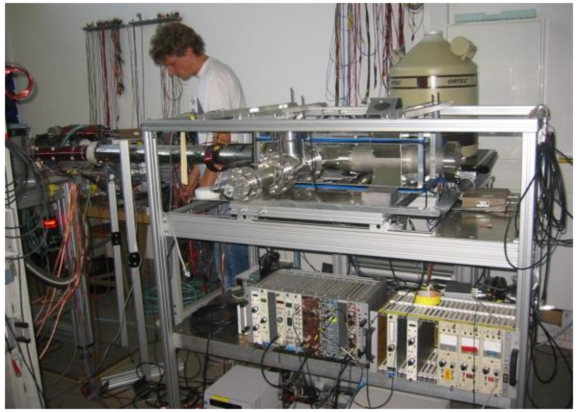
Neutrinos

TRISEP 2024 Summer School

Thomas Brunner
McGill University
July 8, 2024

My Career Path



Studied Physics at the Technical University Munich (2001 – 2011)

- Undergraduate research project
- Diploma thesis (MSc equivalent)
    - Investigation of positronium formation on cold surfaces
- PhD project, stationed at TRIUMF, Vancouver
    - In-trap decay spectroscopy with the TITAN EBIT

Post doctoral research fellow at Stanford (2011 – 2015)

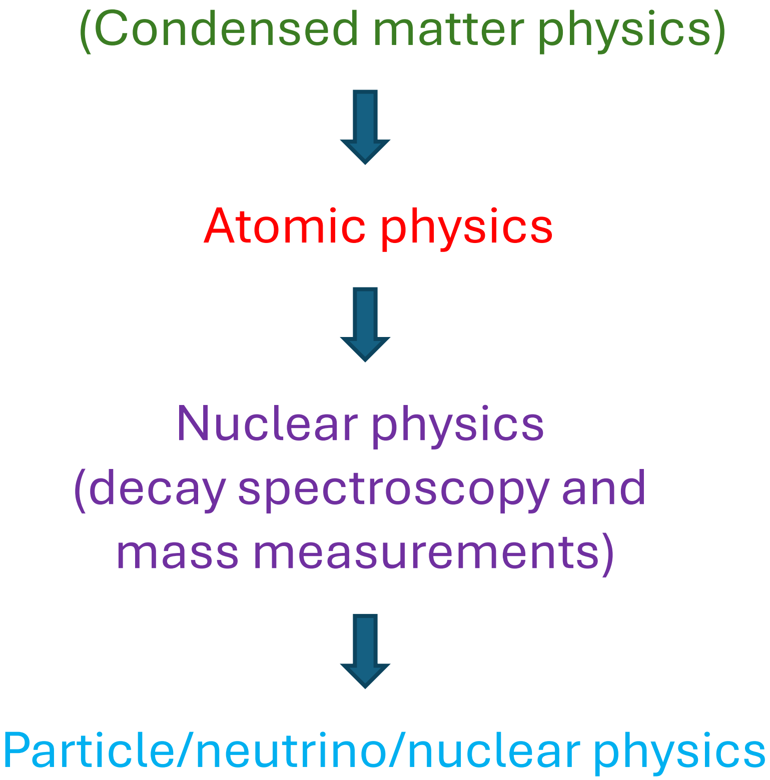
- EXO-200, nEXO, and Ba-tagging

Assistant professor at McGill (2015 – 2020)

- EXO-200, nEXO, Ba-tagging, and in-trap decay spectroscopy

Associate professor at McGill (2020 – now)

- nEXO, Ba-tagging, and in-trap decay spectroscopy



(Condensed matter physics)

⬇

Atomic physics

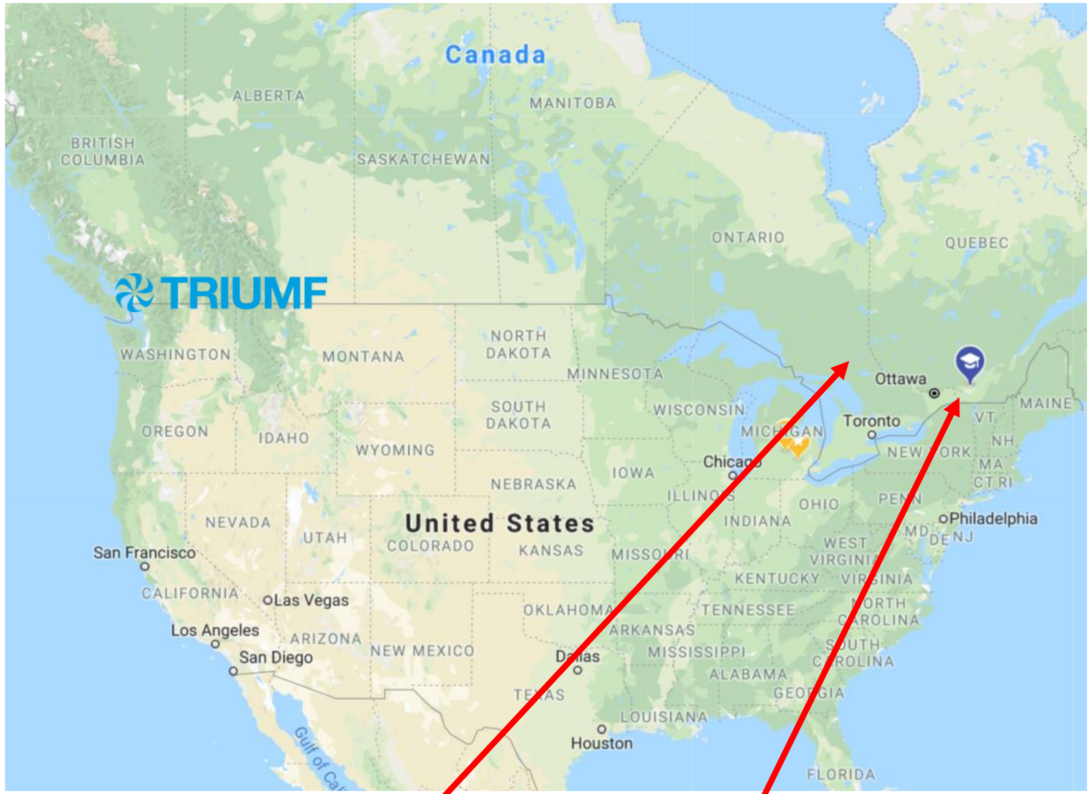
⬇

Nuclear physics
(decay spectroscopy and
mass measurements)

⬇

Particle/neutrino/nuclear physics

McGill University in Montreal



SNOLAB

McGill

Outline

Lecture 1:
Historical overview –
What we know

- Birth and discovery of neutrinos
- Neutrino sources
- Wu and Goldhaber experiment
- Solar neutrino problem
- Neutrino oscillations

Lecture 2:
What we would like to know

- Neutrino mass measurements
  - KATRIN
  - PROJECT 8
- Sterile neutrinos

Lecture 3
Neutrinos as messengers –
What we can learn from studying neutrinos

- Neutrinos as messenger particles in astrophysics

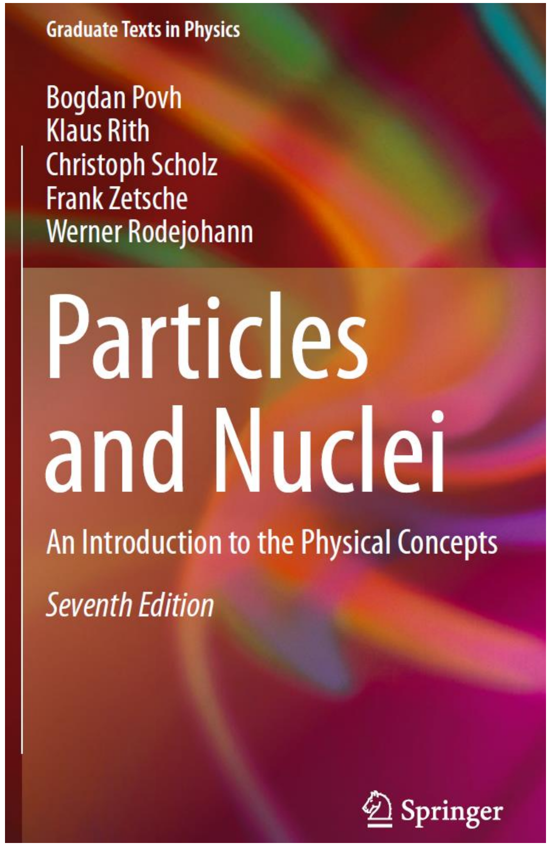
Goal: Give an overview on our understanding of neutrinos

Resources & Acknowledgements

- Thanks to all the people that knowingly and unknowingly provided material and slides for these lectures, in particular M. Dolinski, D. Moore, and K. Leach.

Likely available at your institutional library

Useful resources:


Graduate Texts in Physics

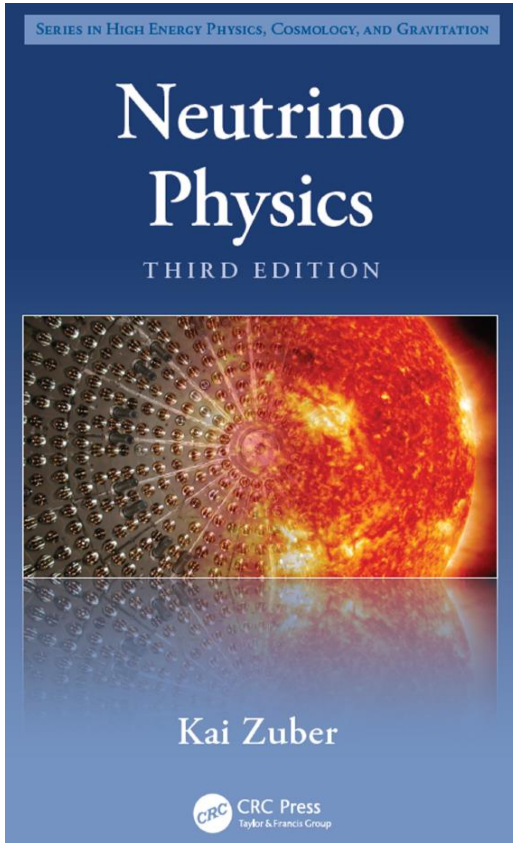
Bogdan Povh
Klaus Rith
Christoph Scholz
Frank Zetsche
Werner Rodejohann

Particles and Nuclei

An Introduction to the Physical Concepts

Seventh Edition

Springer

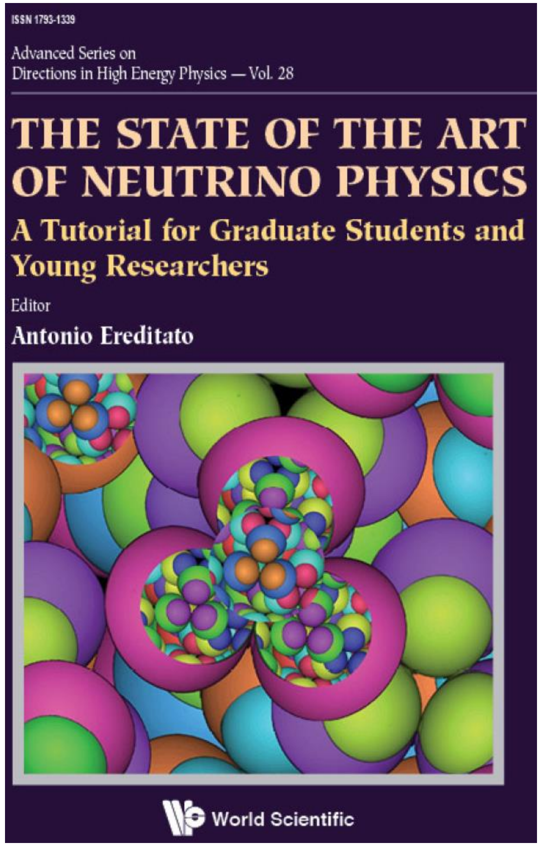

Series in High Energy Physics, Cosmology, and Gravitation

Neutrino Physics

THIRD EDITION

Kai Zuber

CRC Press
Taylor & Francis Group


ISSN 1793-1339

Advanced Series on
Directions in High Energy Physics — Vol. 28

THE STATE OF THE ART OF NEUTRINO PHYSICS

A Tutorial for Graduate Students and Young Researchers

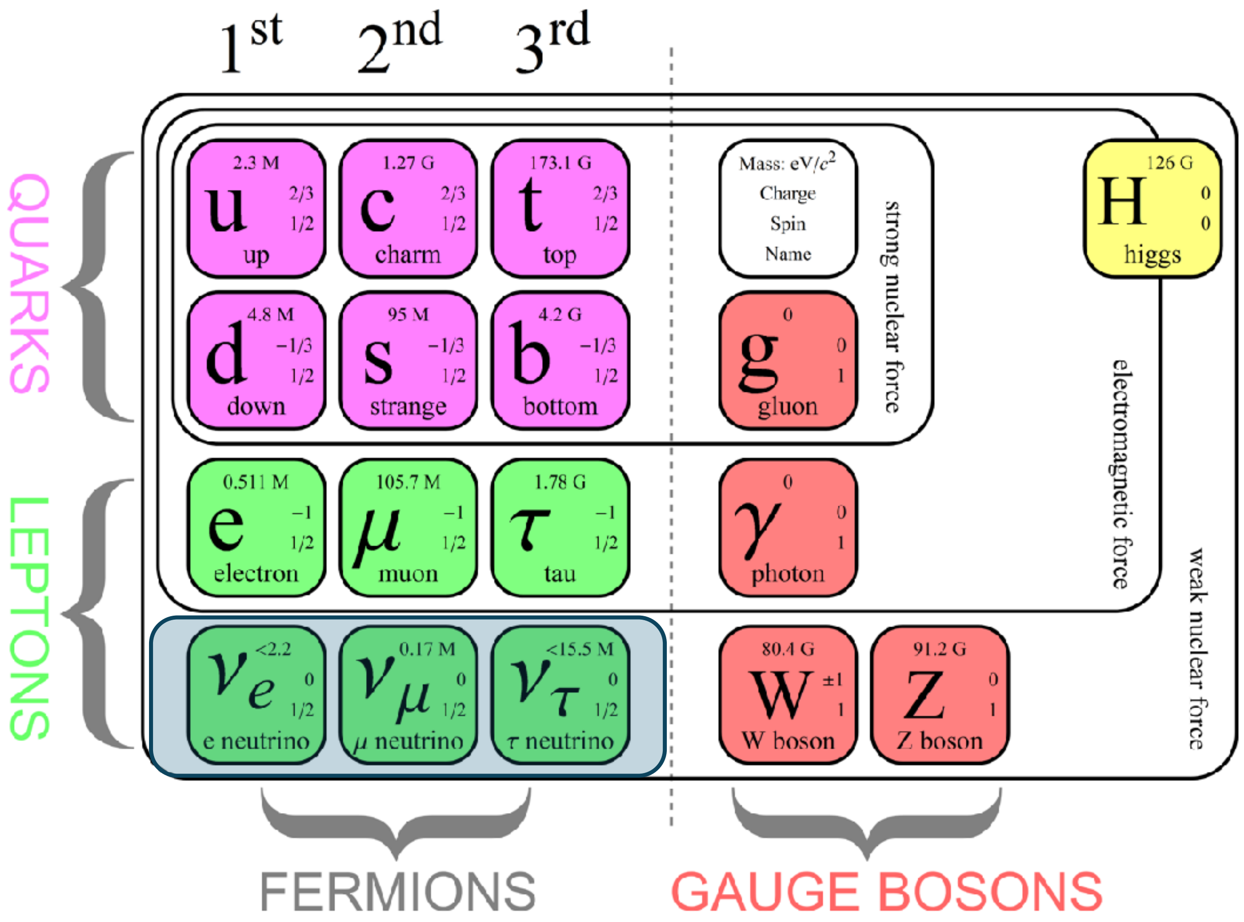
Editor
Antonio Ereditato

World Scientific

… and of course Wikipedia ;-)

Neutrinos in the Standard Model

- Neutrinos in the SM:
  - Fundamental Spin ½ particle
  - Are Leptons
  - Only interact via the weak force
  - Electrically neutral
  - Most abundant particles with mass in the universe, yet we do not even know their mass
  - 60 billion solar neutrinos penetrate us per cm^2 every second
- The Standard Model has been extremely successful in describing particle physics experiments and even predicting the existence of particles.



Some of the Big Questions in Cosmology and Particle Physics

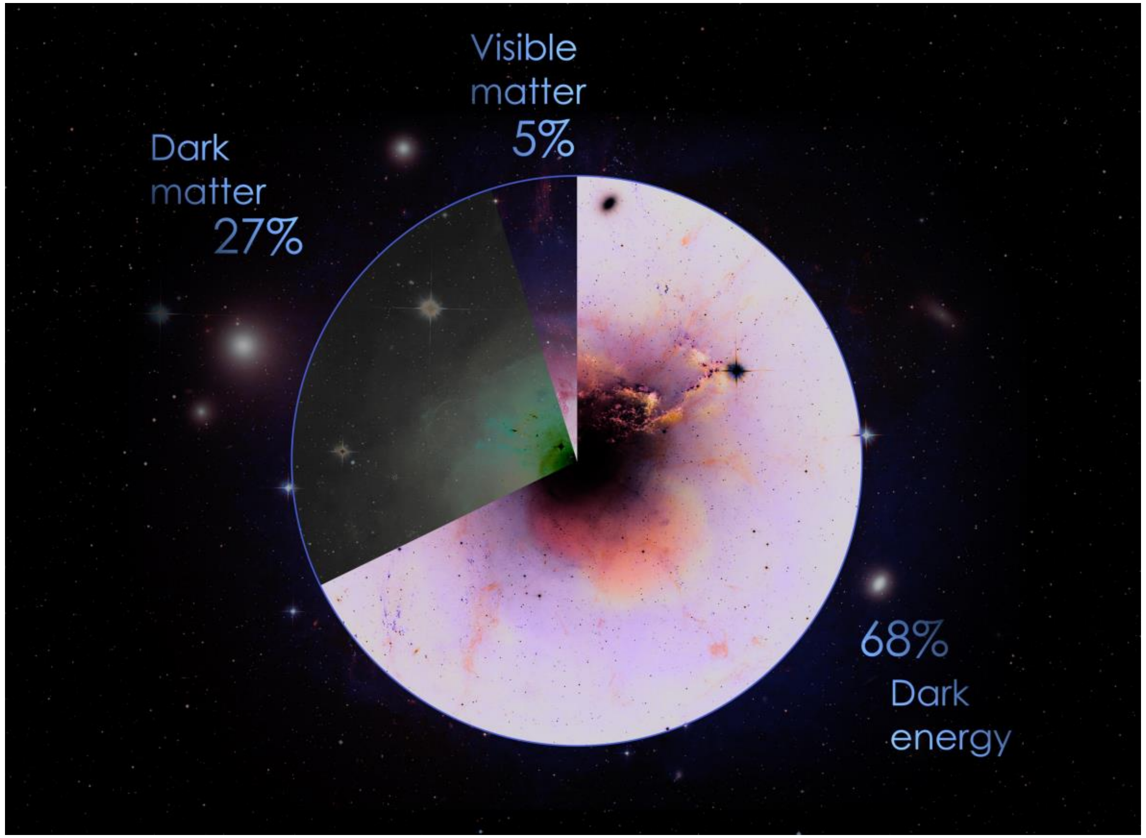


Figure: NASA

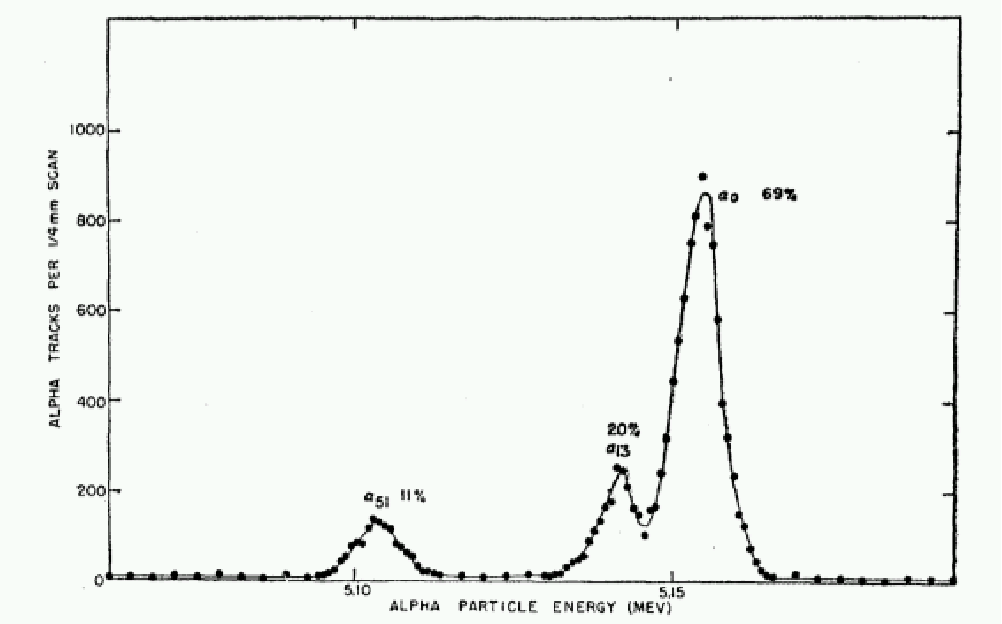
- 95% of the mass/energy density of the Universe is of as yet unknow composition
- What is Dark Energy?
- What is Dark Matter?
- Why is matter so abundant? (and dominant over anti-matter)?
- Why is gravity so weak?
- Why are neutrinos so light?

Neutrinos may hold the key to answering some of these questions.

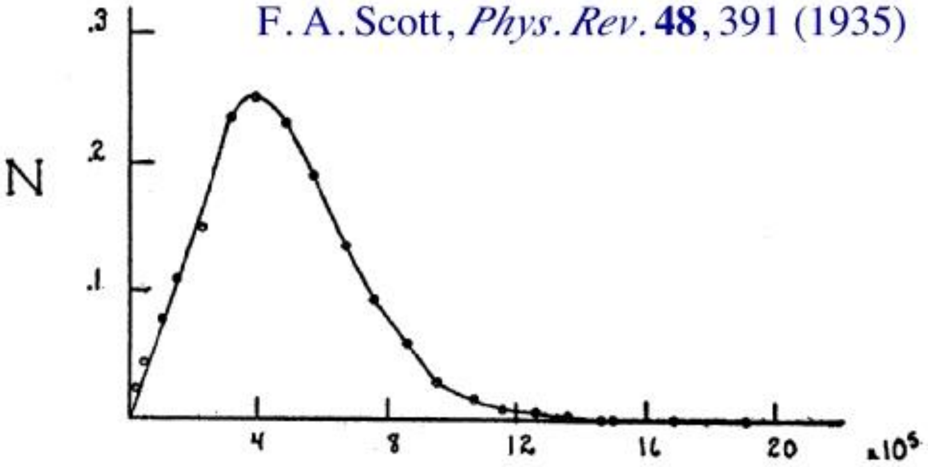
How it all started

Discovery of different types of radiation

- α and β decay were discovered over a century ago.
- While studying β decays scientists made a surprising discovery:
  β decay does not seem to conserve energy!

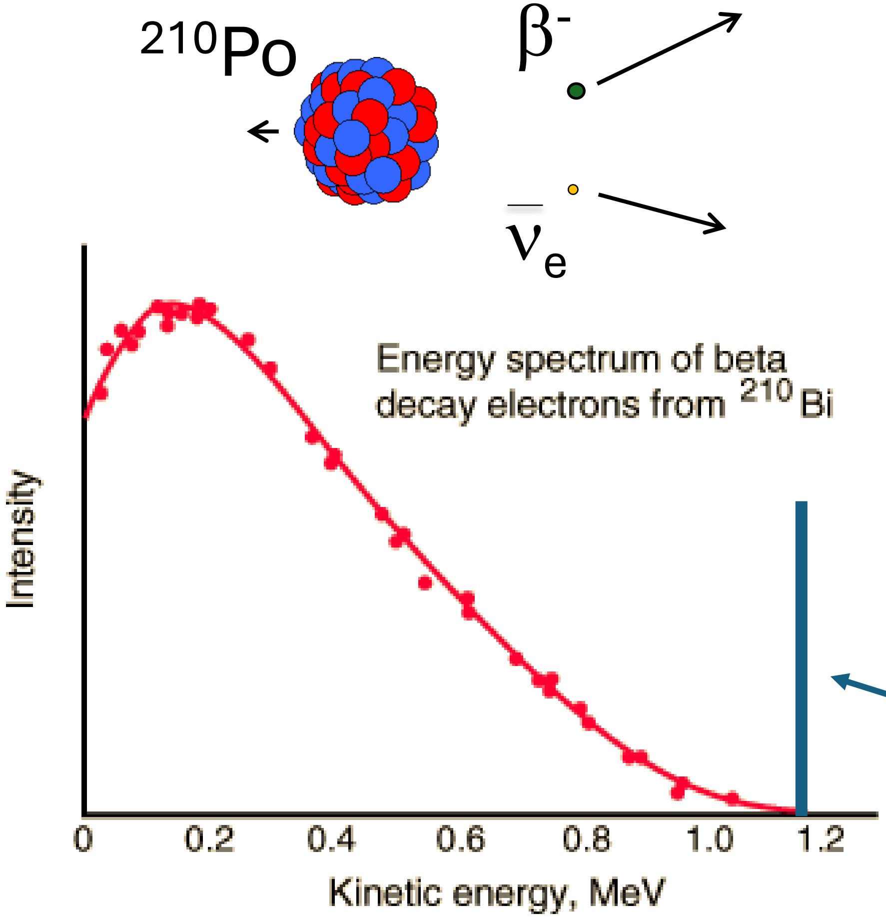


α-decay spectrum (Pu-239)


F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

β -decay spectrum

Energy and angular momentum conservation



G. J. Neary, Roy. Phys. Soc. (London), A175, 71 (1940).

Spin = 1/2

$$^{210}_{83}Bi \rightarrow {}^{210}_{84}Po + e^-(+\bar{\nu})$$

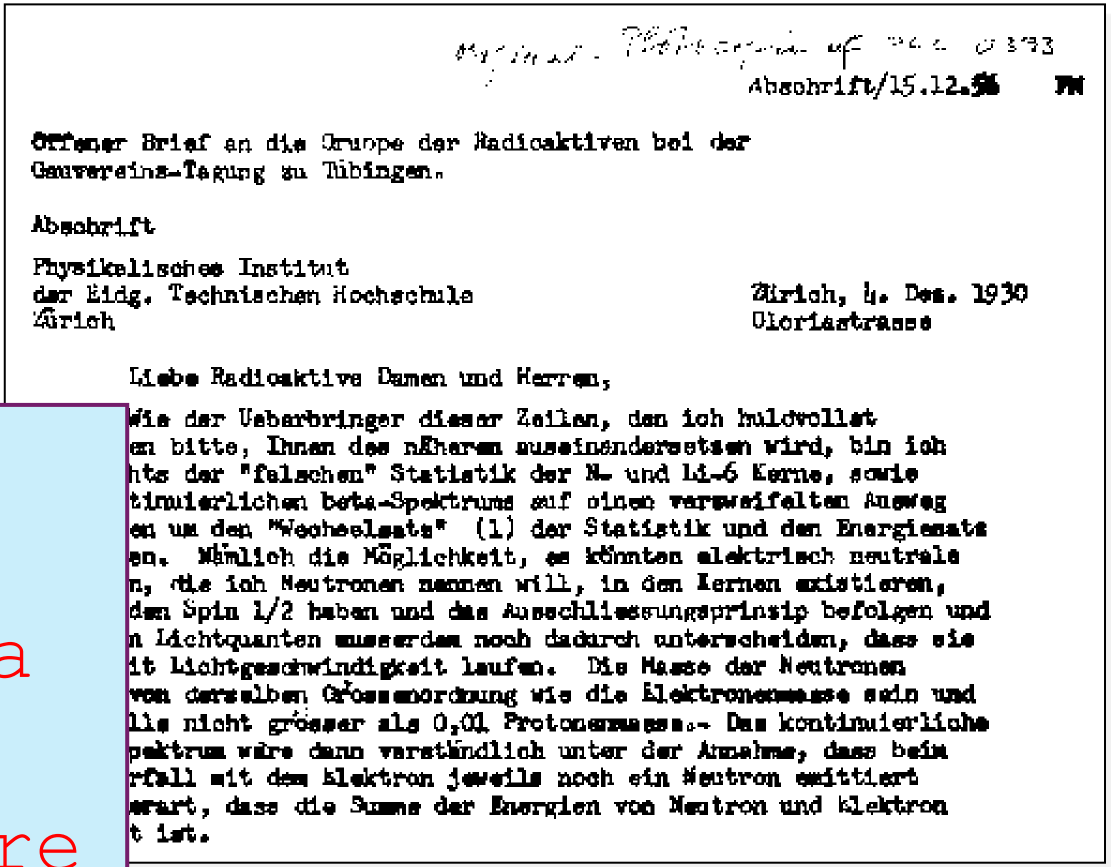
(1^-) (0^+)

A two-body decay would result in a peak at the Q-value

Pauli invents neutrinos 1930 to explain nuclear β decay

Dear Radioactive Ladies and Gentlemen,

... I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy [in β decay].



[illegible] Photocopie of [illegible] 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
en bitte, Ihnen des näheren auseinandersetzen wird, bin ich
hts der "falschen" Statistik der N- und Li-6 Kerne, sowie
tinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
en um den "Wechselsatz" (1) der Statistik und den Energiesatz
en. Nämlich die Möglichkeit, es könnten elektrisch neutrale
n, die ich Neutronen nennen will, in den Kernen existieren,
den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
n Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
it Lichtgeschwindigkeit laufen. Die Masse der Neutronen
von derselben Grössenordnung wie die Elektronenmasse sein und
lls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche
pektrum wäre dann verständlich unter der Annahme, dass beim
rfall mit dem Elektron jeweils noch ein Neutron emittiert
erart, dass die Summe der Energien von Neutron und Elektron
t ist.

@pauli

I have done a terrible thing. I have postulated a particle that cannot be detected. #Desperate-measure

How do we detect neutrinos?

We know of 4 types of fundamental interactions in nature

- **Gravity**: every object is affected

  (it is actually a property of space-time)

- **Weak force**: affects most particles including neutrinos

- **Electromagnetism**: affects all particles with charge

- **Strong force**: affect only quarks

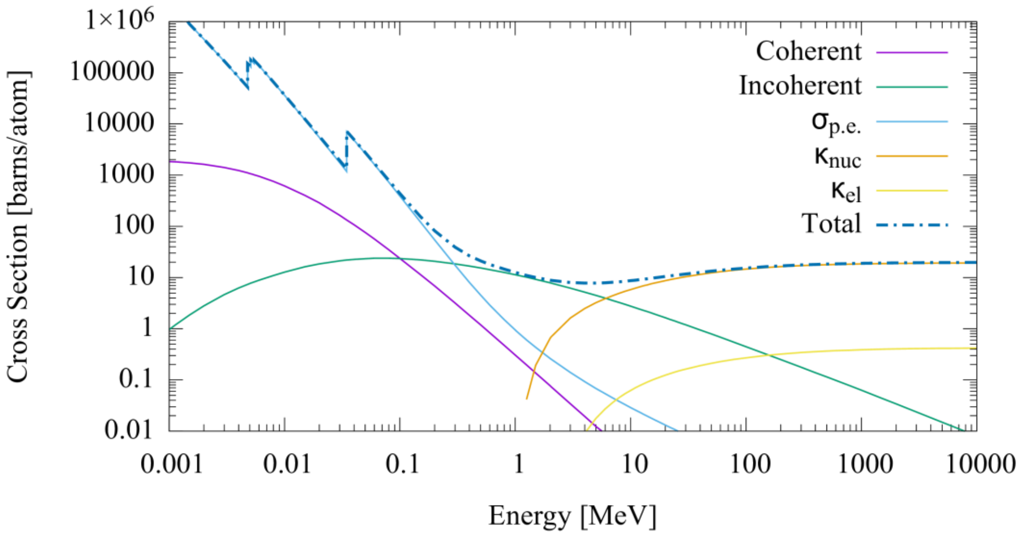
Neutrinos having no electric charge interact only by the weak force (and gravity)

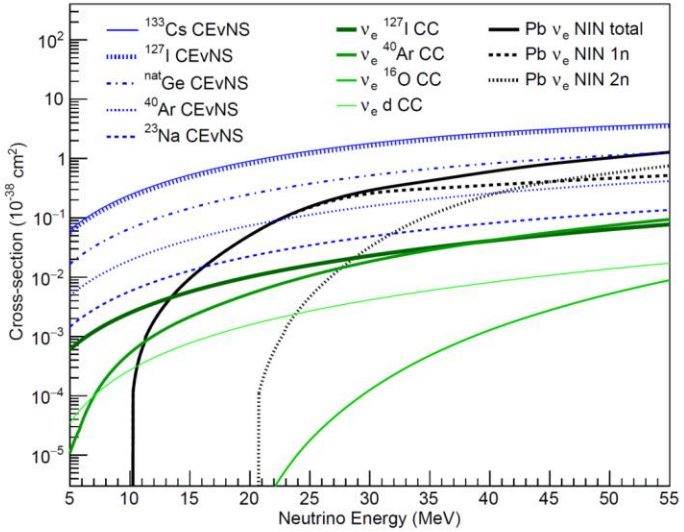
→ ***interact very little***

Neutrino detection not impossible – only challenging

Photon-Matter Cross Section

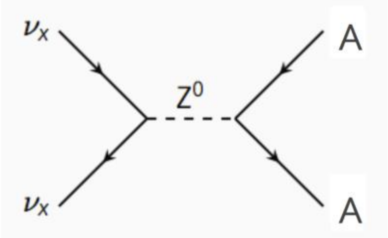
Neutrino-Matter Cross Section





Source: Pershey, NEUTRINO2022

CC: Charged Current interaction
CEvNS: Coherent Elastic ν Nucleon Scattering (see e.g. D. Akimov et al, Science 357 (2017))



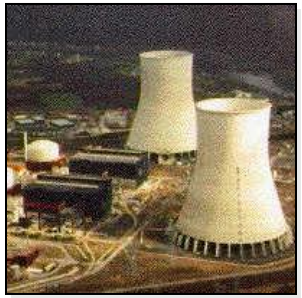
Cross section of order ~10^{-24} cm^2

Orders of magnitude smaller cross section

Cross section of order ~10^{-38} cm^2

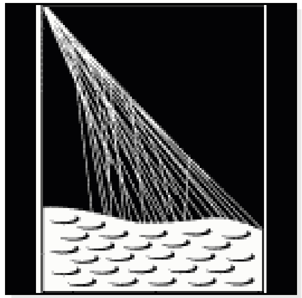
Sources of neutrinos: artificial and natural

✓ Nuclear Reactors
(power stations, ships)

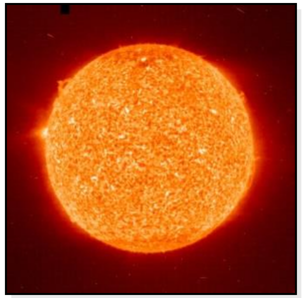


✓ Particle Accelerator

✓ Earth's Atmosphere
(Cosmic Rays)

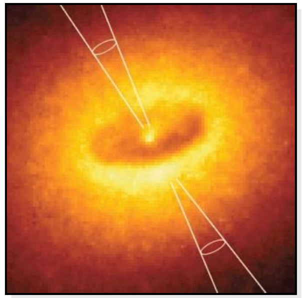


✓ Earth's Crust
(Natural
Radioactivity)

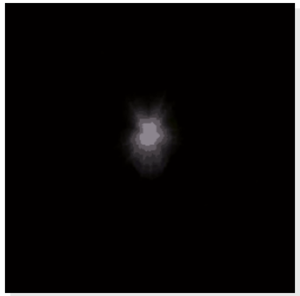


Sun ✓

Supernovae
(star collapse)
SN 1987A ✓



Astrophysical
Accelerators ✓



Big Bang
(here 330 ν/cm^3)
Indirect Evidence

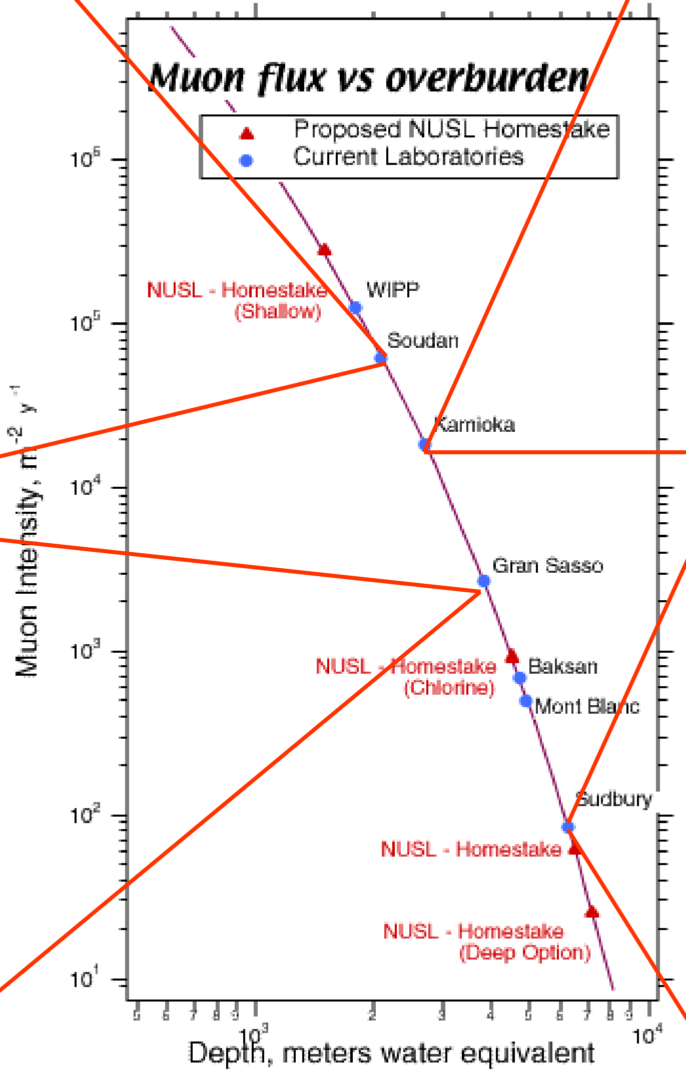
ν detectors require massive shielding against cosmogenic BGNDs

6 orders of magnitude reduction in cosmic ray flux

sea level: $10^9\ \mu/m^2/y$

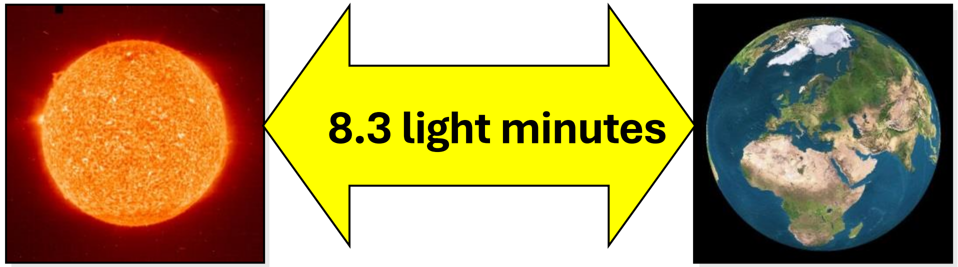
$1\ \mu/cm^2/min$

https://doi.org/10.1016/j.nima.2018.06.038

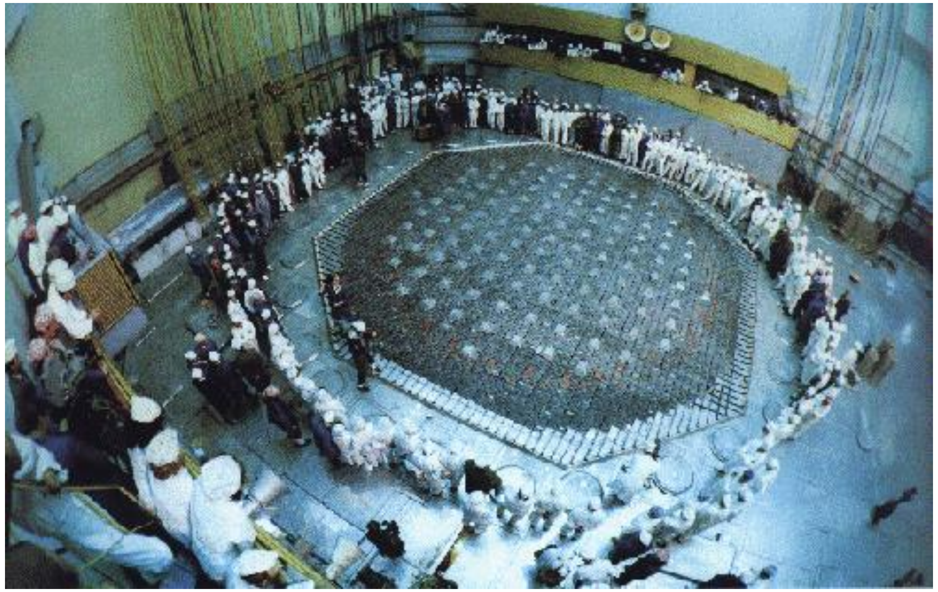


Radioprotection from neutrinos ?

- Mean free path of neutrinos from a reactor in lead is ~ 0.3 light years !



- A big nuclear reactor makes 6 x 10^{20} neutrinos/s: at 20 meter distance (just outside the building) only one neutrino every 3 sec interacts with our body !



<u>Bethe & Peierls 1934:</u>
"… this implies that one evidently never will be able to detect Neutrinos."

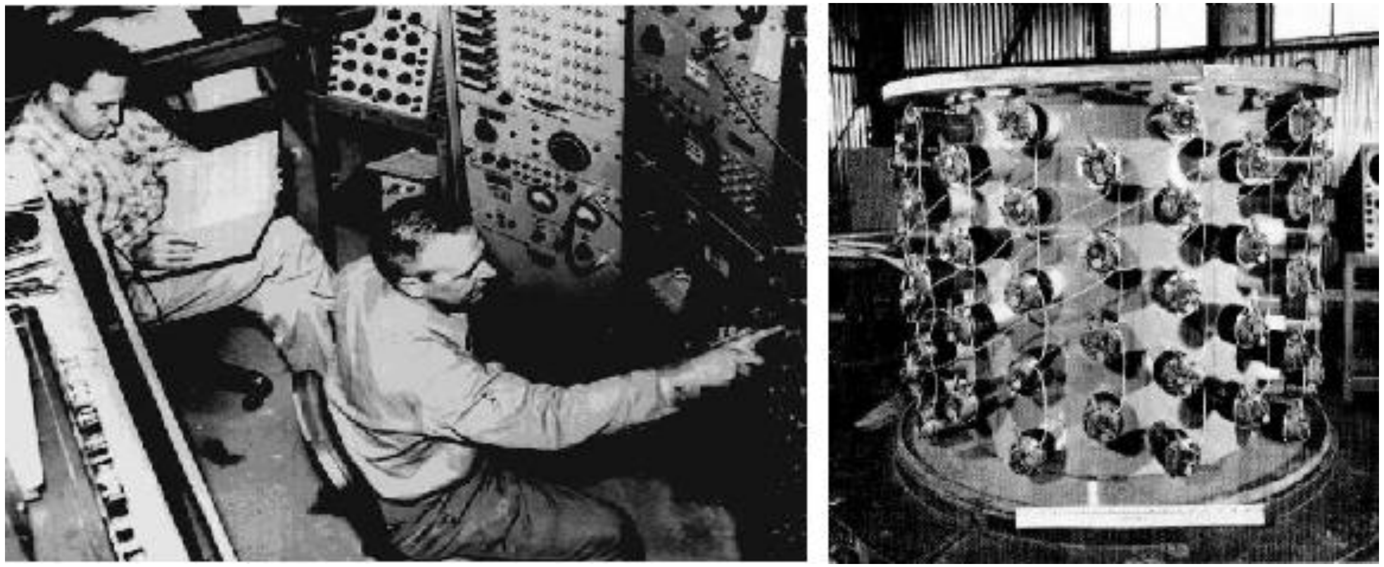
1956: Cowan and Reines detects neutrinos

Detection through inverse β decay

$$\bar{\nu}_e + p \rightarrow n + e^+ \longrightarrow \text{Annihilates with } e^- \text{ into (two) } \gamma$$

From reactor

$$n + {}^{113}Cd \rightarrow {}^{114}Cd^* \rightarrow {}^{114}Cd + \gamma$$



- 200 liters of water with about 40 kg of dissolved $CdCl_2$
- **Detected 3 neutrinos per hour.**
- Reactor off → signal disappeared
- Predicted cross-section of 6 x 10^{-44} cm^2 → measured cross-section was 6.3 x 10^{-44} cm^2

C. L. Cowan, Jr. *et al.*
Detection of the Free Neutrino: a Confirmation
Science **124,** 103-104(1956)
DOI:10.1126/science.124.3212.103

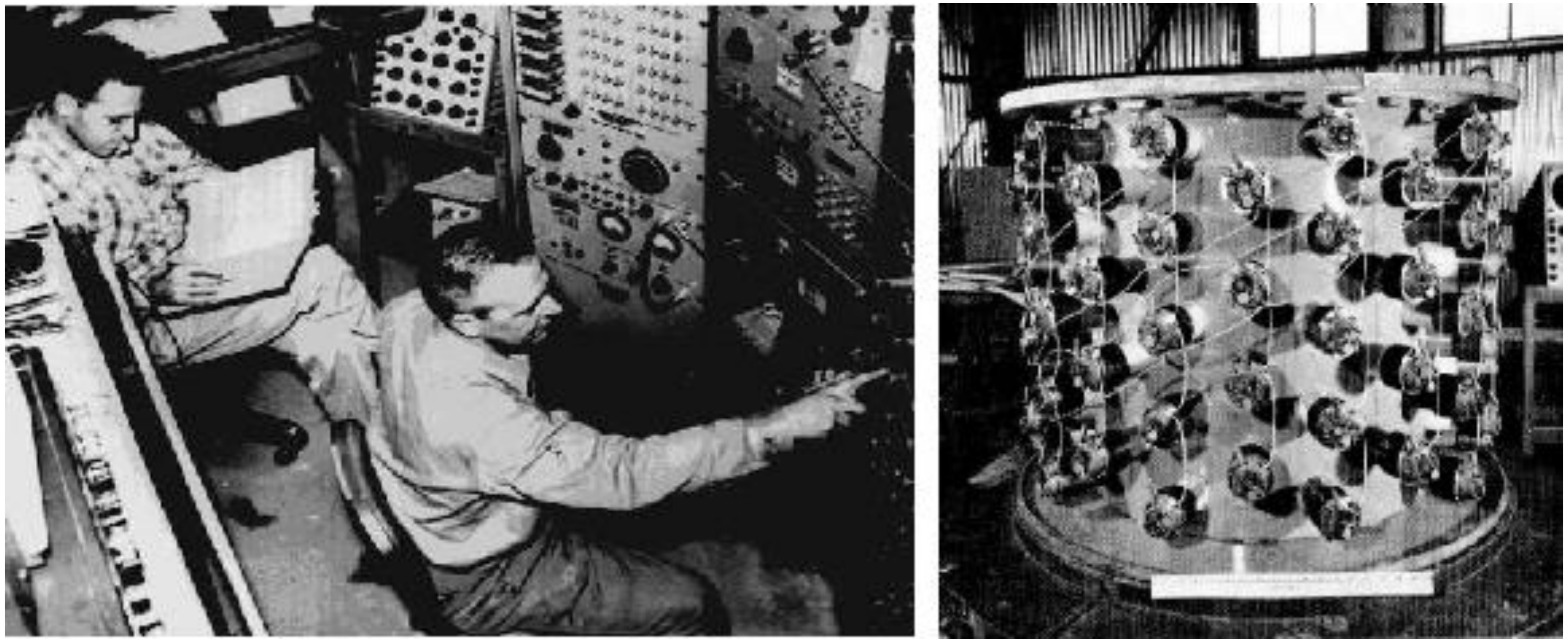
1956: Cowan and Reines detects neutrinos

`“[Prof. Pauli], we are happy to inform you that we have definitely` **`detected neutrinos`** `from fission fragments by observing inverse beta decay of protons.”`

- F. Reines and C. Cowan (1956)

`“Everything comes to him who knows how to wait.”`

- W. Pauli (1956)



Nobel Price 1995
F. Reines

Neutrino = anti neutrino?

- **Question**: How to determine whether $\nu = \bar{\nu}$?

Neutrino = anti neutrino?

- How to determine whether $\nu = \bar{\nu}$?

$$\left.\begin{aligned} \bar{\nu}_e + n &\rightarrow p + e^- \\ \nu_e + n &\rightarrow p + e^- \end{aligned}\right\}$$

Same cross section for $\nu = \bar{\nu}$.

- Ray Davis searches for $\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ at Brookhaven Reactor in 4000 l CCl_4.
- Non-observation led to result:

$$\bar{\sigma}(\bar{\nu}_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}) \leq 2 \times 10^{-42}\ \mathrm{cm}^2 \text{ per atom}$$

Discover new flavor of neutrinos

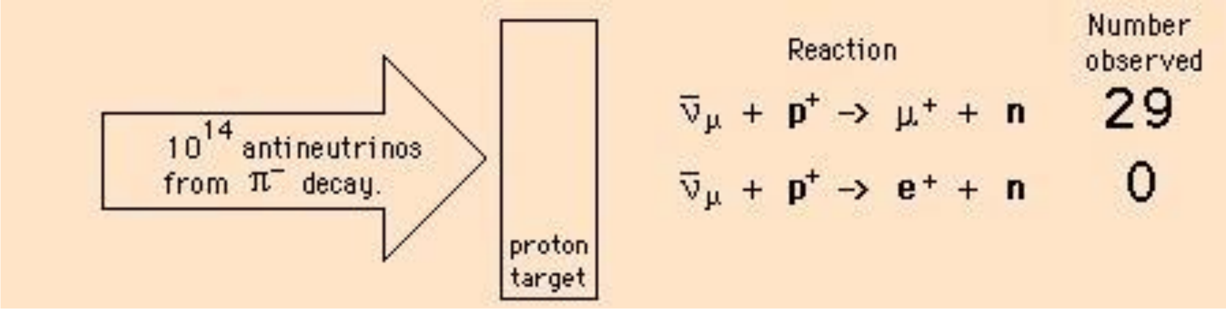

Leon M. Lederman


Melvin Schwartz


Jack Steinberger

Nobel Prize 1988

1962, first neutrino beam at Brookhaven National Lab.



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

Tau neutrino detected directly at Fermilab in 2000.

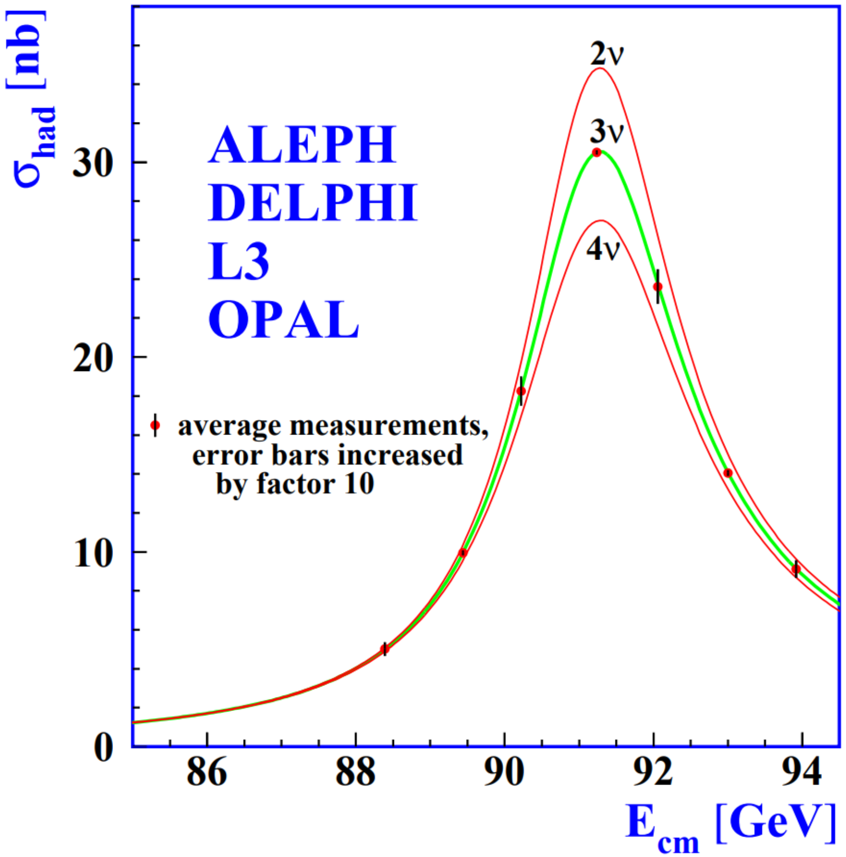
Three types of ν

1953 (confirmed 1956) - Reines and Cowan discover the electron neutrino (Nobel Prize for Fred Reines in 1995).

1962 - Danby, et. al., discover the muon neutrino (Nobel Prize 1988).

2000 - DONUT collaboration discovers the tau neutrino.

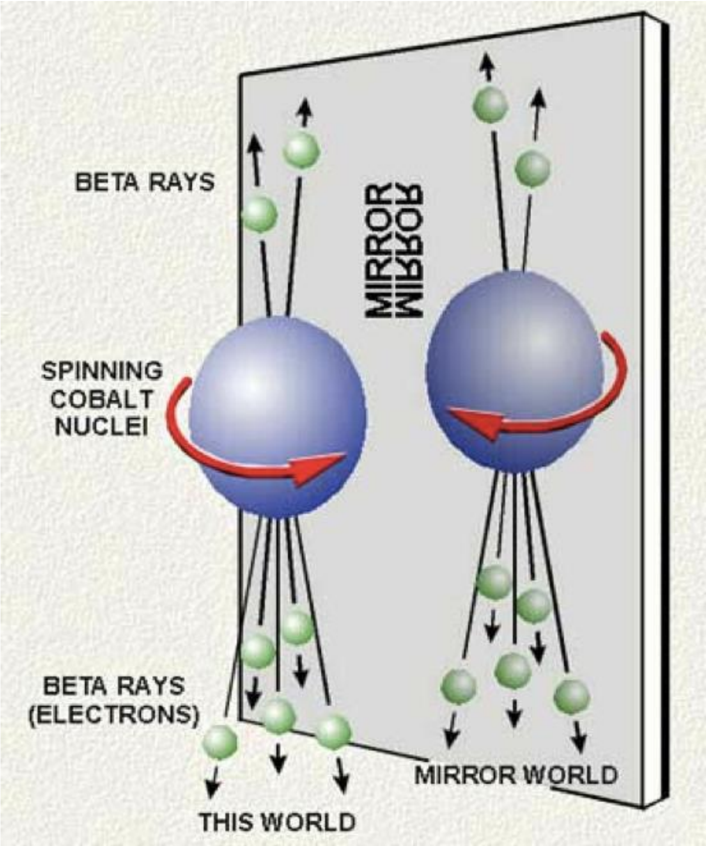
0509008 (arxiv.org)



Curves indicate predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass

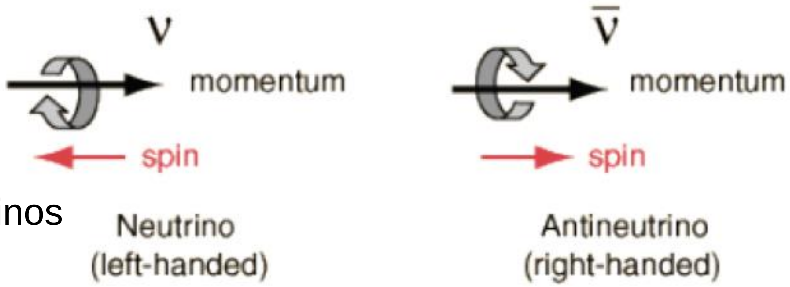
- Hadron production cross-section around the Z resonance suggests three ν
- Cosmology measures the total number of neutrino species, consistent with 3!

Parity violation and CP

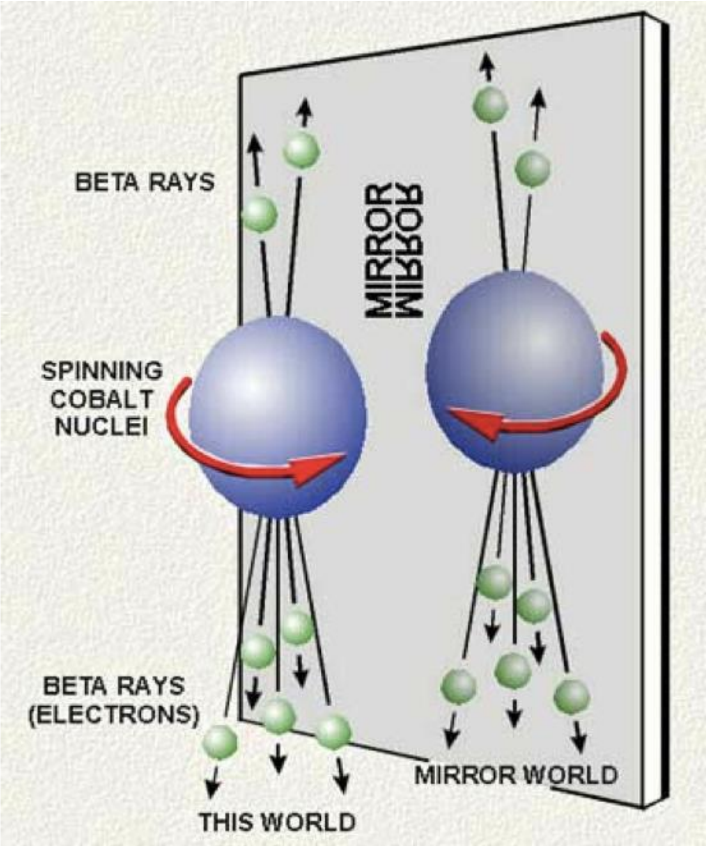


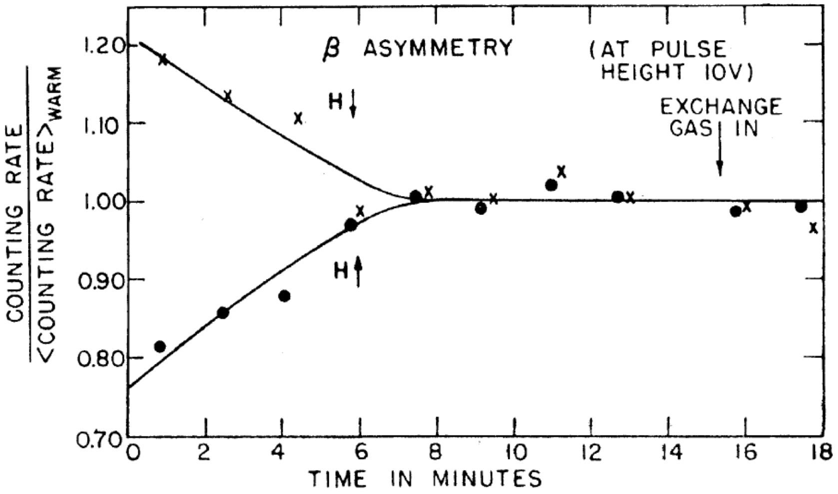
- You might think the laws of physics should remain unchanged in our world or in a mirror world, but weak interactions violate that symmetry dramatically [Wu, et al. Phys. Rev. 105, 1413]. Maybe CP is the right conserved quantity?

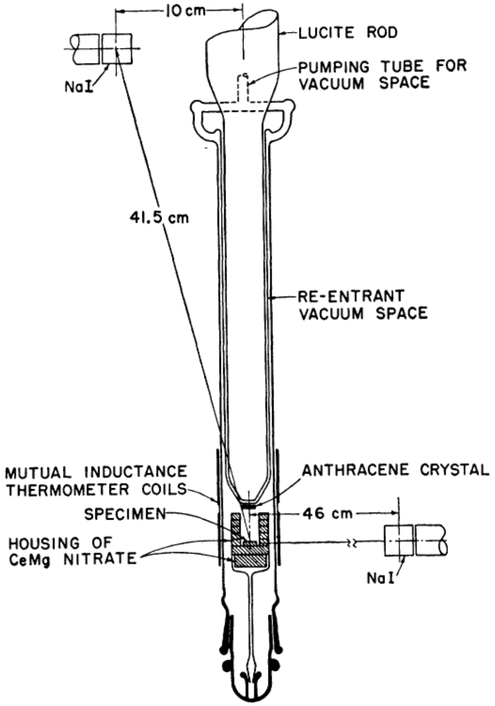
- We know that CP is also violated by weak interactions in the quark sector, but it’s too weak to explain the matter-antimatter asymmetry.

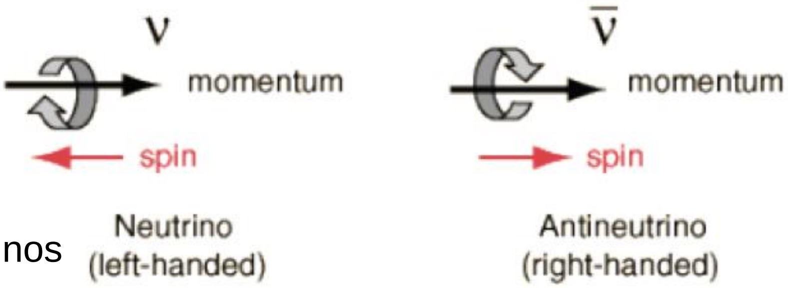


Parity violation in weak interactions









$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$

- Nuclear spin aligned with B-field.
- Parity conservation implies that any process and its mirror process occur with the same probability.
- Weak interaction could be parity symmetric if there were no preference in the direction of emission, because then a flip in the direction of emissions in the "mirror" world would look no different from the "real" world because there were equal numbers of emissions in both directions anyway.

Goldhaber Experiment

Maurice Goldhaber

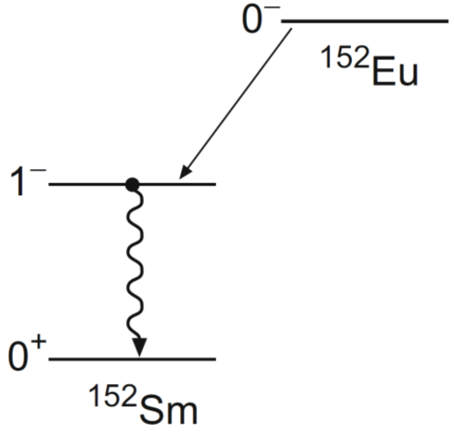
- Goal to measure the helicity of neutrinos
- Helicity of a particle :

$$h = \vec{s} \cdot \frac{\vec{p}}{||\vec{s}||\,||\vec{p}||}$$

→ If $\underline{h = 1}$, the particle is right-handed

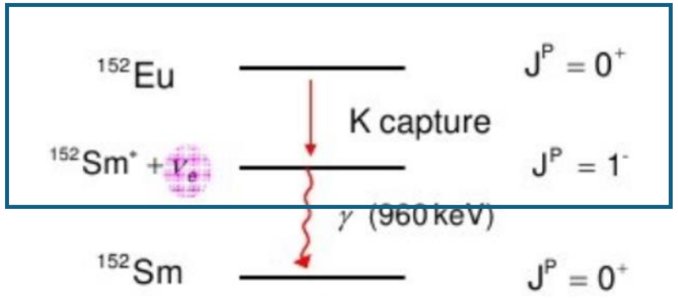
→ If $\underline{h = -1}$, the particle is left-handed

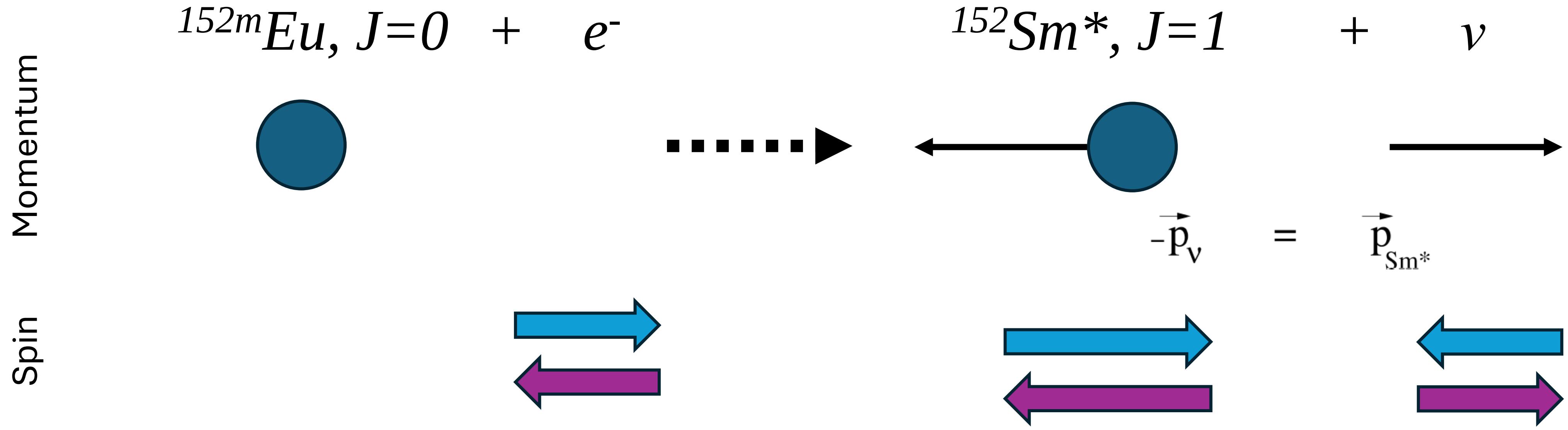
- The reaction : ${}^{152m}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e \rightarrow {}^{152}Sm + \nu_e + \gamma$



Goldhaber Experiment: What is the helicity of neutrinos?

$$^{152m}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e$$



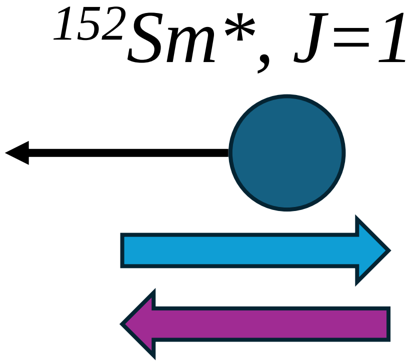


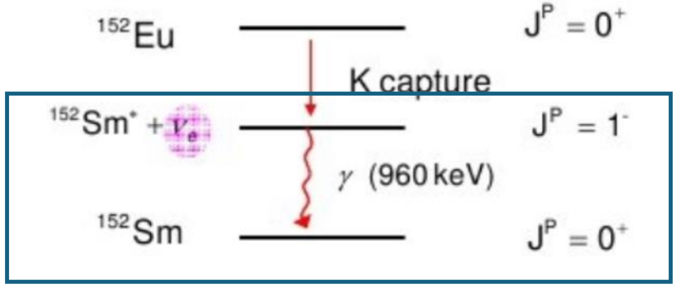
Spin of Sm parallel to e⁻ spin
Spin of Sm anti-parallel to ν spin

$$h(Sm) = h(\nu_e)$$

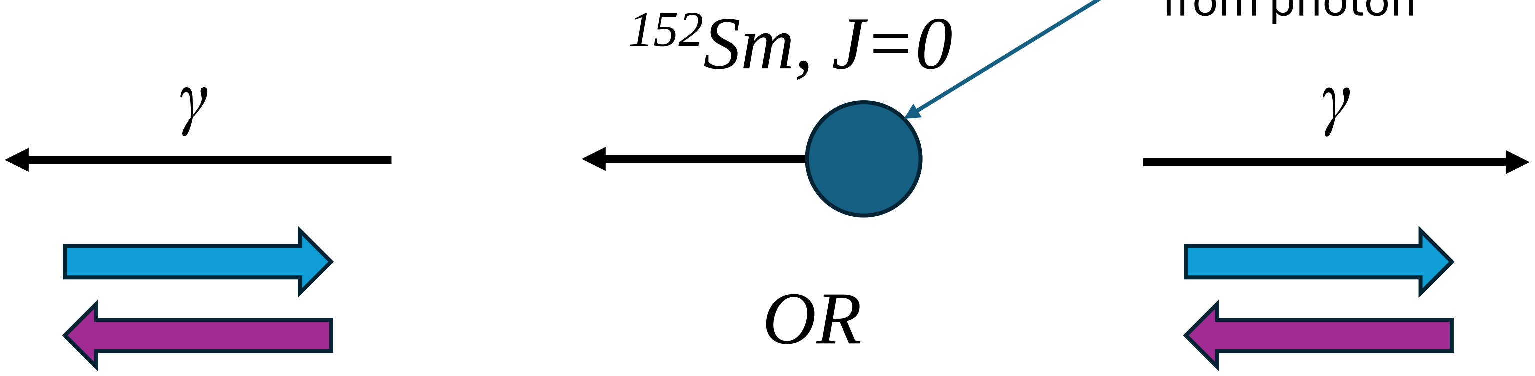
Goldhaber Experiment: What is the helicity of neutrinos?

- Spin of ^{152}Sm* is opposite to spin of neutrino!
- Photon spin parallel to that of ^{152}Sm* prior decay.
- Direction of spin of photon is opposite of neutrino!





^{152}Sm gets a small recoil from photon



Emitted in direction of Sm*

$$h(\gamma) = h(\nu_e)$$

Emitted in opposite direction of Sm*

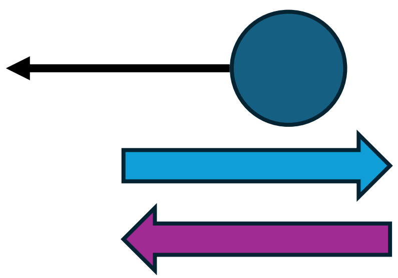
$$h(\gamma) = - h(\nu_e)$$

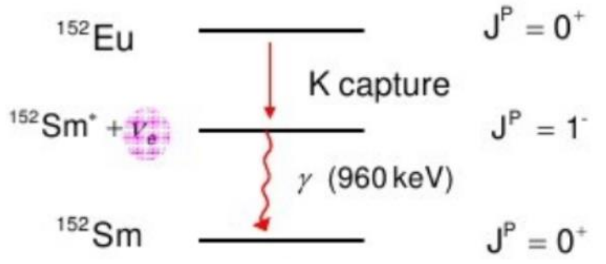
Goldhaber Experiment: What is the helicity of neutrinos?

Need to measure:

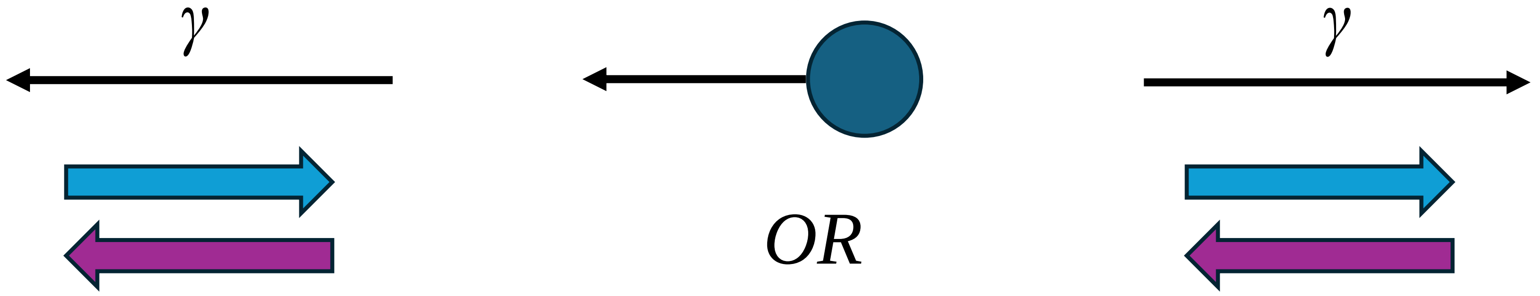
1) Direction of emission of the photon
2) Polarization of the photon

$^{152}Sm^*, J=1$





$^{152}Sm, J=0$



Emitted in direction of Sm*

$$h(\gamma) = h(\nu_e)$$

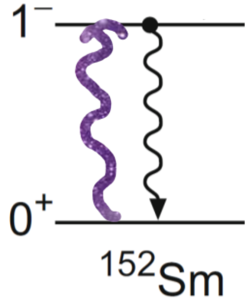
Emitted in opposite direction of Sm*

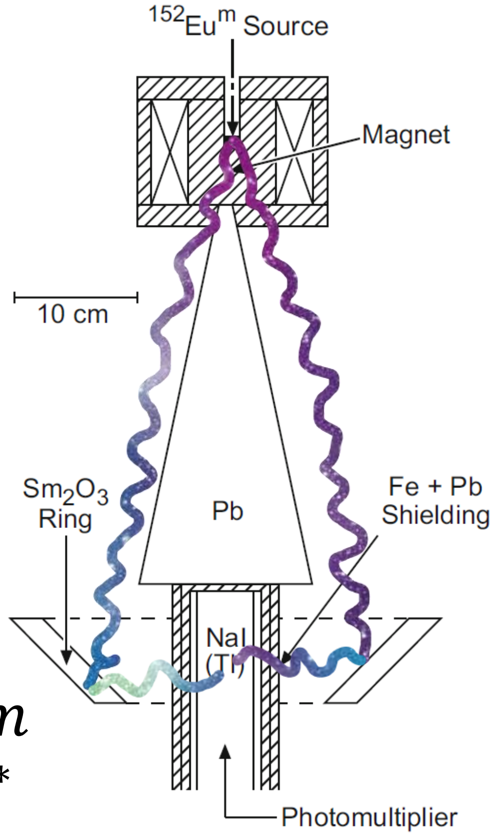
$$h(\gamma) = - h(\nu_e)$$

Goldhaber Experiment: 1) Photon direction

- Resonant scattering:
  - Photon energy must be slightly larger than 960 keV
  - This is the case for photons which have been emitted in the direction of the Eu → Sm recoil (doppler effect)

→ Resonant scattering only possible for “forward” emitted photons which carry polarization of the Sm* and thus polarization of neutrinos.

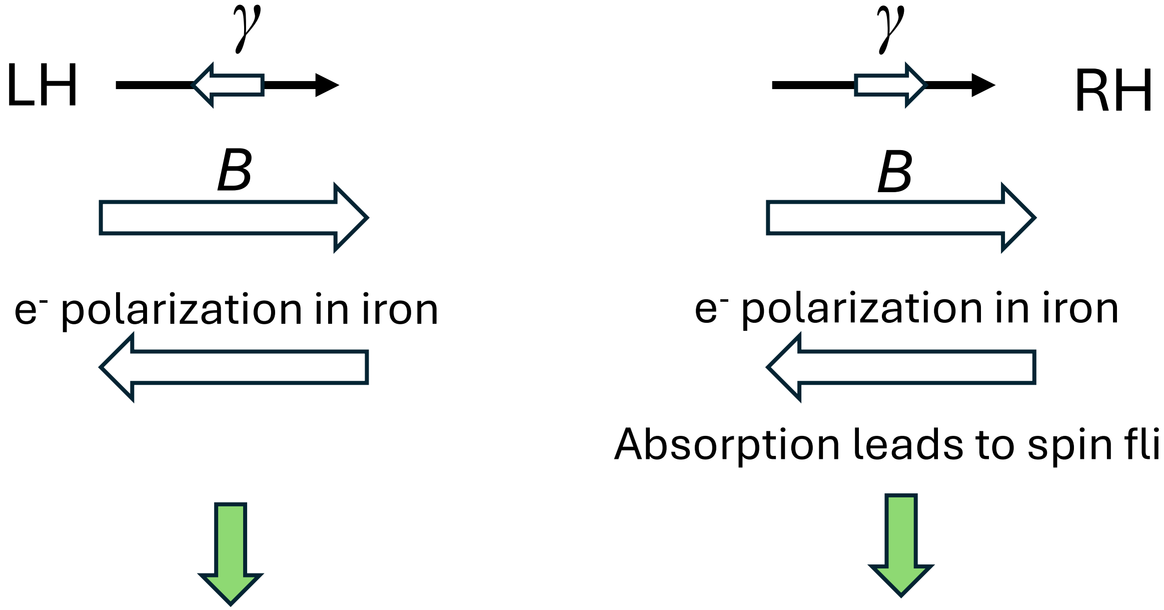




$$\gamma + {}^{152}Sm \to {}^{152}Sm^* \to {}^{152}Sm + \gamma$$

Goldhaber Experiment: 2) Photon polarization

- Measurement of polarization of photons:
  - Transmission through magnetized iron is polarization dependen
  - Compton scattering in magnetized iron:



LH γ

B

e$^-$ polarization in iron

LH photons less absorbed:
Good transmission

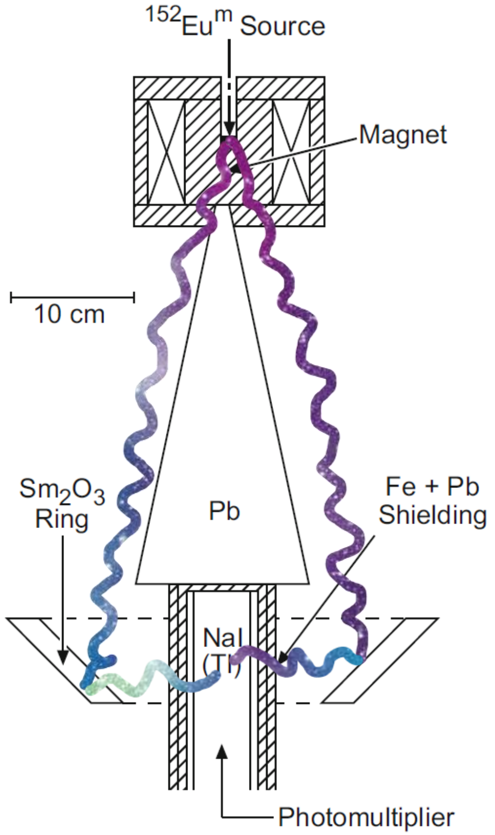
γ RH

B

e$^-$ polarization in iron

Absorption leads to spin flip

RH photons Compton scatter:
Poor transmission



Photons with polarization anti-parallel to magnetization undergo less absorption

Results of the experiment

- Only resonantly scattered photons detected → $h(\gamma) = h(\nu_e)$

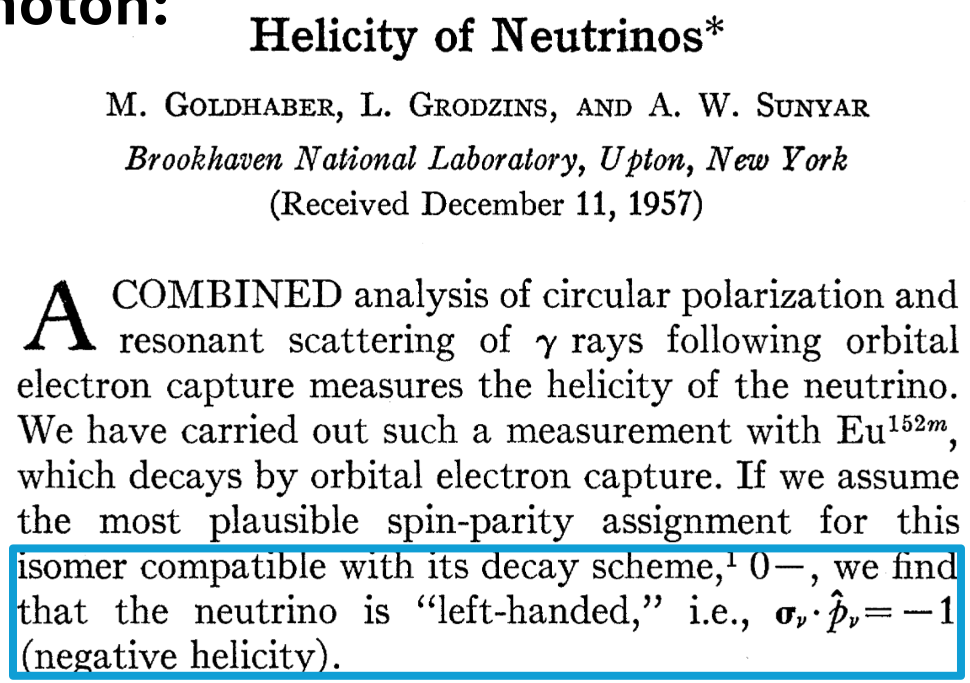
- B-field in flight direction of γ → measure LH γ
- B-field opposite flight direction of γ → measure RH γ

Figure 14: Photograph of Lee Grodzins with the helicity-of-neutrino experimental set-up.

Determine polarization of photon:

$$h(\gamma) = h(\nu_e) = -1$$

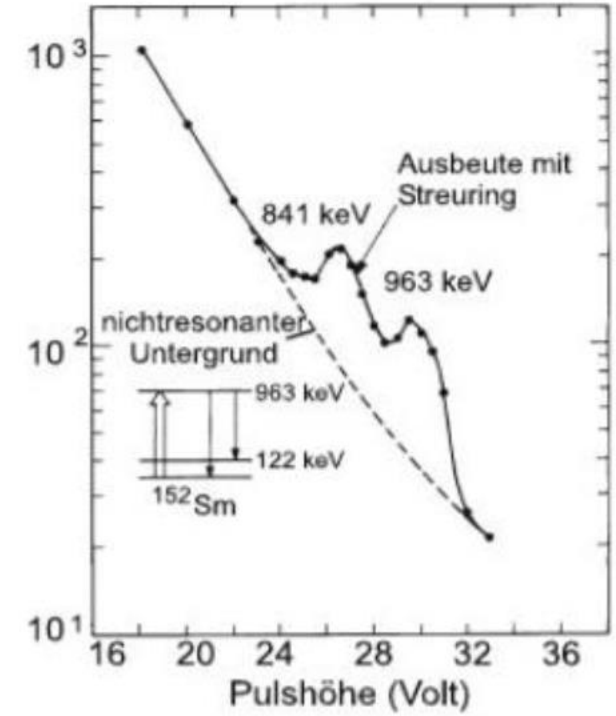
- **Neutrinos are LH**
- **Anti-neutrinos are RH**

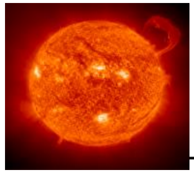


Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).



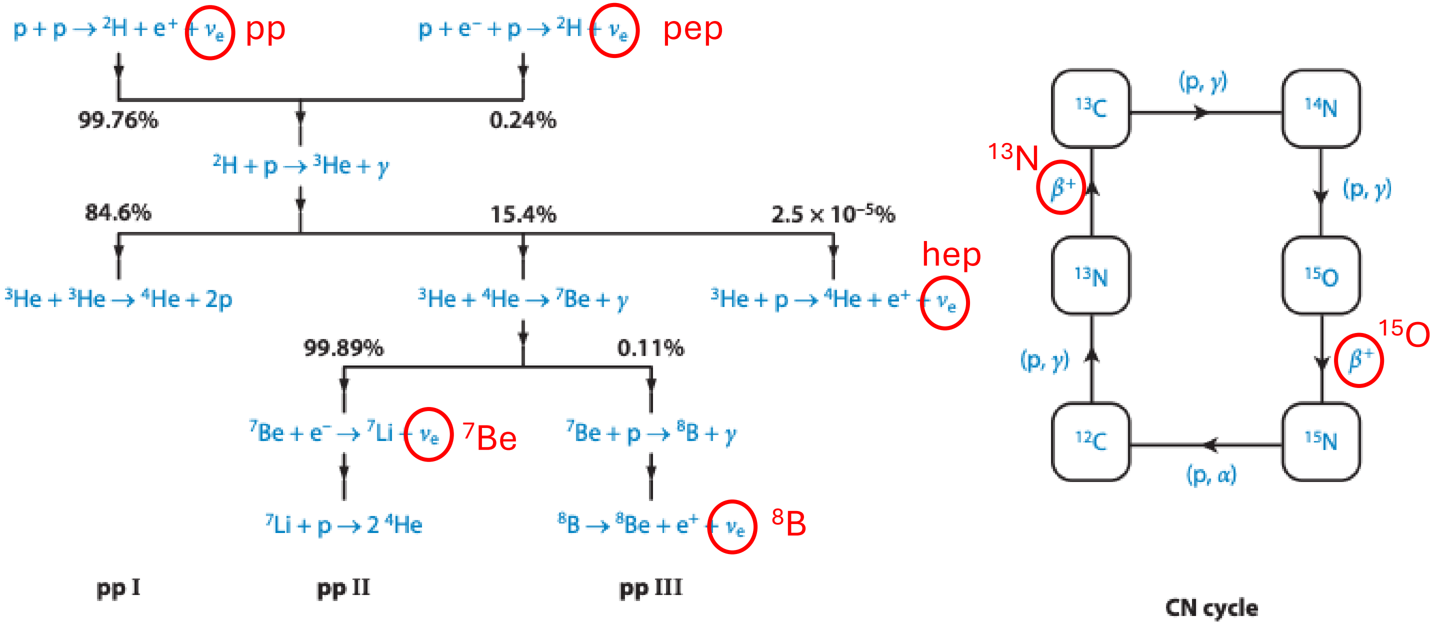


Solar neutrino problem

Slide from D. Moore

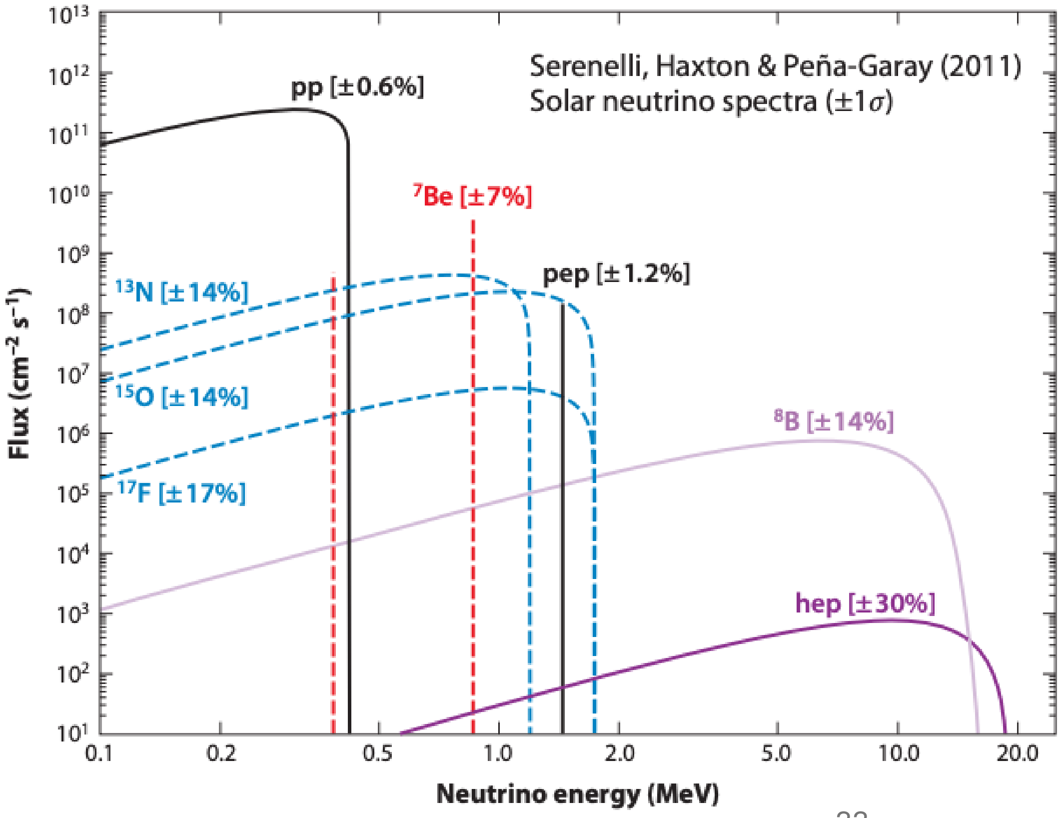
- As we already discussed, the most ubiquitous source of MeV neutrinos at Earth is the Sun
  - The “standard solar model” (SSM) was worked out by John Bahcall and others at Caltech in the 1960’s, but is quite complex

Solar neutrino generation cycles:



https://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081811-125539

Predicted solar neutrino flux:

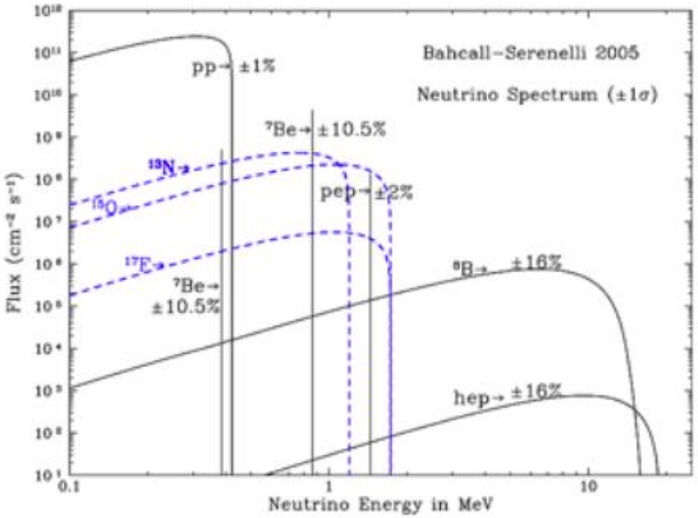


Detecting Neutrinos from the Sun

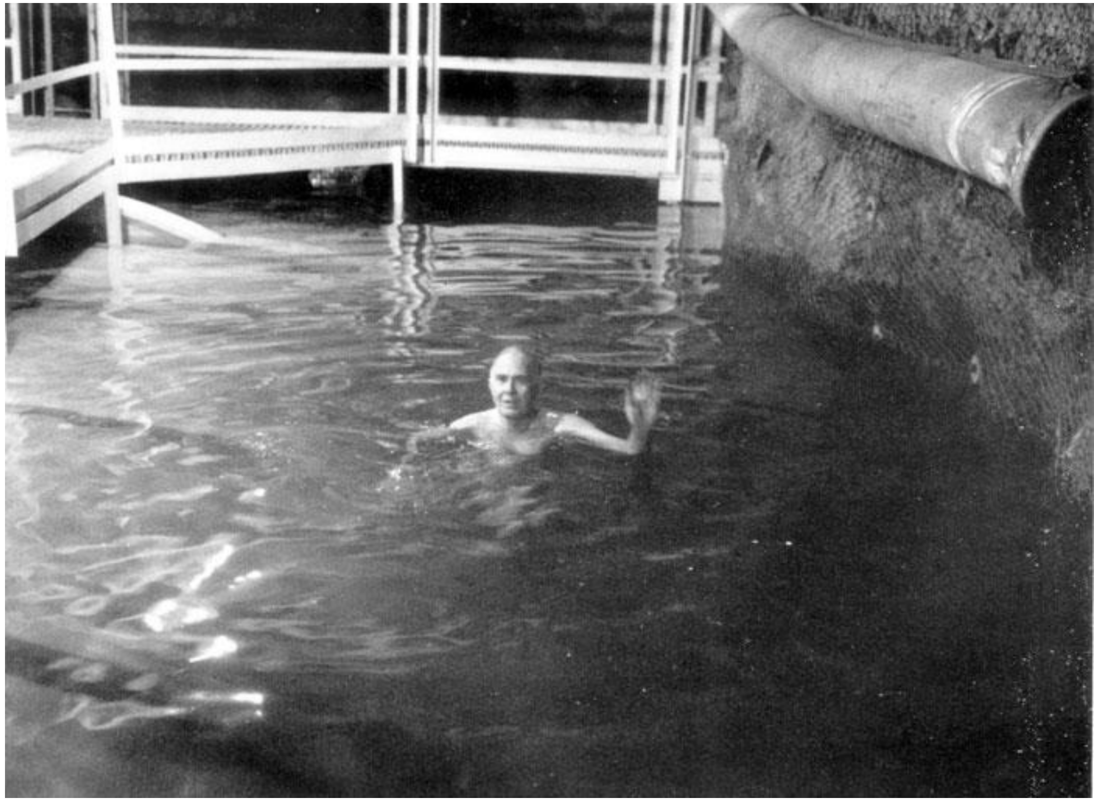
$$^{37}\mathrm{Cl} + \nu_e = {}^{37}\mathrm{Ar} + e^-$$

Reaction threshold: 0.814 MeV
$T_{½}(^{37}\mathrm{Ar})$ = 35.01 days (100% EC)

600 tons of dry clean fluid (perchloroethylene C_2Cl_4)
Produced only 15 atoms per month !



The Homestake detector was built by Ray Davis to test John Bahcall's Standard Solar Model.



Solar Neutrino Puzzle

Solar Neutrino Unit (SNU):
ν flux producing 10^{-36} captures/s/target atom

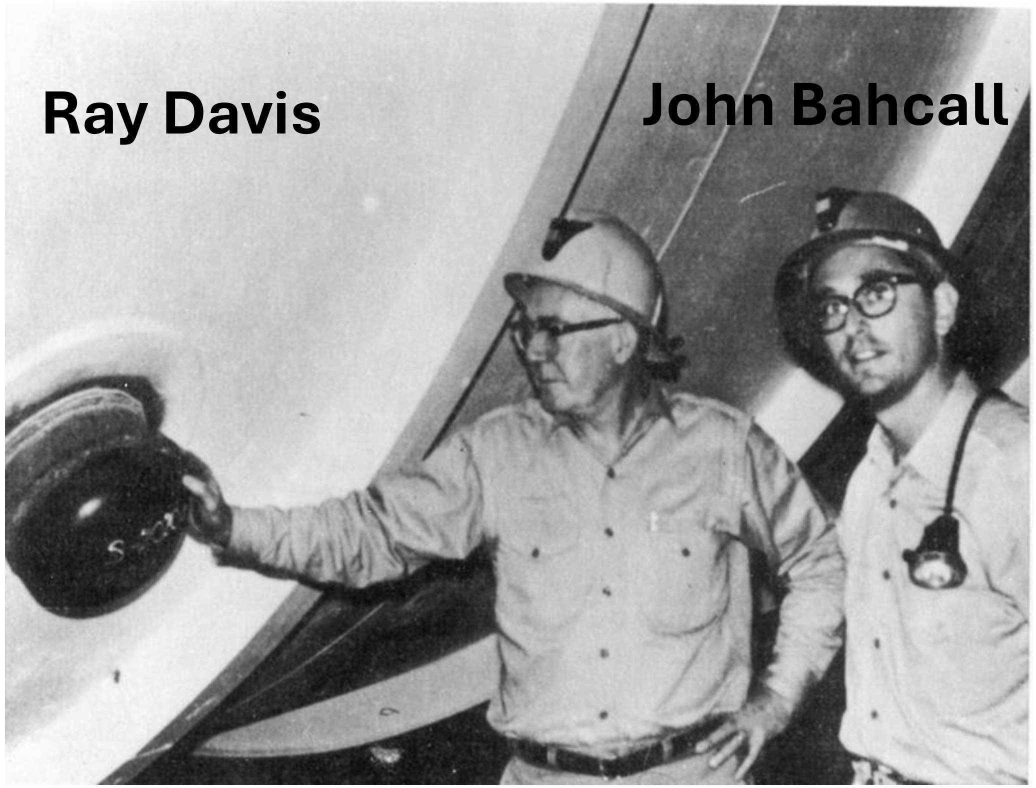
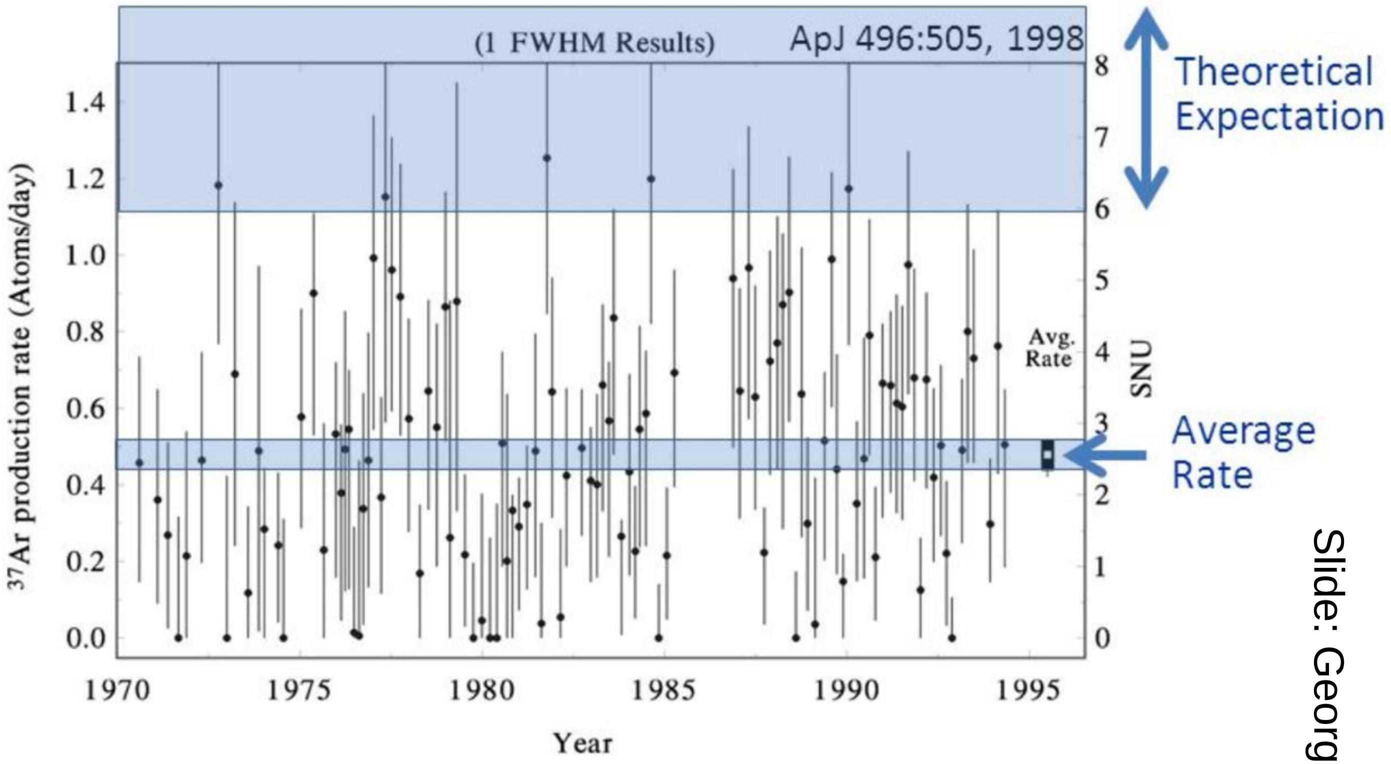


Photo: Courtesy of Raymond Davis, Jr. and John Bahcall



Average (1970–1994) $2.56 \pm 0.16_{\text{stat}} \pm 0.16_{\text{sys}}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

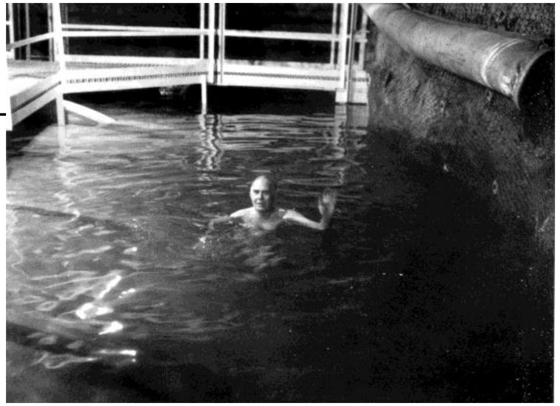
“Solar Neutrino Problem” since 1968

Slide: Georg Raffelt

Far too few (~1/3) solar neutrinos were seen compared to predicted solar production !

Solar neutrino problem

Homestake experiment (1968-1994)



2002

R. Davis

- First experimental measurement was from Ray Davis in the Homestake experiment

(Threshold 0.814 MeV)

  - Counted roughly ~30 ^{37}Ar atoms produced in a tank with ~600 tons of perchloroethylene (first results in 1968)
    - Only ~1/3 of what Bahcall had predicted from solar model!
    - No one believed Davis did the experiment right
      - And if they did, they didn't believe Bahcall's solar model

M. Koshiba 2002

- The deficit of solar neutrinos was confirmed by Kamiokande (late 1980s)

$$\nu + e^- \rightarrow \nu + e^-$$

(sensitive to all flavors, but cross-section is ~6x higher for ν_e)

- Further confirmation of a deficit from "gallium" experiments Gallex and SAGE:

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

(Threshold 0.233 MeV)

Where are the missing neutrinos?

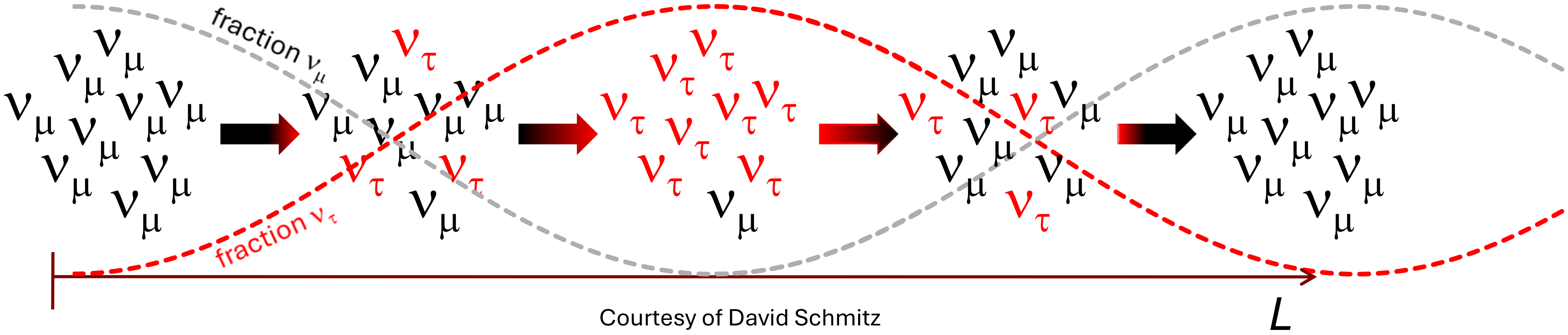
Astrophysics Wrong?

Experiment Wrong?

Bruno Pontecorvo

Neutrino Change Flavors?

Neutrino Flavor Oscillation

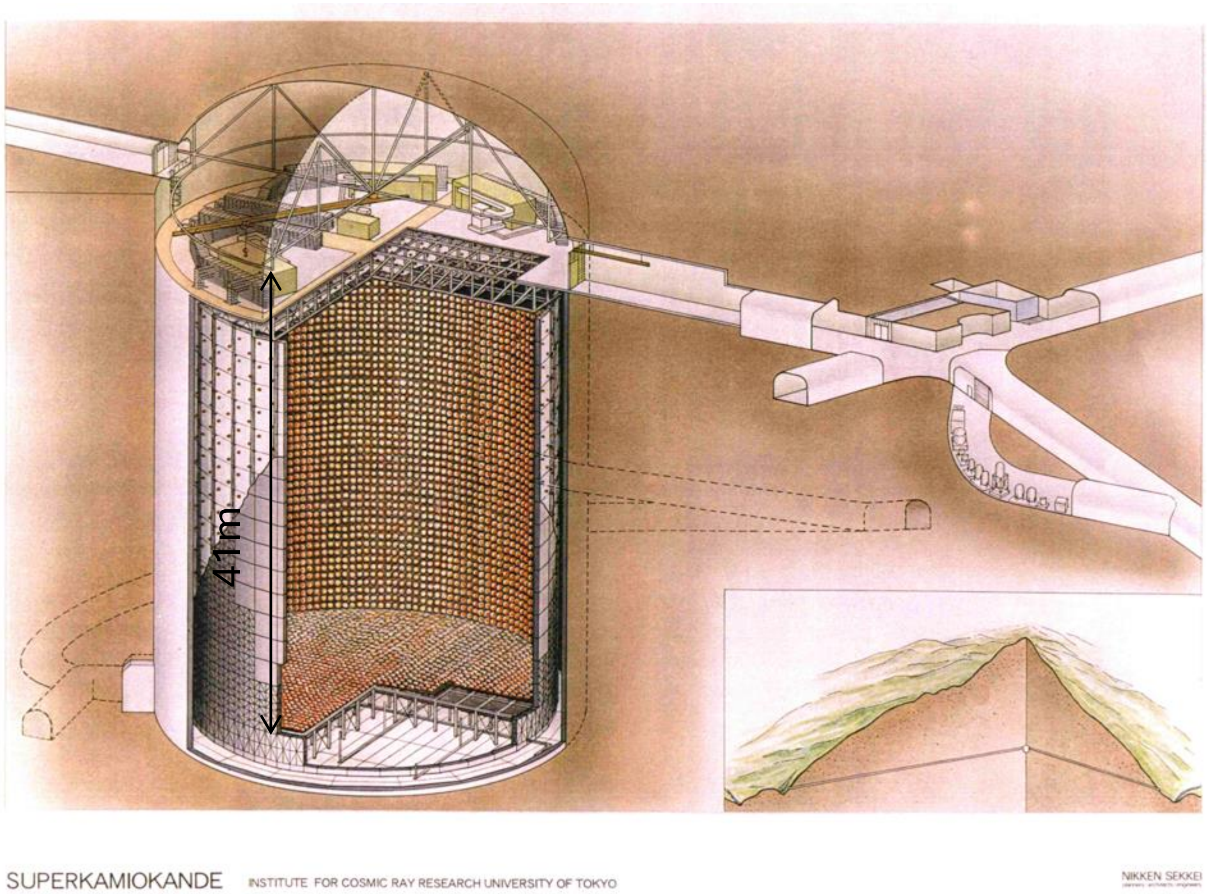


Courtesy of David Schmitz

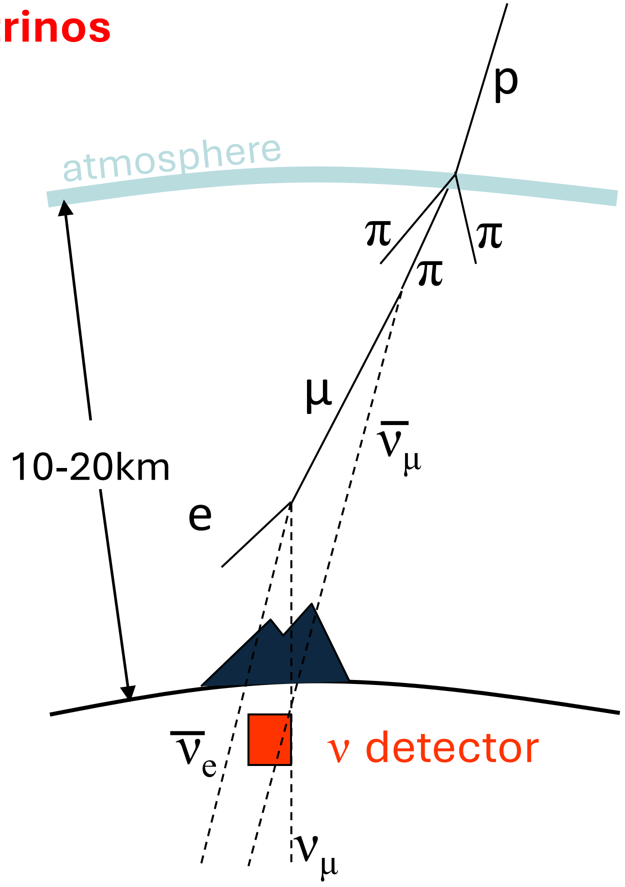
- Flavor change is a result of matter wave interference
- Neutrinos need to have different mass for this interference to take place

Neutrinos need to have non-zero mass!

The Super-Kamiokande Detector



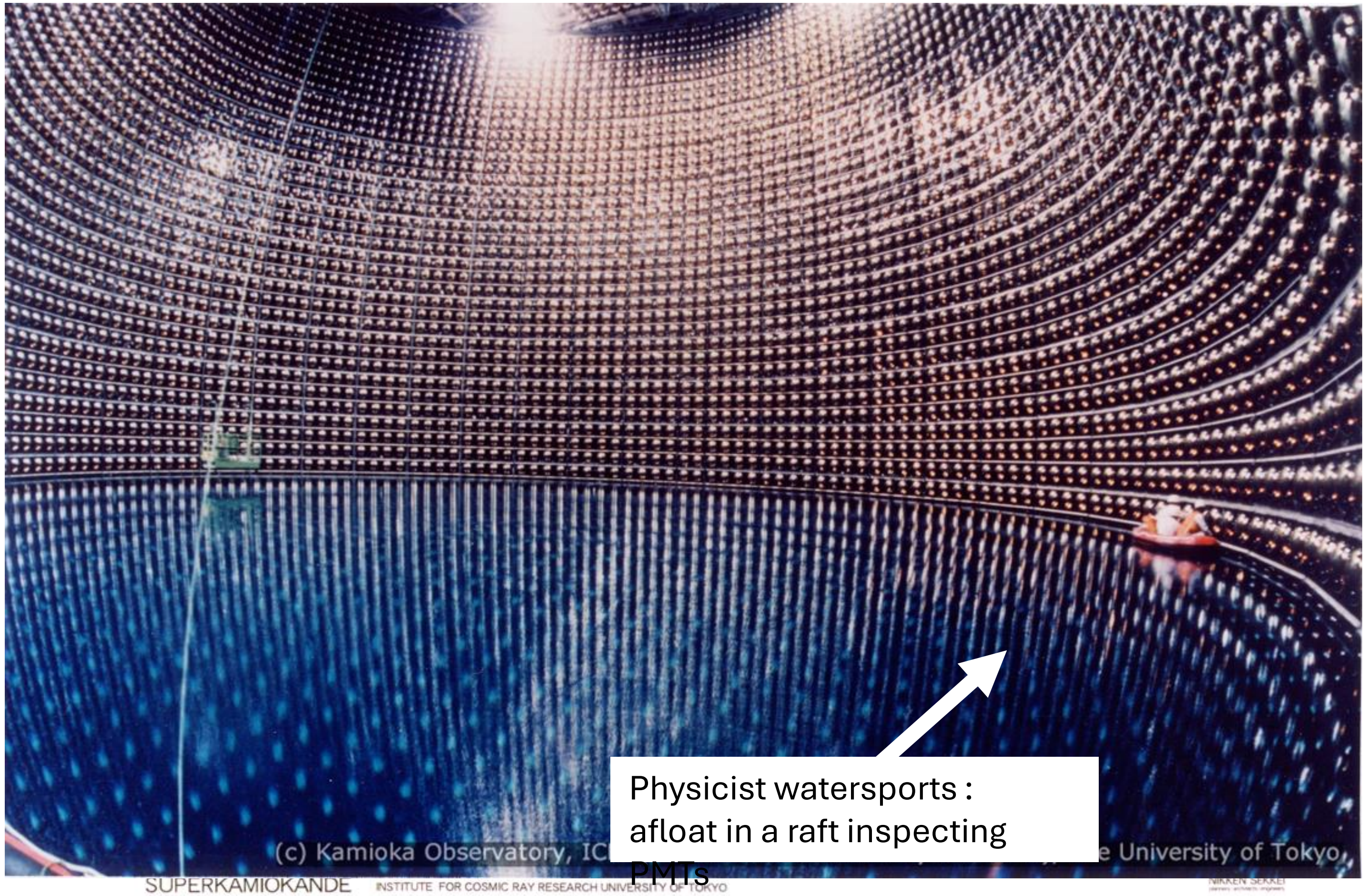
Super K can identify the direction of neutrinos



50,000 tonnes of ultra clean water (20 times larger mass than Kamiokande)

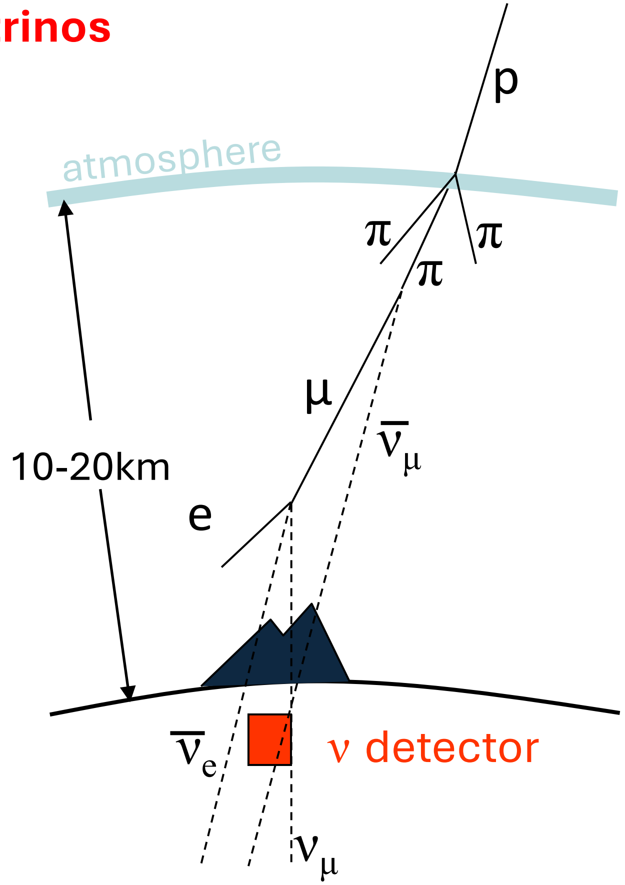
11,200 photomultiplier tubes

The Super-Kamiokande Detector



Physicist watersports : afloat in a raft inspecting PMTs

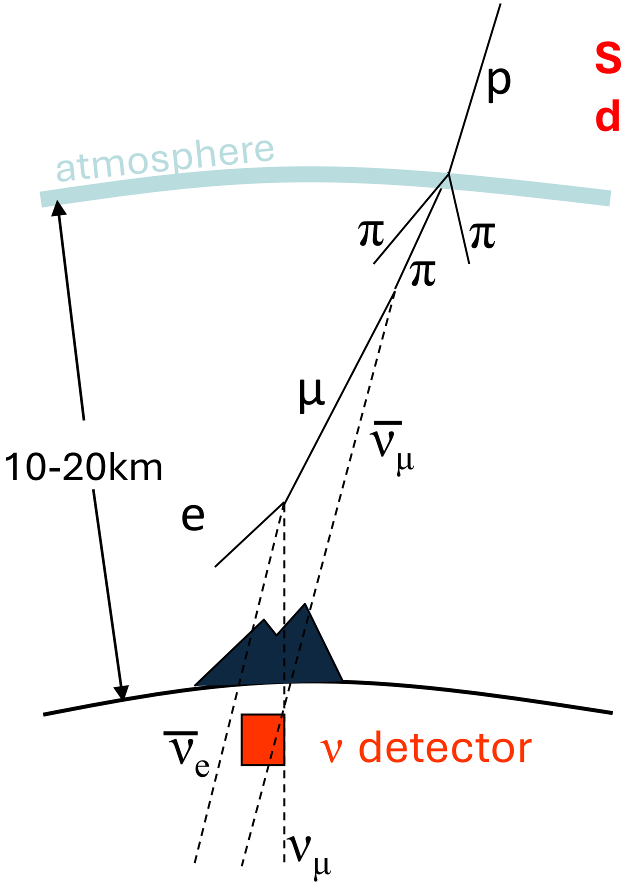
Super K can identify the direction of neutrinos



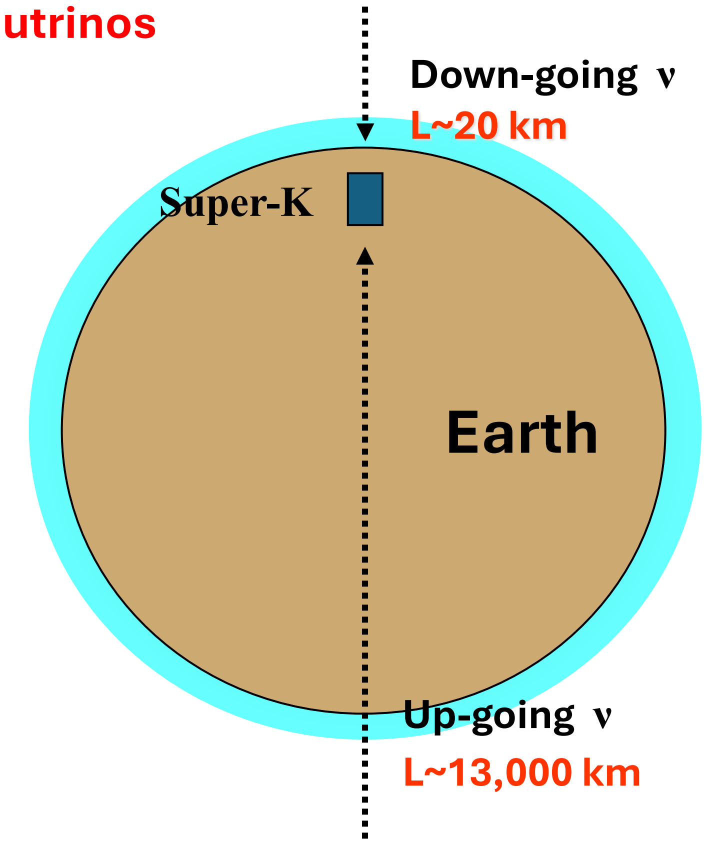
50,000 tonnes of ultra clean water (20 times larger mass than Kamiokande)

11,200 photomultiplier tubes

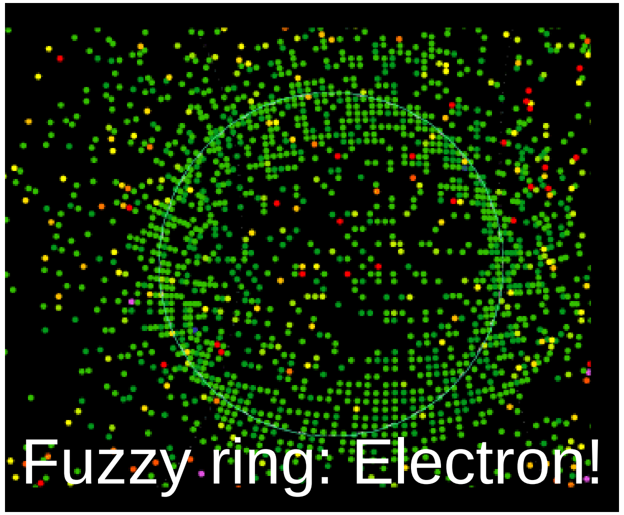
Atmospheric Neutrino



Super K can identify the direction of neutrinos



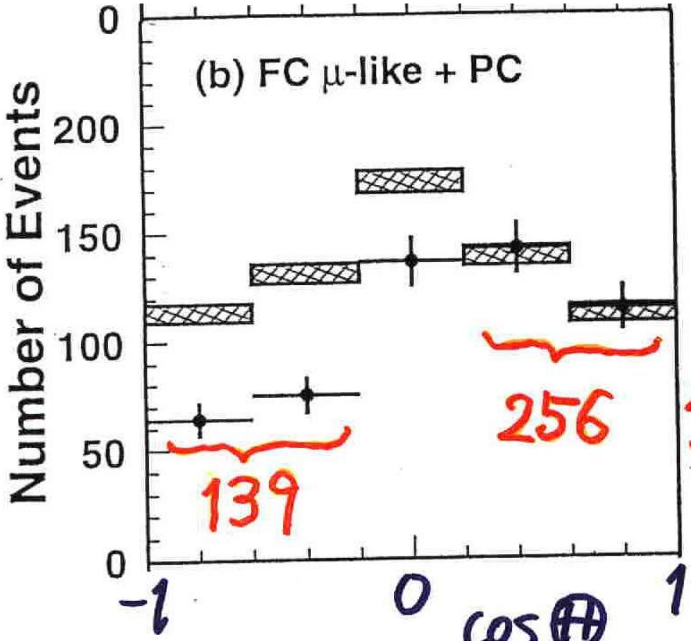
Graphics: SuperK



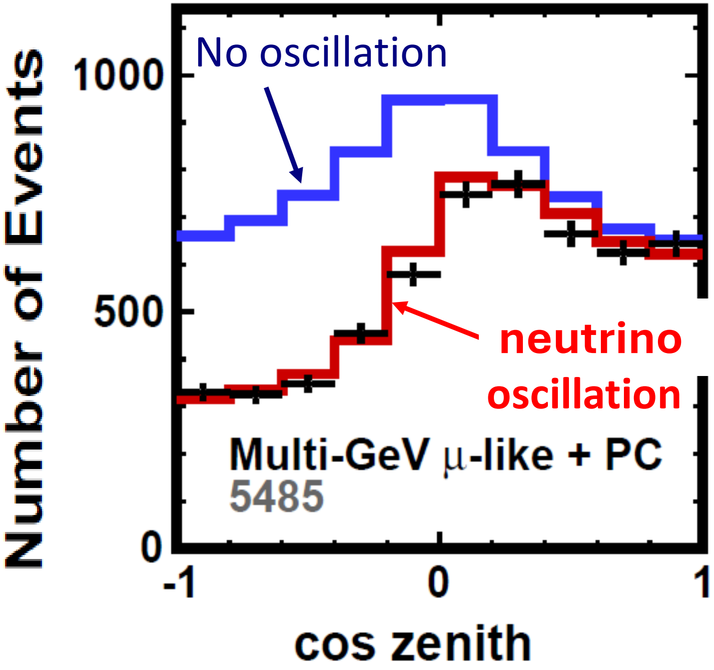
SuperK results

Takaaki Kajita
Nobel Prize 2015

Super-K @Neutrino98



Super-K (2015)



Takaaki Kajita,
Nobel Prize
Lecture, 2015

Number of events plotted:

<u>531 events</u>

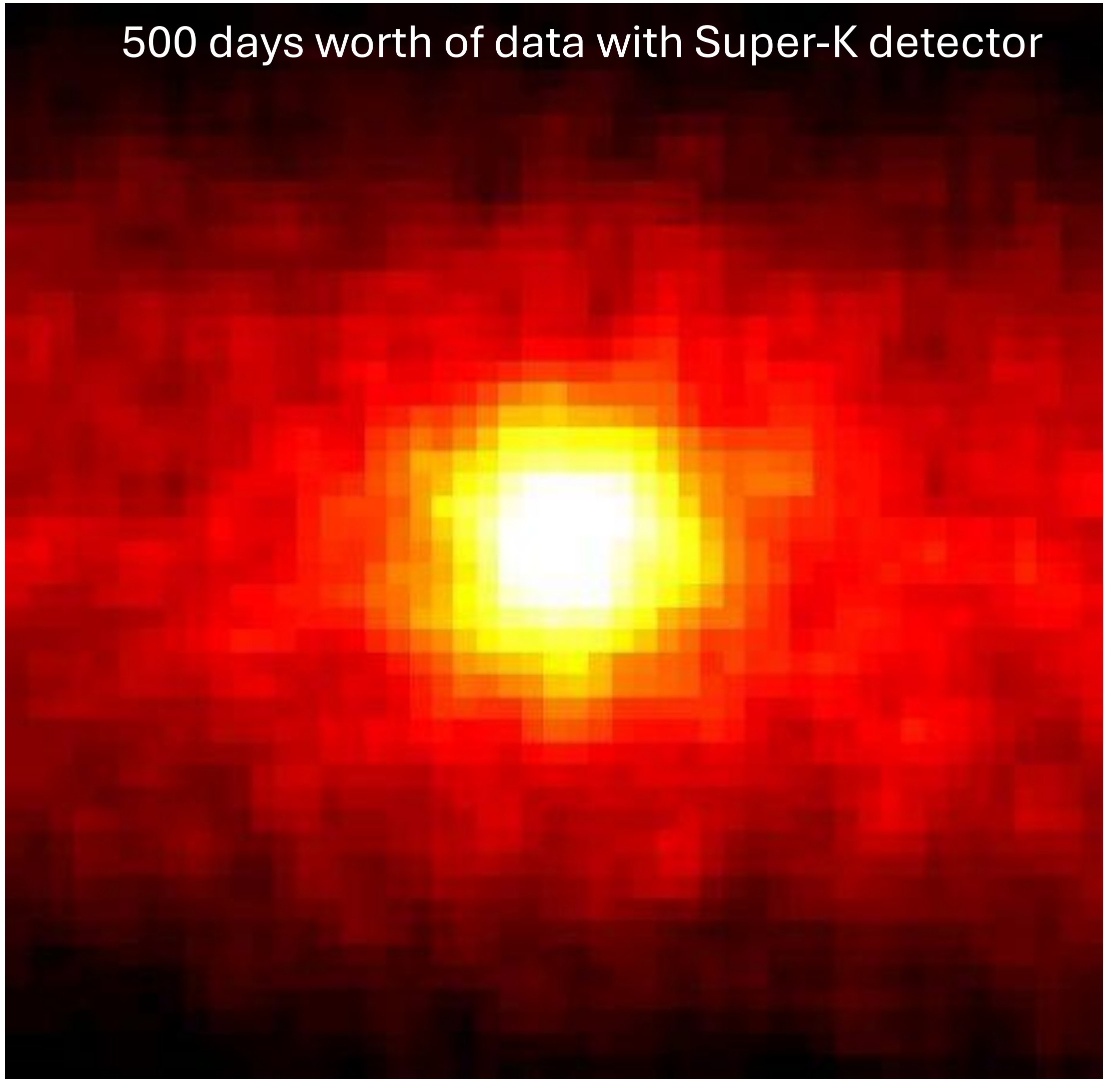
<u>5485 events</u>

The Sun imaged with neutrinos!

SuperK cannot provide solution to the missing ν_e from the sun, but…

Question: While this is a cool pictures, why should we care about taking a neutrino-picture of the sun?

Question: How long does it take a neutrino to leave the sun?



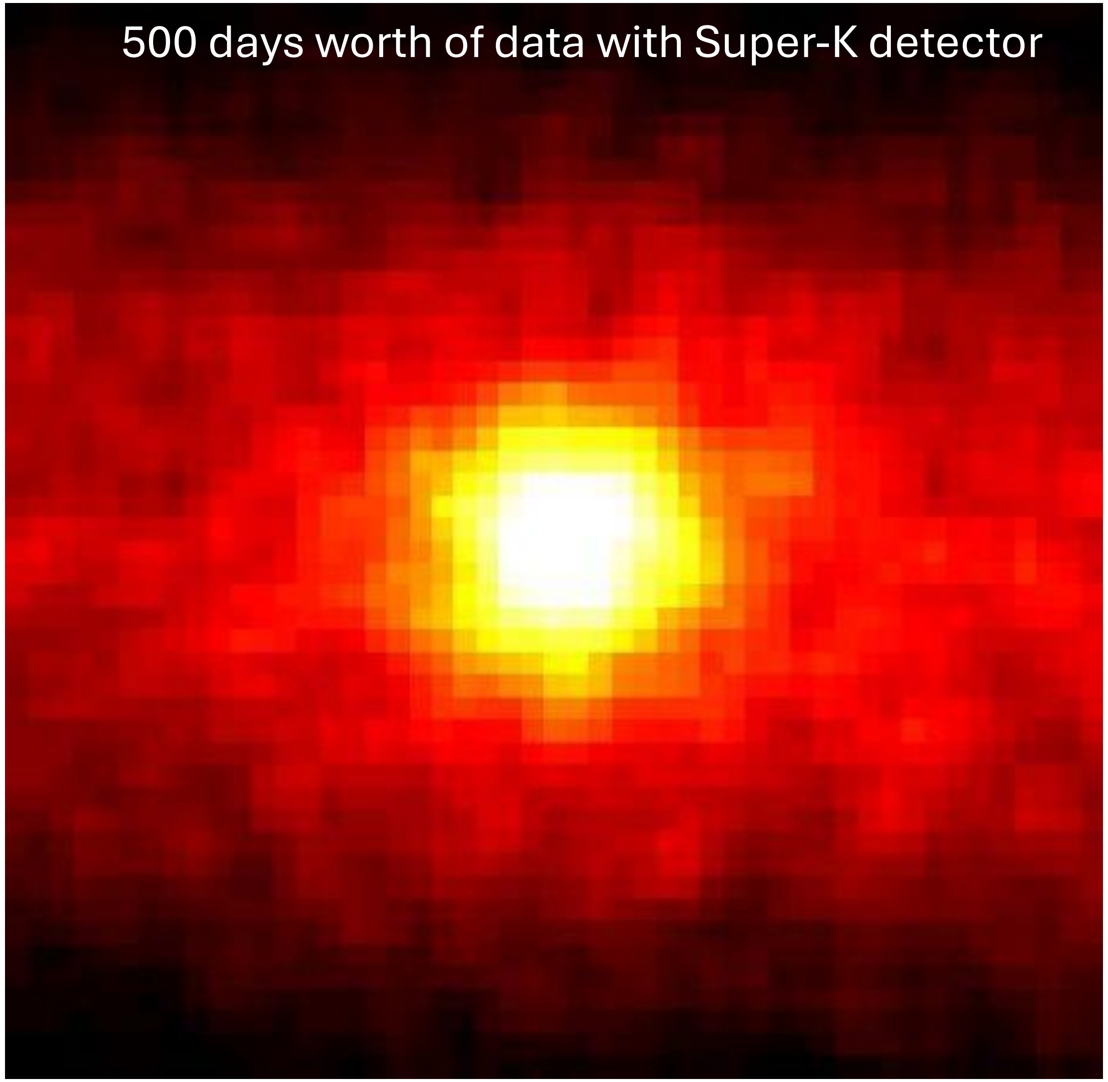
The Sun imaged with neutrinos!

SuperK cannot provide solution to the missing ν_e from the sun, but…

Question: While this is a cool pictures, why should we care about taking a neutrino-picture of the sun?

Question: How long does it take a neutrino to leave the sun?

Question: and light?

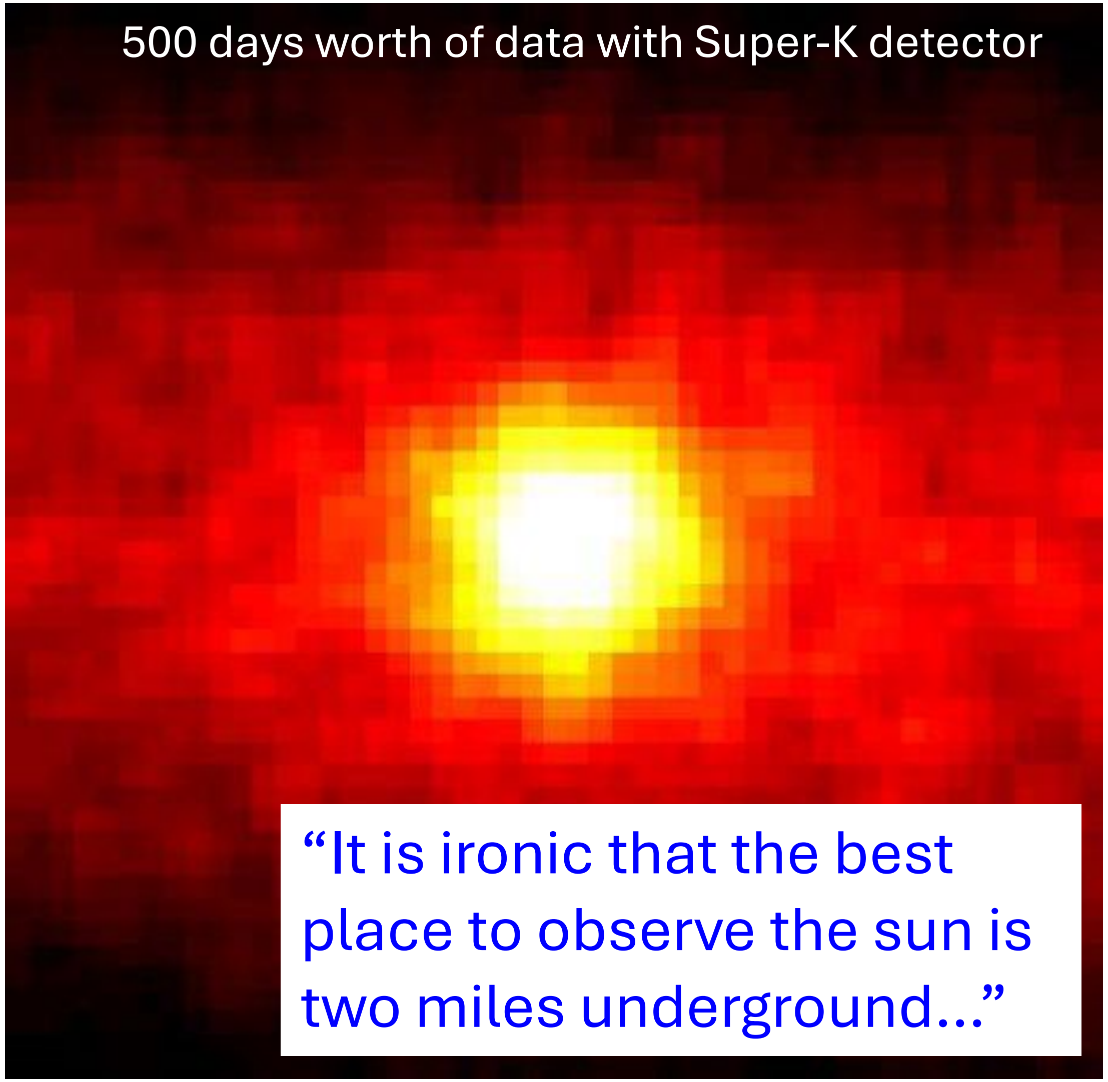


The Sun imaged with neutrinos!

SuperK cannot provide solution to the missing ν_e from the sun, but…

While sunlight takes about 30,000 – 100,000 years to work its way out from the center to the surface of the Sun, neutrinos take just two seconds

→ Neutrinos can be used as probes for nuclear processes


500 days worth of data with Super-K detector

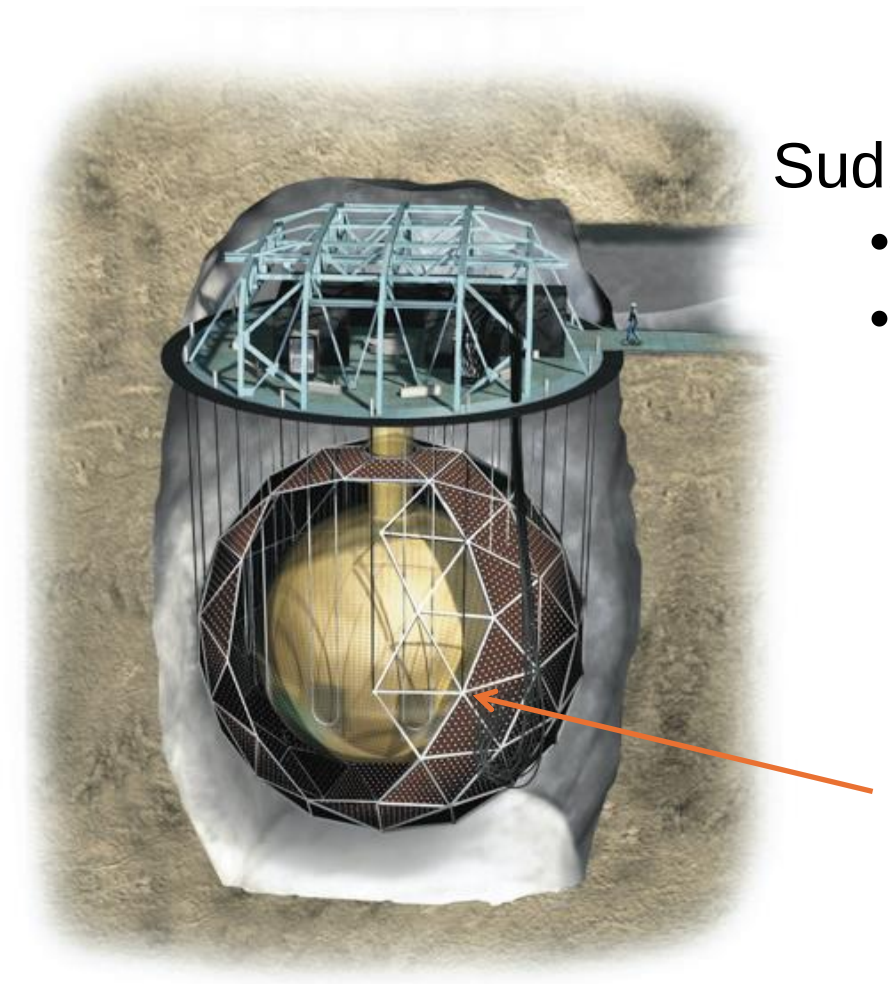
"It is ironic that the best place to observe the sun is two miles underground…"

- Art McDonald

Sudbury Neutrino Observatory (SNO)

Sudbury Neutrino Observatory: combine CC, NC sensitivity

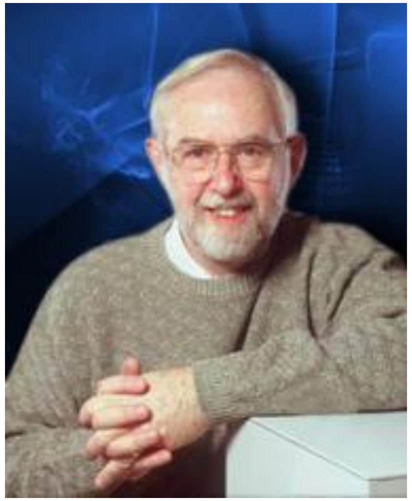
- Measure both ν_e disappearance AND total ν_X flux
- Confirm where missing electron neutrinos went



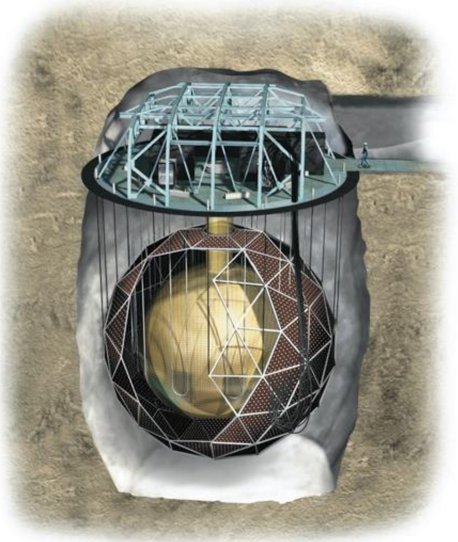
1000 tonnes of ultra-pure heavy water (D_2O) housed in a clear acrylic vessel 12 m in diameter, located a mile underground in a nickel mine in Sudbury, Ontario, Canada.

Sudbury Neutrino Observatory

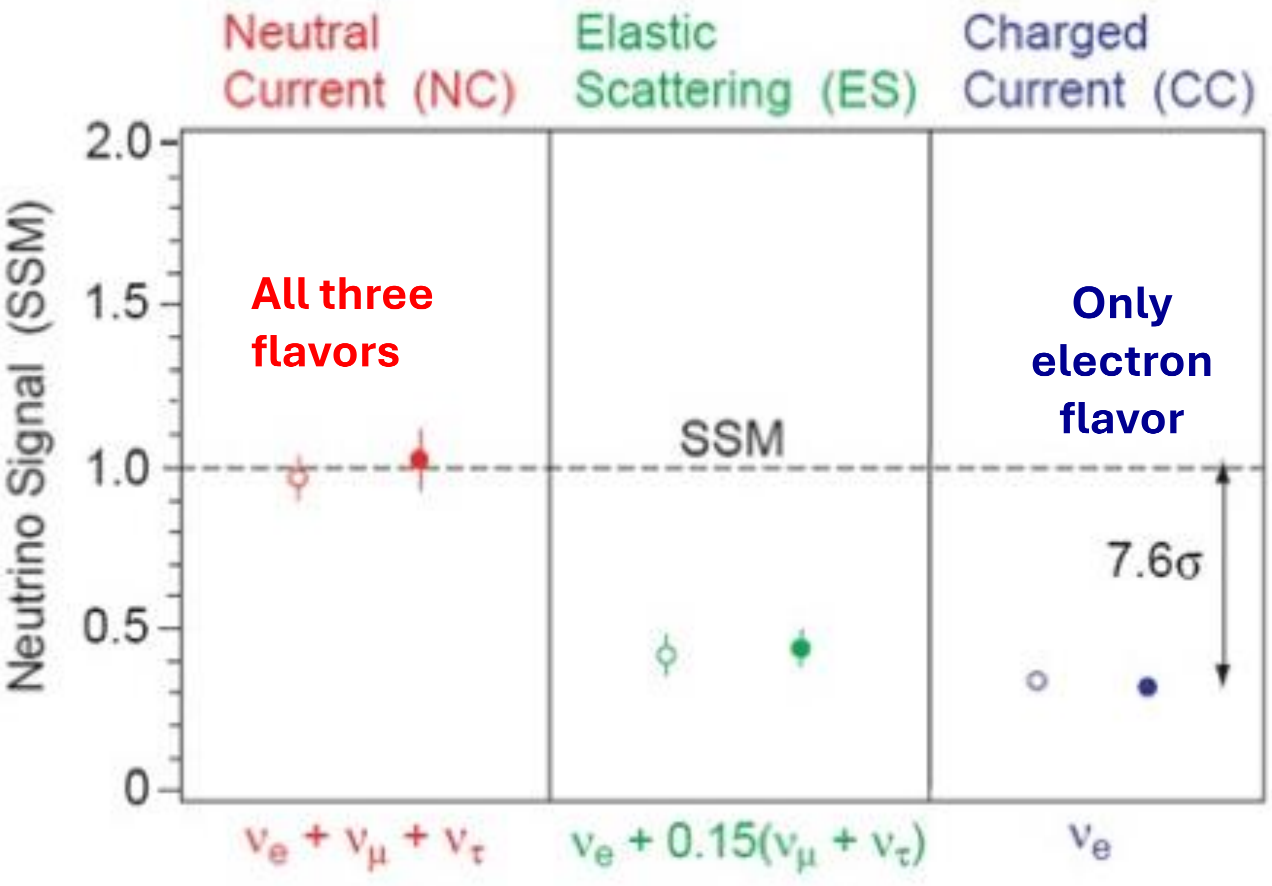
Solving the solar neutrino problem (2002)



Art MacDonald
Nobel Prize
(2015)

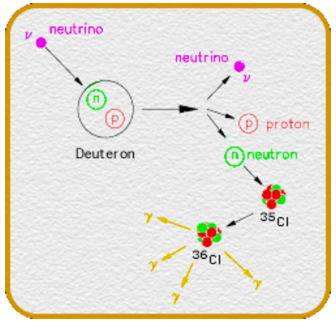


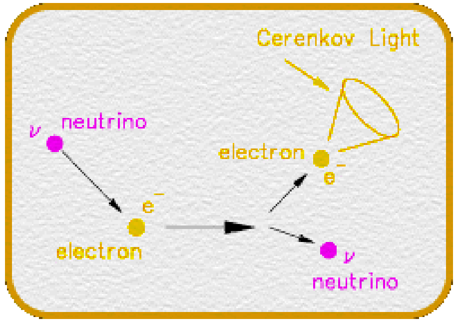
Sudbury Neutrino Observatory with 1,000 tonnes of D_2O

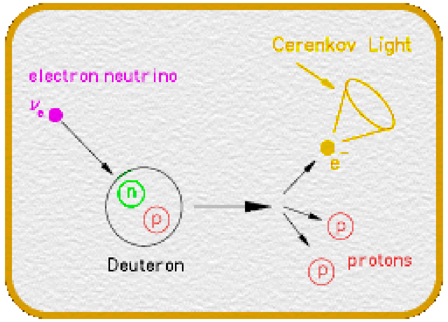


All three flavors

Only electron flavor







Missing neutrinos changed into other flavors!

Solar neutrino problem

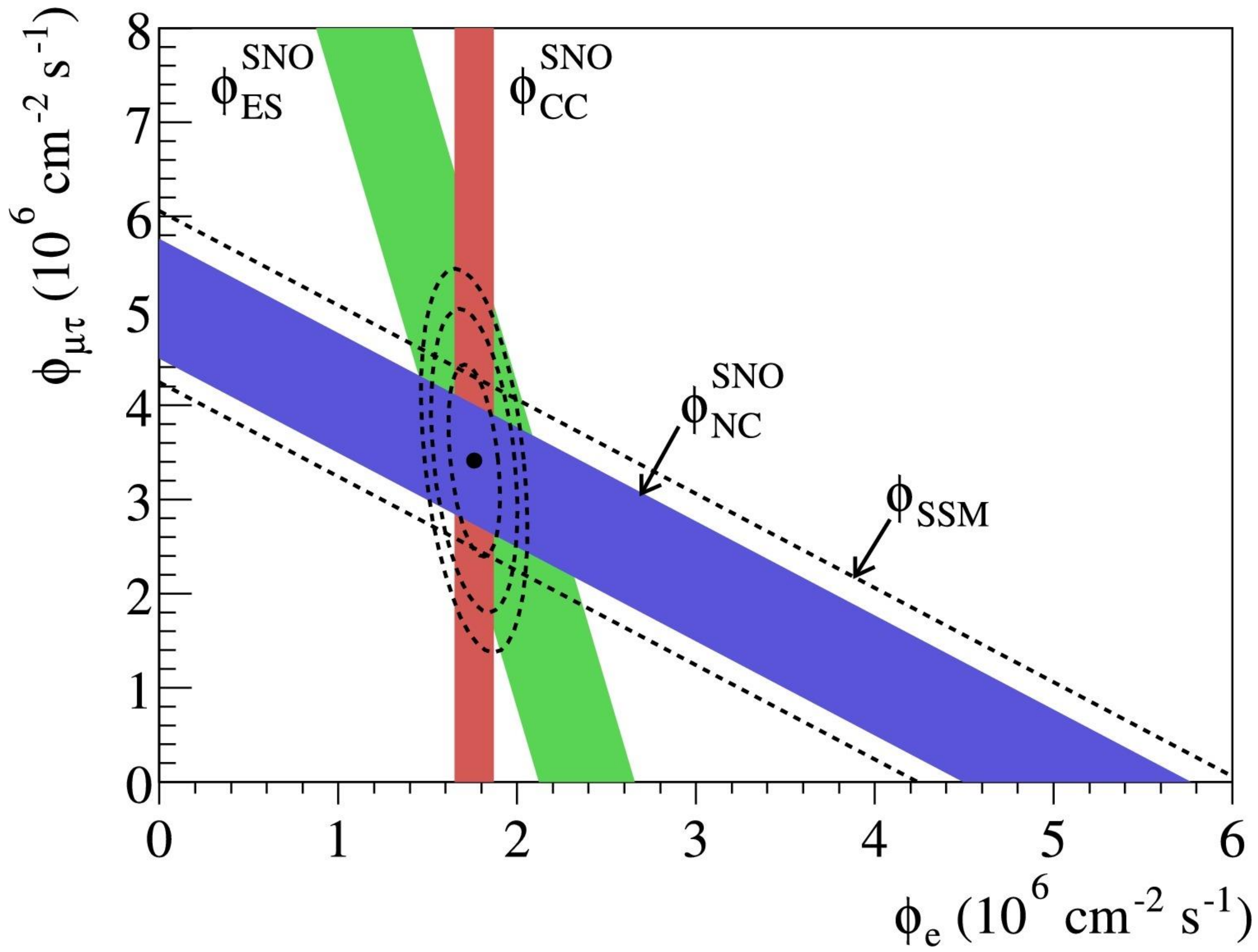
- Only ~5 years after the proposal, SNO began construction in Sudbury, Ontario (with loan of ~$300M D_2O from Canadian nuclear energy agency)
- Measured 3 types of interactions:

$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)}$$

$$\nu_x + e^- \rightarrow \nu'_x + e'^- \qquad \text{(ES, CC\&NC)}$$

$$\nu_x + d \rightarrow \nu'_x + n + p \qquad \text{(NC)}$$

- Perfect agreement with SSM for NC, deficit for CC (2002)!



https://www.sciencedirect.com/science/article/pii/S0550321316300736

T. Kajita

A. McDonald

2015

Neutrino mixing, mass, and 0νββ

In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

$$\begin{aligned} \nu_{m1}(t) &= e^{-i(\boxed{E_1 t} - p_1 L)} \nu_{m1} \\ \nu_{m2}(t) &= e^{-i(\boxed{E_2 t} - p_2 L)} \nu_{m2} \\ \nu_{m3}(t) &= e^{-i(\boxed{E_3 t} - p_3 L)} \nu_{m3} \end{aligned}$$

$E_i = m_i c^2$
Evolve in time
with *m_i & E*

"Weak interaction eigenstate"

this is the state of definite flavor:

interactions couple to this state

"Mass eigenstate"

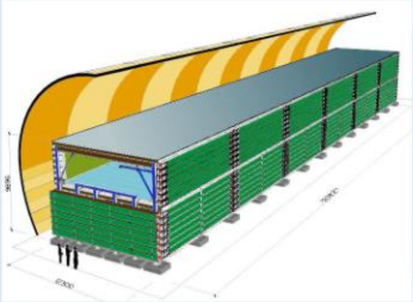
this is the state of definite energy:

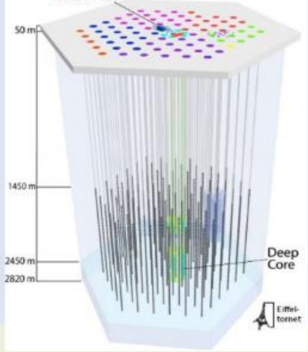
propagation happens in this state

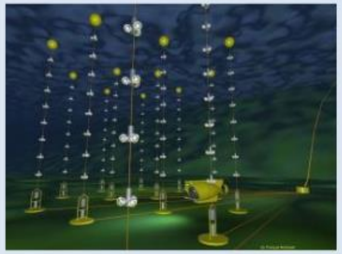
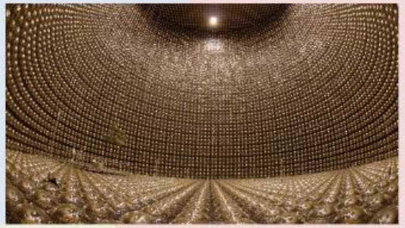
- The elements of the MNSP matrix are determined in oscillation experiments.
- Oscillation experiments can only determine Δm_{ij}^2, the squared mass difference between two eigenstates.

Many exciting results in neutrino oscillations (partial list)

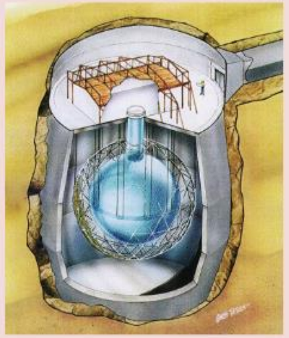
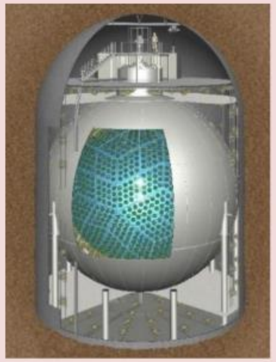
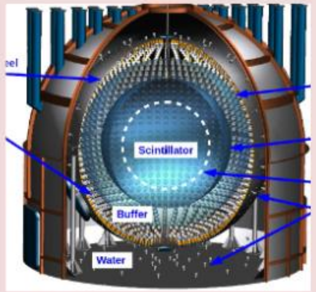
Atmospheric neutrino oscillation experiments



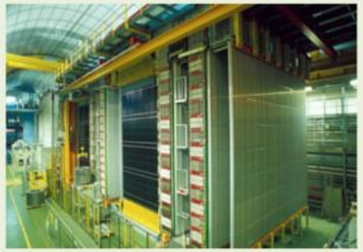


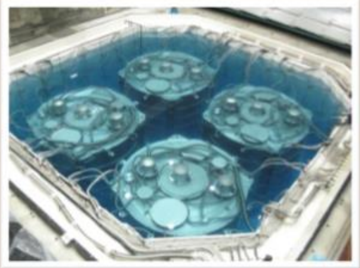
Solar neutrino oscillation experiments

Accelerator based neutrino oscillation experiments



3 flavor(type) neutrino oscillation experiments



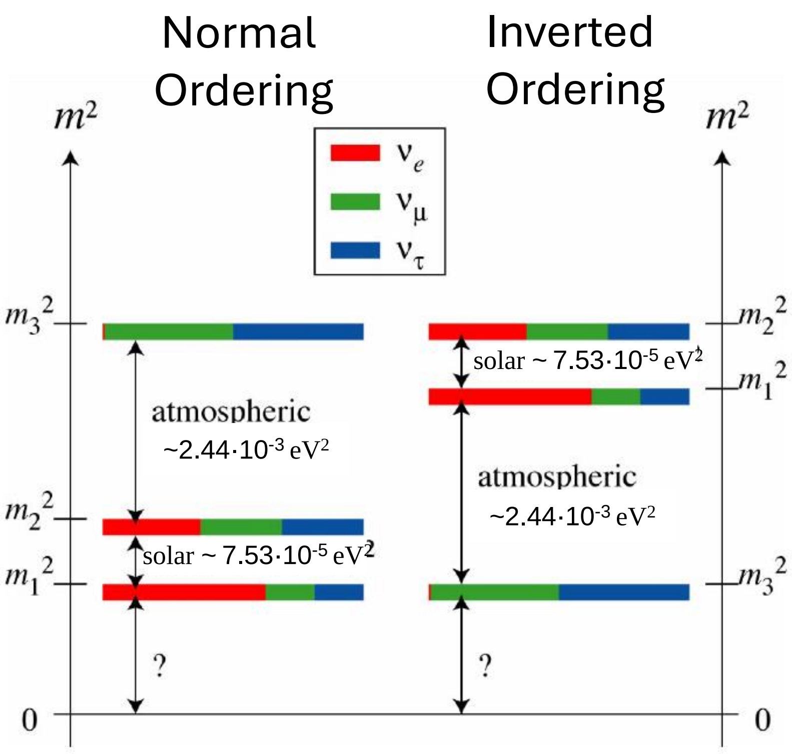
Slide from Takaaki Kajita, NEUTRINO 2022

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

$\sin^2(\theta_{12})$	0.307 ± 0.013
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23})$	$0.536^{+0.023}_{-0.028}$ …
Δm^2_{32}	0.002444 ± 0.000034 eV^2
$\sin^2(\theta_{13})$	0.0218 ± 0.0007

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



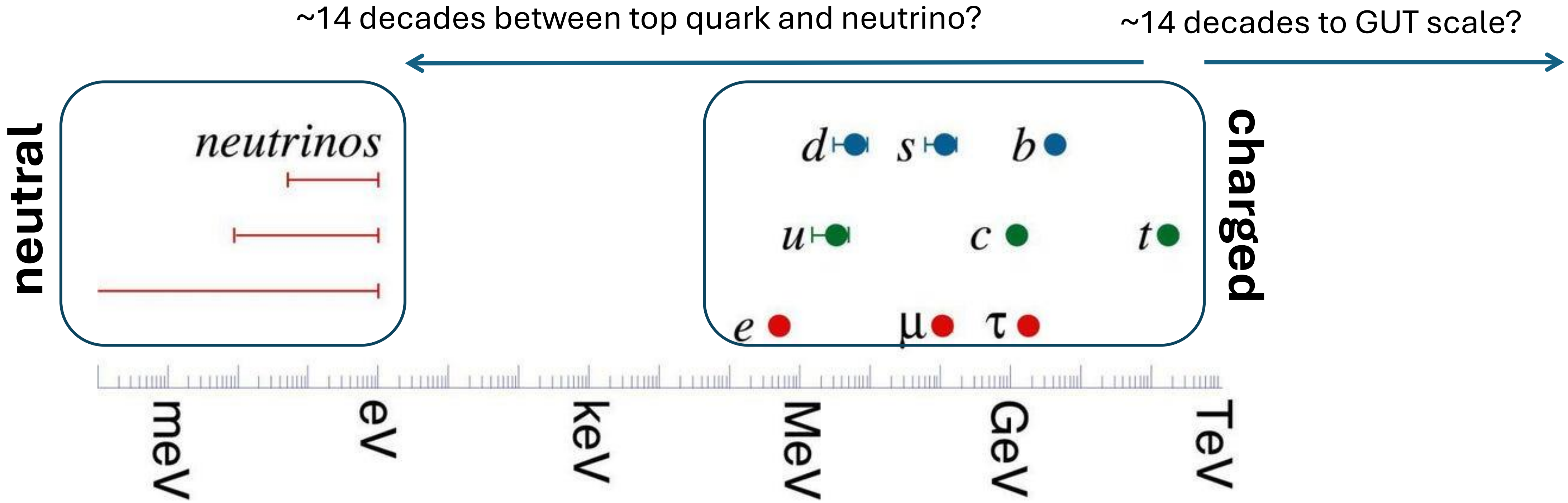
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{“atmospheric”}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{“reactor"}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“solar”}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

$$\sin^2\theta_{23} \qquad \sin^2\theta_{13} \qquad \sin^2\theta_{12}$$

Precision measurments can be made with neutrino beams!

Slide: Michelle Dolinski, TRISEP2021

Spin ½ Fermion Mass spectrum


~14 decades between top quark and neutrino?

~14 decades to GUT scale?

Adopted from: Hitoshi

- Neutrinos are 6 orders of magnitude lighter than the next heavy particle.
- What determines the mass scale hierarchy of elementary particles?
- Is the Higgs mechanism responsible for neutrino mass?
- Perhaps neutrinos are very different from other fermions, such as a Majorana particle?

Electrically neutral neutrinos

Generation

Charge	**1st**	**2nd**	**3rd**
1	e^+	μ^+	τ^+
2/3	u	c	t
1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
0	ν_e	ν_μ	ν_τ
-1/3	d	s	b
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
-1	e^-	μ^-	τ^-

Neutrinos do not carry charge
What about lepton number?

Could it be that the mass and charge peculiarities are somehow related?

Say that for neutrinos $\bar{\nu} = \nu$, since they have no charge…

But… isn't there a lepton number to conserve?

No worries: lepton number conservation is not as "serious" as -say- energy conservation

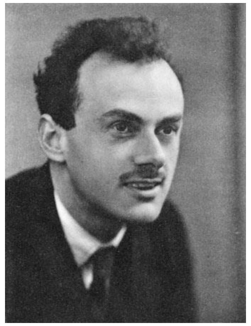
Lepton number conservation is just an empirical notion.

Basically, lepton number is conserved "because", experimentally, $\bar{\nu} \neq \nu$. But the distinction could derive from the different helicity states.

Quantum Nature of the Neutrino

"Dirac" neutrinos

$\nu \neq \bar{\nu}$



$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$

"Majorana" neutrinos

Could help explain the origin of matter!

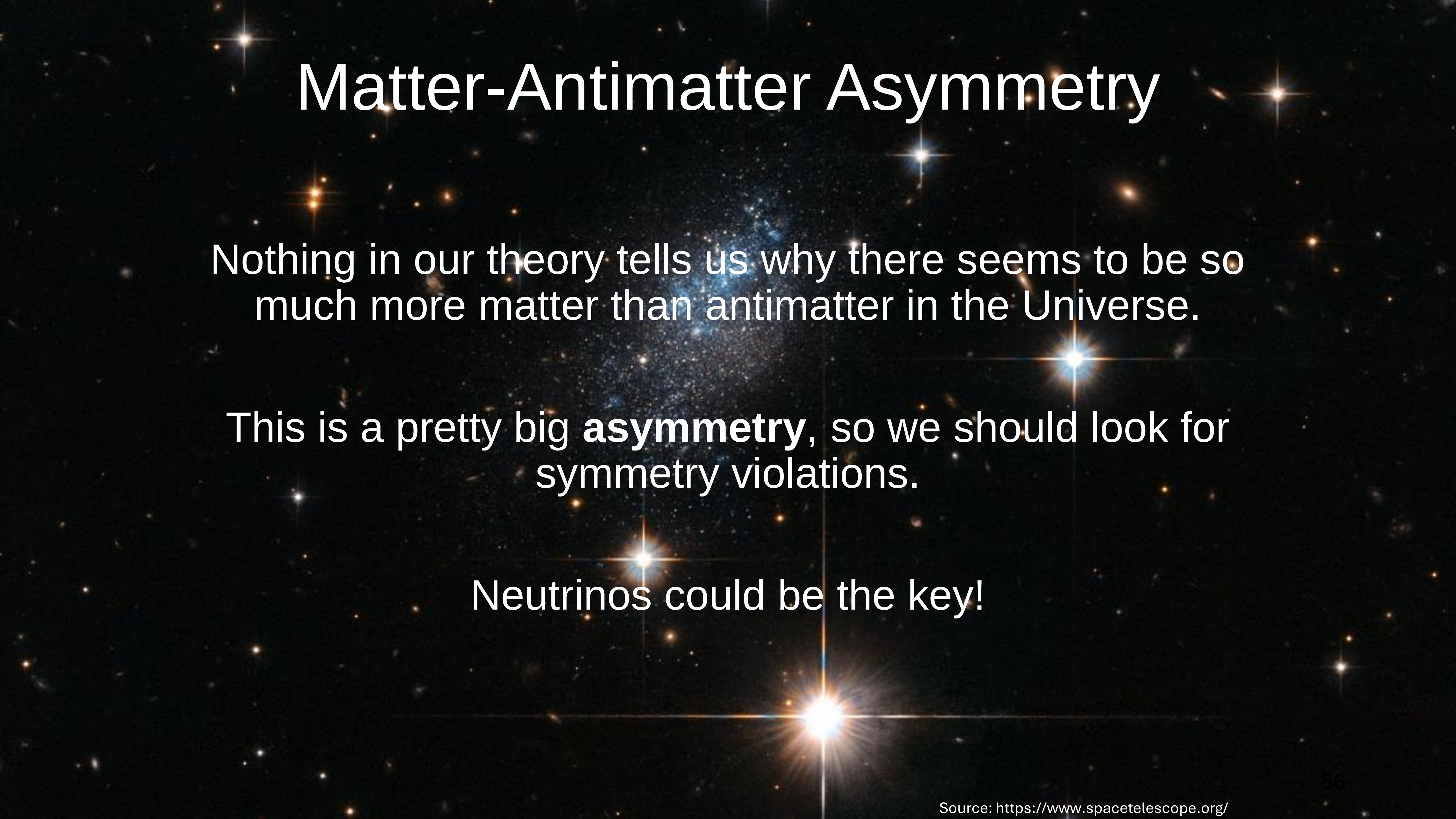
$\nu = \bar{\nu}$

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature chose to proceed is an open experimental question, although Majorana neutrinos are favored by theory.

The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Matter-Antimatter Asymmetry



Nothing in our theory tells us why there seems to be so much more matter than antimatter in the Universe.

This is a pretty big **asymmetry**, so we should look for symmetry violations.

Neutrinos could be the key!

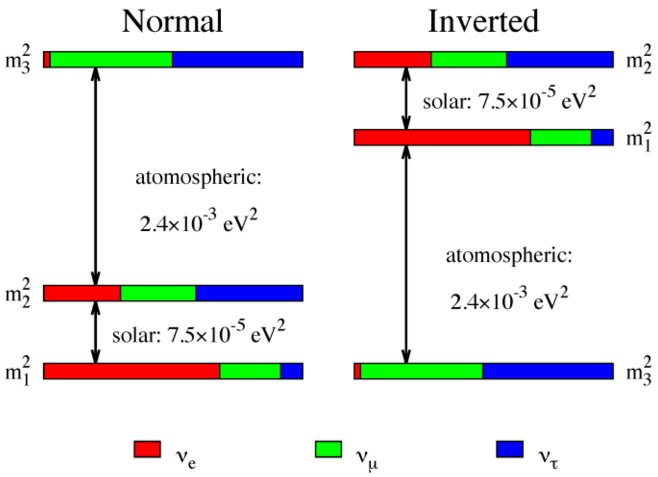
Source: https://www.spacetelescope.org/

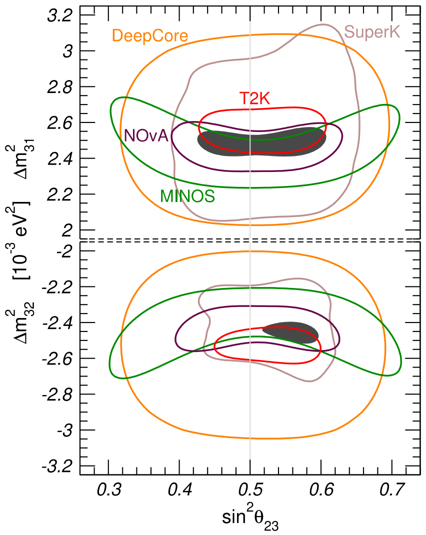
Open questions in neutrino physics

- Despite lots of progress, there are still major open questions in neutrino physics:
  - What are the origin of neutrino masses (and why are they so light)? What is their absolute mass scale?
  - What is the nature of neutrinos (Dirac or Majorana)?
  - What is the mass hierarchy (ordering)?
  - Is θ_{23} maximal?
  - Is there CP violation? What is δ_{CP}?
  - Are there sterile neutrinos?

Lectures on 0νββ by Jeanne Wilson

Lectures on oscillation experiments by Blair Jamieson





$$\begin{bmatrix} c_{13} & 0 & s_{13}e^{\boxed{-i\delta_{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{\boxed{i\delta_{CP}}} & 0 & c_{13} \end{bmatrix}$$