Matter

Antimatter

& the Ghostly Neutrino

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TARGET Summer Lectures

U.S. DEPARTMENT OF ENERGY

Fermilab

Matter is all around us

It takes the form of common things we know

from the very small

Matter is all around us

to the very LARGE

It fills our universe

But what is matter?

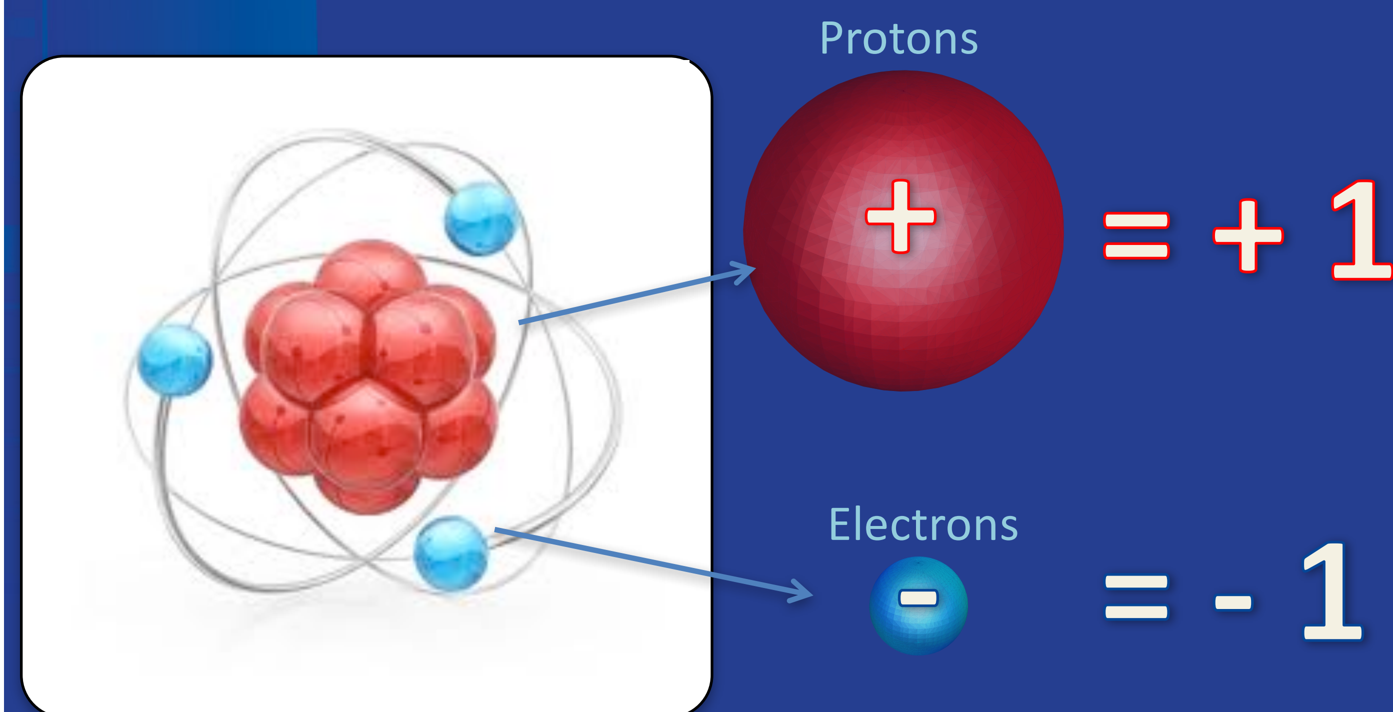
Why is there so much of it?

How did it come to dominate the entire universe?

Matter

- At its heart though we define matter in terms of the sub-atomic particle that make up everything

- That kitten is really a collection of particles

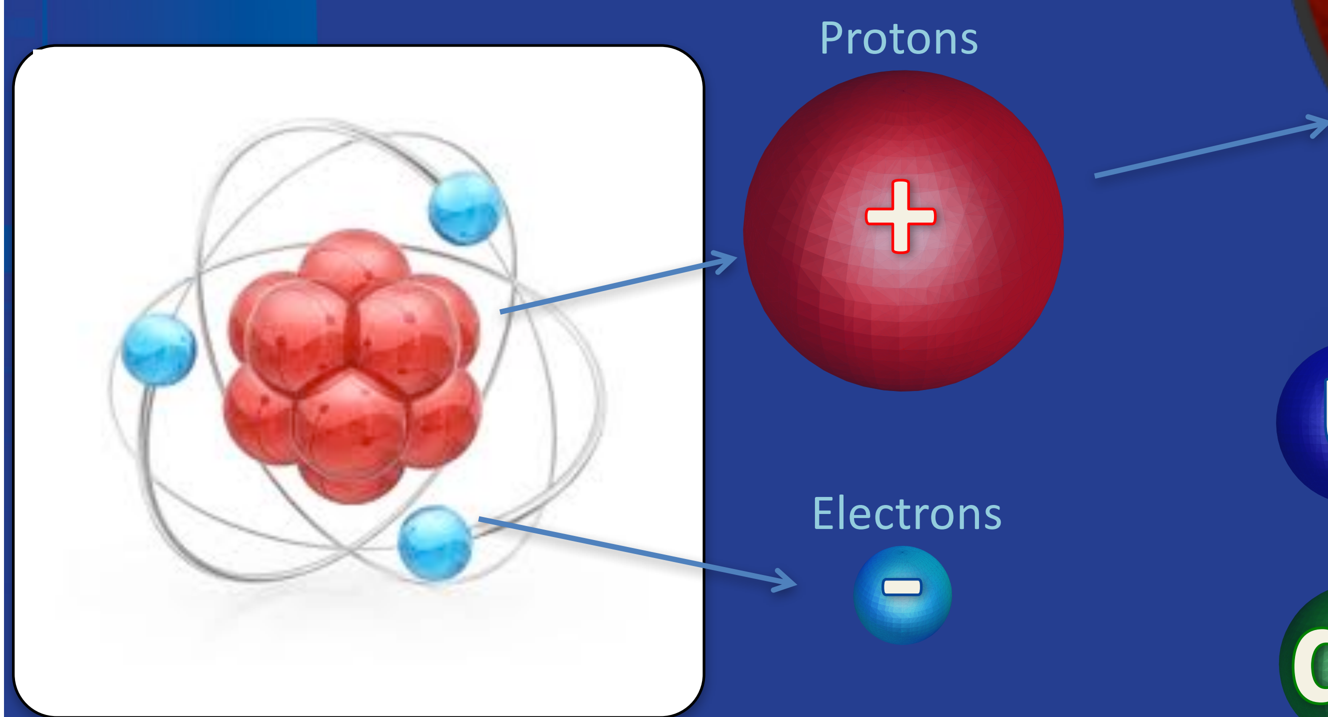


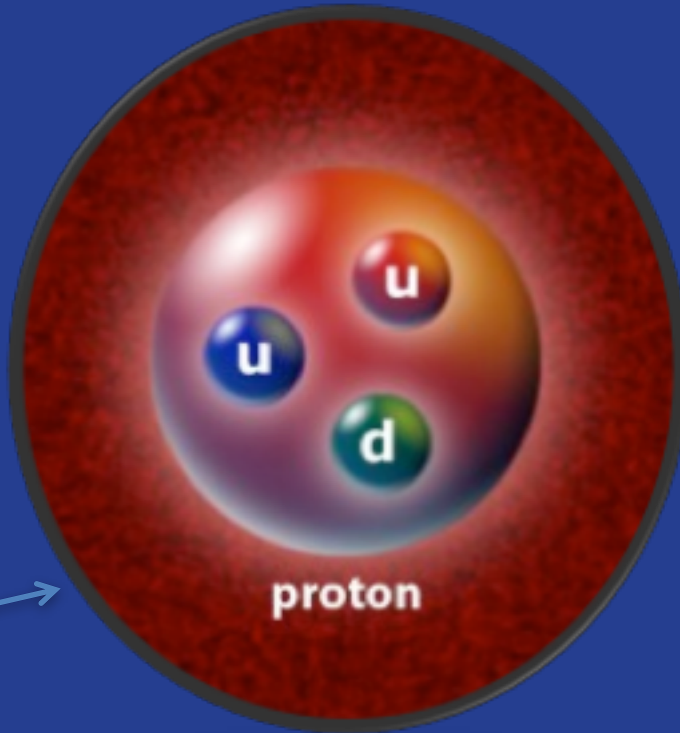
These particles have mass (weight) & electric charges

and other quantum numbers that define “*who*” they are

Matter

- For some particles, like the proton, we can go deeper inside them
- We can look at the QUARKS that make them up



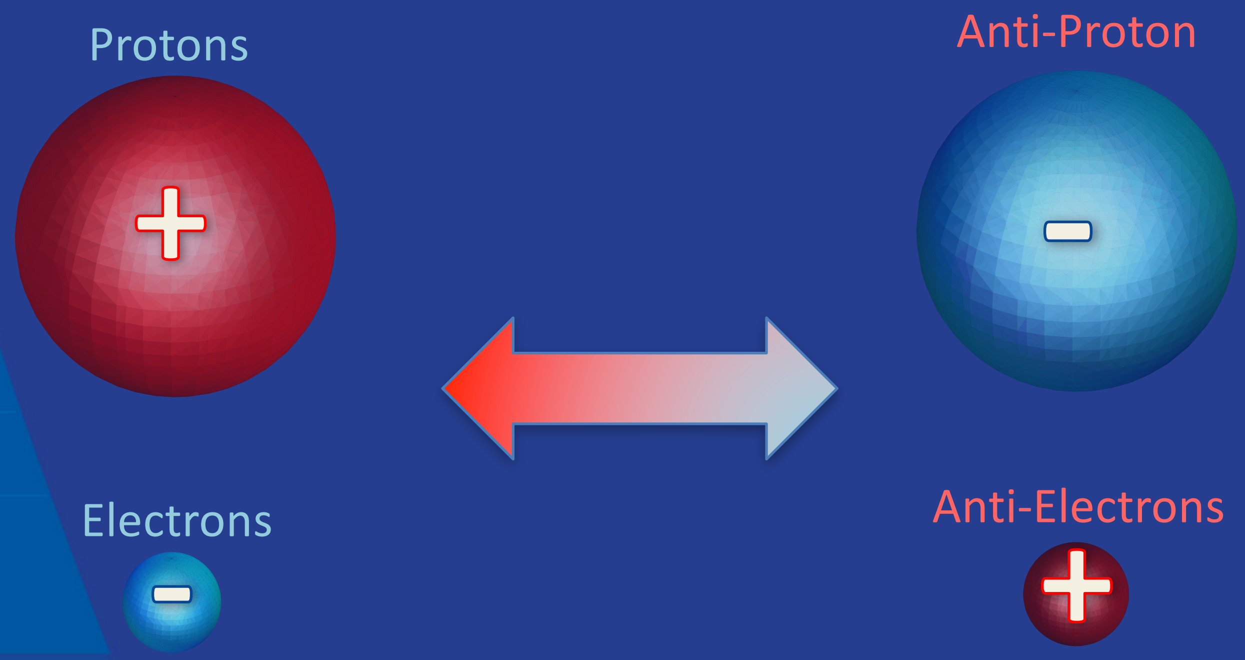


$u = +\frac{2}{3}$

$d = -\frac{1}{3}$

Anti-Matter

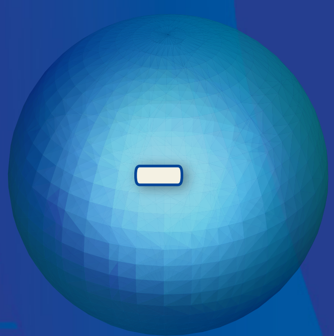
- What about Anti-Matter?
- Anti-matter particles are the twins of all the normal sub-atomic particles
  - They have the same weight and quantum properties
  - But they have their electric charge flipped



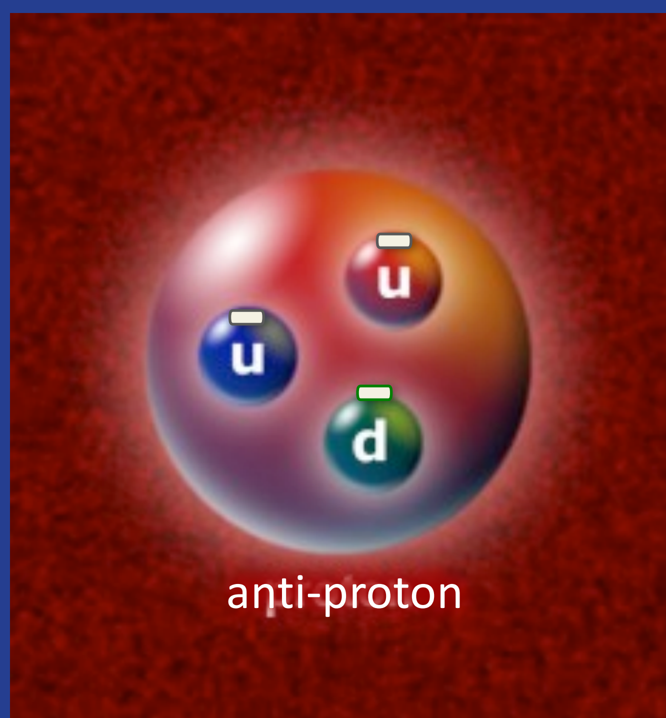
Anti-Matter

- This holds for particles and collections of particles
- The anti-proton it has the same type of substructure as the proton, but with anti-quarks inside

Anti-Proton



Anti-Electrons

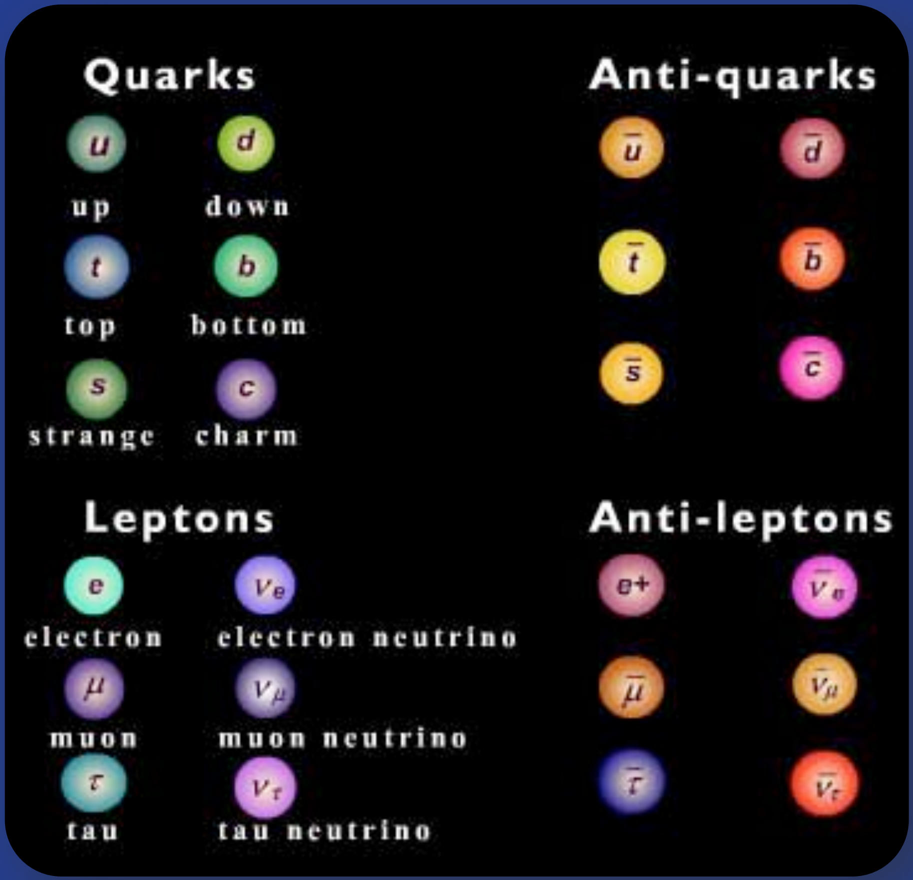


$\bar{u} = -\frac{2}{3}$

$\bar{d} = +\frac{1}{3}$

Anti Matter is Real

- This works for all the subatomic particles
- Every particle has it's anti-twin
- And experimentally we have made and measured them!



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

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

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

Leptons spin = 1/2

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

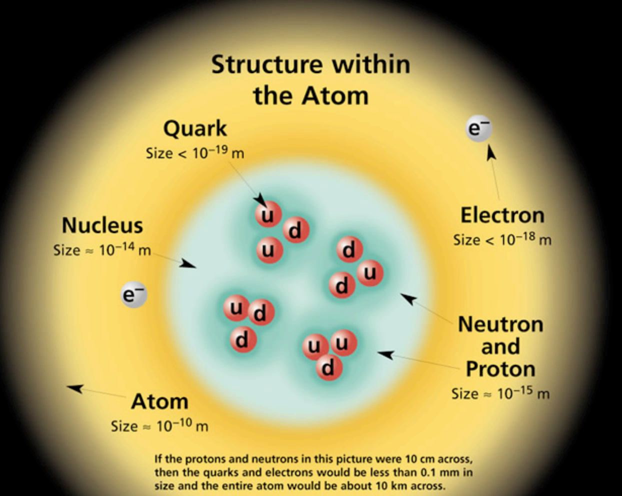
Quarks spin = 1/2

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

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

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

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

Unified Electroweak spin = 1

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

Strong (color) spin = 1

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

Color Charge

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

Quarks Confined in Mesons and Baryons

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

Residual Strong Interaction

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

PROPERTIES OF THE INTERACTIONS

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

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

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

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

Mesons $q\bar{q}$

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

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

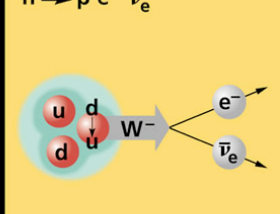
Matter and Antimatter

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

Figures

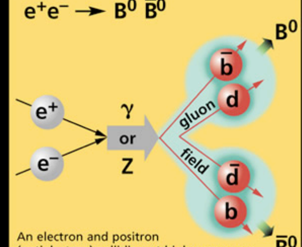
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

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



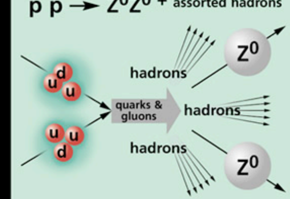
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

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



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

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



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

The Particle Adventure

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

This chart has been made possible by the generous support of:
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American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

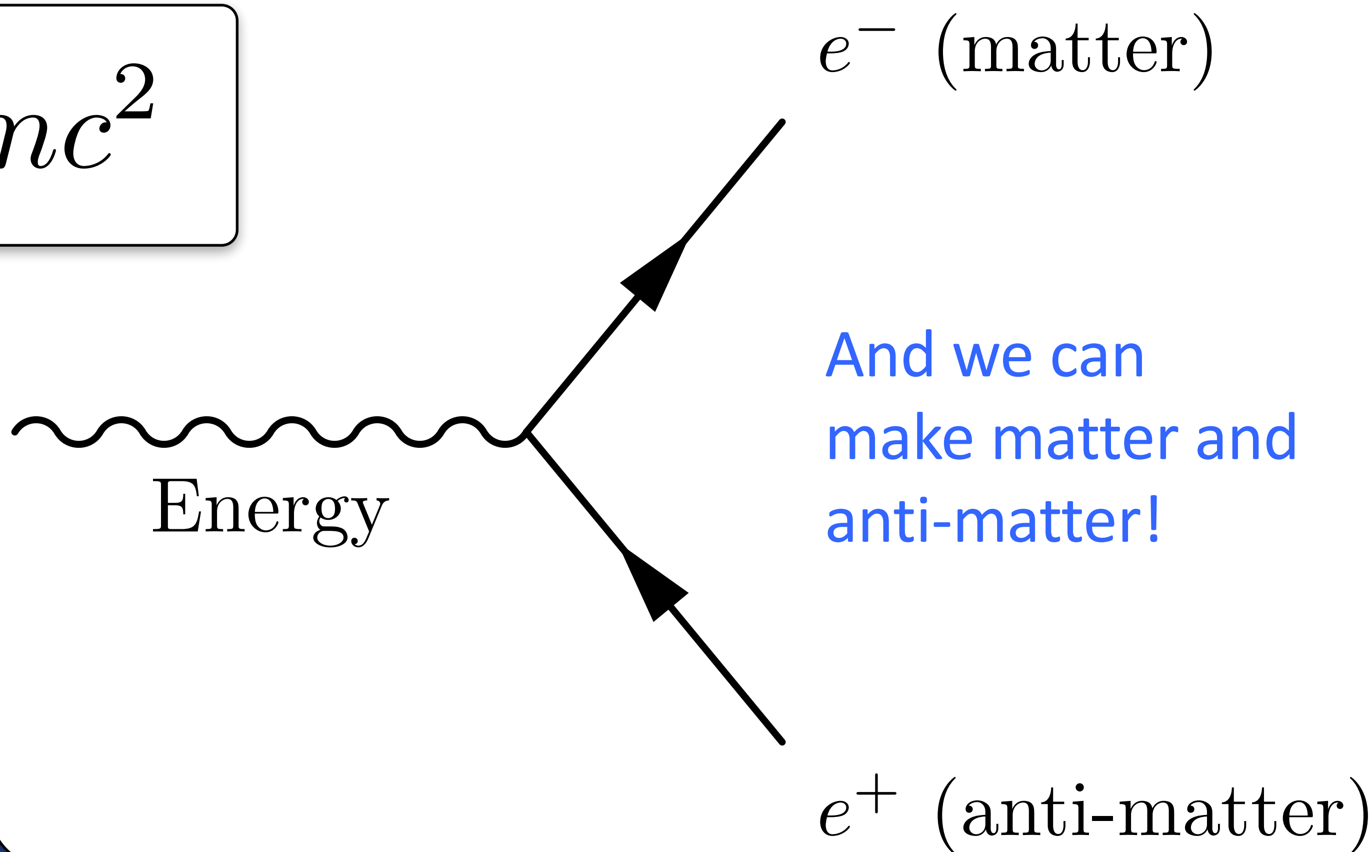
http://CPEPweb.org

Making Anti-matter

- How do we make Anti-matter?
  - It's easy, we use Einstein

$$E = mc^2$$

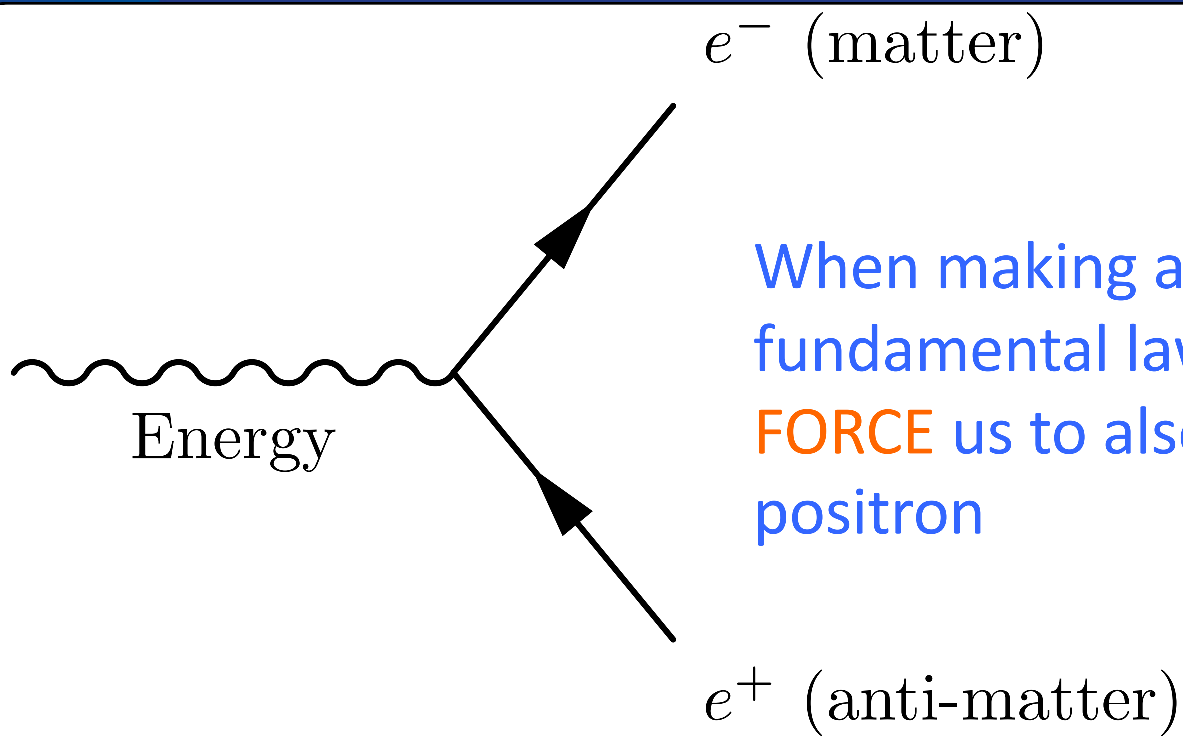
We convert pure energy into mass



And we can make matter and anti-matter!

Making Anti-matter

- When we make particles this way we ALWAYS make BOTH matter and anti-matter in equal parts

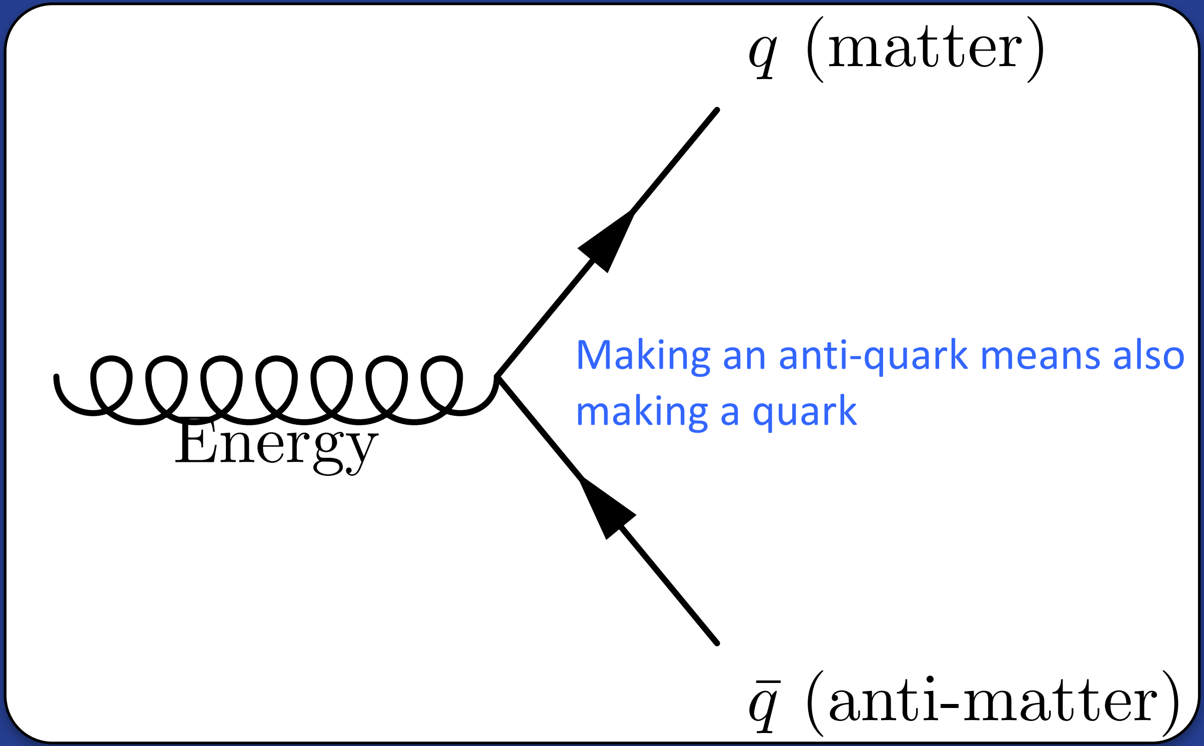


When making an electron, the fundamental laws of physics FORCE us to also make an positron

This is the case when I make “leptons” (electrons, muons, taus…)

Making Anti-matter

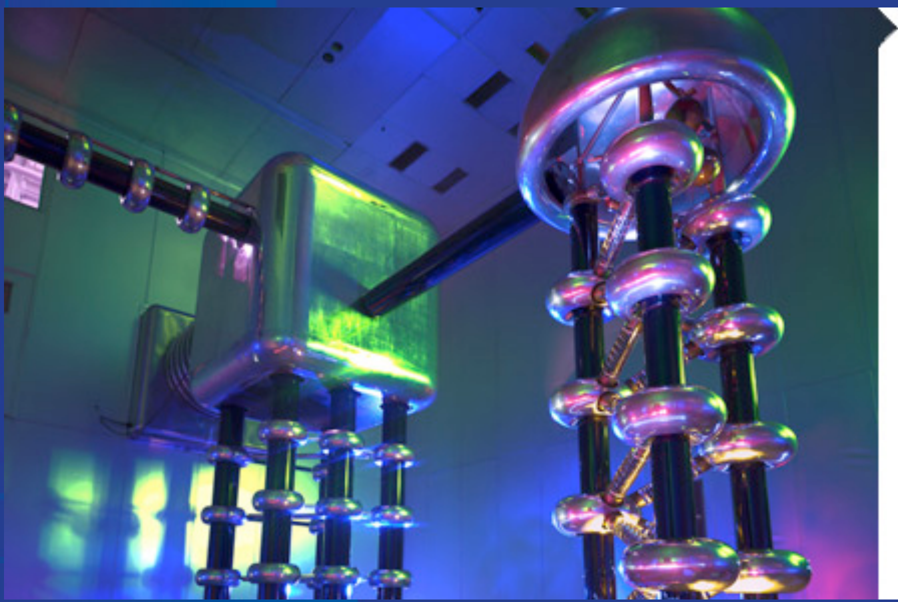
This is also the case when I make quarks or particles that contain quarks



- This is the case when I try to use any of the fundamental forces to make any type of matter or anti-matter from energy

Making Anti-matter

- This is great if you have a particle accelerator!



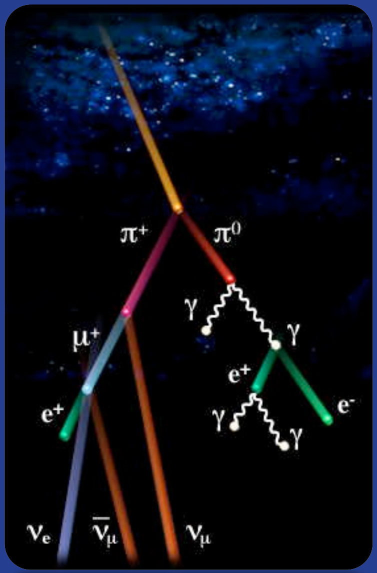
1. You can start with normal protons (here we use Hydrogen)

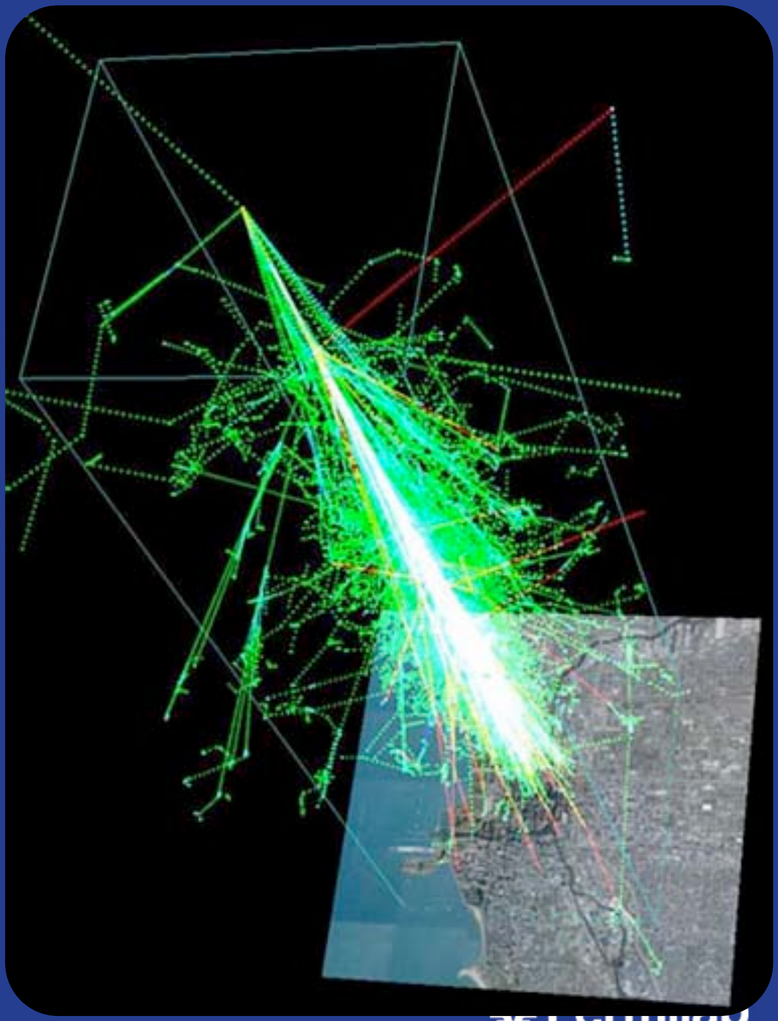
2. Send them through miles of accelerator tunnels boosting them to near the speed of light

3. Then collide them with targets (or each other) to liberate the energy and make lots of matter and anti-matter

Making Anti-matter in Nature

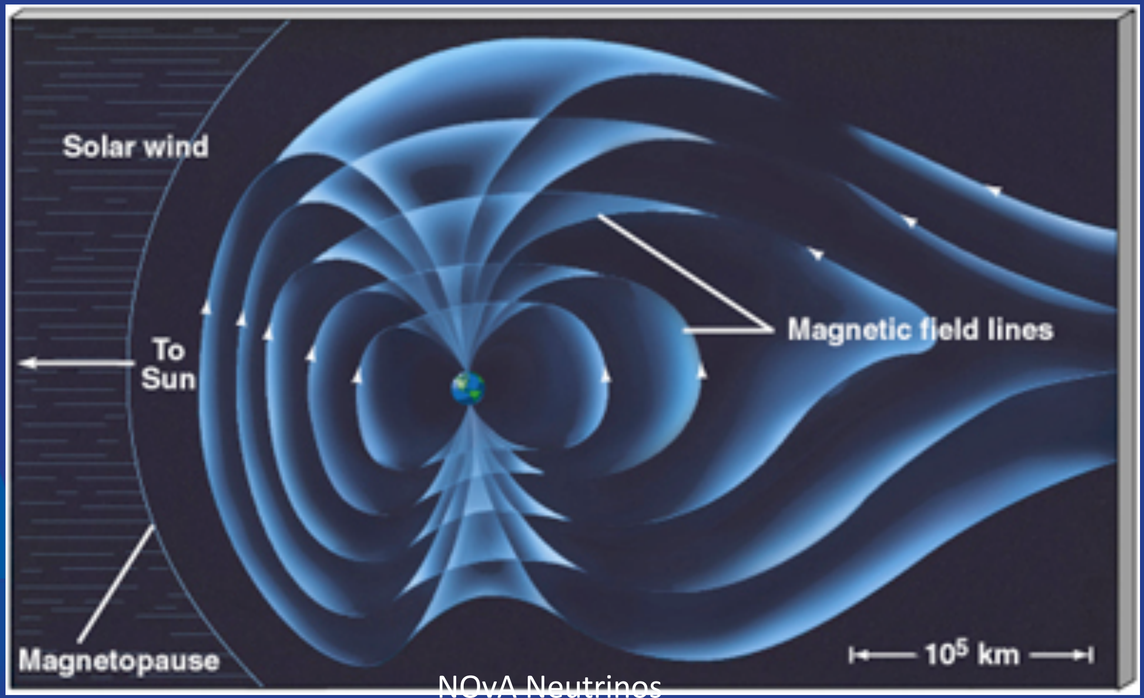
- Does nature make anti-matter?
  - With cosmic rays
    - Protons hit gas in the upper atmosphere and create shows of new particles





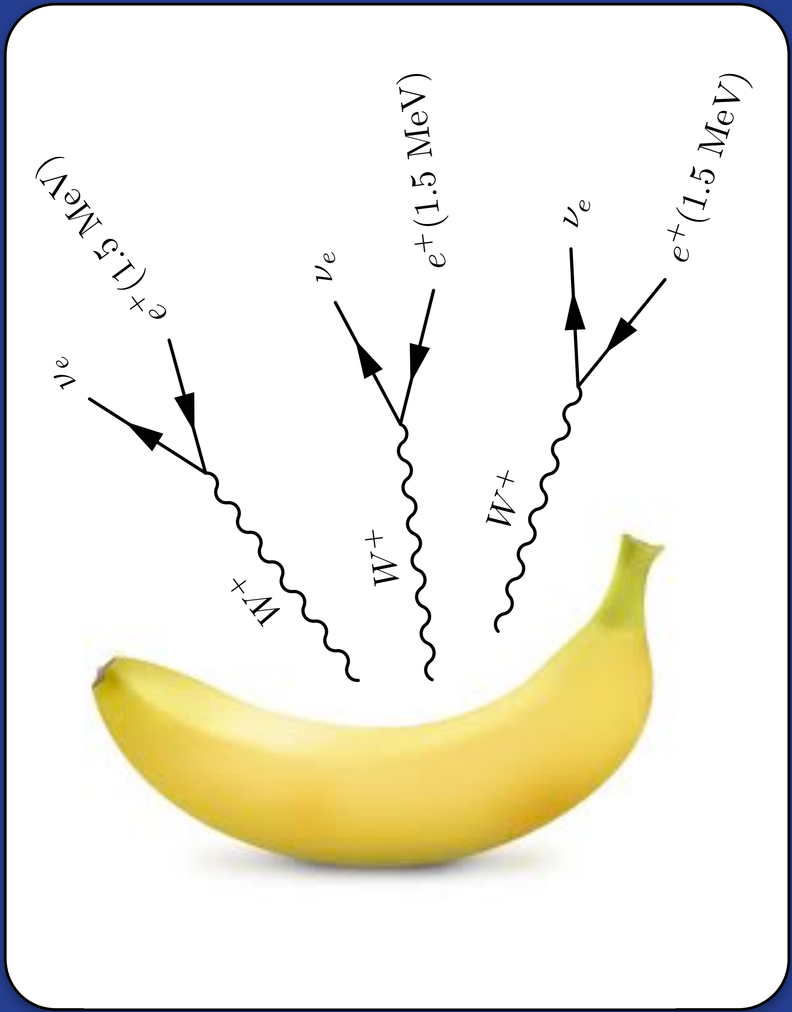
Making Anti-matter in Nature

- Does nature make anti-matter?
  - With cosmic rays
  - With “natural” accelerators caused by magnetic fields (Van Allen belts w/ Earth’s magnetic field)



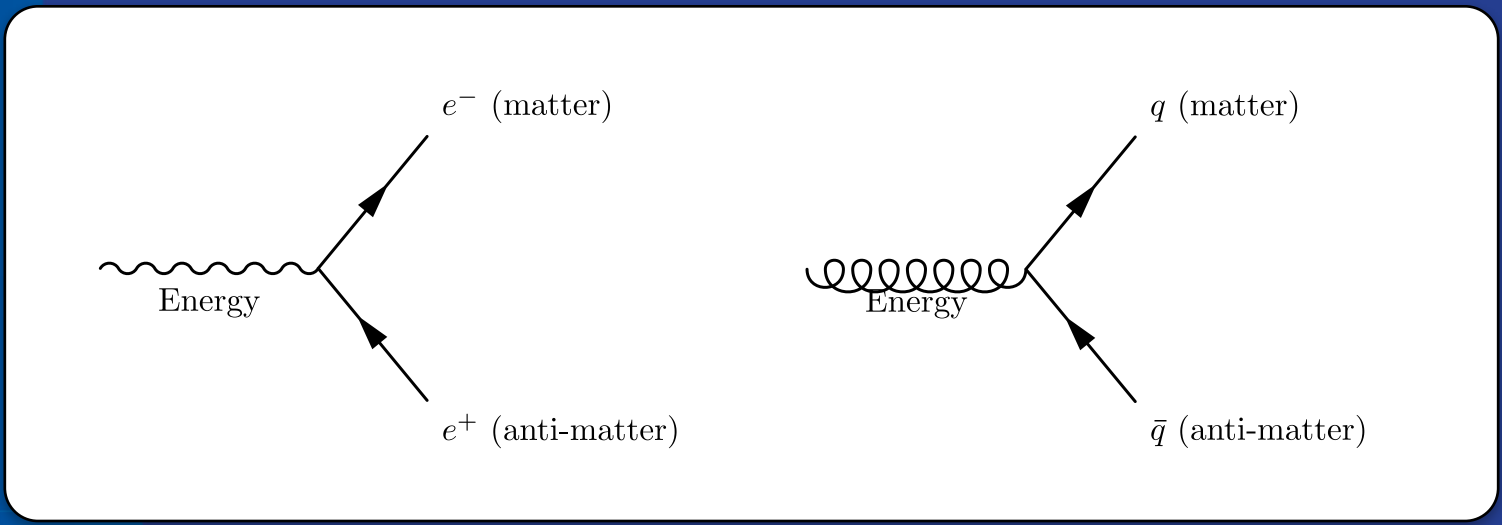
Making Anti-matter in Nature

- Does nature make anti-matter?
  - With cosmic rays
  - With "natural" accelerators (earth's magnetic field)
  - Even bananas!
    - ^{40}K has a decay mode that gives off a positron about every 75 min ($\beta^{+}\approx$1.5 MeV)



Making Anti-Matter in Nature

- And in HOT the early universe energy was convert into matter/anti-matter pairs through the processes of leptogenesis and baryogensis



- ***And it was always made in equal parts***

This is a problem

IF…Matter and Anti-matter are created in equal parts

Where are the:

Anti-kittens

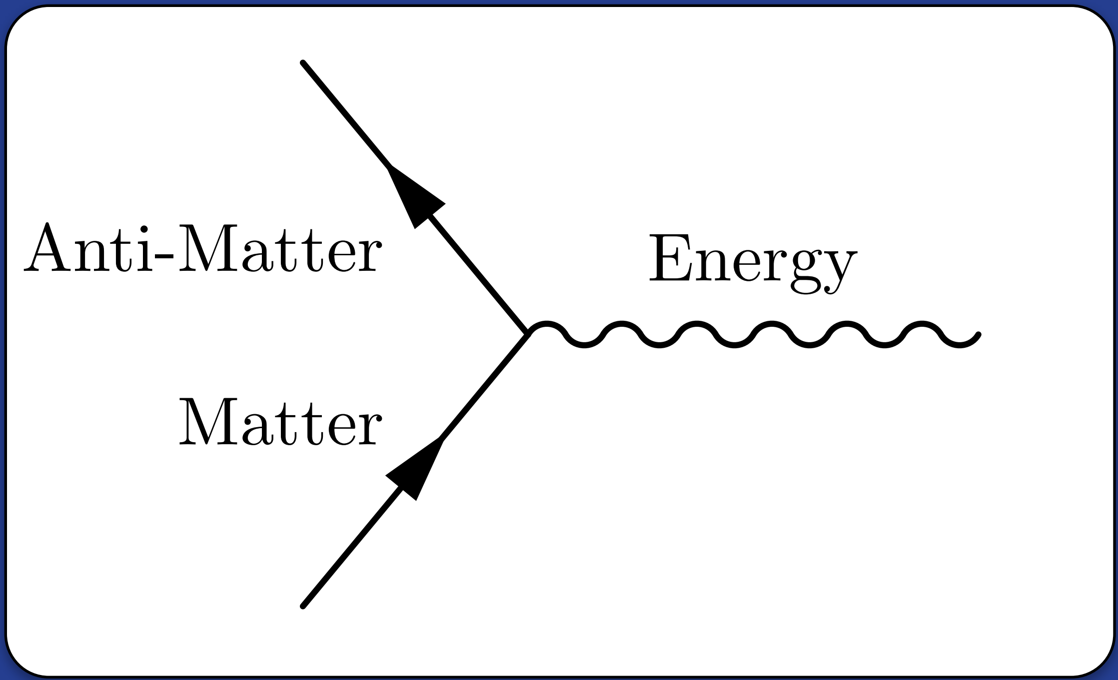
Anti-worlds

Anti-babies

Answer: They annihilated

- When you bring Matter and Anti-matter together the Einstein process works in reverse and the particles annihilate back into energy

$$mc^2 = E$$



Answer: They annihilated

- When you bring Matter and Anti-matter together the Einstein process works in reverse and the particles annihilate back into energy

kitten

+

Anti-kitten

=

Energy

- So where did all the anti-matter go?
  - It annihilated with all the matter to leave behind photons (light)
  - We are "leftovers" of matter that didn't get annihilated
  - The ratio of the amount of matter we see today to the number of relic photons we see tells us the asymmetry between matter/anti-matter:

$$\frac{n_B}{n_\gamma} = \left(6.1^{+0.3}_{-0.2}\right) \times 10^{-10}$$

Big Questions:

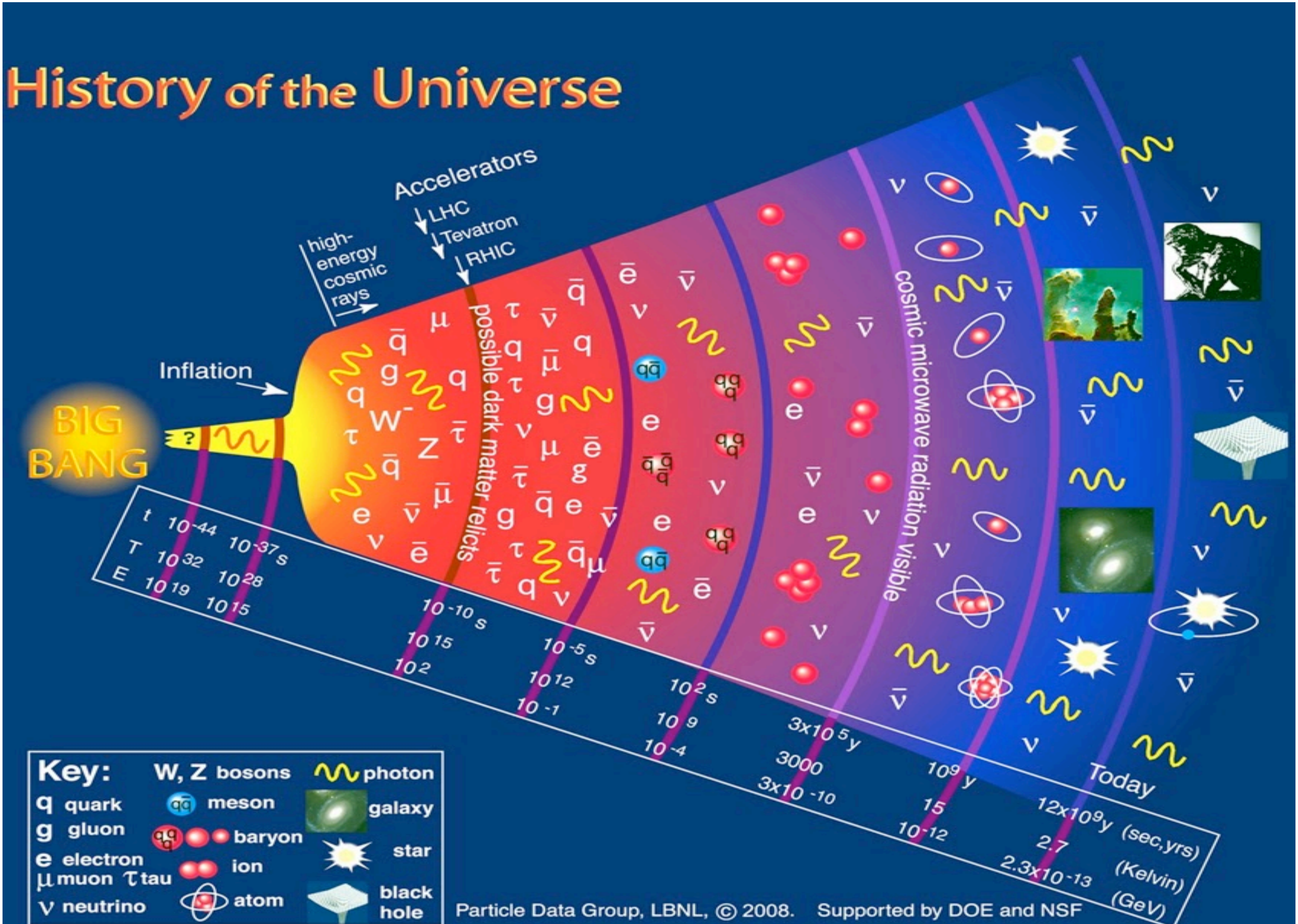
- **Why was there one extra proton for every 1.6 billion proton/anti-protons pairs that annihilated?**

- This is what we call the matter/anti-matter asymmetry problem
- This is one of the leading questions in particles physics
  - help us understand the history of the universe

- Do we understand this?
  - We have seen matter/anti-matter asymmetries in K-mesons and B-mesons (but it’s not big enough)

Where can an asymmetry come from?

- Do we understand this?
  - Maybe
  - We have seen matter/anti-matter asymmetries in K-mesons and B-mesons decays (but it's not big enough)
- So we look to what happened after the big bang


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5s
1012
10-1
102s
109
10-4
3x105y
3000
3x10-10
109y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

A Cosmic Hint

- One hint we have is that today the universe is filled by Us (matter) and neutrinos

- And neutrinos are special because….

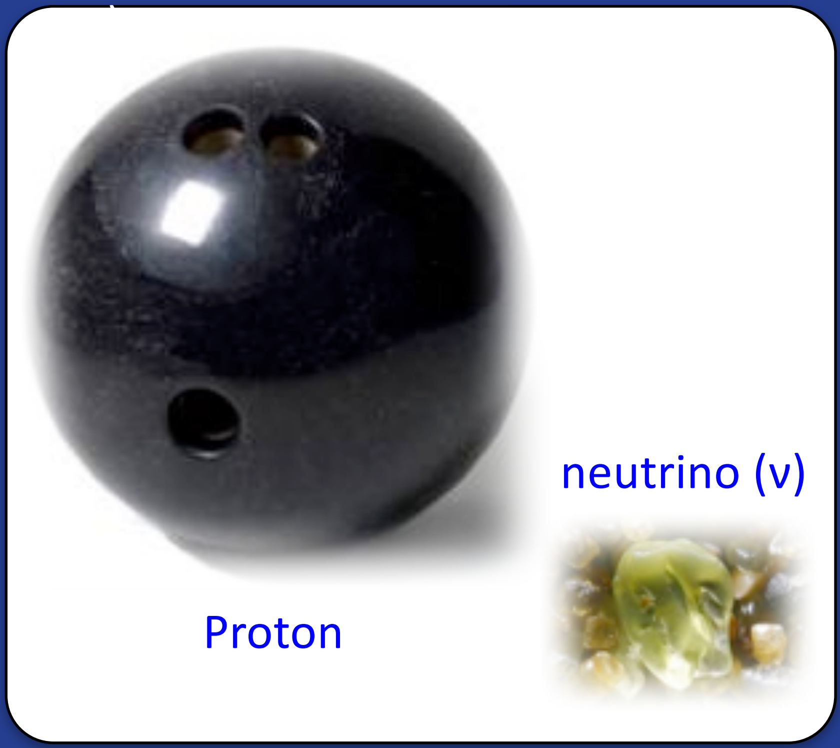
They may be their own anti particle!

- If this were the case then matter and anti-matter could "mix" through a special process involving neutrinos and leptogenisis

What is a neutrino?

- A neutrino is small
  - It’s the smallest massive particle we know of
- Its so small that we don’t even know how small it is yet
  - We only have limits on how small it must be

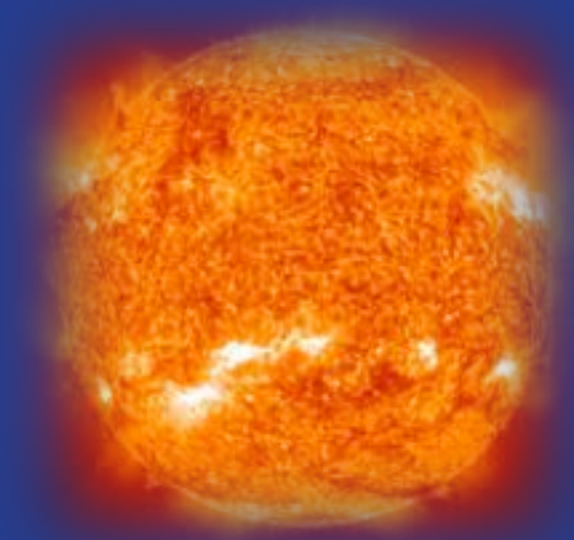
A neutrino at least 3.5 billion times smaller than a proton (<0.28



This is like comparing a bowling ball to a single grain of sand

What is a neutrino?

- They are EVERY where!
- They are the most prevalent massive particle in the universe



ν_e

$\bar{\nu}_e$ ν_e ν_e ν_e

$\bar{\nu}_e$ ν_e ν_e

$\bar{\nu}_e$ ν_e

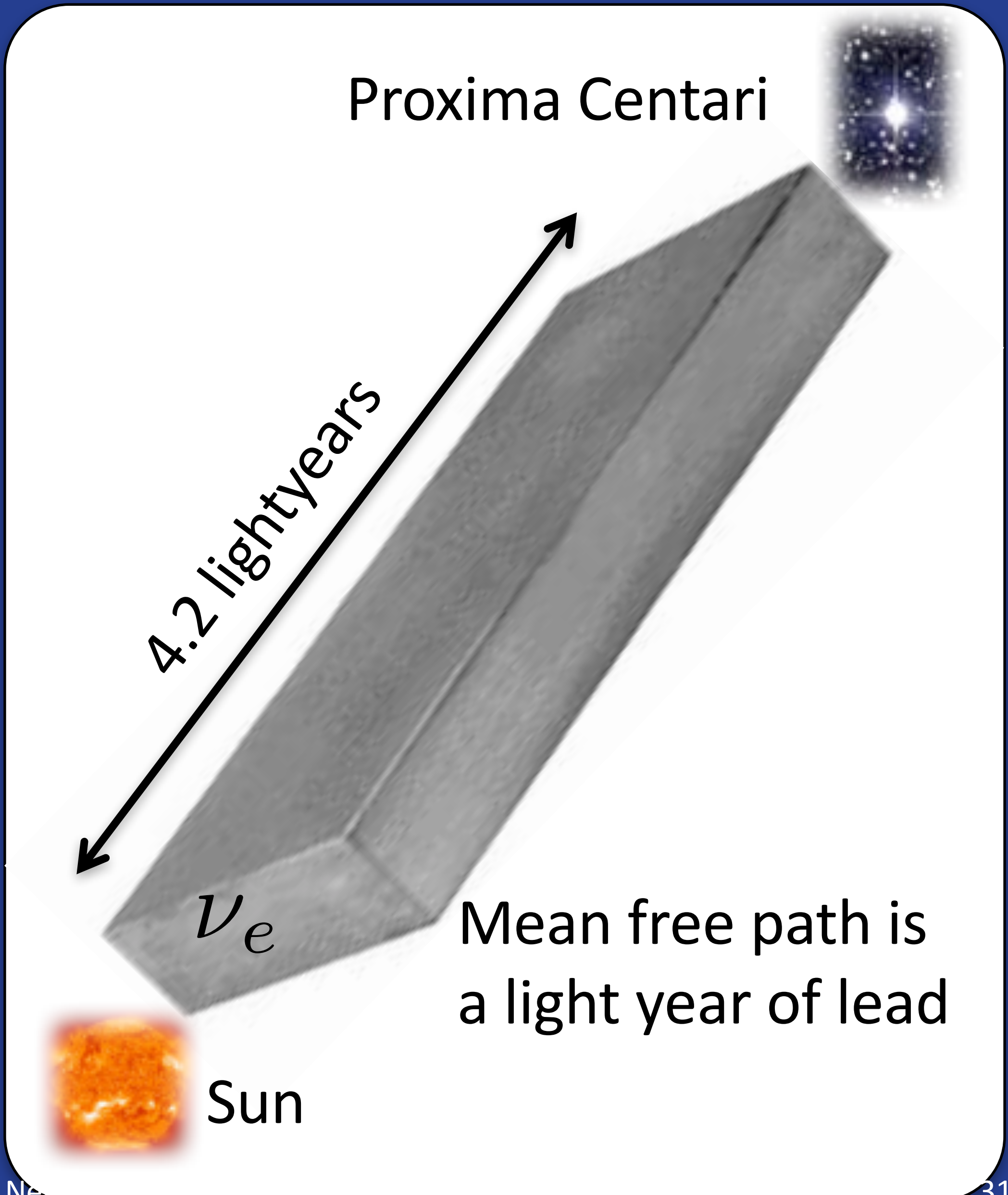
$\bar{\nu}_e$ ν_e $\bar{\nu}_e$

ν_e $\bar{\nu}_e$

- 100 billion ν's pass through your tumbnail each second

What is a neutrino?

- They interacts VERY weakly with other matter
- This means you can send them great distances with out them interact
- For example:
  - Through space
  - Through the earth
  - Through stars!



The NOνA Experiment

- (In a nutshell)

Using a gigantic detector to figure out the neutrino mass ordering

this

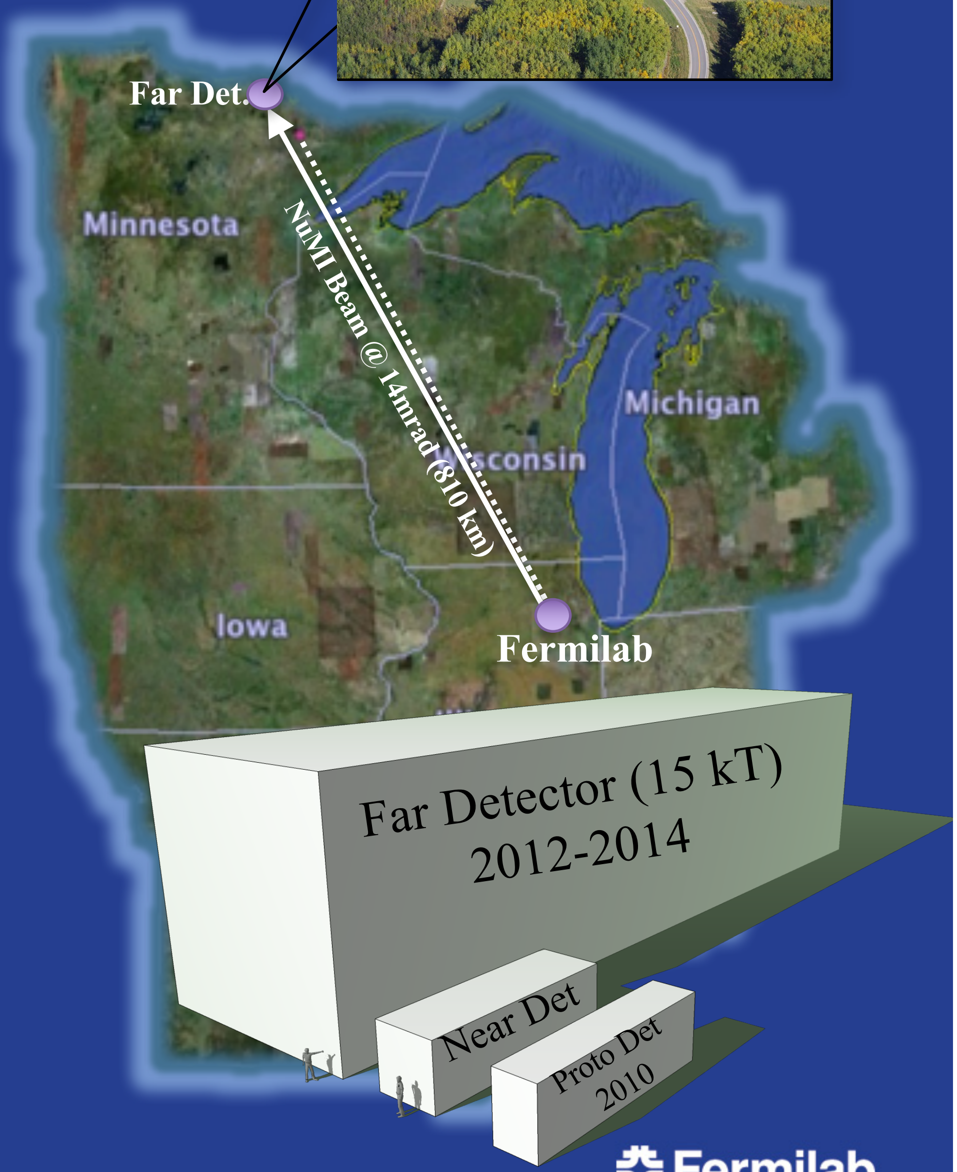
or this

Neutrino 2014, Boston MA

The NOvA Experiment

- NOvA is an experiment to investigate the properties of neutrinos and determine if neutrinos are responsible for the matter/anti-matter asymmetry of the universe.

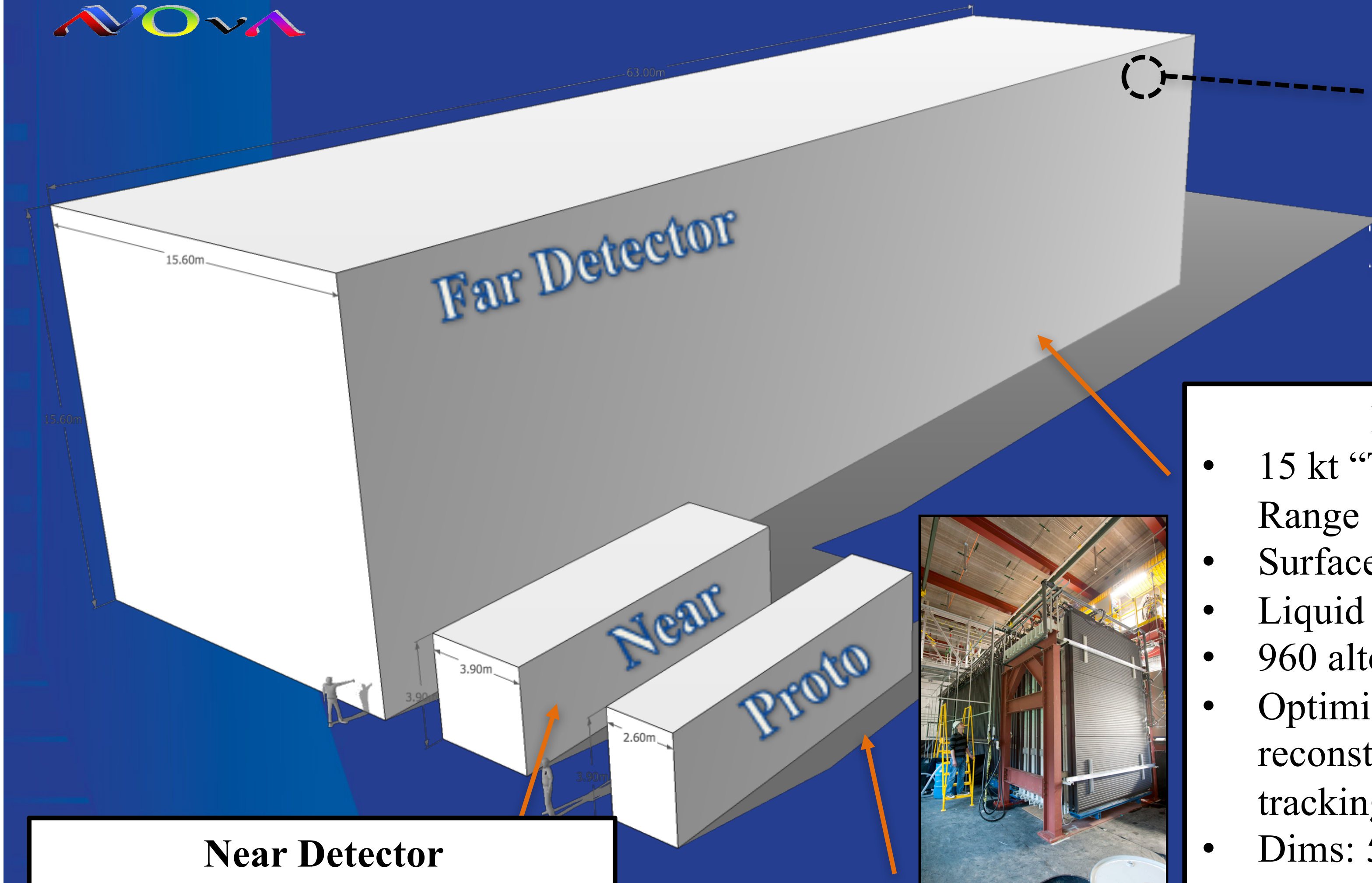
- It includes:
  - Doubling the power of the Fermilab beam to make the world's most intense neutrino beam
  - Building a 30 million lb totally active *surface* detector to detect the beam
  - Shooting both ν and anti-ν beam through the earth



The NOvA Collaboration

International Collaboration of:
Over 204 Scientists, Students and Engineers from 38 institutions and 7 countries

NOvA Detectors



Far Detector

- 15 kt "Totally Active", Low Z, Range Stack/Calorimeter
- Surface Detector
- Liquid Scintillator filled PVC
- 960 alternating X-Y planes
- Optimized for EM shower reconstruction & muon tracking, $X_0 \approx 40$cm, $R_m \approx 11$cm
- Dims: 53x53x180 ft
- "Largest Plastic Structure built by man"
- Began construction May 2012
- First operation est. Sep. 2012 (cosmics)

Near Detector

Identical to far detector
1:4 scale size
Underground Detector
Optimized for NuMI cavern rates
-- 4x sampling rate electronics

Near Det. Protype

In operation 2010-Present on surface at FNAL in NuMI and Booster beam line

BIG Detectors

Airbus A380-800

- Similar size to NOνA
- Only 560 tons
- Not totally active
- Unable to measure θ_{13}
- Can not resolve θ_{23} ambiguity
- Optimized for fuel economy and passenger capacity
- Capacity: 853 passengers
- Cost: $389M/ea
- "Largest commercial aircraft built by man"
- Construction start 2004
- First operation Oct. 2007 (Singapore Airlines)

Near Detector

Identical to far detector
1:4 scale size
Underground Detector
Optimized for NuMI cavern rates
-- 4x sampling rate electronics

Near Det. Protype

In operation 2010-Present on surface at FNAL in NuMI and Booster beam line

NOvA Measurements

- NOvA measures four distinct transitions over an 810 km baseline at a central energy of 2GeV:

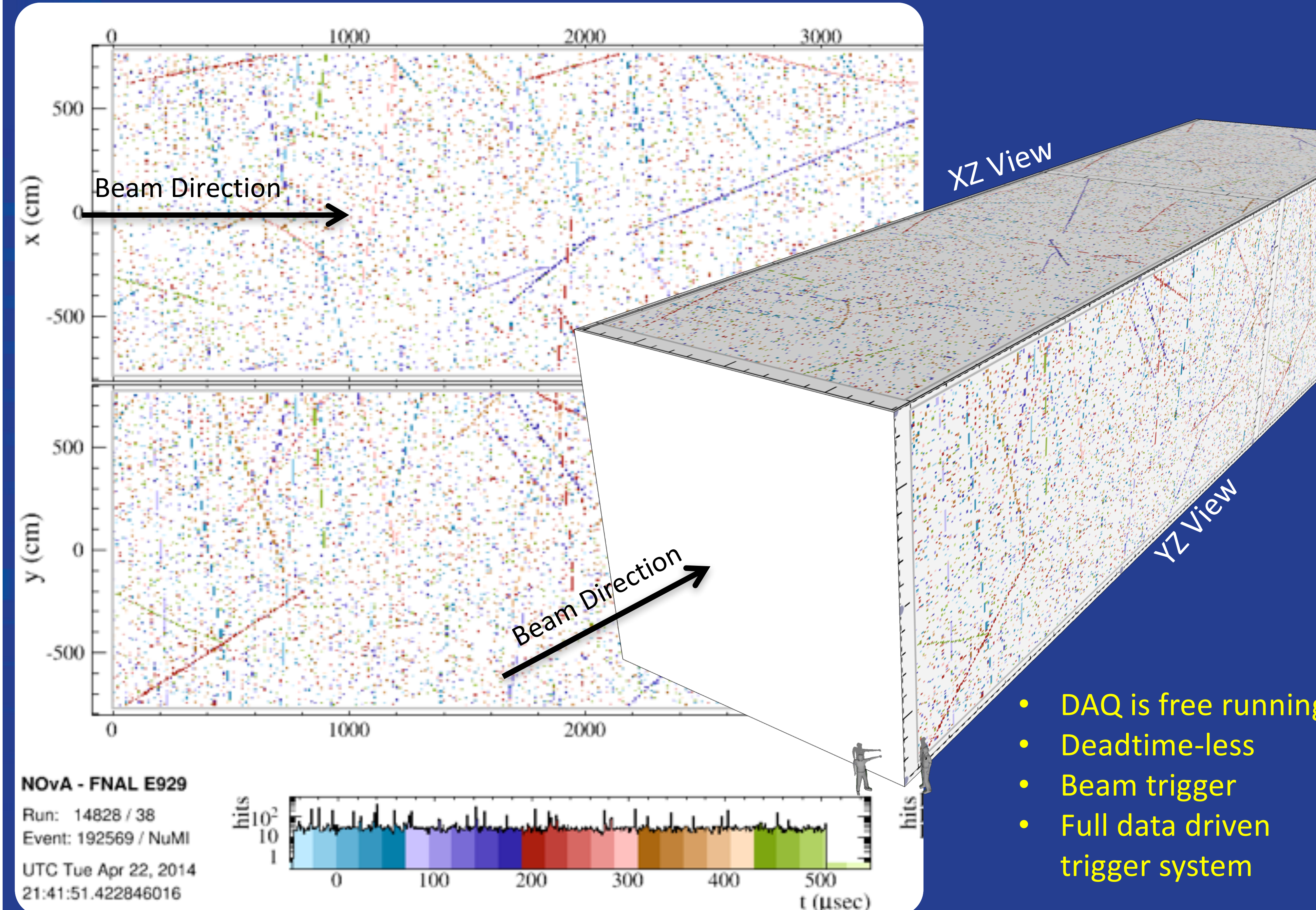
$P(\nu_\mu \rightarrow \nu_e)$ & $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
appearance

$P(\nu_\mu \rightarrow \nu_\mu)$ & $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
disappearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1^2)}$$
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$
$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

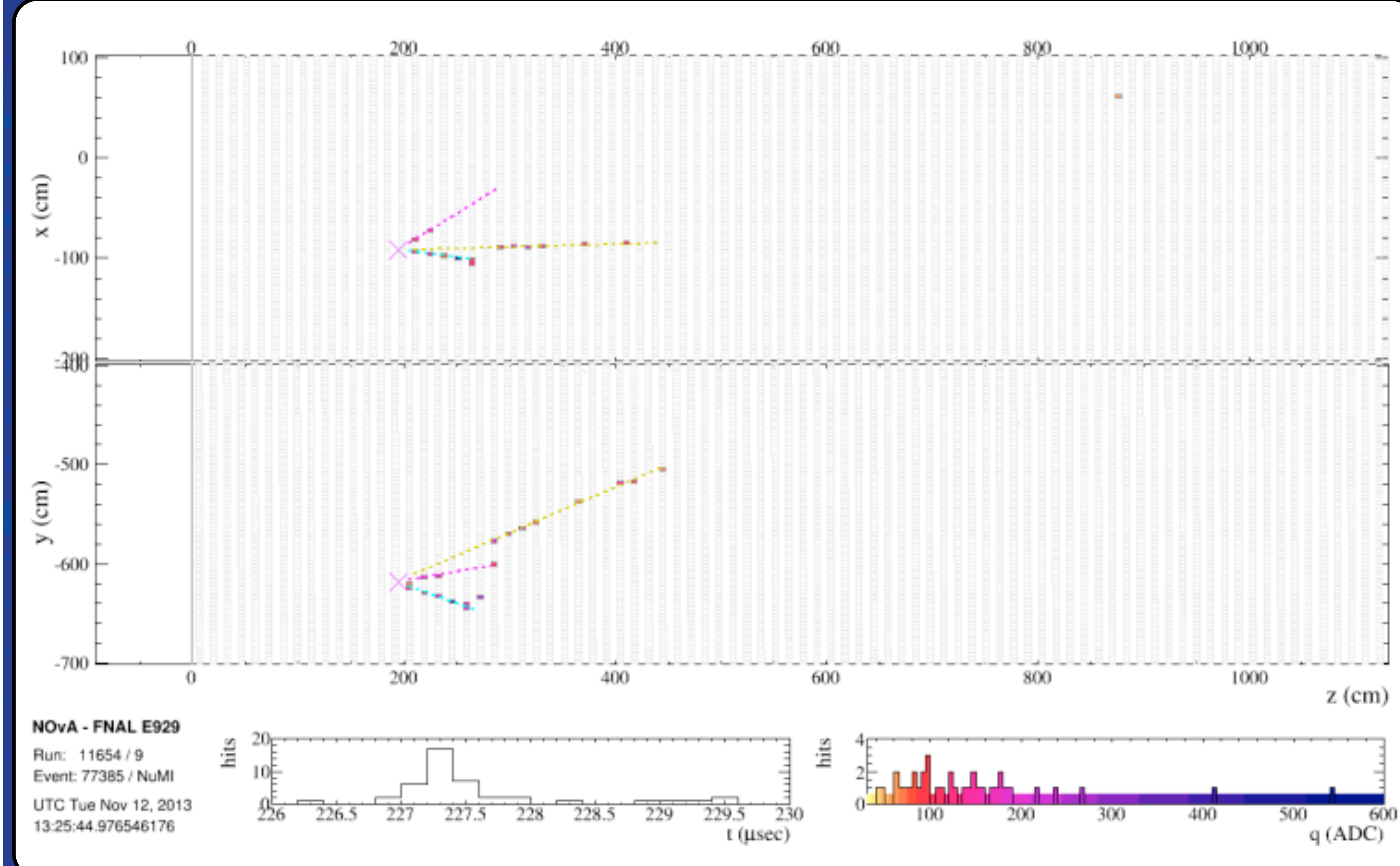
$$\text{Where:} \quad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \quad \Delta = \Delta m^2_{31} \frac{L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- The transition probability is dependent on θ_{13},θ_{23},δ_{CP} and Δm_{31}
- The reactor measurements do not have the these dependencies

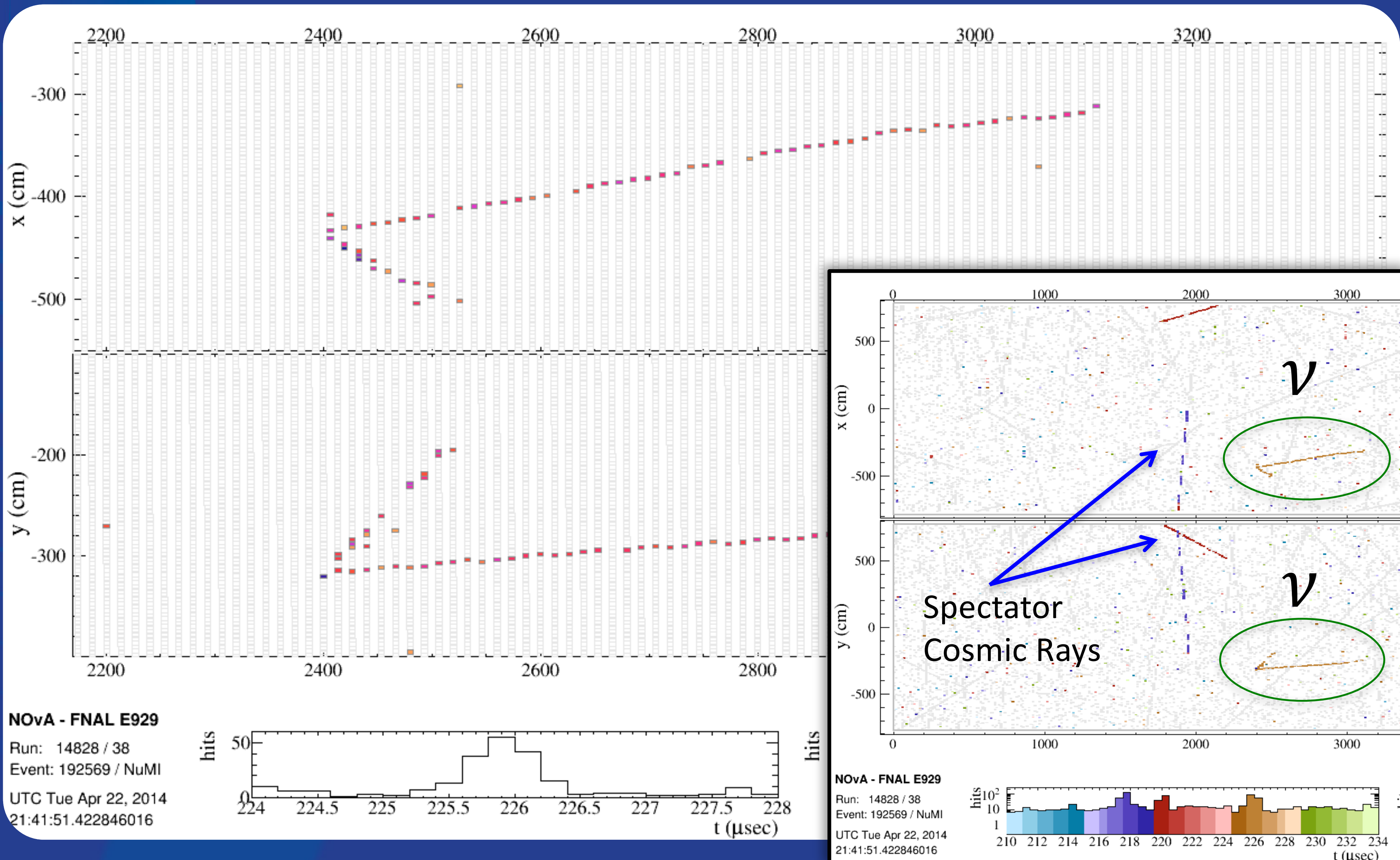


- DAQ is free running
- Deadtime-less
- Beam trigger
- Full data driven trigger system

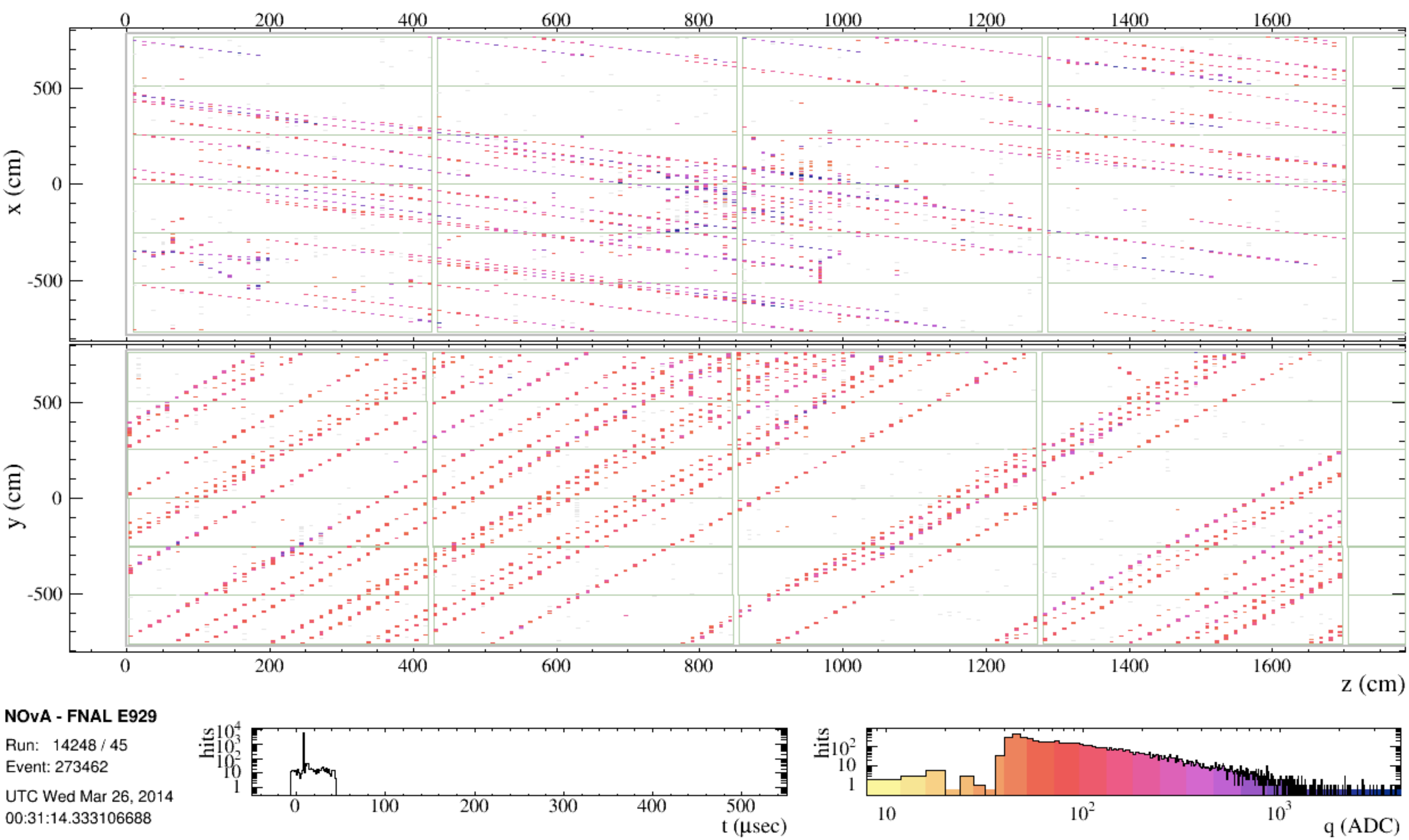
ν #1 [Nov. 12, 2013]



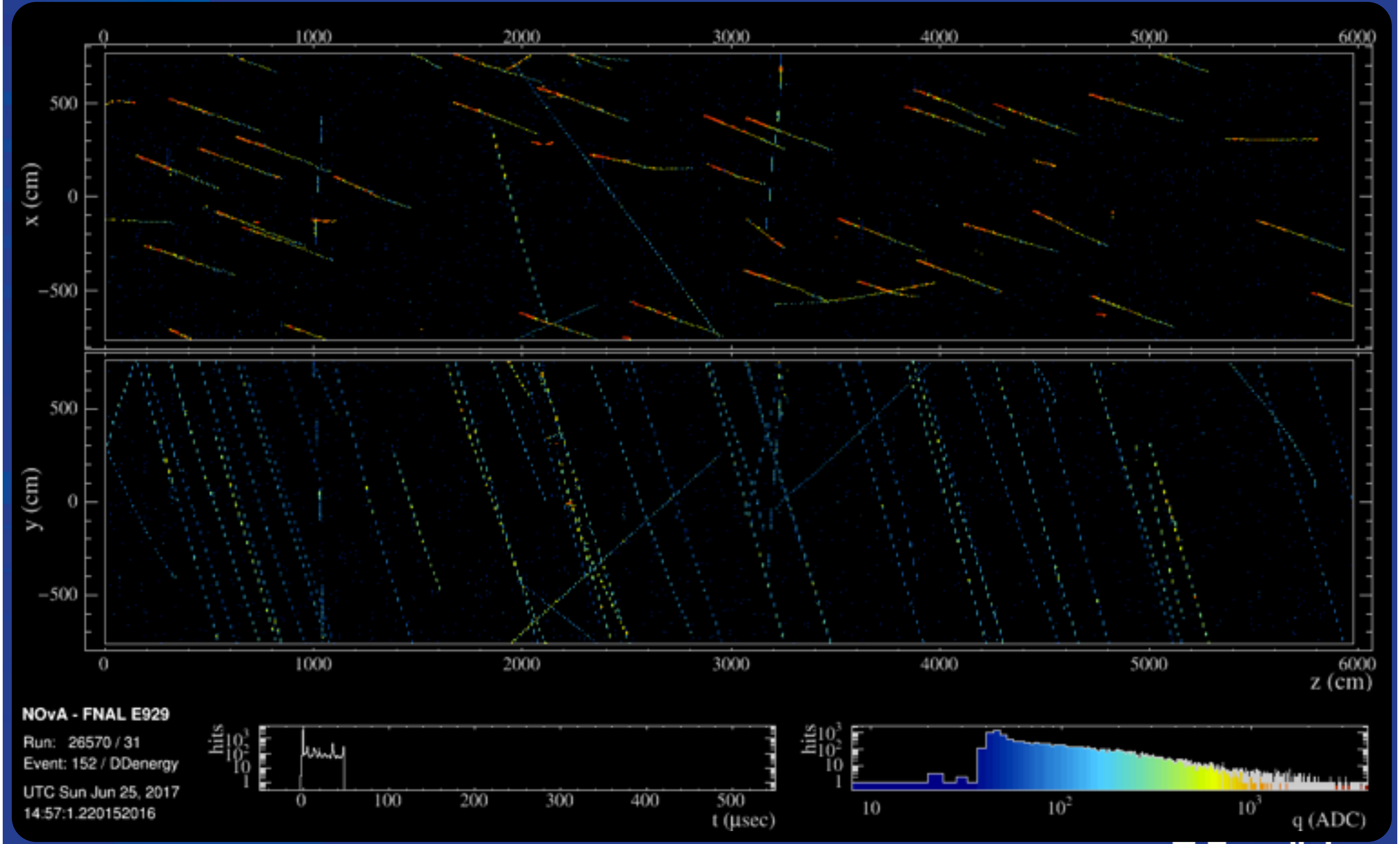
ν_μ-CC Candidate



Air Showers (triggered)

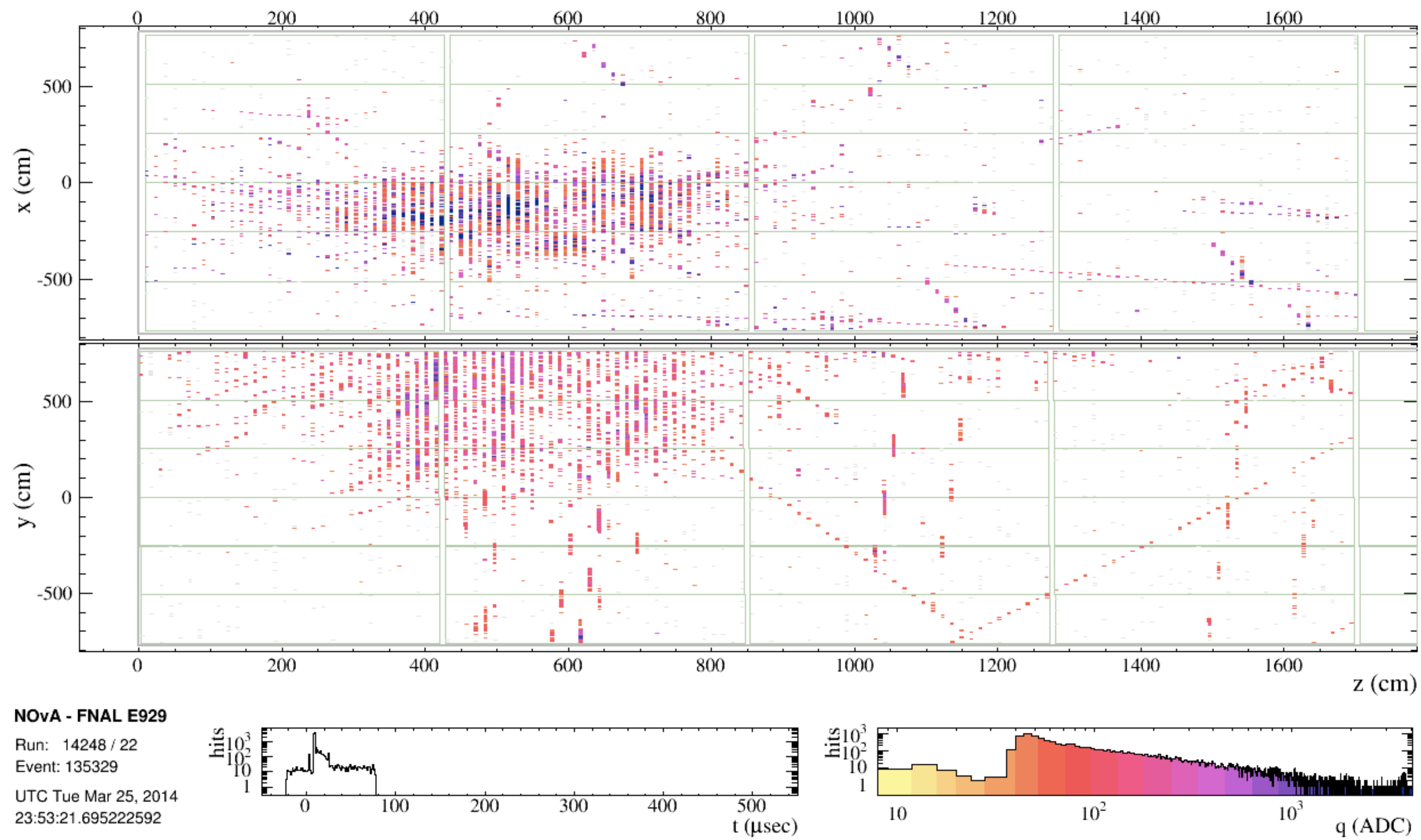


Air Showers



x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 26570 / 31
Event: 152 / DDenergy
UTC Sun Jun 25, 2017
14:57:1.220152016
hits
t (μsec)
q (ADC)

High Energy (triggered)



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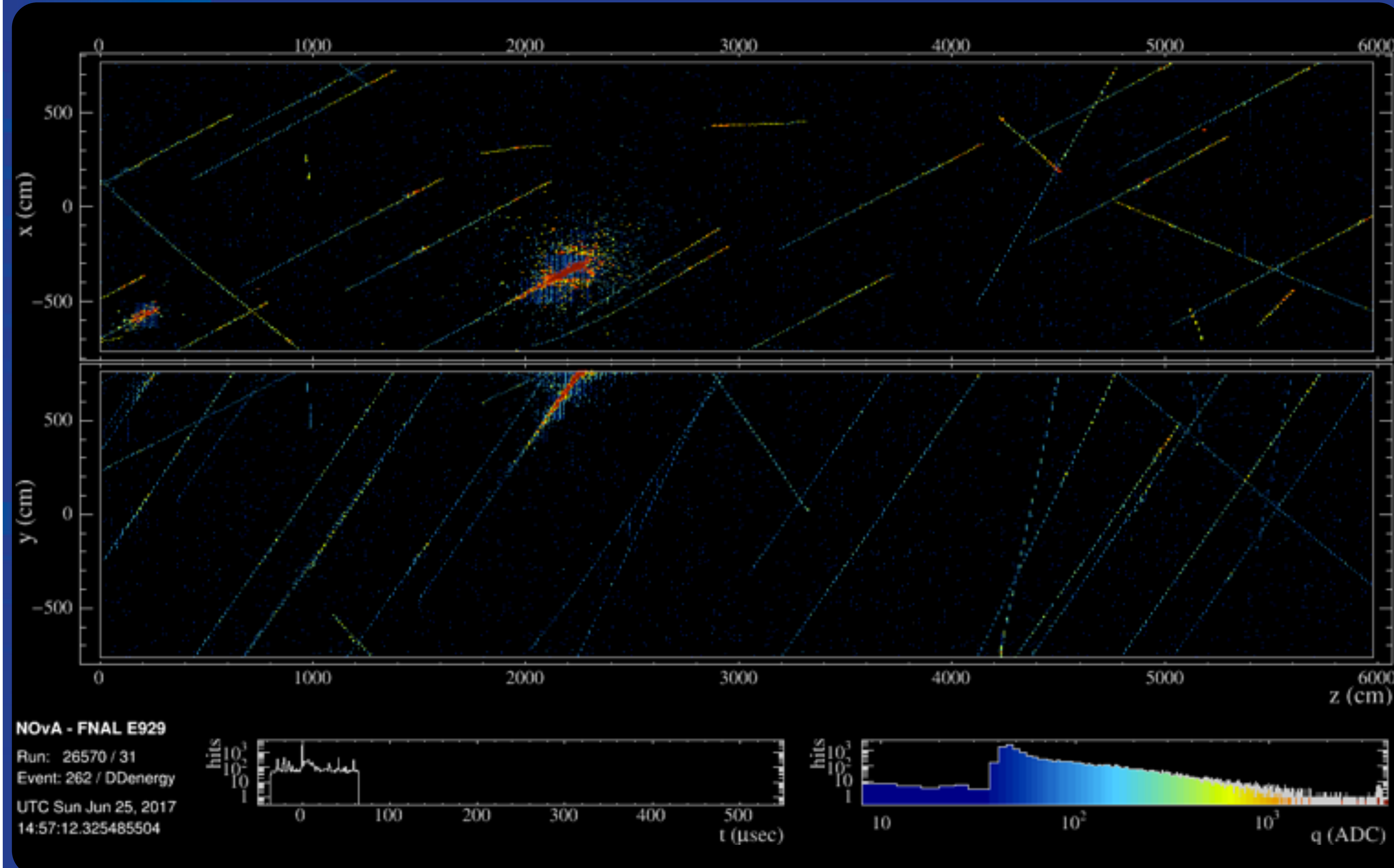
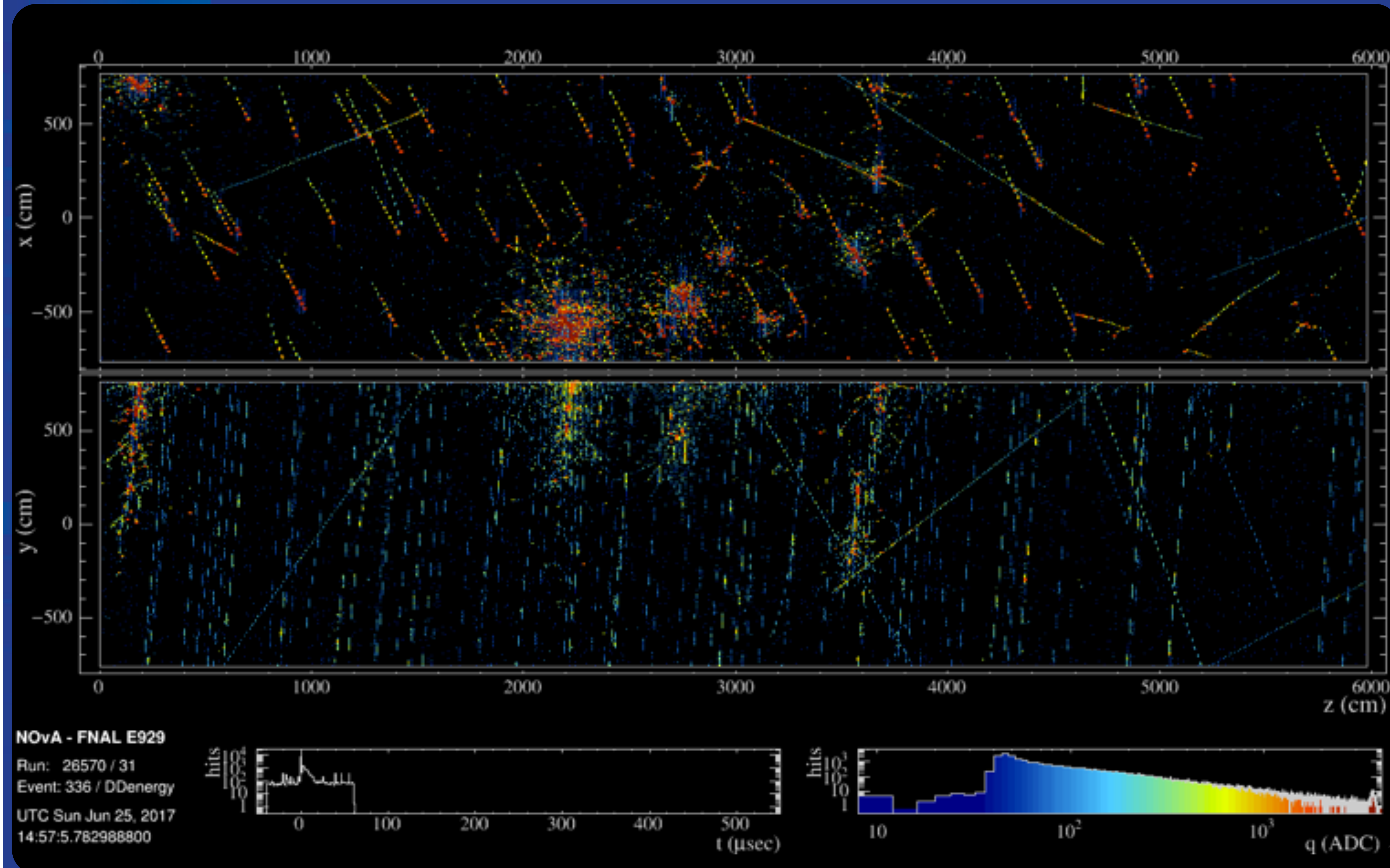


High Energy (triggered)



What will we learn?

- We get measurements about the fundamental properties of neutrinos
  - This is important because ν's are all around us
  - They shape our universe
  - We will learn about their masses

- We will also learn if ν's are the missing part of the matter/anti-matter puzzle
  - We may learn the answer to why are "we" here instead of "anti-we".

- ***Now let's go see NOνA!***