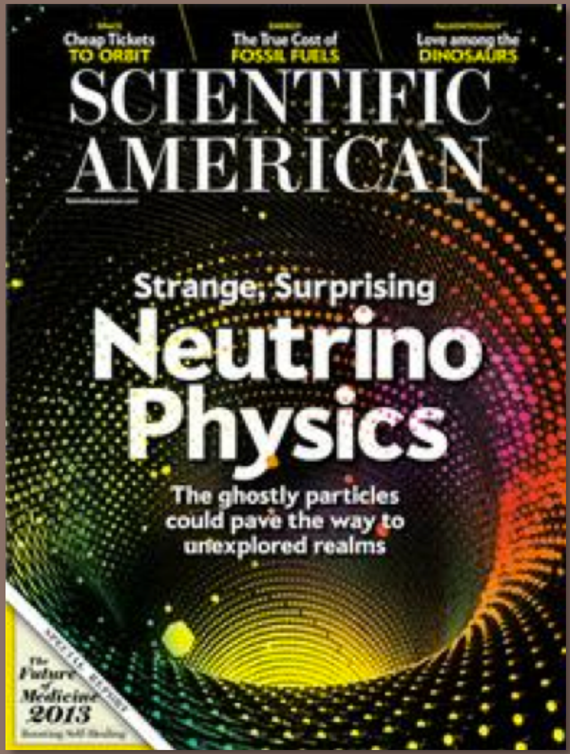
NEUTRINOS

Sam Zeller
Fermilab

HCPSS

Aug. 22, 2014



- survey of neutrino experiments
- what we've learned & where we are headed
- not just missing energy, but a particle we can do a lot with …

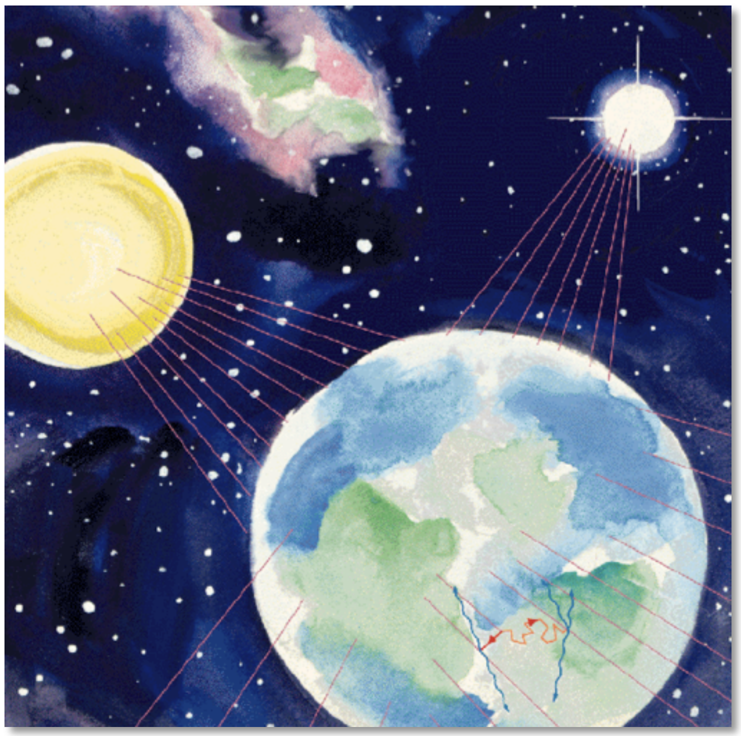
Neutrinos Are Everywhere

- together with photons, neutrinos are by far the most abundant particles in the universe …

ν's generated in Big Bang

ν's power the sun

produced in the Earth's atmosphere and interior



ν's drive supernovae explosions

ν's are produced by particle accelerators and nuclear reactors

even bananas are ν emitters

- some we make ourselves, some we get for free

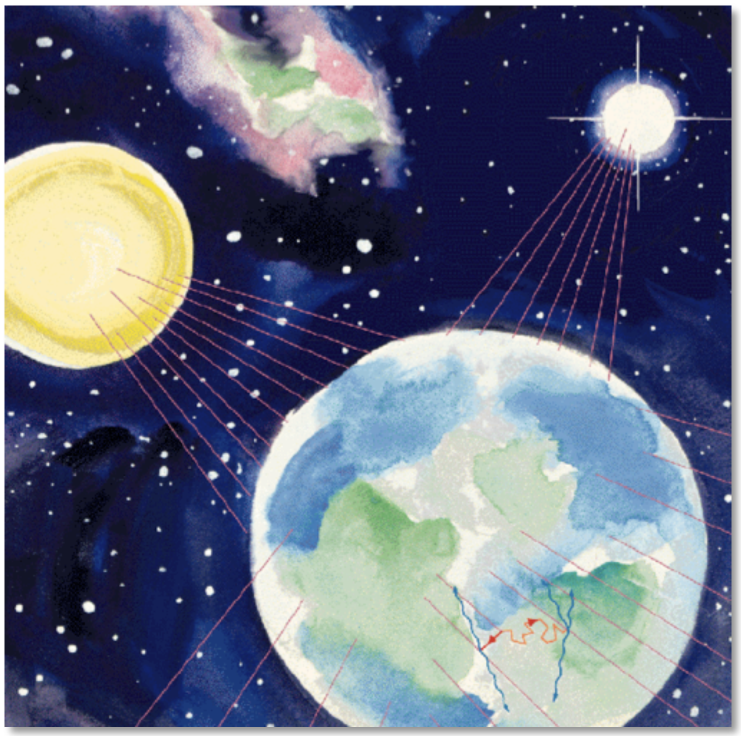
Neutrinos Are Everywhere

- together with photons, neutrinos are by far the most abundant particles in the universe …

ν's generated in Big Bang

ν's power the sun
(400 trillion ν's/sec)

produced in the Earth's atmosphere and interior
(50 billion ν's/sec)



ν's drive supernovae explosions

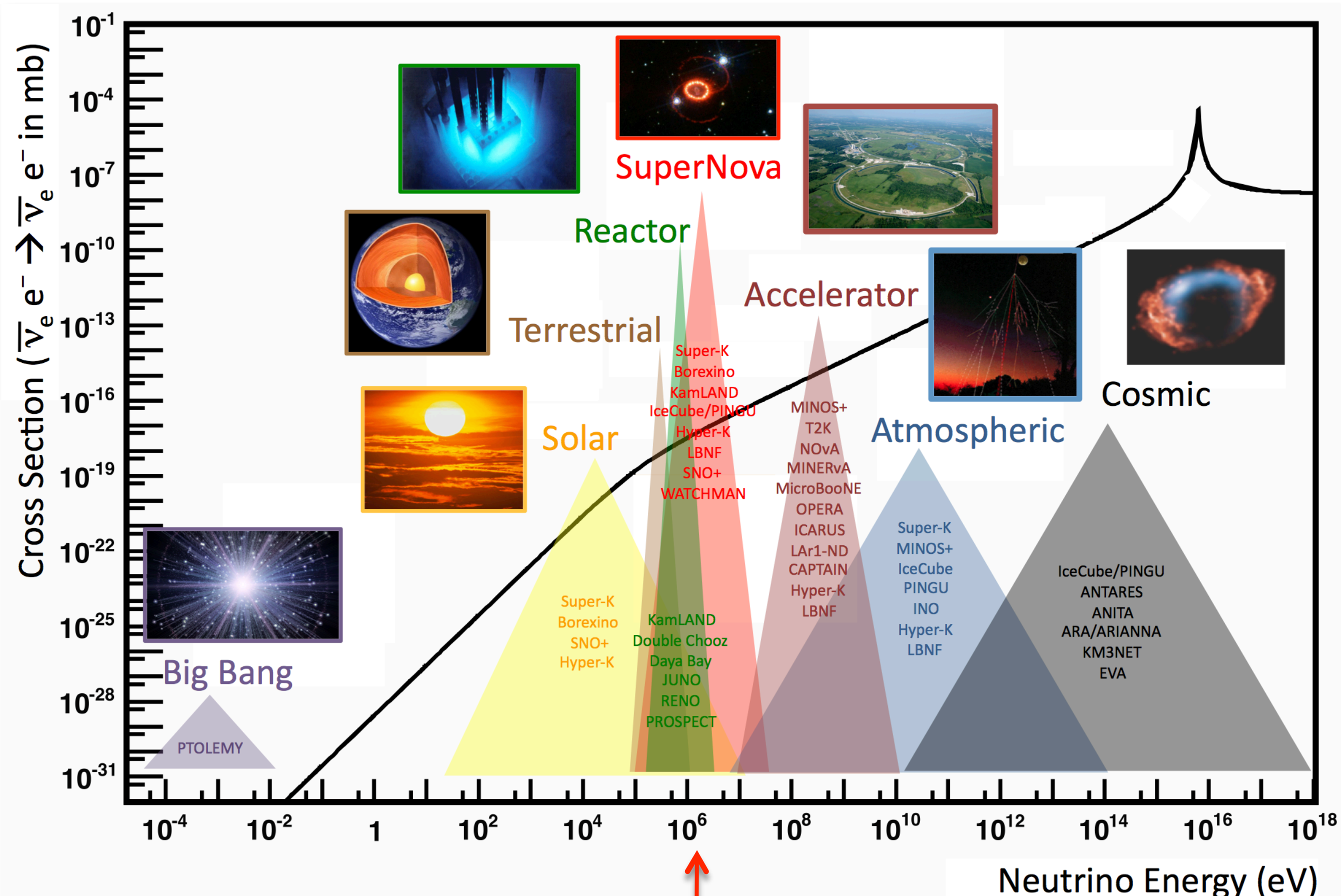
ν's are produced by particle accelerators and nuclear reactors
(10-100 billion ν's/sec)

even bananas are ν emitters
(million ν's/day)

- their energies span more than 16 orders of magnitude …

Many Sources of Neutrinos

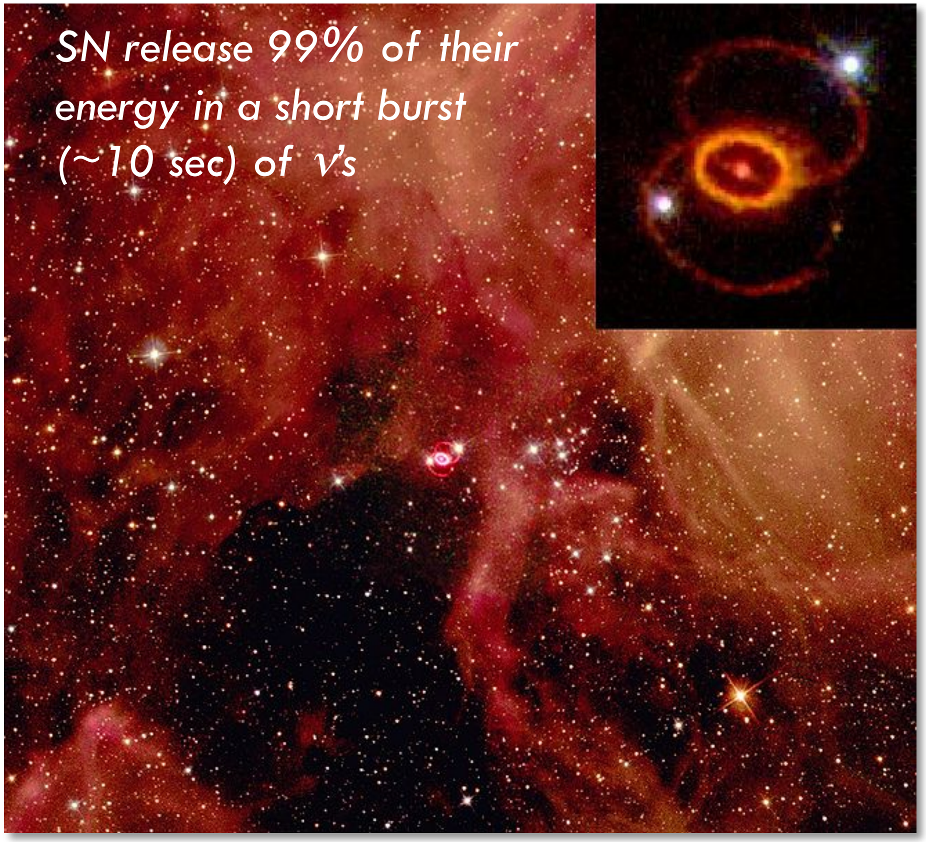
- these neutrinos span an enormous energy range (eV to PeV)



example: supernova neutrinos!

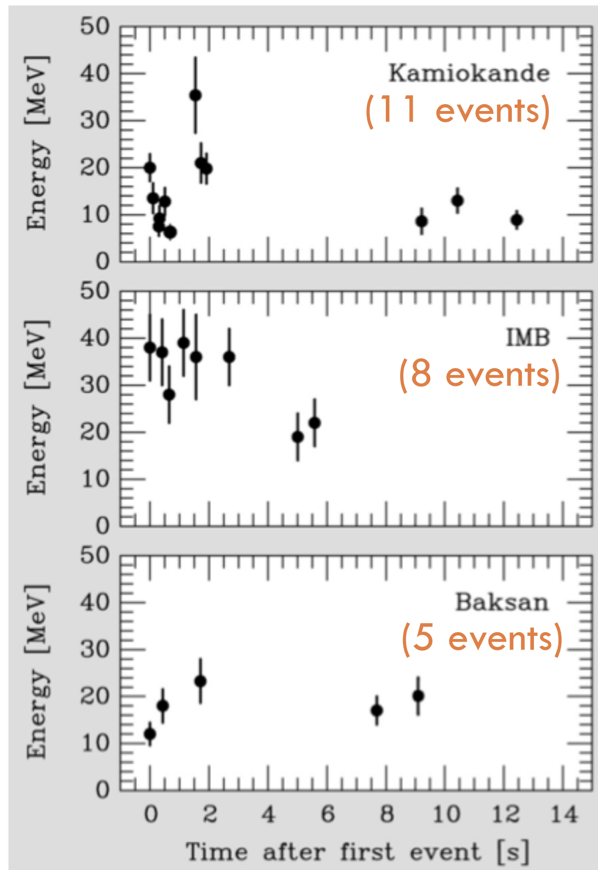
- hard to find another particle with the same dynamic range as the neutrino
- we have detected neutrinos from almost all of these sources

Supernova Burst Neutrinos



we have detected ν's from one and only one such event: SN 1987A (released more ν's than our sun will produce in its lifetime)

- ν's play a crucial role in the life and death of massive stars



SNEWS

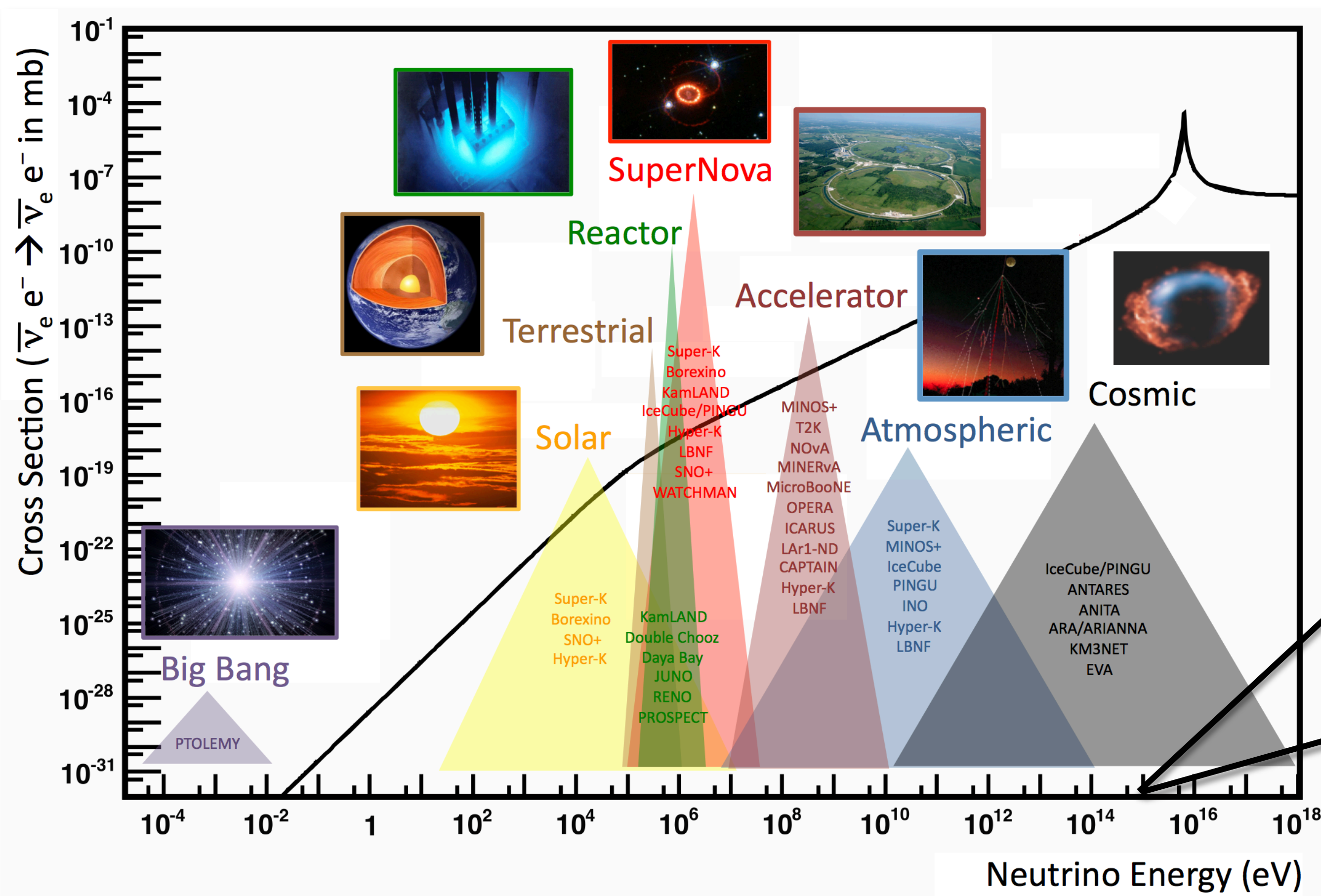
- many neutrino experiments are connected through the SNEWS network
  SuperNova Early Warning System

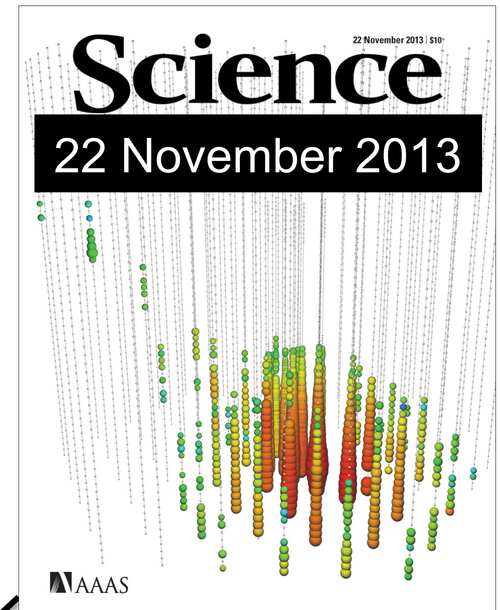
- some of the failed acronyms:
  (http://snews.bnl.gov/amuse.html)

P = Point	*S = Several*
O = Over	*U = Under*
T = There	*G = Ground*
A = At	*A = Alarms*
T = That	*R = Ring*
O = Old	*B = Before*
E = Exploding	*A = Arriving*
S = Star	*R = Radiation*

Many Sources of Neutrinos

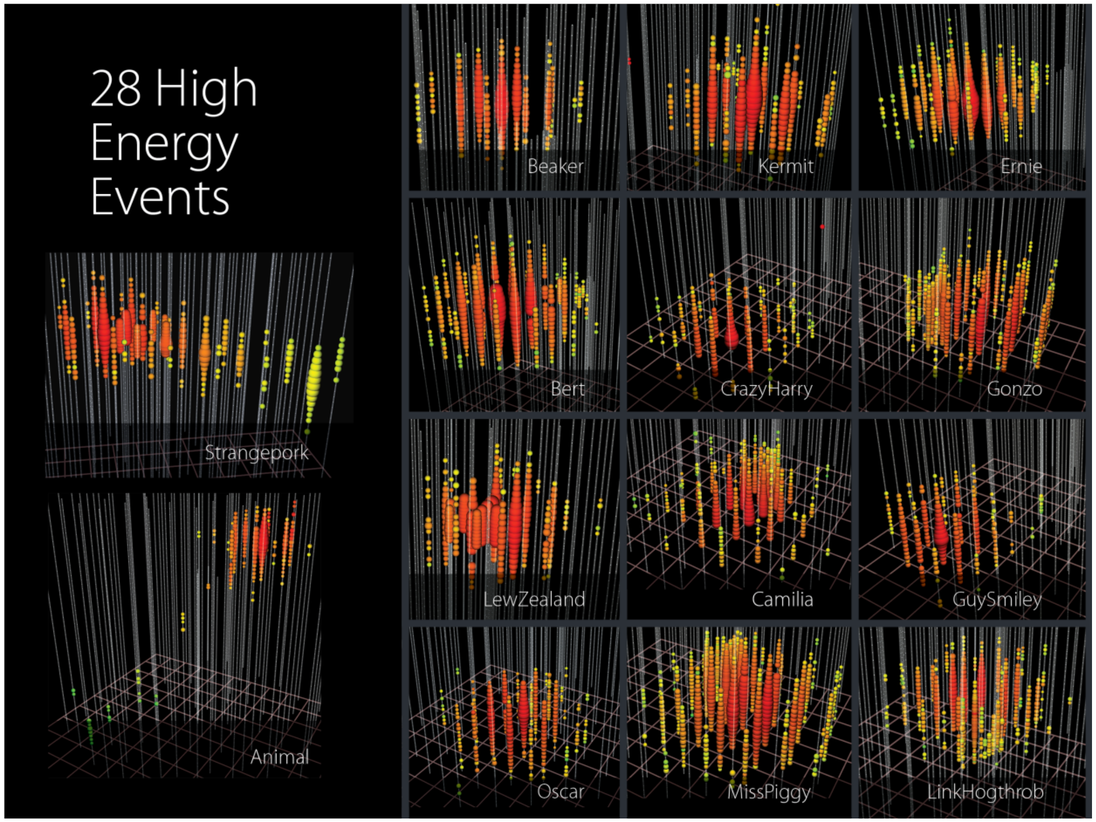
- these neutrinos span an enormous energy range (eV to PeV)





~1000 TeV neutrino from Ice Cube

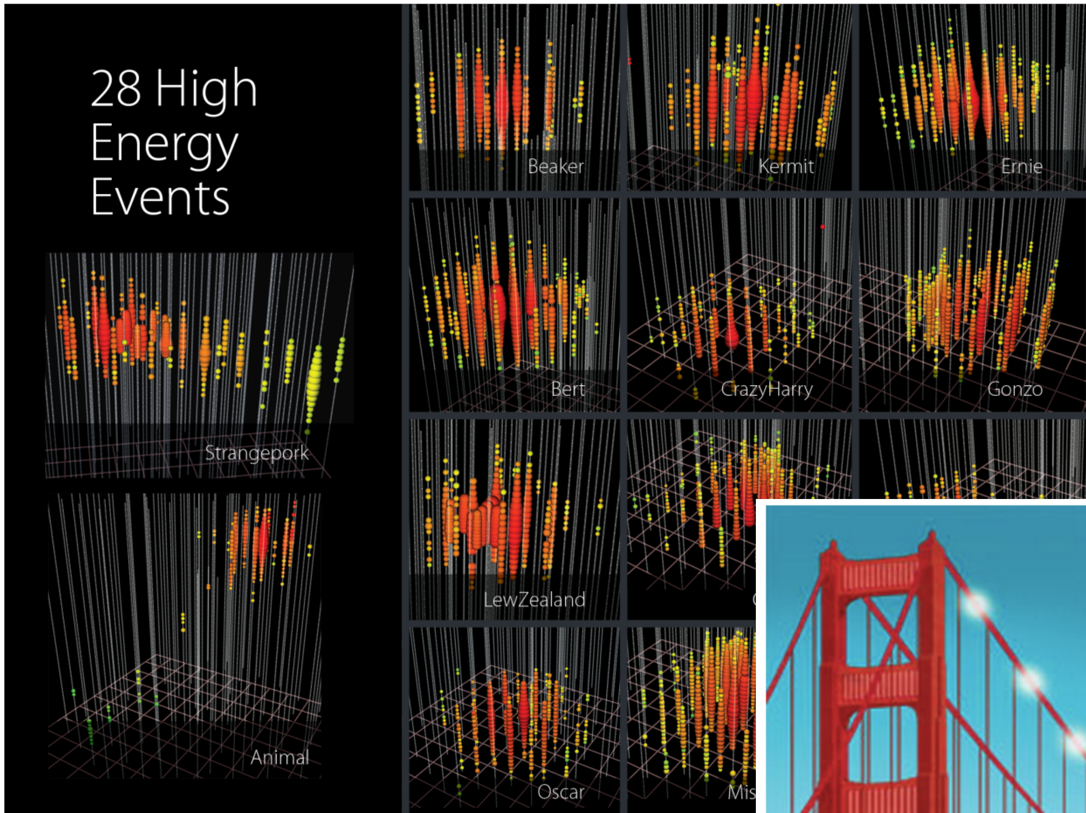
Many Sources of Neutrinos



- have since observed 28 extremely high energy ν events in Ice Cube

Many Sources of Neutrinos

- have since observed 28 extremely high energy ν events in Ice Cube



Additional Reading

Towards High-Energy Neutrino Astronomy

A Historical Review

Christian Spiering[a]

DESY, Platanenallee, D-15738 Zeuthen

Abstract. The search for the sources of cosmic rays is a three-fold assault, using charged cosmic rays, gamma rays and neutrinos. The first conceptual ideas to detect high energy neutrinos date back to the late fifties. The long evolution towards detectors with a realistic discovery potential started in the seventies and eighties, with the pioneering works in the Pacific Ocean close to Hawaii and in Lake Baikal in Siberia. But only now, half a century after the first concepts, such a detector is in operation: IceCube at the South Pole. We do not yet know whether with IceCube we will indeed detect extraterrestrial high energy neutrinos or whether this will remain the privilege of next generation telescopes. But whatever the answer will be: the path to the present detectors was a remarkable journey. This review sketches its main milestones.

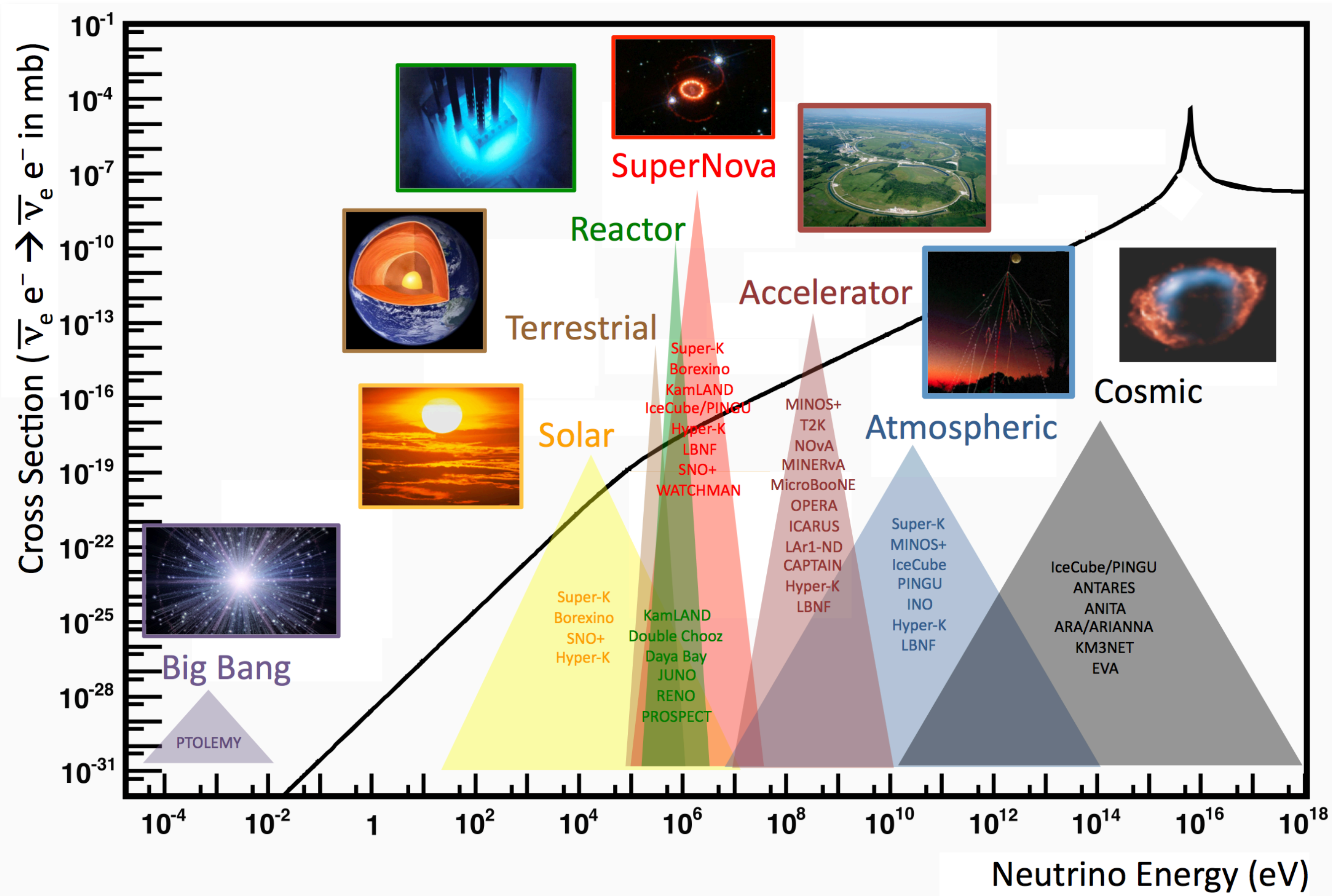
- good review article

  http://arxiv.org/abs/arXiv:1207.4952

- neutrinos are unique messengers and powerful tools for probing astrophysical sources beyond our solar system

Many Sources of Neutrinos

- these neutrinos span an enormous energy range (eV to PeV)



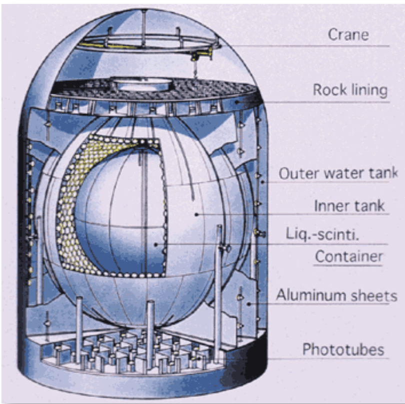
- this is one reason why ν's are so special

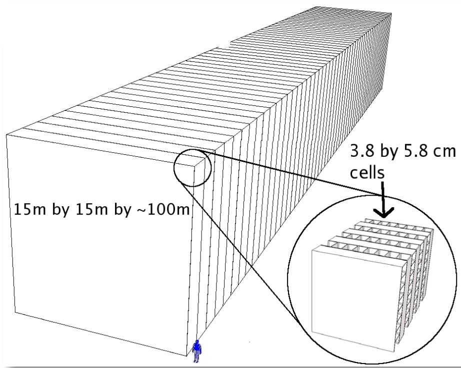
have allowed us to study phenomena across radically different energy scales

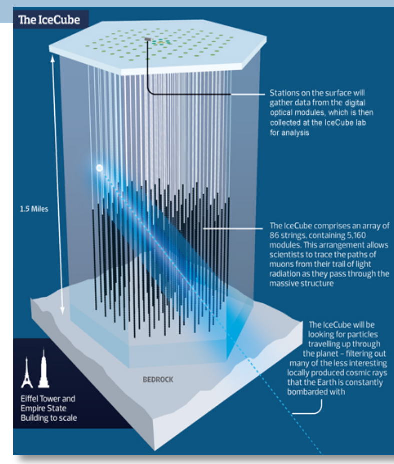
- but detecting ν's is not without its challenges

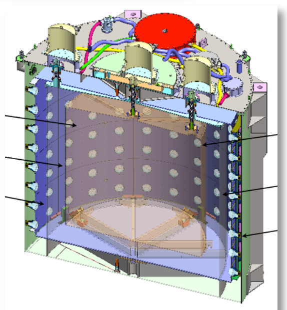
- *clever experiments had to be conceived to overcome the very small ν interaction probability*

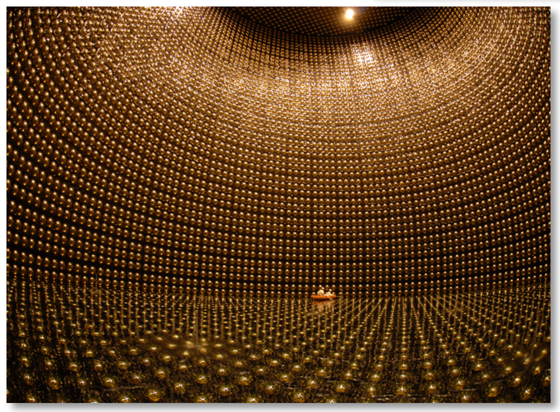
Lots of Neutrino Detectors Today

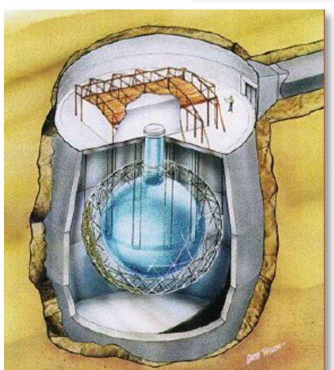


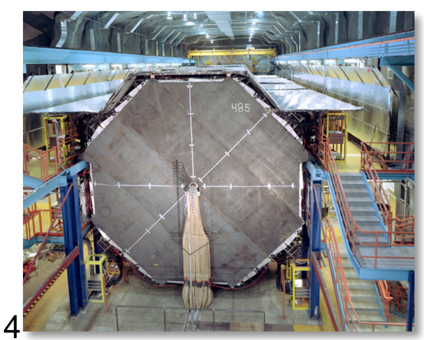










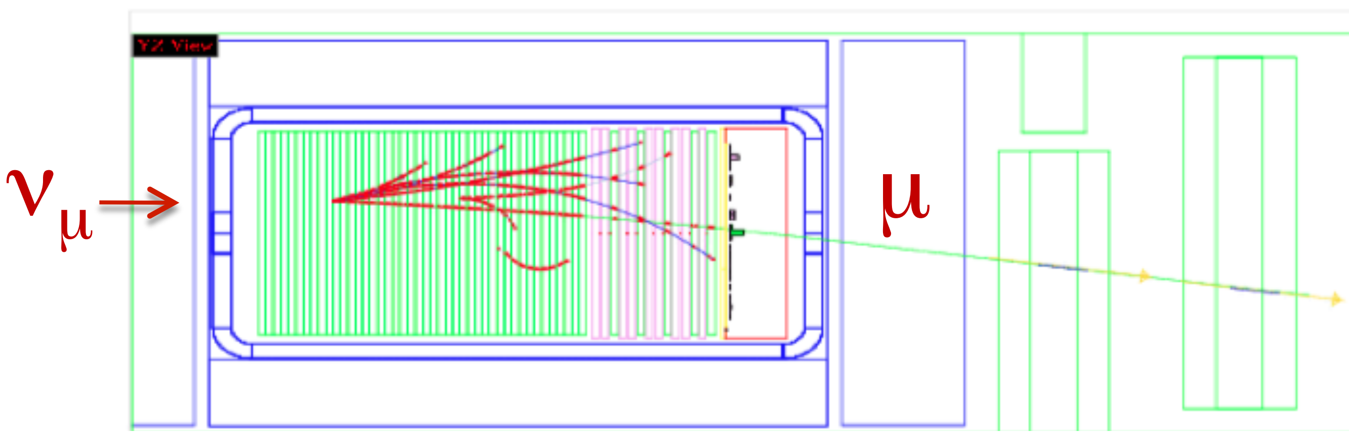


- the fact that **ν's rarely interact** means that we need **large detectors** to collect enough ν events for study
  - *to increase the chances that the ν will do something and make its presence known*
- usually large containers of matter surrounded by detection elements

Neutrino Detection

- but most of the neutrinos will sail through these devices undetected
  - **need a lot of ν's**
  - **need to put a lot of material in its way**

- also, keep in mind: you can never detect the ν's themselves; you have to detect the products of their interactions and work backwards



- tell tale signature:

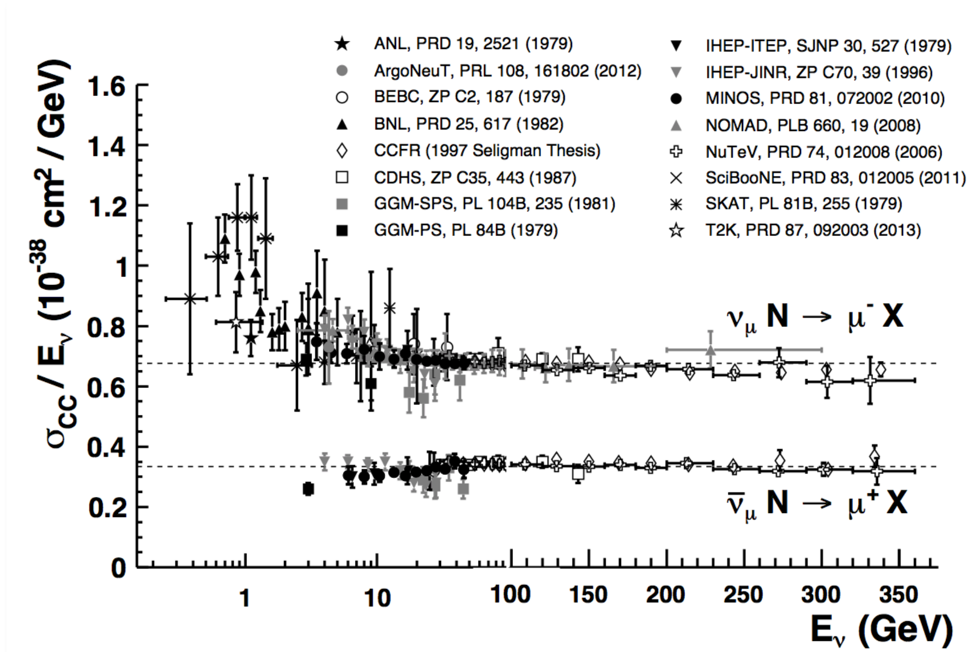
  "nothing in, something out"

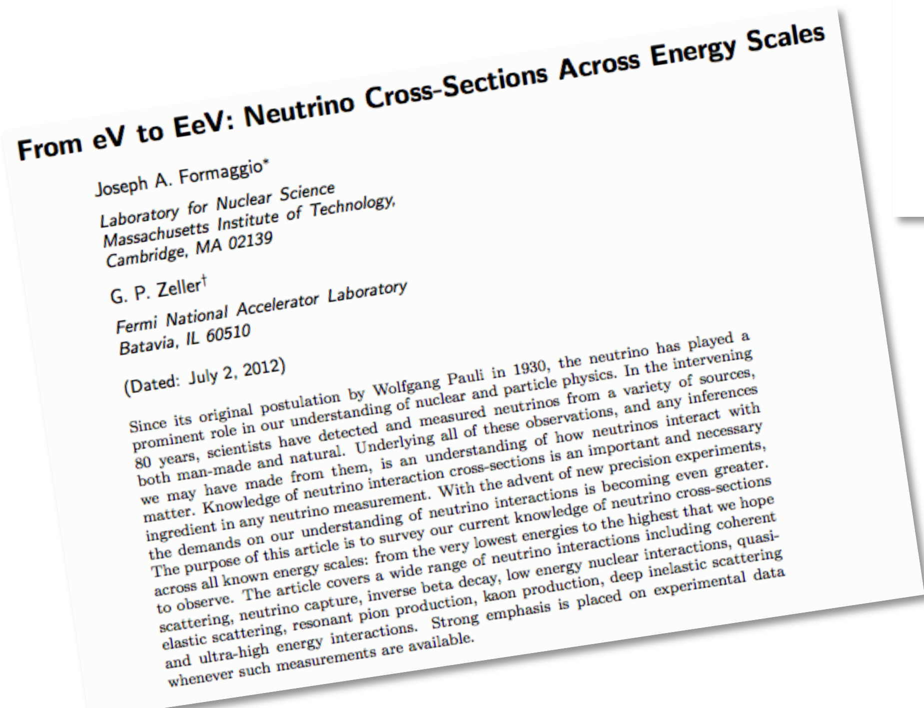
(example: NOMAD detector)

- knowing how a ν interacts is really important! *(ArgoNeuT, MiniBooNE, MINERvA, MicroBooNE, NOMAD, SciBooNE, T2K)*

Additional Information

* you can look in the PDG for neutrino cross section plots …





From eV to EeV: Neutrino Cross-Sections Across Energy Scales

Joseph A. Formaggio*
Laboratory for Nuclear Science
Massachusetts Institute of Technology,
Cambridge, MA 02139

G. P. Zeller†
Fermi National Accelerator Laboratory
Batavia, IL 60510

(Dated: July 2, 2012)

Since its original postulation by Wolfgang Pauli in 1930, the neutrino has played a prominent role in our understanding of nuclear and particle physics. In the intervening 80 years, scientists have detected and measured neutrinos from a variety of sources, both man-made and natural. Underlying all of these observations, and any inferences we may have made from them, is an understanding of how neutrinos interact with matter. Knowledge of neutrino interaction cross-sections is an important and necessary ingredient in any neutrino measurement. With the advent of new precision experiments, the demands on our understanding of neutrino interactions is becoming even greater. The purpose of this article is to survey our current knowledge of neutrino cross-sections across all known energy scales: from the very lowest energies to the highest that we hope to observe. The article covers a wide range of neutrino interactions including coherent scattering, neutrino capture, inverse beta decay, low energy nuclear interactions, quasi-elastic scattering, resonant pion production, kaon production, deep inelastic scattering and ultra-high energy interactions. Strong emphasis is placed on experimental data whenever such measurements are available.

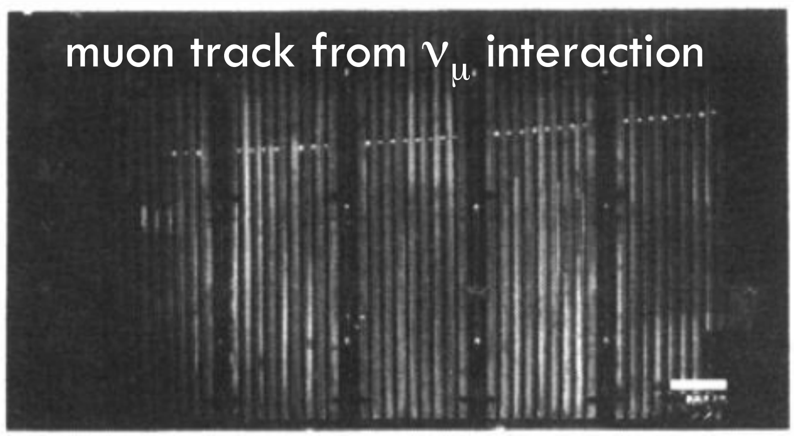
* review of neutrino interactions
Rev. Mod. Phys. 84, 1307 (2012)
http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.84.1307

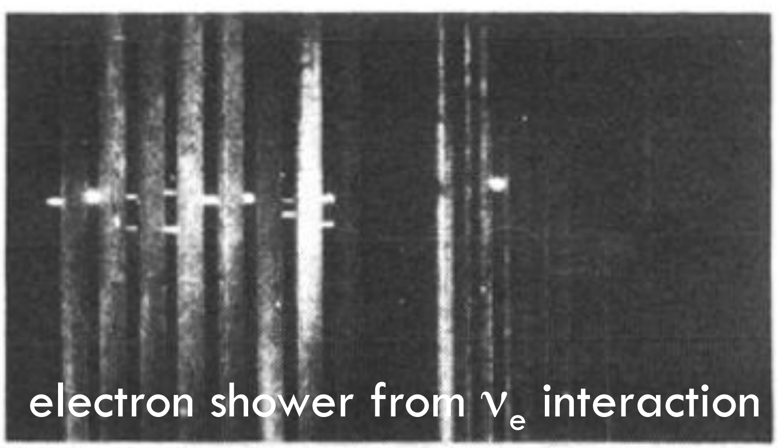
Neutrino Flavor

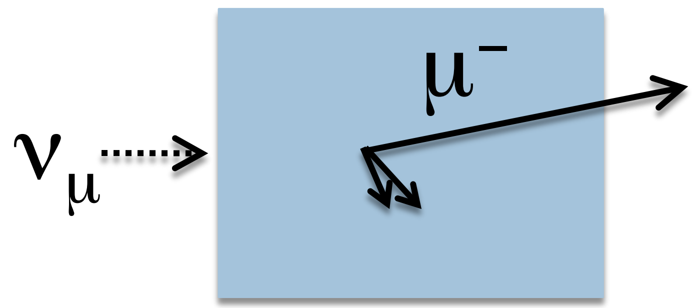
- you can tell what type of ν you have based on how it interacts

(knowing what type of ν you have is an important part of ν oscillation measurements)

spark trail could be photographed, circa 1962

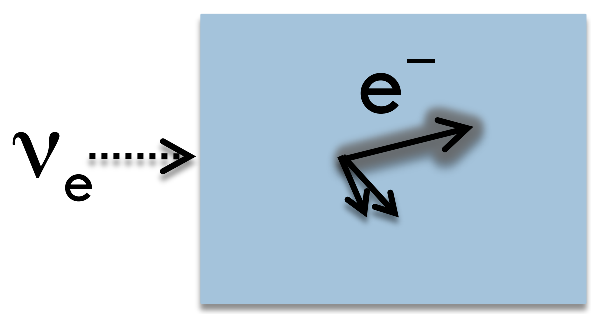






ν_μ produce a nice long μ track

this is how we identify the "flavor" of the ν



ν_e produce an e^- shower

So Far …

- the basics:

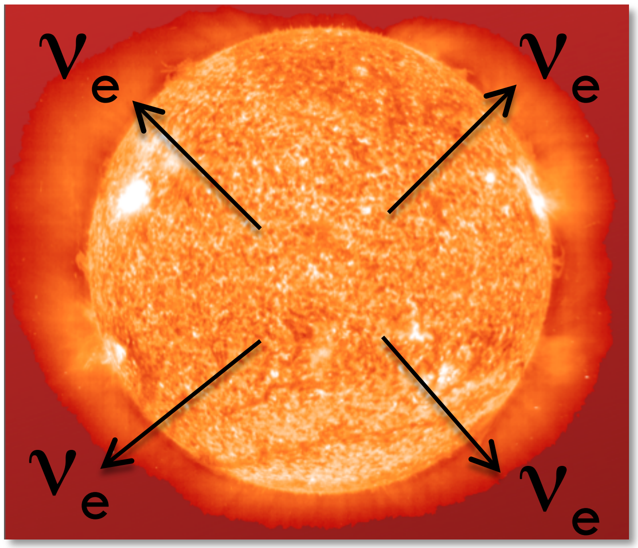
  - many different sources of neutrinos that span a large energy range

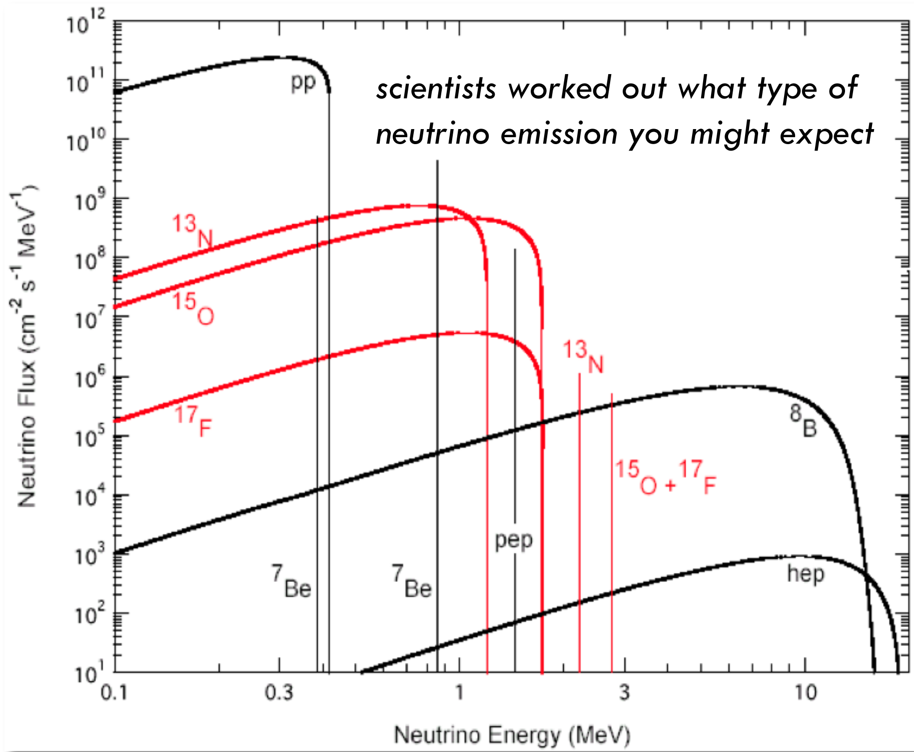
  - we need large detectors to study them

  - we can tell what type of neutrino we have (ν_e, ν_μ, ν_τ) and its energy based on the particles it creates when it interacts

Our Sun

- nuclear processes that power the sun produce a huge number of ν's



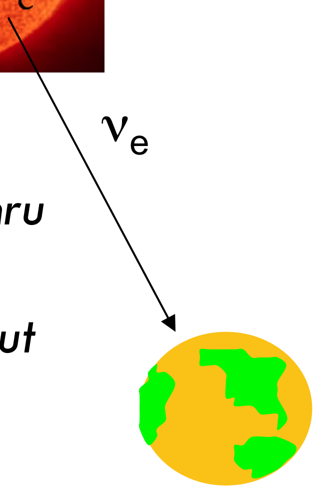


- this is how the sun generates its energy – a series of nuclear reactions each producing electron neutrinos

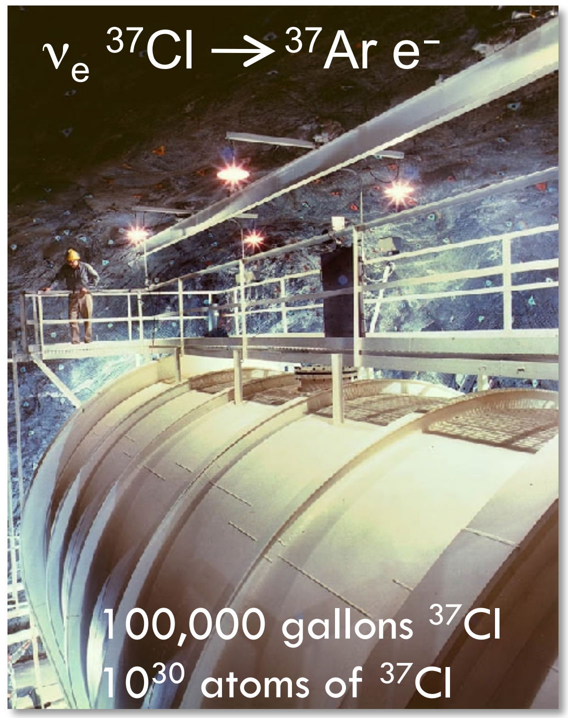
- the idea was to detect these solar ν's to understand what's going on in the core of the sun

Solar Neutrinos

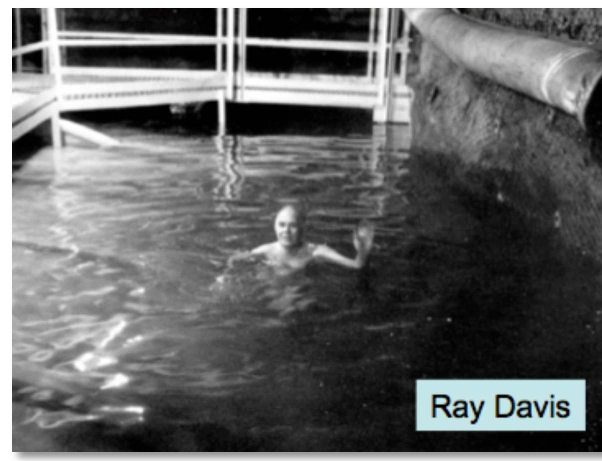
- In the 1960's, Ray Davis builds the first large scale detector to look for ν's from the sun … radiochemical detector cost ~\$4M (today dollars)



ν's pass unhindered thru the sun; it takes about 9 mins for the ν's to reach earth



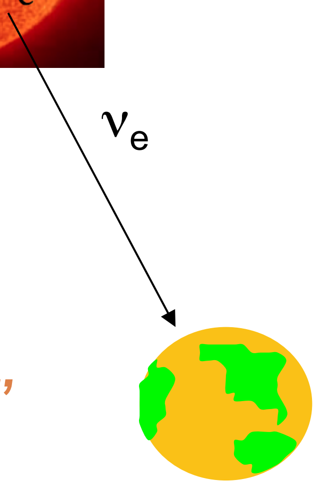
(an interesting and difficult experiment)



- ν's recognized as a tool to do astrophysics and as a means to learn about the sun

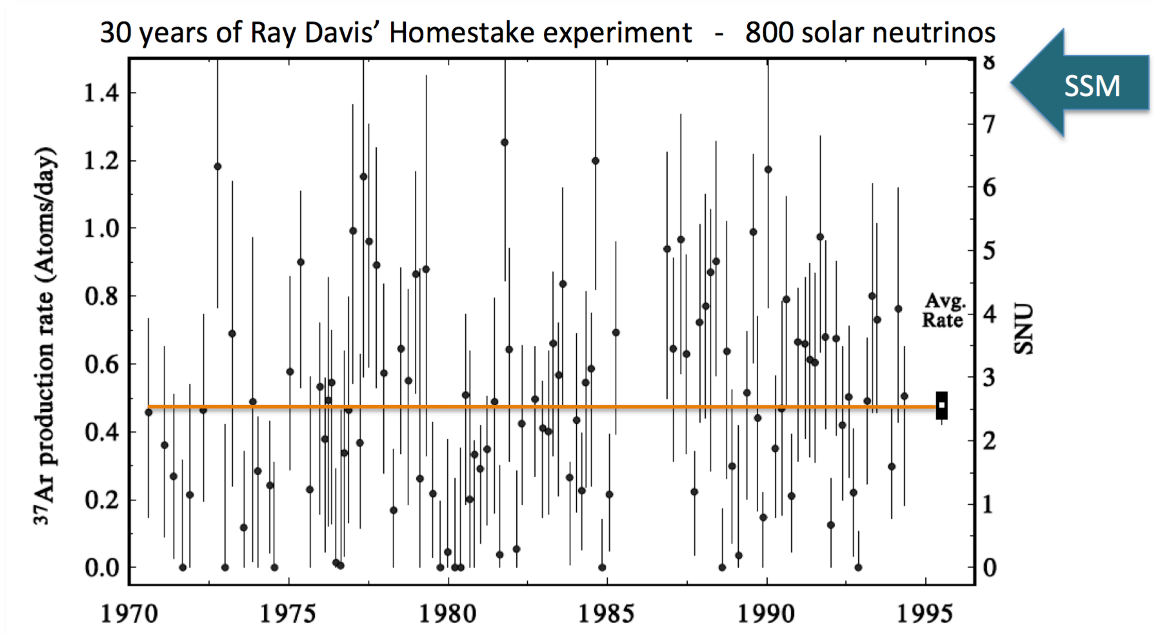
What Did He Find?

- by the time they get to earth, see only ~1/3 of the ν_e's expected →



"solar neutrino problem"

- here is where things start getting weird



- over the next 30 years, this deficit would be observed in many different detectors
- it would turn out that it wasn't the sun we didn't understand, but the neutrino!

More Missing Neutrinos

- another class of neutrino experiments saw a similar tale, this time studying **atmospheric neutrinos** (much higher in energy than solar ν's)

- ν's can be produced when high energy protons from deep space slam into the earth's atmosphere

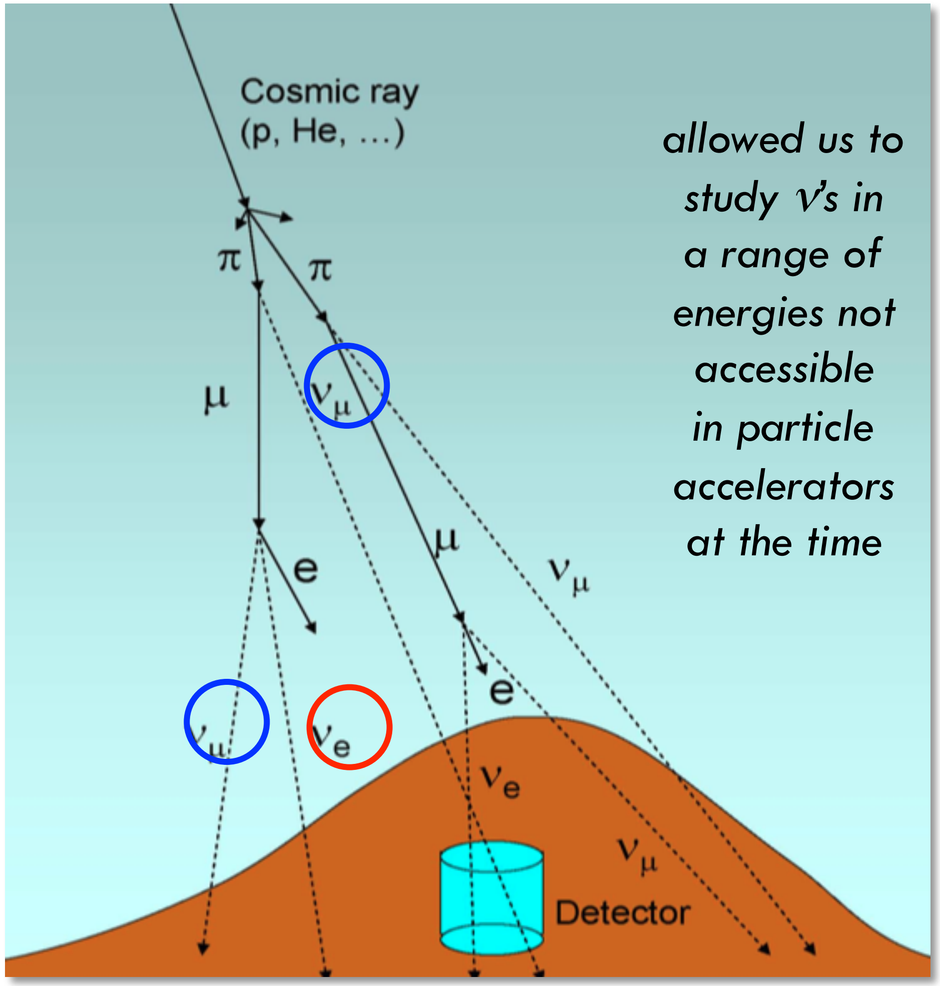
$\nu_\mu : \nu_e = 2:1$

(fixed by the π/μ cascade)

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

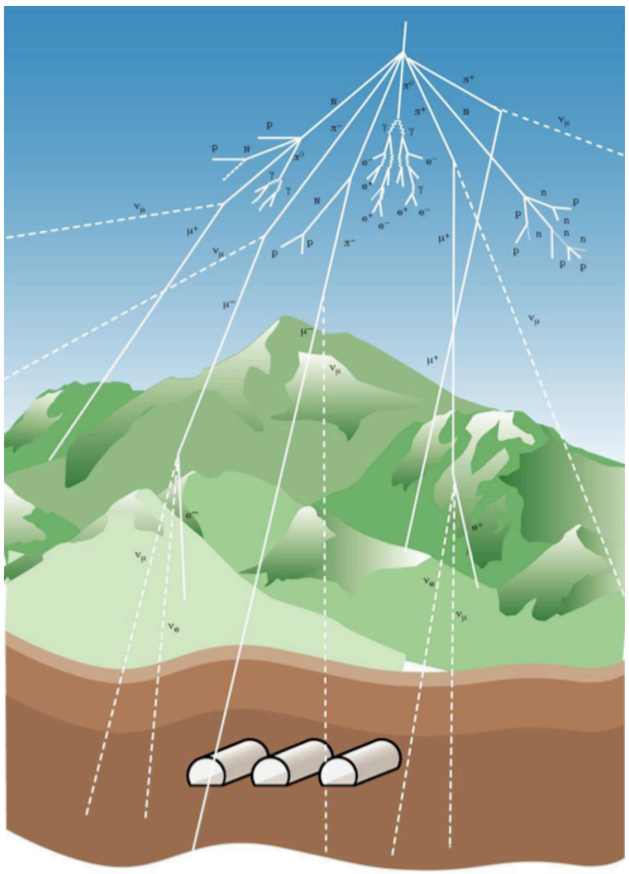
$\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

- get two ν_μ for every ν_e (this ratio could be tested in large underground detectors)

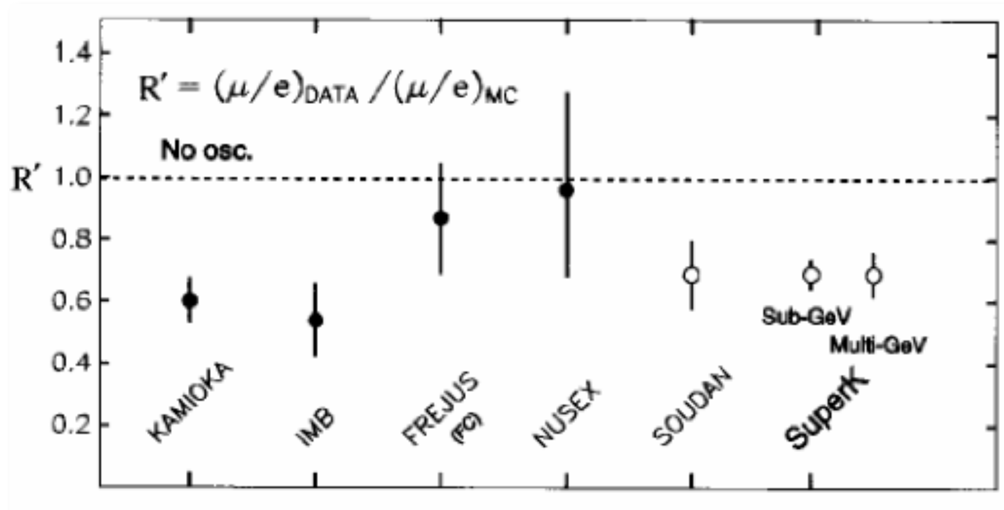


More Missing Neutrinos

atmospheric neutrinos
(ν_μ:ν_e should arrive
in 2:1 ratio)



- again, the shortfall was quite large



- another mystery: fewer ν_μ than expected; roughly half of the predicted atmospheric ν_μ's are missing! "atmospheric ν anomaly"

- so for decades, we see less ν_e from the sun and less ν_μ from the atmosphere

Neutrino Oscillations

- this is a very recent discovery in the world of modern particle physics

(news was coming out when I was in graduate school)

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to use a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of Federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of six years in prison for each, to run concurrently with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge carried a possible death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge Matsch.

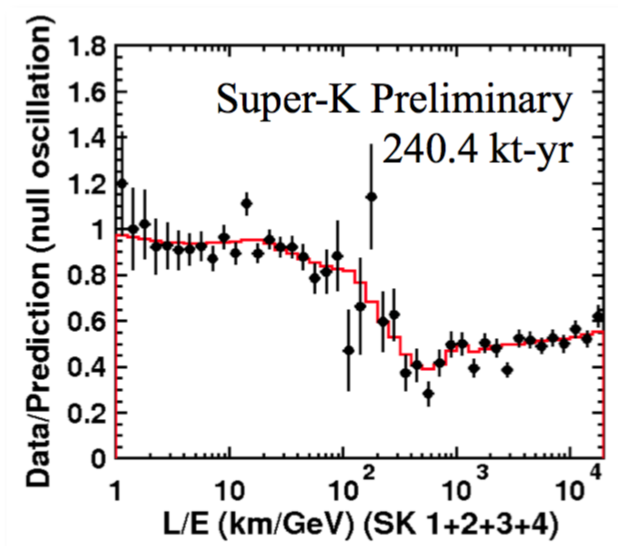
Bajram Curri, in no
Yugoslavia in three

Refugees
A Bitte

PADESH, Albania,
dent Slobodan Milose
via has unleashed t
tary operation in the
the end of the war in
thousands of ethnic
the border area wi
reducing their village
At least 10,000
streamed through

(NY Times, June 1998)

- by 1998, we were convinced, ν's oscillate (must have mass)



- Super-K atmospheric ν results remain the most cited paper in experimental HEP (>4000 citations)

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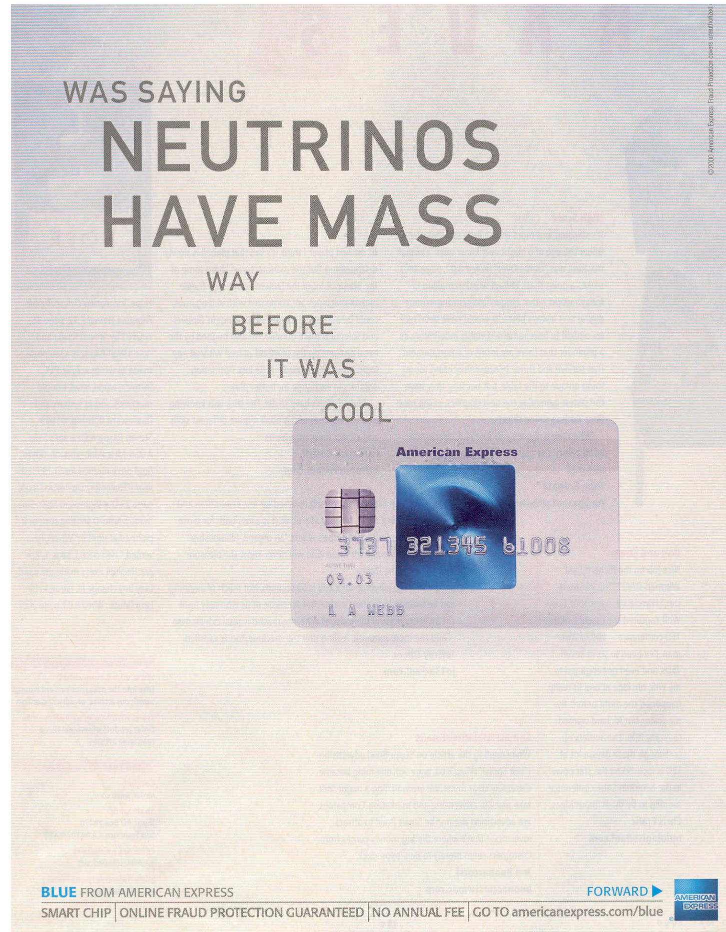
PADESH, Albania,
dent Slobodan Milose
via has unleashed th
tary operation in the
the end of the war in
thousands of ethnic
the border area wi
reducing their village
At least 10,000
streamed through

(NY Times, June 1998)

- this even made it into ads →



- ν oscillation studies commenced on 4 continents

This is a Big Deal

- it is the 1st known particle interaction indicating physics "beyond the Standard Model"

ν oscillations caught us off guard

(first crack in this extremely successful theoretical framework that we have constructed to explain all of the particles & their interactions)

this was unexpected

- the hope is that ν's may help us answer ?'s about the universe we live in by studying these transformations and how often they occur under various conditions *(L, E, flavors)*

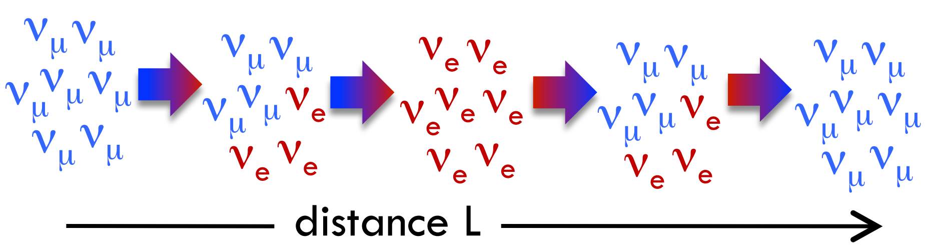
- *because ν's are so abundant, even a small mass can have important consequences*

Neutrino Oscillations

- ν's can gradually change into another kind & back again; this flavor changing is called **"neutrino oscillations"**; quantum mechanical effect

- can write down a simple eqn; tells you probability that a ν starting off life as one type can be observed later as another type

$$\nu_\mu \rightarrow \nu_e$$



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

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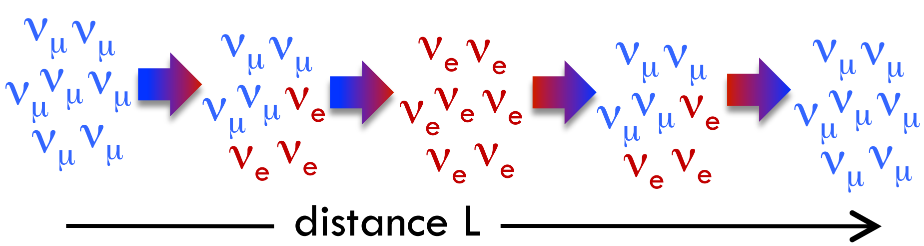

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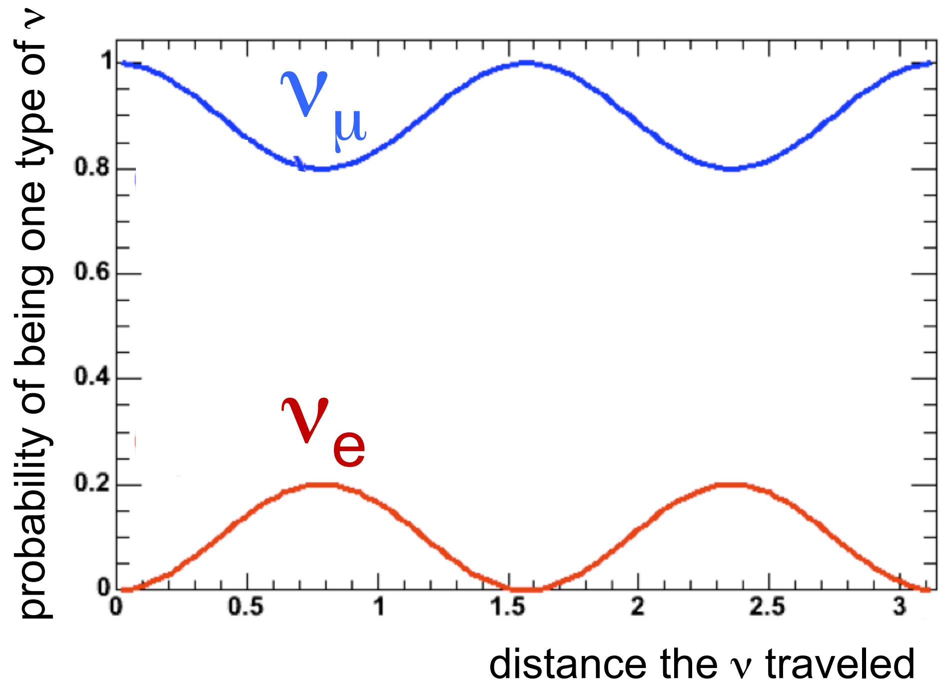

- two principle ways to study:
  - disappearance
  - appearance

(some of the most powerful experiments look for both)

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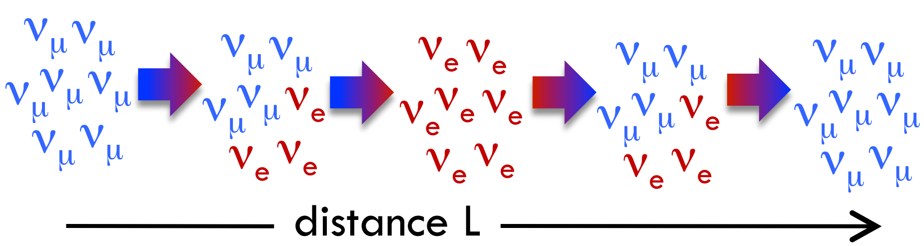

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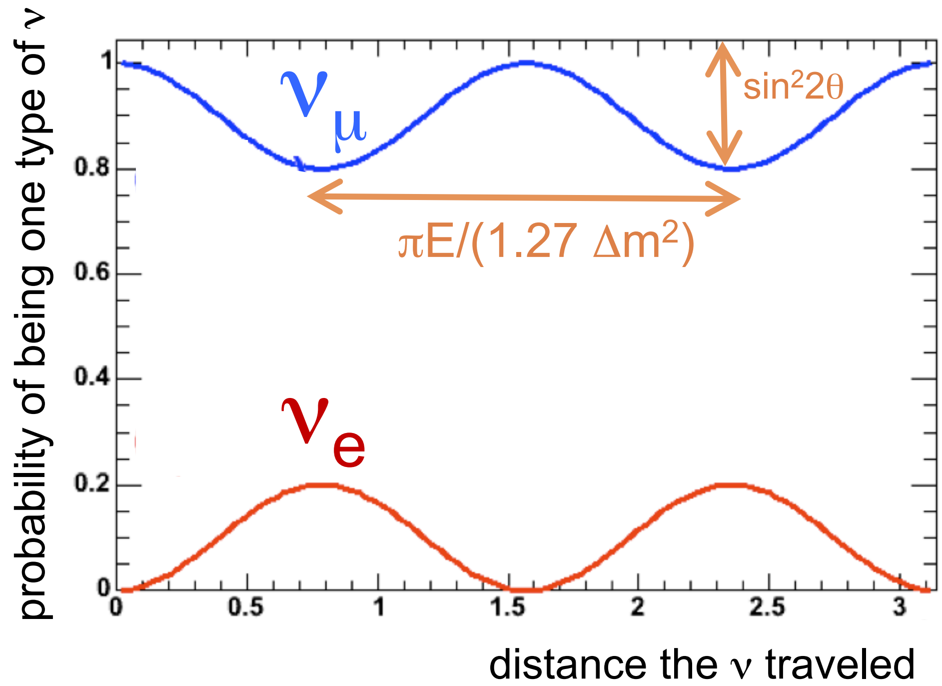

- ν's must have mass to oscillate
- depends on Δm^2, θ and L, E_ν

(need to give just a few #'s to describe what's going on)

Neutrino Oscillations

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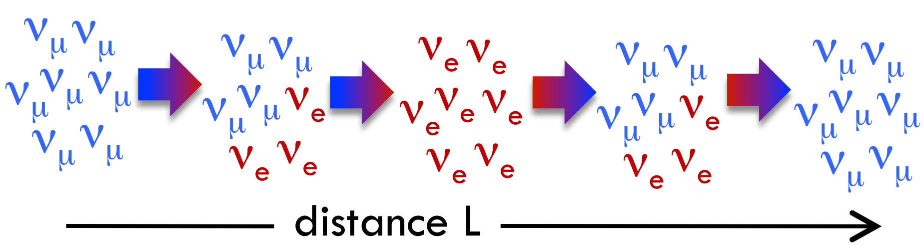

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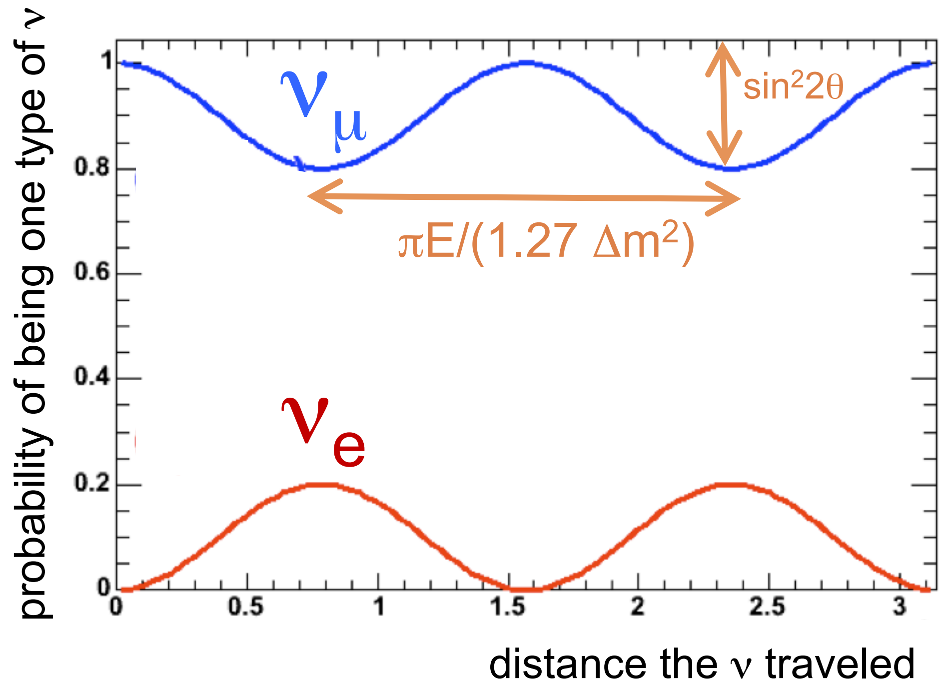
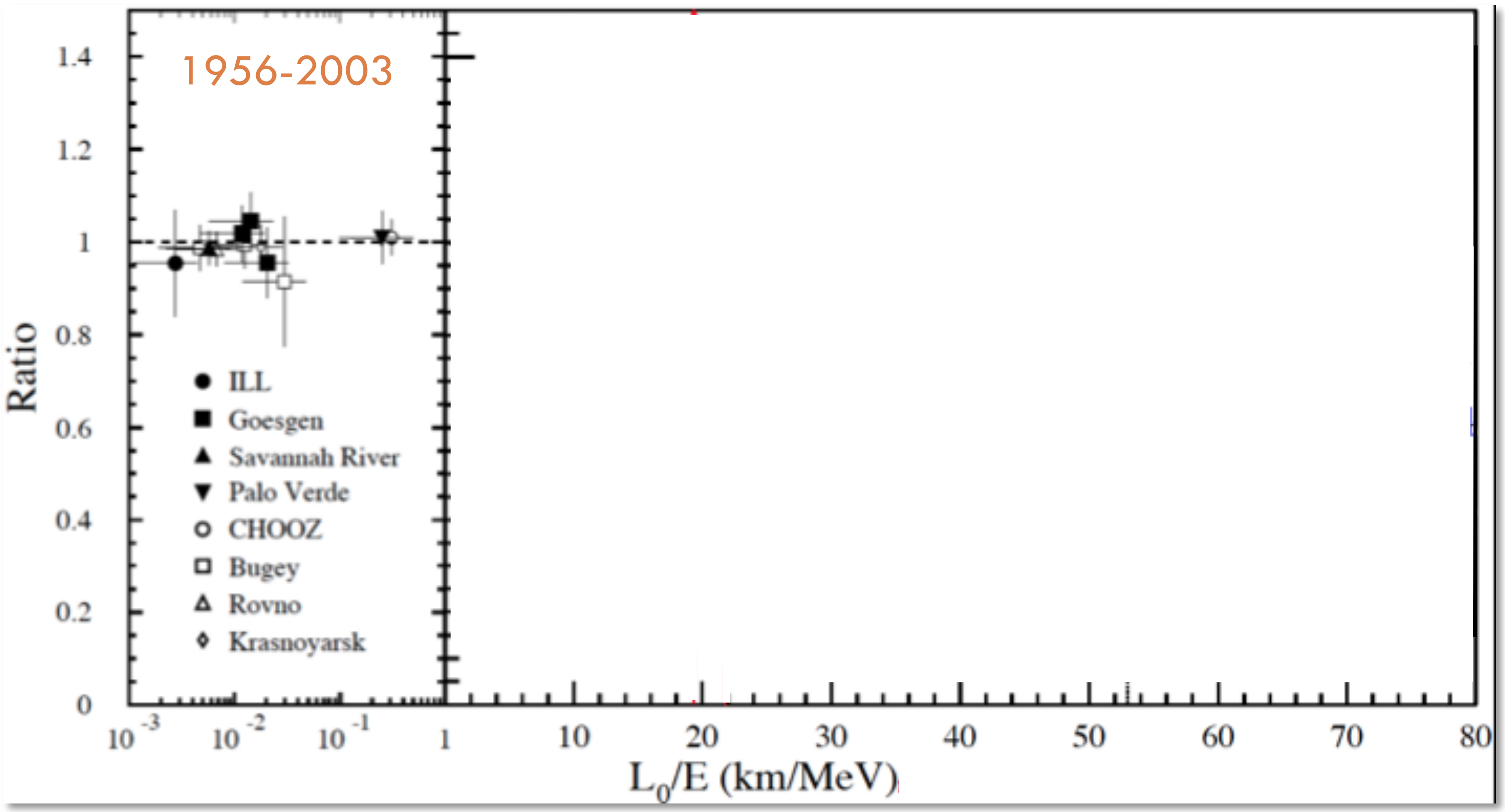


"At present this is highly speculative- there is no experimental evidence for neutrino oscillations..." D.J. Griffiths (1995), *Introduction to Quantum Mechanics*

Location, Location, Location

- in the 1960's, scientists had started thinking "is there anything else?" - maybe ν transitions?

Maki
Sakata
Nakagawa



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Bruno Pontecorvo

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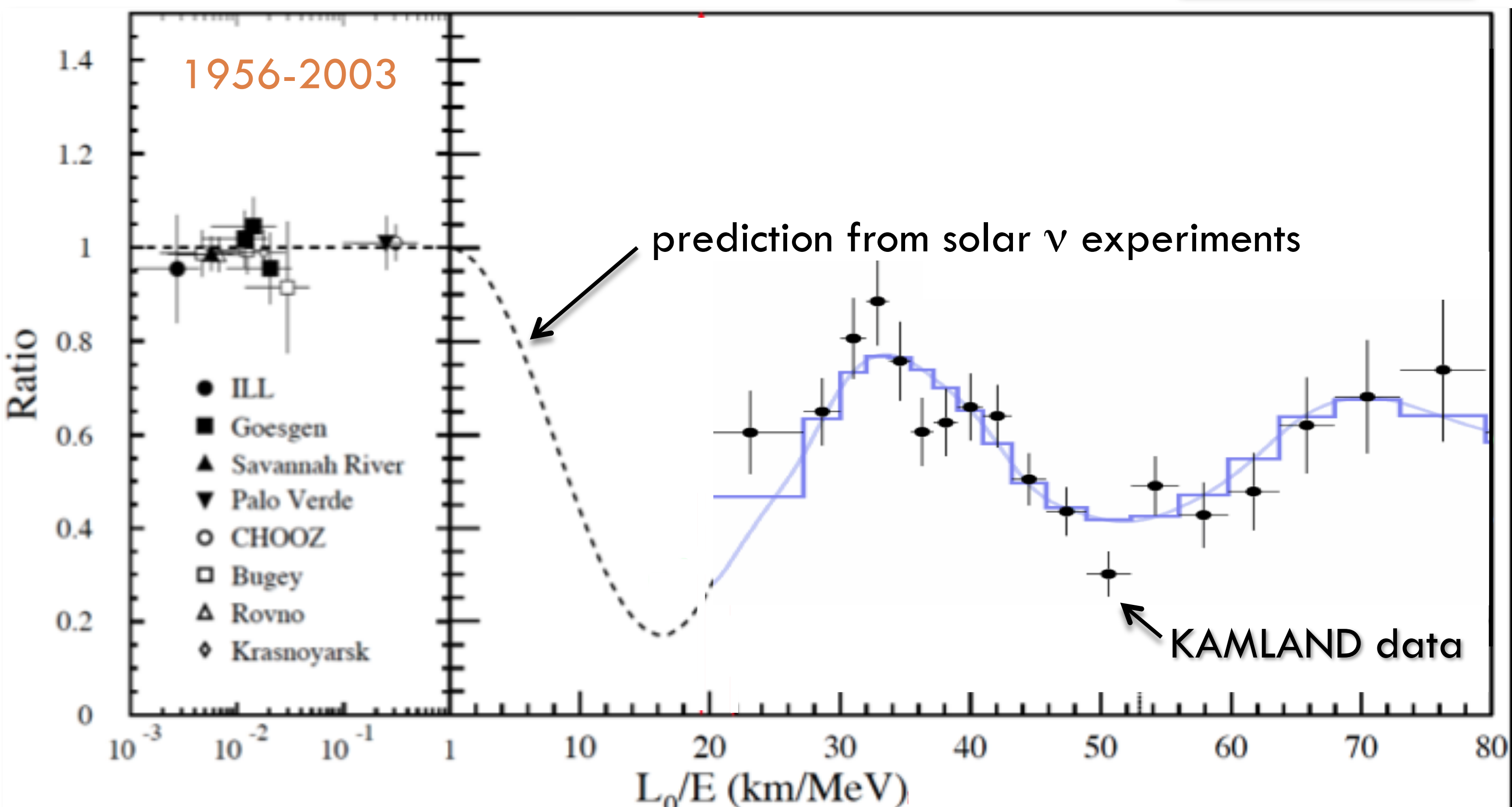
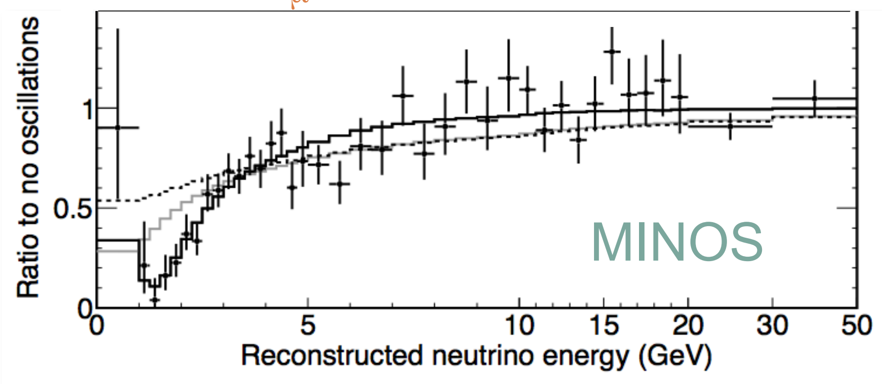


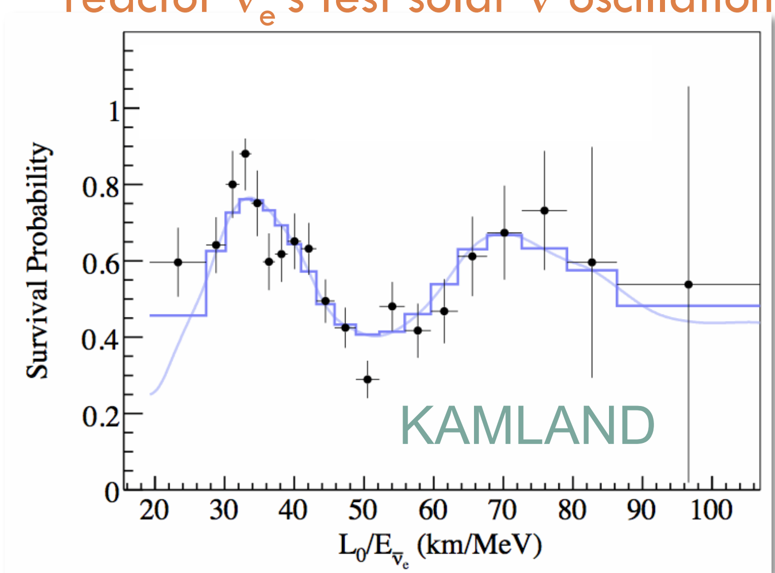
important to take big steps

Today

accelerator ν_μ's test atmospheric ν oscillations:



reactor $\overline{\nu}_e$'s test solar ν oscillations:



- we have observed this quantum mechanical phenomenon now in ν's produced in multiple sources
  - *sun*
  - *earth's atmosphere*

  } "wild neutrinos"

  - *particle accelerators*
  - *nuclear reactors*

  } "tame neutrinos"

- it took multiple experiments & approaches to rule out other possibilities for what could be going on *(our ν sources work together)*

- we see large effects!

The Basics of Neutrino Mixing

- neutrino oscillations are characterized by a mixing matrix:

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}}_{\theta_{13}=\text{small mixing}} \times \underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar}} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

atmospheric | θ_{13}=small mixing | solar

this allows us to understand the results from ν experiments

$$V_{MNS} \sim \begin{pmatrix}0.8 & 0.5 & \mathbf{0.2}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}$$

neutrinos

$$V_{CKM} \sim \begin{pmatrix}1 & 0.2 & 0.001\\ 0.2 & 1 & 0.01\\ 0.001 & 0.01 & 1\end{pmatrix}$$

quarks

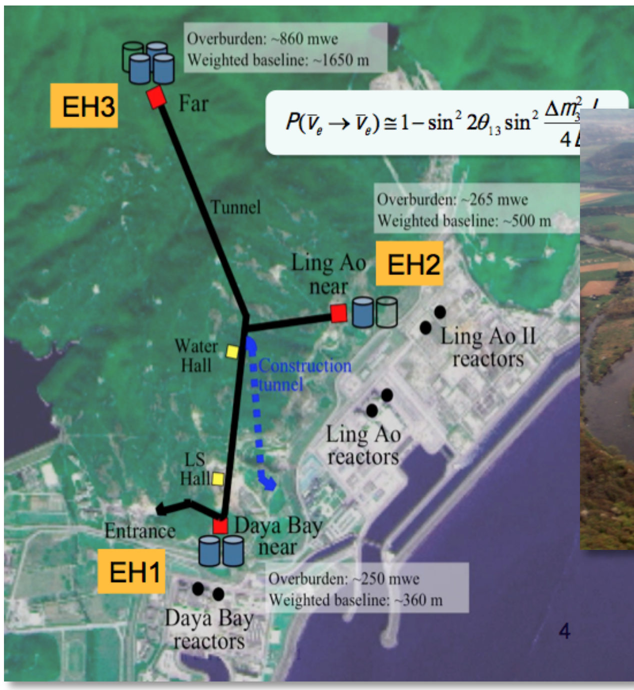
- <u>we know pretty well</u>:
  - *mixing angles (θ_{23}, θ_{12}, and θ_{13} ← recently!)*

My Niece

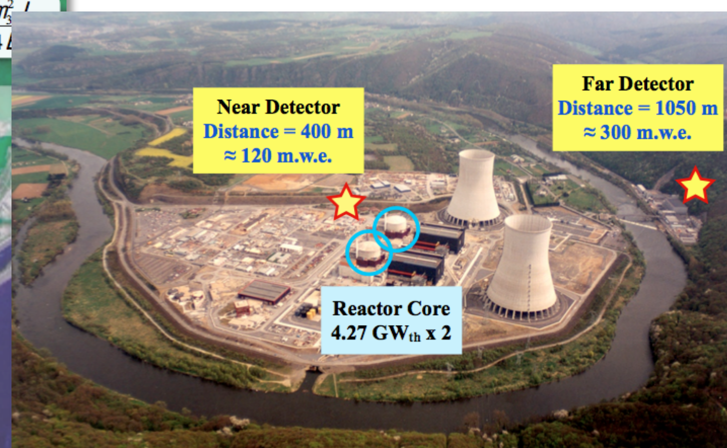
Do you know what this last mixing angle is yet?

Reactor Neutrino Experiments

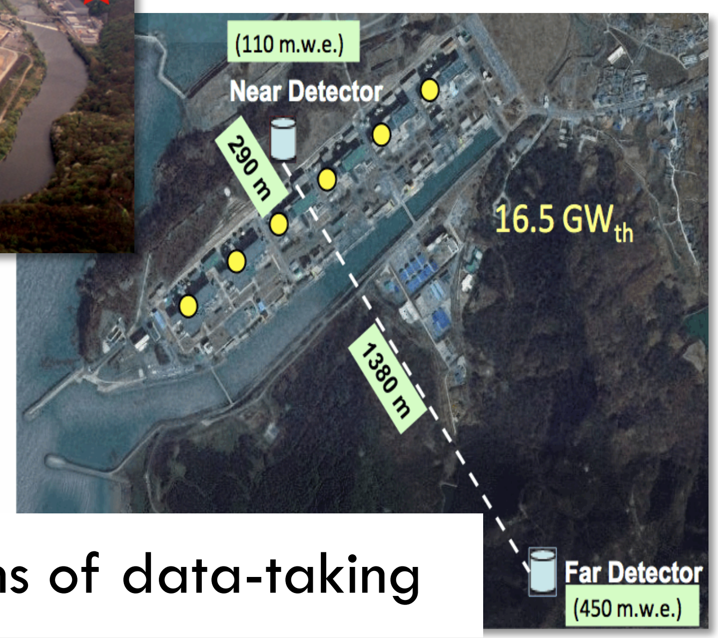
- **Daya-Bay** (China)
  - *6 reactors, 8 detectors*
  - *Sept 2011 - present*



- **Double Chooz** (France)
  - *2 reactors, 1 detector (ND in 2014)*
  - *Apr 2011 - present*



- **RENO** (Korea)
  - *6 reactors, 2 detectors*
  - *August 2011 - present*



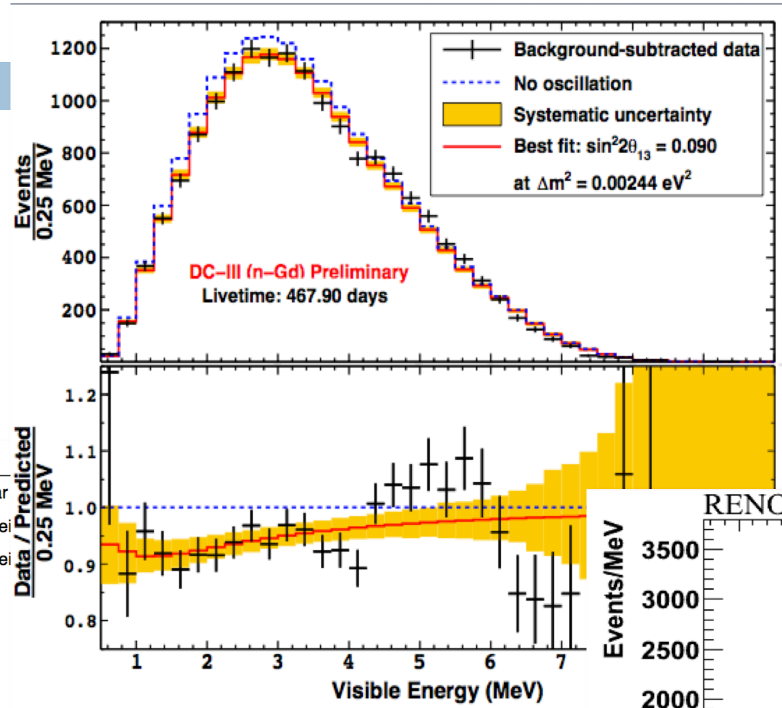
- clear evidence for a $\overline{\nu}_e$ deficit in first months of data-taking

θ_{13}

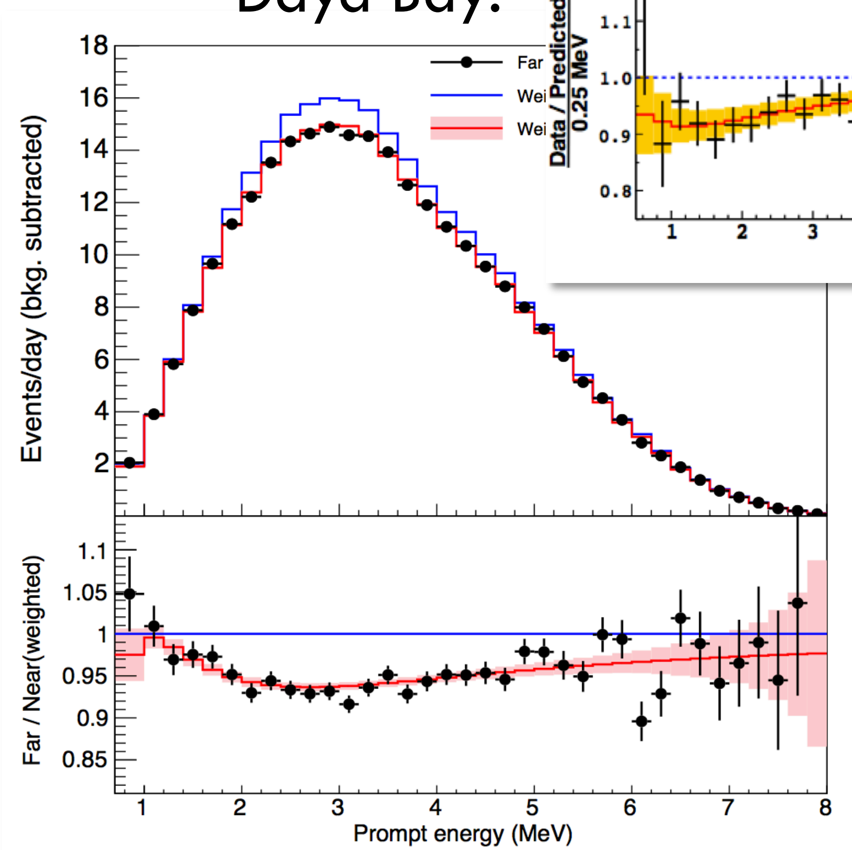
- now θ_{13} is the most well-measured mixing

latest results shown in June 2014

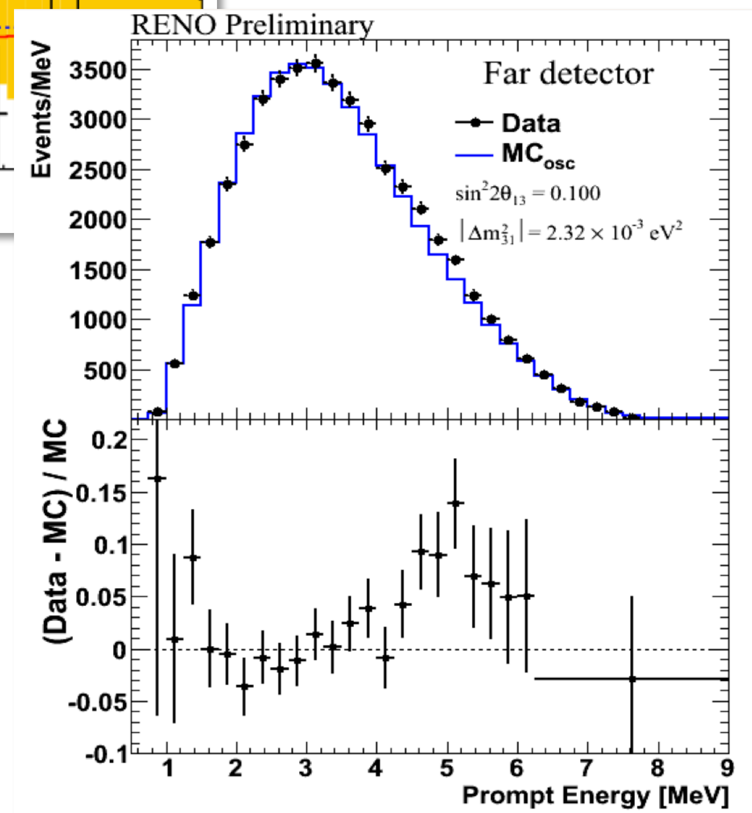
Double Chooz:



Daya Bay:



RENO:



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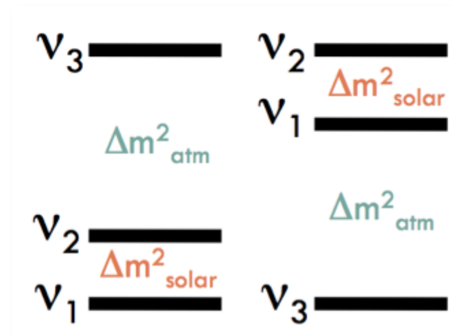
atmospheric θ_{13}=small mixing   solar



normal   inverted

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quarks

- we know pretty well:
  - *mixing angles (θ_{23}, θ_{12}, and θ_{13} ← recently!)*
  - *mass differences (Δm^2)*

- but there are some very important things we don't know!

Big Questions

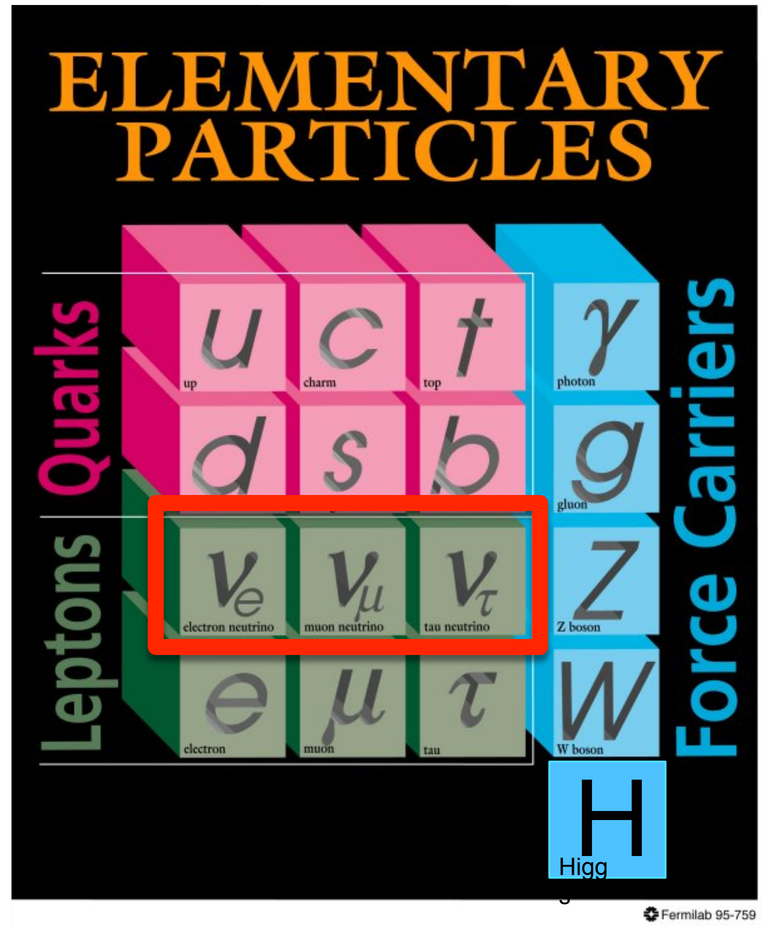
- we are missing some important information …

  - *is our picture correct?*
  - *how much do neutrinos weigh?*
  - *which neutrino is the heaviest and which is the lightest (MH)?*
  - *do neutrinos and antineutrinos oscillate in the same way (CP)?*
  - *what is the nature of the ν?*
  - *are there more than 3 kinds?*

$\theta_{13} \neq 0$!!

why we exist?

we don't know some pretty basic stuff!



are these small details or are they paradigm shifting?

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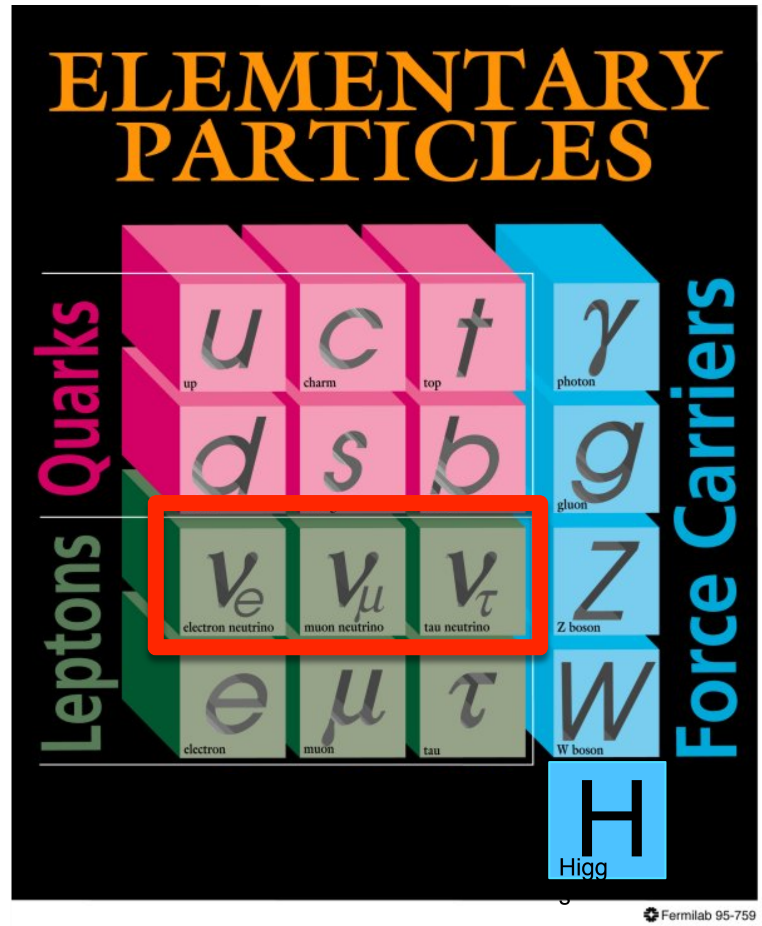
accelerator neutrinos



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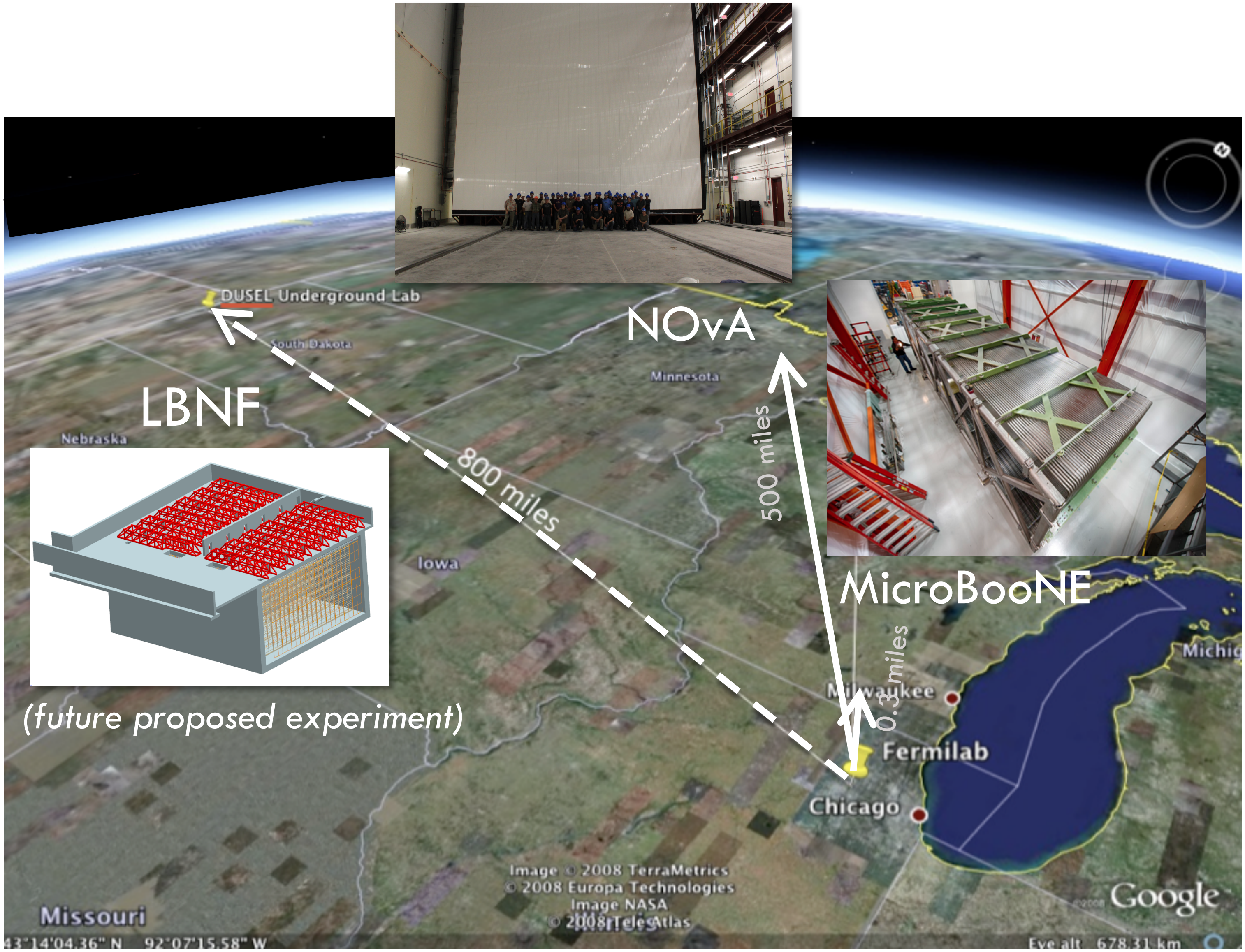
Neutrinos at Fermilab

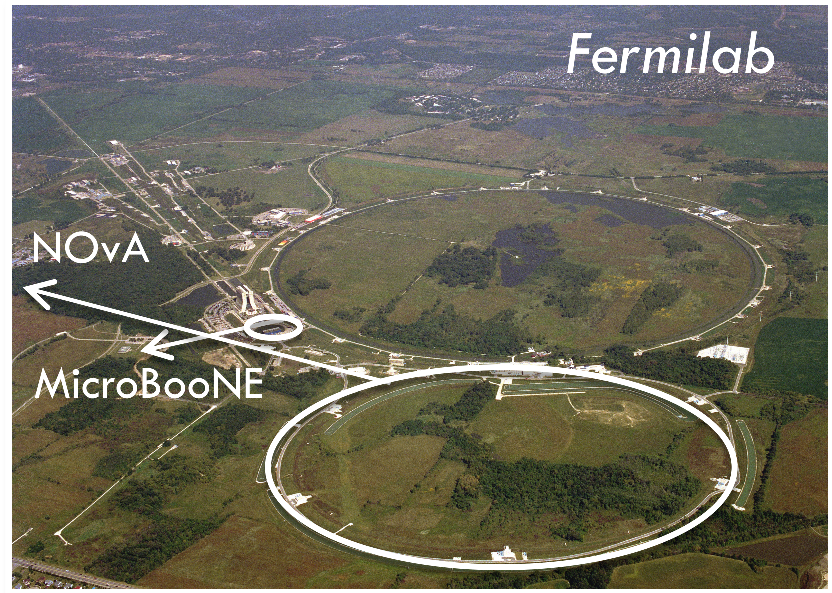


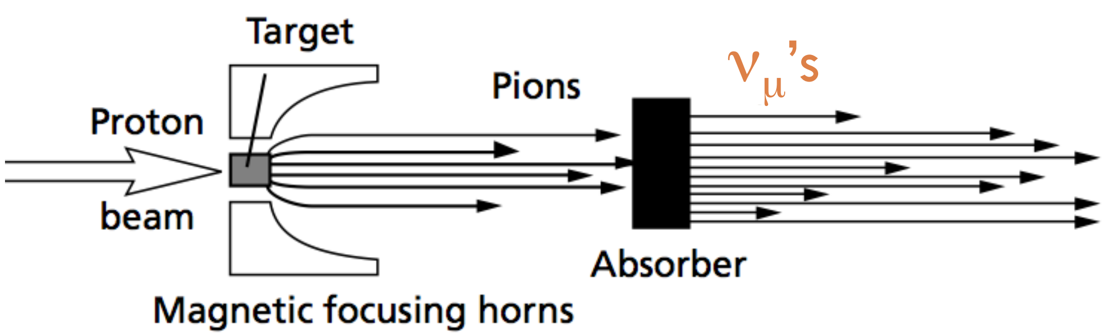
advances in accelerator technology are allowing us to probe distances (L), energies (E_ν) not easily accessible in nature or with nuclear reactors

Making Neutrinos

- so, we can also produce ν's for experiments using particle accelerators

- and aim them at a detector





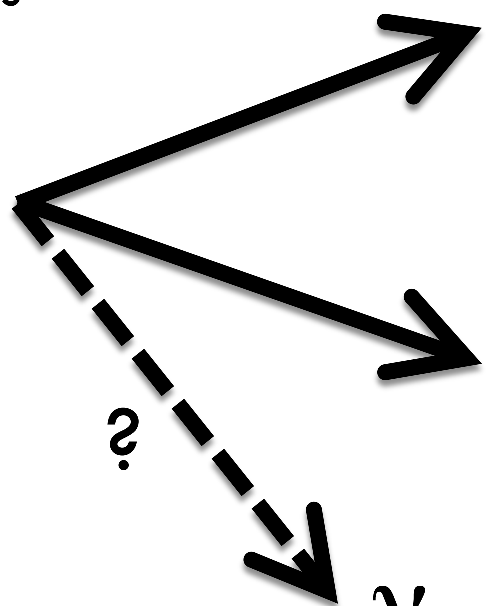
massive detector

get a well-known flavor of neutrinos

Where are the ν_μ's Going?

the ν_μ has two choices
(maybe three)

ν_μ

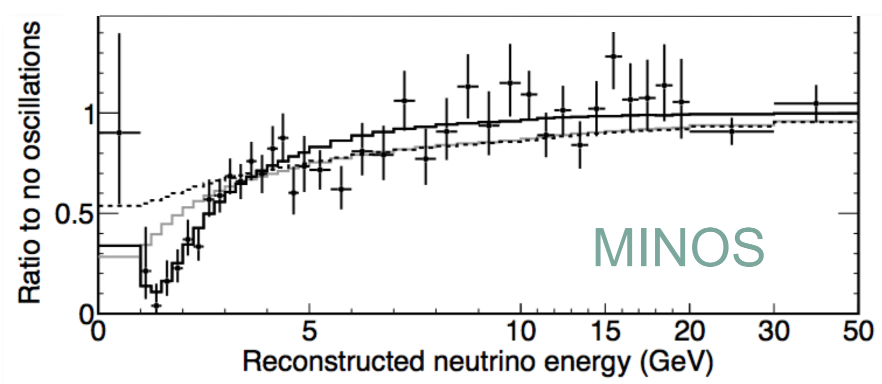


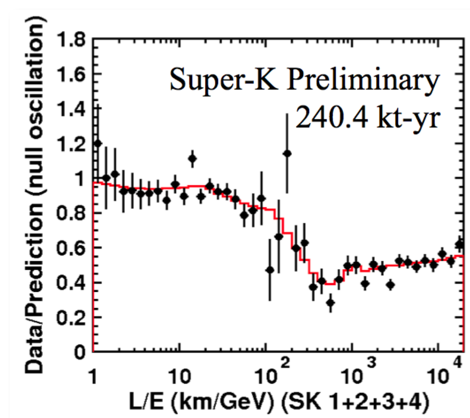
ν_τ (most of the time)

ν_e (every now and then)

ν_s

it's one thing to see the ν's disappearing but also want to confirm that they are re-appearing as another flavor of ν that was previously absent from the beam





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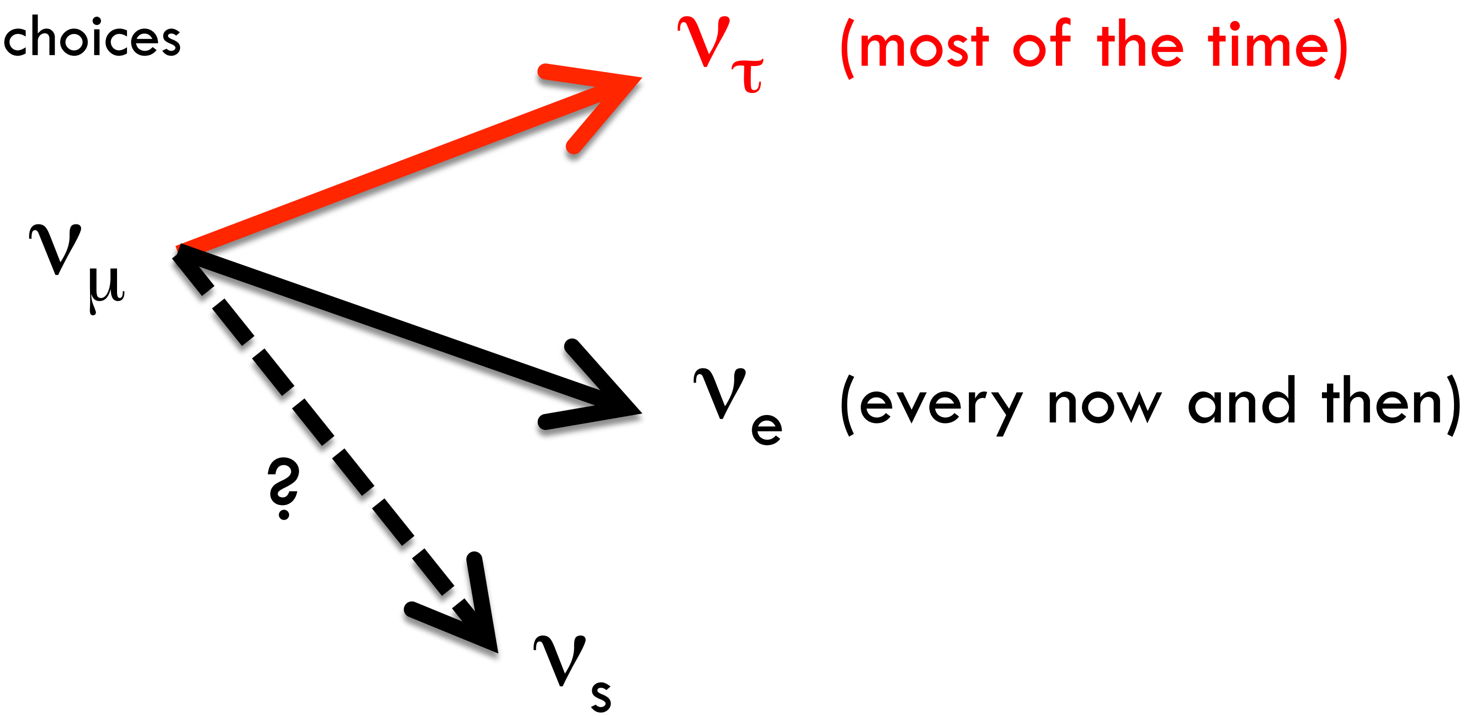
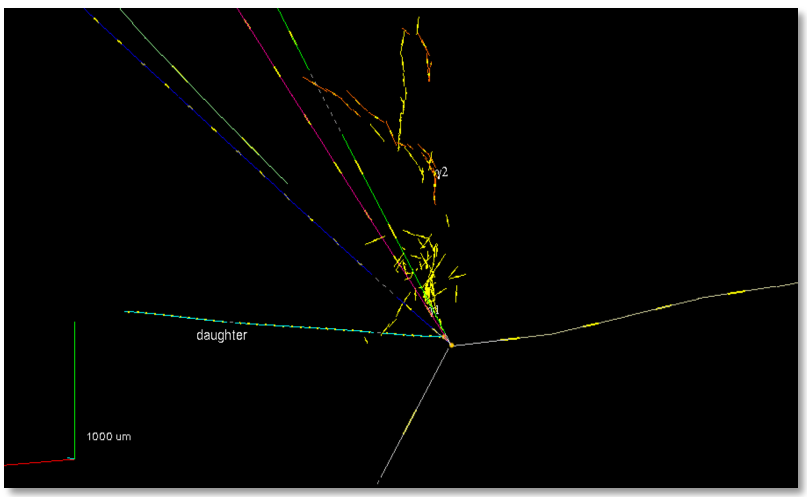
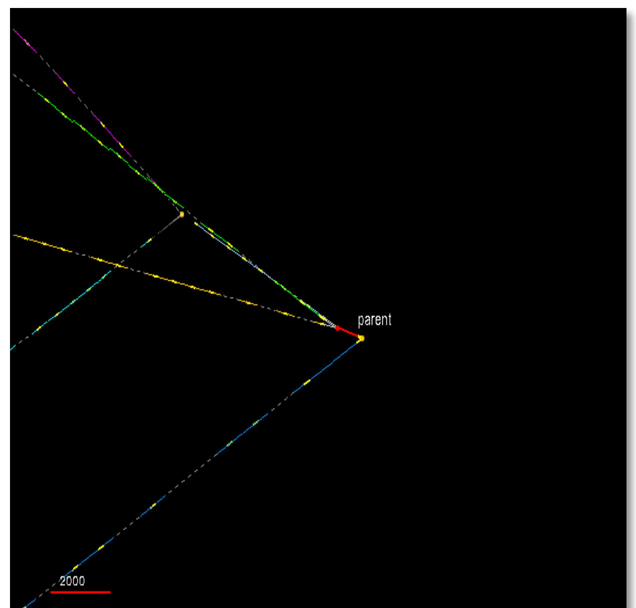


- want to confirm the hypothesis that $\nu_\mu \rightarrow \nu_\tau$ is the cause of the disappearance effect seen in atmospheric & accelerator-based ν's
- need an experiment capable of detecting short-lived τ's

$\nu_\mu \rightarrow \nu_\tau$

- 400 GeV proton from CERN SPS to produce beam above ν_τ threshold
- emulsion to detect τ decay
  (decay length is only a few mm)
- *largest production ever of nuclear emulsion: 200,000 bricks ~ 1 kton*



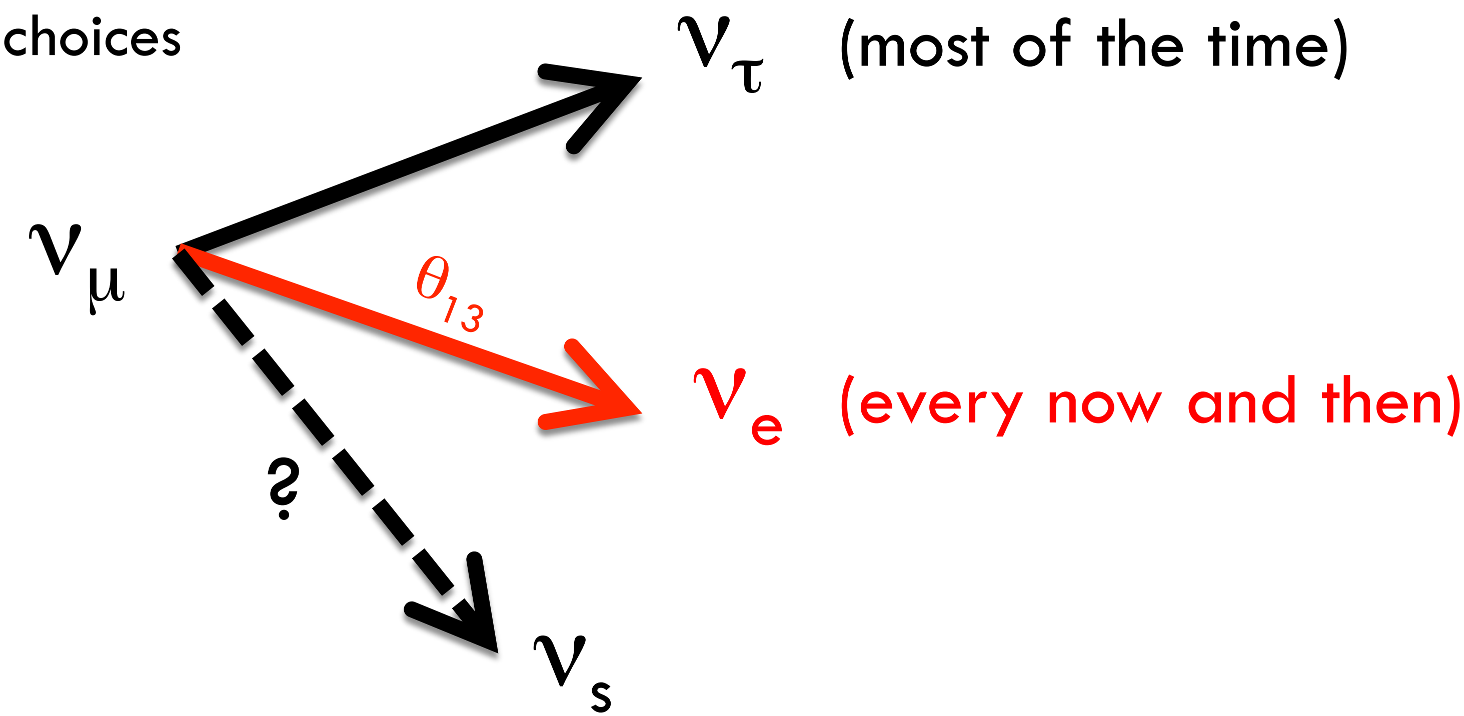


OPERA

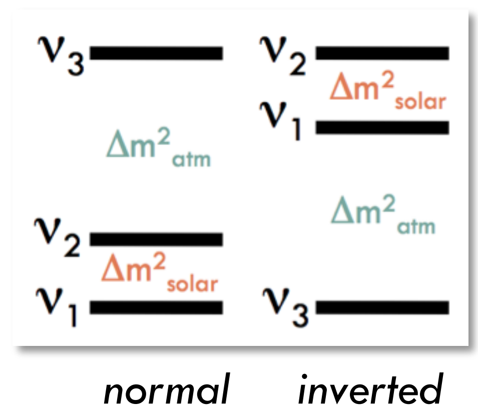
- June 2014: OPERA reported observation of a 4th ν_τ candidate (4.2σ)

Where are the ν_μ's Going?

the ν_μ has two choices
(maybe three)



- measurements of subdominant $\nu_\mu \rightarrow \nu_e$ are of great importance because they are very sensitive to mass hierarchy & uniquely sensitive to CP violation



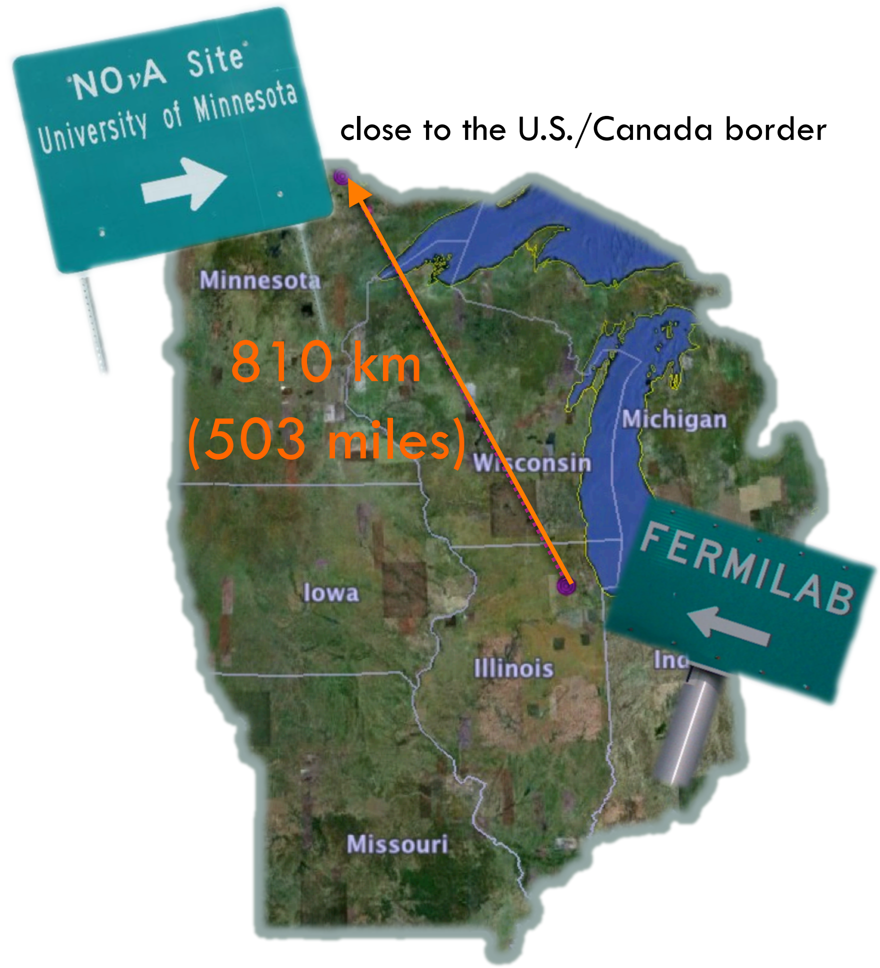
NOvA

- will measure $\nu_\mu \rightarrow \nu_e$ oscillations over a distance of 810 km using the world's most intense ν beam and an off-axis detector

- will study both $\nu, \bar{\nu}$

  - *very precise ν oscillation measurements (test our picture)*
  - *which ν is the lightest and which is the heaviest (MH)?*
  - *first hint at $\not{C}P$*

- this will be the largest distance an accelerator source of ν's has ever been sent … the larger the distance the larger the MH, CP effects



NOvA Detector

- you need a really large detector to study neutrino oscillations across this large a distance

- 14 kton liquid scintillator

(2.8 million gallons)

NOvA Detector

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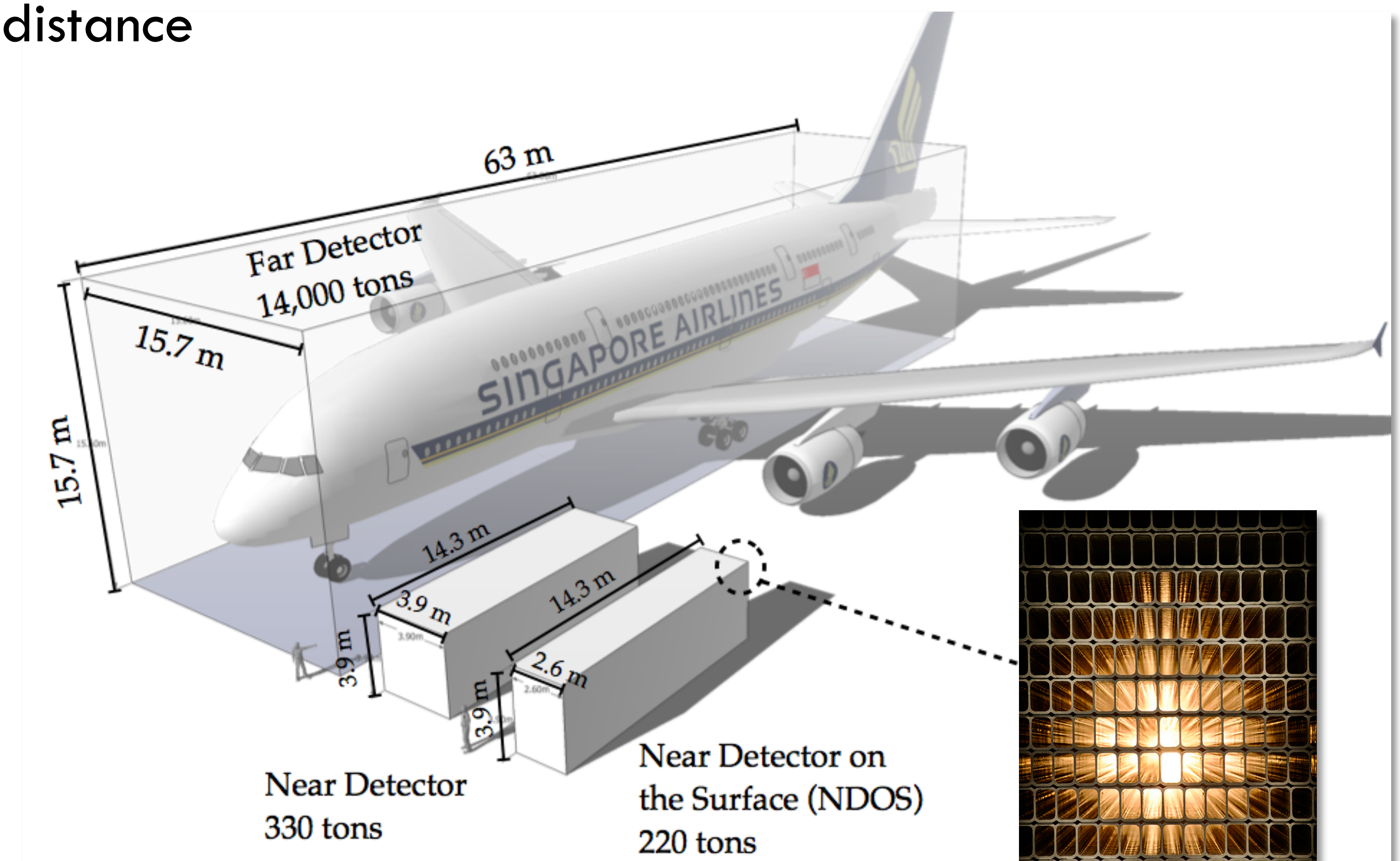


- 14 kton liquid scintillator

"largest plastic structure ever built"

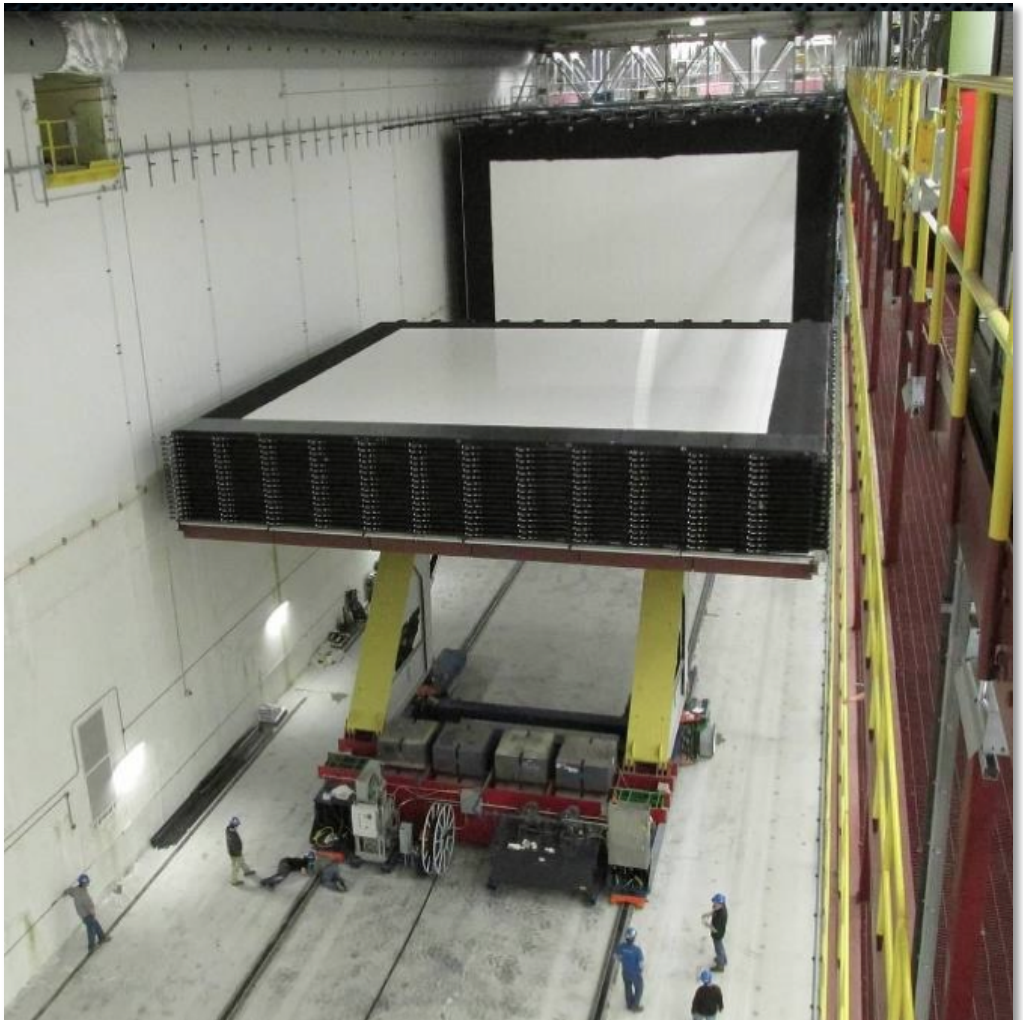
- both a near and far detector

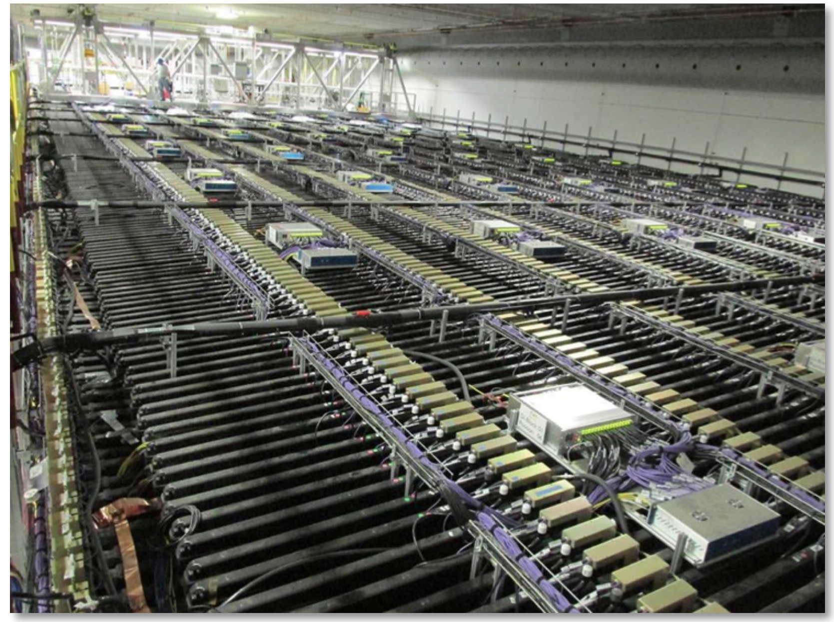
NOvA Near Detector at Fermilab

the near detector is important to sample the flavor composition and spectrum of the neutrinos before they've had a chance to oscillate

NOvA Far Detector in Minnesota

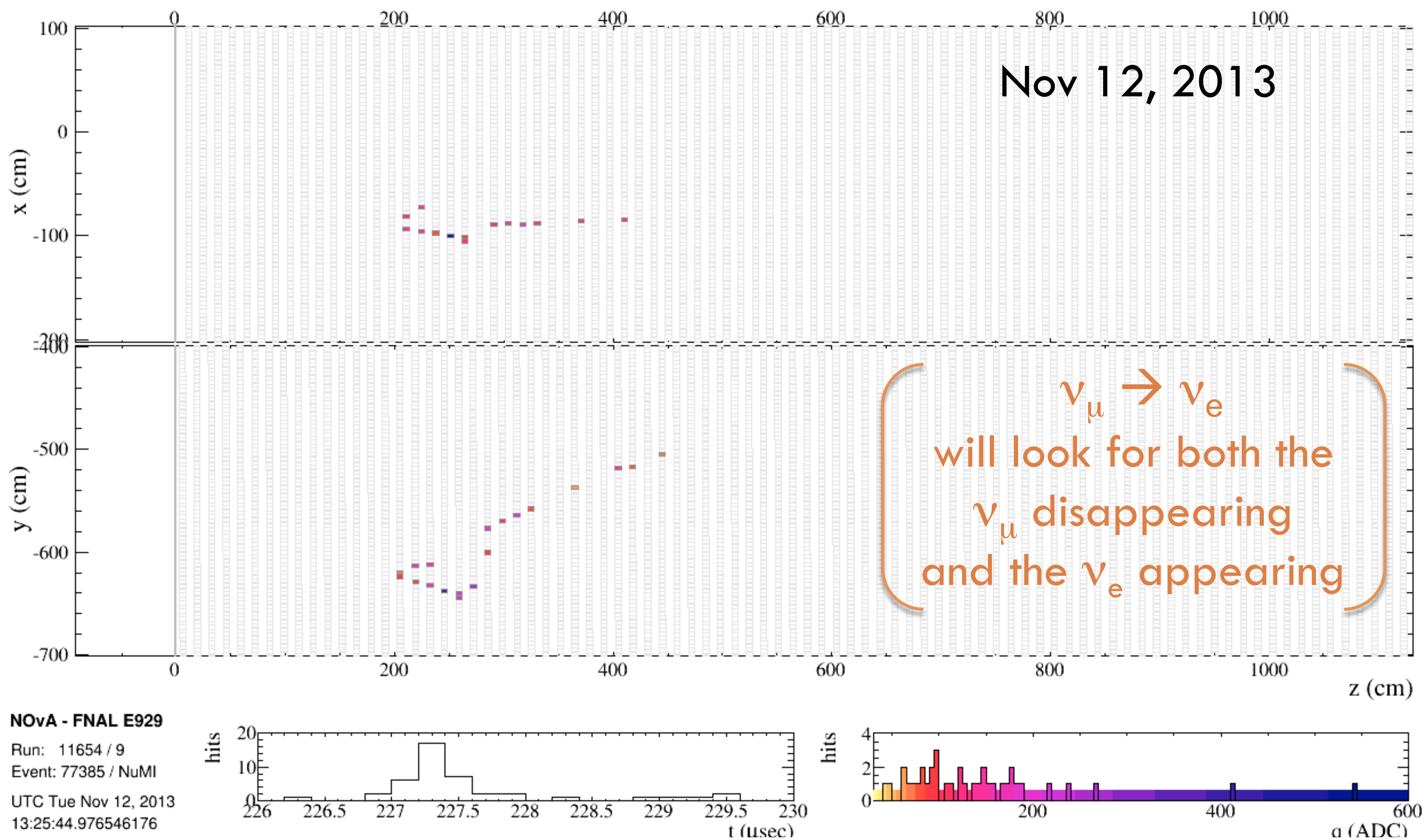
- over 4 stories high





- *28 blocks*
- *32 planes in a block, each weighing 417,000 lbs*
- *both near and far detectors are now complete!*

First Neutrino in NOvA!



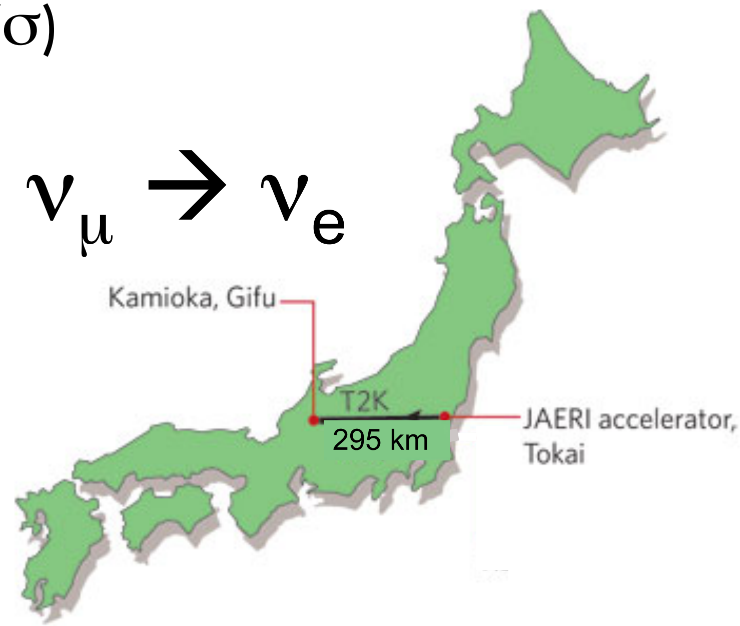
$\nu_\mu \rightarrow \nu_e$

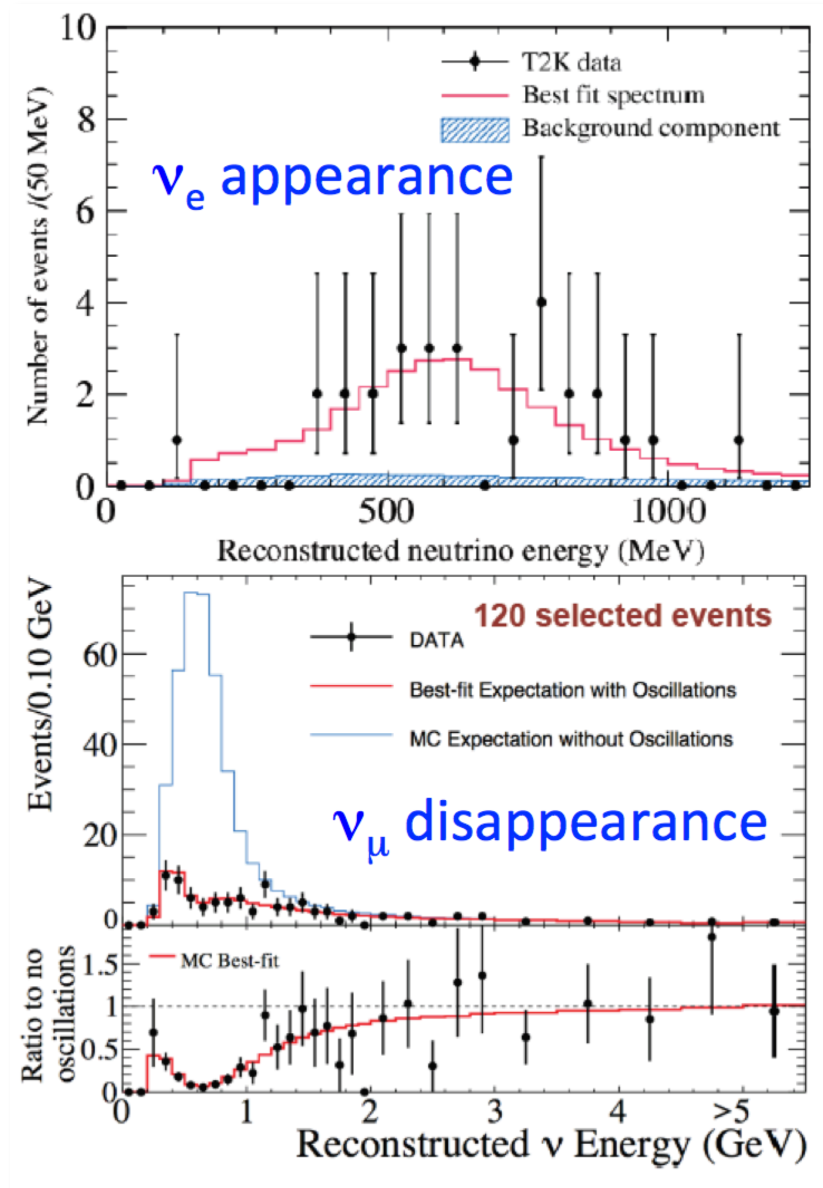
will look for both the ν_μ disappearing and the ν_e appearing

T2K

- 1st definitive observation of the explicit appearance of one flavor of ν arising from another flavor thru oscillations (>7σ)

$\nu_\mu \rightarrow \nu_e$





- combination of results from reactor & accelerator sources (NOvA, T2K) is very important for testing our ν picture

Big Questions

we don't know some pretty basic stuff!

- we are missing some important information …

  - *how much do neutrinos weigh?*
  - *is our picture correct?*
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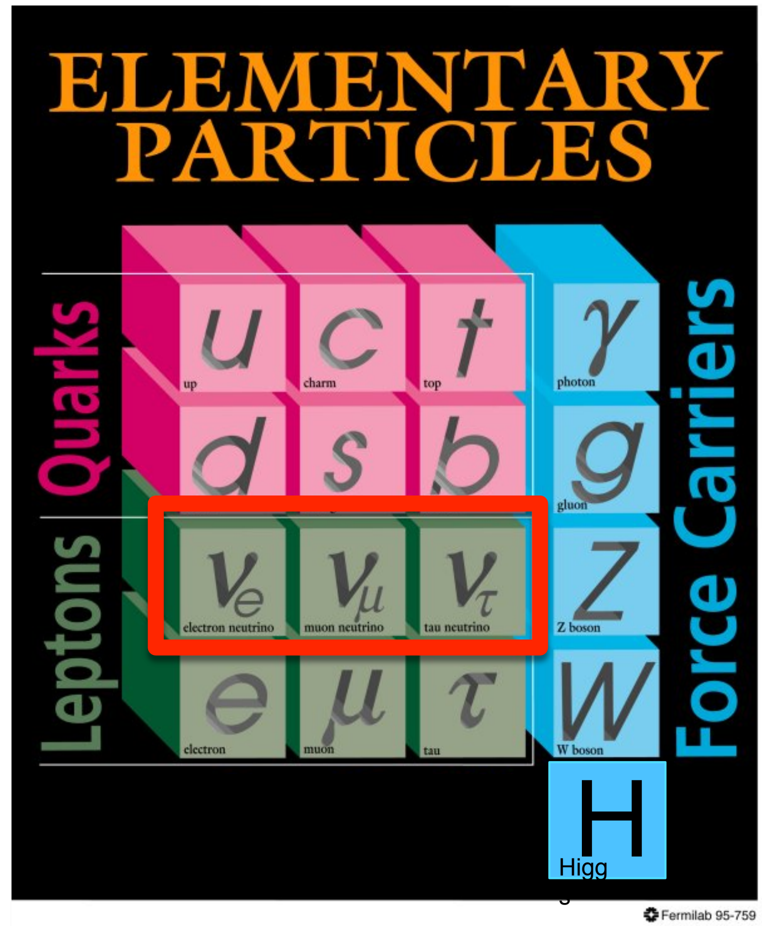
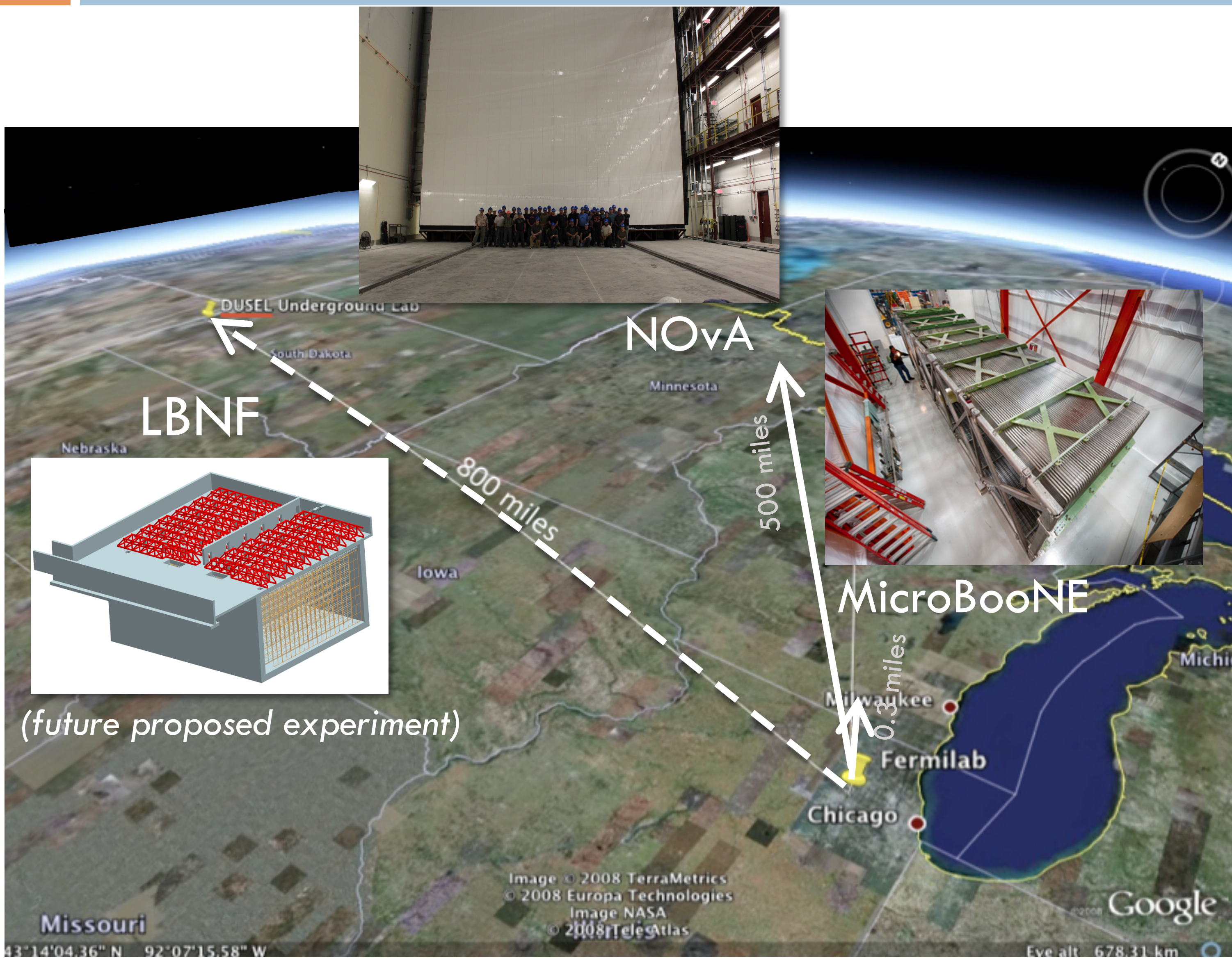
θ_{13}

why we exist?



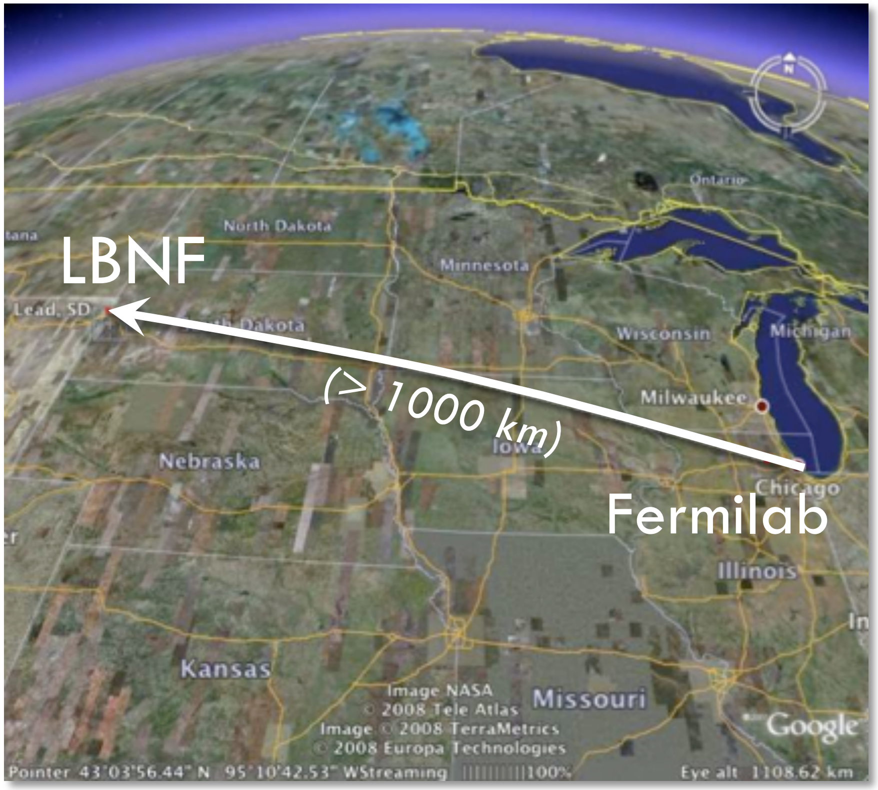
are these small details or are they paradigm shifting?

Neutrinos at Fermilab

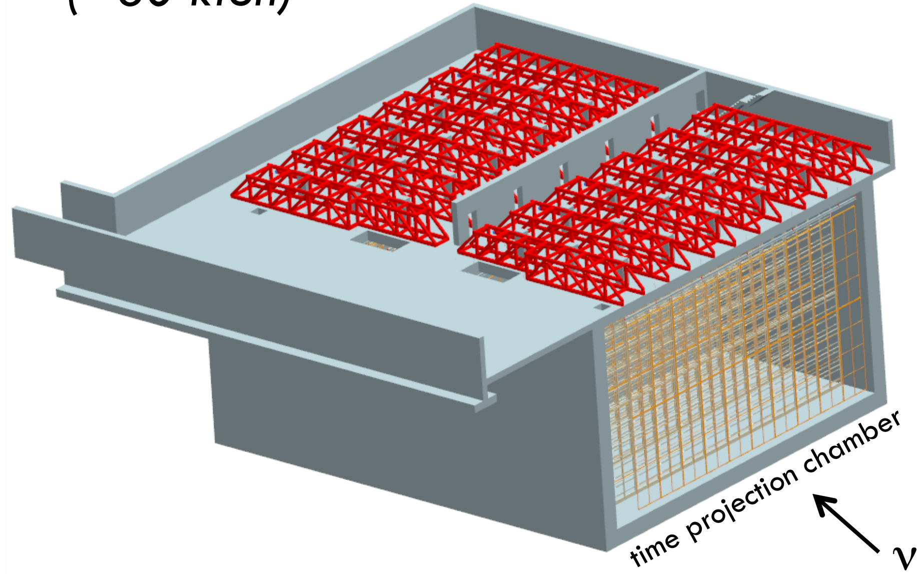


- we are already planning our next steps
- **L**ong **B**aseline **N**eutrino **F**acility
- new type of neutrino detector

LBNF



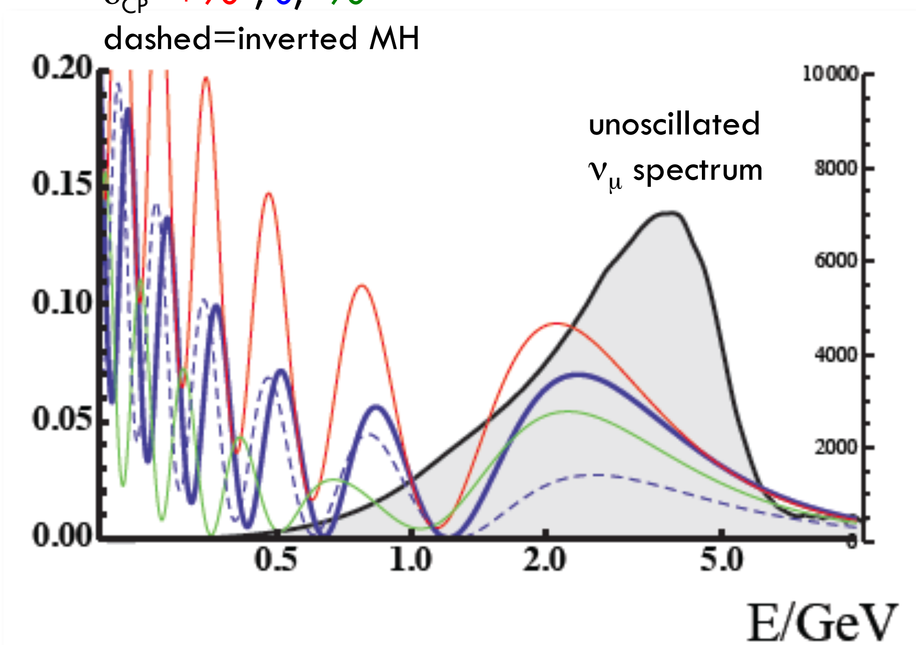
- three ingredients:
- <u>long-baseline</u>
  - *optimized for joint CP̸, MH determination*
- <u>liquid argon TPC</u>
  - *very high resolution detector*
  - *high ε, so need less detector mass (~30 kton)*



- <u>on-axis, wide band beam</u> (ν, $\bar{\nu}$)
  - *want to measure the spectrum of ν's across largest possible dynamic range*

This is What LBNF Can Do

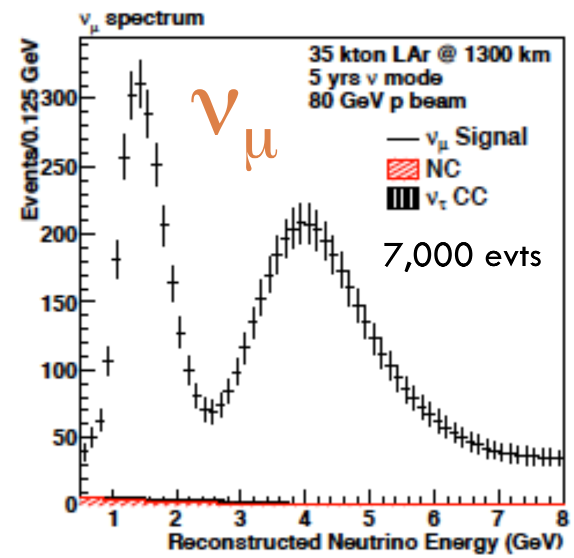
ν_e oscillation probability
δ_{CP}=+90°, 0, -90°
dashed=inverted MH

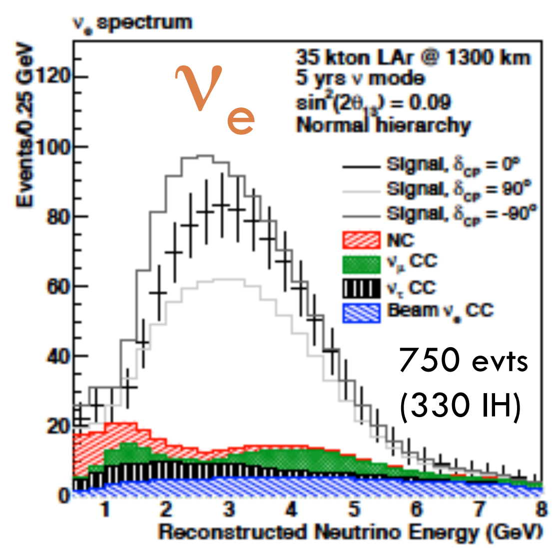


$\nu_\mu \rightarrow \nu_e$

disappearance

appearance

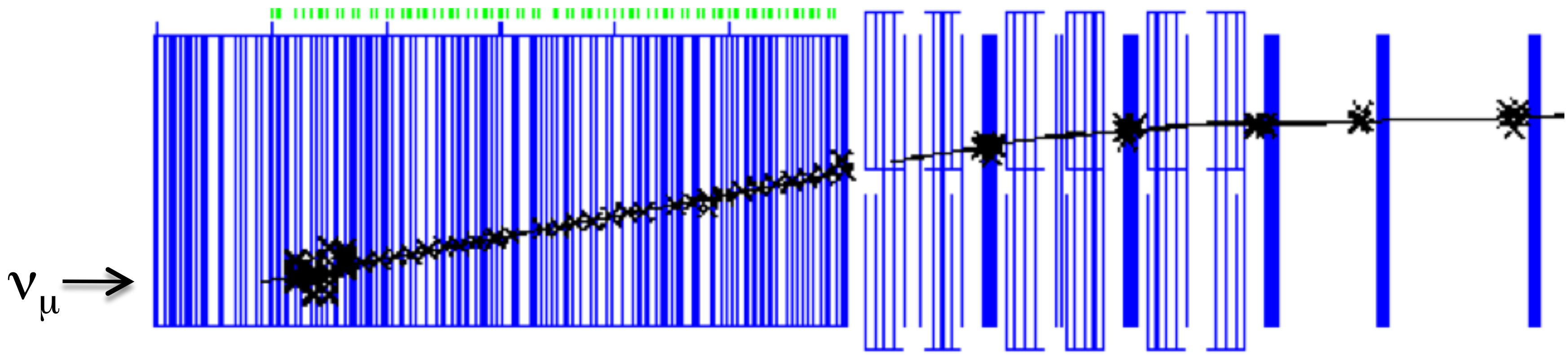




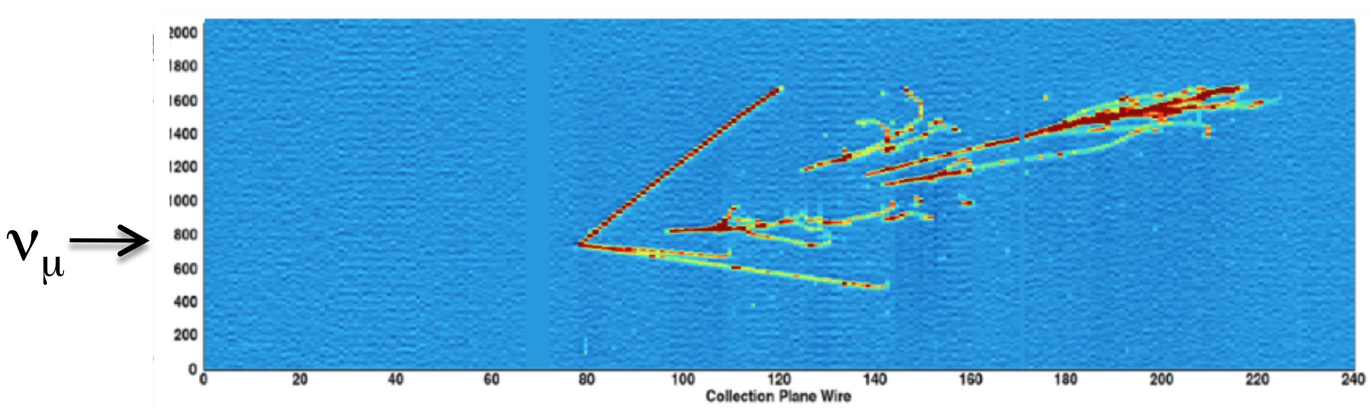
- plus, underground LBNF detector will be exquisitely sensitive to atmospheric ν's, supernova ν's, and proton decay

Liquid Argon TPCs

- my thesis experiment (2002):



- the type of neutrino detector that I work on now (LAr TPC):

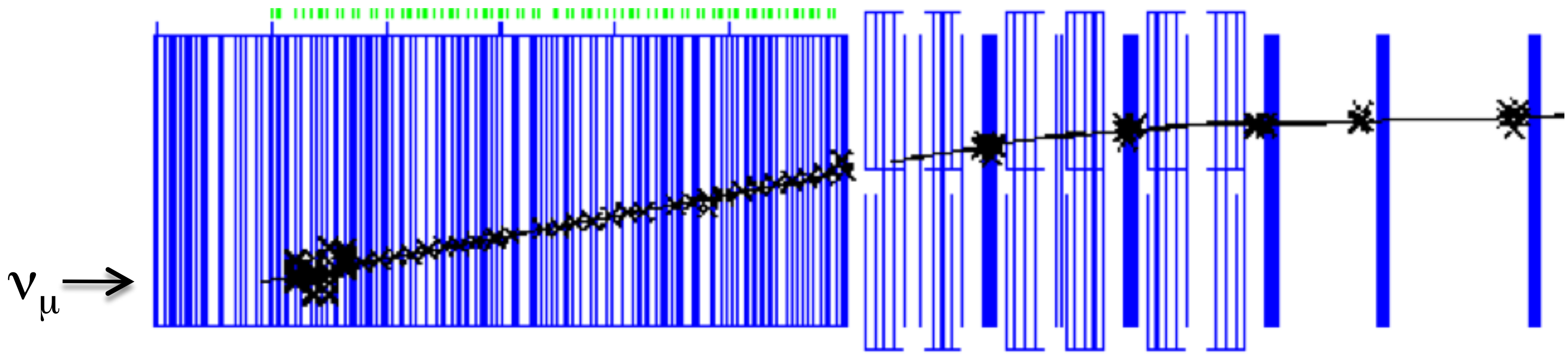


data from the very first liquid argon TPC in the U.S.

(can see everything that happens and record each track digitally)

Liquid Argon TPCs

- my thesis experiment (2002):



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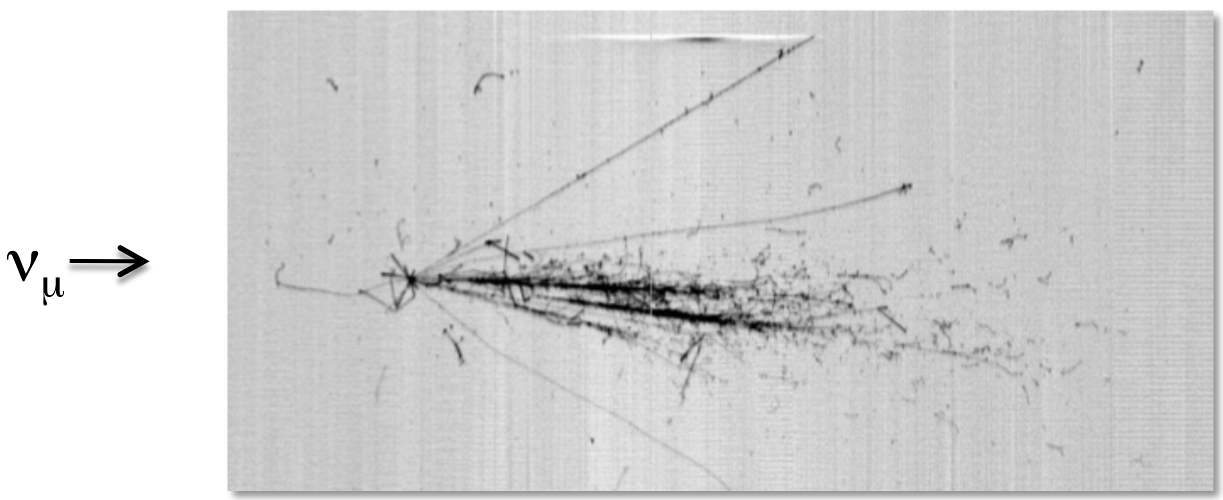
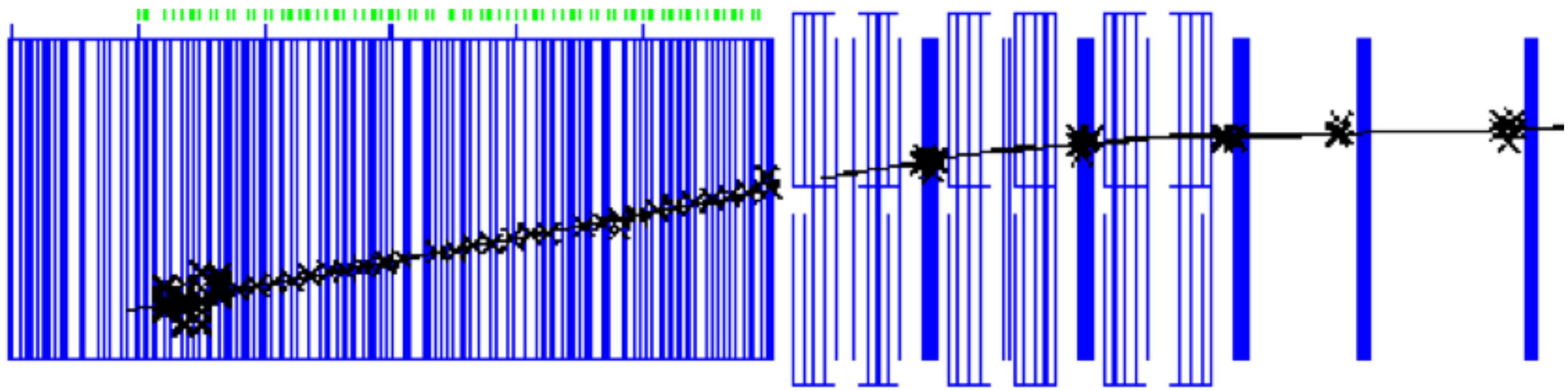


example of a ν interaction from the ICARUS detector in Italy

Liquid Argon TPCs

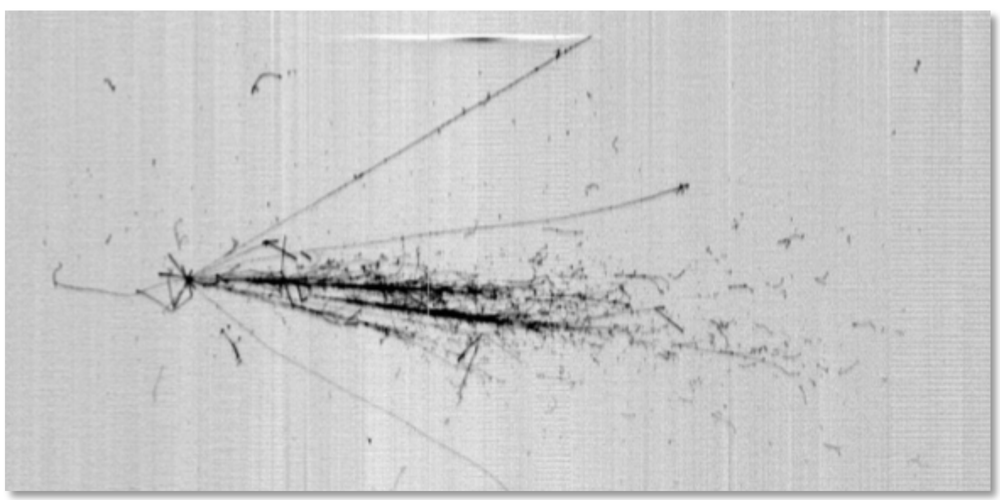
- my thesis experiment (2002):

$\nu_\mu \rightarrow$



- the type of neutrino detector that I work on now (LAr TPC):

$\nu_\mu \rightarrow$



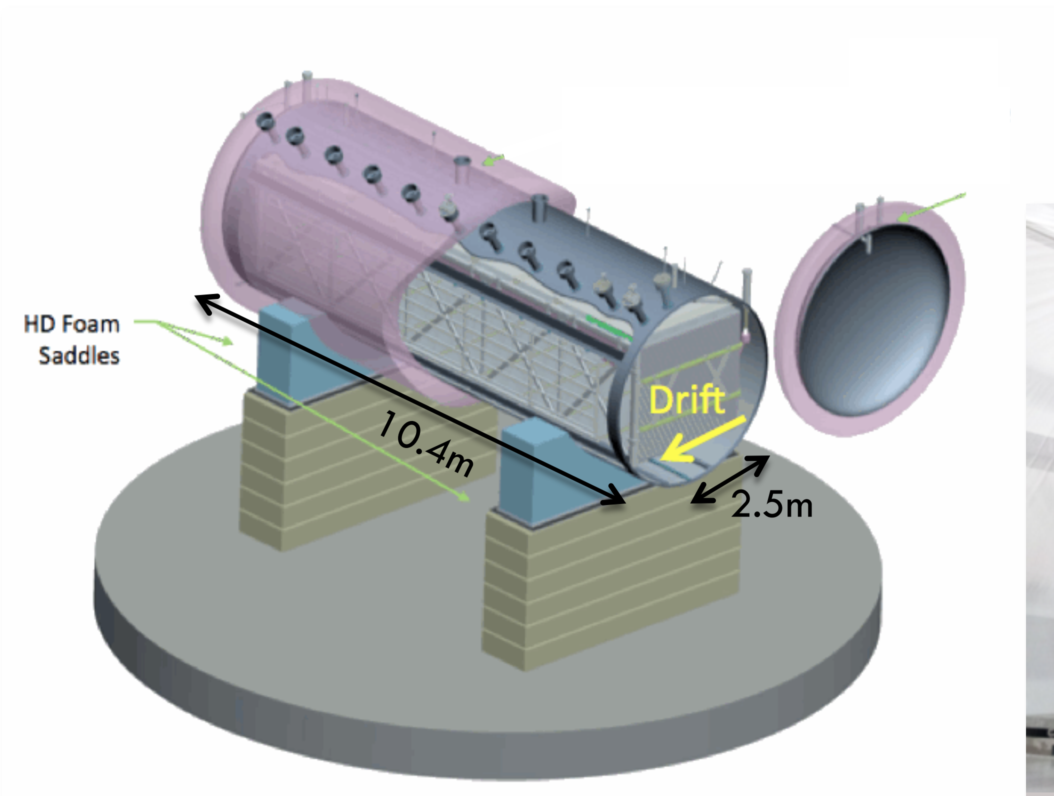
- these detectors are a very powerful tool

- we are really excited about this technology

MicroBooNE

- idea is to start out small to gain some experience
- 170 ton liquid argon TPC, the largest ever built in the U.S.

  (grid of wires submerged in liquid argon and placed under high voltage)



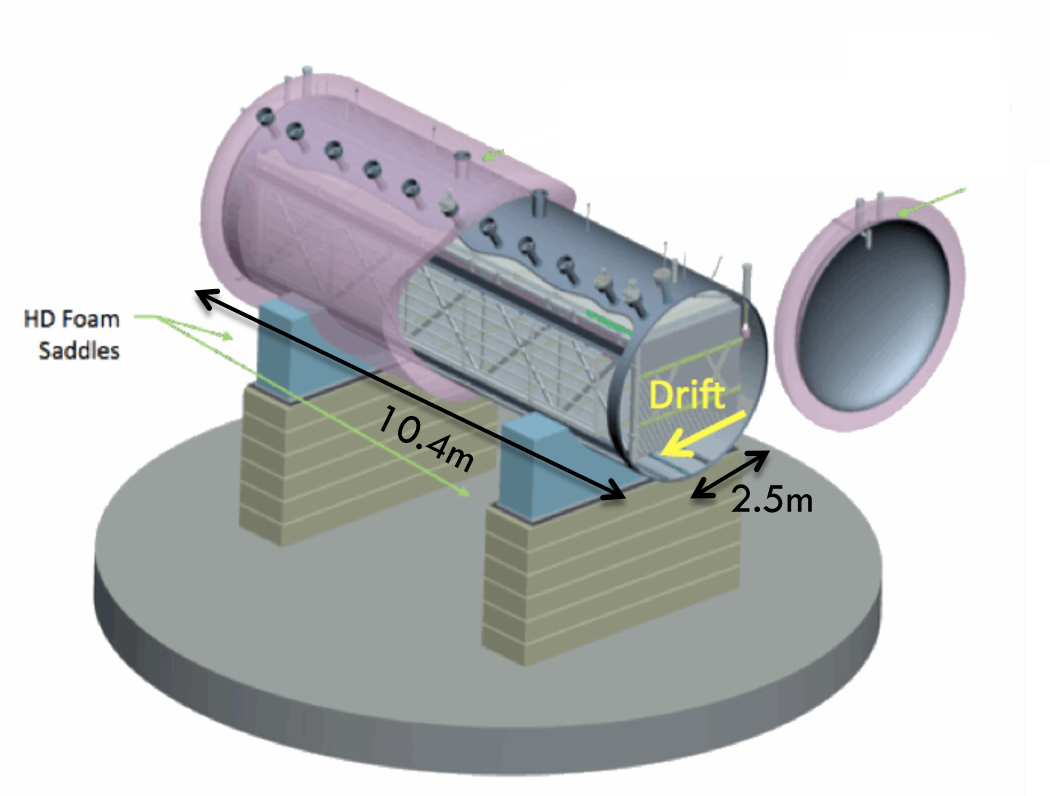
- about the size of a school bus

MicroBooNE TPC
2013

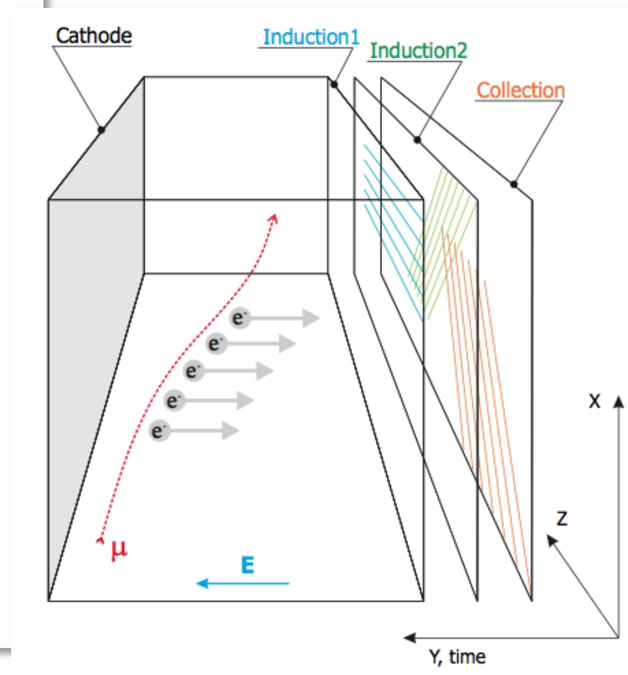
MicroBooNE

- idea is to start out small to gain some experience
- 170 ton liquid argon TPC, the largest ever built in the U.S.

(grid of wires submerged in liquid argon and placed under high voltage)



- about the size of a school bus



electronically imprints the particle track pattern

MicroBooNE

cryostat

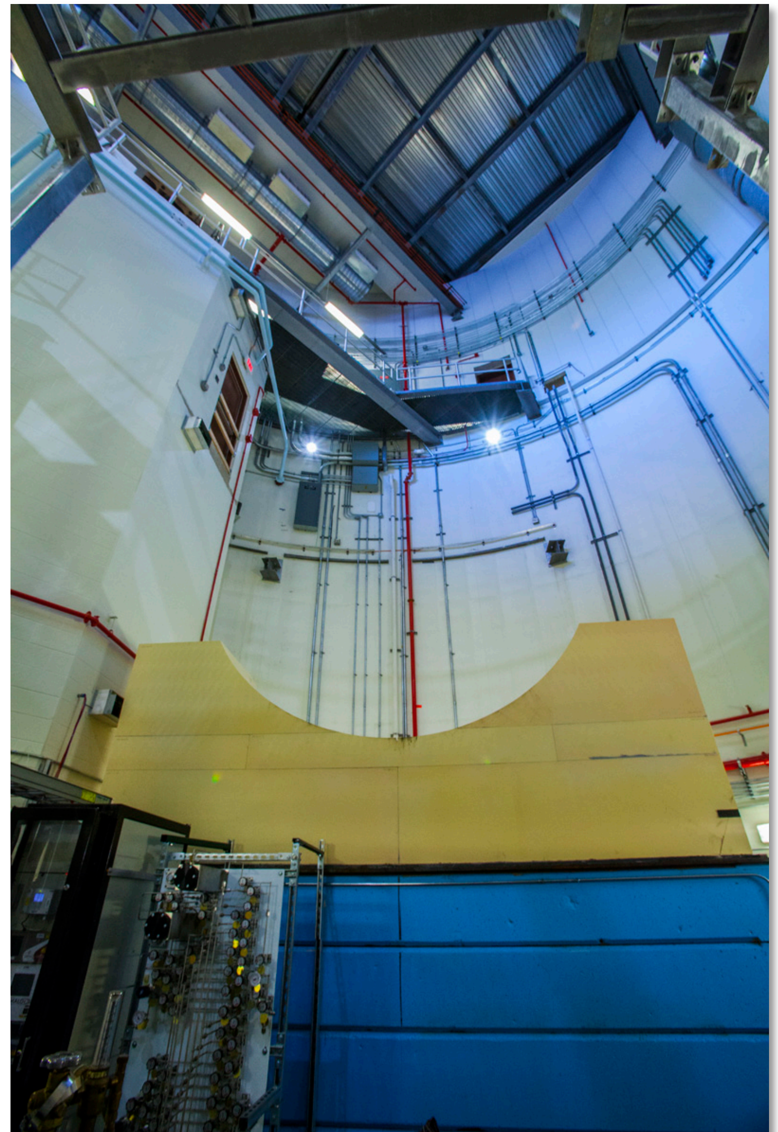
TPC

MicroBooNE

(includes in-liquid electronics)

MicroBooNE

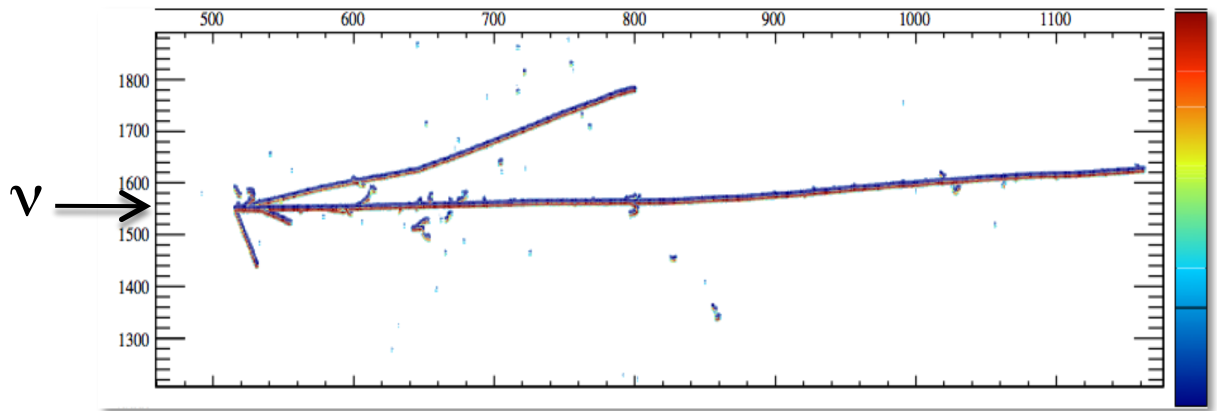
- new building where the detector will eventually be housed is ready and is being outfitted



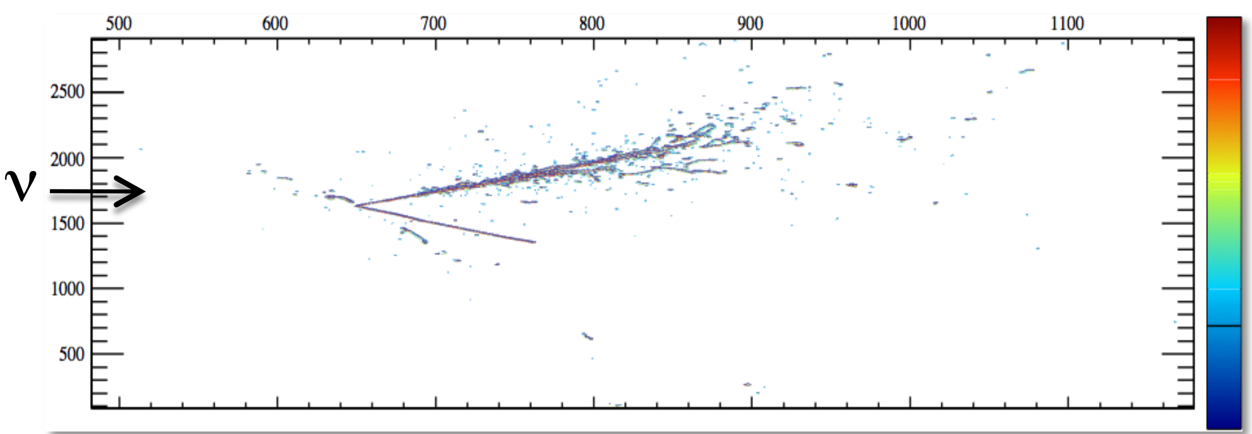
MicroBooNE

MicroBooNE

MicroBooNE



(simulated ν interactions in the detector)



- we are commissioning this new detector now
- ν's this winter!

(1) how do neutrinos interact in argon?

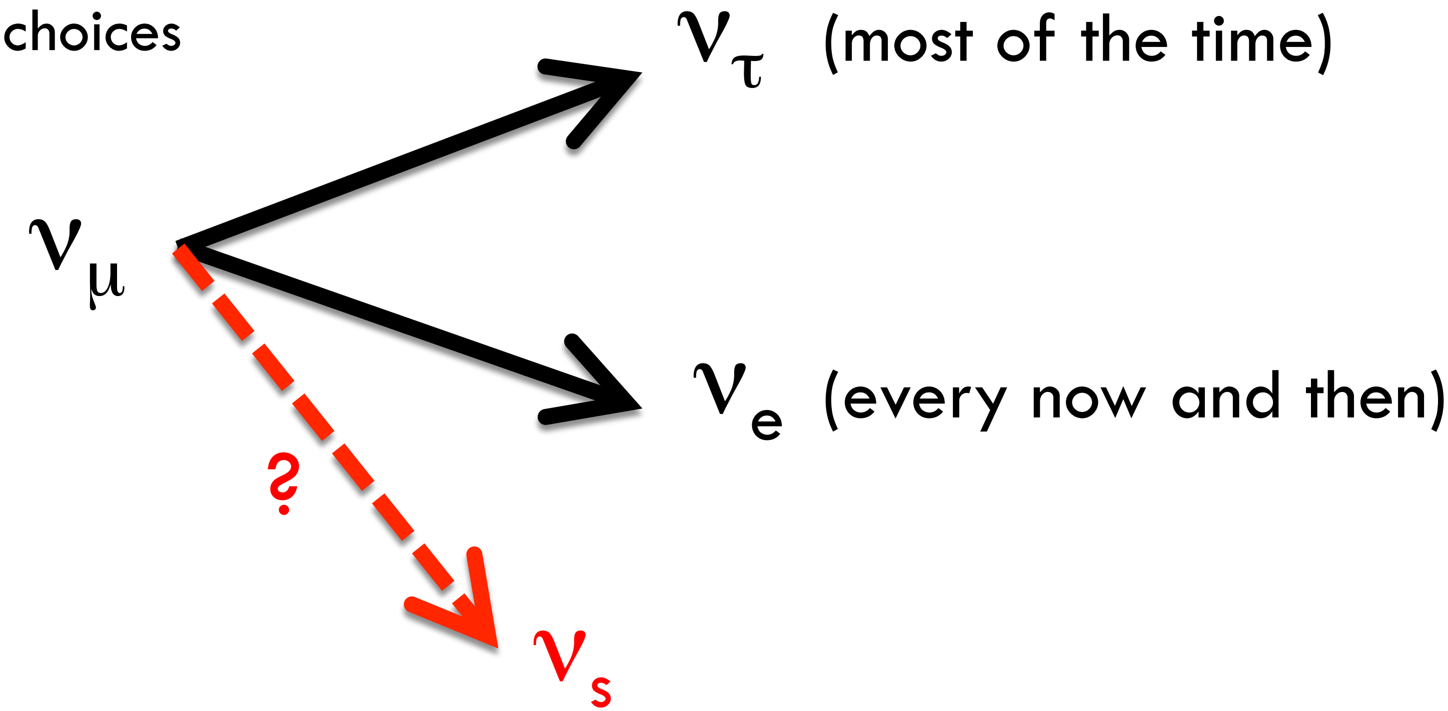
(2) important test of LAr TPC technology

(3) are there more than 3 neutrinos?

sterile neutrinos?

Where are the ν_μ's Going?

the ν_μ has two choices (maybe three)



- evidence for a light sterile neutrino would be a major discovery

Additional Reading

Light Sterile Neutrinos: A White Paper

K. N. Abazajian[a],[1] M. A. Acero,[2] S. K. Agarwalla,[3] A. A. Aguilar-Arevalo,[2] C. H. Albright,[4,5] S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a],[3] V. Barger,[8] P. Bernardini,[9] F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15] D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20] B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24] J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29] X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34] D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23] B. T. Fleming[a],[18] J. A. Formaggio[a],[23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42] G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43] V. V. Gorbachev,[43] D. S. Gorbunov,[43] R. Guenette,[18] A. Guglielmi,[44] F. Halzen,[46,8] J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3] P. Huber[b],[16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53] G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58] P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61] M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64] W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31] W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39] A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44] G. B. Mills,[34] D. Minic,[16] L. Miramonti,[17] D. Mohapatra,[16] R. N. Mohapatra,[51] C. Montanari,[74] Y. Mori,[75] Th. A. Mueller,[76] H. P. Mumm,[77] V. Muratova,[27] A. E. Nelson,[78] J. S. Nico,[77] E. Noah,[15] J. Nowak,[79] O. Yu. Smirnov,[69] M. Obolensky,[40] S. Pakvasa,[80] O. Palamara,[18,52] M. Pallavicini,[81] S. Pascoli,[82] L. Patrizii,[83] Z. Pavlovic,[34] O. L. G. Peres,[36] H. Pessard,[32] F. Pietropaolo,[44] M. L. Pitt,[16] M. Popovic,[5] J. Pradler,[84] G. Ranucci,[17] H. Ray,[85] S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16] C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53] M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93] D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96] J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34] L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63] J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103] M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

[1] *University of California, Irvine*

[2] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*

[3] *Instituto de Fisica Corpuscular, CSIC and Universidad de Valencia*

[4] *Northern Illinois University*

[5] *Fermi National Accelerator Laboratory*

[6] *University of Basel*

[a] Section editor
[b] Editor and corresponding author (pahuber@vt.edu and jmlink@vt.edu)

* whitepaper on sterile neutrinos
  arXiv:1204.5379 [hep-ph]
  http://arxiv.org/abs/arXiv:1204.5379

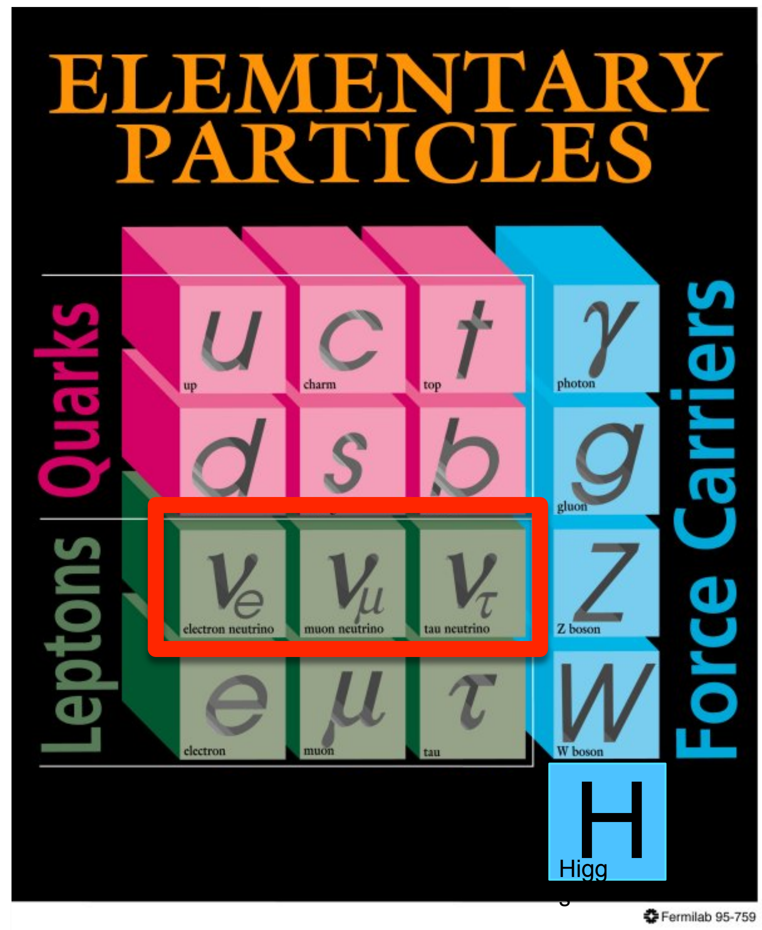
Big Questions

we don't know some pretty basic stuff!

- we are missing some important information …

  - ***is our picture correct?***
  - ***how much do neutrinos weigh?***
  - ***which neutrino is the heaviest and which is the lightest (MH)?***
  - ***do neutrinos and antineutrinos oscillate in the same way ($\not{C}P$)?***
  - ***what is the nature of the ν?***
  - ***are there more than 3 kinds?***

radioactive decays



are these small details or are they paradigm shifting?

Neutrino Mass

- tightest constraints come from analysis of cosmological data, $\Sigma m_\nu \lesssim 0.2$ eV
- use beta decay as a means to measure m_ν
- need a lot of stats, good E resolution

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

these are not table top experiments

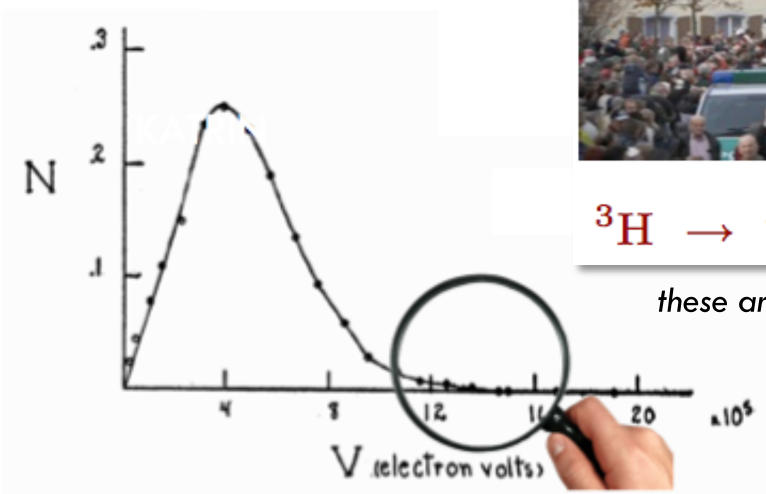
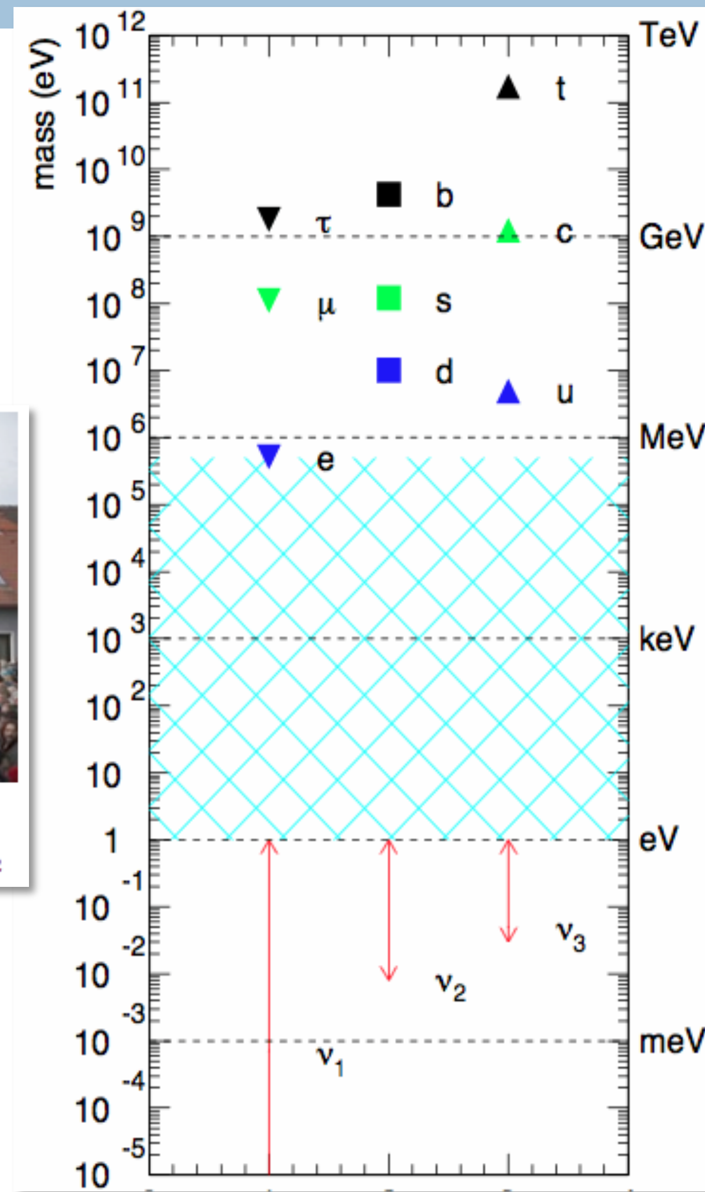


FIG. 5. Energy distribution curve of the beta-rays.

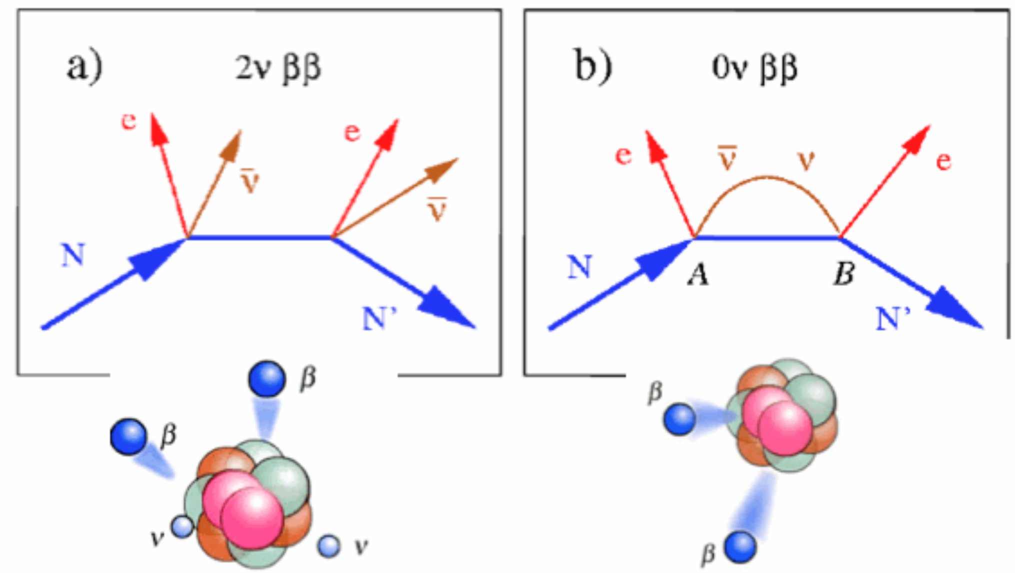
Fermi
1933

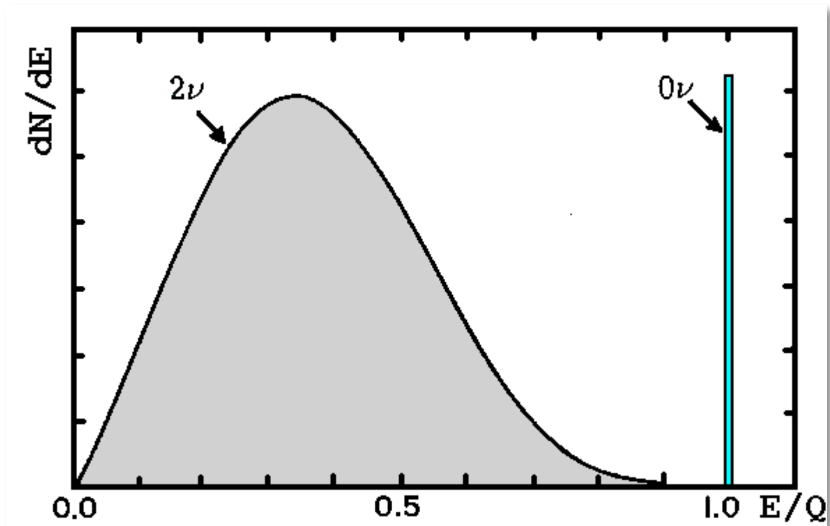


Nature of the Neutrino

(this is another mystery story)

- since the neutrino has no electric charge it can be it's own antiparticle ($\nu = \overline{\nu}$)
- are neutrinos Dirac or Majorana?





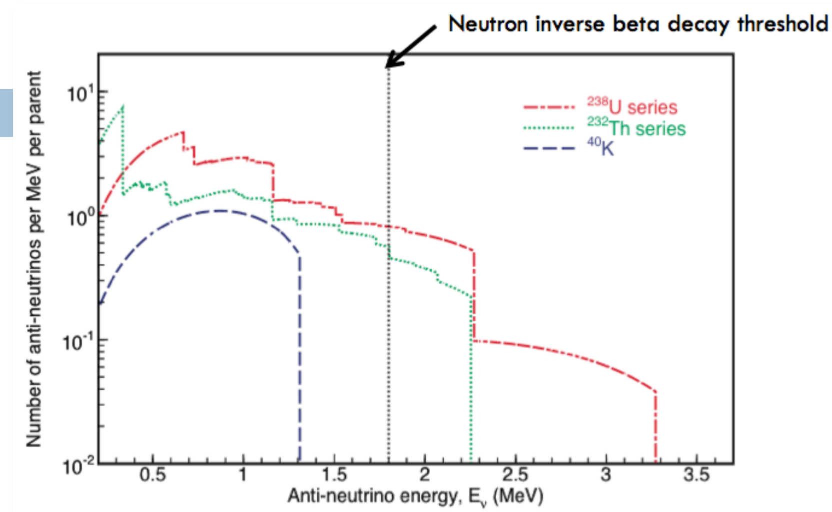
- if ν's are Majorana particles ($\nu = \overline{\nu}$) then it allows this special process ($0\nu\beta\beta$)

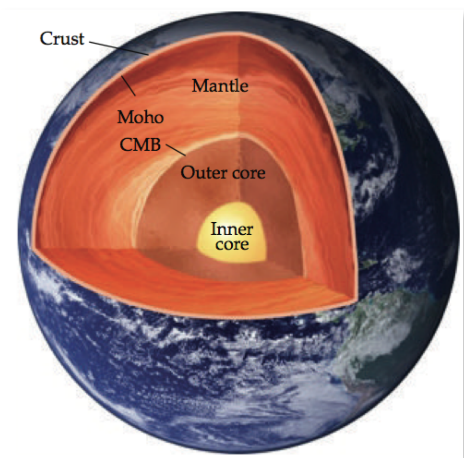
this is why we haven't put m_ν into *the Standard Model* – *we don't know which to choose!*

GeoNeutrinos

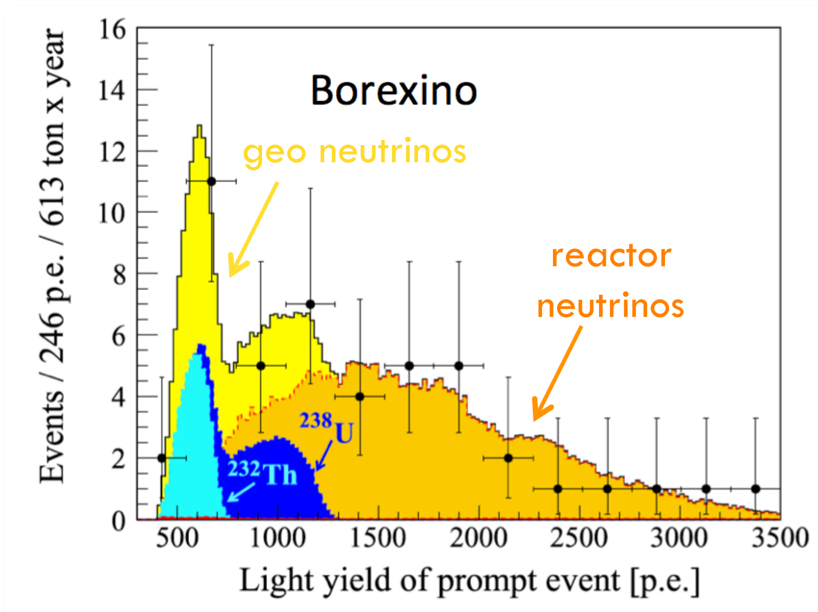
- radioactive decays of U and Th in the earth's crust and mantle provide a source of very low energy antineutrinos

- have been recently detected by
  - KAMLAND (arXiv:1303.4667)
  - Borexino (PLB 722, 4 (2013))



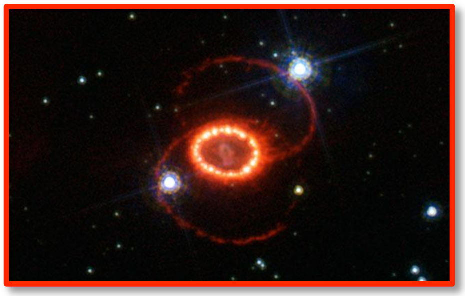


- means to measure the heat output of our planet

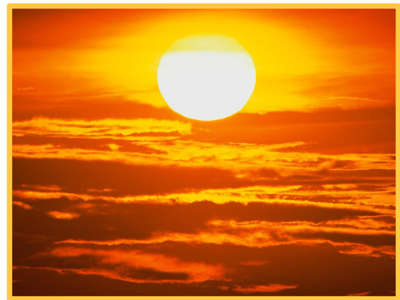


ν's can provide info on earth's internal radioactivity not obtainable by any other means

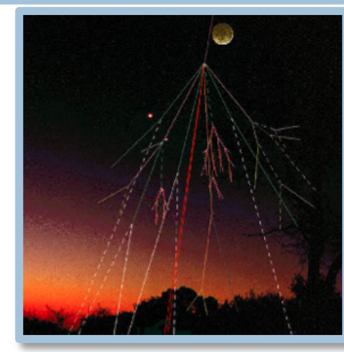
Neutrino Sources



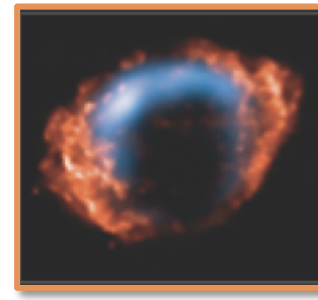
supernova neutrinos



solar neutrinos



atmospheric neutrinos



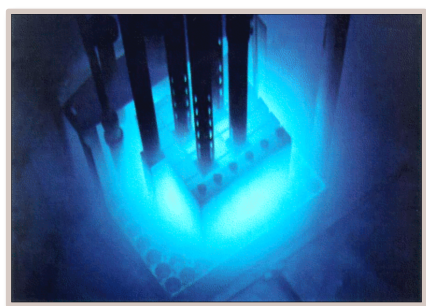
cosmic neutrinos

neutrinos from the heavens ("wild")

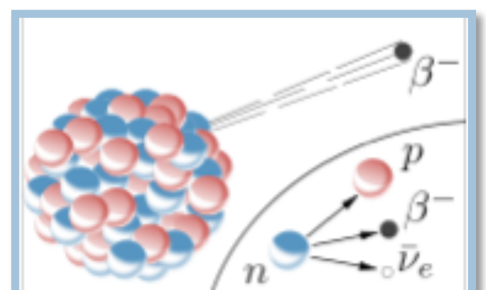
---

neutrinos from the earth ("tame")

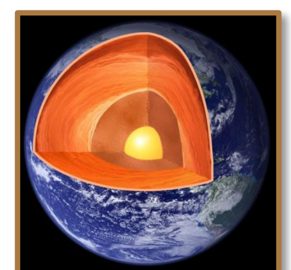
accelerator neutrinos



reactor neutrinos



radioactive decays



geo neutrinos

Neutrino Scorecard

	absolute mass scale	nature of the neutrino	mass hierarchy	$\not{CP}$	more than 3 ν's?	is our picture correct?
β decay	✔					✔
0νββ decay	✔	✔				✔
astrophysics & cosmology	✔		(✔)		✔	✔
atmospheric			(✔)			✔
reactor			(✔)		✔	✔
accelerator			✔	✔	✔	✔

Conclusions

- neutrino physics continues to be an incredibly exciting field
- some very important ν experiments in the next decade and beyond will be working to answer some big questions:

- is our picture correct?
- what are the ν masses & why so small?
- what is the ordering of the ν masses?
- do ν's violate CP?
- are ν's Majorana?
- are there more than 3 ν's?

cosmic ν's
β decay
reactor ν's
atmospheric ν's
$0\nu\beta\beta$ decay
accelerator ν's

- nature gave us all of these ν sources and ν oscillations, now we want to know what it all means!

Backups

Timeline

- **1932**: new particle postulated to solve energy non-conservation problem in β decay: the neutrino
- **1956**: $\overline{\nu}_e$ discovered
- **1958**: neutrinos are left-handed
- **1962**: ν_μ discovered
- **1973**: neutral currents!

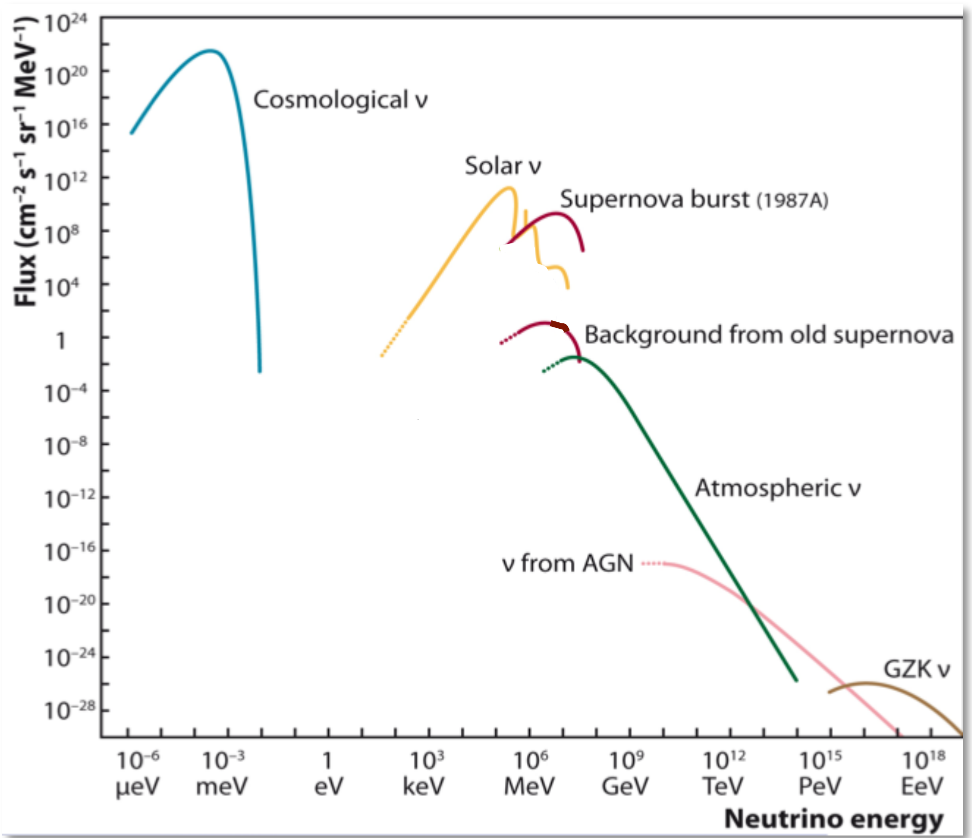
- **1970's**: ν cross sections measured up to 130 GeV
- **1980's**: initial ν oscillation searches
- **1990's**: ν's as a probe (we know how to use the ν)

discoveries all along the way!

- **1998**: neutrinos oscillate (really important year for ν physics!)
- **2000**: ν_τ detected

Neutrinos are Unique Messengers

- neutrinos can directly convey astronomical information



neutrino astronomy

- they are not deflected by interstellar magnetic fields

  → *point back to their source*

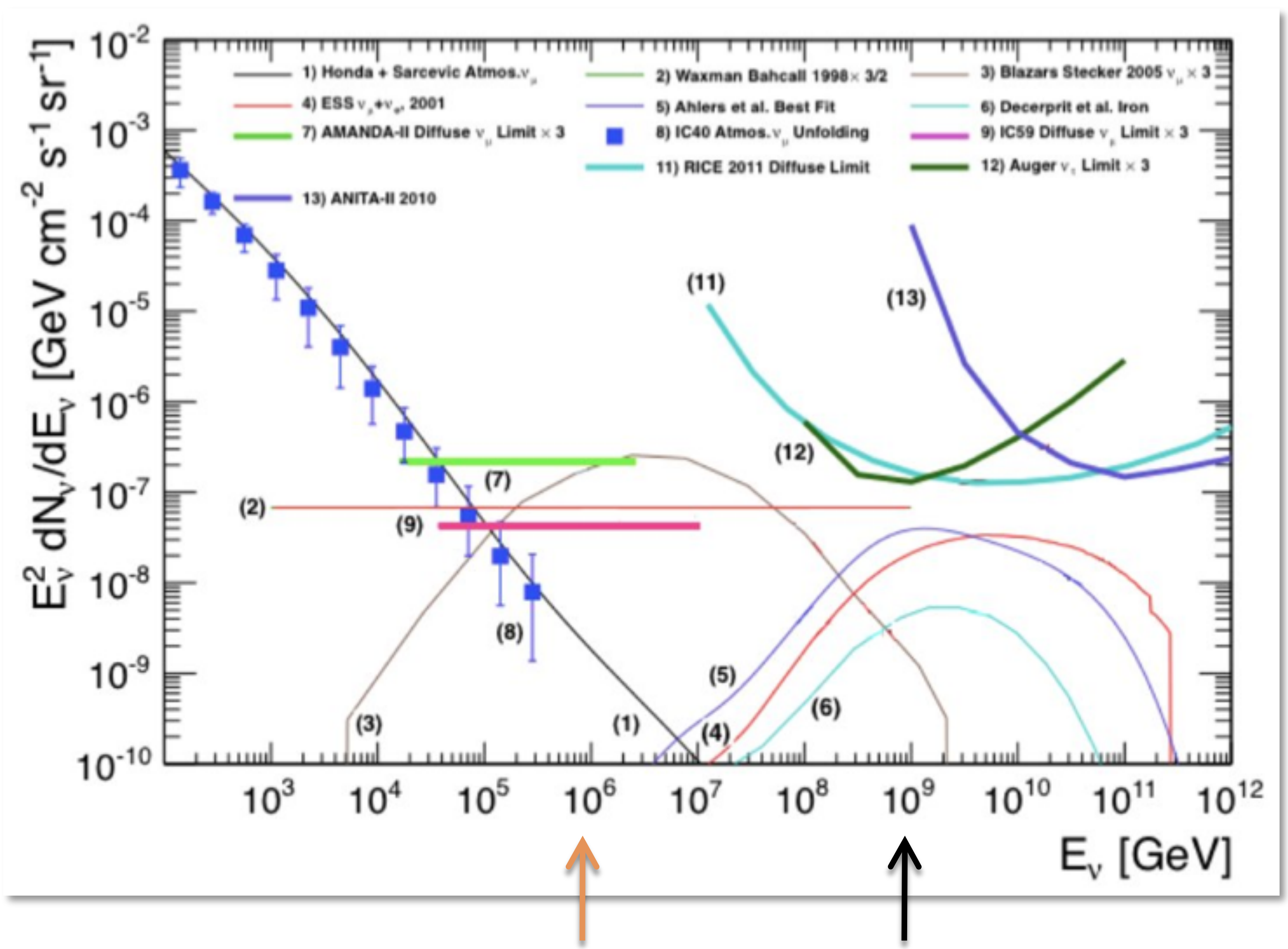
- they rarely interact with matter

  → *arrive directly from regions where light cannot come*

- ν's carry information about the workings of the highest energy and most distant phenomenon in the universe

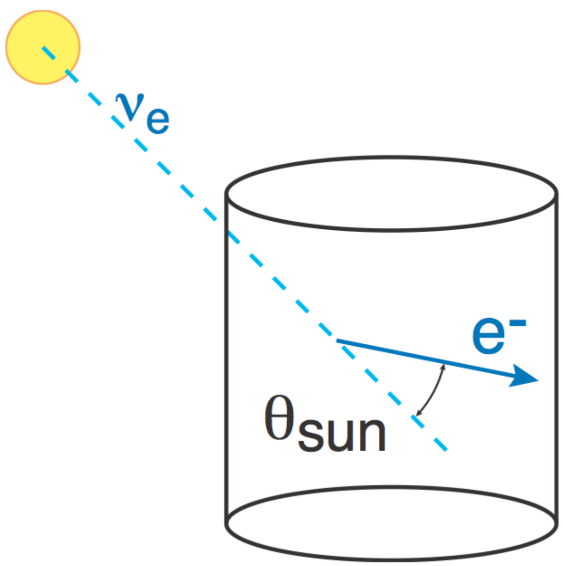
Ultra High Energy Neutrinos

- see conventional neutrinos from known sources (earth's atmosphere) up to ~400 TeV
- beyond that, there are limits from large detector arrays & ν telescopes looking for ν's not coming from the atmosphere



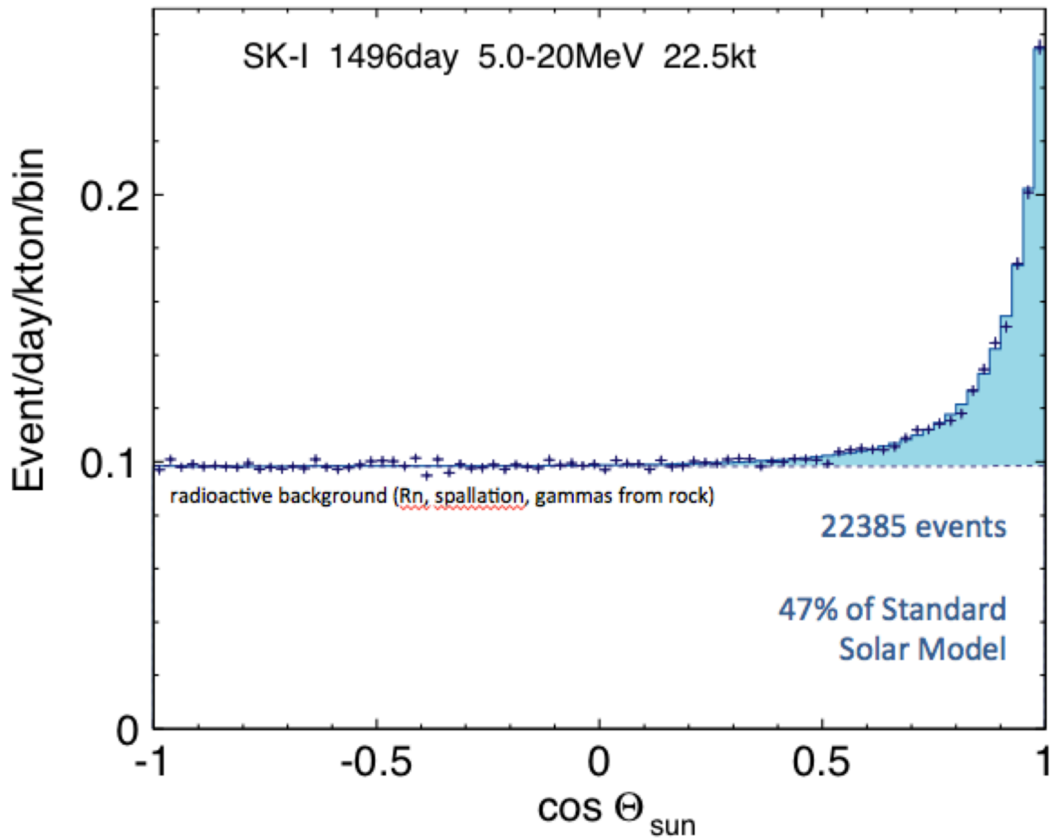
S. Zeller, HCPSS, 08/22/14

Super-K and Solar Neutrinos

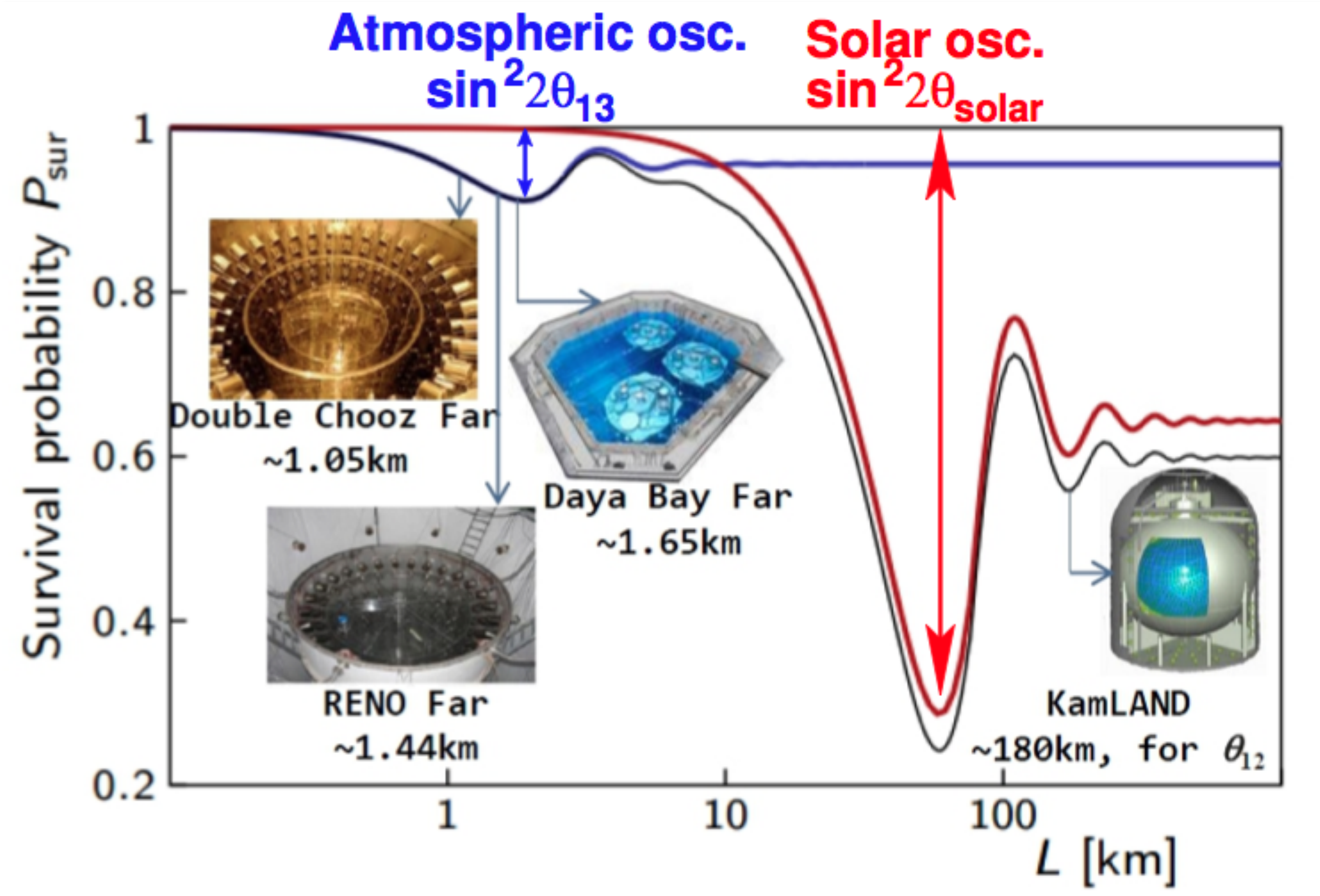


neutrino scattering off atomic electrons

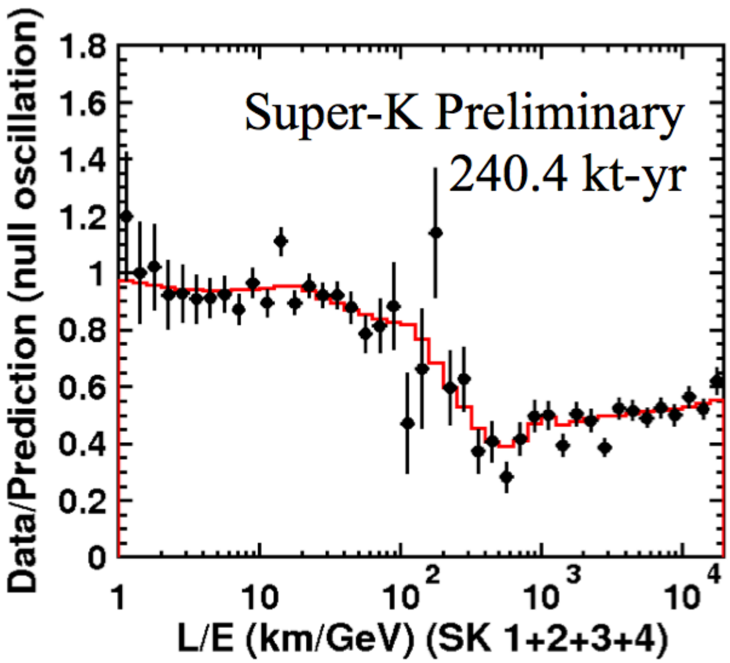
directional detection



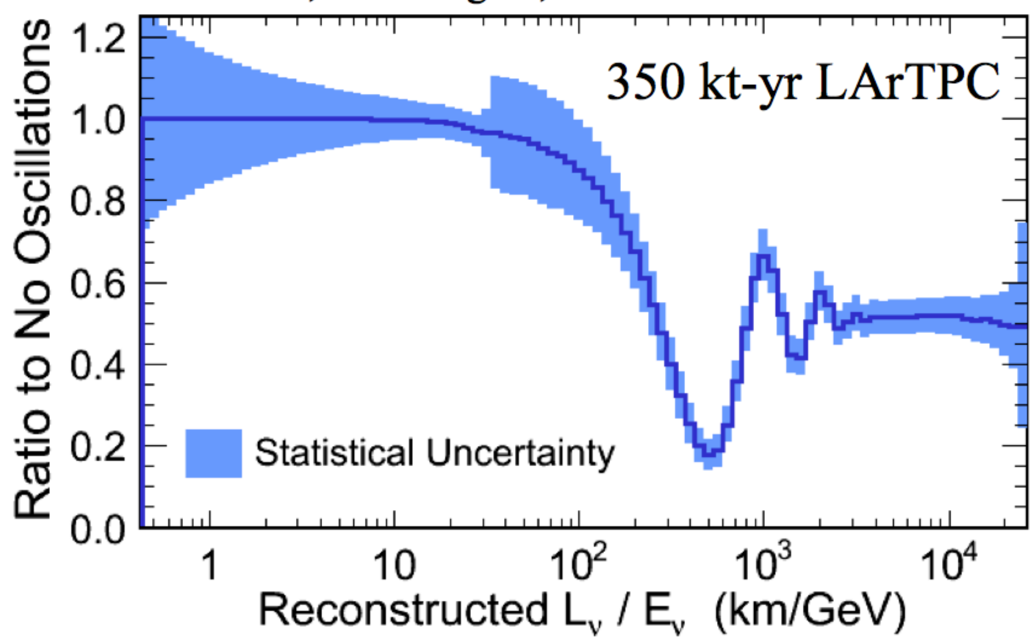
Reactor Neutrinos



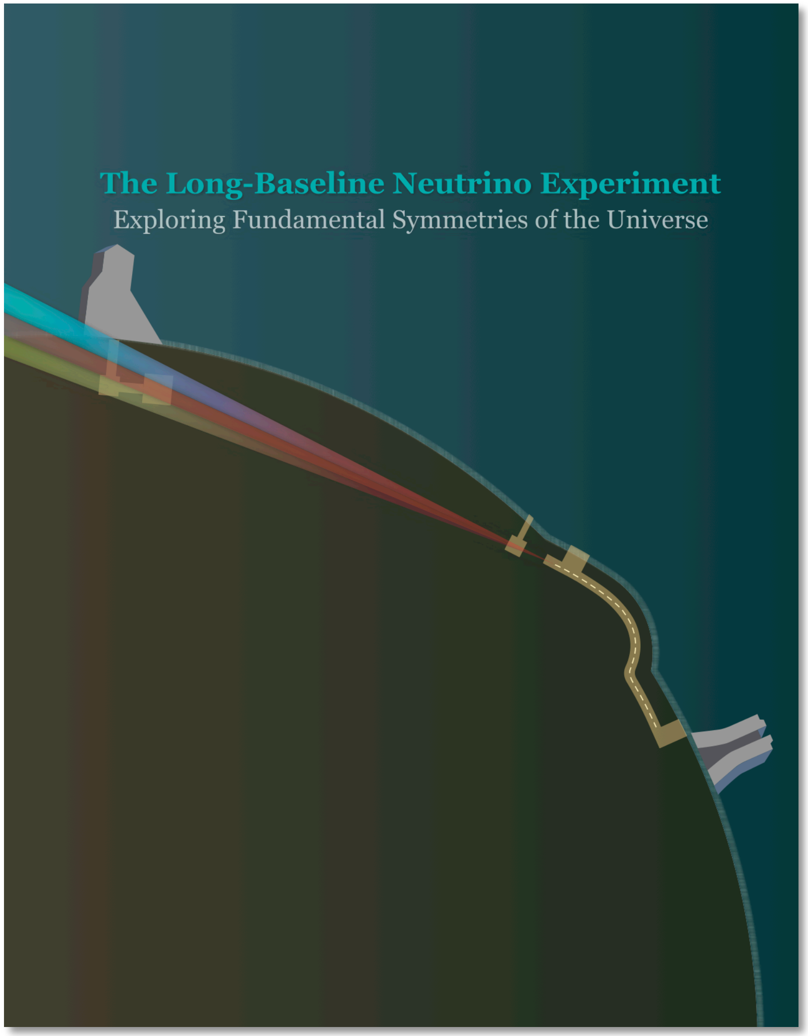
Atmospheric Neutrinos



A. Blake, H. Gallagher, ISOUPS 2013



Want to Know More?



* long-baseline neutrino experiment science opportunities document

https://sharepoint.fnal.gov/project/lbne/LBNE%20at%20Work/science%20doc%20pdfs/lbne-sci-opp.pdf

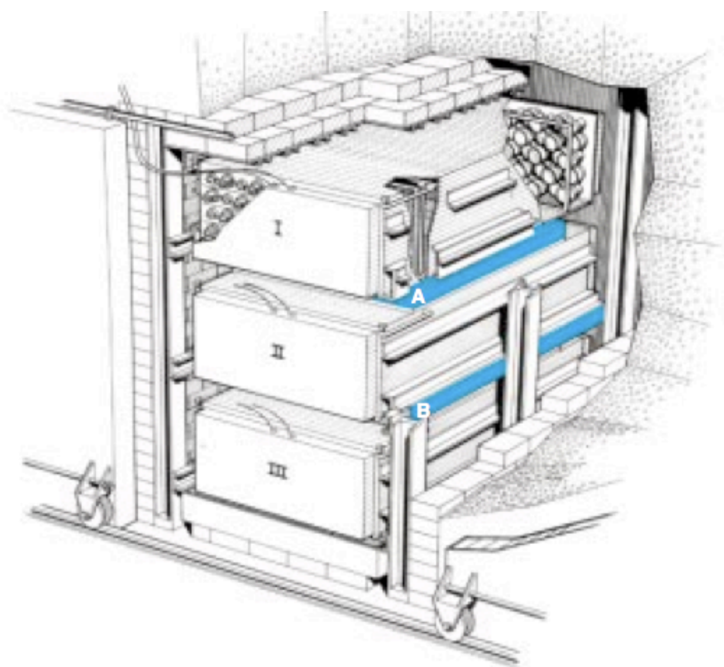
A Little Bit of History

- discovery of the neutrino
- **1956**: observe $\bar{\nu}_e$'s emitted by a nuclear reactor

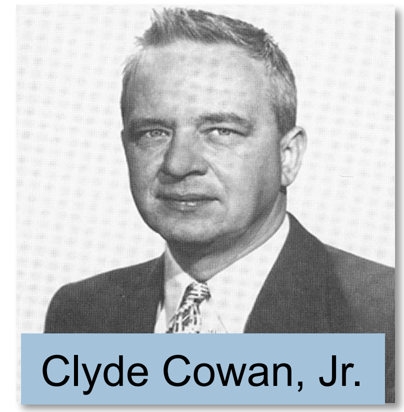
$$\bar{\nu}_e \, p \rightarrow e^+ \, n$$

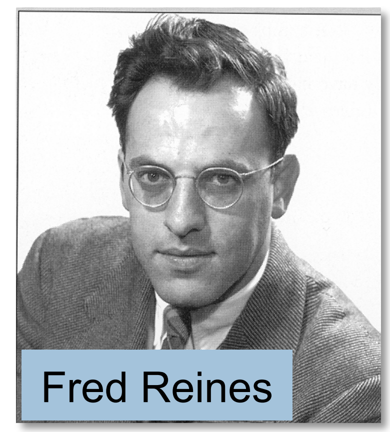
(inverse beta decay)

Savannah River nuclear reactor



- tanks filled with liquid scintillator, instrumented with photomultiplier tubes
  - *novel detector at the time*
- <u>need a lot of neutrinos and a lot of detector</u>





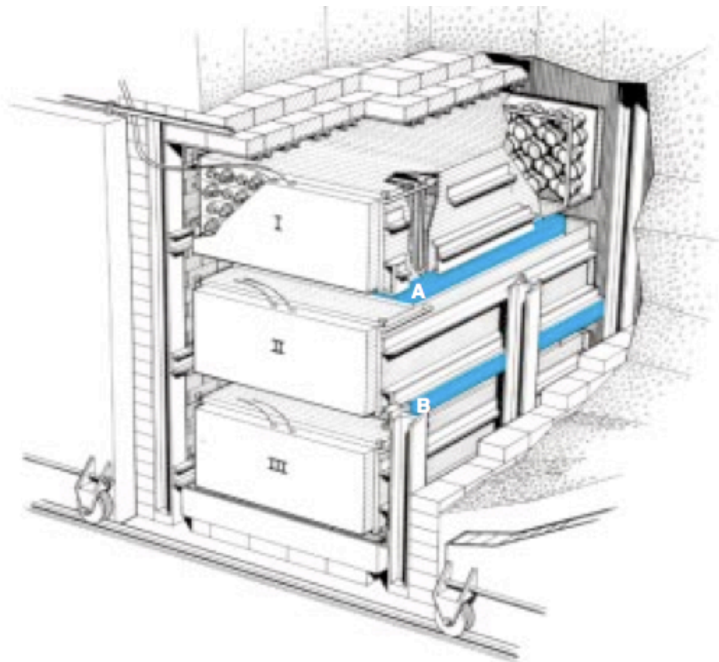
A Little Bit of History

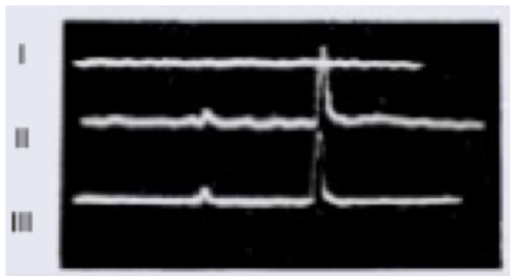
- discovery of the neutrino
- **1956**: observe $\overline{\nu}_e$'s emitted by a nuclear reactor

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

(inverse beta decay)

Savannah River nuclear reactor





positron scope

neutron scope

Clyde Cowan, Jr.

Fred Reines

(photographs of oscilloscope traces)

(2 coincident blips = neutrino!)