



# WELCOME TO THE WORLD OF NEUTRINOS!

Dr. Alexander Booth (he / him)

Universidad Católica del Norte, Chile

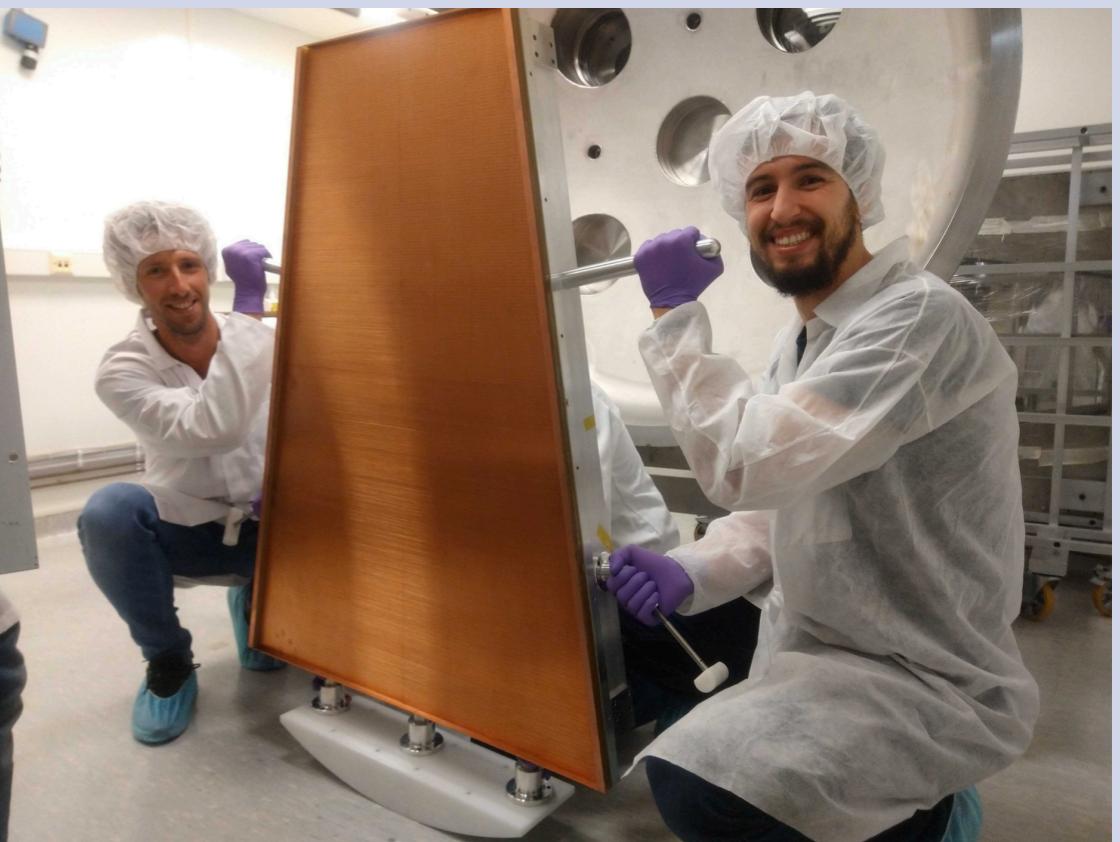
Oct. 9th, 2024



Queen Mary  
University of London



# I am a Particle Physicist!



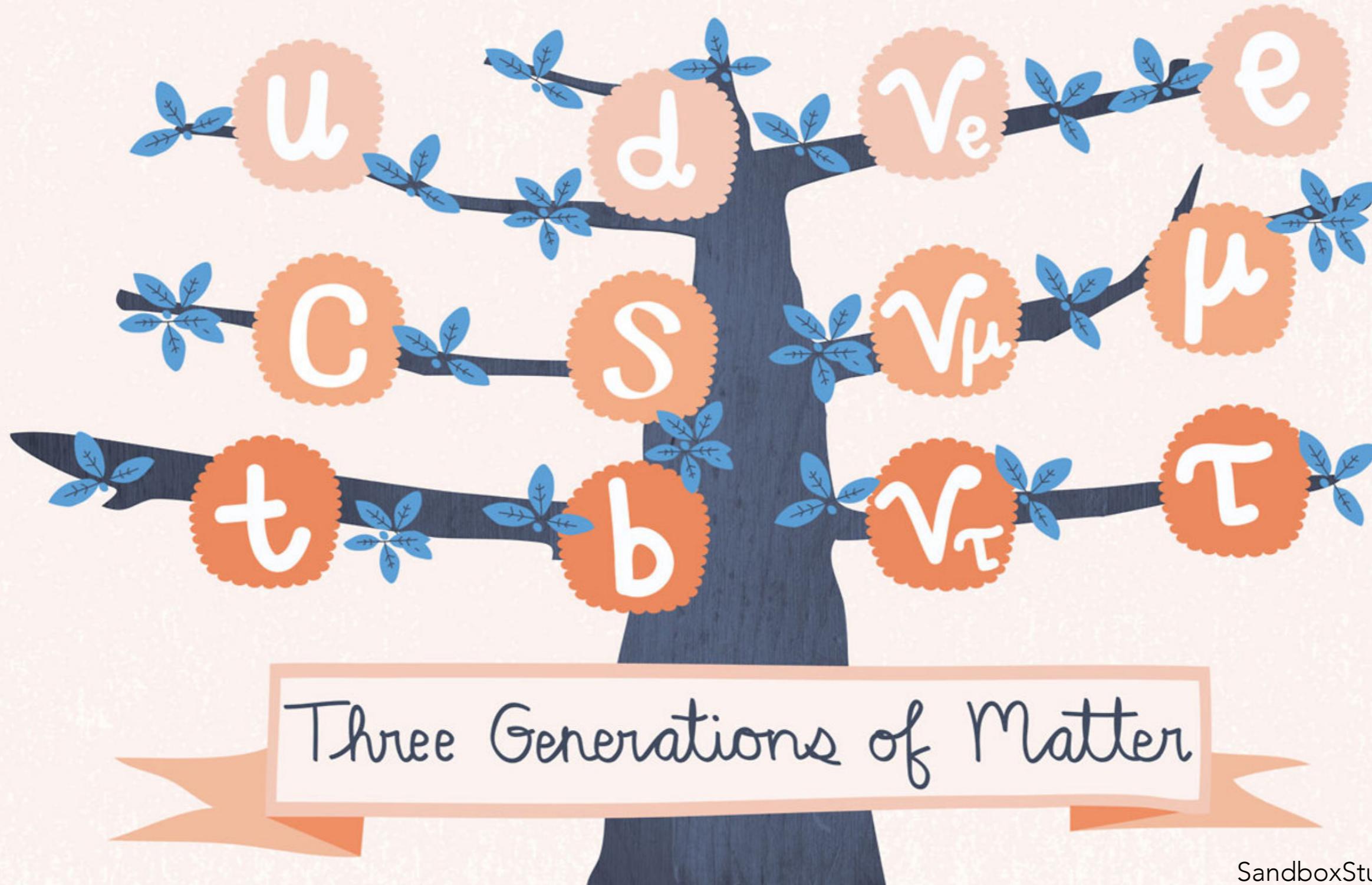
# A Bit More About Me...



# What are Neutrinos?



QUARKS

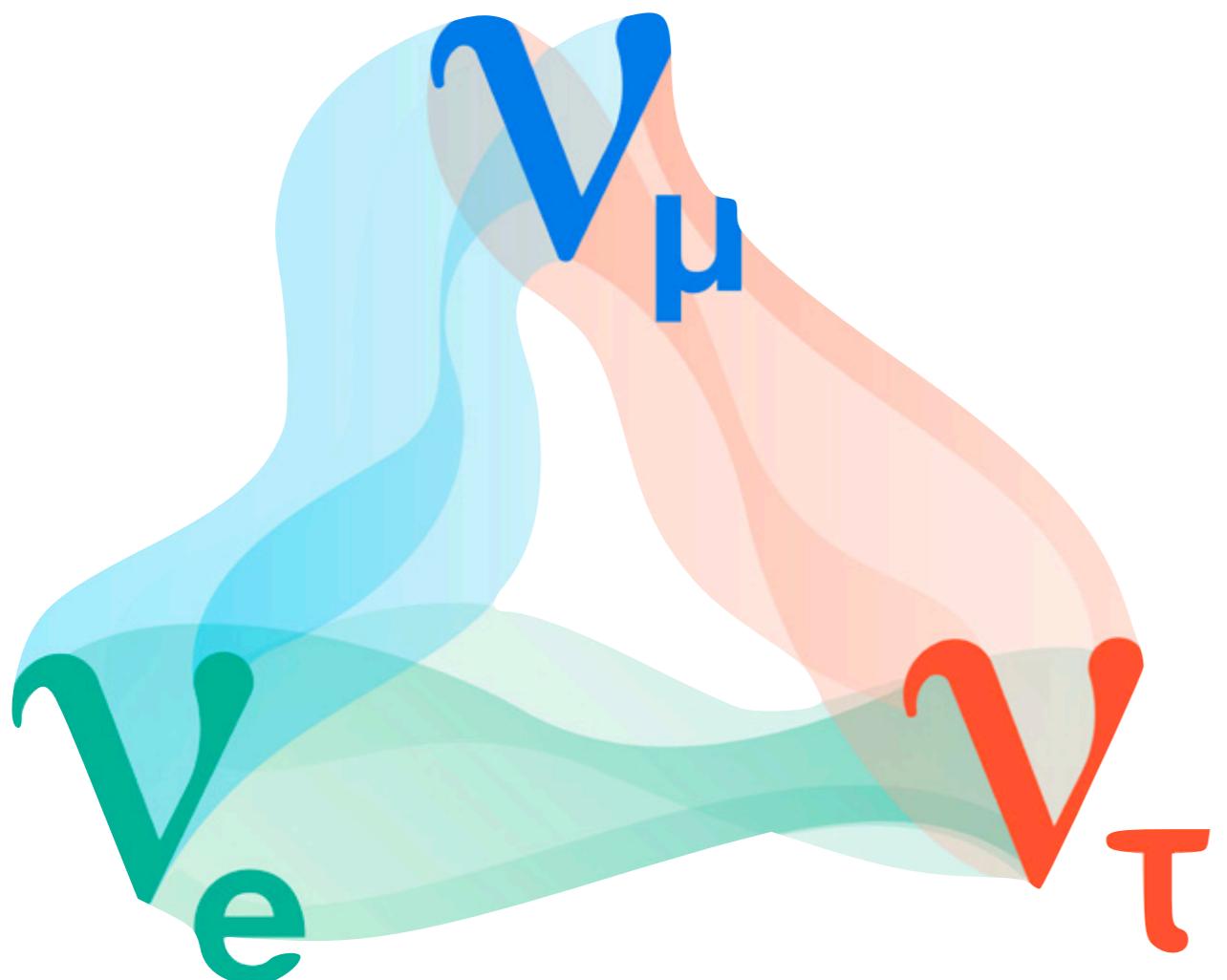


LEPTONS

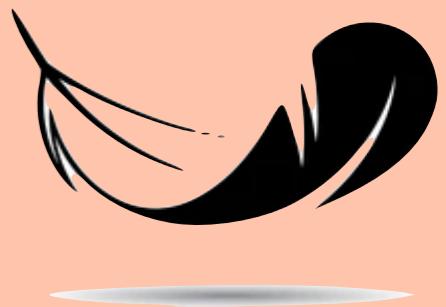
SandboxStudio, Chicago



# Neutrinos are...

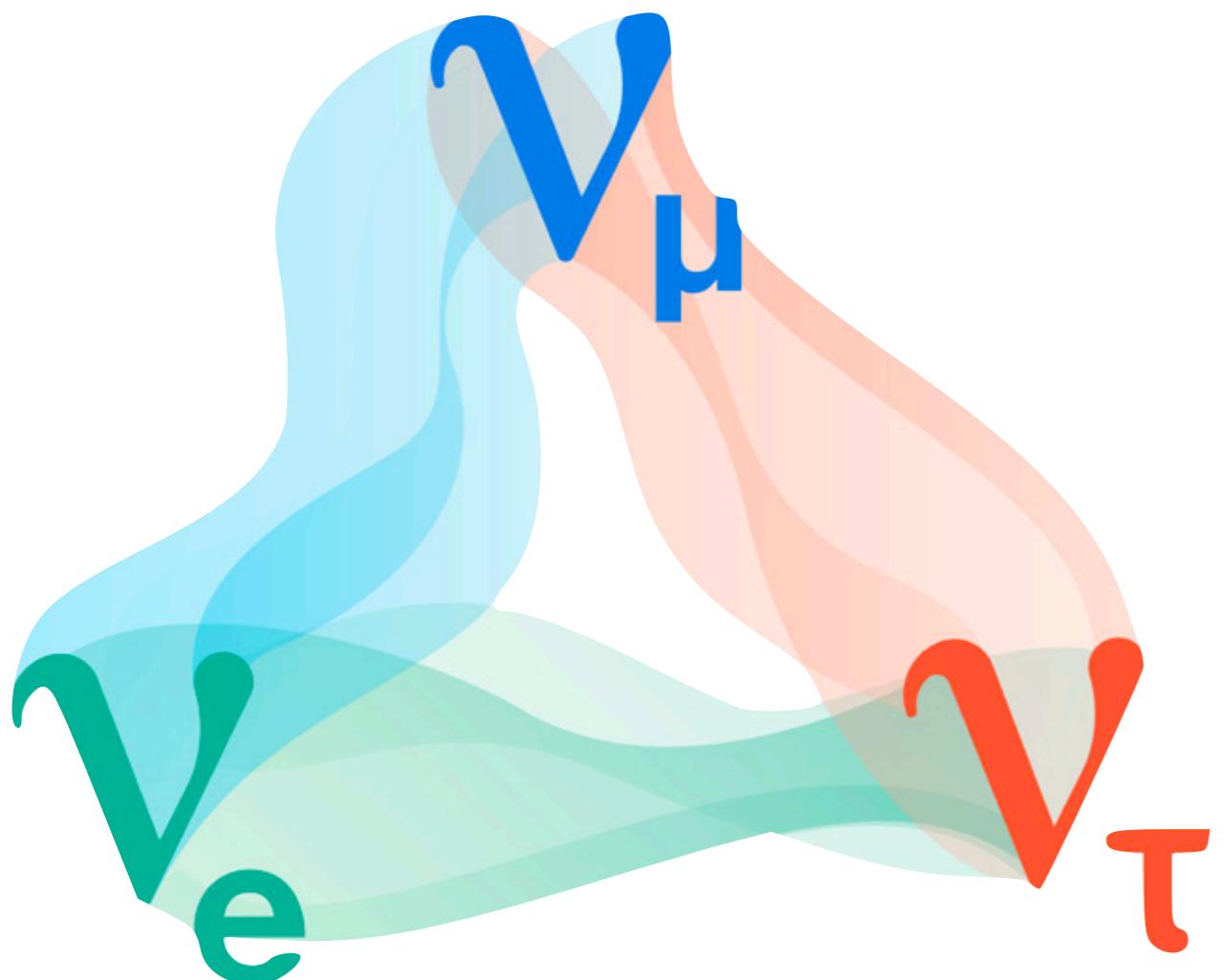


Lightweight

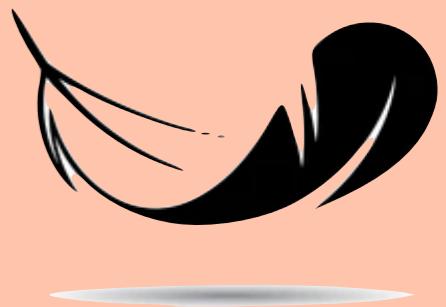




# Neutrinos are...



Lightweight

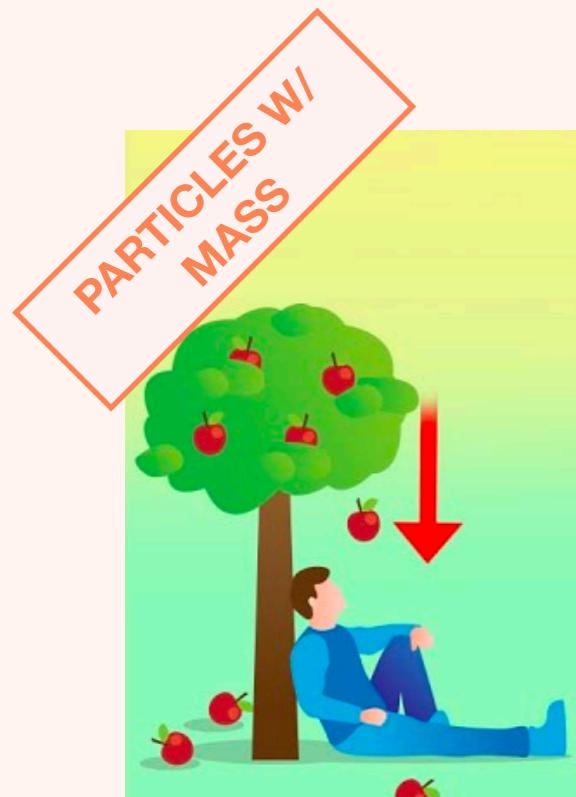


Neutral

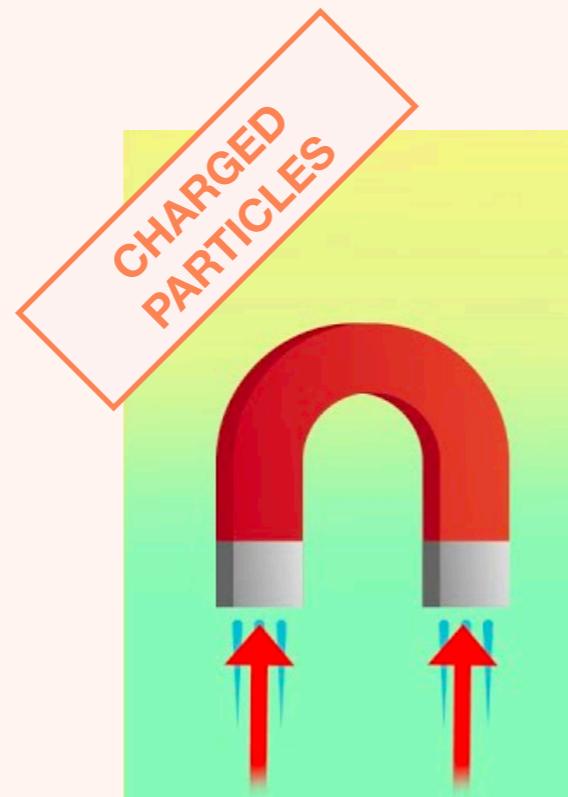




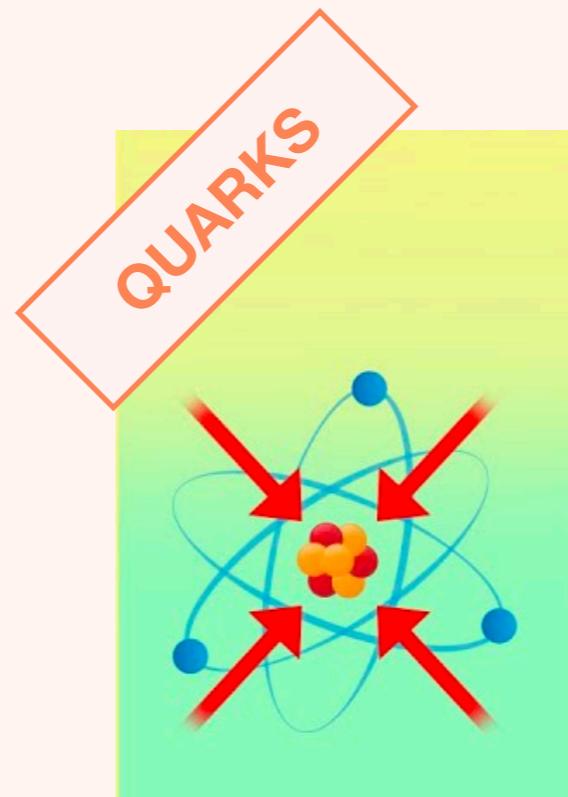
# Four Fundamental Forces



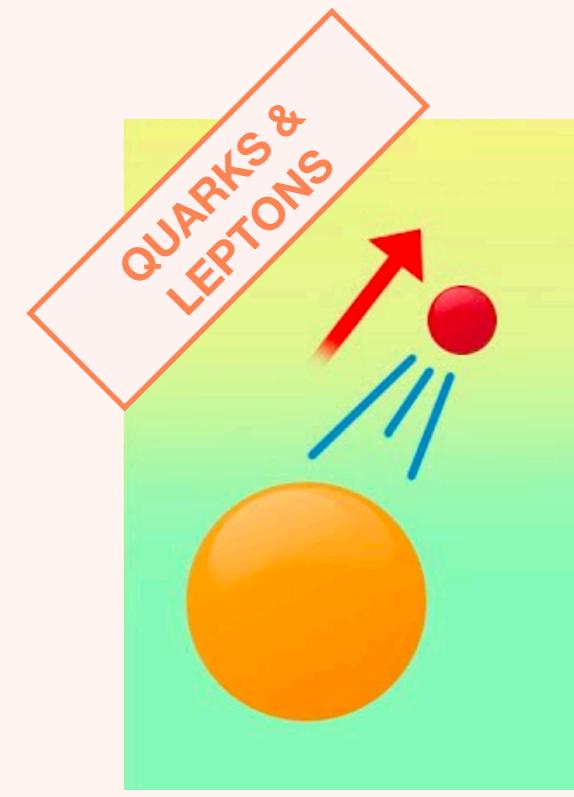
**GRAVITATIONAL  
FORCE**



**ELECTROMAGNETIC  
FORCE**



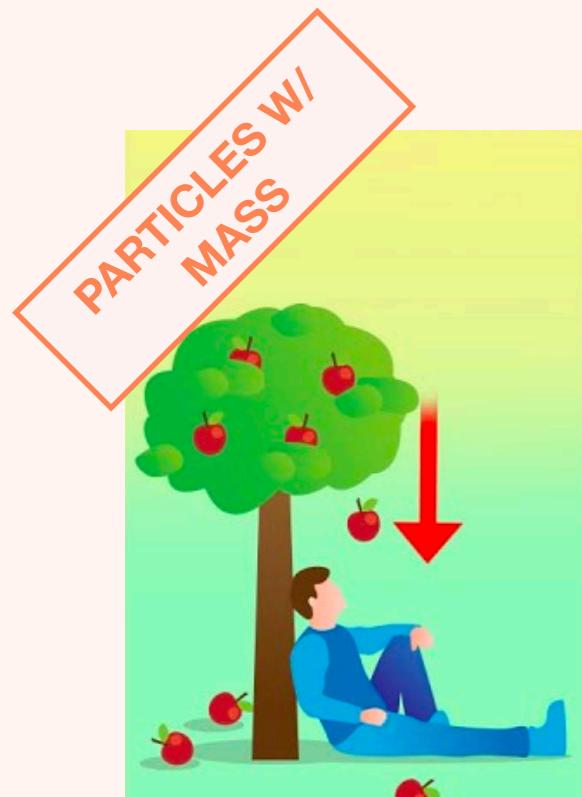
**STRONG NUCLEAR  
FORCE**



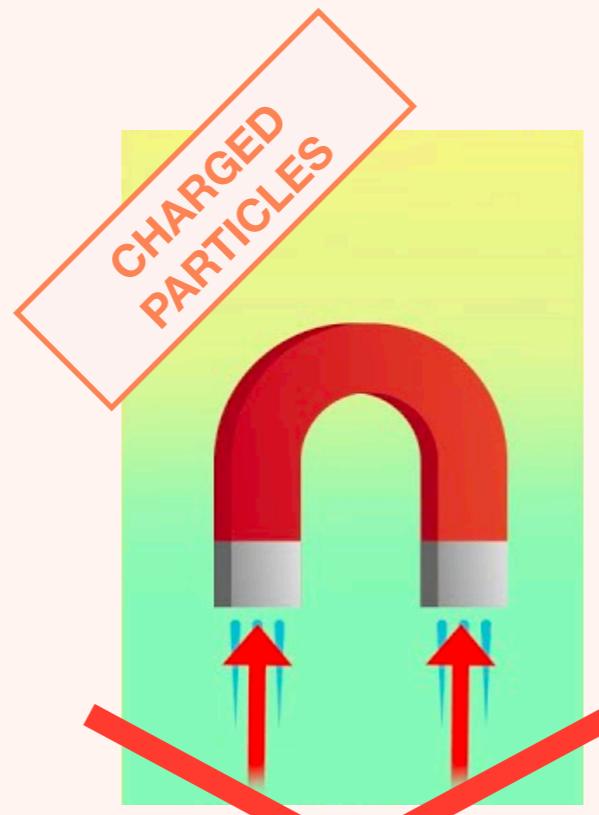
**WEAK NUCLEAR  
FORCE**



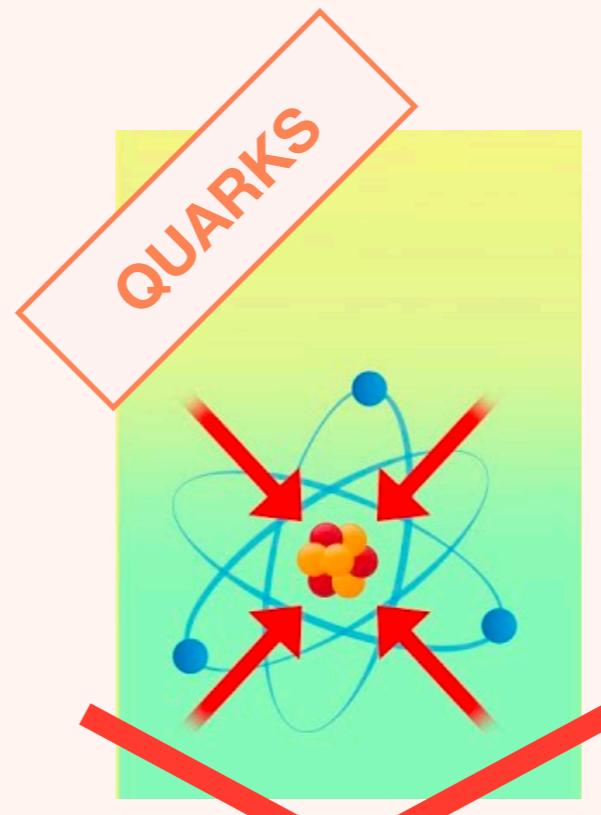
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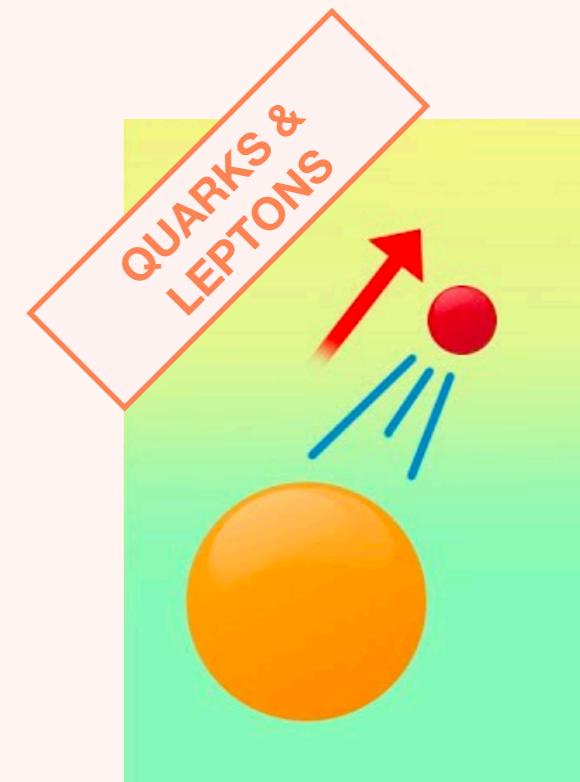
**GRAVITATIONAL FORCE**



**ELECTROMAGNETIC FORCE**

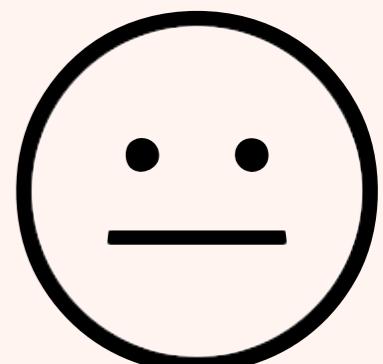


**STRONG NUCLEAR FORCE**



**WEAK NUCLEAR FORCE**

Neutral





Neutrinos are produced inside the Sun by nuclear fusion reactions. How many of these neutrinos pass through your thumbnail every second?



- A) 650
- B) 65,000
- C) 65,000,000
- D) 65,000,000,000



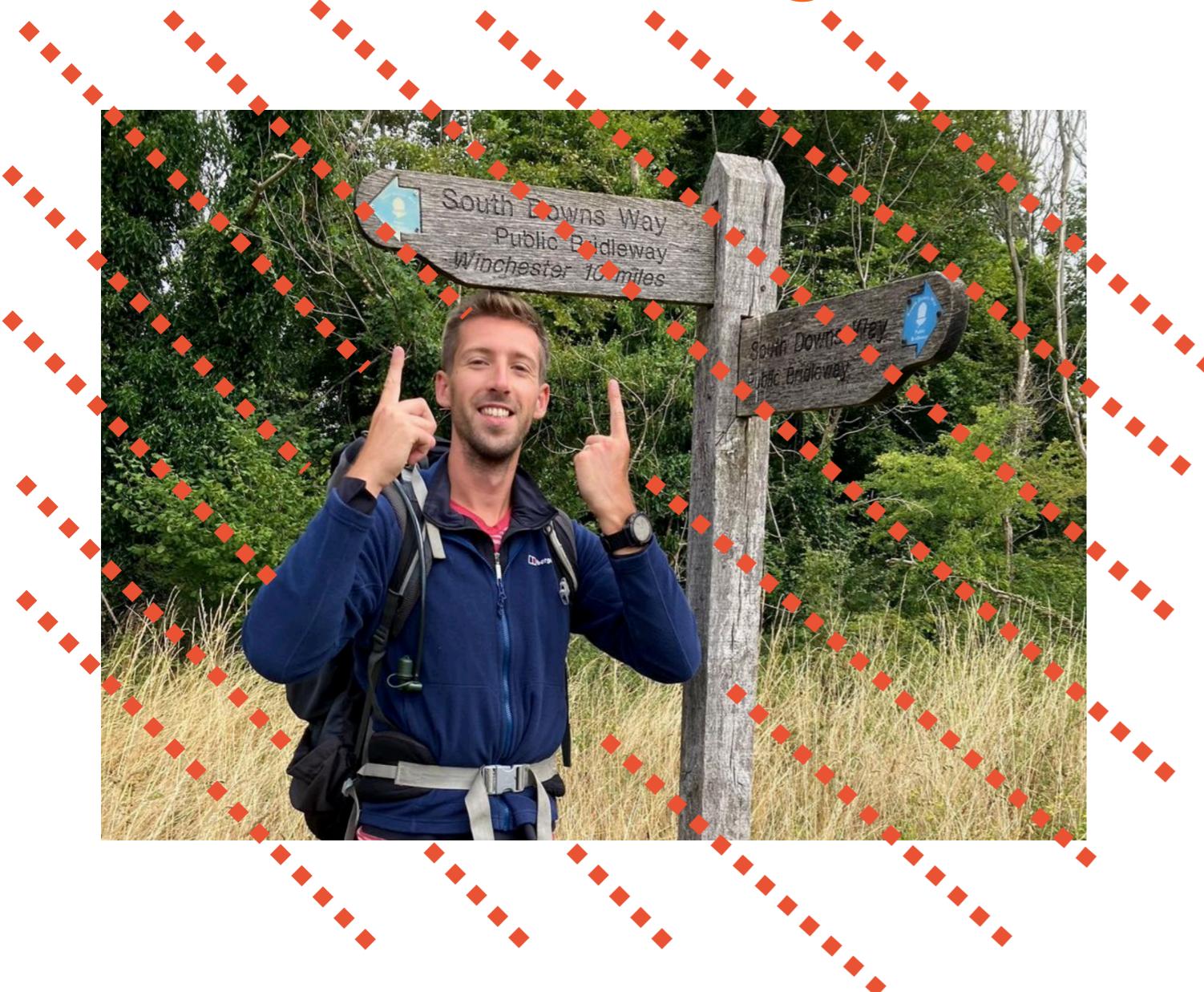
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- B) 65,000
- C) 65,000,000
- D) 65,000,000,000



Our bodies are traversed by trillions of neutrinos every second. How many neutrinos will you interact with in your lifetime on average?



- A) 1
- B) 10
- C) 100
- D) 1,000



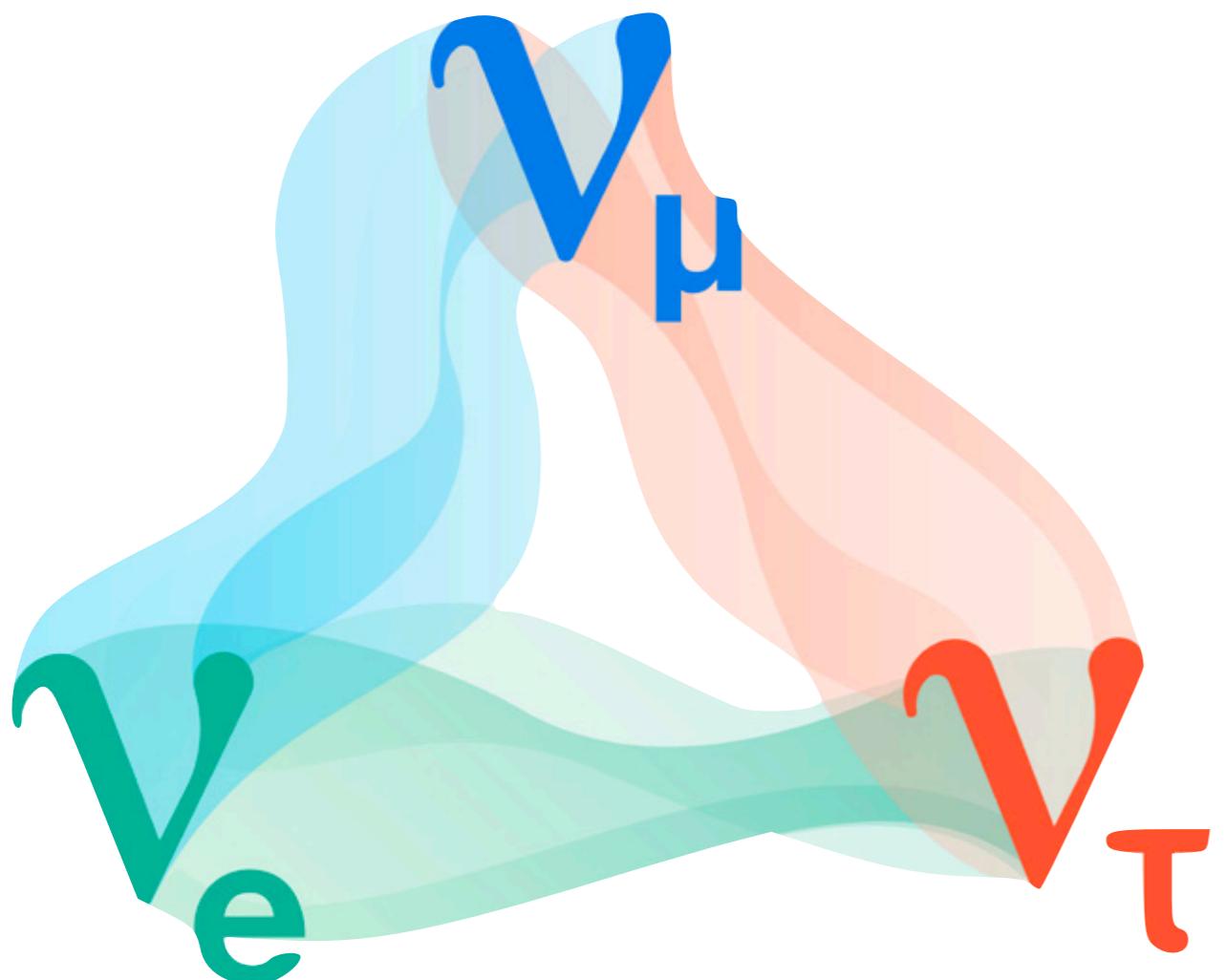
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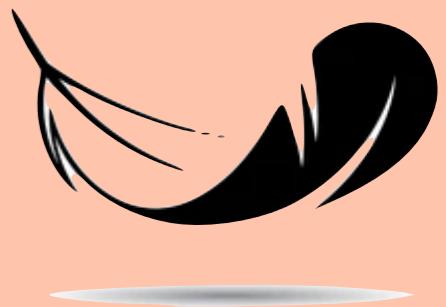
- A) 1
- B) 10
- C) 100
- D) 1,000



# Neutrinos are...



**Lightweight**



**Difficult to  
detect!**



# Neutrinos come in three flavours



Electron neutrino



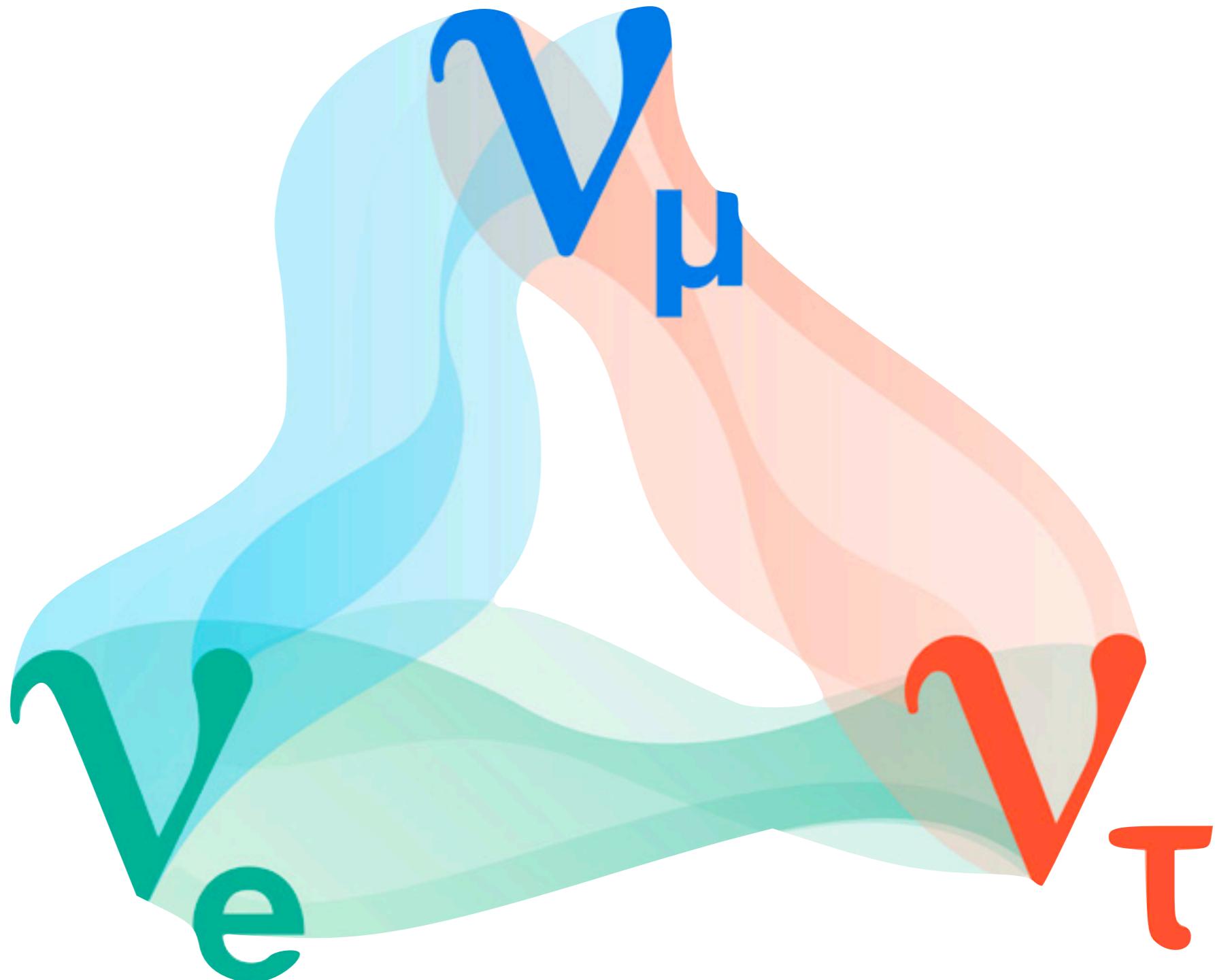
Muon neutrino



Tau neutrino

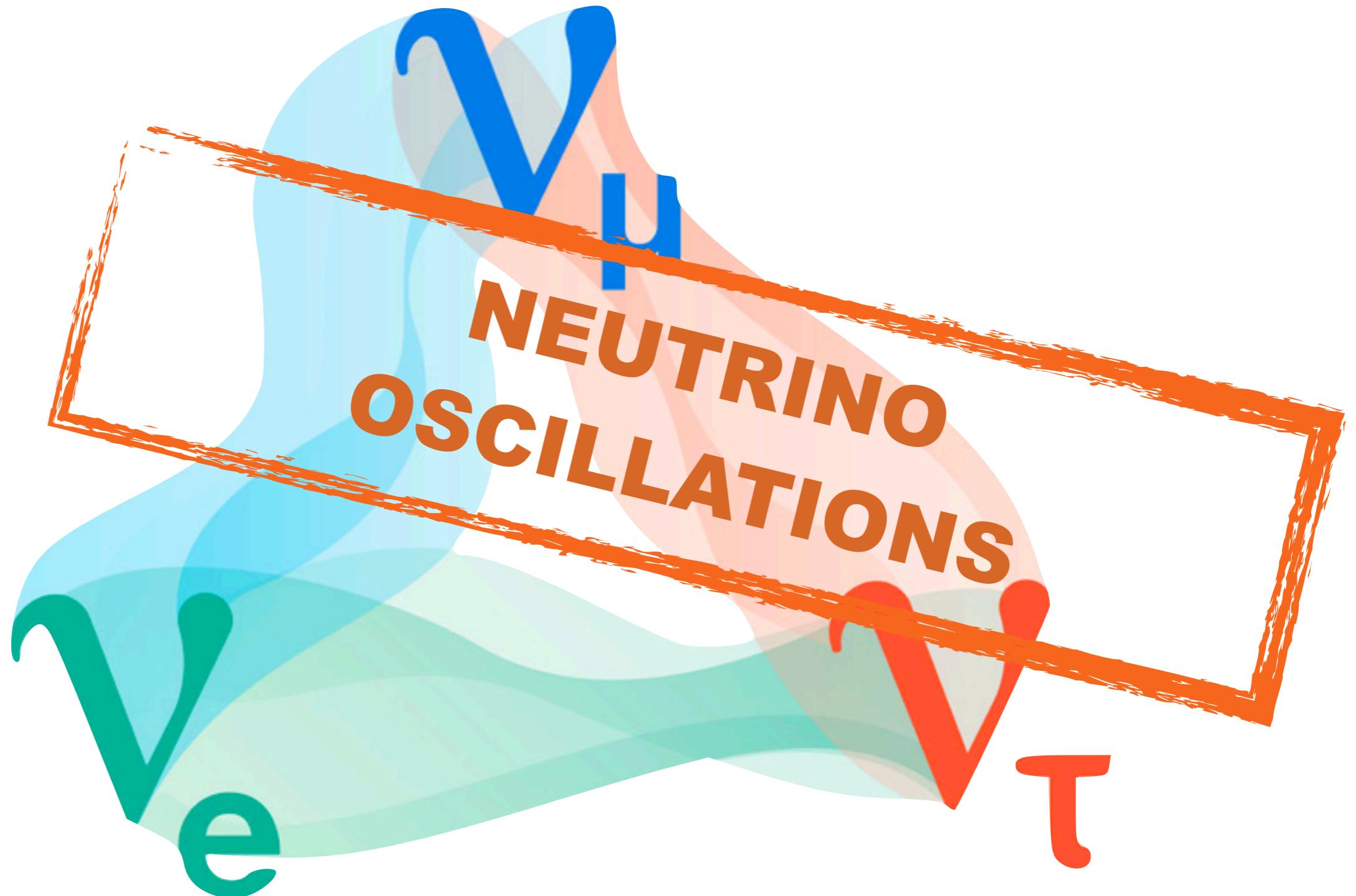


# Neutrinos change flavour when they propagate





# Neutrinos change flavour when they propagate





# How do neutrino oscillations work?



+



+



=



**Neutrino flavour states  
are combinations of mass  
states - a  
“superposition”.**



# How do neutrino oscillations work?



+



+



=



**Neutrino flavour states are combinations of mass states - a “superposition”.**

**The different masses of the 3 states means they propagate at different speeds - changing the mixture.**



# How do neutrino oscillations work?



+



+



=



**Neutrino flavour states are combinations of mass states - a “superposition”.**

The different masses of the 3 states means they propagate at different speeds - changing the mixture.

Neutrinos produced in a certain flavour state can recombine as a different flavour state after propagation.

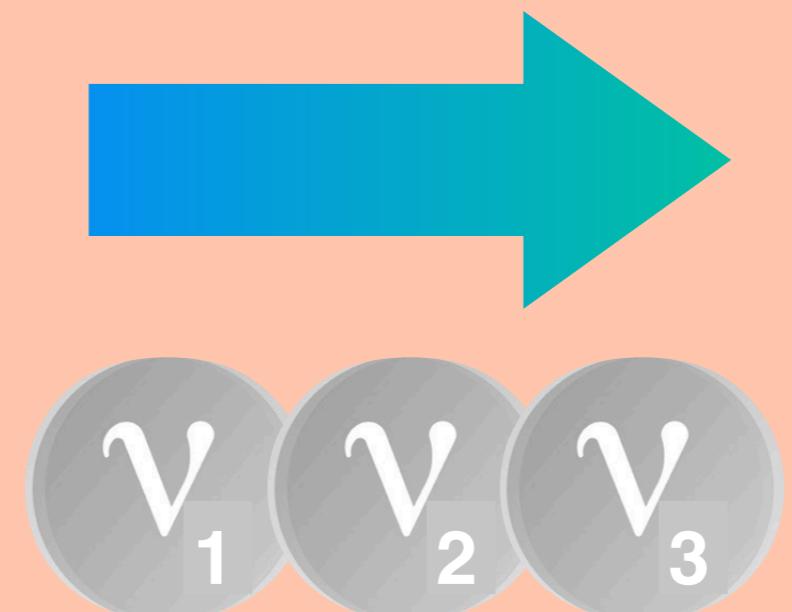


# Neutrino Oscillations

Neutrinos are produced as **flavour states**



Propagate as **mass states**

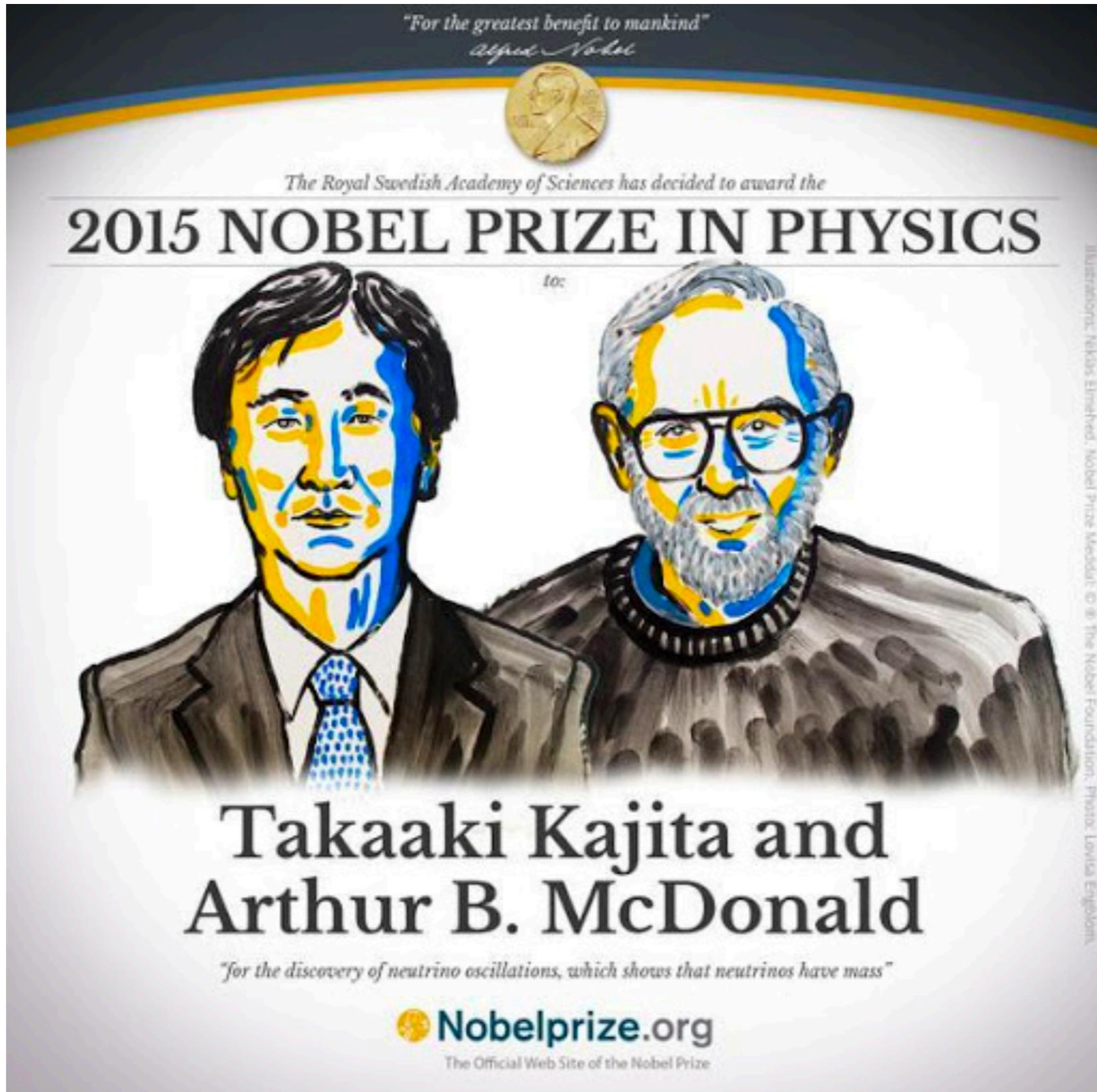


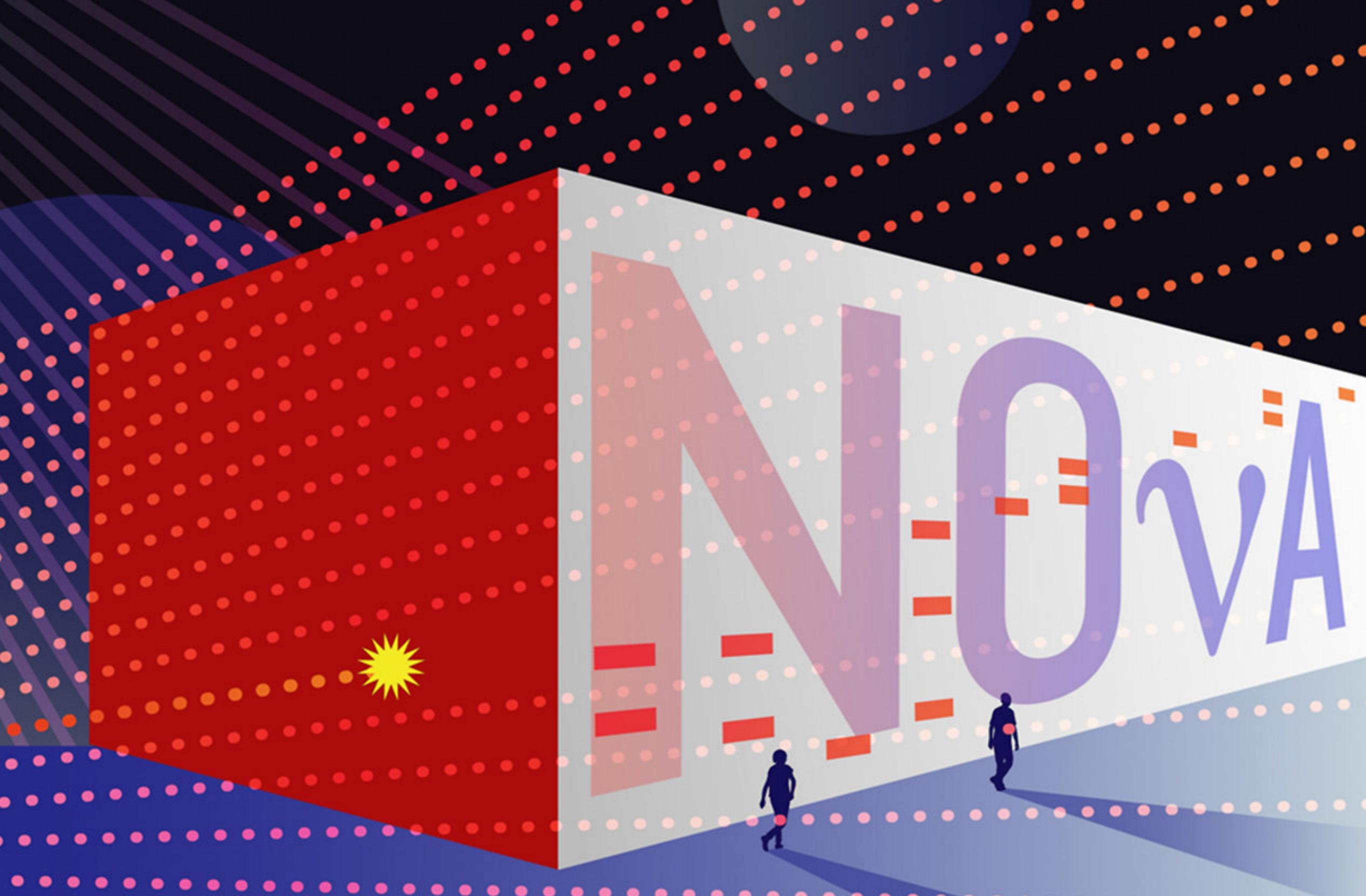
Detected as **flavour states**





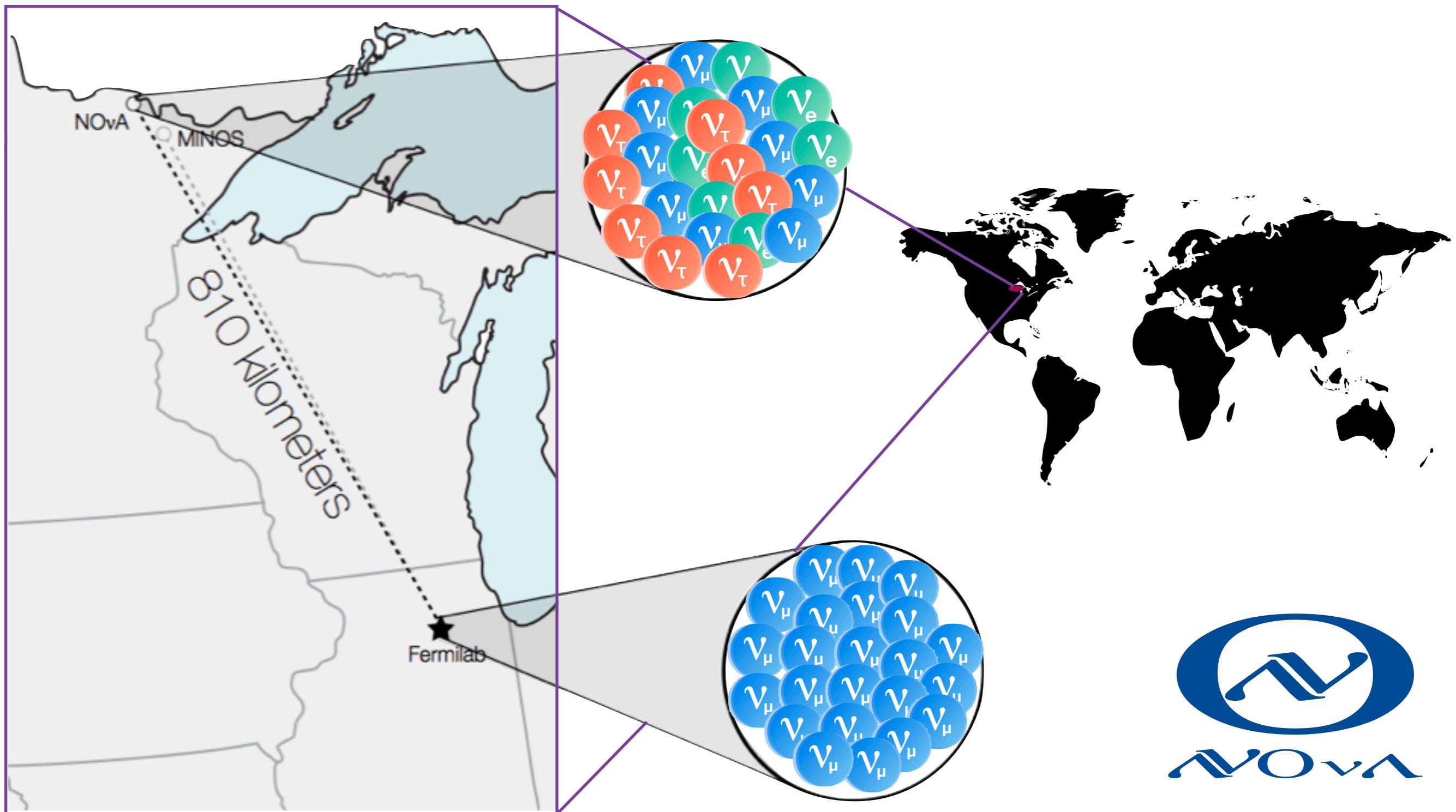
# Neutrino Oscillations



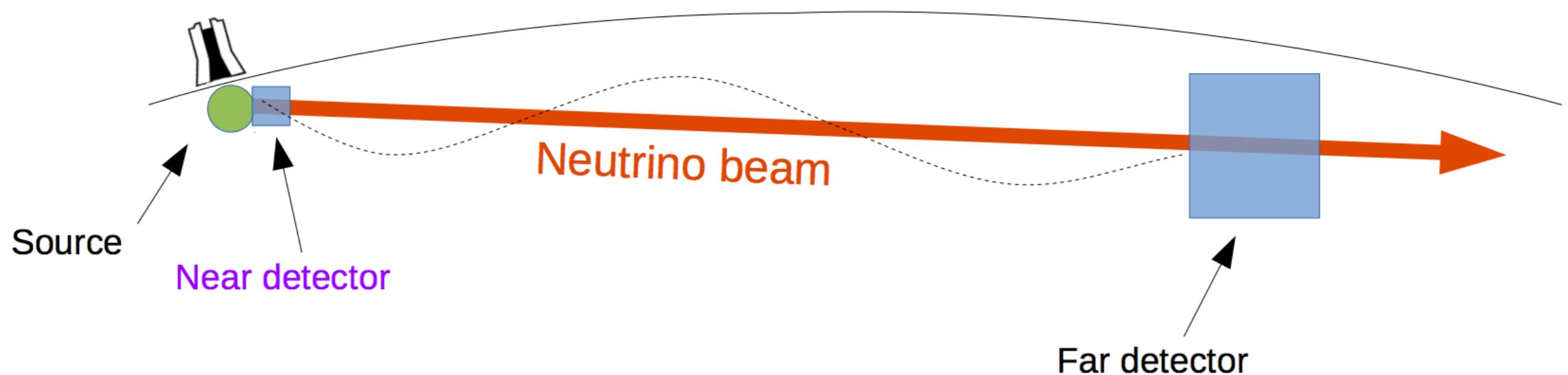




# The NOvA Experiment



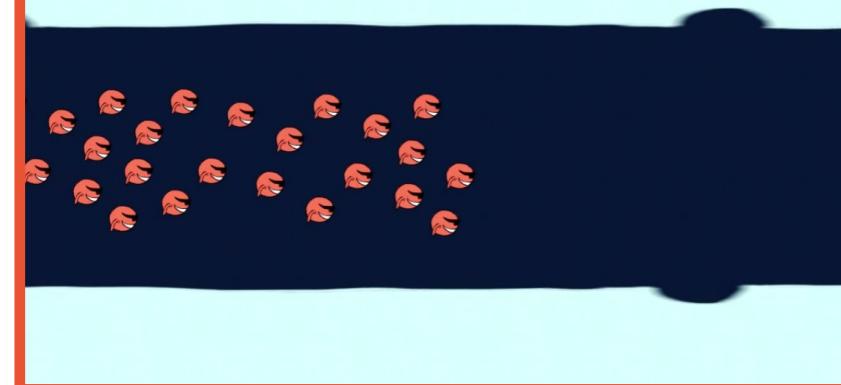
# Remember the Earth is NOT flat!



# How To Make a Neutrino Beam



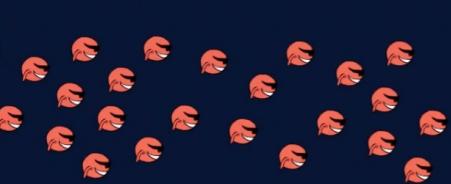
OUR ACCELERATOR PROPELS PROTONS



# How To Make a Neutrino Beam



OUR ACCELERATOR PROPELS PROTONS



WE SMASH THE PROTONS INTO A GRAPHITE TARGET



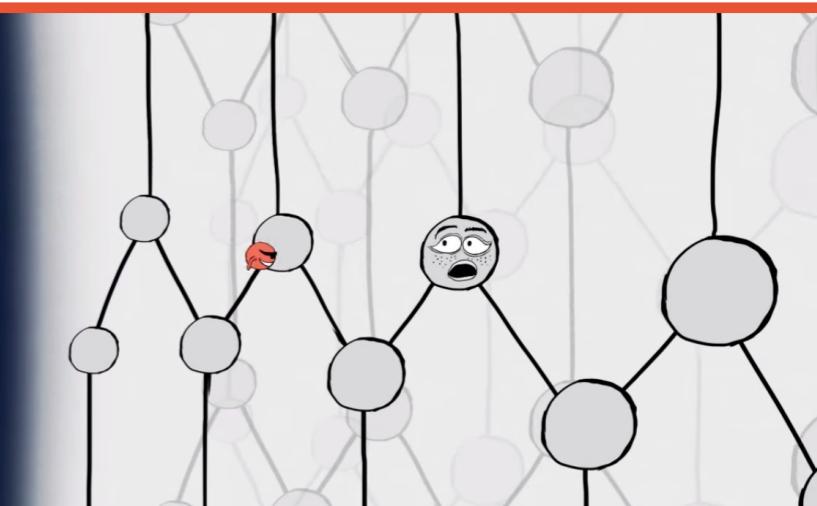
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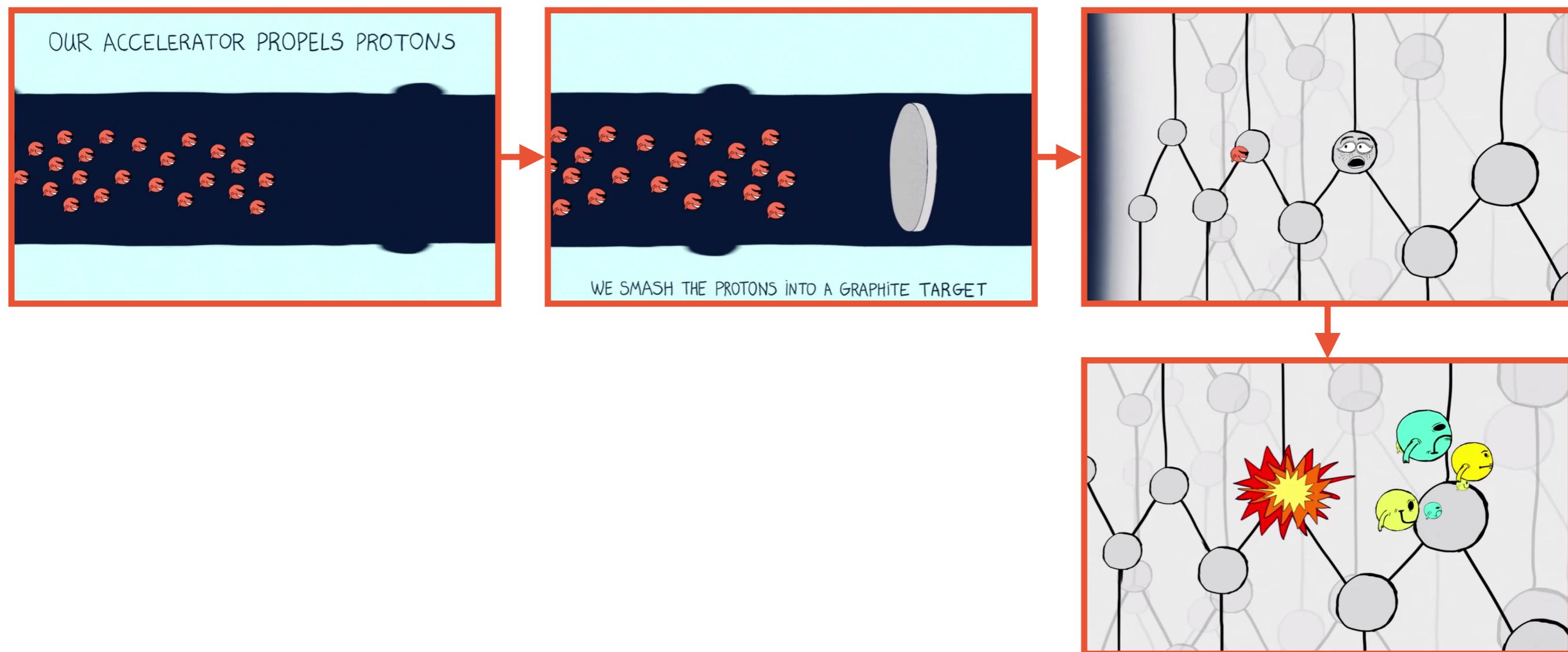
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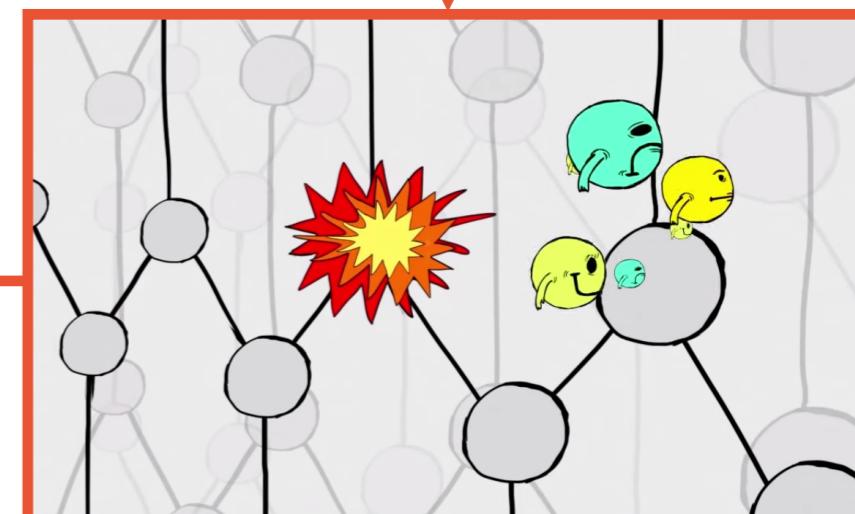
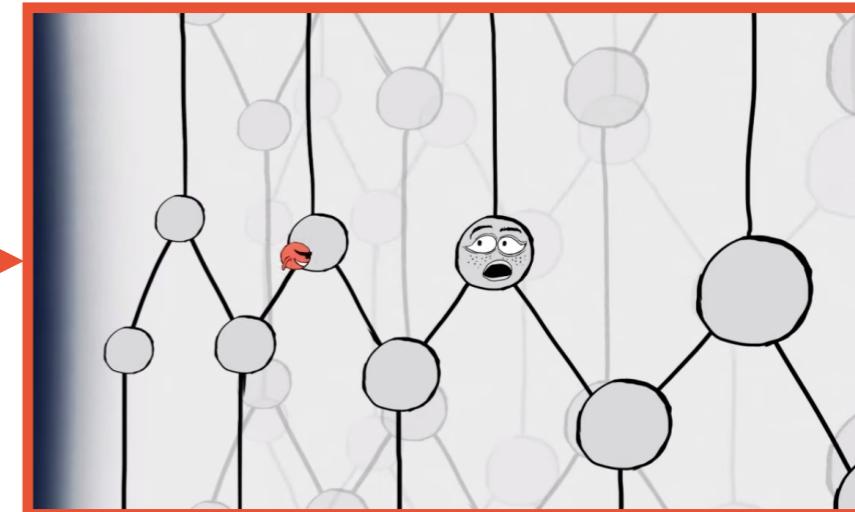


WE SMASH THE PROTONS INTO A GRAPHITE TARGET

COLLISIONS WITH THE NUCLEI



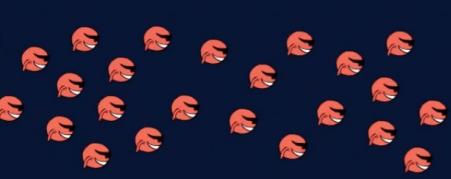
PRODUCE NEW PARTICLES



# How To Make a Neutrino Beam

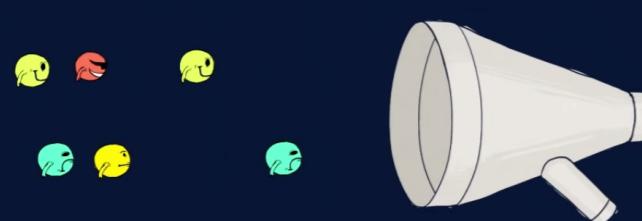


OUR ACCELERATOR PROPELS PROTONS



WE SMASH THE PROTONS INTO A GRAPHITE TARGET

A MAGNETIC HORN SELECTS POSITIVE PIONS



AND FOCUSES THEM INTO A NARROW BEAM

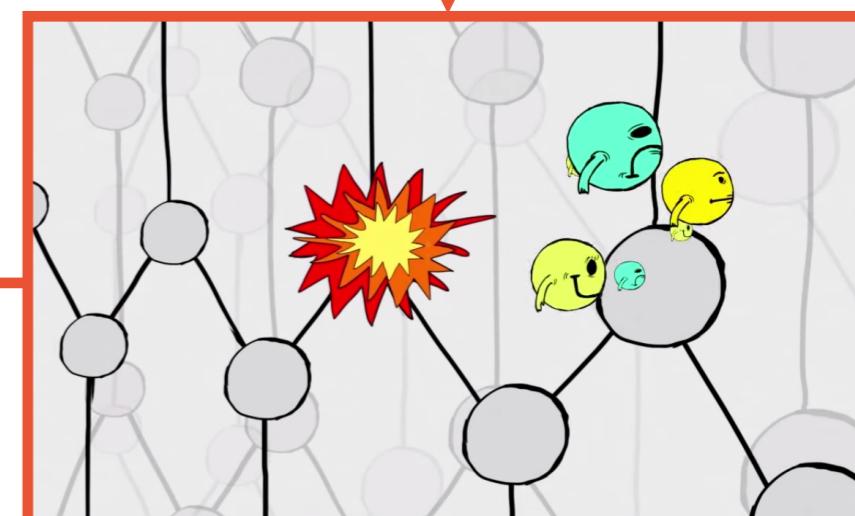
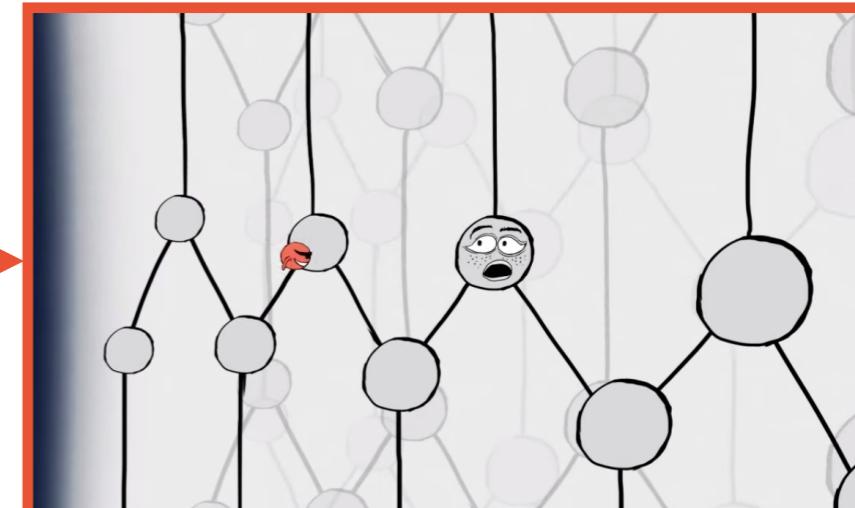
COLLISIONS WITH THE NUCLEI

PRODUCE NEW PARTICLES

$\oplus$  PIONS

NEUTRONS

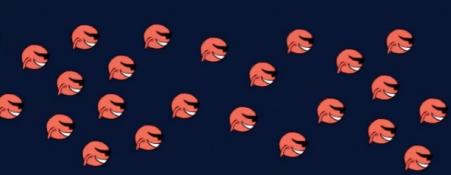
$\ominus$  PIONS



# How To Make a Neutrino Beam

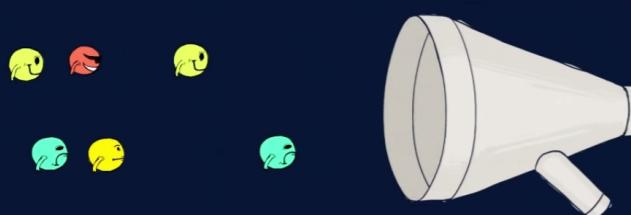


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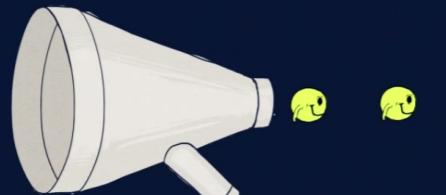
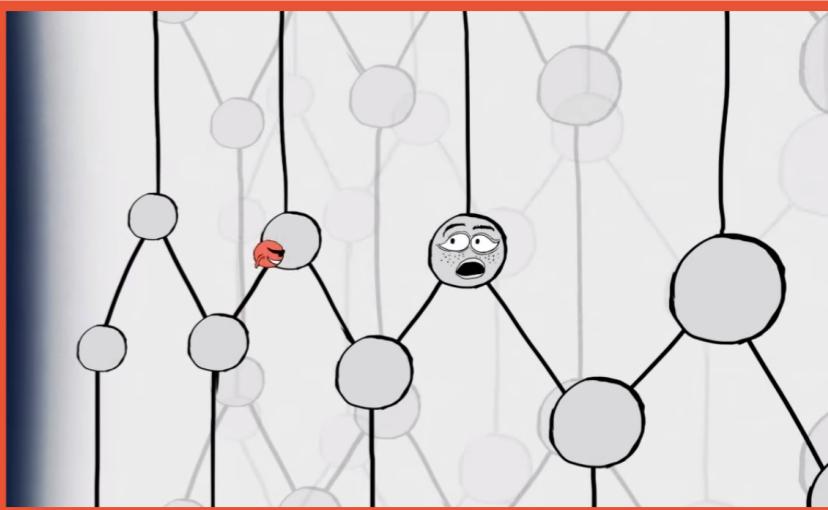
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COLLISIONS WITH THE NUCLEI



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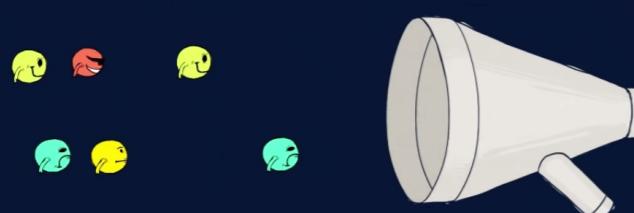


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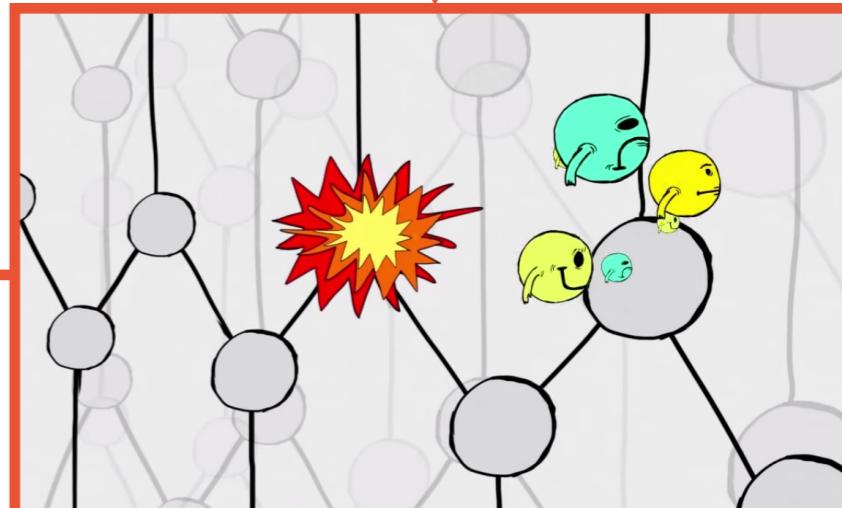
COLLISIONS WITH THE NUCLEI

PRODUCE NEW PARTICLES

+ PIONS

- PIONS

NEUTRONS



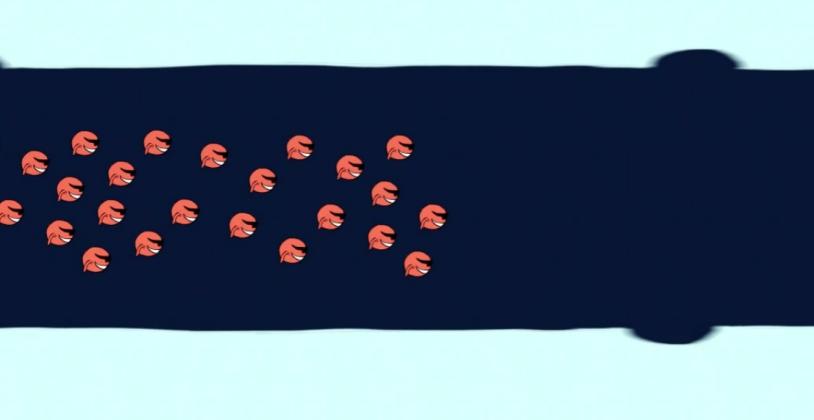
POSITIVE PIONS SPONTANEOUSLY DECAY INTO...



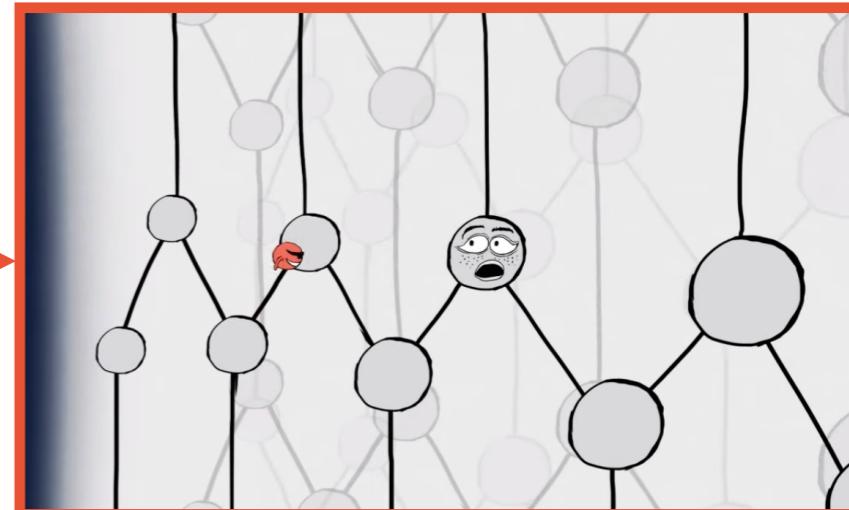
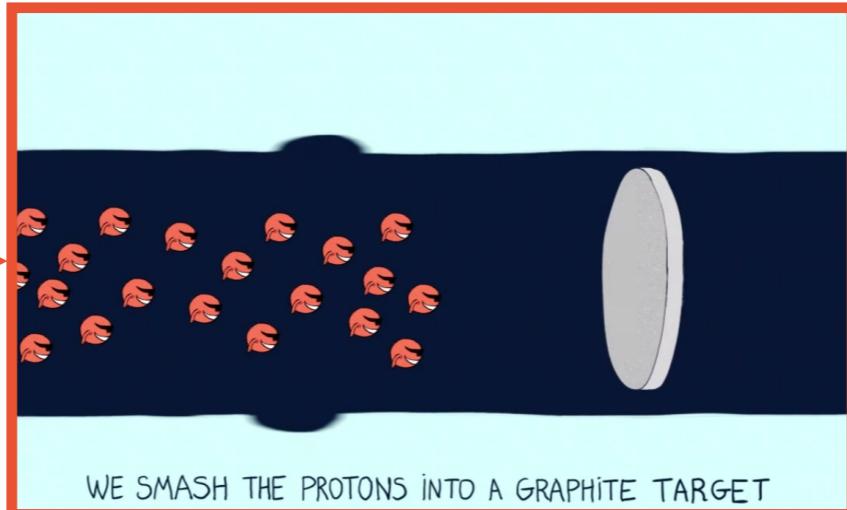
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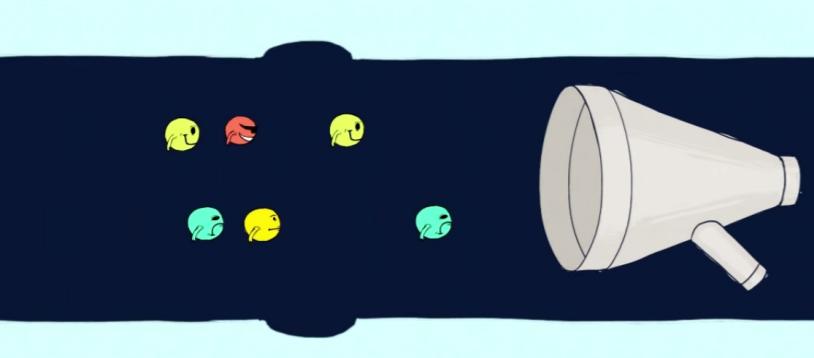
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WE SMASH THE PROTONS INTO A GRAPHITE TARGET

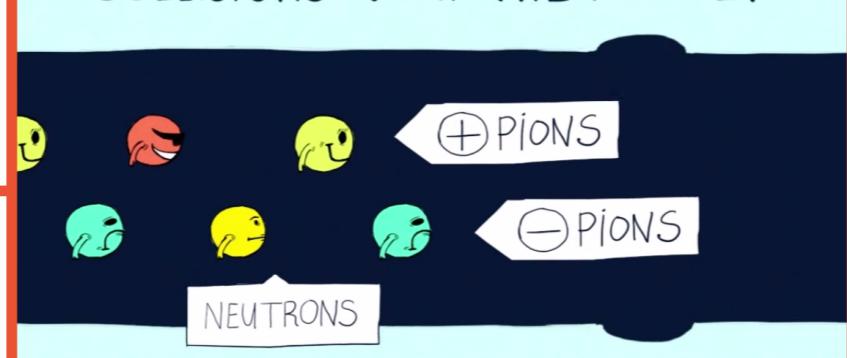


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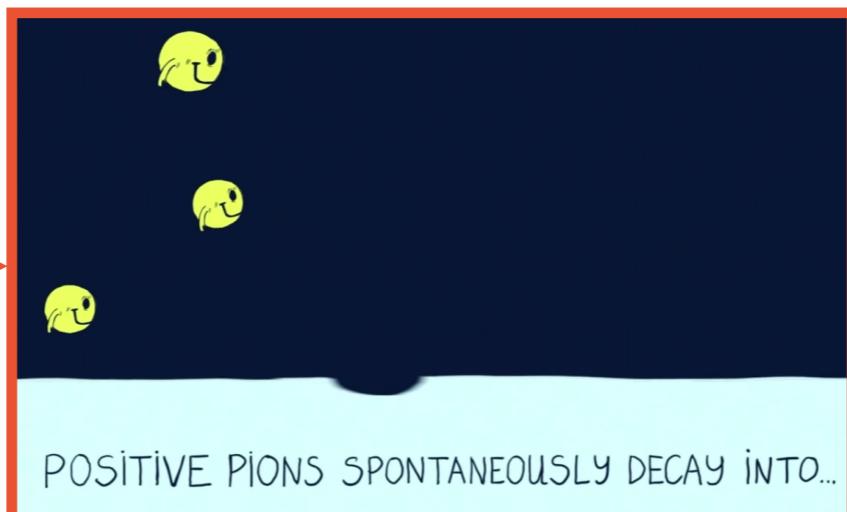
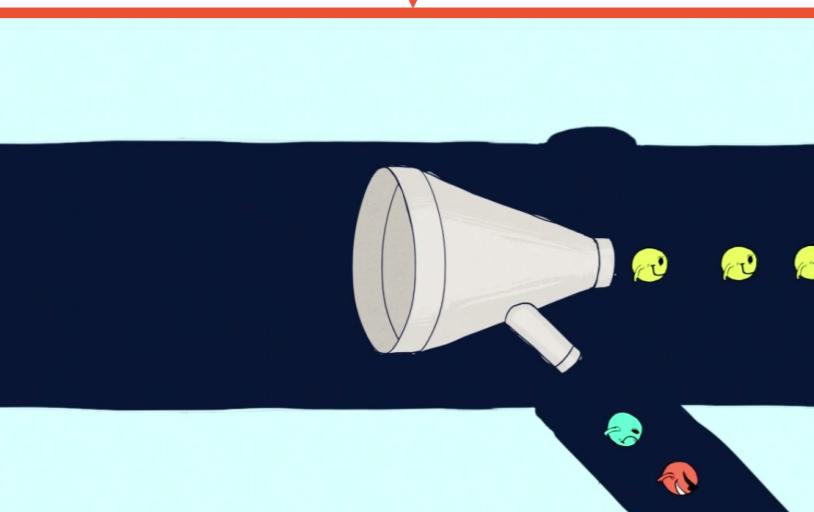
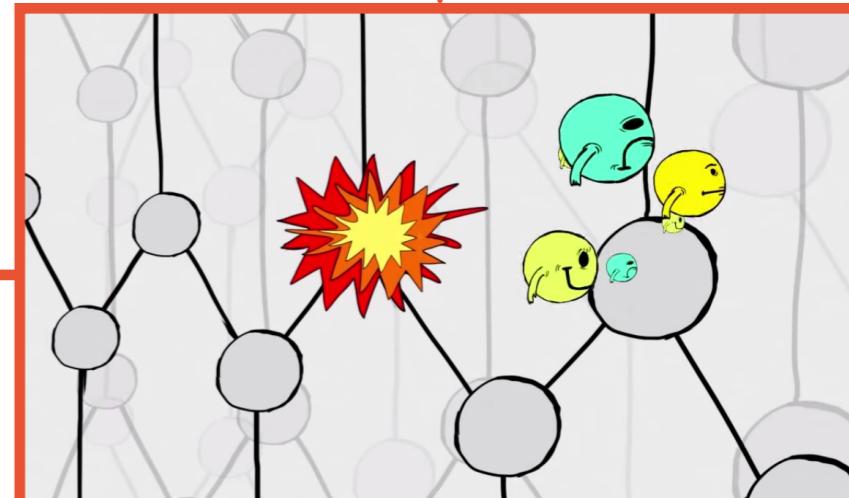


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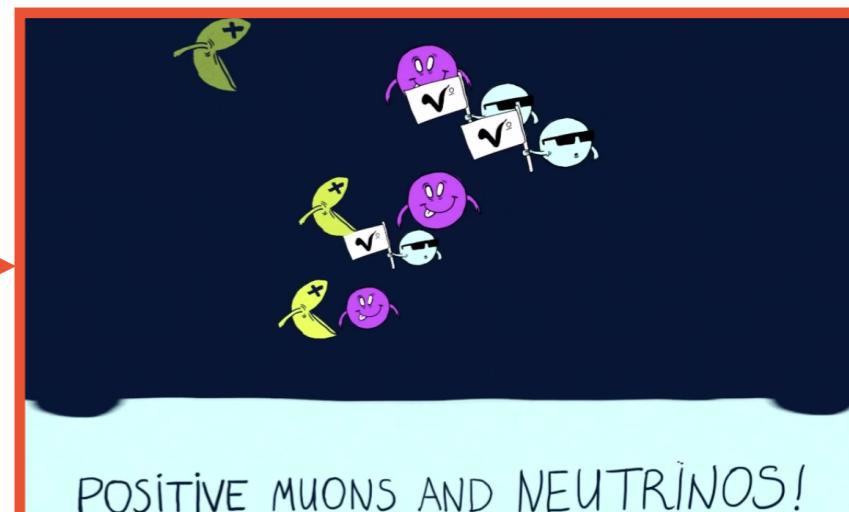
COLLISIONS WITH THE NUCLEI



PRODUCE NEW PARTICLES

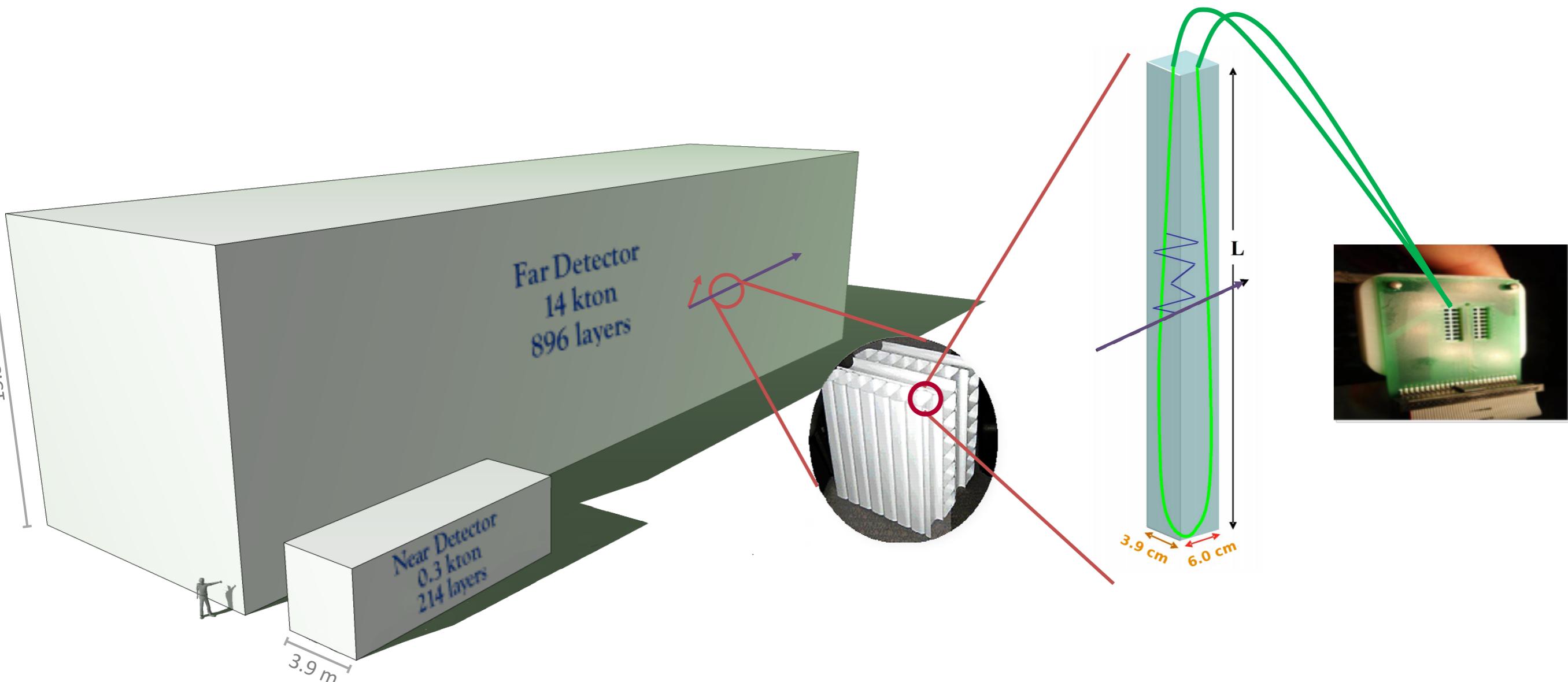


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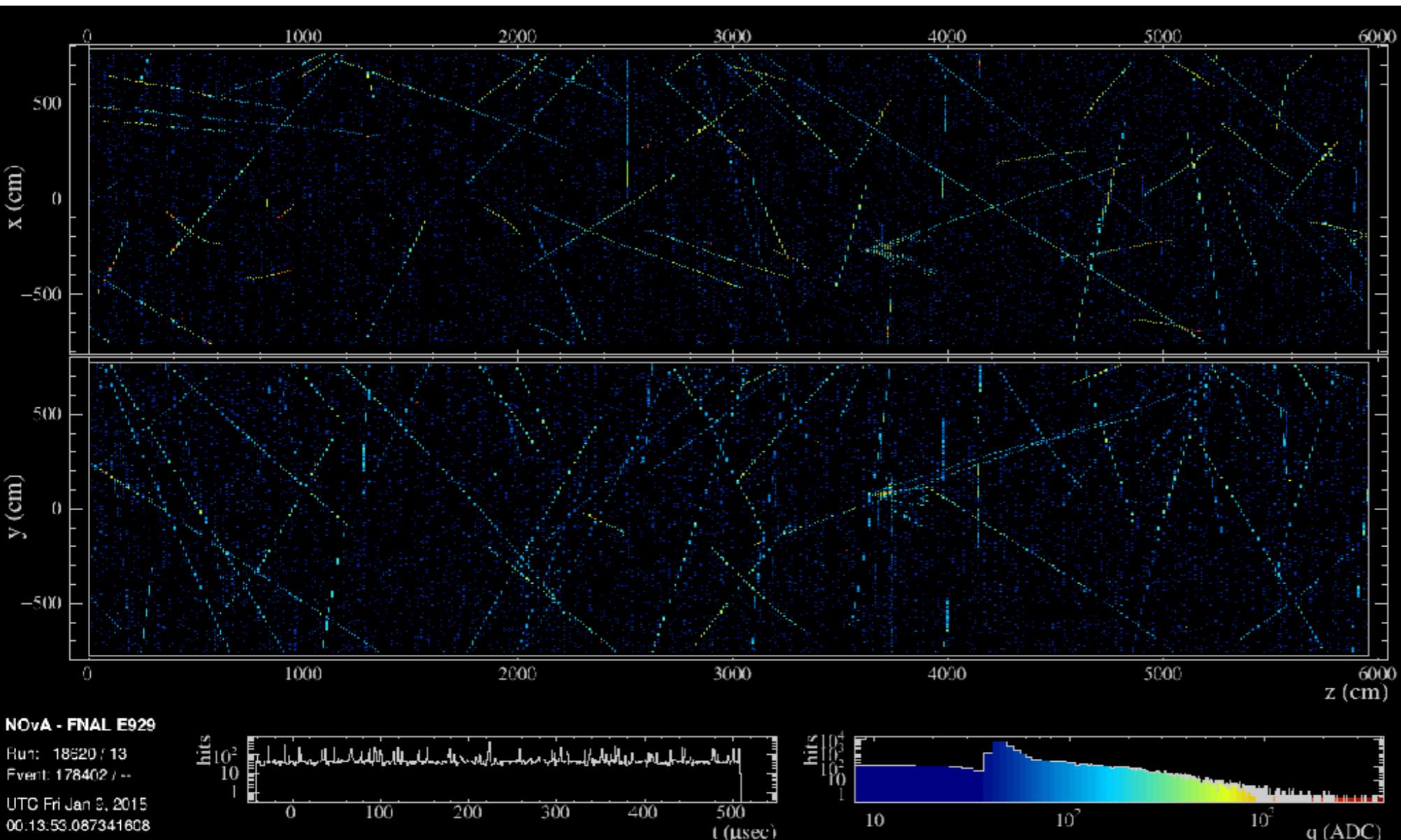


POSITIVE MUONS AND NEUTRINOS!

# The NOvA Detectors

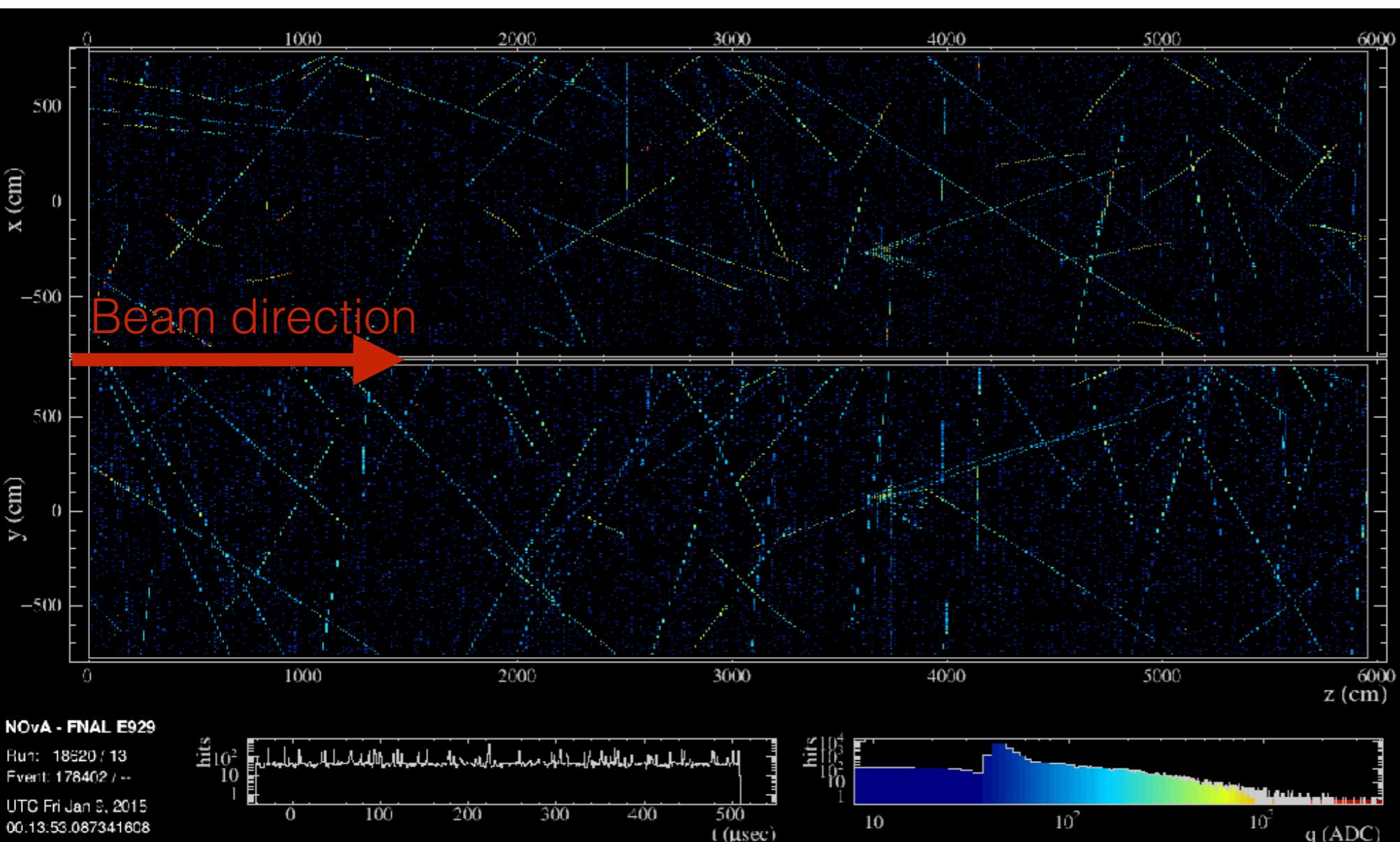


# Far Detector (550 $\mu$ s Readout window)



Lots of cosmic rays  
(11 billion per day!)

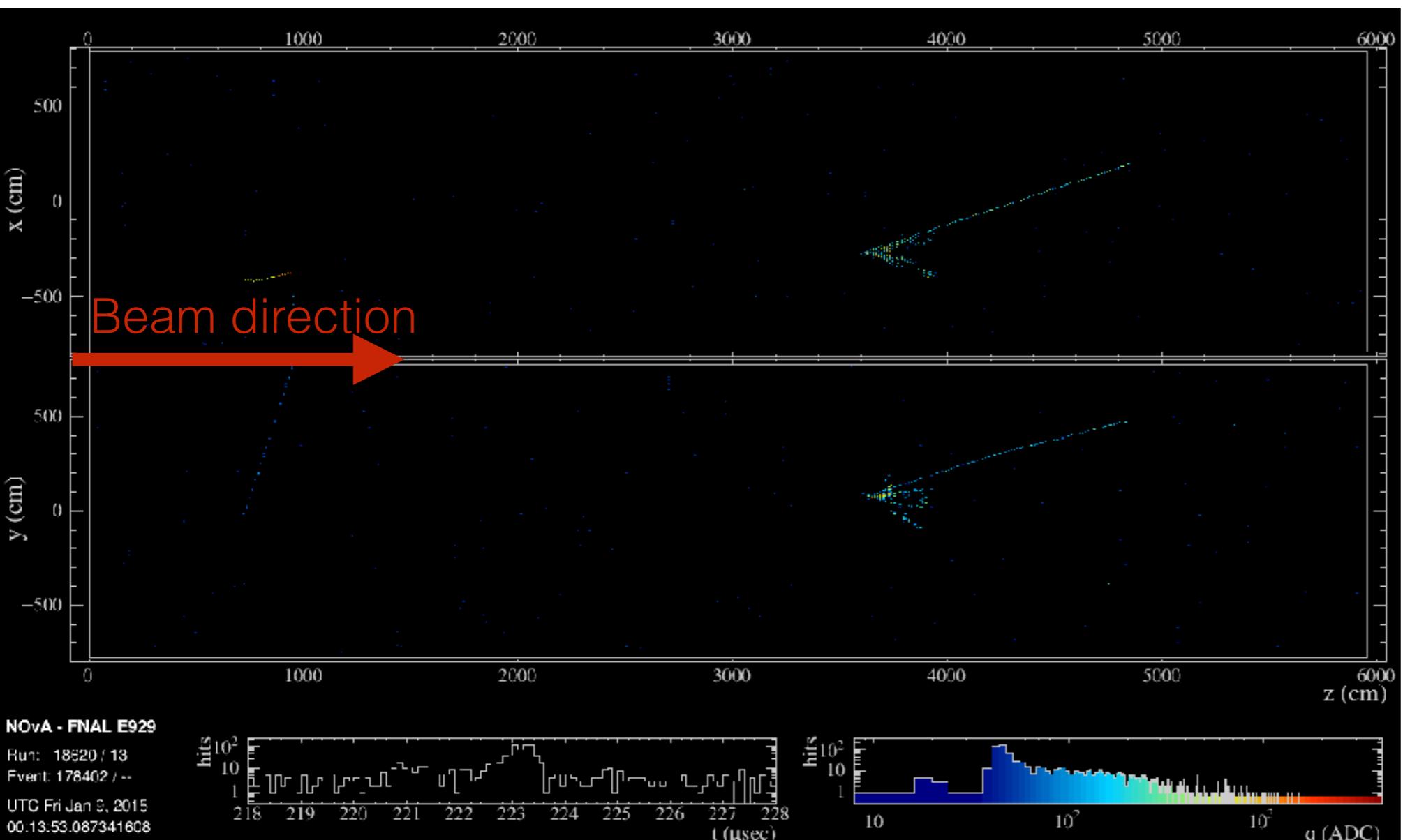
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Can you find the  
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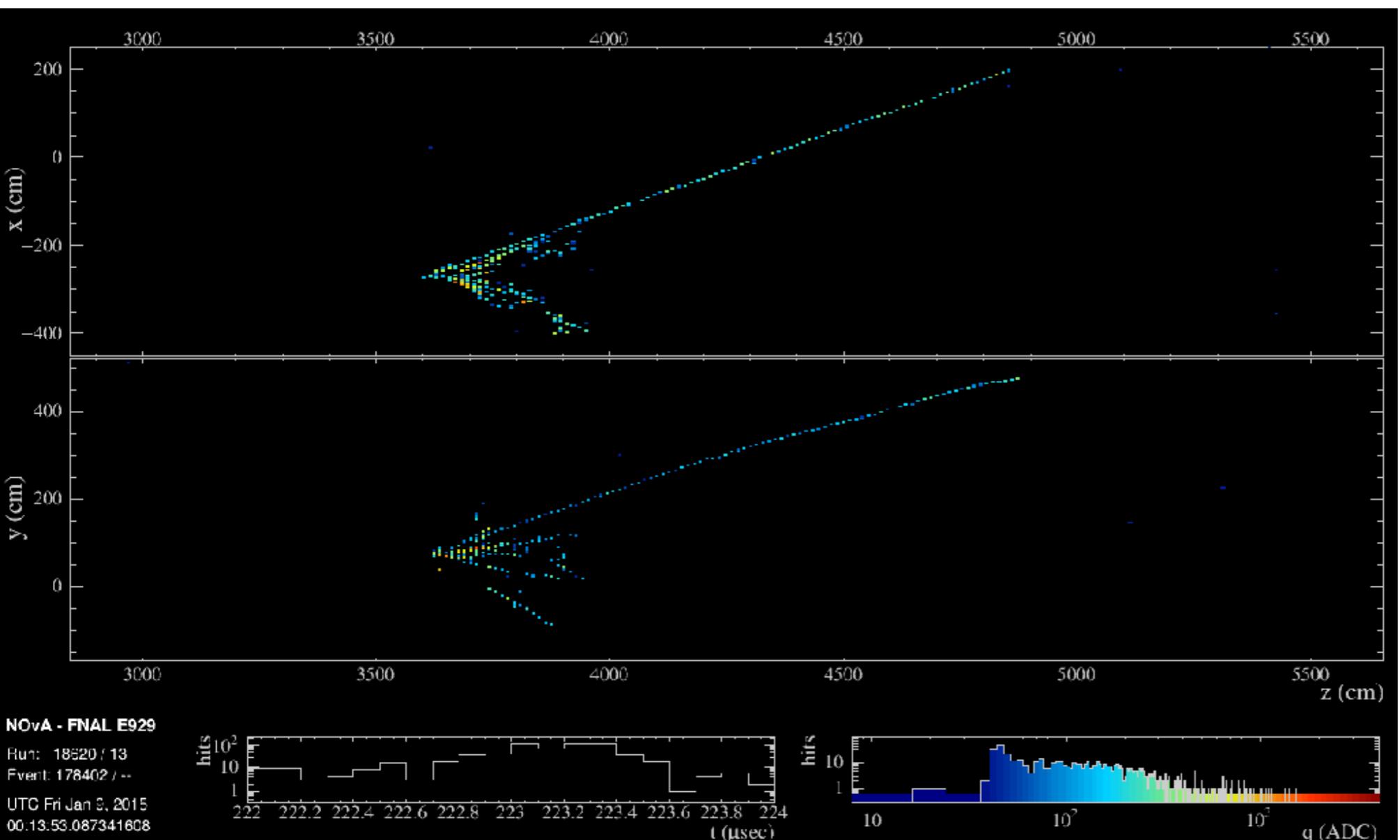
# Far Detector (With Help from Timing...)



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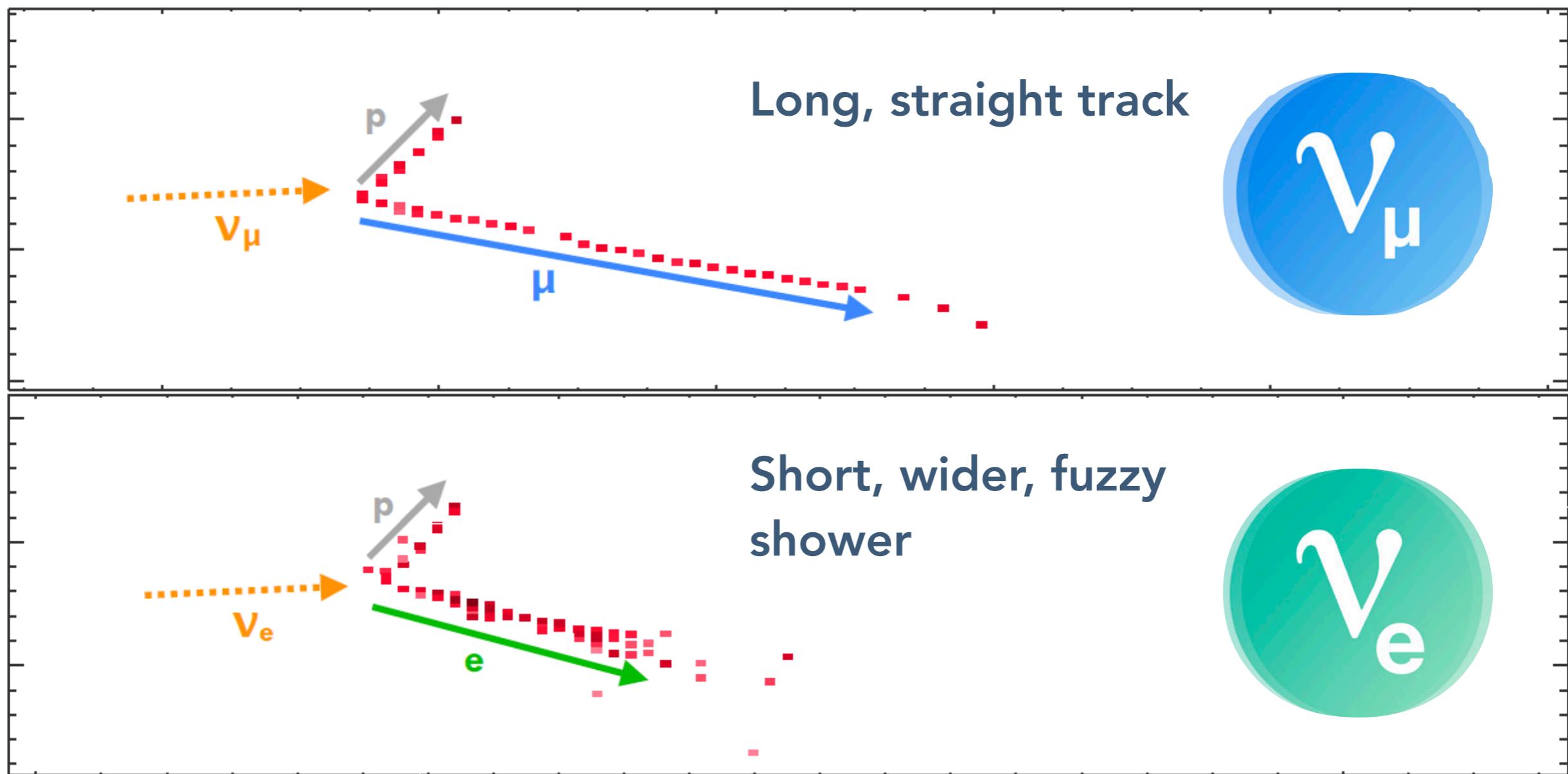


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Can you find the  
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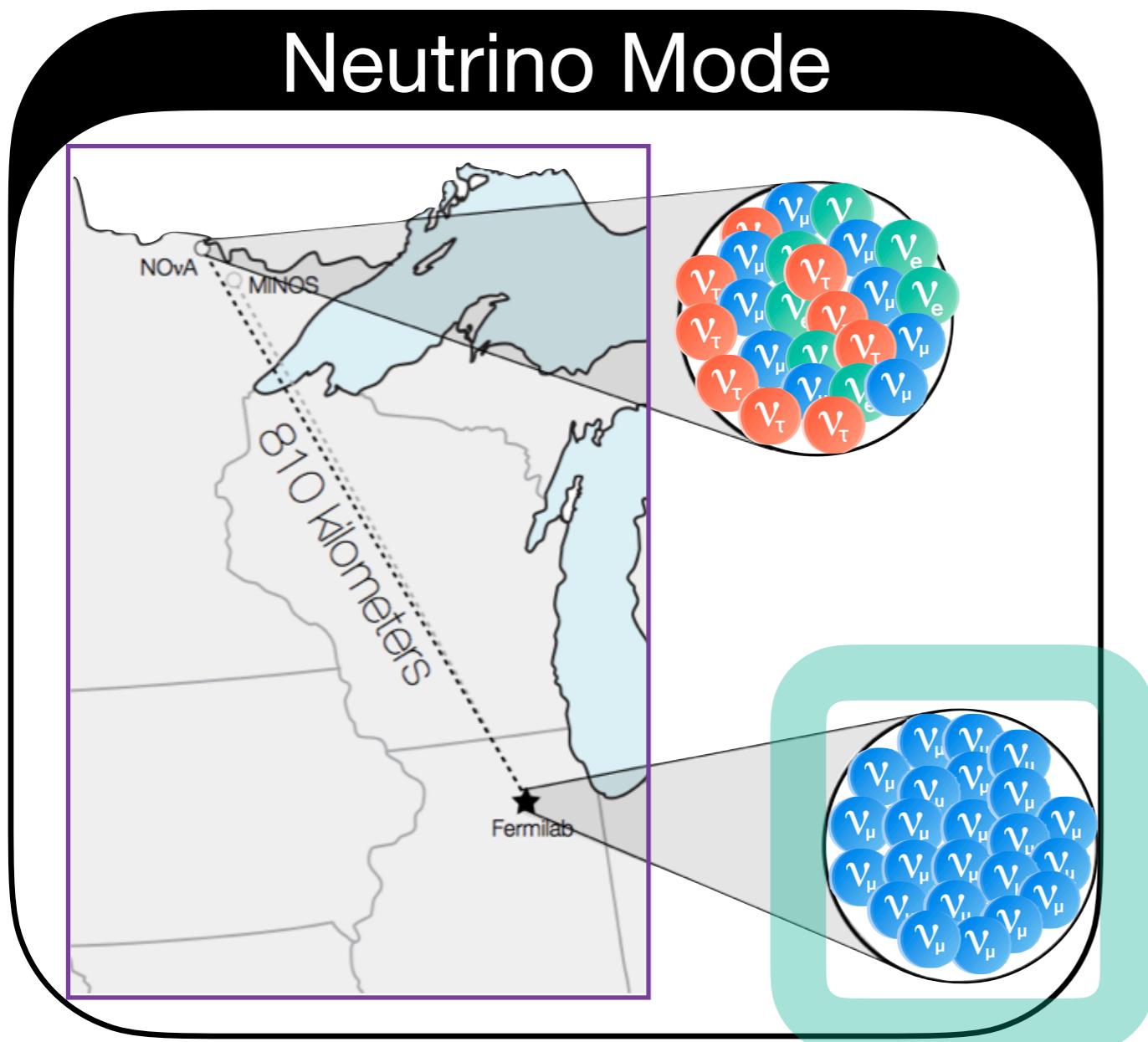


# How can we distinguish between muon neutrinos and electron neutrinos?



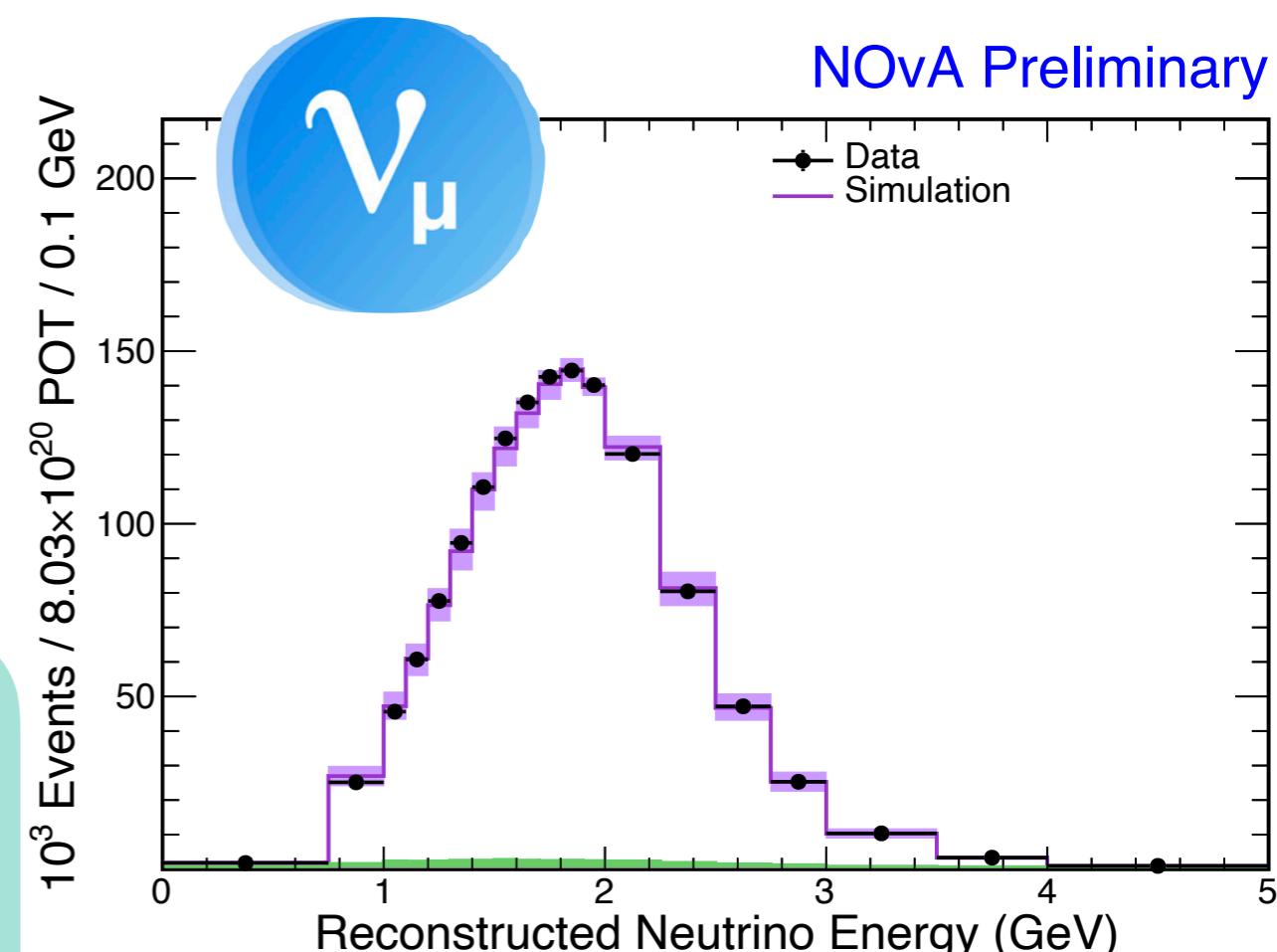
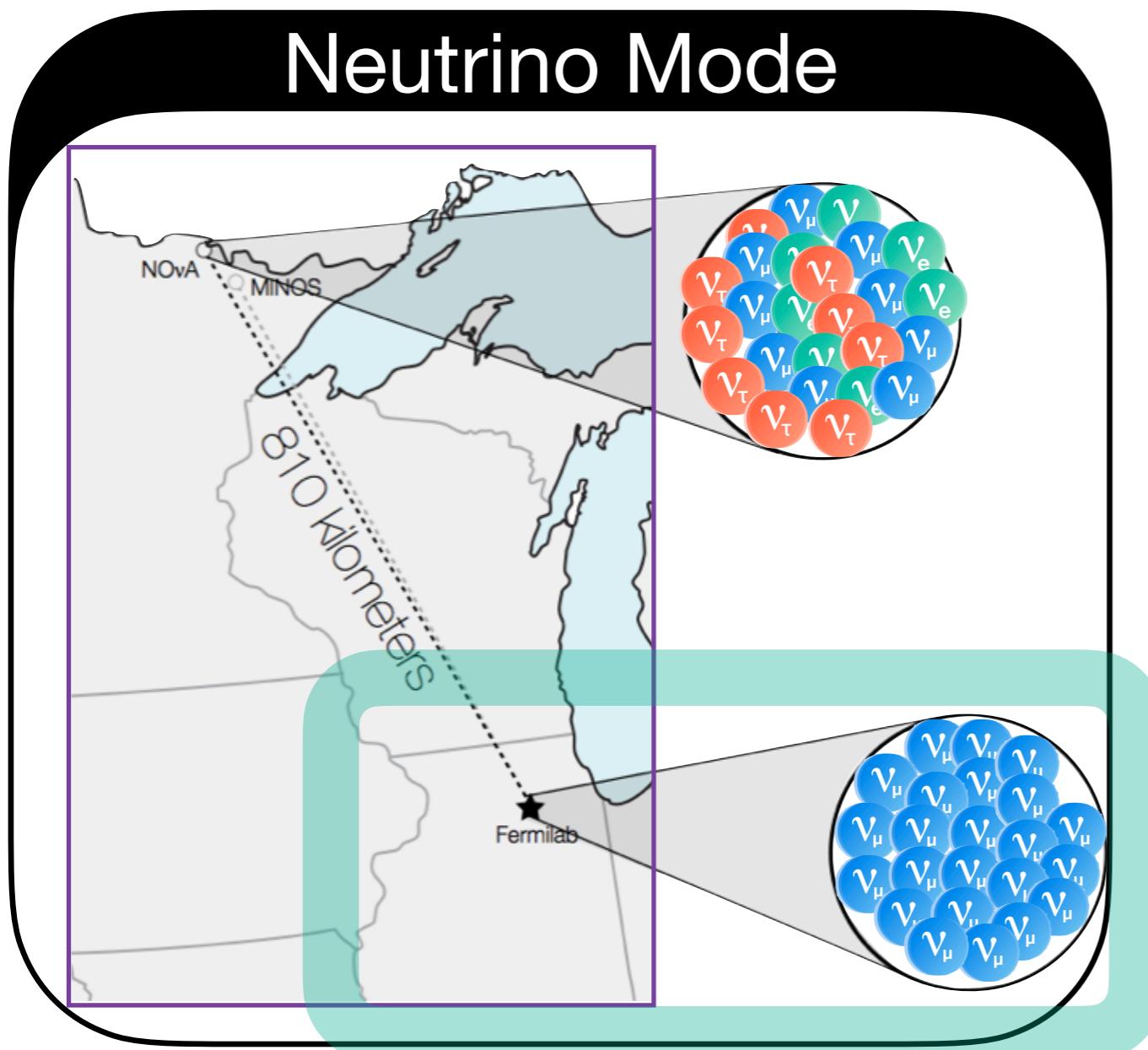
# How does NOvA Measure Oscillations?

Source:



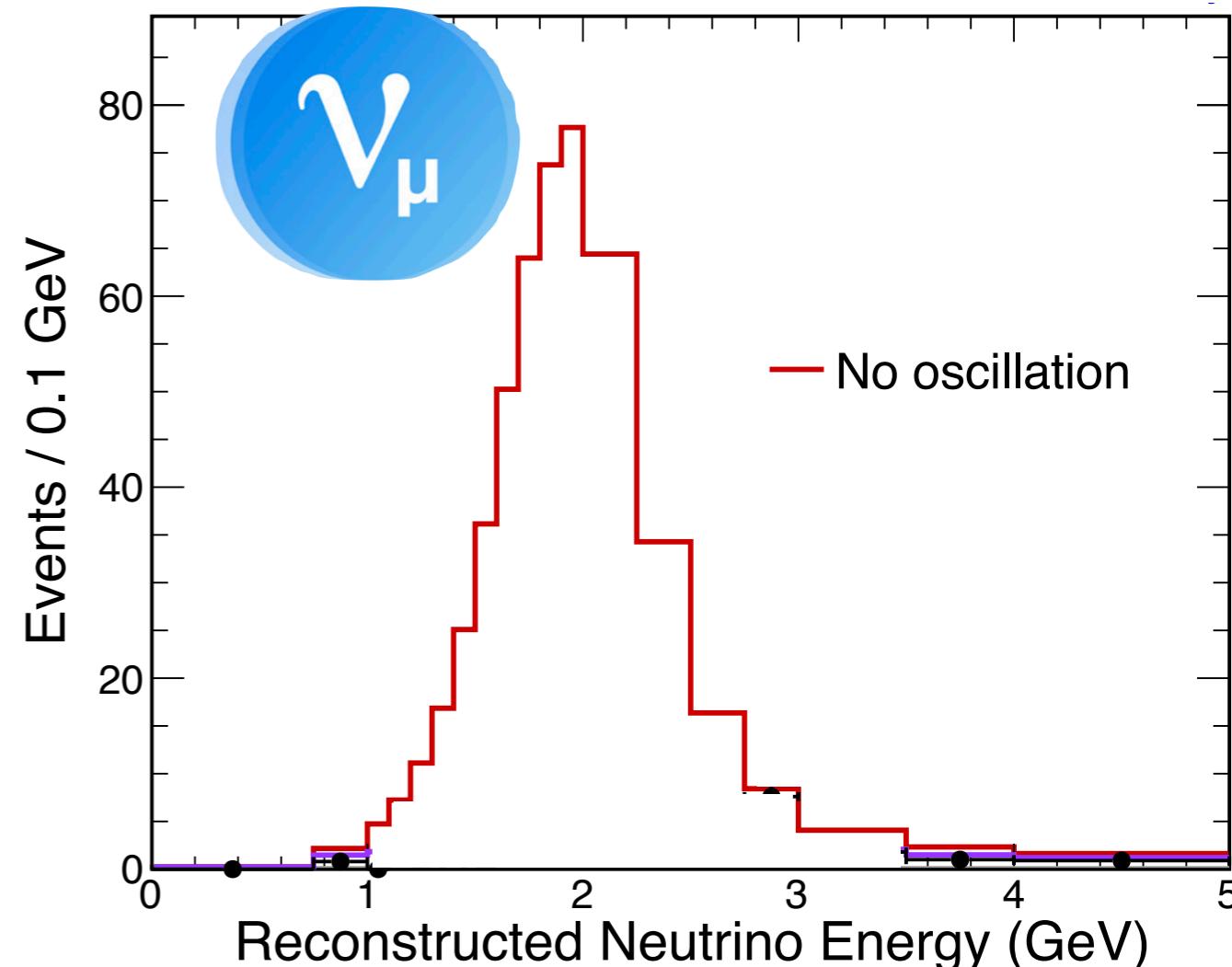
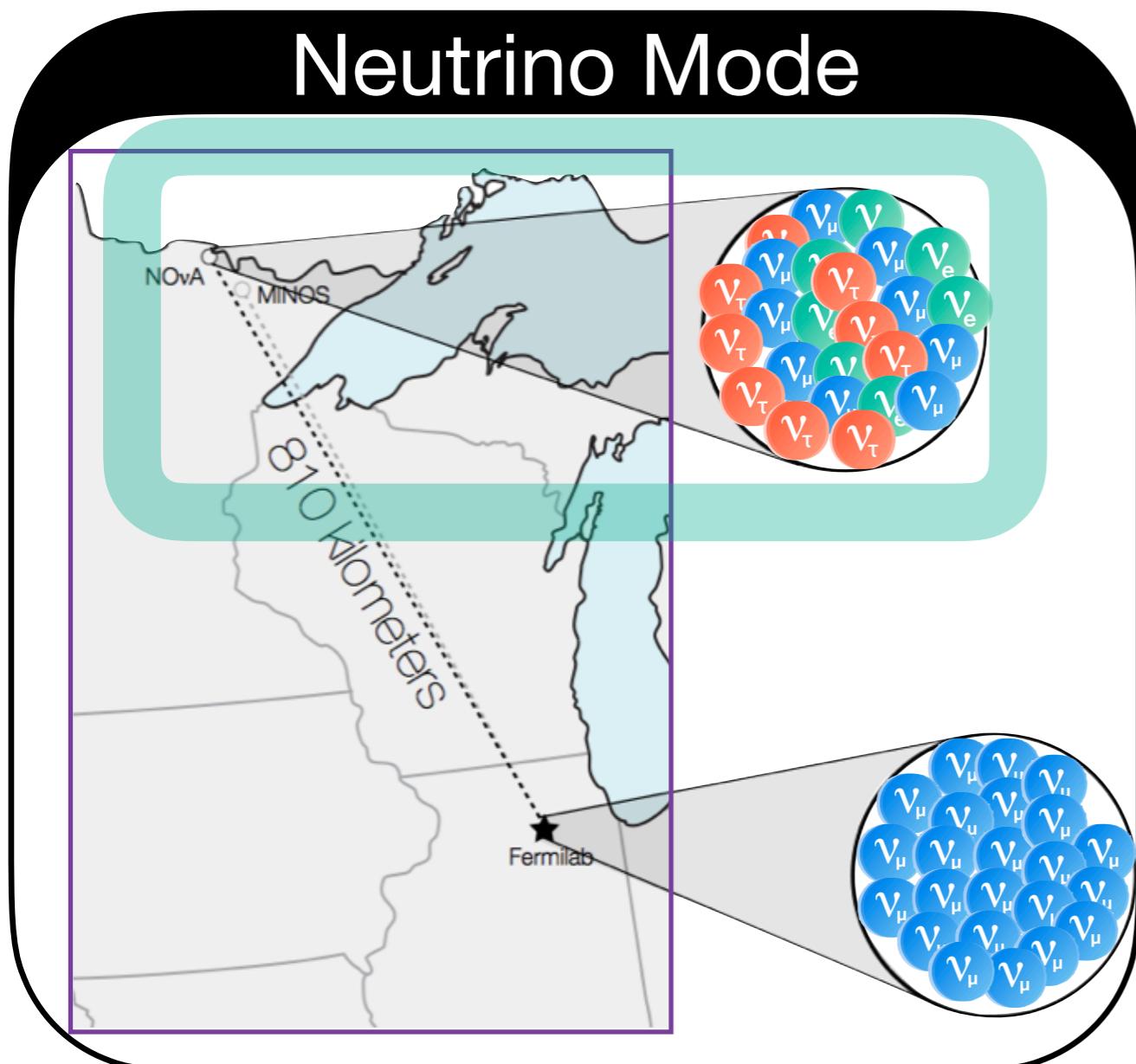
# How does NOvA Measure Oscillations?

## At the Near Detector:



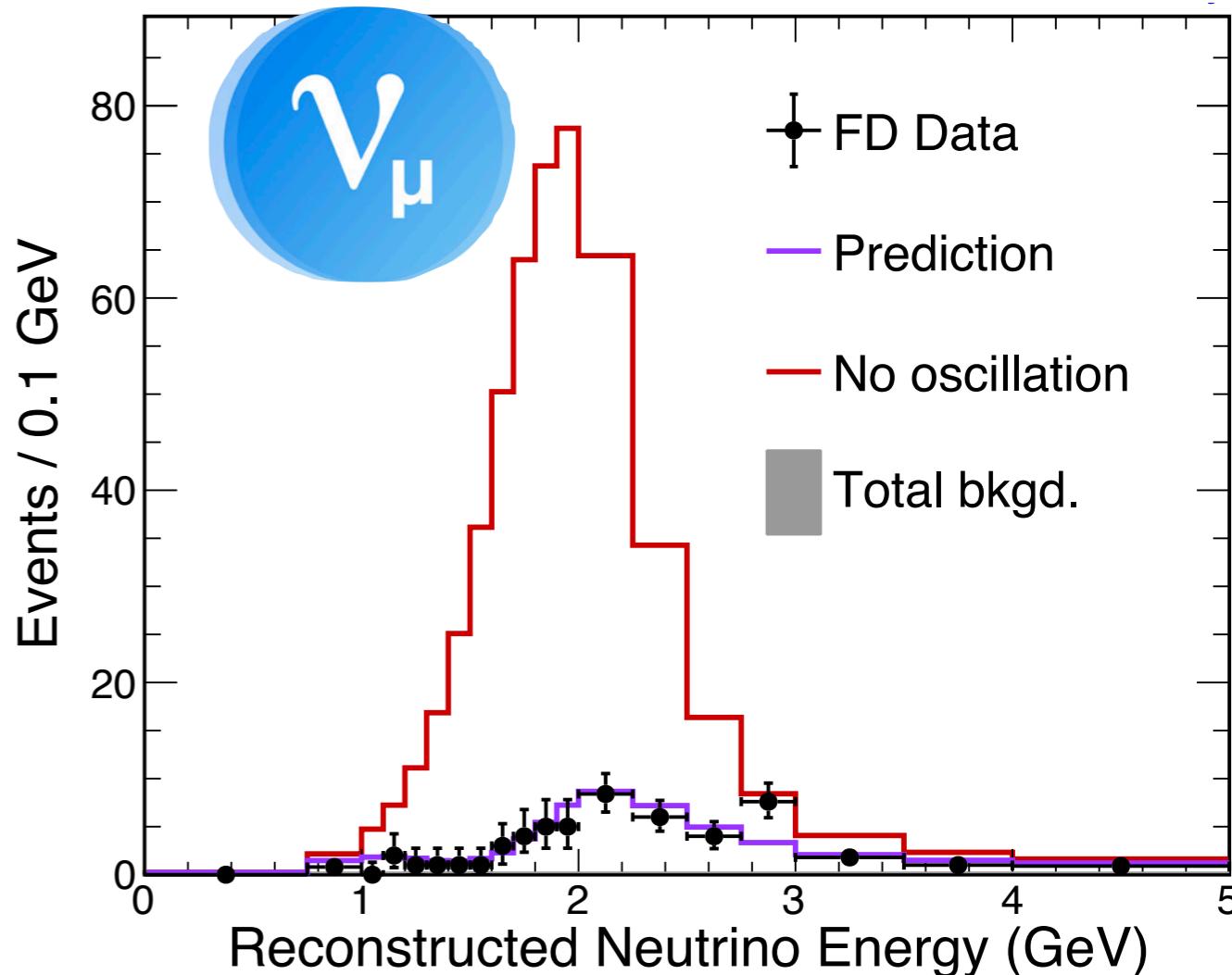
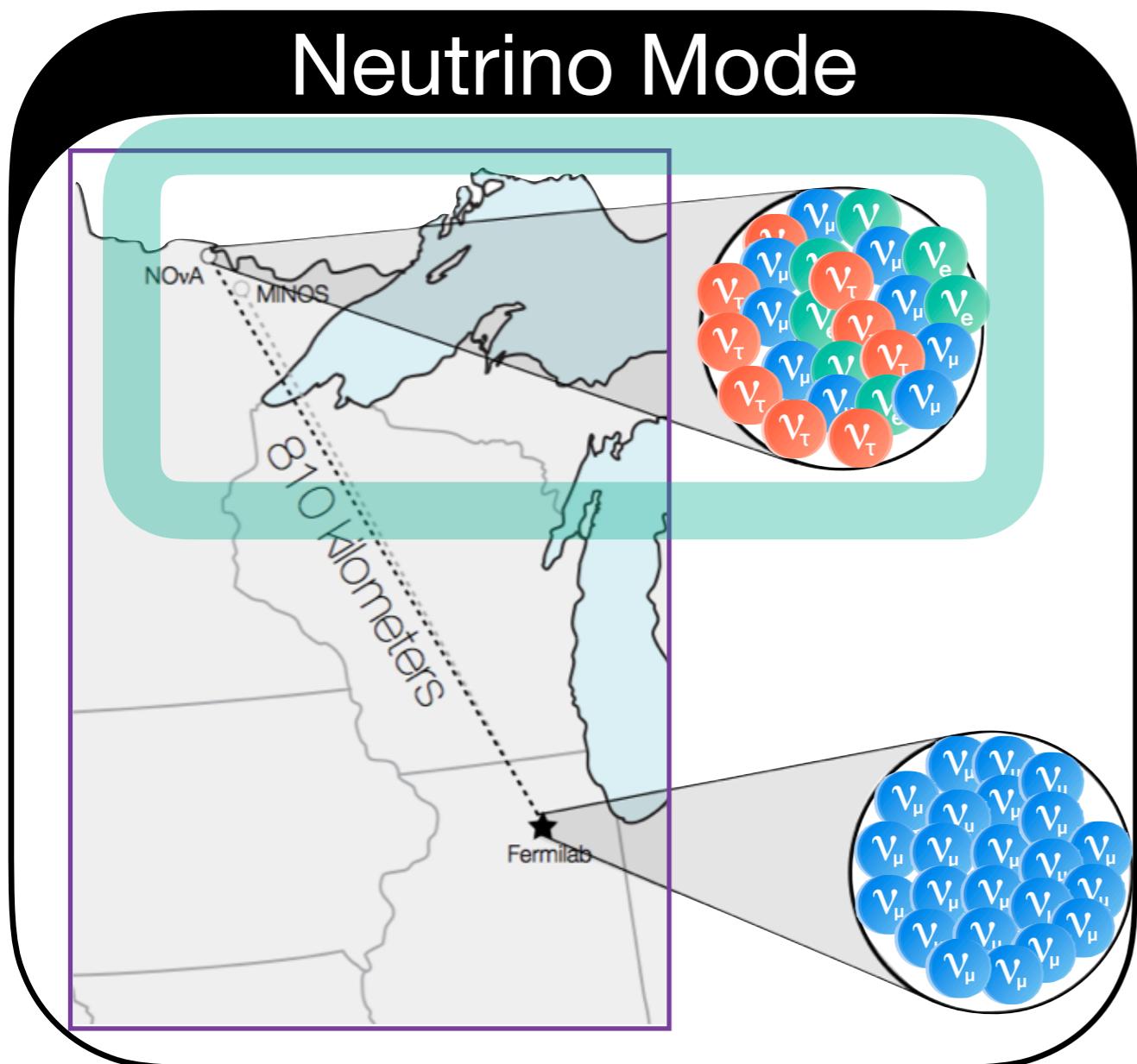
# How does NOvA Measure Oscillations?

## At the Far Detector:



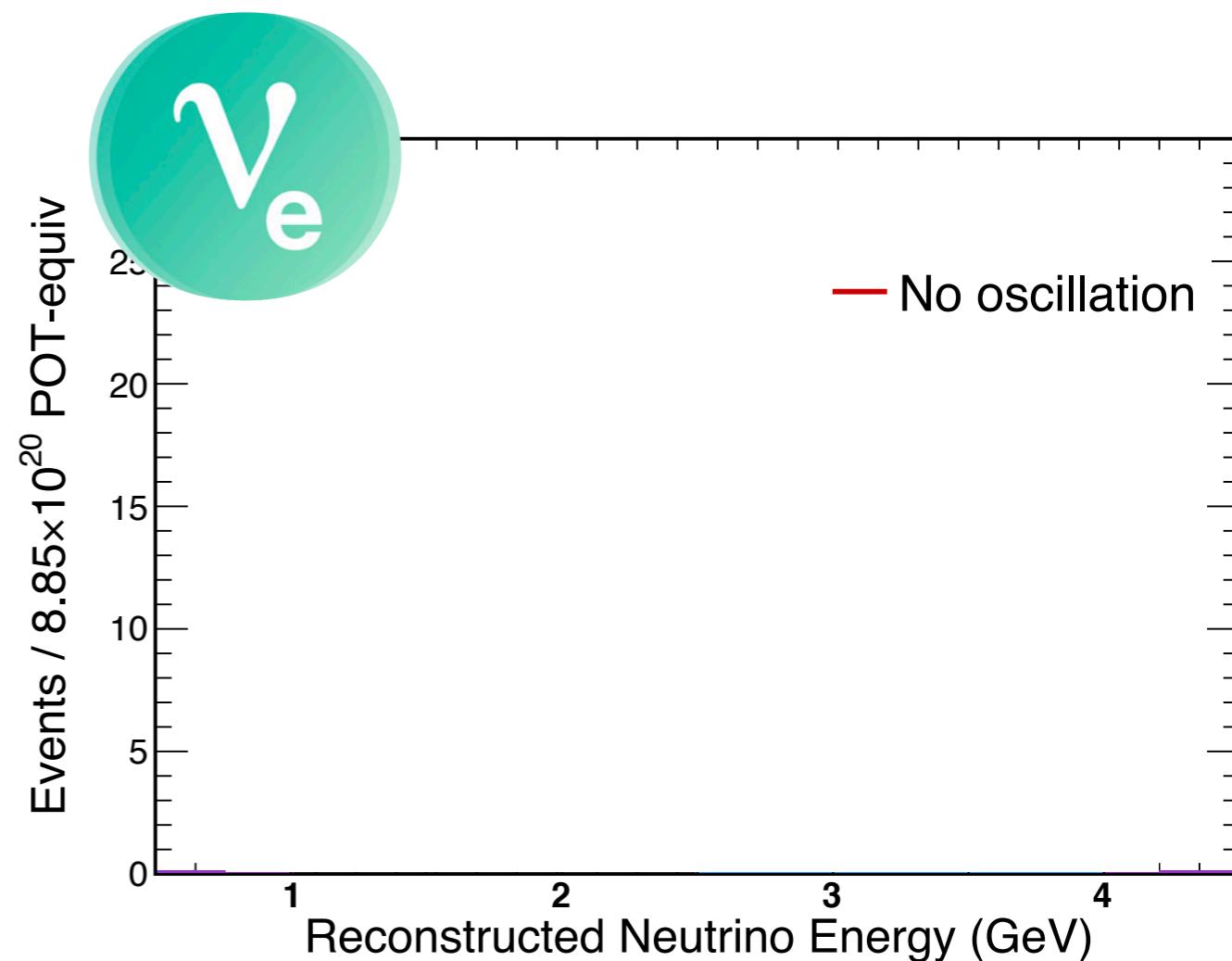
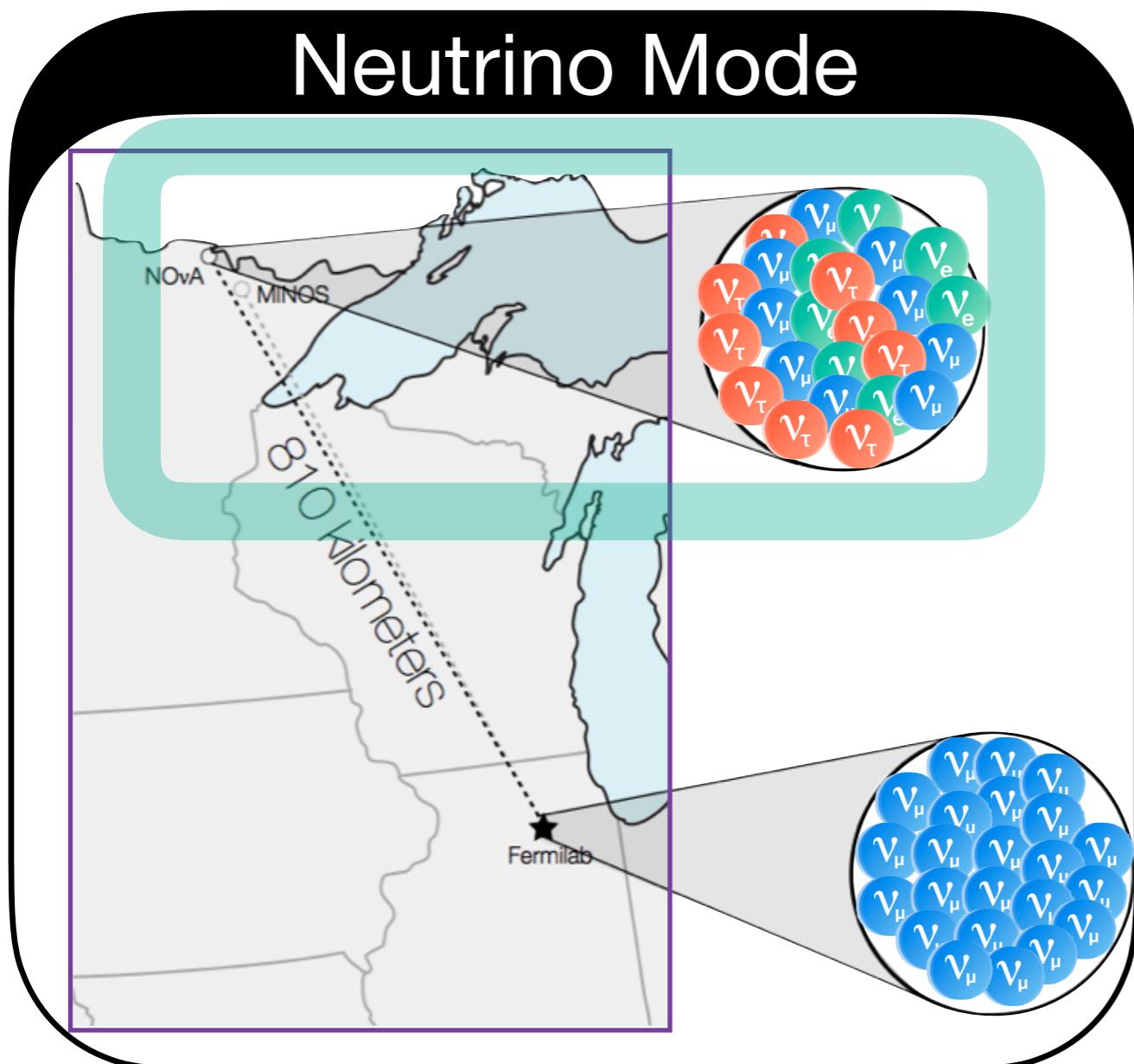
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## At the Far Detector:



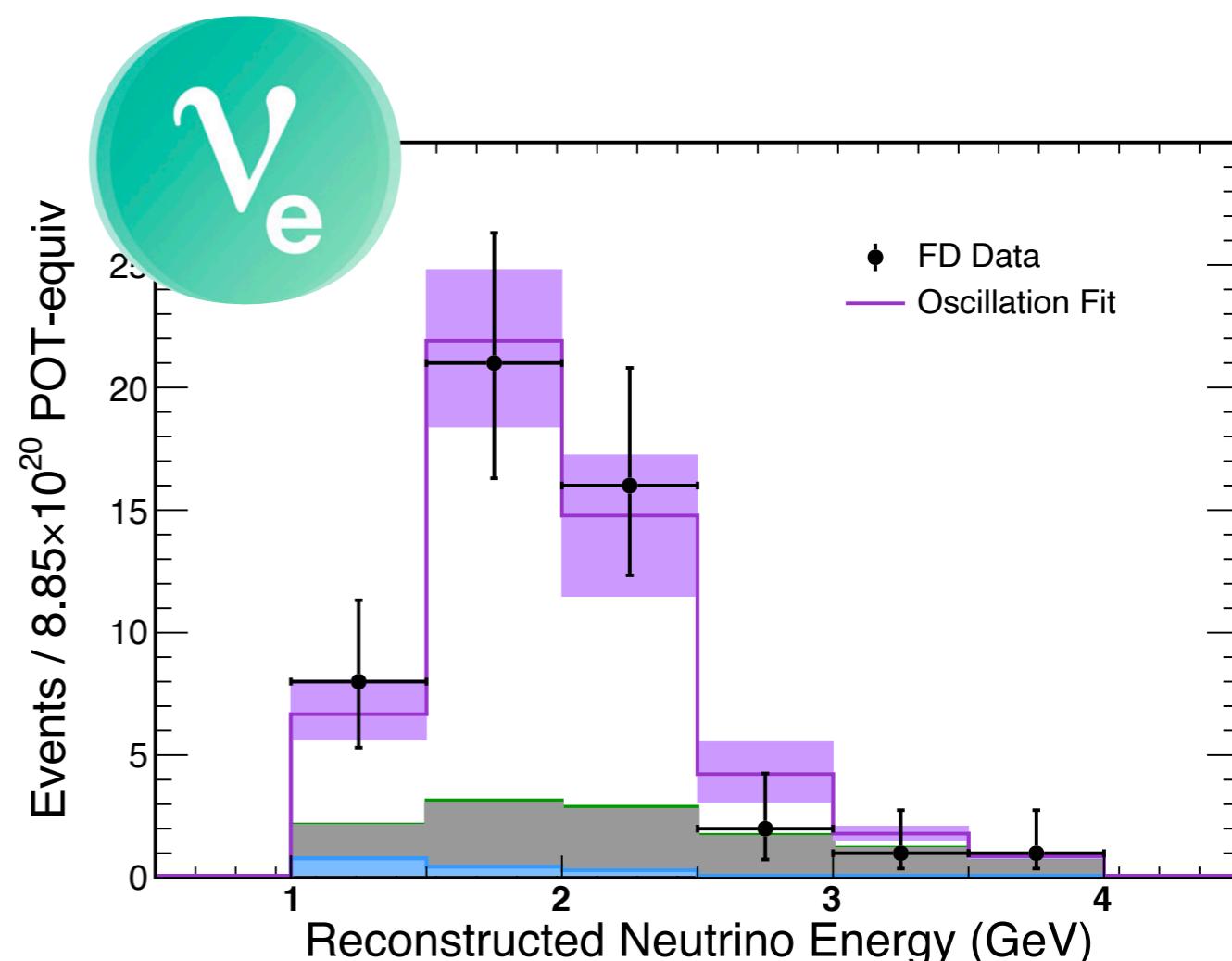
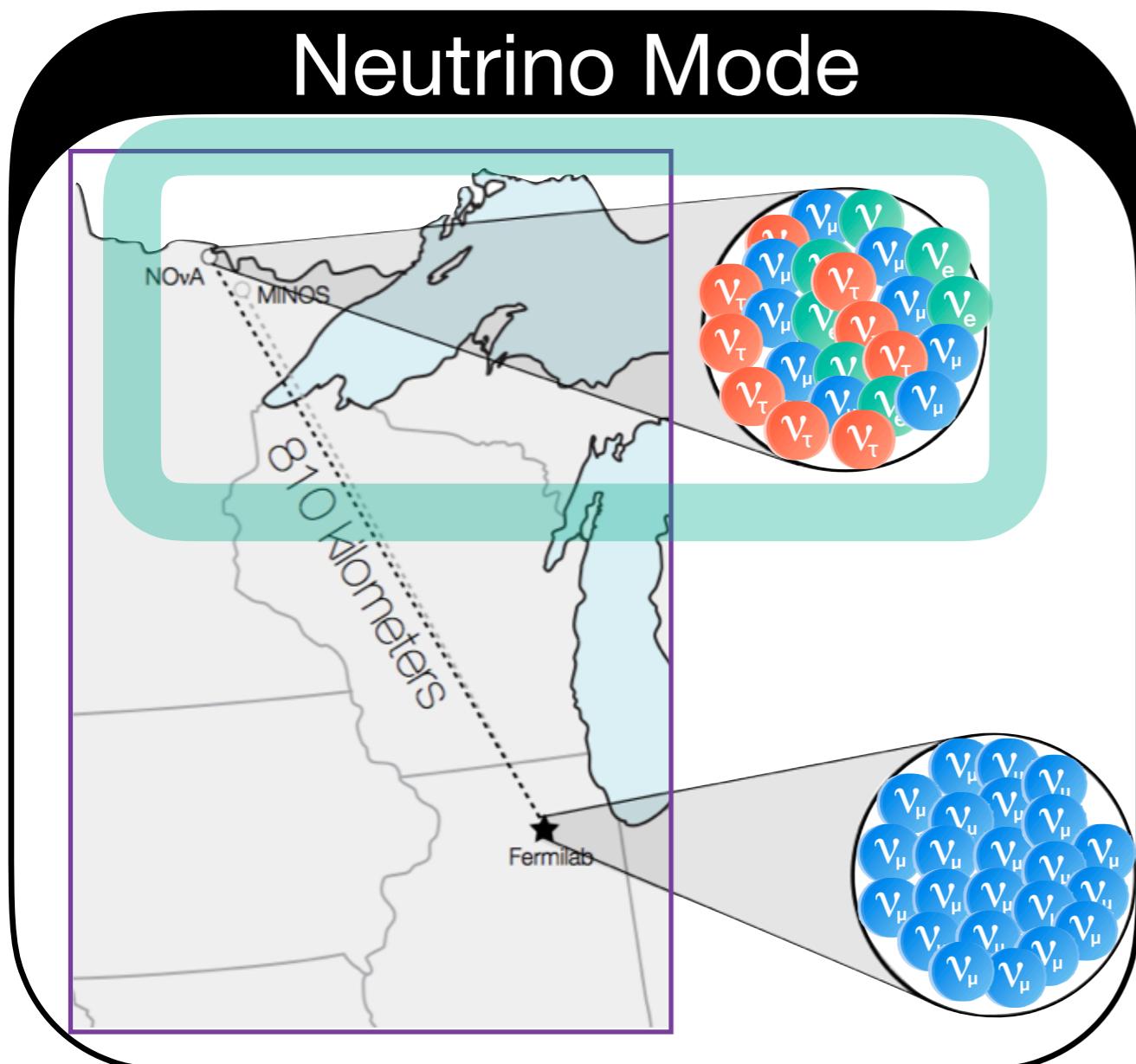
# How does NOvA Measure Oscillations?

## At the Far Detector:



# How does NOvA Measure Oscillations?

## At the Far Detector:





# A Small Aside...

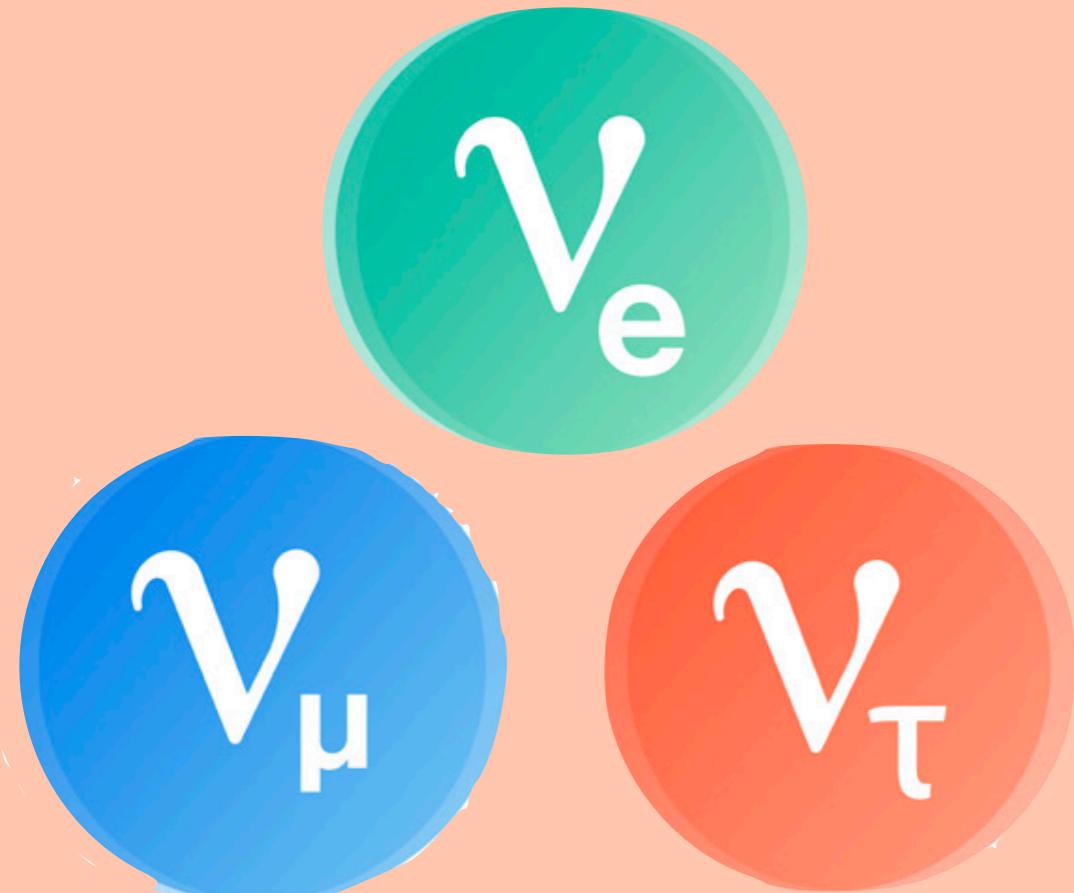


Matter

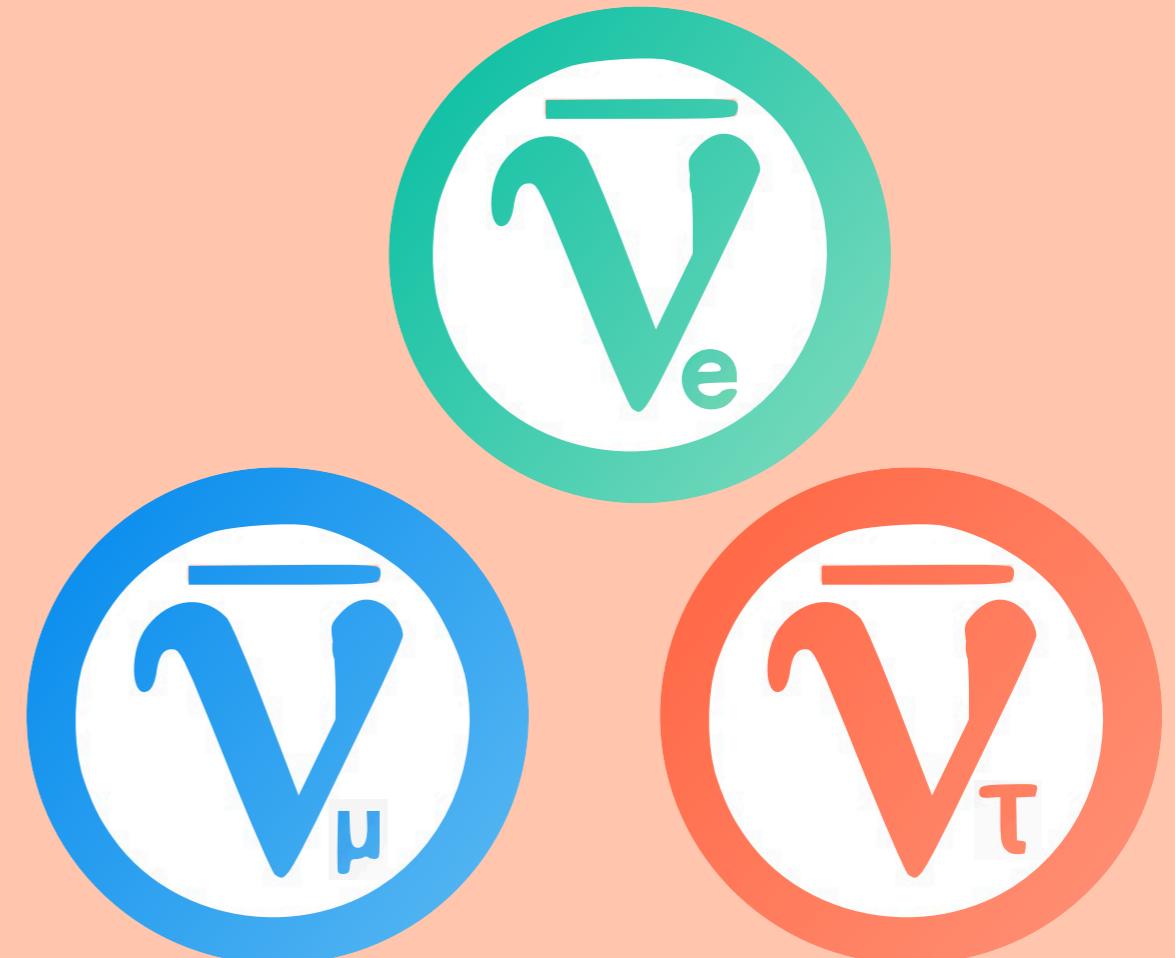


Antimatter

# A Small Aside



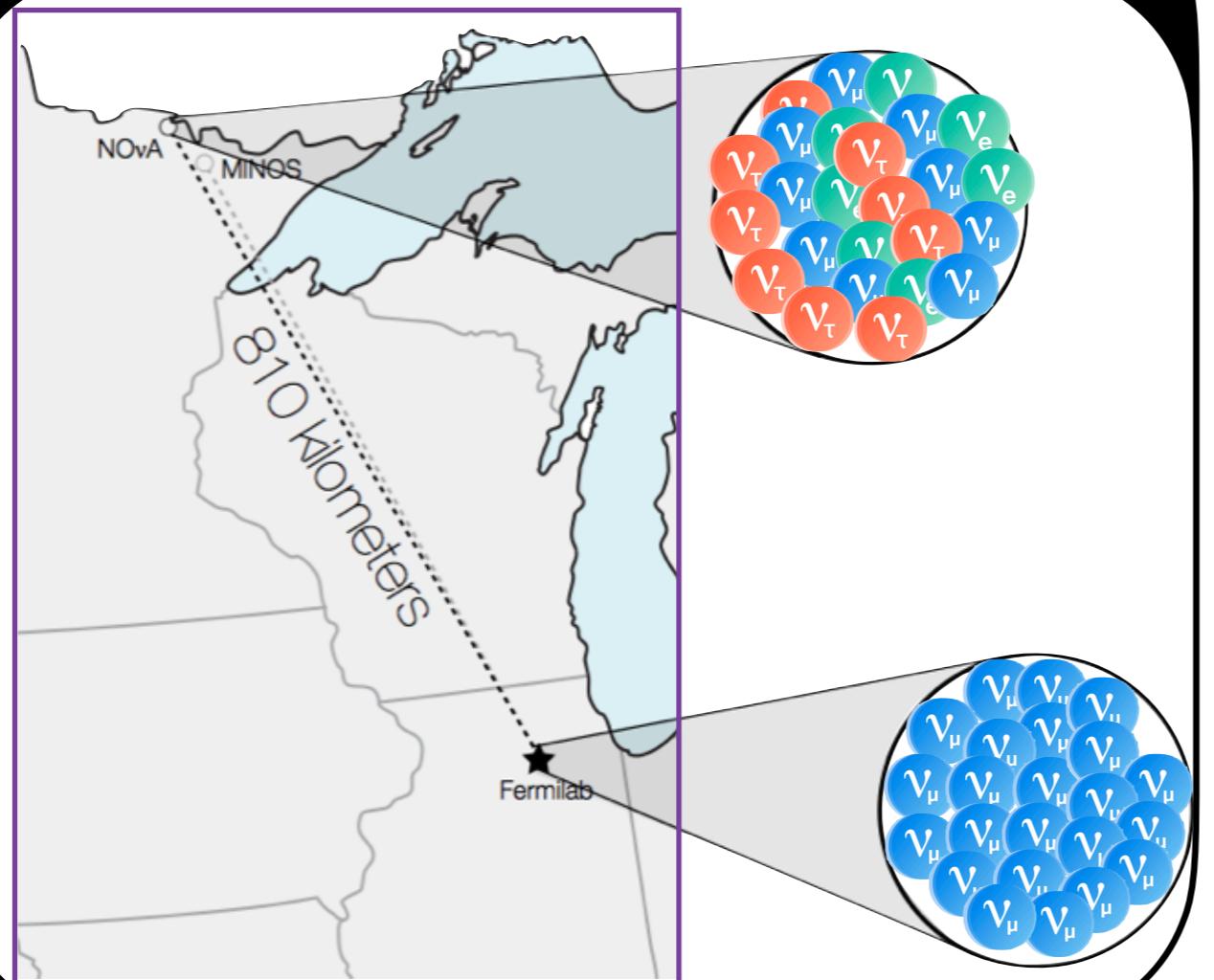
Neutrinos



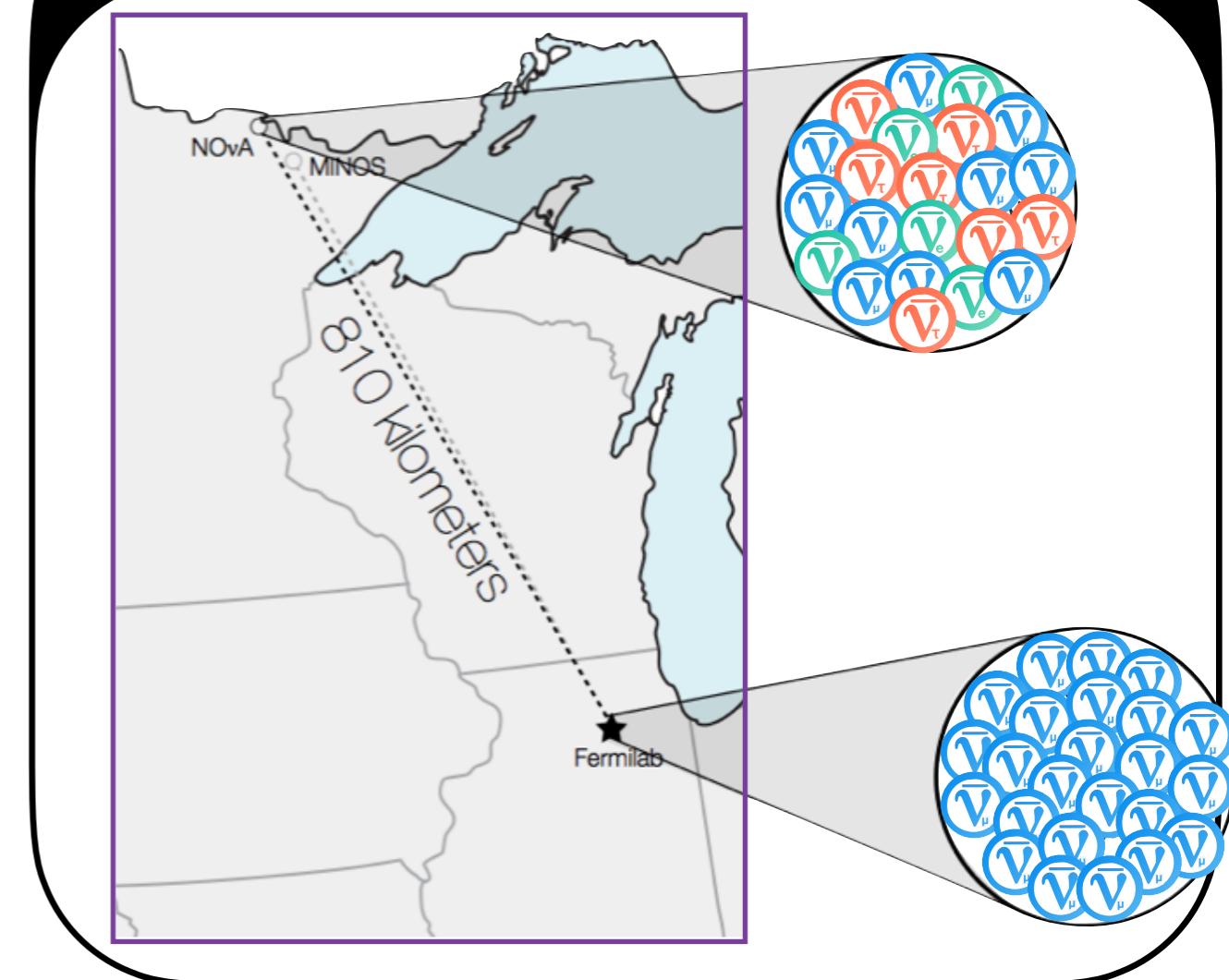
Antineutrinos

# How does NOvA Measure Oscillations?

## Neutrino Mode

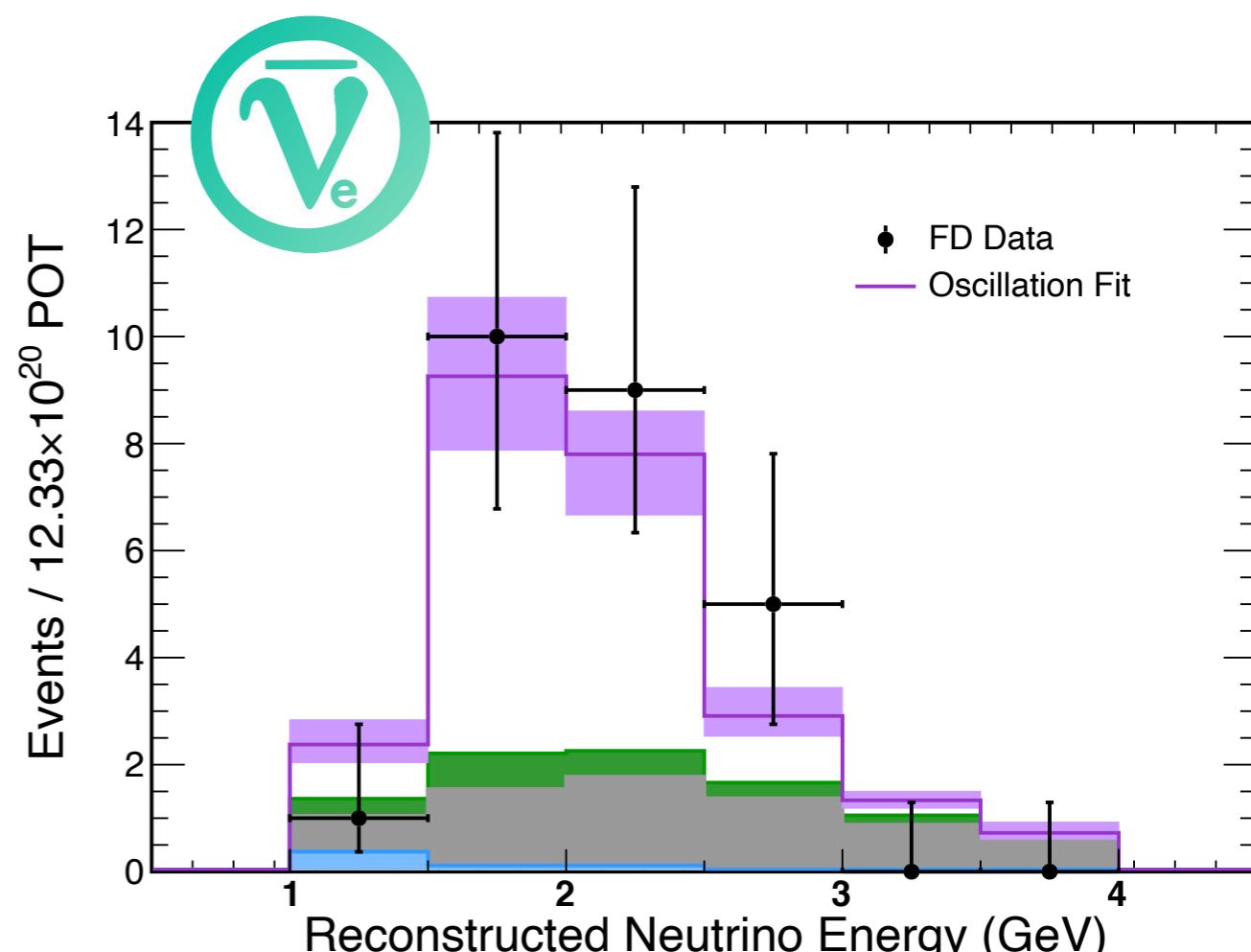
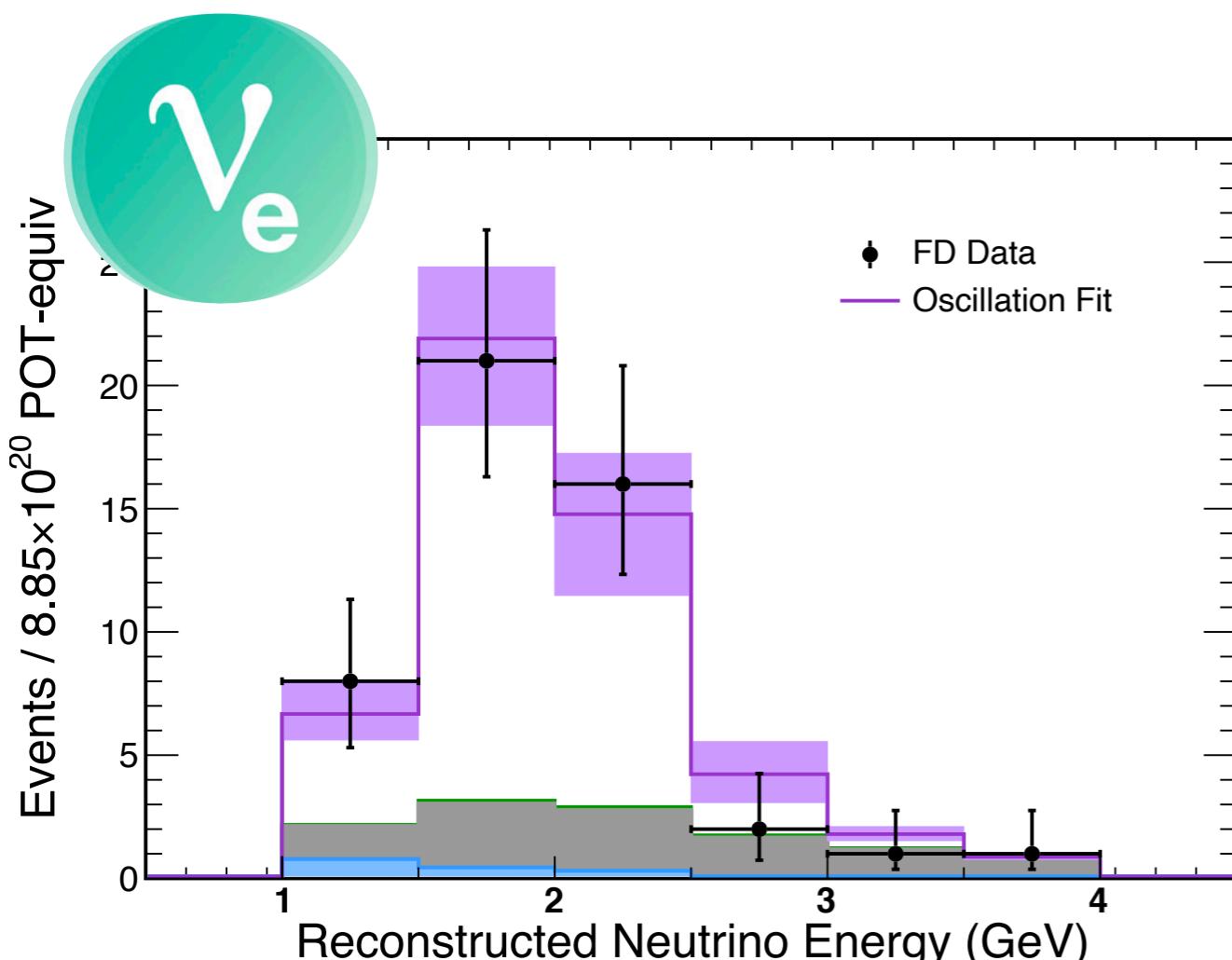


## Antineutrino Mode



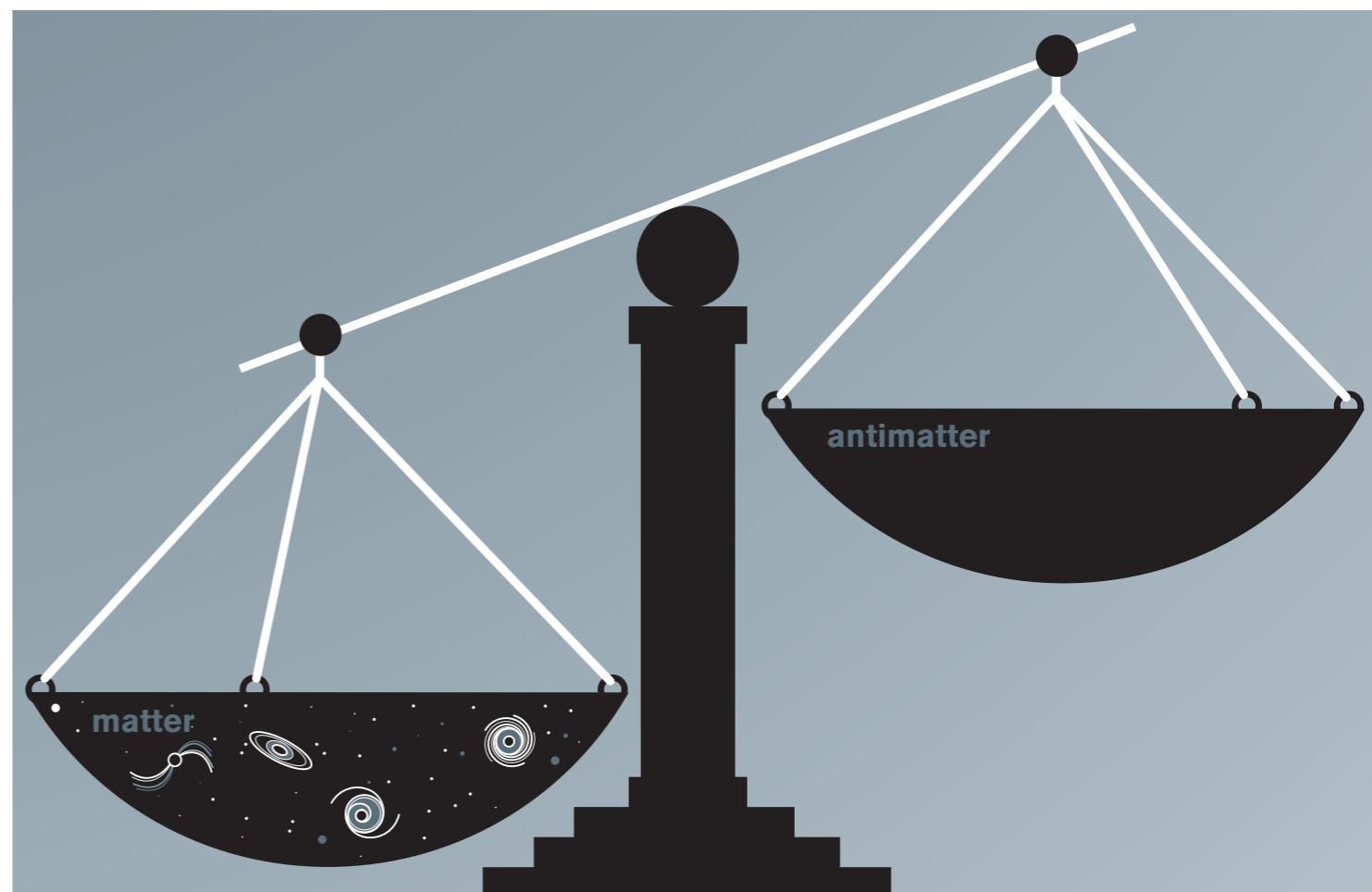
# How does NOvA Measure Oscillations?

## At the Far Detector:





# Why are we interested in whether or not neutrinos & antineutrinos oscillate differently?





The Universe began with the big bang - matter and antimatter created in equal quantities





# However...



13.8 billion  
years later...

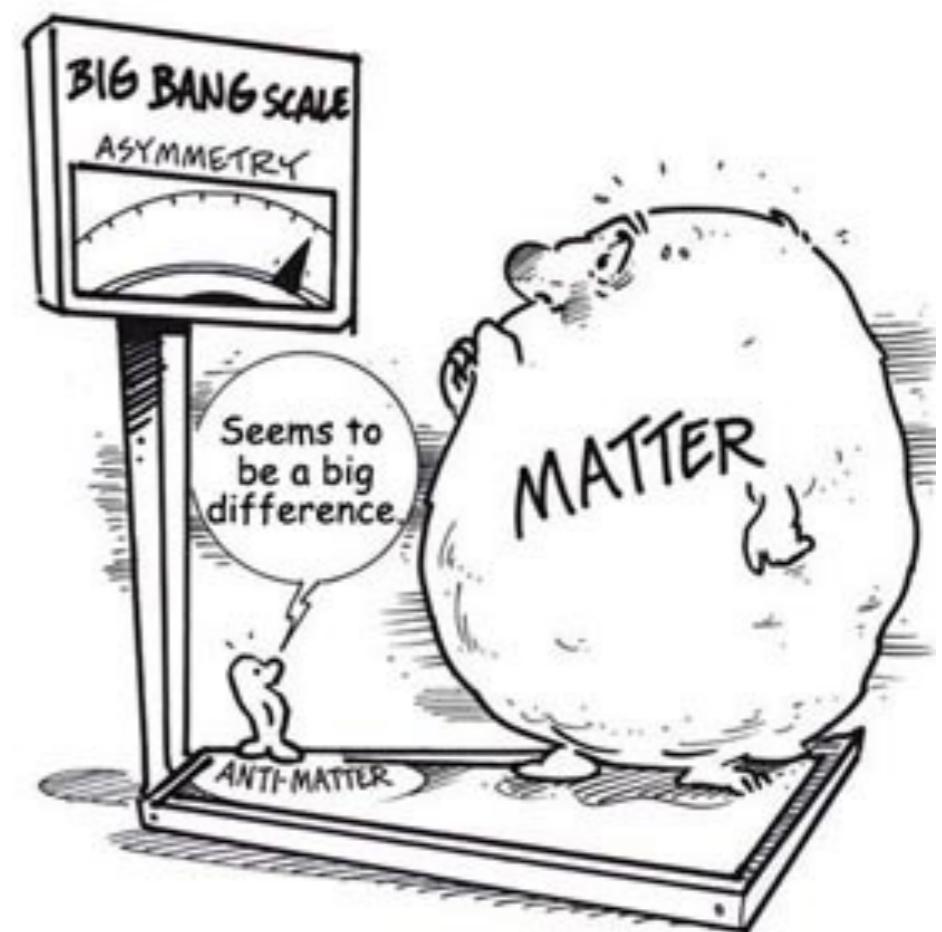




# Where did all of the antimatter go?



13.8 billion  
years later...

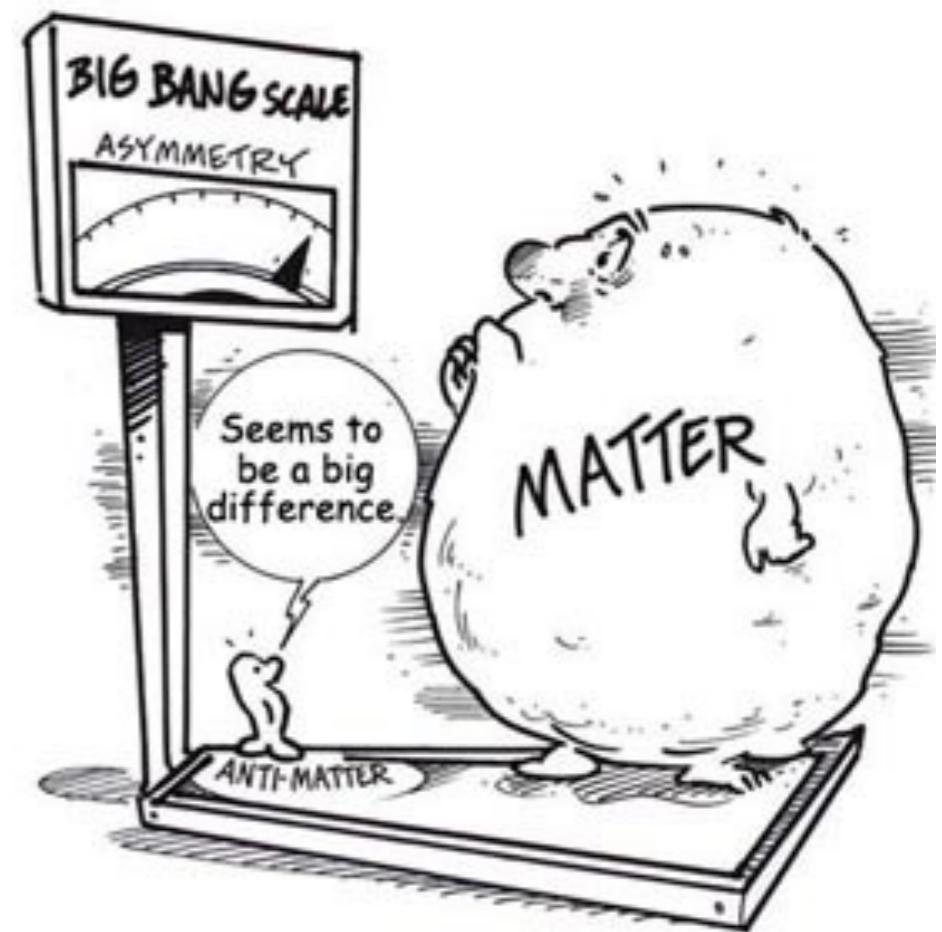




# Neutrinos could hold the answer!



13.8 billion  
years later...



# Other Open Questions & the Future...

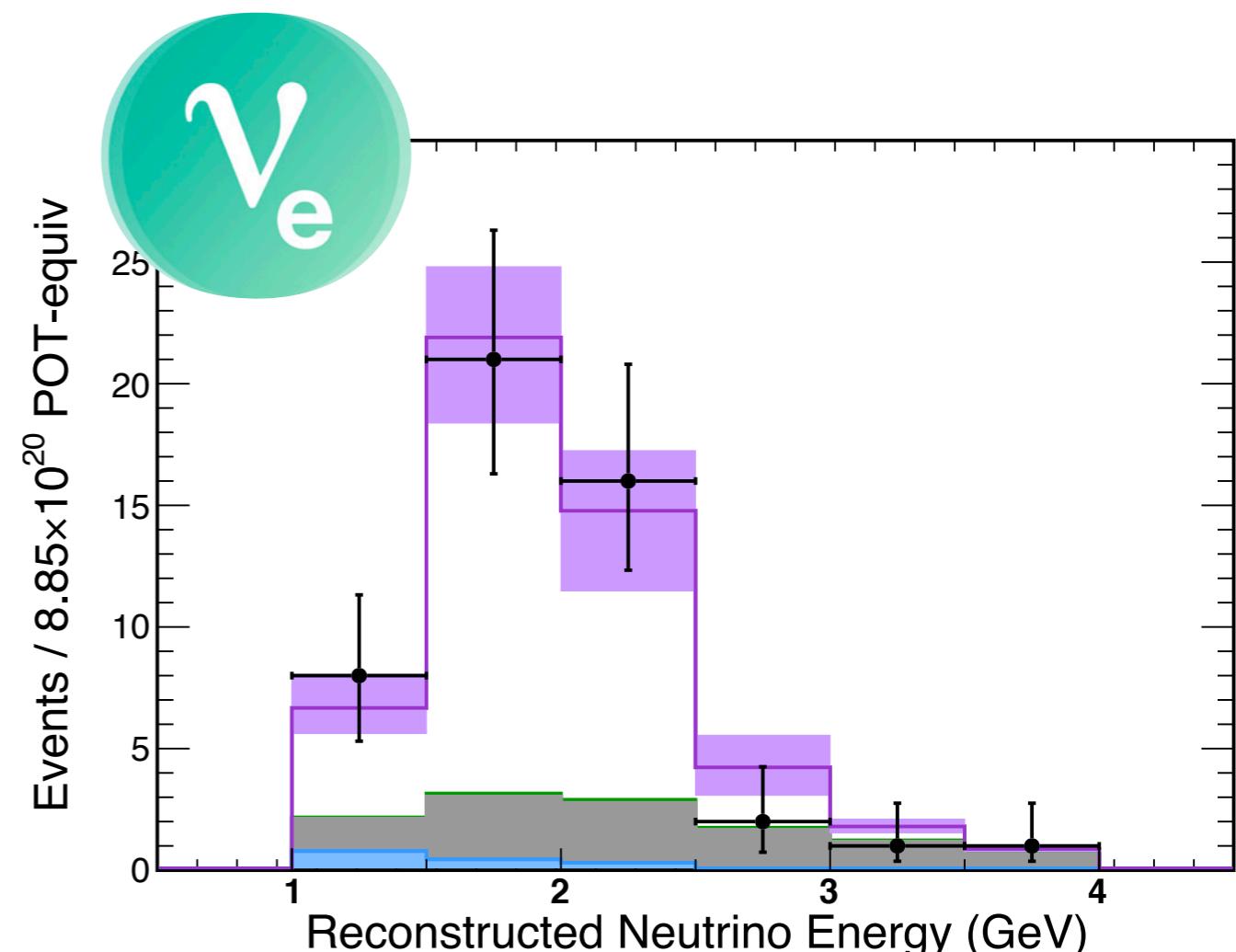
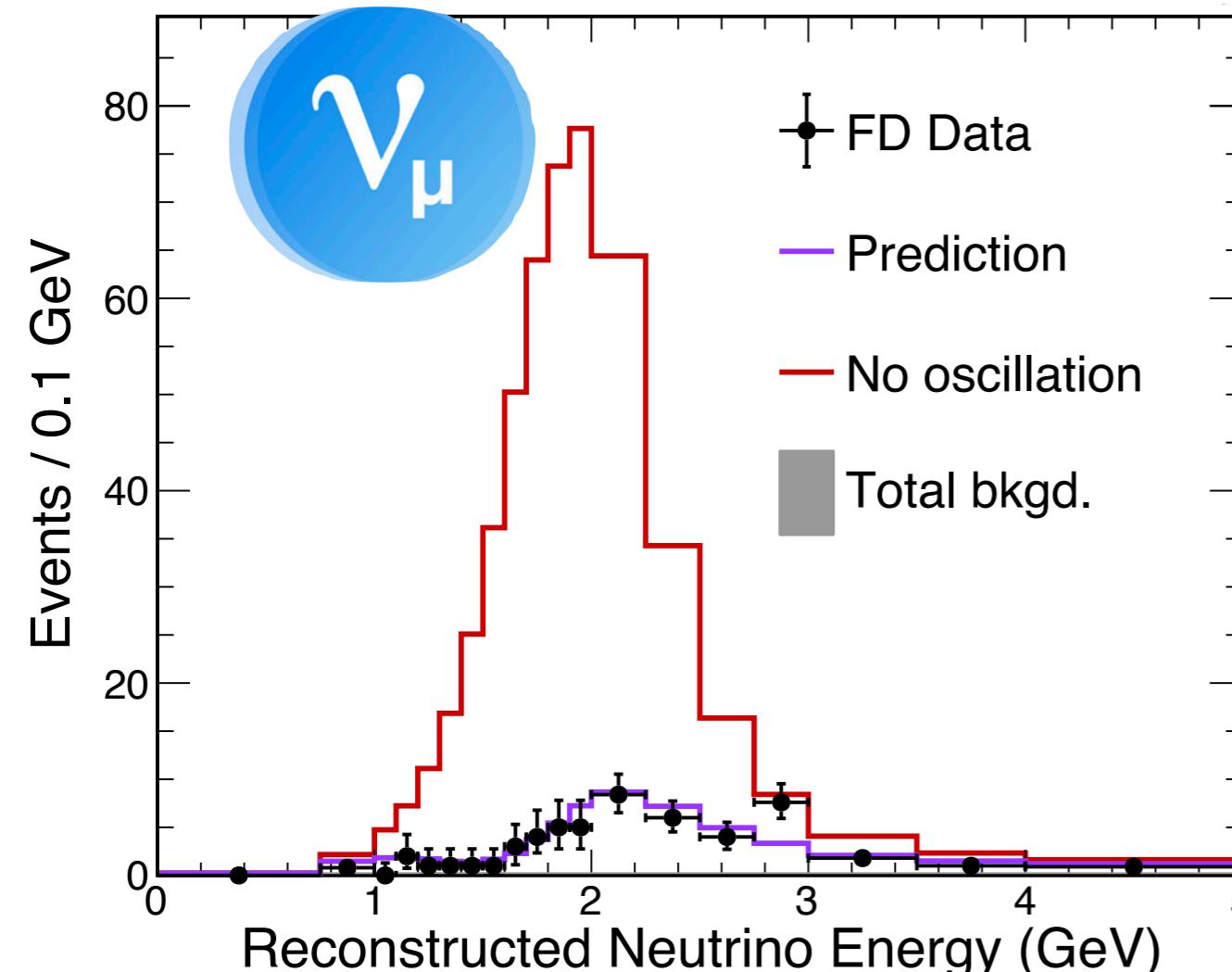


Is the neutrino **mass ordering normal** or **inverted**?

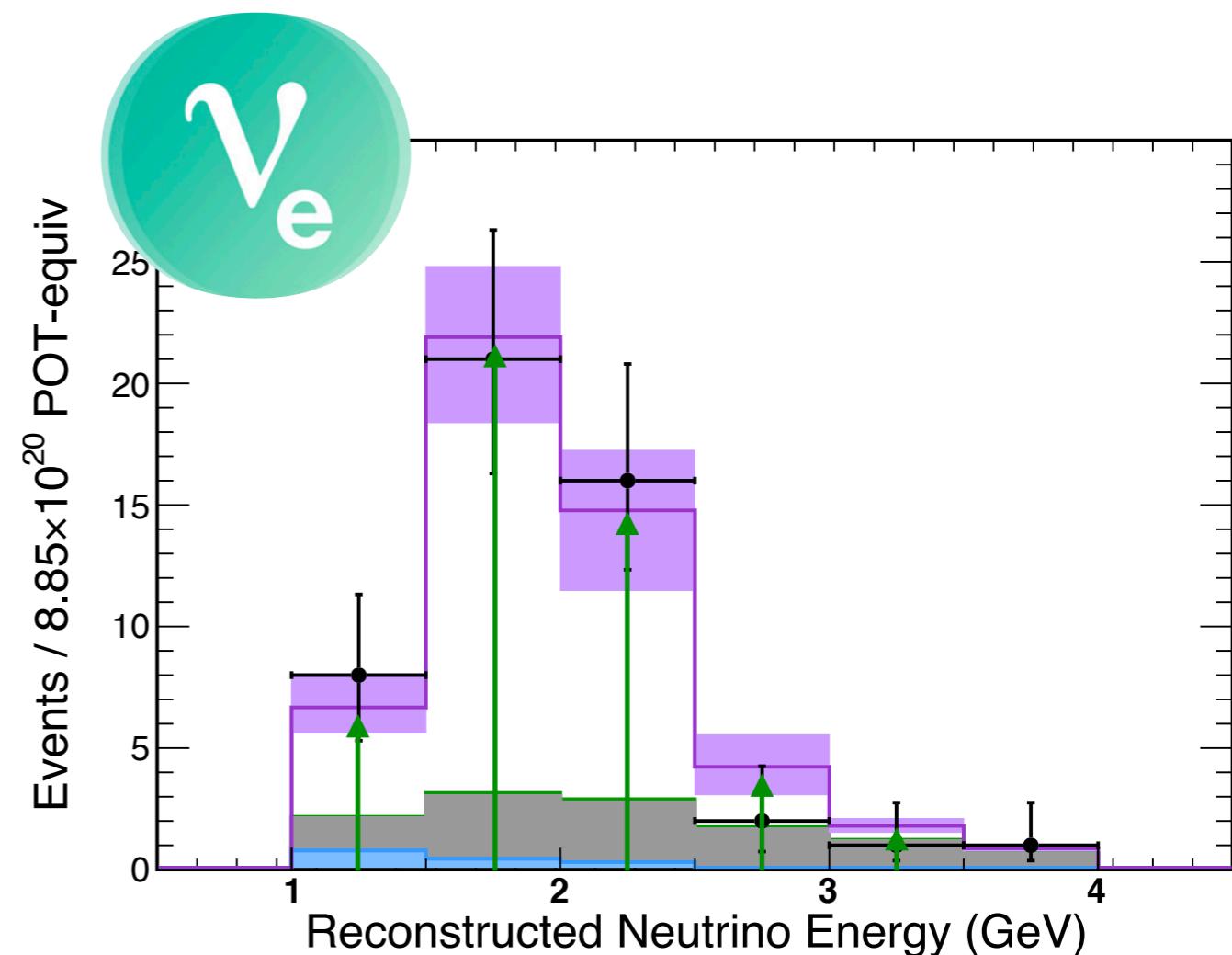
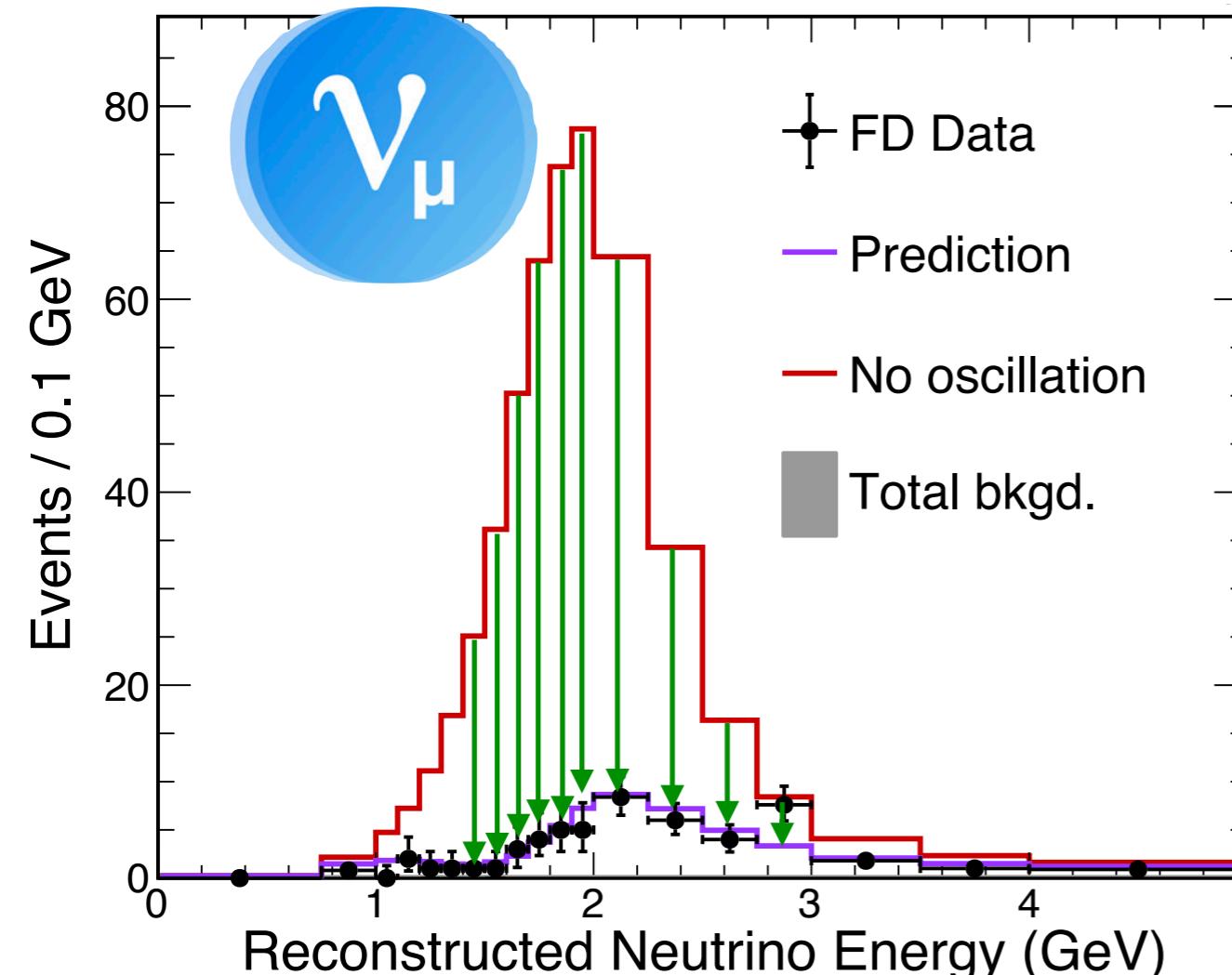
Is there an **exact symmetry** between  $\mu$  and  $\tau$  flavours?

**Next generation** long baseline experiments, like **DUNE**, will definitively answer these questions.

# Parametrising Neutrino Oscillations

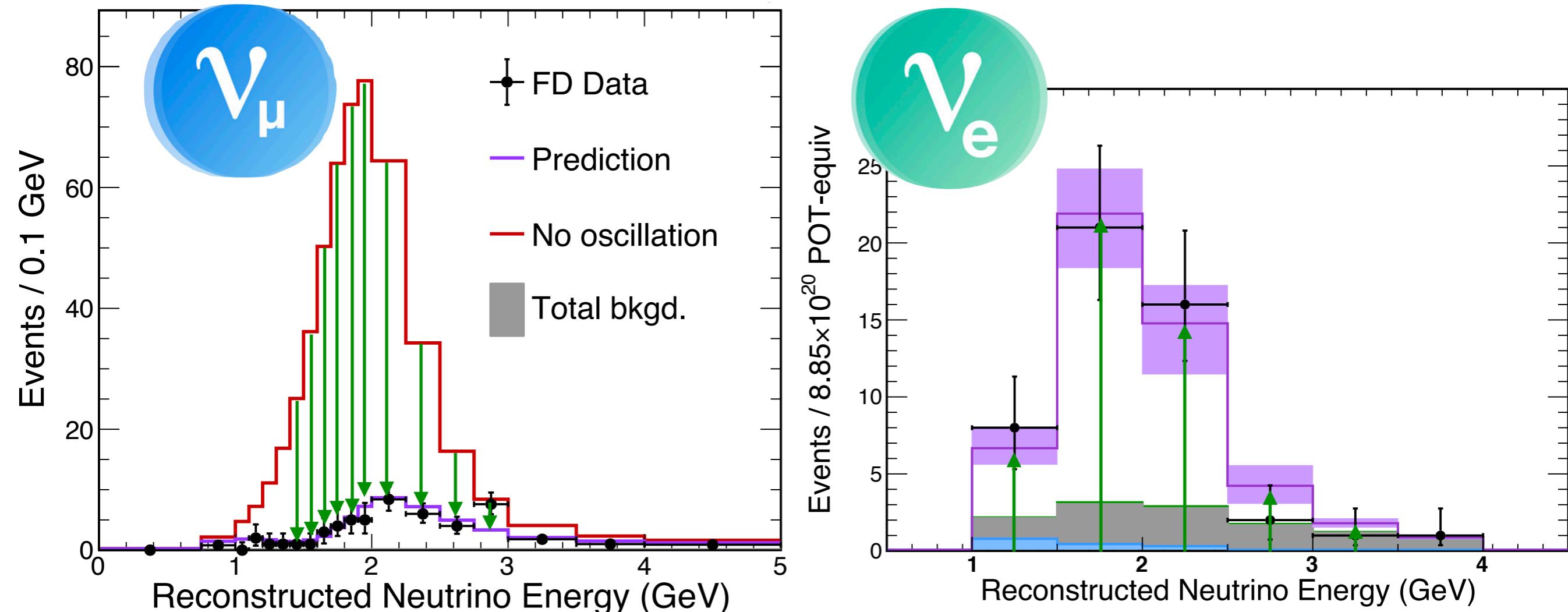


# Parametrising Neutrino Oscillations



$$P(\nu_\alpha \rightarrow \nu_\beta) \sim P(\theta_{23}, \theta_{13}, \delta, \theta_{12}, \Delta m_{21}^2, \Delta m_{32}^2, \Delta m_{31}^2)$$

# Parametrising Neutrino Oscillations

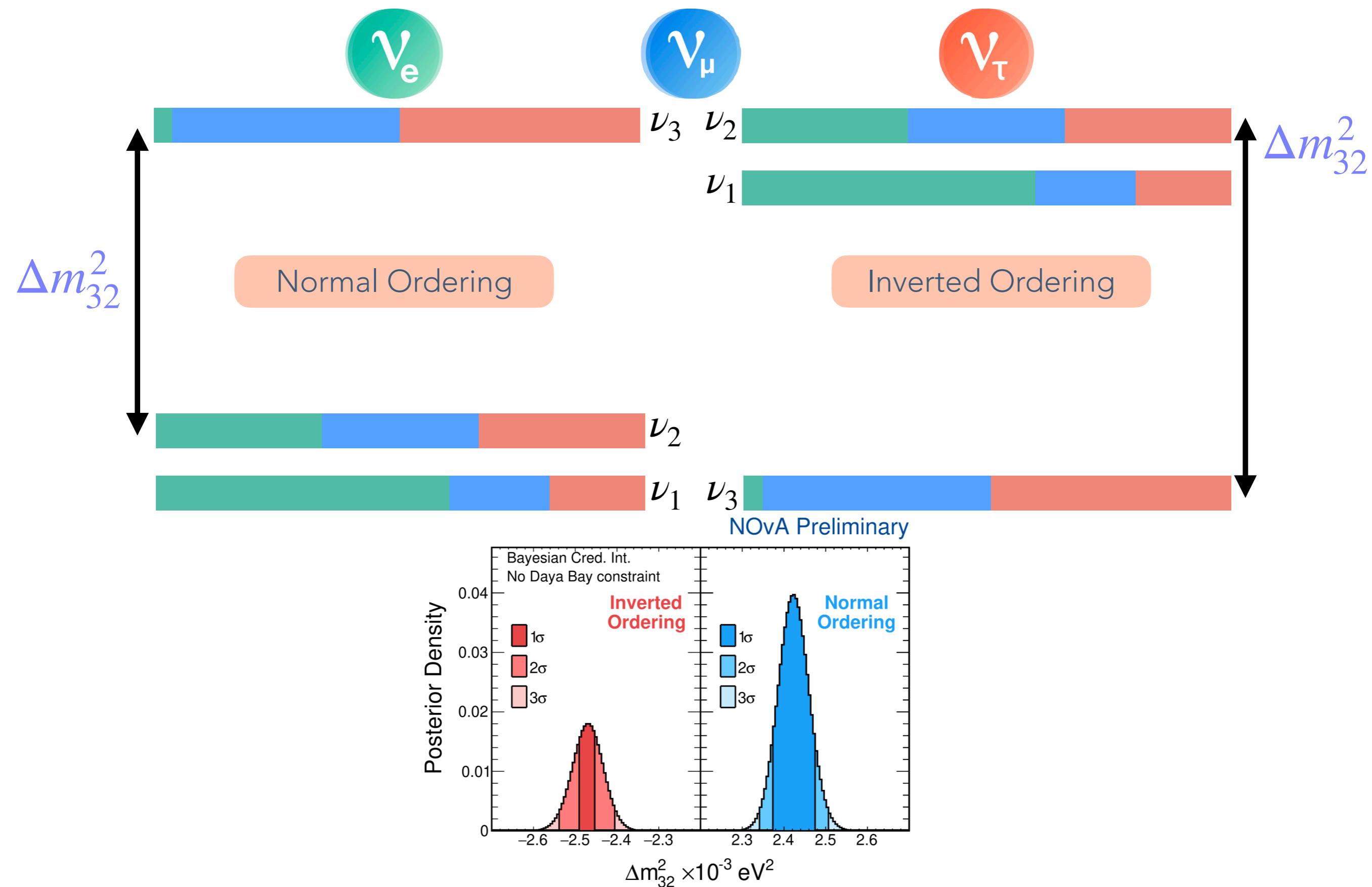


$$P(\nu_\alpha \rightarrow \nu_\beta) \sim P(\theta_{23}, \theta_{13}, \delta, \theta_{12}, \Delta m_{21}^2, \Delta m_{32}^2, \Delta m_{31}^2)$$

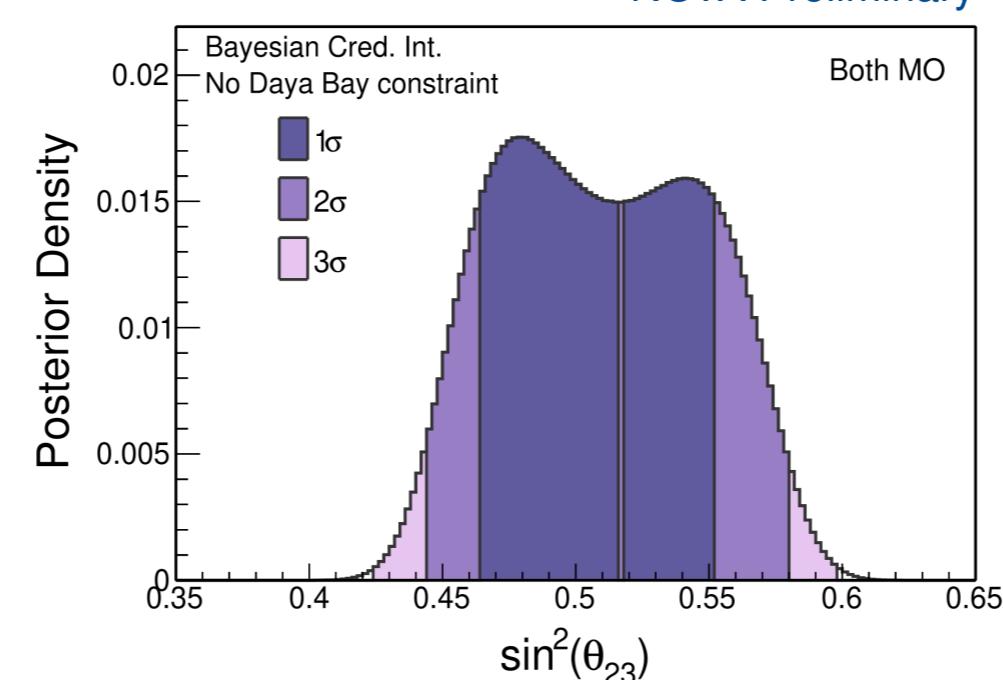
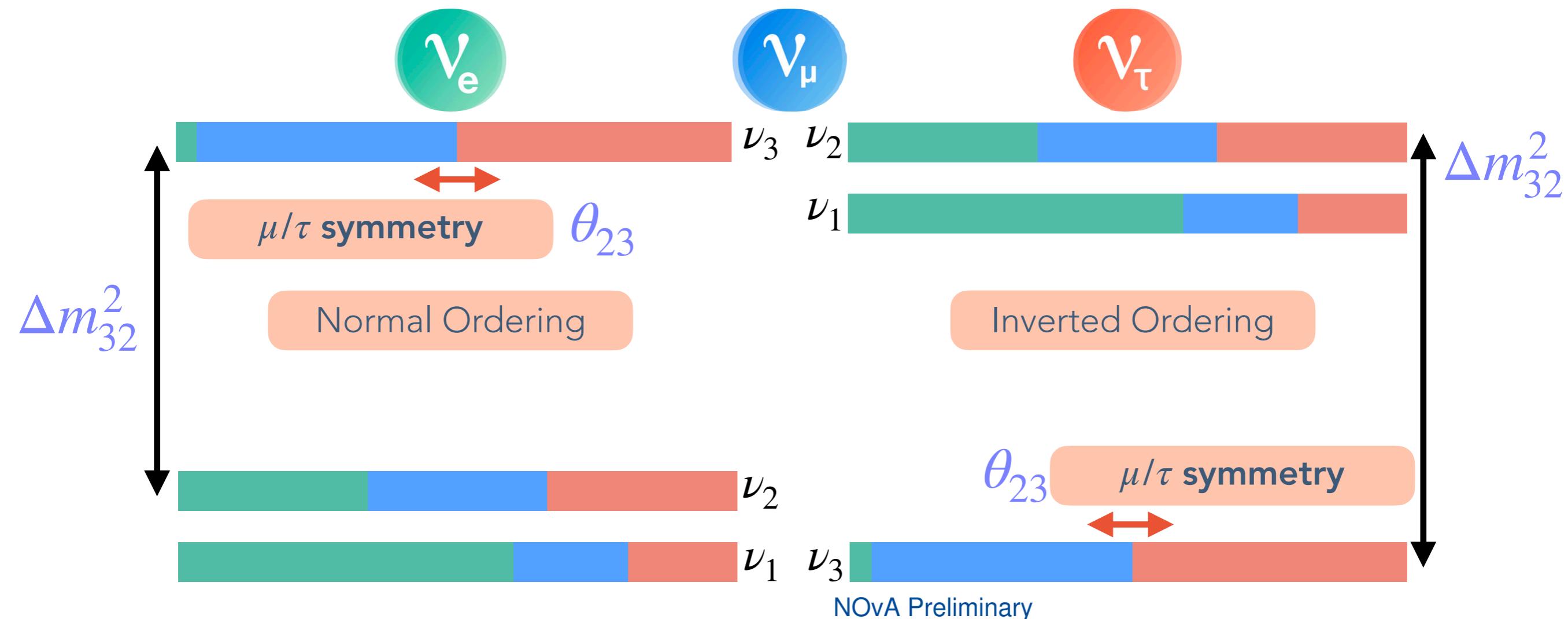
$\mu/\tau$  symmetry

Mass ordering

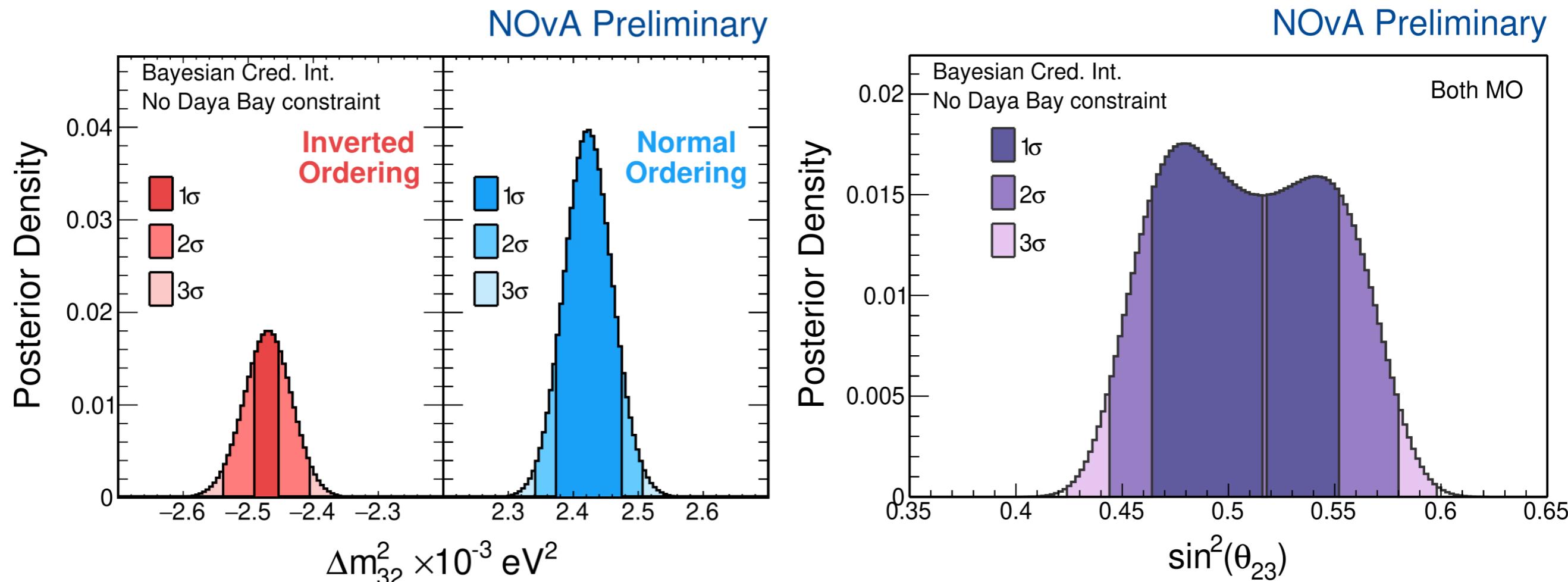
# Open Questions: Neutrino Mass Ordering



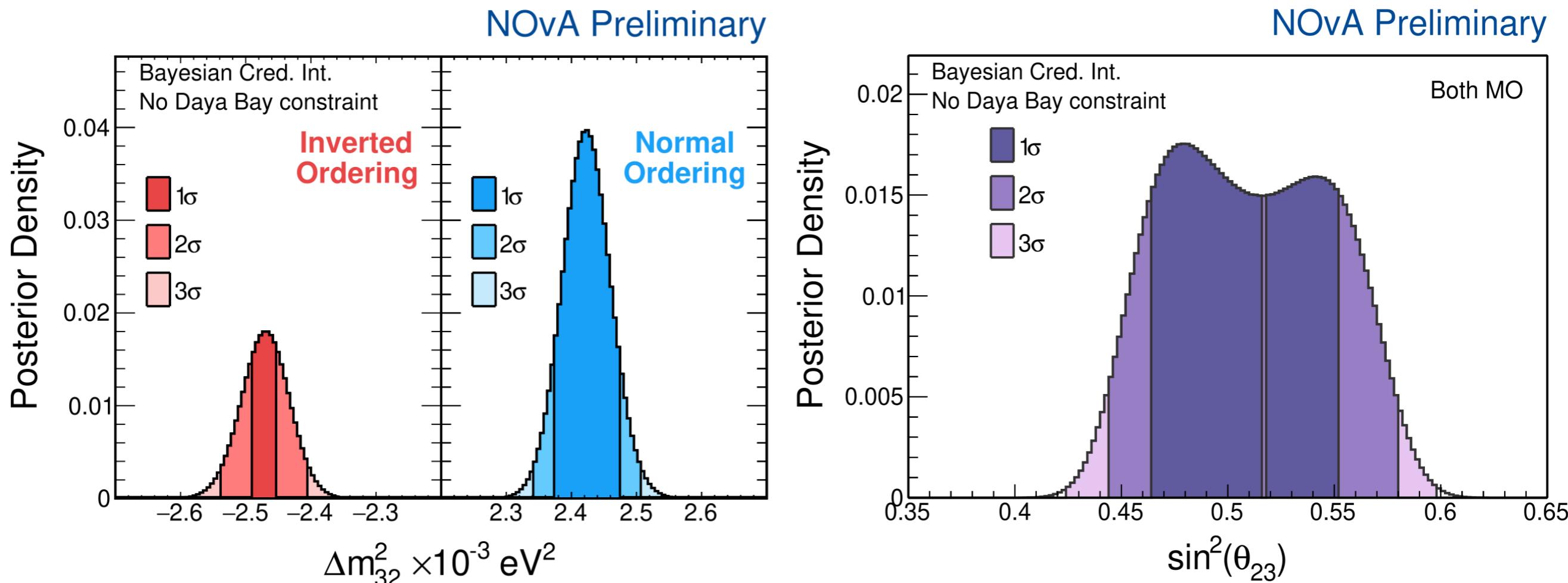
# Open Questions: $\mu/\tau$ Symmetry



# No Strong Constraints!



# How Can We Do Better?

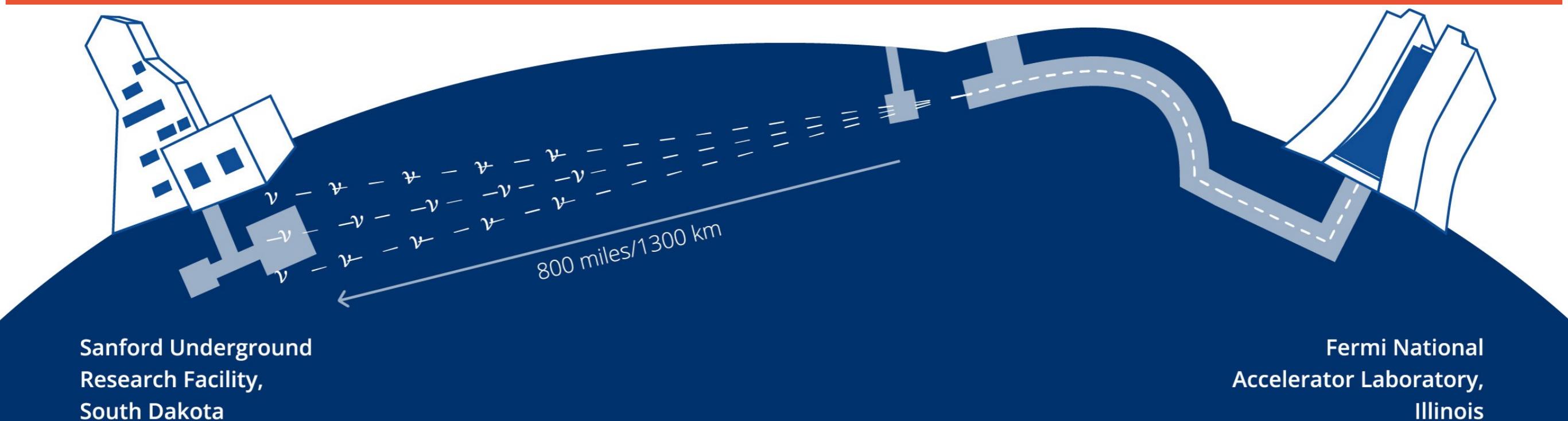


MORE NEUTRINOS

LARGER TARGET

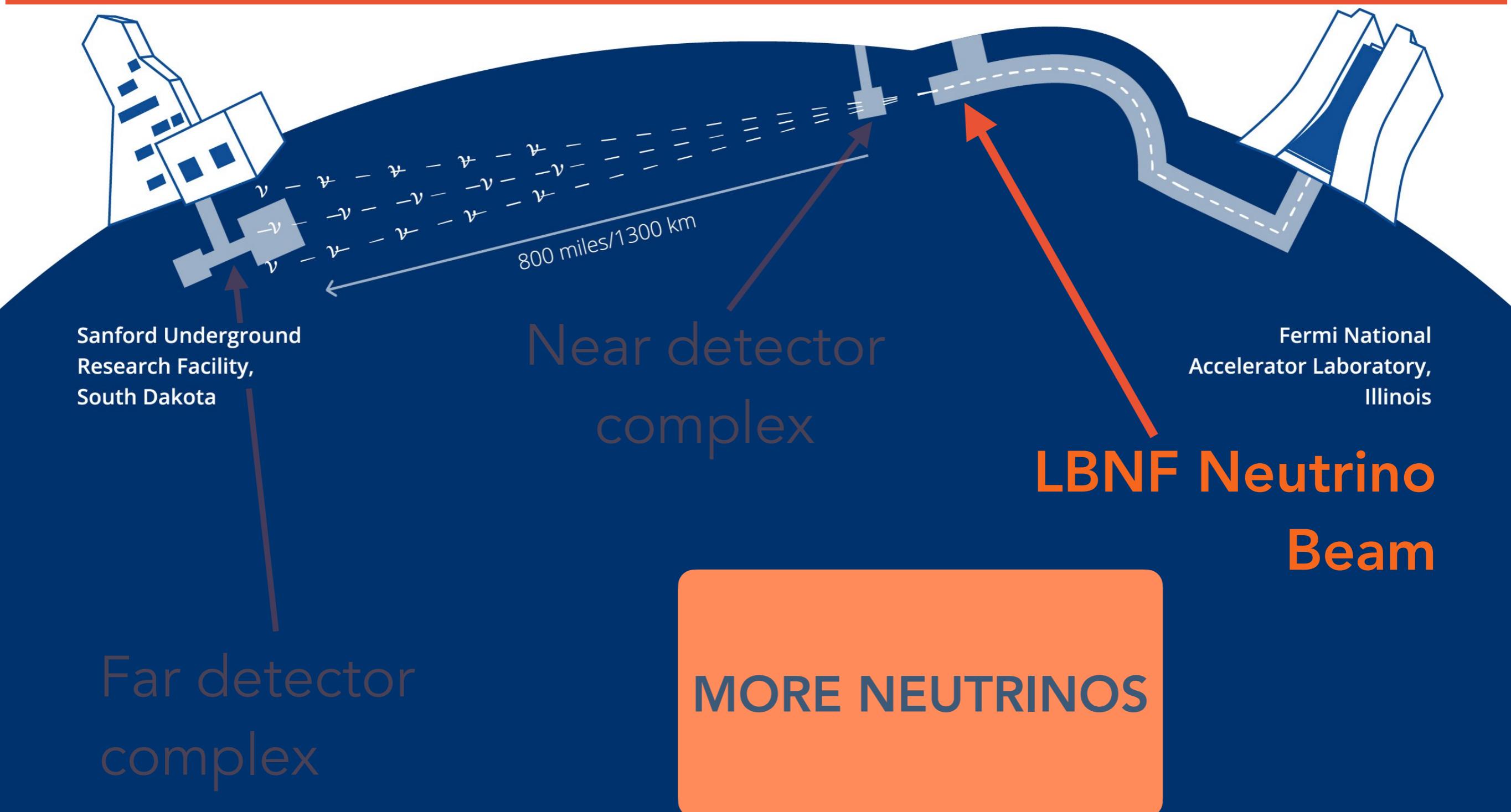
BETTER FLAVOUR  
IDENTIFICATION

# The Next Generation

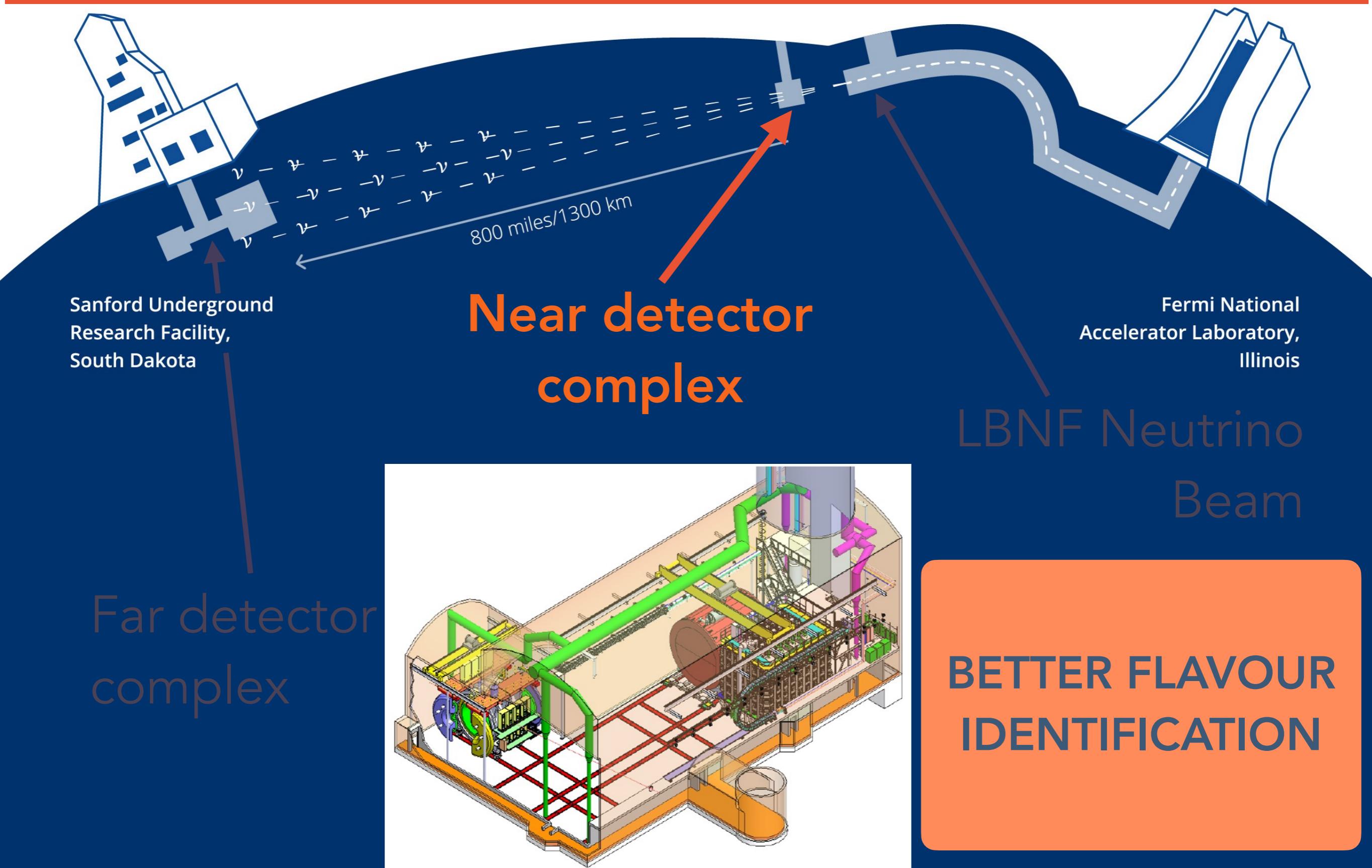


DEEP UNDERGROUND NEUTRINO EXPERIMENT

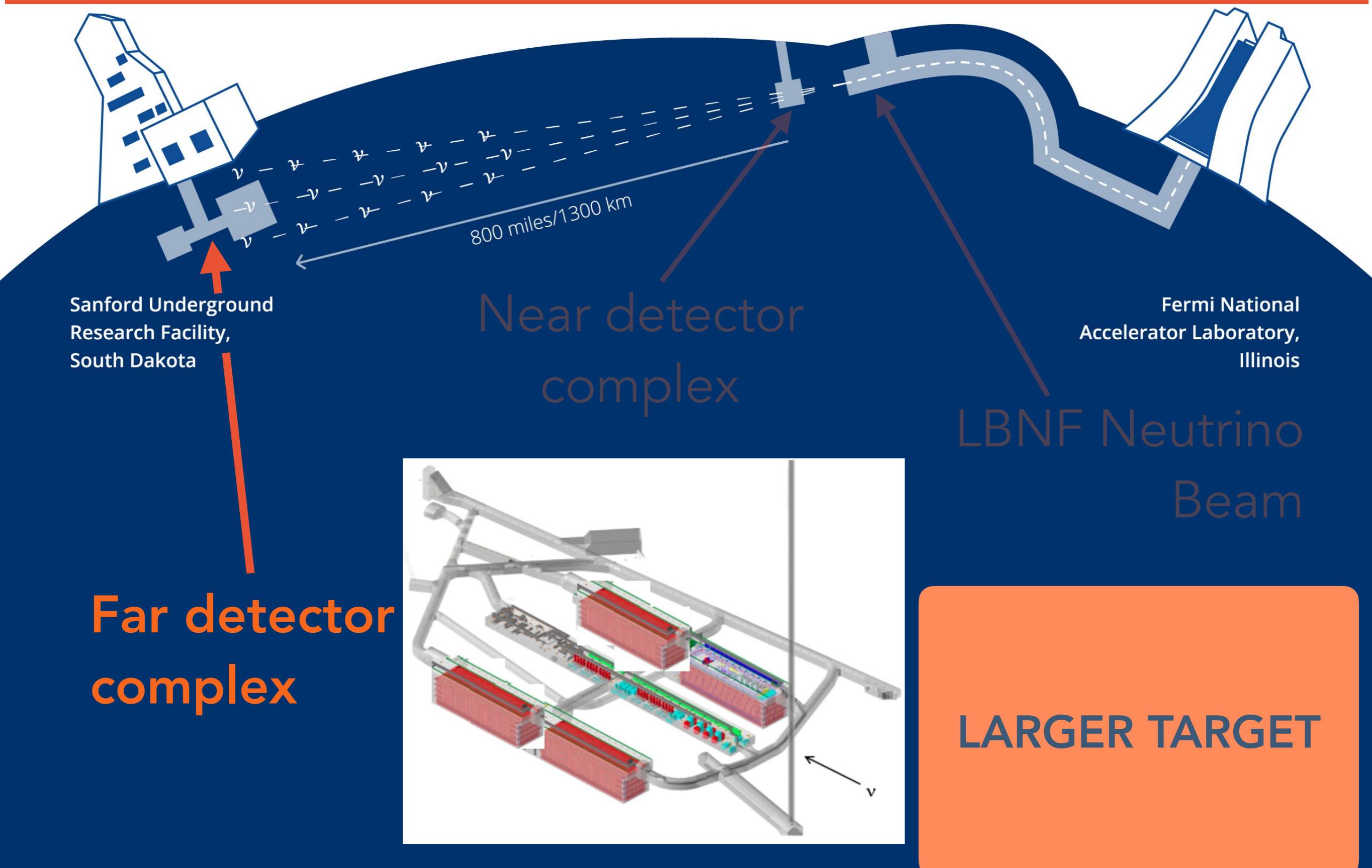
# The Next Generation



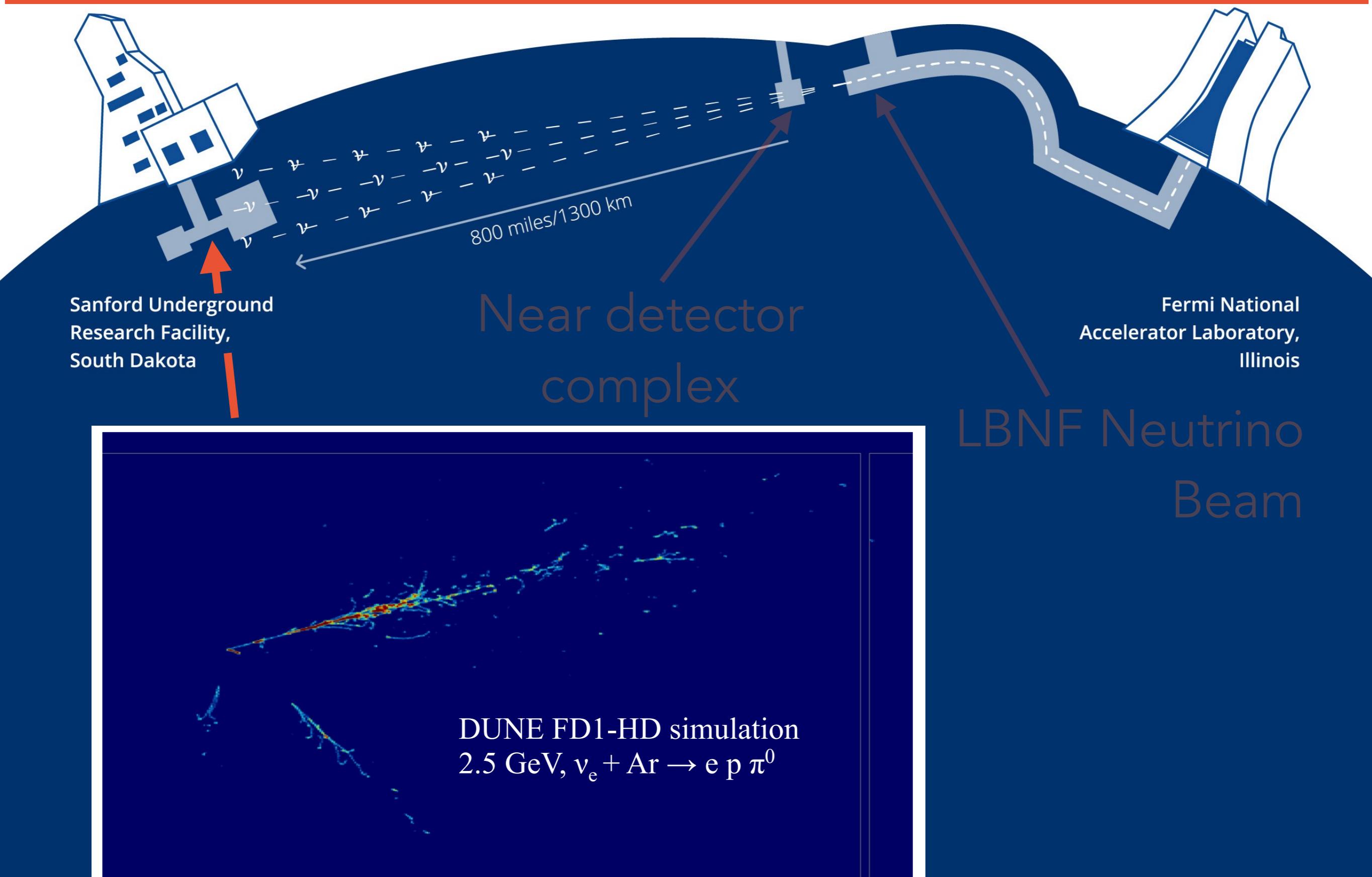
# The Next Generation



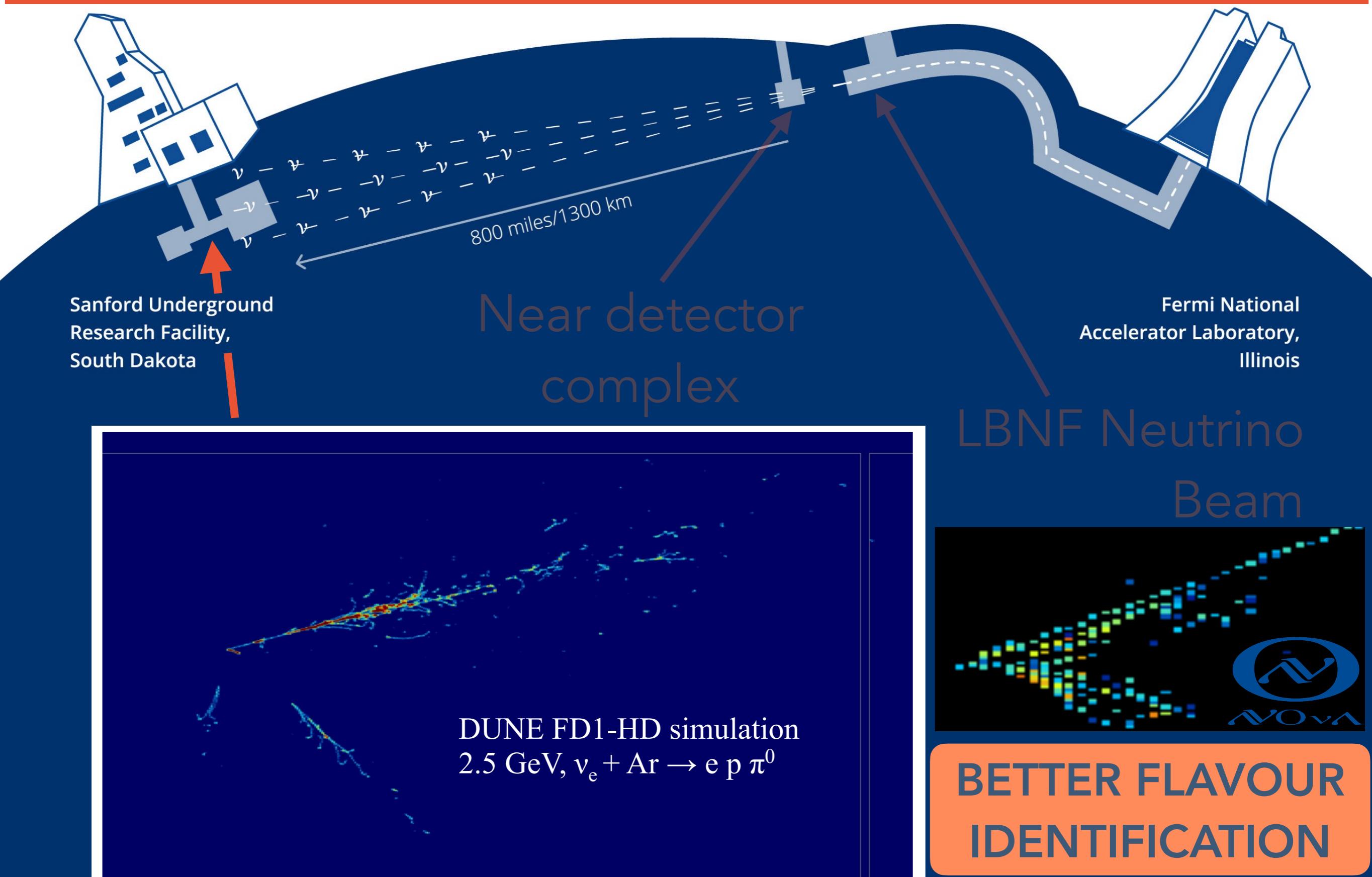
# The Next Generation



# The Next Generation



# The Next Generation



# Things to Remember About Neutrinos...

**Lightweight** but very important for the **evolution of the Universe!**

They are **everywhere** but are really **really difficult to detect.**

**NOvA** can use **neutrino oscillations** to help discover whether neutrinos are behind the **matter / antimatter asymmetry** in the Universe.

The **next generation** of long baseline experiments will study **neutrino oscillations** in **unprecedented detail**, answering some of the **most important** questions in physics.



# QUESTIONS?

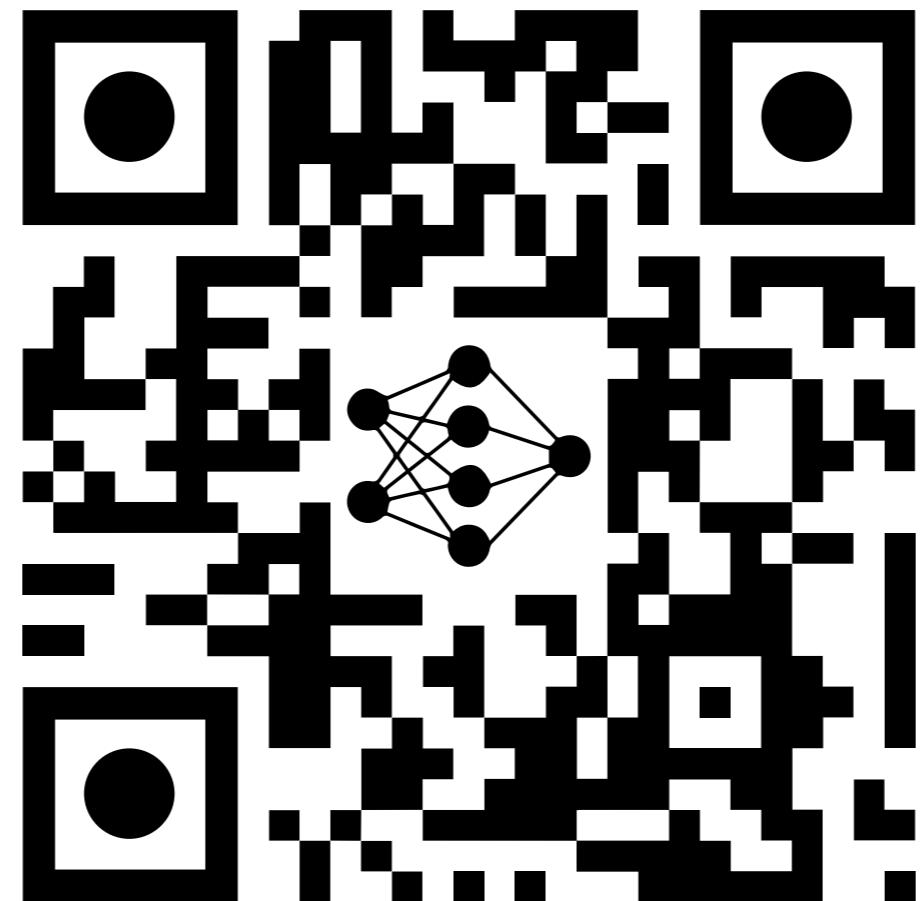


Queen Mary  
University of London

$\nu$   
NEUTRINO



# Can you distinguish between muon neutrinos and electron neutrinos?



**<https://nusoft.fnal.gov/nova/public/nova-events/nova-events/>**