Neutrino physics

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IPHC, Strasbourg

July 13^{th} 2018

Since the beginning of this school…

- you have had lots of presentations involving neutrinos:

02/07	Introduction to astrophysics 1
03/07	Introduction to astrophysics 2
03/07	**KM3Net**
04/07	Introduction to Particle Physics @CPPM
05/07	BAO
06/07	Super-Novae
07/07	**SuperNemo**
13/07	Particle Physics 1 @IPHC

- finally, we are going a bit more in depth about the ν…
- and after this lecture you'll still hear about them:

16/07	Particle Physics 2 @IPHC
19/07	**JUNO**

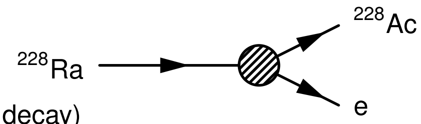
Outlook

- Neutrino History and Properties
- Using Neutrinos as a Probe of the Universe
- Neutrino Oscillations
- Neutrino Masses
- Neutrino in relation to Matter/AntiMatter asymmetry

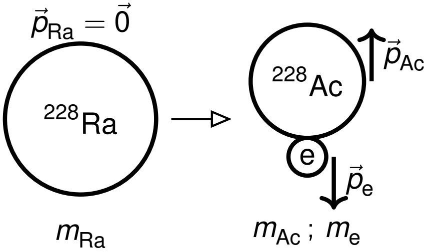
The birth of the neutrino: measuring the β spectra

1896 Becquerel discovery of radiation

- β decay: e emission



- e observed should have known energy (2-body decay)



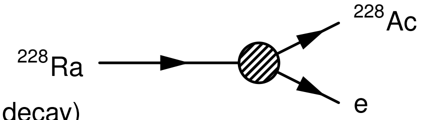
$$E_{\mathrm{Ra}} = E_{\mathrm{Ac}} + E_{\mathrm{e}} \quad ; \quad \vec{p}_{\mathrm{Ra}} = \vec{p}_{\mathrm{e}} + \vec{p}_{\mathrm{Ac}} \quad ; \quad E^2 = m^2 + |\vec{p}|^2$$

$$\Rightarrow E_{\mathrm{e}} = \frac{m_{\mathrm{Ra}}^2 - m_{\mathrm{Ac}}^2 + m_{\mathrm{e}}^2}{2 m_{\mathrm{Ra}}}$$

The birth of the neutrino: measuring the β spectra

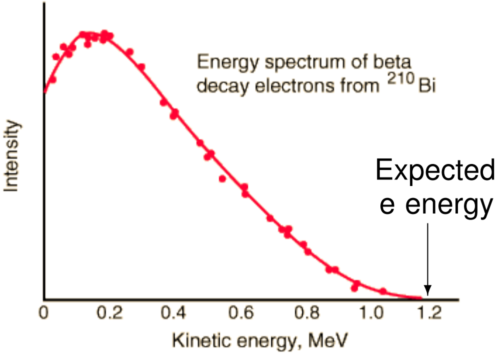
1896 Becquerel discovery of radiation

- β decay: e emission



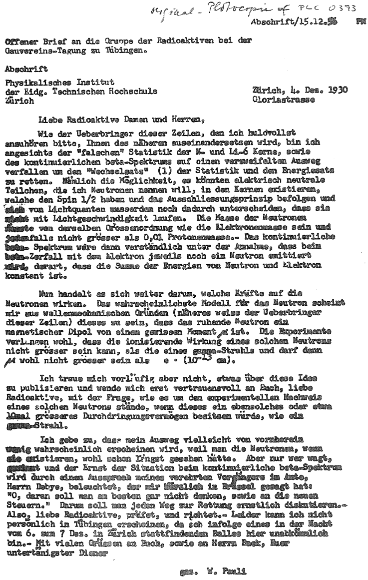
- e observed should have known energy (2-body decay)

1914 Chadwick observed continuous electron spectra from β-decay



Expected e energy

The birth of the neutrino: A letter from W. Pauli (1930)



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. Dez. 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 Grossenordnung 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 magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

W. Pauli, Phys. Today **31N9** (1978) 27.

Copyright © The Nobel Foundation 1945

The birth of the neutrino: A letter from W. Pauli (1930)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the “wrong” statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a **desperate remedy** to save the “exchange theorem” of statistics and the law of conservation of energy. Namely, the possibility that **there could exist in the nuclei electrically neutral particles**, that I wish to call **neutrons**, which have **spin 1/2** and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that **in beta decay a neutron is emitted in addition to the electron** such that the sum of the energies of the neutron and the electron is constant. . . **I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist.** But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: “Oh, It’s well better not to think about this at all, like new taxes”. From now on, every solution to the issue must be discussed. Thus, dear radioactive people, **look and judge.**

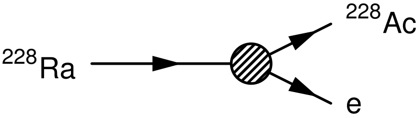
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,
W. Pauli

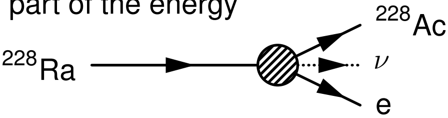
[translation to english: `http://www.pp.rhul.ac.uk/~ptd/TEACHING/PH2510/pauli-letter.html`]

The birth of the neutrino: quick (theoretical) acceptance

1896 Becquerel's β decay: e emission



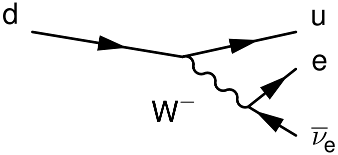
1930 Pauli's β decay: invisible ν emitted carries away part of the energy



1934 Fermi incorporated the ν in the electroweak theory

  - Pauli's "neutron" renamed as neutrino due to discovery of "atomic" neutron (1932)

- Current "Standard Model" view of β decay:



First measurement of neutrinos: “Project Poltergeist”

- First step: find adequate ν emitter…

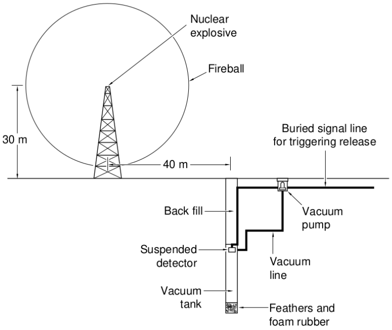
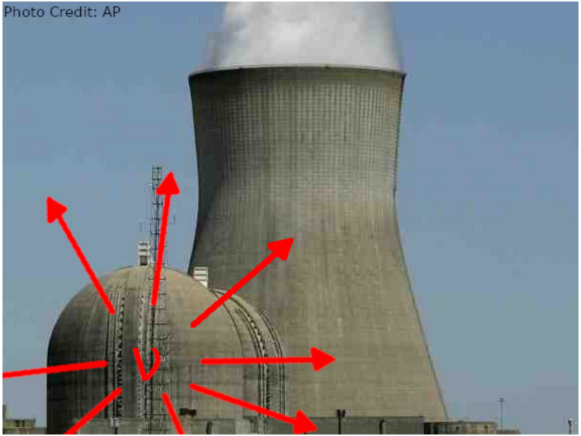


Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

Los Alamos Science Number 25 1997



`http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02`

First measurement of neutrinos

1995

1956 Reines and Cowan detected ν from Savannah River reactors

- β decay: $\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$
- To measure neutrinos,
  "invert" the process:

$$\mathrm{p} + \overline{\nu}_\mathrm{e} \rightarrow \mathrm{n} + \mathrm{e}^+$$

  - source of $\overline{\nu}_\mathrm{e}$: nuclear reactor
  - target: p in water
  - $\mathrm{e}^+ + \mathrm{e}^- \rightarrow 2\gamma$
  - Cd in water capture produced n

$$^{108}\mathrm{Cd} + \mathrm{n} \rightarrow {}^{109m}\,\mathrm{Cd} \rightarrow {}^{109}\,\mathrm{Cd} + \gamma$$

  - γ emissions separated by $3 - 10\ \mu s$

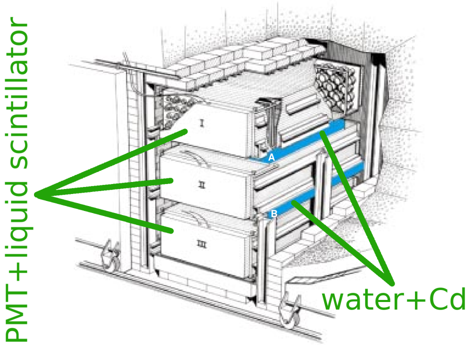


Figure 4. The Savannah River Neutrino Detector—A New Design
The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. The protons in the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The target tanks were sandwiched between three scintillation detectors (I, II, and III). Each detector contained 1,400 liters of liquid scintillator that was viewed by 110 photomultiplier tubes. Without its shield, the assembled detector weighed about 10 tons.

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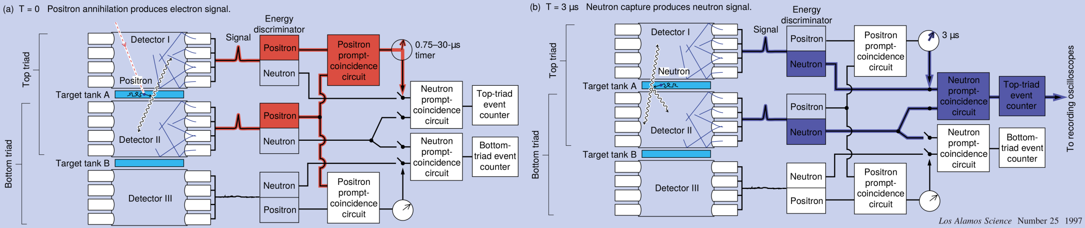
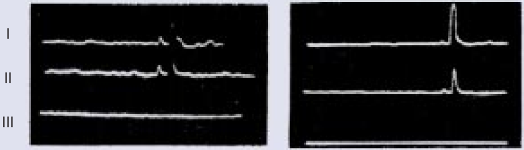
Delayed-Coincidence Signals from Inverse Beta Decay

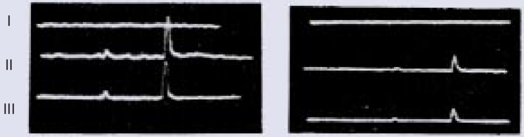

(a) T = 0 Positron annihilation produces electron signal.

(b) T = 3 µs Neutron capture produces neutron signal.

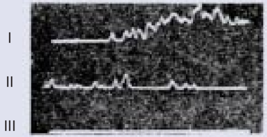
Los Alamos Science Number 25 1997



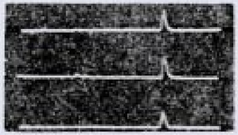
(a) Positron scope **GOOD** Neutron scope



(b) Positron scope **GOOD** Neutron scope



(c) Neutron scope **BAD**


(d) Neutron scope **BAD**

(e) Positron scope **BAD**


(f) Neutron scope **BAD**

Neutrino properties

1957 Wu shows weak interaction violates parity

1958 Goldhaber measures ν are left-handed

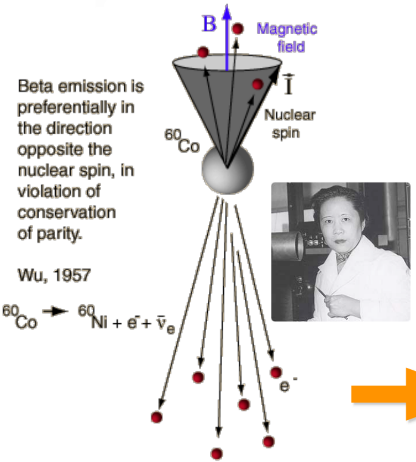
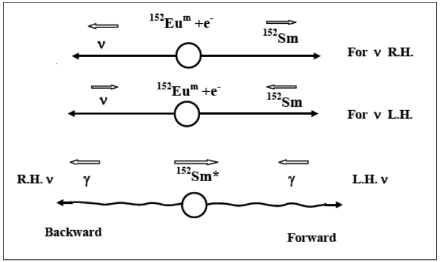
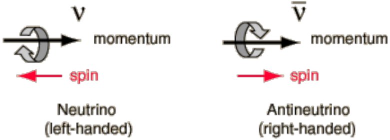


Figure 1. The relation between the directions of the γ-ray and the recoiling nucleus for different signs of neutrino helicity. The solid arrows show the direction of motion and the hollow arrows show the spin direction.





Neutrino properties

1962 Lederman, Schwartz, Steinberger discover ν_μ (1988)

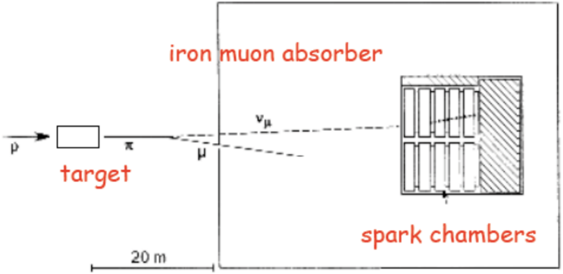
- there is more than one type of ν!

decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

neutrino detection

$$\nu_\mu + N \rightarrow \mu^- + X$$

$$\nu_\mu + N \not\rightarrow e^- + X$$



first neutrino beam

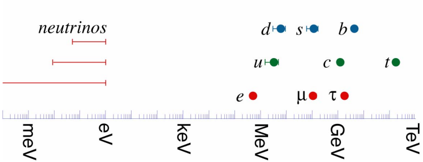
1967 Standard Model of elementary particles proposed

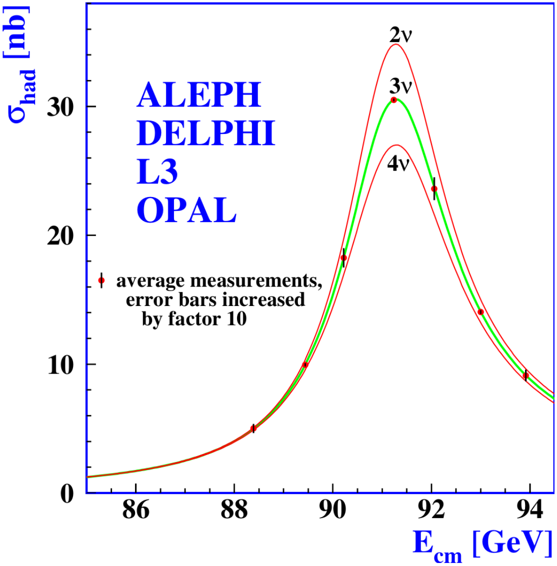
- Model works well up to now. . .
- . . . however, no ν mass foreseen

2000 DONUT discovers ν_τ

The Standard Model and Neutrinos

- Standard Model poses $m_\nu = 0$
  - In SM, m_f from Higgs mechanism: need L and R helicities
  - (interacting) ν only have L field
  - now know: $0 < \sum_j m_{\nu_j} < \mathcal{O}(1\text{ eV})$
  - even assuming ν_R exists, $m_\nu \lll m_{f\setminus\{\nu\}}$



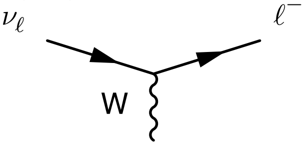


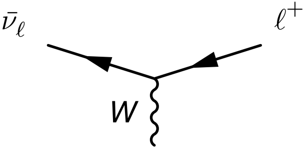
- From Z^0 width measurement
  - only 3 ν with $m_\nu < 45$ GeV
  - from SM symmetries, and small m_ν $\Rightarrow$ only 3 families of particles

Neutrino Interaction with matter

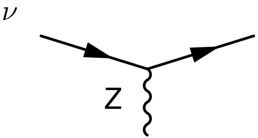
Looking on the ν side of the interaction

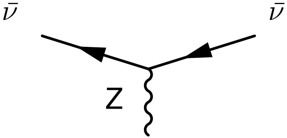
Charged Current (CC) interaction :





Neutral Current (NC) interaction :

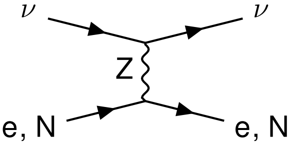


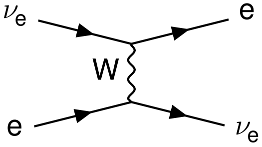


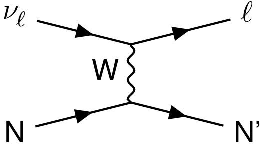
- Measure of produced lepton (ℓ) $\rightarrow$ define ν flavor
- May measure recoil of nucleus or hadronization

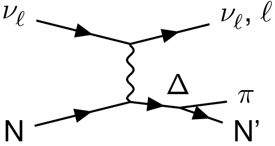
Neutrino Interaction with matter

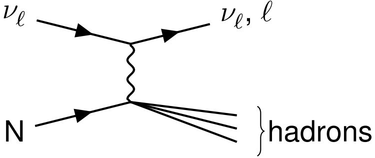
Classifications regarding what happens on nuclei


Elastic


ν_e – e elastic

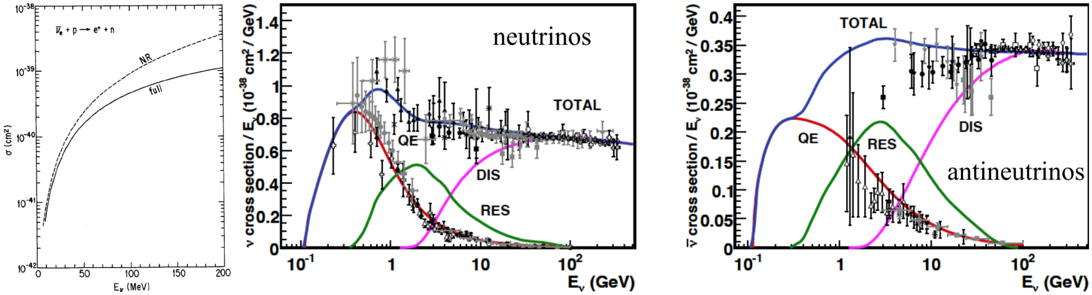

Quasi-Elastic (QE)


Resonant (RES)


Deep Inelastic (DIS)

- For detection purposes, need to consider nuclear effects at low energy

Neutrino Interaction with matter: cross section



- data from ν_μ CC cross section (per nucleon)
- low cross section:
  - for $E_\nu \sim 3$ MeV → $\mathcal{O}$(1 light-year of lead)
  - for $E_\nu \sim 1$ GeV → $\mathcal{O}$(1 a.u. of lead)
  - for $E_\nu \sim 40$ TeV → $\mathcal{O}$(Earth's diameter @ Earth's density)

Using neutrinos to measure the Universe

- Potential to test astrophysical models since:

1965 Detection of Cosmic Rays ν: gold mine exps, . . . , SK, IceCube
1970 Detection of Solar ν: Homestake (🏅 2002), . . . , SNO, SK, Borexino
1987 Detection of ν from SN1987A: Kamiokande (🏅 2002), IMB, Baksan

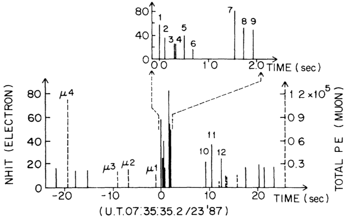


FIG. 9. The time sequence of events in a 45-sec interval centered on 7:35:35 UT 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu1$–$\mu4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

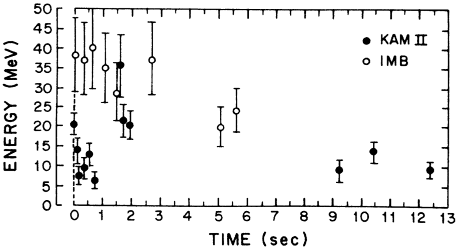


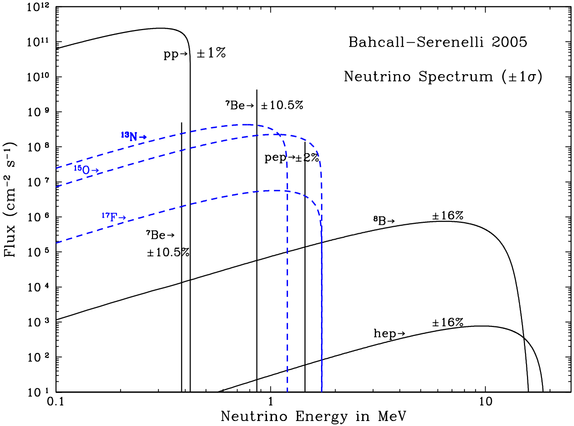
FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t = 0$.

Phys. Rev. D38 (1988) 448-458.

2013 Detection of astrophysical ν: IceCube

Verifying the Standard Solar Model with Neutrinos

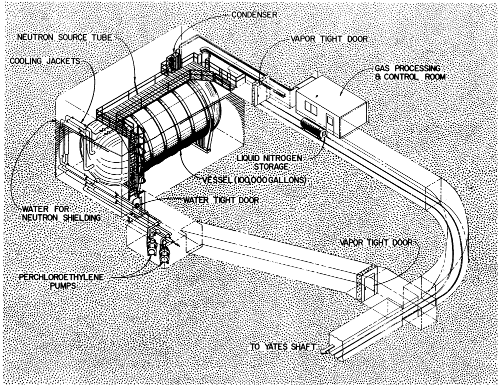
- The Solar Model predicts the Sun produces ν_e during the reactions to fuse H in He.
  - The pp chain:
    ① $^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{2}\mathrm{He} + \gamma$
    ② $^{2}_{2}\mathrm{He} \rightarrow {}^{2}_{1}\mathrm{H} + \mathrm{e}^{+} + \nu_e$
    ③ $^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$
    ④ $^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H}$
  - Other chains produce varying amounts and energies of ν_e
  - ν produced at center of the sun reaches surface in ∼ 2 s
    - ★ same for γ takes $\mathcal{O}(10^6$ year)...



- Idea: Measure ν from Sun to check model!

Verifying the Standard Solar Model with Neutrinos: Homestake

- Build detector with 100k gallons of tetrachloroethylene (common cleaning fluid)
  - Detector 1.5 km below surface in Homestake Mine
  - Detect neutrinos through: $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}$
    - Energy threshold: 0.814 MeV
  - Every few weeks, count how many ${}^{37}\mathrm{Ar}$ produced
    - Extract ${}^{37}\mathrm{Ar}$, count decays (τ=35d)… expected ~1 count/day



Astrophysical Journal 496:505-526 (1998)

Verifying the Standard Solar Model with Neutrinos: Exp. Results

- Discrepancy on “expected” and “observed” rate of $\nu \Rightarrow$ “Solar Neutrino Problem”
  - Homestake: observed 2.56 ± 0.23 SNU; expected 8.1 ± 1.2 SNU

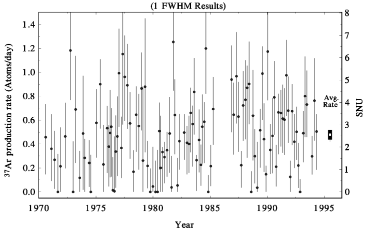
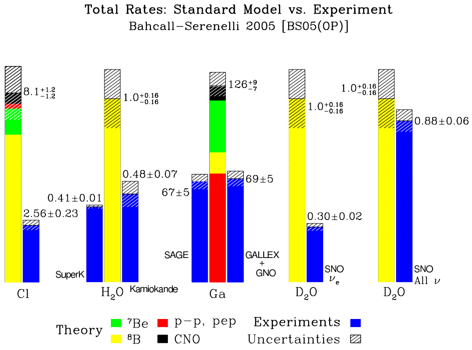


FIG. 13.—Homestake Experiment—one FWHM results. Results for 108 individual solar neutrino observations made with the Homestake chlorine detector. The production rate of ^{37}Ar shown has already had all known sources of nonsolar ^{37}Ar production subtracted from it. The errors shown for individual measurements are statistical errors only and are significantly non-Gaussian for results near zero. The error shown for the cumulative result is the combination of the statistical and systematic errors in quadrature.

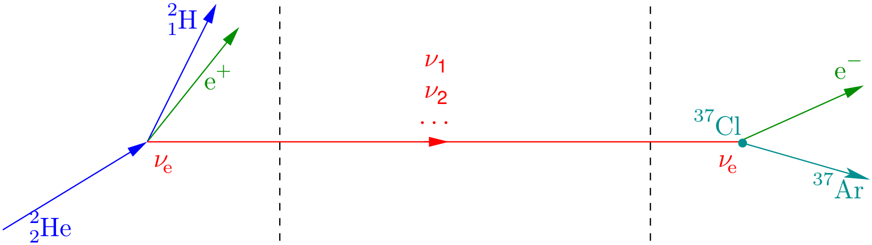
Astrophysical Journal. 496: 505-526. (1998)



- Lowering the detection threshold energy [GALLEX/GNO, SAGE]:
  - Replace $^{37}\mathrm{Cl}$ by $^{71}\mathrm{Ga}$ as target: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e$
  - Detection threshold: 233 keV
- Still deficit of $\nu \ldots \rightarrow$ oscillations?

Neutrino Oscillation (in vacuum) – overview

ν production | ν propagation | ν detection



$$|\nu_e\rangle = \sum_j U^*_{ej} |\nu_j\rangle$$

$$|\nu_j\rangle \to e^{-iE_j t} |\nu_j\rangle$$

$$|\nu_j\rangle = \sum_\alpha U_{\alpha j} |\nu_\alpha\rangle$$

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

- For oscillations to happen $\{|\nu_\alpha\rangle\}$ and $\{|\nu_j\rangle\}$ different

Neutrino Oscillations – simplest case

2 flavor case, vacuum

- 2 ν interaction flavours (ν_e and ν_μ)
- mass eigenstates $\{|\nu_j\rangle\} = \{|\nu_1\rangle, |\nu_2\rangle\} \neq \{|\nu_\alpha\rangle\}$ flavour eigenstates
- mixing matrix U: $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$ with $UU^\dagger = \mathbb{1}$ (ie, U rotation matrix)

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

- Propagate through space time as plane waves in mass state:

$$|\nu_e, t\rangle = \sum_j U^*_{ej} e^{-iE_j t} |\nu_j\rangle = \cos\theta e^{-iE_1 t} |\nu_1\rangle + \sin\theta e^{-iE_2 t} |\nu_2\rangle$$

- $P(\nu_e \to \nu_e, t) = ||\langle\nu_e|\nu_e, t\rangle||^2 = 1 - \sin^2(2\theta)\sin^2[(E_2 - E_1)t/2]$
- Given m_i small: $E_i = \sqrt{m_i^2 + p^2} \approx p + \frac{1}{2}\frac{m_i^2}{p}$ and $t \approx L$, therefore $(E_2 - E_1)t \approx \frac{1}{2}\frac{m_2^2 - m_1^2}{p} L \approx \frac{\Delta m^2 L}{2E}$

$\Rightarrow$ $P(\nu_e \to \nu_e, L) = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

Neutrino Oscillations

3 flavor case, vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}}, \qquad \Delta m^2_{jk} = m^2_j - m^2_k$$

- 3 known ν interaction flavours : ν_e, ν_μ and ν_τ $\Rightarrow$ matrix U is 3×3

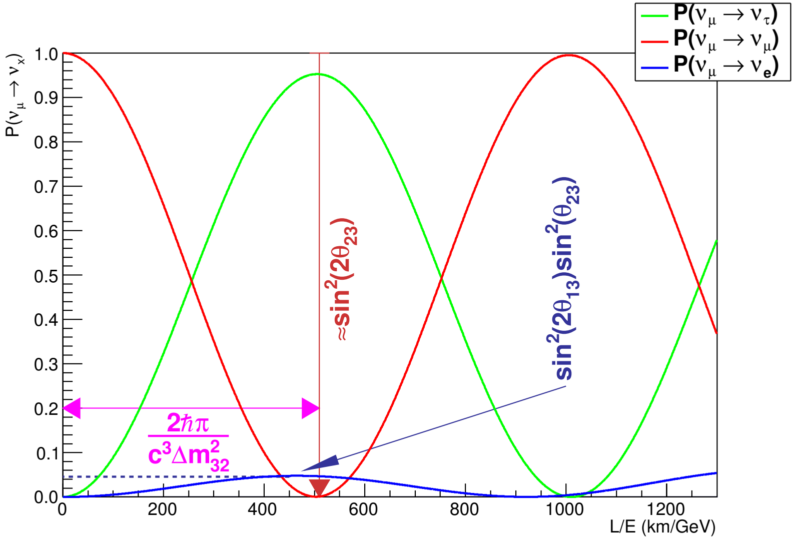
$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{“atmospheric sector”}} \times \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{“reactor sector”}} \times \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{“solar sector”}}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

- θ_{23}, θ_{13}, θ_{12}: ν mixing angles
- δ_{CP}: leptonic CP violation phase
- Δm^2_{32}, Δm^2_{21}: ν mass splitting
  - Note: $\Delta m^2_{31} = m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21}$

Neutrino Oscillations

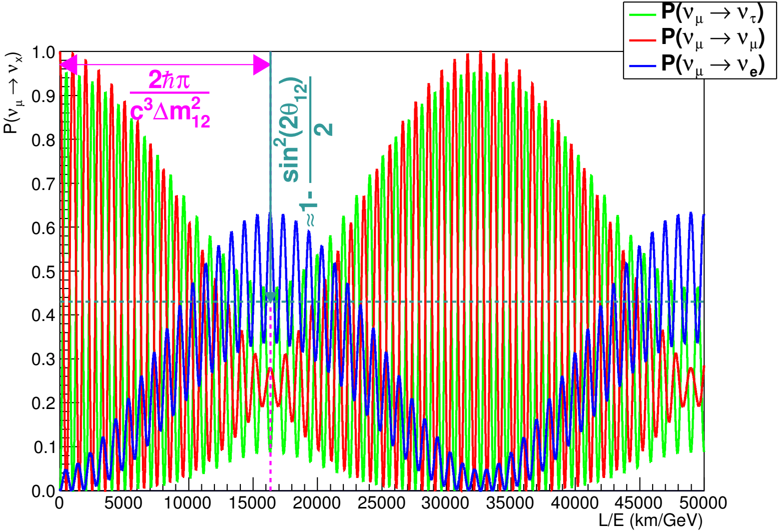
3 flavor case, vacuum



$\theta_{12} = 34^\circ$, $\theta_{13} = 8.8^\circ$, $\theta_{23} = 45^\circ$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ eV^2/c^4, $\Delta m^2_{32} = 2.43 \cdot 10^{-3}$ eV^2/c^4, $\delta_{CP} = 0^\circ$.

Neutrino Oscillations

3 flavor case, vacuum



$\theta_{12} = 34^\circ$, $\theta_{13} = 8.8^\circ$, $\theta_{23} = 45^\circ$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ eV^2/c^4, $\Delta m^2_{32} = 2.43 \cdot 10^{-3}$ eV^2/c^4, $\delta_{CP} = 0^\circ$.

Neutrino Oscillations Matter Effects

- In vaccum Hamiltonian H_0 is

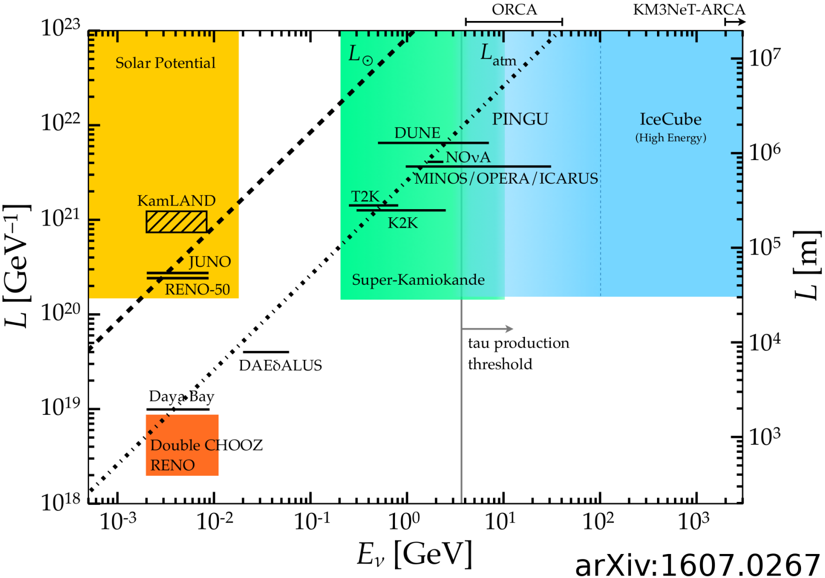
$$H_0 = \frac{1}{2E} U \,\mathrm{diag}(m_1^2, m_2^2, m_3^2)\, U^\dagger$$

  - NB: $H = H' + \alpha \mathbb{1}$, α term is global phase → H and H' same for oscillations
- In matter, Hamiltonian $H_m = H_0 + H_{int}$, with H_{int} describing interaction ν – matter
  - Of interest here is the elastic scattering where coherence of ν preserved
  - ν – u and ν – d not interesting as $H_{int}^u \propto \mathbb{1}$ and $H_{int}^d \propto \mathbb{1}$
  - ν – e interesting: $H_{int}^e = \mathrm{diag}(V^W, 0, 0) + V^Z \mathbb{1}$, with $V^W = \pm\sqrt{2} G_F N_e$
    - ★ N_e: electron density in medium
    - ★ $+$ sign for ν and $-$ sign for $\bar{\nu}$
- For 2-flavor osc.: $\theta \to \theta_m$ matter mixing angle related to matter-eigenstates $|\nu_i^m\rangle$

$$\tan 2\theta_m = \frac{\tan 2\theta}{1 \mp N_e/N_e^r}\,;\ \Delta m_m^2 = \Delta m^2 \cos 2\theta \sqrt{\left(1 \mp \frac{N_e}{N_e^r}\right)^2 + \tan^2 2\theta}\,;\ N_e^r = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2} G_F}$$

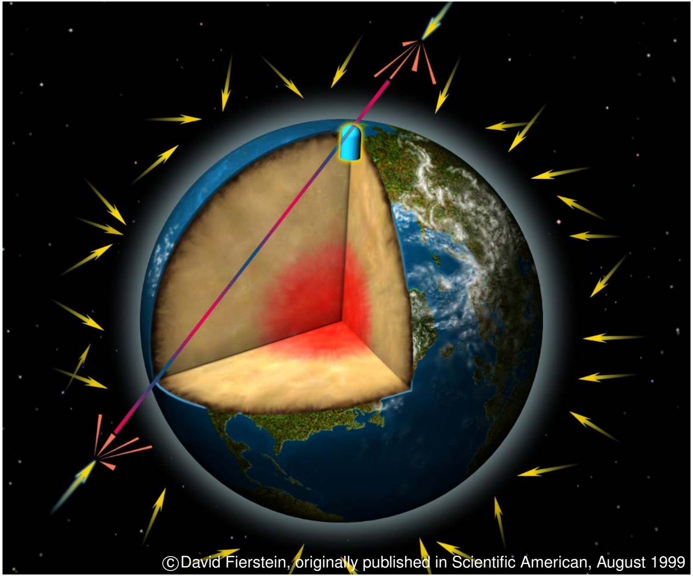
- Resonance condition for specific densities if ν and $\Delta m^2 > 0$ (or $\bar{\nu}$ and $\Delta m^2 < 0$)
- Large matter effects in Solar (Δm_{21}^2) & Atmospheric (Δm_{32}^2) ν
- As δ_{CP}, produce $\nu - \bar{\nu}$ asymmetry observable in experiments

Experimental Overview

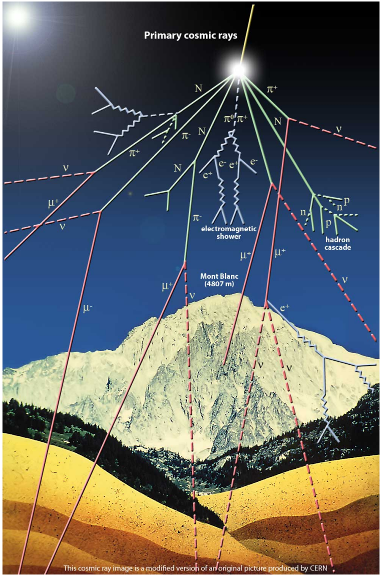


arXiv:1607.02671

Atmospheric Neutrinos

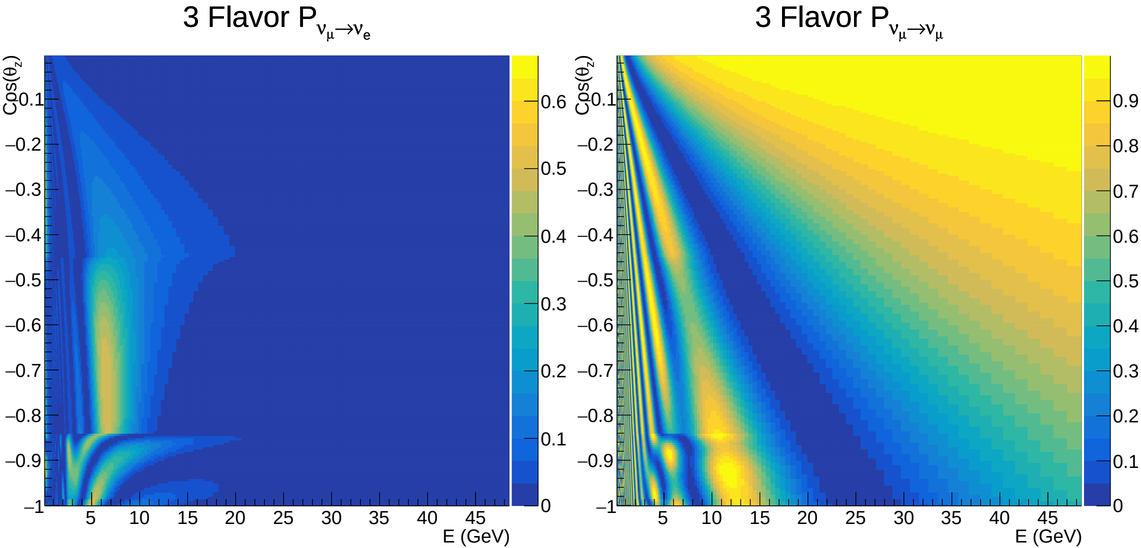


©David Fierstein, originally published in Scientific American, August 1999



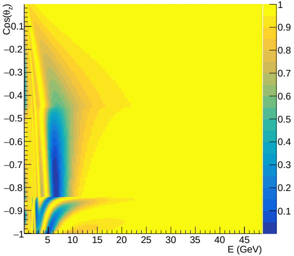
This cosmic ray image is a modified version of an original picture produced by CERN

Atmospheric Neutrinos: Neutrino Oscillation Signatures

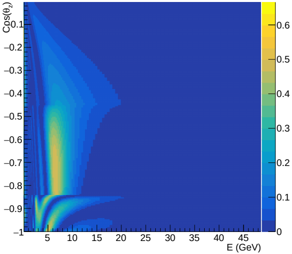


Atmospheric Neutrinos: Neutrino Oscillation Signatures

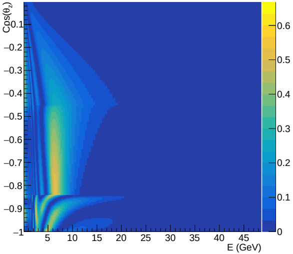
3 Flavor $P_{\nu_e \to \nu_e}$



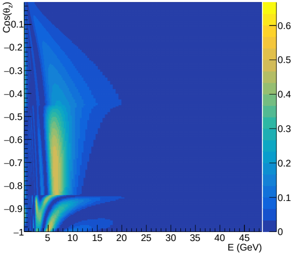
3 Flavor $P_{\nu_e \to \nu_\mu}$



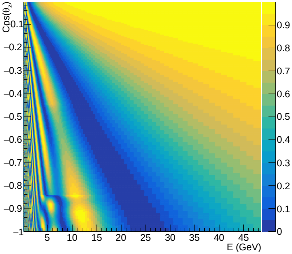
3 Flavor $P_{\nu_e \to \nu_\tau}$



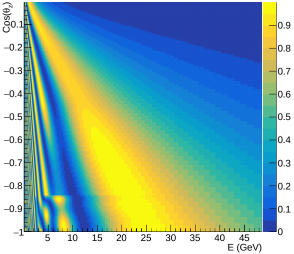
3 Flavor $P_{\nu_\mu \to \nu_e}$



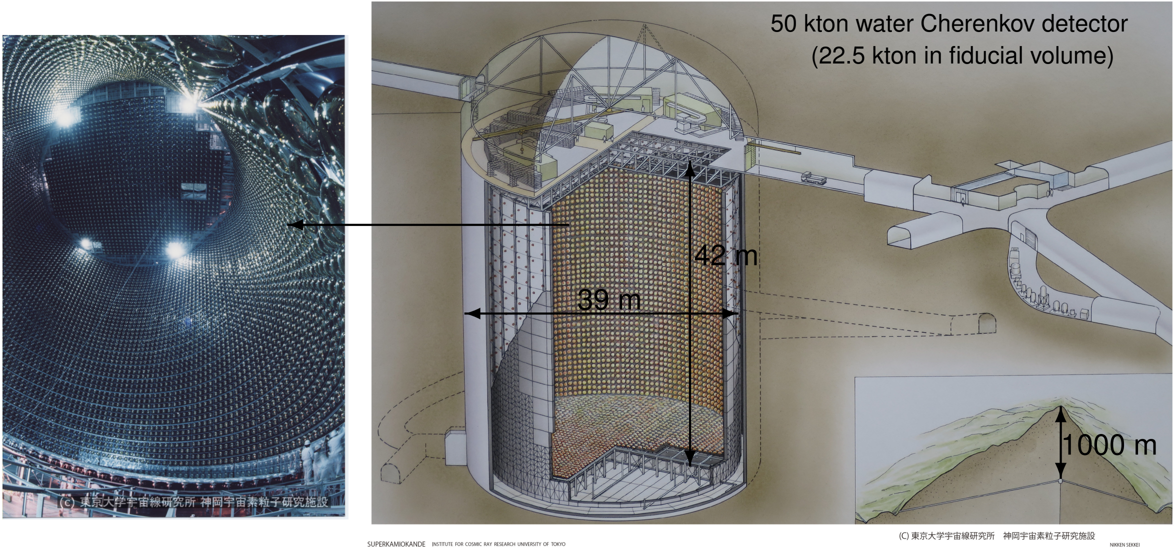
3 Flavor $P_{\nu_\mu \to \nu_\mu}$



3 Flavor $P_{\nu_\mu \to \nu_\tau}$

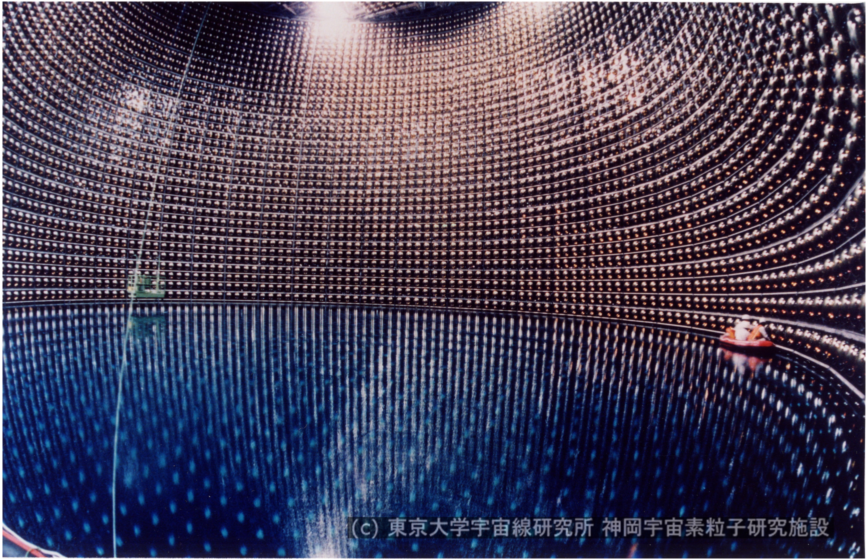


The Super-Kamiokande Detector

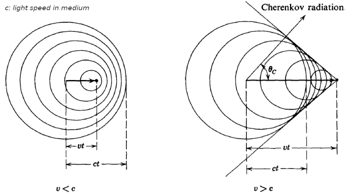


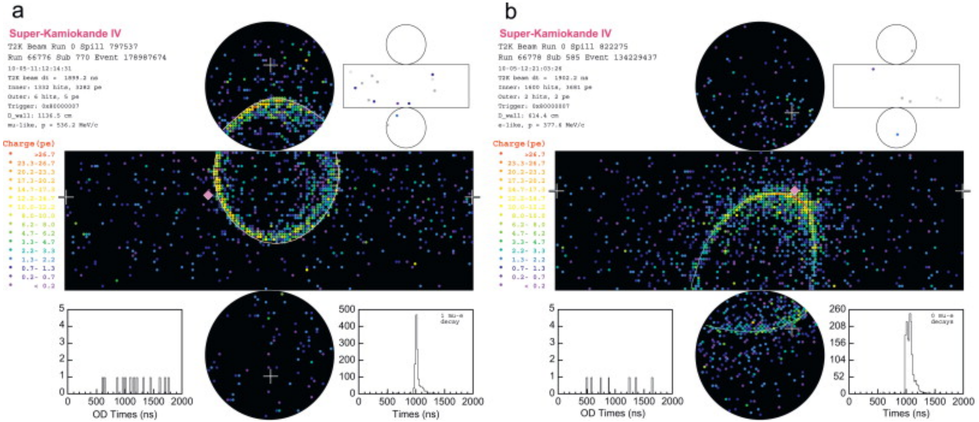
50 kton water Cherenkov detector
(22.5 kton in fiducial volume)

The Super-Kamiokande Detector

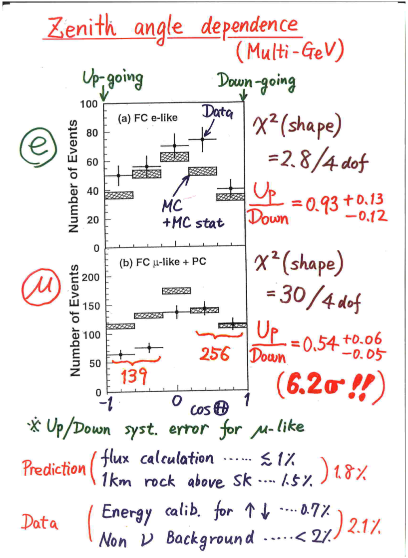


Detecting ν at Super-Kamiokande





Discovery of Neutrino Oscillations: Super-Kamiokande 2015



Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

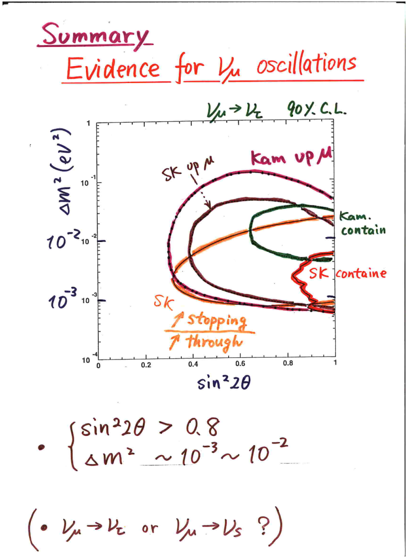
$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation ...... ≲ 1%
1km rock above SK .... 1.5%) 1.8%

Data (Energy calib. for ↑↓ 0.7%
Non ν Background ..... < 2%) 2.1%



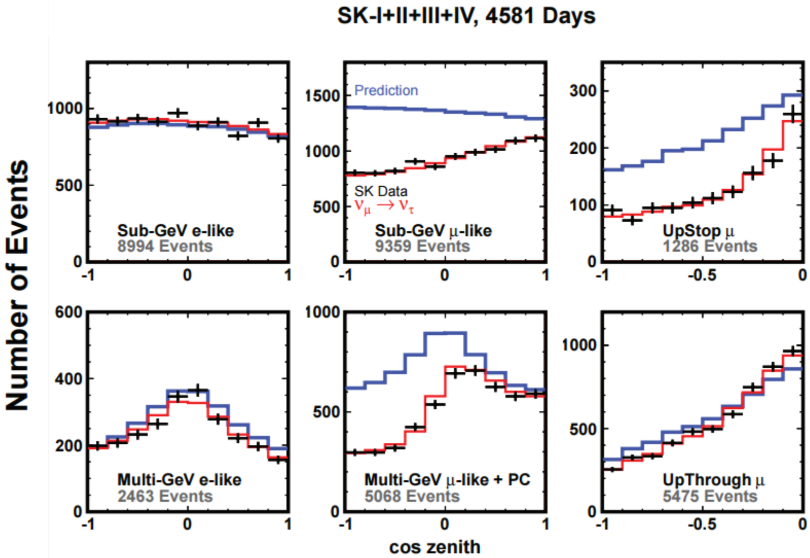
Summary

Evidence for ν_μ oscillations

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

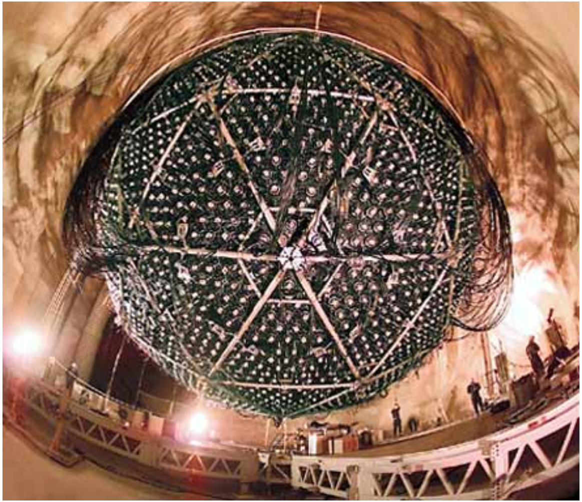
(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Recent Super-Kamiokande results



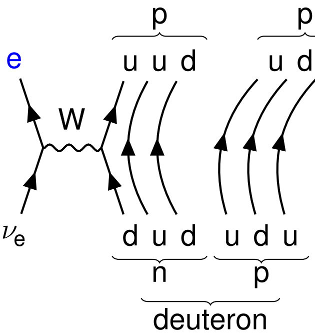
Sudbury Neutrino Observatory (SNO)

- Located at Sudbury mine located in Canada
- Acrylic vessel filled with D_2O surrounded by H_2O
- 9600 PMTs configures in a geodesic sphere
- Very low energy threshold of $\sim$1 MeV



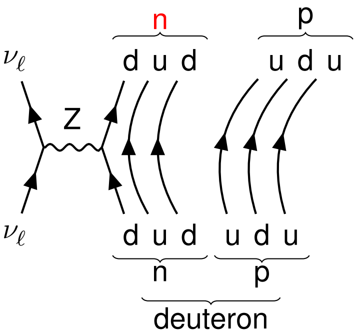
SNO: detecting neutrinos

CCQE reaction



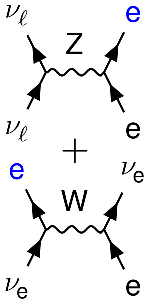
ν_e only

NC reaction



all ν

ES reaction



ν_e enhanced

- CCQE and ES: e can be seen via Cherenkov radiation
  - For ES: $\sigma_{\text{ES}}^{\nu_\mu} = \sigma_{\text{ES}}^{\nu_\tau} \approx 0.15\sigma_{\text{ES}}^{\nu_e} \Rightarrow \approx 7:1:1$ $(\nu_e : \nu_\mu : \nu_\tau)$ at detection
- NC: need to detect free n (different strategies implemented)

SNO: detecting neutrinos

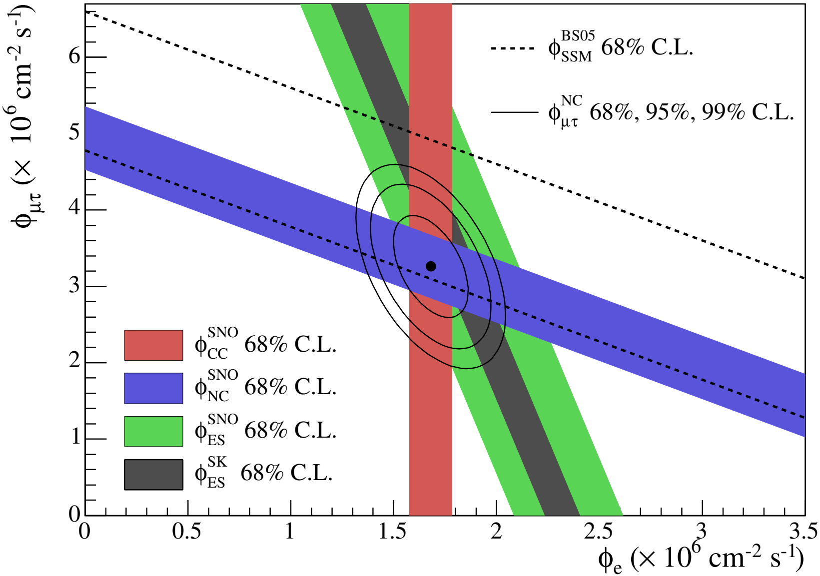
- Split up into three distinct phases:

1. Neutron captures on ^{2}H forming ^{3}H and causing a 6.25 MeV γ to be released
    - 14.4% efficiency in neutron capture
    - Ran from November 1999 through May 2001
2. 2 tonnes of NaCl added: $^{35}\mathrm{Cl} + \mathrm{n} \rightarrow {}^{36}\mathrm{Cl} + \gamma$
    - Increases efficiency up to 40% and releases a 8.6 MeV γ
    - Ran from July 2001 through September 2003
3. Proportional counters using Helium added: $^{3}\mathrm{He} + \mathrm{n} \rightarrow \mathrm{p} + {}^{3}\mathrm{H}$
    - 30% efficient with an entirely different technology to measure NC events
    - Ran from November 2004 through December 2006

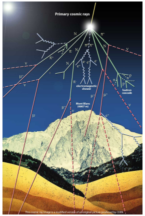
- All three phases could see CCQE and ES

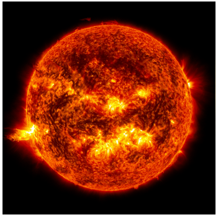
Discovery of Neutrino Oscillations: SNO

2015



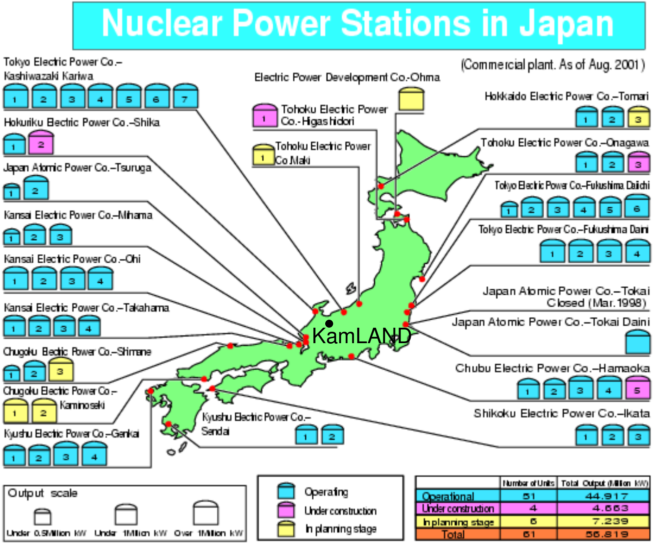
Studying Neutrino Oscillations: Neutrino Sources



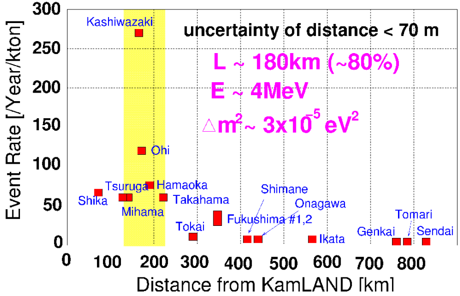


- We already discussed the two main natural sources to study ν oscillation:
  - Good: "free" abundant ν sources
  - Bad: can't adjust *L*, *E* or composition
  - Tricky: understanding ϕ emmitted essential
- But we can also produce our own ν!
  - Good: Control *L*, may also control *E* and composition
  - Bad: potentially "expensive" ν
  - Good and Bad: extra detectors useful to understand ϕ emmitted, but also expensive

Map of nuclear reactors “close” to Kamioka mine



	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	6	7.239
Total	61	56.819



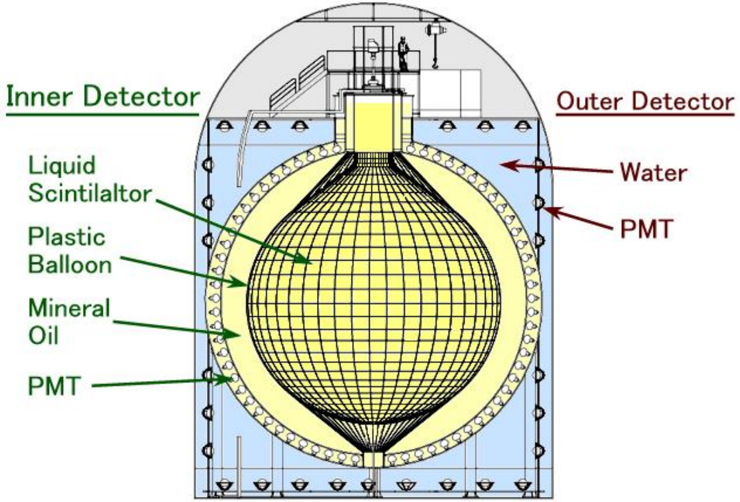
uncertainty of distance < 70 m

L ~ 180km (~80%)

E ~ 4MeV

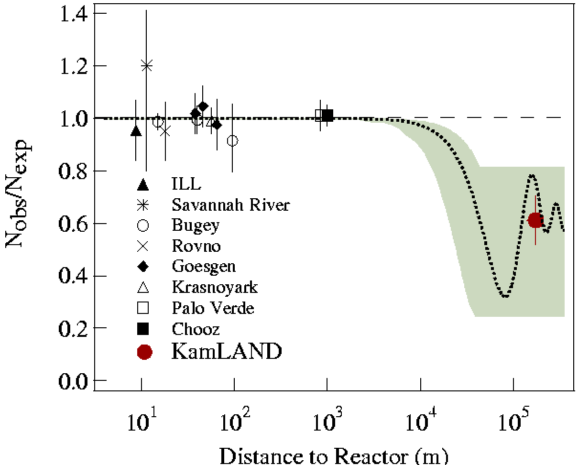
$\triangle m^2 \sim 3\times10^{-5}$ eV^2

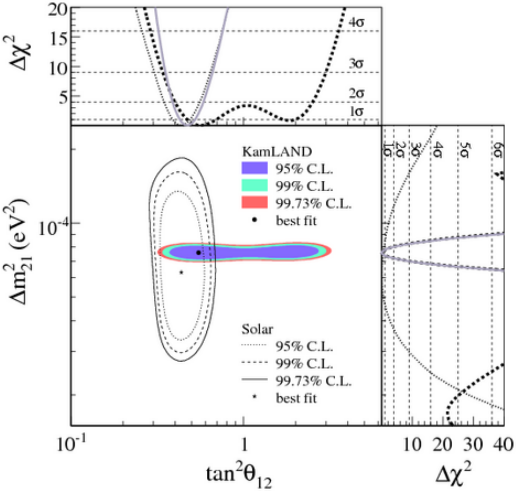
Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)



- Located in Kamioka mine, Japan
- ν target: liquid scintillator
- Measure $\bar{\nu}$ produced by nuclear reactor
- Many baselines (L), but well placed to study $\Delta m^2_\odot$ (Δm^2_{21})
- Very complementary to Solar experiments

KamLAND & Solar results





Search for θ_{13}

- θ_{13} roughly regulates $\nu_e \leftrightarrow \{\nu_\mu, \nu_\tau\}$ for short L
  - Atmospheric ν at good L/E, but ϕ is a 2:1 mix of ν_μ and ν_e
  - Solar flux is pure ν_e but 1–2 mixing dominant (same for KamLAND) [MSW/'wrong L']

- θ_{13} smallest of mixing angles
  - $\Rightarrow$ subdominant effect in first studies
  - need good understanding of ϕ
  - if $\theta_{13} = 0$, no possible CPV in lepton sector

- Need to design new series of experiments geared towards measuring it
  - Started data taking circa 2011
  - Currently best known mixing angle...

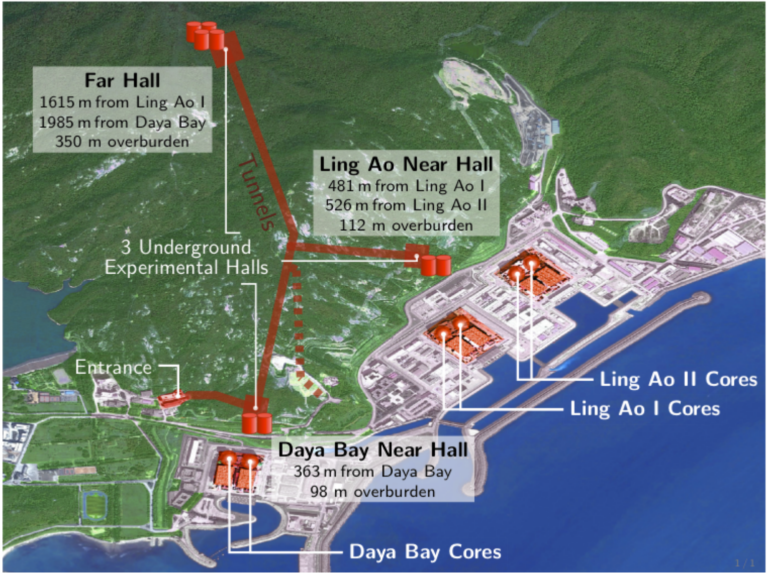
DayaBay, RENO, Double Chooz

- Reactor ν
- Measure $\overline{\nu}_e \to \overline{\nu}_e$
- "Only" sensitive to θ_{13}

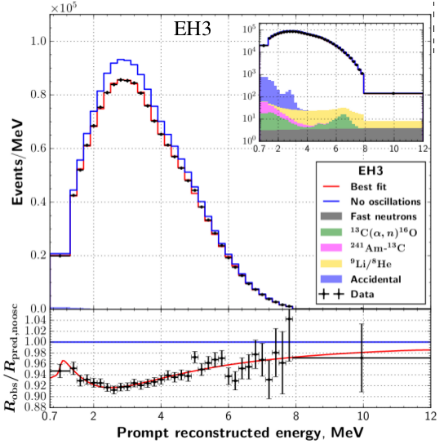
T2K, NOvA

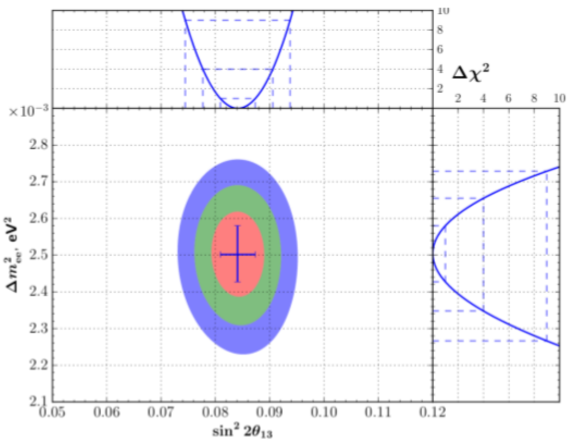
- Long Base Line (LBL) accelerator ν
- Measure $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \overline{\nu}_e$
- Sensitive jointly to θ_{13} and δ_{CP} (and NMO)

DayaBay: experiment layout

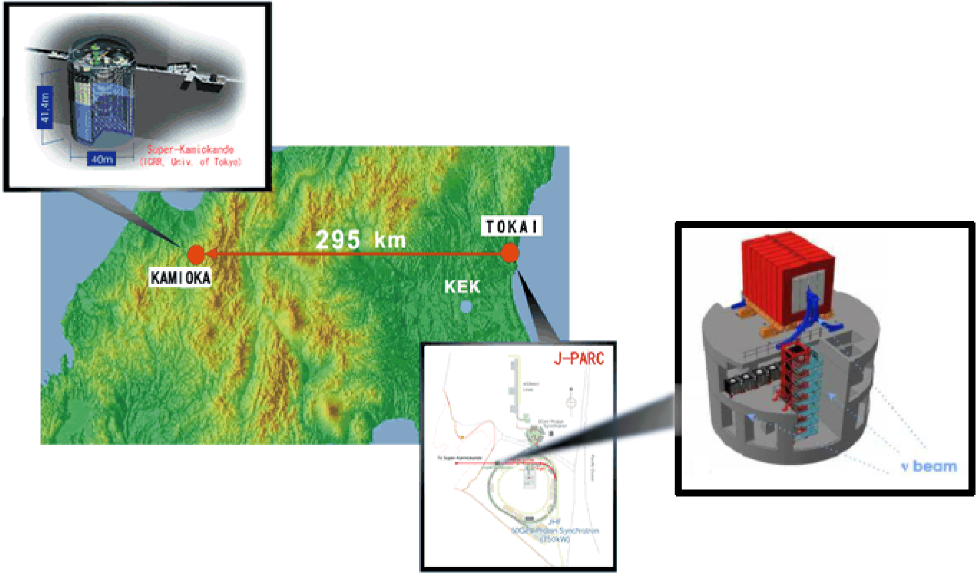


DayaBay


×10⁵
EH3
Events/MeV
1.0
0.8
0.6
0.4
0.2
0.0
EH3
Best fit
No oscillations
Fast neutrons
$^{13}C(\alpha,n)^{16}O$
^{241}Am-^{13}C
$^{9}Li/^{8}He$
Accidental
Data
10^0
10^1
10^2
10^3
10^4
10^5
0.7
2
4
6
8
10
12
$R_{obs}/R_{pred,noosc}$
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
Prompt reconstructed energy, MeV


$\Delta\chi^2$
10
8
6
4
2
×10⁻³
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
Δm^2_{ee}, eV²
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
$\sin^2 2\theta_{13}$

Tokai 2 Kamiokande (T2K): layout

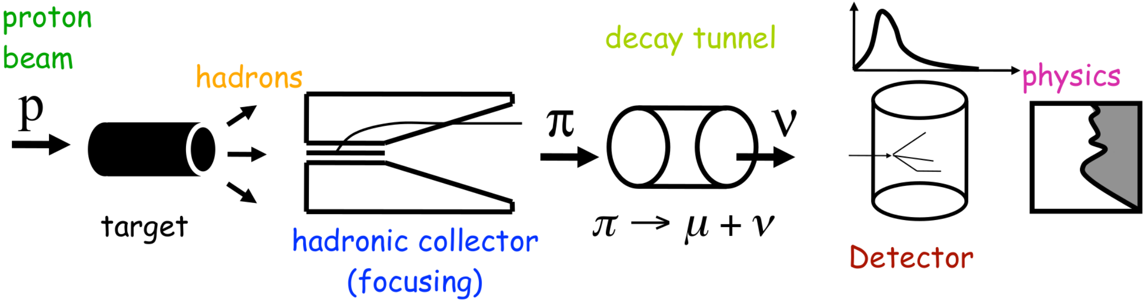


Neutrino Beams: how to make them?

- Problem: ν is neutral $\Rightarrow$ acceleration, energy selection techniques do not work

Neutrino Beams: how to make them?

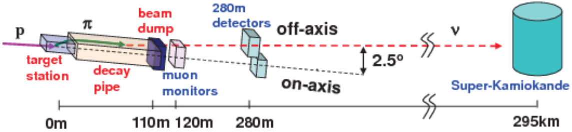
- Problem: ν is neutral $\Rightarrow$ acceleration, energy selection techniques do not work
- Solution: produce beams of charged particles that will decay into ν
  - unfortunately cannot make mono-energetic ν beams. . . (off-axis technique helps)

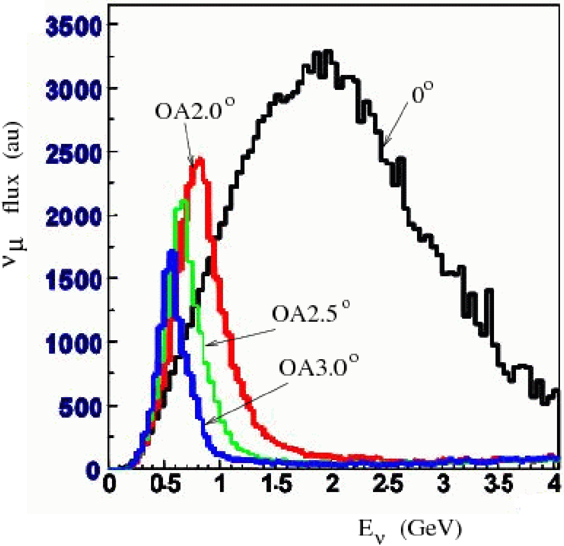


- Other ‘options’: Neutrino factory (μ storage ring), Beta beams
  - Not yet realised

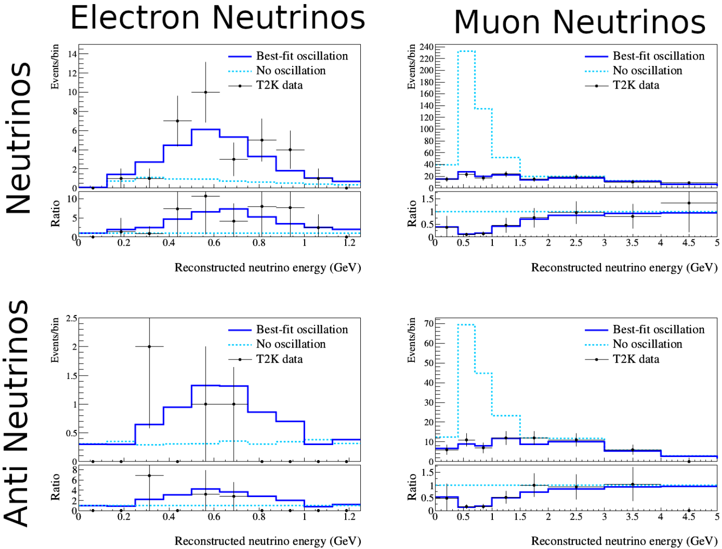
The T2K Neutrino Beam

- “Traditional” ν beam:
  - $\sim$99 % ν_μ
  - Hadronic Collector ‘selects’ $\nu/\bar{\nu}$ beam
- “Off-axis” beam:
  - lower overall ϕ
  - smaller E spread
  - At “max E”, higher ϕ than for “on-axis”





T2K: CCQE-like data distribution



arXiv:1707.01048

T2K: results

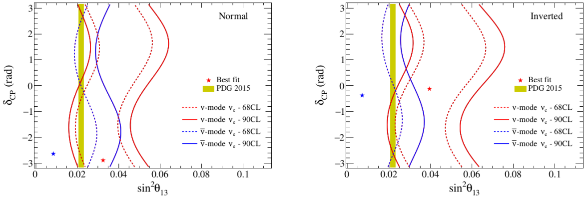
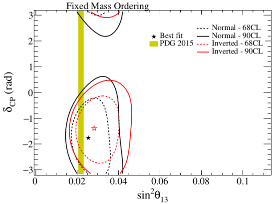


FIG. 39. Contours in the $\sin^2\theta_{13}$–δ_{CP} plane using T2K-only data, obtained by analysing either the ν- or $\bar{\nu}$-mode appearance datasets are compared for both orderings. Both ν- and $\bar{\nu}$-mode disappearance datasets were used in all fits. The yellow band corresponds to the reactor value on $\sin^2\theta_{13}$ from the PDG 2015 [75].



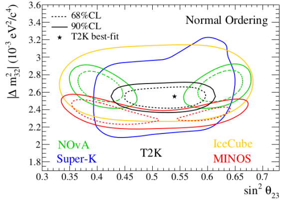


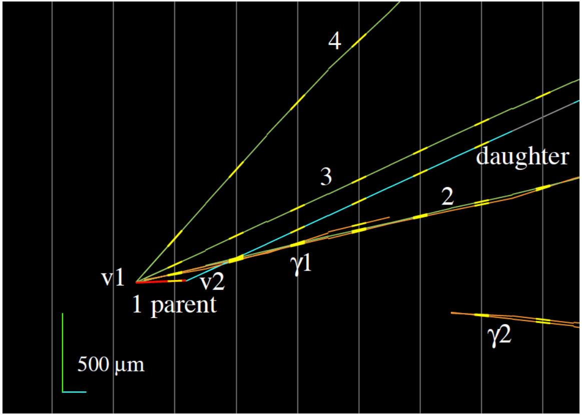
FIG. 37. Two-dimensional constant $\Delta\chi^2$ contours for oscillation parameters δ_{CP} and $\sin^2\theta_{13}$ using T2K data only. The yellow band corresponds to the reactor value on $\sin^2\theta_{13}$ from the PDG 2015 [75].

FIG. 40. Allowed region at 90% confidence level for oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{32} using T2K data with the reactor constraint ($\sin^2(2\theta_{13}) = 0.085 \pm 0.005$). The normal mass ordering is assumed and the T2K results are compared with NOνA [86], MINOS [87], Super-K [88], and IceCube [89].

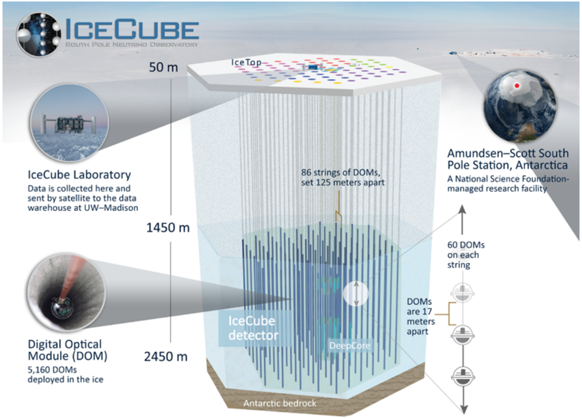
arXiv:1707.01048

Old/Other Neutrino Oscillation Experiments (not complete list)

OPERA – ν_τ appearance



IceCube/DeepCore – $\theta_{23}, \Delta m^2_{32}$

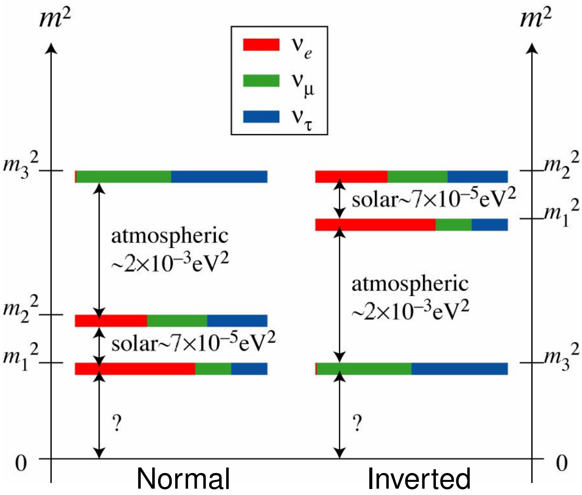


regular osc.: NOνA, MINOS, RENO, Double Chooz, Borexino, Antares

sterile osc.: MINOS+, MiniBOONE, μBOONE, DANSS, NEOS, Prospect, Stereo, SOLID

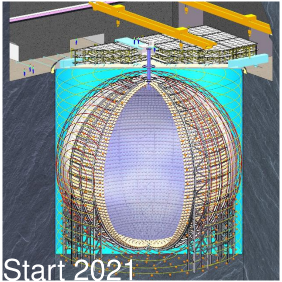
What we do not know at this point…

- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
- $P(\nu_\alpha \to \nu_\beta) \overset{?}{=} P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
- Mixing Matrix U is Unitary?
- Are there Sterile ν?
- ν Majorana or Dirac Particle
- Can ν explain Matter/AntiMatter asymmetrie?



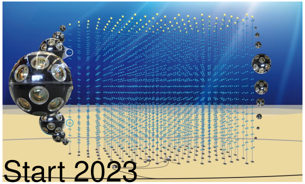
Future Neutrino Oscillation Experiments (not complete list)

JUNO – NMO



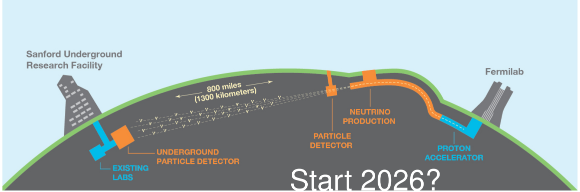
Start 2021

ORCA, PINGU – NMO

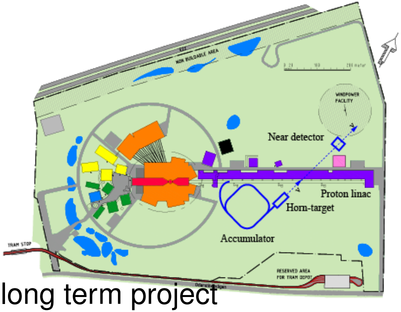


Start 2023

DUNE, T2HK, ESSνSB – δ_{CP} (+NMO)



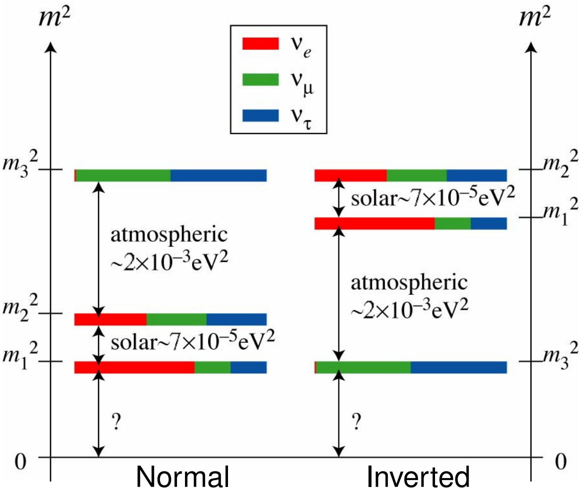
Start 2026?



long term project

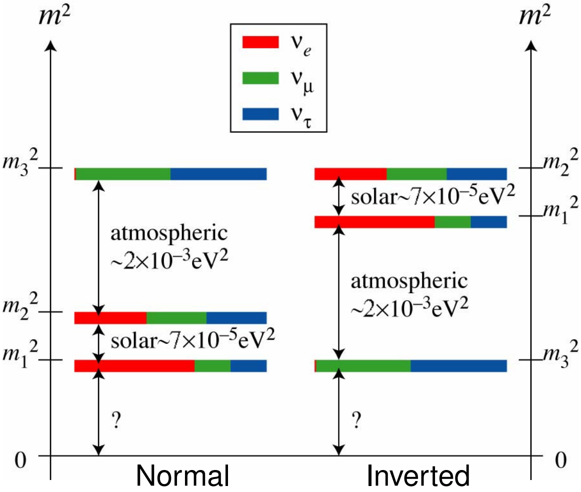
What we do not know at this point…

- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
  $\Rightarrow$ Km3Net/ORCA, JUNO
- $P(\nu_\alpha \to \nu_\beta) \overset{?}{=} P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
  $\Rightarrow$ LBL accelerator future projects
- Mixing Matrix U is Unitary?
- Are there Sterile ν?
- ν Majorana or Dirac Particle
  $\Rightarrow$ SuperNemo
- Can ν explain Matter/AntiMatter asymmetrie?



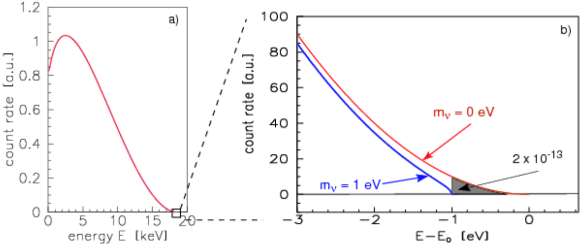
What we do not know at this point. . .

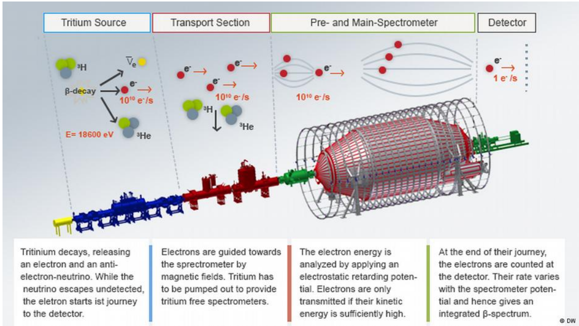
- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
- $P(\nu_\alpha \to \nu_\beta) \overset{?}{=} P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
- Mixing Matrix U is Unitary?
- Are there Sterile ν?
- ν Majorana or Dirac Particle
- Can ν explain Matter/AntiMatter asymmetrie?



Absolute Neutrino Mass: Direct Measurement

- $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathsf{e} + \overline{\nu}_\mathsf{e}$
  - Well know β-transition energy
  - Measures $m_\beta = \sqrt{\sum_i |U_{ei}|^2}$
- Current limits: $m_\beta < 2$ eV
- Future/Current Projects:
  - KATRIN:
    - ★ Mac-E filter spectrometer
    - ★ Started this year
    - ★ Sensitivity: 0.2 eV
  - Project 8:
    - ★ Single Electron Cyclotron Radiation
    - ★ towards using atomic tritium
    - ★ now: demonstrating technology
    - ★ Sensitivity: 40 meV





Tritinium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the eletron starts ist journey to the detector.

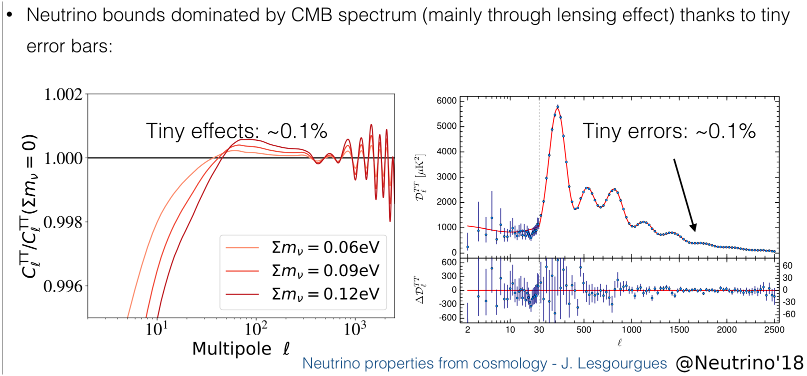
Electrons are guided towards the sprectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Absolute Neutrino Mass: Cosmology

- ν play a role in structure formation in the universe
  - some model dependency in results
    - ★ or we are really getting cosmology wrong. . . and getting good fits while at it
  - Measures $\sum m_\nu$ (and N_ν^{eff})
- Current limits: $\sum m_\nu < 250 - 600$ meV

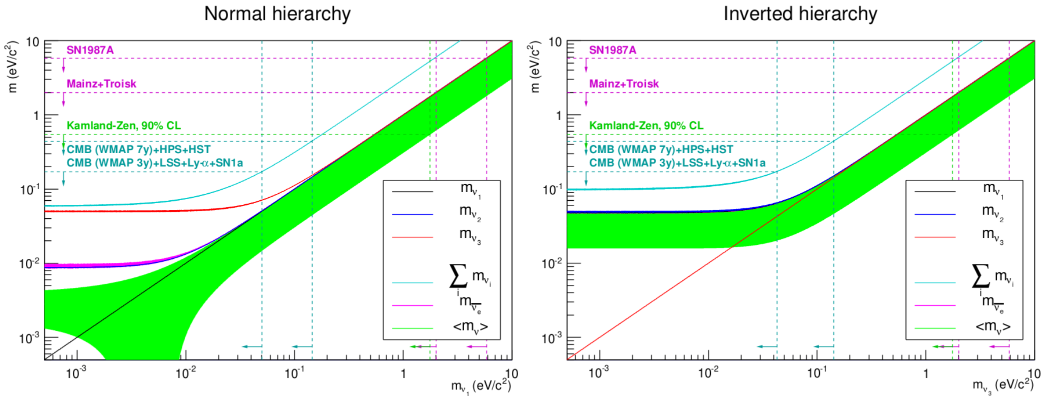


- Neutrino bounds dominated by CMB spectrum (mainly through lensing effect) thanks to tiny error bars:

Neutrino properties from cosmology - J. Lesgourgues @Neutrino'18

Absolute Neutrino Mass

- Other techniques:
  - SN ν time of flight $\rightarrow m_{\nu_e} < 5.8$ eV [SN 1987A]
  - $2\beta0\nu$ decay (if Majorana ν) $\rightarrow m_{\beta\beta} = |\sum U_{1j}^2 m_{\nu_j}| < 61 - 165$ meV
  - Ho decay ($m_{\nu_e} \neq m_{\overline{\nu}_e}$?) $\rightarrow m_{\nu_e} < 225$ eV
- Comparing them all (limits from 2012):



What we do not know at this point. . .

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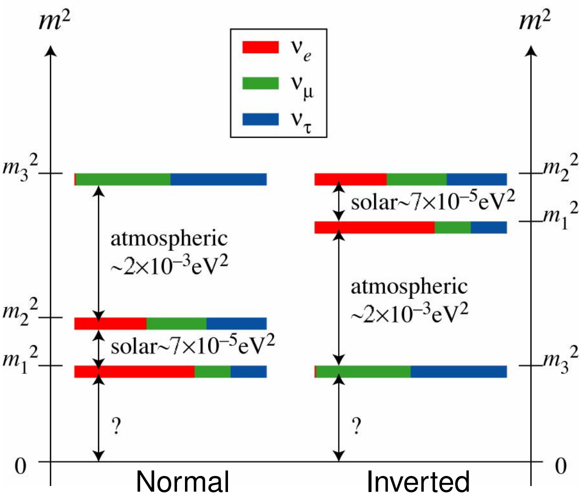
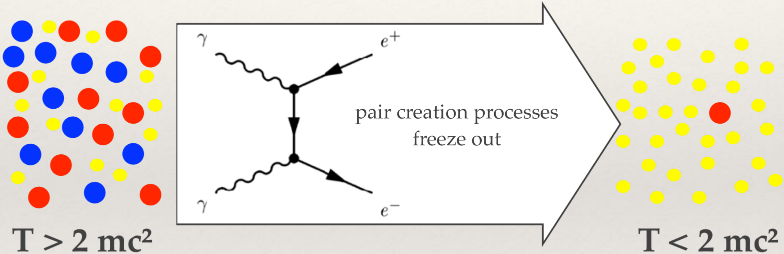


Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons. e.g. Canetti/MaD/Shaposhnikov arXiv:1204.4186



pair creation processes freeze out

$T > 2\ mc^2$

$T < 2\ mc^2$

CMB constraint on baryon-to-photon ratio η:
$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$
(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$
(PDG)

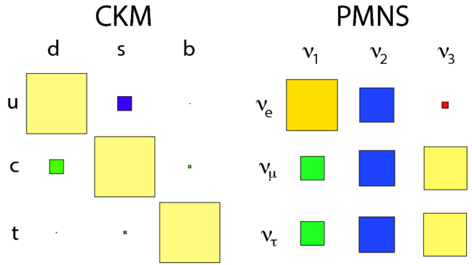
M. Drewes @ Neutrino'18

How to produce Baryon Asymmetry?

Sakharov Conditions (1967):

- Baryon number violation
  - ie, can have a reaction that produces f and not $\bar{f}$
- C and CP violation
  - ie, f and $\bar{f}$ don't behave alike
  - exists on quark sector, but too small → tied to ν δ_{CP}?
- Deviation from thermal equilibrium
  - ie, processes non reversible
  - can get this from expansion of the universe

ν and the Baryon Asymmetry



- Quark & Neutrino sectors very different
  - PMNS $J_{CP} = 0.033 \sin \delta_{CP}$; CKM $J_{CP} \approx 3 \cdot 10^{-5}$
  - PMNS J_{CP} could explain observedy asymmetry (in some models) if $|\sin \delta_{CP}| > 0.7$
- ν induced Baryon Asymmetry $\rightarrow$ Leptogenesis
  - Many different theories, with different requirements
  - Dirac vs Majorana. . . SeeSaw usually base for these theories
  - In any case, large $|\sin \delta_{CP}|$ in ν good indicator of large CP violation in ν also
- At this point, need more data (discoveries)!

What we do not know at this point…

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- Neutrino Mass Ordering
- $P(\nu_\alpha \to \nu_\beta) \overset{?}{=} P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
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