Neutrino Group

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IPHC, Strasbourg

17 October 2018

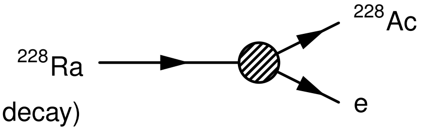
Outlook

- Neutrino History and Properties
- Using Neutrinos as a Probe of the Universe
- Neutrino Oscillations
- Neutrinos @ IPHC

The birth of the neutrino: measuring the β spectra

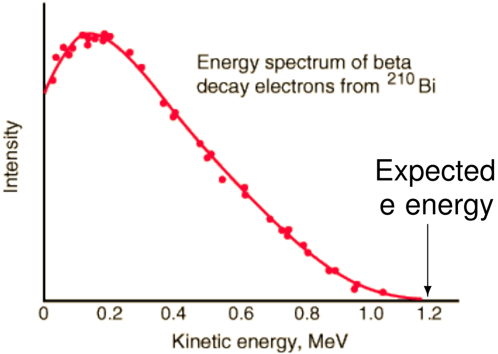
1896 Becquerel discovery of radiation

- β decay: e emission



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

1914 Chadwick observed continuous electron spectra from β-decay



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

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

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

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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.

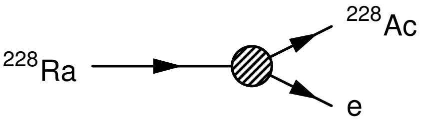
Your humble servant,

W. Pauli

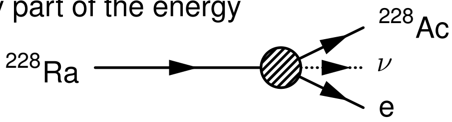
[translation to english: `http://www.pp.rhul.ac.uk/~ptd/TEACHING/PH2510/pauli-letter.html`]

The birth of the neutrino: quick (theoretical) acceptance

1896 Becquerel's β decay: e emission



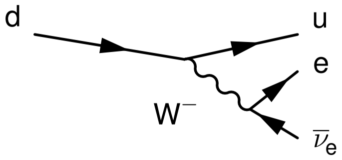
1930 Pauli's β decay: invisible ν emitted carries away part of the energy



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 1995

1956 Reines and Cowan detected ν from Savannah River reactors

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

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

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

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

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

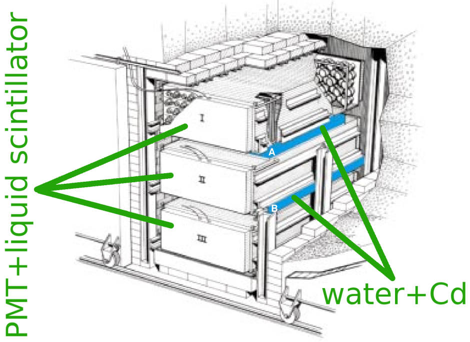


Figure 4. The Savannah River Neutrino Detector—A New Design
The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. The protons in the water provided the target for inverse 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.

Los Alamos Science Number 25 1997

Neutrino properties

1962 Lederman, Schwartz, Steinberger discover ν_μ ( 1988)

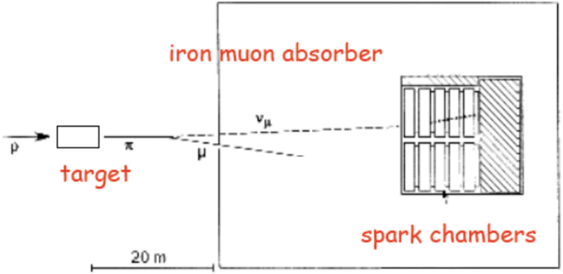
- there is more than one type of ν!

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

neutrino detection

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

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



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

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

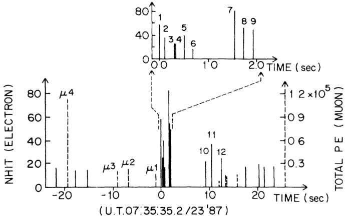


FIG. 9. The time sequence of events in a 45-sec interval centered on 7:35:35 UT 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT, $N_{\rm hit}$ (left-hand scale). Dashed lines 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.

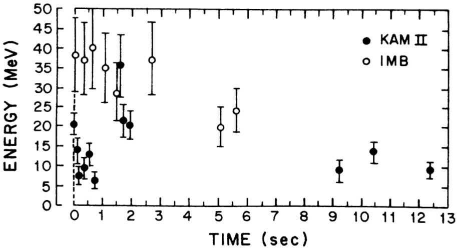


FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t=0$.

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

2013 Detection of astrophysical ν: IceCube

Verifying the Standard Solar Model with Neutrinos

- 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

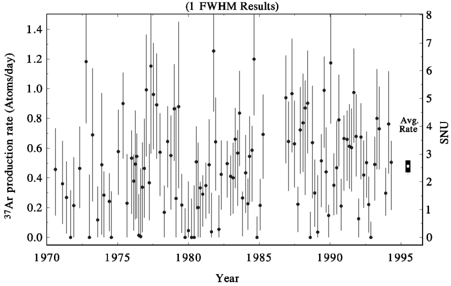
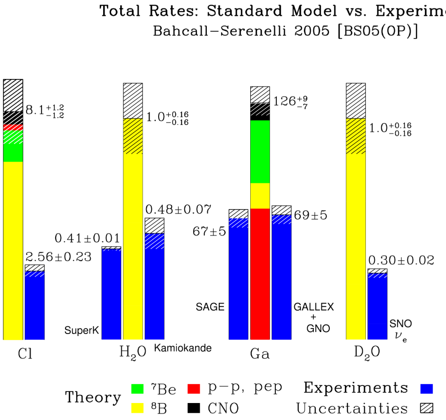
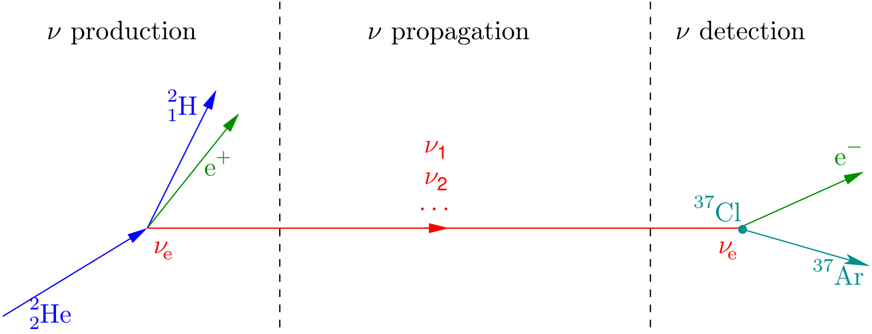


FIG. 13.—Homestake Experiment—one FWHM results. Results for 108 individual solar neutrino observations made with the Homestake chlorine detector. The production rate of ^{37}Ar shown has already had all known sources of nonsolar ^{37}Ar production subtracted from it. The errors shown for individual measurements 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)



Neutrino Oscillation (in vacuum) – overview



$|\nu_e\rangle = \sum_j U^*_{ej} |\nu_j\rangle$ $\quad$ $|\nu_j\rangle \rightarrow e^{-iE_j t} |\nu_j\rangle$ $\quad$ $|\nu_j\rangle = \sum_\alpha U_{\alpha j} |\nu_\alpha\rangle$

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

- For oscillations to happen $\{|\nu_\alpha\rangle\}$ and $\{|\nu_j\rangle\}$ different $\Rightarrow$ ν has non zero mass

Neutrino Oscillations – simplest case

2 flavor case, vacuum

- 2 ν interaction flavours (ν_e and ν_μ)
- mass eigenstates $\{|\nu_j\rangle\} = \{|\nu_1\rangle, |\nu_2\rangle\} \neq \{|\nu_\alpha\rangle\} = \{|\nu_e\rangle, |\nu_\mu\rangle\}$ 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 $\nu_\tau \Rightarrow$ matrix U is 3×3

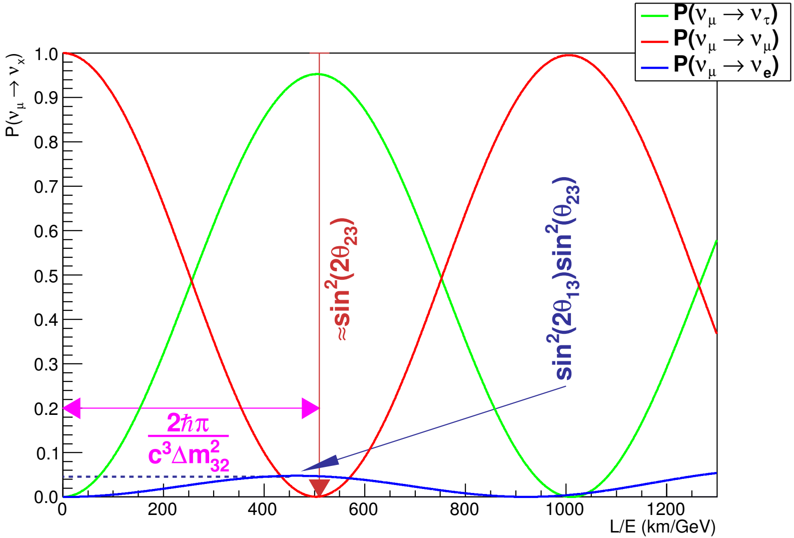
$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{“atmospheric sector”}} \times \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{“reactor sector”}}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

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

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

Neutrino Oscillations

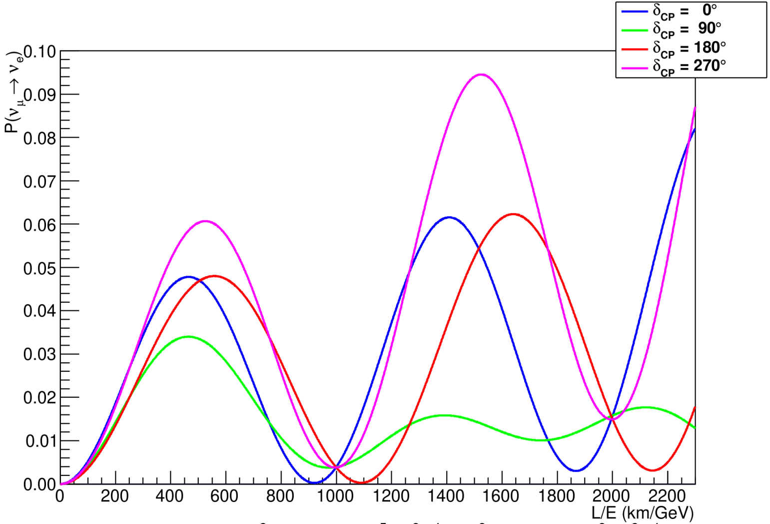
3 flavor case, vacuum



$\theta_{12} = 34^\circ$, $\theta_{13} = 8.8^\circ$, $\theta_{23} = 45^\circ$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ 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



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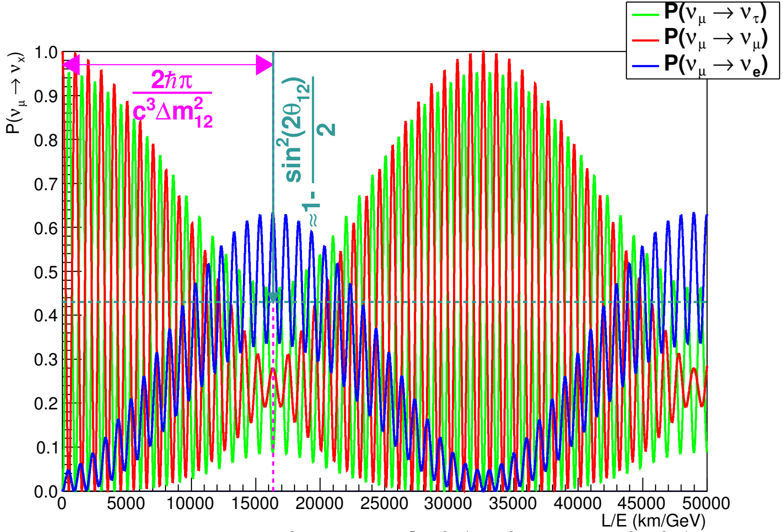
Neutrino Oscillations

3 flavor case, vacuum



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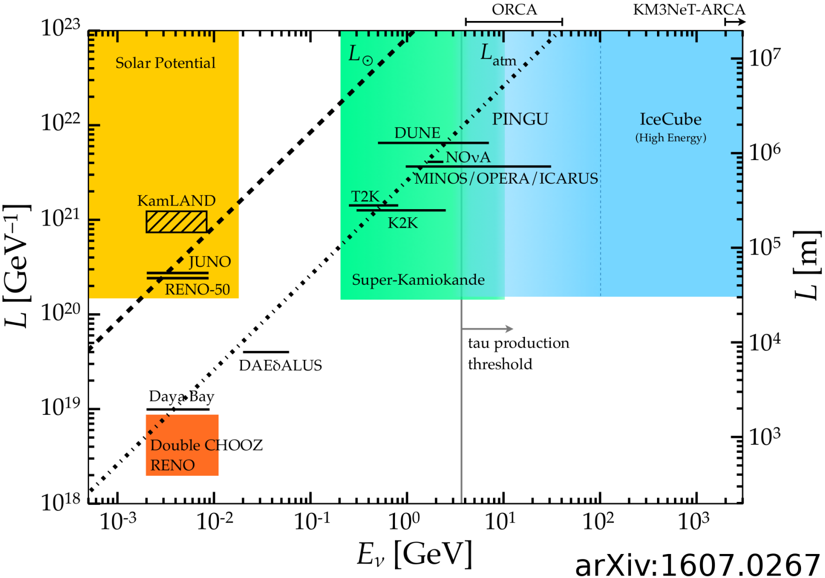
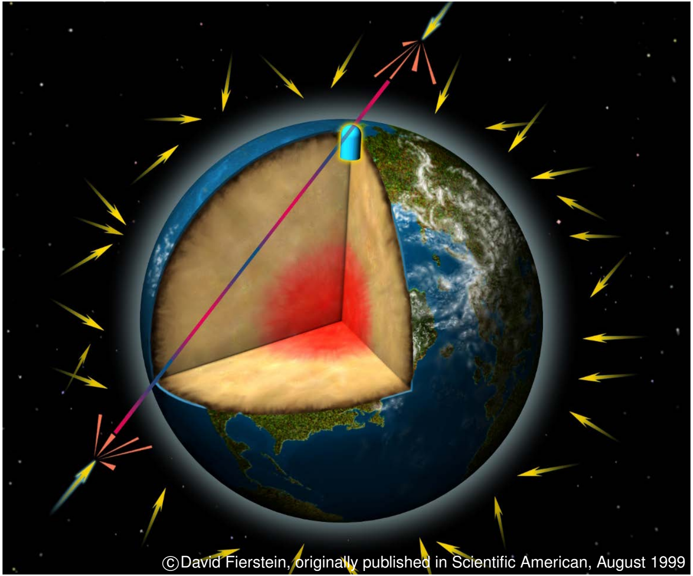
Experimental Overview

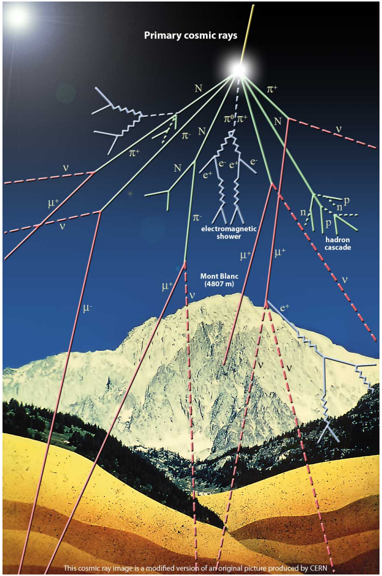


arXiv:1607.02671

Atmospheric Neutrinos

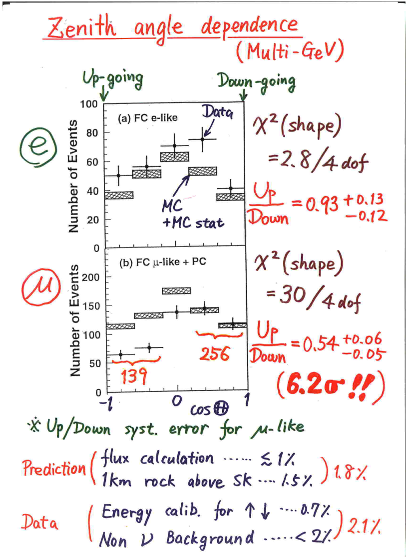


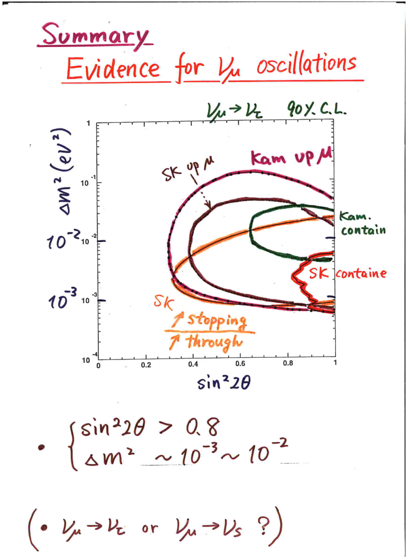
©David Fierstein, originally published in Scientific American, August 1999



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

Discovery of Neutrino Oscillations: Super-Kamiokande 2015

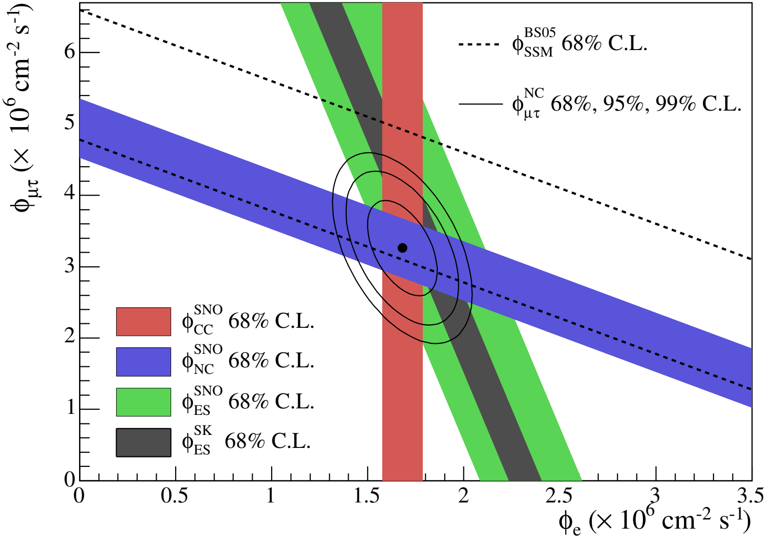




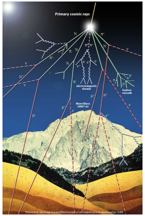
Discovery of Neutrino Oscillations: SNO

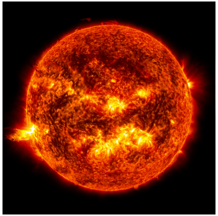
2015

...also solves Solar Neutrino Problem!



Studying Neutrino Oscillations: Neutrino Sources

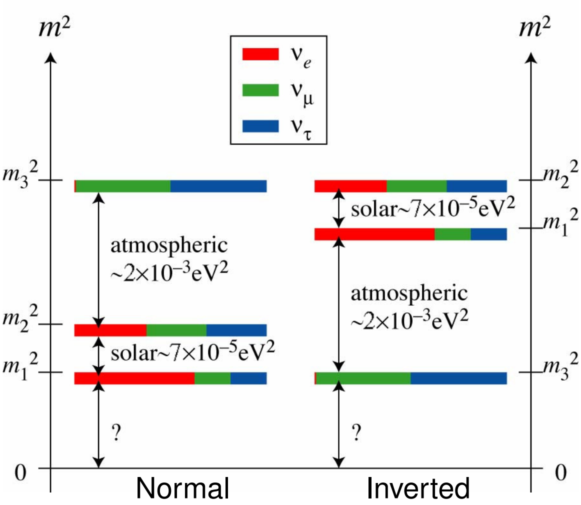




- We already discussed the two main natural sources to study ν oscillation:
  - Good: “free” abundant ν sources
  - Bad: can’t adjust *L*, *E* or composition
  - Tricky: understanding ϕ emmitted essential
- But we can also produce our own ν!
  - Good: Control *L*, may also control *E* and composition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

What we do not know at this point…

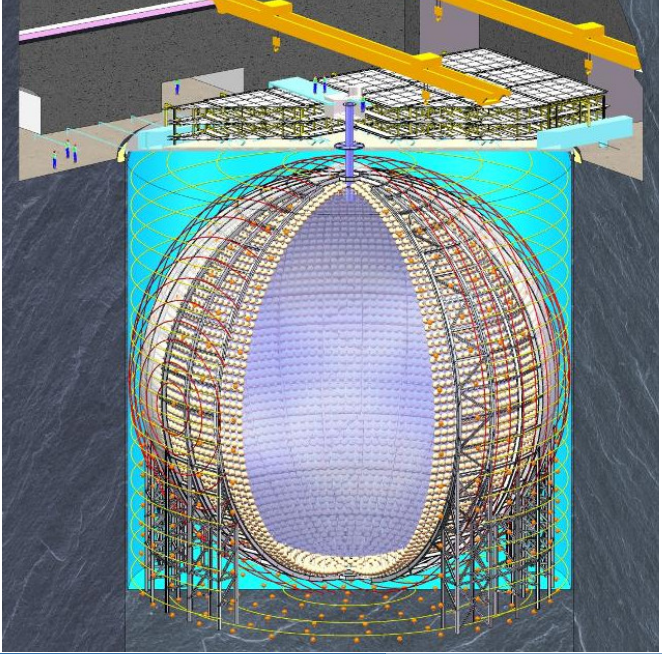
- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
  $\Rightarrow$ JUNO
- $P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$
  $\Rightarrow$ ESSνSB
- Mixing Matrix U is Unitary?
- Are there Sterile ν?
- ν Majorana or Dirac Particle
- Can ν explain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



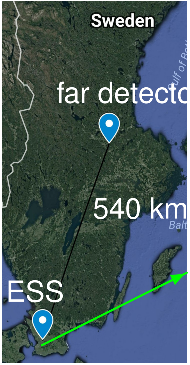
Neutrinos @ IPHC

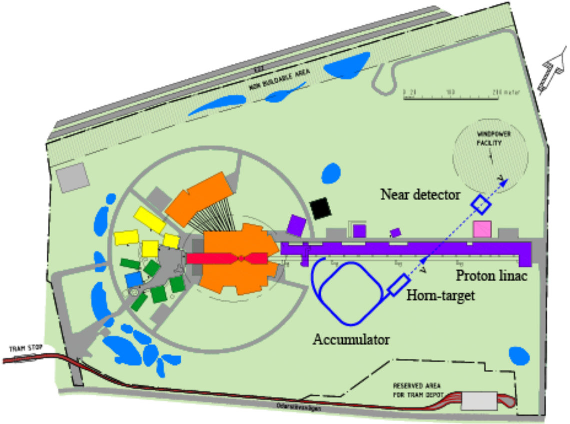
NMO ⟶ JUNO : reactor + solar + ...

CP-violation ⟶ essνsb : accelerator + ...



- Located in China
- 20 kton ν target mass
- built to detect ν from nuclear reactors
- excellent energy resolution
- observe fast oscillations
  - first time to observe Δm^2_{32} and Δm^2_{21} together
- main goal: NMO
- Construction end: 2021





- Located in Sweden
- Upgrade ESS facility to produce ν beam
- $\mathcal{O}$(1 Mton) far detector
- Started design this year

- Main goal: measure CP violation
- Optimally placed at 2^{nd} oscillation maxima
  - better for CPV, worse for NMO

Stage & Thèses

- TIPP: likely will propose a project
- Stage M2: will propose one internship
  - we have already been contacted by Julie
  - if others interested let us know, we could consider a second subject
- Thèse: will propose a ESSνSB subject
- Contact me for more info (jpandre@iphc.cnrs.fr).