Neutrino Oscillations

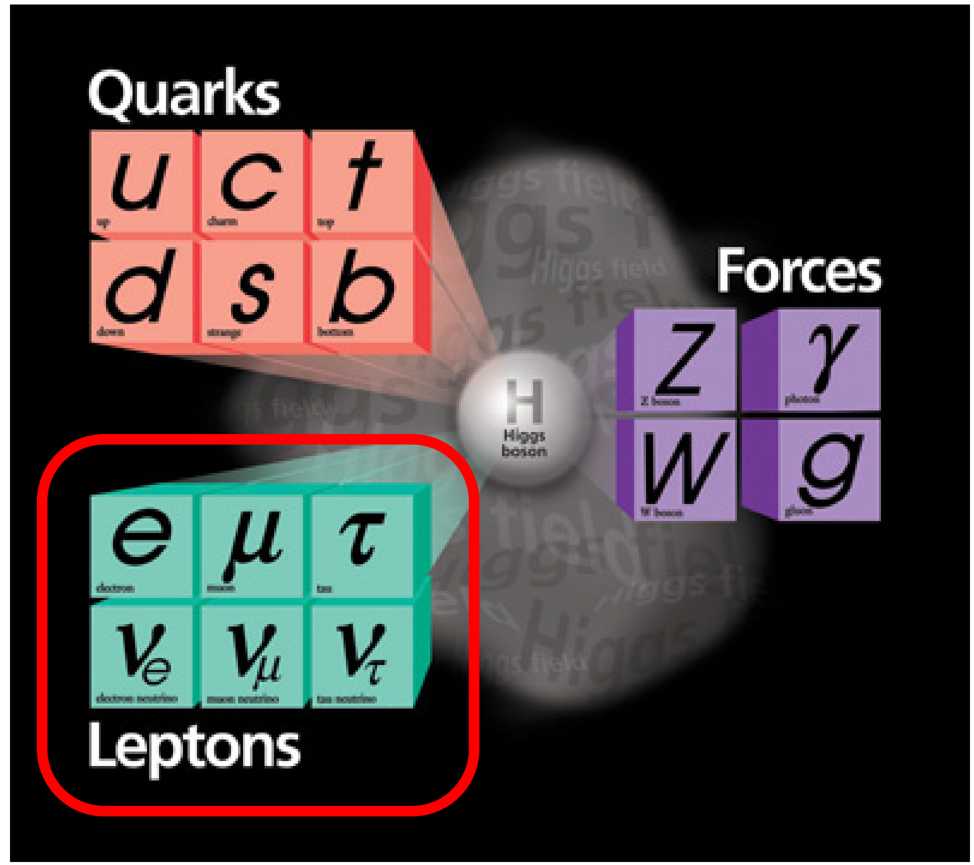
Peter H. Garbincius – at Fermilab since 1976
home of world's *former* highest energy particle accelerator
December 2, 2018 - first presented: November 8, 2015

- **2015 *Nobel Prize*!**
- **why is it so exciting?**
- **historical perspective**
- **how science works:**

  observations → puzzles → questions → theories → predictions → experiments

- **continuing questions**

particle physicists' "Periodic Table"



we'll be discussing neutrinos ν_e, ν_μ, ν_τ, and their associated charged leptons

e^-, μ^-, τ^-

non-accelerator particle physics

- Often done deep in mines
  to minimize background from cosmic rays
- Different techniques than high energy physics
  - High sensitivity, high purity
  - radiochemical analysis, nuclear & atomic physics
  - detection of slow neutrons
- MeV range (Million electron-Volts)
  - not GeV (Billion electron-Volts)
  - or TeV (Trillion electron-Volts)

  study ν properties in ≤ eV (electron-Volt) range

important steps in Neutrino Oscillations

(many Nobel Prizes along the way)

1912 - Victor Hess (1936) - discovery of cosmic radiation in 1912 - (big impact later)

1920 – Arthur Eddington proposes fusing hydrogen into helium to power the sun

1930 - Wolfgang Pauli – proposed neutrinos – ***discovery of Exclusion Principle (1945)***

1933 - Enrico Fermi – Weak Interactions - ***neutron-induced nuclear reactions (1938)***

1938 - Hans Bethe (1967) – theory of nuclear reactions for energy production in stars

1956 - Frederick Reines (1995) – detection of electron neutrino (Clyde Cowan deceased)

1962 - Lederman, Schwartz, Steinberger (1988) - discovery of the muon neutrino (2 ν)

1967 - Raymond Davis (2002) – detection of cosmic neutrinos
– deficit of observed ν_e from sun $\rightarrow$ solar neutrino problem

1973 - Makoto Kobayashi and Toshihide Maskawa (2008) - prediction of
at least 3 families of quarks (and leptons)

1975 - Martin Perl (1995) – discovery of the Tau Lepton
2001 - DONUT Experiment (Fermilab) – discovery of tau neutrino 3^{rd} ν

1987 - Masatoshi Koshiba (2002)– detection of cosmic neutrinos - 1983-1988

1998 - Takaaki Kajita (2015) Super-KamiokaNDE and

2002 - Arthur McDonald (2015) SNO (Herbert Chen deceased)
- discovery of neutrino oscillations - showing neutrinos must have mass

at least three threads – solar physics

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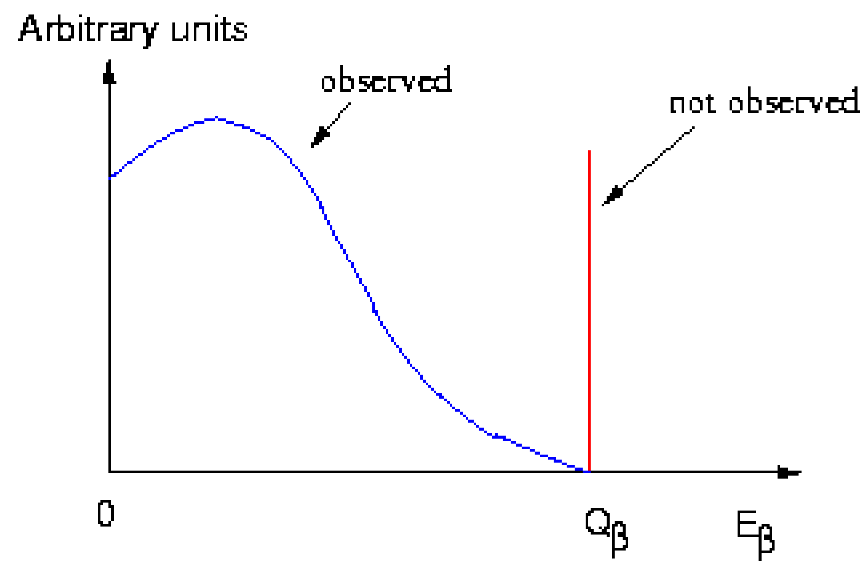
neutrino properties thread

- α, β, γ radioactivity discovered in early 1900s
- by conservation of energy and momentum for a two-body decay, it was expected energy of β-particles (electrons) to be a ***single*** energy for each decay of one particular decay chain
  $N \rightarrow N' + \beta$ but the β-particles ($= e^-$) had different energies



- ***BIG PROBLEM***

$\rightarrow$ three-body decay

- $N \rightarrow N' + e^- + X$

not observed

bold solution proposed by Wolfgang Pauli in 1930

to preserve conservation of ***E, p, Spin***
unknown *X* particle would be ***neutral***
(no electrical charge) with ***Spin*** = ½,
small mass m(X) ≤ m(e⁻) = *M(proton)*/1836,
and which ***interacts very weakly with matter***

Pauli called it the "neutron" - this was before the discovery of the neutron (*udd*), a strongly interacting particle with $M(n) \approx M(p)$ in 1932

Soon thereafter, Fermi referred to Pauli's particle as the ***neutrino*** (little neutral one in Italian)

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 Grössenordnung 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.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum. I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons. which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant... ....

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

Your humble servant,

W. Pauli

so β-decay is really:

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

Pauli was disappointed that he proposed a particle which he thought could never be observed

then

1933 - Enrico Fermi – theory of Weak Interactions including β^- decay

1956 - Frederick Reines (1995) – detection of reactor ν_e (along w Clyde Cowan who died before the Prize)

26 years after Pauli's prediction!

1962 – Leon Lederman, Mel Schwartz, Jack Steinberger (1988) - discovery of the ν_μ (there are 2 neutrinos)

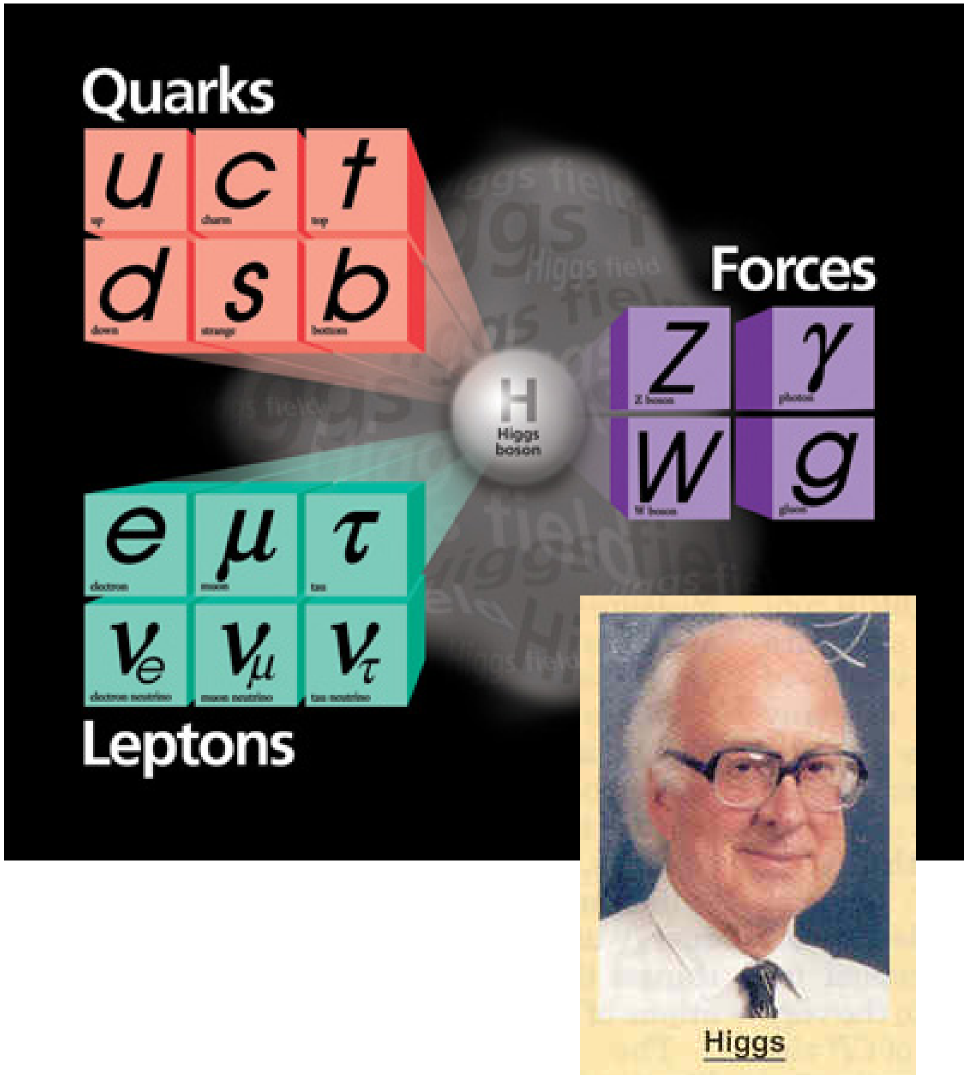
1975 - Martin Perl (1995) – discovery of the τ lepton

2001 - DONUT Experiment (Fermilab) – discovery of ν_τ (a 3rd neutrino)

…each of these has its own story

but more surprises to come…

particle physicists' "Periodic Table"

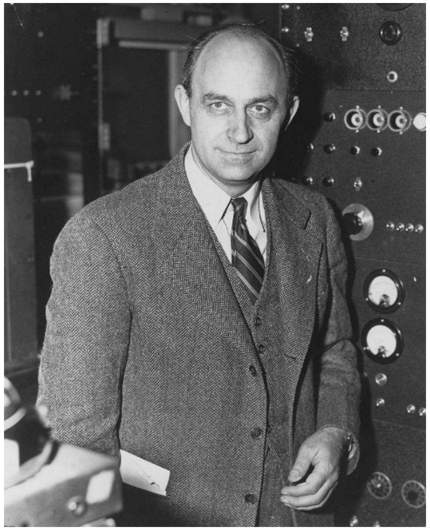


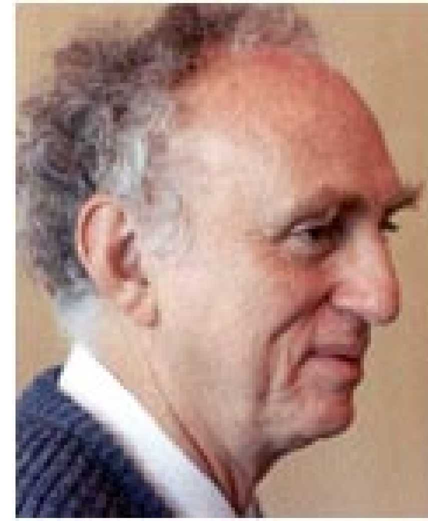
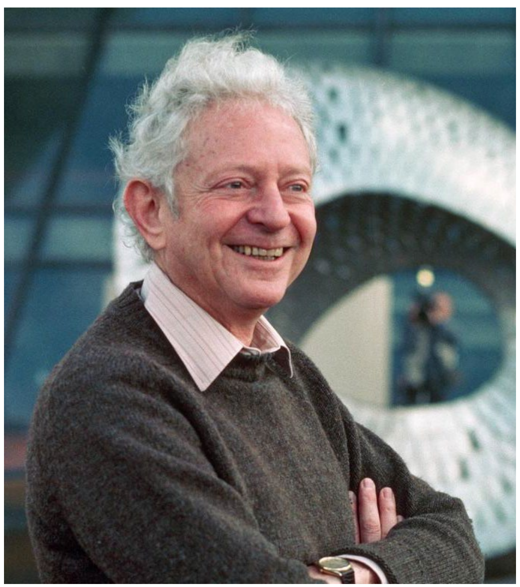
Quarks, Leptons, & Forces

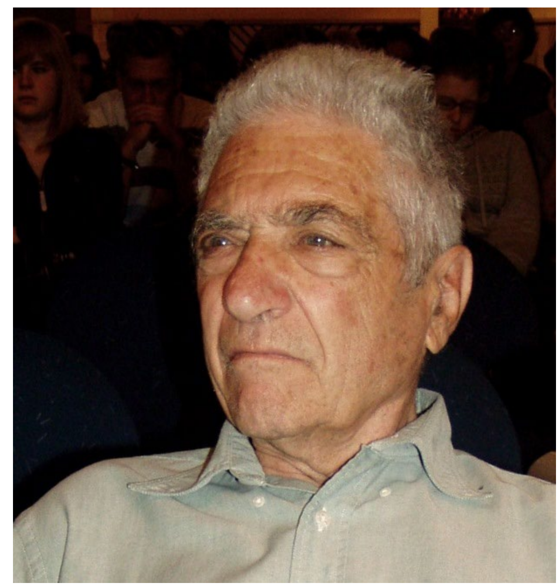
b, t, ν_τ discovered at FNAL

Electromagnetism
Strong Nuclear Force
Weak Nuclear Force
(radioactive decay)
Gravity is too weak for us

fundamental particles
no size – without parts
can't break them apart
(at least with today's accelerators)



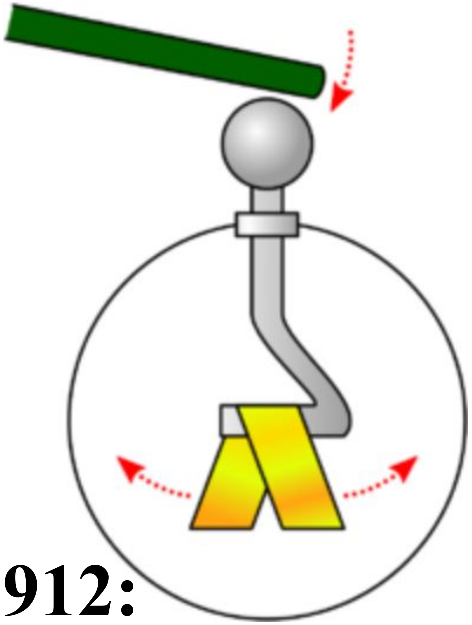


cosmic thread

Victor Hess

Nobel Prize

1936



Balloon ascents in 1912:

Ionization *decreased* from 0 m – 1 km height

terrestrial radiation

Ionization *increased* from 1 km – 5 km height

not from earth

12 april 1912: Ionization at 2-3 km height

did NOT decrease during solar eclipse

not from sun

Ray Davis – search for solar ν_e

- in order to check theoretical models of energy production in stars
- sun produces 60 Billion $\boldsymbol{\nu_e}$ per cm^2 per sec on earth. Virtually all pass thru you unnoticed!
- 615 metric tons of dry cleaning fluid, observe few MeV solar $\boldsymbol{\nu_e + {}^{37}Cl \rightarrow {}^{37}A + e^-}$

  same as inverse β-decay

  $$\boldsymbol{\nu_e + n \rightarrow p + e^-}$$

- according to the Standard Solar Model, Ray expected to produce one ^{37}A atom per day, but only observed one ^{37}A atom every 2.5 days

the solar neutrino problem

extremely difficult measurement, detect < one ^{37}A atom per day! in 2 x 10^{30} atoms - needle in a haystack!

Many people didn't believe Ray's result, but nobody could disprove his result and other experiments started to confirm it

Standard Solar Model was checked, refined, & fit all other observations!

Something strange in the neighborhood!

Homestake Mine, Lead, South Dakota
where DUNE experiment will be constructed!

meanwhile, back in the world of hadrons

in the1960's K_s^0 $(d\bar{s}) \leftrightarrow \overline{K_s^0}$ $(\bar{d}s)$

matter ↔ anti-matter oscillations were discovered

1964: Jim Cronin and Val Fitch (1990) discovered

violation of the ***CP*** symmetry in the K^0 oscillations

1973 - Kobayashi and Maskawa (2008) predicted

at least 3 families of quarks and

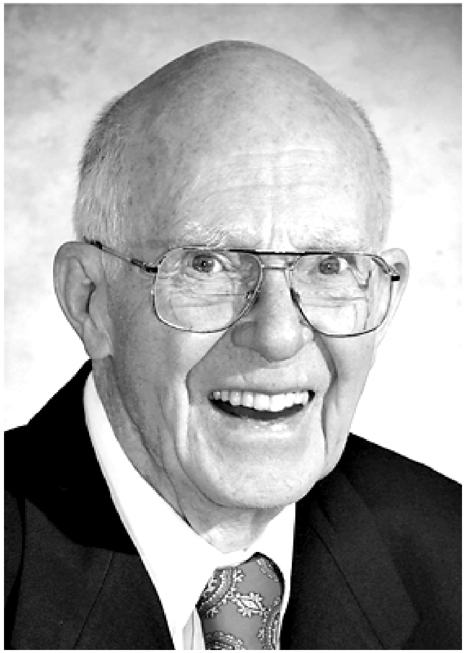
CP-violating transitions and oscillations

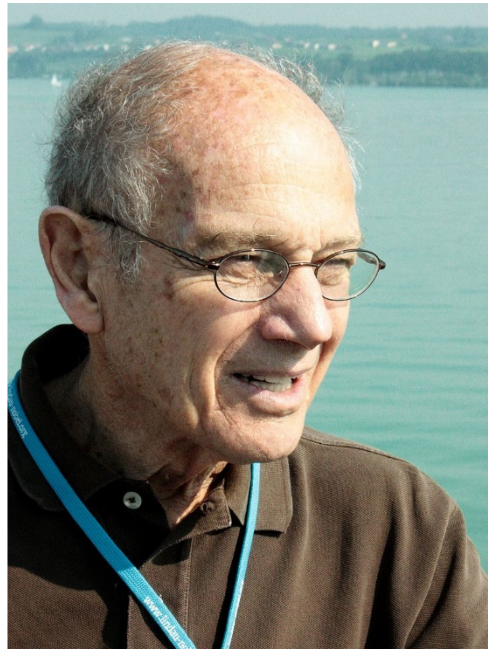
1977: at Fermilab, Leon Lederman *et al.*,

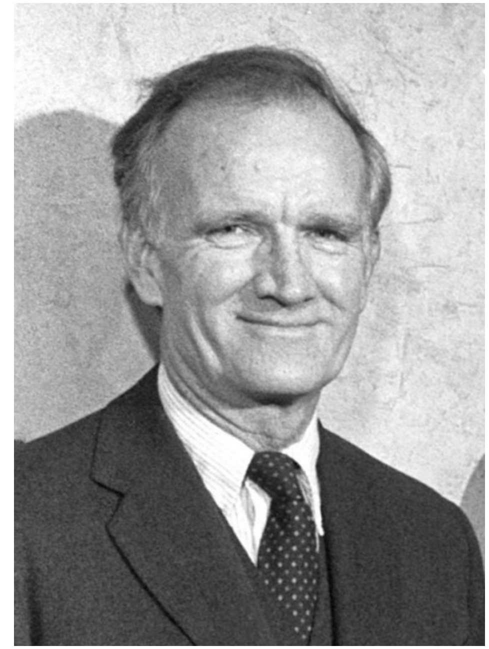
discovered ***b-*** or ***bottom quark***, 3rd matter family

and discovery of ***t-*** or ***top quark*** in 1995

~ 2000: observed $B^0 \leftrightarrow \overline{B^0}$, and $B_s^0 \leftrightarrow \overline{B_s^0}$ oscillations

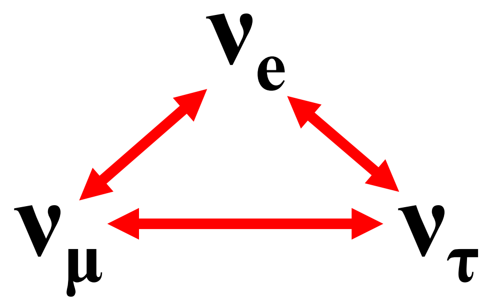






Koshiba

if matter can oscillate, why not neutrinos?



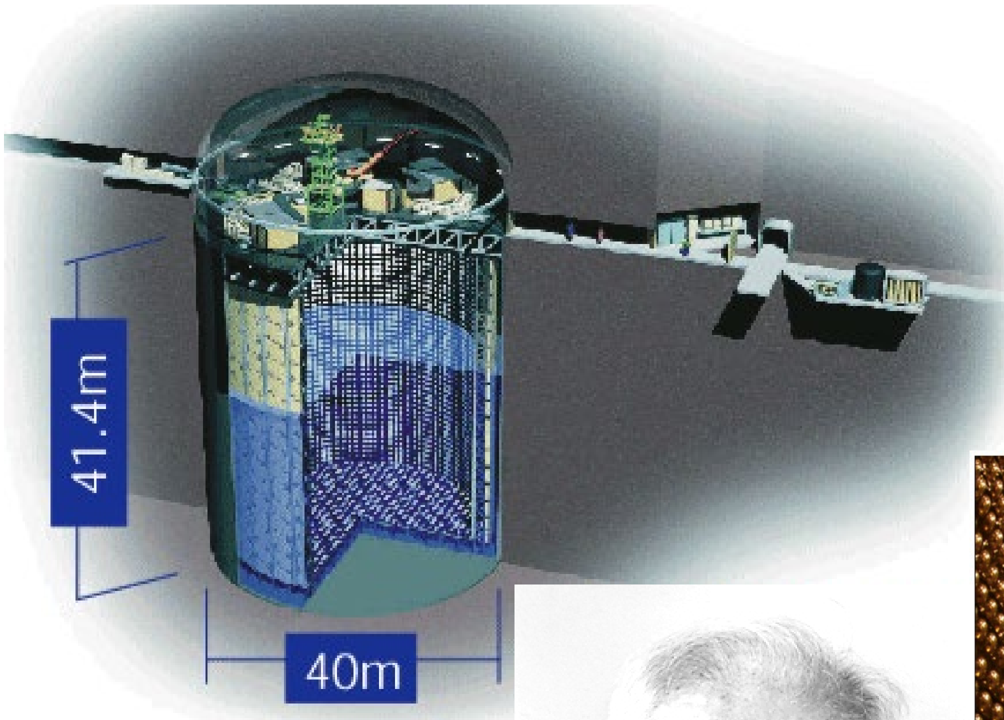
maybe that could resolve the solar neutrino problem, that during their trip from sun $\rightarrow$ earth some of the expected solar ν_e had oscillated $\nu_e \rightarrow \nu_\mu$ or ν_τ which weren't observable in Ray Davis' experiment …

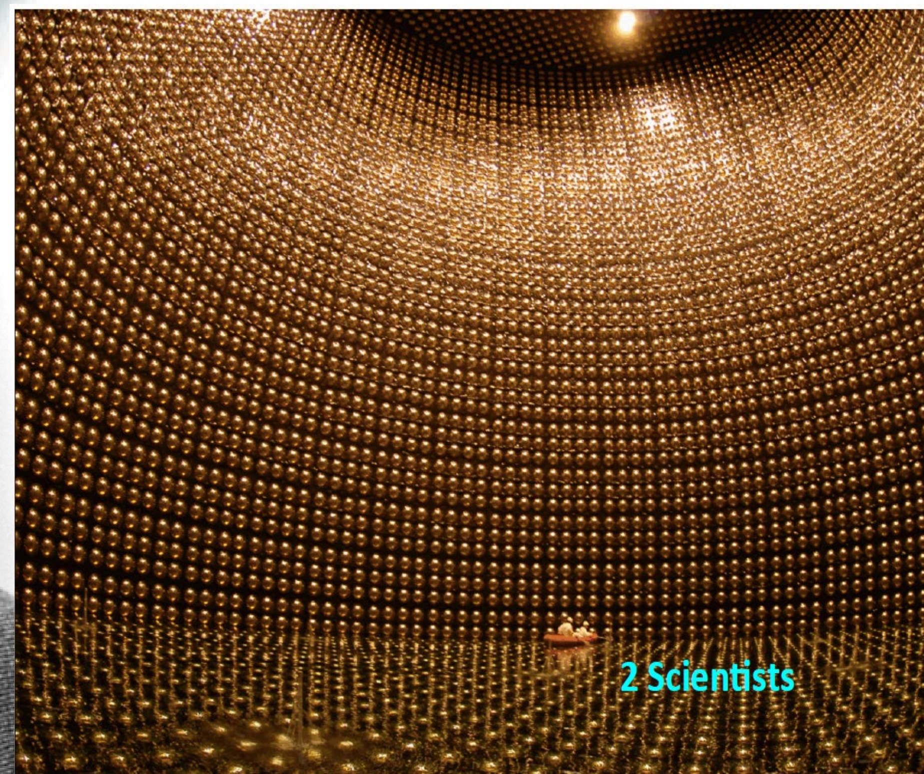
cosmic (high energy) neutrinos 10s or 100s of GeV or greater

1983-1988 - Masatoshi Koshiba (2002) *et al*.
built the *KamiokaNDE* detector in a Zinc mine in Kamioka, Japan
Kamioka Nucleon Decay Experiment
3,000 tons water w 1,000 photomultipliers
they did not observe proton decay
diamonds are forever…
but did observe cosmic ray neutrinos
and also ν_e from SN1987A
also similar IMB exp = Rep. Bill Foster's thesis exp

for ν physics – bigger is better $\rightarrow$ Super-K

Super-KamiokaNDE
50,000 tons of water &
13,000 photomultipliers
1 km deep underground





E. Kerns, T. Kajita, and Y. Totsuka, Detecting Massive Neutrinos, Scientific American **281**, 64 - 71 (1999).

Super-K detects ν_e & ν_μ produced by high energy cosmic rays in the atmosphere

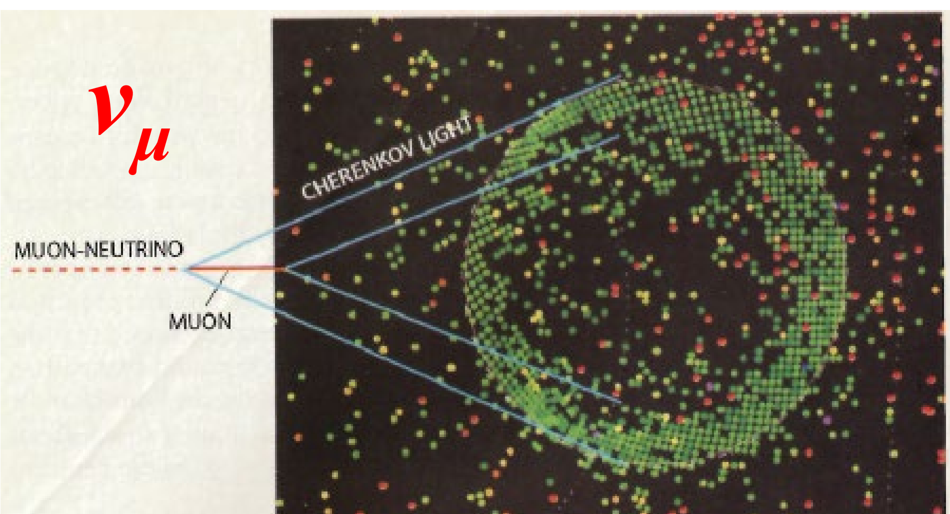
Charged current neutrino interactions:

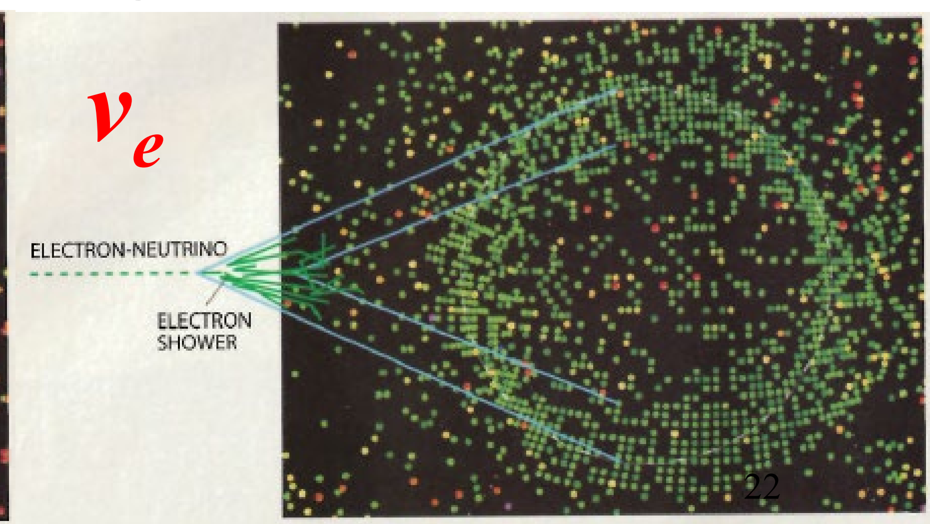
$$\nu_\mu + N \rightarrow \mu^- + X \qquad \bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

$$\nu_e + N \rightarrow e^- + X \qquad \bar{\nu}_e + N \rightarrow e^+ + X$$

but *not many* ν_τ or $\bar{\nu}_\tau$ interactions

can't tell positive from negative leptons





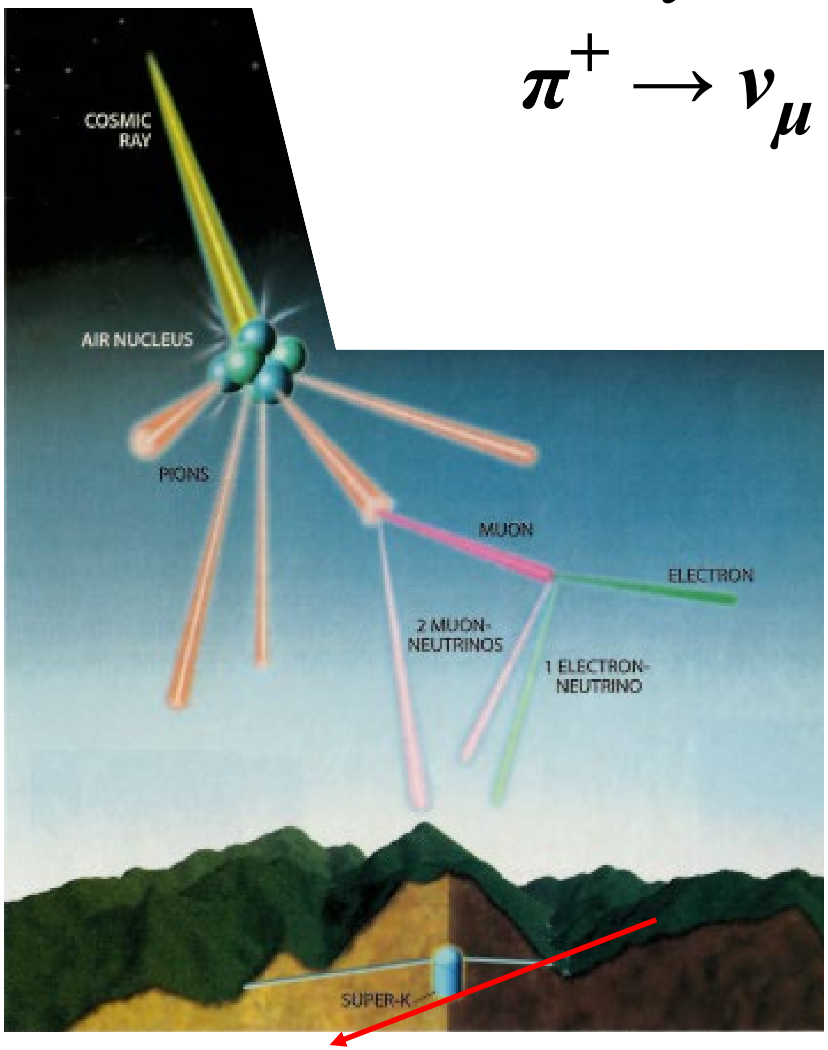
In the upper atmosphere high energy cosmic rays

γ, p, Fe + **air** $\rightarrow$ hadronic shower with many $\pi^{\pm}$

with decay chain

$$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}}$$



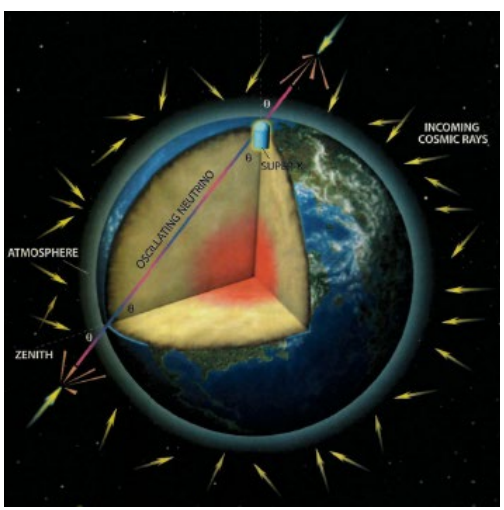
expect **~2 μ-like neutrinos** for every ***e*-like neutrino** but few **τ-like neutrinos**

for downward-going ν, Super-K found **1.3** ν_{μ} per ν_{e}

a clear ***deficit***

What could this be?

- Incorrect calculation of expected ratio
- Inefficiency for ν_μ events
- Neutrino oscillations? If so,
  - are $\nu_\mu \rightarrow \nu_e$? then $\#\nu_\mu \downarrow$, $\#\nu_e \uparrow$
  - are $\nu_\mu \rightarrow \nu_\tau$? then $\#\nu_\mu \downarrow$, $\#\nu_e$ stays the **same**
  - Check these by studying azimuthal dependence



downward-going ν, distance ~ 15 km

ν produced overhead

upward-going ν, distance ~ 12,800 km

ν produced on the other side of earth

ν are not absorbed in passing thru earth, but have ***longer time to oscillate***

phenomonology of ν oscillations

for two neutrinos $\nu_\mu \rightarrow \nu_x \rightarrow \nu_\mu$ ... *etc.*
exactly same for 3 ν, math more complicated

by quantum interference of two states $\nu_\mu - \nu_x$

ν_μ disappearance $\rightarrow$ oscillate into ν_x

Starting out with a pure ν_μ beam, the probability of seeing ν_μ as a function of Energy & Distance:

$$P\nu_\mu(E,L) = 1 - \sin^2(2\theta_{\mu x})\,\sin^2(1.27\,\Delta m^2_{\mu x}\,L/E)$$

where L = distance in km, E = energy in GeV,

$\Delta m^2_{\mu x} = m^2(\nu_\mu) - m^2(\nu_x)$ (note ***square***!)

$\sin^2(2\theta_{\mu x})$ = coupling strength $\nu_\mu \leftrightarrow \nu_x$

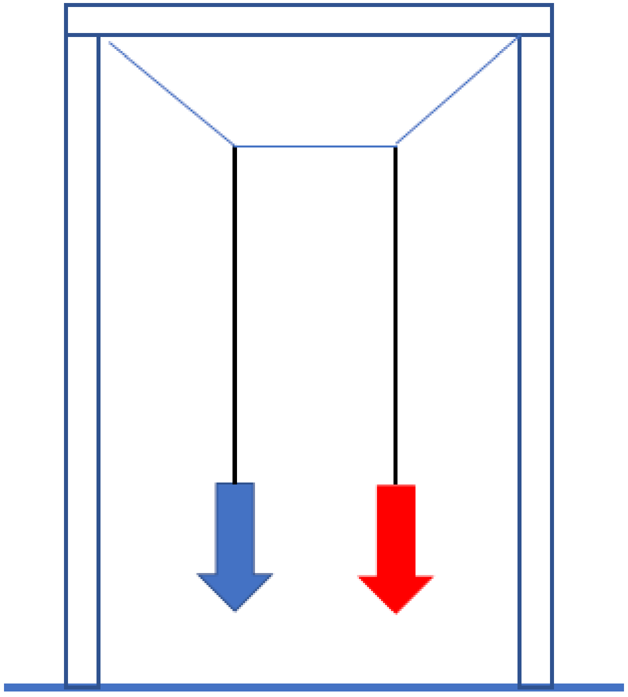
analog demonstration of neutrino oscillations

$$Pv_{\mu}(E,L) = 1 - \sin^2(2\theta_{\mu x}) \sin^2(1.27\, \Delta m^2_{\mu x}\, L/E)$$

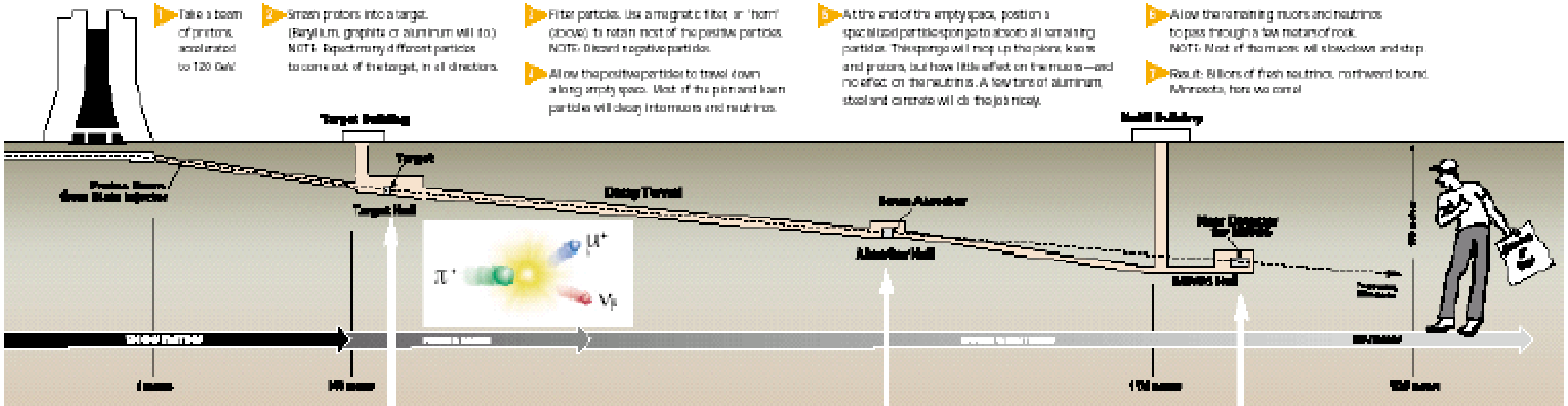
https://www.youtube.com/watch?v=gyQHpknSnSg

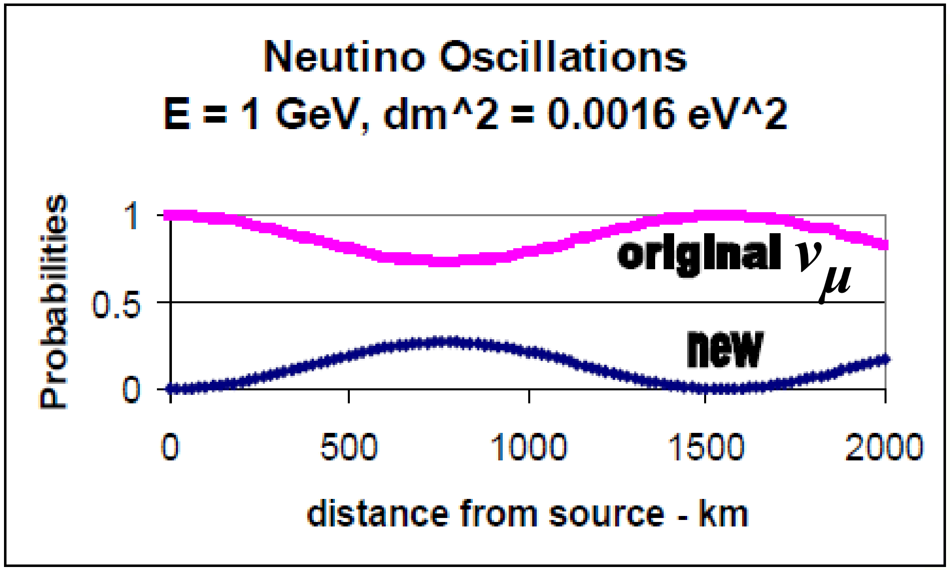
click URL for demo video:

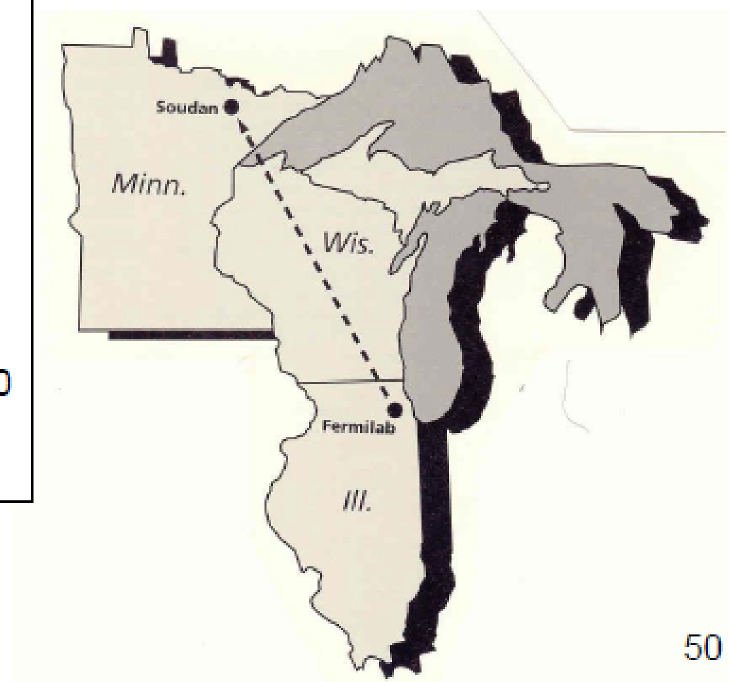
- coupled pendula demo



NUMI – Neutrinos at the Main Injector



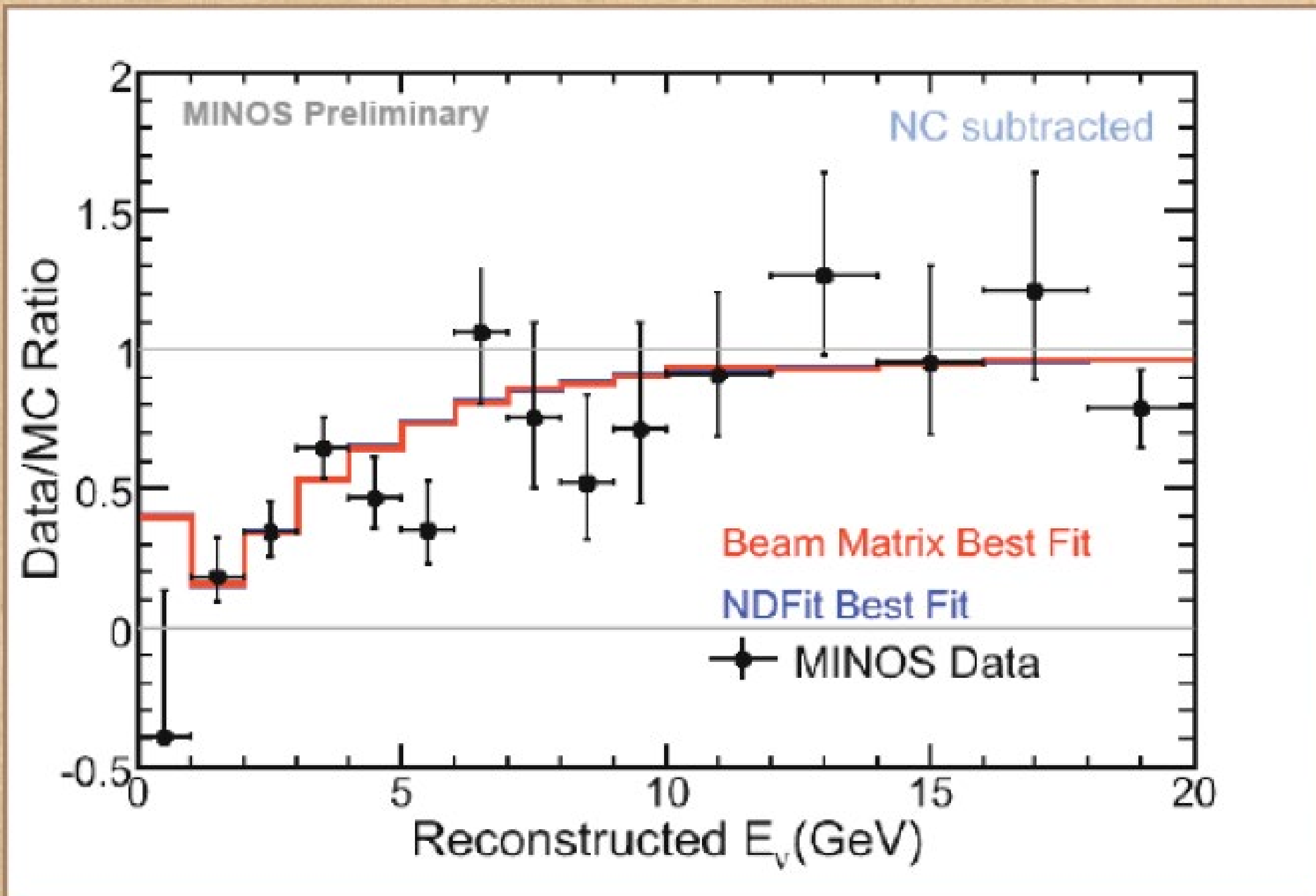




a 735 km long beam, right thru the earth! 10 km deep

50

first NuMI results – July 31, 2006

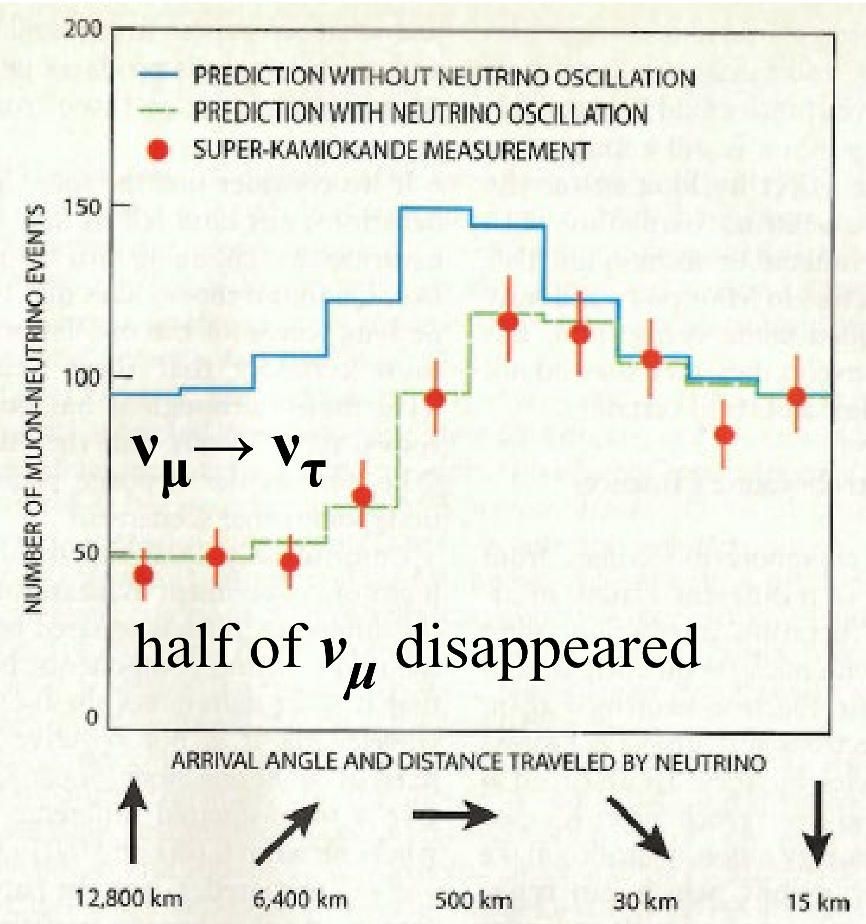


$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$

56

for all angles of ν_μ , Super-K finds



inconsistent w no oscillation

$\#\nu_e$(upward) = $\#\nu_e$(down)

no observed $\nu_\mu \rightarrow \nu_e$

consistent with oscillations

of $\nu_\mu \rightarrow \nu_\tau$ with parameters:

$\sin^2(2\theta_{\mu\tau}) \sim 1$ (limit > 0.82)

$\Delta m^2_{\mu\tau} = 0.0005\text{-}0.0060\ eV^2$

heavier m(ν) = 0.02-0.08 eV

<< m(e^-) = 511,000 eV

neutrinos have ~ million times less mass than electrons

FIRST DIRECT OBSERVATION OF NEUTRINO OSCILLATIONS

so either ν_μ or ν_τ has mass, or both

Why do ν oscillations imply at least one non-zero ν mass?

- quantum mechanics says so:
  - need different wavelengths for the 2 ***ν*** in order to have interference phenomena
  - this means different masses at same energy!
- simpler way of thinking about it:
  - $\boldsymbol{\nu_\mu}$ must "know" when to switch to $\boldsymbol{\nu_\tau}$ and back
  - so the neutrinos must have internal "clocks"
  - if neutrinos are massless, they will travel at $\boldsymbol{v = c}$ and their clocks won't run (time dilation)
  - so they must have some mass to oscillate

meanwhile, deep in a nickel mine in Ontario the Sudbury Neutrino Observatory = SNO

12 meter (40 ft) diameter plastic sphere filled with

1,000 tons of heavy water **D_2O**

a few of 9,500 PMTs installed

SNO plays a different game to directly study much lower energy 5-15 MeV solar *ν*

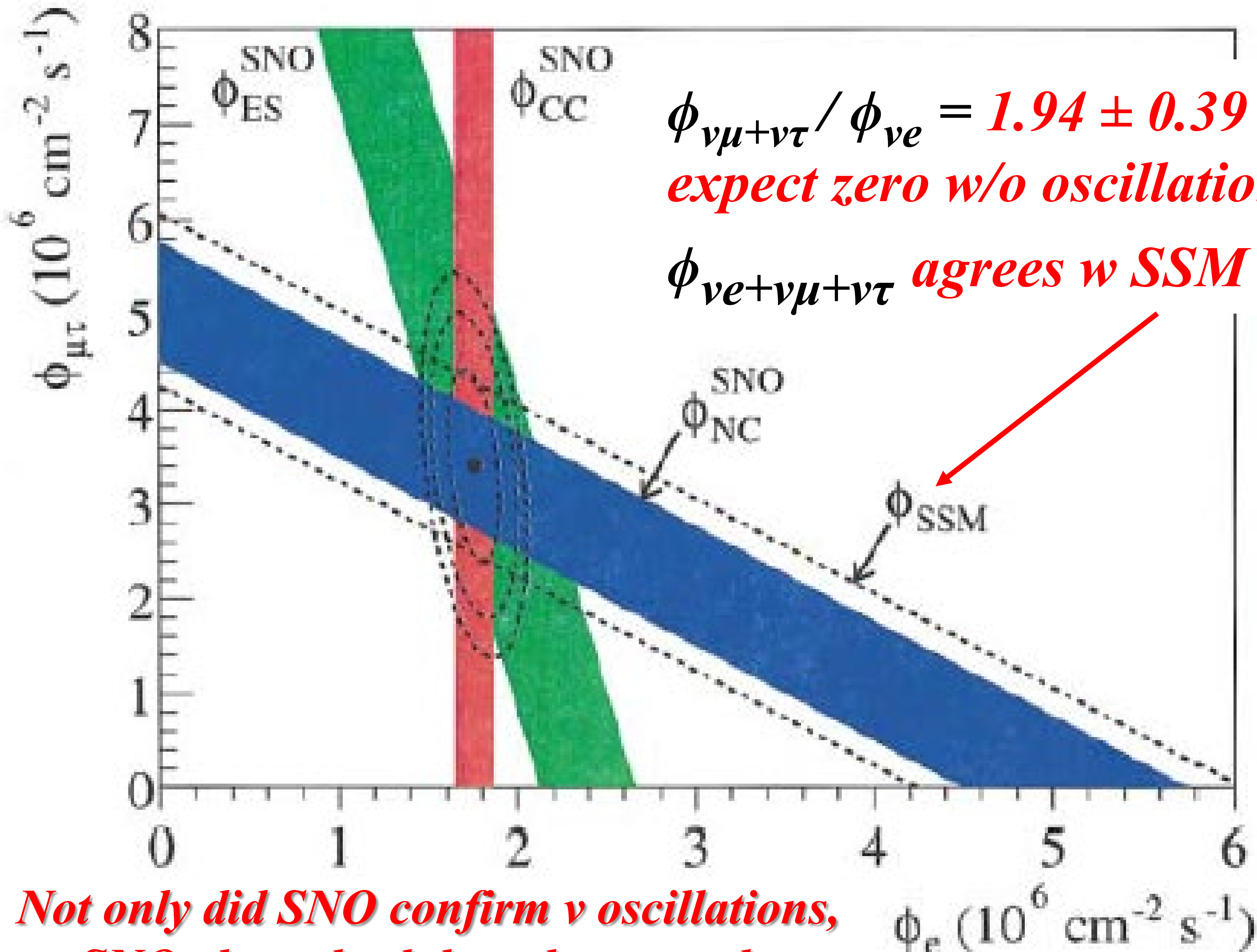
D in **D$_2$O** is Deuterium = ^{2}**H** = **n + p +** e^-

Three possible interactions:

	ν_e	ν_μ	ν_τ
Charged Current CC:	√	x	x
$\nu_e + n(p) \rightarrow e^- + p(p)$ – *detect* e^-			
Neutral Current NC:	√	√	√
$\nu + n + p \rightarrow \nu + n + p$ – *detect neutron*			
$\nu + e^- \rightarrow \nu + e^-$ **scattering**	√	**improbable**	
final e^- **follows direction of** *ν (from sun)*			

(improbable = 15.4%)

SNO data for E_ν > 5 MeV



$\phi_{\nu\mu+\nu\tau} / \phi_{\nu e}$ = ***1.94 ± 0.39***

expect zero w/o oscillations!

$\phi_{\nu e+\nu\mu+\nu\tau}$ ***agrees w SSM***

Not only did SNO confirm ν oscillations, SNO also solved the solar ν puzzle

2015 Nobel Prize in Physics was awarded to

Takaaki Kajita
Super-K

Arthur B. McDonald
SNO

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

New discoveries about (neutrinos') deepest secrets are expected to change our current understanding of the history, structure and future fate of the universe.

remaining questions & studies on neutrinos

Appearance of ν_e in a ν_μ beam – NOvA

Appearance of ν_τ in ν_μ beam– OPERA CNGS

Hierarchy of ν masses and absolute masses

Is there *CP*-violation for neutrinos?
Are ν-oscillations different than $\bar{\nu}$-oscillations?

If only matter ↔ anti-matter oscillations,
are neutrinos their own anti-particles,
as are γ, Z^0, π^0, η, ρ^0, ω, ϕ, J/ψ, Υ ?

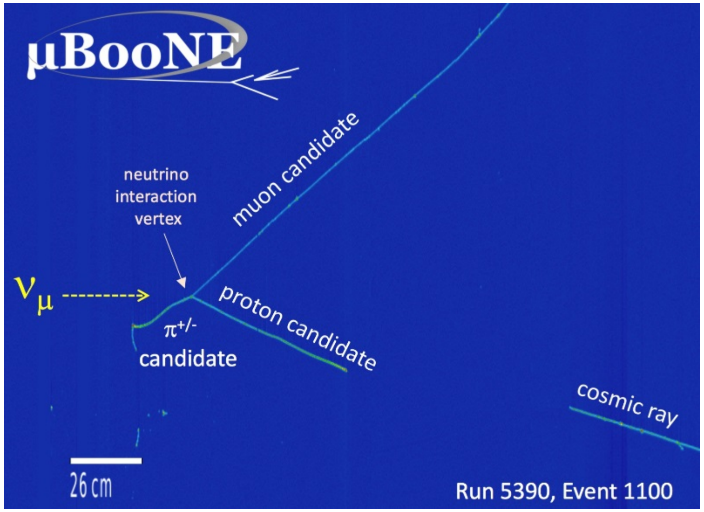
new knowledge always leads to new questions!

what's next?

on the drawing boards (not yet approved):

Hyper-K = ~1 million tons of water, ??? PMTs
with ν beam from J-PARC

DUNE (***D***eep ***U***nderground ***N***eutrino ***E***xp) in
Homestake Mine, Lead, South Dakota
1.5 km deep - right where Ray Davis worked!
35 K tons Liquid Argon
TPC detector
with ν beam
from Fermilab



both will search for ***CP*** violation: ν-osc $\neq$ $\bar{\nu}$-osc,
Super Nova ν and nucleon decay, and study cosmic ν

things to remember about ν-oscillations

It took century-long series of experiments

We know about 3 families of leptons & neutrinos

are there more? if so, they would be

MUCH heavier & have weirder properties!

We ***did*** understand how the sun works,

but understanding neutrinos got in our way

Neutrinos oscillate between kinds or "*flavors*"

Do we understand neutrinos? Not very well!

have been many surprises & new puzzles

still lots of work ahead…

https://nusoft.fnal.gov/nova/public/ ←

backup slides

It is very exciting for us physicists
to see it all come together and be
rewarded by a Nobel Prize

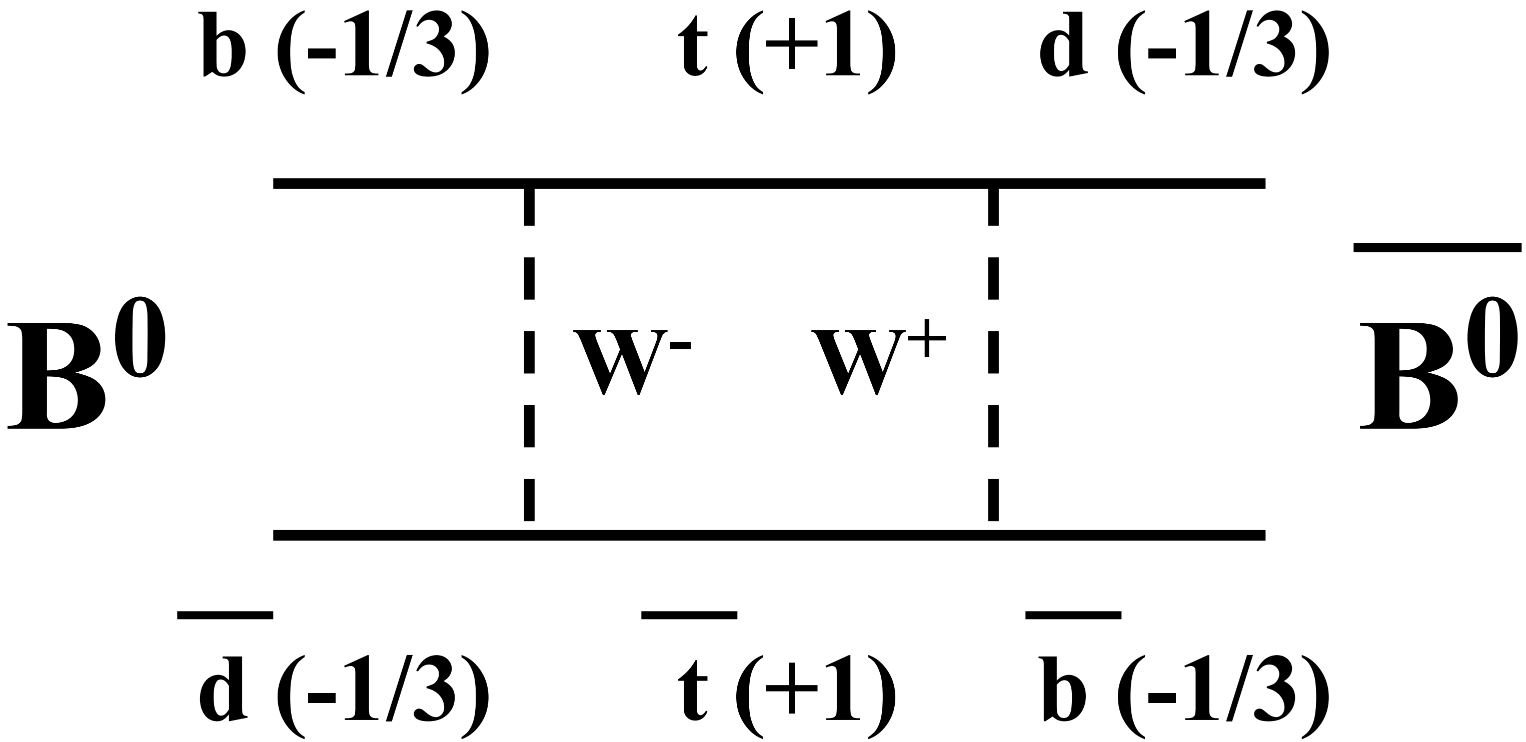
view Super-K events: (not running Dec 2018)

http://www-sk.icrr.u-tokyo.ac.jp/realtimemonitor/

NOvA events: (running today, I hope!)

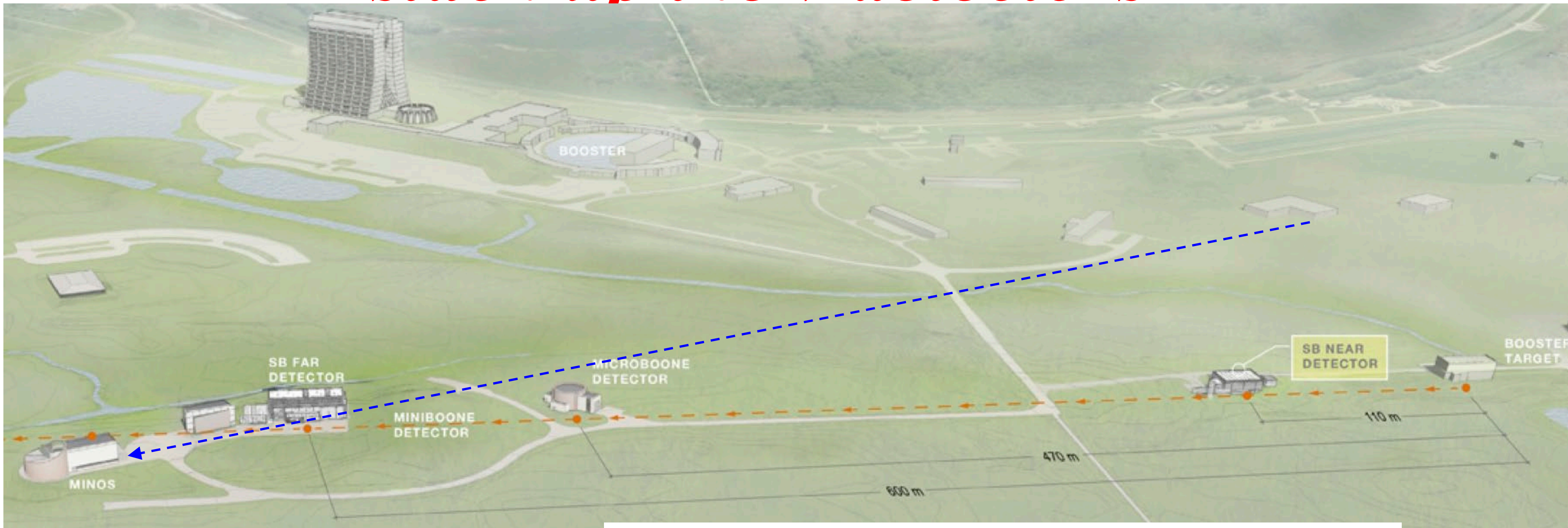
https://nusoft.fnal.gov/nova/public/

meson ↔ anti-meson oscillations



Fermilab has evolved from a proton (anti-proton) → ν and μ lab

stack up the ν detectors



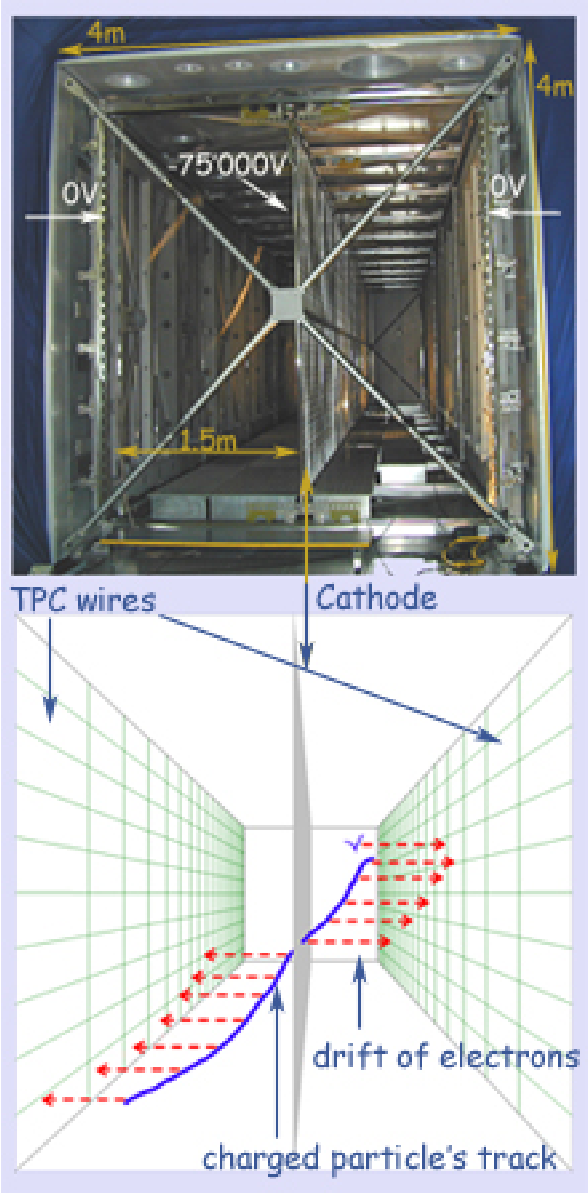
Current and Future Neutrino Detectors at Accelerator Facilities

detector name	distance	tonnage	technology
Fermilab - Booster Neutrino Beam (BNB) - 8 GeV primary proton beam			
SBND	110 m	112 T	Liquid Argon TPC
MicroBooNE	470 m	170 T	Liquid Argon TPC
ICARUS	600 m	480 T	Liquid Argon TPC
Fermilab - Main Injector (NuMI) - 120 GeV primary proton beam			
MINERvA	1 km	8.3 T	plastic scintillator + nuclear targets and muon magnetic spectrometer
NOvA near	1 km	300 T	liquid scintillator
NOvA far	735 km	14,000 T	liquid scintillator
DUNE (future)	1,300 km	35,000 T	Liquid Argon TPC
DUNE near detector		not yet designed	
J-PARC - 30 GeV primary proton beam - Japan			
Super-K	295 km	50,000 T	water Cerenkov
Hyper-K (proposed)	~300 km	0.5-1 MT	water Cerenkov

NOvA Far Detector – 14 KTons

63% liquid scint.
37% PVC structure

ICARUS – 480 Tons Liquid Argon moved from CERN (Gran Sasso) → Fermilab



Neutrino Interactions

- ν's interact very weakly (the weak force!)
- total νp cross section (interaction probability)

  $\sigma(\nu p) = 6.7 \times 10^{-39}\ cm^2$ at 1 GeV

  $\sigma(pp) = 2.2 \times 10^{-26}\ cm^2$ (strong force)

  $\sigma(\gamma p) = 2 \times 10^{-28}\ cm^2$ (E.M. force - photons)
- EM force/Gravitation $\approx 10^{36}$ between 2 protons
- only 650 out of 1 billion ν's interact before reaching Soudan (735 km earth)
- only 40 out of 1 trillion ν's interact in detector

MINOS

ν_e and slow neutron detection

- ***Reines and Cowan (liquid scintillator)***

$$\bar{\nu}_e + p \to n + e^+ \quad \text{prompt annihilates} \quad e^+ e^- \to \gamma\, \gamma\, (\gamma)$$

$$\text{after few } \mu\text{-sec} \quad n + Cd^{113} \to Cd^{114} + \text{many } \gamma$$

- ***Ray Davis (cleaning fluid)***

$$\nu_e + Cl^{37} \to e^- + Ar^{37} \quad (t_{1/2} = 35 \text{ days})$$

electron capture + Auger electron

$$Ar^{37} + e^- \to \nu_e + Cl^{37} + e^- \ (2.82 \text{ KeV})$$

- ***SNO (heavy water = D_2O $\quad$ $D = n + p$)***

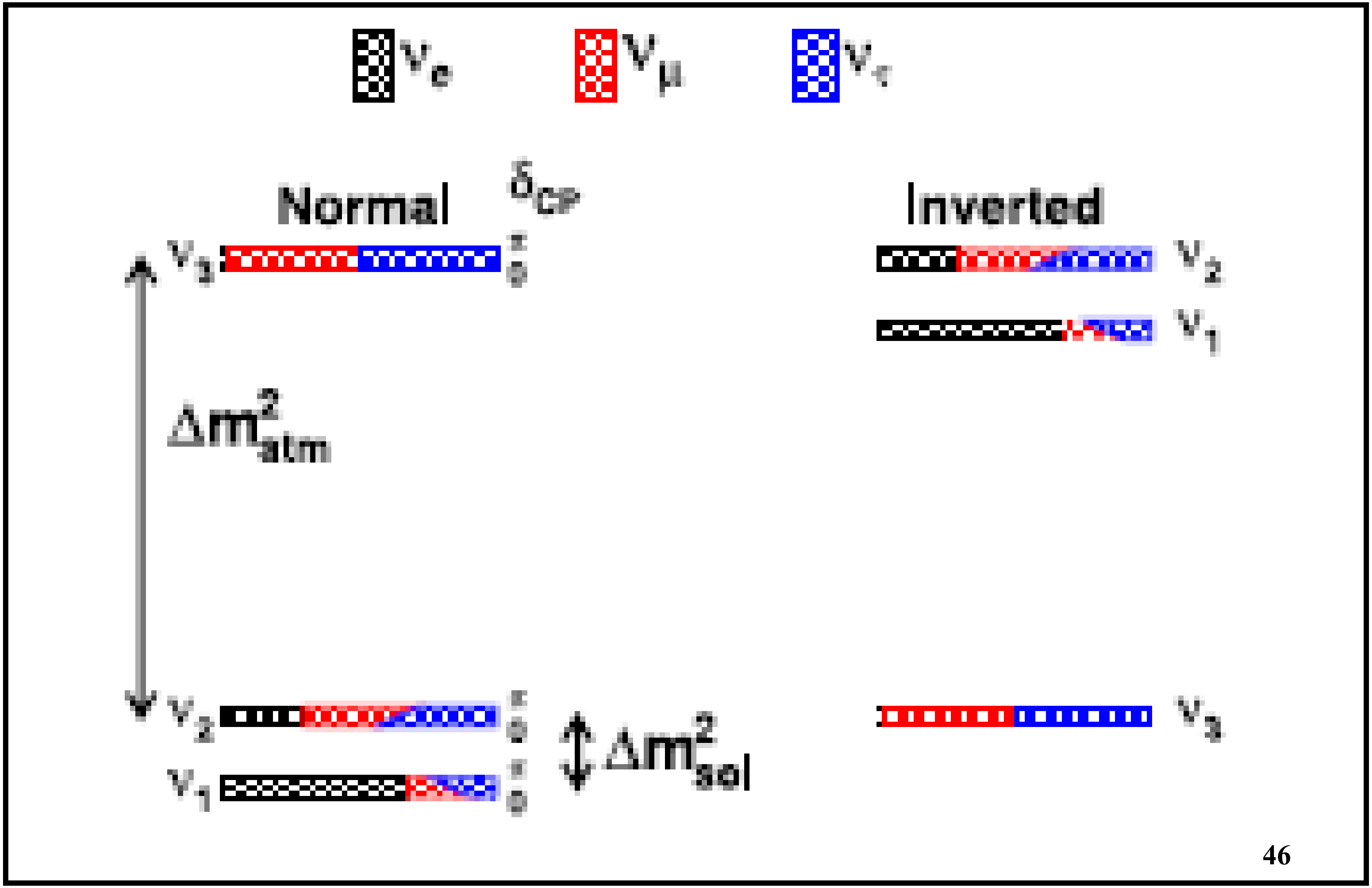
NC for all ν_x: $\nu_x + d(np) \to \nu_x + n \text{ (detect)} + p$

$$n + d(pn) \to t(pnn) + \gamma \ (6.3 \text{ MeV})$$

$$n + Cl^{37} \to Cl^{38} \ (t_{1/2} = 37 \text{ min}) \to \beta \ \& \ \gamma \ (4.8 \text{ MeV}$$

$$n + He^3(ppn) \to p + t(pnn) \ (0.76 \text{ MeV})$$

Neutrino Mass Hierarchy



Neutrino Mass Hierarchy

Mass Eigenstates — *Neutrino Flavors*: $\nu_e\ \nu_\mu\ \nu_\tau$

these oscillate — **what we detect**

m_1	$\sim 2/3\ \nu_e + 1/6\ \nu_\mu + 1/6\ \nu_\tau$
m_2	$\sim 1/3\ \nu_e + 1/3\ \nu_\mu + 1/3\ \nu_\tau$
m_3	$\sim ½\ \nu_\mu + ½\ \nu_\tau$

We have learned that either:

normal hierarchy: $m_1 < m_2 << m_3$

similar to $m_e : m_\mu : m_\tau :: 0.5 : 105 : 1{,}777$ **MeV or**

inverted hierarchy: $m_3 << m_1 < m_2$

can't tell since Δm_{ij}^2 **is in the oscillation eq.**

this presentation leans heavily on:

- Nobel Prize website: http://www.nobelprize.org/

  popular:

  http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/popular.html

  advanced:

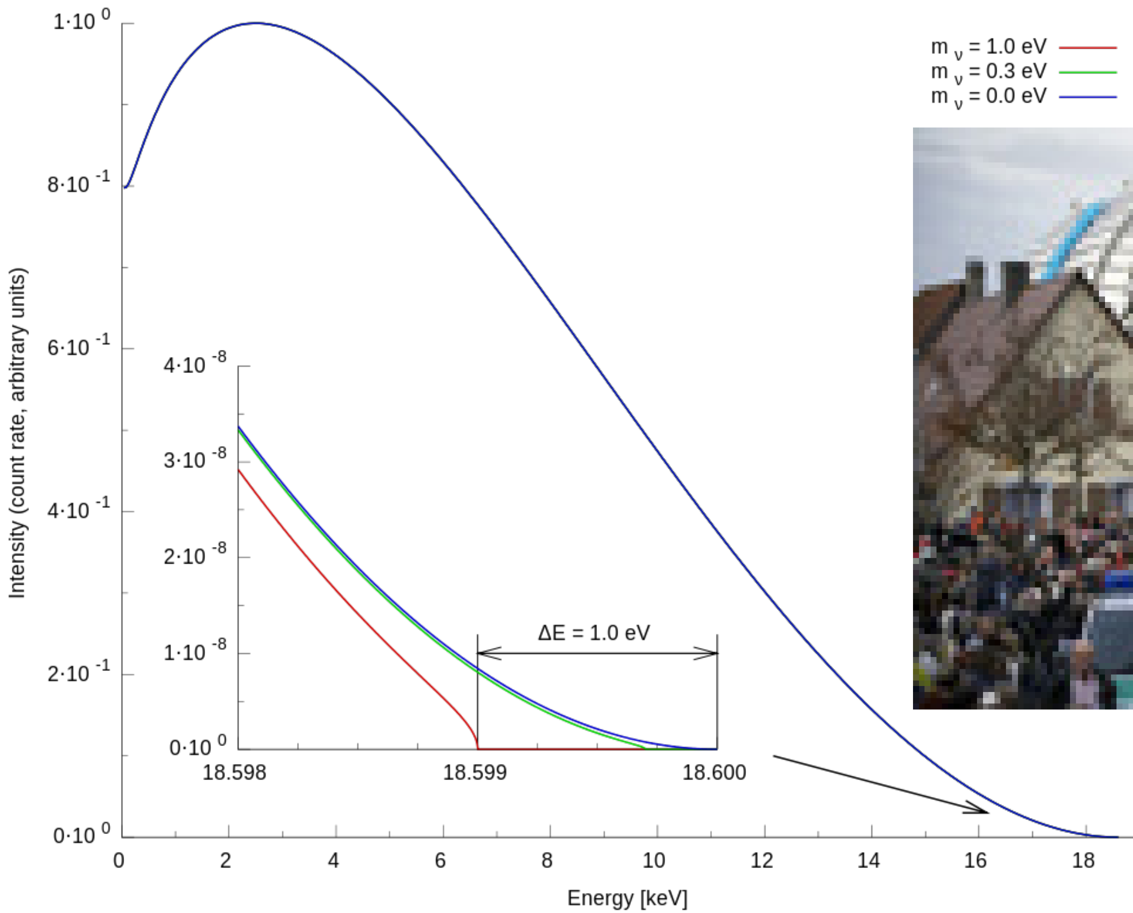
  http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/advanced.html

- Scientific American:
  - E. Kerns, T. Kajita, & Y. Totsuka, **281**, August, 1999
  - A.B. McDonald, J.R. Klein, & D.L. Wark, **288**, April, 2003
- primary scientific publications:
  - Y. Fukuda *et al*., Physical Review Letters 81, 1562 (1998)
  - Q.R. Ahmad *et al*., Physical Review Letters 87, 071301 (2001)
  - Q.R. Ahmad *et al*., Physical Review Letters 89, 011301 (2002)
- Wikipedia – always a good first choice

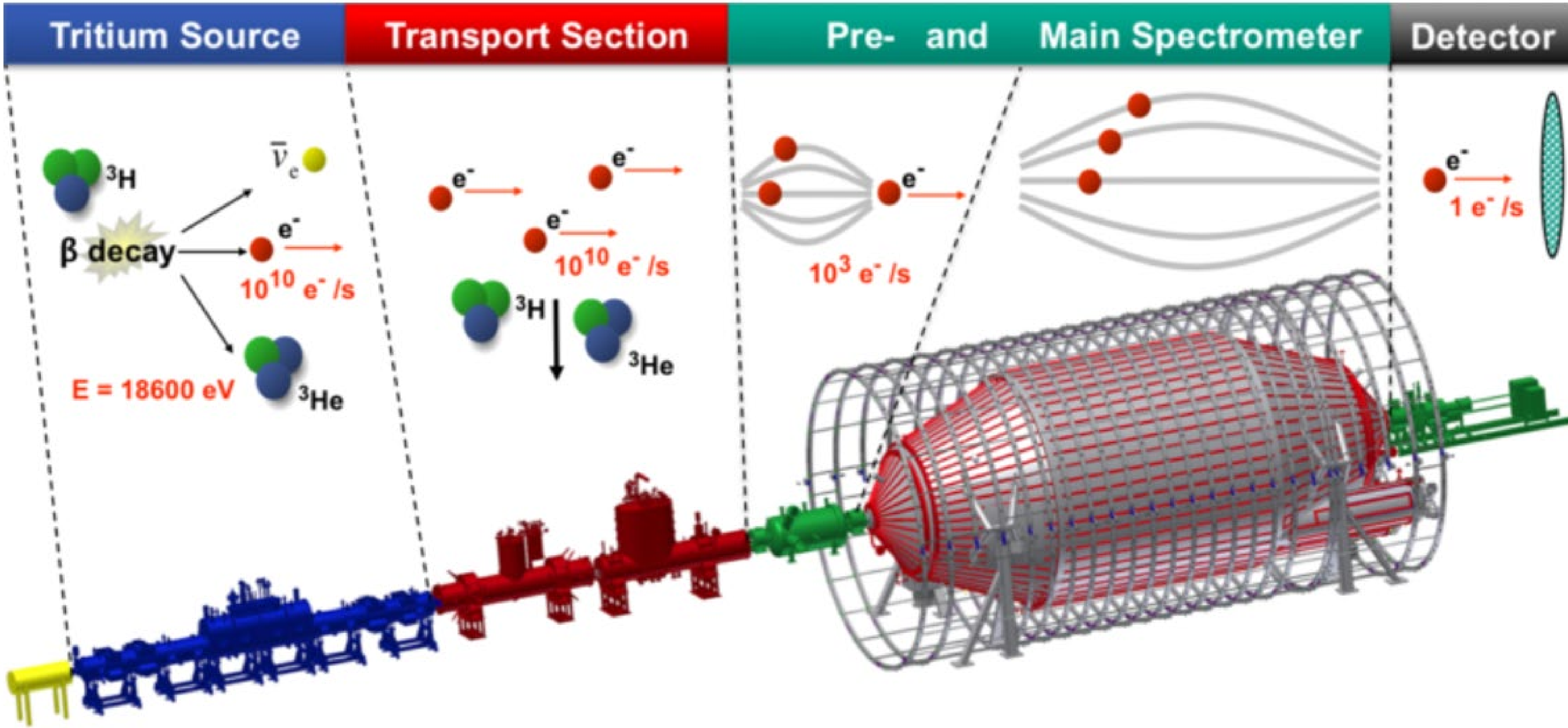
measuring the absolute Mass of $\bar{\nu}_e$

KATRIN: **KA**rlsruhe **TRI**tium **N**eutrino exp

$$^3H = t(p,n,n) \rightarrow {}^3He(p,p,n) + e^- + \bar{\nu}_e$$



what's inside the KATRIN experiment?



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

neutrino sources

- β-decay of radioactive nuclei and particles

- Accelerator – choose beams of ν_μ or anti-ν_μ
- Solar ν_e – Ray Davis, Super-K, SNO, *et al*.
- Reactor anti-ν_e – Reines & Cowan observation
- Atmospheric ν – produced by interaction of cosmic rays in upper atmosphere – Super-K
- SuperNova ν – KamiokaNDE and IMB - neutrinos from SN1987A
- Cosmic ν (from outside solar system, galaxy) – IceCube at South Pole, public lecture by Francis Halzen last June

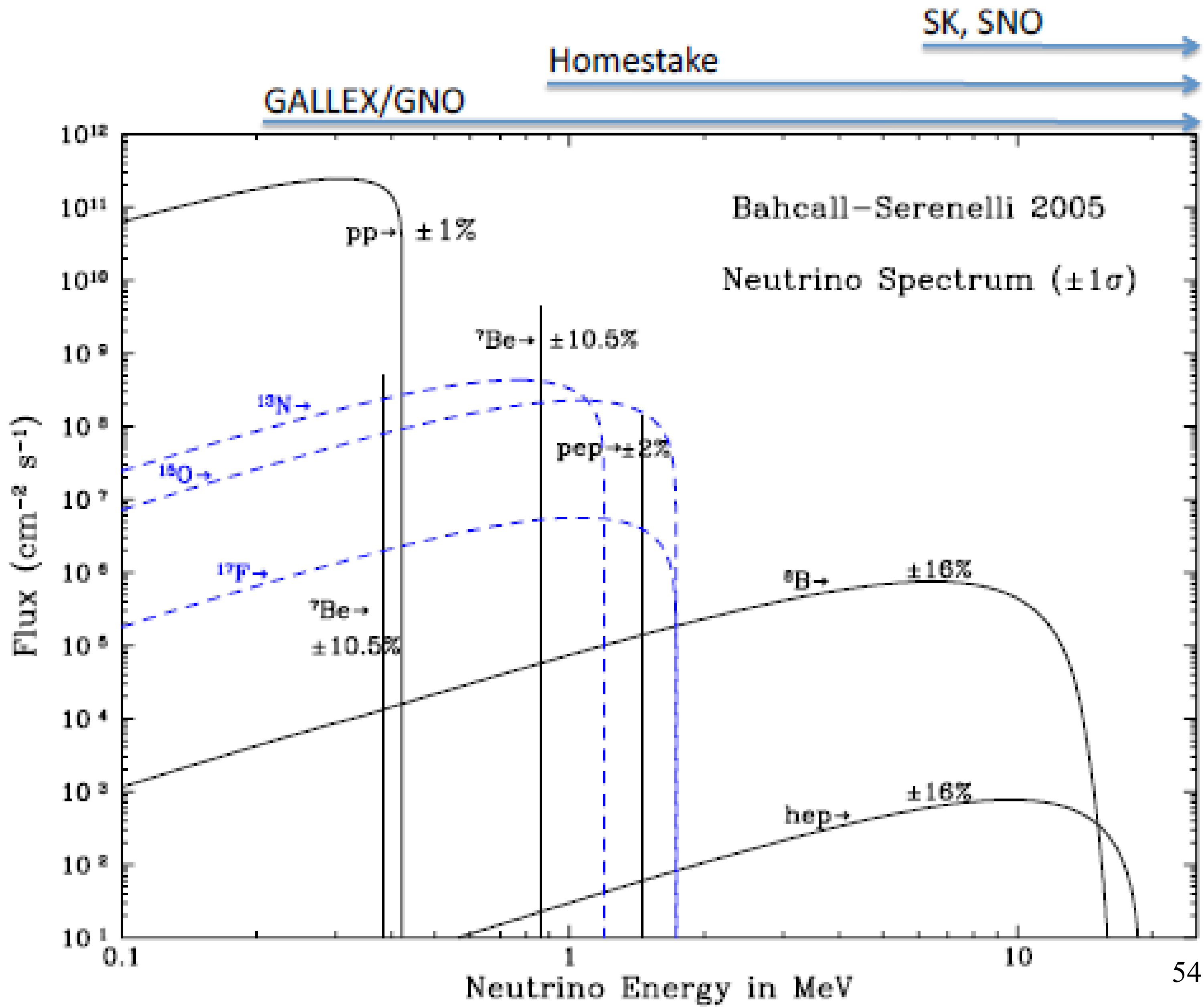
β-decay: $n \rightarrow p + e^- + \overline{\nu}_e$

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

solar: $\nu_e + n \rightarrow p + e^-$

"Standard Solar Model"

flux = #***ν*** per cm^2 per second per MeV



SNO results

$$\phi_{\nu e}^{CC} = 1.76 \pm uncertainties$$

$$\phi_{\nu e+\nu\mu+\nu\tau}^{NC} = 5.09 \pm uncertainties$$

$$\phi_{\nu e}^{ES} + 0.154*\phi_{\nu\mu+\nu\tau}^{ES} = 2.39 \pm uncertainties$$

$$\rightarrow \phi_{\nu\mu+\nu\tau} / \phi_{\nu e} = 1.94 \pm 0.39$$

expect zero without oscillations!

ϕ is the ν "***flux***" = #ν (10^6) per cm^2 per second with $E_\nu > 5\ MeV$

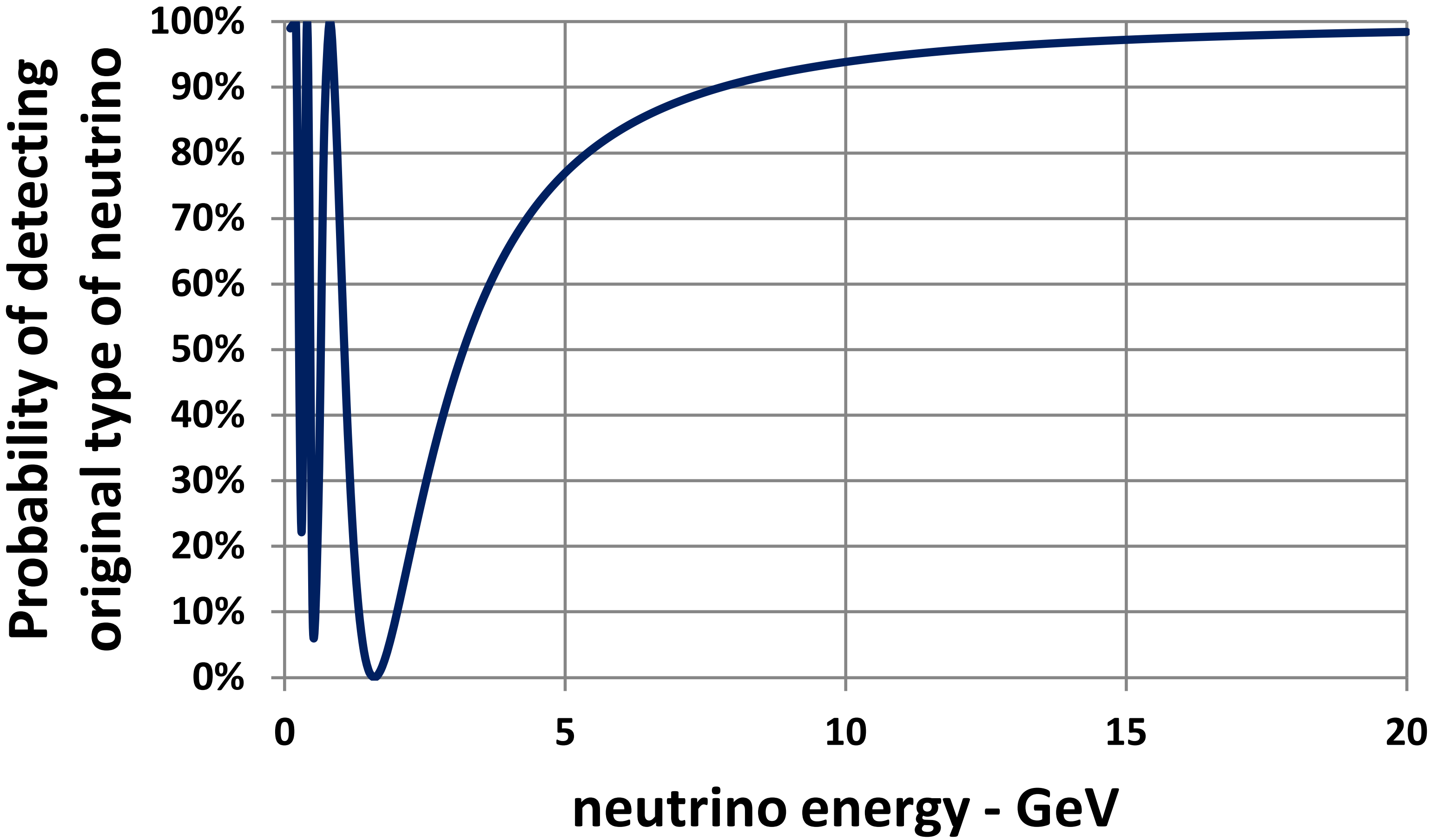
One of the joys of giving a public lecture is that you often don't have to discuss the uncertainties. In a scientific presentation, you spend lots of time explaining how well you understand your measurement, i.e. the uncertainties.

cosmic thread

- **In reactions between radiation and atoms, charged ions are often produced. Victor Hess, using balloons, measured in 1912 atmospheric ionization as function of altitude. To his surprise he found that the ionization first decreased, but later for the highest altitudes, increased strongly. He concluded that a penetrating radiation is evident on the earth from outside. He could also exclude that this radiation emanates from the sun. *Cosmic rays were discovered.***
- **Balloon ascents in 1912:**
  - **Ionization *decreased* from 0 m – 1 km height**
    terrestrial radiation
  - **Ionization *increased* from 1 km – 5 km height**
    not from earth
  - **Ionization at 2-3 km height**
    ***did NOT decrease during solar eclipse* 12april1912**
    not from sun

Victor Hess
Nobel Prize 1936

for NuMI ν_μ beam → MINOS
Fermilab → Minnesota = 730 km



what's next?

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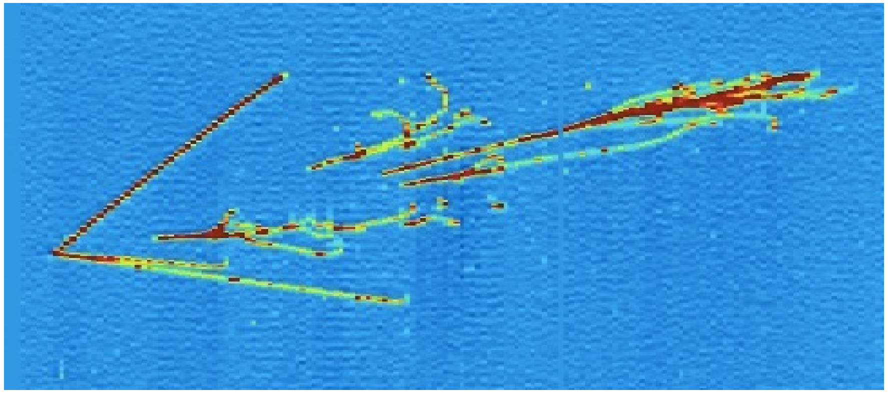

similar event from ArgoNeut

both will search for ***CP*** violation: *ν*-osc ≠ $\overline{\nu}$-osc,
Super Nova ***ν*** and nucleon decay, and study cosmic ***ν***

answer to a question
How can I see particles at home?

Amazon sells a cloud chamber for $ 100

*** See the video of building a cloud chamber at the end of this:
http://www.symmetrymagazine.org/article/january-2015/how-to-build-your-own-particle-detector

Other cloud chamber references:
http://quarknet.fnal.gov/resources/QN_CloudChamberV1_4.pdf
http://bizarrelabs.com/cloud.htm

Lots of links here:
http://www.bing.com/search?q=Make+a+Cloud+Chamber&FORM=QSRE1