Neutrino mass hierarchy: Theory and phenomenology.

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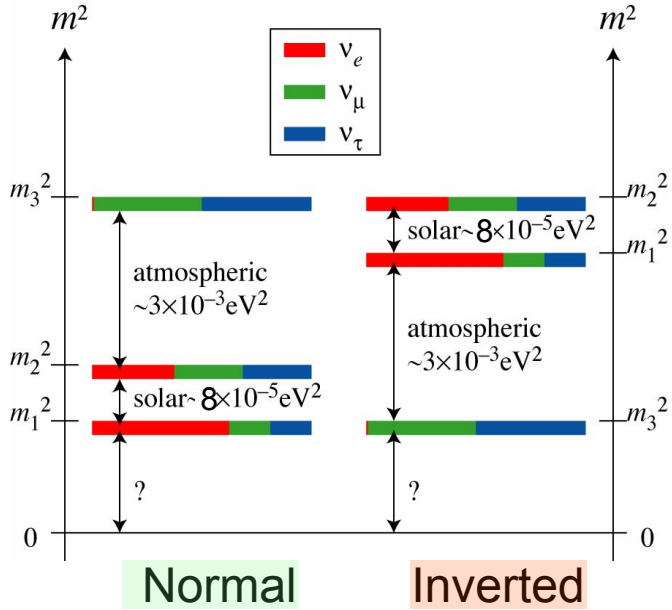
Contents

- Why would one like to know the mass ordering?
- How to measure the mass ordering?
- Technological approaches to measure the mass ordering

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)

  [plus some recently growing interest in the transition regime: m_1 (for NO) ~ $|\Delta m_{31}^2|$]
- 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



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

Why would one like to know the mass ordering?

Origin of neutrino mass
(simple example: effective Majorana mass, charged leptons diagonal)

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

$$M_\nu^{\rm diag} \simeq m_3 \begin{pmatrix} \varepsilon^2 & & \\ & \varepsilon & \\ & & 1 \end{pmatrix} \qquad M_\nu^{\rm diag} \simeq m_1 \begin{pmatrix} 1 & & \\ & 1 & \\ & & \varepsilon \end{pmatrix} \qquad M_\nu^{\rm diag} \simeq m_3 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

Hierarchy: normal | Hierarchy: inverted | 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)

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

Hierarchy: normal | Hierarchy: inverted | Degenerate case

- **Very different structure of neutrino mass matrix!**

Mass hierarchy as texture and model discriminator

- Typically re-covered in more complicated cases, e.g. including charged lepton mixings, $\theta_{13}>0$ etc:

Hierarchy: normal vs. Hierarchy: inverted

$$\begin{pmatrix} \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & 1 \end{pmatrix} \quad M_\nu \quad \begin{pmatrix} 1 & 0 & \varepsilon \\ 0 & 1 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & \varepsilon \end{pmatrix}$$

$$\begin{pmatrix} 1 & \varepsilon^2 & 1 \\ \varepsilon^2 & \varepsilon & \varepsilon^2 \\ 1 & \varepsilon^2 & 1 \end{pmatrix} \quad M_\nu \quad \begin{pmatrix} 1 & \varepsilon^2 & 1 \\ \varepsilon^2 & 1 & \varepsilon^2 \\ 1 & \varepsilon^2 & 1 \end{pmatrix}$$

(example from hep-ph/0612169)

- Translates into flavor symmetry models
  (Albright, Chen, hep-ph/0608137)
  See also: talk by Morimitsu Tanimoto

- Neutrino mass ordering is the prime model discriminator!

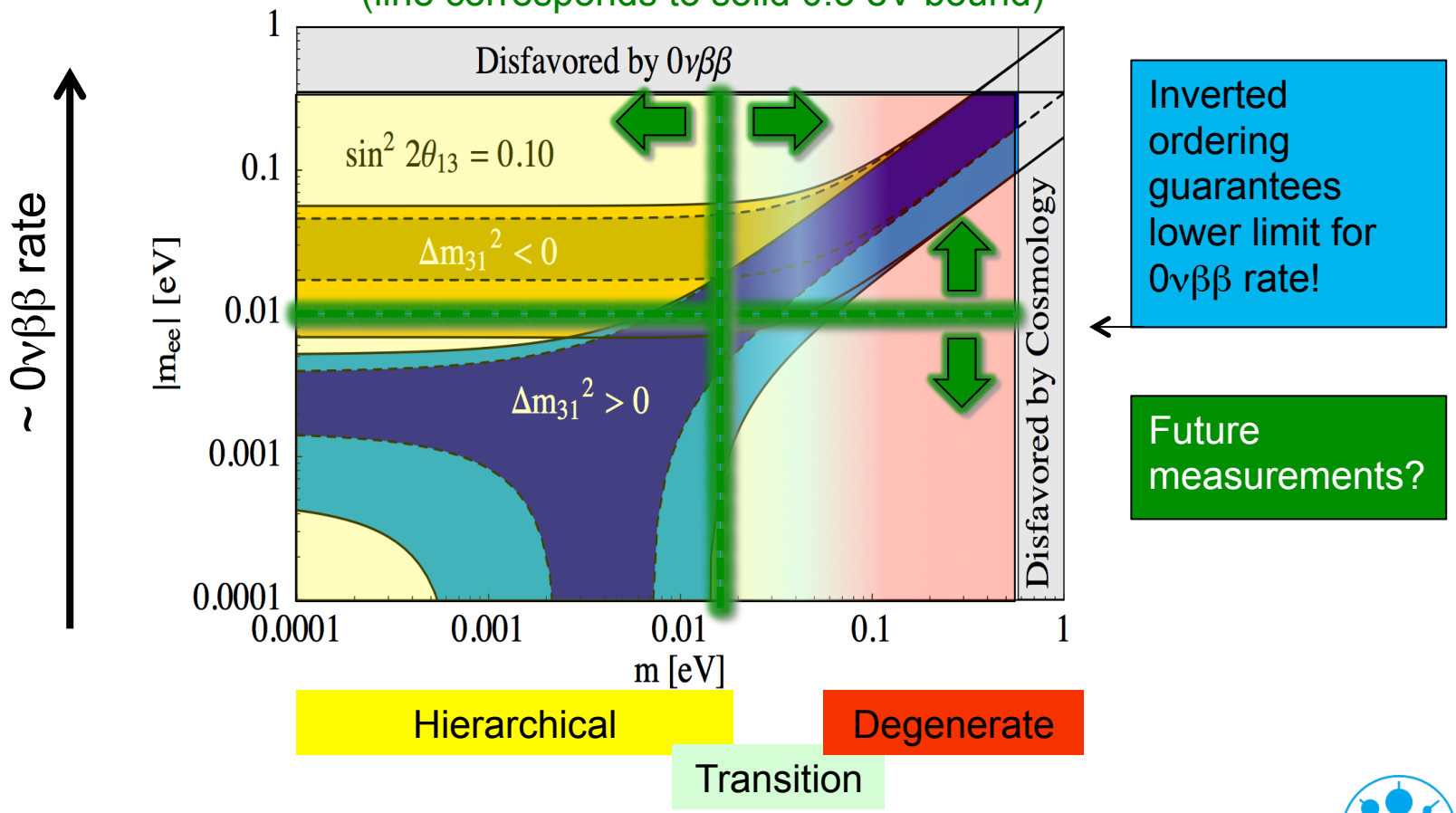
TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Neutrinoless double beta decay

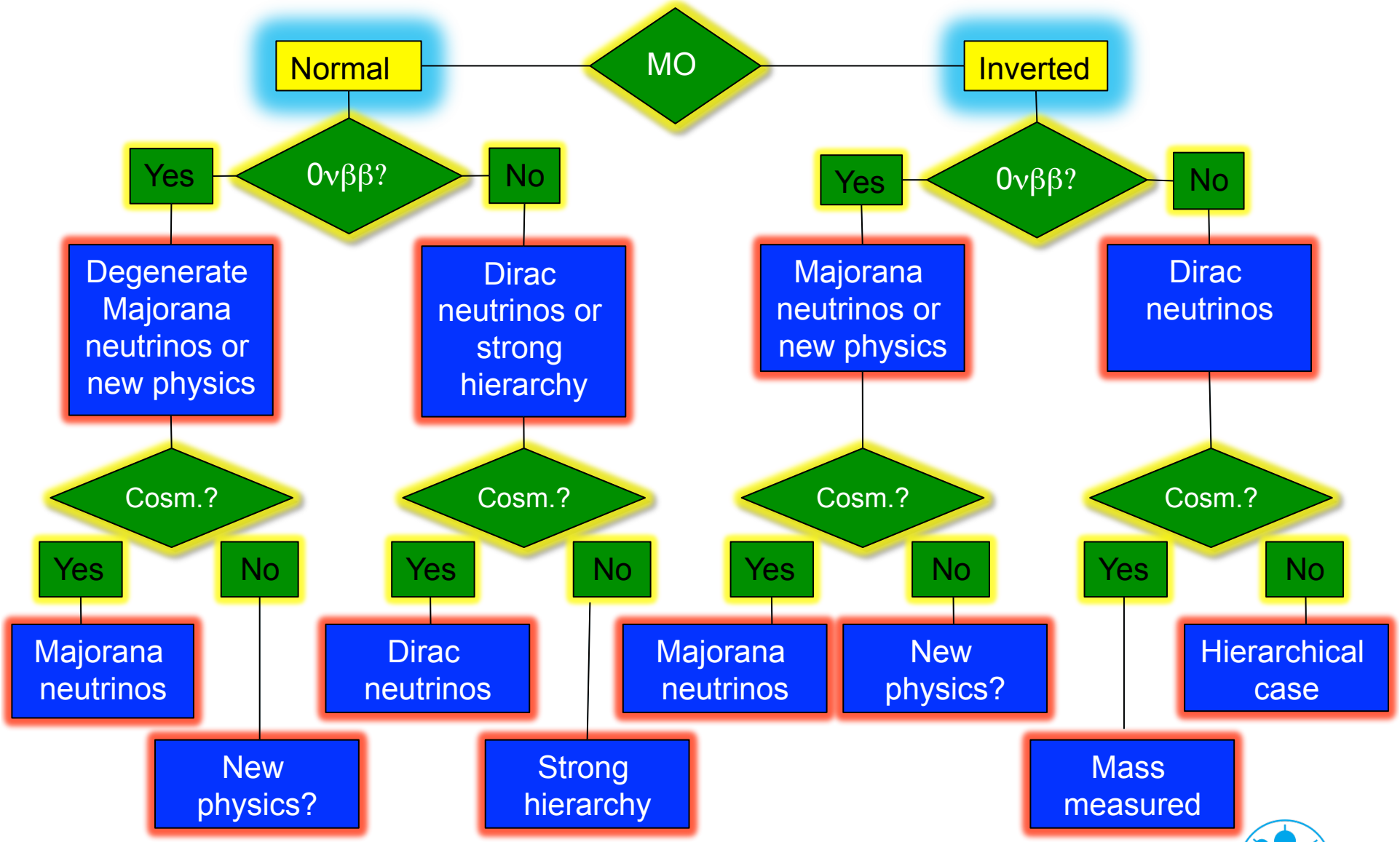
- If neutrinos are Majorana neutrinos, they will mediate 0νββ.
- The 0νββ rate depends on the hierarchy in degenerate regime:

(line corresponds to solid 0.3 eV bound)



(from: Lindner, Merle, Rodejohann, hep-ph/0512143; see talk by Martin Hirsch)

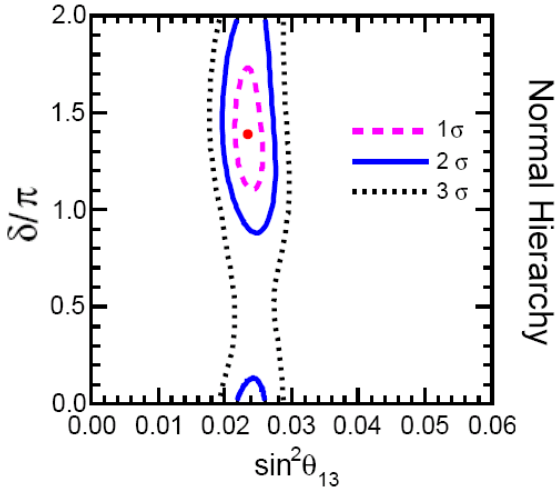
Impact of direct mass ordering (MO) measurement



How to measure the mass ordering?

Current status and perspectives for existing equipment

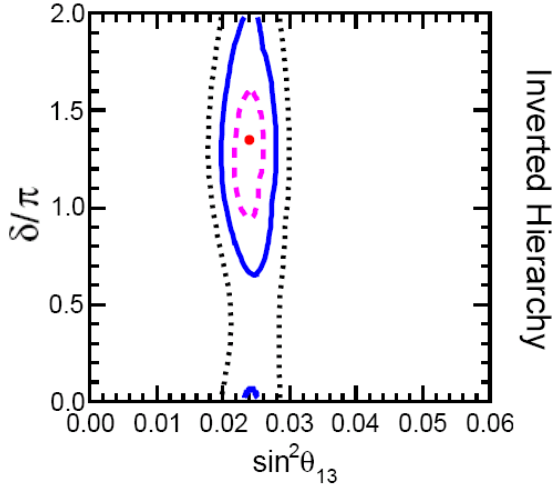
- Indication for δ_{CP}, no evidence for mass hierarchy



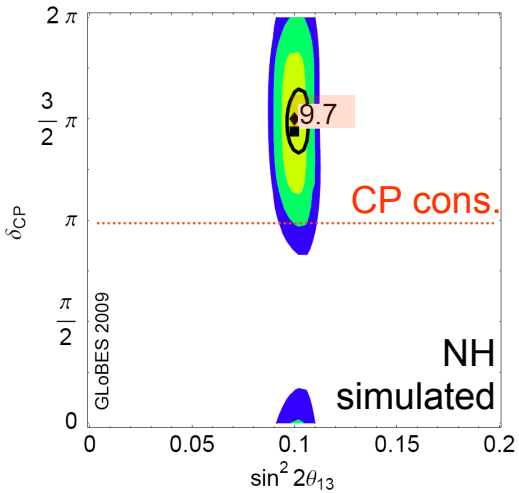
LBL Acc + Solar + KL
+ SBL Reactors
+ SK Atm

Capozzi et al, arXiv:1312.2878;
see also Forero, Tortola, Valle, arXiv:
1405.7540 and www.nu-fit.sorg

Main difference: NOvA data!



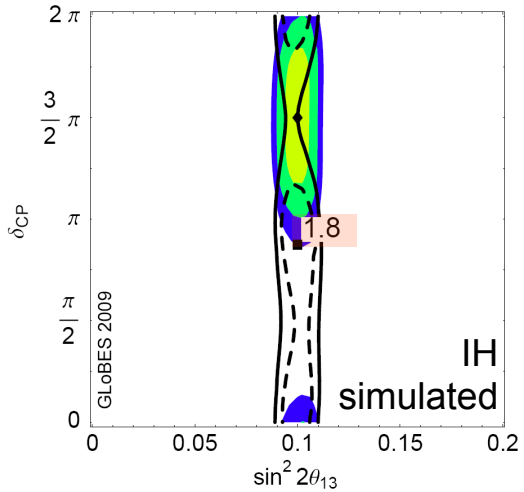
- Potential of existing equipment



T2K, NOvA,
Double Chooz, Daya Bay;
5 years each

High CL determination requires new equipment

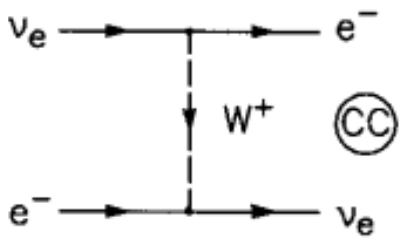
Huber, Lindner, Schwetz, Winter,
JHEP 0911 (2009) 044

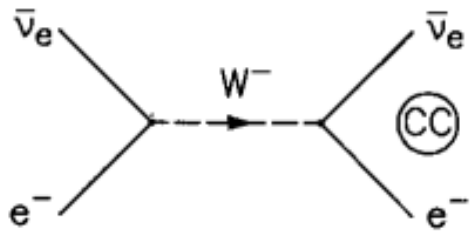


Method 1: Matter effects in neutrino oscillations

- 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)





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

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

Y: electron fraction ~ 0.5

(electrons per nucleon)

Parameter mapping … for two flavors, constant matter density

Oscillation probabilities in

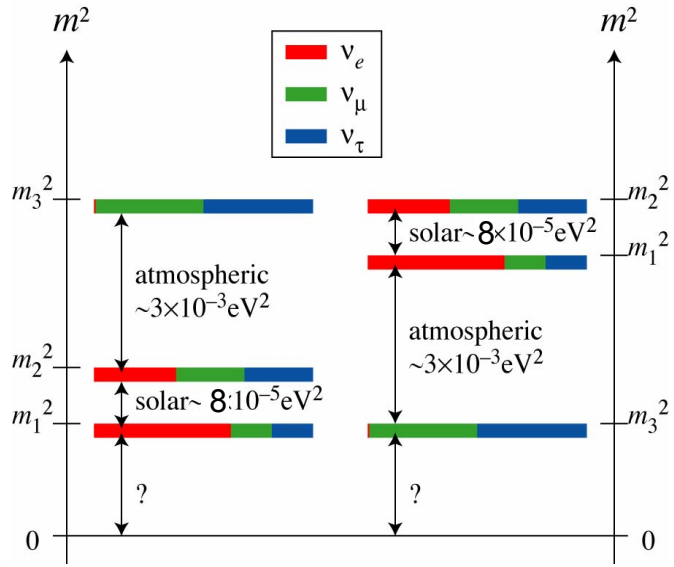
vacuum: $$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$$

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

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

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

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



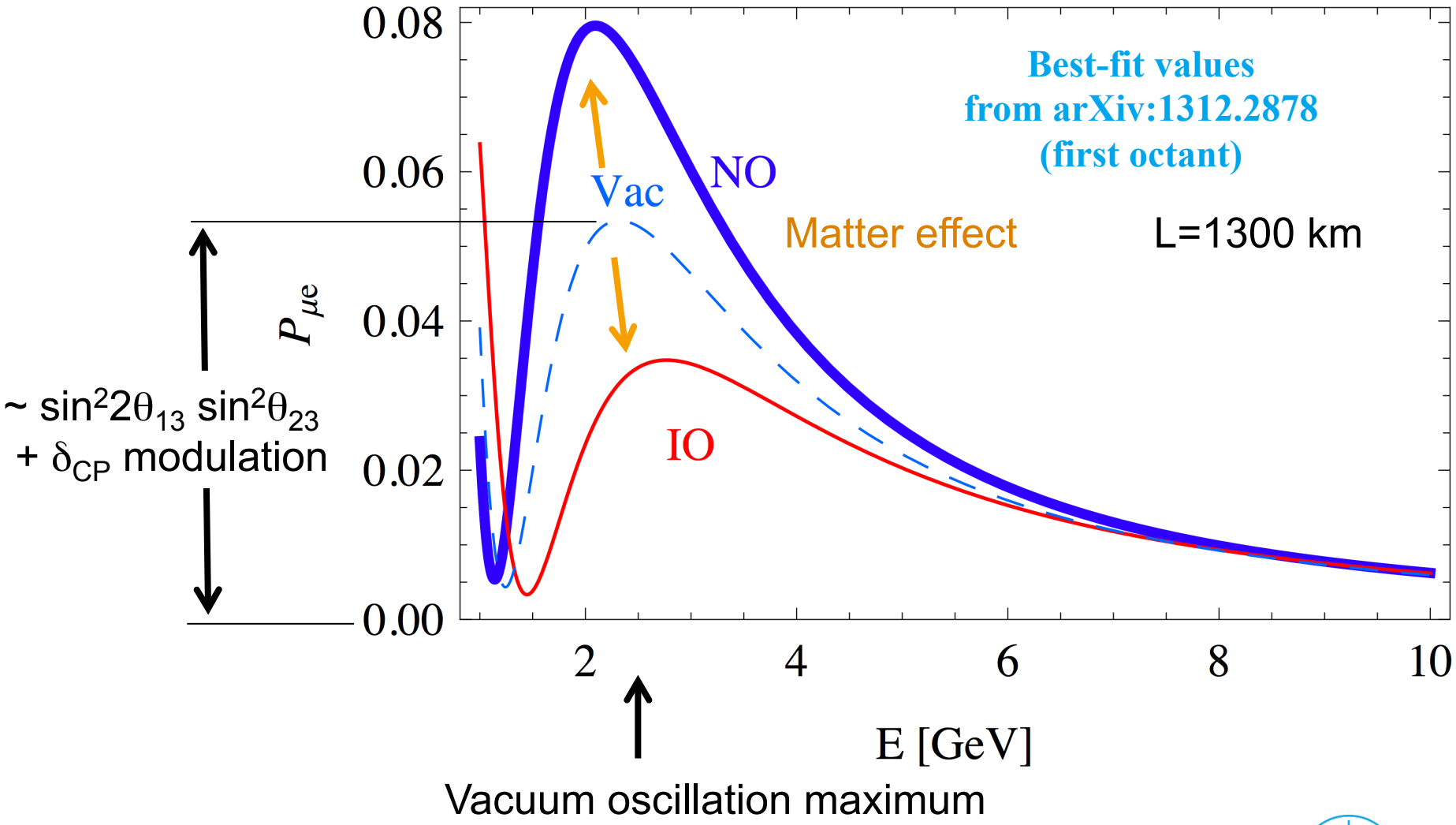
Normal $\Delta m_{31}^2 > 0$ Inverted $\Delta m_{31}^2 < 0$

Enhancement condition

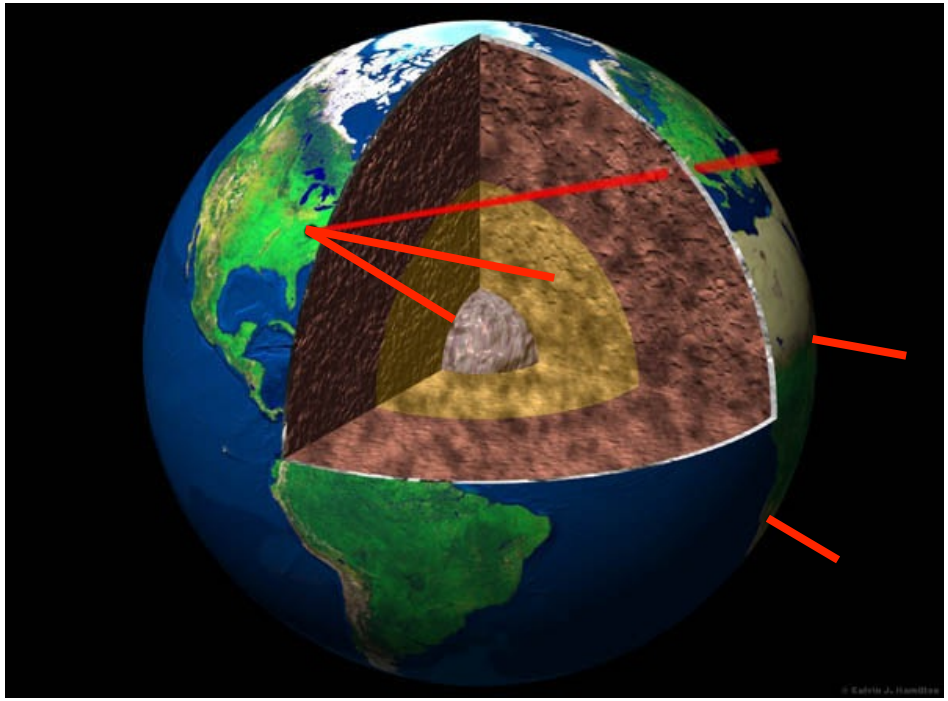
$$\cos 2\theta \rightarrow \hat{A}$$

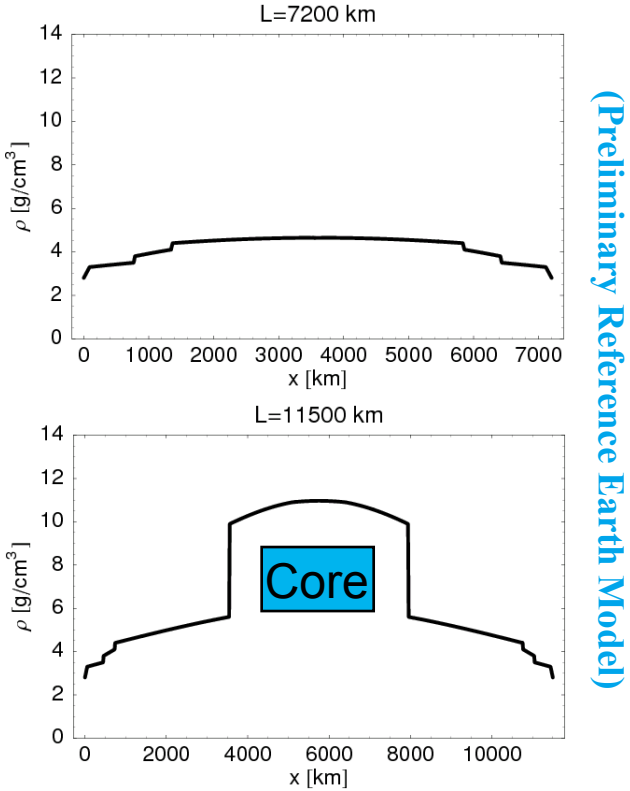
	Normal	**Inverted**
Neutrinos	Resonance	Suppression
Antineutrinos	Suppression	Resonance

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



Matter profile of the Earth … as seen by a neutrino





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

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

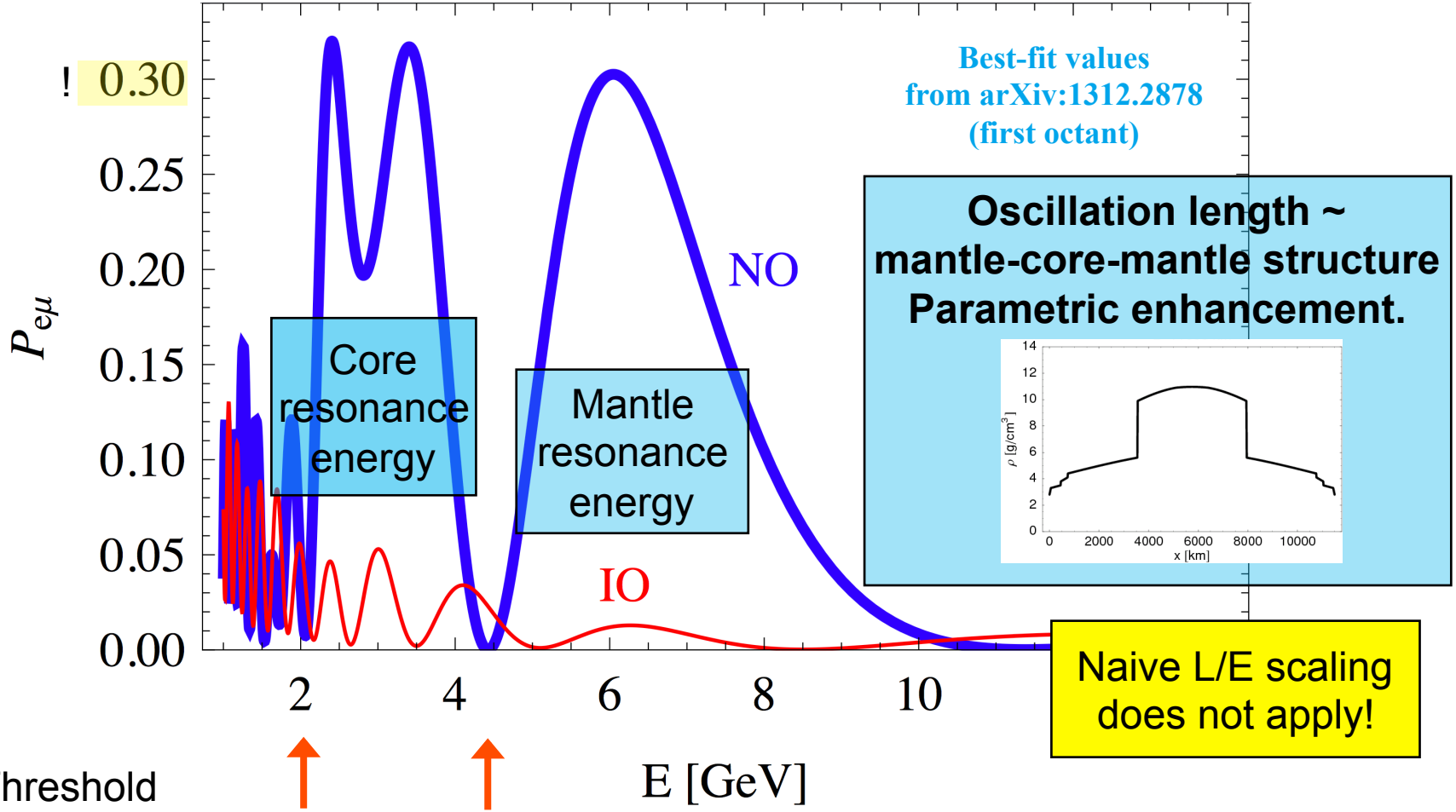
For ν_μ appearance, Δm_{31}^2:

- $\rho \sim 4.7$ g/cm^3 (Earth's mantle): **$E_{res} \sim 6.4$ GeV**
- $\rho \sim 10.8$ g/cm^3 (Earth's outer core): **$E_{res} \sim 2.8$ GeV**

Mantle-core-mantle profile

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

> Probability for L=11810 km



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

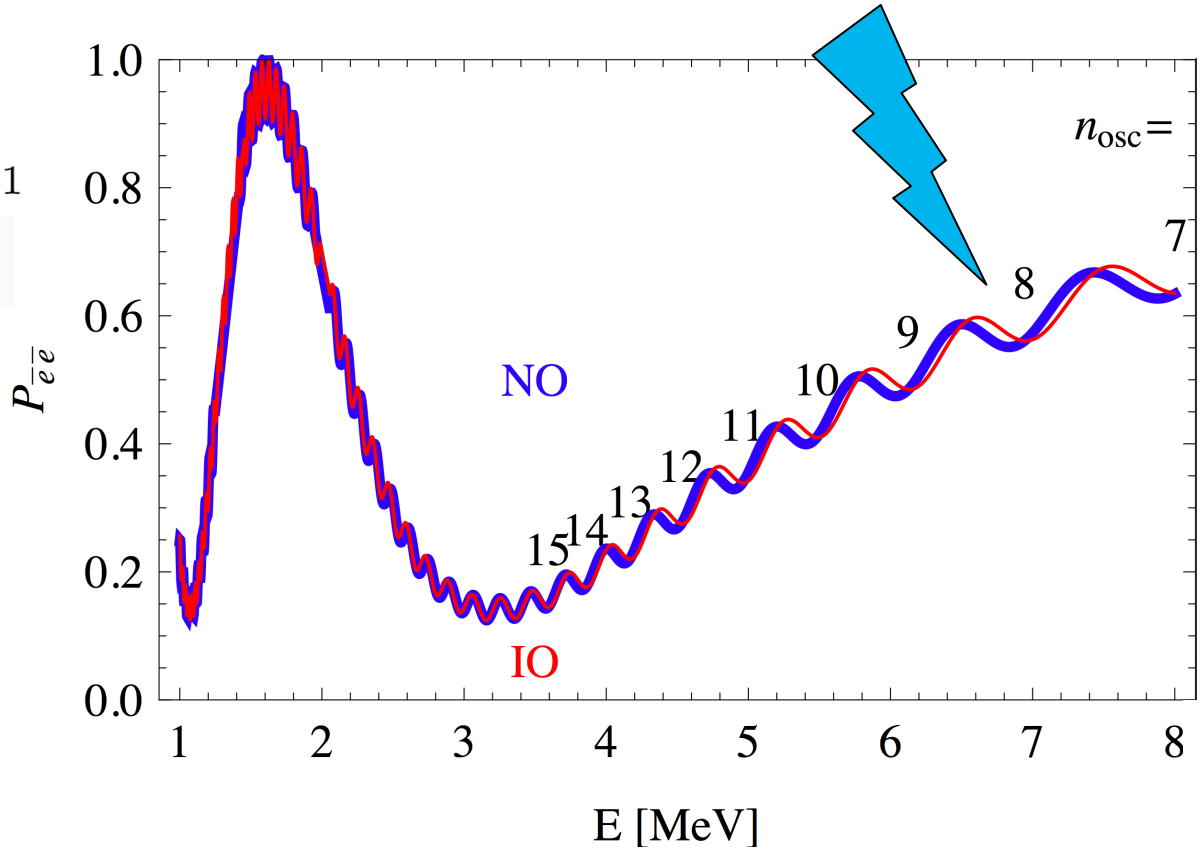
Method 2: Disappearance probabilities

- 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

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

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Probabilities apparently different (unphysical effect!)



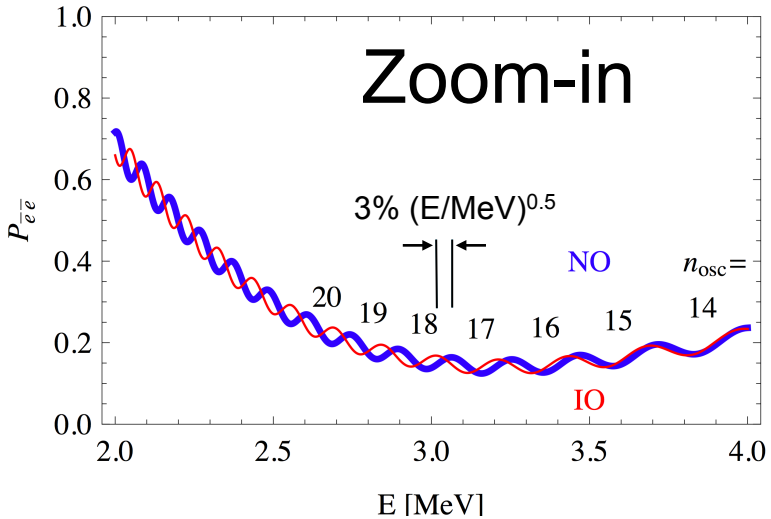
Method 2: Disappearance probabilities

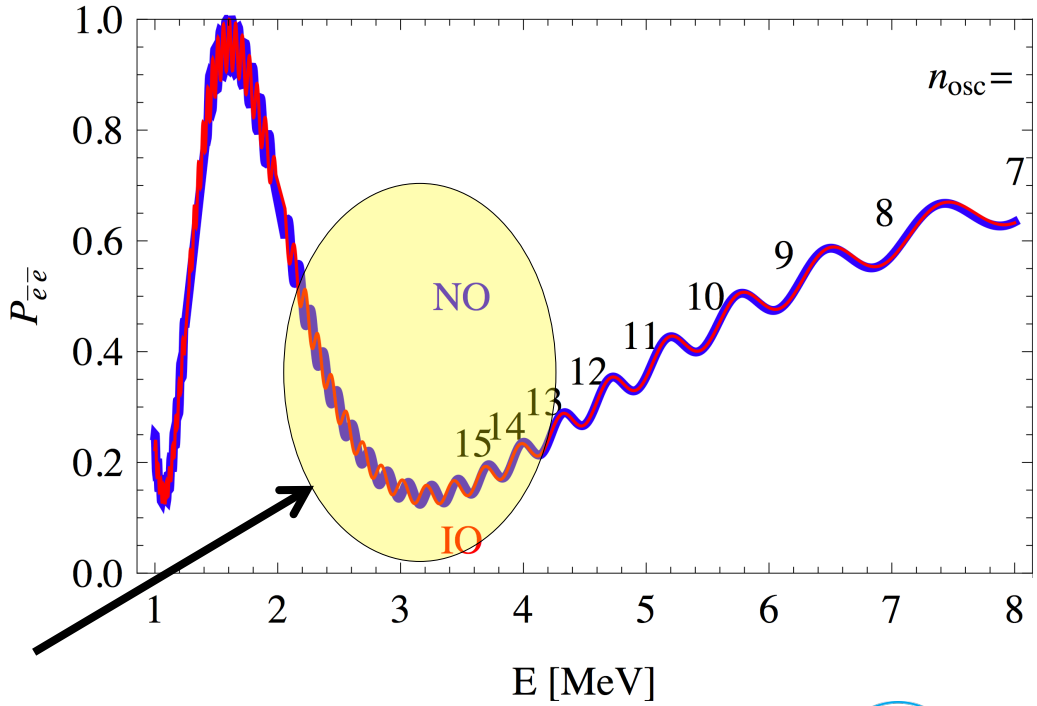
- The disappearance Δm^2 depends on the channel. Consequence e. g.

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

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

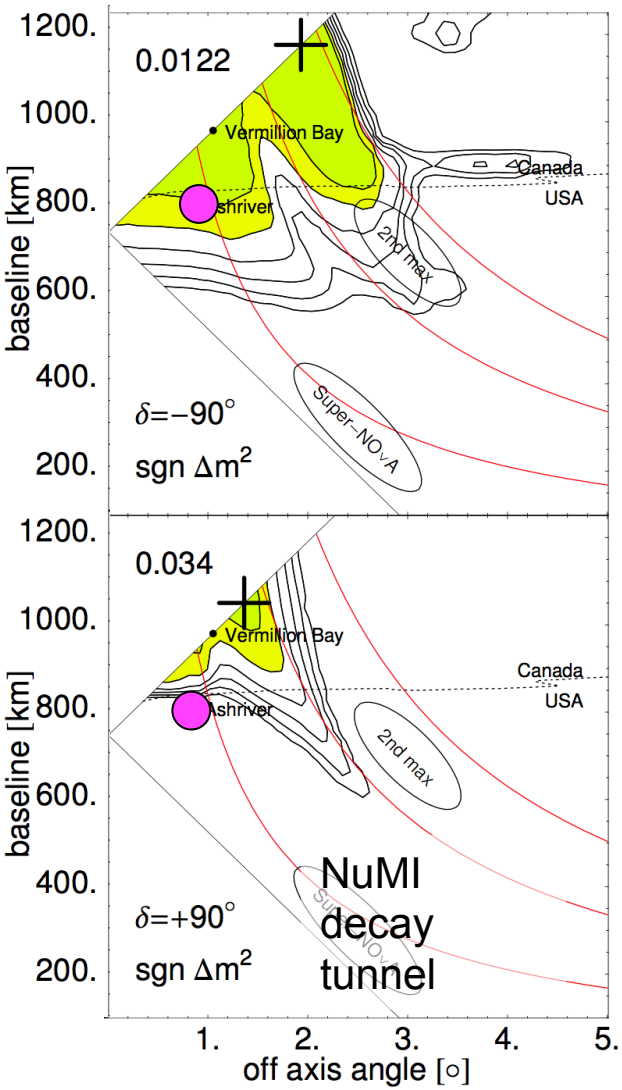
- Now first oscillation maxima match. Discrimination by higher osc. Maxima. Need energy resolution!





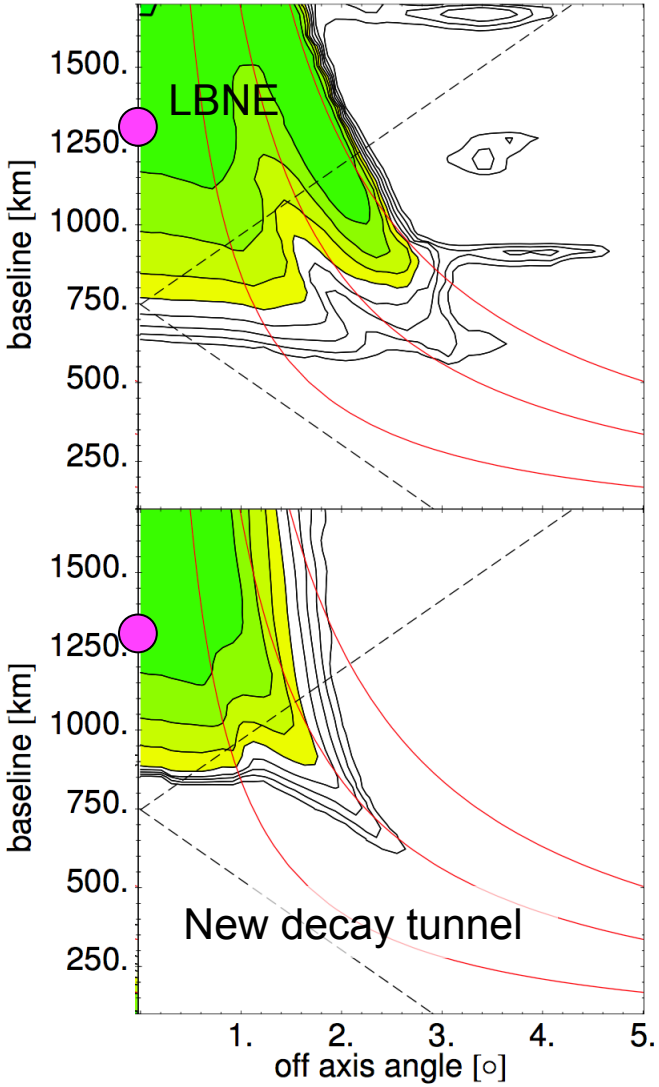
Technologies to measure the mass ordering

The “classics”: Long-baseline experiments



- Mass ordering wants long baselines >> 500 km and energies ~ few GeV
- LBNE optimal for mass hierarchy

(Barger, Huber, Marfatia, Winter, hep-ph/0703029; see also LBNE, arXiv: 1311.0212)

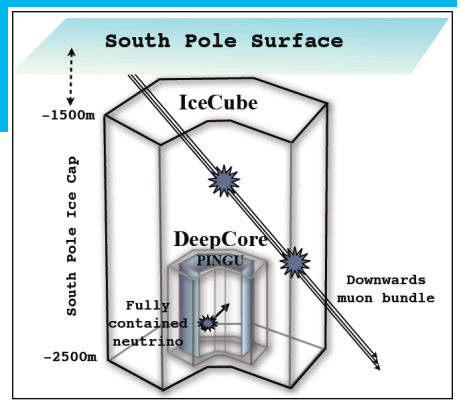


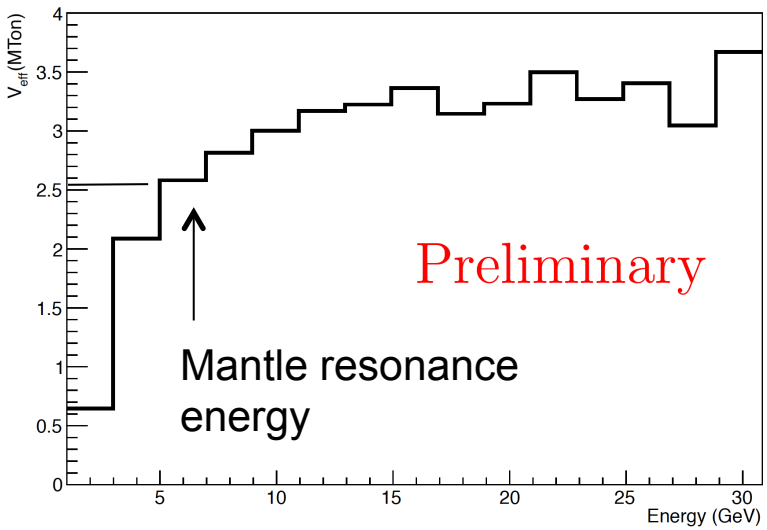
See talks this afternoon …

Emerging technologies: Atmospheric νs

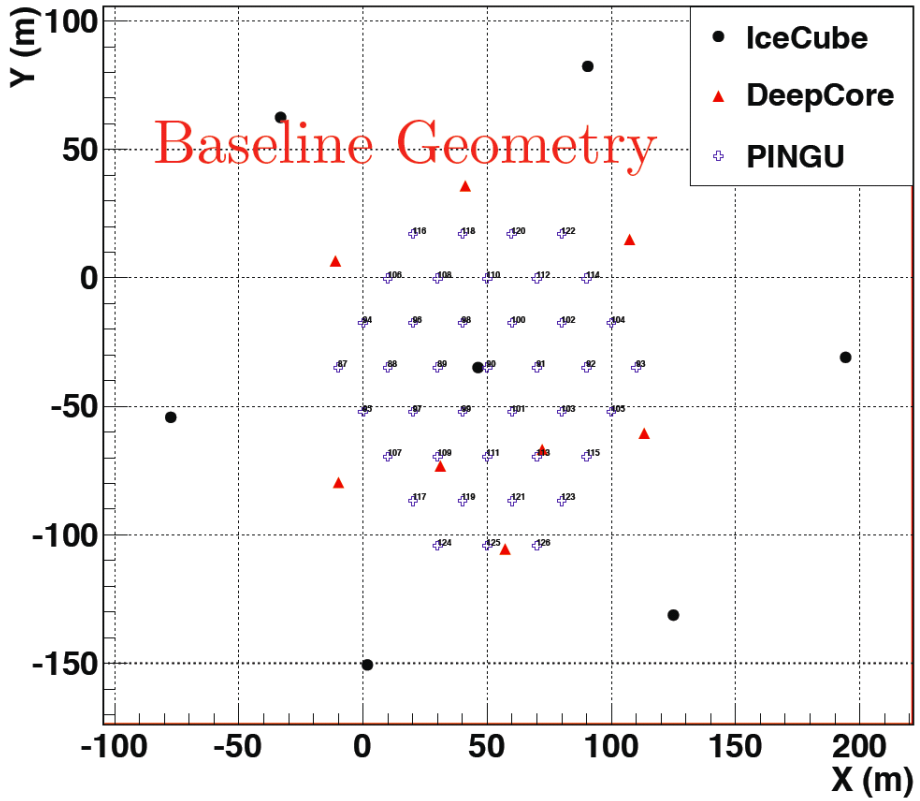
- Example: PINGU
  (“Precision IceCube Next Generation Upgrade“)
- 40 additional strings, 60 optical modules each
- Lower threshold, few Mtons at a few GeV
- ORCA, INO: similar methods

Talks by M. de Jong, D. Grant, D. Indumathi





(a) $V_{\rm eff}(\nu_\mu)$

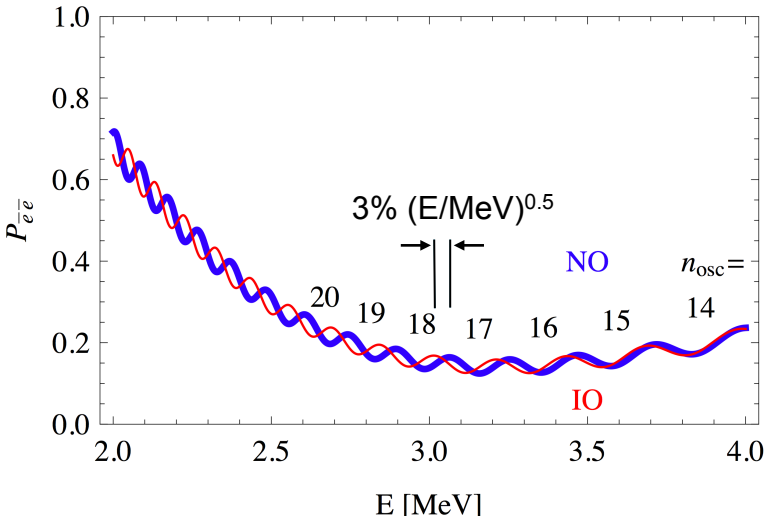


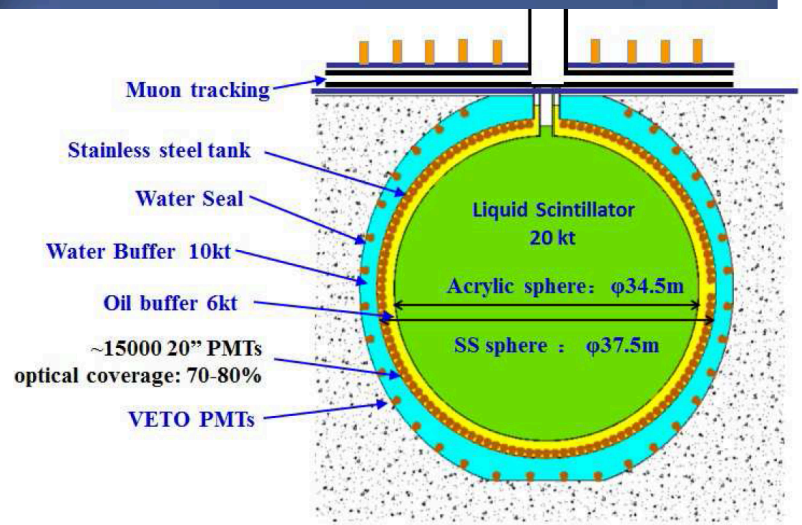
(PINGU LOI, arXiv:1401.2046)

Emerging technologies 2: Reactor experiments

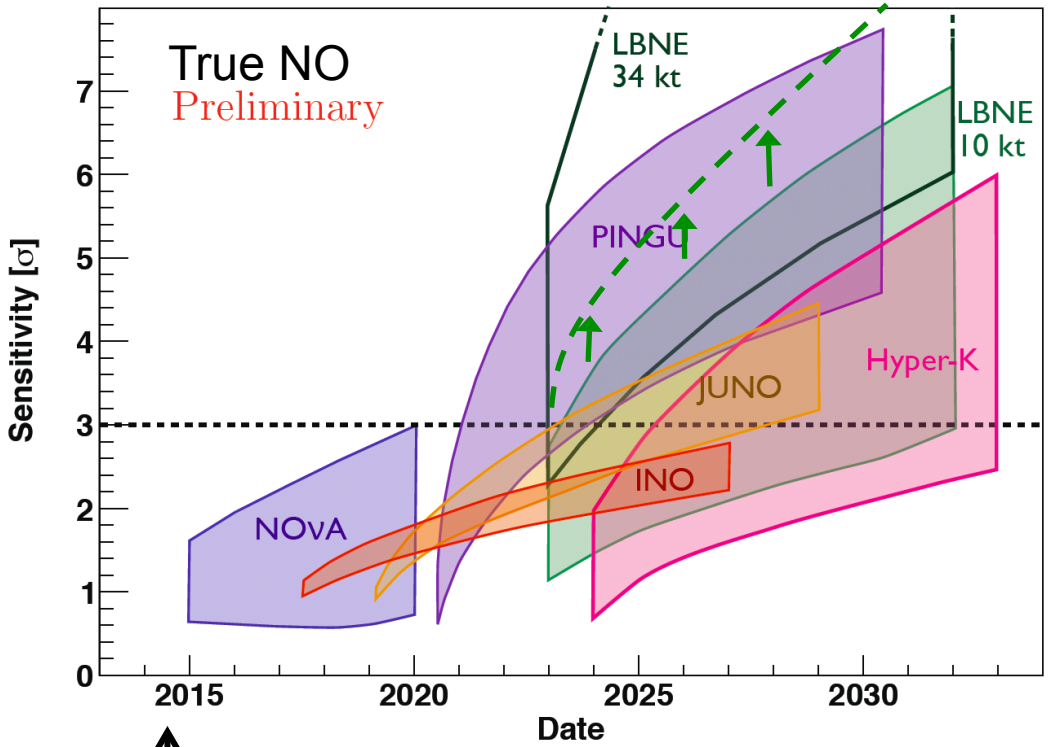
See talk by Liangian Wen

- Jiangmen Underground Neutrino Observatory (JUNO) [formerly Daya Bay-II]
- L=53 km
- Excellent energy resoluton (3% (E/MeV)$^{0.5}$) requires O(100%) PMT coverage

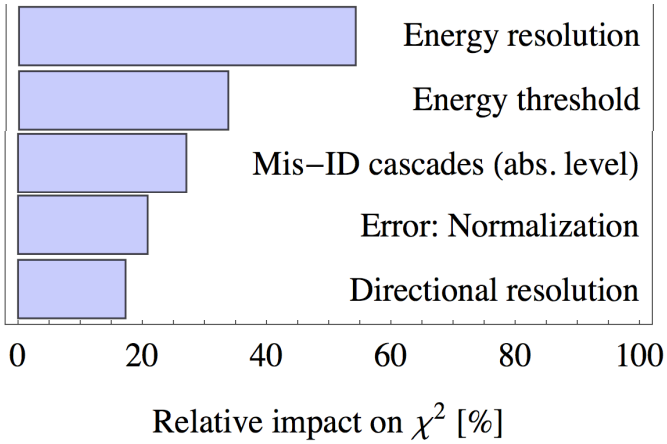




Time evolution, risks?



(version from PINGU LOI, arXiv:1401.2046; based on Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822v1; LBNE dashed curve from arXiv:1311.1822v2)



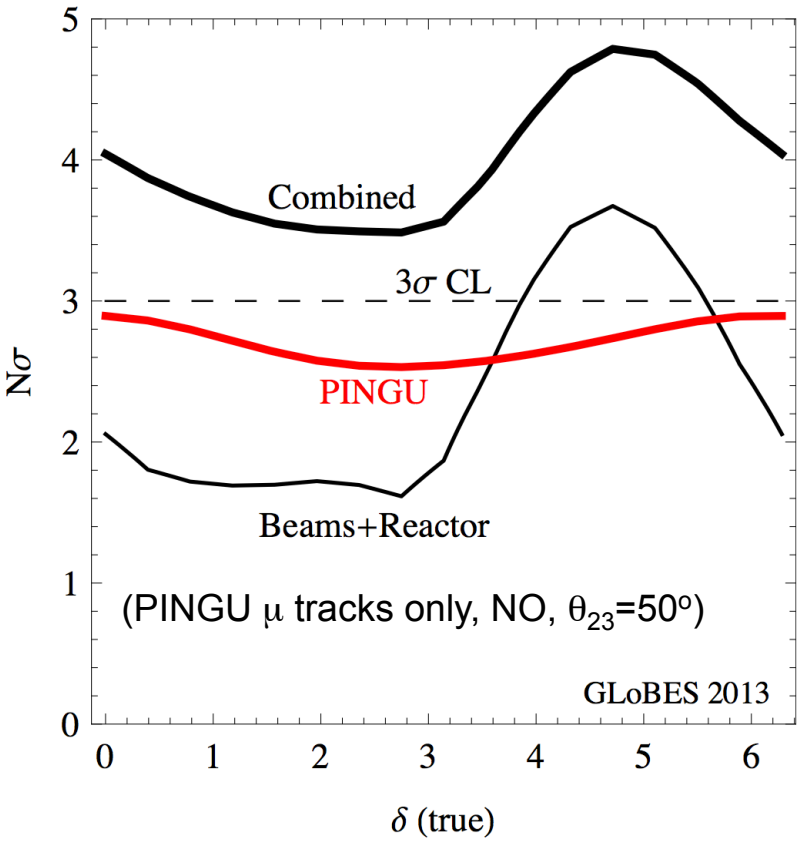
Bands:

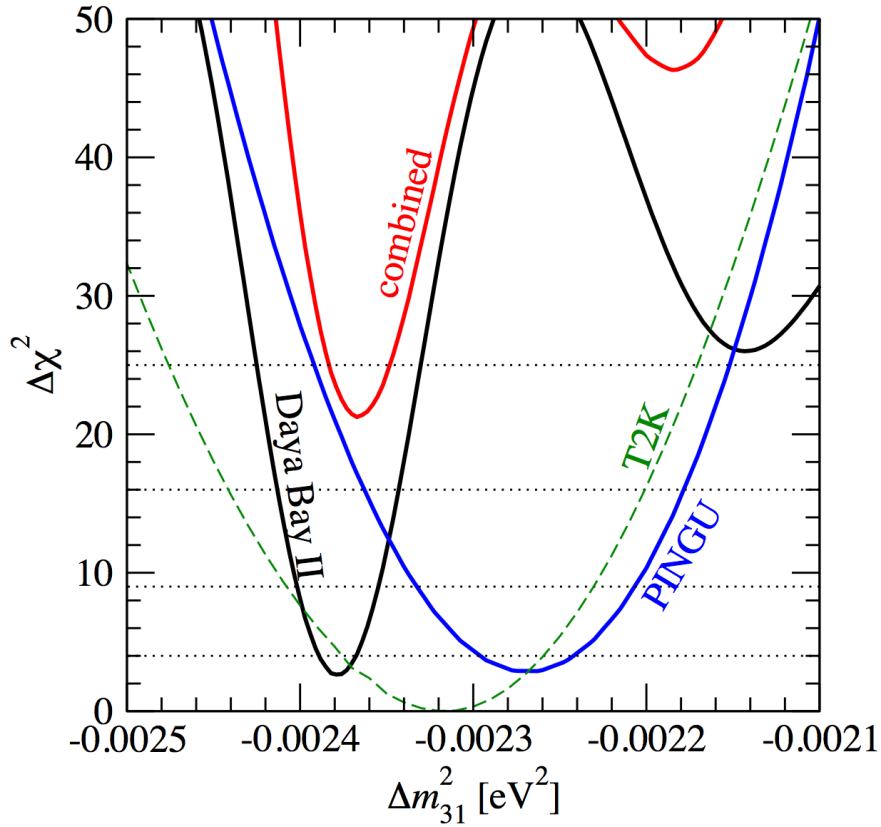
- Beam experiments: δ_{CP}
- PINGU, INO: θ_{23}
- JUNO: Energy resolution (3%-3.5%) $(E/MeV)^{0.5}$

Caveats:

- LBNE sensitivity scales with (true) θ_{23} as well (dashed curve)
  see e.g. Fig. 9 in arXiv:1305.5539
- Energy resolution, directional resolution etc major challenges for PINGU/INO as well
  WW, arXiv:1305.5539

Benefits of having different techniques





- Complementarity different impact of δ_{CP} (true)
  WW, arXiv:1305.5539;
  see also (for INO): Ghosh, Thakore, Choubey, arXiv:1212.1305

- Synergy by combination of different parameter space topologies
  Blennow, Schwetz, arXiv:1306.3988

Summary and conclusions

- The mass ordering is one of the prime indicators of flavor models
- Meaningful statements on neutrino mass schemes and nature of neutrino mass require direct measurent of neutrino mass ordering, as well as $0\nu\beta\beta$ and cosmology/direct neutrino mass bounds
- There are currently three approaches to the mass ordering measurement:

	Long baseline beam (e. g. LBNE)	Atmospheric (e. g. PINGU)	Reactor long baseline
Benefit	Robust, clean signal	Predictable timescale/cost	Independent technology
Risk (osc. params.)	δ_{CP}, θ_{23}	θ_{23}	-
Challenges	Timescale	Energy res., directional res., particle ID	Energy resolution!!!

- Having all three approaches will guarantee high-CL determination and independent confirmation