Neutrino Physics

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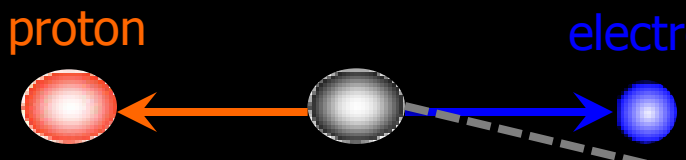
Fermilab
July 27, 2010

What is a Neutrino?

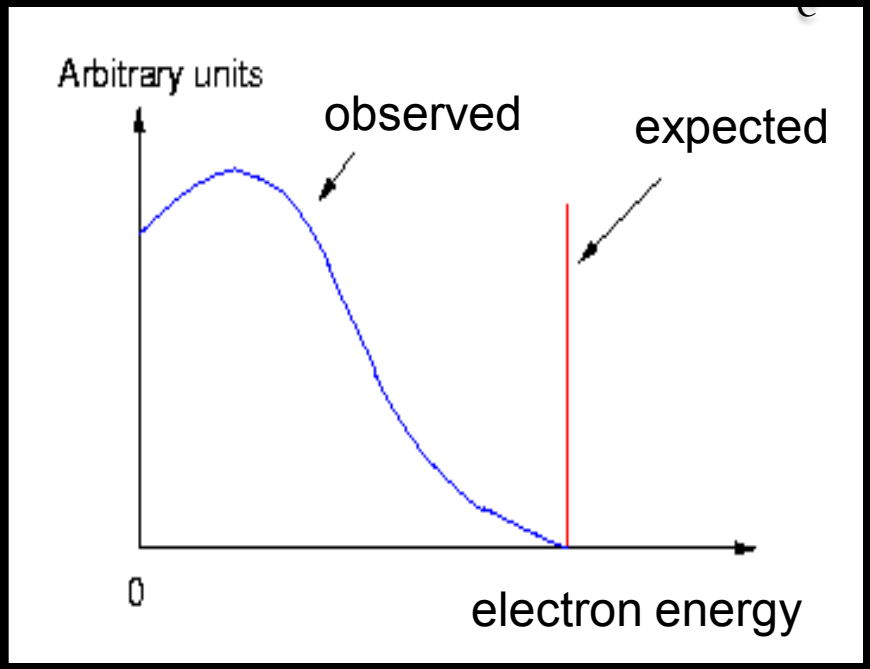
- Breakfast Cereal
- Japanese rhythm and blues band
- Penny-sized jumping spider
- Tiny neutral particles
  - Weigh almost nothing
  - Almost never interact
  - Named by an Italian (Fermi)
  - Symbolized by a Greek (ν)

The first Energy Crisis…

- in 1930 there was a crisis in particle physics!



$(A, Z) \rightarrow (A, Z+1) + e^- + \overline{\nu}_e$



It was well known that nuclei could change from one variety to another by emitting a **"beta"** (electron).

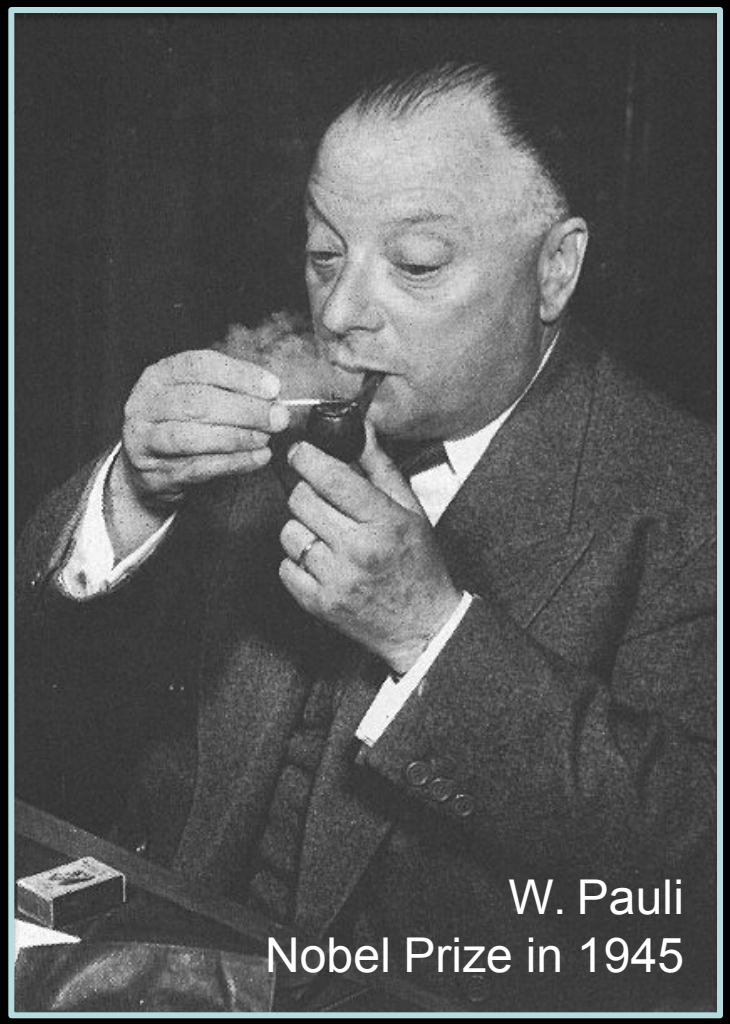
Some were ready to abandon **Conservation of Energy** to explain this missing energy

$\overline{\nu}_e$

. . . until W. Pauli proposed his **"desperate remedy"**, the neutrino, which invisibly carried away the missing energy – and the neutrino was born

A “desperate remedy”

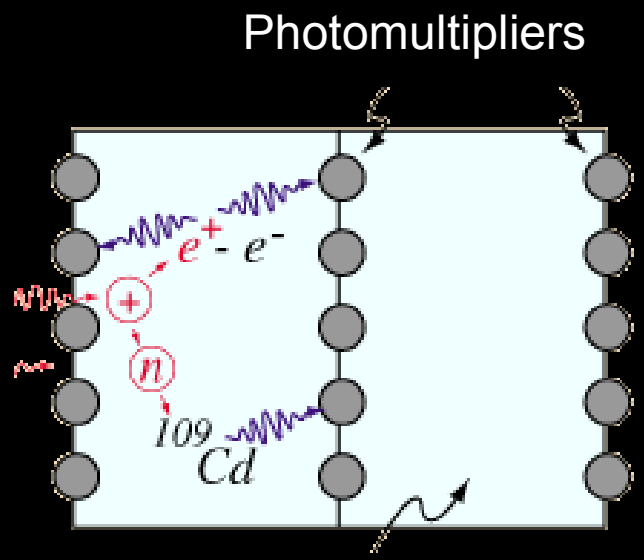
- the neutrino was thought to be a neutral, massless particle



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

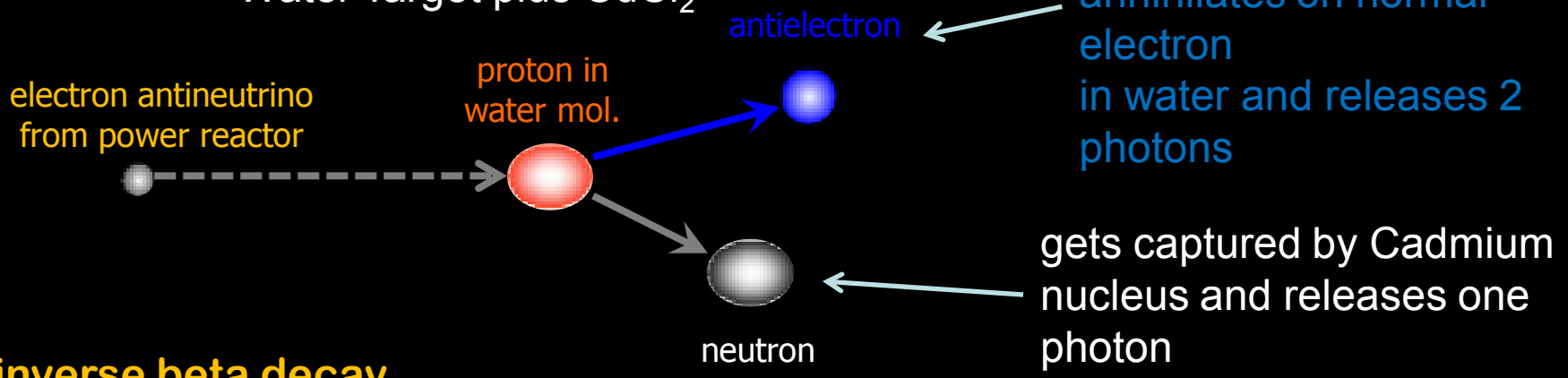
- W. Pauli (1931)

26 years later…the ν is seen!



- **How did Reines and Cowan do it?**
- **can't see a neutrino directly since all particle detectors are based on seeing *charged particles***

method for observation was called "inverse beta decay", the opposite of what made Pauli think of the neutrino in the first place



inverse beta decay

Why did it take so long to see neutrinos?

– Average distance between interactions: mean free path
  - Probability of interaction/particle
  - Number of particles/kg
  - Number of kg/m^3

$$d_{lead} = \frac{1.66 \times 10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}$$

atomic mass unit

ν-N cross-section

density of lead

neutrinos produced in a reactor typically have a few MeV of energy

$d \approx 1.5 \times 10^{16}$ meters

<u>neutrinos produced at an accelerator</u> typically have a few GeV of energy

$d \approx 1.5 \times 10^{12}$ meters (1 billion miles)

What about a proton with a few GeV of energy?

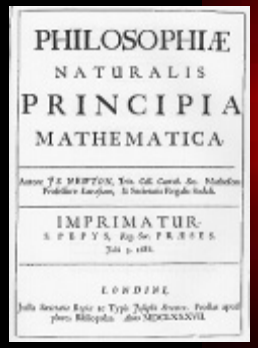
d ≈10cm in lead

Why neutrino physics is hard…

- Neutrinos only feel the weak force
  - You have to use very intense sources of neutrinos
  - You have to use very large detectors
  - You have to wait a long time…

The next energy crisis: What makes the sun shine?

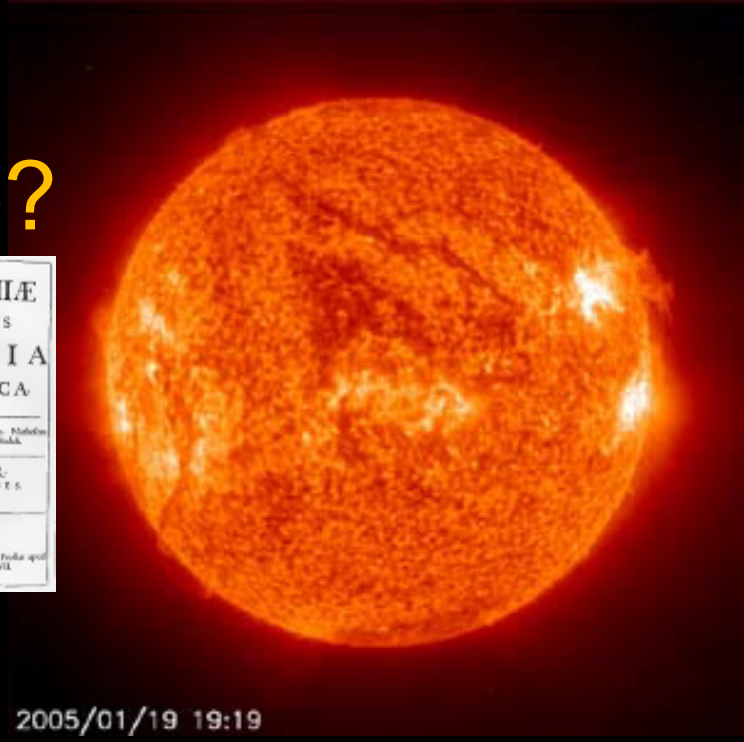
- Newton (1700's): sun weighs 2 million trillion trillion kilograms (2×10^{30}kg)


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR:

LONDINI

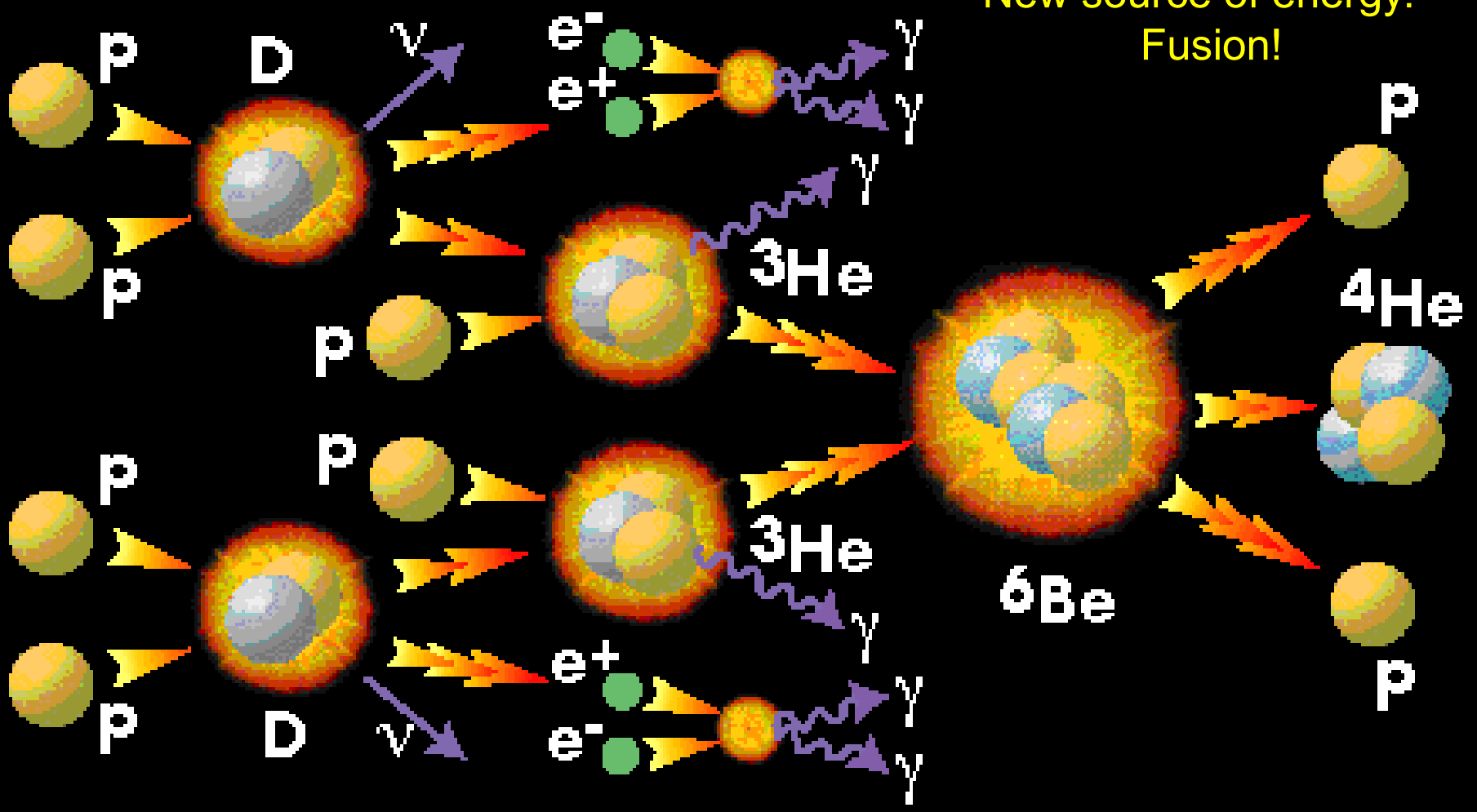
- We get about a million Joules for a kg of fuel



- We know how bright the sun is (4×10^{26} Joules/second)
- Calculation: the sun will only burn 2 centuries…
- There are buildings older than that…how can this be?

You guessed it: Neutrinos

New source of energy: Fusion!



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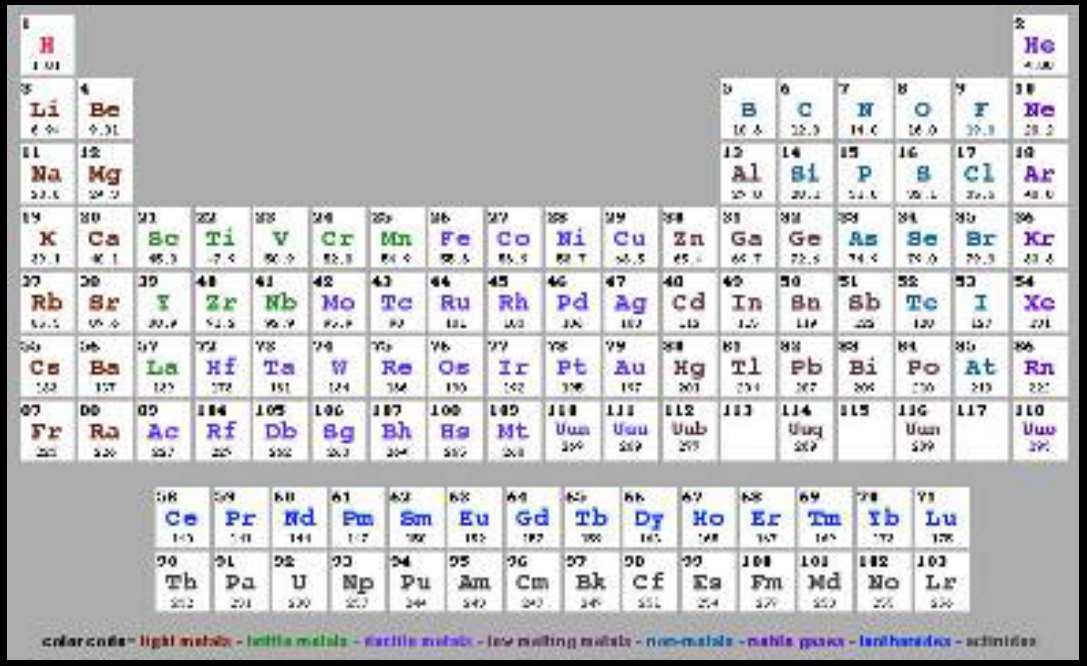
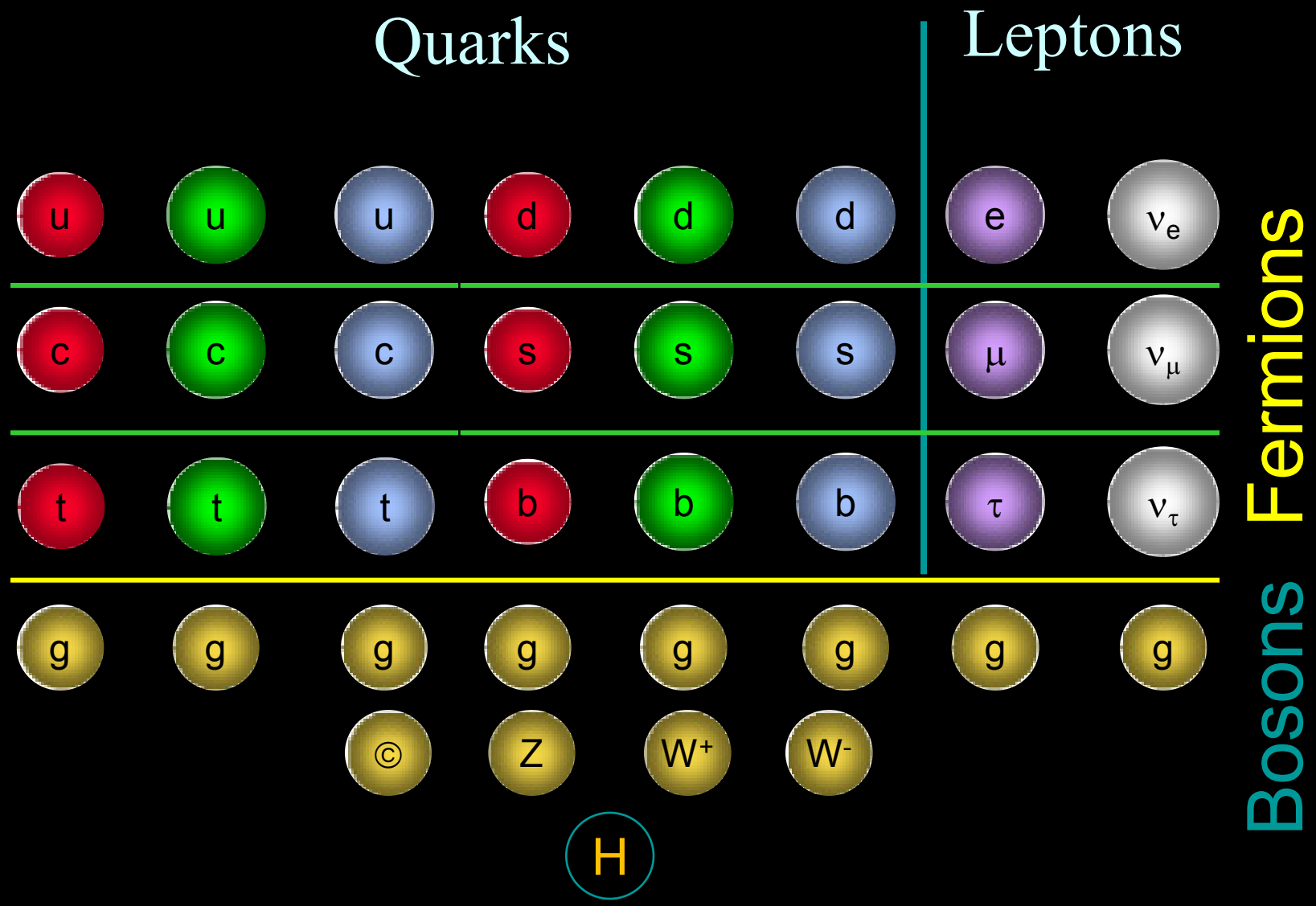
As more and more nuclei interact…

- Neutrinos are what mediate the interaction between different nuclei
- As more and more nuclei collide, new stable states are formed and before you know it…



Relative abundances of elements in the universe depend on how many neutrinos there actually are around!

80 years later…The Standard Model



From H. Prosper's lecture

80 Years later…Forces

Strong Force 1

Binds protons and neutrons to form nuclei

Electromagnetic Force 10^{-2} (Photon)

Binds electrons and nuclei to form atoms

Weak Force 10^{-5} (W & Z Bosons)

Causes radioactivity

Gravitational Force 10^{-39} (Graviton)

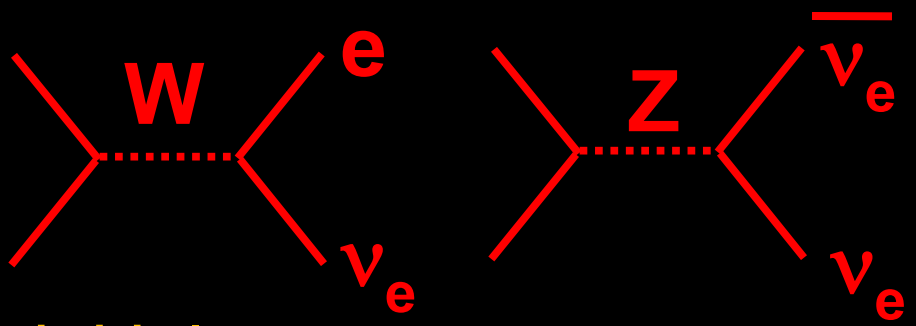
From H. Prosper's lecture

Editorial Comment…

- See any similarities?

Neutrino Sources

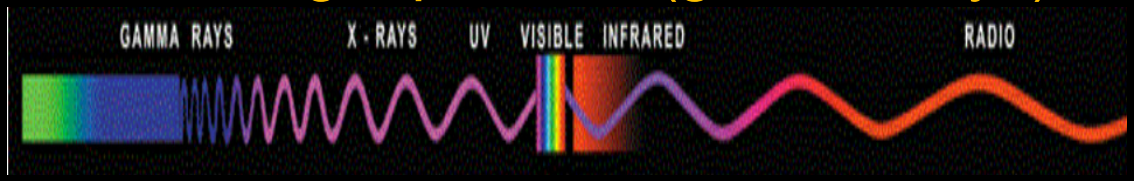
- Every time there is a weak process, neutrinos can be made

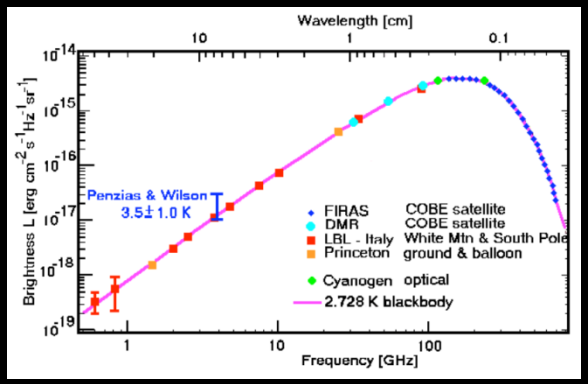


- The more energy in the initial state, the more energy in the neutrino
  - Relic Neutrinos from Big Bang
  - Neutrinos from Bananas
  - Neutrinos from Nuclear Reactors (Sun)
  - Neutrinos from Atmosphere
  - Neutrinos from Accelerators
  - Neutrinos from Active Galactic Nuclei…

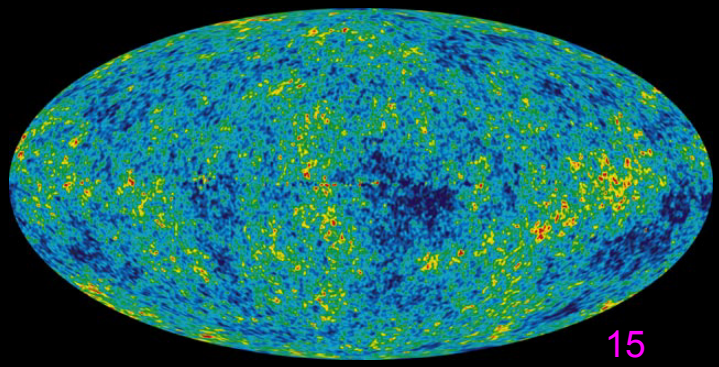
How do we know there are neutrinos from the Big Bang?

- Remember last week's lecture by Donna Kubik?
  - Very hot universe (10^{12}K), start out with very short wavelength photons (gamma rays)





  - As universe expands, those γ's redshift to longer wavelengths, now they are at 1.1mm, and we're left with 3K photons filling the universe



- What do you think Neutrinos from the big bang did?

Big Bang Neutrinos

- Imagine the beginning of the universe: so many neutrinos around that they can annihilate
- As universe expands, fewer ν's around… they stop annihilating

$$\Gamma = <\sigma\ n\ v> \simeq \frac{16 G_F^2}{\pi^3}\ (g_L^2 + g_R^2)\ T^5$$

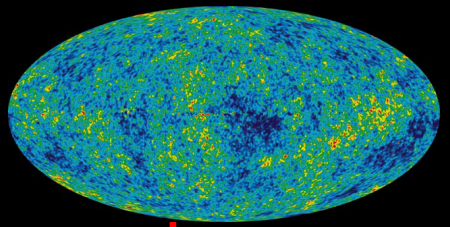
Annihilation Rate

$$H(t) = 1.66 g_*^{1/2} \frac{T^2}{m_{\rm Planck}}$$

Expansion Rate

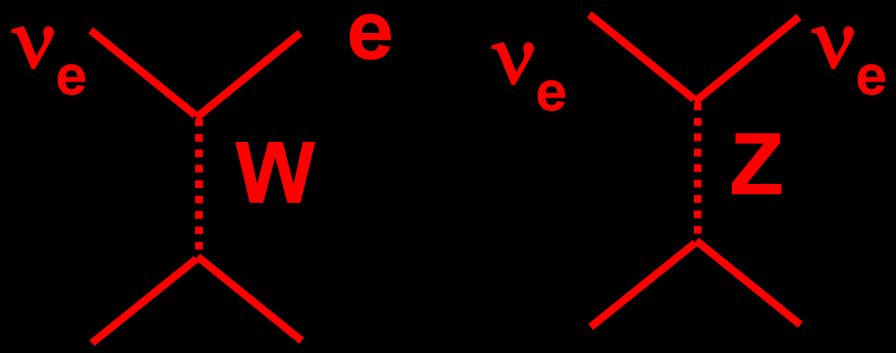
$$T_D(\nu_e) \simeq 2.4\ {\rm MeV}$$
$$T_D(\nu_{\mu,\tau}) \simeq 3.7\ {\rm MeV}$$

- Then the ν's decoupled (1 second after Big Bang), nothing else to do but chill…
- Estimate: ~400 / cm^3 of space, E ~0.17meV
  - Billion times more than protons
  - They have yet to be seen, but ideas abound…



Neutrino Interactions

- They are the lightest particles around, so they can't decay to anything else



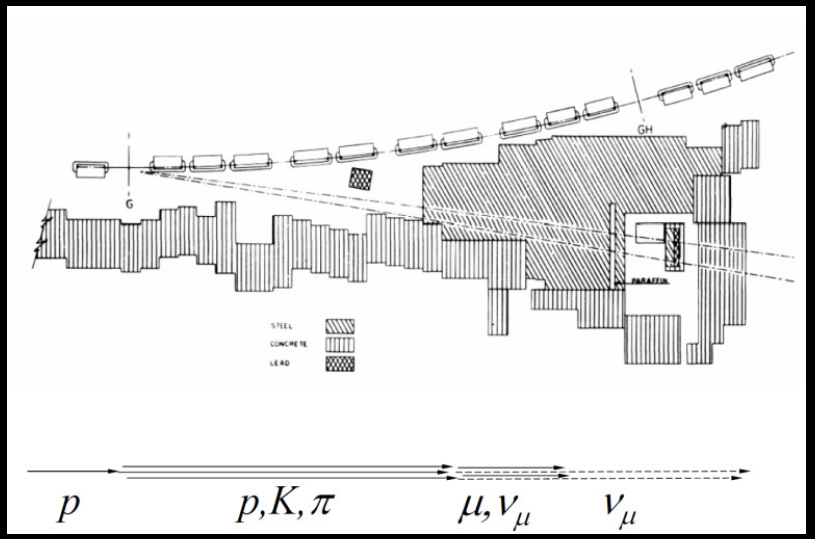
- The more energy the neutrino has, the more chance it has to interact
  - More final state particles that can be made with more initial energy

Not one neutrino, but 3… the first accelerator-made ν beam

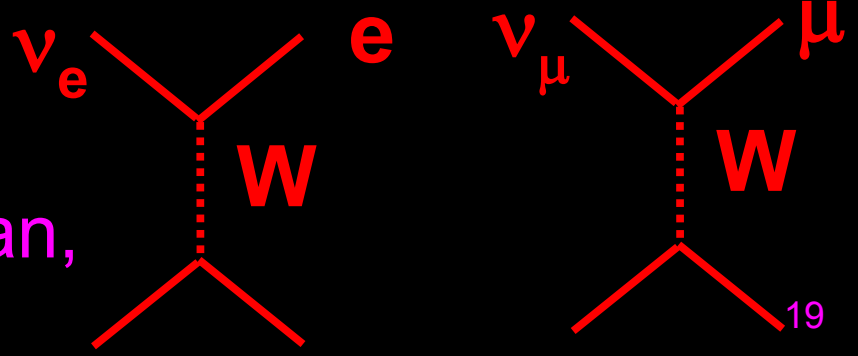
- After the discovery of the muon, physicists started asking the question: why don't we see the decay $\mu \rightarrow e\,\gamma$?
  - Should proceed through intermediate state $\mu \rightarrow e\,(\nu\bar{\nu}) \rightarrow e\,\gamma$
  - But if the $\nu\bar{\nu}$ pair that was produced weren't really a particle and its anti-particle, then they couldn't annihilate to a photon…
  - Look at how ν's are produced: $\pi \rightarrow \mu\,\nu$

Making Neutrinos from Proton Beams

- 1963: First ν beam from an accelerator:
  - Protons
  - Target
  - Shielding
    - steel, concrete, lead

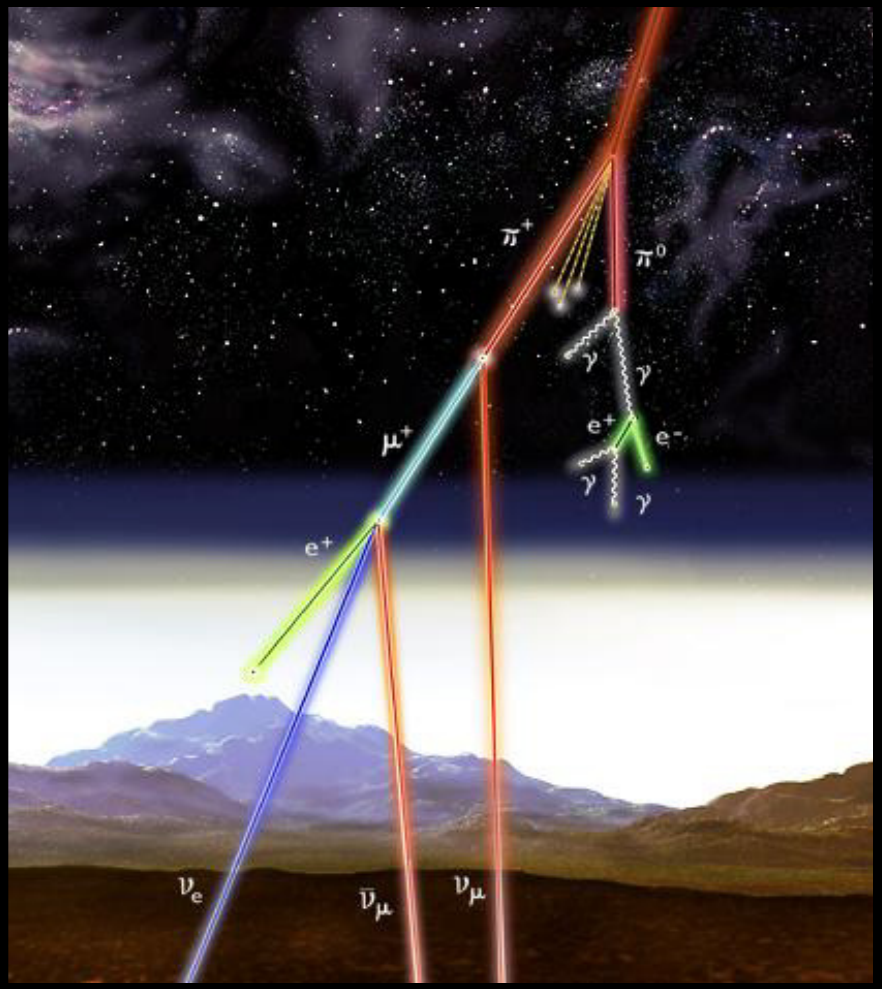


- Neutrino Detector: spark chambers
  - Signal: see nothing coming in, and see a muon coming out…
- Beam concept won Nobel Prize for Lederman, Schwartz, Steinberger



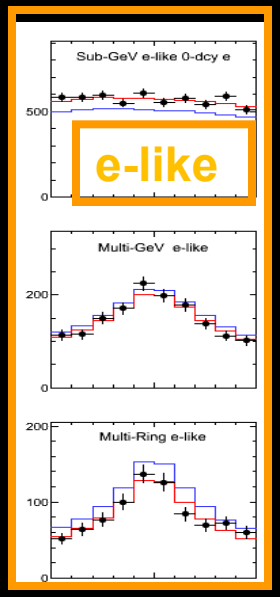
Neutrinos from the Atmosphere

- High energy protons are whizzing all over the universe, when they hit the Earth's atmosphere, they too make neutrinos
- should reach Earth with ν_μ and ν_e in a 2:1 ratio
- How far do neutrinos from atmosphere travel to get to the detector located near surface of the earth?

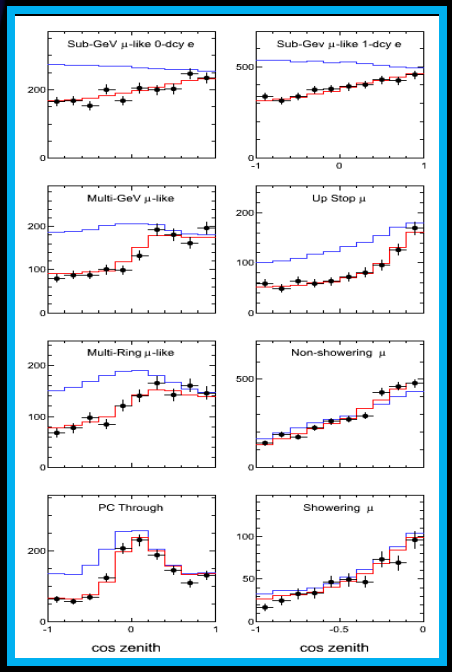


Neutrinos at many distances…

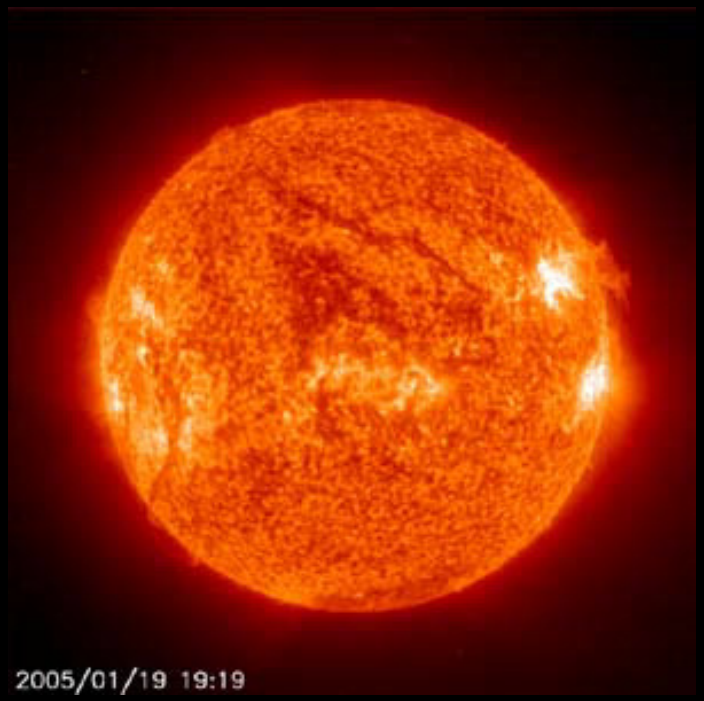
- Measurements of neutrinos from atmosphere:
  - 80 to 10,000km
  - Muon Neutrinos from above don't disappear
  - Muon Neutrinos from below disappear
  - Electron neutrinos don't seem to be disappearing at all!

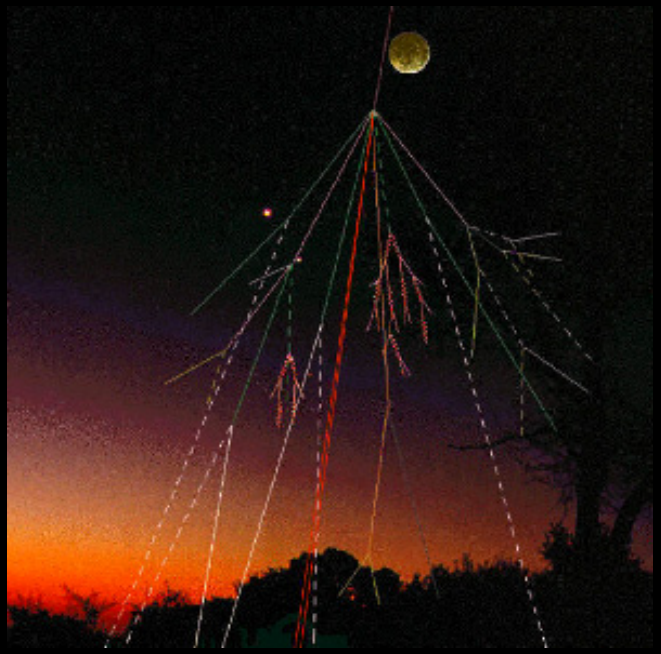


μ-like



The Case of the Missing Neutrinos

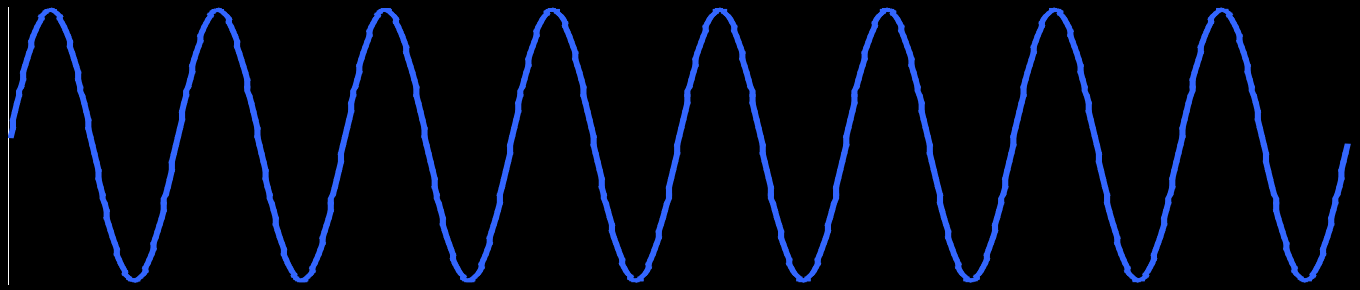




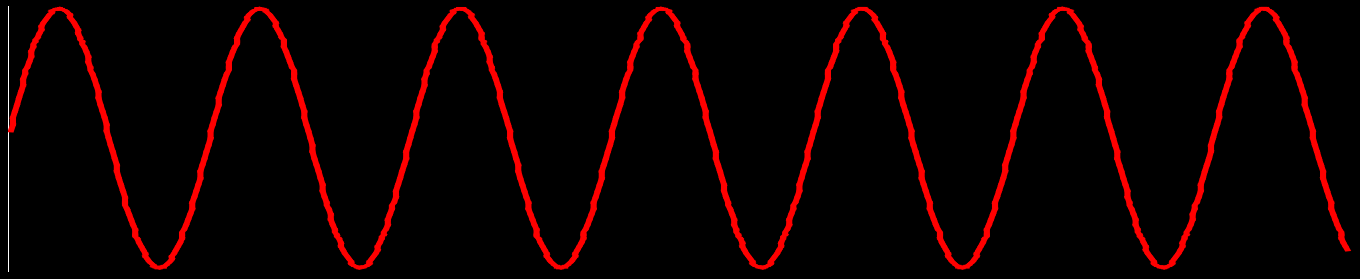
- Neutrinos from the sun:
  ~1/3 the number expected (brr….)
- Atmospheric neutrinos:
  ~1/2 the number expected were observed
- Neutrinos from Los Alamos:
  5X as many electron-type neutrinos as expected

How can something become nothing?

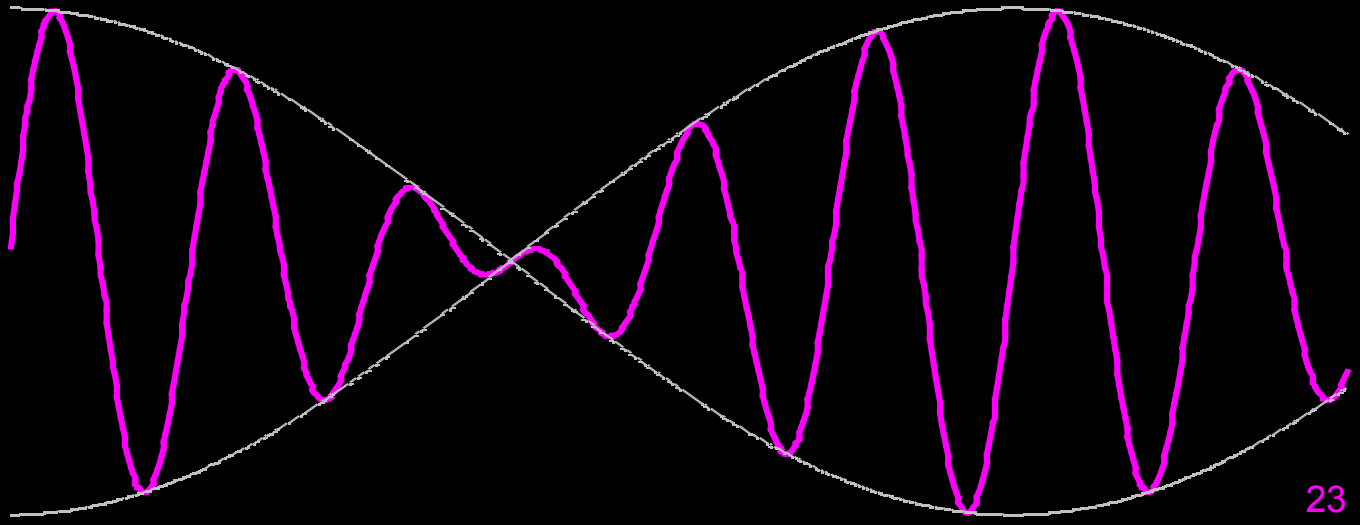
wave 1



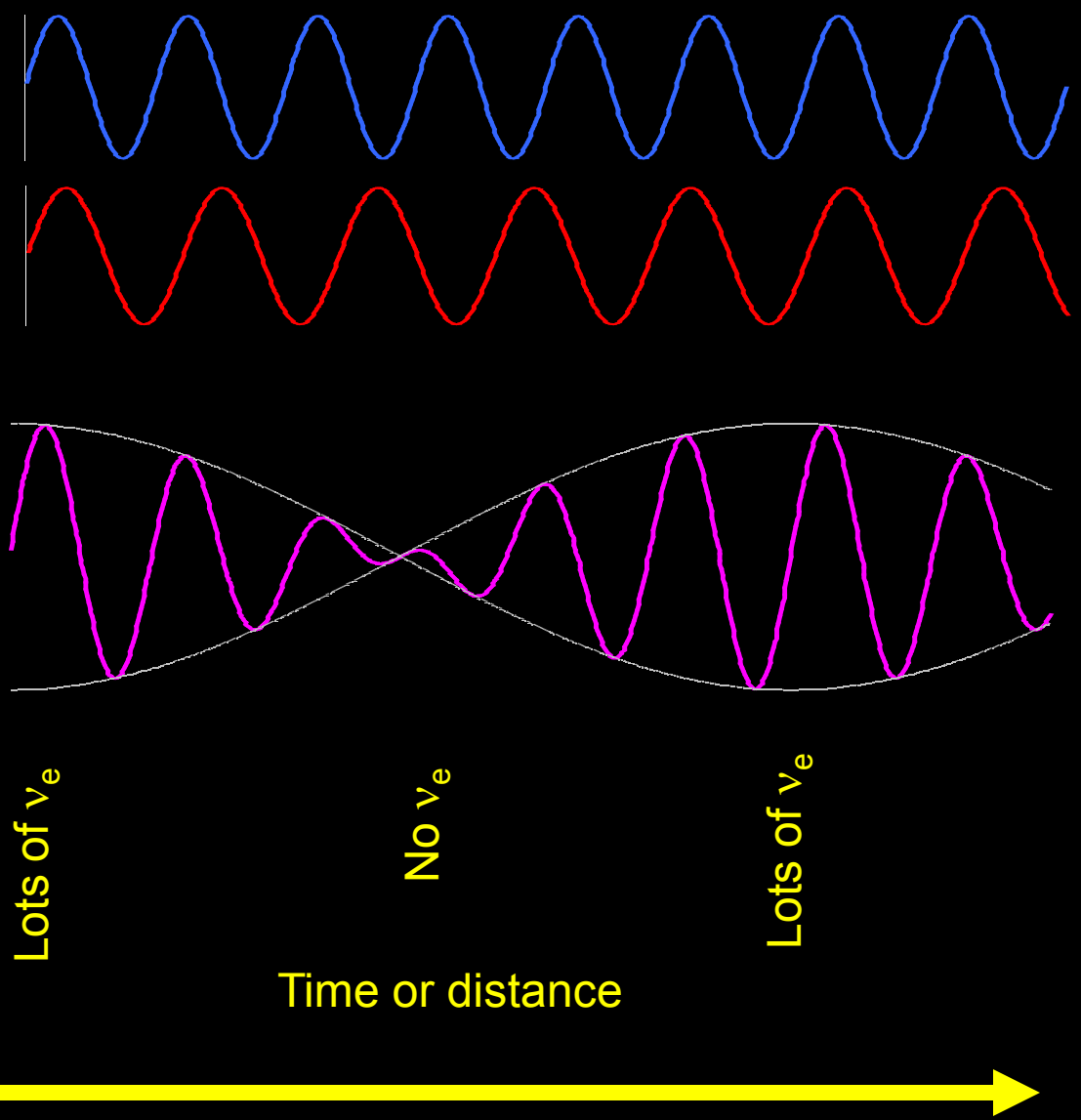
wave 2



wave 1
+ wave 2



Neutrino Oscillations



If neutrinos are waves of slightly different frequencies:

Over time, they disappear and reappear

The bigger the frequency difference, the faster the disappearance

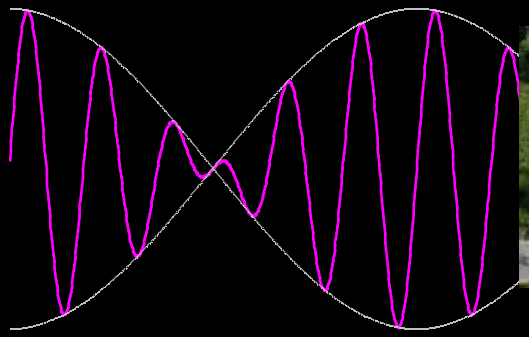
Particles are like waves particle mass determines its frequency

Measuring neutrinos oscillating: Measuring mass differences

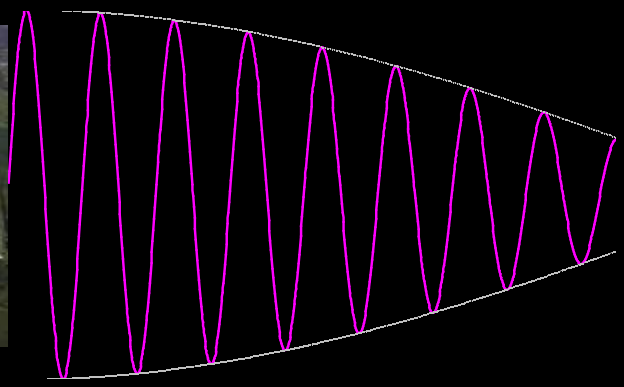
If one kind of neutrino disappears, another kind must appear

What are we doing with neutrinos at Fermilab?

- Studying how neutrinos change from one flavor to another
  - MiniBooNE: short distance oscillations (Kane County)

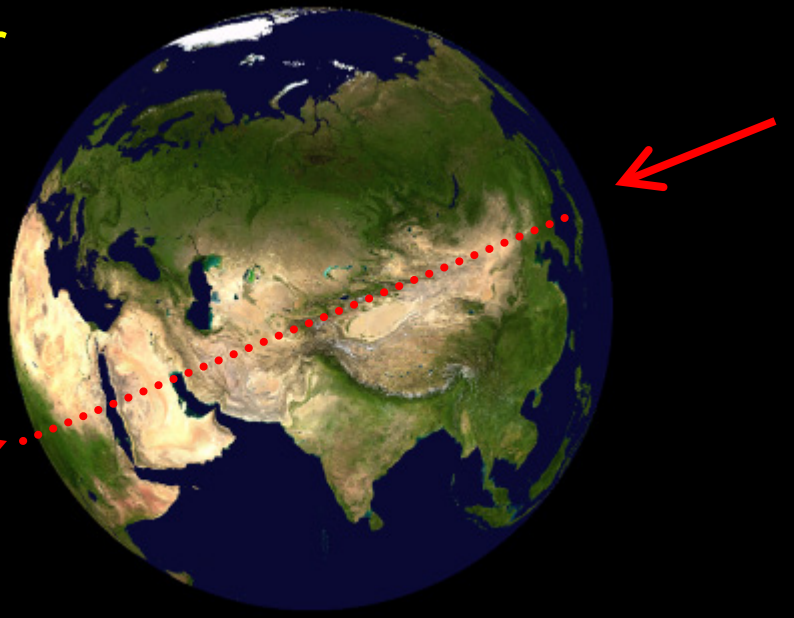


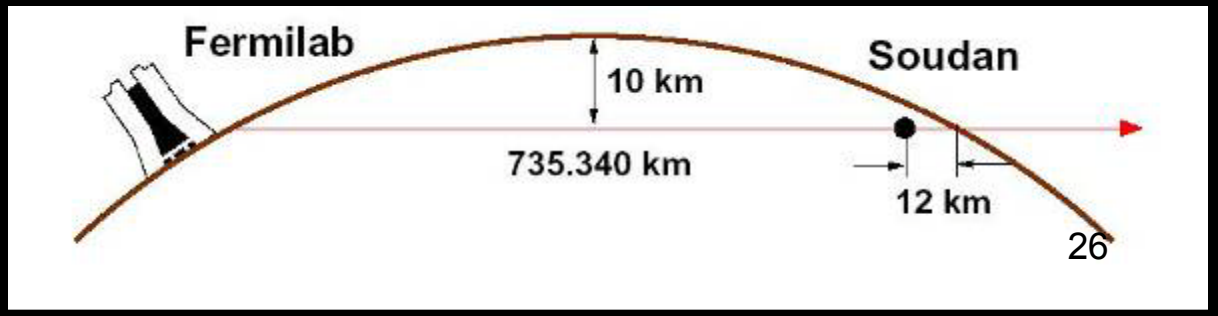
  - MINOS: long distance oscillations: (from here to Minnesota)



Why Minnesota?

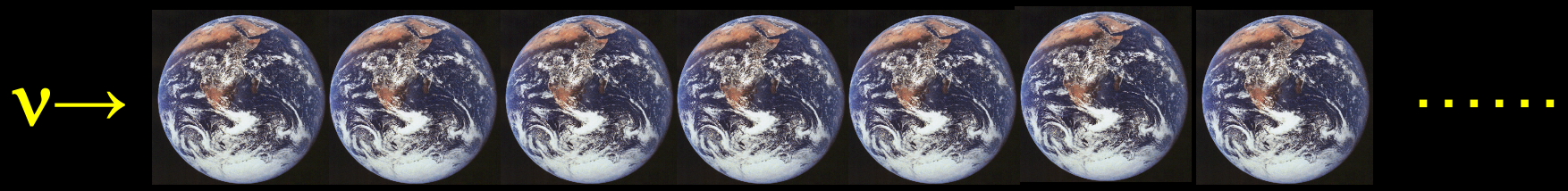
- The state with the most saunas per capita in the US
- They have the best iron mines
- Measurements of neutrinos from atmosphere:
  - Neutrinos have to go at least a few hundred miles to change at all
  - So we have to send a beam of neutrinos far enough through the earth so that they will have had at least that much time to change…





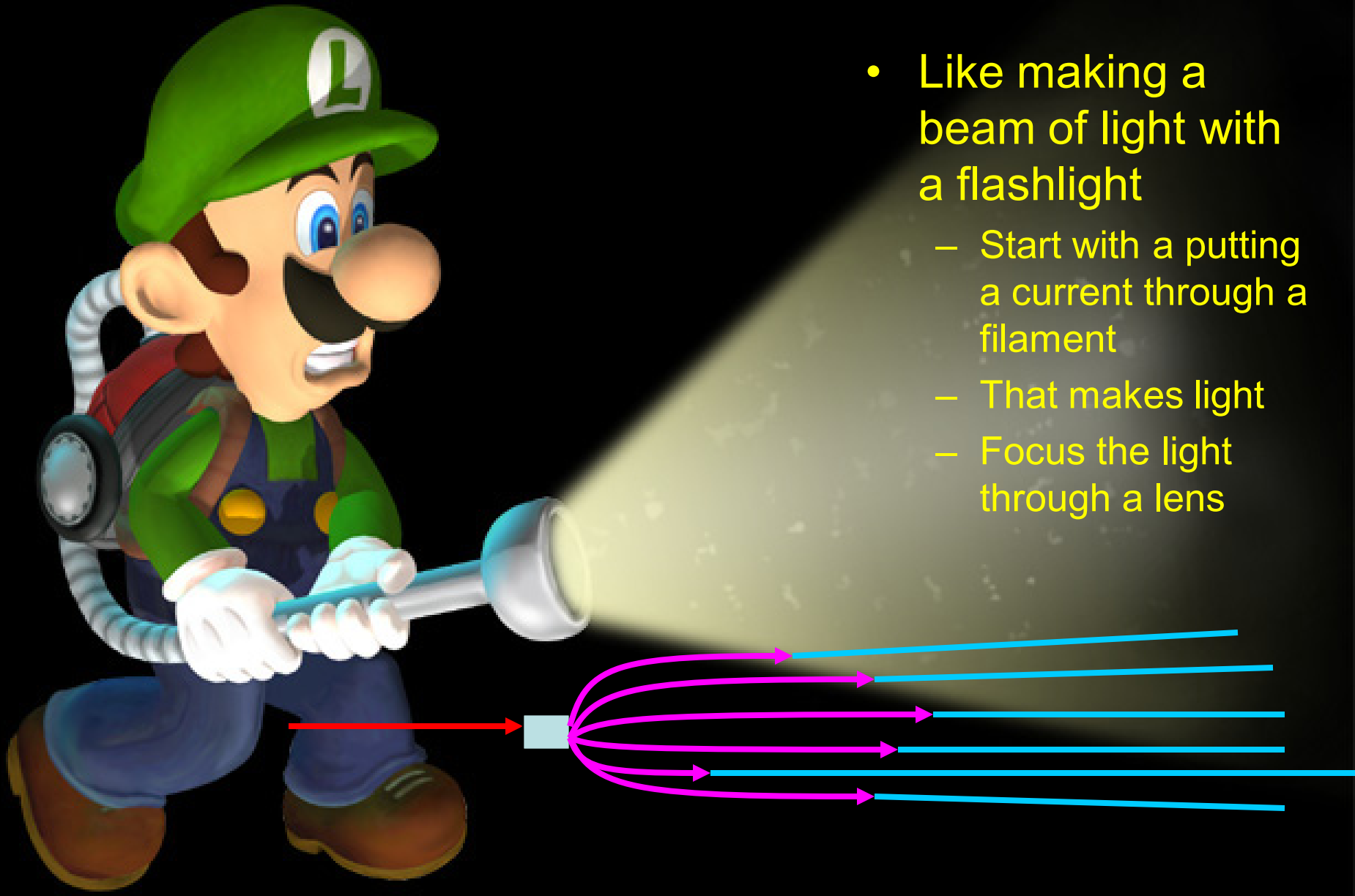
How do you get neutrinos from here to Minnesota?

- Just shoot them!
- Don't need a tunnel all the way there



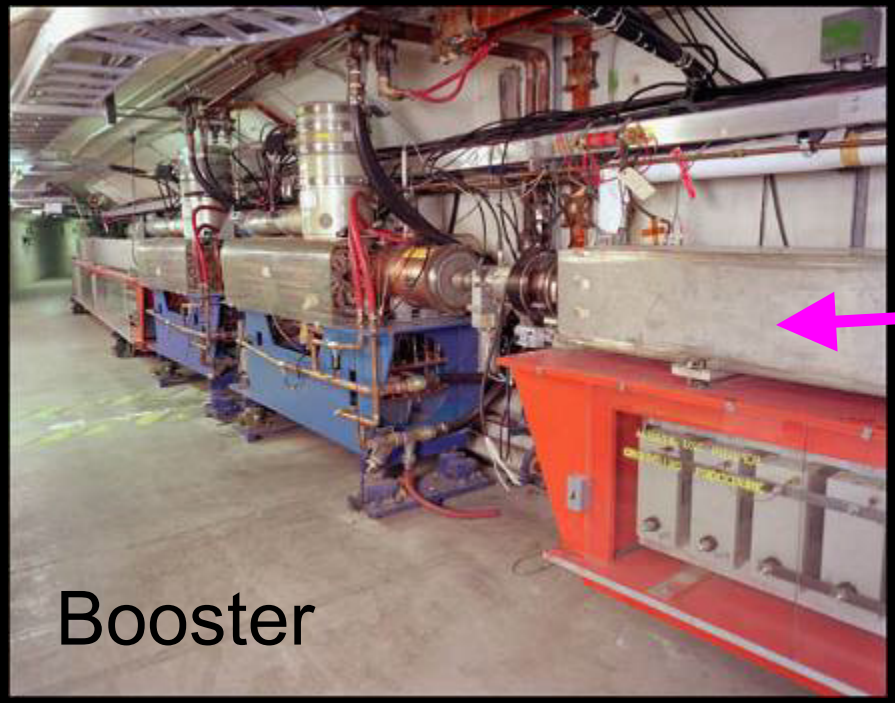
- The catch:
  - Need lots of neutrinos
  - Need lots of detector

How can you make a beam of neutrinos?

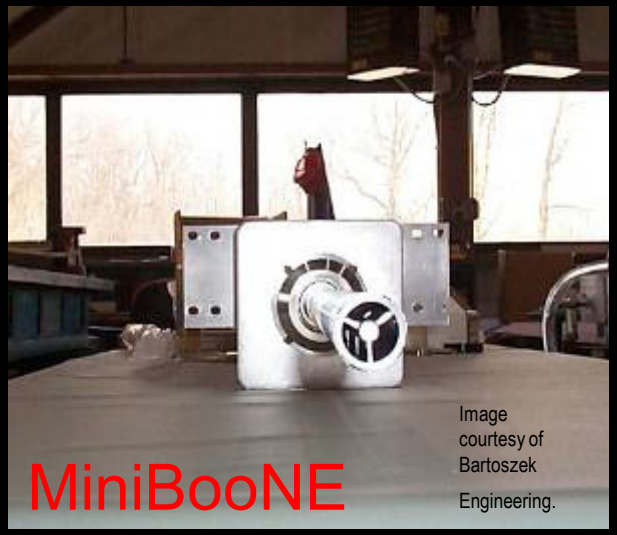


- Like making a beam of light with a flashlight
  - Start with a putting a current through a filament
  - That makes light
  - Focus the light through a lens

protons→target→unstable particles→neutrinos

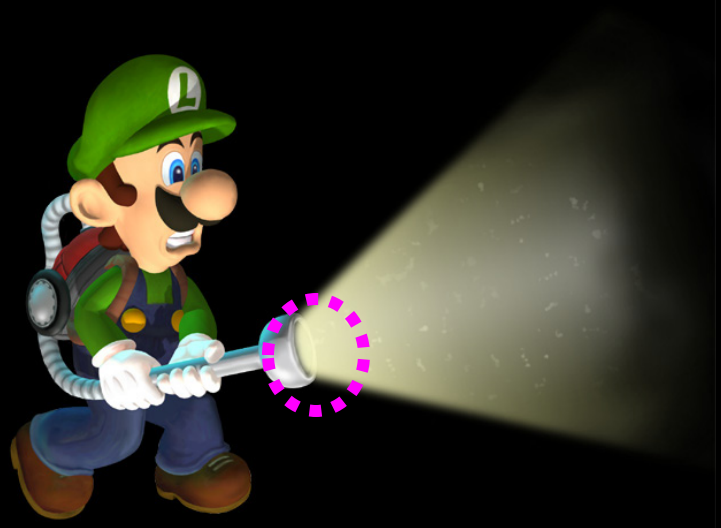

Booster

Main Injector



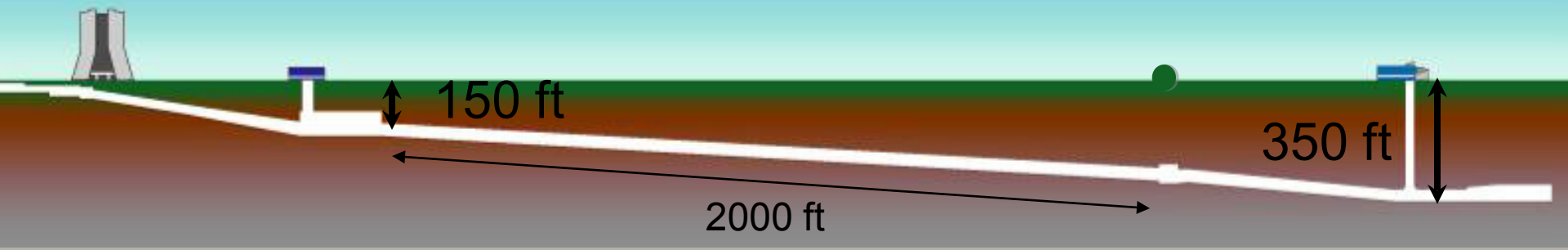
These targets see 10's' of trillions of Particles:
How can you keep something cool when you keep pumping energy into it?

MiniBooNE power: 50 kWatts
MINOS power: 200kWatts
Hair Dryer: 1500Watts



- MiniBooNE Horn:
  - Has pulsed >100 million times
  - 5 times a second!
- MINOS Horns
  - 10 million pulses
  - Once every 2 seconds
- Horn Currents: ~200,000 Amps
- 200,000 toasters!

Beamline for MINOS



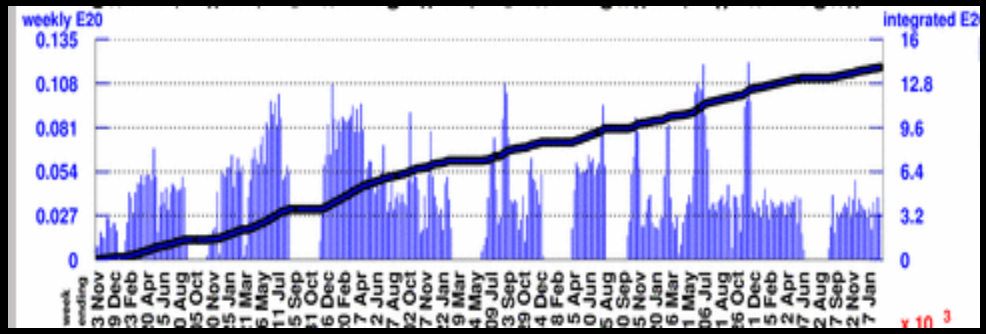
- Miners excavated a mile of underground tunnels
- Inserted 6’ tall pipe
- Filled the rest back up with concrete: 3000 cement trucks’ worth of cement
- Two large halls
  - Target hall: filled with target, horns shielding blocks
  - Near Detector Hall: 150ft long, filled with MINOS Near detector
- 3½ year construction—just to dig the hole, light switches came later…

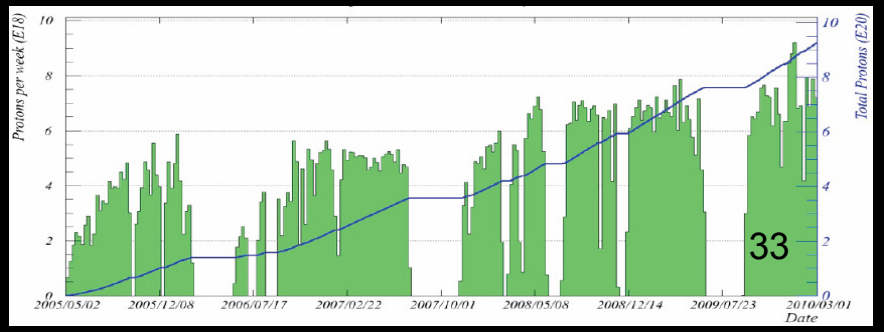
Ode to those who put the protons right on target

- In order to make neutrinos, someone has to accelerate protons
- Direct them through the beamline
- Hit the target
- And never miss!
- Like walking a mile with a glass full of milk that you cannot spill…
  - Over and over and over again for years…
- And what thanks do they get?

MiniBooNE: 1x10^{21} protons in 6 years!!!

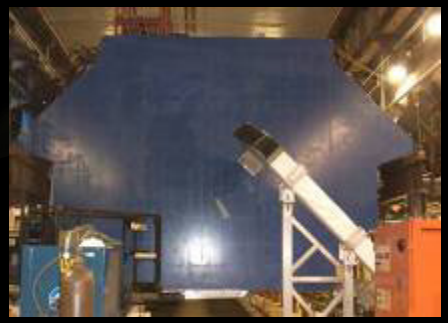
MINOS: 10x10^{20} protons in 5 years!!!





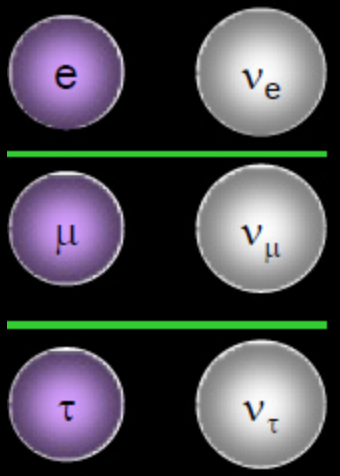
How many detectors are there?

MINOS: how many muon neutrinos “DISAPPEAR”



MiniBooNE: how many electron neutrinos APPEAR

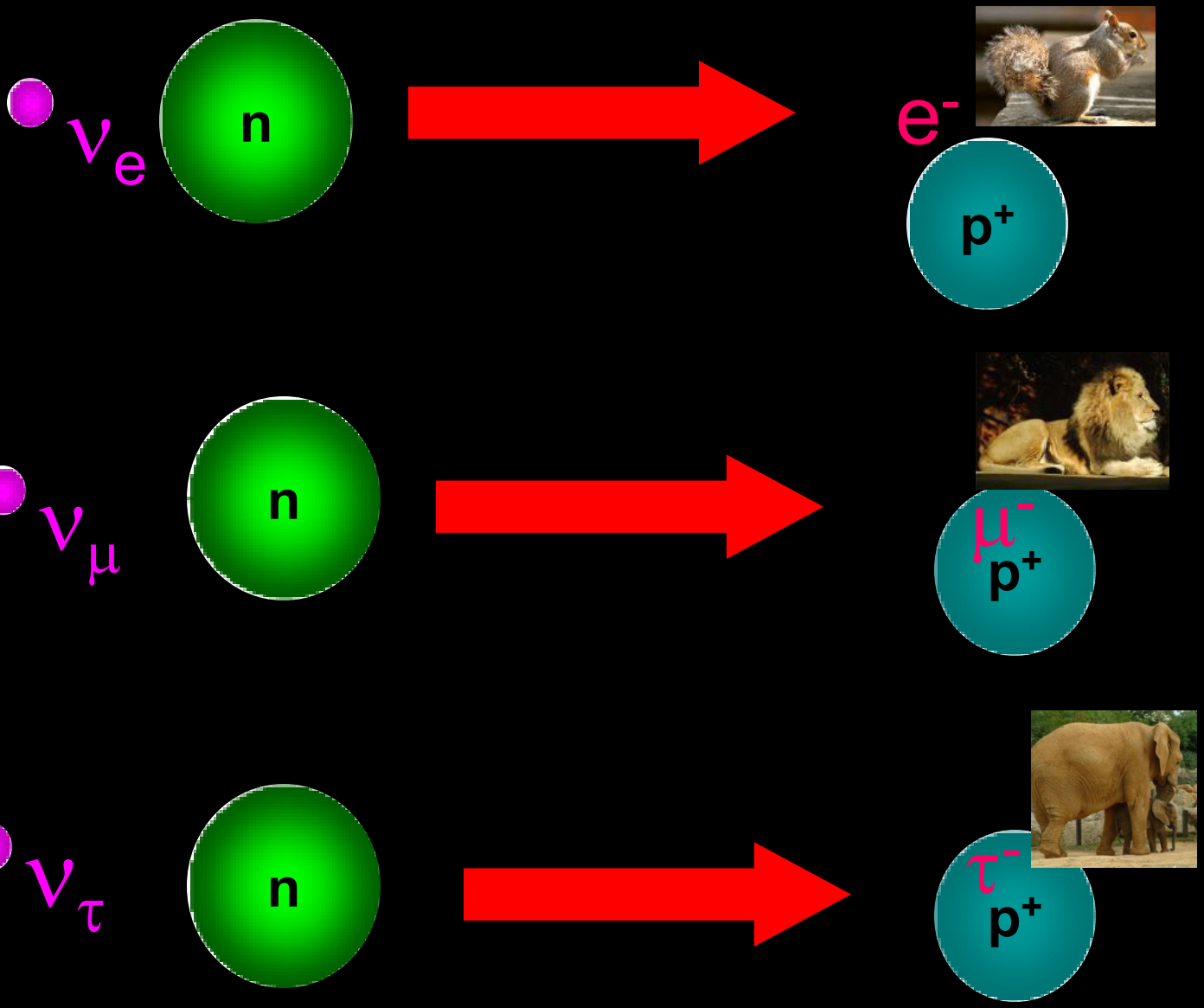
How can you see a neutrino?



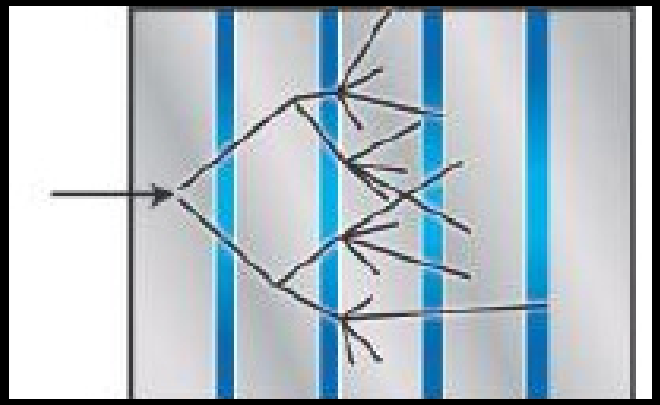
- These three neutrinos (ν's) are associated with three charged particles, who are as different in size as
  - Squirrel (e: electron)
  - Lion (μ: muon)
  - Elephant (τ: tau)

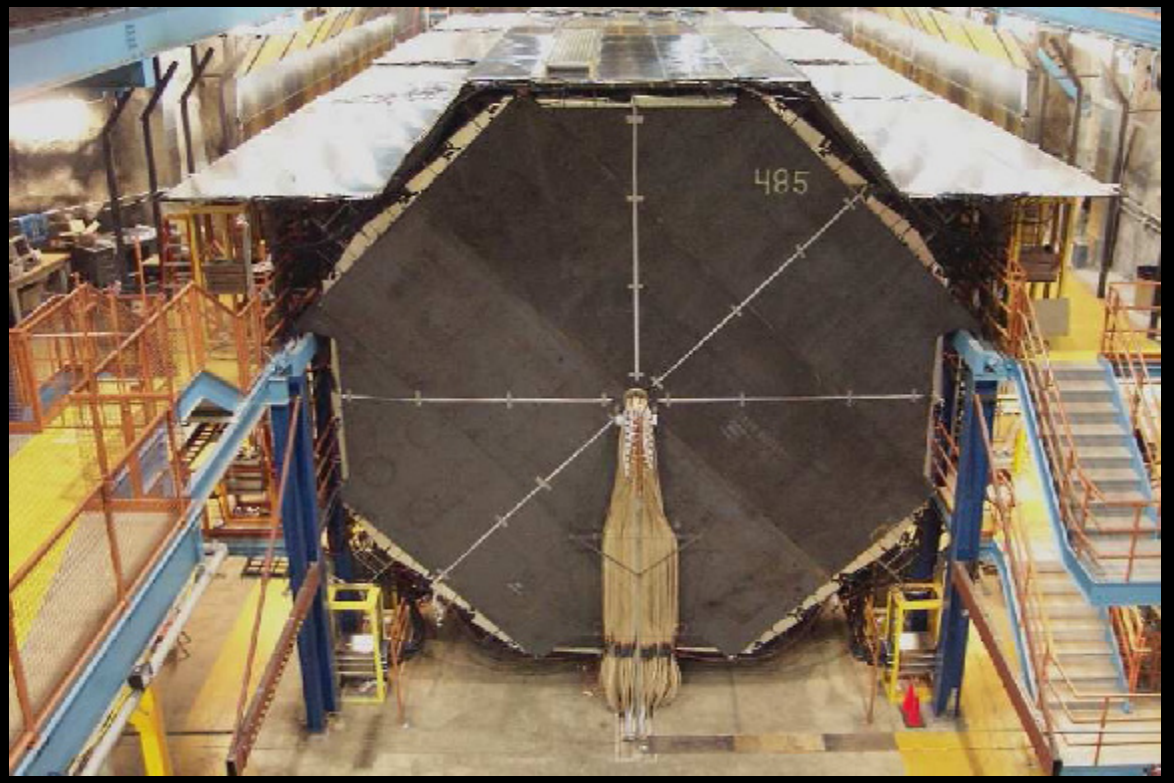
You can't see the neutrino, but you can see their partners

What kind of neutrino is it?

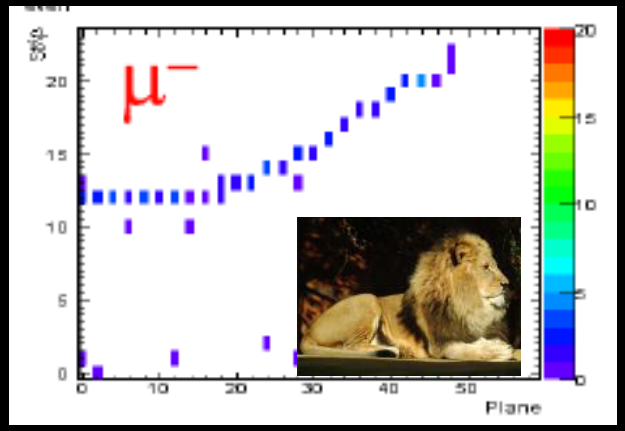


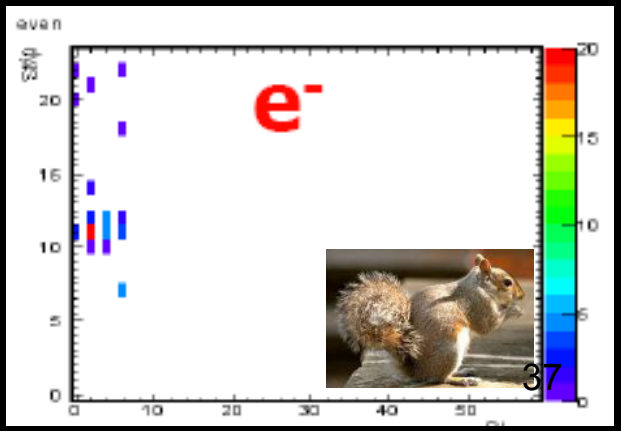
MINOS





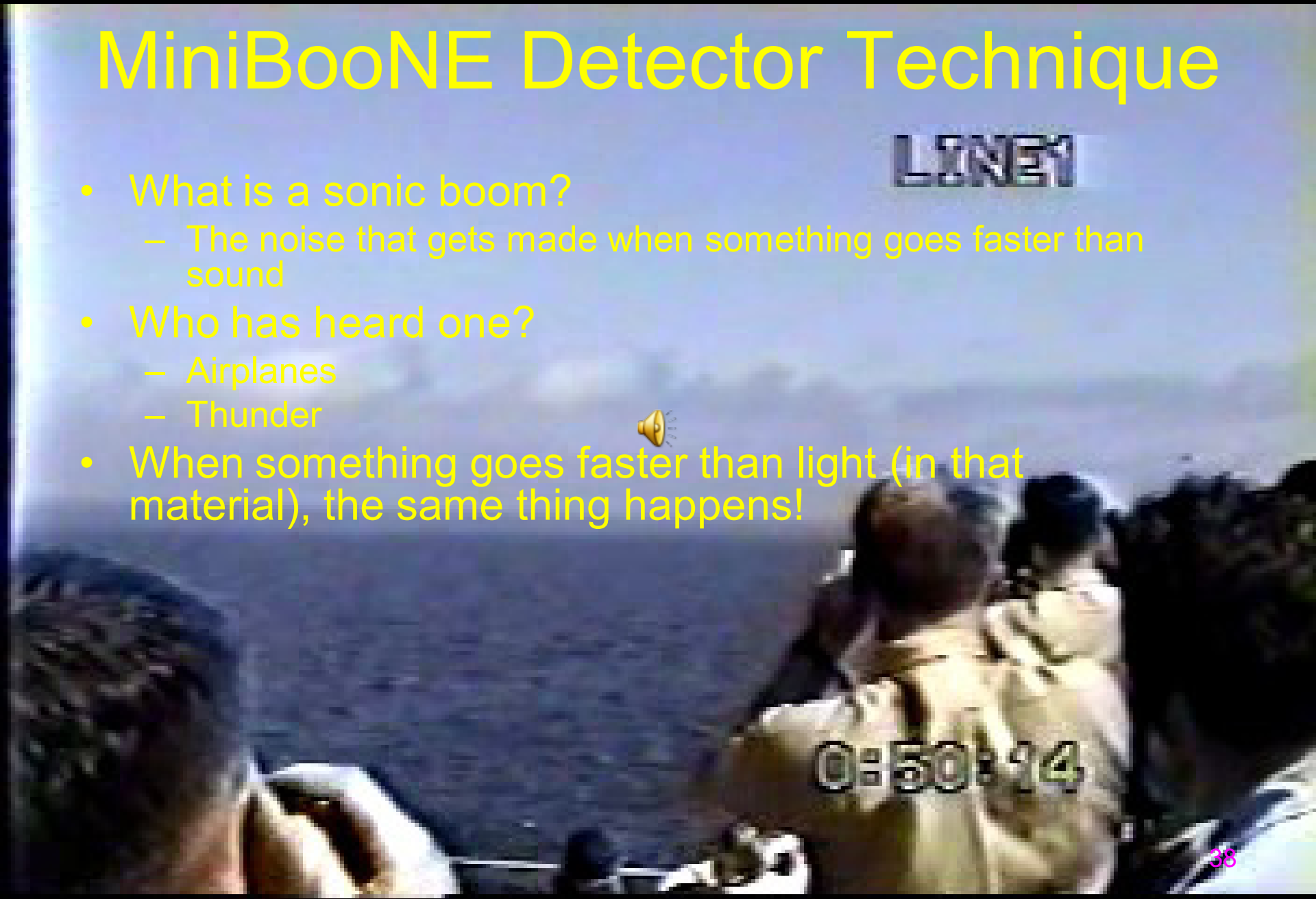
MINOS Detector:
5,400 tons of steel and plastic
Not just any plastic: it gives off light
when charged particles go through it
Collect the light: more particles, more light



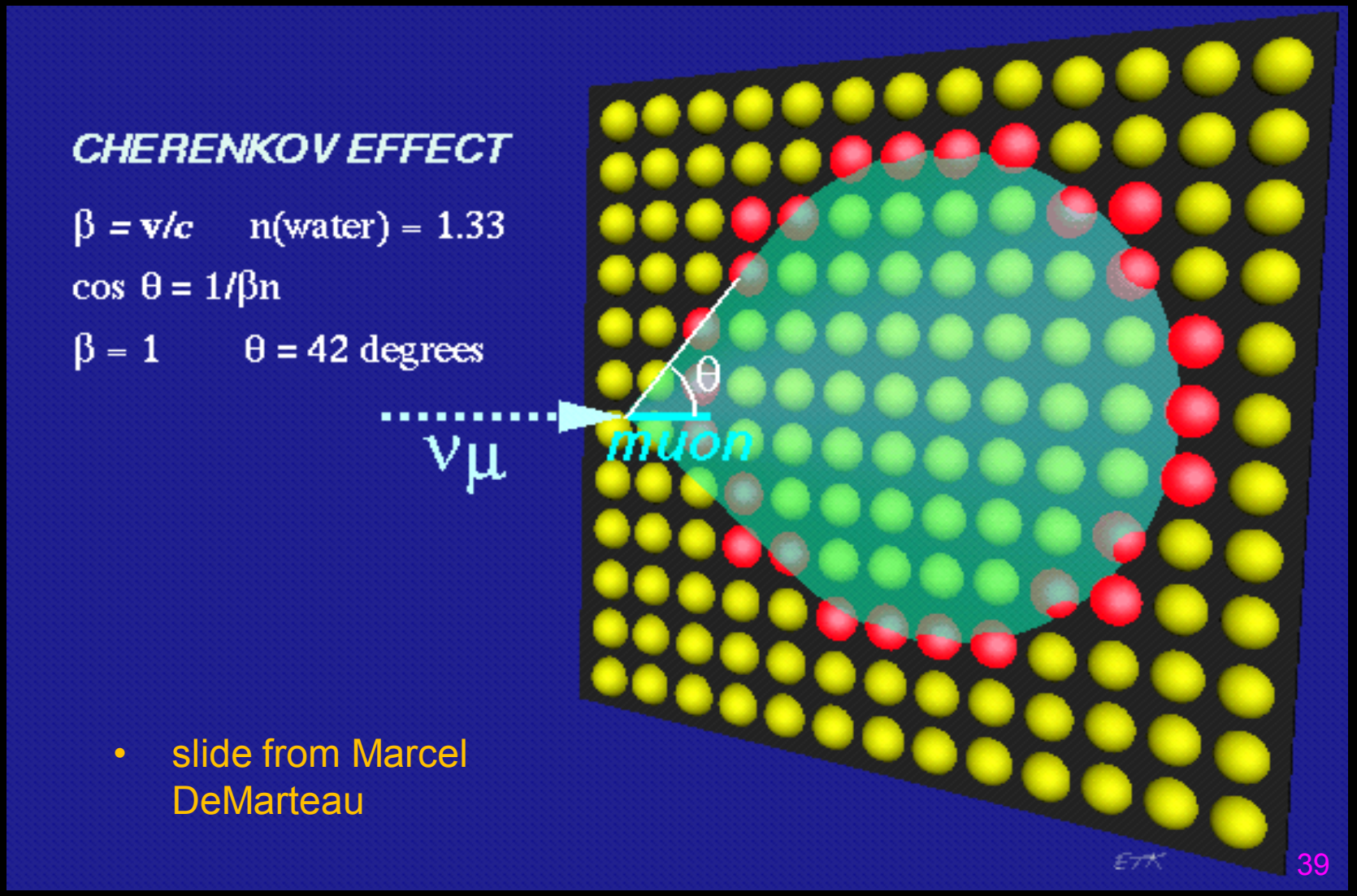


MiniBooNE Detector Technique

- What is a sonic boom?
  - The noise that gets made when something goes faster than sound
- Who has heard one?
  - Airplanes
  - Thunder
- When something goes faster than light (in that material), the same thing happens!



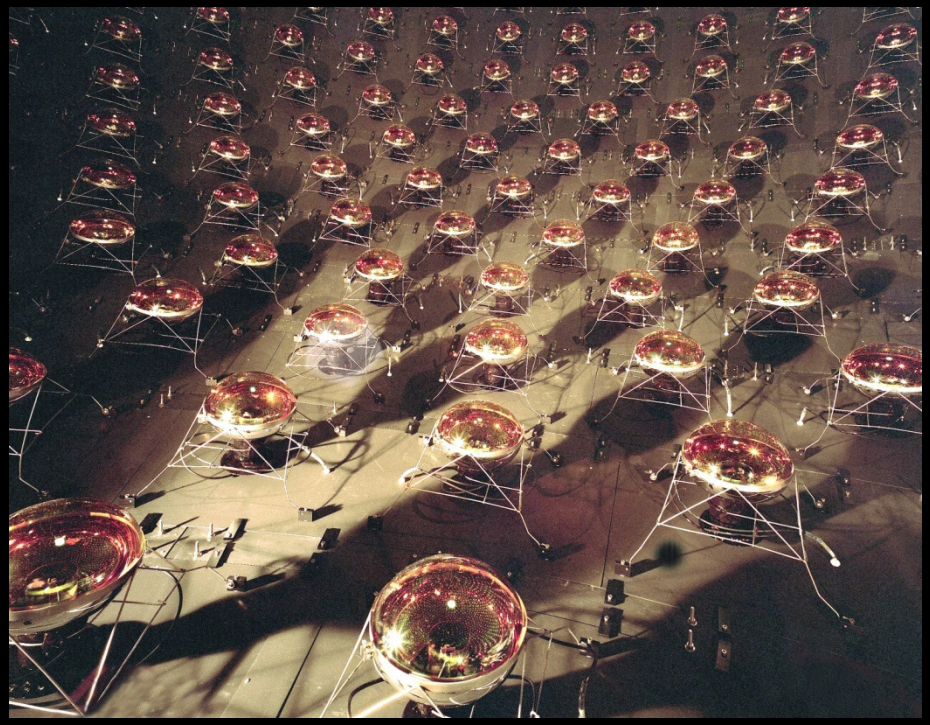
Cerenkov Radiation



- slide from Marcel DeMarteau

MiniBooNE Detector

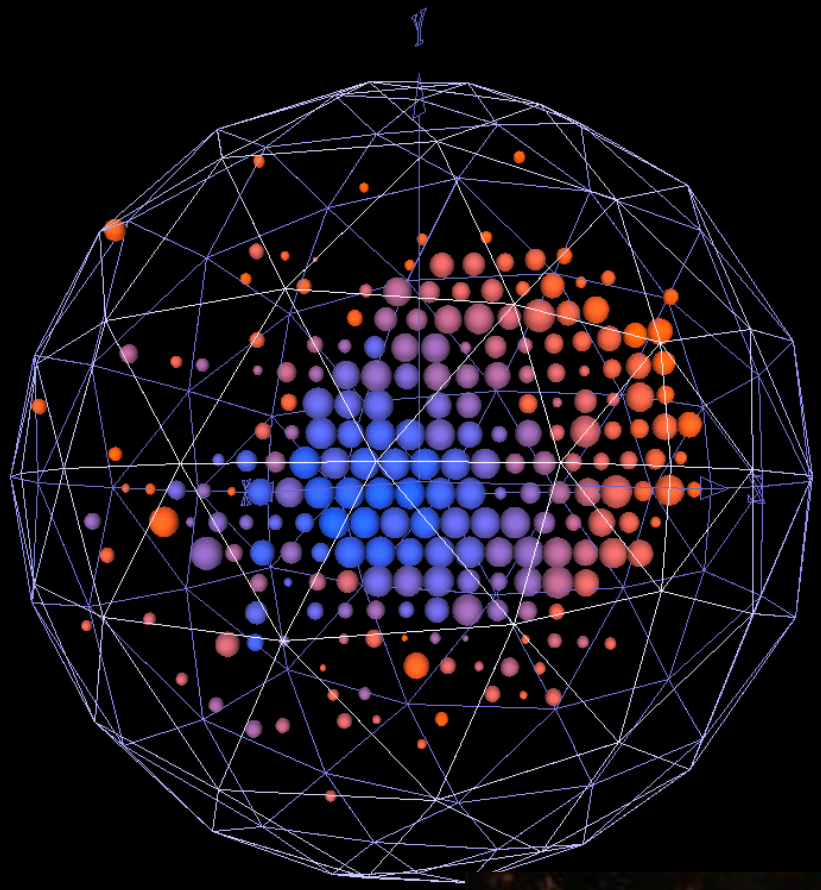
- tank contains 250,000 gallons of **mineral oil** (neutrino target)
  - 44 tanker trucks worth
  - 800 tons
- lined w/ 1520 **PHOTOTUBES** (electronic "eyes" of the detector)

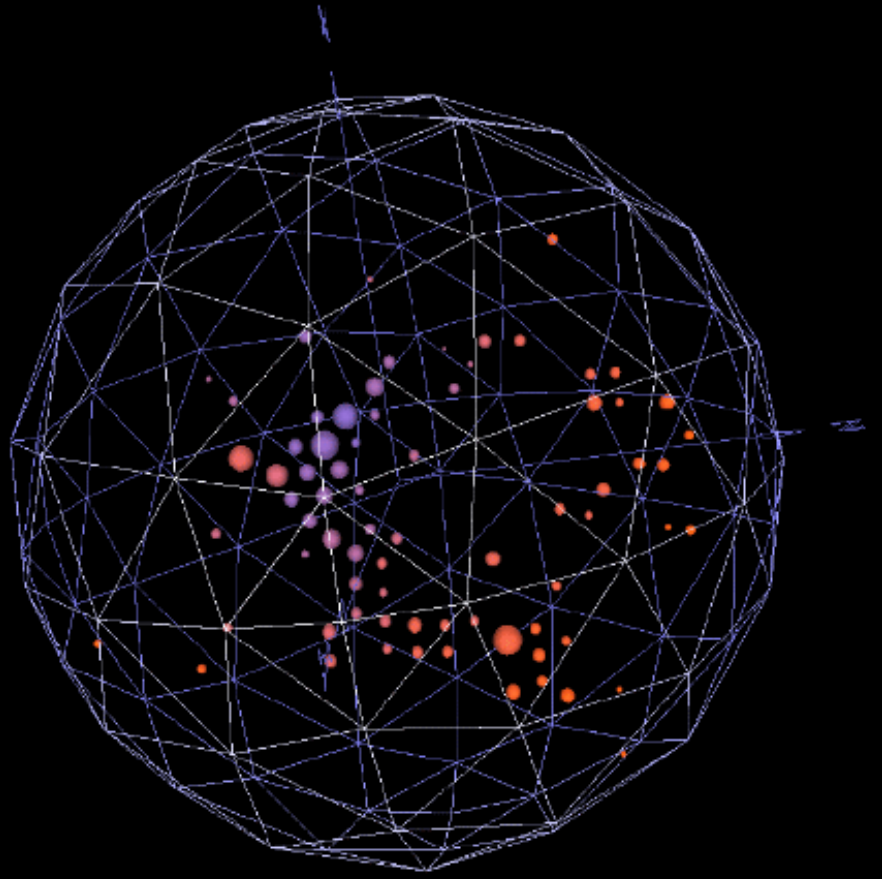


Phototubes work like inverse light bulbs

- produce an electrical signal whenever light strikes them

Neutrino Patterns in MiniBooNE



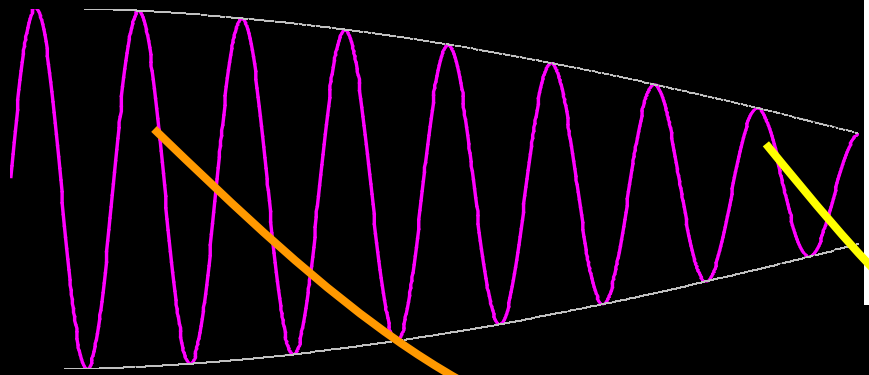


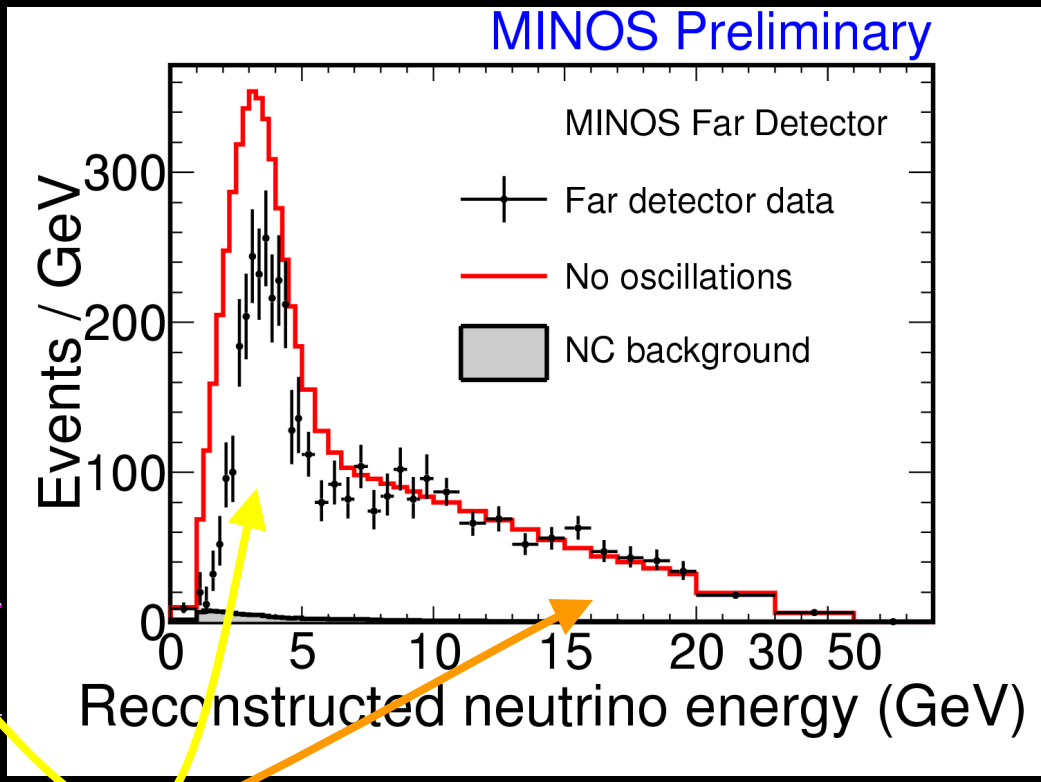
muon

electron

Results from MINOS

- First results were shown March 30, 2006:
  - Auditorium was packed
  - 204 ν_μ events seen
  - Expect 50% more if no oscillations!

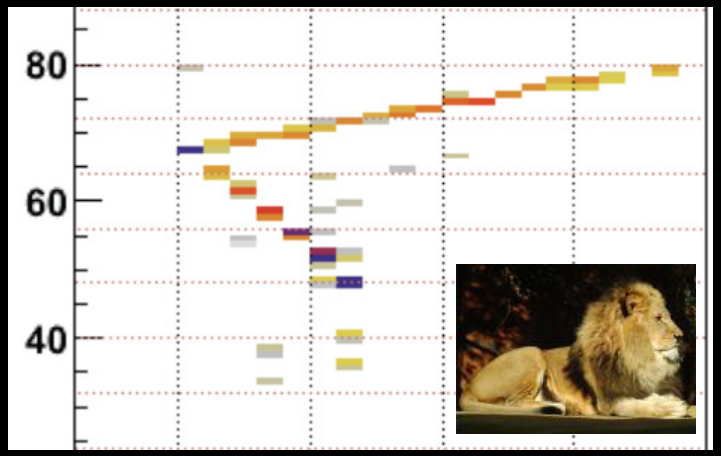


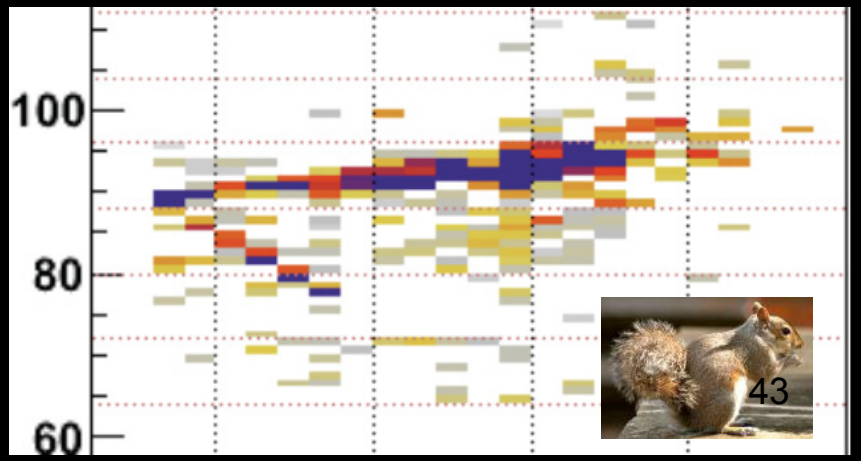


- Four years later: we are still seeing them disappear, we now see 1986 events instead of 2451
- Trying to understand if electron neutrinos appear, and if muon anti-neutrinos disappear at same rate:

What's Next?

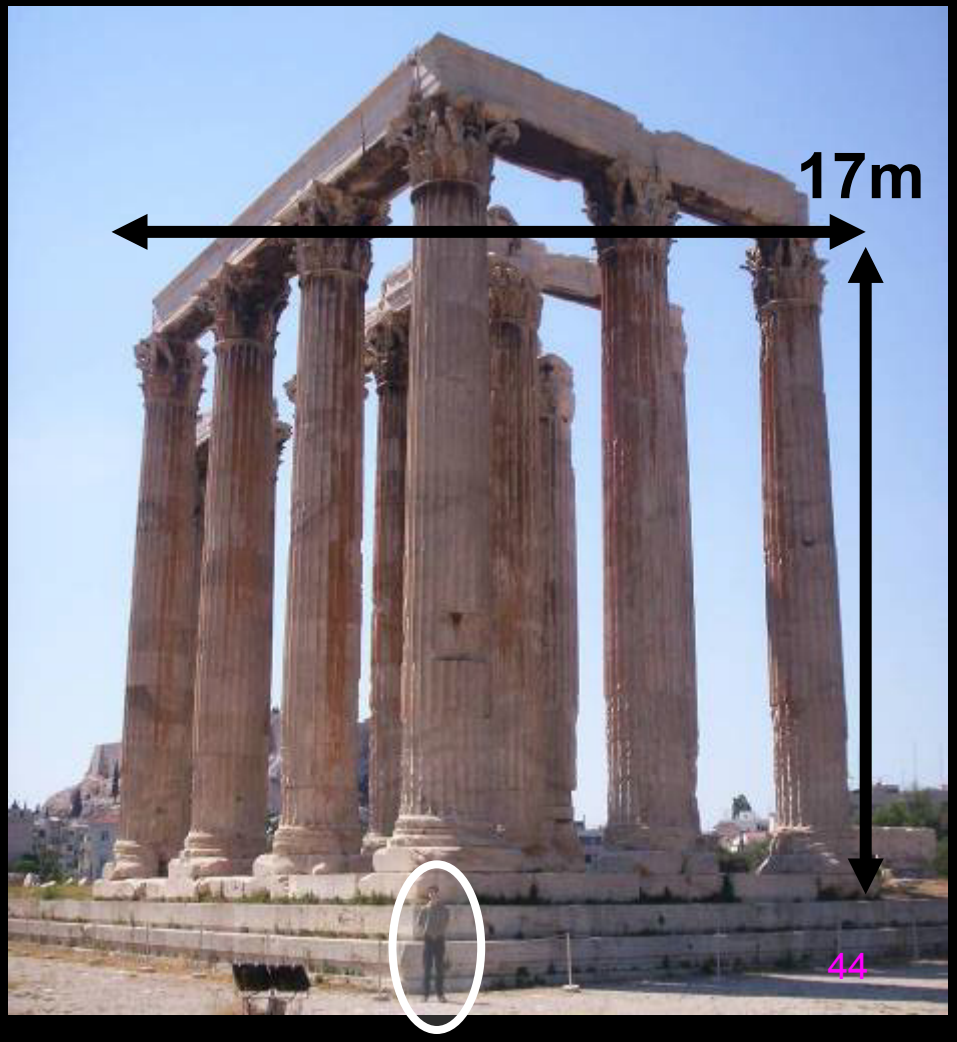
- MINERvA:
  - New detector
  - New community of nuclear physicists
  - Same beam as MINOS
- New eyes on the way neutrinos interact
- Will help next generation of oscillation experiments





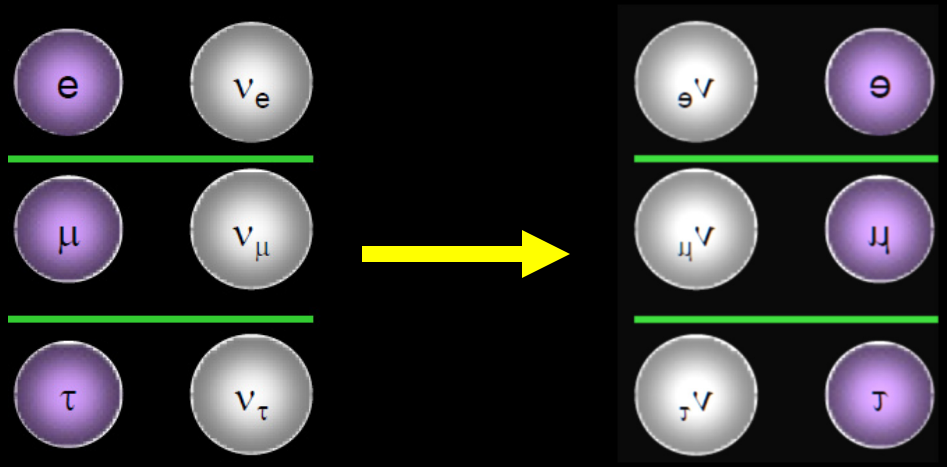
What's next for Oscillations?

- Just around two corners: NOvA
  - Will use the same neutrino beamline as MINOS
  - Brand new HUGE detector in northern Minnesota: better able to distinguish electrons (squirrels) from anything else
  - Best chance for seeing neutrino anti-neutrino differences!



Why Neutrinos and Anti-Neutrinos?

- Every fundamental particle has an anti-matter partner



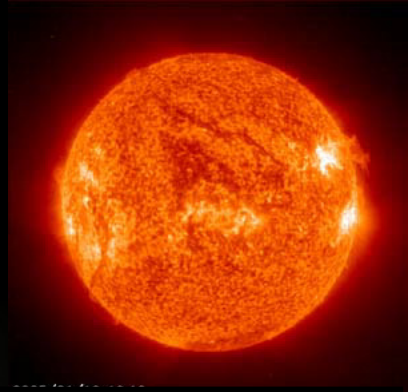
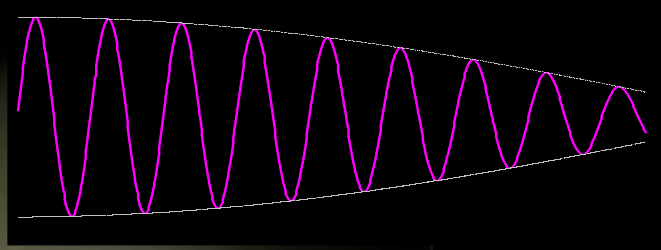
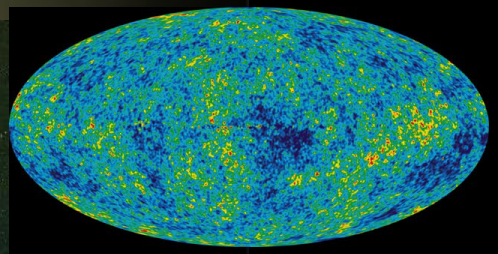
- When they meet, they annihilate into pure energy
- Alternatively, energy can become matter plus anti-matter

So you might ask…

- The early Universe had a lot of energy. Where is the anti-matter in the Universe?
- Good question… how do we know it isn't around today?
  - look for annihilations.
  - As far away as we can tell, today there aren't big matter and anti-matter collisions

  - Maybe it's the neutrinos which are different from anti-neutrinos! Stay tuned…

Why study Neutrinos?

- They tell us where we've been
  - Neutrinos created during the big bang had huge impact on evolution of universe
    - What the abundances of elements are
- There are more of them around than any other particle besides light
  - If we say we want to understand the universe…
- They may be the reason that we are here today….
  - If neutrinos and antineutrinos act differently

Conclusions