Finally about neutrinos.

We will simply do a calculation of the spectra and number of events that the LBNF/DUNE experiment will see.

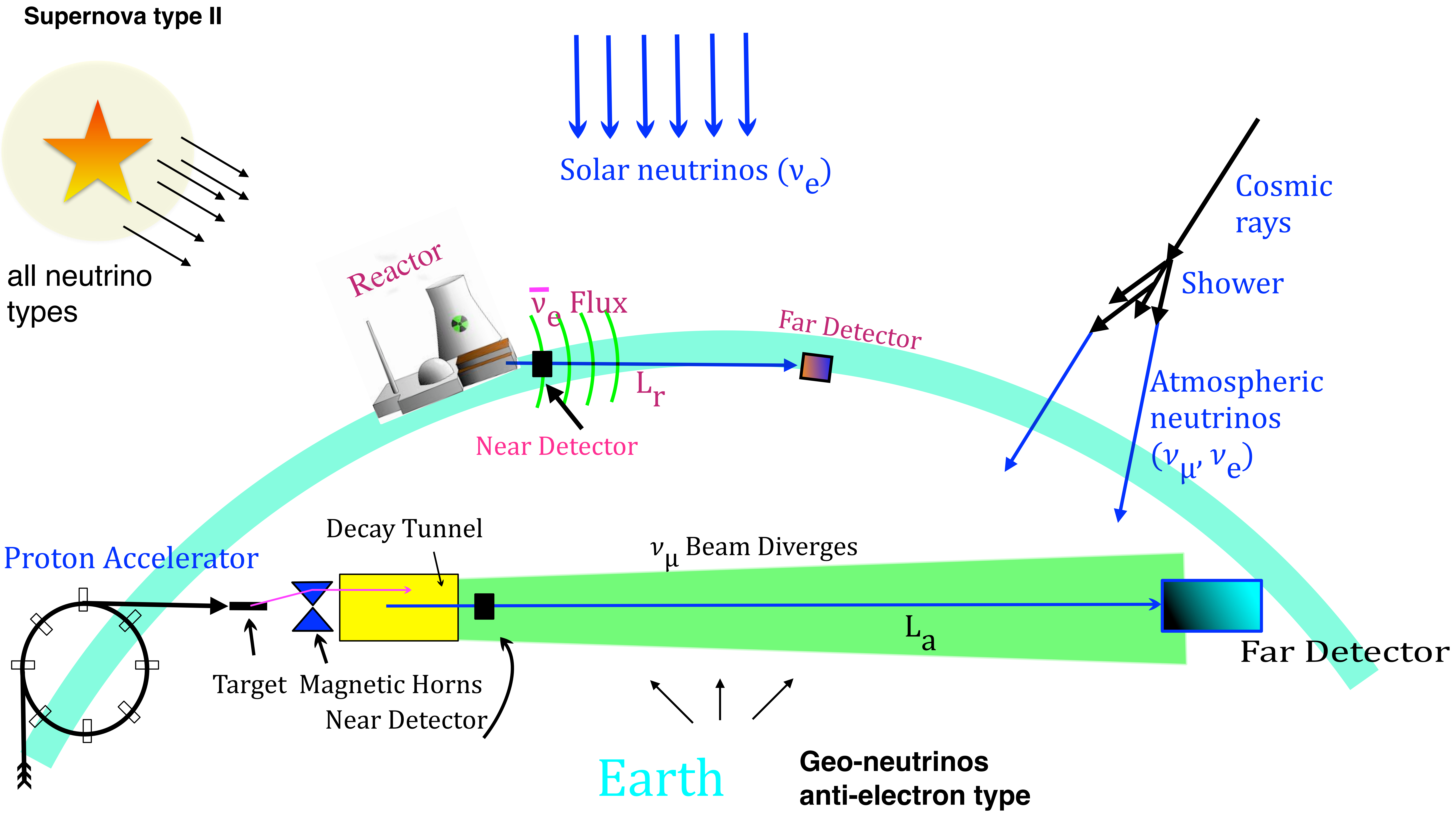
Neutrinos are particles that do not stick to ordinary matter. They are emitted in radioactive decays. We learned this earlier.

Why bother with them ?   Well, because we have recently learned that we know nothing about 90% of the matter around us, and we need to know. There may be aliens hiding in that dark matter !

Also, what about anti-matter ? Where is it in the universe ?

Milind Diwan, June 15, 2023

Neutrino Sources



Supernova type II

all neutrino types

Solar neutrinos (ν_e)

Cosmic rays

Shower

Atmospheric neutrinos (ν_μ, ν_e)

Reactor

$\bar{\nu}_e$ Flux

Far Detector

L_r

Near Detector

Proton Accelerator

Decay Tunnel

ν_μ Beam Diverges

L_a

Far Detector

Target Magnetic Horns

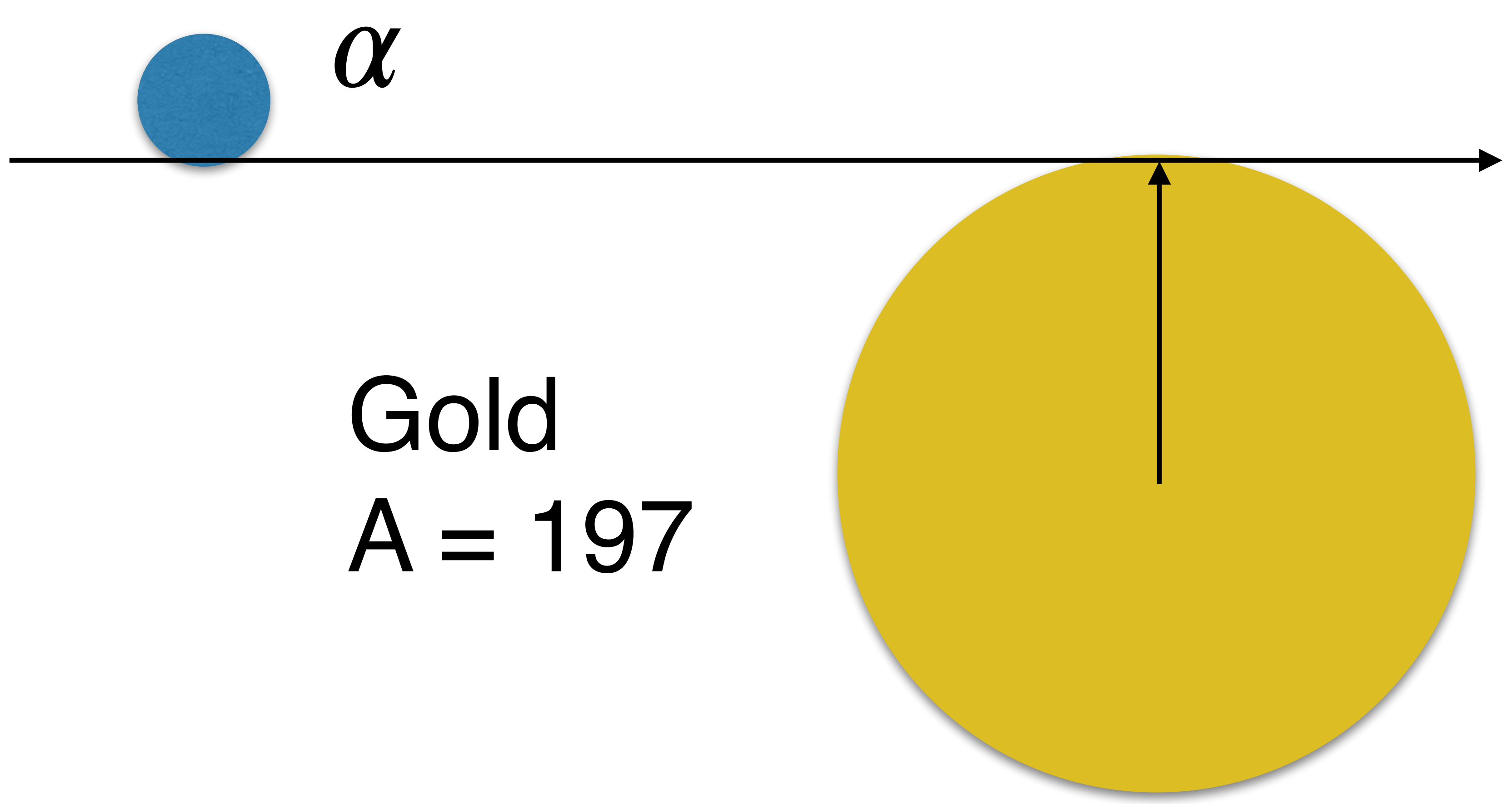
Near Detector

Earth

Geo-neutrinos anti-electron type

Natural and manmade sources of led us to understand the properties of neutrinos in much greater detail. We have done all these measurements at various degrees.

What happens when a subatomic particles hits something ?
Cross section for particle collisions



Radius of a gold nucleus is

$$R = 1.2\times\sqrt[3]{197}\,fm = 7\,fm$$

fm is $10^{-15}m$

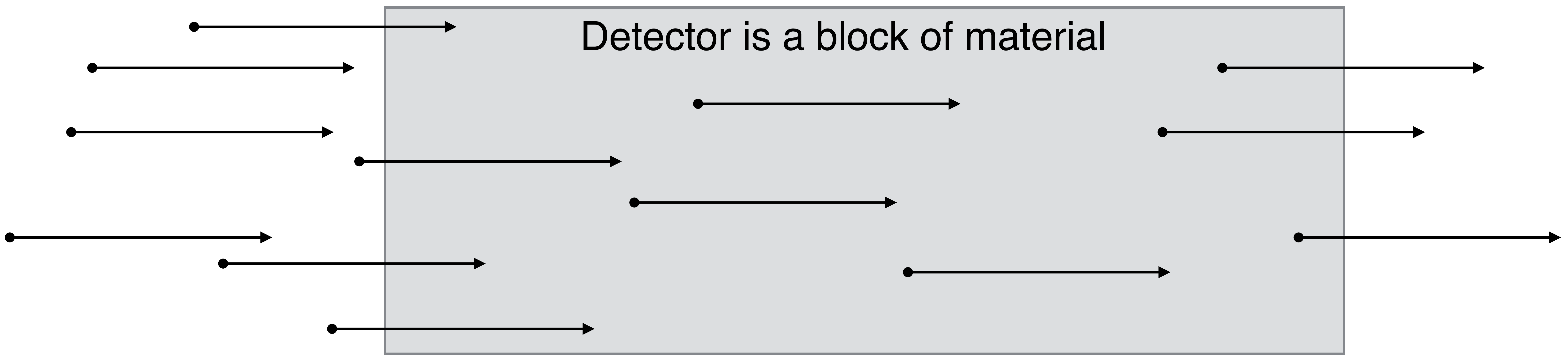
Cross section for alpha particle is then

$$\sigma \approx \pi \mathrm{R}^2 \approx 1.5\times10^{-24}\,cm^2$$

In particle physics, the cross section between any two particles is the area transverse to their relative motion within which they must meet in order to interact. It is the effective size. It is in units of area.

Neutrino Cross sections are extremely small ~10^{-38} cm2/GeV

To a neutrino a Gold nucleus is smaller by ~12 orders of mag.



As particles penetrate material, there is a reduction in the flux (particle/area/sec)

$$F(x) = F(0)e^{-\sigma\rho x}$$

$$\lambda = 1/(\sigma\rho)$$

λ is the mean free path

σ is the cross section

ρ is the density of targets

(In water $\rho \sim 6\times10^{23} cm^{-3}$)

For 1 GeV neutrino interactions $\sigma \sim 10^{-38}$ and

$$\lambda = \frac{1}{10^{-38} \bullet 6\times10^{23}} \approx 10^{12}\, meters!$$

In ordinary matter neutrinos just penetrate through with very rare interactions.

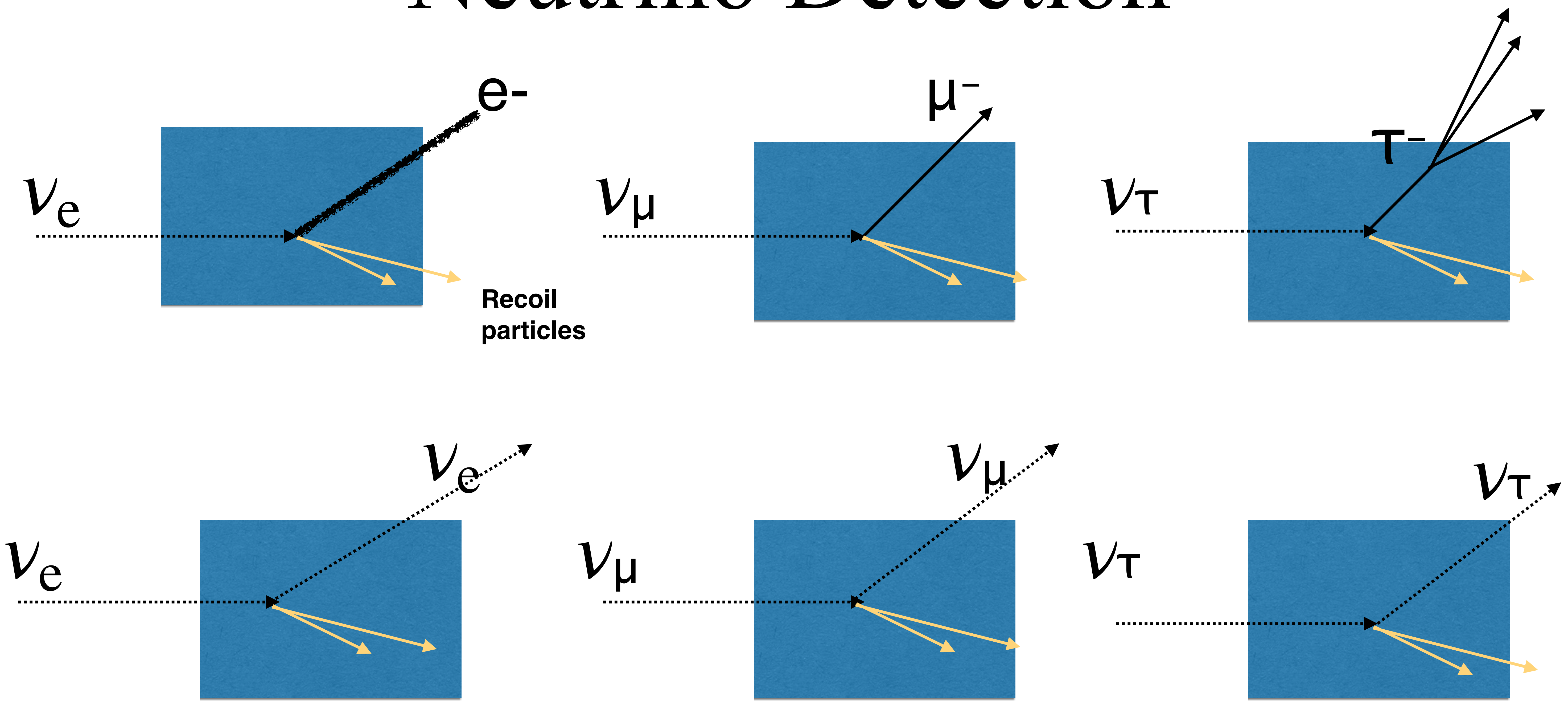
Weak interactions of neutrinos

Particles of a given kind are all identical. All electrons are absolutely identical. There are no birth marks. Nevertheless, there are 3 kinds of electron type particles called flavors.

Particle	Symbol	Mass	Associated Neutrino
Electron	e	1	ν_e
Muon	μ	200	ν_μ
Tau	τ	3500	ν_τ
	Negative Electrical Charge		Neutral

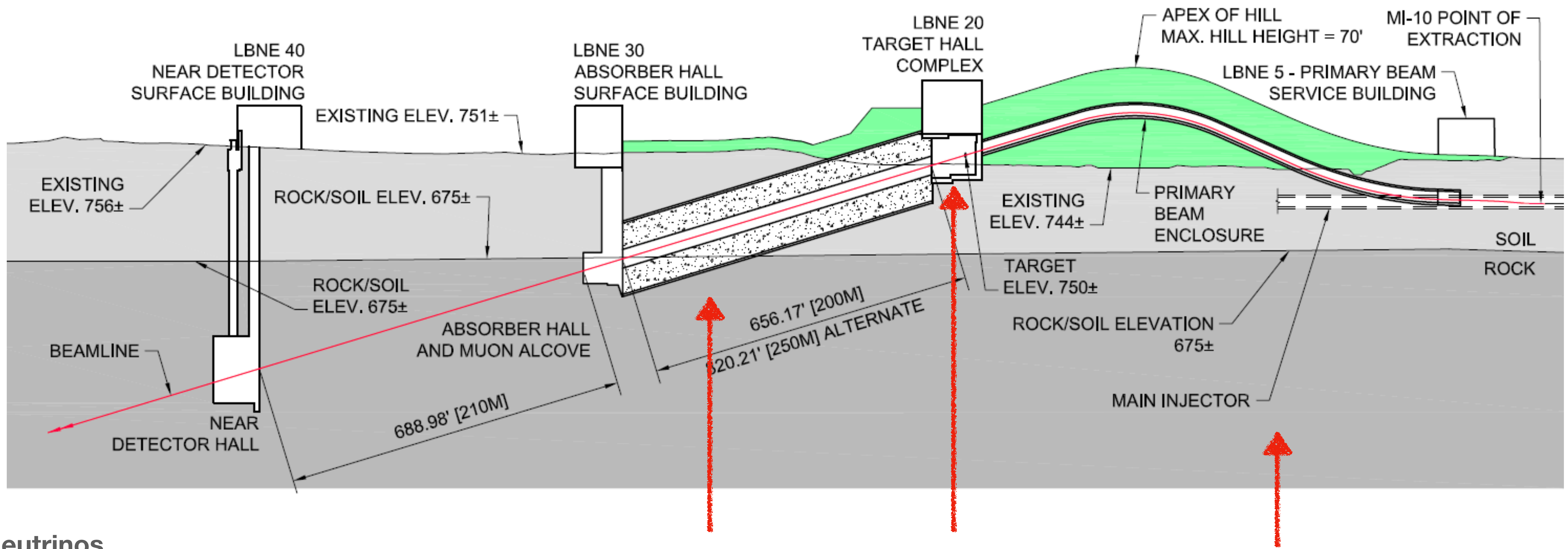
All these have anti-particles with opposite charge. However, for neutral neutrinos the exact meaning of having anti-particles is not yet clear.

Neutrino Detection



- *The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.*
- *Neutrino collision on atoms in detectors produces a charged lepton. (Charged Current)*
- *The electron, muon, tau have very different signatures in a detector.*
- *Neutrino can also collide and scatter away leaving observable energy. (Neutral Current)*

How does the DUNE experiment work ?



Muon neutrinos go flying down into the earth

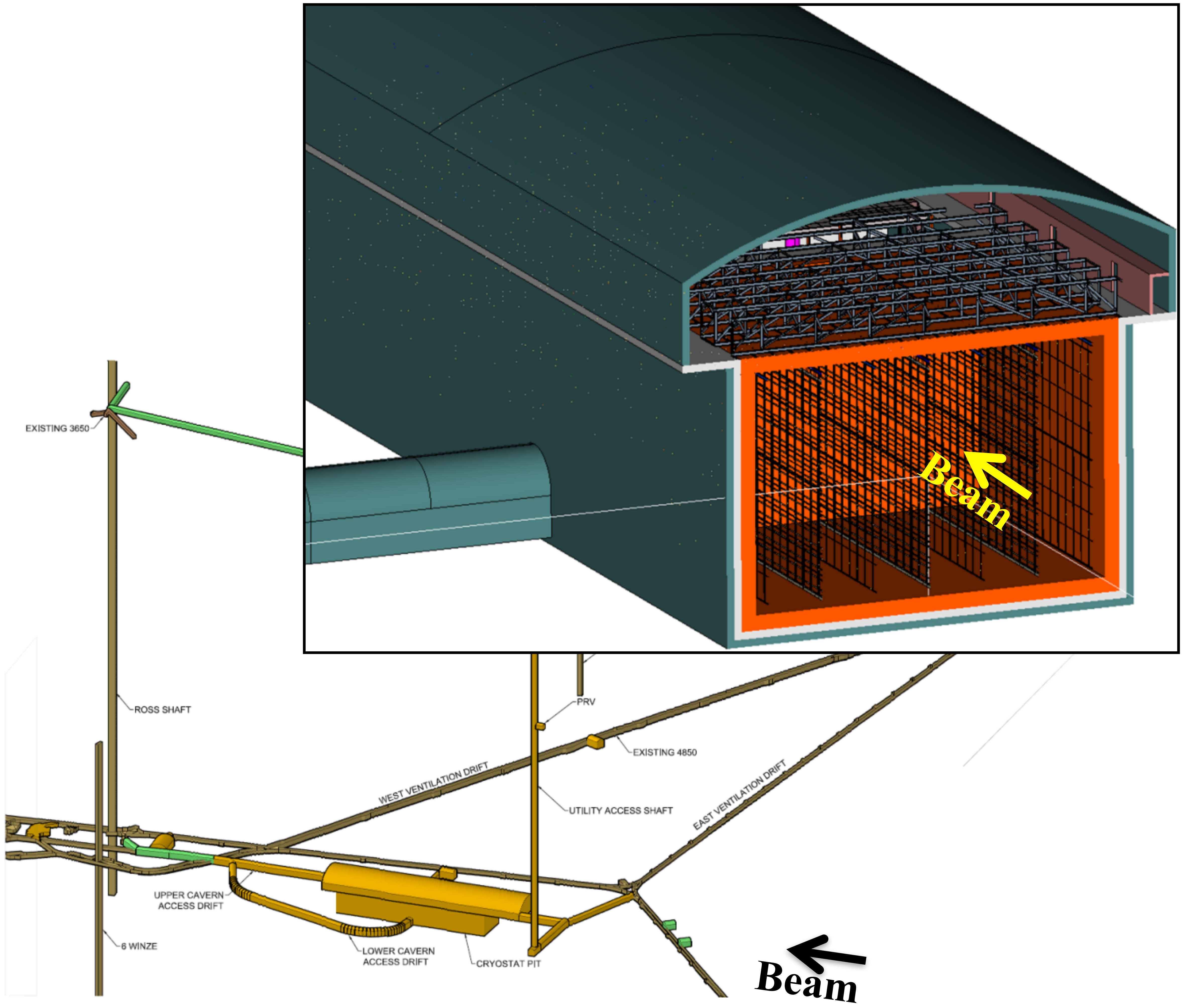
Pion particles are made in the target and decay in this tunnel

$\pi^+ \to \mu^+ \nu_\mu$

It hits a target in this hall

High energy proton beam at 1 MW at 120 GeV is made at Fermilab.

The beam emerges from the ground into a detector in South Dakota. Remember that the Earth is round.



- ***Four detectors in a common cavern at 4850 ft. depth***
- ***Active volume of each detector: 10000 tons each = 40 kt fiducial mass***
- ***TPC design:***
  - ***3.6 m drift length***
  - ***5 mm wire spacing***
  - ***three stereo views***
  - ***S/N ~ 10***

Challenges for scale up are under control : Purity, installation, safety

How do we know what we will see ? And what ?

- ***We can simulate all of the above.***
- ***We have a detailed simulation of the beam spectrum.***
- ***And from the beam spectrum we know how many neutrinos go to South Dakota.***
- ***From their energy we can predict the numbers of events we will see.***
- ***We also know that the muon neutrinos we will send have weird properties and they will change in flight. This is what we are after.***

If neutrinos have mass; the massive states need not be the same as the Weak interaction states. A neutrino could be in a classic superposition of states.

This will lead to interference effects

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

Massive Neutrinos

Flavored neutrinos

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= | < \nu_b | \nu_a(t) > |^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

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

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

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

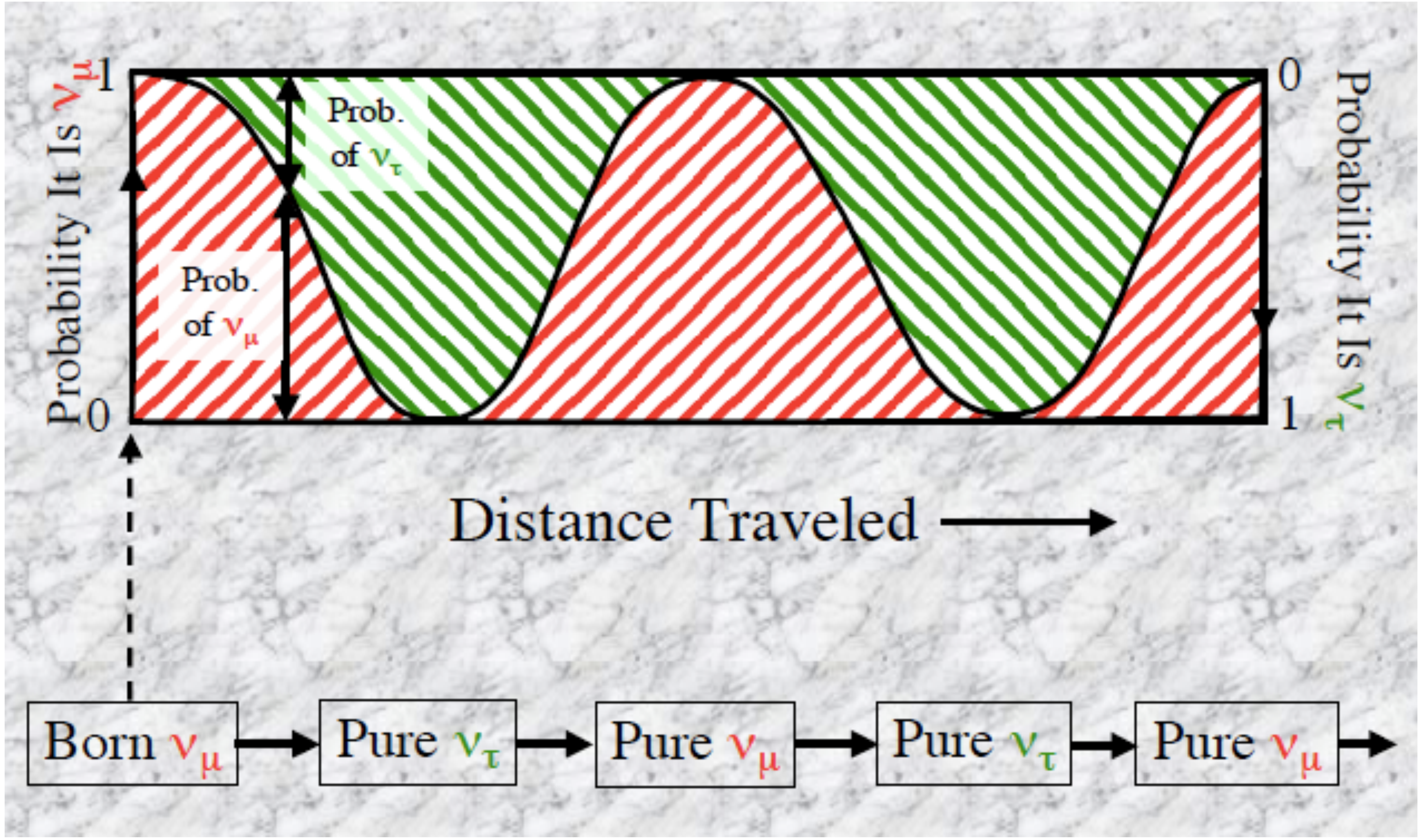
Definition

$Appearance: \nu_a \rightarrow \nu_b \quad \Rightarrow$ Make beam type (a) and Detect (b) after some distance to see if neutrino (a) tranformed to (b).

$Dis-appearance: \nu_a \rightarrow \nu_a \quad \Rightarrow$ Make beam type (a) and Detect (a) to see how many are left after traveling some distance

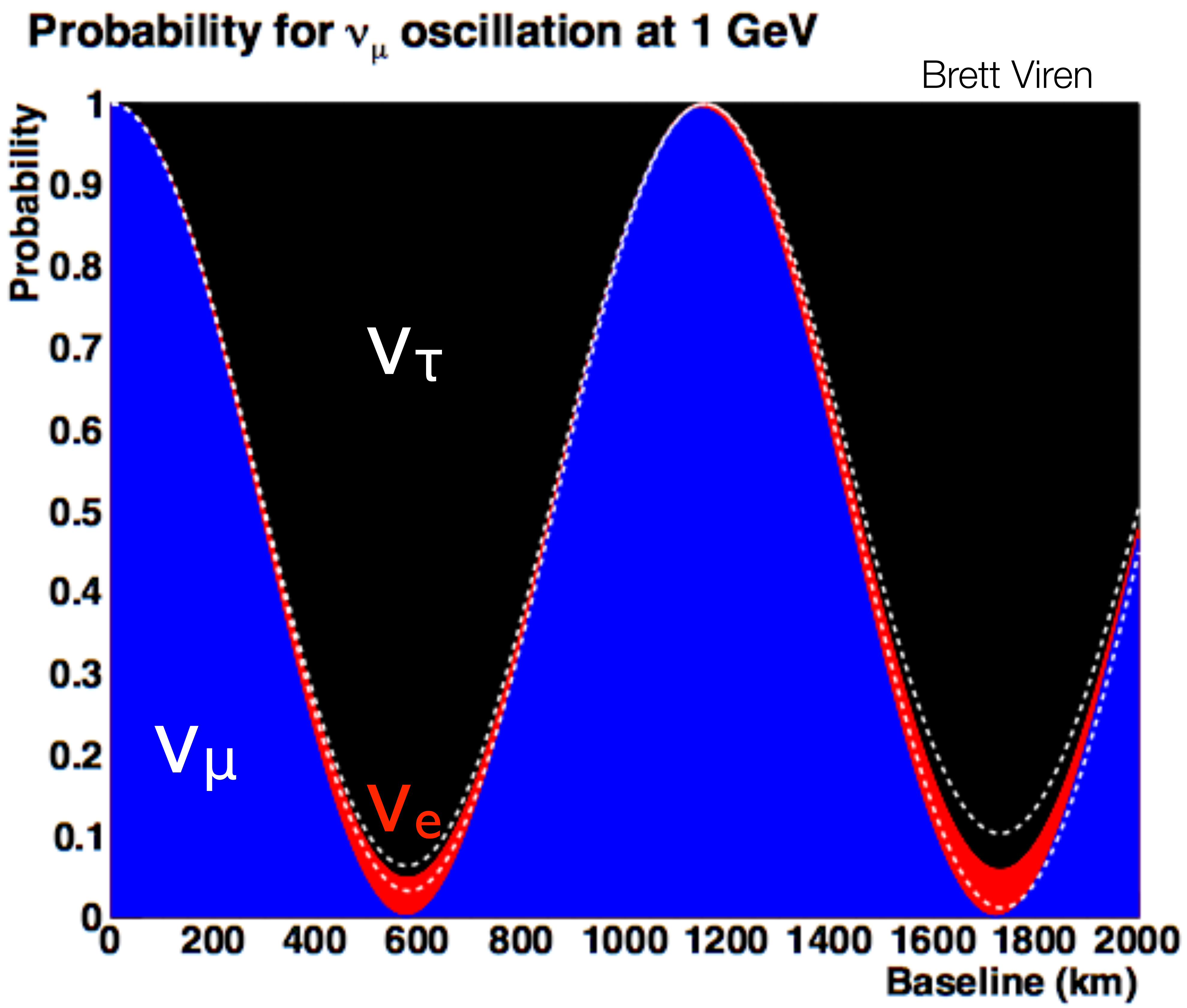
- **In both cases we must know how many (a) type were created and sent to the far detector. A precise prediction in the far detector is needed.**
- **In the first case, we must know if any events will fake the signature of (b) (these are called backgrounds.**
- **In the second we must know how many (a) to expect.**

Picture with θ = 45 deg



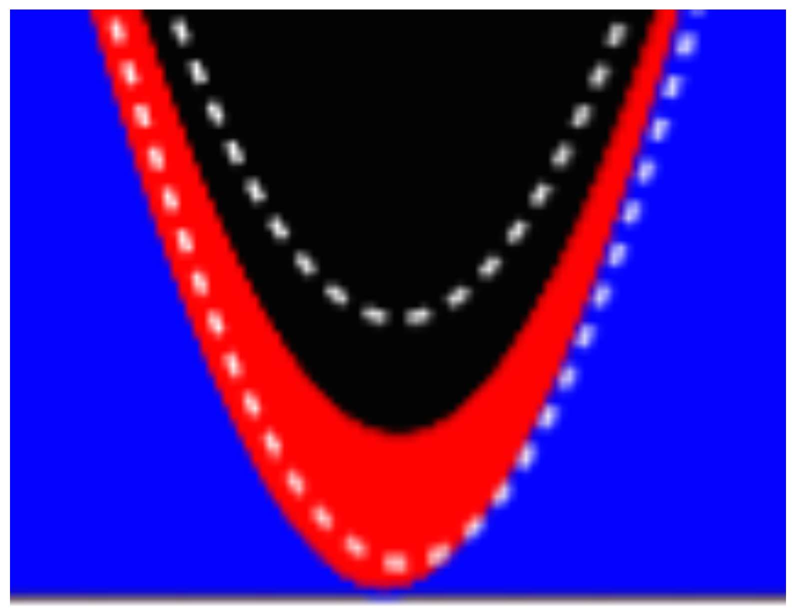
Everything we know about neutrino properties comes from this astonishing effect.

The full picture of the oscillation effect starting with pure muon type neutrino for 3 neutrinos.



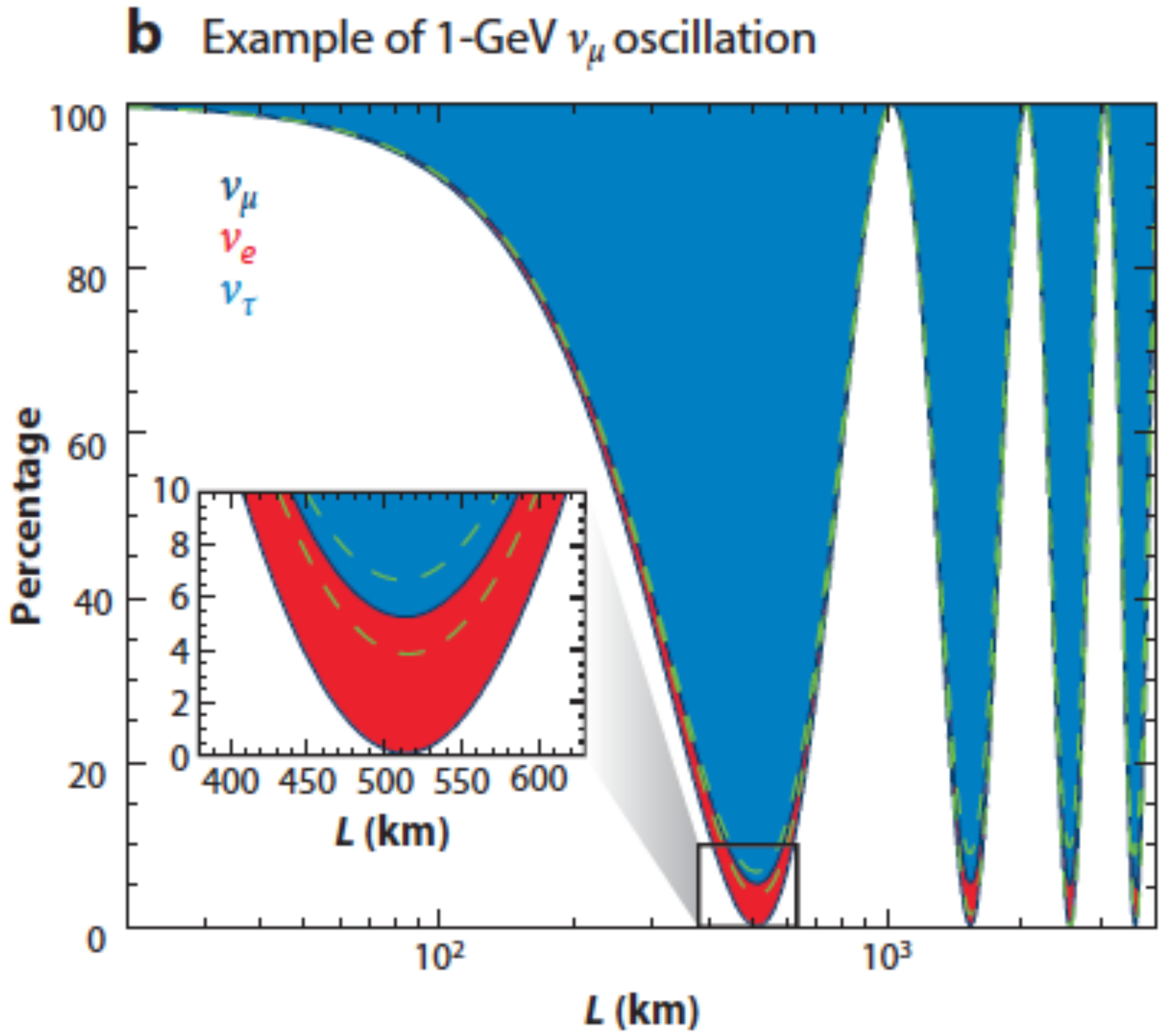
Dashed white lines correspond to CP violation or the unknown phase.

Notice that for sizable effects one needs long distances and large energies.



- There are precise predictions:
  - Large Matter Effects (not yet seen in a laboratory experiment)
  - Potentially large CP violation (not yet seen)
  - We should measure this picture with a detailed spectrum. We need to measure electron and muon type of neutrinos at high energies.

Accelerator long-baseline



Exercise:

We are going to calculate this plot.

Then we will apply this plot to the expected event spectrum at the far detector.

In the end, we will know how many events to expect and whether we can perform the intended measurement.

Originally this calculation was done in 2002 which started this project.

$$goal: P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Why do we want to measure this neutrino versus antineutrino asymmetry ?
Is there anyone here made of anti-matter ?

NASA Webb deep field image of a huge number of galaxies.

- What happened to the anti-matter that was surely made in equal amounts at the beginning ? We need no annihilations when we look far.
- The big bang must have produced equal amounts of matter and anti-matter. Is it simply separated at huge distances ?
- Does this have a connection to the huge amount of dark matter ?
- Is there a neutrino/antineutrino asymmetry that caused the anti-matter to disappear in the early universe ?