Credit: symmetry magazine

Neutrino Physics
Experimental I

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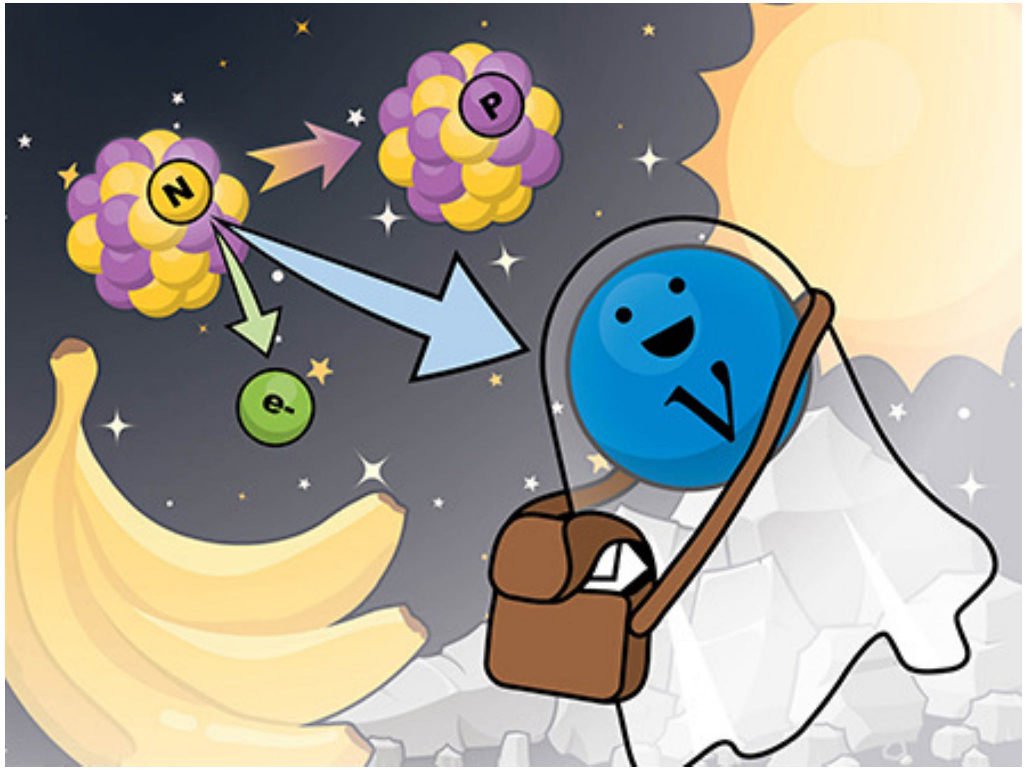
TAE 2023 – International Workshop on High Energy Physics
Centro de Ciencias Pedro Pascual
September 11th, 2023

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

Why do we study neutrinos?



Credit: Tiffany Bowman, Brookhaven National Laboratory.

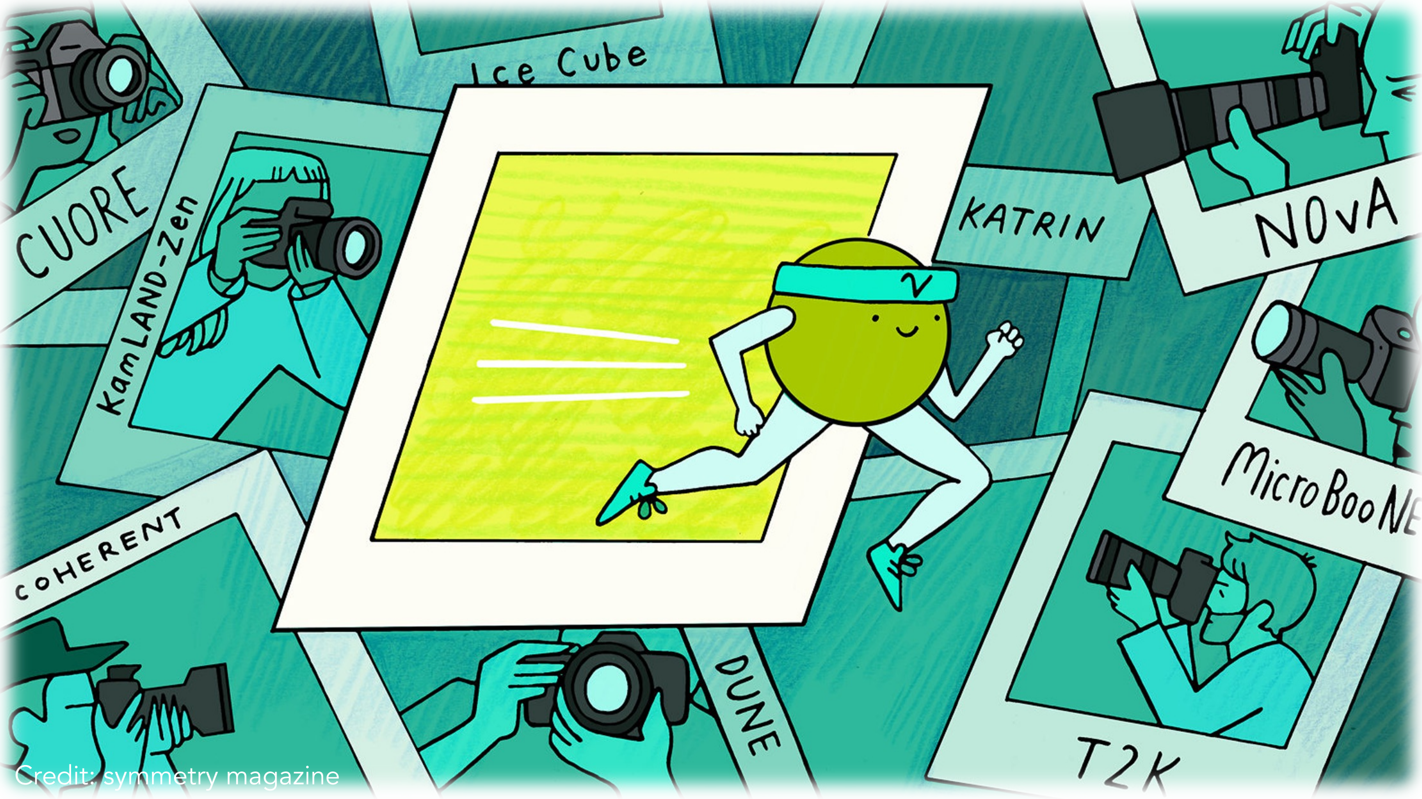
Neutrinos are abundant, but the most elusive particles.

Q — Enigmatic particles, not fully understood

A — Provide answers to our understanding of the universe

Why do we study neutrinos?

- Experimentalists have made enormous progress in measuring neutrino properties
  → Data-driven field with unexpected results!
- Theorists have been able to explain most of the data with simple models (such as the three-flavor framework to explain neutrino oscillation results).



Credit: symmetry magazine

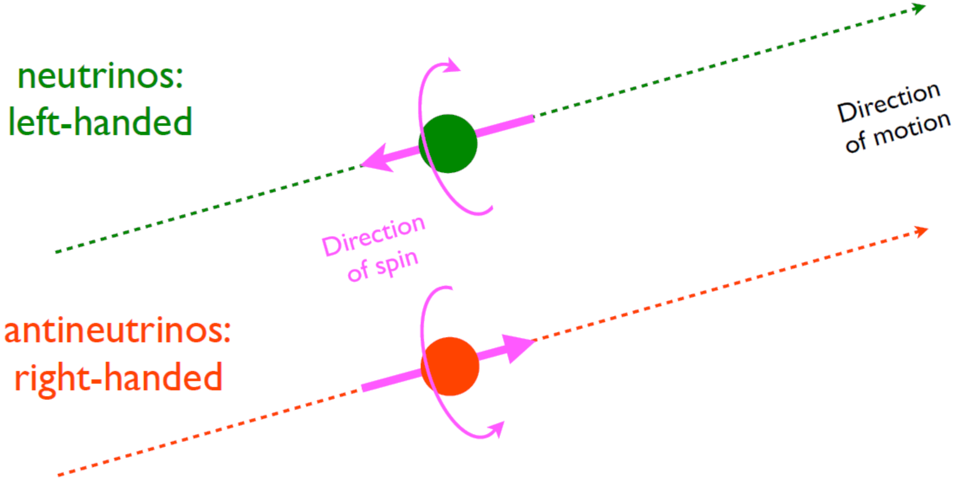
Great experimental prospects to solve neutrino open questions in the next decades

NEUTRINOS IN THE STANDARD MODEL

Neutrinos in the Standard Model

Particles of the Standard Model

- Standard Model leptons
- Neutral charge
- 3 neutrino flavors (at least)
- Weak interaction (and gravitational)
- Strictly massless (not)

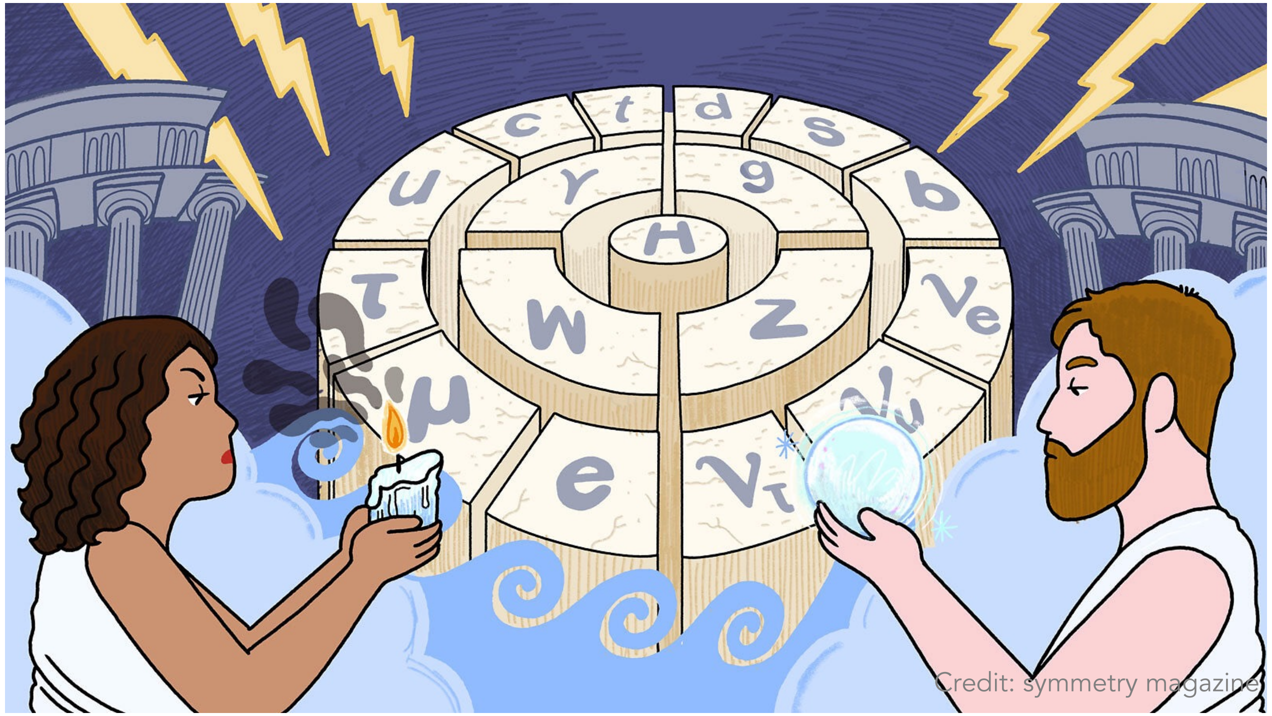


neutrinos:
left-handed

antineutrinos:
right-handed

Direction of motion

Direction of spin



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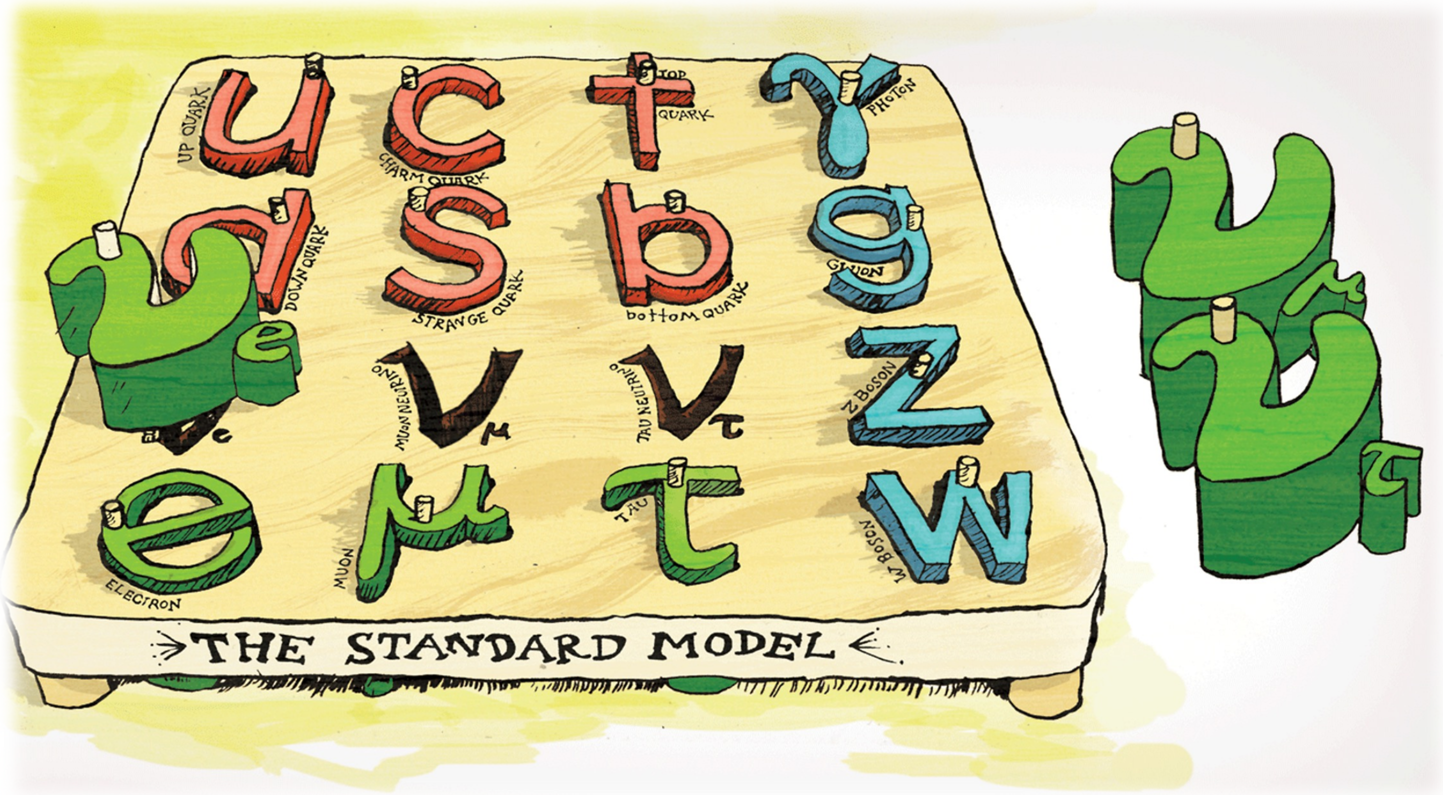
Neutrinos beyond the Standard Model



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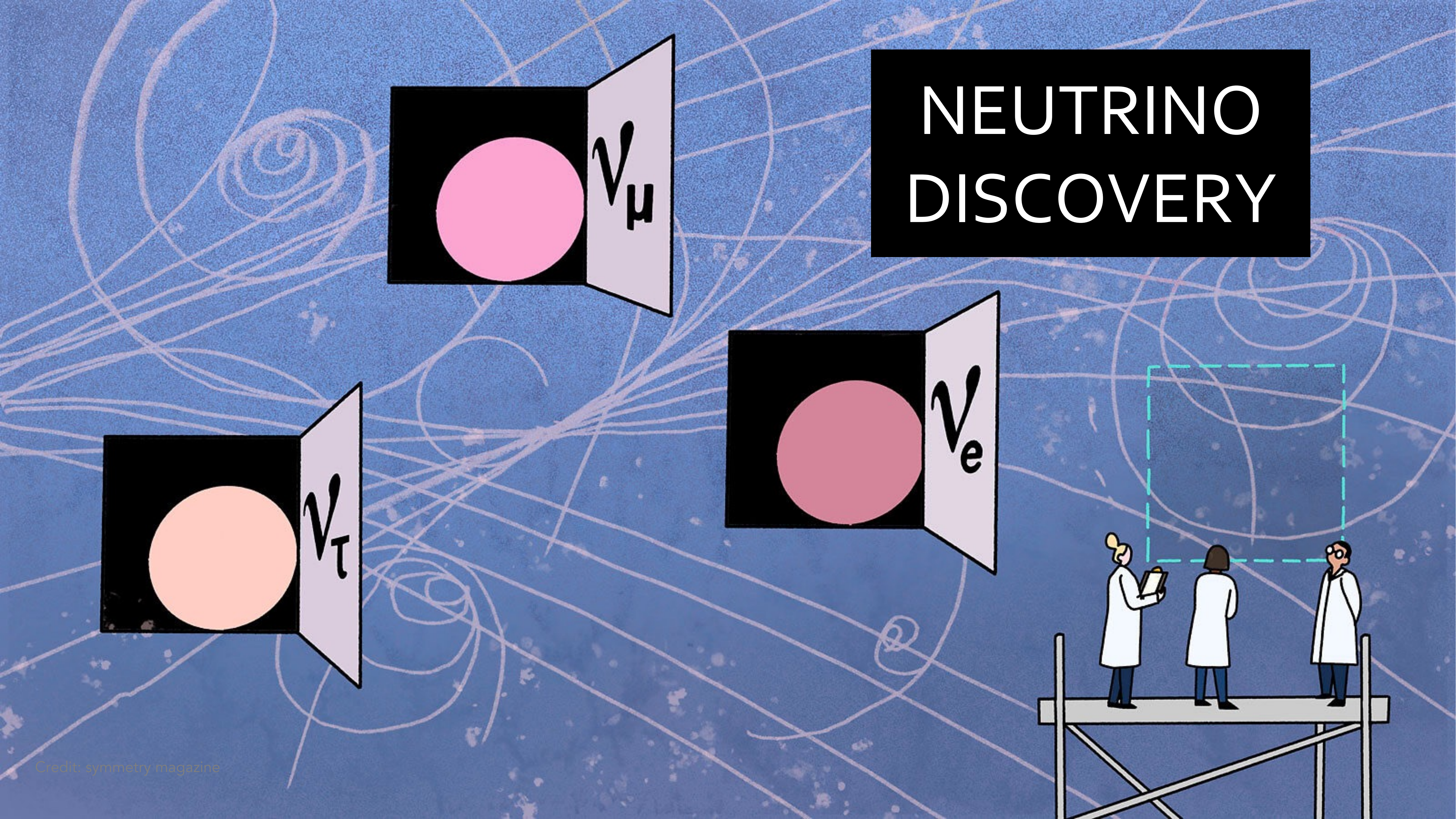
Experimental evidence of the need for Physics Beyond the Standard Model to explain neutrino oscillations.

NEUTRINO DISCOVERY

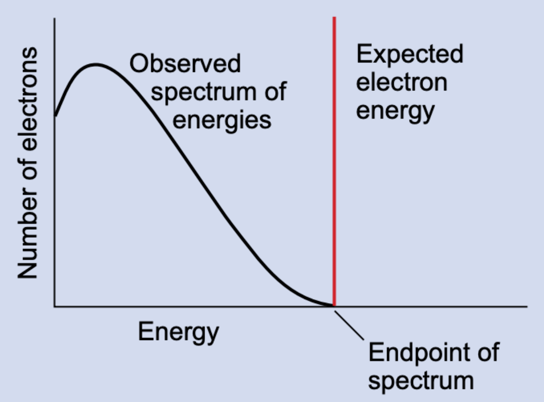


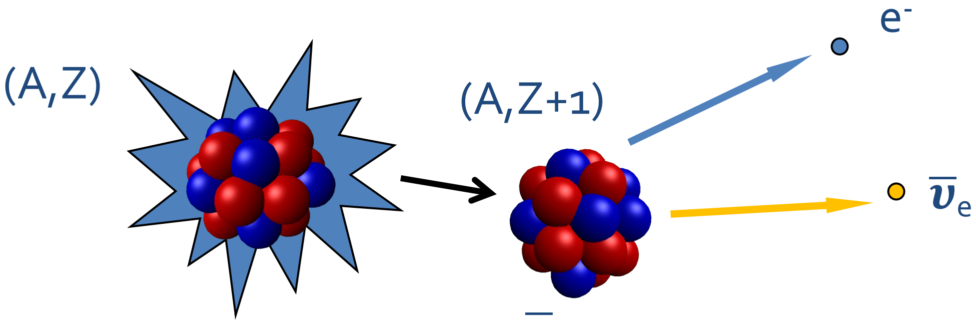
Credit: symmetry magazine

Neutrino postulation

1910-1920 – Experiments by Lise Meitner and others on radioactive decay showed β-decay problem: E and momentum conservation.

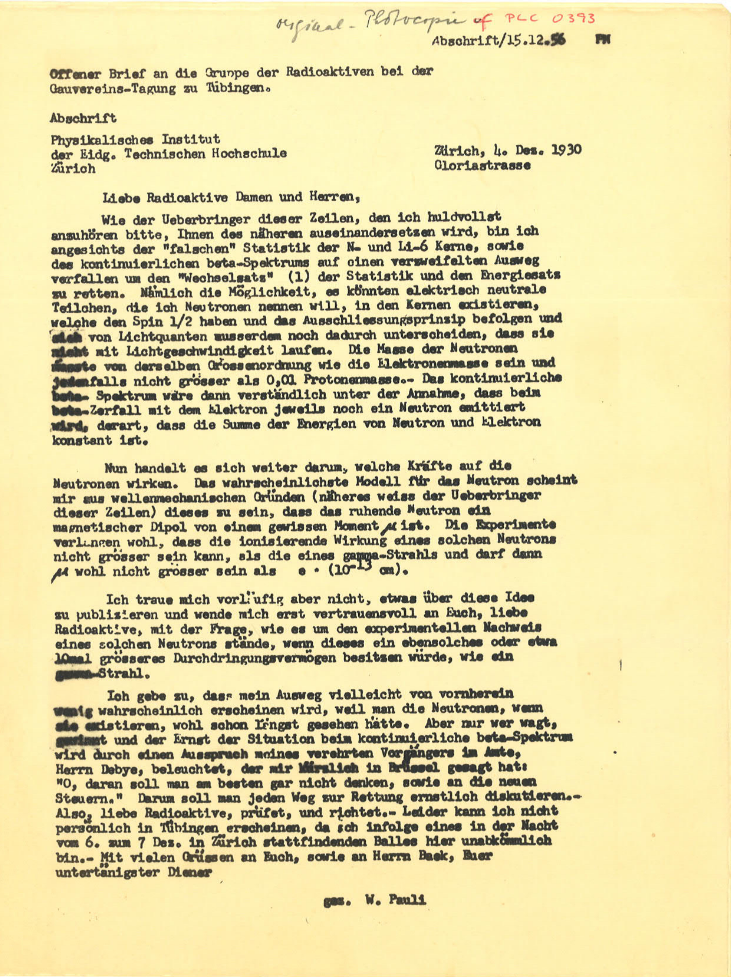
1930 - Pauli proposed the ν as a ”desperate remedy” to solve the β-decay problem: a light, spin ½, neutral particle.





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

1933 - Pauli's suggestion was developed into proposed theory for beta decay by Enrico Fermi who also provided the name “neutrino”.



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

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

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

gez. W. Pauli

Pauli´s letter outlining his theory at the Tübingen conference in 1930

Neutrino discovery

1951 - Cowan and Reines (Los Alamos, USA) initially thought that neutrino bursts from the atomic weapons that were then occurring could provide the required flux.

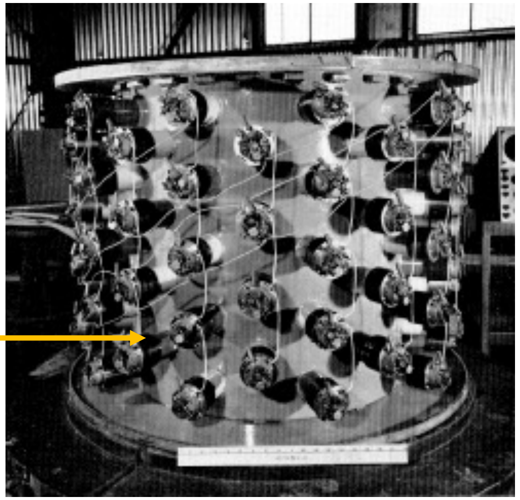
1954 - Hanford experiment - insufficient evidence to claim discovery.

1956 - The neutrino (ν_e) was directly observed by Cowan & Reines.

Nuclear reactor at Savannah River (SC, USA)

$\bar{\nu}_e$

25 m



$\bar{\nu}_e$ produced by β-decay

$\bar{\nu}_e$ detected by inverse β-decay:

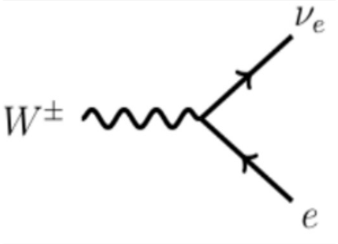
$$\bar{\nu}_e + p \rightarrow n + e^+$$

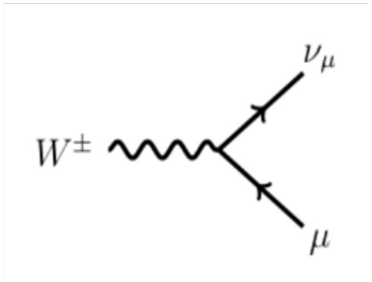
Neutrino detector :
1 m^3 liquid scintillator

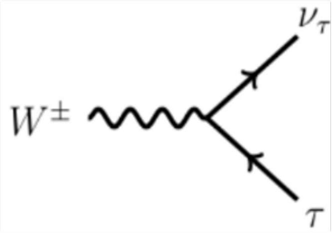
Reines - 1995

Neutrinos cannot be detected by the particle detectors, but they can interact and produce new particles sensitive to electro-magnetic fields and, therefore, perceptible.

Types of neutrinos







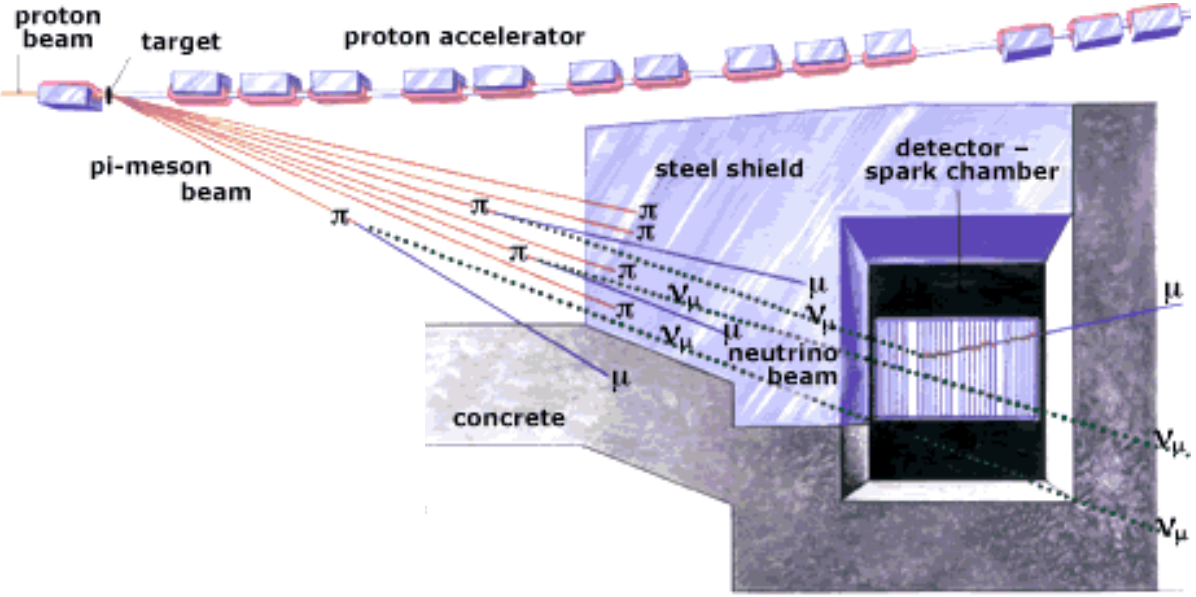
The neutrino flavour is defined by the charge lepton flavour that goes with in the the charge current interactions.

3 leptons with charge -> 3 neutrinos.

1962 - discovery of ν_μ using a beam of protons from the Brookhaven's Alternating Gradient Synchrotron.

First detection of accelerator neutrinos!


Lederman, Schwartz y Steinberger - 1988



2000 – detection of ν_τ at the DONUT experiment

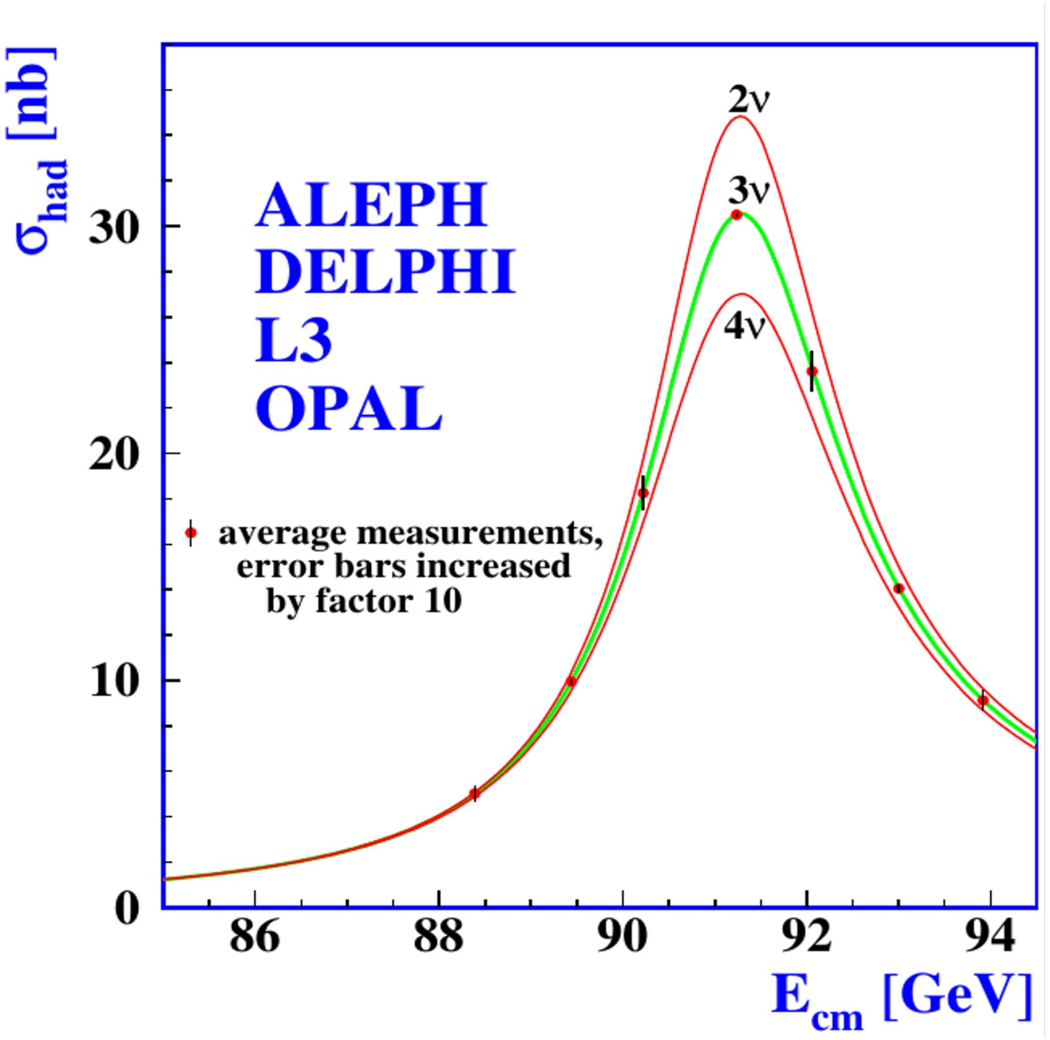
Number of neutrinos

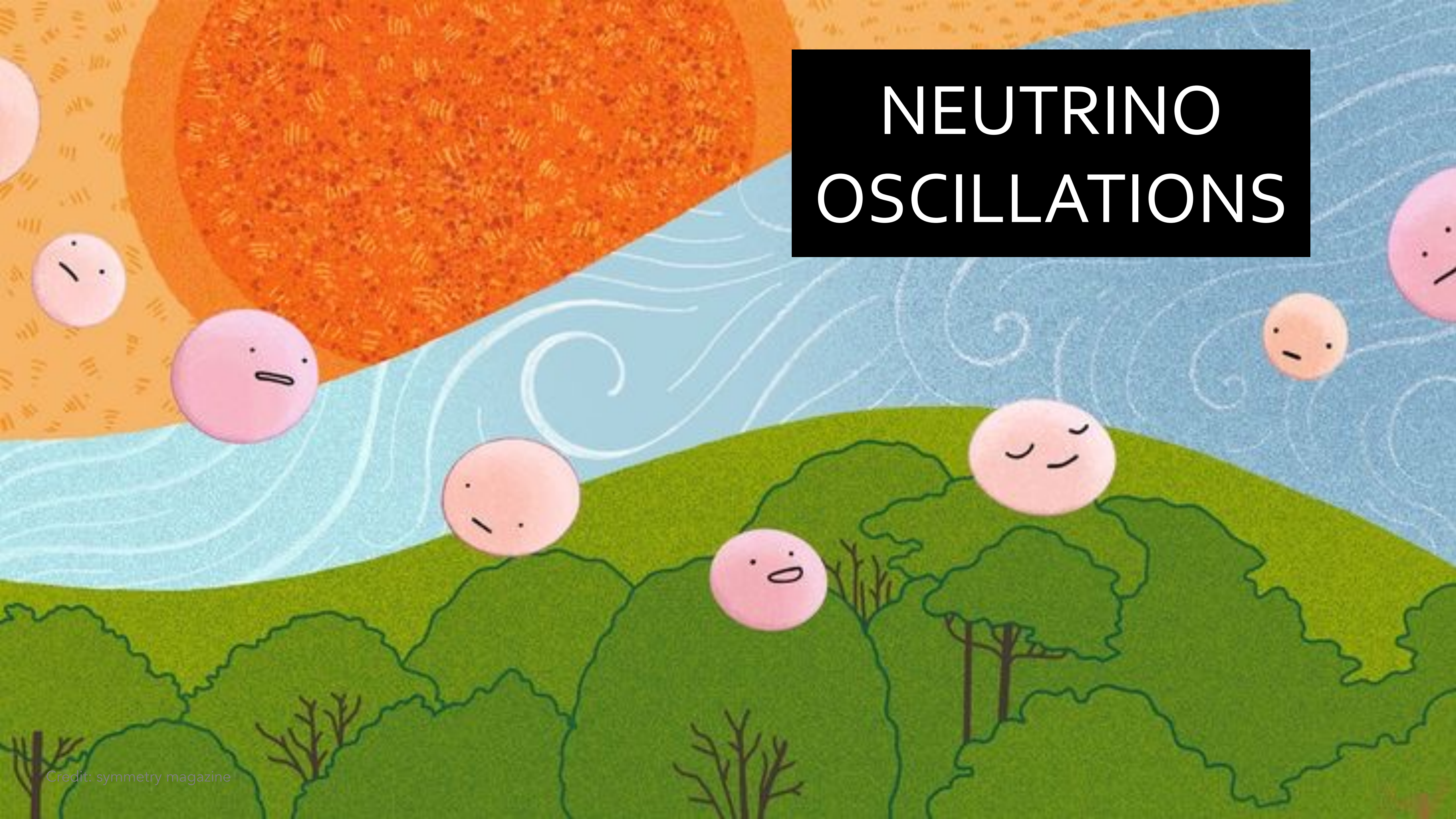
- Unstable particles have an intrinsic uncertainty (width) in their mass (from Heisenberg's uncertainty principle ΔE·Δt > ħ/2).
- The width is proportional to the number of decay modes and their probability.
- The width of the Z boson is ~2.5 GeV and 20% of the time a Z decays into neutrinos.

1989 - The 4 detectors of LEP (the predecessor of the LHC at CERN) measured the width which is proportional to the number of neutrinos.

N = 2.984 ± 0.008.

(*) There are 2 options left:
- Very heavy neutrinos (> mZ/2 ≈ 45 GeV).
- Neutrinos that do not couple to Z -> sterile.

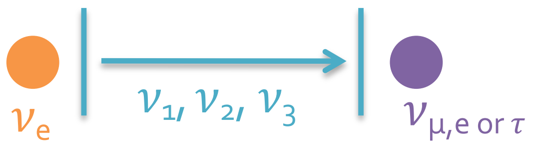




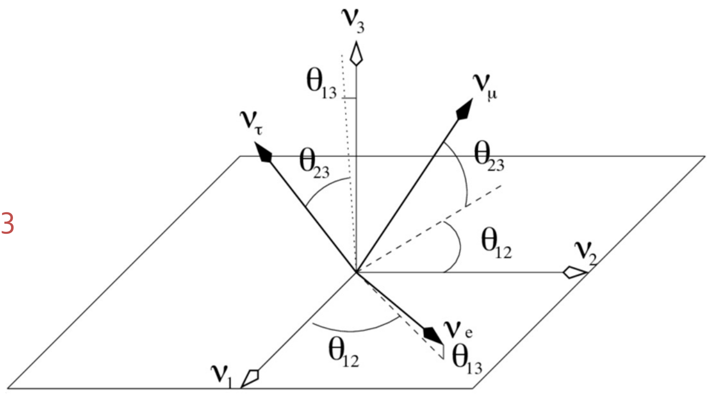
NEUTRINO OSCILLATIONS

Credit: symmetry magazine

Neutrino oscillations



- ν's generated in definite **flavour states** (ν_f): ν_e, ν_μ, ν_τ
- Propagate as **mass** states (ν_m): ν_1, ν_2, ν_3
- Flavour and mass states related by the mixing matrix: $\nu_m = U\,\nu_f$



Pontecorvo, Maki, Nakagawa, Sakata (**PMNS**) **mixing matrix**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{-i\alpha 1} & 0 & 0\\ 0 & e^{-i\alpha 2} & 0\\ 0 & 0 & 1\end{pmatrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Atmospheric + LBL
$\nu_\mu \rightarrow \nu_\tau$

Reactors + LBL
$\nu_\mu \rightarrow \nu_e$

Solar + KamLAND
$\nu_e \rightarrow \nu_{\mu,\tau}$

[Majorana]
Not accessible in osc. exp. only 0νββ

Experimentally detected in states of definite flavor: project back onto flavor basis at detector.
3 neutrinos -> Parametrization using 3 angles (θ_{12}, θ_{23}, θ_{13}), 1 CP violation phase (δ).

Neutrino oscillation probability

Oscillation probability:

$$P_{\nu_\alpha\to\nu_\beta}(L,E)=\delta_{\alpha\beta}-4\sum_{i>j}Re\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)-2\sum_{i>j}Im\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

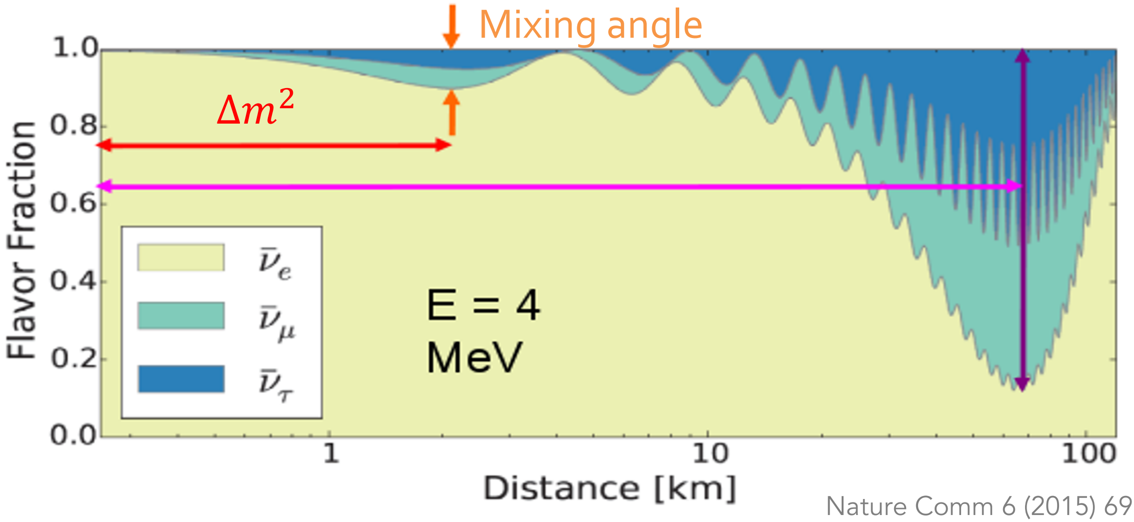
Different experimental sensitivities (varying L&E) to measure the 6 oscillation parameters:

$$\theta_{12},\,\theta_{23},\,\theta_{13},\,\Delta m^2_{12},\,\Delta m^2_{31},\,\delta_{CP}$$

δ_{CP} only possible if all 3 angles are not 0 -> need to measure all of them

Experimental approaches:

- **Appearance:** search for neutrinos from a flavour not present in the source.
- **Disappearance:** search for the missing neutrinos from a flavour present in the source.

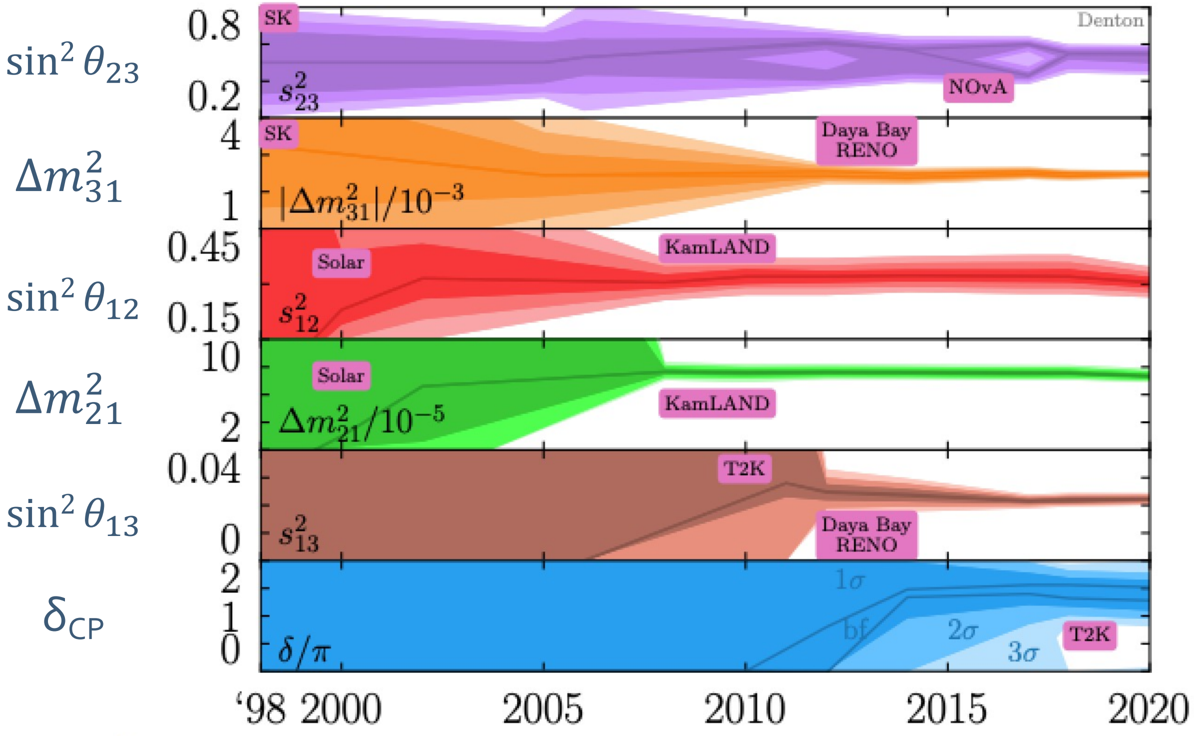


Nature Comm 6 (2015) 6935

Neutrino oscillation parameters

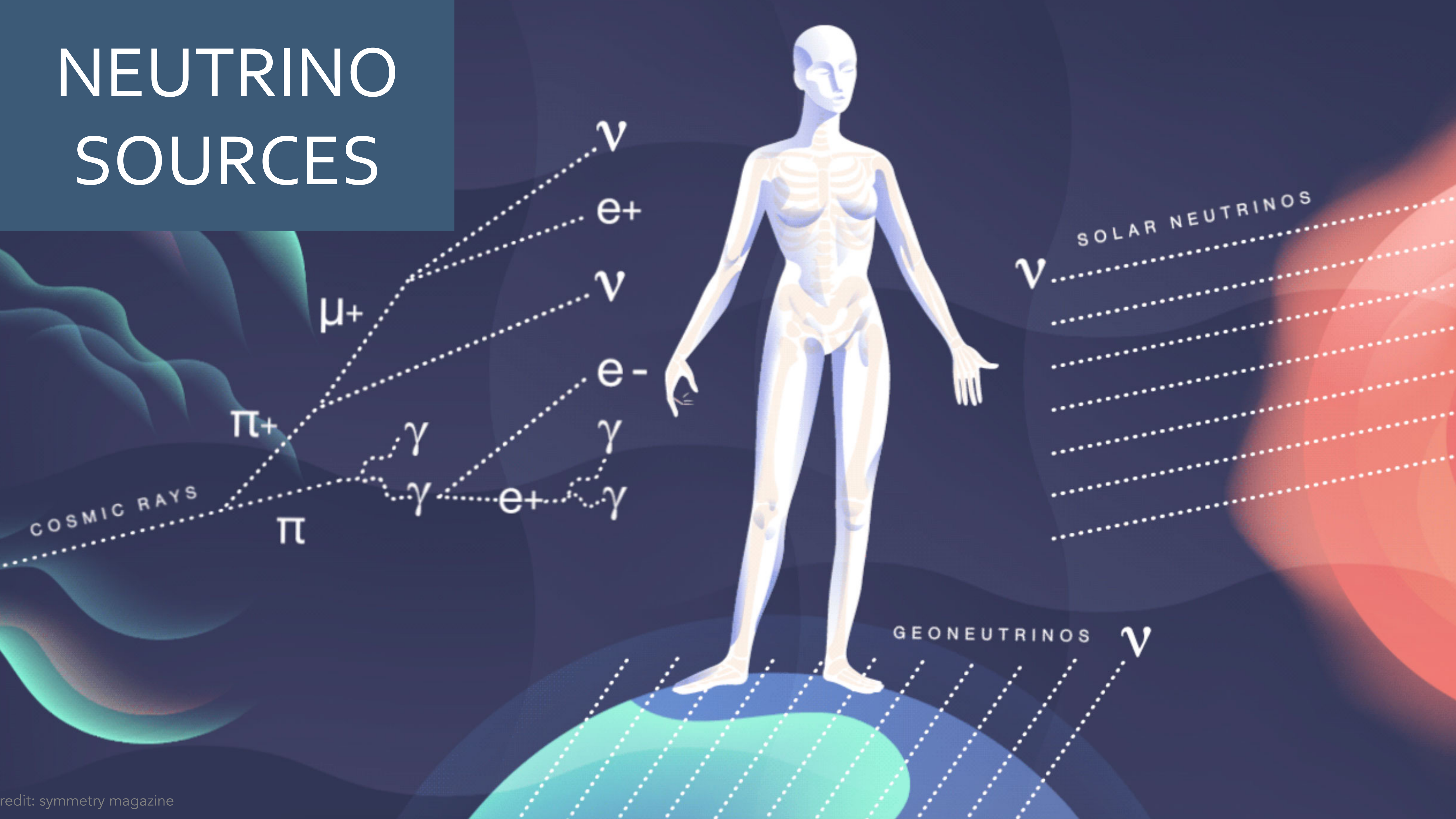
Evolution of experimental measurements

From P. Denton, Neutrino22



- ✓ Experimentally measured parameters: θ_{12}, Δm^2_{12}, θ_{23}, θ_{13}, Δm^2_{31}
- ? Unknown parameters: mass ordering (sing of Δm^2_{31}), δ_{CP}, θ_{23} octant

NEUTRINO SOURCES



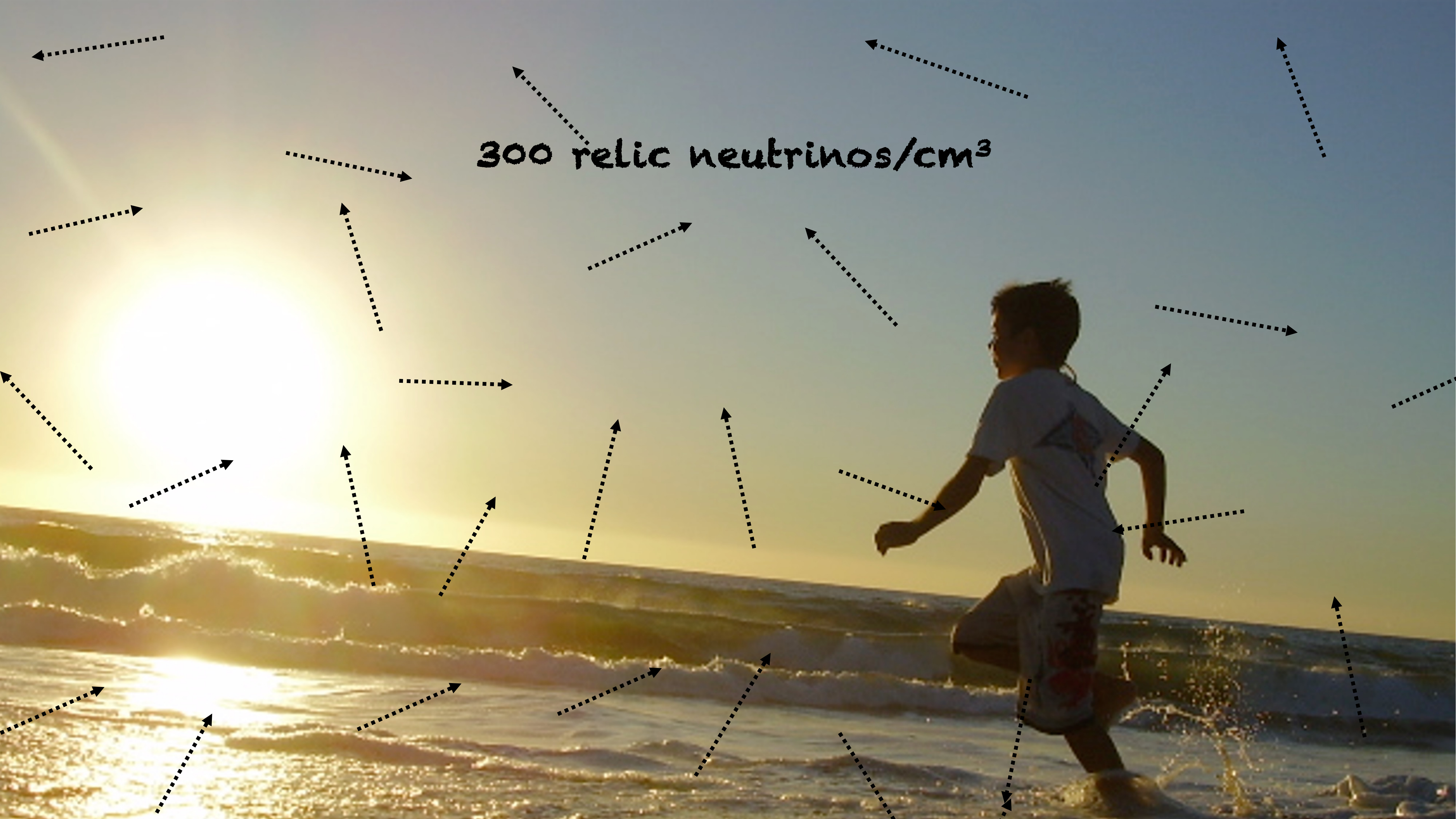
redit: symmetry magazine


400 neutrinos/s


65×10^9 neutrinos/cm^2/s

23 february 1987

billions of neutrinos in 10 seconds


300 relic neutrinos/cm^3

Where are neutrinos coming from?

Neutrino sources

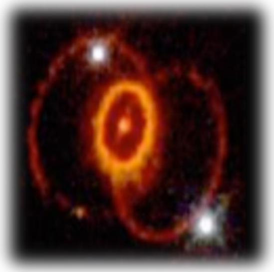
Reactor

Accelerator

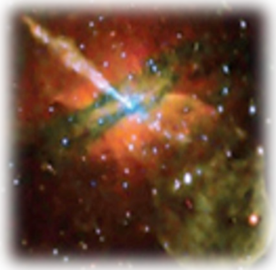
Sun

Terrestrial

Atmospheric



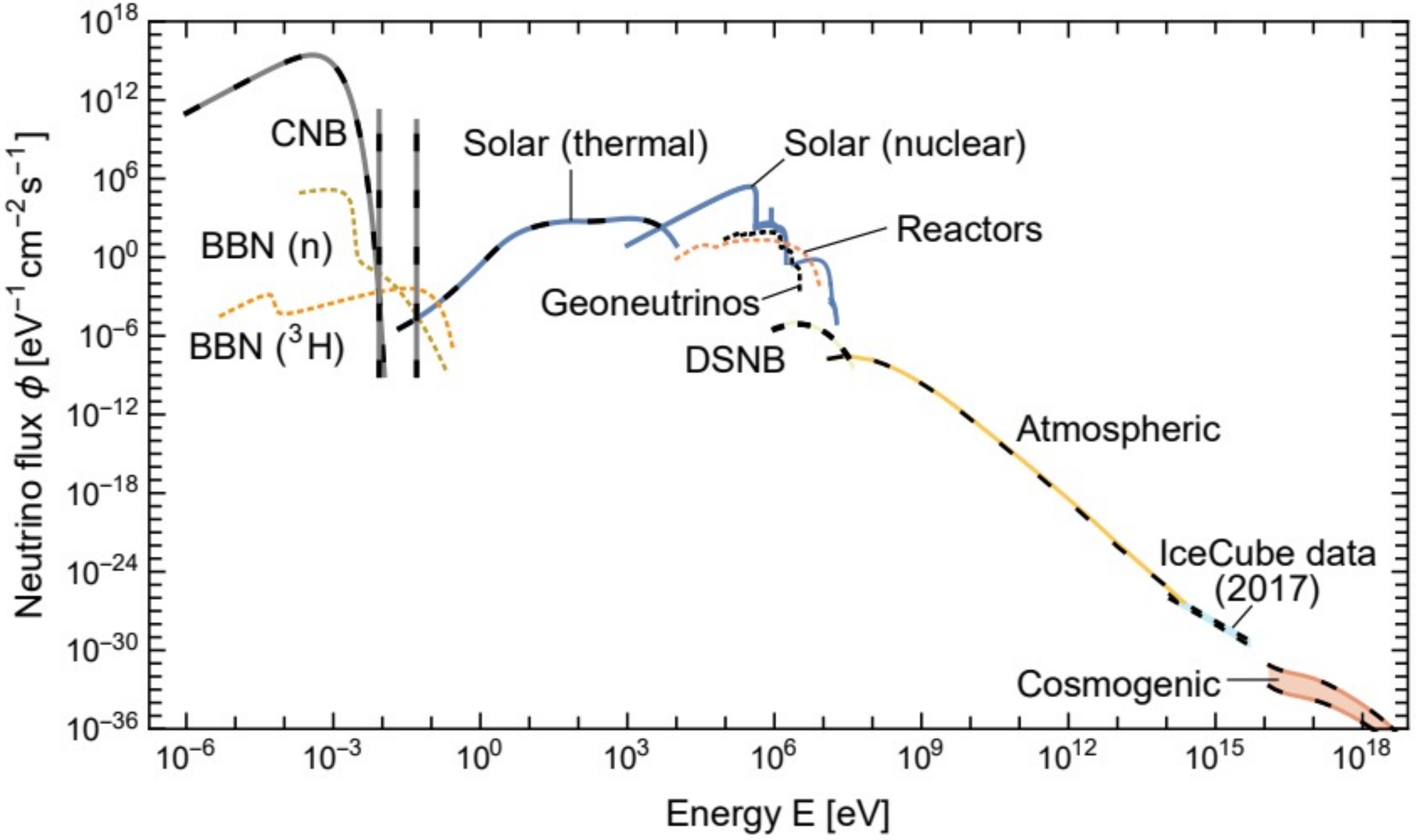
galactic &
extragalactic



Supernova

Big Bang

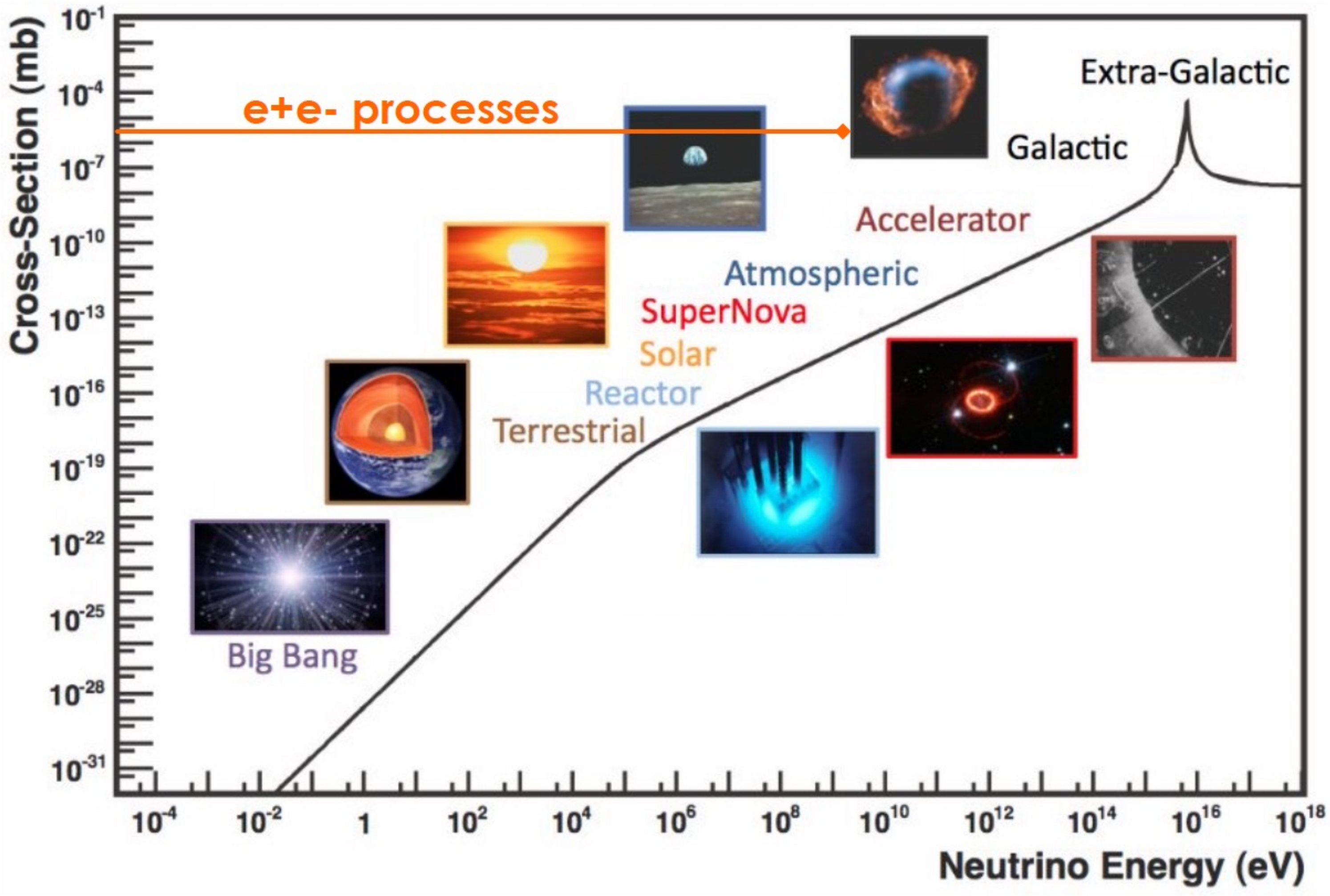
Where are neutrinos coming from?



Rev. Mod. Phys. 92 (2020) 045006

Many neutrino sources with covering a broad energy range!

Neutrino interaction cross-section

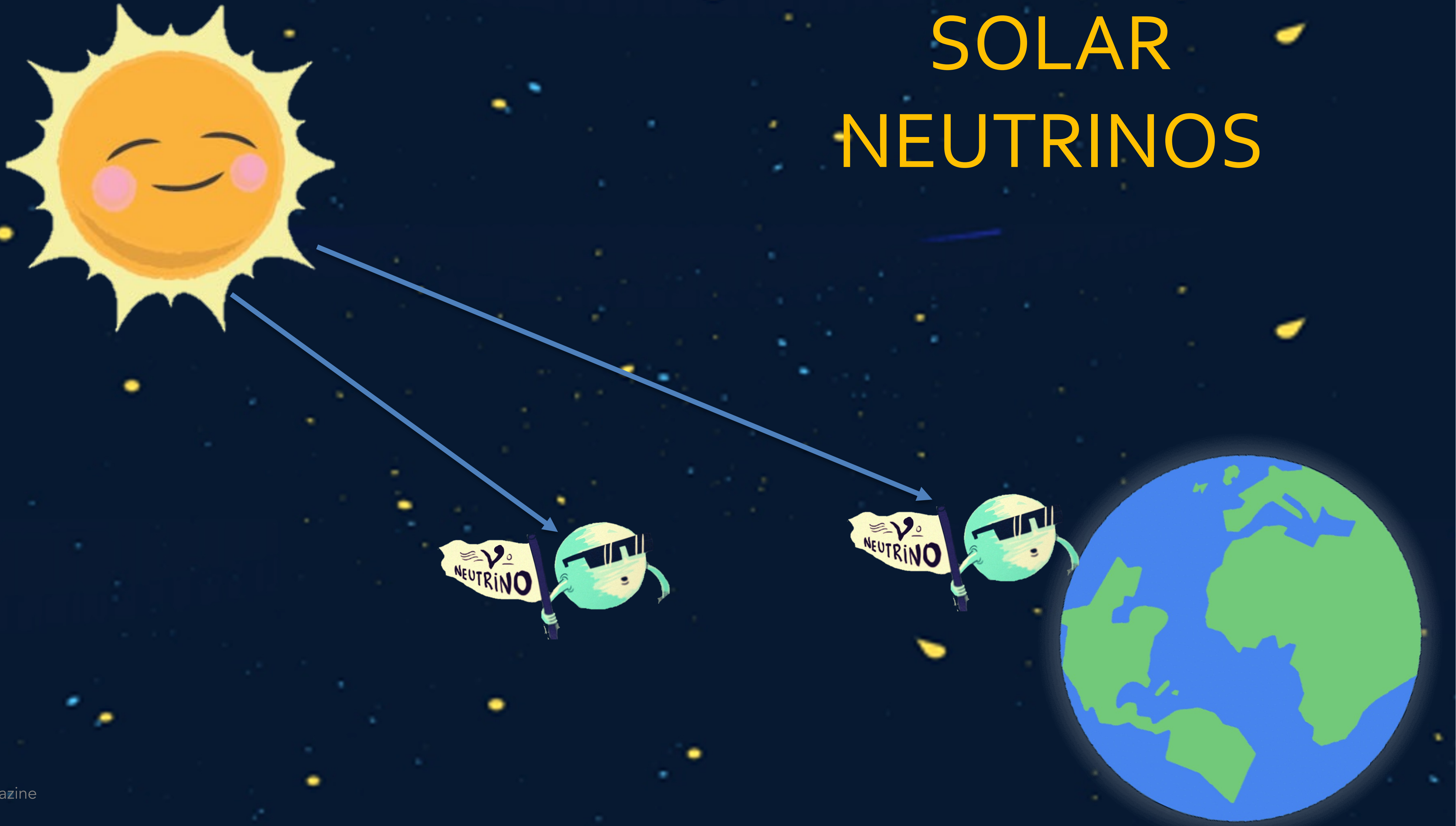


1 mb = 10^{-21} cm^2

Very difficult to detect neutrinos!

Need massive detectors

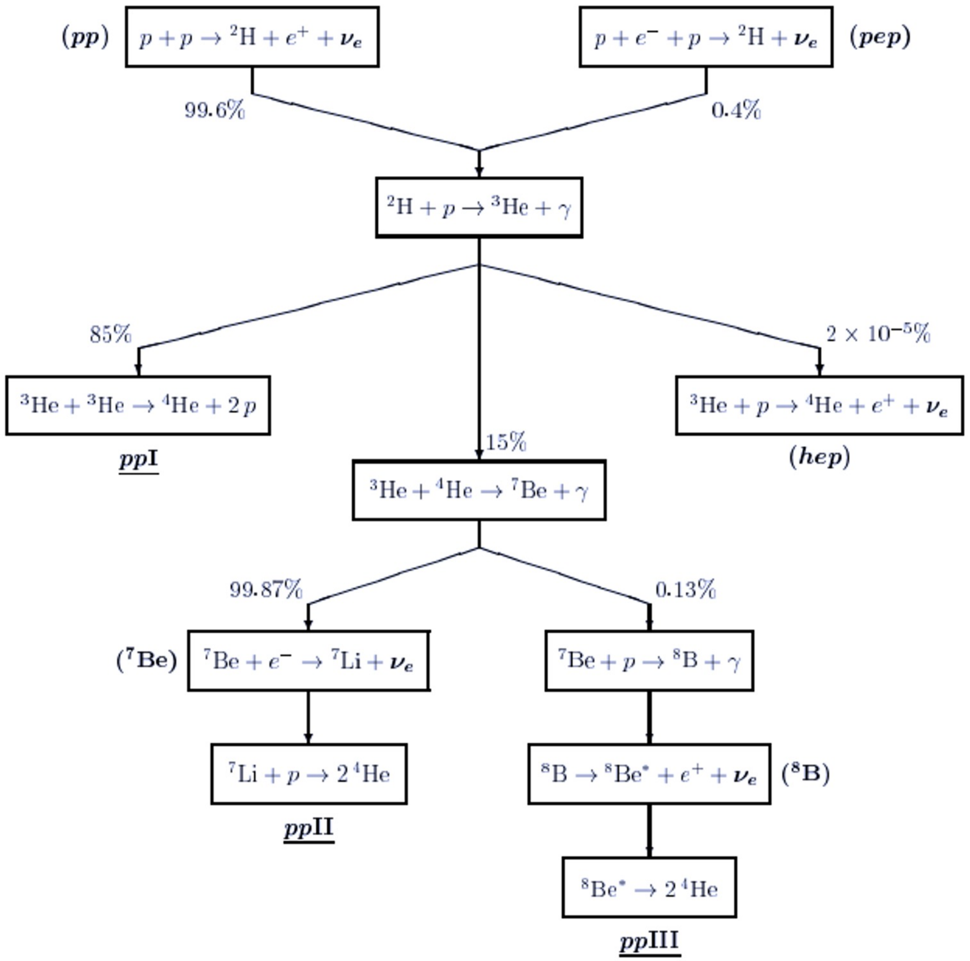
SOLAR NEUTRINOS



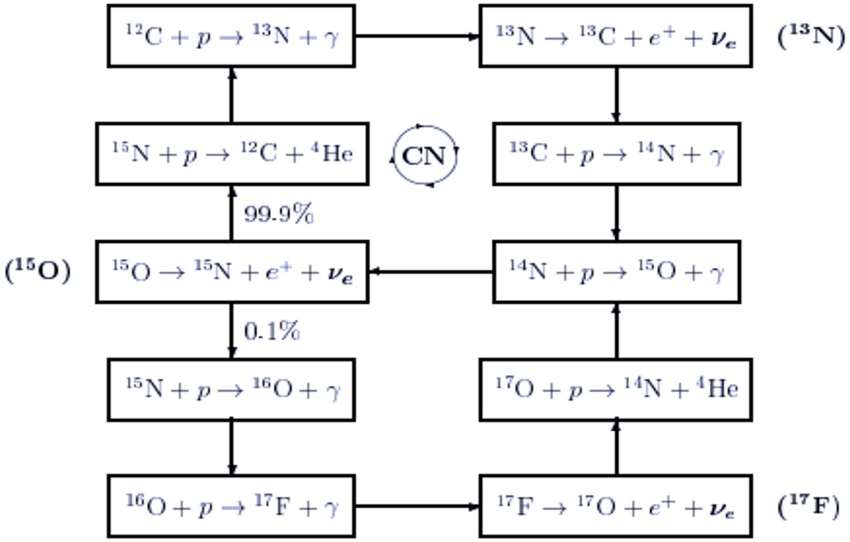
Credit: symmetry magazine

Solar neutrinos

pp chain (98.4% fusion energy)



CNO chain (1.6% fusion energy)

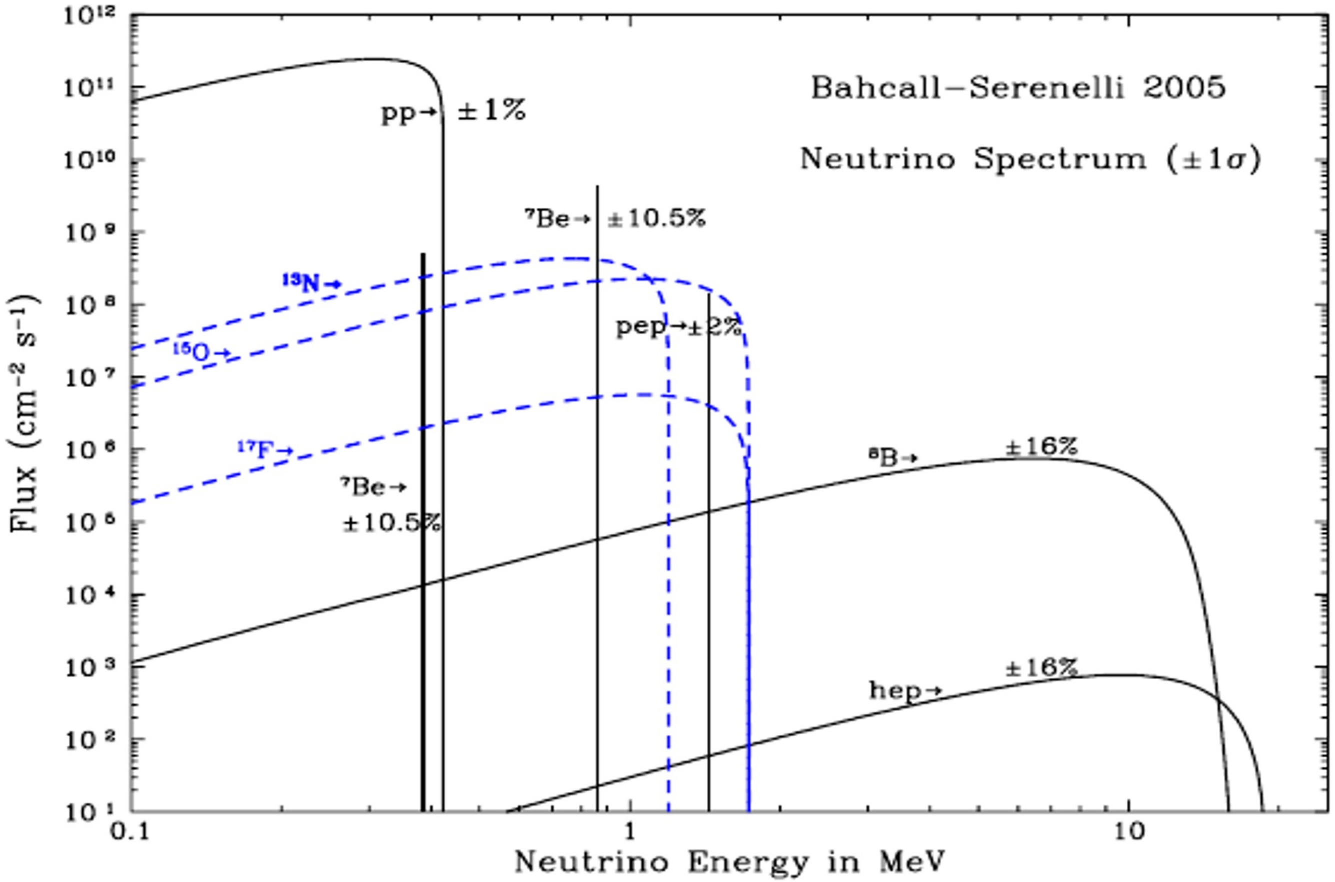


Both chains produce ν_e

Neutrinos are the sole direct probes of the Sun’s core

Solar neutrinos

Energy spectrum



Homestake experiment

Davis - 2002

1968 - Solar ν detection by Davis → ν_e rate smaller tan expected.

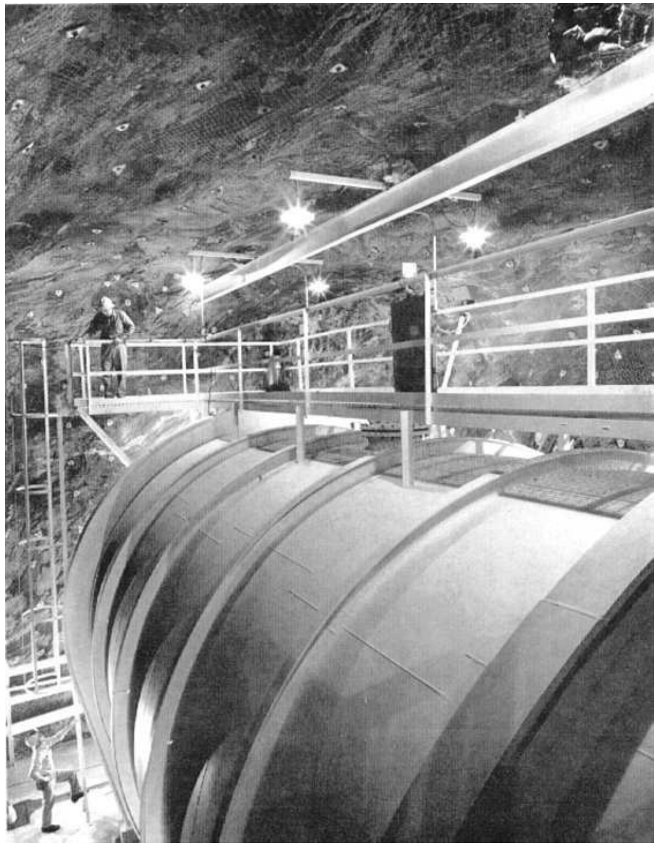
- Goal: Measurement of the flux of solar neutrinos (1970-1994)
- Detection mode: based on the inverse beta reaction: $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- Results: The flux measured is 1/3 of the solar model predictions "the solar neutrino problem"
- Possible causes: theory and/or experiment were wrong

1957 - Pontecorvo postulated oscillation theory of $\nu \rightarrow \bar{\nu}$.

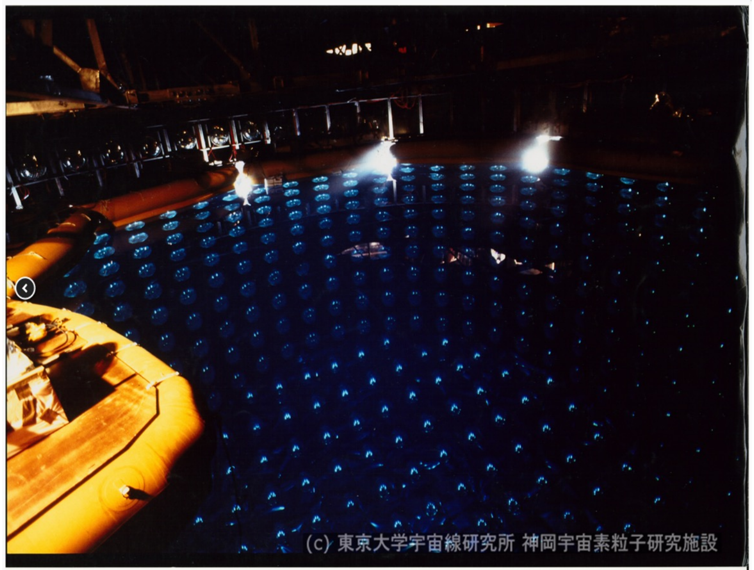
1962 - Maki, Nakagawa y Sakata proposed a two-flavor mixing theory and latter built a general model.

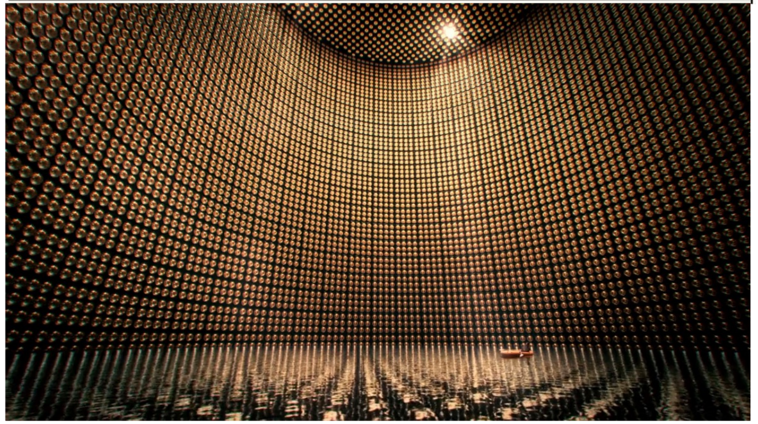
Flavor oscillations imply that neutrinos are massive →

Physics Beyond the Standard Model



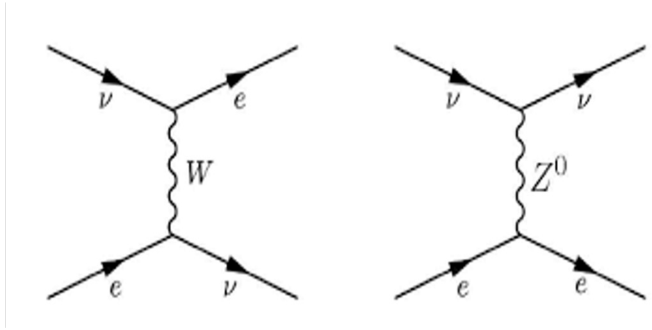
Kamiokande and Super-K experiments





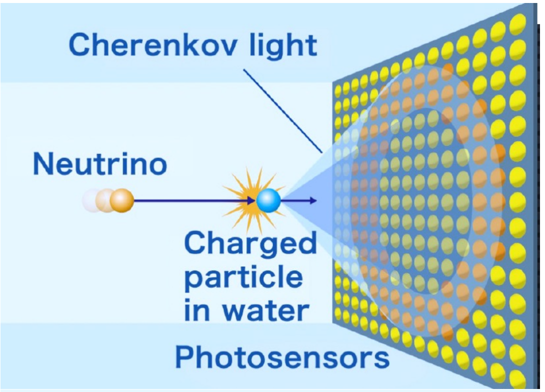
1983 – KamiokaNDE: Water Cherenkov detector.
Mostly ν_e detected by the reaction:

$$\nu_l + e^- \rightarrow \nu_l + e^-$$



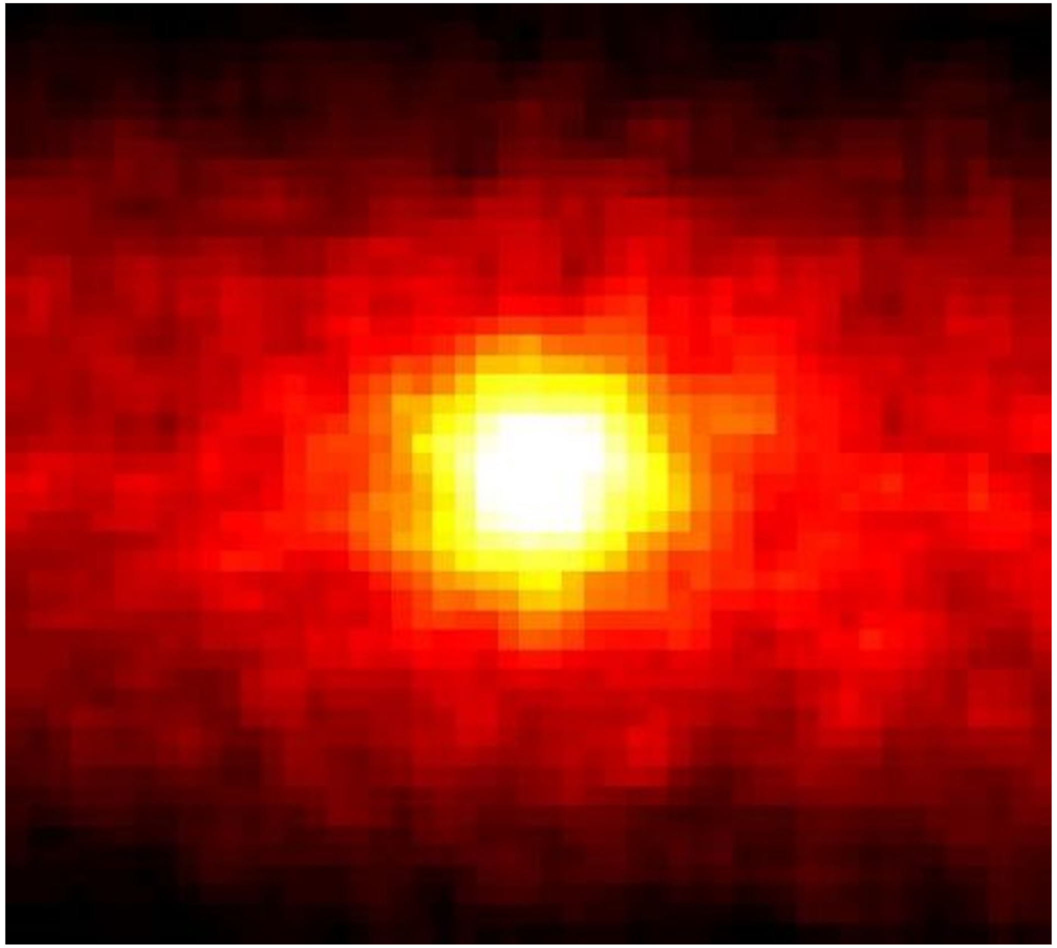
1996 – Super-KamiokaNDE

Both confirmed deficit of solar neutrinos
(0.4 expected neutrinos)



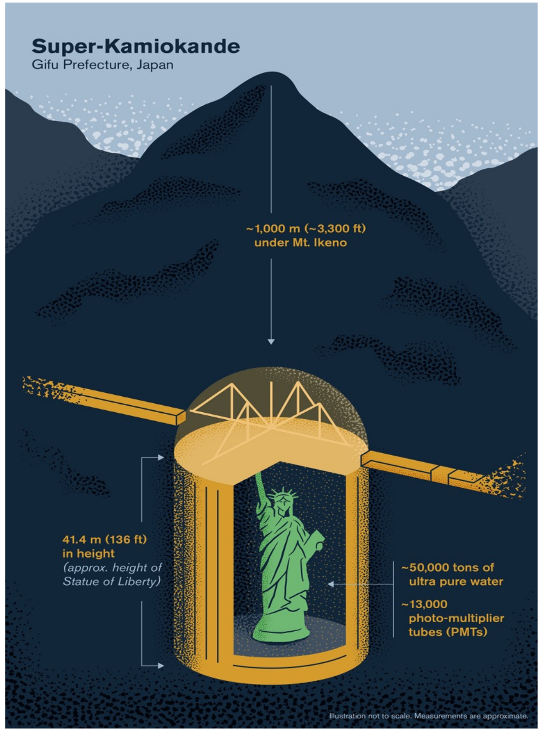
Charged particles propagating in a medium with a speed exceeding that of light in that medium emit Cerenkov radiation.
Detected as a ring by large area photo-multipliers.

Sun "neutrinography”



Sun “neutrinography” taken by Super-Kamiokande 1 km underground.

500 days exposure time.



SNO experiment

2001: SNO detected solar neutrino oscillation measuring the total neutrino flux.

Detection methods:

- Elastic scattering: mostly ν_e

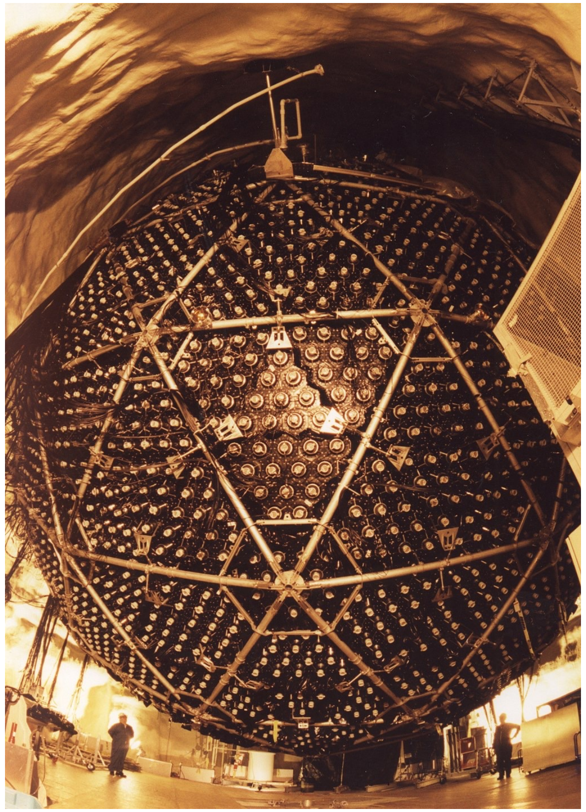
$$\nu_l + e^- \rightarrow \nu_l + e^- \quad \text{(ES)}$$

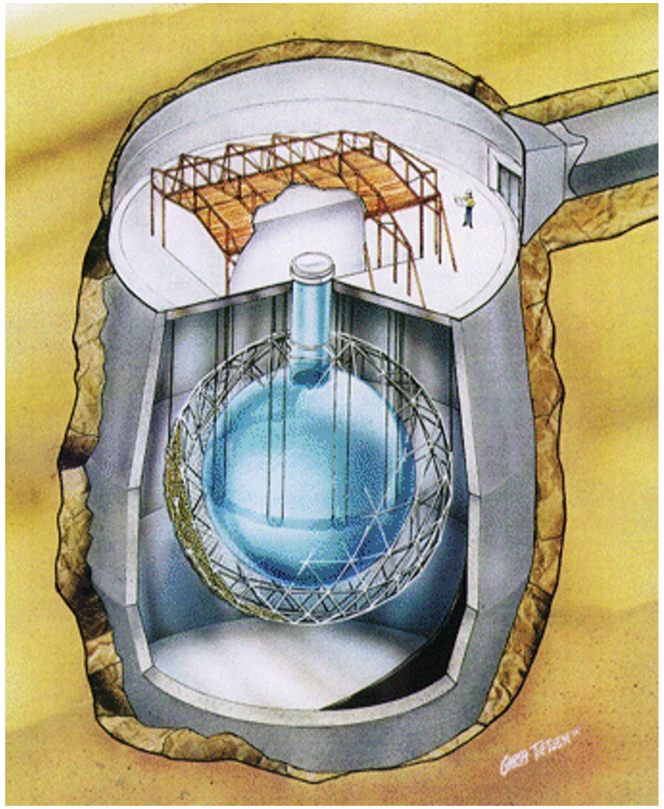
- Charged current: only ν_e

$$\nu_e + \mathrm{D} \rightarrow e^- + p + p \quad \text{(CC)}$$

- Neutral current: all flavours

$$\nu_l + \mathrm{D} \rightarrow \nu_l + p + n \quad \text{(NC)}$$





1 kton D_2O contained by a 12 m acrylic vessel
9600 PMT's mounted in a geodesic support structure

McDonald, Kajita -2015

SNO experiment

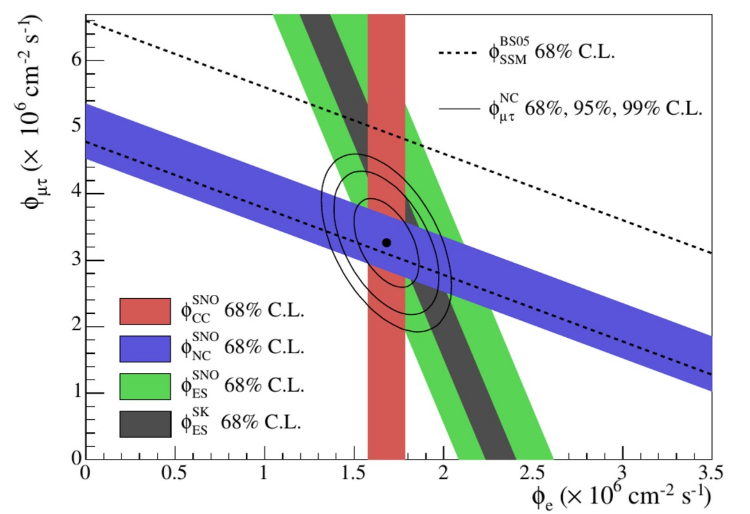
2001: SNO detected solar neutrino oscillation measuring the total neutrino flux

$$\begin{aligned}
\Phi_{\mathrm{SNO}}^{\nu_e} + r^{\mathrm{ES}}\,\Phi_{\mathrm{SNO}}^{\nu_{\mu,\tau}} &= \Phi_{\mathrm{SNO}}^{\mathrm{ES}} \\
\Phi_{\mathrm{SNO}}^{\nu_e} &= \Phi_{\mathrm{SNO}}^{\mathrm{CC}} \\
\Phi_{\mathrm{SNO}}^{\nu_e} + \Phi_{\mathrm{SNO}}^{\nu_{\mu,\tau}} &= \Phi_{\mathrm{SNO}}^{\mathrm{NC}}
\end{aligned}$$

$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{ES}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.046$$

$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{CC}}}{\Phi_{\mathrm{SSM}}} = 0.290 \pm 0.017$$

$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{NC}}}{\Phi_{\mathrm{SSM}}} = 0.853 \pm 0.075$$



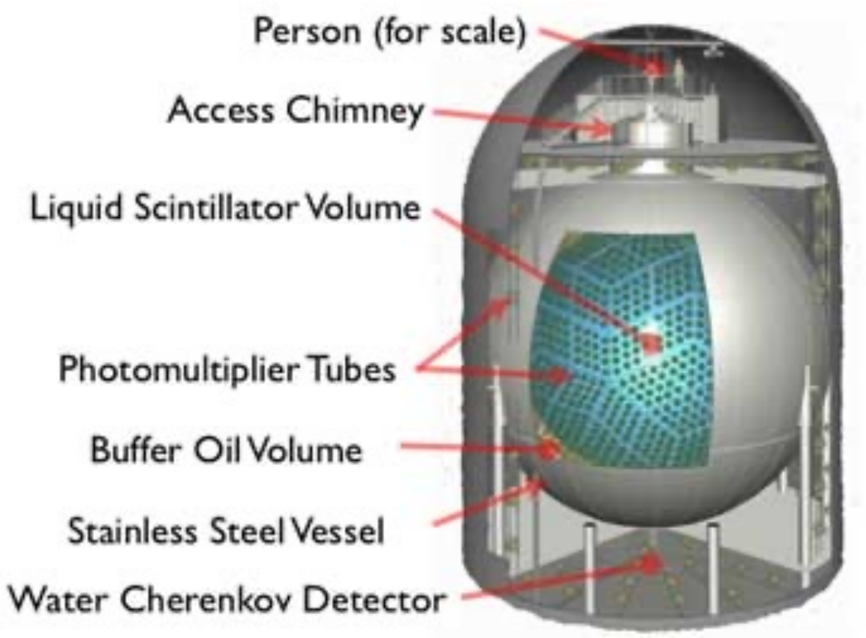
Flavor oscillations imply that neutrinos are massive ⟶

Physics Beyond the Standard Model

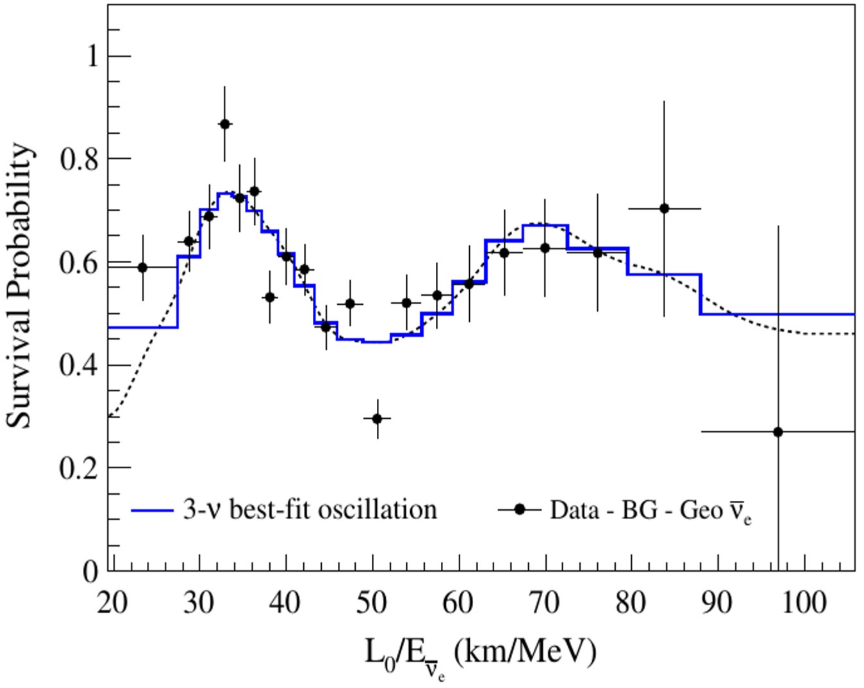
McDonald, Kajita -2015

KamLAND experiment

Same oscillation using $\bar{\nu}_e$ from all nuclear power plants of Japan

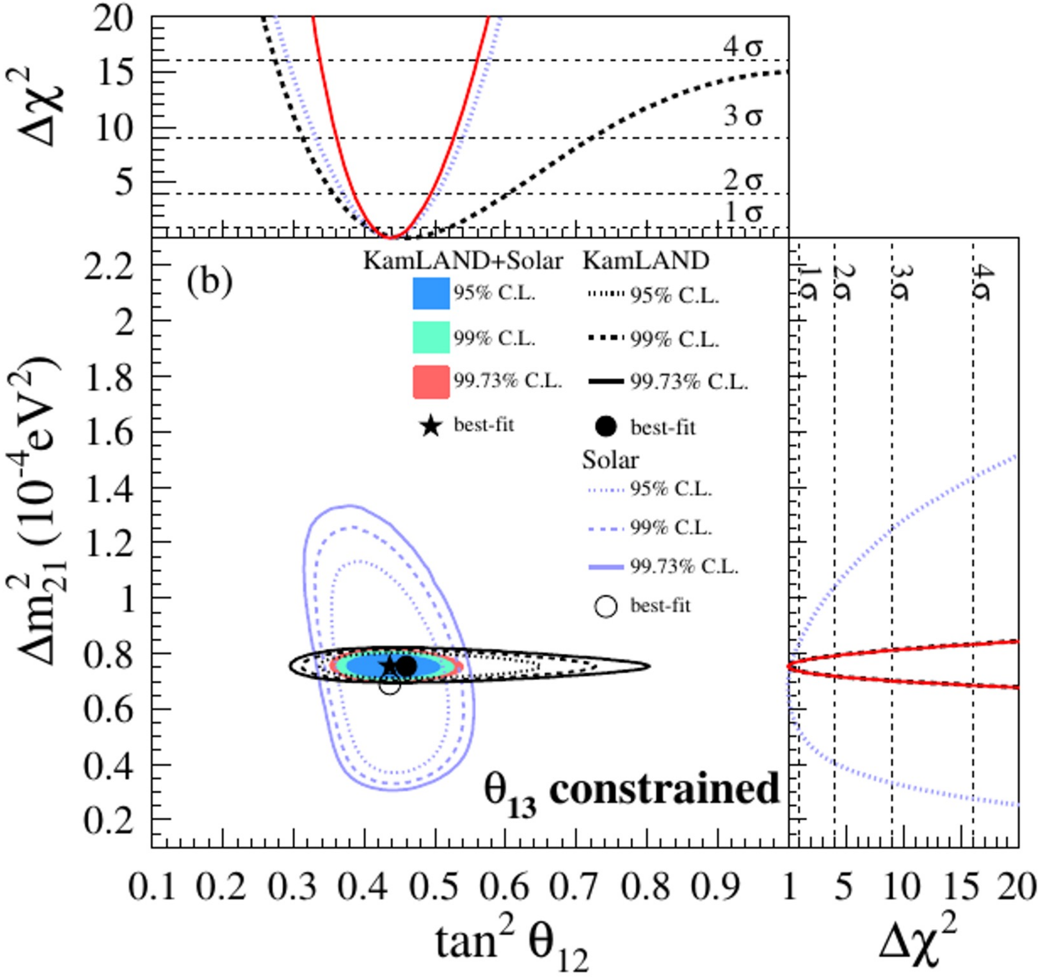


$$P_i = \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L_i}{4E}\right)$$



Liquid scintillator: Charged particles (and γ-rays) produce light.
The light yield is proportional to particle energy.
The light is detected by large area photo-multipliers.

Measurements of θ12



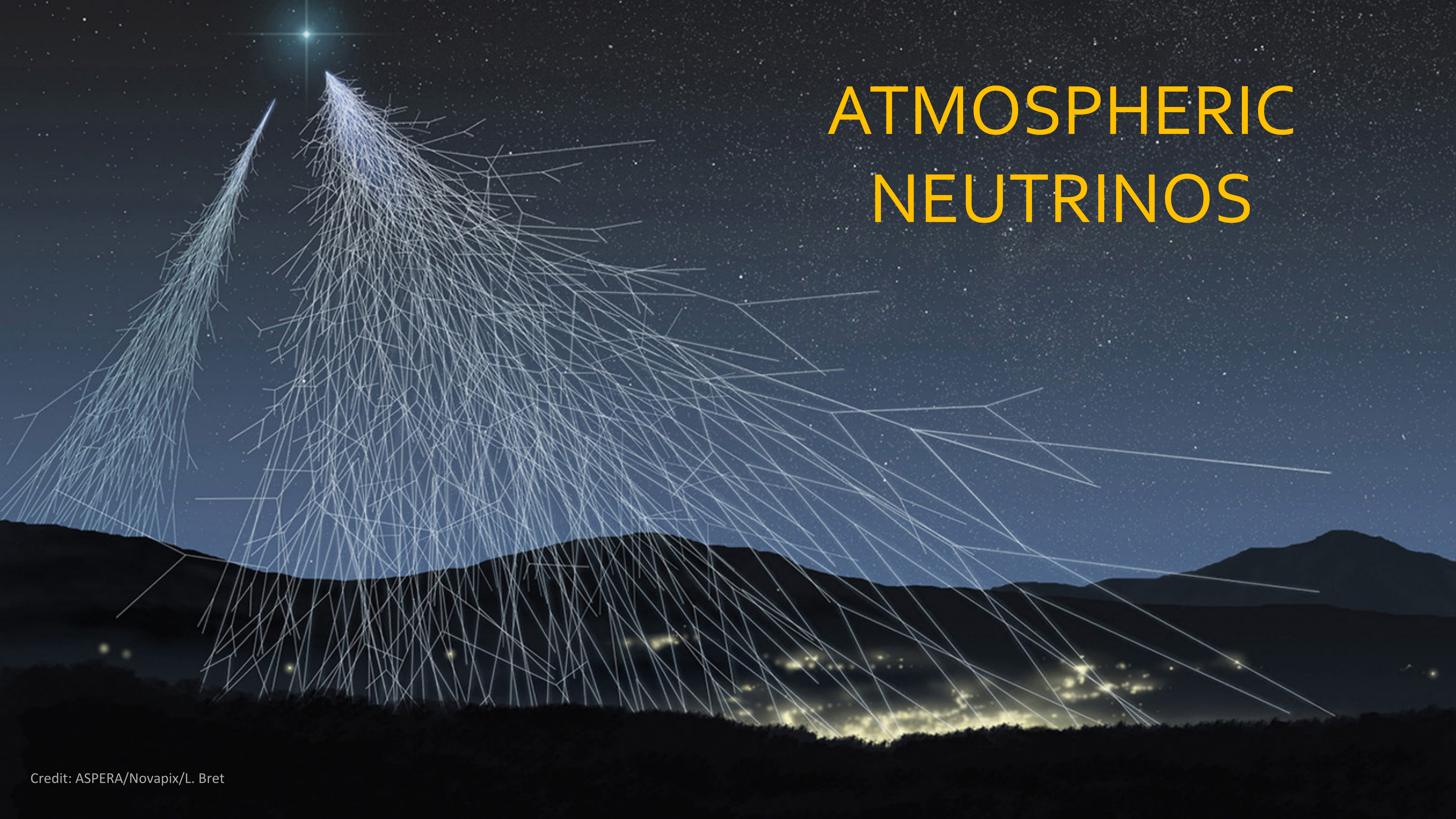
The combination of experiments determines:

$\theta_{12} \sim 33°$

KamLAND measures a mass difference:

$\Delta m^2_{21} \sim 7.5 \cdot 10^{-5}$ eV^2

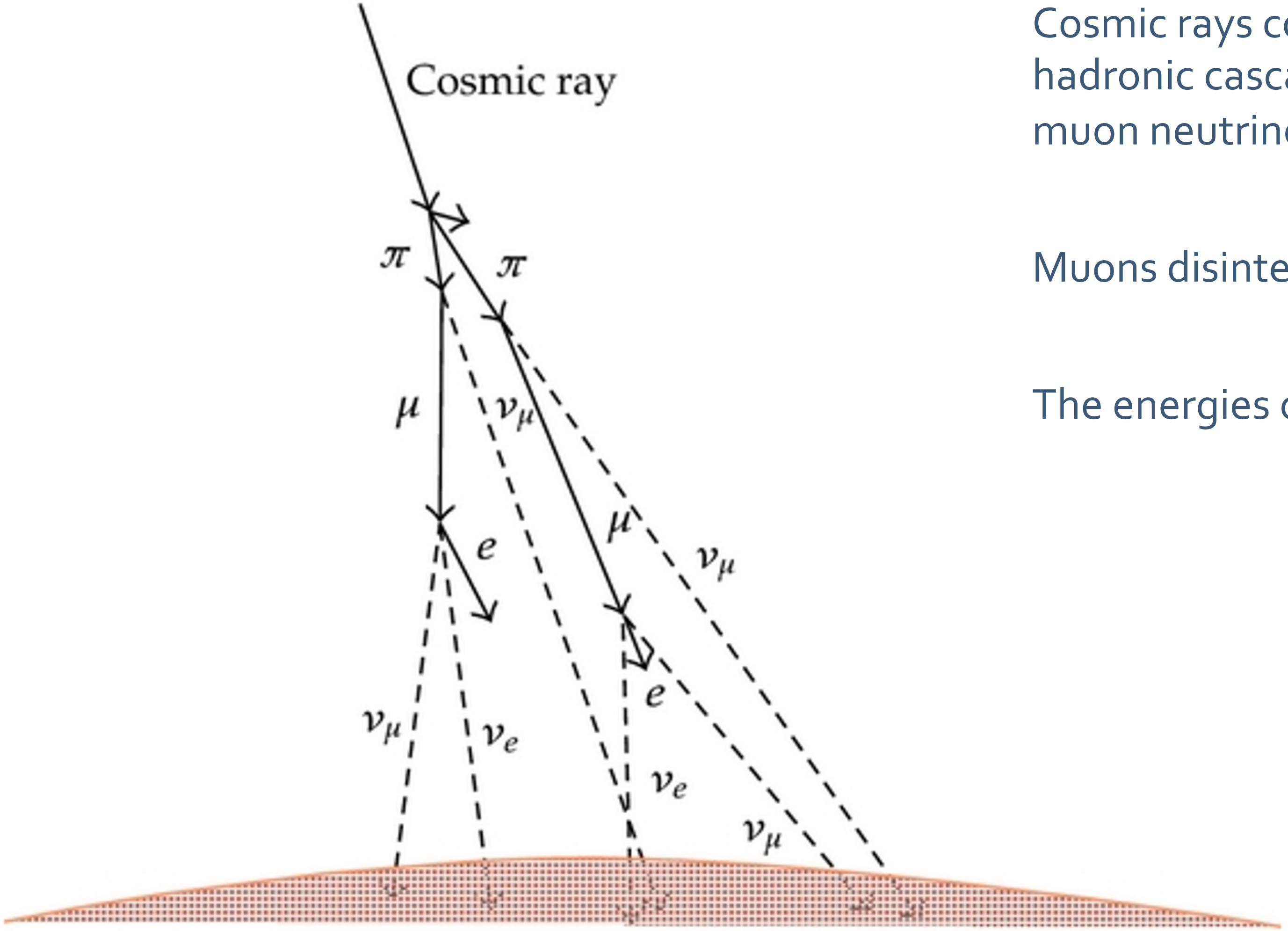
The propagation states in dense media are different than in vacuum. Using “matter effects” in the Sun, we know $m_2 > m_1$.



ATMOSPHERIC NEUTRINOS

Credit: ASPERA/Novapix/L. Bret

Atmospheric neutrinos



Cosmic rays collide with nuclei in the atmosphere, creating hadronic cascades (pions) that disintegrate into muons and muon neutrinos.

Muons disintegrate producing muon and electron neutrinos.

The energies of these neutrinos are in the GeV range.

Super-Kamiokande experiment

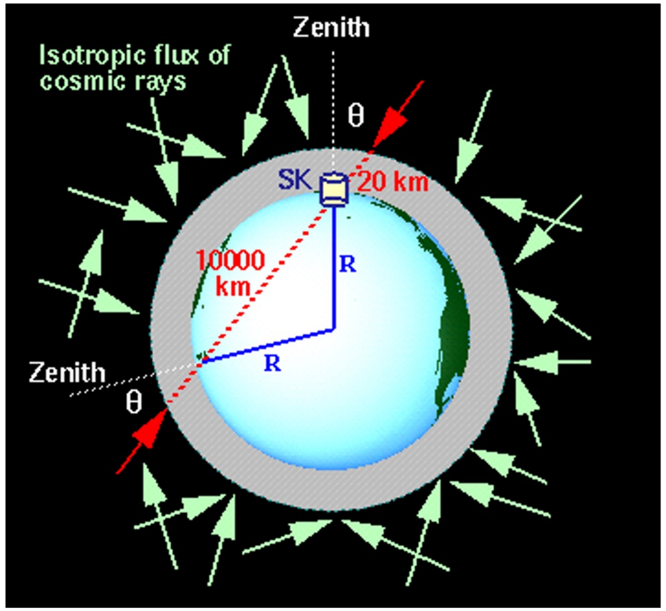
Another problem: multiple experiments observed less ν_μ than expected.

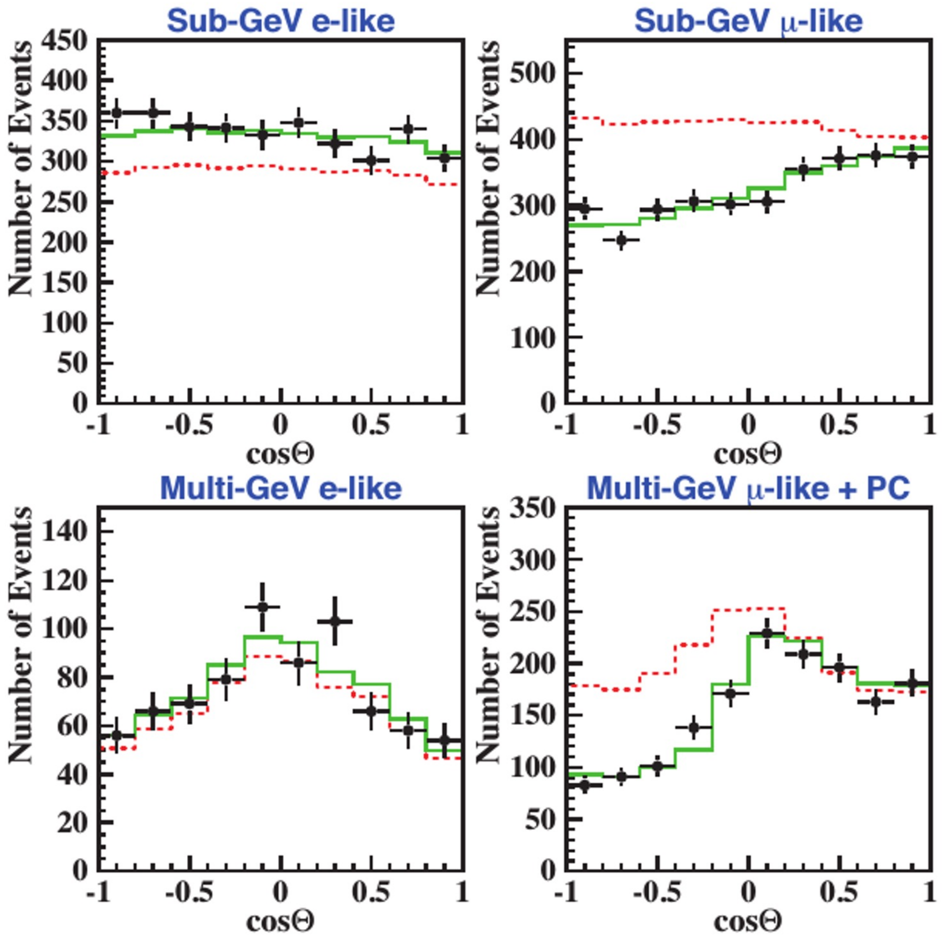
1998 - the Super-Kamiokande experiment solved the problem: the ν_μ were oscillating at ν_τ.

NEUTRINOS HAVE MASS!

The ν_μ coming from above hardly change.

Many ν_μ that cross the earth become ν_τ.

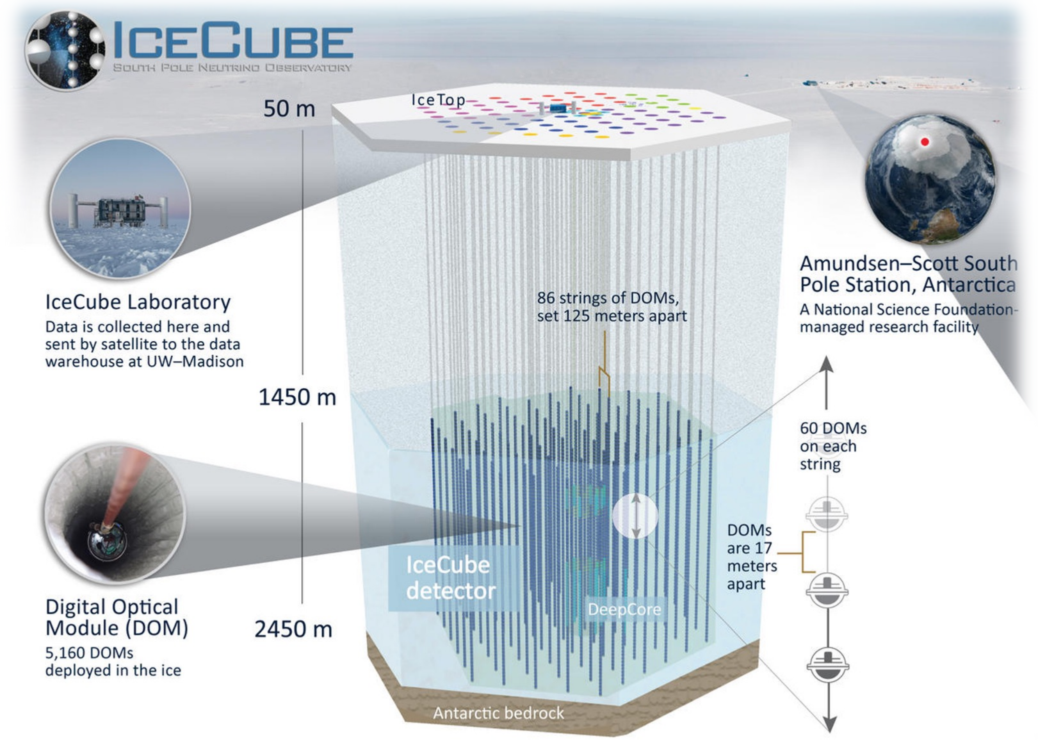


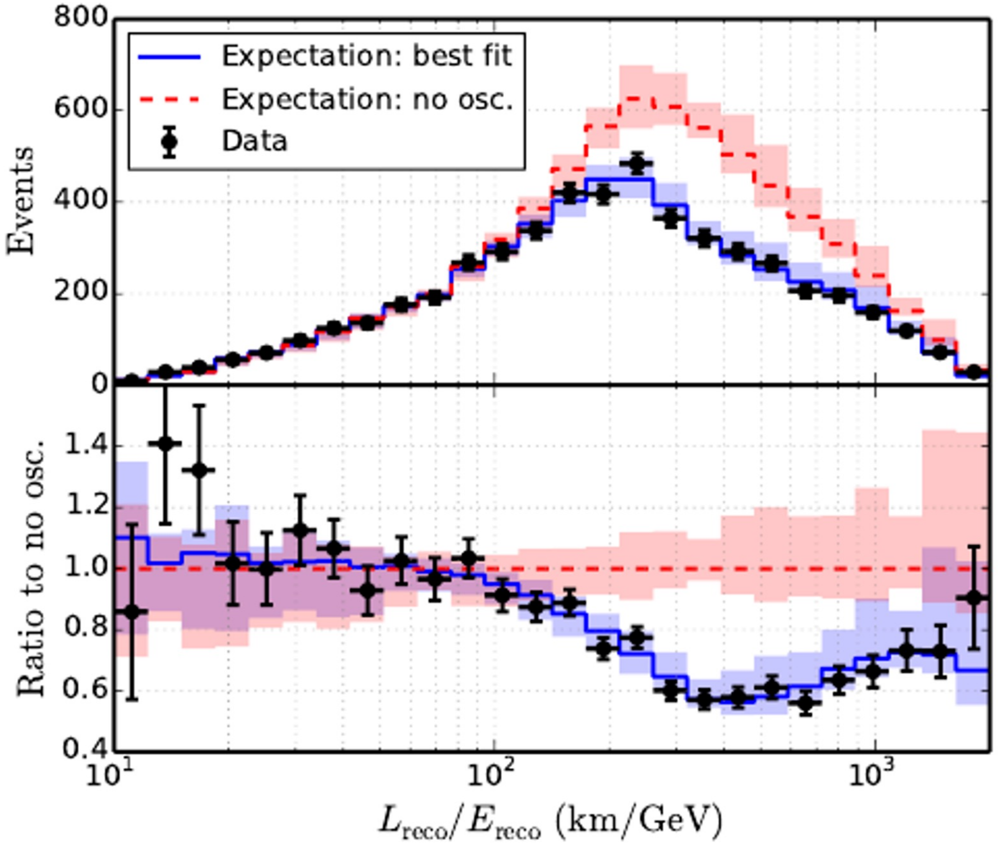


McDonald, Kajita -2015

IceCube experiment

The IceCube experiment at the South Pole detects atmospheric neutrinos using 1 km^3 of ice as a Cherenkov detector.



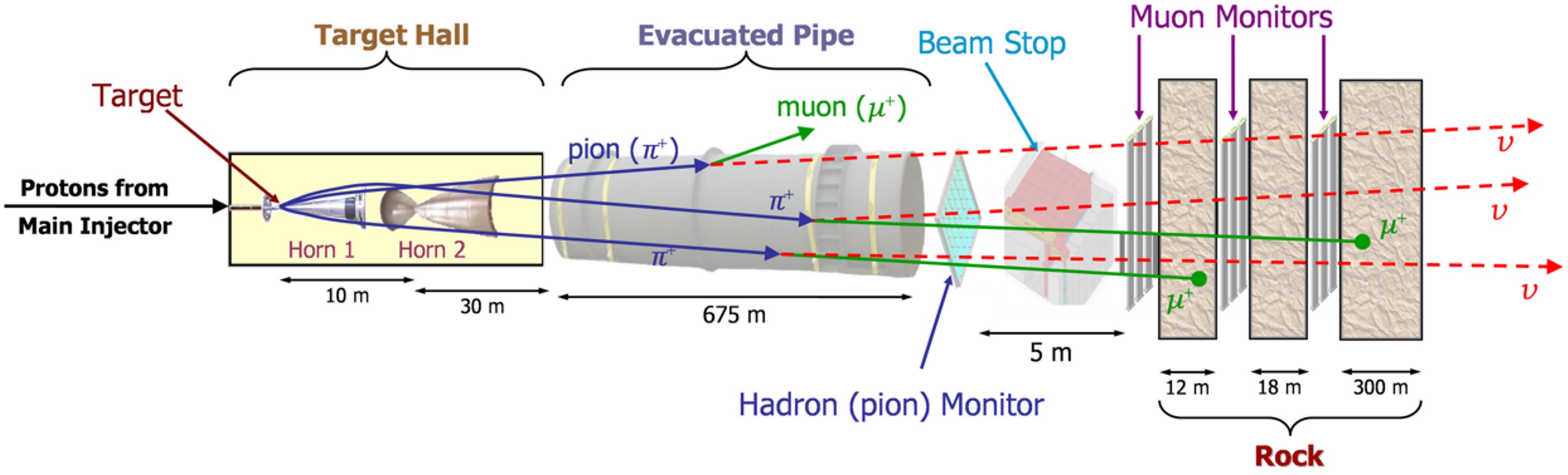


ACCELERATOR NEUTRINOS

redit: symmetry magazine

Accelerator neutrinos

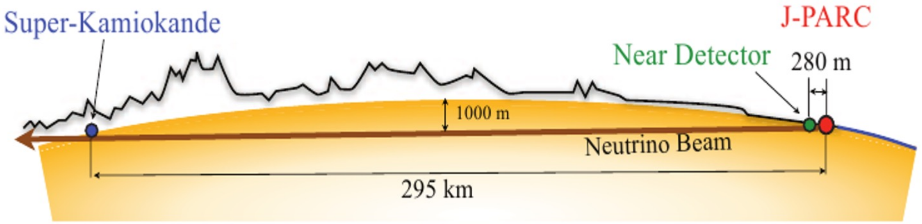
- Artificial muon neutrino beams can be created using protons from an accelerator.
- The protons collide with a fixed target, producing mesons (π, K…).
- The positively (or negatively) charged mesons are focused using magnetic horns and directed into a tube where they decay into muons and muonic neutrinos. The muons are absorbed in the rock at the end of the tube. The neutrinos continue their way.



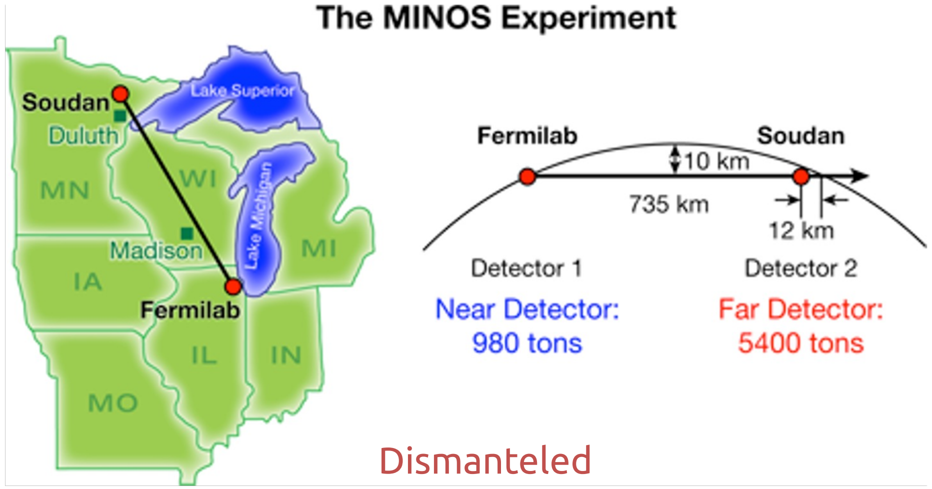
Accelerator neutrinos

- Long-distance oscillations (> 100 km).
- A detector close to the accelerator measures the flux of neutrinos before they can oscillate.
- A far detector measures the flux after traveling a distance. Many of the ν_μ vanish (oscillate to ν_τ).

T2k

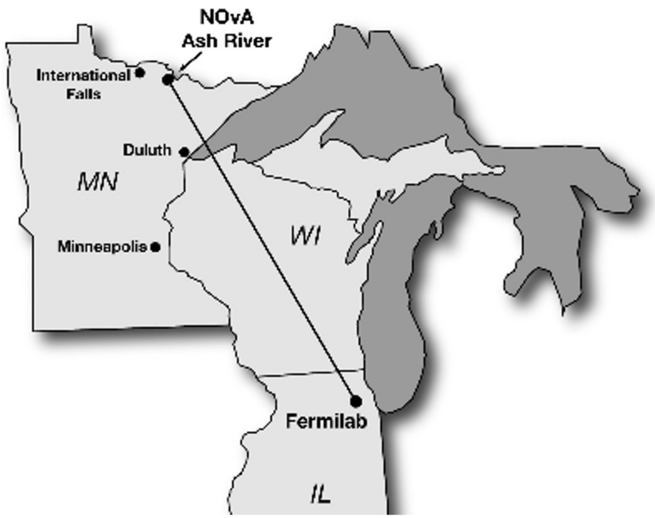


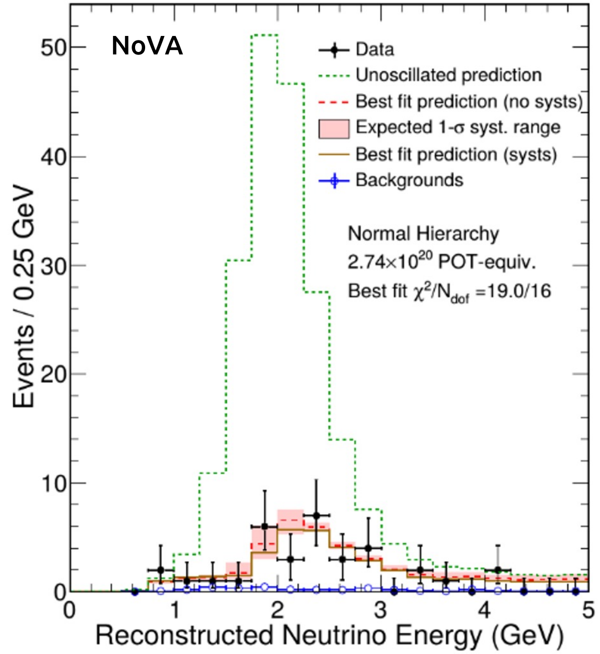
MINOS



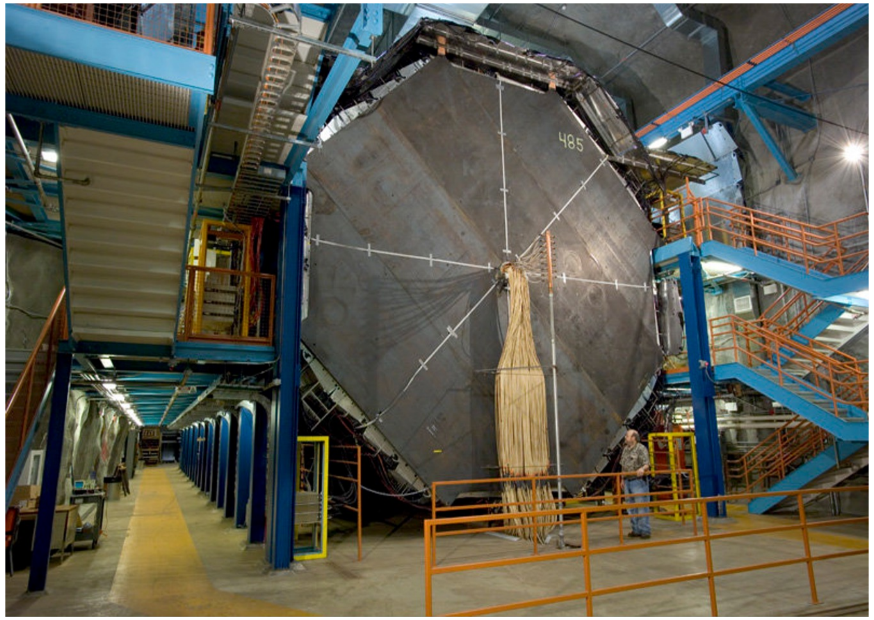
Dismanteled

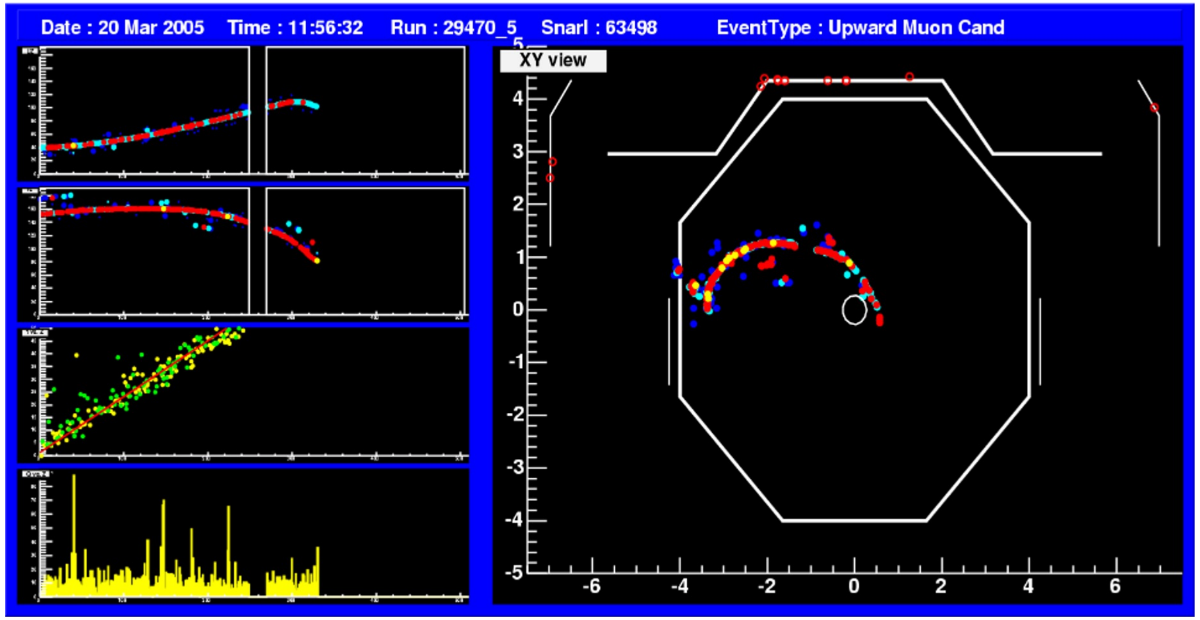
NoVA





MINOS far detector



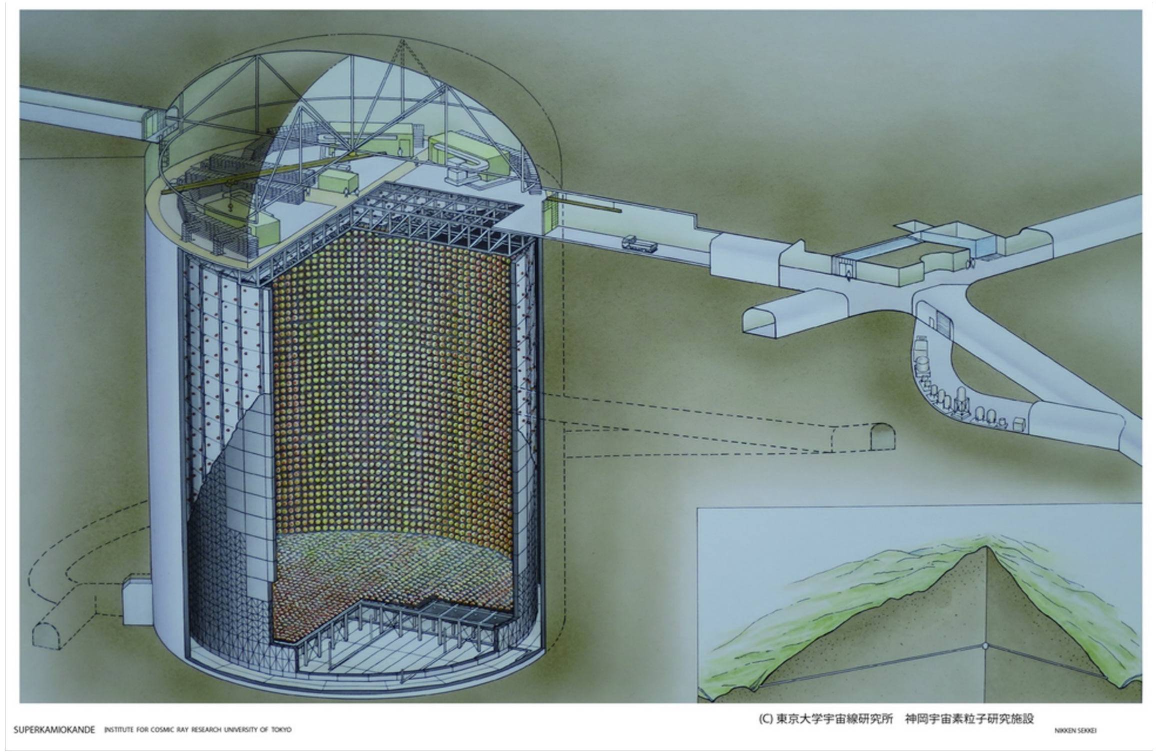


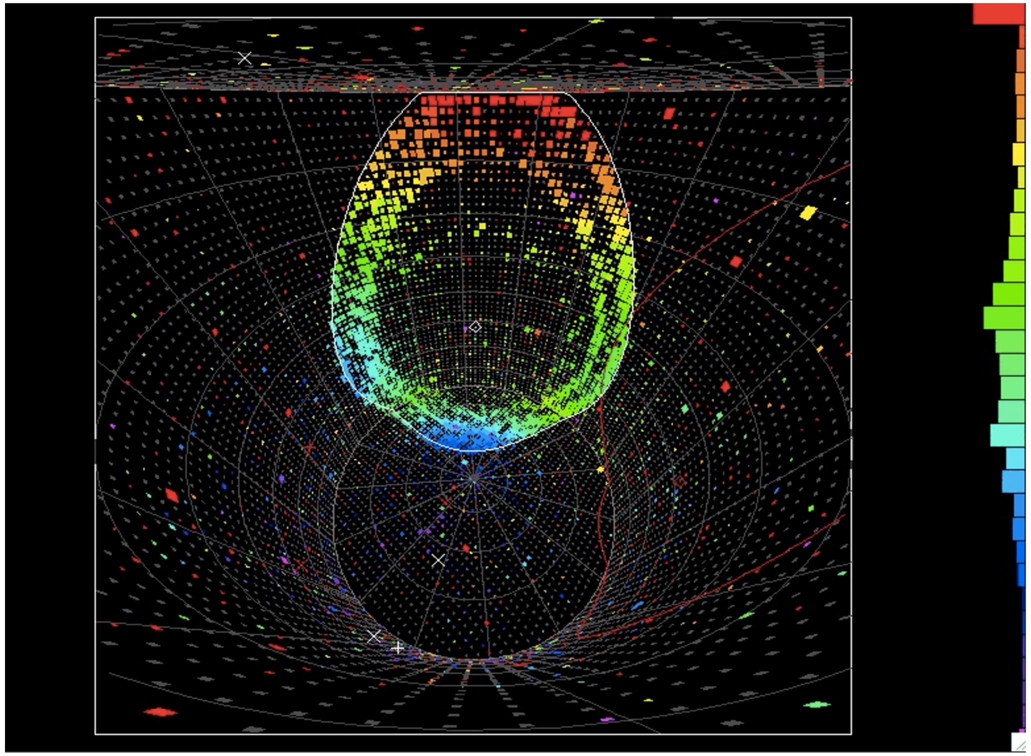
Tracking detector: Reconstruction of charged leptons tracks

Magnetized steel and plastic scintillators ~700 m underground.

ν_μ produces μ: bended track depending on μ charge

T2K far detector (Super Kamiokande)

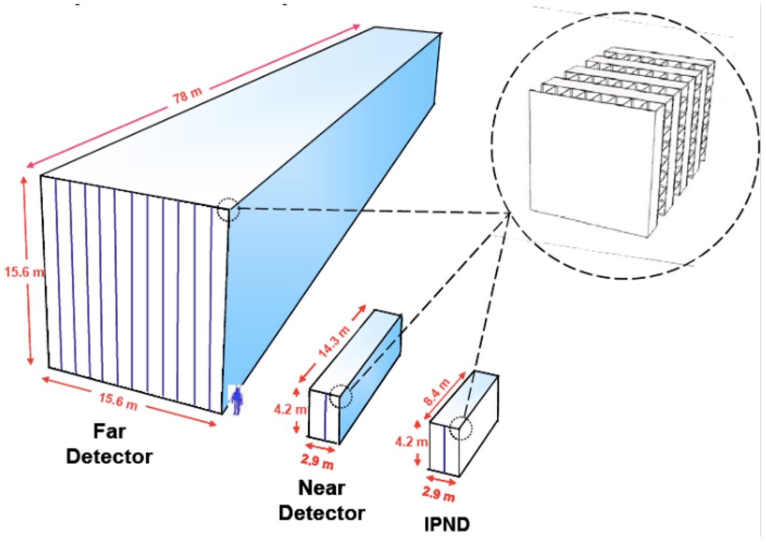


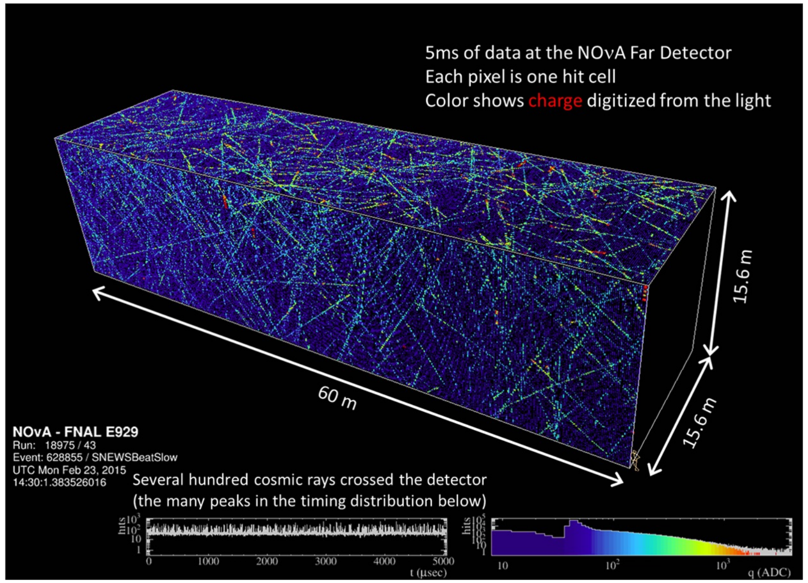


Water Cherenkov 1km underground at 295km from the target

ν_μ produces a μ: Cherenkov radiation ring

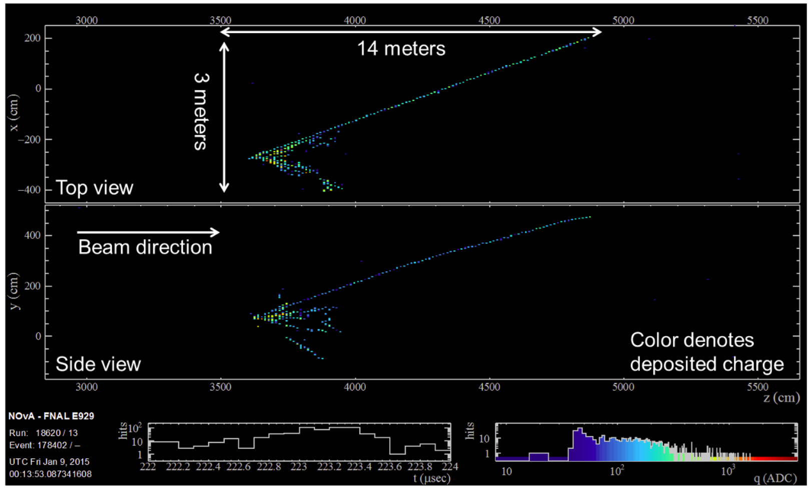
NoVA far detector





5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

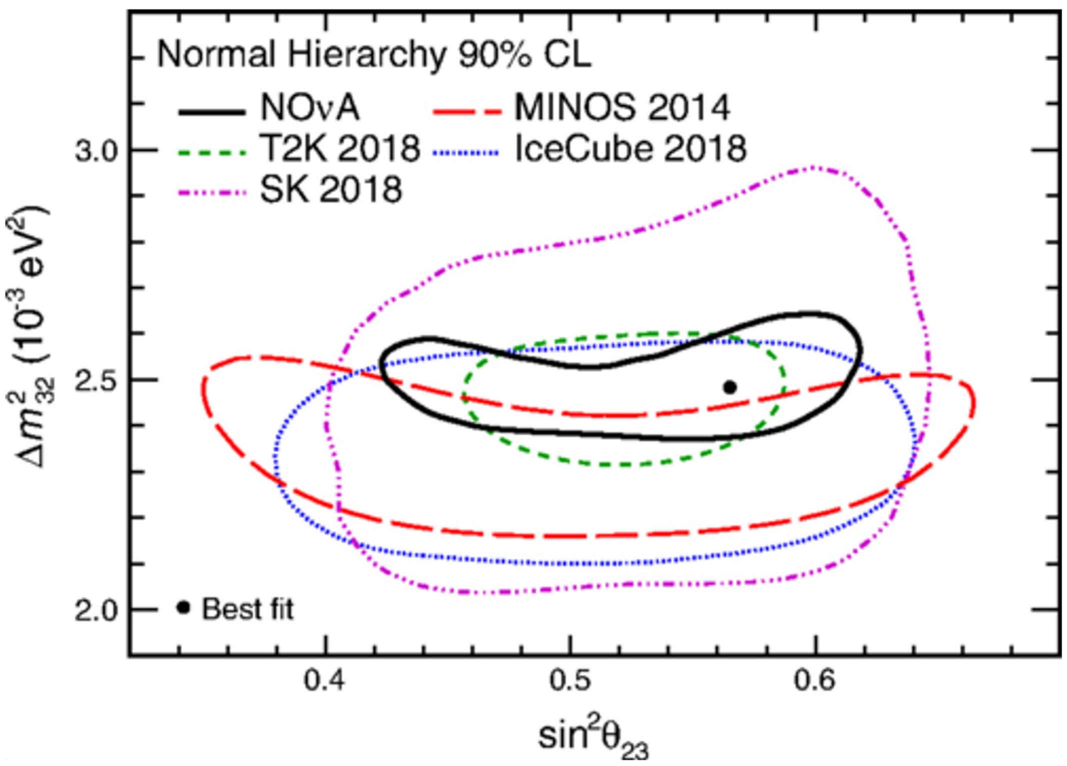
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)



Plastic scintillator at surface: 14-kton detector are made up of 344000 cells of PVC filled with liquid scintillator.

ν_μ produces a μ: long track + other particles

Measurements of θ23



The combination of the experimental results determines:

$$\theta_{23} \sim 49^\circ$$

(… but 45º still possible)

Flavor symmetry?

Mass difference x100 bigger than $\Delta m^2{}_{21}$

$$|\Delta m_{23}{}^2| \sim 2.5\cdot 10^{-3}\ \mathrm{eV}^2$$

We don´t know if $m_3 > m_2$.

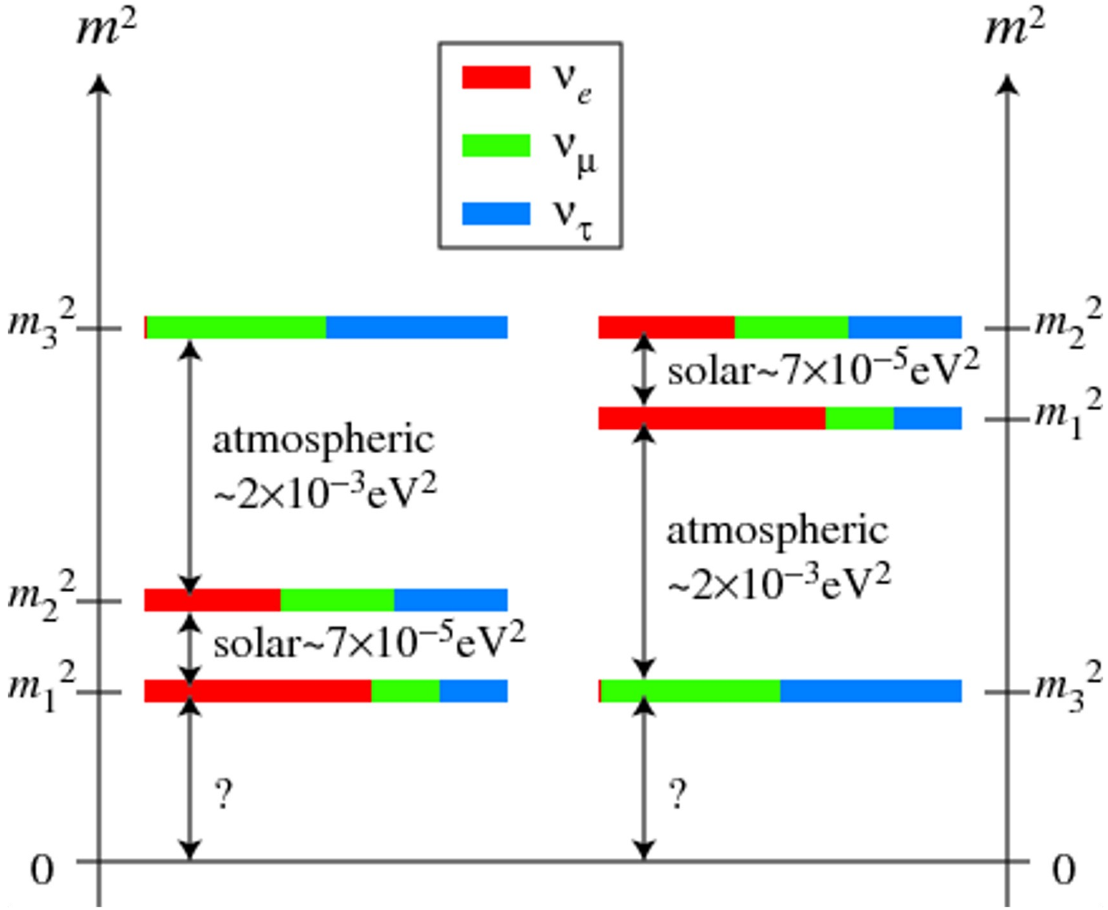
Mass ordering

3 mass states -> 2 mass differences:

$$\Delta m^2_{32} + \Delta m^2_{21} = \Delta m^2_{31}$$

Matter effects at the Sun probe that $m_2 > m_1$.

Which is the lightest neutrino?
Two possibilities for mass ordering



REACTOR NEUTRINOS

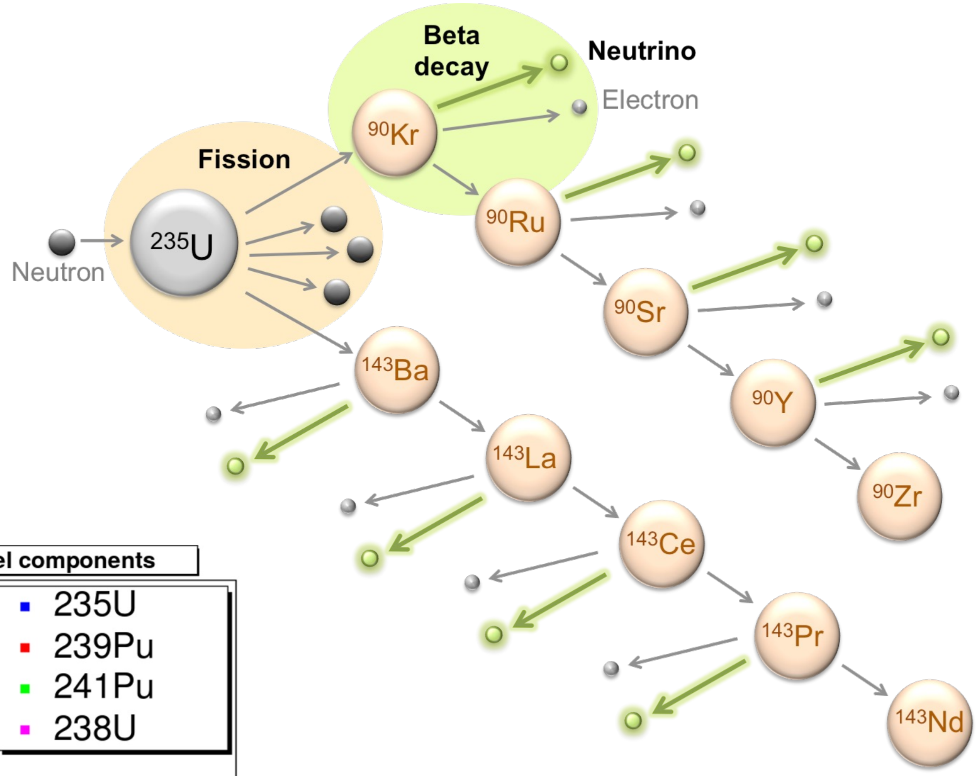
Credit: symmetry magazine

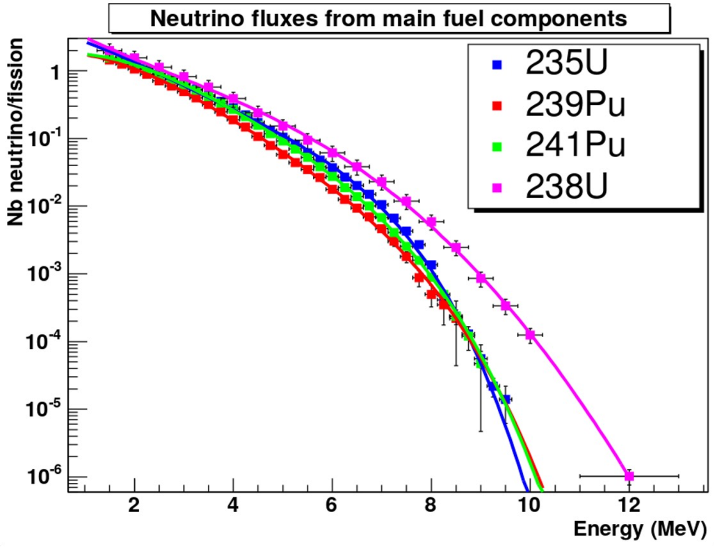
Nuclear reactor neutrinos

Fission of nuclear fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) generates radioactive fission products with excess neutrons, which undergo β^- disintegrations.

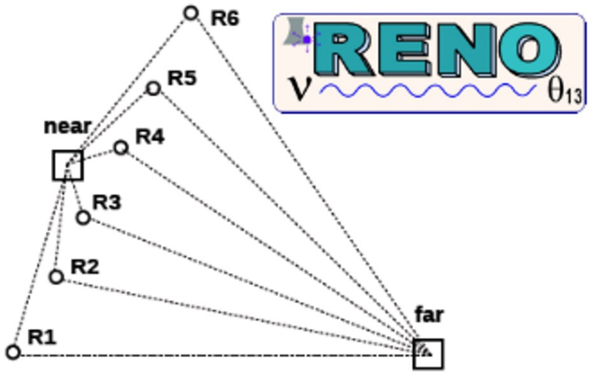
$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \overline{\nu}_{e}$$

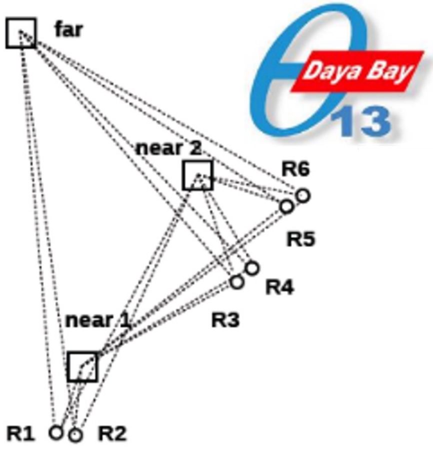
On average, 200 MeV and 6 antineutrinos are released per fission.





Nuclear reactor neutrinos



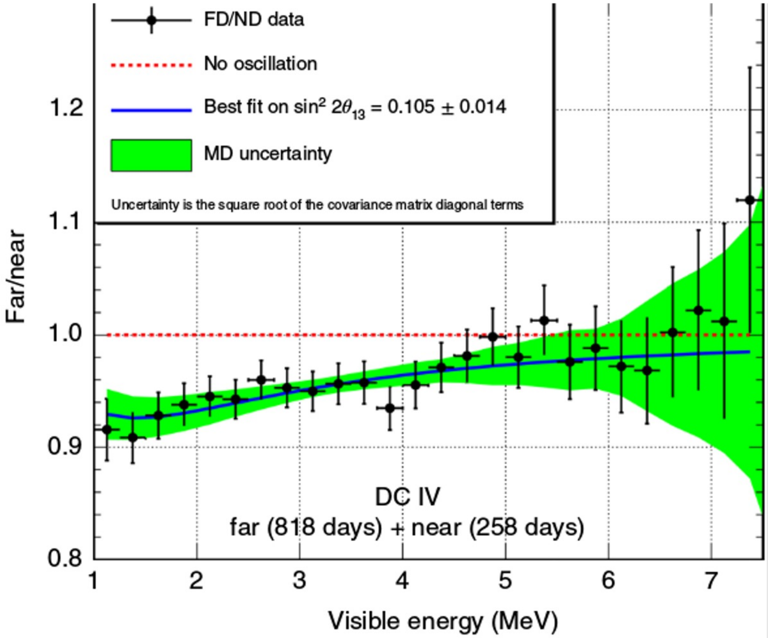


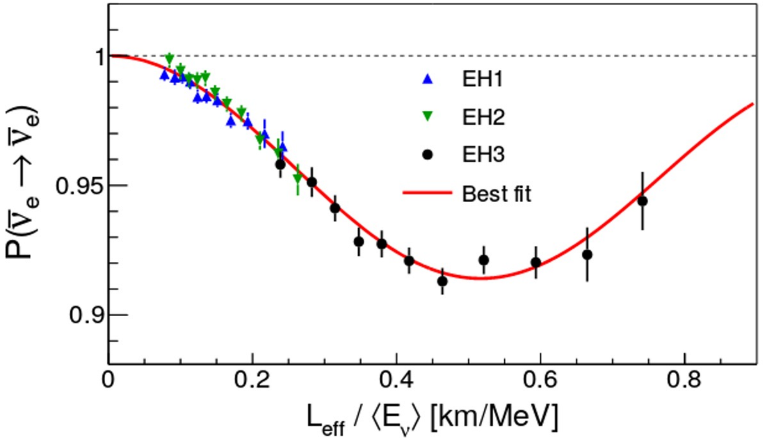
Experiments with two identical detectors:

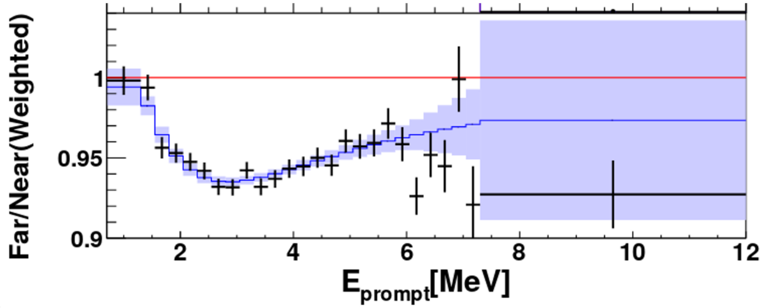
- Near Detector near the reactors measures the flux of antineutrinos before they oscillate.
- Far Detector measures the flux near the oscillation maximum.

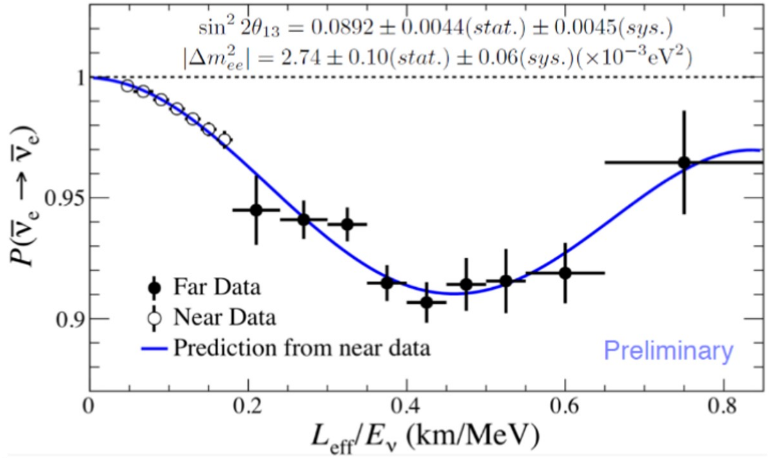
Systematic uncertainties on reactor flux and antineutrino detection are drastically reduced by using identical near and far detectors.

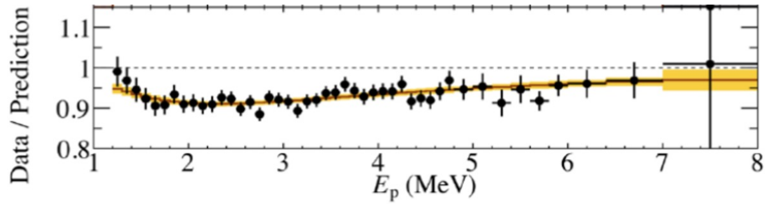
Double Chooz, Daya Bay & RENO results



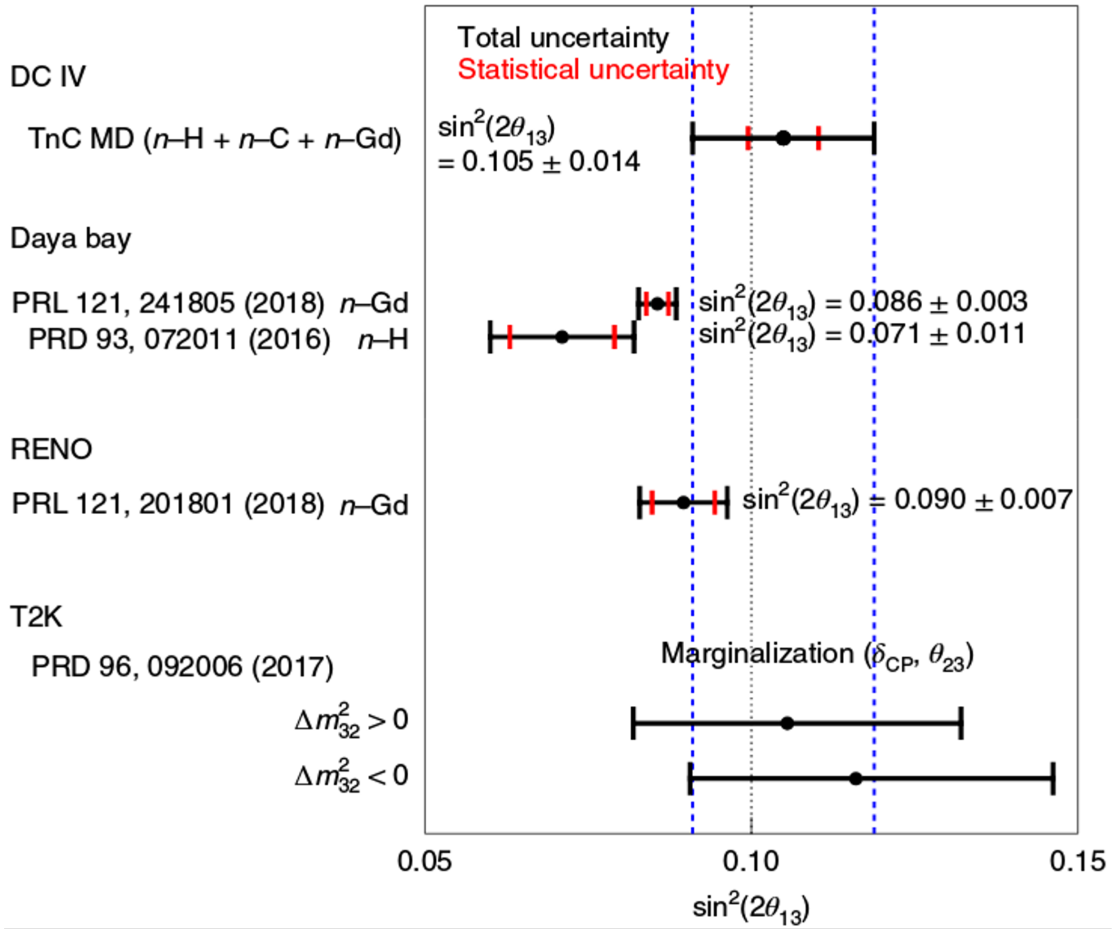








Measurements of θ13



The experimental combination determines

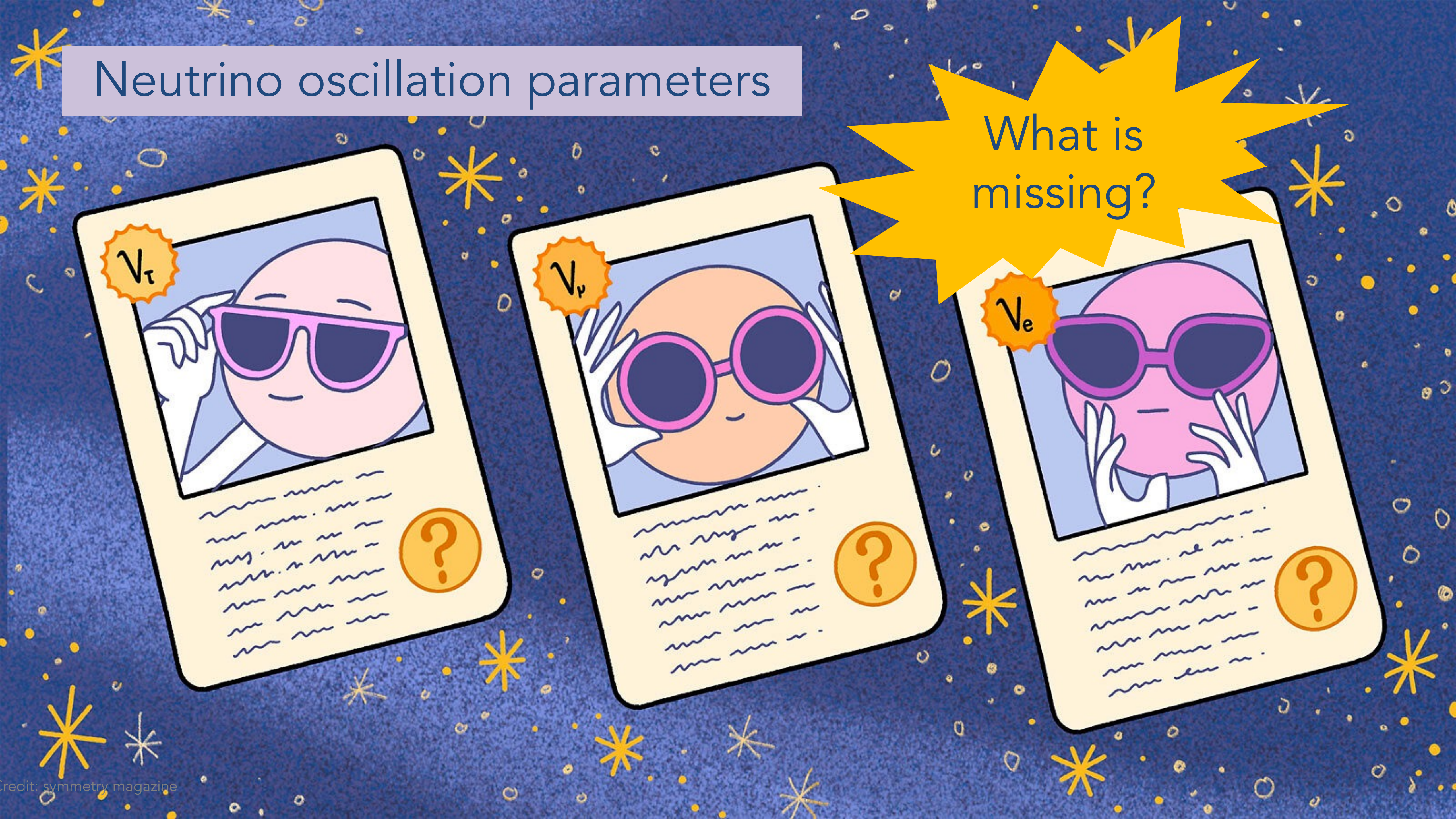
$\theta_{13} \sim 8.6^{\circ}$

Much smaller than the other angles.

3 mixing angles are not zero.

Measuring CP violation at the leptonic sector is possible!

Neutrino oscillation parameters



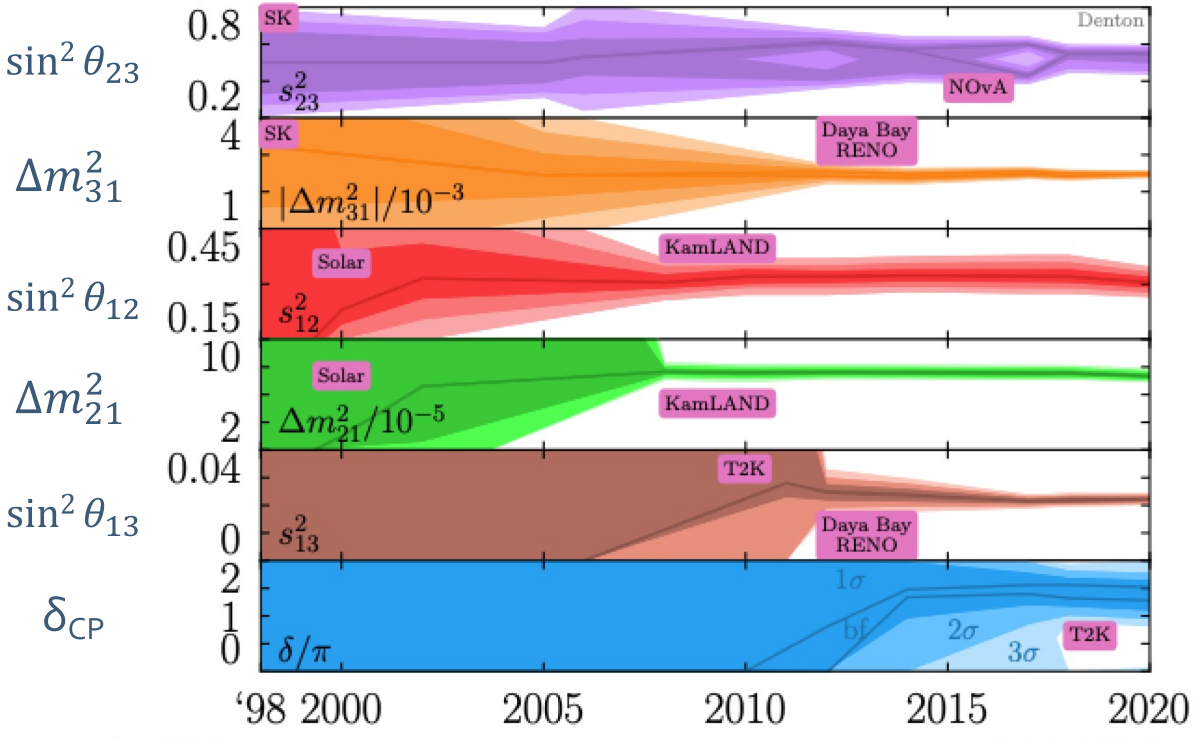
What is missing?

Credit: symmetry magazine

Neutrino oscillation parameters

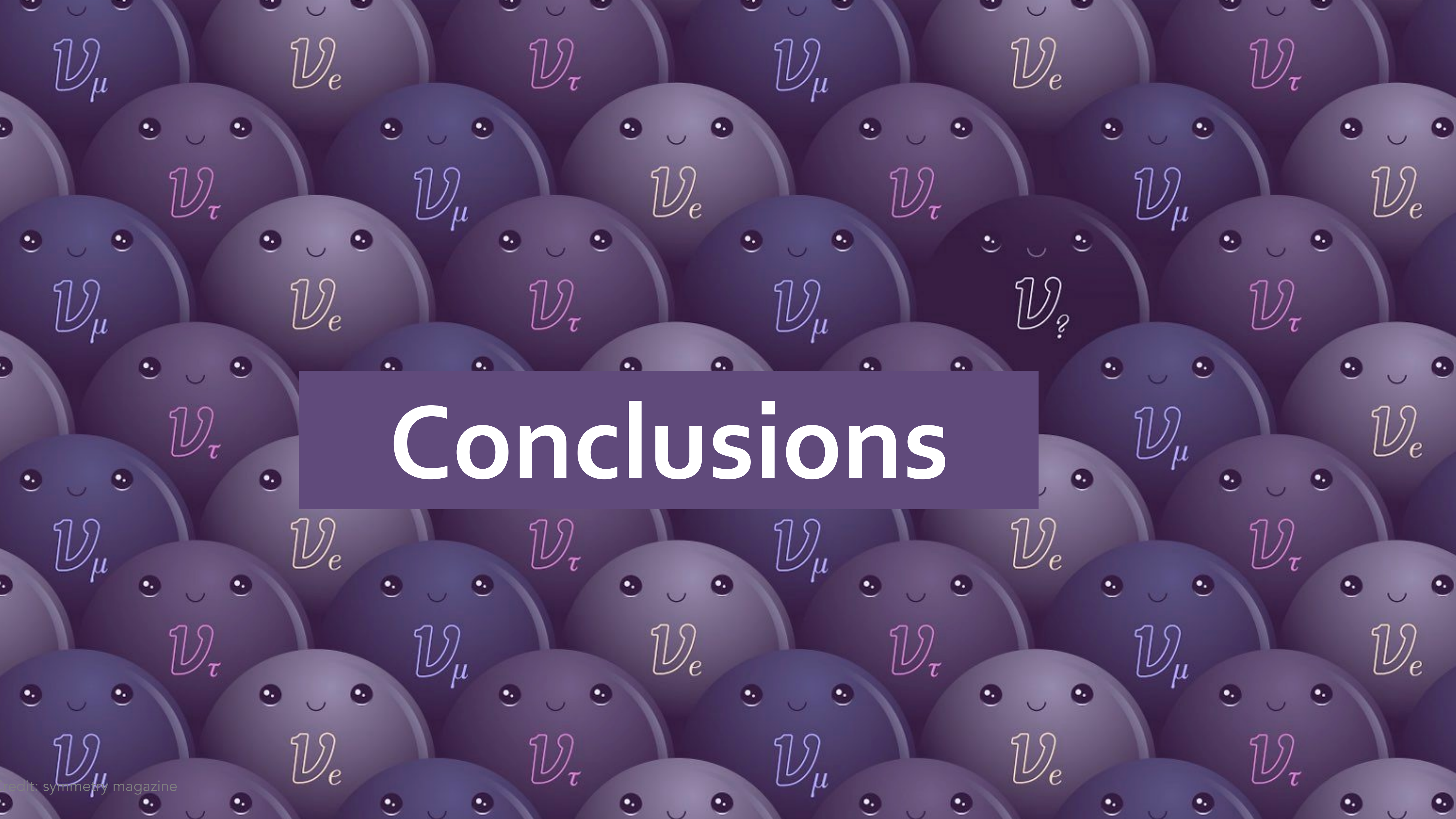
Evolution of experimental measurements

From P. Denton, Neutrino22



✓ Experimentally measured parameters: θ_{12}, Δm^2_{12} , θ_{23}, θ_{13}, Δm^2_{31}

? Unknown parameters: mass ordering (sing of Δm^2_{31}), δ_{CP}, θ_{23} octant

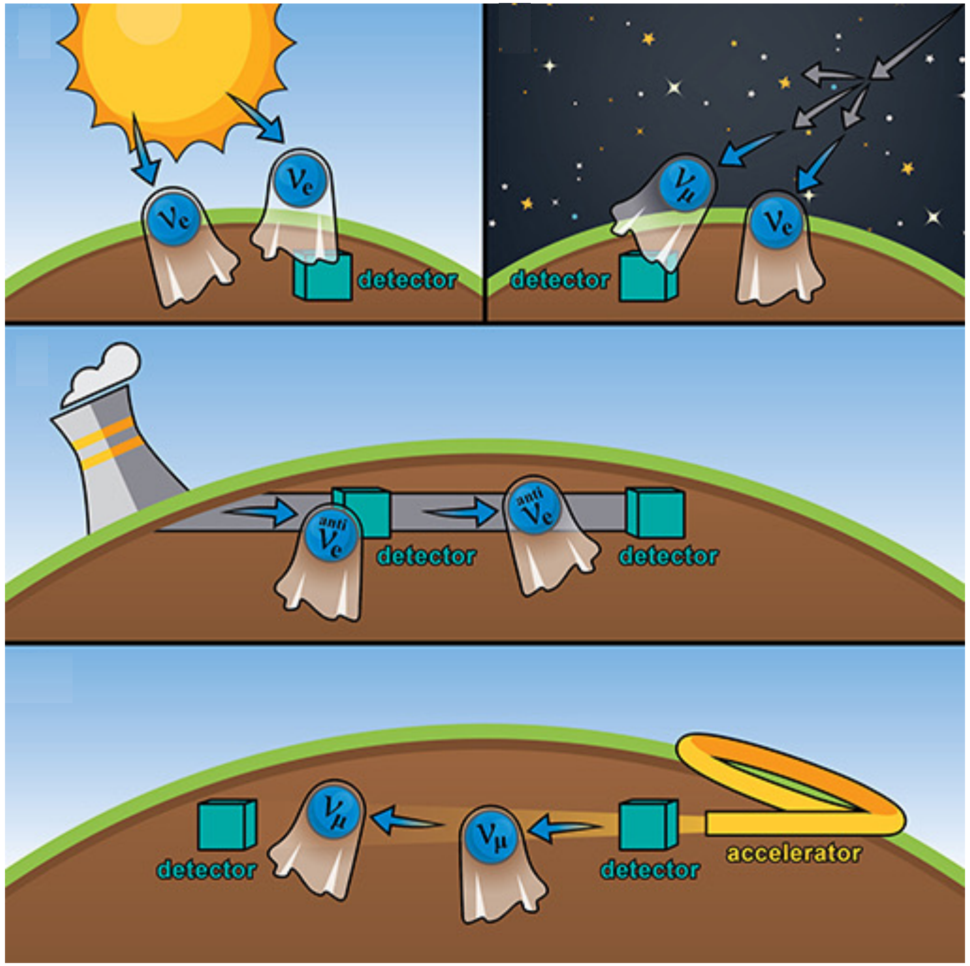


Conclusions

redit: symmetry magazine

Conclusions

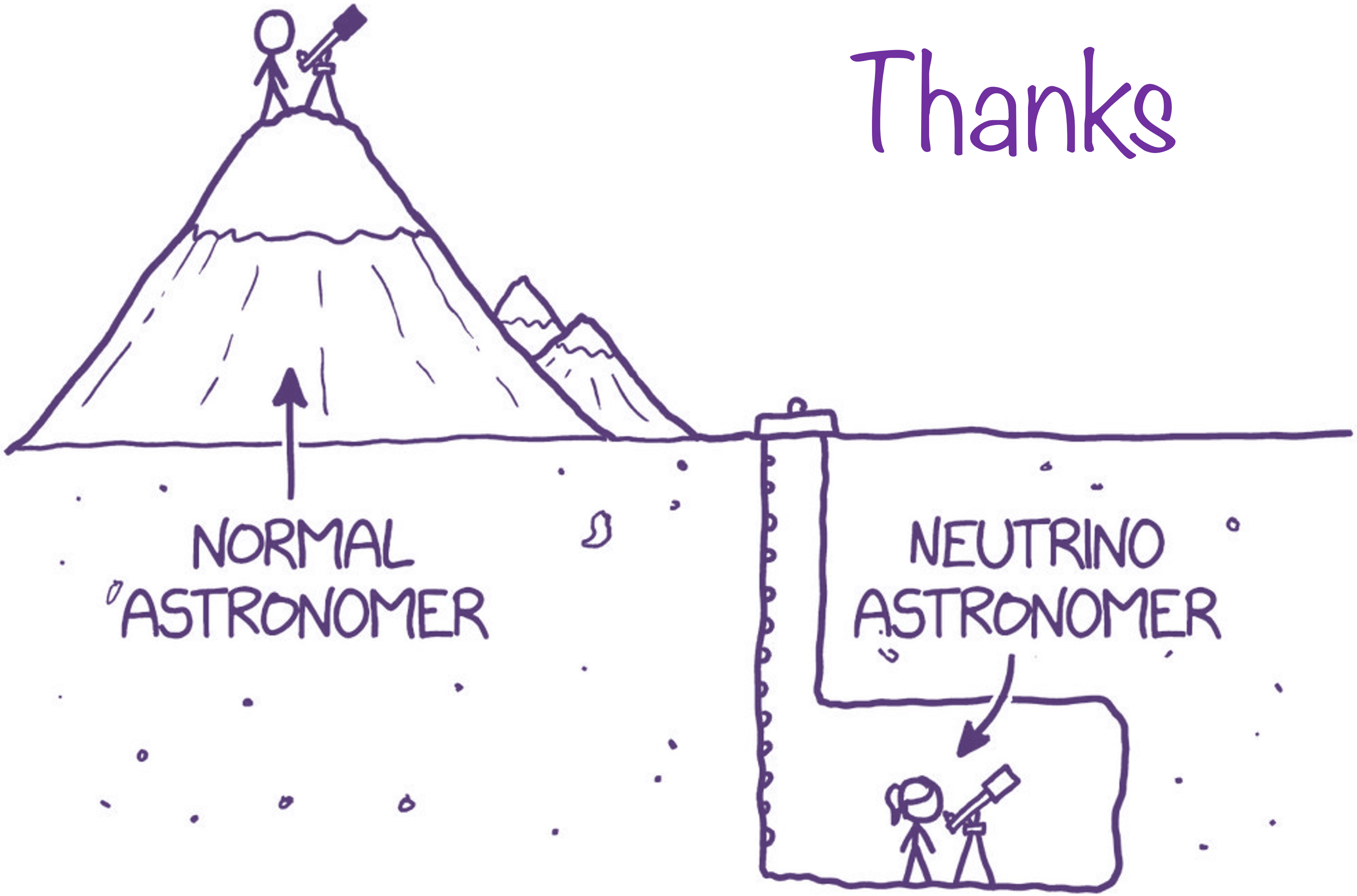
- Neutrinos are the most abundant matter particles of the Standard Model.
- Experimental evidence of the need for Physics Beyond the Standard Model to explain neutrino oscillations.
- Neutrino oscillations discovered experimentally, and neutrino oscillation parameters measured experimentally using different neutrino sources (solar, atmospheric, accelerator and reactor neutrinos) and detector technologies.



Credit: Tiffany Bowman, Brookhaven National Laboratory.

Still neutrino unknown properties! … to be continued (tomorrow)

Thanks



Credit: Randall Munroe

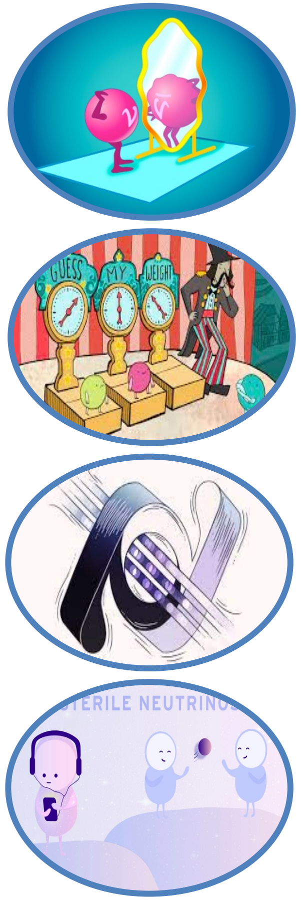
Neutrino unknowns

1. **Neutrino mixing**
   Is the CP symmetry violated in the neutrino sector? CP-violation is one of the 'Sakharov conditions' to explain the matter-antimatter asymmetry in the Universe.

2. **Neutrino mass**
   How are the three neutrino mass states ordered from lightest to heaviest (neutrino "mass ordering")? What is the absolute scale of neutrino masses?

3. **Neutrino nature**
   Is the neutrino its own antiparticle? Are neutrinos Majorana particles?

4. **Neutrino species**
   Are there sterile neutrino species in addition to the three active ones participating in the weak interactions?



Credit: symmetry magazine

Powerful experimental program to answer these questions!