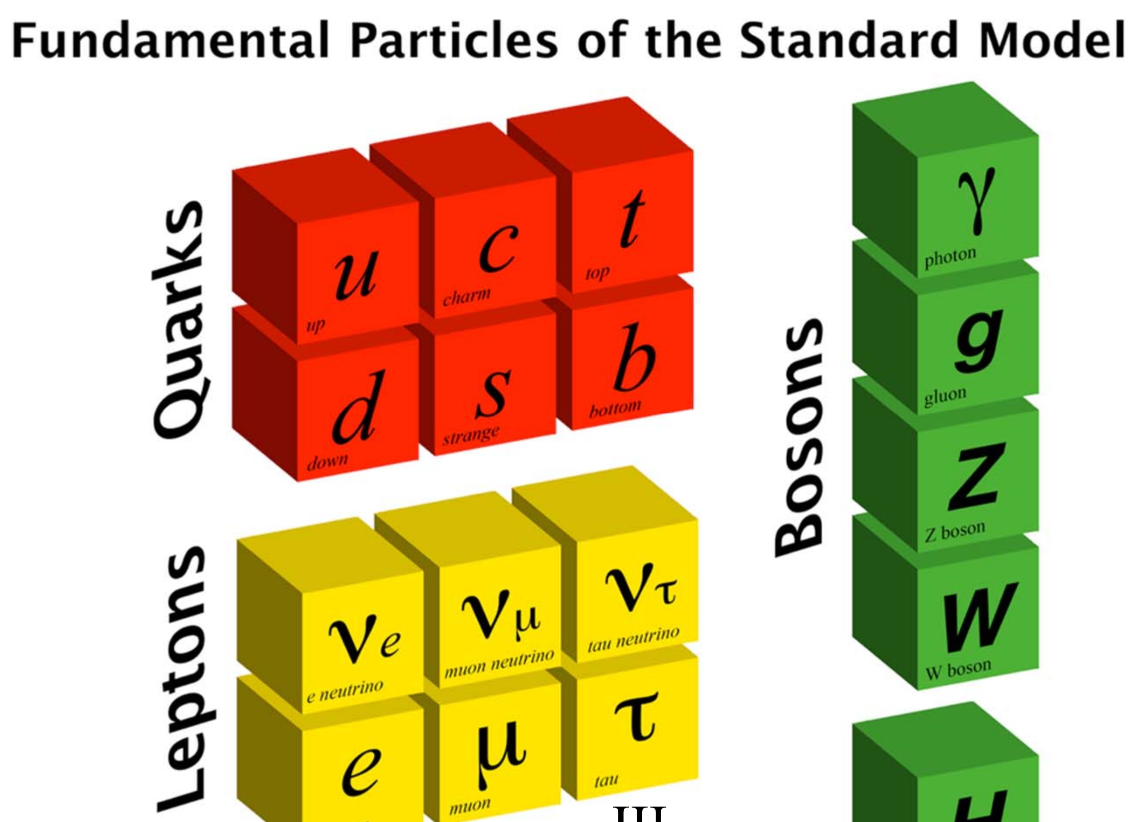
Neutrinos, neutrinos, neutrinos

l **Model** explains interactions of “matter particles” (a.k.a. - Leptons and Qua
rrier particles” (a.k.a. - Bosons).

odel, Neutrinos are neutral **massless** leptons that only interact via the Weak f

nerations (or flavors) of particles with similar properties...so three flavors of n



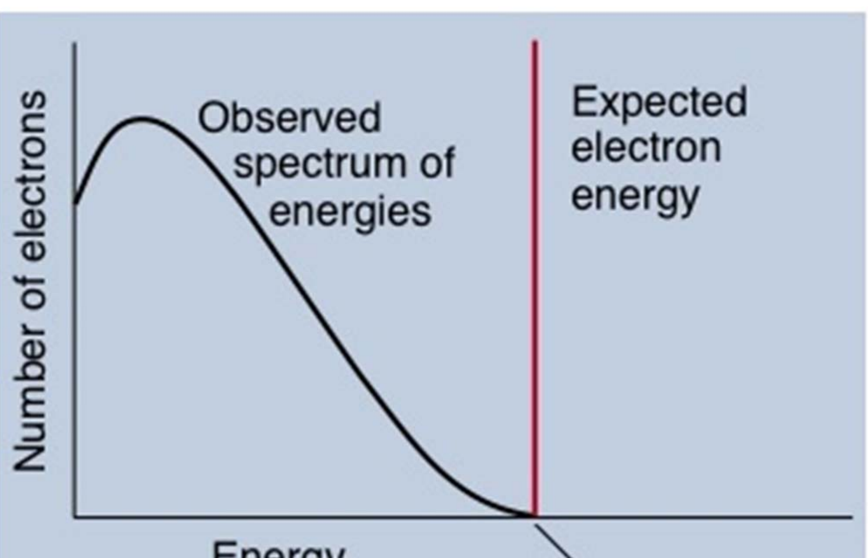
y is a process in which an atom increases its atomic number by 1

rticles (i.e. - energetic electrons) were thought to arise from **n → p + e⁻**

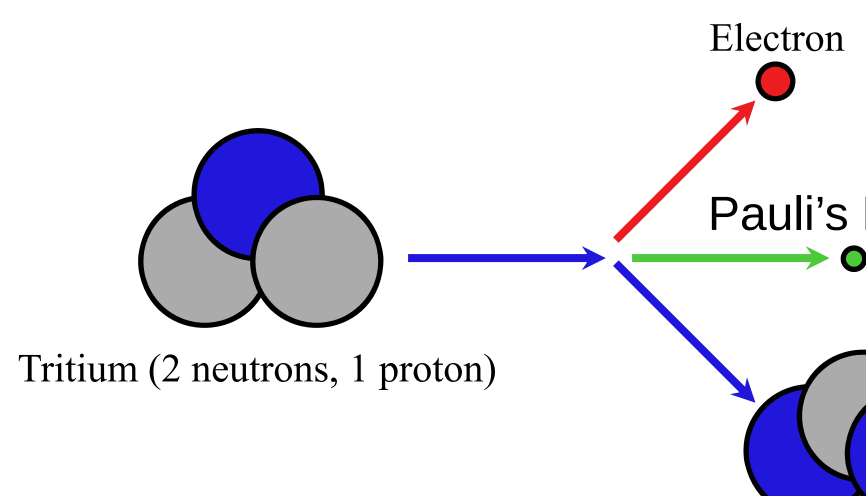
produce electrons with a **specific KE**...not what was observed !

Wolfgang Pauli postulated there must be also be a very small neutral p
in Beta decay to explain the unexpected spectrum and maintain Conser

ral particle had to have a very small mass to allow the occasional decay where the e
vith most of the available kinetic energy.



Two-Body Final Stat
Three-Body Final Stat



oactive Ladies and Gentlemen,

rer of these lines, to whom I graciously ask you to listen, will explain to you in mor
ve hit upon a desperate remedy to save the … the law of conservation of energy. N
that there could exist in the nuclei electrically neutral particles, that I wish to call n
e spin 1/2 and obey the exclusion principle …

of the neutrons should be of the same order of magnitude as the electron mass and i
arger than 0.01 proton masses. The continuous beta spectrum would then become
able by the assumption that in beta decay a neutron is emitted in addition to the ele
n of the energies of the neutron and the electron is constant...

Now called **ne**

"I have done a terrible thing. I have postulated a particle that cannot be detected."

Neutrinos first detected experimentally in 1956 by Cowan and Reine

ced two tanks (~200 liters total) of water next to a nuclear reactor, and surround
detectors that could observe photons.

ng for a unique signature of coincident+delayed photons, they could count the ra

g the nuclear reactor off, they confirmed that the neutrino rate diminished.

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

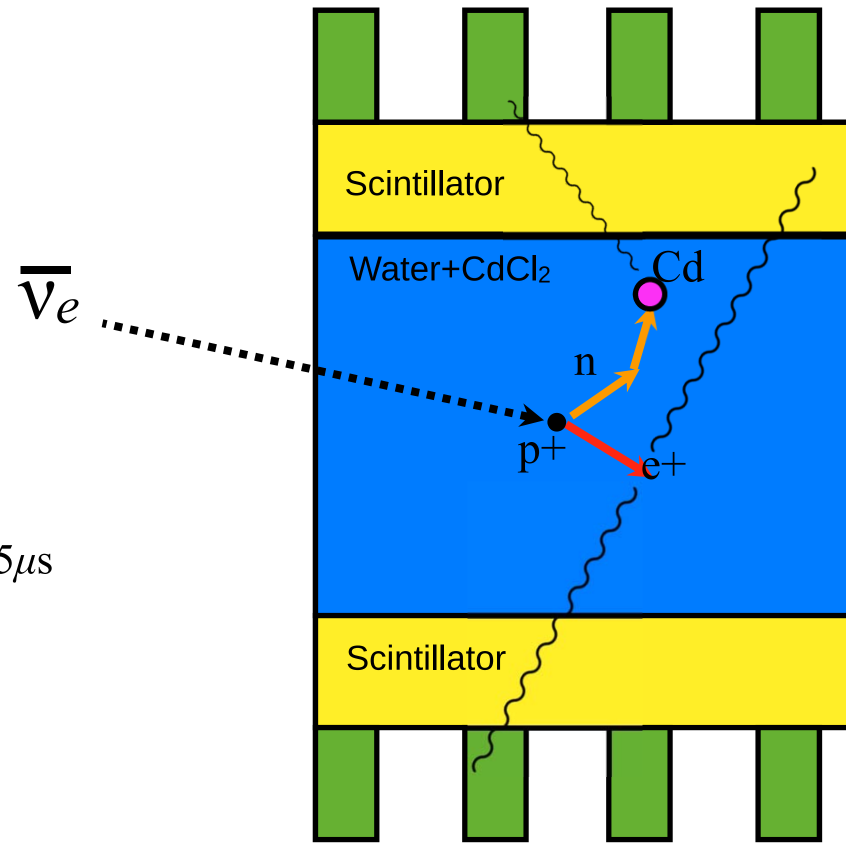
$$+ p^+ \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd}^* \rightarrow {}^{109}\mathrm{Cd} + \gamma$$

Delayed by $\sim 5\mu s$

by
ctor



"Thanks for message. Everything comes to him who knows how to wait."

Water target, doped with

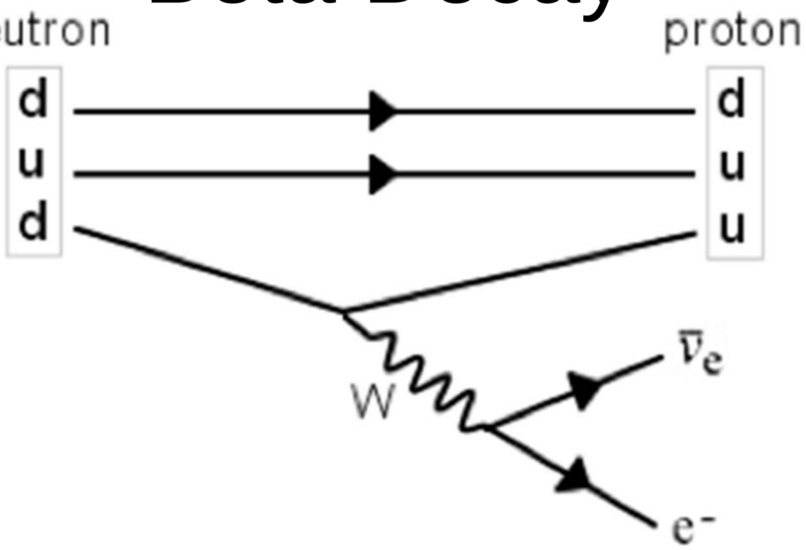
k force is conveyed by W and Z bosons.

y is an example of a process caused by the Weak force.

eraction includes a neutrino, it's guaranteed to be the weak force!

almost transparent to neutrinos .. They could pass through many
efore interacting!

Beta Decay



Weak force is 10^{-11} the stre
the electromagnetic fo

late 1960s the number of neutrinos from the Sun was measured by
the Homestake Mine*) to be ~2/3 lower than predicted.

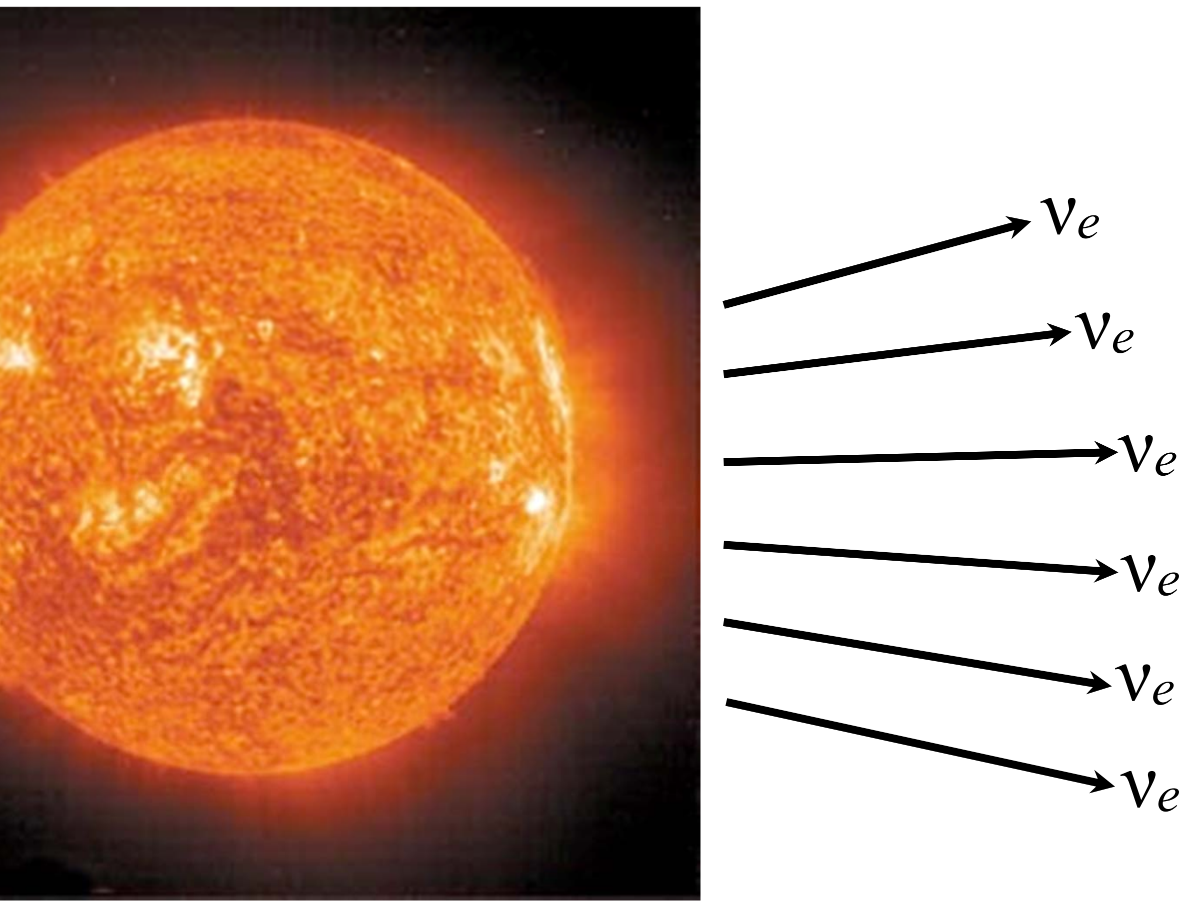
- iment was located ~4800 ft underground
- t of neutrinos was referred to as the "Solar Neutrino Problem"

Half-li

From the Sun

$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}$

,000,000 neutrinos from the
eam through every square
r on the Earth every second!



Reliable calculations existed
of this flux

$+ p^+ \rightarrow {}^2\mathrm{H} + e^+ + \nu$

if the neutrinos aren't really missing, but rather **changing thei**
y before they get detected?

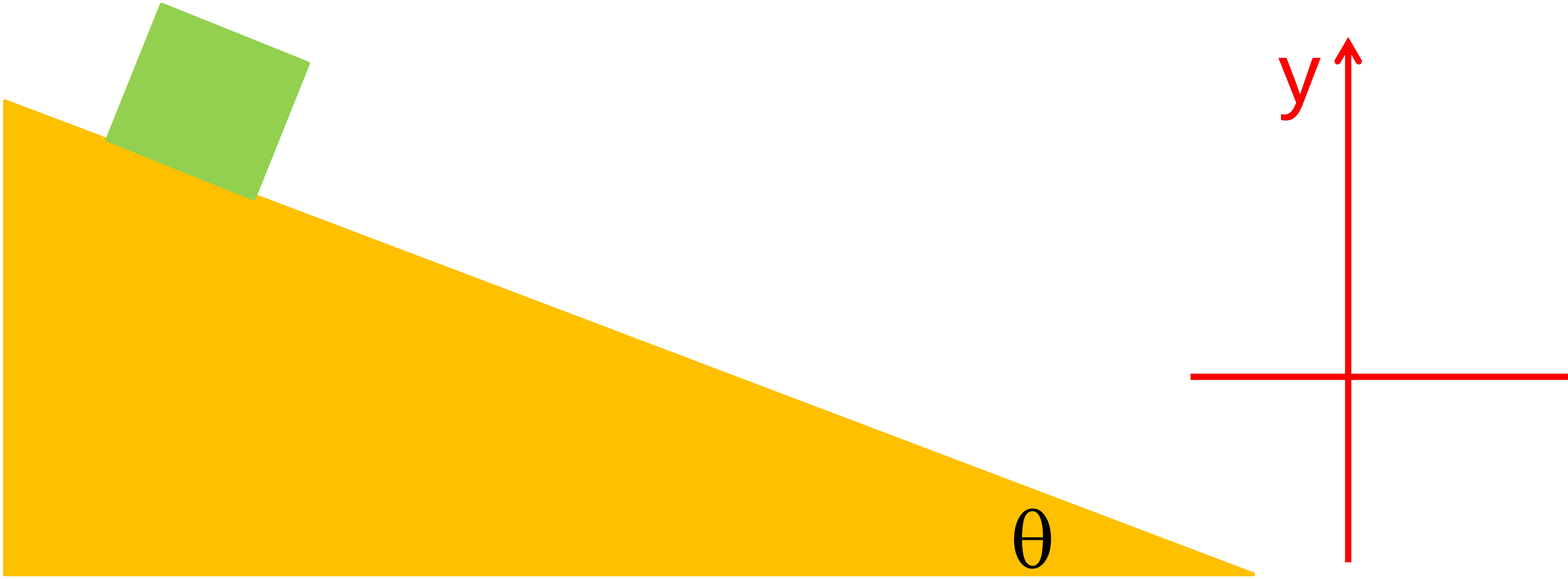
How can they change their identity?

ually knew at that time that oscillations could occur, but only
cles that have mass!

problem: In the SM, neutrinos are massless!

es a small diversion to explain….

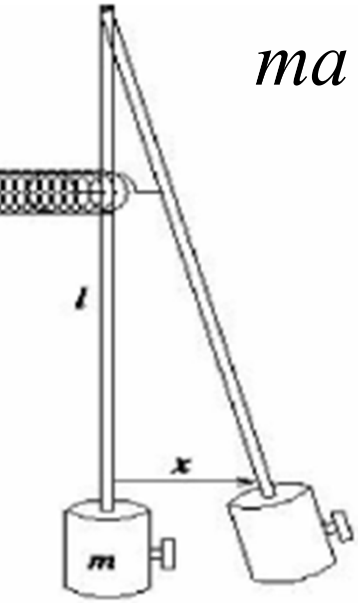
Warning
Math
incoming



Given θ, find a_x and a_y **using the coordinate system sh**

Hey… That's not simple … liar!

d why the %$&!X*$ would I do it like that?
ch more natural to use a rotated coordinate systen
e result at the end will be the same, but the rotated



$$ma = \sum F$$

$$Left: \; m\ddot{x} = -m\frac{g}{\ell}x - k(x-y) \quad \Rightarrow \quad \ddot{x} + \omega_0^2 x = -\frac{k}{m}(x -$$

$$Right: \; m\ddot{y} = -m\frac{g}{\ell}y - k(y-x) \quad \Rightarrow \quad \ddot{y} + \omega_0^2 y = -\frac{k}{m}(y -$$

$$Adding: \; \Rightarrow \; (\ddot{x}+\ddot{y}) + \omega_0^2(x+y) = 0 \quad \Rightarrow \quad \ddot{X} = -\omega_0^2 X$$

$$Subtracting: \; (\ddot{x}-\ddot{y}) + \left(\omega_0^2 + \frac{2k}{m}\right)(x-y) = 0 \quad \Rightarrow \quad \ddot{Y} = -\left(\omega_0^2\right.$$

$$X(t) = A\cos(\omega_0 t + \phi_0) \qquad Y(t) = B\cos(\omega_1 t + \phi_1)$$

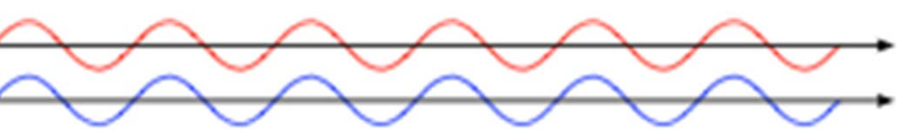
utions X = x+y and Y= x-y are "*decoupled*".

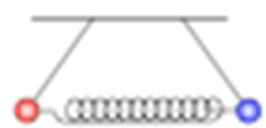
y evolve independent of each other vs time (ω_0 vs ω_1)

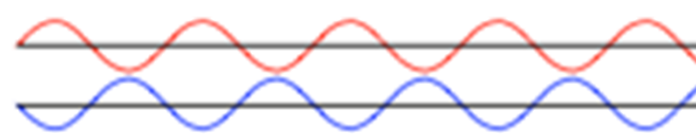
ed the "*normal modes*" of the system.

nally, ω_0 and ω_1 are the eigenvalues, and X, Y are the eigenfunctions of the

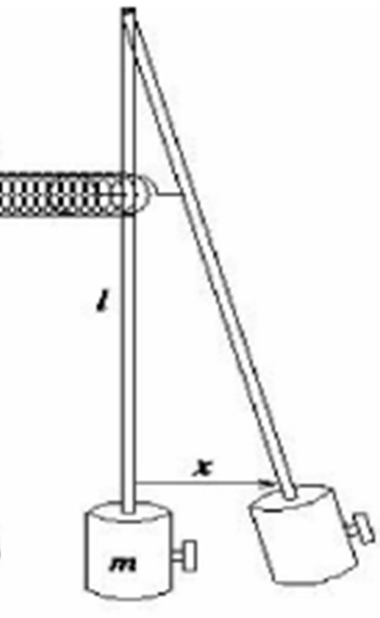
y correspond to the masses oscillating in phase (X) and out of phase (Y)







idual masses' motions are given by: $x = (X+Y)/2 \qquad y = (X-$



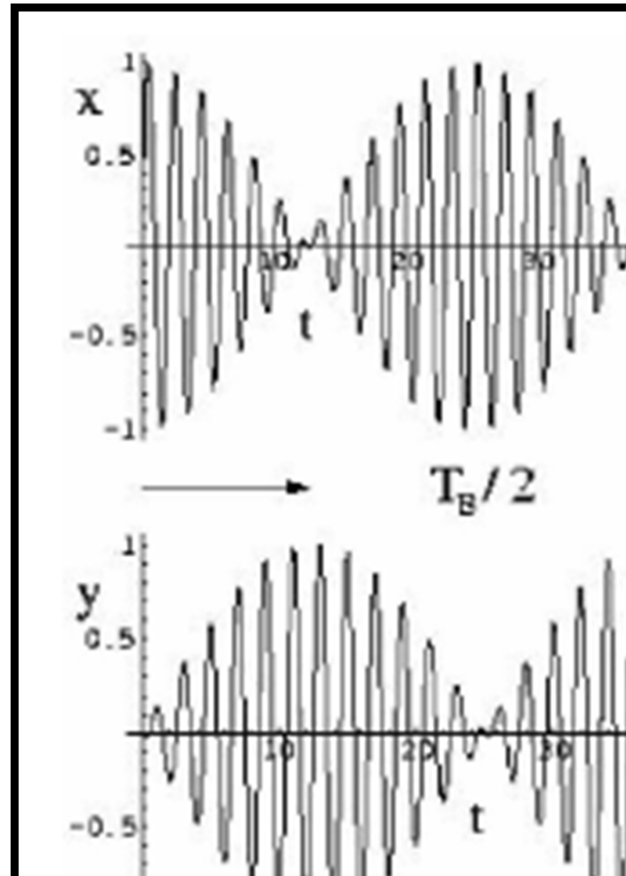
Consider the case where: $X_0=Y_0=2a \rightarrow x_0=2a$, y=(
(No y motion at all at t=

Solutions are then;

$$x=\frac{1}{2}(X+Y)=a\cos(\omega_0 t)+a\cos(\omega_1 t)=2a\cos\left(\frac{\omega_1-\omega_0}{2}t\right)\cos\left(\right.$$

$$y=\frac{1}{2}(X-Y)=a\cos(\omega_0 t)-a\cos(\omega_1 t)=2a\sin\left(\frac{\omega_1-\omega_0}{2}t\right)\sin\left(\right.$$

to see that at t=0, get $x_0=2a$, y=0
what happens as time evolves?
mass oscillates at $(\omega_1+\omega_0)/2$, with
itude modulated by a slow oscillation
$_0)/2$. BEATS !!
t happens when $t=\pi/(\omega_1+\omega_0)$?
o motion in x, all of it in y!
ocess goes back & forth!



neutrinos are produced as "flavor" states
through the weak interaction ($W^+ \rightarrow \mu^+ \nu_\mu$.)
mplicity, assume 2 neutrino species)

ow that quantum states will evolve as energy
since $E=mc^2$) eigenstates,
and ν_2 . (more detail in backup slides)

avor" states are a linear superposition
mass eigenstates.

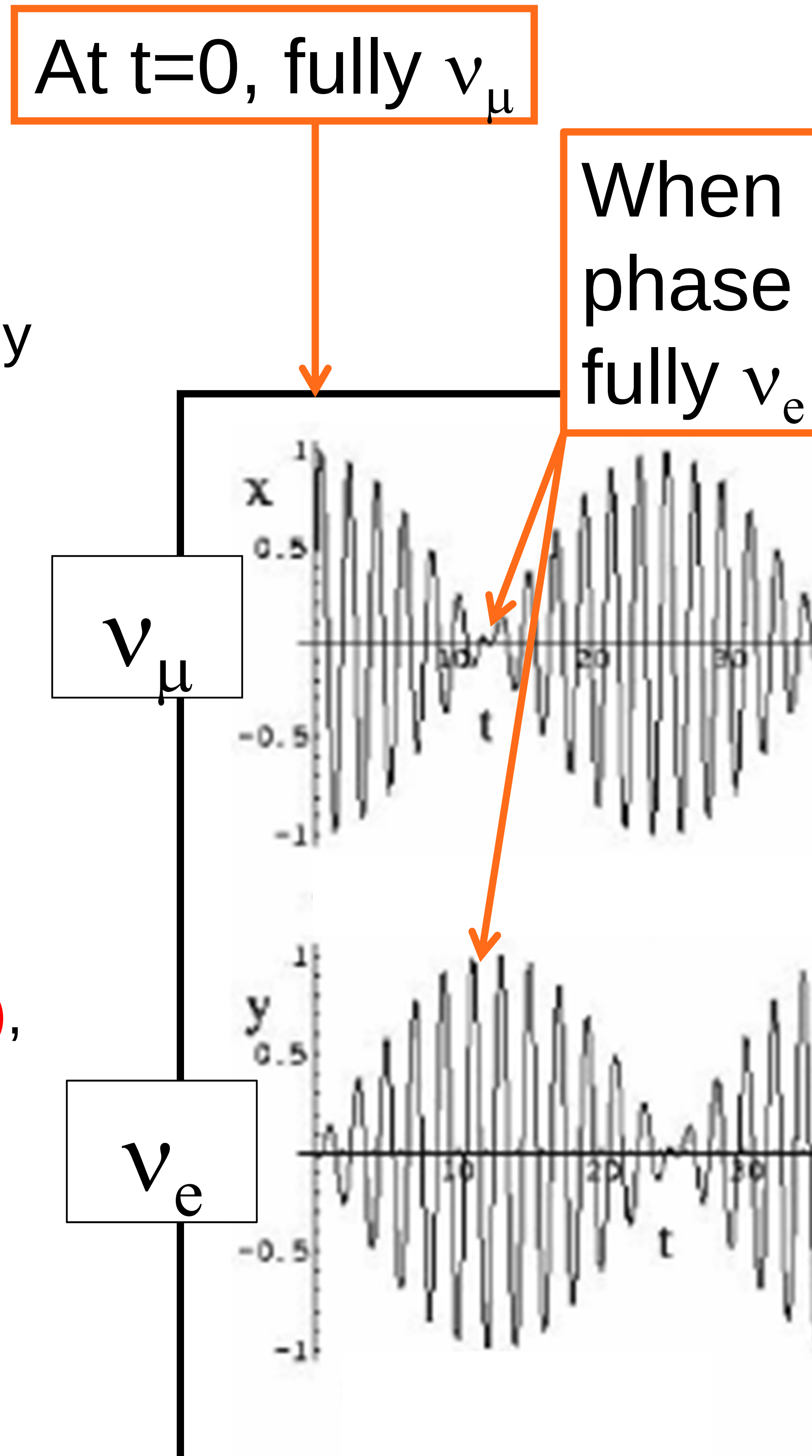
$$\nu_1 \cos\theta + \nu_2 \sin\theta$$

$$-\nu_1 \sin\theta + \nu_2 \cos\theta$$

Why written like this?

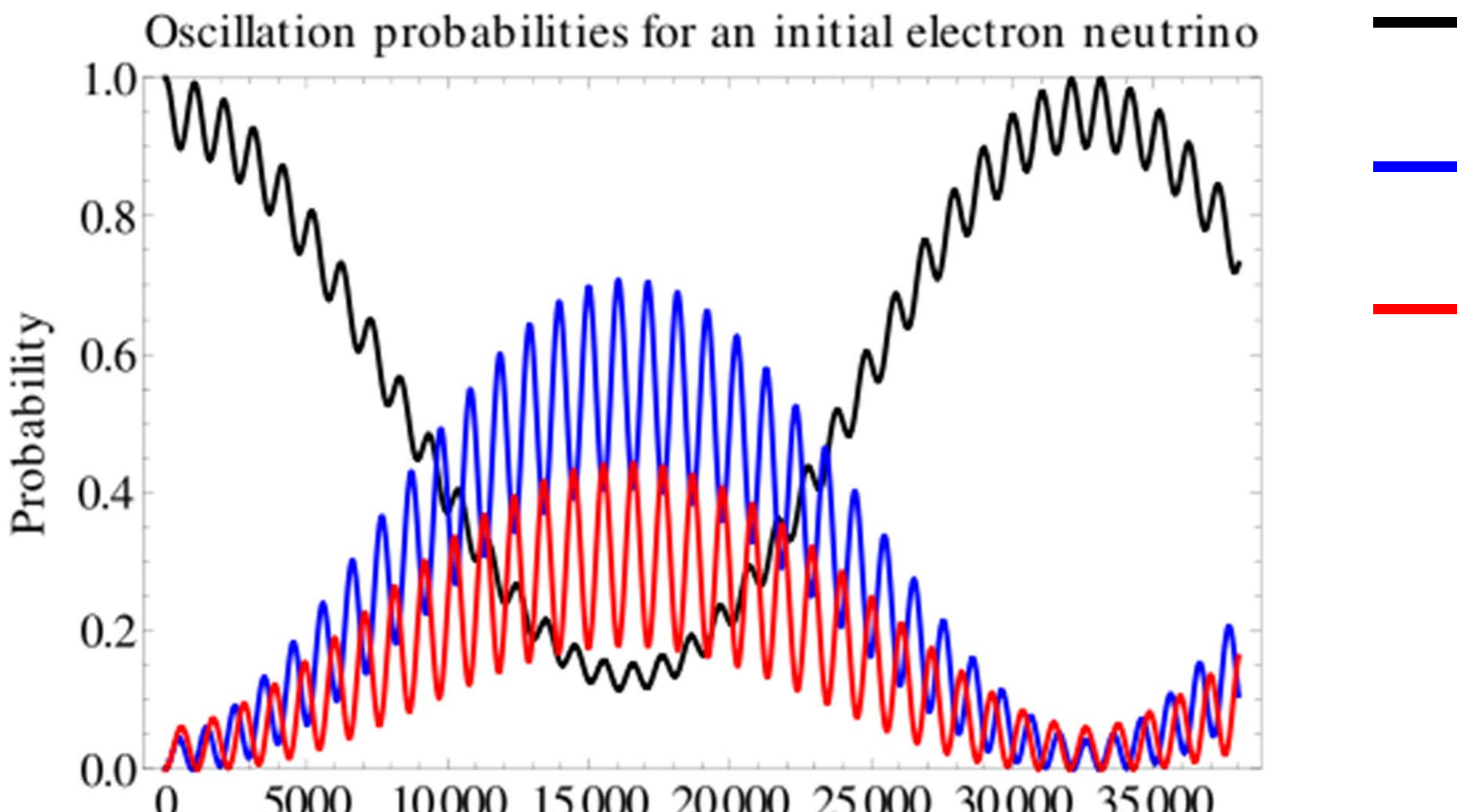
he two mass eigenstates evolve differently
, (one with m_1c^2t and the other with $\sim m_2c^2t$),
ome time, a ν_e component will emerge!
to the way energy transferred from x motion into
on for the coupled pendula)

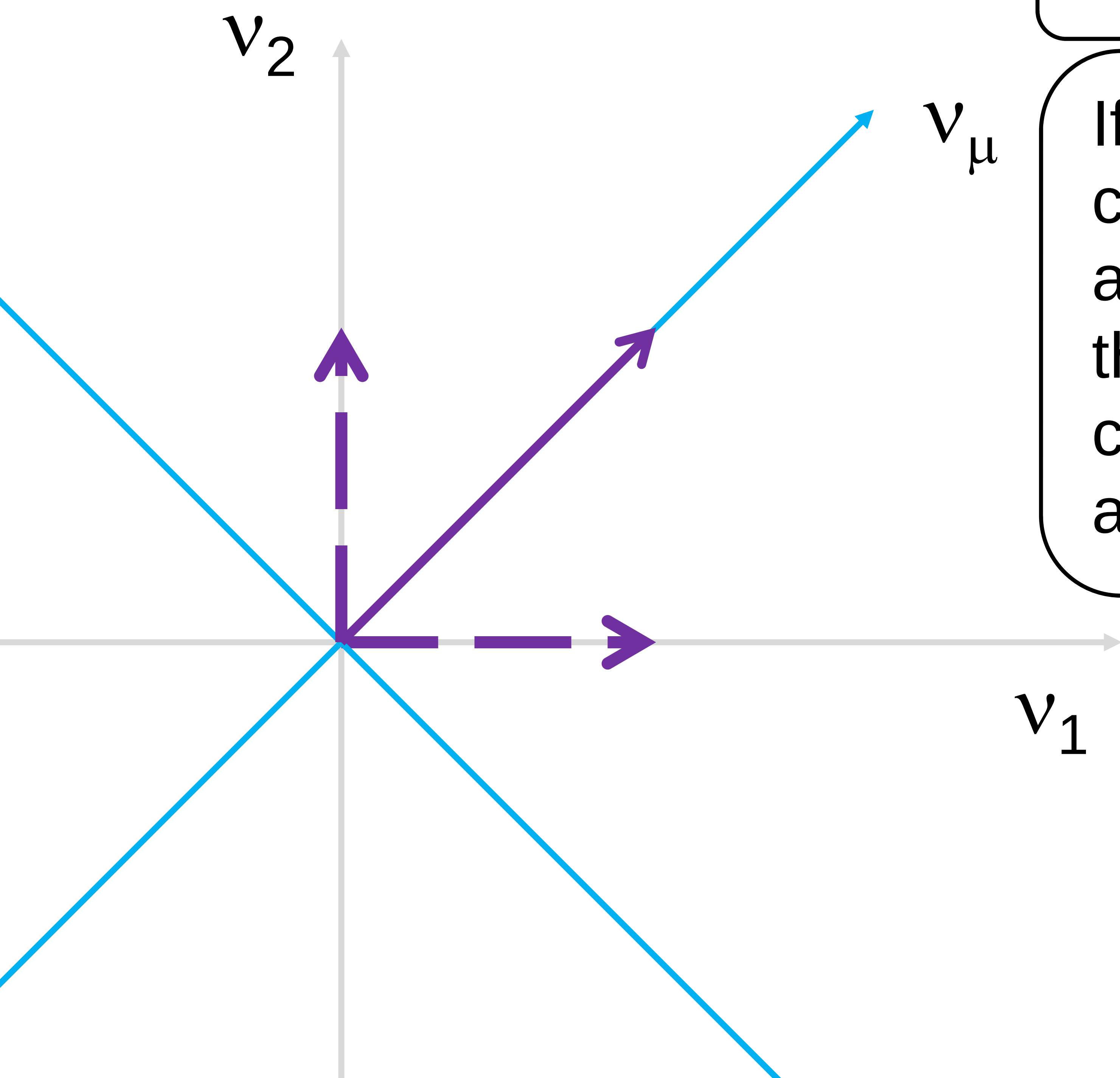
the right time, there is 100% chance of
a ν_e and 0% chance of finding a ν_μ!



nly with a 50-50 mix, will one have a probability tha
es between 0 and 100% of finding the neutrino in a
ecific flavor.
ere, long range oscillations, of initially pure electron
utrino beam.

how
t the
um value,
~16000,
s not zero





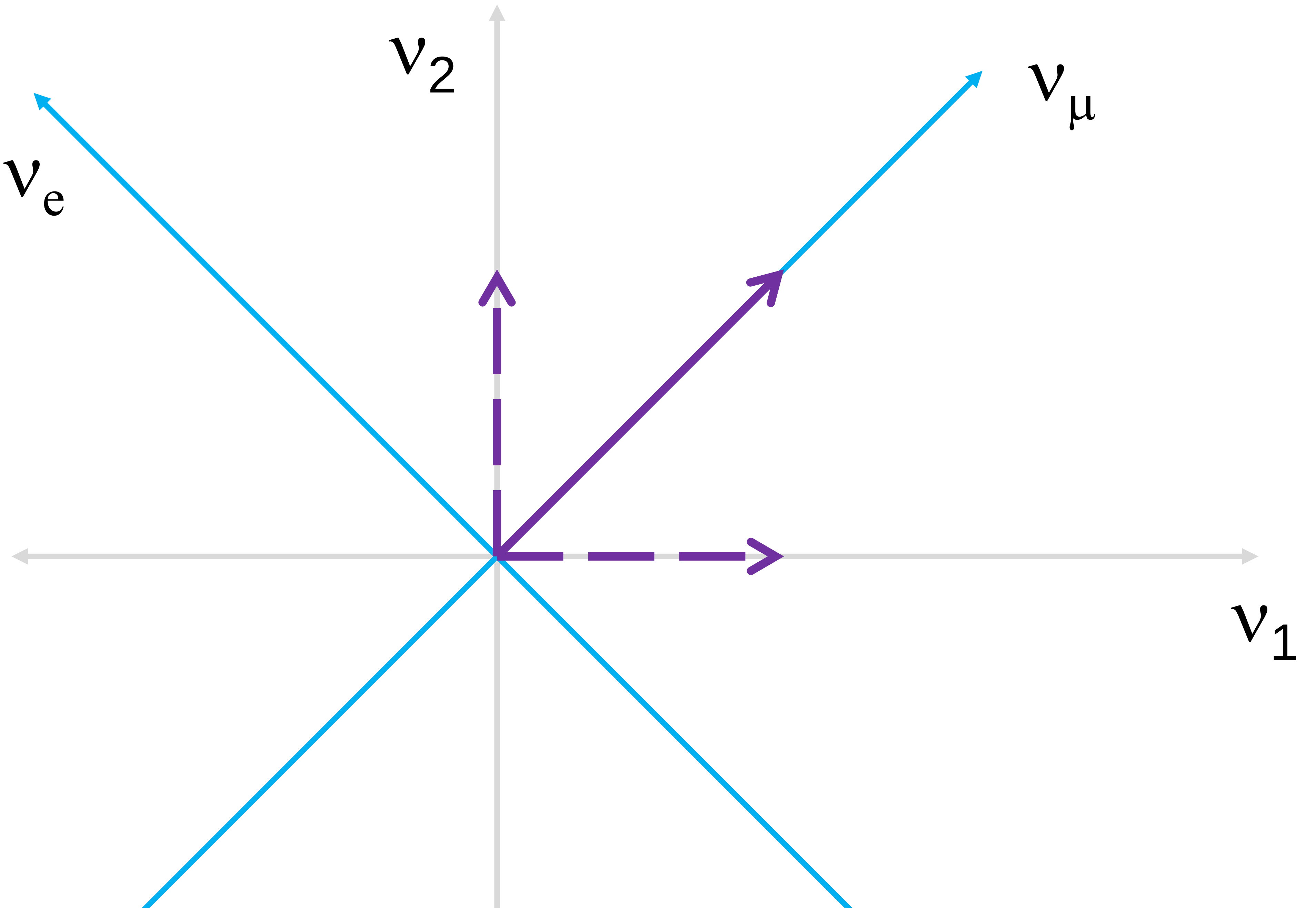
Suppose you start off
pure ν_μ “beam”

If the ν_1 and ν_2
components oscill
at the same frequ
the relative phase
changes, and they
always add up to

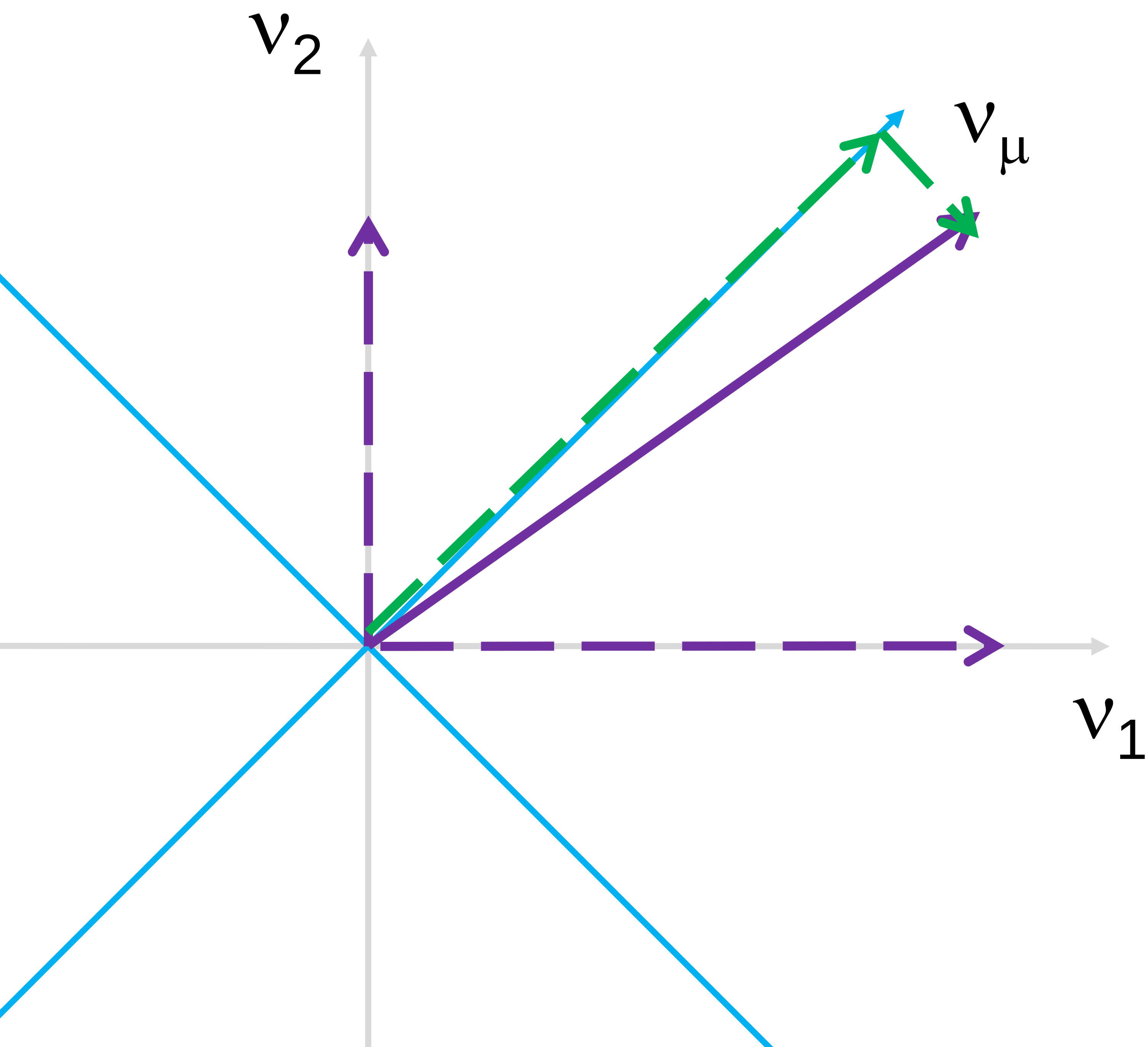
ν_μ cannot oscil
into ν_e

at if the components oscillate at a different frequency?

$= E/h = (mc^2)/h$… this is the same as saying $m(\nu_1) \neq m(\nu_2)$



ne ν_1 component doubles, while ν_2 only increases by 50%
ome time t.



After time t, the
has acquire
non-zero
ν_e compone

The different m
have resulted in
varying amoun
and ν_μ, after st
with 100%

If you look at a
time, you migh
$P(\nu_e)$=100%
$P(\nu_\mu)$=0%

an be shown" that the probability of oscillation is:

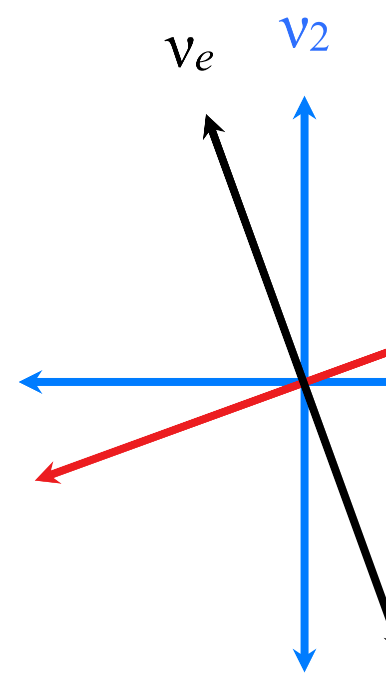
$$\nu_e = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m_{12}^2 L}{E_\nu}) \qquad \Delta m_{12}^2 = m_1^2 - m_2^2$$

L = distance
by neutri
E_ν = neutrin

sitivity to difference in squared masses, and the level of "

$$\nu_1\cos\theta + \nu_2\sin\theta$$
$$-\nu_1\sin\theta + \nu_2\cos\theta$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



sitivity to oscillation is maximum when:

$$1.27\frac{\Delta m^2 L}{E_\nu} \sim \frac{\pi}{2}$$

nding on the experiment type, you may have control over L and/
you know L and E_ν → determines sensitive Δm^2 range.
rally, L is fixed, so one can study the oscillation probability versu

How do we study neutrinos?

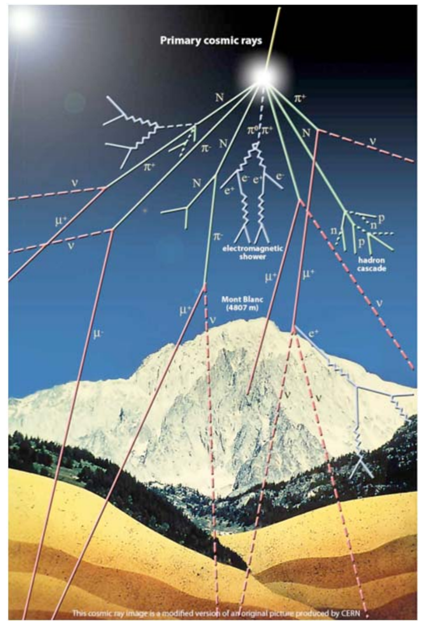
neutrino oscillations we need:

e (many different types available...intensity is important)

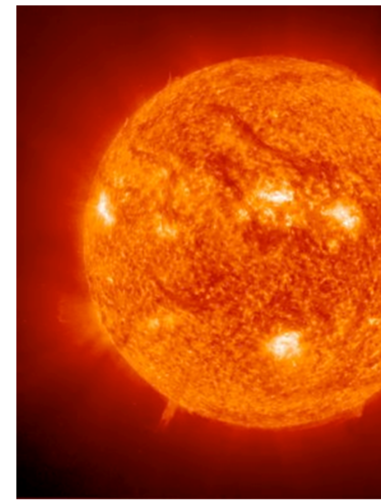
ectors (to accumulate sizeable statistics)

nderstanding of signal vs. background

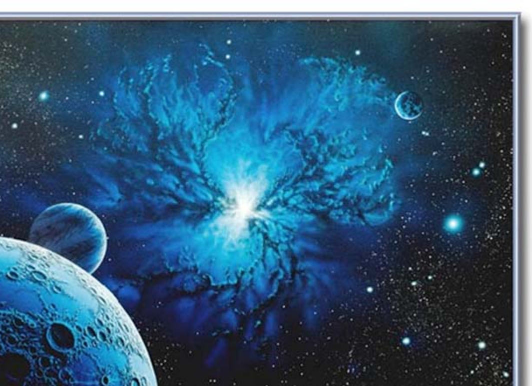
Nuclear Reactors

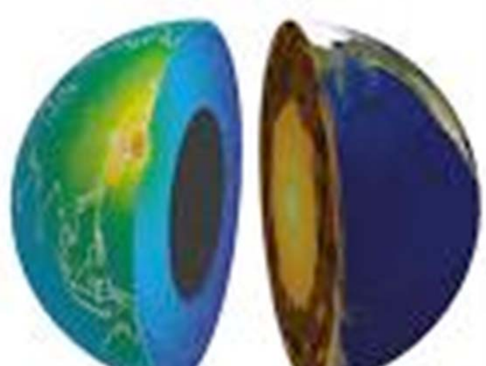


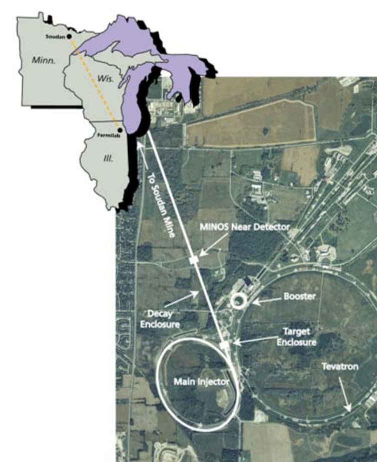
Cosmic Ray Showers

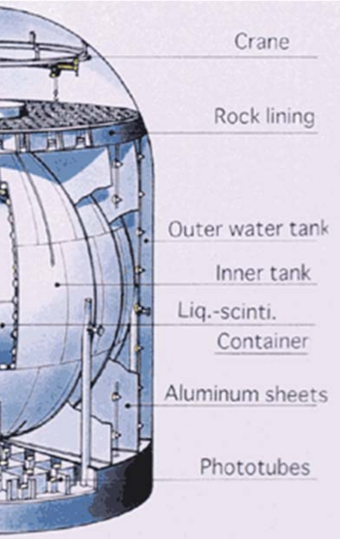


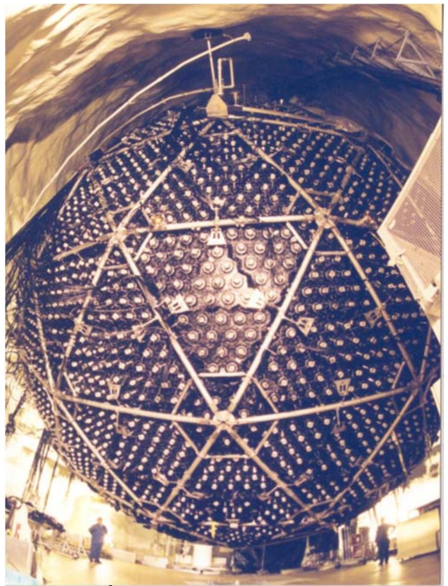
The Sun





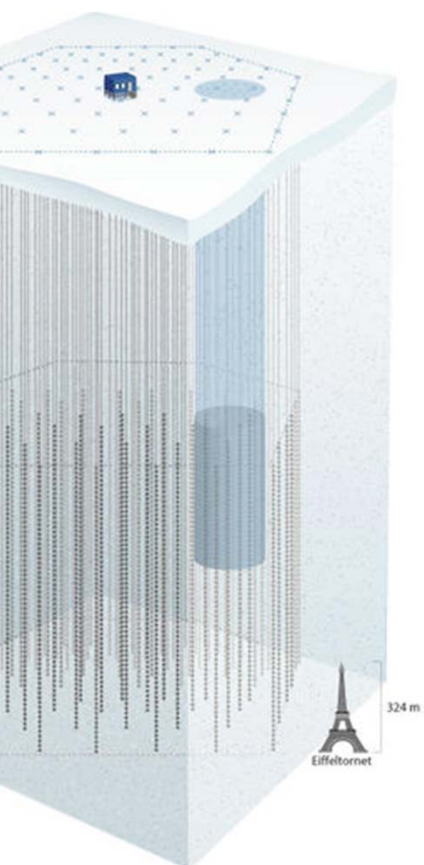


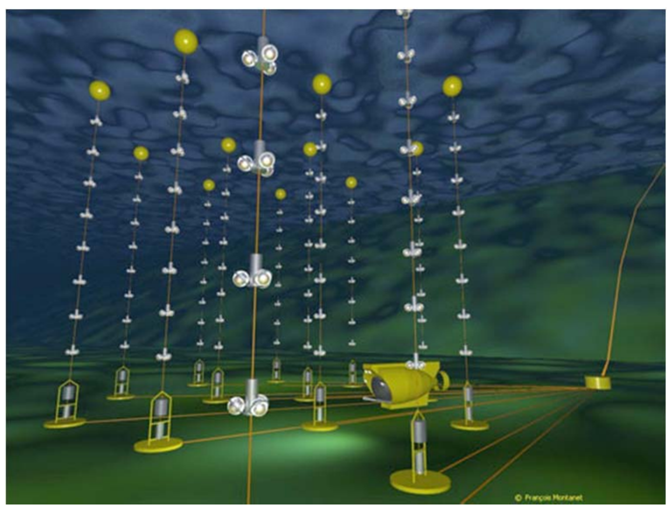




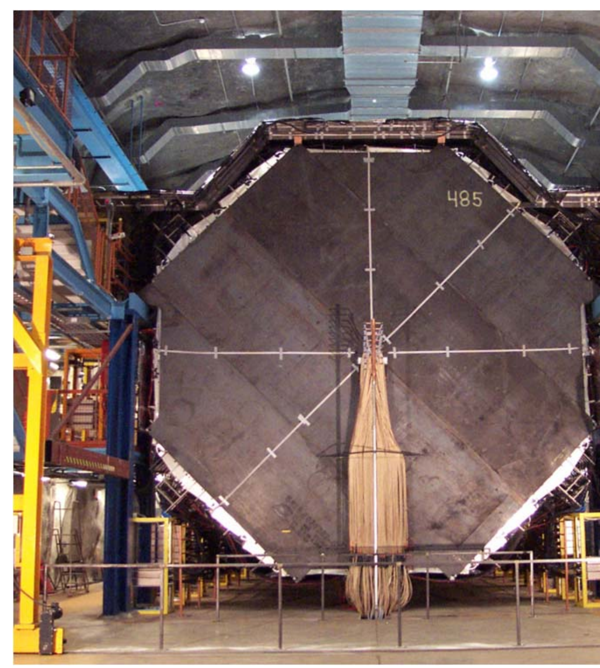
Atmospheric Neutrinos
(KamLand, SNO, etc...)

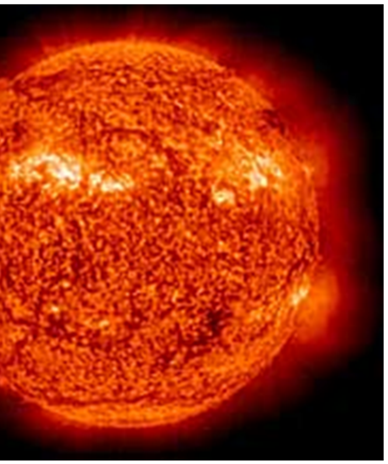
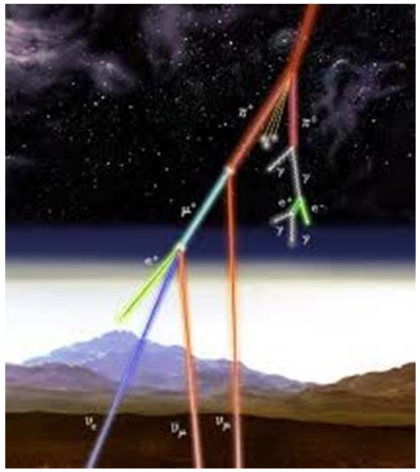
Reactor Experiments
(Double Chooz, Daya Bay,





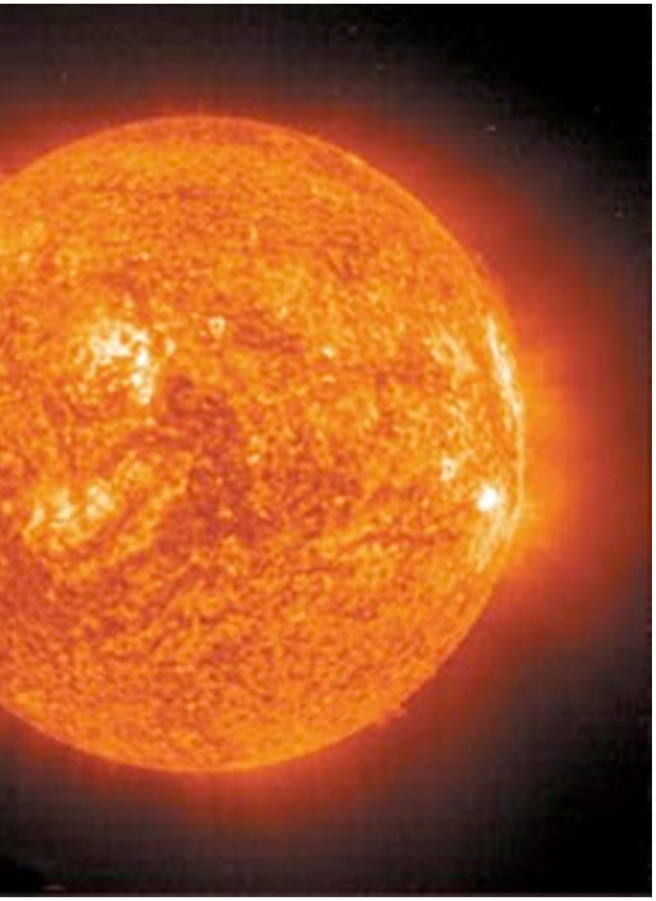
ANTARES (@ Mediterranean

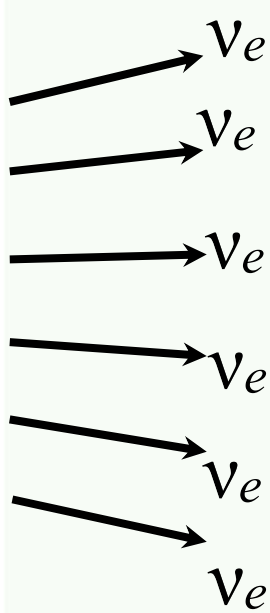


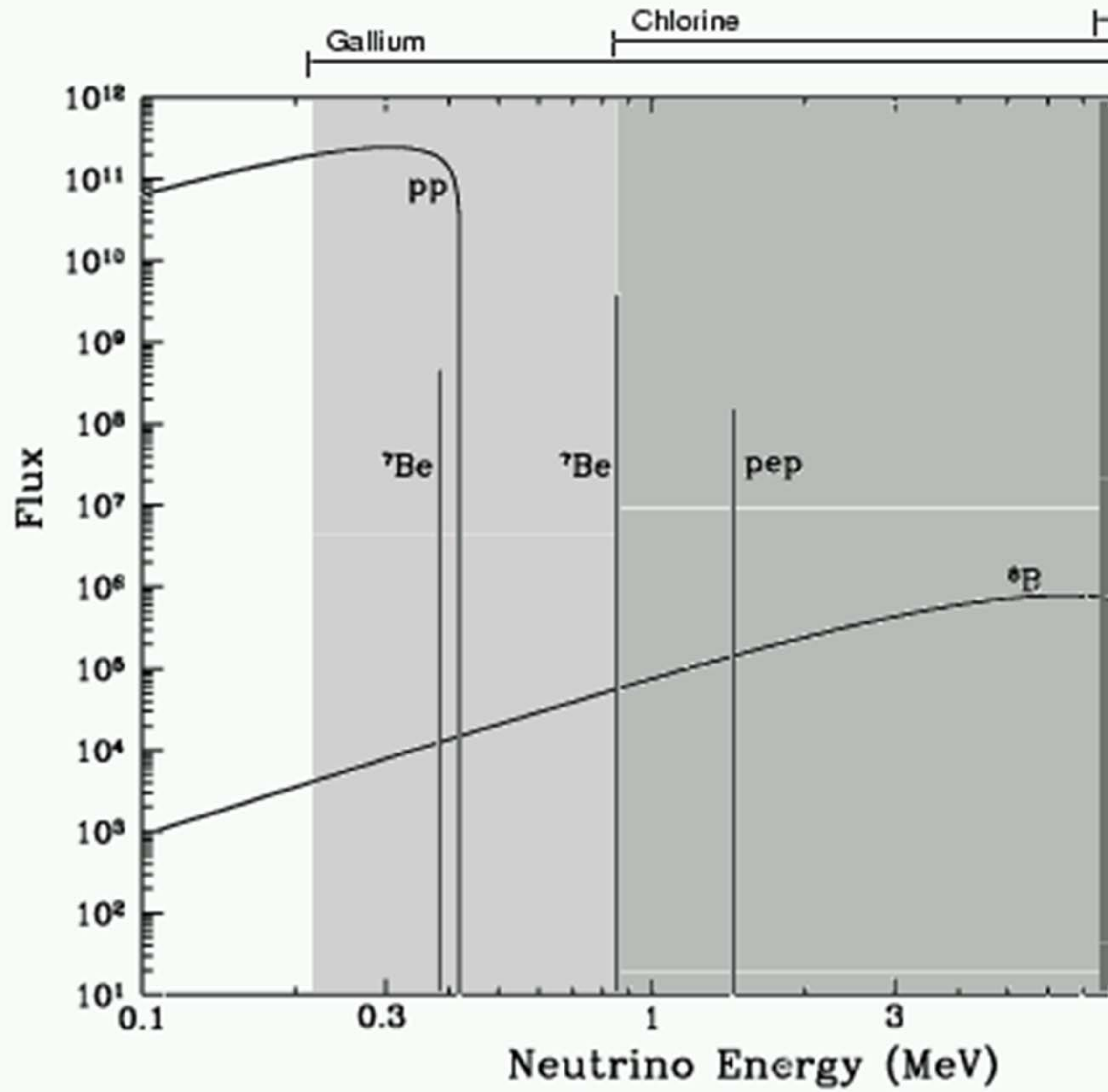
Sun	Atmosphere	Accelerators	Nuc po pla
			
ν_e	ν_μ:ν_e ~2:1	ν_μ	ν
10 MeV	~GeV	~GeV	<10 M
152 million	20-13,000	10-100's	10-10

ere are other sources, but these have contributed

00,000 neutrinos from the
n through every square cm
e Earth every second!







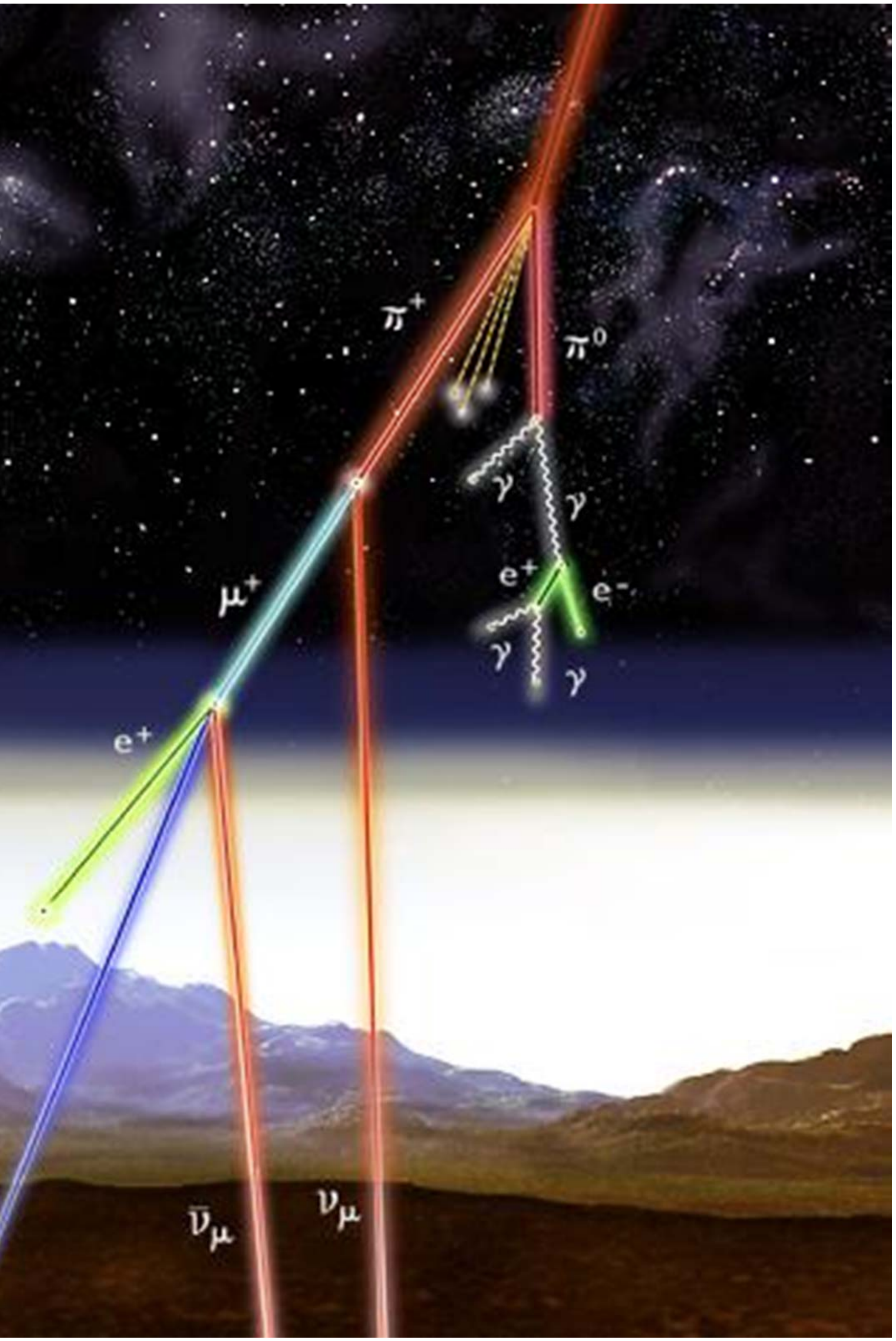
$p^+ \rightarrow\ ^2H + e^+ + \nu_e$

Solar Fusion

ral nuclear processes contribute.

mono-energetic and discrete energies.

uld be" all ν_e if no oscillations ! (why is this?)

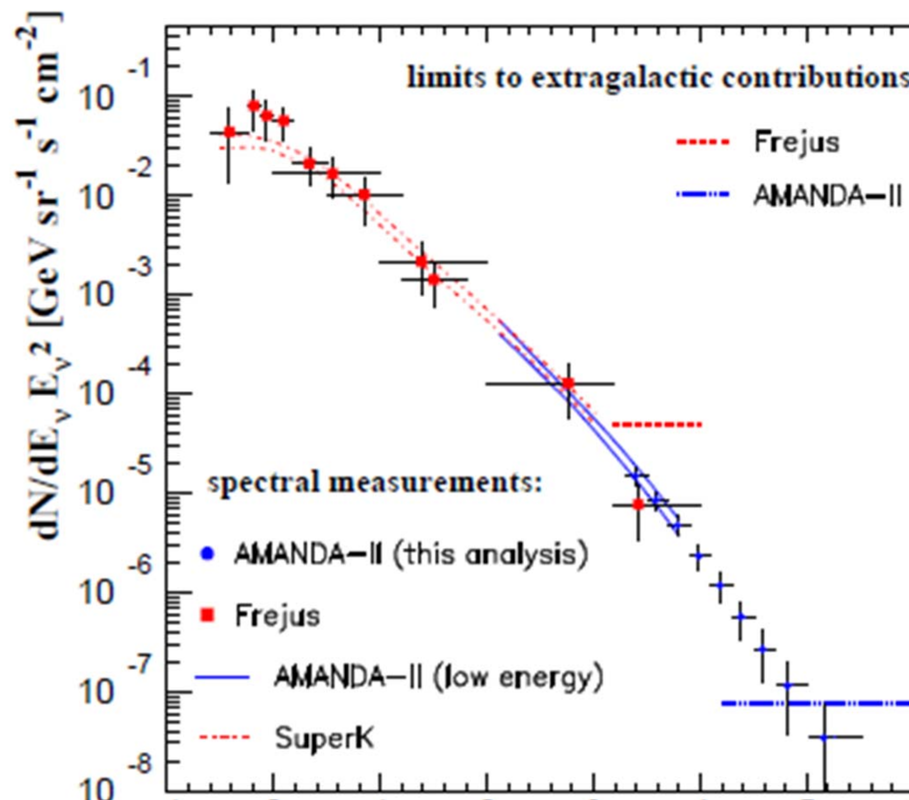


- $\pi^\pm$ produced in cosmic ray interactions
- The neutrinos mostly come from the d

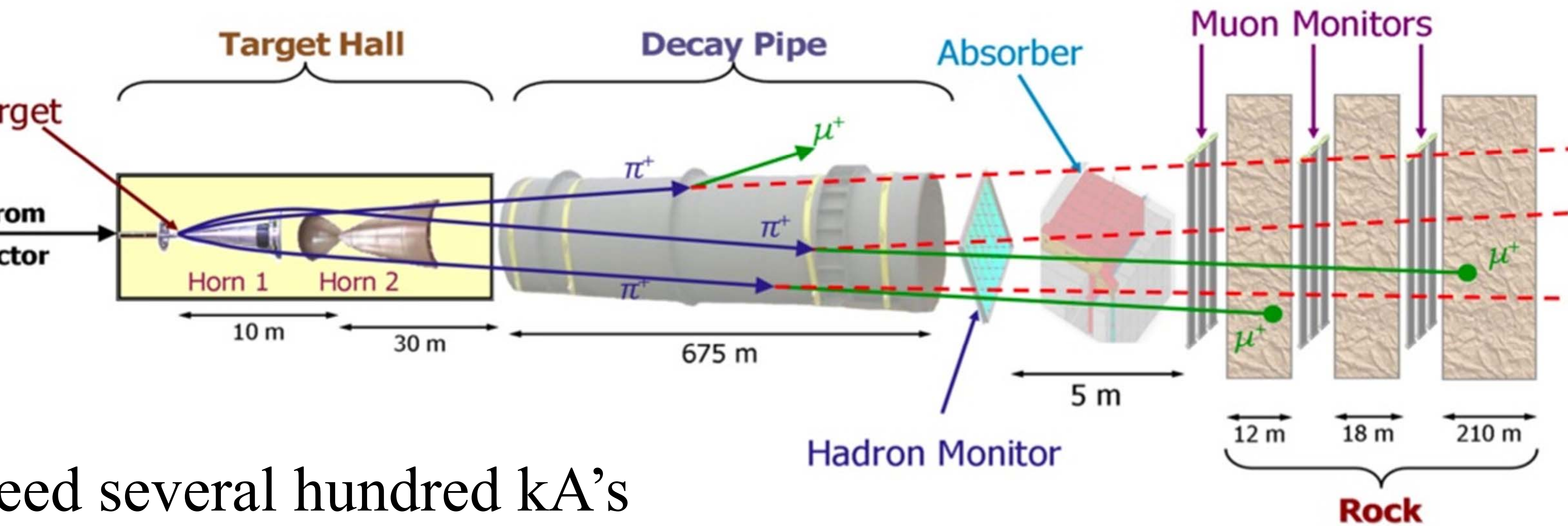
$$\pi^+ \to \mu^+ \nu_\mu \text{ then } \mu^+ \to e^+ \nu$$

$$\pi^- \to \mu^- \bar{\nu}_\mu \text{ then } \mu^- \to e^- \bar{\nu}$$

- Two μ-neutrinos for every one e-neutr
- Energies ~10^3X solar ν energies



Magnetic focusing "horns" steer the final-state hadrons from the proton-Target collision towards the neutrino experiment



eed several hundred kA's flowing through horns!

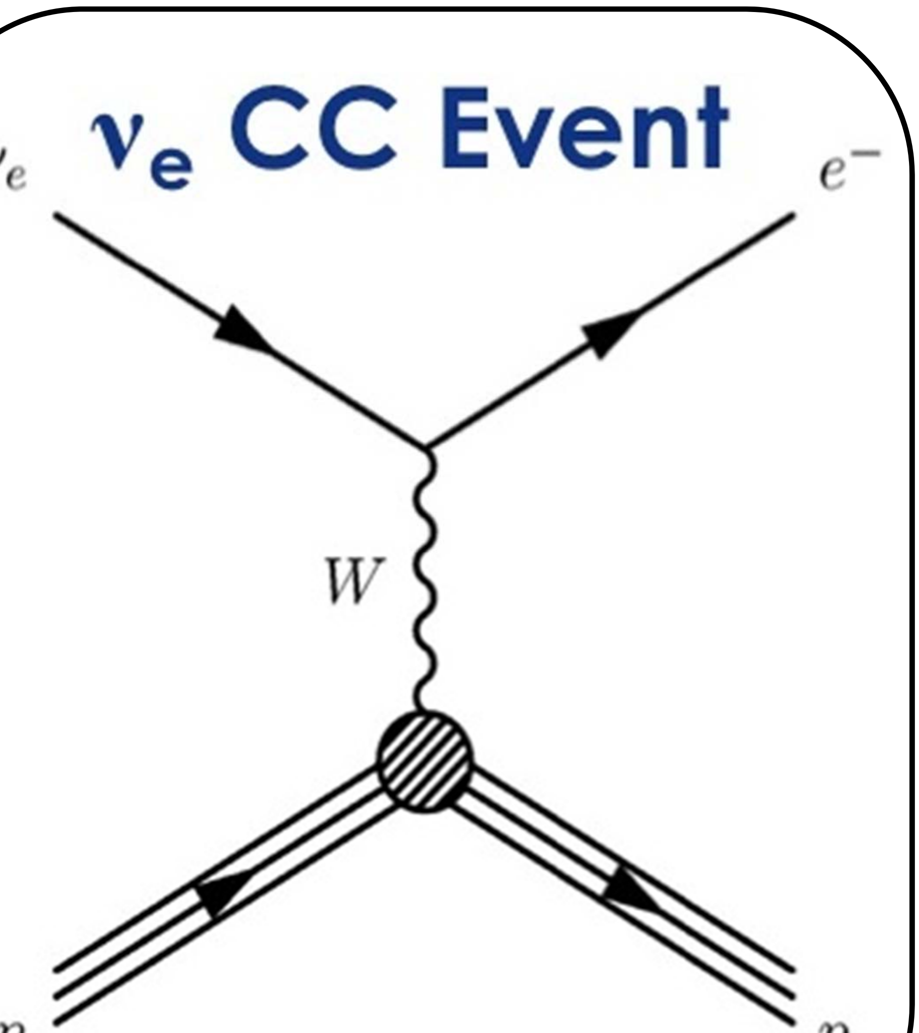
read of neutrino energies…. Good in many ways

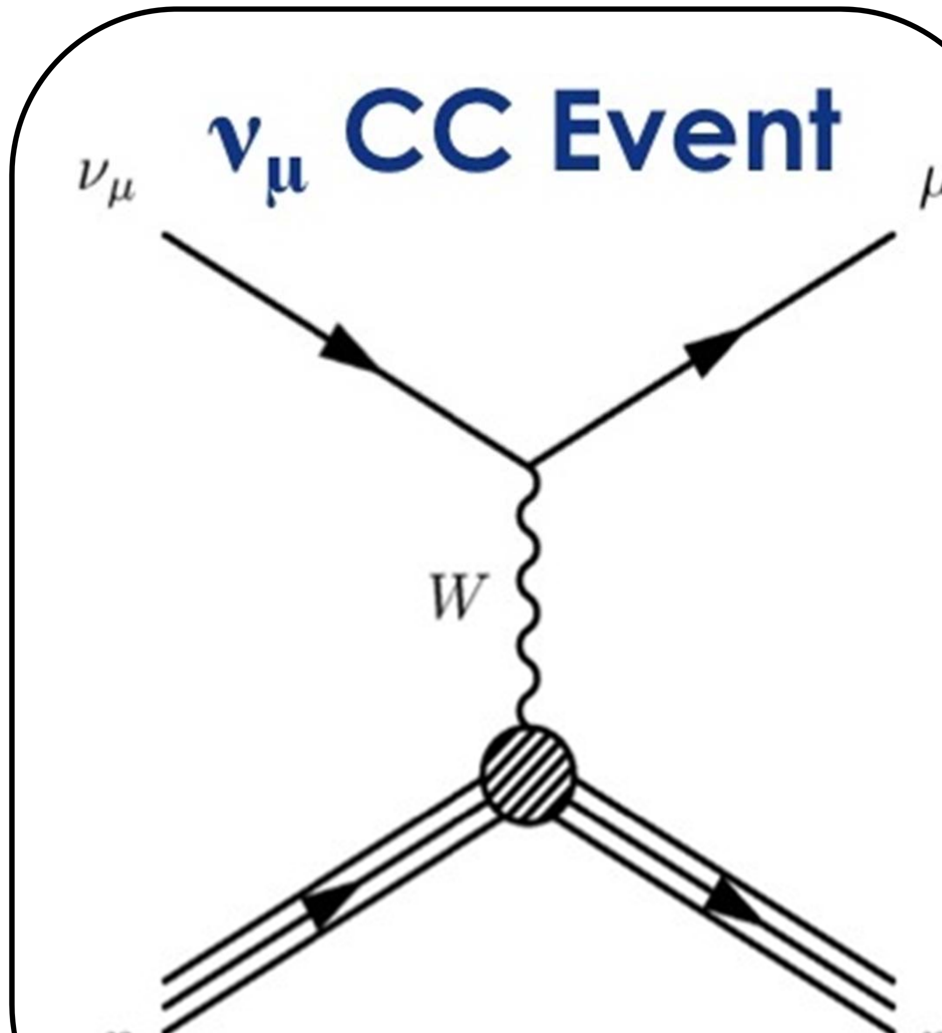
n get a beam of ~pure ν_μ!

cused, but still some divergence

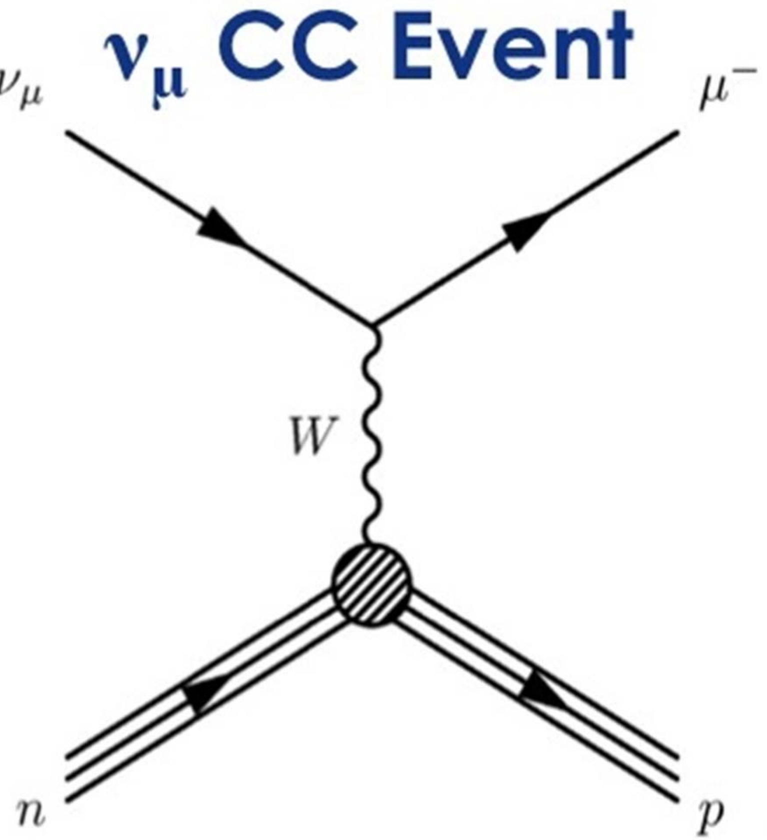
we can talk about detecting them, we have to kno
interact with matter! (coming up)
signatures do they have?

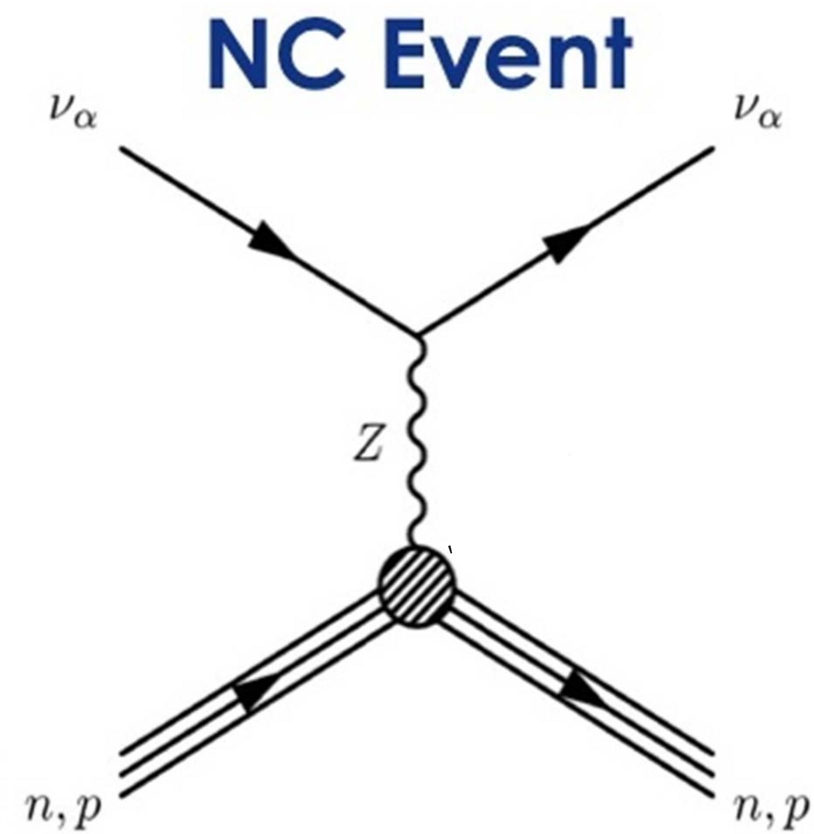
ator neutrino experiments look for oscillations by studying the data obse
ery pure beam of muon neutrinos is aimed at a far detector:
rance" - Do we see an excess of electron neutrino events?
pearance" - Do we see a deficit of muon neutrino events?
d-Current interactions are the "signal" events that allow the neutrino
ied, via identification of the charged lepton flavor.





so get interactions where the neutrino scatters off the nucleus by
ging a Z^0 boson. As the Z^0 is neutral, there is no change in charg





se a ν_e from the sun oscillated into a ν_μ.
u think you'd see the process on the left?

M(μ)=105 MeV/c2 ….and what were the typical energies of ν_e's from the su

eed to know type of neutrinos coming from the sou
N_{prod}(E)].

Often, have a "near" detector, which is close enoug
that neutrinos will not have had time to oscillate.

Let's say for concreteness, we know we produce ν

easure the ν_μ spectrum a distance L away [N_{far}(E)

$N_{far}(E) \neq N_{prod}(E)$ (after correcting for acceptance),
uld be evidence od neutrino oscillations.

he deviation consistent with:

$$P \quad = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{\quad})$$

theoretical speculation...flavor oscillations really happen!

98: Super Kamiokande experiment in Japan confirms neutrino oscillat

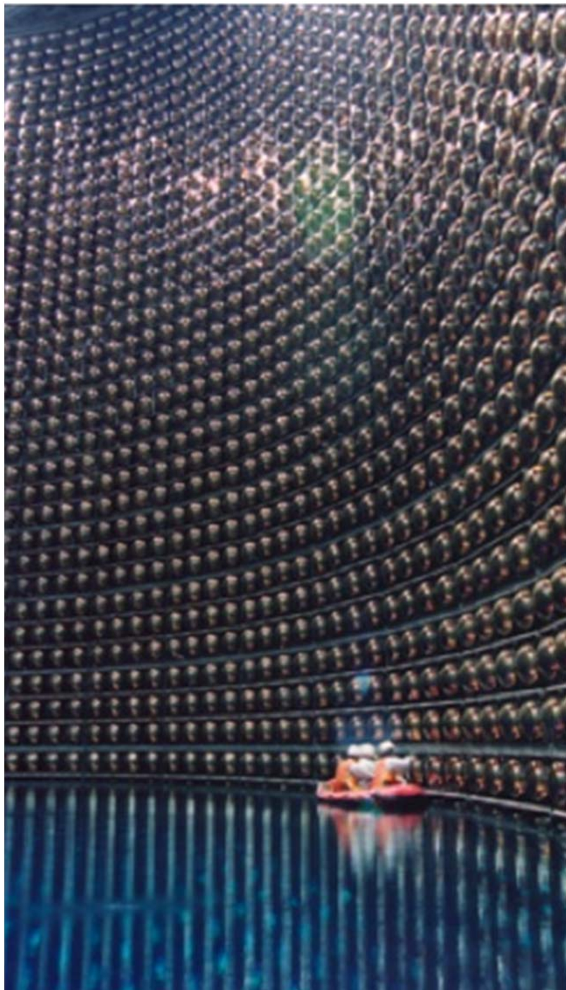
from **cosmic-rays** entering the Earth's atmosphere.

ons imply that neutrinos must have non-zero masses.

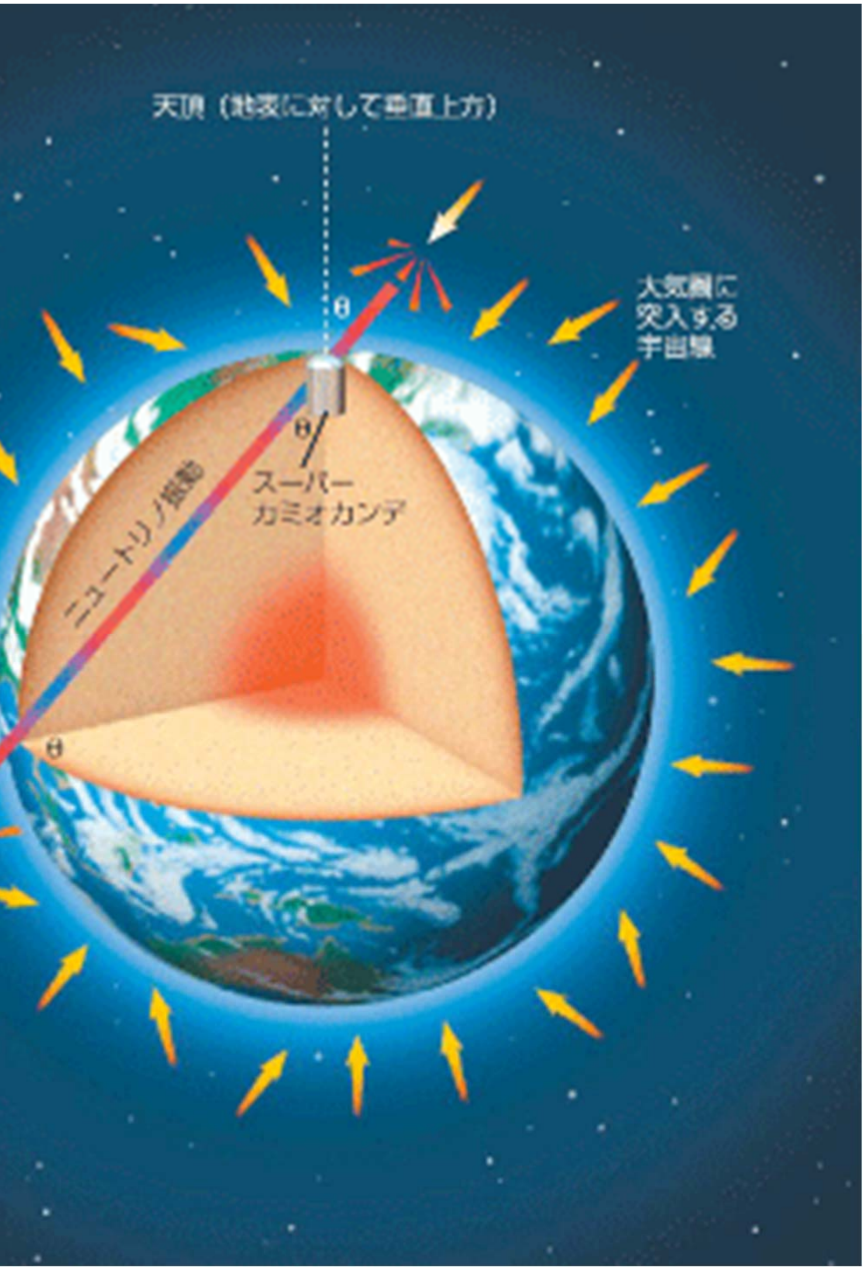
nt experiments confirm that Solar neutrino deficit originates from neutrino oscillat

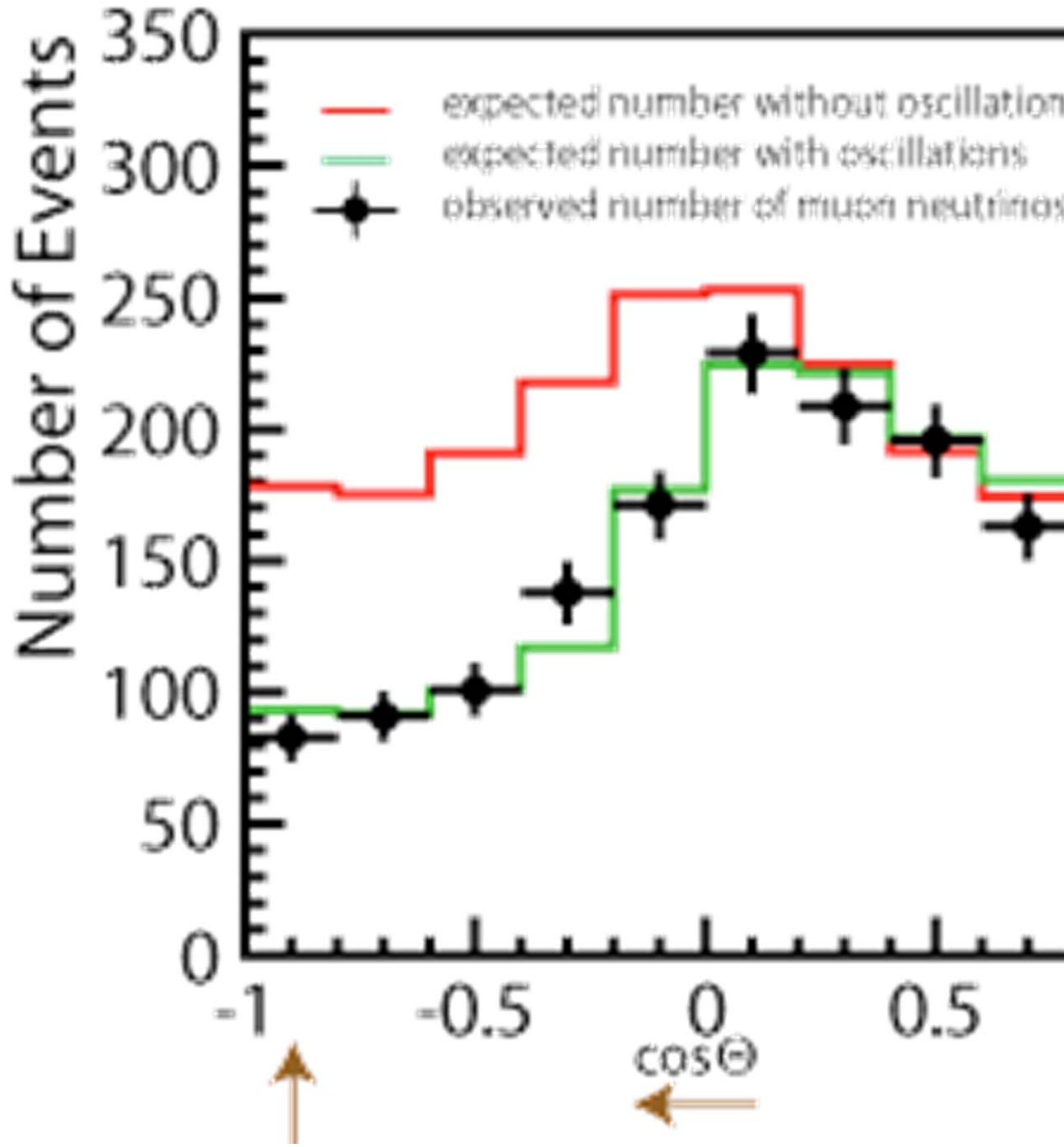
sterday in Japan, physicists announced a discovery that trinos have mass. Now, that may not mean much to nericans, but it may change our most fundamental -- from the nature of the smallest subatomic particles he universe itself works, and indeed how it expands." ger issue is that these kinds of findings have ions that are not limited to the laboratory. They affect e of society -- not only our economy, but our very view ur understanding of our relations with others, and our time."

- President Clinton at MIT commencement



, one controls “L” by looking at upward vs downward going neutr

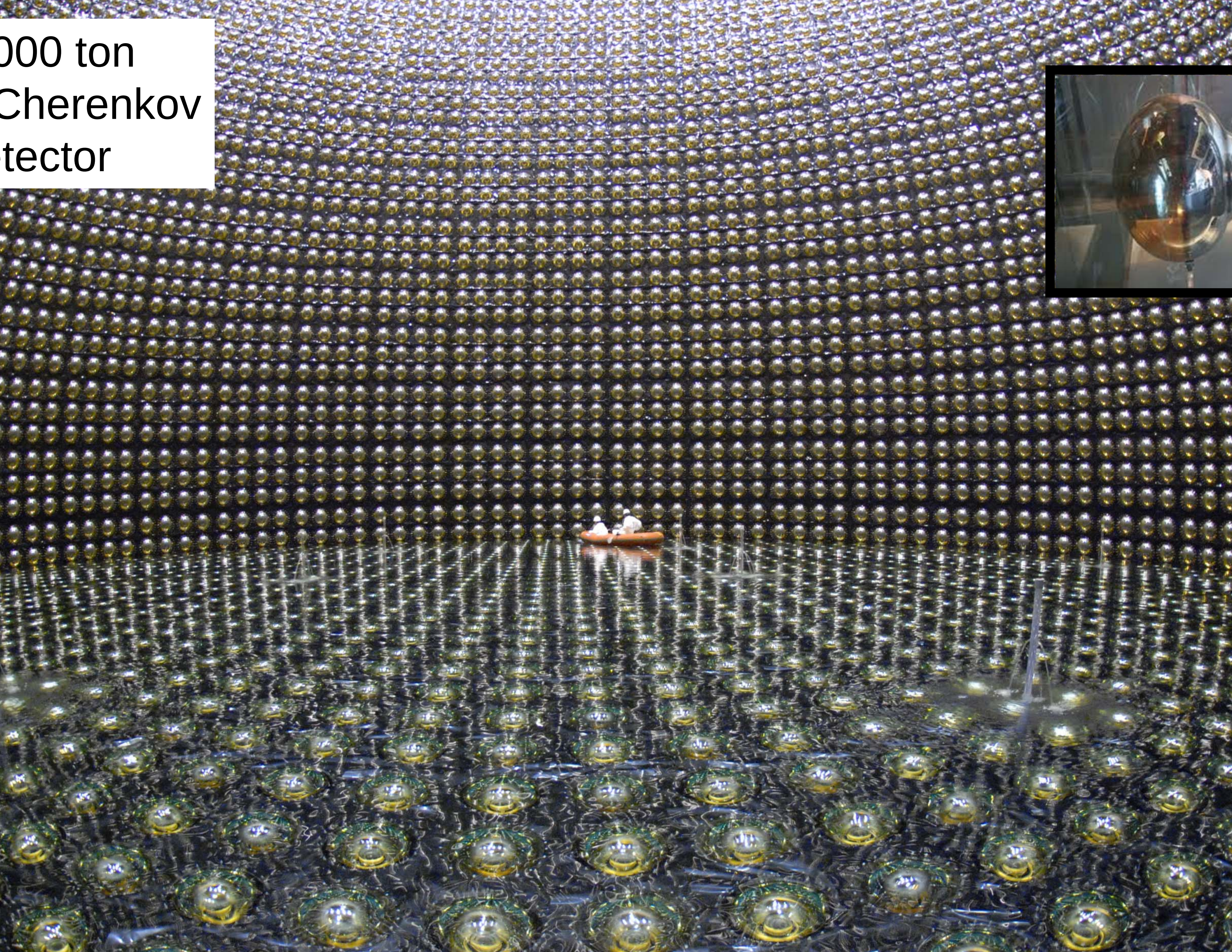




Upward going
L~13000 km

Dow
going

000 ton
Cherenkov
tector



ov Detectors.

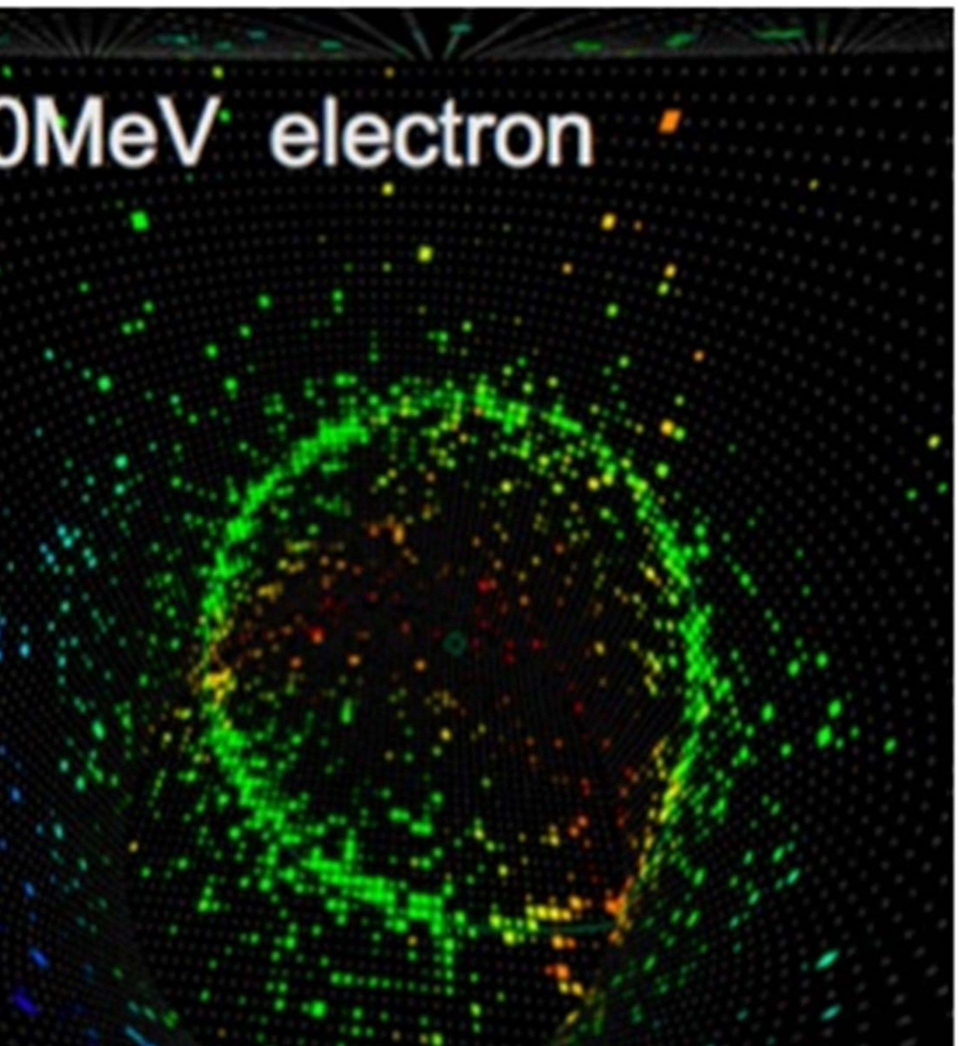
raversing medium faster than light emit Cerenkov light at a characteristic angle.

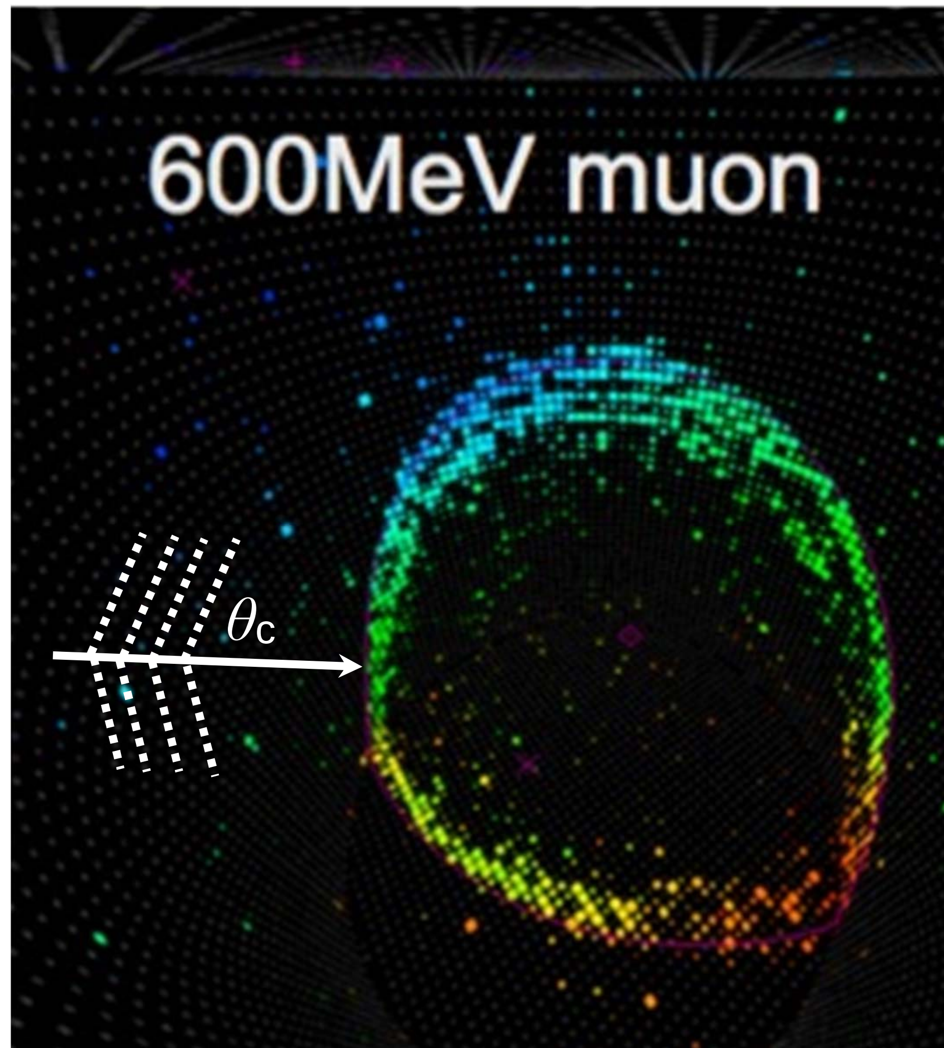
light collected and produces signals on PhotoMultiplier Tubes (PMTs)

s: straight trajectories lead to crisp rings

ons: showering and multiple scattering produce fuzzy rings

ecay into two gammas, which each appear as electron-like rings





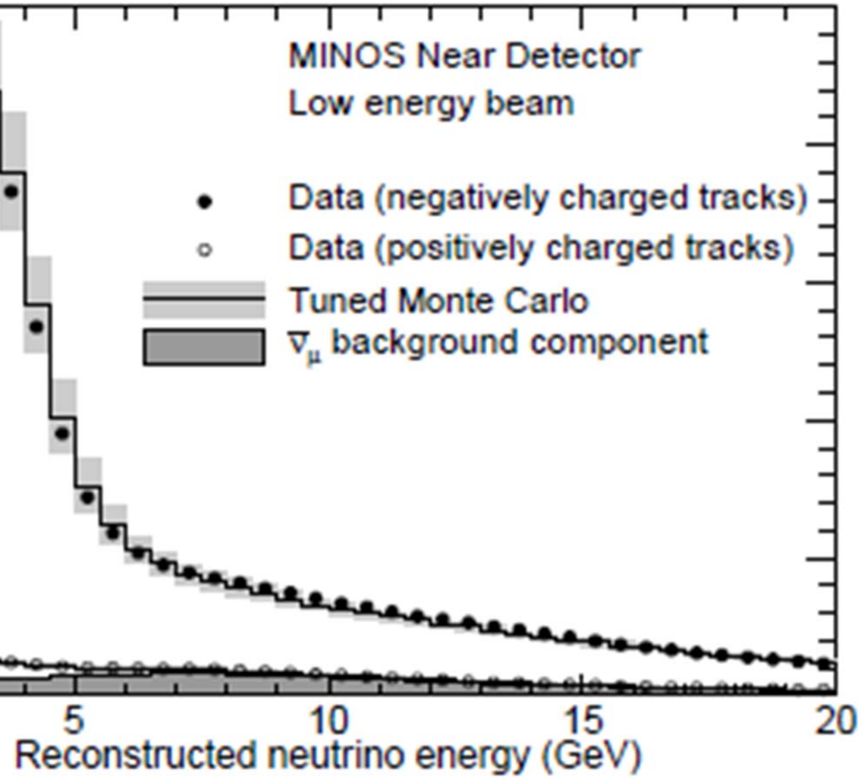
l neutrino experiments will be running in the coming years

OS still running for several more years.

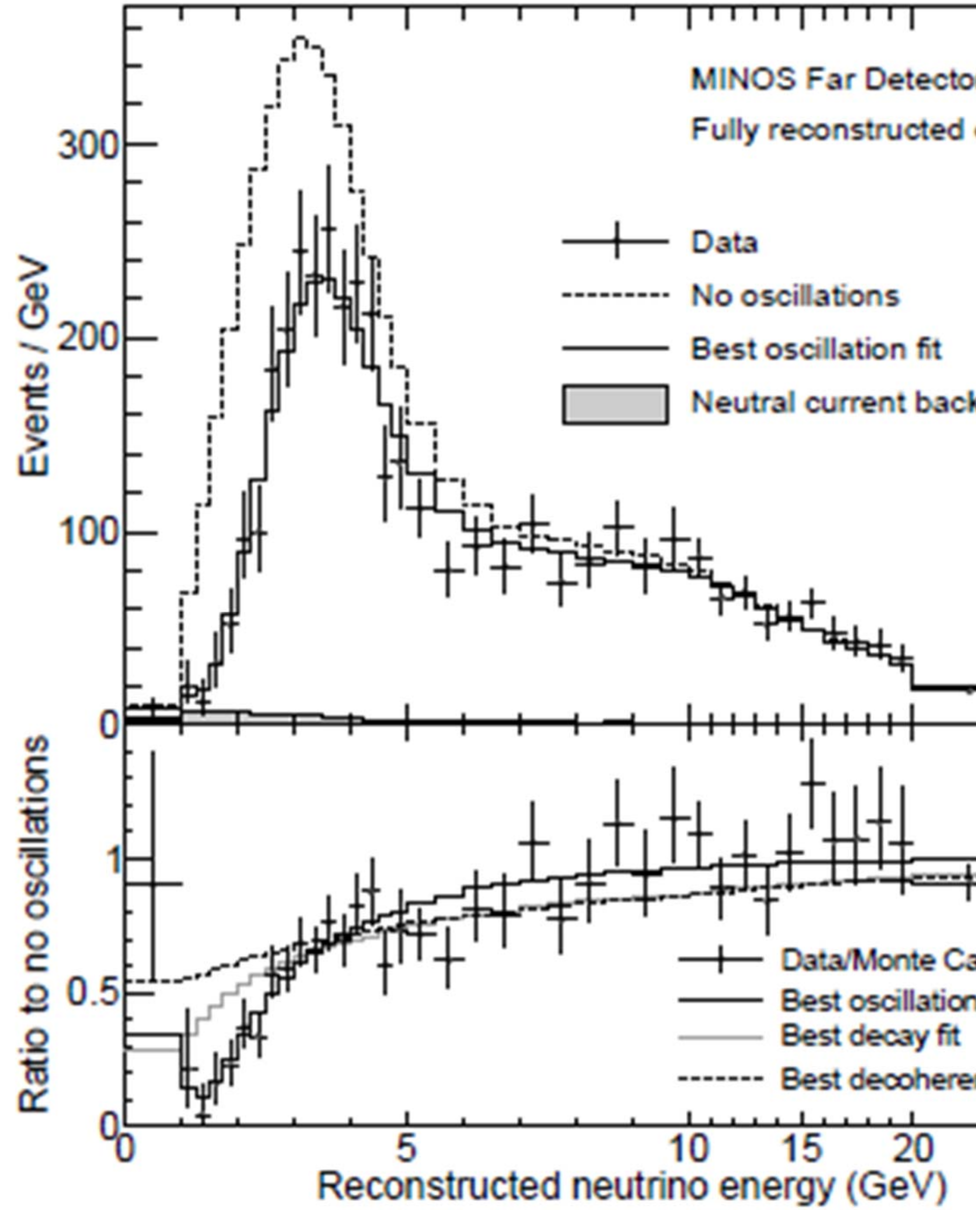
A (L=810km, 0.9° off-axis) construction has recently begun.

(L=295km, 2.5° off-axis) commissioning now in Japan.

ector reconstructed ν energy



Far detector reconstructed ν energ
and ratio to with no oscillation hyp



$$= \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E_\nu})$$

ar dip and rise as expected

$$\left|\Delta m^2\right| = \left(2.32 \pm 0.10\right)\times 10^{-3}$$

uclear reactors close by
ource of electron antineutrinos

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

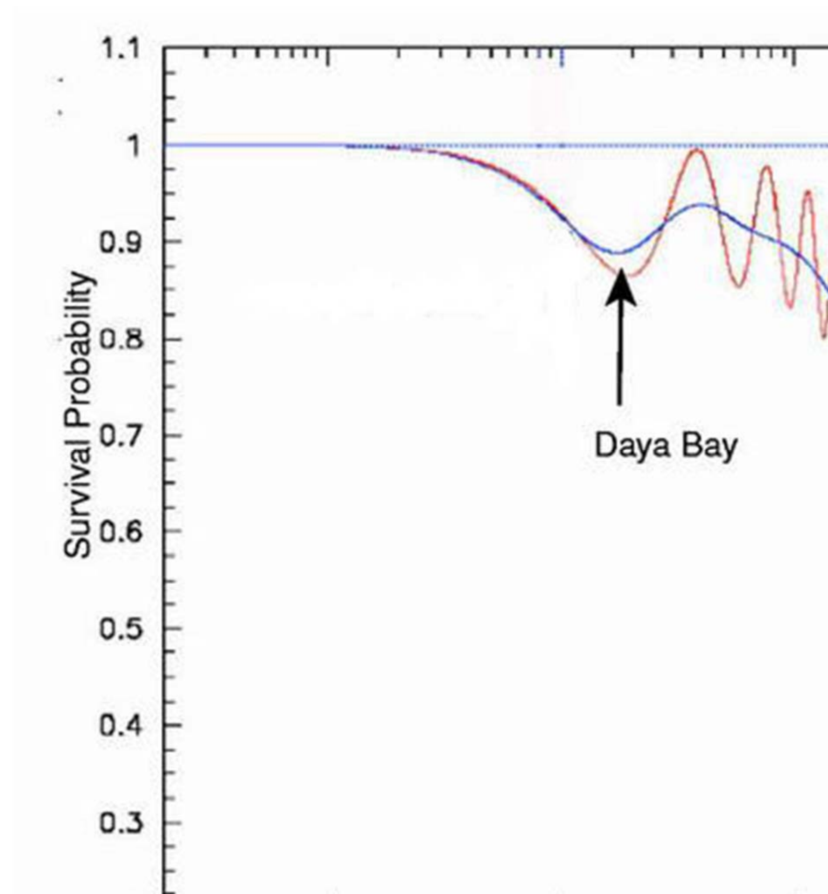
tage: ν flux is ~1000X larger
reviously mentioned sources !

Daya Bay Experiment in China (US, China, Eu

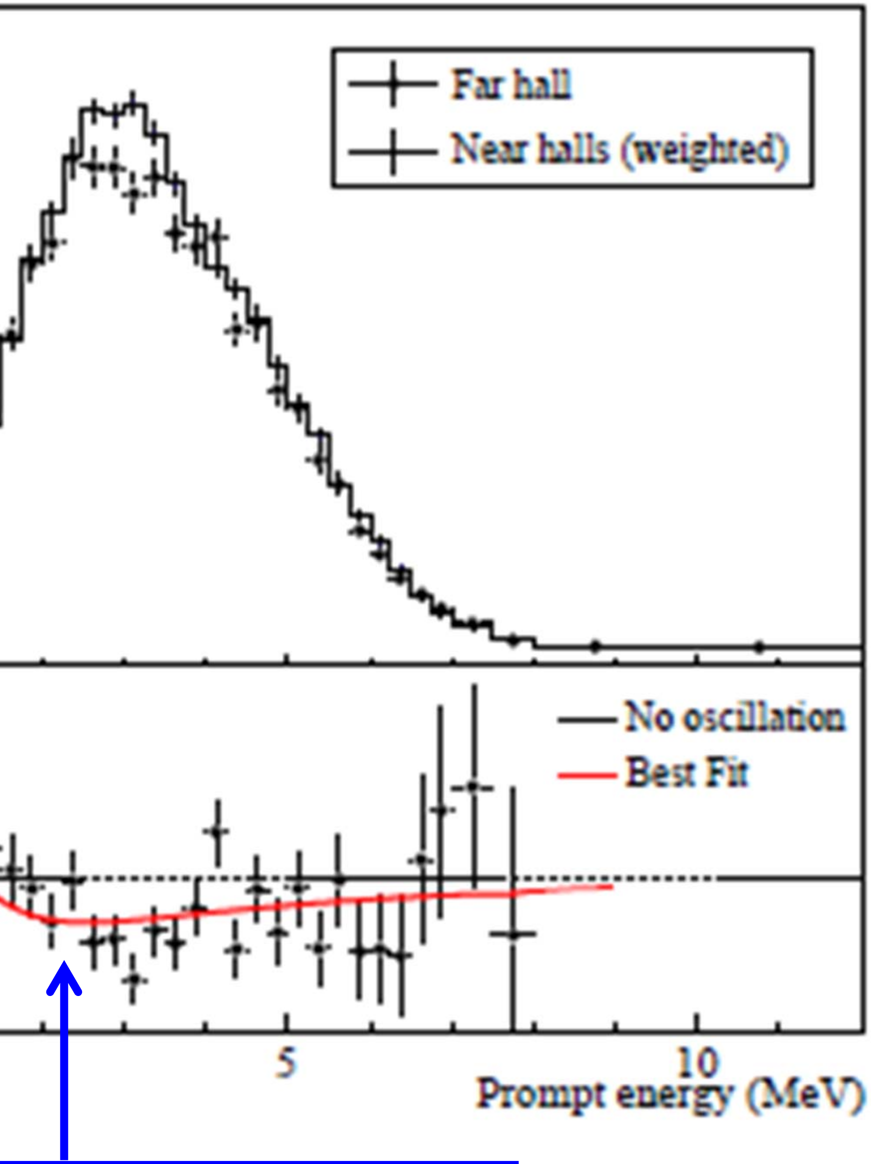
Detect $\bar{\nu}_e$ by inverse β-decay

$\bar{\nu}_e + p \rightarrow n + e^{+}$ (using same technique as Reines & Cowan!)

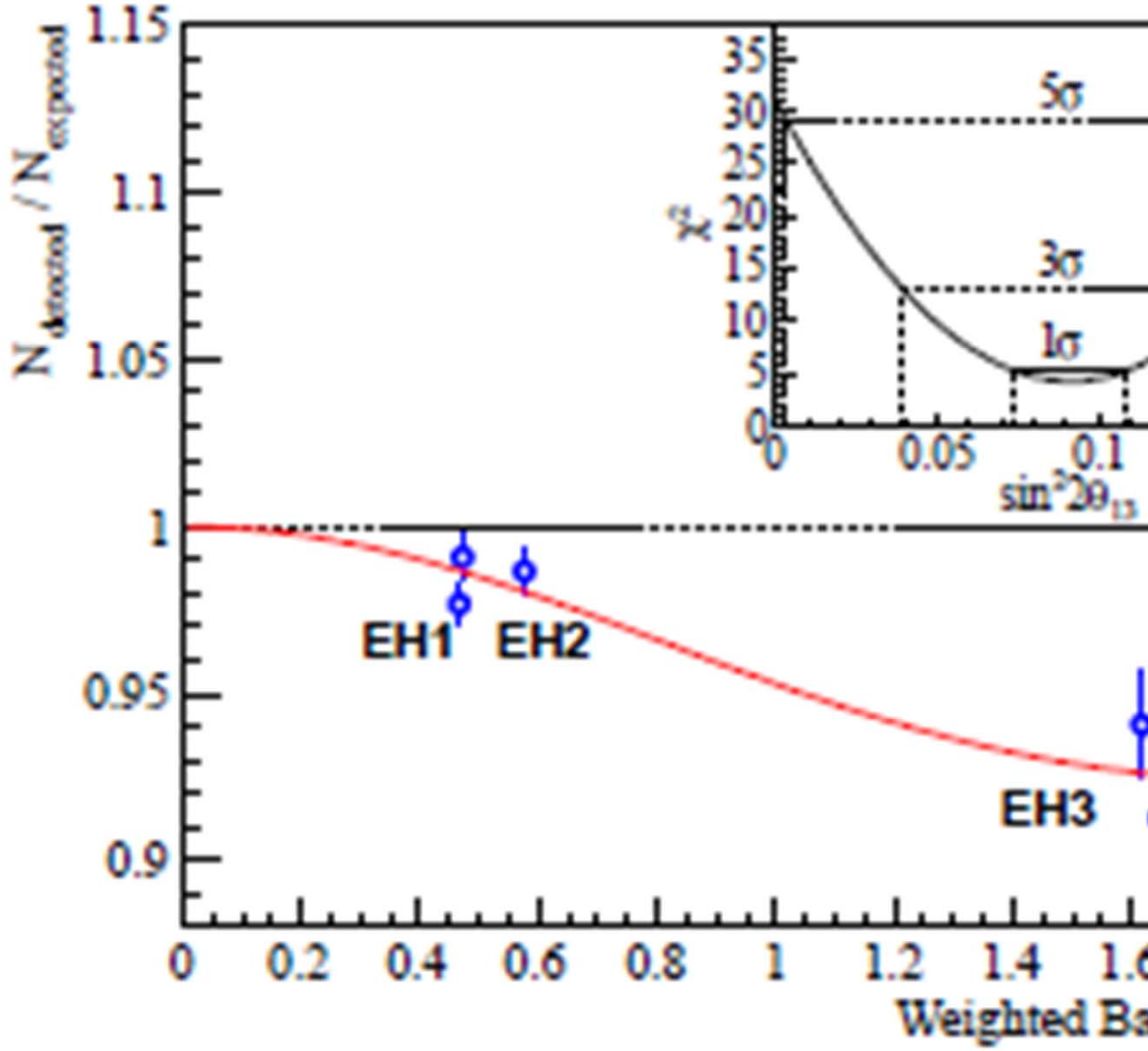
Distance tuned to be sensitive to mixing betwe
ν_1 and ν_3



cent …just this year



Maximum deficit
~10%. Recall
de of oscillation



$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016 \pm$$

ow there are three active flavors of neutrinos

corresponding mixing angles

independent Δm^2 (Δm_{12}^2 , Δm_{13}^2 [$\Delta m_{23}^2 = \Delta m_{13}^2 - \Delta m_{12}^2$])

he complex phase (allows for CP Violation, a critical necessity

produce the matter-antimatter asymmetry in the Universe)

$$= \left(\quad U \quad \right) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- U is a 3x3 mixing matrix (3 flavor
- Analogous to the 2x2 case for 2

  (But, 4 free parameters, as opposed t

o-Maki-Nakagawa-Sakata (PMNS) Mixing Matrix:

$$\begin{matrix} 0 & 0 \\ \cos(\theta_{23}) & \sin(\theta_{23}) \\ -\sin(\theta_{23}) & \cos(\theta_{23}) \end{matrix} \Bigg) \times \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \times \Bigg(\begin{matrix} \cos(\theta_{12}) & \sin(\\ -\sin(\theta_{12}) & \cos \\ 0 & \end{matrix}$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \end{pmatrix}$$

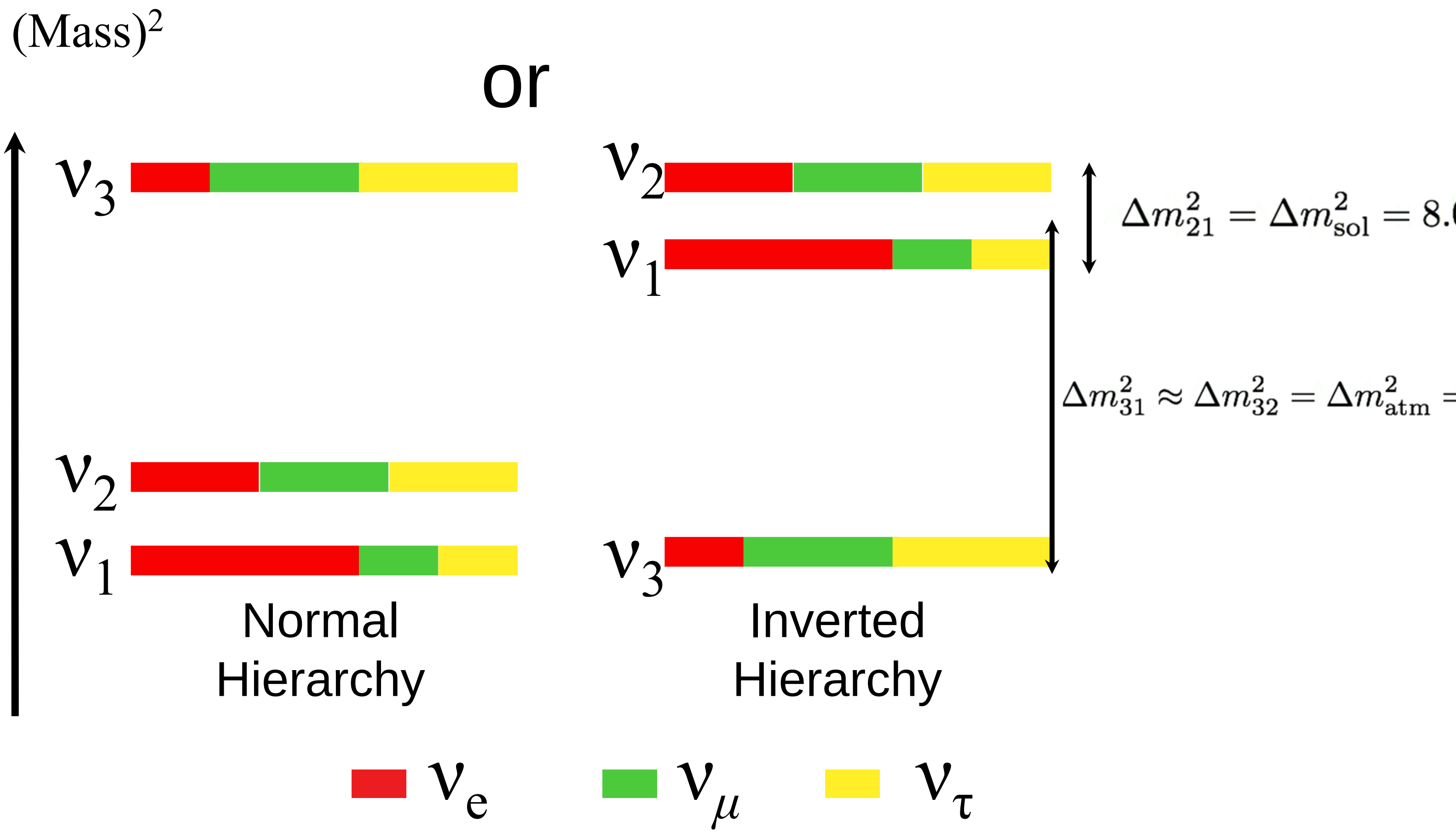
g angles and mass splittings are measured (w/some accuracy)

no mixing angles are quite large compared to those in

ark sector? Why?

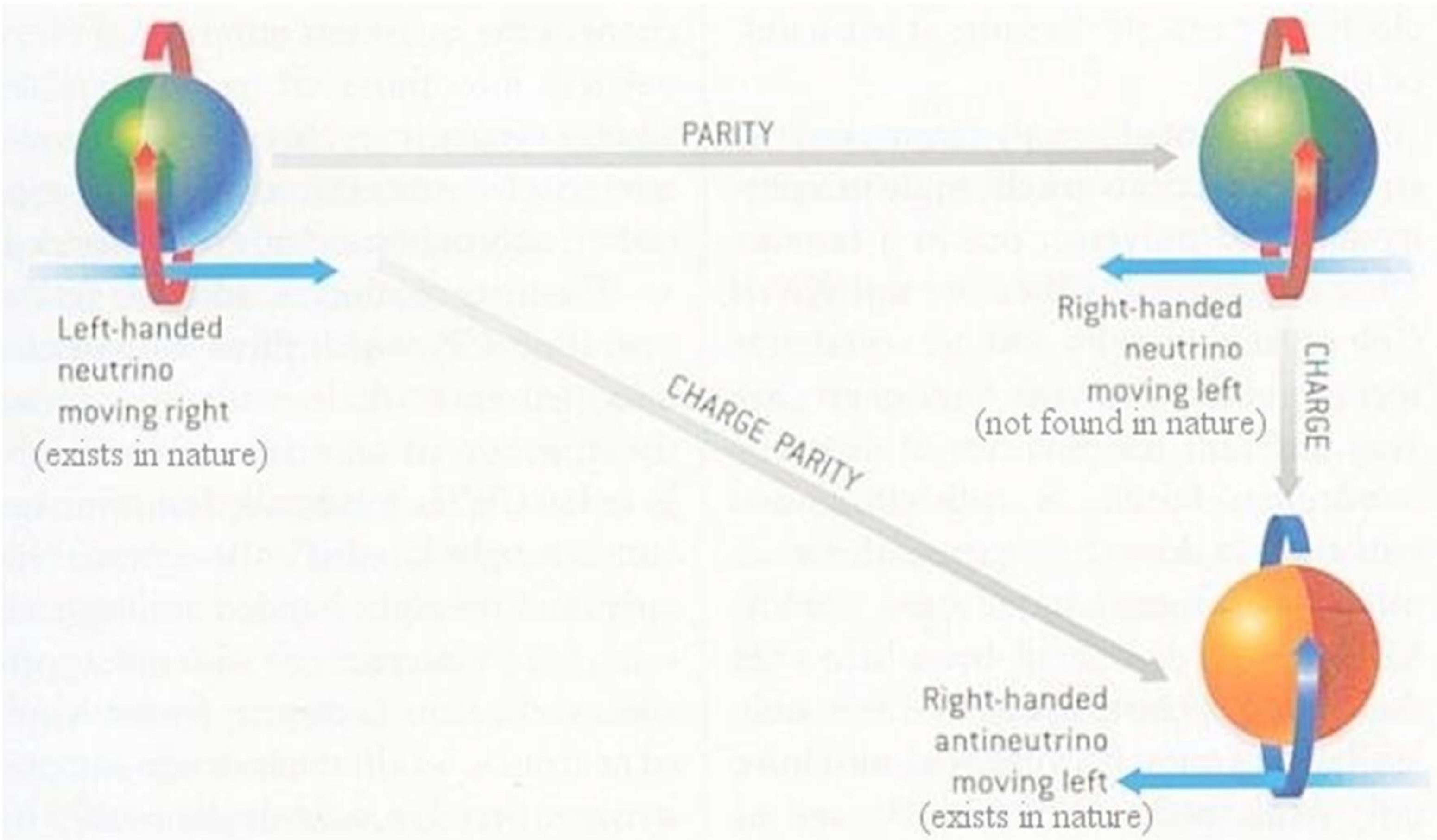
0.3 eV (Cosmological bound)

8×10^{-5} eV^2
2.4×10^{-3} eV^2
~34°
~37°
~9°
CPV?



at: $\Delta m_{12}^2 = m_1^2 - m_2^2$ does not tell us the absolute mass of eith

Charge Parity transformation.

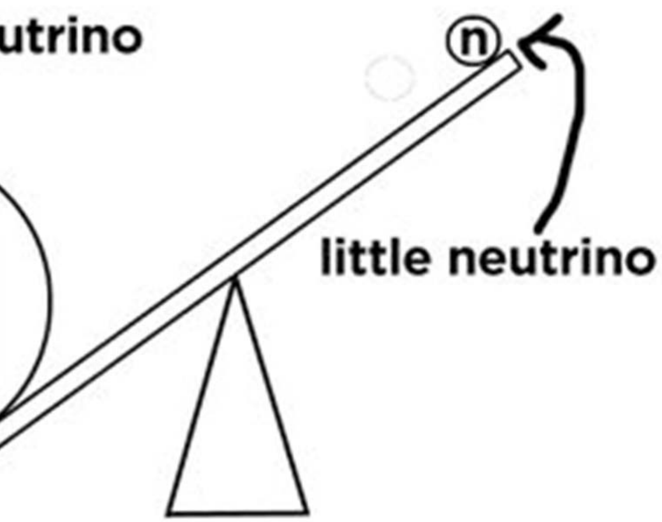


lation implies a process is not symmetric between matter and ter.

lation is believed to be a necessary ingredient to a Universe s (all matter and no antimatter)

ant for the future will be to measure the phase δ in the

genesis"+"Seesaw" - Postulates very heavy right-handed neutrinos (N) wit
ear the GUT (10^{15} GeV) scale, were produced in the Big Bang and underg
decay that violates CP.
neutrino decay creates an imbalance of charged-leptons, which gets conve
matter-antimatter asymmetry of the universe.
eavy right-handed heavy neutrinos violate CP, it's possible their light left-
might also.



eesaw Mechanism

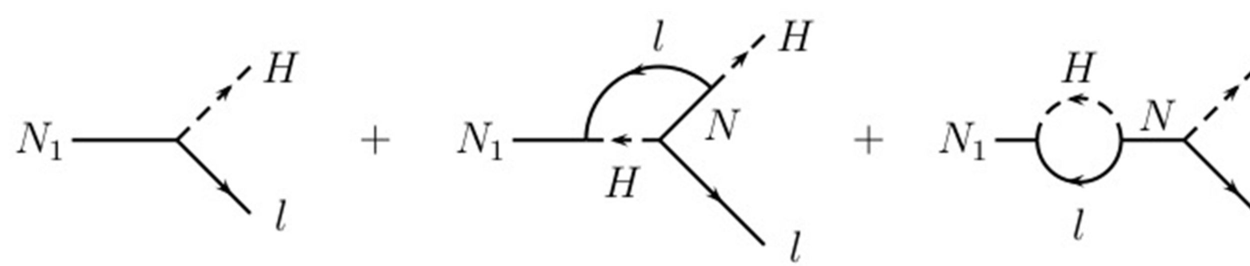


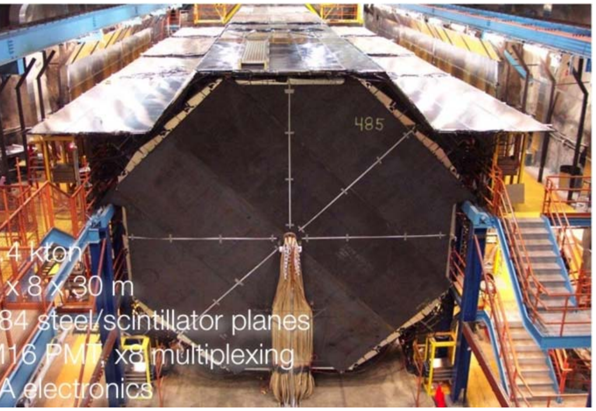
Figure 1: Tree level and one-loop diagrams contributing to heavy neutrino
interference leads to Leptogenesis.

...g calorimeter detectors.

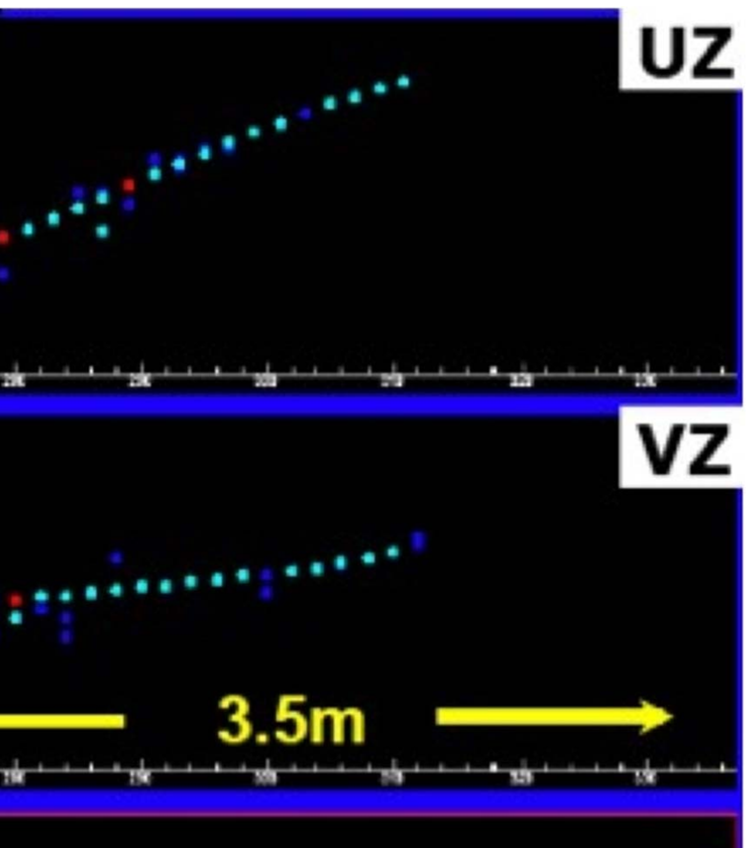
...ating strips distributed throughout detector that produce light when particles pass through.

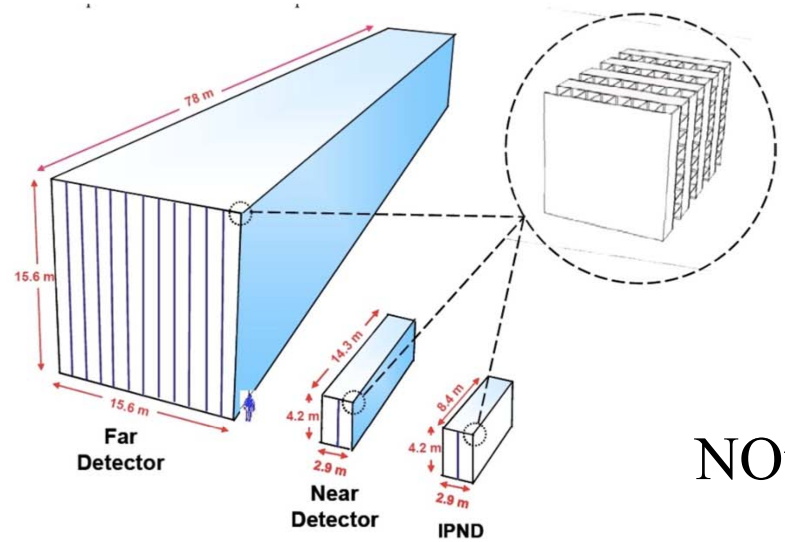
...ntillator light via fiber optic readout that connects to a PMT.

...t event in 3D by merging information from alternate coordinate views.

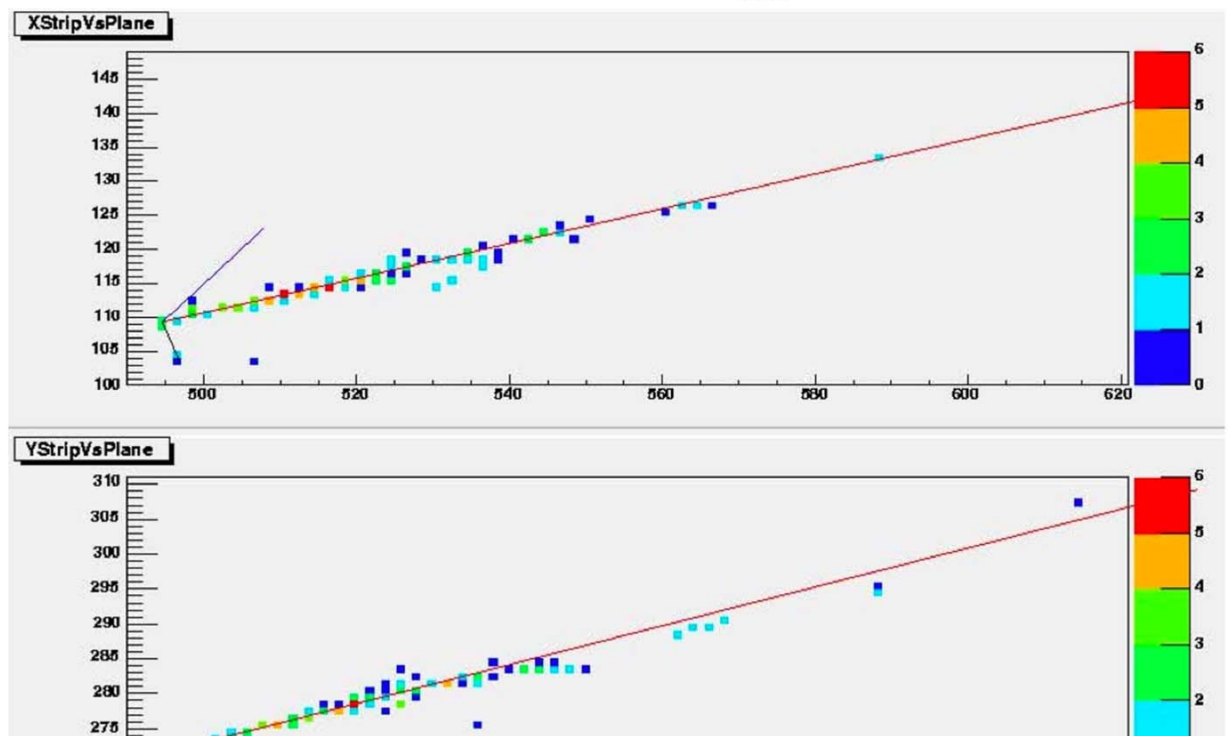


MINOS

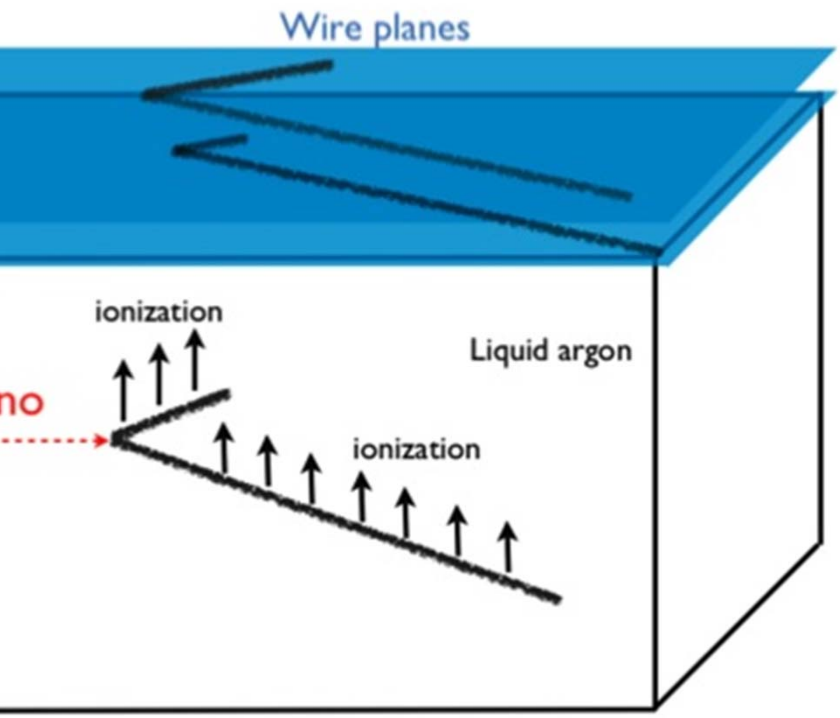


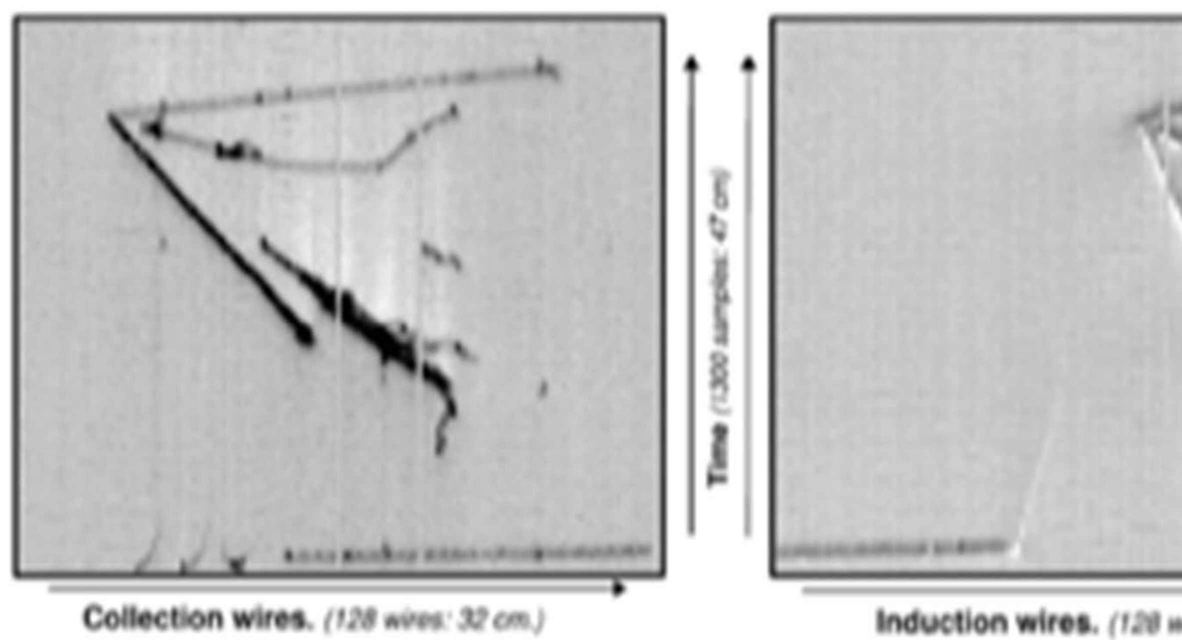


NOvA



eractions in the TPC produce charged particles that ionize the argon as they travel.
drifted along E-field to wireplanes, consisting of wires spaced a few millimeters apart.
wires within a plane provides position measurements...multiple planes give independent views.
ire pulse information is combined with known drift speed to determine drift-direction coordinate.
light also present, can be collected by Photomultiplier Tubes and used in triggering.
ap (1% atmosphere), fairly dense, and a source of abundant ionization/scintillation.





Images from ICARUS* 50-liter TPC.

*Pioneering LArTPC work done by the ICARUS colla

: ionization electrons and scintillation light can both be used for detection.

are highly purified (<0.1ppb), ionization can be drifted over long distances.

dielectric properties accommodate very large voltages.

re dense, so they make a good target for neutrinos.

relatively cheap and easy to obtain (1% of atmosphere).

	He	Ne	Ar	Kr	Xe
[K] @ 1atm	4.2	27.1	87.3	120.0	165.0
[g/cm^3]	0.125	1.2	1.4	2.4	3.0
ength [cm]	755.2	24.0	14.0	4.9	2.8
leV/cm]	0.24	1.4	2.1	3.0	3.8
on [γ/MeV]	19,000	30,000	40,000	25,000	42,000

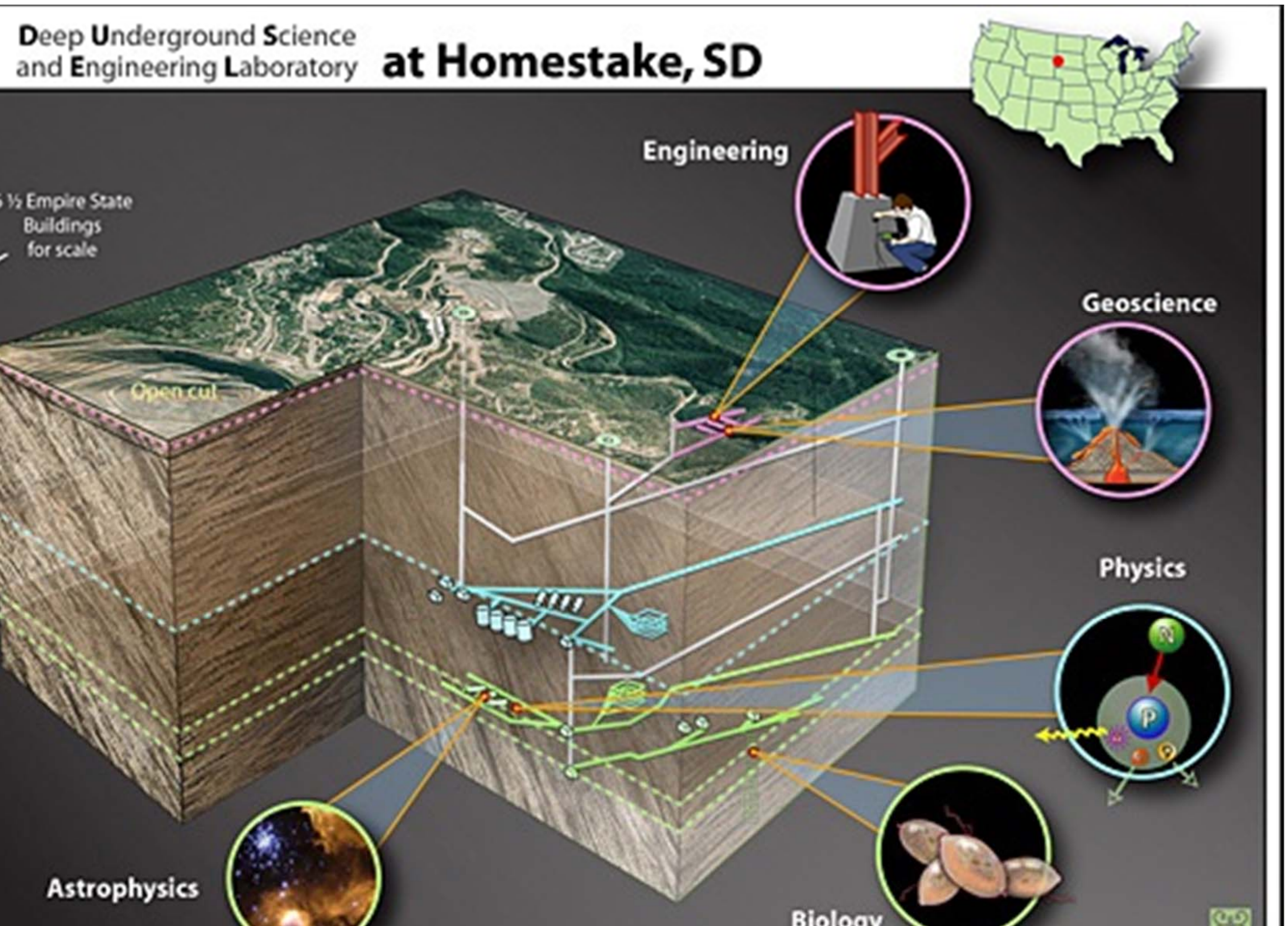
put this huge detector someplace deep to reduce cosmic background.

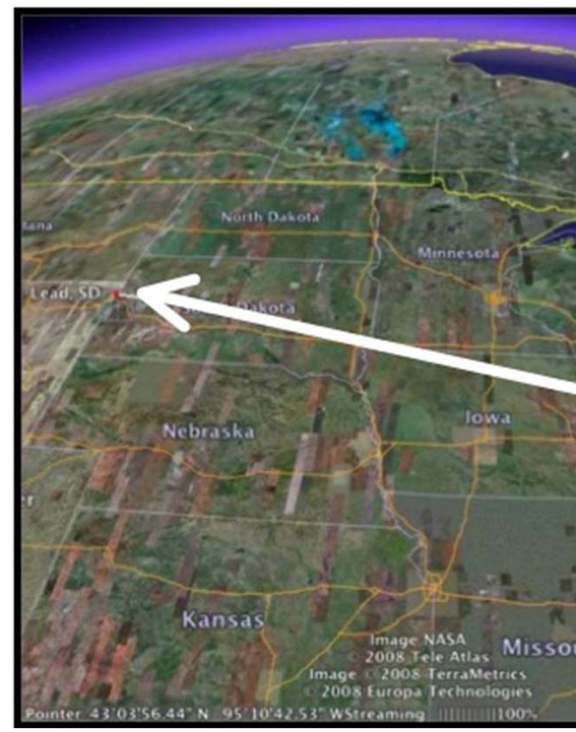
required is still unknown (could be 300ft. or 4800ft. level)

X" at Fermilab could send intense neutrino beam 1300km to this far-site location.

LBNE plan does not include Project X (starts with 700kW beam, and a large far-site detector module)

this to Project X (2.3MW) beam + more modules

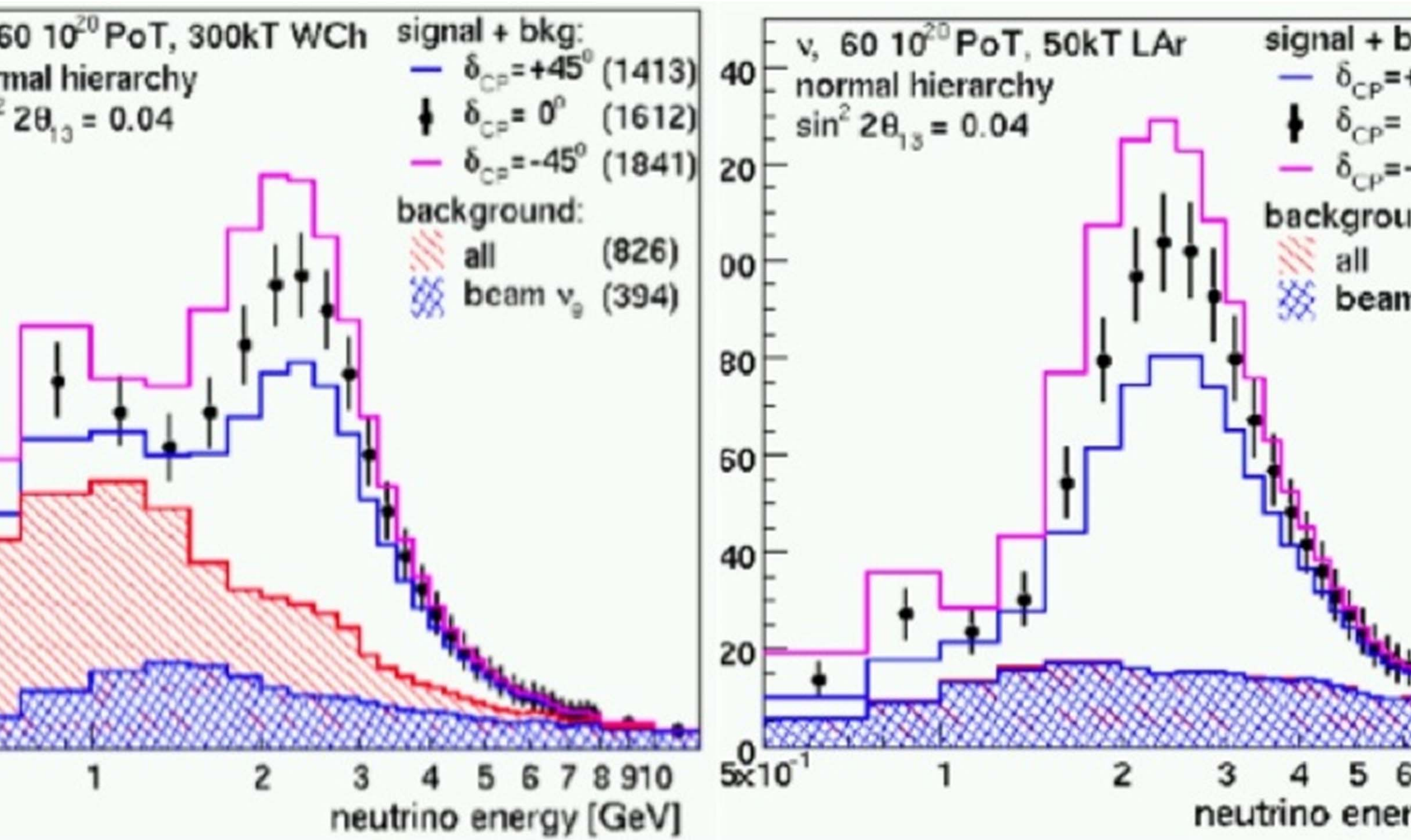




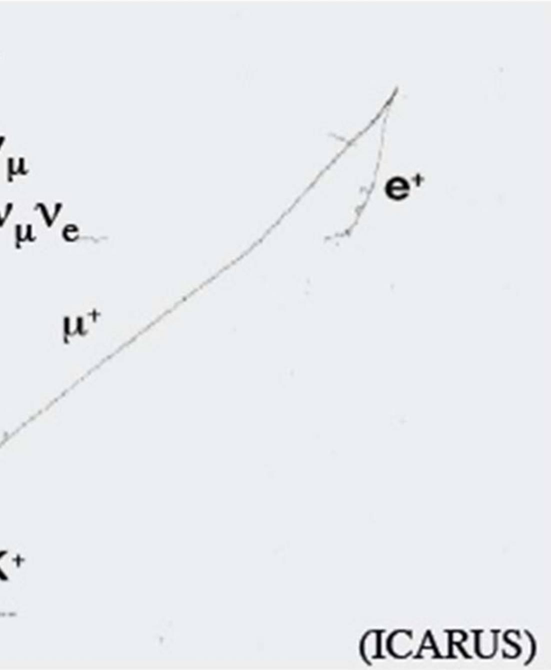
Neutrino beam f

Fermilab to DUS

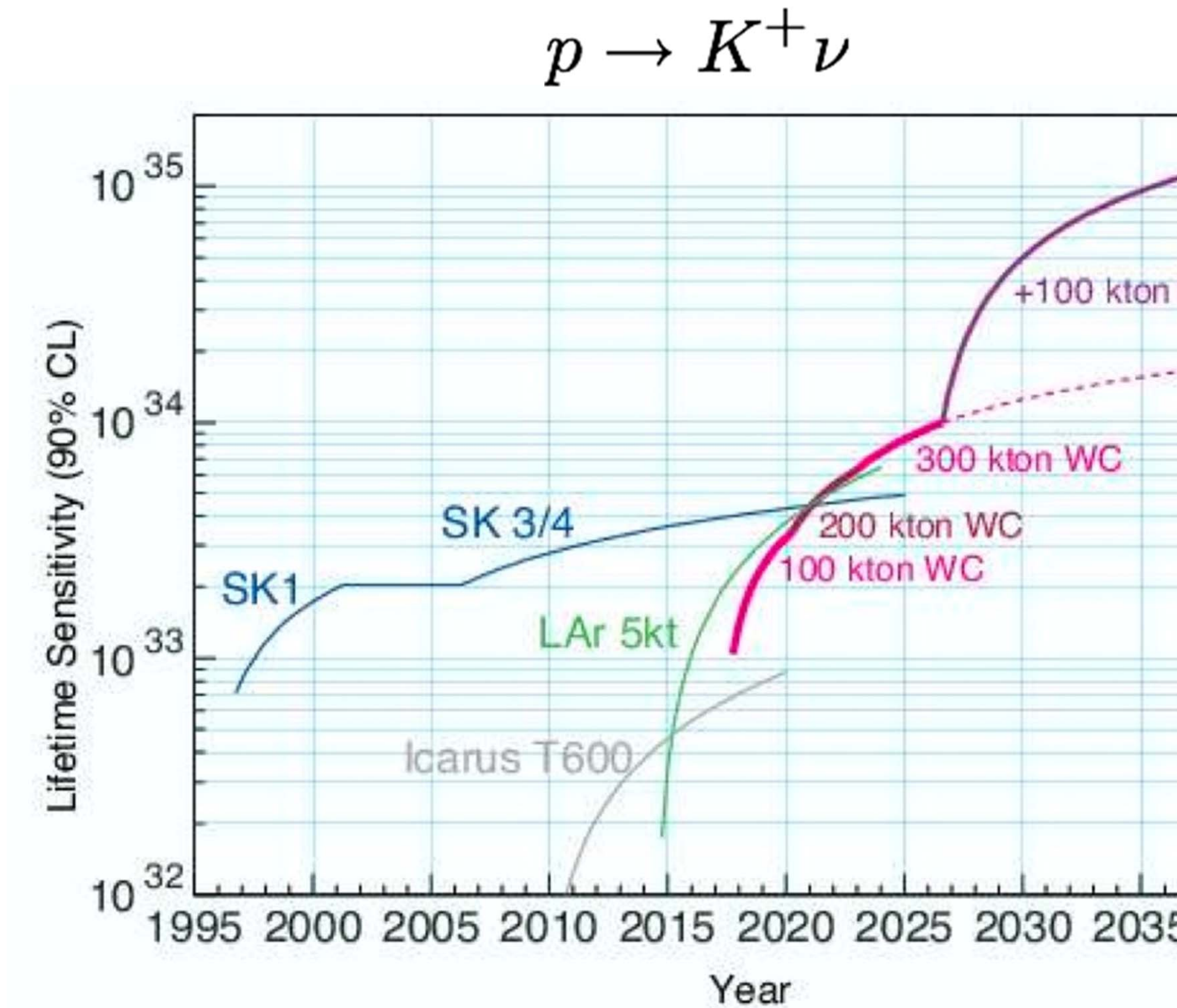
d "appearance" distributions:



BNE

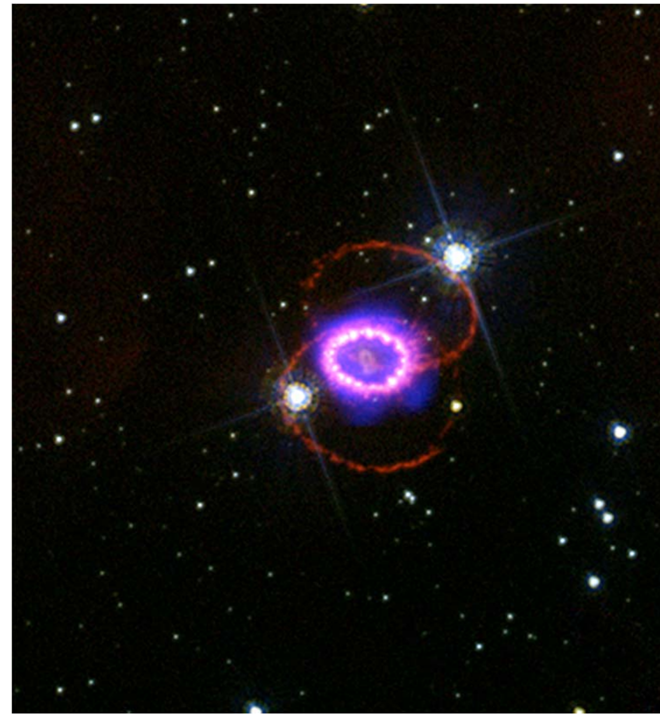


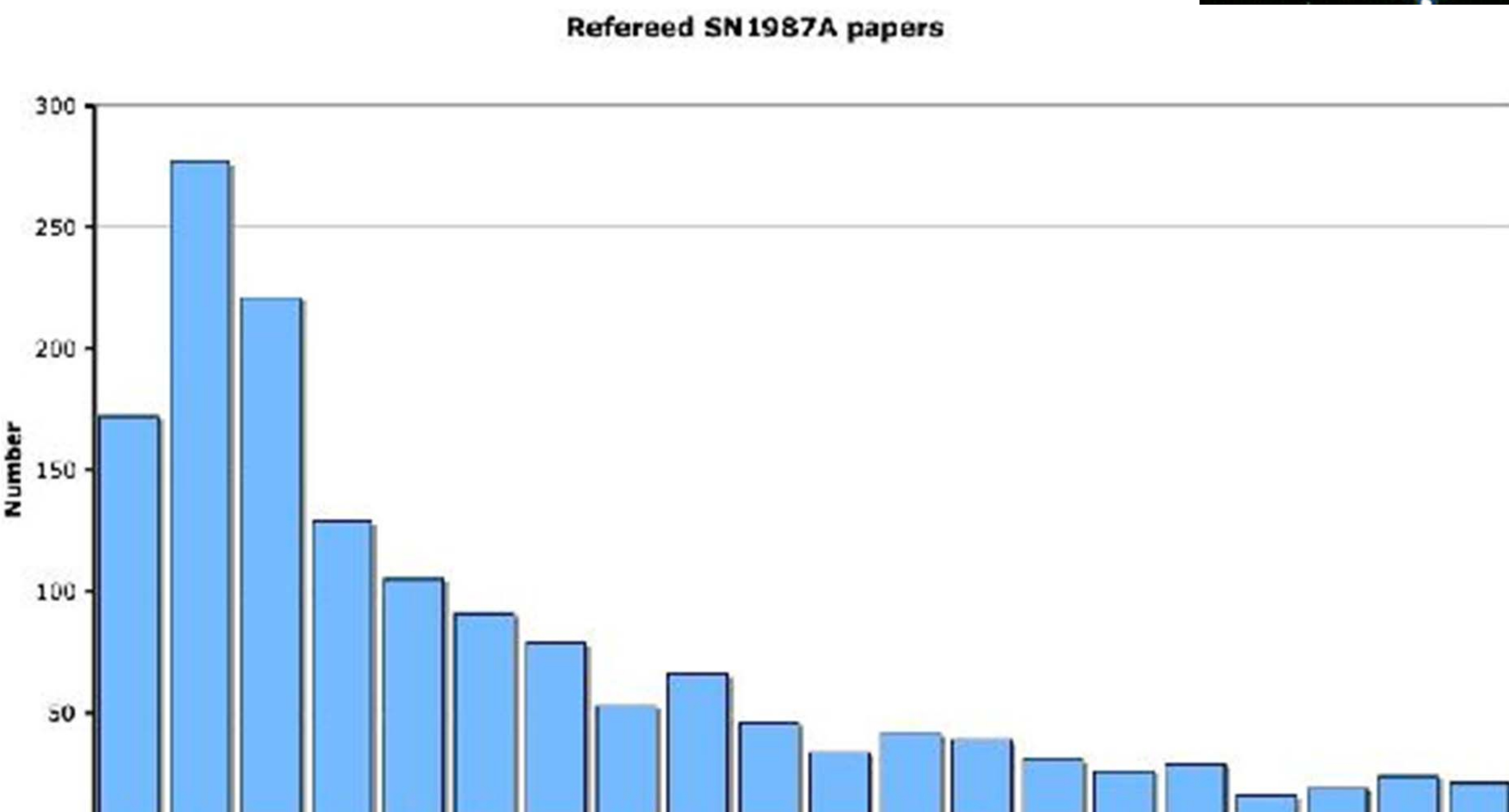
roton decay channel
is produced below
kov threshold, so
Cs have advantage.



me:
cy = 0.14
und = 1.2evts/100kty
cy = 0.98

uperNova happens, most of the energy is
way in a huge burst of neutrinos.
last ~10s, and includes neutrinos of all





an neutrinos oscillate?

eutrinos are made as either (ν_e, ν_μ) through the weak interaction. e.g $W^+ \rightarrow \mu^+\nu$

that quantum states will evolve as energy (mass) eigenstates

me-dependent S.E. is: $i\hbar \frac{d}{dt}\psi(t) = H\psi(t)$

l: $\psi(t) = e^{-\frac{i}{\hbar}Ht}\psi(0) = (1 - \frac{i}{\hbar}Ht + \frac{1}{2!}\left(\frac{i}{\hbar}Ht\right)^2 + \ldots)\psi(0),$

ow, the time-independent Schrodinger equation is: $\mathrm{H}\psi(0) = E\psi(0).$

ing this in the above then gives:

$$\psi(t) = e^{-\frac{i}{\hbar}Et}\psi(0)$$

ormal modes (eigenfunctions, in QM) evolve in time as

ergy (mass, since $E=mc^2$) eigenstates!