Neutrino Physics

Milind Diwan

4/25/2007

- What are neutrinos ?
- Why study them ?
- Properties
- Natural/man-made sources

Stony Brook has some of the best people in this field
Yang, Shrock, Marx, Jung, ...

Thanks to many for slides.
esp: SK, SNO, Kamland, Minos

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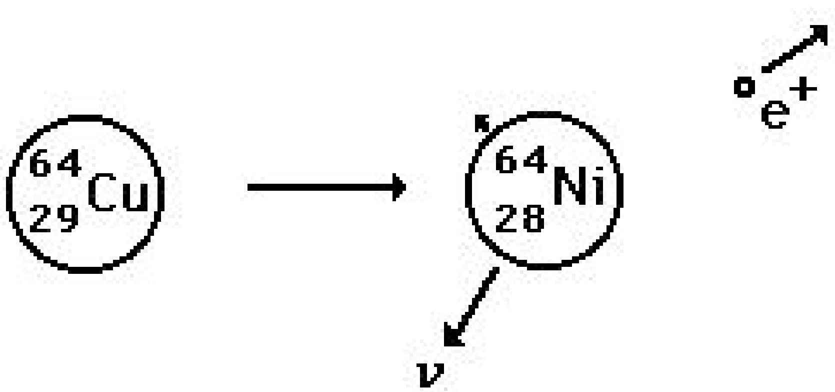
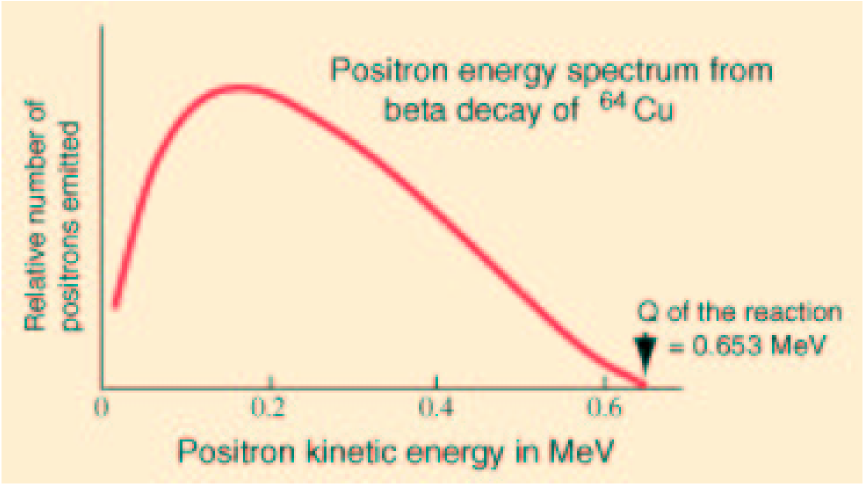
- Neutrinos (ν) are electrically neutral almost massless particles emitted in decays of radioactive nuclei (beta decays).

- Every emission of Beta particle is accompanied by a neutrino.





- In 1930, W. Pauli proposed the neutrino because the observed beta decay appeared to violate energy conservation.
- At that time the proton, electron and the photon (light) were the only known elementary particles.
- The neutrino is now an essential building block of the universe.
- The neutrino is the cause or the consequence of extraordinary and deep principles of nature.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

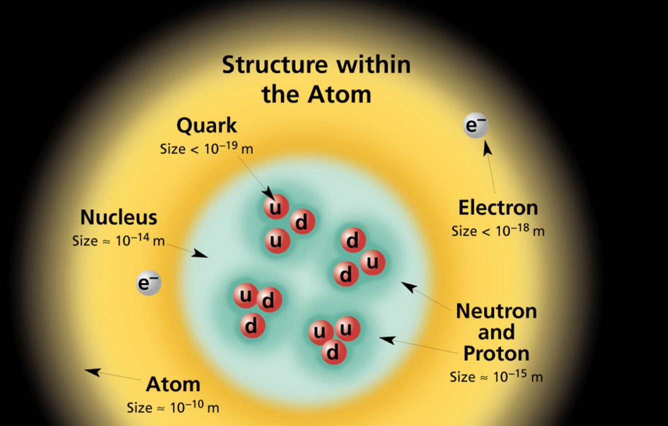
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



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.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

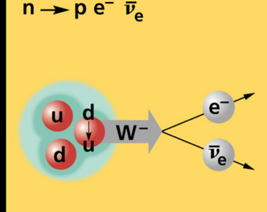
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

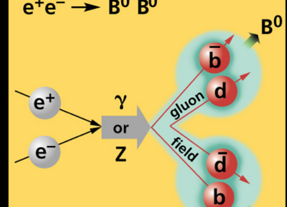
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \to p\, e^-\, \bar{\nu}_e$



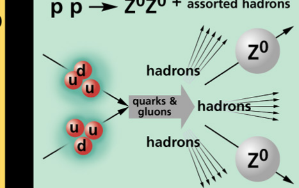
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \to B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \to Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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FERMIONS

matter constituents
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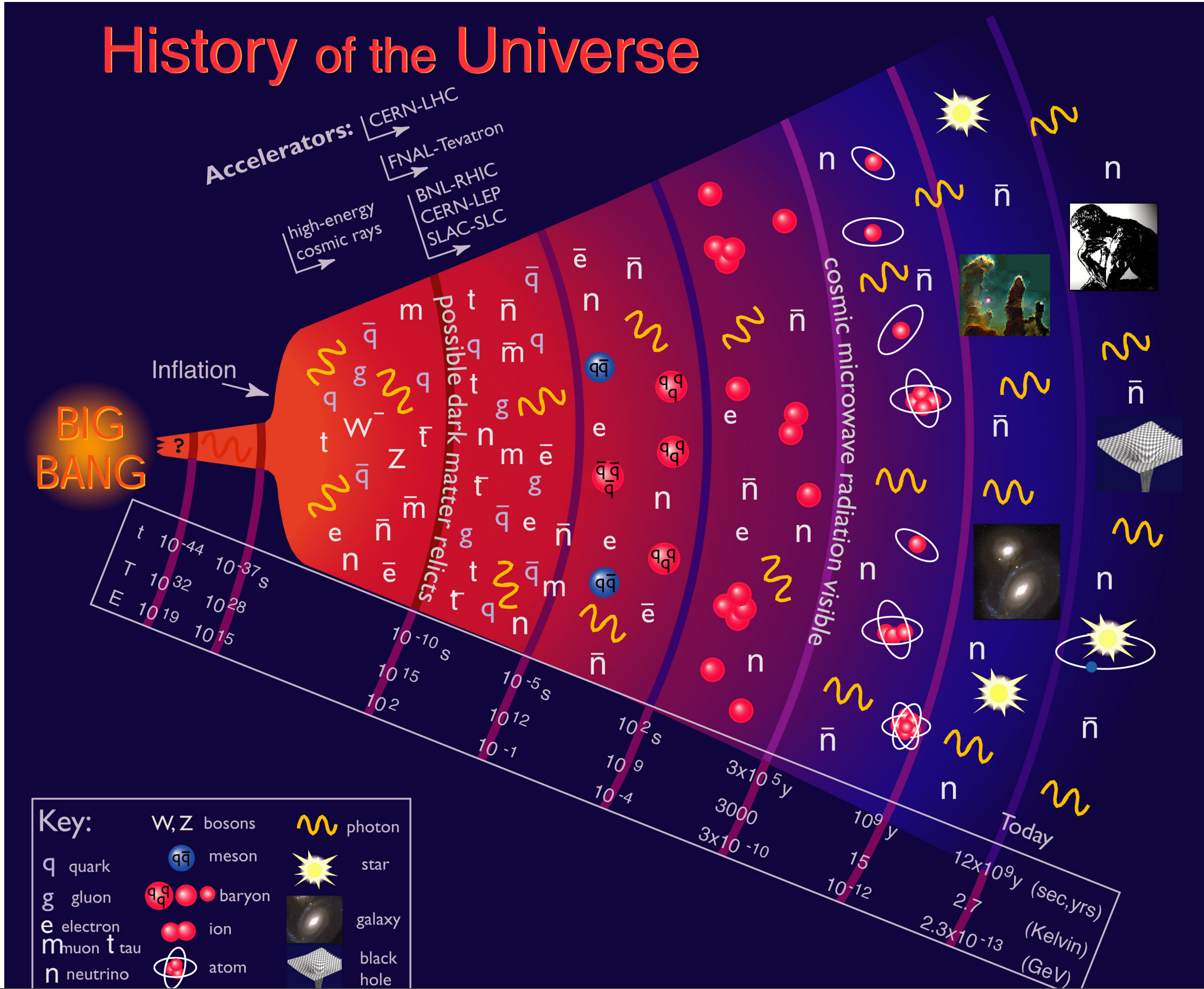

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

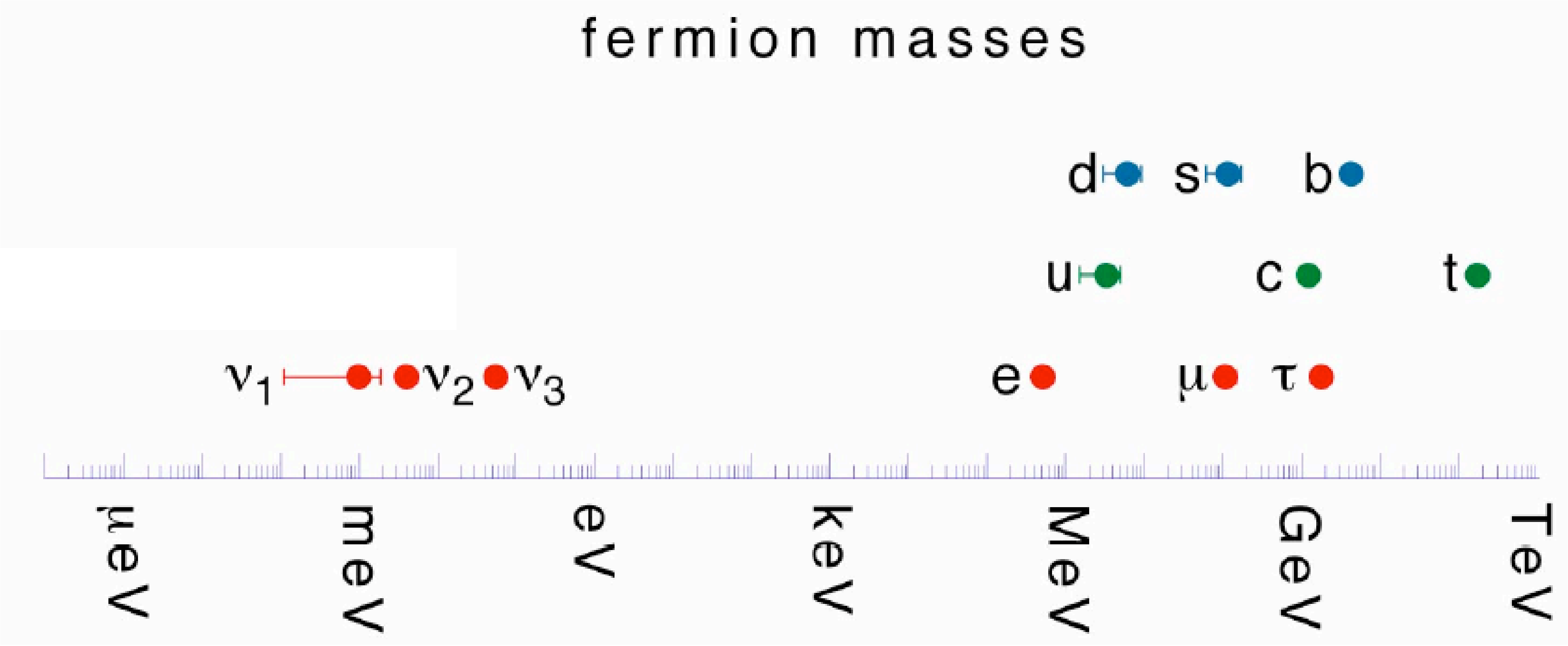
Some reading

- BIG BANG by Simon Singh
- GREAT DESIGN by Robert Adair
- GOD PARTICLE by Leon Lederman

Neutrino properties

- Nearly massless. (New evidence that they have tiny masses)
- No electric charge. Interactions are Weak.
- Paired with charged particles called Leptons (electron, muon, tau).
- When they interact they either convert to the lepton they are engaged to or they stay the same.
- They spin only counter-clockwise as they fly. (Anti-neutrinos spin clockwise as they fly)

Current picture of masses from oscillations puzzling.



hierarchy

Interaction rates

$$N_{evts} = F \times \sigma \times N_{targs} \times \epsilon$$

- Rate of events(events per sec) : N_{evts}
- Flux: $F/cm^2/sec$
- Cross section: $\sigma \quad cm^2$
- Number of targets: 1 ton of water has 6×10^{29} protons and neutrons.
- Efficiency for practical detectors: ϵ
- Flux, cross section, efficiency are functions of neutrinos energy ($1eV : 1.6 \times 10^{-19} J$)

Examples of sources

- Energy and Flux of neutrinos from various sources.
  - The SUN ! below 0.5 MeV $10^{11} cm^{-2} s^{-1}$
    at $\sim$ 3-14 MeV $3 \times 10^6 cm^{-2} s^{-1}$
  - Cosmic rays hitting the atmosphere
    at 1 GeV $\sim 5000 m^{-2} s^{-1}$
  - From radioactive decays in the Earth
    $10^6 - 10^7 cm^{-2} s^{-1} < 3$ MeV from U/Th decays.
  - SuperNova neutrinos. 11 were seen in 1987 in two large detectors.
  - Microwave background neutrinos. Very cold 2.7^o ! $300 cm^{-3}$
    Multiply by velocity to get flux.
  - Nuclear reactors. $10^{13} - 10^{15} cm^{-2} s^{-1}$ $\leq$5 MeV. Falls as $1/r^2$ with distance from reactor.
  - Accelerators. $5 \times 10^{-5}/m^2$ per proton (E$\sim$ 1 GeV) at 1 km.

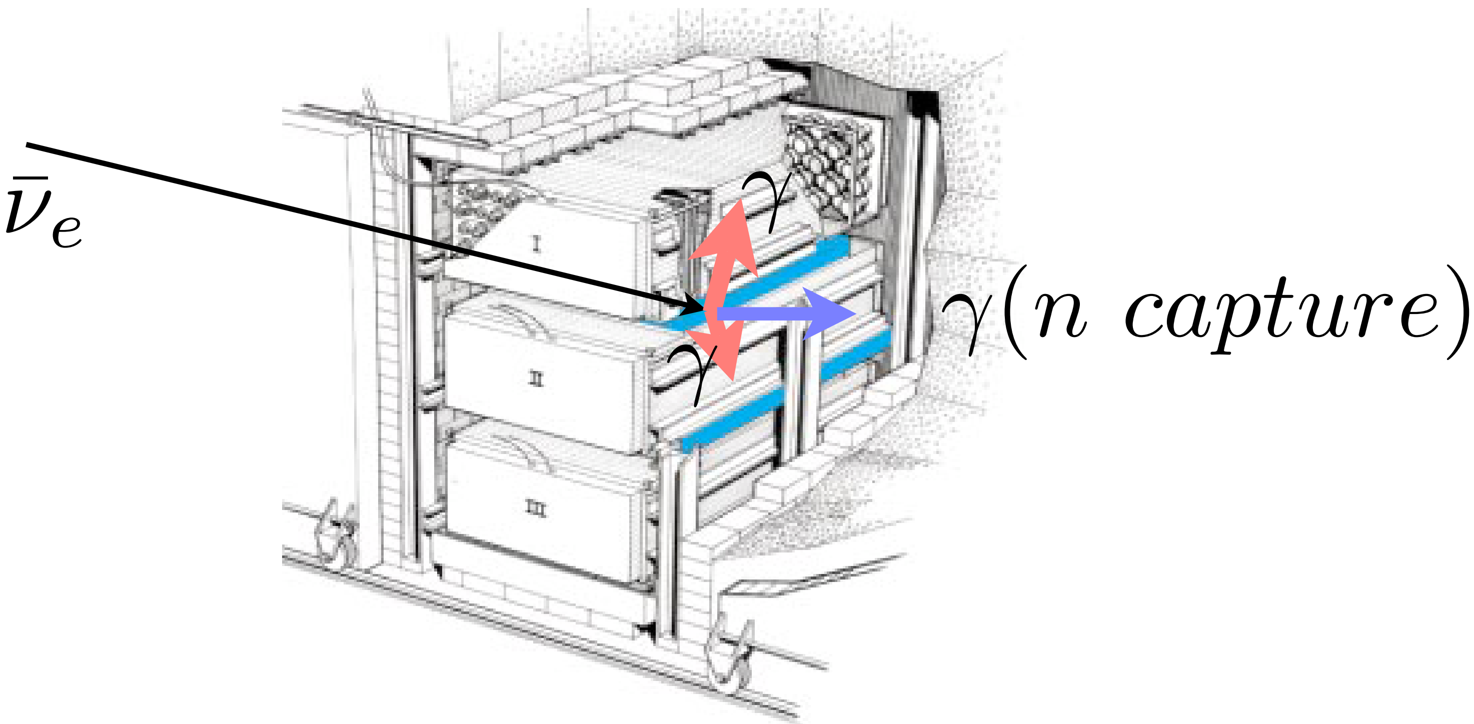
Cross sections

- Cross section of neutrinos on various targets are small. Detectors must be very large to see enough events.
  - at $\sim 1 MeV$ on protons, neutrons, deuteron
    $\sim 10^{-44} cm^2$
  - at $\sim 10 MeV$ on Clorine, Carbon, etc.
    $\sim 10^{-42} - 10^{-41} cm^2$
  - high energies (1 GeV) on protons and neutrons
    $\sim 10^{-38} \times (E_\nu / GeV) cm^2$
  - high energies (GeV) on electrons
    $\sim 10^{-41} \times (E_\nu / GeV) cm^2$

Reines and Cowan experiment

Pauli bet a case of champagne that nobody would ever detect a neutrino. In 1956, Clyde Cowan and Fred Reines detected antineutrinos emitted from a nuclear reactor at Savannah River in South Carolina, USA. Pauli kept his promise.

"Detection of the Free Neutrino: A Confirmation", C.L. Cowan, Jr., F. Reines, F.B. Harrison, H.W. Kruse and A.D. McGuire, Science 124, 103 (1956).



Reines and Cowan experiment. Result

$\bar{\nu}_e + p \to n + e^+$, wait few μs, $n +\ {}^{108}Cd \to\ {}^{109}Cd + \gamma$

Detect e^+ and γ in sequence to reduce background.

There was 200 kg of water. 1.3×10^{28} free protons.

Detector was placed 11 m from the reactor and 12 m deep.

Observed ~ 3 events per hour.

Confirmed by turning the reactor off.

$$10^{13} cm^{-2} s^{-1} \times 3600 s \times 6 \times 10^{-44} cm^2 \times 1.3 \times 10^{28} protons \times \sim 0.1$$

Nobel prize for Reines in 1995.

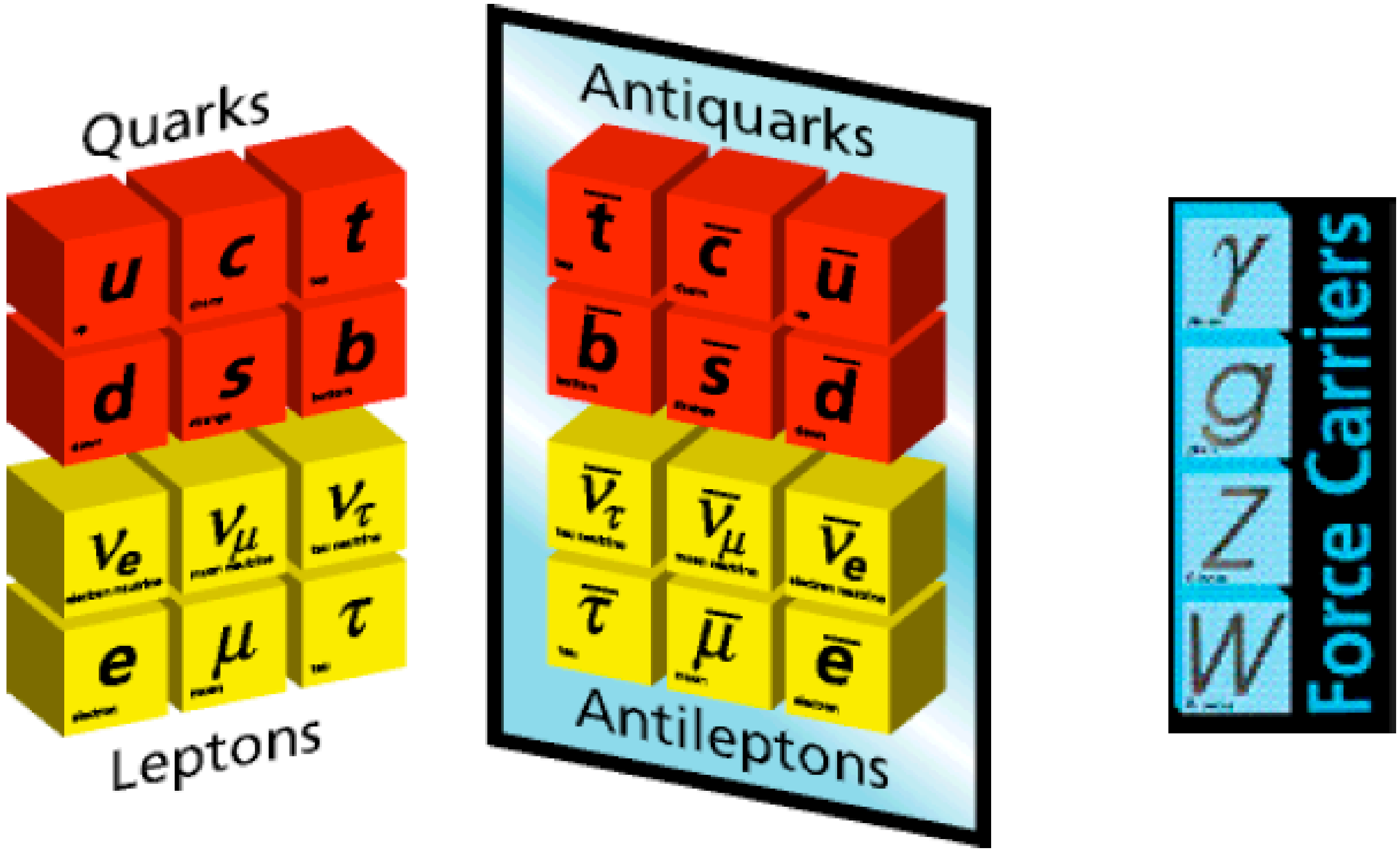
Homework ?

- Calculate the size of detector needed to see 100 events from the Sun, cosmic rays, reactors, accelerators, etc.

Neutrino puzzles

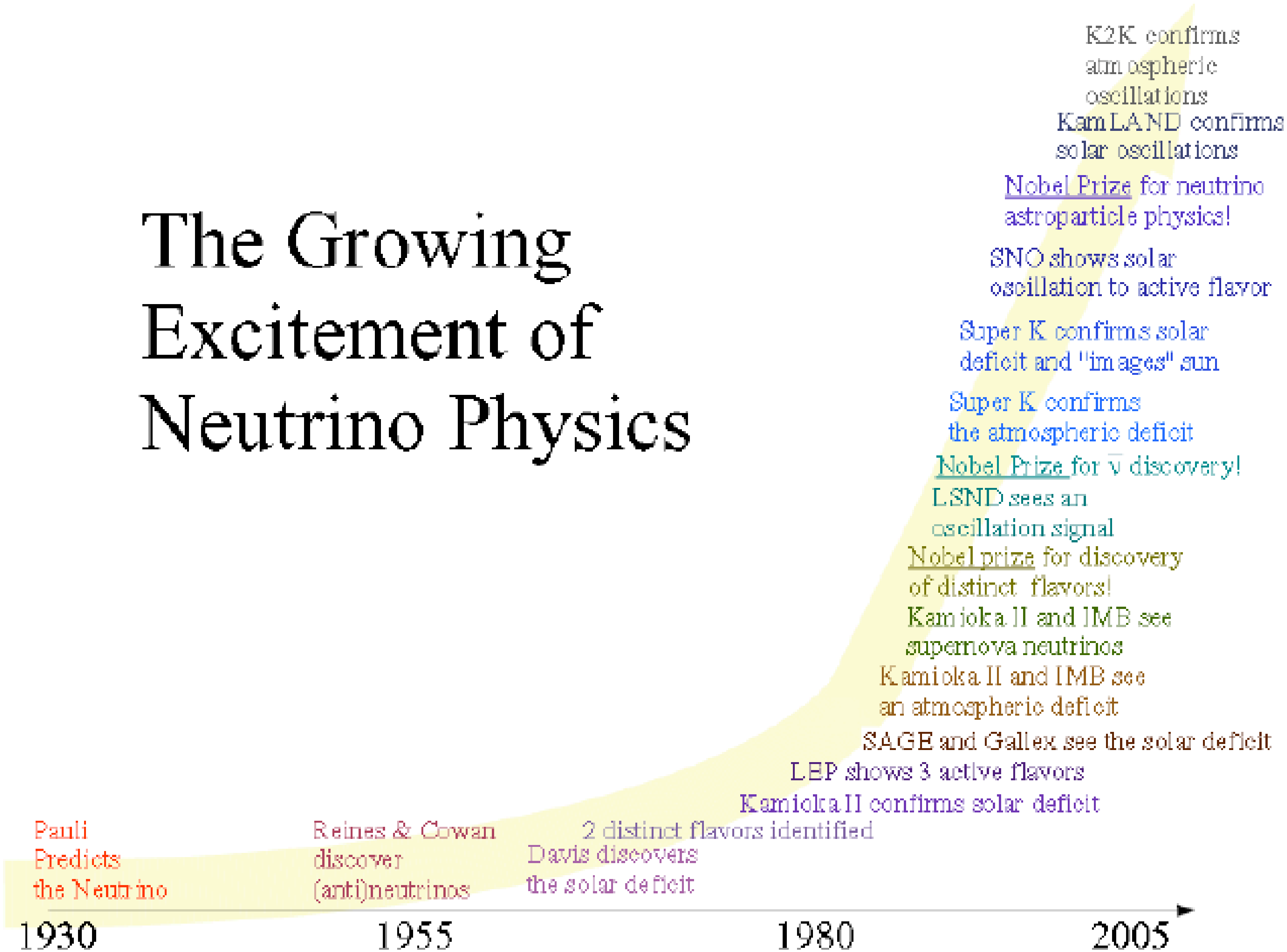
- Do they have mass ? Why so small ?
- If they have mass what implications on left-right properties ?
- Can they turn into each other ?
- What implications for the structure of the universe ?
- What is the relationship to quarks ?

The Standard Model



This picture needs revision

The Growing Excitement of Neutrino Physics



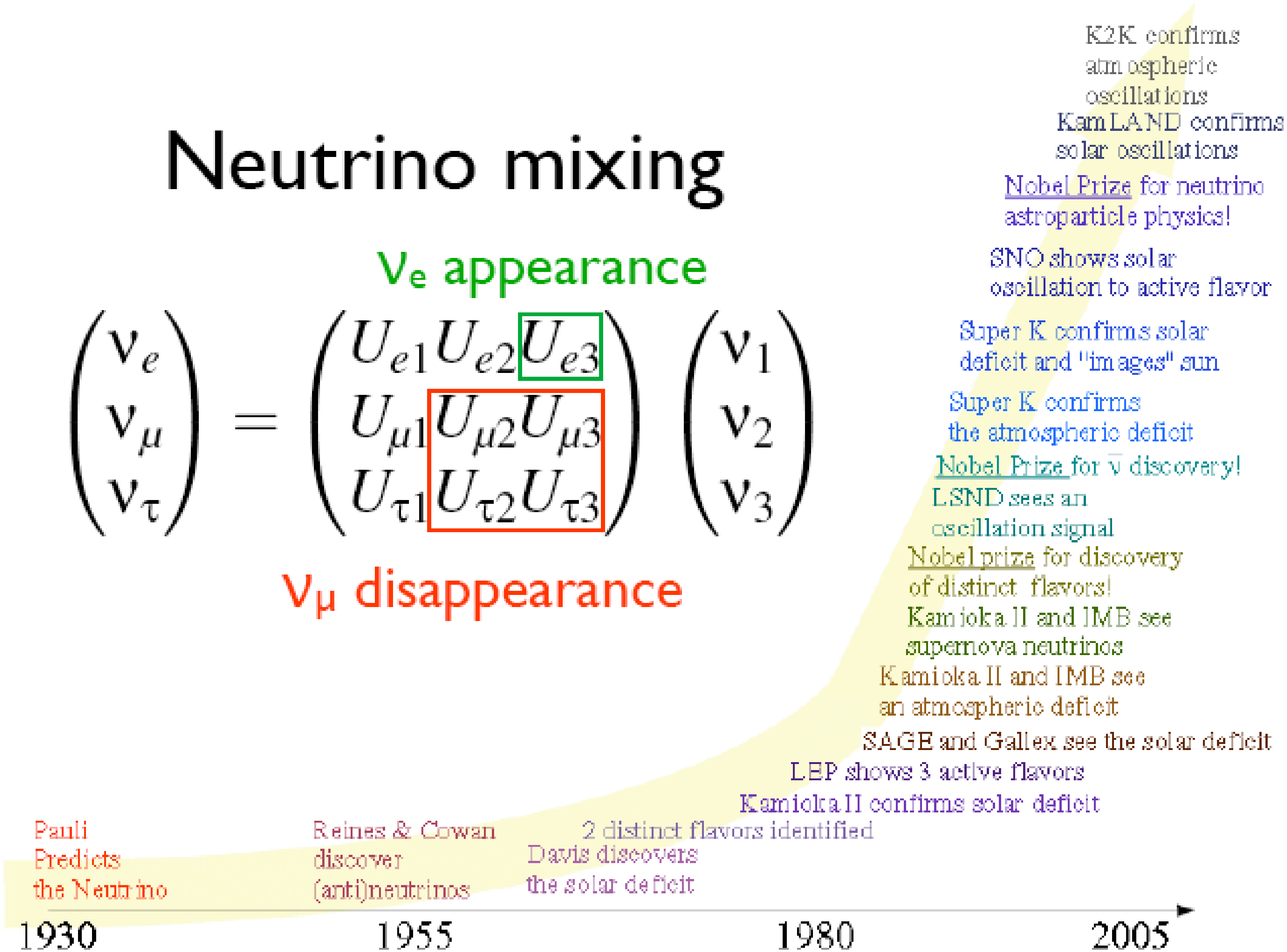
From APS neutrino study

Neutrino mixing

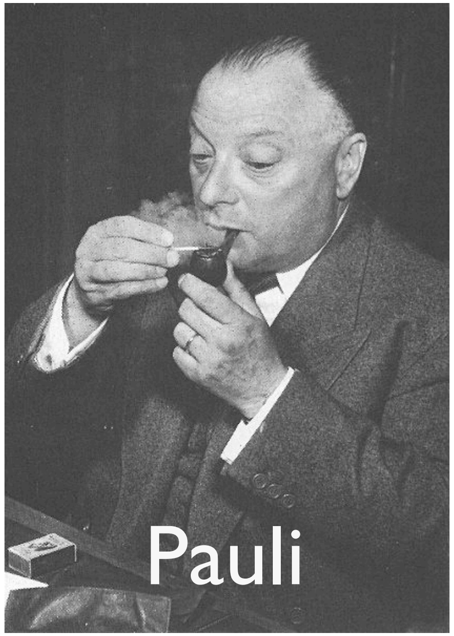
ν_e appearance

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

ν_μ disappearance



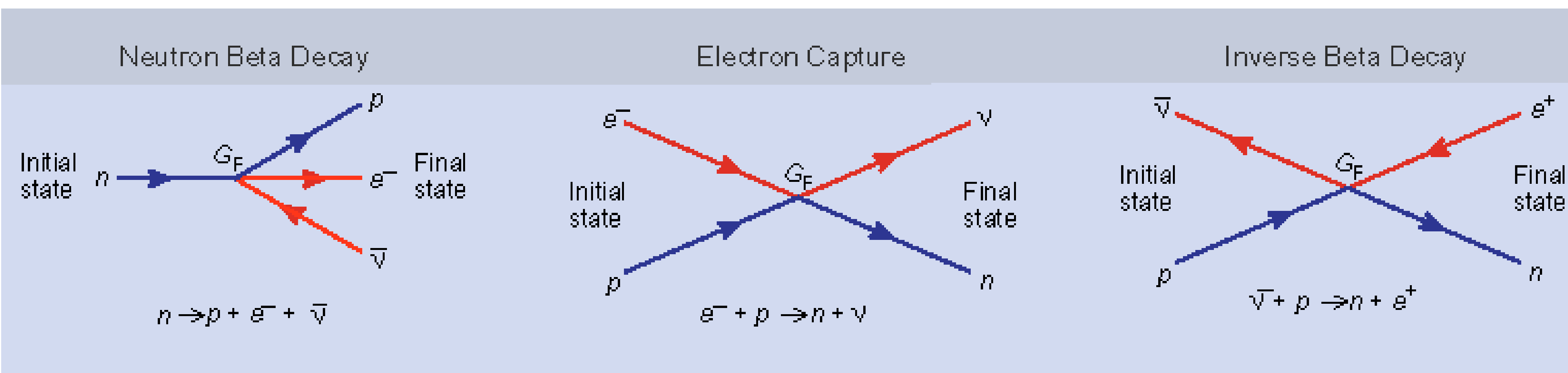
From APS neutrino study



Inventor

Developer

Oscillator



Brief review of oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

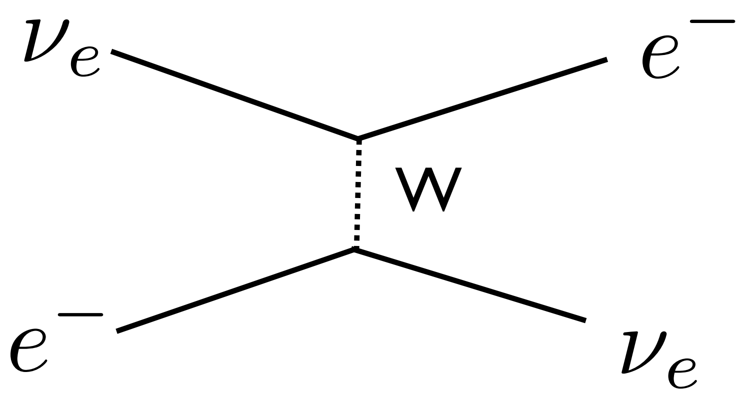
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

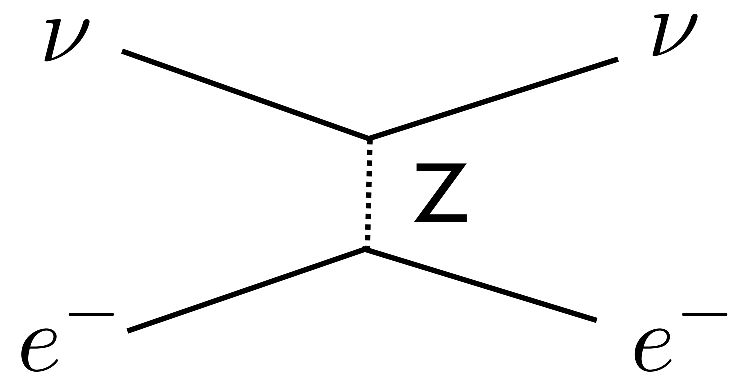
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

$$i\frac{d}{dx}\nu_f = HR_\theta \nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e ($\bar{\nu}_e$): $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

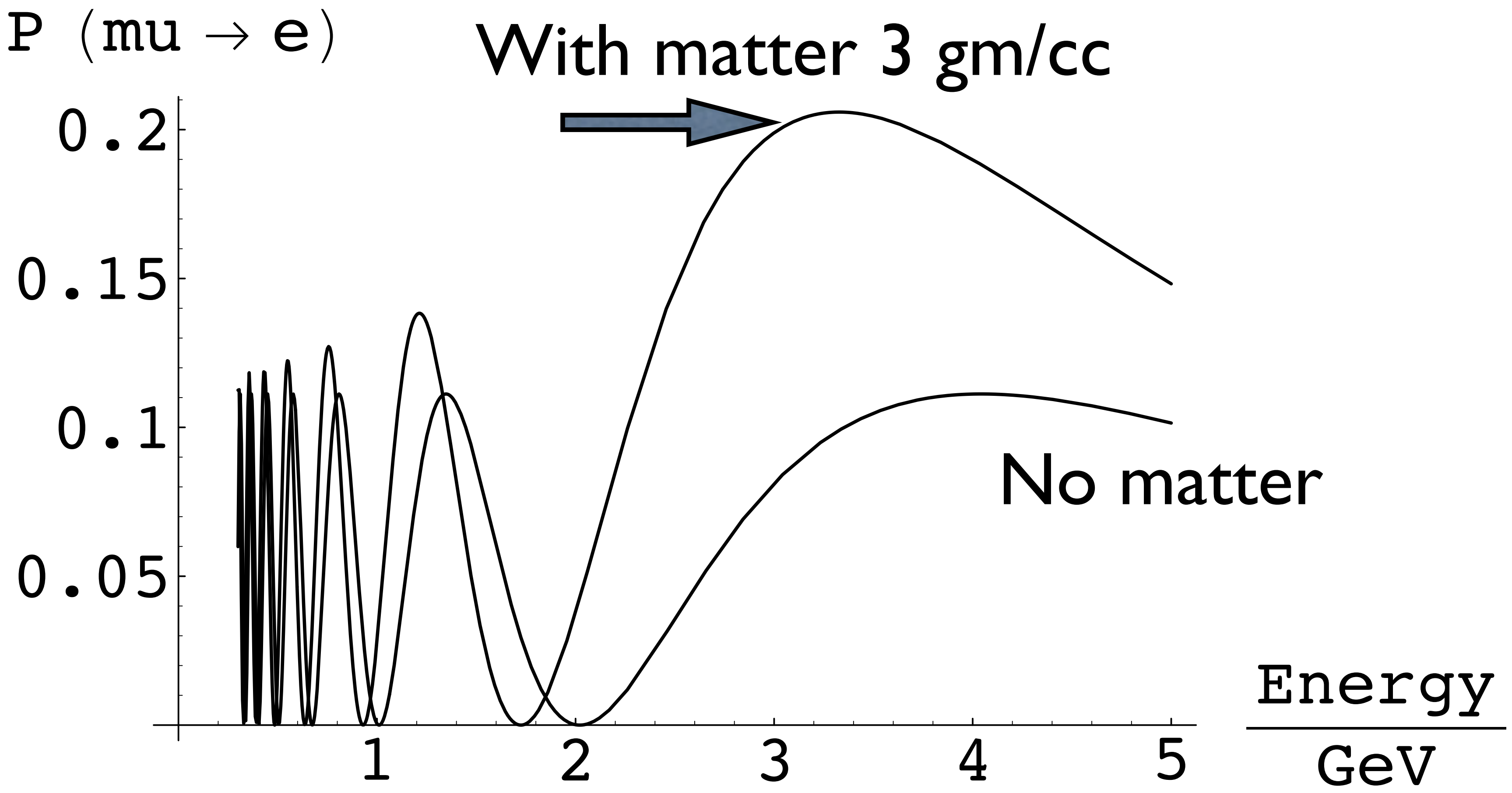
$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix}m_2^2-m_1^2 & 0\\ 0 & m_1^2-m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & -\sqrt{2}G_F N_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \tag{3}$$

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2+\sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \tag{4}$$

Important only if electron neutrinos in the mix

2-neutrino picture

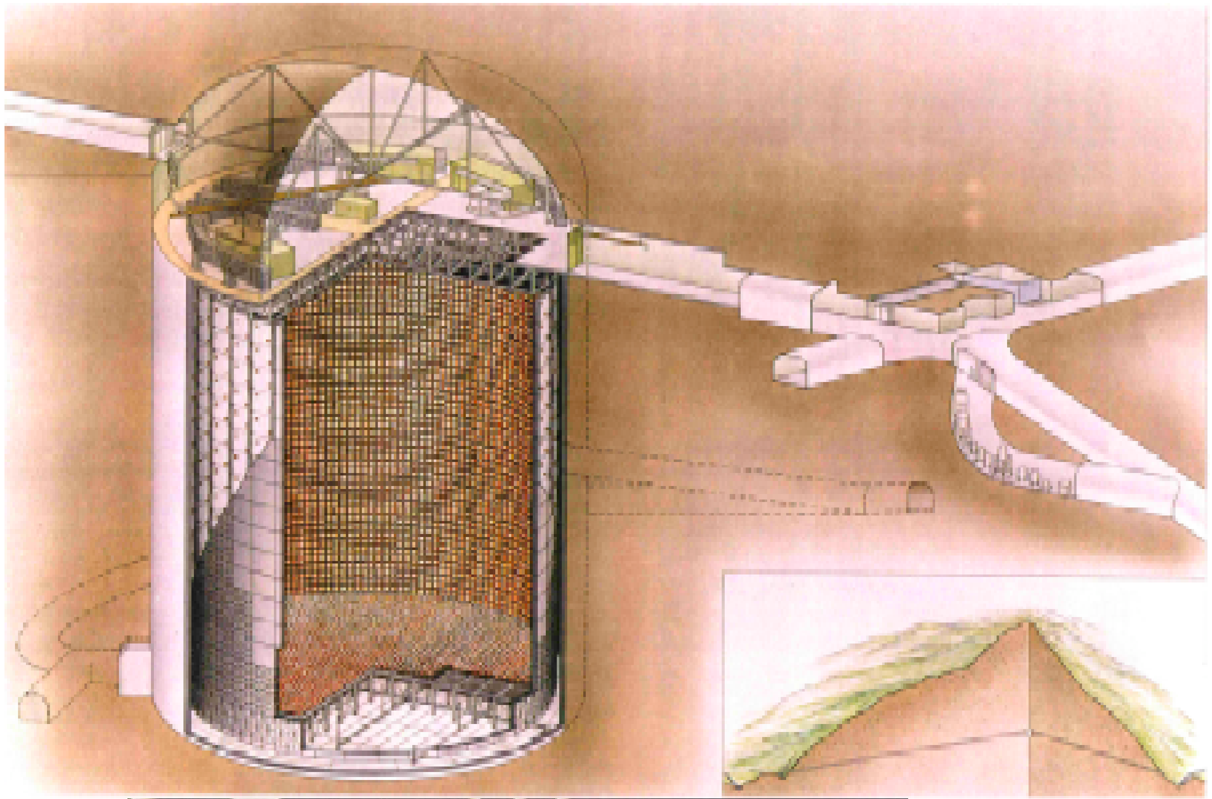


Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

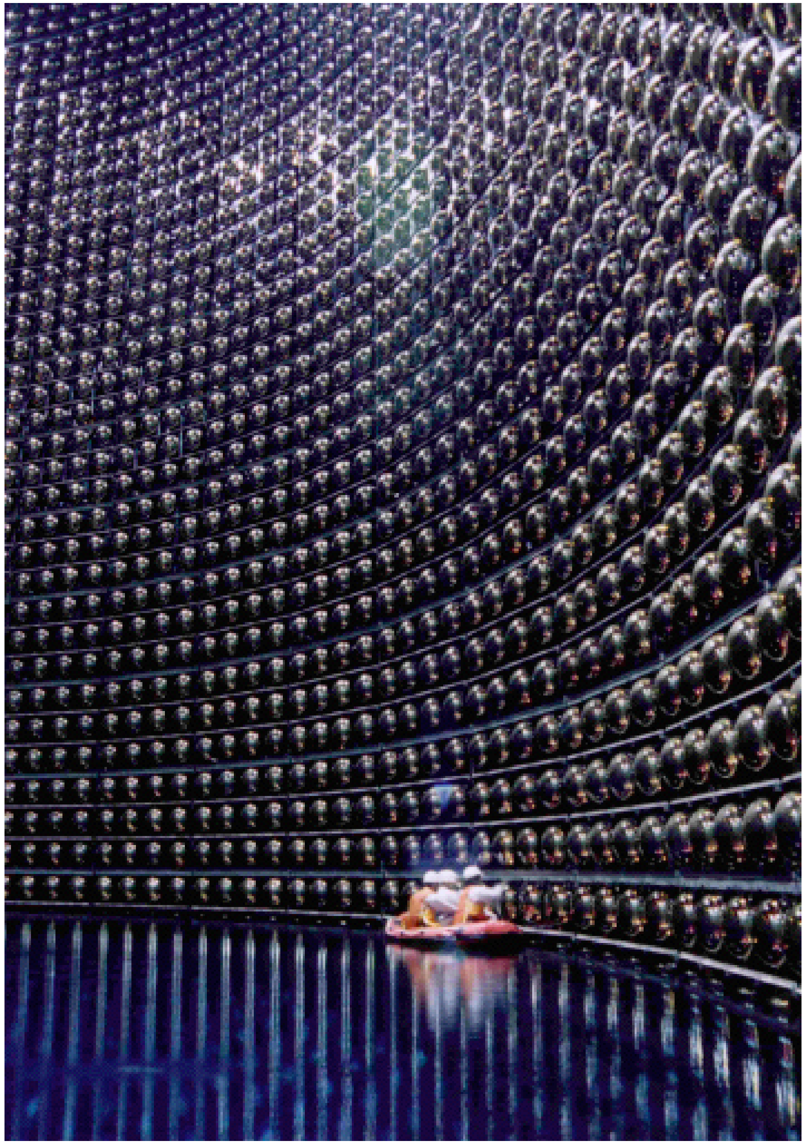
Key new evidence

- Super KamiokaNDE (SK): observe atmospheric neutrinos.
- Sudbury Neutrino Observatory (SNO): observed solar neutrinos.
- KAMLAND reactor experiment
- MINOS neutrino accelerator beam experiment

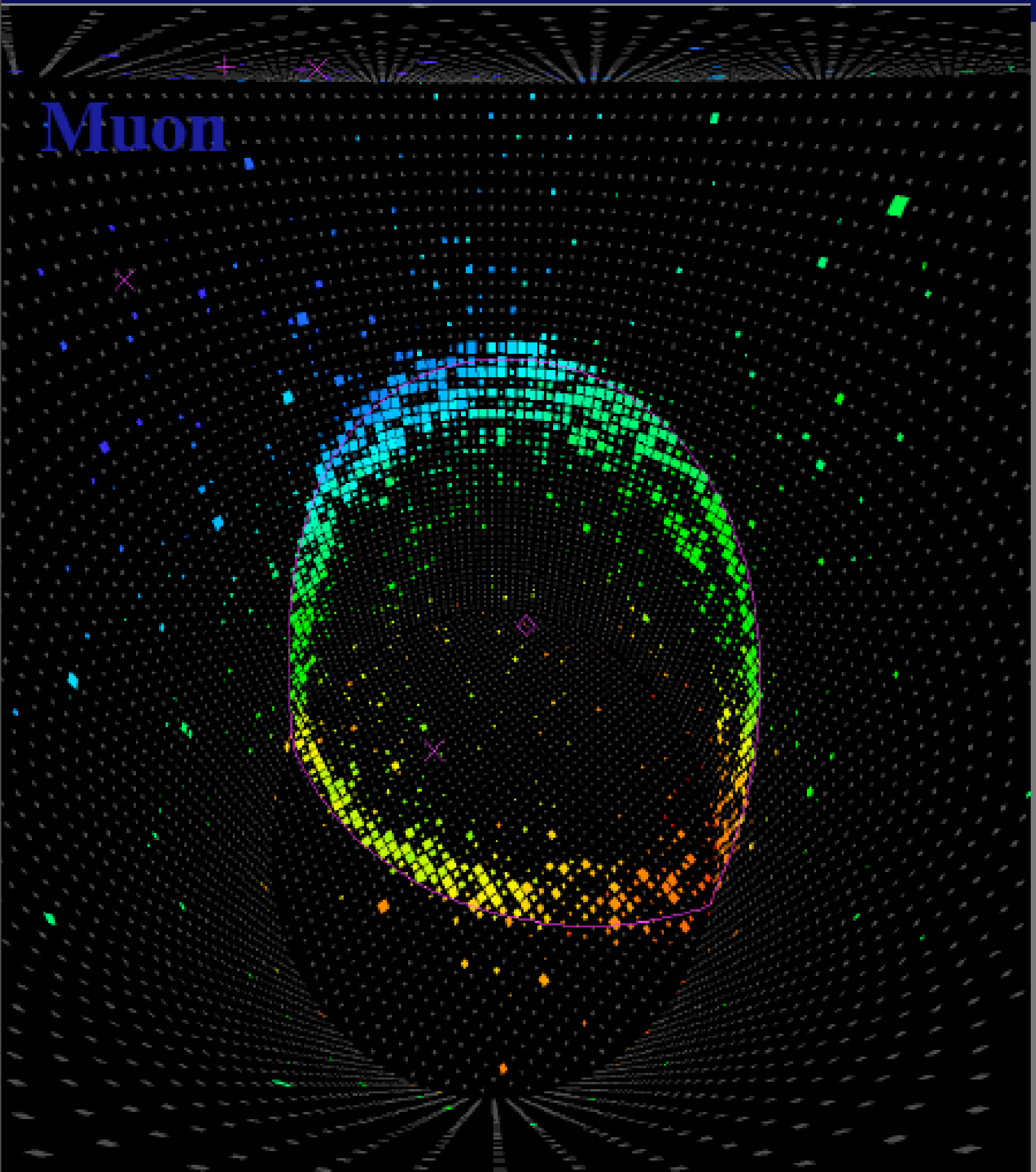
Apologies to many other pioneering experiments

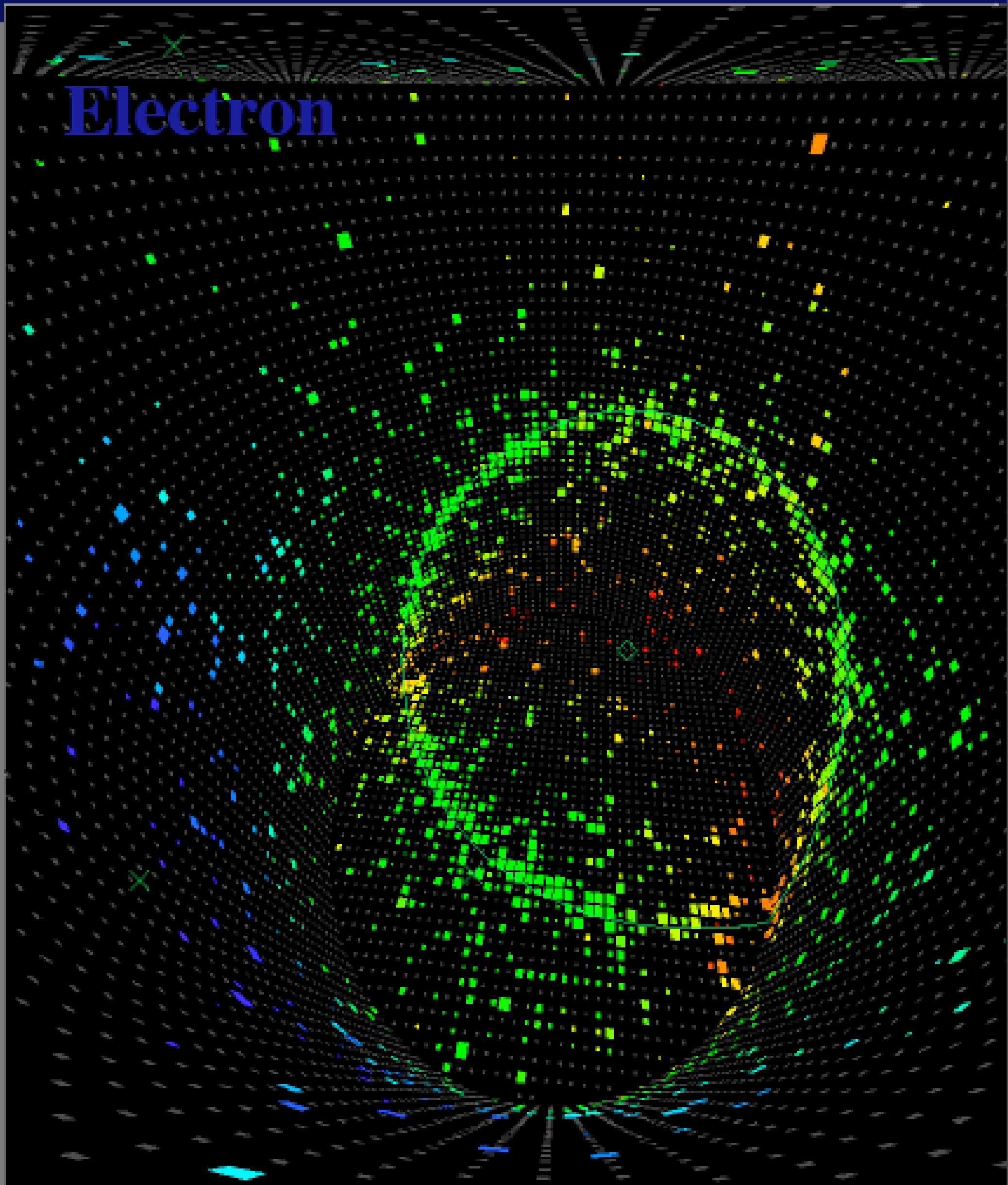


SuperKamiokaNDE



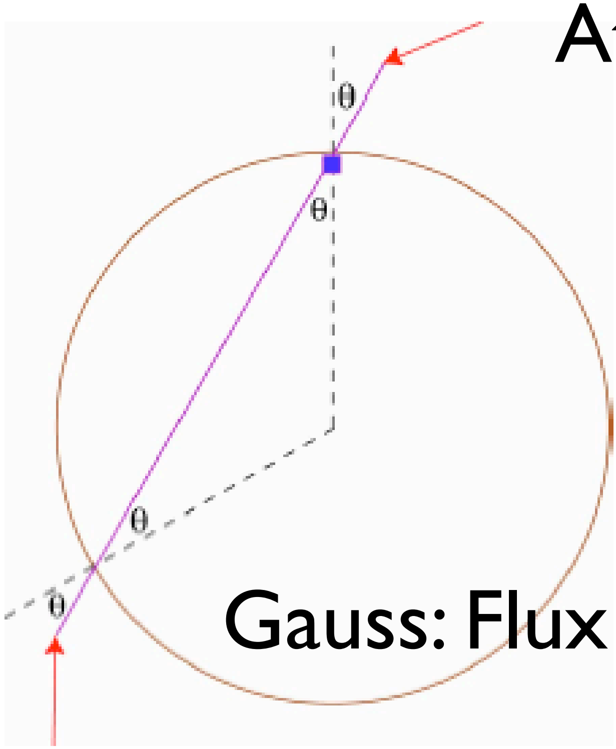
Particle Identification

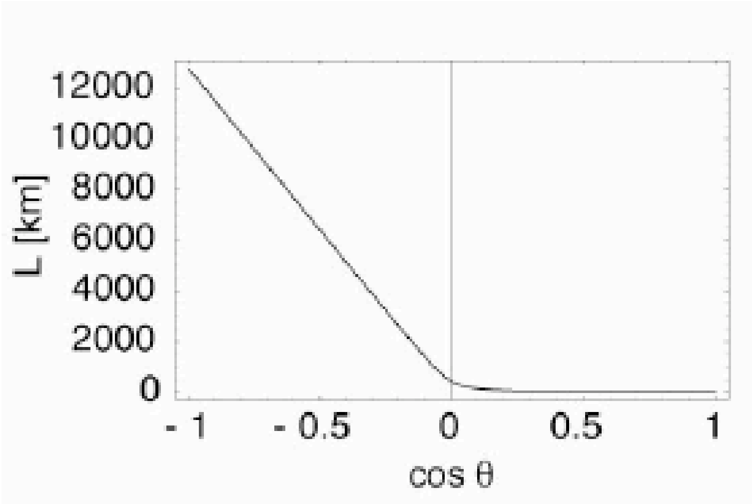


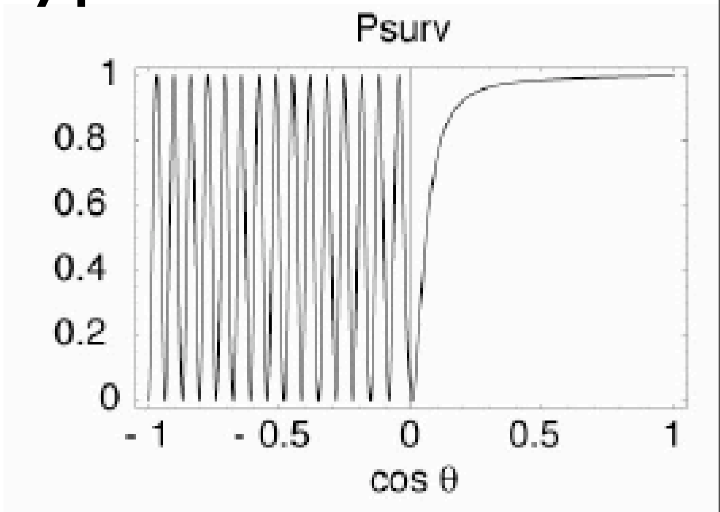


Atmospheric neutrinos as a source for oscillation experiments

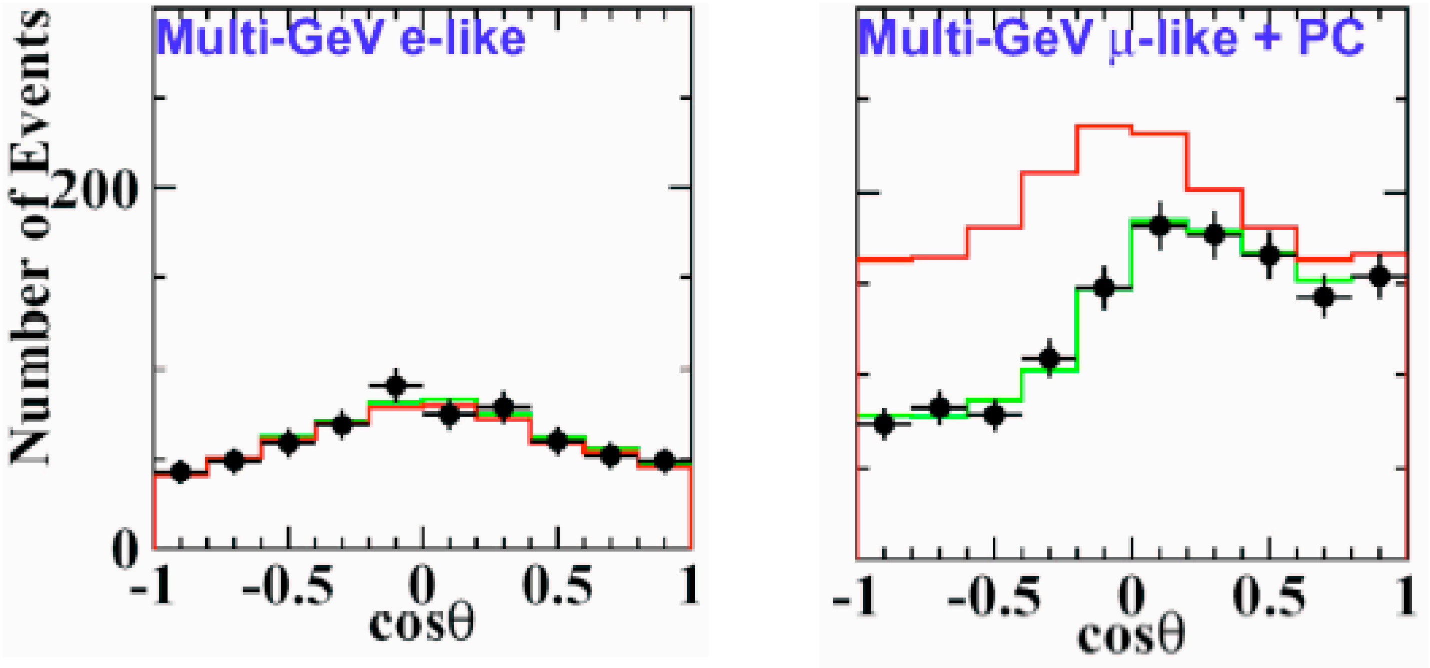
Atm. neutrinos 2:1 mu:e type





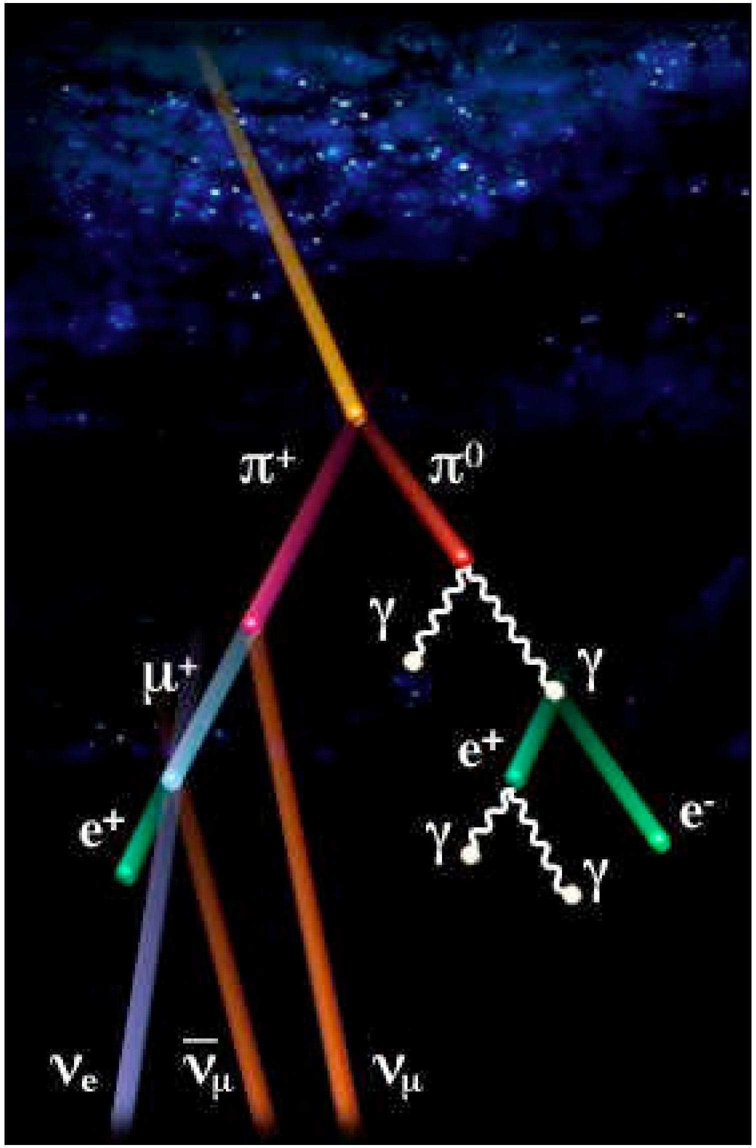


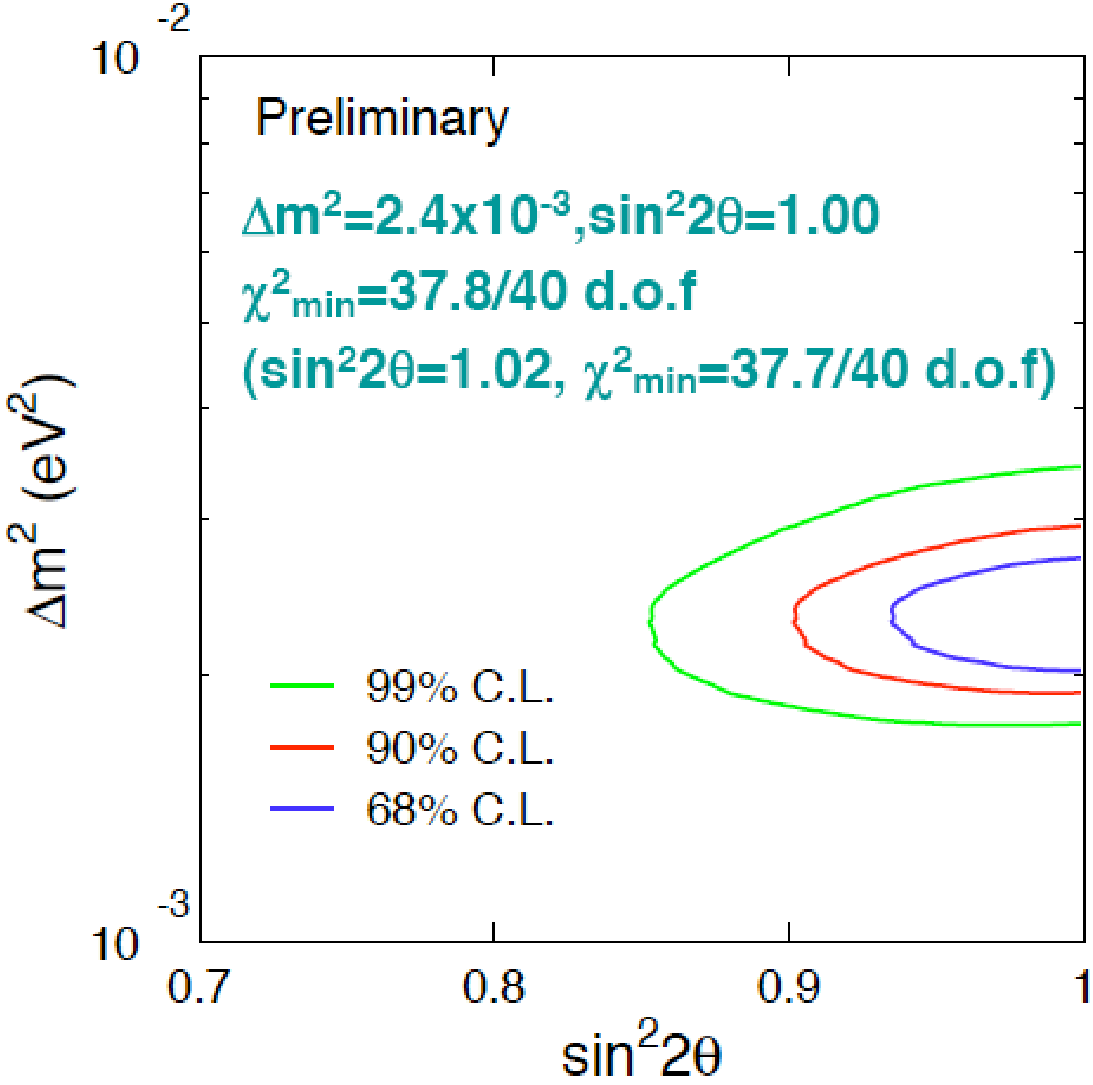
Gauss: Flux inside spherical shell isotropic



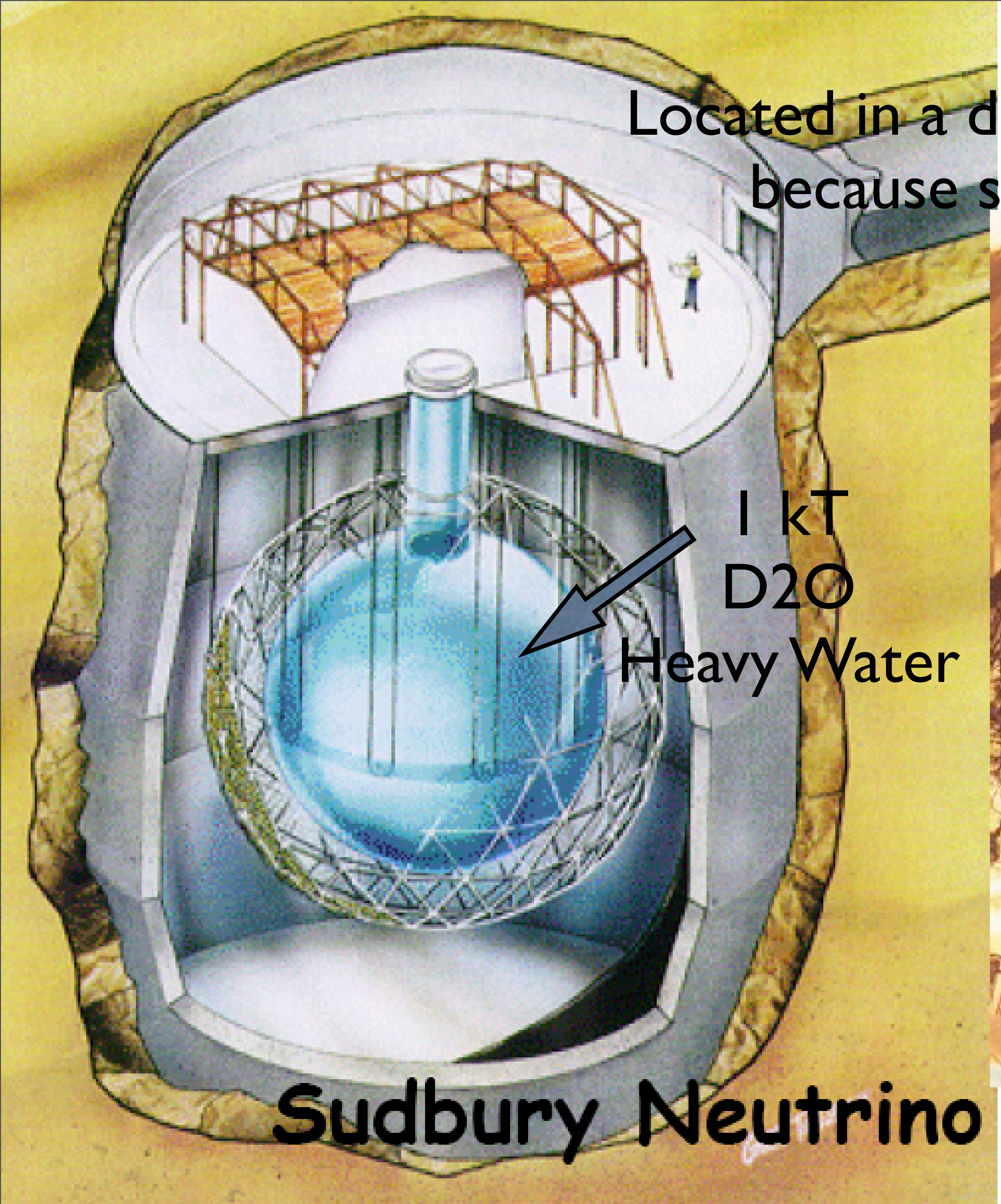
Evidence for neutrino oscillations from SuperK

SuperK result

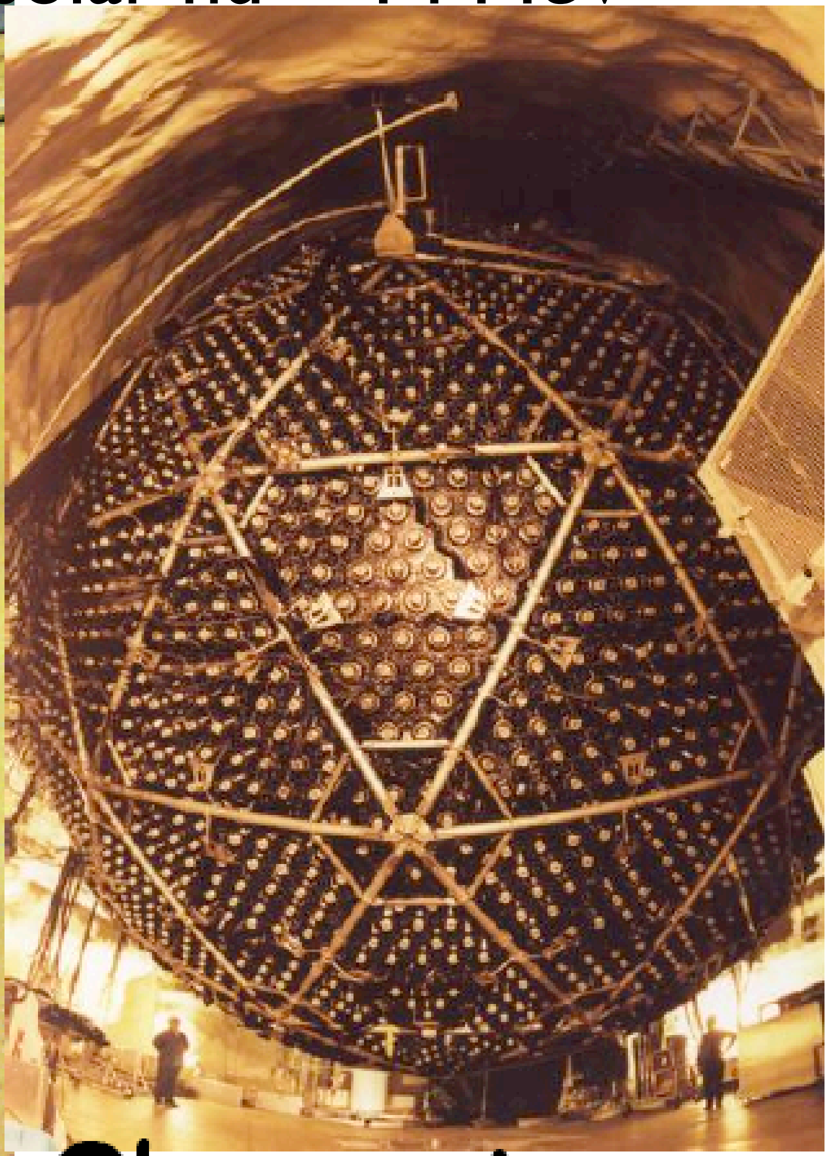




Located in a deep mine ~ 6000 mwe
because solar nu < 14 MeV

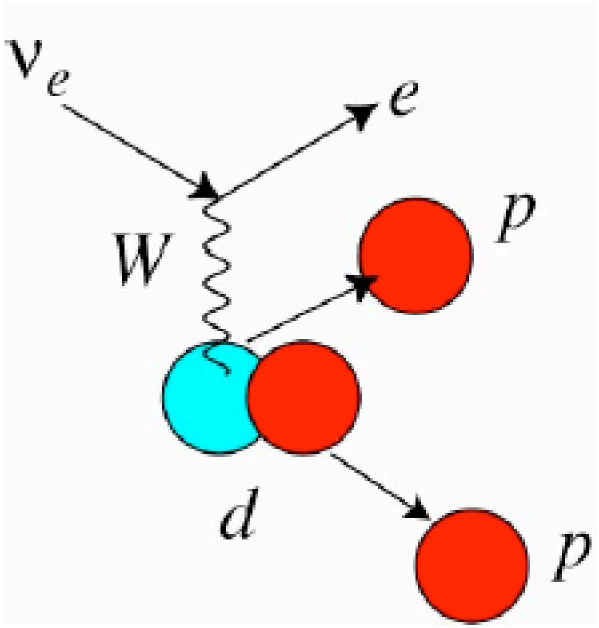


1 kT
D_2O
Heavy Water

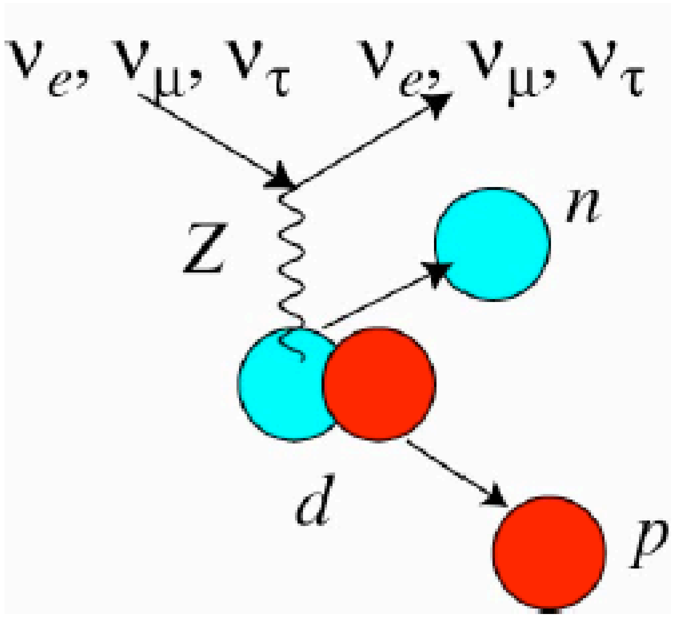


Sudbury Neutrino Observatory

Why does SNO use $300M worth of heavy water?



Charged Current

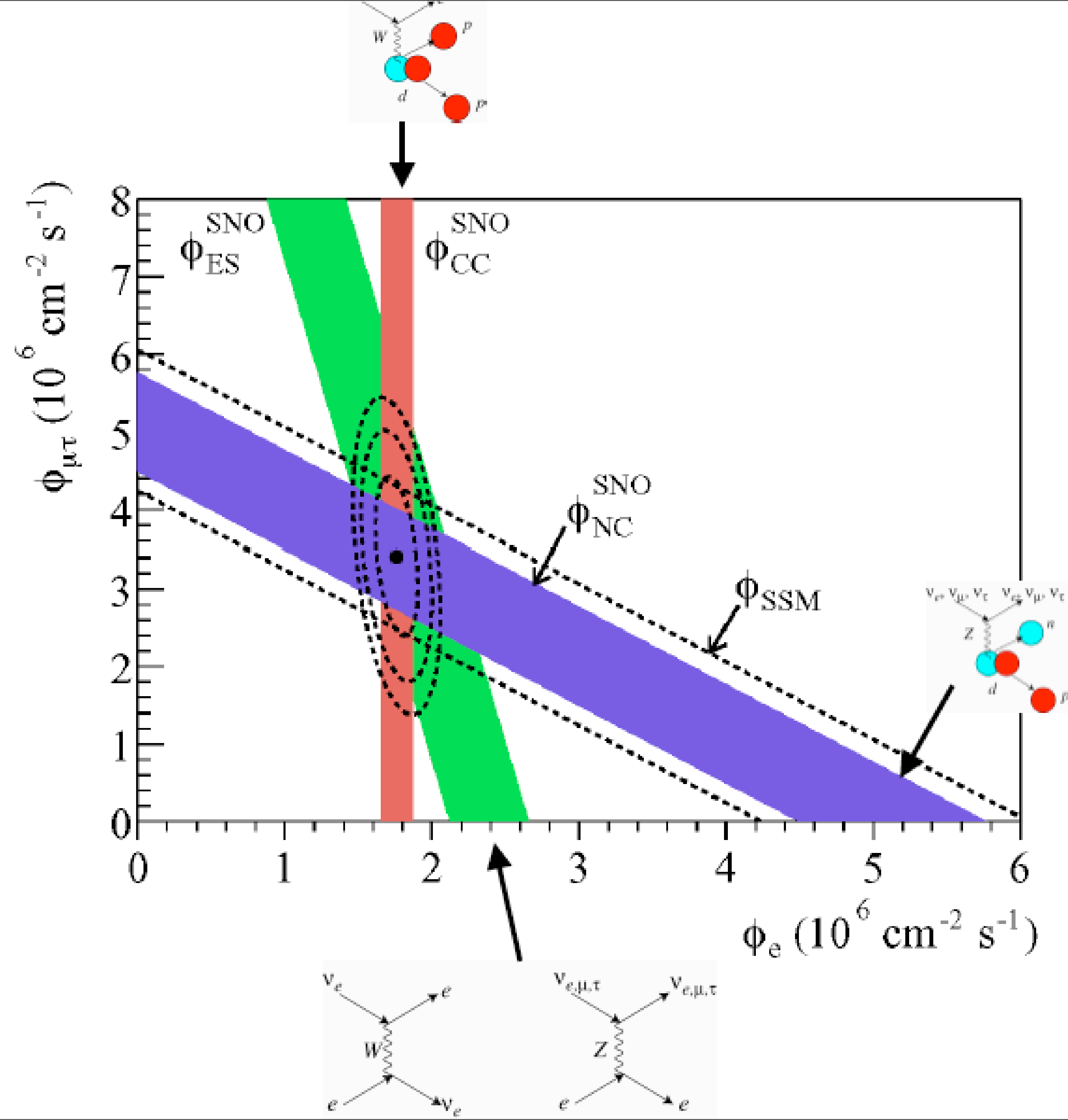


Neutral Current

Fluxes

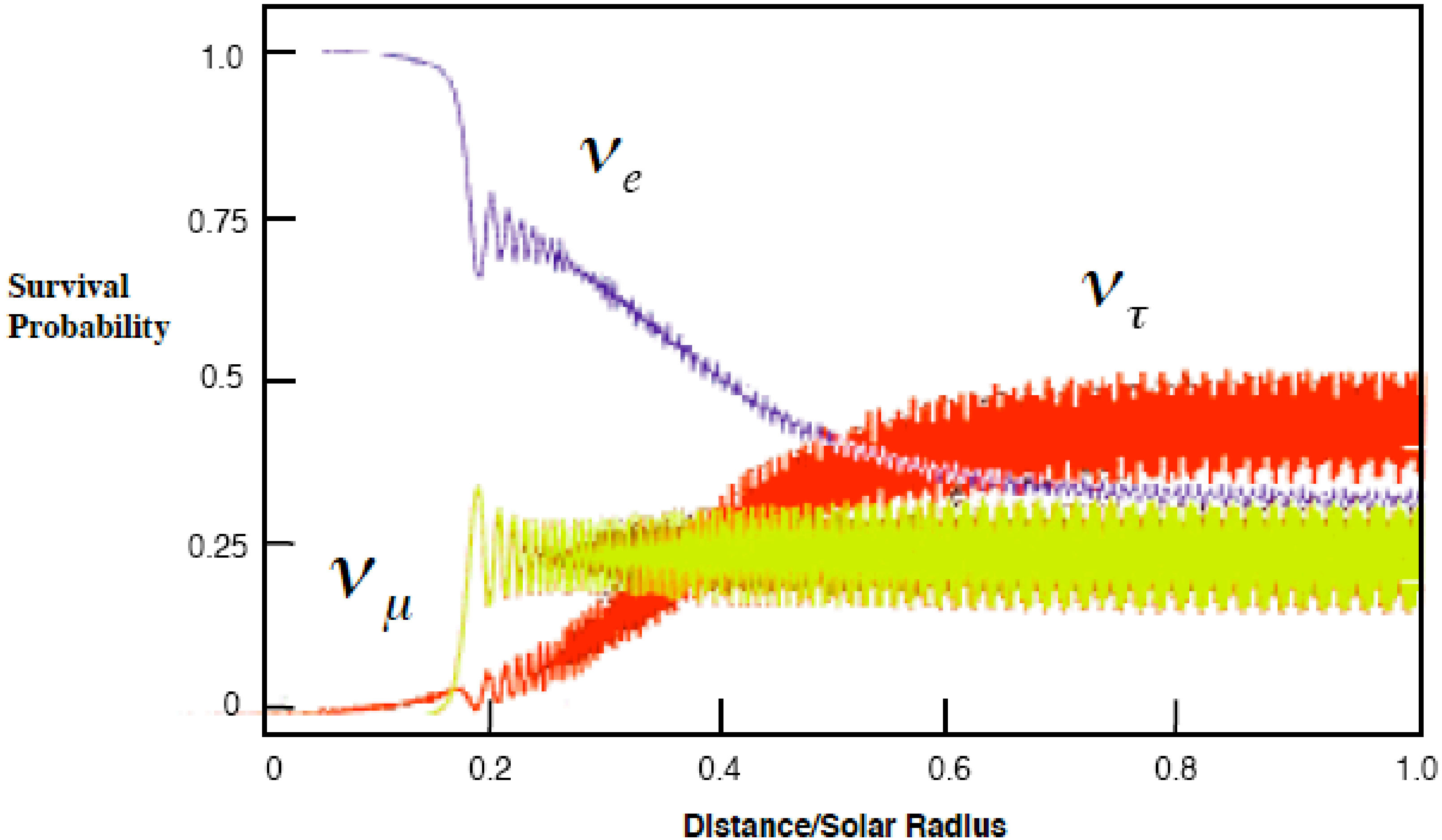
(10^6 cm^{-2} s^{-1})

ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05

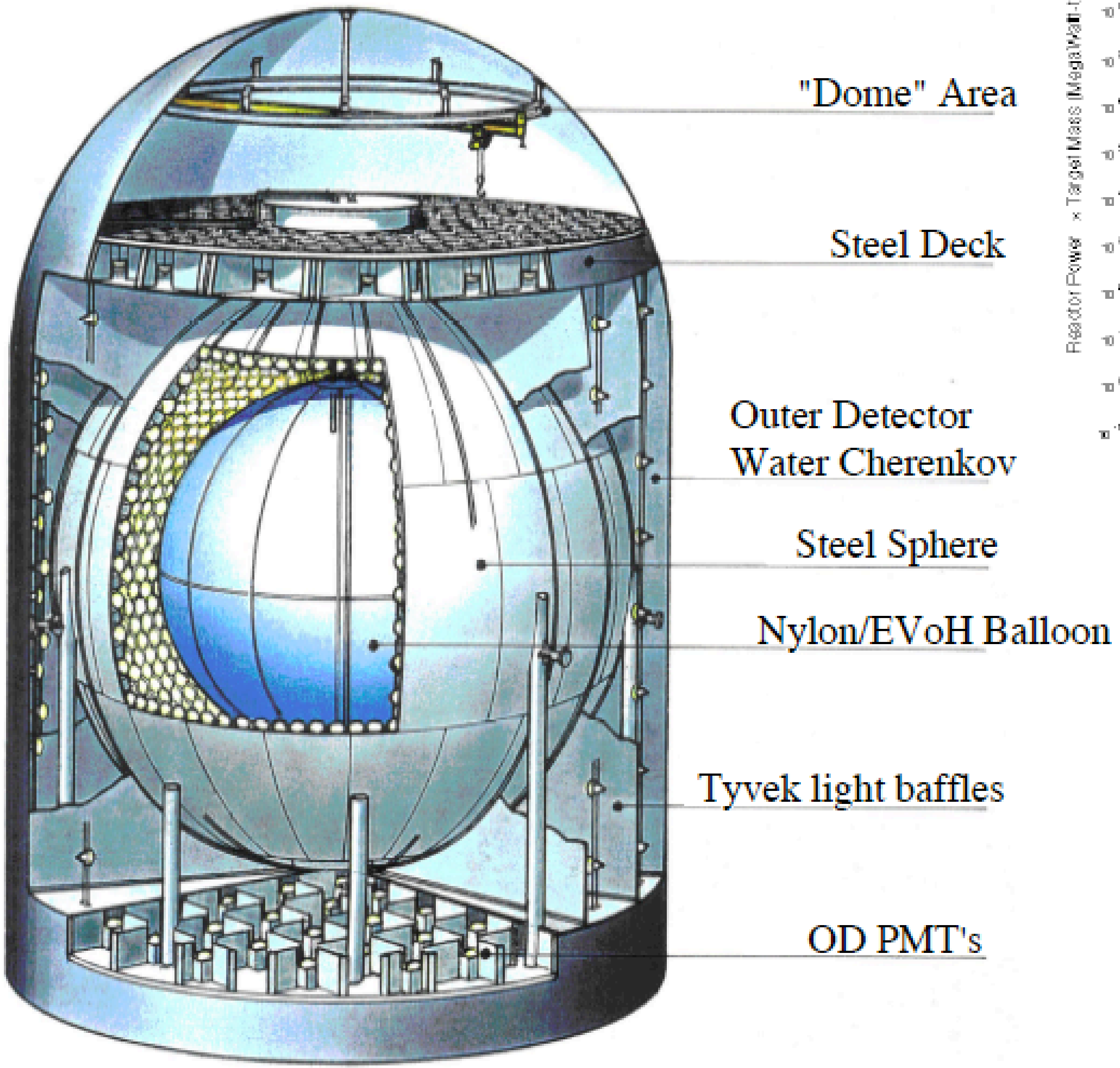


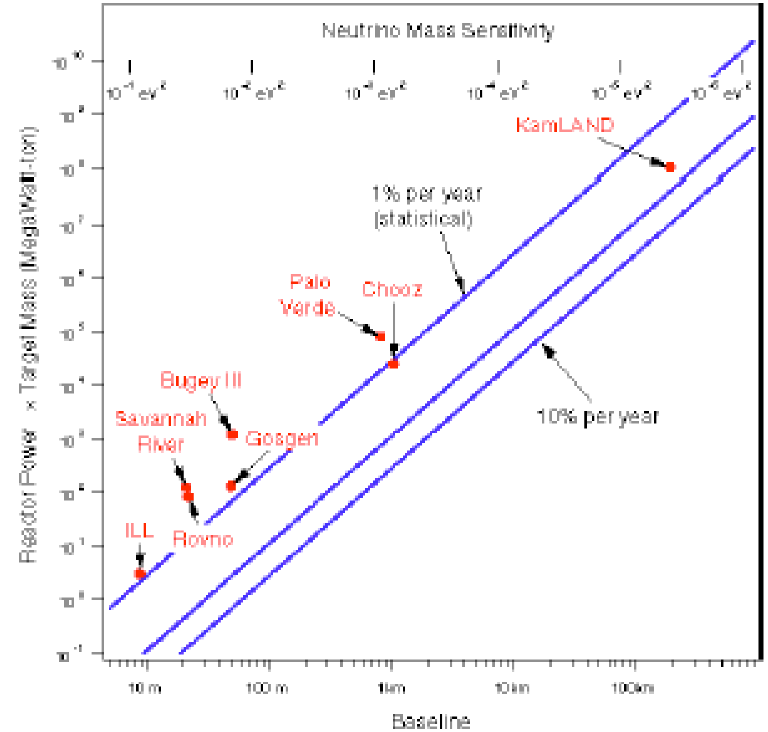
MSW Effect

ν_e NC and CC ν_τ ν_μ NC only

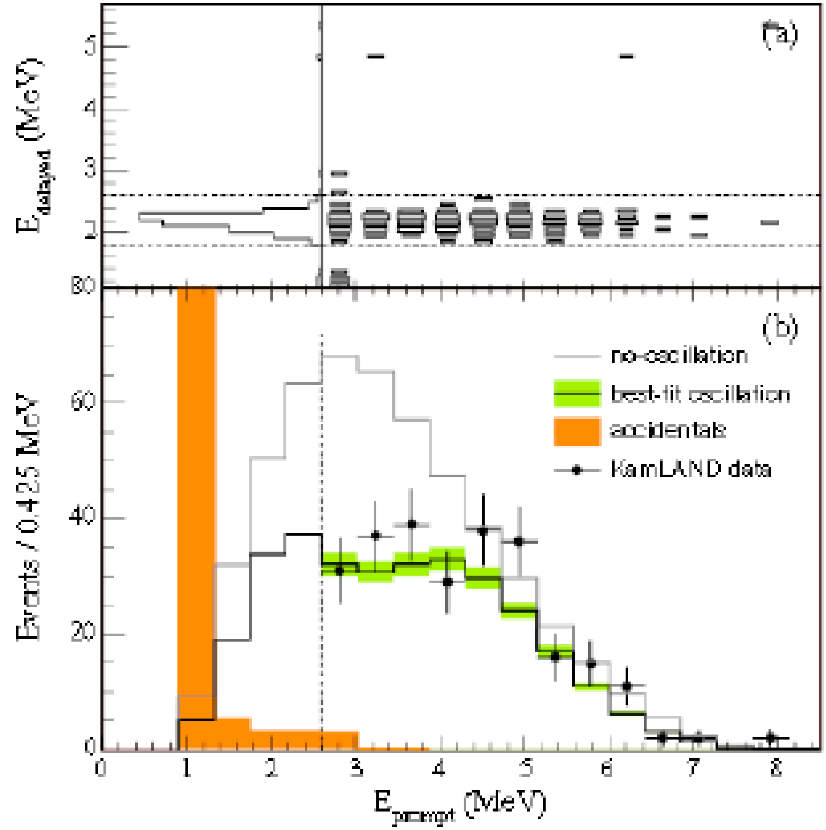


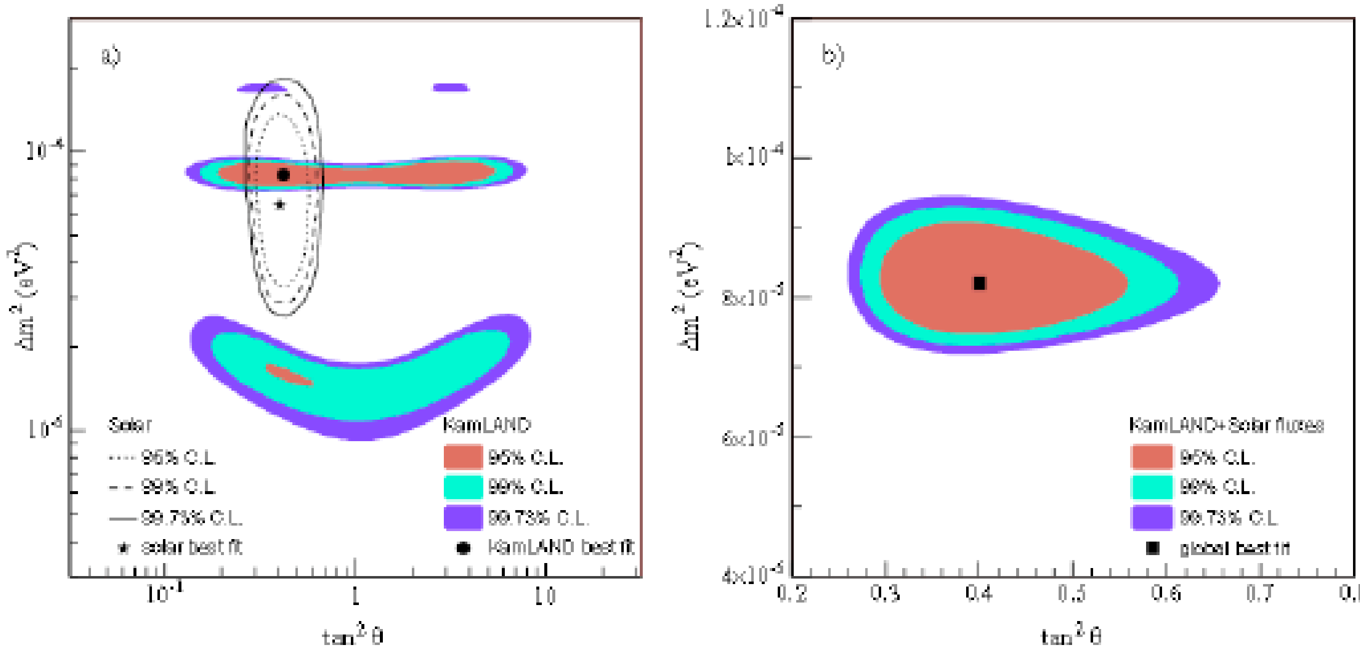
KamLAND



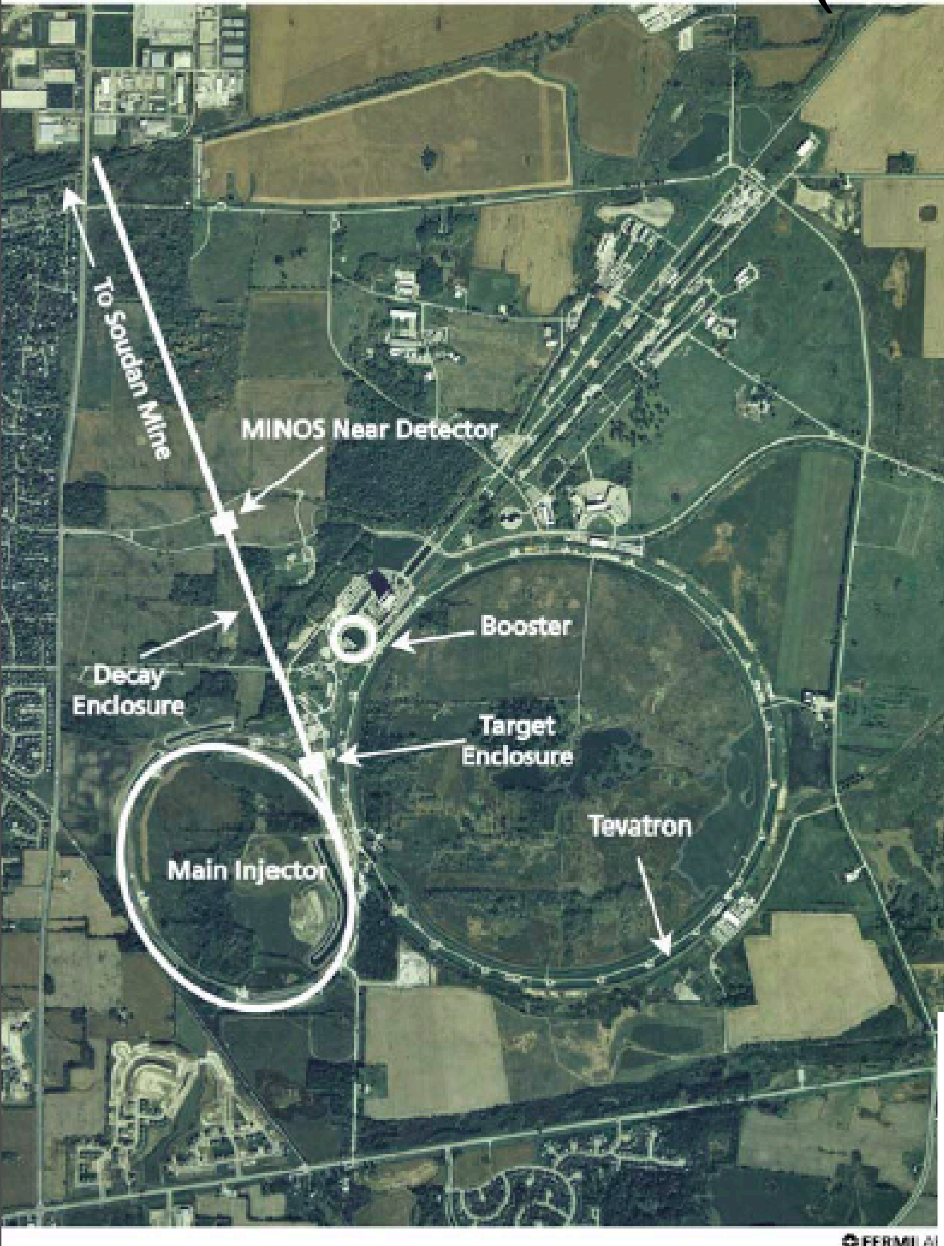


much bigger version of Reines and Cowan


(a)
E_delayed (MeV)
(b)
no-oscillation
best-fit oscillation
accidentals
KamLAND data
Events / 0.425 MeV
E_prompt (MeV)

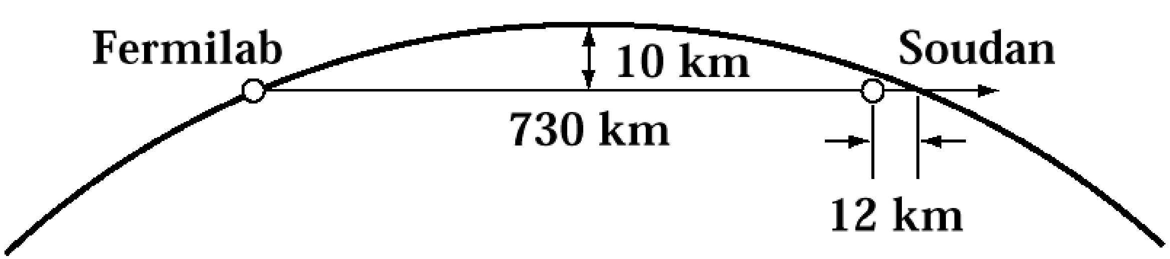

a)
Solar
95% C.L.
99% C.L.
99.73% C.L.
solar best fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
KamLAND best fit
Δm² (eV²)
tan² θ
b)
KamLAND+Solar fluxes
95% C.L.
99% C.L.
99.73% C.L.
global best fit
Δm² (eV²)
tan² θ

(Fermilab) Main Injector Neutrino Oscillation (running)

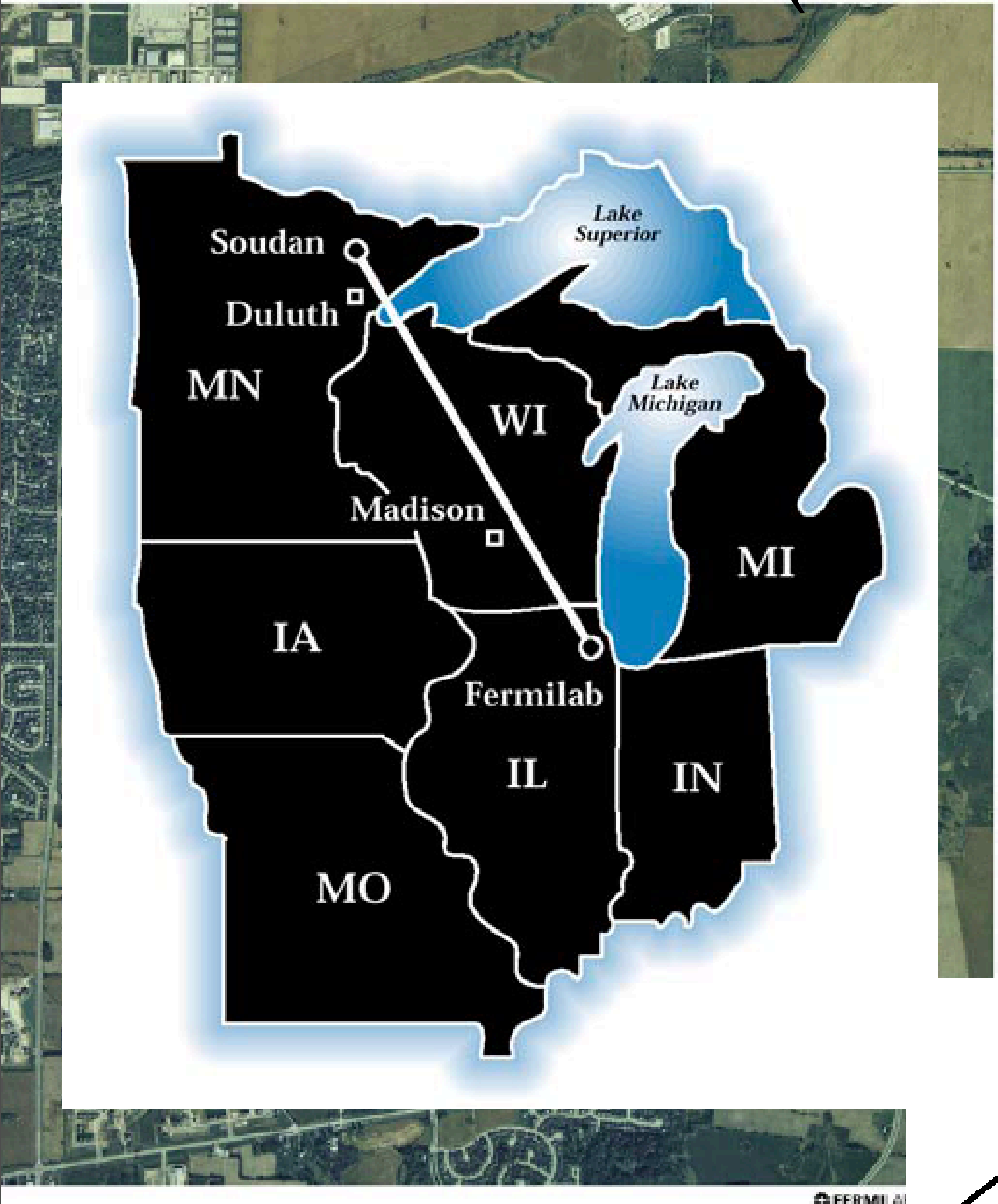


- 120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7μs)
- 1.9 s cycle time
- *i.e.* ν beam `on' for 8.7μs every 1.9 s
- 2.5×10^{13} protons/pulse
- 0.3 MW on target !
- Initial intensity

  2.5×10^{20} protons/year



(Fermilab) Main Injector Neutrino Oscillation (running)



- ★ 120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7μs)
- ★ 1.9 s cycle time
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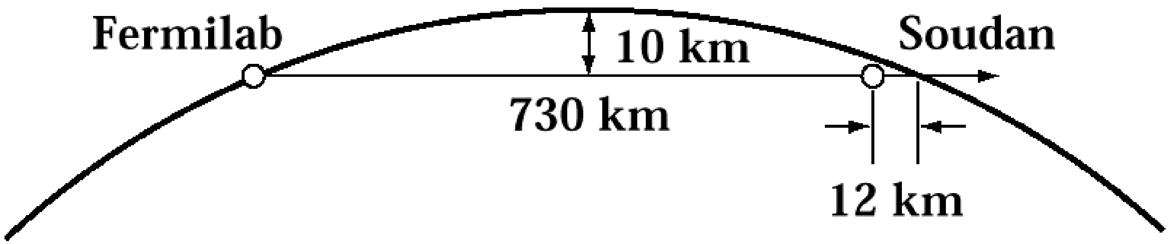
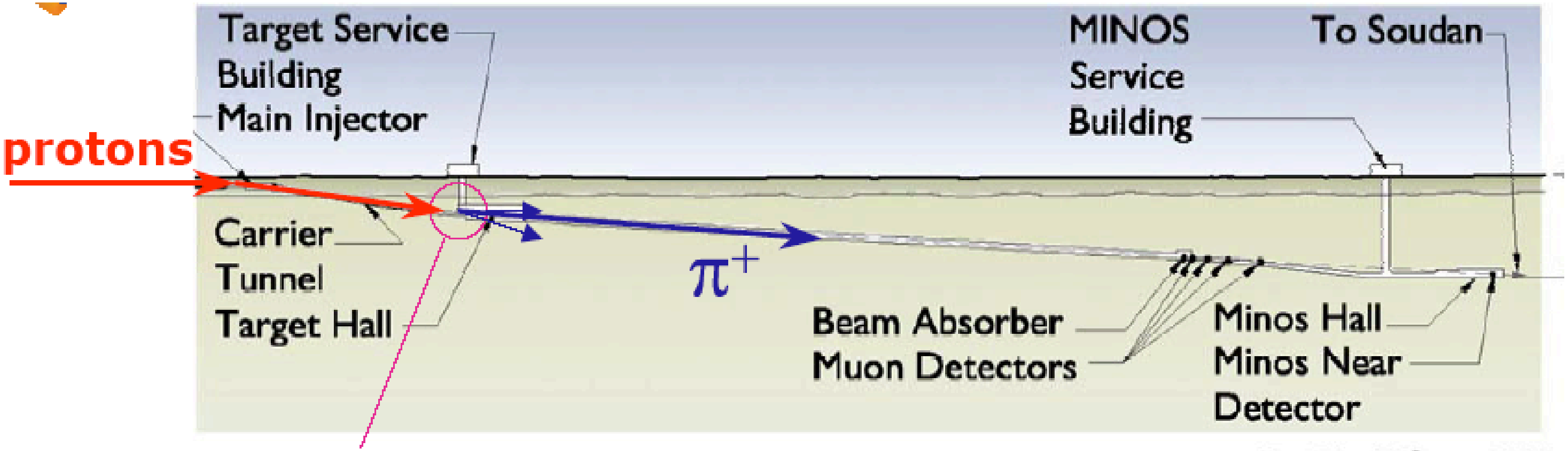
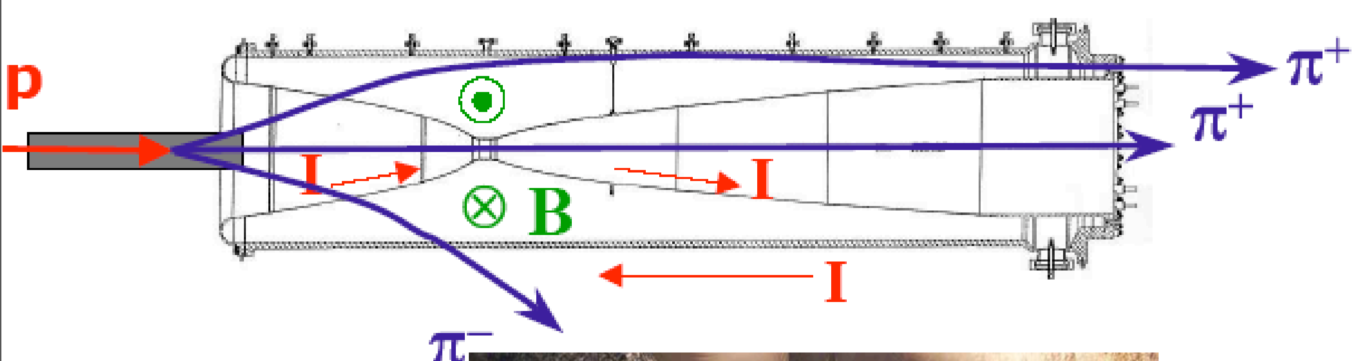


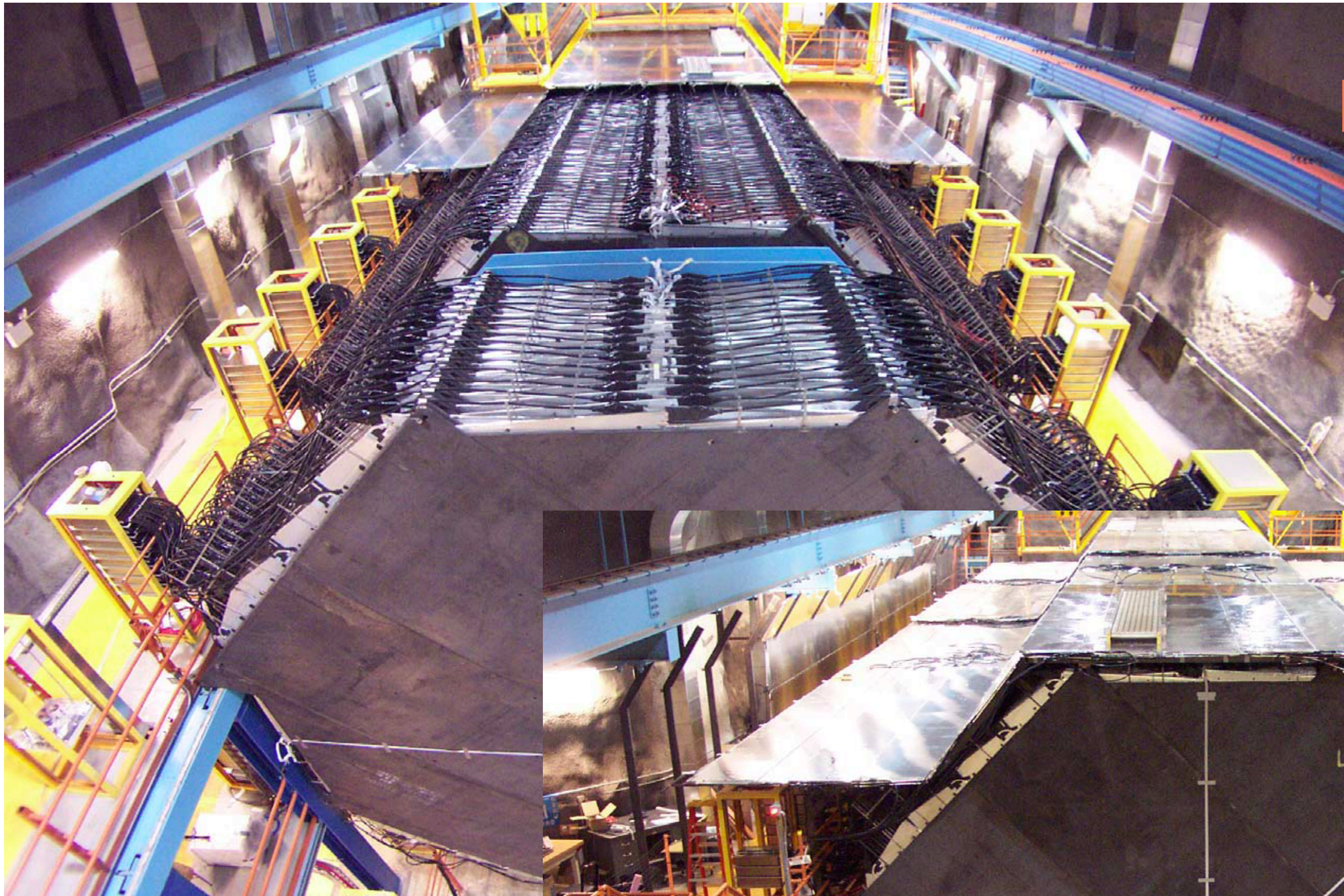


- **Horn pulsed with 200 kA**
- **Toroidal Magnetic field $B \sim I/r$ between inner and outer conducters**

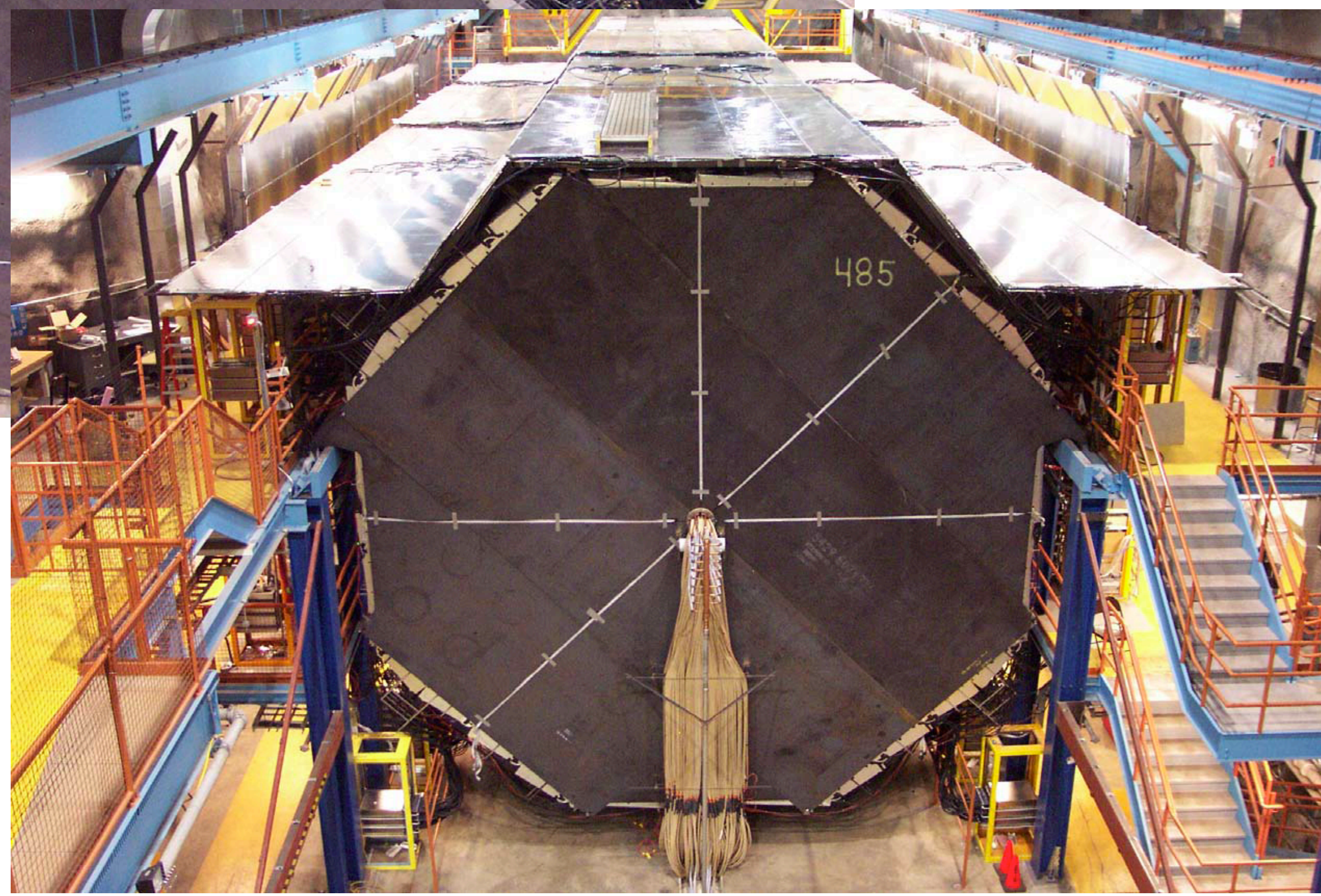


Fully operational in Soudan mine at 2341 ft 730 km from FNAL

Minos detector: Iron/ scintillator 5kT

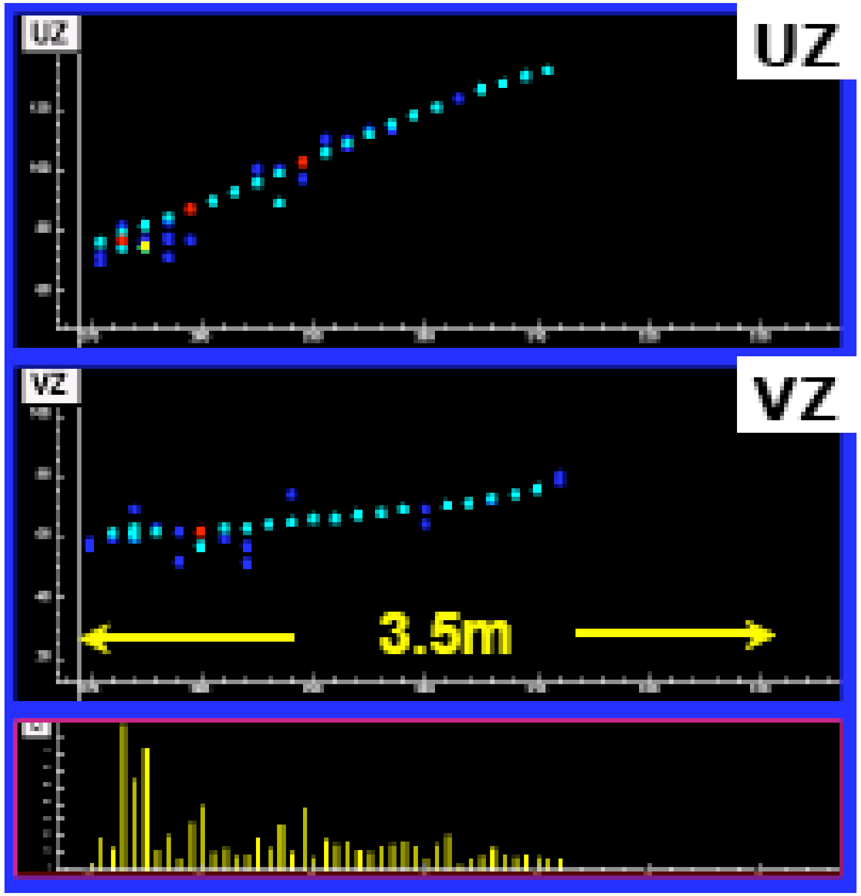


Fully operational in Soudan mine at 2341 ft 730 km from FNAL

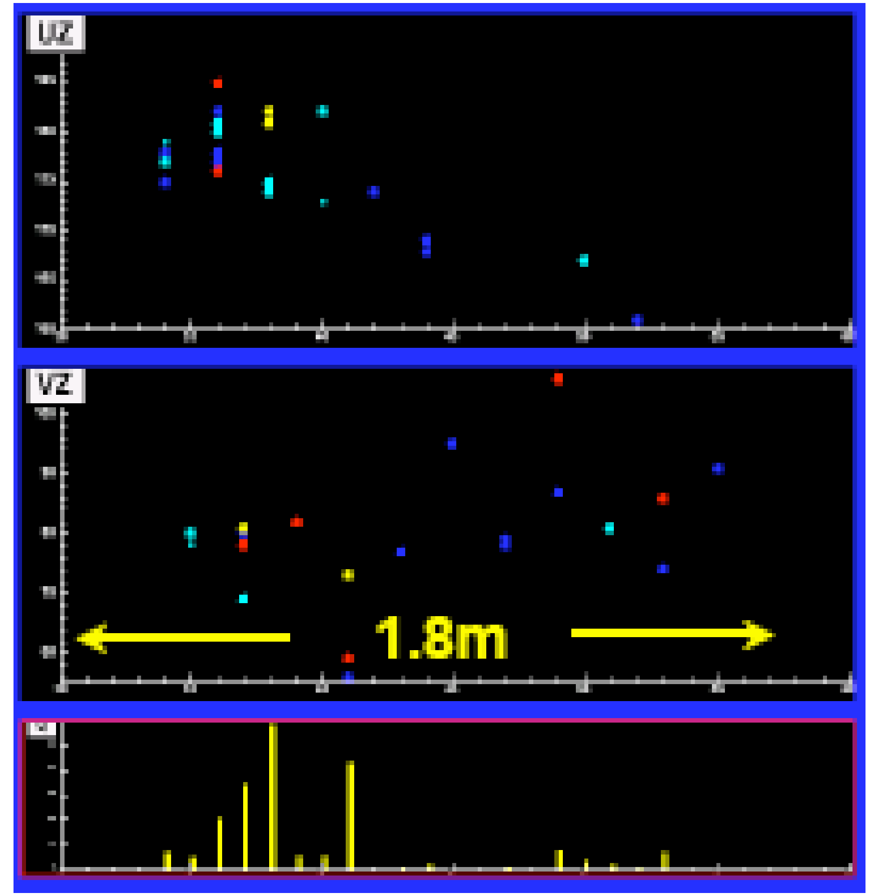


Minos detector: Iron/ scintillator 5kT

ν_μ CC Event

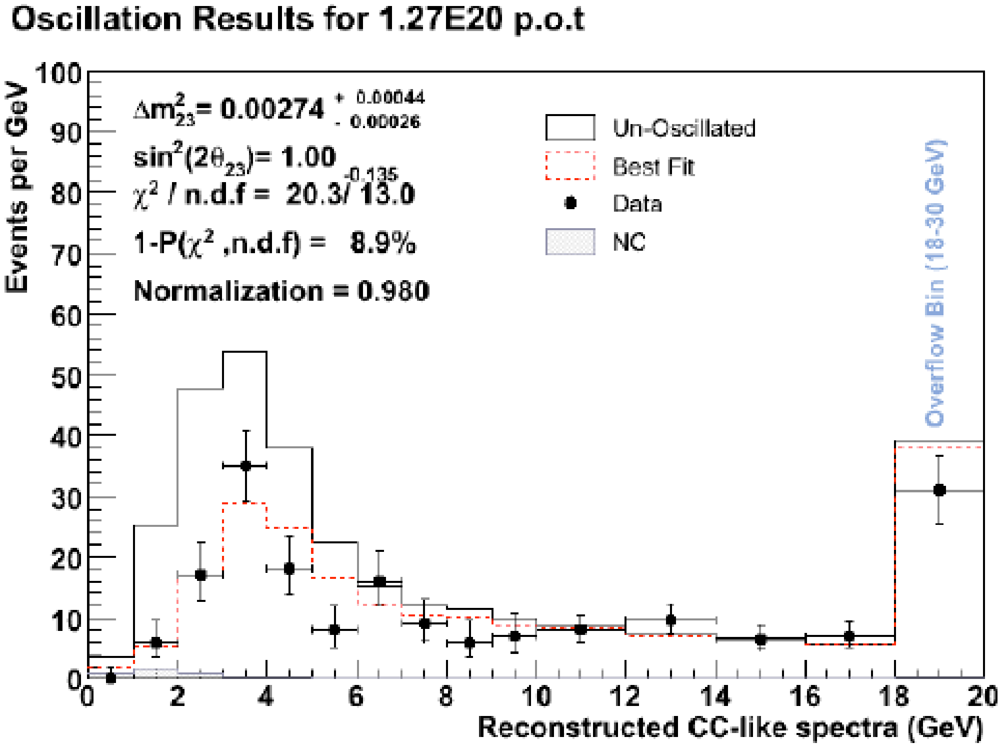


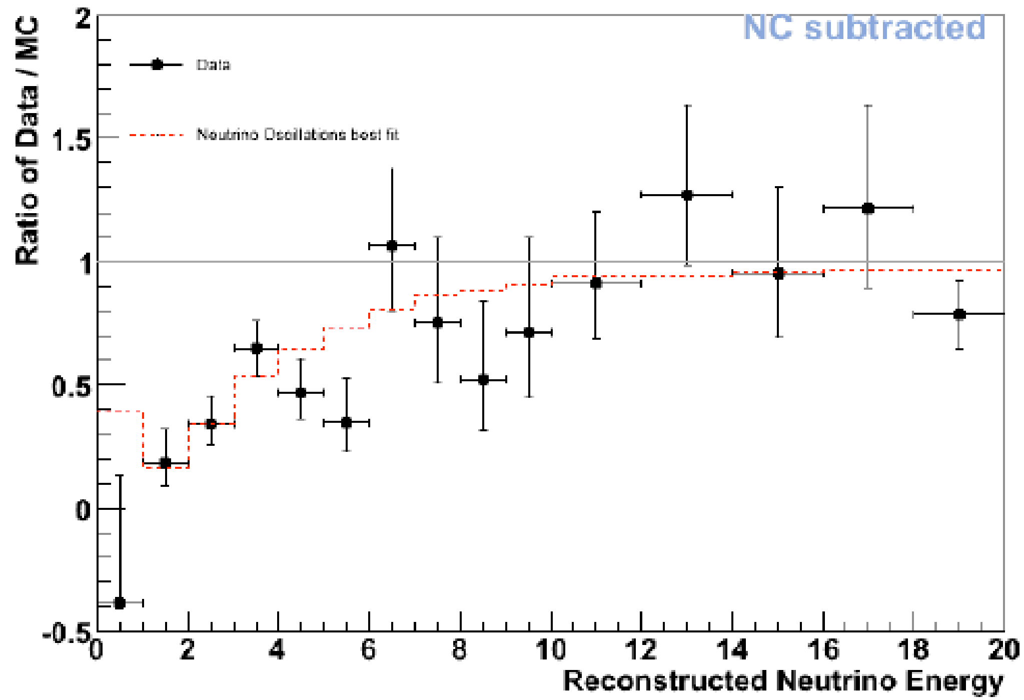
NC Event



- long μ track+ hadronic activity at vertex
- short event, often diffuse

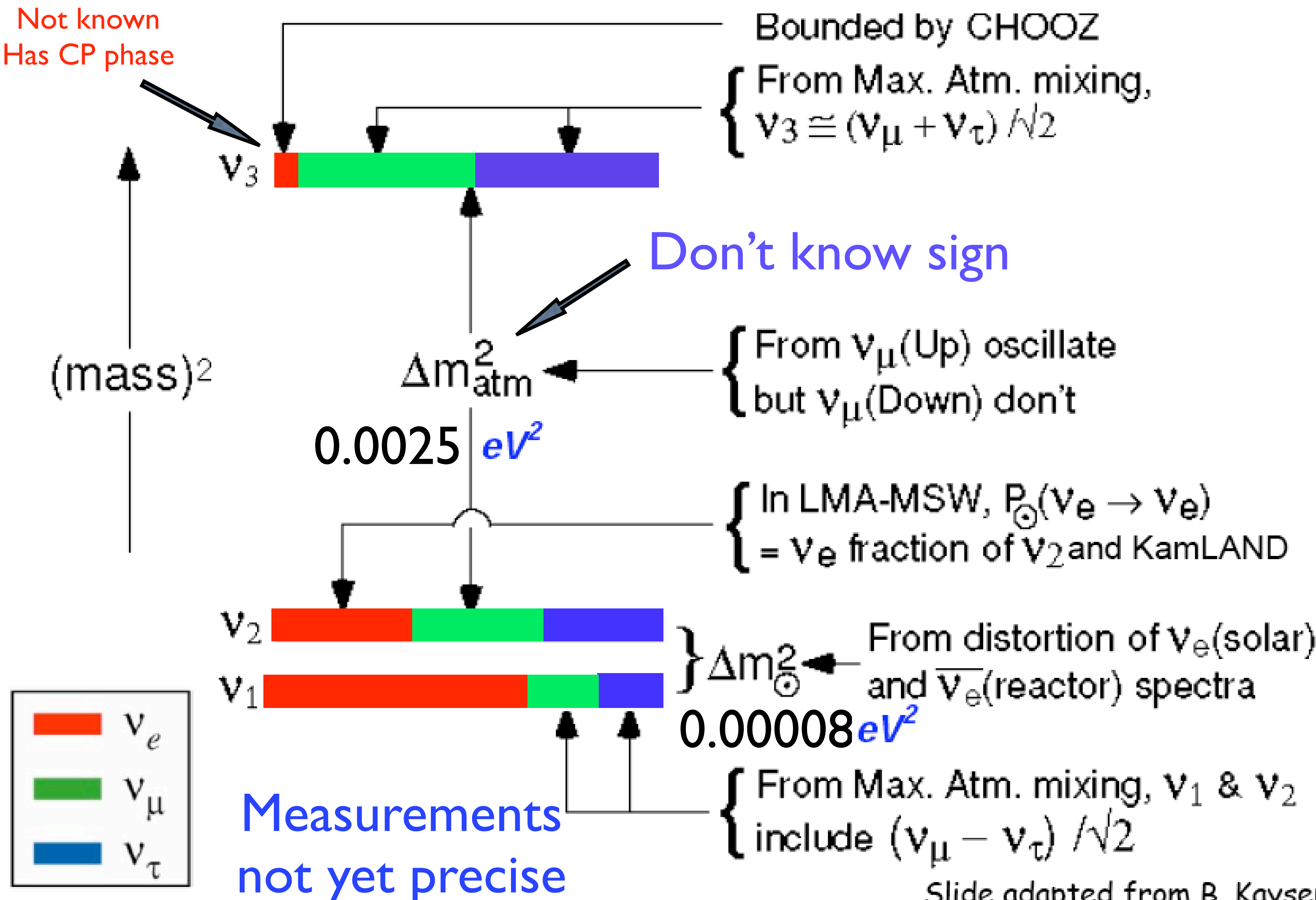
Best-fit spectrum and ratio





- Strong energy-dependent suppression of ν_μ events observed (**5.9 standard deviation effect below 5 GeV**)
  - consistent with the neutrino oscillation hypothesis
  - *with more data, we can test and rule out alternative hypotheses, such as neutrino decay, which predict a different energy dependent suppression of the ν_μ rate*

What do we know and how do we know it



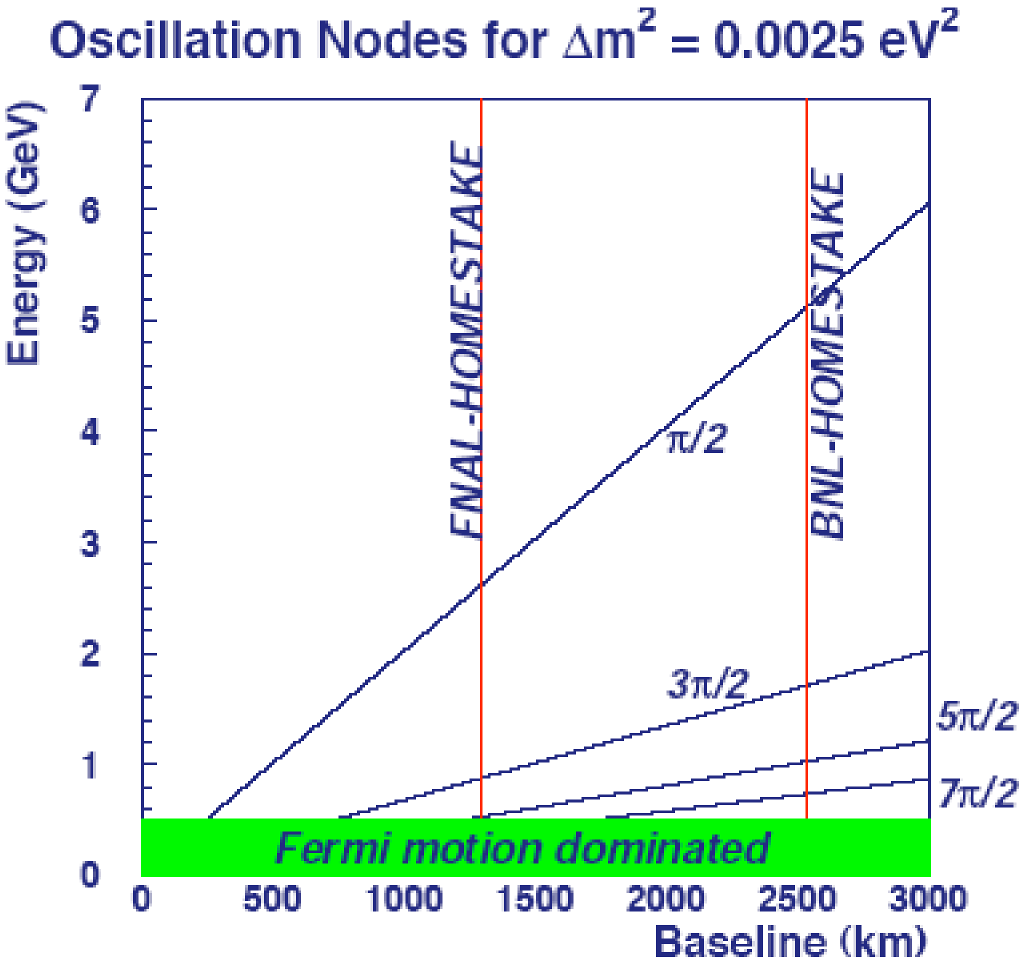
Slide adapted from B. Kayser

New Age of Accelerator Neutrinos

- For more precise experiments need pure beams of muon type neutrinos (or anti-neutrinos)
- Better controlled characteristics: energy, spectrum, backgrounds, pulsed.
- High energy (>1 GeV) to provide events with long muons. Better resolution.
- Generally called Long Baseline Experiments.

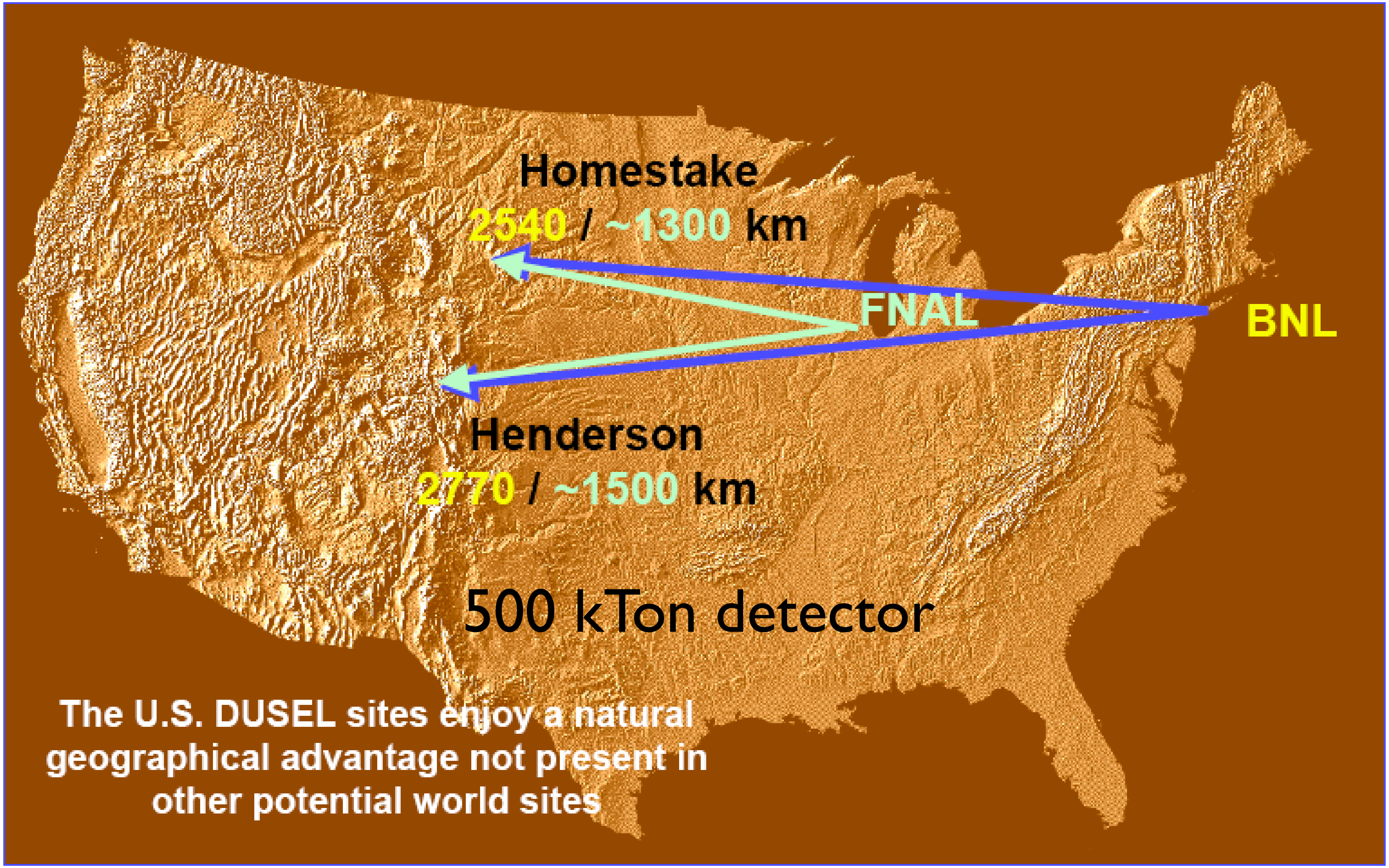
Ultimate Ambitions !

- Must see multiple nodes in a spectrum for precise measurements
- Need E: 1-6 GeV
- Need ~2000 km
- Need intense beam.
- Need very large



(M. Diwan, hep-ex/0407047)

Super Neutrino Beam to DUSEL Candidate Sites



Great puzzles for you

- What is the origin of the left/right asymmetry ?
- Are neutrinos and antineutrinos the same but have opposite spin ?
- Do neutrinos and antineutrinos transform in the same way ?
- How do we detect the cold neutrinos all around us ? (Perhaps with the Mariachi detector)