Neutrinos!

Present Understanding & Future Prospects

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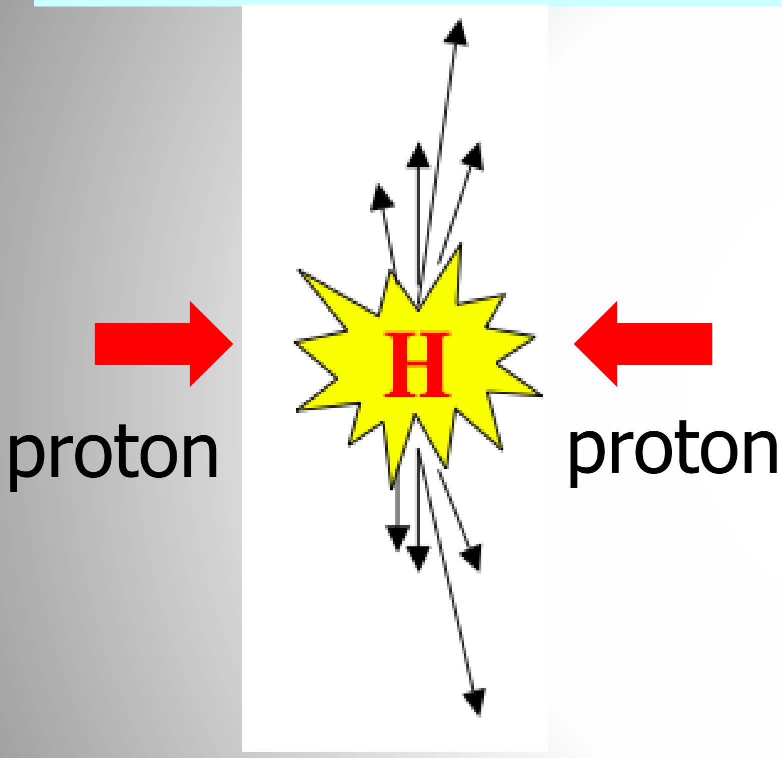
Chulalongkorn University
Bangkok, Thailand

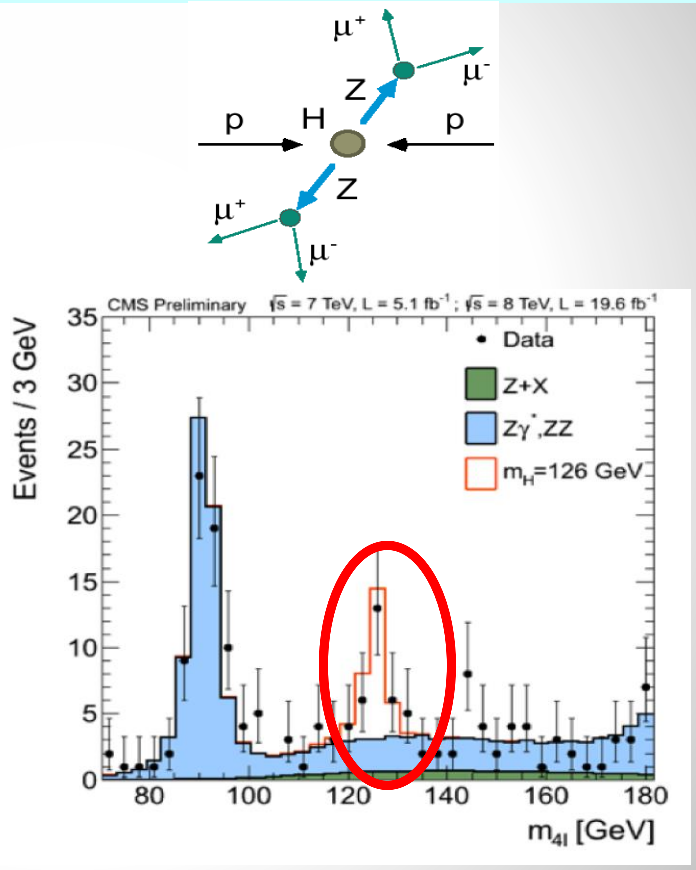
A bit of History…

July 2012:
Thailand joins the CMS Experiment at CERN

2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the Large Hadron Collider, after about 40 years of experimental searches to find it

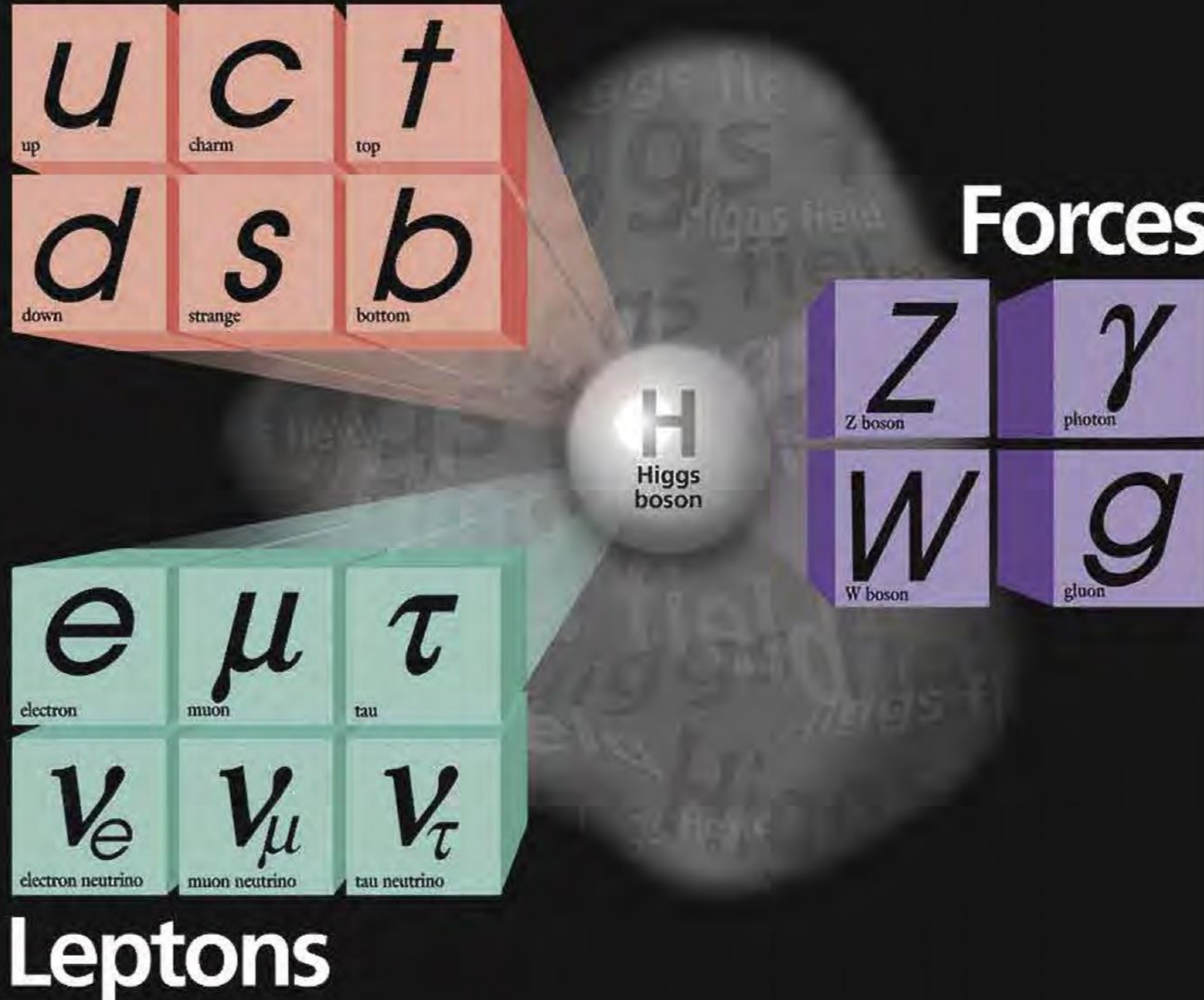




2013

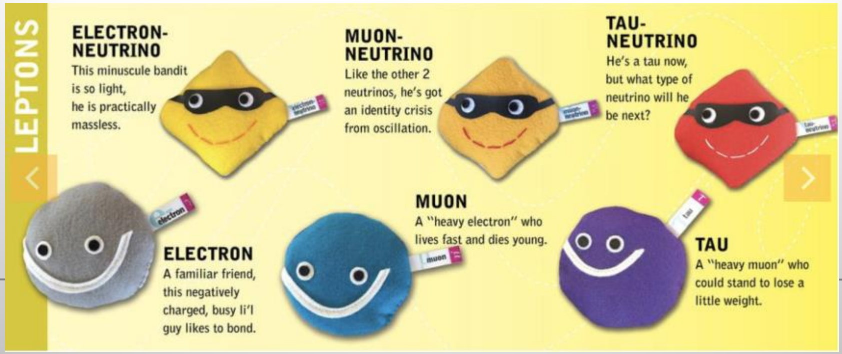
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

The Standard Model



Neutrinos

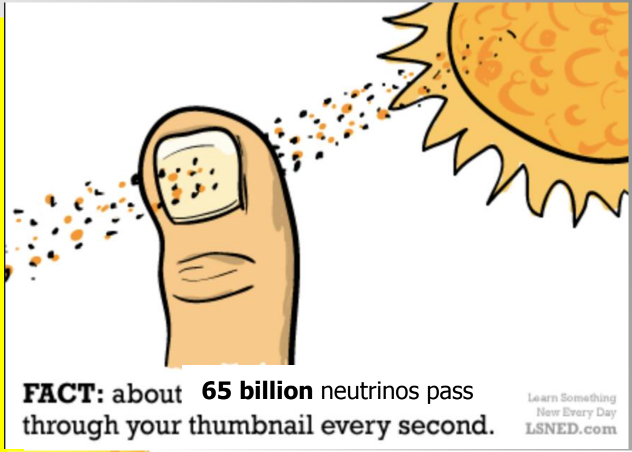
Neutrinos come in three different types: three flavors

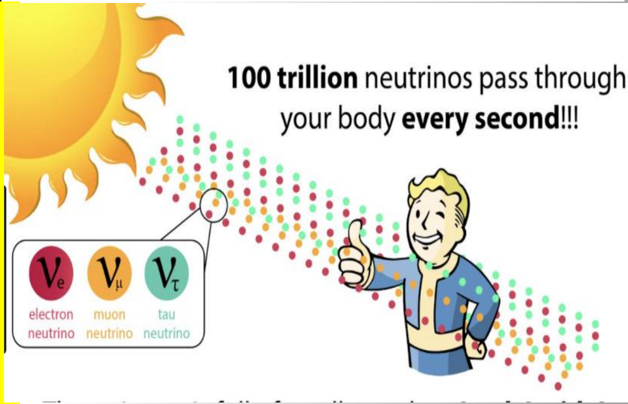


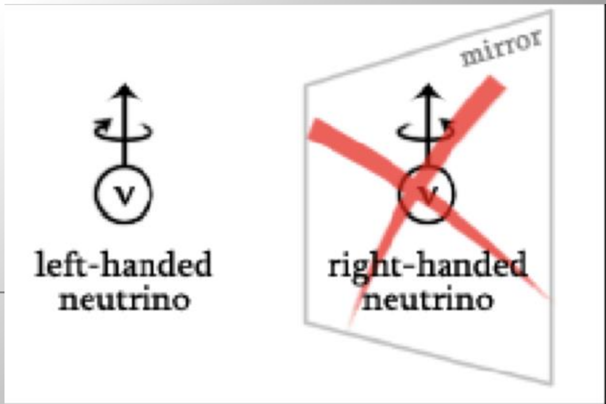
Neutrinos

- 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 ($\sim 10^{13}$ km) be stopped with 50% chance
- There are a billion neutrinos for each atom in the Universe. There are $\sim 3.10^{8}$ neutrinos per cubic meter- relic neutrinos
- Their sheer number must mean they have important role in the Universe
- Neutrinos have a fixed chirality ->

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







Neutrinos

Neutrinos are mysterious particles

- Have only very weak interactions
- The only neutral matter particles in the Standard Model
- Neutrinos could be their own anti-particle
- Are mass-less in the (minimal) Standard Model but were recently found to have very tiny masses
- Neutrinos are Chameleons: They can change flavour!!

At the same time neutrinos are essential parts of our Universe and our very existence, and can provide answers to some of the key fundamental questions today: matter-antimatter asymmetry, dark matter…

Neutrinos

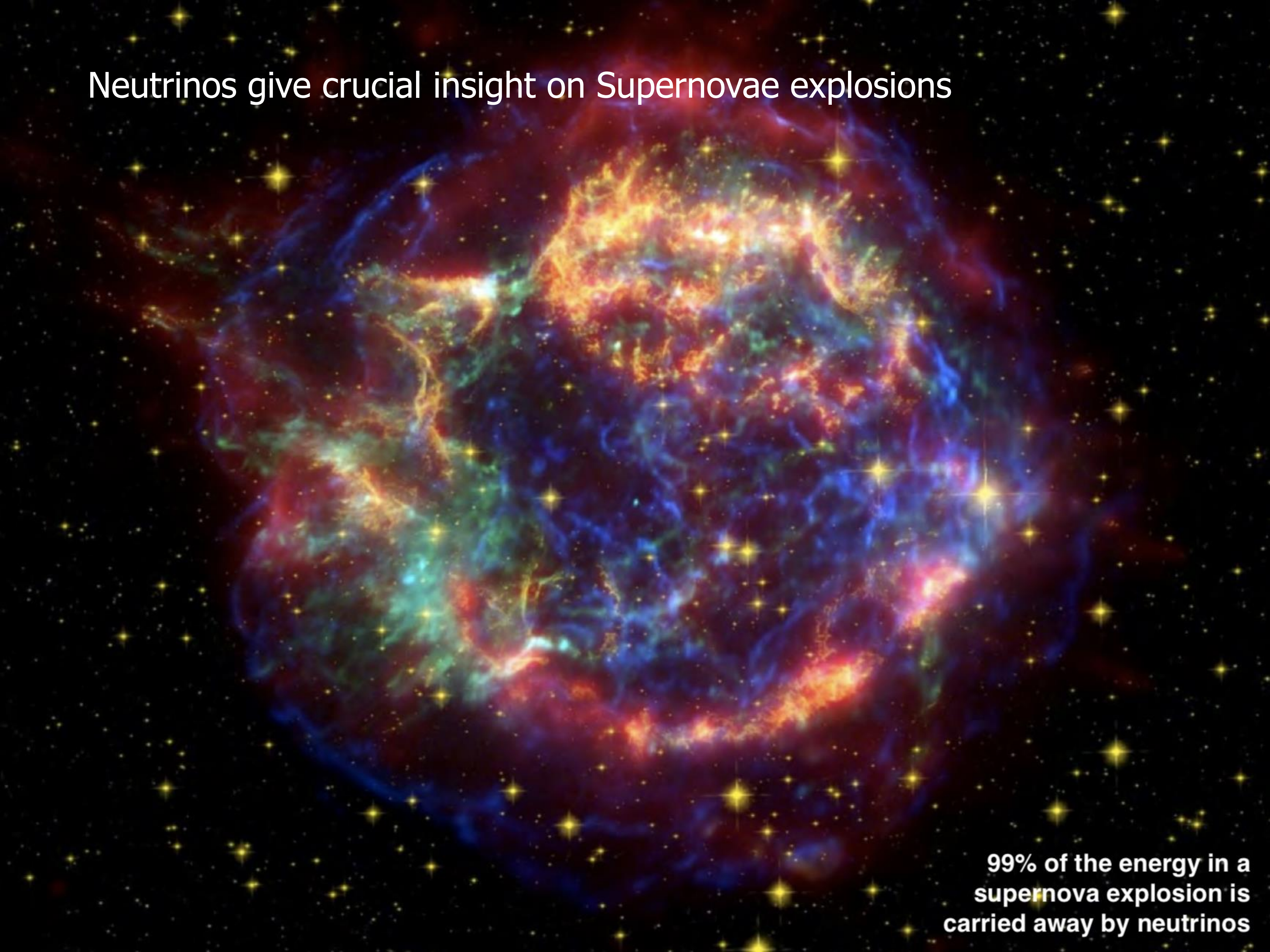
Neutrinos are mysterious particles

- Neutrinos are produced everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Primordial neutrinos from the big bang
  - Neutrinos from Supernova explosions
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, radioactive decay, even from your body

Neutrinos are the most abundant matter particles in our Universe

Plenty of neutrinos in the Universe

Neutrinos give crucial insight on Supernovae explosions



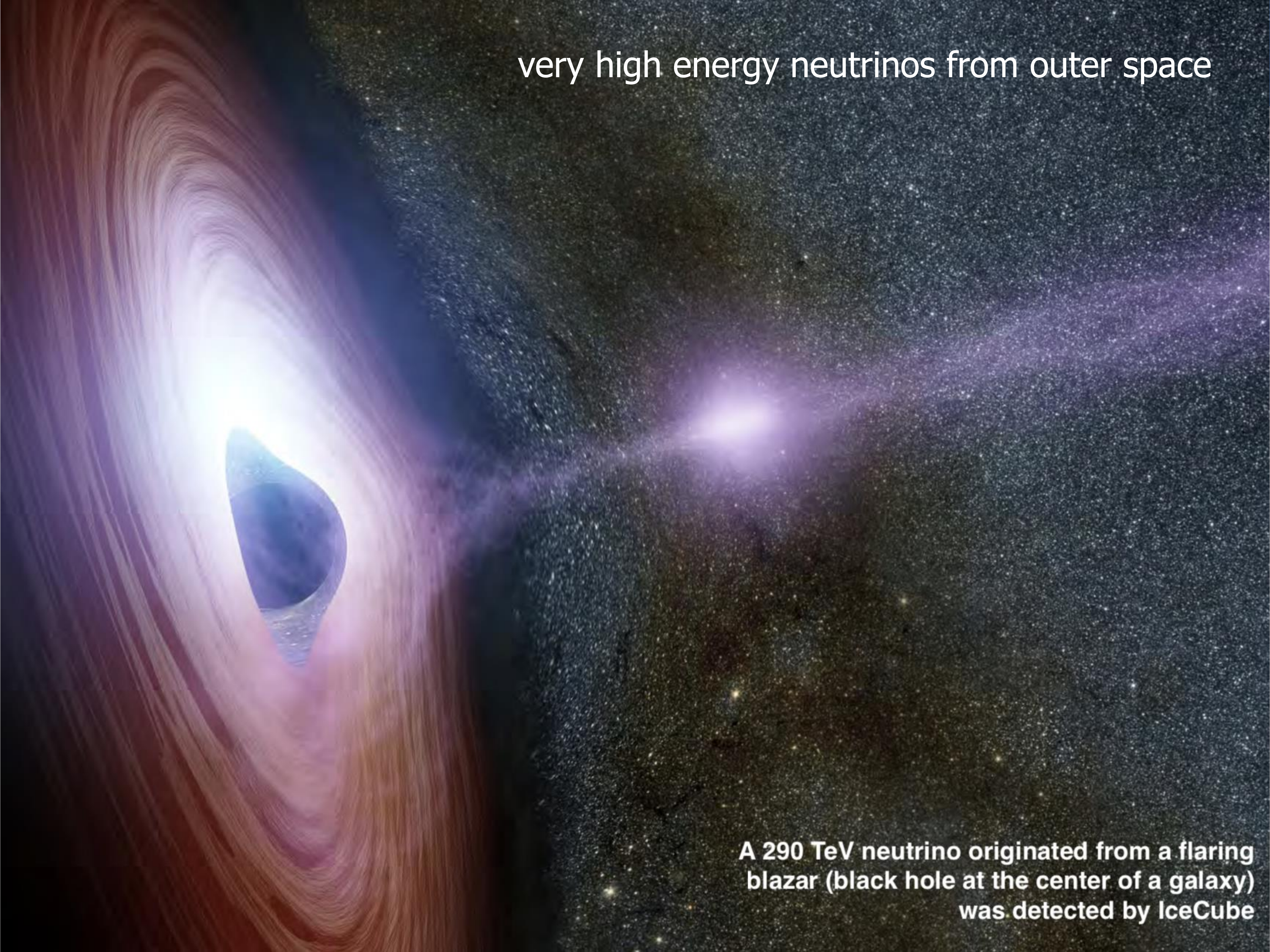
99% of the energy in a supernova explosion is carried away by neutrinos

Neutrinos allow us to to look into the heart of the sun

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

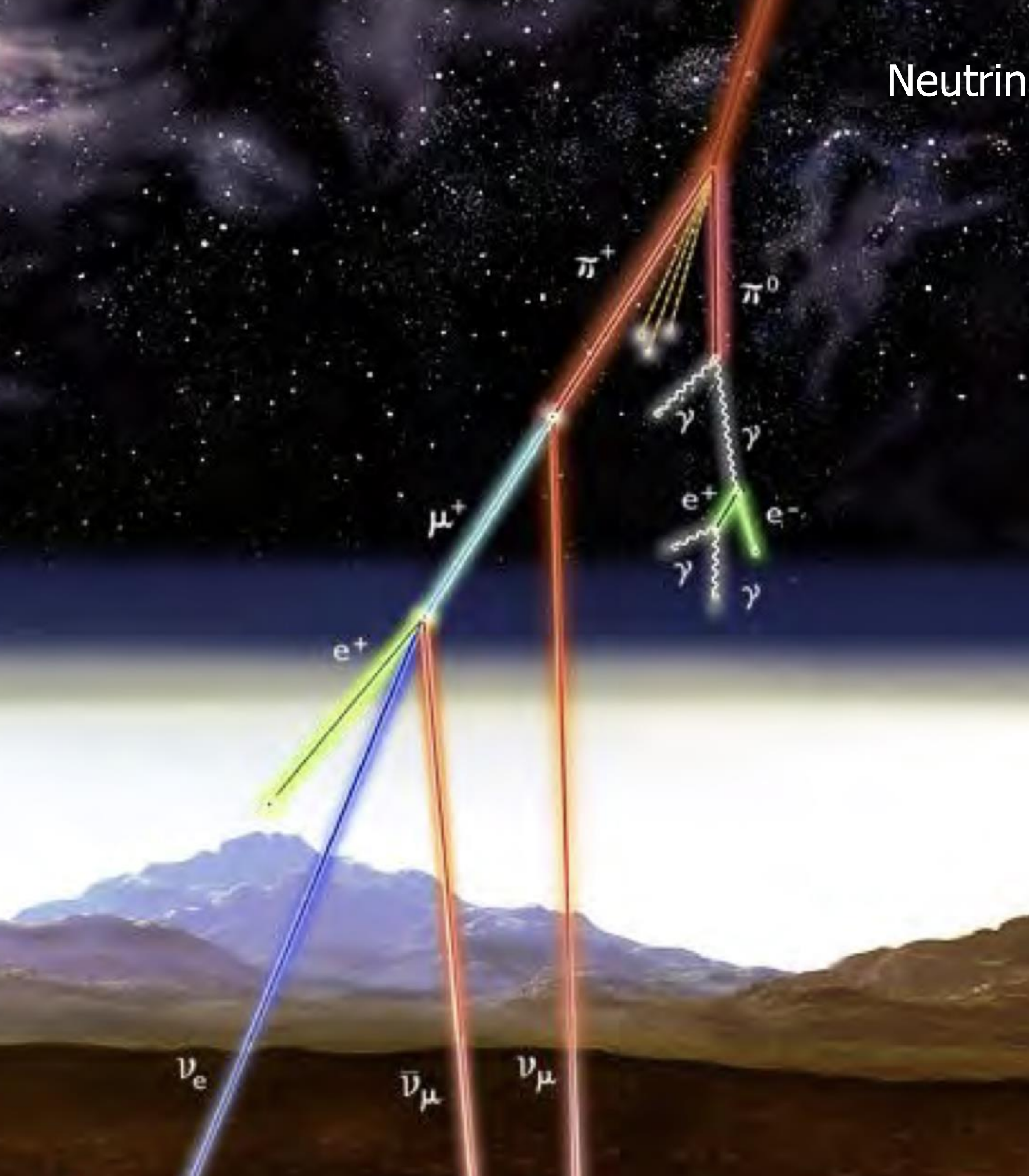
(with a flux of $\sim 10^{11}/cm^2/sec$ at the Earth)

very high energy neutrinos from outer space



A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube

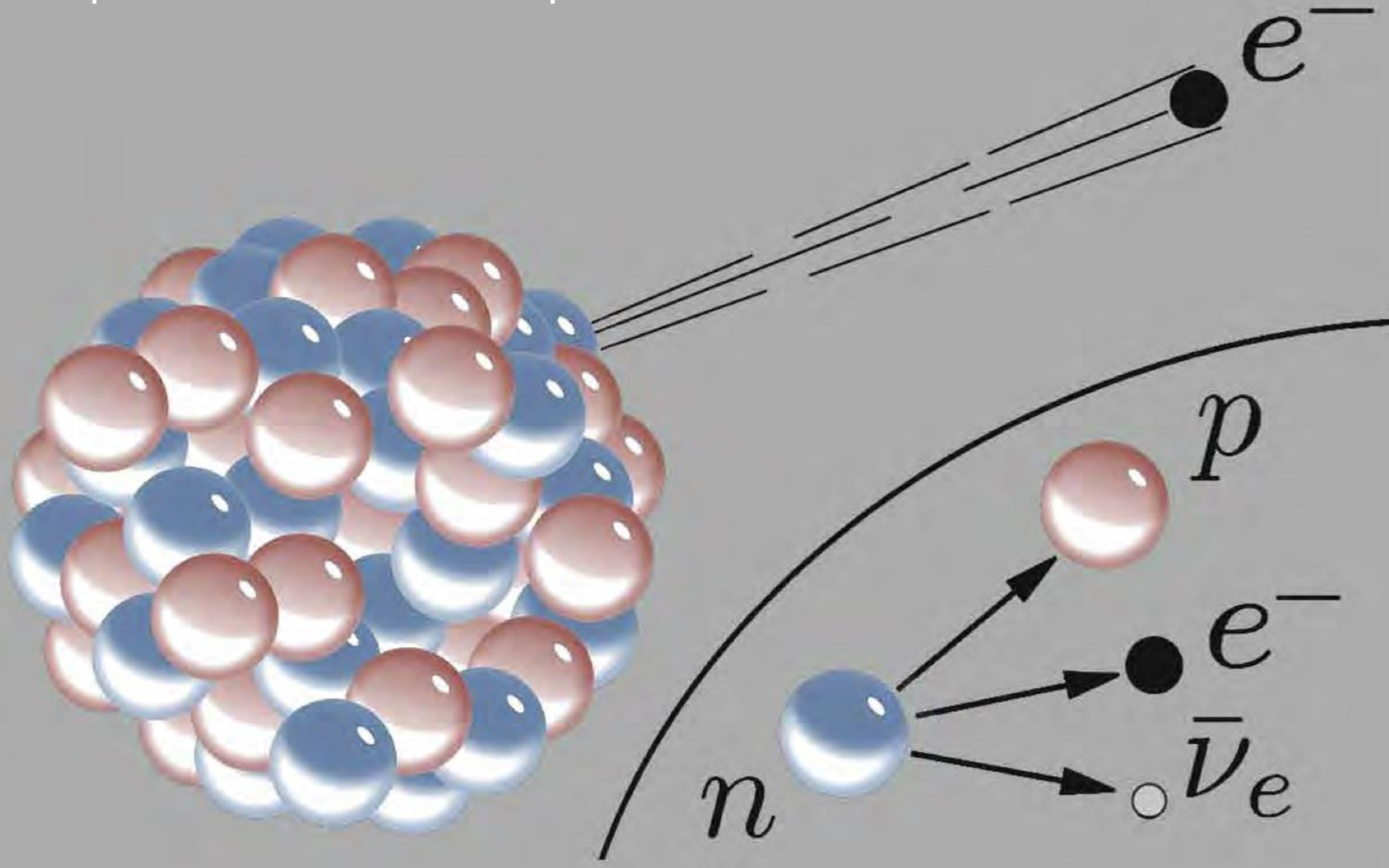
Neutrinos from cosmic rays



Neutrinos are also produced in the atmosphere

Reactors produce > 10^{21} neutrinos per second

Radioactive beta-decay
The process that led to the postulation of the neutrino



Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

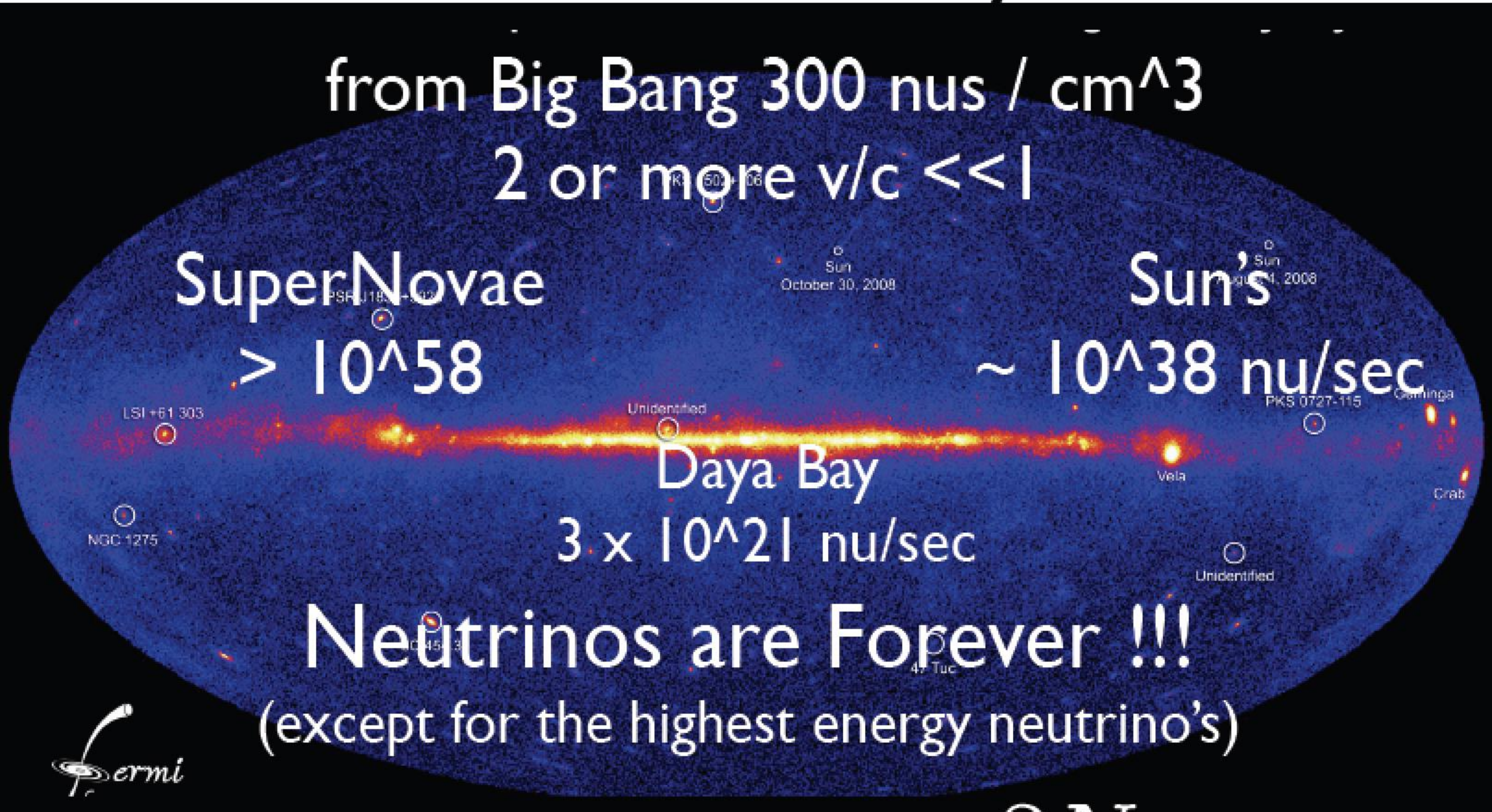
~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

Neutrinos are Forever !!!

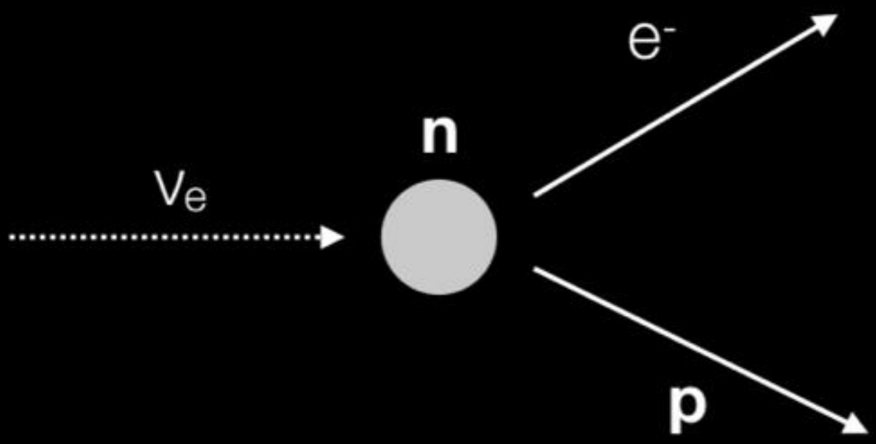
(except for the highest energy neutrino's)



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

Neutrinos interact very weakly with matter

detecting neutrinos is challenging



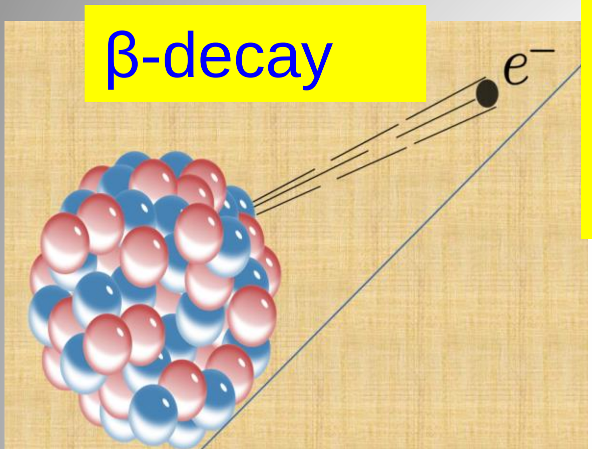
Very large detectors are needed

And often they are placed far underground

Most neutrino detectors are placed deep underground to shield them against cosmic rays

10^{-6} reduction for DUNE, 1.5 km underground

Neutrinos were introduced in 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?

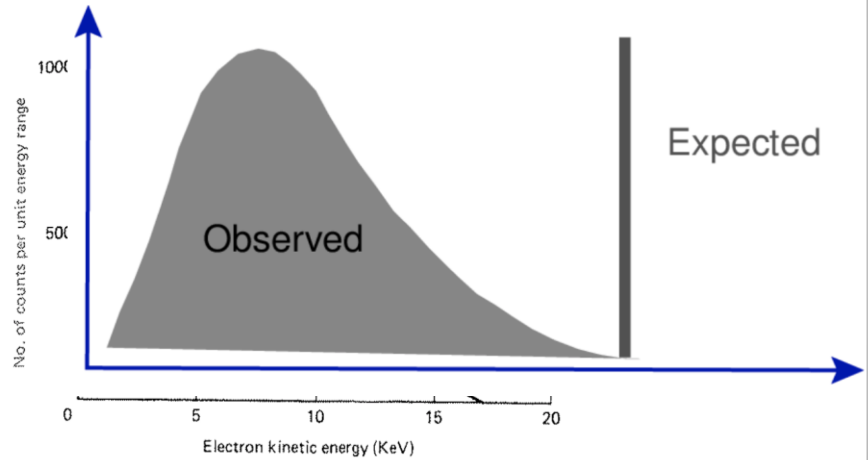


Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \to ^3_2He$). (*Source:* Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Pauli proposed instead the process:

$$n \to p^+ + e^-$$

But he believed we could never detect this particle!!

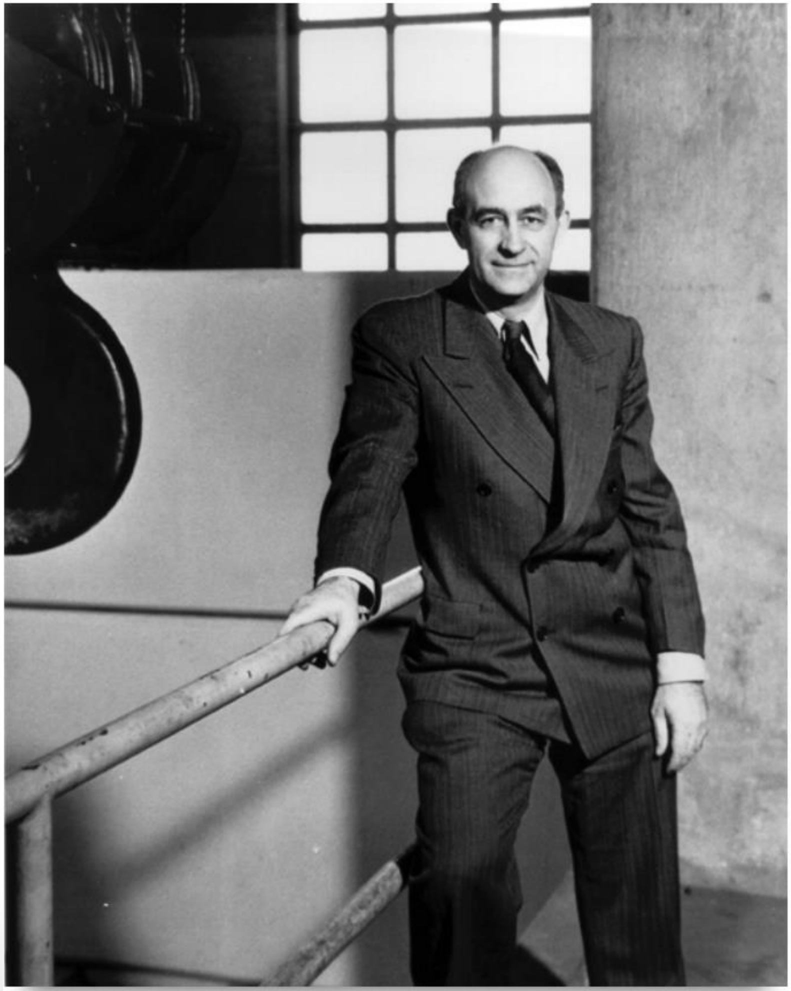
Neutrinos are known to us since 1934!

1934
Enrico Fermi, father of the world's first nuclear reactor, coined the term "neutrino" which is Italian for "little neutral"

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

This is one of the keystone papers for the Later development of the Standard Model

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

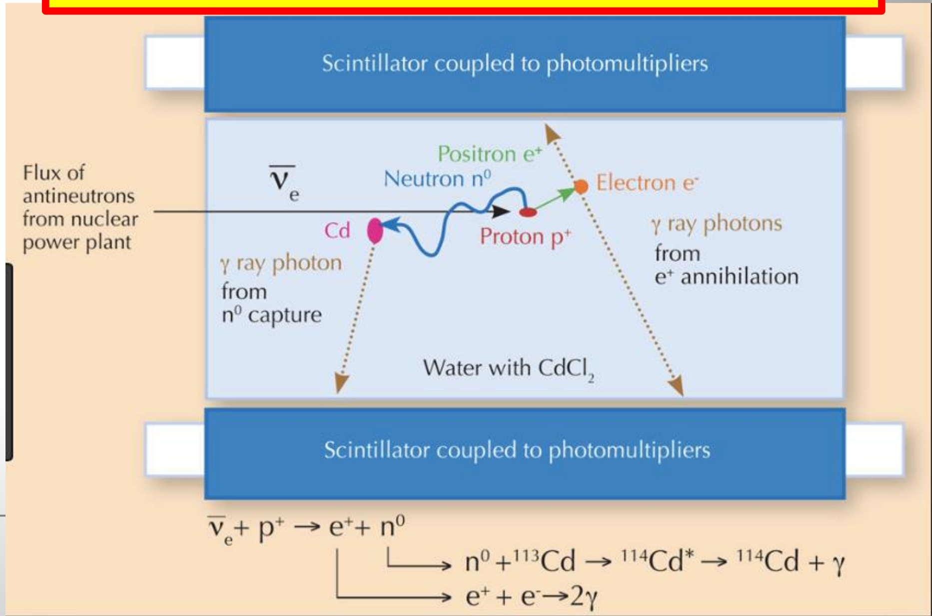
$$\bar{\nu}_e + p \Rightarrow n + e^+$$

5 μsecond delay

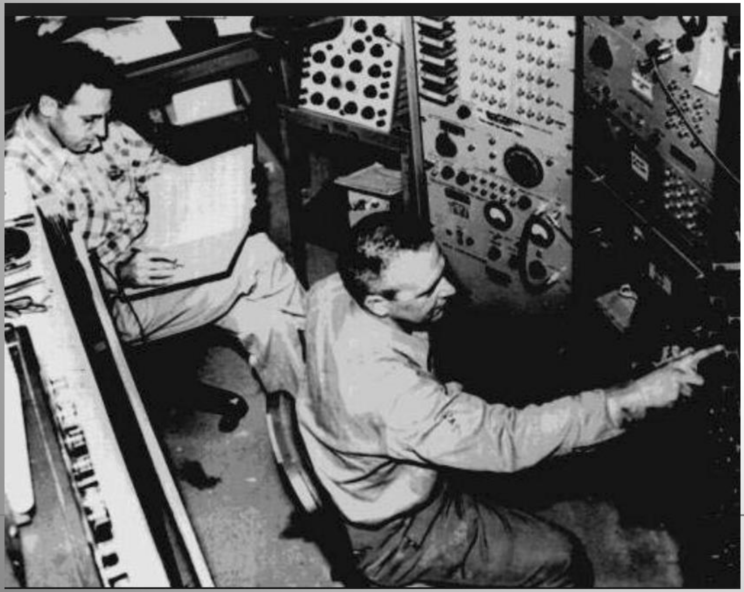
$$e^+ + e^- \Rightarrow \gamma + \gamma$$

n-capture by cadmium

The neutrino really exists!



The Discovery of the Neutrino



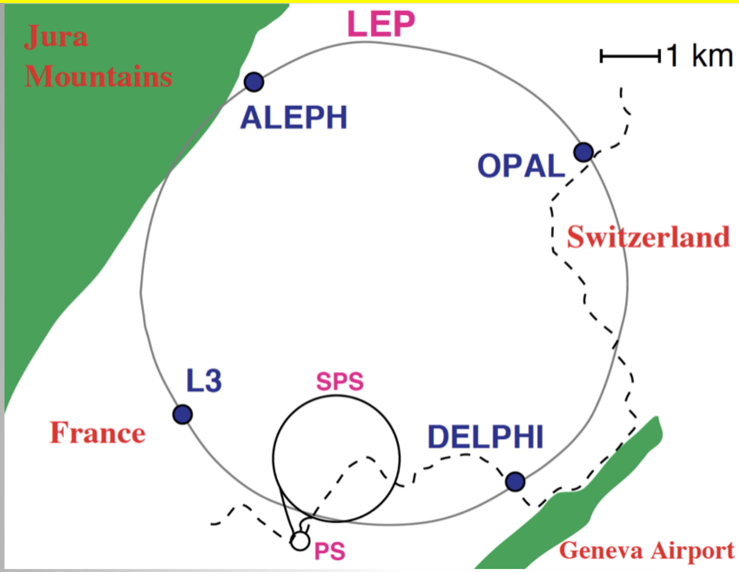
This was however not the first idea of Cowan and Reines.

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!

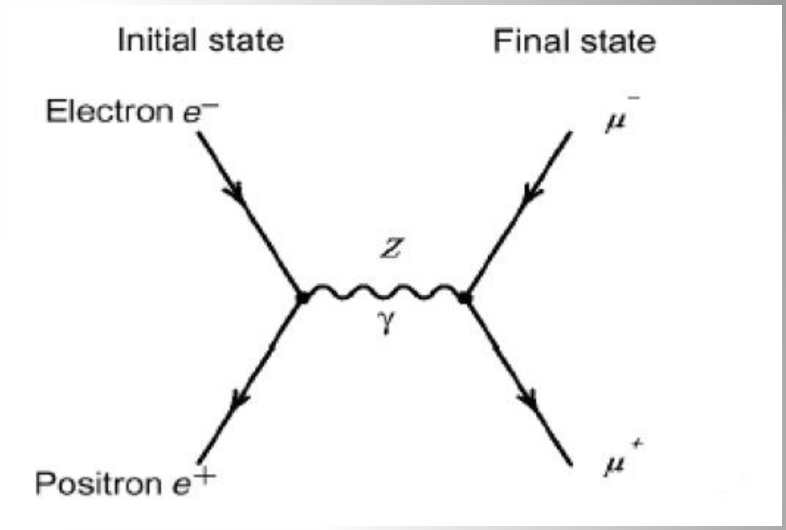
They abandoned that idea when the realized there were certain 'practical problems' for the detector… (to survive)

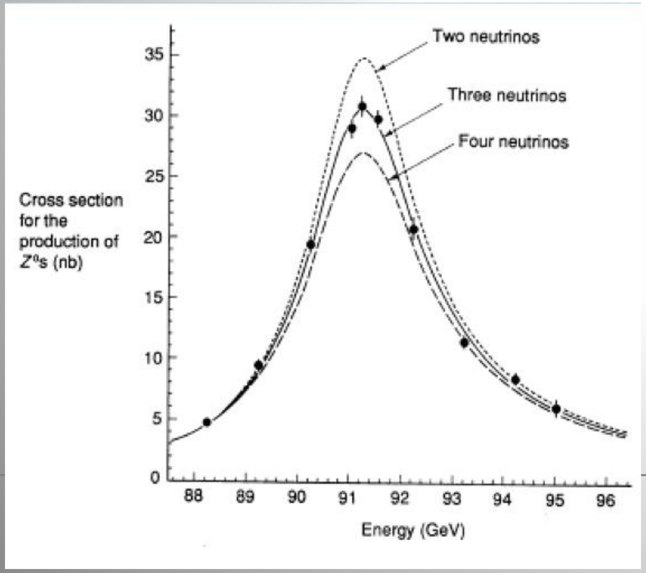
How Many Different Neutrinos?

LEP e+e- collider at CERN (1988-2000)



Detailed study of the Z-boson





The width of the Z-boson gives the number of neutrinos

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

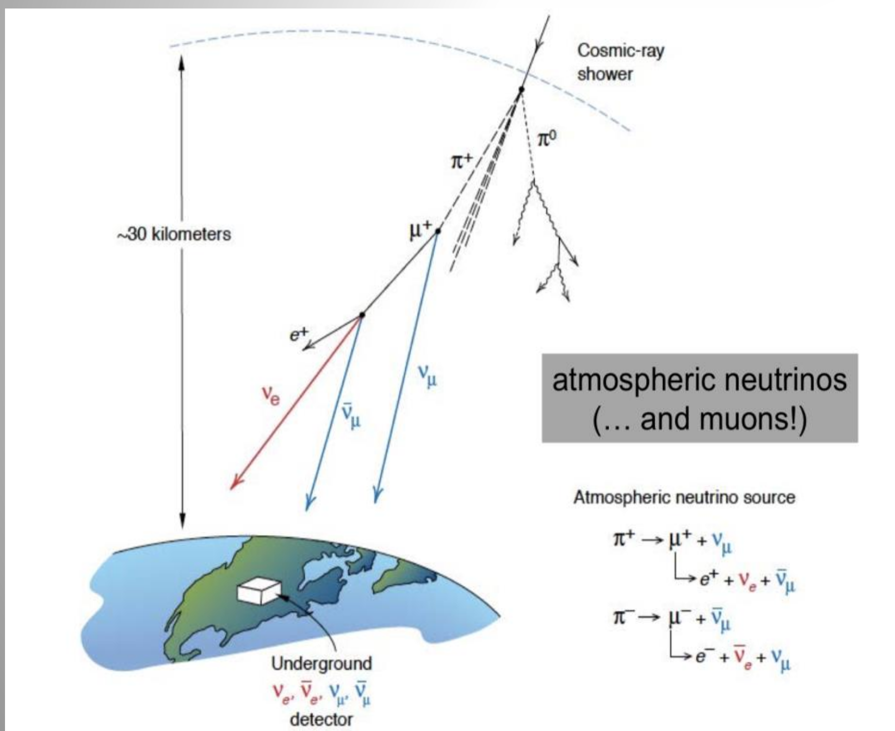
$$N_\nu = 2.99 \pm 0.02$$

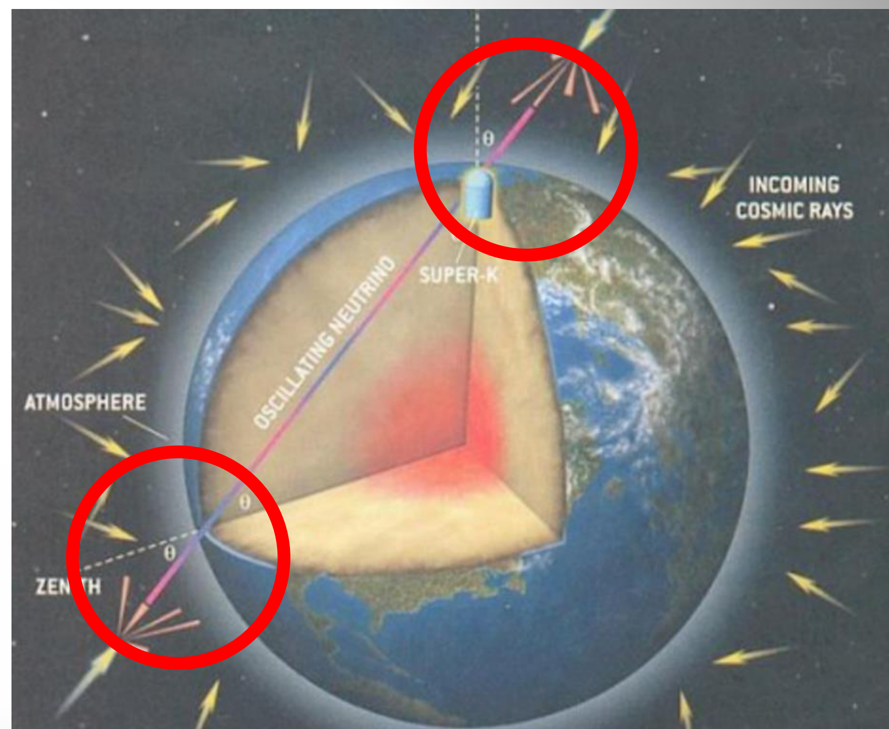
LEP: three active neutrinos with mass<45 GeV

Atmospheric Neutrinos

Cosmic rays hit the atmosphere at 30 km height.
These produce particles that decay and give neutrinos

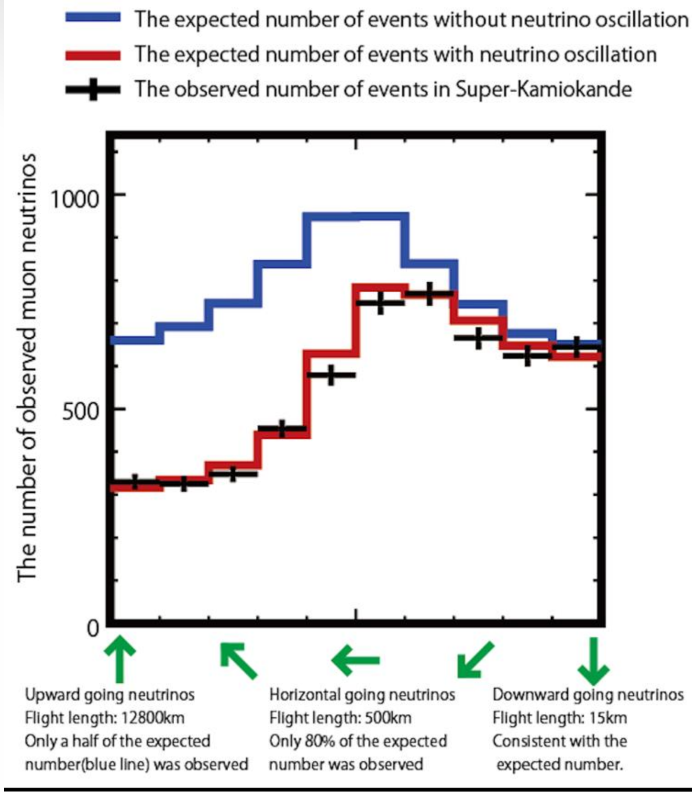
Some neutrinos are produced close to the detector.
Others thousands of km away from it





Neutrinos hitting the detector ‘from below’ travelled much longer than others

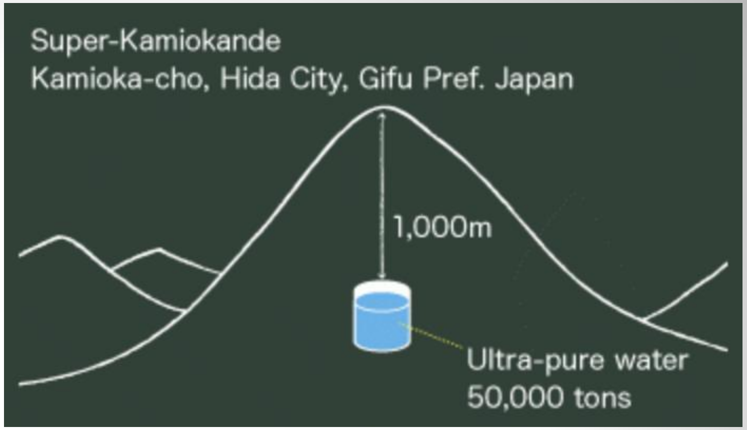
Neutrinos Oscillate! (1998)

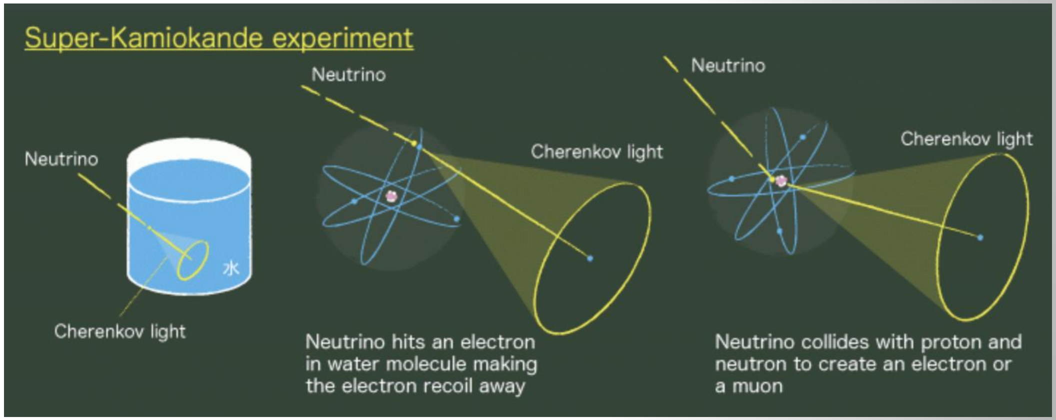


1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

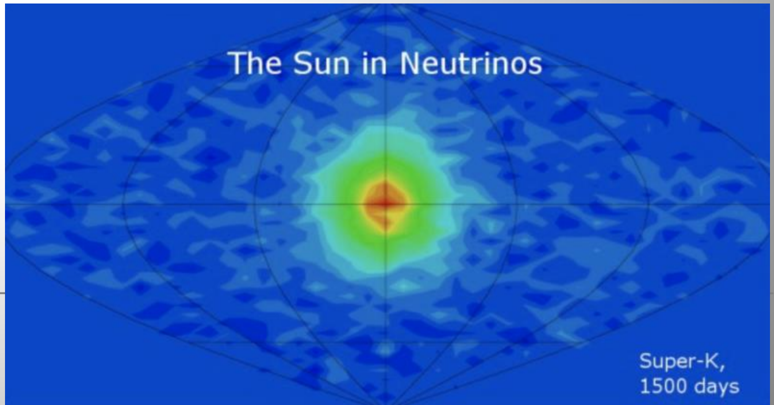
They announced first evidence of neutrino oscillations. The experiment showed that muon neutrinos disappear as they travel through the earth to the detector It also explained the earlier observed solar neutrino discrepancy.

SuperKamiokande



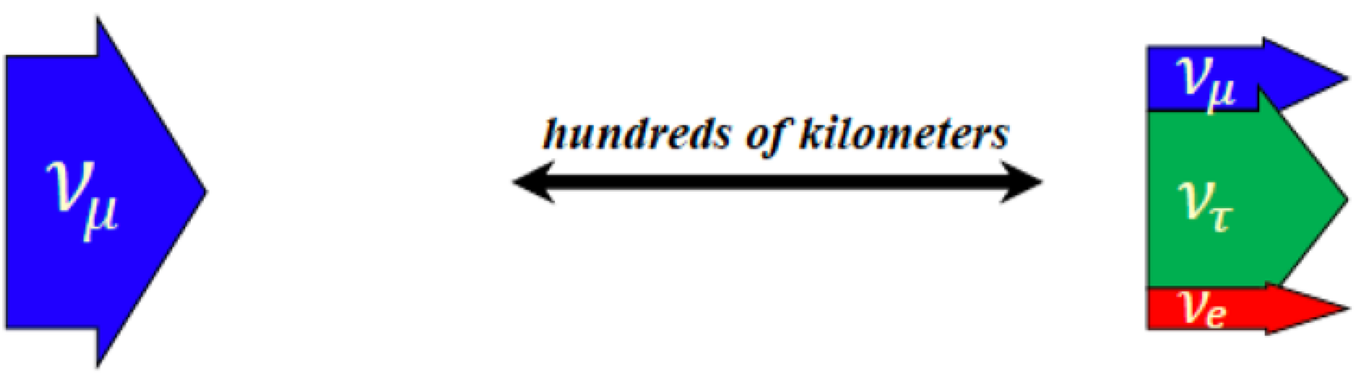


50,000 tons of ultra-pure water, watched by 13,000 photomultipliers



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 -> Neutrinos have mass!!



Neutrino oscillations

- Each flavour state is a linear combination of mass states:

Neutrino interaction

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \; |\nu_i\rangle$$

Neutrino travel through space

Flavour state
$\alpha = e, \mu, \tau$

PMNS lepton mixing matrix

Mass state
i= 1, 2, 3

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

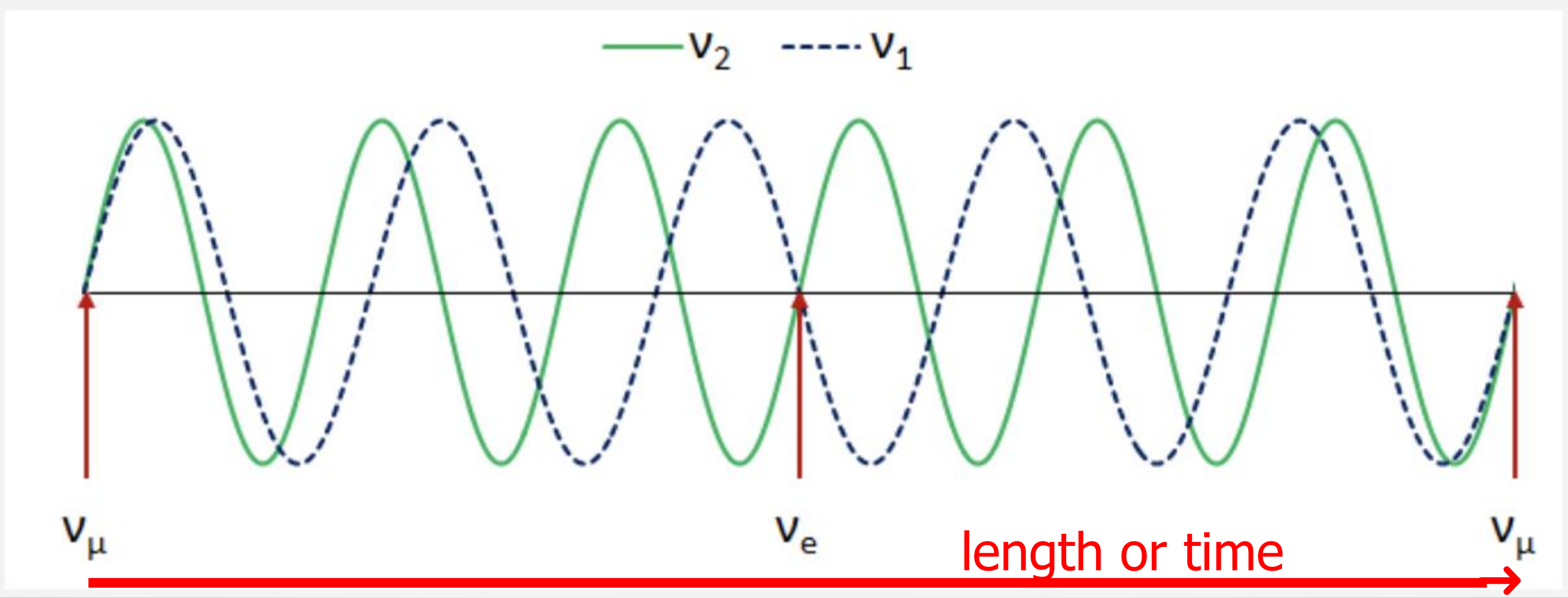
Flavor states

Neutrino Oscillations

The bizarre world of Quantum Mechanics: particles and waves

Take that the neutrino particle is a hybrid of two mass states v1 and v2 as it travels through space the associated waves of these mass states advance at a different rate

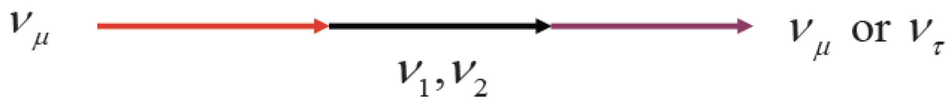
Hence the picture looks as follows:



The neutrinos change identity (flavor) along the way…!!

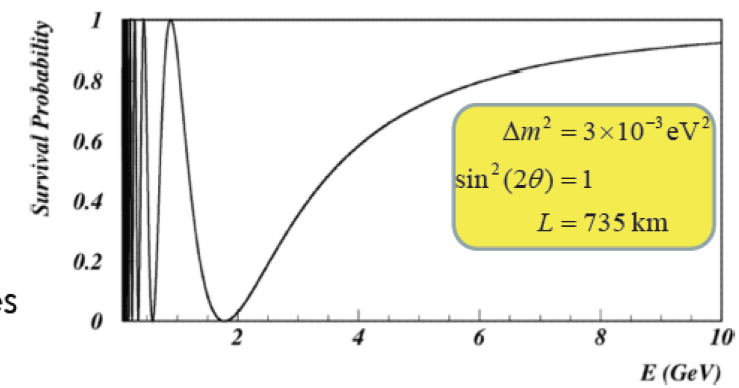
Neutrino Oscillations

Neutrino oscillations is a pure Quantum Mechanical effect
The effect depends on the mass difference between flavor states



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

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



- $\Delta m^2_{21} = m^2_2 - m^2_1 \approx 8 * 10^{-5}\ \mathrm{eV}^2$ => wavelength of ~100km
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2 * 10^{-3}\ \mathrm{eV}^2$ => wavelength of ~1km

Absolute mass values? Mass hierarchy?

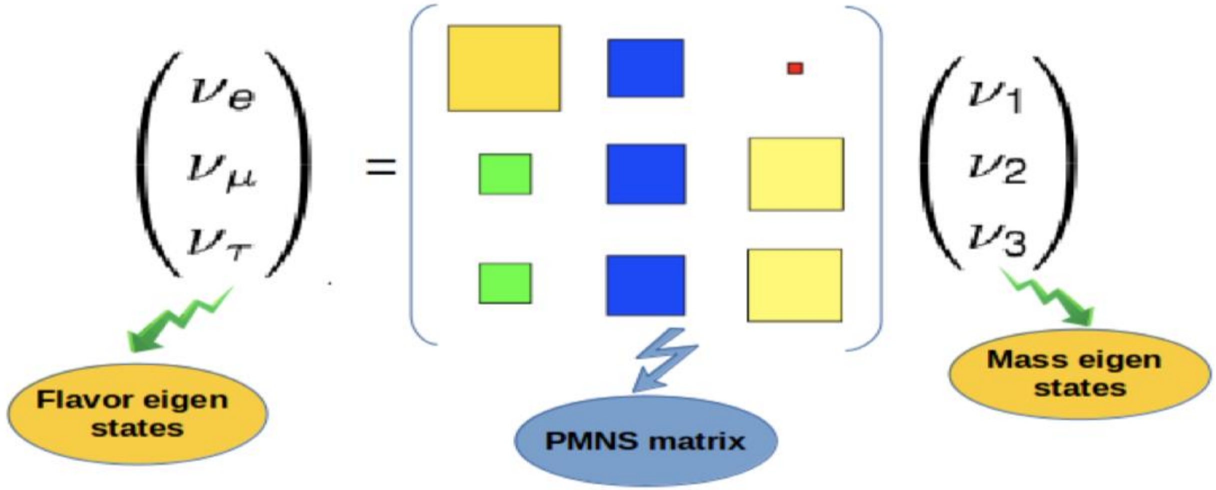
Neutrino Oscillations

- 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

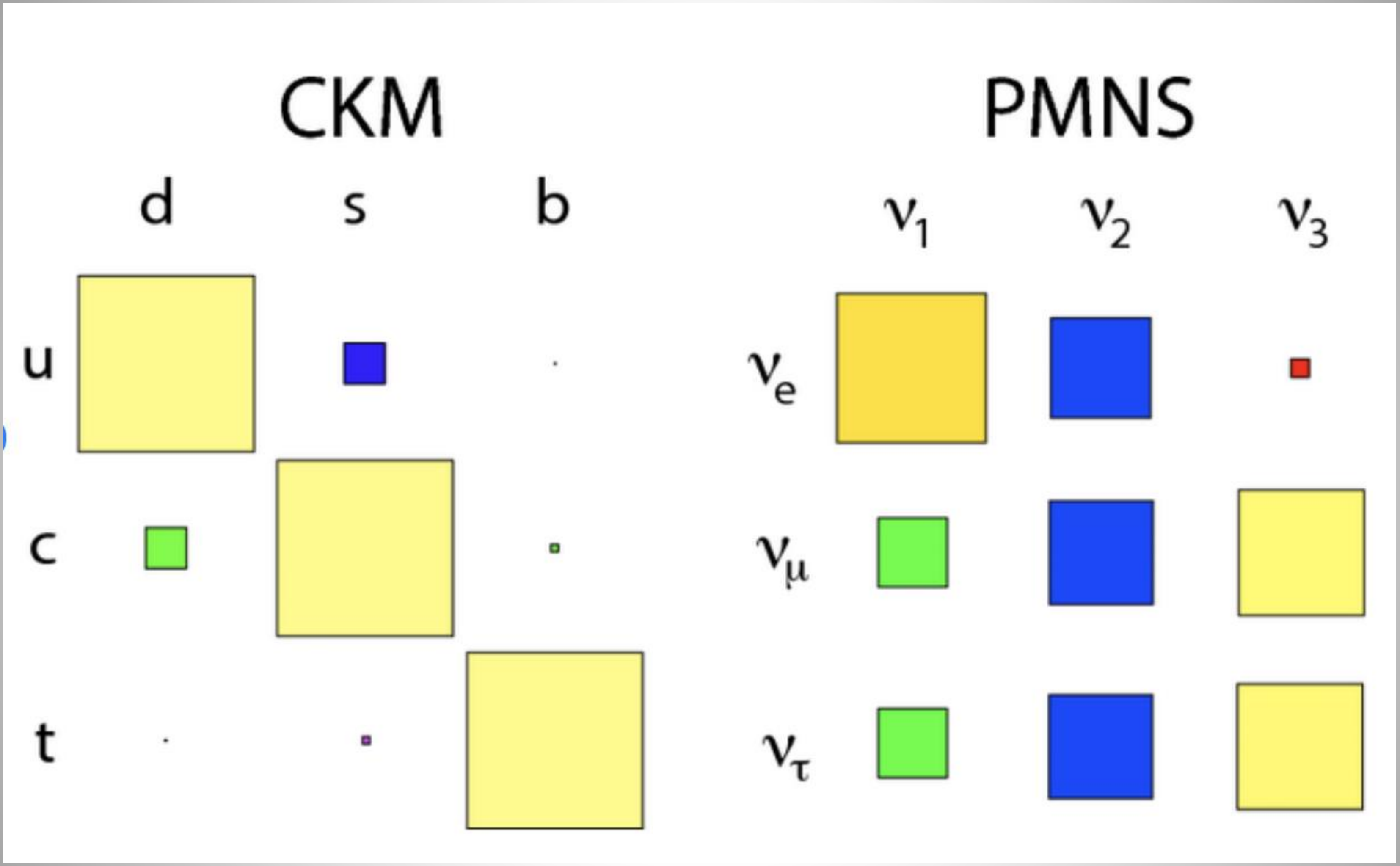
LBL experiments in the US and Japan

Neutrino Oscillations

- Standard 3-flavour ν-oscillation framework:



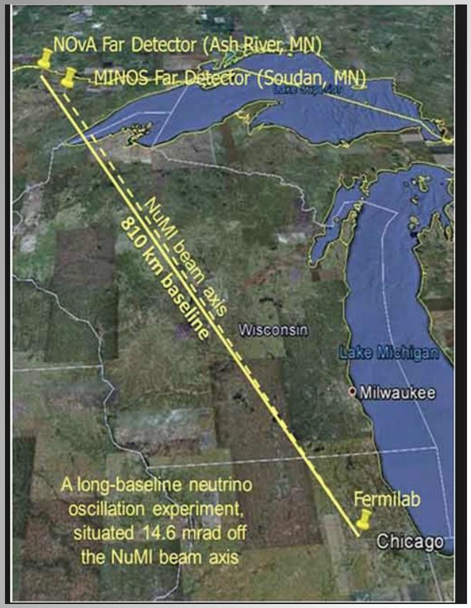
Quarks & Leptons

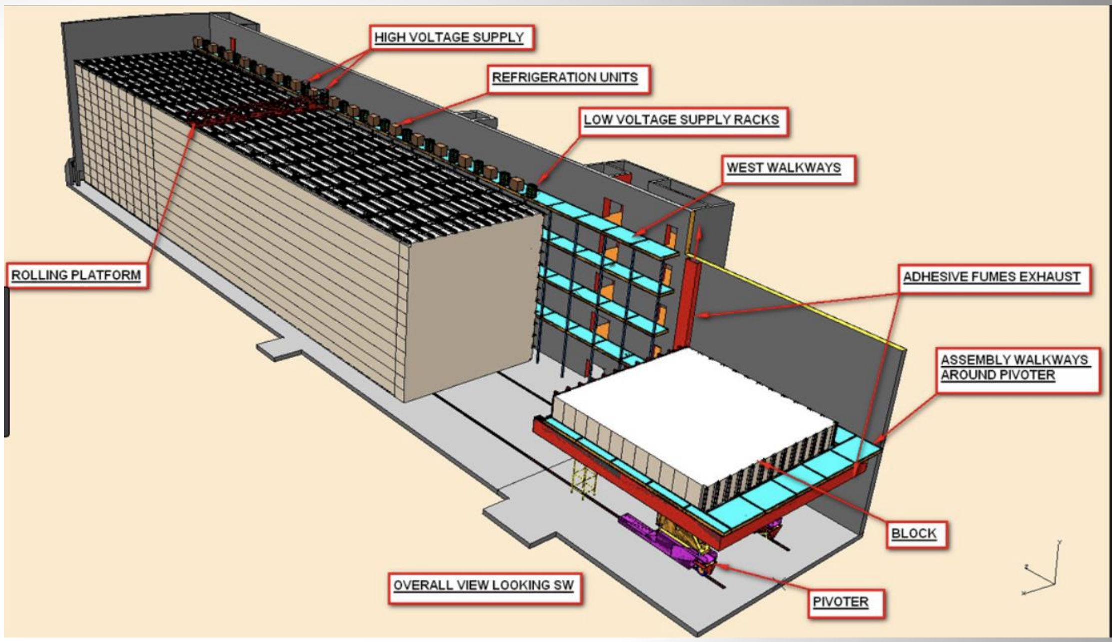


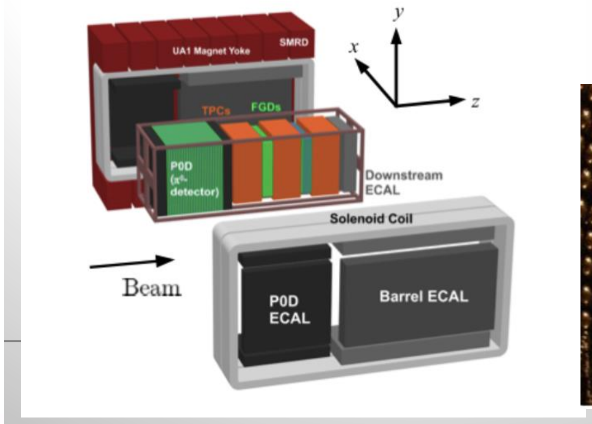
Very different flavor mixing matrix for Quarks and Leptons !!

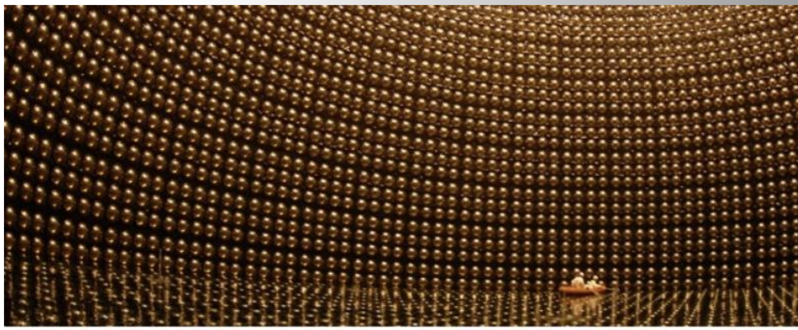
Neutrinos from an Accelerator

The T2K and NOVA LBL Experiments





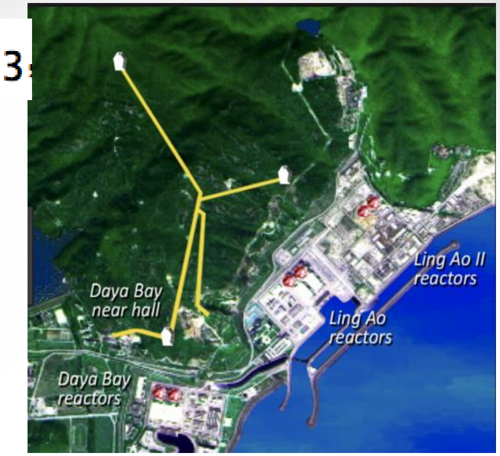


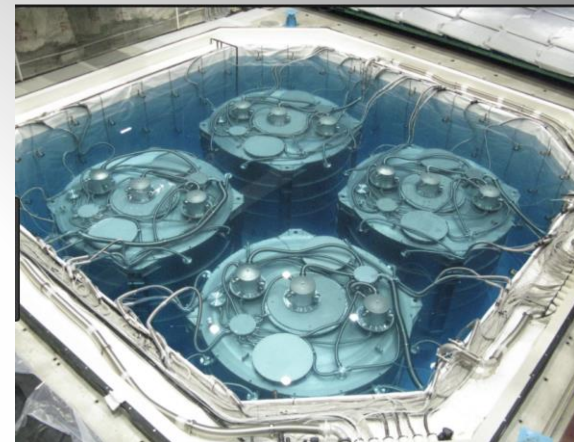


Short Baseline Experiments

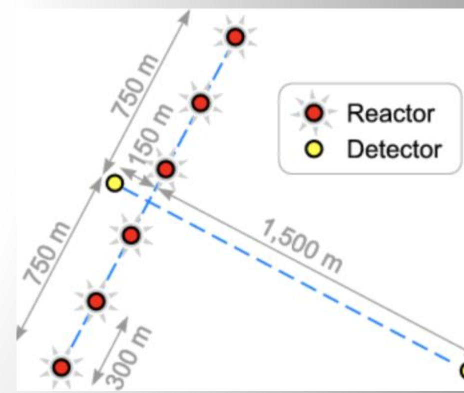
Measuring the mixing angle θ_{13}

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

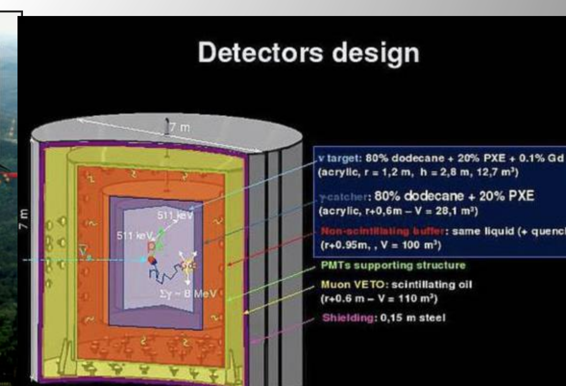




RENO (South Korea)
Two anti-neutrino detectors
(liquid scintillator based)
~up to 1.5 km of 6 reactors



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



Taking all available data together…

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

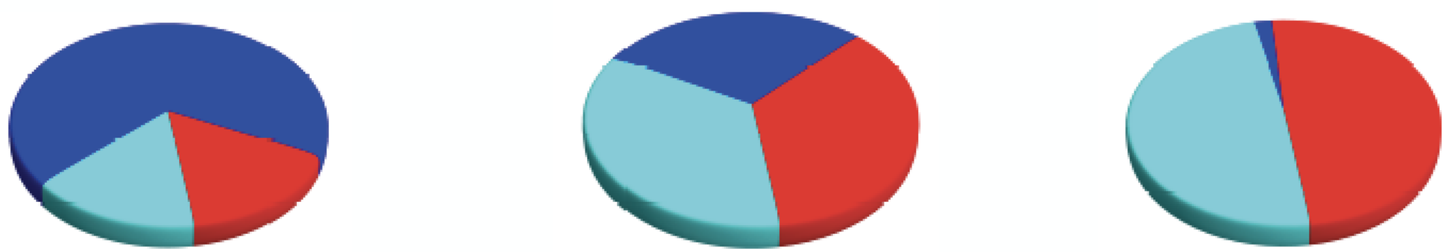
To explore Beyond the Standard Model ~ 10 times better precision needed

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	ν_2	ν_3
most ν_e		least ν_e



$\nu_e =$

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$

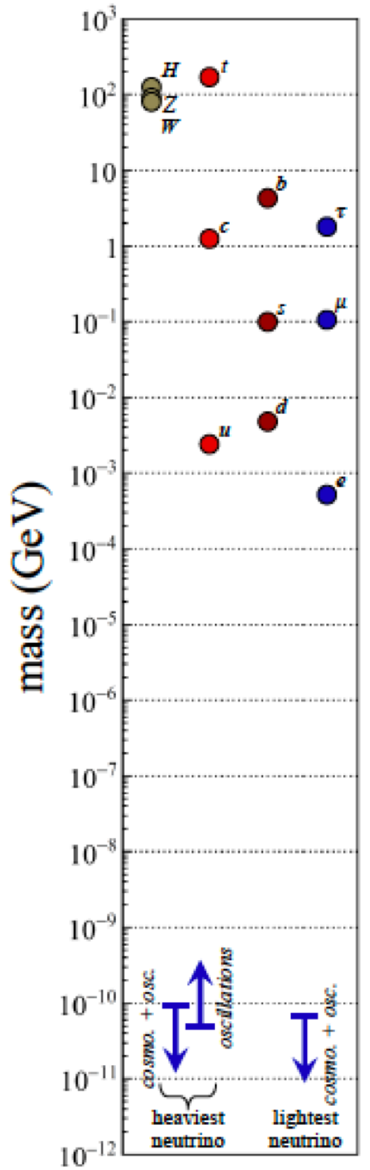
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$

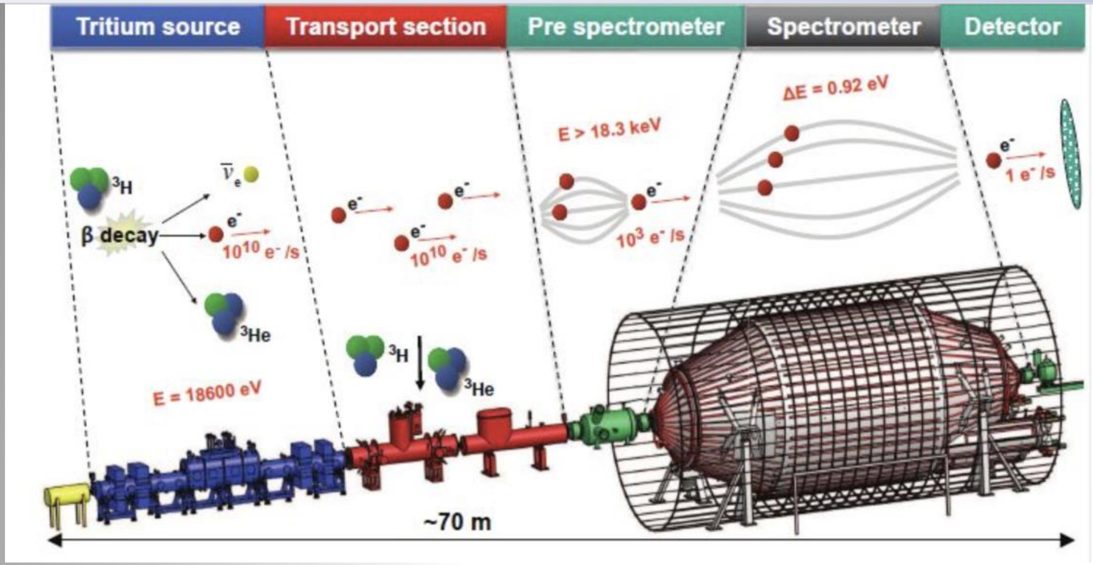
Unitarity
SK, Opera
ICECUBE ?

Neutrinos have Mass

- This was not expected in the minimal Standard Model
- The masses are very small, eg less than ~1 eV for electron neutrinos. This is ~ a million times smaller than the electron mass
- Unlikely that these small masses can be explained by the Higgs mechanism
- Proposed mass generating mechanisms require Physics Beyond the Standard Model !!



Katrin Experiment: the Mass of ν_e



The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

Recent result $M\nu_e < 1.1$ eV (September 2019)

Open Questions: CP Violation?

Do neutrinos and anti-neutrinos oscillate differently ?

Charge-Parity (CP) violation

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

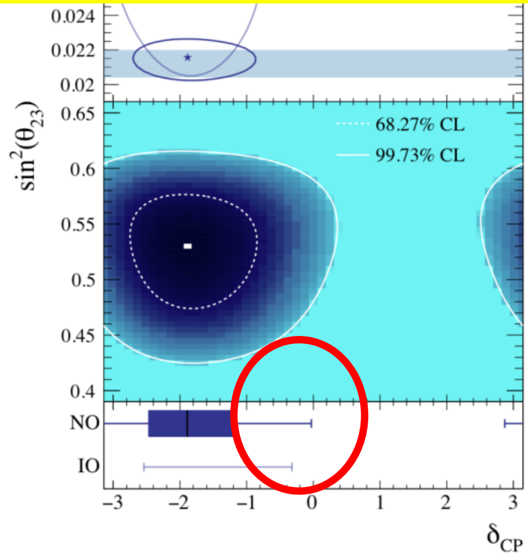
part-per-billion level of matter/antimatter asymmetry in early universe

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 (neutr**

Breaking news: T2K exp.
sin**δ**= 0 excluded at 3**σ** !!
to appear in Nature



$\sin\delta \neq 0$?

Leptonic CP violation?

Neutrinos could be the key to one of the most important questions today:
Where is the anti-matter in our Universe?

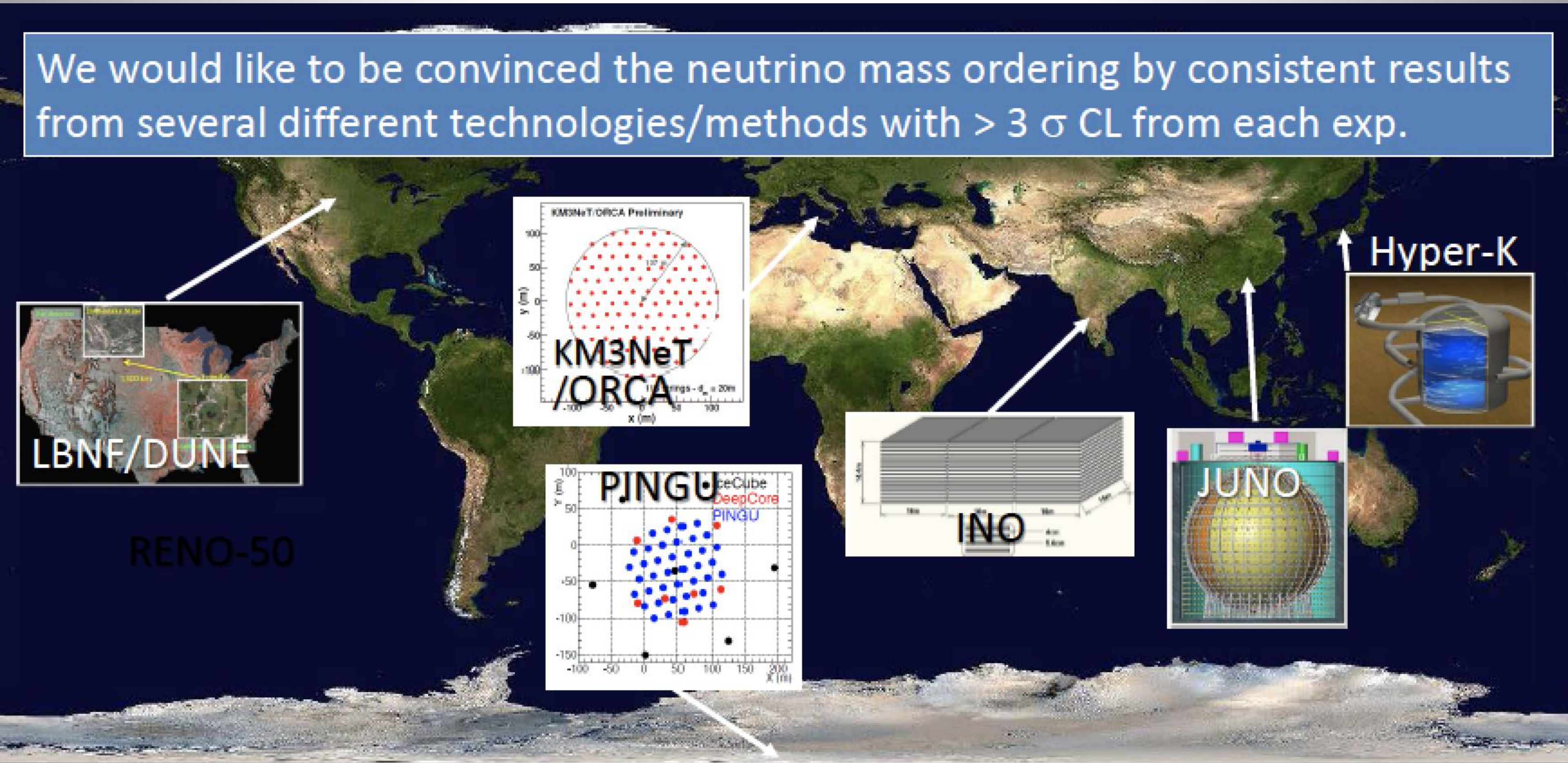
[1] M. Fukugita and T. Yanagida (1986); rich history since then.

The Future

“The age of precision physics with neutrinos”

Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question

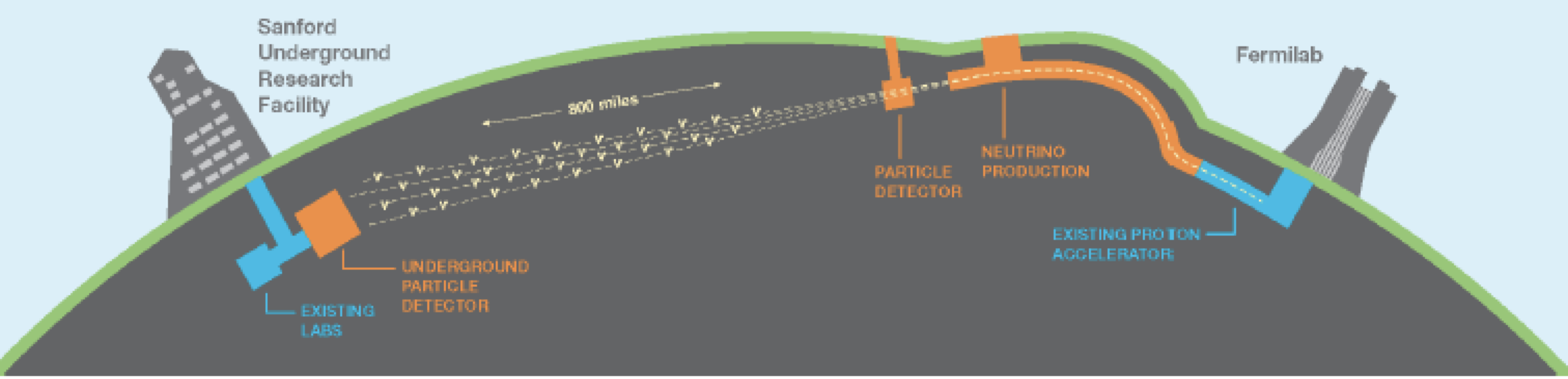


DUNE

<u>D</u>eep <u>U</u>nderground <u>N</u>eutrino <u>E</u>xperiment

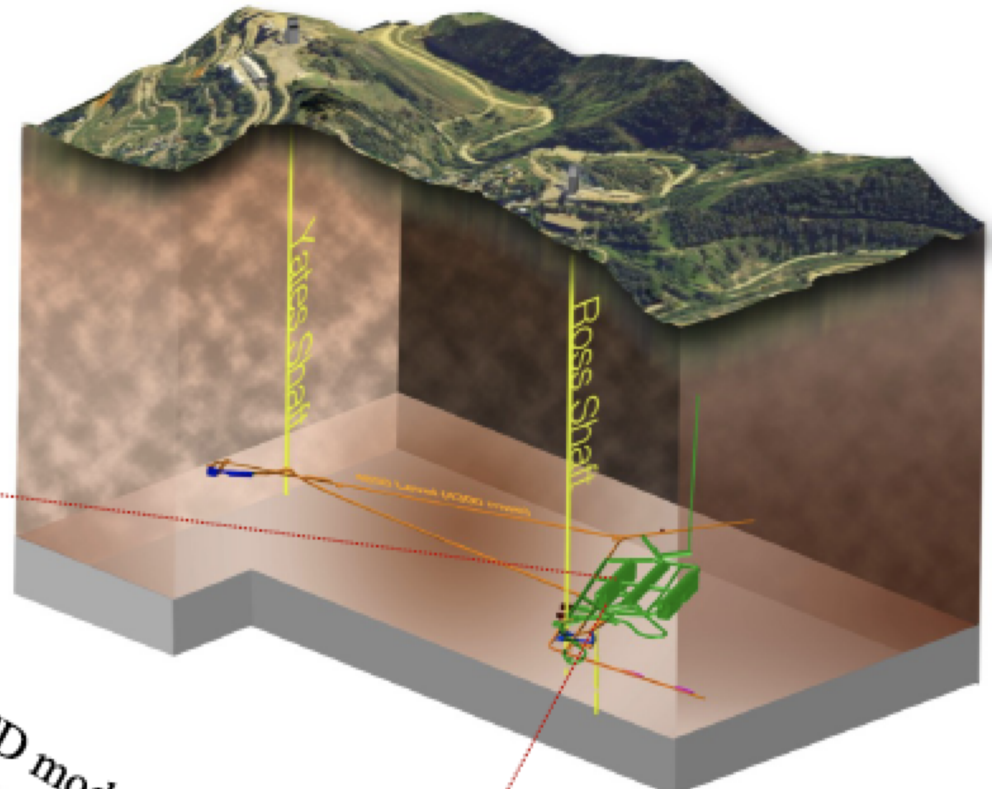
A next generation experiment for **neutrino science**, **nucleon decay**, and **supernova physics**

First data in 2026

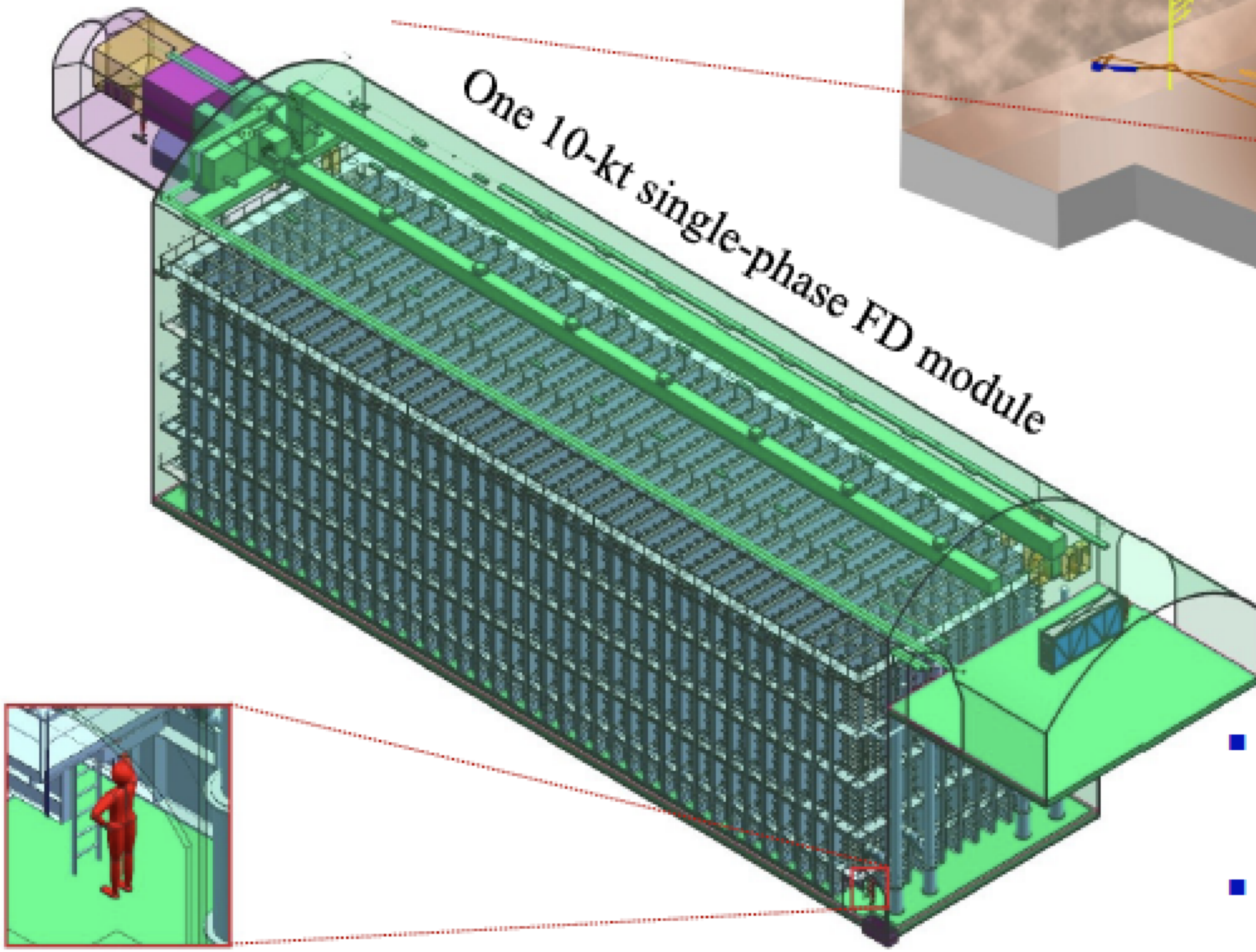


DUNE Far Detector

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



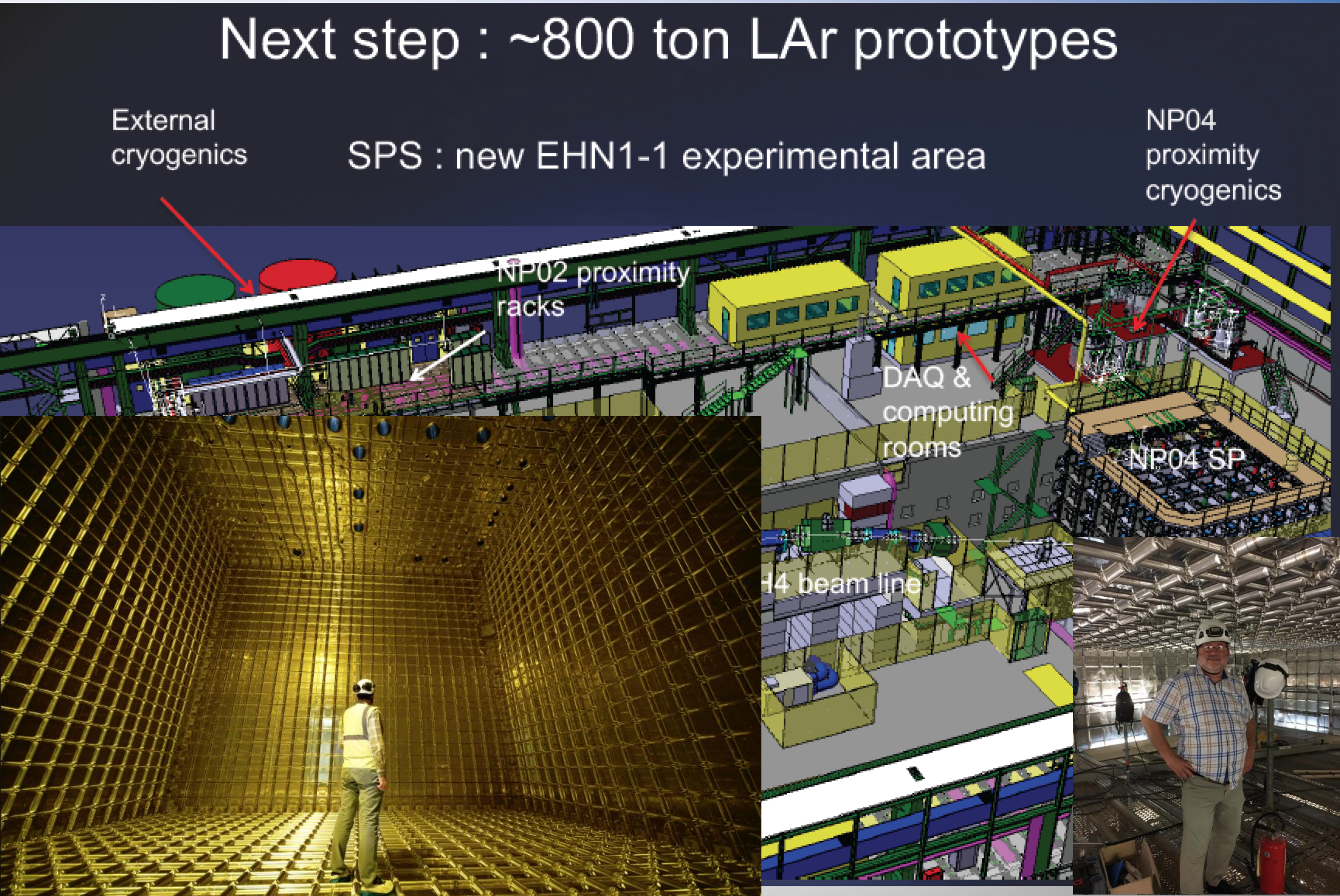
Sanford Underground Research Facility (SURF)



1.5 km underground

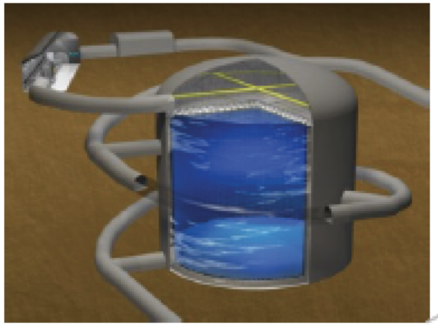
- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

The ProtoDUNEs at CERN



Hyper-Kamiokande

Upgrade of the Super-kamiokande experiment in Japan



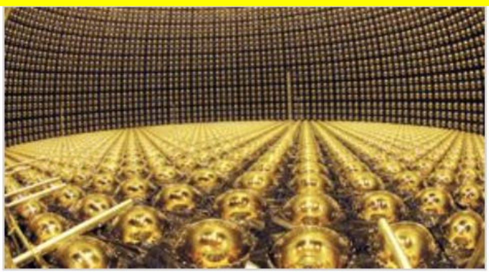
Hyper-K

First data in 2026

J-PARC

Accelerator Complex

Breaking News 16/12



Japan will build the world's largest neutrino detector

Cabinet greenlights US$600-million Hyper-Kamiokande experiment, which scientists hope will bring revolutionary discoveries.

utrino and nucleon decay detector

fiducial mass : ~10 × Super-K

photon sensitivity than Super-K

etector capability, technology still evolving

tion maximum by 2^{nd} tank in Korea under study

Sub-GeV ν beam

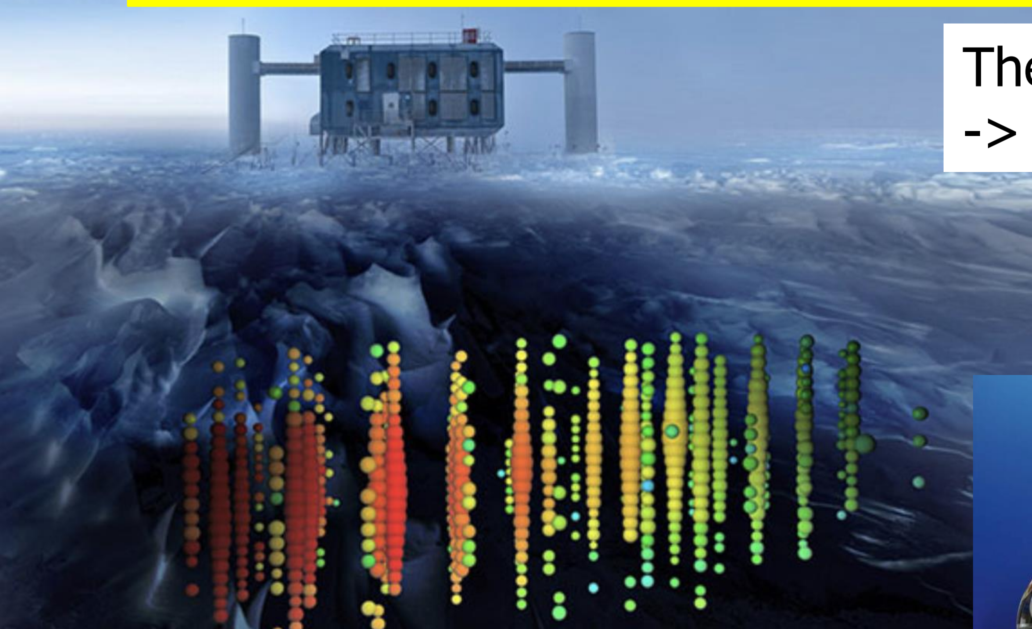
orld-leading ν-beam by upgraded J-PARC

is a priority project by MEXT's Roadmap

start construction in FY2019, operation in FY2026

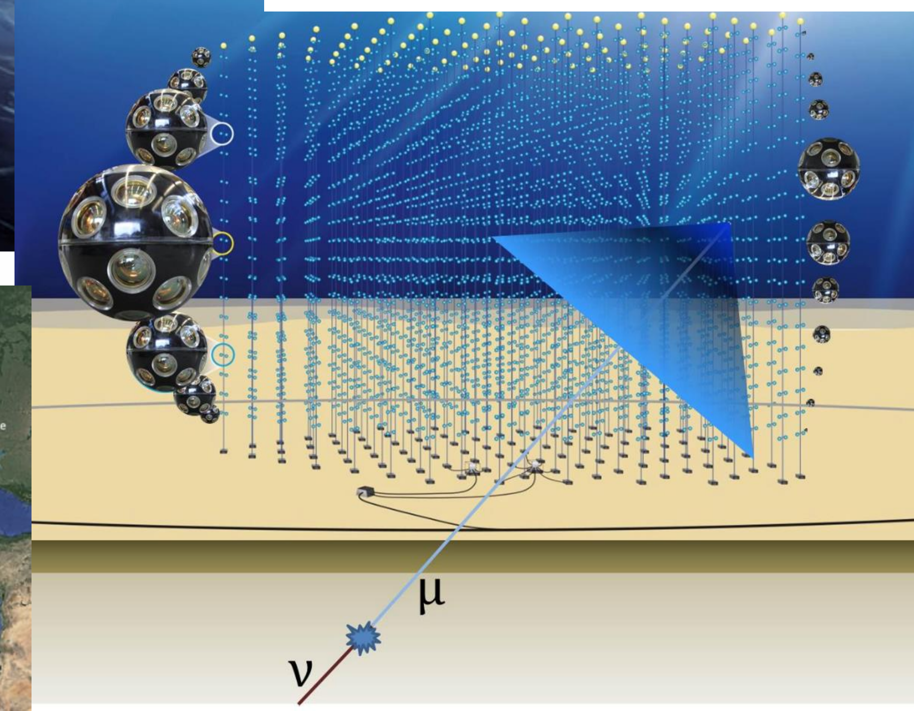
Neutrino Astronomy

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

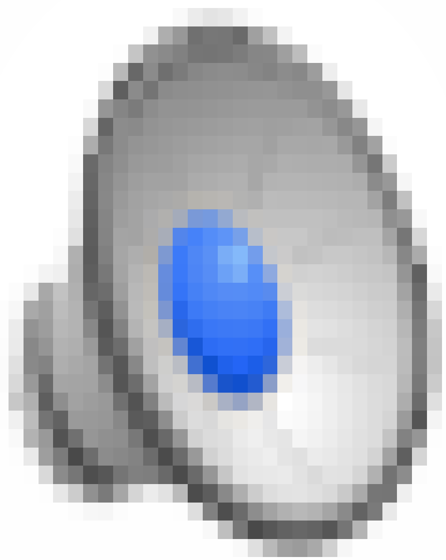


The IceCube Experiment
-> In the ice of Antartica

The KM3NET Experiment
-> In the Mediterranian sea



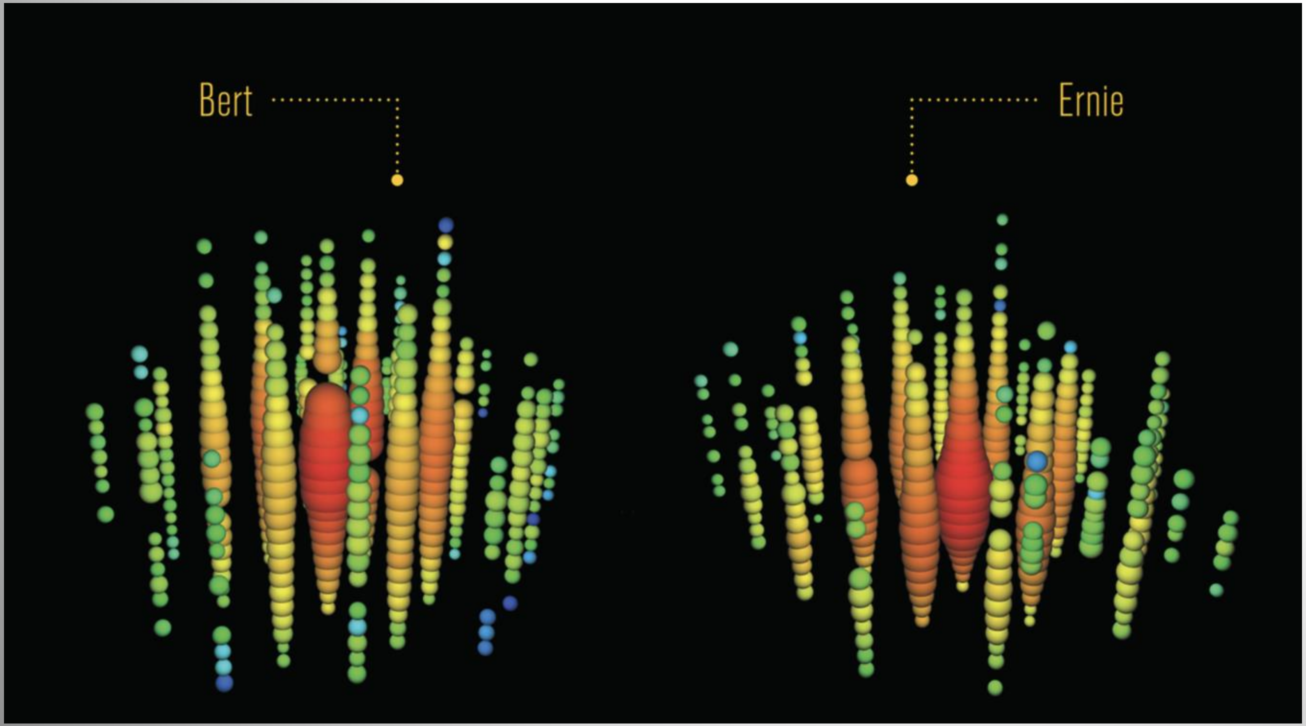
Neutrinos in the Ice



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 named "Bert" and "Ernie

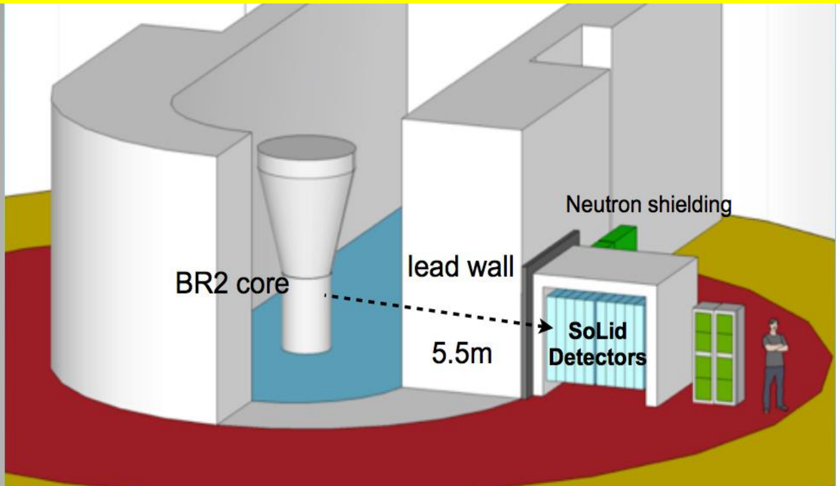


Are there more than 3 Neutrinos?

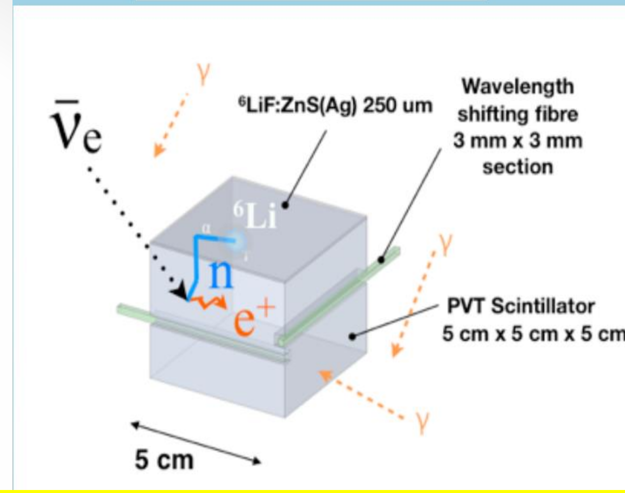
- Is there is a 4th (5th…) neutrino then it has to be quasi-sterile, ie should not couple significantly to other fermions and bosons, as we know from measurements at LEP
- Could mix with the known neutrinos
- Some indication since more than 10 years (LSND, reactor anomalies, Gallium anomalies)
- The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

New Short Baseline Experiments will check!

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

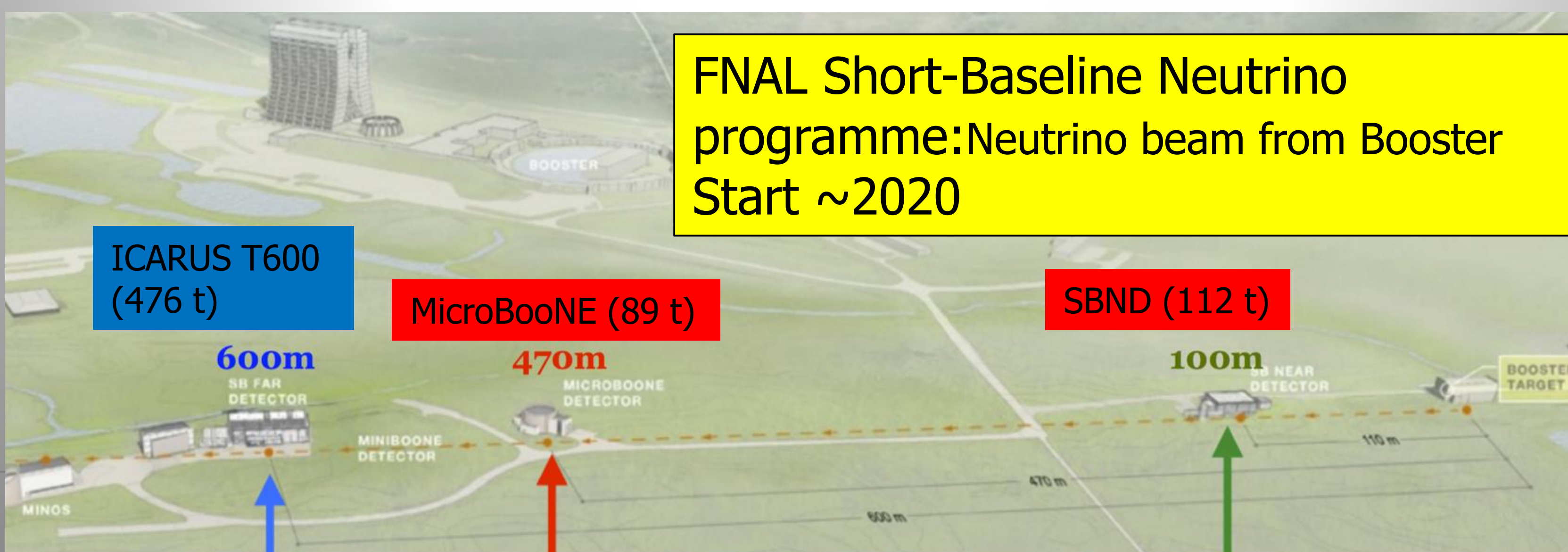


$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Also: Prospect, STEREO, DANSS, NEOS

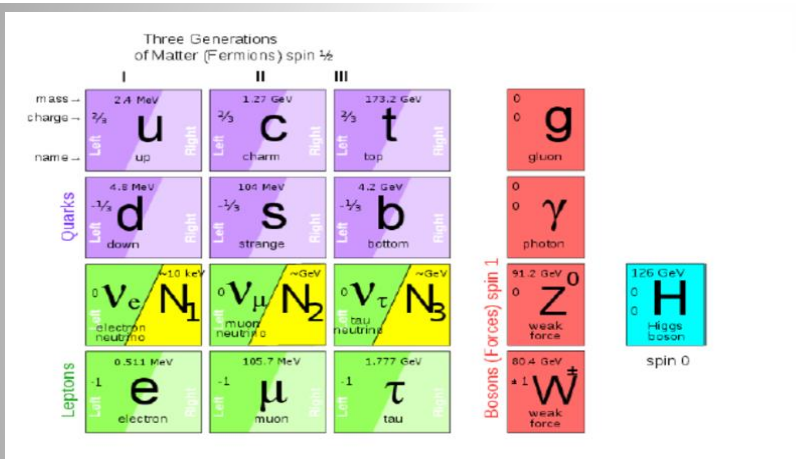
FNAL Short-Baseline Neutrino programme: Neutrino beam from Booster
Start ~2020

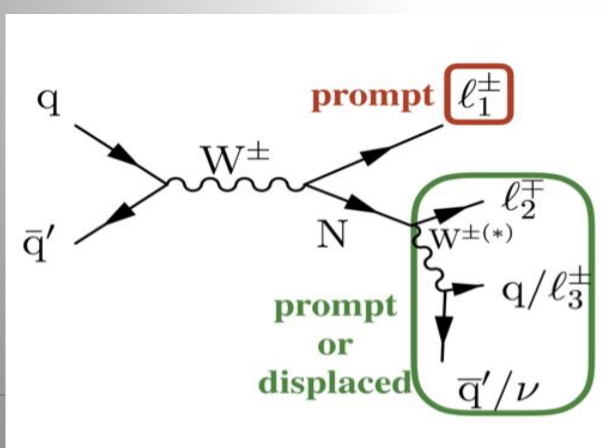


Neutrinos @ the LHC: Examples

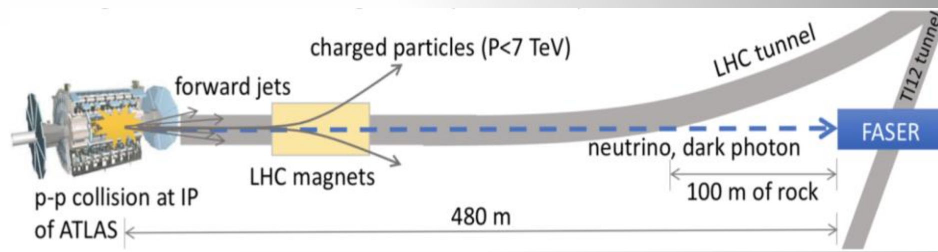
Searches for right-handed neutrinos at the LHC

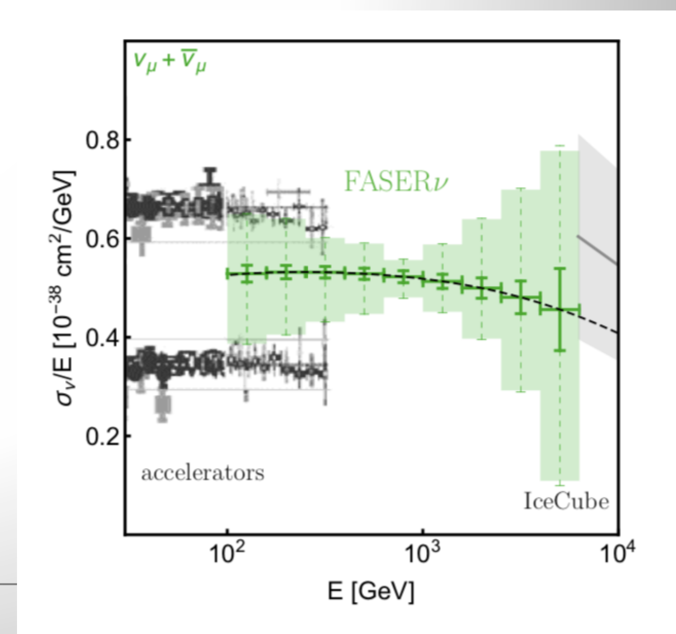
νMSM (Neutrino Minimal Standard Model)





XSEN and FASER-Nu are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors

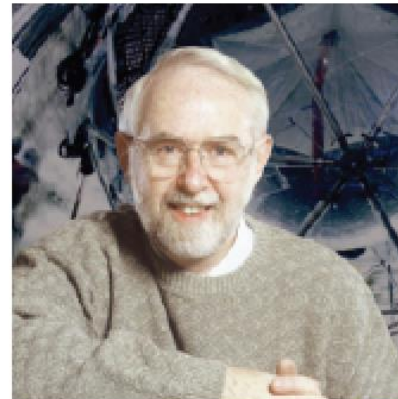




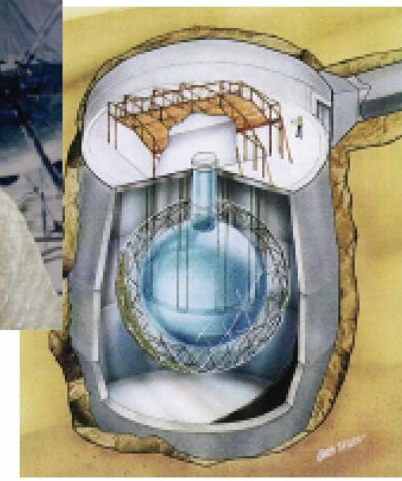
NOBEL 2015

"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 Other Nobel prizes for Neutrino Physics
- 2002: R. Davis and M. Koshiba
- 1995: F. Reines
- 1988: L. Lederman, M. Schwartz and J. Steinberger

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.
- High energy right-handed partners? Strong CP violation? More than 3 neutrinos? Non Standard Interactions? Are neutrinos their own anti-particle?
- The history of neutrino research has been full of surprises. What surprise is waiting for us next??
- Now comes the age of neutrino precision physics and neutrino astronomy: look inside the sun, understand supernovae explosions, multi-messenger astronomy…