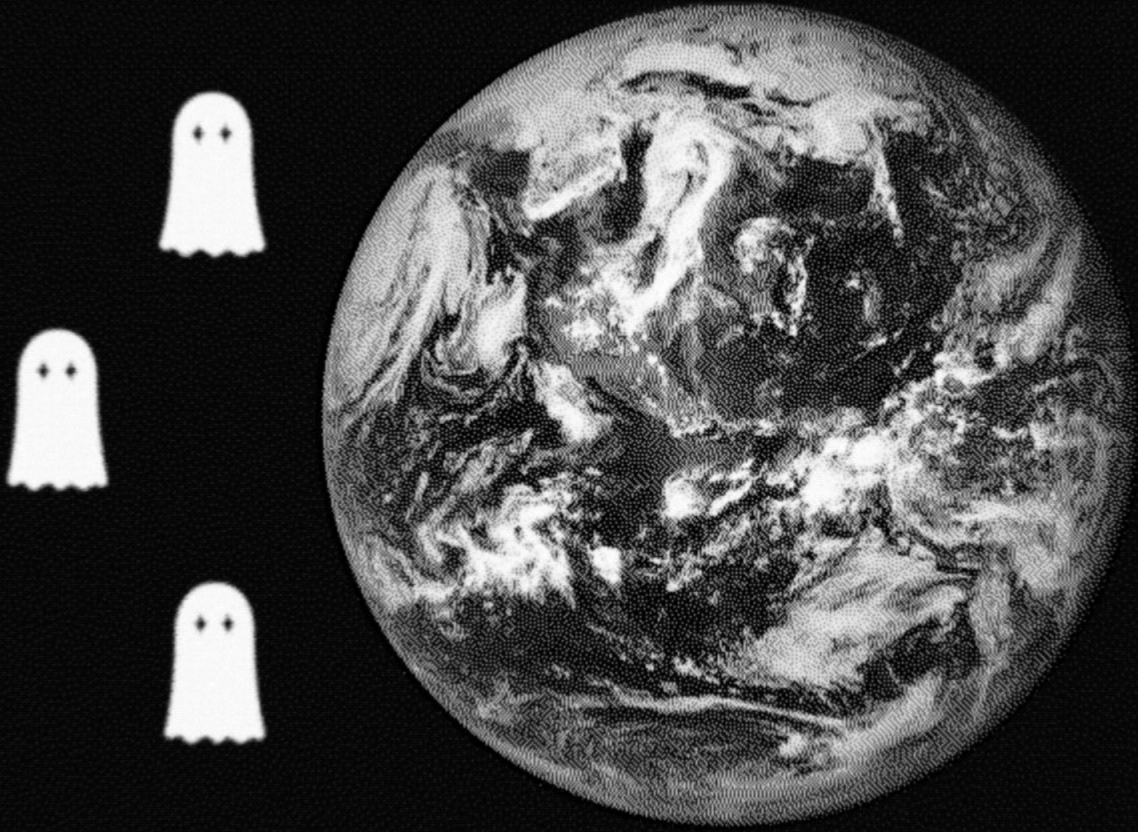
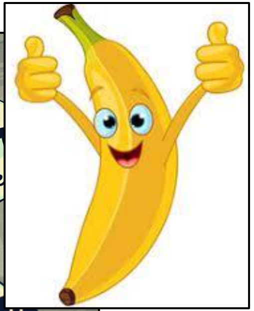
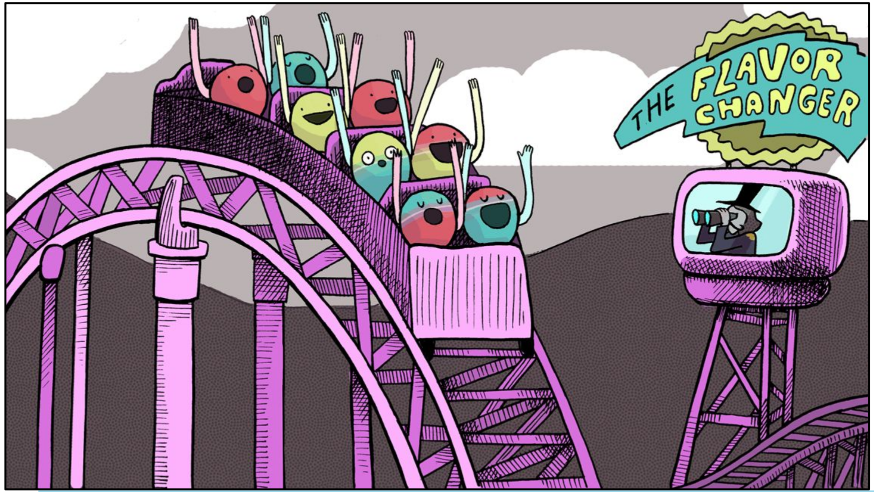
Neutrinos (AKA The Ghost Particle)

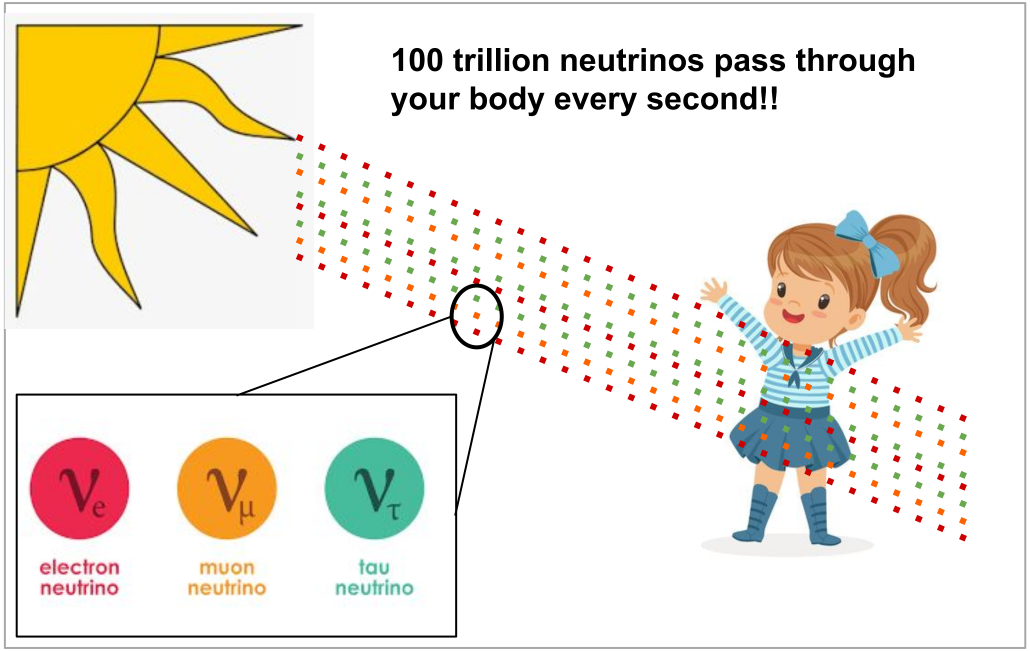


Credit : ScienceNews

Fermilab







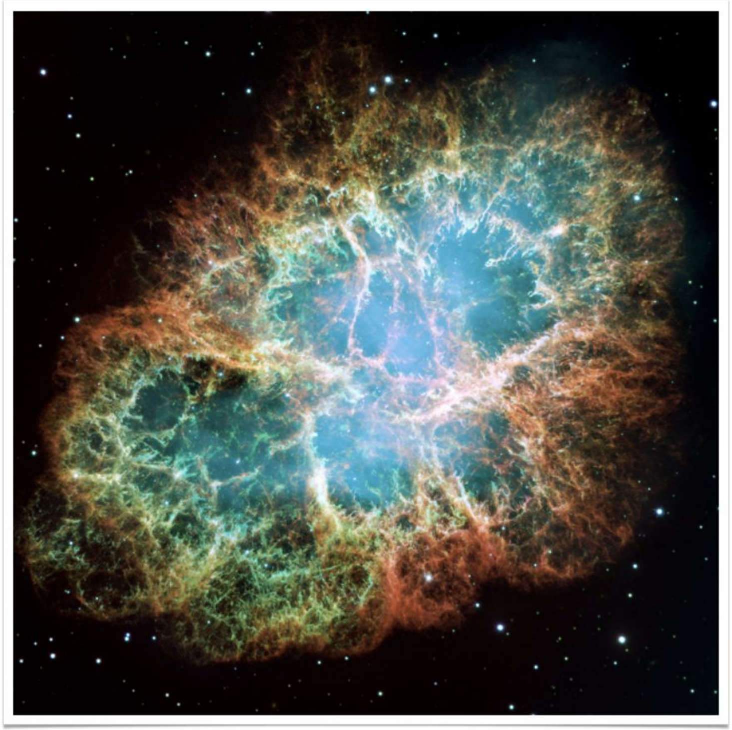
Meghna Bhattacharya (Fermilab)

June 6th, 2024

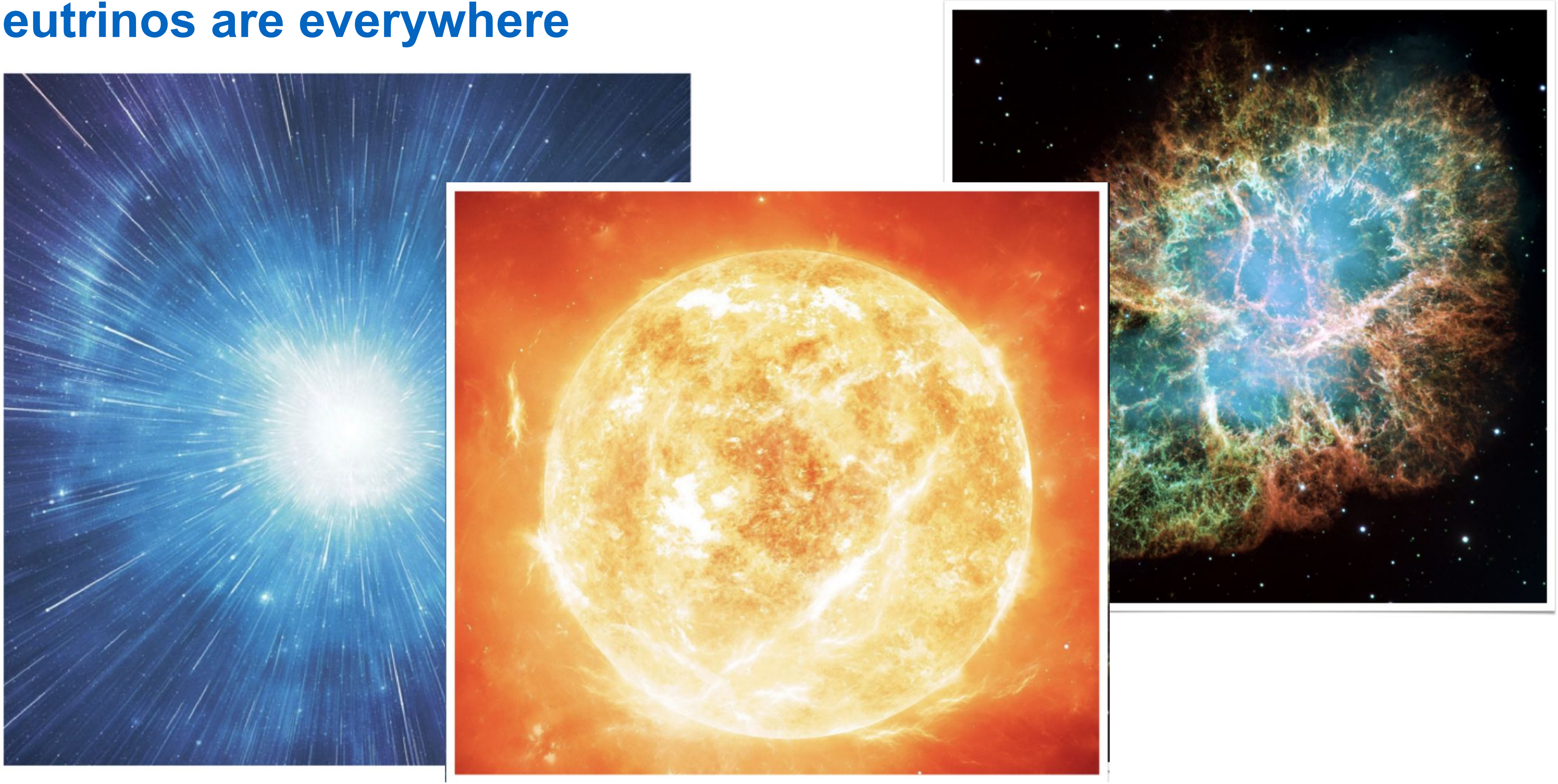
Summer Lecture Series

Neutrinos are everywhere

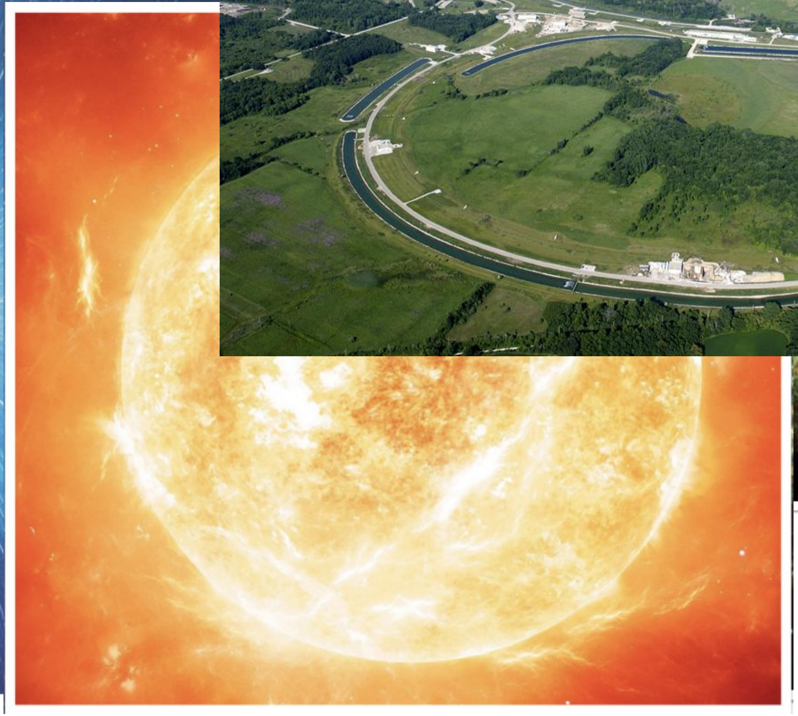
Neutrinos are everywhere



Neutrinos are everywhere



Neutrinos are everywhere



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Neutrinos are everywhere

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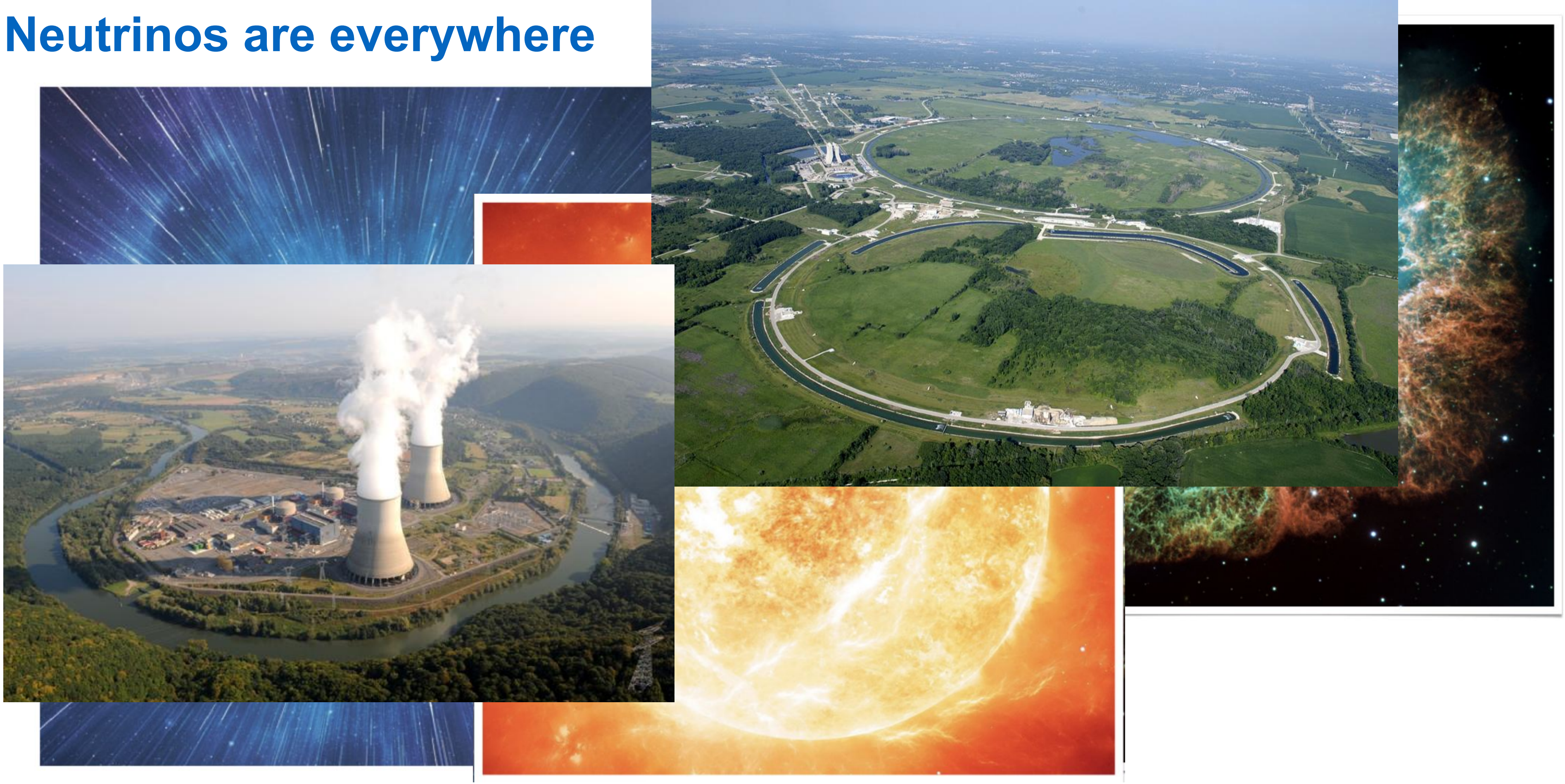
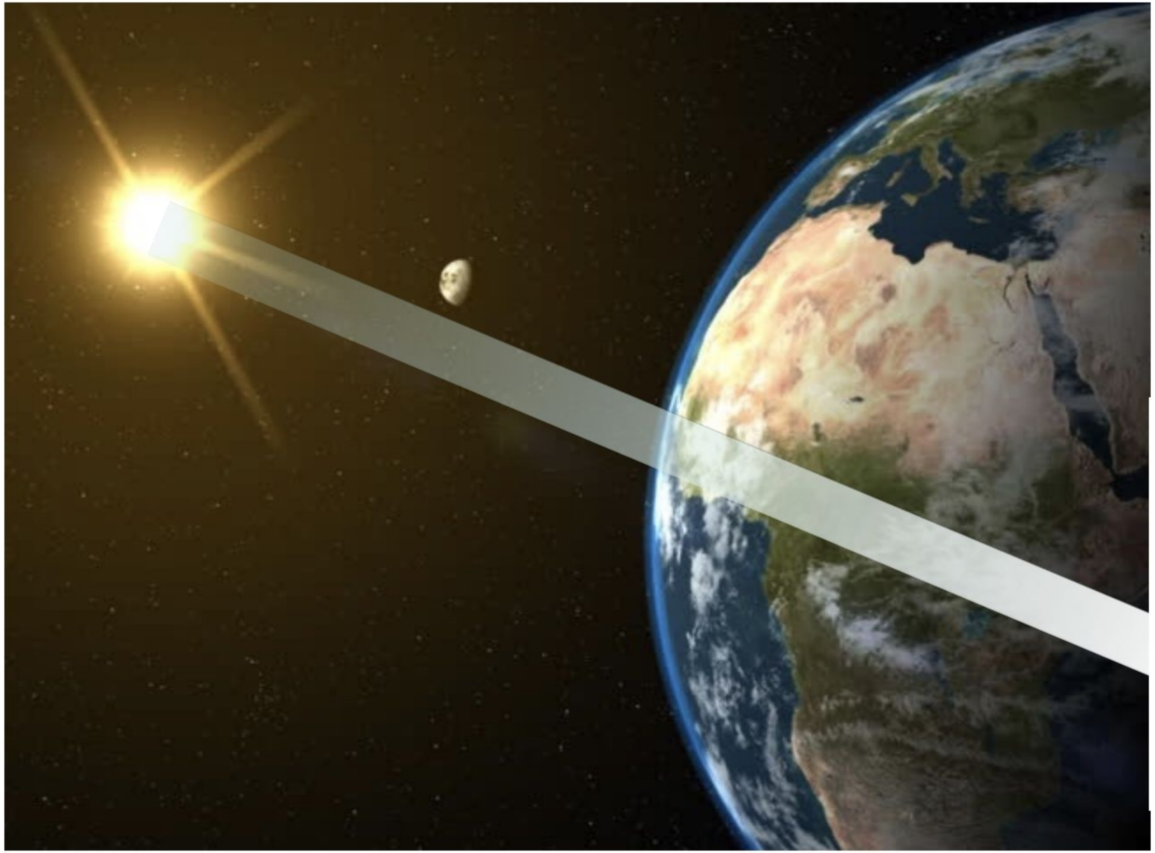
Neutrinos are everywhere

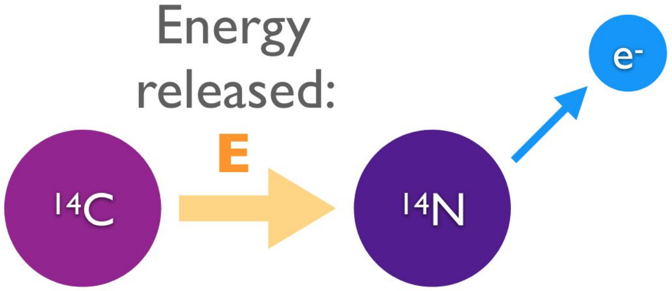


Neutrinos are everywhere

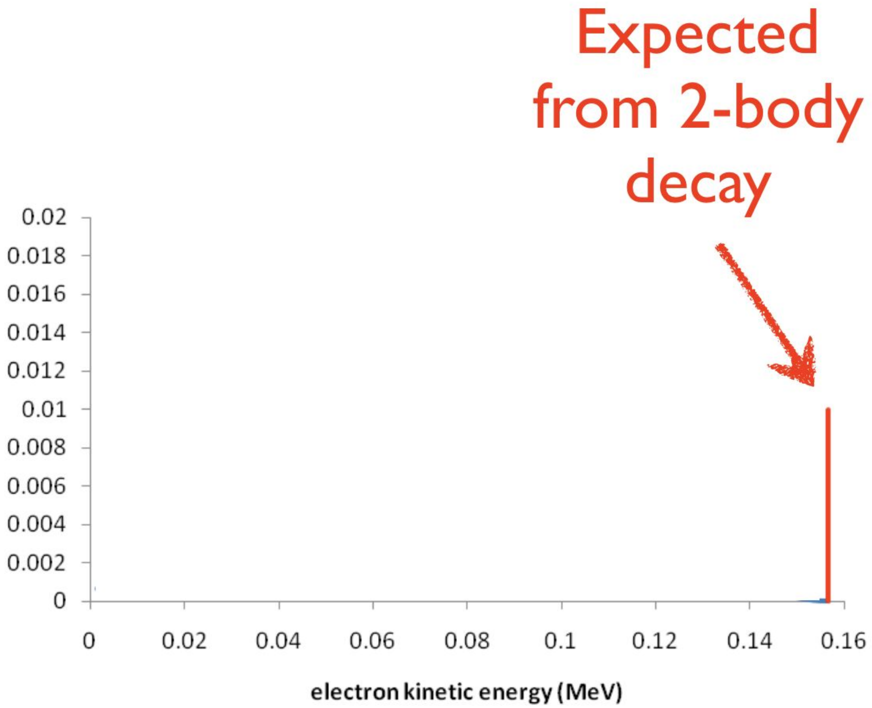
Neutrinos are everywhere….. But



Let’s time travel to 1930s : time for some history



Conservation of energy and momentum ⟶ all e- produced with same energy in a 2-body decay



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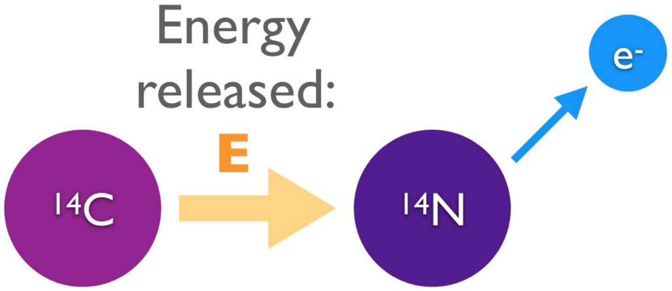
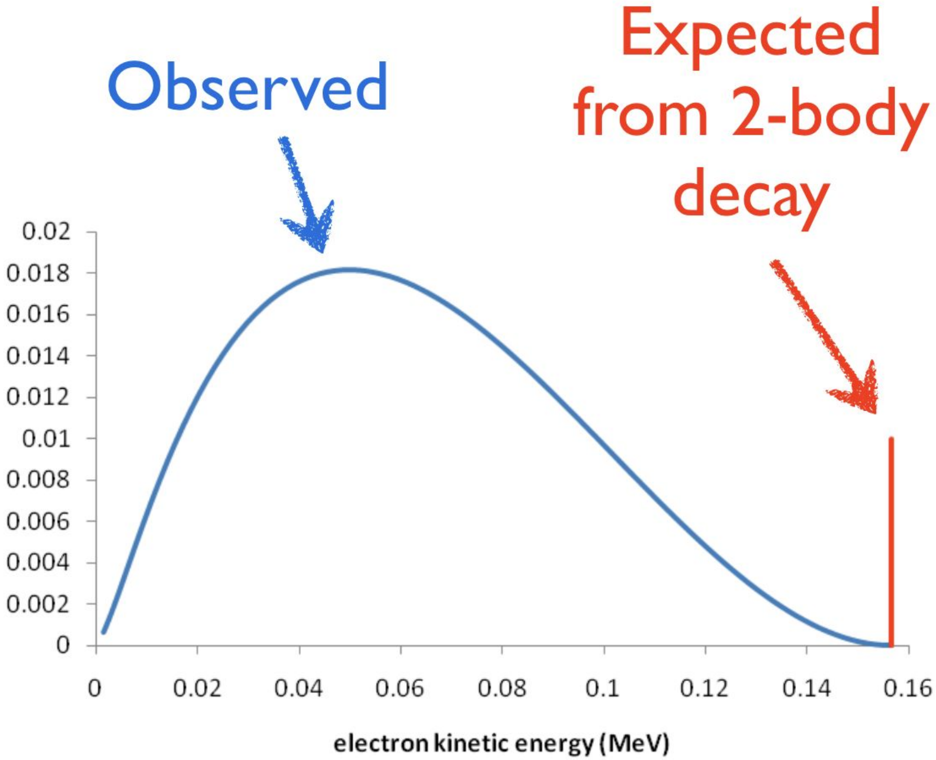


Energy not conserved?

What's going on?



Pauli's "Desperate Remedy":

Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich
anzuhören bitte, Ihnen des näheren auseinanderset
angesichts der "falschen" Statistik der N- und Li
des kontinuierlichen beta-Spektrums auf einen ver
verfallen um den "Wechselsatz" (1) der Statistik
zu retten. Nämlich die Möglichkeit, es könnten el
Teilchen, die ich Neutronen nennen will, in den K
welche den Spin 1/2 haben und das Ausschliessungs
sich von Lichtquanten ausserdem noch dadurch unte
nicht mit Lichtgeschwindigkeit laufen. Die Masse
müsste von derselben Grossenordnung wie die Elekt
jedenfalls nicht grösser als 0,01 Protonenmasse.-
beta- Spektrum wäre dann verständlich unter der A
beta-Zerfall mit dem Elektron jeweils noch ein Ne
wird, derart, dass die Summe der Energien von Neut
konstant ist.

Nun handelt es sich weiter darum, welche K
Neutronen wirken. Das wahrscheinlichste Modell f
mir aus wellenmechanischen Gründen (näheres weiss
dieser Zeilen) dieses zu sein, dass das ruhende N
magnetischer Dipol von einem gewissen Moment μ is
verlangen wohl, dass die ionisierende Wirkung ein
nicht grösser sein kann, als die eines gamma-Stra
μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the
Gauverein meeting in Tübingen.

Copy

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

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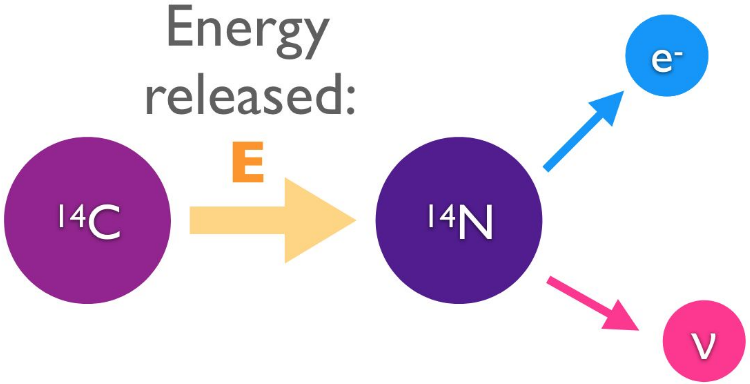
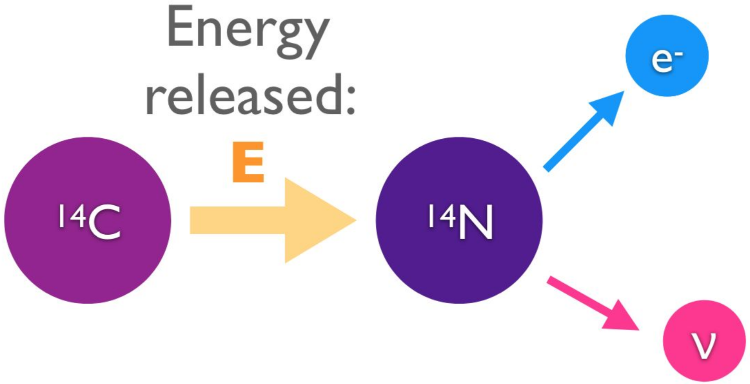
Pauli's "Desperate Remedy":



- β-decay, a three-body process with a new particle
  - Electrically neutral
  - Light
  - Not yet observed

Pauli's "Desperate Remedy":

"I have done a terrible thing, I have postulated a particle that can not be detected"



- β-decay, a three-body process with a new particle
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  - Light
  - Not yet observed

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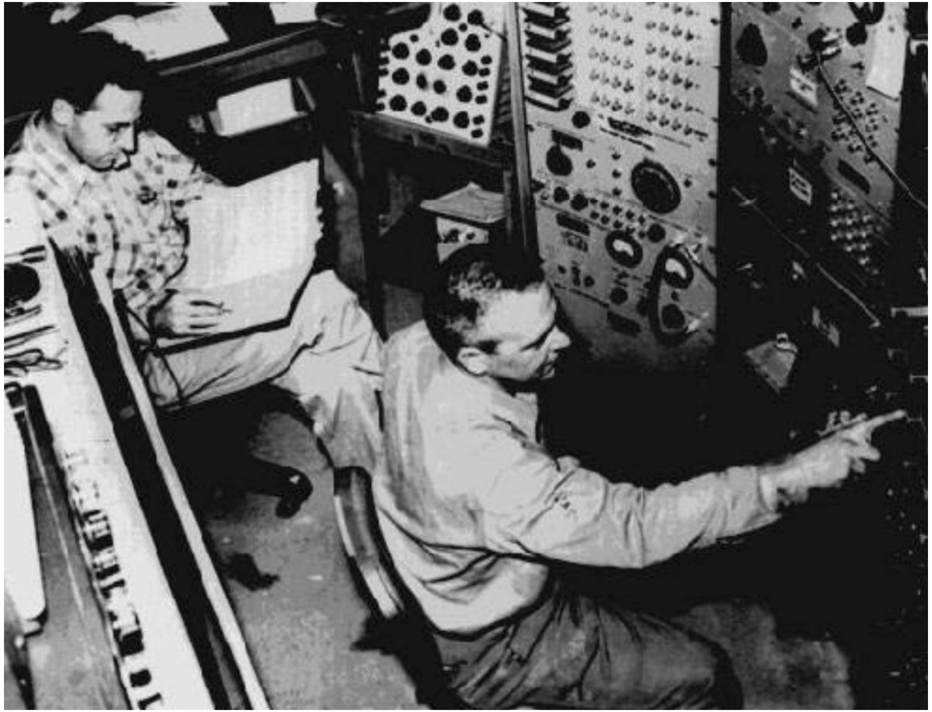
Neutrinos observed by Reins and Cowan: 1956

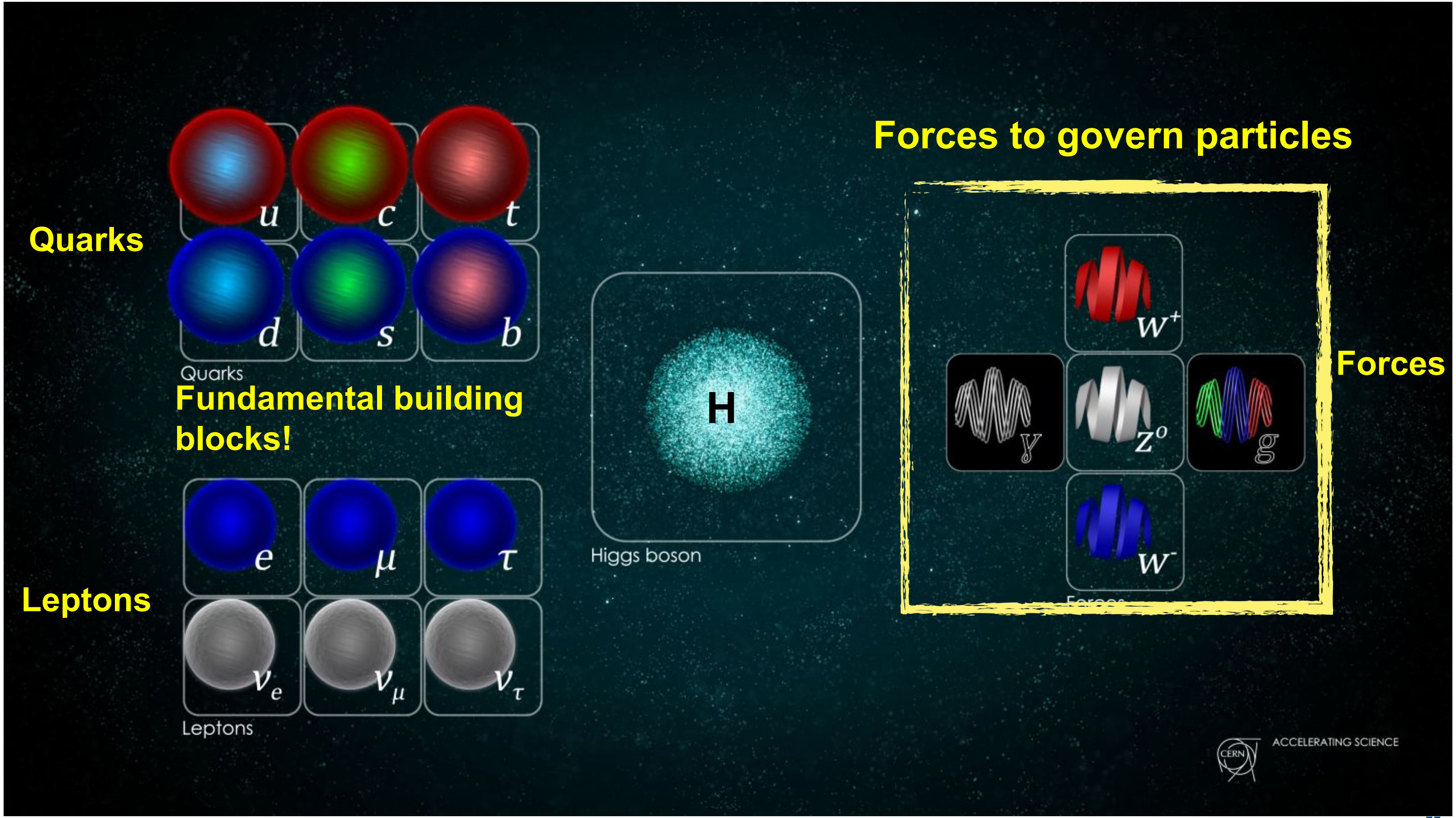
Fred Reines and Clyde Cowan eventually detected the neutrino in 1956 in an experiment at the Savannah River nuclear power plant



Telegram sent to Pauli on 14th June, 1956:

"We are happy to inform you that we have definitely detected neutrinos"

The Standard Model - Zoo of Particles



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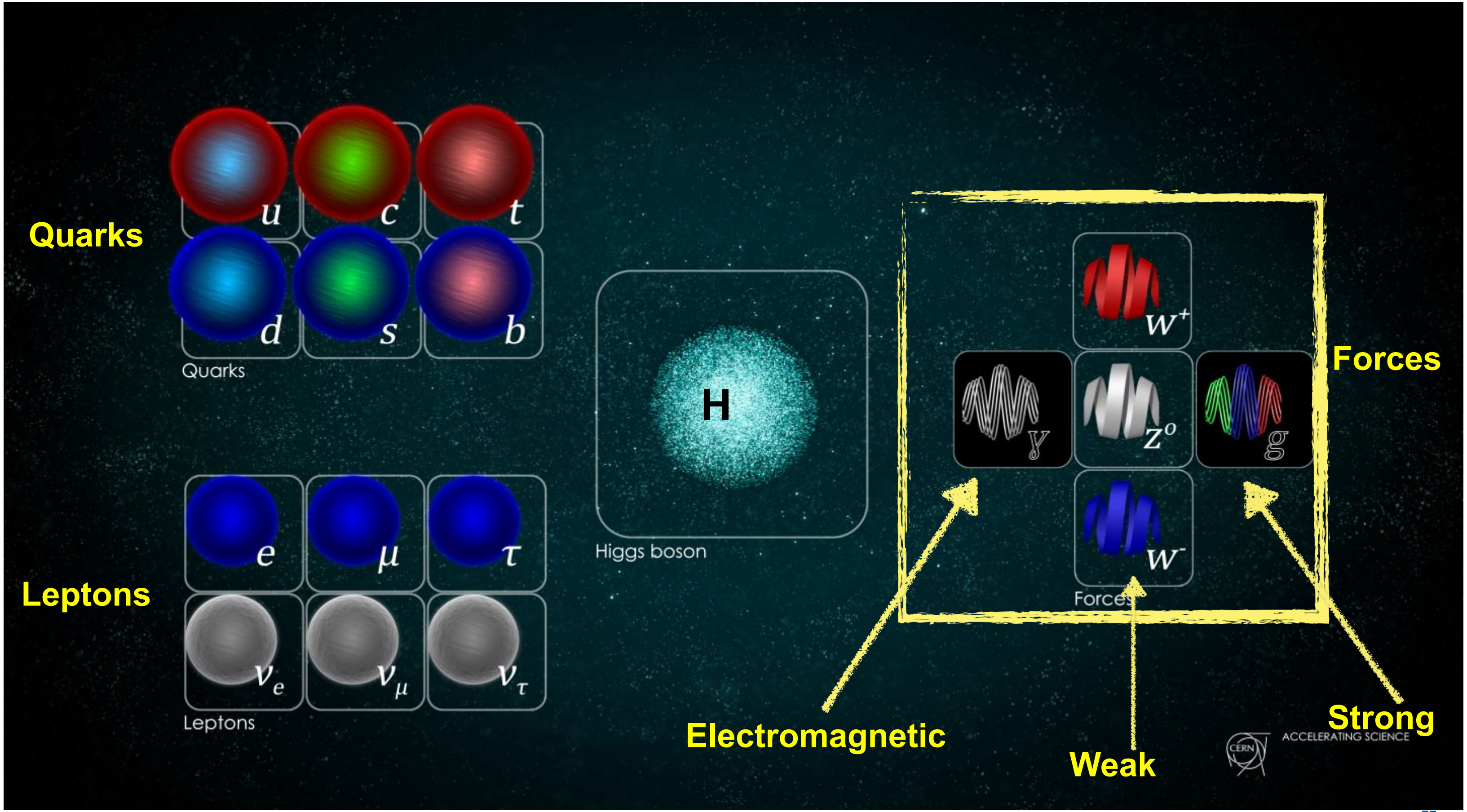
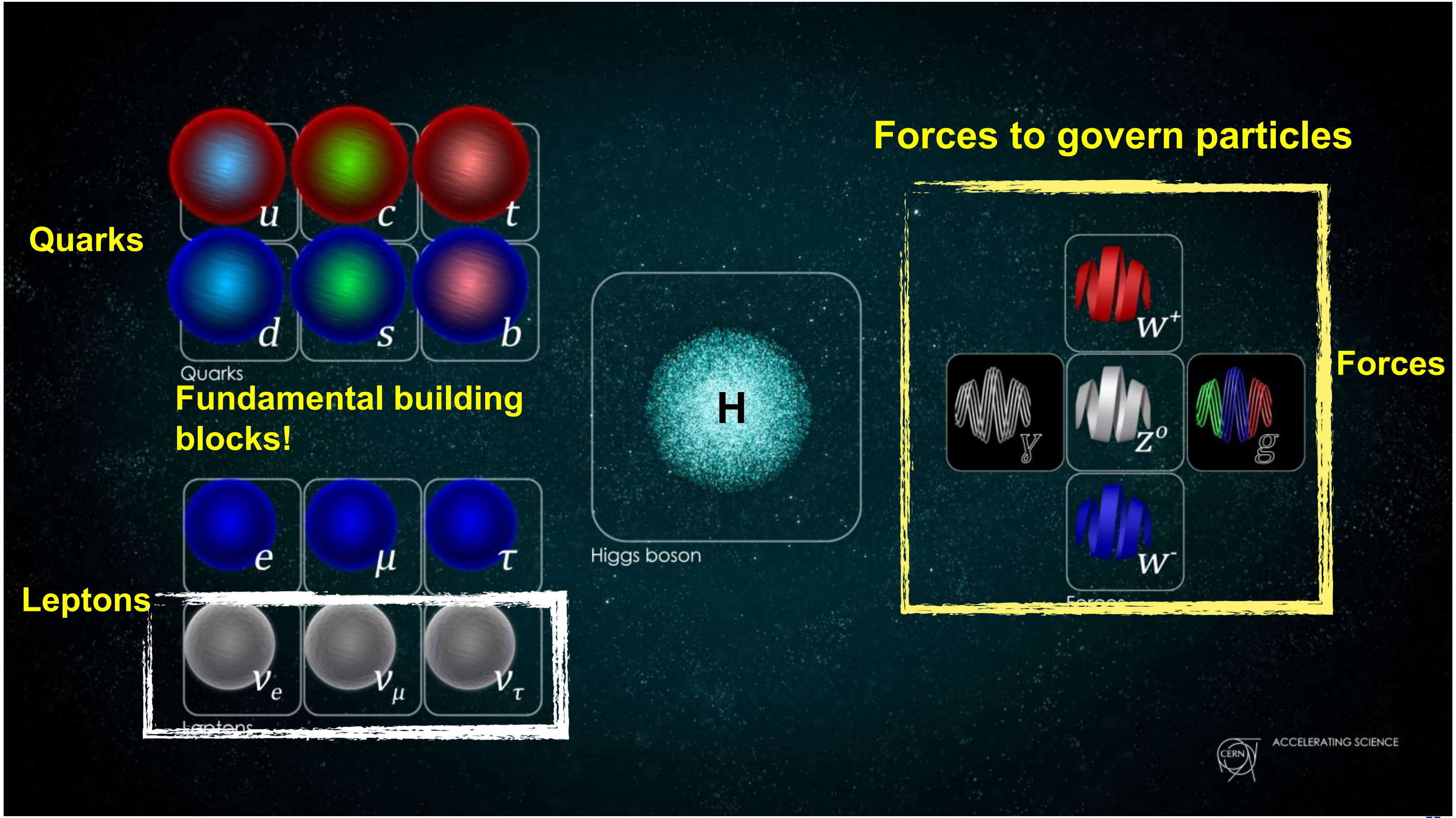
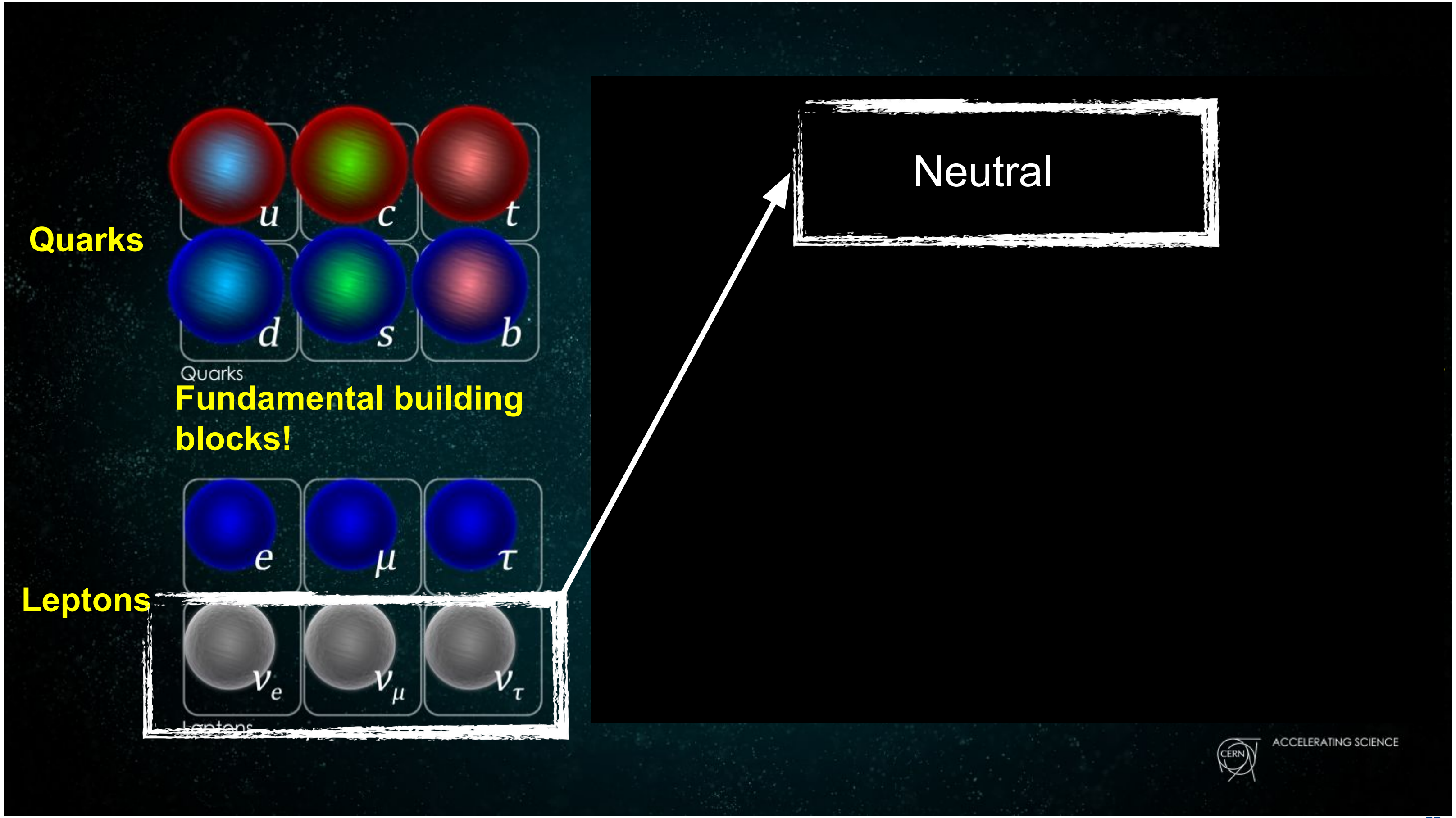
The Standard Model - Zoo of Particles



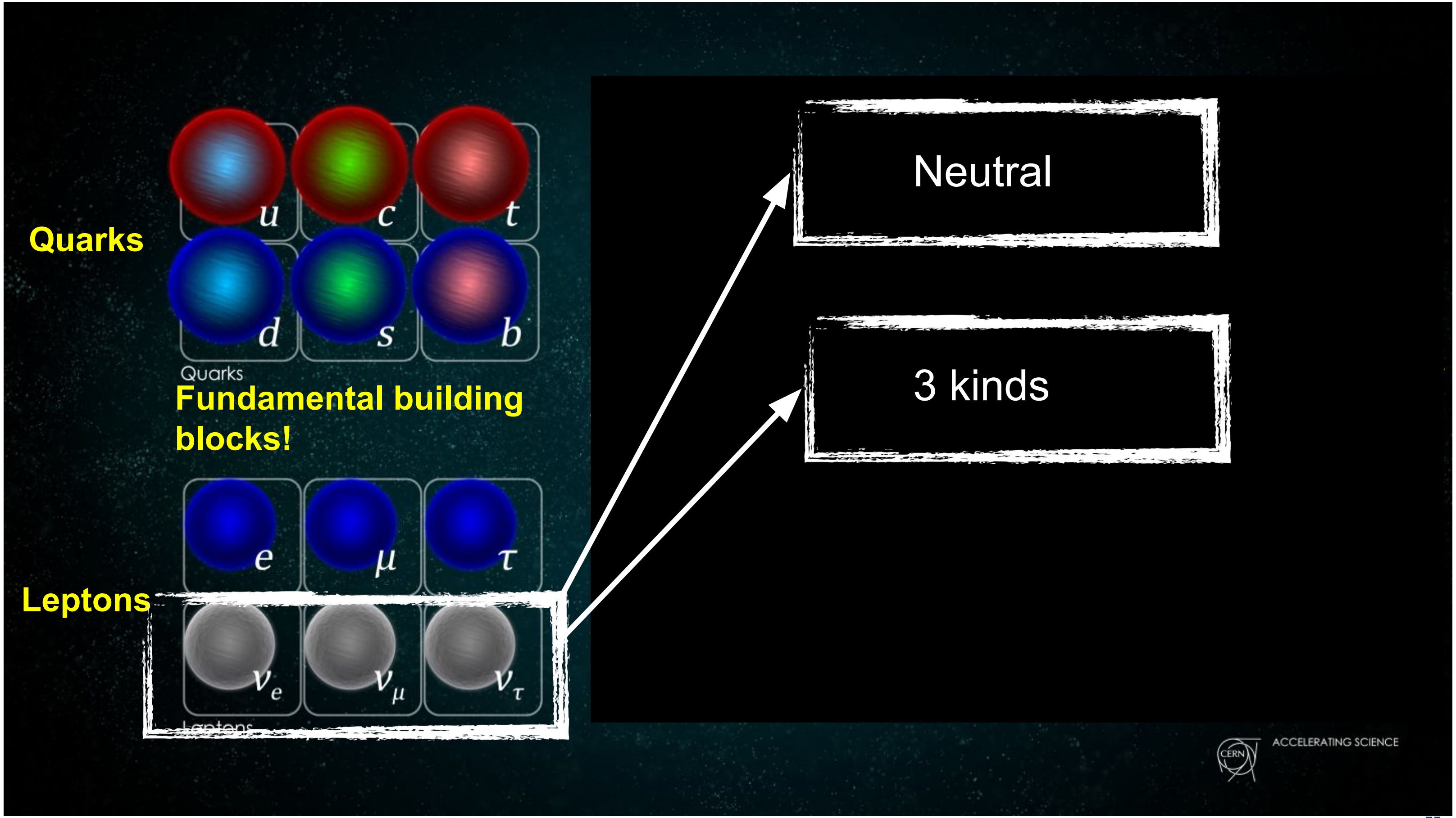
The Standard Model - Zoo of Particles



The Standard Model - Zoo of Particles



The Standard Model - Zoo of Particles



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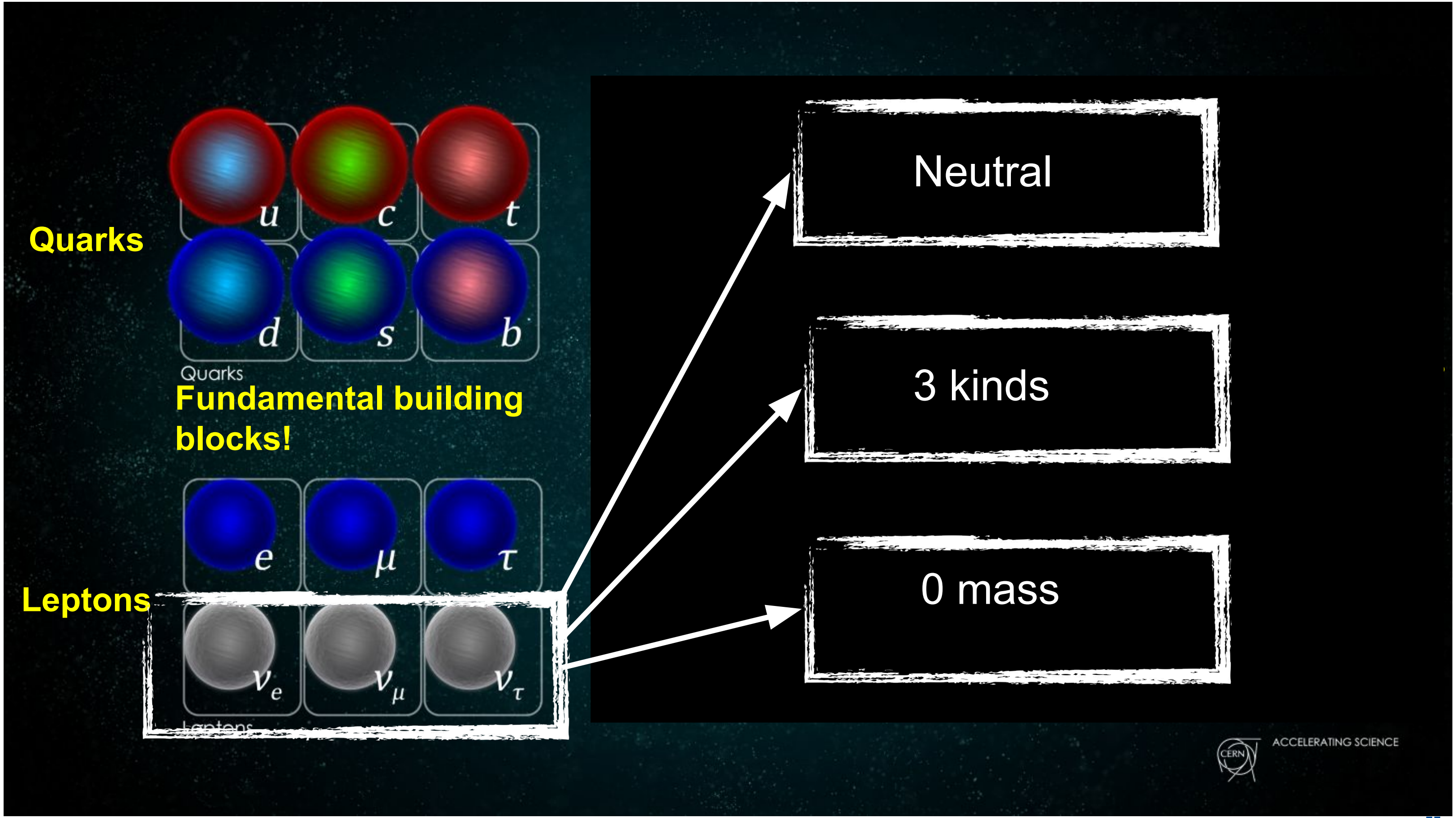
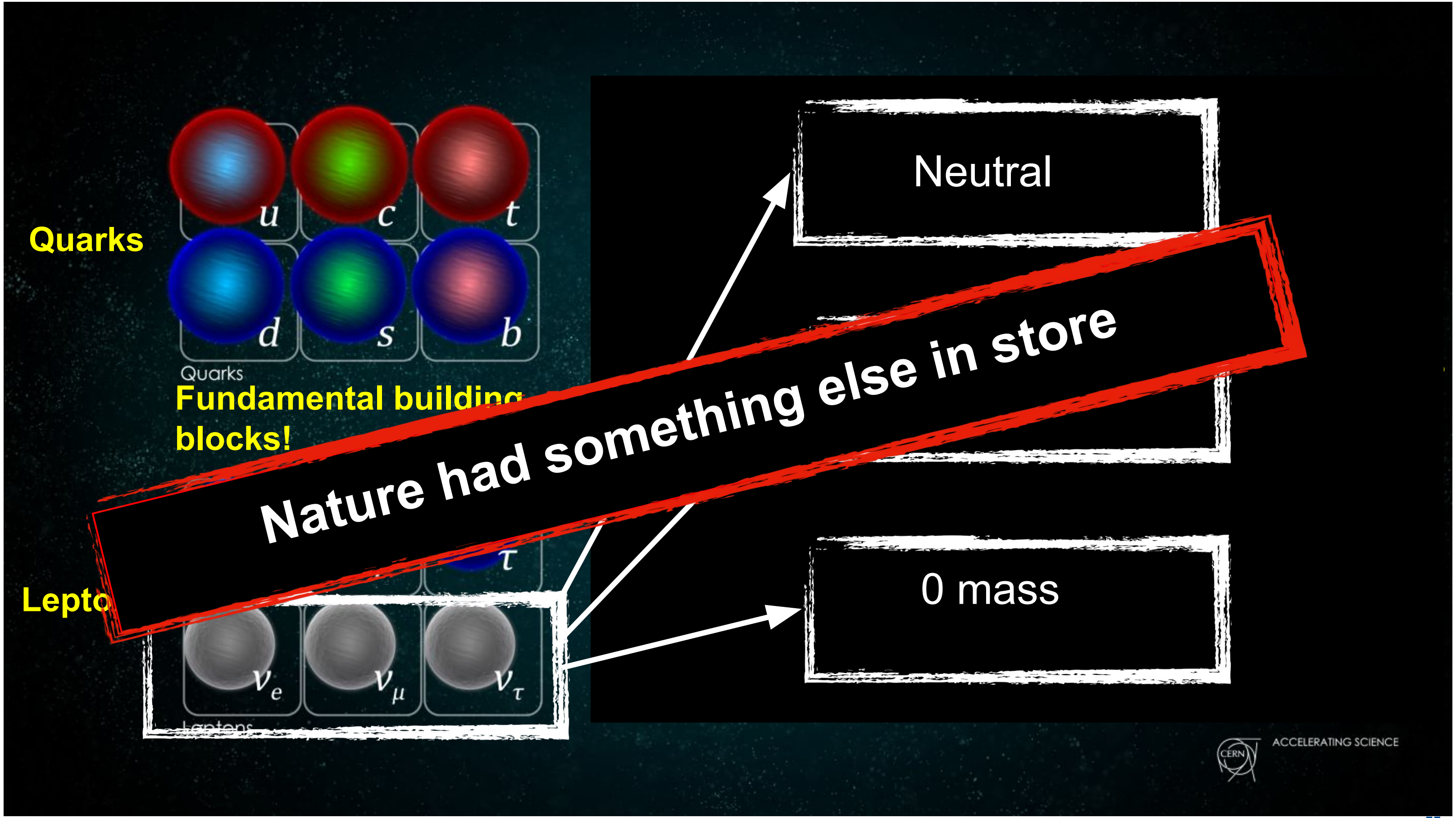
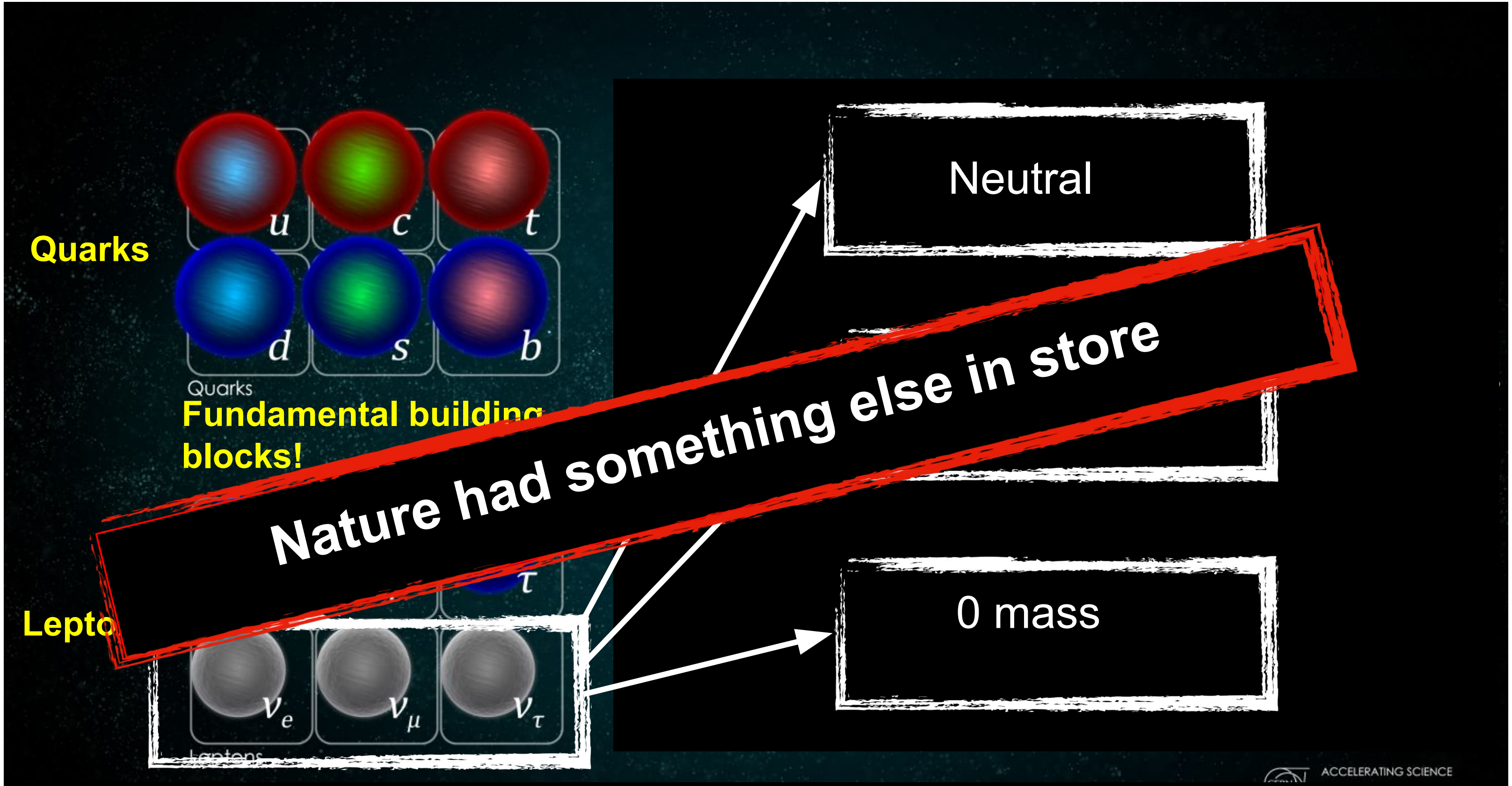
The Standard Model - Zoo of Particles



The Standard Model - Zoo of Particles



The Standard Model - Zoo of Particles



Does the Standard Model grasp the whole picture?
Are there puzzle pieces to Universe that Standard Model does not quite place?

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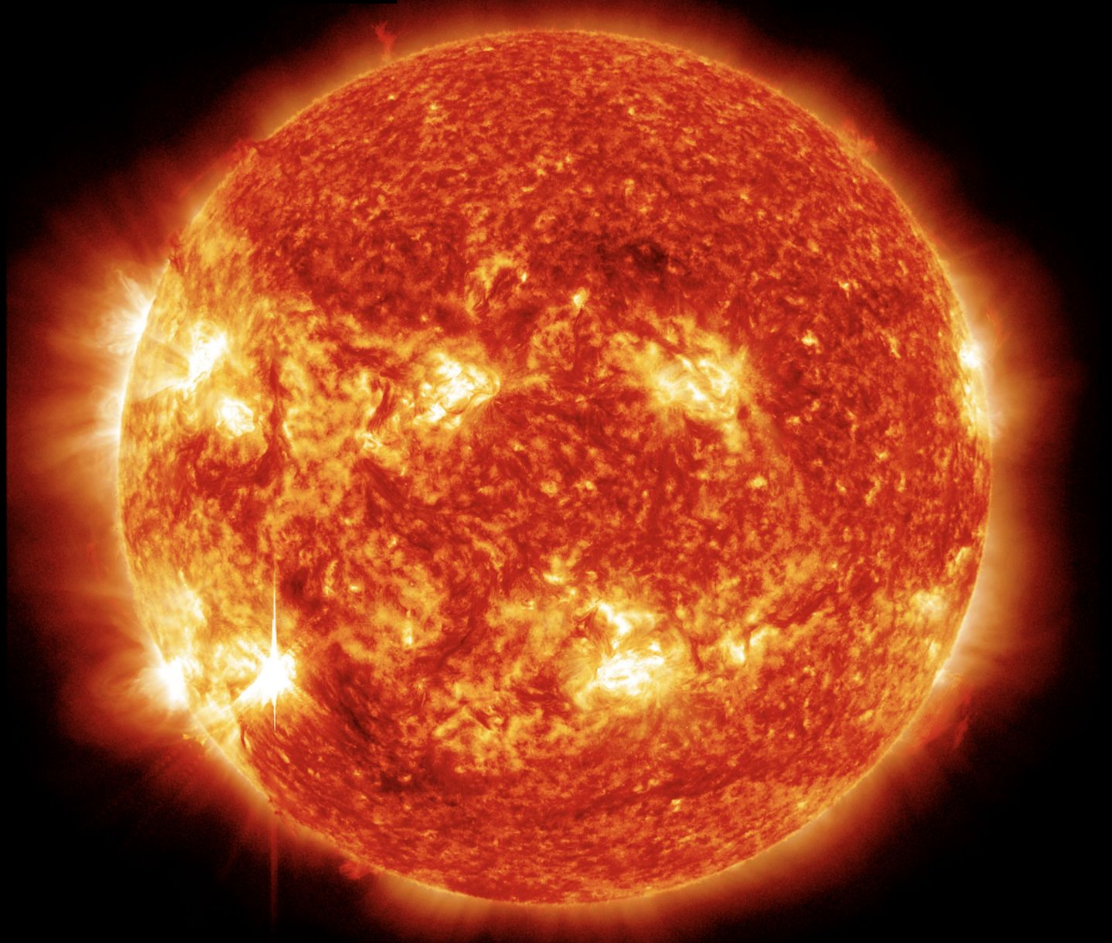
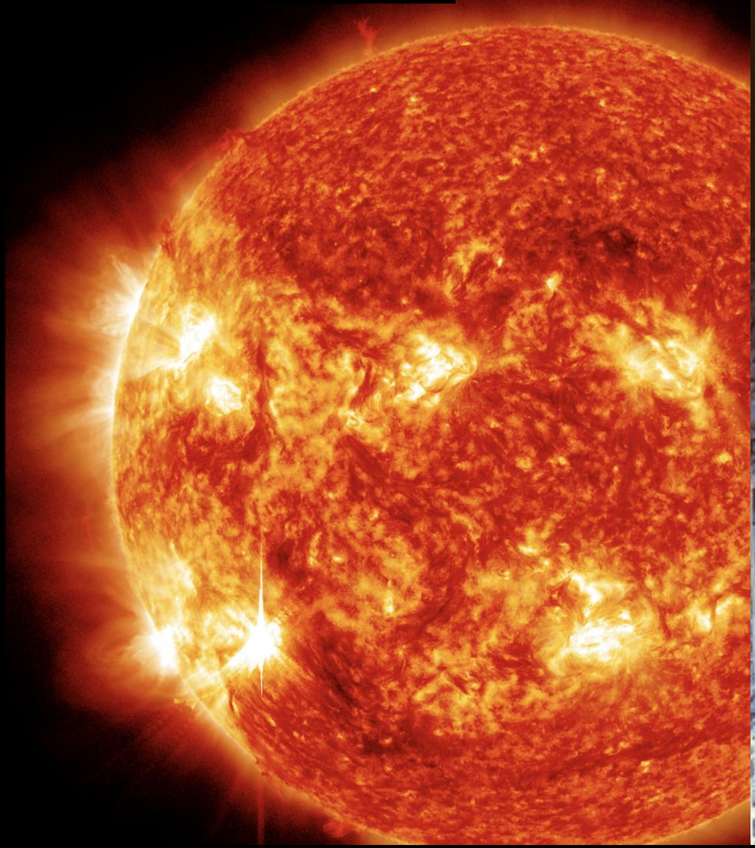
The Solar Neutrino Puzzle

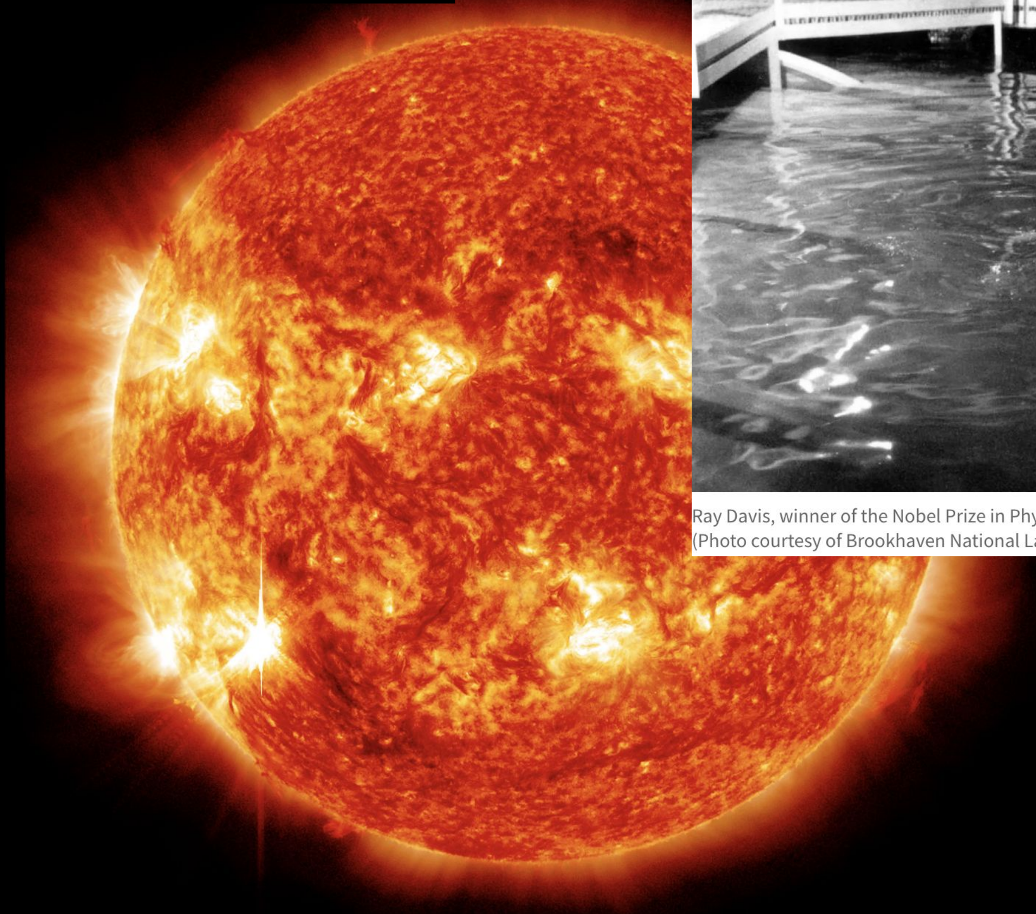


The Solar Neutrino Puzzle



Ray Davis devised an experiment to measure neutrinos from sun in late 1960s

The Solar Neutrino Puzzle



Ray Davis, winner of the Nobel Prize in Physics in 2002, takes a swim in the Homestake mine, circa 1971.
(Photo courtesy of Brookhaven National Laboratory)

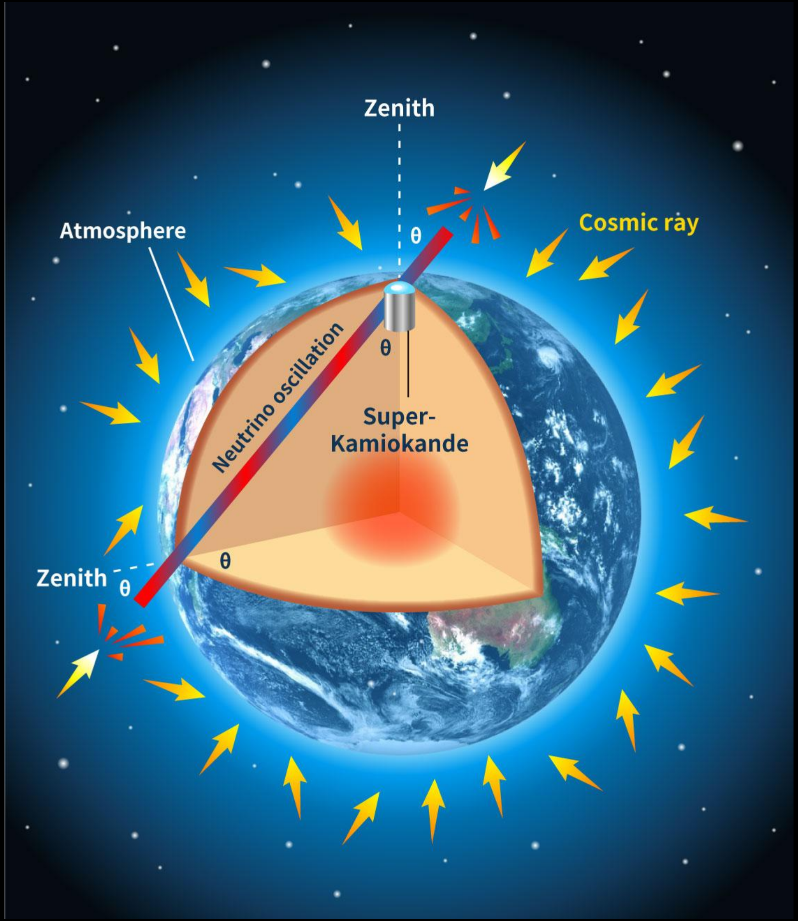
Number of neutrinos expected based on theoretical models of solar fusion **>** **Number of neutrinos detected**

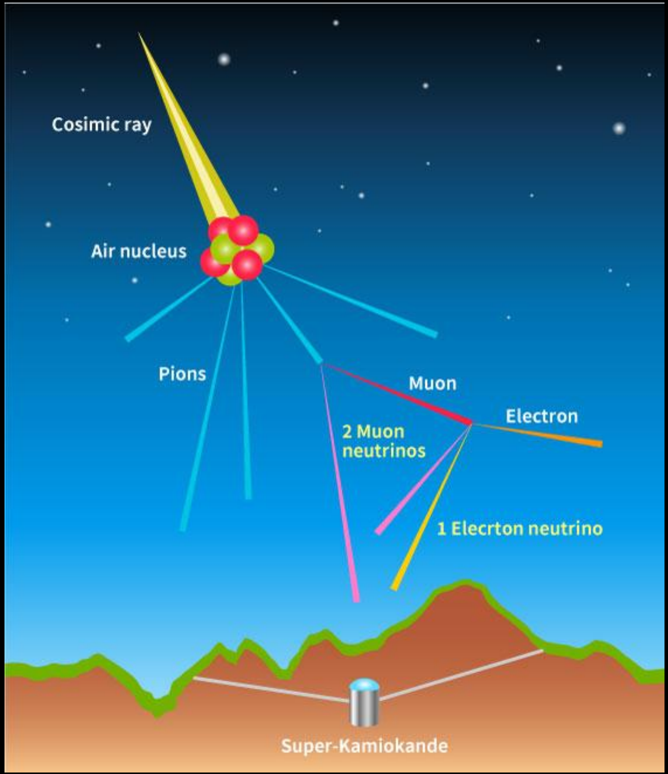
Wanted

ν_e

The Missing Neutrinos

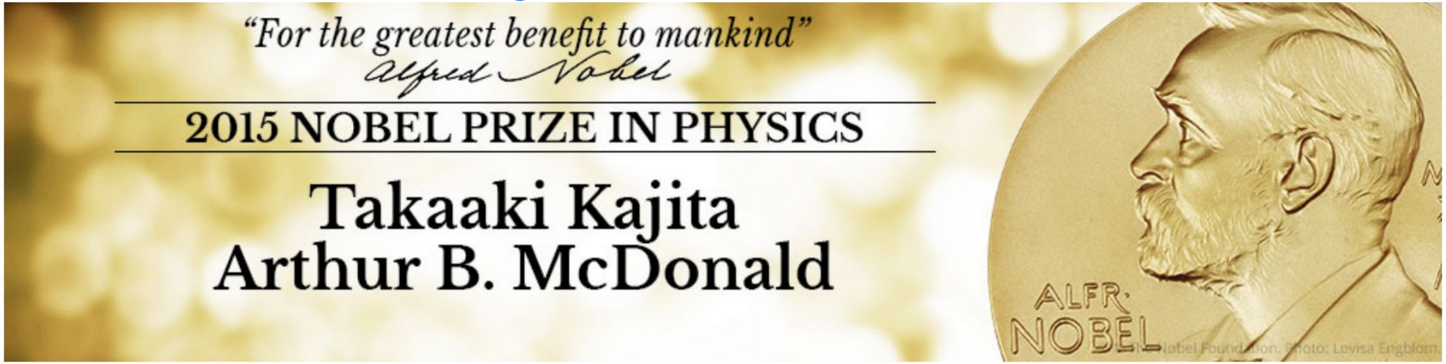
Atmospheric Neutrinos



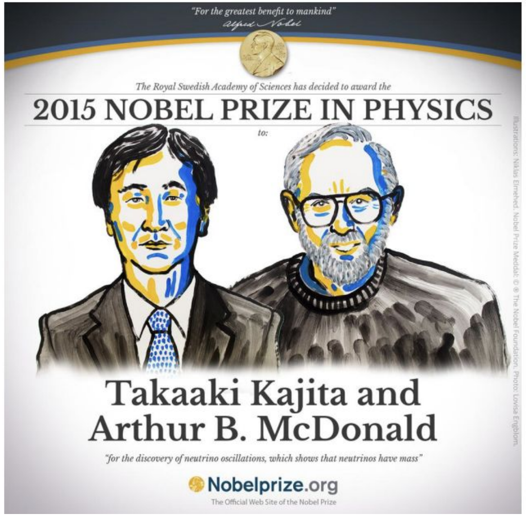


Number of neutrinos expected > Number of neutrinos observed

2015 Nobel Prize in Physics



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



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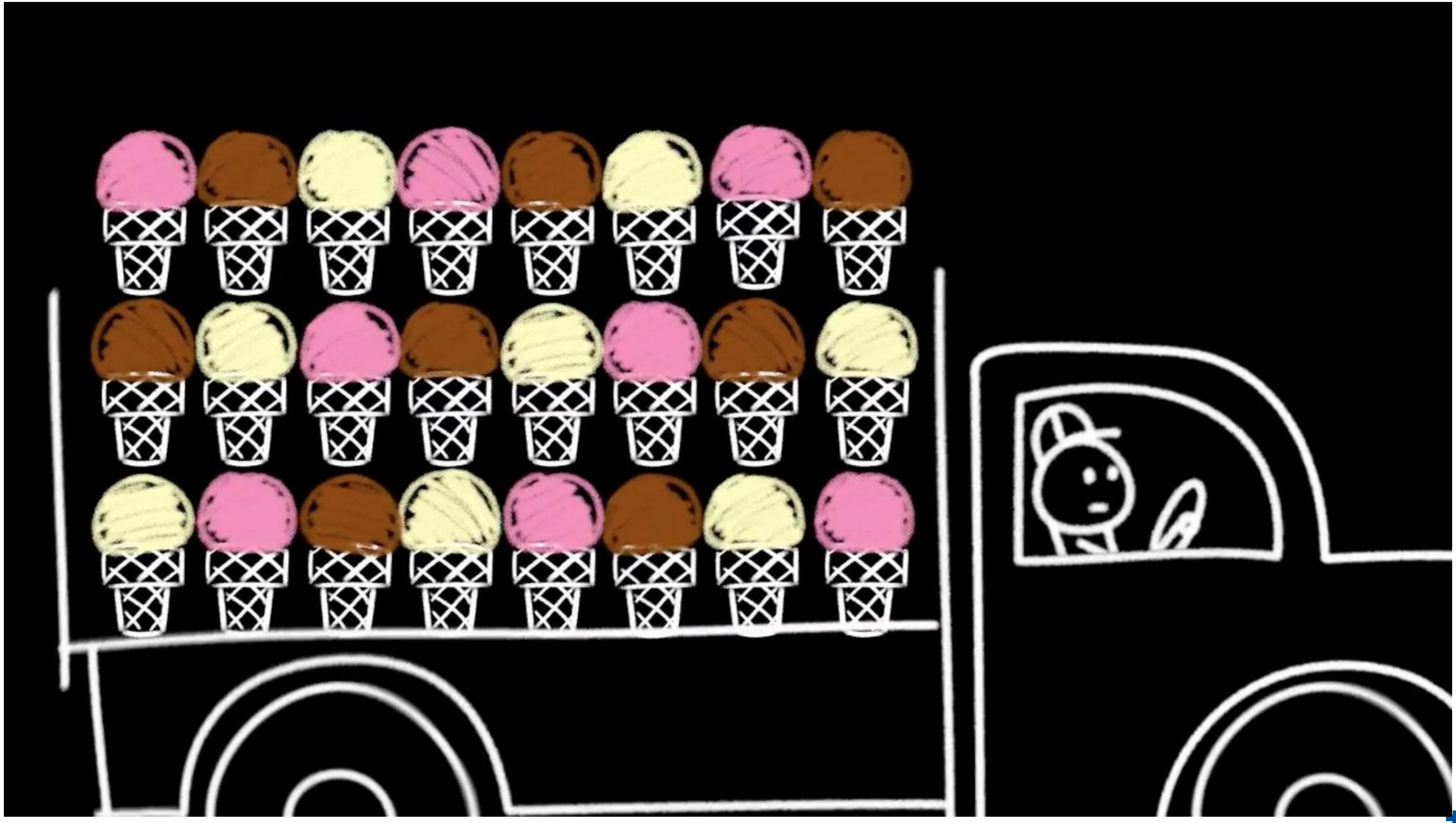
Mystery of Changing Identities: Neutrino Flavors

Flavors? Ice cream!



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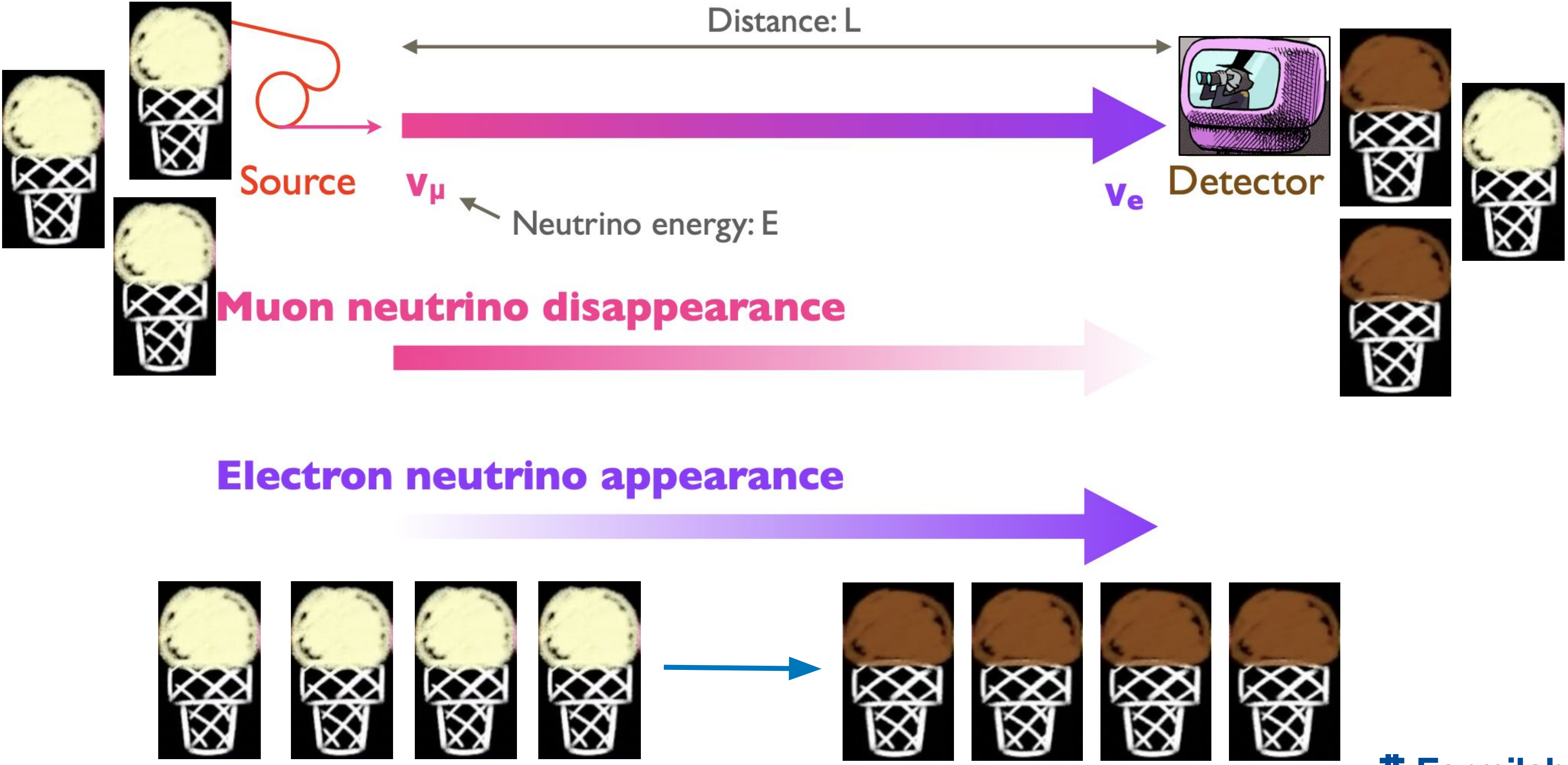
Mystery of Changing Identities: Neutrino Flavors

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino Oscillations



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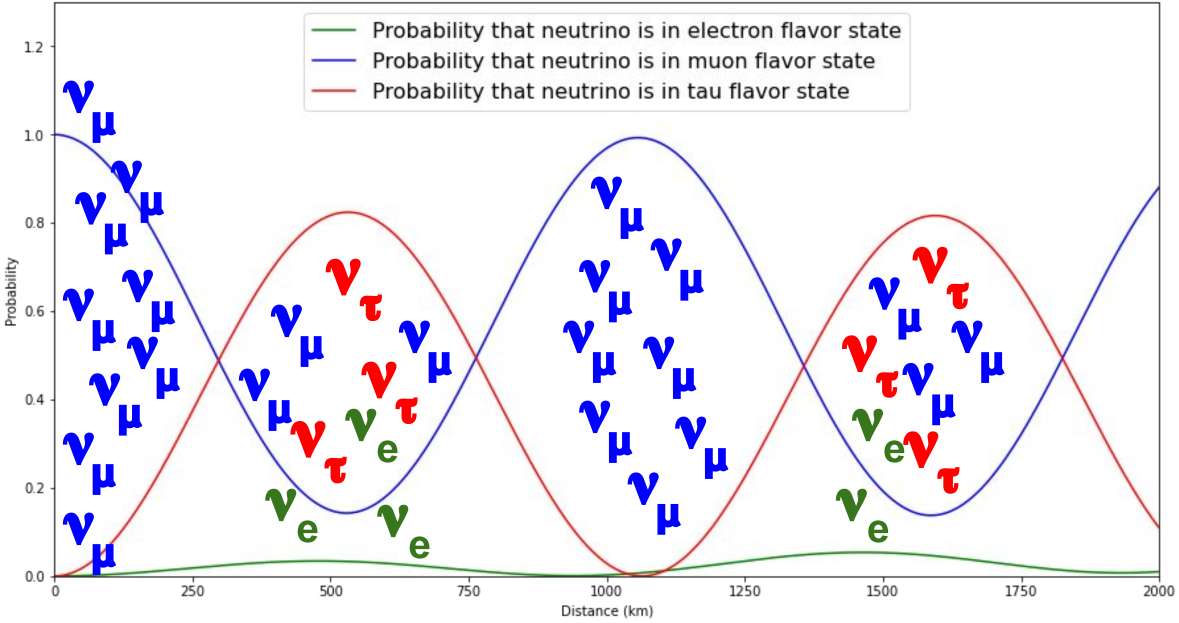
Neutrino Oscillation

Diagram shows the probability of changing to another type of neutrino as it travels

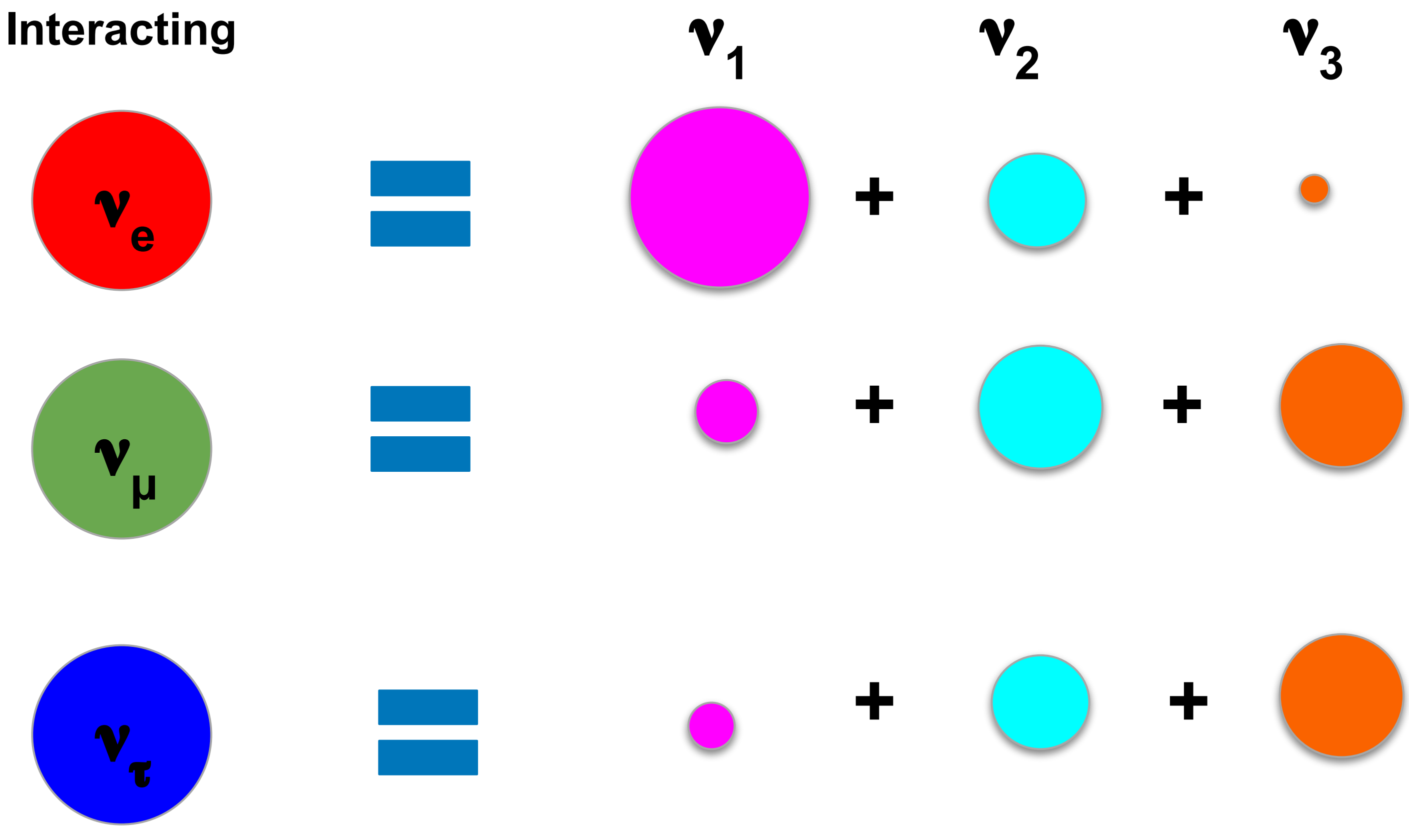


Neutrino Oscillation: The Dance That Proves Neutrinos Have Mass!

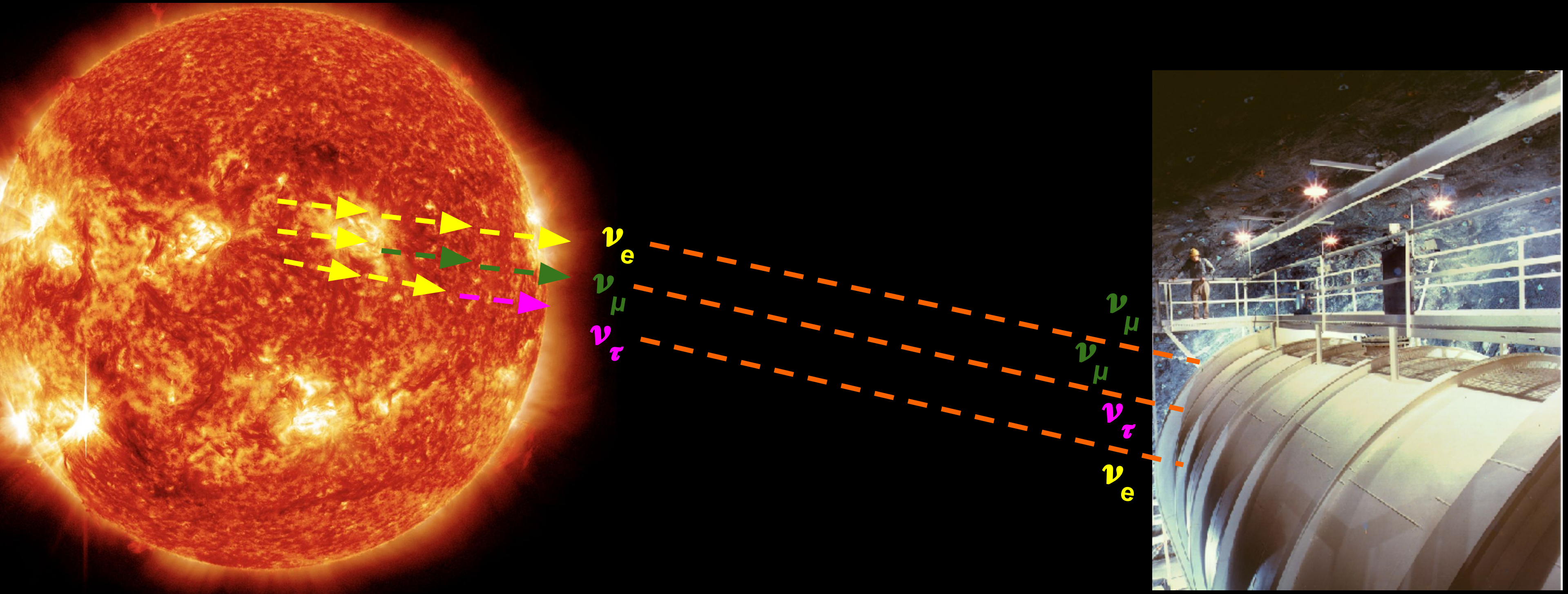
Interacting | **Traveling**

Definite flavors | **Definite mass**

A cool video explaining how oscillations occur



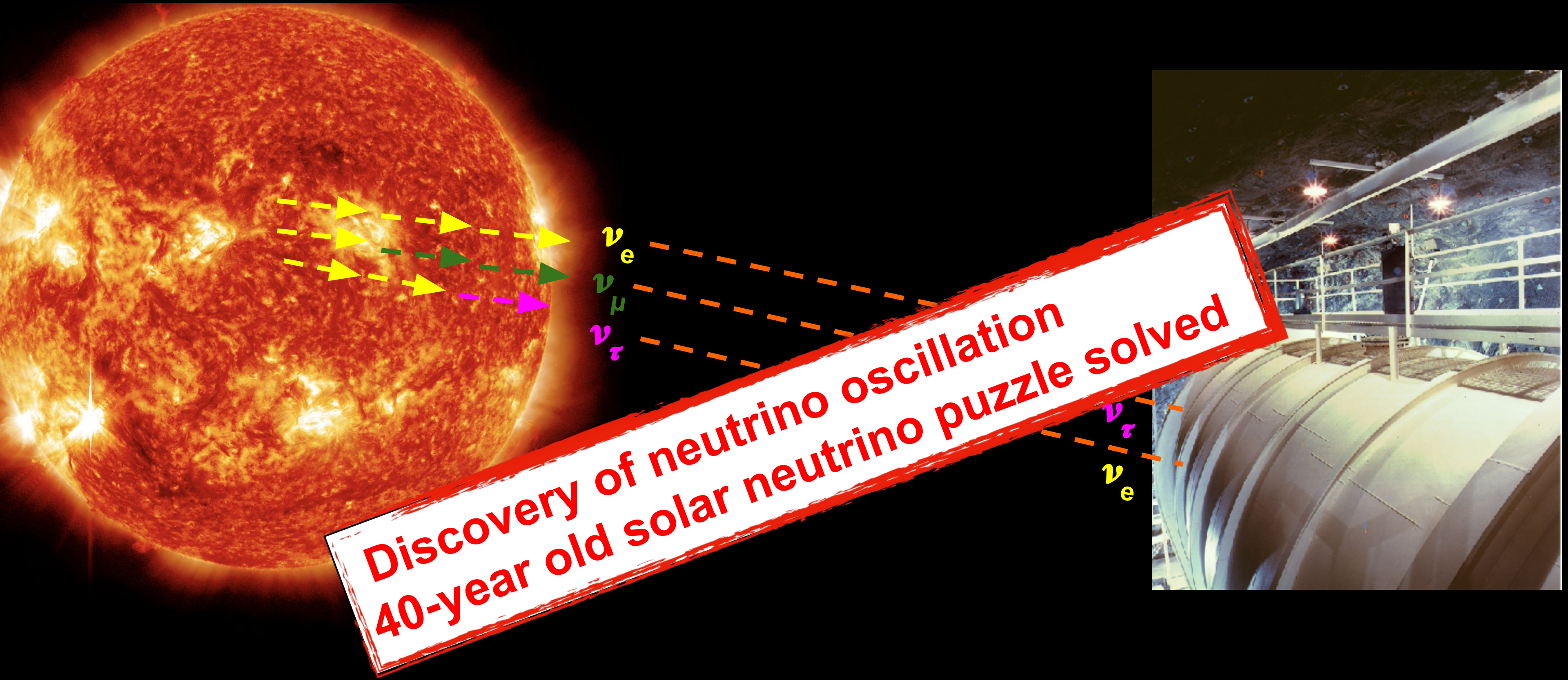
The Solar Neutrino Puzzle



Davis only looked for ν_e known to be produced in the sun

By the time they reach the detector, ½-⅔ have changed to ν_μ or ν_τ

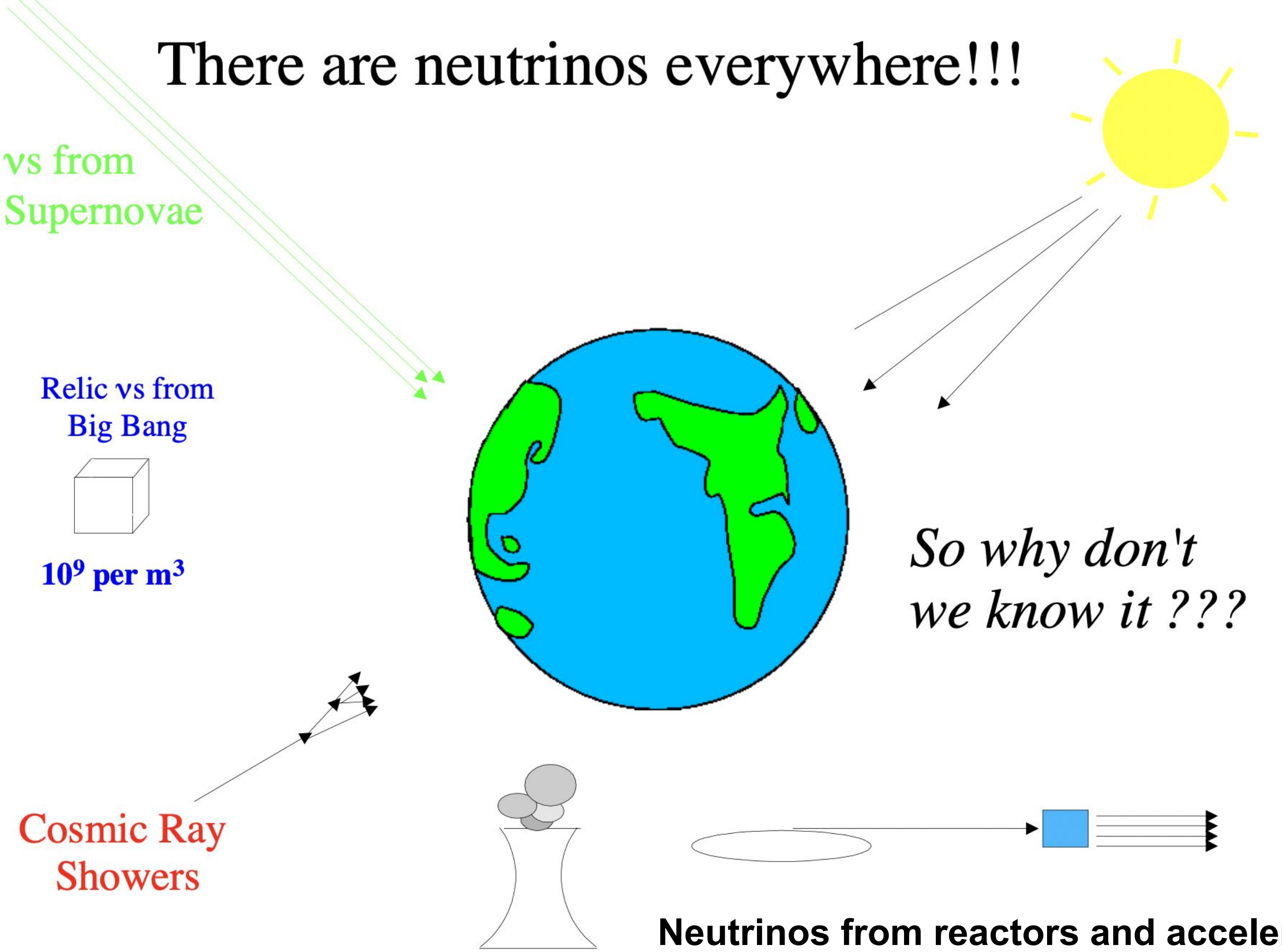
The Solar Neutrino Puzzle



Davis only looked for ν_e known to be produced in the sun

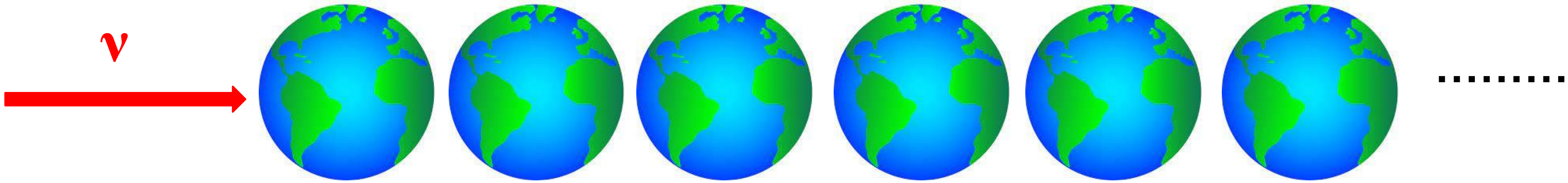
By the time they reach the detector, ½-⅔ have changed to ν_μ or ν_τ

There are neutrinos everywhere!!!



Neutrinos from reactors and accelerators

Neutrinos interact 100,000,000,000 times less often than quarks

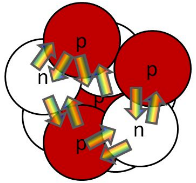


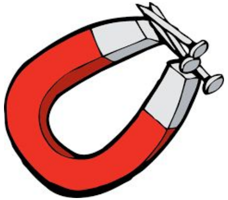
A neutrino has a good chance of traveling through 200 earths before interacting at all

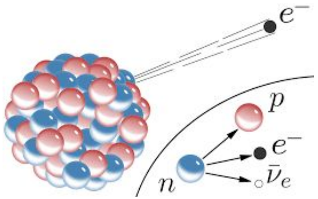
Why is that?

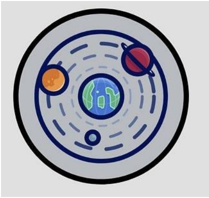
Neutrinos interact via?

Force	Strength	Range
Strong	1	10^{-15} m
Electromagnetism	1/137	infinite
Weak	10^{-6}	10^{-18} m
Gravity	6×10^{-39}	infinite



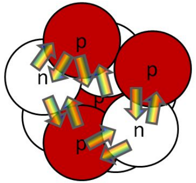
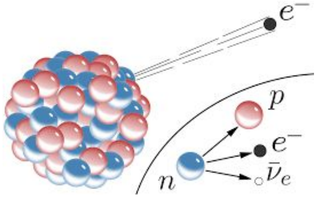
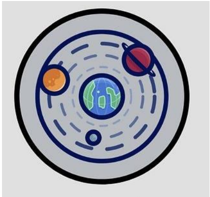






Why is that?

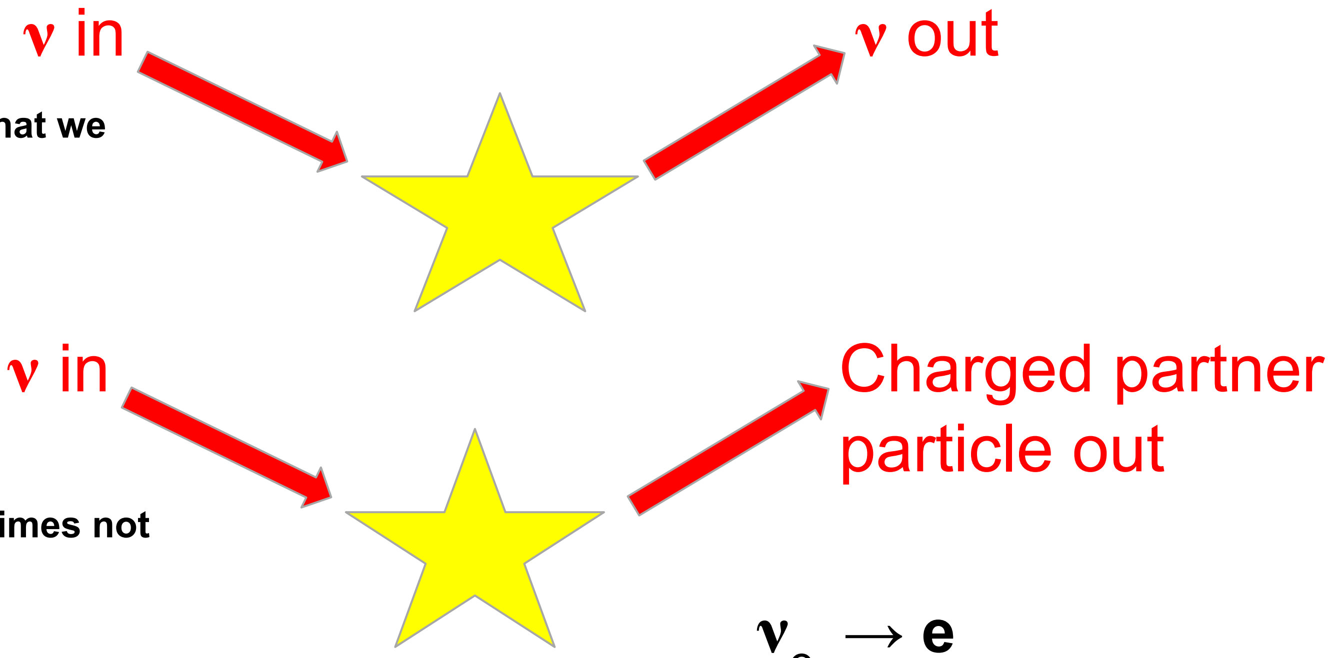
Neutrinos interact via?

		Strength	Range
❌**Strong**		1	10^{-15} m
❌**Electromagnetism**		1/137	infinite
✅**Weak**		10^{-6}	10^{-18} m
✅**Gravity**		6×10^{-39}	infinite

Weak Interactions

Sometimes what we expect

…. and sometimes not



$\nu_e \rightarrow e$

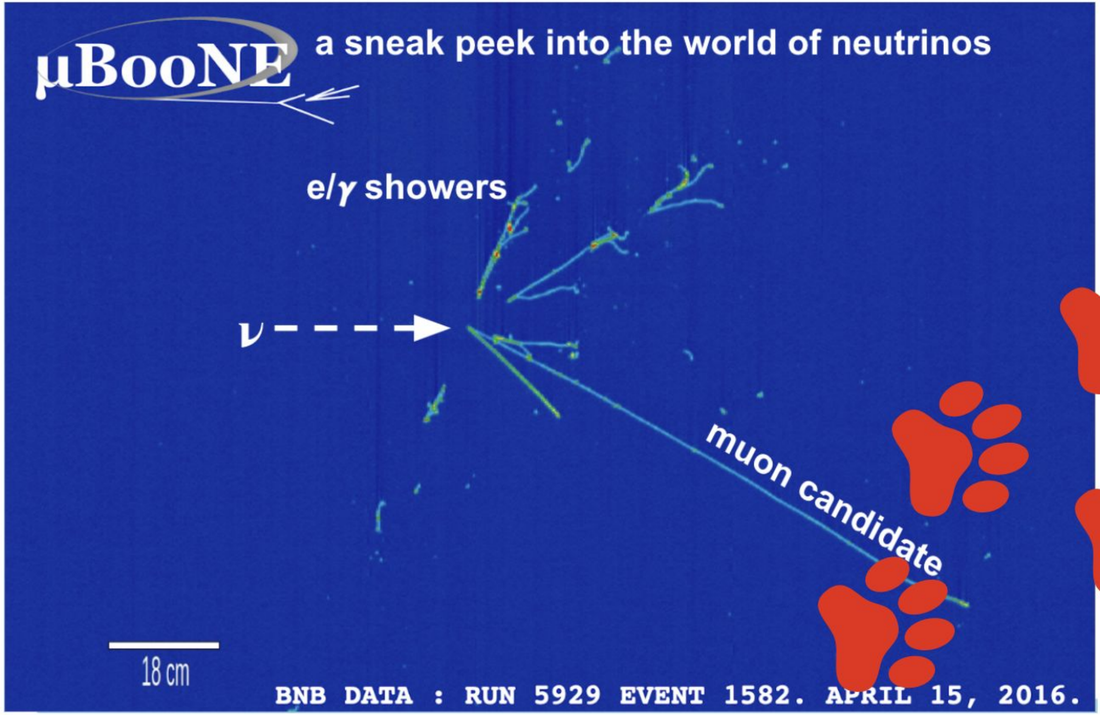
$\nu_\mu \rightarrow \mu$

$\nu_\tau \rightarrow \tau$

Weak Interactions

We can only detect charged particles!

In a neutrino interaction - we never see the neutrino, just the charged particles from the interaction



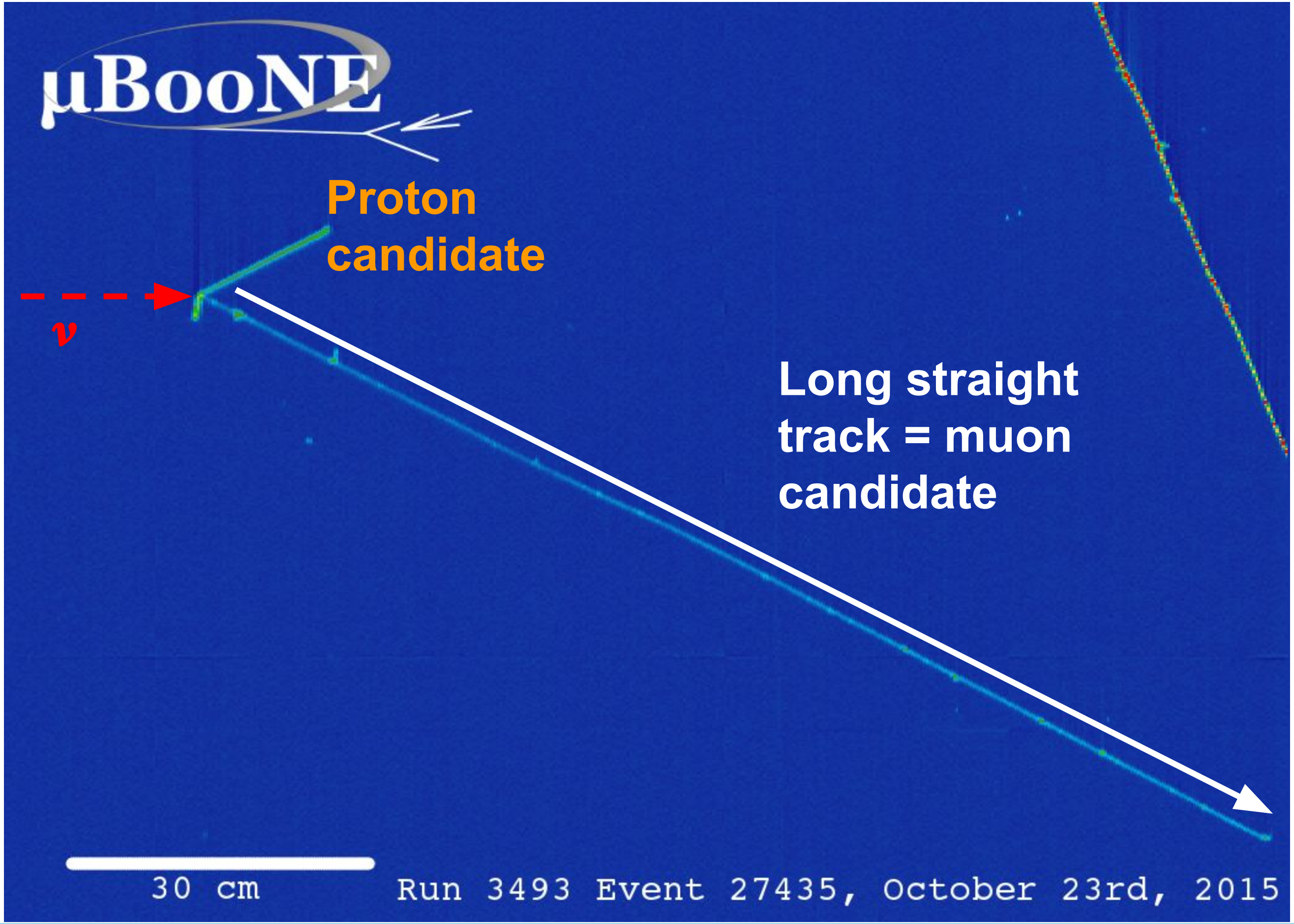
Electrons
Muons
Taus

All leave different footprints

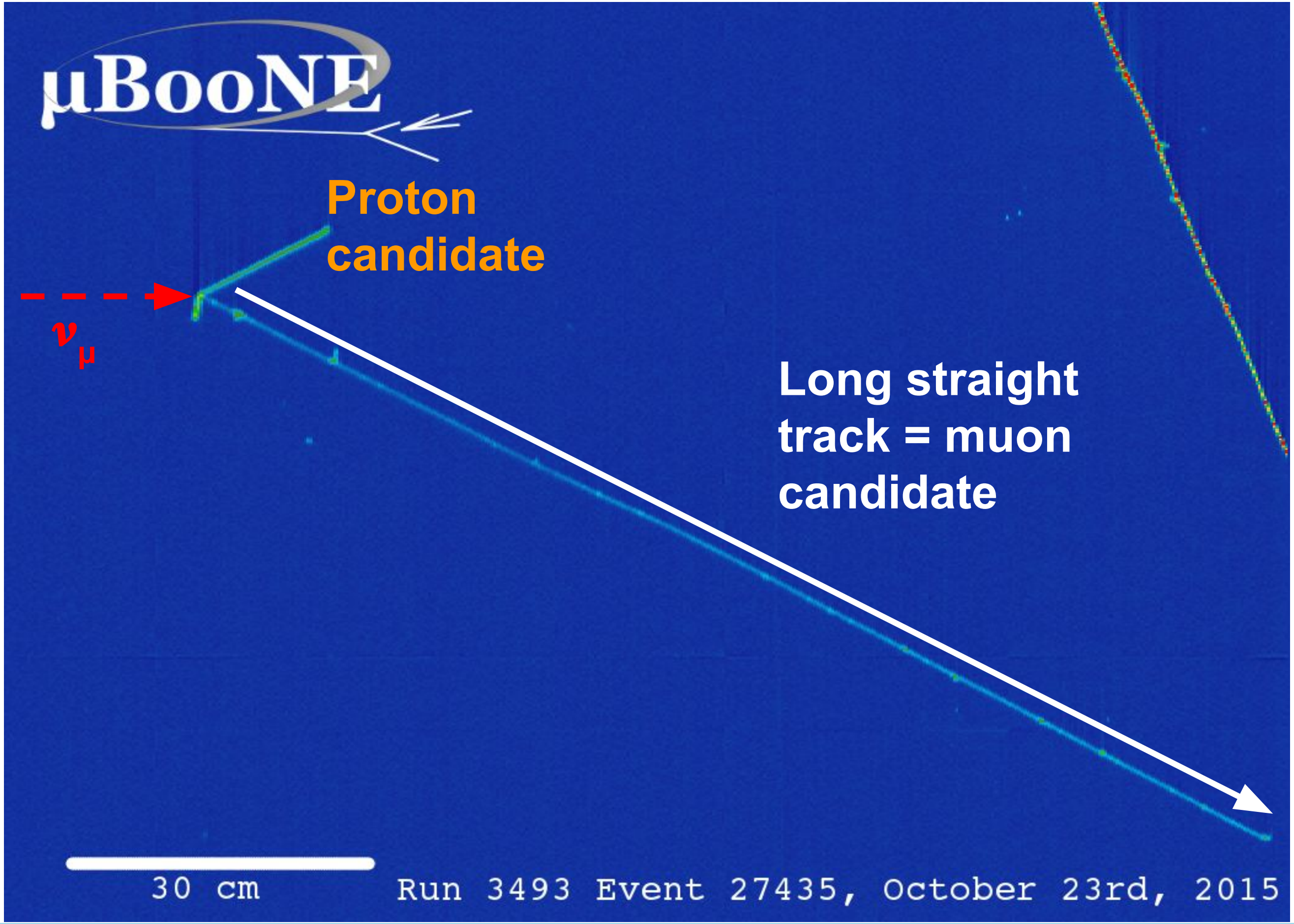
Let’s play a game

Photo Credit: symmetry magazine

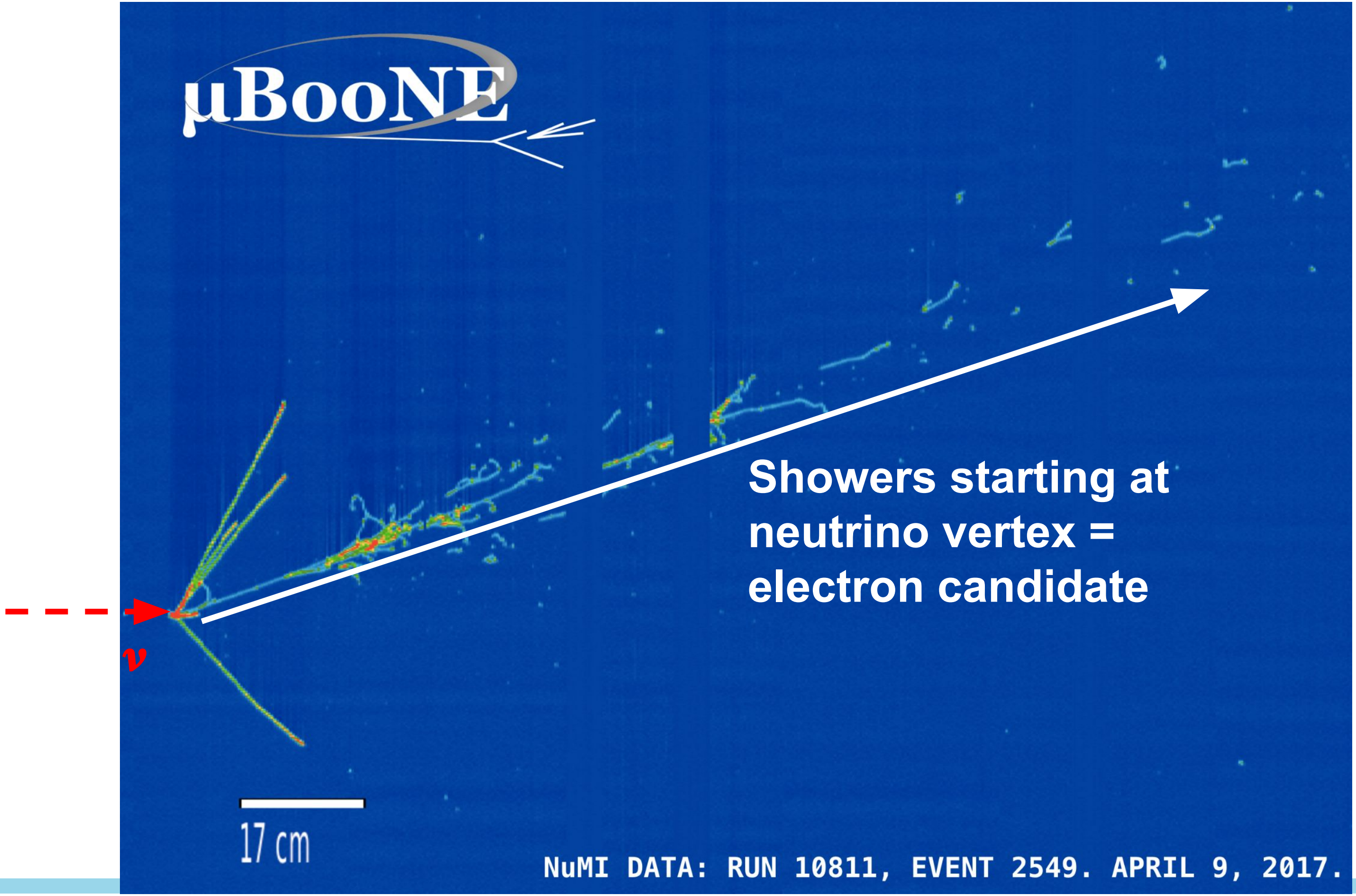
Guess Neutrino Flavor :



Guess Neutrino Flavor :



Guess Neutrino Flavor :



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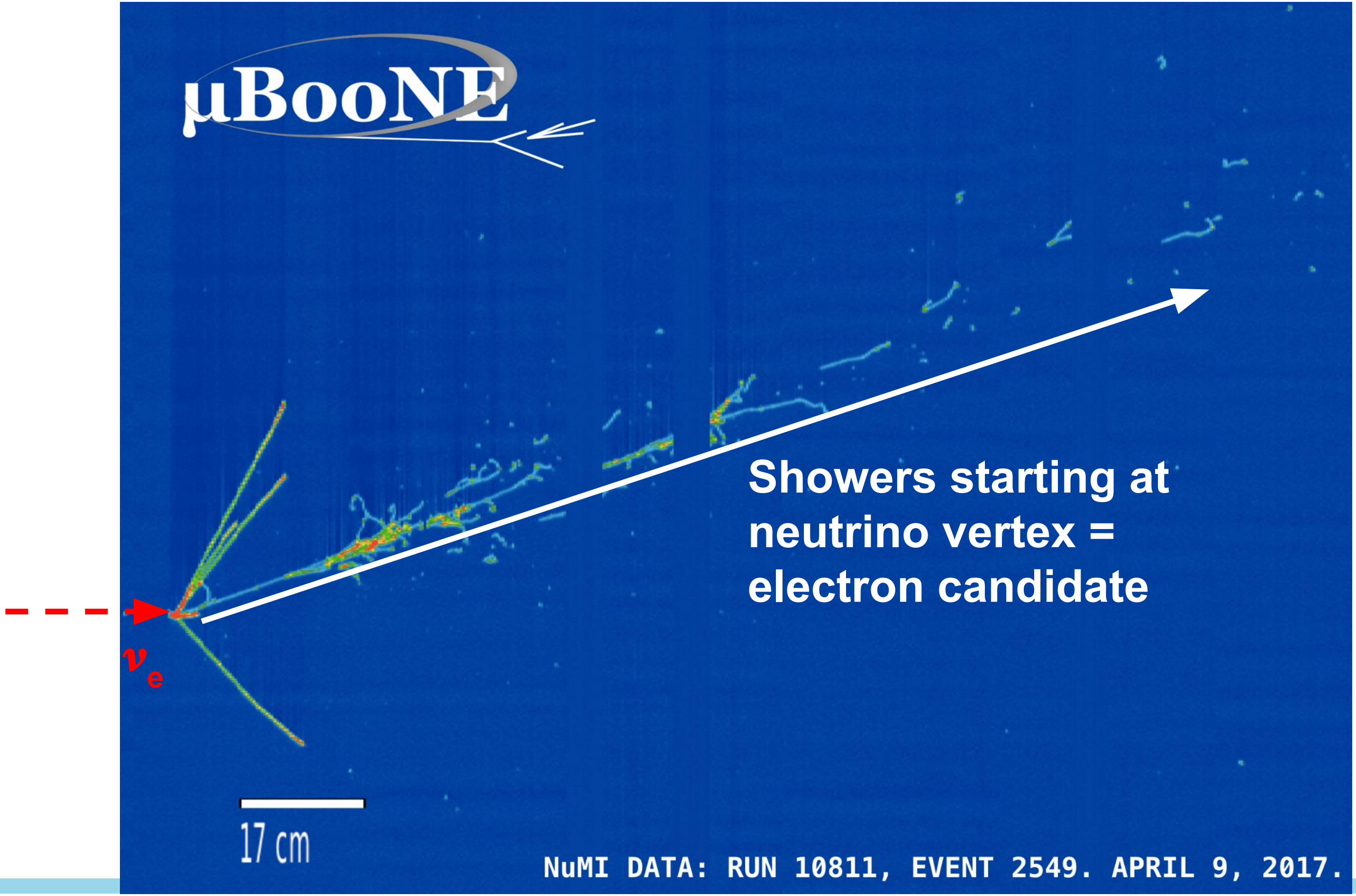

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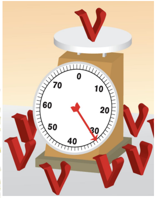
Open Questions about Neutrinos

How many neutrinos are there?

How much do they weigh?



Which neutrino is heaviest? Which one is lightest?

Are neutrinos their own anti particles?

How do neutrinos get mass?

The Worldwide Search Party

JUNO

KM3NeT

P-ONE

NOvA

BOREXINO
GRAN SASSO

ICECUBE
NEUTRINO OBSERVATORY

μBooNE

SHORT-BASELINE
SBND
NEAR DETECTOR

T2K

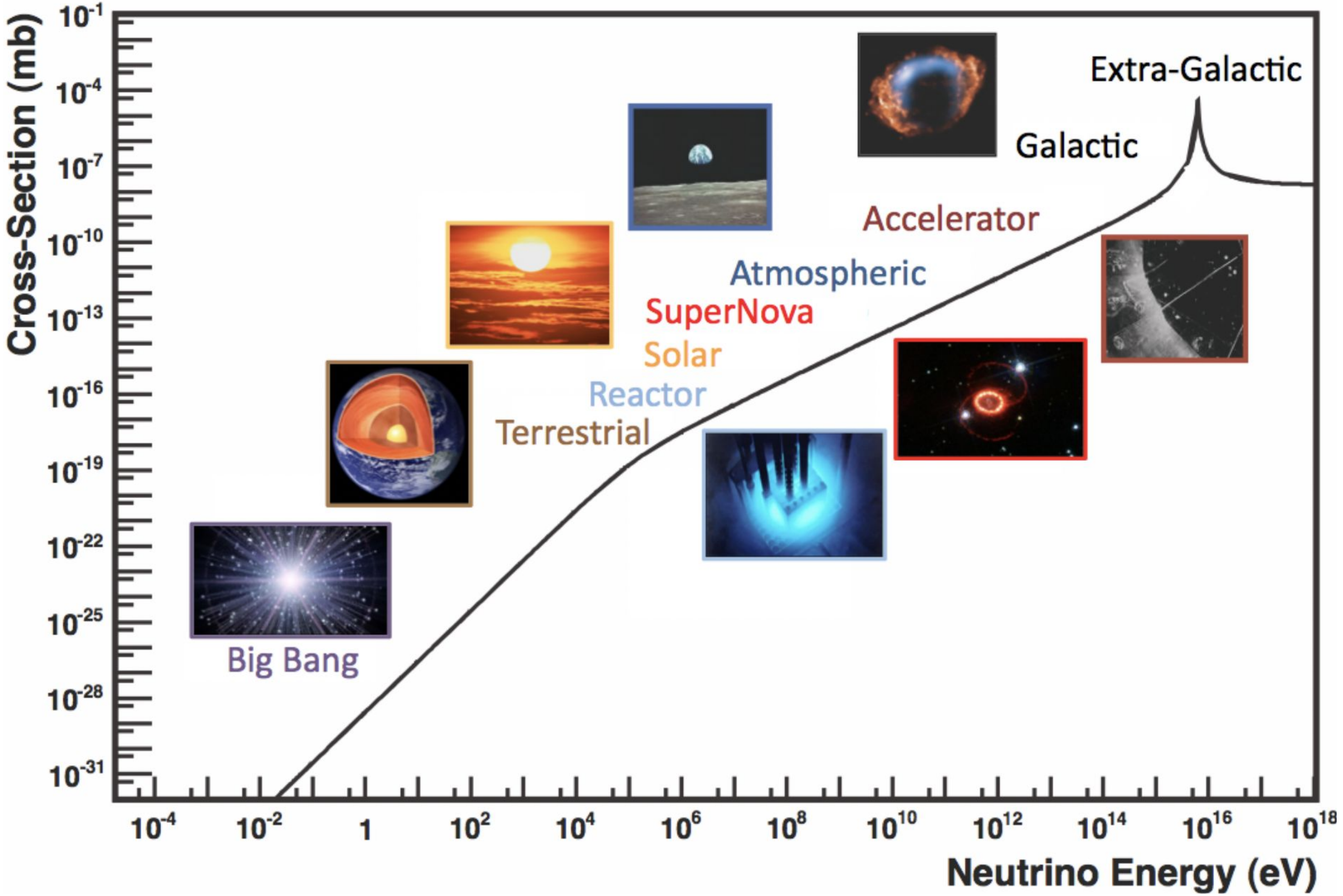
Imaging Cosmic And Rare Underground Signals

Hyper-Kamiokande

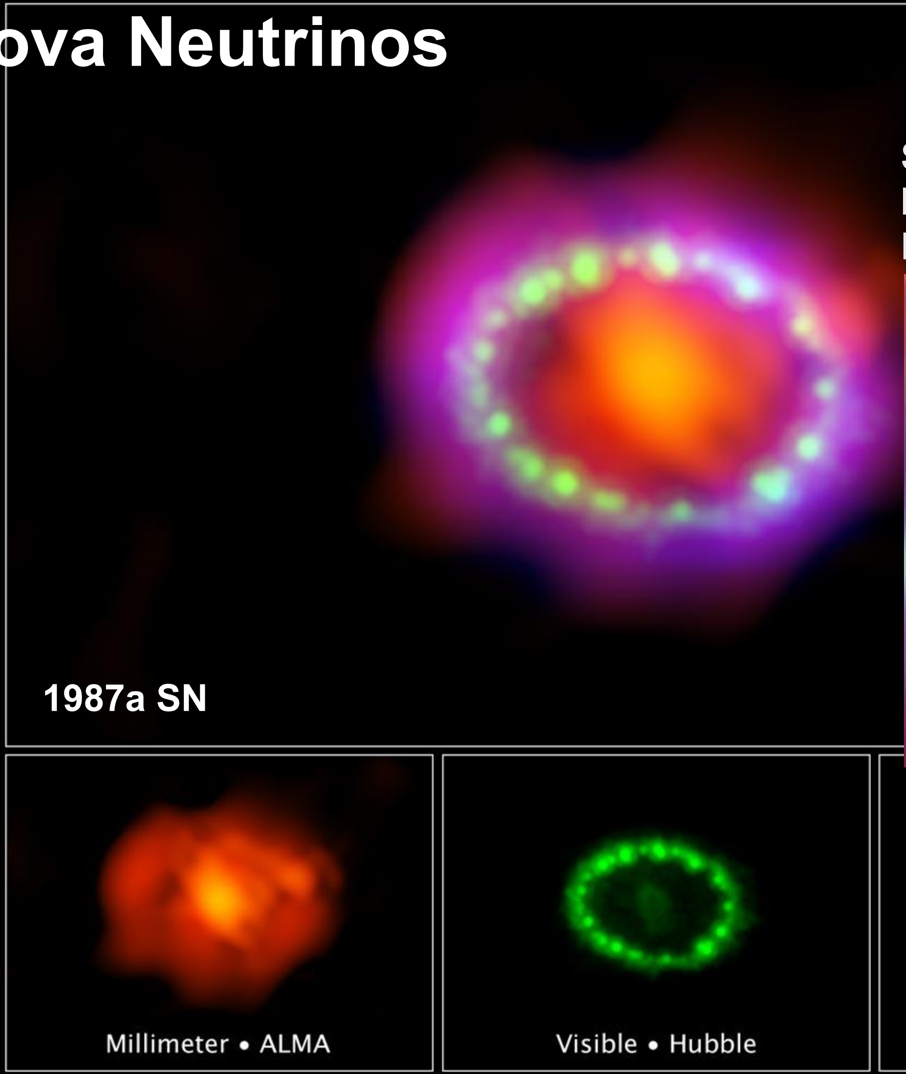
essnusb

DUNE

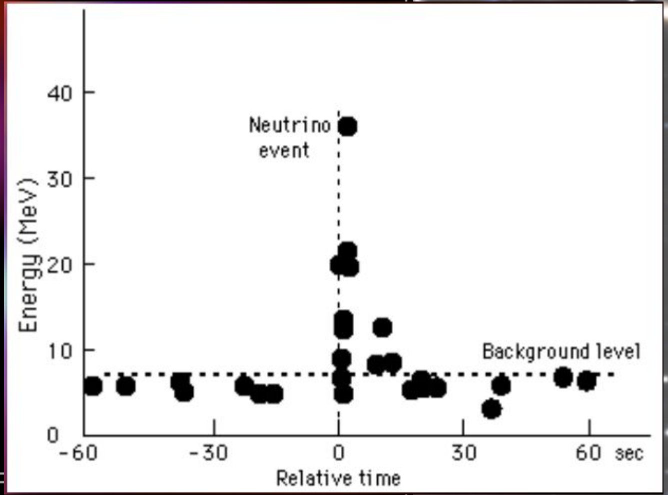
HYPER K


Cross-Section (mb)
10-1
10-4
10-7
10-10
10-13
10-16
10-19
10-22
10-25
10-28
10-31
10-4
10-2
1
102
104
106
108
1010
1012
1014
1016
1018
Neutrino Energy (eV)
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang

Supernova Neutrinos



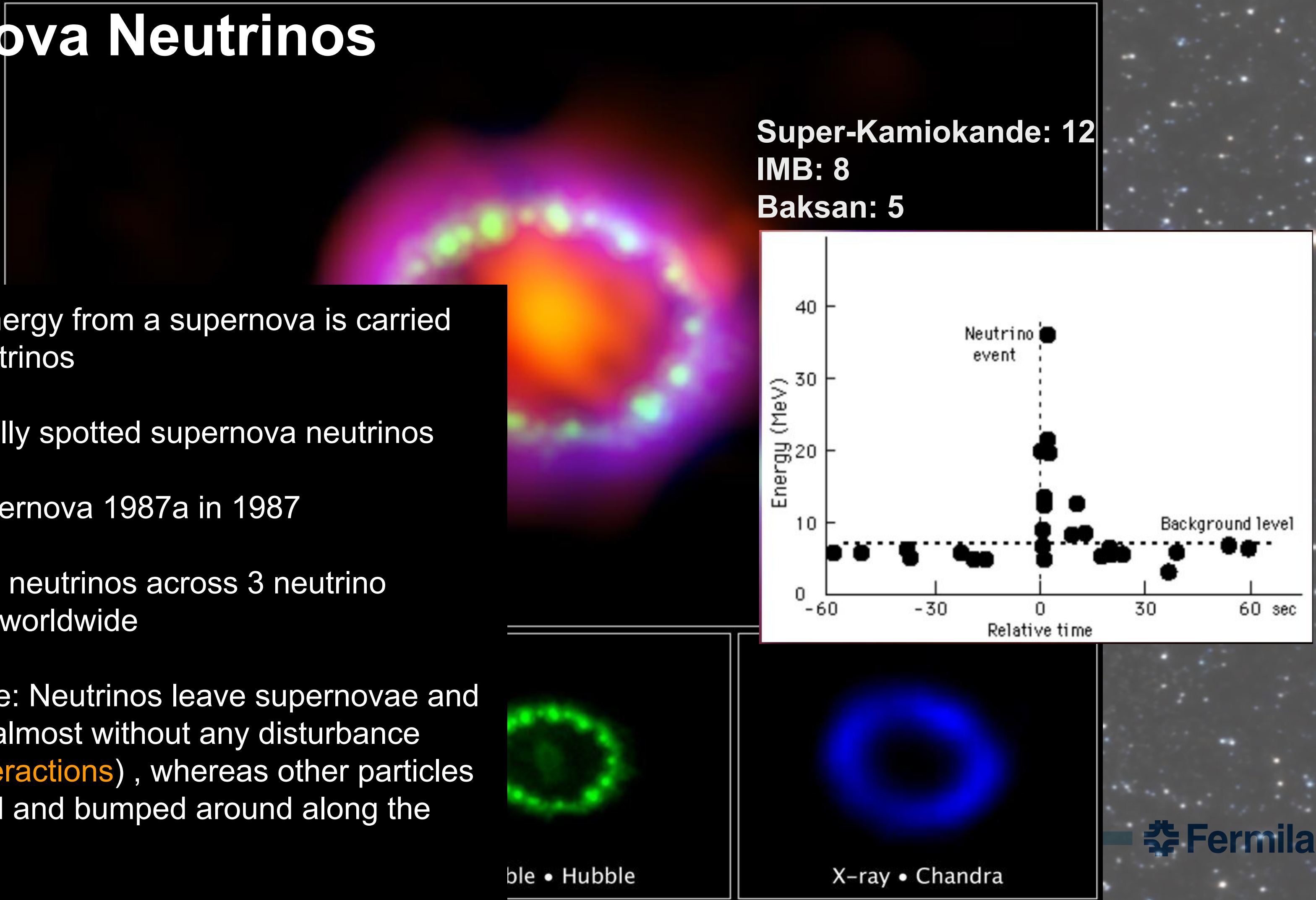
Super-Kamiokande: 12
IMB: 8
Baksan: 5



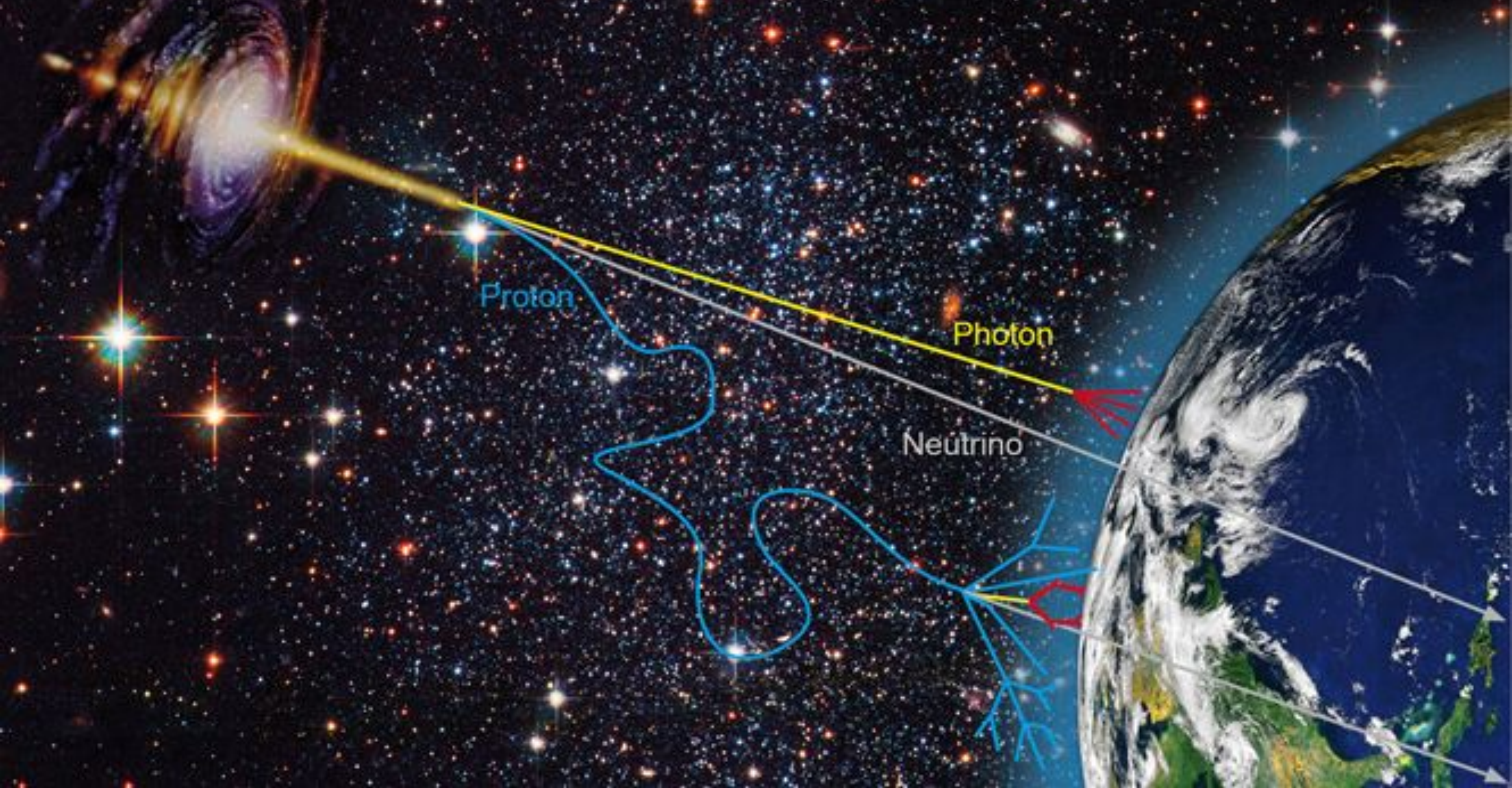
Supernova Neutrinos

- 99% of energy from a supernova is carried off by neutrinos
- successfully spotted supernova neutrinos once!
  - Supernova 1987a in 1987
- ~ 2 dozen neutrinos across 3 neutrino detectors worldwide
- Advantage: Neutrinos leave supernovae and reach us almost without any disturbance (weak interactions) , whereas other particles get jostled and bumped around along the way

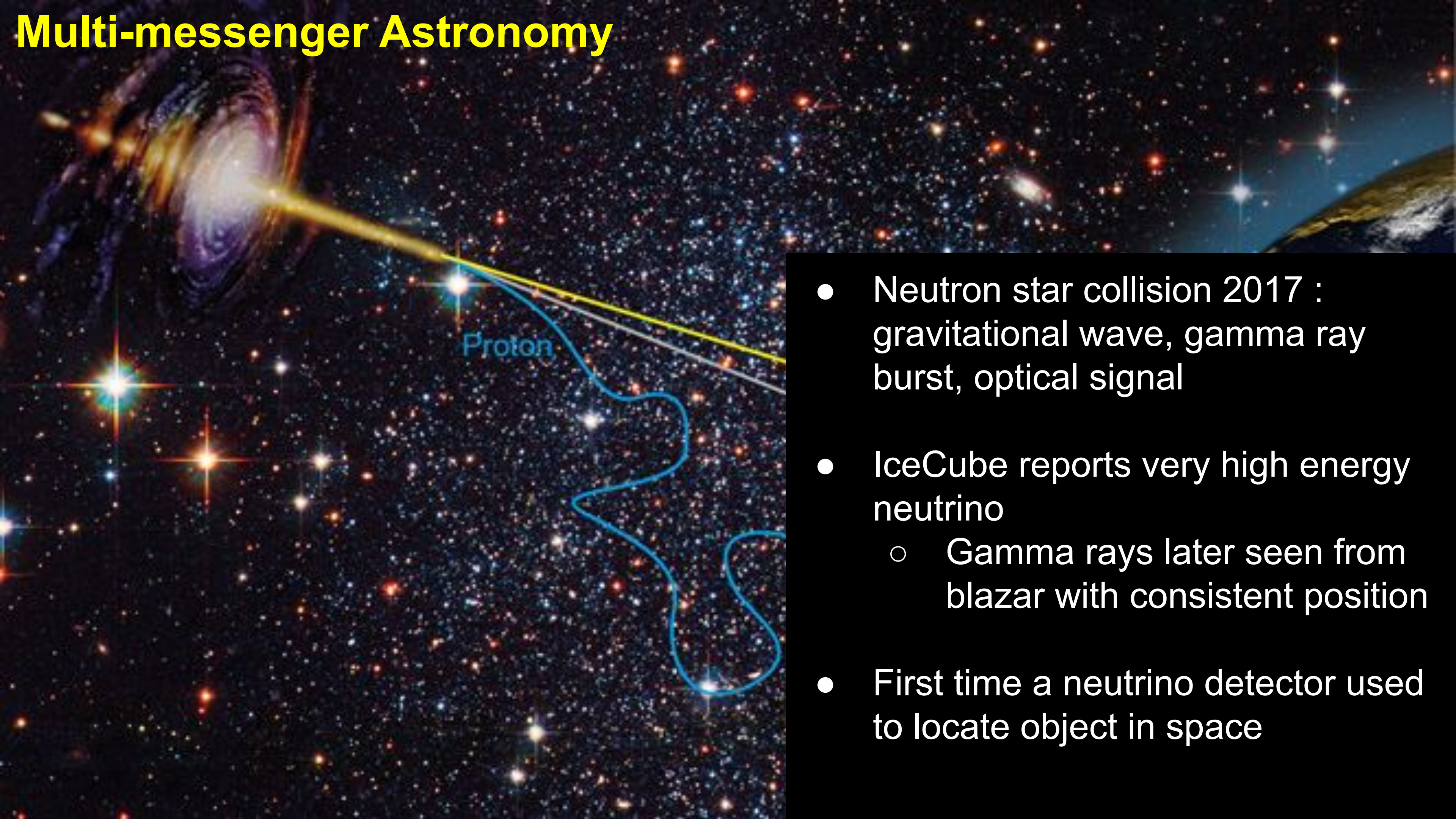
Super-Kamiokande: 12
IMB: 8
Baksan: 5



Multi-messenger Astronomy



Multi-messenger Astronomy



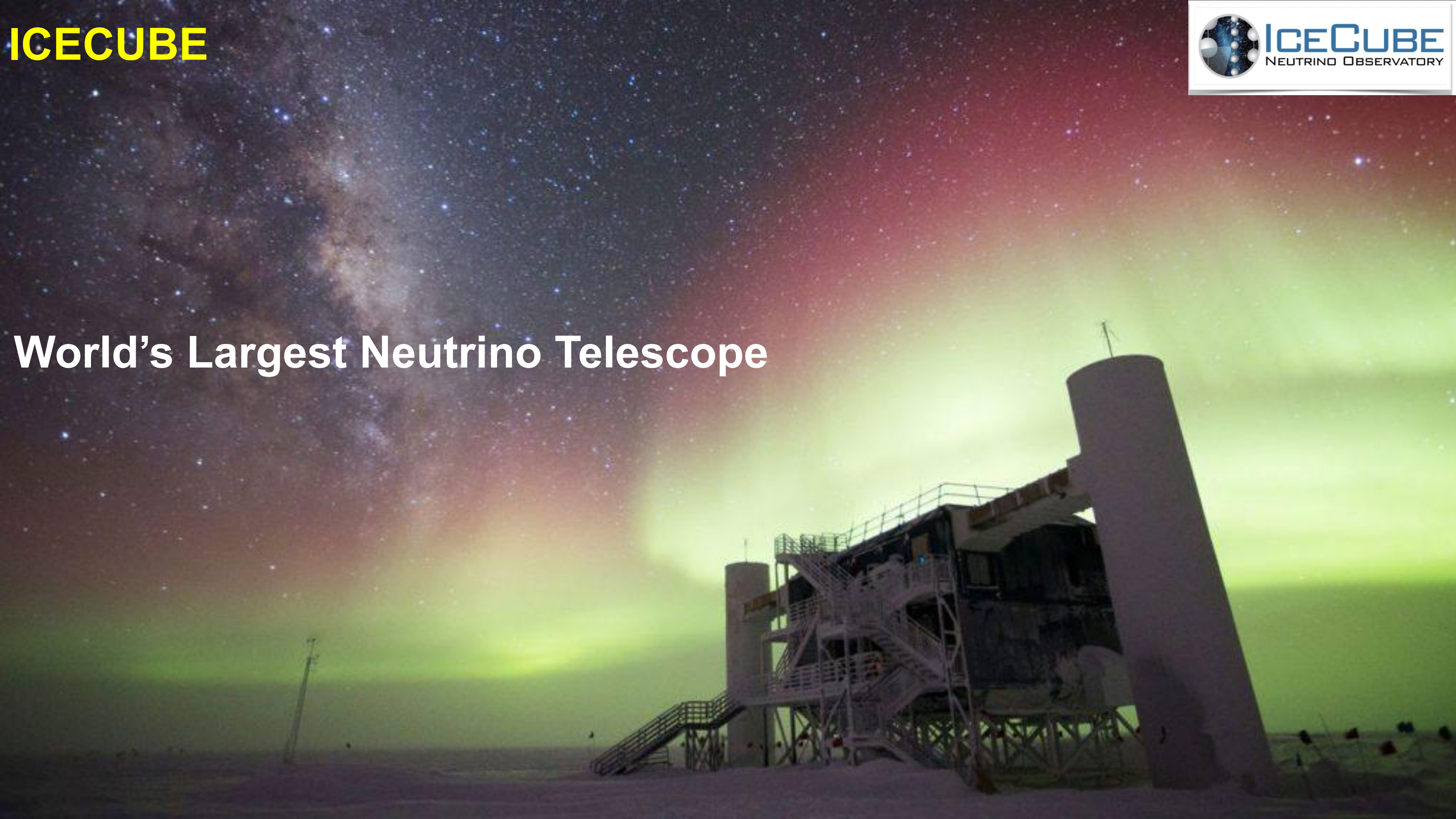
- Neutron star collision 2017 : gravitational wave, gamma ray burst, optical signal

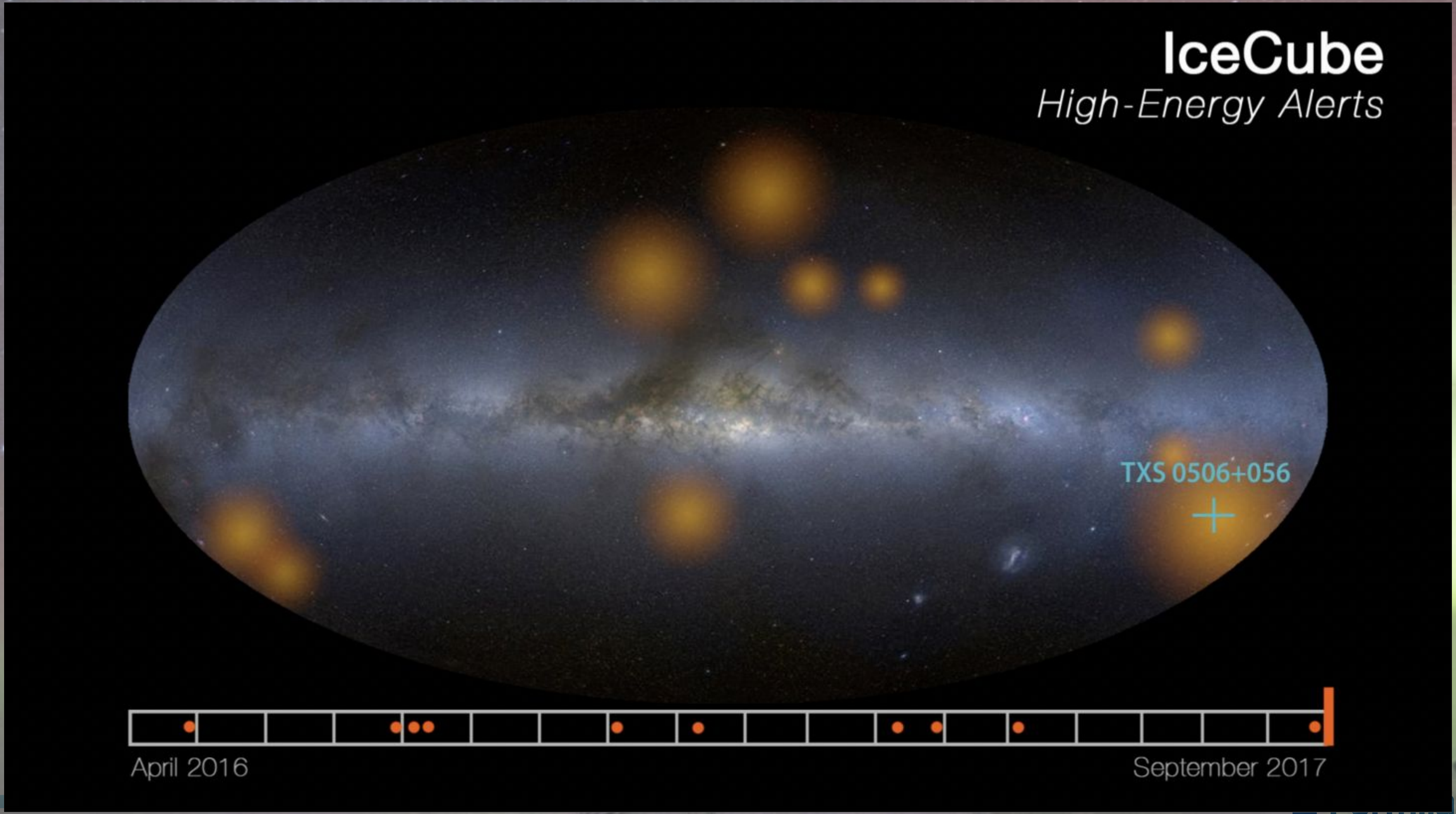
- IceCube reports very high energy neutrino
    - Gamma rays later seen from blazar with consistent position

- First time a neutrino detector used to locate object in space

ICECUBE

World’s Largest Neutrino Telescope




IceCube
High-Energy Alerts
TXS 0506+056
April 2016
September 2017

Neutrino Experiments

There are 4 types/sources of experiments:

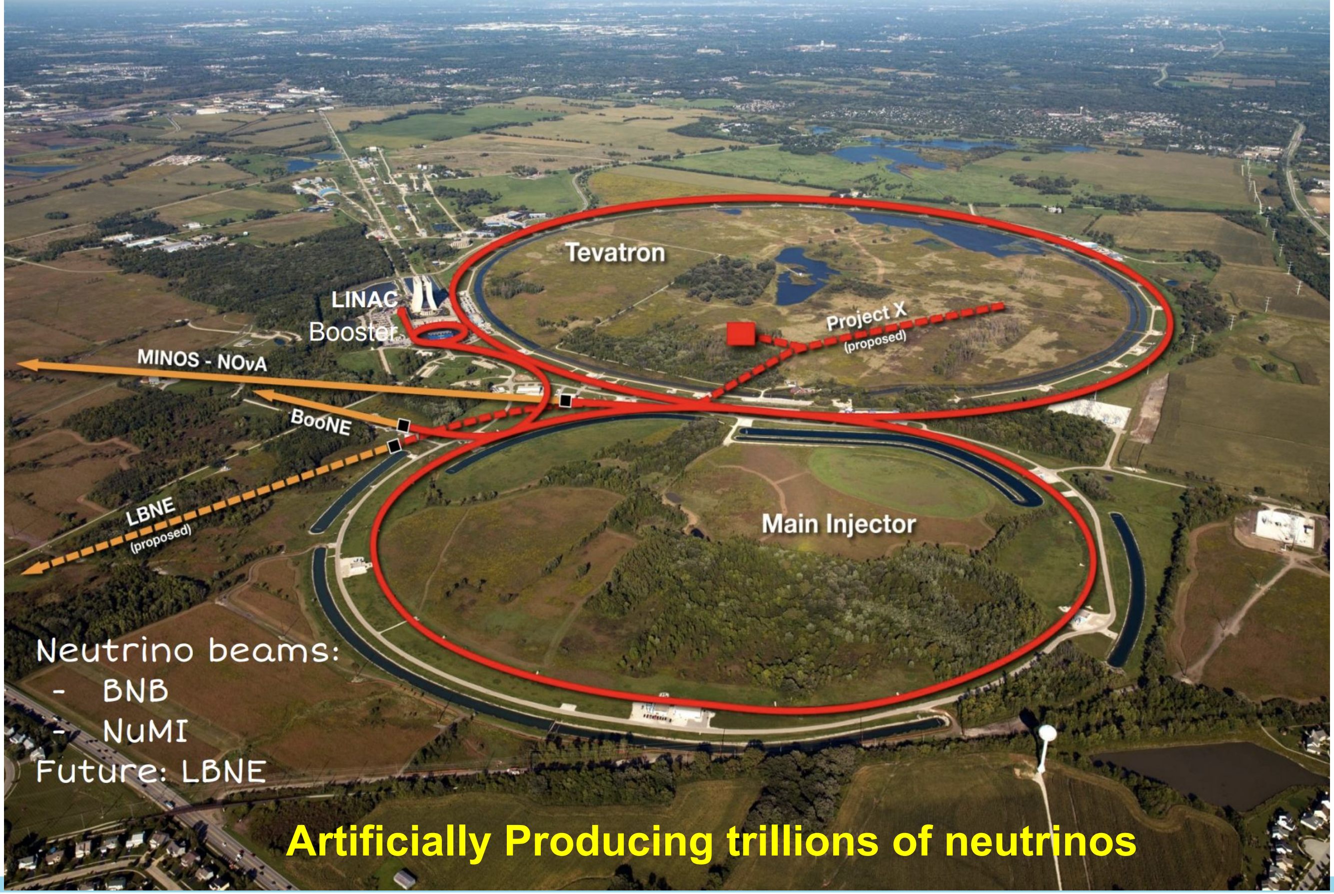
- **Solar**
- **Atmospheric**
- **Reactor**
- **Accelerator**

Natural sources (Solar, Atmospheric)

Artificial sources (Reactor, Accelerator)

Let's talk about this! (Accelerator)

Fermilab Accelerator Complex



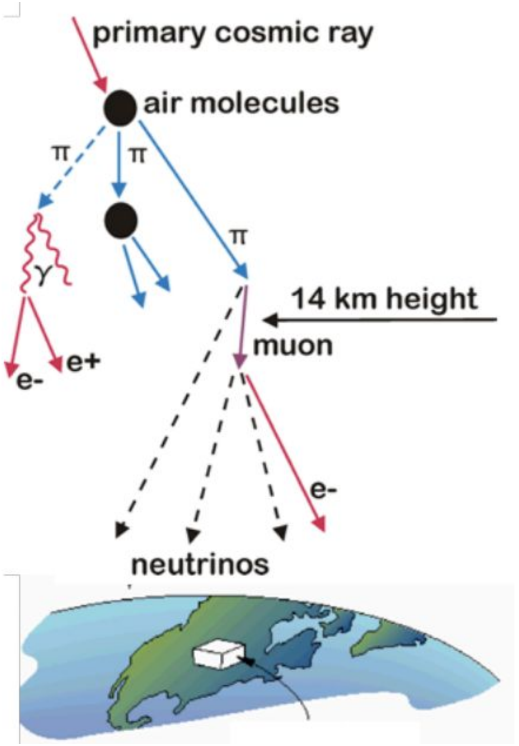
Neutrino beams:
- BNB
- NuMI

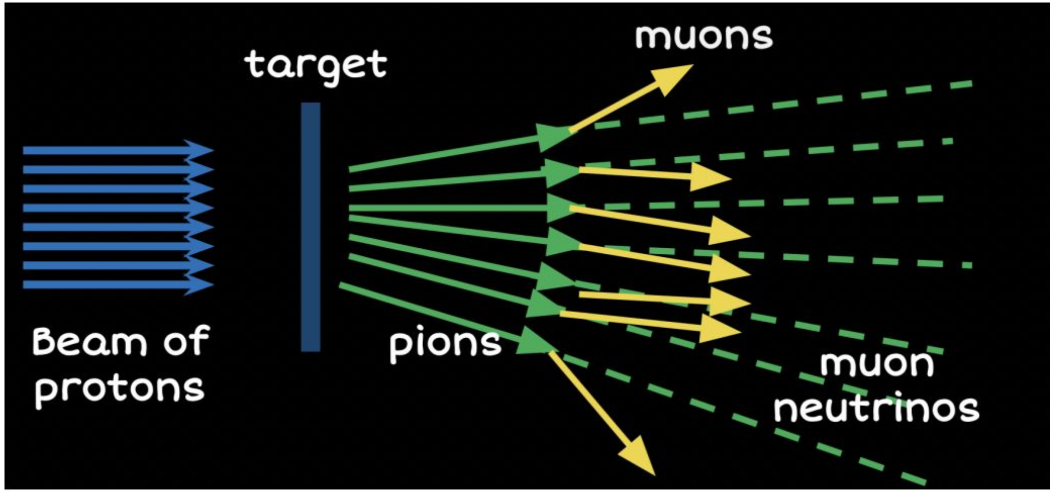
Future: LBNE

Artificially Producing trillions of neutrinos

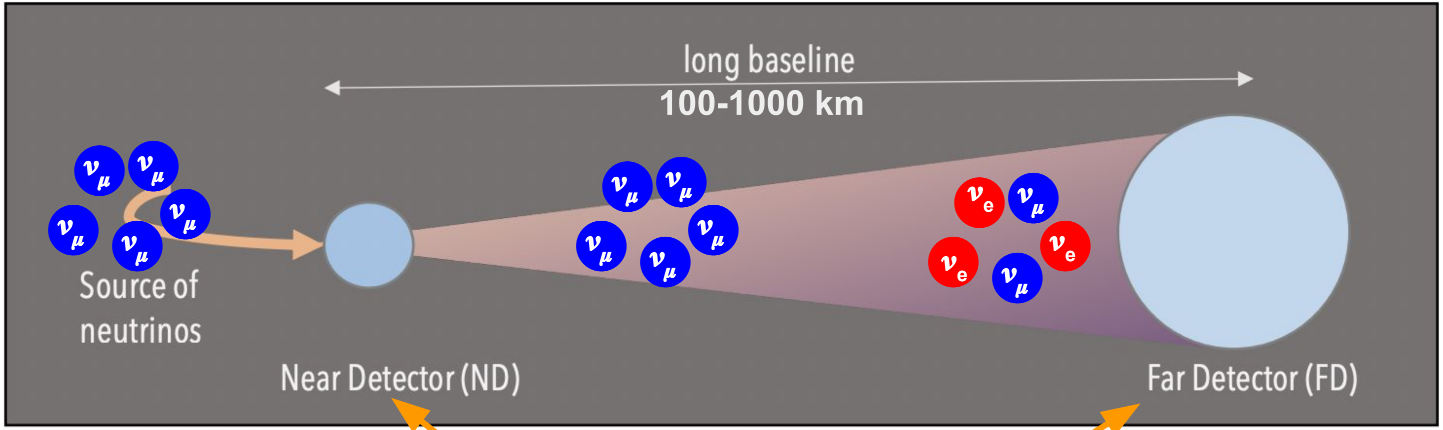
Produce Neutrinos at Lab

We use same technique as nature





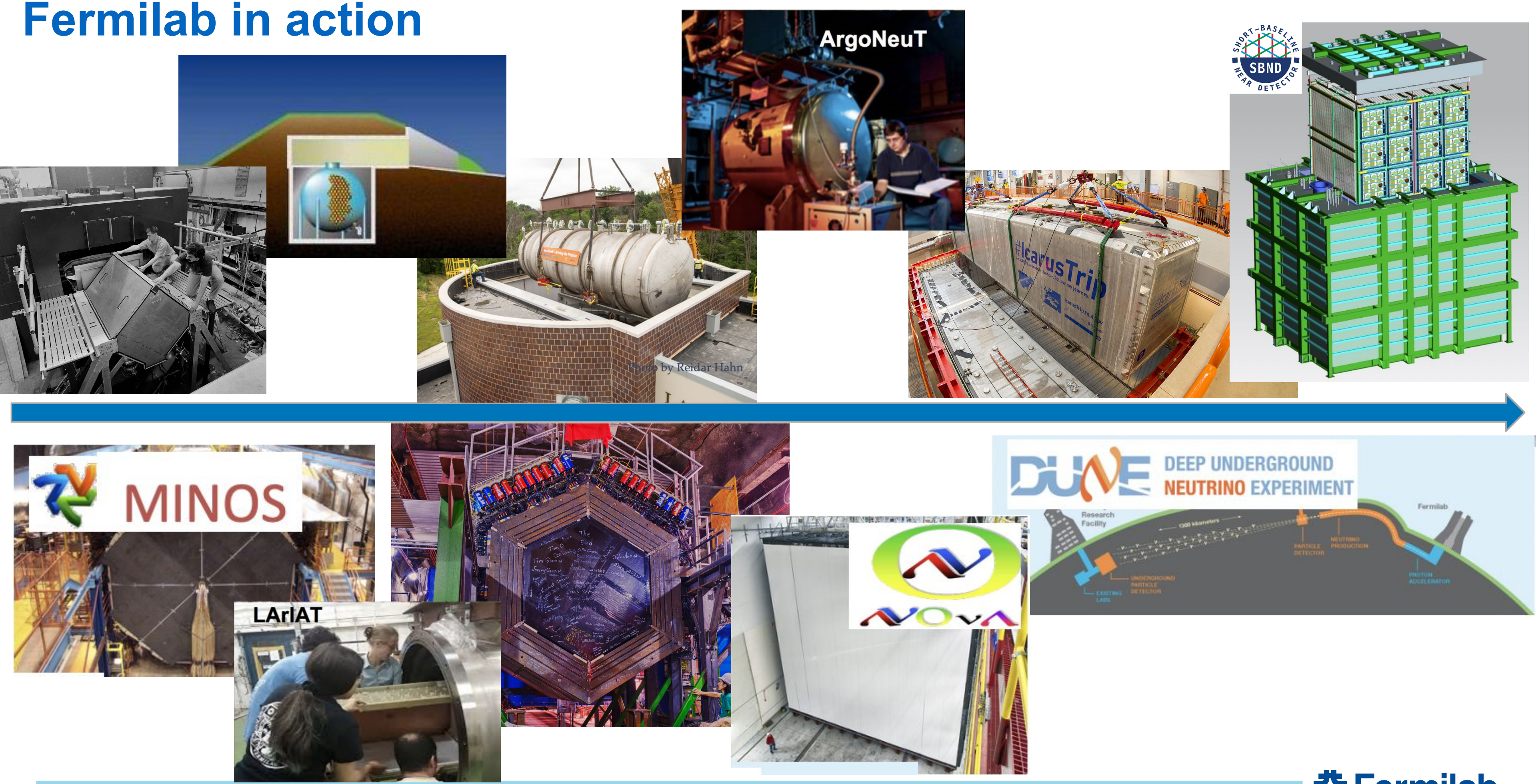
Accelerator Neutrino Strategy



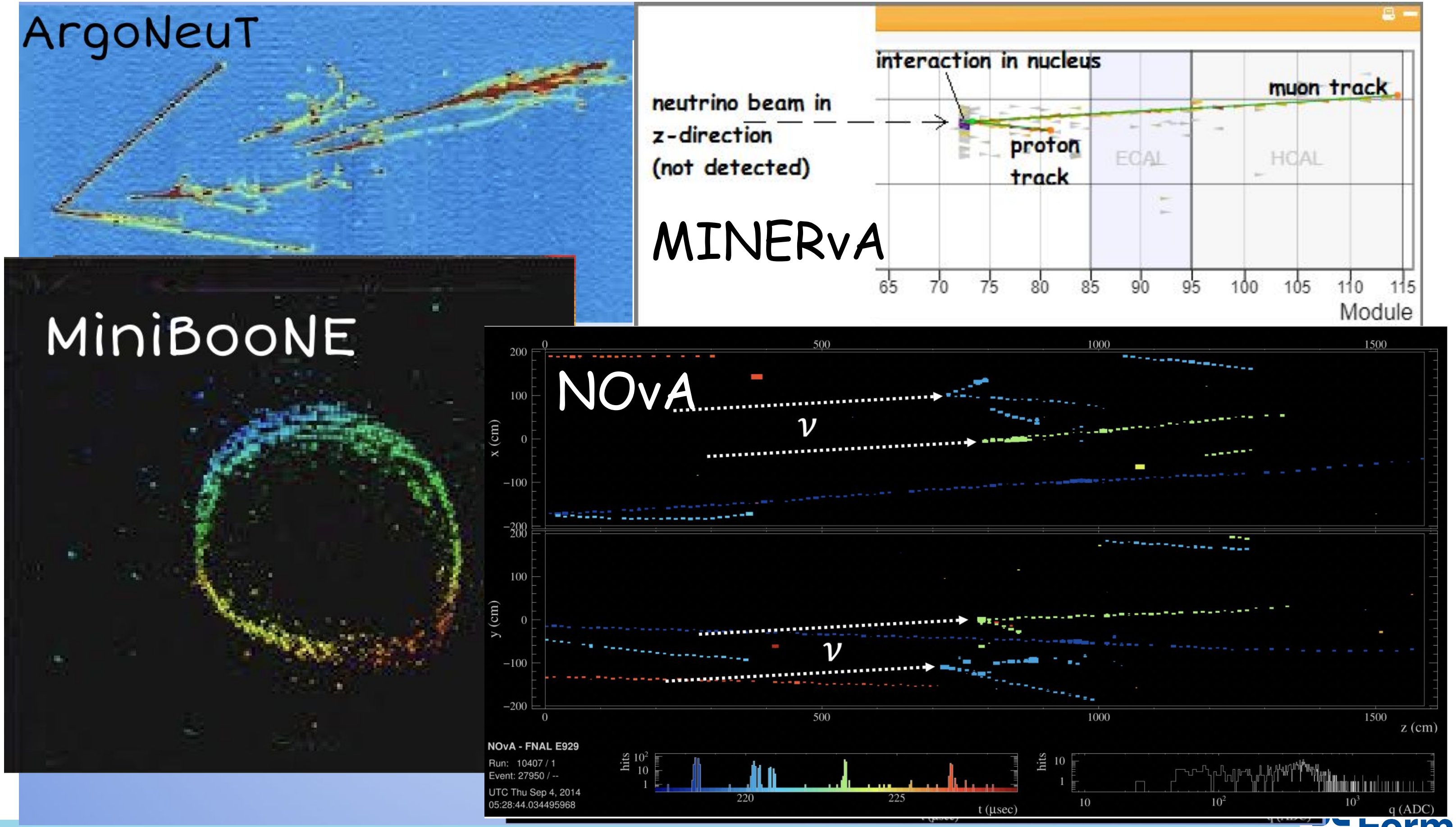
Two functionally identical detectors

Count the neutrinos at Near and Far Detector

Fermilab in action



What Do the Detectors See?

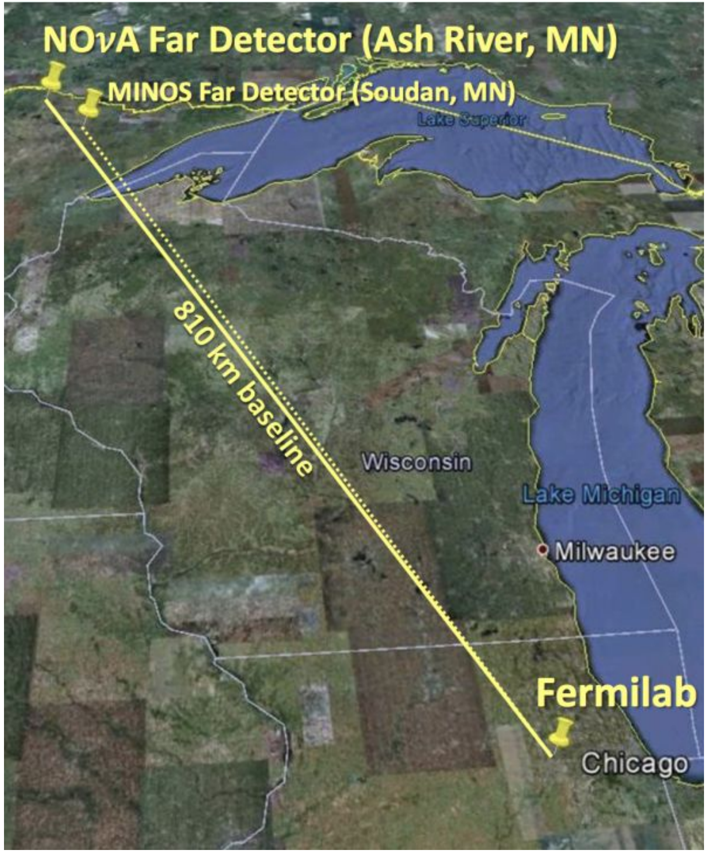


NOvA

- Sends a beam of muon neutrinos 810 km (500 miles) from Fermilab to Northern Minnesota
- Consists of 2 detectors, one here at Fermilab, one in Minnesota
- Detects the number of muon and electron neutrinos in each detector

Near Detector

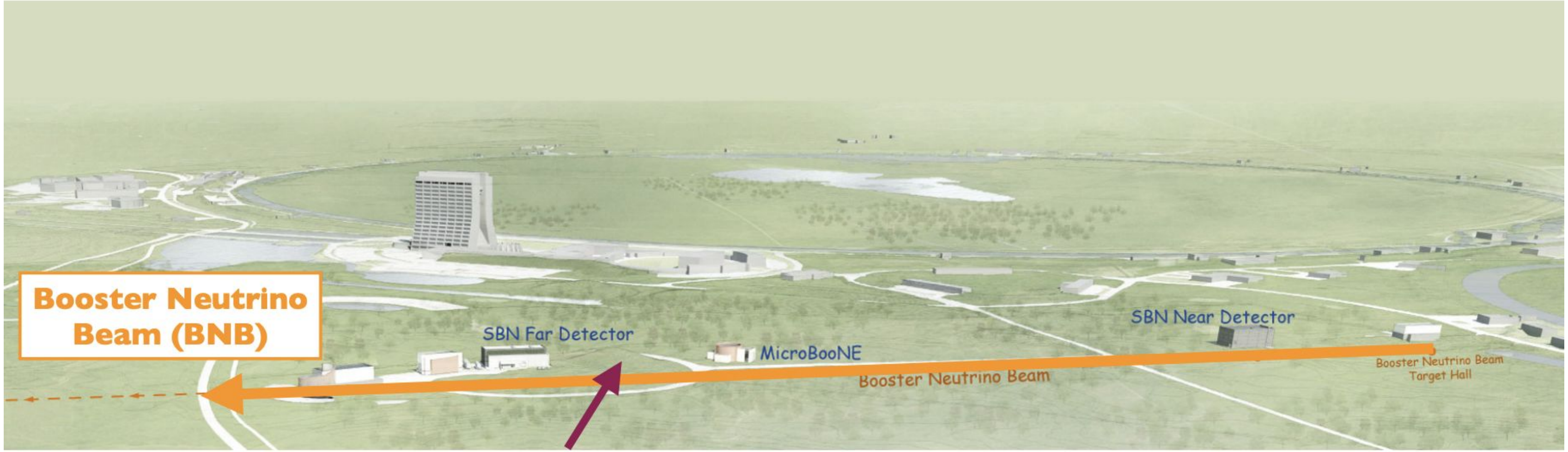
Far Detector



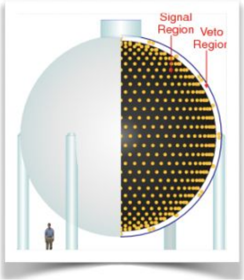
Chasing Neutrino Puzzles in 21st Century

Brand new detector technology!

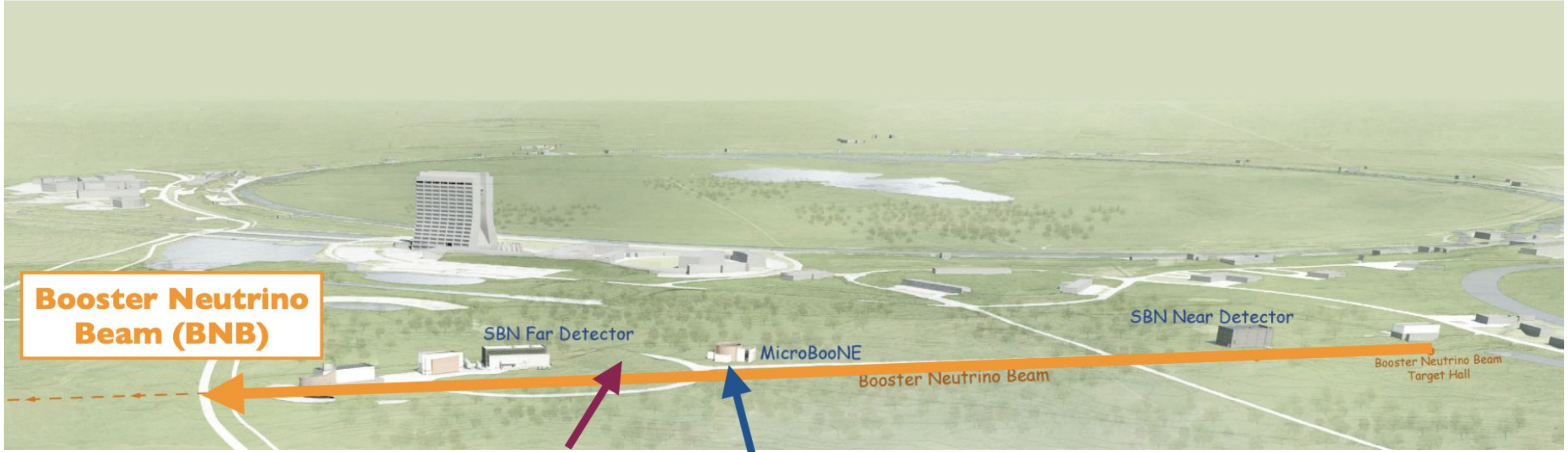
A Suite of Experiments at Fermilab



MiniBooNE

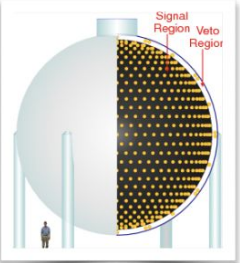


A Suite of Experiments at Fermilab



MiniBooNE

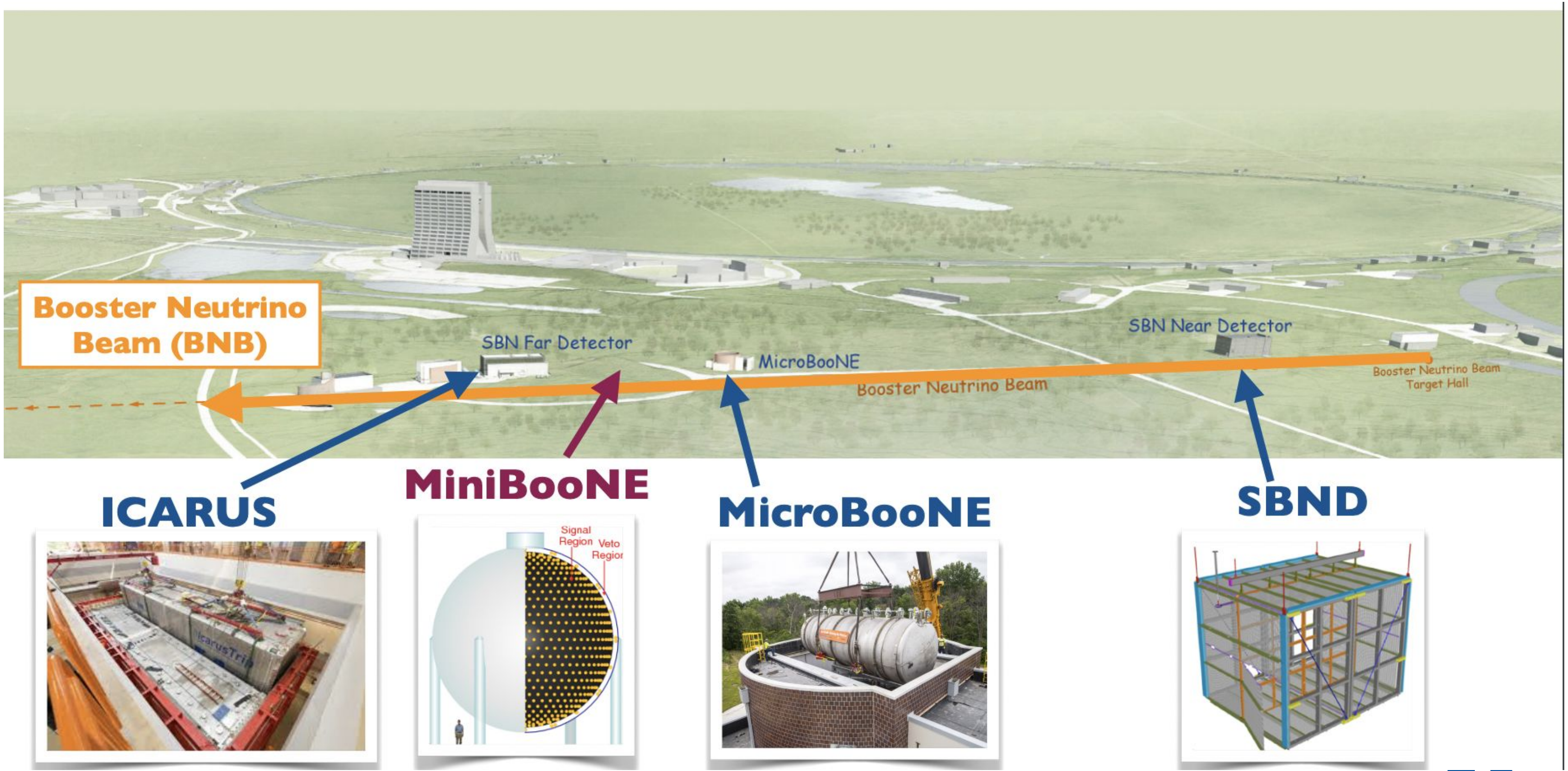
500m



MicroBooNE

470m

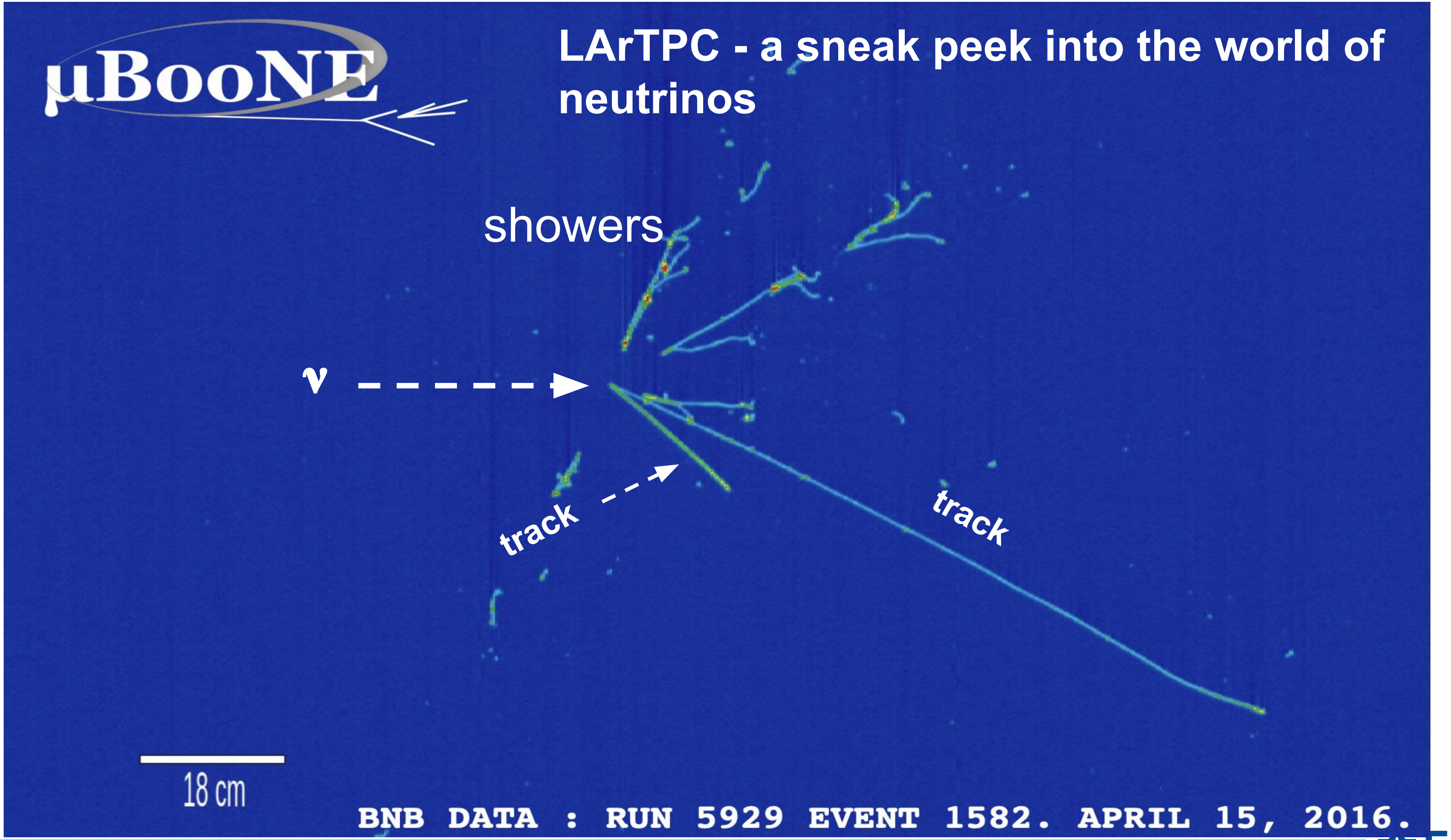
A Suite of Experiments at Fermilab



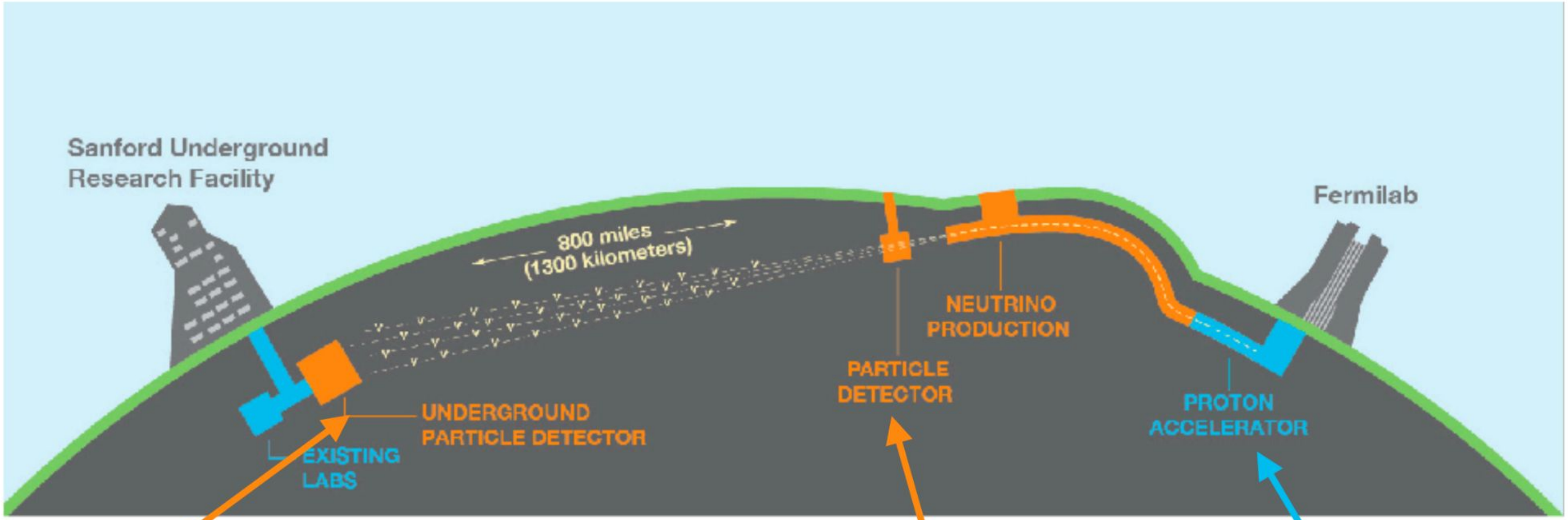
MicroBooNE

MicroBooNE

MicroBooNE in a Nutshell



Deep Underground Neutrino Experiment



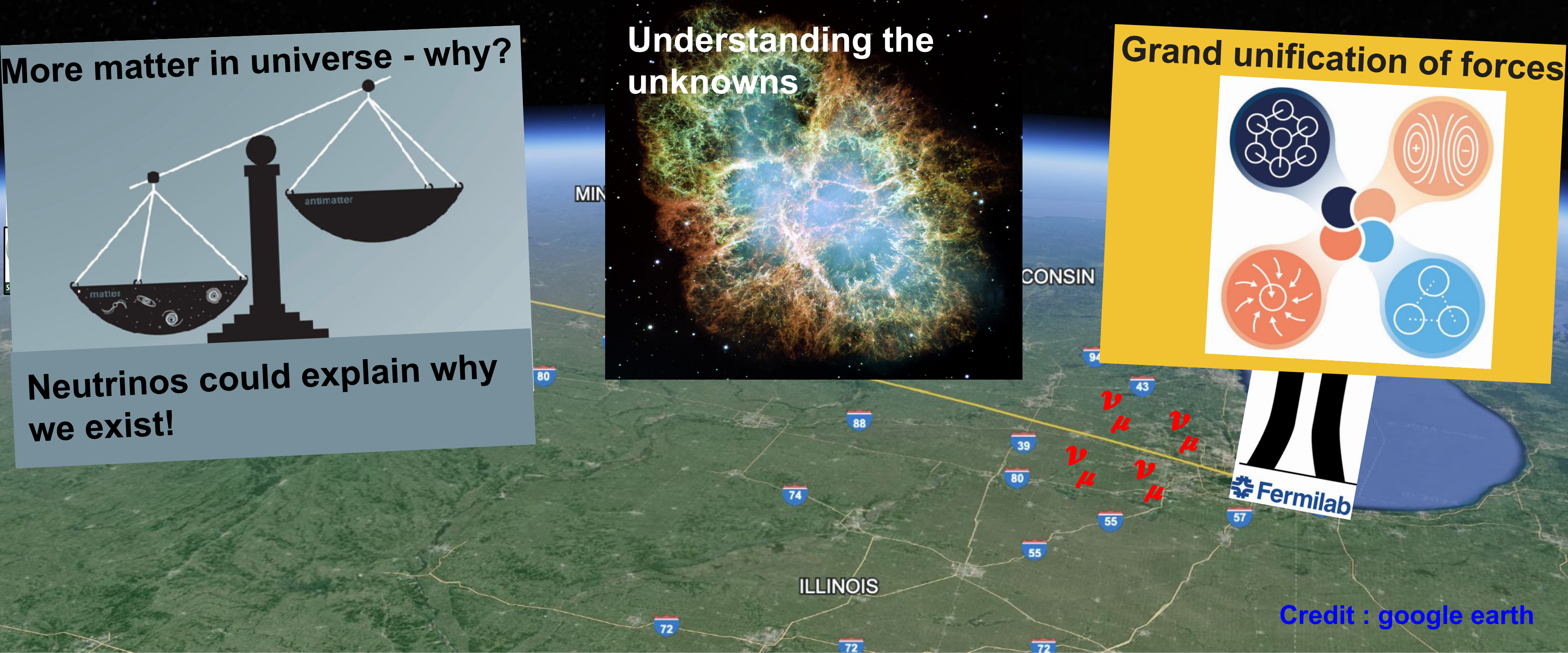
Measure at far detector: look for differences to near detector!

Travel a long distance …

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

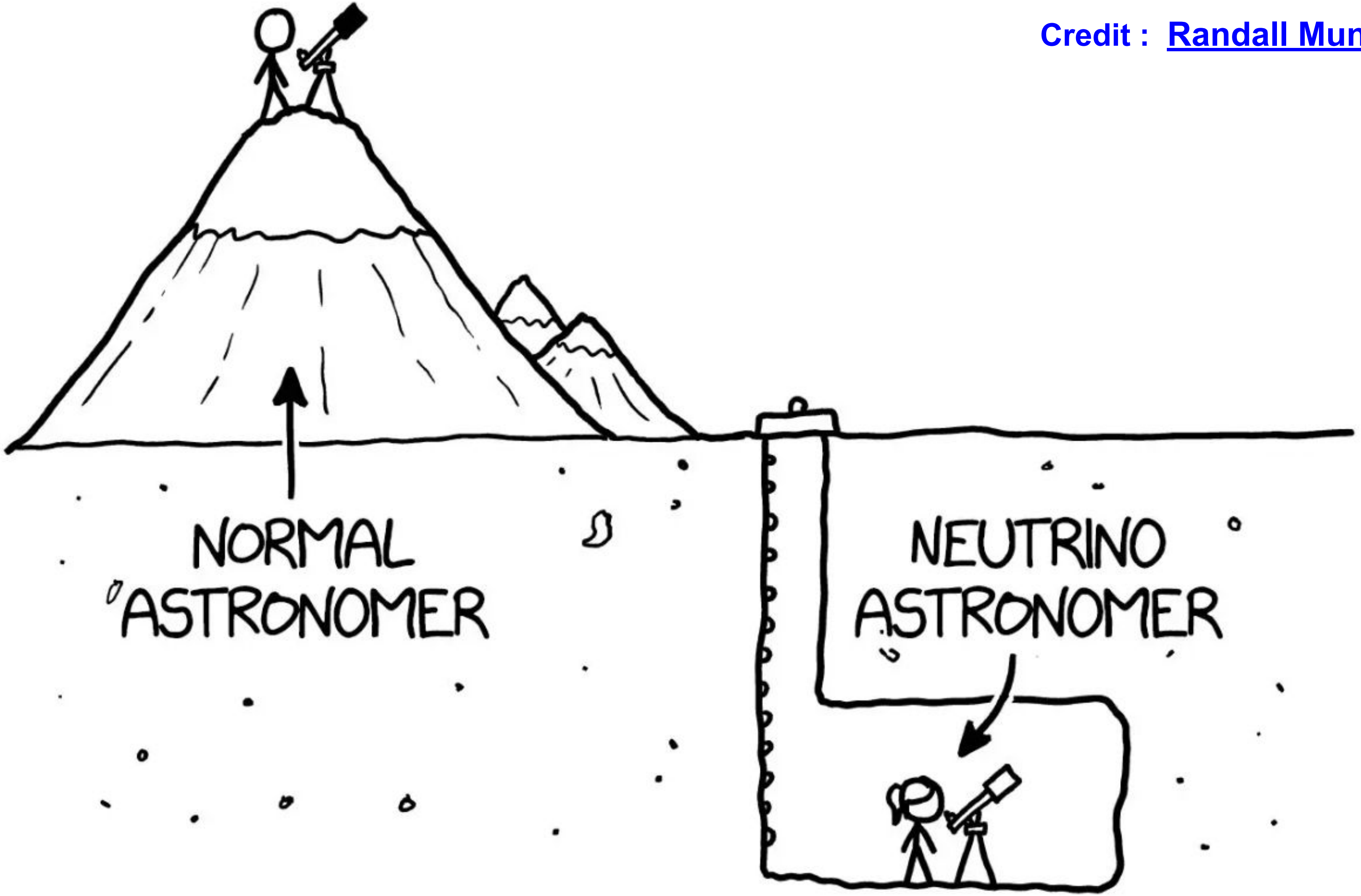
Make neutrinos using particle accelerator

Deep Underground Neutrino Experiment

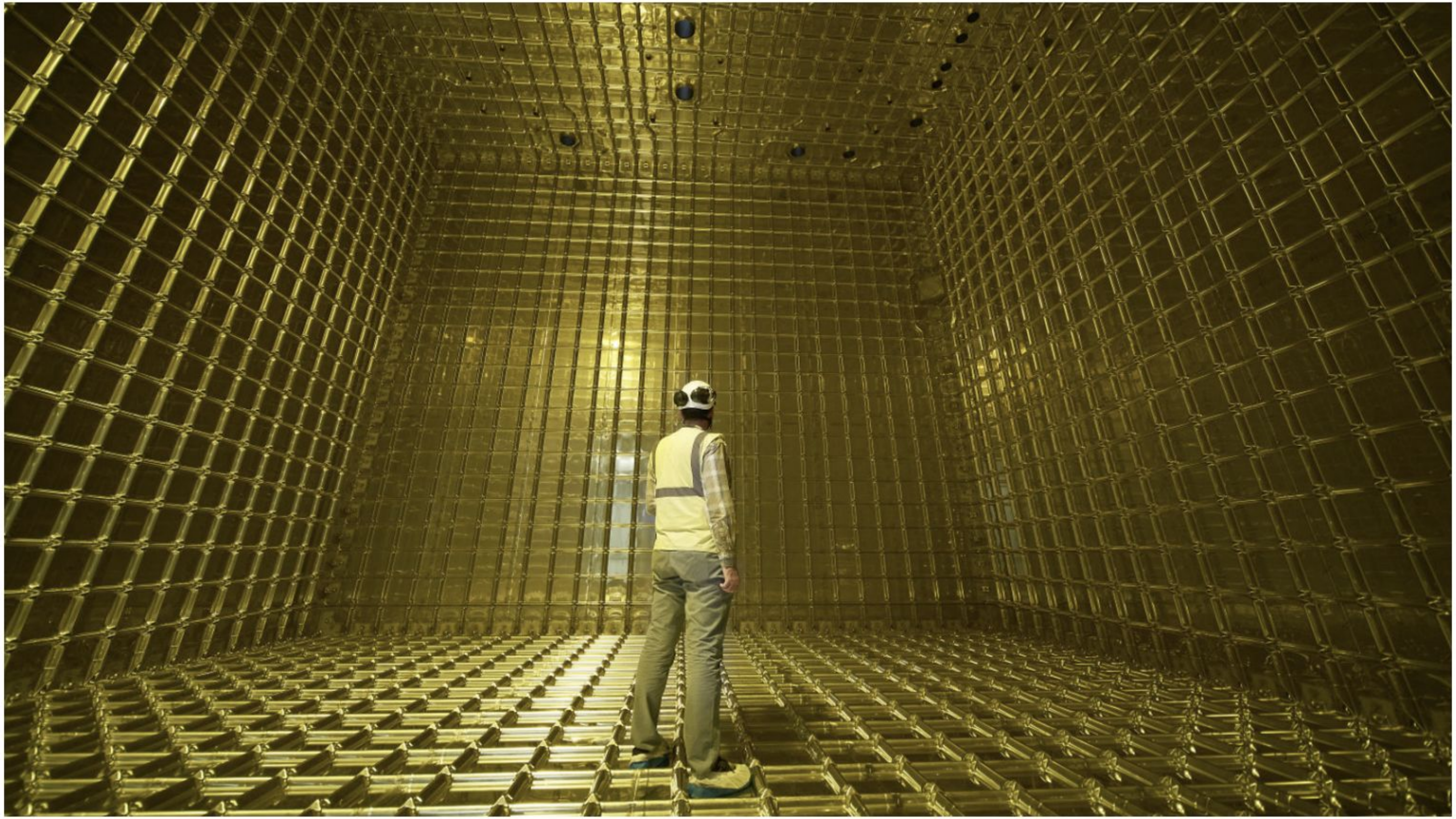


Credit : google earth

Credit : [Randall Munroe]



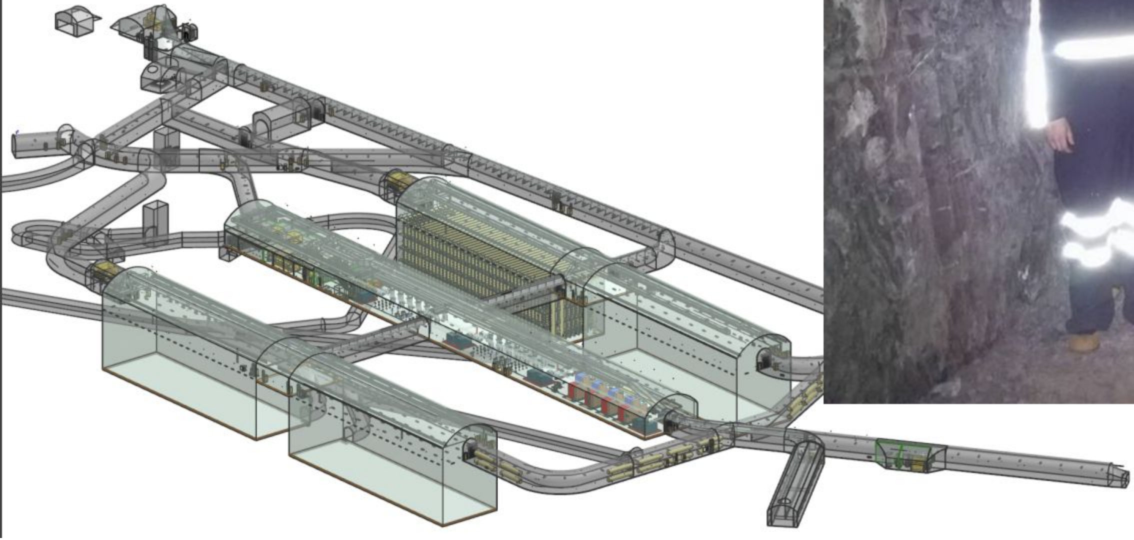
Inside a Liquid Argon Time Projection Chamber *A fiddler inside ProtoDUNE*



The DUNE Far Detector

Right: The Far Detector in May 2016.

- **Detector complex in 2025**
- **Data taking starts at end of this decade**

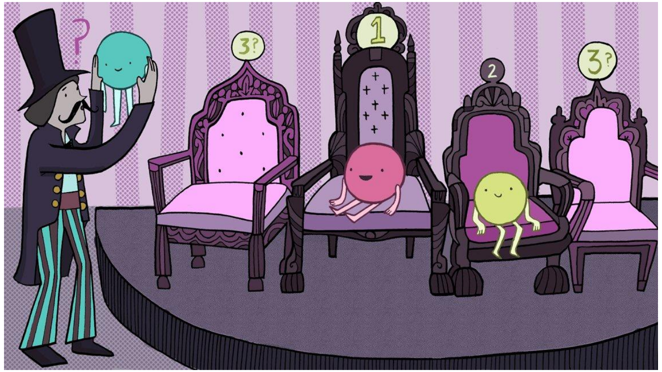


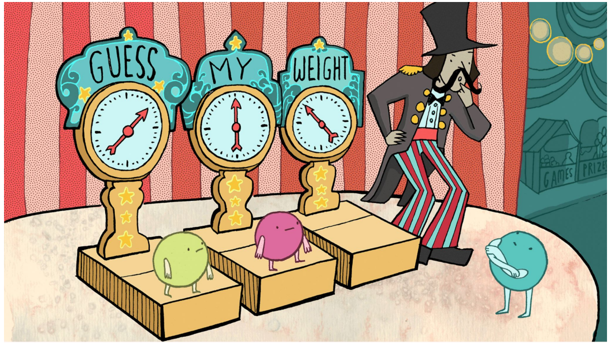
The DUNE Far Detector

Right: The Far Detector in May 2016.

The Quest Continues

- Neutrinos are one of the least-well-understood particles in the Standard Model
- Neutrino oscillation is beyond the Standard Model, and opens the door to exciting new possibilities
- However, a lot remains that we don't understand
- New experiments with advanced technology!





Thank you for listening!

Back up

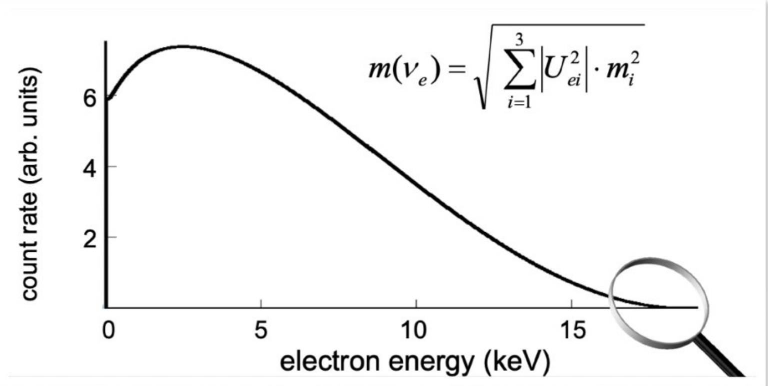
MEASURING THE NEUTRINO MASS

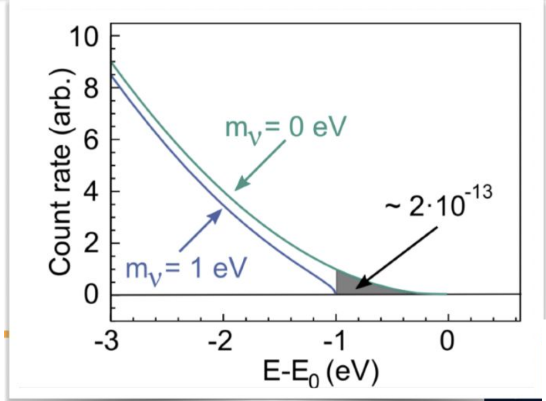
$$\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

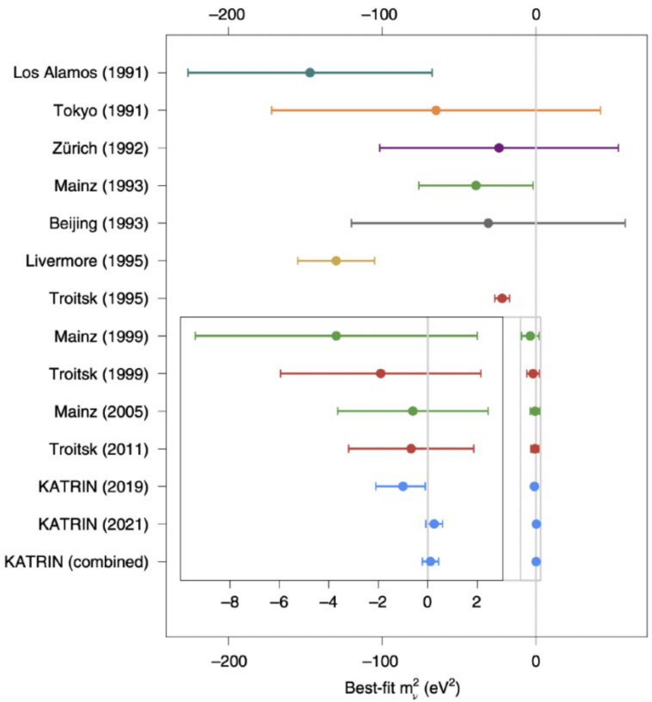
- Neutrino oscillation tells us that neutrinos have mass

- But not the absolute mass (only the Δm^2 differences)





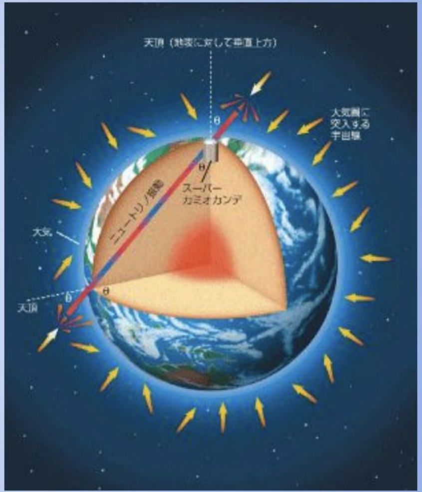
MEASURING THE NEUTRINO MASS



- New KATRIN result: Nature Physics volume 18, pages 160–166, 14th February 2022
- **World's best constraint on neutrino mass**
- Best fit: $m_\nu = 0.26 \pm 0.34\ eV^2c^{-4}$
- Upper limit of $m_\nu < 0.8\ eVc^{-2}$ at 90% confidence level

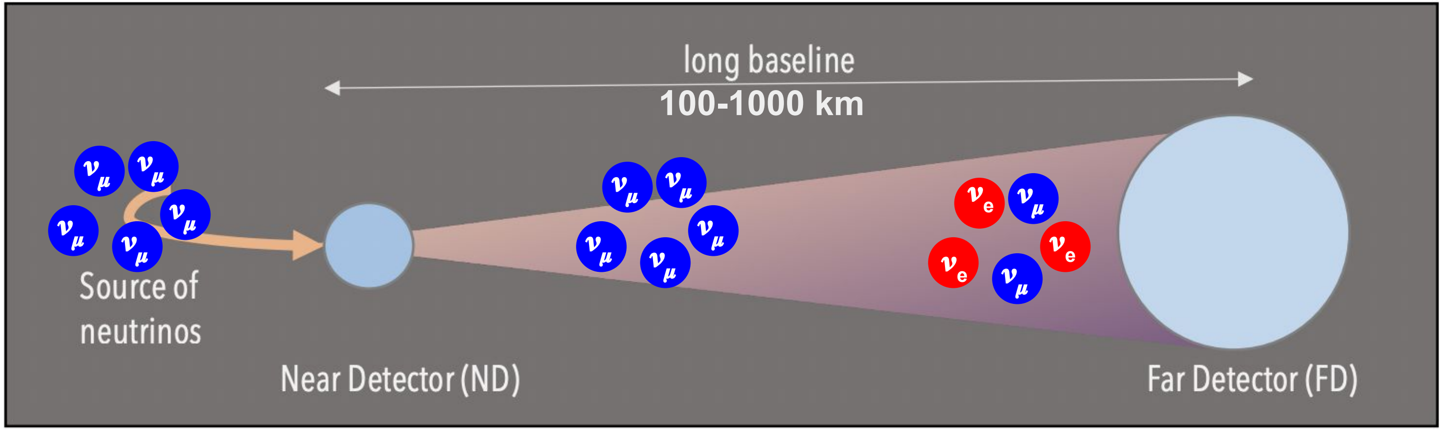
In 1998, Super-Kamiokande (Japan) announced the finding of neutrinos with non-zero mass.

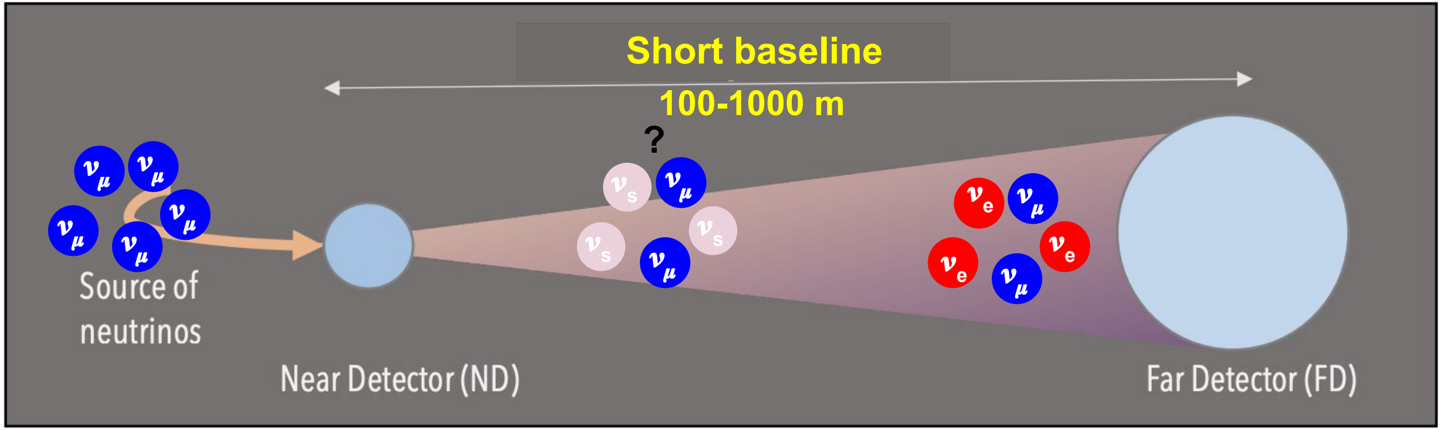
Study neutrino oscillations using atmospheric neutrinos.



Atmospheric neutrinos produced by the decay of particles resulting from interaction of particles with the Earth's atmosphere.

Neutrino Oscillations

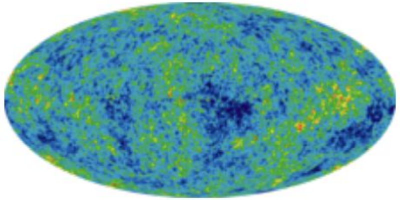


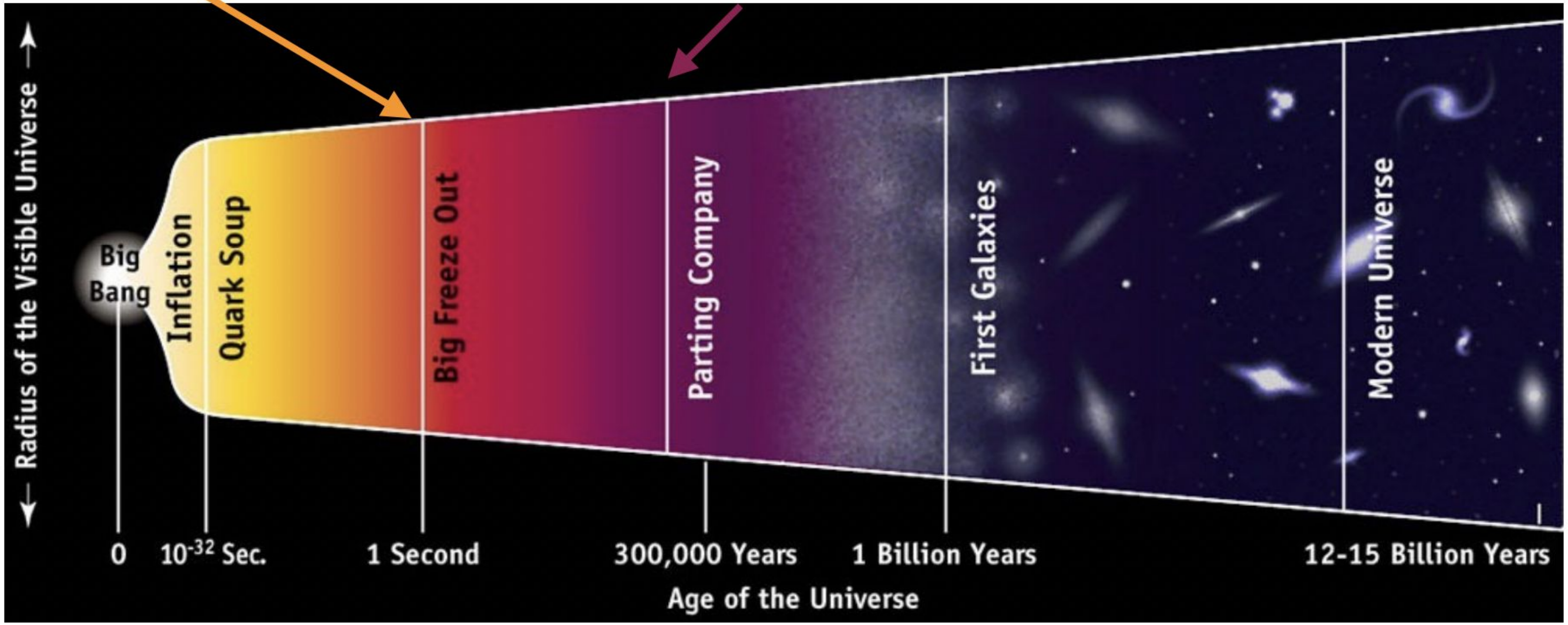


Cosmic Neutrino Background

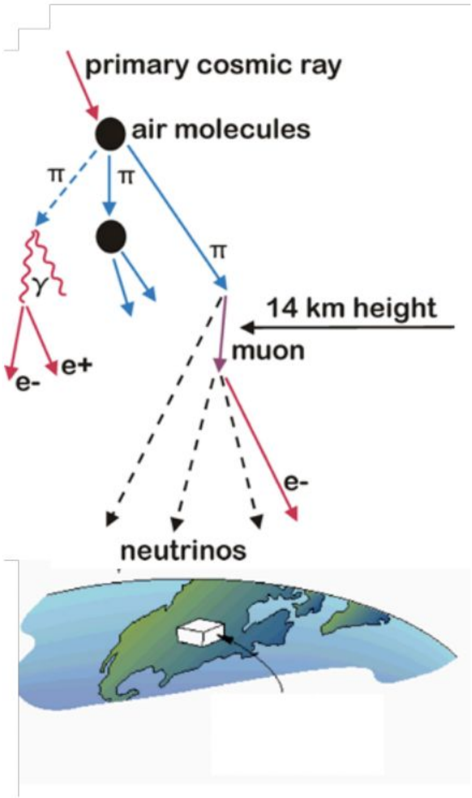
Big-Bang Relic Neutrinos:
I second old

Cosmic Microwave Background:
~300,000 years old





Atmospheric Neutrinos

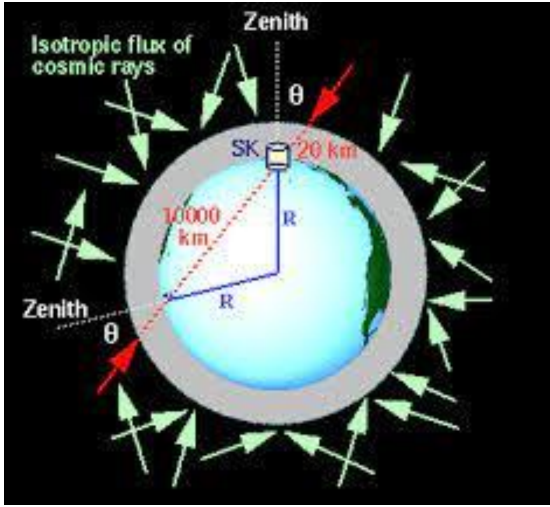


Cosmic rays (mostly protons) interact in the upper atmosphere producing particle showers

Roughly 2:1 muon neutrinos to electron neutrinos expected

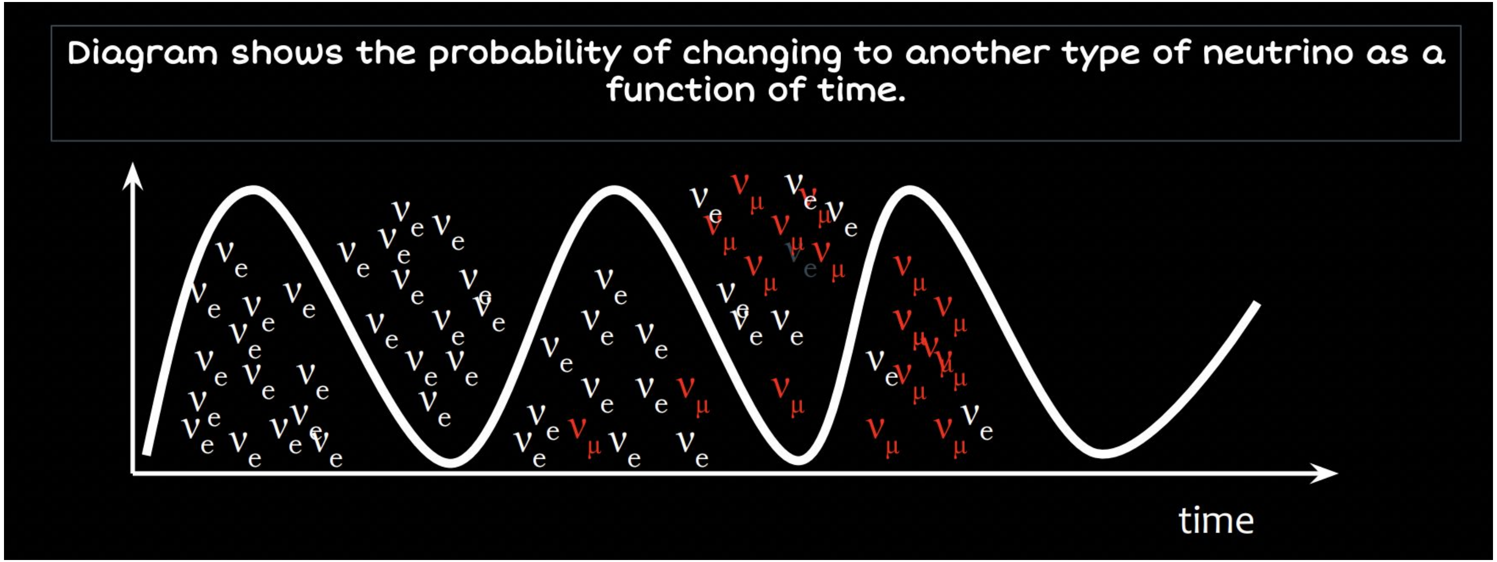
The Kamiokande detector set out to measure this ratio

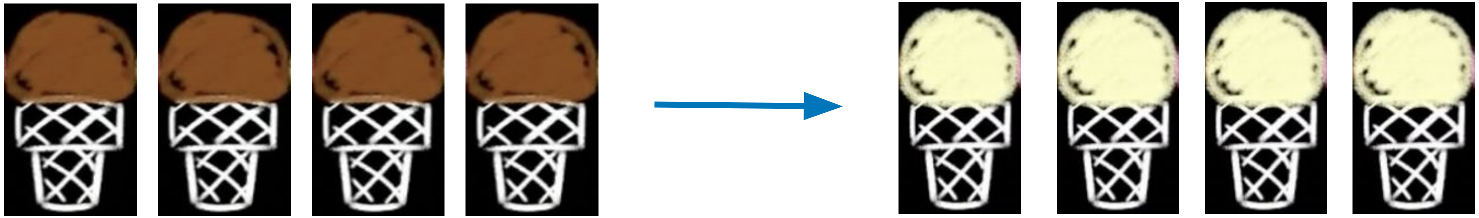
- Super-Kamiokande, a larger analogue is currently still running in Japan.



Fermilab

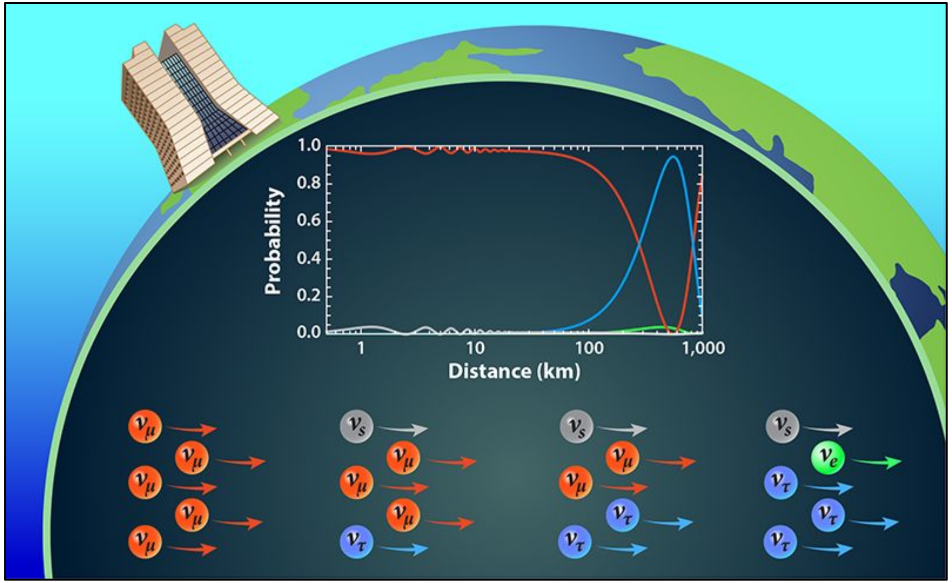
Neutrino Oscillations

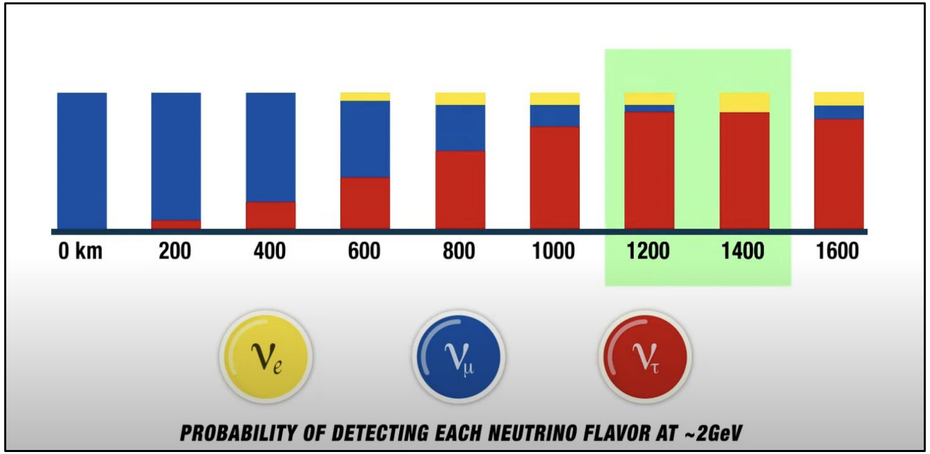




Fermilab

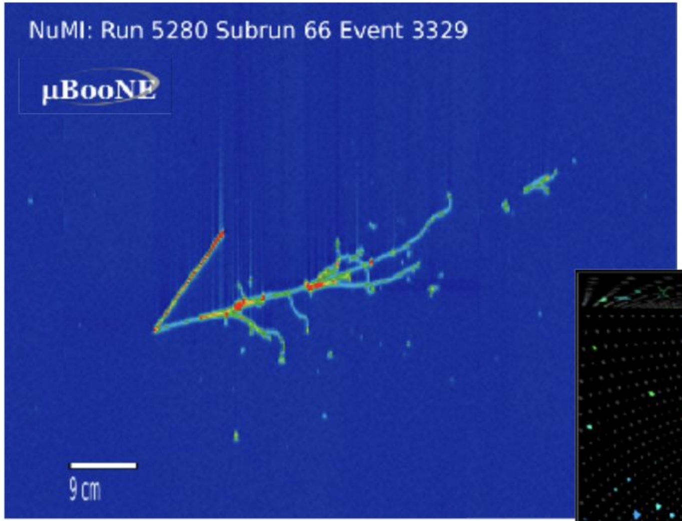
Neutrino Oscillation in a Nutshell

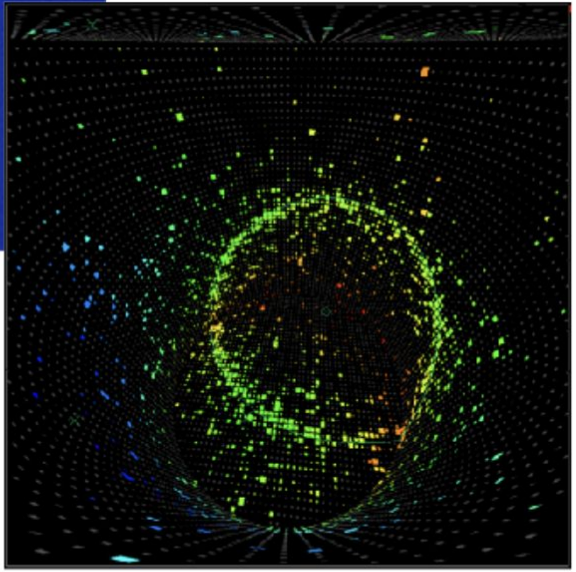




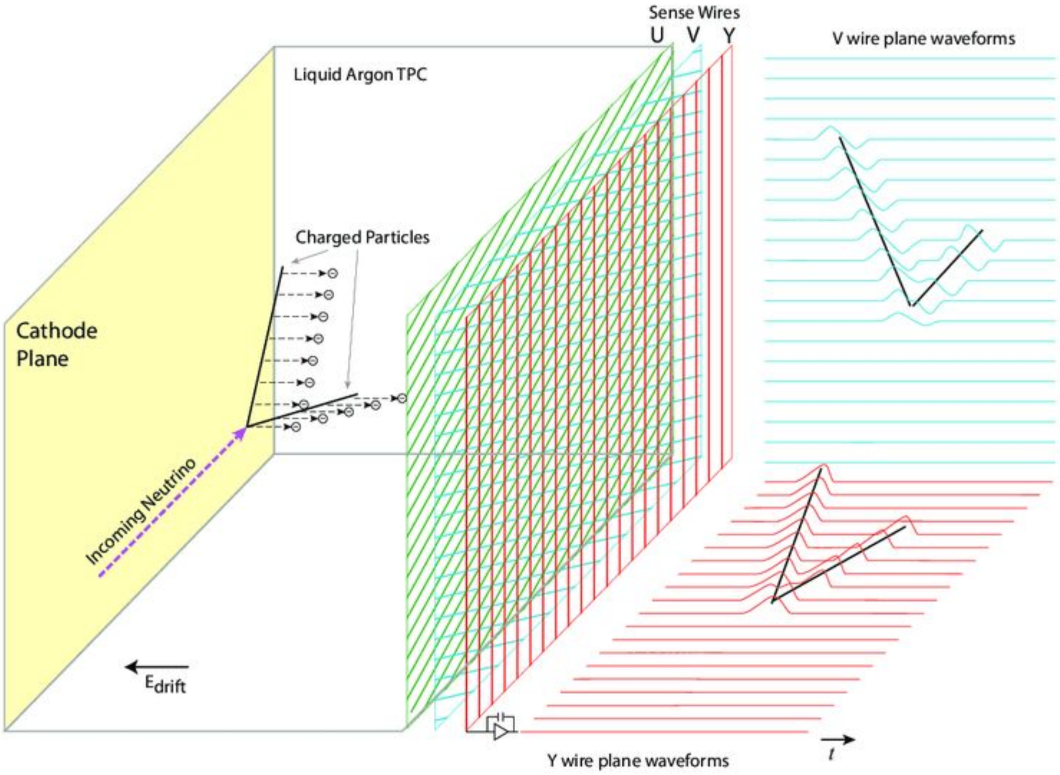
Why New Detector Technology : Liquid Argon ?

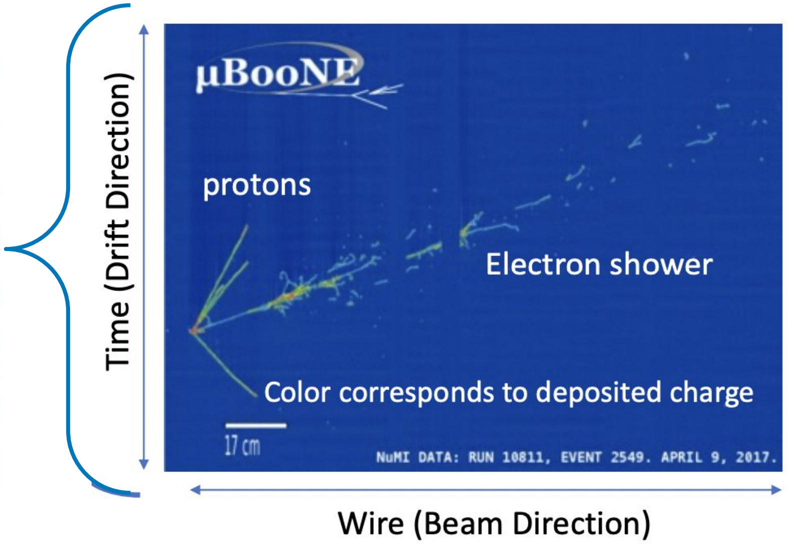
- Very high resolution images
- Very low threshold
- Can separate electrons from photons
- Calorimetric and tracking information





The Crux of LArTPC

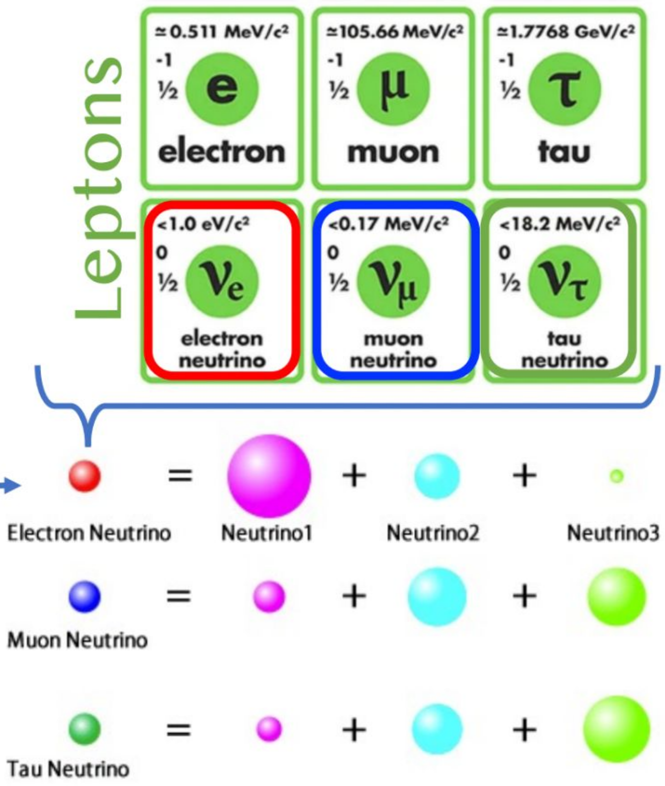




- **Excellent particle imaging detector**
- **mm scale spatial resolution**
- **Light signal by PMTs Current generation LArTPCs**

Neutrino Oscillation

- Neutrinos propagate as mass states, which are not the same as the flavor states they interact in:
  - Fundamental particles with definite mass: ν_1, ν_2, ν_3
  - Definite flavors (interact to produce corresponding lepton): ν_e, ν_μ, ν_τ



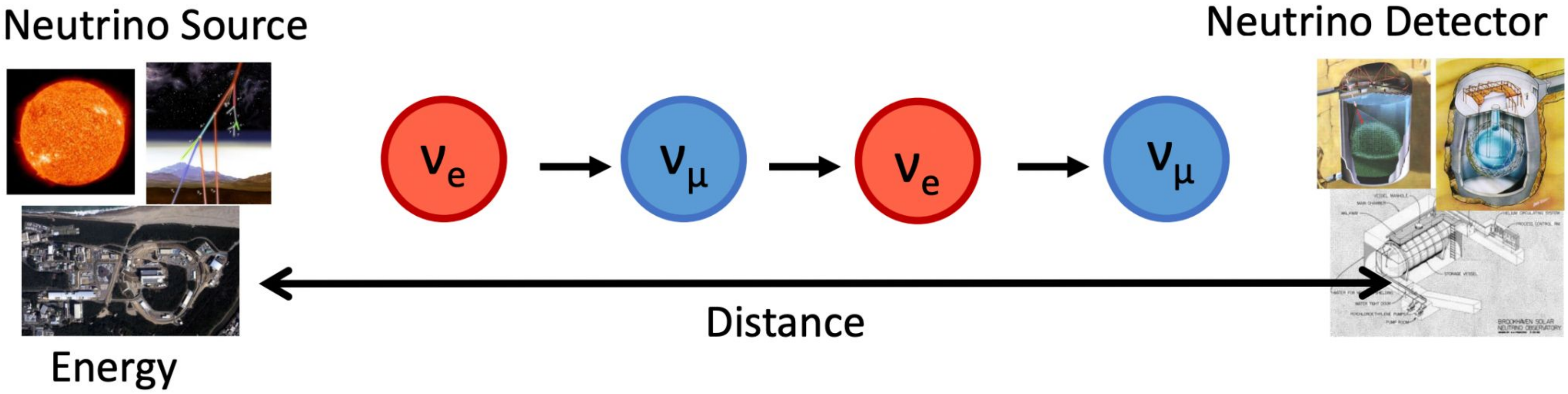
- Flavor states are a superposition of mass states related by unitary transform:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Interact ← (flavor states) (mass states) → Travel

As neutrinos travel the states interfere and oscillations occur

Neutrino Oscillation



Neutrino mass states:

$$\nu_1 = \nu_\mu \cos\theta - \nu_e \sin\theta$$
$$\nu_2 = \nu_\mu \sin\theta + \nu_e \cos\theta$$

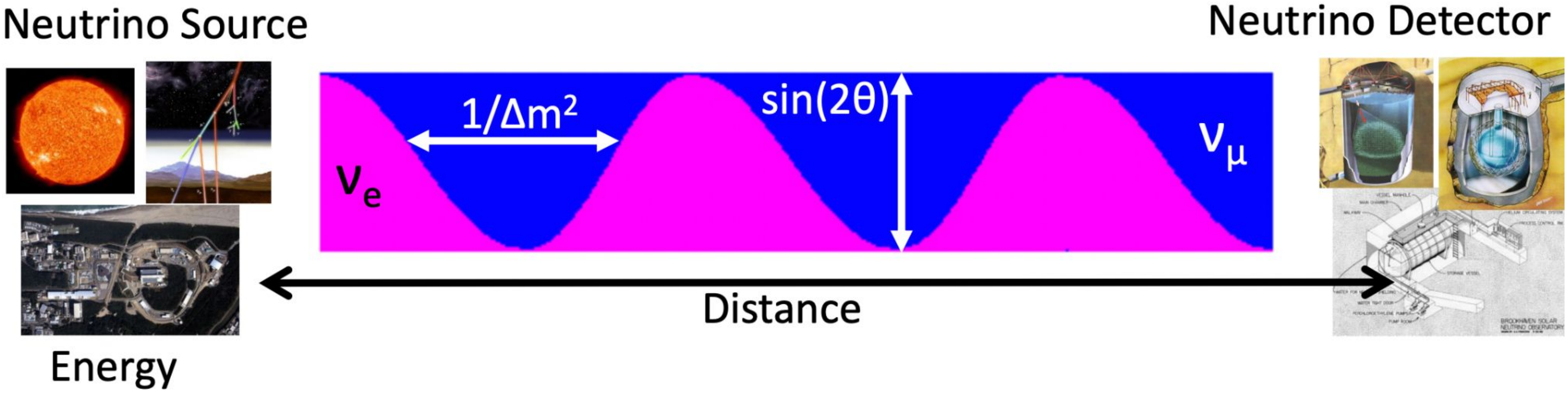
$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Propagate mass states with $e^{-i\mathrm{E}t}$, and rearrange to find time-evolution of flavor state:

$$\nu_\mu(t) = -\sin\theta e^{-i\mathrm{E}_1 t}\nu_1 + \cos\theta e^{-i\mathrm{E}_2 t}\nu_2$$

Fermilab

Neutrino Oscillation in a Nutshell



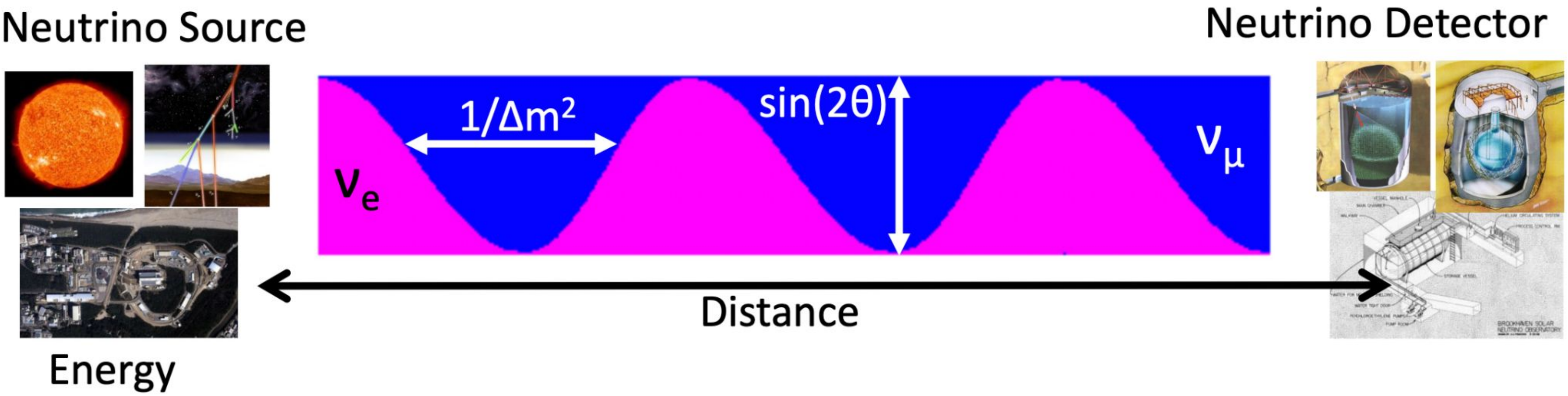
Oscillation probability for two neutrinos: $P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{E}\right)$

Experimentally controlled: L (distance between production and detection)
(at least in accelerator neutrinos) E (energy of neutrino)

Measured parameters: Difference in mass of neutrinos: $\Delta m^2 = m_1^2 - m_2^2$
Mixing angle (how mass and flavor states relate): θ

Fermilab

Neutrino Oscillation in a Nutshell



Oscillation probability for two neutrinos: $P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{E}\right)$

Experi… …ection)

(at least …

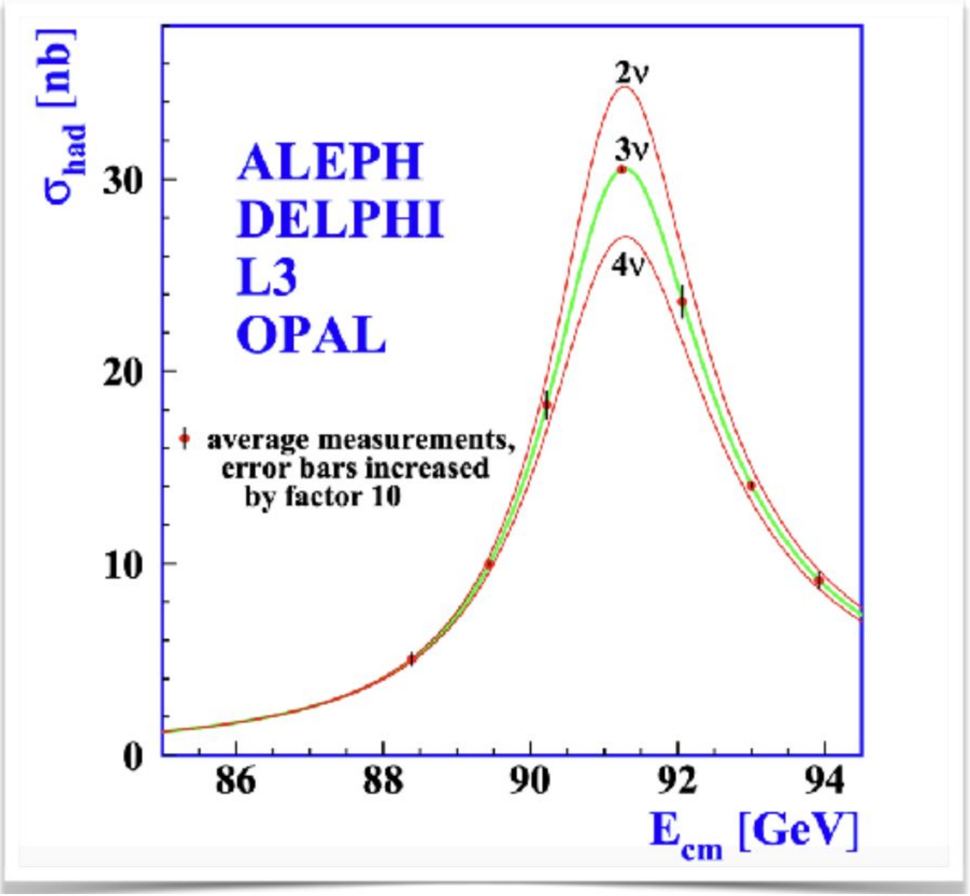
Oscillations mean neutrinos must have mass → physics beyond the standard model, and more to learn

Measu… … – m_2^2

Mixing angle (how mass and flavor states relate): θ

Neutrino Flavors :

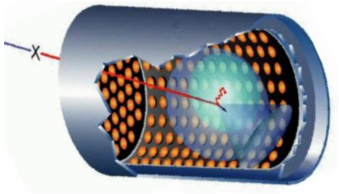
- 3 flavors that can be produced in decays of Z bosons
- 3 "active" flavors



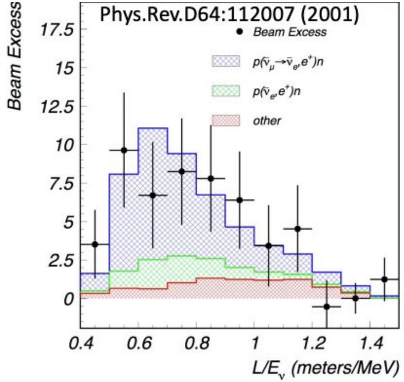
Anomalies in Neutrino Sector

$\overset{(-)}{\nu}_\mu \to ? \to \overset{(-)}{\nu}_e$

LSND



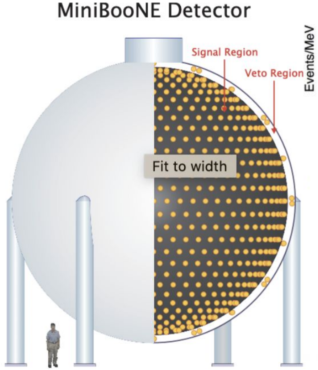
<u>L</u>iquid <u>S</u>cintillator <u>N</u>eutrino <u>D</u>etector

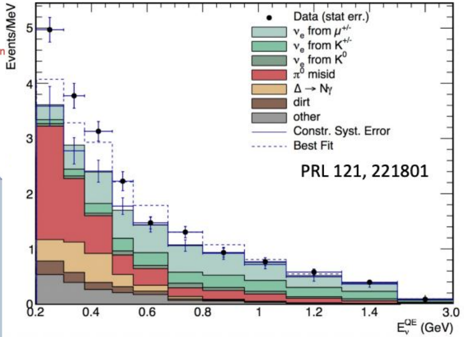


~3.8 σ excess

excess $\bar{\nu}_e$

MiniBooNE



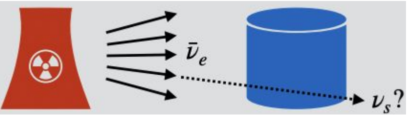


~4.8 σ excess

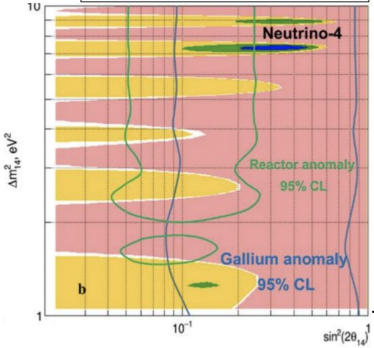
excess ν_e

$\overset{(-)}{\nu}_e \to ?$

Reactor Anomaly



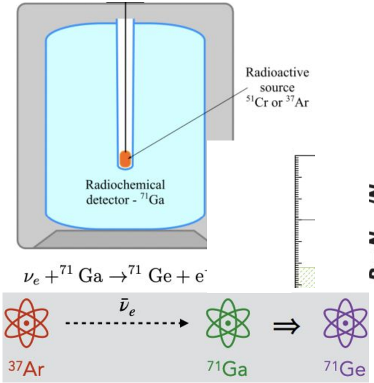
PRD 104 (2021) 3, 032003



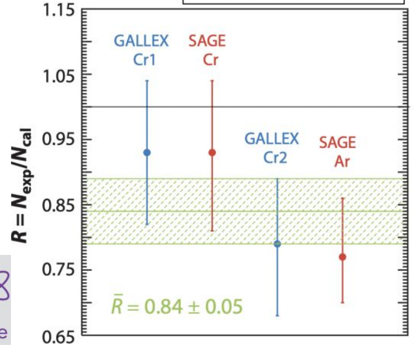
~3 σ deficit

$\bar{\nu}_e$ deficit

Gallium Anomaly



arXiv:1901.08330



~3 σ deficit

ν_e deficit

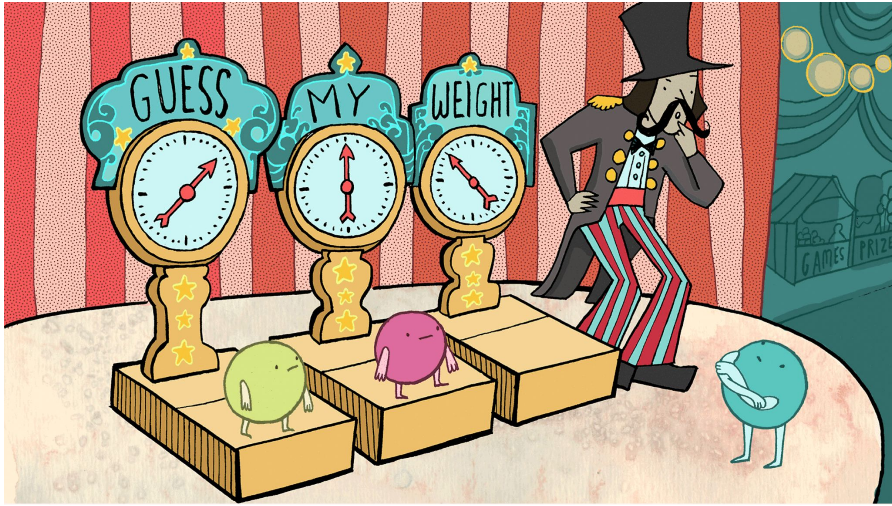
Neutrino Oscillation: The Dance That Proves Neutrinos Have Mass!

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrinos change flavors (outfits)

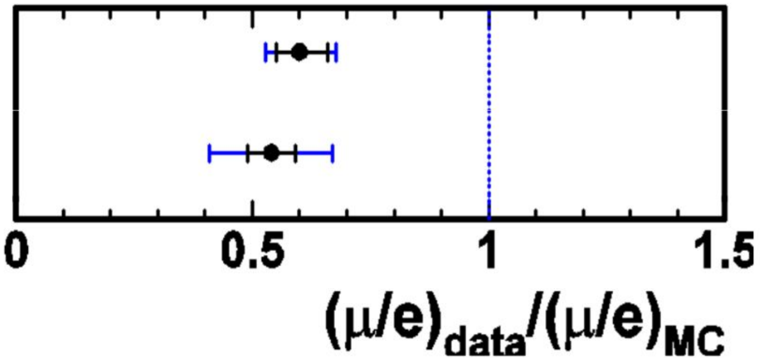
↓

not moving infinitely fast (since changing outfits takes time!)



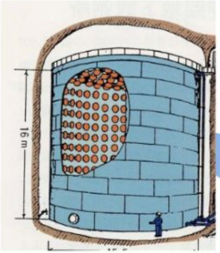
massless particles: travel at speed of light, no "time" to waste (or change flavors)

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric ν_μ events was observed.

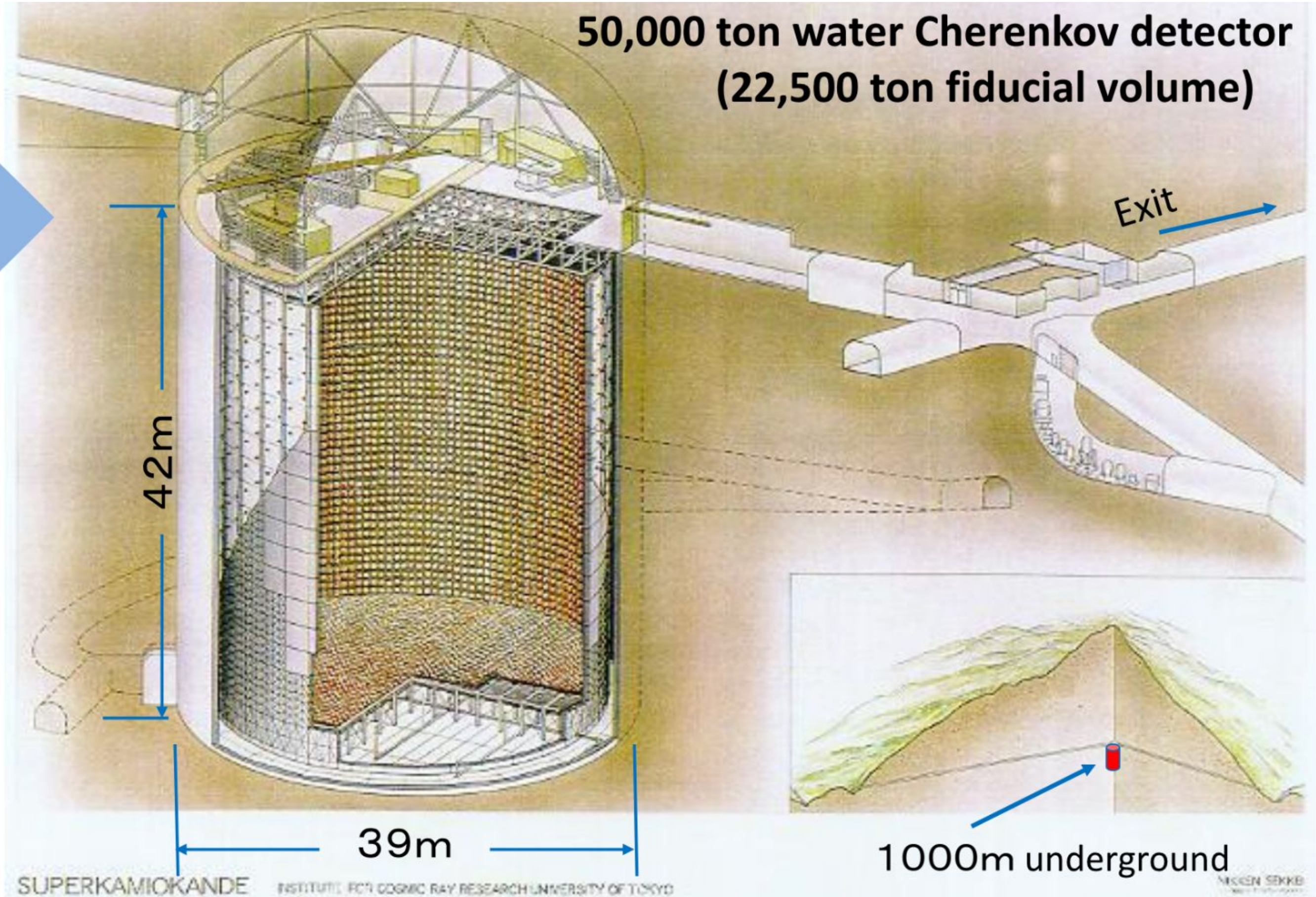


Taken from Takaaki Kajita's slides

Super-K



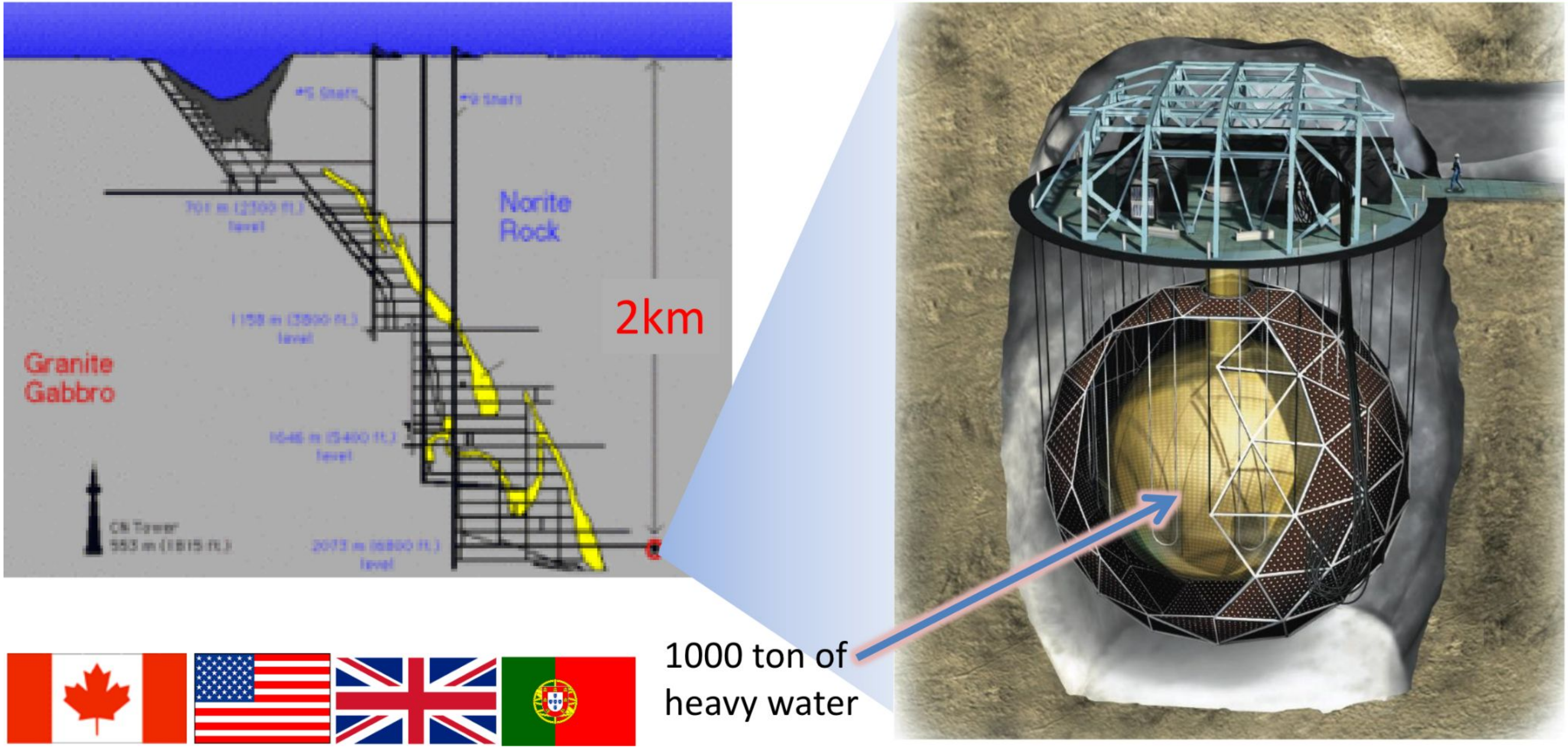
More than 20 times larger mass



~130 collaborators from:

Taken from Takaaki Kajita's slides

SNO



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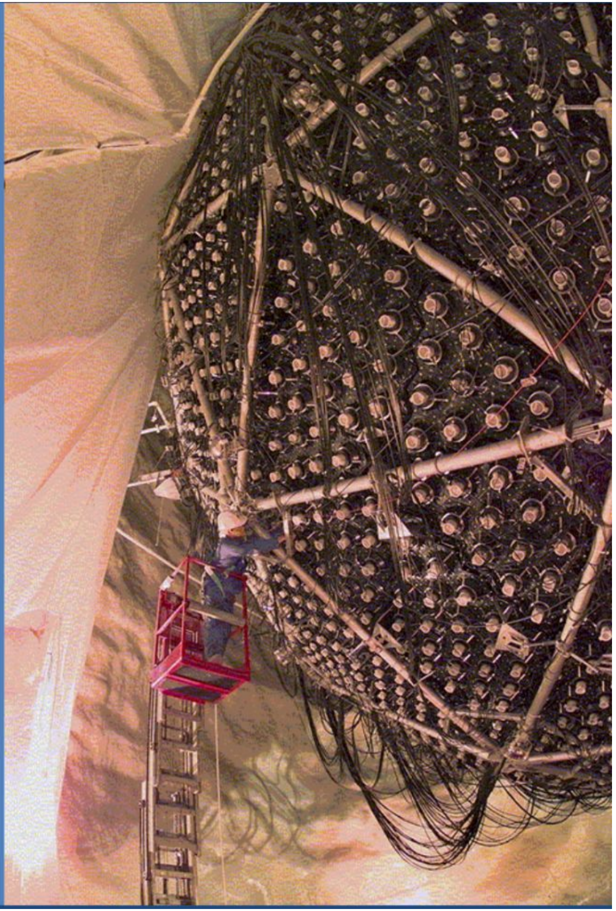
SNO

One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions.

Filled with pure and heavy water in April 1999.



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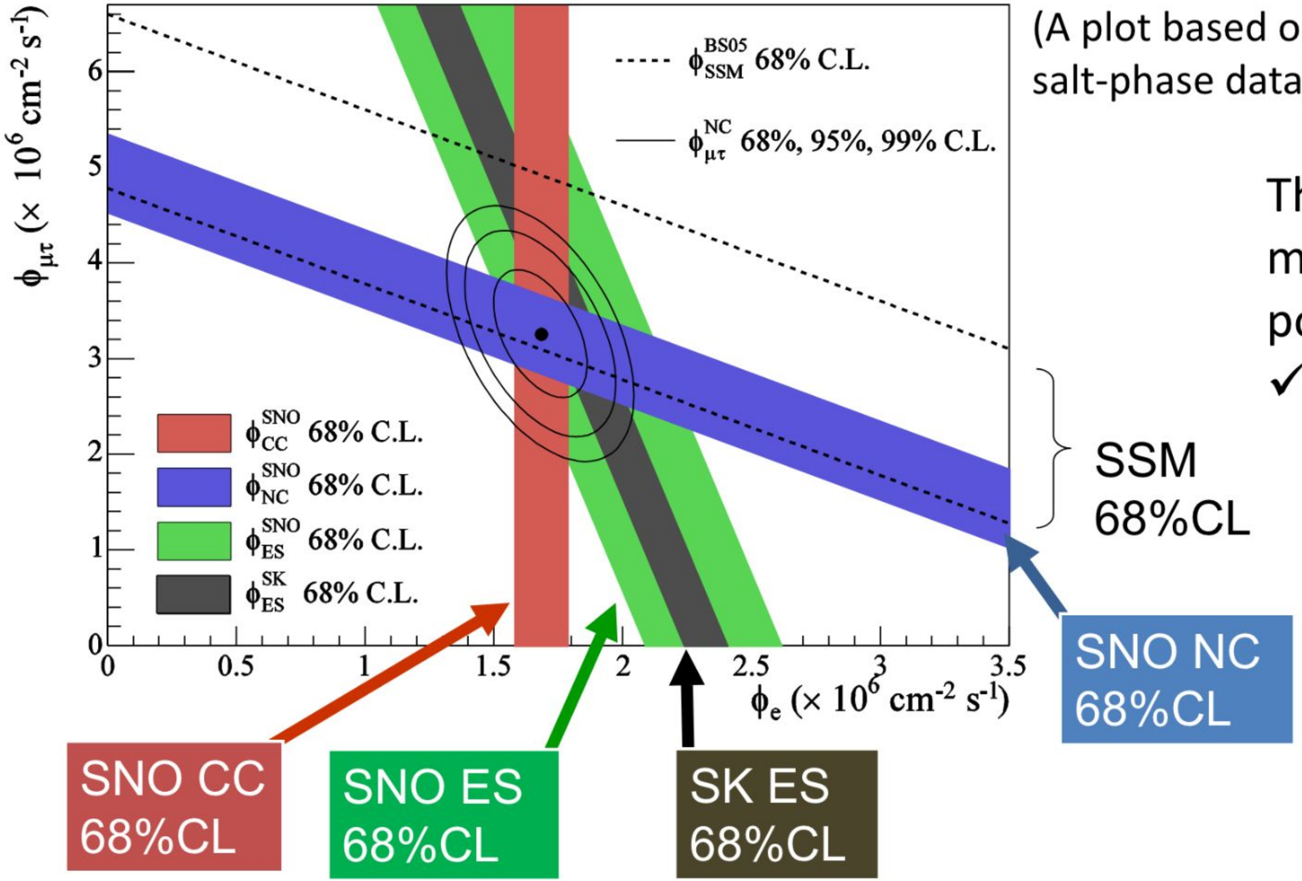
SNO



(A plot based on the salt-phase data)

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

Three (or four) different measurements intersect at a point.

✓ *Evidence for (ν_μ+ν_τ) flux*

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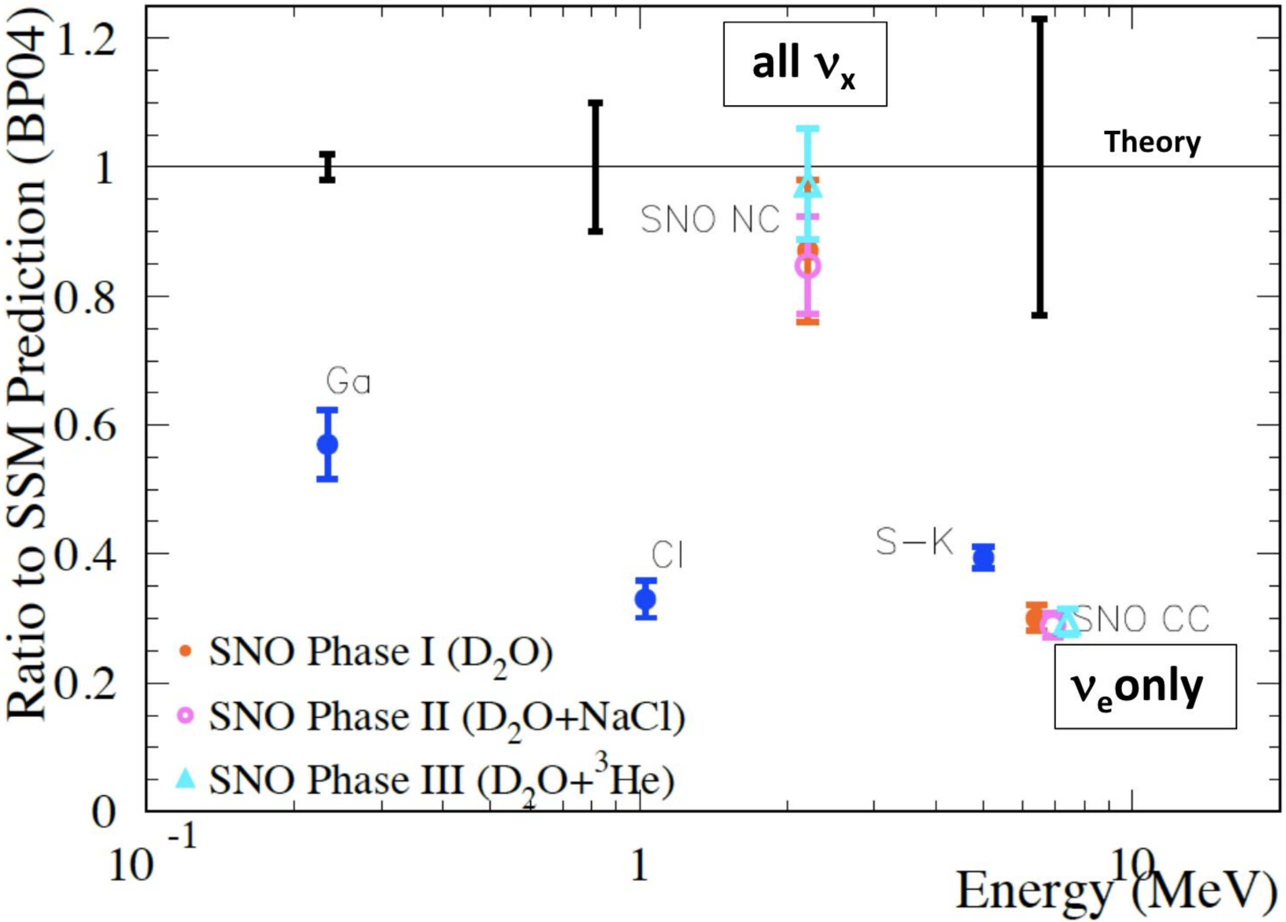
SNO



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