Neutrinos!

Present Understanding & Future Prospects

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7th International Conference on New Frontiers in Physics (ICNFP2018)

Contents

- Introduction and a bit of historical context
- The observation of neutrino oscillations
- Massive neutrinos!
- Open questions and (near) future experimental effort
- Summary

The "Standard Model"

Over the last 100 years: combination of

Quantum Mechanics and Special Theory of relativity

along with all new particles discovered has led to the

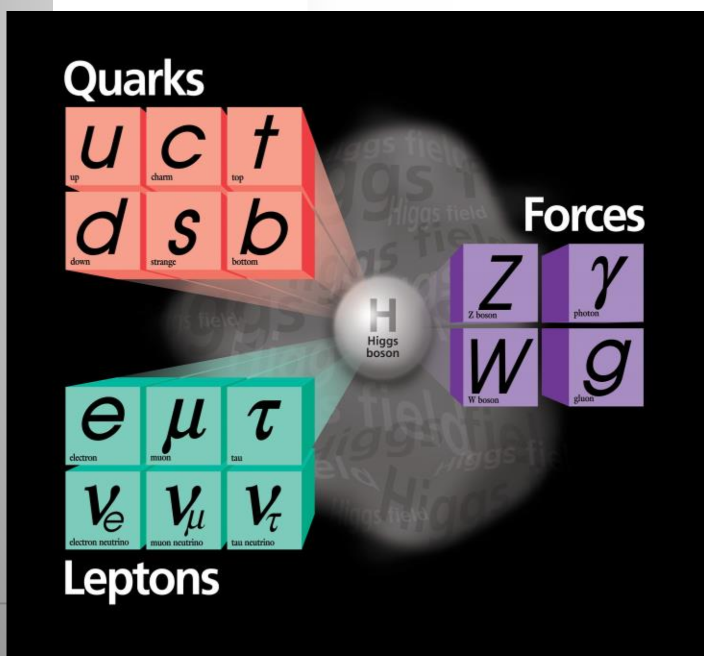
Standard Model of Particle Physics.

The new (final?) "Periodic Table" of fundamental elements:

Fermions

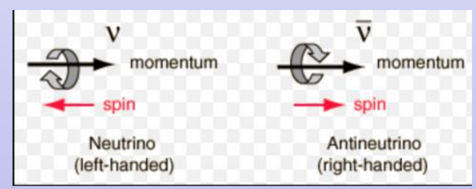
Bosons

Matter particles



Force particles

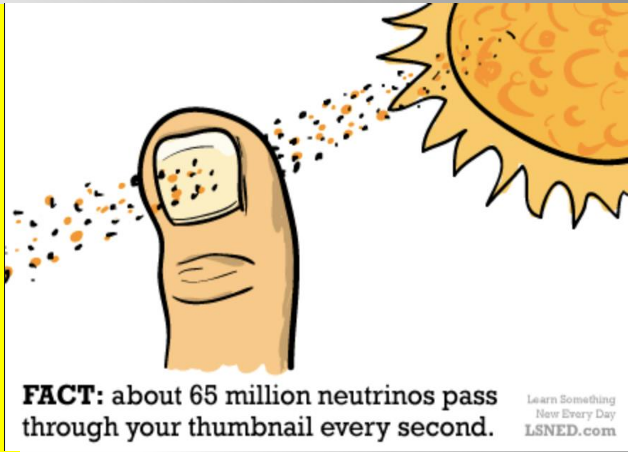
Neutrinos are leptons that do not feel the strong force (no color) or the electromagnetic force (no charge). They interact only weakly.

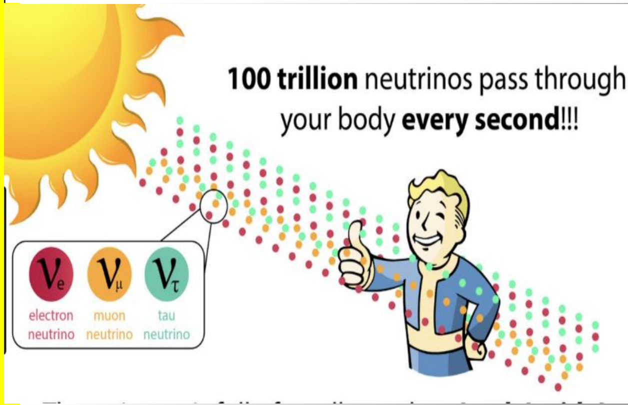


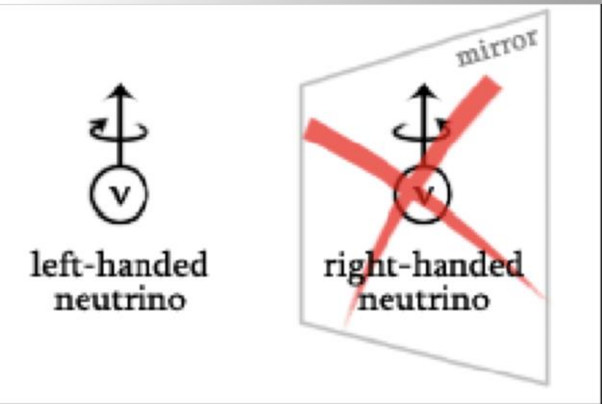
In the Standard Model they are massless, move with the speed of light and neutrinos are always left handed (opposite for ant-neutrinos)

Neutrinos

- Neutrinos are fundamental particles
- Neutrino are ghostly particles
- Trillions (10^{12}) of neutrinos pass per second through you for every second of your life! They come from the sun
- Neutrinos need a light year of lead (~10^{13} km) be stopped with 50% chance
- There are a billion neutrinos for each atom in the Universe. There are ~3.10^{8} neutrinos per cubic meter- relic neutrinos
- Their sheer number must mean they are important
- Neutrinos have a fixed chirality ->







An (American) billion = 10^{9} = 1000000000

Neutrinos

Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) Standard Model
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos come from everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Relic/supernova neutrinos
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, radioactive decay, even from your body

Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

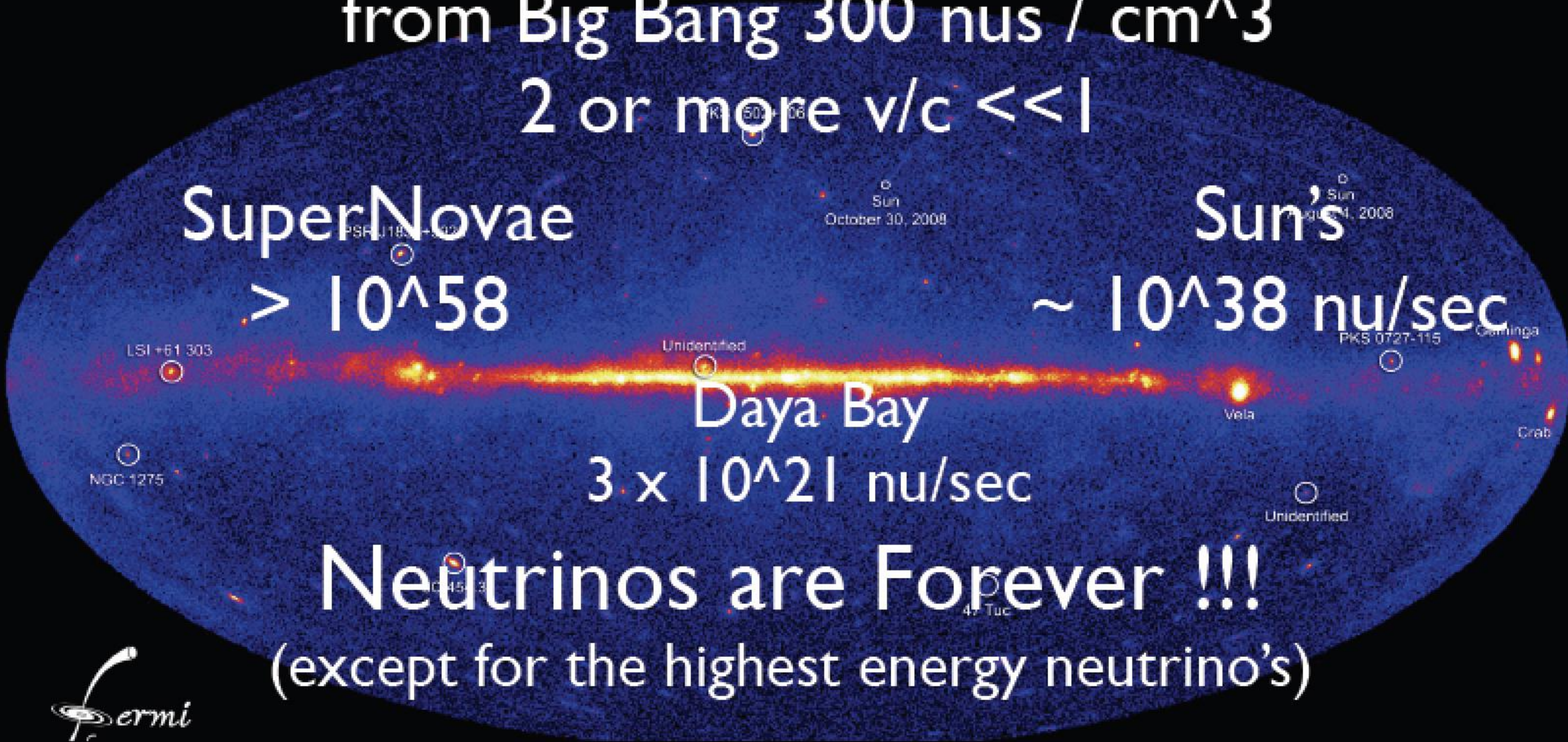
~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

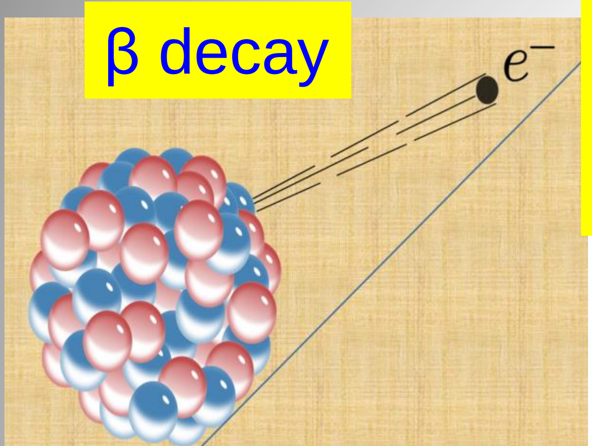
Neutrinos are Forever !!!

(except for the highest energy neutrino's)



therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrinos are know to us since 1930!



If the process is A -> B + electron, the energy of the electron should be at a fixed value. This is not the case! Energy-momentum not conserved in Beta-decays?

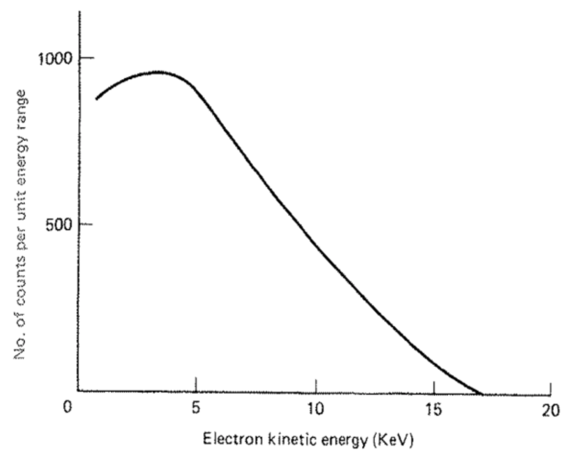


Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \rightarrow ^3_2He$). (Source: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Pauli proposed instead the process:

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

...At least in (controversial) theory

Neutrinos are know to us since 1930!

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 dürfte 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.

Pauli Letter Collection, CERN

Pauli did not believe energy-momentum conservation was violated
He proposed a desperate way out: a new 'invisible' particle
He called it the neutron.
He also stayed away from the conference because of a ball in Zurich..

Neutrinos are know to us since 1934!

1934

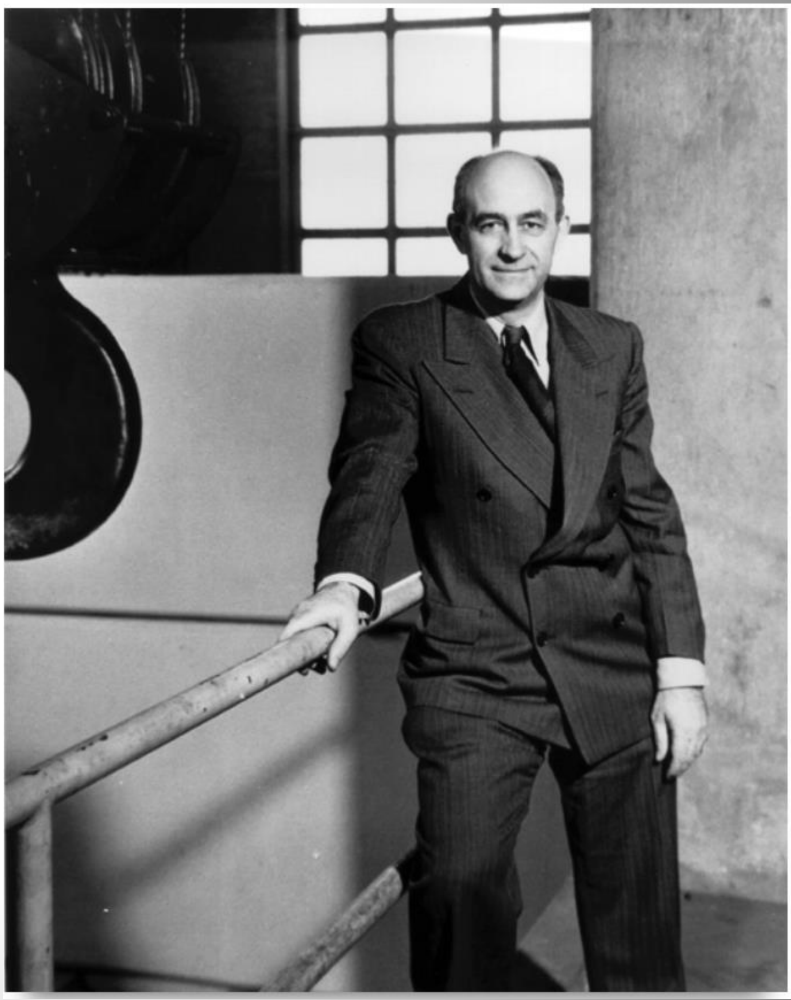
Enrico Fermi, father of the world's first nuclear reactor, coined the term "neutrino" which is Italian for "little neutral"

The name neutron had meanwhile been claimed for the discovered nucleon partner of the proton

He proposed a theory for Beta-decay including the neutrino, a first formulation of the weak force…

Funny enough his paper got refused by Nature magazine

(criticism: nothing practical in this paper)



The Discovery of the Neutrino

It took 26 years to detect this particle. Cowan and Reines put a detector close to the reactor in South Carolina and observed the inverse beta decay process (few events/hour)

Reactors give 10^{19} neutrinos/sec

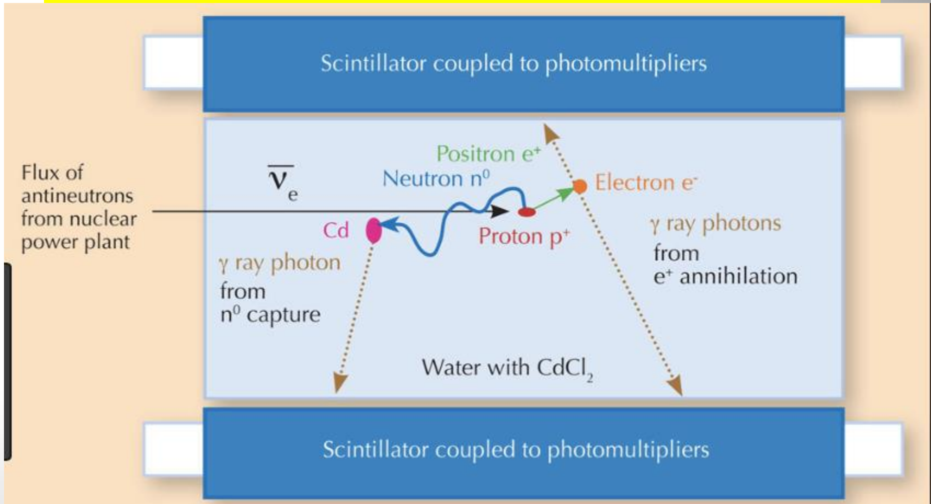
The neutrino really exists!

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

5 μsecond delay

$$e^+ + e^- \Rightarrow \gamma + \gamma$$

n-capture by cadmium

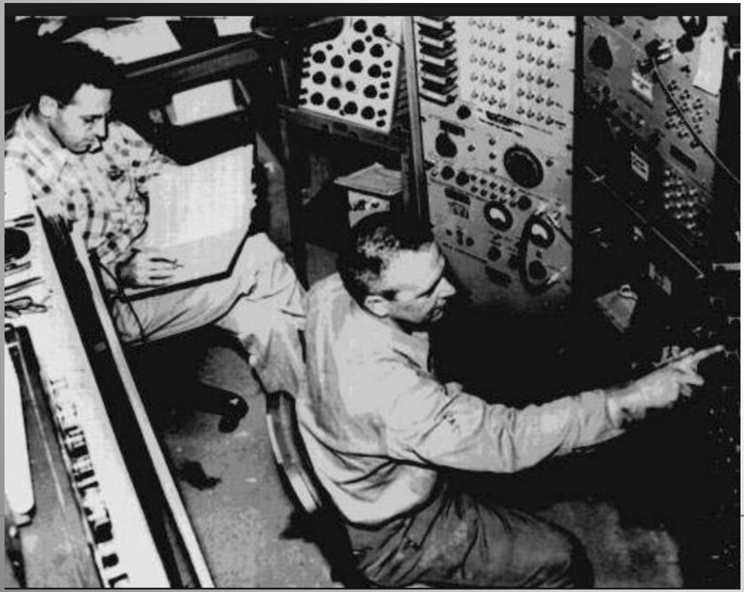


$$\bar{\nu}_e + p^+ \rightarrow e^+ + n^0$$

$$n^0 + {}^{113}Cd \rightarrow {}^{114}Cd^* \rightarrow {}^{114}Cd + \gamma$$

$$e^+ + e^- \rightarrow 2\gamma$$

The Discovery of the Neutrino



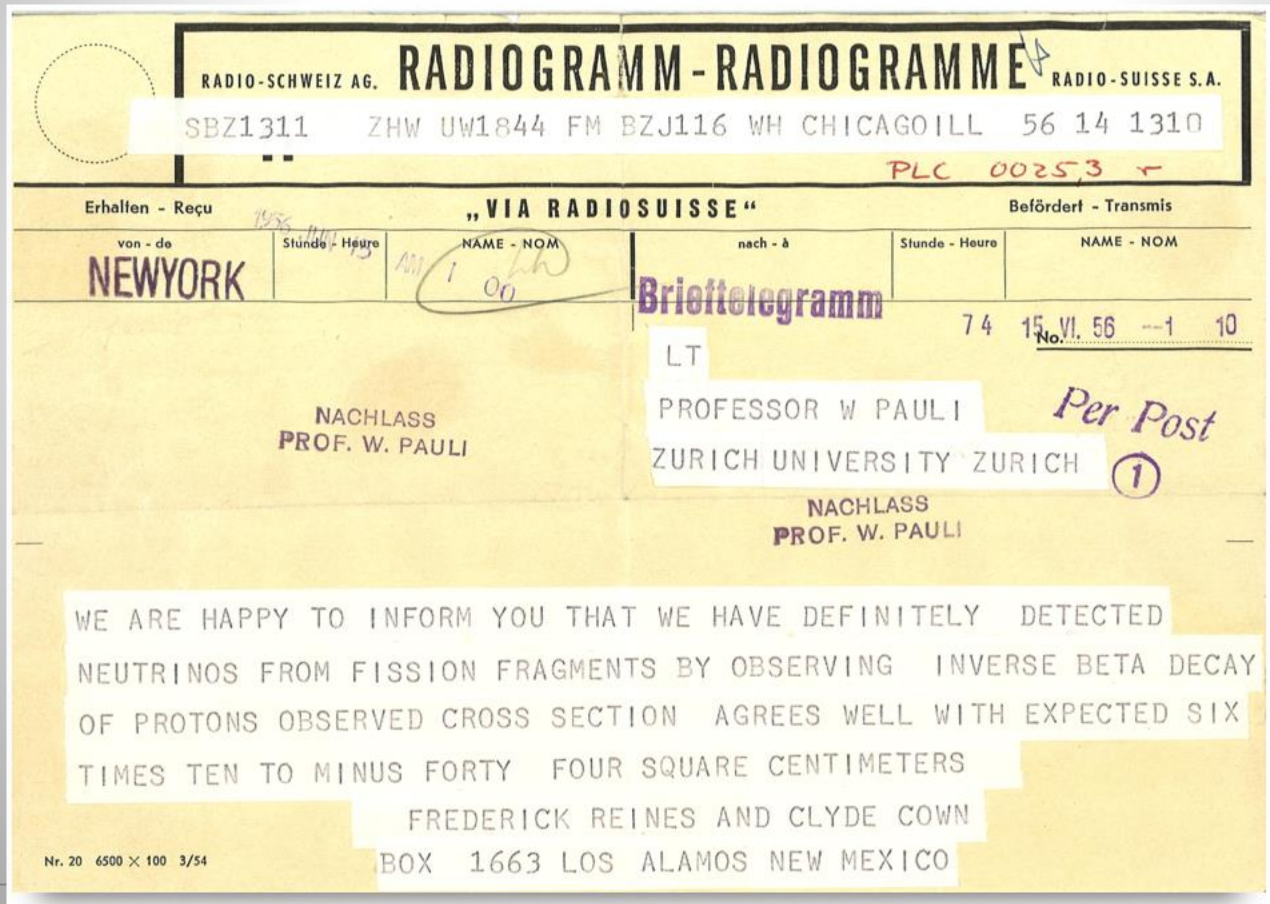
This was however not the first idea of Cowan and Reines.

They had originally proposed (and got approved for) putting an experiment close to an even more intense source of neutrinos nml 100m distance from an atomic blast!

They abandoned that idea when the realized there were certain 'practical problems' for the detector… (to survive)

The Discovery of the Neutrino

1956: the first experimental evidence from project "Poltergeist", informing Wolfgang Pauli..



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

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

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

More Neutrino Personalities

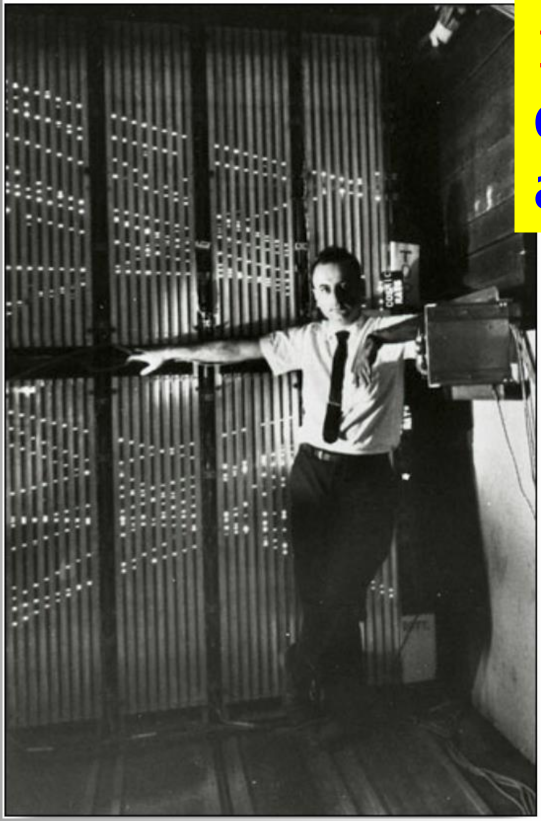
1937: Ettore Majorana
He postulated that neutrinos could be their own antiparticles. This special class of particles came to bear his name: Majorana particles

Majorana disappeared in 1938 on a boat trip from Sicily

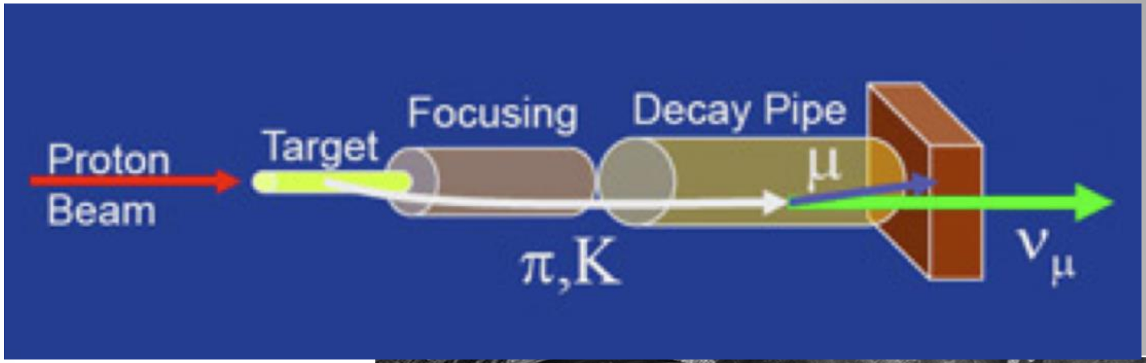
1957: Bruno Pontecorvo
He hypothesized that neutrinos may oscillate, or change from one type to another and would go on to develop that theory over the years as more flavors were discovered.
He also predicted that supernovae, the giant explosion of a dying star, would release an enormous amount of energy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

Pontecorvo disappeared … to the east block in 1950

Neutrinos in the 1960s

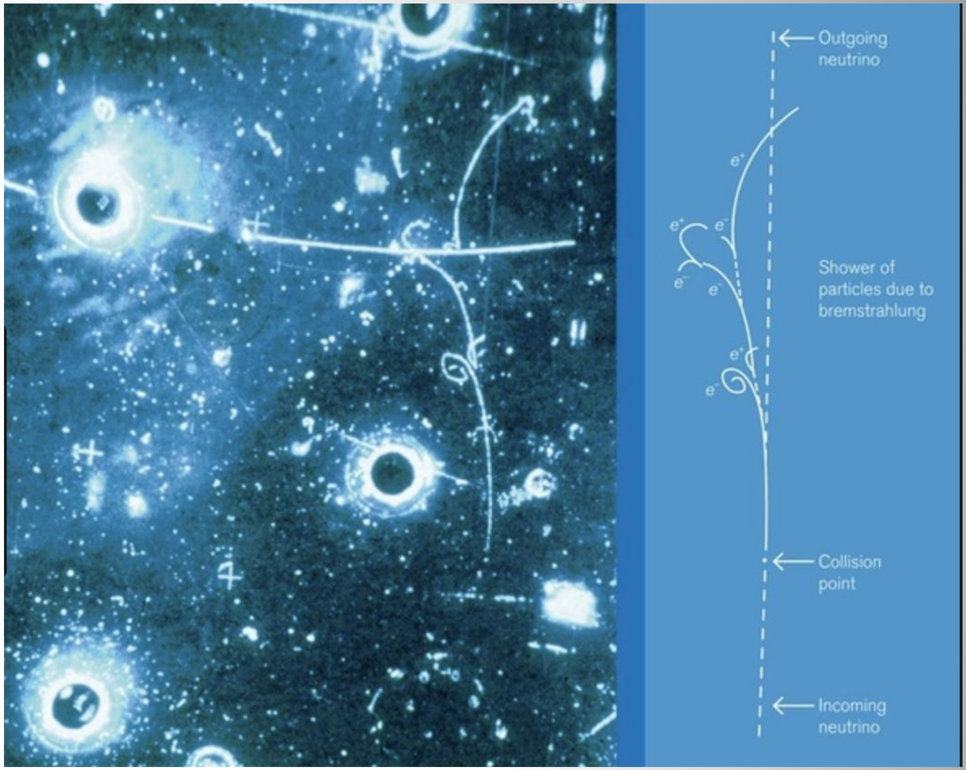


1962: Lederman, Schwartz and Steinberger discovered the existence of second type of neutrino at the AGS in Brookhaven: the muon neutrino



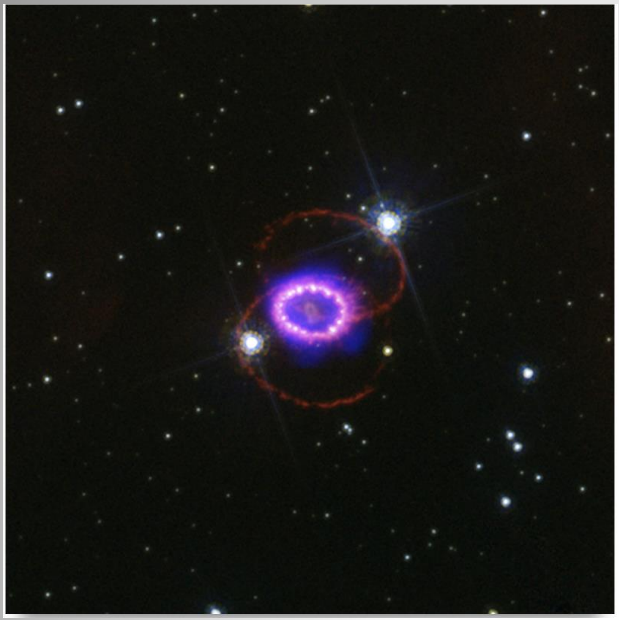
1968: Davis and Bahcall and the solar neutrino problem. Only 1/3 of the expected (electron) neutrino rate was observed. What was wrong?

Neutrinos in the 1970s



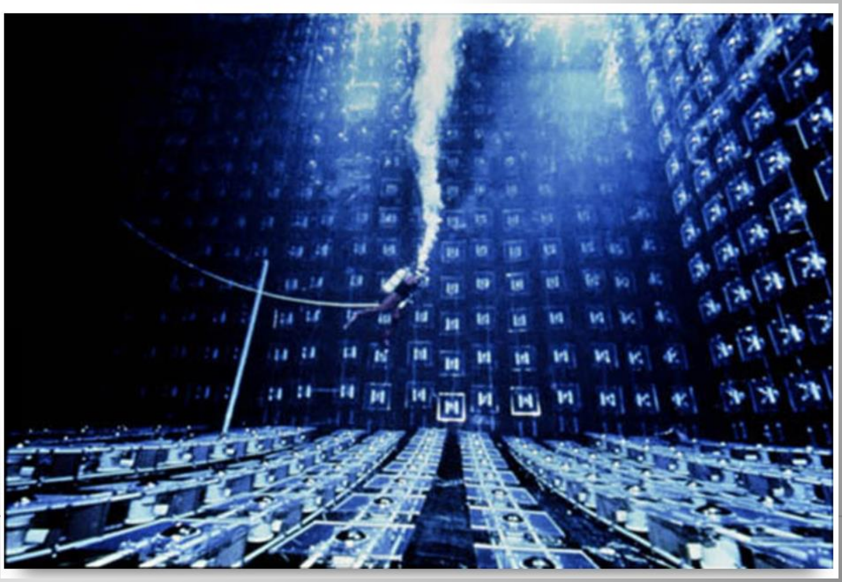
1973: Discovery of the "neutral currents" as predicted from the Electroweak Theory: neutrino + proton -> neutrino +X
A triumph for the emerging Standard Model

Neutrinos in the 1980s

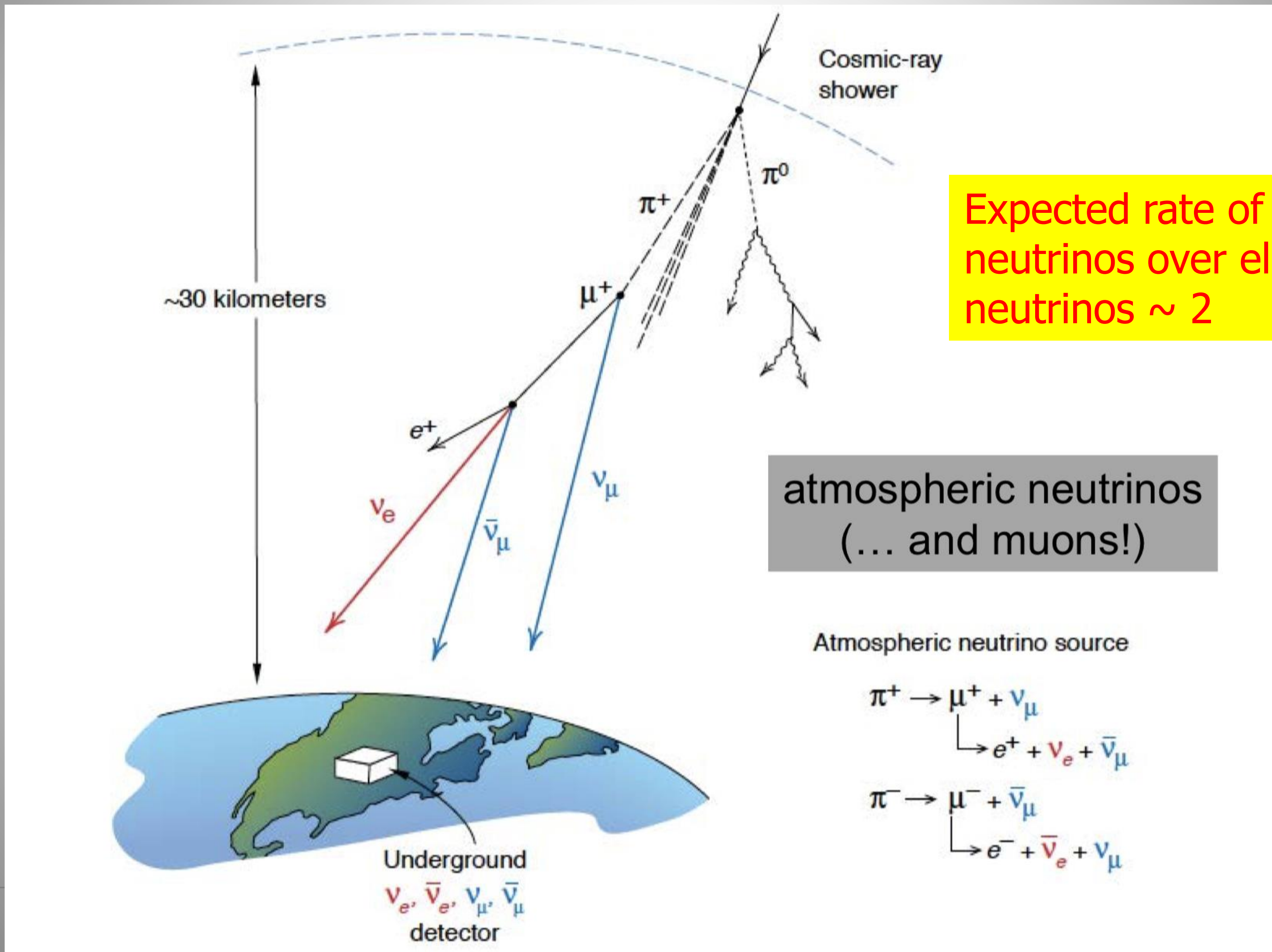


1987: A supernova, a dying star, exploded in the Large Magellanic Cloud. Most of the energy is released as neutrinos. The Kamiokande and IMB experiments –both large experiments conceived to detect proton decays– saw a dozen of neutrino events during the burst of O(10) seconds.
The neutrinos arrive at the earth before the light does (and could trigger an SN observation)

1987: Kamiokande (Japan) and IMB (US) detect atmospheric neutrinos. Echoing the solar neutrino problem: the experiment found a smaller ratio of muon neutrinos to electron neutrinos than expected. This became the atmospheric neutrino anomaly



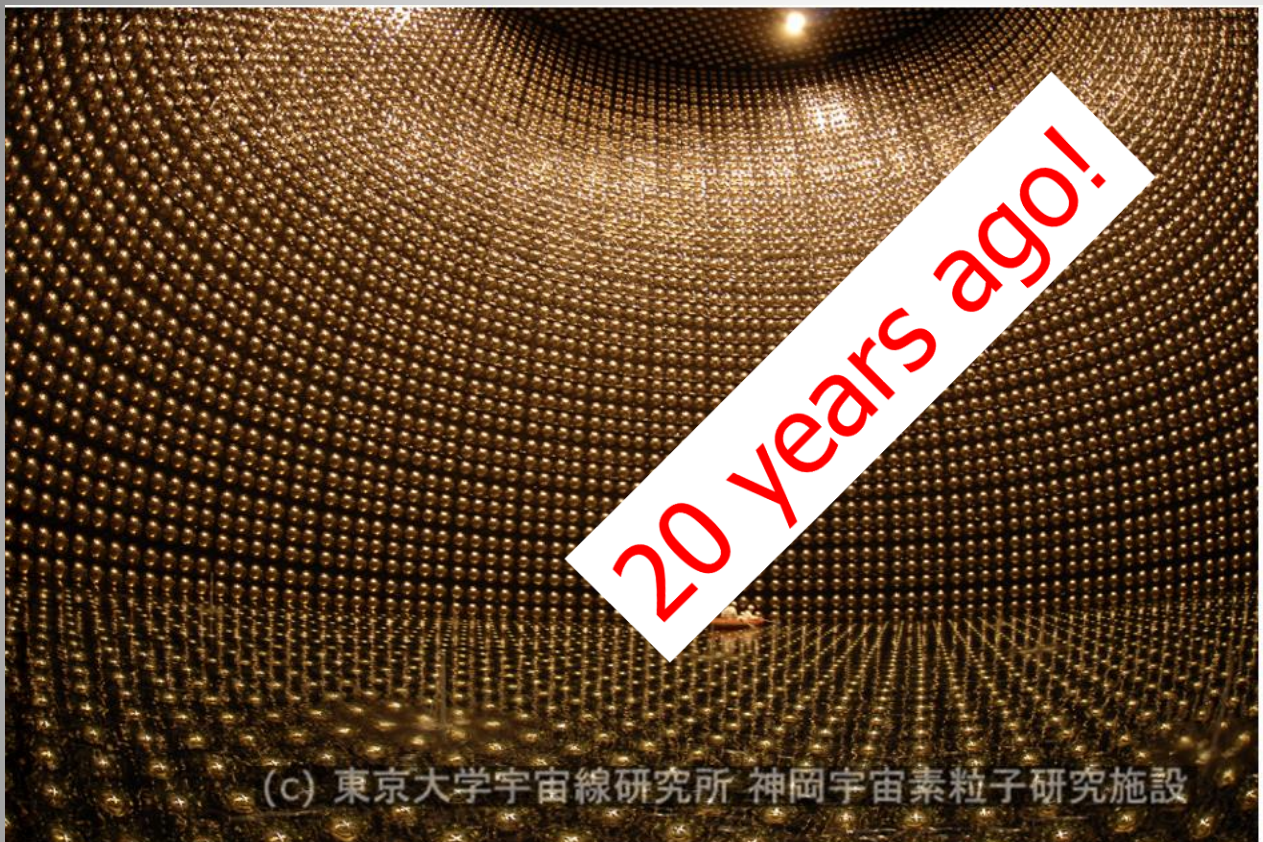
Atmospheric Neutrinos

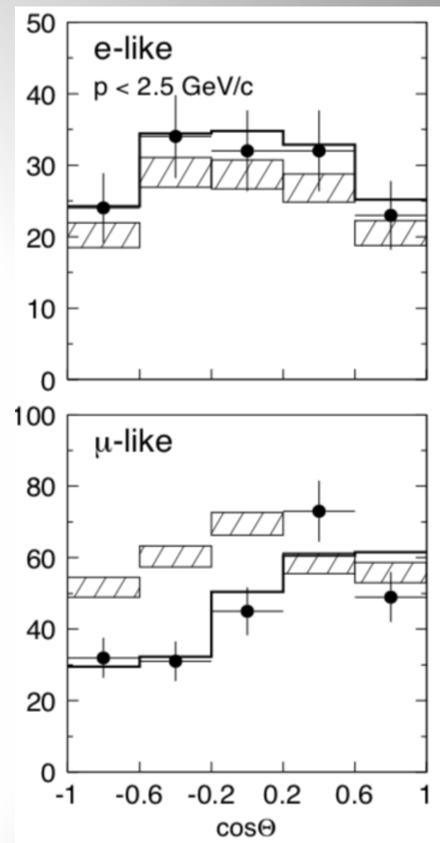


Expected rate of muon neutrinos over electron neutrinos ~ 2

atmospheric neutrinos
(… and muons!)

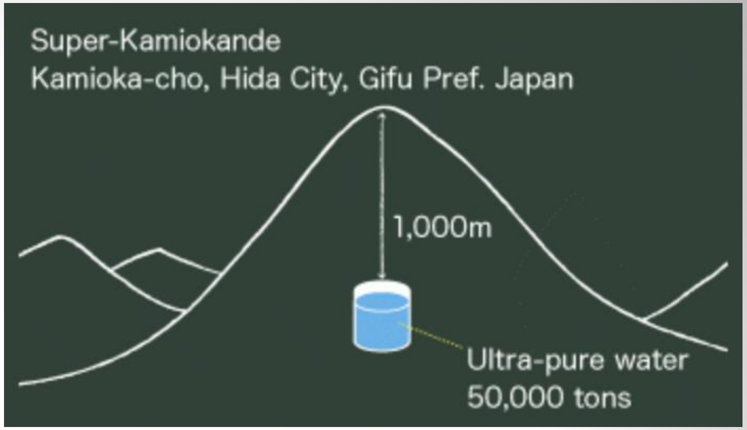
Neutrinos in the 1990s

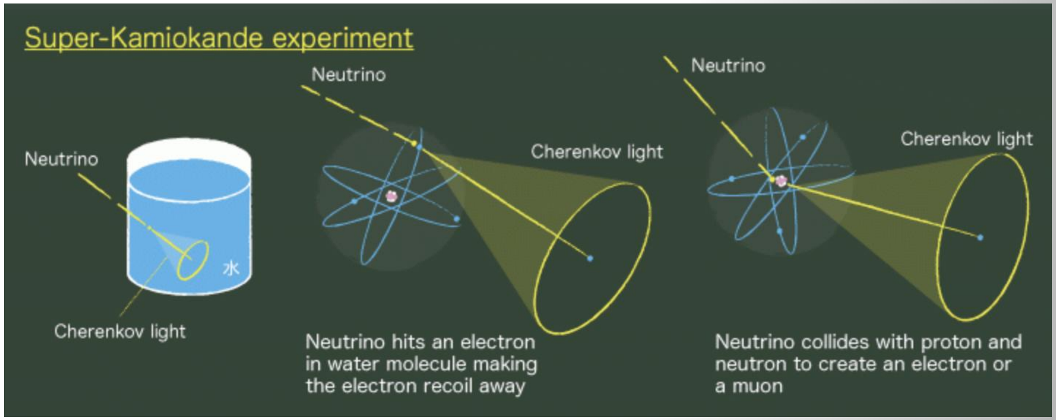




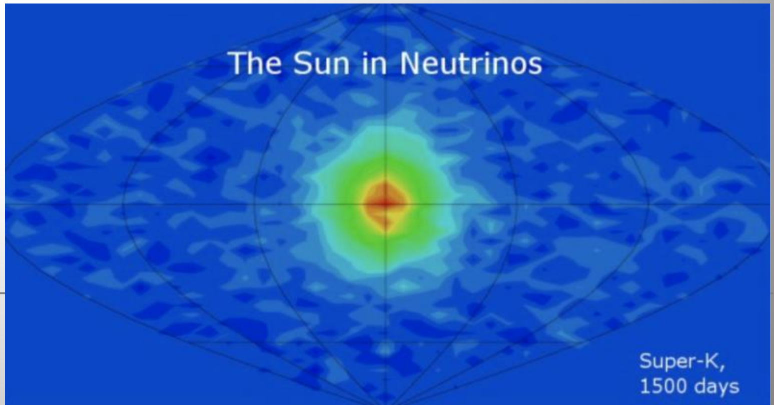
1998: The Super-Kamiokande experiment in Japan (10 x Kamiokande) used a massive underground detector filled with ultrapure water.
They announced first evidence of neutrino oscillations which must mean that at least some of the flavors have non-zero mass. The experiment showed that muon neutrinos disappear as they travel through the earth to the detector

SuperKamiokande

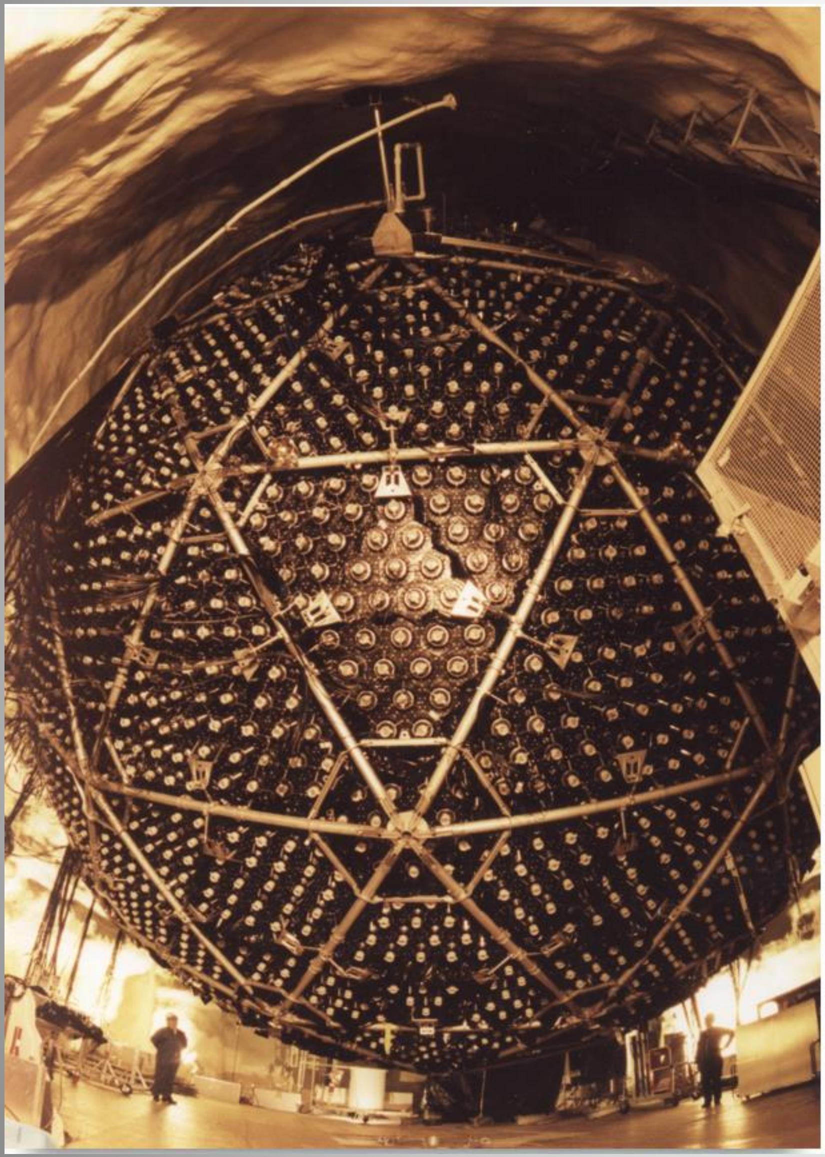




50,000 tons of ultra-pure water, watched by 13,000 photomultipliers



Neutrinos in 2000+

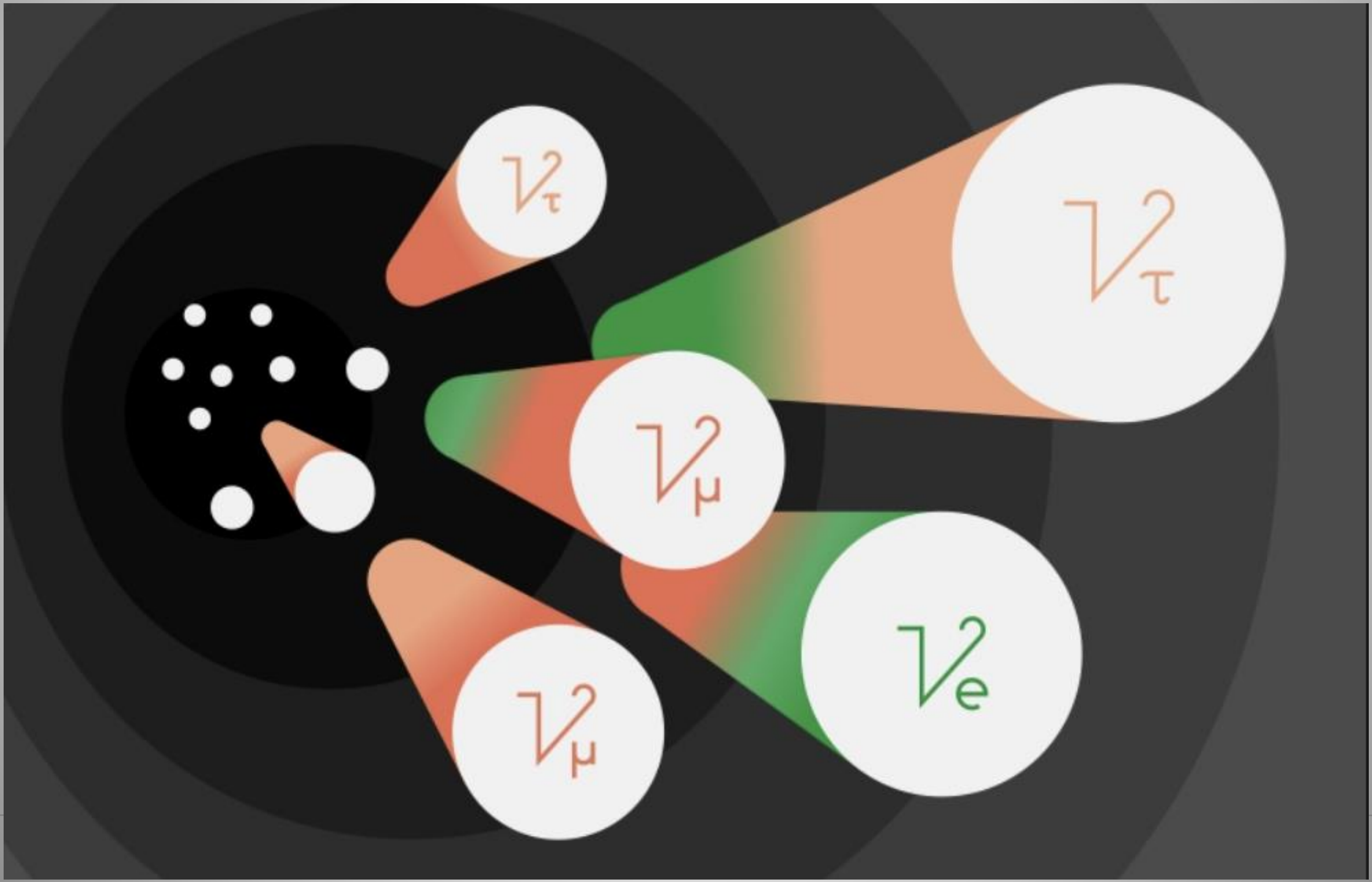


2002: The Sudbury Neutrino Observatory (SNO) used heavy water in a detector deep underground in Canada, announced conclusive evidence on solar neutrino oscillations. This was the final answer to Ray Davis' solar neutrino problem: Neutrinos from the sun transformed from the electron variety onto other flavors as they travelled to earth

1000 tons of heavy water in a 6m radius vessel, viewed by 9600 photomultiplier tubes

Neutrinos Oscillations!

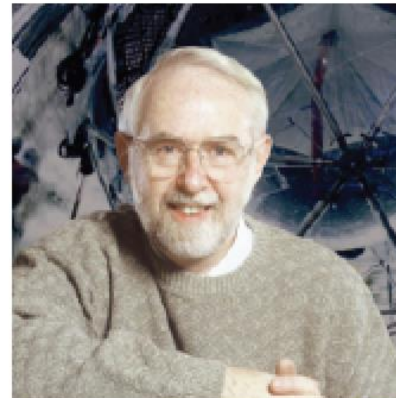
Atmospheric and solar neutrinos oscillate!!

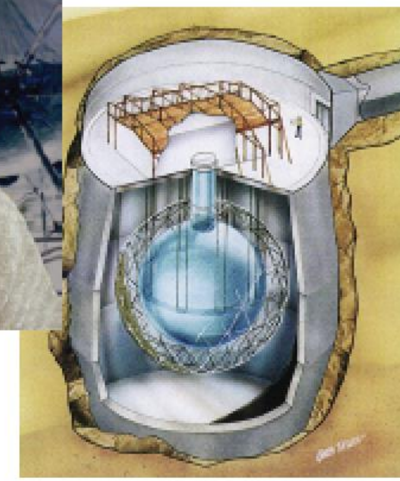


NOBEL 2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Takaaki Kajita
SuperKamiokaNDE





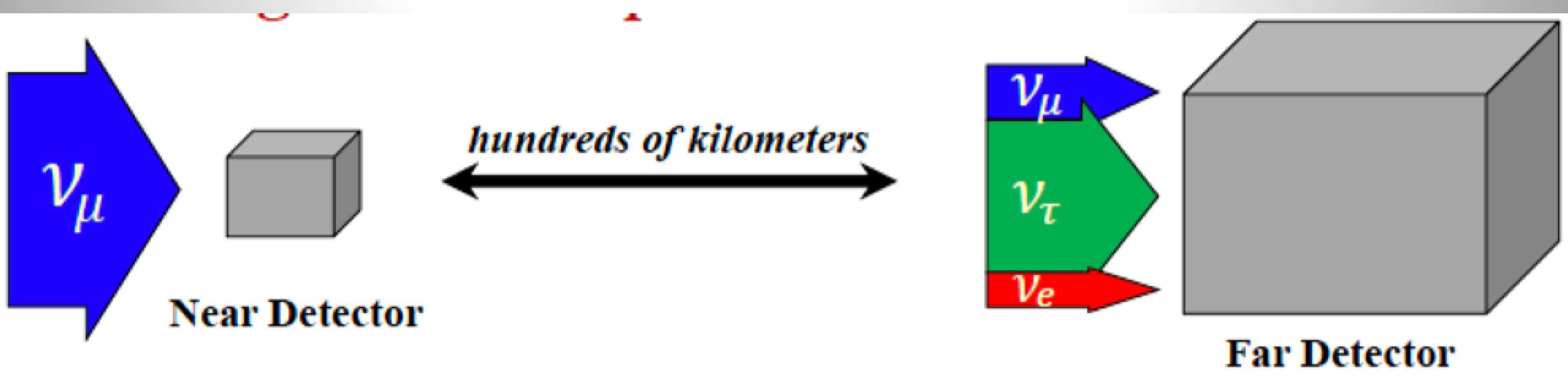
Art McDonald
SNO

"for the discovery of neutrino flavor transformations, which shows that neutrinos have mass"

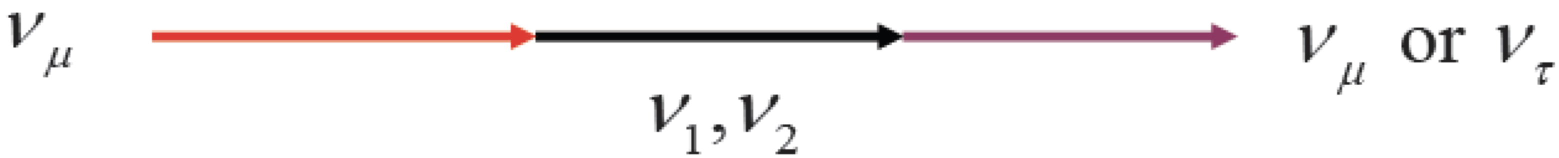
3 More Nobel prizes for Neutrinos since 1988
-1988: R. Davis and M. Koshiba
-1995: F. Reines
-1988: L. Lederman, M. Schwartz and J. Steinberger

Neutrino Oscillations

- Important discovery in 1998: neutrino oscillations
- 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. The probability of measuring a particular flavour for a neutrino varies between 3 known states as it propagates through space
- Neutrino oscillations only possible if neutrinos have a non-zero mass

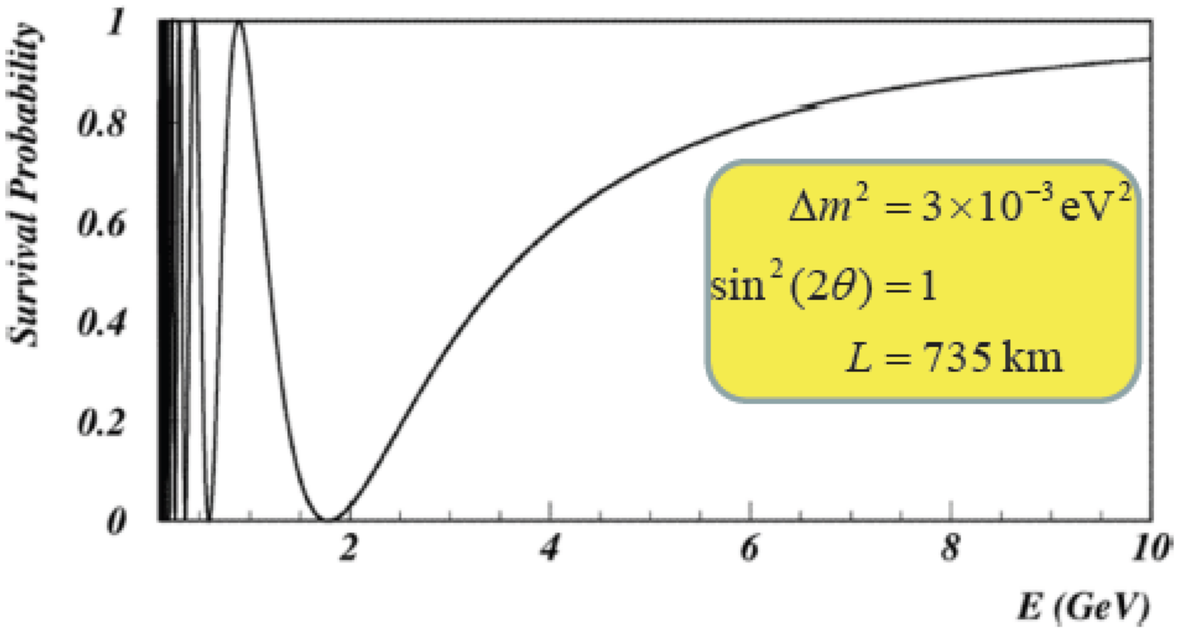


Neutrino Oscillations



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



Neutrino Oscillations

Pontecorvo-Maki-Nakagawa-Sakata Matrix (analogous to the CKM)

unitary matrix

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

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\ U_{13}(\theta_{13}, \delta)\ U_{12}(\theta_{12}, 0)$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{+i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$ $\quad \times\ \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

In total 6 parameters to determine

- -3 angles
- -2 mass differences
- -1 CP violation phase

Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}} \approx \sin^2 2\theta_{ij} \sin^2(\frac{\Delta m^2_{ij} L}{4E})$$

Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

ν_μ disappearance

Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

ν–less double beta decay

Neutrino Oscillations

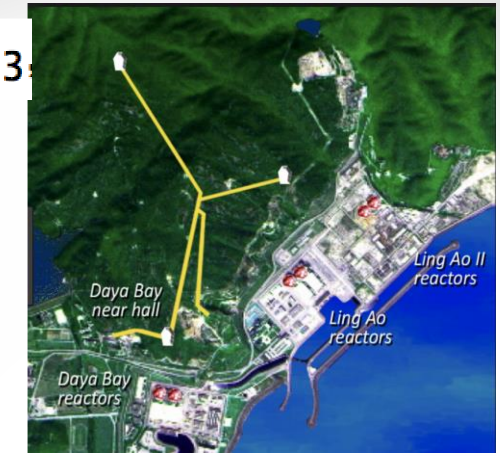
- Since 20 years an active field of study and data from many experiments collected:
  - Long baseline accelerator experiments (LBL)
  - Short baseline reactor experiments
  - Atmospheric neutrinos
  - Solar Neutrinos
  - Neutrinoless double beta decay experiments

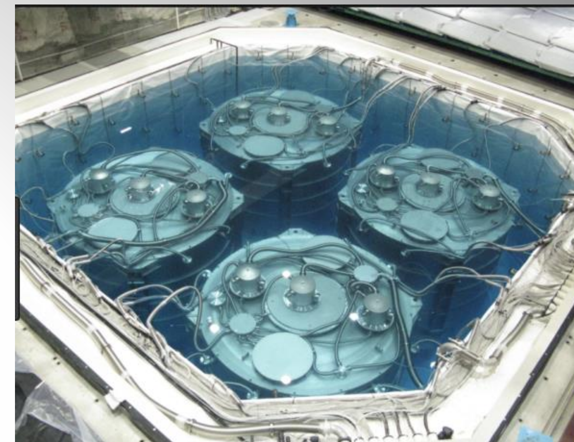
LBL experiments in the US and Japan

Short Baseline Experiments

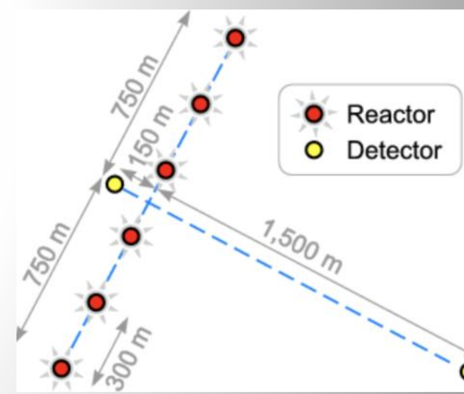
Measuring the mixing angle θ_{13}

Daya Bay (China)
Eight anti-neutrino detectors
(liquid scintillator based)
within 2 km of 6 reactors

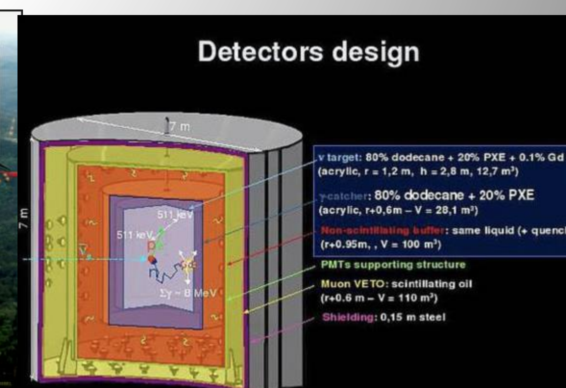




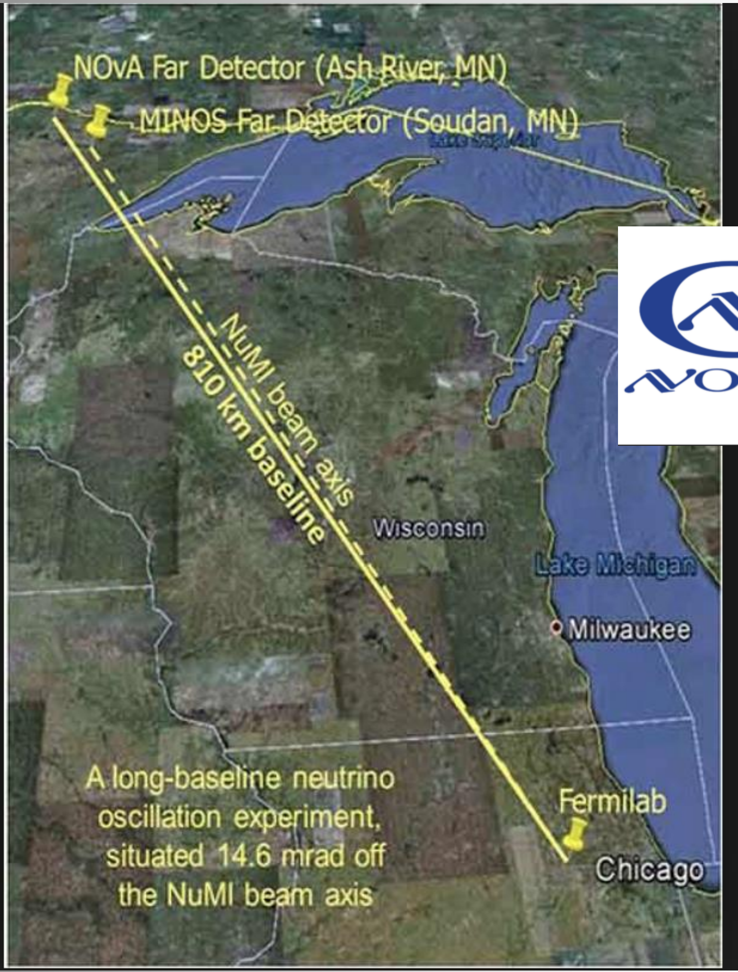
RENO (South Korea)
Two anti-neutrino detectors
(liquid scintillator based)
~up to 1.5 km of 6 reactors

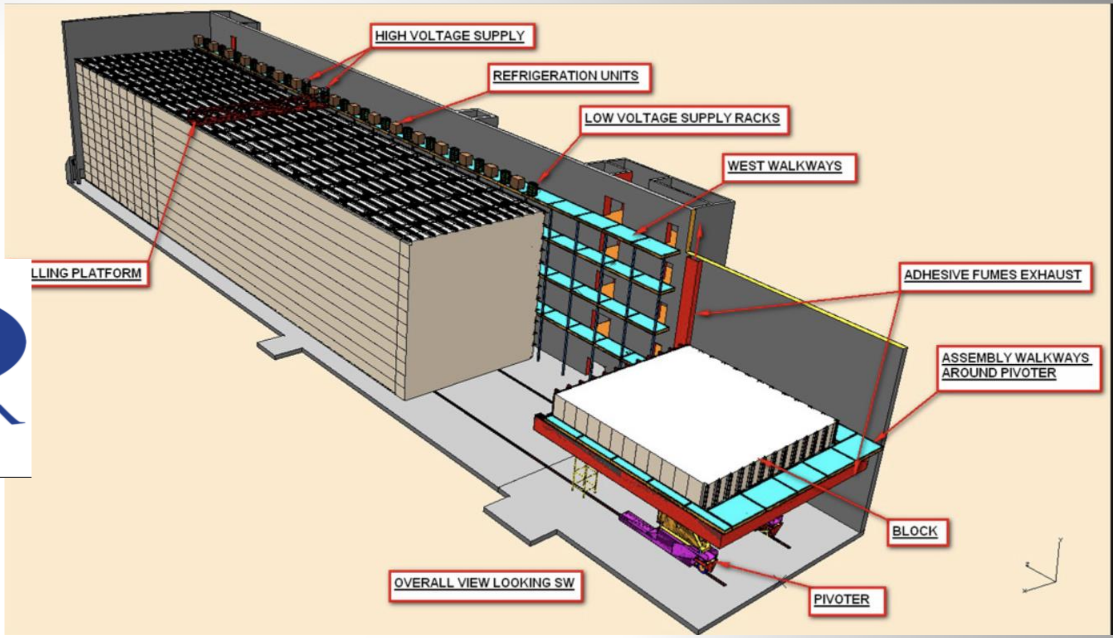


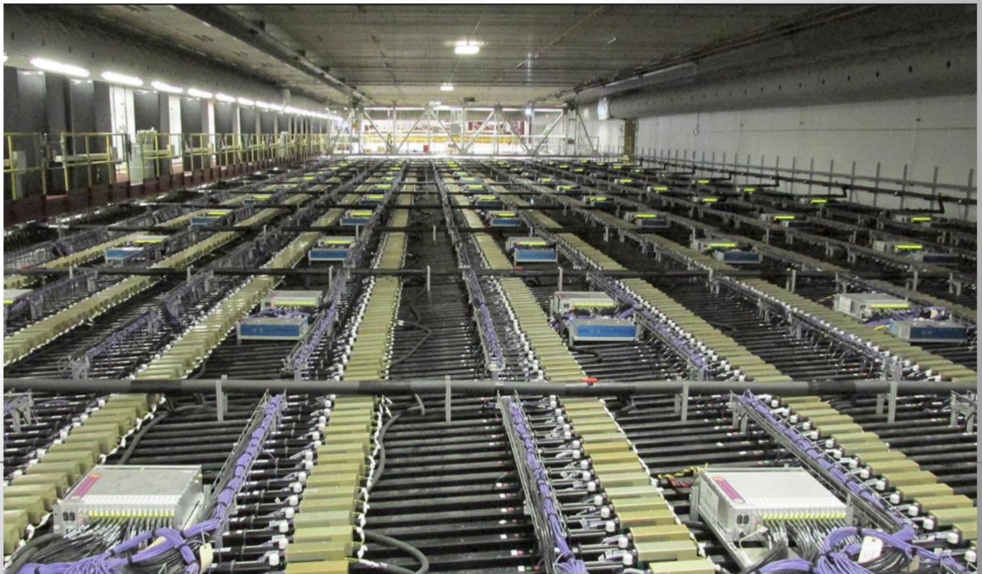
Double Chooz (France)
Two anti-neutrino detectors
(liquid scintillator based)
within 0.4-1 km of the reactors



The NOVA LBL Experiment







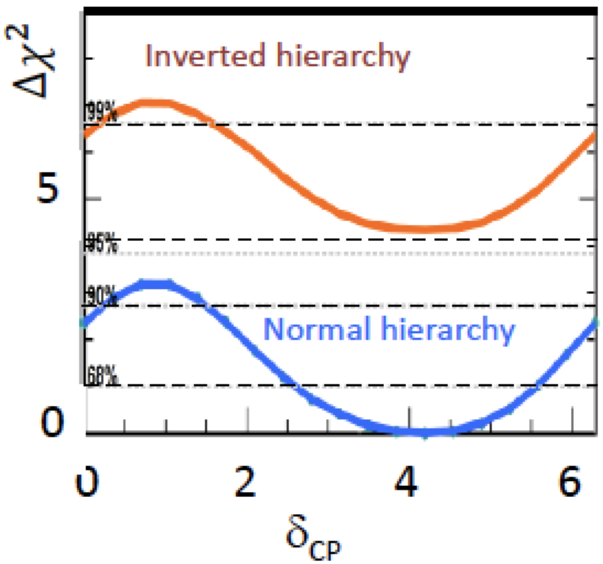
The T2K LBL Experiment

- Neutrino Beam from j-parc
  - Beam power 50 – 450 kW
- Far Detector
  - SuperKamiokande
  - 40 kton water Cherenkov

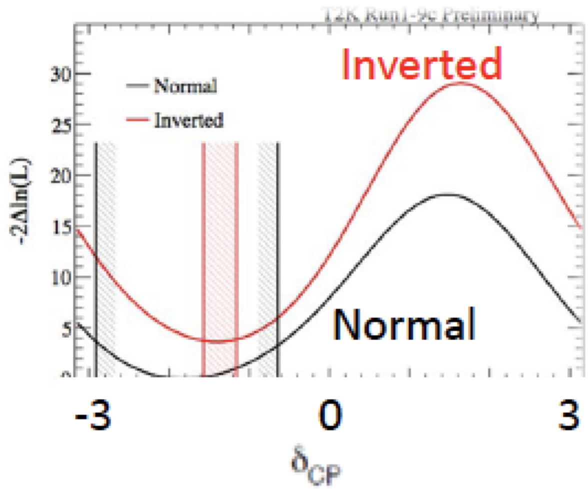
Neutrino Oscillations

Most recent results present at the Neutrino2018 conference in Heidelberg June 2018

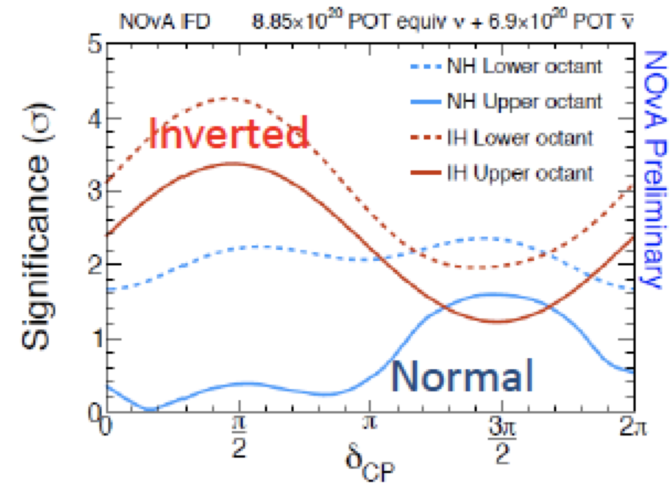
Super-K *atmospheric (Y. Hayato)*



T2K *(M. Wascko)*



NOvA *(M. Sanchez)*



Summary report of T. Kajita

Already some interesting indications:

➔ ***NO favored by these 3 experiments at ~(1 ~ 2) sigma level each.***

➔ ***These experiments give some favored δ_{CP} region(s).***

Neutrino Oscillations

Results from the measurement : global fits

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{\rm CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

http://www.nu-fit.org/?q=node/12

Neutrinos Have Mass

Neutrinos have mass

But they are very light! See-saw mechanism? – Heavy (possibly GUT-scale) RH neutrinos alongside light LH neutrinos:

$$m_\nu \sim \frac{m_{\rm EW}^2}{m_{\rm GUT}} \sim \frac{(10^2\ \text{GeV})^2}{10^{15}\ \text{GeV}}$$

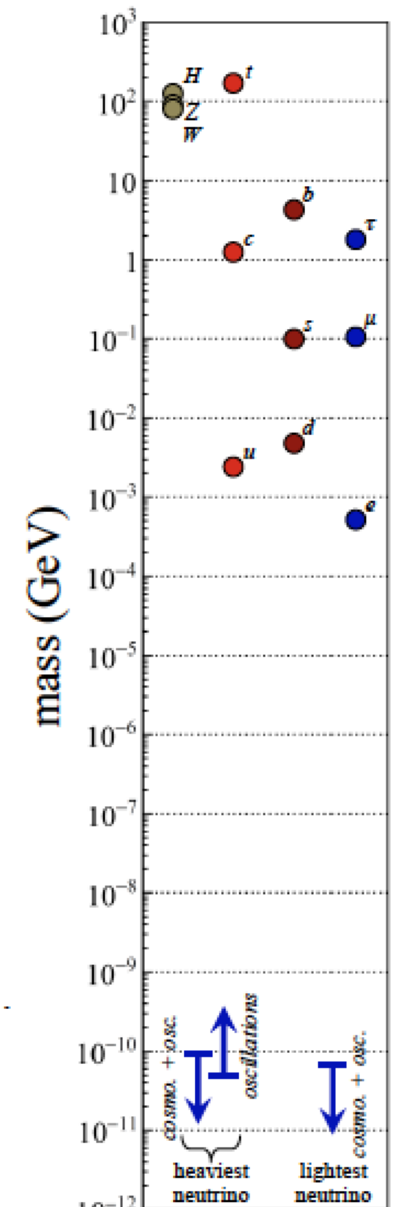
$$\sim 10^{-11}\ \text{GeV}$$

- Would imply that the **physics of neutrino mass** is connected to **extremely high energy scales** (or at least new physics of some kind).

Potential new physics signatures in oscillation expts:

non-unitarity, non-standard interactions, >3 neutrinos, large extra dimensions, effective CPTv, decoherence, neutrino decay, ...

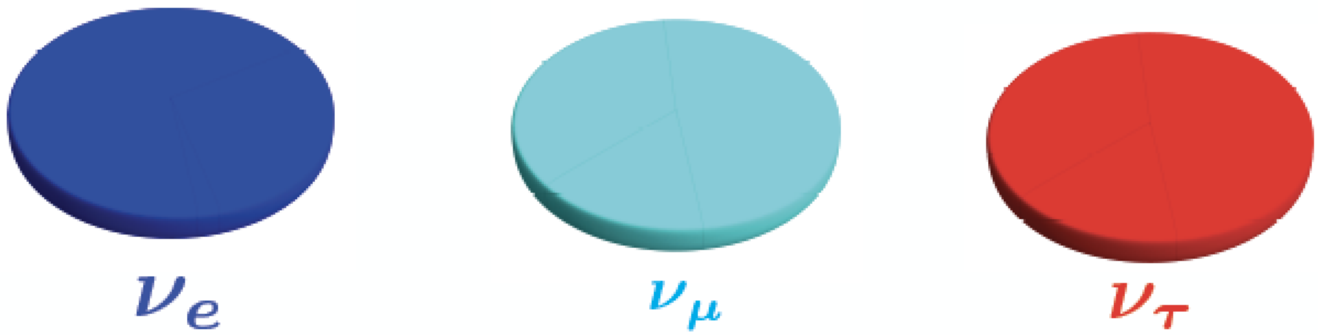
Now textbook material, the see-saw mechanism goes back to P. Minkowski (1977); M. Gell-Mann, P. Ramond and R. Slansky (1979); and T. Yanagida (1979)



Neutrino Oscillations

Neutrino Flavor or Interaction States:

$W^+ \to e^+ \nu_e$ $\quad$ $W^+ \to \mu^+ \nu_\mu$ $\quad$ $W^+ \to \tau^+ \nu_\tau$



provided $\boldsymbol{L/E} \ll \mathbf{0.5}\ \mathrm{km/MeV} = \mathbf{500}\ \mathrm{km/GeV}$!!!

$\sim$ 1 picosecond in Neutrino rest frame !!!

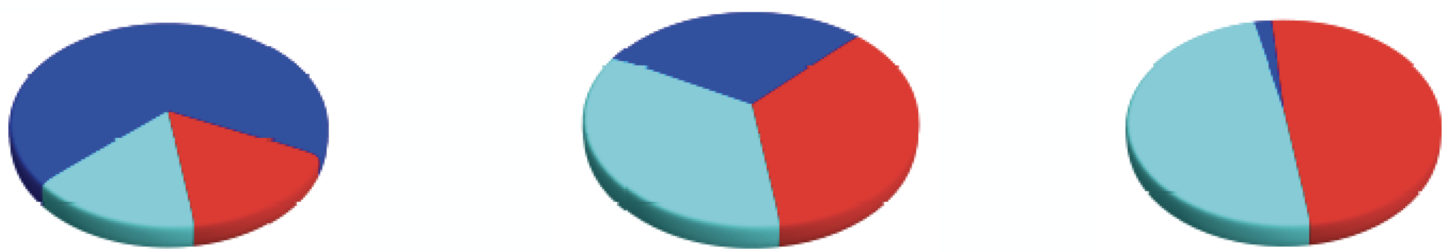
1 picosecond= 10^{-12} seconds

Neutrino Oscillations

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \to \nu_k = \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

ν_1 most ν_e | ν_2 | ν_3 least ν_e



$\nu_e =$

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

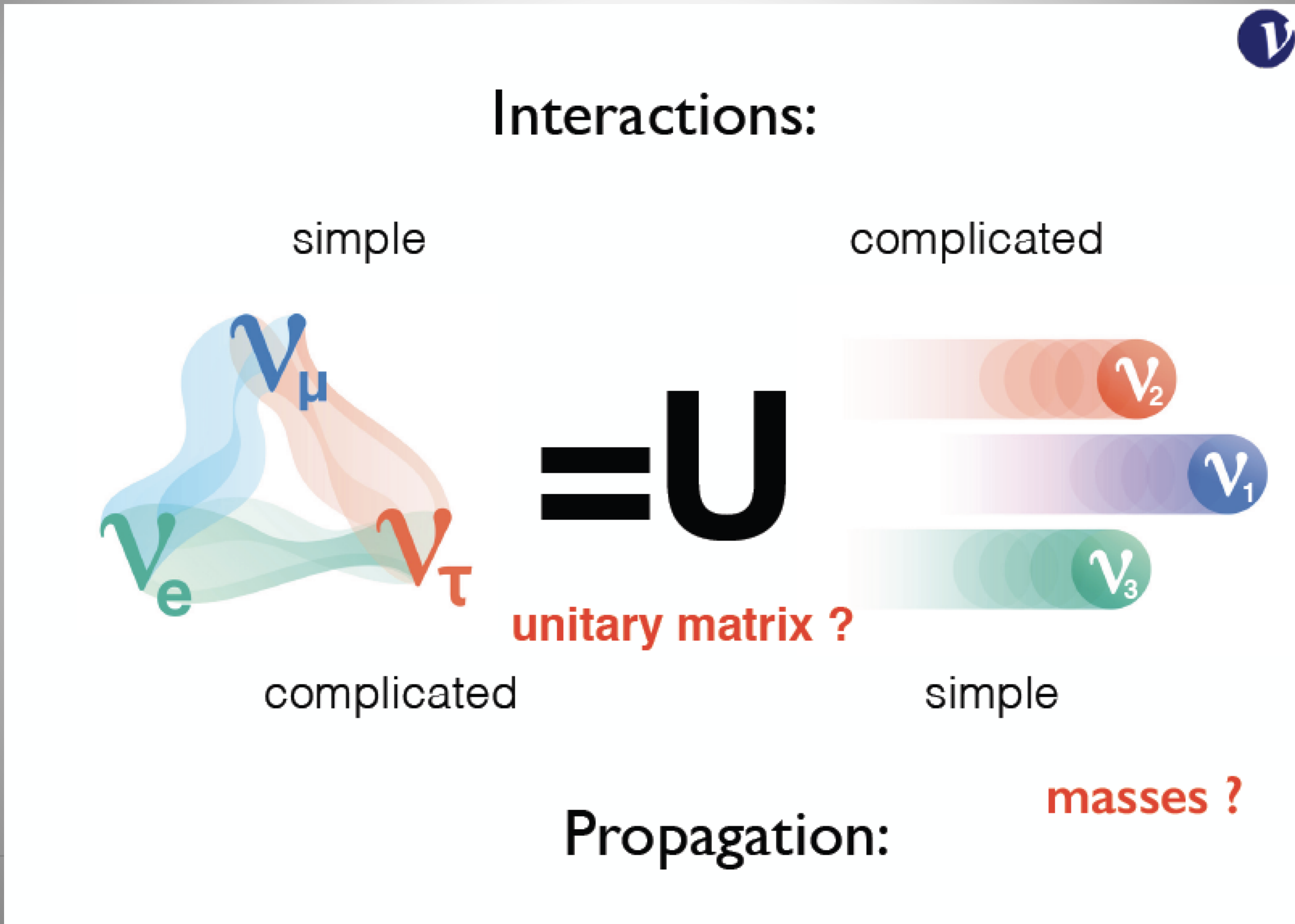
$\nu_\mu =$

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$

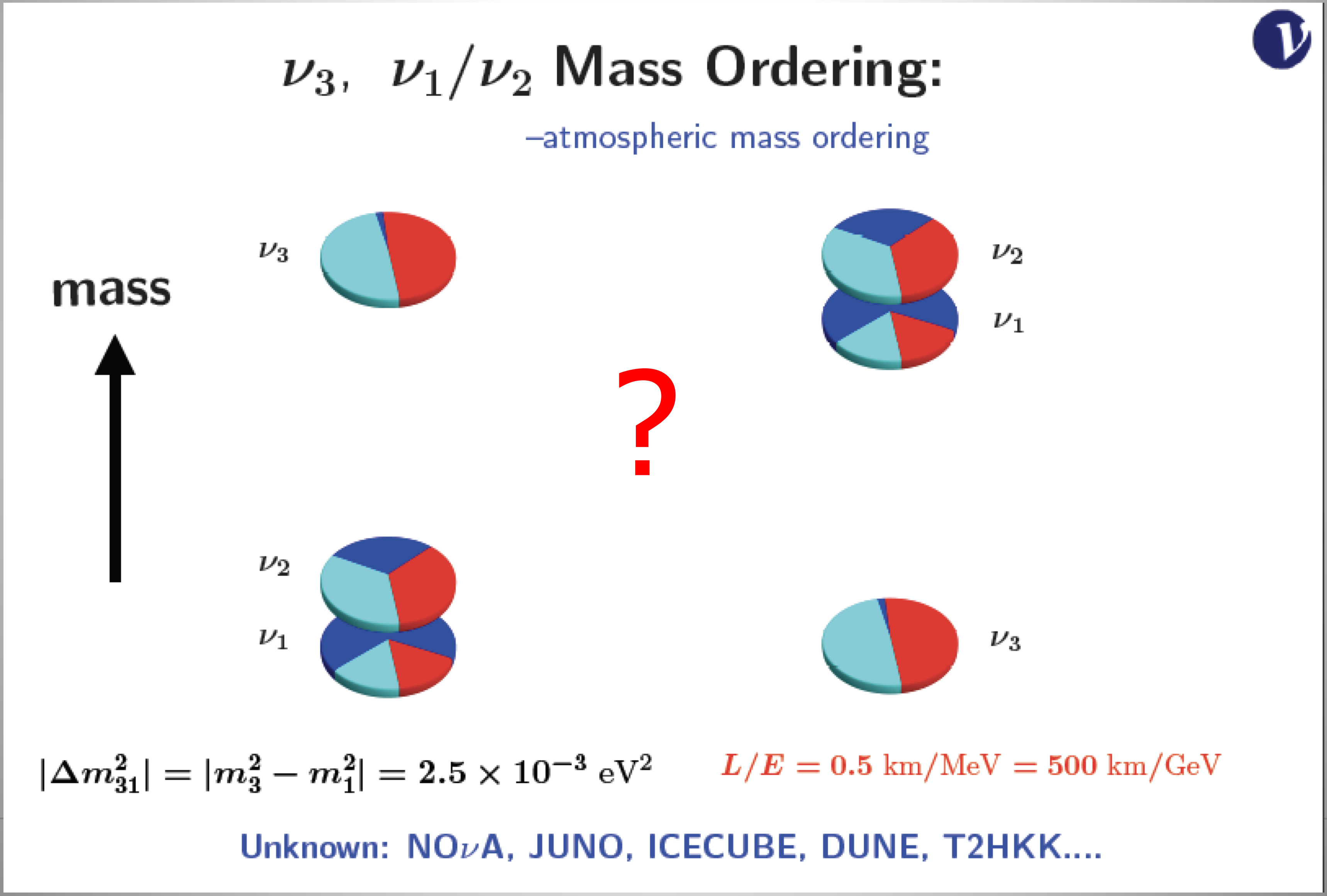
Unitarity
SK, Opera
ICECUBE ?

Neutrino Oscillations



Open Questions: The Mass Ordering?

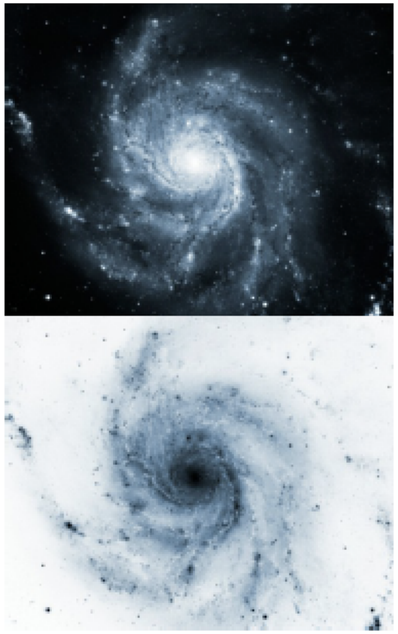
Presently we determine the absolute difference in mass, not the sign of it



Open Questions: CP Violation?

Do neutrinos and anti-neutrinos oscillate differently ?

CP violation



New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe

Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

Leptogenesis[1] is a workable solution for the baryon asymmetry, but need to first **find *any* leptonic (neutrino) *CP*v**

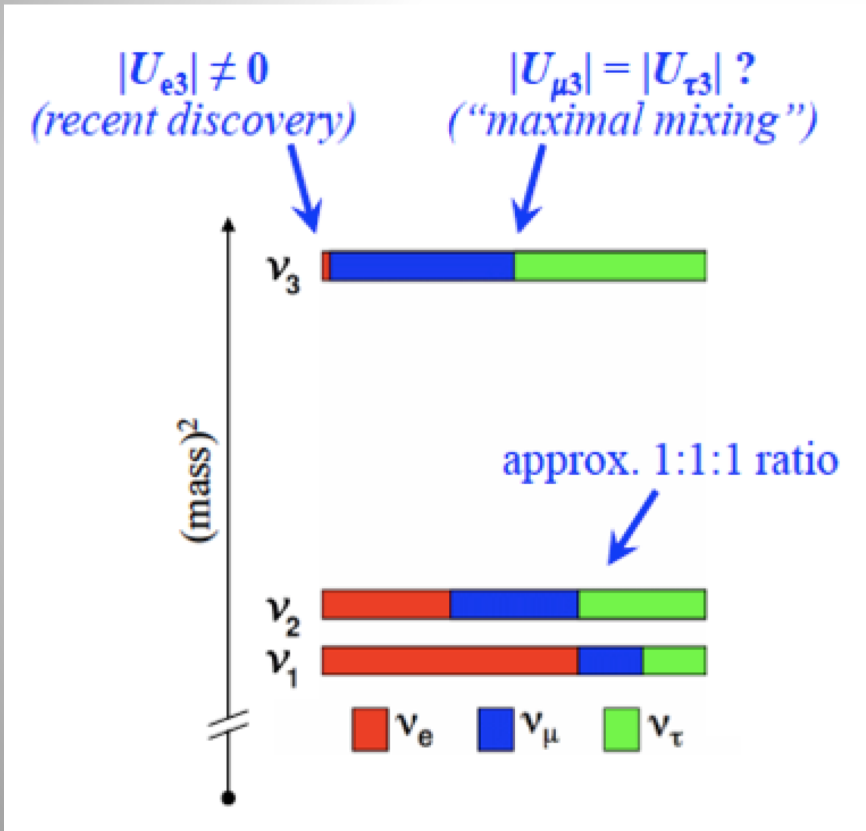
$\sin\delta \neq 0$?

Leptonic CP violation?

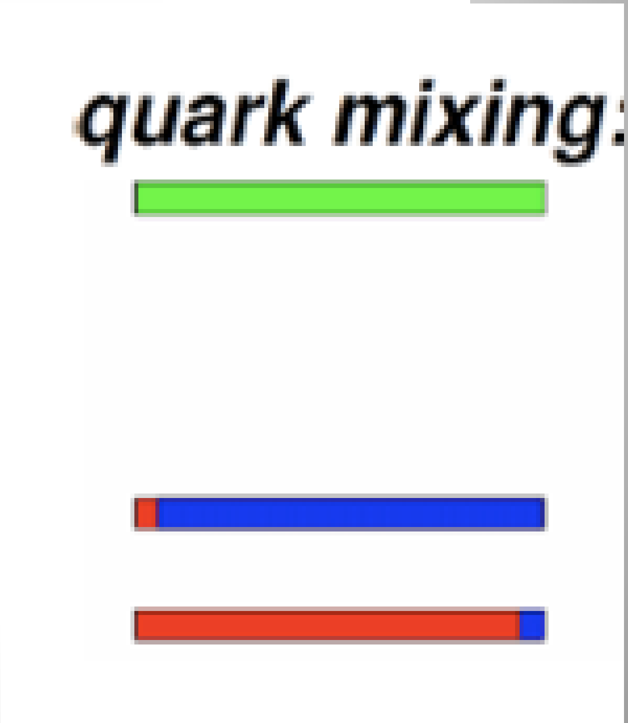
[1] M. Fukugita and T. Yanagida (1986); rich history since then.

Open Questions: Neutrino mixing

Why is Neutrino mixing so different from quark mixing?
What does that tell us?

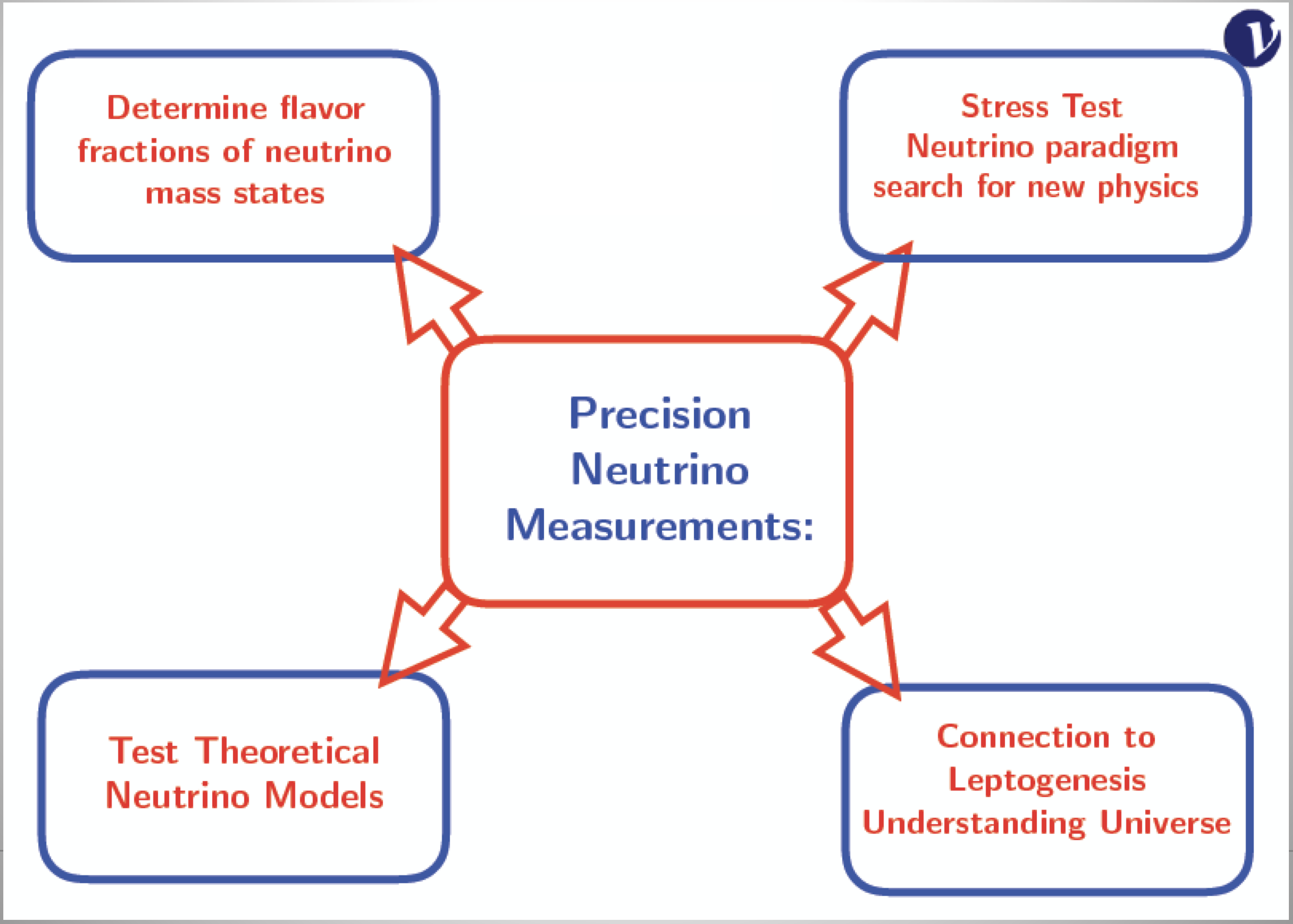


CKM Matrix



Precision Neutrino Physics

We are entering the era of precision neutrino physics !!

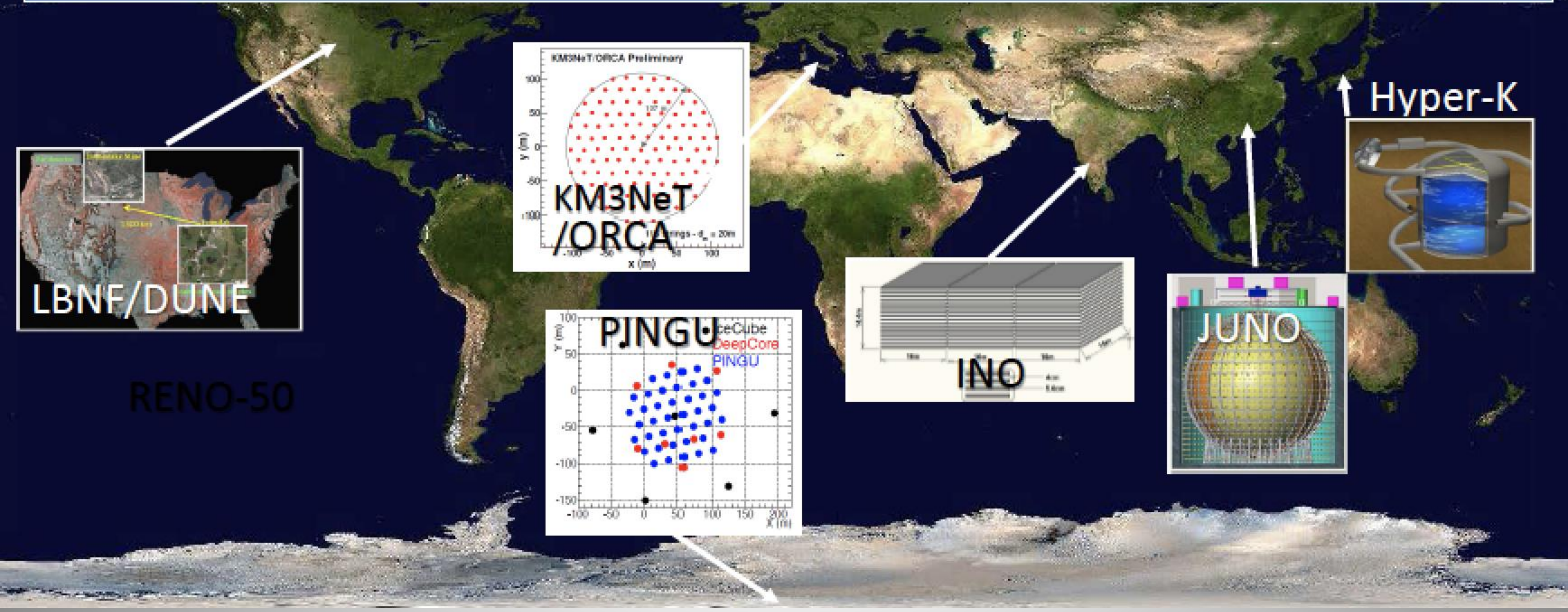


The Future

Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question

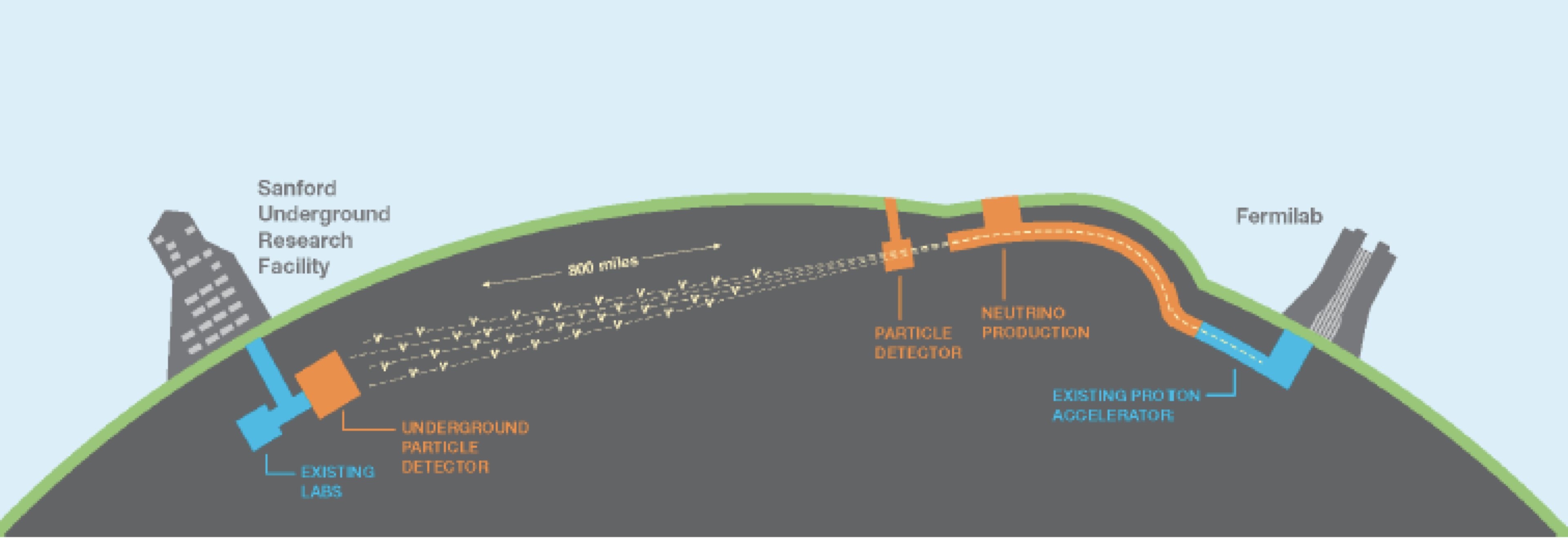
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



DUNE

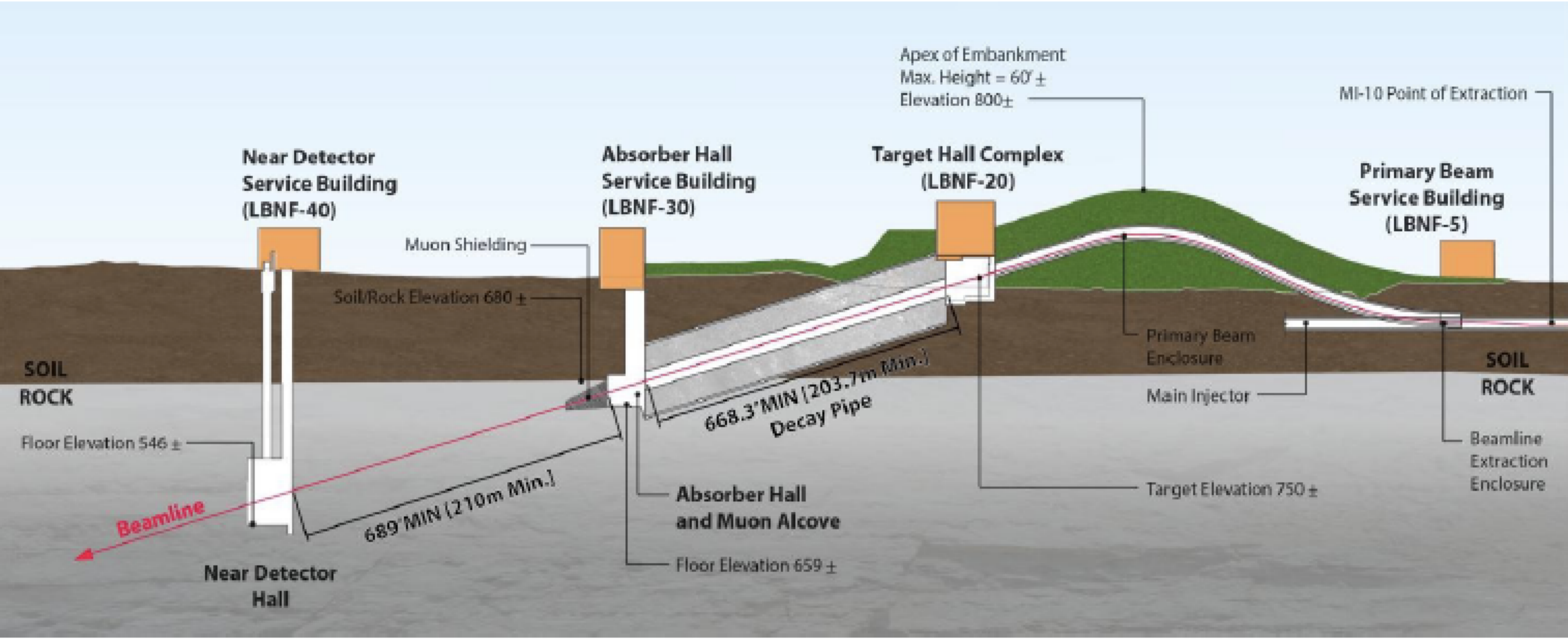
Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science**, **nucleon decay**, and **supernova physics**



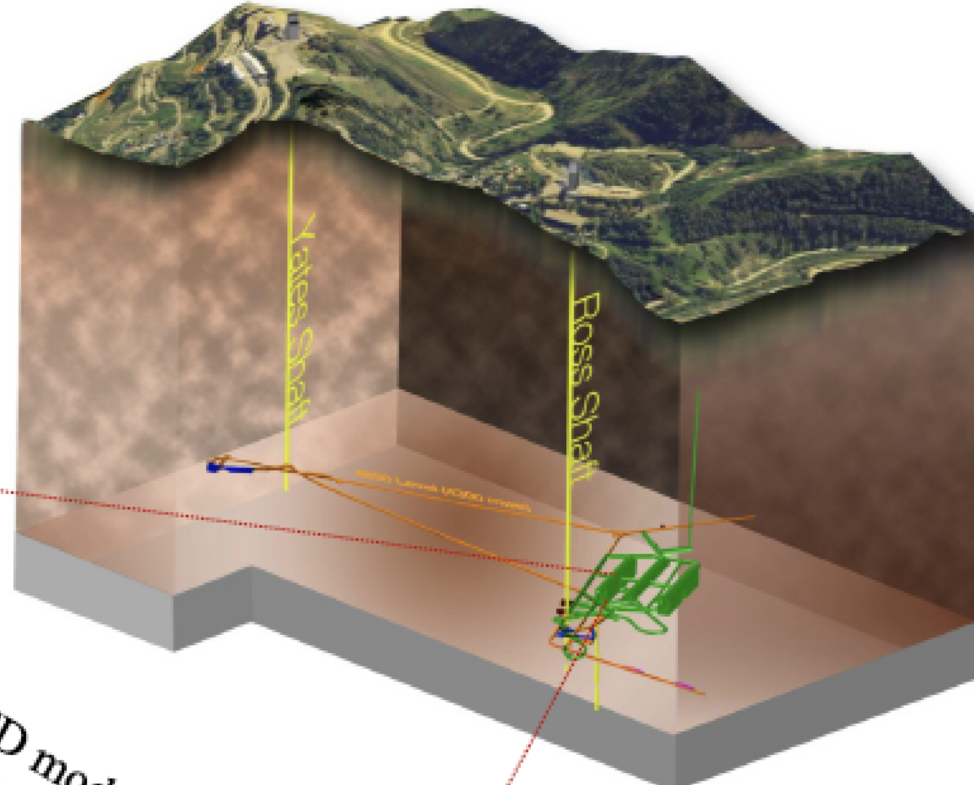
Long Baseline Neutrino Facility (LBNF)

- **DUNE:** The international scientific collaboration
- **LBNF:** DOE/Fermilab-hosted facilities project, with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.1 MW, upgradable to 2.4 MW

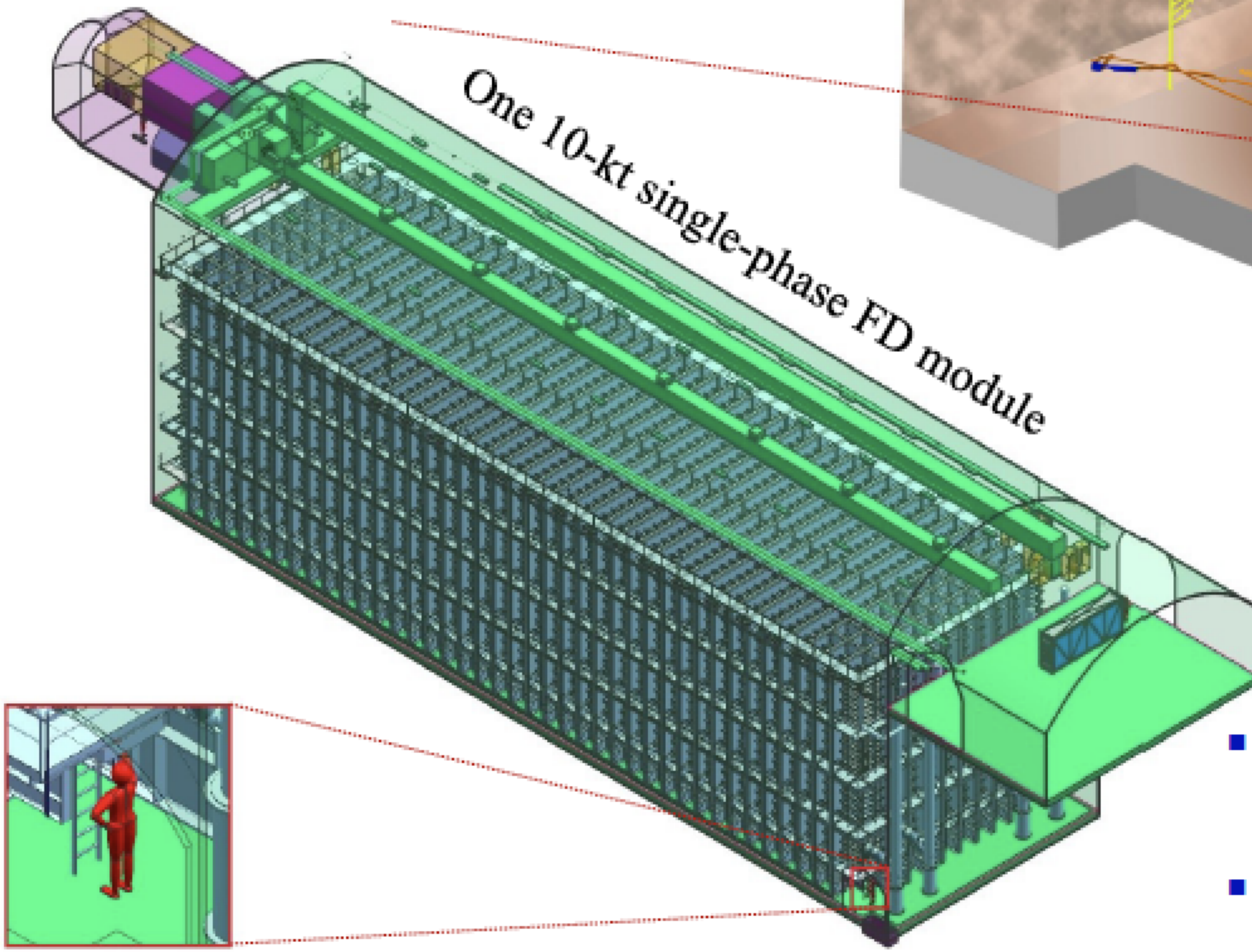


DUNE Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850' level of SURF



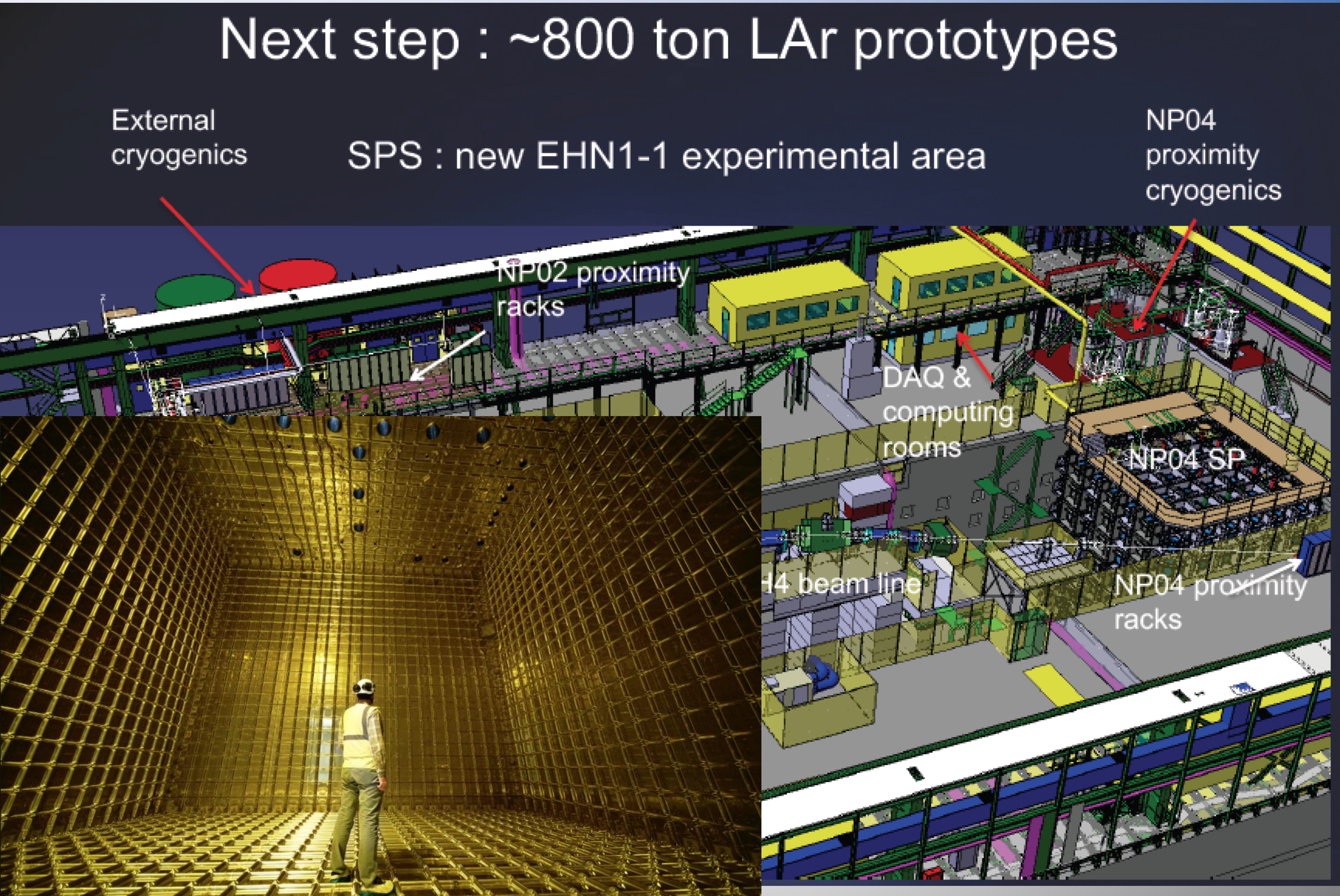
Sanford Underground Research Facility (SURF)



1.5 km underground

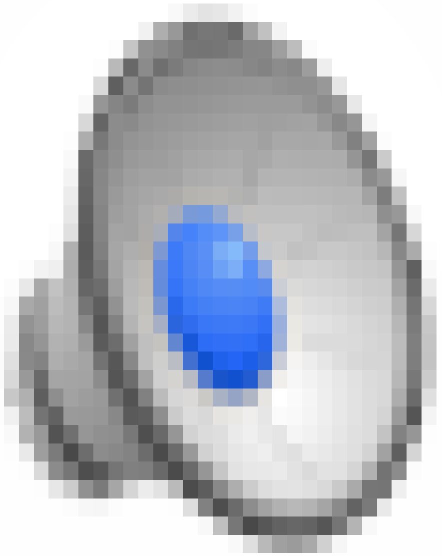
- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

The ProtoDUNEs at CERN



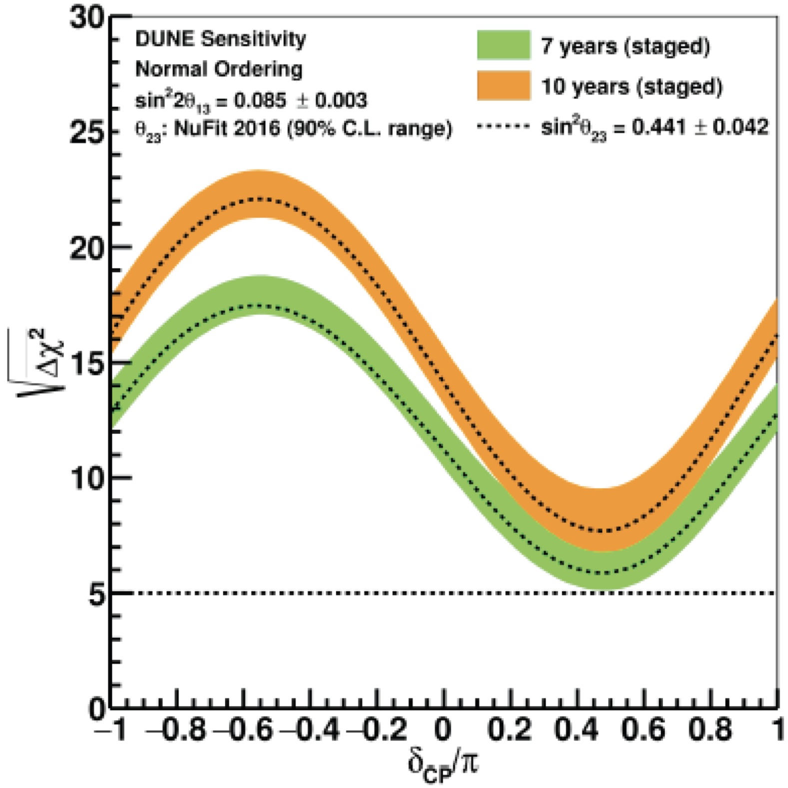
Liquid Argon Time Projection Chamber

The 'electronic' bubble chamber for neutrino experiments



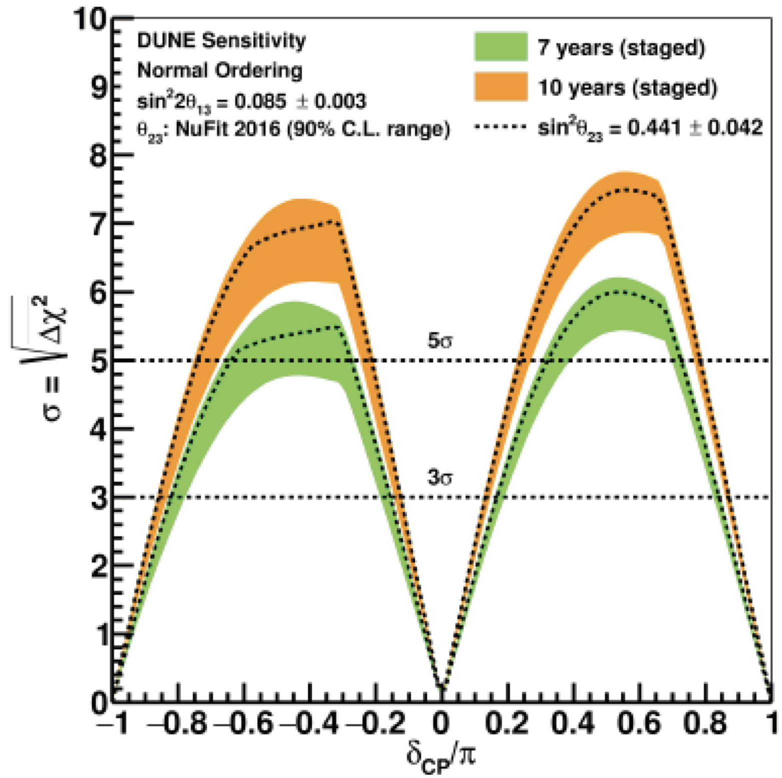
DUNE Prospects

Mass Ordering



Width of band indicates variation in possible central values of θ_{23}

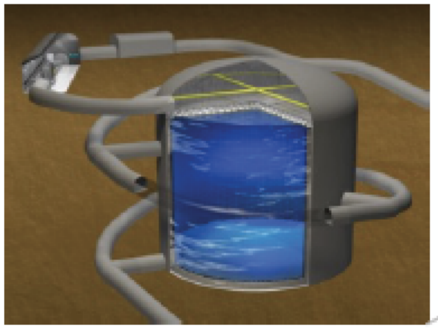
CP Violation



Width of band indicates variation in possible central values of θ_{23}

Also: Proton decay, Solar & atmospheric neutrinos, Supernova …

Hyper-Kamiokande



Hyper-K

J-PARC
Accelerator Complex

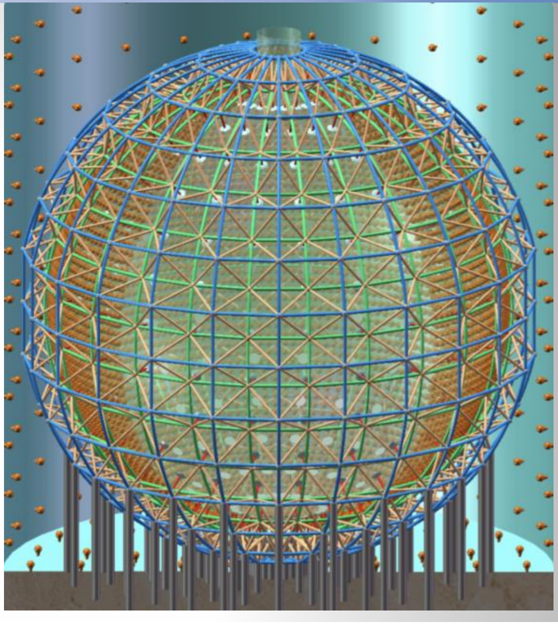
- ✓Gigantic neutrino and nucleon decay detector
  - ✓186 kton fiducial mass : ~10 × Super-K
  - ✓× 2 higher photon sensitivity than Super-K
  - ✓Superb detector capability, technology still evolving
  - ✓2nd oscillation maximum by 2nd tank in Korea under study
- ✓MW-class world-leading ν-beam by upgraded J-PARC
- ✓Project now is a priority project by MEXT's Roadmap
  - ✓Aiming to start construction in FY2019, operation in FY2026

Sub-GeV ν beam

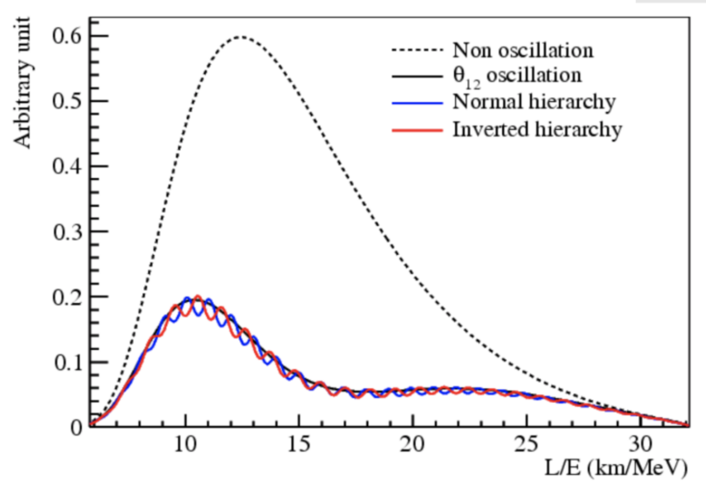
The JUNO Experiment

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose liquid scintillator detector (~20 times the size of present detectors, including 18000 20” PMTs) being built in a dedicated underground laboratory (700 m underground) in China and expected to start data taking in 2021.

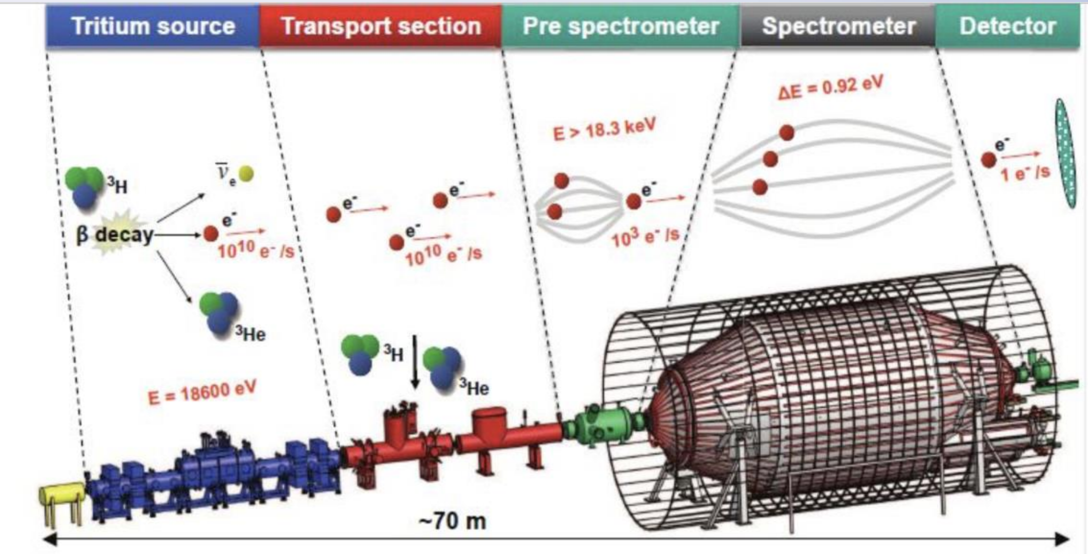
Its main physics goal is the determination of the neutrino mass ordering using electron anti-neutrinos from two nuclear power plants at a baseline of about 53 km. With an unprecedented energy resolution of 3% at 1 MeV, JUNO will be able to determine the mass ordering with a significance of 3-4 sigma within six years of running.



The JUNO Collaboration has ~several hundred physicists



Katrin Experiment: the Mass of ν_e



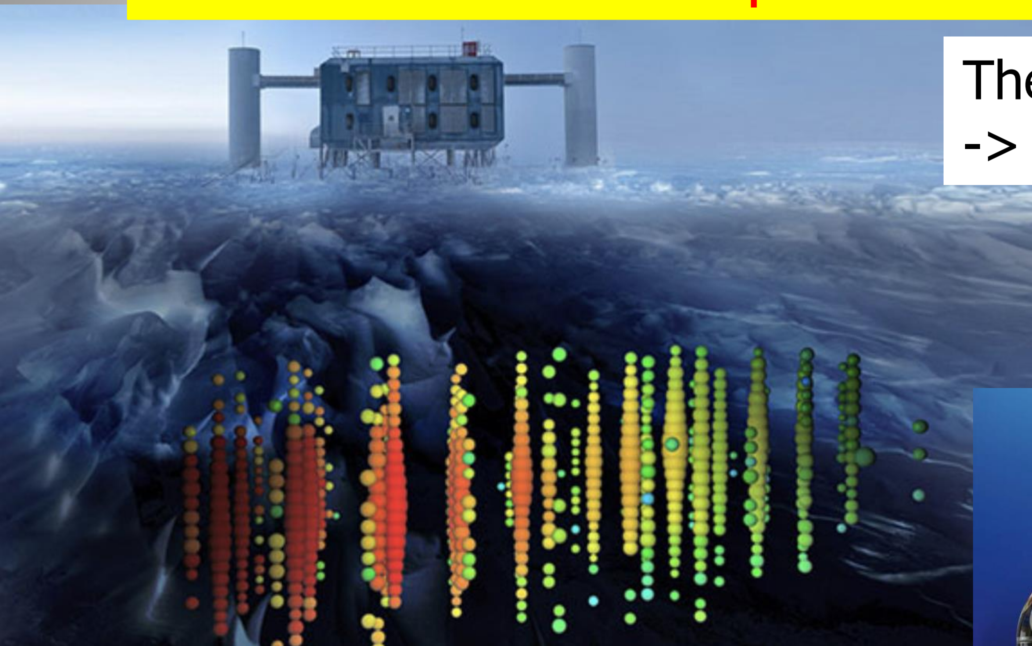
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to improve the current direct limit on this mass scale by an order of magnitude, with a projected sensitivity of 0.2eV To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum, using a high-intensity, windowless gaseous tritium source and a high-resolution electrostatic spectrometer.

Data taking starting in 2018

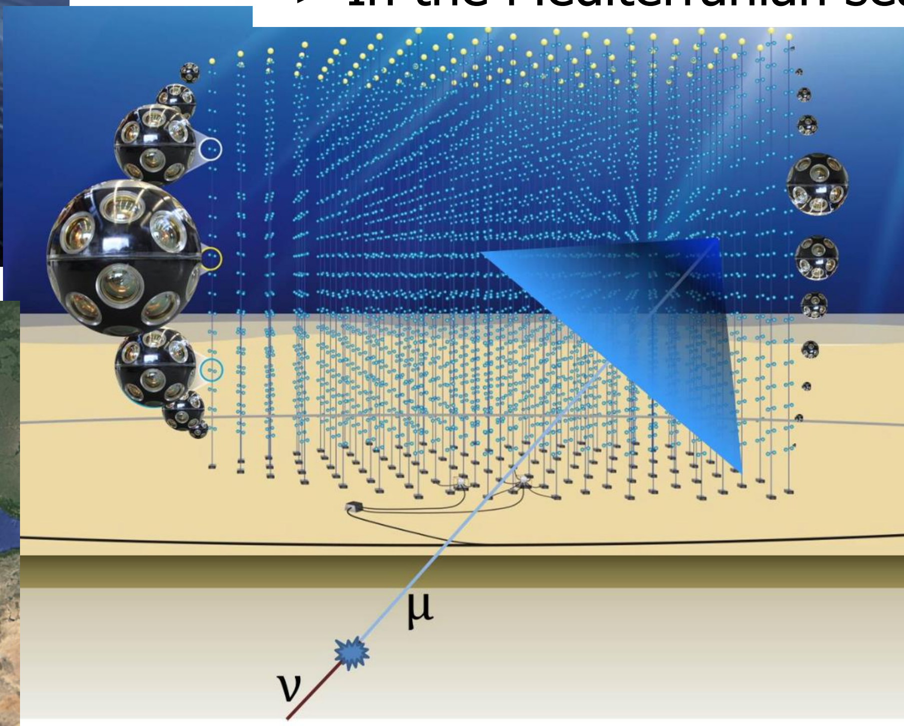
Neutrino Astronomy

Build Gigantic detectors 1 km^3 of size and beyond…
Use the resources of planet Earth

The IceCube Experiment
-> In the ice of Antartica



The KM3NET Experiment
-> In the Mediterranian sea

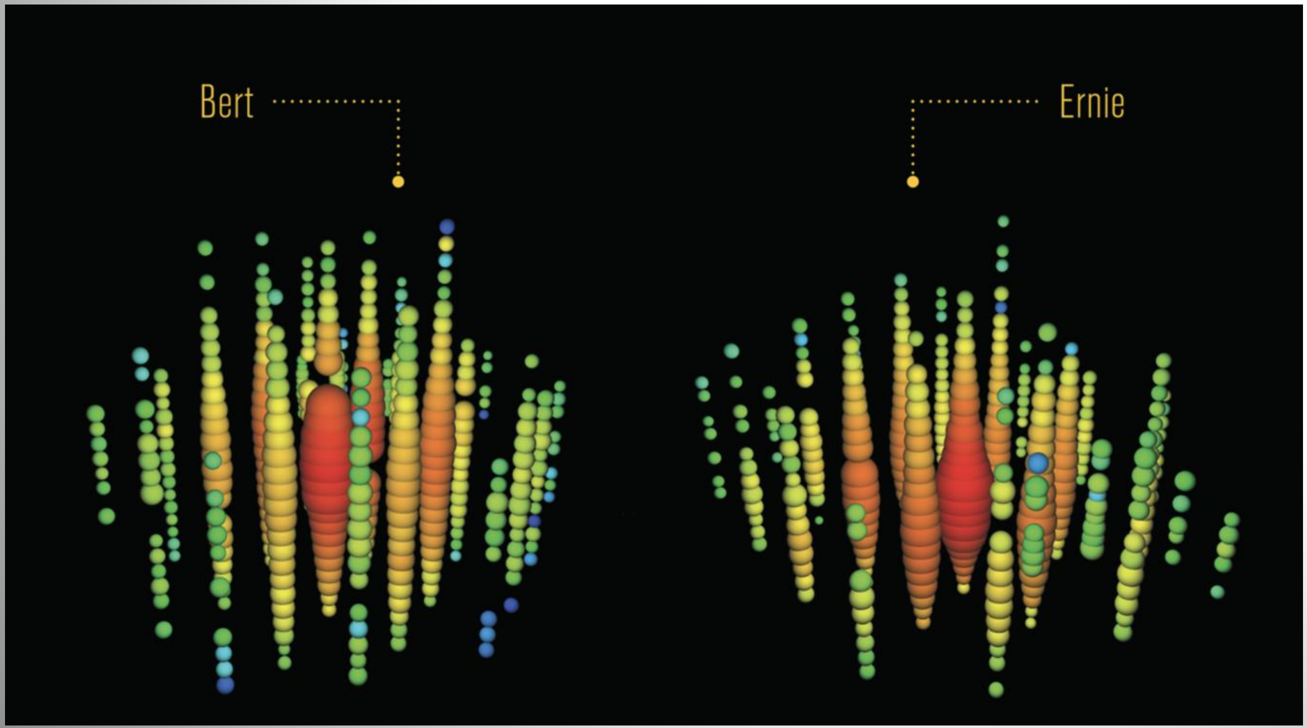


Neutrinos in the Ice

Most Energetic Neutrino Interactions

2012: Extra-galactic neutrinos with Energies around 1-2 PeV observed in the IceCube detector (1 PeV = 10^6 GeV)

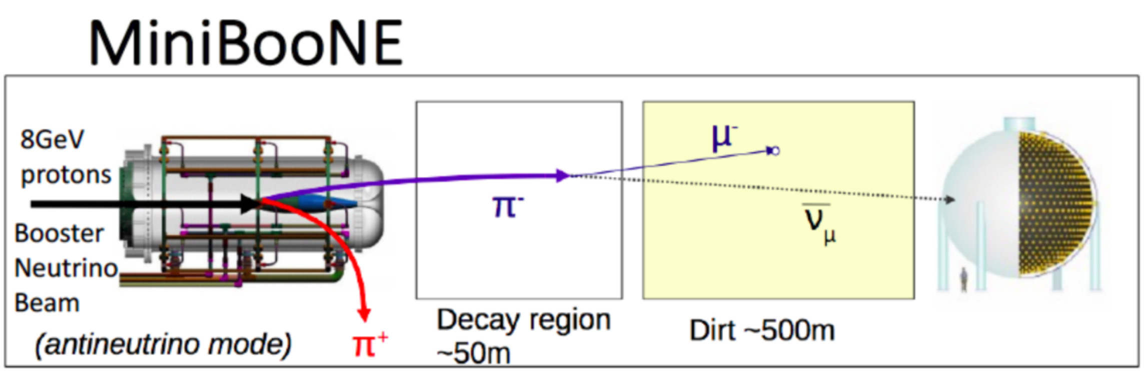
They were dubbed "Bert" and "Ernie



Are there more than 3 Neutrinos?

- Is there is a 4th (5th…) neutrino then it has to be quasi-sterile, ie should not couple significantly to other fermions and bosons, as we know from measurements at LEP
- Could mix with the known neutrinos
- Some indication since more than 10 years (LSND, reactor anomalies, Gallium anomalies)
- The interpretation is still controversial/unclear..

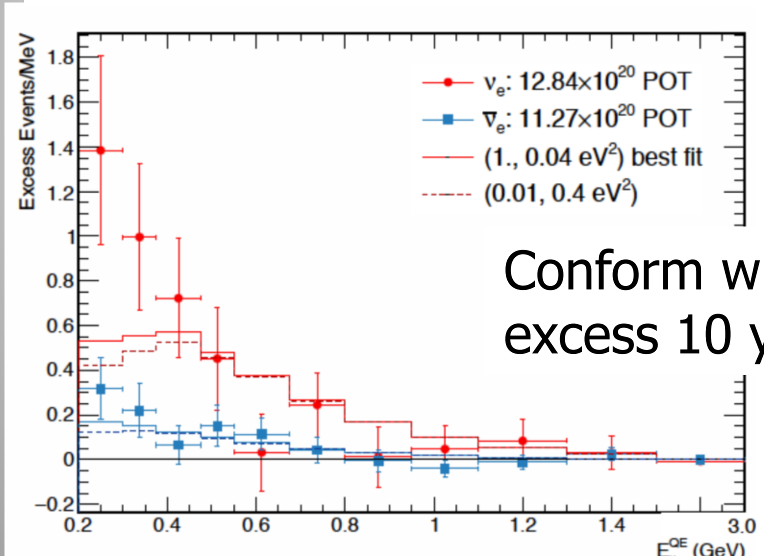
MiniBooNE May 2018



Search for electron neutrino appearance in short baseline accelerator experiment.

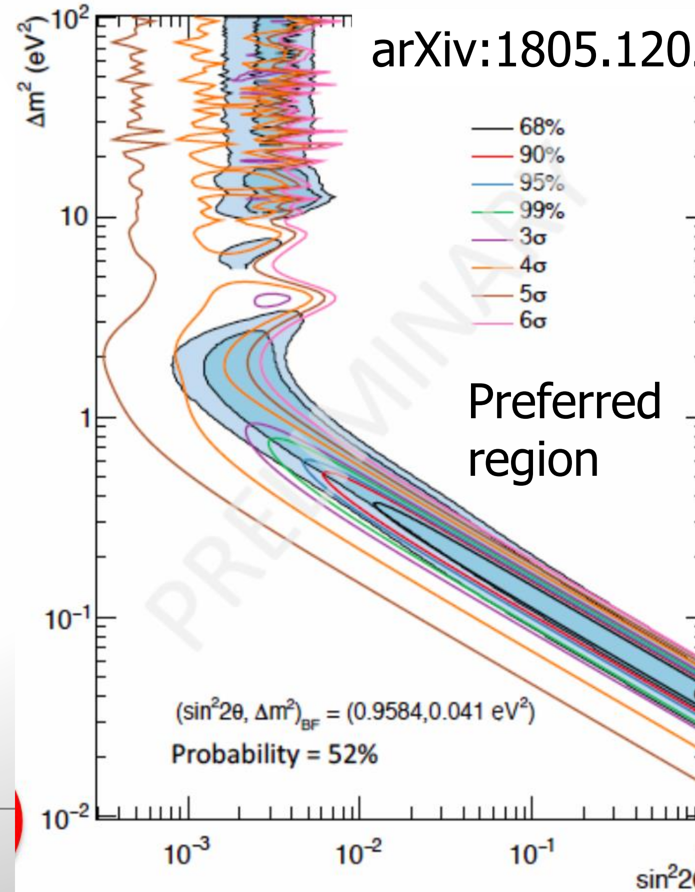
6.3 sigma excess reported combining the data with LSND

Excess of events over expectation



Conform with LSND excess 10 years ago

arXiv:1805.12028

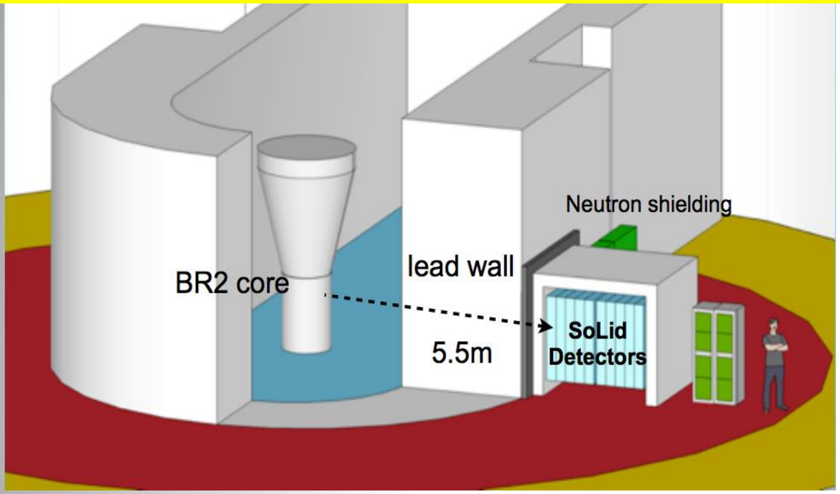


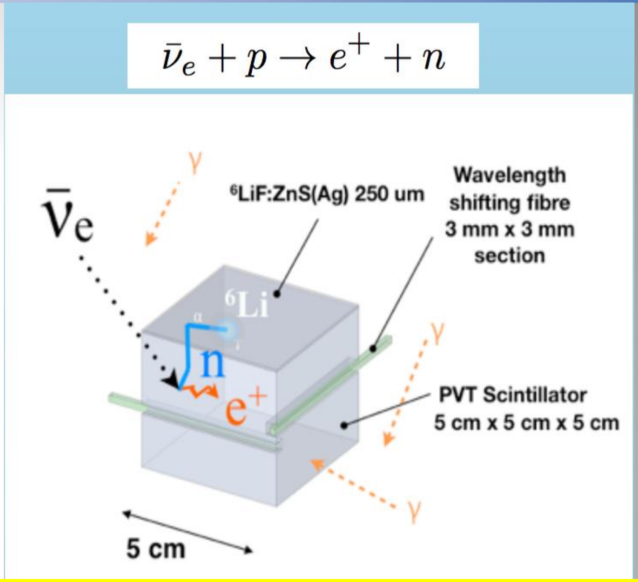
Preferred region

Caused by a new sterile neutrino?
The jury is still out..

New Short Baseline Experiments will check!

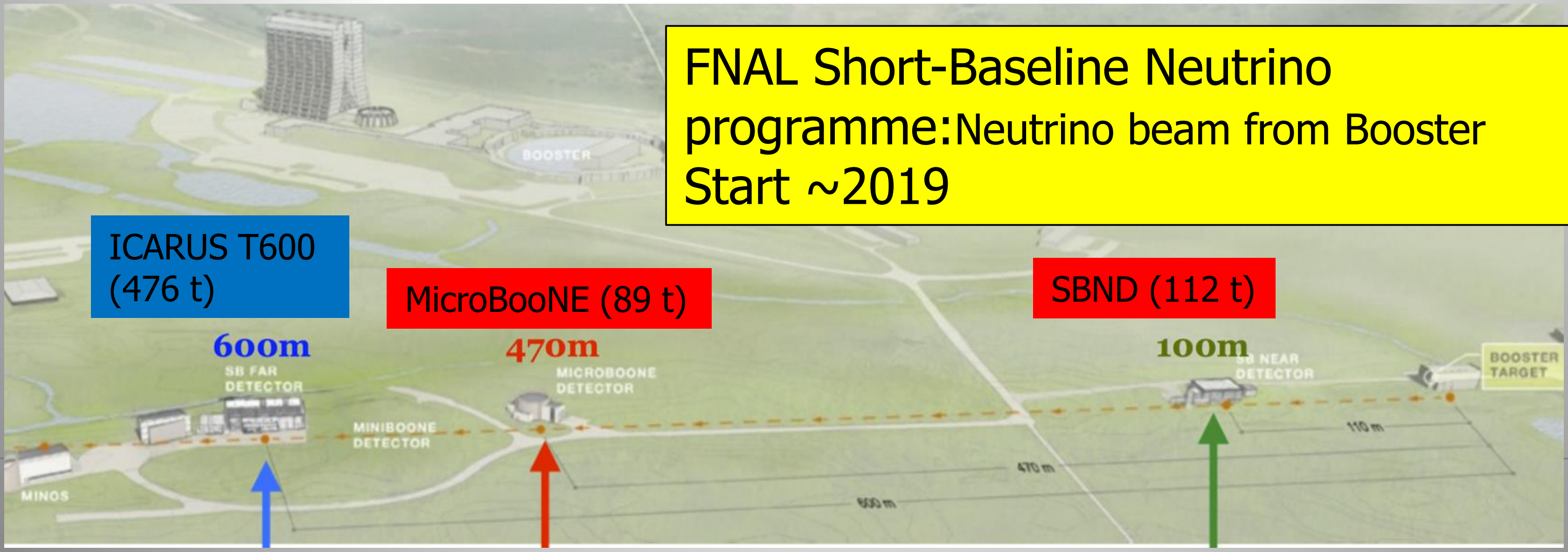
Experiments at reactors, eg the SoLid experiment @BR2 reactor in Belgium





Also: Prospect, STEREO, DANSS, NEOS

FNAL Short-Baseline Neutrino programme: Neutrino beam from Booster
Start ~2019



A Multi-Frontier Problem

Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)

CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
“neutrino astronomy”

Cosmic Neutrino
Background

Leptogenesis?

Sterile Neutrino
Dark Matter?

SUMMARY: Neutrinos

- Neutrinos were first detected in 1956
- Neutrino oscillations established since 1998
- Neutrino are unique: they are the only neutral fermions we know of.
- Majorana? High energy right-handed partners? Strong CP violation? More than 3 neutrinos?...
- 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…

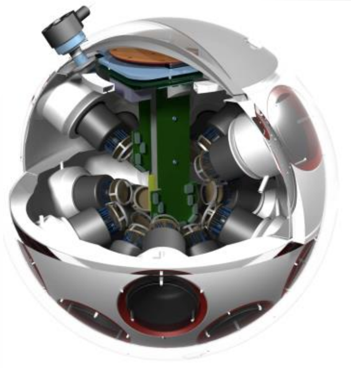
Note: Town Meeting of the European neutrino community planned for
22-24 October @ CERN
https://indico.cern.ch/event/740296

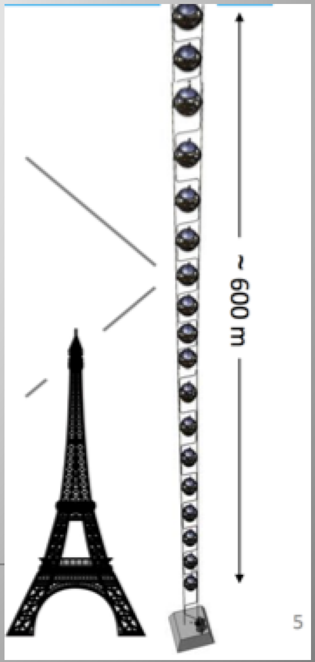
KM3NeT

Neutrino Astronomy!!

The several cubic kilometer neutrino telescope KM3NeT of is under construction in the deepest seas of the mediterranian. KM3NeT scientists will search for neutrinos from distant astrophysical sources such as supernovae, gamma ray bursts or colliding stars

The ORCA telescope is the instrument for KM3NeT scientists studying neutrino properties exploiting neutrinos generated in the Earth's atmosphere. Arrays of thousands of optical sensors will detect the faint light in the deep sea from charged particles originating from collisions of the neutrinos and the Earth.

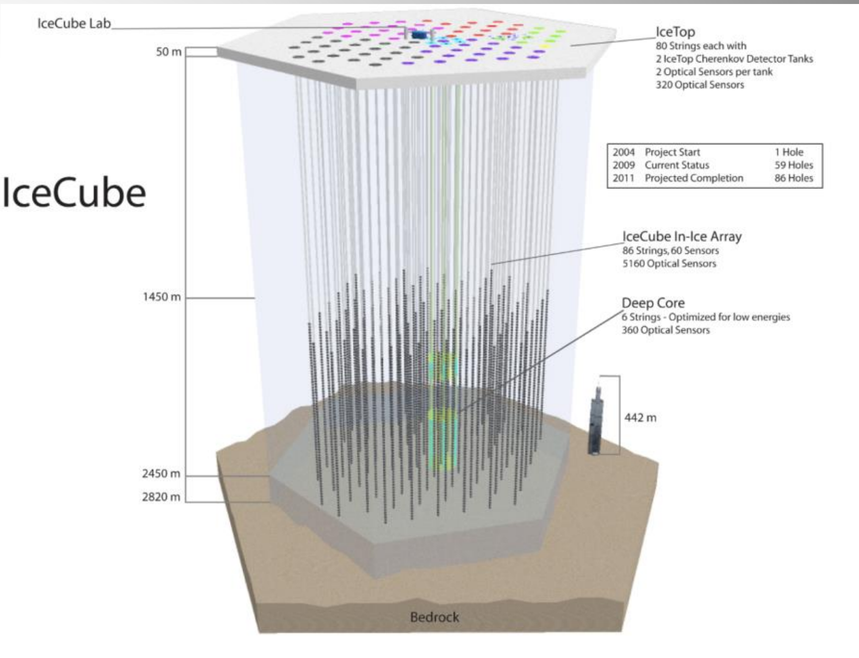




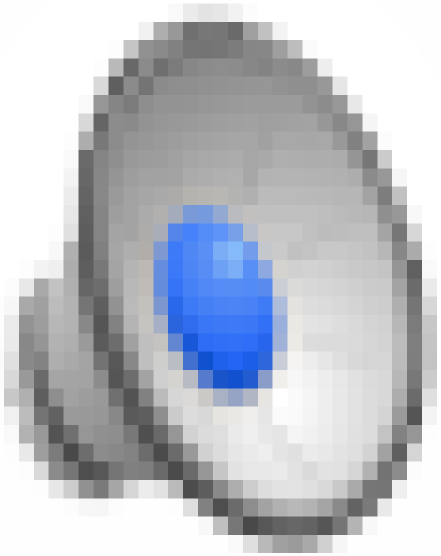
IceCube

Neutrino Astronomy!!

High energy neutrino telescopes such as IceCube can measure flavor oscillations using large atmospheric neutrino data sets. These observations are highly complementary to accelerator and reactor neutrino measurements, as they probe higher neutrino energies and a wide range of baselines. This enables probes of the unitarity of the PMNS matrix and searches for new physics, including sterile neutrinos and NSI, in addition to measurements of the atmospheric mixing parameters.



The DUNE Experiment

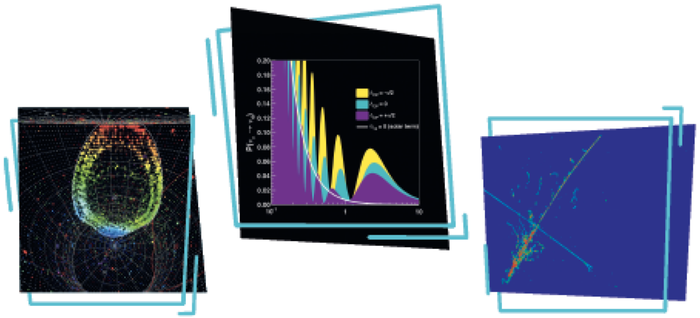


CERN and Neutrinos

Workshop on statistical issues in modern neutrino physics

PHYSTAT - ν 2019

22-25 January 2019
CERN



Topics Include:
- Model selection and parameter estimation
- Limit setting, discovery
- Systematic uncertainties
- Unfolding
- Machine learning

https://indico.cern.ch/event/735431
PhyStat-Nu-CERN@cern.ch

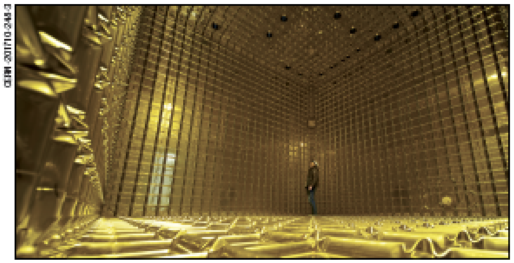
Scientific Programme Committee:
- **Robert Cousins**, UCLA
- **Glen Cowan**, Royal Holloway University London
- **Kyle Cranmer**, New York University
- **Mark Hartz**, Kavli IPMU (WPI), University of Tokyo and TRIUMF
- **Patrick Huber**, Virginia Tech
- **Tom Junk**, Fermilab
- **Mikael Kuusela**, Ecole Polytechnique Federale de Lausanne
- **Manfred Lindner**, Max Planck Institute
- **Xin Qian**, Brookhaven National Laboratory
- **Yoshi Uchida**, Imperial College London

Local Organizing Committee:
- **Olaf Behnke**, DESY
- **Albert de Roeck**, CERN
- **Louis Lyons**, Imperial College London and University of Oxford
- **Davide Sgalaberna**, CERN

Viewpoint

A golden age for neutrinos

20 years since the discovery of neutrino oscillations, a complete understanding is within our grasp.



Inside a prototype detector module for the international DUNE experiment, which was built at CERN and is about to be filled with liquid argon before undergoing its first tests with beam.

By Albert De Roeck

On 3 July 1998, researchers working on the Super-Kamiokande experiment in Japan announced the first evidence for atmospheric-neutrino flavour oscillations. Since neutrinos can only oscillate among different flavours if at least some of them have a non-zero mass, the result proved that neutrinos are massive, albeit with very small mass values. This is not expected in the Standard Model.

Neutrino physics was already an active field, but the 1998 observation sent it into overdrive. The rich scientific programme and record attendance of the Neutrino 2018 conference in Heidelberg last month (see p37) is testament to our continued fascination with neutrinos. Many open questions remain: what generates the tiny masses of the known neutrinos, and what is their mass ordering? Are there more than the three known neutrino flavours, such as additional sterile or right-handed versions? Is there CP violation in the neutrino sector and, if so, how large is it? In addition, there are solar neutrinos, atmospheric neutrinos, cosmic/supernova neutrinos, relic neutrinos, geo-neutrinos, reactor neutrinos and accelerator-produced neutrinos – allowing for a plethora of experimental and theoretical activity.

Many of these questions are expected to be answered in the next decade thanks to vigorous experimental efforts. Concerning neutrino-flavour oscillations, new results are anticipated in the short term from the accelerator-based T2K and NOvA experiments in Japan and the US, respectively. These experiments probe the CP-violating phase in the neutrino-flavour mixing matrix and the ordering of the neutrino mass states; evidence for large CP violation could be established, in particular thanks to the planned ND280 near-detector upgrade of T2K.

The next generation of accelerator-based experiments is already under way. The Deep Underground Neutrino Experiment (DUNE) in South Dakota, US, which will use a neutrino beam sent from Fermilab, is taking shape and two large prototypes of the DUNE far detector are soon to be tested at CERN. In Japan, plans are shaping up for Hyper-Kamiokande, a large detector with a fiducial volume around 10 times larger than that of Super-Kamiokande, and this effort is complemented with other sensitivity improvements and a possible second detector in Korea for analysing a neutrino beam sent from J-PARC in Japan. These experiments, which are planned to come online in 2026, will allow precision neutrino-oscillation measurements and provide decisive statements on the neutrino mass hierarchy and CP-violating phase.

Important insights are also expected from reactor sources. In China, the JUNO experiment should start in 2021 and could settle the mass-hierarchy question and determine complementary oscillation parameters. Meanwhile, very-short-baseline reactor experiments – such as PROSPECT, STEREO, SoLid, NEOS and DANSS – are soon to join the hunt for sterile neutrinos. Together with detectors at the short-baseline neutrino beam at Fermilab (SBND, MicroBooNE and ICARUS), the next few years should see conclusive results on the existence of sterile neutrinos. In particular, the recently reported update on the intriguing excess seen by the MiniBooNE experiment will be scrutinised.

Together with the ever-increasing sensitivities achieved by double-beta-decay experiments, which test whether neutrinos have a Majorana mass term, the SHiP experiment is proposed to search for right-handed neutrinos, while KATRIN in Germany has just started its campaign to measure the mass of the electron antineutrino with sub-eV precision. The interplay with astronomy and cosmology, using detectors such as IceCUBE and KM3NeT, which survey atmospheric neutrinos, further underlines the vibrancy and breadth of modern neutrino physics. Also, the European Spallation Source, under construction in Sweden, is investigating the possibility of a precise neutrino-measurement programme.

Neutrino experiments are spread around the globe, but Europe is a strong player. A discussion forum on neutrino physics for the update of the European strategy for particle physics will be hosted by CERN on 22–24 October. Clearly, neutrino science promises many exciting results in the near future.

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