Fermilab

Operated by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Physics # 1 & #2

Dr. Herman B. White
Fermi National Accelerator Laboratory
August 14, 2014

ASP2014

Dakar, Senegal

OUTLINE

What is the universe made of?

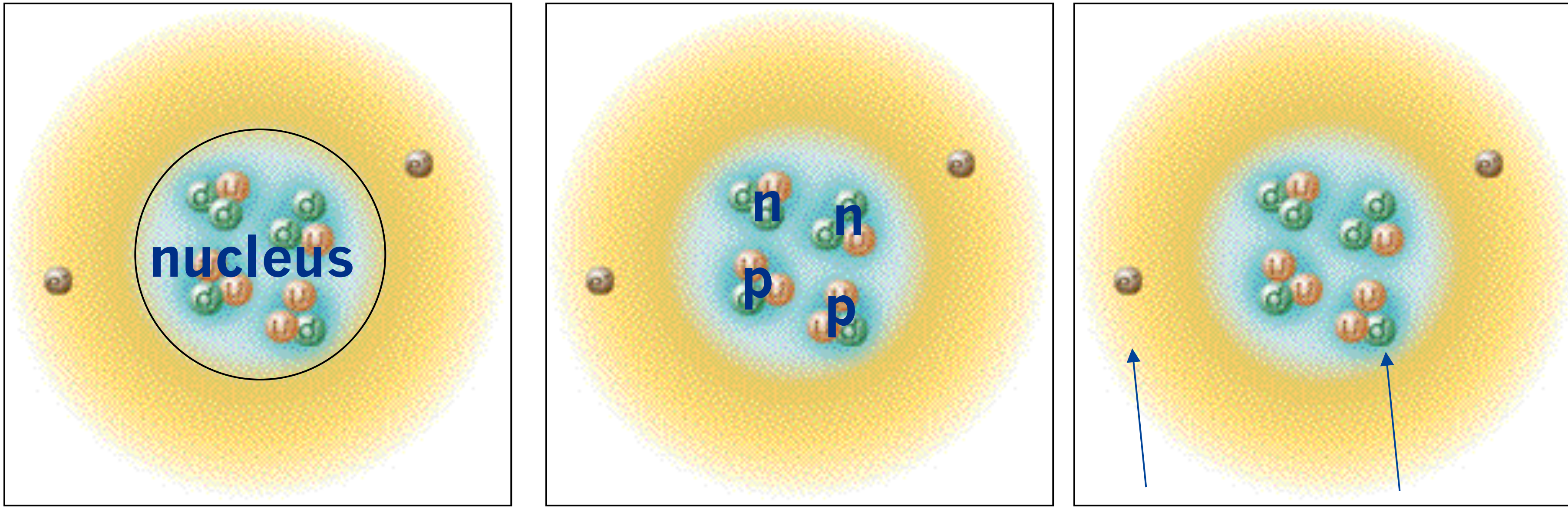
Standard Model and understanding of the universe

Discovery of the Neutrino

Properties of the Neutrino

Experimental Techniques

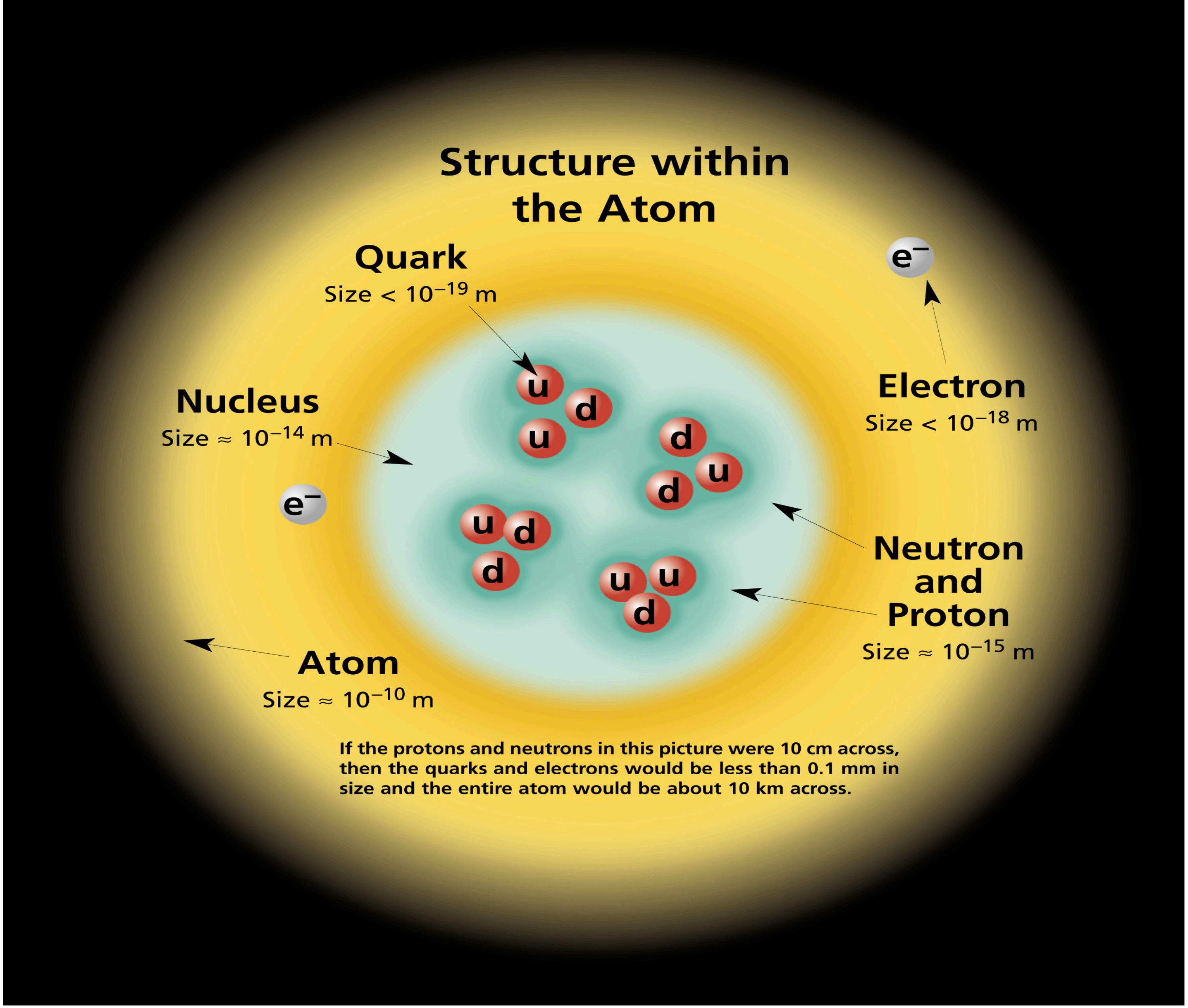
Everything that we can see is made of electrons, and smaller particles.



Electron **Quark**

0.000000000000000001 m
nano nano meter

higher beam particle energy = smaller size you can see


Structure within the Atom
Quark
Size < 10^{-19} m
e⁻
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
u
d
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Fixed Target Mode of Experimentation

(a beam of particles and a stationary target)

Colliding Beams Mode of Experimentation

(Counter rotating nearly head-on beam-beam collisions)

Collider Tevatron
Collider LHC

Fixed Target
Using the Early Tevatron

$$E_{CM} \simeq 2E_{beam}$$

$$E_{CM} \simeq \sqrt{2ME_{beam}}$$

Early Tevatron~1960 GeV
LHC ~7 TeV

~40 GeV

E_{beam} = 800 GeV

Different advantages in both techniques

Beam-Beam

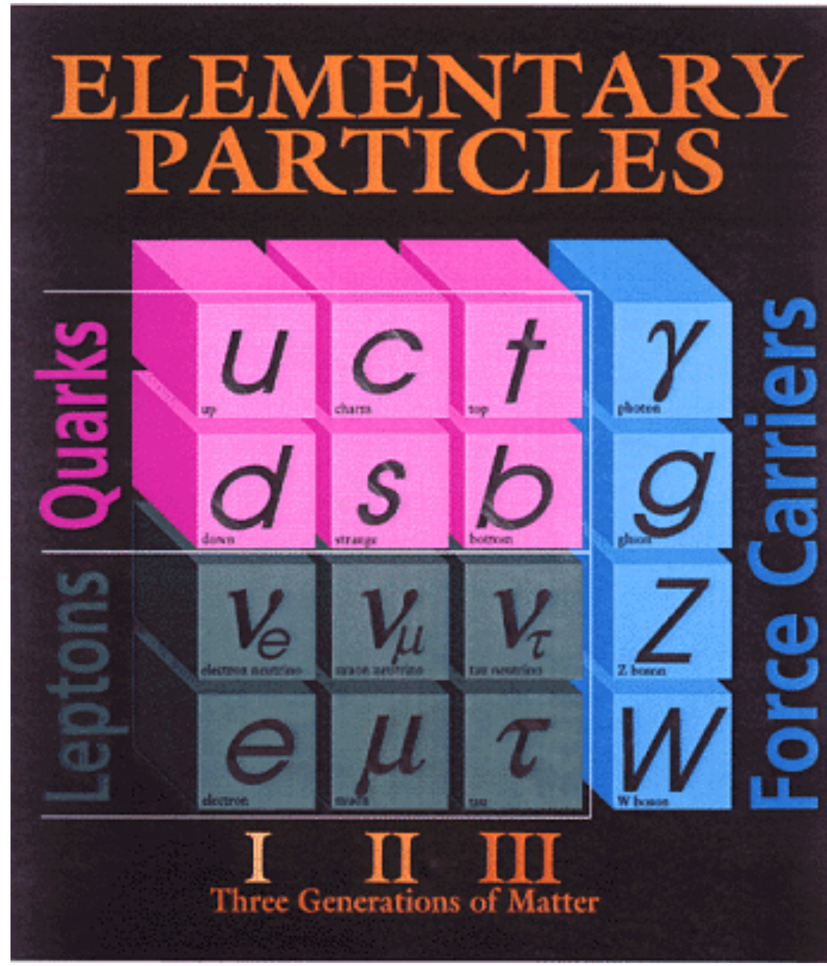
- About twice the collision energy and luminosity of $\sim 10^{32}/cm^2/sec$ and slightly higher now
- Close approximation to the interaction site location

Fixed Target

- Many targeting centers and Avagadro's number
- Mostly limited by the beam energy
- Higher Luminosity (10^{13} Protons/min extracted which leads to $\sim 10^{36}/cm^2/sec$ luminosity)

Particles

- **Discoveries**
  - top quark 1995
  - bottom quark 1977
  - ν_t (tau neutrino) 2000
  - direct CP violation 1999
  - (with CERN)



- **Some critical measurements**
  - *t* and *W* mass 1998
  - QCD at highest energies 1988
  - proton structure 1984-95
  - charm lifetimes 1985-95

Fermilab, 1977

Before electronic data analysis, individuals visually examined photographs of Bubble Chamber particle interactions.

Physics Drivers

1940's	Basic Nuclear Structures Studies	Cyclotrons
	Nuclear Structure	
	-QED	
1950's-60's	Particle and Particle Properties	Synchrotrons
1960's-70's	Substructure	
	-QCD	
1980's-2000	Finishing the Standard Model	Lepton Colliders
		SSC, TeV
2000-----	Search for new particles	LHC, TeV
	Symmetries and New Matter Types	

P5 **May 2014**

(Particle Physics Project Prioritization Panel)

Science Drivers

Higgs Field 2012

Neutrino Mass

Dark Matter

Cosmic acceleration :dark energy and inflation

Explore the unknown:

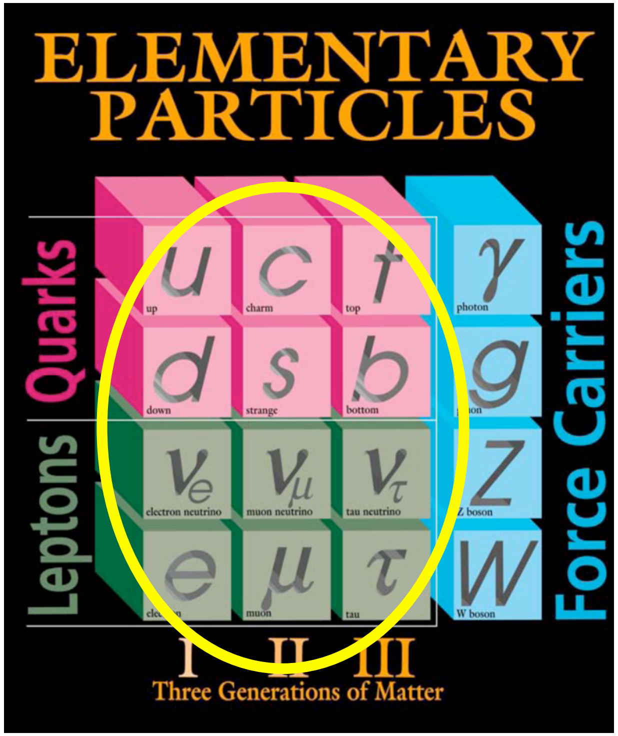
new particles, interactions, and physical principles

The Intensity Frontier

Physics of Flavor

- Flavor phenomena
  - Essential to shaping physics beyond the SM.

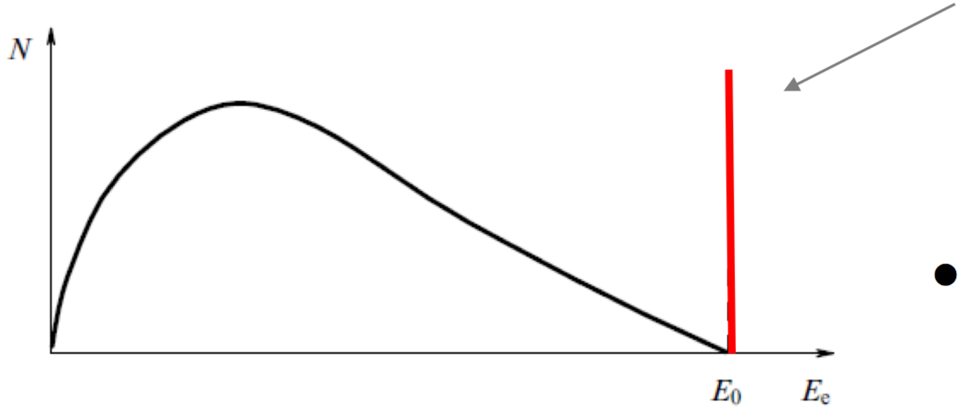
- SM is incomplete:
  - Neutrino Masses (flavor)
    - Exciting new physics seen in the laboratory
  - Baryon Asymmetry of the Universe (flavor)
  - Dark Matter
  - Dark Energy



Courtesy : Fermilab Strategic Plan

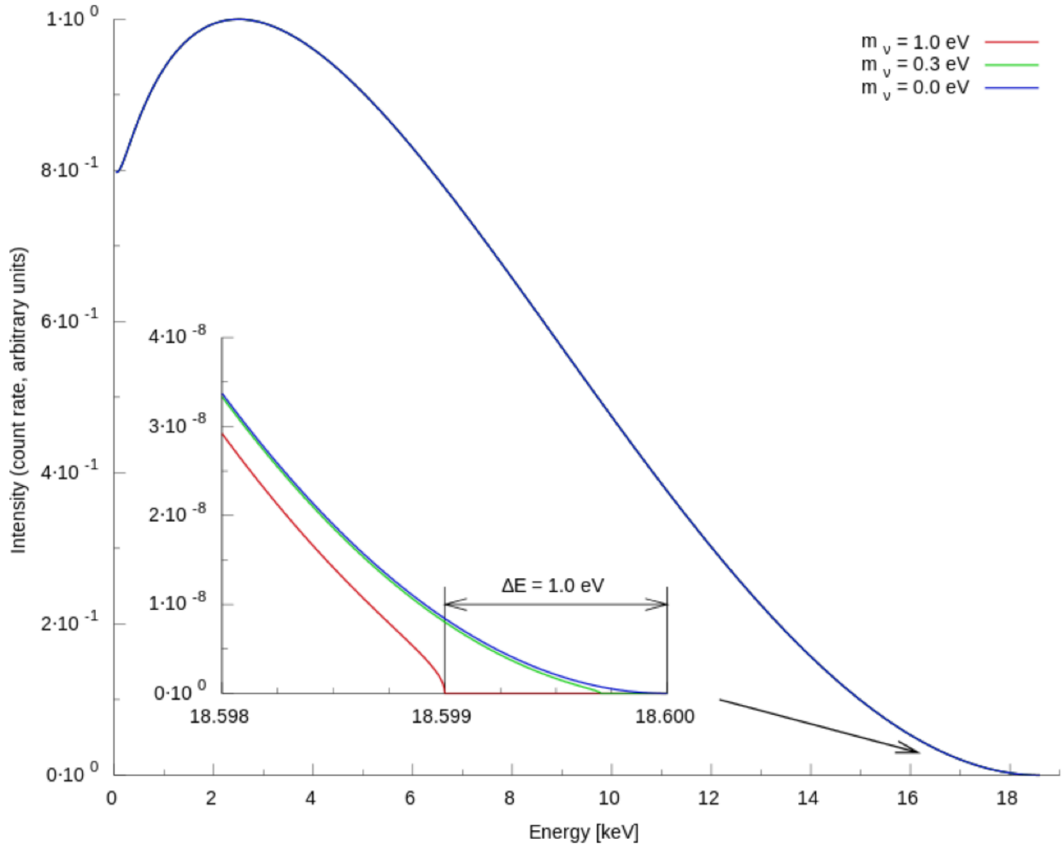
- One can probe the properties of the universe by looking for extremely rare processes
- Complementary alternative to using higher energies
- The medium-term future of accelerator-based particle physics on US soil is the intensity frontier:
  - Neutrino experiments (NOvA, LBNF, MINOS, MINERvA, and others…)
  - Precision measurements (g-2)
  - Rare decays (Mu2e)

- 1930 Pauli introduces neutrino
- Explains continuous beta spectrum



- Expected discreet spectrum for two body decay
- Observed continuous beta spectrum

$$^3_1\mathrm{T} \rightarrow ^3_2\mathrm{He}^{1+} + e^- + \bar{\nu}_e$$

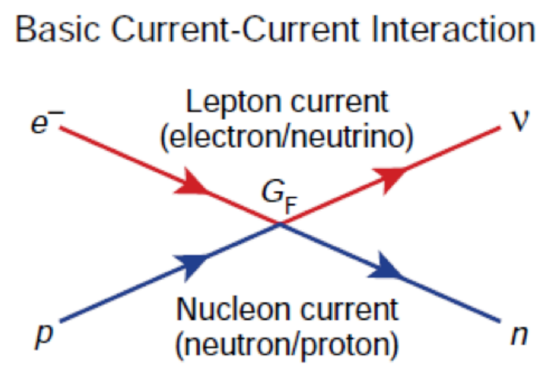


$$m(\nu_e) < 2 \text{ eV } (95\%\text{C.L.})$$

Mark Messier, Indiana University, IF-19JUN14

Weak interactions

- 1934 Fermi develops Theory of Beta Decay

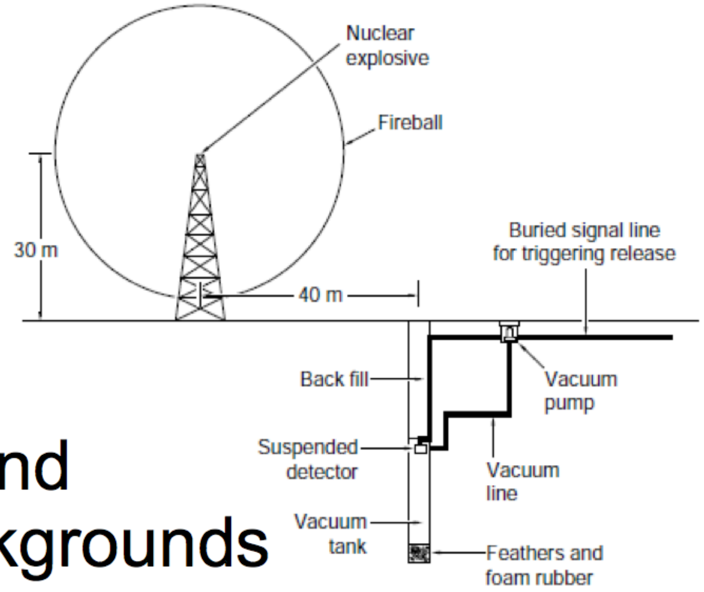


- Bethe-Peierls calculate the cross section for neutrino interaction $\sigma_{\nu p} \sim 5 \times 10^{-44} cm^2$

Need a large mass (order of a light year or so, of steel) to absorb this particle

Žarko Pavlović , IF-5JUN14

Neutrino Detection and Sources



Need intense
source of neutrinos

Nuclear bomb

- Almost went with it, but found a better way to handle backgrounds

Nuclear reactor

- Source of electron anti neutrinos
- 1956 Cowan & Reines detect first neutrinos

$$\bar{\nu} + p \to n + e^{+}$$

Žarko Pavlović , IF-5JUN14

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Neutrino Physics measurements

Another way to study matter – antimatter symmetry or asymmetry is the study of neutrino interactions.

The study of neutrino mass, and various flavors of these particles

Neutrinos:
Produced in the sun, supernovas, the earth, cosmic rays, reactors, medical isotopes, and accelerators. About 10^{14} pass through us, and even more through the many miles of the earth thickness every second. Maybe one in 10^{5} might interact while passing through the earth.

Questions on Neutrinos

Are Neutrinos their own anti particles?

Is there a mass hierarchy that we can examine?

Does CP violation apply in the neutrino sector?

Are sterile neutrino sufficient or required?

How do we address the mass scale of neutrinos?

Neutrino mixing and oscillations

Sources of Neutrinos

Solar
Atmospheric
Super Nova

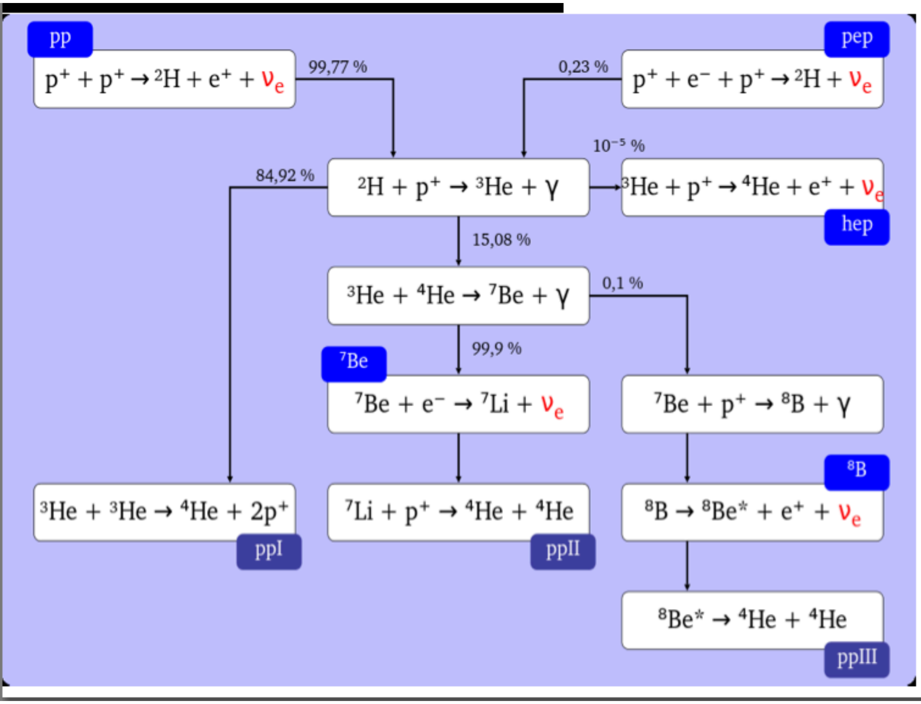
} not controlled Production

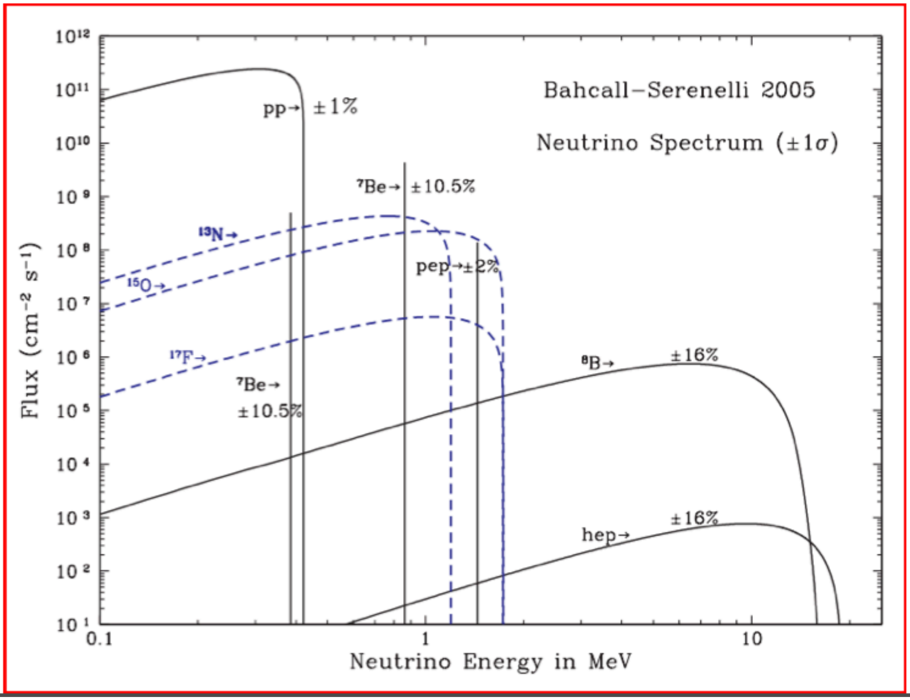
Radioactive Materials
Reactors
Accelerators

} controlled Production

Standard Solar Model Neutrino

Flux ~ $10^{11}/cm^2/s$





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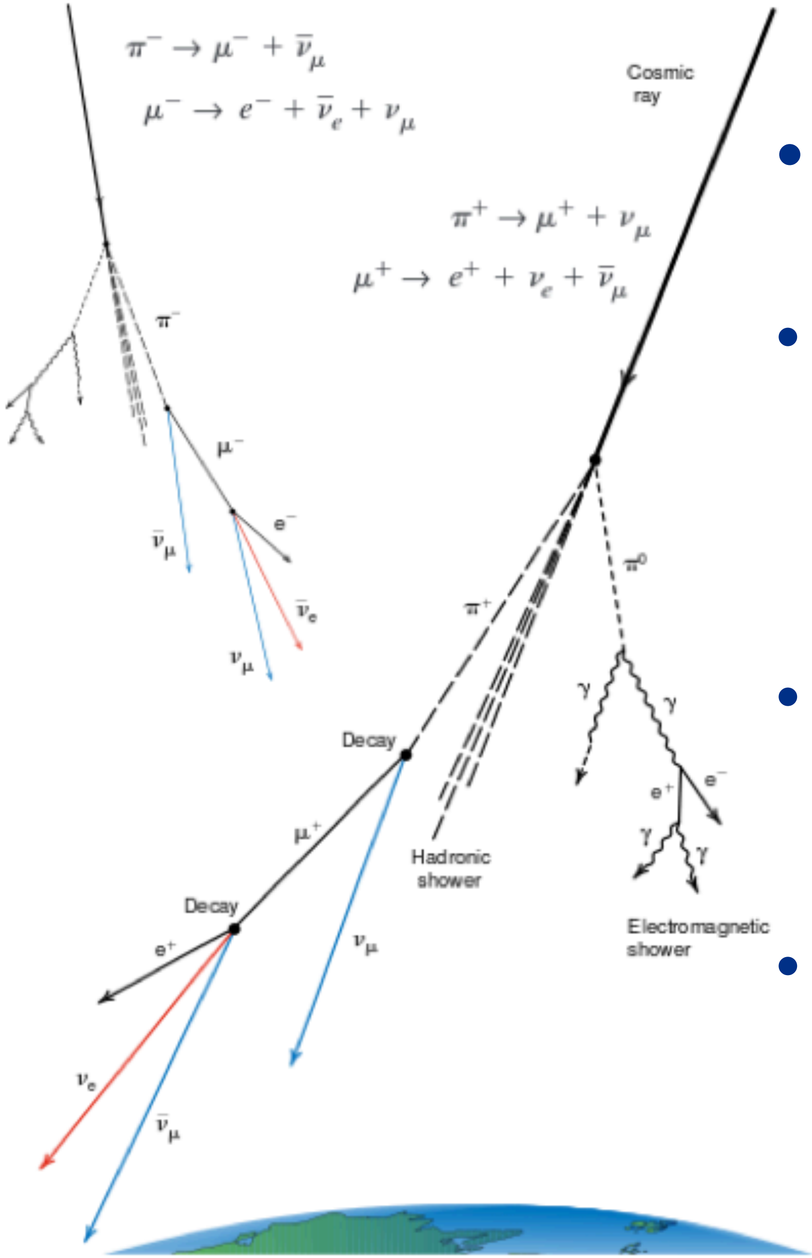
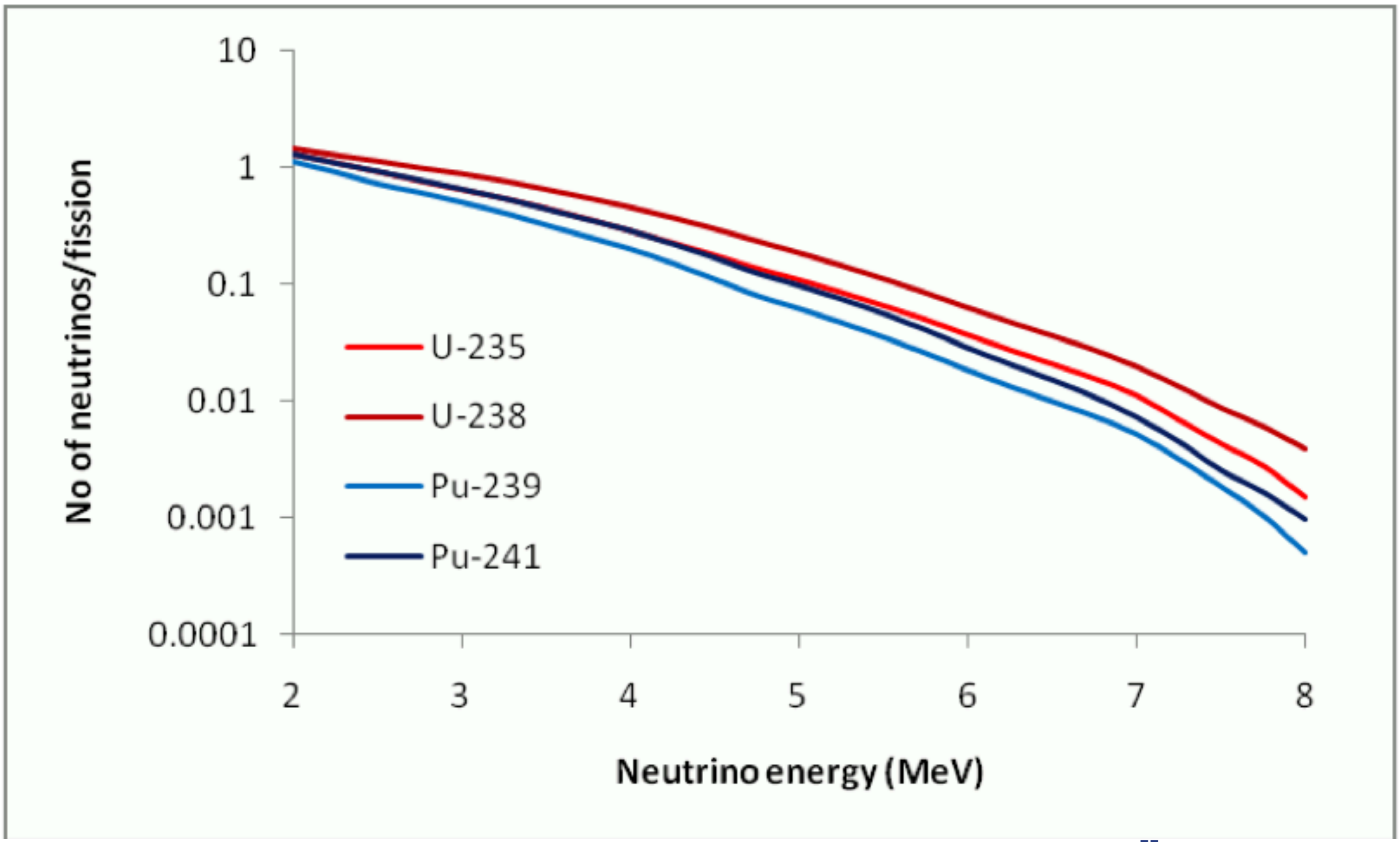


- Atmospheric neutrinos
- Cosmic rays (mostly protons) interact in upper atmosphere creating hadronic showers (mostly pions)
- Roughly 2:1 muon neutrinos to electron neutrinos
- Total fluxes known to ~20%, however ratios at few % level

Reactor Neutrinos

Neutrinos from beta decays of fission products

Average reactor core produces ~10^{20} ν_e/s

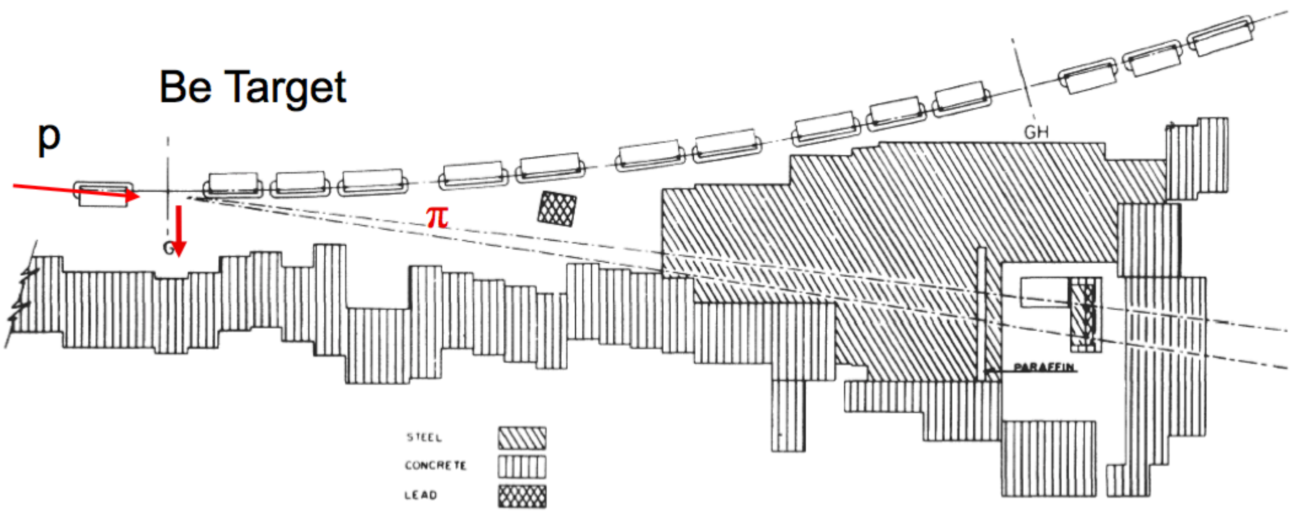


NEUTRINO BEAMS FROM ACCELERATORS

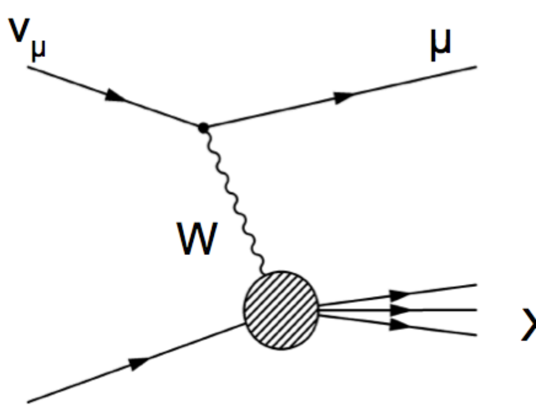
- Idea independently proposed by Pontecorvo and Schwartz
- 1962 Lederman, Schwartz & Steinberger using AGS at BNL

$$p+Be \rightarrow \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$

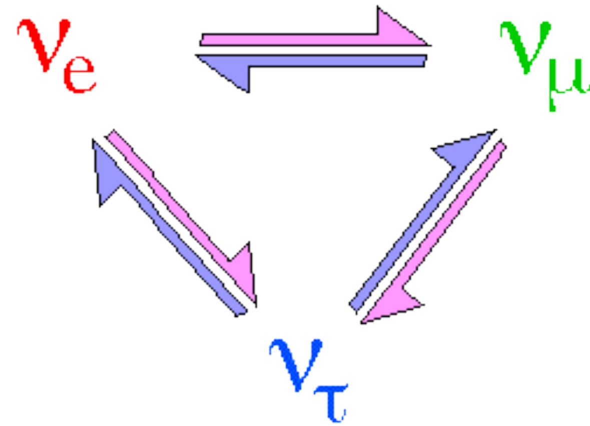
- Detected muon neutrino → existence of two kinds of neutrinos



Phys.Rev.Lett. 9, 36 (1962)



Neutrinos:



The elusive neutrinos are among the most abundant of the tiny particles that make up our universe. To understand the universe, one must understand neutrinos.

Their behavior is different from other particles.

Opening a "new" window

New and future info: θ_{13}, $\bar{\nu} = \nu$, mass ordering, CP violation

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As they move along they change from one flavor to another, such as, $\nu_\mu \rightarrow \nu_\tau$ and back again. Neutrino masses are tiny; their mass is probably no more than one millionth the mass of an electron. Accelerators are the best way to create and control neutrino particles for study.

The standard and most frequently used neutrino beams, are produced from decays of pions and kaons, with the dominant two-body decays into π and ν_μ providing most of the flux. Neutrinos originating from K decays give a higher energy flux, their energies reaching close to the energy of the parent kaon while the neutrinos from pion decays are limited in the parent pion energy.

As in the case for the Kaon complex, the principle behind neutrino oscillations is the fact that if neutrinos have mass, then a generalized neutrino state can be expressed either as a superposition of different mass eigenstates or of different flavor eigenstates. This is mainly a restatement of a well-known quantum mechanics theorem that, in general, several different basis vector representations are possible, these different representations being connected by a unitary transformation such as the CKM matrix. (Ref: Wojcicki Lecture, 1997)

$|\nu_\alpha> = \nu_e, \nu_\mu, \nu_\tau$

$|\nu_i> = \nu_1, \nu_2, \nu_3$

$|\nu_\alpha> = \quad U \quad |\nu_i>$ Where U is unitary

$$P(\nu_a \rightarrow \nu_b) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

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Neutrino oscillations

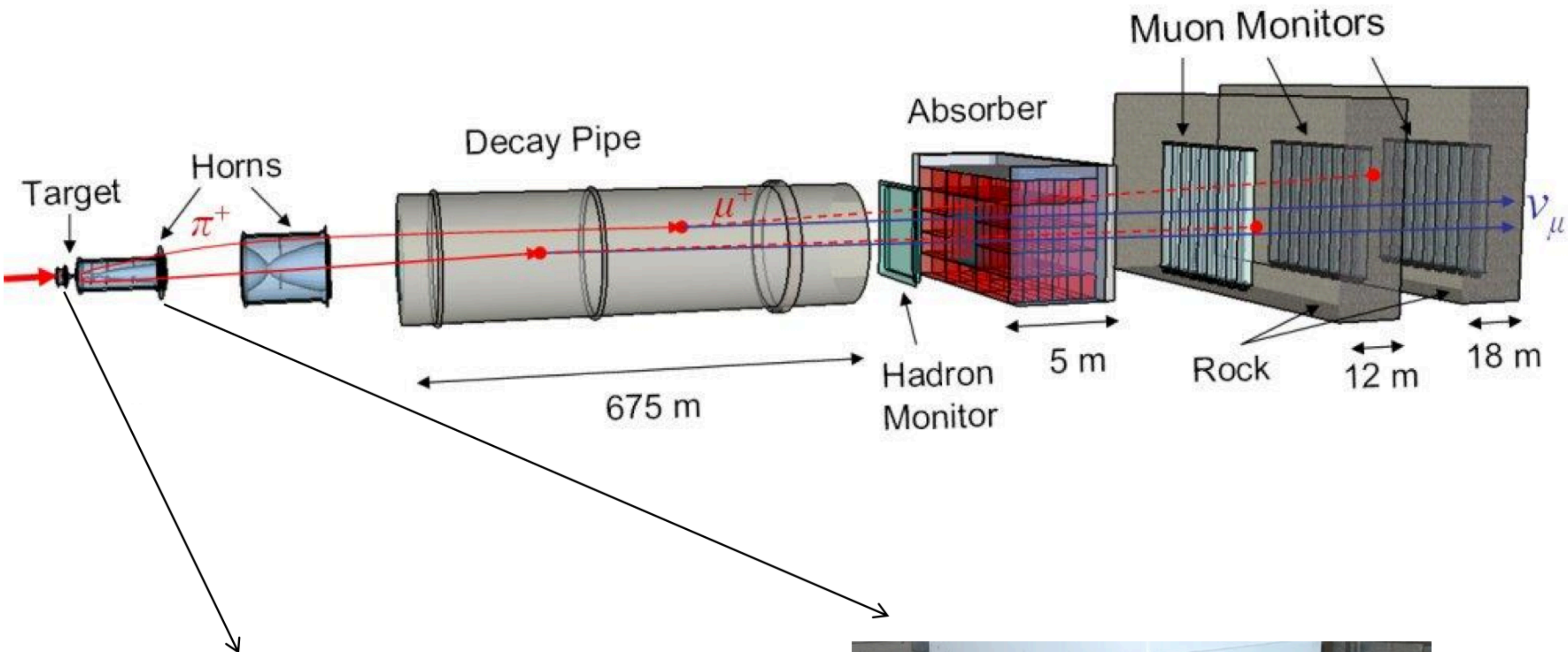
$$\left|\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{array}{c}\nu_1\\ \nu_2\\ \nu_3\end{array}\right\rangle$$

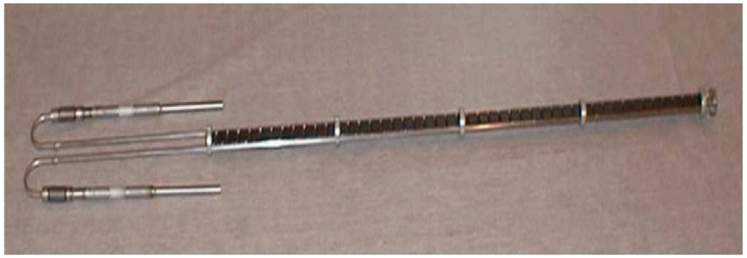
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

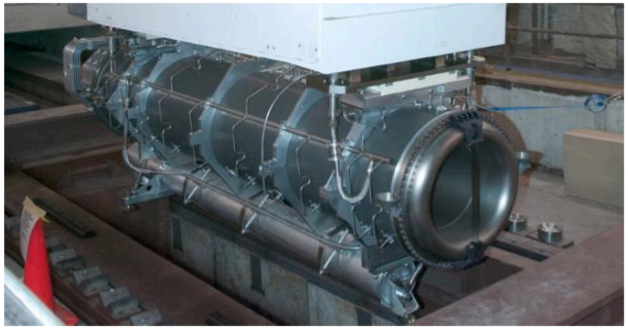
$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert \simeq 2\times 10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	$\nu_e \to \nu_e$ $\nu_e \to \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor
$\theta_{23} \simeq 45^\circ$	$\theta_{13} = 9^\circ$	$\theta_{12} \simeq 35^\circ$

$$\delta = ?\ \mathrm{sgn}(\Delta m^2_{31})?$$

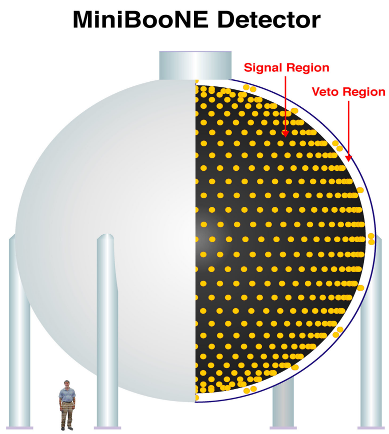
Fermilab neutrino beams - NuMI

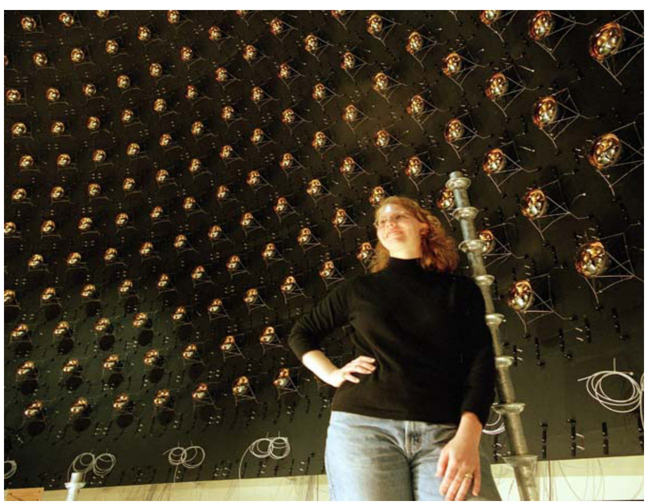






Intensity Frontier: Neutrinos now





The Intensity Frontier

Neutrinos From Beam Production

- Dominant source is pion decay $\pi \rightarrow \mu + \nu_\mu$ (BR≈100%)
  - Simple 2 body decay in CM system
  - Neutrino energy:

$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- Neutrinos boosted in the direction of the proton beam

$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

Žarko Pavlović , IF-5JUN14

Horn Focusing

Angle of neutrinos from pion decays with respect to pion momentum ~$1/\gamma$

Pions emerge from target with angle ~$2/\gamma$

Removing pion divergence would increase flux by ~25x

Simon van der Meer developed magnetic device to focus secondaries emerging from the target

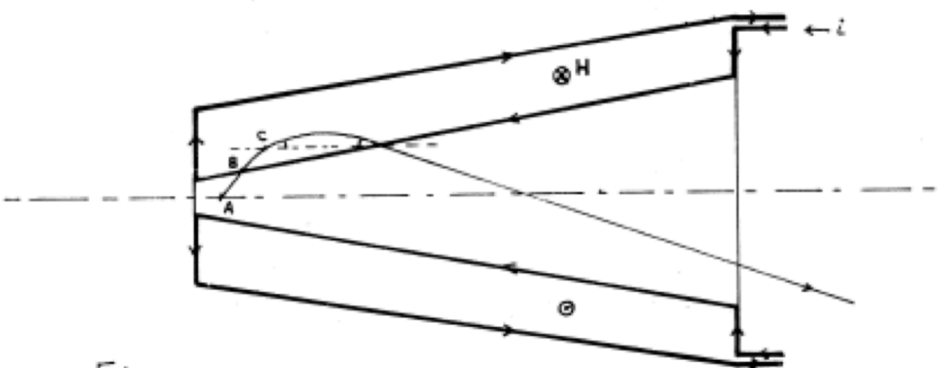


Fig. 2

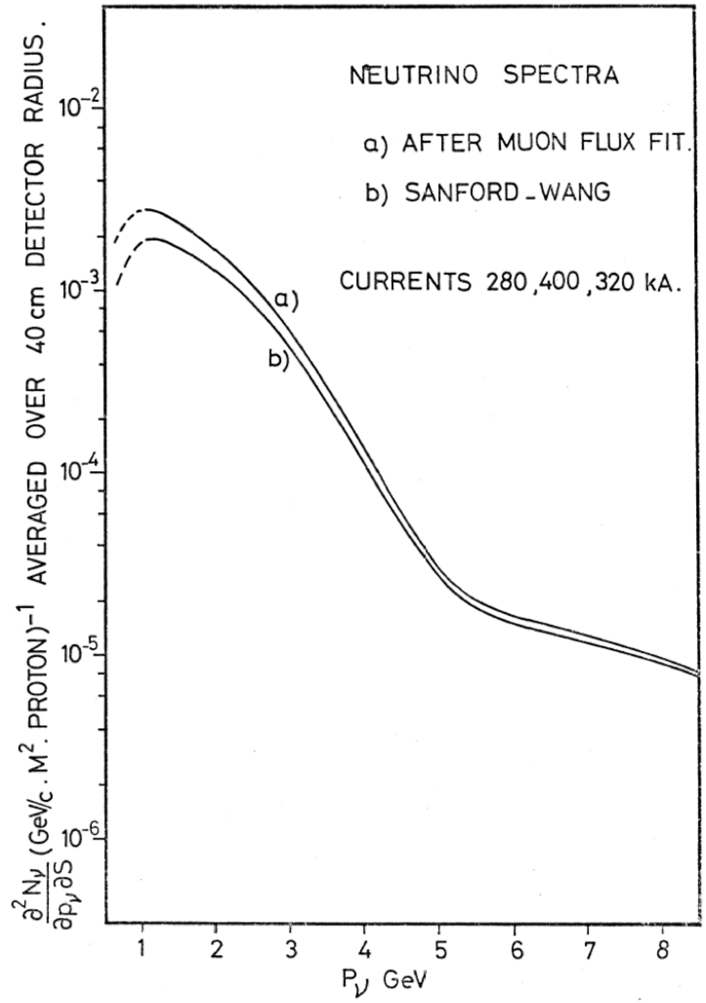
Žarko Pavlović , IF-5JUN14

Past neutrino experiments had to apply corrections

More often than not flux prediction didn't match data

- Using some process with known cross section

Flux uncertainty large 10-30%



At higher energies, the flux prediction were improved.
See: Stefanski and White Parameterization

NEUTRINO EVENT RATES ⇒

Requirements: protons+target ⇒ pions ⇒ neutrinos +detector

The number of events will be proportional to: cross-section * detector mass * flux * time

Thus for precise measurement we need:

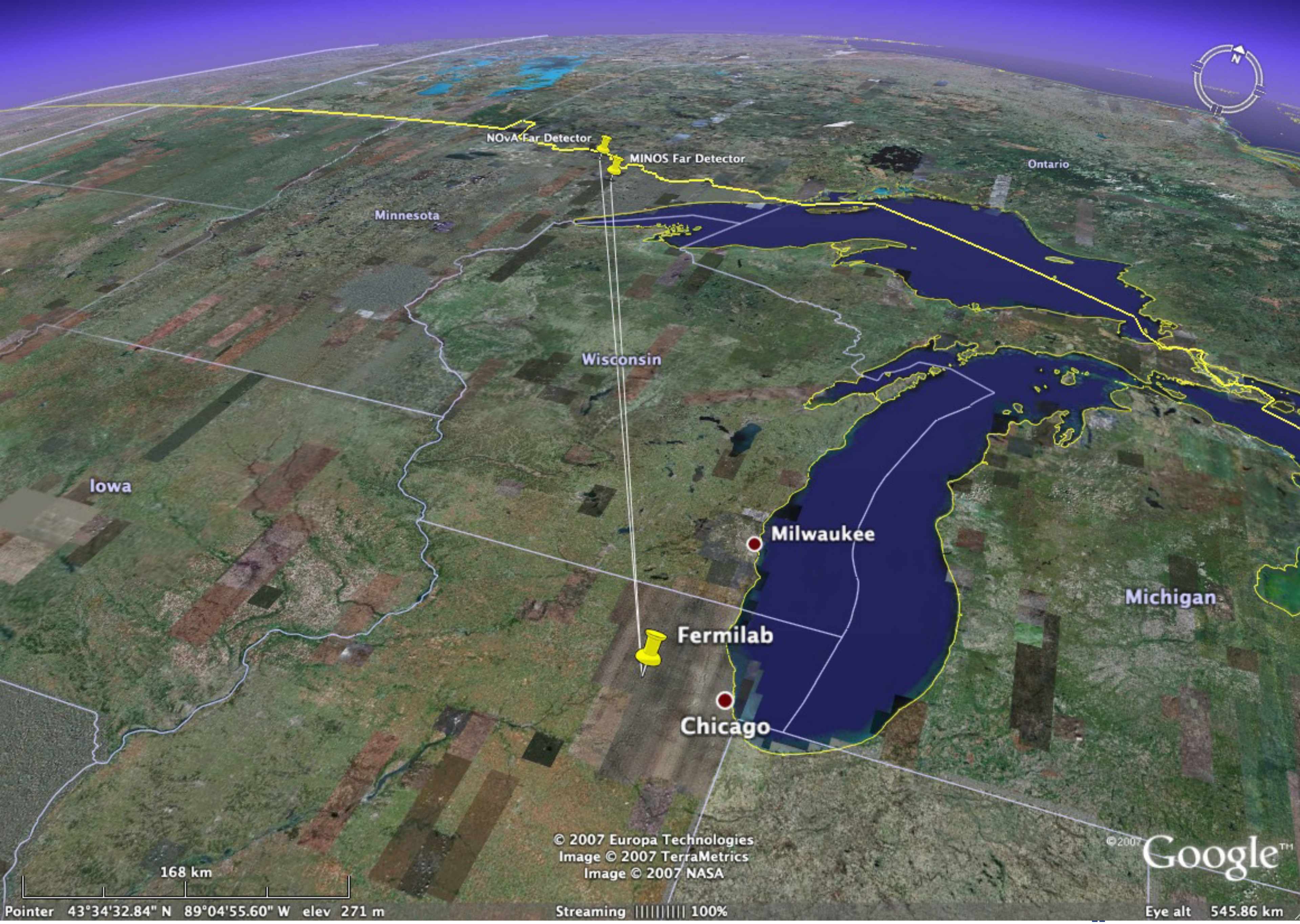
A large detector mass and a large ν flux (ie. intense proton beam)

The neutrino oscillations in the atmospheric domain are dominated by two parameters, the mass squared difference, Δm^2_{13}, and mixing angle $\sin^2(2\theta_{23})$.

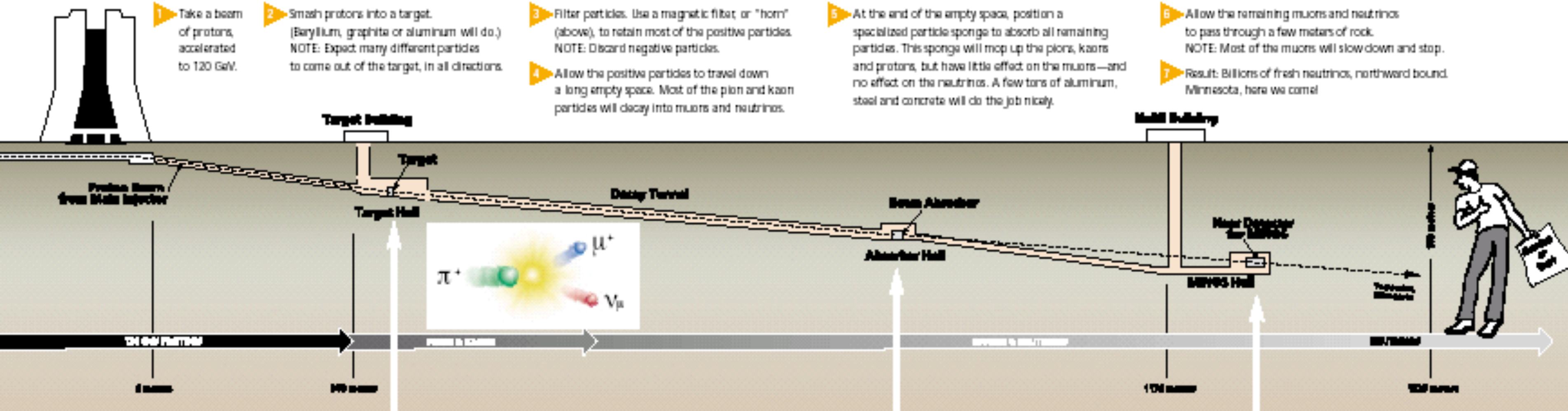
Typical experiments looks for disappearance of ν_μs interactions. The formula, in the two-favor approximation, for the ν_μ survival probability, is given by

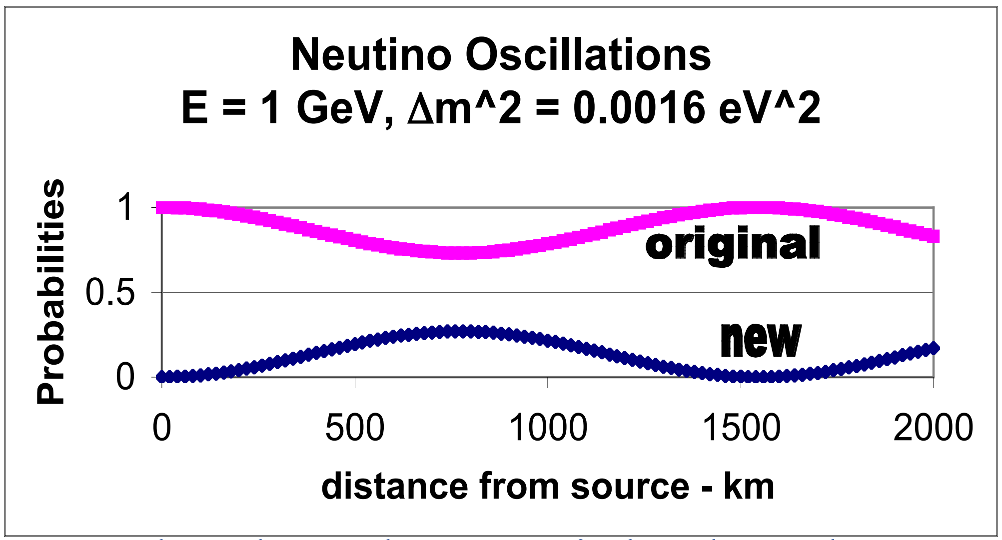
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E).$$

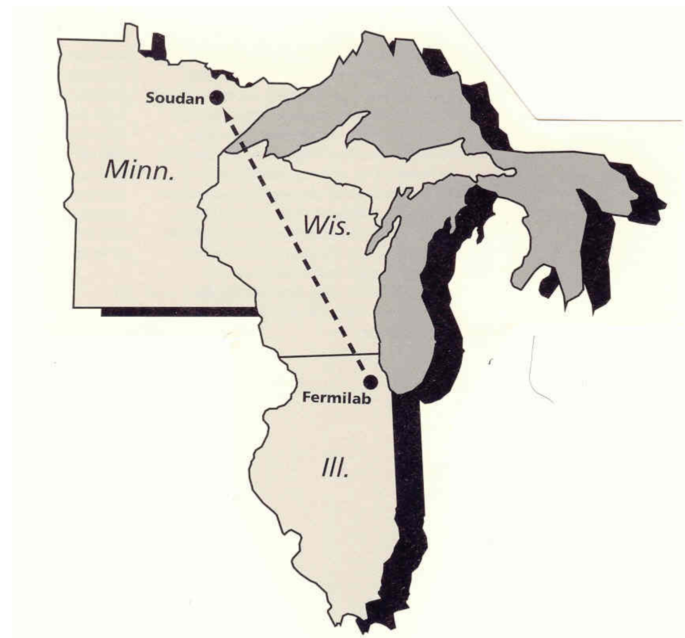
Ref:(ACCELERATOR NEUTRINO PHYSICS Å CURRENT STATUS AND FUTURE PROSPECTS
S. G. Wojcicki Stanford University, Stanford, CA, USA), 2010


NOvA Far Detector
MINOS Far Detector
Ontario
Minnesota
Wisconsin
Iowa
Milwaukee
Michigan
Fermilab
Chicago
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA
168 km
Pointer 43°34'32.84" N 89°04'55.60" W elev 271 m
Streaming 100%
Eye alt 545.86 km

NUMI – Neutrinos at the Main Injector







735 km long beam, right thru the earth!

10 km deep

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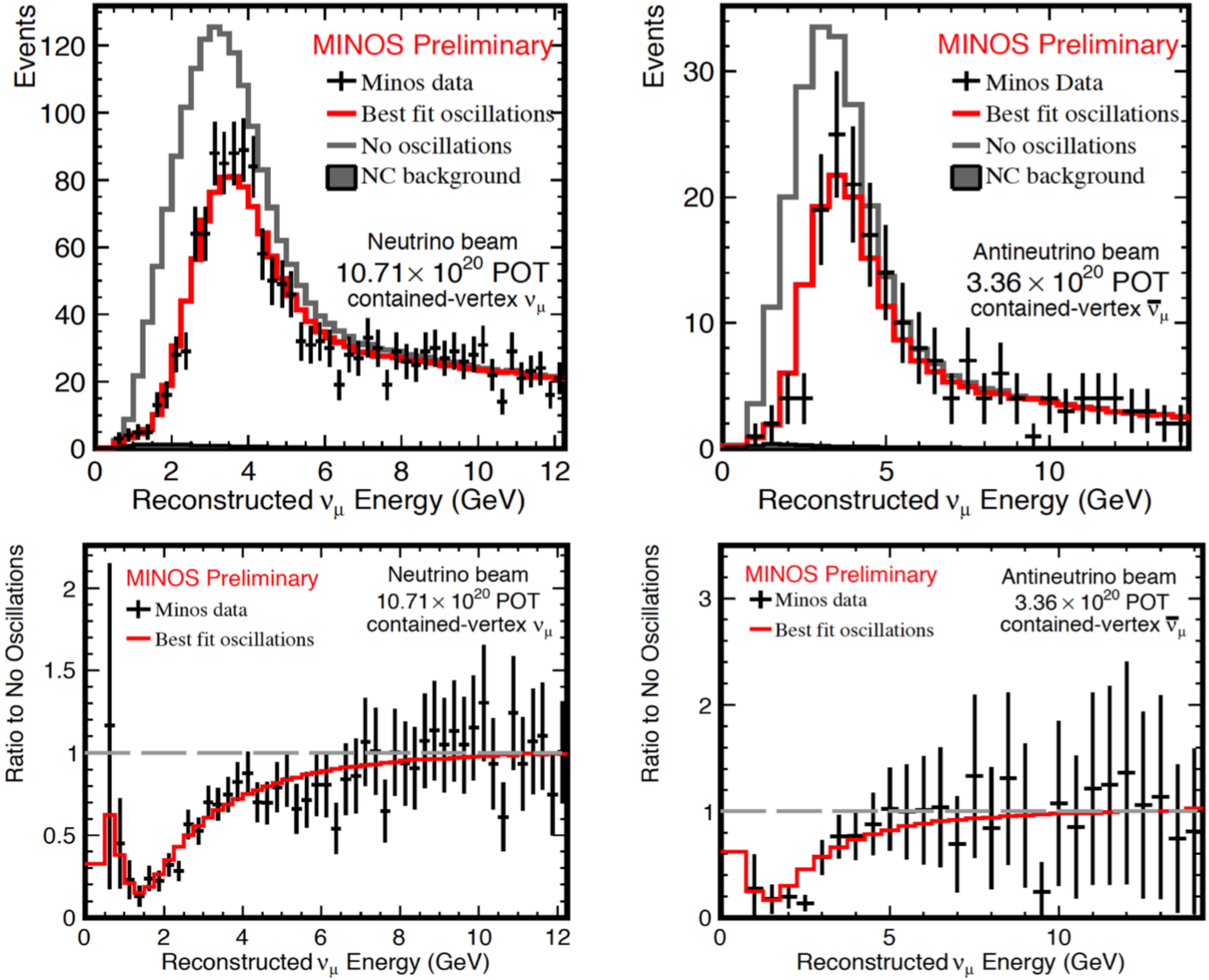
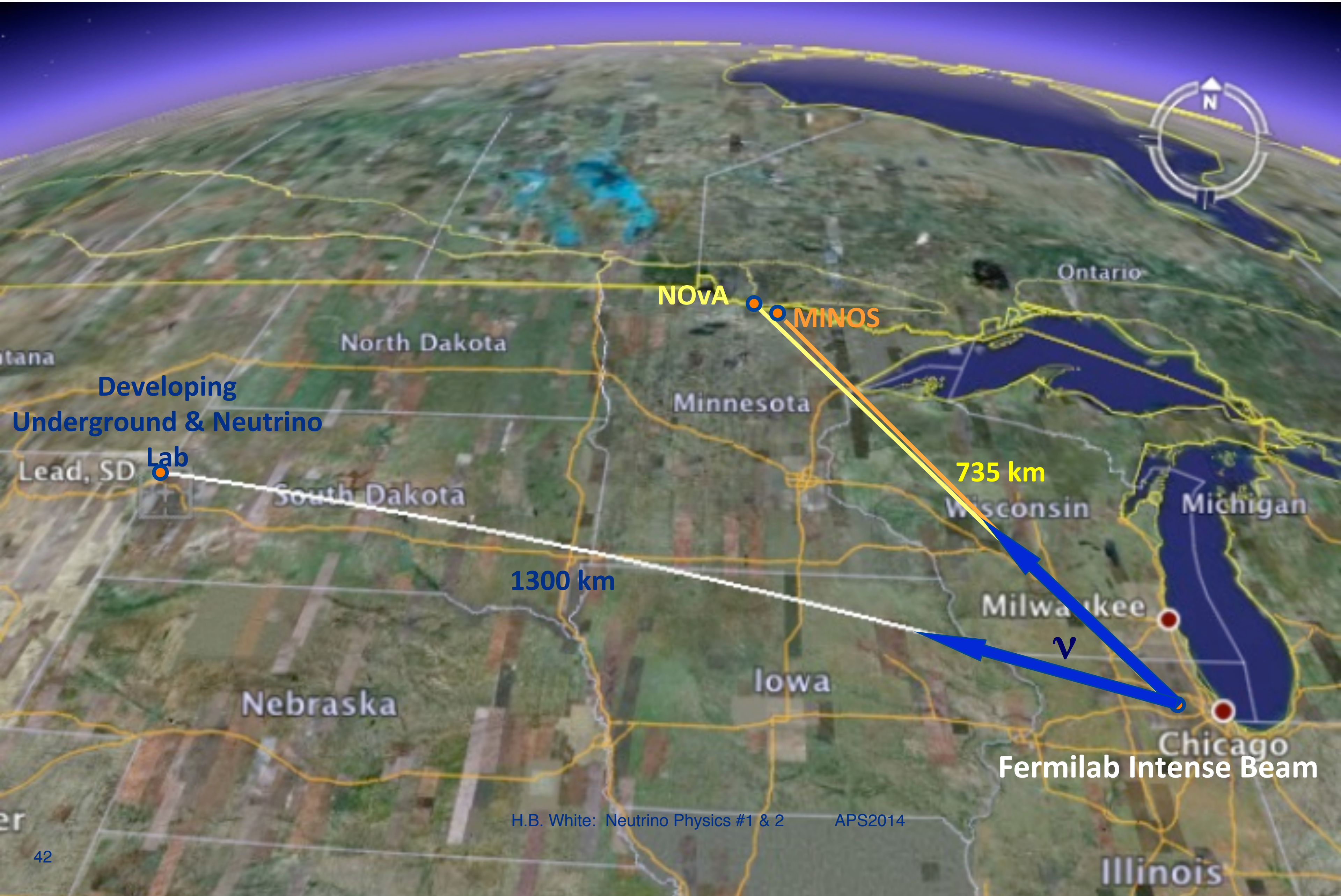
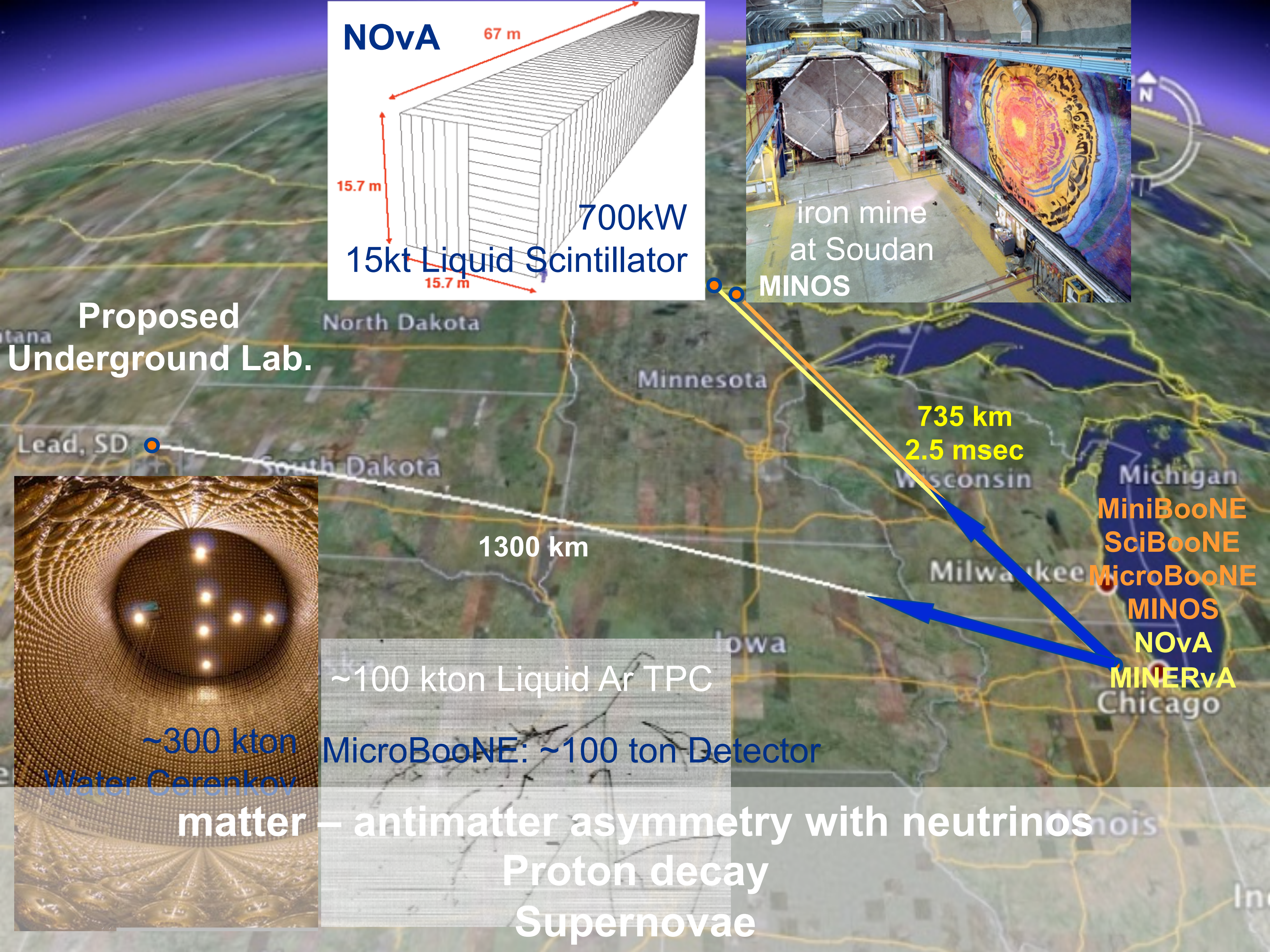


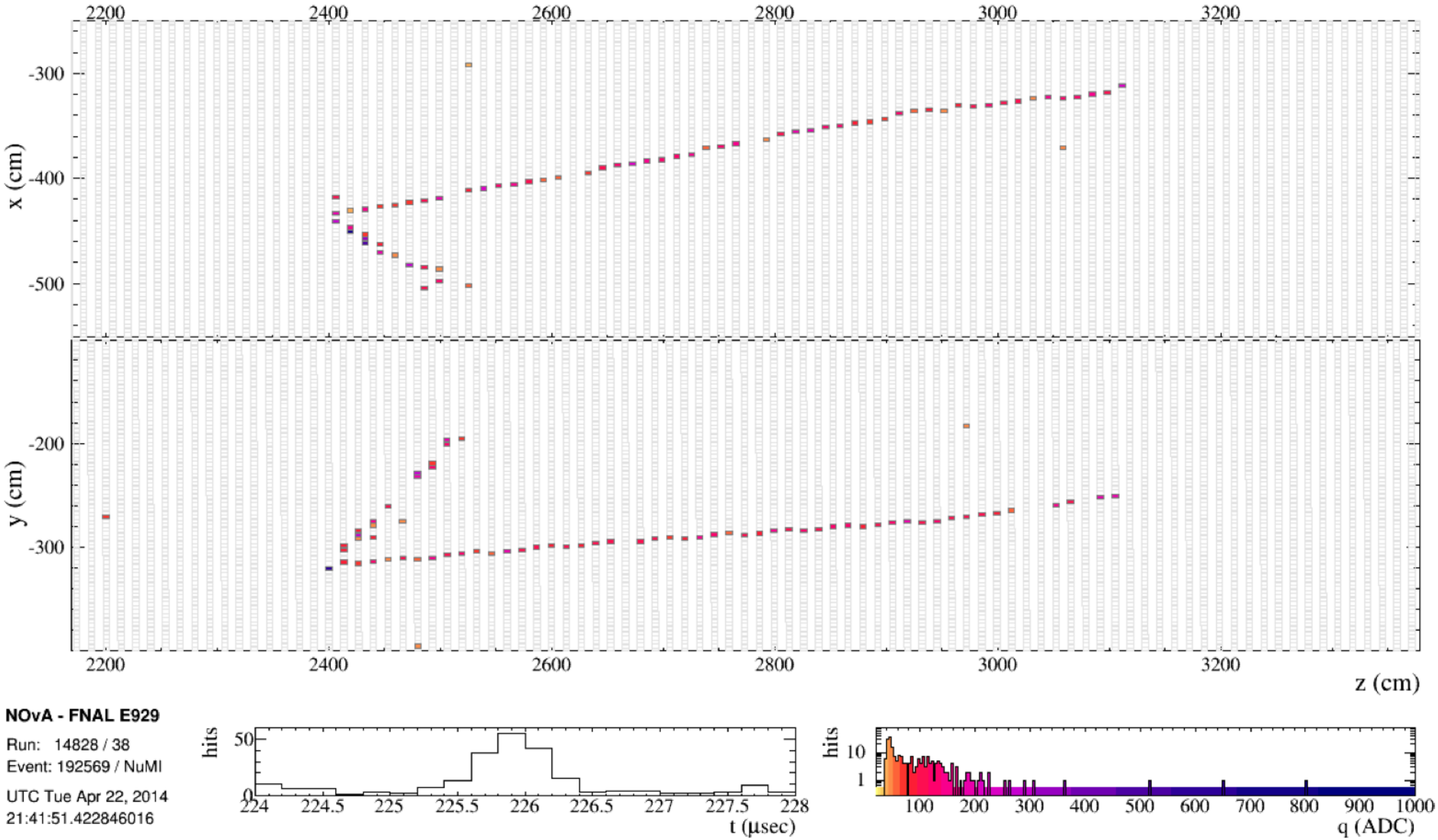
Mark Messier, Indiana University, IF-19JUN14

Future Planning for Fermilab

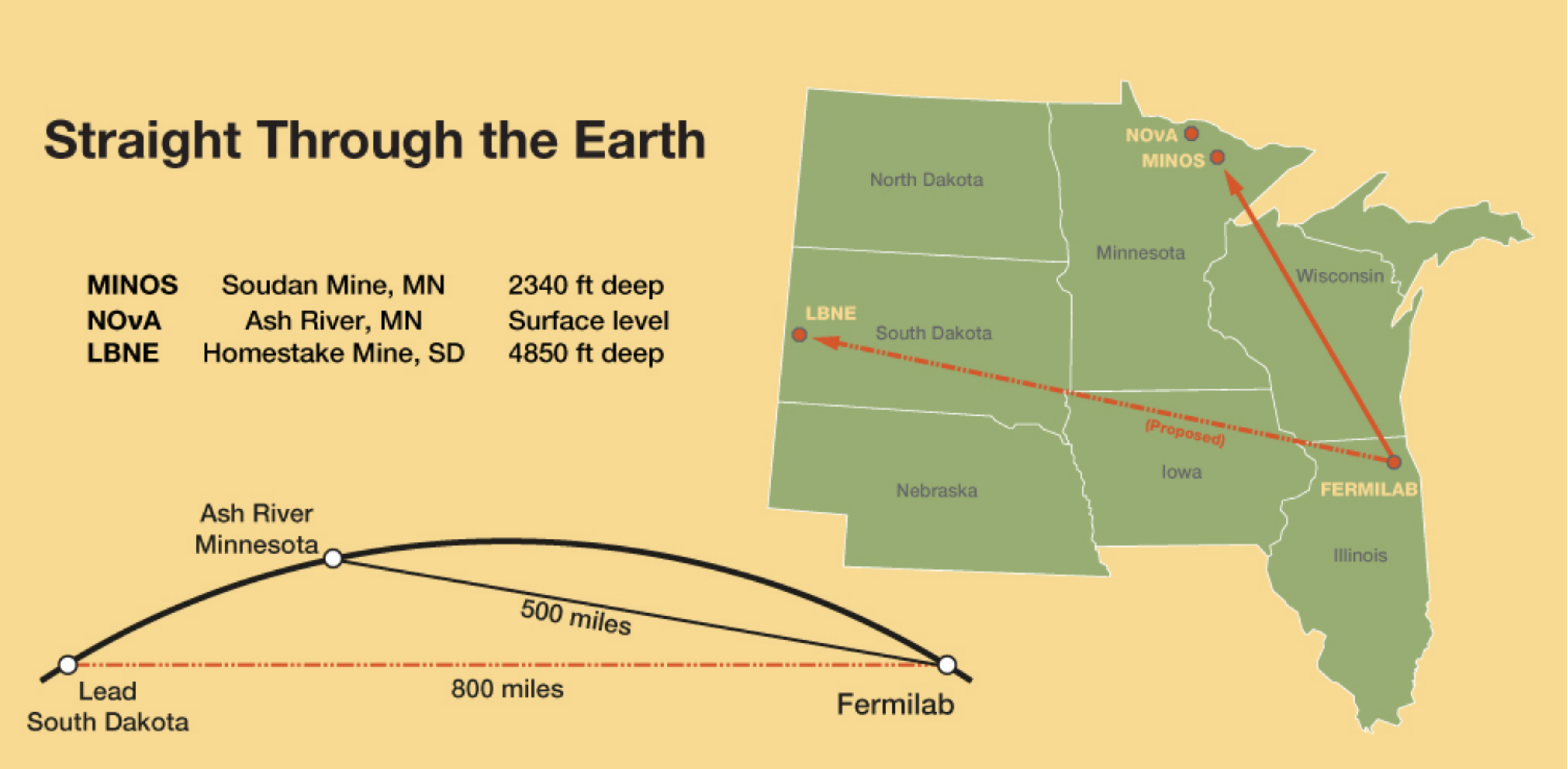



NOvA
67 m
15.7 m
15.7 m
700kW
15kt Liquid Scintillator
iron mine
at Soudan
MINOS
Proposed
Underground Lab.
North Dakota
Minnesota
Lead, SD
South Dakota
735 km
2.5 msec
Wisconsin
Michigan
MiniBooNE
SciBooNE
MicroBooNE
MINOS
NOvA
MINERvA
Milwaukee
Chicago
1300 km
Iowa
~100 kton Liquid Ar TPC
MicroBooNE: ~100 ton Detector
~300 kton
Water Cerenkov
matter – antimatter asymmetry with neutrinos
Proton decay
Supernovae

14,700 tons, 810 km, expected to fully start in 2014-15


x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14828 / 38
Event: 192569 / NuMI
UTC Tue Apr 22, 2014
21:41:51.422846016
hits
t (μsec)
hits
q (ADC)

Intensity Frontier: Aiming neutrinos through 500 miles of earth to study their family behavior…



Physics Laboratories around the world

Prospects for some future experiments

Some fixed Target

Experiments engaged include:

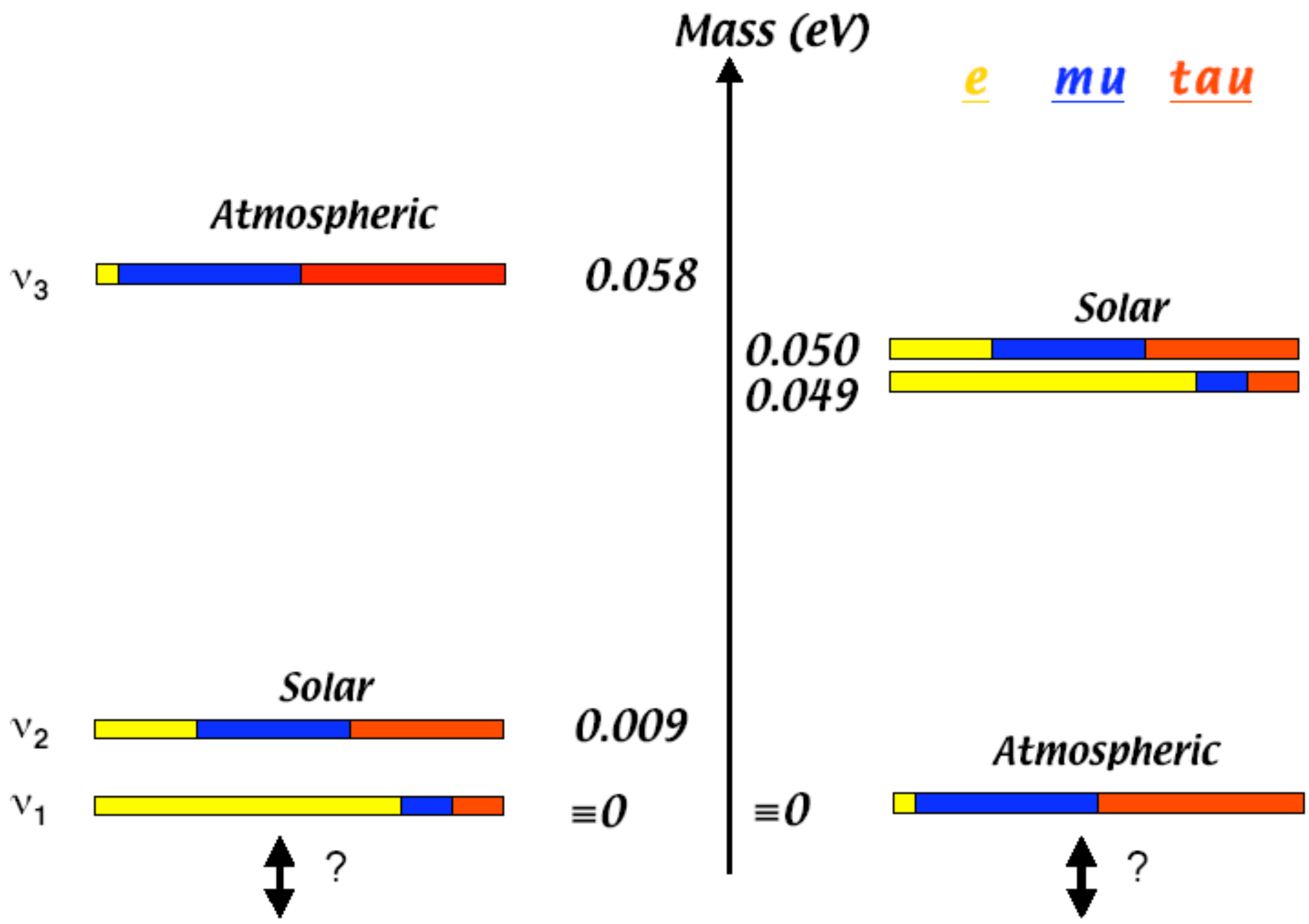
Super-Kamiokande
MINOS
OPERA
K2K, T2K
BOONe 's
MINERνA
NOνA
LBNF (proposed)

The current focus is mass hierarchy: that is which ν is heaviest?

Study of matter-antimatter symmetry

Search for more ν's, if any

Laza Rakotondravohitra of Madagascar
ASP2010 and MINERvA Ph.D. candidate



Neutrino 2014: K.S. Babu, Oklahoma State University, 2JUN14

DISCOVERY

- Extracting and understanding a phenomena for the first time!
- Leading to answers and often more questions
- Usually a piece of a puzzle that took some time to ascertain
- Often connecting many separate fields of study
- Enjoyment!

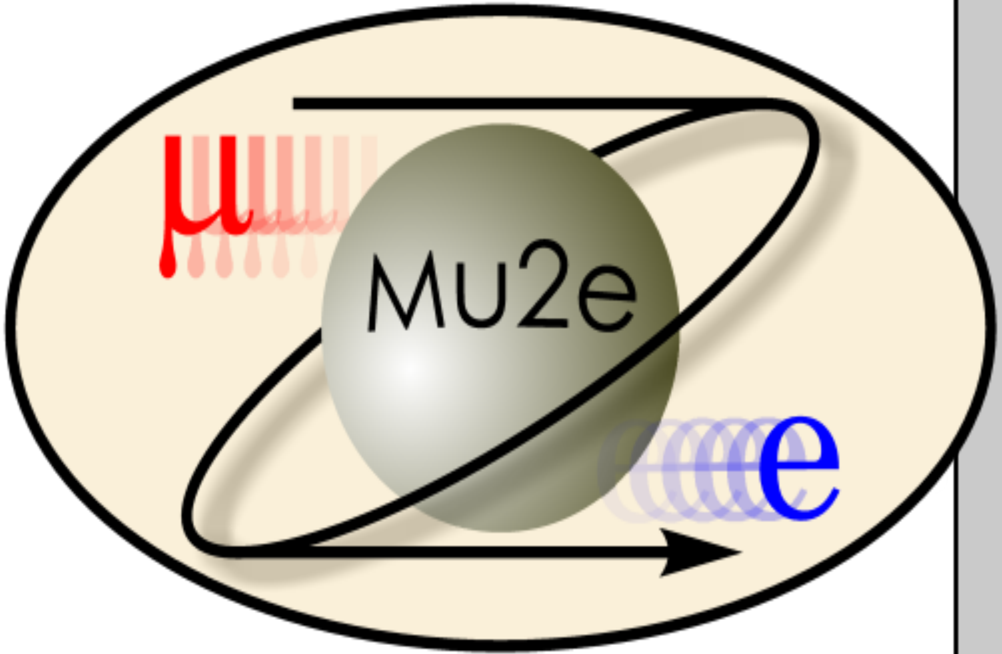
Conclusions

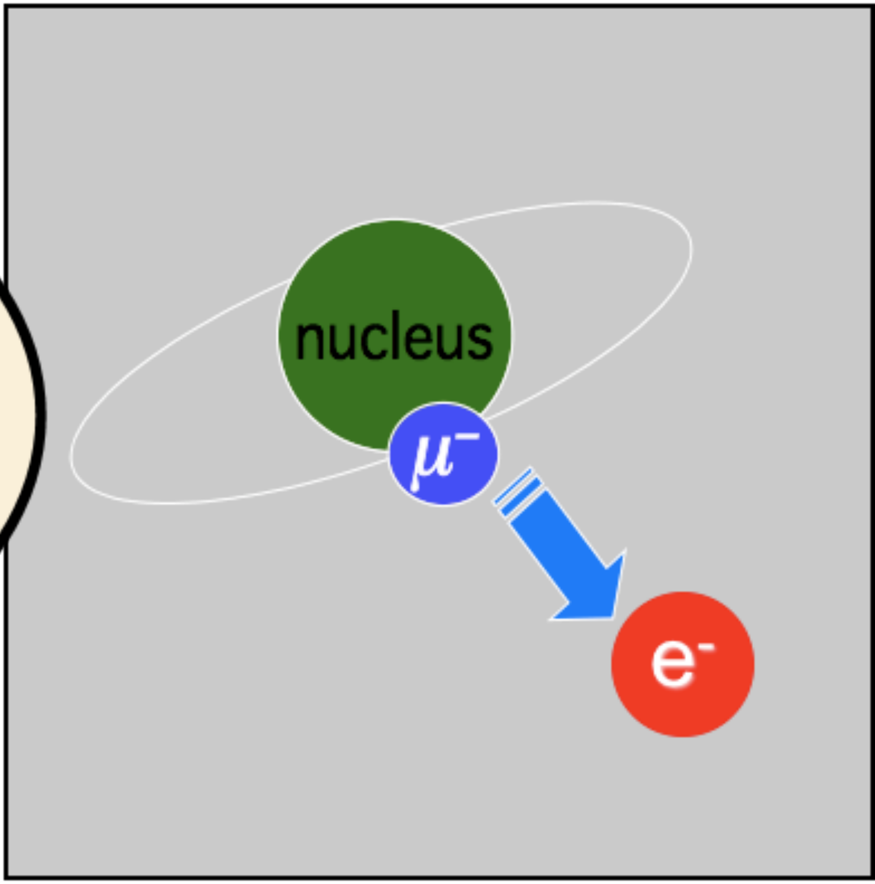
We continue to smash the nuclei that make up our universe and everyday we learn something new!

Join Us And Enjoy The Excitement!!

Muon to Electron Conversion

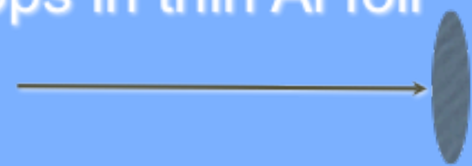
$$\mu^- N \rightarrow e^- N$$





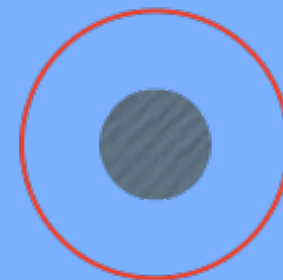
Overview Of Processes

μ^- stops in thin Al foil



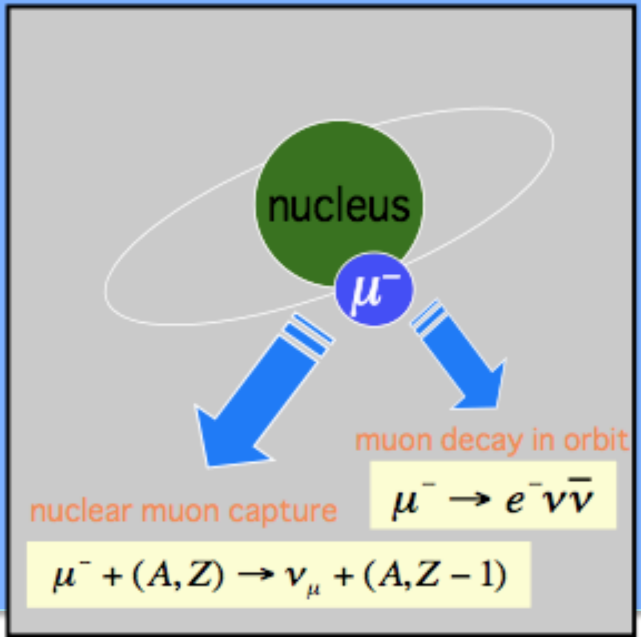
the Bohr radius is ~ 20 fm,
so the μ^- sees the nucleus

μ^- in 1s state



Al Nucleus
~4 fm

muon capture,
muon "falls into" nucleus:
normalization



60% capture
40% decay

Decay in Orbit:
background

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DETECTOR AND SOLENOID