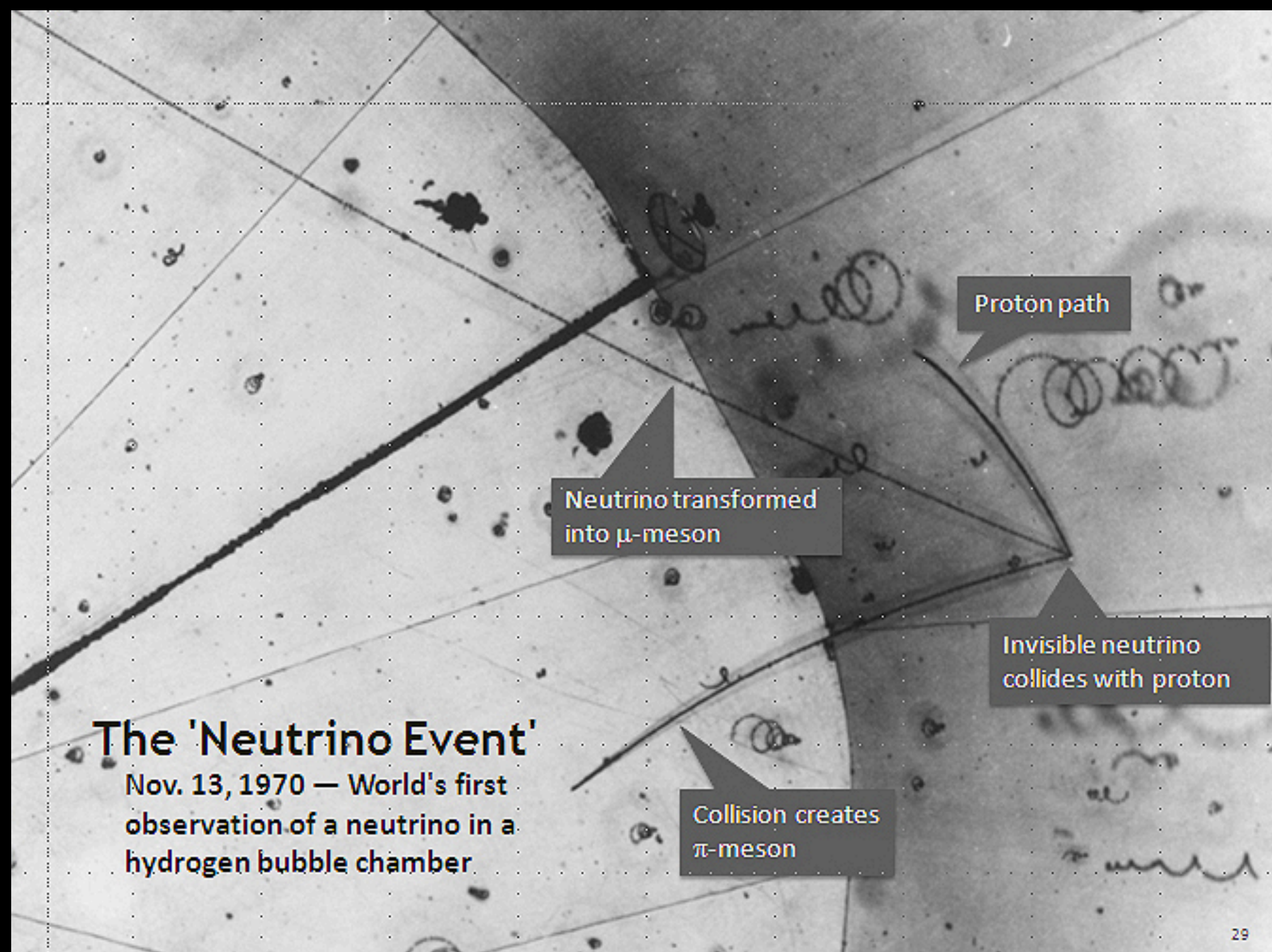
THE AMAZING NEUTRINOS



European Research Council
Established by the European Commission

University of Sussex

Bruno Zamorano
Brighton - 26 June 2017

NOνA

About myself

- Studied Physics and got a PhD on Astroparticle Physics at the University of Granada (Spain) in 2014, working on ultra-high-energy cosmic rays
- Joined the University of Sussex group of Experimental Particle Physics the same year to work on neutrino oscillations

@Bruno_Zamorano

About being a particle physicist

- Being a particle physicist is cool! You meet people from all over the world, travel, learn and work on interesting projects
- Lots of transferable (and employable!) skills

Some skills you develop

Data analysis (statistics)

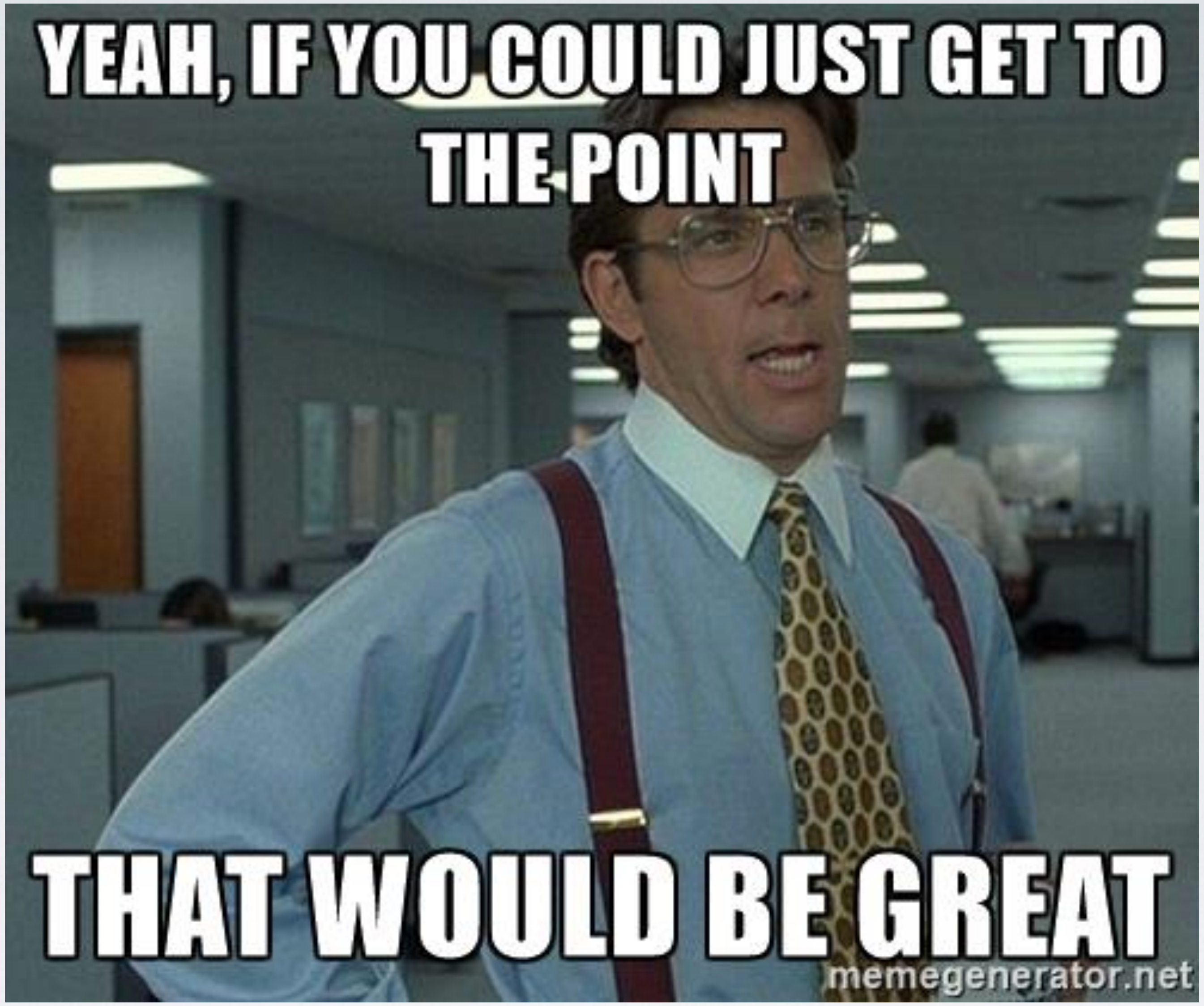
Software development

Communication skills

Collaboration and leadership

. . .

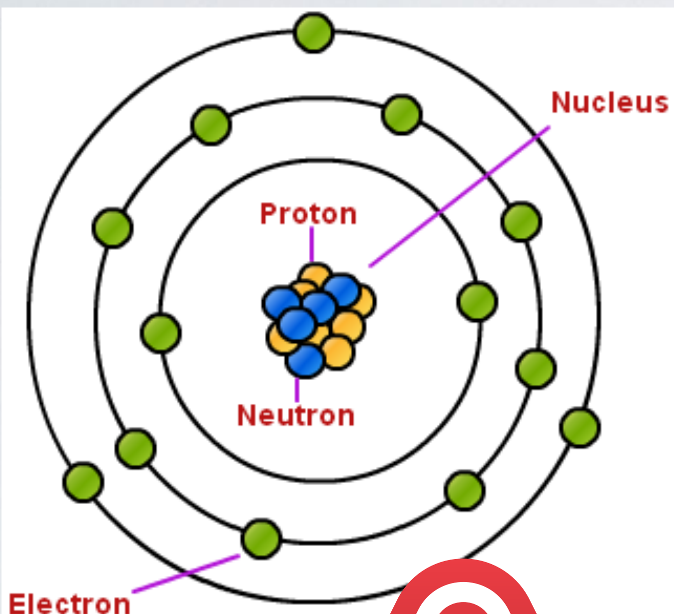
@Bruno_Zamorano



Now let's talk about neutrinos!

What is a neutrino??

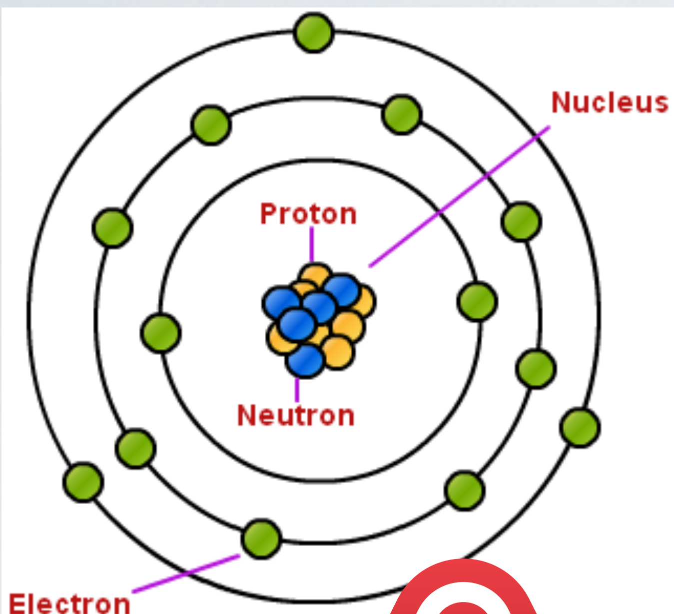
- Do you remember your neutrons, protons and electrons?

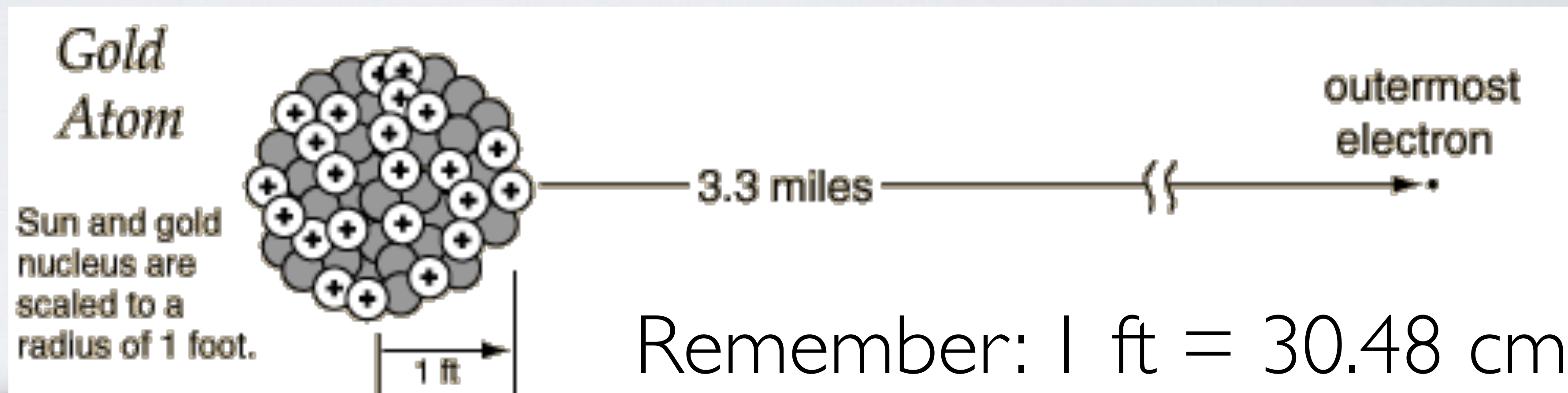


Not to scale!

What is a neutrino??

- Do you remember your neutrons, protons and electrons?





Remember: 1 ft = 30.48 cm

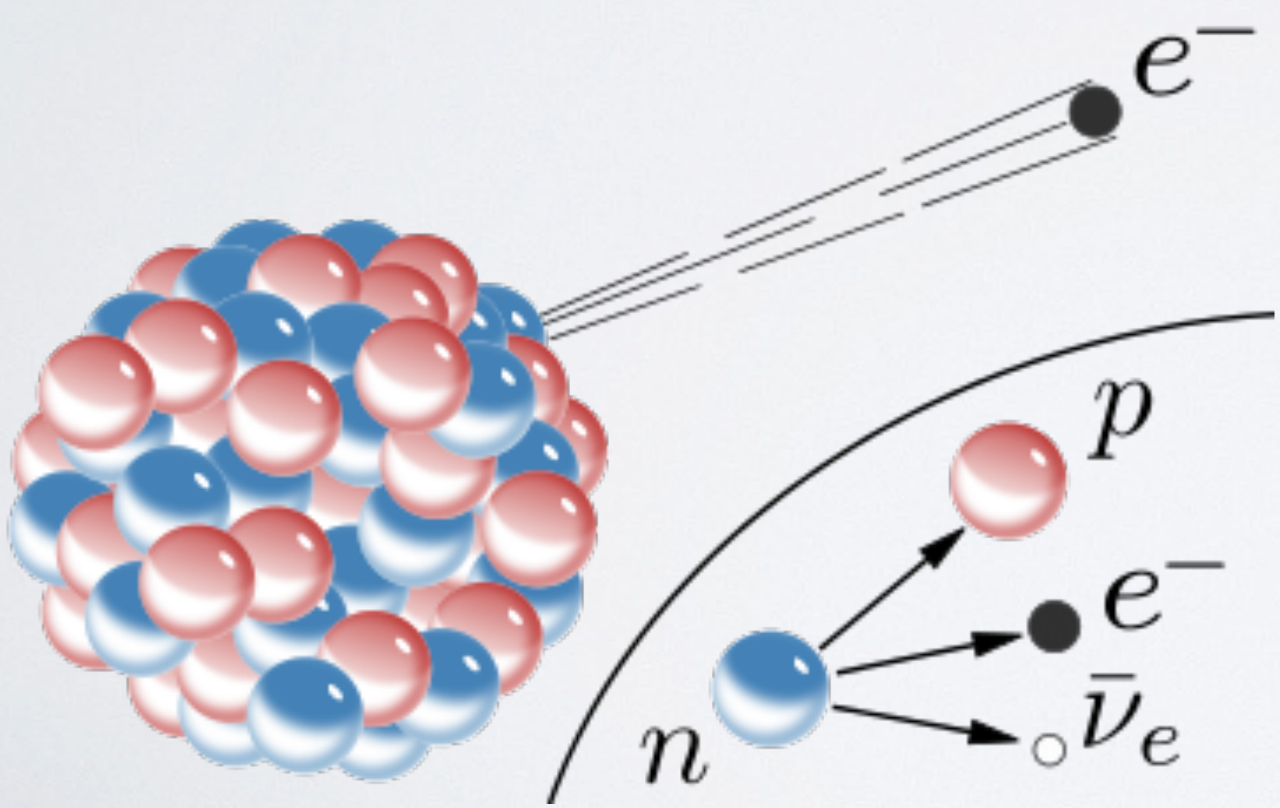
Not to scale!

- If we put one of these "super-sized" gold atoms, its outermost electron would be in Portslade

What is a neutrino??

- Do you remember your neutrons, protons and electrons?

- Well, it turns out neutrons aren't stable and they decay (~15 minutes). This is the famous beta radiation



Beta "radiation"

I know you

and you

but who are you??

What is a neutrino??

- The energy of proton + electron didn’t add up to the neutron
- Solution: conservation of energy is violated

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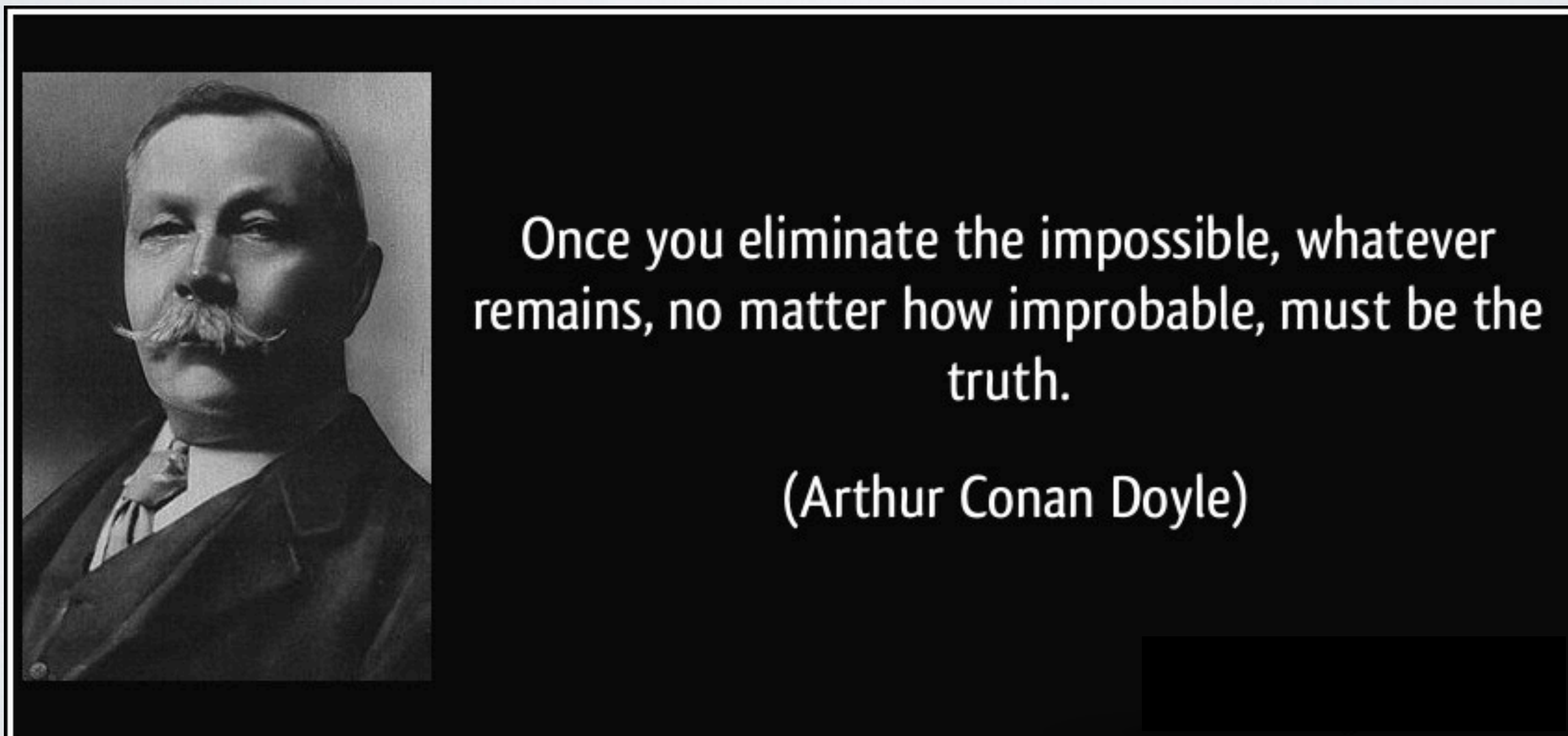
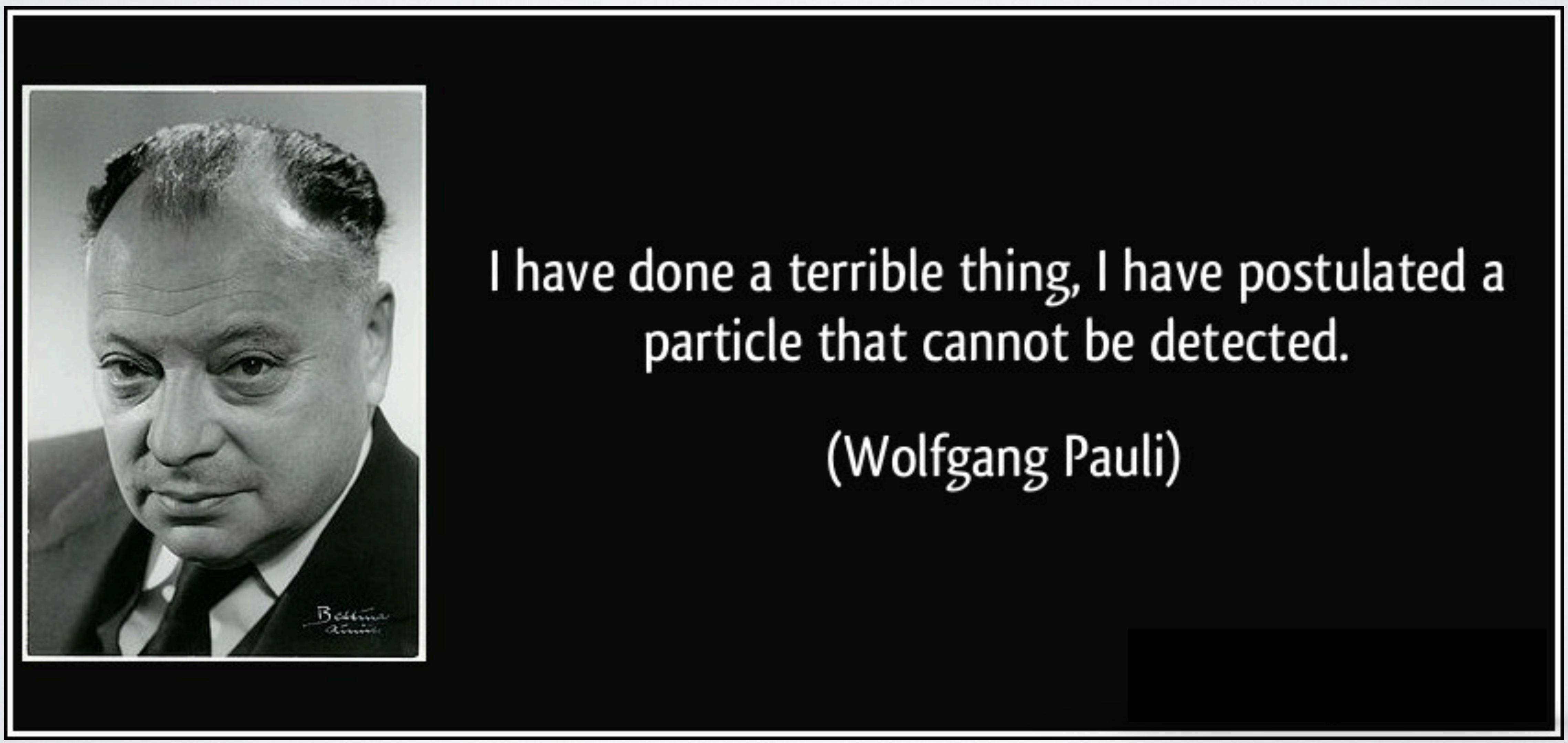


What is a neutrino??

- Alternative: imagine an "invisible" particle carrying the missing energy
- Neutrino (Italian for "small neutron")



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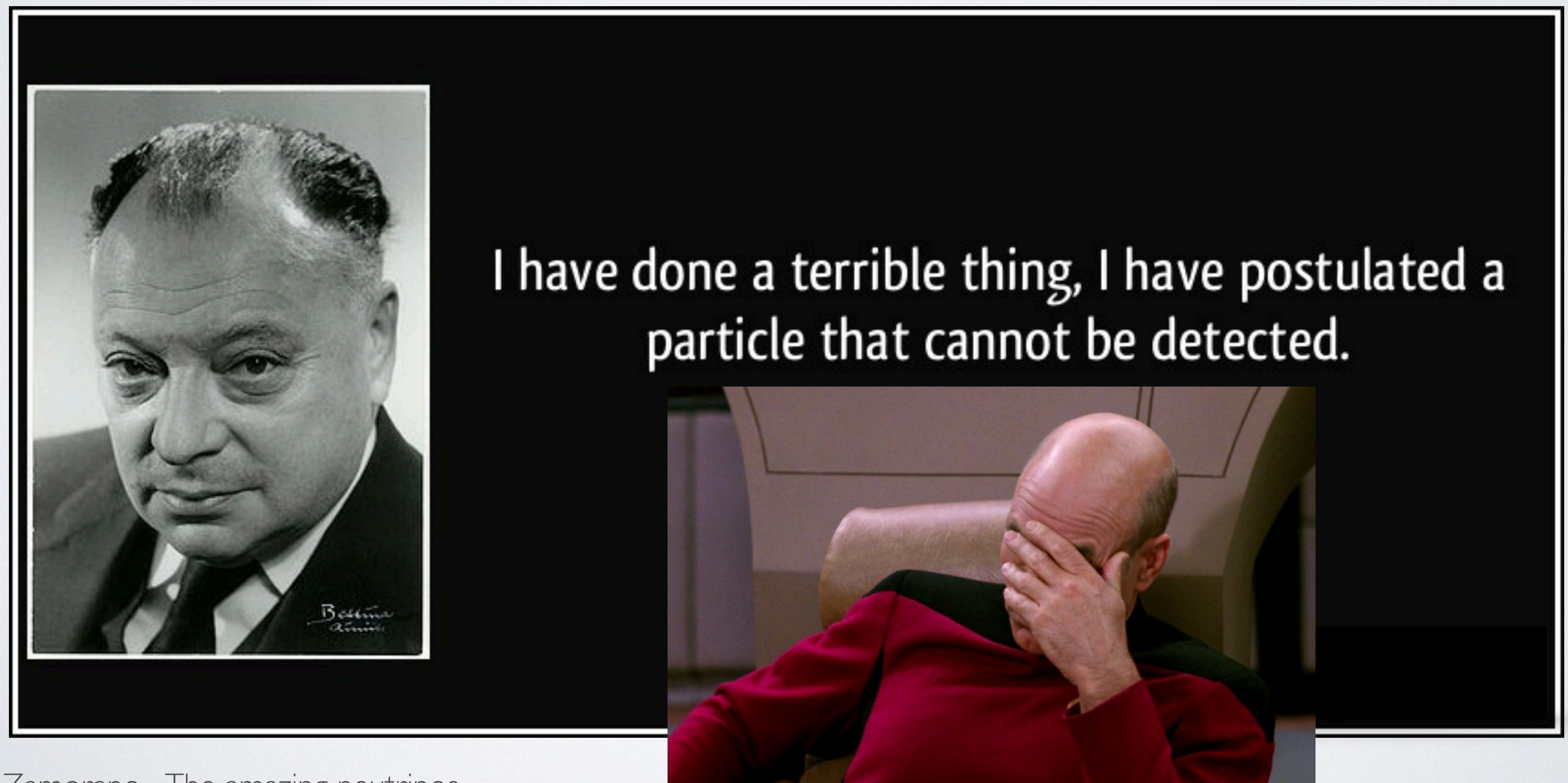
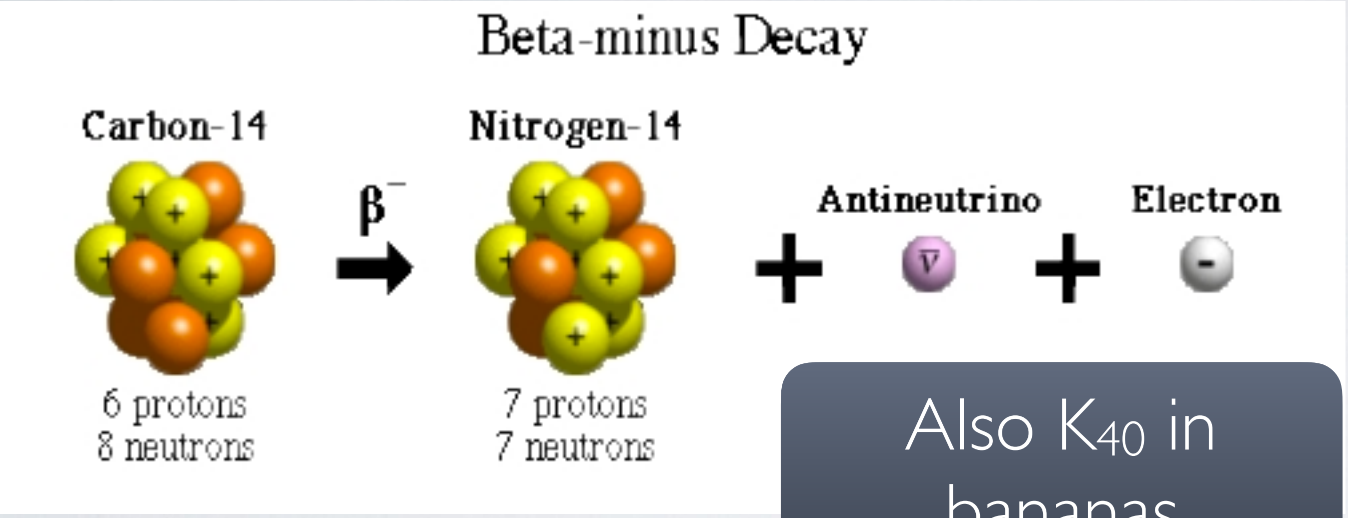
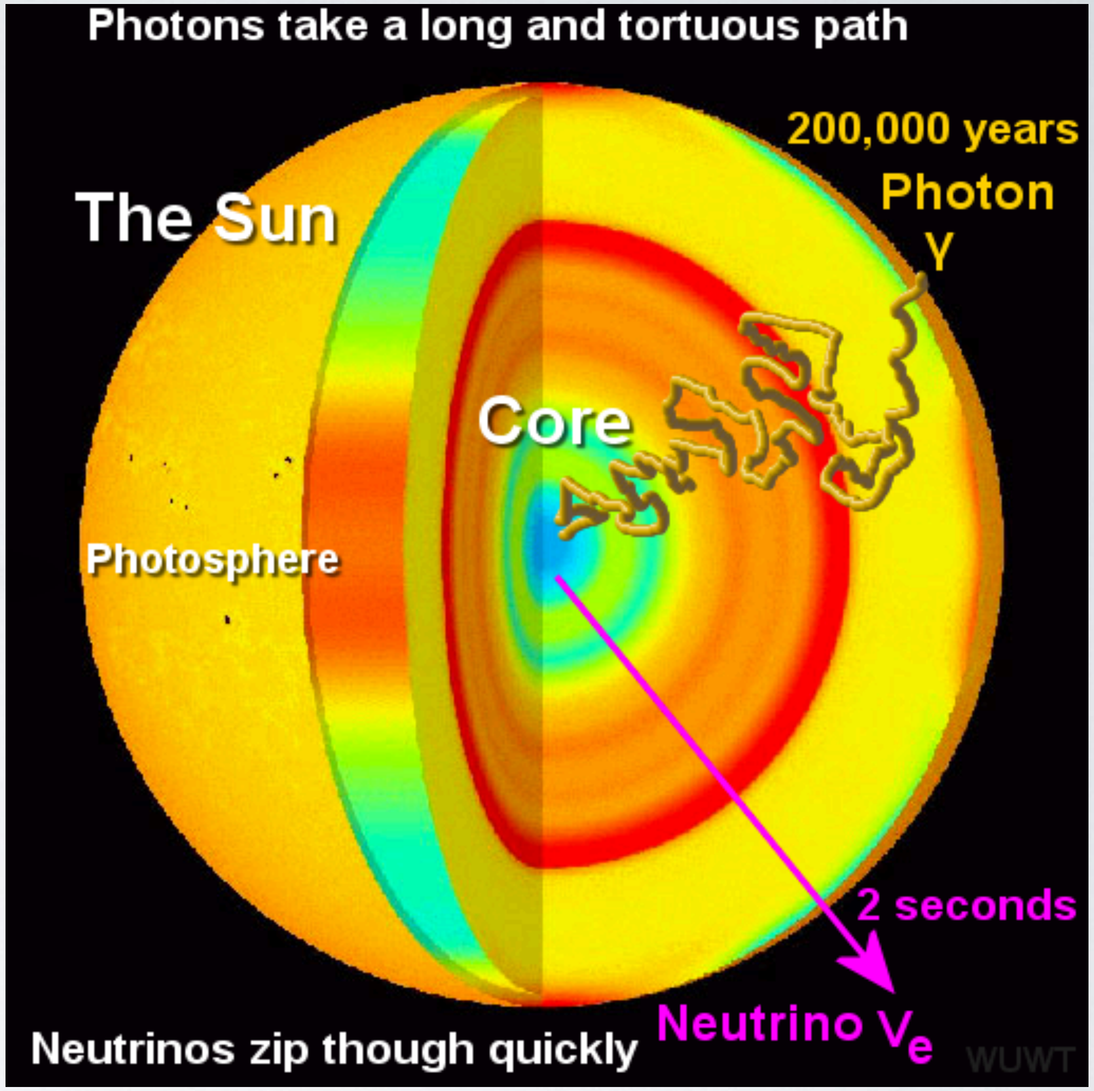


Where can you find neutrinos?



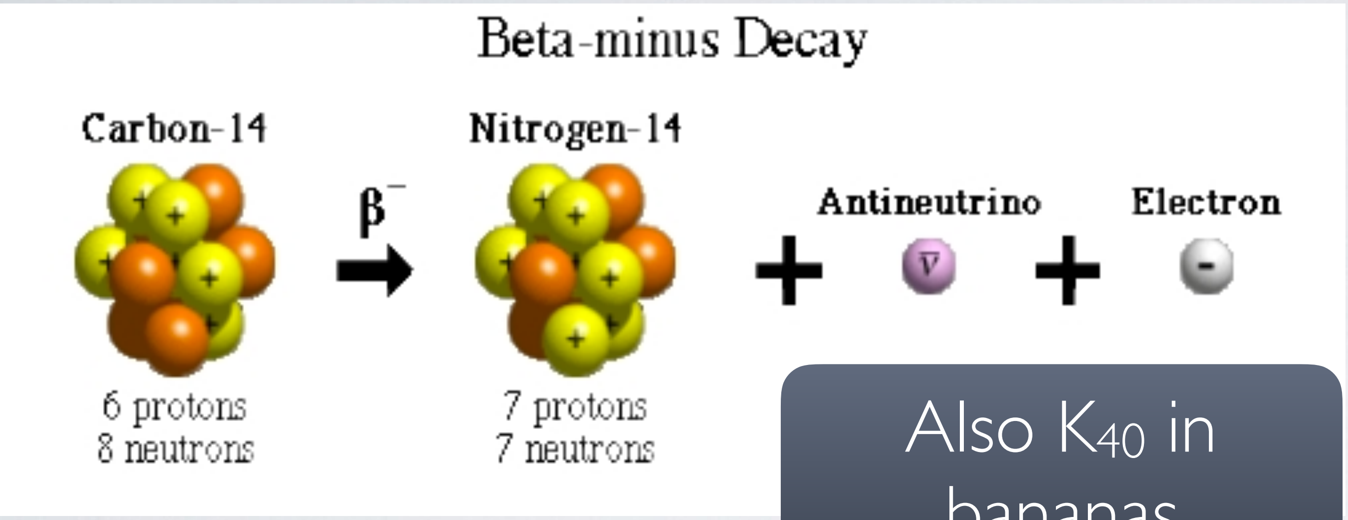
Also K_{40} in bananas

Radioactivity



Stars

Where can you find neutrinos?



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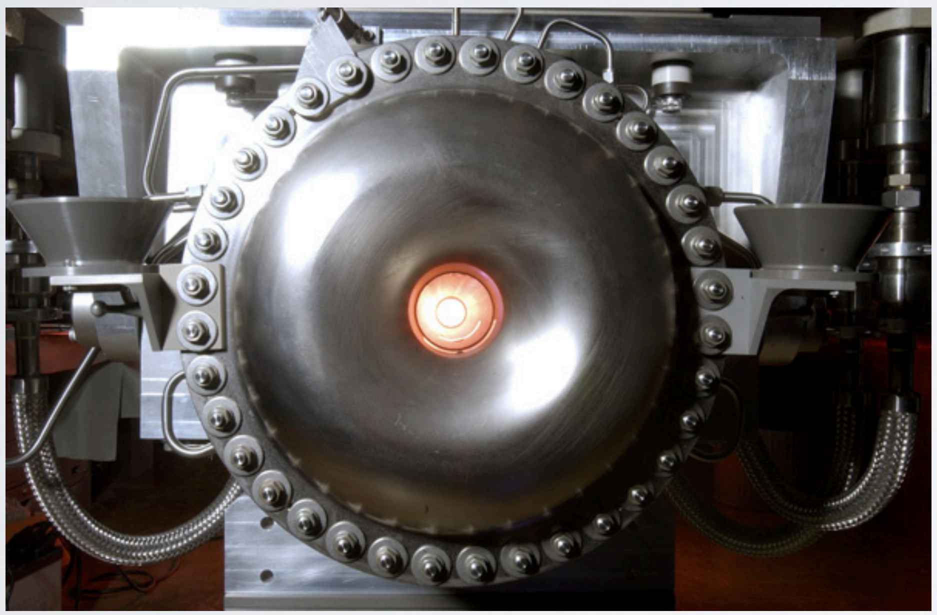
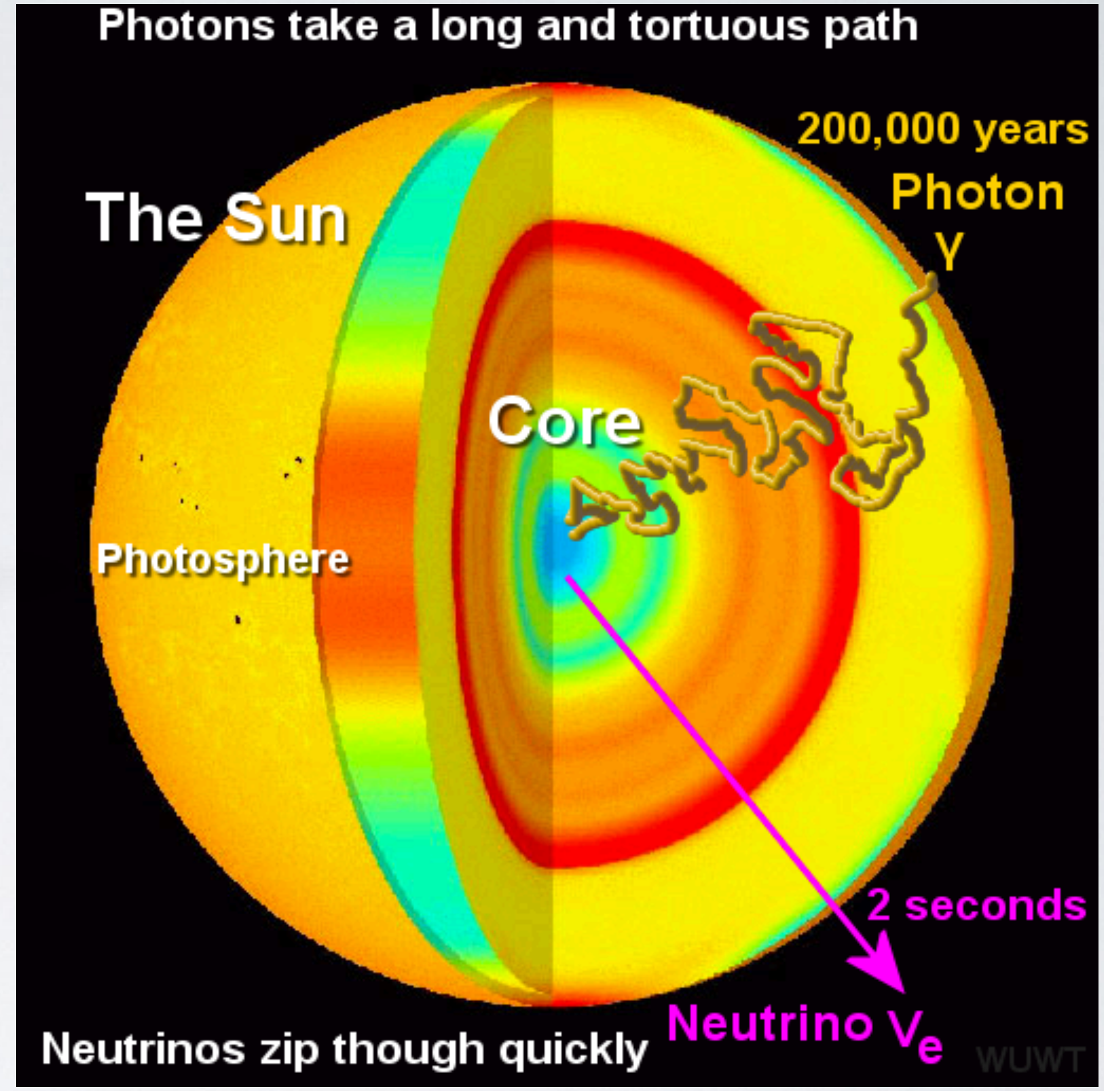


Made in colliders



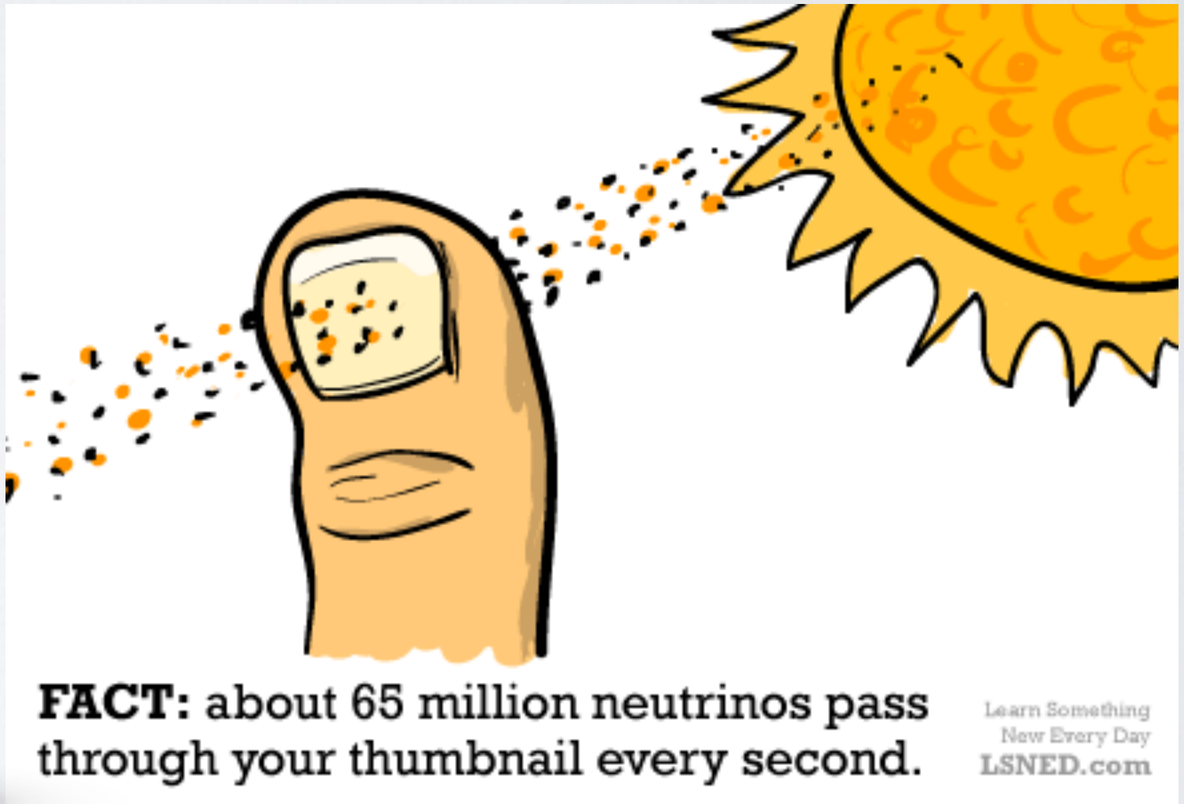
Stars

- Also: atmospheric neutrinos, cosmological neutrinos, …

In fact, neutrinos are ubiquitous!

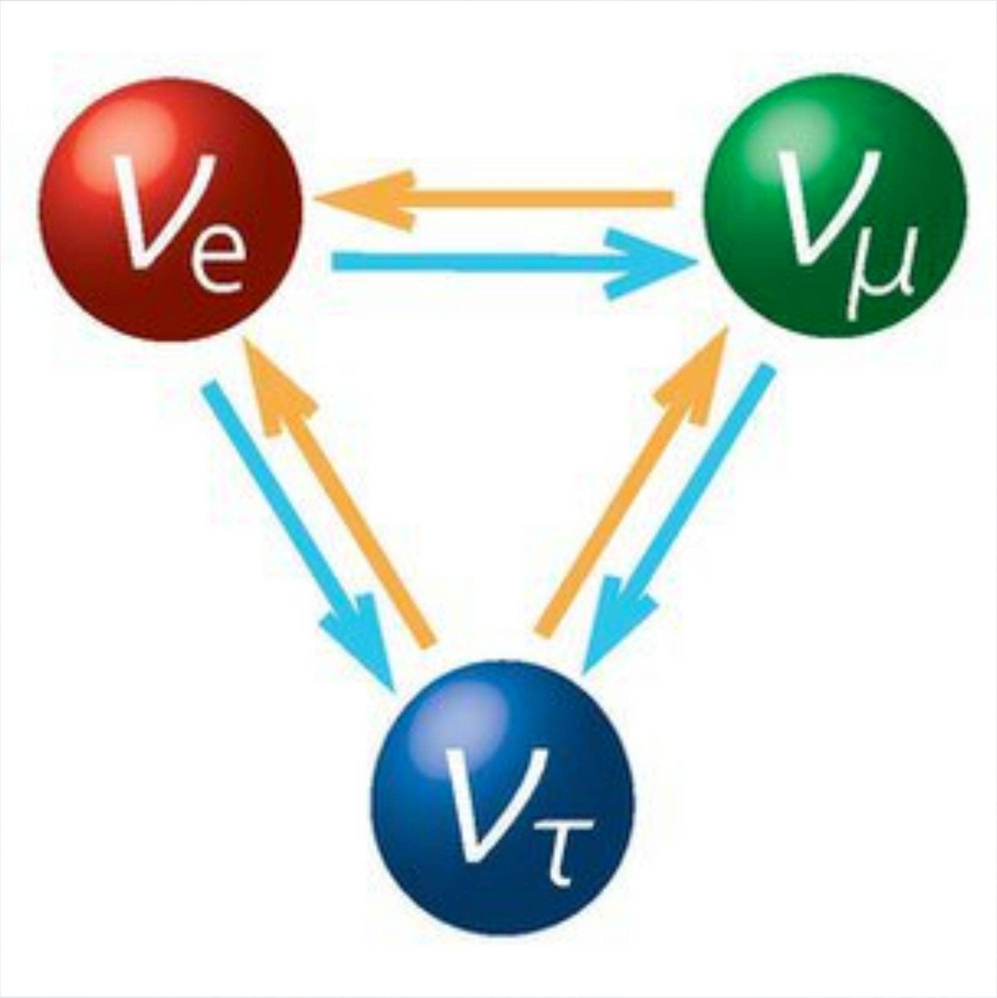
- Human body ~ 20 mg of K_{40}. Humans emit 340 M neutrinos per day!

- Yet your body will stop ~ 1 neutrino in your lifetime!



Neutrinos oscillate!

- It turns out there isn't just one "type" of neutrinos, but three. They have funny names: electron neutrino, muon neutrino and tau neutrino



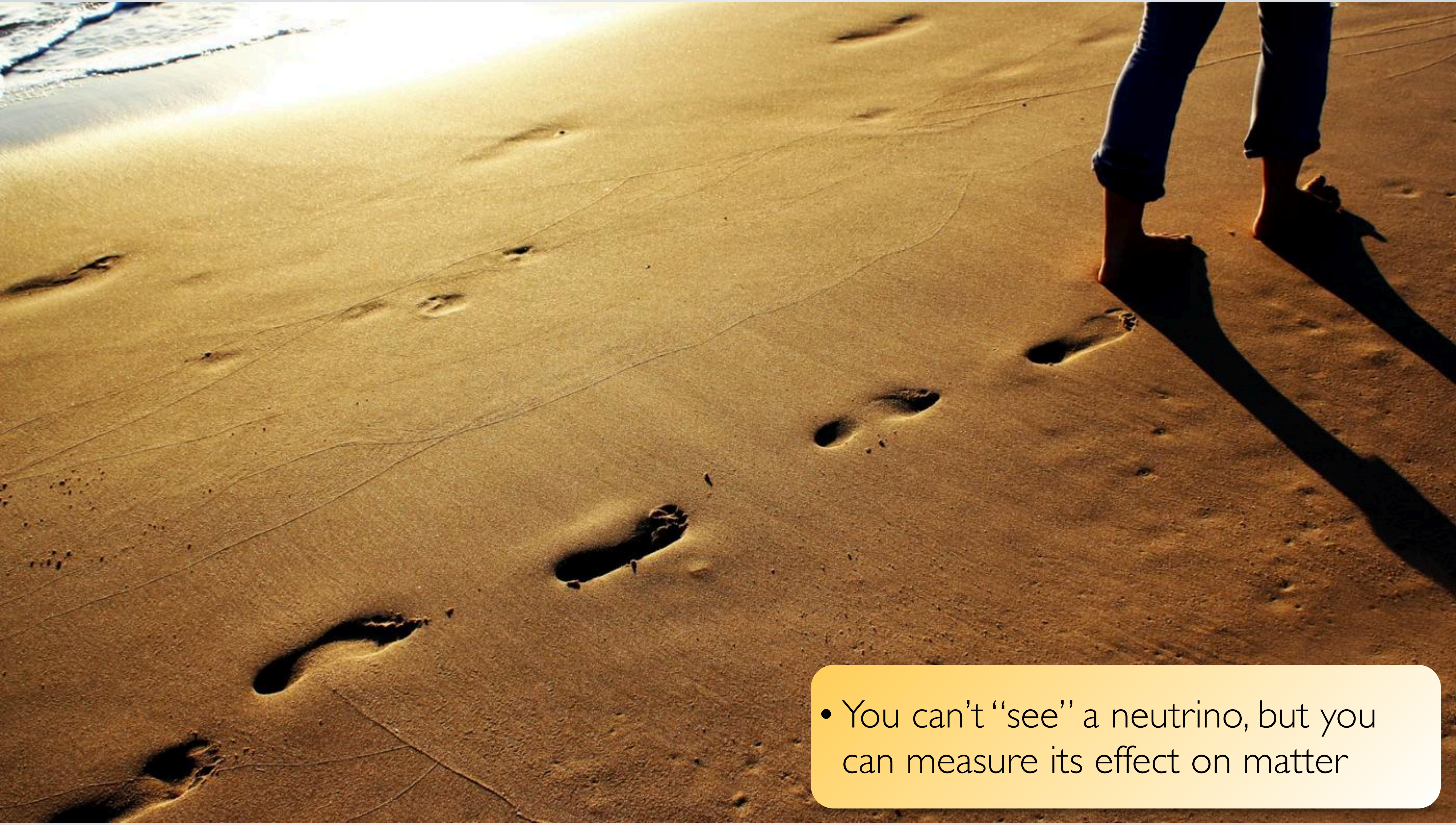
Now what should I wear tonight..?

Neutrinos oscillate!

- You always produce a given type (say muon) of neutrinos, but that changes as they travel!

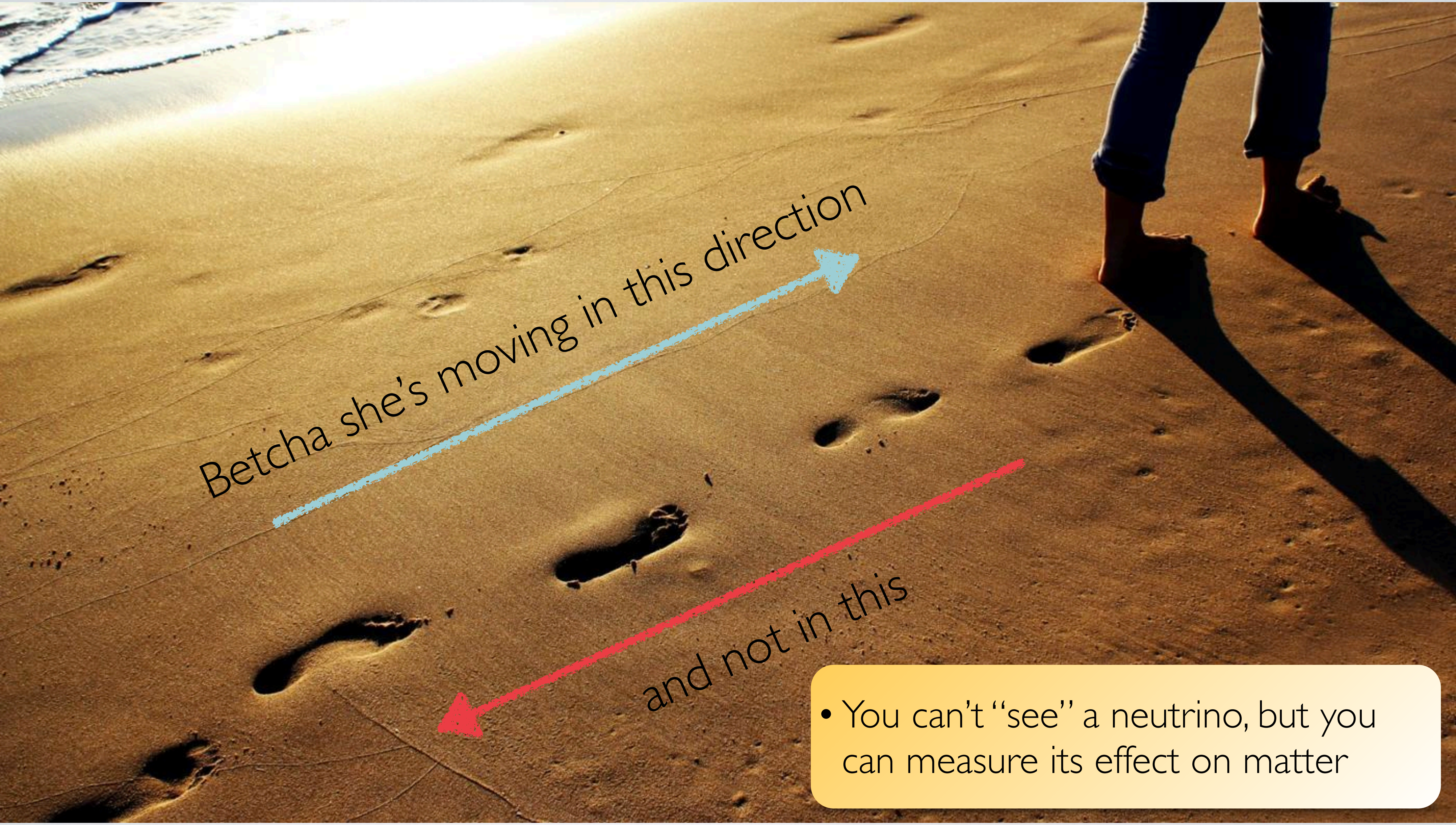
- Like a tennis ball that turned into a cricket ball after being served

So how does one detect a neutrino?



- You can't "see" a neutrino, but you can measure its effect on matter

So how does one detect a neutrino?



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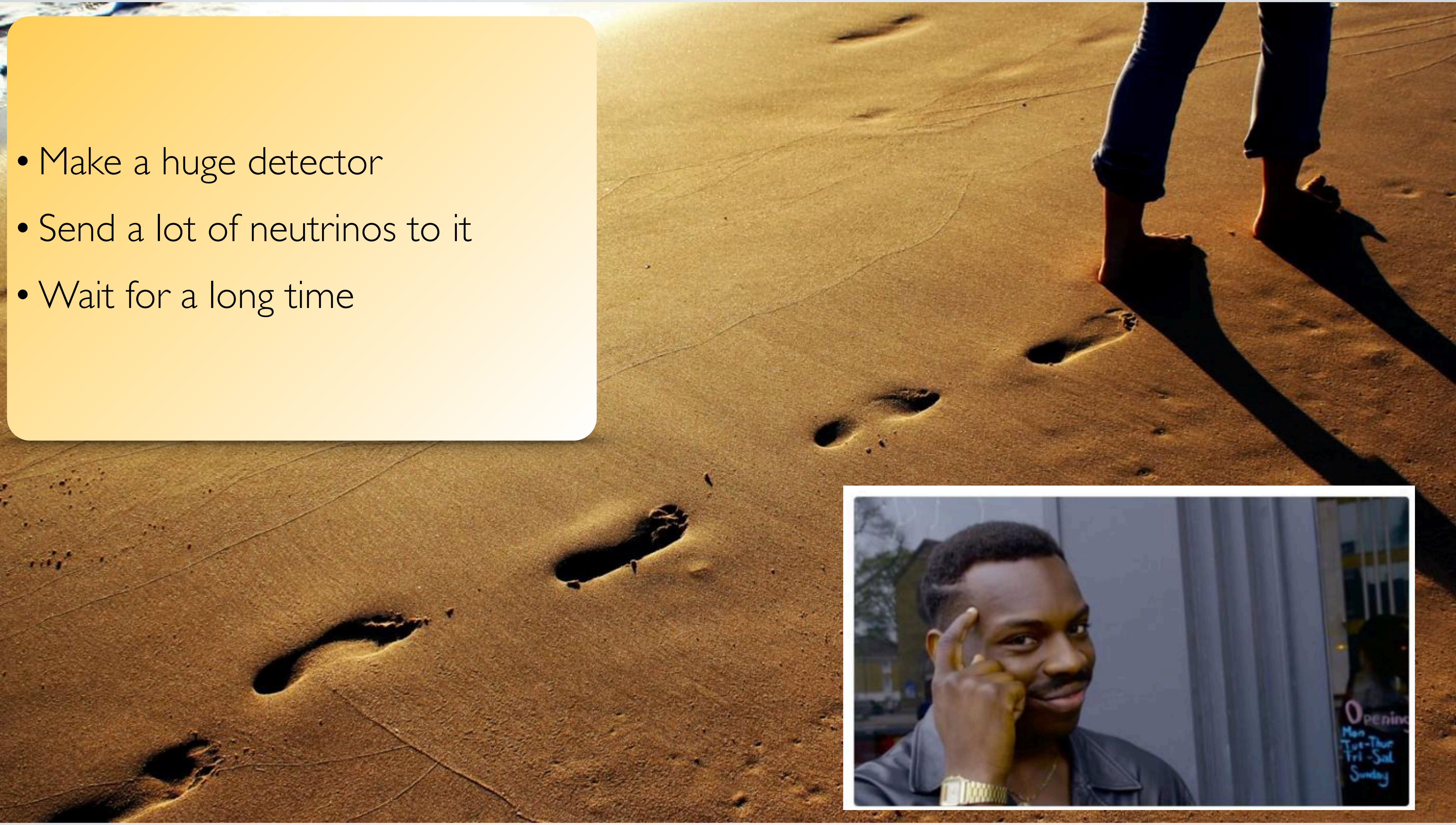
So how does one detect a neutrino?



- Make a huge detector
- Send a lot of neutrinos to it
- Wait for a long time

How does a neutrino experiment look like?

- The days when a single antisocial weirdo could perform an experiment in their home-made lab are gone

That's clever me standing behind a much taller guy

How does a neutrino experiment look like?

- The days when a single antisocial weirdo could perform an experiment in their home-made lab are gone

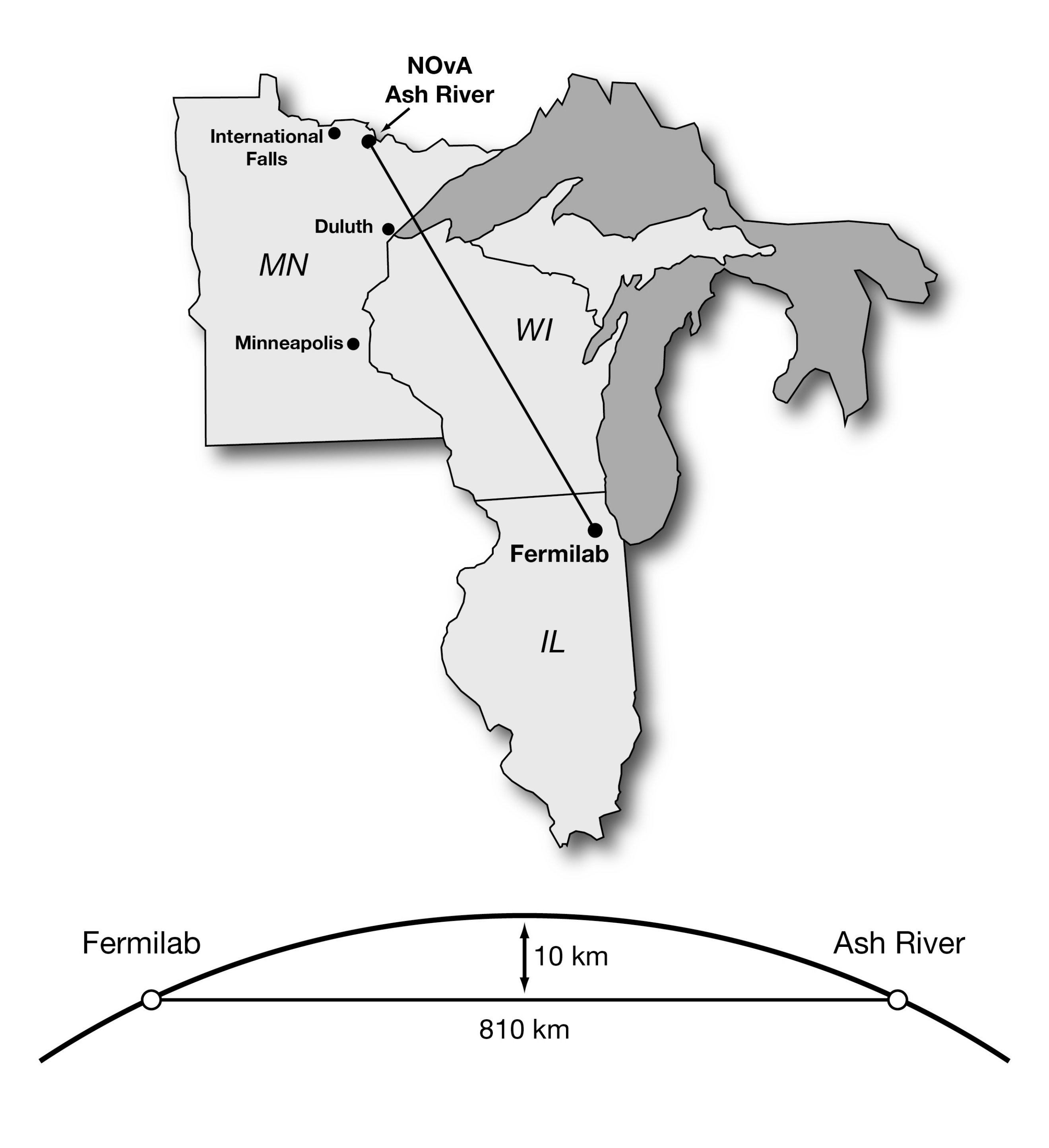
But there are some really great news

Truly international endeavours (e.g., NOvA involves 7 countries and plenty more nationalities)

No longer a male-only field!

The NOvA experiment

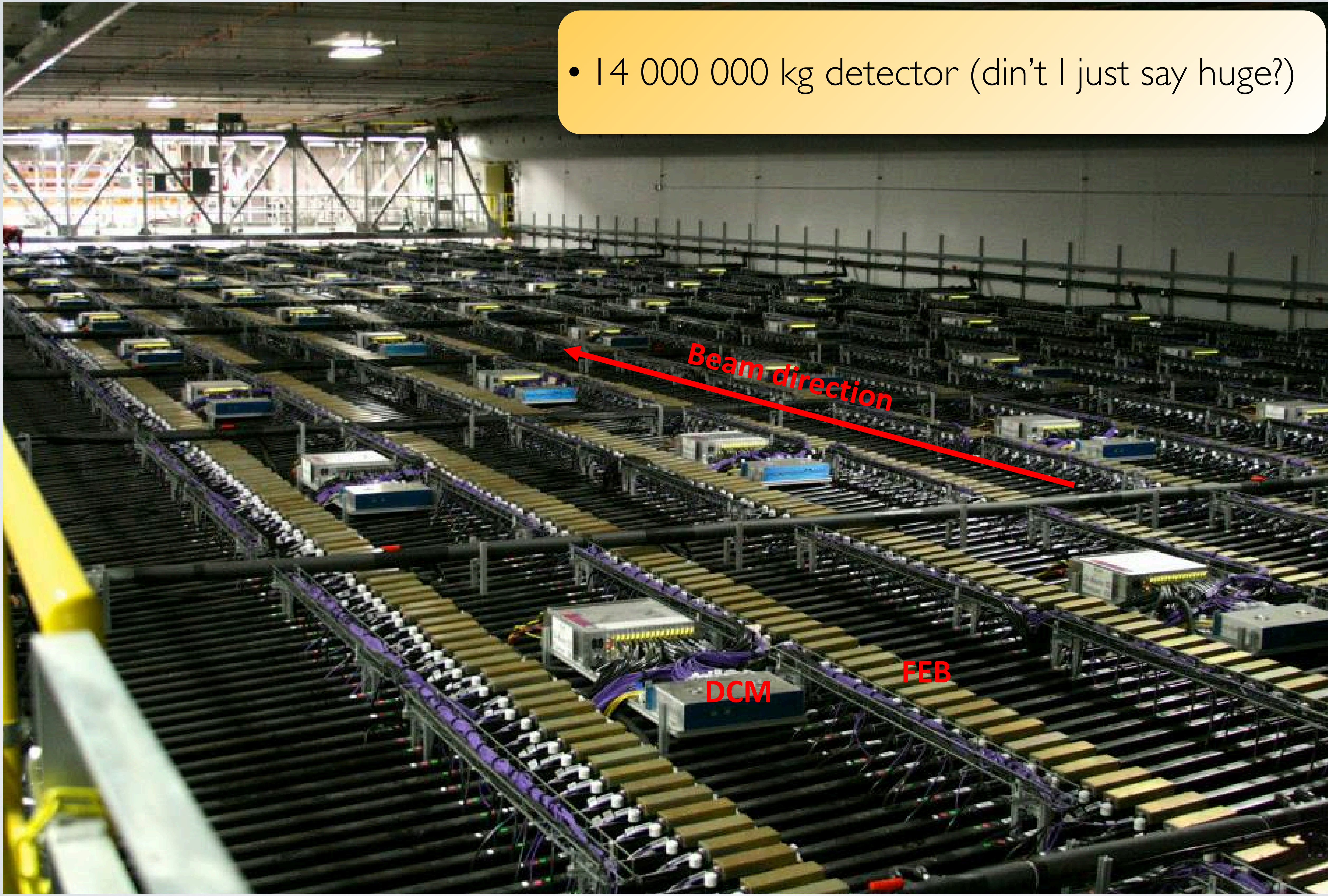
- NuMI Off-Axis ν_e Appearance
- Send neutrinos across Earth for 810 km
- Detect them twice: in a near detector at 1 km and a far detector much further
- Infer what happened to your neutrinos by comparing both measurements



NOvA Far Detector

NOvA Far Detector

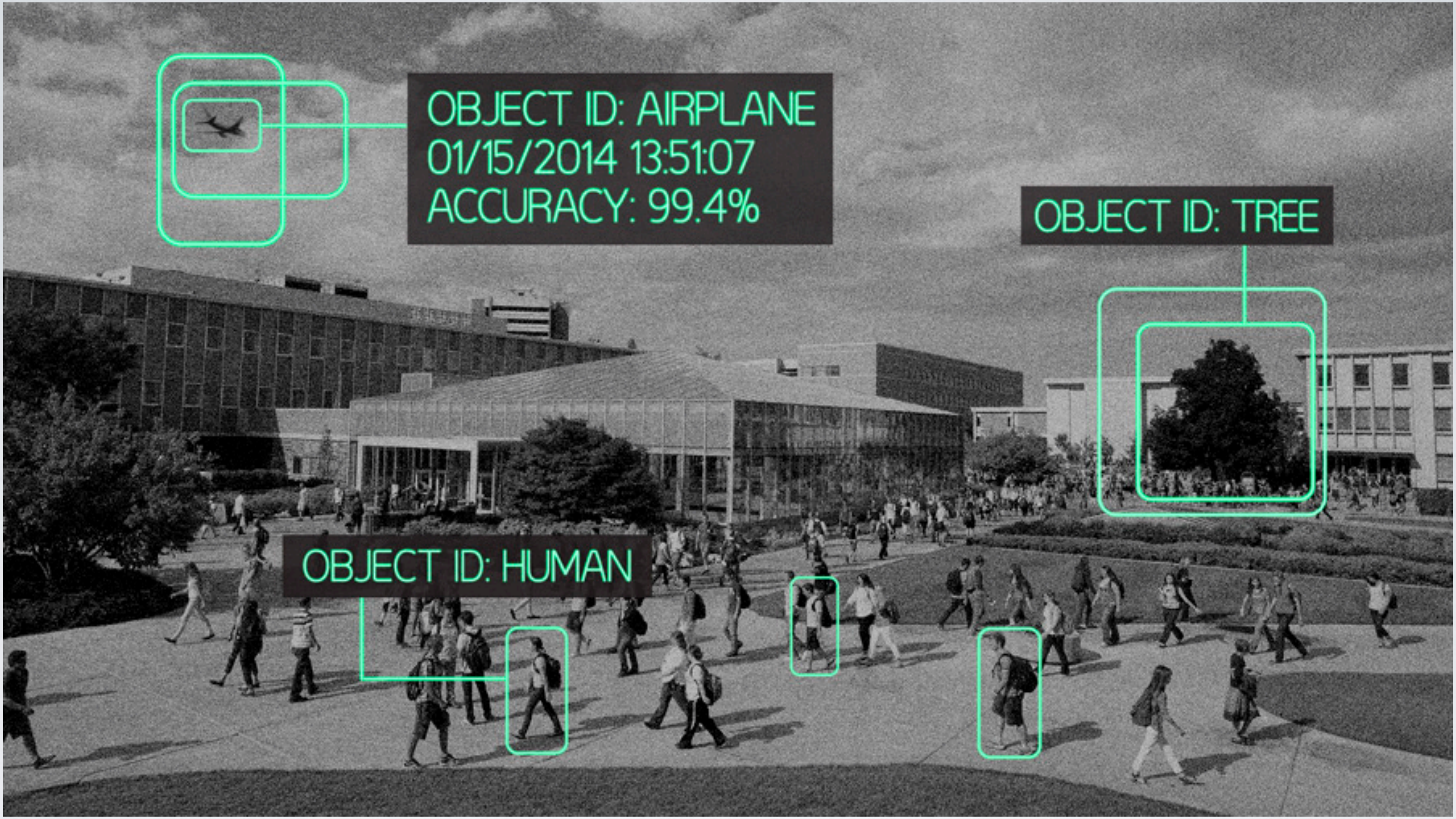
- 14 000 000 kg detector (din't I just say huge?)



NOvA Far Detector

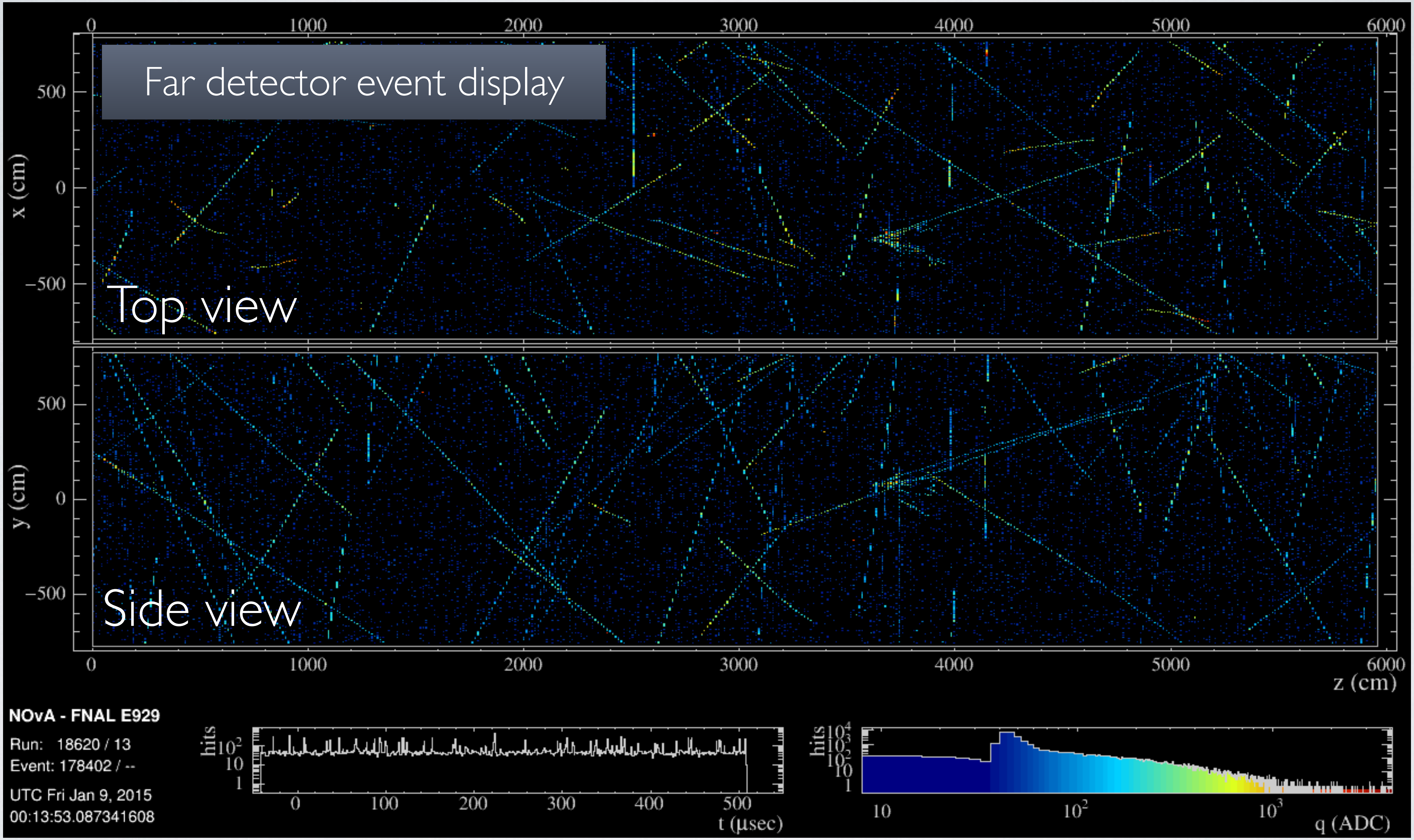
- Yes, huge indeed

Identifying neutrinos in the NOvA detector



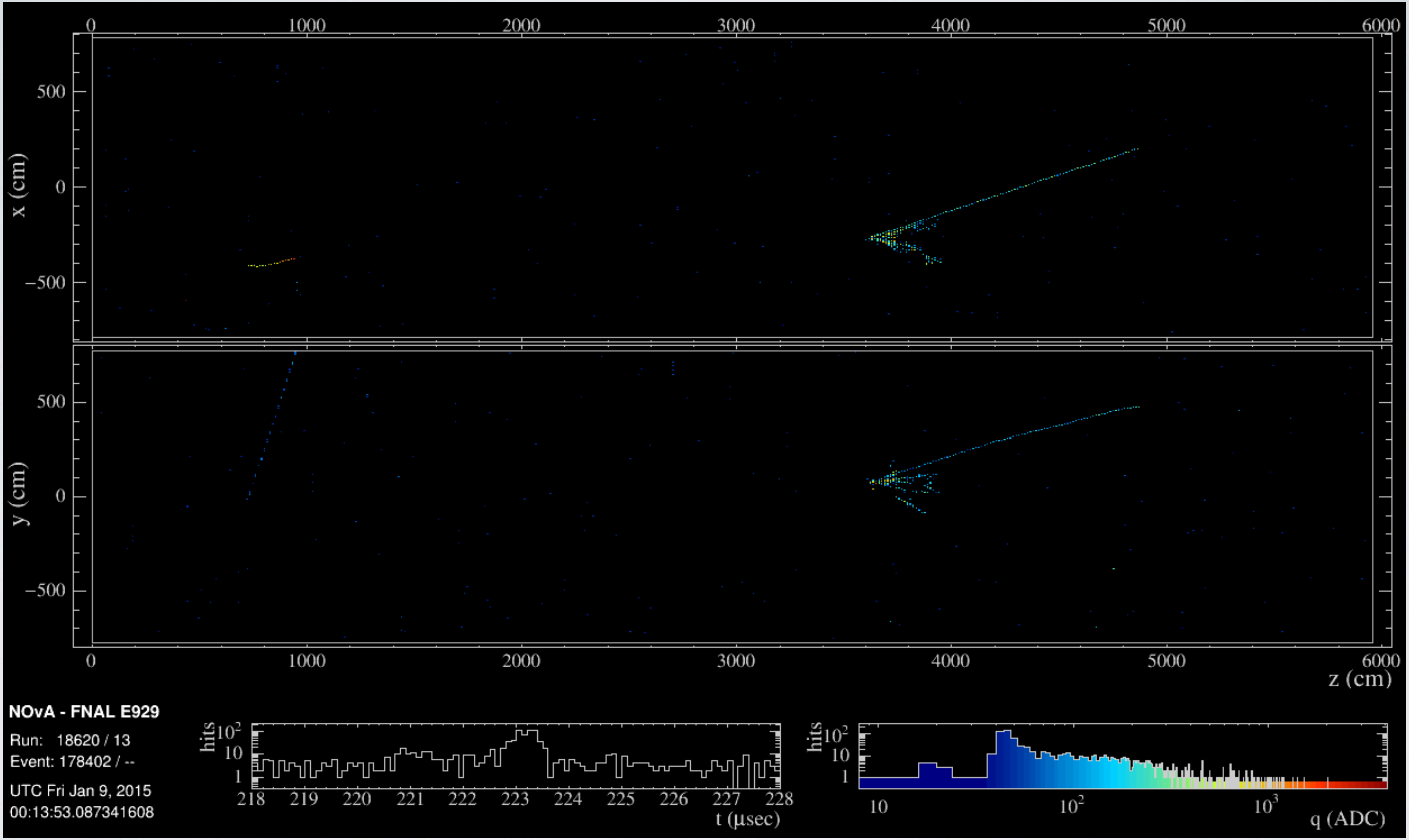
- First usage of image-recognition in particle physics!

Real events (FD)



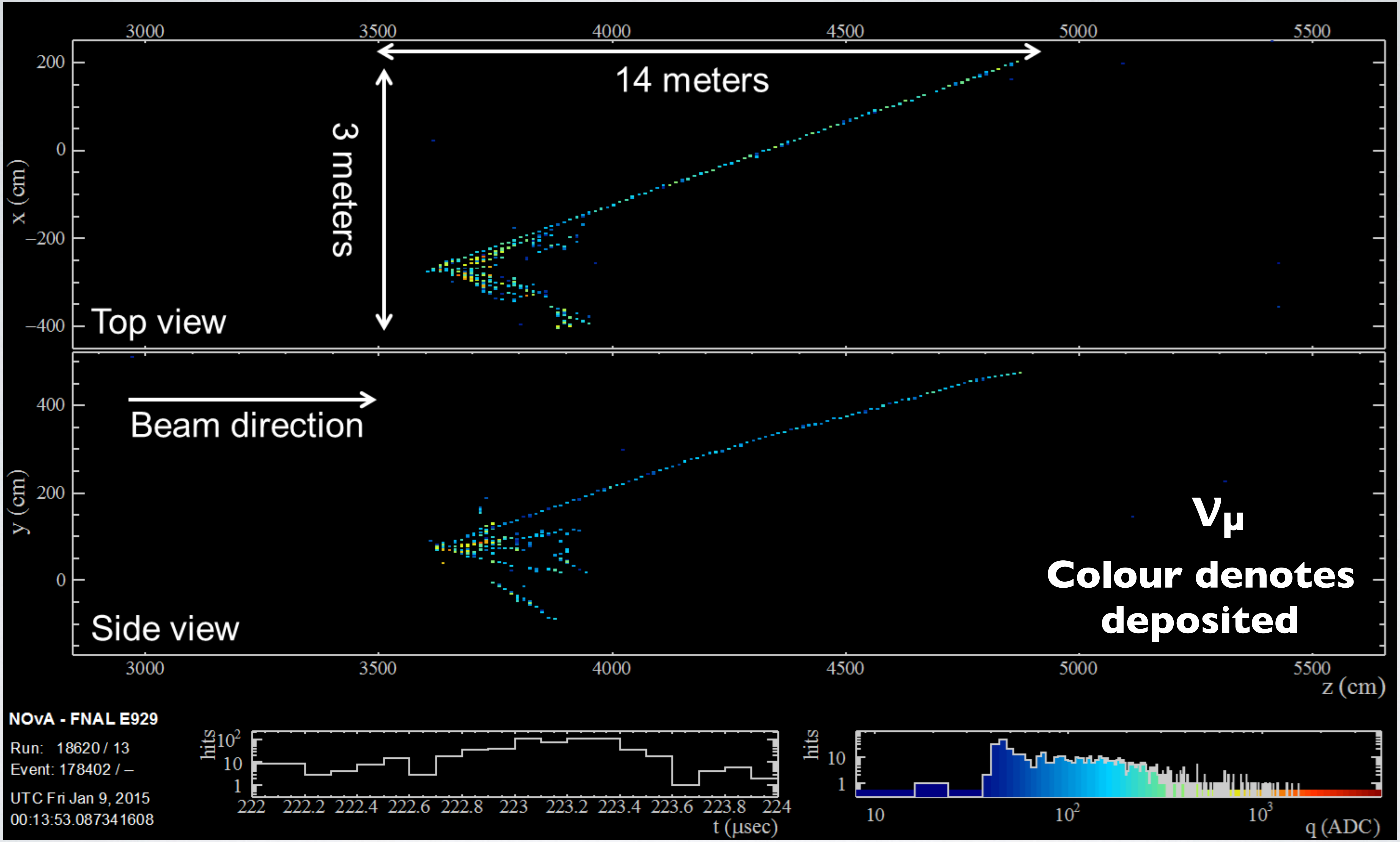
1 / 2000th of a second (colours show charge)

Real events (FD)



Zoomed on 1/100 000th of a second

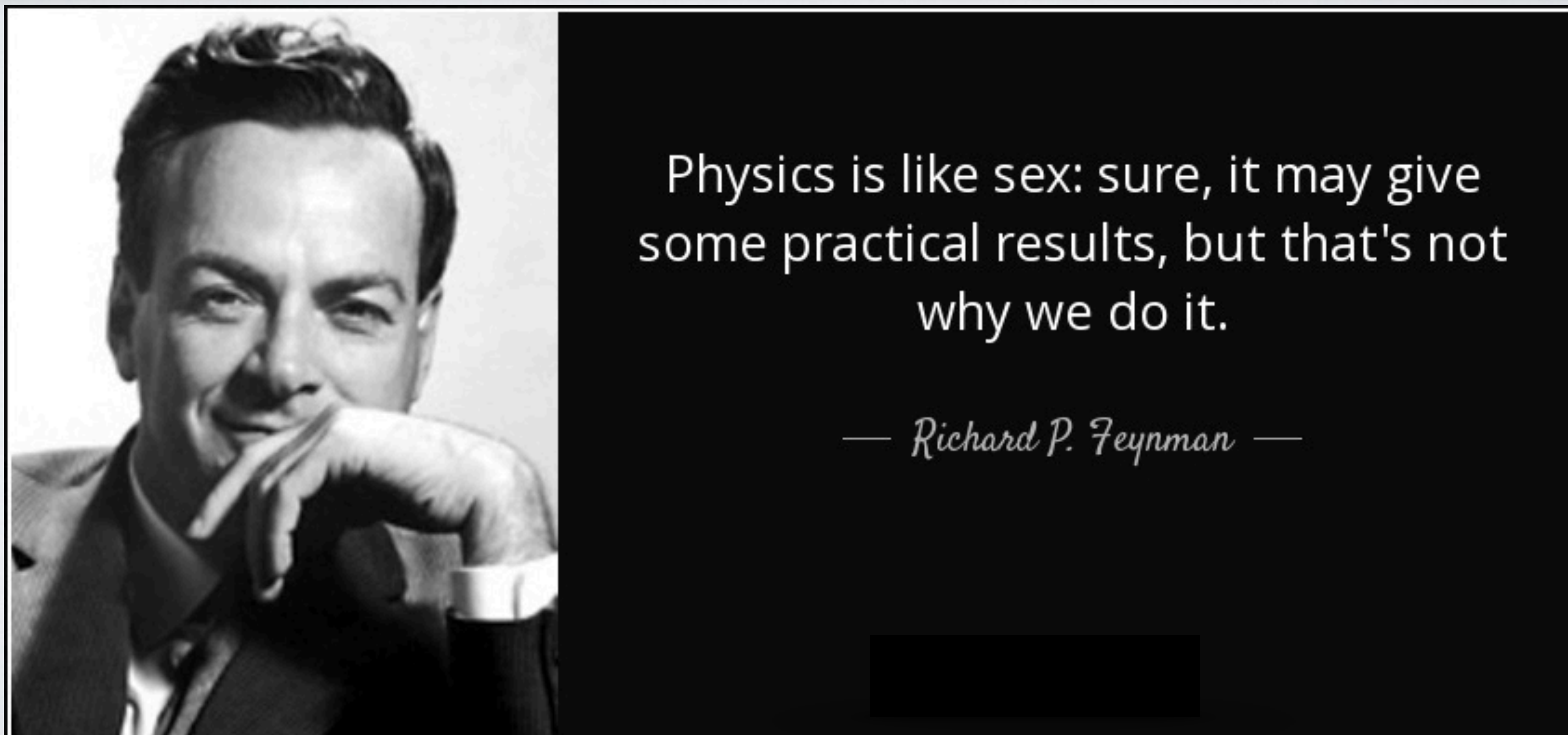
Real events (FD)



Zoomed on the neutrino interaction

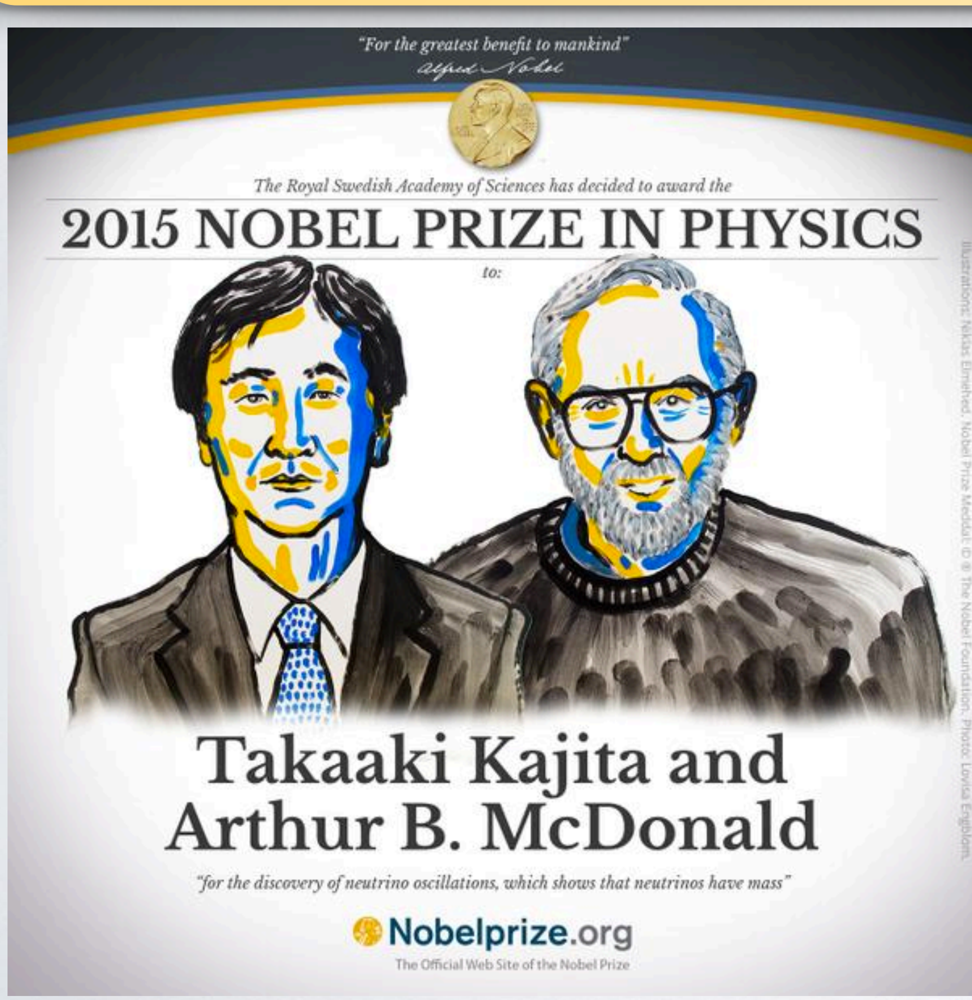
Are neutrinos useful?

- ~~I don't care~~
- Actually, they are! They can be used to detect nuclear activity (non-proliferation of nuclear weapons, nuclear reactor security monitoring,…)
- They're also used in various fields to explore the inside of the unreachable: e.g. Stars (Astrophysics) and Earth (Geophysics & Geology)



Why is neutrino oscillation important?

- Quantum effect observed at macroscopic scale! (typically some hundred km)
- Nobel prize 2015 and Breakthrough prize 2016
- Many open questions: in particular, do neutrinos and *antineutrinos* oscillate in the same way?

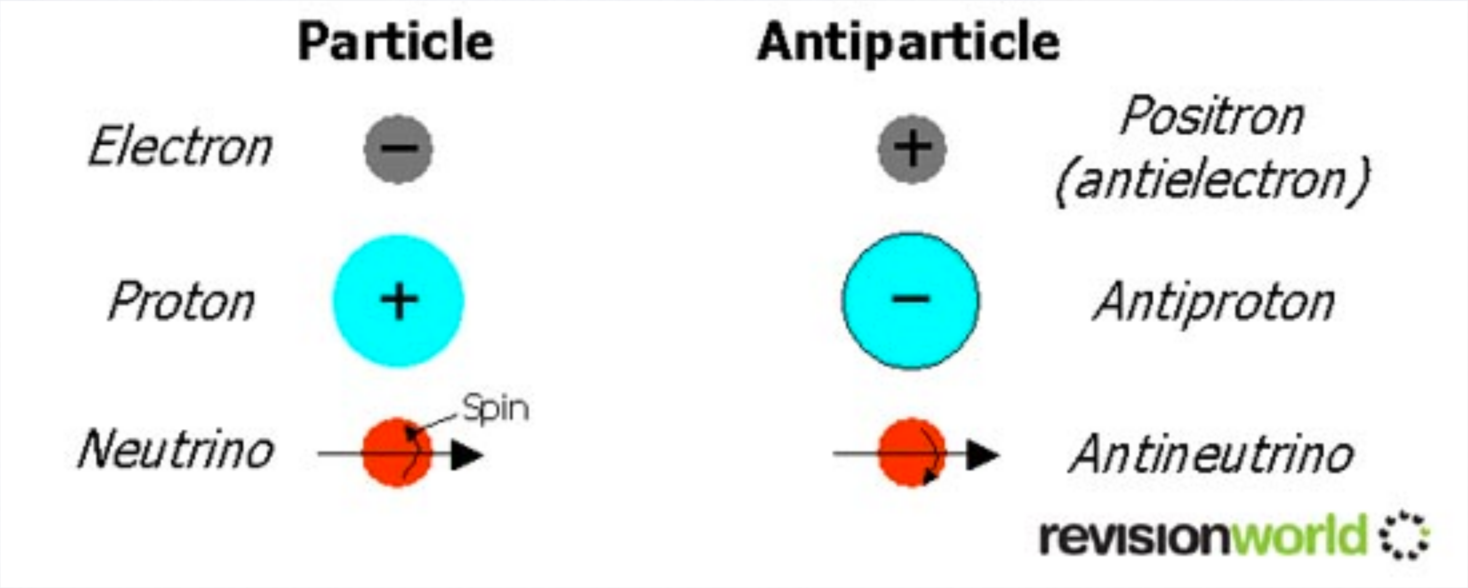


When have you seen these many physicists in a tux..?

Antineutrinos??

Hold your horses!

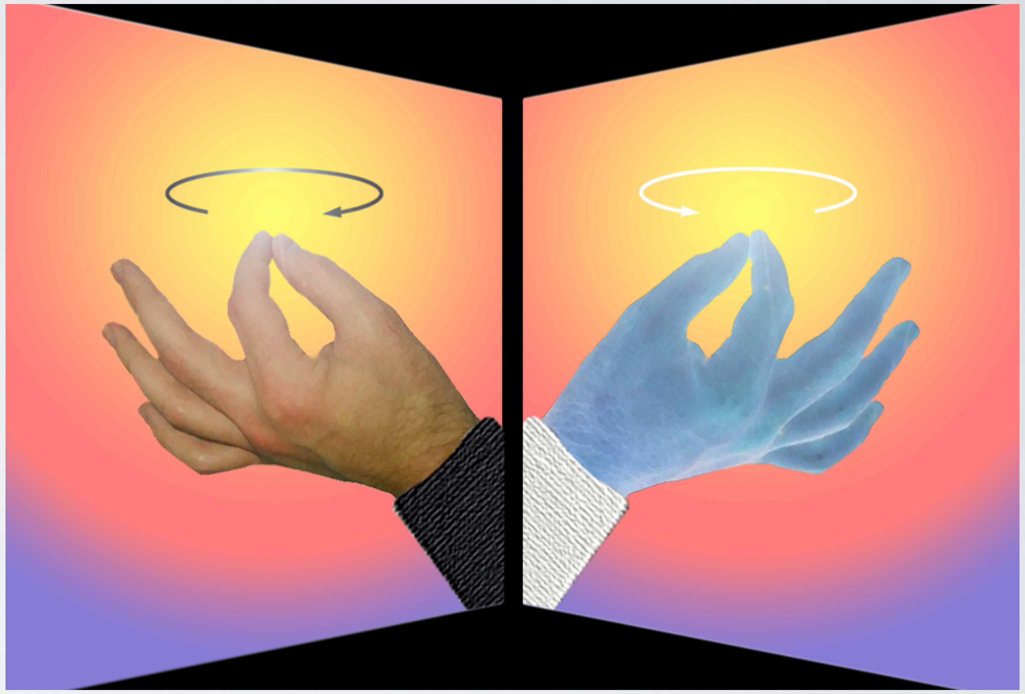
Did you just say *antineutrino*?



Why is there such a matter-antimatter asymmetry?

- There were a lot of neutrinos and antineutrinos in the early universe, so perhaps the answer lays on them…

Why is there such a matter-antimatter asymmetry?



But to make things more complicated, neutrinos may end up being their own antiparticle…

- There were a lot of neutrinos and antineutrinos in the early universe, so perhaps the answer lays on them…

Summary

- Neutrinos are neutral, very light particles, which are produced in various natural processes, including radioactivity
- They are very hard to catch! They interact very softly with matter and mostly travel unaffected
- There are three types of neutrinos, and each of these types can oscillate into the others when they travel a long distance
- Neutrinos can be used to explore the inside of stars and the Earth
- And it's possible they can hinder one of the most fundamental questions of all times: why are we made of matter?

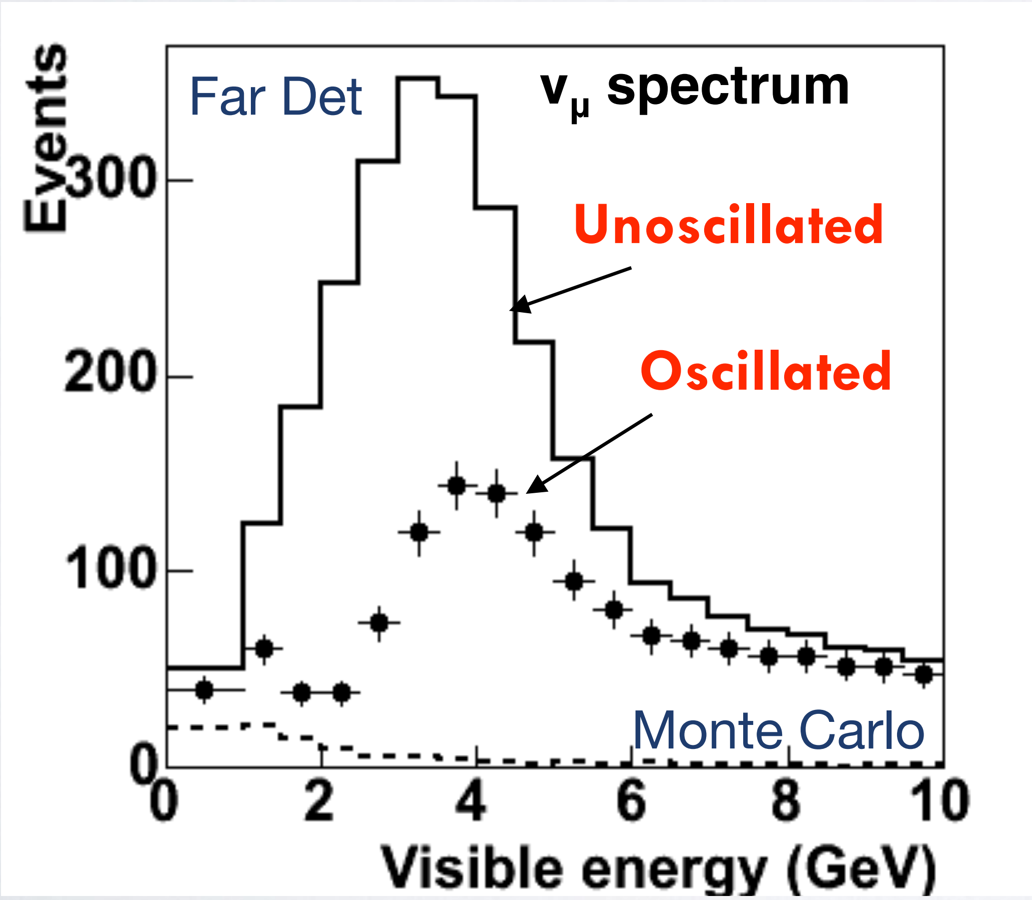
BACKUP SLIDES

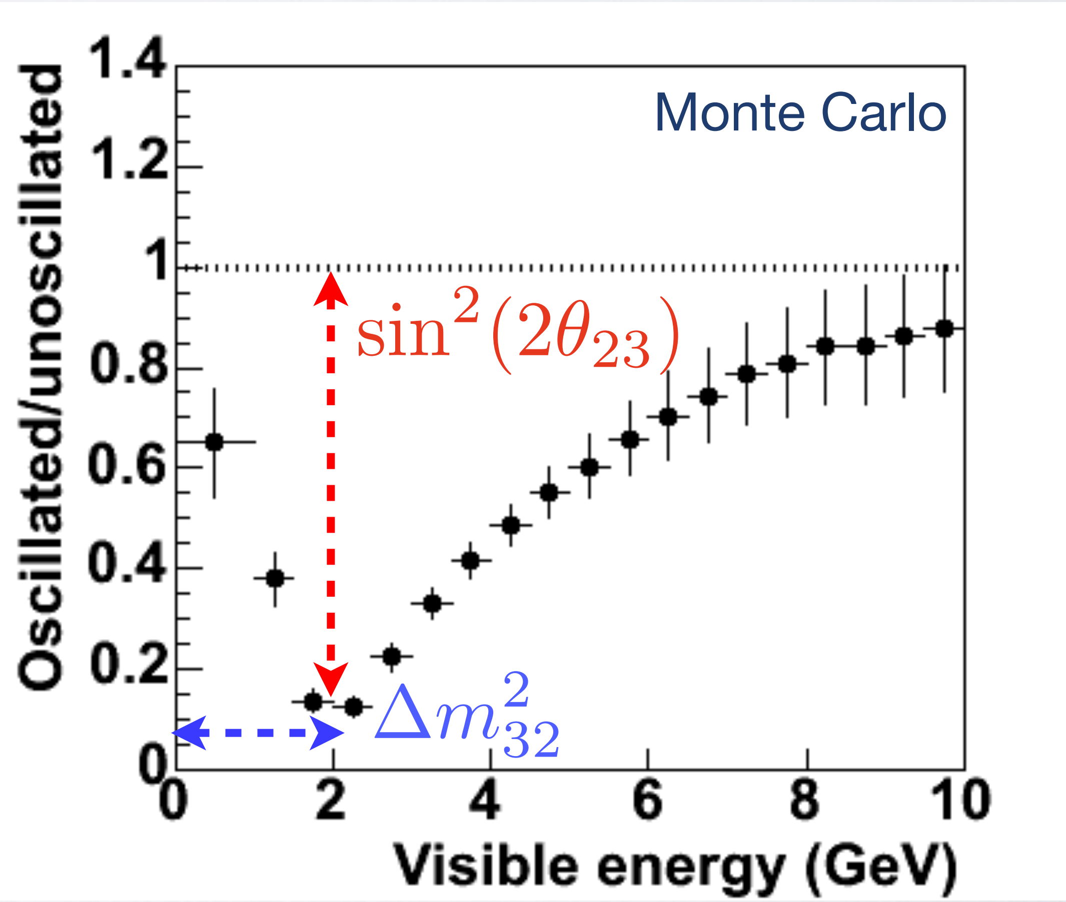
These aren't the slides you're looking for

Disappearance analysis in a nutshell…

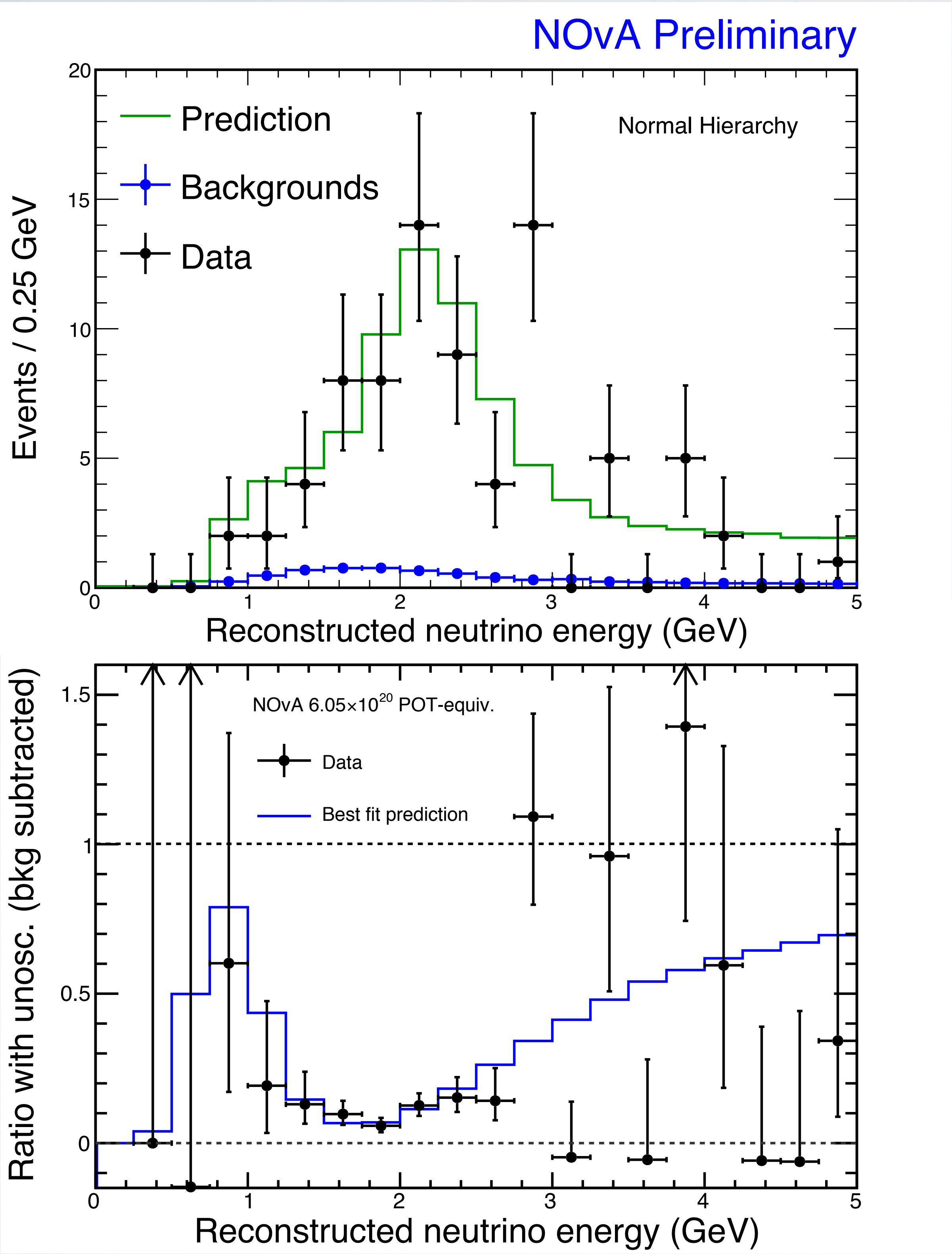
Identify contained ν_μ CC events in both detectors → Measure both energy spectra → Measure oscillation from comparison between near and far energy spectra

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$





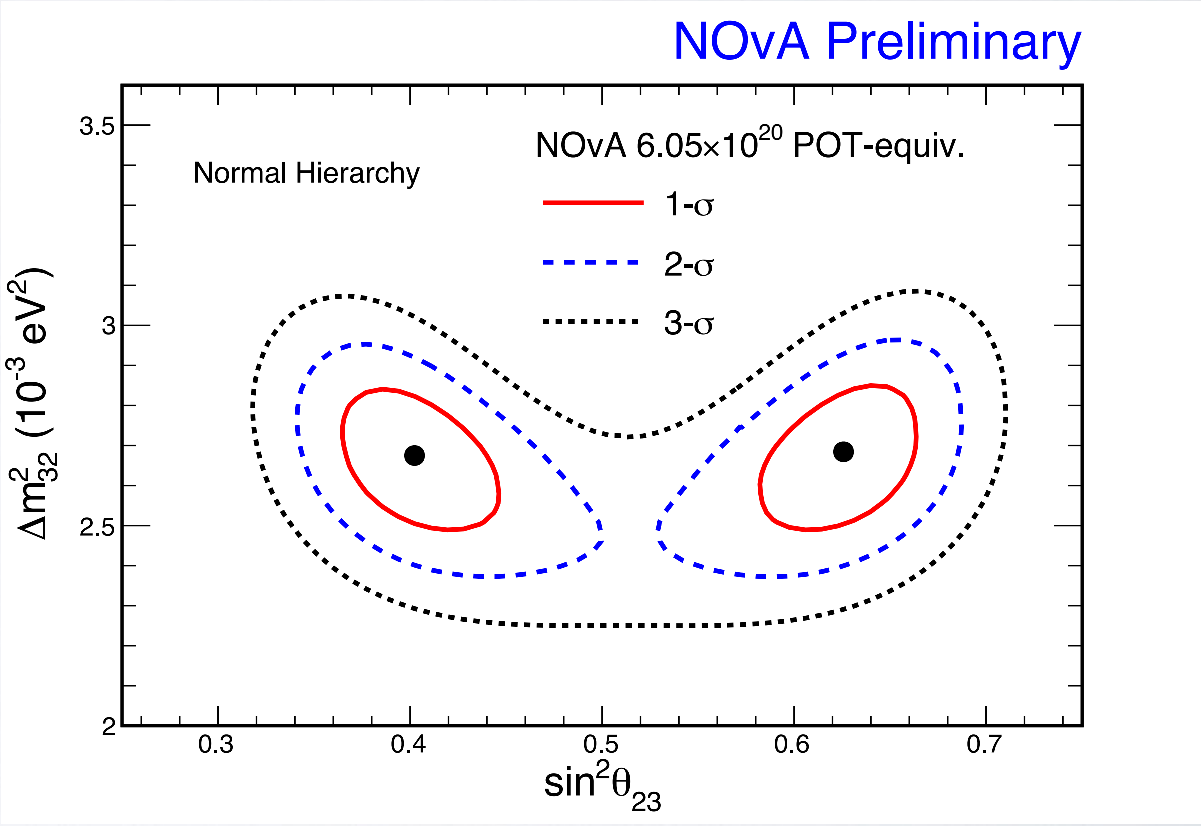
NOvA



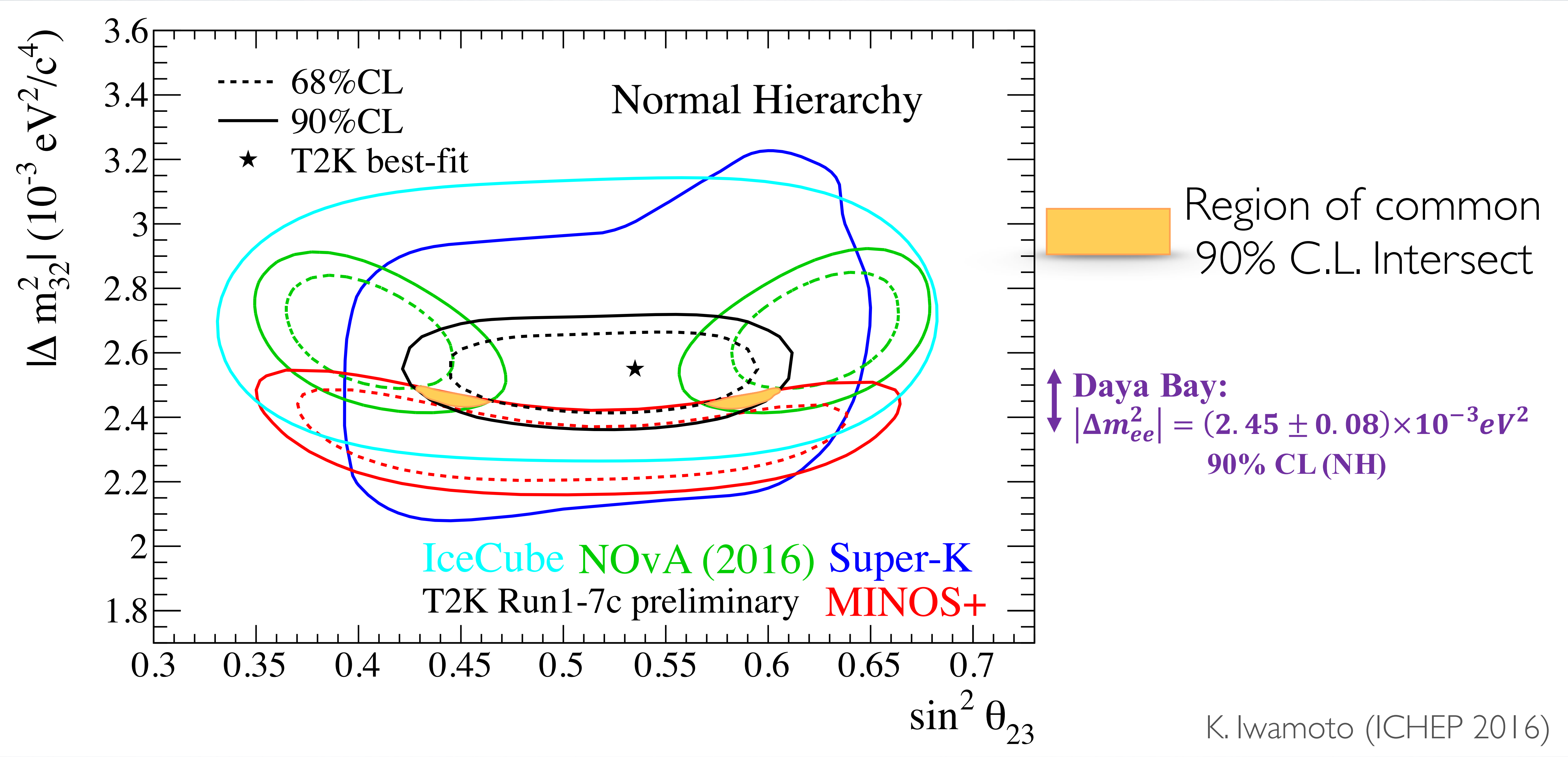
- 473 expected without oscillations
- 82 with oscillations. 78 observed

$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3} \mathrm{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} \; (0.63^{+0.02}_{-0.03})$$

Maximal mixing disfavoured at 2.5σ



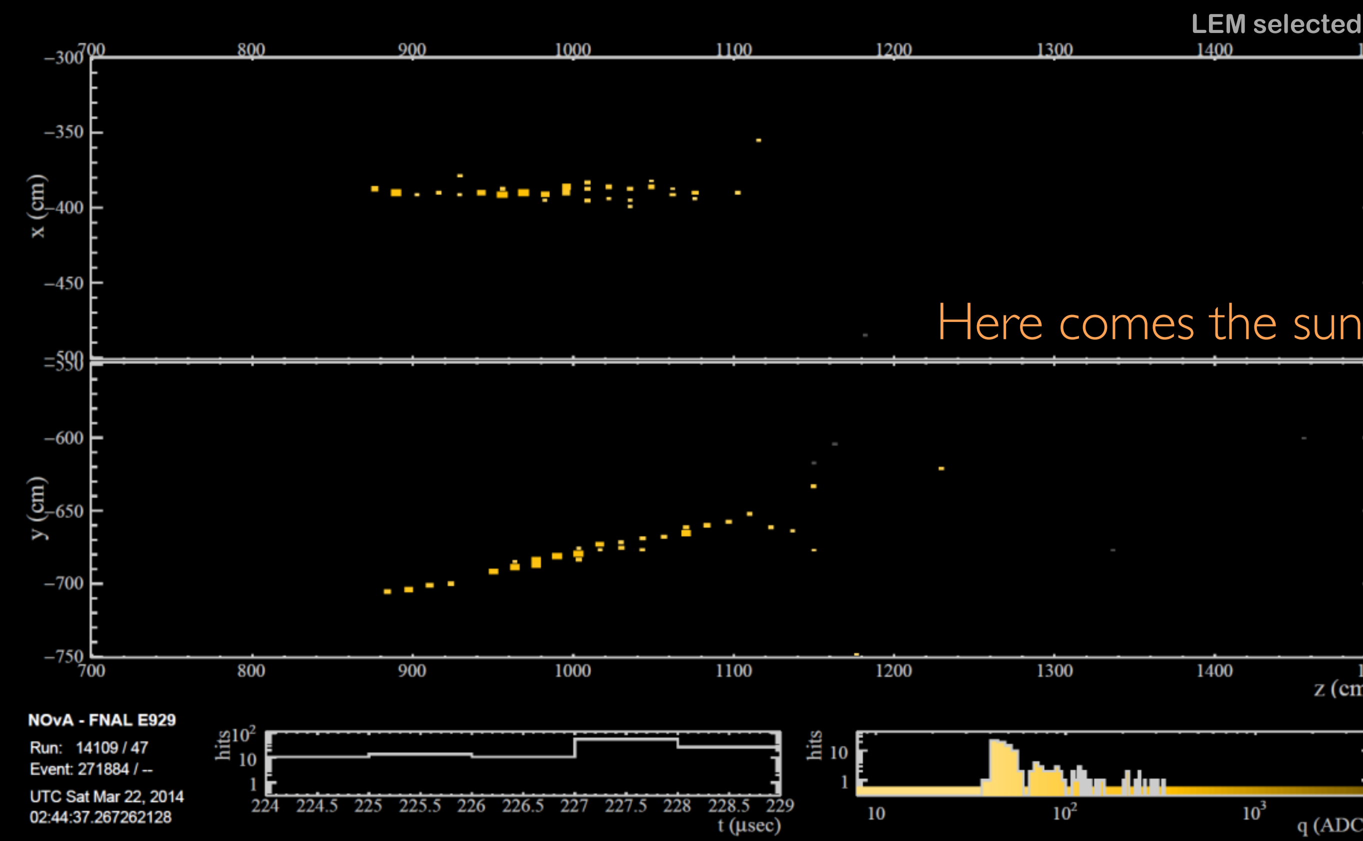
Comparison

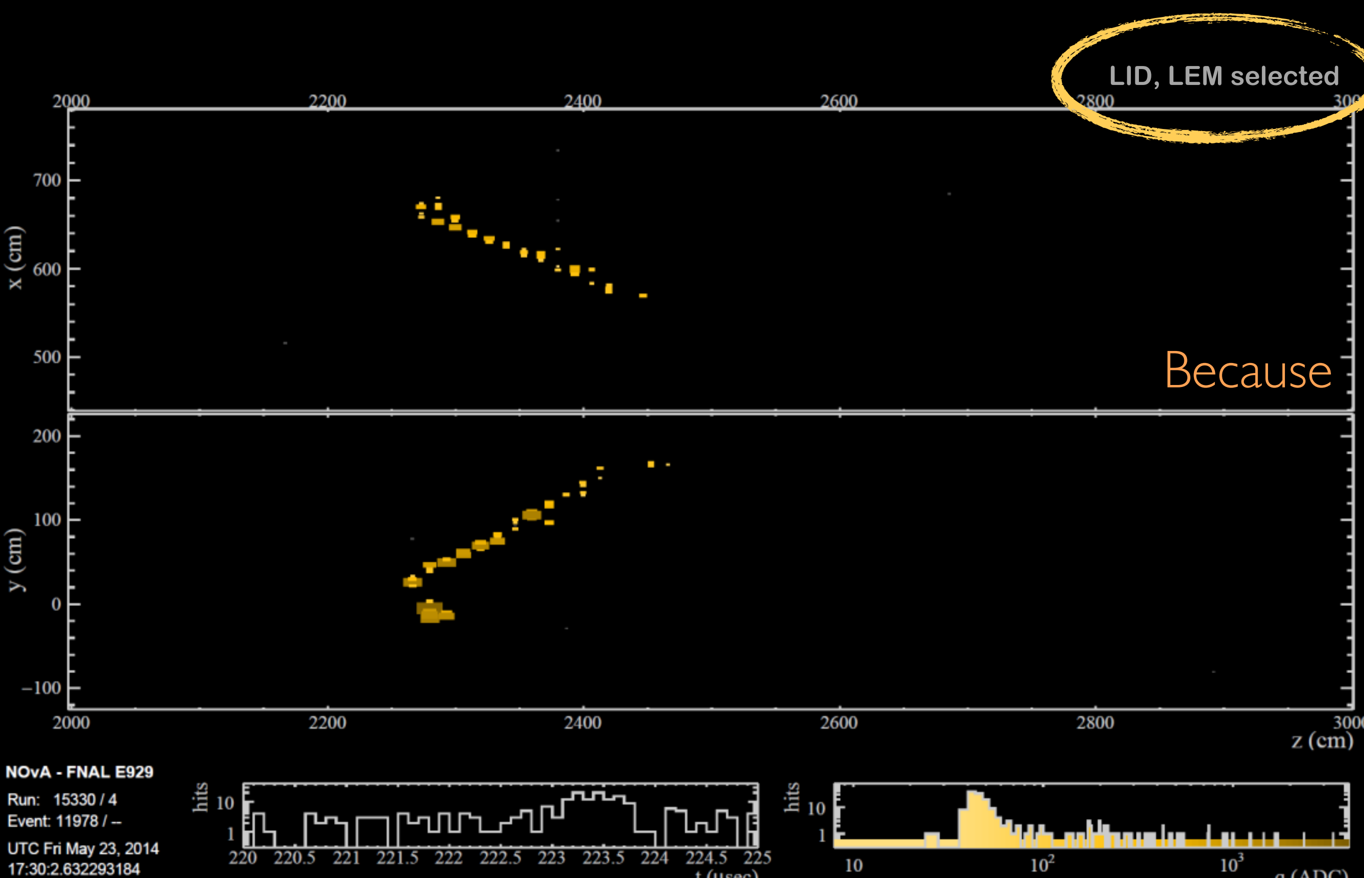


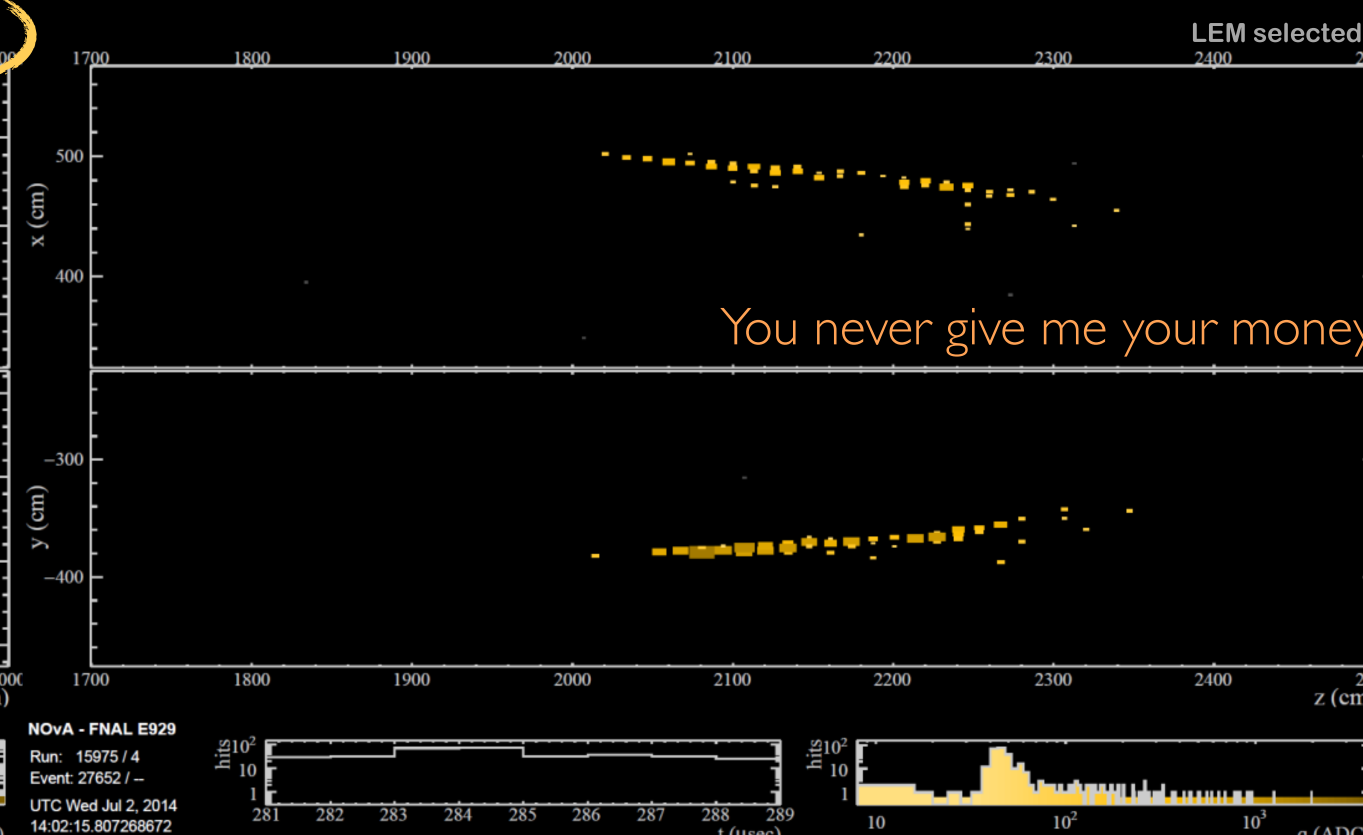
K. Iwamoto (ICHEP 2016)

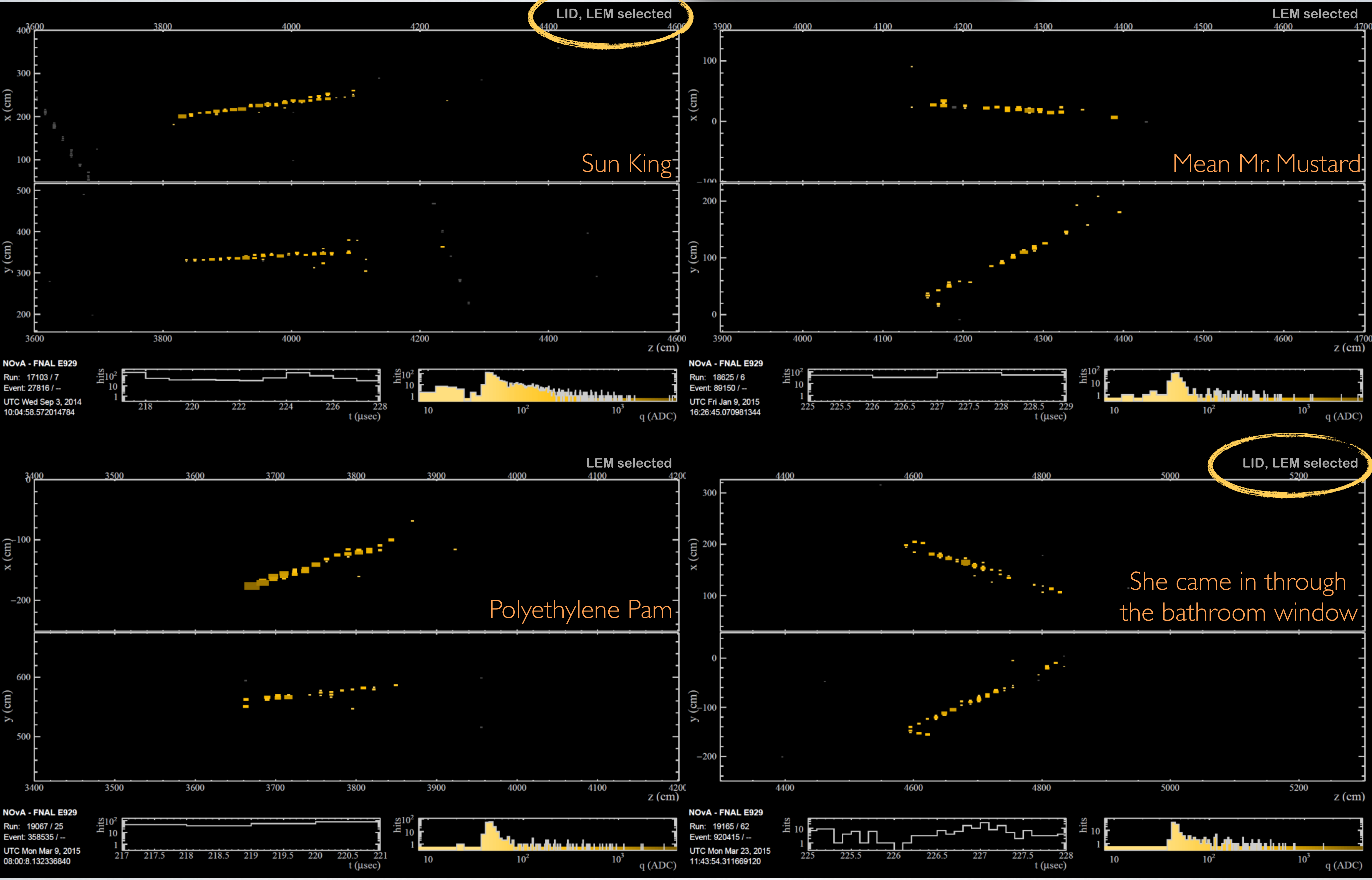
- Small tension across experiments
- More data should shed light on whether it's just a statistical fluctuation


ν_e candidates

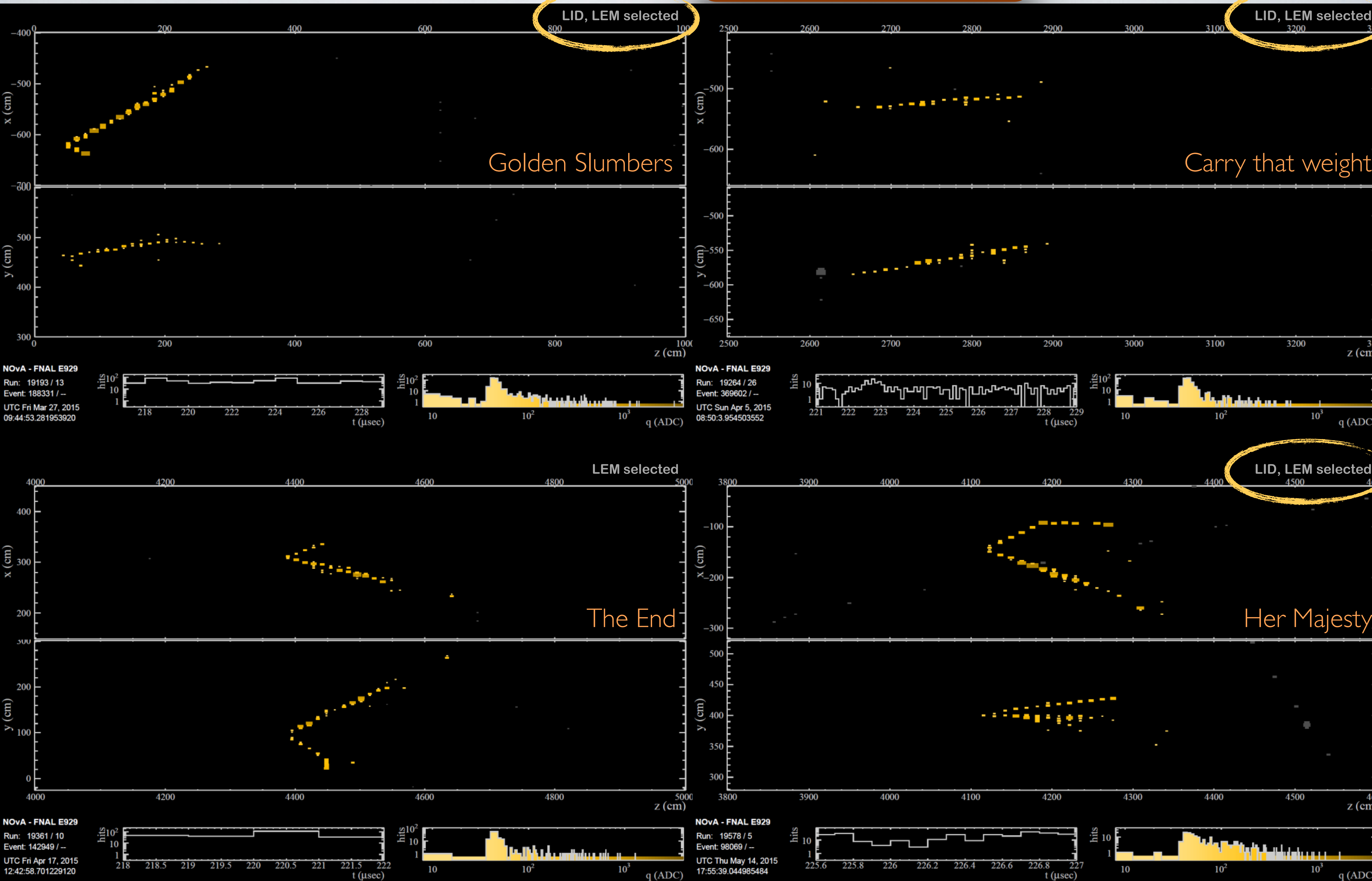

LEM selected
Here comes the sun
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14109 / 47
Event: 271884 / --
UTC Sat Mar 22, 2014
02:44:37.267262128
hits
t (μsec)
q (ADC)


LID, LEM selected
Because
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
hits
t (μsec)
q (ADC)


LEM selected
You never give me your money
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15975 / 4
Event: 27652 / --
UTC Wed Jul 2, 2014
14:02:15.807268672
hits
t (μsec)
q (ADC)


LID, LEM selected
Sun King
LEM selected
Mean Mr. Mustard
LEM selected
Polyethylene Pam
LID, LEM selected
She came in through
the bathroom window
NOvA - FNAL E929
Run: 17103 / 7
Event: 27816 / --
UTC Wed Sep 3, 2014
10:04:58.572014784
NOvA - FNAL E929
Run: 18625 / 6
Event: 89150 / --
UTC Fri Jan 9, 2015
16:26:45.070981344
NOvA - FNAL E929
Run: 19067 / 25
Event: 358535 / --
UTC Mon Mar 9, 2015
08:00:8.132336840
NOvA - FNAL E929
Run: 19165 / 62
Event: 920415 / --
UTC Mon Mar 23, 2015
11:43:54.311669120
x (cm)
y (cm)
z (cm)
t (μsec)
q (ADC)
hits

Electron neutrino appearance

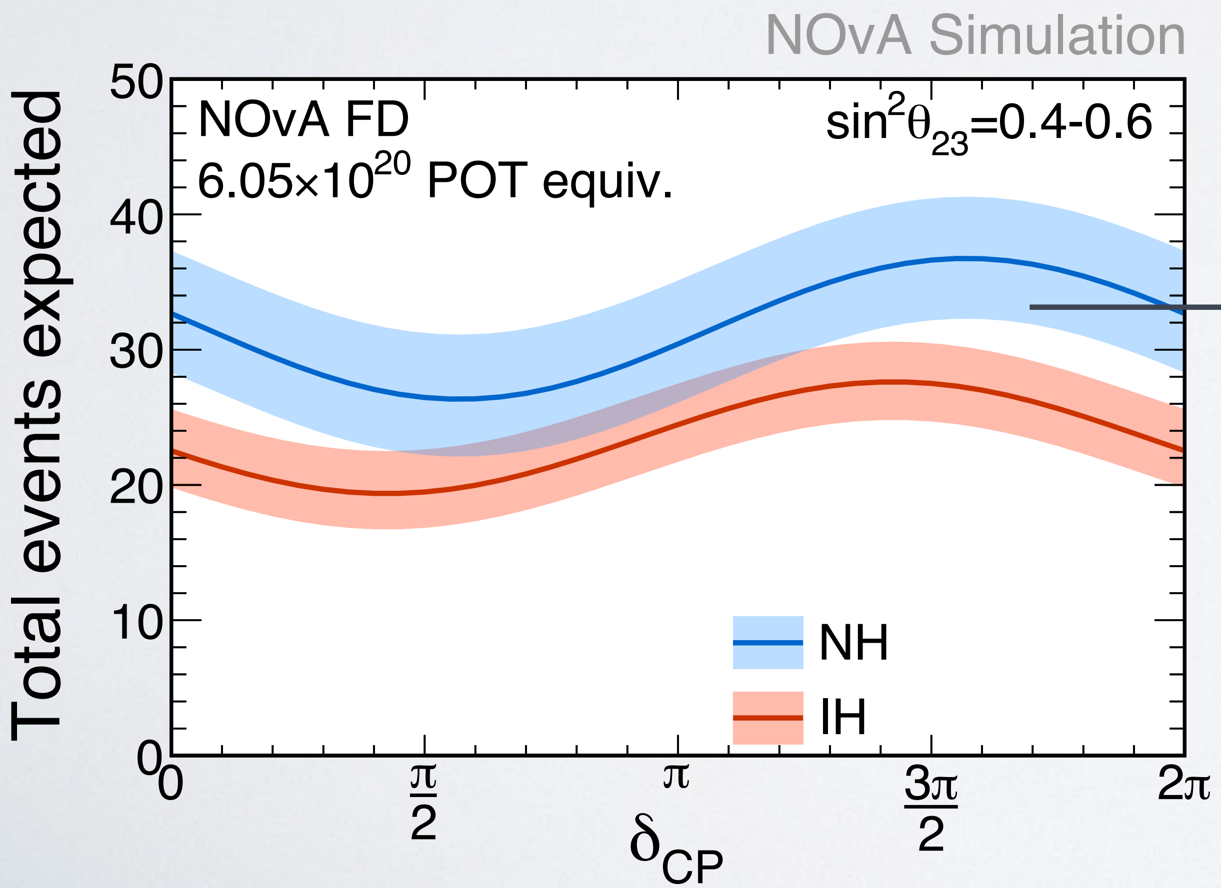


Appearance analysis in a nutshell…

Identify ν_e CC events in both detectors

Use ND measurements to predict backgrounds in the FD

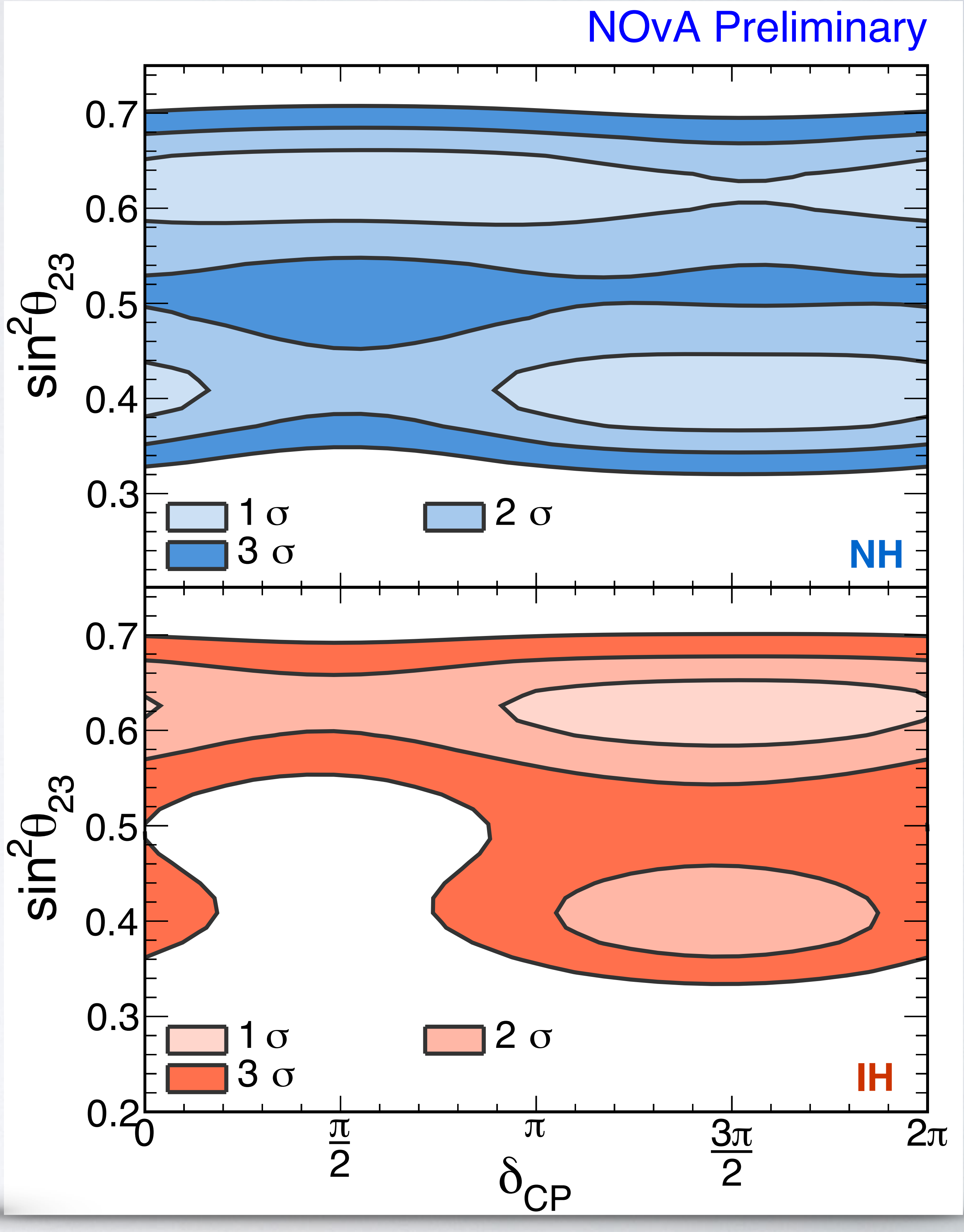
Interpret any FD excess over predicted backgrounds as ν_e appearance



Number of observed events constraints δ_{CP} and mass hierarchy

NOvA

- Include θ_{23} and Δm^2_{32} from disappearance analysis
- Not a joint analysis yet! Systematics and rest of the oscillation parameters not correlated
- Best fit to NH, $\delta_{CP} = 1.49\pi$ and $\sin^2(\theta_{23}) = 0.40$
- But best fit IH-NH has $\Delta X^2 = 0.47$
- IH, lower octant around $\delta_{CP} = \pi/2$ disfavoured at 3σ
- Antineutrino data planned for Spring 2017 will help resolve degeneracies



Next generation experiments

1st generation

2nd generation

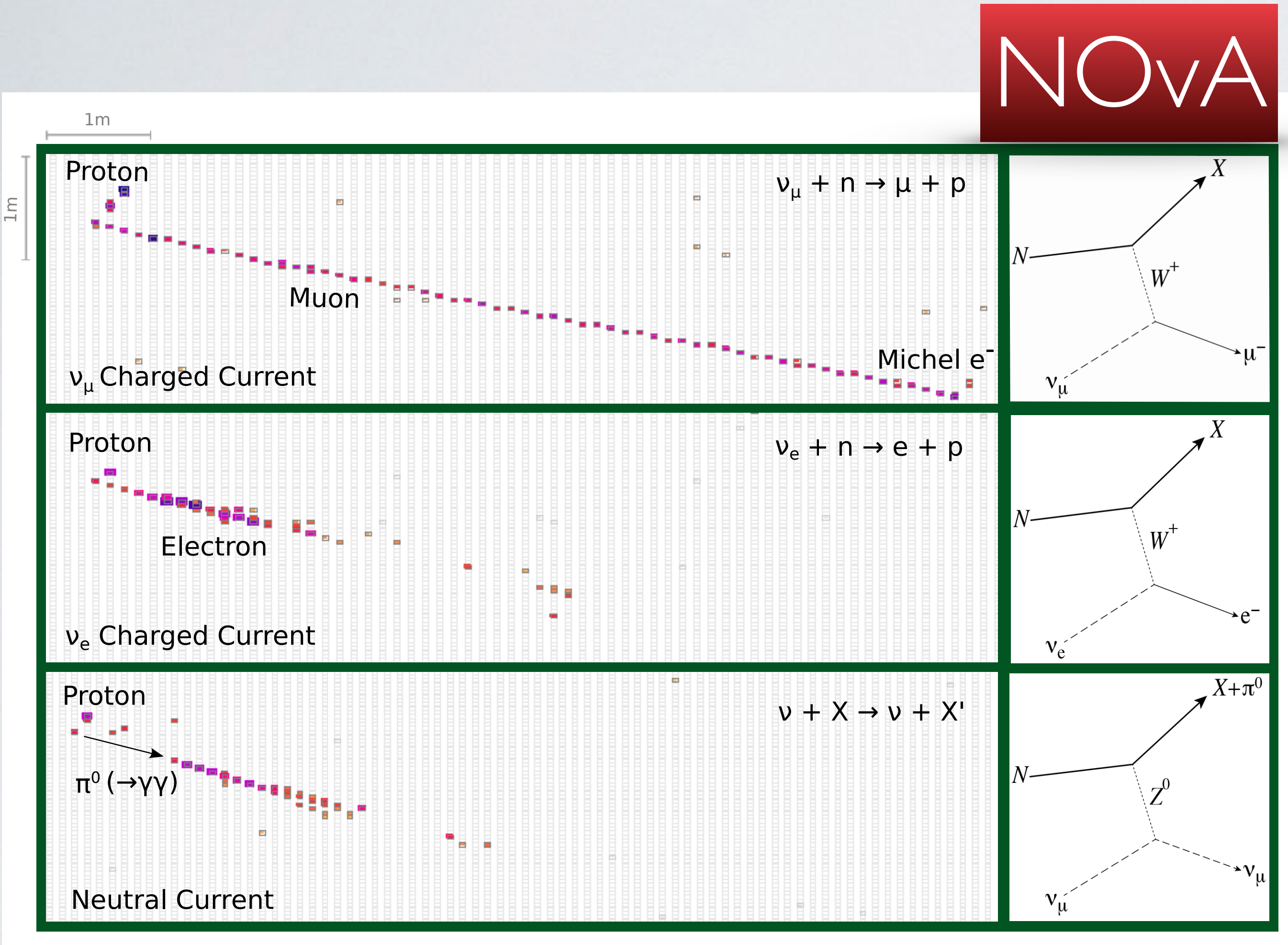
3rd generation

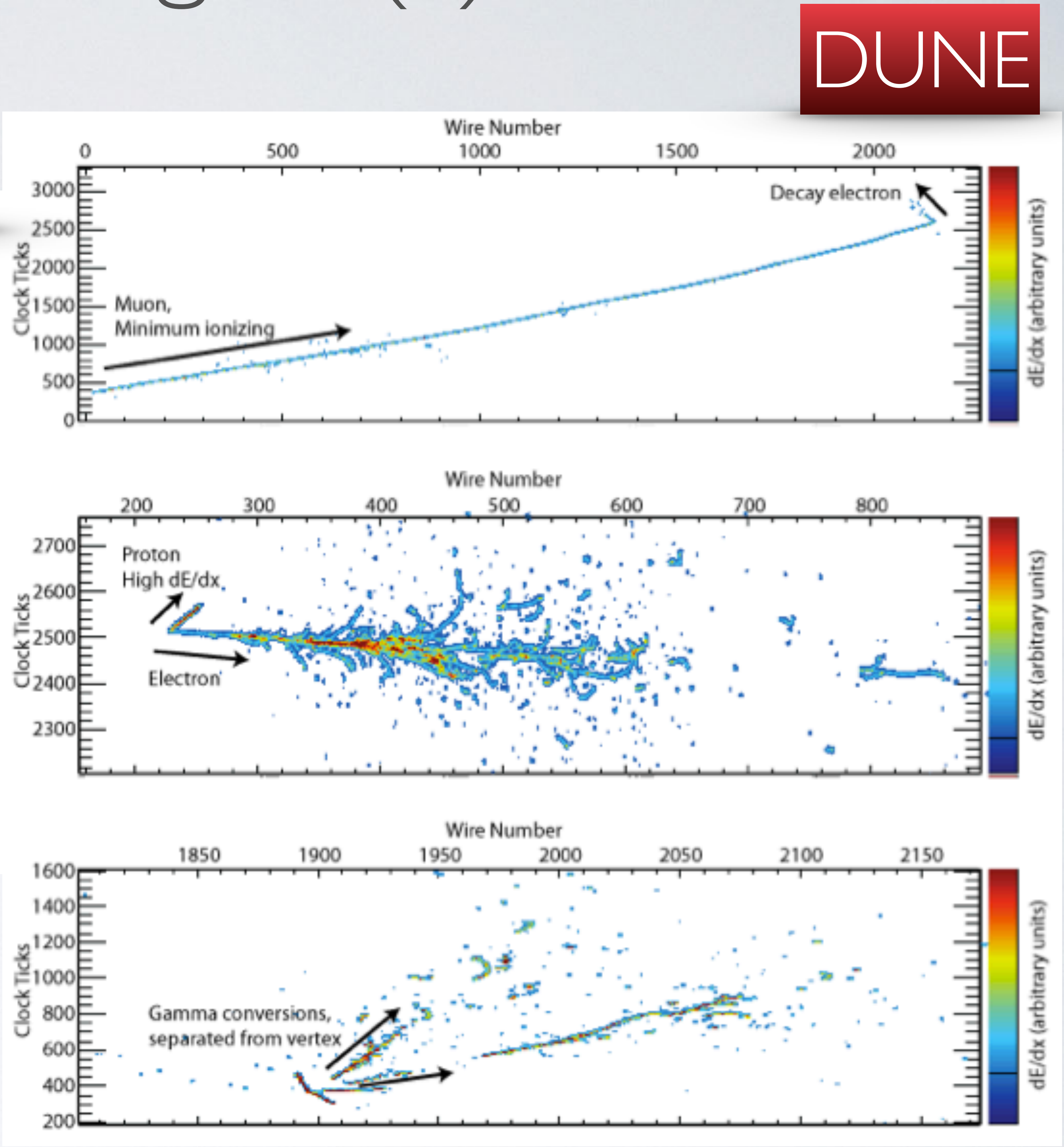
- Higher intensity beams can provide more neutrinos and allow for a longer baseline
- Similarly, larger mass can allow to collect more neutrinos
- Finally, higher detector resolution allows for better background rejection

In the US, DUNE is being planned with a baseline of 1300 km, a new 2.3 MW beam and high resolution liquid argon detectors

In Japan, HyperK is also being planned with an upgrade to 1.3 MW beam and 500 kton detector

Event topologies (II)





"Like going from a set of pictures to 3D HD video"

COSMIC RAYS

Discovered more than 100 years ago

- Victor Hess: Ionisation increased with altitude (1912)
- Bothe and Kolhörster: non-electromagnetic (1929)
- Pierre Auger: Extensive Air Showers (1938)

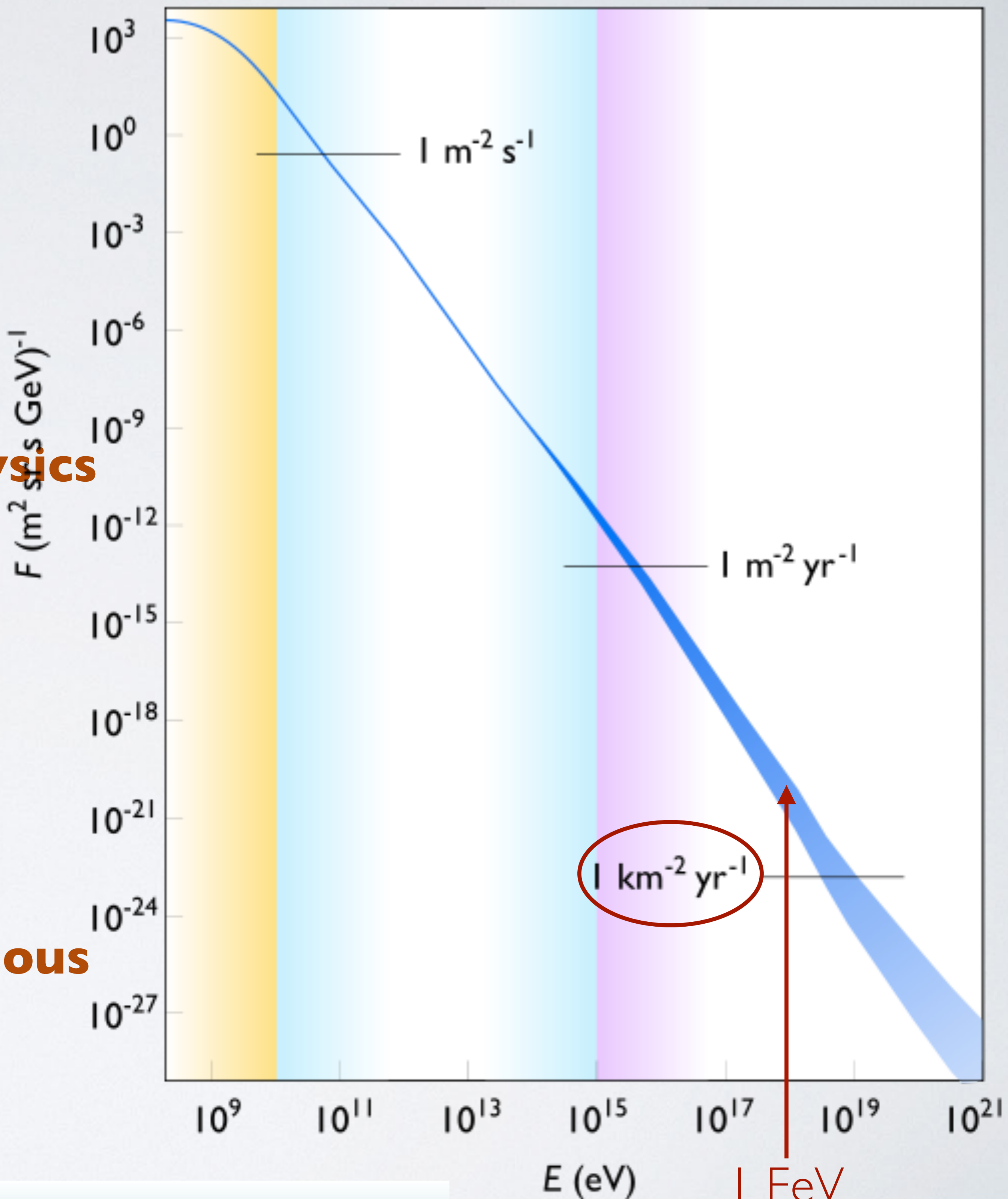
Shaped the development of Particle Physics

- Skobeltsyn: Discovery of positron (1929)
- Anderson and Neddermeyer: Discovery of muon (1936)
- Powell: Discovery of pion (1947)

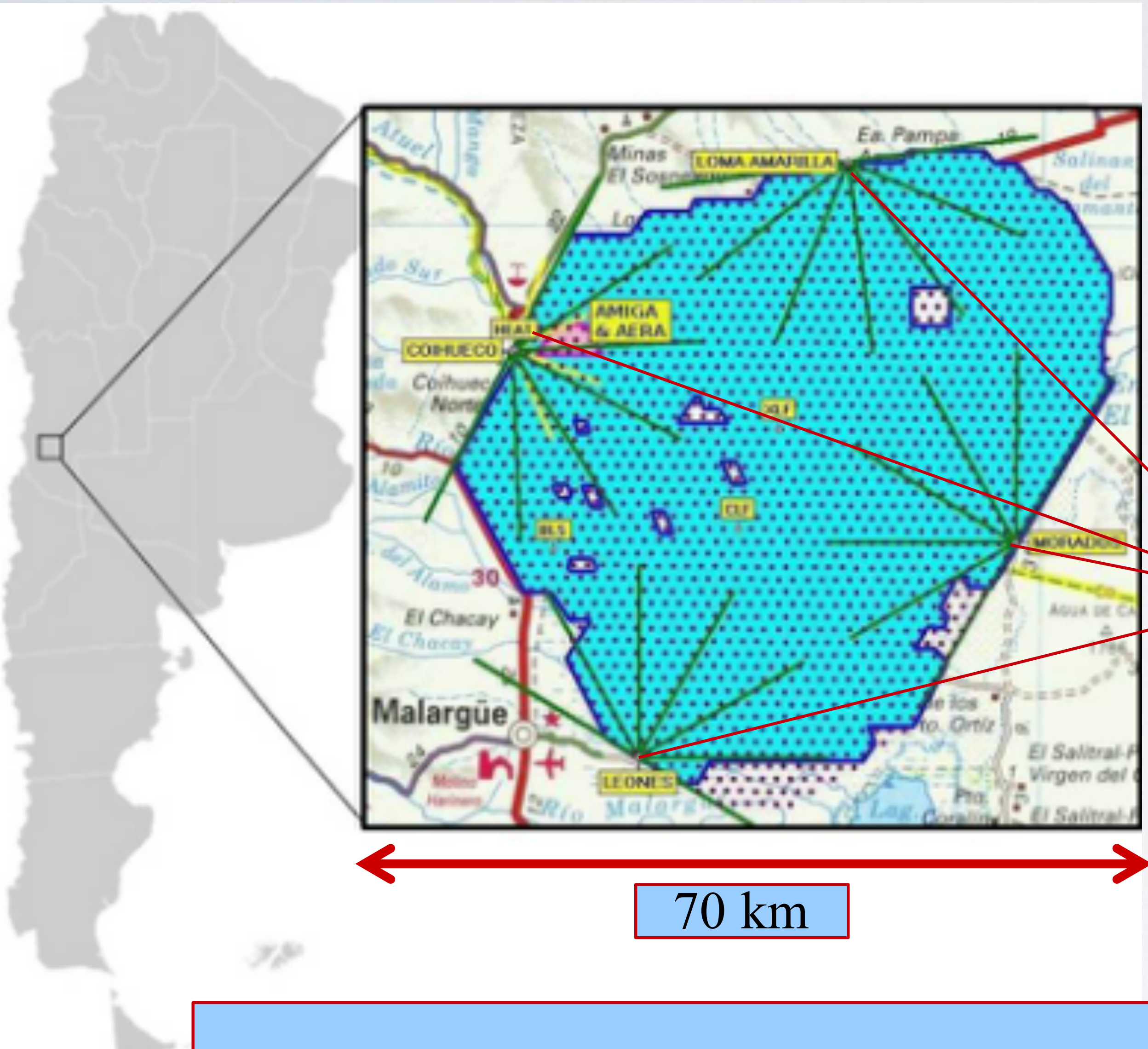
Most of their properties remain mysterious

- Origin?
- Source of acceleration?
- Composition?

They are scarce and with energies beyond human reach!



The Pierre Auger Observatory



- Located near Malargüe (Argentina)
- More than **3000 km²**
- **Hybrid detector**
- **4** Fluorescence sites with 6 telescopes each (FD)
- More than **1600** water Cherenkov detectors (SD)

- FD → Longitudinal development of
- the E.M. Shower (14% duty cycle)

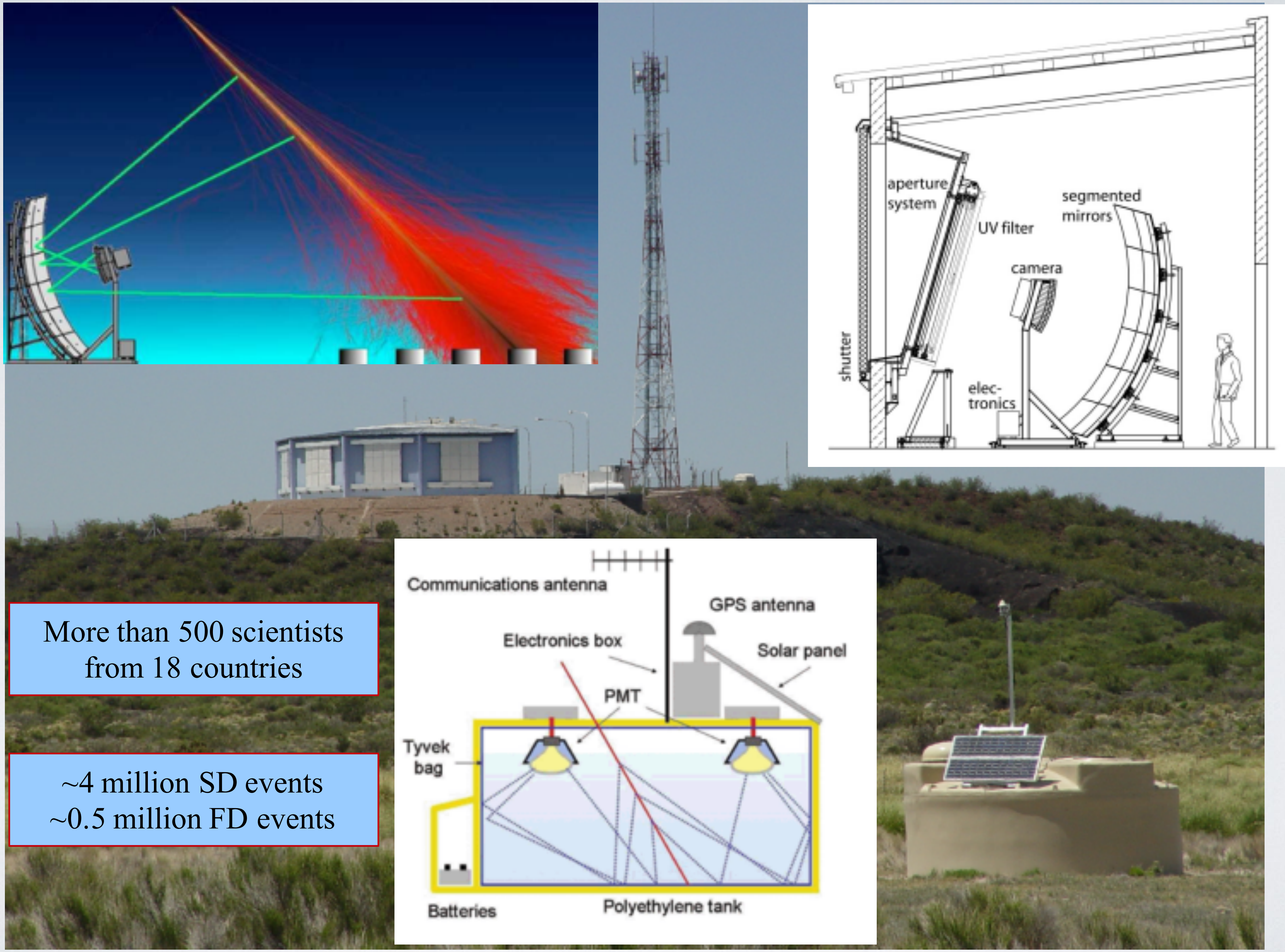
- SD → Transversal sampling of
- the shower front (~100% duty cycle)

Two independent and complementary detectors!

↓

Data-driven calibration

Detection technique



More than 500 scientists from 18 countries

~4 million SD events
~0.5 million FD events

man Bldg. L. Barker. 1408 Chap-

MEN WANTED

for hazardous journey, small wages, bitter cold, long months of complete darkness, constant danger, safe return doubtful, honor and recognition in case of success.

Ernest Shackleton 4 Burlington st.

MEN—Neat-appearing young men pleasing

Mad

Hopeless

Possible