Neutrino Oscillation Experiments

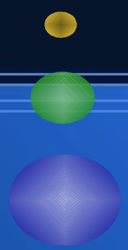
Neutrino Mixing

ν_e

ν_μ

ν_τ

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$



m$_1$

m$_2$

m$_3$

Oscillation physics

ββ0ν

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

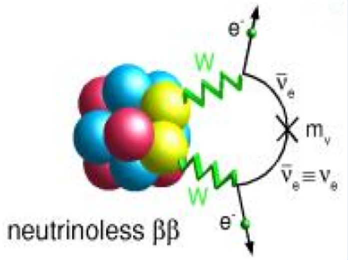
θ_{23}

interference sector

θ_{13}, δ

Solar sector

θ_{12}

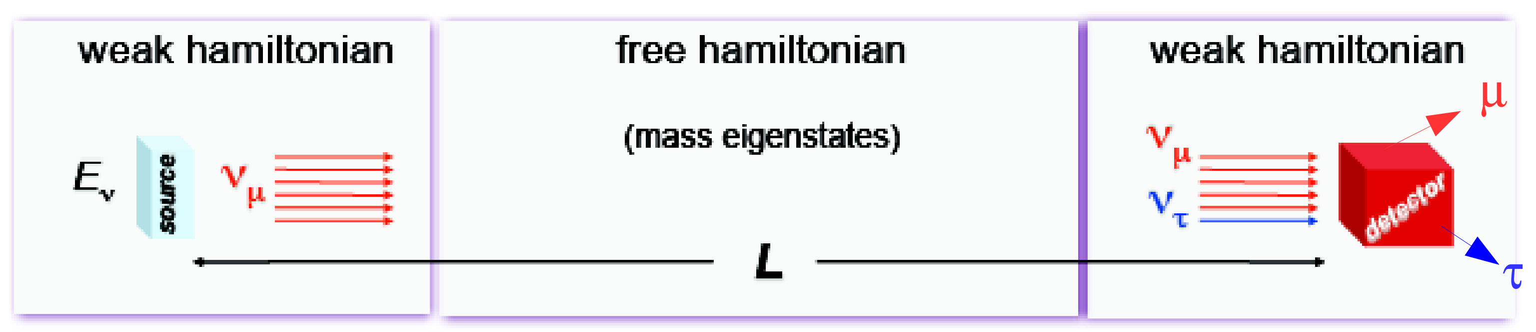


α_1, α_2

Physics Beyond The Standard Model!!!

Neutrino Oscillations

- If neutrinos are massive and have different masses…



Oscillation parameters: $(\theta_{12}, \theta_{13}, \theta_{23})$, $(\Delta m^2_{21}, \Delta m^2_{31})$, δ

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

Oscillation probability:

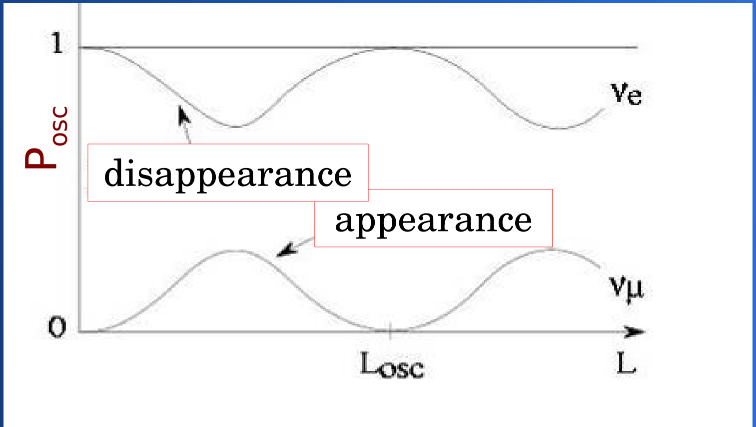
$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = |\sum_{i=1}^{n} \sum_{j=1}^{n} U_{\alpha i}^* U_{\beta j} \langle \nu_j | \nu_i(t) \rangle|^2$$

If θ_{13} small and $\Delta m^2_{21} << \Delta m^2_{32}$: 2ν oscillation

amplitude

frequency

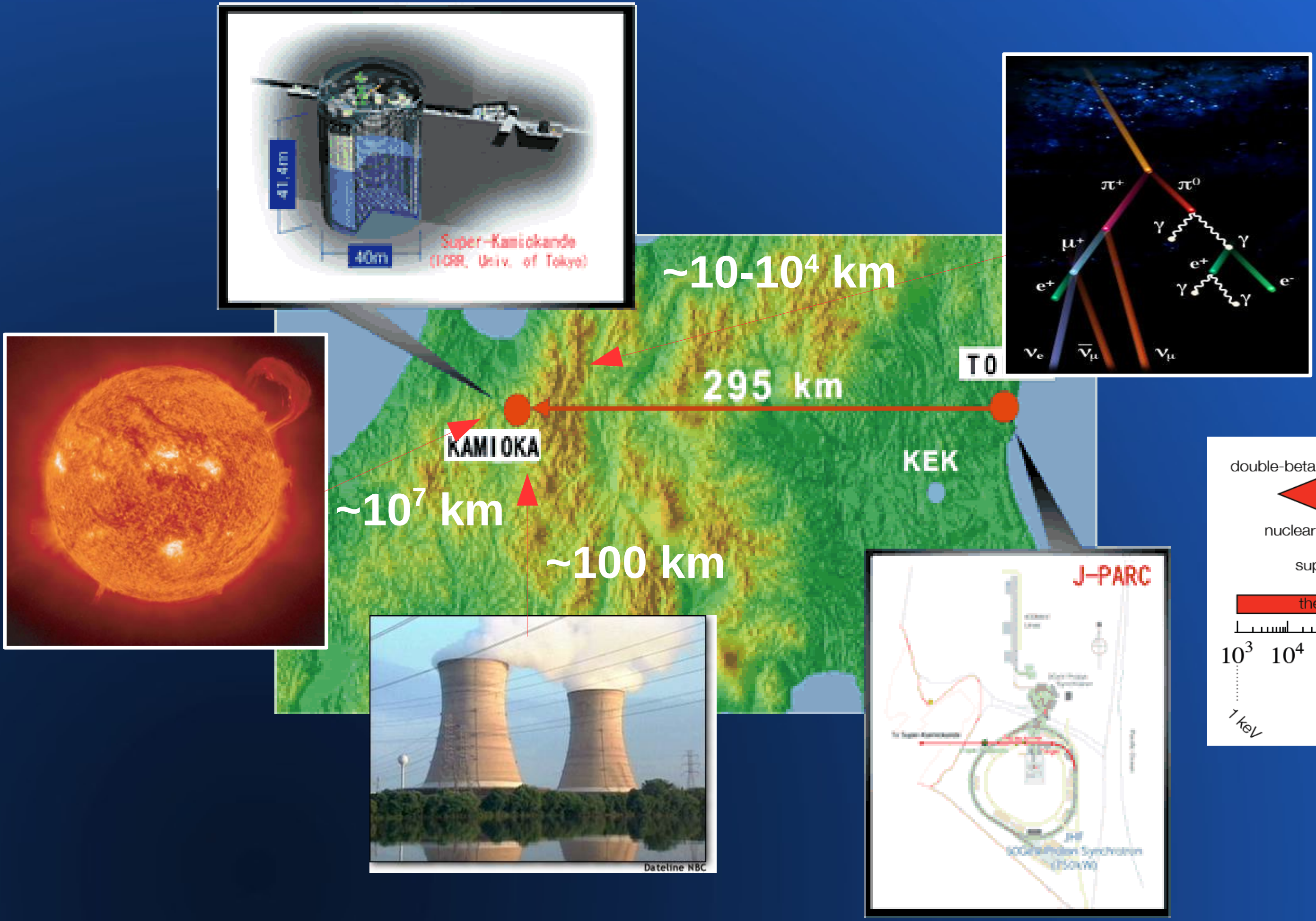
$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$



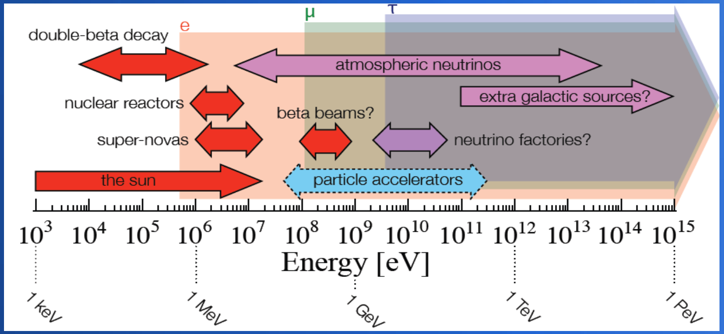
Oscillation probability is a function of L/E

Physics Beyond The Standard Model!!!

Neutrino Sources and Baselines



- Natural and human-made sources
- Wide range of energies
- Several possible baselines

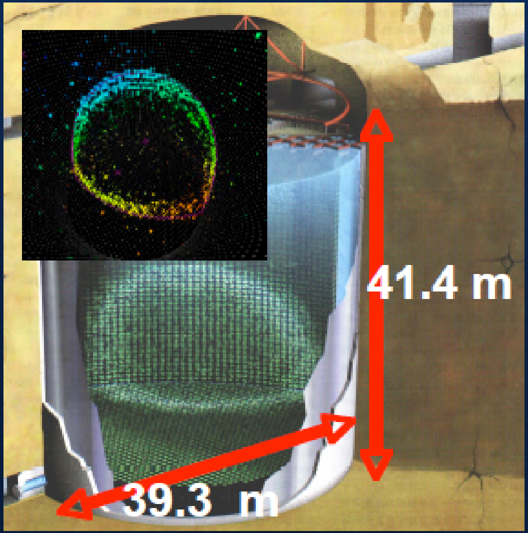


Neutrino Detectors

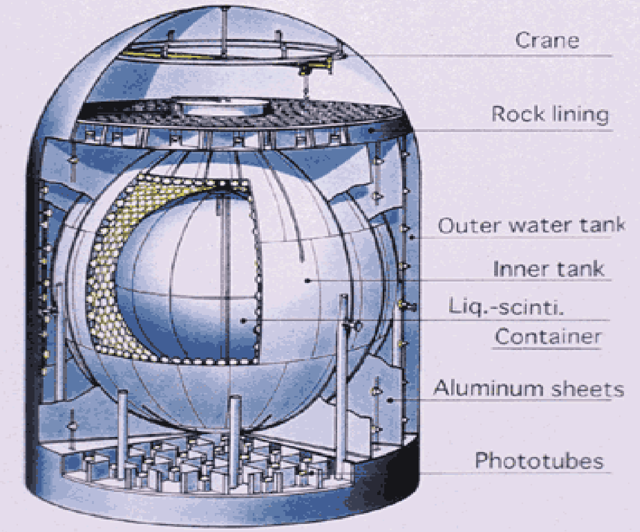
- Radiochemical experiments: Homestake, Gallex, ...
- Cherenkov: SuperKamiokande, MiniBooNE,...
- Scintillator calorimeters: KamLAND, Double Chooz..
- Tracking calorimeters: MINOS, NOvA, …
- LAr TPCs: ICARUS, MicroBooNE, DUNE,
- Emulsions: OPERA

MINOS

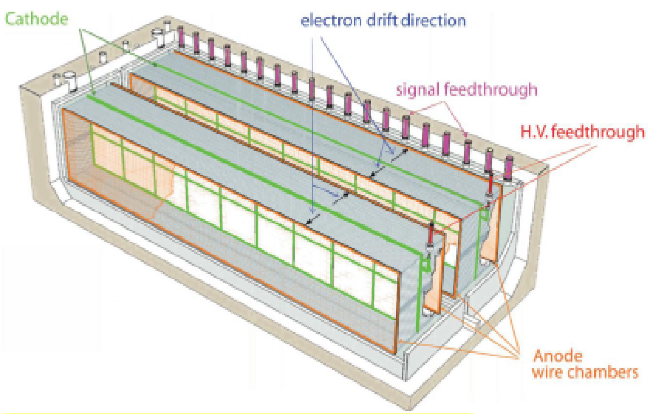
SuperK



KamLAND



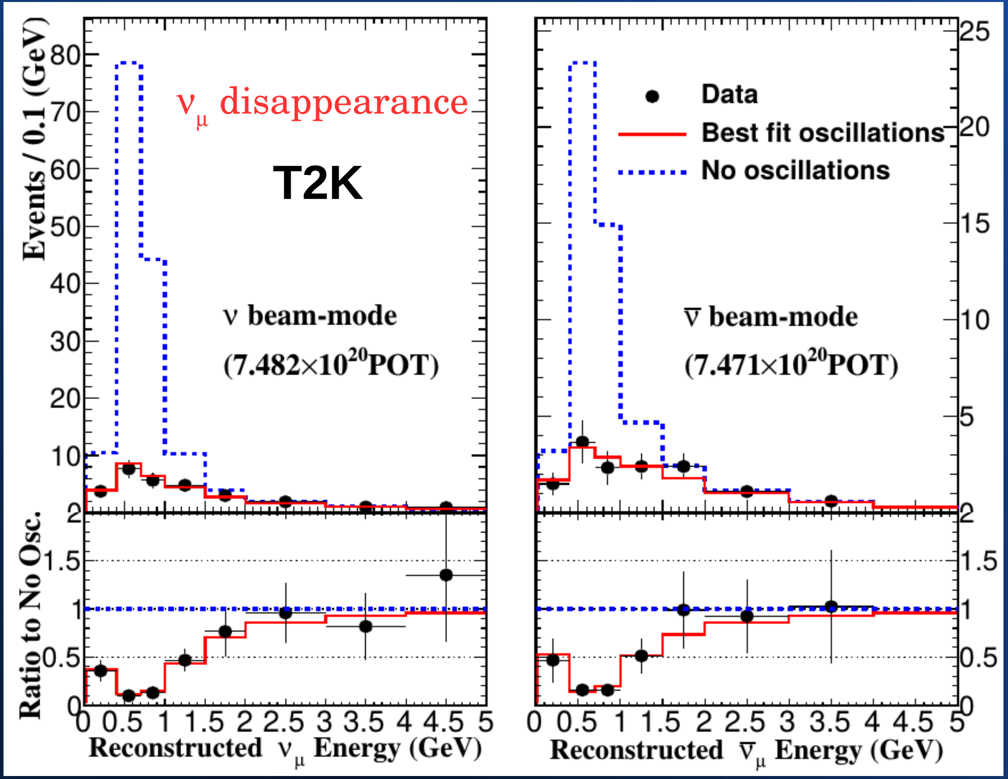
ICARUS

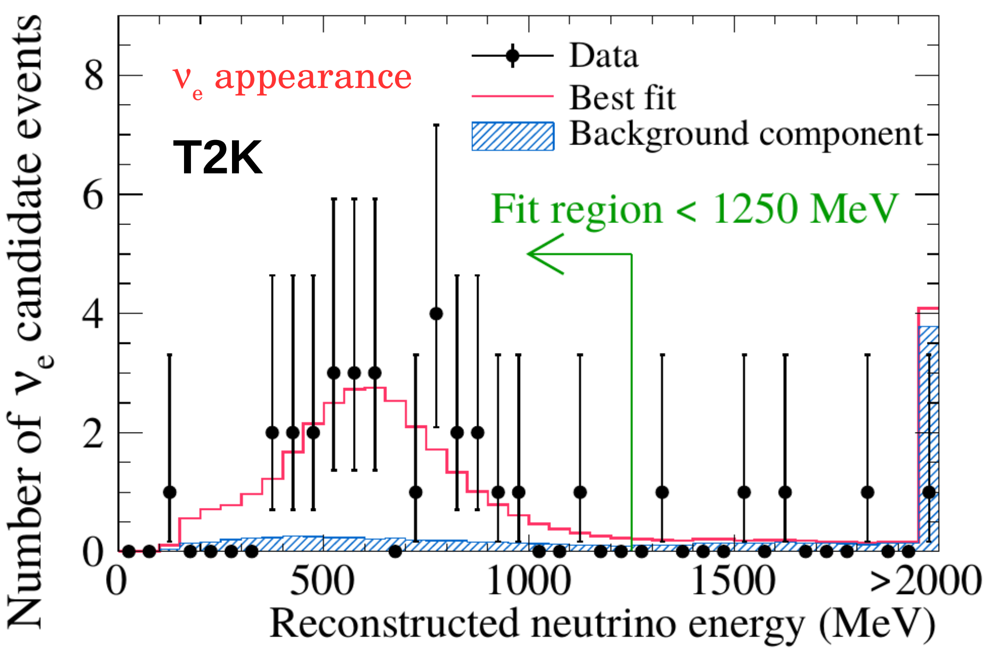


Huge mass to compensate the low ν xsections!

Neutrino Oscillation Signal

- Disappearance: deficit in the observed neutrinos and distortion in the E spectrum
- Appearance: observation of an unexpected neutrino flavor



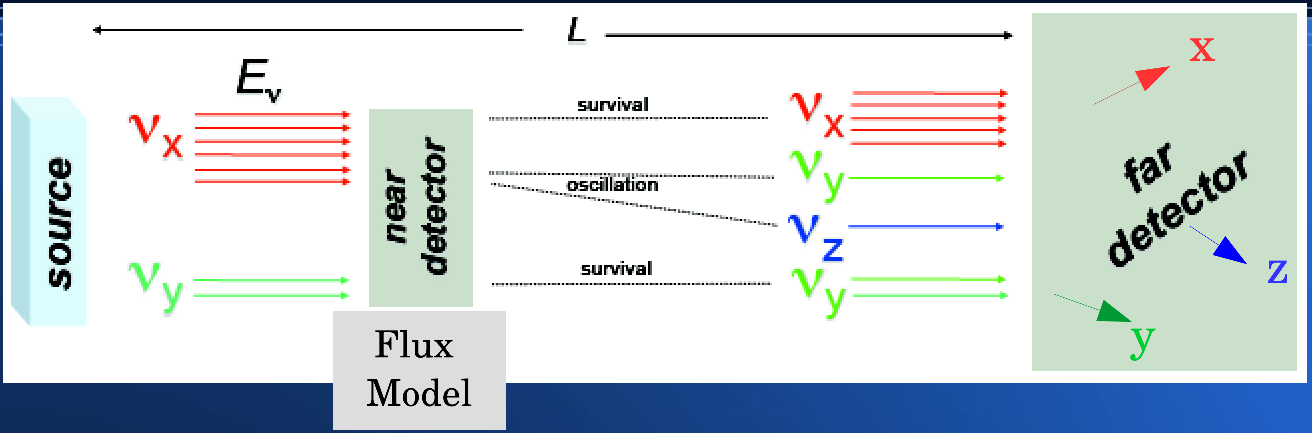


- Oscillation parameters estimation: fit observed data to the model:

$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$

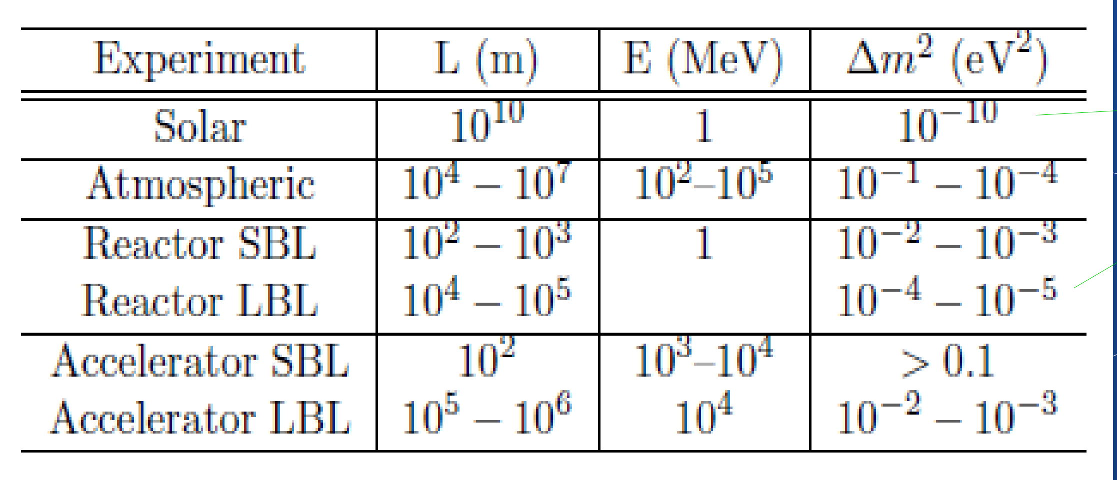
Neutrino Experiments

Known flux before oscillation



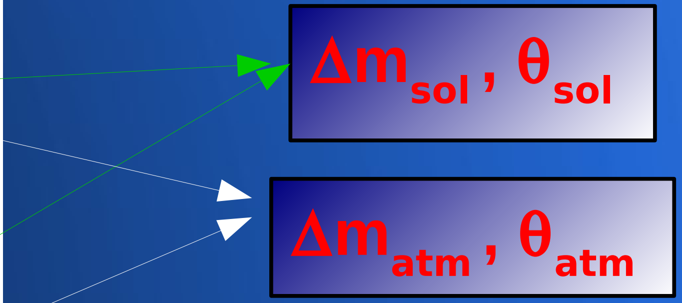
Comparison with no-oscillation expectation

Experiment classification depending on L/E



Experiment	L (m)	E (MeV)	Δm^2 (eV^2)
Solar	10^{10}	1	10^{-10}
Atmospheric	$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor SBL Reactor LBL	$10^2 - 10^3$ $10^4 - 10^5$	1	$10^{-2} - 10^{-3}$ $10^{-4} - 10^{-5}$
Accelerator SBL Accelerator LBL	10^2 $10^5 - 10^6$	10^3–10^4 10^4	> 0.1 $10^{-2} - 10^{-3}$

2ν Oscillations



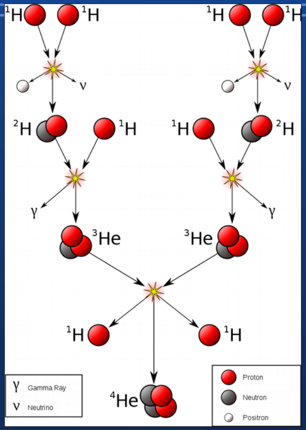
Δm_{sol} , θ_{sol}

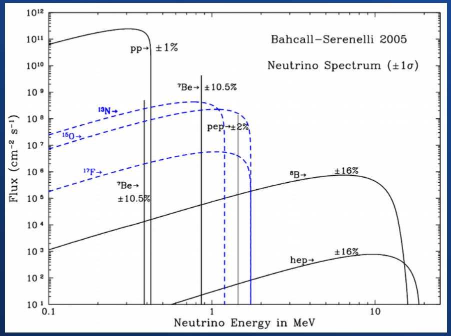
Δm_{atm} , θ_{atm}

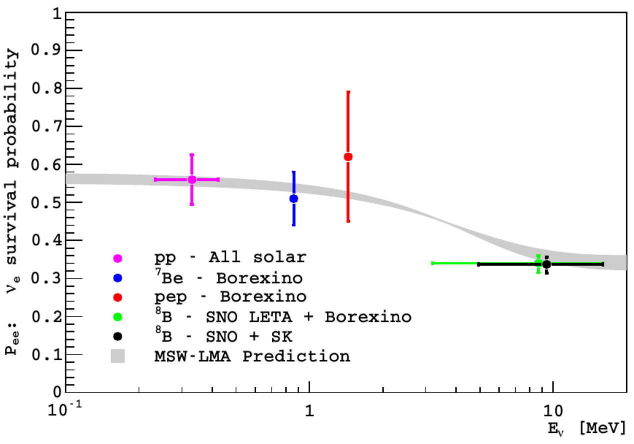
$$P_{\alpha\beta} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$

Solar and Atm. Experiments

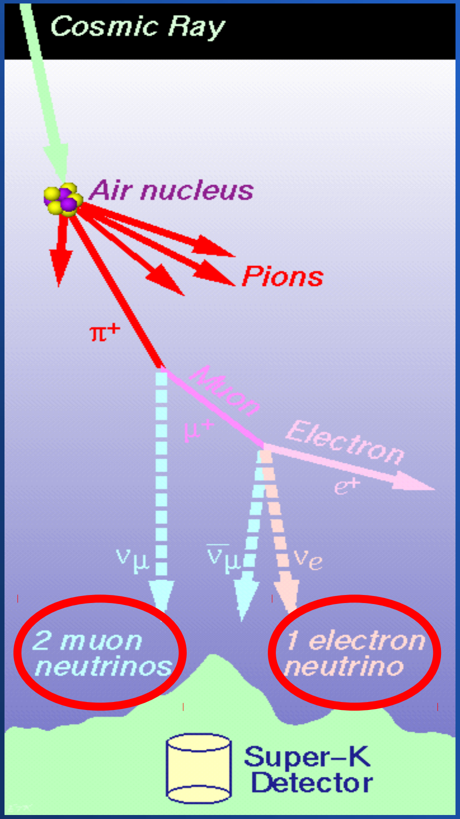
Solar



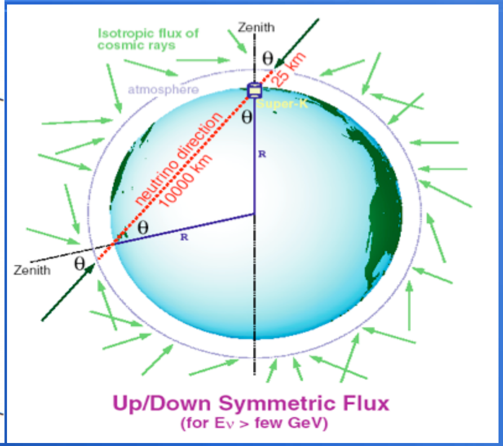


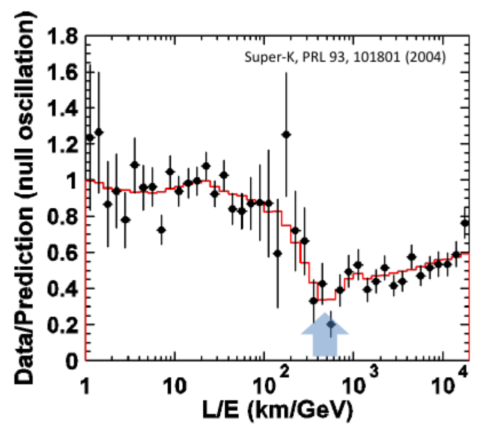


Atmospheric



$L/E \sim 1 - 10^4$ km/GeV



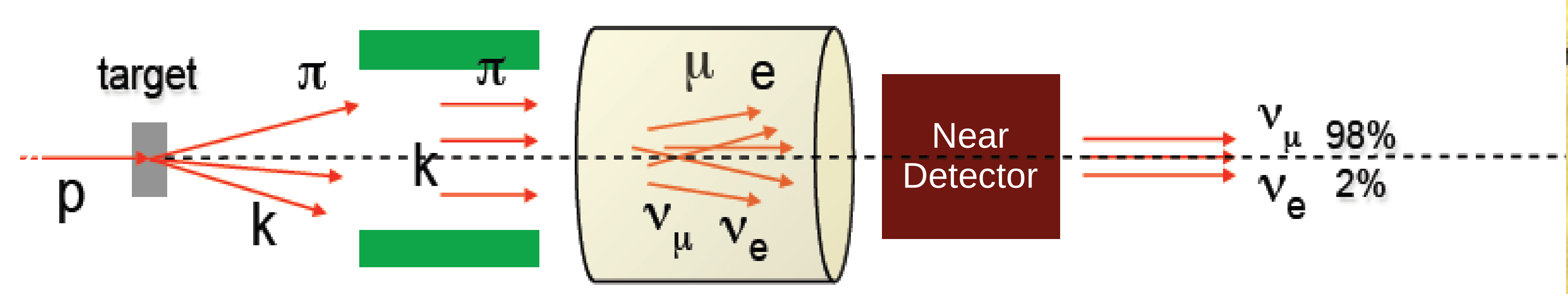


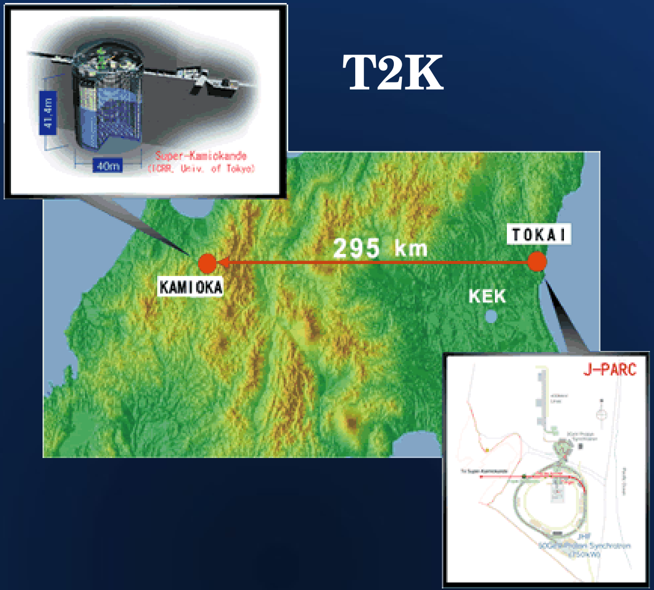
θ_{sol}, Δm^2_{sol}
measurement

2ν Disappearance experiments

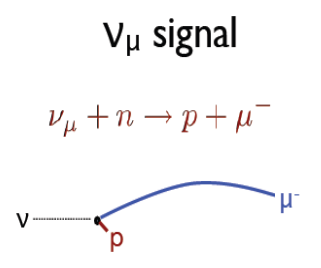
θ_{atm}, $|\Delta m^2_{atm}|$
measurement

Accelerator Experiments





T2K

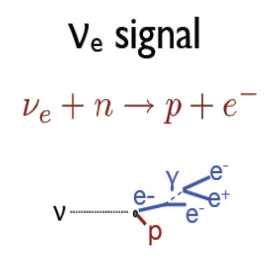


ν_μ signal

$$\nu_\mu + n \rightarrow p + \mu^-$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - sin^2 2\theta_{23} sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right)$$ ► θ_{atm}, $|\Delta m^2_{atm}|$

Disappearance experiment



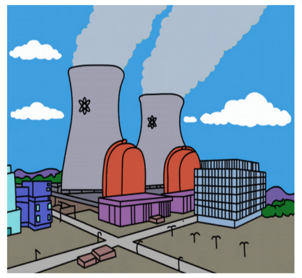
ν_e signal

$$\nu_e + n \rightarrow p + e^-$$

$$P(\nu_\mu \rightarrow \nu_e) \approx sin^2 2\theta_{13} sin^2\theta_{23} sin^2 \left(\frac{\Delta m^2_{31} L}{4E}\right)$$ ► θ_{13}

Appearance experiment

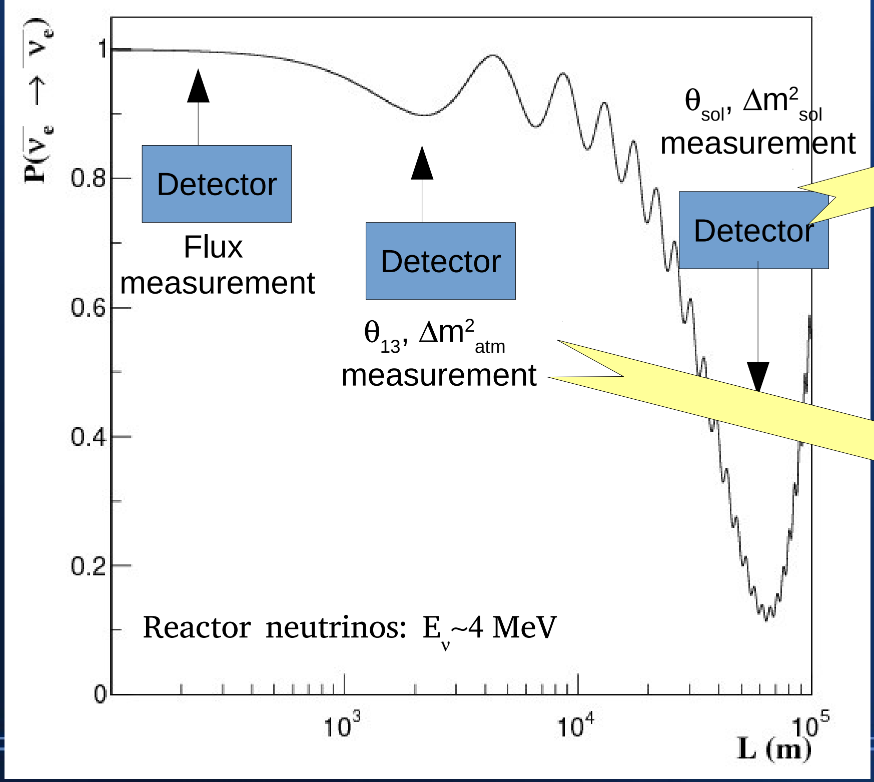
Reactor Neutrino experiments

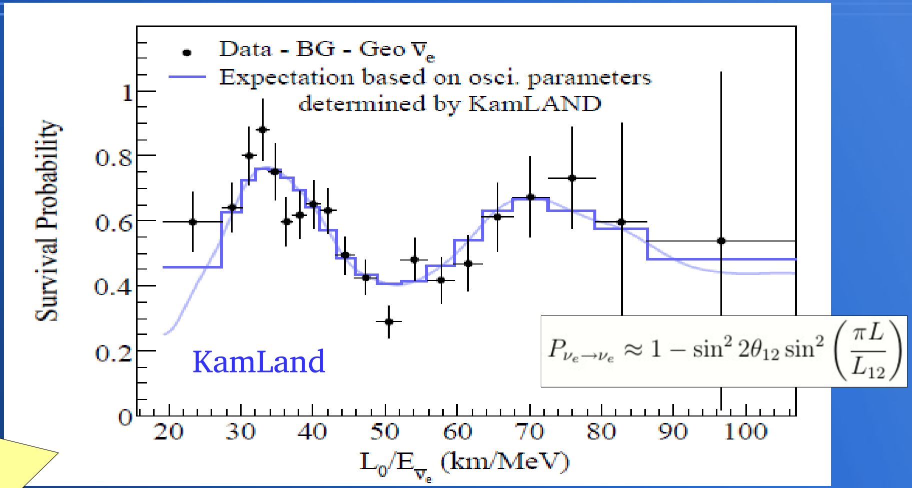


Nuclear Reactors:
intense source of $\bar{\nu}_e$

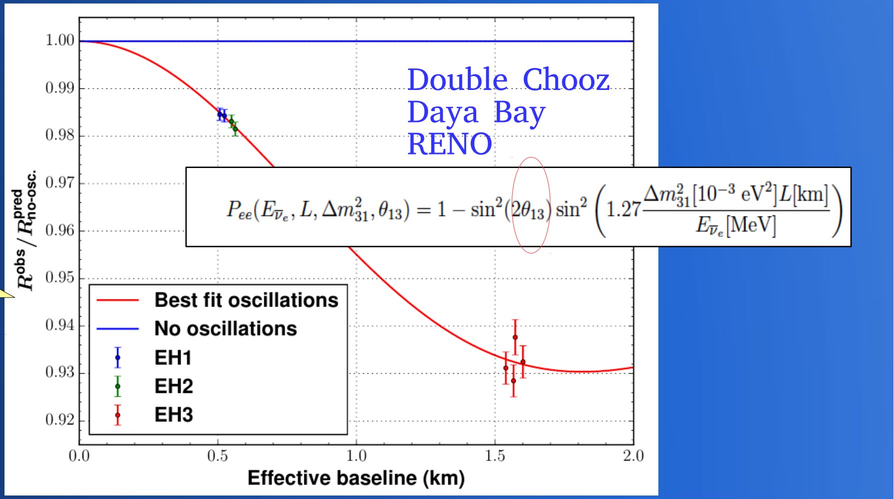
Disappearance probability

IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$





$$P_{\nu_e \rightarrow \nu_e} \approx 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\pi L}{L_{12}} \right)$$

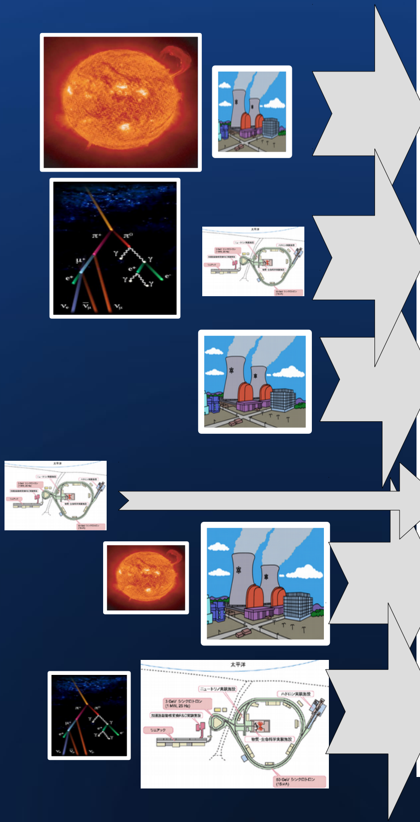


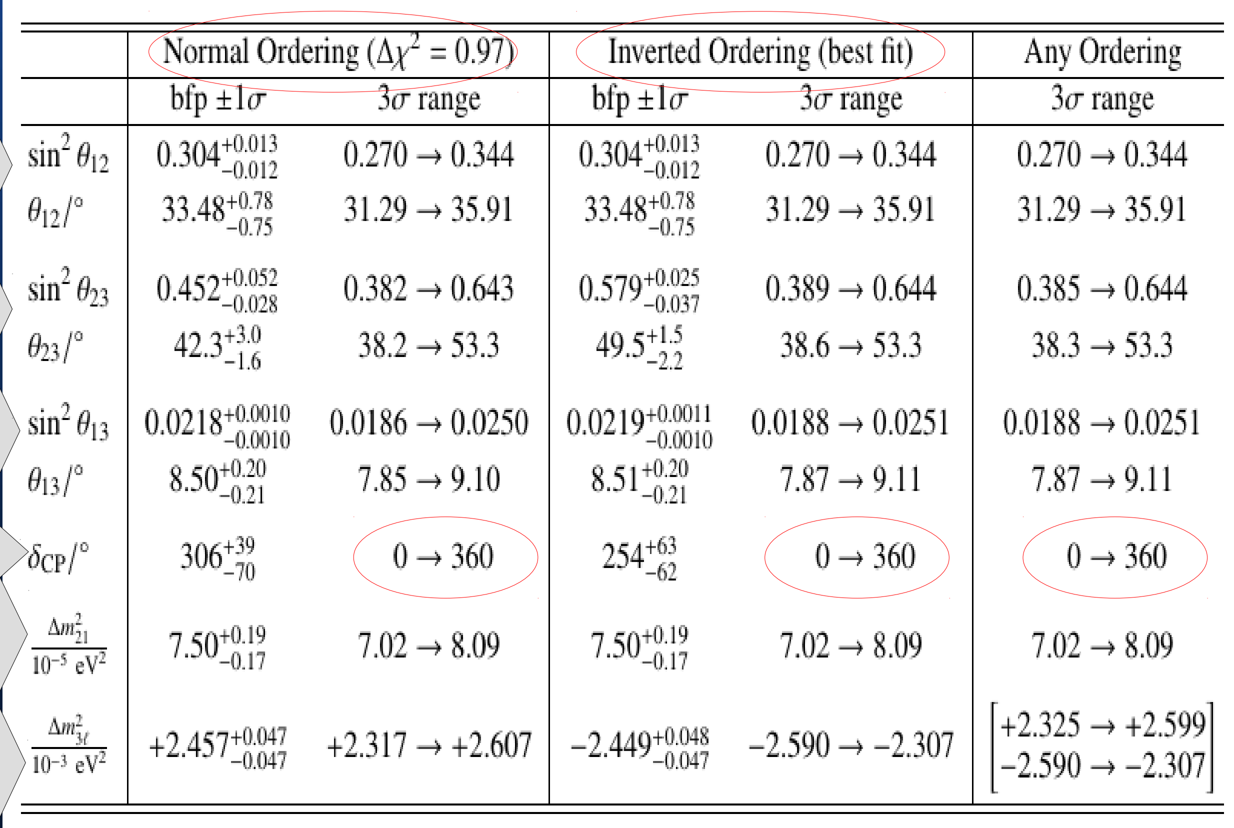
$$P_{ee}(E_{\bar{\nu}_e}, L, \Delta m^2_{31}, \theta_{13}) = 1 - \sin^2(2\theta_{13}) \sin^2 \left(1.27 \frac{\Delta m^2_{31}[10^{-3}\ \mathrm{eV}^2] L[\mathrm{km}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]} \right)$$

2ν disappearance experiments

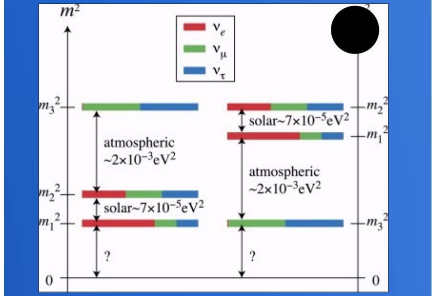
3ν Global Analysis

- All the experimental data can be analyzed together assuming 3ν oscillations





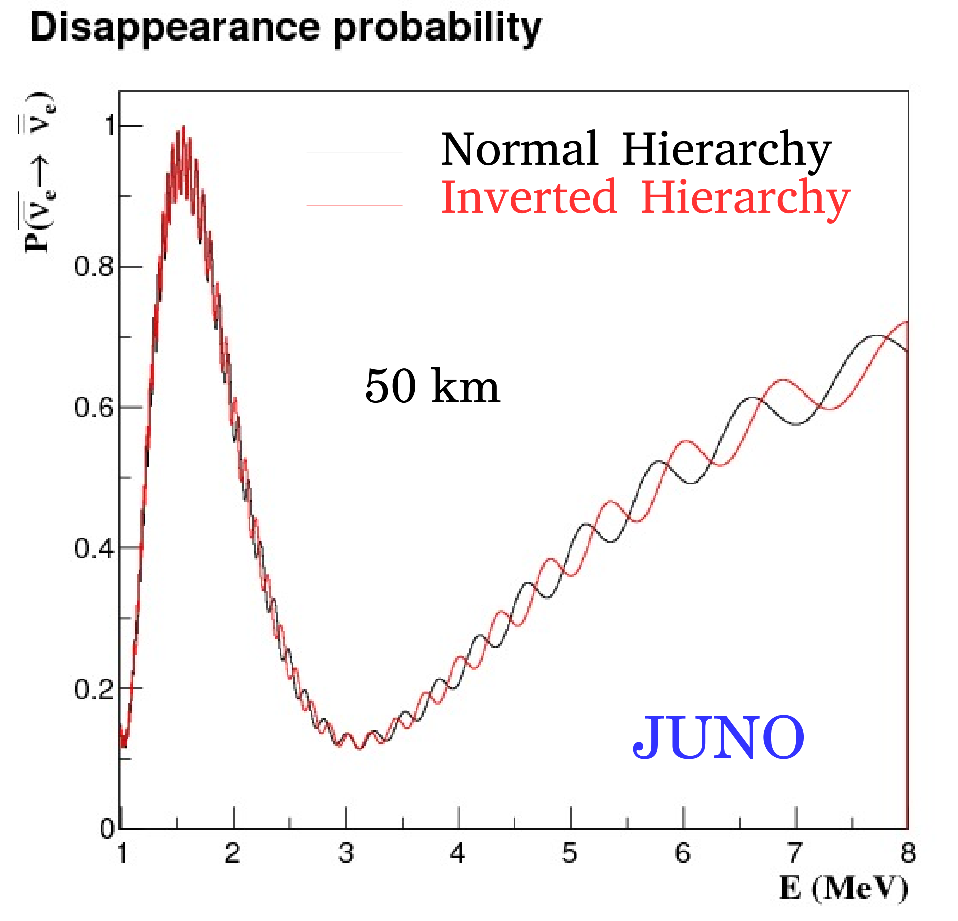
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

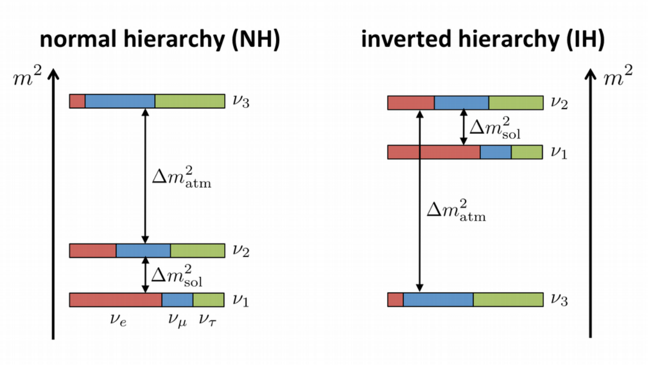


- How to measure MH and δ_{cp}?: running experiments sensitive to 3ν oscillations

3ν Reactor Experiments

- MH can be determined if good E resolution





$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \end{aligned}$$

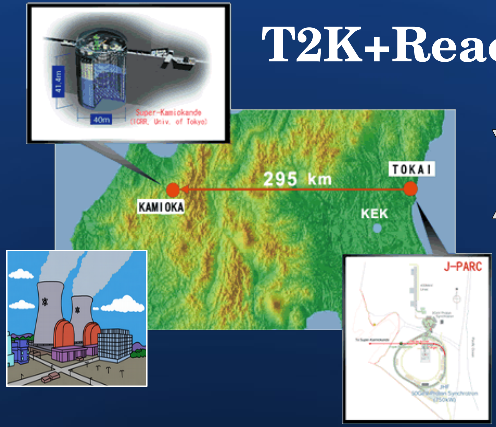
$$\Delta_{ij} = 1.27 \Delta m^2_{ij} L/E$$

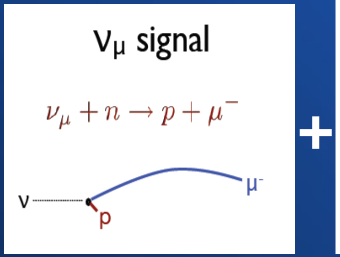
3ν Accelerator Experiments

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = |\sum_{i=1}^{n}\sum_{j=1}^{n} U^*_{\alpha i}U_{\beta j}\langle\nu_j|\nu_i(t)\rangle|^2$$

Access to CP violation and mass hierarchy!

T2K+Reactors

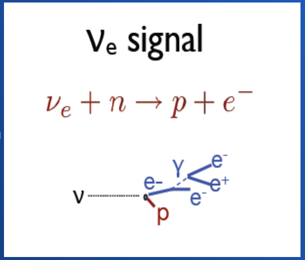



ν_μ signal

$\nu_\mu + n \to p + \mu^-$

ν_μ disappearance

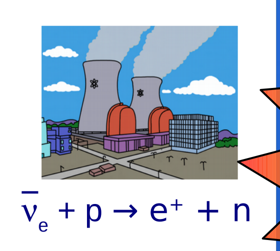
+


ν_e signal

$\nu_e + n \to p + e^-$

ν_e appearance

+

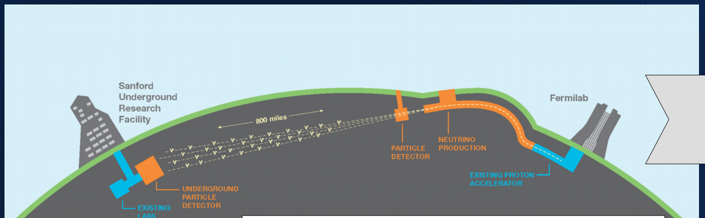

$\bar{\nu}_e + p \to e^+ + n$

$\bar{\nu}_e$ appearance

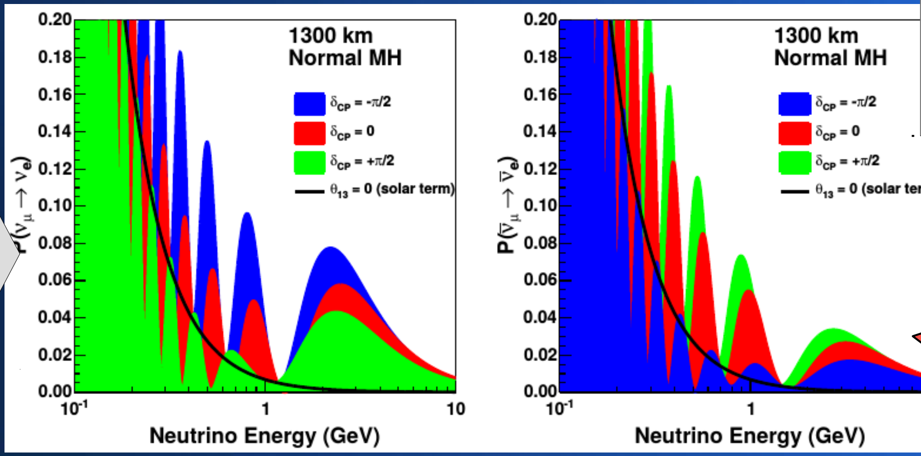
=

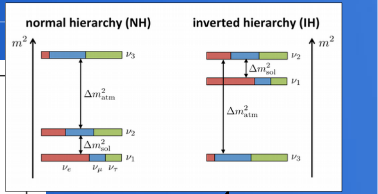
"δ_{CP}"

DEEP UNDERGROUND
NEUTRINO EXPERIMENT



Optimized E/L!!!





δ_{CP}

Summary

- Neutrinos are the first proof of physics Beyond the Standard Model
  - Neutrinos oscillate, ergo they are massive particles
- Neutrino oscillation probability is a function of E/L
  - Oscillation experiments are defined according to a given E/L
- Solar and LBL accelerator experiments (same E/L)
  - oscillation in the solar sector: θ_{12}, Δm^2_{21}
- Atmospheric and accelerator LBL experiments (same E/L):
  - oscillation in the atmospheric sector: θ_{23}, Δm^2_{32}
- Reactor experiments: proof of interference sector: θ_{13}
- Current and future experiments: analyze data in 3ν scenario
  - Access to mass hierarchy (DUNE) and CP violation (T2K, DUNE)