Physicists Hail Major Breakthrough After Discovering Neutrinos Just Little Italian Neutrons

https://www.theonion.com/physicists-hail-major-breakthrough-after-discovering-ne-1844363984

CHICAGO—Confirming the search for the mysterious Godfather particle was finally over, physicists at the University of Chicago hailed what they call a major breakthrough Monday after discovering **neutrinos are just little Italian neutrons.** “We’ve long believed neutrinos were created by nuclear reactions inside stars, but the truth is they’re just neutrons that originated in Tuscany, Piedmont, Sicily, and other regions of the Italic Peninsula,” said astrophysicist Dr. John Marder, whose experiments that involved shooting beams of neutrinos from a particle accelerator allowed scientists to observe that the Italian neutrons left behind nearly imperceptible trails of marinara sauce. “Over 100 trillion neutrinos pass through your body every second, but you never feel their little chef’s hats or big, bushy, black mustaches. That’s because matter has little effect on neutrinos; they only interact via the weak nuclear force to gesticulate wildly about nearby pizzerias or argue about the proper way to make a gravy. Discovering they are fluent in Italian has revolutionized our understanding of the quantum world.” At press time, Marder decried the idea that all neutrinos have mafia ties as a harmful, scientifically incorrect stereotype.

QuarkNet Summer Session for Teachers: The Standard Model and Beyond

Allie Reinsvold Hall

https://quarknet.org/content/quarknet-summer-session-teachers-2020

Summer 2020

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Ancient Greeks to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. Particle physics at the Large Hadron Collider (LHC)
4. Beyond the Standard Model at the LHC
5. **Neutrino physics**
6. Dark matter and cosmology

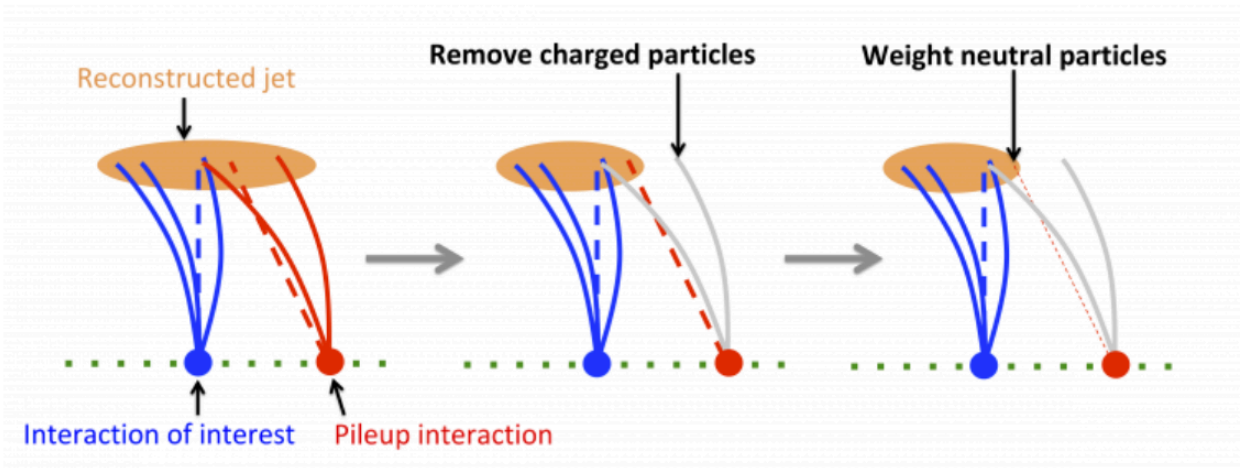
Many thanks to Kirsty Duffy for letting me borrow some of her slides!

Loose ends – questions

- When searching for supersymmetry, how do you know you have found one of the particles and not something else?
  - Theorists tell us what to look for; if SUSY exists, we should find evidence in many different types of events, all consistent with what the theorists predicted
- Is supersymmetry a way to describe dark matter or is that something else?
  - Dark matter could be made of "sparticles" in SUSY, but dark matter could be unrelated to SUSY. SUSY also solves other problems.
- Has evidence of supersymmetry been obtained from the LHC?
  - No ☹ But we're still looking!
- What about string theory?
  - SUSY is one ingredient for string theory, but even if we find SUSY that doesn't mean string theory is right

Loose ends – questions

- How do we ensure that the particles we are studying originated in the main collision and not one of the concurrent pileup collisions?



https://cms.cern/news/how-cms-weeds-out-particles-pile

- What is the source of the protons at the LHC? How much mass have we collided?
  - Protons start from a bottle of hydrogen gas. One bottle can fuel the LHC for 200,000 years

Loose ends – questions

- Is there a limit to how quickly you can disregard data?
  - Hardware trigger has 3.8 μs to decide; software trigger has 200 ms to decide
  - Throw boring events away as soon as possible so you have more time to sort the really interesting events from the kinda interesting events
- I still don't understand how they are able to choose the tiny amount of data they keep compared to what is collected.
  - Example triggers: save all events with missing momentum > 150 GeV; save all events with a muon with pT > 30 GeV; save all events with two photons with mass > 100 GeV
  - Trade-off between rates (how much you save) and physics ability
- Have any interesting results been found through random data collection vs data collected that meets set criteria?
  - These are called "minimum bias" events and are useful to double check what we are doing
- For the quadruplet top quark result, the ATLAS result was nearly 5σ but the CMS result was only 2.6σ (less likely to be a real discovery). Why did ATLAS record such a significantly different result than CMS?
  - Different amounts of data, different analysis techniques, random fluctuations

Neutrino Physics

I have done a terrible thing: I have postulated a
particle that cannot be detected.
- Wolfgang Pauli, 1930

Homework discussion

- Introduce yourself to today's group.

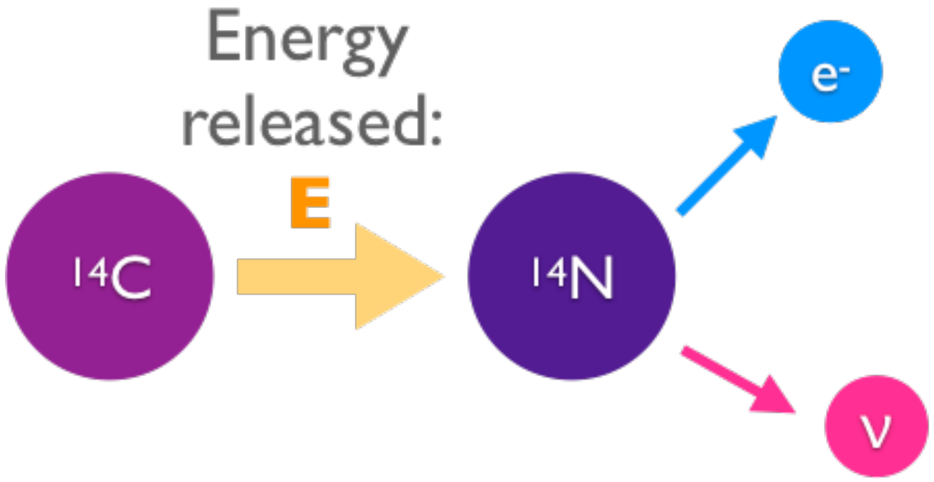
Discuss the following questions about the Gizmodo article:

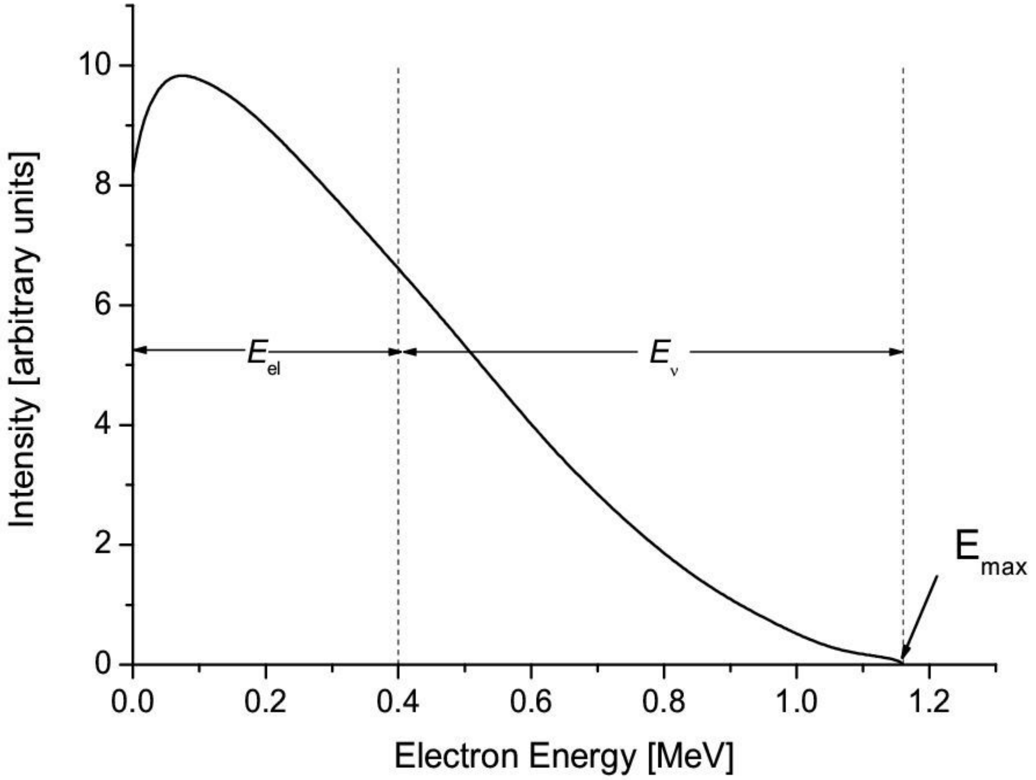
https://gizmodo.com/why-the-u-s-is-betting-it-all-on-the-most-puzzling-par-1843517654

- What part of the article stood out to you?
- What are the similarities and differences between neutrino experiments and collider experiments like ATLAS and CMS at the LHC?
- What is one of the questions that DUNE is trying to answer?

Where to find neutrinos

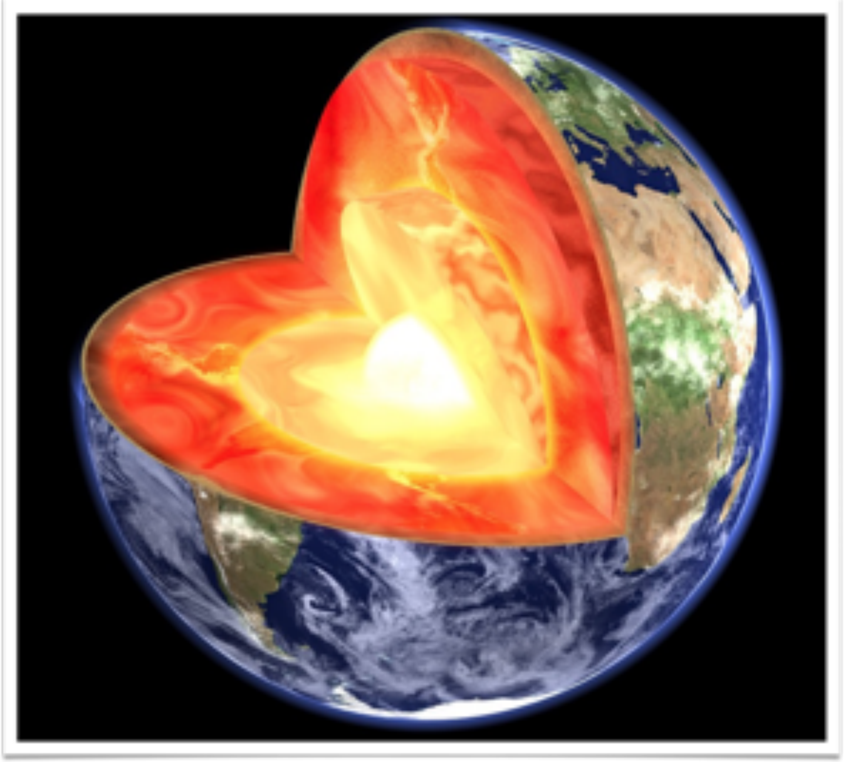
- Radioactivity: Continuous energy spectrum of electrons from β decay is why Pauli proposed neutrinos in 1930





Where to find neutrinos

- Produced in radioactive β decays from the Earth's core or natural radioactive isotopes all around us



Where to find neutrinos

- Nuclear reactions in stars and supernova explosions

Crab Nebula after a supernova. Credit: NASA, ESA, J. Hester, A. Loll (ASU)

Where to find neutrinos

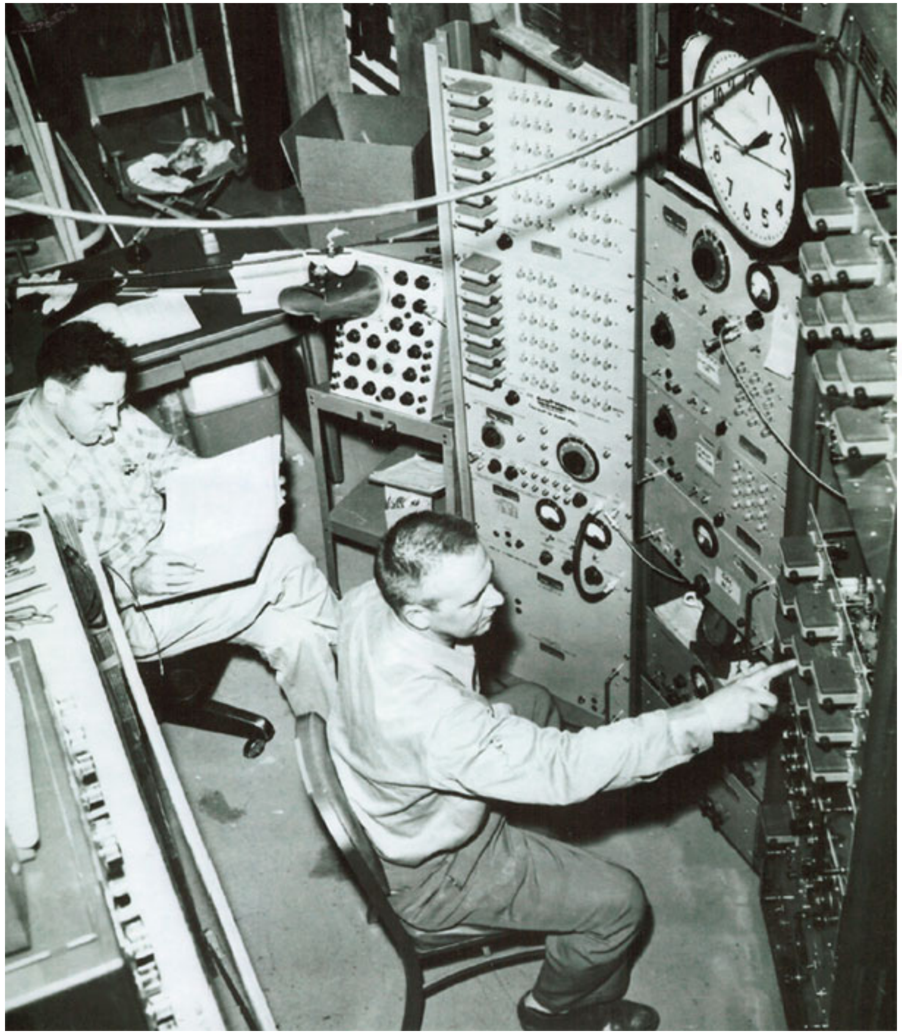
- Produced at nuclear reactors or from particle accelerators

How to detect neutrinos

- Neutrinos only interact via the weak force
- Would need a light year of lead to have a 50% chance of interacting

Recipe for neutrino experiment

1. Use an intense neutrino source to produce neutrinos to study
2. Build the biggest detector possible to increase chances of interacting
3. Minimize backgrounds from other sources (go underground)
4. Collect data over a long period and analyze results



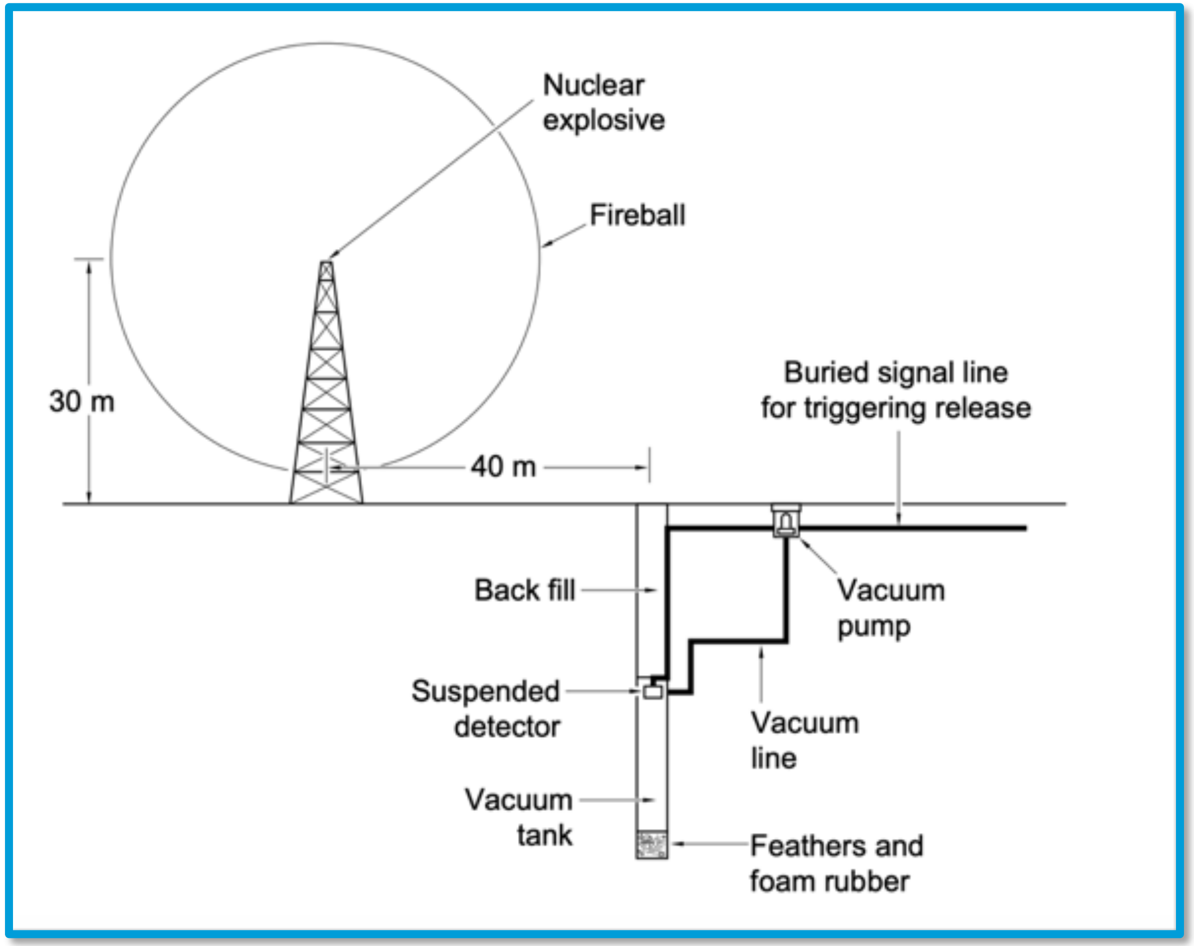
Cowan and Reines at the 1956 Savannah River experiment; Image Credit: Los Alamos National Laboratory

Intense neutrino source?

- Project Poltergeist (Cowan, Reines) originally planned to detect neutrinos from a nuclear bomb explosion

Simple plan:

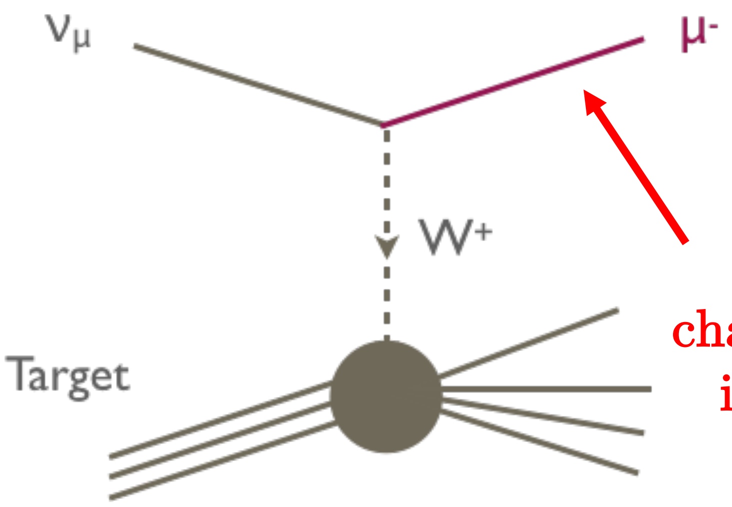
1. Explode a nuclear bomb
2. At the same time, drop a neutrino detector down a shaft (to protect it from the ground shaking)
3. Detect neutrinos
4. Wait until the radiation dies down to recover the detector
5. ...repeat?



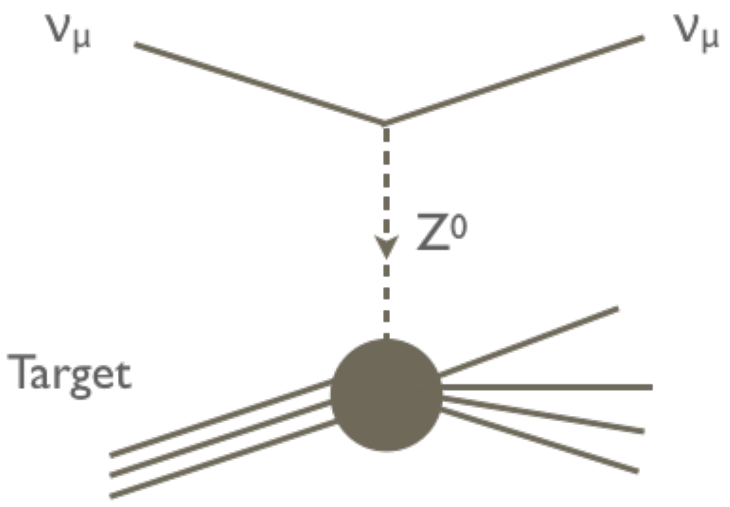
- Eventually decided to use nuclear reactors instead

How do neutrinos interact?

- We can never "see" neutrinos
- What we can (sometimes) see are the **particles that neutrinos produce** when they interact
- Then try to infer the presence of the neutrino and its flavor



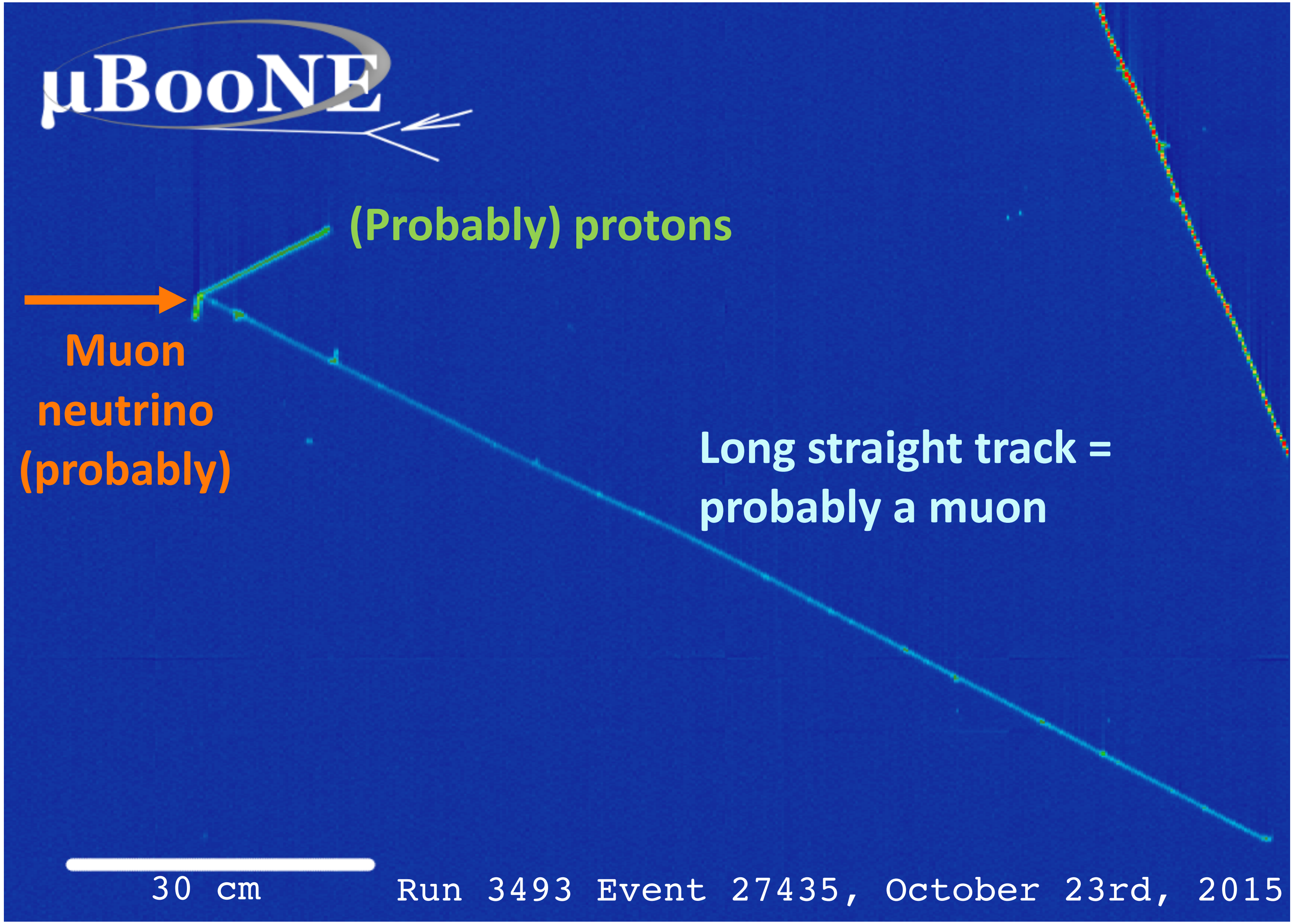
Focus on charged-current interactions today



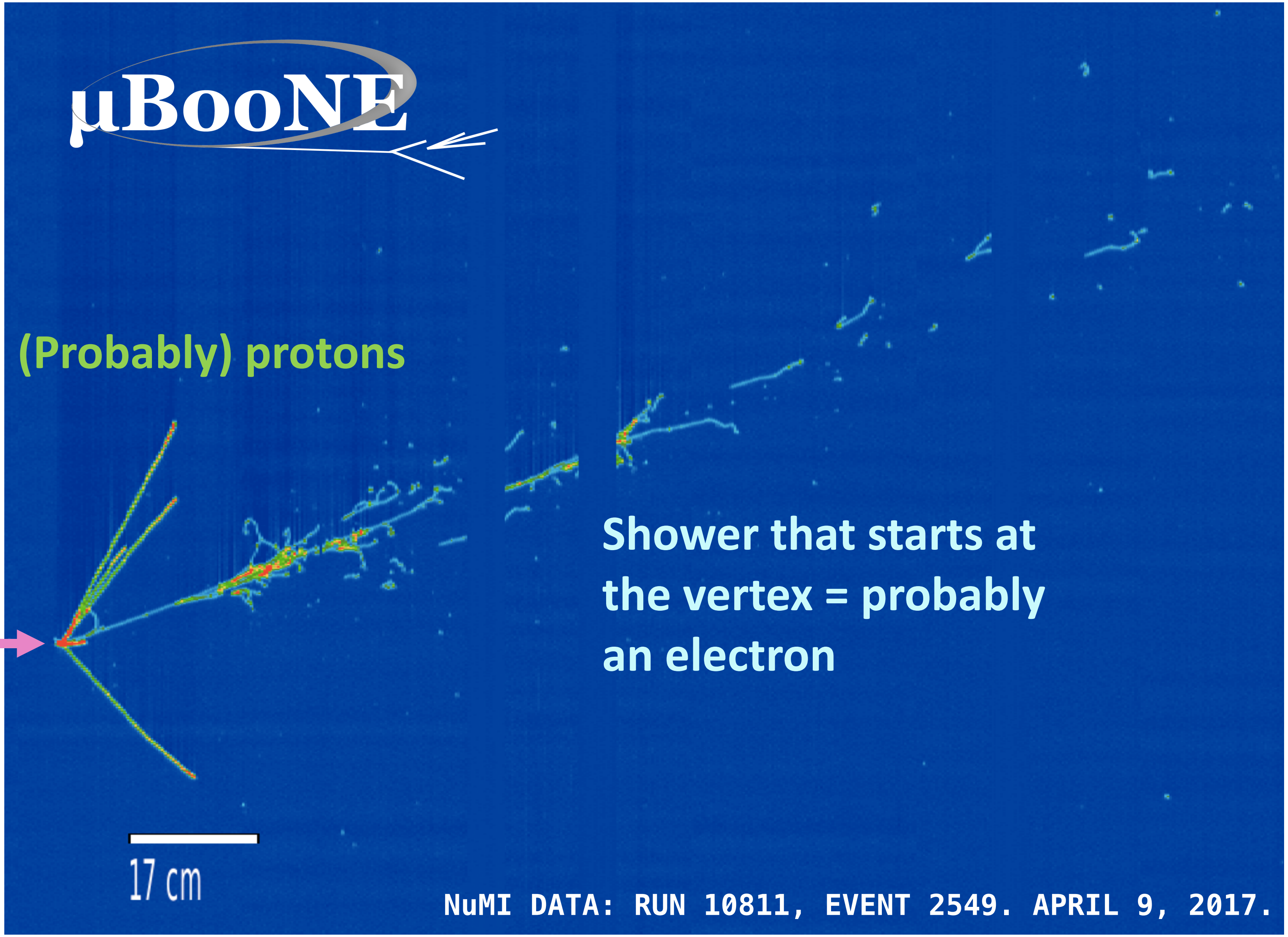
Charged-current interaction
→ Exchange of W boson
→ Lepton produced with **same flavor as original neutrino**

Neutral-current interaction
→ Exchange of Z boson
→ Independent of neutrino flavor
→ No way to know what flavor neutrino interacted

What does a neutrino interaction look like?

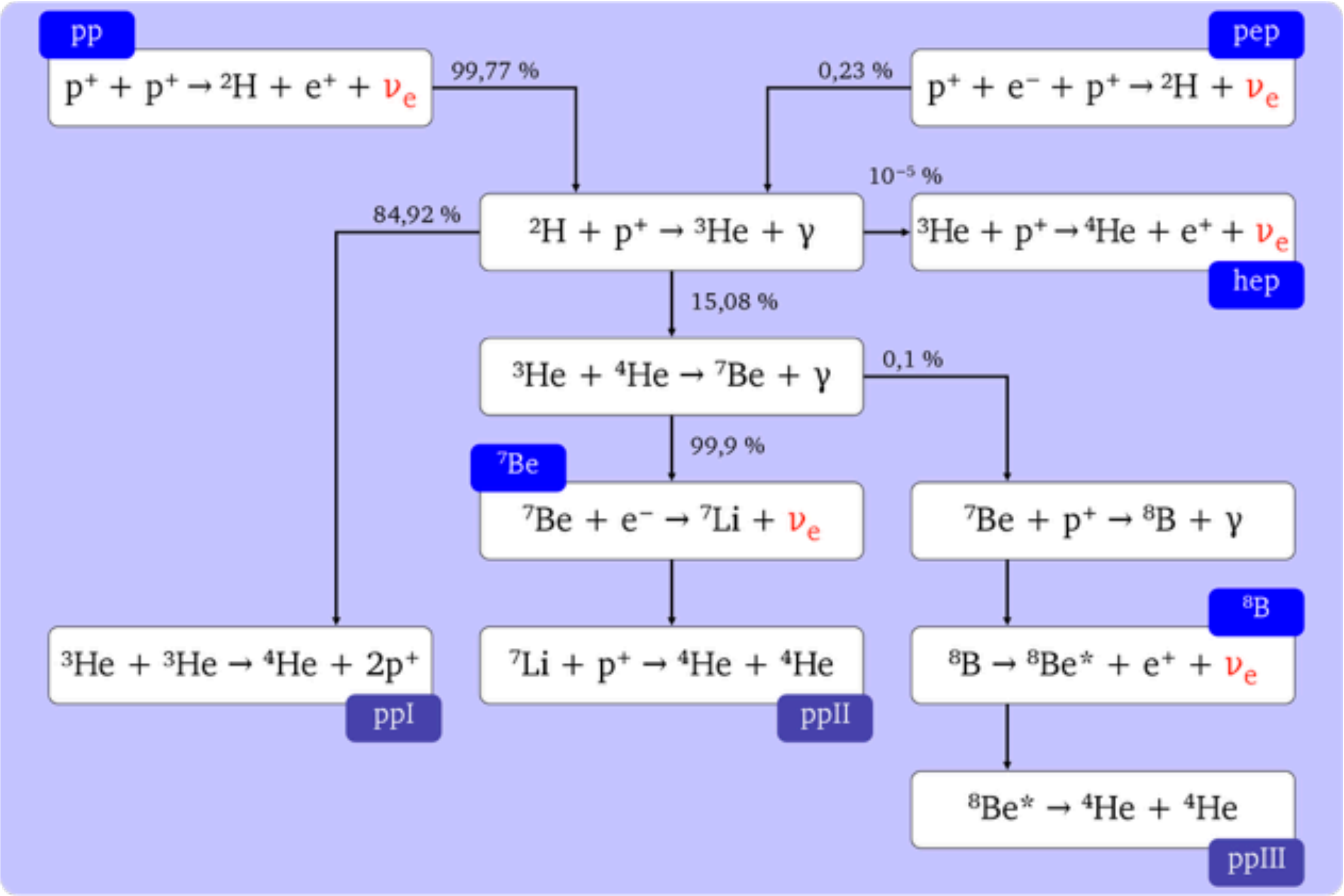


What does a neutrino interaction look like?



Electron neutrino (probably)

Solar neutrinos



- The sun's energy comes from **nuclear fusion** via the pp and pep chains
- Multiple stages produce **low-energy electron neutrinos**

The case of the missing neutrinos

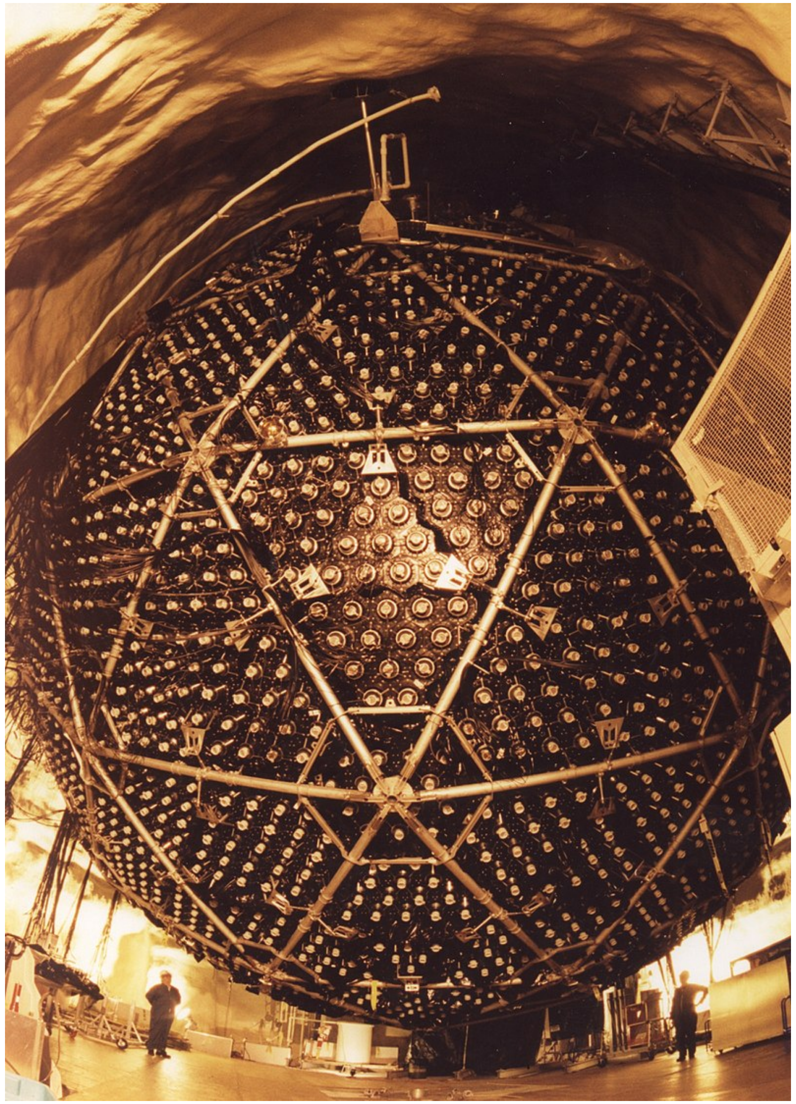
- Ray Davis (1914 - 2006) led the Homestake experiment to measure neutrinos from the sun
- Experiment ran in 1960s - 1980s
- 100,000 gallon tank of dry cleaning fluid
- 4850 feet underground in the Homestake mine in South Dakota
- Look for Ar from $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
- Expected **36 Ar atoms** per month
- Observed **2-3 times fewer neutrinos** than prediction

Davis's Homestake experiment

The suspects

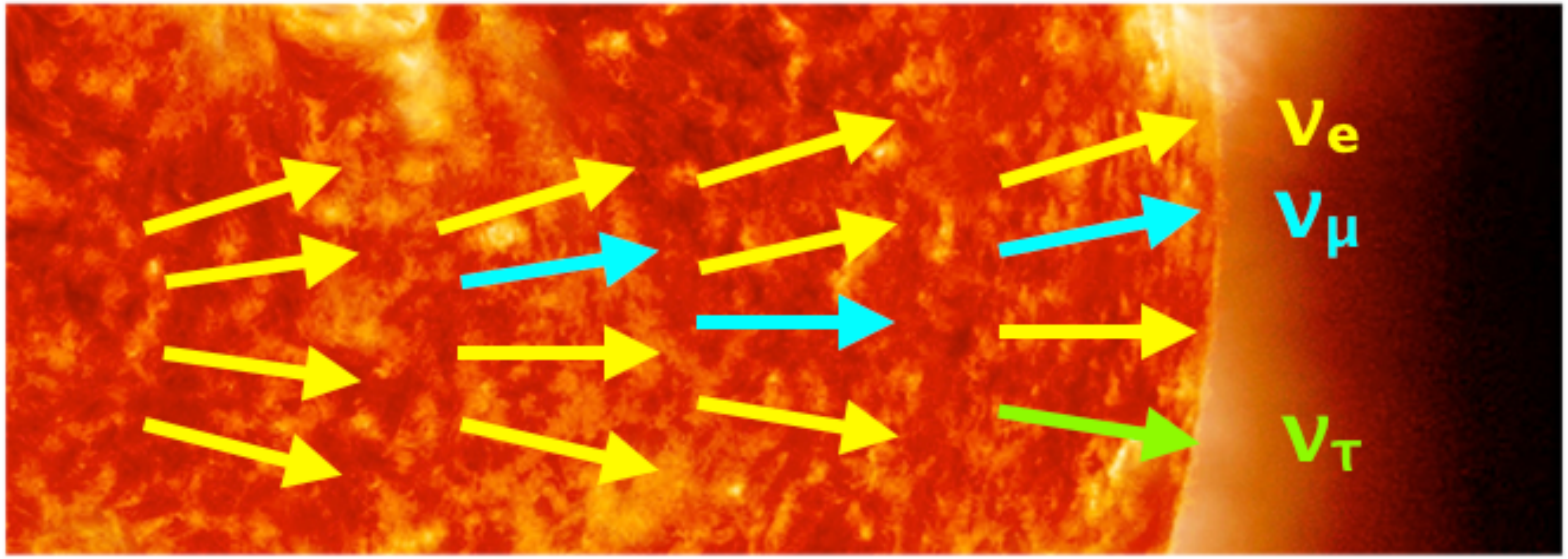
- Bad experimental data?
  - Results backed up by different experiments (Kamiokande, GALLEX, SAGE, SNO)
- Bad solar models?
  - Sudbury Neutrino Observatory (SNO) in Canada could measure all three types of neutrino via the **neutral** current interaction
  - Could also measure electron neutrinos alone
  - Total number of neutrinos matched solar models

Fun facts about SNO:
- 7000 feet underground
- Operated 1999 – 2006
- Director Art McDonald


Sudbury Neutrino Observatory

The culprit: neutrino oscillations

- SNO results unambiguously confirmed that **neutrinos change flavor**
- Neutrino states depend on whether they are interacting or traveling freely
- Davis only looked for ν_e, known to be produced in the sun
- By the time they leave the sun, ½-⅔ have changed to ν_μ or ν_τ
- Evidence is now overwhelming that neutrino oscillations occur

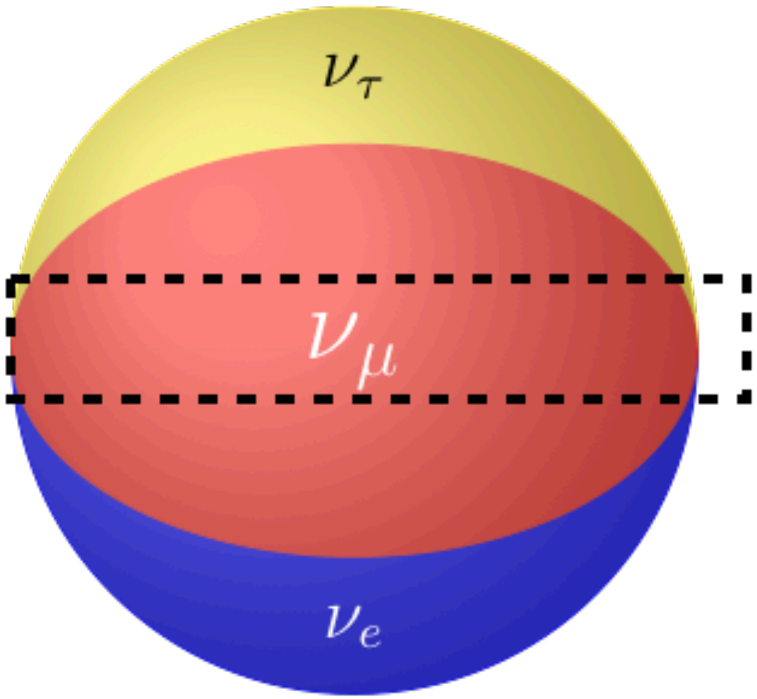


2002 Nobel Prize:
Ray Davis (Homestead), Masatoshi Koshiba (Kamiokande II)

2015 Nobel Prize:
Art McDonald (SNO), Takaaki Kajita (Super-Kamiokande)

Beach balls and neutrinos

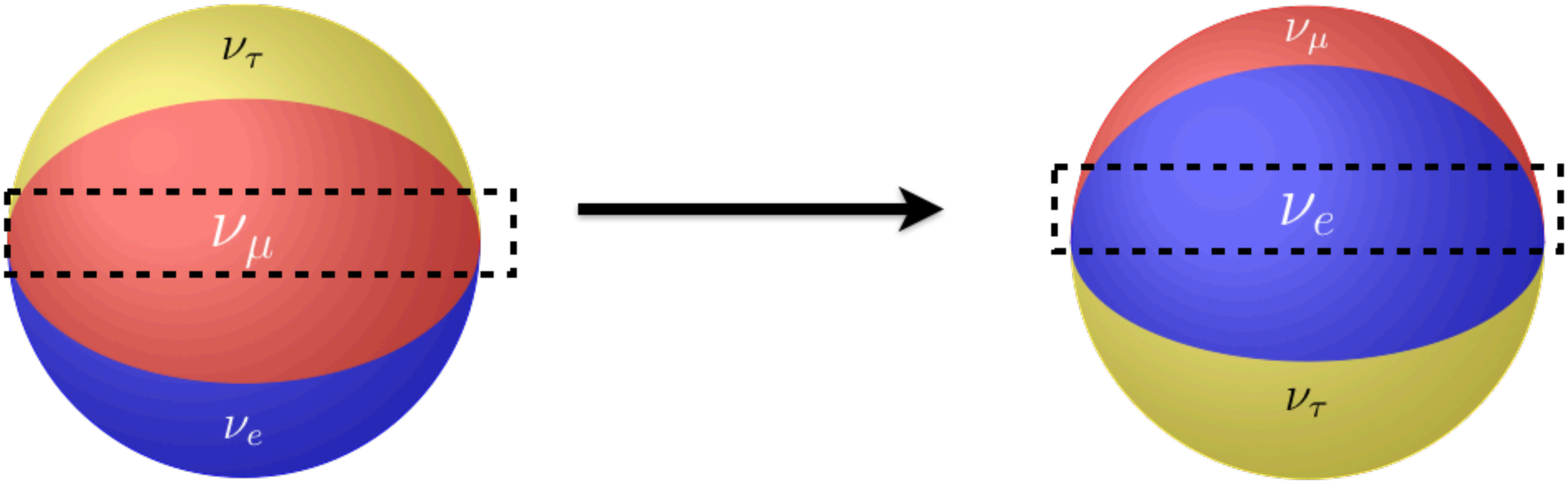
- Can only see one color at a time – to you, the beachball is red



L. Pickering

Beach balls and neutrinos

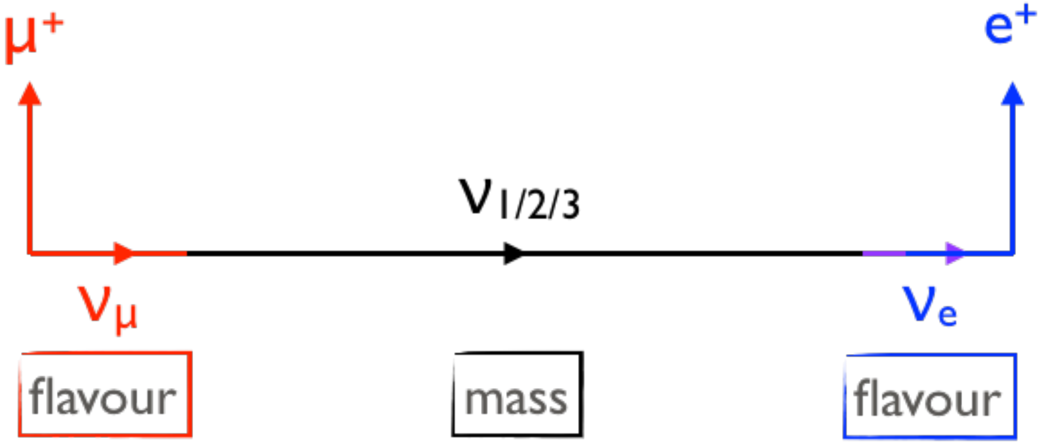
- Can only see one color at a time – to you, the beachball is red
- But if you throw it to your friend, it looks blue!

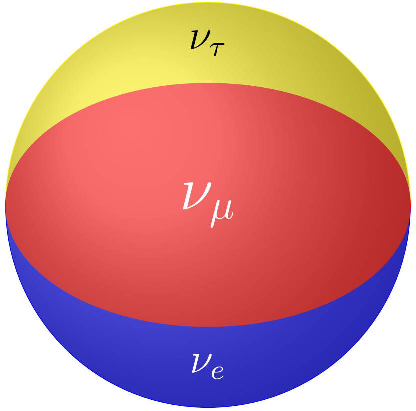


L. Pickering

Neutrino oscillations

- Neutrinos in free space are in **mass states** (like the colorful beachball)
- But when we observe them, we observe the neutrino **flavor states** (colors)





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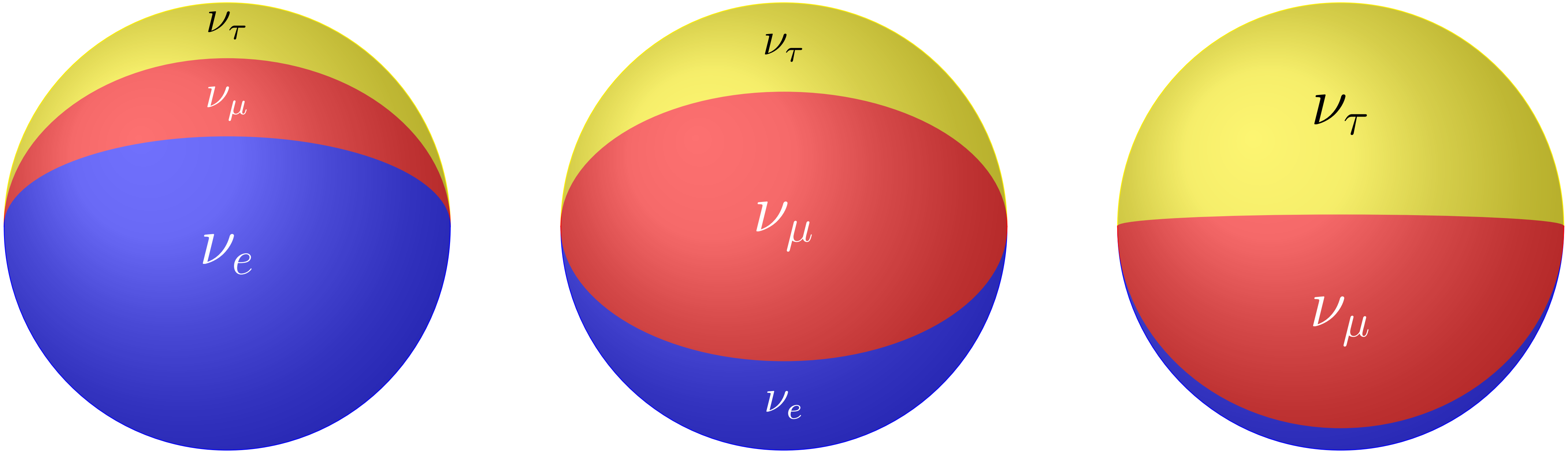
Neutrino oscillations

- But there isn't only one beachball...

Mass states → ν_1 ν_2 ν_3

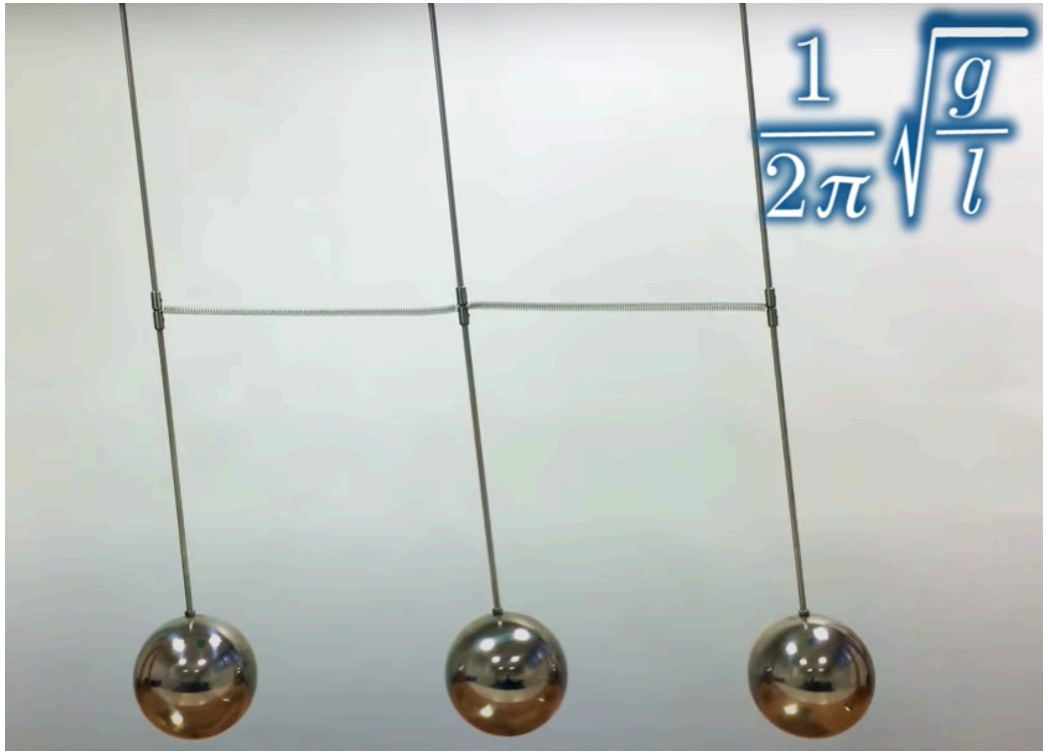


L. Pickering

Homework discussion

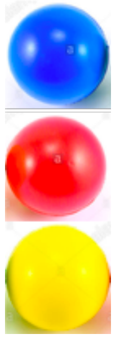
- Show off your pendulum (if you want to). What were the challenges in building it? What did you do differently from the online instructions?
- How does this relate to neutrino oscillations? What part of the pendulum's motion corresponds to the neutrino mass states and what part corresponds to the neutrino flavor states?

- Pendulum normal modes $\rightarrow$ neutrino mass states
- Start one pendulum oscillating $\rightarrow$ start with only electron neutrinos
- Over time, others start moving $\rightarrow$ chance to find neutrino in different flavor states

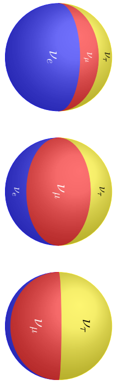


PMNS matrix

- PMNS matrix (Pontecorvo, Maki, Nakagawa, and Sakata) describes how to relate flavor states to the mass states
- Similar to the CKM matrix we discussed for quarks



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



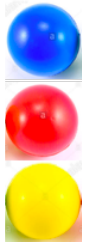
L. Pickering

PMNS matrix

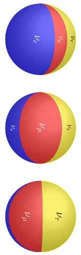
- PMNS matrix (Pontecorvo, Maki, Nakagawa, and Sakata) describes how to relate flavor states to the mass states
- Three mixing angles – $\boldsymbol{\theta_{12}}, \boldsymbol{\theta_{23}}, \boldsymbol{\theta_{13}}$ – that describe the mixing between two mass states
- One phase $\boldsymbol{\delta_{CP}}$ that we'll come back to later
  - Relates to whether neutrinos and antineutrinos behave differently

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino oscillation probability

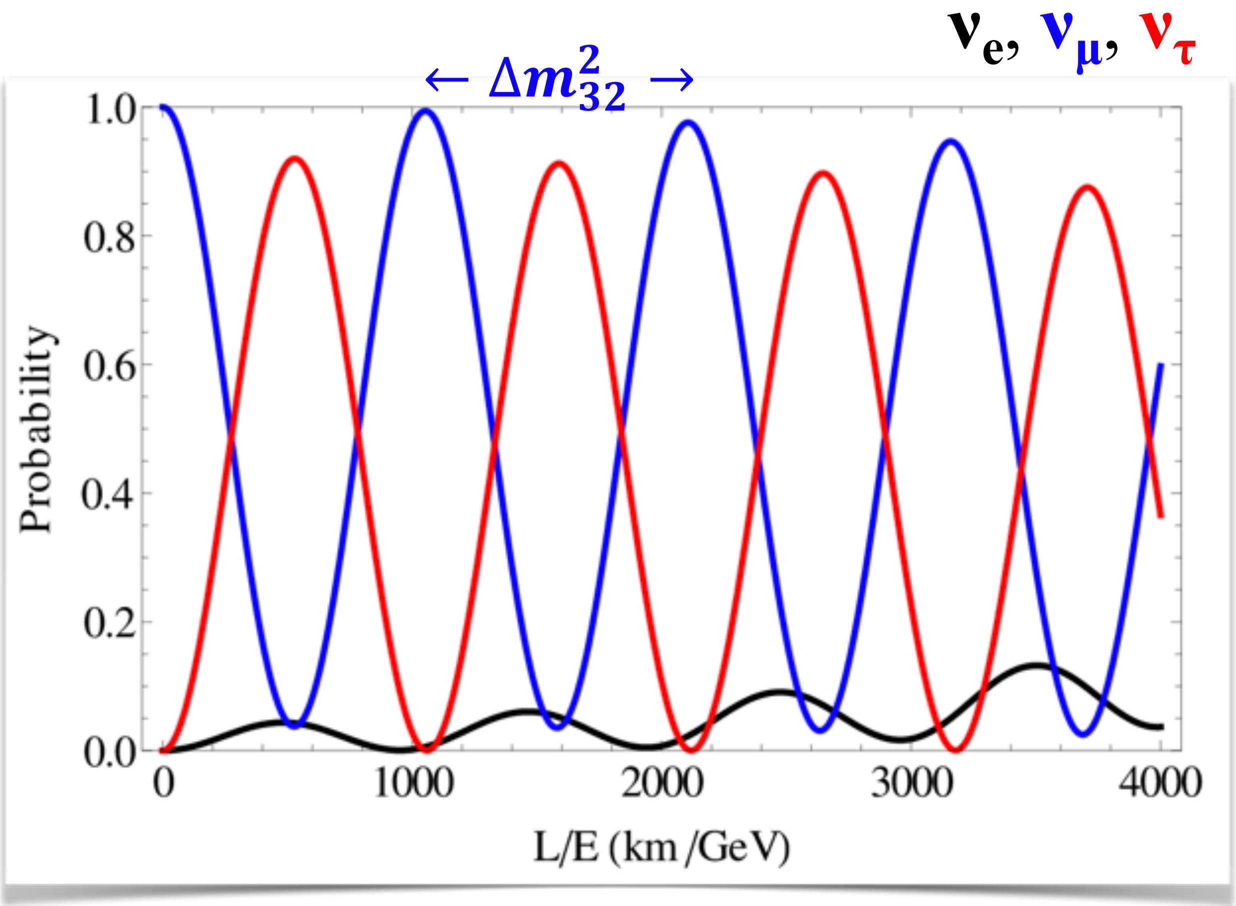
- Imagine we have a **muon neutrino** (ν_μ) with **energy E**
- Let it travel some **distance L**, then calculate the **probability to still measure a muon neutrino**

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

Depends on mixing parameters θ_{13}, θ_{23}

and the mass-squared splitting:

$$\Delta m^2_{32} = \Delta m^2_3 - \Delta m^2_2$$



Neutrino oscillation parameters

- Thanks to many experiments around the world, using different sources of neutrinos, we have measurements of almost all neutrino oscillation parameters:

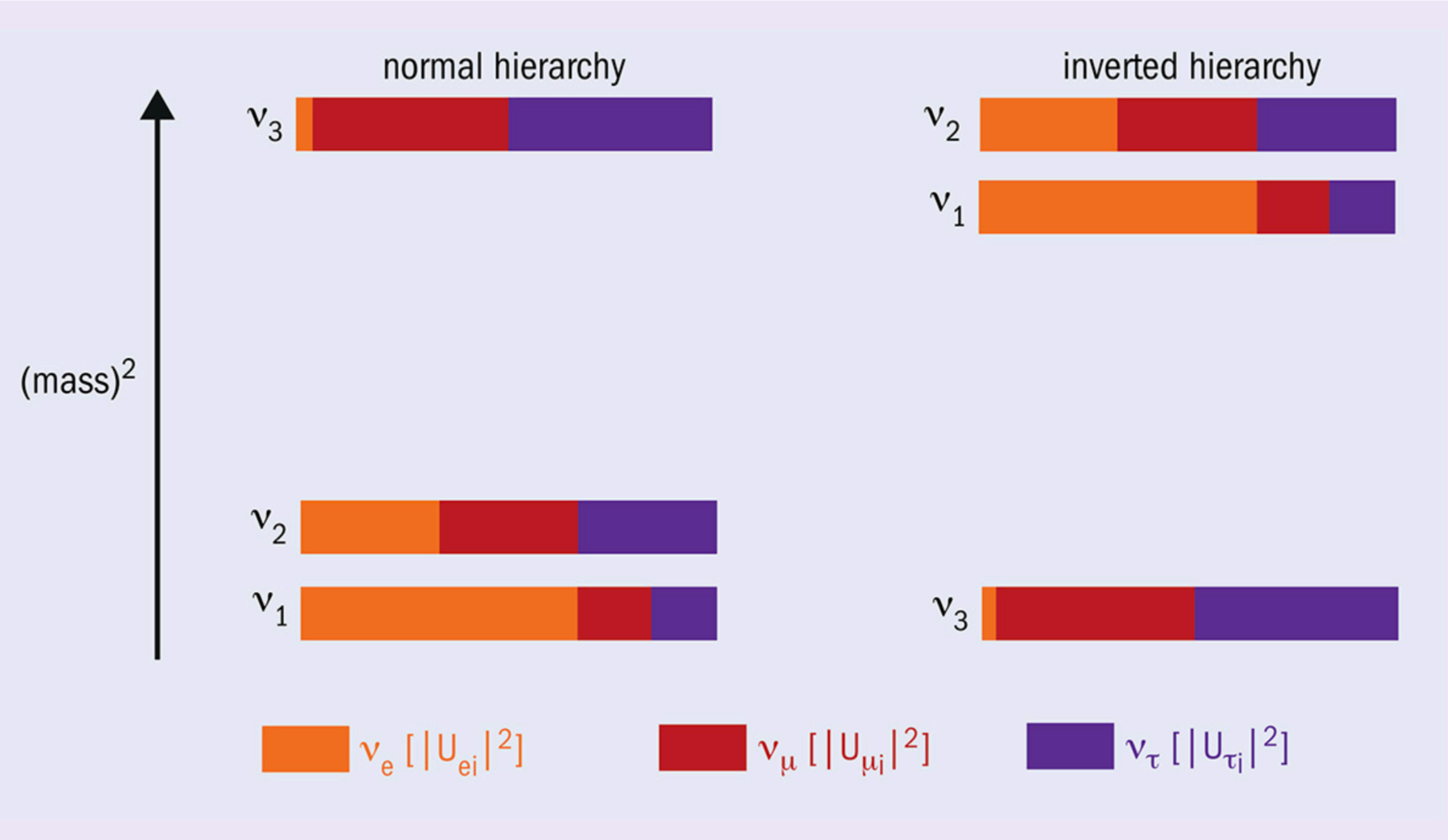
θ_{12} ✔ solar ✔ reactor
θ_{23} ✔ atmos. ✔ accel.
θ_{13} ✔ solar ✔ reactor ✔ atmos. ✔ accel.
Δm^2_{21} ✔ solar ✔ reactor
$|\Delta m^2_{32}|$ ✔ atmos. ✔ accel.
δ_{CP} ? atmos. ? accel.

$$\theta_{12} = 33.62^\circ {}^{+0.78^\circ}_{-0.76^\circ}$$
$$\theta_{23} = 47.2^\circ {}^{+1.9^\circ}_{-3.9^\circ}$$
$$\theta_{13} = 8.54^\circ {}^{+0.15^\circ}_{-0.15^\circ}$$

$$\Delta m^2_{21} = (7.53 \pm 0.18)\times 10^{-5}\ eV^2$$
$$\Delta m^2_{32} = (2.44 \pm 0.06)\times 10^{-3}\ eV^2$$

Mass-hierarchy problem

Which neutrino is heaviest? (What's the sign of Δm^2_{32}?)



https://cerncourier.com/a/tuning-in-to-neutrinos/

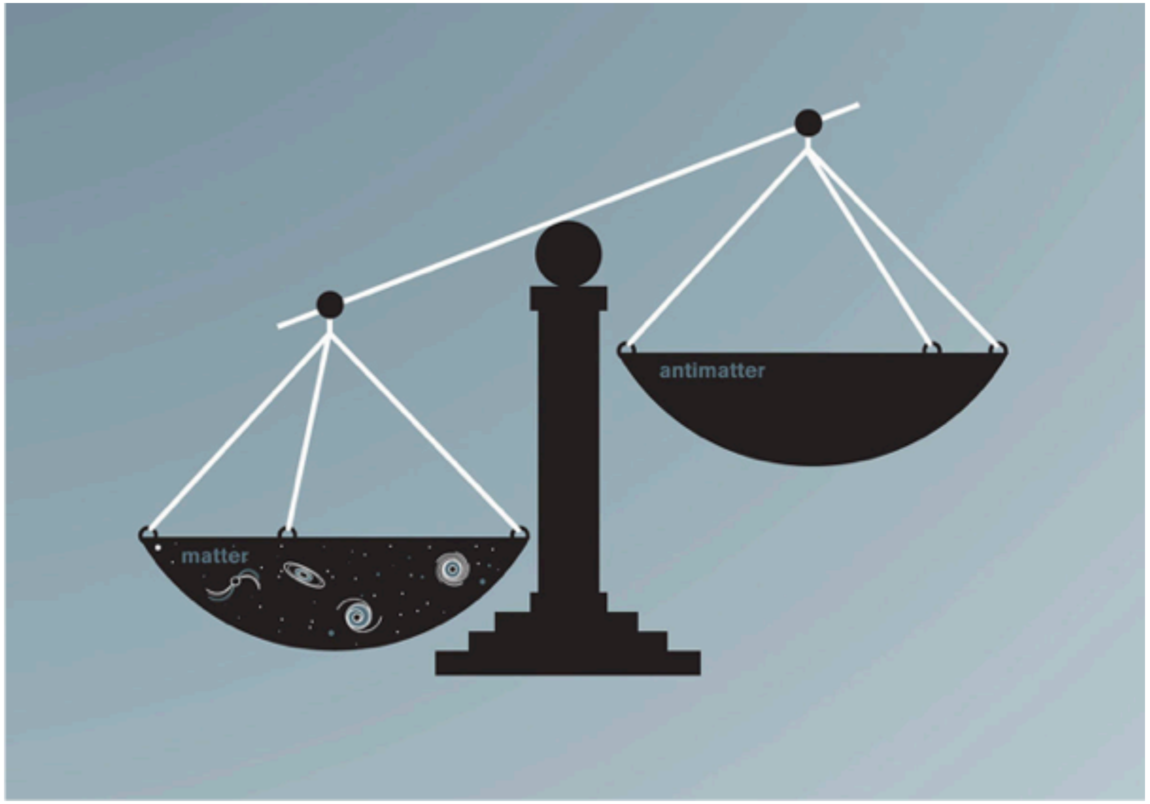
Why do we exist?

- Is neutrino oscillation different for neutrinos and antineutrinos?
- Processes that **violate CP symmetry** ↔ particles and antiparticles are different

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq$ Something

(+)− [Something else x $\sin \delta_{CP}$]

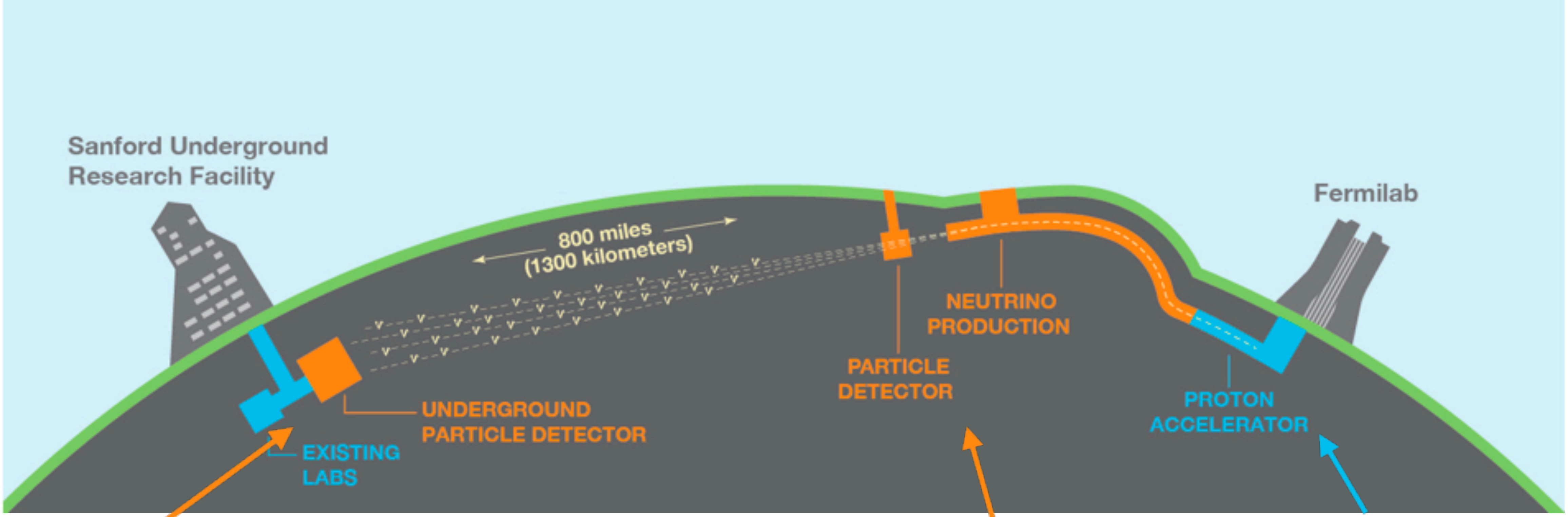
$+$ (CP-even, solar, matter effect terms))



Artwork by Sandbox Studio, Chicago

- T2K (Japan) and NOνA (Fermilab)
- April 2020: T2K released new results giving hints that δ_{CP} is non-zero
  - CP-conservation is ruled out at 2σ

Deep Underground Neutrino Experiment



Measure at far detector: look for differences to near detector!

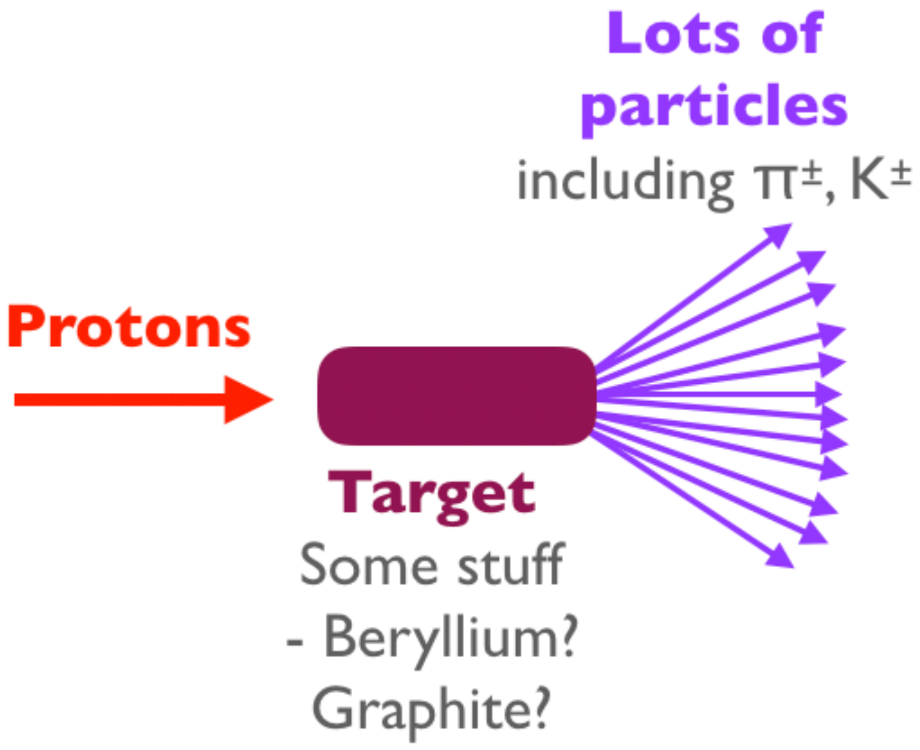
Travel a long distance ...

Measure at near detector: confirm neutrino flavors, energies, interactions

Make neutrinos using particle accelerator

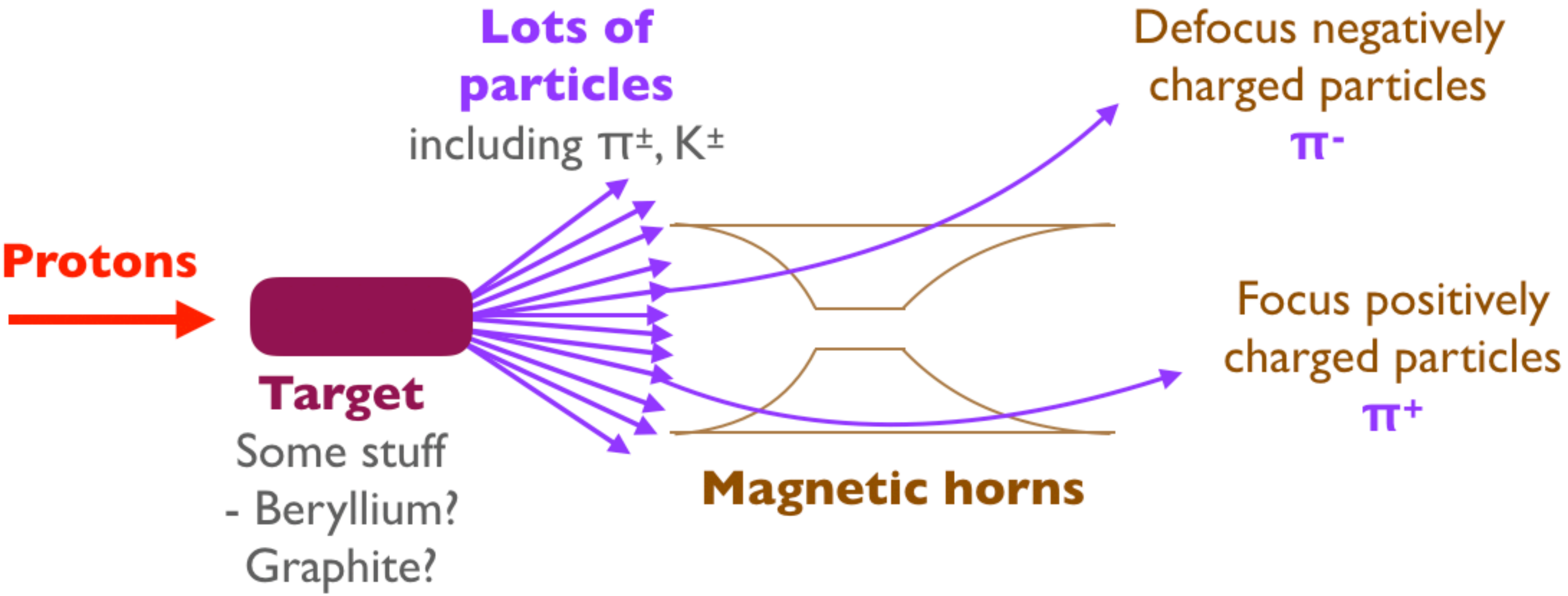
How to make a neutrino beam

- Two accelerators that can make neutrino beams: Fermilab and J-PARC in Japan



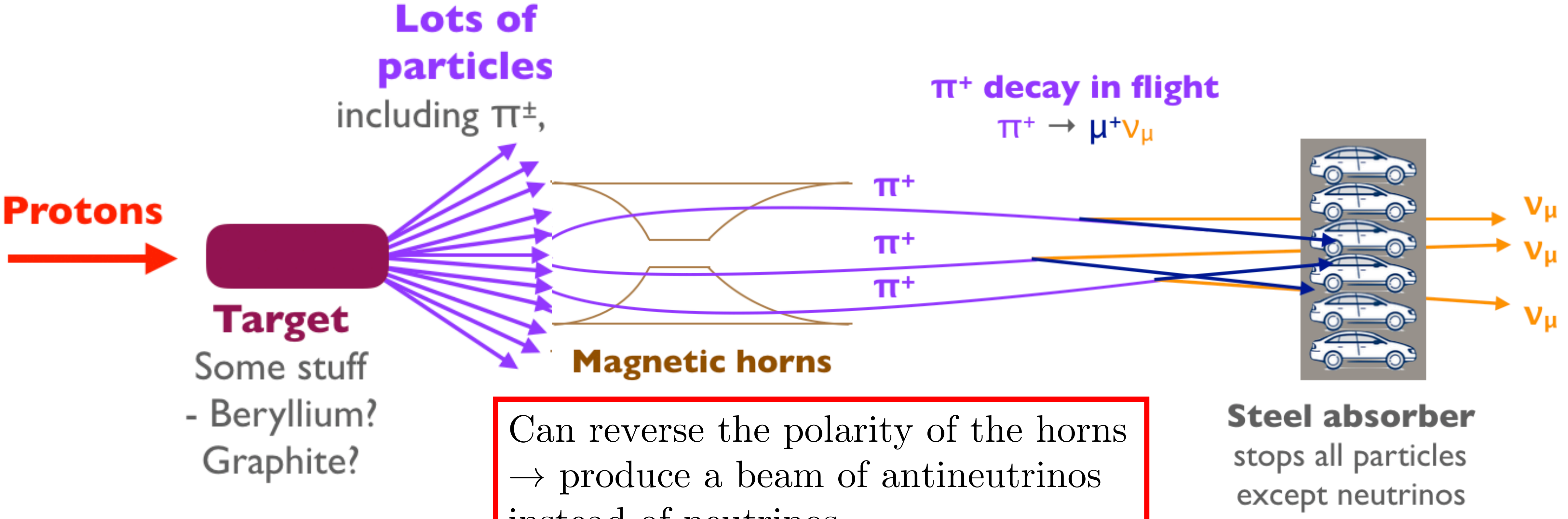
How to make a neutrino beam

- Two accelerators that can make neutrino beams: Fermilab and J-PARC in Japan
- Use a magnetic horn to select positive or negative pions



How to make a neutrino beam

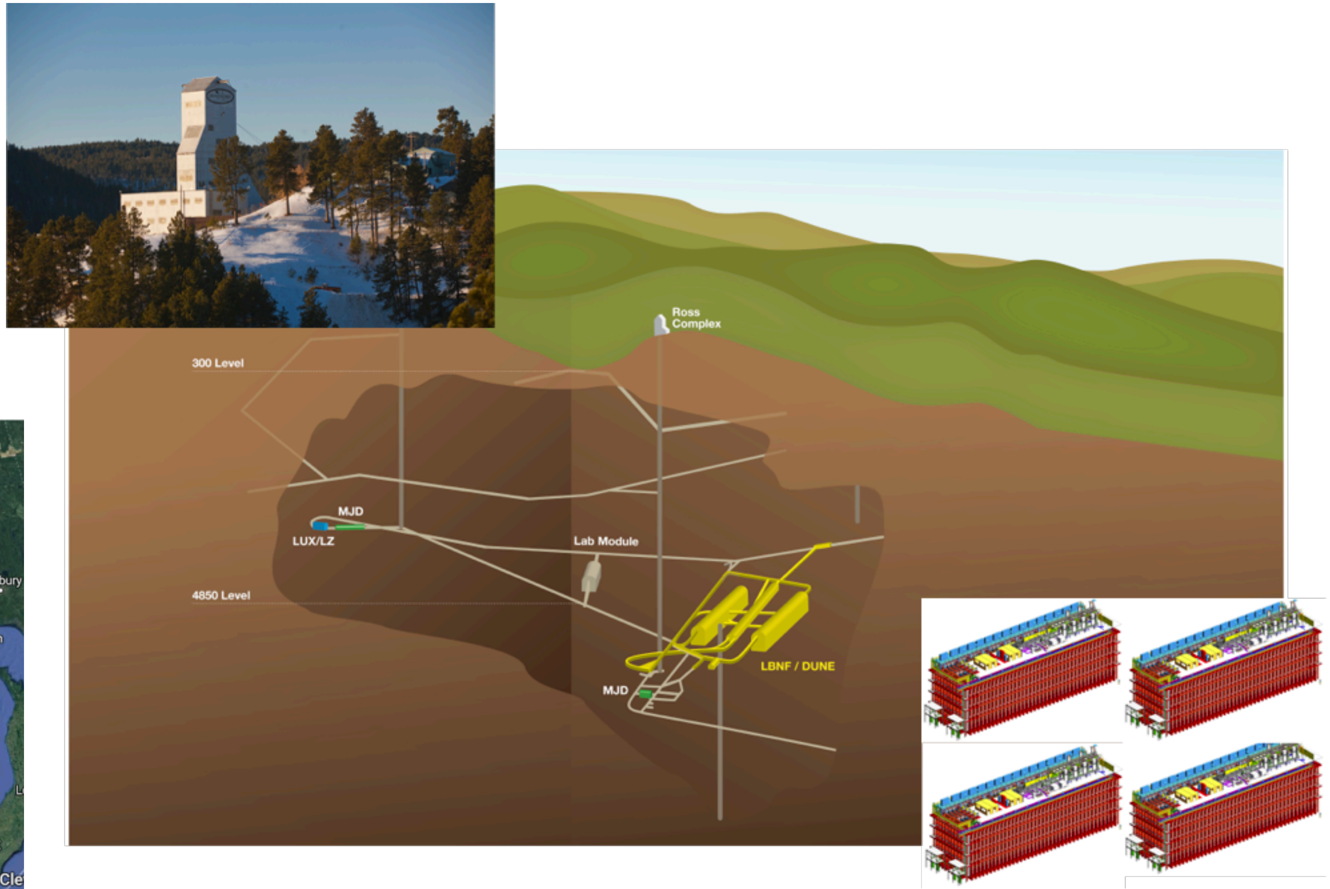
- Two accelerators that can make neutrino beams: Fermilab and J-PARC in Japan
- Use a magnetic horn to select positive or negative pions
- Focus pions, get rid of other decay products... get beam of neutrinos!

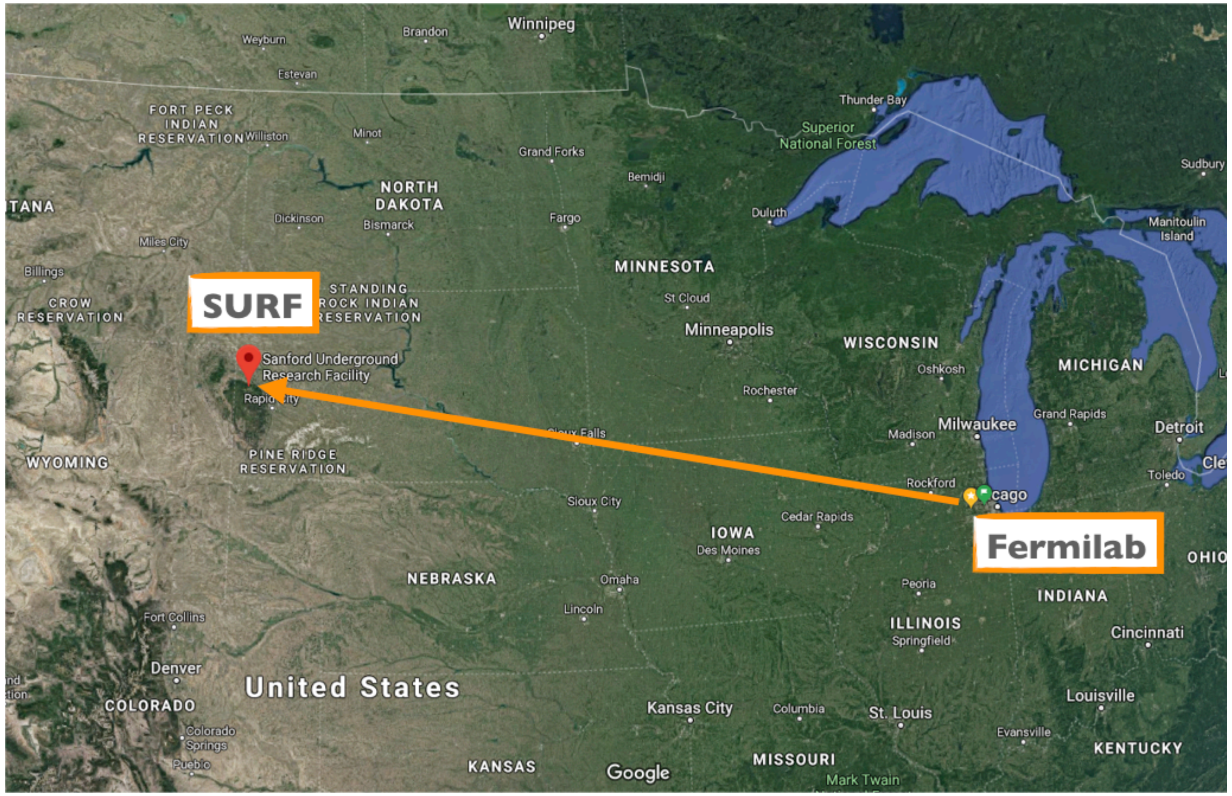


Can reverse the polarity of the horns
→ produce a beam of antineutrinos
instead of neutrinos

DUNE facilities

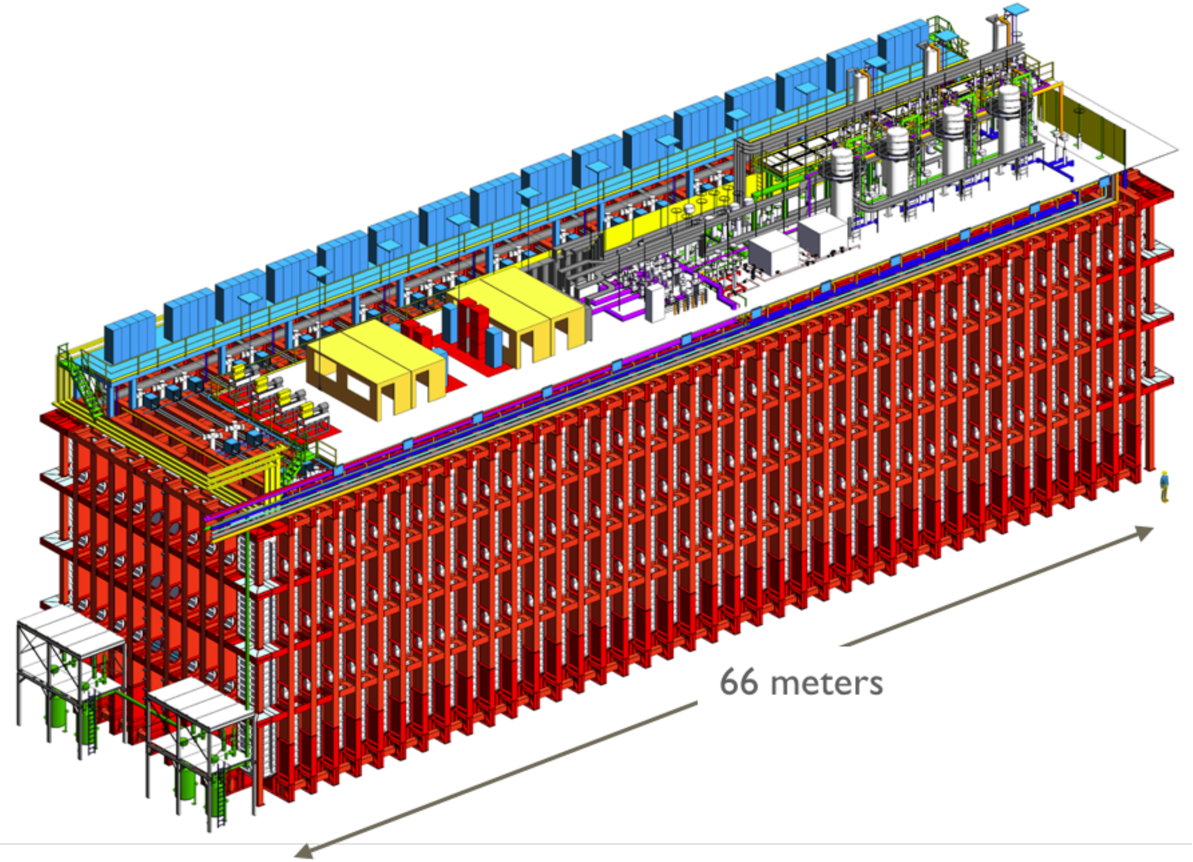
- Excavations happening now
- First data-taking planned for 2026

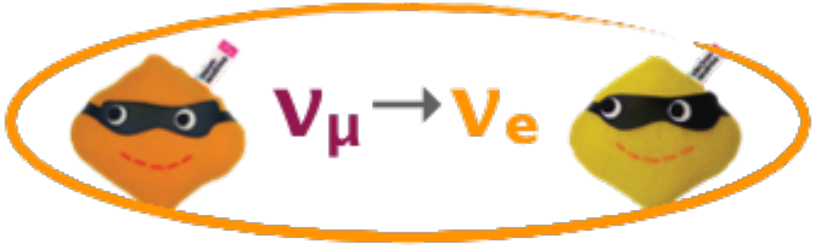


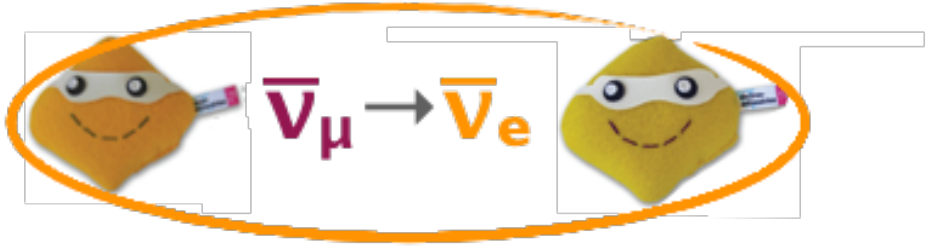


DUNE physics

- Far detector made of four gigantic tanks of liquid Argon
  - same technology as MicroBoone event displays showed earlier
  - Total 40 kton
  - ProtoDUNE at CERN testing the technology now
- Study both muon neutrino and muon antineutrino beams
  - Difference in behavior indicates CP violation

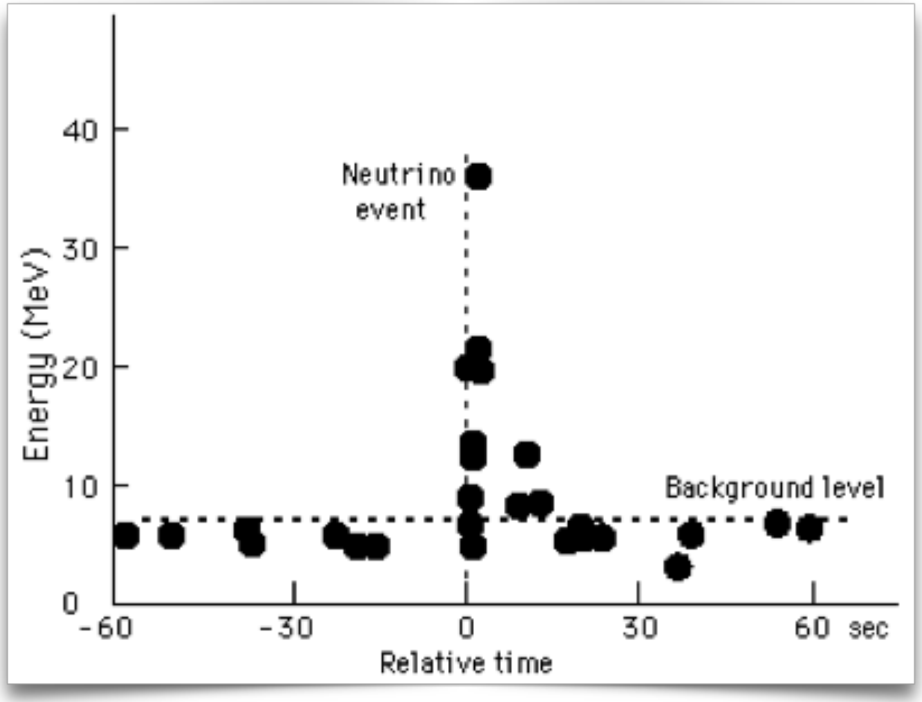


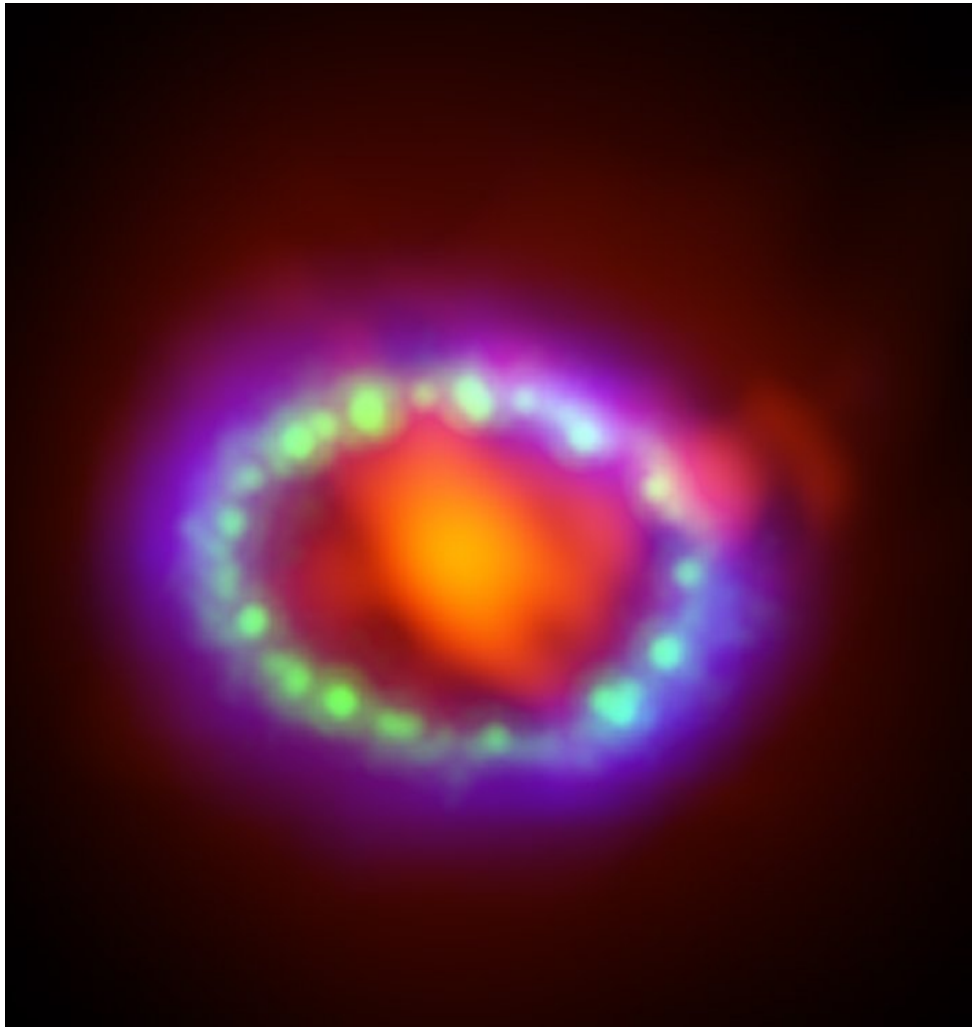




Supernova 1987A

- 25 neutrinos detected from the 1987A supernova explosion
  - Super-Kamiokande: 12
  - IMB: 8
  - Baksan: 5

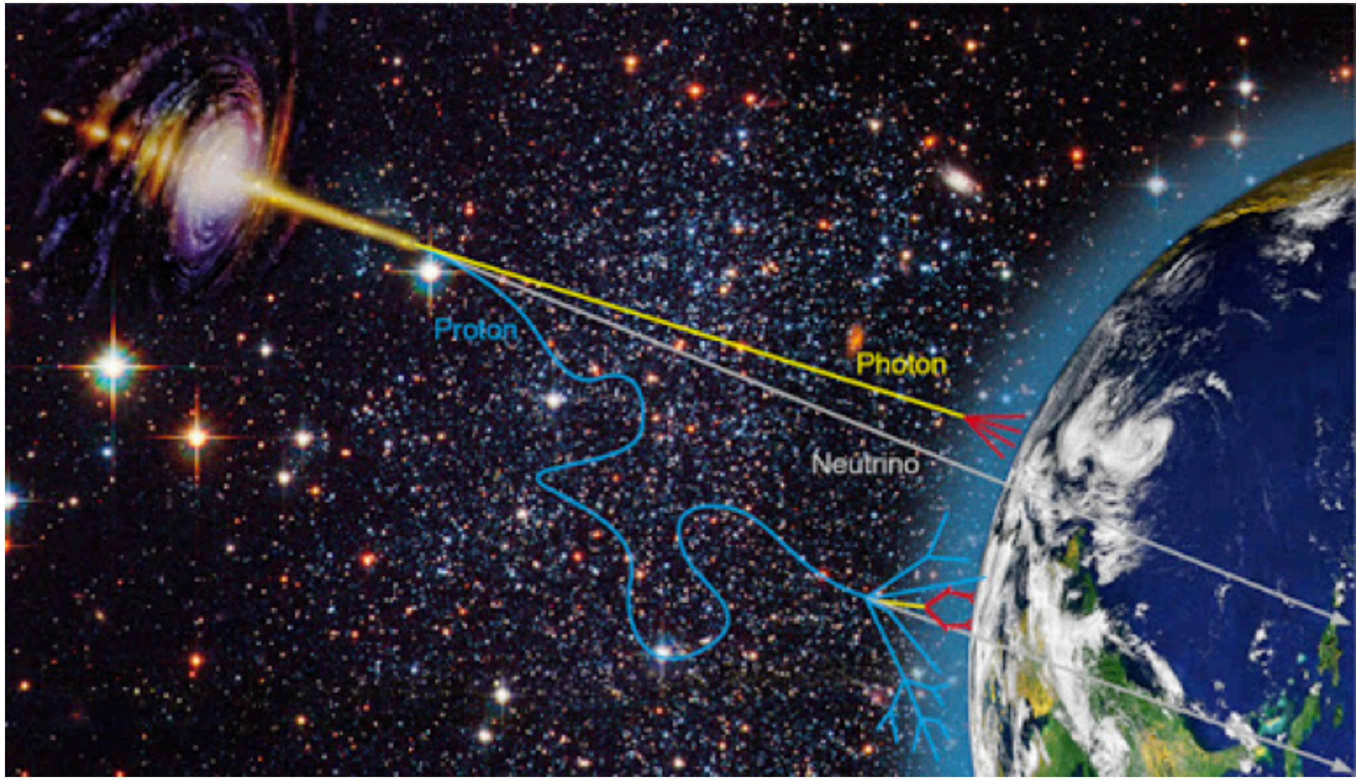




ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory

Multi-messenger astronomy

- Neutrinos are the first signal to arrive on Earth from a supernova
  - Can escape the explosion immediately because they do not interact
  - Light arrives 2-3 hours later, once the explosion becomes transparent
- September 2017: IceCube sees extremely-high energy neutrino event $\rightarrow$ gamma rays later seen from blazar with consistent position
- Supernova Early Warning System (SNEWS), Astrophysical Multi-messenger Observatory Network (AMON) connect many different detectors
  - Neutrinos, gravitational waves, cosmic rays, electromagnetic signals



Conclusions

- Neutrinos are the most difficult SM particle to detect
- First evidence we have of physics beyond the Standard Model
  $\rightarrow$ neutrinos tell us that our understanding of particle physics is incomplete!
- Neutrinos oscillate — changing flavor as they travel over long distances
- There is a lot that we don't know
  - Can they explain matter/antimatter asymmetry?
  - What are their masses? How do they gain mass?
  - Are there "sterile" neutrinos?
- DUNE experiment at Fermilab will help answer some of these questions
- Neutrinos + gravitational waves + traditional observatories give us new ways of learning about the cosmos

Homework assignment – lecture 5

1. Read the dark matter primer and do activities 2 and 4 from the Perimeter Institute's dark matter lesson (sent via email). The full lesson is available for download at https://resources.perimeterinstitute.ca/collections/senior-high-gr-11-12/products/the-mystery-of-dark-matter?variant=17146201478
   - Using Newton's Law of Gravity to predict rotational speeds and compare to observational data of the mass of galaxies and speed of orbiting stars

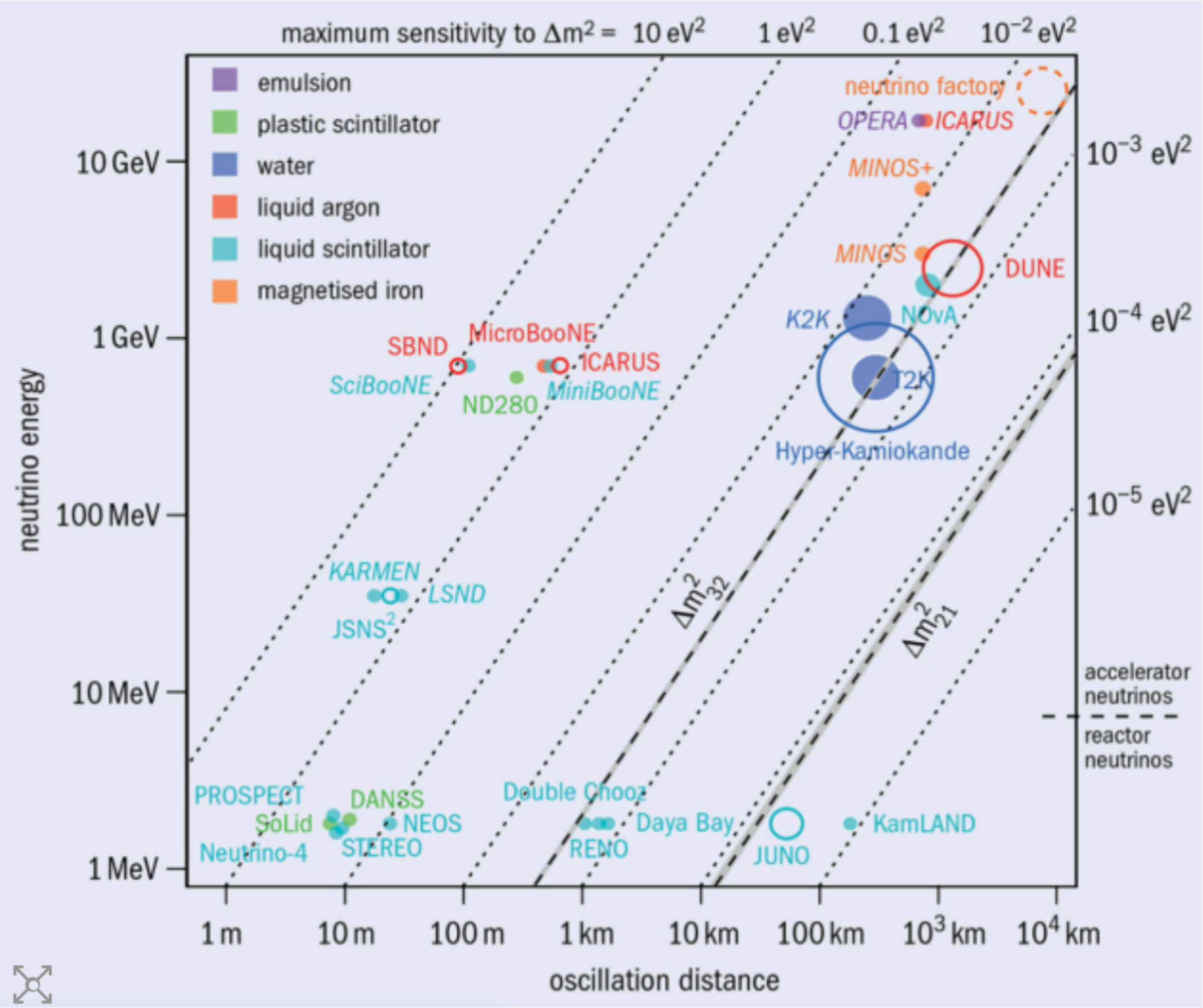
2. Fill out weekly survey

- Additional, optional resources are posted to the course website
- Email me with any concerns or questions

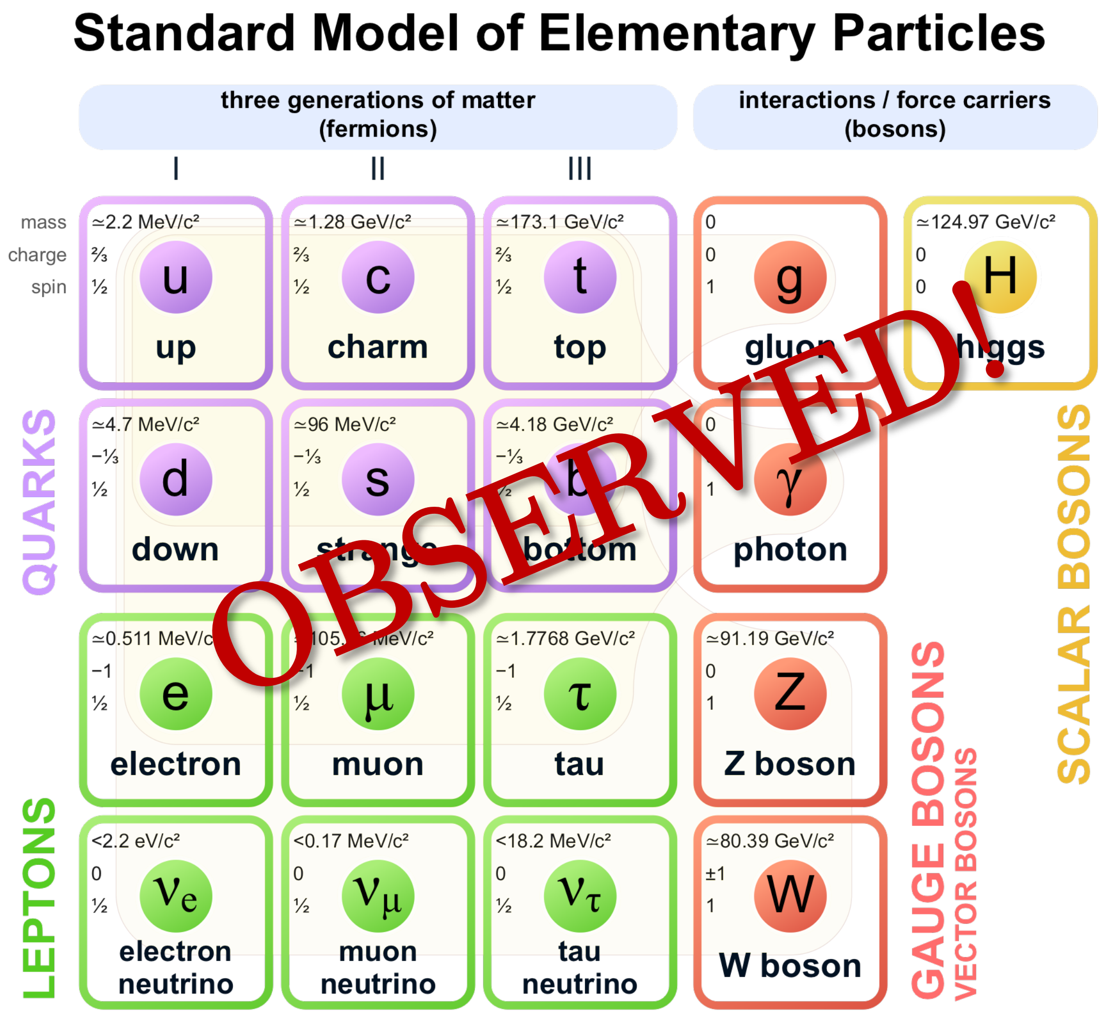
End of Part 4

Neutrino experiments

https://cerncourier.com/a/tuning-in-to-neutrinos/



Standard Model



Observations:

- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN