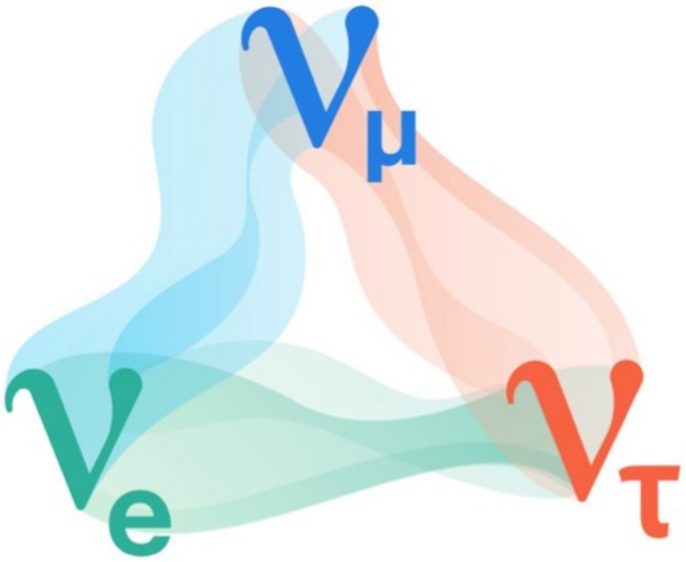
Neutrino Physics

Samira Hassani

Rencontres d'été de physique
de l'infiniment grand à l'infiniment petit

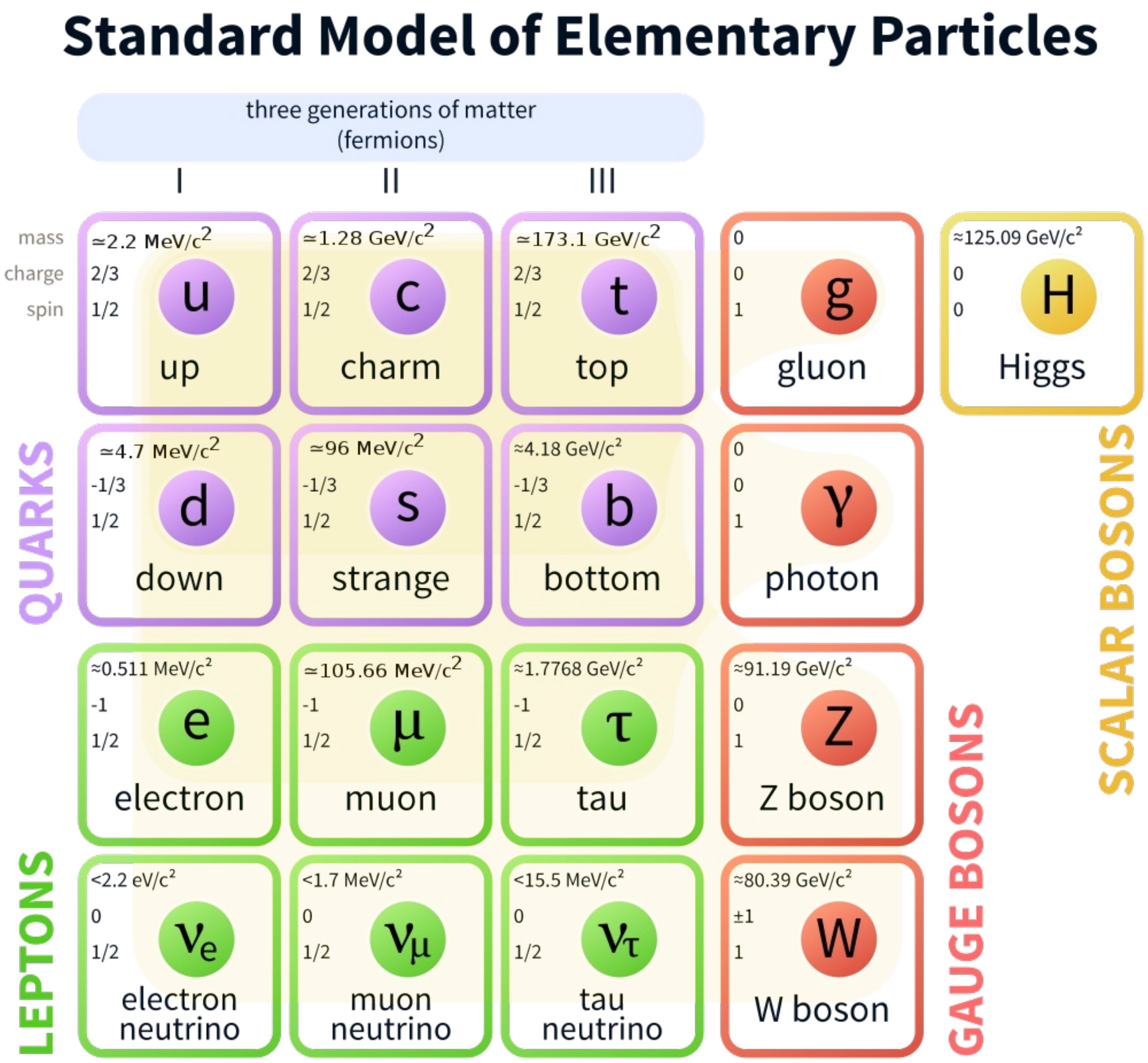
July 17th 2023



Outline

> “The most tiny quantity or reality ever imagined by human being.’
>
> F. Reines (Nobel 1995)

Introduction

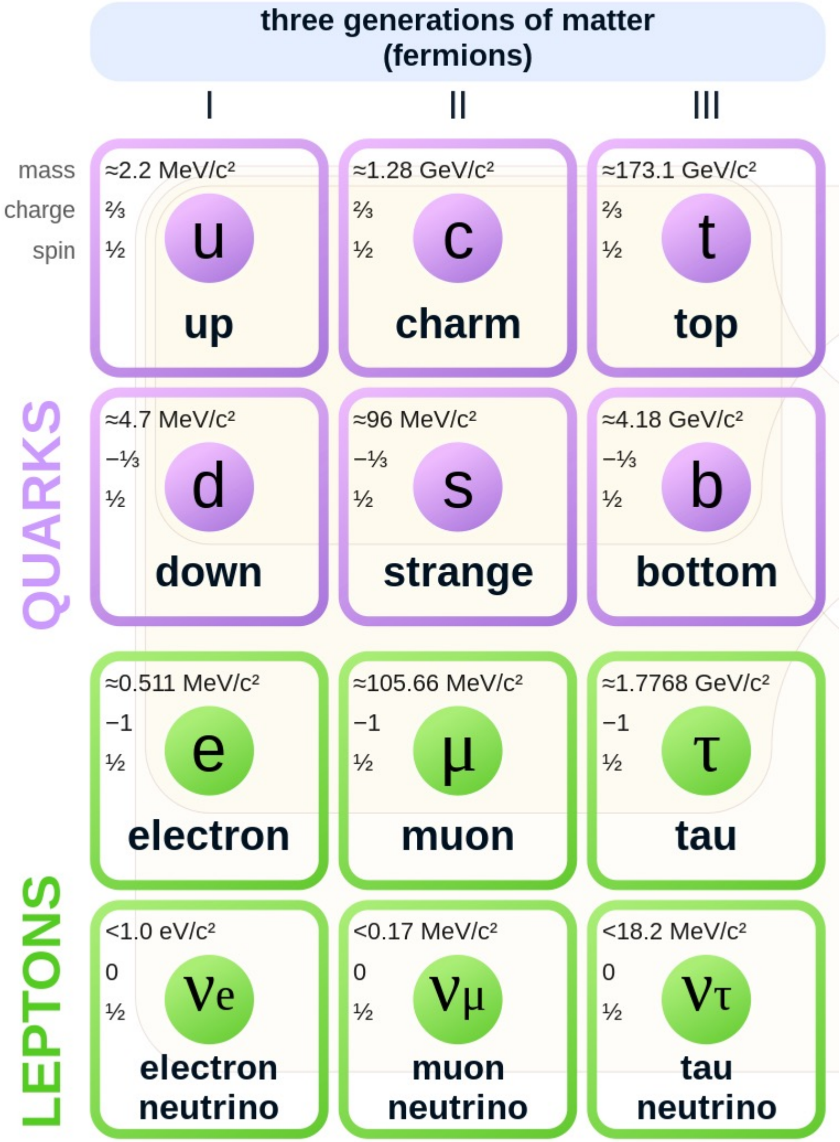


Standard Model of Elementary Particles

	three generations of matter (fermions)				
	I	II	III		
mass charge spin	≈2.2 MeV/c^2 2/3 1/2 u up	≈1.28 GeV/c^2 2/3 1/2 c charm	≈173.1 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.7 MeV/c^2 -1/3 1/2 d down	≈96 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.66 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	

- Electrons and u and d quarks are the elementary constituents of matter (i.e. without internal structure).
- The neutrino plays an important role in the transformation of matter.
- Neutrinos and photons are by far the most abundant elementary particles in the universe.
- Neutrinos, as messengers, serve as unique probes for a wide range of physics phenomena that span vastly different scales. These include:
  - Weak Interactions
  - Nucleons
  - Nuclei
  - The Earth
  - The Sun
  - Supernova explosions
  - The Origin of Ultra-High Energy Cosmic Rays
  - The Universe

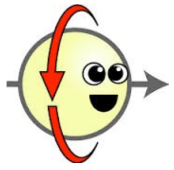
Neutrinos in the Standard Model



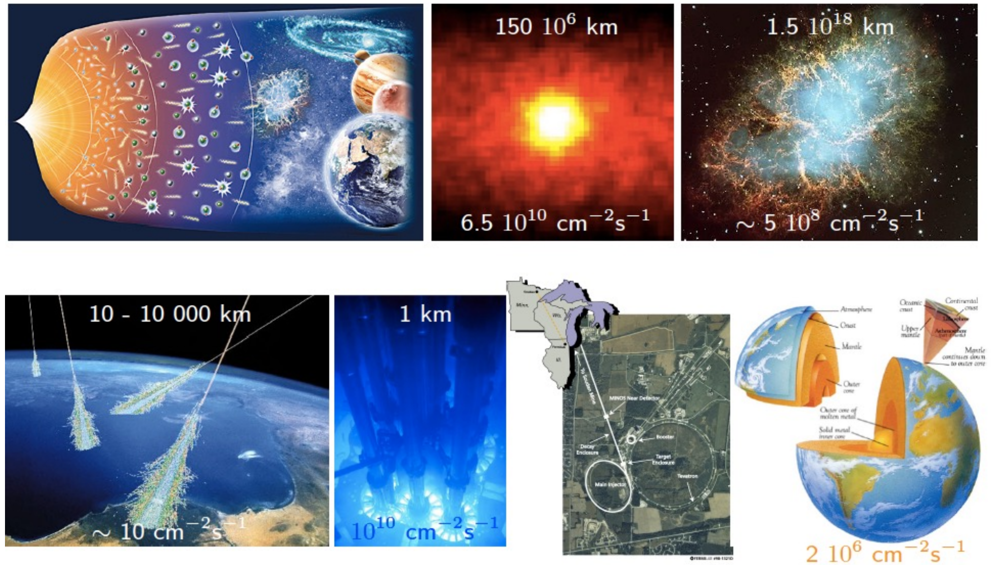
three generations of matter (fermions)

		I	II	III
QUARKS	mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top
		≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom
LEPTONS		≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau
		<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino

- Neutrinos are **neutral** leptons
- In the Standard Model, **neutrinos are massless**
- Neutrinos are spin ½
- **Neutrinos are purely left-handed**



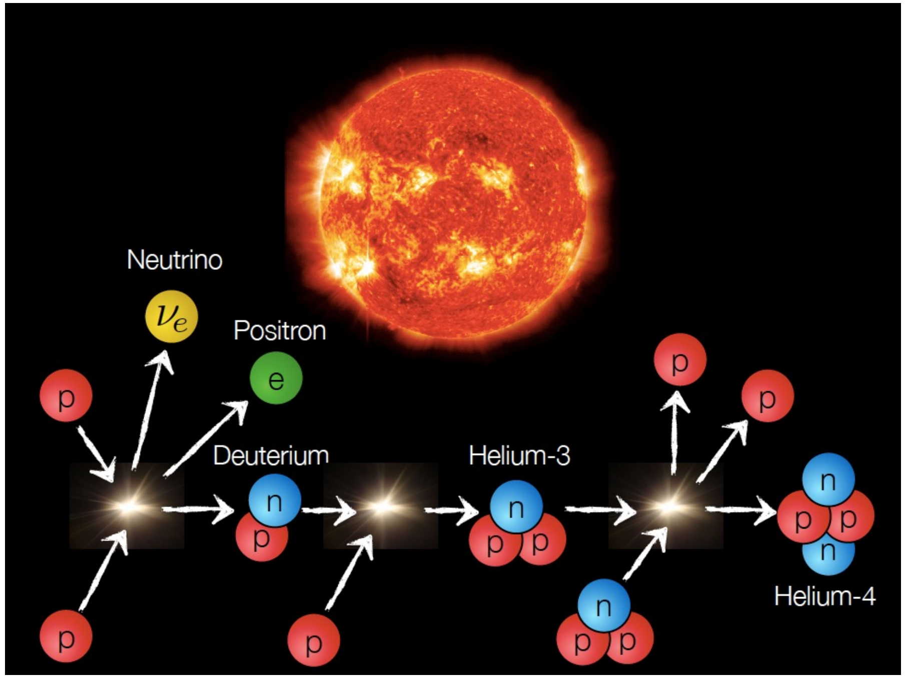
- **3 generations of neutrinos** and their corresponding leptons
- **3 types de neutrinos** : ν_e , ν_μ ,ν_τ « **flavor** »
- Neutrinos carry **lepton number L**
- The only known forces they experience are the weak force and gravity.
- They exhibit an extremely low level of interaction with other forms of matter.
  → **Neutrinos are difficult to detect and study**



1. Neutrino Sources

Ubiquitous Neutrinos
They are Everywhere !

Sun: Thermonuclear Fusion



We are literally bathed in neutrinos!

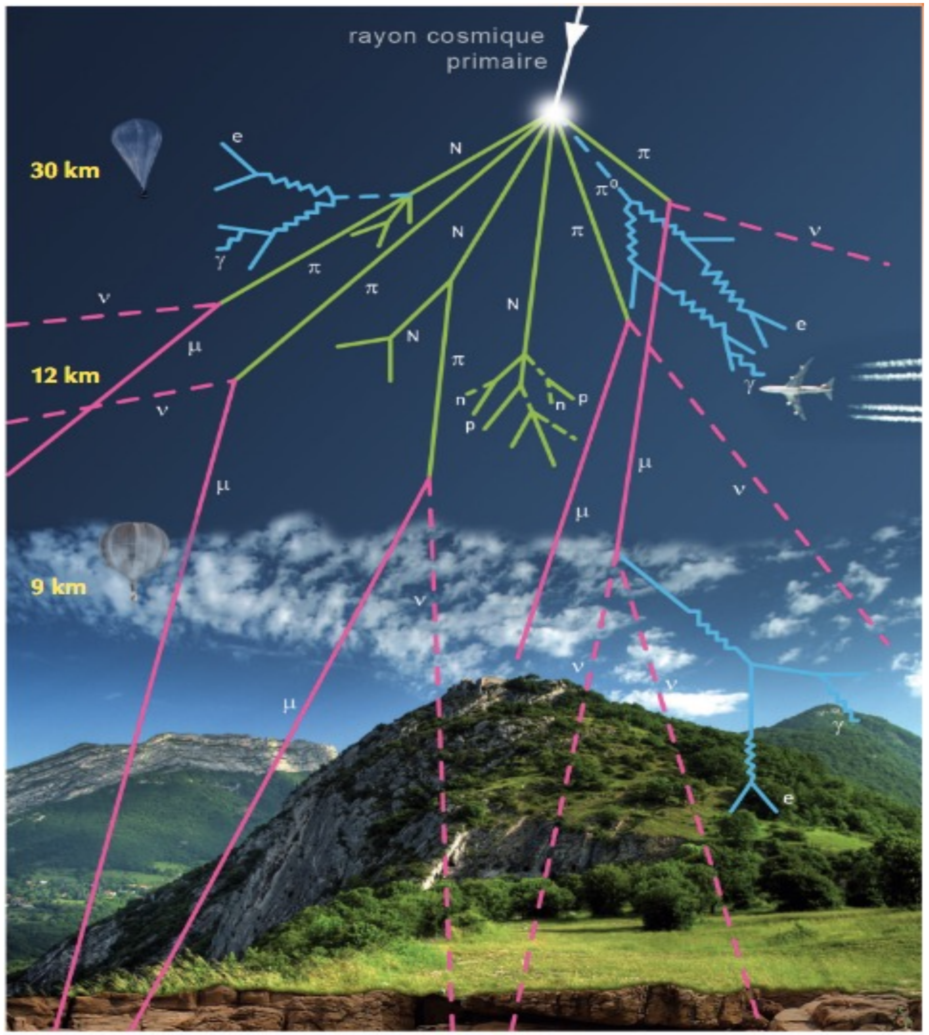
- 10^{38} neutrinos per second produced by the Sun (flux of about 10^{11}/cm^2/sec at the Earth)

- 65 billion solar neutrinos travel through your thumb nail per second

65 billions /cm^2/sec

Neutrinos are Everywhere !

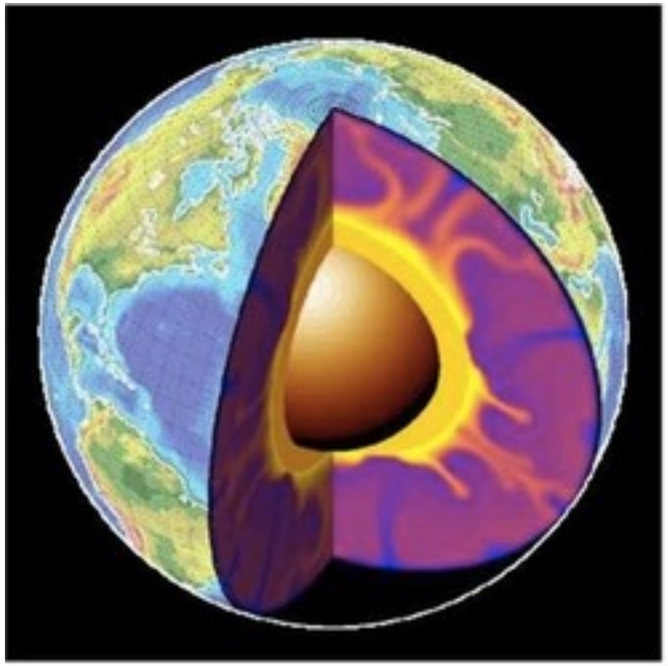
Atmosphere: Cosmic Ray Cascade



1 neutrino /cm^2/sec

Neutrinos are Everywhere !

Earth: Natural Radioactivity (^{238}U, ^{232}Th, ^{40}K)



7 millions /cm^2/sec

Neutrinos are Everywhere !

Universe

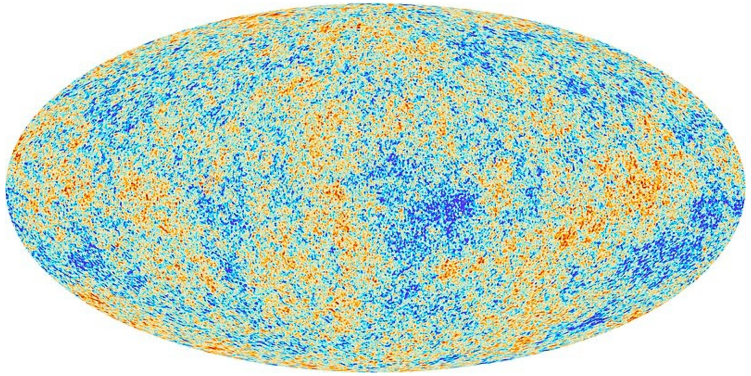
Supernova :

(star explosion)

left: before explosion / right: shortly after

SN 1987A produced 10^{58} neutrinos
(99% of the energy of the explosion)
25 detected by par 3 experiments

Cosmic Neutrinos from the Big Bang



300 /cm^3

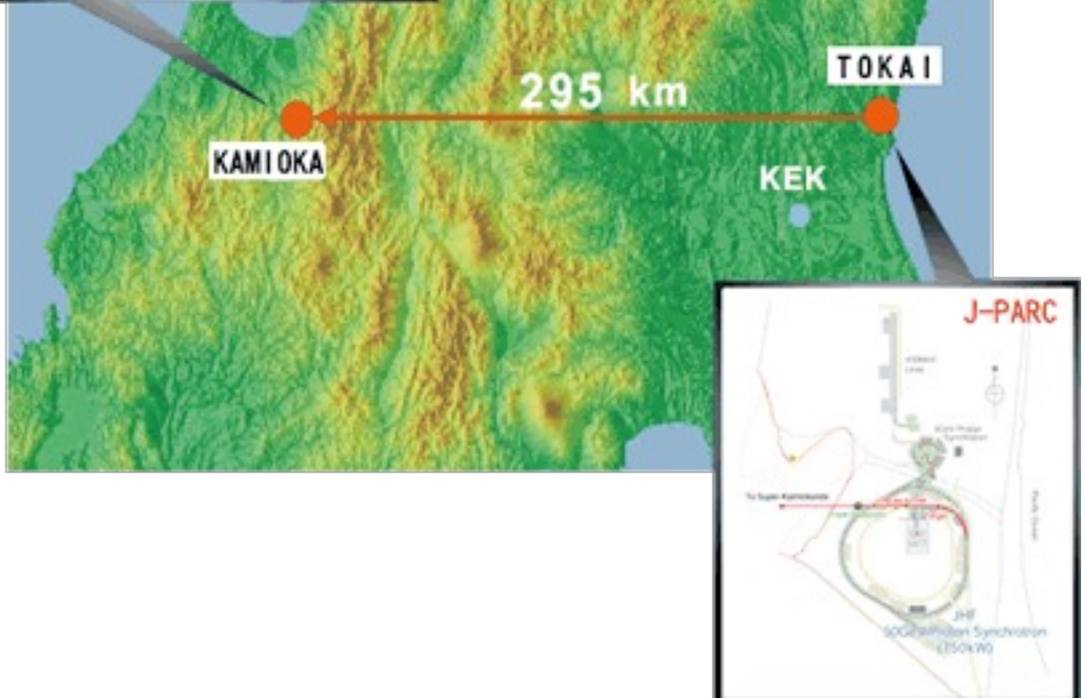
Neutrinos can be produced on Earth

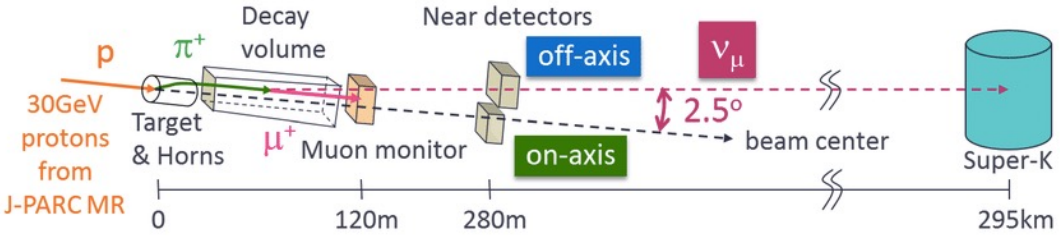
Nuclear Reactors

Flux 10^{13} /cm^2/sec

Neutrinos can be produced on Earth

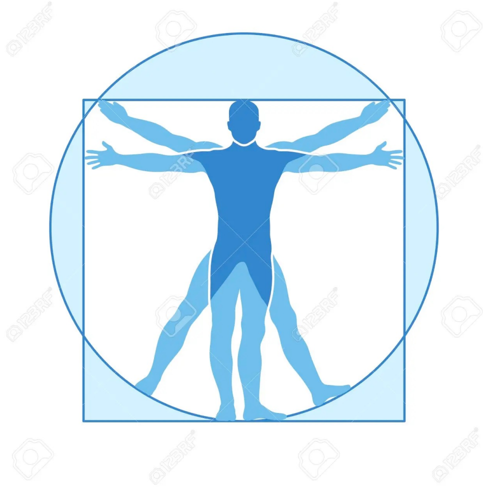
Accelerators : Particle beams in Japon, USA, CERN, …





Neutrinos can be produced on Earth

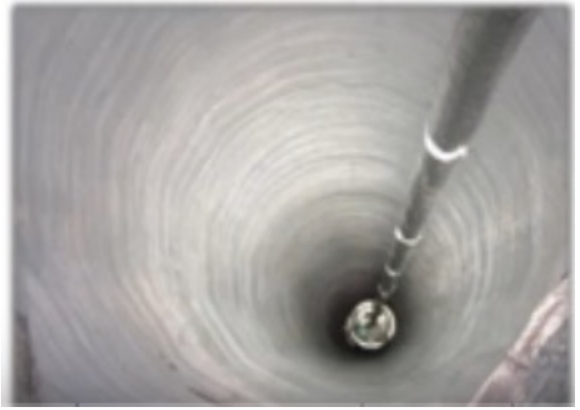
Each one of us is a neutrino emitter:
(20 mg of radioactive potassium ^{40}K in the human body
4000 neutrinos /sec →340 millions /jour)

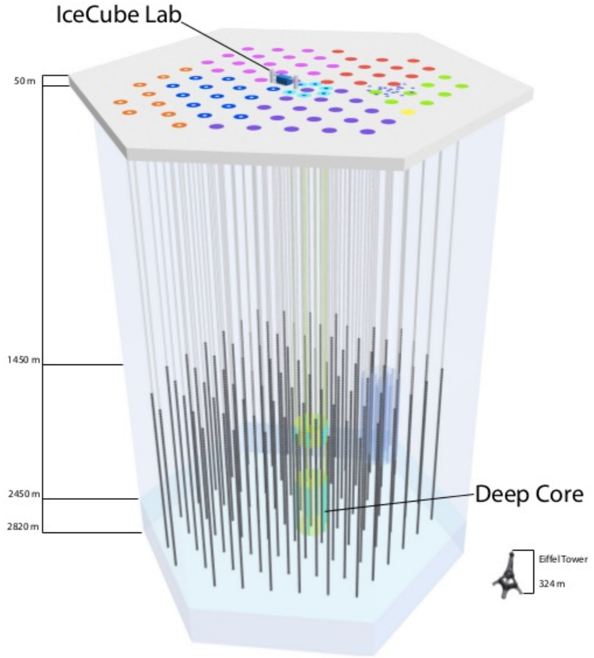


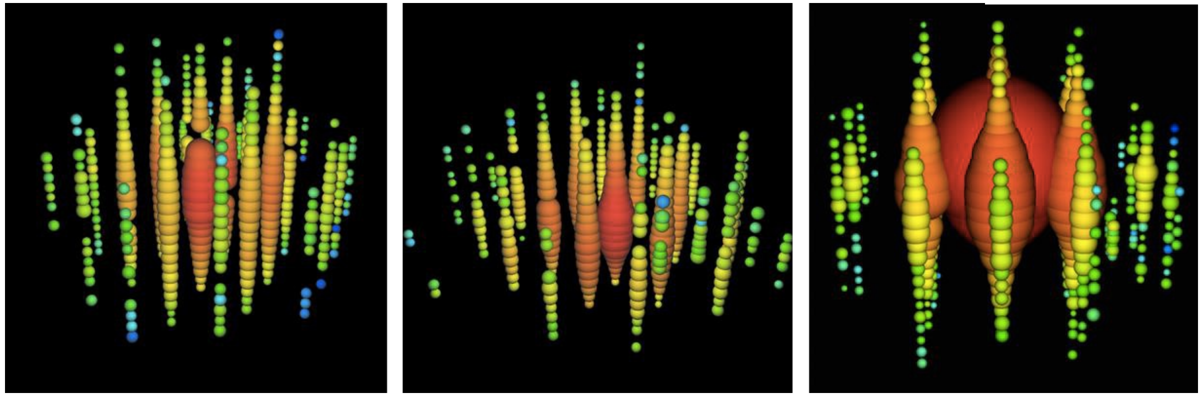
A banana emit ≈ 10 neutrinos/ sec

Extra-galactic neutrinos

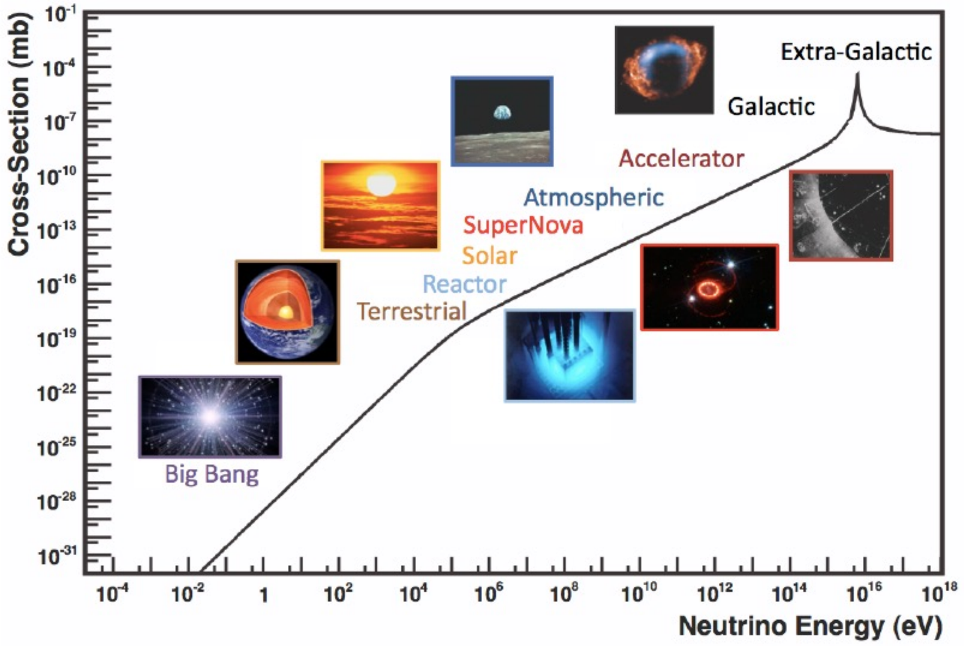
Extraordinary detection: IceCube has observed neutrino events with energies of PeV (10^{15} eV)!

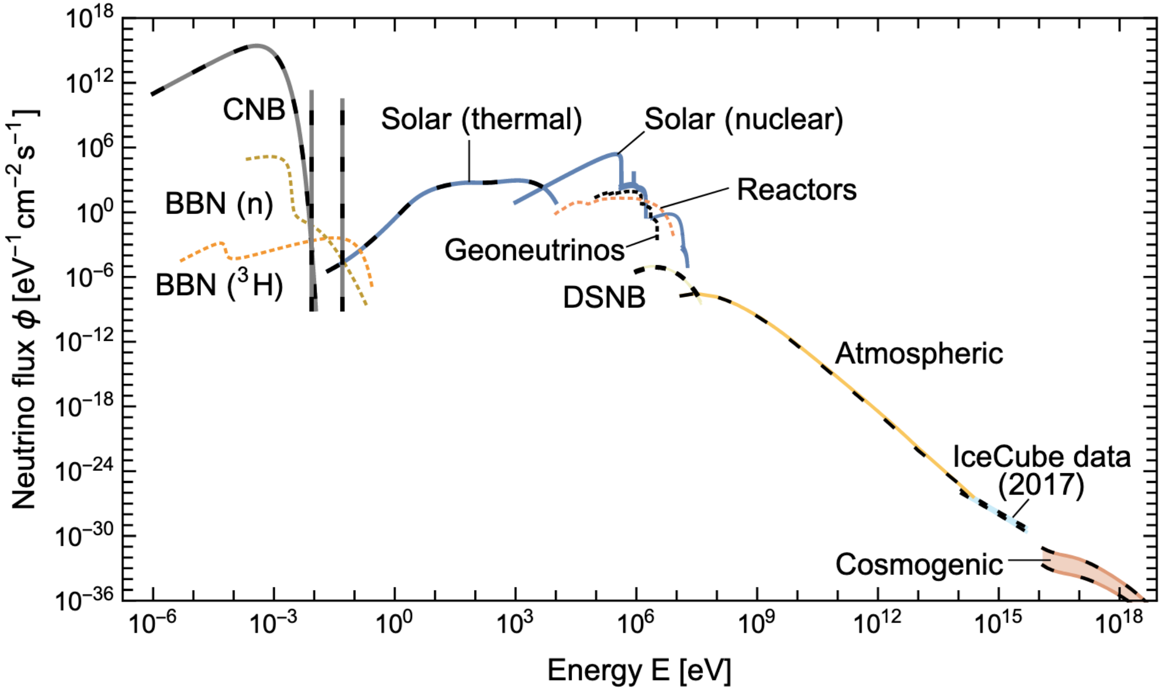






The Origins of Neutrinos

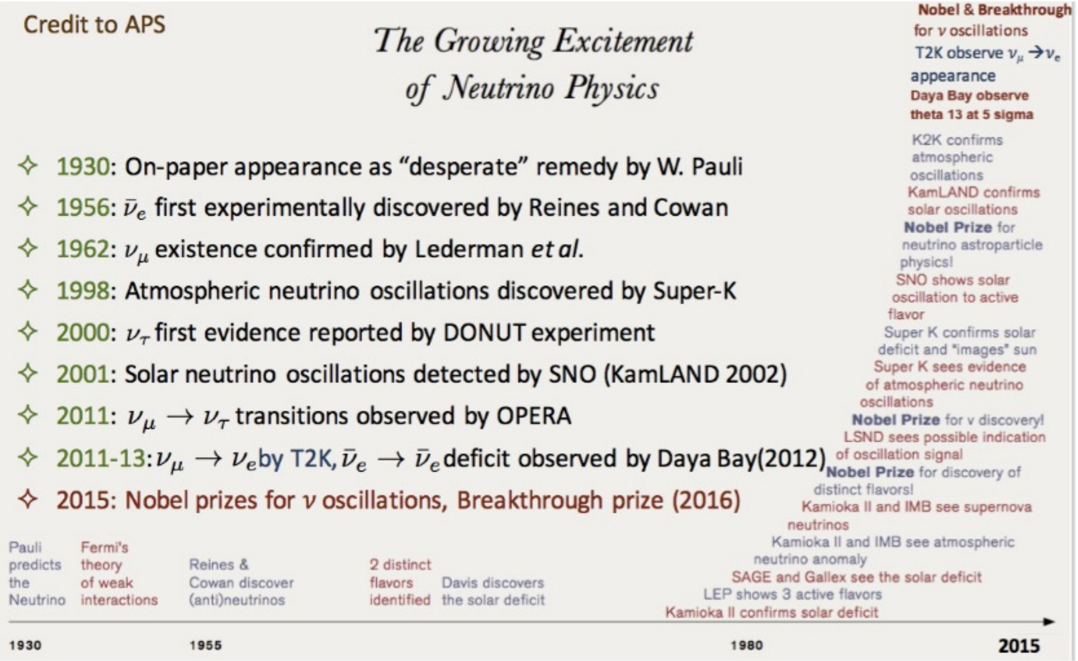




- Neutrinos cover an enormous energy range of 24 orders of magnitude, stemming from various sources and production mechanisms.

- This wide range of neutrino energies opens up exciting possibilities for neutrino physics research, with plenty of opportunities for discovery and new knowledge.

“ ’ Within the hour that you will be listening to this talk, approximately 100,000,000,000,000,000,000 neutrinos will pass through your body.’



Credit to APS

The Growing Excitement of Neutrino Physics

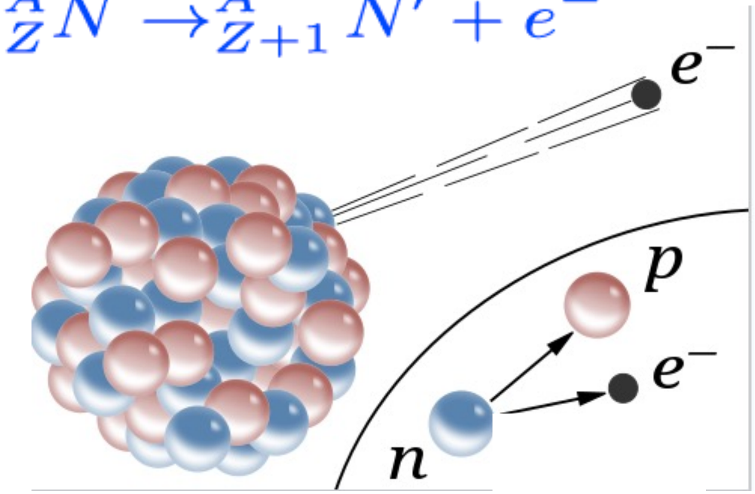
- ✧ 1930: On-paper appearance as “desperate” remedy by W. Pauli
- ✧ 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- ✧ 1962: ν_μ existence confirmed by Lederman *et al.*
- ✧ 1998: Atmospheric neutrino oscillations discovered by Super-K
- ✧ 2000: ν_τ first evidence reported by DONUT experiment
- ✧ 2001: Solar neutrino oscillations detected by SNO (KamLAND 2002)
- ✧ 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA
- ✧ 2011-13: $\nu_\mu \rightarrow \nu_e$ by T2K, $\bar{\nu}_e \rightarrow \bar{\nu}_e$ deficit observed by Daya Bay(2012)
- ✧ 2015: Nobel prizes for ν oscillations, Breakthrough prize (2016)

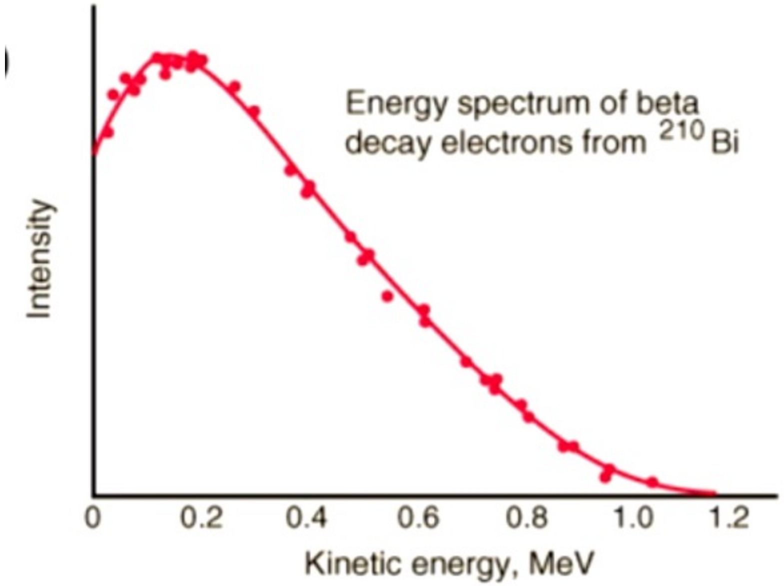
2. Neutrino History

Nuclear Physics before 1930

- 1911-1914: problem of continuous beta decay spectrum

$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^-$$



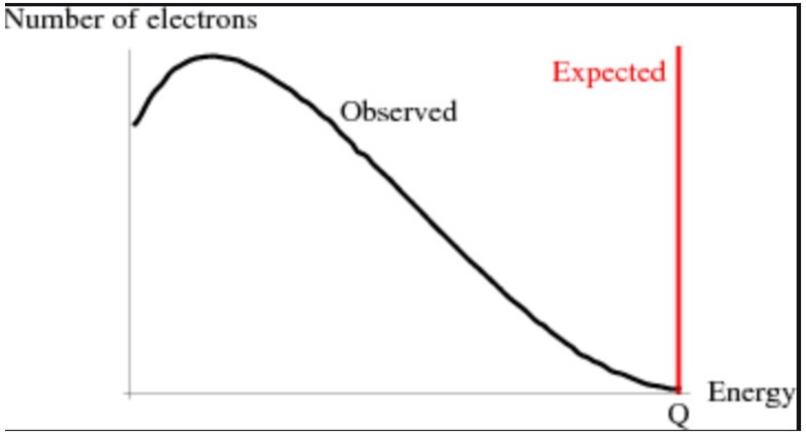


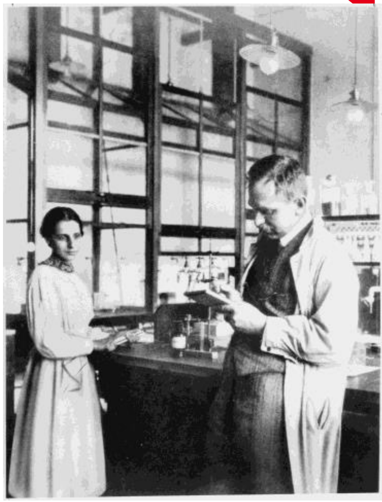
- From energy and momentum conservation, expected fixed kinetic energy of electron

$$E_{\text{electron}} \simeq (M_N - M_{N'})c^2 = Q = \text{constante}$$

Nuclear Physics before 1930

- 1911: L. Meitner & O. Hahn observed continuous β decay spectrum
- 1914 : confirmed by Chadwick





L. Meitner & O. Hahn
(Nobel 1944 only him!!)

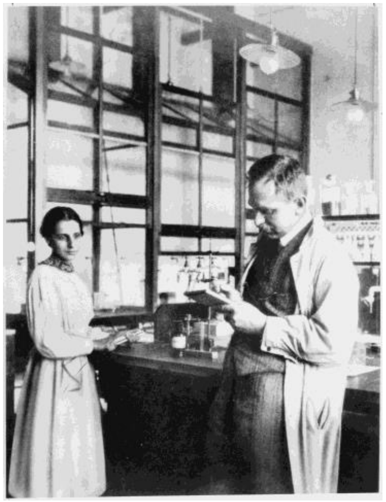
Chadwick
(Nobel 1935)

Nuclear Physics before 1930

- 1911: L. Meitner & O. Hahn observed continuous β decay spectrum
- 1914 : confirmed by Chadwick

- N. Bohr was close to giving up the conservation of energy!

"... This would mean that the idea of energy and its conservation fails in dealing with processes involving the emission and capture of nuclear electrons. This does not sound improbable if we remember all that has been said about peculiar properties of electrons in the nucleus."



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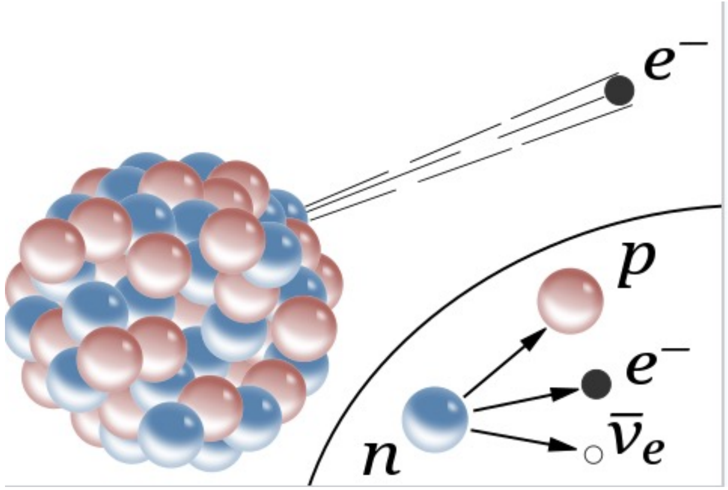
Pauli proposed a New Particle

- 1930: Postulated by Pauli to resolve the problem of continuous β-ray spectra, and reconcile nuclear model with spin-statistics theorem.

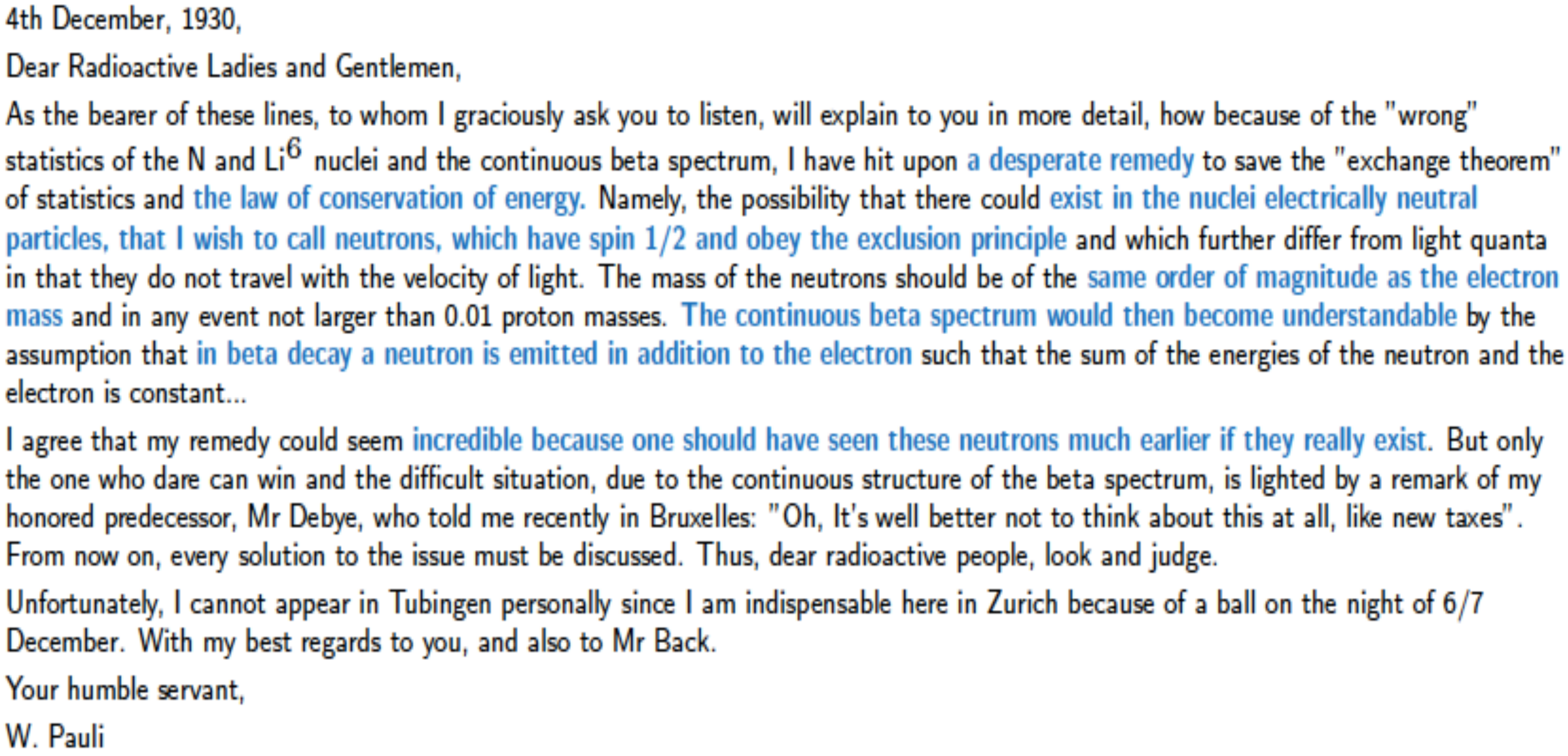


Wolfgang Pauli
(Nobel 1945)

There exists an unknown particle that carries away the missing energy!

Neutrinos: a desperate remedy

Pauli writes a letter to colleagues attending a conference in Tübingen proposing a “solution”:



4th December, 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 Li^6 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 honored 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.

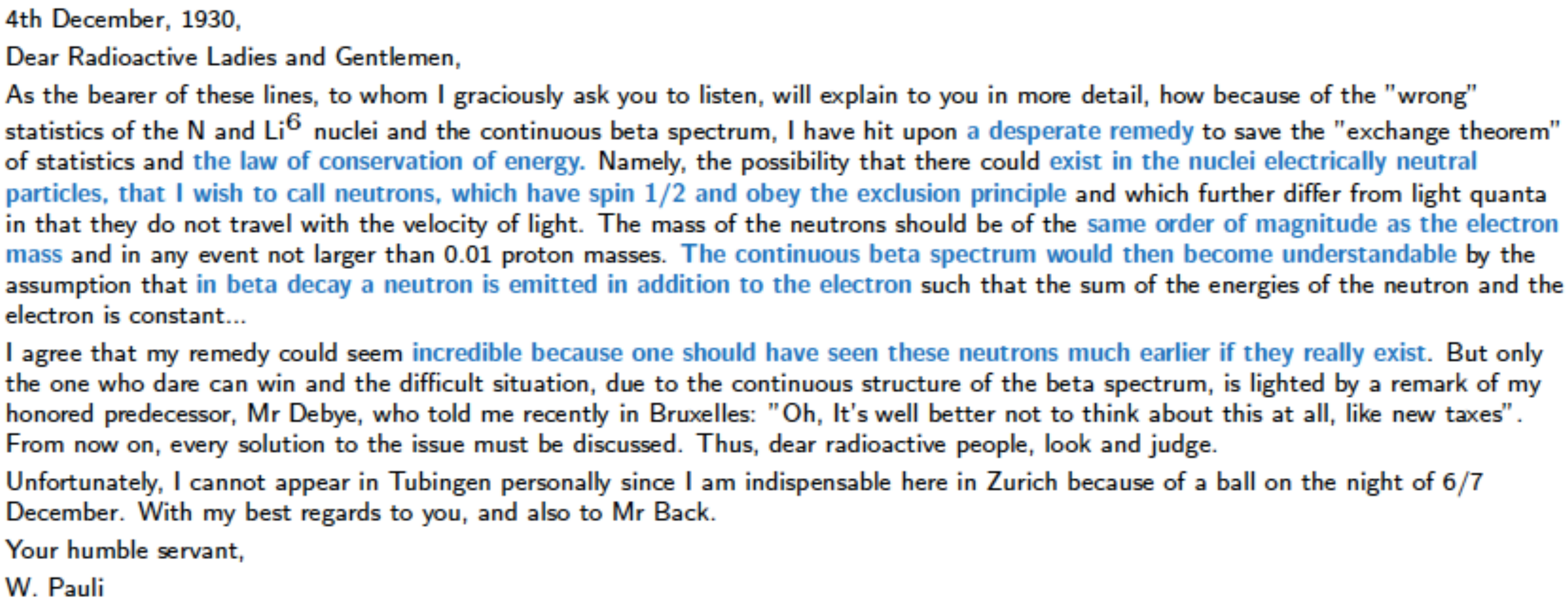
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli

Wolfgang Pauli
(Nobel 1945)

Neutrinos: a desperate remedy



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Wolfgang Pauli
(Nobel 1945)

Pauli told his friend Walter Baade:
"Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally!"

Worst Pauli's insult to a theory: *"Not even wrong"*
He wagers a case of champagne that no one would ever detect his elusive postulated particle

Neutron Discovery

- **1932: Chadwick discovers the neutron:**
  - $m_{neutron}$ = 1.0014 x m_{proton} → too heavy → not Pauli's particle

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

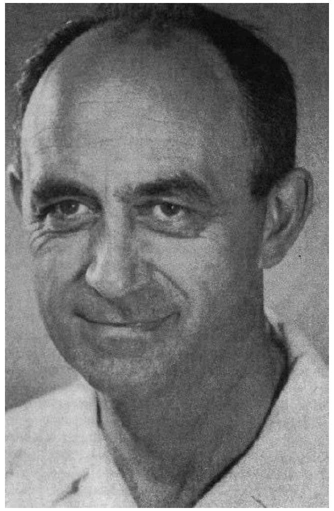
> *"... their mass can not be very much more than the electron mass. In order to distinguish them from heavy neutrons, mister Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero... It seems to me plausible that neutrinos have a spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons: the hypothesis that they have a magnetic moment seems to me not funded at all."*
>
> *W. Pauli*

Wolfgang Pauli
(Nobel 1945)

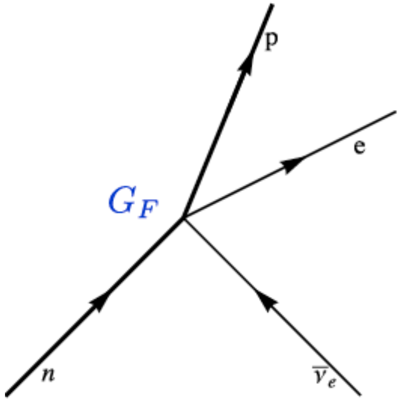
Theory of β Decay

- **1933: Fermi theory of Weak Interactions** (father of the world's first nuclear reactor)
- He constructs a new fundamental interaction analogous to QED but with a different strength
- Prediction for the cross-section to be too small to ever be observed...
- Nature magazine did not publish his article :

  "contained speculations too remote from reality to be of interest to the reader….."



Enrico Fermi
(Nobel 1945)



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

- **1934 : Bethe-Peierls compute the neutrino cross section using this theory**
- Cross-section $\sigma_{\nu p} \approx 10^{-44}$ cm^2 (E_ν=2 MeV) to be compared to $\sigma_{\gamma p} \approx 10^{-25}$ cm^2
- The mean free path of a neutrino before interacting is about 1.6 light-years of lead, which is 10^5 times the distance between the Earth and the Sun.
- They conclude : *"...there is no practically possible way of observing the neutrino"*

Bethe and Peierls
(Bethe, Nobel 1967)

More Neutrino Personalities

- 1937: Ettore Majorana
- He postulated that neutrinos could be their own antiparticles.
- This special class of particles came to bear his name: Majorana particles

Majorana disappeared in 1938 on a boat trip from Sicily

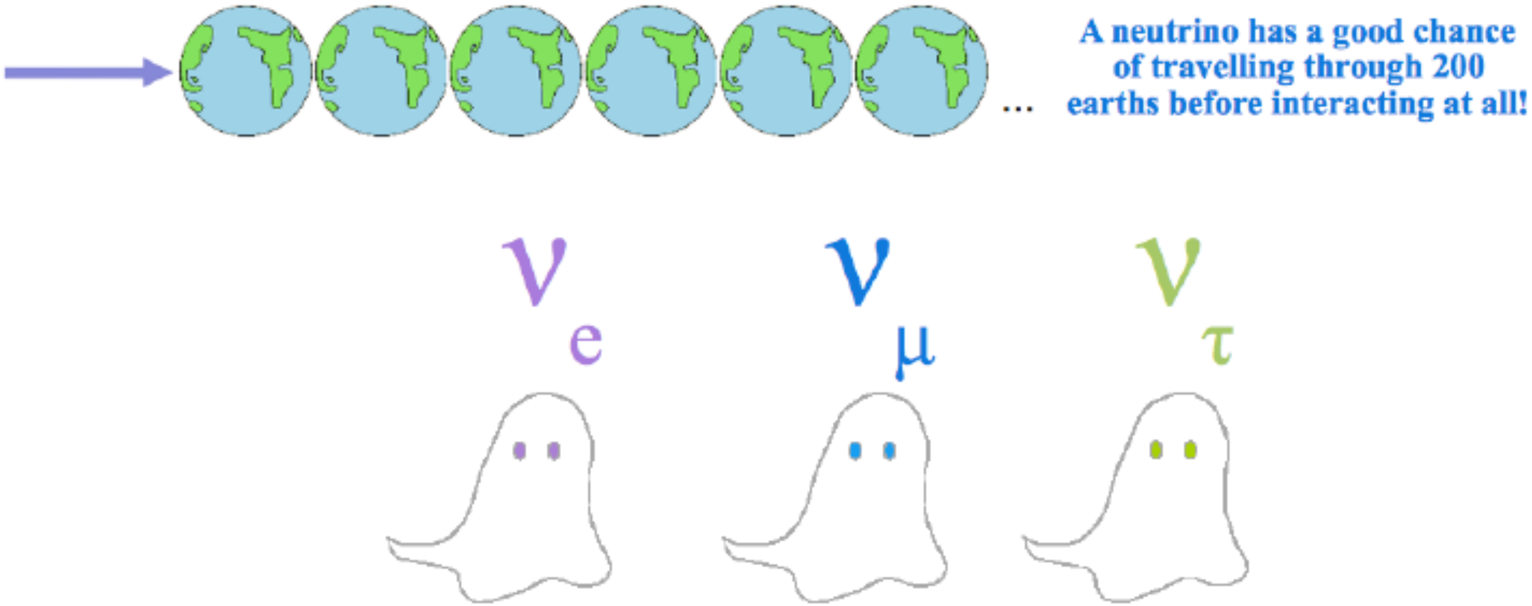
Ettore Majorana

- 1957: Bruno Pontecorvo
- He hypothesized that neutrinos may oscillate, or change from one type to another and would go on to develop that theory over the years as more flavors were discovered.
- He also predicted that supernovae, the giant explosion of a dying star, would release an enormous amount of energy in the form of neutrinos

Pontecorvo disappeared … to the east block in 1950

Бруно Понтекорво

Neutrinos : How to detect them?



A neutrino has a good chance of travelling through 200 earths before interacting at all!

But They Do Interact !

- 1946 Pontecorvo : Not so desperate…

$$N_{CC} = \Phi_{\nu} \times \sigma \times \# \text{ of targets} \times \text{Time}$$

- In a 1000kg detector, a 10^{11} /s/cm^2 → few events per day

Бруно Понтекорво

But They Do Interact

Projet Poltergeist (1951) at Los Alamos

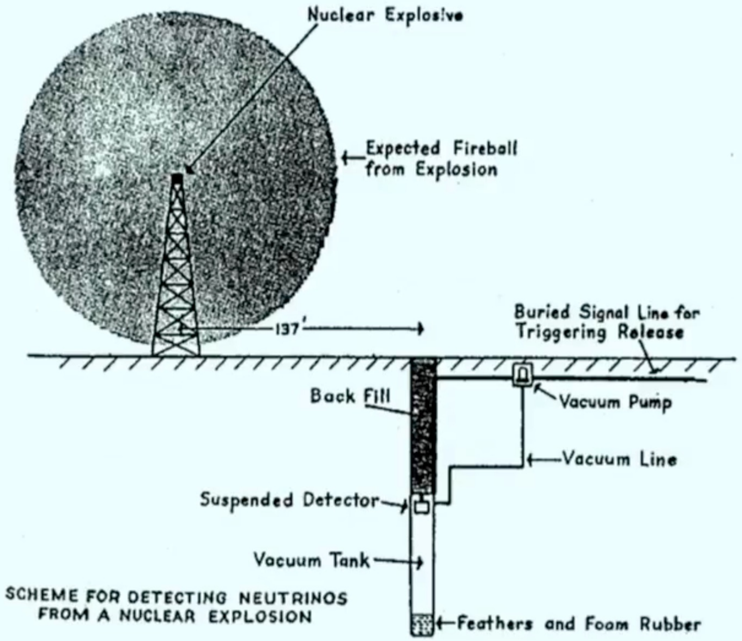
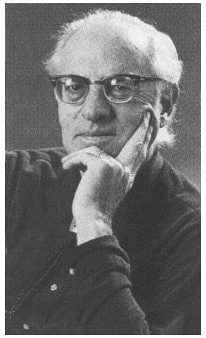


FIGURE 5.1 Scheme for detecting neutrinos from a nuclear
(Cowan, 1964).

"The idea that such a sensitive detector could be operated in the close proximity (within a hundred meters) of the most violent explosion produced by man was somewhat bizarre"
Frederick Reines, Nobel Lecture



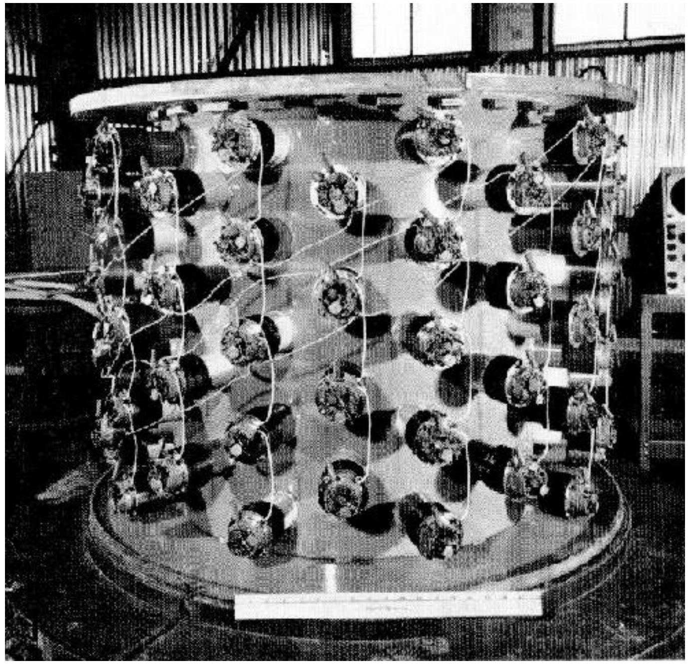
Reines
(Nobel 1995)

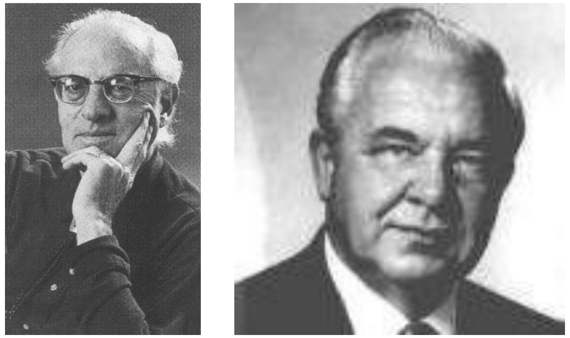
Cowan
(died 1974)

- **The initial idea :** was to detect the neutrinos produced by a nuclear explosion, with an underground detector close to the explosion area !
- Use a detector of several tons suspended in a vacuum that would be dropped at the moment of the explosion to avoid seismic waves.

But They Do Interact

1953 : Put a detector near nuclear reactor at Hanford (USA)





Reines
(Nobel 1995)

Cowan
(died 1974)

- **The second idea : detection of neutrinos produced in a nuclear reactor by measuring the inverse beta decay reaction**

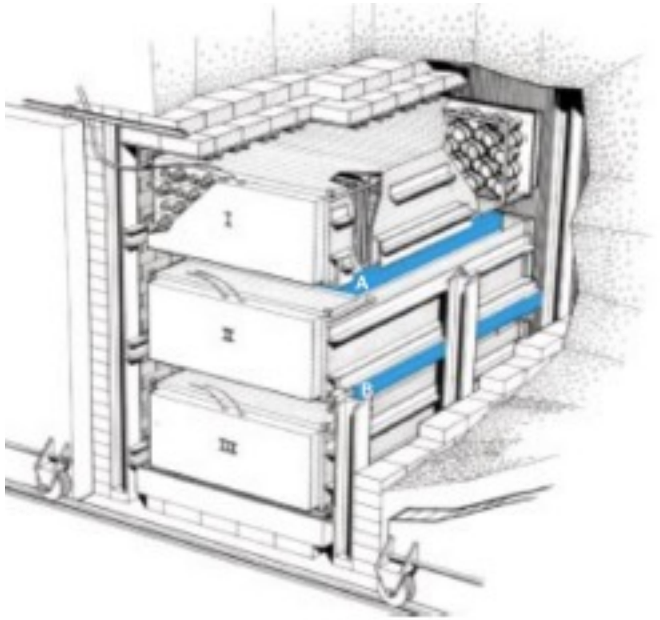
$$\bar{\nu}_e + p \rightarrow n + e^+$$

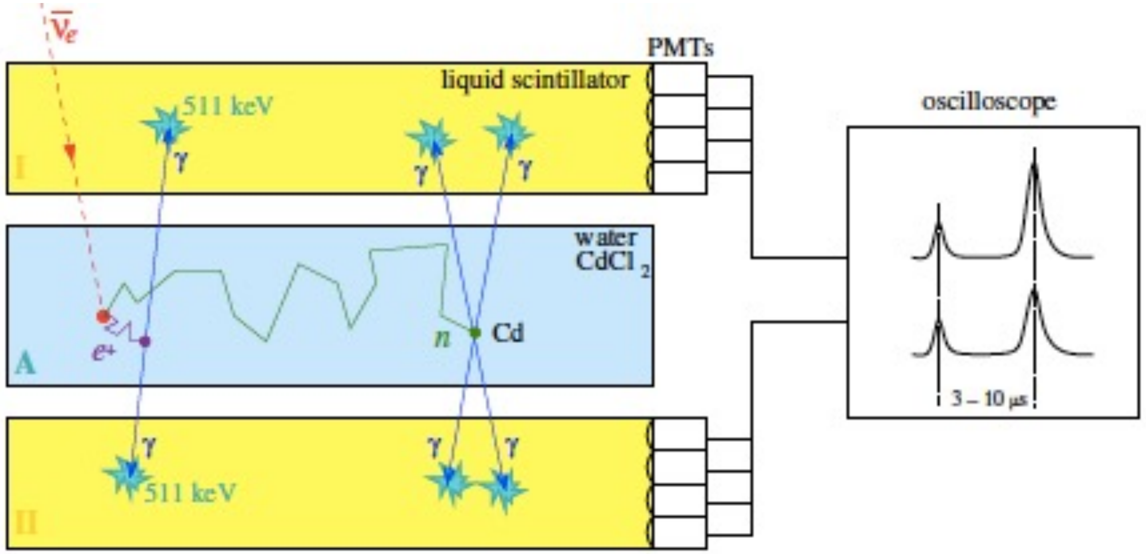
- However, their initial attempts at detecting neutrinos at Hanford were unsuccessful.
- The neutrino flux was too low, and background level much higher than expected due to cosmic rays.

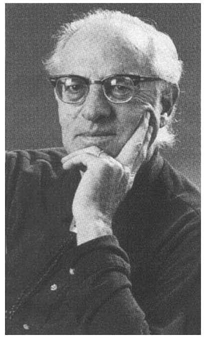
anti-neutrino $\bar{\nu}_e$ Discovery

Finally 1956: Put a detector near nuclear reactor Savannah River (USA)

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





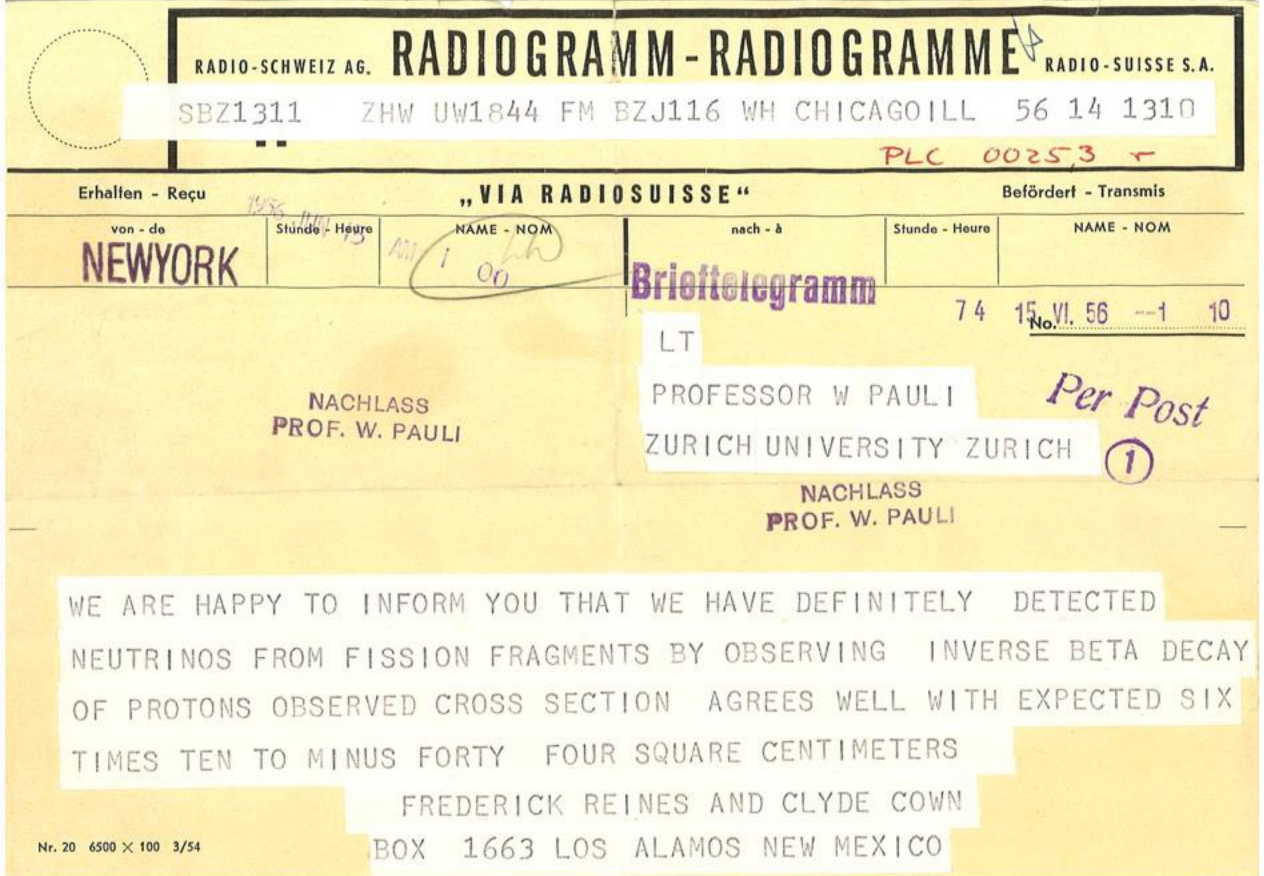


Reines
(Nobel 1995)

Cowan
(died 1974)

- Big detector (400 L) filled with water with and cadmium chloride (CdCl2)
- Detection of γ : Measure positron (e+e− →γ γ) and neutron(nN→ N*→ N + γs) in **delayed coincidence in order to get rid of backgrounds.**
- Out of 5 x 10^{13} /s/cm^2 of $\bar{\nu}_e$ emitted by the reactor→ only 3 events per hour were detected.
- Modern versions of the Reines & Cowan experiment, such as Chooz, Dchooz, Daya Bay, and RENO, are still making discoveries today

$\bar{\nu}_e$ Discovery



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post ①

NACHLASS
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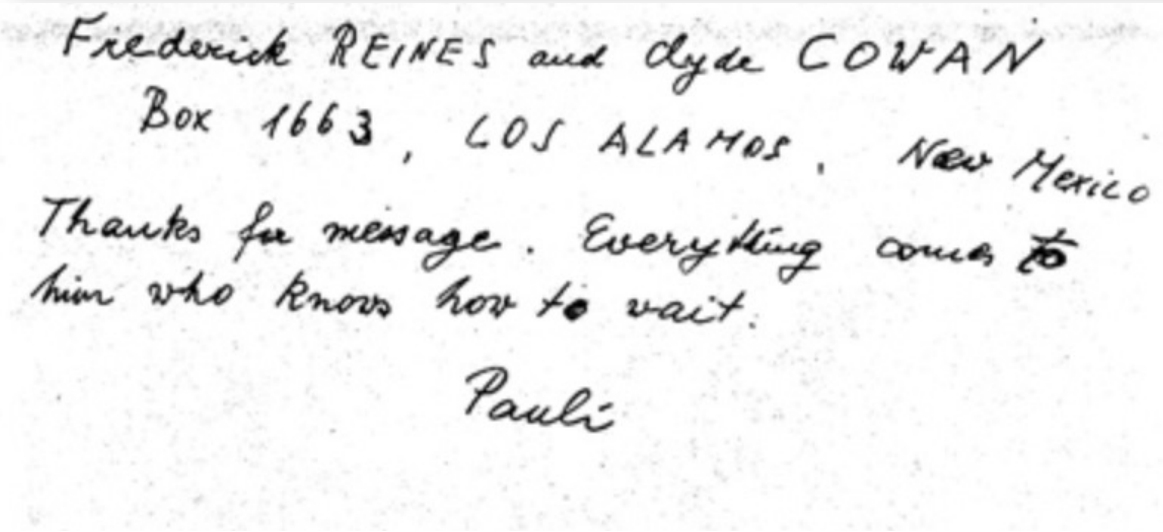
NACHLASS
PROF. W. PAULI

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

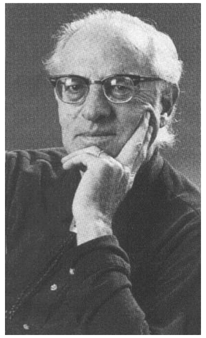
Nr. 20 6500 × 100 3/54



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

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

Pauli



Reines
(Nobel 1995)

Cowan
(died 1974)

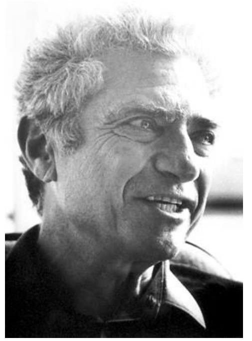
Wolfgang Pauli
(Nobel 1945)

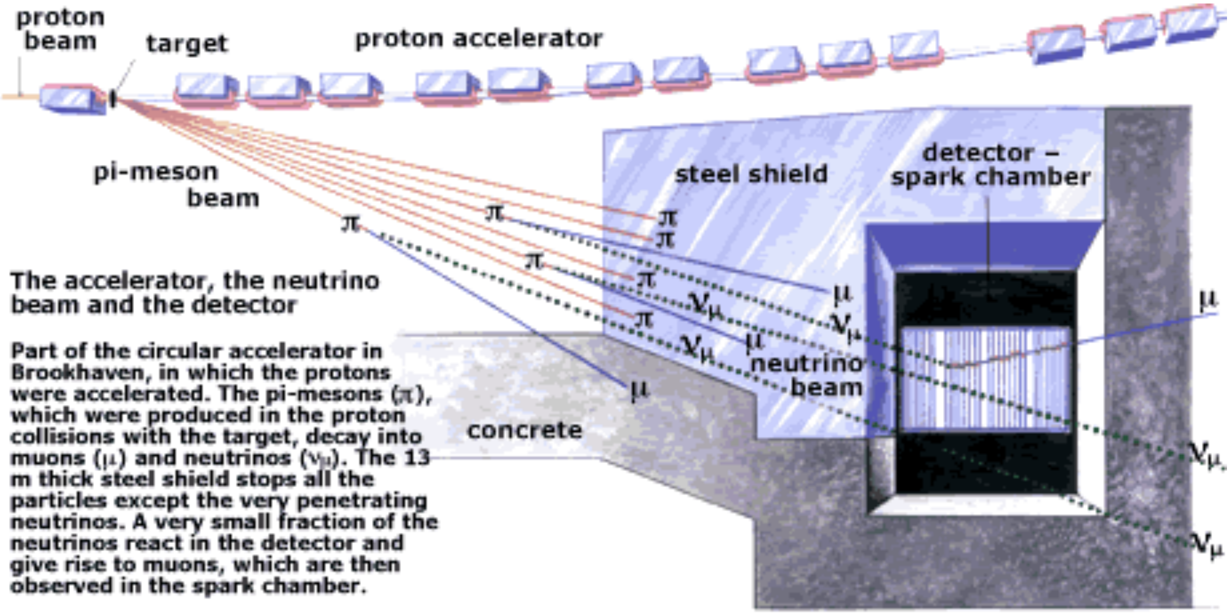
The second neutrino ν_μ Discovery

- **1962: L. Lederman, M. Schwartz, J. Steinberger discover second type of neutrino (at BNL): ν_μ**
- Detect neutrino flavor by detecting corresponding charged lepton


Lederman


Schwartz
(Nobel 1988)

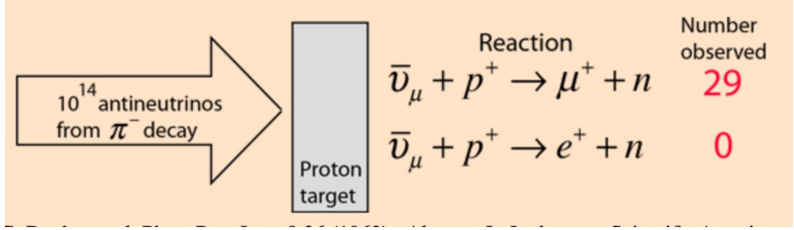

Steinberger



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.



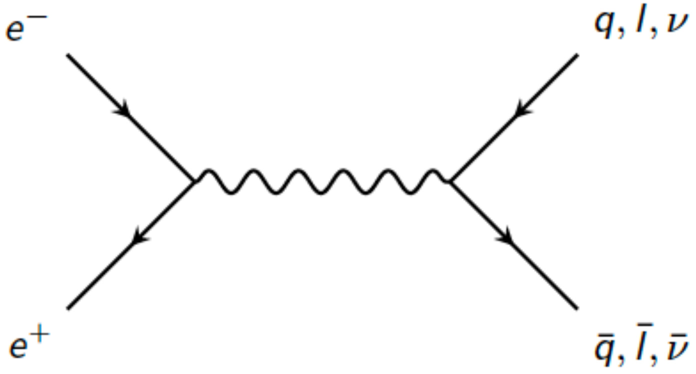
Reaction	Number observed
$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$	29
$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$	0

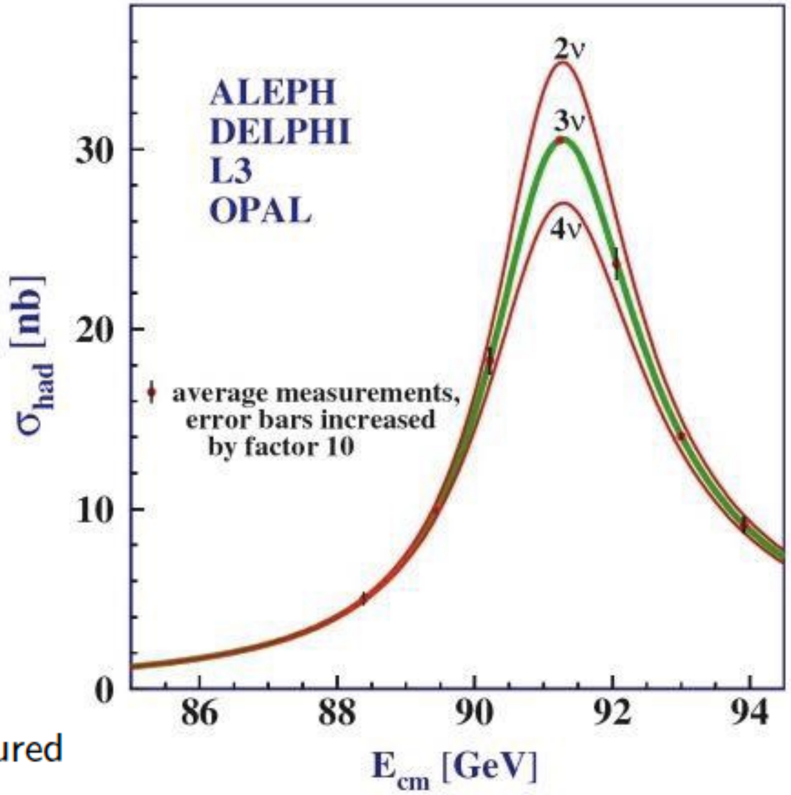
- Modern versions of Lederman, Schwartz, Steinberger experiment are accelerator neutrino experiments: Minos, Opera, T2K, NovA,…

Number of Neutrinos in the Standard Model

- **1989, the first LEP (CERN)** measurements of the Z width provided information about the number of families of neutrinos.
- The LEP demonstrates that **there are 3 (and only 3) families of neutrinos.**

$$e^+e^- \to Z^0 \to f\bar{f}$$





$$Z^0 \to q\bar{q}\,(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b})$$

$$Z^0 \to l\bar{l}\,(e^-e^+, \mu^-\mu^+, \tau^-\tau^+)$$

$$Z^0 \to \nu\bar{\nu}\,(\nu_e\bar{\nu_e}, \nu_\mu\bar{\nu_\mu}, \dots)$$

Total width: $\Gamma \sim$ decay probability

Partial widths: $\Gamma_i \sim$ branching rate

$\Gamma_Z, \Gamma_l, \Gamma_{\text{had}}$ - measured

Γ_ν - calculated

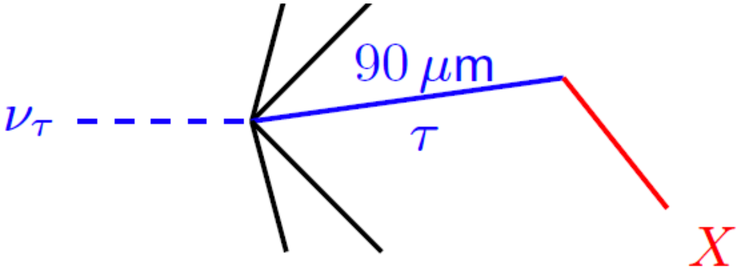
$$\boxed{\Gamma_Z = \Gamma_{\text{had}} + 3\Gamma_l + N_\nu\Gamma_\nu \Rightarrow N_\nu = 2.99 \pm 0.02}$$

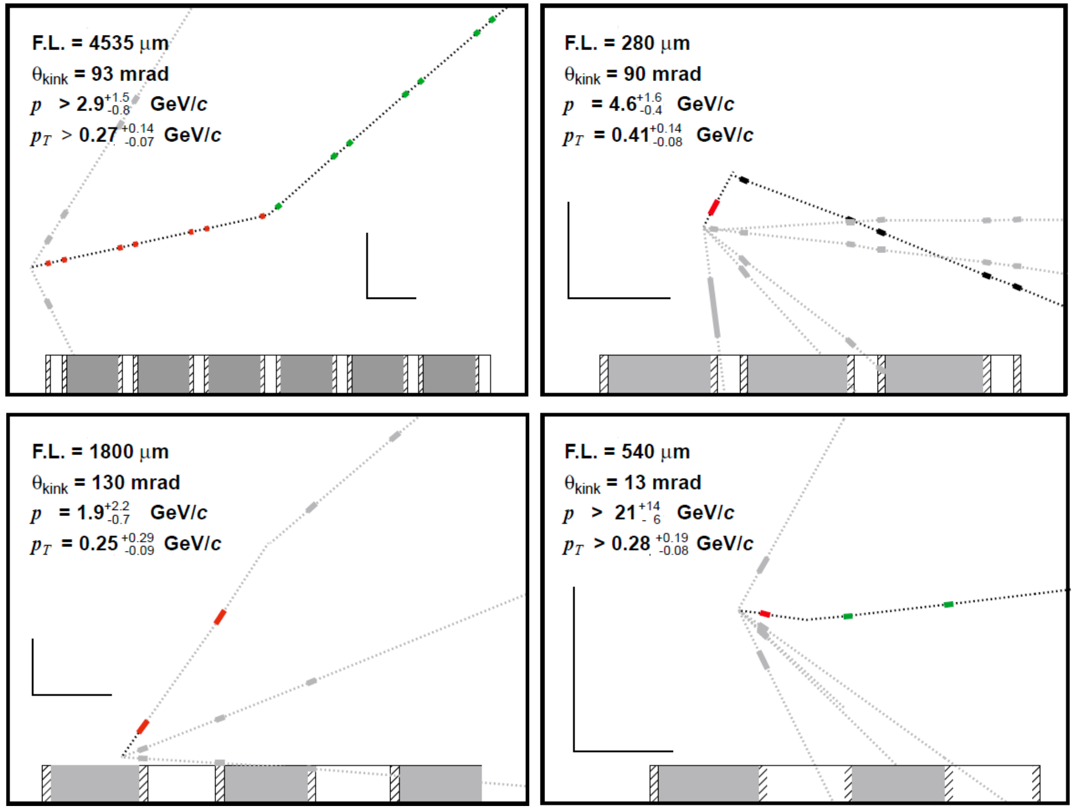
The third neutrino ν_τ Discovery

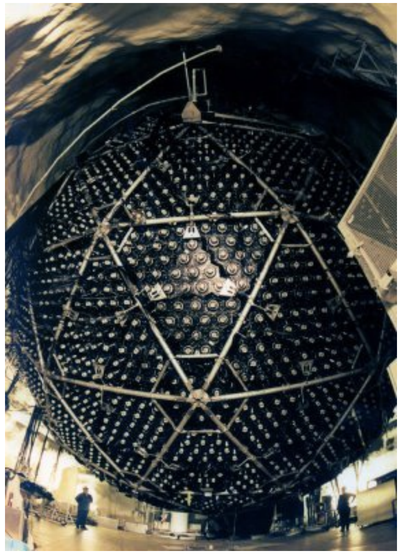
- Detecting a ν_τ is a challenge :
  - has to produce a τ lepton
  - One has to track a τ
  - lifetime is 3×10^{-13} s (ct = 90 μm)

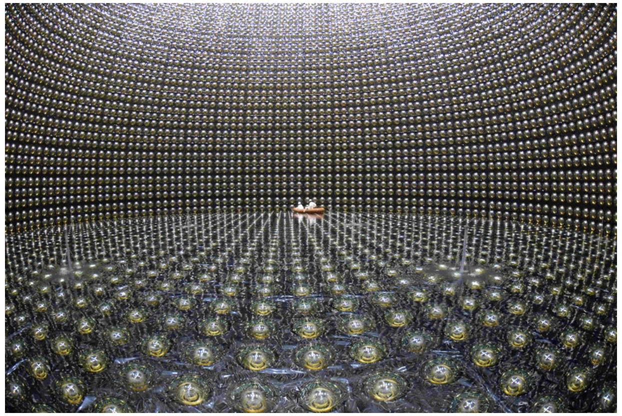
- Need emulsion

- 2000 : DONUT@FermiLab
  - DONUT searched for decays into 1 charged particle (86% of τ decays)
  - Out of 10^{13} neutrinos, only 1000 ν interactions recorded out of which 4 were identified as ν_τ







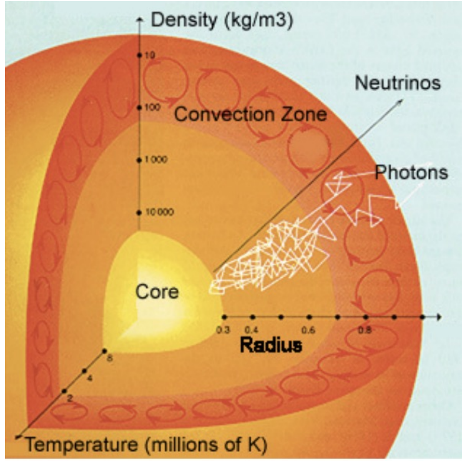


3. Neutrino Detection

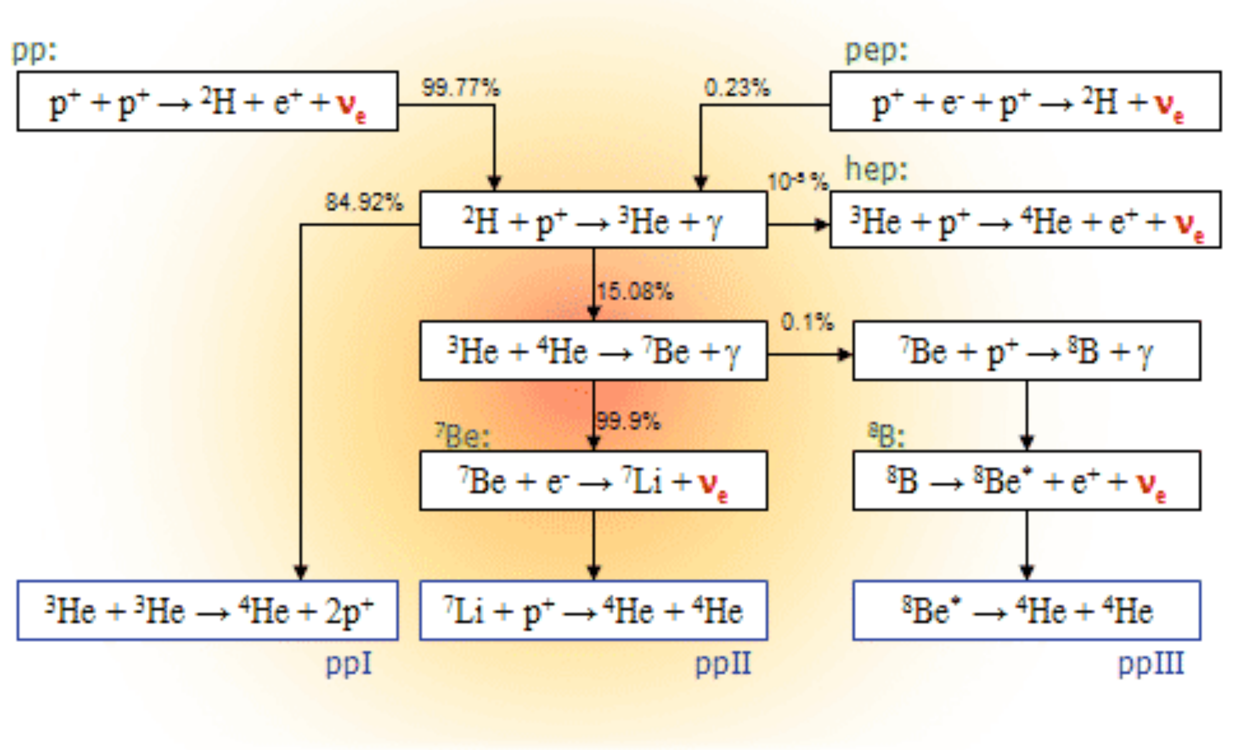
A succession of anomalies and surprises !

Stars Shine Neutrinos

1939: Bethe establishes the theory of stelar nucleosynthesis



Composition:
73% hydrogen (H)
25% helium (He)
2% other elements



pp: $p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99.77%

0.23%

pep: $p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

84.92%

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

hep: $^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

15.08%

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

0.1%

$^7Be + p^+ \rightarrow {}^8B + \gamma$

99.9%

^{7}Be: $^7Be + e^- \rightarrow {}^7Li + \nu_e$

^{8}B: $^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

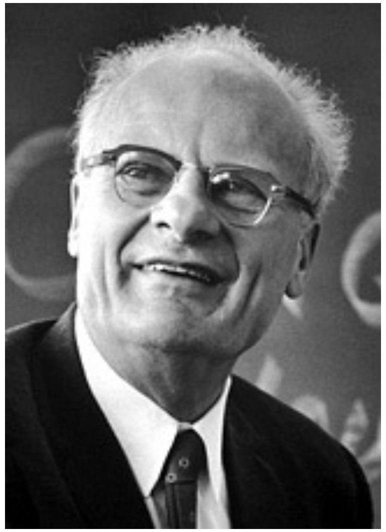
ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

$^8Be^* \rightarrow {}^4He + {}^4He$

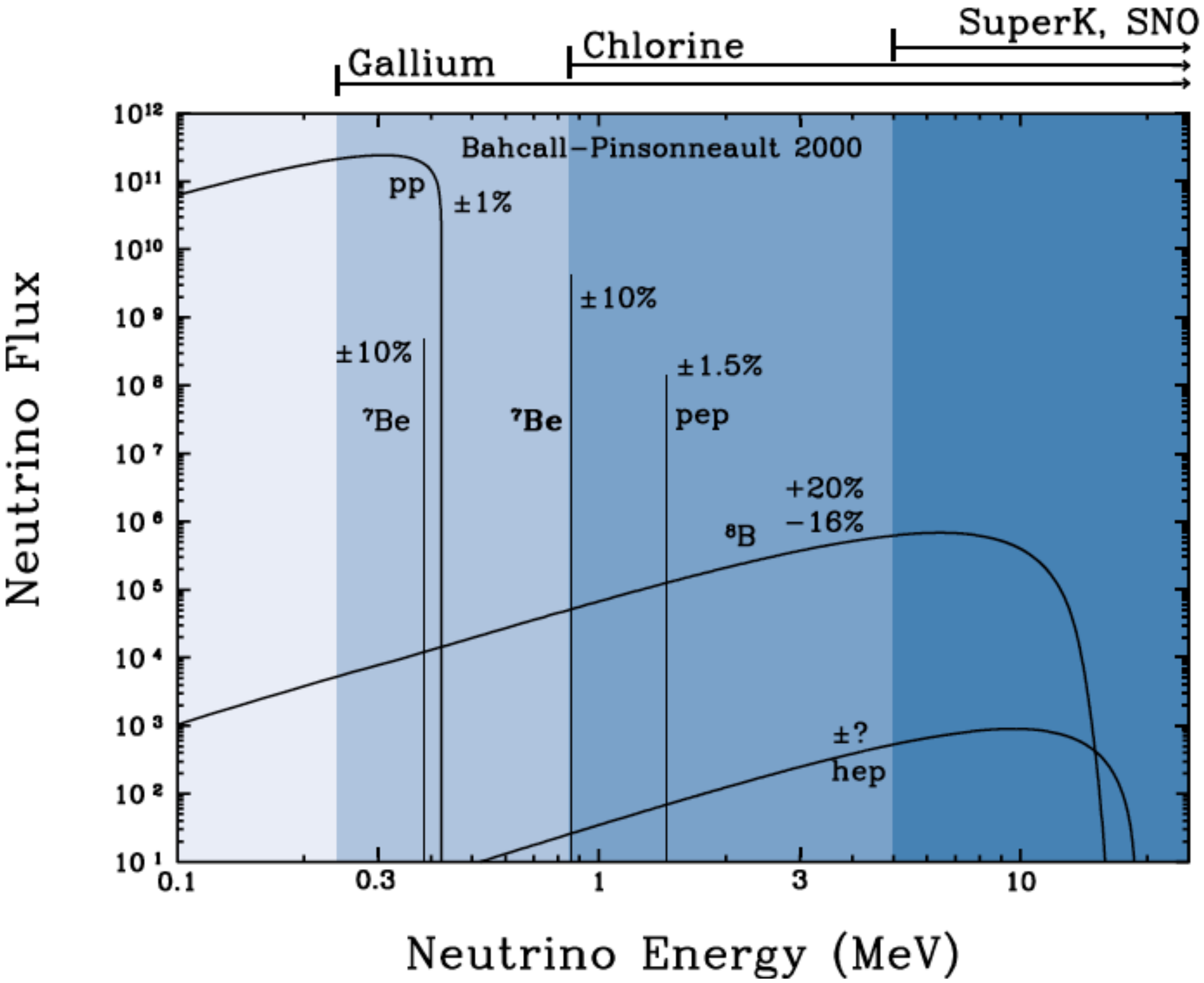
ppIII



Bethe
(Nobel 1967)

Theoretical Solar Models

1960: J. Bahcall predicted the energy spectrum of solar neutrinos.



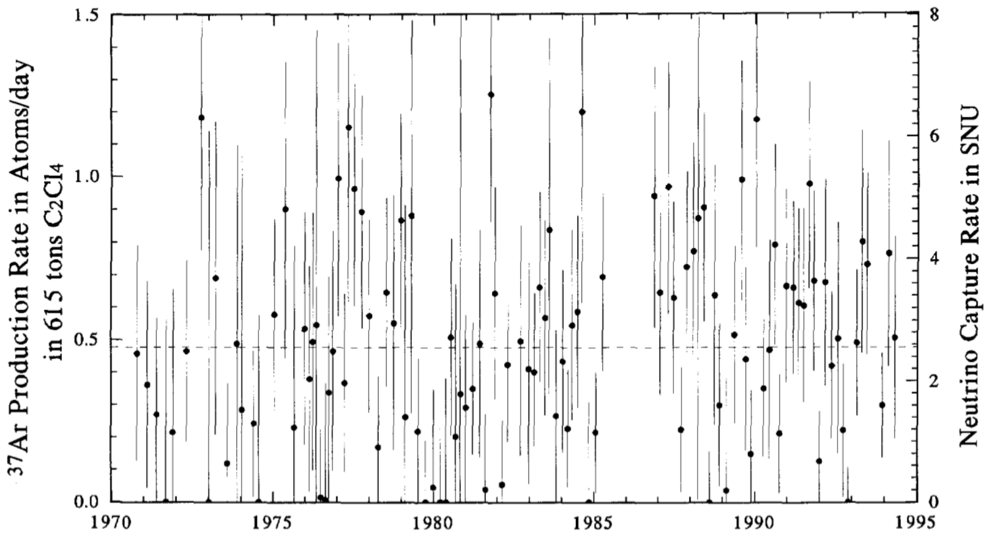
J. Bahcall

Solar Neutrino Problem

- **Late 1960's: R. Davis (BNL) built experiment to detect solar neutrinos**
- 400,000 L of perchloroethylene C_2Cl_4, 1478 meters underground in Homestake Mine
- neutrino capture $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (threshold 814 keV) → collect Ar to obtain solar neutrino
- 1 ν_e / day only transmutes chlorine to Argon

Raymond Davis
(Nobel 2002)

25 years of data collection



Result : 2.56 ± 0.20 SNU

Solar Model (7.6 ± 1.2 SNU)

$\nu_e^{exp}/\nu_e^{theo} \approx 1/3$

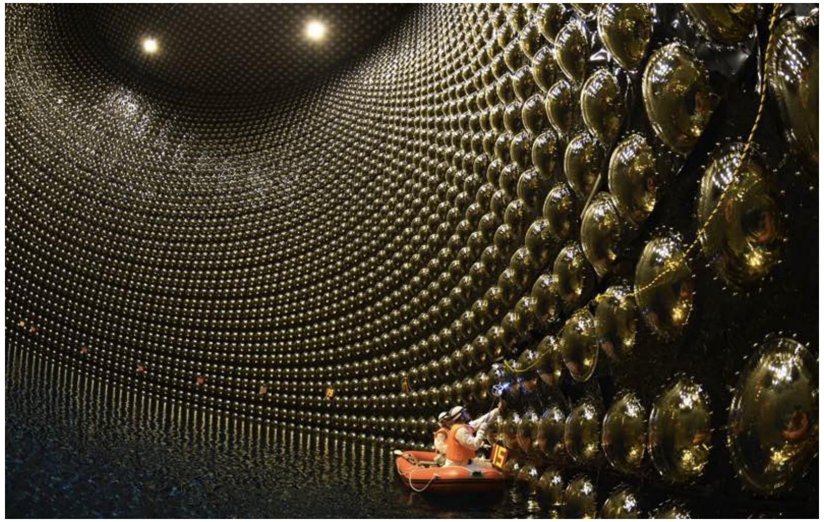
Solar Neutrino Problem: Only 1/3 of the solar neutrinos predicted by Bahcall are detected!?

Deficit confirmed by several experiments

(Solar Neutrino Unit: 1 SNU = 10^{-36} capture/target atom/s)

Atmospheric Neutrino Anomaly

- **1998: SuperKamiokande (originally proton decay experiment) detected atmospheric neutrinos deficit**
  - 50 kton water tank (40m x 40m), 1km underground
  - Inner detector ~11 000 photo sensors (PMTs)
  - Outer detector ~1 800 PMTs to veto cosmic
  - Particles are identified by their Cherenkov rings
    - Muons produce sharp Cherenkov rings in the detector
    - Electrons scatter more so produce “fuzzier” rings



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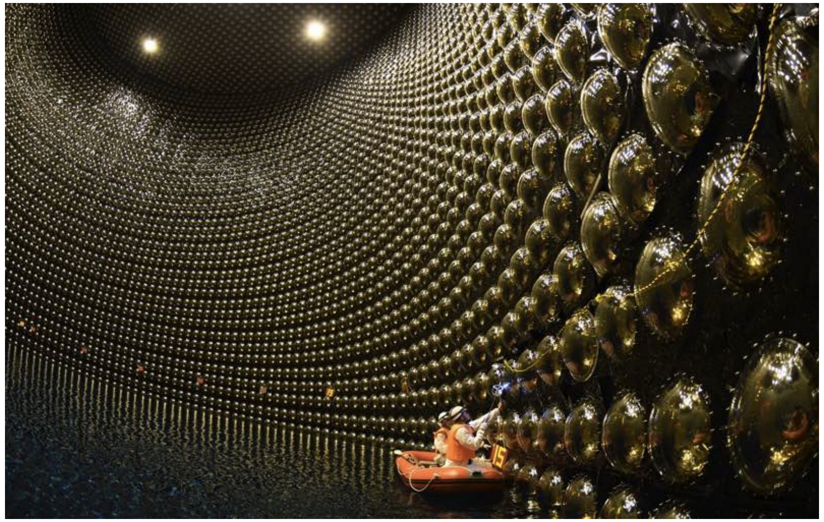
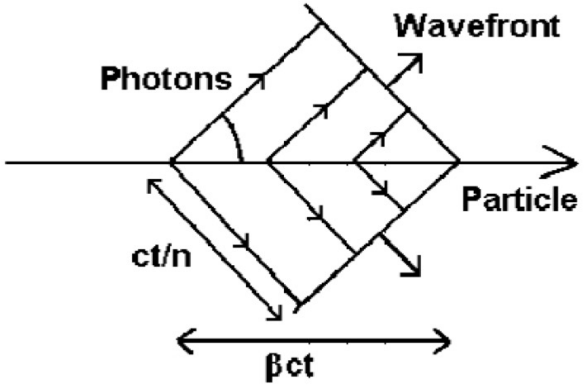
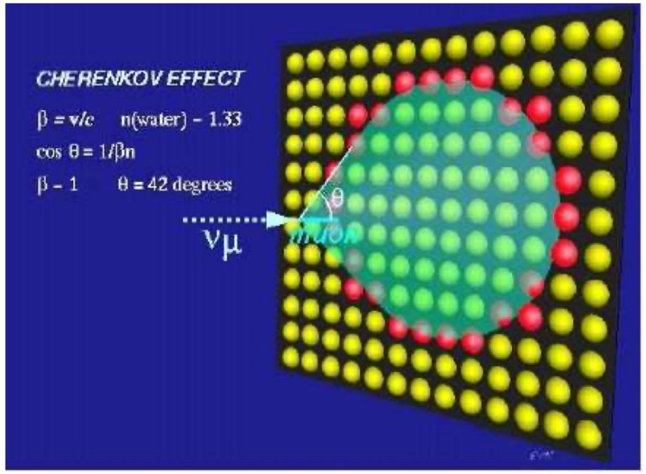
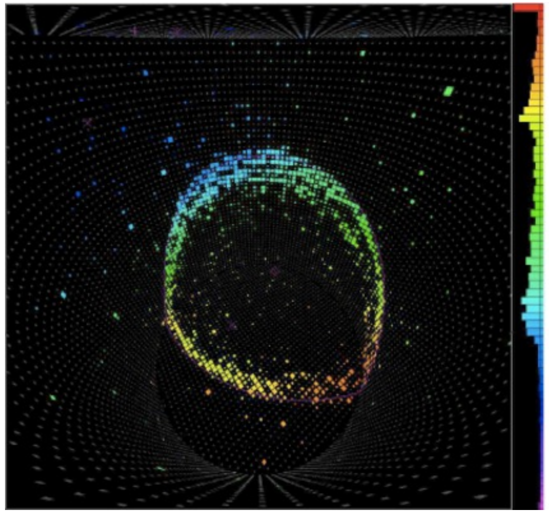


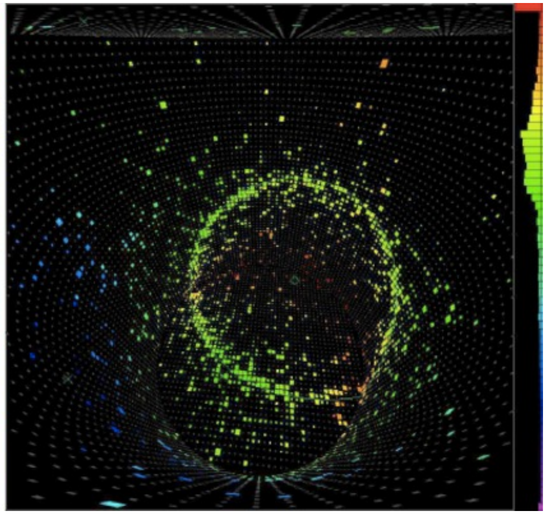




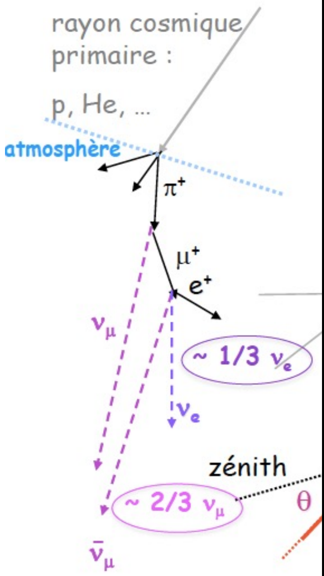
Muon-like ring (sharp)

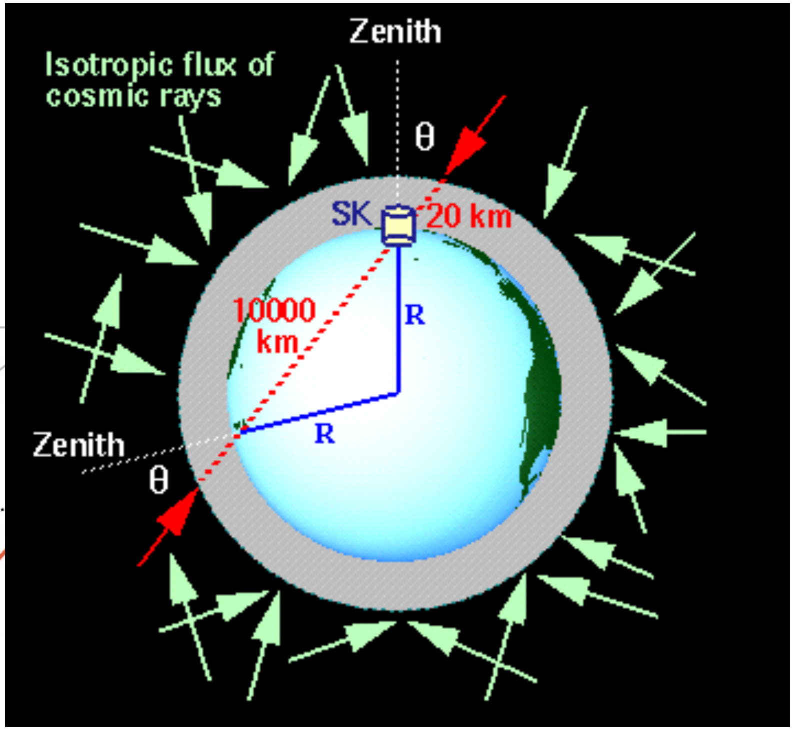


Electron-like ring (fuzzy)

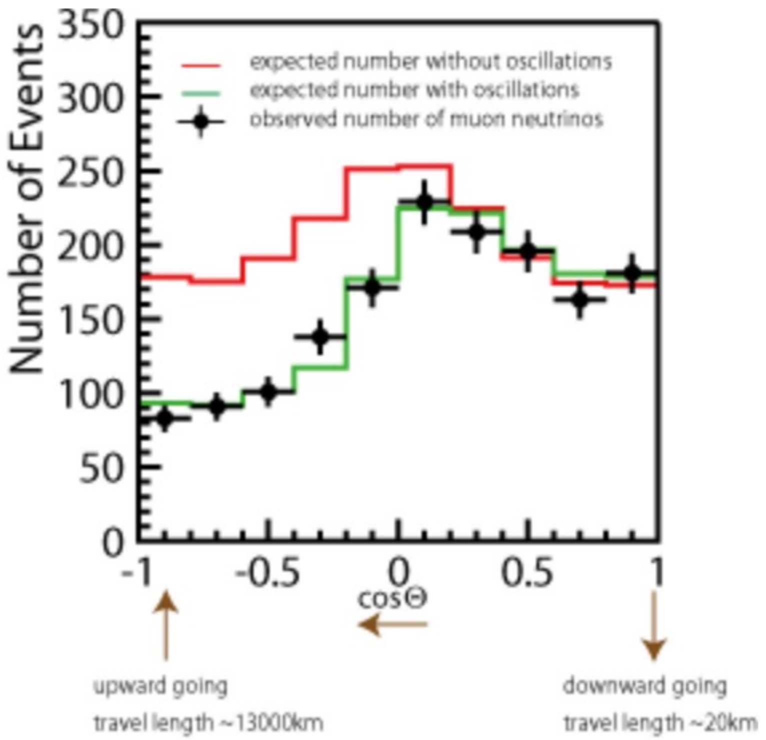


Atmospheric Neutrino Anomaly





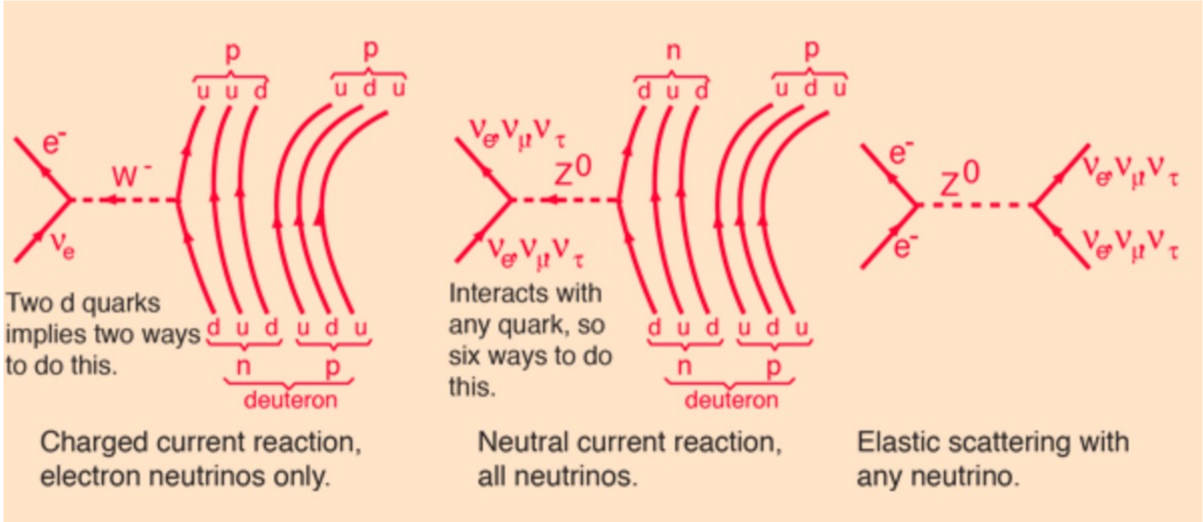
ν can tell time ! → ν have a mass



- Isotropy of the cosmic rays > 2GeV → $\boxed{\dfrac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1}$
- But Super-Kamiokande finds → $\boxed{\dfrac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04}$
- A striking feature in the zenith angle distribution for ν_μ: the deficit occurred only in the upward-going sample, where the neutrinos had passed through the Earth before being detected.

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 different reactions sensitive to different neutrino flavors:
  1. **Charged Current** : $\nu_e + d \rightarrow p + p + e^-$ only sensitive to ν_e ("**neutrino in-charged lepton out** »)
  2. **Neutral Current** : $\nu_x + d \rightarrow p + p + n + \nu_x$ sensitive to all flavors ("**neutrino in-neutrino out**")
  3. **Elastic Scattering** : $\nu_x + e^- \rightarrow e^- + \nu_x$ much weaker than CC, NC processes, mostly sensitive to ν_e



Two d quarks implies two ways to do this.

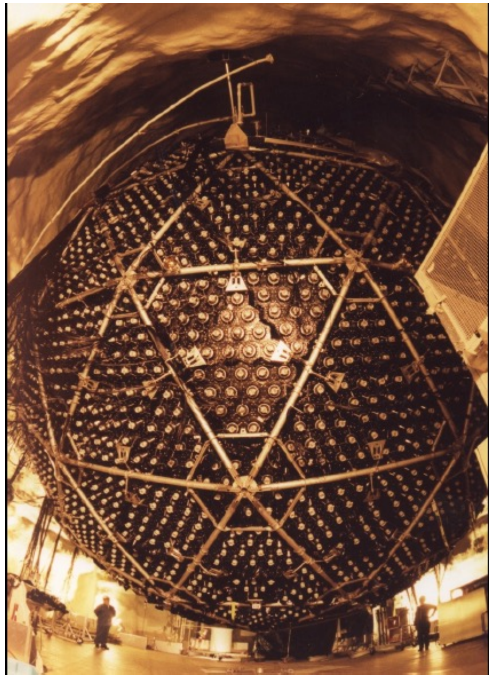
Interacts with any quark, so six ways to do this.

Charged current reaction, electron neutrinos only.

Neutral current reaction, all neutrinos.

Elastic scattering with any neutrino.

Sudbury Neutrino Observatory (Canada)



Solar Neutrino Solution

The Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\, p\, p \;\Rightarrow \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \qquad (\nu \text{ remains a } \nu)$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.301 \pm 0.033$$

Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos change flavor.

For solar neutrinos, $P(\nu_e \rightarrow \nu_e) = 0.3$.

Change of flavor does not change the total number of neutrinos.

The total flux, $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$, should agree with Bahcall's prediction.

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (5.54 \pm 0.32 \pm 0.35) \times 10^6/\text{cm}^2\text{sec}$

Theory*: $\phi_{total} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

*Bahcall, Basu, Serenelli

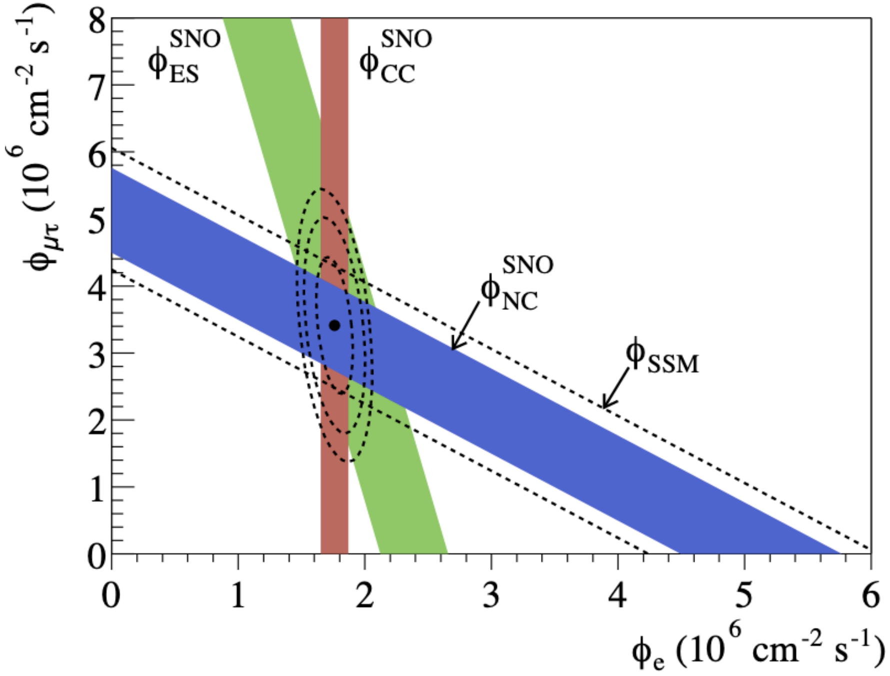
John Bahcall and Ray Davis both stuck to their results for several decades, and both were ***right*** all along.

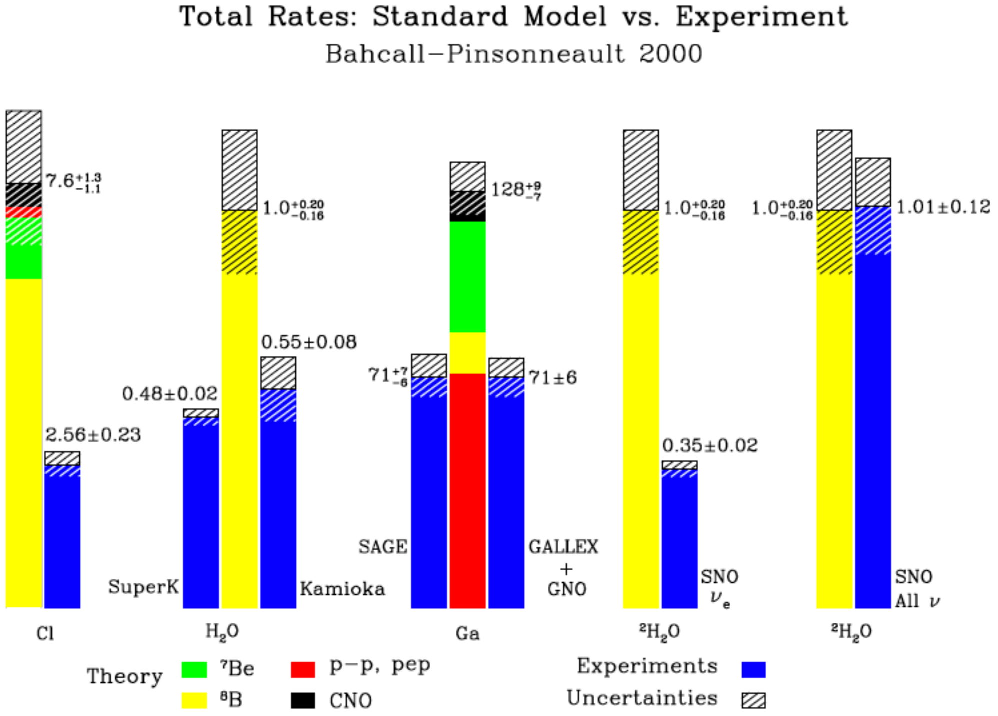
Solar Neutrino Problem

- **2001: The SNO Experiment: conclusive evidence for flavor change**

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

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

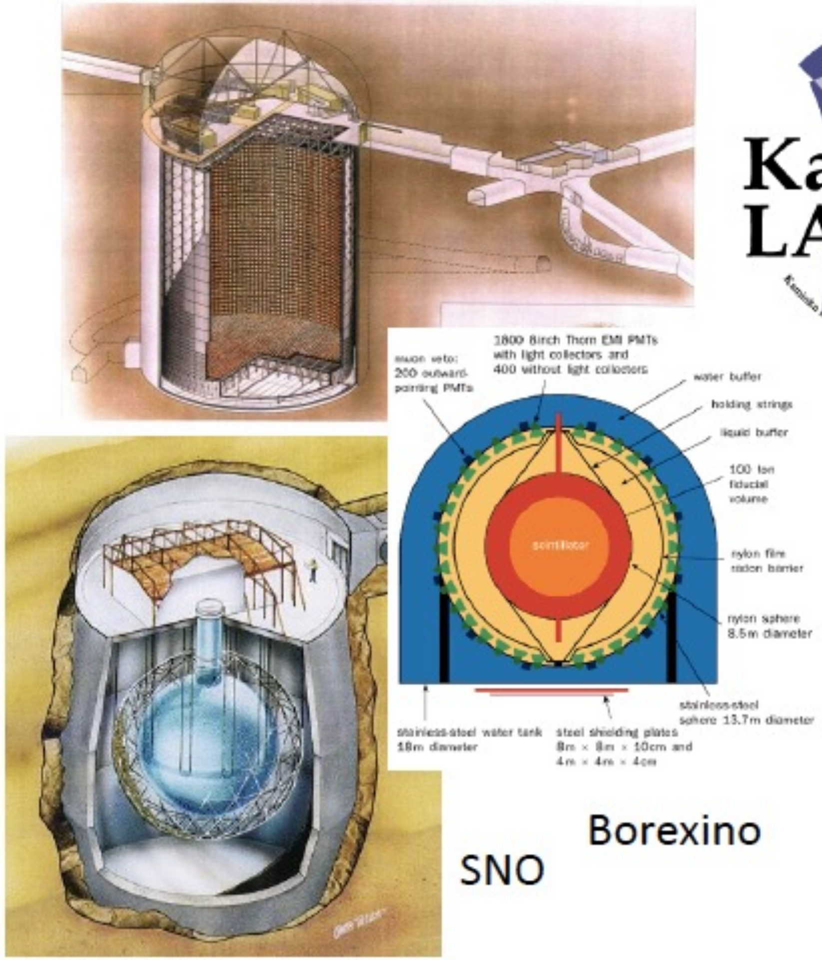




- All the neutrinos coming from the sun arrive, but not all of them are ν_e !
- Two-thirds of the neutrinos produced in the sun transform into a different flavor before reaching the detector.

And many other experiments and results…

SuperKamiokande



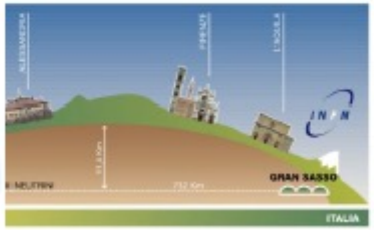
Borexino

SNO

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

MINOS, Opera



NOvA

T2K

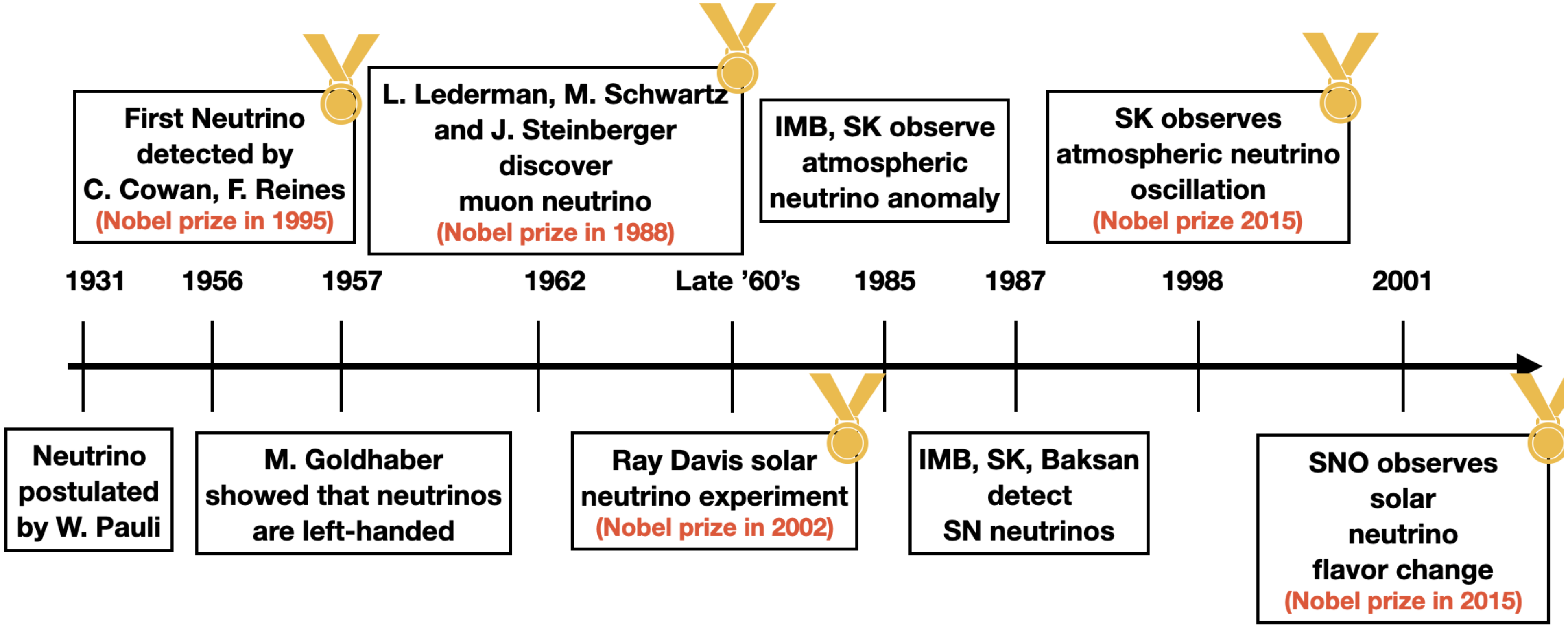
DOUBLE CHOOZ

Daya Bay

θ_{13}

RENO

Neutrino History



1931
Neutrino postulated by W. Pauli

1956
First Neutrino detected by C. Cowan, F. Reines
(Nobel prize in 1995)

1957
M. Goldhaber showed that neutrinos are left-handed

1962
L. Lederman, M. Schwartz and J. Steinberger discover muon neutrino
(Nobel prize in 1988)

Late ’60’s
Ray Davis solar neutrino experiment
(Nobel prize in 2002)

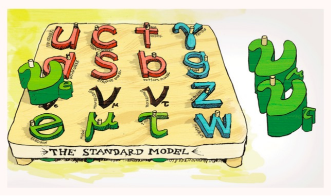
1985
IMB, SK observe atmospheric neutrino anomaly

1987
IMB, SK, Baksan detect SN neutrinos

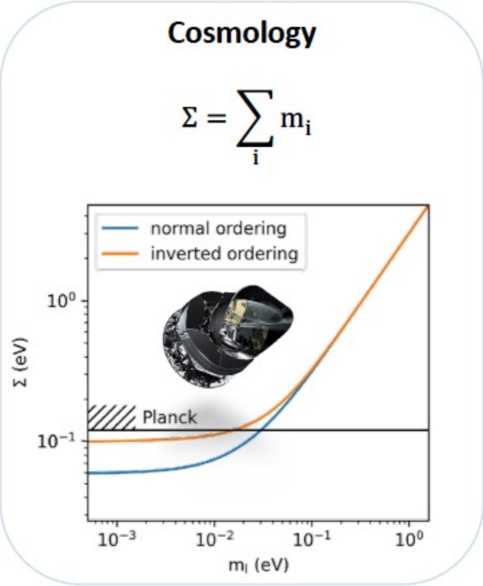
1998
SK observes atmospheric neutrino oscillation
(Nobel prize 2015)

2001
SNO observes solar neutrino flavor change
(Nobel prize in 2015)

- Theoretical birth was difficult and highly hypothetical.
- First experimental observation occurred 26 years later.
- The observation of neutrinos, and more recently neutrino oscillations, has opened up an entire field of investigation and led to investments of several million dollars!
- Latest neutrino Nobel prize awarded to observation of flavor change of neutrinos: only possible for massive neutrinos however neutrinos are massless in the SM→ conclusive evidence for physics beyond the Standard Model!

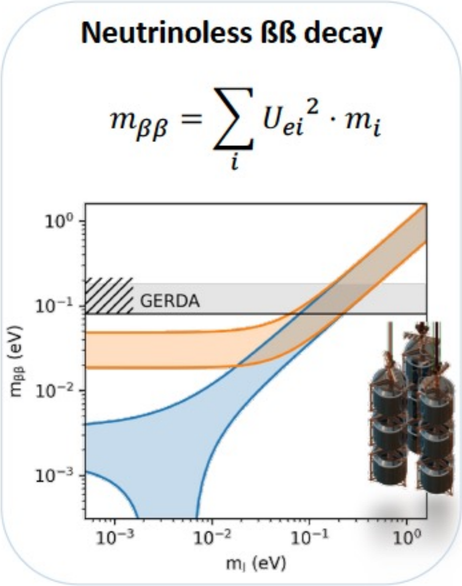


Limits on Neutrino Mass(es)



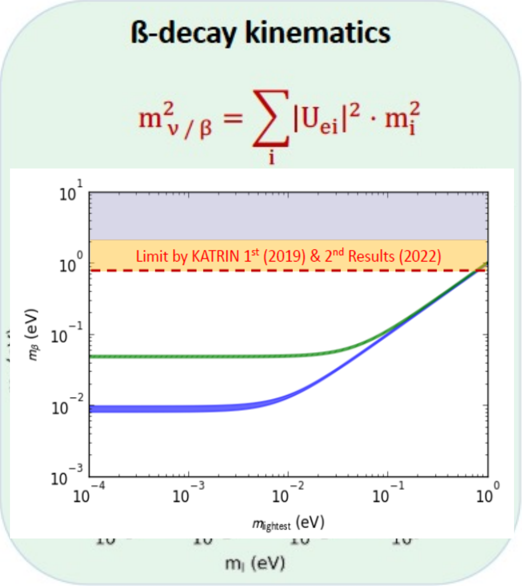
Cosmology

$$\Sigma = \sum_i m_i$$



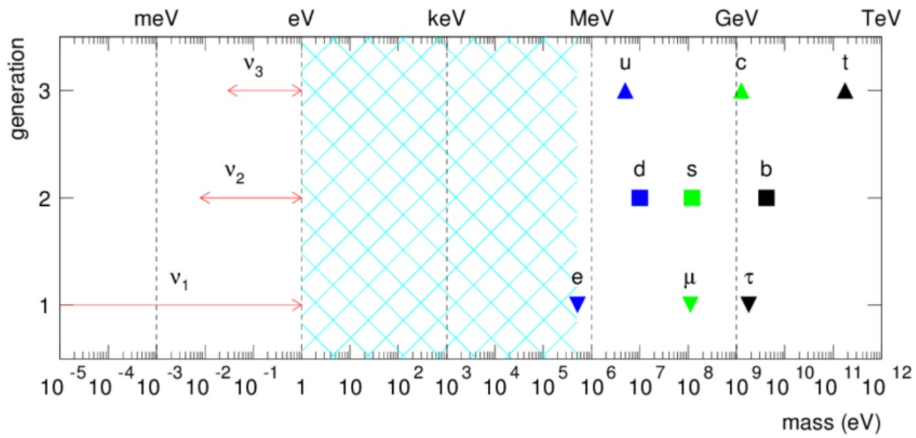
Neutrinoless ßß decay

$$m_{\beta\beta} = \sum_i U_{ei}^{\,2} \cdot m_i$$



ß-decay kinematics

$$m^2_{\nu/\beta} = \sum_i |U_{ei}|^2 \cdot m_i^2$$

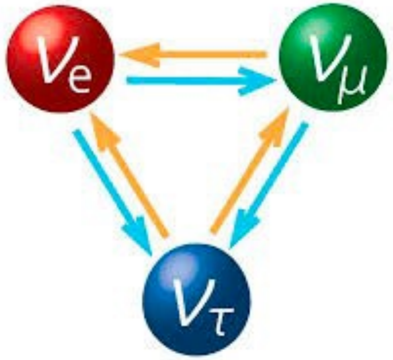


- KATRIN: first sub-eV neutrino mass limit from a direct experiment (measurement of the electron β−spectrum), **$m_\nu < 0.8$ eV (90% C.L.)**

- Cosmological observations provide upper bounds on the sum of the masses of all three flavors of neutrinos, but they do not provide direct measurements of individual neutrino masses : **$\Sigma\ m_\nu < 0.12$ eV (95% C.L.)**

- The reason why neutrino mass is more than one million times smaller than the mass of electron or quarks is shrouded in mystery.

The Big Bang Theory: The Speckerman Recurrence

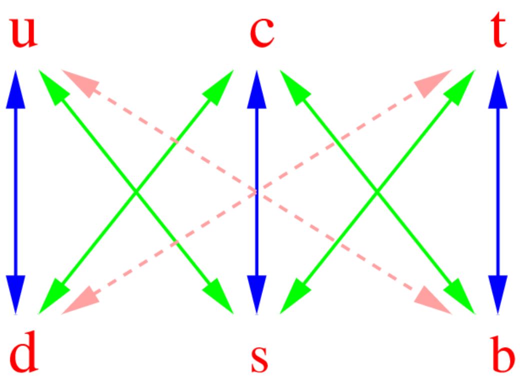


4. Neutrino Oscillations

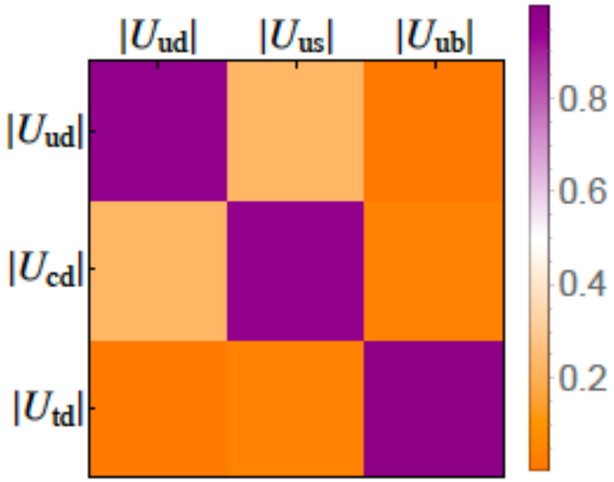
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

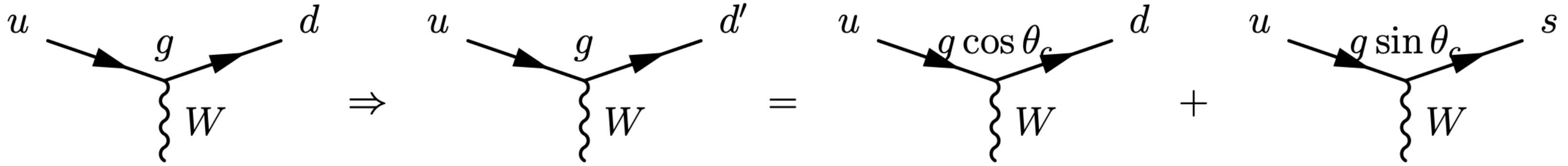
Quark Mixing

- Flavor mixing already present in the SM in the quark sector via the CKM matrix
- CKM matrix measured to a very good accuracy
- Small mixing angles in the quark sector, CKM matrix is close to a diagonal matrix



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$





$\theta_{12}^{CKM} = 13.1°$,

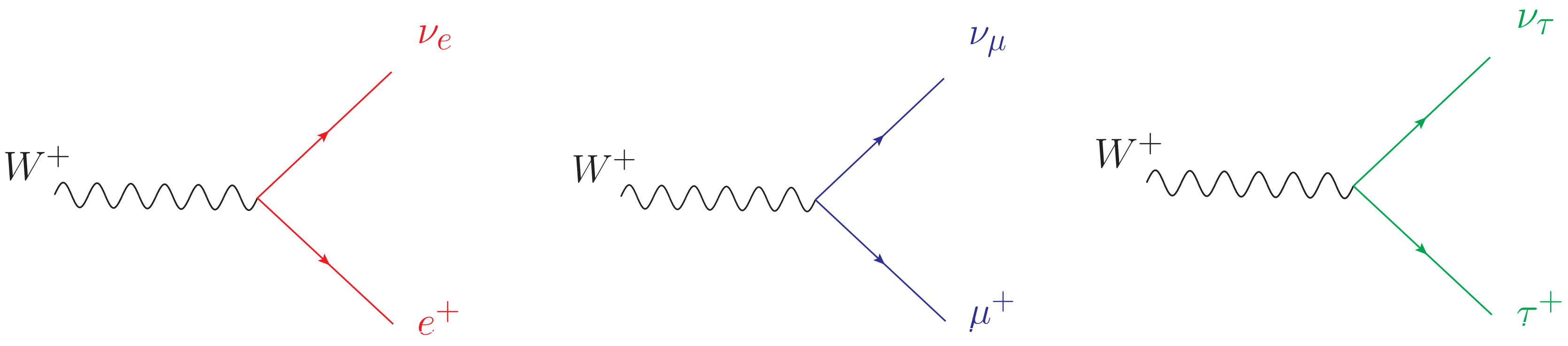
$\theta_{13}^{CKM} = 0.2°$,

$\theta_{23}^{CKM} = 2.3°$

Lepton Mixing

$$\mathcal{L}_{\text{gauge}-\text{lepton}} \supset -\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{e} & \bar{\mu} & \bar{\tau} \end{pmatrix} W_\mu^- \gamma_\mu P_L\, U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + h.c.$$

The neutrino flavour basis:



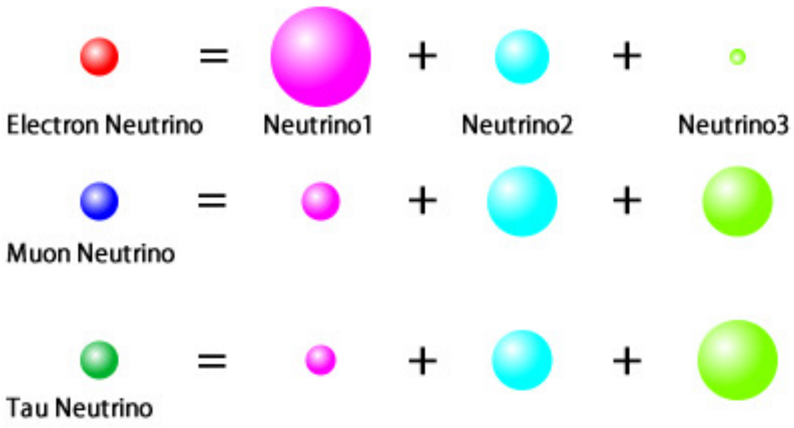
States produced in a charged current interaction in combination with e, μ, τ

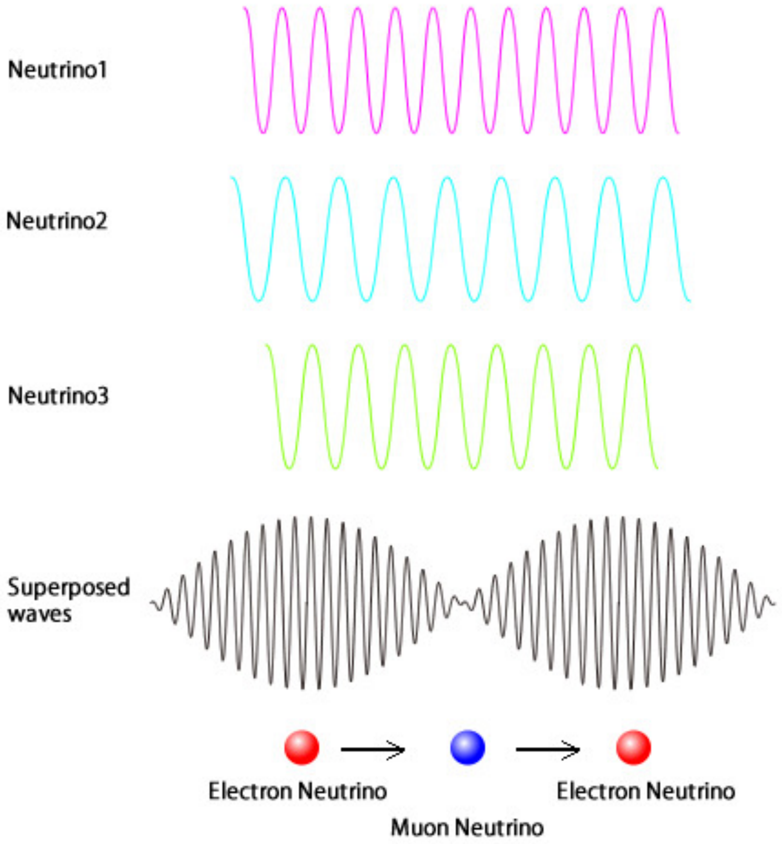
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Eigenstates of the free Hamiltonian

Each neutrino flavor state is a sum of proportions of the three neutrino mass states!

Neutrino Oscillations

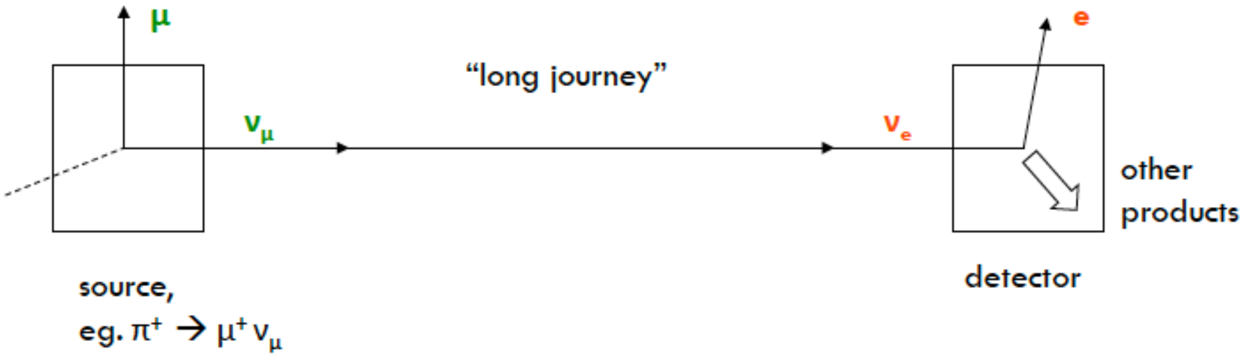




- Neutrinos exhibit the properties of a particle as well as a wave.
- neutrino1, neutrino2 and neutrino3, each with different mass eigenstates, travel through space as waves that have a different frequency.
- The flavor of a neutrino is determined as a superposition of the mass eigenstates.
- The type of the flavor oscillates, because the phase of the wave changes.

What is Neutrino Oscillation?

- From Quantum Mechanics, we know that particles can act as waves.
- Particles can exist in different states, and, in addition, they can change from one state to another.
- This change, however, requires two things:
  - Particles must have mass (they must have “internal clocks”).
  - Different particle states must have different masses.
- **Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavour (electron, muon, or tau) can later be measured to have a different flavour.**



Production
Flavour
States

Propagation
Massive states
(eigenstates of the
Hamiltonian)

Detection
Flavour
states

Neutrino Mixing

Eigenstates are related through a rotation matrix.
Pontecorvo–**M**aki–**N**akagawa–**S**akata (**PMNS**) matrix

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Neutrino mixing is expressed in terms of three **mixing angles:** θ_{12},θ_{13},θ_{23}.
One CP-Violating phase: δ_{CP} required to have an imbalance between neutrino and anti-neutrino vacuum oscillations.

Neutrino Oscillations in Vacuum

Plane wave derivation

- Let us suppose that a neutrino of flavor α is produced at t_0. It is therefore a superposition of the mass eigenstates that we assume to be plane waves with spatial momentum p:

$$|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i} |\nu_i(\mathbf{p})\rangle$$

- The mass eigenstates are eigenstates of the free Hamiltonian:

$$\hat{H}|\nu_i(\mathbf{p})\rangle. = E_i(\mathbf{p})|\nu_i(\mathbf{p})\rangle, \quad E_i(\mathbf{p})^2 = \mathbf{p}^2 + m_i^2$$

- The time evolution operator from t_0 →t is given by $e^{-i\hat{H}(t-t_0)}$ and therefore the state at time t is given by:

$$|\nu_\alpha(t)\rangle = e^{-i\hat{H}(t-t_0)}|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i} e^{-iE_i(\mathbf{p})(t-t_0)}|\nu_i(\mathbf{p})\rangle$$

Neutrino Oscillations in Vacuum

- The probability that at time t the state is in flavour β:

$$P(\nu_\alpha \to \nu_\beta)(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(t-t_0)} \right|^2$$

$$= \sum_{i,j} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} e^{-i(E_i - E_j)(t-t_0)}$$

- Since the neutrinos are ultra-relativistic, we can approximate

$$E_i(\mathbf{p}) - E_j(\mathbf{p}) \simeq \frac{1}{2} \frac{m_i^2 - m_j^2}{|\mathbf{p}|} + \mathcal{O}(m^4)$$

- Neutrinos propagate at almost the speed of light.

$$L \simeq t - t_0, v_i \simeq c$$

$$\boxed{P(\nu_\alpha \to \nu_\beta)(L) \simeq \sum_{i,j} e^{i \frac{\Delta m^2_{ji} L}{2E}} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}}$$

Neutrino Oscillation : 2-flavor approximation

- In the simplest case of two-family mixing, the mixing matrix depends on just one mixing angle:

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

- Appearance probability

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)}$$

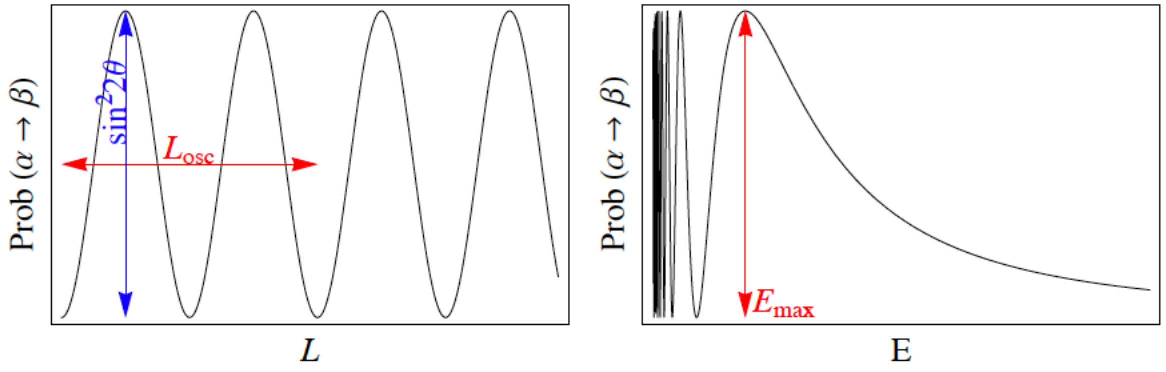
Amplitude

Frequency

- Disappearance or survival probability

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

- The probability of oscillation depends on:
  - the energy of the neutrino E
  - the distance traveled L
  - the difference in mass Δm^2
  - the mixing angle parameter θ



- θ and Δm^2 are properties of the neutrinos,
- L and E are properties of the experiment

→**The important number for a neutrino experiment is therefore the ratio L/E**

Neutrino Oscillation : 2-flavor approximation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

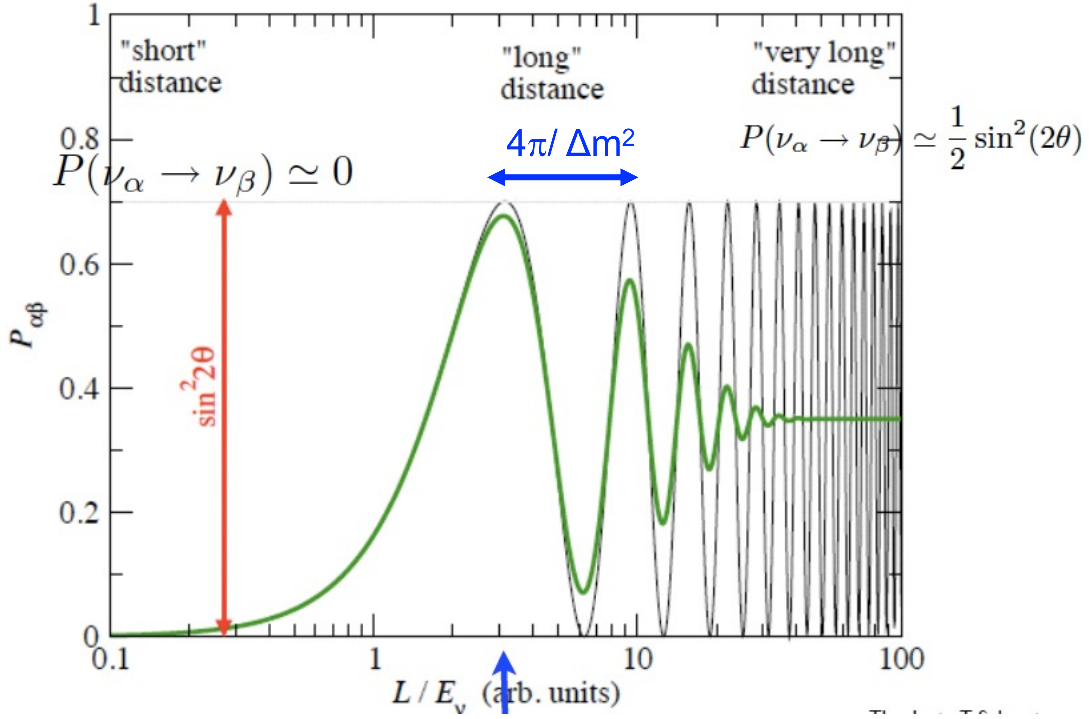
- Optimal experiment: $\frac{E}{L} \sim \Delta m^2$
- If $\frac{E}{L} \gg \Delta m^2$ → Oscillation suppressed

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2 2\theta \left(\Delta m^2\right)^2$$

- If $\frac{E}{L} \ll \Delta m^2$ → Fast oscillation regime

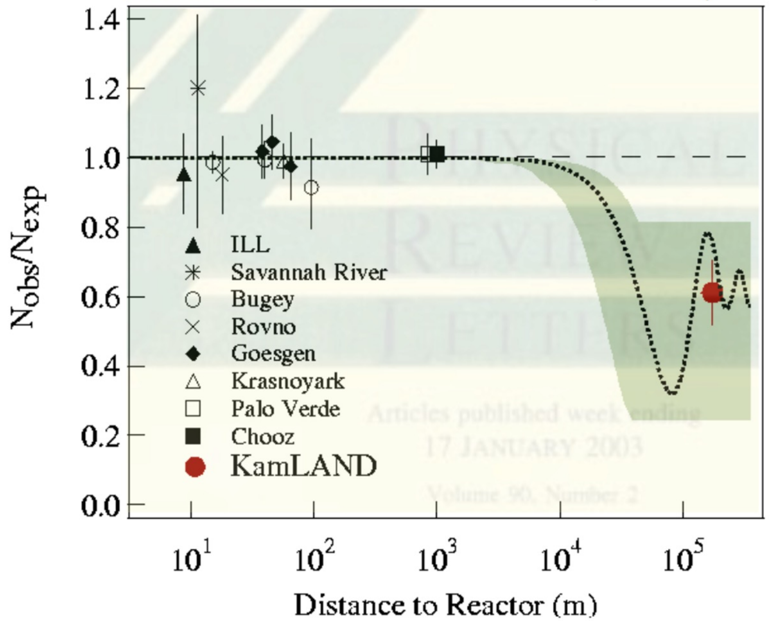
$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \,\langle\sin^2 \frac{\Delta m^2 L}{4E}\rangle \simeq \frac{1}{2}\sin^2 2\theta = |U^*_{\alpha 1}U_{\beta 1}|^2 + |U^*_{\alpha 2}U_{\beta 2}|^2$$

Equivalent to incoherent propagation: sensitivity to mass splitting is lost

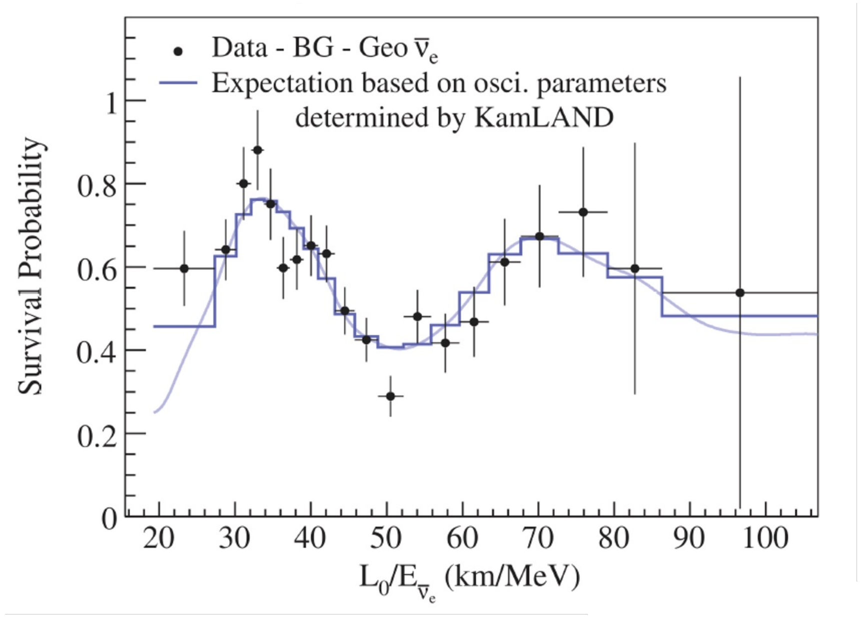


KamLAND observes neutrino oscillation from nuclear reactors

First KamLAND Results (2002)

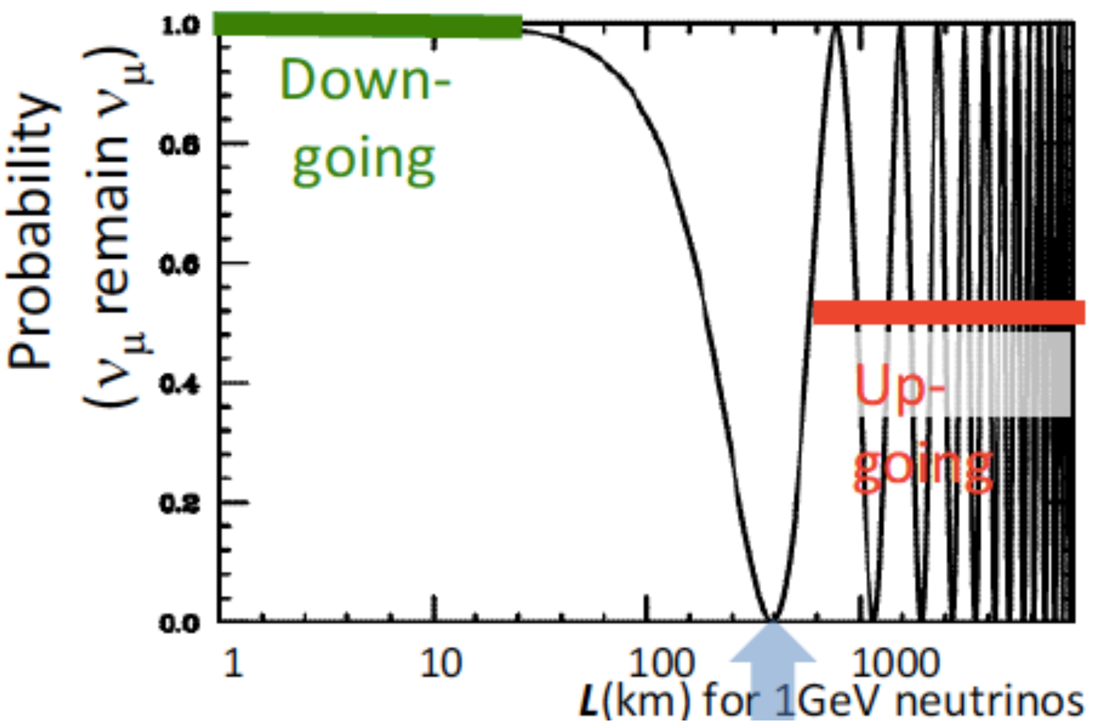


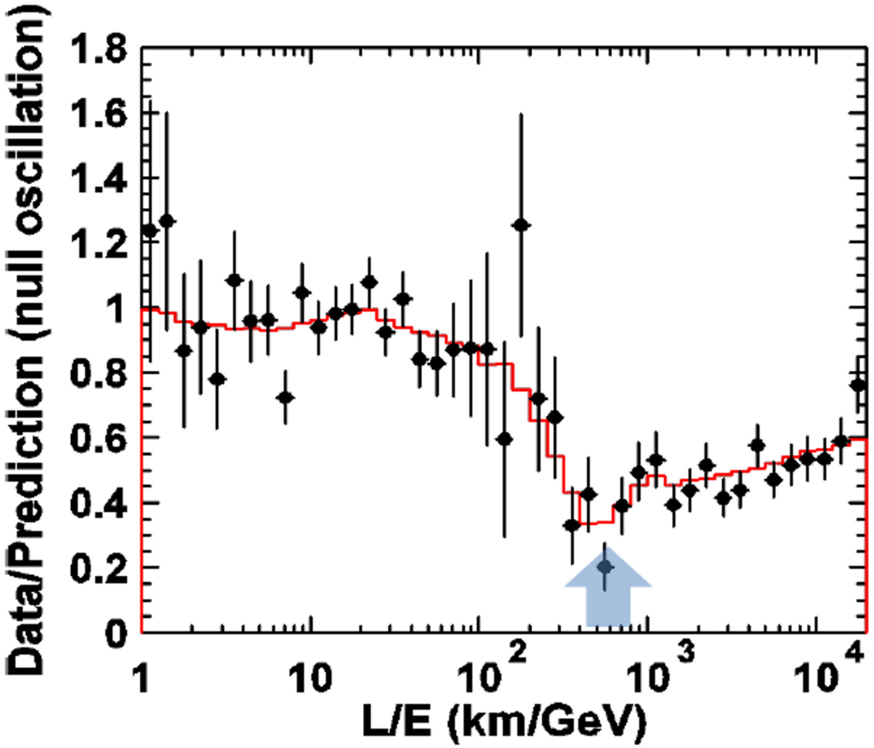
$$\overline{\nu}_e \rightarrow \overline{\nu}_e$$



- **2002 : KamLAND sees very well the oscillation of neutrinos from nuclear reactors.**
- KamLAND was located at about 200 km of nuclear reactors and all the experiments before KamLAND were too close to the nuclear reactor (few km) to see the oscillation.
- **2004: First result: KamLAND sees full neutrino oscillation**
- The Survival Probability is computed from the number of $\bar{\nu}_e$ produced by the nuclear reactor and detected by KamLAND. It depends on the ratio between the distance KamLAND-nuclear reactor and the energy of the neutrinos.

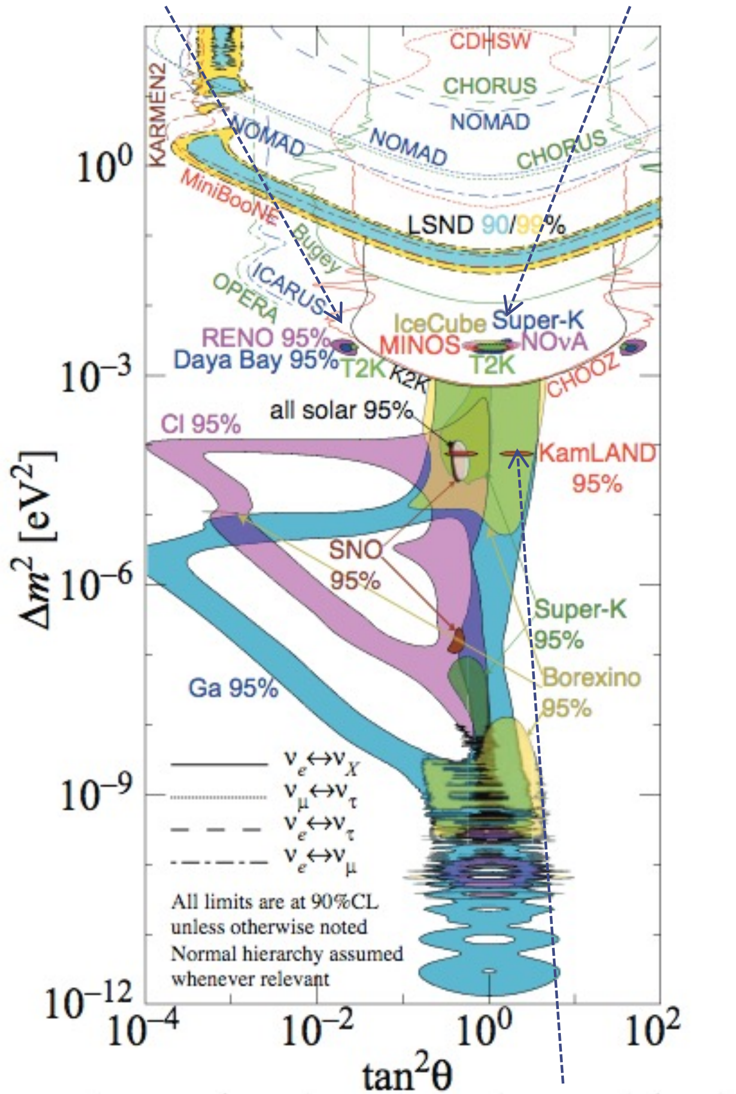
First observation of neutrino oscillation from atmospheric neutrinos in SuperKamiokande





- 2004, using only the high distance/energy (L/E) resolution events, SuperKamiokande showed that the measured ν_μ survival probability has a dip corresponding to the first minimum of the theoretical survival probability near L/E=(500 km/GeV).
- This was the first evidence that the neutrino survival probability obeys the sinusoidal function predicted by neutrino oscillations.

Mesuring Oscillation Parameters



Reactor Sector

Atmospheric Sector

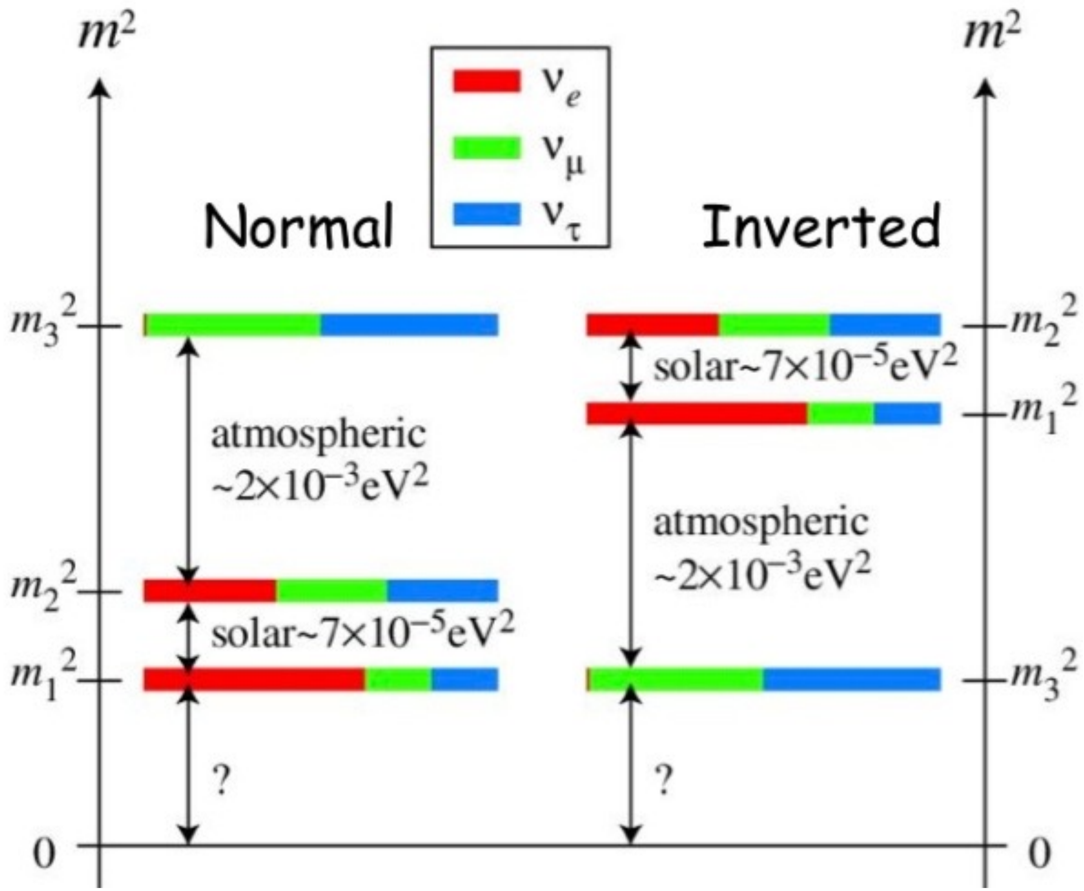
Solar Sector

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ /10^{-1}	3.18 ± 0.16	2.71–3.70	5.2%
$\sin^2\theta_{23}$ /10^{-1} (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	4.9%
$\sin^2\theta_{23}$ /10^{-1} (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	4.8%
$\sin^2\theta_{13}$ /10^{-2} (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	3.0%
$\sin^2\theta_{13}$ /10^{-2} (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.80–2.00	
δ/π (IO)	1.54 ± 0.13	1.14–1.90	

arXiv:2006.11237

- Most of the parameters measured with < 5% precision.
- θ_{23} is known with 5% precision.
- Remaining parameters are δ_{CP} and the mass ordering.

Mass Hierarchy



- The oscillation probability is sensitive to the squared mass differences of the three neutrino : $\Delta m^2_{ij} = m^2_i - m^2_j$

m_{min} ? ?

$$m_1 = m_{\text{min}}$$
$$m_2 = \sqrt{m^2_{\text{min}} + \Delta m^2_{\text{sol}}}$$
$$m_3 = \sqrt{m^2_{\text{min}} + \Delta m^2_{\text{A}} + \Delta m^2_{\text{sol}}/2}$$

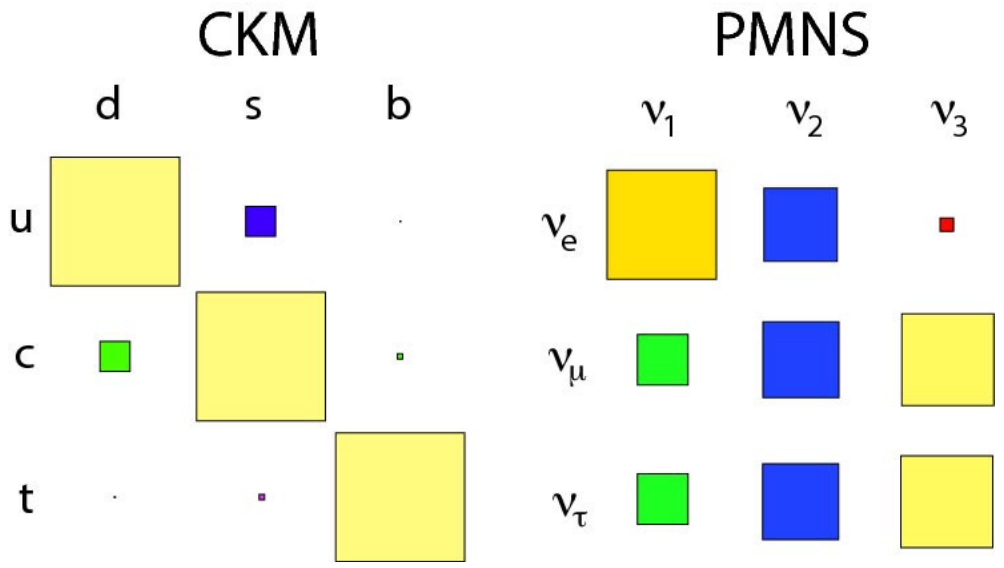
$$m_3 = m_{\text{min}}$$
$$m_1 = \sqrt{m^2_{\text{min}} + |\Delta m^2_{\text{A}}| - \Delta m^2_{\text{sol}}/2}$$
$$m_2 = \sqrt{m^2_{\text{min}} + |\Delta m^2_{\text{A}}| + \Delta m^2_{\text{sol}}/2}$$

- Is $m_3 > m_2 > m_1$ or is the ordering different?

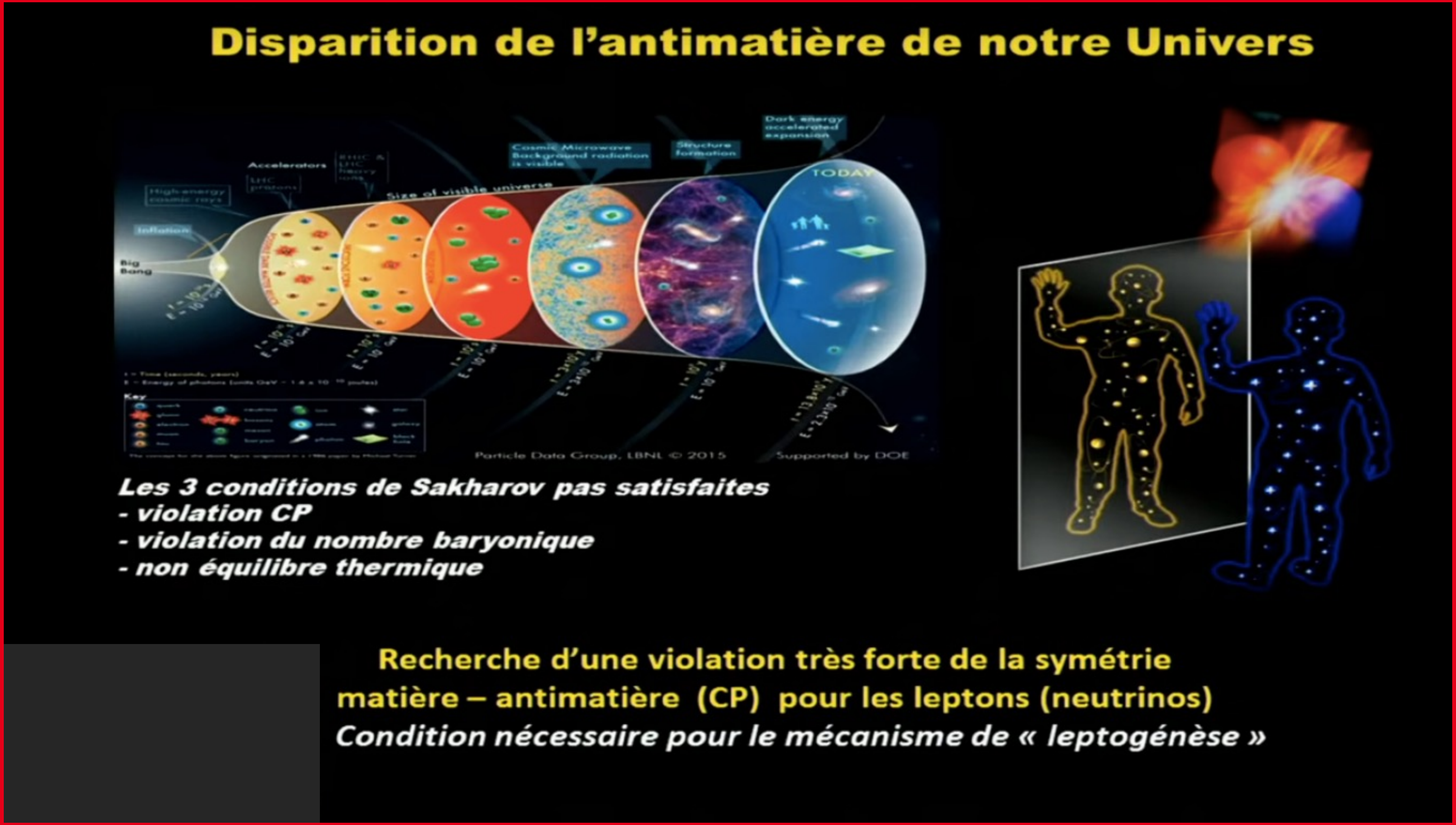
Lepton Mixing

- Striking difference to quark mixing pattern: different origin of flavor

- **Quark mixing**:
  - small mixing angles,
  - CKM matrix almost diagonal
  - masses are hierarchical
  - CP-Violating phase: δ_{CP} small



- **Lepton mixing**:
  - large mixing angles
  - Mass Hierachy : is the mass ordering the same for charged and neutral leptons?
  - δ_{CP} parametrizes different oscillations for neutrino and anti-neutrino, what is it value?
    - If not 0,π then new fundamental source of CP violation (and first in leptonic sector!)



Disparition de l'antimatière de notre Univers

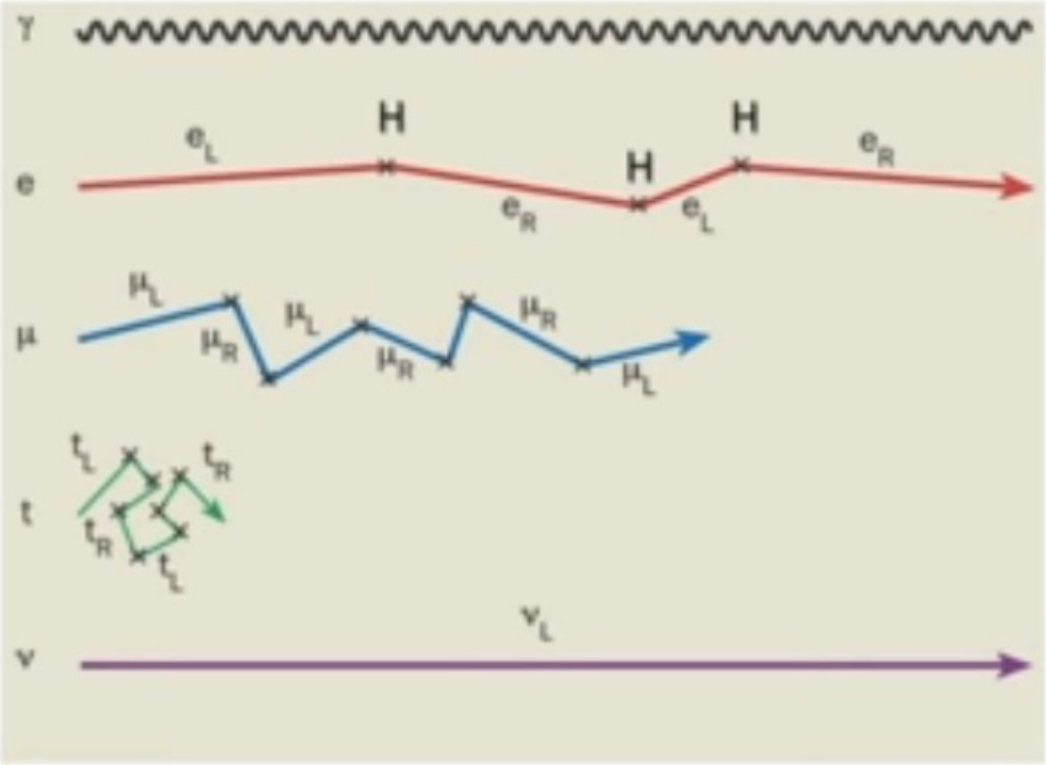
Particle Data Group, LBNL © 2015 Supported by DOE

Les 3 conditions de Sakharov pas satisfaites
- violation CP
- violation du nombre baryonique
- non équilibre thermique

Recherche d'une violation très forte de la symétrie matière – antimatière (CP) pour les leptons (neutrinos)

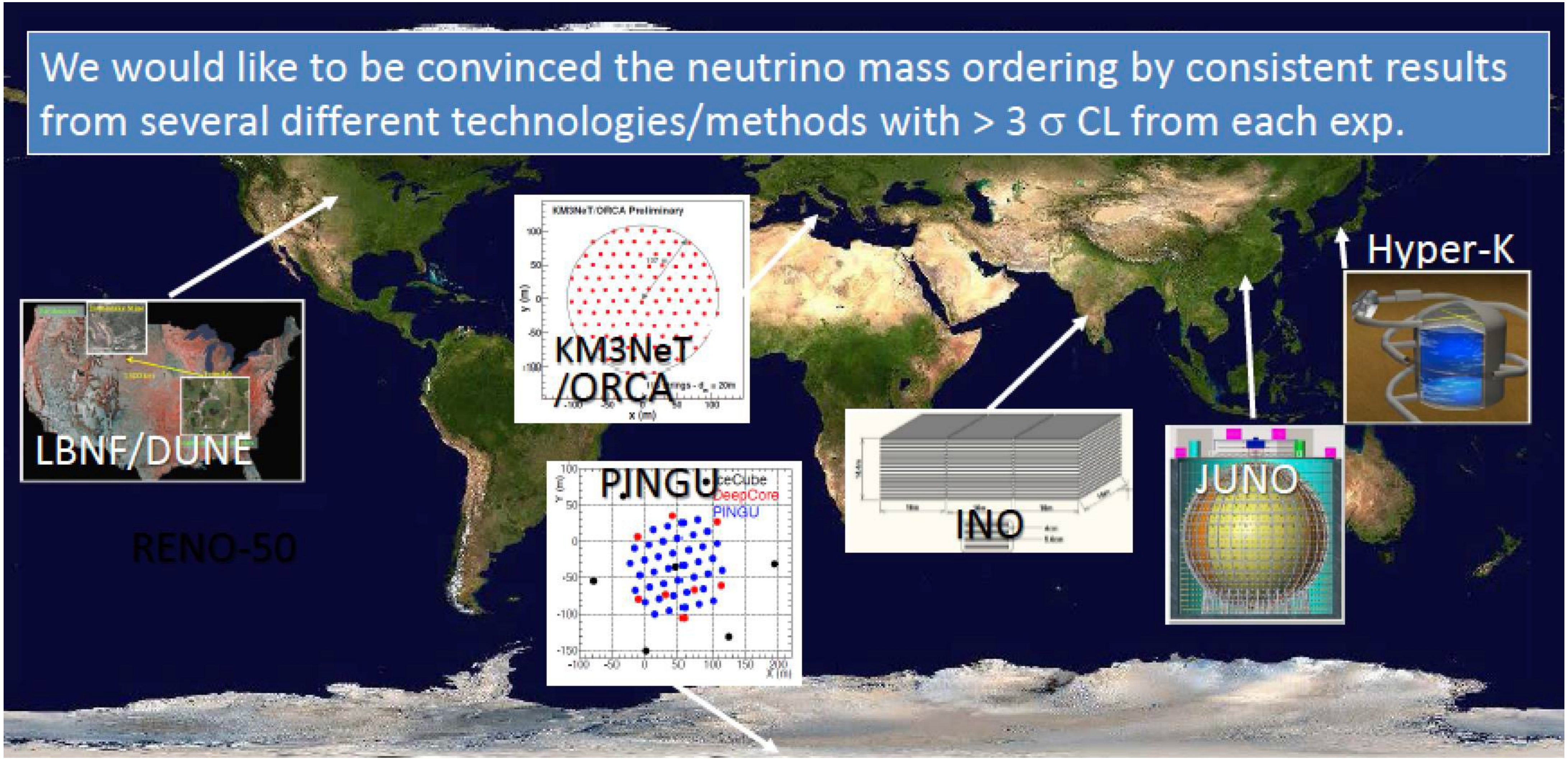
Condition nécessaire pour le mécanisme de « leptogénèse »

MÉCANISME DE LA BALANCE : SEE-SAW



Neutrinos de Majorana

Future Neutrino Experiments



We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.

Summary: Neutrinos

- Theoretical birth was difficult and highly hypothetical in 1930.
- Neutrinos were first detected in 1956.
- Neutrino oscillations established since 1998.
- Neutrino are unique: they are the only neutral fermions we know of.
- The history of neutrino research has been full of surprises. What surprise is waiting for us next??
- Next comes the age of neutrino precision physics and neutrino astronomy, and…