The elusive neutrino

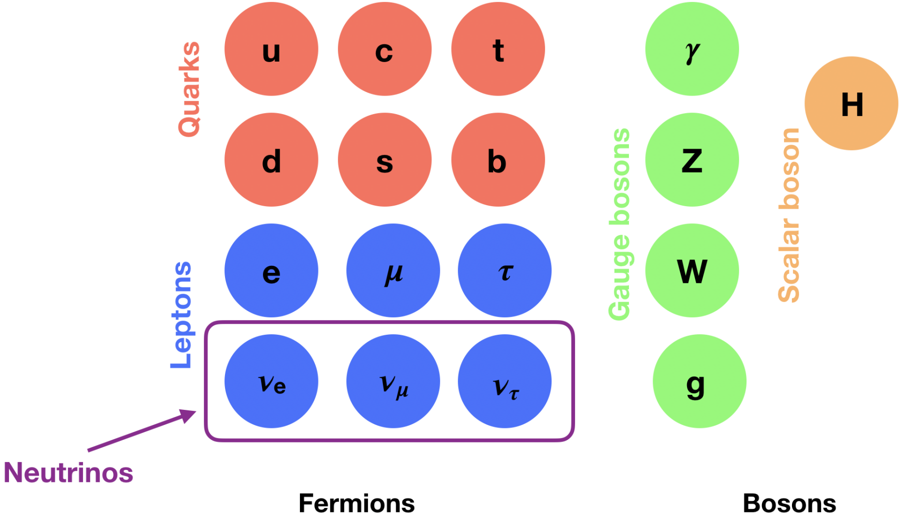
Julia Gehrlein

Brookhaven National Laboratory

BNL Physics Department Summer Lecture series

22. June 2021

Introduction: Neutrinos



Introduction: Neutrinos

- second most abundant particle in the Universe:

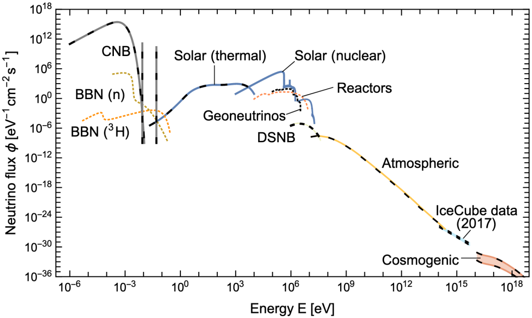
  a billion times more neutrinos than matter particles in the Universe

- 10^{38} neutrinos per second produced by the Sun

  (flux of $\sim\ 10^{11}/\text{cm}^2/\text{sec}$ at the Earth)

  65 billion solar neutrinos travel through your thumb nail per second

Introduction: Neutrinos



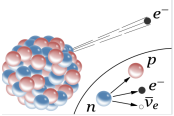
[Vitagliano, Tamborra, Raffelt ’19]

- neutrino energies span 24 orders of magnitude
- different neutrino sources and production mechanisms
- lots of room for exciting neutrino physics & lots to learn!

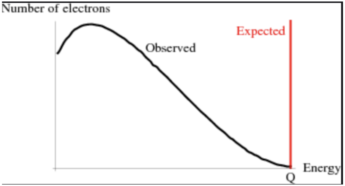
How did we get there?

Neutrino history

- before 1930:
  problem of continuous beta decay spectrum
  beta decay: nuclear transition $(A, Z) \to (A, Z+1)$ with electron emission

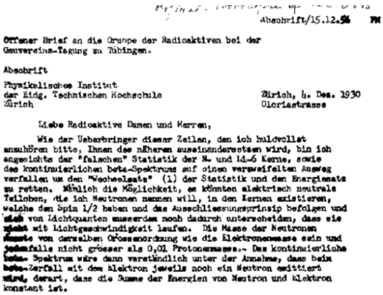


  from energy and momentum conservation $\to$ expected fixed kinetic energy of electron!



Neutrino history

- Dec 1930: Pauli proposed a new particle "neutron"



Abschrift/15.12.56

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

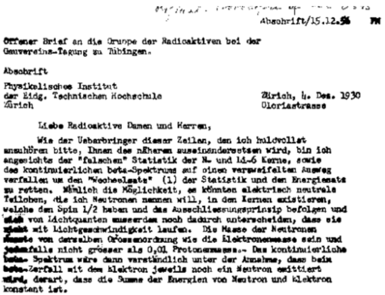
Liebe Radioaktive Damen und Herren,

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.

"Dear radioactive ladies and gentlemen,...I have hit upon a desperate remedy to save the ... energy theorem. Namely the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 ... The mass of the neutron must be ... not larger than 0.01 proton mass. ...in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant."

Neutrino history

- Dec 1930: Pauli proposed a new particle "neutron"



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 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.

"Dear radioactive ladies and gentlemen,...I have hit upon a desperate remedy to save the ... energy theorem. Namely the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 ... The mass of the neutron must be ... **not larger than 0.01 proton mass.** ...in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant."

Q: How did Pauli know the upper limit on the "neutron" mass?

Neutrino history

- 1932: Chadwick discovers the neutron:

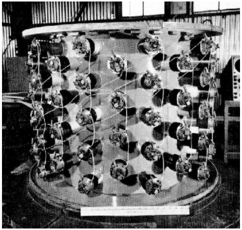
  $m_{neutron} = 1.0014 \times m_{proton} \rightarrow$ too heavy $\rightarrow$ not Pauli's particle

- 1933: Enrico Fermi popularized the name "neutrino" (little neutron)

$\rightarrow$ neutrino was born!

Neutrino history

- 1956: first detection of neutrinos by Reines and Cowan
- neutrino discovery using inverse beta decay $\overline{\nu_e} + p \rightarrow n + e^+$
- cross section is small $\sigma \sim 10^{-43}\text{cm}^2$ (mean free path of neutrino in lead would be 1.6 light-years=10^5 Earth-Sun distance) $\rightarrow$ use extreme measures to detect neutrinos
  - big detector (400 l) filled with water with $CdCl_2$ in solution

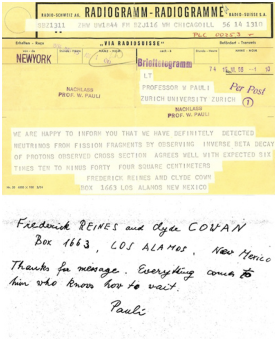


Neutrino history

- 1956: first detection of neutrinos by Reines and Cowan
- neutrino discovery using inverse beta decay $\overline{\nu_e} + p \rightarrow n + e^+$
- cross section is small $\sigma \sim 10^{-43}\text{cm}^2$ (mean free path of neutrino in lead would be 1.6 light-years=10^5 Earth-Sun distance) $\rightarrow$ use extreme measures to detect neutrinos
  - big detector (400 l) filled with water with $CdCl_2$ in solution
  - large flux $\rightarrow$ nuclear reactor with $10^{13}\nu/\text{sec}/\text{cm}^2$

Neutrino history

- 1956: first detection of neutrinos by Reines and Cowan
- neutrino discovery using inverse beta decay $\overline{\nu_e} + p \rightarrow n + e^+$
- use detectors filled with water with $\mathrm{CdCl_2}$ in solution near nuclear reactor with flux $10^{13} \nu/sec/\mathrm{cm}^2$
- electron neutrinos discovered!



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

74 15.VI.56 --1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN

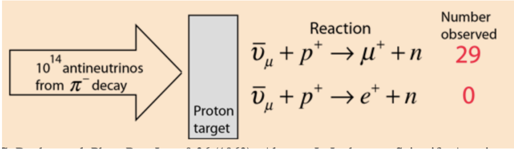
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

Neutrino history

- 1962: L. Lederman, M. Schwartz, J. Steinberger discover second type of neutrino (at BNL): muon neutrino



- detect neutrino flavor by detecting corresponding charged lepton

- third type of neutrino (tau neutrino) discovered by DONUT in 2000

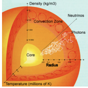
Neutrino history

Knowledge at the time ($\sim$ 1965)

- neutrinos exist!
- have very small cross sections
- no evidence for neutrino mass $\rightarrow$ symmetry in SM that lepton flavor is conserved (every neutrino flavor produced arrives as the same neutrino flavor)
- formulation of Standard Model in early 70's with massless neutrinos

Solar neutrino problem

- late 1960's: R. Davis (BNL) built experiment to detect solar neutrinos

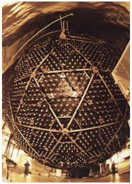


- 380 m^3 (100,000 gallon) tank of perchloroethylene, a common dry-cleaning fluid, 1478 meters underground in Homestake Mine
- neutrino capture $\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$, collect Ar to obtain solar neutrino flux
- compare observation to theoretical solar models by J. Bahcall

$$\nu_e^{exp}/\nu_e^{theo} \approx 1/3 \Rightarrow \text{solar neutrino problem}$$

Solar neutrino problem

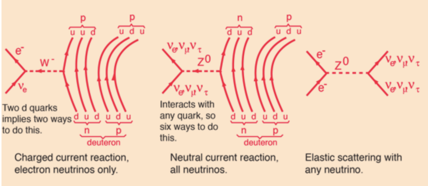
- solar neutrino problem persisted until SNO provided a solution in 2001
- SNO: 1 kT heavy water, 2 km underground in Sudbury mine, Ontario



- three possible neutrino detection mechanisms
  - CC: $\nu_e + d \to e^- + p + p \to$ only sensitive to ν_e ("neutrino in-charged lepton out")
  - NC: $\nu_x + d \to p + n + \nu_x$, $x = e, \mu, \tau \to$ sensitive to all flavors ("neutrino in-neutrino out")
  - ES: $\nu_x + e^- \to e^- + \nu_x \to$ much weaker than CC, NC processes, mostly sensitive to ν_e

Solar neutrino problem

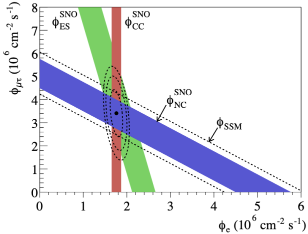
- solar neutrino problem persisted until SNO provided a solution in 2001



- measurement (in units $10^6\ \nu/\text{cm}^2/\text{s}$)

$$\phi_e = 1.76^{+0.05}_{-0.05}(stat)^{+0.09}_{-0.09}(syst)$$

$$\phi_{\mu,\tau} = 3.41^{+0.45}_{-0.45}(stat)^{+0.48}_{-0.44}(syst)$$

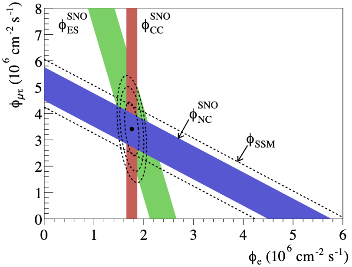


[SNO, 2002]

Solar neutrino problem

- solar neutrino problem persisted until SNO provided a solution in 2001
- measurement (in units $10^6\ \nu/\mathrm{cm}^2/\mathrm{s}$)

$$\phi_e = 1.76^{+0.05}_{0.05}(stat)^{+0.09}_{-0.09}(syst)$$
$$\phi_{\mu,\tau} = 3.41^{+0.45}_{0.45}(stat)^{+0.48}_{-0.44}(syst)$$

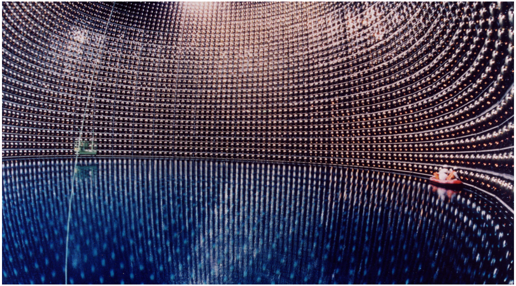


[SNO, 2002]

- all neutrinos from the Sun arrive but not all of them are ν_e!
- two thirds of electron neutrinos produced in Sun transformed into other flavor before reaching the detector

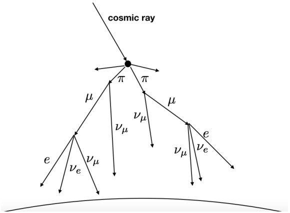
Atmospheric neutrino deficit

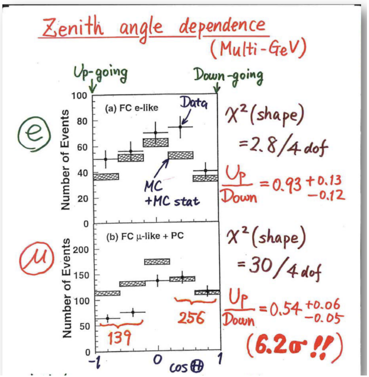
- 1998: SuperKamiokande (originally proton decay experiment) detected atmospheric neutrinos deficit
- SuperKamiokande: 50 kt water,1km underground, Mozumi mine, Japan



Atmospheric neutrino deficit

- 1998: SuperKamiokande detected atmospheric neutrinos deficit





- SuperKamiokande sensitive to ν_e, ν_μ
  $\rightarrow$ found deficit of upward going (Earth traversing) ν_μ

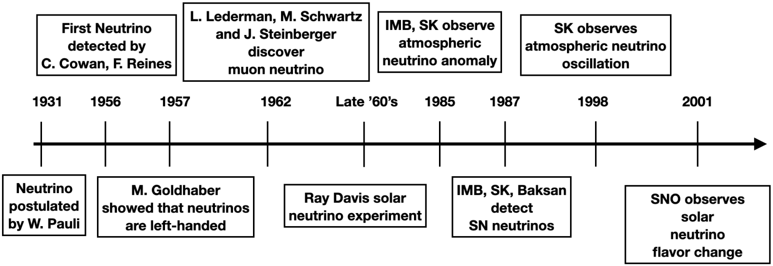
Atmospheric neutrino deficit

- solution: produced muon neutrinos have transformed into a different flavor

$\Rightarrow$ Neutrino oscillations

Neutrino history

- observation of neutrinos and more recently neutrino oscillations opened whole field of investigation and led to millions of dollars investments!

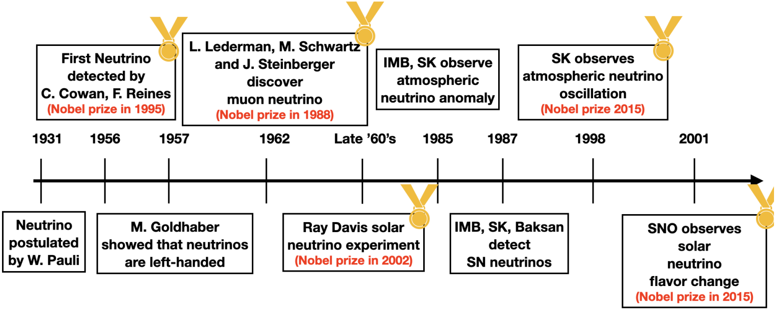


many more important experimental and theoretical steps in neutrino physics in between

Q: How many Nobel prizes have been awarded so far in the field of neutrino physics?

Neutrino history

- observation of neutrinos and more recently neutrino oscillations opened whole field of investigation and led to millions of dollars investments!



many more important experimental and theoretical steps in neutrino physics in between

Surprising phenomenon: Neutrino oscillations

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

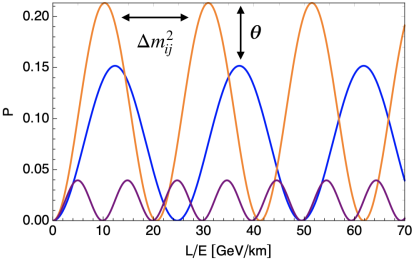
Neutrino oscillations

produce neutrino of flavor α with energy E

probability to detect neutrino with flavor β at distance L is

in the 2-flavor approximation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \quad \Delta m_{ij}^2 = m_i^2 - m_j^2$$



Q: What happens if neutrinos are massless?

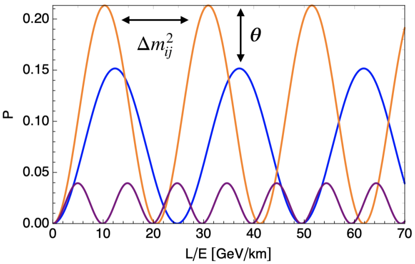
Neutrino oscillations

produce neutrino of flavor α with energy E

probability to detect neutrino with flavor β at distance L is

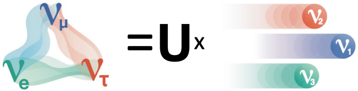
in the 2-flavor approximation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$



happens only for massive neutrinos $\rightarrow$ SM is incomplete!

Neutrino oscillations



flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos

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

U_{PMNS}: relates flavor and mass states

parametrized by 4 parameters (3 angles, 1 phase)

Neutrino oscillations

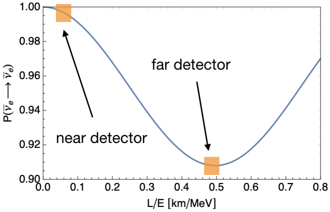
observation of neutrino oscillations introduced at least 6 new parameters to the Standard Model:

3 mixing angles, one CP violating phase, 2 mass splittings

$\Rightarrow$ **need** to measure them

How do you measure oscillation probabilities?

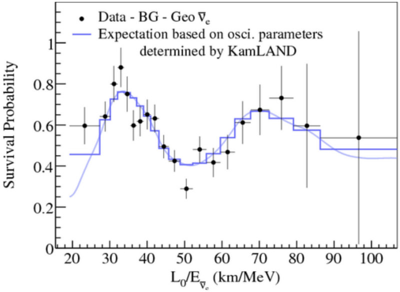
- need to know initial neutrino flux: use near detector close to source
- oscillations develop with distance: need far detector to detect neutrinos at a certain distance
- ratio of events at far detector/near detector gives probability (not that easy in reality)



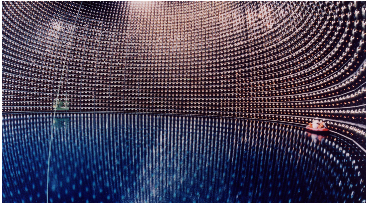
Neutrino oscillations

How do you measure oscillation probabilities?

- disappearance experiments: neutrino of flavor α is produced and detected
- appearance experiments: neutrino of flavor α is produced but flavor β is detected



Atmospheric mixing [hep-ex/9807003]



SuperKamiokande measured atmospheric mixing parameters:

$$\theta_{23} \approx 45^\circ$$

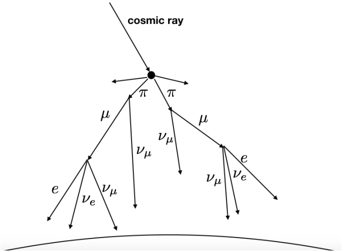
$$|\Delta m^2_{32}| \approx 2.2 \cdot 10^{-3}\ \mathrm{eV}^2$$

very large flavor mixing between ν_2 and ν_3

Neutrino oscillations-measurement

Example of oscillation measurement using Cherenkov light (e.g. SuperKamiokande, IceCube):

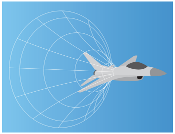
- neutrinos produced in atmosphere



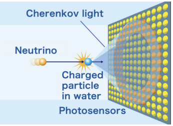
- identify neutrino flavor in experiment by identifying the produced charged lepton (in charged current interactions) using **Cherenkov radiation**

Neutrino oscillations-Cherenkov radiation

- Cherenkov radiation:
  charged particle (electron or muon) moving through medium faster than the speed of light in that medium (speed of light $\sim$ 0.75 c in water) $\rightarrow$ shock wave generated similar to supersonic aircraft in the air

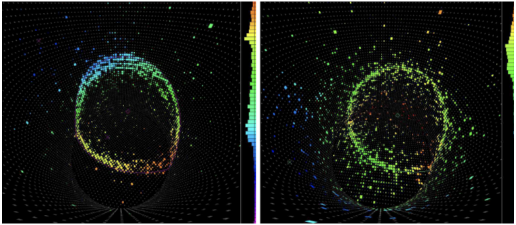


  $\rightarrow$ visible "optical shockwave" of Cherenkov radiation emitted in a cone and detected as ring by photomultiplier tubes



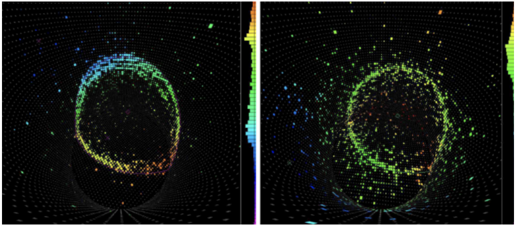
Neutrino oscillations-Cherenkov radiation

- electron ring: fuzzy (electromagnetic shower) $\leftrightarrow$ muon ring: smoother

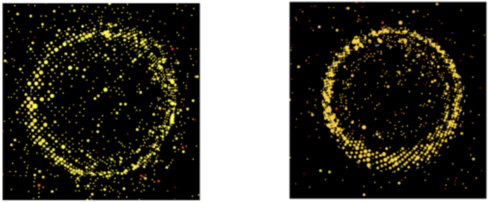


Neutrino oscillations-Cherenkov radiation

- electron ring: fuzzy (electromagnetic shower) $\leftrightarrow$ muon ring: smoother

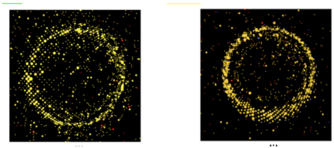


left: a muon event, right: an electron event

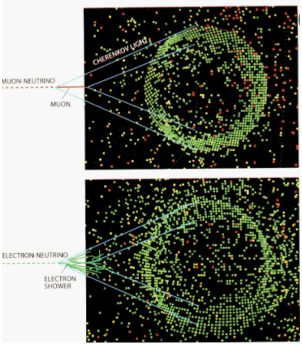


Neutrino oscillations-Cherenkov radiation

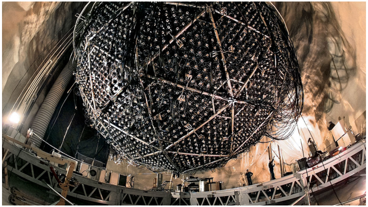
- electron ring: fuzzy (electromagnetic shower) $\leftrightarrow$ muon ring: smoother



right: a muon event, left: an electron event



Solar mixing [nucl-ex/0309004]



SNO measured solar mixing parameters:

$$\theta_{12} \approx 30.2^\circ$$

$$\Delta m^2_{21} \approx 5 \cdot 10^{-5}\ \text{eV}^2$$

large mixing between $\nu_1,\ \nu_2$!

Last mixing angle has been measured by DayaBay experiment with large contribution from BNL

DayaBay measured reactor mixing parameters:

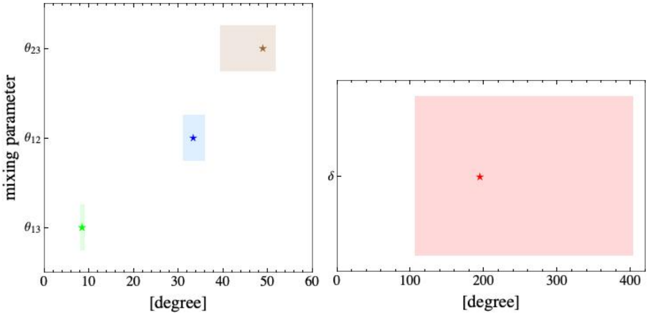
$$\theta_{13} \approx 8.4^\circ$$

$$|\Delta m^2_{32}| \approx 2.5 \cdot 10^{-3}\ \text{eV}^2$$

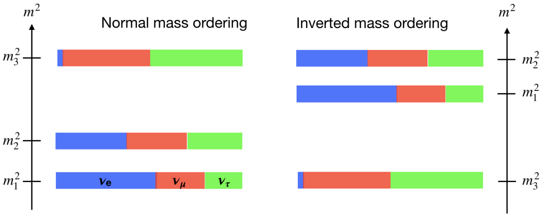
non-zero mixing between $\nu_1,\ \nu_3$!

Neutrino oscillations

agreement between different experiments $\rightarrow$ global knowledge about mixing angles



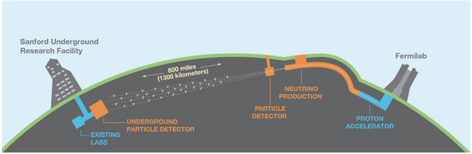
Neutrino oscillations

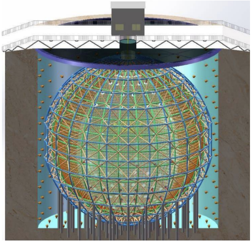


- mass ordering unknown
  - NO: $m_1 < m_2 < m_3$
  - IO: $m_3 < m_1 < m_2$
- mass splittings:
  - one "large" mass splitting $|\Delta m_{32}^2| \approx 2.51 \times 10^{-3}$ eV^2
  - one "small" mass splitting $\Delta m_{21}^2 \approx 7.42 \times 10^{-5}$ eV^2

Neutrino oscillations-future

- DUNE/T2HK: long baseline accelerator experiments, JUNO: medium baseline reactor experiment



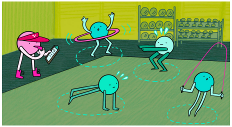


  - measure $\delta \rightarrow$ Is there CP violation in the lepton sector?
  - precision measurement of all mixing angles $\rightarrow$ Is $\theta_{23} = 45^\circ$?
  - mass ordering $\rightarrow$ NO vs IO
- new physics in oscillations?

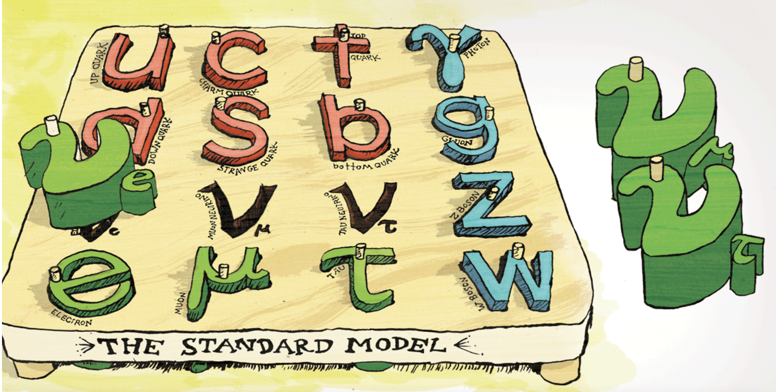
Neutrino oscillations

Implications of neutrino oscillations

- What have we learned?
  - SM is incomplete: Neutrinos are massive
  - lepton flavor is not conserved
  - very large flavor mixing
  - small neutrino masses
- What will we learn in the future?
  - precision measurement of mixing matrix
  - mass ordering
  - CP violation in lepton sector
  - new physics?

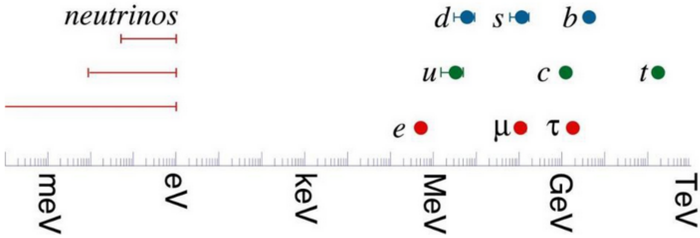


Neutrino phenomenology & theory



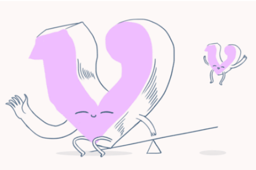
Neutrino theory

- consequence of neutrino oscillations $\rightarrow$ massive neutrinos! very compelling sign for new physics
- neutrino mass generation: not possible in the SM, need new particles!
- many ideas for mass generation, explain smallness of neutrino mass



Neutrino theory-neutrino masses

- consequence of neutrino oscillations $\rightarrow$ massive neutrinos! very compelling sign for new physics
- neutrino mass generation: not possible in the SM, need new particles!
- many ideas for mass generation, explain smallness of neutrino mass
- popular idea: seesaw mechanism: introduce heavy, sterile neutrinos whose mass suppresses the light neutrino masses $m_\nu \sim (y_\nu v_H)^2/M_N$



Q: Assume $m_\nu = 0.1$ eV, $y_\nu = 1, v_H = 246 \times 10^9$ eV, how big must M_N be?

Neutrino theory-neutrino masses

- consequence of neutrino oscillations $\rightarrow$ massive neutrinos! very compelling sign for new physics
- neutrino mass generation: not possible in the SM, need new particles!
- many ideas for mass generation, explain smallness of neutrino mass
- popular idea: seesaw mechanism: introduce heavy, sterile neutrinos whose mass suppresses the light neutrino masses $m_\nu \sim (y_\nu v_H)^2/M_N$
- $M_N \approx 10^{14}$ GeV generally predicted to be very large $\rightarrow$ untestable
- theory work needed to develop more testable mechanisms/new searches for neutrino mass generation

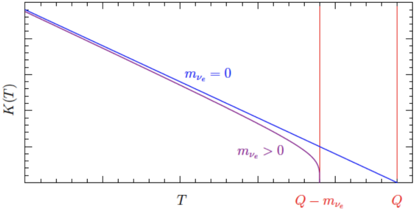
Neutrino phenomenology-neutrino masses

- want to measure absolute neutrino mass
- **Q: How do we measure the absolute neutrino mass?**

W. Pauli, 1900-1958

Neutrino phenomenology-neutrino masses

- want to know absolute neutrino mass
- **Q: How do we measure the absolute neutrino mass?**
- Tritium beta decay at KATRIN experiment: measure maximal energy of electron, the difference to maximally released energy in this decay is the neutrino mass

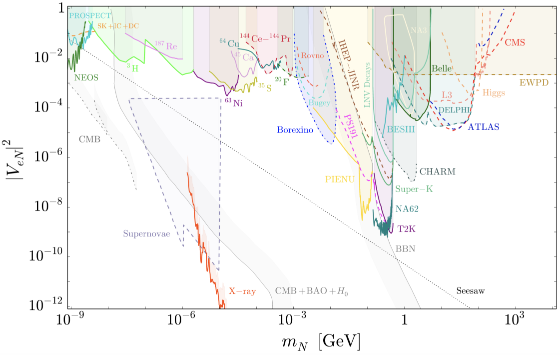


- sensitivity to "effective mass" $m_{\nu_e} \gtrsim 0.2$ eV

$$m_{\nu_e} = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$$

Neutrino phenomenology-additional neutrino generations

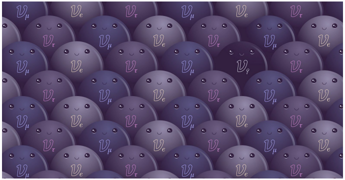
- Are there additional neutrino generations?
- example: constraints on mixing with electron neutrino



[Bolton, Deppisch, Dev '19]

Neutrino phenomenology-connections to new physics

- neutrino sector is least probed sector of SM $\rightarrow$ room for new physics
- new neutrino interactions?
- connections of neutrinos to Dark Matter?
- connections of neutrinos to matter-anti matter symmetry of Universe?



Neutrino phenomenology

- neutrinos in cosmology (sensitivity to neutrino mass scale, cosmic neutrino background, number of neutrinos)
- neutrino scattering experiments, neutrinoless double beta decay
- neutrinos in astrophysics, neutrinos from Supernovae, ...
- ultra high energy neutrinos
- pratical applications: reactor monitoring, geoneutrinos, solar physics, etc ...
- many more neutrino topics which would need another lecture

Summary

Take home message:

- neutrino physics is exciting!
- active field of research in experiment and theory
- room for something unexpected
- lots to do and learn, we have just started exploring the neutrino sector

Thank you for your attention!

[Artwork by Sandbox Studio, Chicago]

Backup: References

- Andre De Gouvea, TASI lectures on neutrino physics, hep-ph/0411274
- Alessandro Strumia and Francesco Vissani, Neutrino masses and mixings and ... , hep-ph/0606054
- Pilar Hernandez, Neutrino physics, 1708.01046
- Fermilab Neutrino University, Neutrino summer lectures series