Neutrino Physics

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CTEQ Summer School

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Outline

Part I: Introduction and Neutrinos as Probes

- Neutrinos in the SM, brief introduction.
- Neutrino experiment challenges
- ν as Probes : Electroweak
- ν as Probes: Nucleon structure and QCD

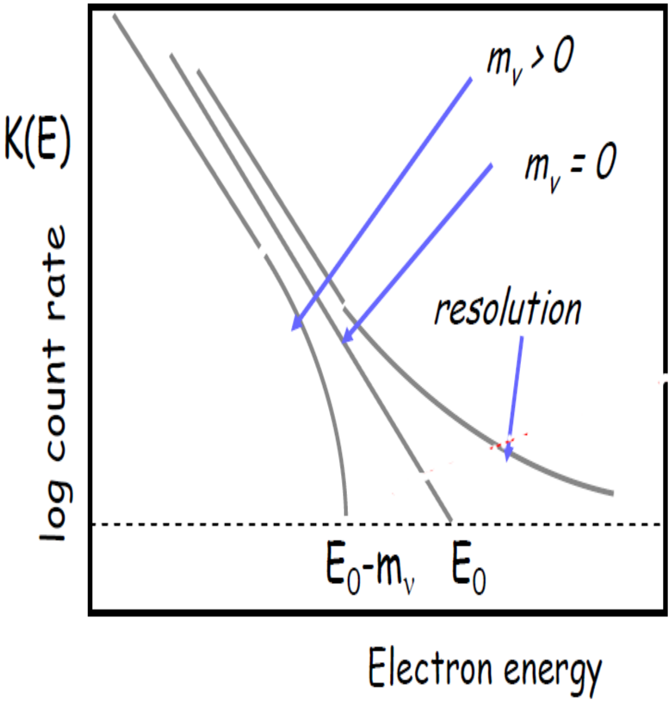
Part II: Neutrino oscillations beyond the SM

- Neutrino mass and oscillations.
- The story of neutrino oscillations.
- Some remaining questions and future

Neutrino Mass

- Direct limits from decay kinematics

m_{ν_e}	< 2.2 eV	^{3}H β-decay
m_{ν_μ}	< 0.16 MeV	π^+ decay
m_{ν_τ}	< 18.2 MeV	τ decay



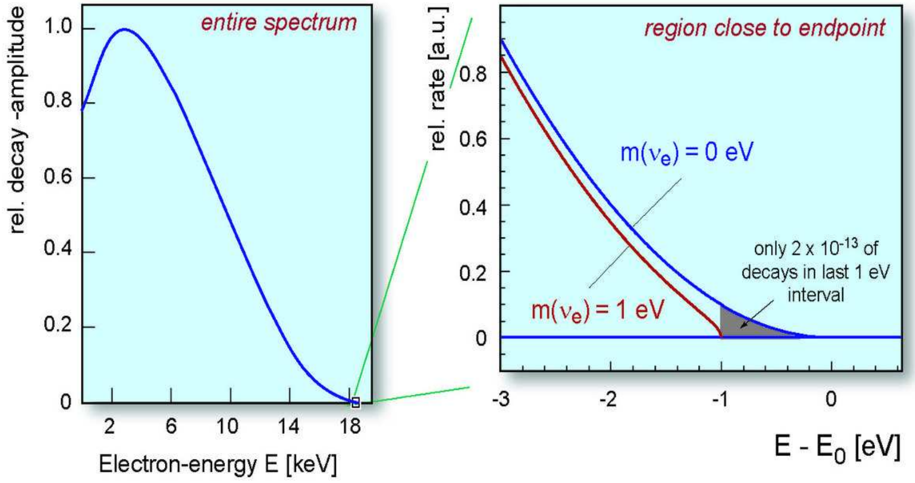
Most sensitive

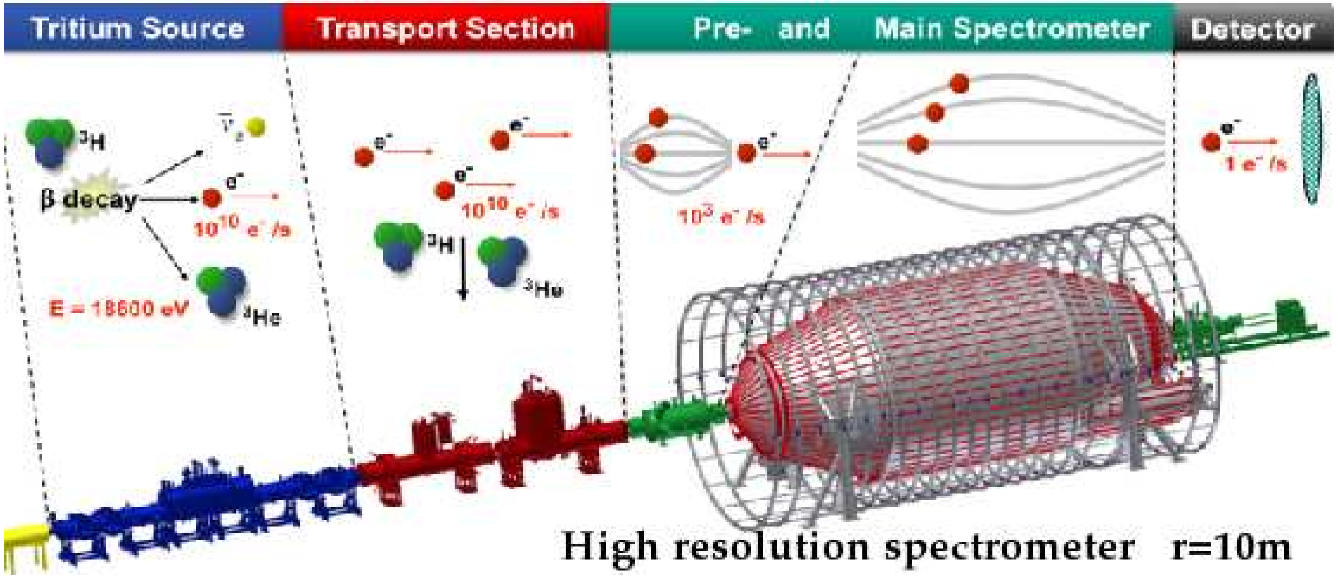
- Measure the end point energy of the electron in Tritium β-decay

$$\boxed{^3H \rightarrow {}^3He + e^- + \overline{\nu}_e}$$

State of the Art (Katrin)

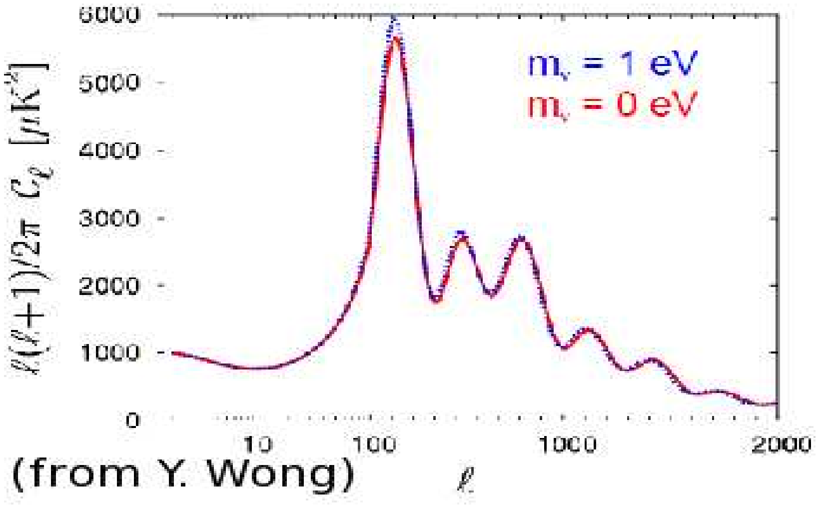
- Katrin experiment (starts 2014)
- Same technique
  $\longrightarrow$ sensitivity $\sim$0.2 eV
- Discovery potential if
  m_{ν_e} >0.35 eV.
  $(m_e = (\sum_i |U_{ei}|^2 m_i^2)^{1/2})$
- Reaching the sensitivity limit of this technique.



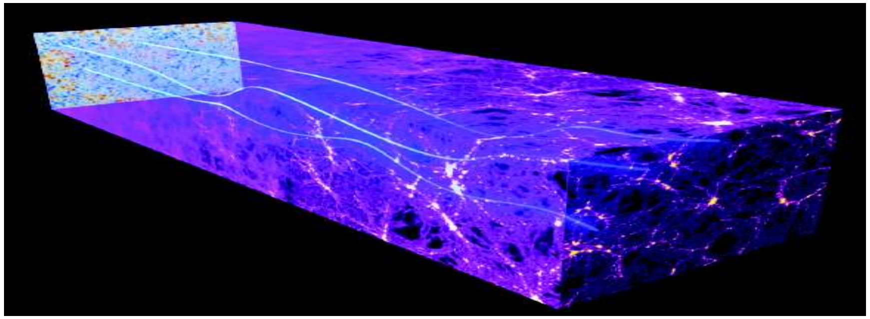


Neutrino Mass from Cosmology

- Neutrinos contribute to the (hot) dark matter of the universe and affect structure formation.
- Cosmological observables (CMB, lensing, galaxy and cluster distributions, etc.) are sensitive to total neutrino mass sum (3 active + sterile)



(from Y. Wong)



Current upper bound from cosmology

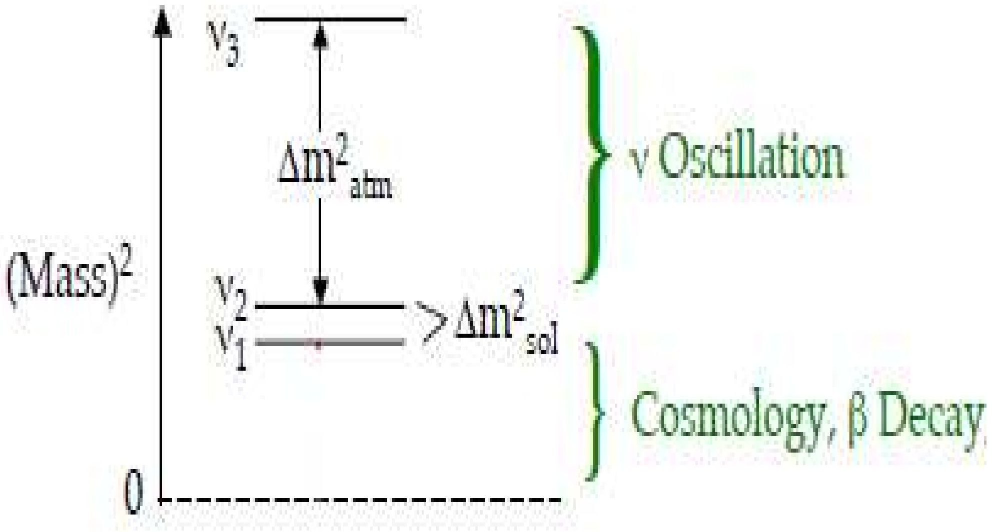
$\Sigma m_\nu < 0.23$ eV at 95% C.L. (Planck+WP+highL+BAO)

- Many model assumptions needed extract neutrino mass sum from observables.

Neutrino mass and cosmology Y.Y.Y. Wong, Ann. Rev. Nucl. Part. Sci.(2011) 61:69-98.

Neutrino Mass from Oscillation

- Absolute mass scale
  - cosmology and β-decay (so far only upper limits)
- How do we know neutrinos mass is non-zero?
  - Lower limits from oscillation experiments for two of three active neutrinos.
  - $\Delta m^2_{\rm atm} \Rightarrow$ heaviest neutrino $m \geq 0.04$ eV



- Currently the most sensitive way to study neutrino mass is to catch one in the act of *oscillating*...

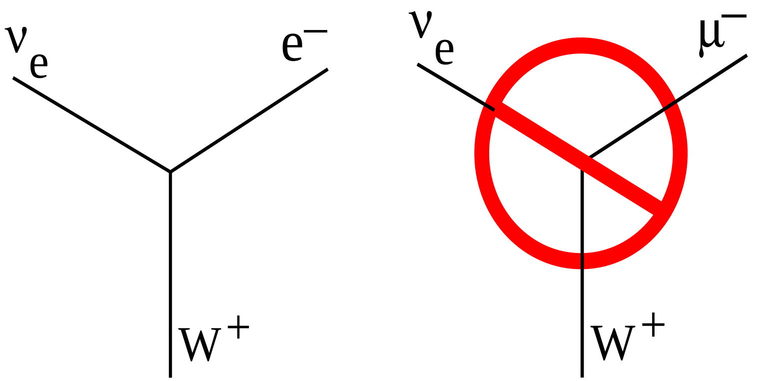
Neutrino Flavor and the SM

- In SM there are three flavors of neutrinos and each has a corresponding charged-lepton.

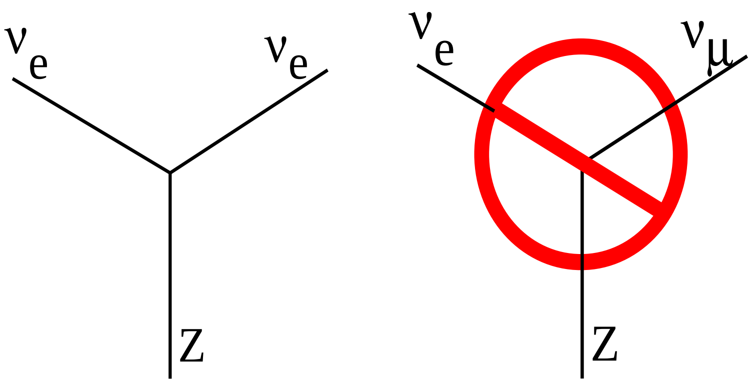
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Flavor change does not occur in SM interactions of leptons.

- Each neutrino produces its associated charged-lepton in CC interactions.



- Flavor changing neutral currents (FCNC) not observed.



- Conservation of *lepton flavor number* also observed for charged-leptons

$$\boxed{\text{Br}(\mu \to e\gamma\,) < 6 \times 10^{-13}}$$

Neutrino Oscillation and the SM

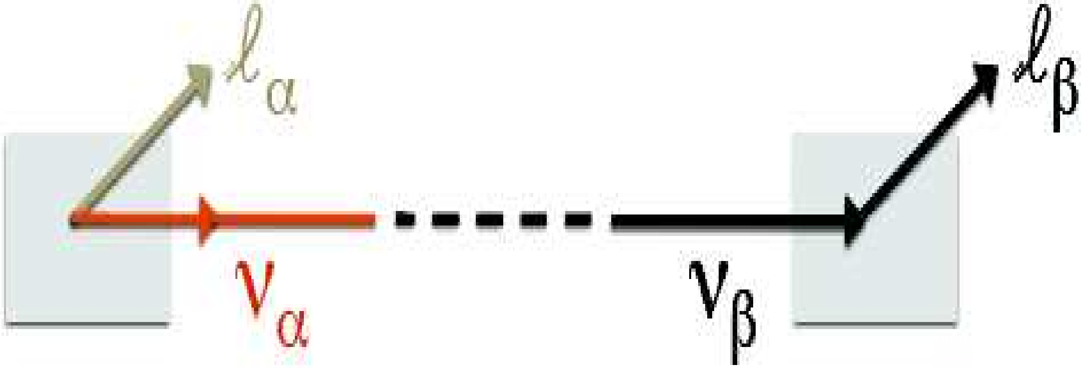
- Neutrino oscillation is a mechanism for flavor change which requires that masses are not zero and not degenerate.

Standard model neutrinos

- are massless $m_\nu = 0$
- Leptons don't mix flavors ΔL_e= ΔL_μ=ΔL_τ= 0

Neutrino oscillation requires

- $m_\nu \neq 0$ and $m_i \neq m_j$
- Lepton flavor mixing.



- Discovery of neutrino oscillation was the first confirmed physics beyond the Standard Model (Nobel Prize 2002, Ray Davis and Masatoshi Koshiba).

Neutrino Oscillation

Mixing between 2 generations:

Weak interaction eigenstates

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

Mass eigenstates

- Produce a neutrino in a pure flavor eigenstate (α), it is a mixture of mass eigenstates.
- Mass eigenstates evolve in time $\nu_i(t) = \nu_i(0) \cdot e^{-iE_i t}$.
- The relative phases of the mass states induce “flavor oscillation” as the state propagates over a time t (or distance $L = ct$).
- Probability of observing the state (β) at a later time t (or after propagating through path length L from the production point) is

Transition probability

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 L/E\right)$$

θ **is the mixing angle**

$\Delta m^2 = (m_i^2 - m_j^2)$ **in eV^2**

E **is the neutrino energy in GeV**

L **is the distance traveled in km**

Transition Probability

Transition probability

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E **is the neutrino energy in GeV**

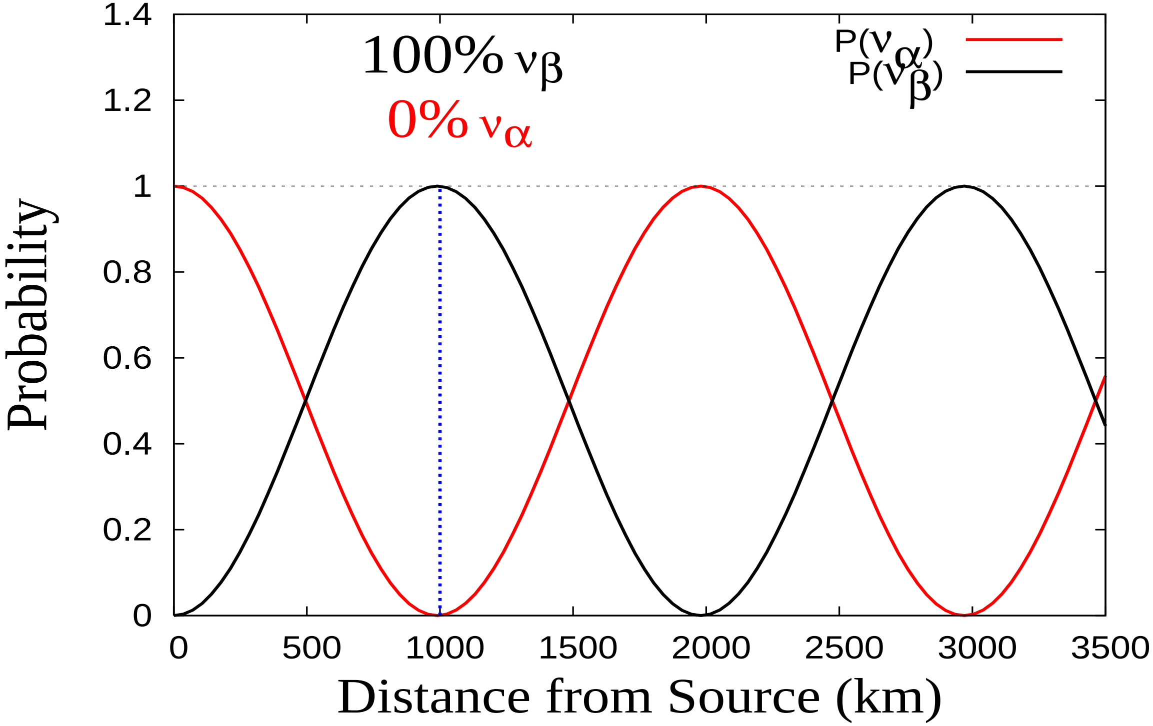
L **is the distance traveled in km**

Flavor composition 'oscillates' between the two states as it propagates.

- Pure ν_α beam with $E_\nu = 2$ GeV.

Δm^2=2.5$\times 10^{-3}$ eV^2

$\sin^2 2\theta$=1



Three Flavor Oscillation

Weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Mixing Matrix (PMNS),

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \mathrm{e}^{\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} \mathrm{e}^{-\mathrm{i}\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillation Experiments measure 6 parameters.

- Three mixing angles θ_{12}, θ_{13}, θ_{23} & phase δ.
- Two independent mass differences: Δm^2_{23}, Δm^2_{12}

Third comes from constraint: $\Delta m^2_{23} + \Delta m^2_{12} + \Delta m^2_{31}$=0

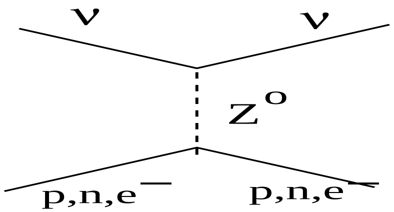
Matter Effects

- What if neutrinos are not propagating in vacuum?

$\boxed{\nu\text{'s interact with } \mathbf{n,p,e^-}}$

Relevant interactions

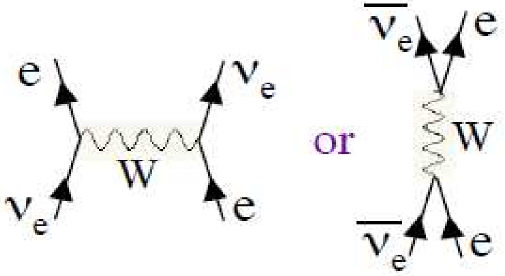
- **Coherent forward elastic scattering -** preserves coherence of ν states, (doesn't change momenta, spins, etc).



same ν_e, ν_μ, ν_τ

- **Only alter oscillations if they differ among ν_e, ν_μ, and ν_τ.**

only ν_e



Matter Effect

- Alter energy levels of propagating eigenstates (*changes the effective mass*).
  - raises effective mass of ν_e
  - lowers effective mass of $\overline{\nu}_e$.
- Increases with neutrino energy.
- Sensitive to the sign of Δm^2.

Interaction potential energy term

$$\boxed{V = \pm\sqrt{2}G_F N_e}$$

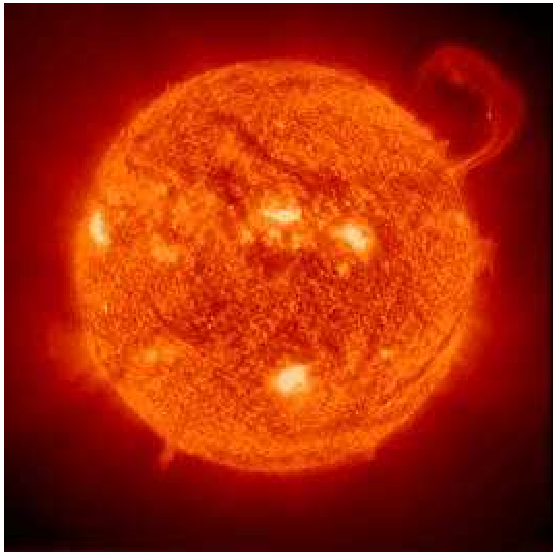
$+$ for ν_e, $-$ for $\overline{\nu}_e$

N_e is electron density.

Analgous to the effect of medium on propagation of light → index of refraction.

The Story of ν Oscillations

Astrophysical sources: First early hints and discoveries.

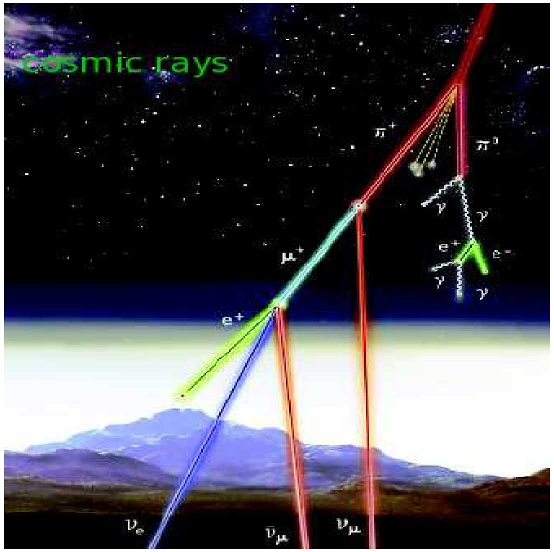


Solar

- $\nu_e <$ few MeV

Atmospheric

- few GeV $\nu_\mu \& \nu_e$



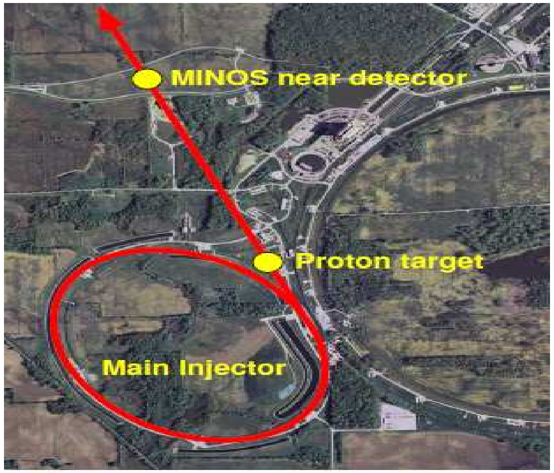
Manmade Sources: Confirmation + precision measurements.

Reactors

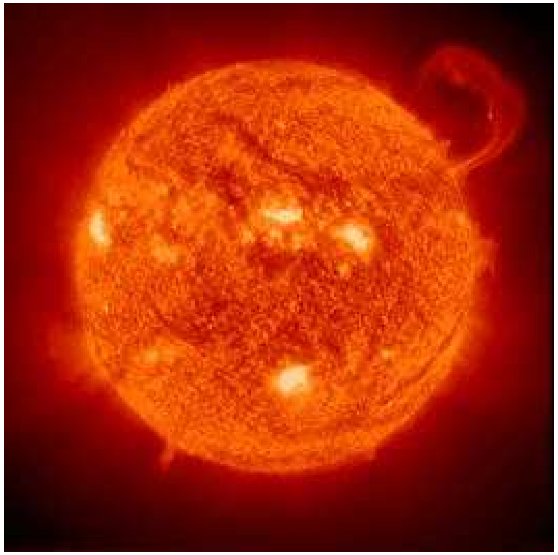
- Point source $<$10 MeV $\overline{\nu}_e$.
- First neutrino detection (1956).

Accelerator

- Collimated beam (mainly ν_μ)
- Energies 0.5-500 GeV.



Solar Neutrinos



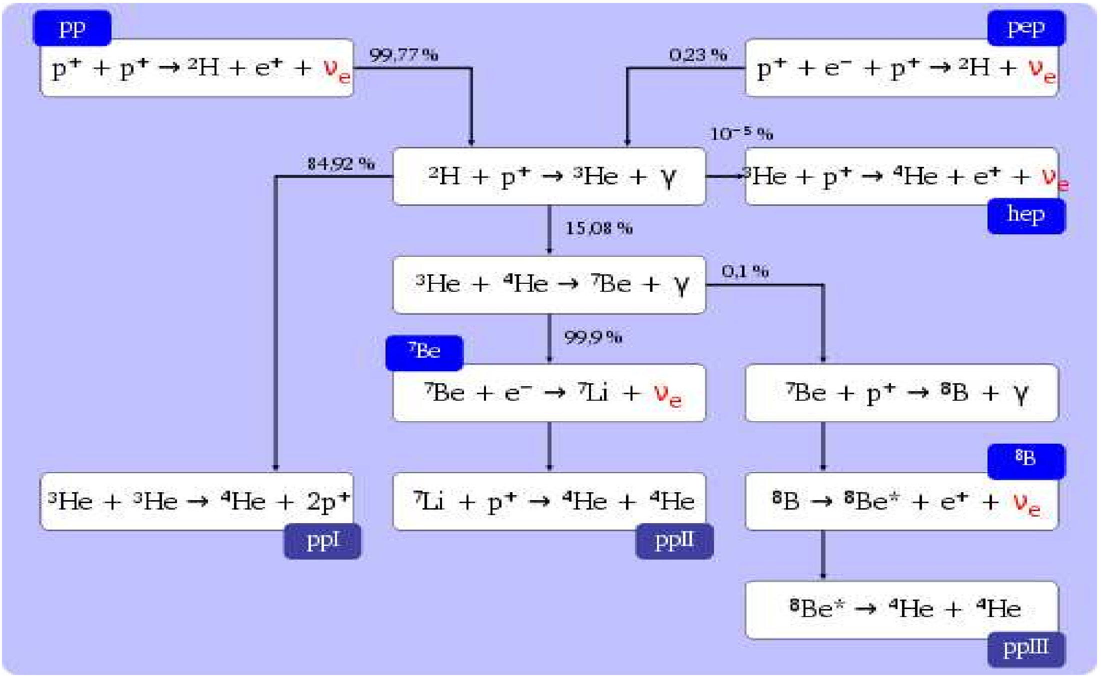
What is the Sun's energy source???

- ⋆ Mid-1800's: Chemical process
  - Sun would burn out in a few thousand years.
- ⋆ Late 1800's: Kelvin-Helmholtz propose gravitational collapse.
  - Energy supply for ∼25 million years...
- ▶ 1929 Atkinson and Houtermans propose **fusion**.

What do Neutrinos have to do with this?

ν_e's are a fusion by-product.

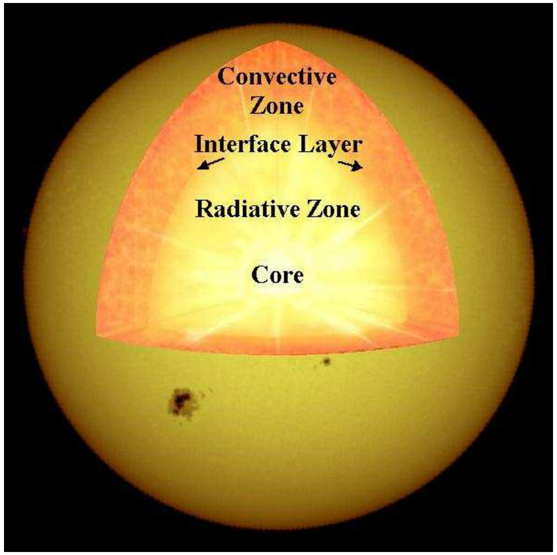
➡ Detection of ν_e's from the sun is definitive evidence for fusion.

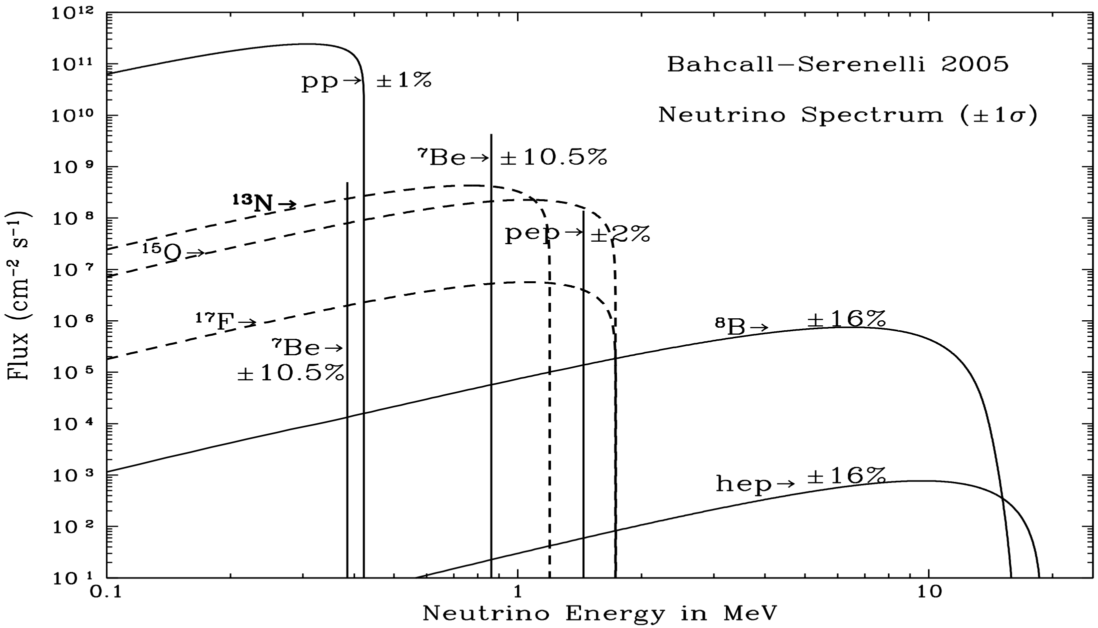


Challenges of Solar Neutrino Detection

⋆ Goal (mid-60’s): devise experiment to detect solar neutrinos.

- ▶ Neutrino production rate predicted from Solar models (1960’s J. Bahcall).





- ▶ Sun emits around 2×10^{38} neutrinos per second !
  ... more than 40 billion neutrinos per second per cm^2 arrive at Earth.
- ▶ Most of the neutrinos have too little energy to detect (pp ν_e sub-MeV).
- ▶ Expected signal rate is very small ($<$1 interaction per day in a very large detector).
- ▶ There are many sources of background (radioactive impurities, cosmic rays etc.)

Enter Ray Davis

Detector method based on the neutrino capture reaction: $\nu_e + \ ^{37}Cl \rightarrow \ ^{37}Ar + e^-$

Ray's Recipe:

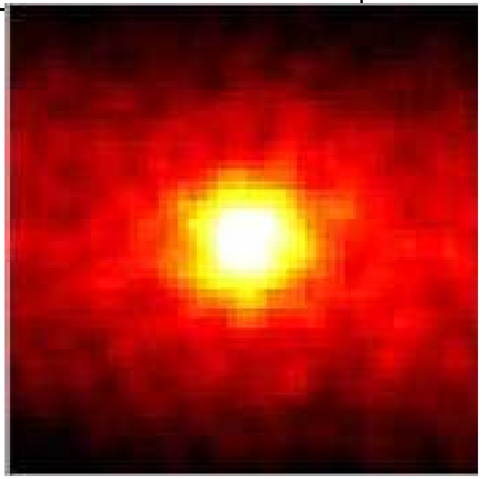
1. Pour 100,000 gallons of (ultrapure) perchlorethylene (C_2Cl_4) in a huge (ultrapure) tank.
2. Bury tank 4,800 ft. deep in Homestake gold mine.
3. Wait 158 days.
4. Separate out the 53 ^{37}Ar atoms produced from the remaining 100,000 gallons of fluid.
5. Repeat every few months for $\sim$20 years.

It worked ! (sort of...)

$$\boxed{\frac{\Phi_{\nu_e}(meas.)}{\Phi_{\nu_e}(SSM)} = 0.34 \pm 0.06}$$

The Solar Neutrino Problem

1. We don’t understand the sun (or any star).
2. We don’t understand the neutrinos.



Neutrino image of the sun

- New techniques agreed with Davis’s results (Gallex and SuperKiokande).
  - SK active detection ($E_\nu > 5$MeV) $\nu_e e^- \rightarrow \nu_e e^-$
- **Common feature of experiments**: sensitive to ν_e’s only, (by design).
- **Neutrino oscillation hypothesis: ν_e’s convert to another flavor and “disappear” before reaching the earth.**

Need a new definitive experiment: <u>SNO (Sudbury Neutrino Observatory)</u>

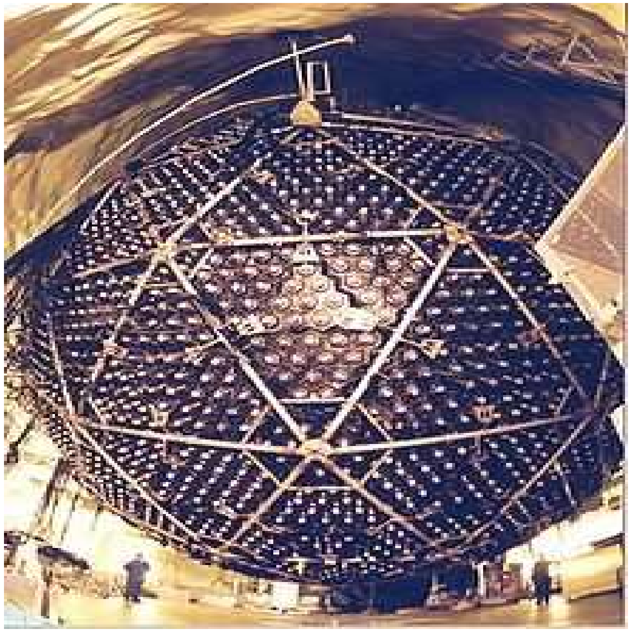
- **Most Important Feature: Sensitive to ALL three (ν_e, ν_μ, ν_τ) types of neutrinos.**

SNO Definitive Results

- 1000 tons of heavy water D_2O

  (deuterium is a weakly bound state of n & p)

- Turned on in 1999 in Sudbury nickel mine, 6800 ft underground.



(CC) $\nu_e + d \to p + p + e^-$ $\quad$ $only\ \ \phi_{\nu_e}$

(NC) $\nu_x + d \to p + n + \nu_x$ $\quad$ $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$

(NC&CC) $\nu_x + e^- \to \nu_x + e^-$ $\quad$ $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$

- Measured ν_e rate agrees with previous expts. (Davis was right!)

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.340 \pm 0.038$$

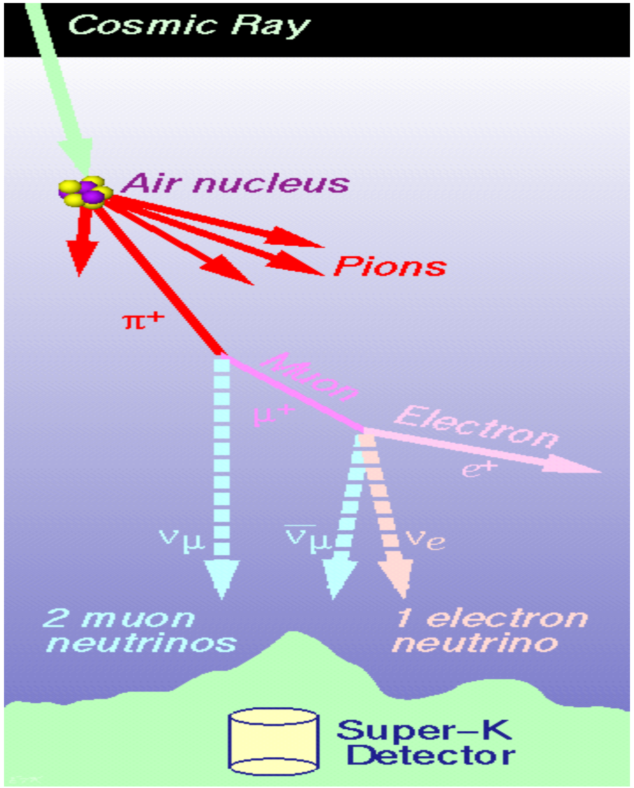
- Measured total flux agrees with solar model prediction. (Bahcall was right!)

  Measured $\quad \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.42) \times 10^6 cm^{-2} s^{-1}$

  Theory $\quad \phi_{TOTAL} = (5.69 \pm 0.91) \times 10^6 cm^{-2} s^{-1}$

Verdict: Neutrino flavor change!

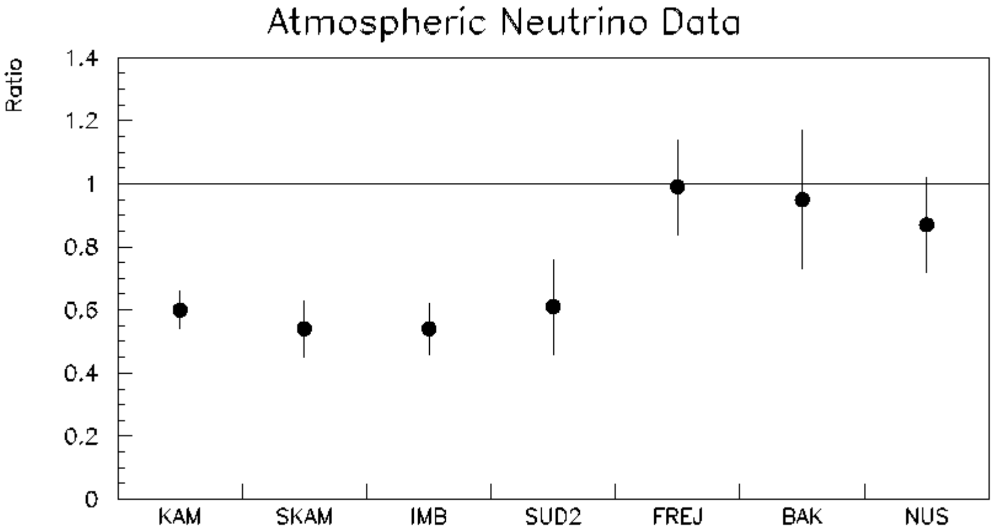
Atmospheric Neutrinos



Expected flavor ratio $N(\nu_\mu)/N(\nu_e) \sim 2$

- ▶ Circa 1990 most experiments measured a ratio of ν_μ to ν_e that is 40% too low.

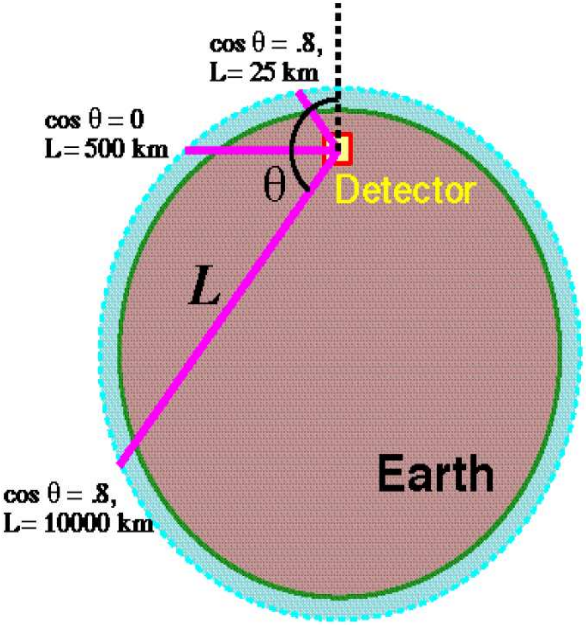
Measured ratio $N(\nu_\mu)/N(\nu_e) \sim 1.2$

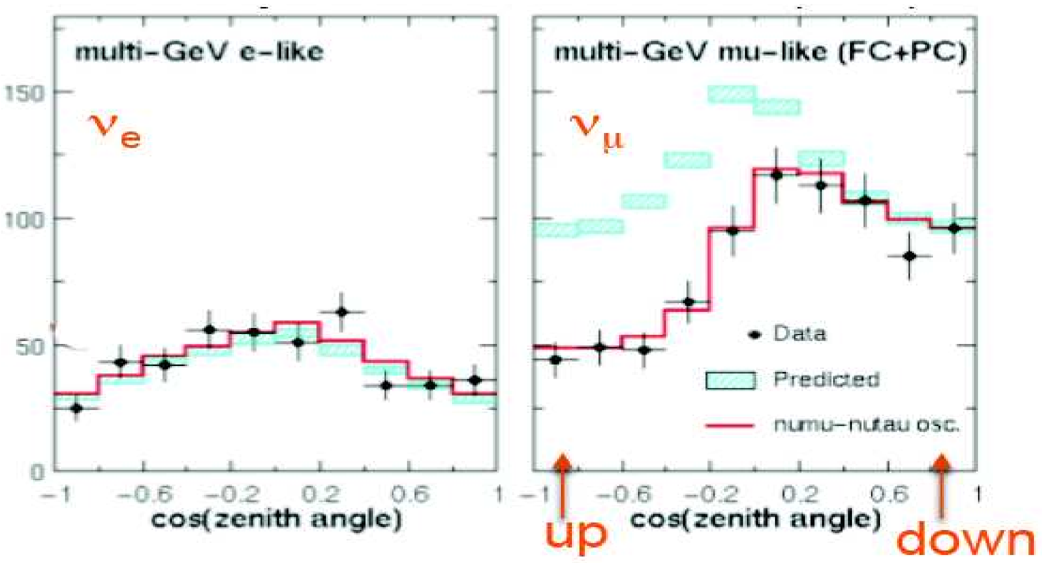


- ▶ Atmospheric neutrino anomaly “too few ν_μ”
  - ▷ Could be explained by ν_μ disappearance.

Atmospheric Neutrinos (cont'd)

- Oscillation Hypothesis ⇒ Path length dependent rate.
- Source provides **variable path length** (50km-12,700km) ⇒ Zenith angle dependence.





- Smoking gun for oscillation hypothesis: Super K measures zenith angle dependence.
  - ▷ ν_μ deficit but no ν_e excess ⇒ $\boxed{\text{Mostly } \nu_\mu \rightarrow \nu_\tau.}$

Accelerator ν Oscillation Experiments

Select the beam energy E and the pathlength L to tune for a particular signal.

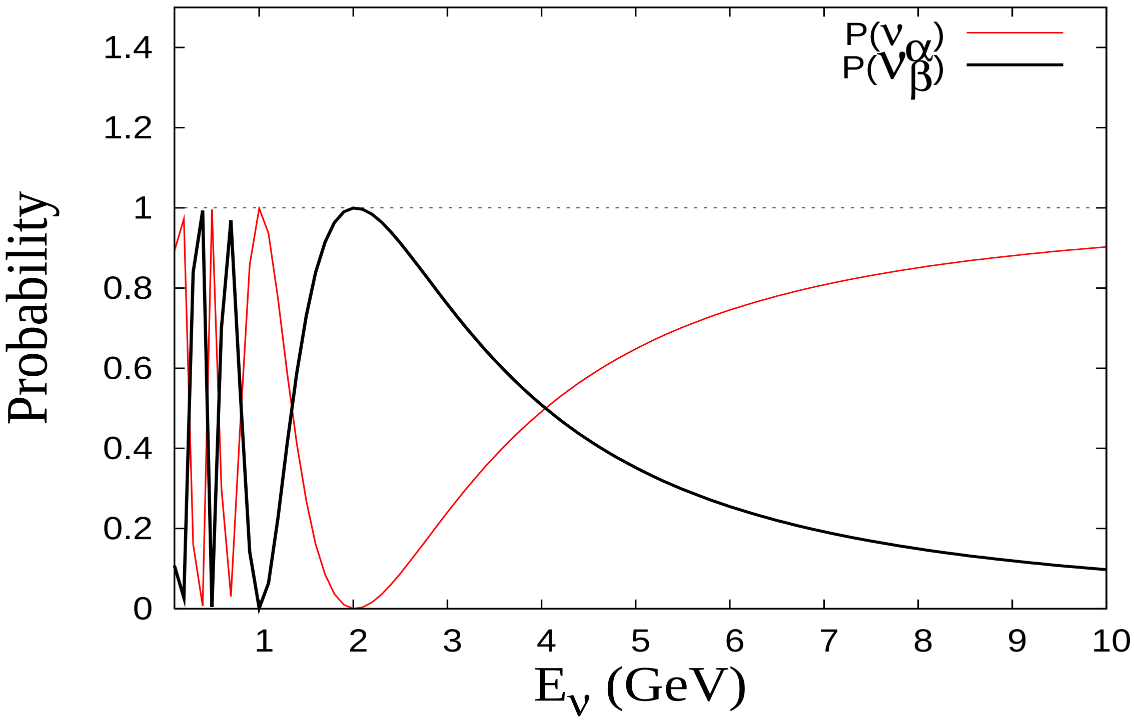
$$\boxed{P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L/E\right)}$$

Probe atmospheric signal region $\boxed{\Delta m^2 \approx 10^{-2} - 10^{-3} \text{ eV}^2}$

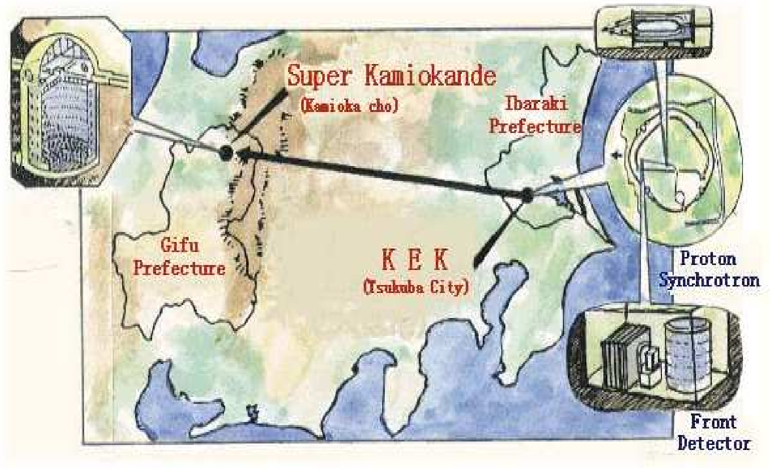
Need long-baseline $\boxed{\frac{L}{E} \approx 10^3 - 10^2 \text{(km/GeV)}.}$

$$\boxed{\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2}$$

- Set $L = 1000$ km
- Beam range should cover first oscillation dip.
  - Energies 1-10 GeV.

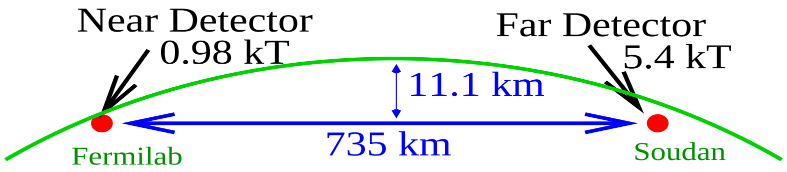


ν_μ Disappearance with a Long-baseline



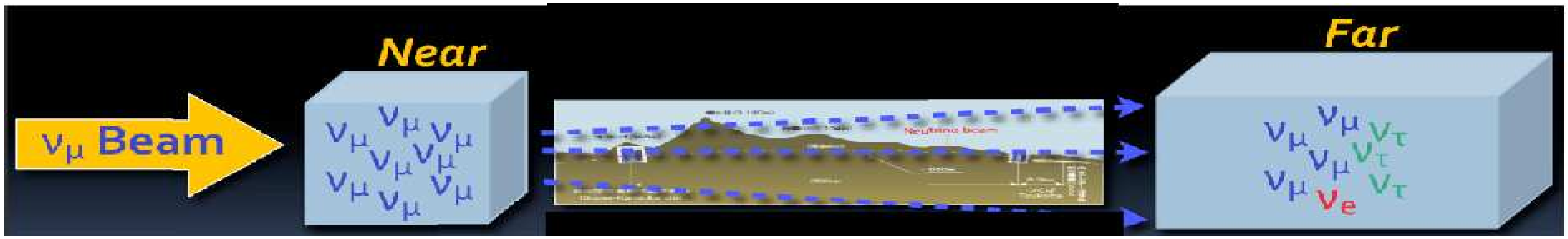
K2K

- KEK beam to SuperKamiokande
- L=250km, $\langle E_\nu \rangle$=1.3GeV
- Completed 2004 (9×10^{19}PoT).



- L=735 km, $< E >= 3$ GeV
- Completed 2012
  - Neutrino mode $> 10^{21}$ PoT
  - Antineutrino mode 3.3×10^{20} PoT

Designing a LBL Experiment



Near Detector measures spectrum **at L=0**.

Far Detector measures spectrum **at L**

"identical" detectors reduce systematic errors.

Which flavor ? ▶ Optimize detector to see the associated final state lepton.

MINOS

Fe-scint., coarse-sampling

- Long μ track

Nova/Minerνa

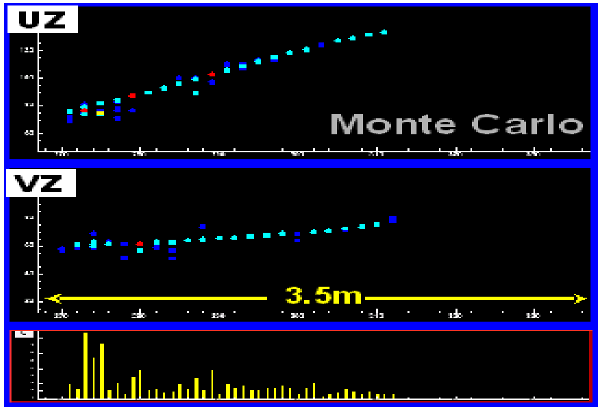
Scintillator strips, fully active

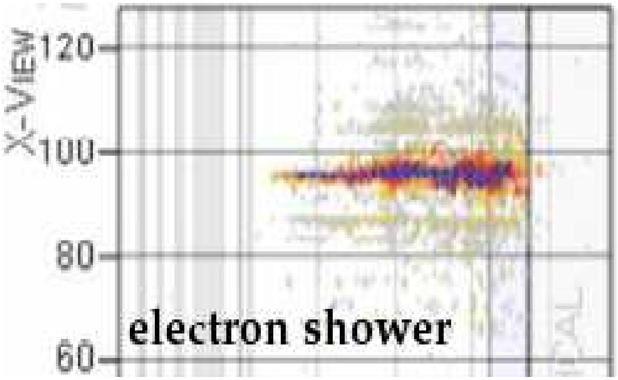
- ν_e shower and NC π^o.

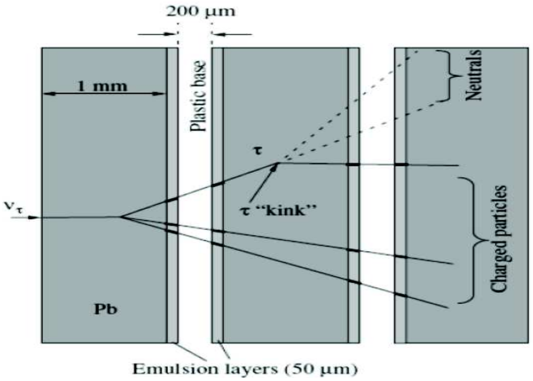
OPERA/DoNuT

Emulsion-tracker.

- τ-decay kink.



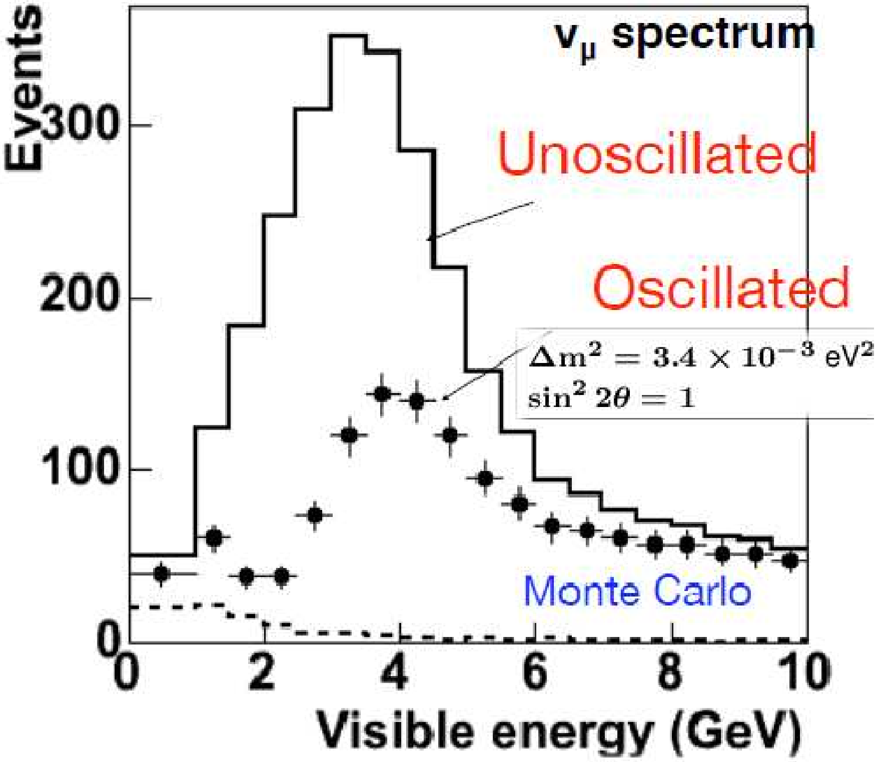


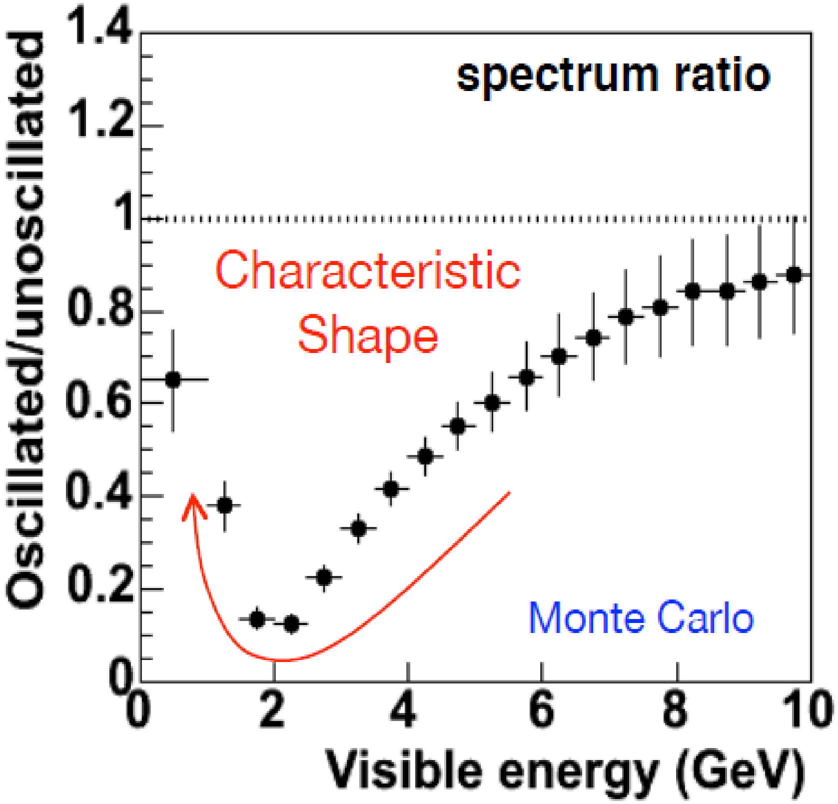


Muon Neutrino Disappearance

Reconstruct $\boxed{E_\nu = E_\mu + E_{\mathrm{HAD}}}$ and measure spectral distortion.

ν_μ Survival probability $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$





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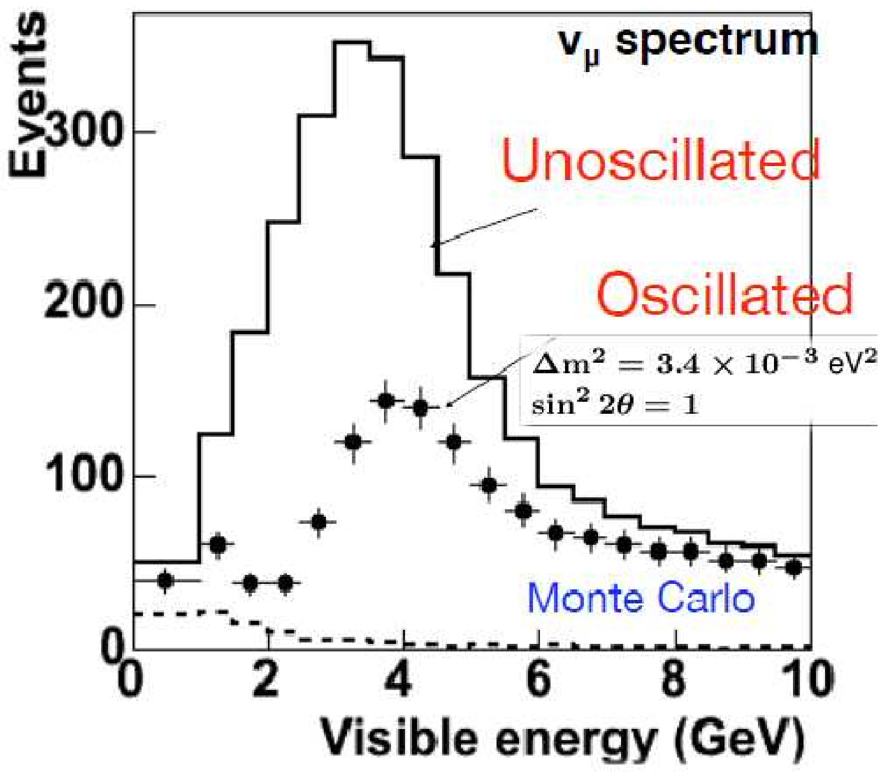

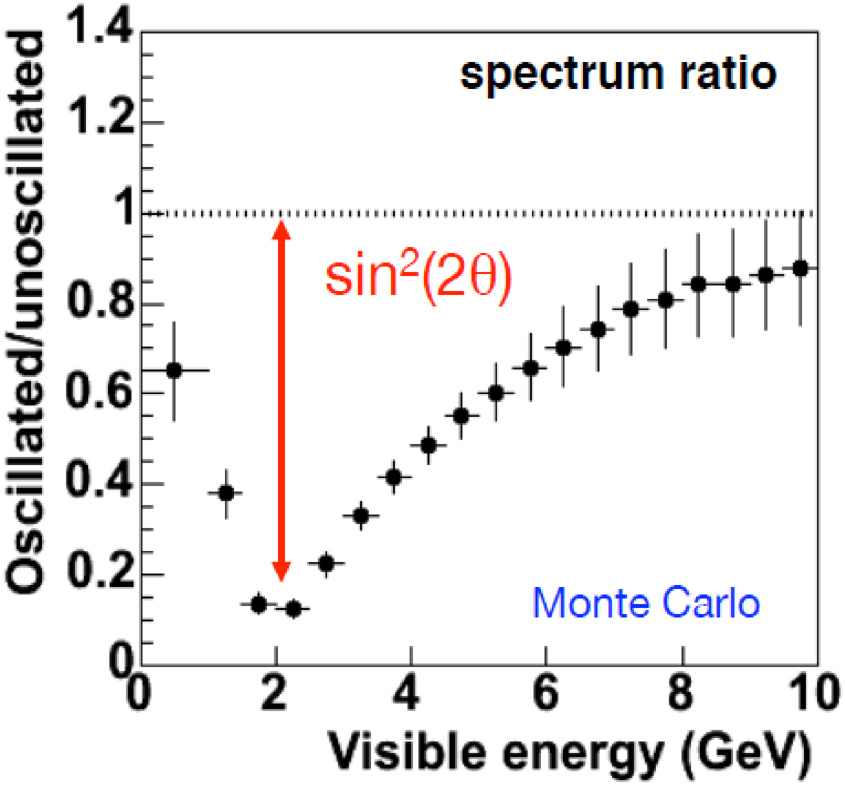

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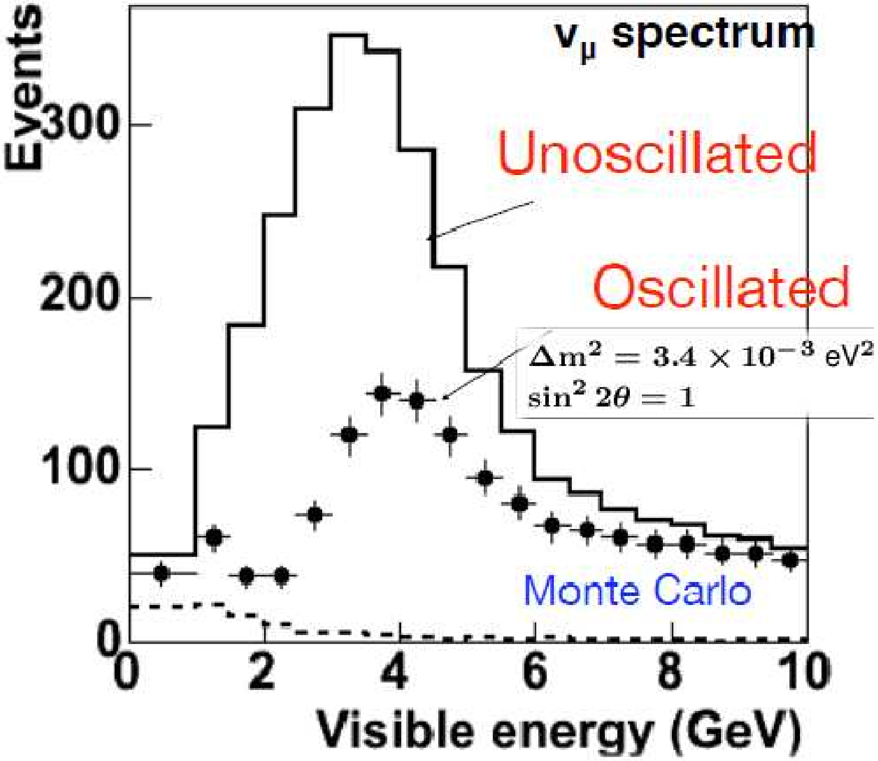
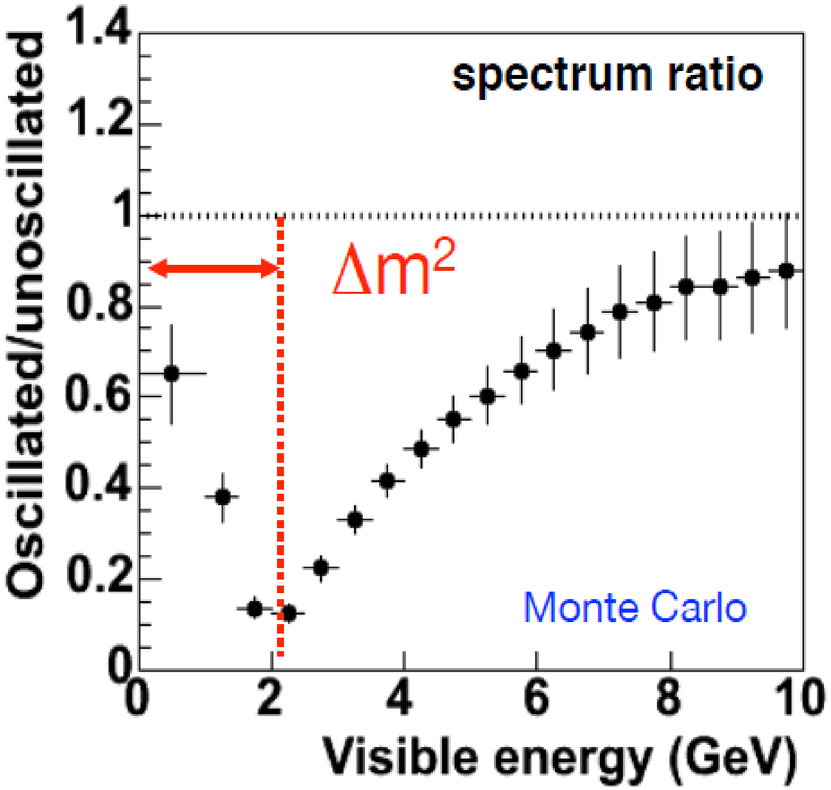
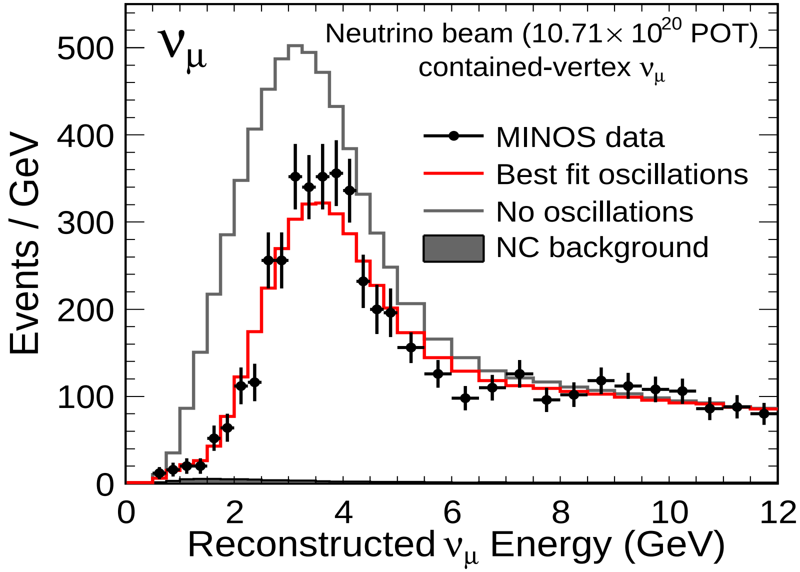
Reconstruct $\boxed{E_\nu = E_\mu + E_{\mathrm{HAD}}}$ and measure spectral distortion.

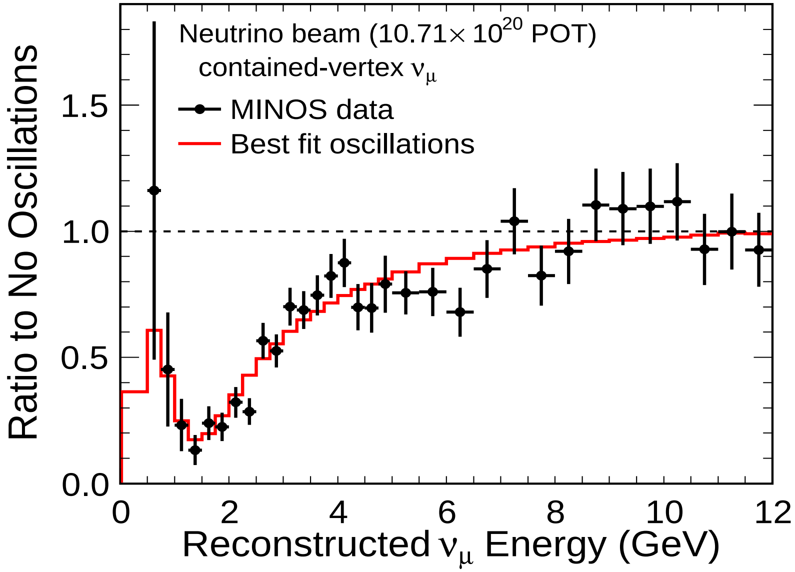
$\boxed{\nu_\mu \text{ Survival probability}}$ $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$

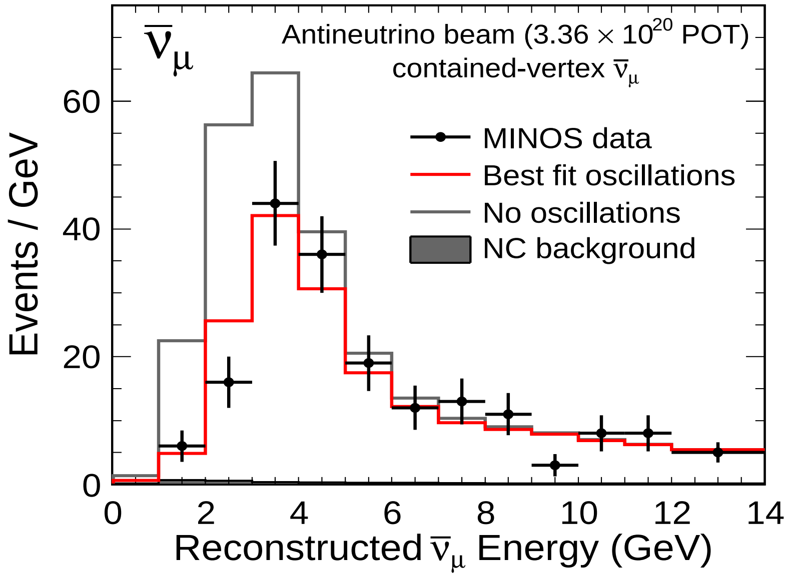


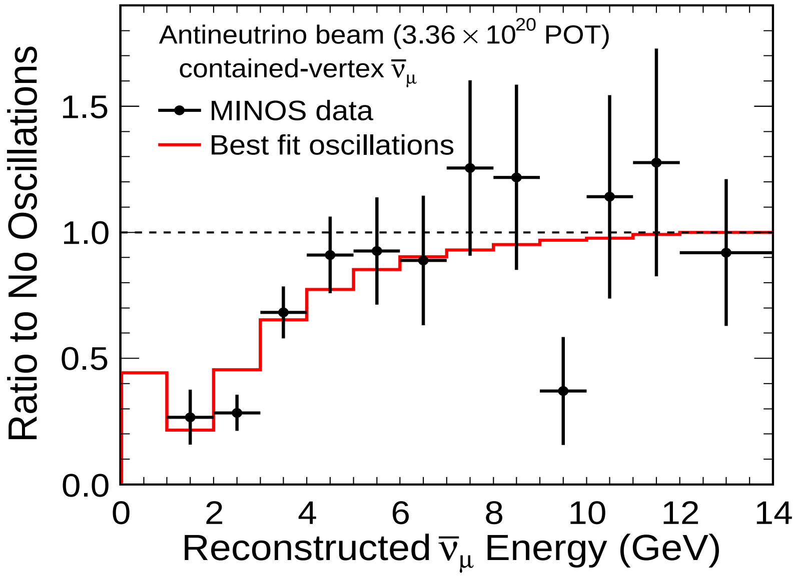


MINOS Disappearance Oscillation Results









Atmospheric Oscillation Parameters

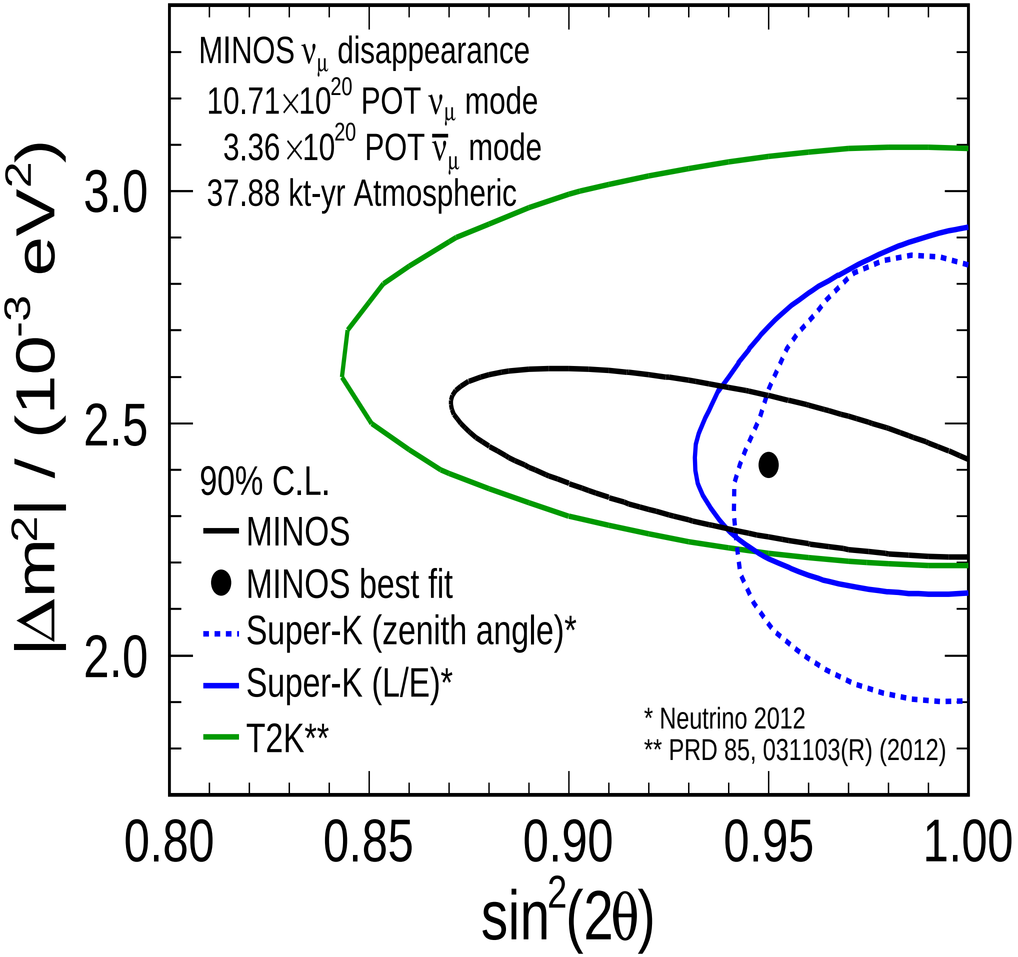
Two-flavor disappearance

$\Delta m^2_{32} = 2.41^{+0.09}_{-0.10} \times 10^{-3}$ eV^2

$\sin^2(2\theta_{23}) > 0.89$ at 90% CL.

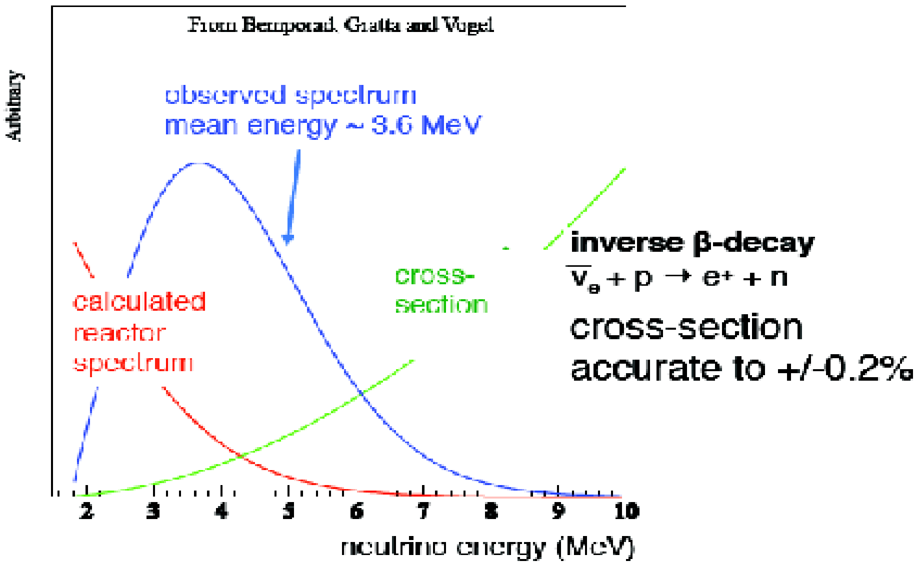
SK says ⇒ $\boxed{\text{Mostly } \nu_\mu \to \nu_\tau.}$

- ▶ ν_τ Appearance
  - ▷ OPERA (since 2006)
    3 ν_τ events.
- ▶ Next Gen: Optimize for ν_e appearance. (Prob≤5%).



Reactor Disappearance Experiment

- Intense source :
  $\overline{\nu}_e$ from β-decays of n-rich fission products
- Energy is fixed:
  range 1-10 MeV $\overline{E} \sim 3.6$MeV

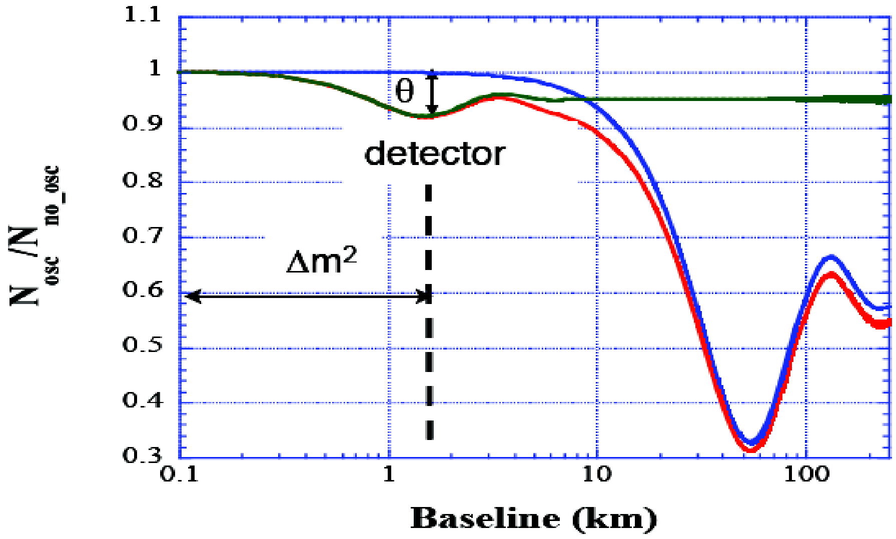


$$P_{\overline{\nu}_e\to\overline{\nu}_e} \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4\mathrm{E}}\right)$$

Select L to design reactor experiment:

$$\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})} \sim \frac{\pi}{2}$$

Amplitude of oscillation $\to \theta$



Reactor Disappearance Experiment (cont’d)

$$P_{\overline{\nu}_{\mathrm{e}} \to \overline{\nu}_{\mathrm{e}}} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4\mathrm{E}}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4\mathrm{E}}\right)$$

Atmospheric $\Delta m^2_{31} = 2.4 \times 10^{-3}$eV^2.

L$\sim$2 km

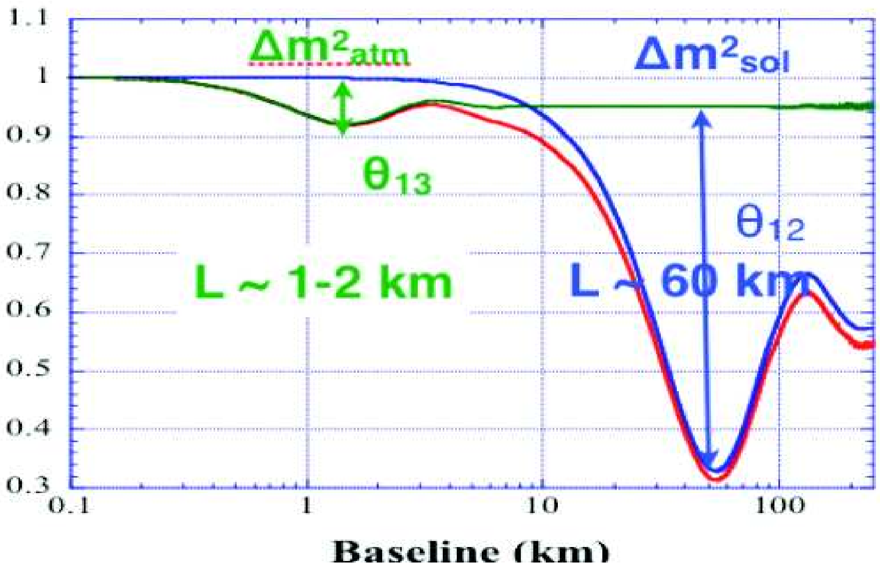
Short-baseline

Solar $\Delta m^2_{12} = 7.6 \times 10^{-5}$eV^2.

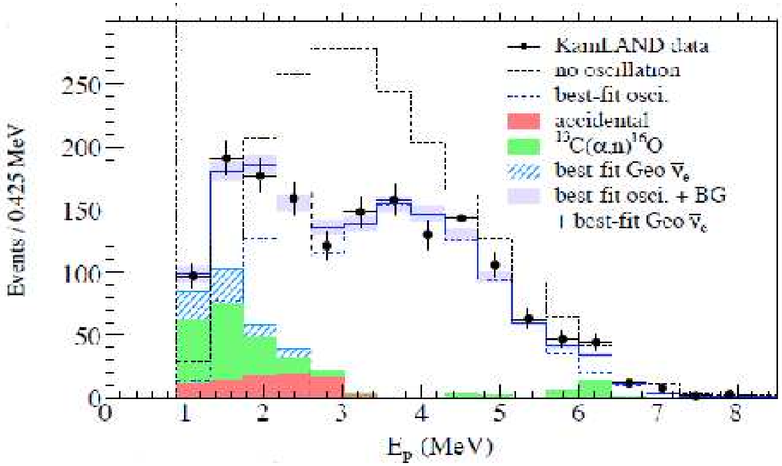
L$\sim$60 km

Long-baseline

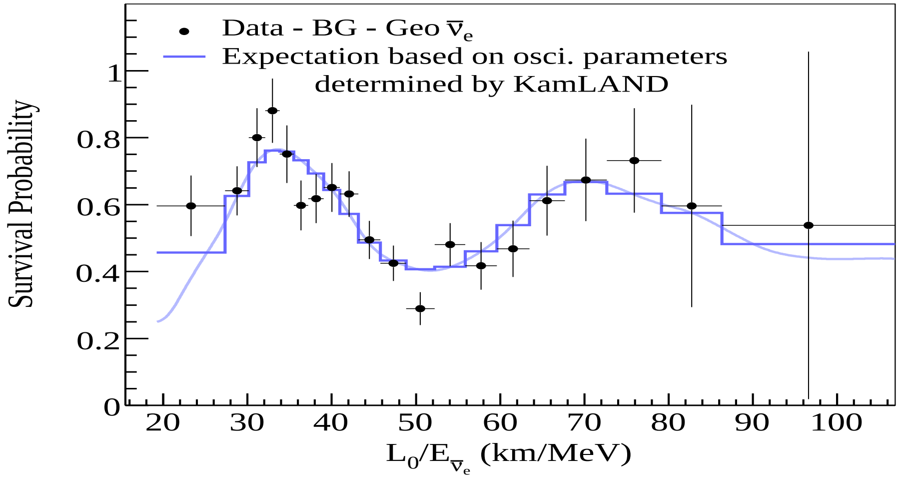
- KamLAND experiment: optimized for Δm^2_{sol}:
  - Practical: Kamioka mine overburden 2700 m.w.e. (reduce backgrounds).
  - 55 reactors within Japan. → Mean flux weighted reactor distance ∼180 km.



KamLAND Results



$$\boxed{E_{\text{prompt}} = E_{\overline{\nu}} - 0.8 \text{ MeV}}$$



- KamLAND measures spectral distortion ⇒ $\frac{L}{E}$ dependence.

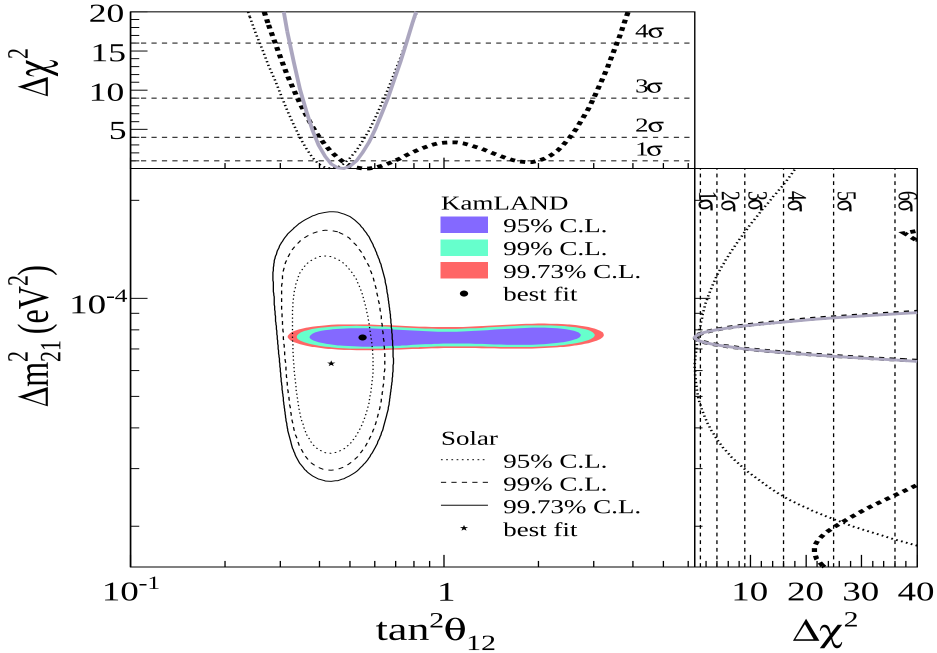
Solar parameters after KamLAND

$\Delta m^2_{21} = (7.62 \pm 0.19) \times 10^{-5}$eV^2.

$\sin^2\theta_{12} = 0.32 \pm 0.02$

Combined: Solar+matter effects vs. KamLAND(no matter effects) ⇒

$$\boxed{\Delta m^2_{21} > 0}$$



The Big Picture (Pre 2012): Mixing

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

“Atmospheric”

Super-K, MINOS

K2K & Opera

Δm^2_{23} & θ_{23}

“Mixed”

θ_{13} & δ ??

Hints: Small

“Solar”

Super-K, SNO

KAMLAND & others

Δm^2_{12} & θ_{12}

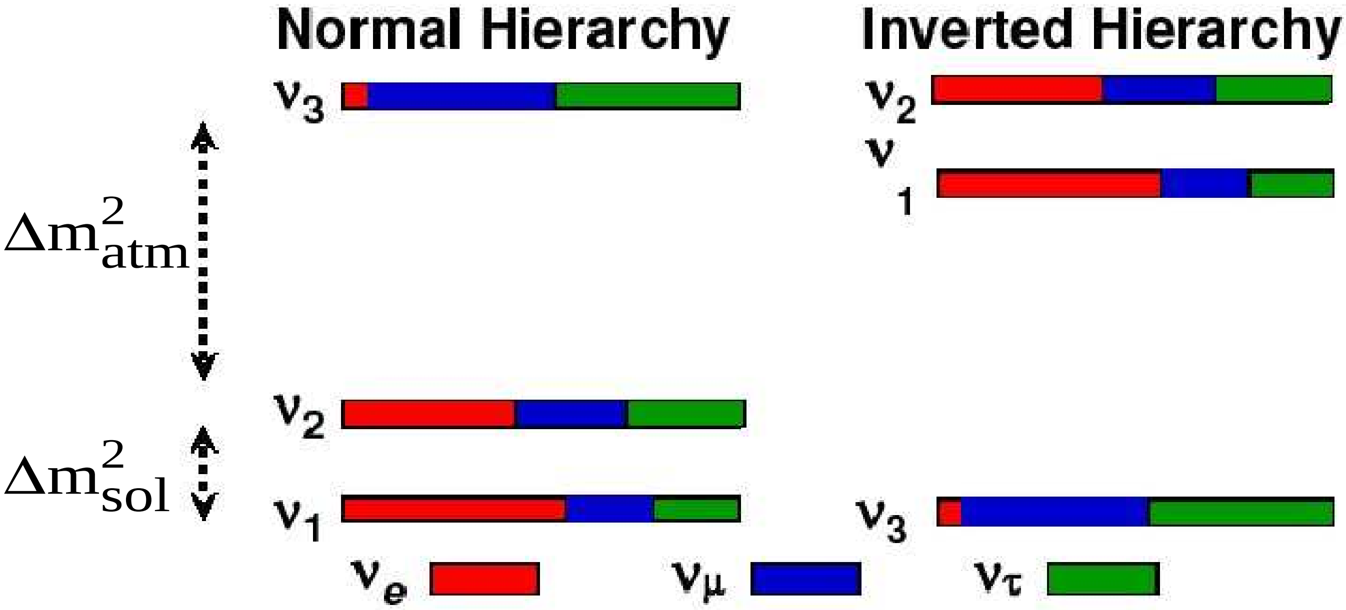
☑ $\theta_{12} = 33.5^\circ \pm 1^\circ$

☑ $\theta_{23} = 45^\circ \pm 4^\circ$

☒ $\theta_{13} \quad (< 11^\circ @ 90\% CL)$

☒ CP violating phase: δ

The Big Picture: Masses



☑ $\Delta m^2_{12} = (7.65 + \pm 0.23) \times 10^{-5}$ eV^2

☑ sign of the mass difference, $\Delta m^2_{21} > 0$.

☑ $\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV^2

Constraint: $\Delta m^2_{32} + \Delta m^2_{12} + \Delta m^2_{31}$=0

☒ *sign of the mass difference,* $\Delta m^2_{31} > 0$?.

Hunt for θ_{13}

SBL Reactor $\bar{\nu}_e$ disappearance

$$P_{\nu_e\to\nu_e} = 1-\sin^2\theta_{13}\,\sin^2\frac{1.27\Delta m^2_{31}L}{E} + \begin{matrix}\text{smaller}\\ \text{sol.term}\end{matrix}$$

- Double Chooz
- Daya Bay
- Reno

LBL Accelerator ν_e appearance

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{13}\,\sin^2\theta_{23}\,\frac{1.27\Delta m^2_{32}L}{E}$$

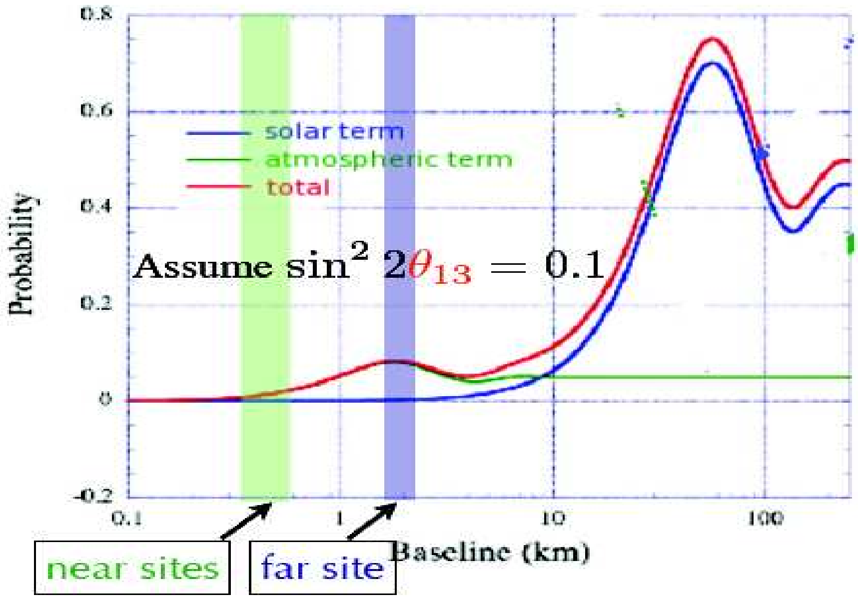
$$+ \text{ terms } (\delta, \text{ matter effects:} \operatorname{sign}(\Delta m^2_{31}))$$

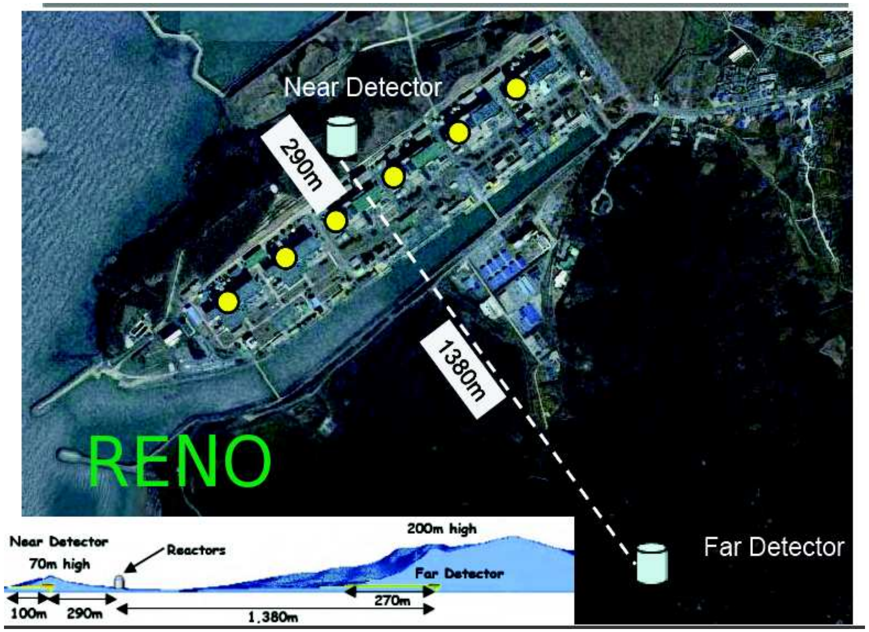
- **T2K**
  - L=295 km, $\langle E_\nu \rangle \approx$0.6 GeV
- **NOνA** (starts this summer).
  - L=810 km, $\langle E_\nu \rangle$=2GeV

Short-Baseline Reactor Experiments

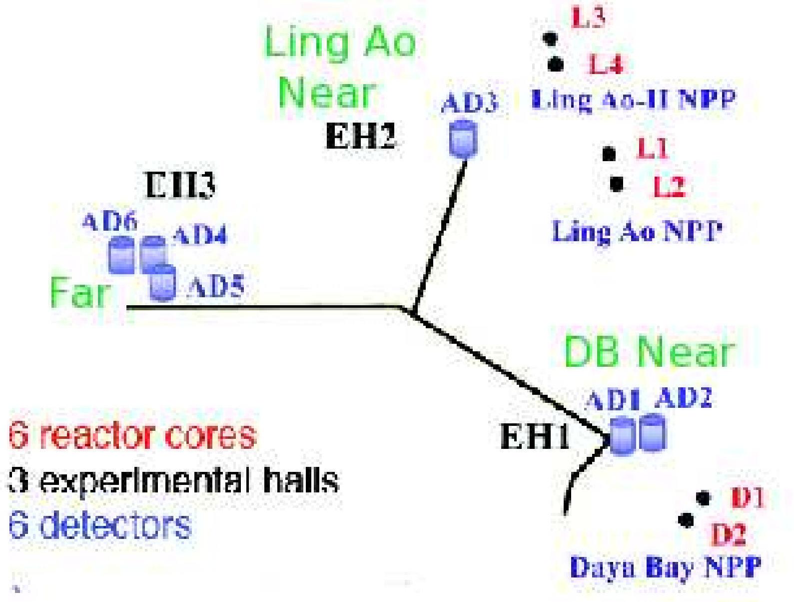
Small mixing $\Rightarrow$ need near detectors.

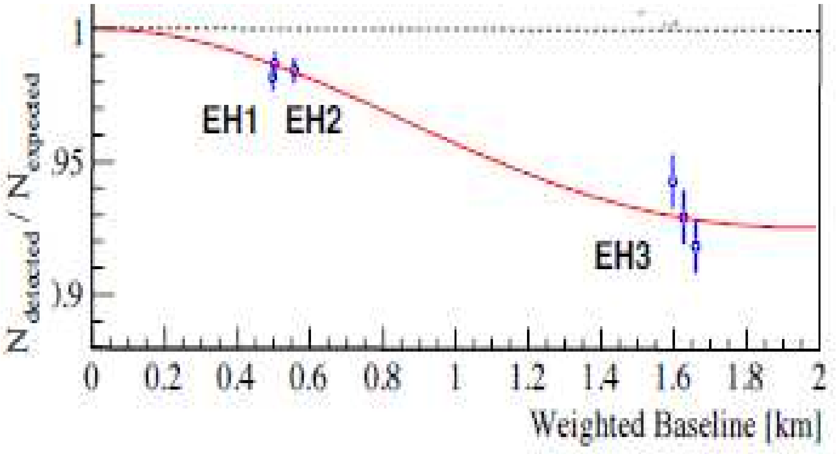
- **Near** (range ≈300m-550m)
  close to reactor to measure flux for normalization (reduce systematics).
- **Far** (range ≈ 1380m-1985m)
  near the first oscillation maximum to maximize sensitivity.(less affected by θ_{12}).





Daya Bay First Results (March 2012)



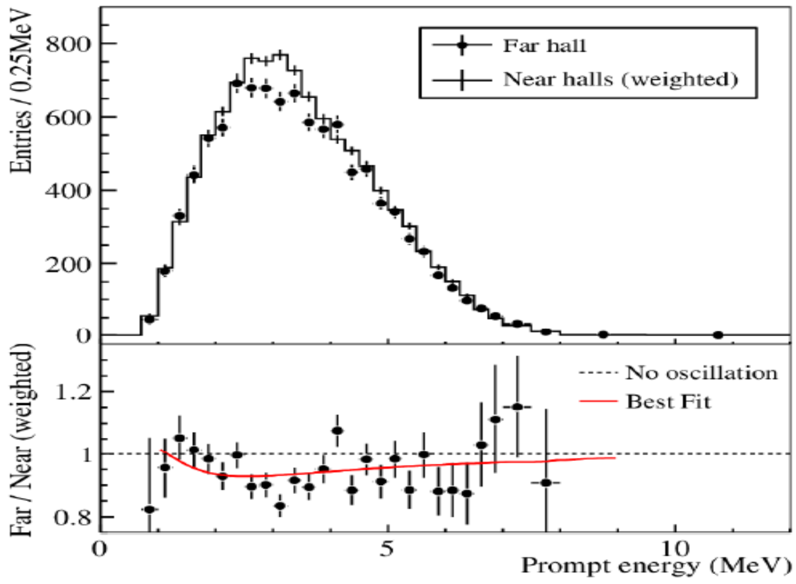


$$\frac{\mathrm{FAR}_{\mathrm{meas}}}{\mathrm{FAR}_{\mathrm{exp}}} = 0.944 \pm 0.007(\mathrm{stat}) \pm 0.003(\mathrm{syst})$$

- Design allows comparison of Near site measurements (control of syst. uncertainties).

$$\boxed{\begin{array}{l}\sin^2 2\theta_{13} = \\ 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})\end{array}}$$

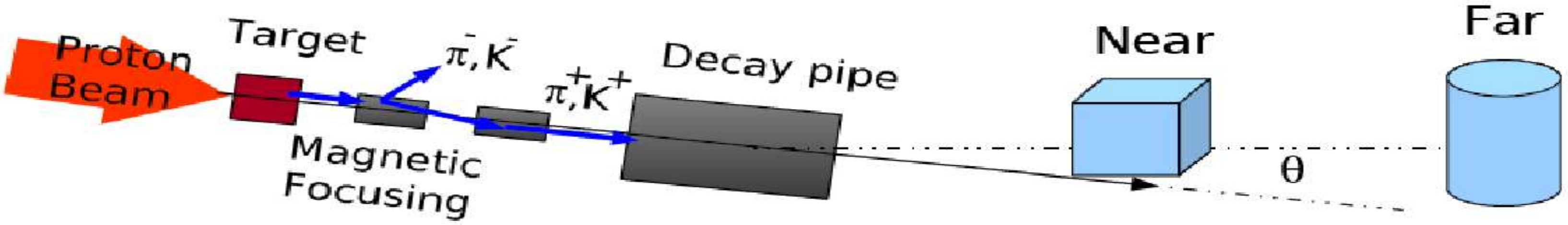
- 5.2σ (rate only)
- Spectral distortion consistent (not used in fit).

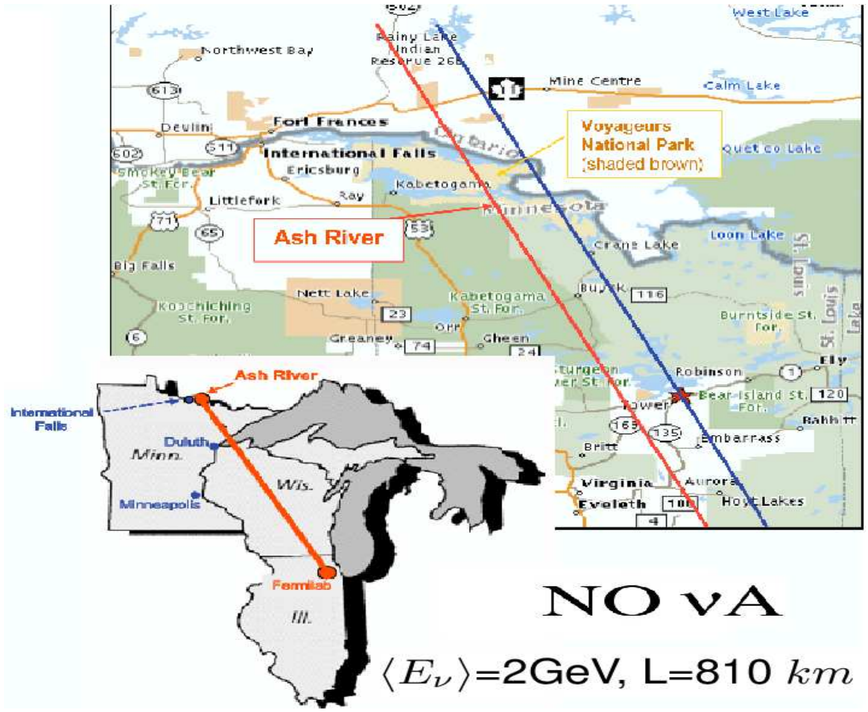


LBL Accelerator ν_e appearance

Common Design Features

- Large *fine-grained* Far and Near detectors: better optimized for ν_e identification.
- Neutrino detectors positioned off the beam axis to reduce backgrounds.





NO νA

$\langle E_\nu \rangle$=2GeV, L=810 km

Why Off-axis Neutrino Beams?

$\nu_\mu \rightarrow \nu_e$ appearance:

Small signal and large background!

- NC events with π° ($\rightarrow 2\gamma$).
- Beam ν_e contamination (from μ and K decay).

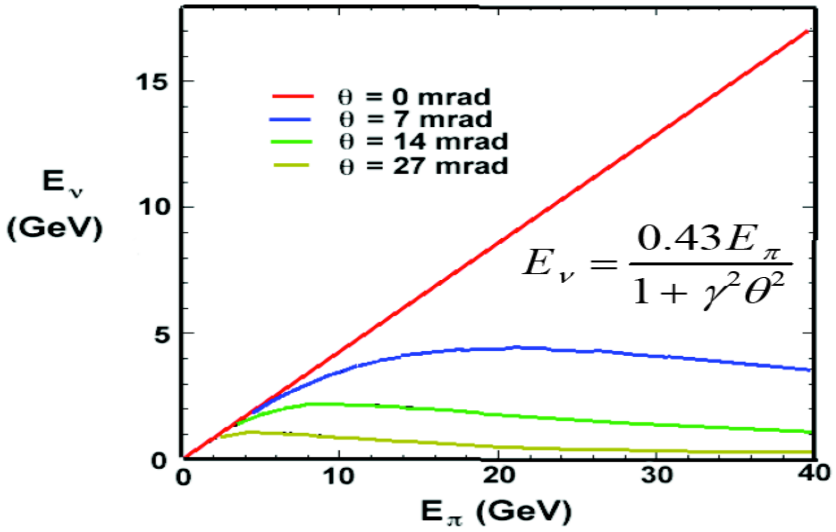
Off-Axis Beam features

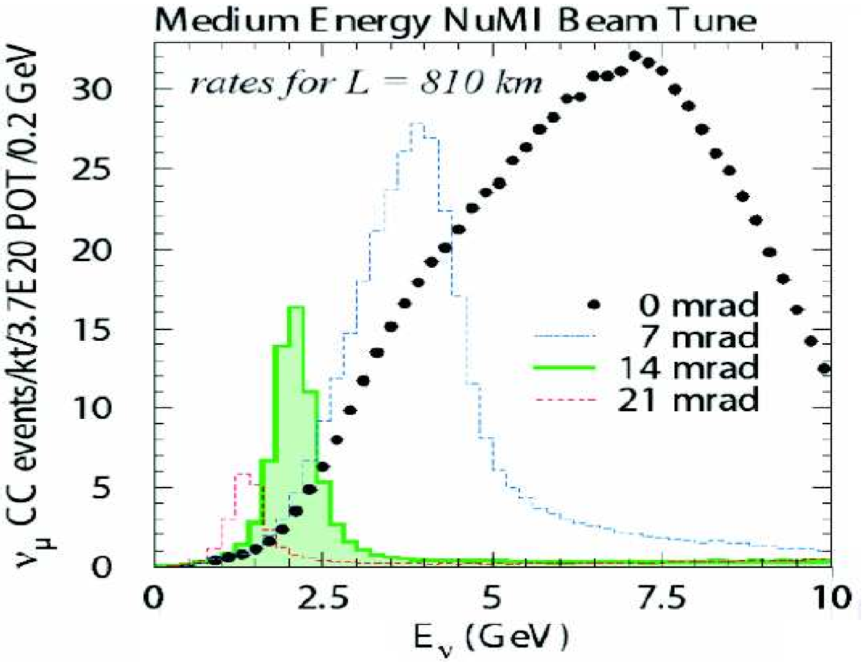
- Narrows spectrum (removes high-energy tail feed-down source of NC-π^o).
- Less beam ν_e contamination.
- Higher flux in the LE signal region.

Off-axis design (E$_\nu$ depends on θ)

- π decay kinematics limit max. E_ν in beam as a function of off-axis angle θ

$$E_\nu = \frac{E_\pi (1 - \frac{m_\mu^2}{m_\pi^2})}{(1 + \gamma^2\theta^2)}$$





$\nu_\mu \longrightarrow \nu_e$ Appearance

- The *disadvantage*/*advantage* of ν_e appearance expts with long-baseline beams is that they are sensitive to three unknowns (θ_{13}, δ, $sign(\Delta m^2_{13})$)

$$P(\nu_\mu \to \nu_e)_{vacuum} =$$

$$\sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\Delta_{atm}$$

$$+\cos^2\theta_{23}\sin^2(2\theta_{12})\sin^2\Delta_\odot$$

$$\mp J_r\sin\delta_{CP}\sin^2\Delta_{atm}\sin\Delta_\odot$$

$$+J_r\cos\delta_{CP}\sin\Delta_{atm}\cos\Delta_{atm}\sin\Delta_\odot$$

(- neutrinos, + antineutrinos)

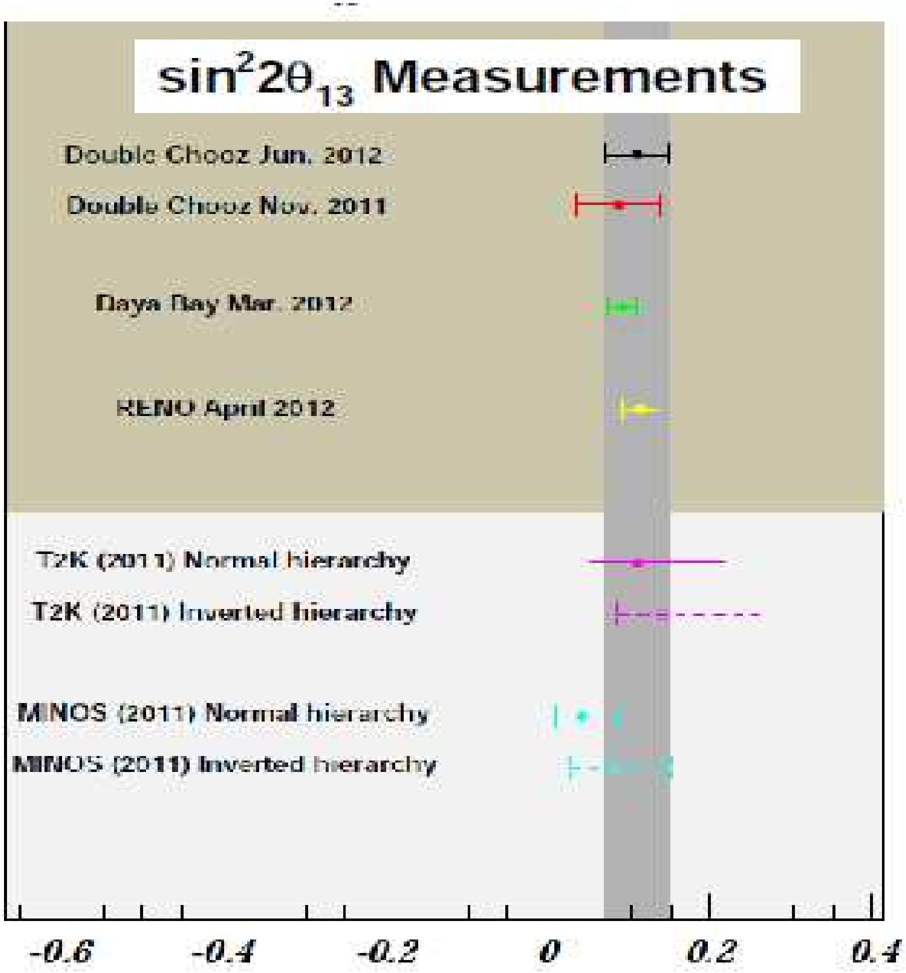
$$J_r = \cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})$$

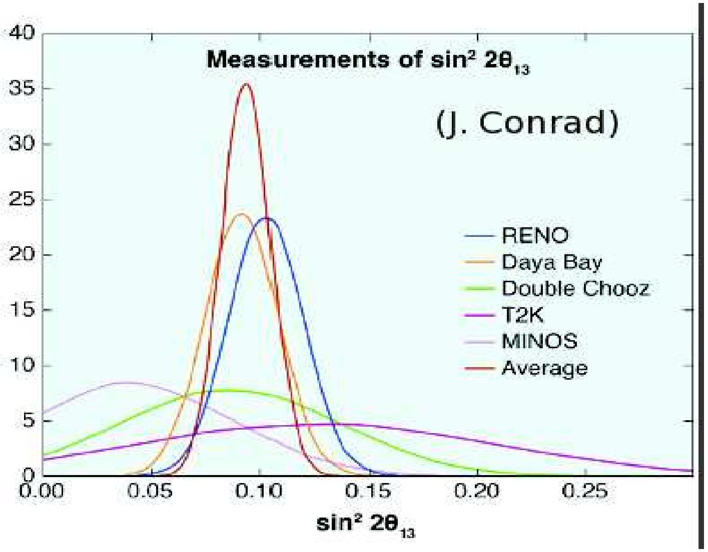
- *dominant term* $\approx \frac{1}{2}\sin^2(2\theta_{13})$ *at osc. max.*
- *small for accelerator longbaseline L/E's*
- *sub-leading CP violating phase terms.*

$$\Delta_\odot = 1.27\Delta m^2_{12}L/E$$
$$\Delta_{atm} = 1.27\Delta m^2_{13}L/E$$

- Sub-leading terms sensitive to δ_{CP}. (Different sign for ν and $\overline{\nu}$).
- Include matter effects $\Rightarrow$ sensitive to sign Δm^2_{13} and changes sign for ν vs. $\overline{\nu}$.

$\sin^2 2\theta_{13}$ Measurement Summary





- mid-2012: results from 5 experiments (reactor+accelerator).
- Daya Bay October 2012 update (significance 7.7σ)

$$\boxed{\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})}$$

$\boxed{\surd}$ $\theta_{12} = 33.5^\circ \pm 1^\circ$

$\boxed{\surd}$ $\theta_{23} = 45^\circ \pm 4^\circ$

$\boxed{\surd}$ $\theta_{13} = 8.7^\circ \pm 0.5^\circ$

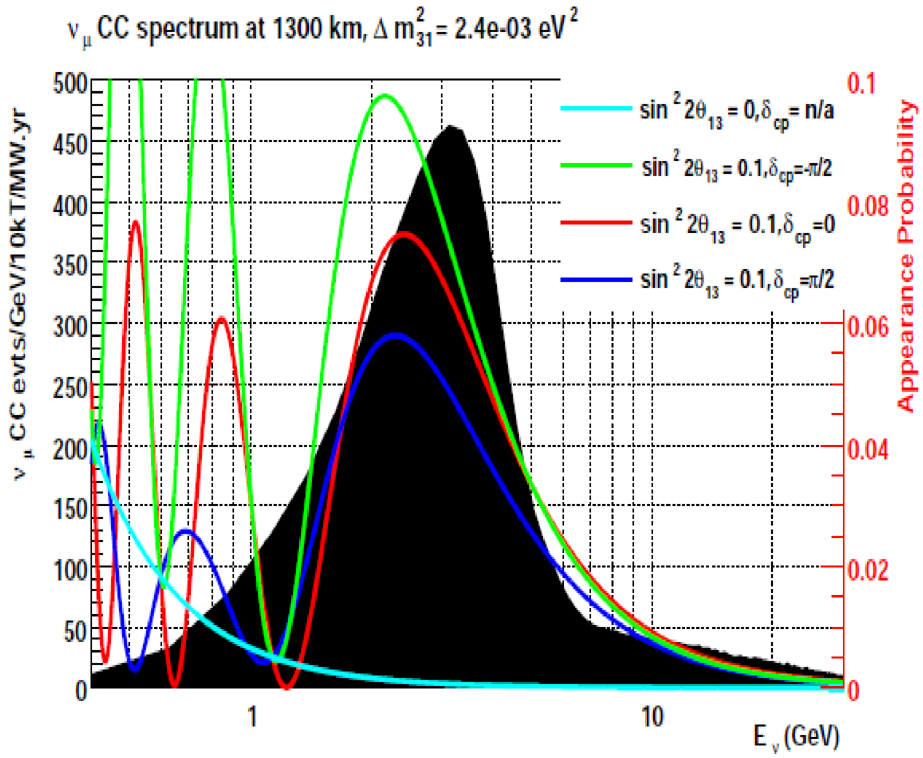
Oscillations What’s Next?

- Is CP symmetry violated in the neutrino sector? → size of δ.
- Ordering of the masses → is m_3 the heaviest or the lightest?
- Are there additional (sterile) neutrino states?
- Theory questions: pattern of masses and mixing?

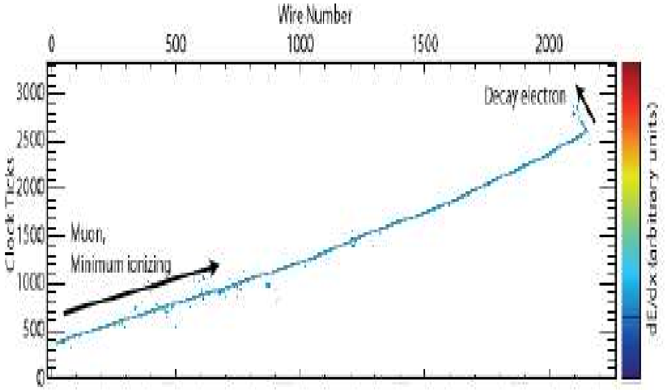
Planning a next generation optimized for δ and hierarchy sensitivity.

- Includes very long baseline L$\sim$1300 km beam Fermilab → Sanford (SURF).

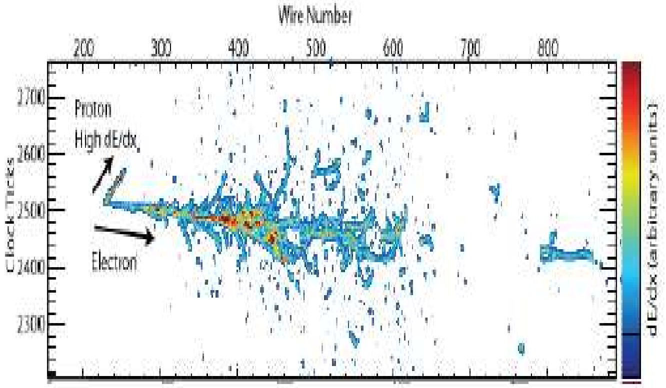
LBNE Snapshot



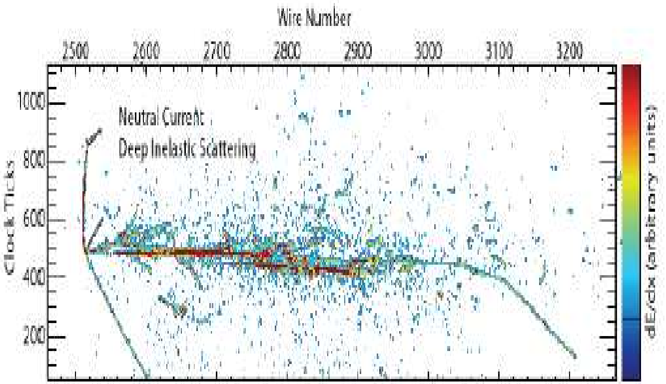
ν_μ CC



ν_e CC

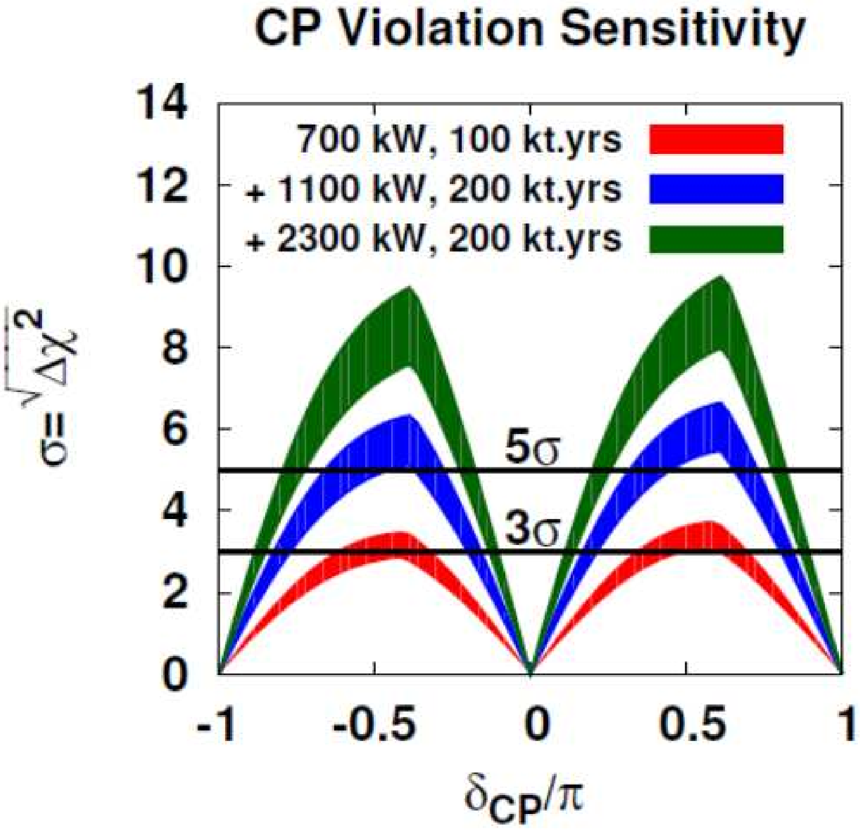


ν_x NC



- High-intensity proton beam ($>$700 kW).
- Beam Covers $1^{\rm st}$ (2.4 GeV) and $2^{\rm nd}$ (0.8 GeV) oscillation maxima.
  - Sensitivity to $\delta \rightarrow$ effect differs.
- 34 kt LAr TPC Far Detector

CP Violation Matters

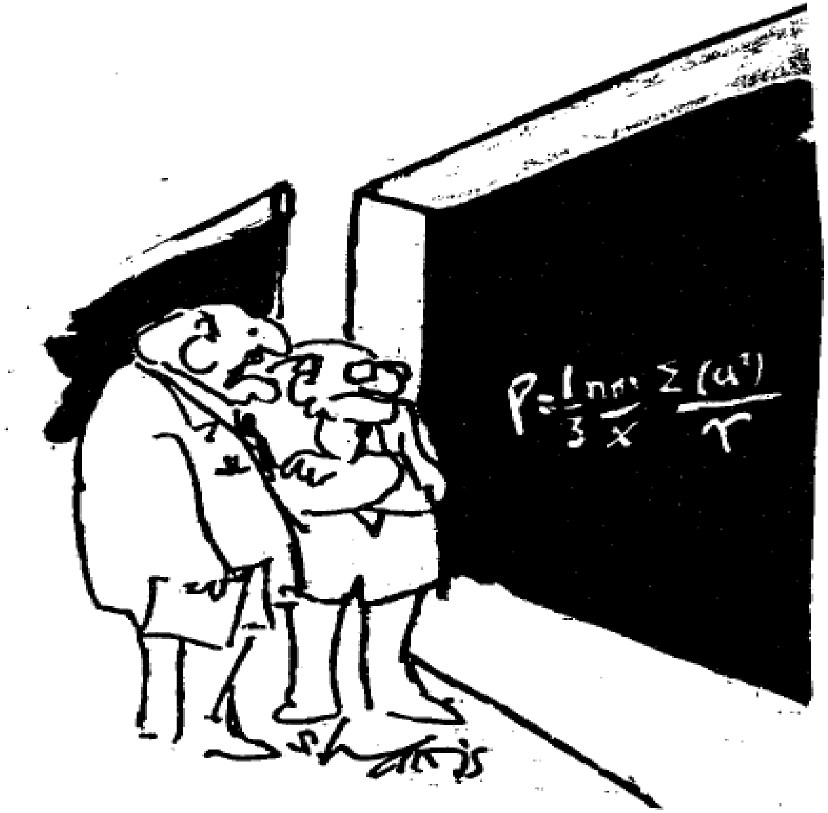


Summary and Outlook

We are making progress towards understanding neutrino interactions and properties

- Neutrino have a long history of probing the standard model.
- Recent revolution understanding properties→ Discovery of mass and mixing
  - Mass splittings and all mixing angles known!

Exciting times for neutrino physics!



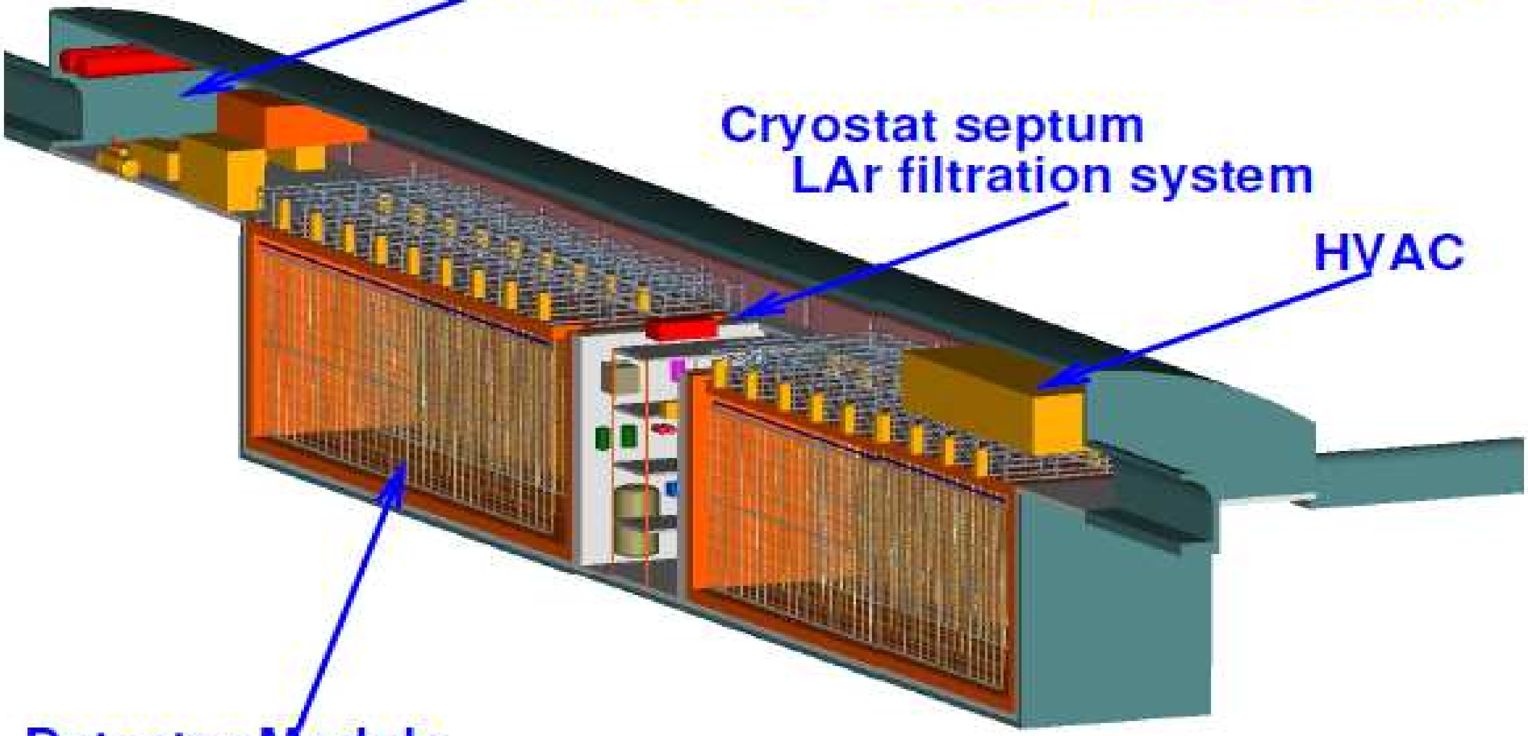
"What's most depressing is the realization that everything we believe will be disproved in a few years."

- Apologies for the many important topics not covered ($0\nu\beta\beta$, sterile neutrinos, SB neutrino oscillation anomalies, etc.)
- Many thanks to previous lecturers for slides (D. Schmitz, J. Morfin, G. Perdue, etc.)

Extra

LBNE LarTPC

A 35 kton fiducial Liquid Argon Time-Projection-Chamber:



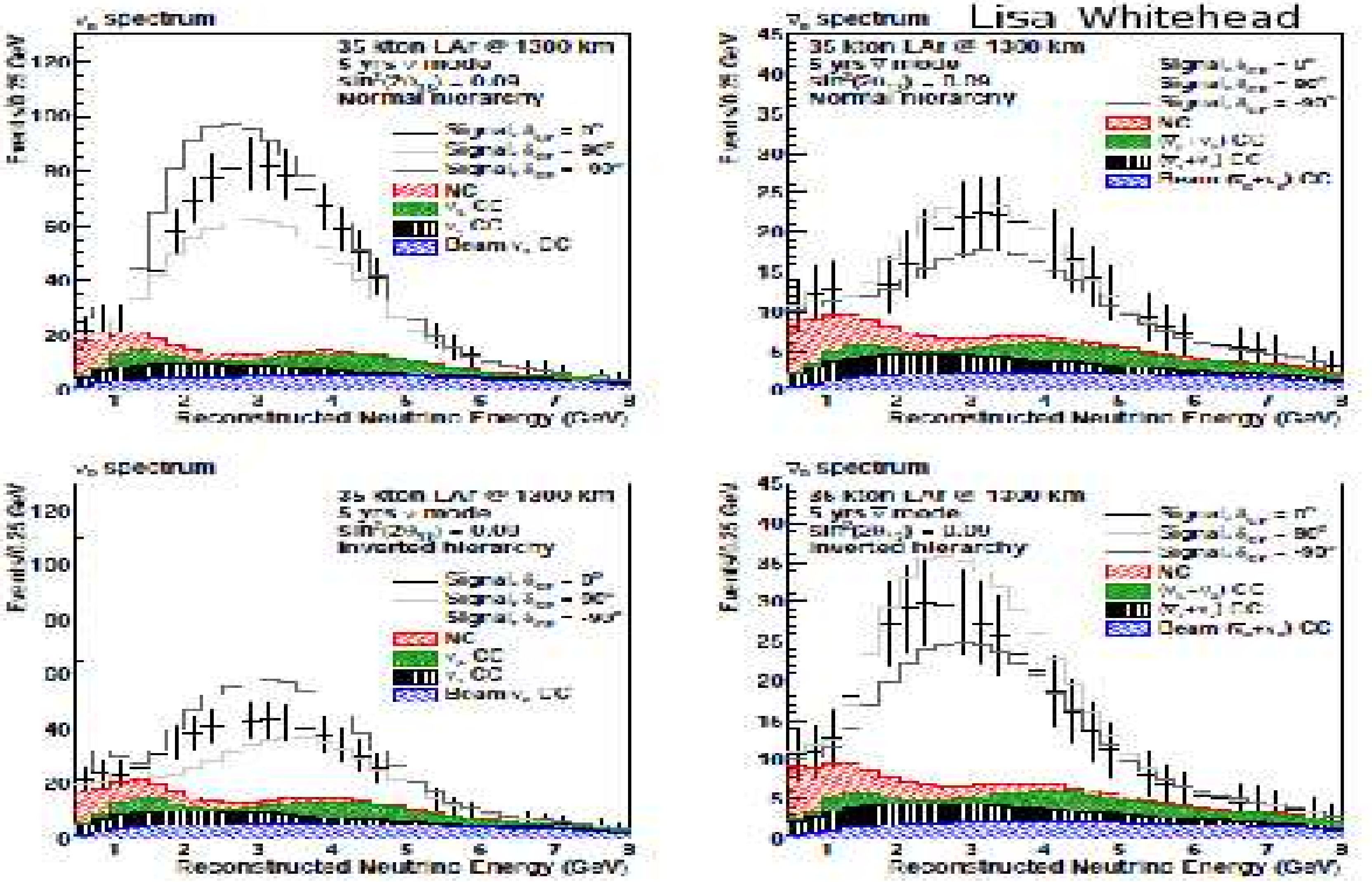
Cryogenics – cold box, buffer storage

Cryostat septum
LAr filtration system

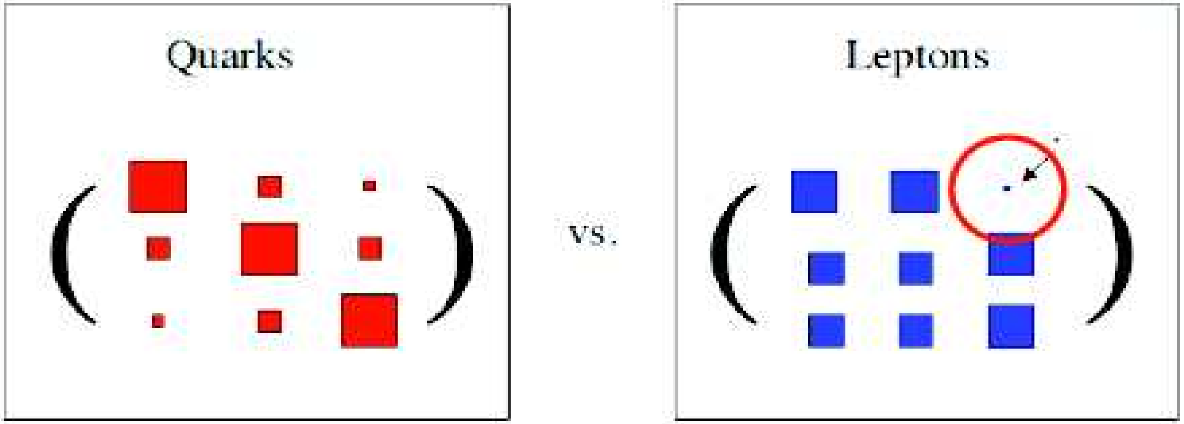
HVAC

Detector Module
2 high x 3 wide x 18 long drift cells x 2 modules

LBNE Spectra

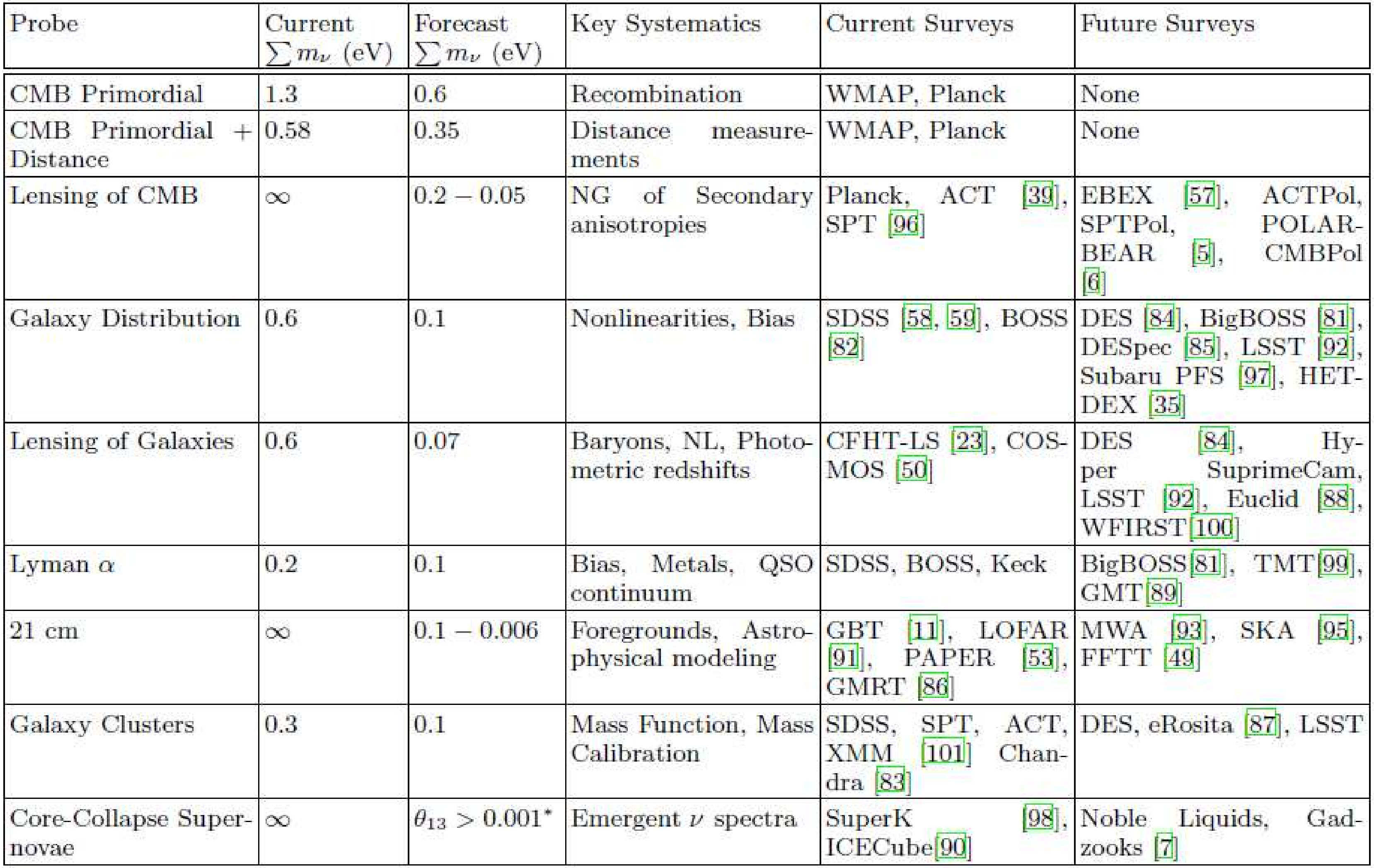


CKM vs. PMNS



Cosmological Mass measurements

Astropart. Phys. 35, 177 (2011)



Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gadzooks [7]

Computing Oscillation Probabilities

$$P(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2$$

$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$
$|\nu_\mu(0)\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$
$|\nu_\mu(t)\rangle = U_{\mu 1}\exp^{-iE_1 t}|\nu_1\rangle + U_{\mu 2}\exp^{-iE_2 t}|\nu_2\rangle + U_{e3}\exp^{-iE_3 t}|\nu_3\rangle$

ΔE for two different mass states in high-energy approximation $p >> m$

$$E_i = \sqrt{p^2 + m_i^2} = p(1 + (\frac{m_i}{p})^2)^{\frac{1}{2}} \approx p(1 + (\frac{1}{2})(\frac{m_i}{p})^2) \approx (E + (\frac{m_i^2}{2E})$$

$$\Delta E \approx \frac{m_i^2 - m_j^2}{2E}$$

Write in terms of $\Delta m^2 = \left(m_i^2 - m_j^2\right)$ and path length $c = 1 \Rightarrow \quad t = L$

General expression $\quad P(\nu_\alpha \to \nu_\beta) =$

$$\delta_{\alpha\beta} - 4\Sigma_{i>j}\Re\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\Sigma_{i>j}\Im\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

Flavor Composition of Neutrino Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$