Neutrino Physics and Experiments
1st - Lecture

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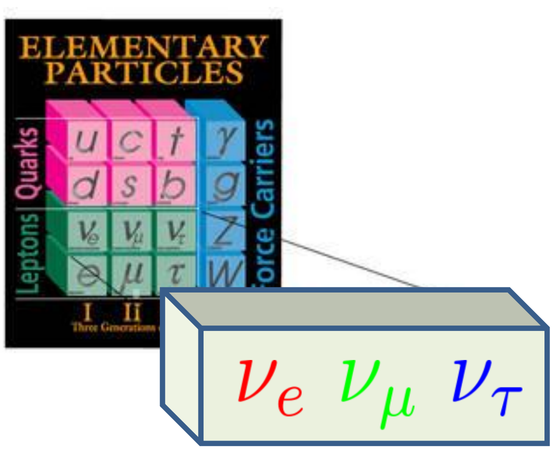
ICFA School 2023

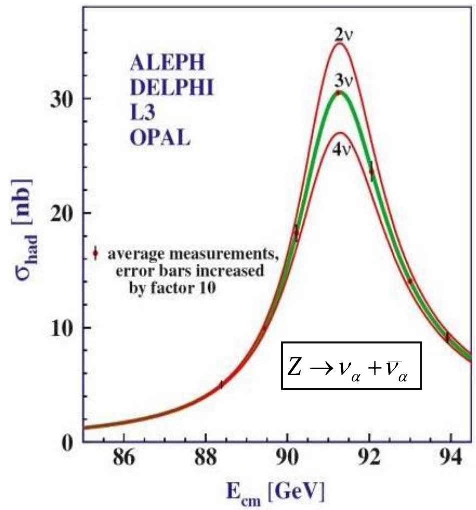
Tata institute of fundamental research
Mumbai -India

Outline

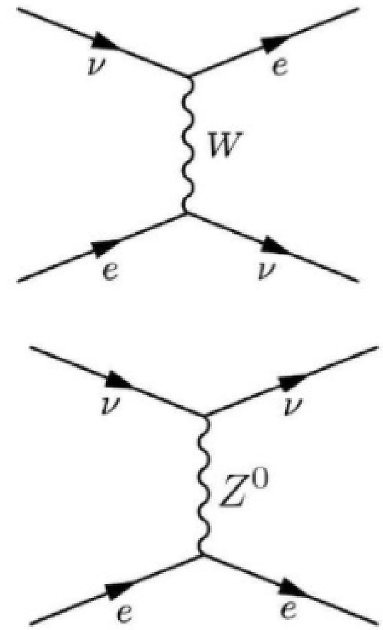
- Neutrino Historical Background
- Neutrino Oscillations
- Three-Neutrino Oscillations: Future
- Beyond Three-Neutrino Oscillations: Sterile Neutrinos.
- Absolute Neutrino Mass
- Astrophysical Neutrinos

Neutrinos – Standard model





$$N_\nu = 2.9840 \pm 0.0082$$



$$m_\nu \bar{\nu}_L \cancel{\nu_R}$$

$$m_\nu = 0$$

in the Standard Model

$$l = \frac{1}{n\sigma} = 10^{17}\ \text{cm} = 10^8 D_{\text{Earth}}$$

normal matter mean free path for 1 MeV neutrino

100 millions of Earth-diameters $\sim$ 0.1 light years

Neutrinos interact weakly with matter

Neutrino Historical Background

Neutrinos – The beginning

(1930) Wolf
proposed a
save the inc
between th
beta(electro
spectrum ar
one.

Observed energy

Radioactive β decay

original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein

art

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-}$$

rgetic spectrum -
y decay

Letter sent to a group of physicists meeting in Tübingen in December 1930

The introduction of the neutrino was a ***desperate remedy*** *for saving energy conservation*

Neutrinos – The Poltergeist Project

Almost 30 years later….

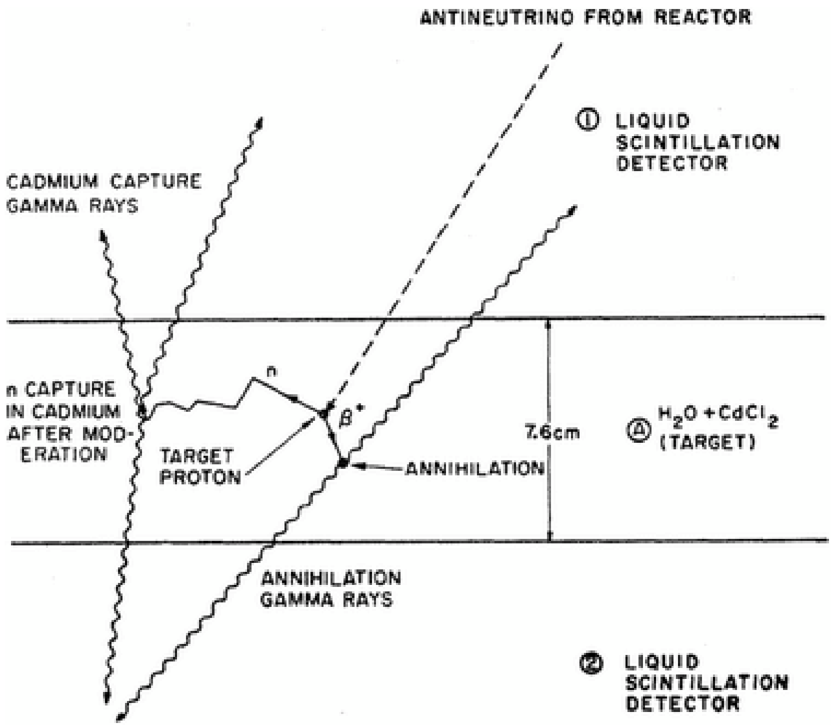
Electron Neutrino ν_e

(1956) Fred Reines and Clyde Cowan build
the first reactor neutrino experiment

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

$$e^+ e^- \rightarrow \gamma + \gamma$$

$$n + Cd \rightarrow Cd^* \rightarrow \gamma + Cd$$



Neutrinos – Muon neutrino

Muon Neutrino ν_μ

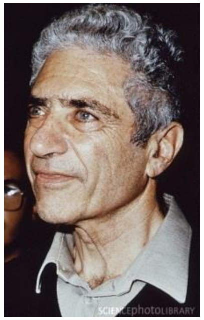
(1962) Lederman, Schwartz and Steinberger
the first accelerator neutrino experiment

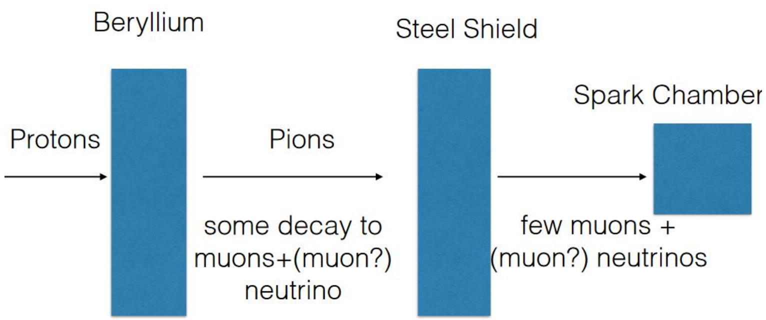
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

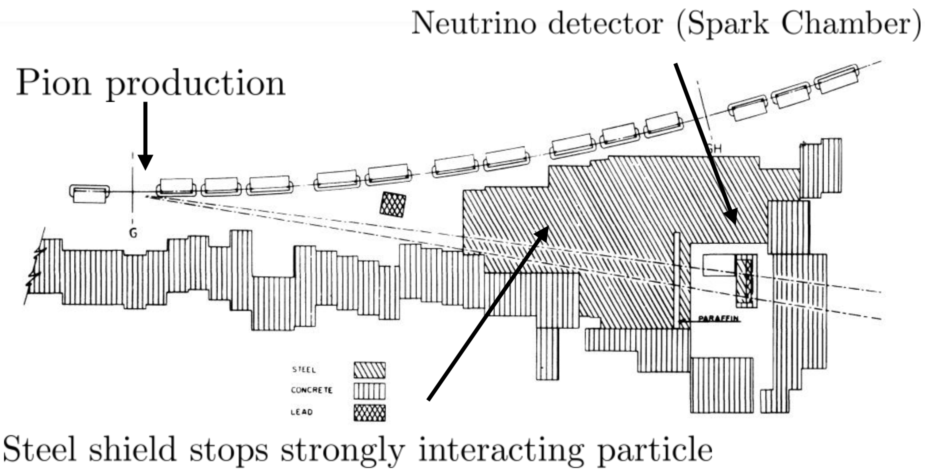
They do not see:

$$\bar{\nu}_\mu + p \rightarrow e^+ + n$$





AGS Neutrino Experiment



Neutrinos – Tau neutrino

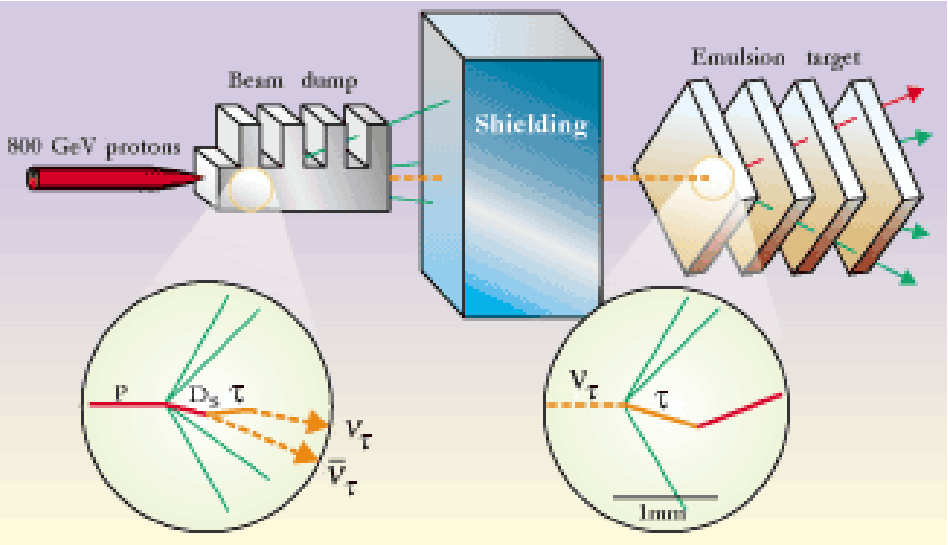
Tau Neutrino ν_τ

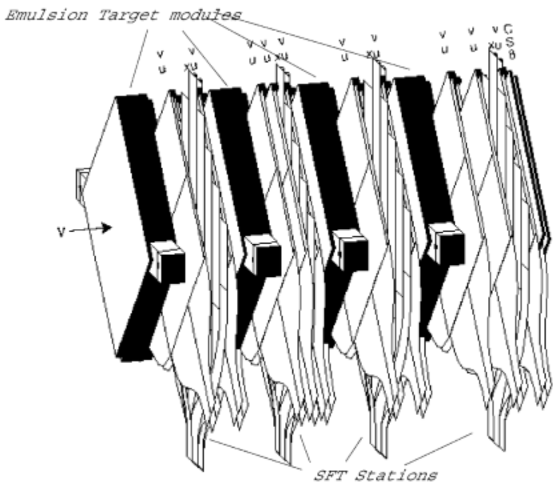
(2000) In Fermilab the DONUT collaboration observed for the first time ν_τ

$$D_s^+ \to \tau^+ + \nu_\tau$$

$$\nu_\tau + n \to \tau^- + X$$

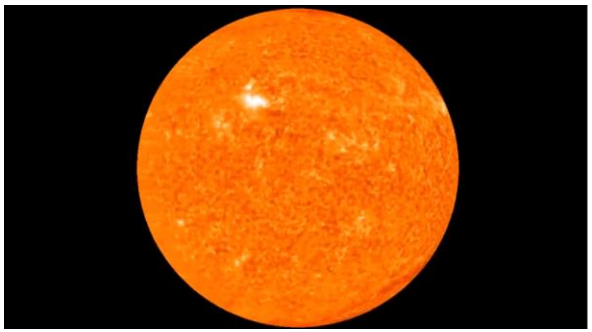
$$\tau^- \to \mu^- + \nu_\tau + \bar{\nu}_\mu$$



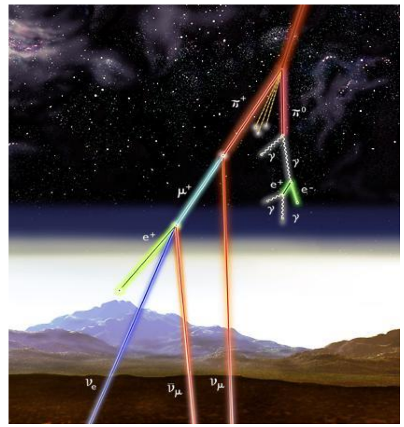


Scintillating Fiber Tracking (SFT)

Neutrino Sources



Solar ν's - MeV



Atms ν's GeV- PeV

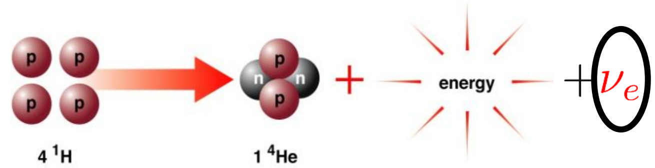
Extragalactic ν's PeV- EeV

Reactor ν's - MeV

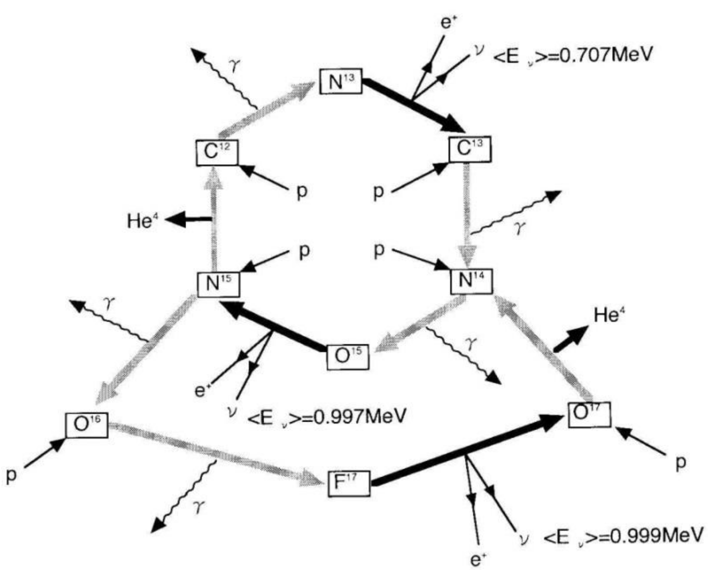
Accelerator ν's - GeV

Solar neutrinos

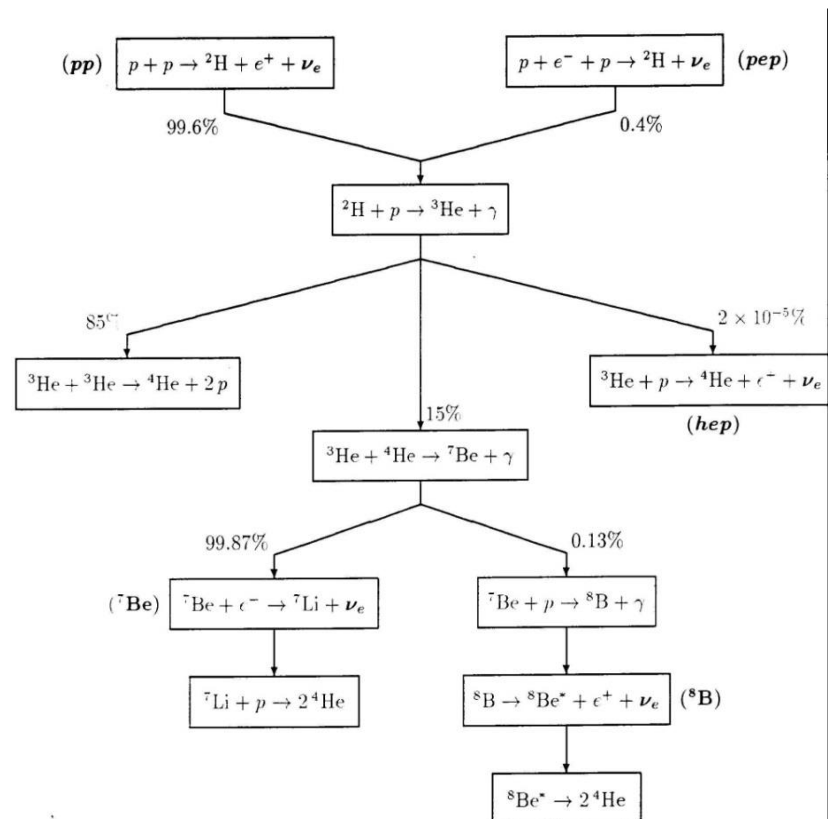
Sun net reaction



$$4p \rightarrow^4_2 H_e + 2e^+ + 2\nu_e + \text{Energy}$$



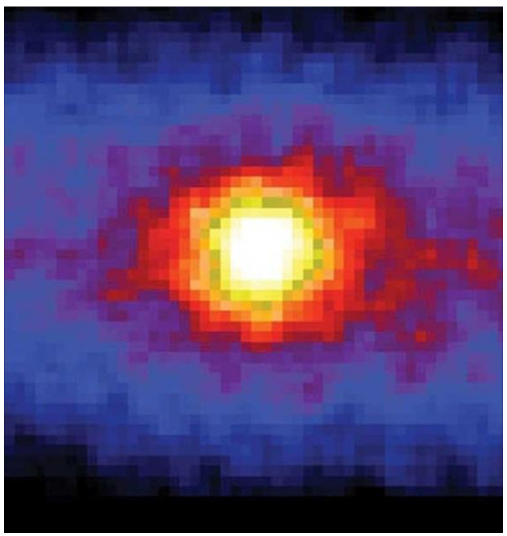
CNO - cycle

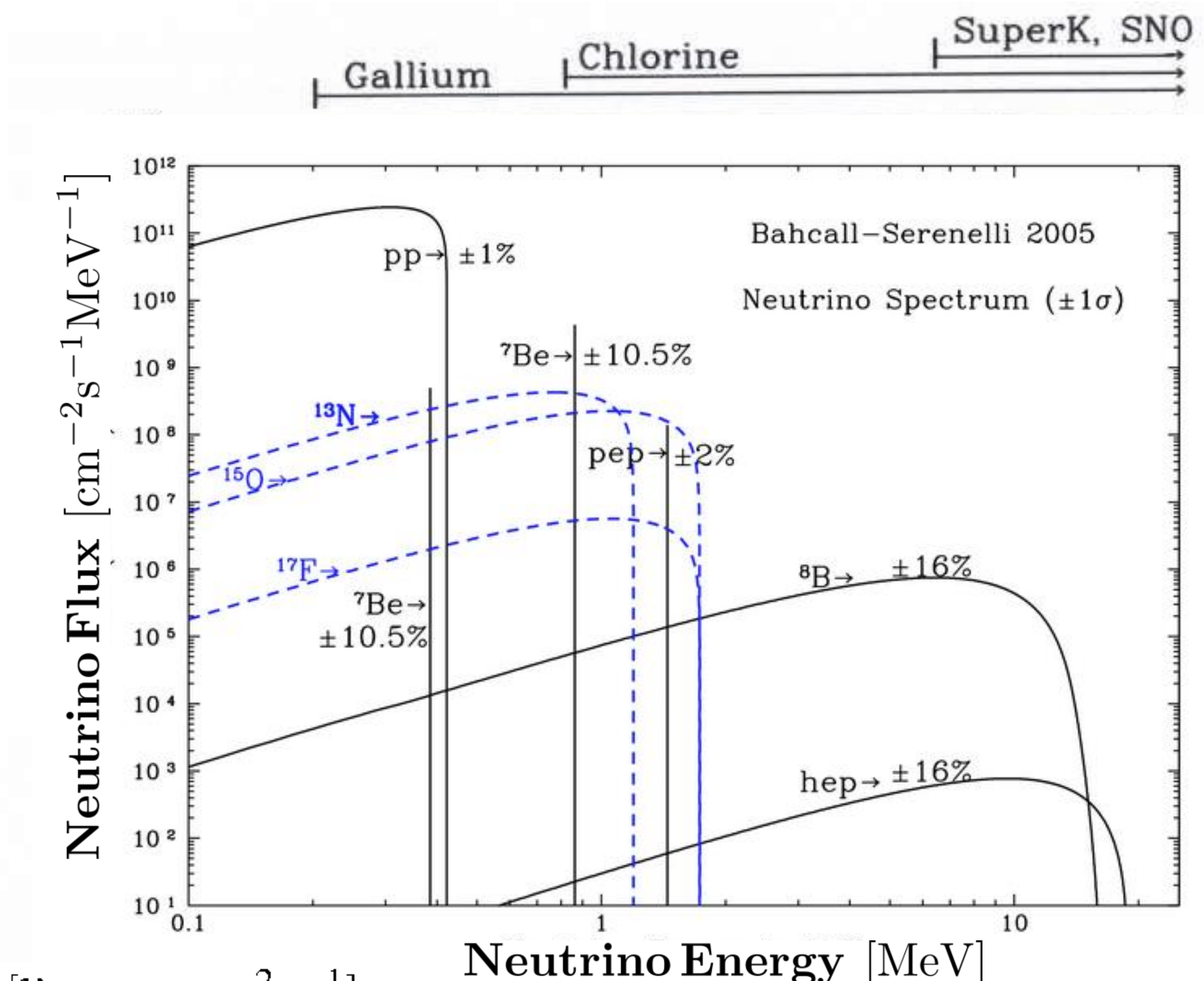


pp - Chain

Solar neutrinos

Sun of neutrinos





$\text{Flux cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ [lines : $\text{cm}^{-2}\text{s}^{-1}$]

Gallium = SAGE & Gallex

Chlorine = Homestake

Homestake experiment


Raymond David Jr. (left) and John Bahcall in miner's

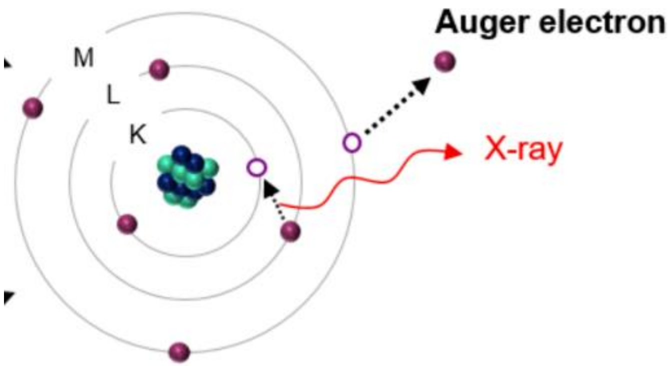
- A large tank of 600 tons of C_2Cl_4 **(Tetrachloroethylene)** located at 1500 m depth in the Homestake Gold Mine in Lead, South Dakota. Solar neutrinos detected through inverse beta decay (IB):

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

- ^{37}Ar atoms are removed every 60 days by purging the liquid with ^{2}He gas and collecting them from the gas stream with an adsorber (Carbon).

The ^{37}Ar sample (with a half-life of 35 days) is placed in a proportional counter decaying via electron capture:

$$^{37}\mathrm{Ar} + e^- \rightarrow \mathrm{Cl} + \nu_e \Rightarrow \text{Auger electrons}$$



Solar Neutrino Problem

Gallium experiments (SAGE and GALLEX):

- Solar neutrinos detected via IB decay:

$$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$$

- After one-month ^{71}Ge atoms are extracted and placed in a proportional counter decaying through:

$$^{71}\text{Ge} + e^- \rightarrow ^{71}\text{Ga} + \nu_e \Rightarrow \text{Auger electrons}$$

Solar Neutrino Problem:

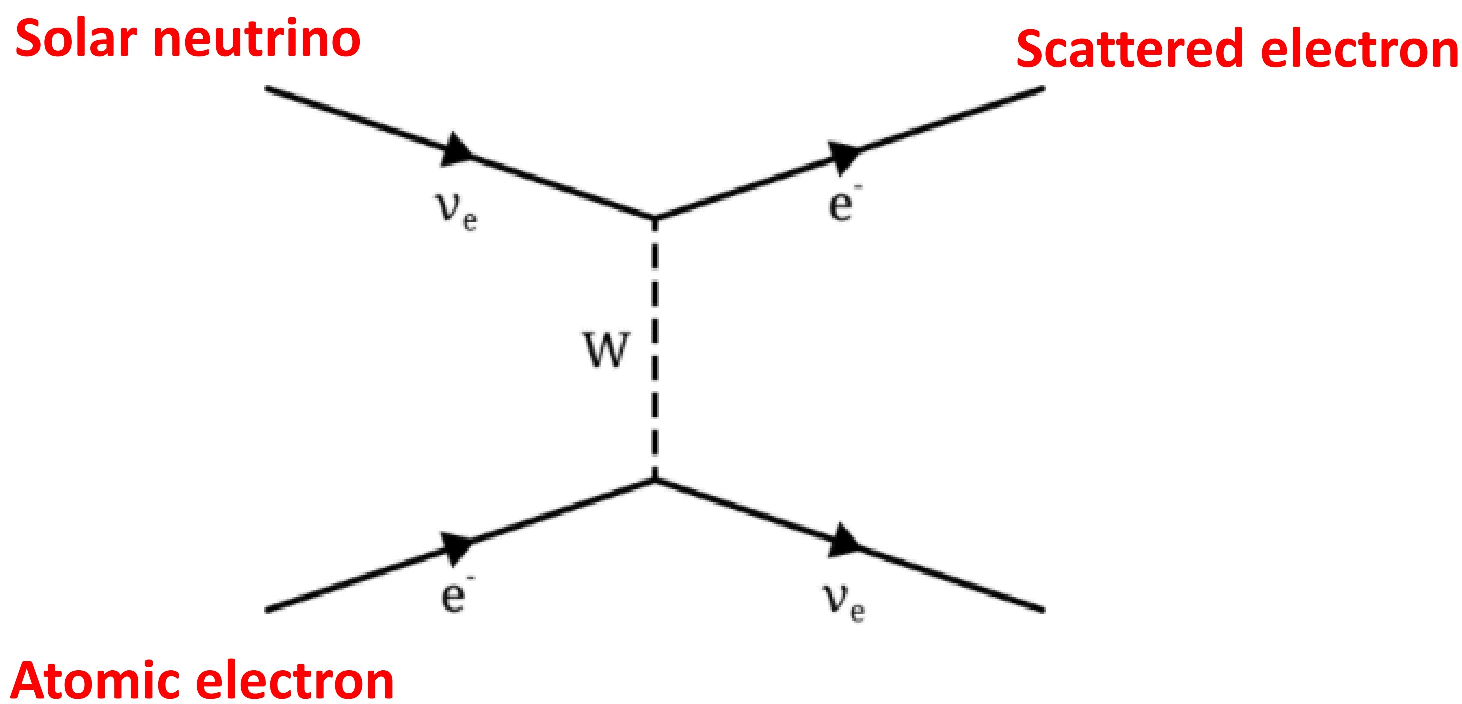
$$R_{\text{SAGE+GALLEX}} = 0.56 \pm 0.04$$

$$R_{\text{Homestake}} = 0.34 \pm 0.03$$

$$R = \frac{\phi^{\nu}_{\text{expt}}}{\phi^{\nu}_{\text{theo}}}$$

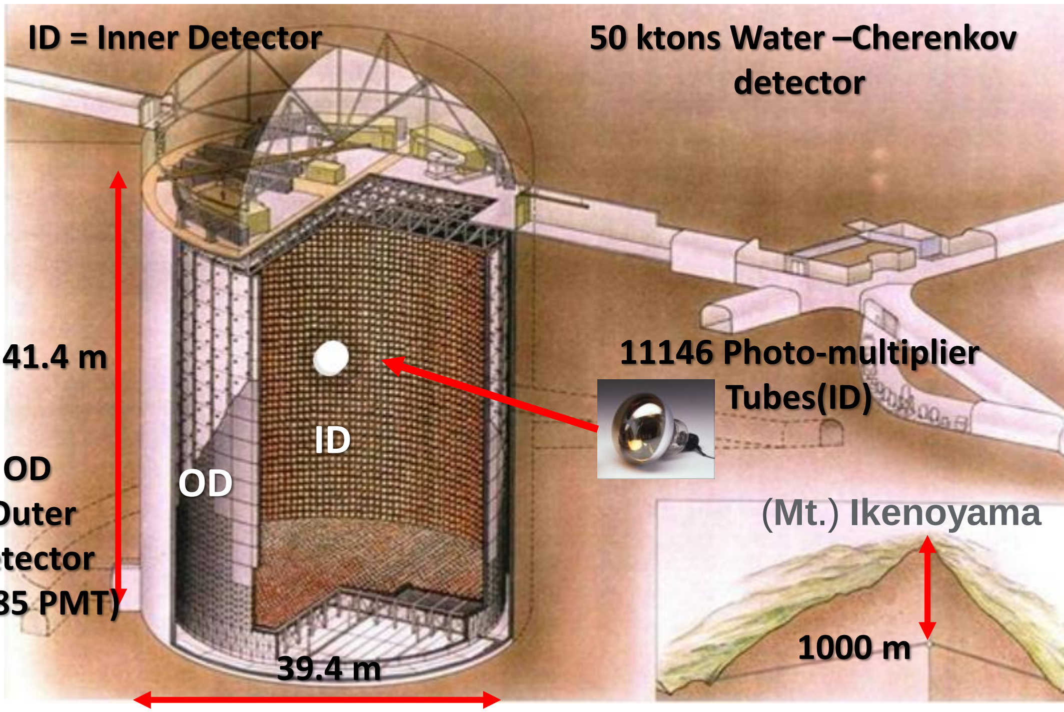
Super-Kamiokande Experiment

- Real-time neutrino event detection: energy and direction.
- Sensitive to Boron-8 neutrinos
- Solar neutrinos are detected via neutrino-electron elastic scattering:

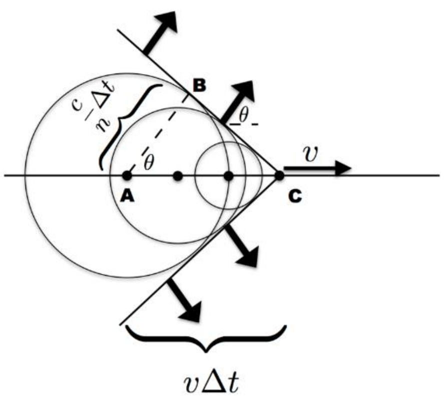


The $\nu_e - e$ NC contribution is part of the SuperK signal

Super-Kamiokande Experiment



Cherenkov Radiation

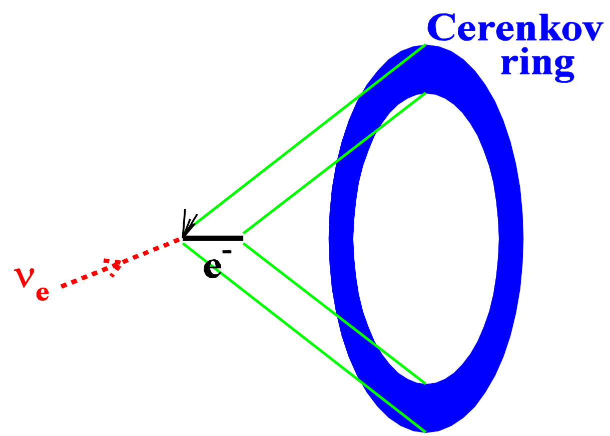


Equivalent to the *sonic boom*

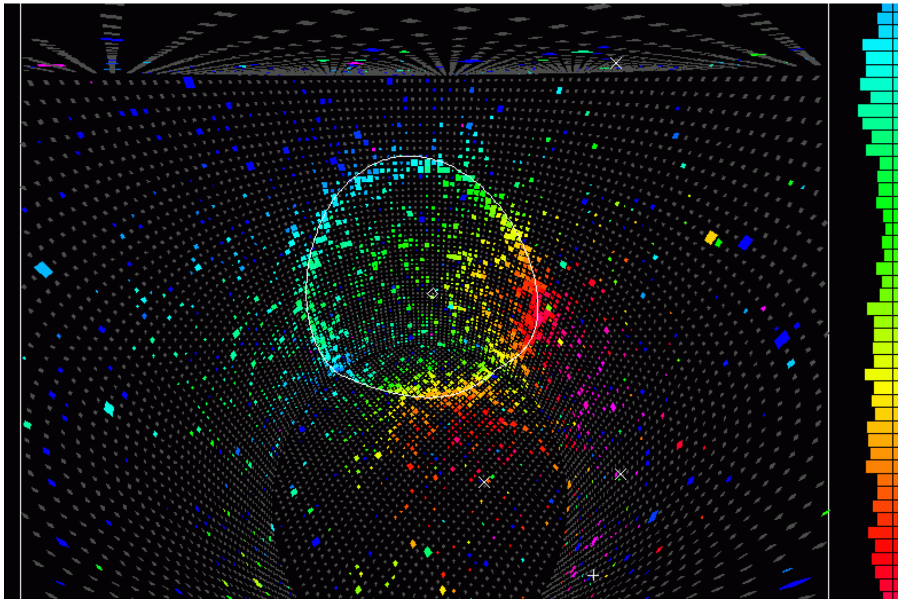
$$v > \frac{c}{n}$$

The particle start emitting radiation

Blue glow in reactors

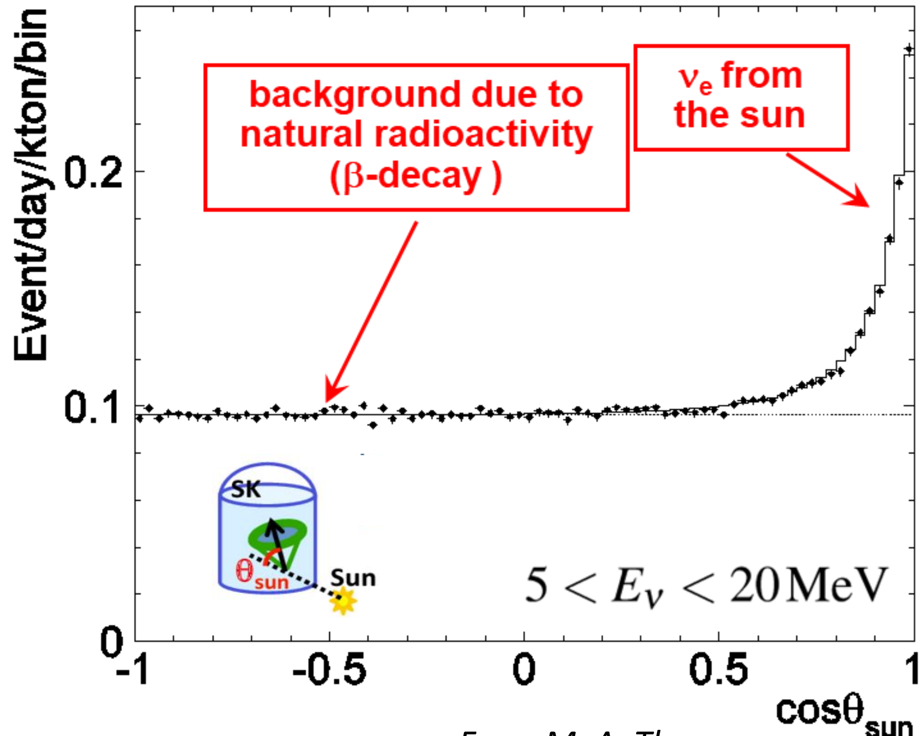


Super-Kamiokande Experiment



Number of Photons ∝ Electron Energy

S.Fukada et al., Phys. Rev. Lett. 86 5651-5655, 2001



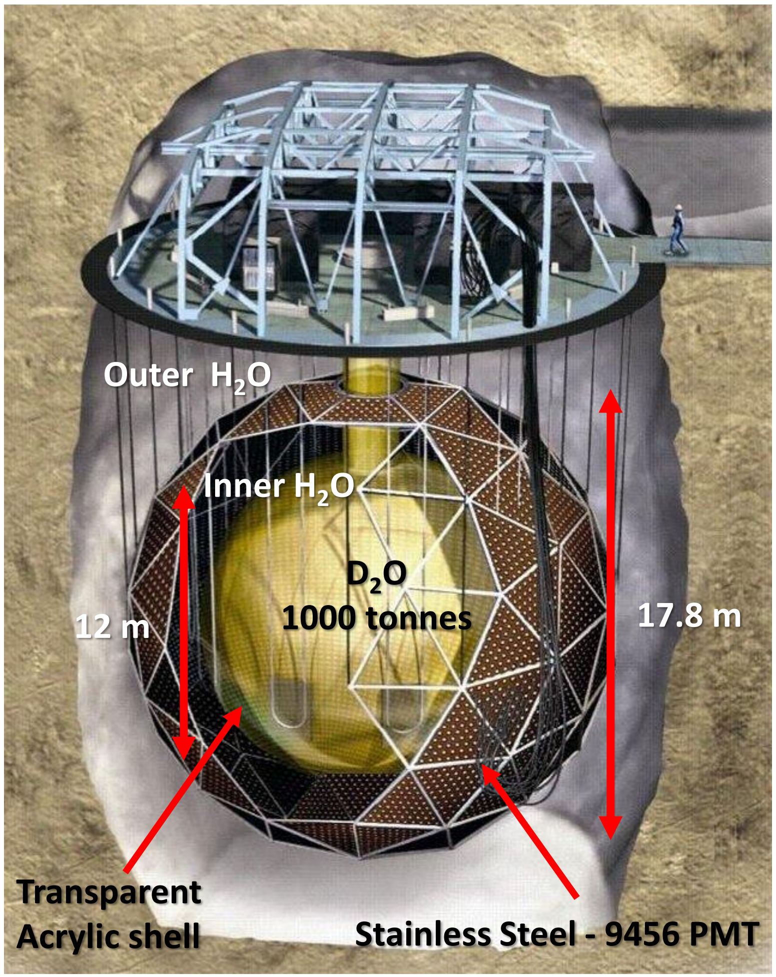
From M. A. Thomson

$$R_{\text{SuperK}} = 0.46 \pm 0.02$$

Solar neutrino deficit confirmation

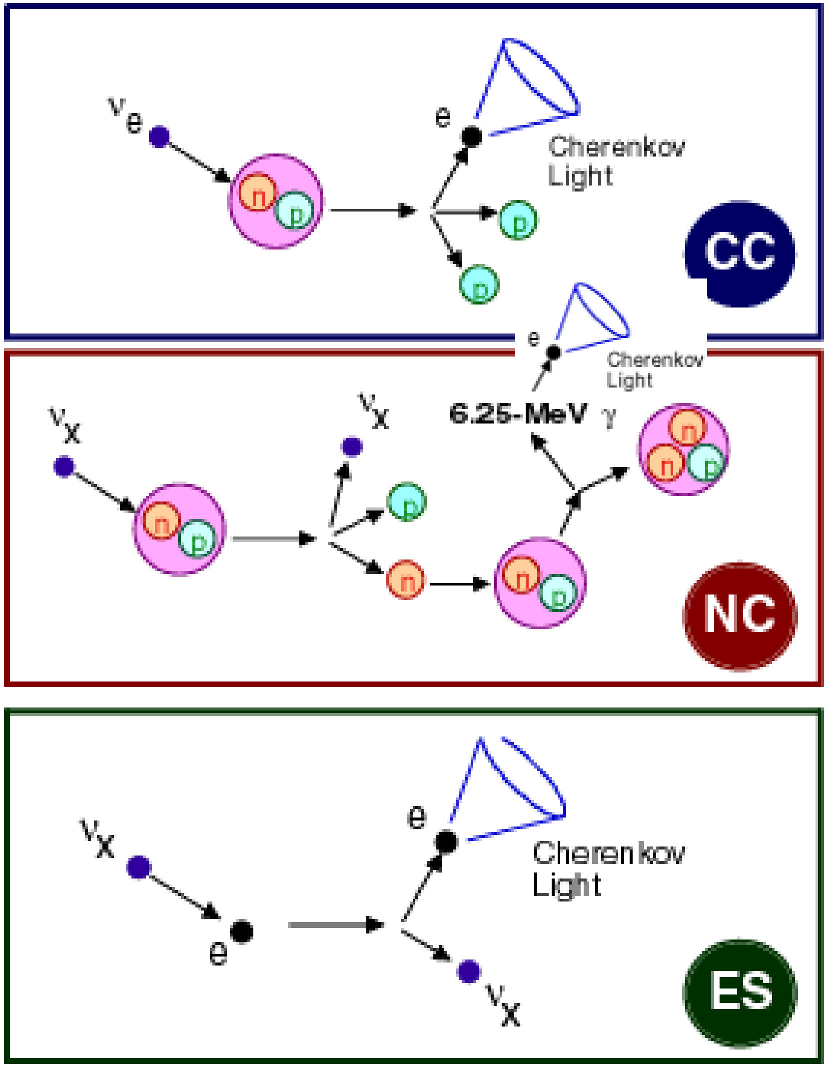
Sudbury Neutrino Observatory (SNO)

SNO: Water Cherenkov detector at Creighton mine 2 km underground. Sensitive to Boron-8 neutrinos



Sudbury Neutrino Observatory (SNO)

Solar neutrinos detected via:



$$\nu_e d \rightarrow p p e^- (\mathrm{CC})$$

$$\phi_{SNO}^{CC} = \phi_{\nu_e}$$

$$\nu_x d \rightarrow \nu_x p n (\mathrm{NC})$$

$$\phi_{SNO}^{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

$$\nu_x e^- \rightarrow \nu_x e^- (\mathrm{ES})$$

$$\phi_{SNO}^{ES} = \phi_{\nu_e} + \frac{1}{6.36} \phi_{\nu_{\mu\tau}}$$

Solution of the solar neutrino problem

$\phi_{SNO}^{CC} = \phi_{\nu_e}$

$\nu_e d \rightarrow ppe^- (\mathrm{CC})$

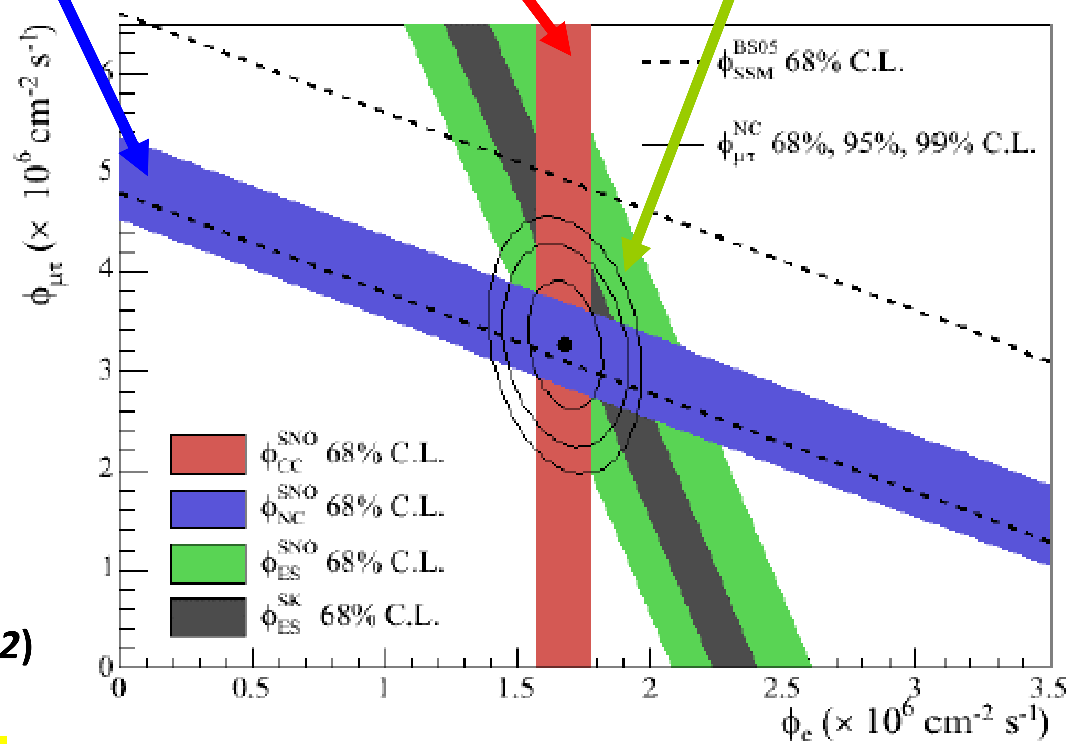
$\phi_{SNO}^{NC} = \phi_{\nu_e} + \phi_{\nu_{\mu\tau}}$

$\nu_x d \rightarrow \nu_x pn (\mathrm{NC})$

$\phi_{SNO}^{ES} = \phi_{\nu_e} + \frac{1}{6.36}\phi_{\nu_{\mu\tau}}$

$\nu_x e^- \rightarrow \nu_x e^- (\mathrm{ES})$

Solar neutrinos flux compatible with the Solar Standard Model

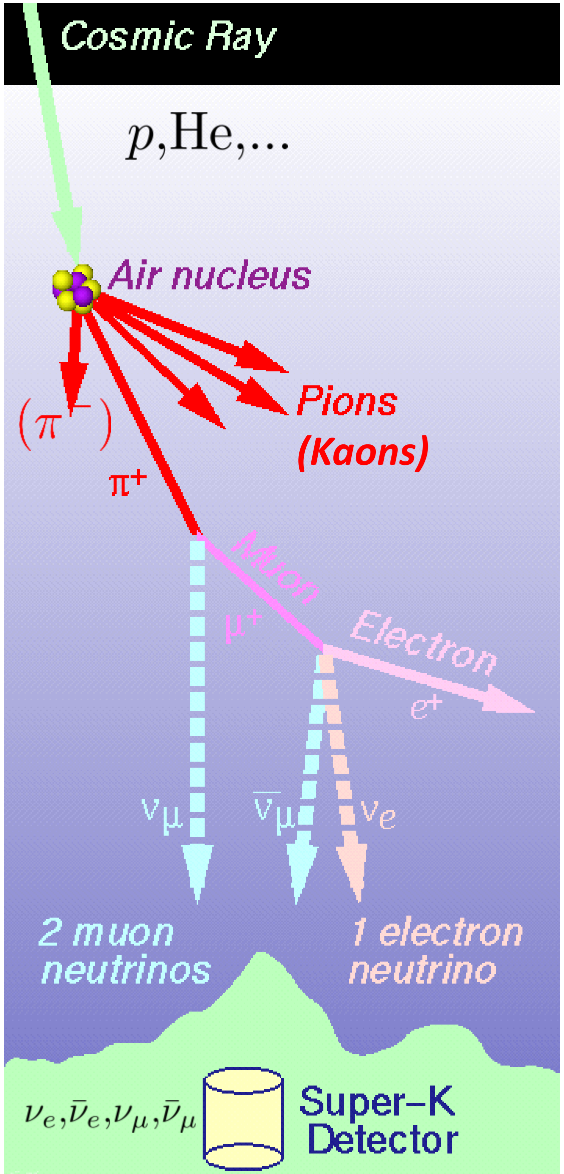


$$\frac{\phi_{SNO}^{NC(e\mu\tau)}}{\phi_{\nu_e}^{SSM}} = 1.01 \pm 0.12$$

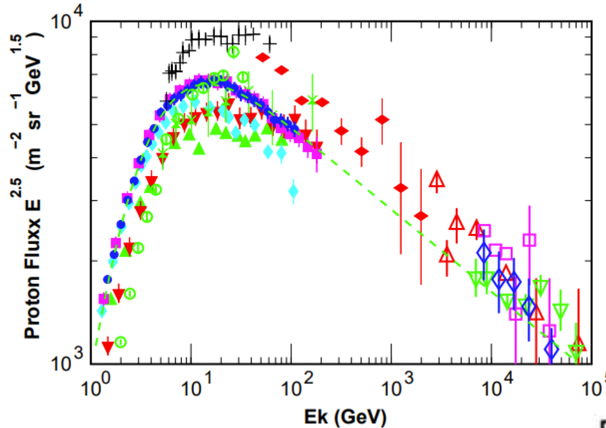
Q.R. Ahmad PRL89,011301 (2002)

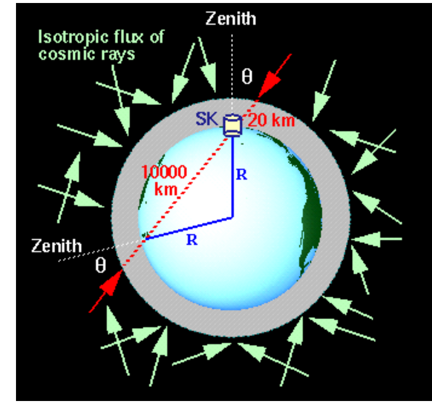
This confirms that the neutrinos from the Sun suffers neutrino conversion

Atmospheric neutrinos



From T.K Gaisser hep-ph/0203272

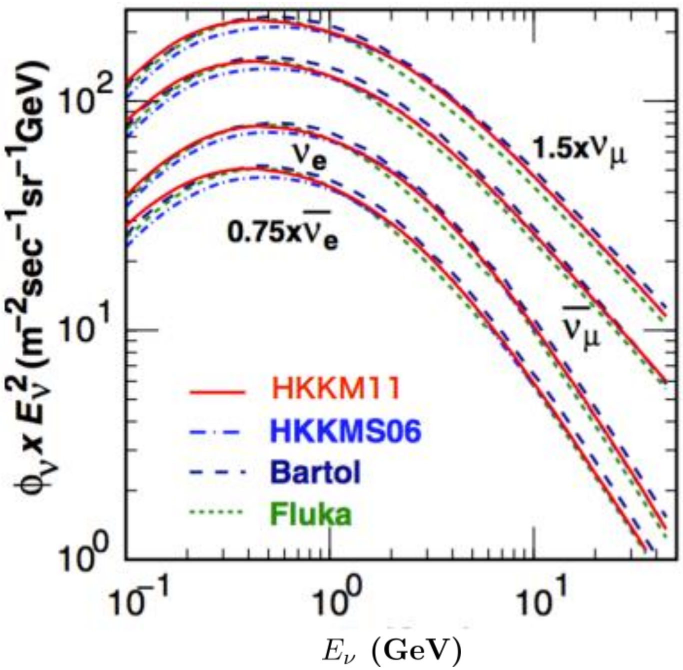




Neutrino flux depends on:

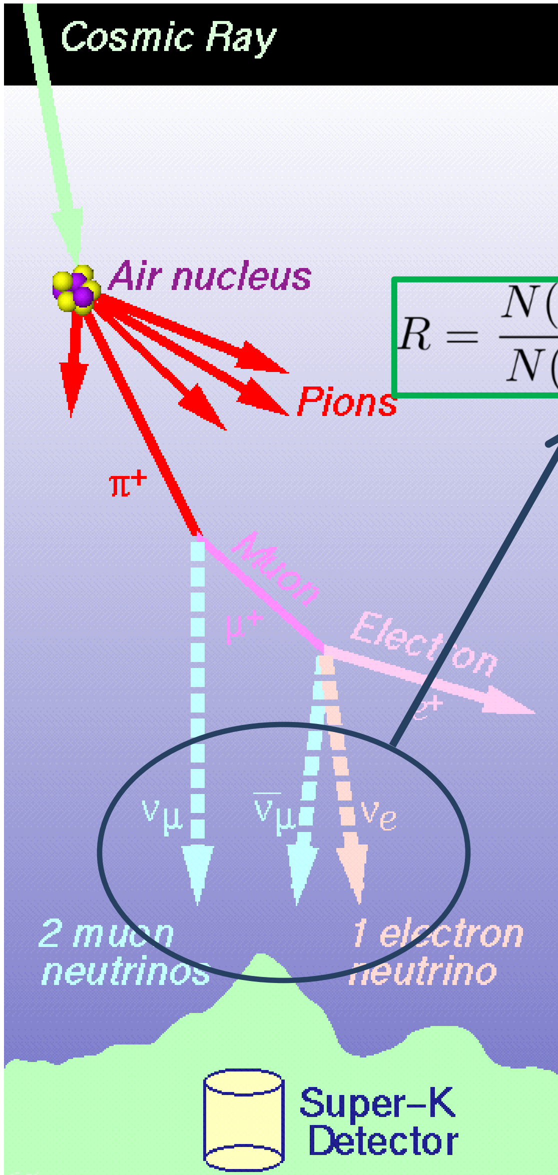
- Primary CR Composition
- Hadronic interactions (CRs+N)
- Solar activity
- Atmosphere modeling
- Geomagnetic field

From Honda et al PRD83, 123001 (2011)



Uncertainty of the absolute ν fluxes about 10-30 %

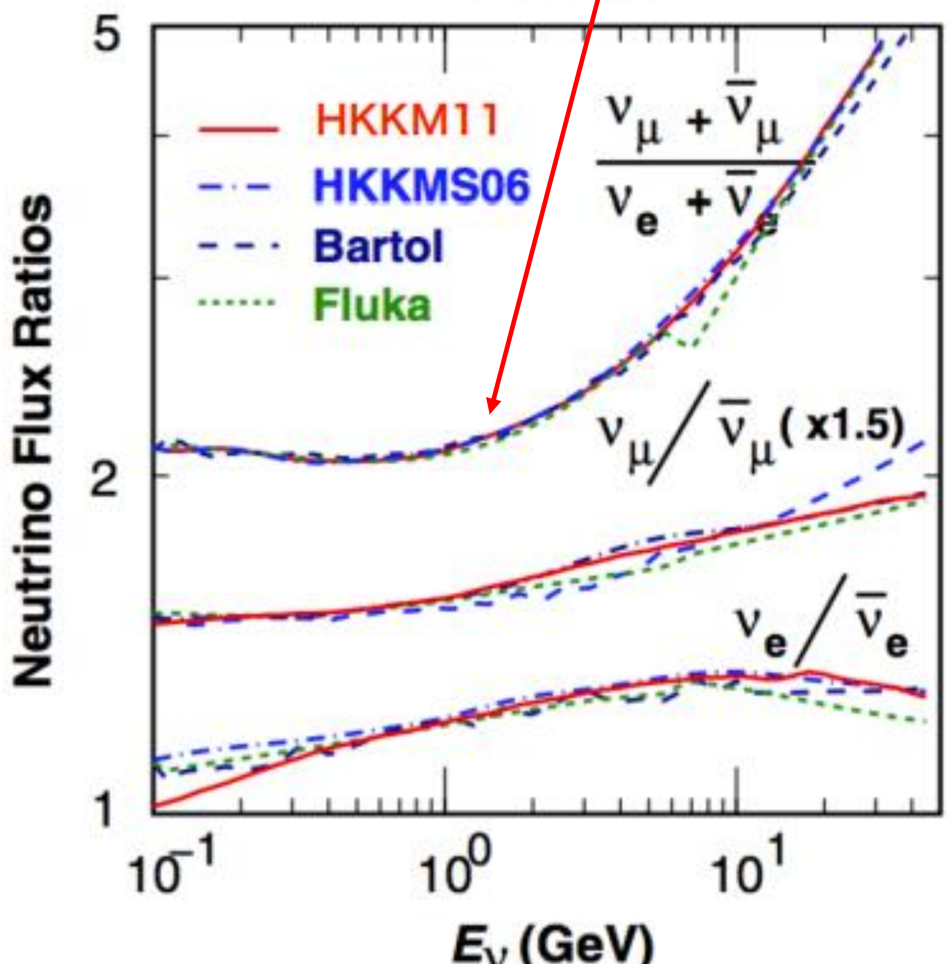
Atmospheric neutrinos



$$R = \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \sim 2$$

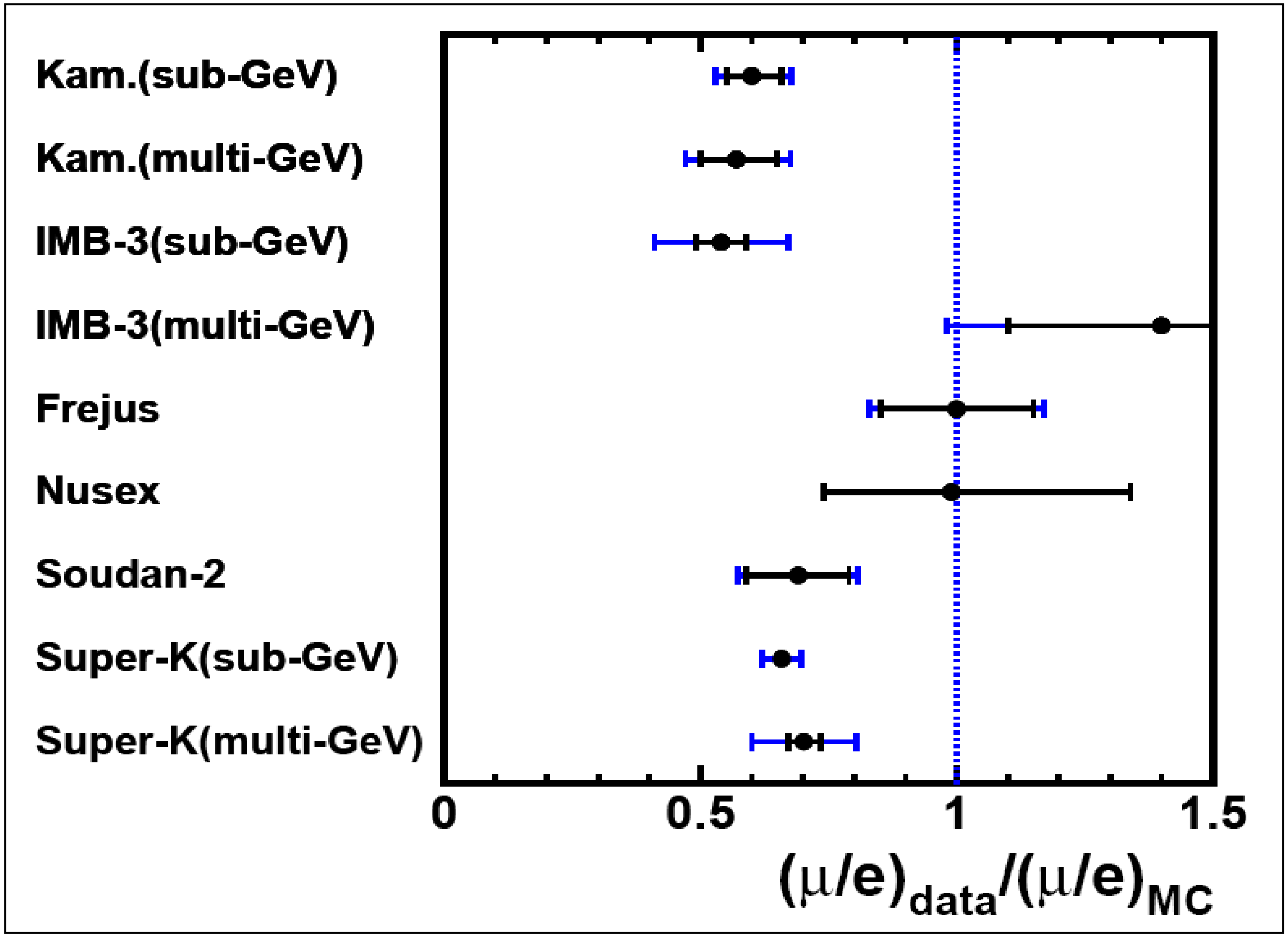
From Honda et al PRD83, 123001 (2011)

High-Energy Muons reach the ground before decaying



Uncertainty about 2 % below 5 GeV

Atmospheric neutrino anomaly



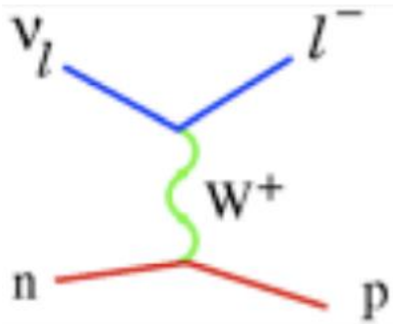
Double ratio

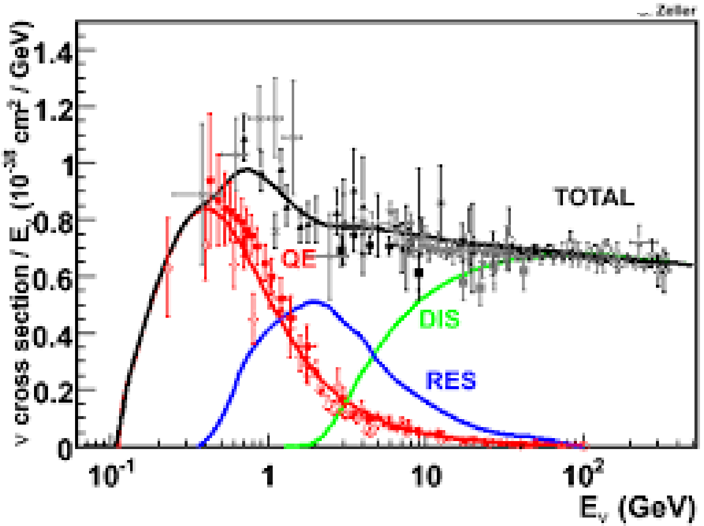
Atmospheric neutrinos- Super-Kamiokande

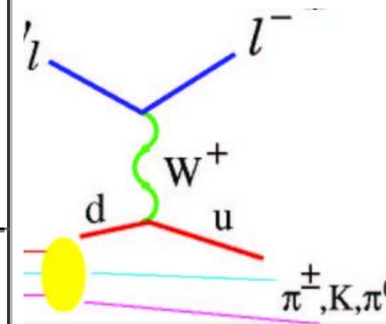
Neutrino interaction:

From J. A. Formaggio, G. Zeller, RMPhysics, 84 (2012)

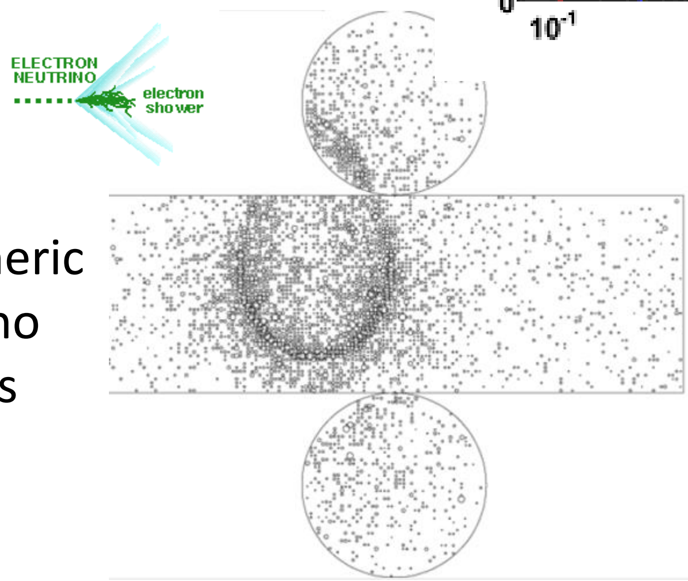
Quasi-Elastic Scatttering | **eep-Inelastic Scatttering**

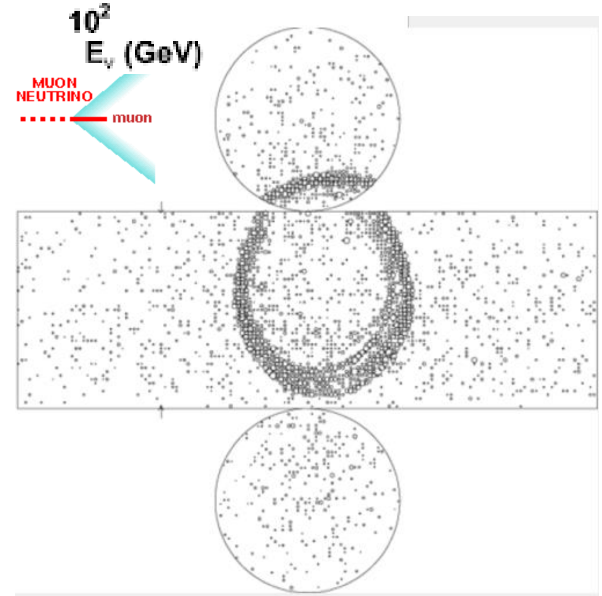






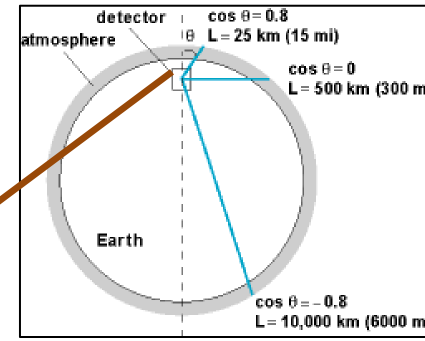
Atmospheric neutrino events



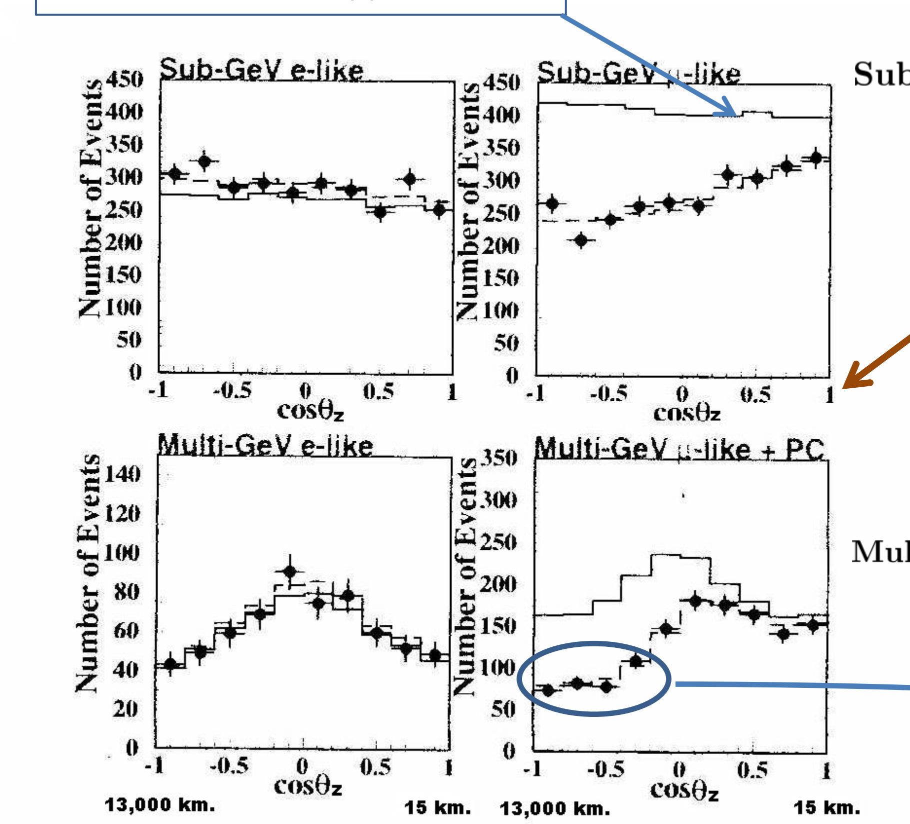


Atmospheric neutrinos

Super- Kamiokande observed in 1998 ***the neutrino oscillations***

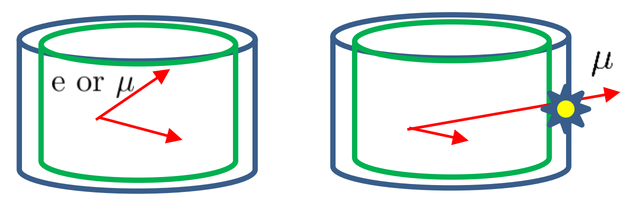


No oscillation hypothesis



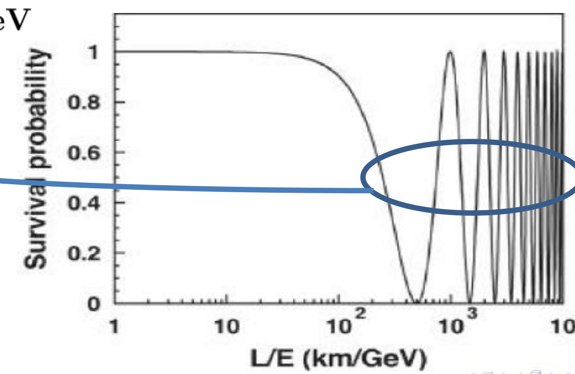
Sub-GeV [0.1,2] GeV

Fully Contained (FC) Partially Contained (PC)



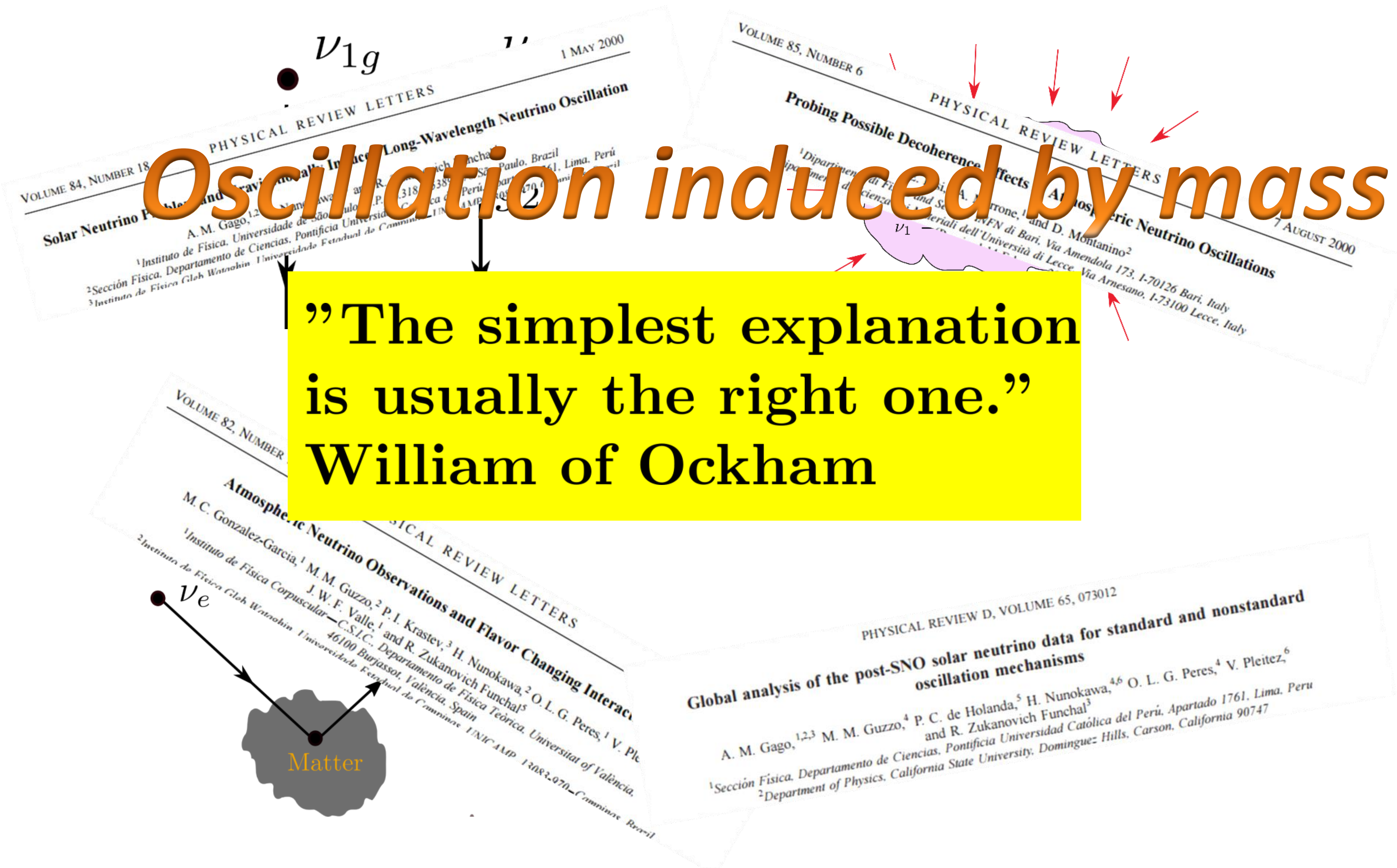
No hit in OD One Cluster in OD

Multi-GeV [1,100] GeV



Y. Fukuda PRL81:1562 (1998)

Solution of atmospheric and solar neutrinos

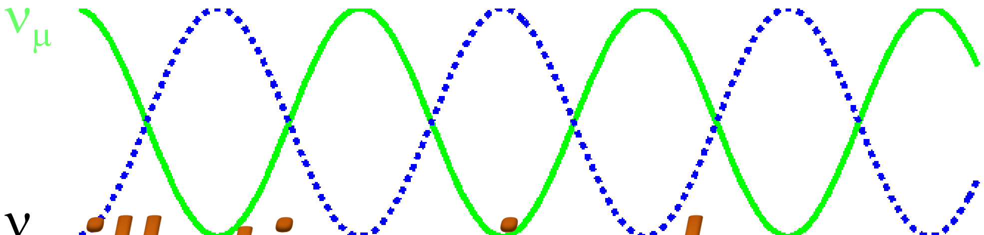


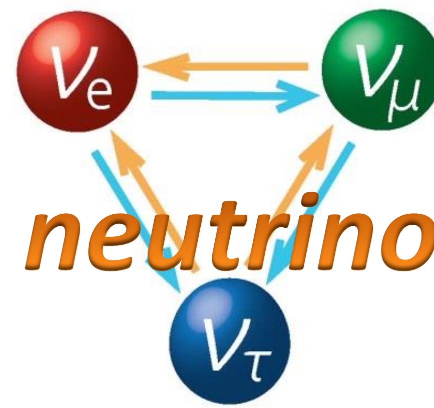
Oscillation induced by mass

"The simplest explanation is usually the right one."
William of Ockham

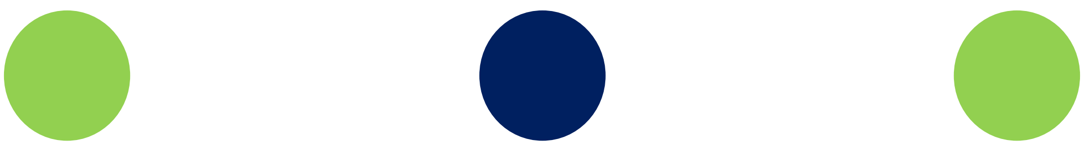
Neutrino Oscillation

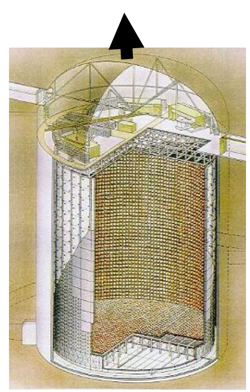
Neutrino oscillations

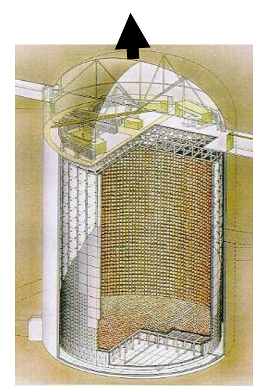




Oscillations imply massive neutrinos







Neutrino oscillation - basics

(1957) *Bruno Pontecorvo*

suggested $\nu \to \bar{\nu}$

inspired on $K_0 \to \bar{K}_0$

Flavour eigenstates ***Mass eigenstates***

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\tilde{\nu}_\alpha} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \underbrace{\frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} U^\dagger}_{H_{osc}} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$i\frac{d}{dt}\tilde{\nu}_\alpha = H_{osc}\tilde{\nu}_\alpha$$

Oscillation amplitude ***Interference phase***

Disappearance

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Appearance

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

Oscillation Wavelength

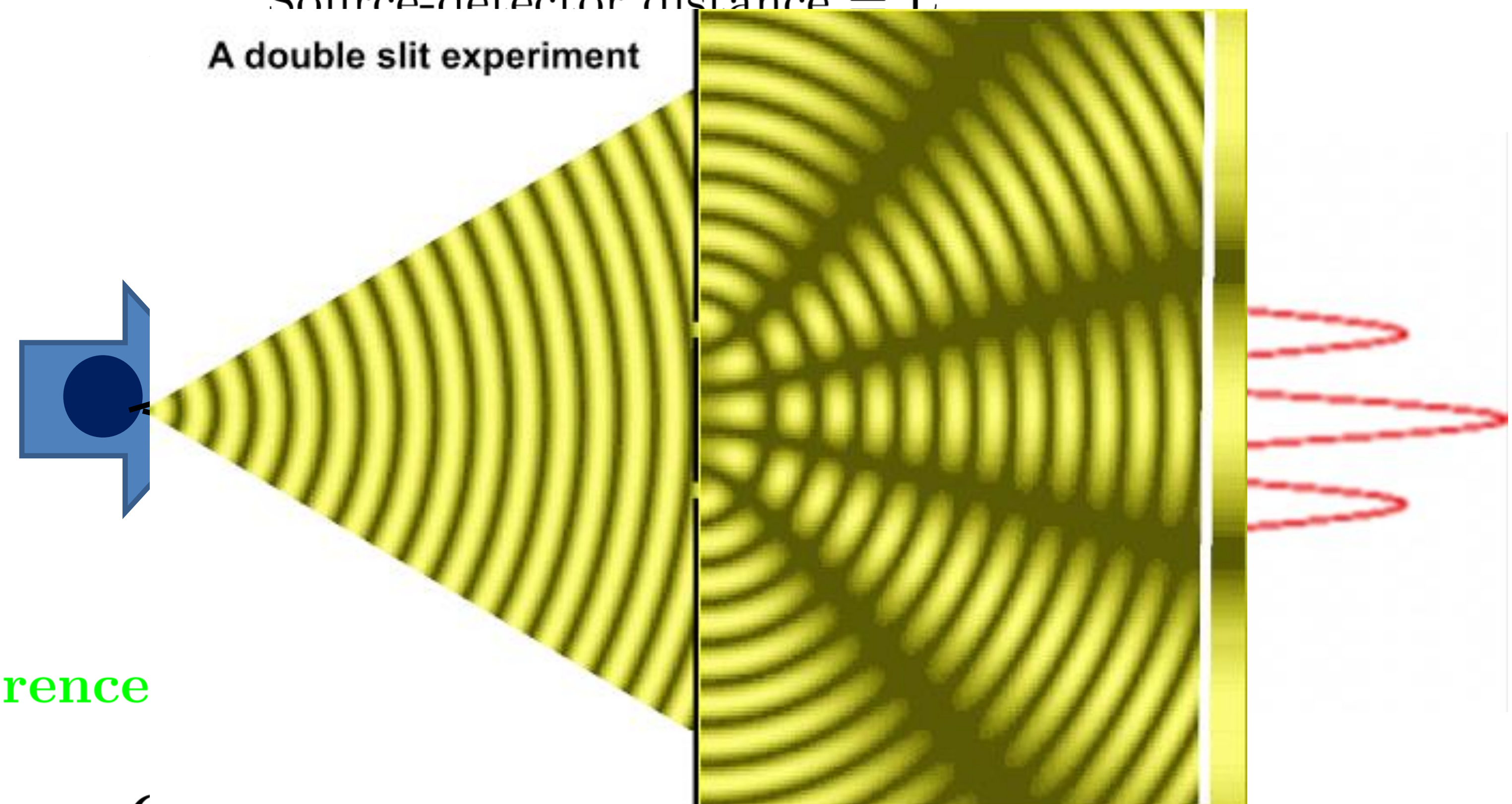
$$L_{osc} = \frac{4\pi E_\nu}{\Delta m^2}$$

Experimental setup: $L \equiv$ source-detector distance $E_\nu \equiv$ neutrino energy

Neutrino oscillation - basics

Double slit interferometer

Source-detector distance = L



Interference

Quintessence of quantum mechanics

Long-distance Interferometry

Three-flavor neutrino oscillation

Atmospheric — U_{PMNS} — ***Solar***

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \times \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}}^{\Delta m^2_{31}} \times \overbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}^{\Delta m^2_{21}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

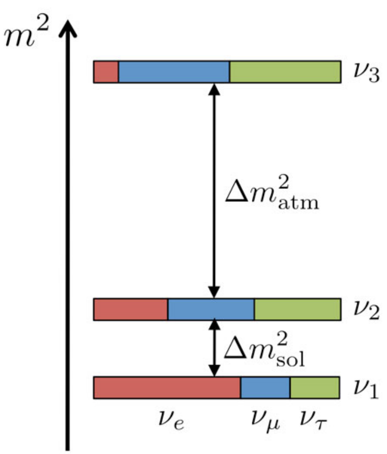
flavour — ***LBL & atms*** — ***Reactors & atms & LBL*** — ***Solar & reactors*** — ***mass***

PMNS =Pontecorvo-Maki-Nakagawa-Sakata ***LBL = Long BaseLine*** $c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

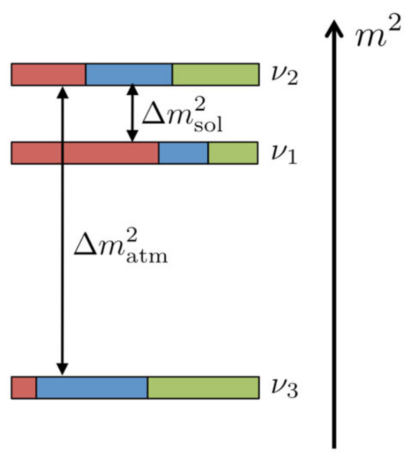
***Still barely known*:**

Mass hierarchy (ordering)

normal hierarchy (NH)



inverted hierarchy (IH)



δ -CP violation phase

$$\Delta P_{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$\boxed{\Delta P_{CP} \propto \sin\delta}$$

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

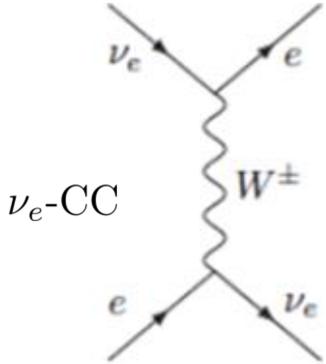
when $\delta \neq n\pi$

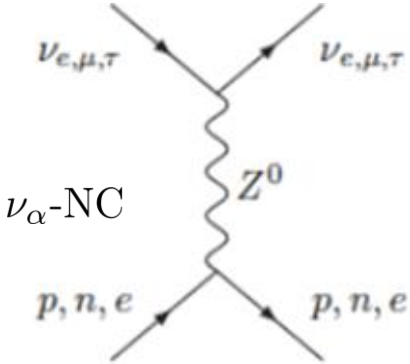
Neutrino oscillations in matter

Neutrino-incoherent scattering is negligible:

$$l_{matter} = 10^5 D_{\mathrm{Earth}},\ E_\nu = 1\ \mathrm{GeV}$$

When neutrinos propagate in matter (e^-, p, n) mostly suffer ***coherent forward elastic scattering*** (e.g its 4-momentum/direction are unchanged) being affected by an effective potential due to:





In a medium of electrons ***non-relativistic, unpolarized*** and ***isotropically distributed*** this effective potential takes the value:

$$\boxed{V_e = \sqrt{2} G_F n_e} \Rightarrow H_{osc} \rightarrow H_{osc} + \sqrt{2} G_F n_e \mathrm{diag}(1,0)$$

L. Wolfenstein, PRD 17, 2369 (1978); D 20, 2634 (1979), S. P. Mikheyev, A. Yu Smirnov, SJNP. 42 (1986) 913.

Neutrino oscillations in matter

$$V_e = \sqrt{2} G_F n_e = 3.82 \times 10^{-14} \mathrm{eV} \left(\frac{Y_e}{0.5}\right)\left(\frac{\rho_{matt}}{1 gr/cm^3}\right)$$

$n_e \rightarrow$ electron number density $\quad Y_e = \frac{N_e}{N_p + N_n}$

$\rho_{matter} \rightarrow$ matter density

$$V_{NC} = -\frac{1}{\sqrt{2}} G_F N_n$$

Works as global phase (common for all flavors)

For constant density:

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E_\nu}\right) \quad \theta \rightarrow \theta_M \quad \Delta m^2 \rightarrow \Delta m_M^2$$

$$\sin^2 2\theta_M = \frac{\Delta m^2 \sin^2 2\theta}{\Delta m^2 \sin^2 2\theta + (A - \Delta m^2 \cos 2\theta)^2}$$

$$\Delta m_M^2 = \sqrt{\Delta m^2 \sin^2 2\theta + (A - \Delta m^2 \cos 2\theta)^2}$$

$$A = 2E_\nu \sqrt{2} G_F n_e = 2E_\nu V_e$$

For antineutrinos $A \rightarrow -A$

Neutrino oscillations in matter

$$\sin^2 2\theta_M = \frac{\Delta m^2 \sin^2 2\theta}{\Delta m^2 \sin^2 2\theta + (A - \Delta m^2 \cos 2\theta)^2}$$

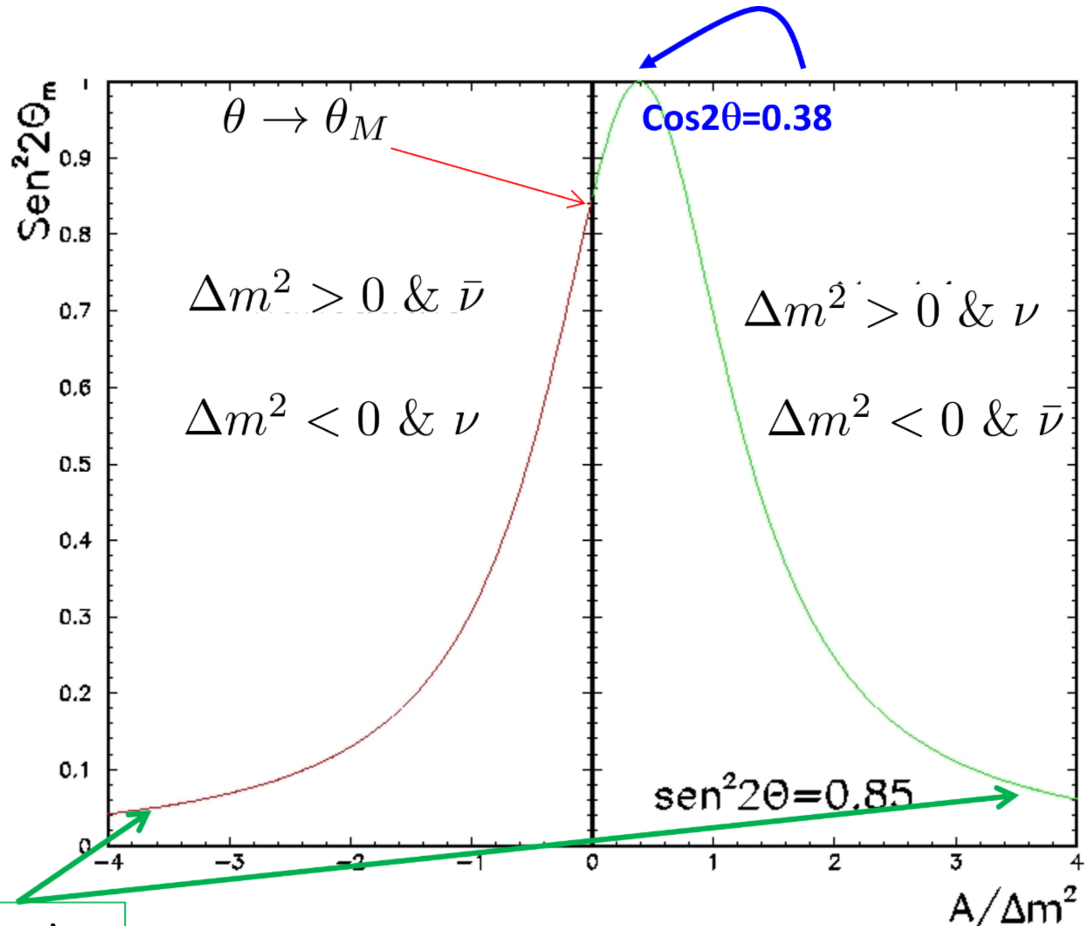
$\sin^2 2\theta_m = 1$ resonance point

$A = \Delta m^2 \cos 2\theta \Rightarrow \theta_m = \frac{\pi}{4}$ (MSW effect).

$A/\Delta m^2 \gg 1 \Rightarrow \sin^2 2\theta_m \to 0$

$A/\Delta m^2 \ll 1 \Rightarrow \sin^2 2\theta_m \to \sin^2 2\theta$

Fake CP, CPT violation $(P_{\nu_\alpha \to \nu_\alpha} \neq P_{\nu_\alpha \to \nu_\alpha})$



The matter effects useful for the determination of Δm^2

Reactor Neutrinos

Reactor Neutrinos

Nuclear reactors works through fission processes.
An example:

$$\overbrace{{}^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n}^{\textbf{chain reaction}}$$

$X_1 \rightarrow {}^{94}_{40}Zr$, $X_2 \rightarrow {}^{140}_{58}Ce$

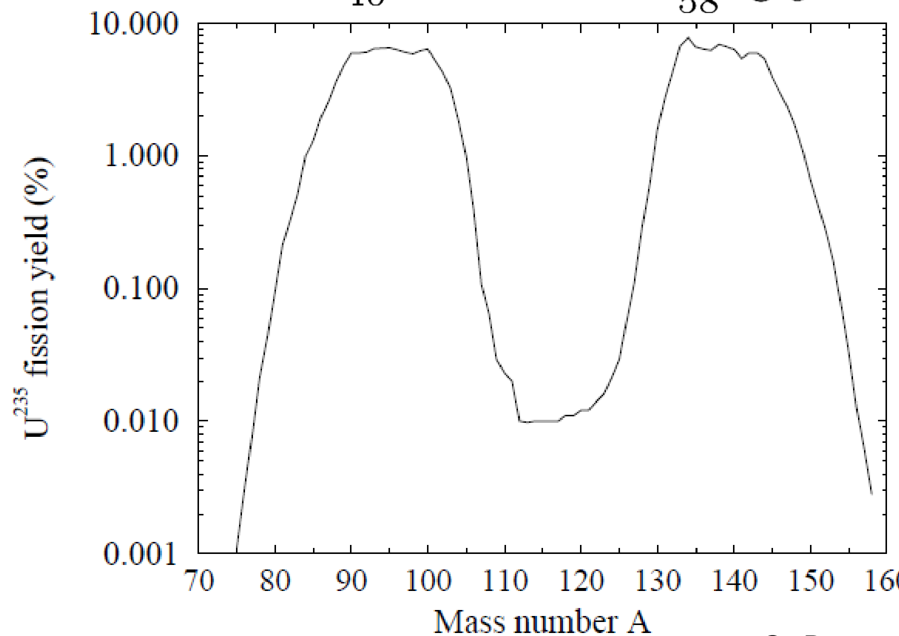
Neutrino production

$$92\,\mathrm{protons} \rightarrow 98\,\mathrm{protons}$$

$$6\,\beta^{-}\mathrm{decay} \rightarrow 6\,\bar{\nu}_e\ \mathrm{per\ fission}$$

Isotropic neutrino flux for commercial reactor of 3 $GW_{thermal}$:

$$6 \times 10^{20}\,\bar{\nu}_e\ \ \mathrm{per\ \ second}$$



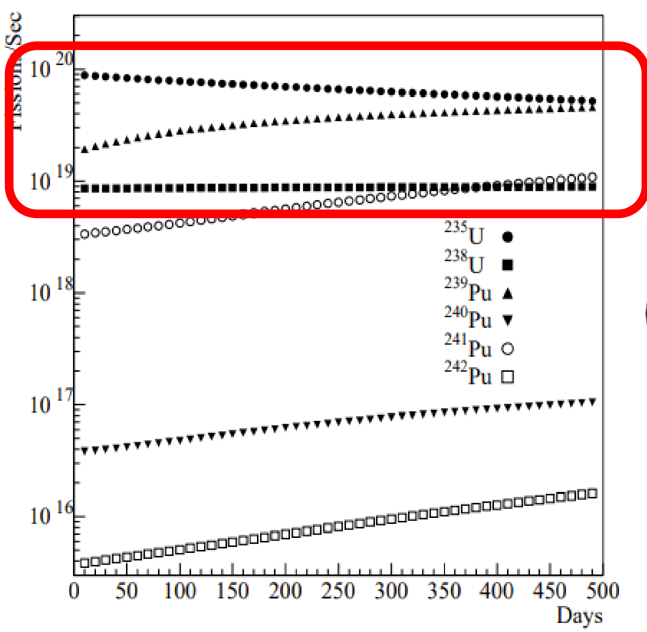
Stable products

C. Bemporad et al, hep-ph/0107277

Reactor Antineutrino Production

Antineutrinos mostly coming from the fission of (commercial reactors) :

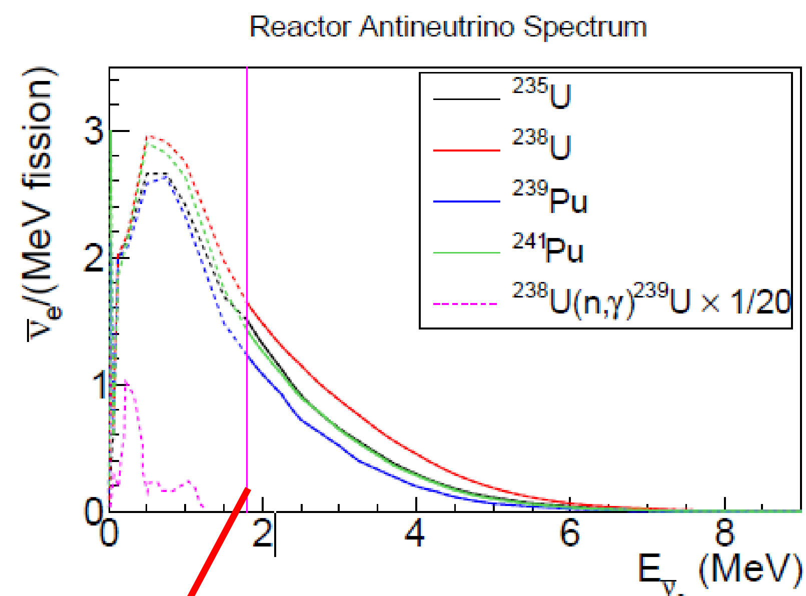
$$^{235}U(58\%),\ ^{239}Pu(29\%),\ ^{238}U(8\%),\ ^{241}Pu(5\%)$$



Fuel cycle

C. Bemporad et al, hep-ph/0107277

$\otimes$



$= \phi_\nu$

*Xin Qian, Jen-Chieh RPP **82,** 036201*

1.8 MeV : **IBD** threshold $< 30\ \%$ of $\bar{\nu}_e(2/6)$

Reactor Antineutrino Detection

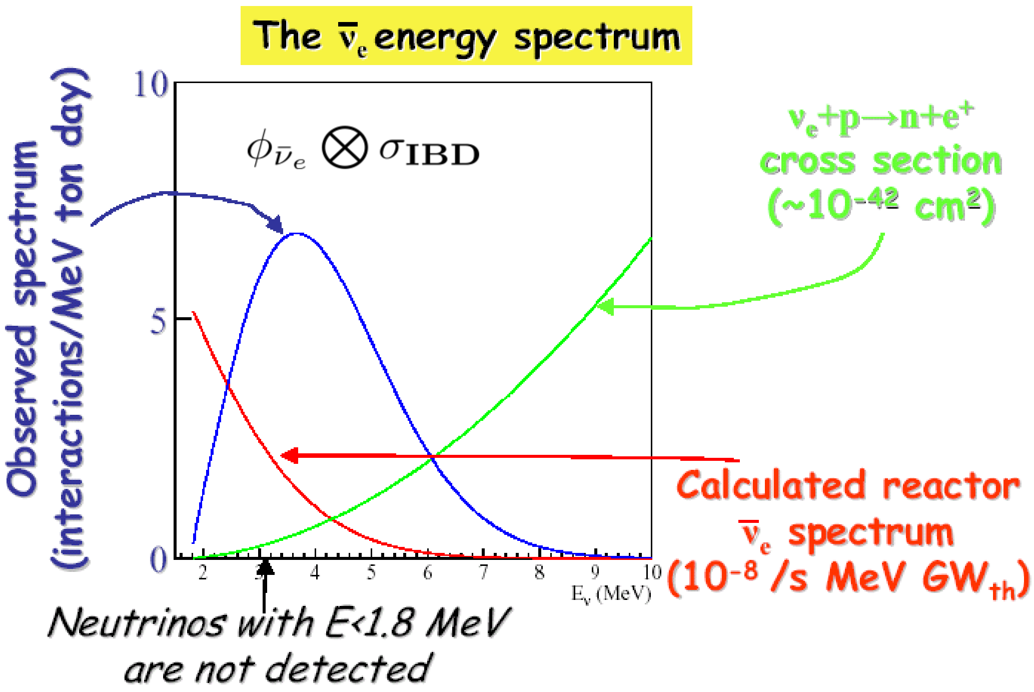
$$\textbf{IBD:}\ \bar{\nu}_e + p \to n + e^-$$

Delayed signal

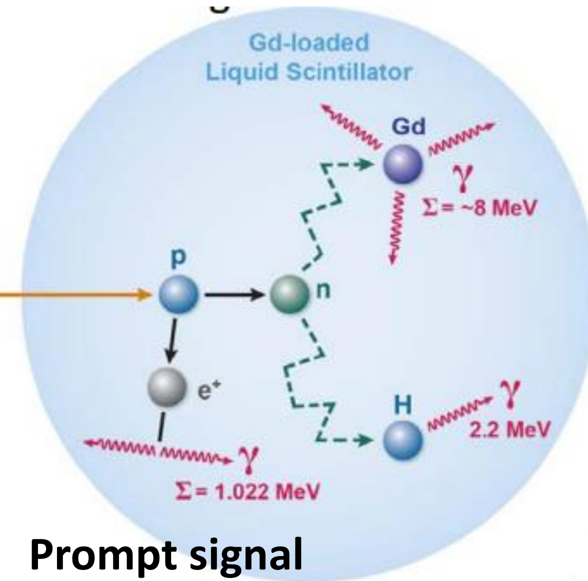
$$n + p \to d + \gamma\,(2.2\,\mathrm{MeV})$$ **180 μs**

or

$$n + Gd \to Gd + \gamma\,(8.0\,\mathrm{MeV})$$ **30 μs**



Courtesy Yifang Wang



Prompt signal

*From Xin Qian, Jen-Chieh RPP **82,** 036201*

$$E_{\mathrm{th}} = \frac{(M_n + M_{e^+})^2 - M_p^2}{2M_p} = 1.806\,\mathrm{MeV}$$

Physics Goals – Reactor Neutrino Experiments

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) - c^4_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$
$$- s^2_{12} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \cos\left(\frac{|\Delta m^2_{32}| L}{2E_\nu}\right) \pm \frac{s^2_{12}}{2} \sin^2 2\theta_{13} \sin\left(\frac{|\Delta m^2_{32}| L}{2E_\nu}\right)$$

+ NH
- IH

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

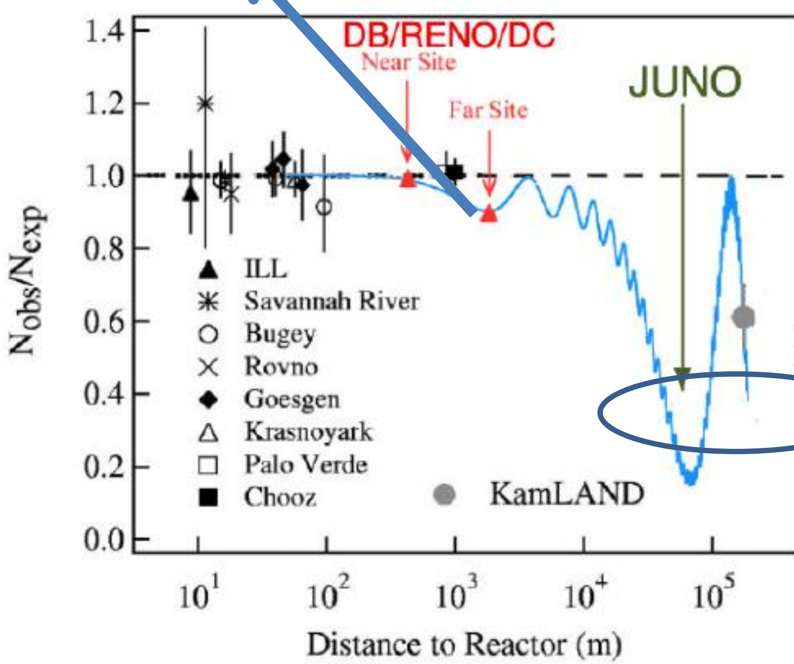
$\Delta m^2_{21} \sim \mathcal{O}(10^{-5}\mathrm{eV}^2)$ Solar scale

$\Delta m^2_{32} \sim \mathcal{O}(10^{-3}\mathrm{eV}^2)$ Atms scale

$L \to \mathrm{m}$

$E_\nu \to \mathrm{MeV}$

$\Delta m^2 \to \mathrm{eV}^2$



LMA (Large Mixing Angle)

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx s^4_{13} + c^4_{13}\left(1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)\right)$$

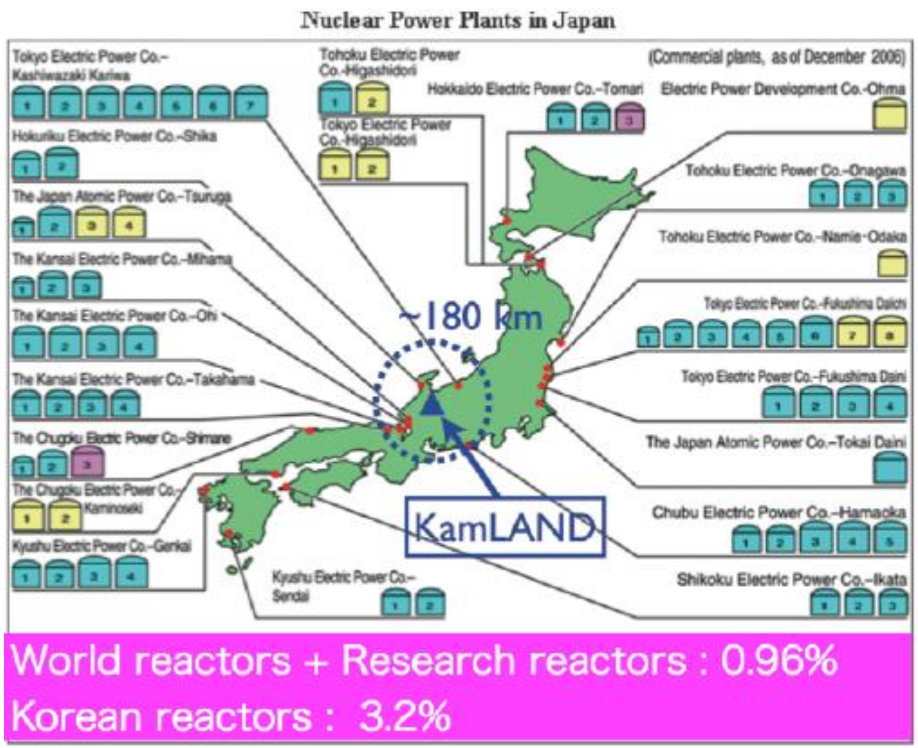
$$\left(\Delta m^2_{21} \frac{L}{E_\nu}\right) \sim \mathcal{O}(1)$$

With good resolution energy
We can see Δm^2_{32} then
hierarchy terms

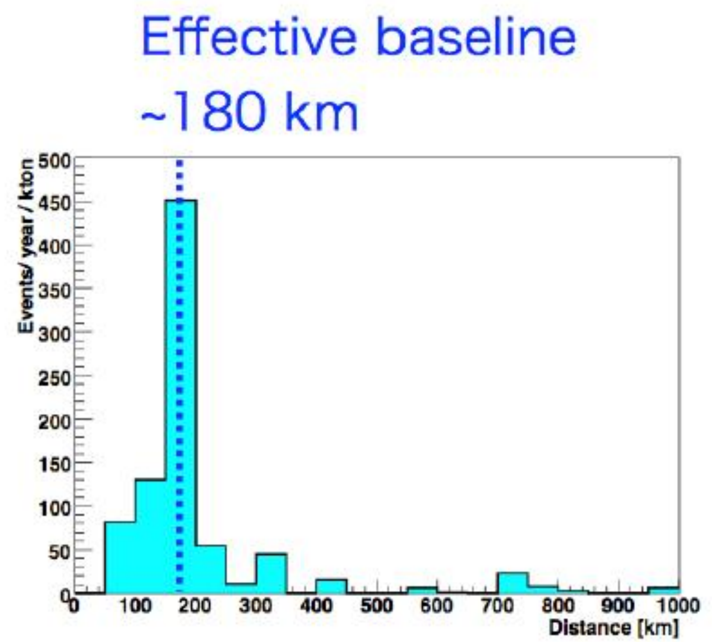
From C. Jollet J. Phys.: Conf. Ser. **2156** 012005 (2022)

Kamioka **L**iquid-scintillator **AN**tineutrino **D**etector (KamLAND)

KamLAND experiment is an antineutrino detector at the Kamioka Observatory, at Gifu, Japan at a depth of 2700 meter water equivalent underground.



55 Nuclear reactors

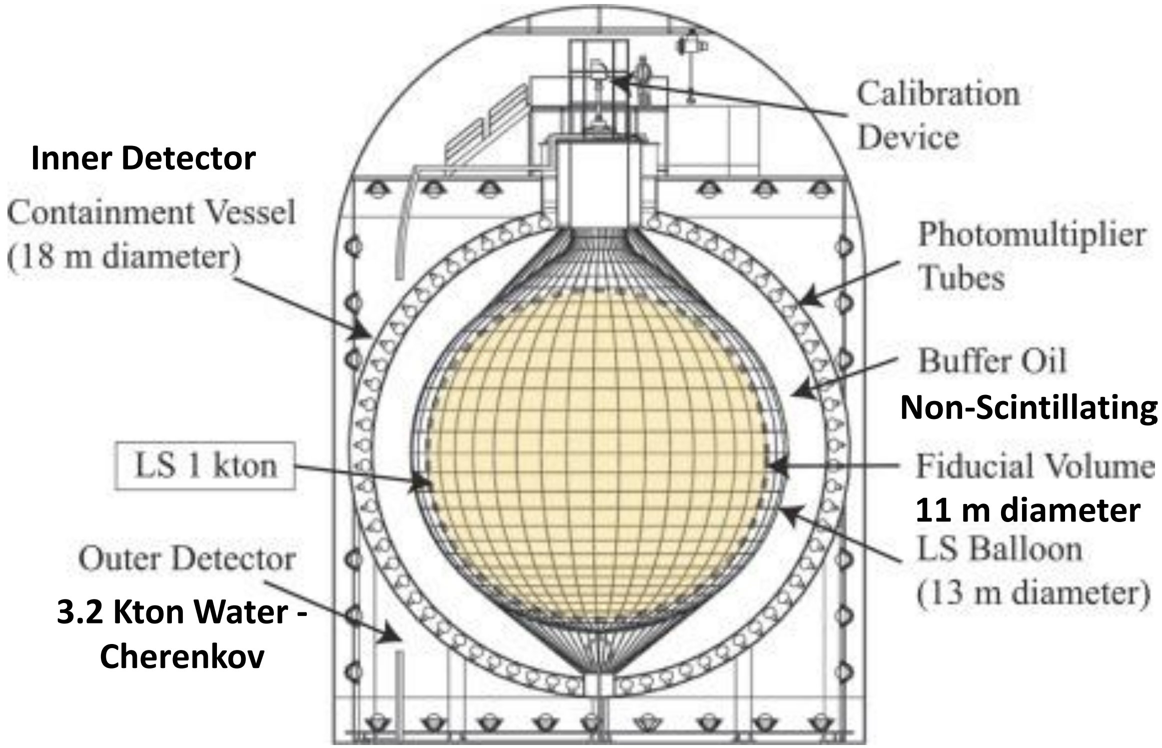


A ***medium baseline*** reactor experiment

From Ichimura Neutrino 2008

Kamioka **L**iquid-scintillator **AN**tineutrino **D**etector (KamLAND)

- One kton Liquid Scintillator Detector surrounded by 1879 PMTs -34 % coverage.
- 0.5 events per kiloton day. The delayed signal comes from hydrogen neutron capture (2.2 Mev γ).
- The Outer Detector works as a cosmic-ray muon veto and shielding from external sources of radioactivity.

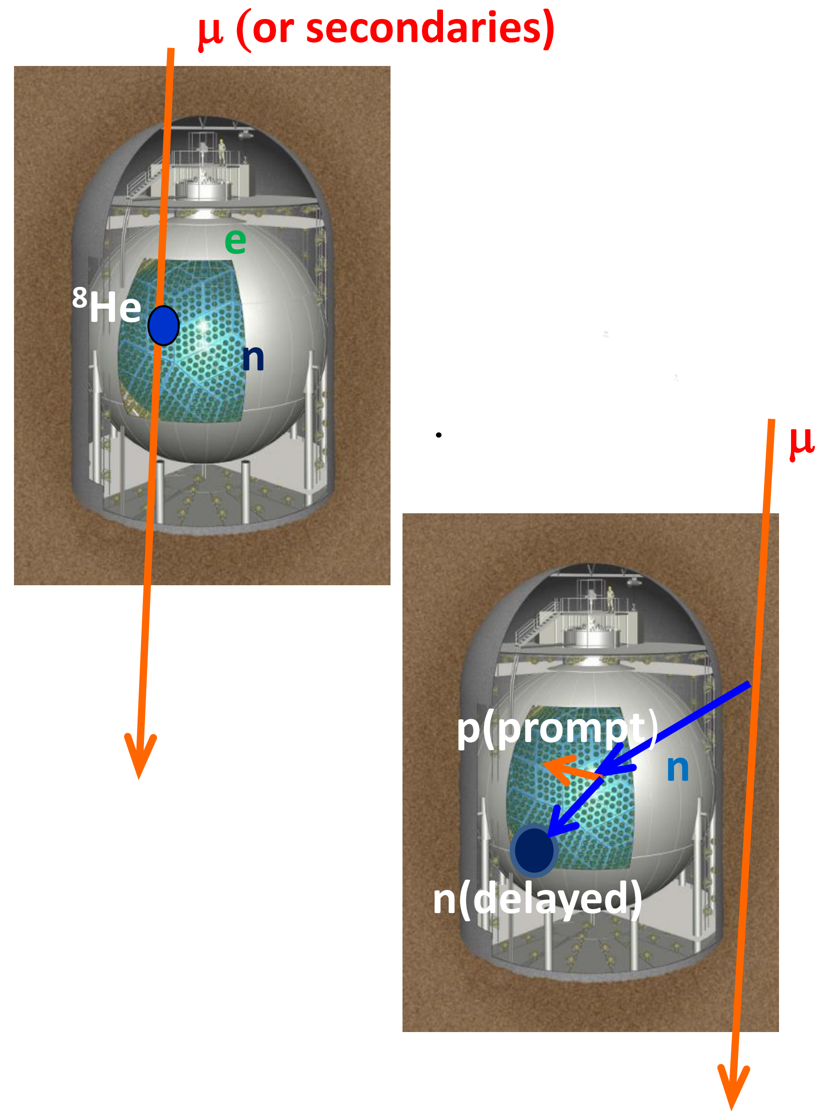


From NPB 908 (2016)

Kamioka Liquid-scintillator ANtineutrino Detector (KamLAND)

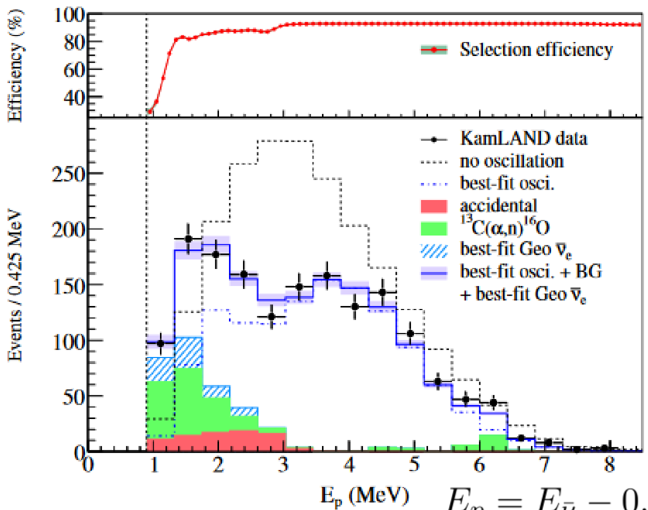
Backgrounds

- Geoneutrinos from ^{238}U and ^{232}Th decay chain.
- ^{9}Li/^{8}He (delayed-neutron β-emitters) produced from cosmic muons (or its secondaries)spallation.
- Fast neutron (from muons interacting with nearby rock) – atmospheric neutrinos.
- ^{13}C(α,n)^{16}O reactions from α-decay of ^{210}Po, daughter of ^{222}Rn. ^{16}O deexcitation (prompt) and n (delayed).

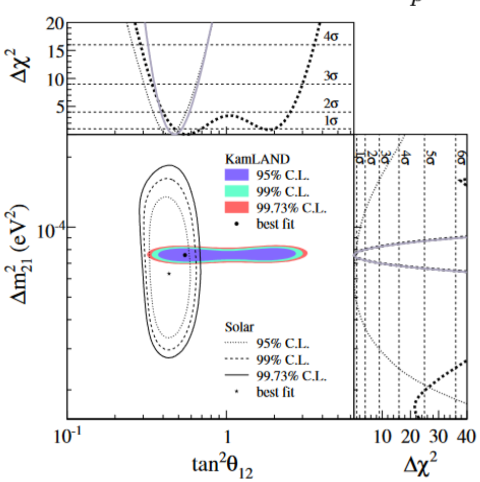


KamLAND – Oscillation results

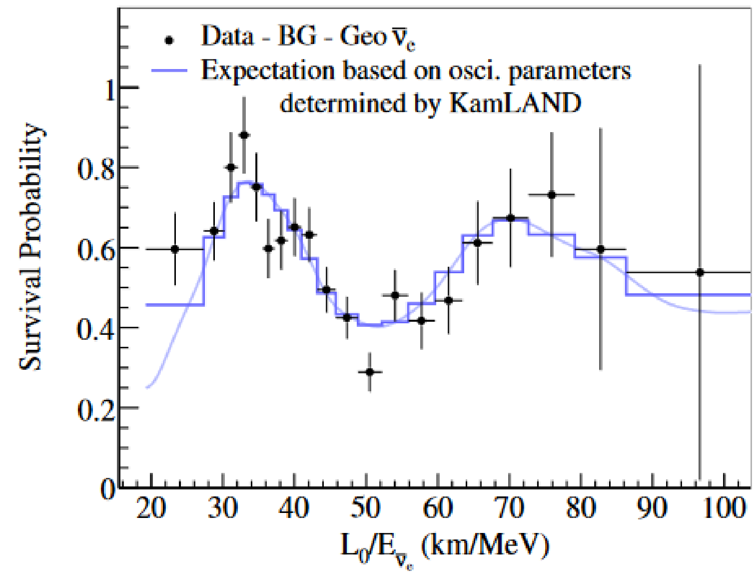
Prompt event energy spectra



$$E_p = E_{\bar{\nu}} - 0.8\text{MeV}$$

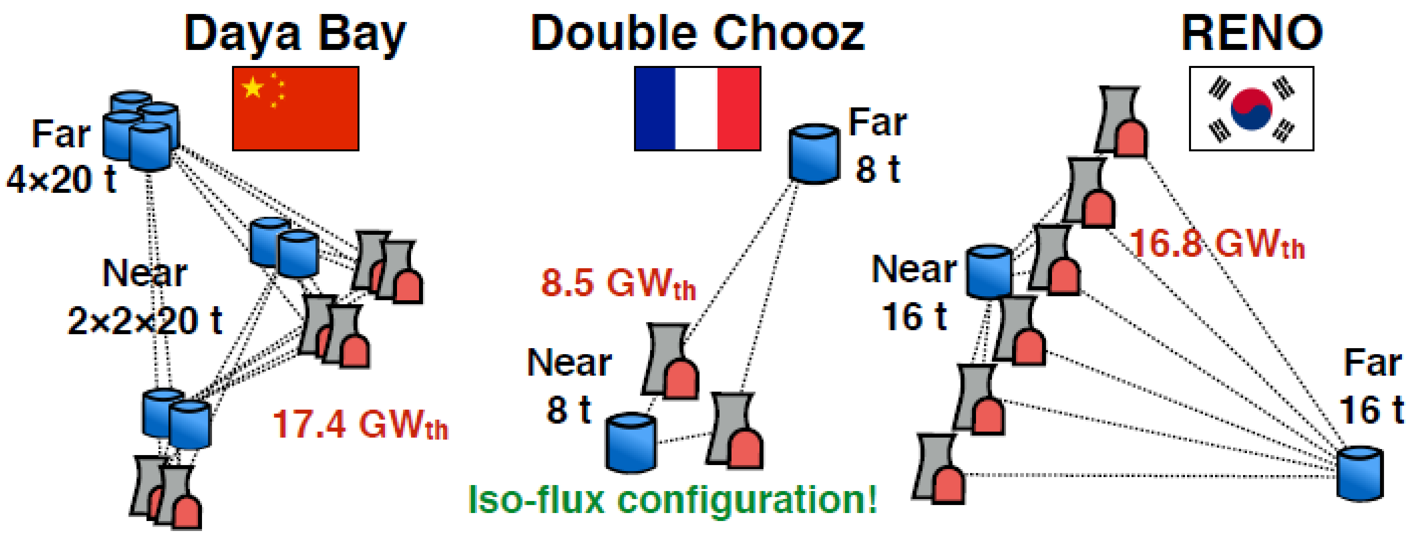


Allowed region neutrino oscillation parameter



Oscillation pattern

Short baselines Reactor experiments

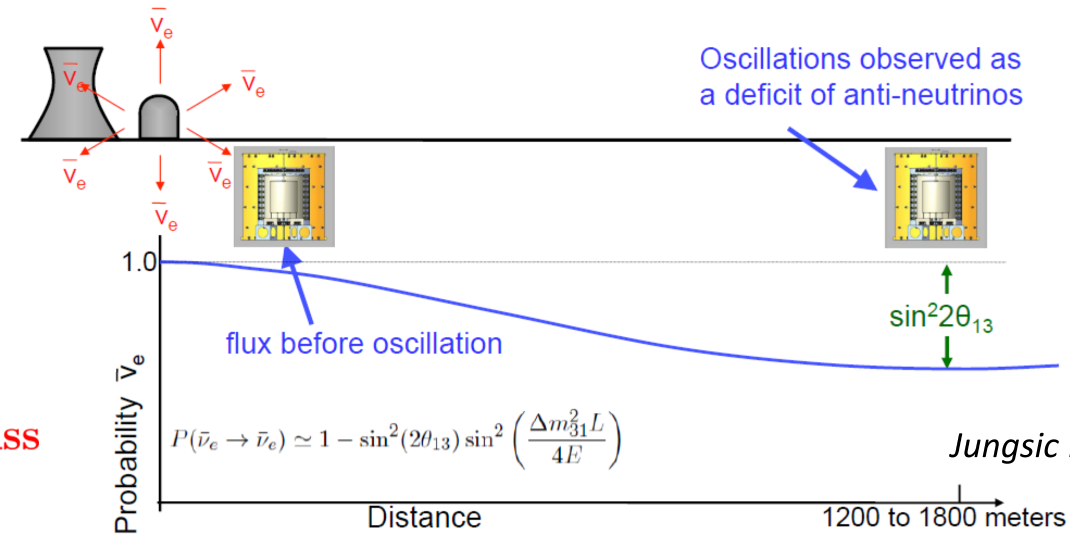


	Power [GWth]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]
Daya Bay	17.4	2x2x20 4x20	365,490 1650	250 860
Double Chooz	8.5	8 8	400 1050	120 300
RENO	16.8	16 16	290 1380	120 450

From C. Jollet J. Phys.: Conf. Ser. **2156** 012005 (2022)

Iso-flux configuration: Near and Far detectors have the same relative contribution from two reactors.

Physics Goal and measurement method



Jungsic Park – IBS-CUP seminar

Detector mass

$$N_{\bar{\nu}} = M \times \phi_{\bar{\nu}} \times \sigma_{\bar{\nu}} \times \epsilon \times P_{\text{surv}}(E_{\bar{\nu}}, L)$$

$$\phi_{\bar{\nu}} \sim \frac{1}{L^2}$$

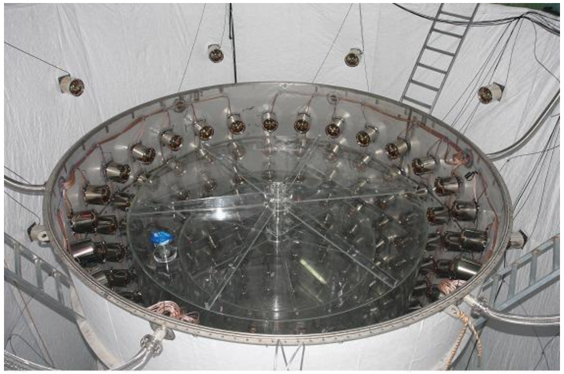
$$\text{Rates} = \frac{N_f}{N_n} = (\frac{M_f}{M_n})(\frac{L_n^2}{L_f^2})(\frac{\epsilon_f}{\epsilon_n})P^f_{\text{surv}}(E_{\bar{\nu}}, L)$$

Relatives efficiencies

far/near measurements for identical detectors reduce systematics uncertainties.

L.A.Mikaelyan, V.V.Sinev, Phys.Atom.Nucl.63:1002-1006,2000; Yad.Fiz.63N6:1077-1081,2000

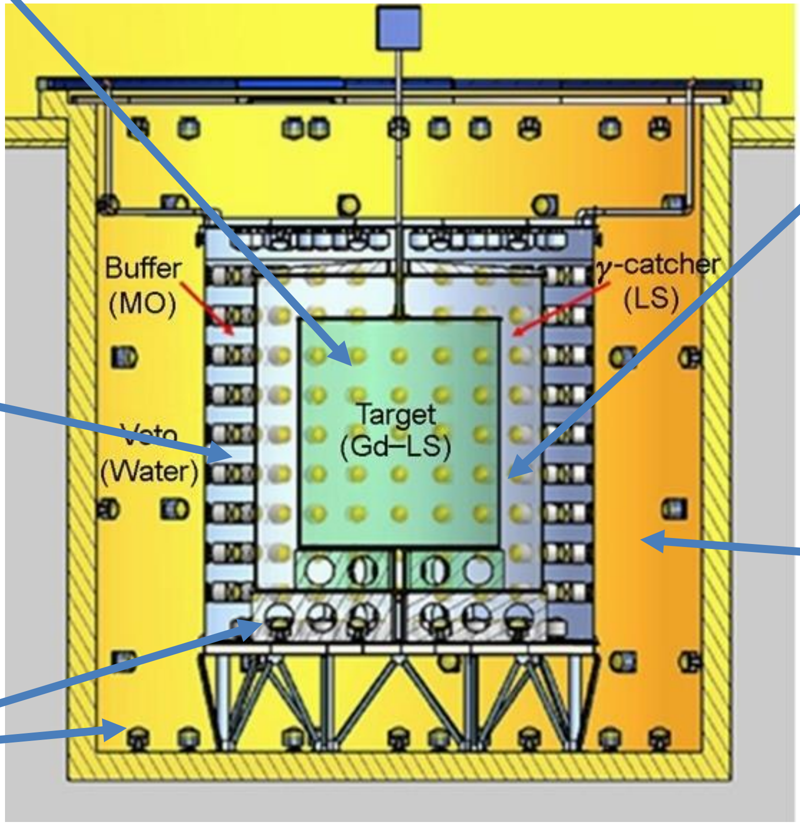
Example: Reno detector



ν-target (16.5 ton): IBD reactions volume. 0.1% Gd loaded liquid scintillator (neutron capture).

γ-catcher (30 ton): pure liquid scintillator to catch gammas from IBD outside target.

Non-scintillating buffer (65 ton): used to shield the scintillating layers from radioactive sources.



Veto (350 ton): water-Cherenkov detector layer to reduce background gammas, neutrons and cosmic muons.

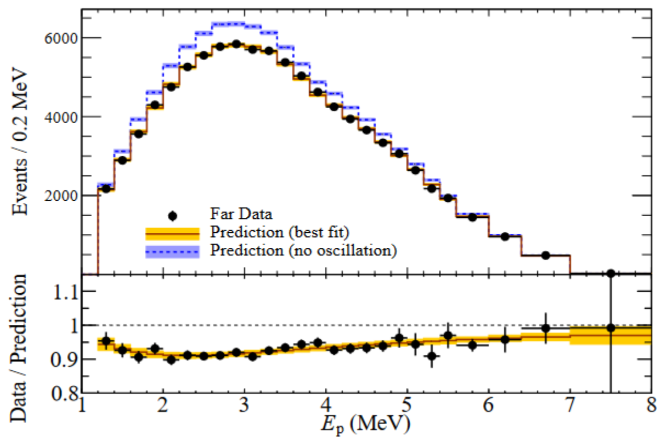
PMTs

354 ID 10” PMTs

67 OD 10” PMTs

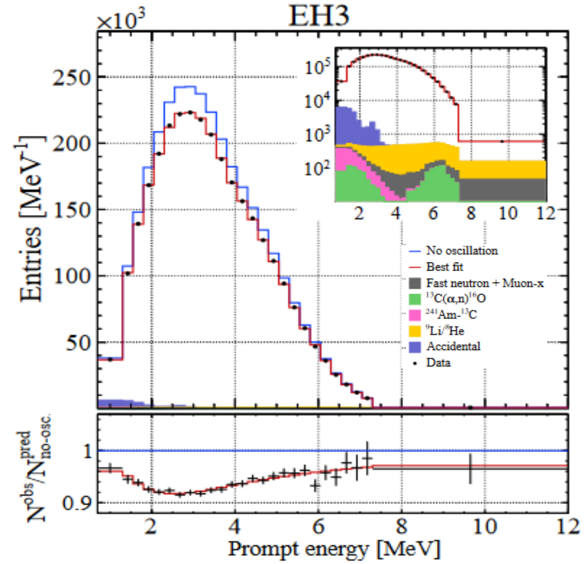
Prompt energy spectra

RENO



G.Bak et al, Phys.Rev.Lett. 121 (2018) 20, 201801

DAYA BAY

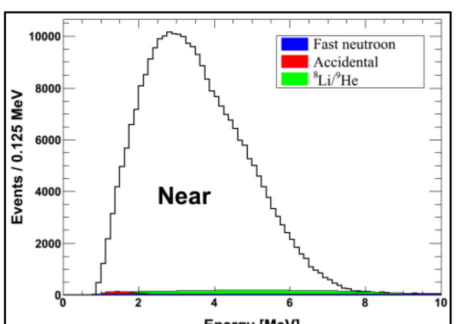


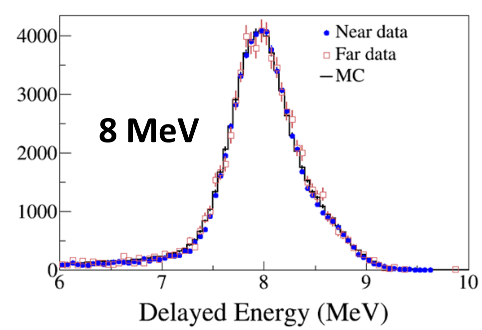
F. P. An, arXiv:2211.14988v1

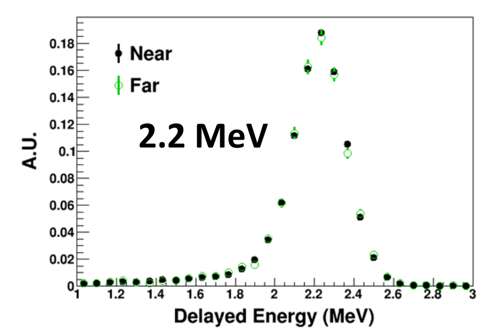
Prompt signal

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

Delayed signal







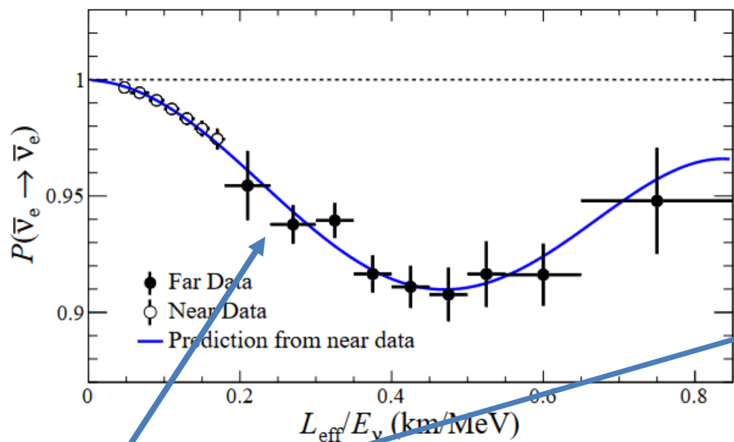
30 μs

180 μs

Taken from Hyunk Wan Seo – IBS-CUP Seminar

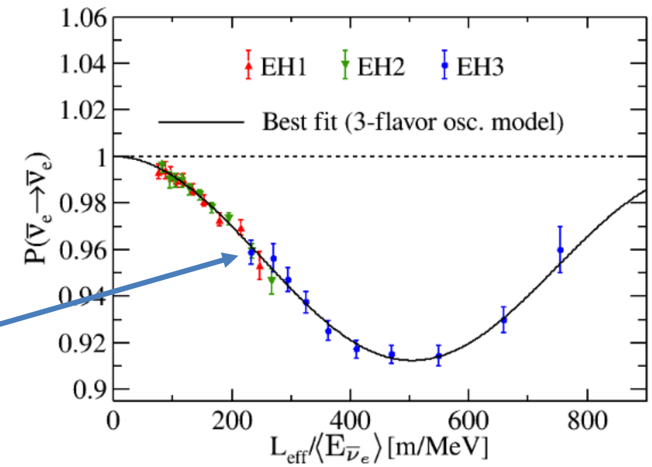
Oscillation parameter measurements

RENO



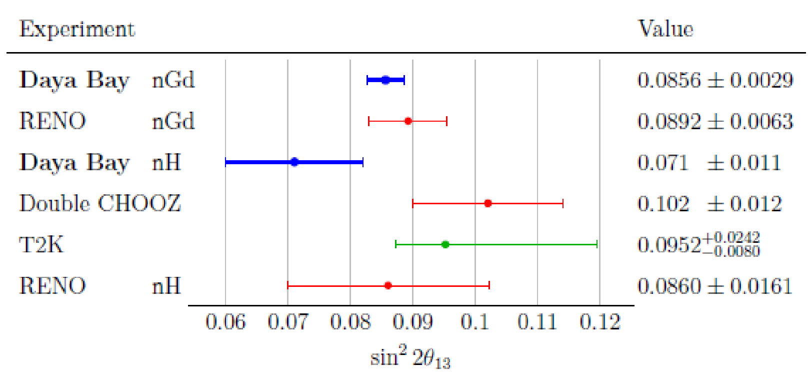
G. Bak et al, Phys.Rev.Lett. 121 (2018) 20, 201801

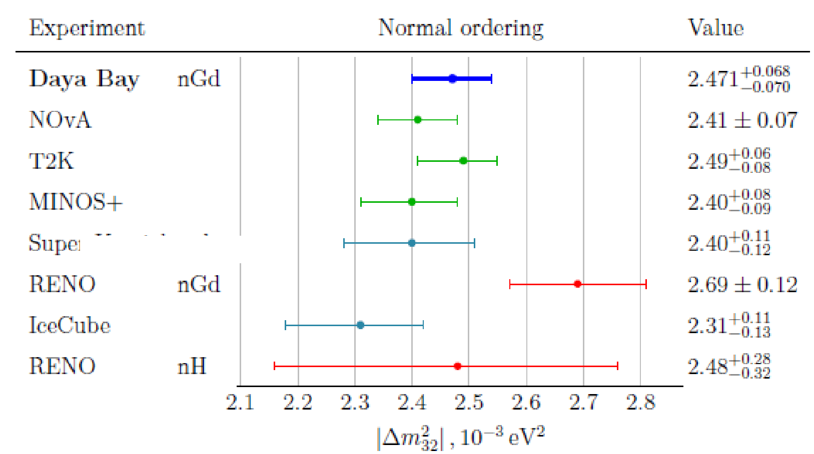
Daya Bay



F. P. An, arXiv:2211.14988v1

Oscillation Pattern



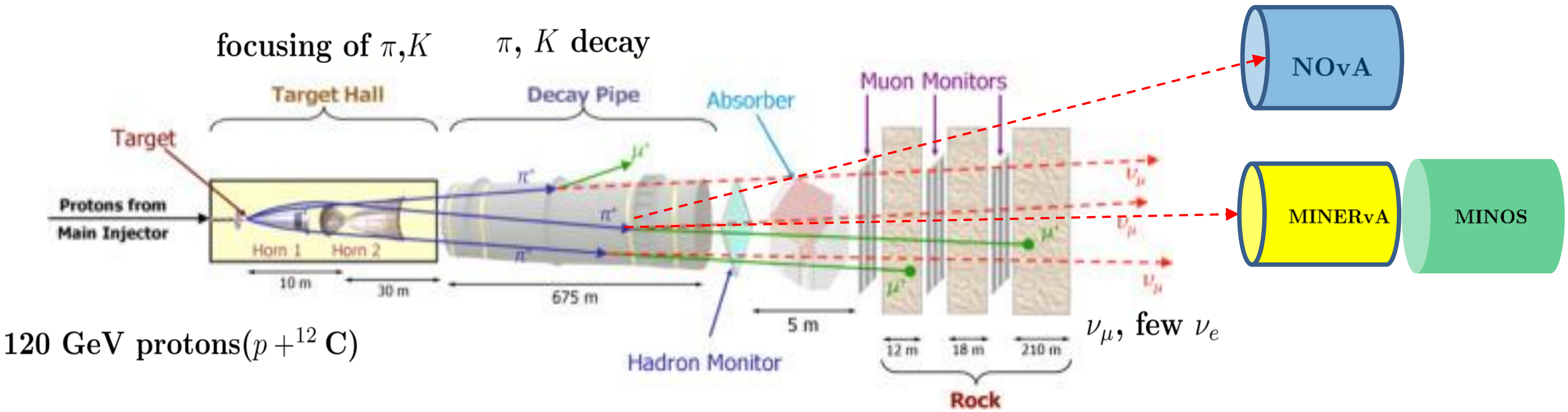


From C. Jollet J. Phys.: Conf. Ser. **2156** 012005 (2022)

Accelerator Neutrinos

Neutrino Beam

NuMI beamline@Fermilab



$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$$K^+ \to \mu^+ \nu_\mu \qquad K^+ \to \pi^0 e^+ \nu_e$$

Proton beam basics

Rules of Thumb

- The number of pions (secondaries) produced is roughly a function of "proton power" (or total number of protons on target x proton energy).
- The higher energy neutrino beam you want, the higher energy p you need.

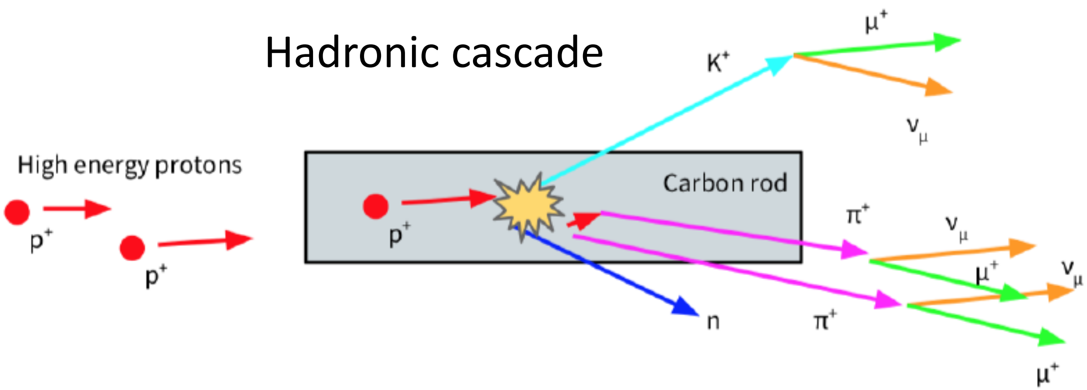
Proton Source	Experiment	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	$1\times10^{20}/4$	0.0052	1.4
FNAL Booster	MiniBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	$3\text{-}6\times10^{20}$	0.3 to 0.7	3-17
CNGS	OPERA	400	0.45×10^{20}	0.48	25
J-PARC	T2K	40-50	11×10^{20}	0.25 to 0.75	0.77

Neutrino Production -Target

Grafite target

protons

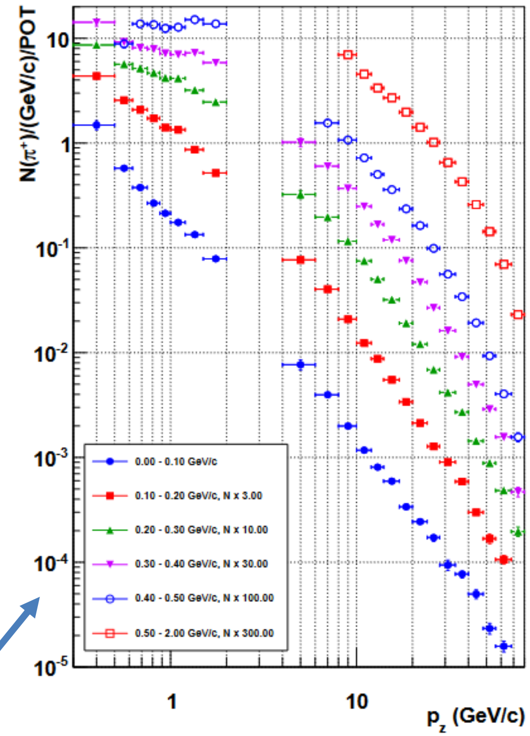
NuMI



- Hadron production uncertainties in Monte Carlo (MC) simulations dominate the uncertainties of the neutrino flux predictions (15–20%), affecting the precision in the ν cross sections measurements ($\sigma = N/\phi\ M$), as well.

- Non-perturbative QCD interactions difficult to model require experimental data for constraining.

Positive pions yields

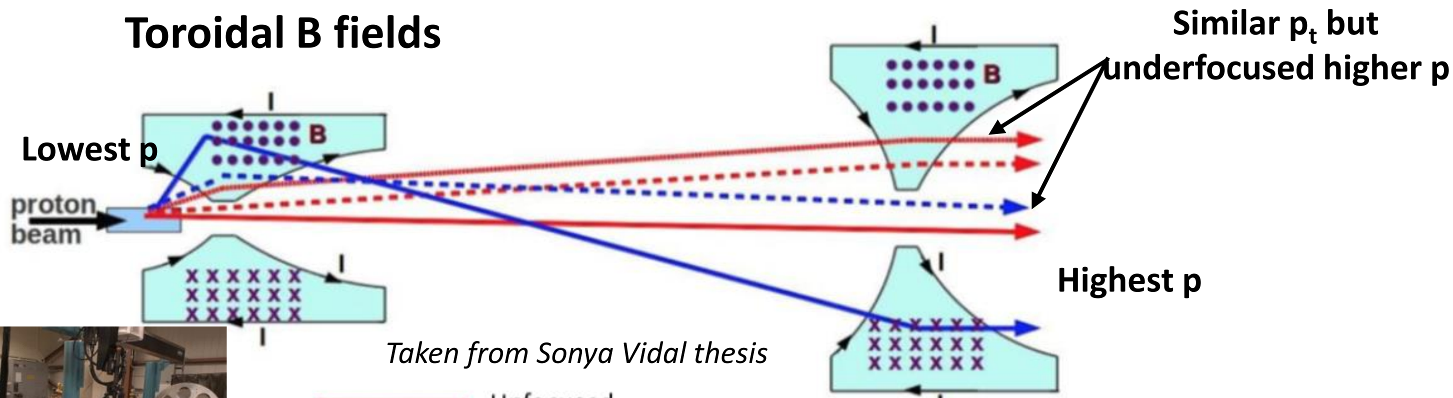


(a)π^+ yields.

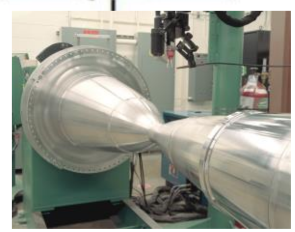
Main Injector Particle Production - expt
J. M. Paley et al, arXiv:1404.5882

MIPP uses the same NuMI target

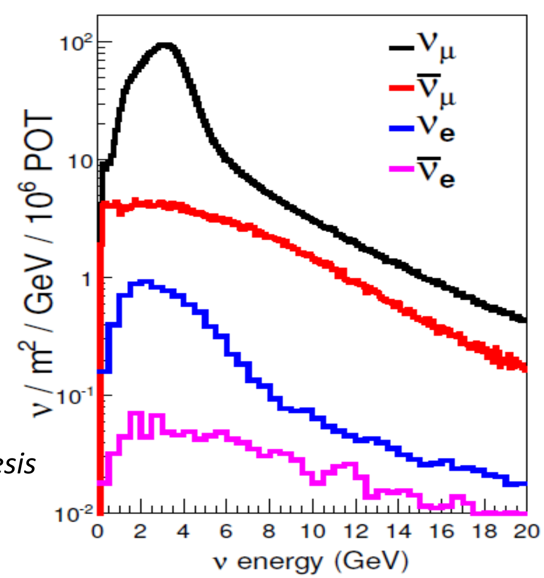
Neutrino Production – focusing and fluxes



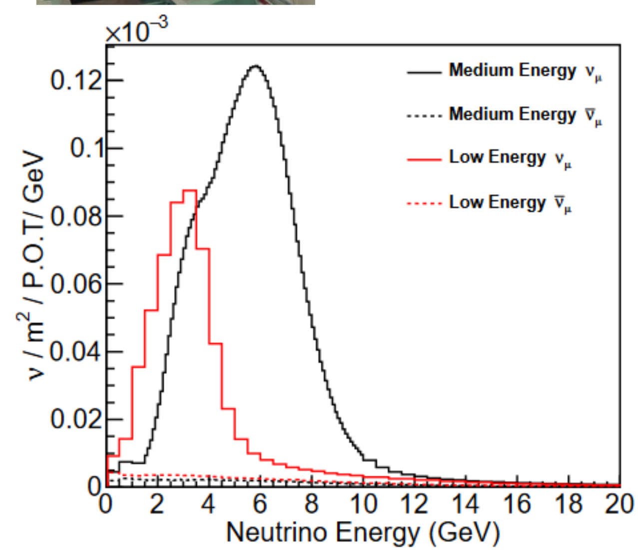
Taken from Sonya Vidal thesis



After focusing

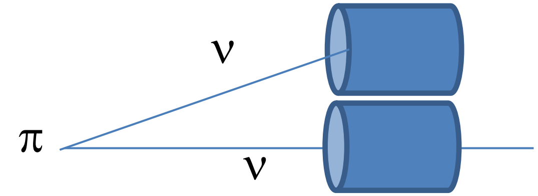


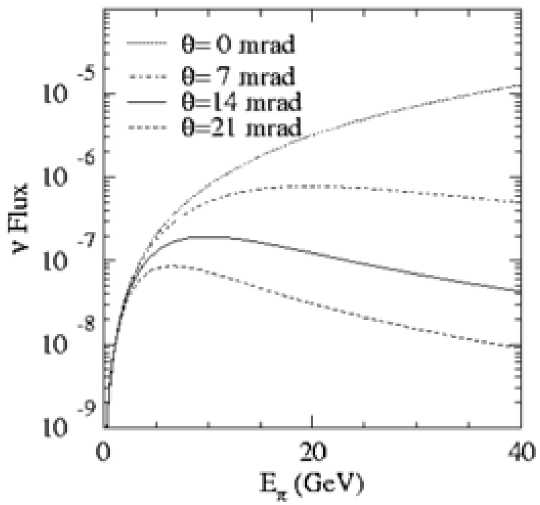
Taken from Leonidas Aliaga thesis



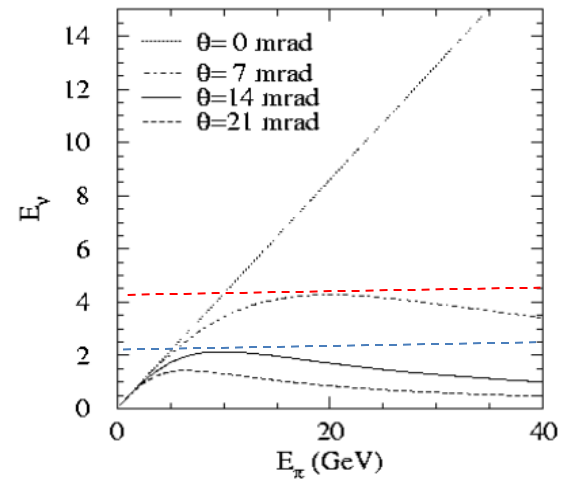
D. Ruterbories PRD 104, 092007 (2021)

Neutrino Off-Axis



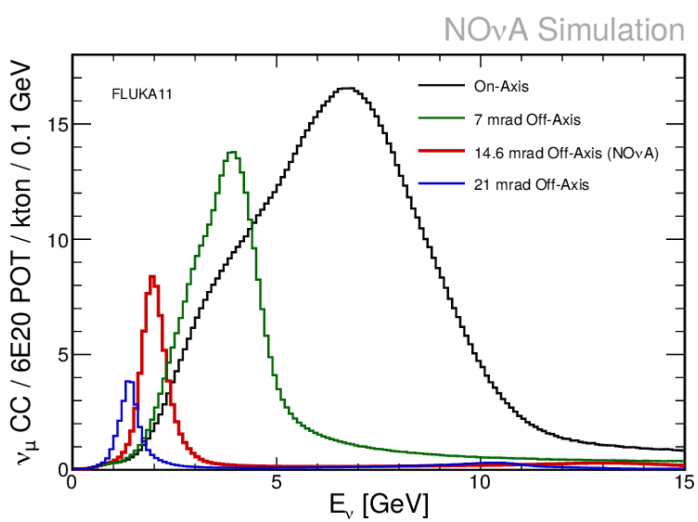


Enhancement of neutrino spectrum



$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

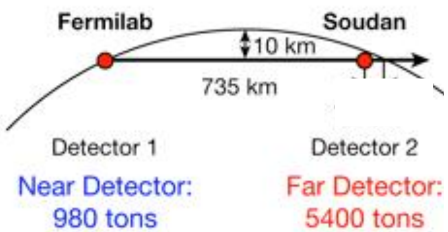
Wide range of pion energies produces small range of neutrino energies.



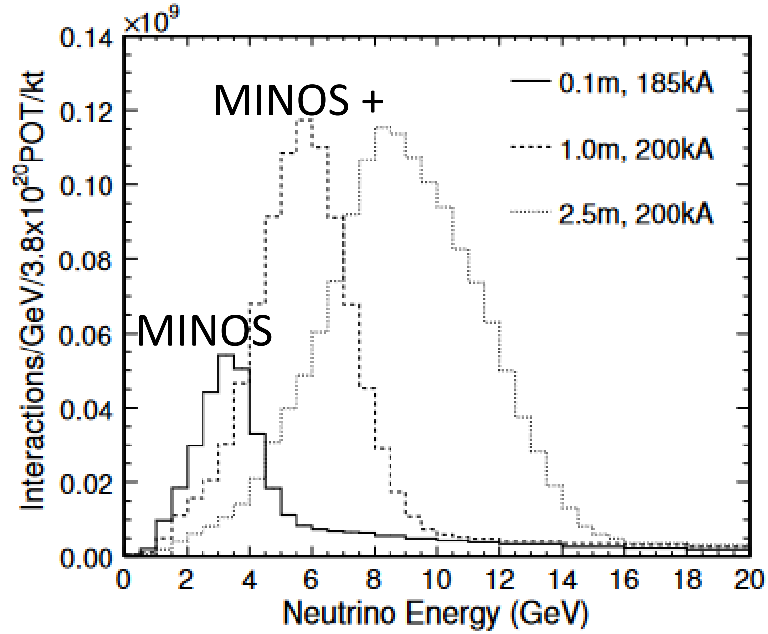
- Oscillations at a single value of L/E can be measured by selecting the appropriate angle.
- A narrow spectrum helps to reduce the background.
- Lower high-energy tail(w/on-axis) reduces NC and taus background.

The MINOS Experiment

The MINOS Experiment



Muon -Neutrino energy spectrum at Near Detector

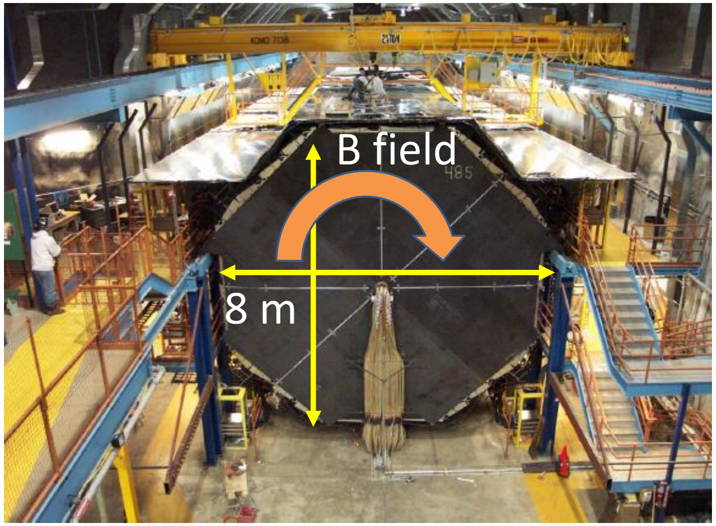


A. Timmons, arXiv:1511.06178

Far/Near helps to reduce systematics such as: beam flux modeling and neutrino cross section uncertainties.

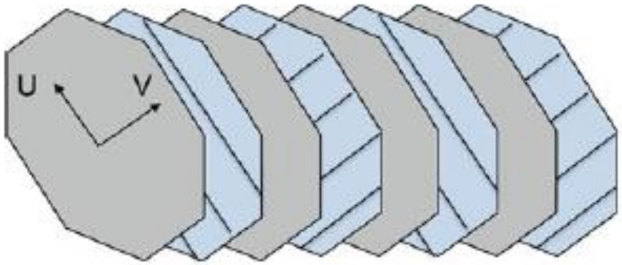
The MINOS Experiment

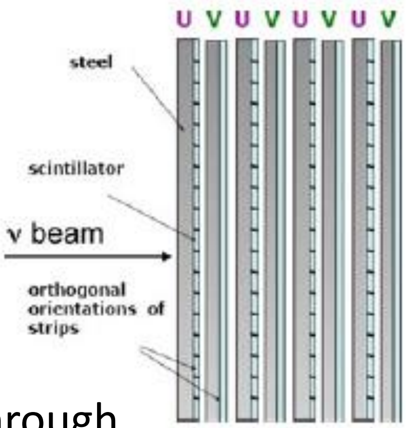
Far detector



- At a depth of 2070 meters-water-equivalent (705 m).
- 486 steel/scintillator planes.
- Each plane consists of a 2.54 cm thick sheet of steel and 1 cm sheet of solid polysterene scintillator.
- 4.0 cm wide strip of scintillators (95,000 strips).
- B field 1.5 Tesla

Taken from J.P. Ochoa doctoral thesis





Scintillator light collected through Wavelength shifting fibers

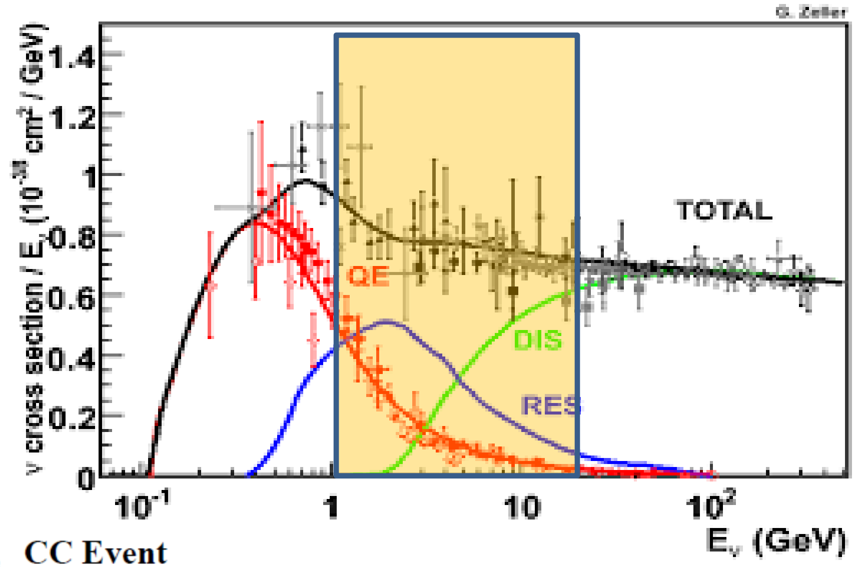
Sampling Calorimeter (Steel/Scintillator) provides tracking and energy deposit

High Z materials: smaller showers that requires finer transverse segmentation.

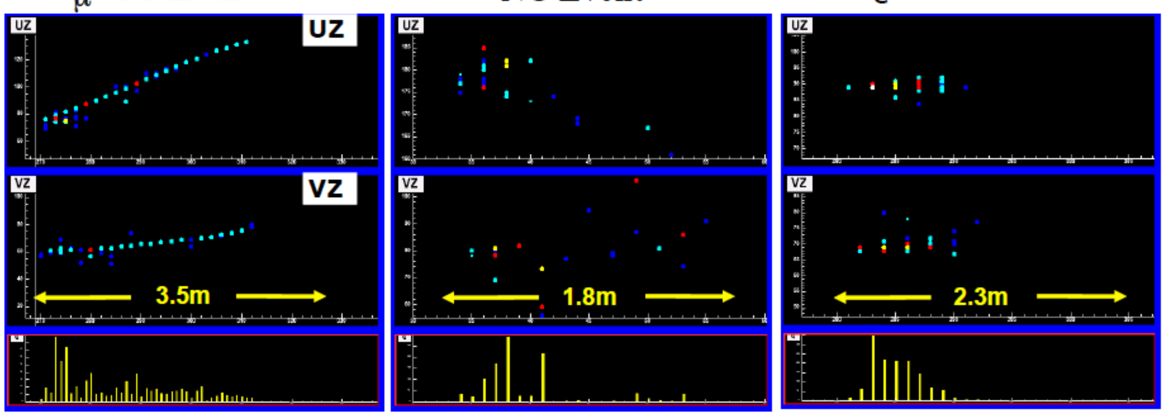
MINOS neutrino interactions and events topology

Neutrino interactions:

$$\nu_\mu(\bar{\nu}_\mu) + X \to \mu^{-(+)} + X'$$
$$\nu + X \to \nu + X'$$
$$\nu_e + X \to e^- + X'$$



ν_μ CC Event | NC Event | ν_e CC Event



- Long muon track + hadronic activity at vertex
- Short showering event, often diffuse
- Short event with typical EM shower profile

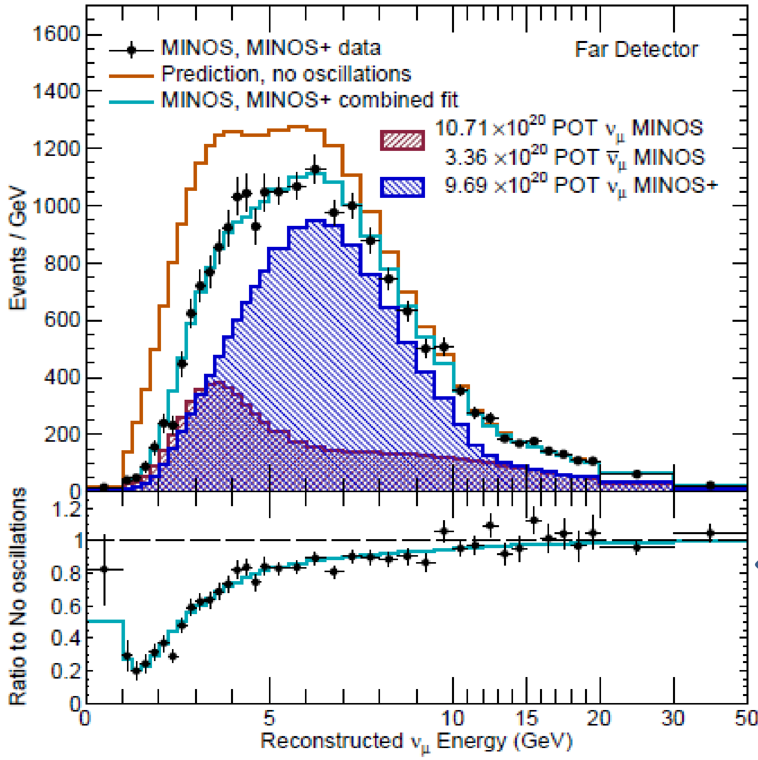
$$E_\nu = E_{\text{shower}} + P_\mu$$

Muon momentum resolution 6 % Range (deposited energy) And 13 % Curvature (B field).

D. Harris Invisibles 2014

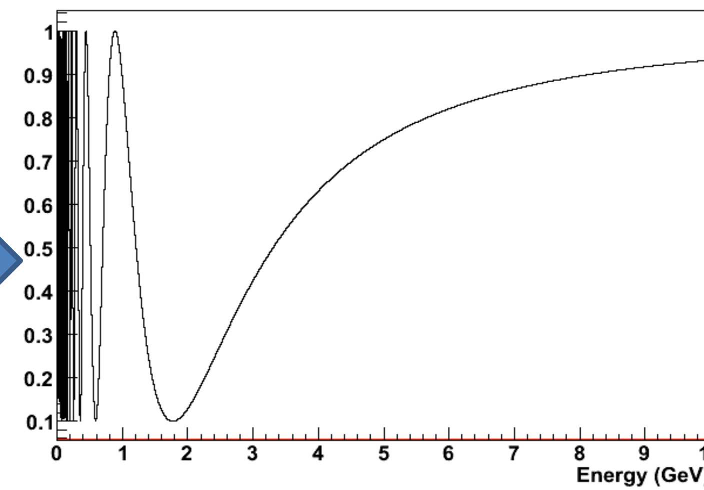
NC is the most relevant background for ν_μ CC producing hadron showers with short tracks.

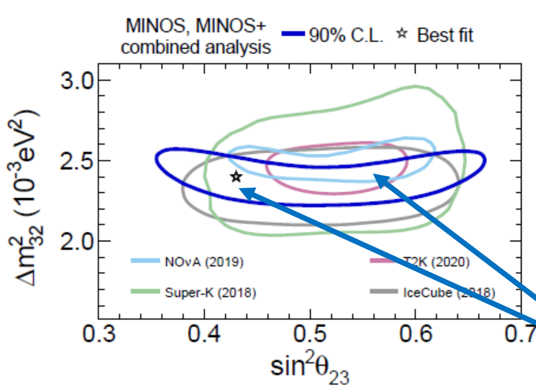
MINOS: Main results – 3ν paradigma



Muon neutrino disappearance

$$P(\nu_\mu \to \nu_\mu)$$



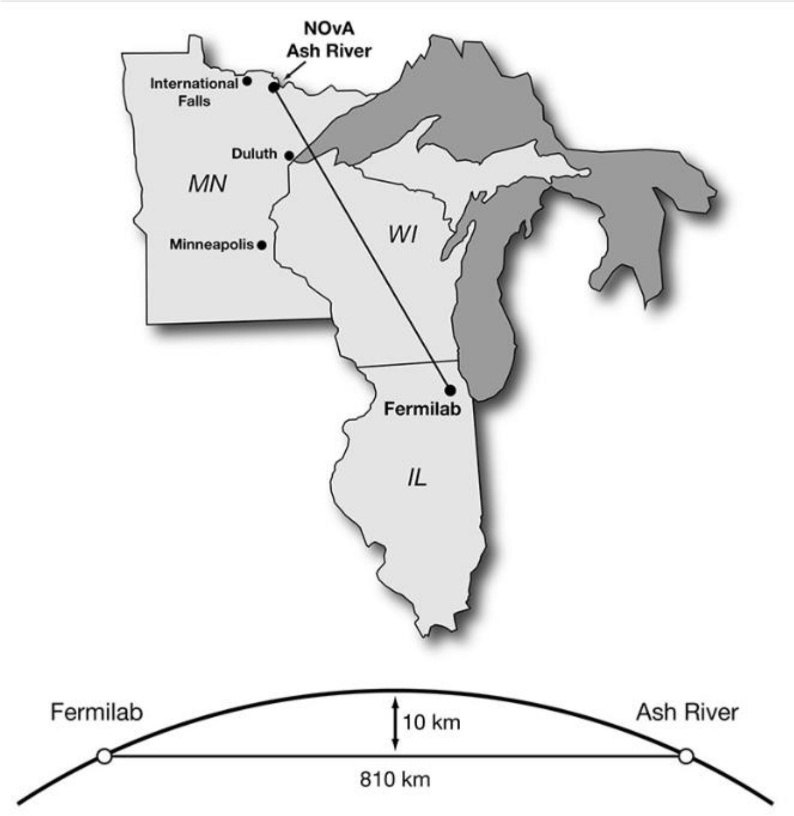


Mass Hierarchy	Parameter	Best fit	Confidence limits
Normal	$\lvert\Delta m^2_{32}\rvert$	2.40	2.31–2.48 (68% C.L.)
	$\sin^2\theta_{23}$	0.43	0.37–0.65 (90% C.L.)
Inverted	$\lvert\Delta m^2_{32}\rvert$	2.45	2.37–2.52 (68% C.L.)
	$\sin^2\theta_{23}$	0.42	0.37–0.65 (90% C.L.)

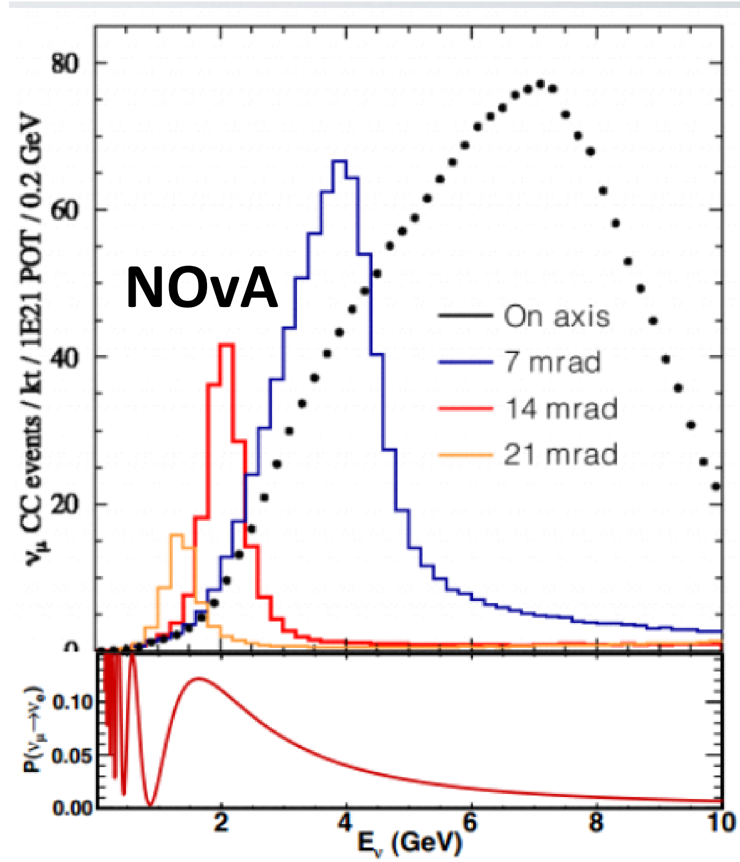
θ_{23} octant degeneracy

P. Adamson et al, PRL. 125 (2020) 13, 131802

The NOvA Experiment



Muon neutrino flux



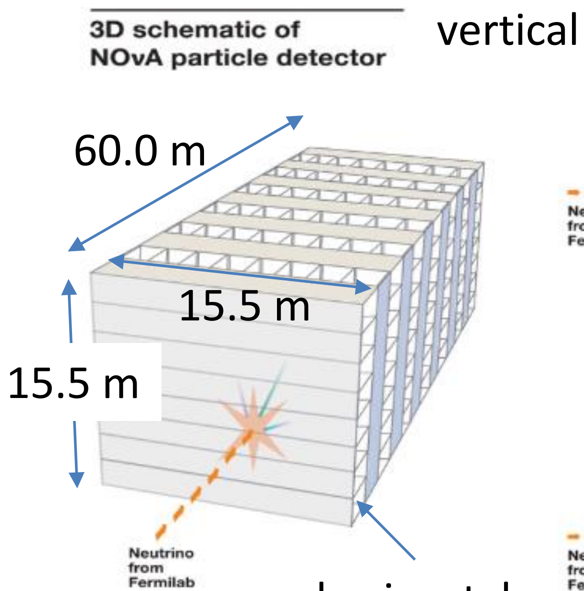
Taken from B. Zamorano Oxford semnar (2015)

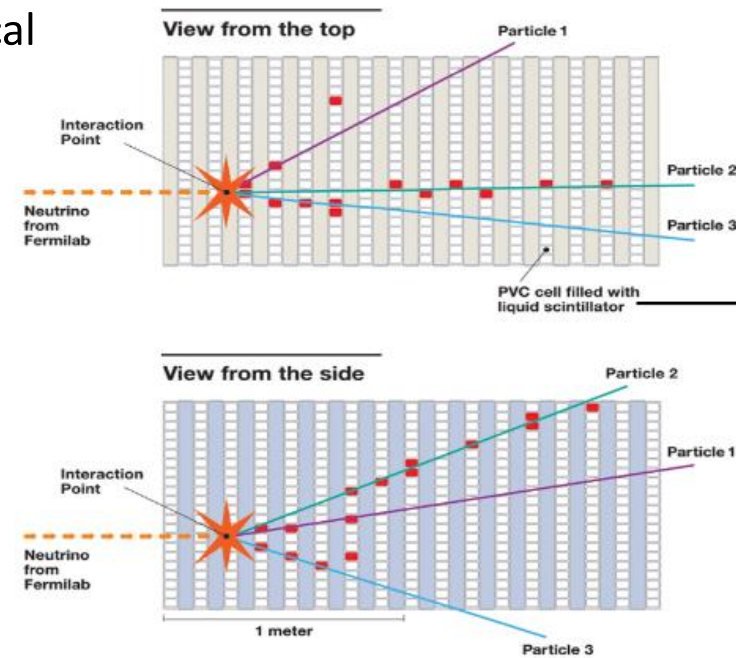
Aimed to measure $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ channels

The NOvA Experiment

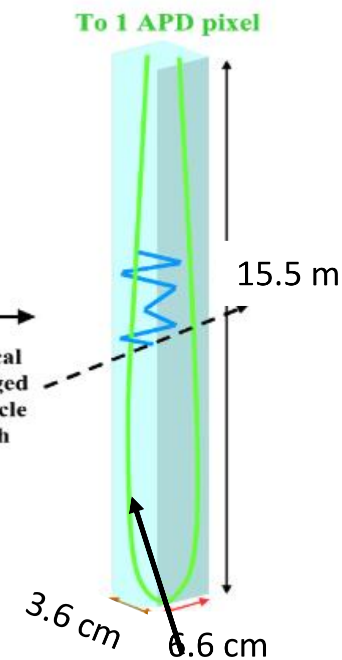
14 kton Far Detector. Extruded plastic cells filled with liquid scintillator (mineral oil 5 % pseudocumene). Tracking calorimeter with 65% active mass.

vertical and horizontal for 3D reconstruction





Single cell



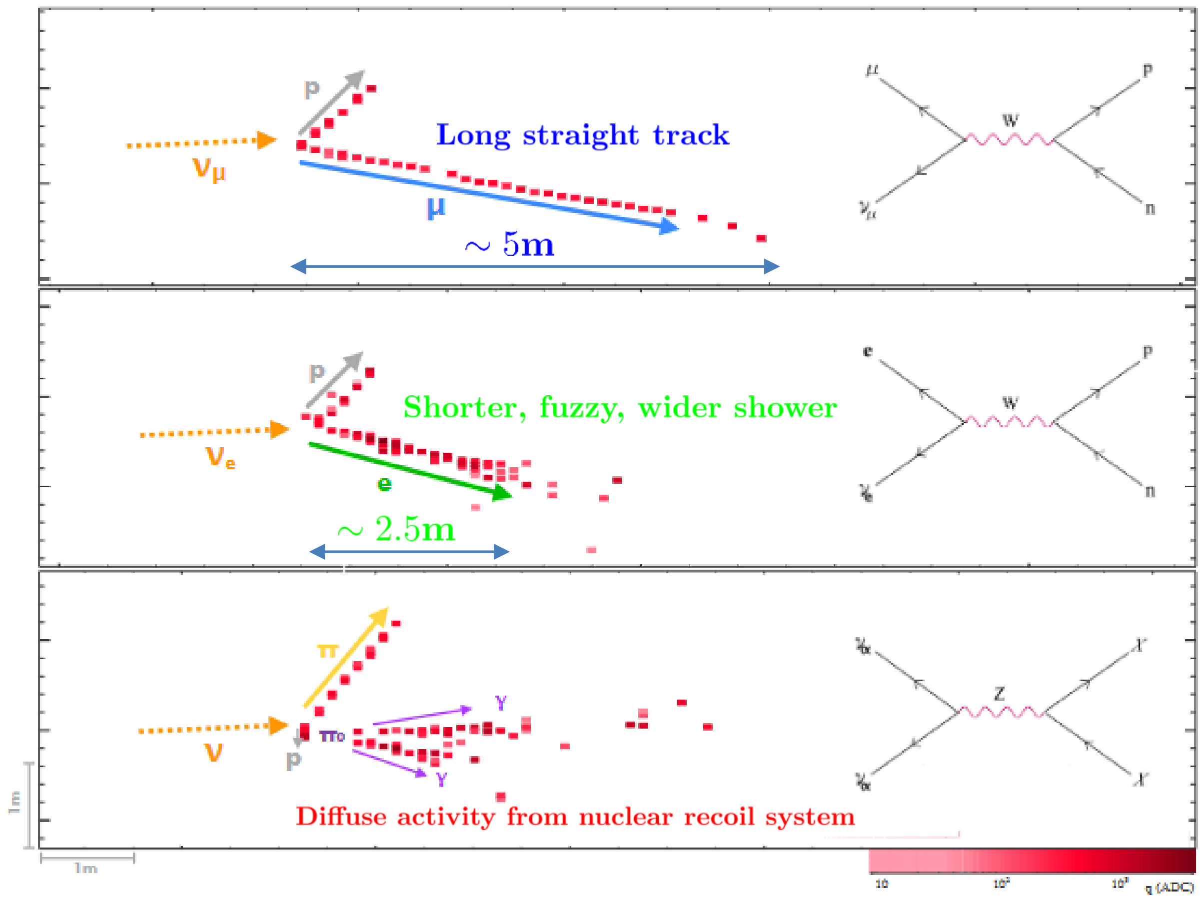
32 cells per module

Light collected by Wavelenght shifting fiber to Avalanche Photo Diode (readout)

Low Z materials longer E.M showers

Adapted from Daisy Kalra, arXiv: 1710.02601

The NOvA Experiment

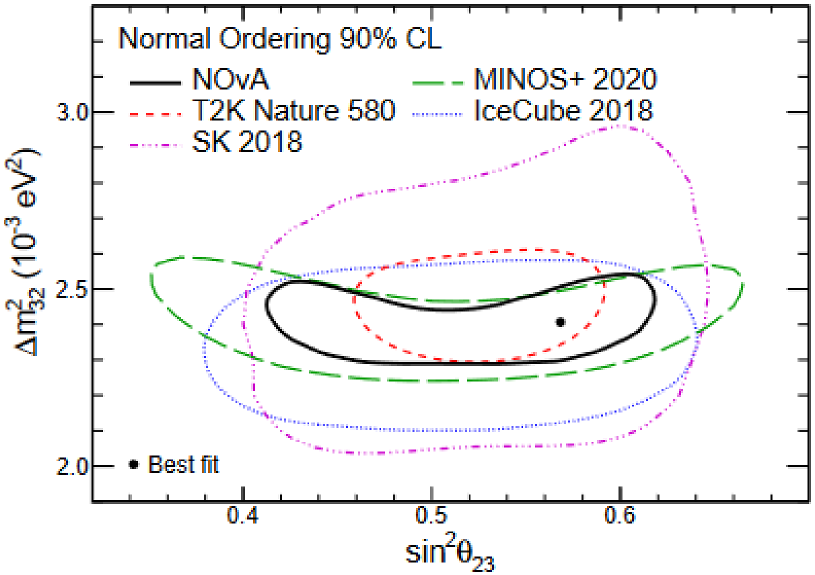


Adapted from Erica Smith PoS PANIC2021 (2022) 289

Backgrounds for $\nu_\mu \to \nu_e$

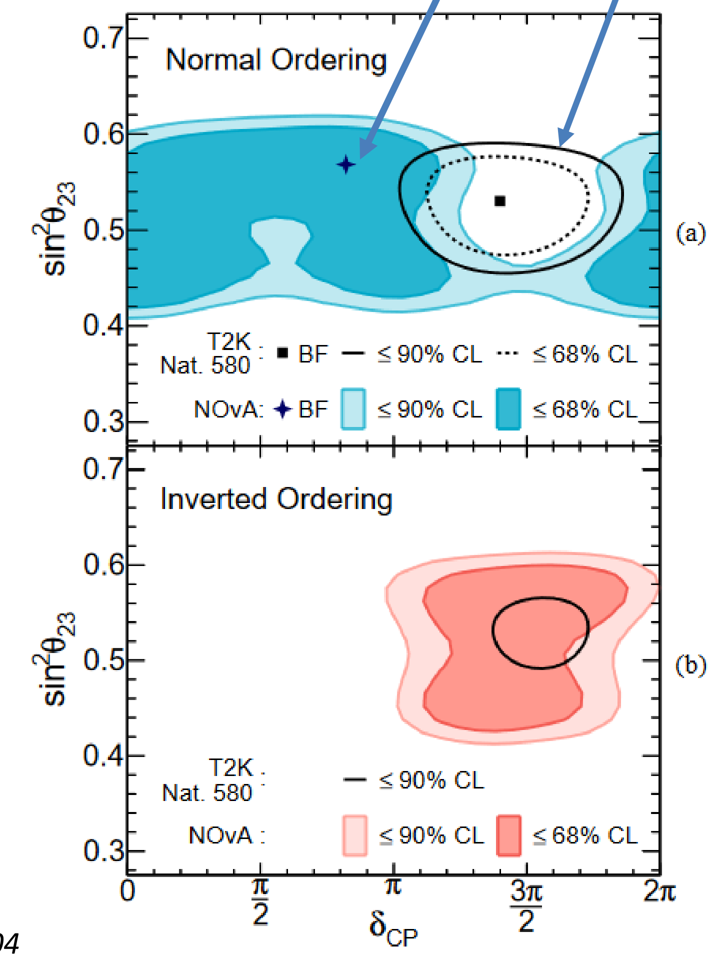
- intrinsic ν_e's in the beam
- $\nu_\mu \to \nu_\tau \Rightarrow \nu_\tau \to \tau \to e^-$ small since ν_μ's-energy below τ threshold
- ν_μNC $\to \pi_0 \to \gamma\gamma$ (mimic electron signal)

The NOvA experiment: Main results



Parameter	Normal ord. UO	Normal ord. LO	Inverted ord. UO	Inverted ord. LO
$\Delta m^2_{32}(10^{-3}\ \mathrm{eV}^2)$	$+2.41 \pm 0.07$	$+2.39$	-2.45	-2.44
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$	0.46	0.56	0.46
$\delta_{CP}(\pi)$	$0.82^{+0.27}_{-0.87}$	0.07	1.52	1.41

Tension between NOvA and T2K



M. Acero et al, Phys.Rev.D 106 (2022) 3, 032004

UO $\rightarrow$ **Upper Octant**
LO $\rightarrow$ **Lower Octant**

Three-flavor oscillation parameters global fit

NuFIT 5.2 (2022)

	Normal Ordering (best fit)			Inverted Ordering ($\Delta\chi^2 = 6.4$)	
	bfp $\pm 1\sigma$	3σ range		bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	4.0 %	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$		$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	4.2 %	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$		$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	2.5 %	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$		$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	15.5 %	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	2.8 %	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	1.0 %	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

End 1st lecture