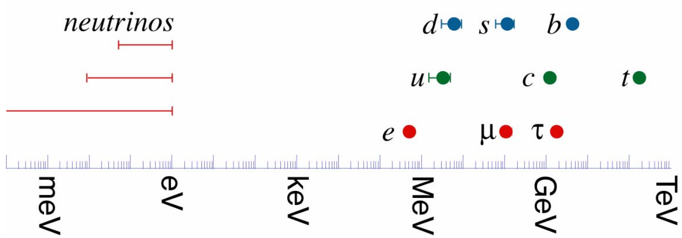
- Baryogenesis = dynamical mechanism to create the matter-anti-matter asymmetry in the early universe from a symmetric state
- Three necessary conditions (Sakharov conditions):
  1) B violation (need to violate baryon number)
     Need to create net baryon number
  2) Out-of-equilibrium processes
     Otherwise any created asymmetry will be washed out again
     (typically implied by expansion of the universe)
  3) **C and CP violation**
     Particles and anti-particles need to “behave“ differently
     Critical: the Standard Model does not have enough CP violation for that! Requires physics beyond the Standard Model (BSM)
- Addendum to 1): Can also come from lepton sector (sphalerons!)
- There are many theories for baryogenesis,
  e.g. electroweak baryogenesis,
  thermal leptogenesis,
  GUT baryogenesis etc



Buchmüller

A simple and self-consistent scenario: “ν-compact“

- Why are the neutrinos more than 250.000 times lighter than the electron?

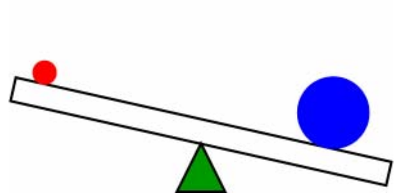


- Seesaw mechanism: Neutrino mass suppressed by heavy partner, which only exists in the early universe?

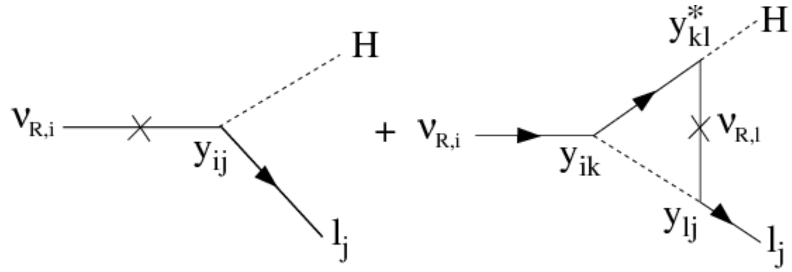
$$m_\nu = \frac{m_D^2}{M_R}$$

← Other SM particles

← Heavy partner



Decay of (thermally produced) M_R origin of matter-antimatter-asymmetry? →
Thermal leptogenesis



- Often quoted experimental evidence:
  - CP violation? Test in neutrino oscillations
  - Requires Majorana nature of neutrino! Test in neutrinoless double beta decay (0νββ)

How solid is the evidence from such experimental tests?

Do we really test thermal leptogenesis with δ_{CP}?

- The *pessimistic* perspective: There is no general connection

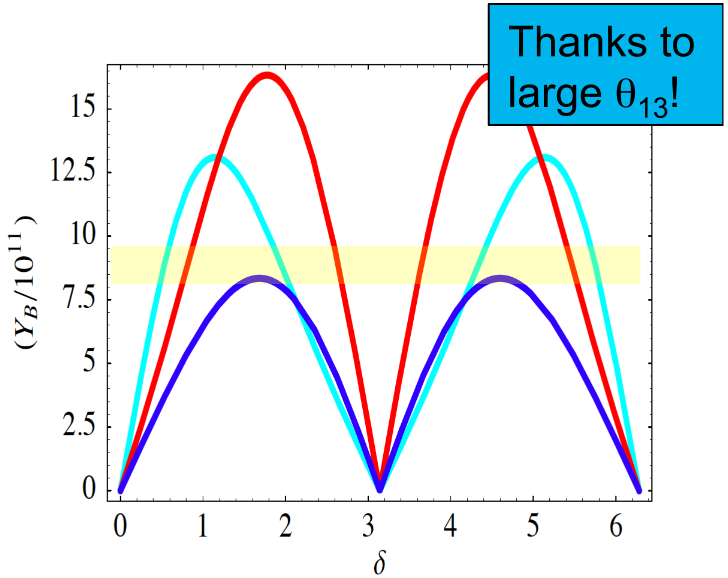
$$y = \frac{1}{v}\sqrt{M_R^{\text{diag}}}\, R \sqrt{M_\nu^{\text{diag}}}\, U_{\text{PMNS}}^\dagger$$

R: arbitrary, $R^T R=1$

Leptogenesis = Not accessible x Measurable

(Casas, Ibarra, 2001)

- The *minimalistic* perspective:
One can find parameters for which the CP violation from δ_{CP} is sufficient to generate the baryon asymmetry
Pascoli, Petcov, Riotto, 2007 →

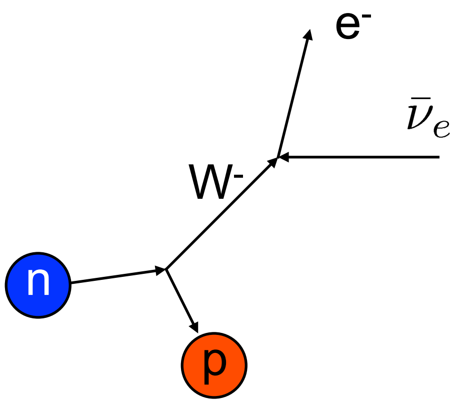


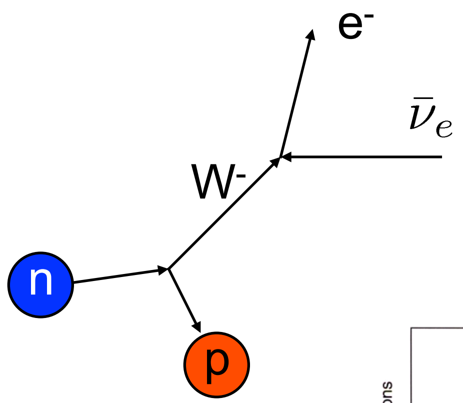
- The *self-consistent* perspective:
However, there is so far no convincing model to imply that

- The *agnostic* perspective:
Why care, we would probably anyways not be able to test that…

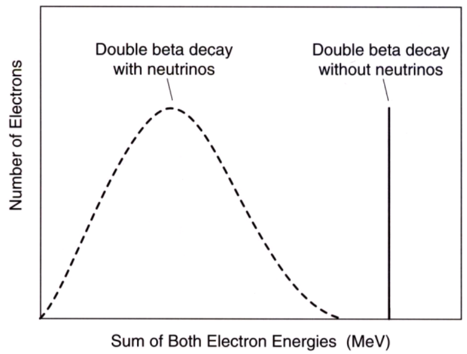
Signature of the Majorana nature: 0νββ

- Two times simple beta decay:

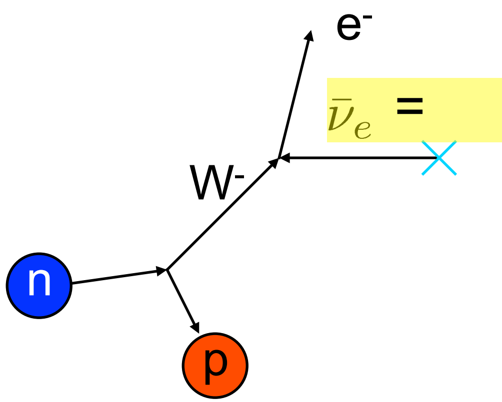


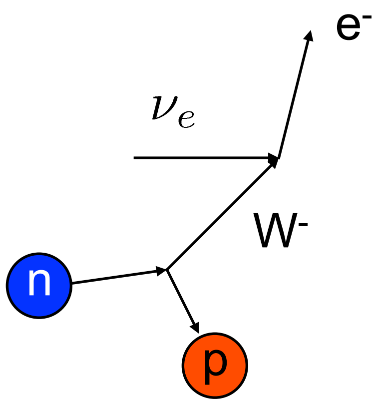


2 x ν
2 x e



- Neutrinoless double beta decay:





0 x ν
2 x e

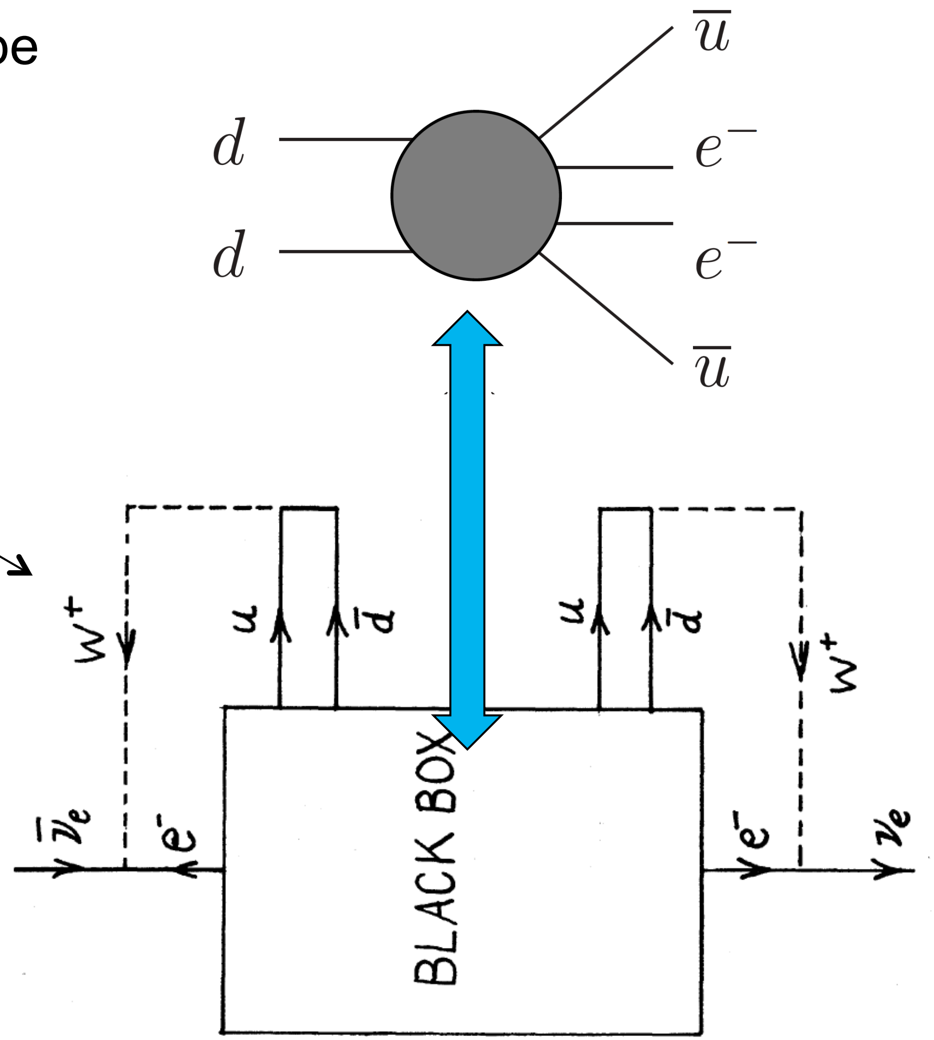
Does 0νββ imply Majorana neutrino masses?

- Neutrinoless double beta decay can be treated as effective d=9 operator:

- This leads to loop-generated Majorana masses
  Schechter, Valle, 1982

- The contribution to neutrino mass may, however, be small
  Dürr, Lindner, Merle, 2012

- Are Majorana neutrino masses the only mechanism leading to 0νββ?



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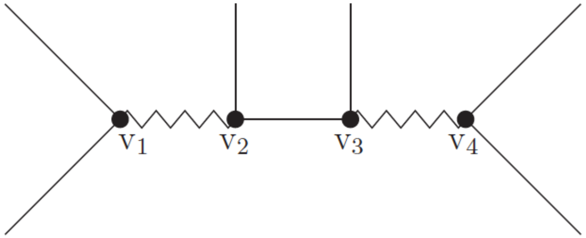
$0\nu\beta\beta$ mechanisms

- There exists a long list of BSM tree-level models which can lead to $0\nu\beta\beta$
  Bonnet, Hirsch, Ota, Winter JHEP 1303 (2013) 055



- The observation of $0\nu\beta\beta$ is a smoking gun signature for lepton number violation and physics BSM, but not (necessarily) for neutrino mass and for the neutrino mass ordering!
- Need direct measurements for mass and mass ordering

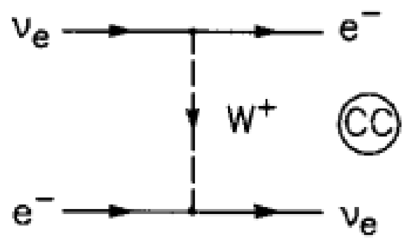
#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, 1)$	$(0, 1)$	$(-1, 1)$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1, 8)$	$(0, 8)$	$(-1, 8)$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2, 1)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2, 1)$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, 1)$	$(+4/3, \overline{3})$	$(+2, 1)$	
			$(+1, 8)$	$(+4/3, \overline{3})$	$(+2, 1)$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, 1)$	$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	
			$(+1, 8)$	$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+1/3, \overline{3})$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+1/3, \overline{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2/3, 3)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2/3, 3)$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+2/3, 3)$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \overline{3})$	$(0, 1)$	$(+1/3, \overline{3})$	RPV [58–60]
			$(-2/3, \overline{3})$	$(0, 8)$	$(+1/3, \overline{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \overline{3})$	$(-1/3, 3)$	$(+1/3, \overline{3})$	
			$(-2/3, \overline{3})$	$(-1/3, \overline{6})$	$(+1/3, \overline{3})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	$(-2/3, \overline{3})$	only with V_ρ and V'_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(-2/3, 6)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \overline{3})$	$(+5/3, 3)$	$(+2, 1)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2, 1)$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, 3)$	$(+4/3, \overline{3})$	$(+2, 1)$	only with V_ρ
			$(+2/3, \overline{6})$	$(+4/3, \overline{3})$	$(+2, 1)$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \overline{3})$	$(0, 1)$	$(+2/3, 3)$	RPV [58–60]
			$(-2/3, \overline{3})$	$(0, 8)$	$(+2/3, 3)$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \overline{3})$	$(+5/3, 3)$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2/3, 3)$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \overline{3})$	$(+1/3, \overline{3})$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(+2/3, 3)$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, 3)$	$(0, 1)$	$(+1/3, \overline{3})$	RPV [58–60]
			$(-1/3, 3)$	$(0, 8)$	$(+1/3, \overline{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, 3)$	$(+1/3, \overline{3})$	$(-2/3, \overline{3})$	only with V'_ρ
			$(-1/3, 3)$	$(+1/3, 6)$	$(-2/3, 6)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, \overline{3})$	only with V'_ρ
			$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 6)$	

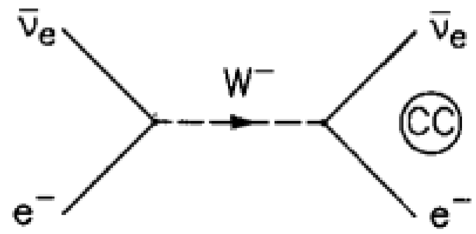
Measurement of the mass ordering and CP violation (phenomenology)

Matter effects in neutrino oscillations

- Ordinary matter: electrons, but no μ, τ
- Coherent forward scattering in matter: Net effect on electron flavor
- Hamiltonian in matter (matrix form, flavor space):

(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)





$$\mathcal{H}(n_e) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

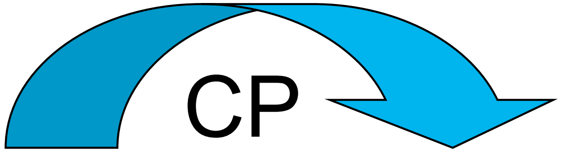
$$V_\nu = +\sqrt{2} G_F n_e, \; V_{\bar{\nu}} = -\sqrt{2} G_F n_e, \; n_e = Y \rho_j / m_N$$

Y: electron fraction ~ 0.5

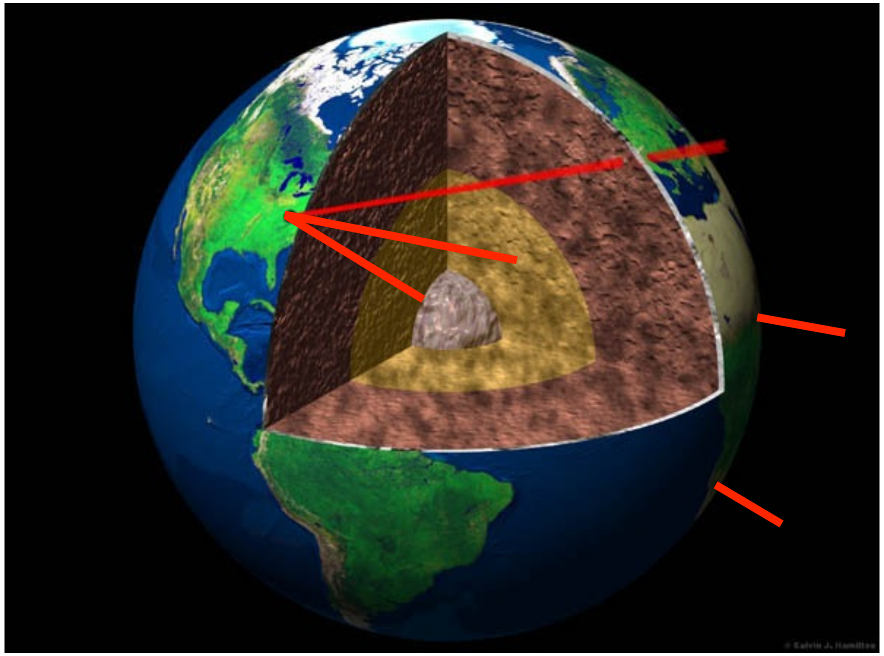
(electrons per nucleon)

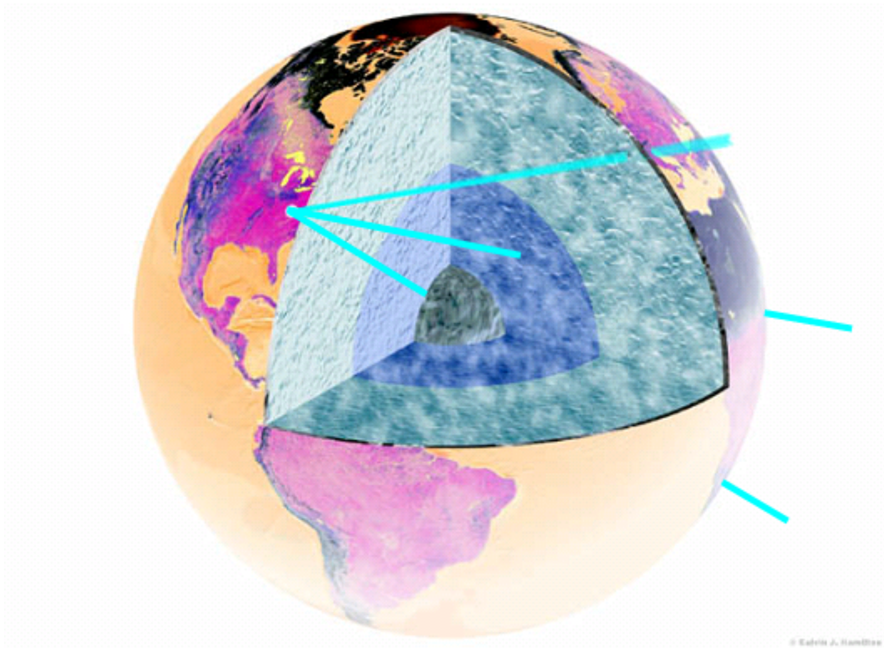
Extrinsic CP violation

- Matter effects violate CP and even CPT “extrinsically“
- Consequence: Obscure extraction of intrinsic CP violation



Need an anti-Earth





Parameter mapping … for two flavors, constant matter density

Oscillation probabilities in

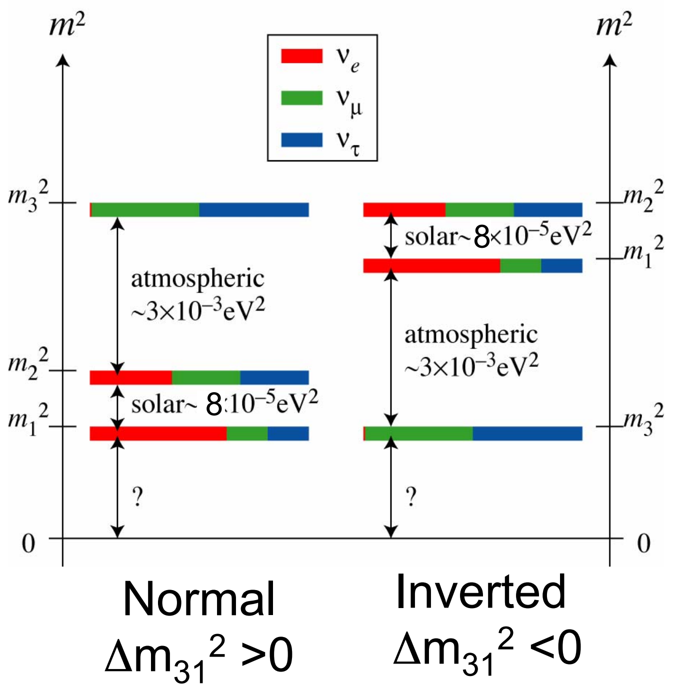
vacuum: $$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$$

matter: $$P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$

$$\Delta \tilde{m}^2 = \xi \cdot \Delta m^2, \qquad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},$$

$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2}$$



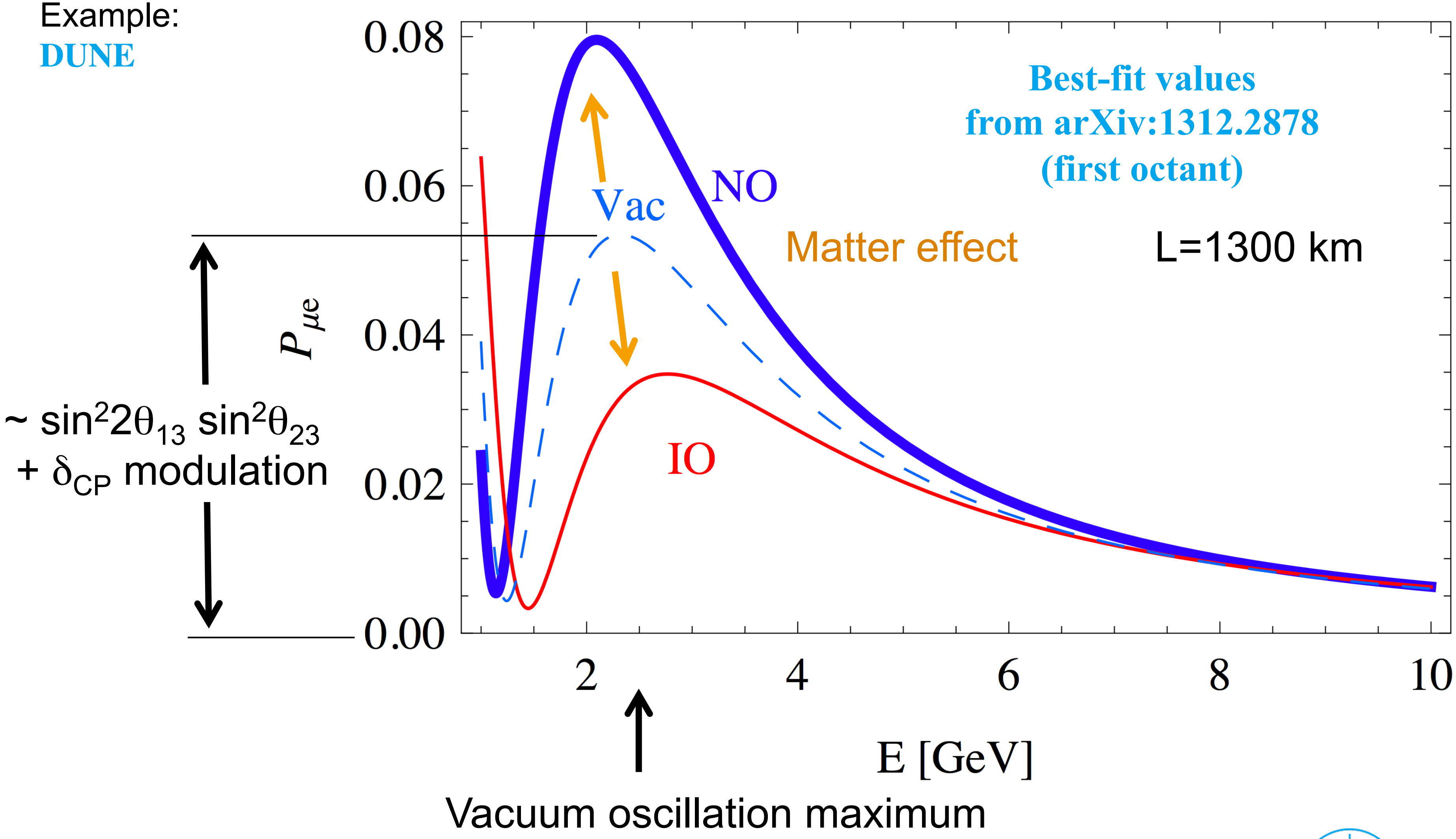
Enhancement condition

$$\cos 2\theta \rightarrow \hat{A}$$

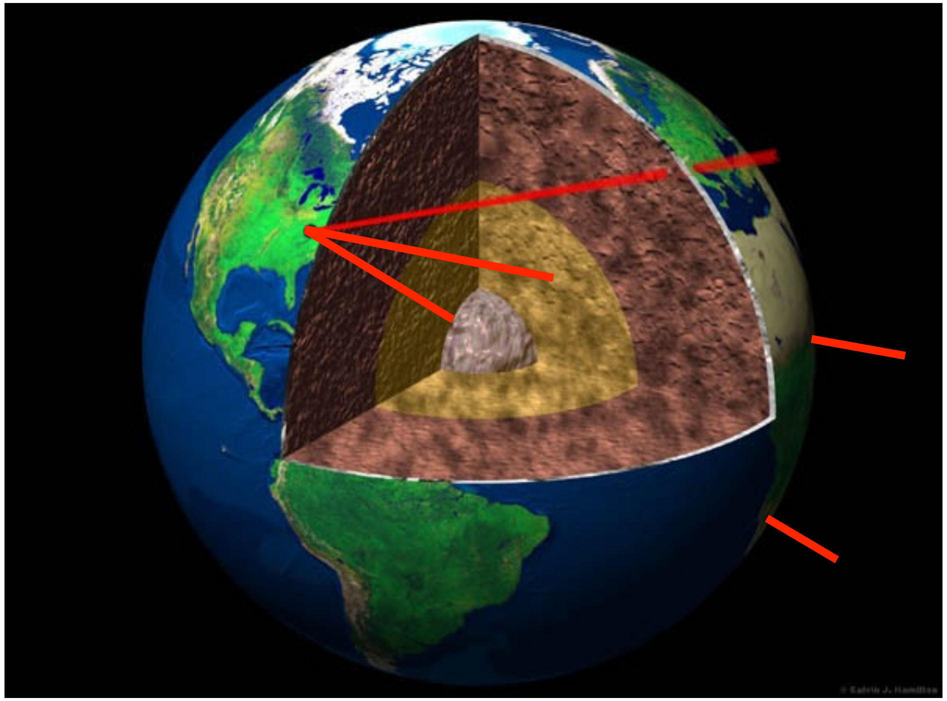
	Normal	Inverted
Neutrinos	Resonance	Suppression
Antineutrinos	Suppression	Resonance

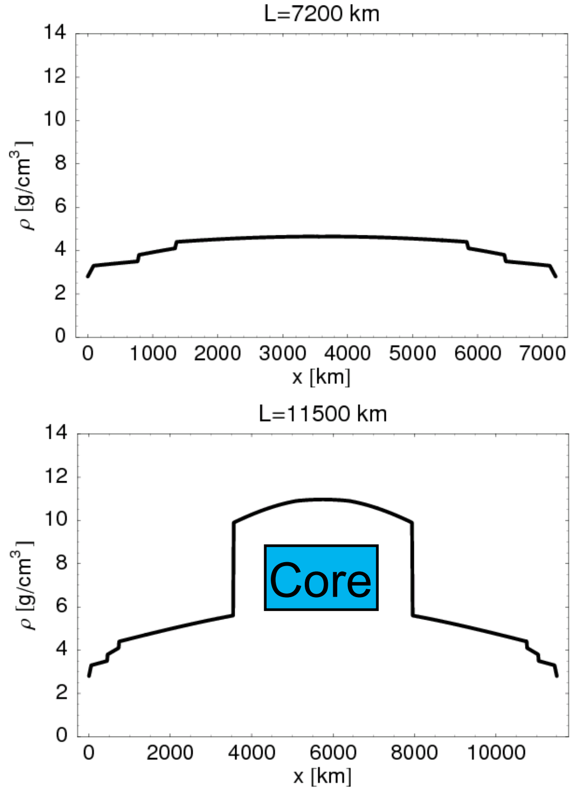
Long baseline experiments (up to first vacuum osc. maximum)

Example:
DUNE



Matter profile of the Earth … as seen by a neutrino





(Preliminary Reference Earth Model)

Resonance energy (from $\hat{A} \rightarrow \cos 2\theta$):

$$E_{\mathrm{res}}\,[\mathrm{GeV}] \sim 13\,200\ \cos 2\theta \, \frac{\Delta m^2\,[\mathrm{eV}^2]}{\rho\,[\mathrm{g/cm}^3]}$$

For ν_μ appearance, Δm_{31}^2:

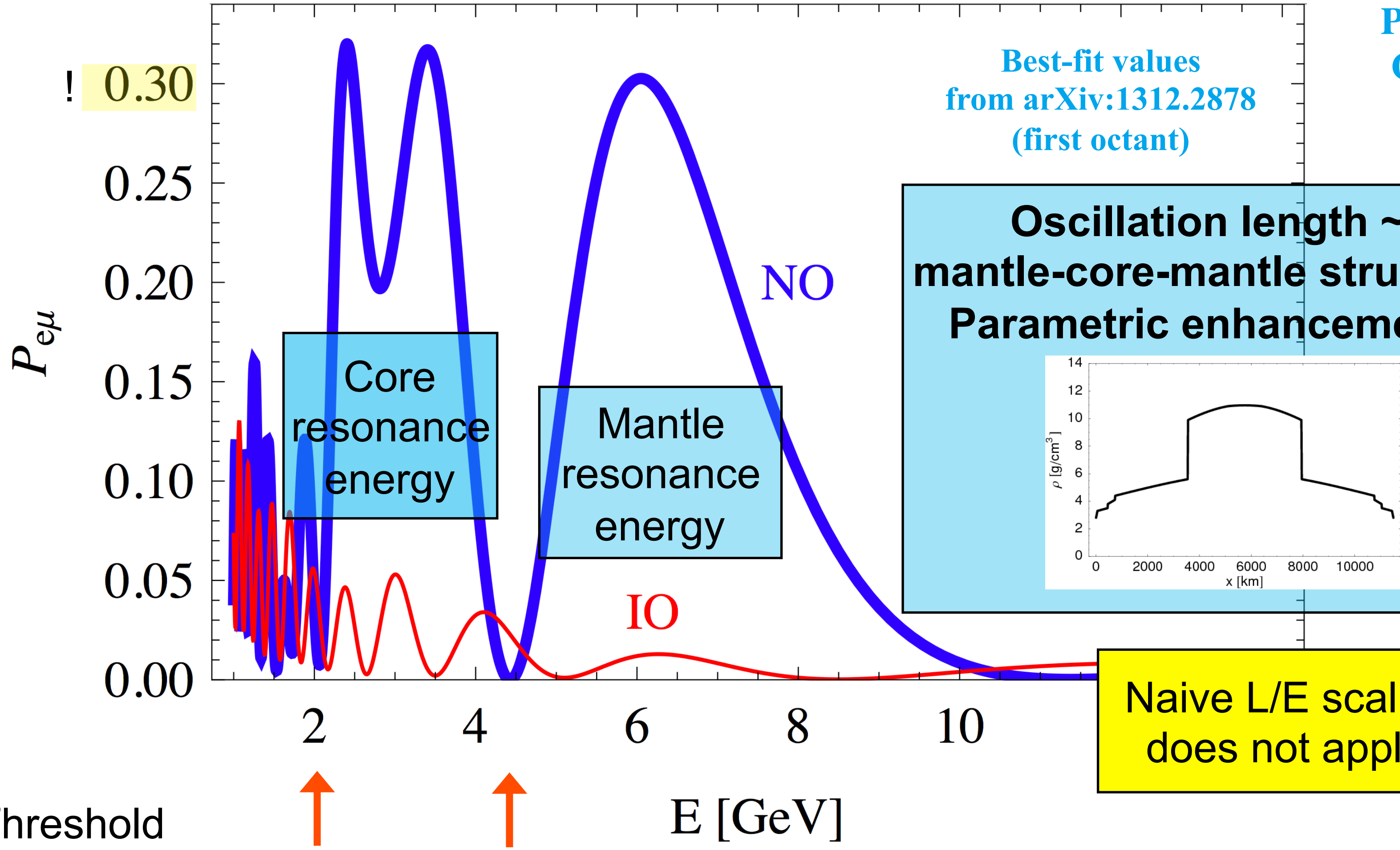
- ρ ~ 4.7 g/cm³ (Earth's mantle): **E_{res} ~ 6.4 GeV**
- ρ ~ 10.8 g/cm³ (Earth's outer core): **E_{res} ~ 2.8 GeV**

DESY

Mantle-core-mantle profile

(Parametric enhancement: Akhmedov, 1998; Akhmedov, Lipari, Smirnov, 1998; Petcov, 1998)

- Probability for L=11810 km



Core resonance energy

Mantle resonance energy

Examples: PINGU, ORCA, INCO

Oscillation length ~ mantle-core-mantle structure Parametric enhancement.

Naive L/E scaling does not apply!

Threshold effects expected at: 2 GeV, 4-5 GeV

Alternative method: Disappearance probabilities

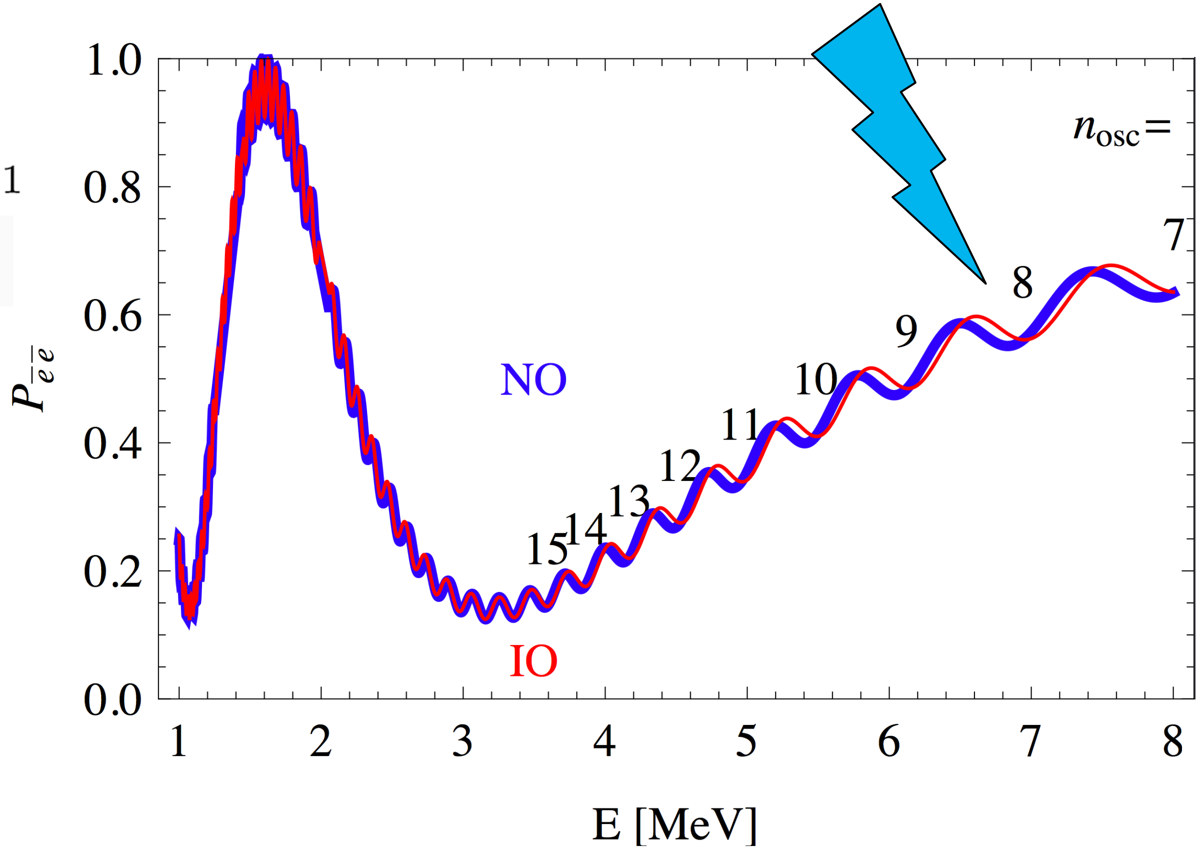
- Works in vacuum, and even for θ_{13}=0
- Just flipping the sign of Δm^2 is not sufficient
- Example: Reactor experiment, L=53 km

Example:
JUNO

$$\Delta m^2_{31} \to -\Delta m^2_{31}$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

Probabilities apparently different (unphysical effect!)



Alternative method: Disappearance probabilities

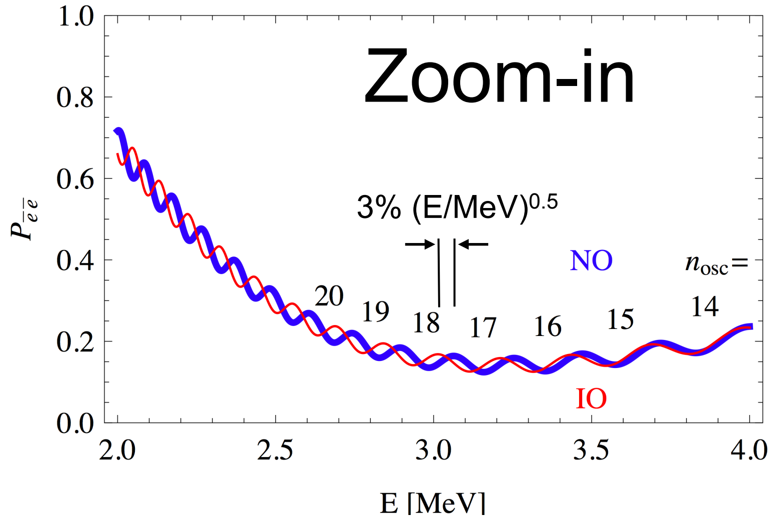
- The disappearance Δm^2 depends on the channel. Consequence e. g.

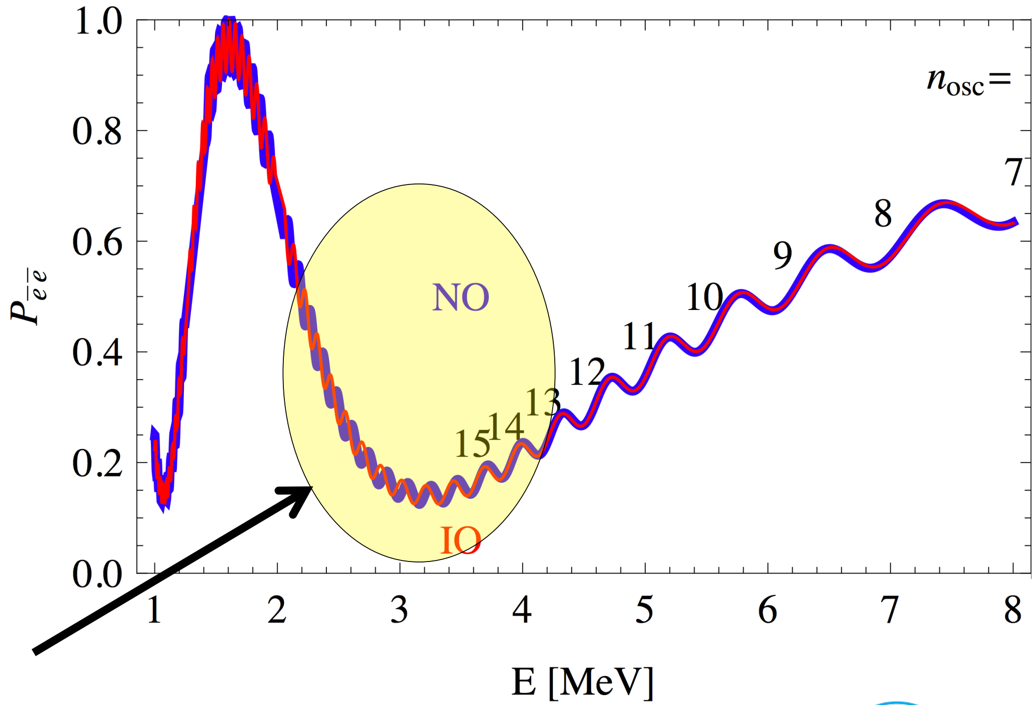
$$|\delta m^2_{\text{eff}}|_e - |\delta m^2_{\text{eff}}|_\mu = \pm \delta m^2_{21} (\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23})$$

de Gouvea, Jenkins, Kayser, hep-ph/0503079;
Nunokawa, Parke, Zukanovich, hep-ph/0503283

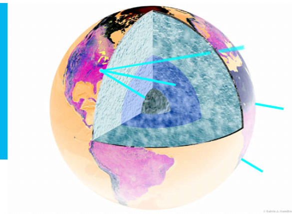
Example:
JUNO

- Now first oscillation maxima match. Discrimination by higher osc. Maxima.
Need energy resolution!





Measurement of CP violation: long-baseline exps



$$P_{e\mu} \simeq \sin^2 2\theta_{13} \begin{array}{c}\cos^2\theta_{23}\\ \sin^2\theta_{23}\end{array} \frac{\sin^2[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})^2}$$

$$\pm\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$\mp\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$+\ \alpha^2 \begin{array}{c}\sin^2\theta_{23}\\ \cos^2\theta_{23}\end{array} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

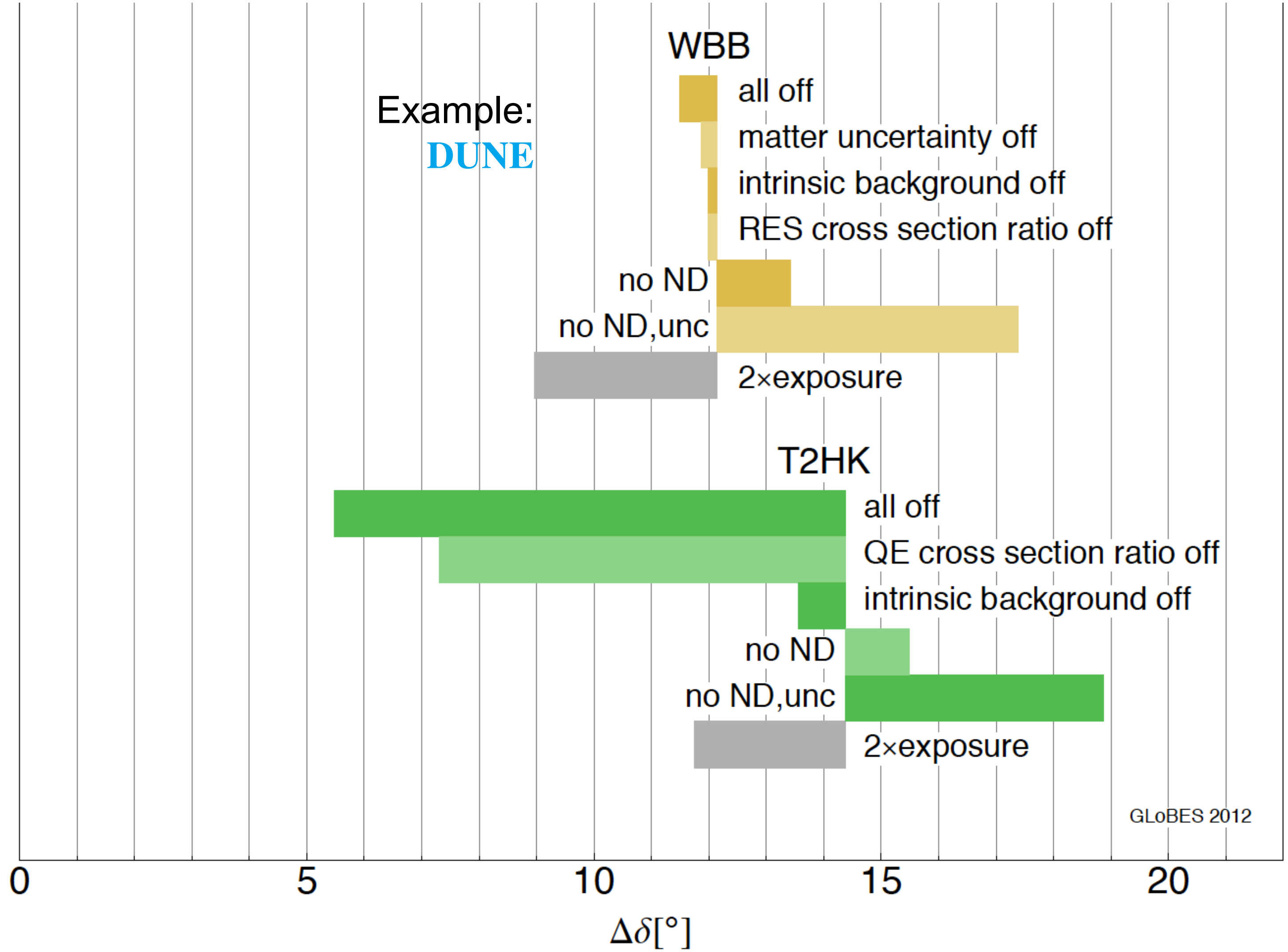
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \hat{A} \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$$

- Antineutrinos: $P_{\bar{e}\bar{\mu}} = P_{e\mu}(\delta_{CP}, \rightarrow -\delta_{CP}, \hat{A} \rightarrow -\hat{A})$
- Silver: $P_{e\tau} = P_{e\mu}(s^2_{23} \leftrightarrow c^2_{23}, \sin 2\theta_{23} \rightarrow -\sin 2\theta_{23})$
- Platinum, T-inv.: $P_{\mu e} = P_{e\mu}(\delta_{CP}, \rightarrow -\delta_{CP})$

Examples:
T2HK
DUNE
NuFact

(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Akhmedov et al, 2004)

The measurement of δ_{CP}: Challenges



Example:
DUNE

Exposure

X-secs

(Coloma, Huber, Kopp, Winter, 2013)

Summary and conclusions

- *Where does neutrino mass come from?*
  Scenarios "ν-simple", "ν-compact", "ν-complex":
  "**ν-compact**" (type-I seesaw) often considered as the leading paradigm in terms of complexity vs. no of problems fixed (but perhaps not the simplest …)
- *Where do mass ordering and CP phase enter?*
  (Yukawa) Couplings, possibly with structure from flavor symmetries
- *Why are these parameters relevant?*
  - Mass hierarchy: Flavor symmetry, interpretation for leptogenesis
  - Mass ordering: Interpretation of $0\nu\beta\beta$, supernova neutrinos, neutrino oscillations
  - CP violation: Leptogenesis
- *Is there a connection with leptogenesis?*
  Not in general. But: One can find a scenario where the δ_{CP}-effect is sufficient
- *What is the role of $0\nu\beta\beta$?*
  Test of lepton number violation and physics BSM. Interpretation in terms of Majorana neutrino contribution requires additional input