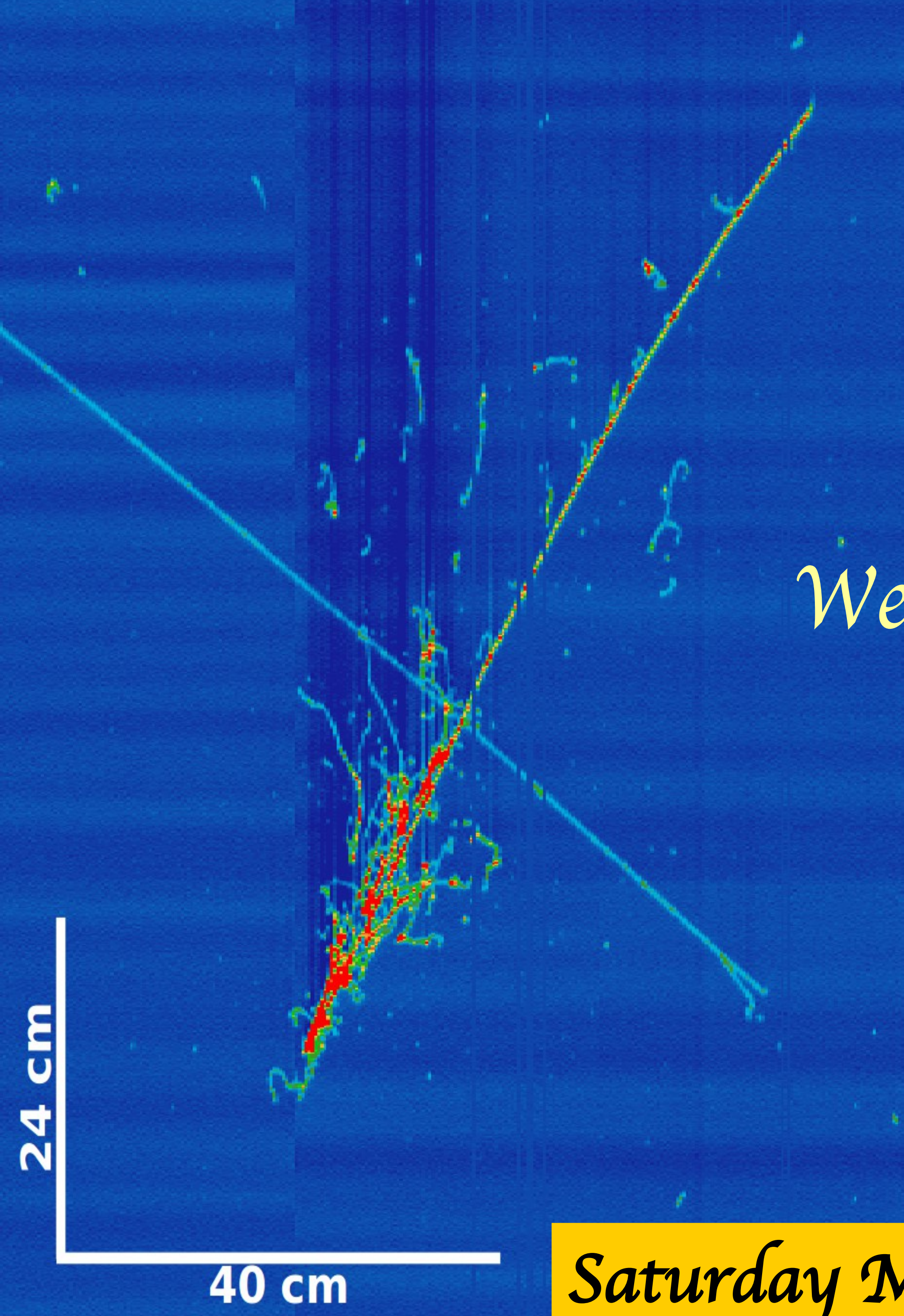
µBooNE



Neutrinos: Weird and Wonderful

Sowjanya Gollapinni
(Kansas State University)

Saturday Morning Physics, April 16, 2016

No such thing as a dumb question

Before we dive in...

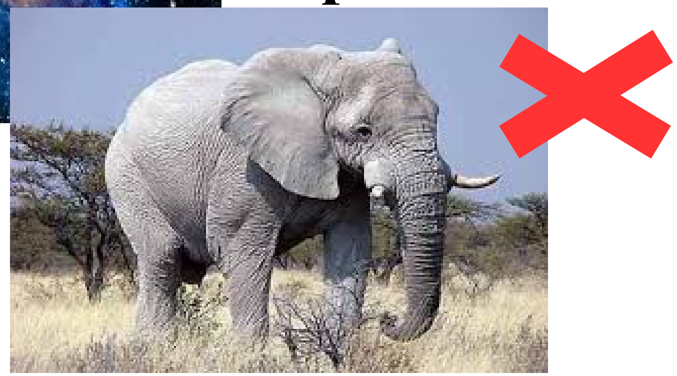
What is the "size" we will be talking about?

Galaxies

Not talking this...

Galaxies

Elephants



Not talking this...

Not talking this...

Galaxies

Elephants

Squirrels

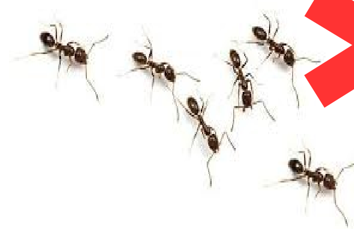
Not talking this...

Galaxies

Elephants

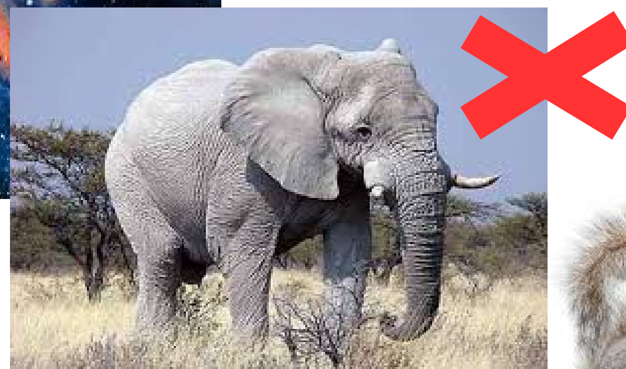
Squirrels

Ants



Galaxies

Elephants

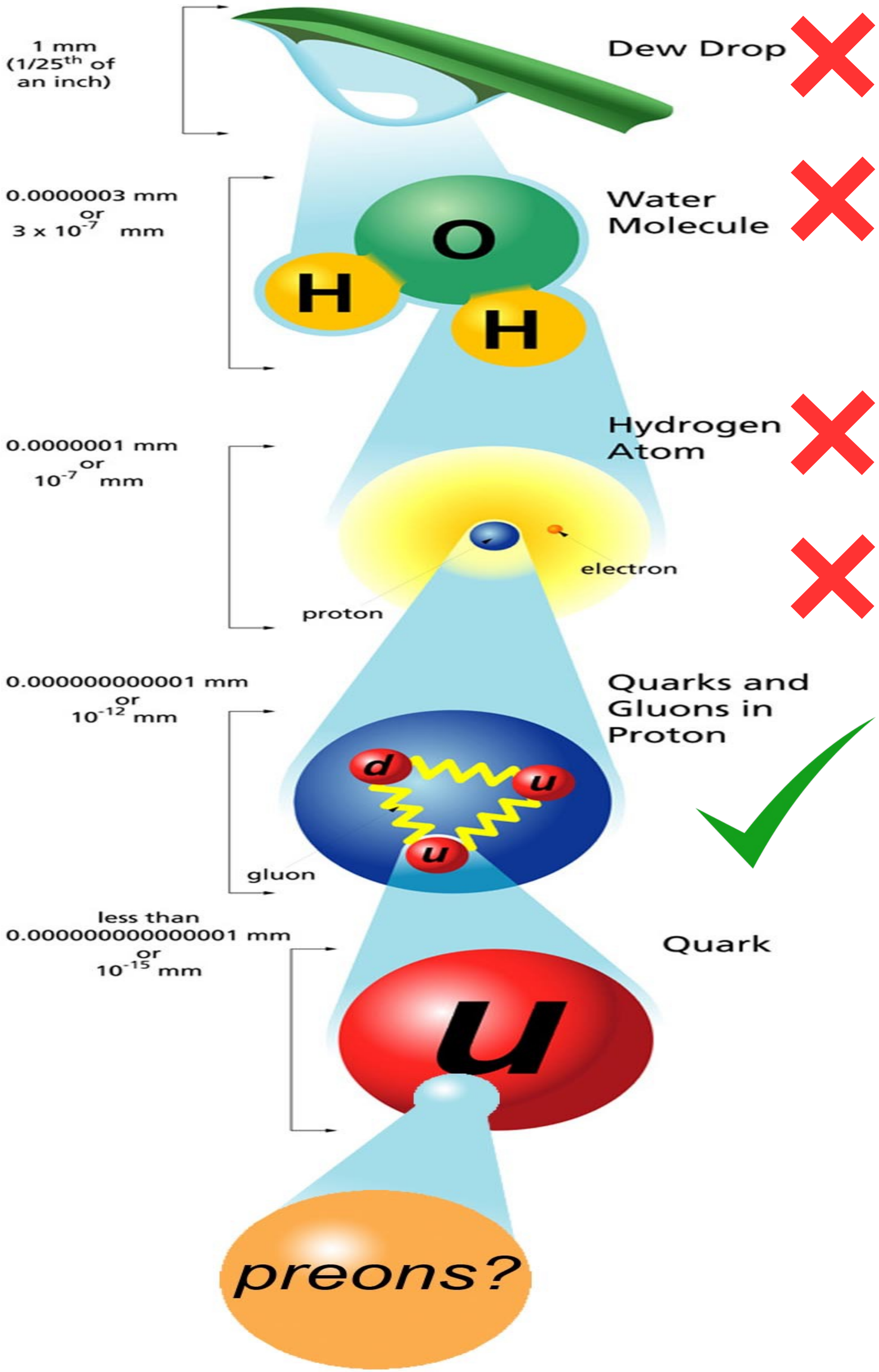


Squirrels

Ants

A dew drop

Not even talking this...



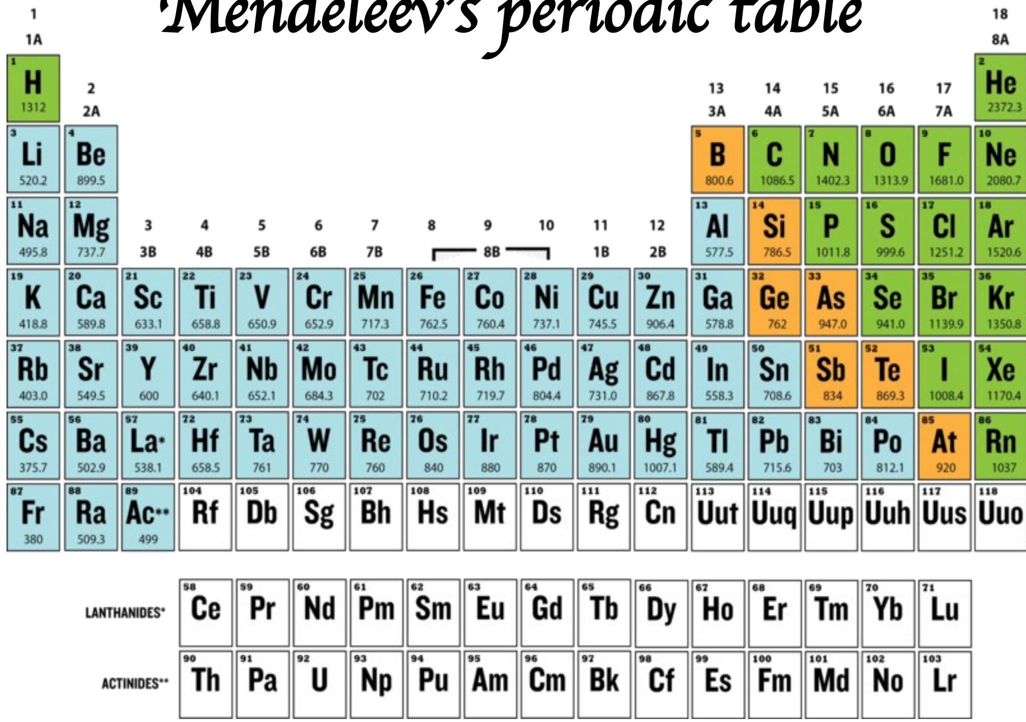
Somewhere here....

Now…how many of you know what this is?

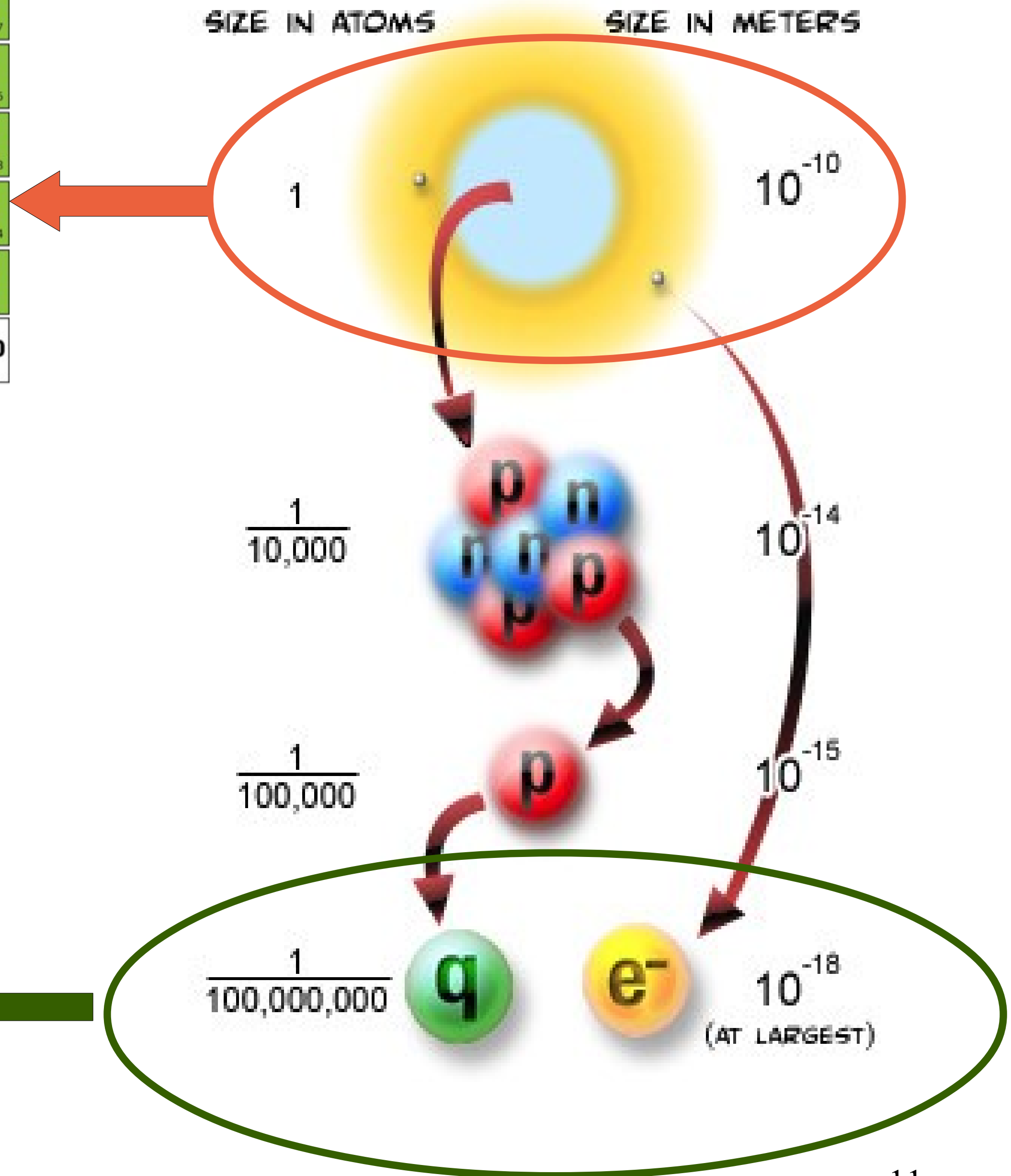
1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** 1312																	2 **He** 2372.3
3 **Li** 520.2	4 **Be** 899.5											5 **B** 800.6	6 **C** 1086.5	7 **N** 1402.3	8 **O** 1313.9	9 **F** 1681.0	10 **Ne** 2080.7
11 **Na** 495.8	12 **Mg** 737.7											13 **Al** 577.5	14 **Si** 786.5	15 **P** 1011.8	16 **S** 999.6	17 **Cl** 1251.2	18 **Ar** 1520.6
19 **K** 418.8	20 **Ca** 589.8	21 **Sc** 633.1	22 **Ti** 658.8	23 **V** 650.9	24 **Cr** 652.9	25 **Mn** 717.3	26 **Fe** 762.5	27 **Co** 760.4	28 **Ni** 737.1	29 **Cu** 745.5	30 **Zn** 906.4	31 **Ga** 578.8	32 **Ge** 762	33 **As** 947.0	34 **Se** 941.0	35 **Br** 1139.9	36 **Kr** 1350.8
37 **Rb** 403.0	38 **Sr** 549.5	39 **Y** 600	40 **Zr** 640.1	41 **Nb** 652.1	42 **Mo** 684.3	43 **Tc** 702	44 **Ru** 710.2	45 **Rh** 719.7	46 **Pd** 804.4	47 **Ag** 731.0	48 **Cd** 867.8	49 **In** 558.3	50 **Sn** 708.6	51 **Sb** 834	52 **Te** 869.3	53 **I** 1008.4	54 **Xe** 1170.4
55 **Cs** 375.7	56 **Ba** 502.9	57 **La*** 538.1	72 **Hf** 658.5	73 **Ta** 761	74 **W** 770	75 **Re** 760	76 **Os** 840	77 **Ir** 880	78 **Pt** 870	79 **Au** 890.1	80 **Hg** 1007.1	81 **Tl** 589.4	82 **Pb** 715.6	83 **Bi** 703	84 **Po** 812.1	85 **At** 920	86 **Rn** 1037
87 **Fr** 380	88 **Ra** 509.3	89 **Ac**** 499	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Uut**	114 **Uuq**	115 **Uup**	116 **Uuh**	117 **Uus**	118 **Uuo**

LANTHANIDES*	58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**
ACTINIDES**	90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

Mendeleev's periodic table

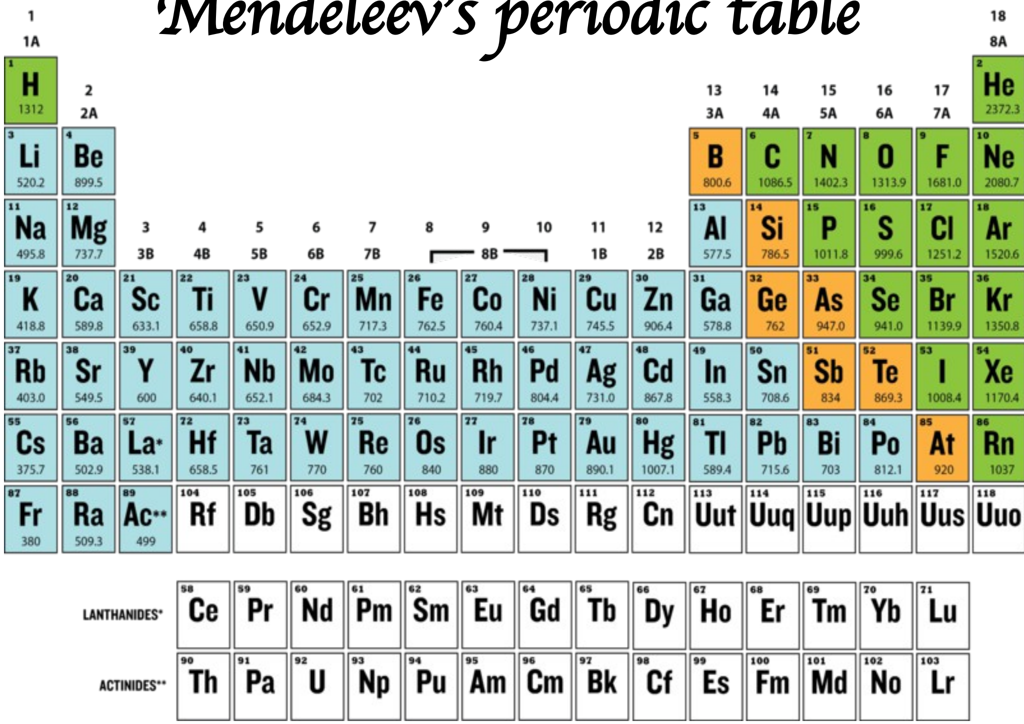


Scale of the atom and its constituents



What table describes the nature at a "million" times smaller length scale than the periodic table of elements?

Mendeleev's periodic table



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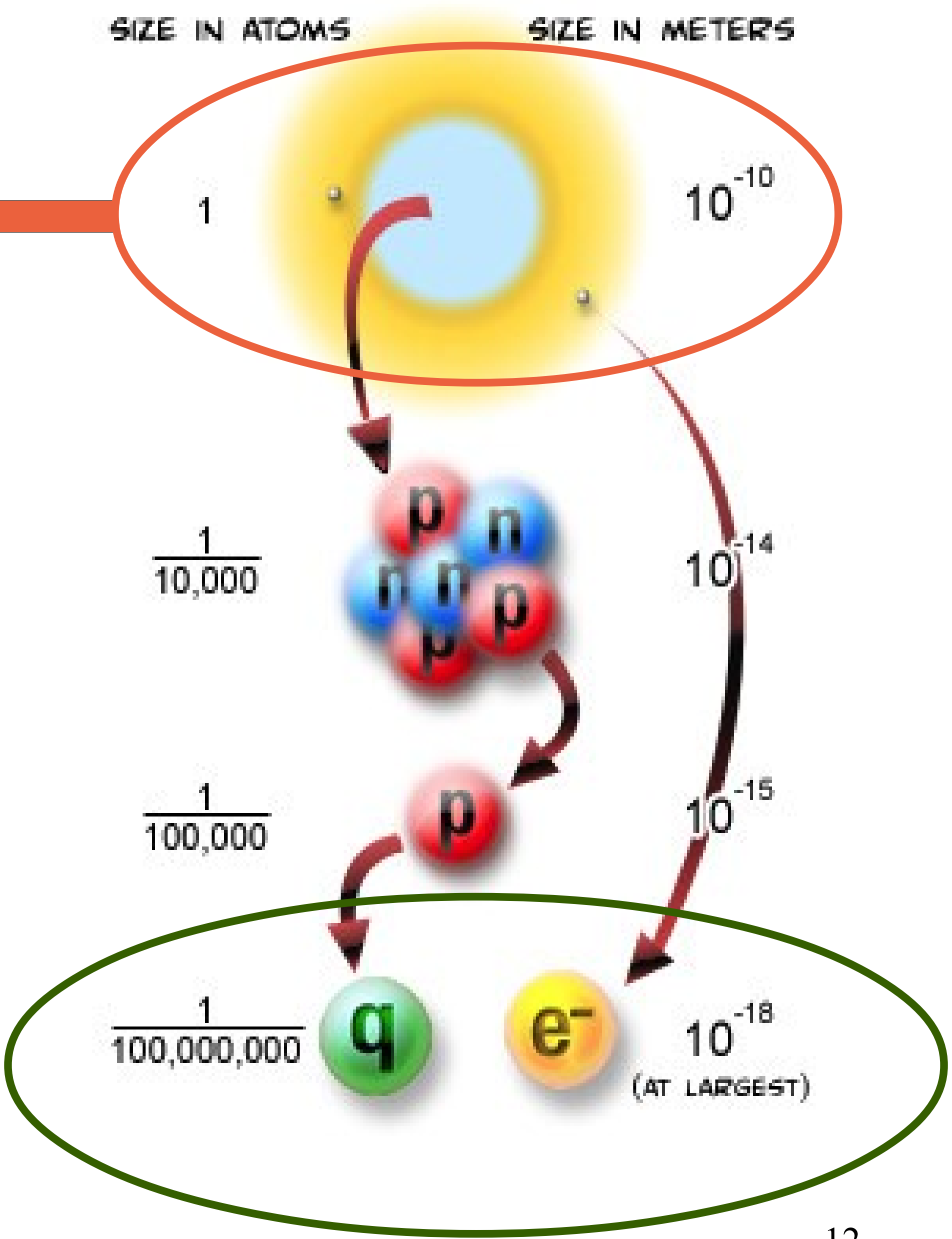
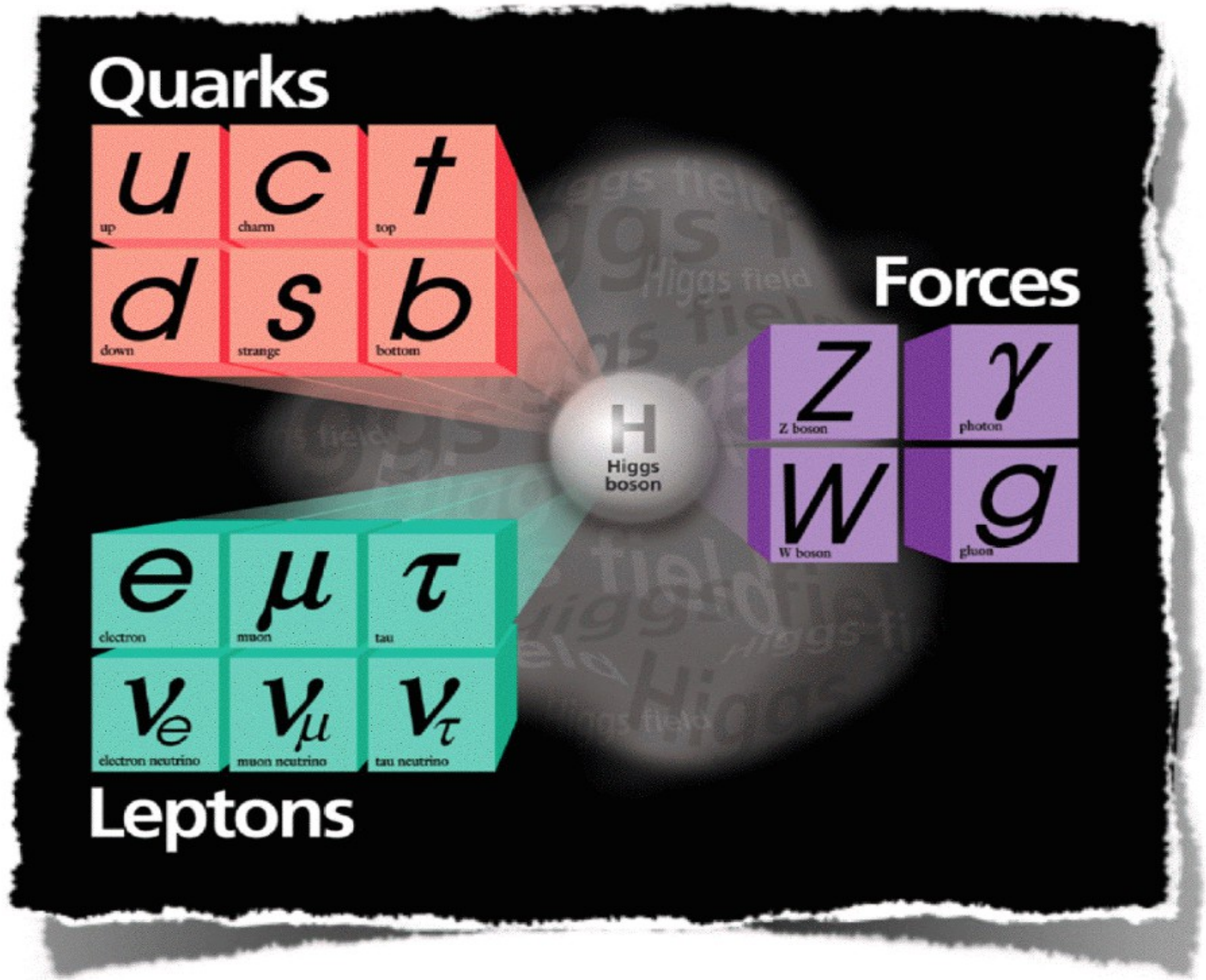


The Standard model of elementary particles!!

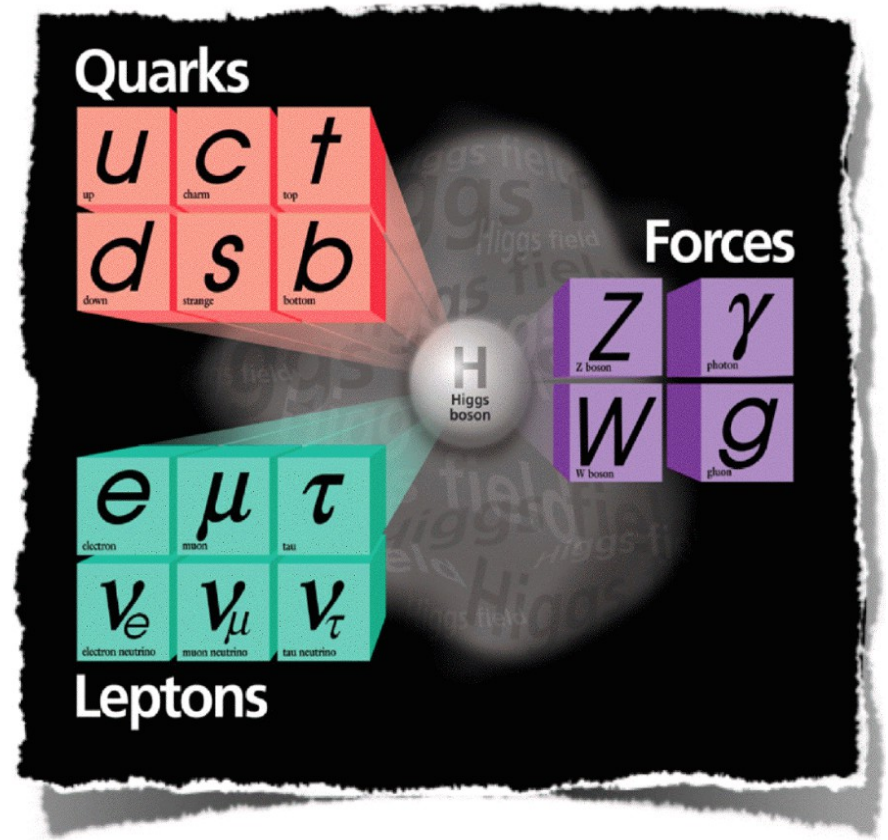
The Standard Model of Elementary particles

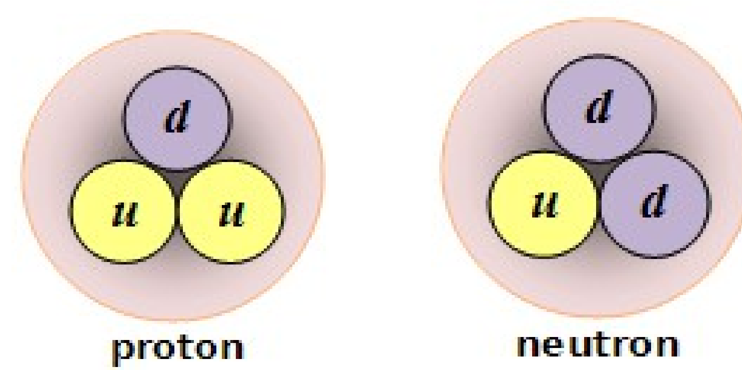


Who can explain this to me?

The Standard Model of Elementary particles

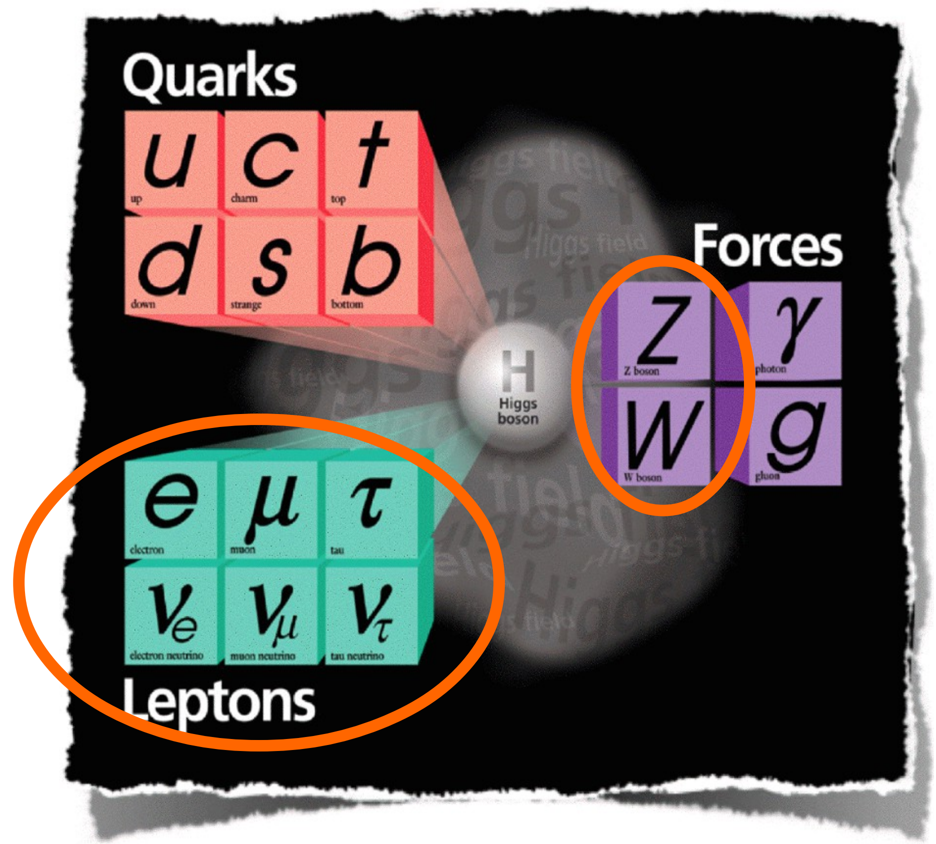
- Theory about fundamental ingredients of matter and how they interact with each other
- Everything known in this world is made of these (and their mirror images)

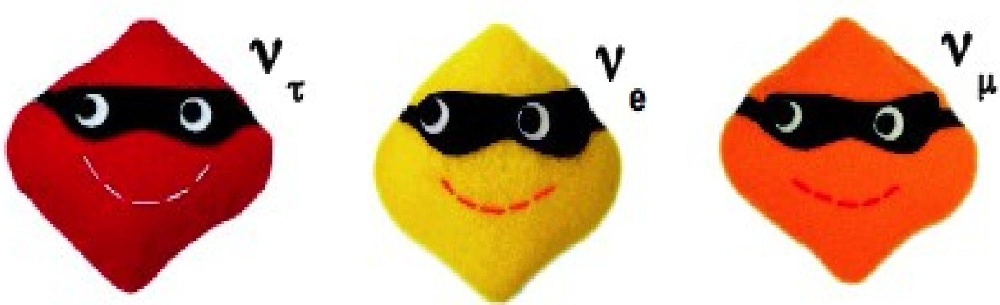


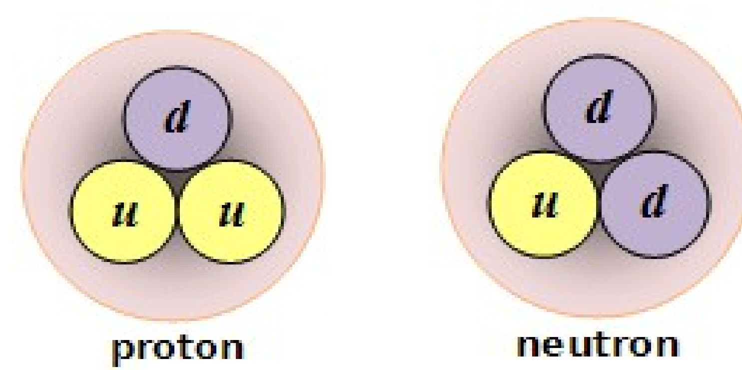


The Standard Model of Elementary particles

- *Theory about fundamental ingredients of matter and how they interact with each other*
- *Everything known in this world is made of these (and their mirror images)*
- *For this talk,*
  we will focus on NEUTRINOS







A Word about Forces...

Gravitational

Strong

Electromagnetic

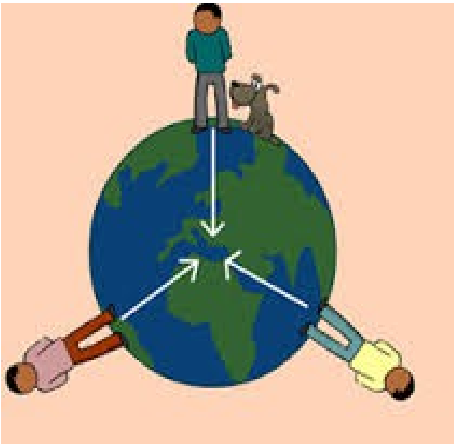
Weak

A Word about Forces...

Gravitational (gravitons)

- Solar System
- Black holes
- Galaxies

(gravitons not yet discovered!)



Strong (gluons)

Electromagnetic (photons)

Weak (W/Z bosons)

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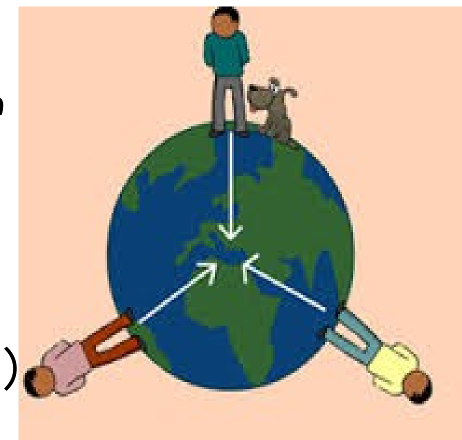
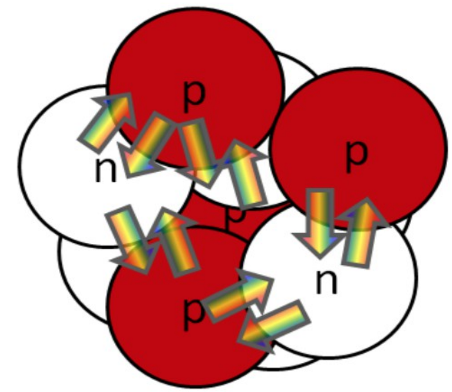


Strong (gluons)

- Binds the nucleus



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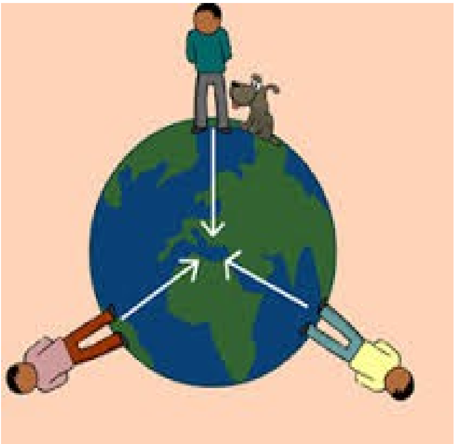

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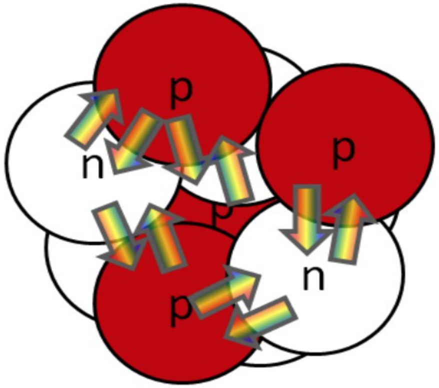
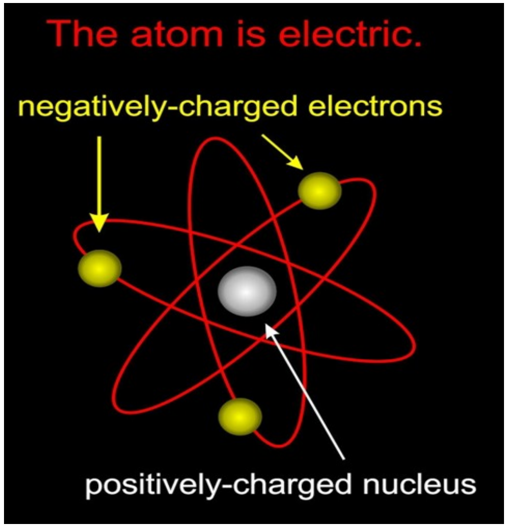


Electromagnetic (photons)

- Atoms
- Chemistry
- Light
- magnets



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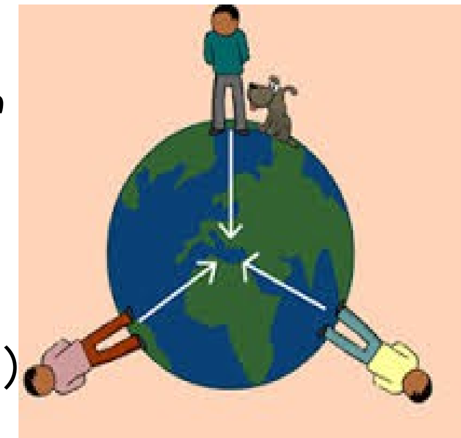

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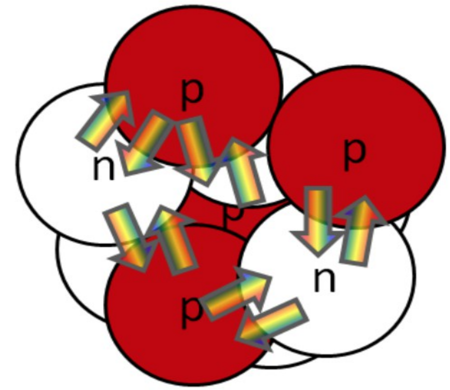

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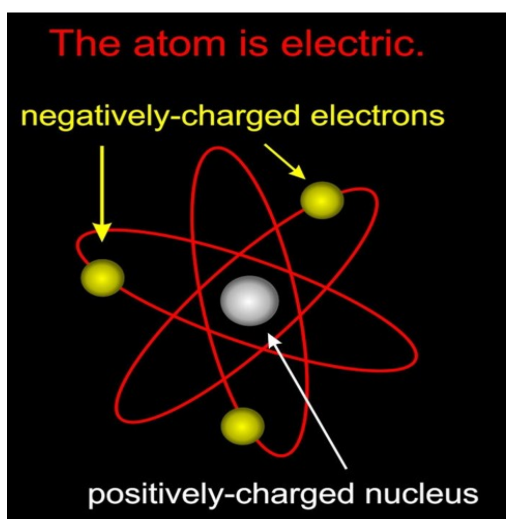
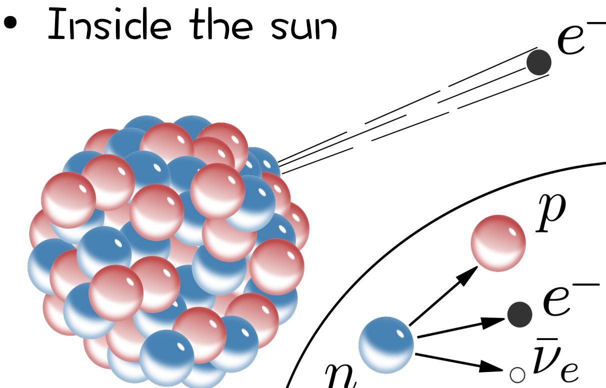


Weak (W/Z bosons)

- Neutron decay
- Radioactive decay
- Inside the sun



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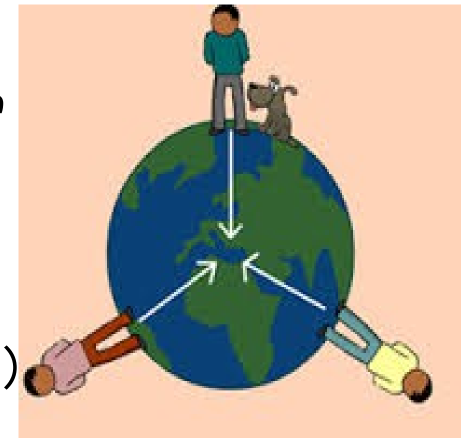

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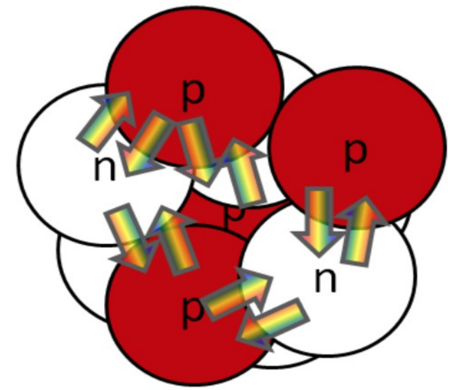

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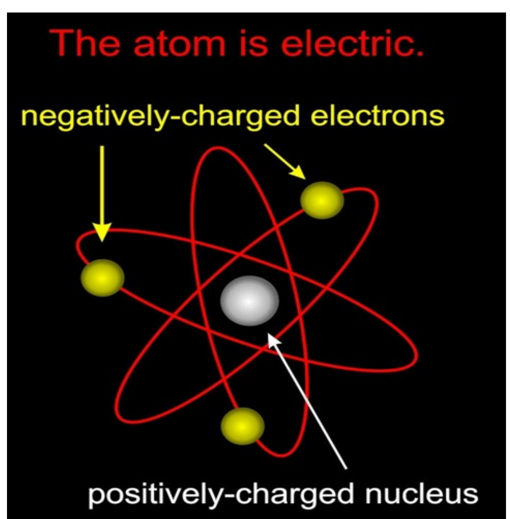
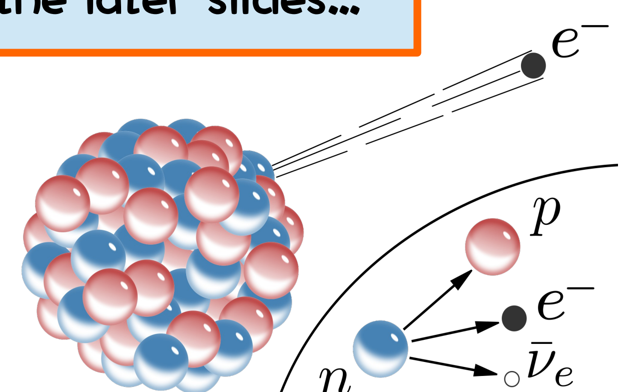


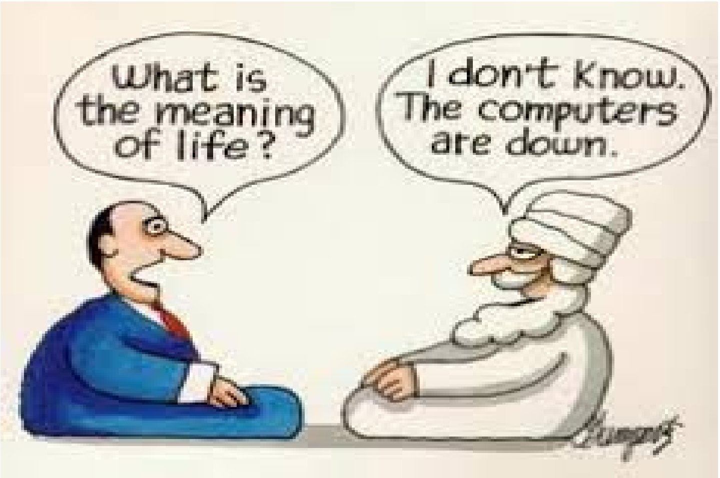
Weak (W/Z bosons)

We will revisit this in the later slides...

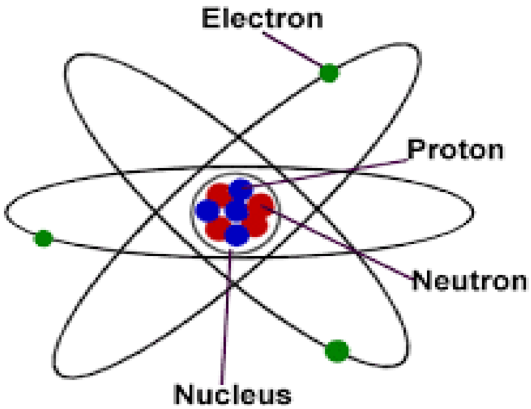


Why Study Neutrinos?

FLAVORS = TYPES



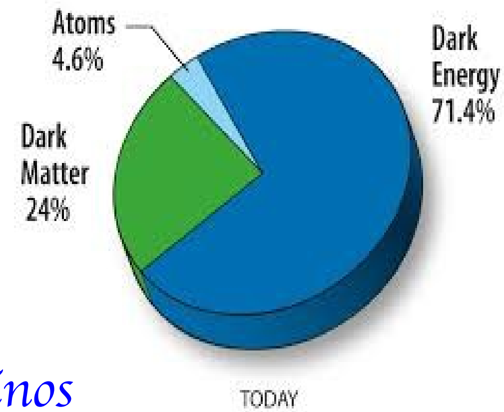
Neutrinos can provide answers to some of the biggest puzzles in the Universe!

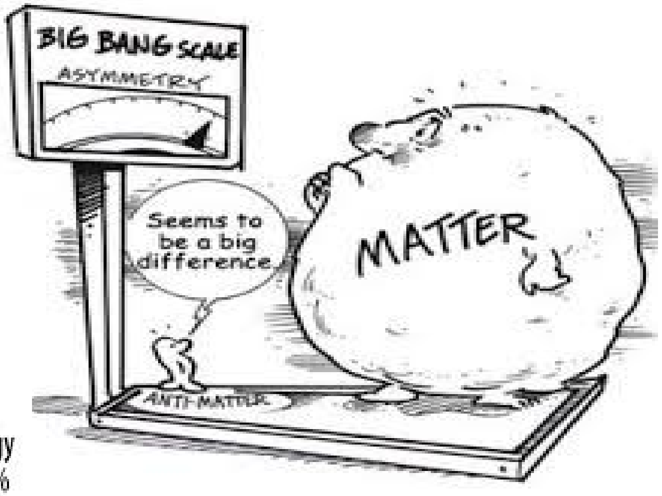


….. from the structure of the Atom to the formation of a Star!

The big world of little neutrinos!

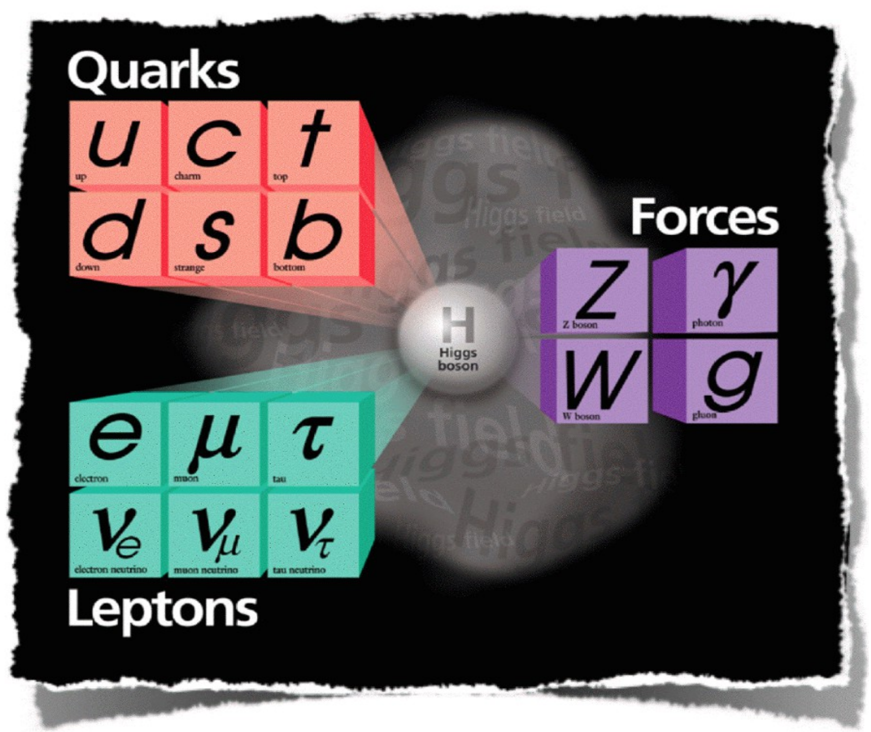
- *Why is there more matter in the Universe than anti-matter?*
- *What is Dark Matter made of?*
- *How are stars formed?*
- *How do stars collapse?*
- *How does Sun shine?*
- *How many flavors does neutrinos come in? How does that impact our understanding of the Universe?*
- *...and so on*





The big world of little neutrinos!

- ***Furthermore,***
  - *Neutrinos gave the first direct evidence that Standard Model is not enough to describe the particle world*
  - *How neutrinos get their mass is still a mystery!?*



?

Q: Where do neutrinos come from?

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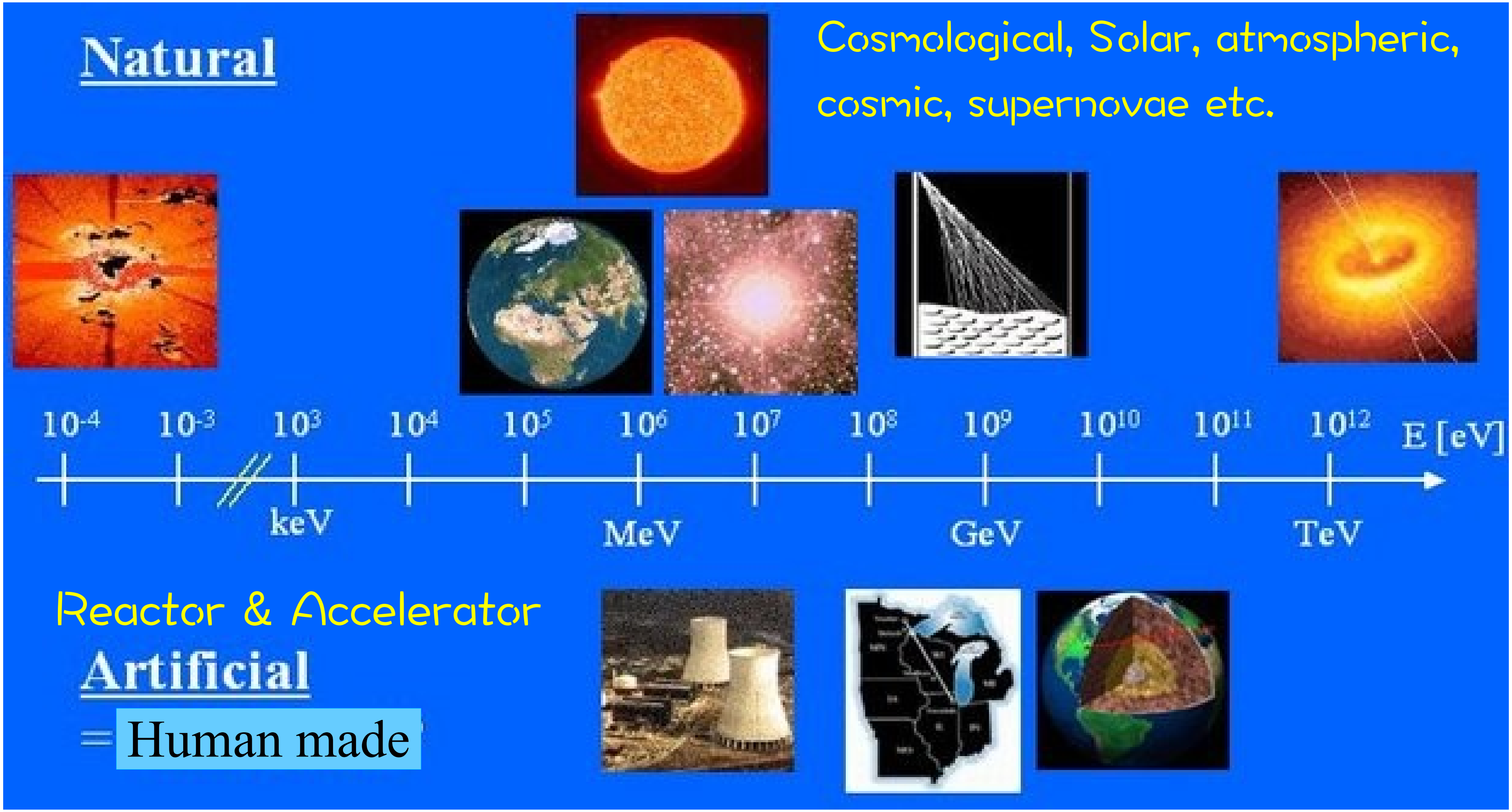
A: almost everywhere!



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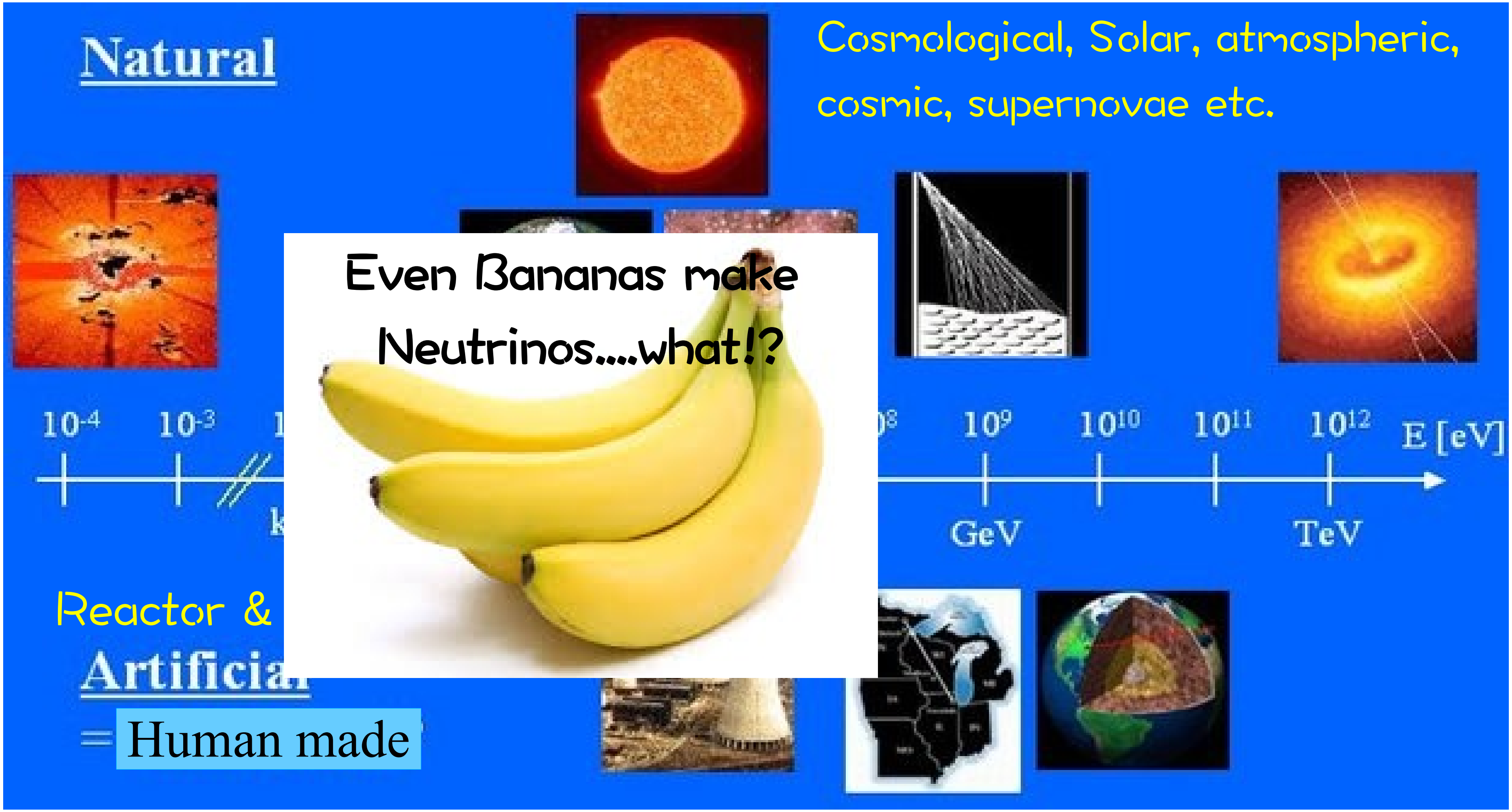

How to detect Neutrinos?

Two things to remember:

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1. They are abundant and easy to produce in copious amounts

   nearly ~100 billion neutrinos go through your thumb…what!?

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Two things to remember:

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   nearly ~100 billion neutrinos go through your thumb…what!?

2. Neutrinos are very, very, very..weakly interacting

   How weak you ask?

Can travel up to 200 earths without interacting!

Actually, can pass through a light year of lead without interacting!!

How to detect Neutrinos?

Two things to remember:

1. They are abundant and easy to produce in copious amounts

   nearly ~100 billion neutrinos go through your thumb...what!?

2. Neutrinos are very, very, very..weakly interacting

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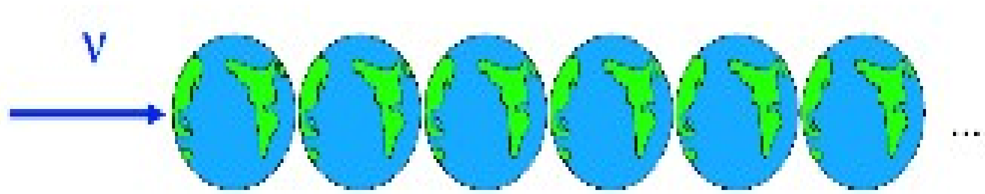


Can travel up to 200 earths without interacting!

So, how the hell do you detect it?

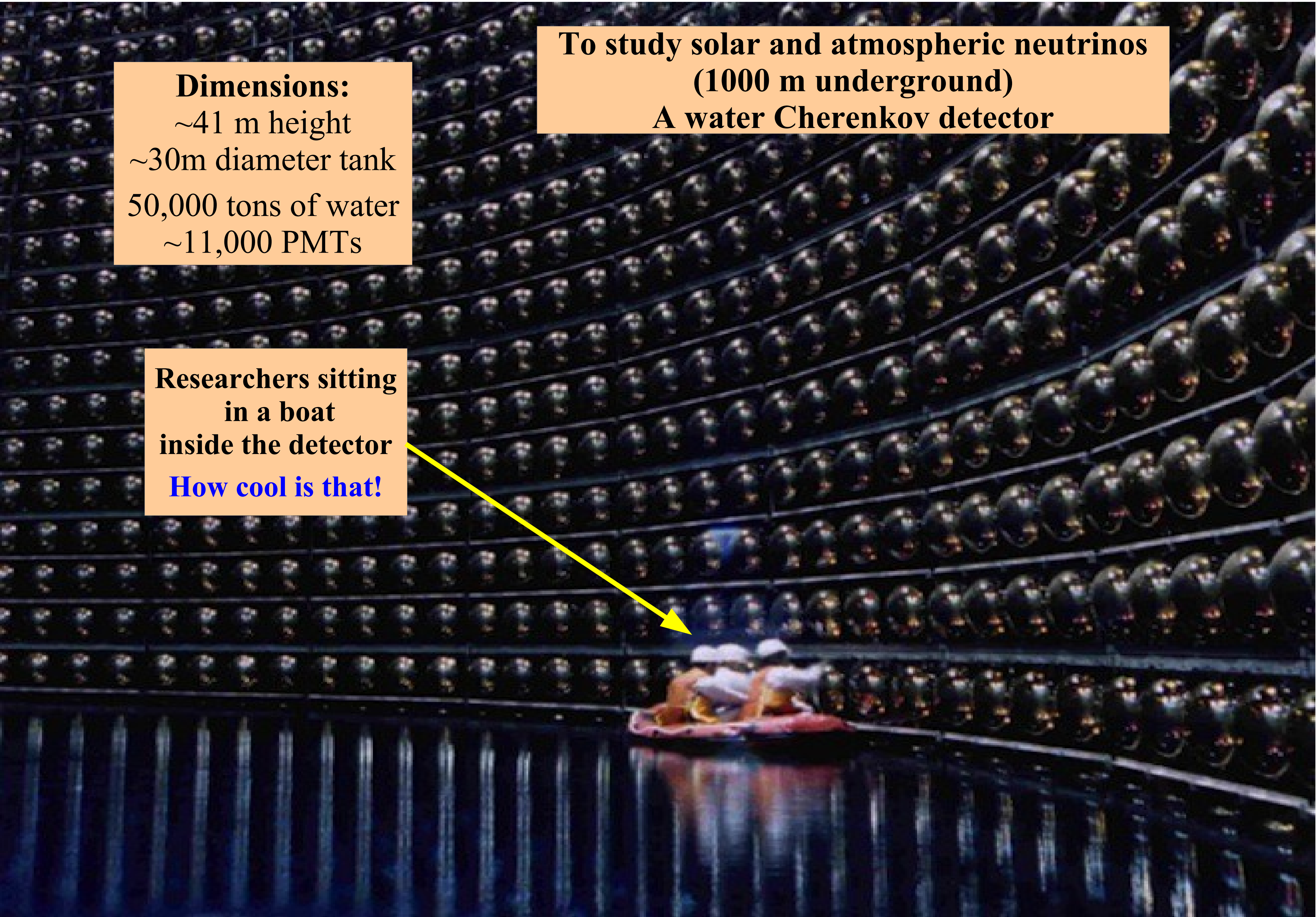
Neutrino Experiments

Strategy:

1. Produce them in large quantities in a well defined area
2. Put something very dense, very big and very sensitive for neutrinos to interact

Lets look at some cool examples!

Super-Kamiokande neutrino experiment in Japan

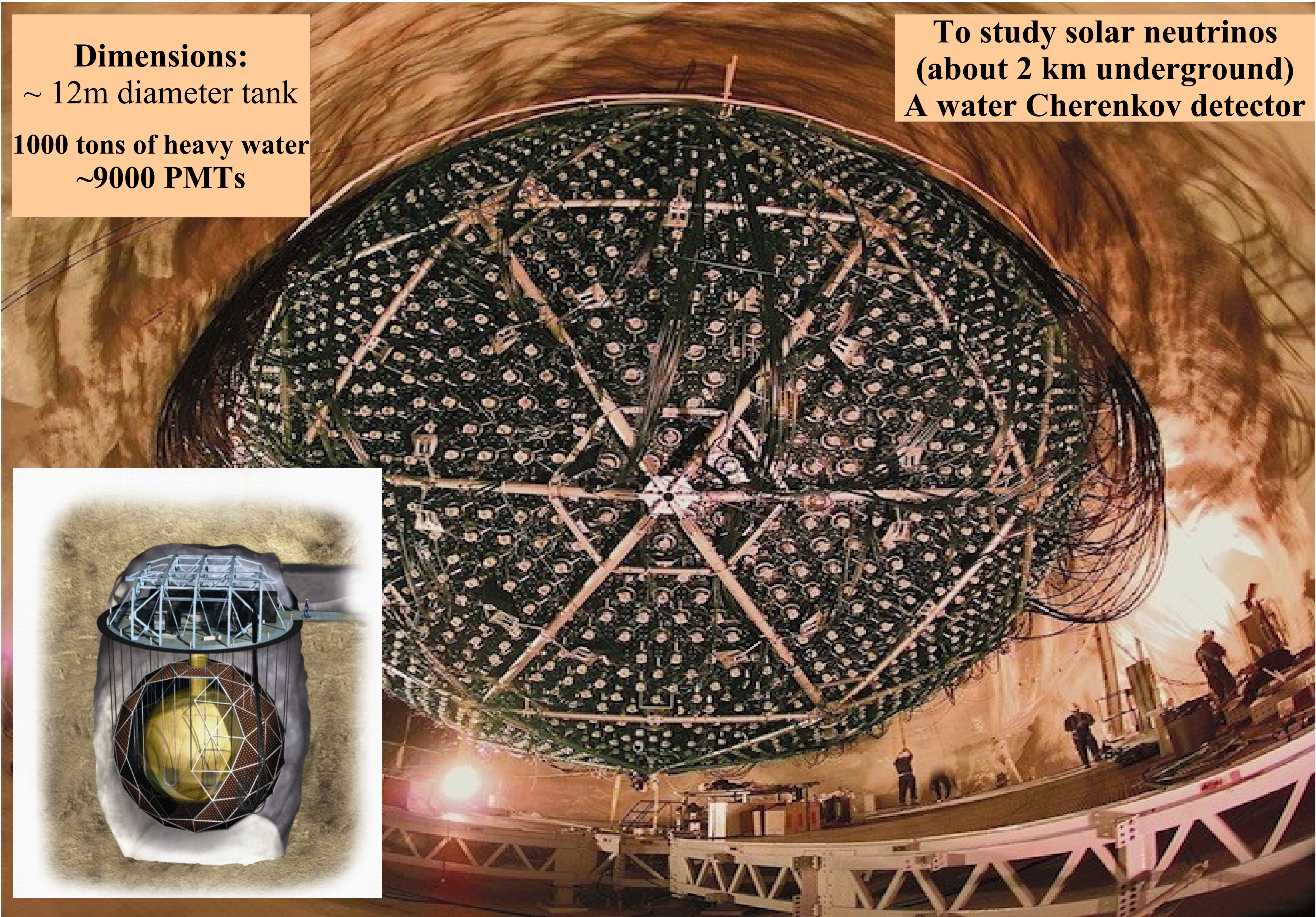


The Sudbury Neutrino Observatory in Canada

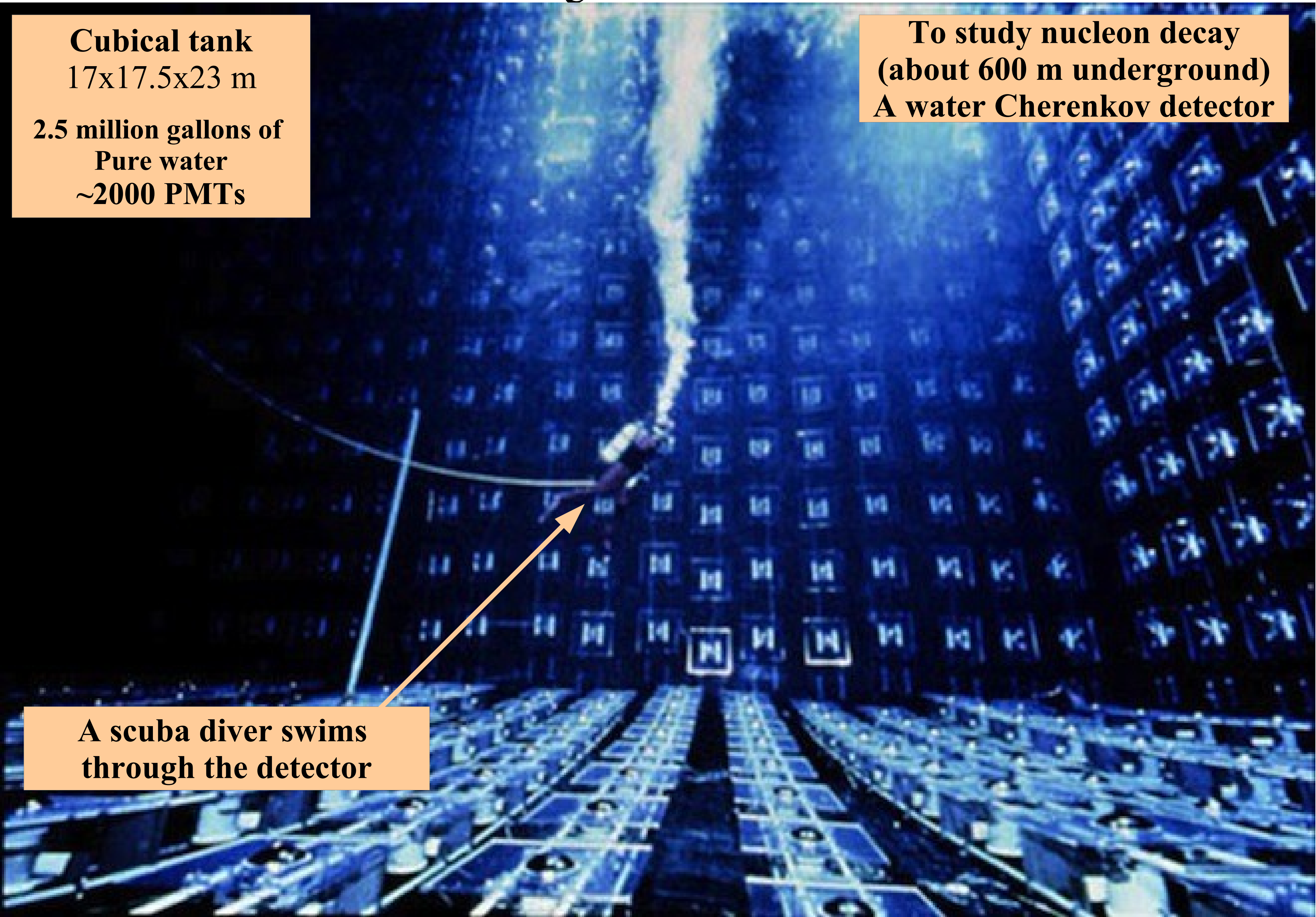
Dimensions:
~ 12m diameter tank

1000 tons of heavy water
~9000 PMTs

To study solar neutrinos
(about 2 km underground)
A water Cherenkov detector



The Irvine-Michigan-Brookhaven detector



The MicroBooNE Detector @ Fermilab

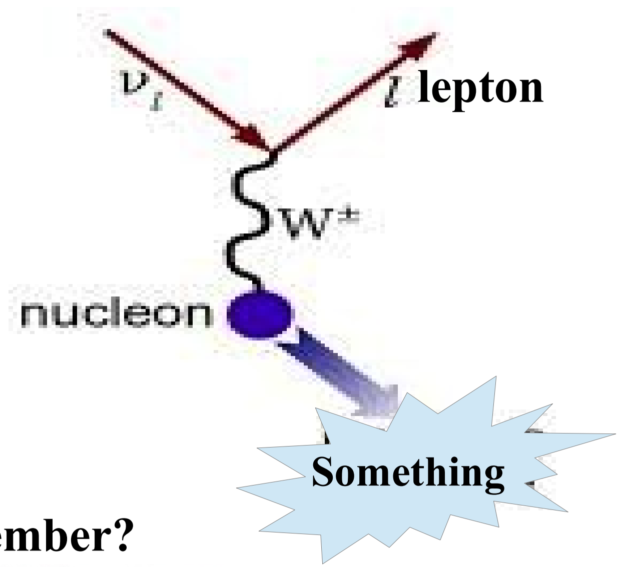
How do neutrinos interact?

Charged current (CC) interactions ($W^{+/-}$ exchange)

Neutral current (NC) interactions (Z exchange)

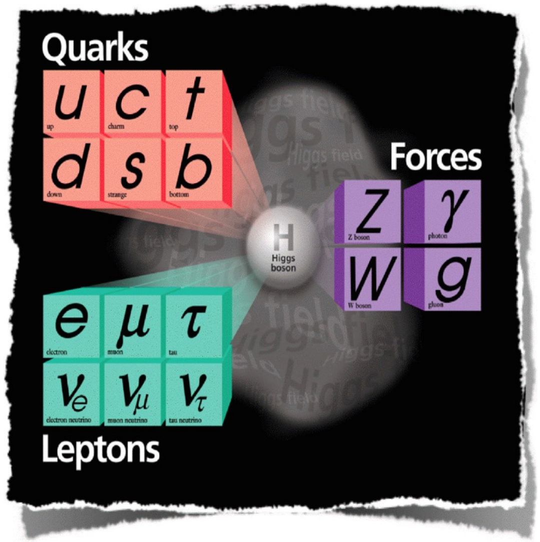
How do neutrinos interact?

Charged current (CC) interactions ($W^{+/-}$ exchange)



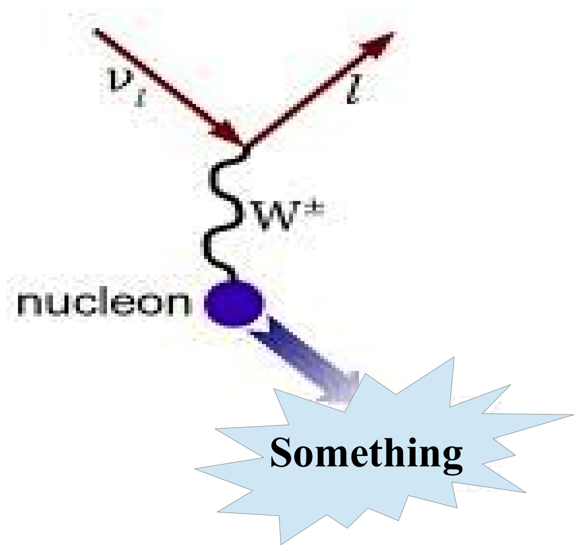
Neutral current (NC) interactions (Z exchange)

Remember?



Neutrinos cannot be detected directly...

Charged current (CC) interactions ($W^{+/-}$ exchange)

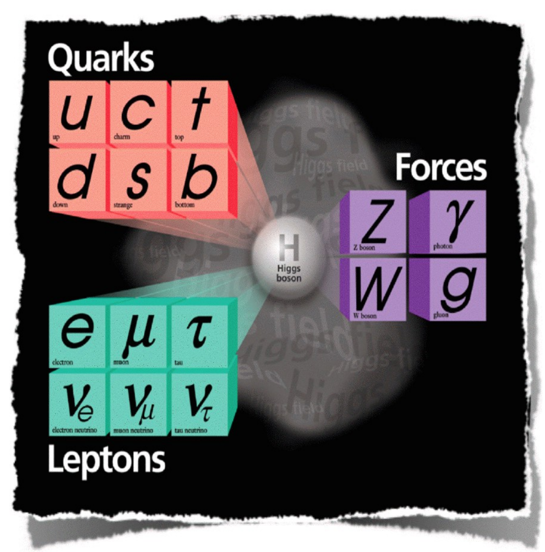


Outgoing lepton determines the neutrino (anti-neutrino) flavor

e.g., $\mu^- \rightarrow \upsilon_\mu$

$\mu^+ \rightarrow$ anti-υ_μ

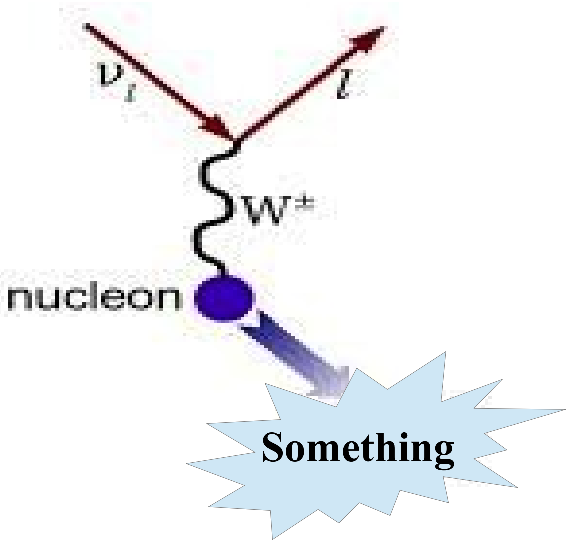
Neutral current (NC) interactions (Z exchange)

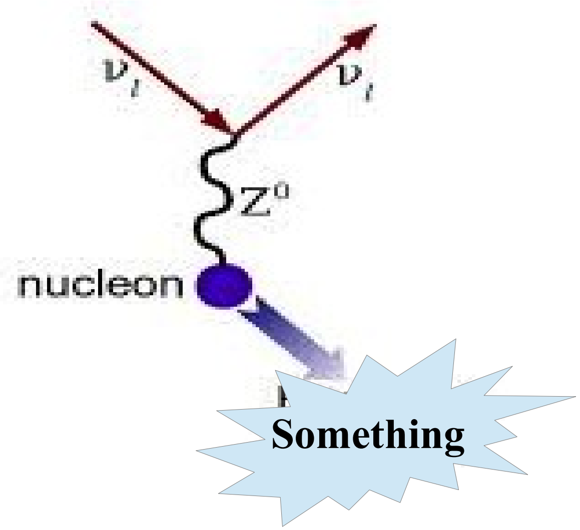


How do neutrinos interact?

Charged current (CC) interactions ($W^{+/-}$ exchange)

Neutral current (NC) interactions (Z exchange)





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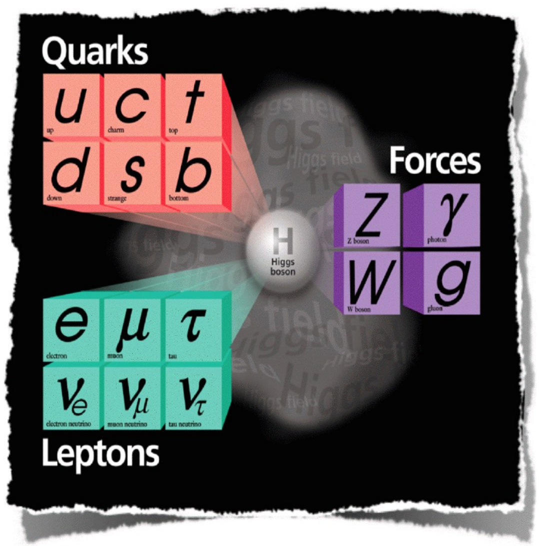

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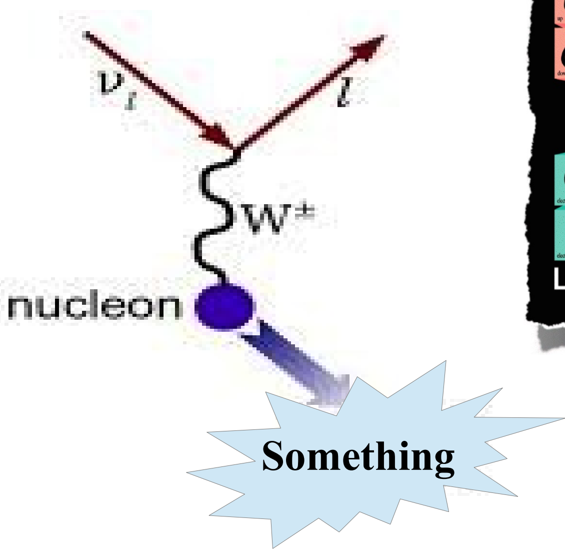

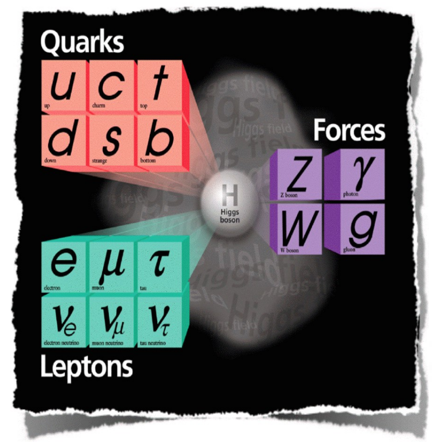

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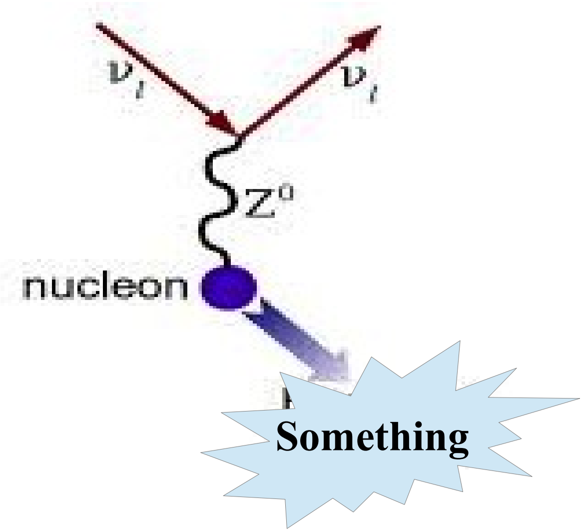

Outgoing lepton determines the neutrino (anti-neutrino) flavor

e.g., $\mu^- \rightarrow \upsilon_\mu$

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- Unlike CC, NC is tricky!
- No outgoing lepton to know neutrino type

Big worry as a background to many analyses!

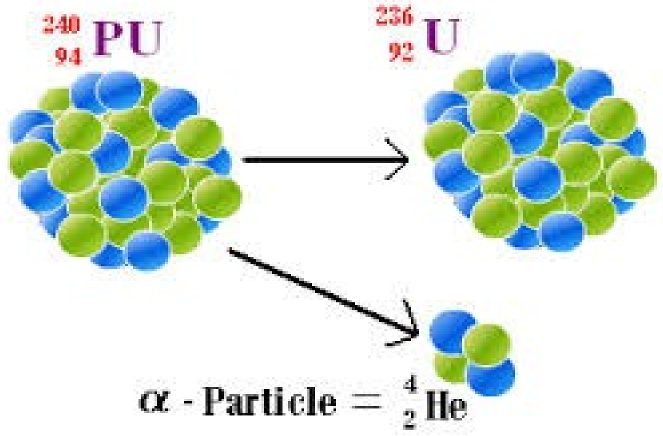
How did we discover neutrinos?

Radioactivity?

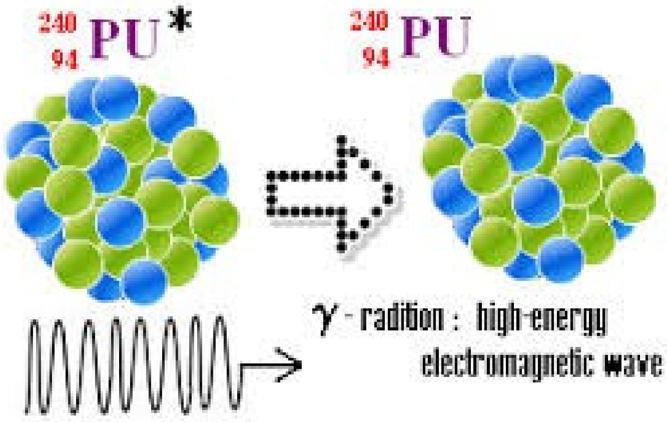
How did we discover neutrinos?

Radioactivity — Nucleus emits particles due to nuclear instability

Alpha decay

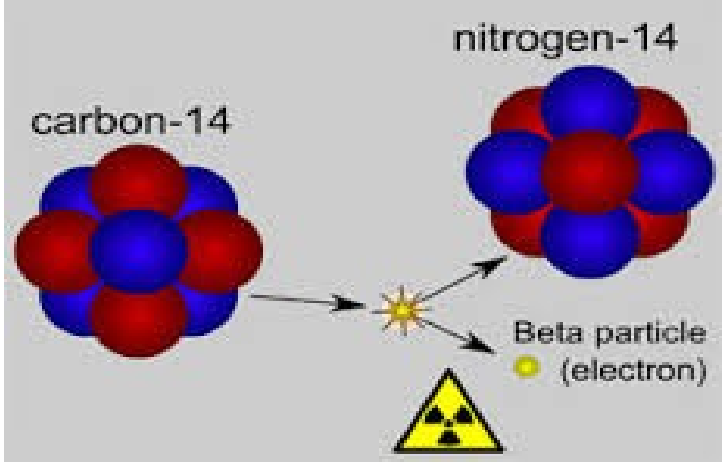


Gamma decay



Beta decay

- Henri Becquerel
- Marie Curie
- 1903 noble prize



How did we discover neutrinos?

$$E=mc^2$$

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$E=mc^2$ (Energy-mass conservation)

- Energy is always conserved
- Energy can neither be created nor destroyed only can be transformed into a different form

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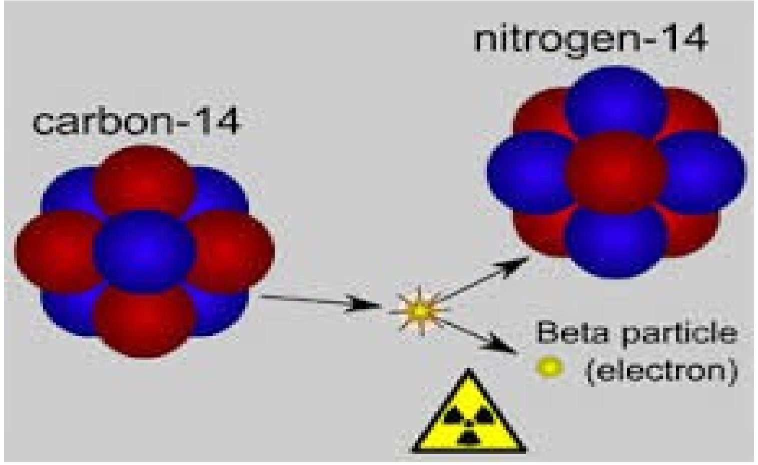
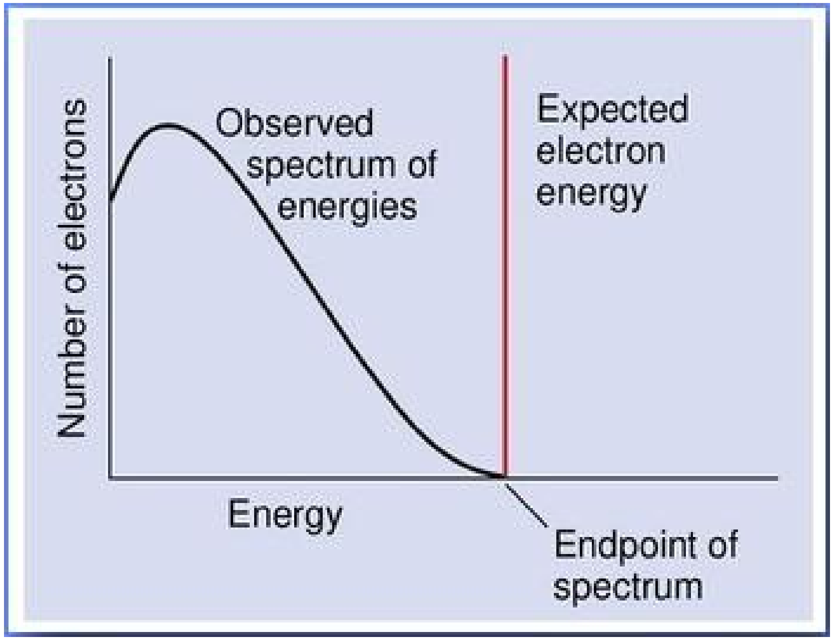
Beta decay before 1930

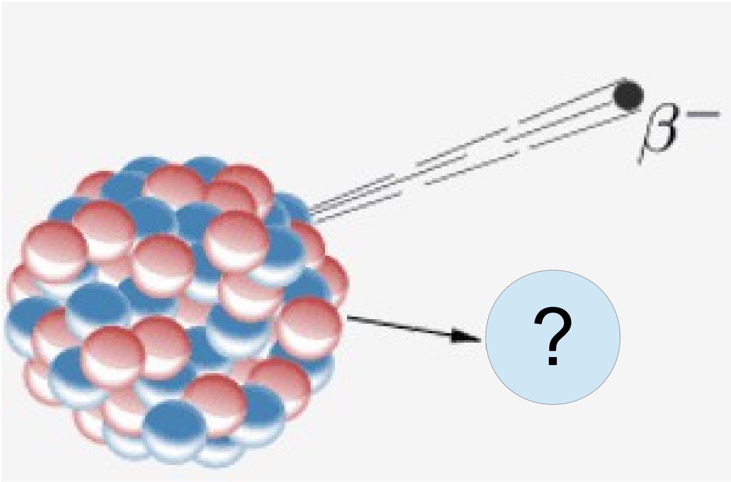


Chadwick, 1914



Wolfgang Pauli and Beta decay

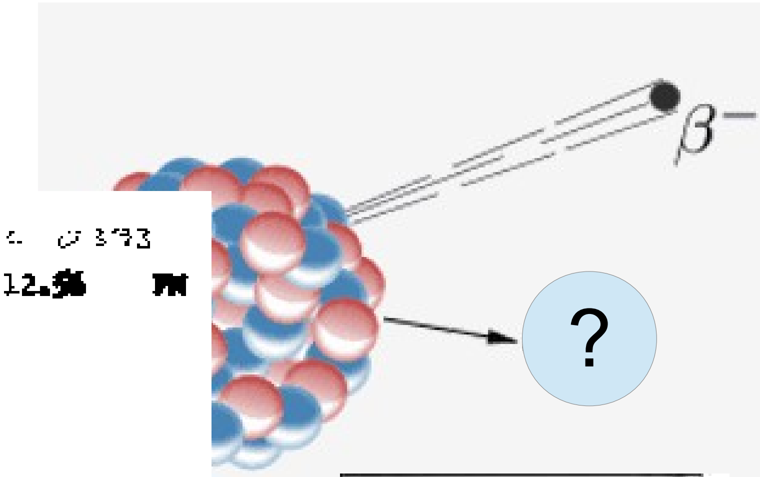
- Could there be another "invisible" particle coming out of the beta decay that can explain the missing energy?
- Invisible → neutral (cannot detect)
- Energy conservation not violated, it was carried away by another neutral particle



- Initially this neutral particle was thought to be the neutron, Chadwick discovered neutron in 1932!
- But Pauli realized that the proposed particle should be massless!

Wolfgang Pauli and Beta decay

- Could there be another "invisible" particle coming out of the beta decay that can



Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen n
welche den Spin 1/2 haben und
sich von Lichtquanten ausserd
nicht mit Lichtgeschwindigkei
Masse von derselben Grössenord
jedenfalls nicht grösser als
beta- Spektrum wäre dann vers
beta-Zerfall mit dem Elektron
wird, derart, dass die Summe
konstant ist.

on, Ch

assles

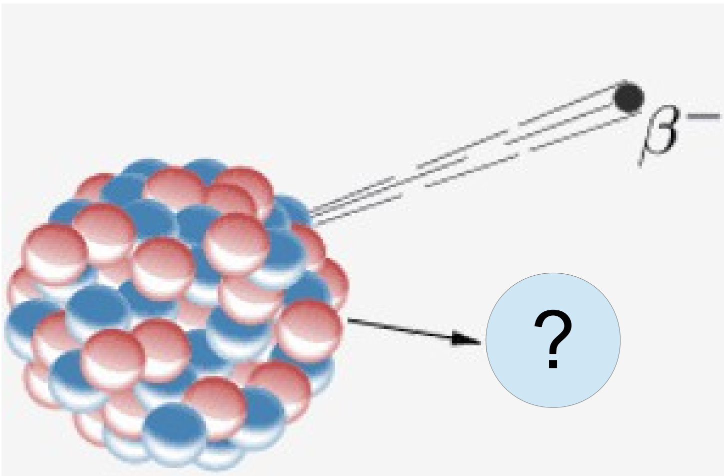
Dear Radioactive Ladies and Gentlemen,

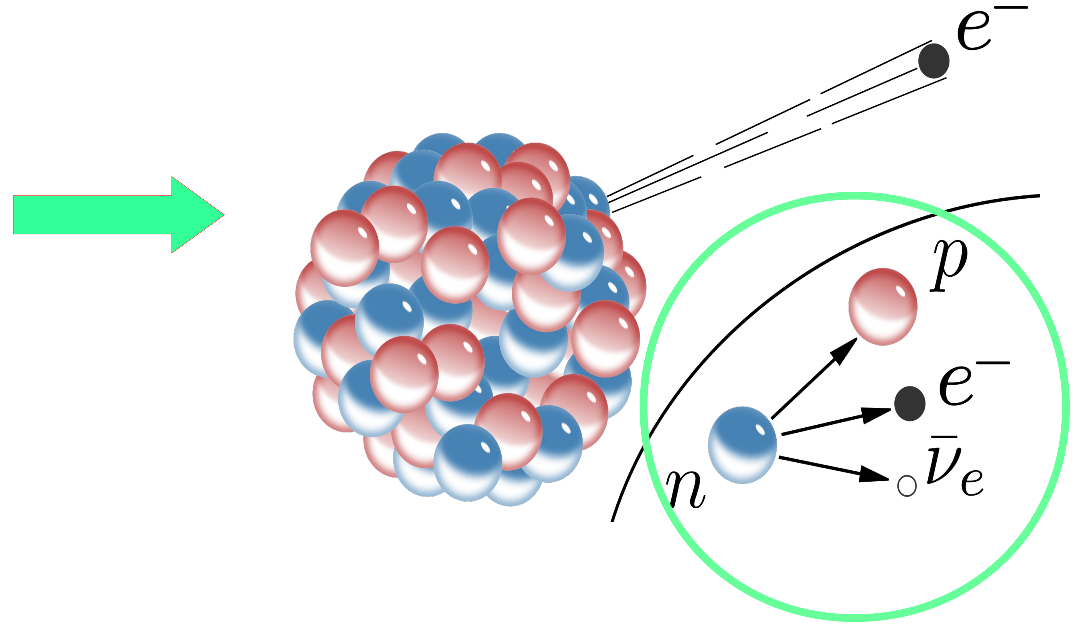
I have done a terrible thing.

I have postulated a particle that cannot be detected

Pauli called this particle as "neutrino" means "little neutral particle"

Wolfgang Pauli and Beta decay





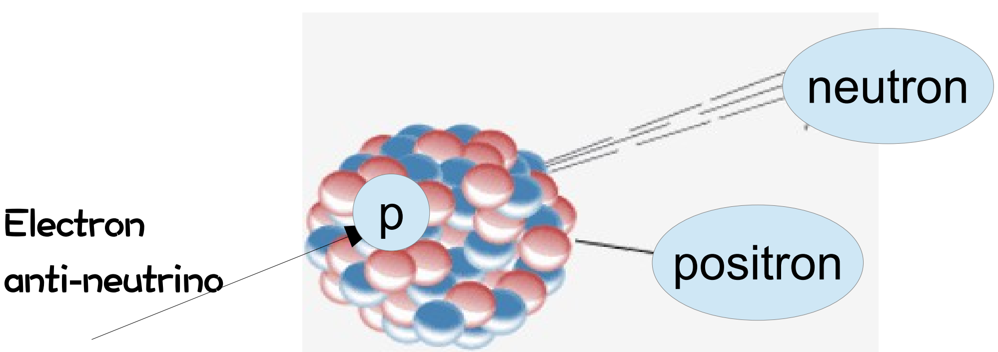
Now, all is left is to discover it!

The discovery of anti-neutrino (1956)

Reines & Cowan

- Artificially produced neutrinos from nuclear reactors
  – emits around 10 trillion anti-neutrinos per cm^2 per sec – a lot!
- Inverse Beta decay

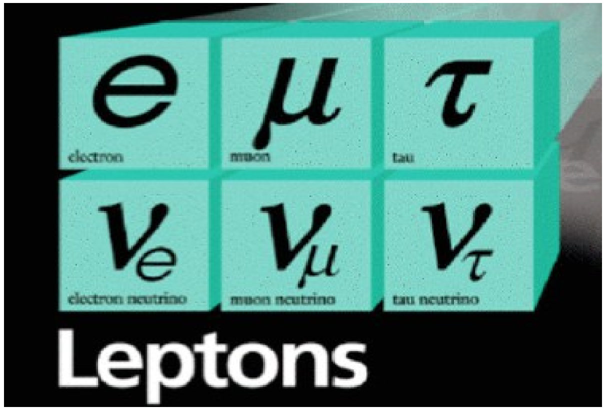
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



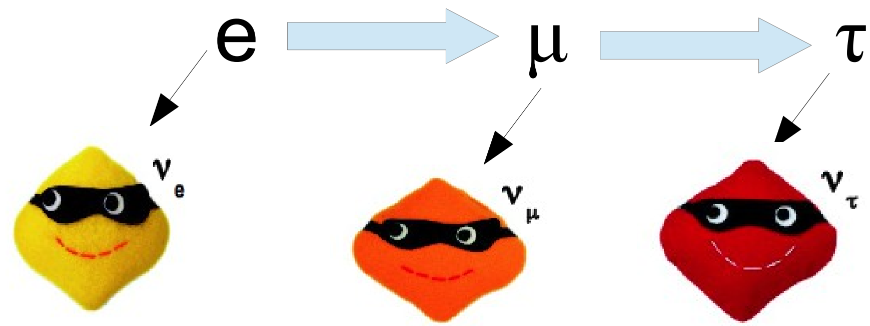
Charge conservation results in emission of an n and e+

1995 noble prize

The discovery of more neutrino types



- *Every charged particle is accompanied by a neutral cousin – rules of Standard Model*



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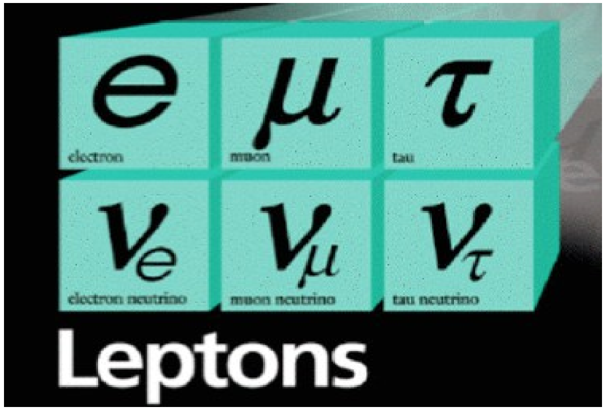

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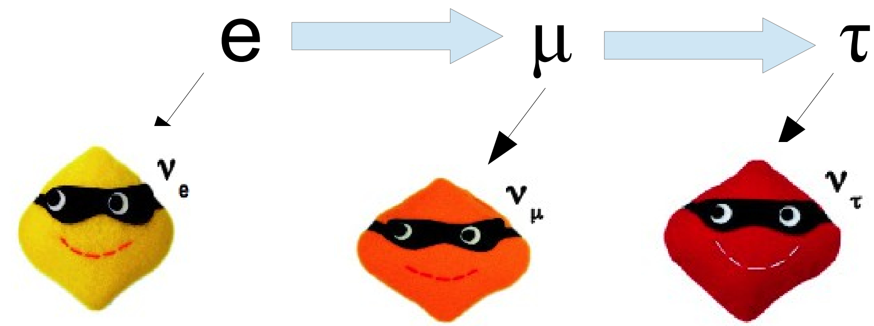
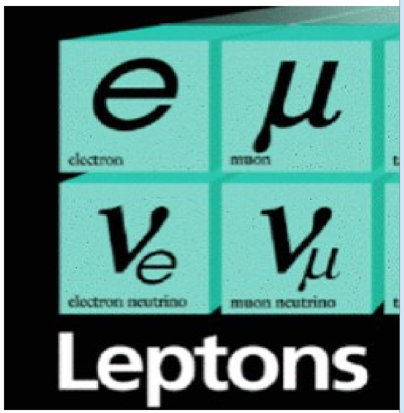


- *In 1988 another type of neutrino was discovered at BNL – muon neutrino*
- *In 2000, another type neutrino was discovered at Fermilab called "tau" neutrino*

The discovery of more neutrino types



Okay, great!

We have found 3 neutrino flavors

electron, muon and tau

That seems like plenty!

But,

Are there more than three neutrino types?

We will come back to this later...

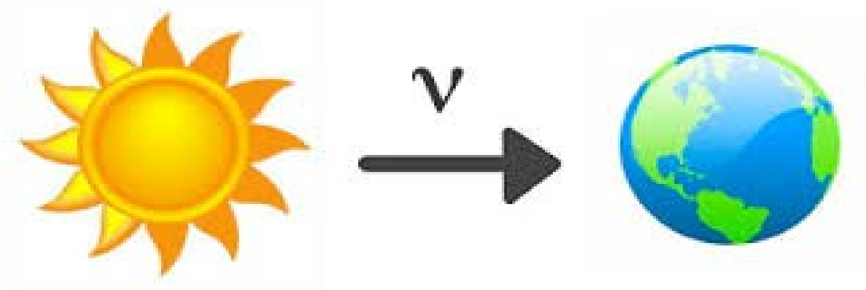
...nied by a

... Model

- In 1988 anothe... neutrino
- In 2000, anoth... "tau" neutrino

Lets think about Solar neutrinos a bit…

- The nuclear reaction processes in Sun emit trillions of “electron” neutrinos



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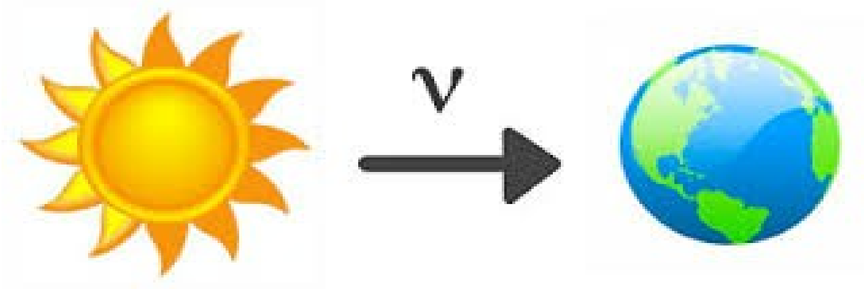
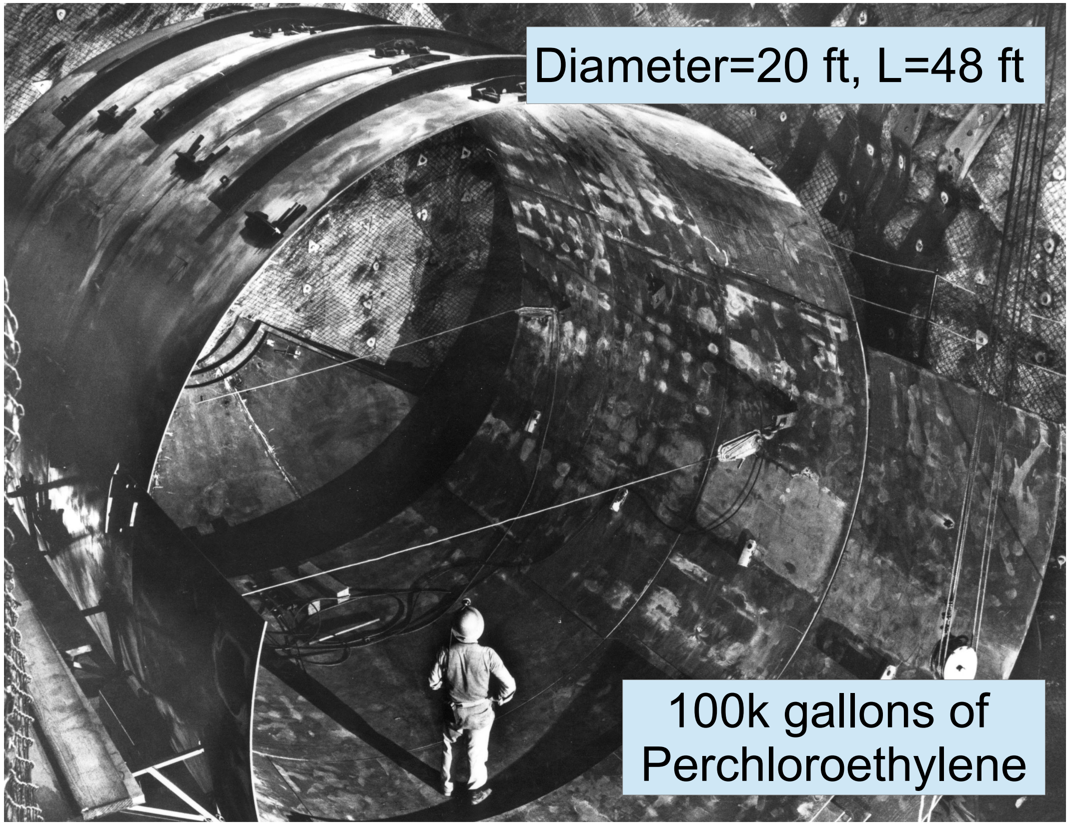


- The HomeStake mine experiment
  — located 4,900 feet underground
- They wanted to measure the solar neutrino flux
  — flux refers to how many neutrinos arrive earth in square cm per sec

What they found changed the course of the neutrino history!!

Built in abandoned mine in South Dakota



The Solar Neutrino Problem

- The HomeStake experiment observed that the
  - "measured" electron neutrino flux << "expected" flux
- Almost 2/3rd of the electron neutrinos were lost along their way from SUN

This was a big puzzle!

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- This result was later confirmed by many experiments such as SNO

SO,

Is the theory wrong? Is the experiment wrong? Where is the problem?

How can neutrinos disappear?

The Solar Neutrino Problem

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  This was a great puzzle!
- This result was later confirmed my many experiments such as SNO

SO,

Is the theory wrong? Is the experiment wrong? Both wrong? Where is the problem?

How can neutrinos disappear?

ANSWER: Neither are wrong!

2002

Ray Davis, John Bahcall

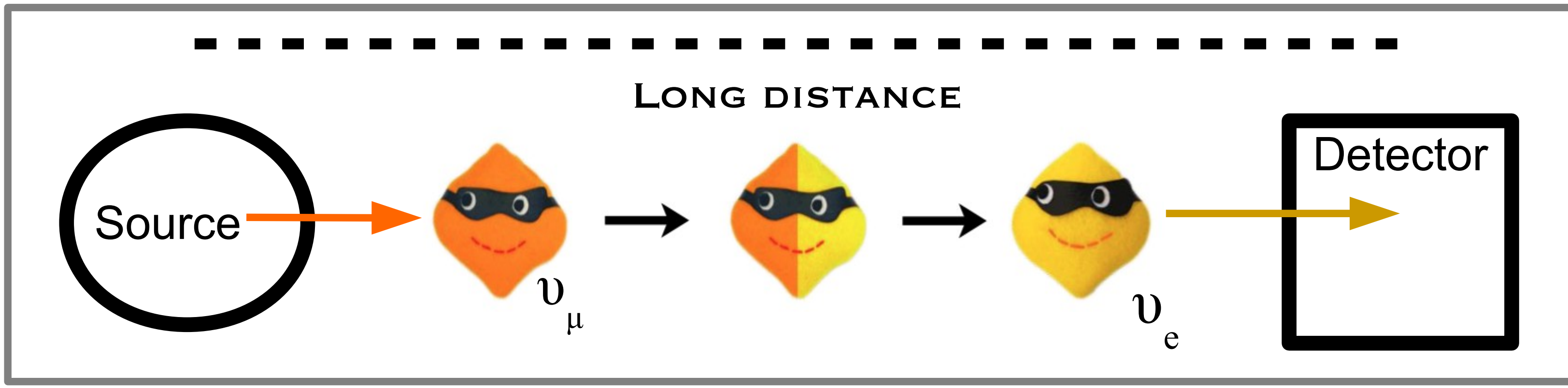
The Solution…

- A neutrino created as one "flavor" can change into another "flavor" as they travel

- So, the electron neutrinos created by sun would have changed flavor along the way to earth and since the other flavor were not accounted for, you see a deficit
- But, as weird as it sounds, why does this happen?

Neutrinos Oscillate!

A neutrino created as one flavor can change into another flavor!

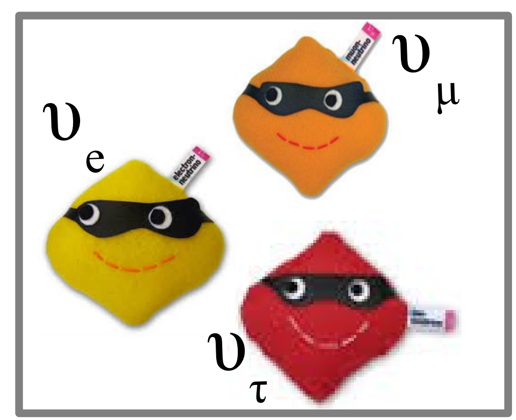


Why?

“MASS” STATES

(THIS IS HOW THEY TRAVEL)

$\neq$



“FLAVOR” STATES

(HOW THEY INTERACT)

THEY TRAVEL AS A COMBINED STATE, BUT, DETECTED AS A SINGLE STATE

Neutrinos Oscillate!

A neutrino created as one flavor can change into another flavor!

Neutrino oscillations between different flavor states can only happen "if they have mass"

Standard Model predicts zero mass to neutrinos

Hence,

This is a compelling evidence showing that the theory that was believed for many years to be perfect cannot accommodate massive neutrinos!

Neutrino Physics took a BIG turn after this!

"MAS
STAT

(THIS IS
THEY TR

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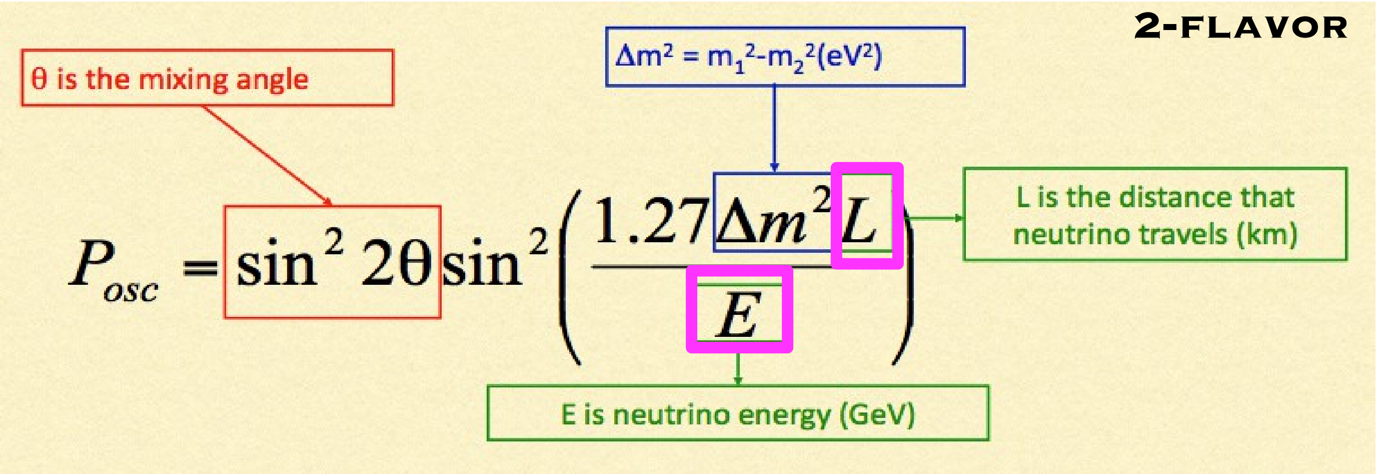
CT)

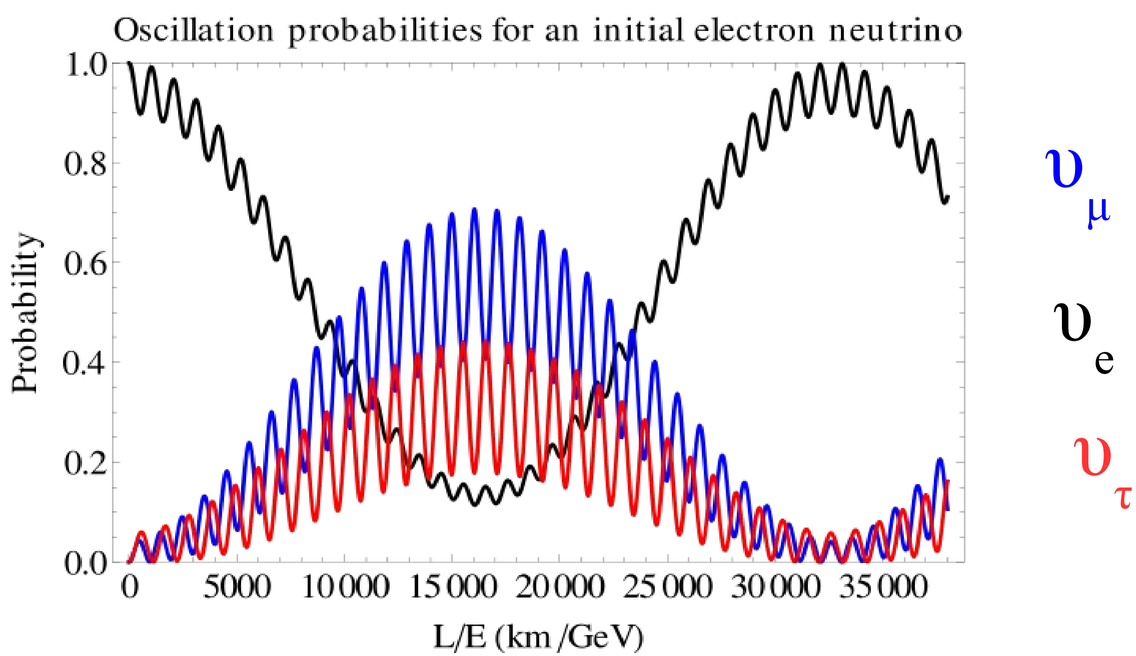
THEY TRAVEL AS A COMBINED STATE, BUT, DETECTED AS A SINGLE STATE

Neutrino Oscillations

Probability of one neutrino flavor converting into another neutrino flavor



Oscillation probability for a electron neutrino as a function of L/E



Neutrino Oscillations

Probability of one

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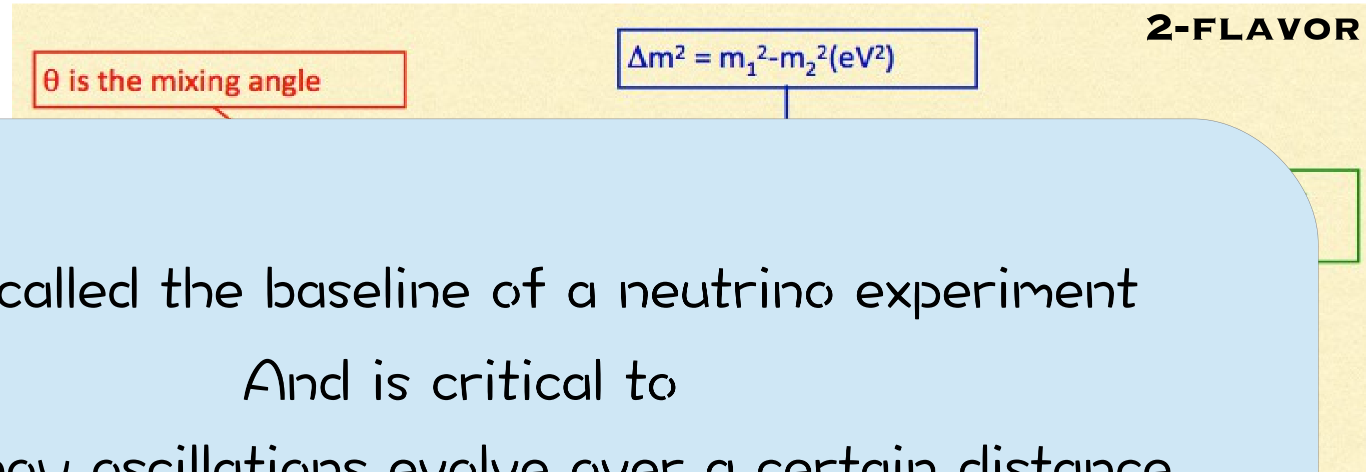


L/E is called the baseline of a neutrino experiment

And is critical to

defining how oscillations evolve over a certain distance..

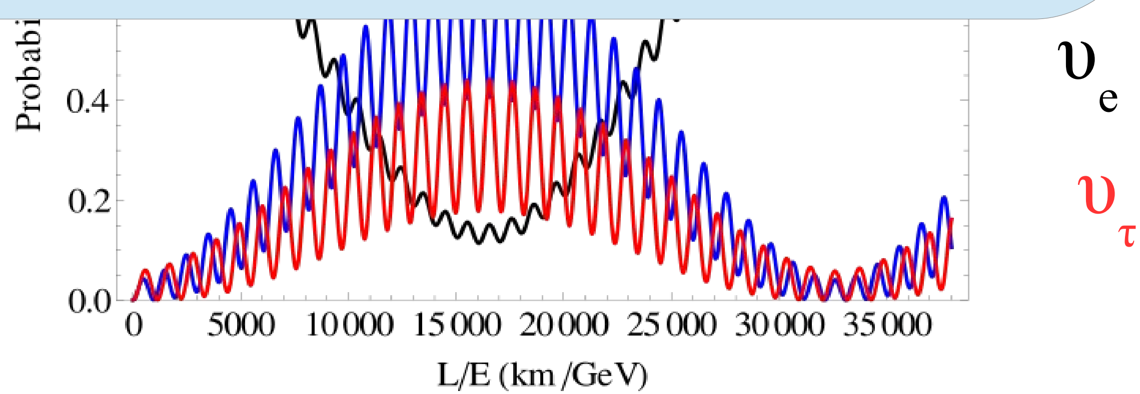
Short-baseline experiments: L is ~1 km

Long-baseline experiments: L is ~1000 km

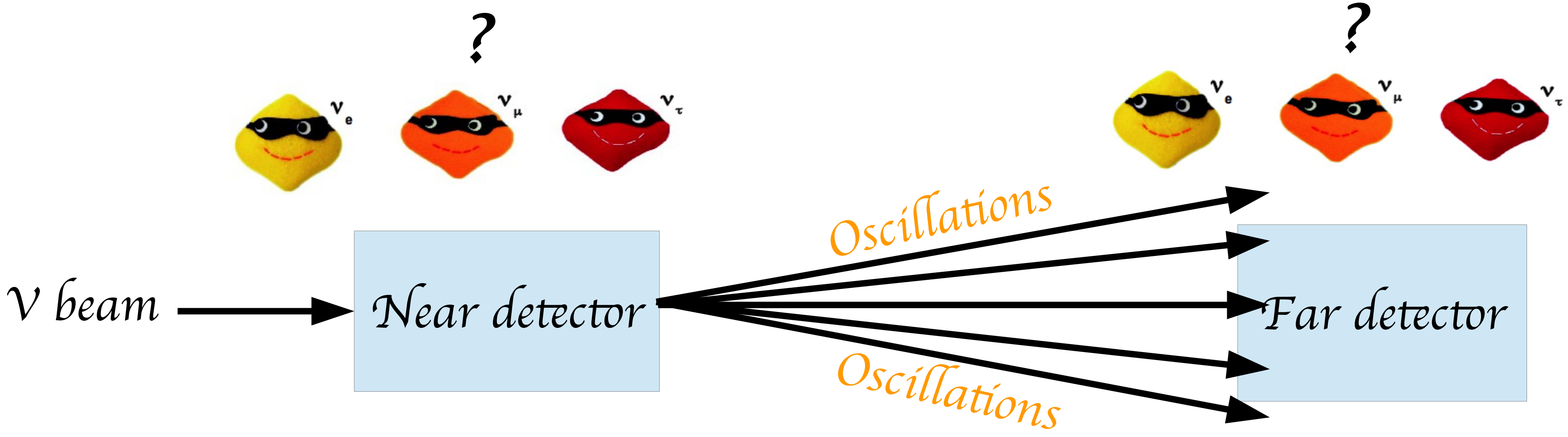
Oscillat

a electron

function of L/E

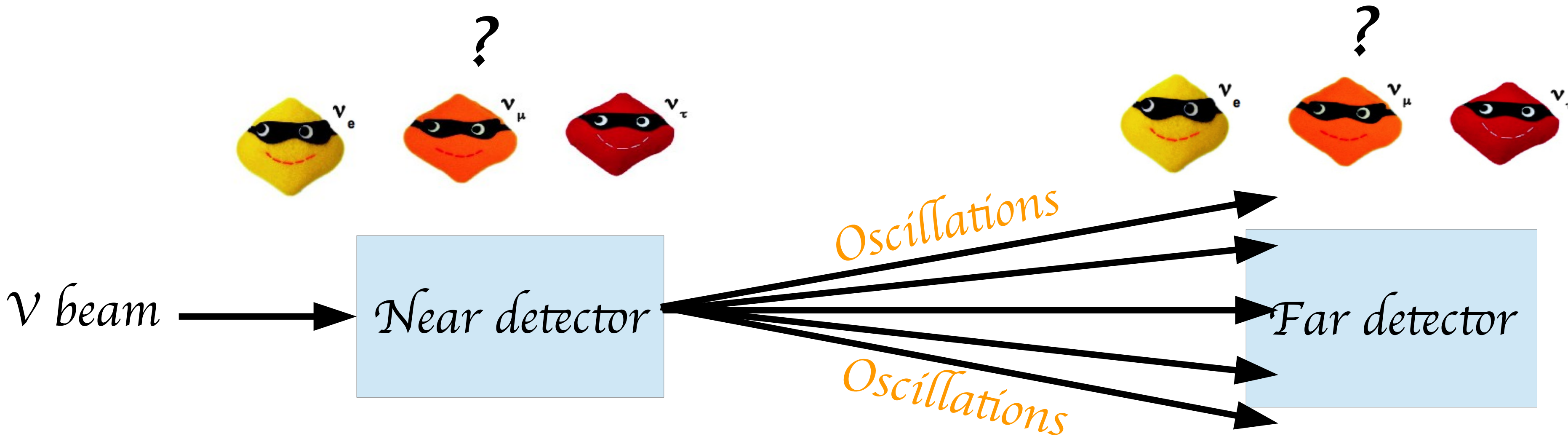


How are oscillations detected?



The measurement of oscillation itself is not as simple as it sounds, many complications lie to make a measurement!

How are oscillations detected?



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Neutrino oscillation experiments are primarily 4 types

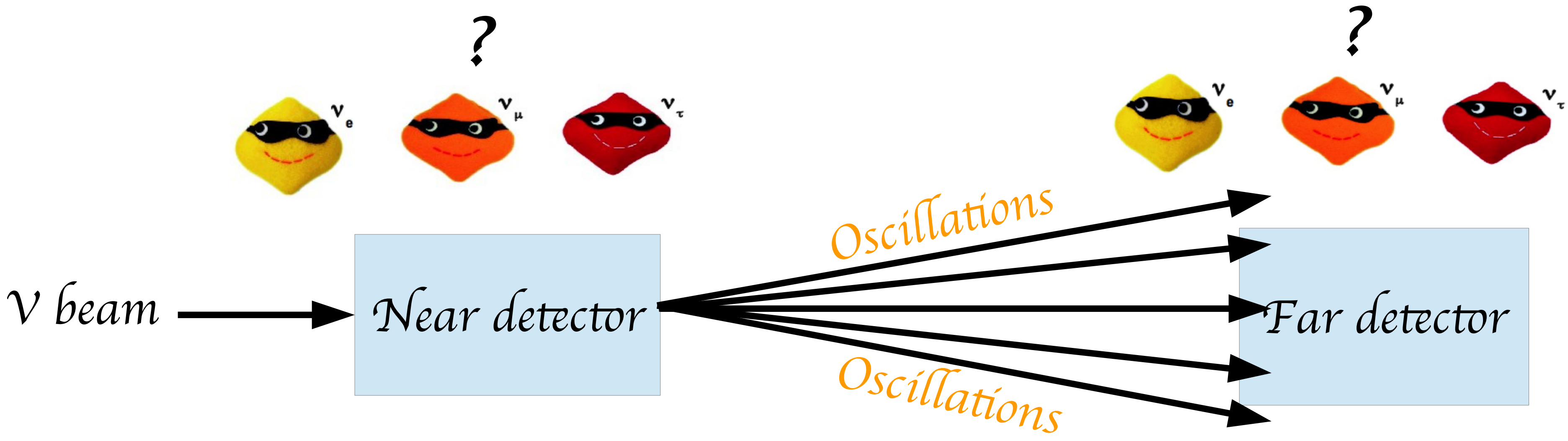
- Solar
- Atmospheric

Natural sources

- Reactor
- Accelerator

Artificial sources

How are oscillations detected?



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Neutrino oscillation experiments are primarily 4 types

- Solar
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Natural sources

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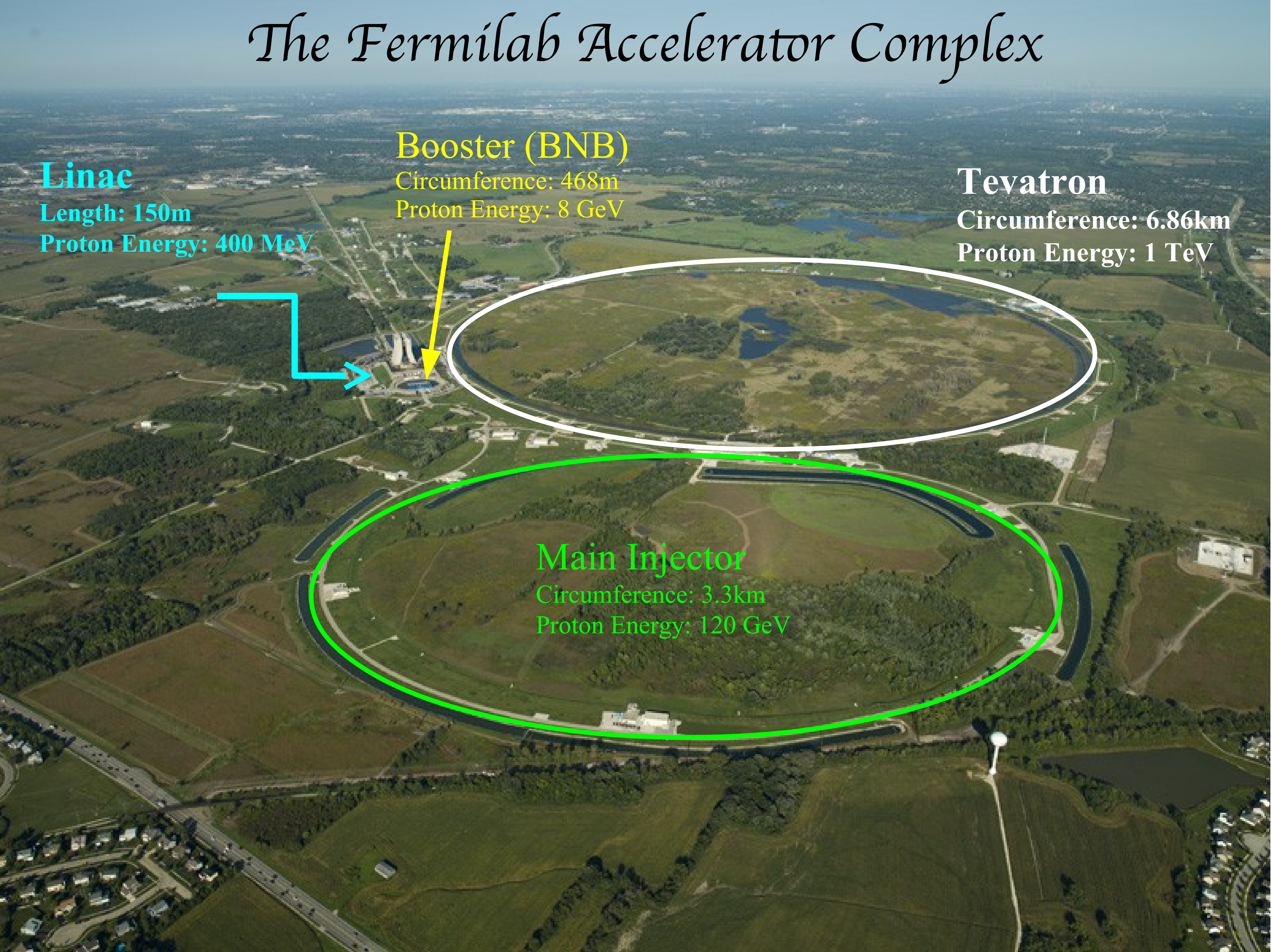
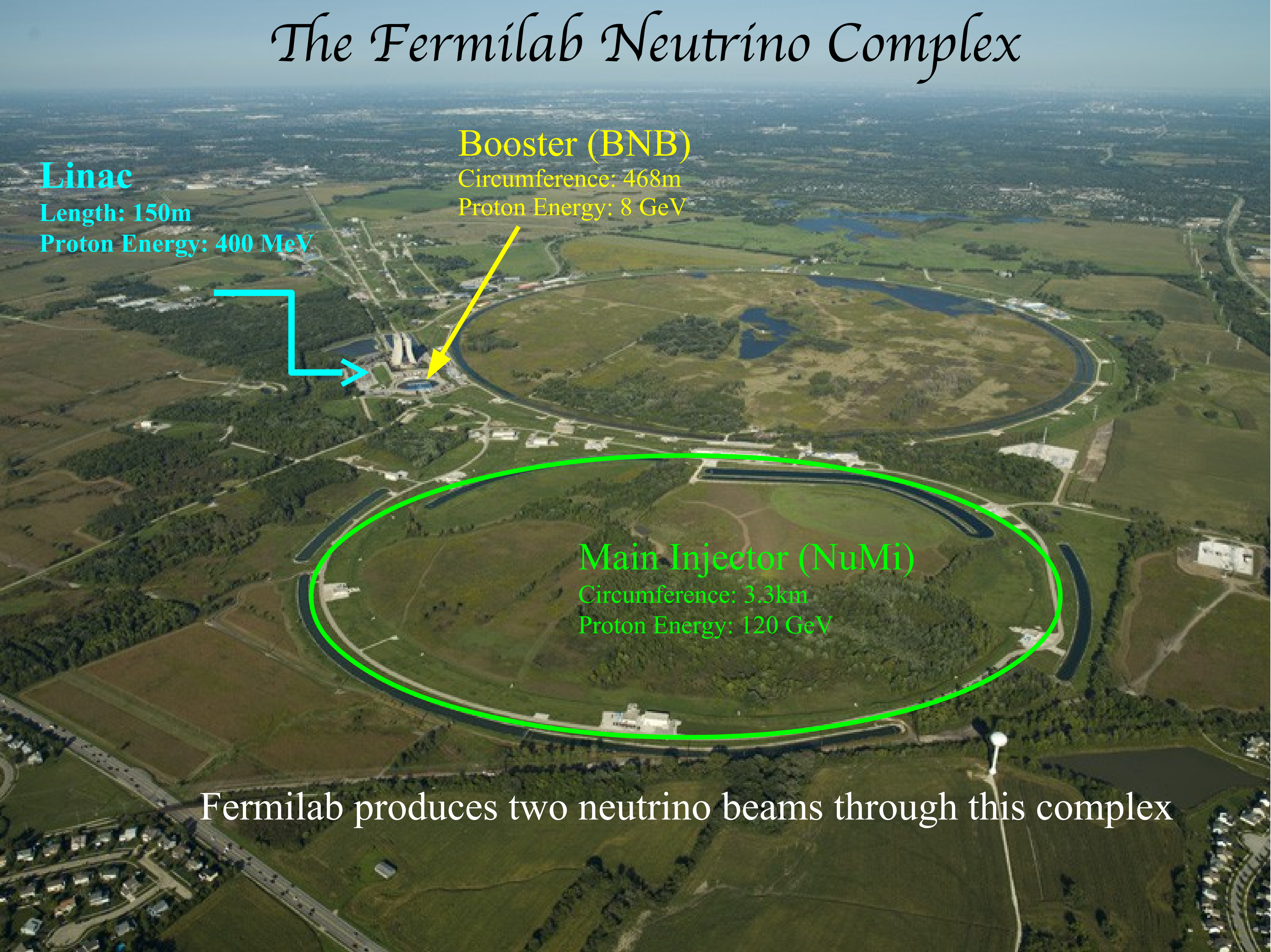
Artificial sources

Lets talk about this a little bit....

The Fermilab Site


The Fermilab Accelerator Complex
Linac
Length: 150m
Proton Energy: 400 MeV
Booster (BNB)
Circumference: 468m
Proton Energy: 8 GeV
Tevatron
Circumference: 6.86km
Proton Energy: 1 TeV
Main Injector
Circumference: 3.3km
Proton Energy: 120 GeV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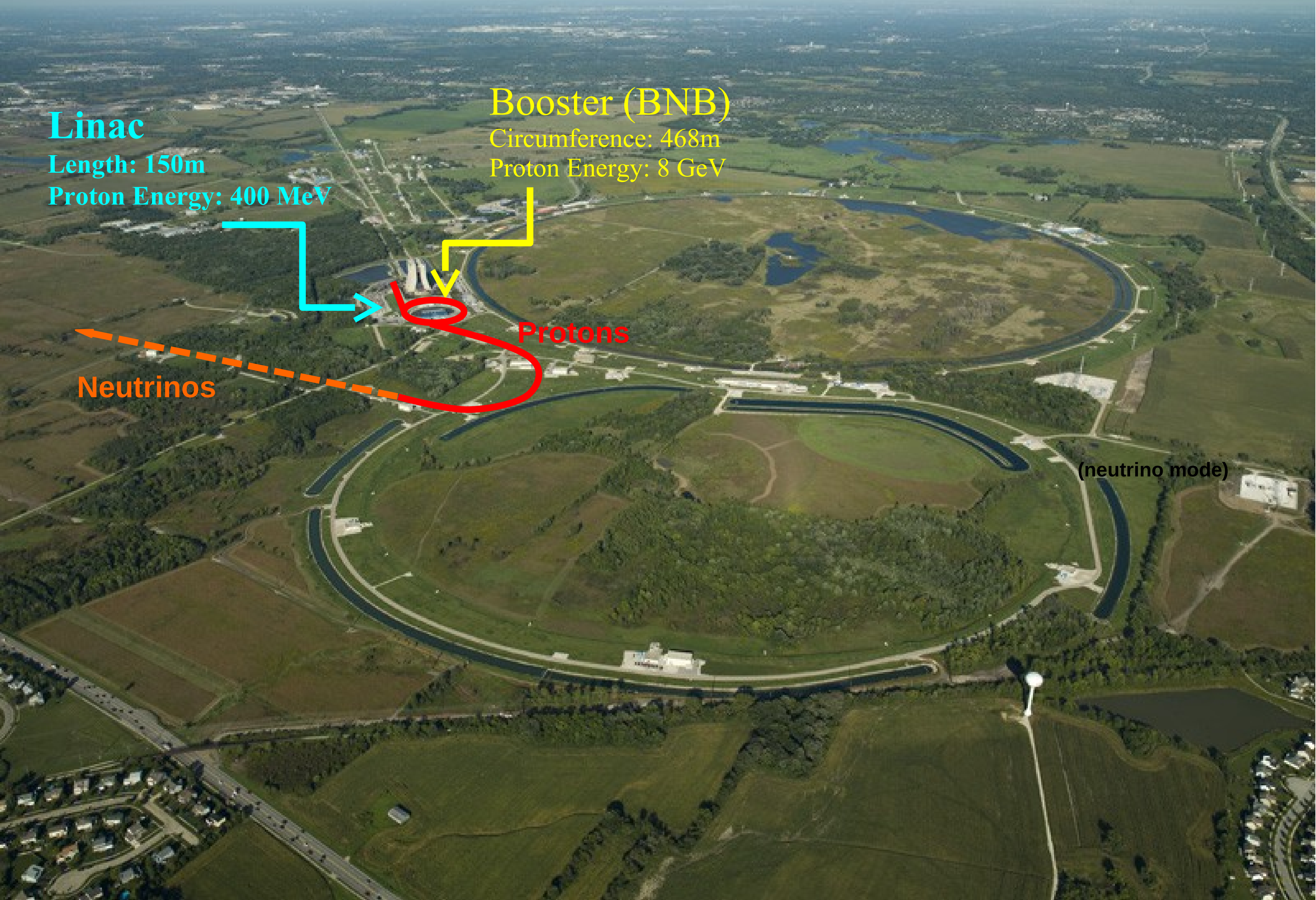
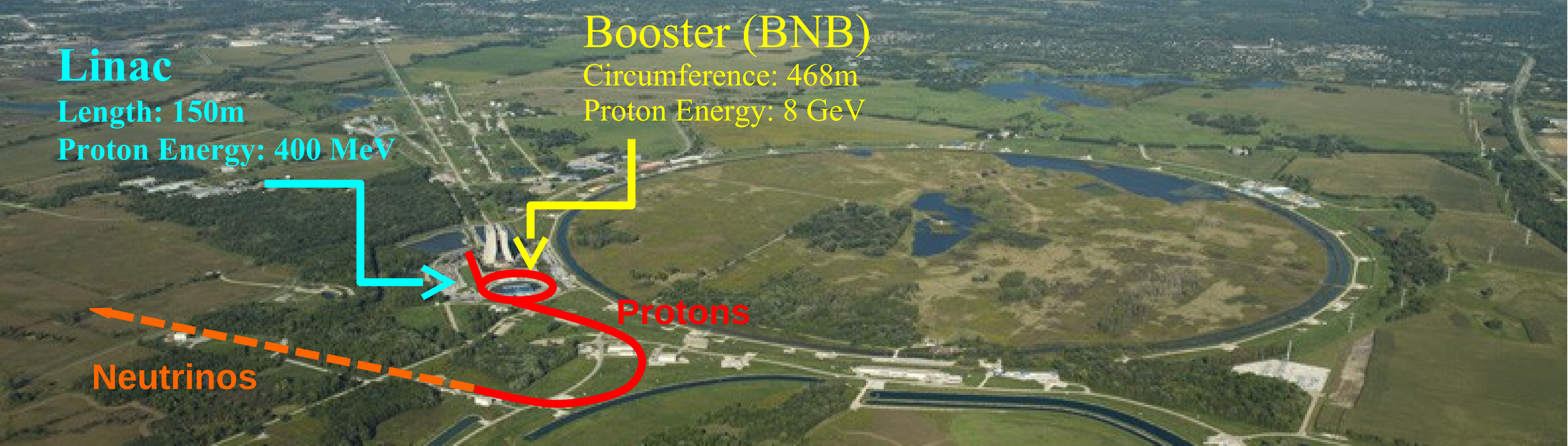
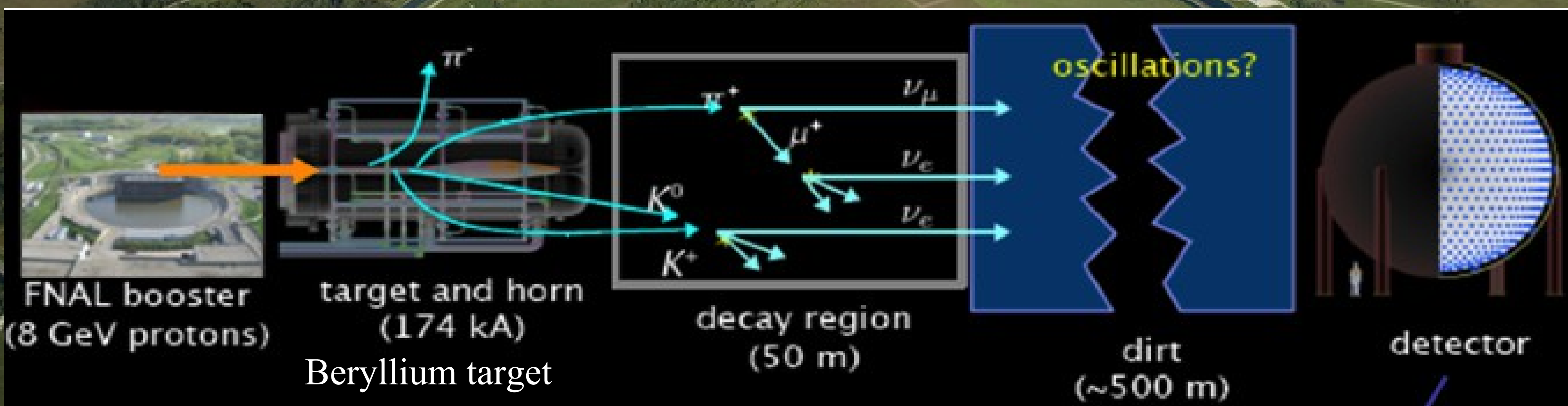
Fermilab produces two neutrino beams through this complex

Fermilab's Booster Neutrino Beam (BNB)



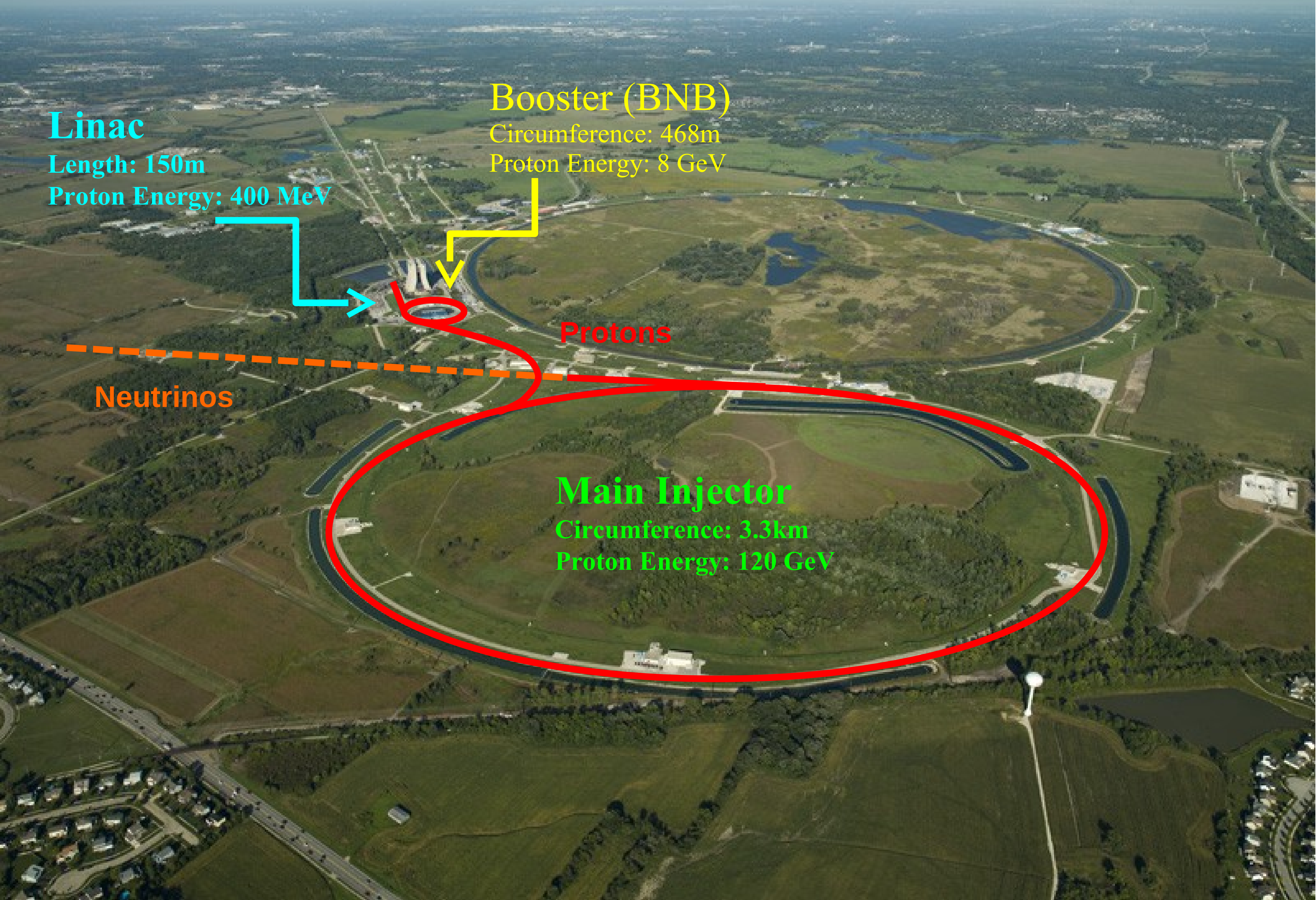
Fermilab's Booster Neutrino Beam (BNB)
How does it work?



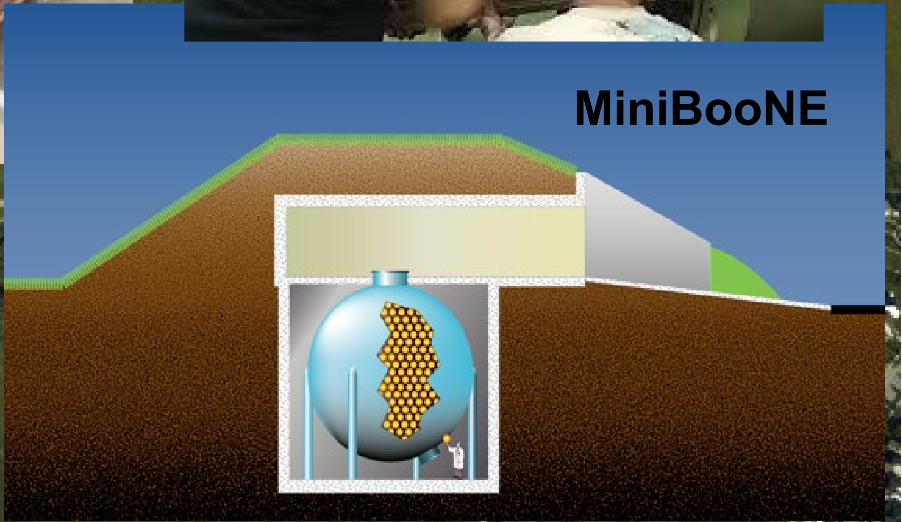


Switching the horn polarity, focuses negatively charged mesons, yielding a anti-ν_μ beam

Fermilab's Neutrinos in the Main Injector (NuMI) beam



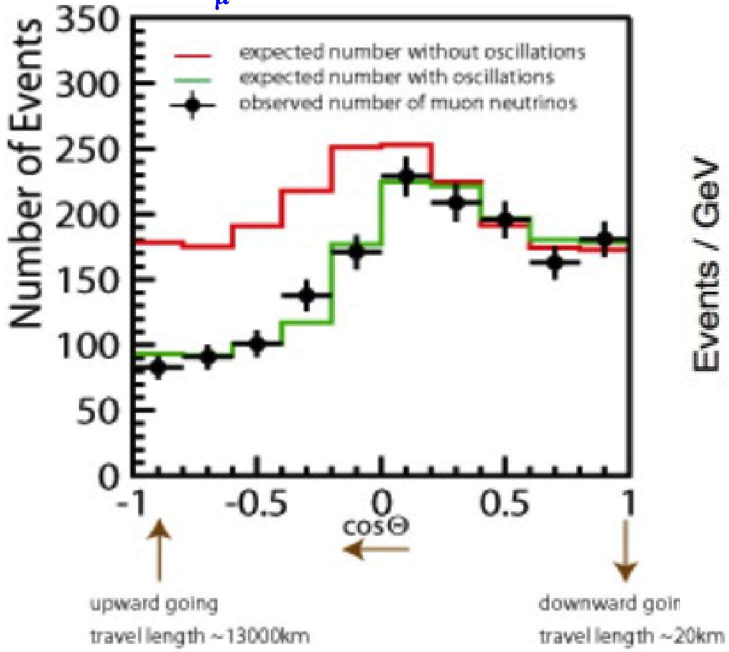
Several Neutrino experiments at Fermilab...

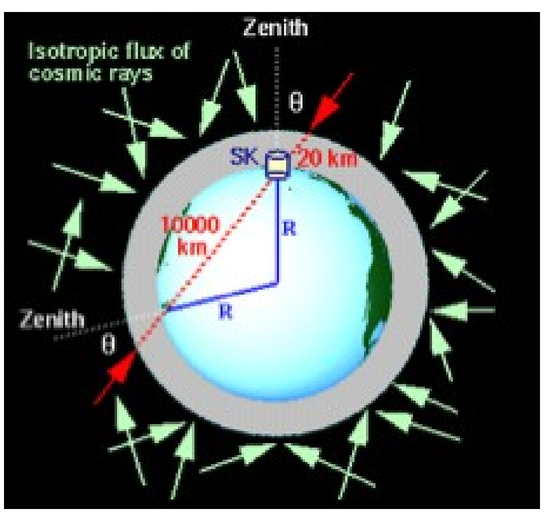


A ton of evidence for Neutrino Oscillations since 1998!

SUPER-K

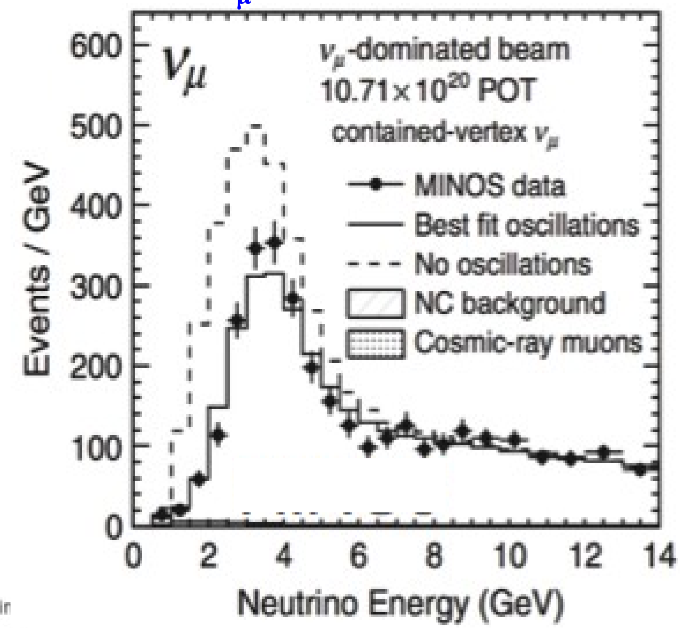
ν_μ disappearance

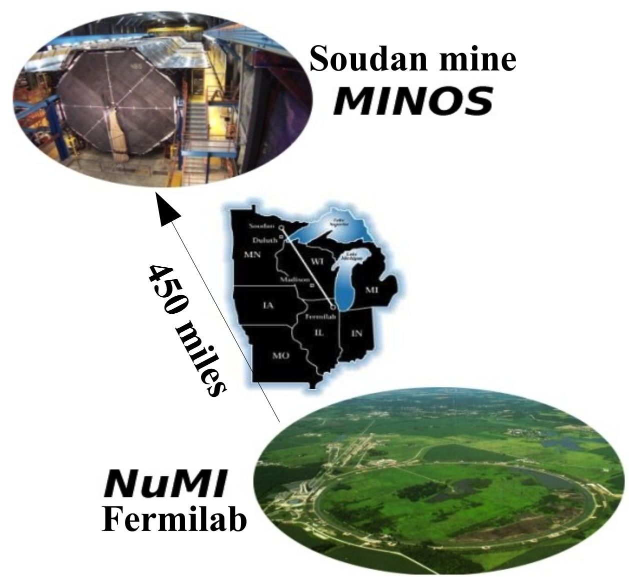




MINOS

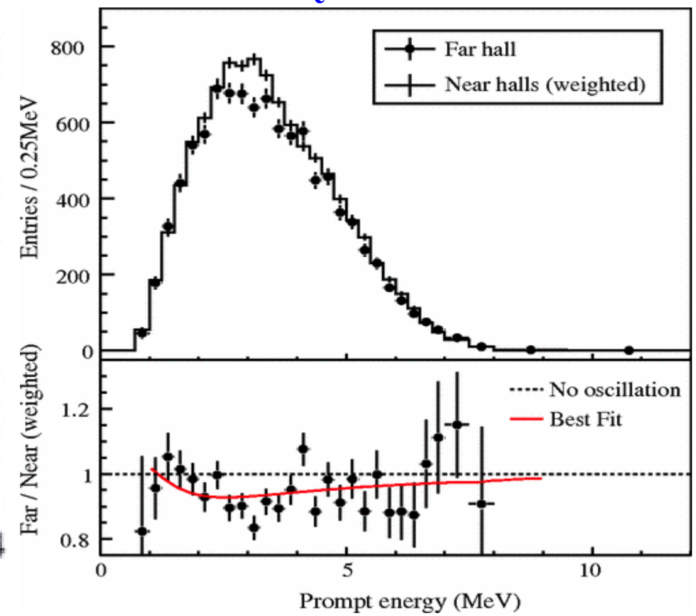
ν_μ disappearance

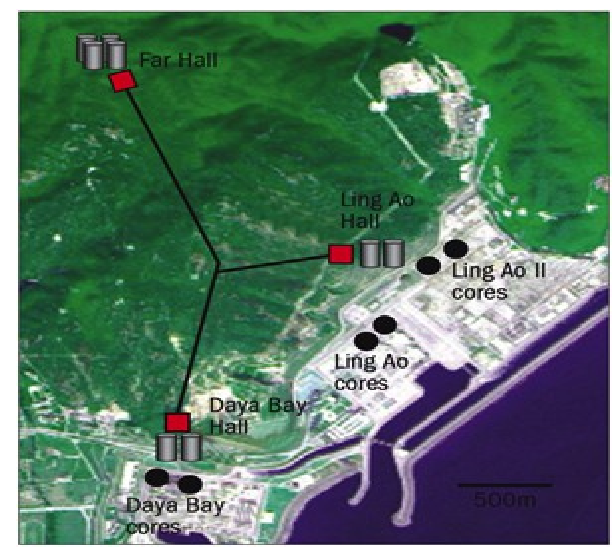




DAYABAY

anti-ν_e disappearance





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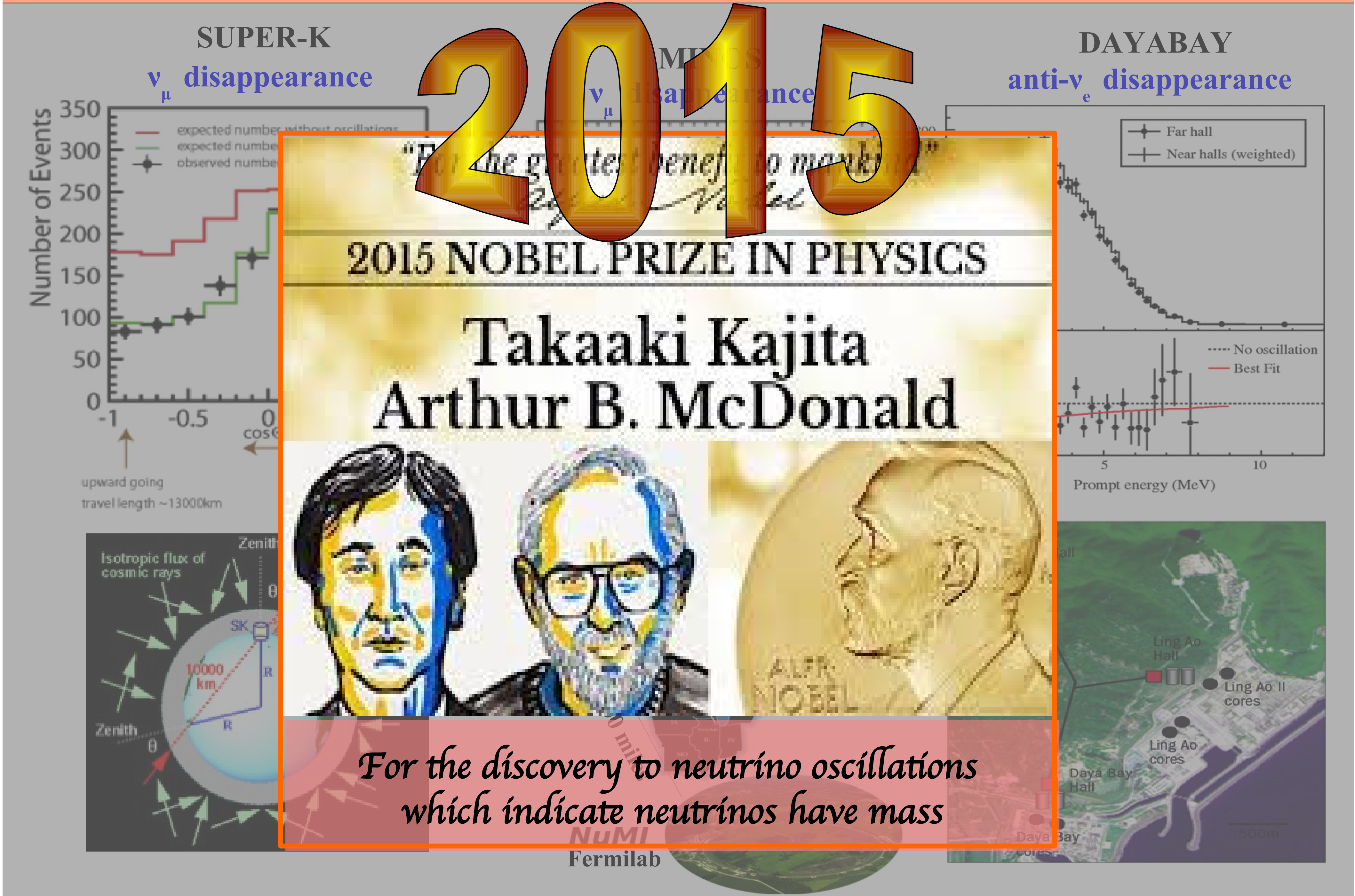


We have come a long way…

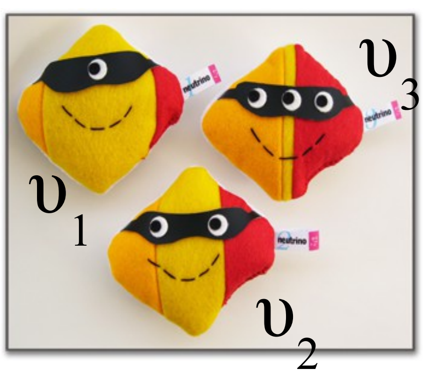
- Neutrinos oscillate; they come in 3 flavors; they have mass
- Unlike quarks, neutrino mixing angles are large!
- Neutrinos and anti-neutrinos behave differently
  - – CP Phase is non-zero – as all 3 angles are non-zero
- Current knowledge of Neutrino Mixing: 3 angles and one phase

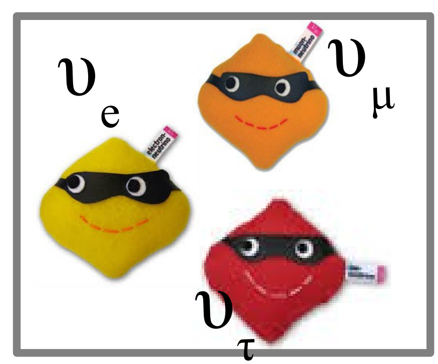
CP Phase:
How neutrinos differ from anti-neutrinos

NEUTRINO MIXING MATRIX

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(THIS IS HOW THEY TRAVEL)





(THIS IS HOW THEY ARE DETECTED)

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(23) Sector: Atmospheric | (13) Sector: Reactor+Accelerator | (12) Sector: Solar+Reactor

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\Delta m^2_{atm} = 2.43^{+0.13}_{-0.13} \times 10^{-3} \mathrm{eV}^2$

$Sin^2\theta_{23} \sim 0.45$

$\Delta m^2_{23} \sim \Delta m^2_{13}$

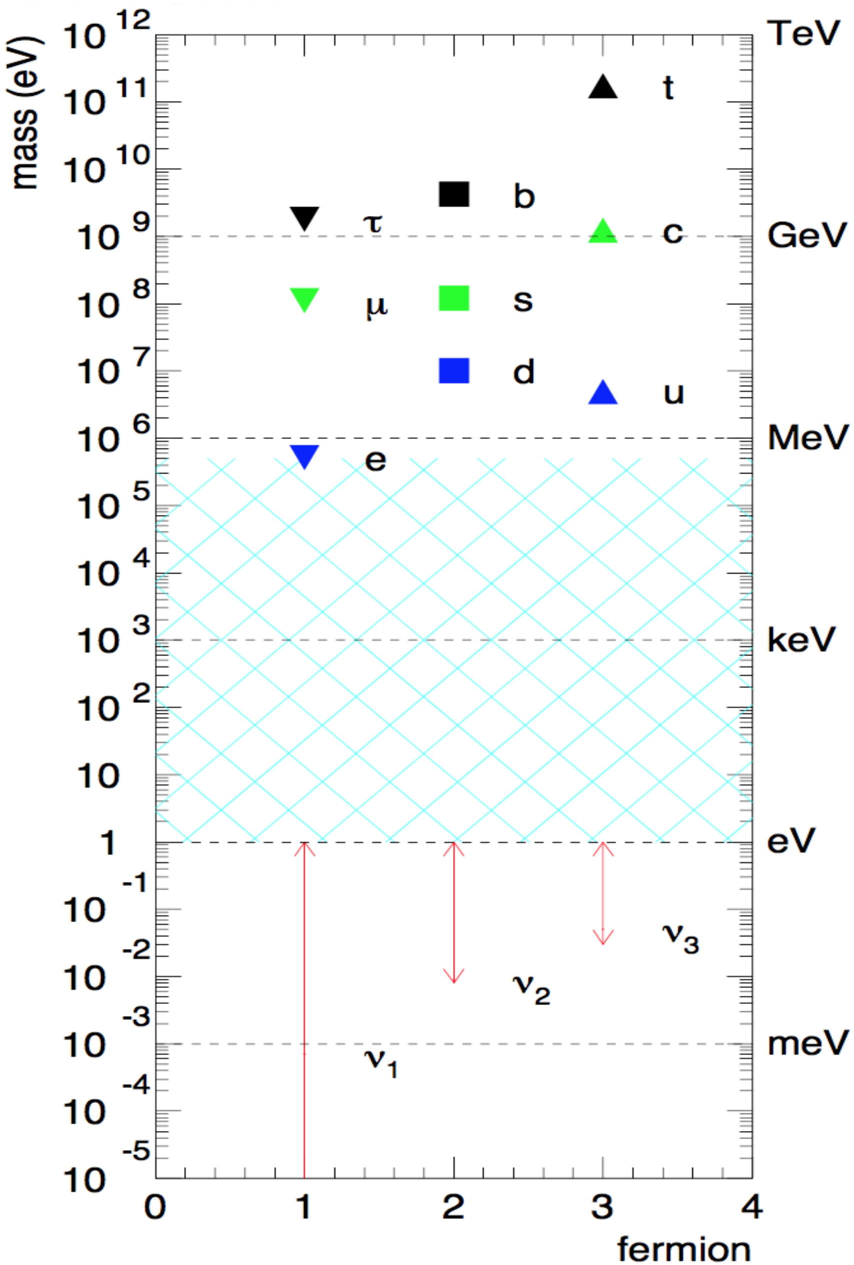
$Sin^2\theta_{13} < 0.02$

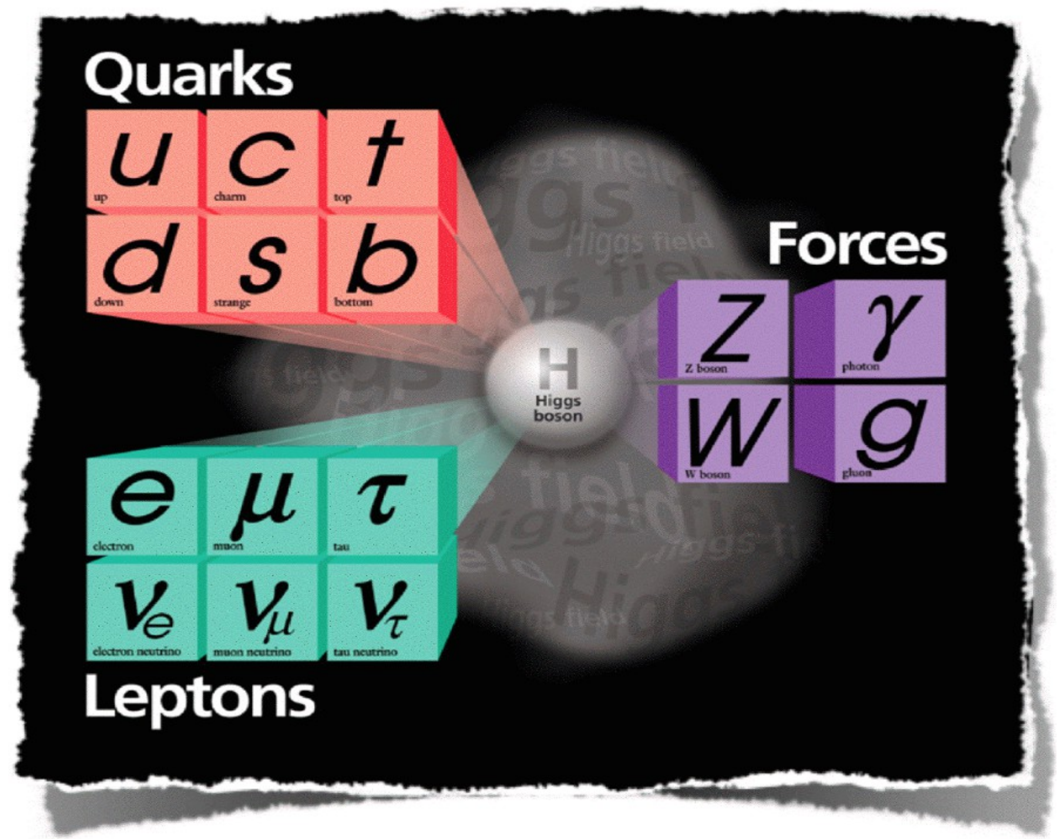
$\Delta m^2_{sol} = 7.59^{+0.20}_{-0.21} \times 10^{-5} \mathrm{eV}^2$

$Sin^2\theta_{12} \sim 0.31$

One of the main goals of Current Oscillation experiments is to make "precision" measurements of θ_{23}, θ_{13} and the mass difference, Δm^2_{23}

Lets take a step back and think about what we learnt...





Note we can only measure neutrino mass square differences not absolute masses...

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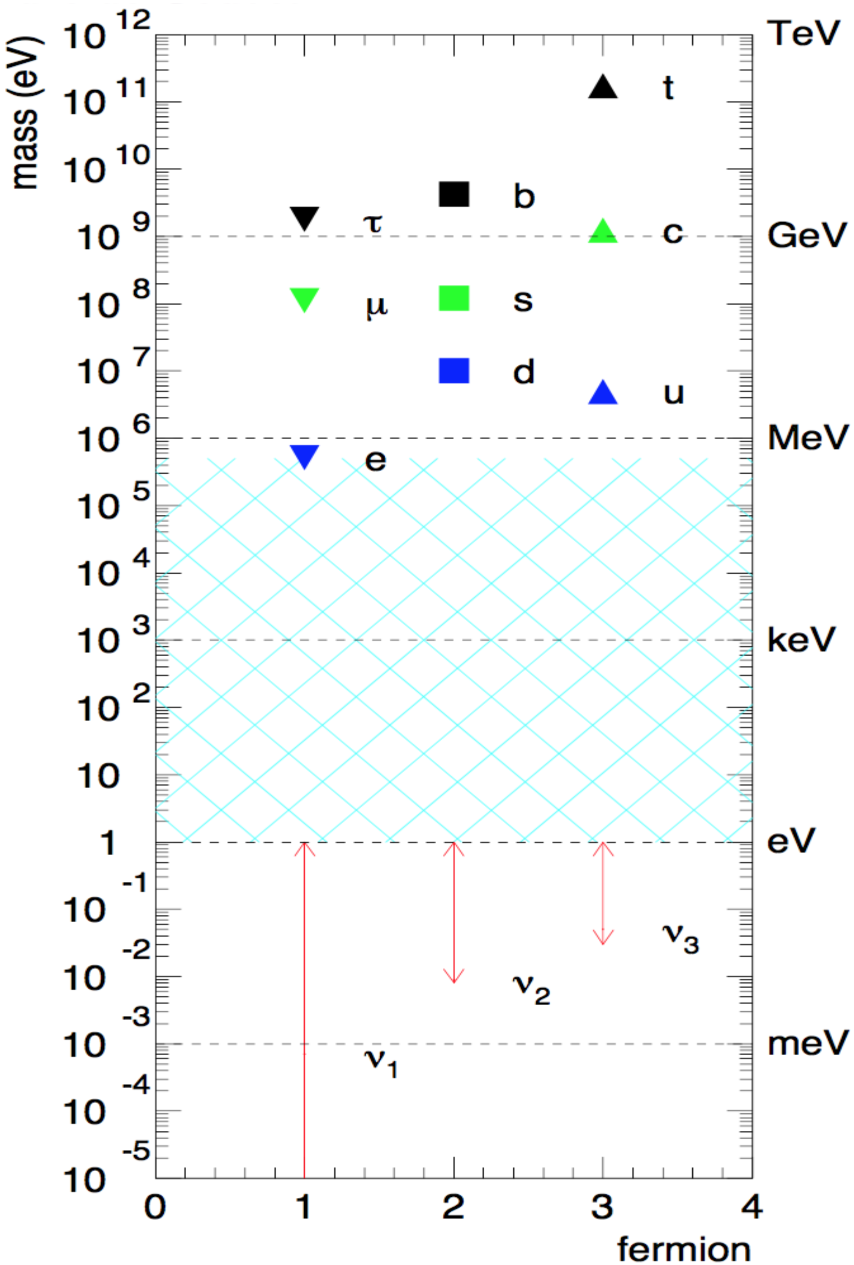
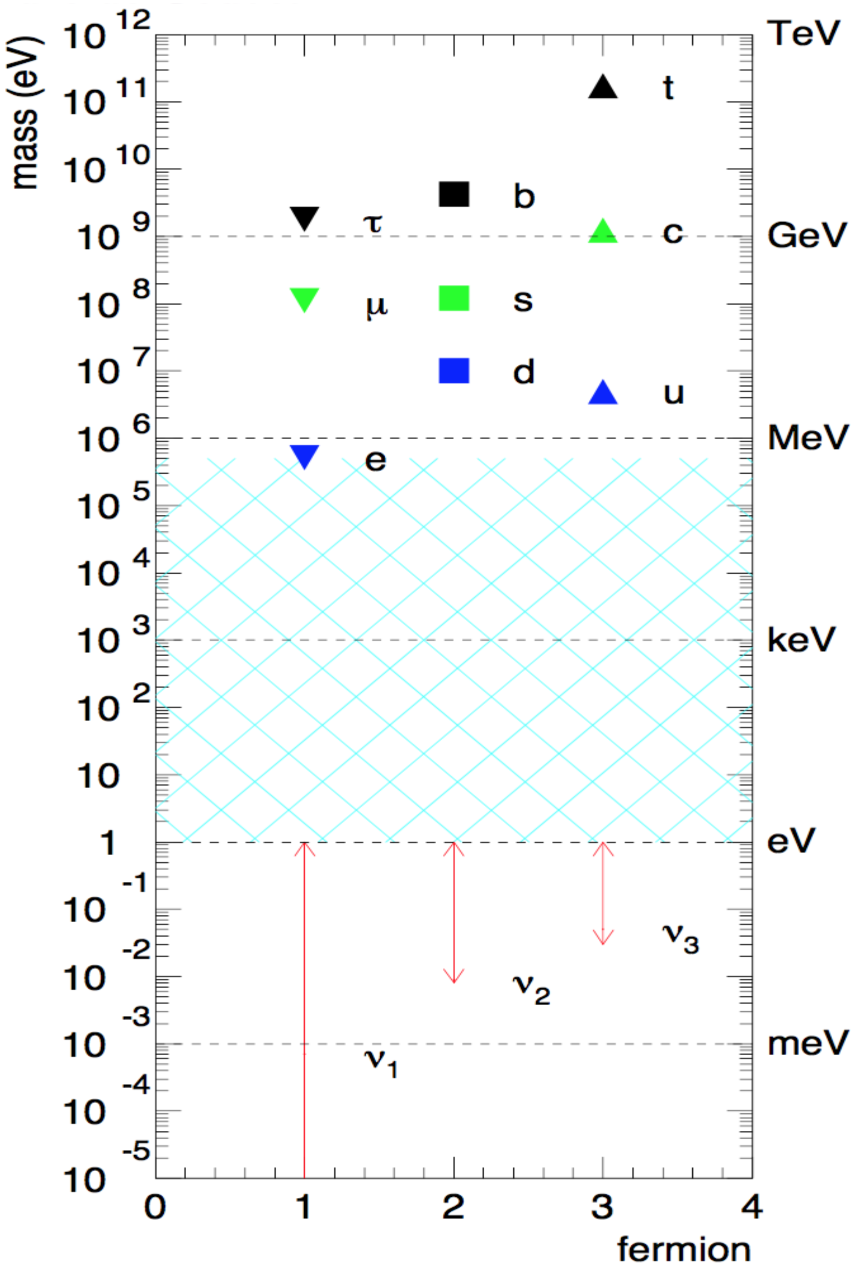
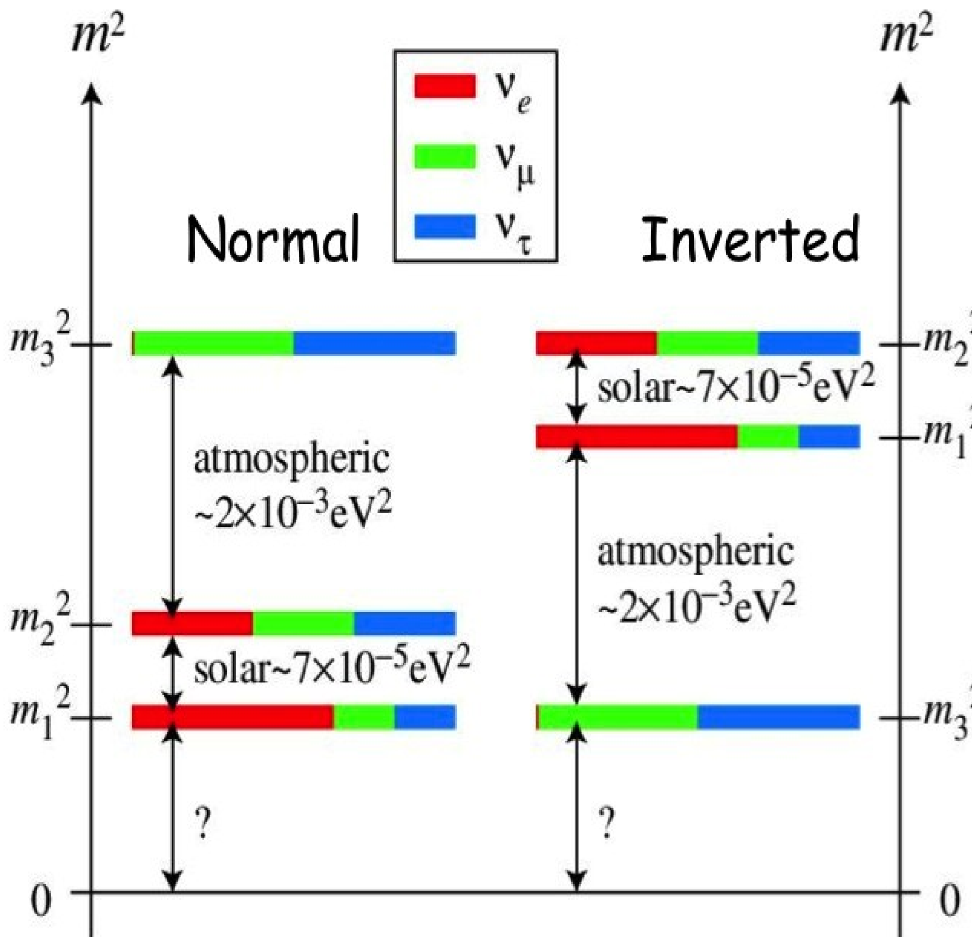


- *Are there ONLY three neutrino flavors?*
- *Why do quarks and leptons exhibit different behavior?*
- *Why is there such large gap between neutrino masses and quark masses?*
- *Are neutrinos their own mirror symmetry?*
  - *do anti-neutrinos oscillate same as neutrinos*
- *What about "absolute" neutrino masses?*

Lets take a step back and think about what we learnt…



- *Neutrino Mass ordering?*
  - *Remember we only know mass differences not exact masses…*



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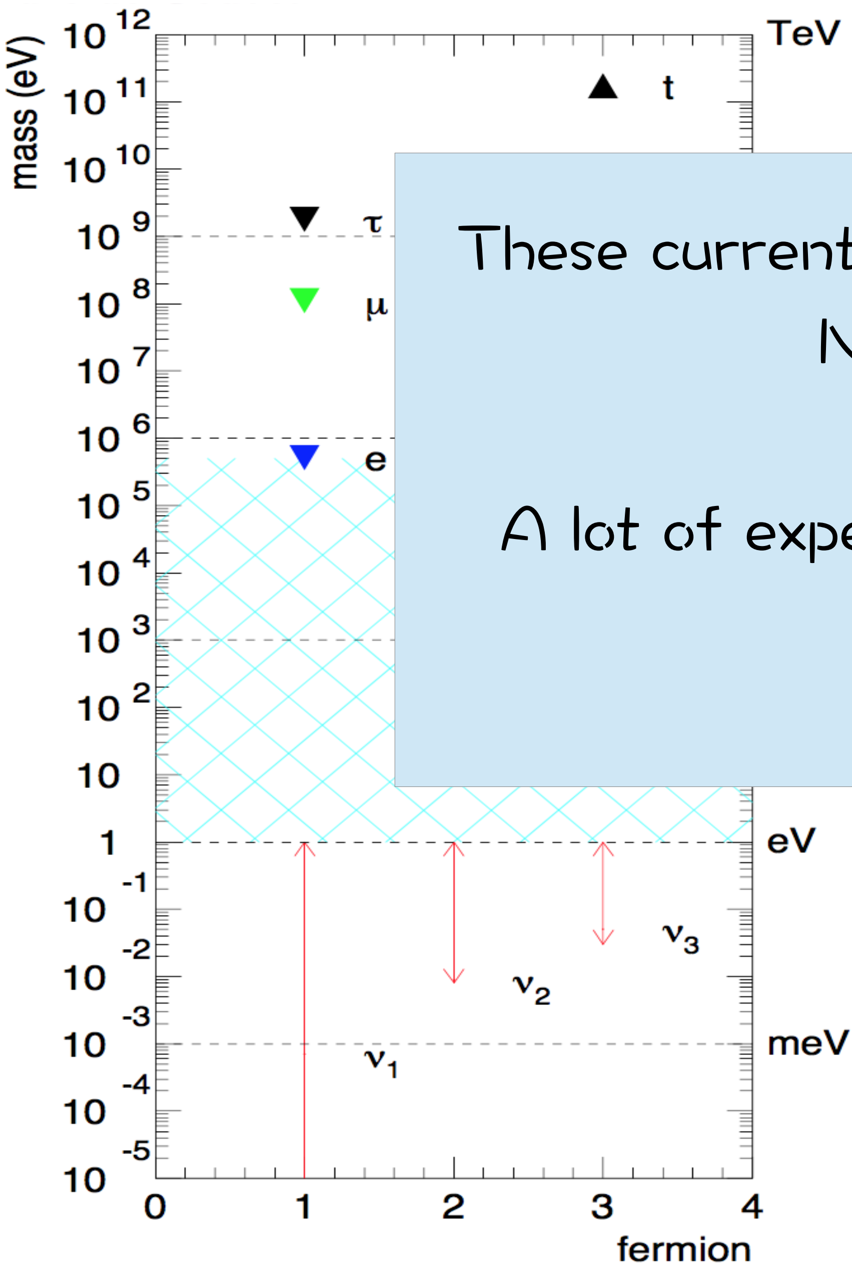

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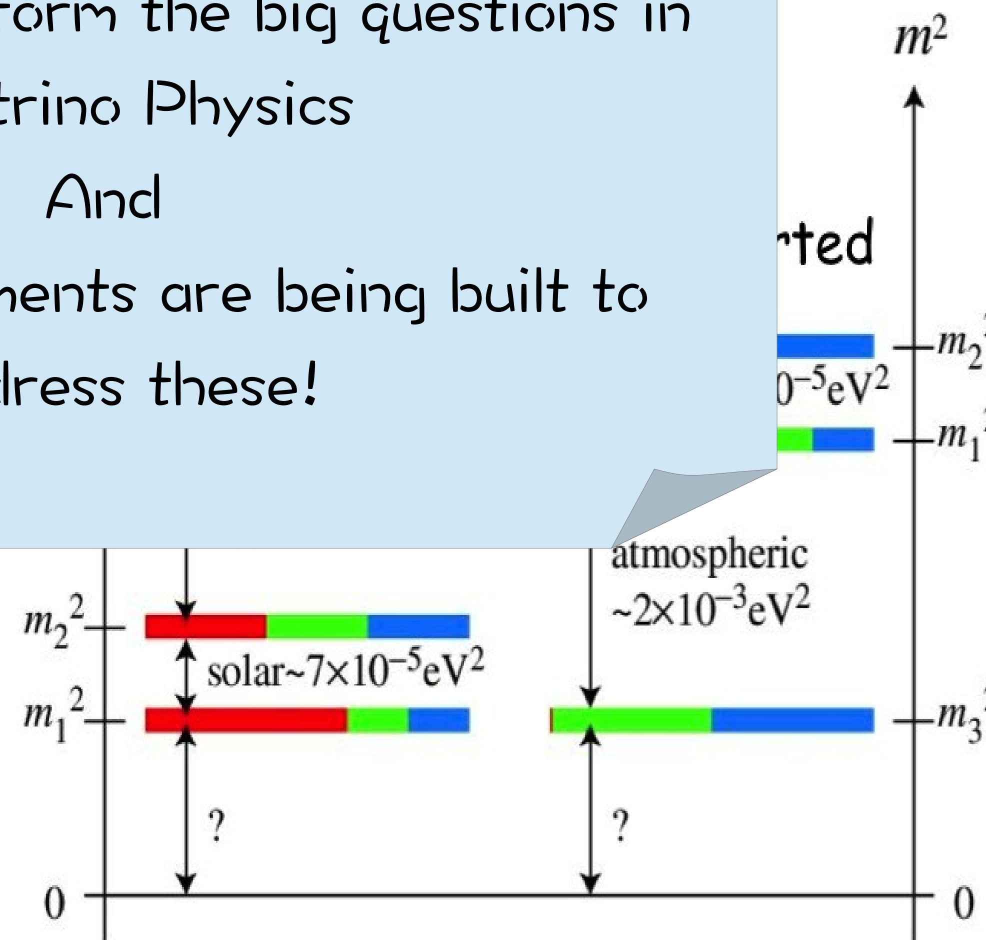


These currently form the big questions in Neutrino Physics

And

A lot of experiments are being built to address these!

Long-baseline experiments

Precision measurements of mixing parameters

Neutrinos mass hierarchy?

CP Violation?

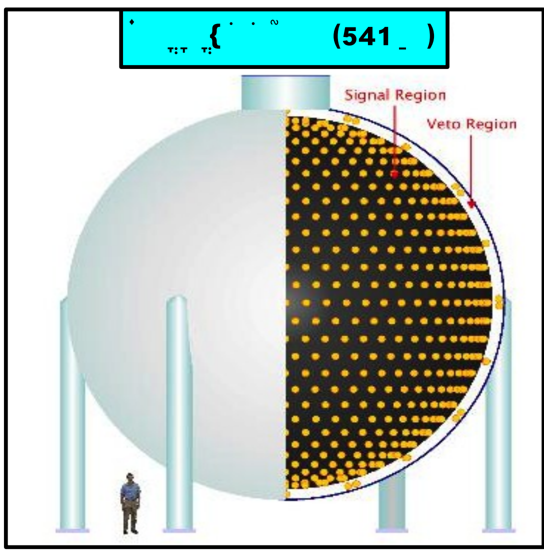
Neutrino vs Anti-neutrino oscillations

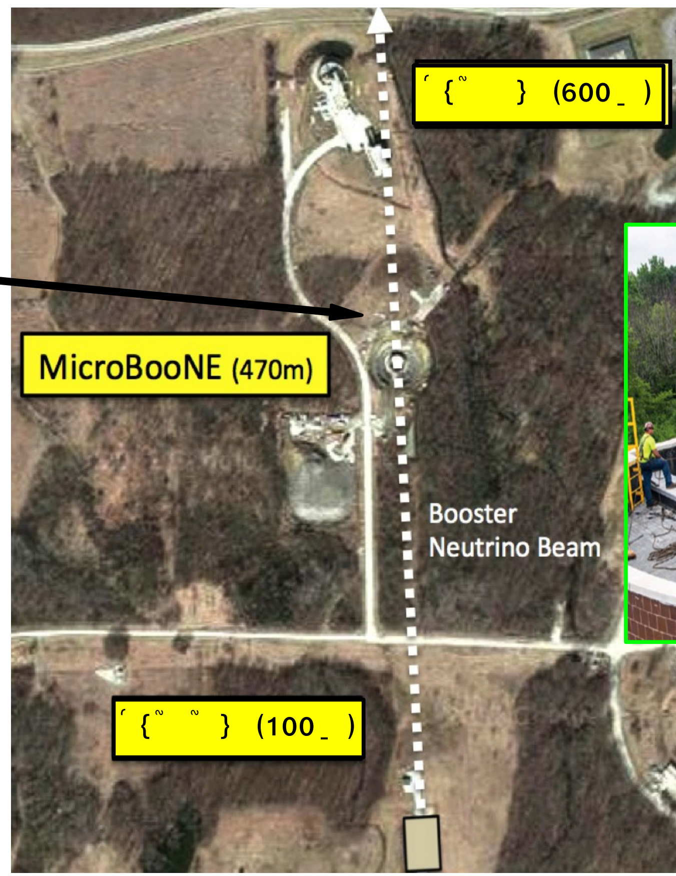
also, T2K in Asia

Short-baseline experiments

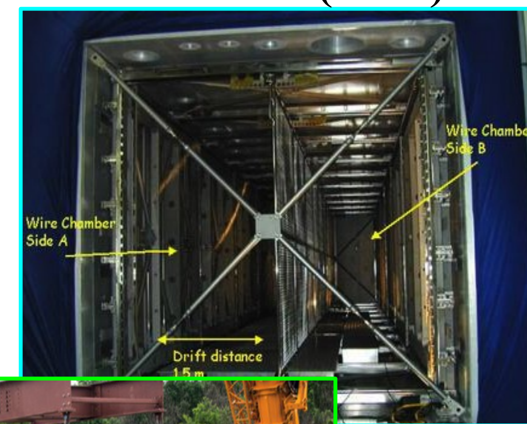
Are there more than 3 neutrino flavors?

– *Sterile neutrinos?*



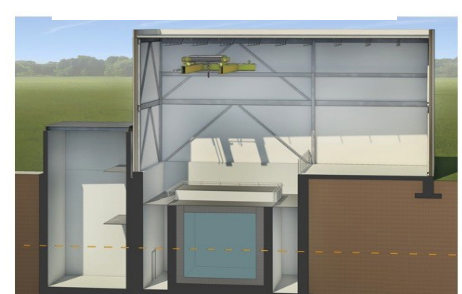


ICARUS (T600)



MicroBooNE

SBN ND



Fermilab Short-baseline experiments

Proposed SBN program

New detector technologies being Implemented to achieve precision...

Liquid Argon Time Projection Chambers are the next generation neutrino detectors

New detector technologies being Implemented to achieve precision...

Liquid Argon Time Projection Chambers
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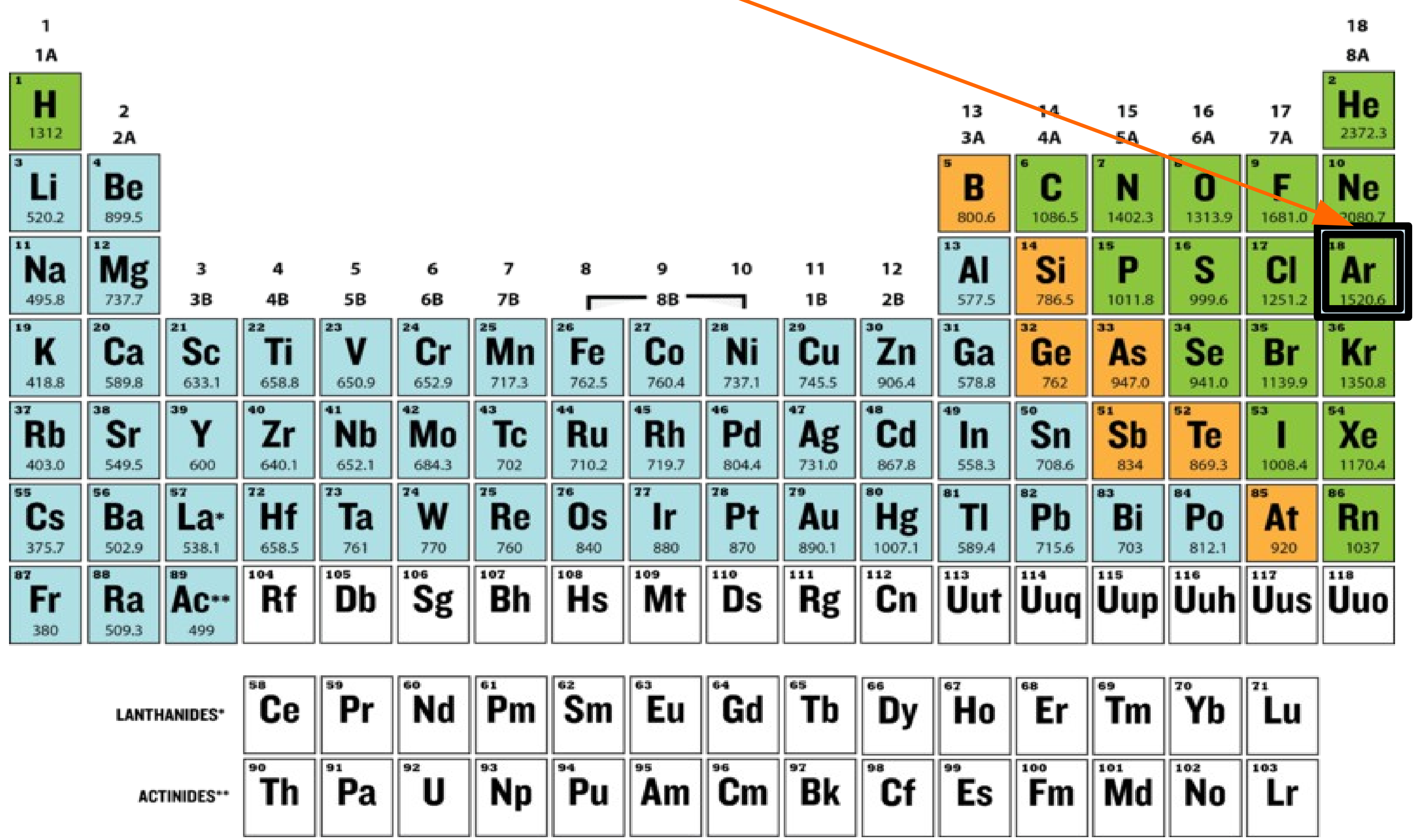
New detector technologies being Implemented to achieve precision...

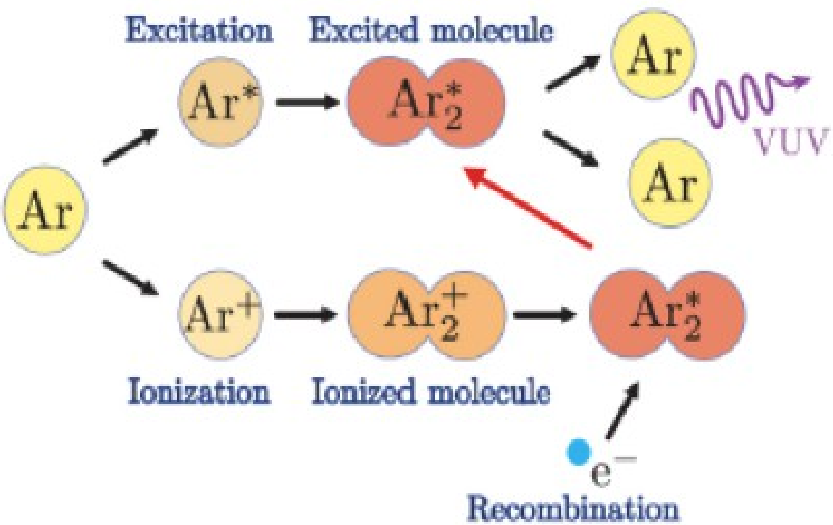
Liquid Argon Time Projection Chambers are the next generation neutrino detectors

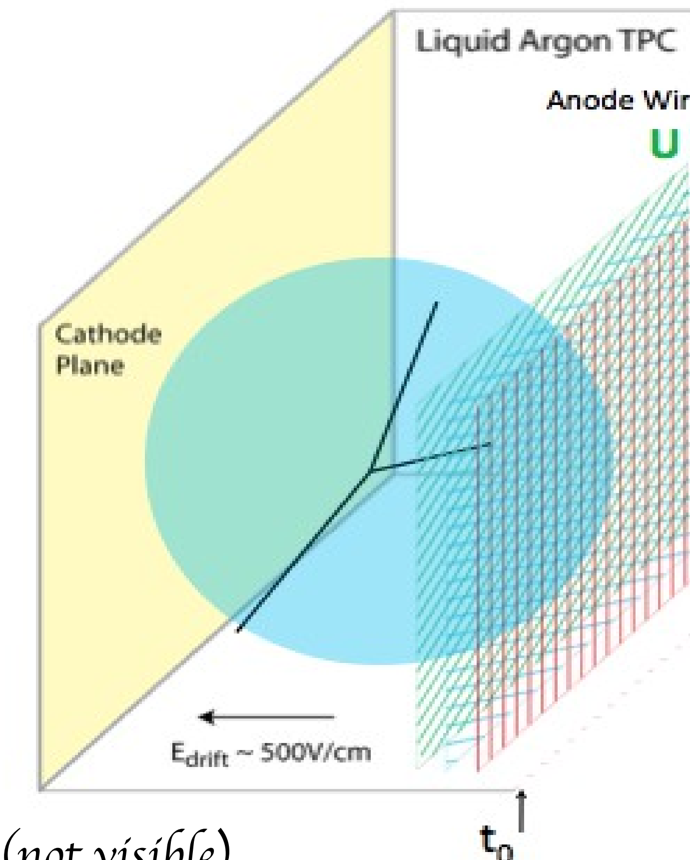


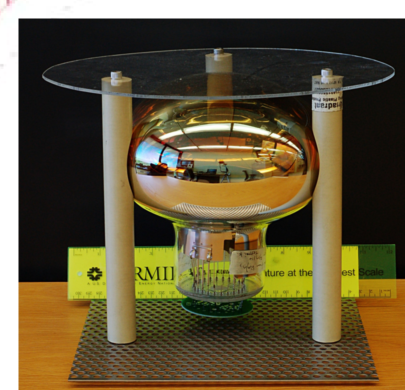
How does a LArTPC work?

Neutrino interactions with LAr in the TPC produces charged particles that cause Ionization and excitation of Argon

- High E field drifts electrons towards finely segmented anode wire planes
- Excitation of Ar produces scintillation light





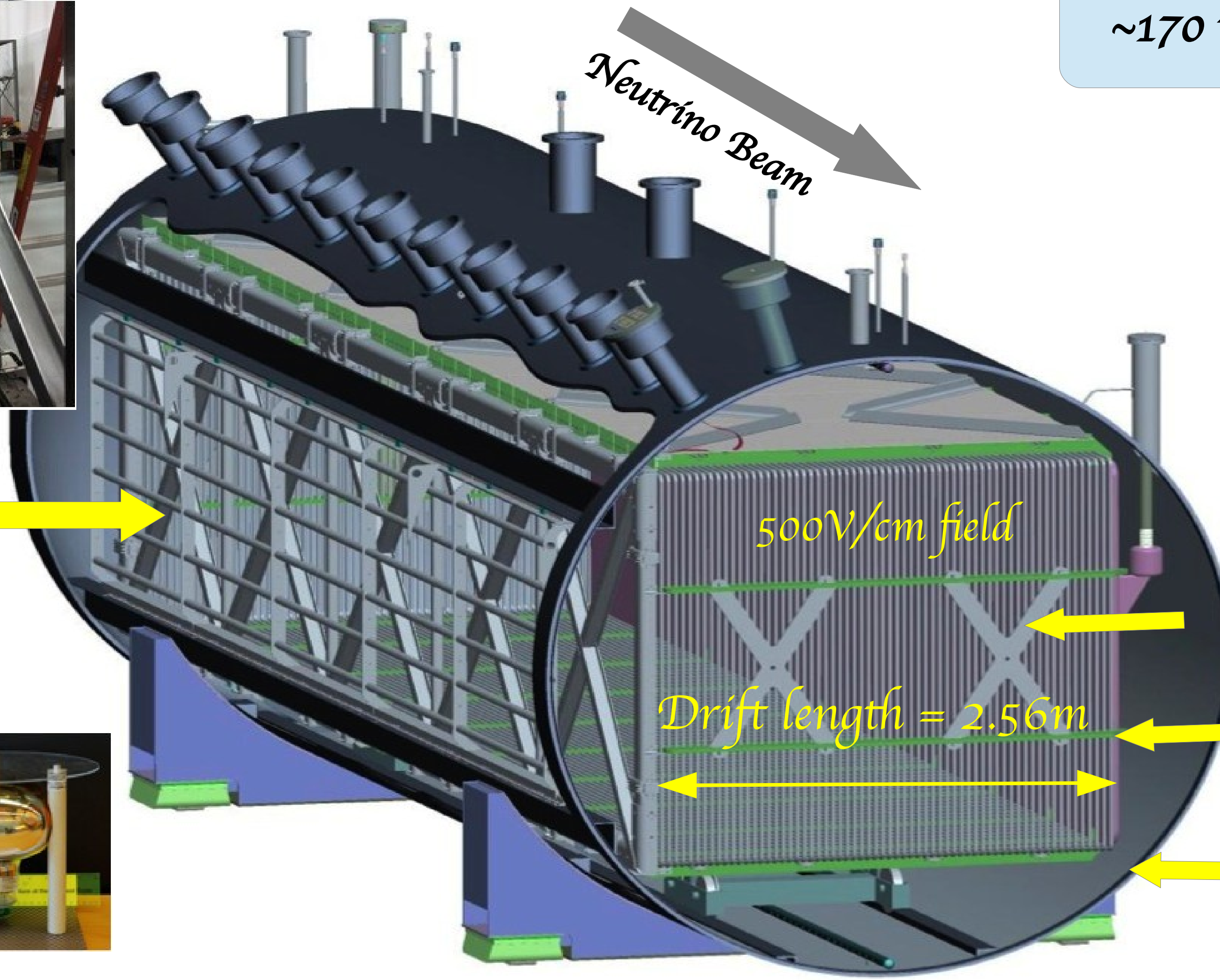


Ar emits light at 128 nm ⟶ VUV range (not visible)
(wavelength shifting mechanism to make it visible)

The not-so-micro MicroBooNE

~170 tons of argon

~8000 wires
Anode
(150 micron)



Field cage

Cathode plane
(-128kV)

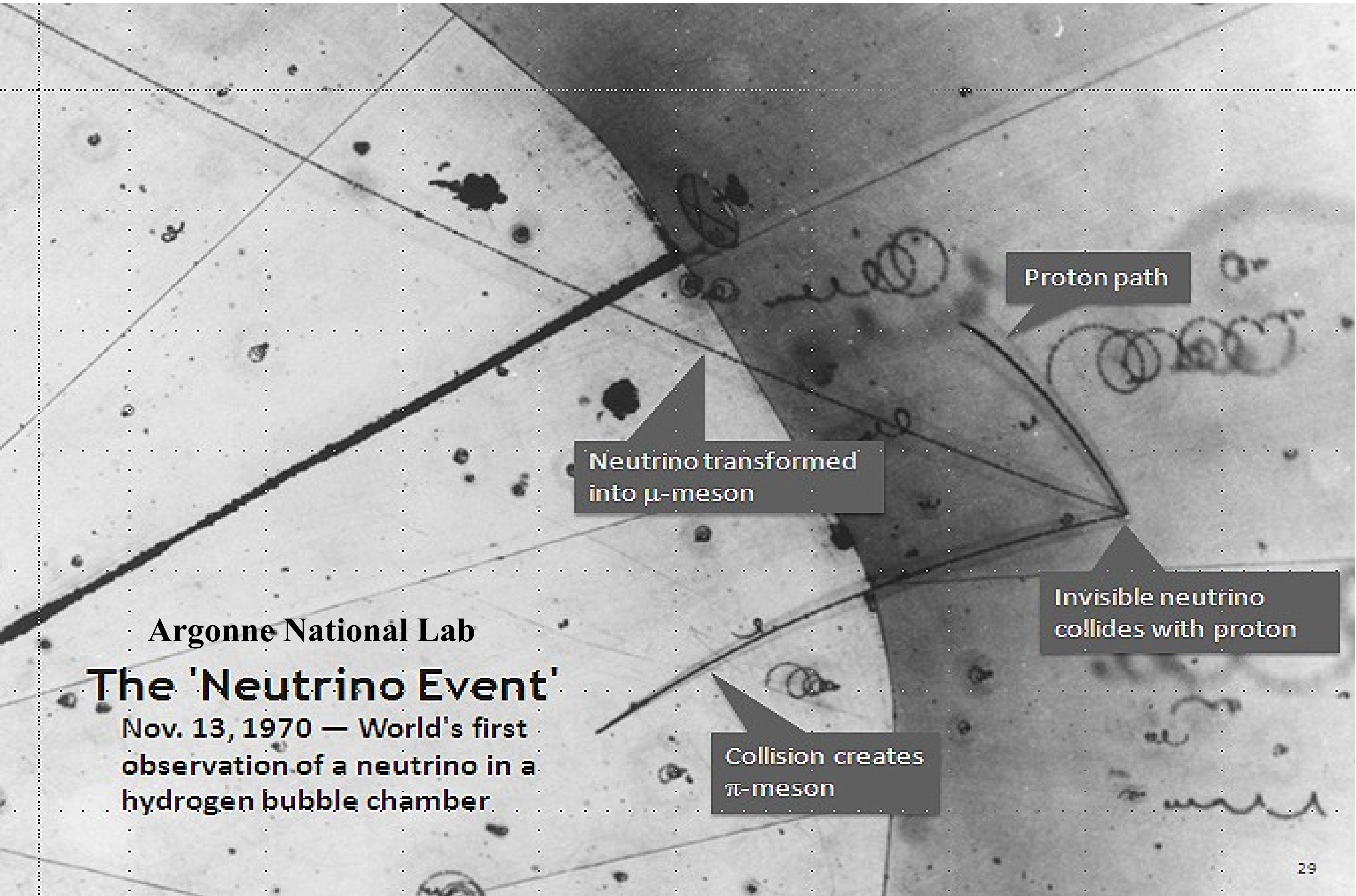
Cryostat

32 8-inch PMTs sit just behind wire planes (not shown in the picture!)

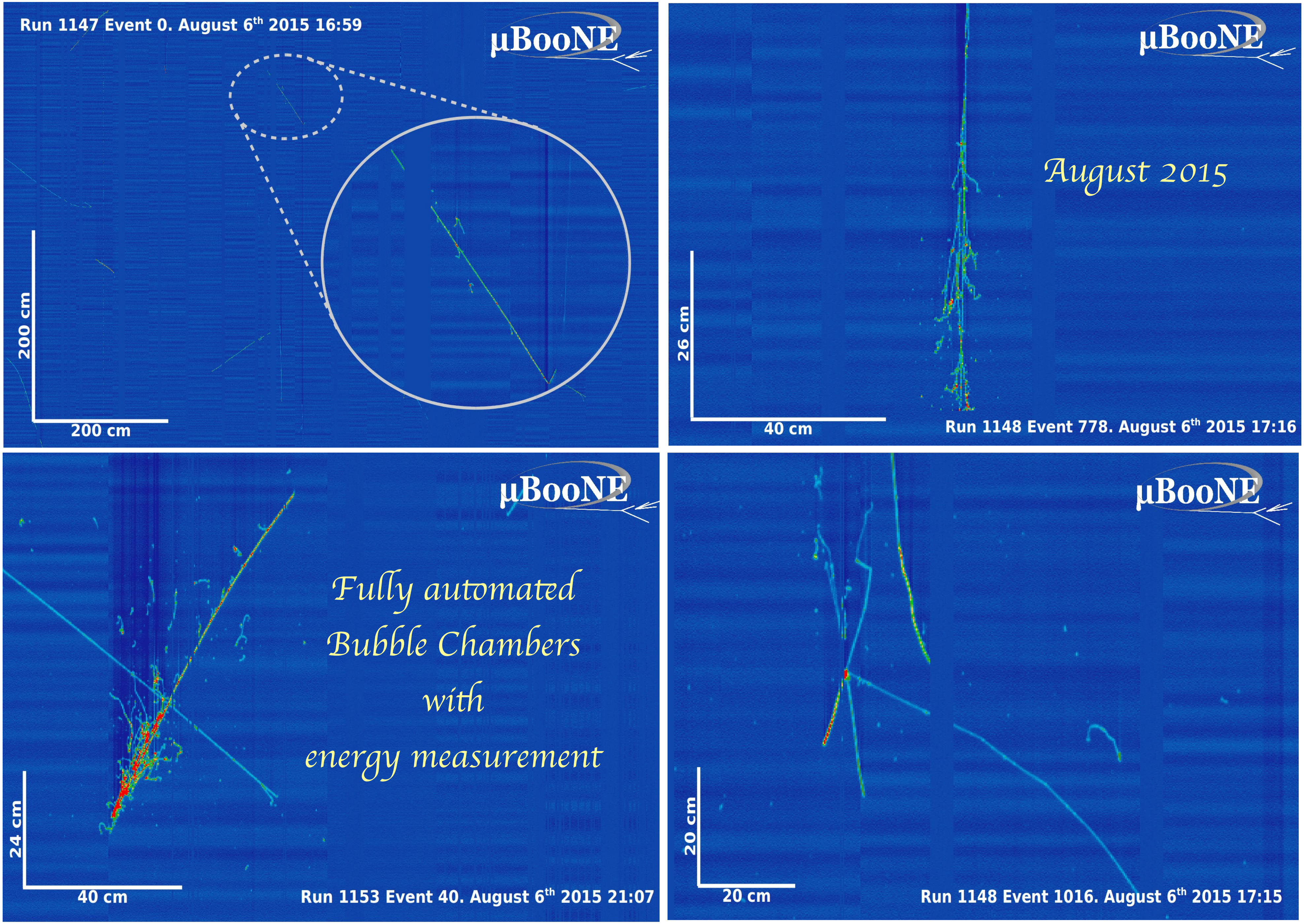
(Roughly the size of a school bus)

MicroBooNE Installation

30 years ago with Bubble Chambers



30 years later…look at the detail achieved!



Neutrinos are a big deal..!

Many more exciting and Weird things to come!

Subscribe to Fermilab Facebook page for updates
on the cool stuff we do :)

Thank you for listening!

Now lets end the session with some ice cream