

Neutrinos, The Universe, and CP Violation

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago



Andrew T. Mastbaum

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Agenda

March 31	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
April 7	Lost and Found: Solar Neutrinos and Oscillations
April 14	Supernova Neutrinos: Neutrinos From the Beyond the Solar System
April 21	Neutrinos in Cosmology (Dr. Marco Raveri, KICP)
April 28	Gone Fission!: Neutrinos at Nuclear Reactors
May 5	The Small Things: Neutrino Mass and Neutrinoless Double-Beta Decay
May 12	How Many Neutrinos Are There? Sterile Neutrinos
May 19	Neutrinos, the Universe, and CP Violation
May 26	<i>No lecture</i> ← !
June 2	Where We Are/Where We're Going: Open Questions and Future Prospects



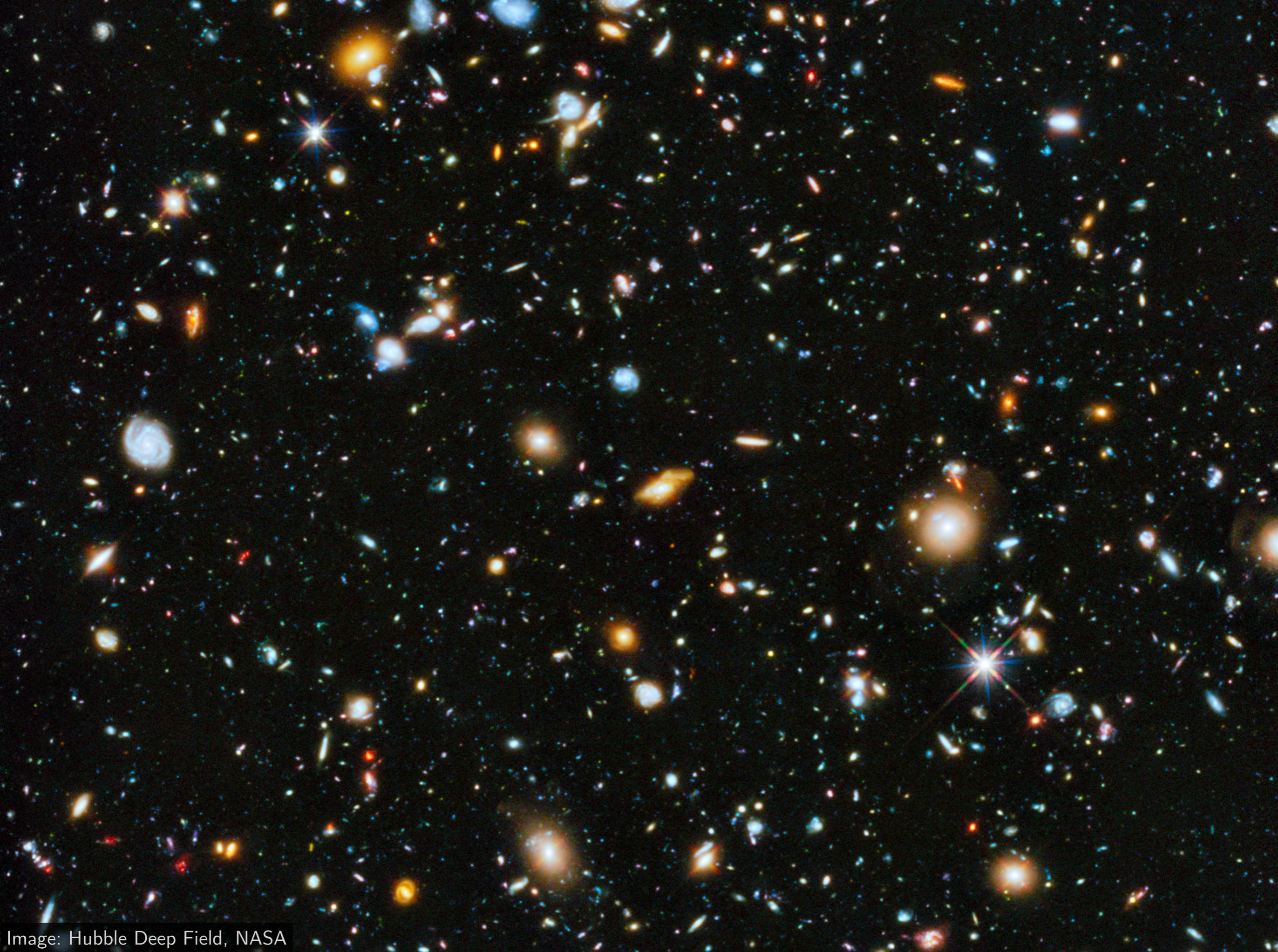
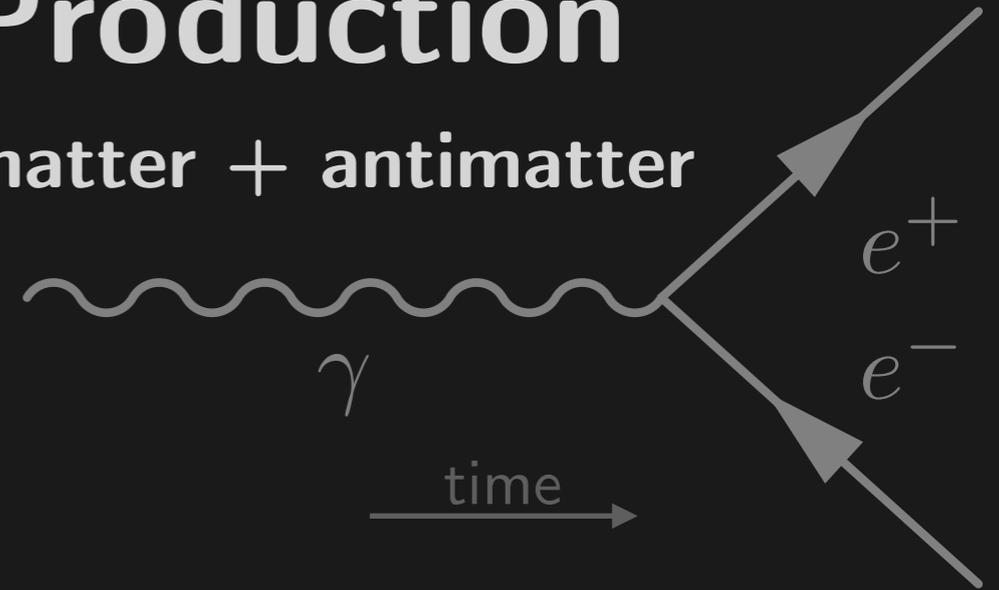


Image: Hubble Deep Field, NASA

$$E = mc^2$$

Pair Production

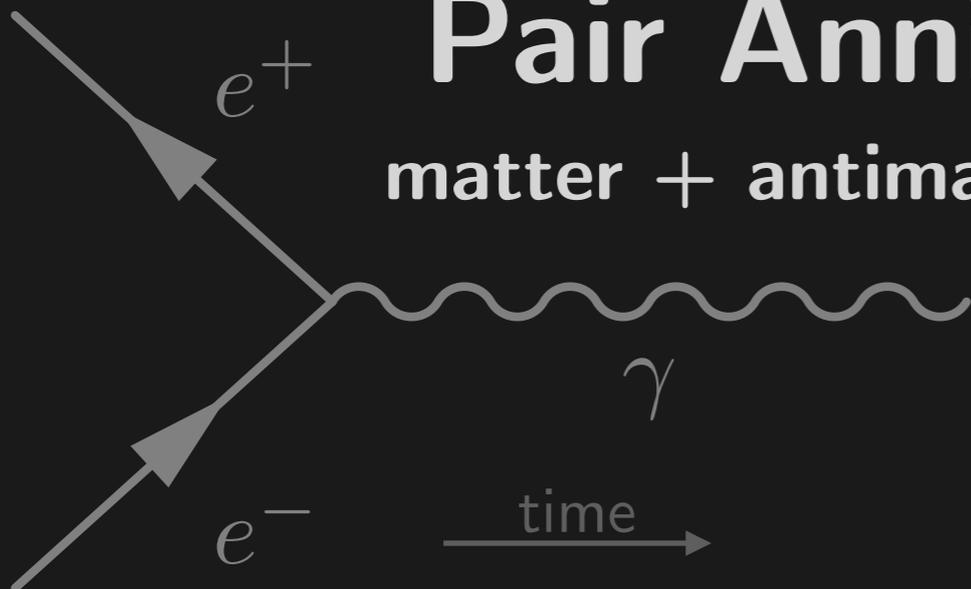
energy \rightarrow matter + antimatter



$$E = mc^2$$

Pair Annihilation

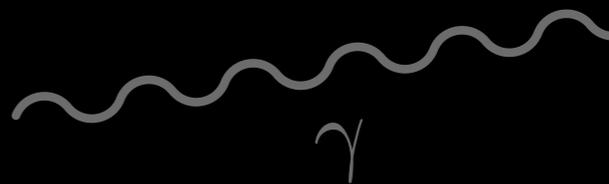
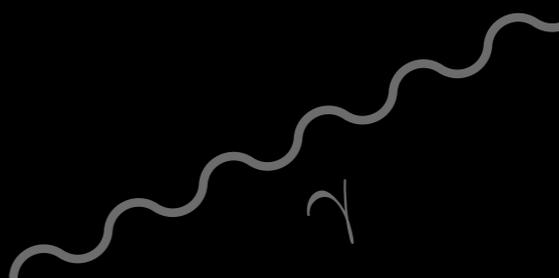
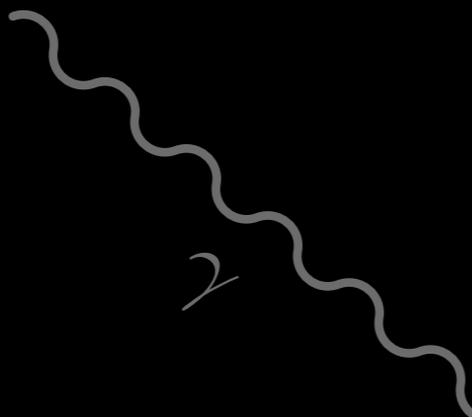
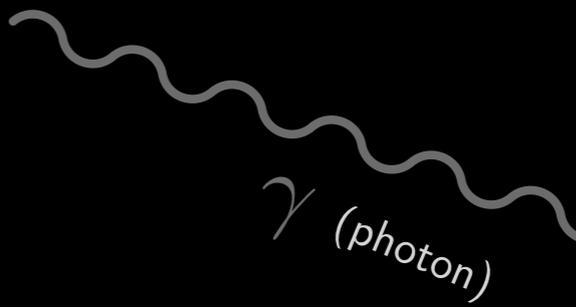
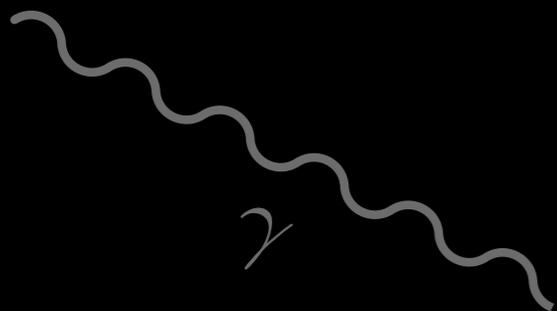
matter + antimatter \rightarrow energy



MATTER

+

ANTIMATTER



MATTER

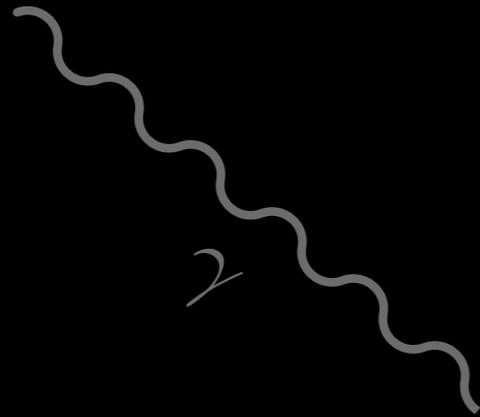
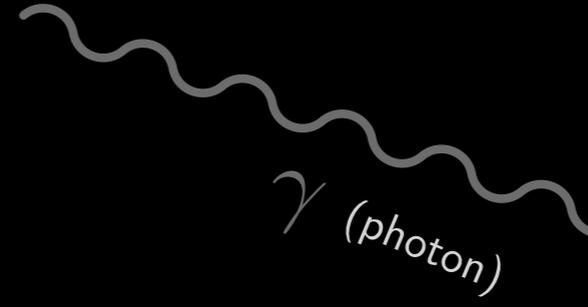
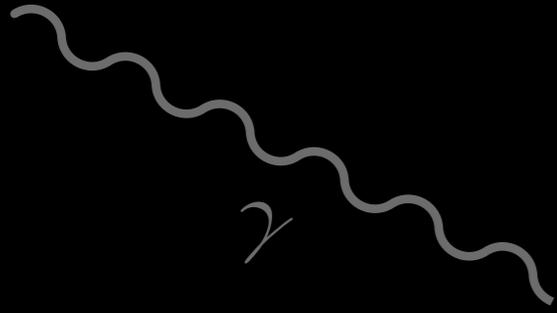
+

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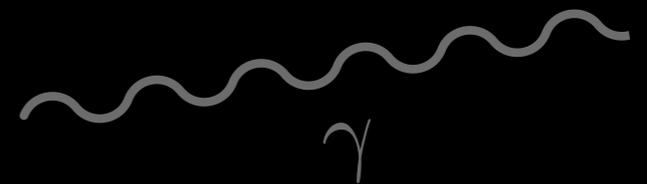
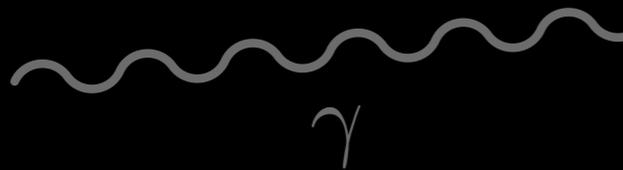
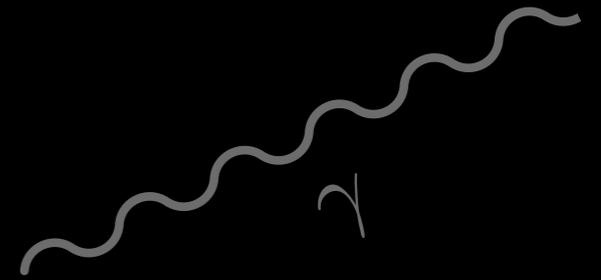
MATTER

+

ANTIMATTER




matter
(baryons)



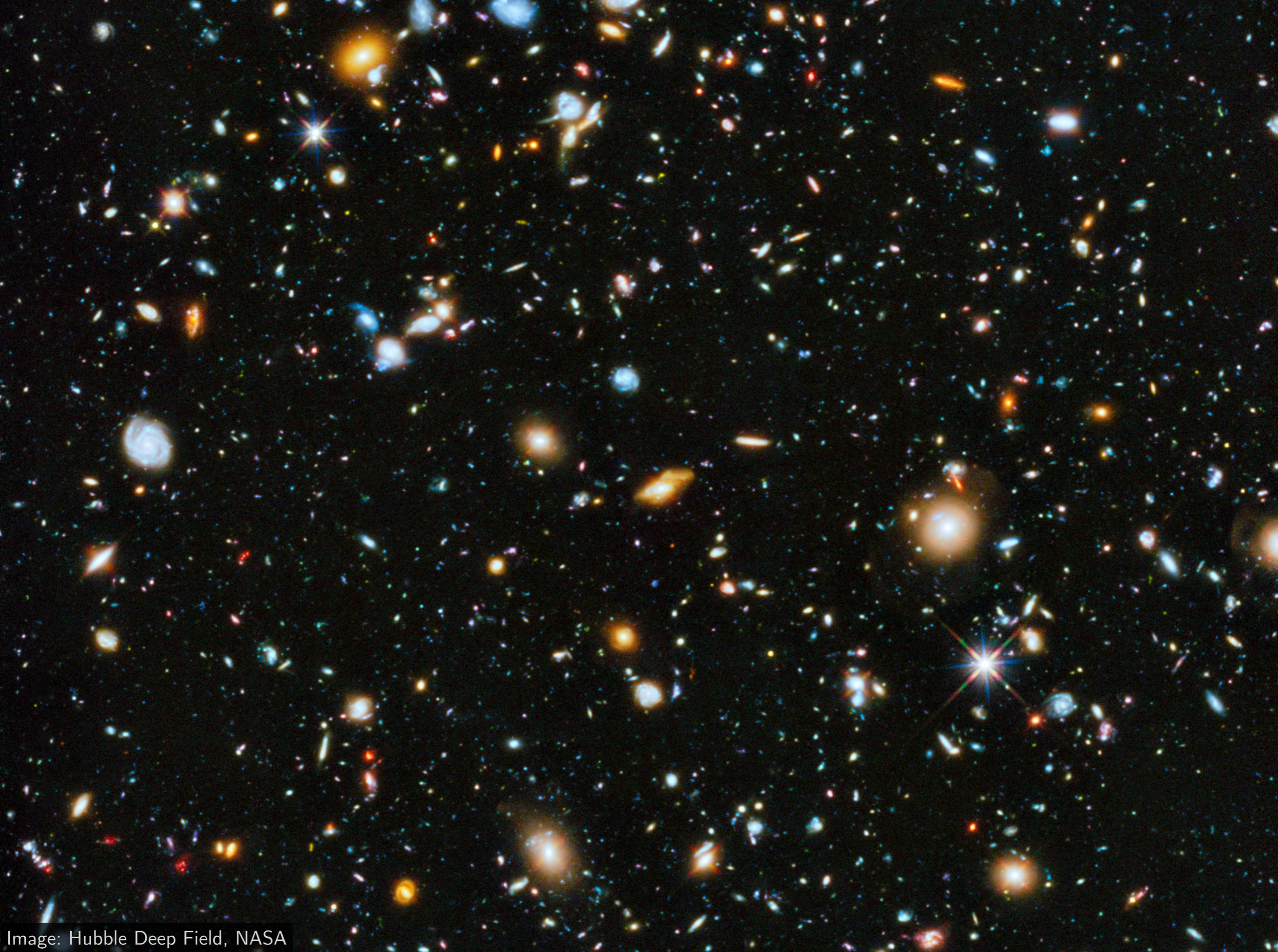


Image: Hubble Deep Field, NASA

Sakharov Conditions

The baryon asymmetry requires:

1. Non-conservation of baryon number B
2. Broken C and CP symmetry
3. Broken thermal equilibrium



Andrei Sakharov

C, P, and CP

Discrete Symmetries in the Standard Model

C: Charge

Change the sign of
the charge

P: Parity

Invert the
coordinates

C, P, and CP

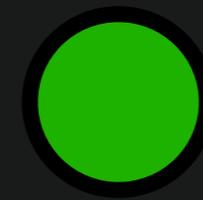
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electron
negative charge
left-handed

C, P, and CP

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$$CP \left(\text{●} \right) =$$

electron
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positive charge
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$$\text{CP}(\nu_\mu \rightarrow \nu_e) =$$

C, P, and CP

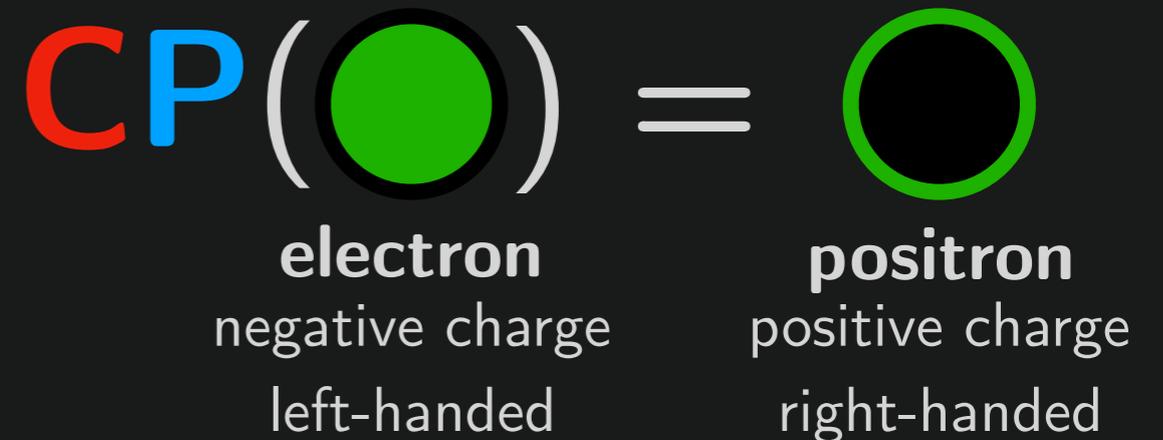
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$$\mathbf{CP}(\nu_{\mu} \rightarrow \nu_e) = \bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$$

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$$\mathbf{CP}(\nu_{\mu} \rightarrow \nu_e) = \bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$$

If CP mirror processes happen at unequal rates,
then the CP symmetry is "broken" (CP Violation, CPV)

Broken at a small level for quarks. Neutrinos too?

Neutrino Oscillations

Neutrino Oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$

Neutrino Oscillations

probability that neutrino changes type → $P(\nu_\alpha \rightarrow \nu_\beta) \sim \underbrace{\sin^2 2\theta}_{\text{overall transition probability}} \sin^2 \left(\frac{\overbrace{\Delta m^2 L}^{\text{difference in masses}}}{\underbrace{E}_{\text{neutrino energy}}} \right)$ $\xleftarrow{\text{distance traveled}}$

Neutrino Oscillations

probability that neutrino changes type \rightarrow

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \underbrace{\sin^2 2\theta}_{\text{overall transition probability}} \sin^2 \left(\frac{\overbrace{\Delta m^2 L}^{\text{difference in masses}}}{\underbrace{E}_{\text{neutrino energy}}} \right)$$

distance traveled

"Atmospheric" & Accelerator

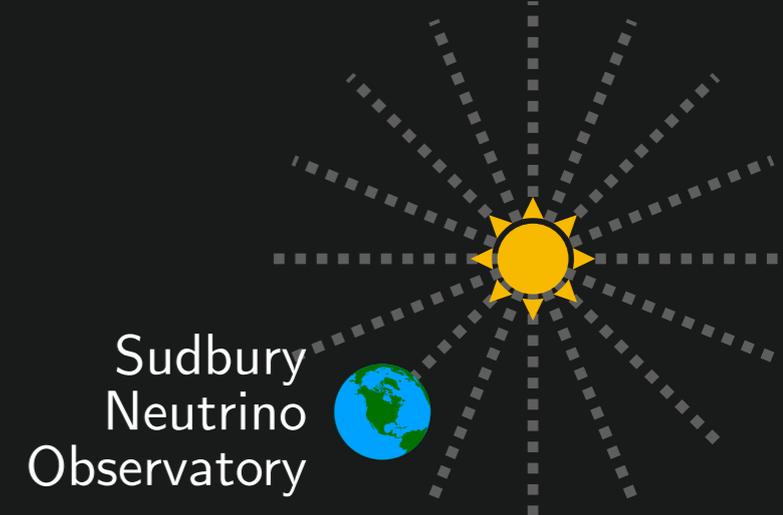
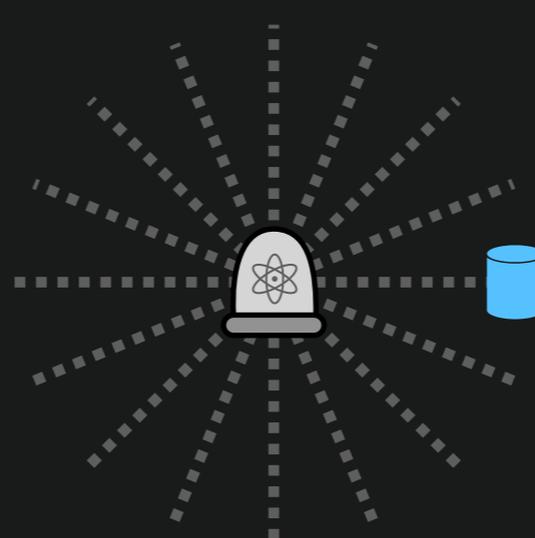
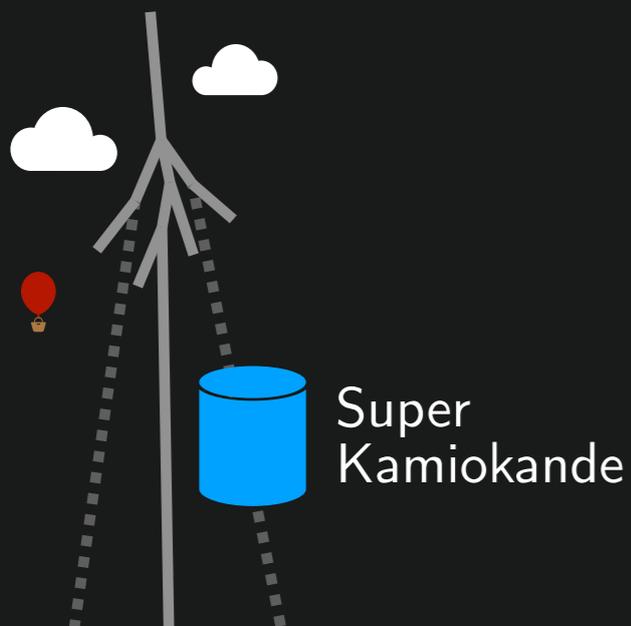
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

"Reactor"

$$\times \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \end{pmatrix}$$

"Solar" & KamLAND

$$\times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



CPV and Neutrino Oscillations

This was an **approximation** considering just two neutrinos at a time

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$

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Considering just the dominant effects for a **CPV** search:

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} \\
 & \times (\Delta m_{31}^2 L/4E_\nu) \frac{\sin(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu) \cos((\Delta m_{31}^2 L/4E_\nu) + \delta_{CP}) \\
 & + \cos 2\theta_{23} \sin 2\theta_{12} \frac{\sin^2(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu)^2
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 \end{aligned}$$

All the
parameters
matter!

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Considering just the dominant effects for a **CPV** search:

Matter effects
Oscillations influenced by Earth's matter density

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} \\ \times (\Delta m_{31}^2 L/4E_\nu) \frac{\sin(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu) \cos((\Delta m_{31}^2 L/4E_\nu) + \delta_{CP}) + \cos 2\theta_{23} \sin 2\theta_{12} \frac{\sin^2(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu)^2$$

All the parameters matter!

CPV and Neutrino Oscillations

This was an **approximation** considering just two neutrinos at a time

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$



Considering just the dominant effects for a **CPV** search:

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 & \quad \text{Oscillations influenced by Earth's} \\
 & \quad \text{matter density} \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - \boxed{G_F n_e / \sqrt{2}})}{(\Delta m_{31}^2 L/4E_\nu - \boxed{G_F n_e / \sqrt{2}})^2} \\
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 \end{aligned}$$

All the
parameters
matter!

CP Violating Phase
If nonzero, changes oscillations for
neutrinos relative to antineutrinos

CPV and Neutrino Oscillations

This was an **approximation** considering just two neutrinos at a time

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$



Considering just the dominant effects for a **CPV** search:

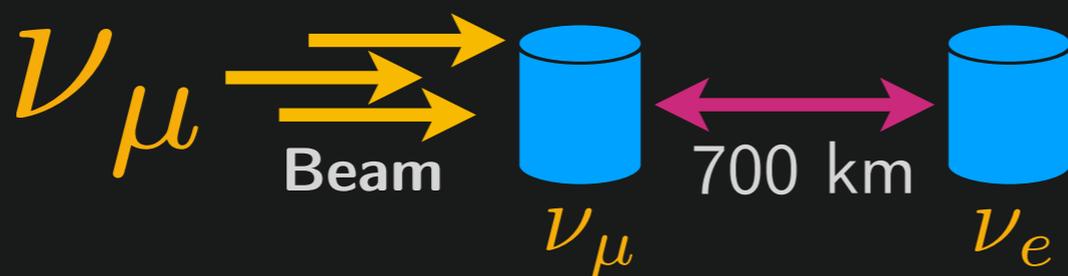
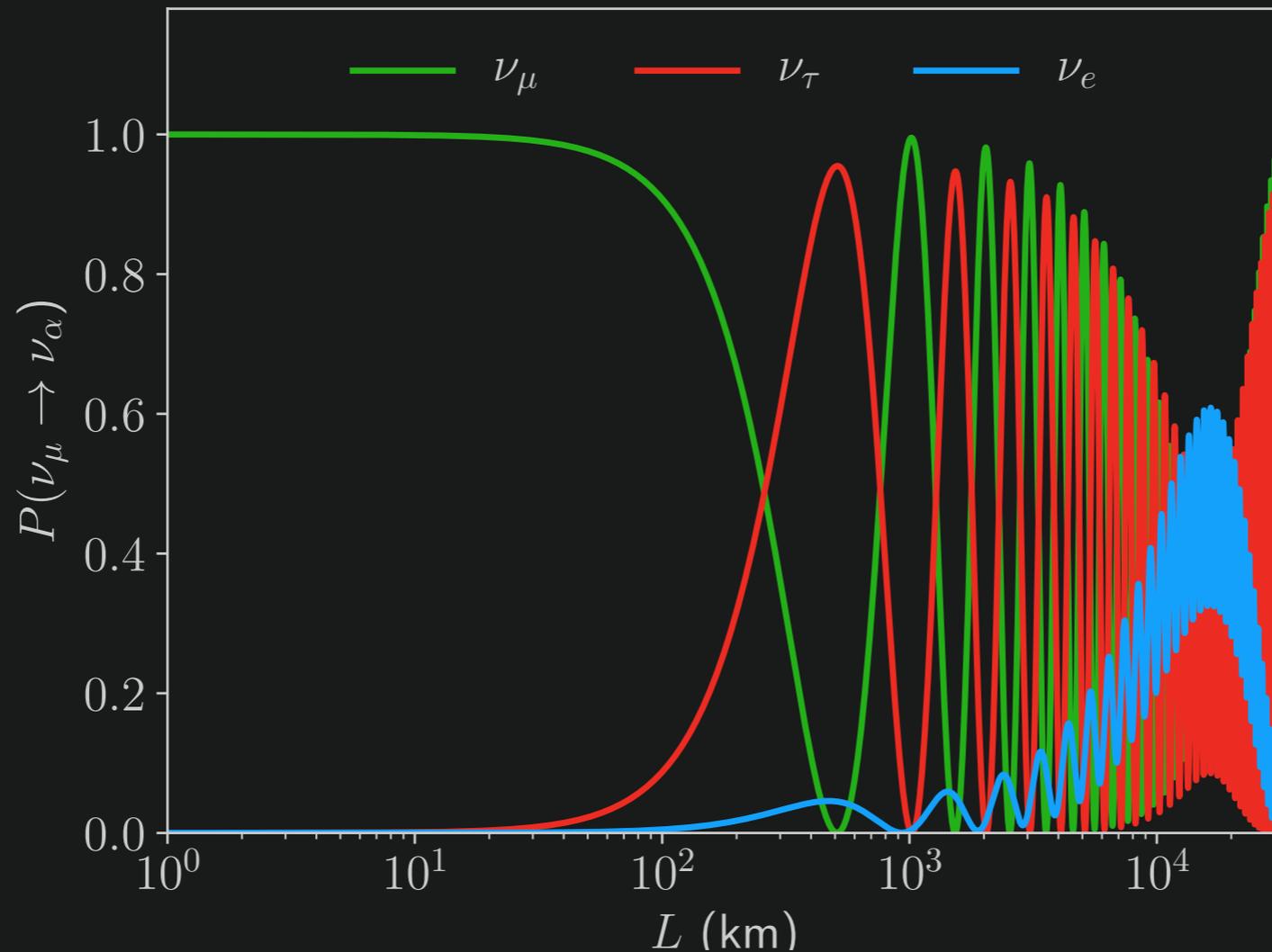
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 & \quad \text{If nonzero, changes oscillations for} \\
 & \quad \text{neutrinos relative to antineutrinos}
 \end{aligned}$$

All the
parameters
matter!

Matter effects and δ_{CP} cause differences for neutrino vs. antineutrino oscillations

The Experiment

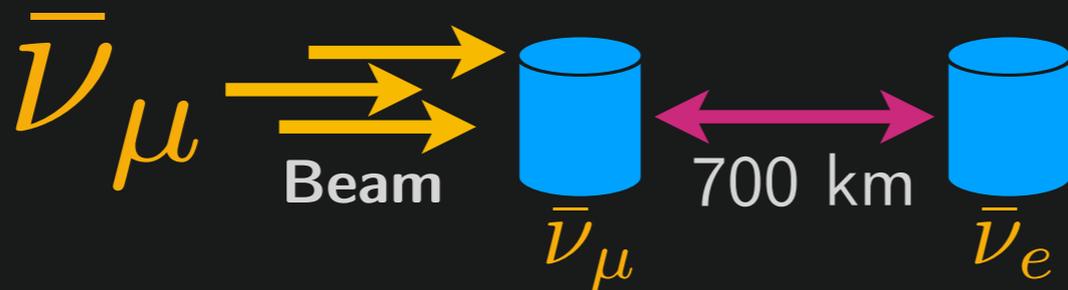
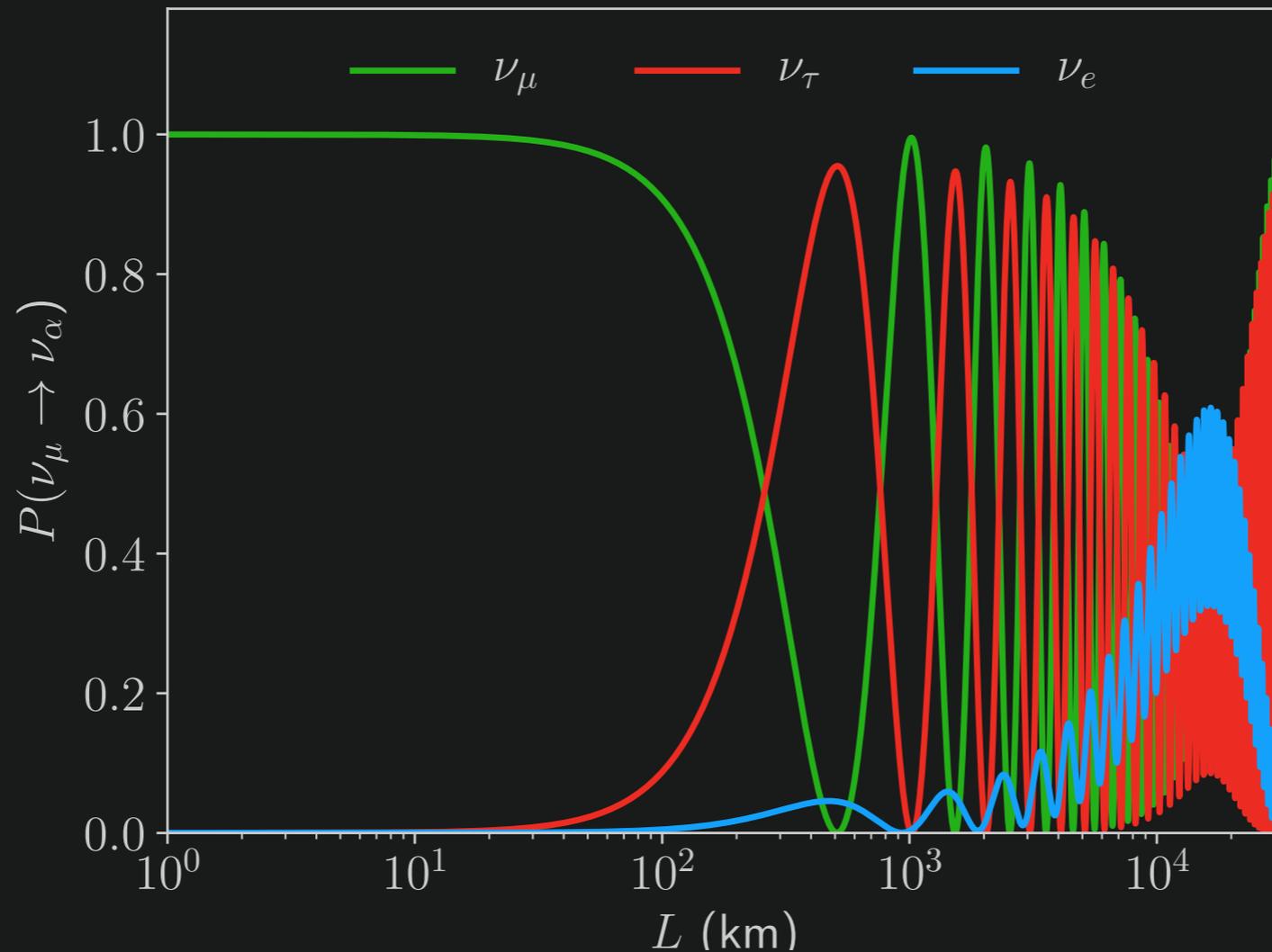
Probability, 1 GeV $\nu_\mu \rightarrow \nu_x$



Do neutrinos & antineutrinos
act the same?

The Experiment

Probability, 1 GeV $\nu_\mu \rightarrow \nu_x$



Do neutrinos & antineutrinos
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Baryogenesis



Majorana Neutrinos Reprise

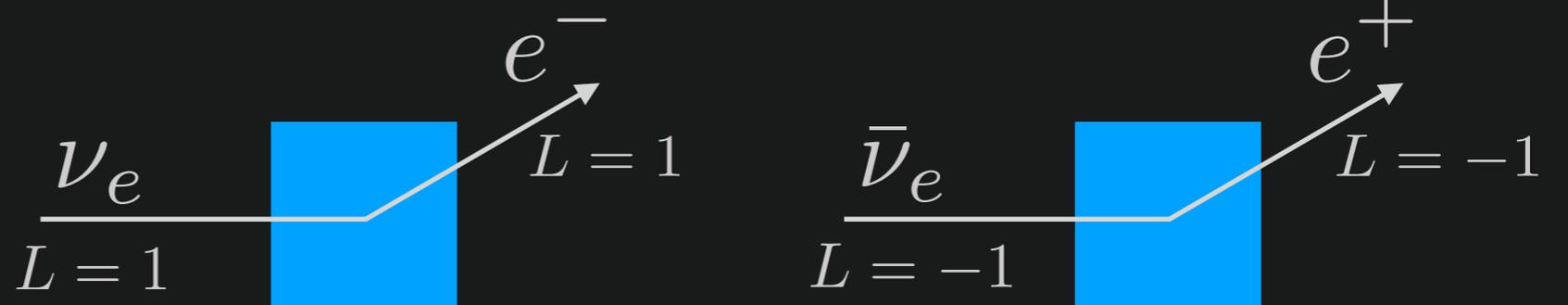
Two possibilities:

Majorana Neutrinos Reprise

Two possibilities:

A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states

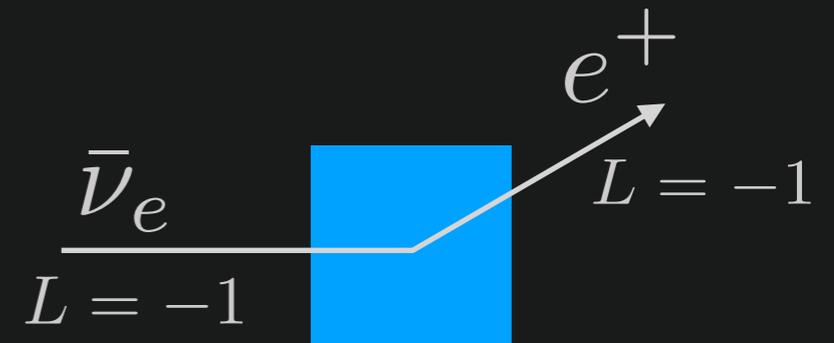
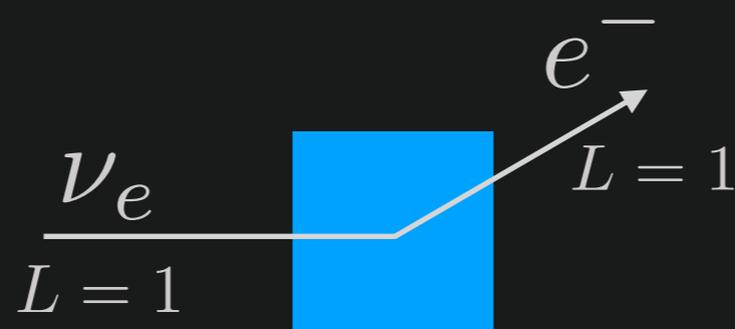


Majorana Neutrinos Reprise

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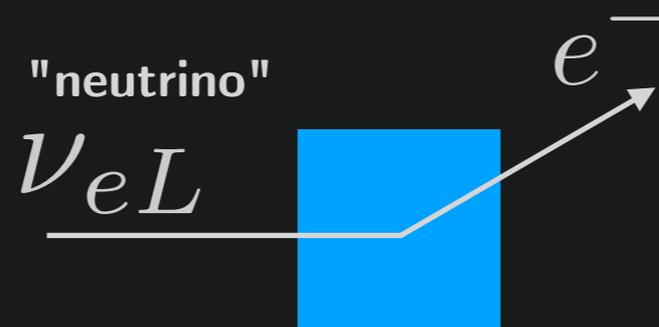
A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states



A Majorana Fermion

Particle and antiparticle are the same, just with left and right handed states



ν Neutrino Mass

Why are the neutrino masses so weirdly tiny?

ν Neutrino Mass

Why are the neutrino masses so weirdly tiny?

The Seesaw Mechanism

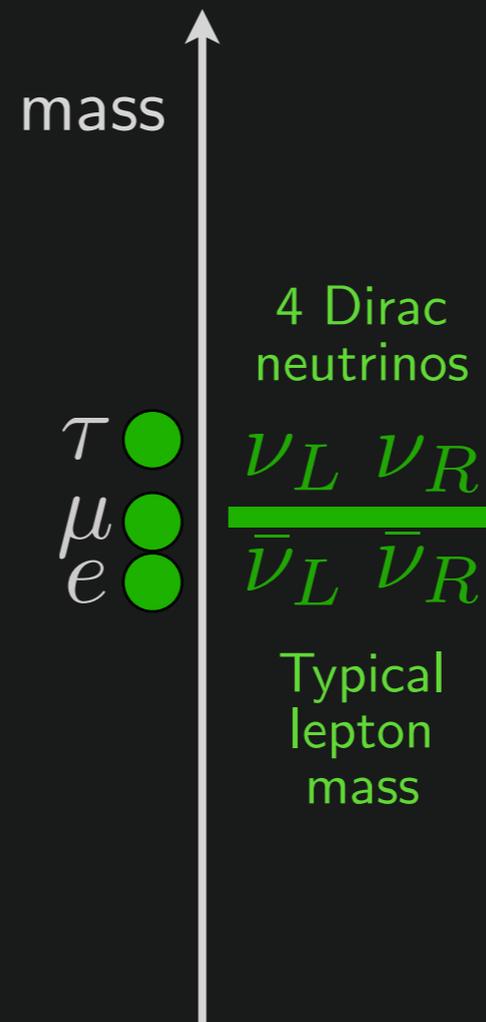
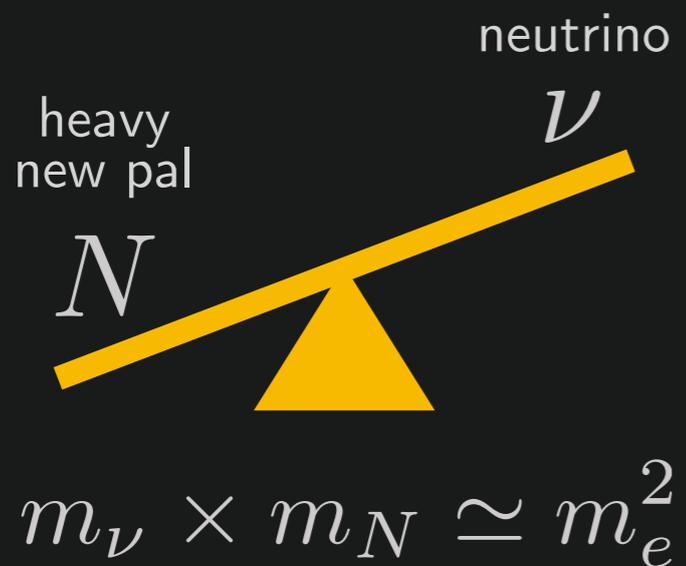


$$m_\nu \times m_N \simeq m_e^2$$

ν Neutrino Mass

Why are the neutrino masses so weirdly tiny?

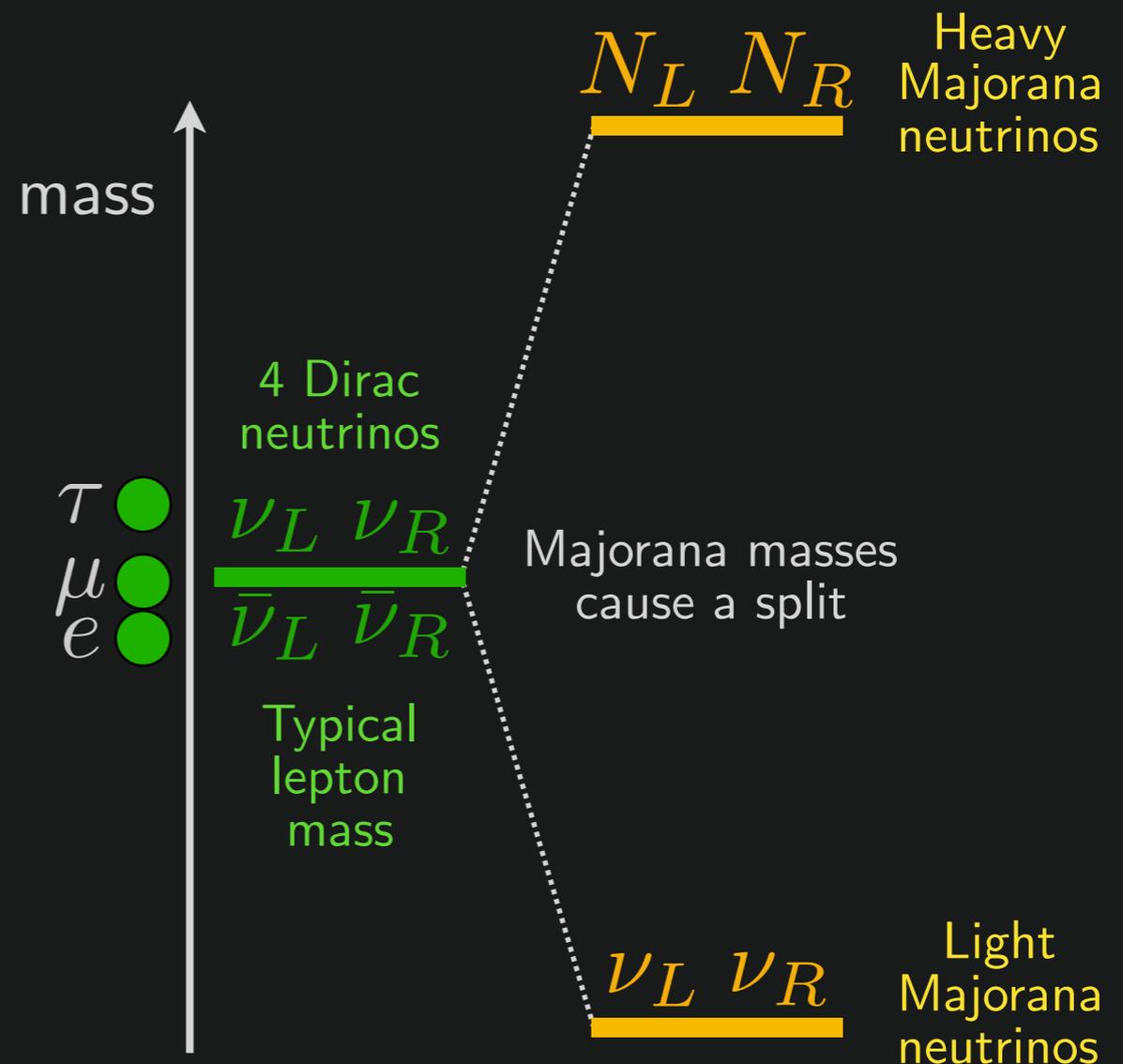
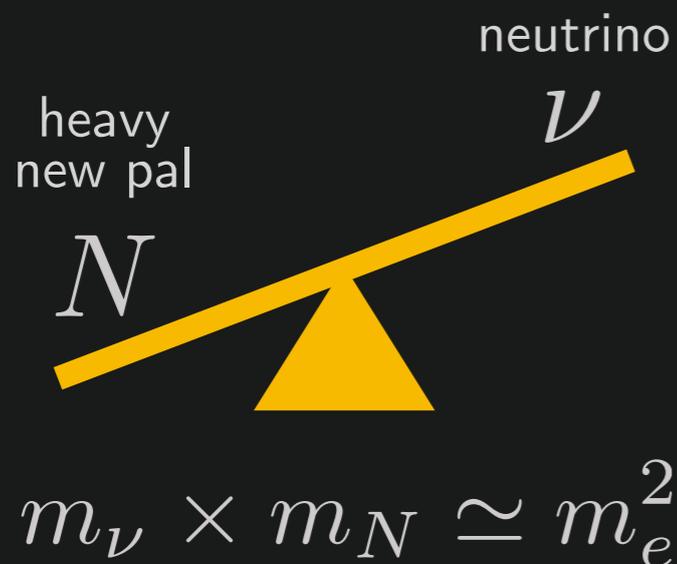
The Seesaw Mechanism



ν Neutrino Mass

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The Seesaw Mechanism



Seesaw Neutrinos

Seesaw Neutrinos

$N_L N_R$ and $\nu_L \nu_R$
get masses in the usual way,
through interactions with the
Higgs Boson

Seesaw Neutrinos

$N_L N_R$ and $\nu_L \nu_R$
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Higgs Boson

The heavy N can decay to lighter
particles and Higgses:

$$N \rightarrow e^+ + H^- \quad N \rightarrow e^- + H^+$$

$$N \rightarrow \nu + H^0 \quad N \rightarrow \bar{\nu} + \bar{H}^0$$

Seesaw Neutrinos

N_L N_R and ν_L ν_R
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$$\mathbf{CP}(N \rightarrow e^+ + H^-) = N \rightarrow e^- + H^+$$

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Seesaw Neutrinos

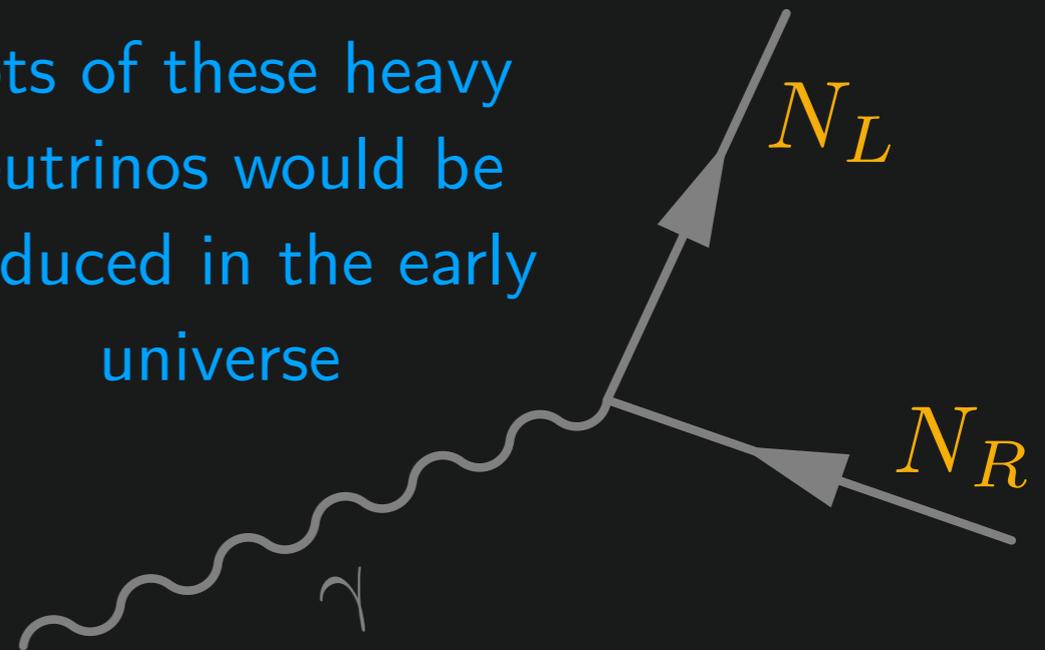
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Lots of these heavy
neutrinos would be
produced in the early
universe



Seesaw Neutrinos

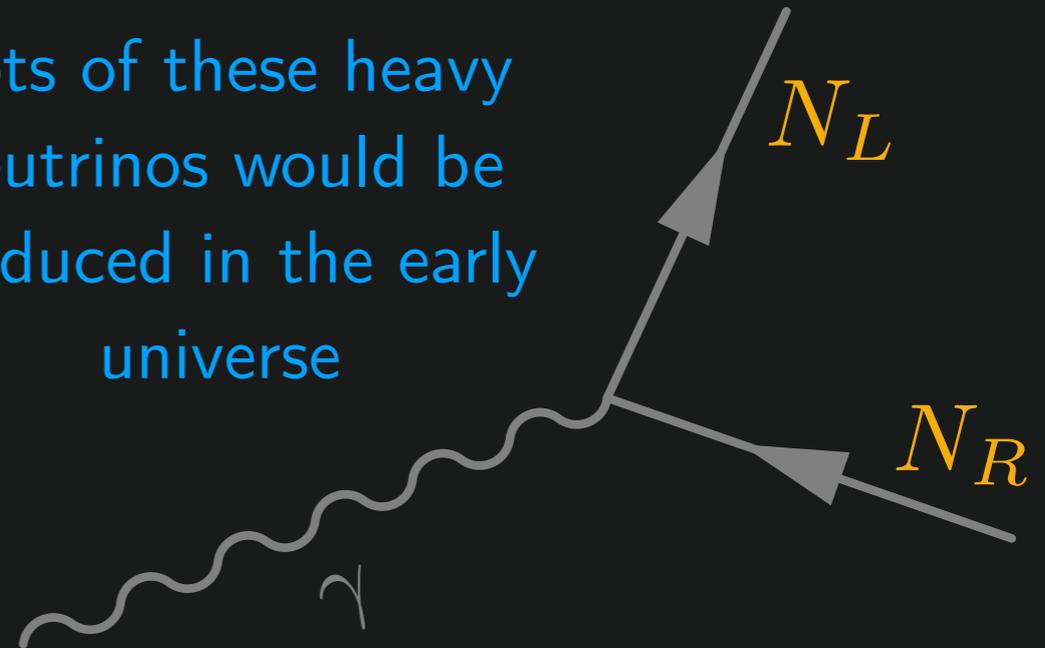
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CP violation would create an imbalance of
matter (leptons) and antimatter (antileptons)

Seesaw Neutrinos

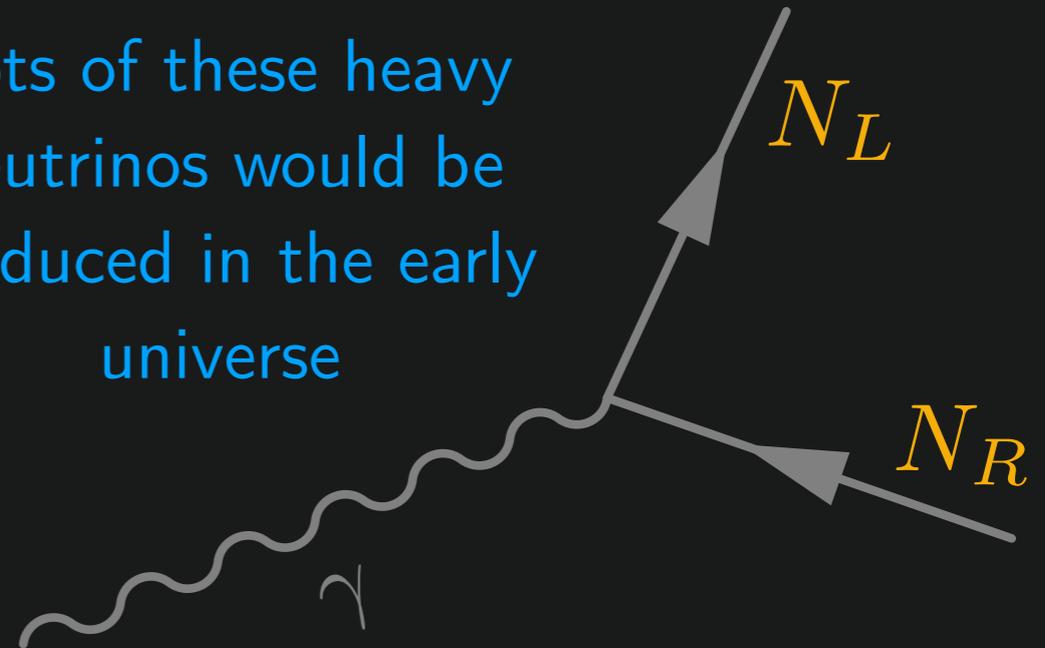
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through interactions with the
Higgs Boson

The heavy N can decay to lighter
particles and Higgses:

$$\text{CP}(N \rightarrow e^+ + H^-) = N \rightarrow e^- + H^+$$

$$\text{CP}(N \rightarrow \nu + H^0) = N \rightarrow \bar{\nu} + \bar{H}^0$$

Lots of these heavy
neutrinos would be
produced in the early
universe



CP violation would create an imbalance of
matter (leptons) and antimatter (antileptons)

But we need an asymmetry in baryons (nuclei and things)...

Leptogenesis

From heavy Majorana neutrino decays,
we get a **lepton** asymmetry...

$$B_i = 0$$

$$L_i \neq 0$$

Leptogenesis

From heavy Majorana neutrino decays,
we get a **lepton** asymmetry...

Which is then converted in to a
baryon asymmetry



A **Standard Model** process
that does not conserve **B** or **L**
(but does conserve **B - L**)

Our Story: A Recap

Start: Why is the Universe full of all this matter?

Our Story: A Recap

Start: Why is the Universe full of all this matter?



Image: NASA

Our Story: A Recap

Start: Why is the Universe full of all this matter?

Need to generate a matter/antimatter imbalance

 **matter**
(baryons)



Our Story: A Recap

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Requires baryon number and CP nonconservation



RIA Novosti archive,
image #25981
Vladimir Fedorenko
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Image: NASA

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Not enough CP violation in quarks... maybe neutrinos?



Image: NASA

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Heavy neutrino decays create a lepton imbalance



Image: NASA

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Image: NASA

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image #25981
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Standard Model processes convert it into a baryon imbalance



Heavy neutrino decays create a lepton imbalance



You Win!

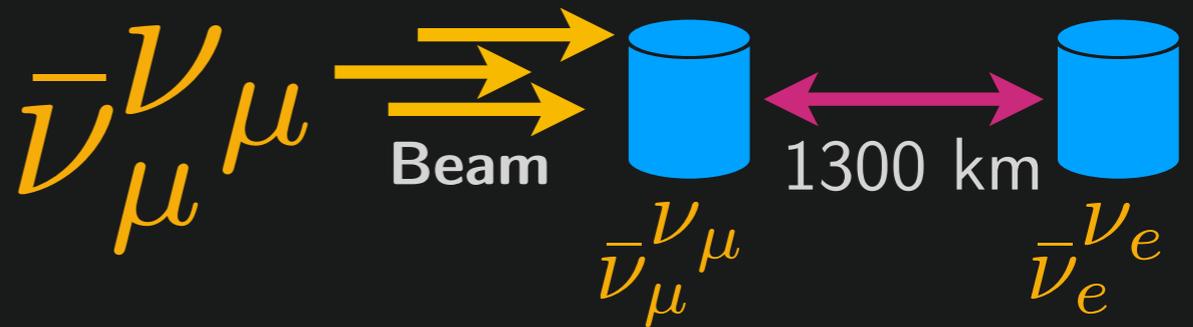
Image: NASA

ν

Hunting for CP Violation

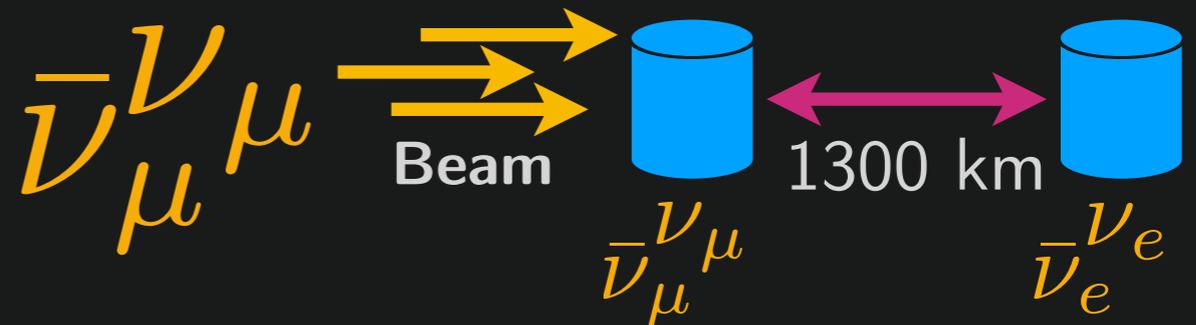
Hunting for CP Violation

Pick a distance where oscillations are maximized and look for wiggles in the energy distribution

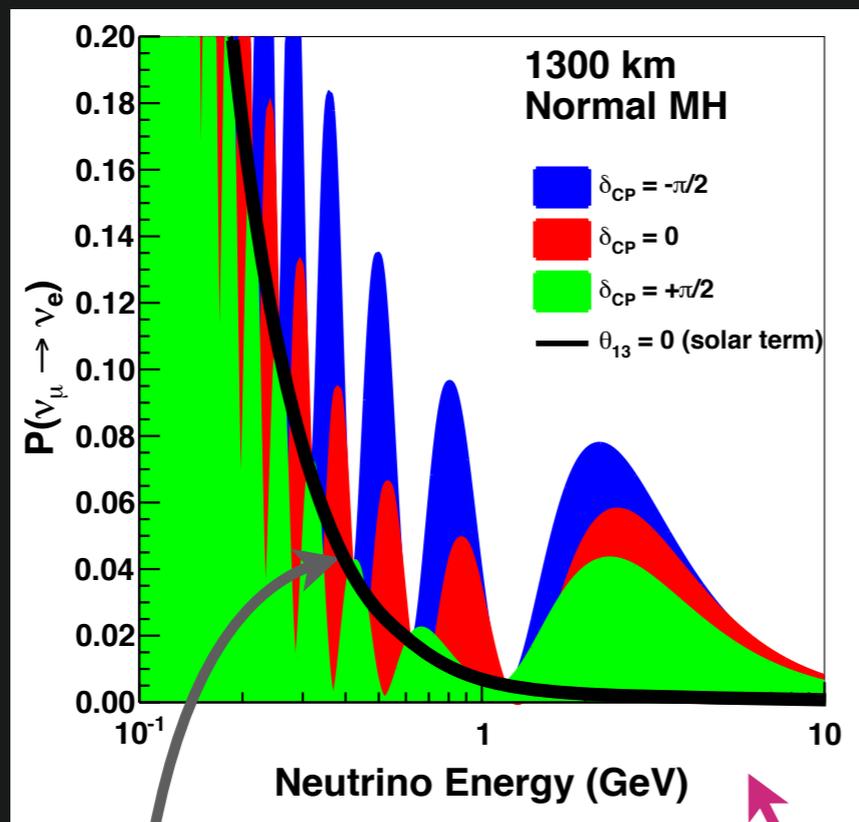


Hunting for CP Violation

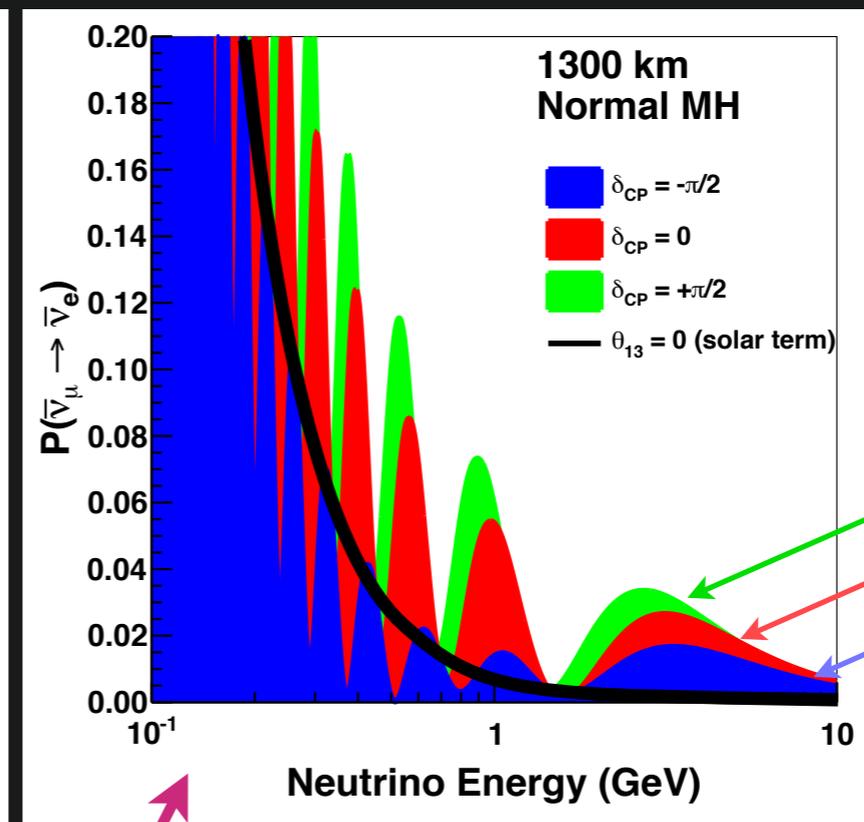
Pick a distance where oscillations are maximized and look for wiggles in the energy distribution



Neutrinos



Antineutrinos



CP violation
No CP violation
CP violation

No wiggles if θ_{13} is zero (reactor experiments!)

Compare wiggles to see if CP is violated

DUNE Conceptual Design Report

Matter Effects



The Earth is full of matter (electrons, not positrons)

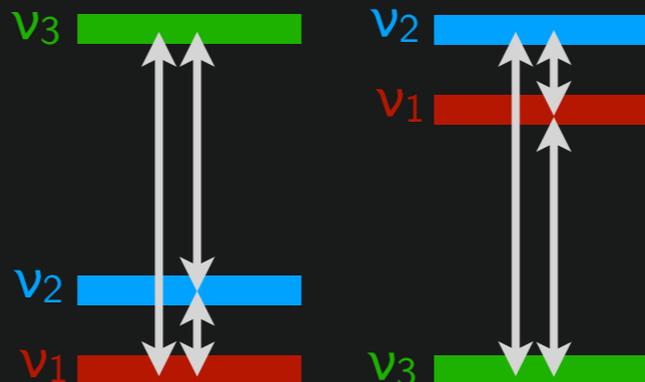
This means neutrinos and antineutrinos are already going to propagate differently, aside from any CP violation going on

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin^2(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})}{(\Delta m_{31}^2 L/4E_\nu - G_F n_e/\sqrt{2})^2} \\
 & \times (\Delta m_{31}^2 L/4E_\nu) \frac{\sin(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu) \cos((\Delta m_{31}^2 L/4E_\nu) + \delta_{CP}) \\
 & + \cos 2\theta_{23} \sin 2\theta_{12} \frac{\sin^2(G_F n_e L/\sqrt{2})}{(G_F n_e L/\sqrt{2})^2} (\Delta m_{21}^2 L/4E_\nu)^2
 \end{aligned}$$

Matter effects

Oscillations influenced by Earth's matter density

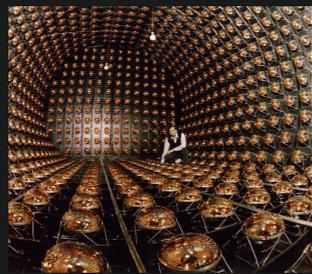
The effect depends on the neutrino mass ordering...



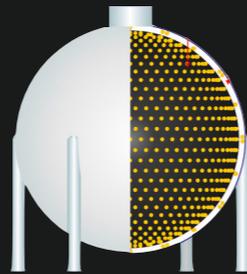
...so we need to measure that at the same time

Sterile Neutrinos and Such

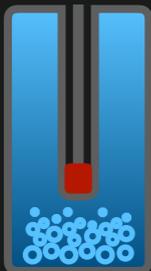
Some experiments hint at
an extra, non-interacting
sterile neutrino



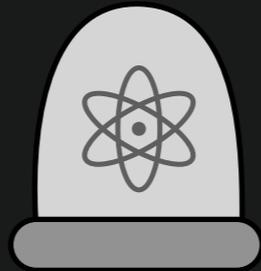
LSND



MiniBooNE



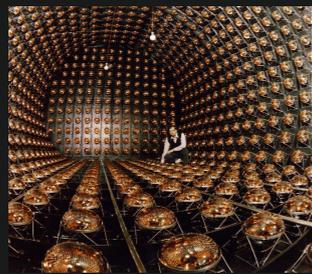
Gallium



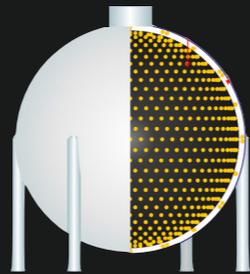
Reactors

Sterile Neutrinos and Such

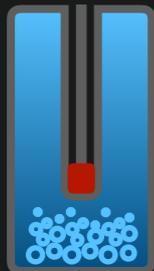
Some experiments hint at an extra, non-interacting **sterile neutrino**



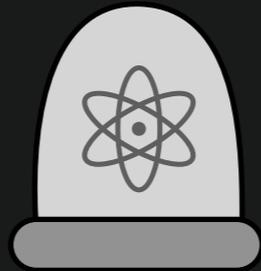
LSND



MiniBooNE

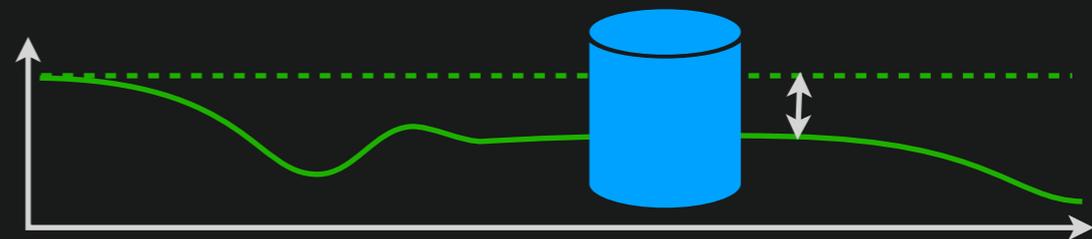


Gallium



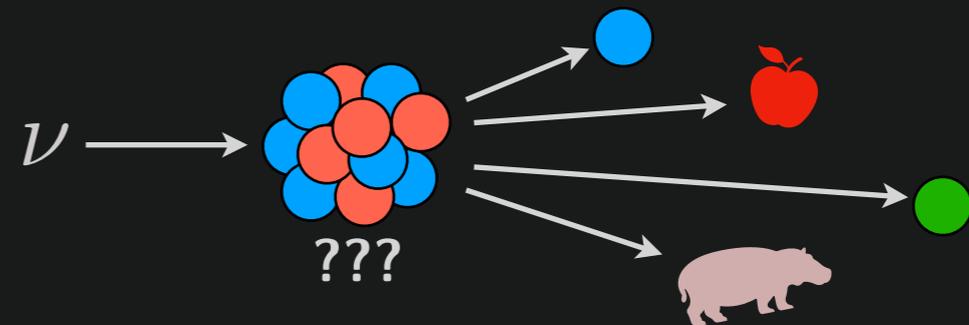
Reactors

Option 1: Sterile Neutrinos



Have to worry about oscillations with four neutrino flavors

Option 2: Neutrino Interaction Models



Need to improve models to account for the anomalies

Neutrino Interactions

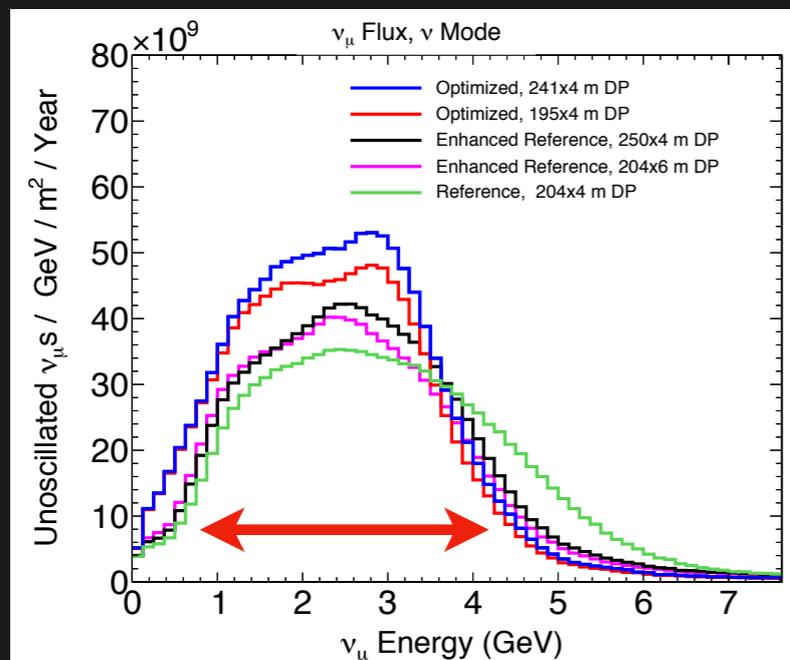
$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$

To measure the **parameters**, you need to know the **neutrino energy**

Neutrino Interactions

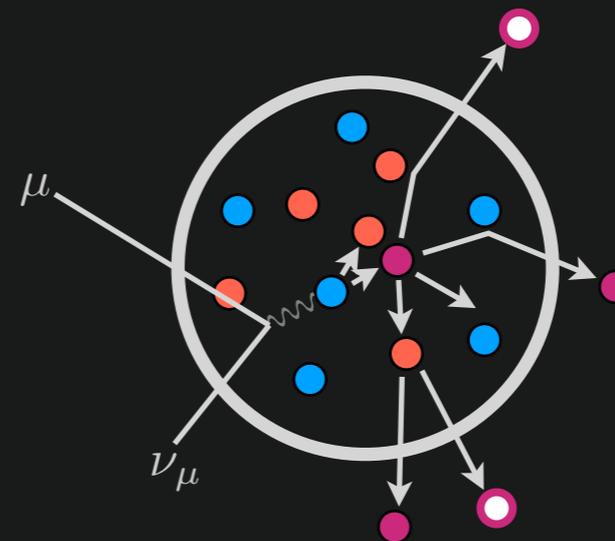
$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E} \right)$$

To measure the **parameters**, you need to know the **neutrino energy**



Neutrinos are really produced with a broad range of **energies**

We can only measure the **neutrino energy** indirectly, based on what comes out



Processes inside nuclei can make this difficult

Drawing based on S. Gollapinni, arxiv:1602:05299

Neutrino Interactions

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Spotted at Fermilab...

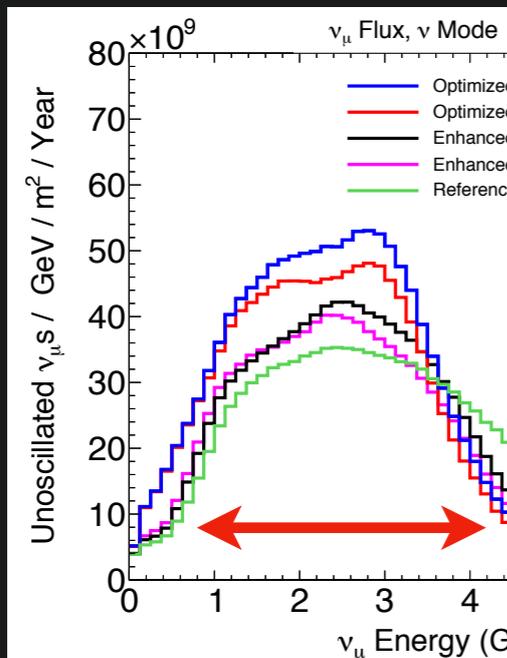
To measure the

neutrino energy

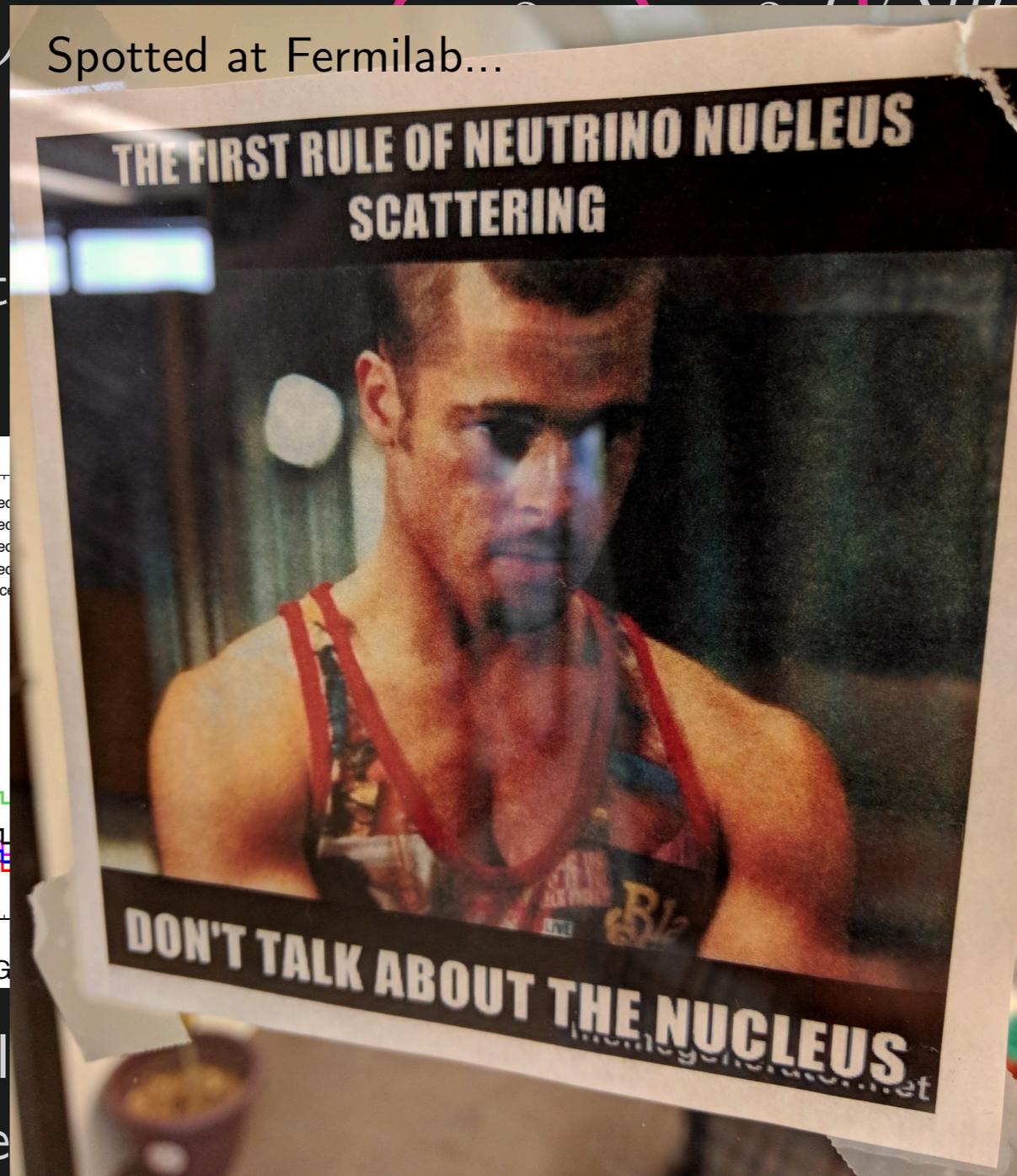
the neutrino energy

what comes out

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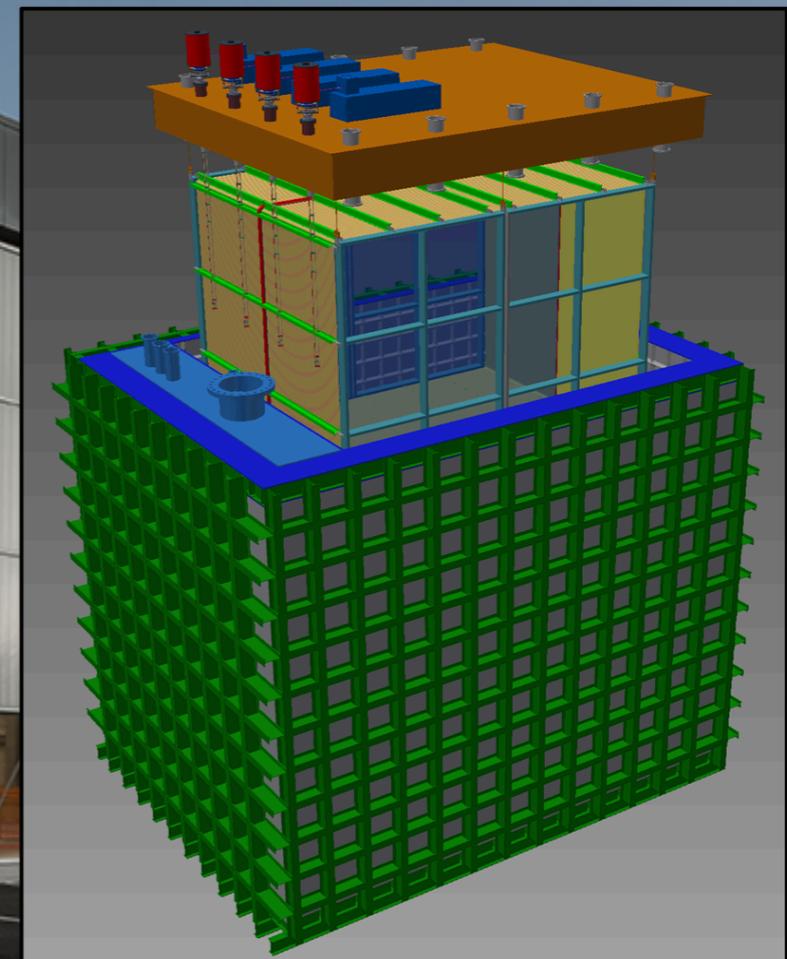
Collapinni, arxiv:1602:05299

SBND

The Short-Baseline Near Detector



SBND will make detailed measurements of neutrino interactions needed for CP violation searches!



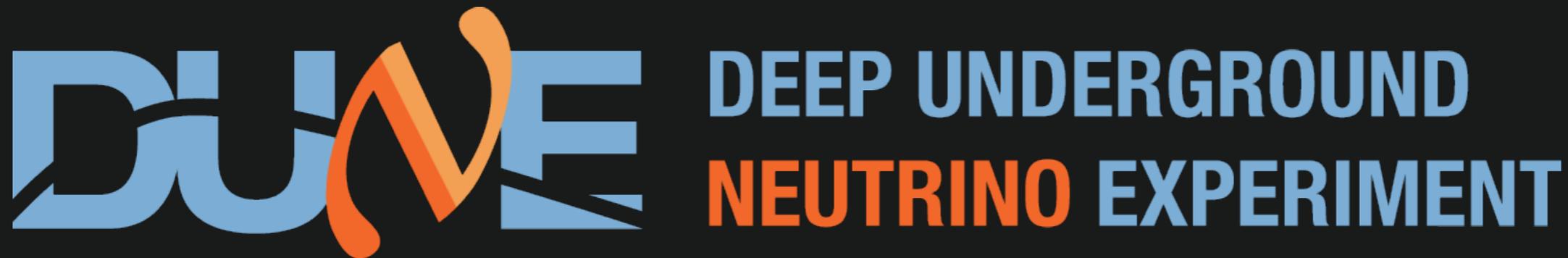
Long-Baseline Experiments

Two large international mega-projects pursuing neutrino CP violation

Long-Baseline Experiments

Two large international mega-projects pursuing neutrino CP violation

Liquid Argon TPCs, located in US: https://www.youtube.com/watch?v=AYtKcZMJ_4c



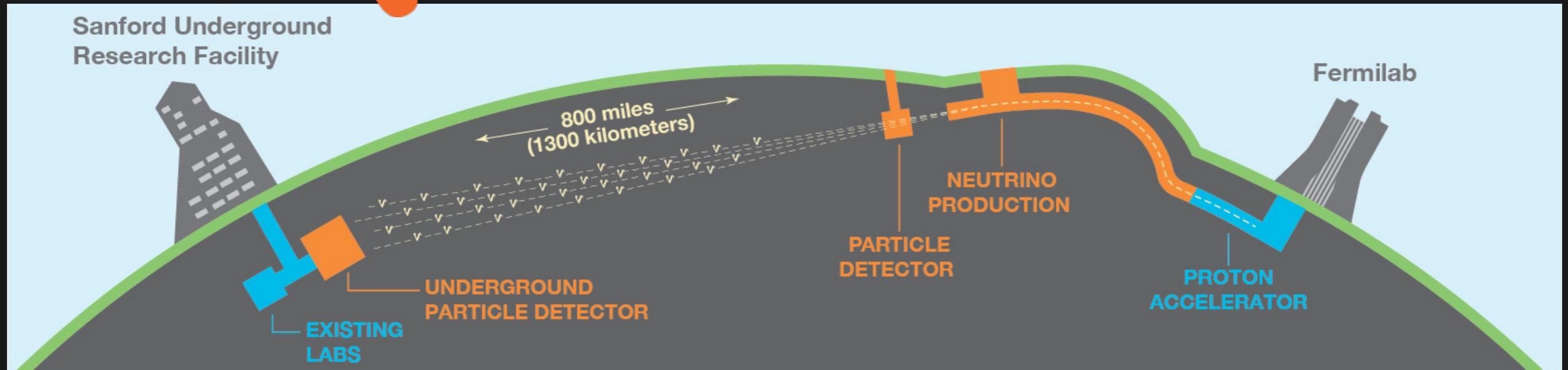
Water Cherenkov detectors, located in Japan:



<https://www.youtube.com/watch?v=JFOE3D2z7LM>

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



https://www.youtube.com/watch?v=AYtKcZMJ_4c

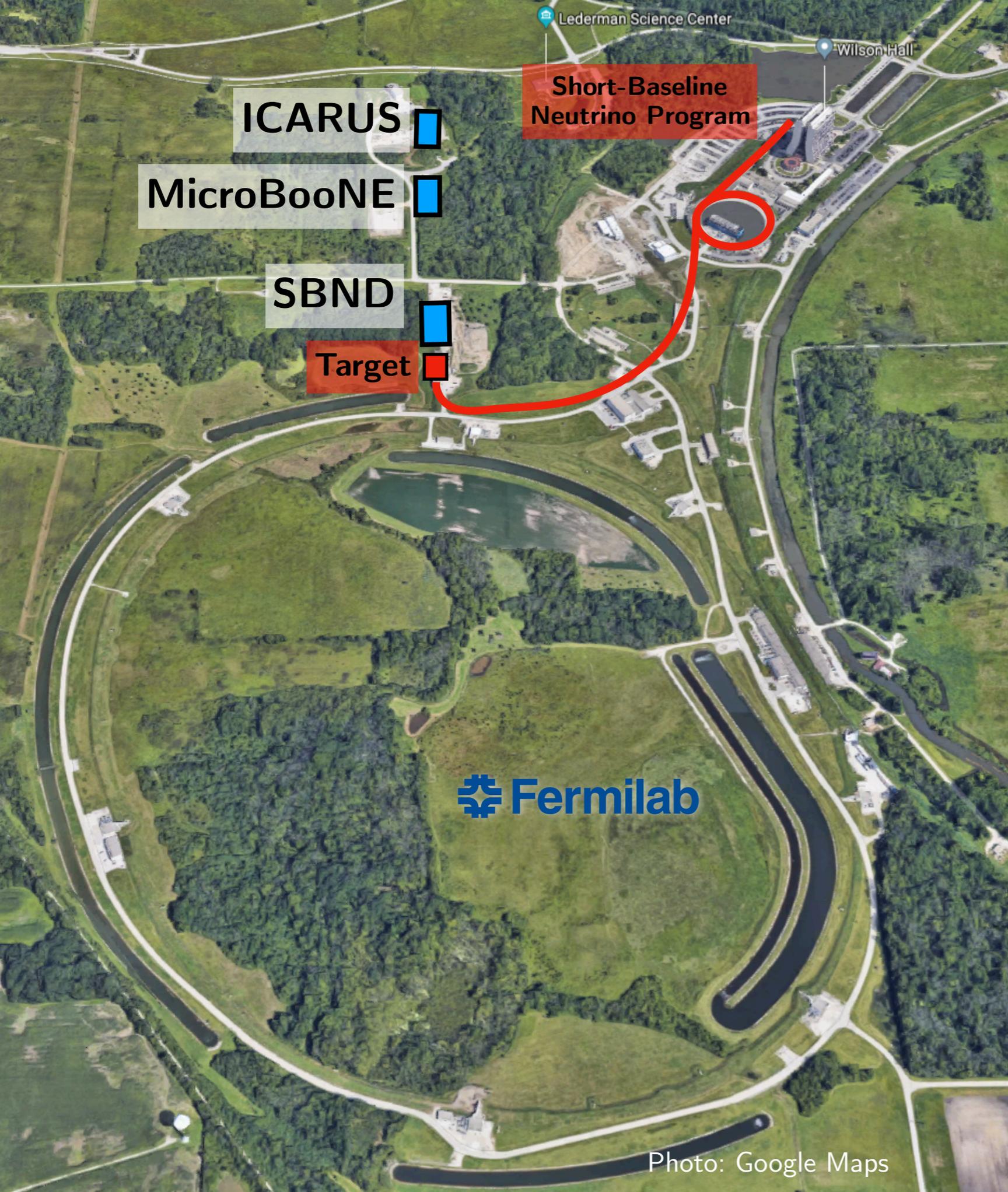


Neutrino Beam

A new, high-powered neutrino beam at Fermilab

Powerful, tunable, and makes neutrinos or antineutrinos!

Construction begins in 2024

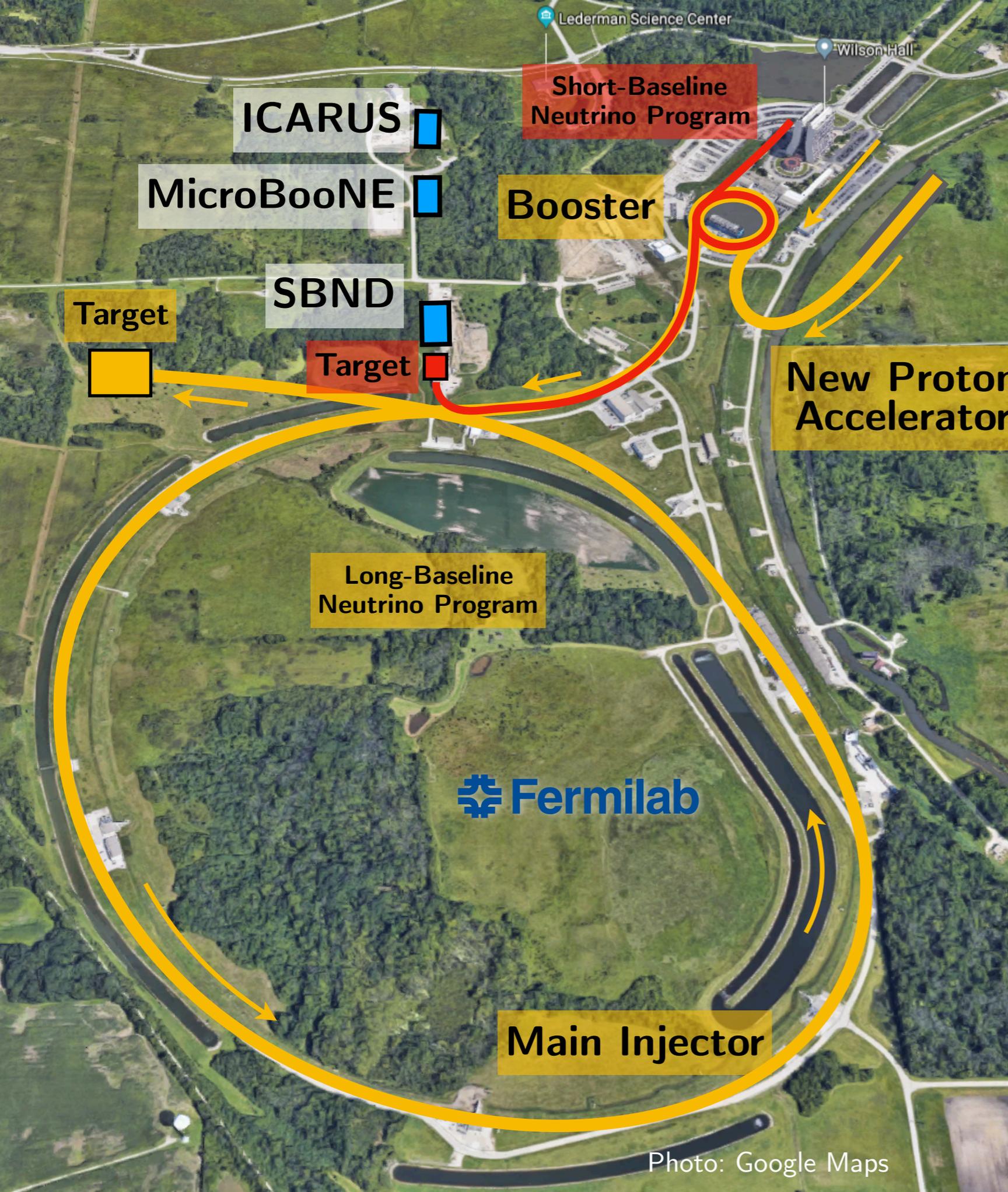


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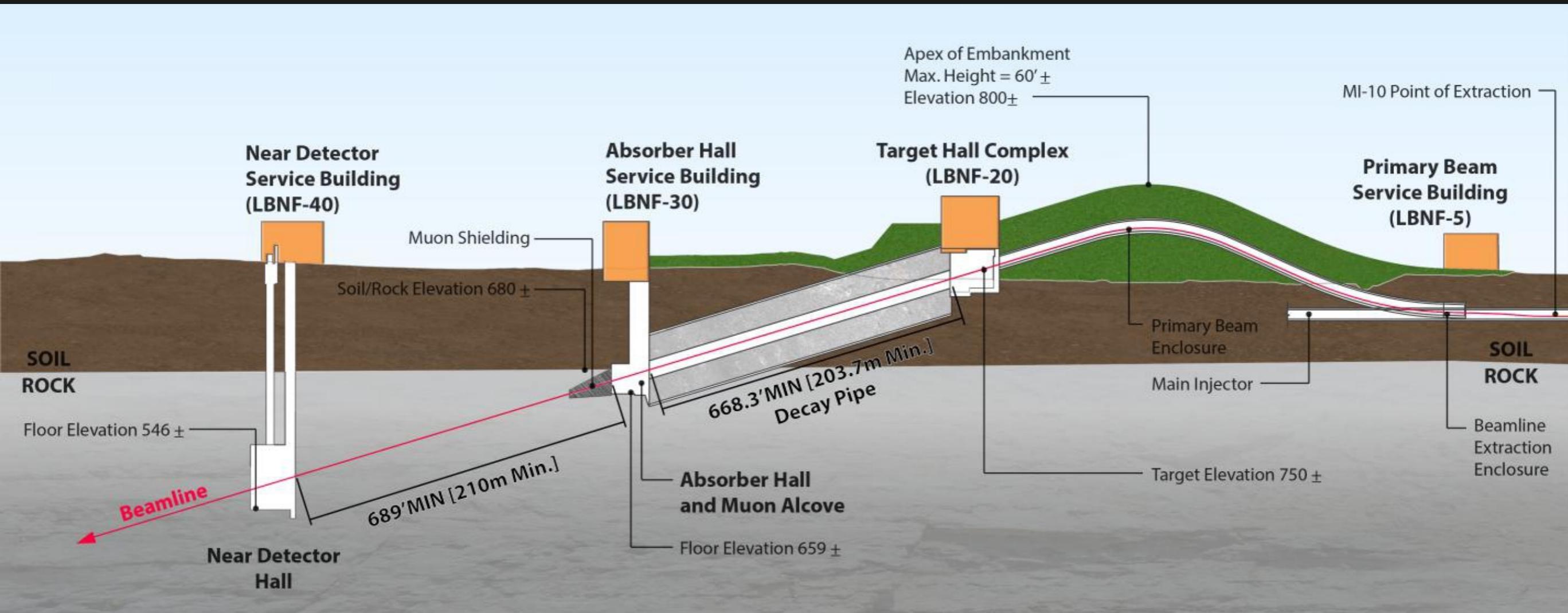
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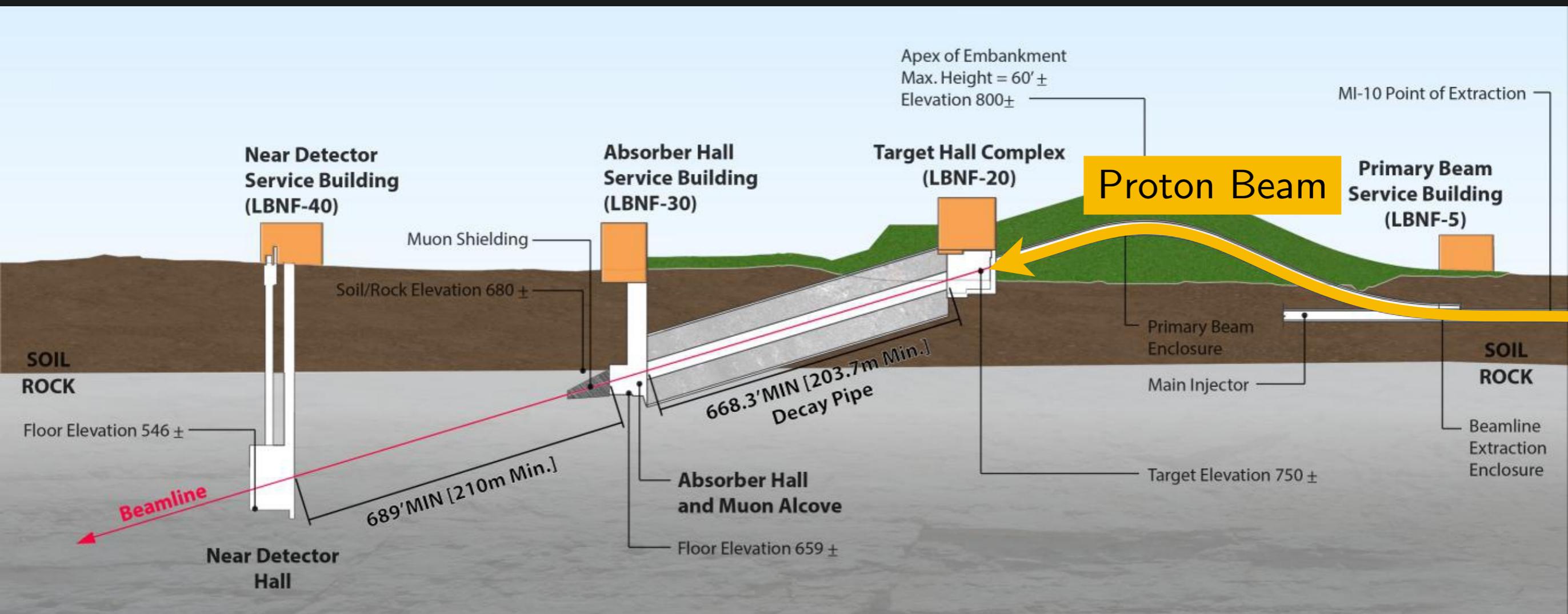
Making the Neutrinos



The accelerated protons are used to make neutrinos in this **target complex**

Neutrino Beam

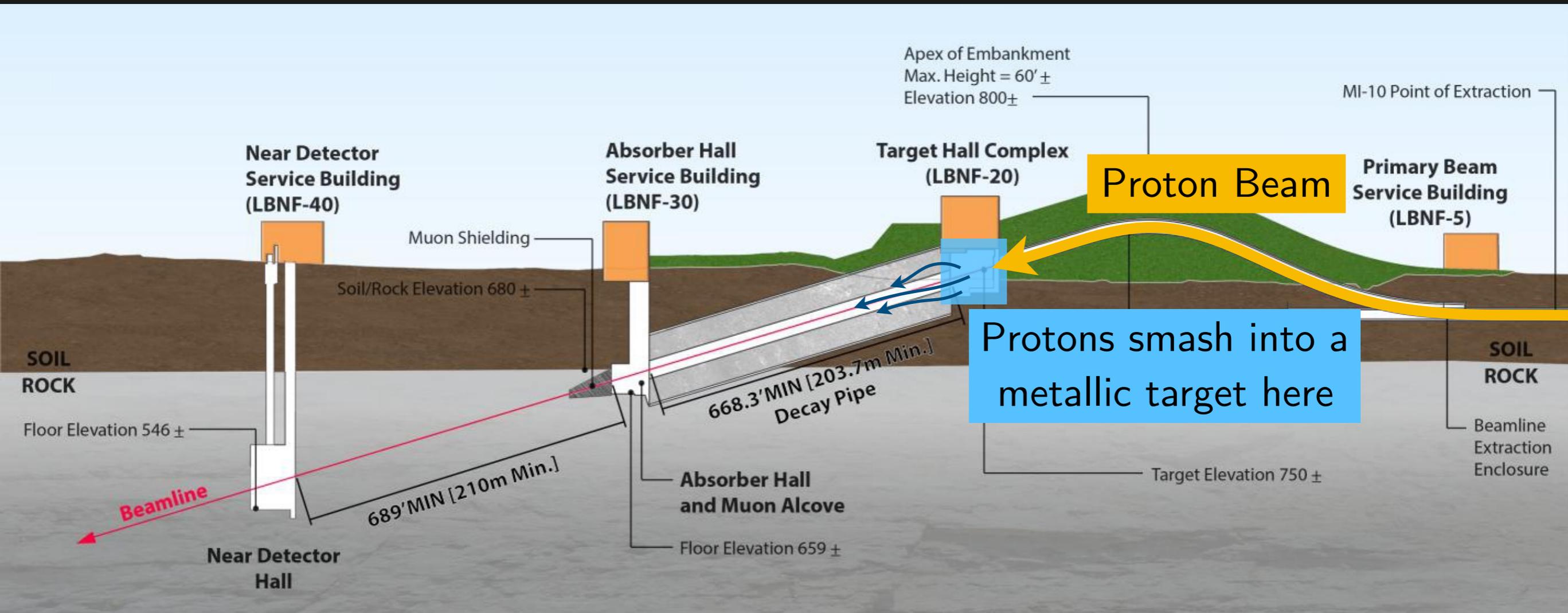
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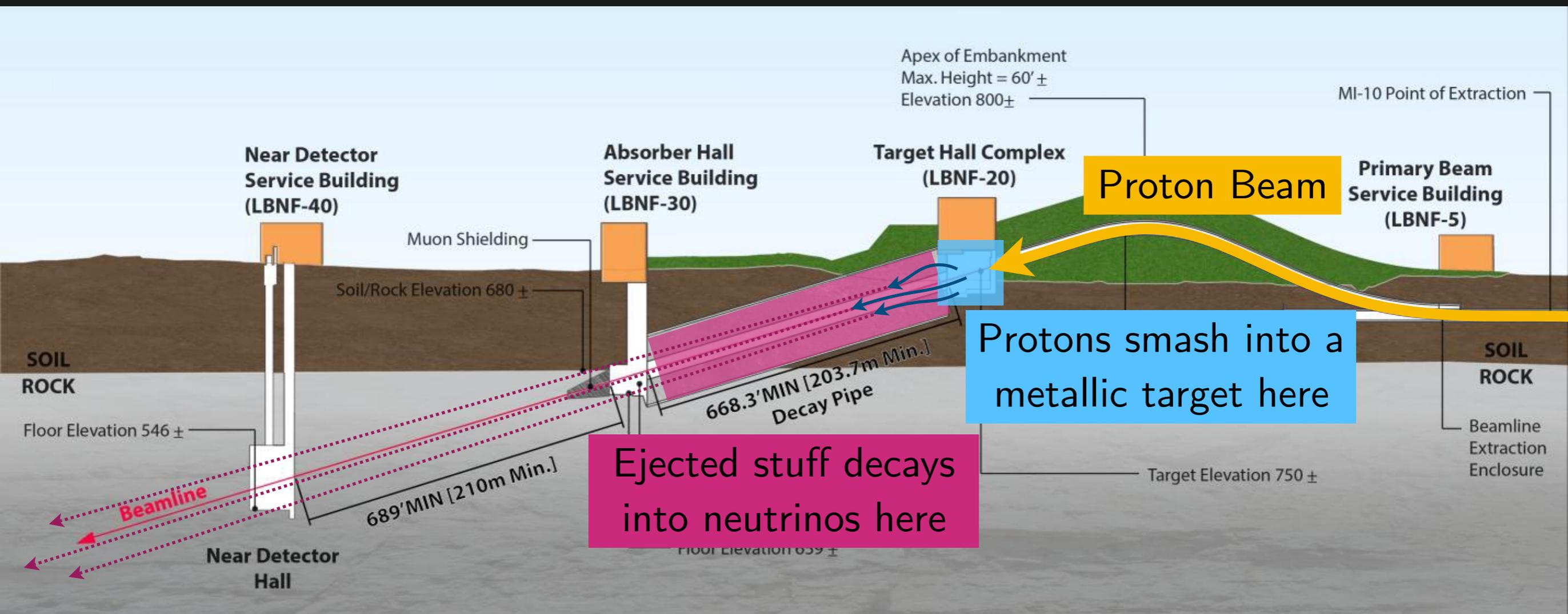
Making the Neutrinos



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Neutrino Beam

Making the Neutrinos

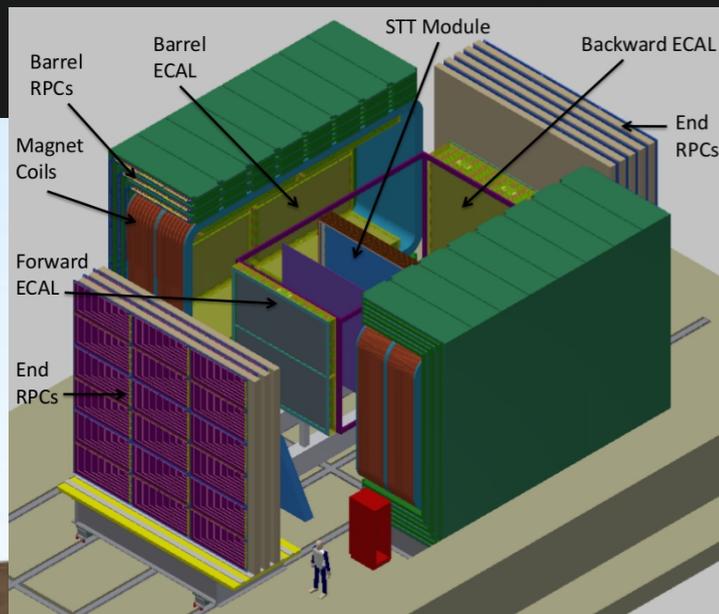


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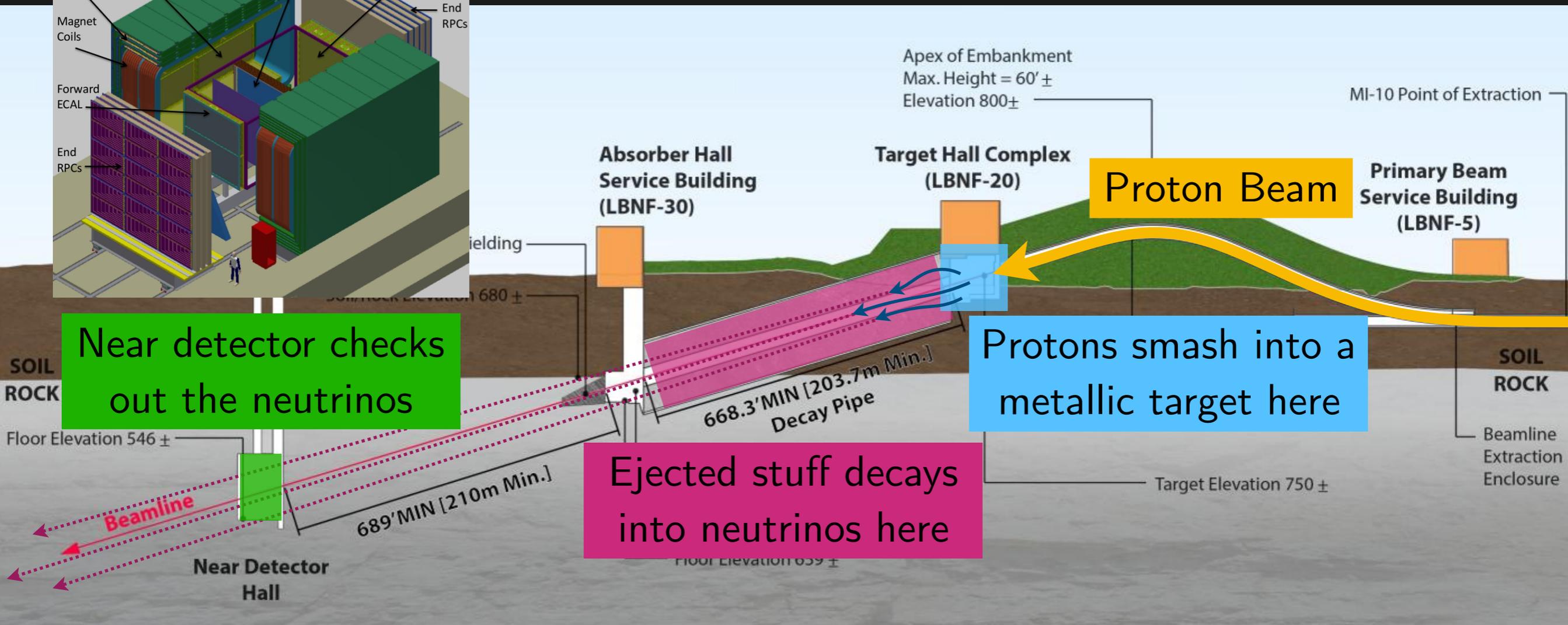
Neutrino Beam

Making the Neutrinos

A ND Concept



Near detector checks out the neutrinos



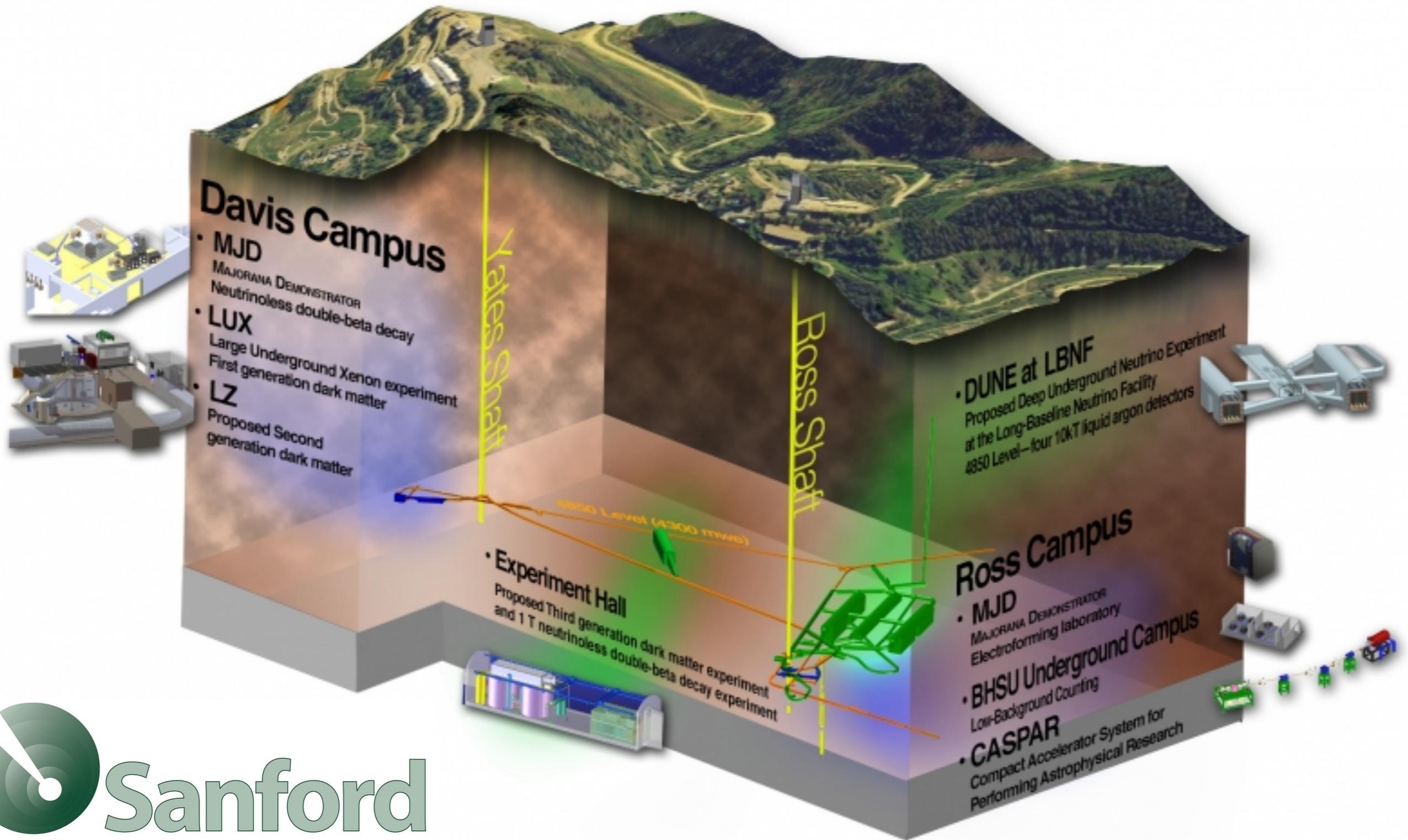
The accelerated protons are used to make neutrinos in this **target complex**



2002

Image © United States Postal Service. All rights reserved.

Destination: South Dakota!



Underground Research Facility

South Dakota Science and Technology Authority



Ross Shaft



**Sanford Underground
Research Facility**
Homestake Mine
Lead, SD



Ross Shaft



Selfie at the Yates Shaft

**Sanford Underground
Research Facility**
Homestake Mine
Lead, SD

The DUNE Far Detector

Detecting the Neutrinos

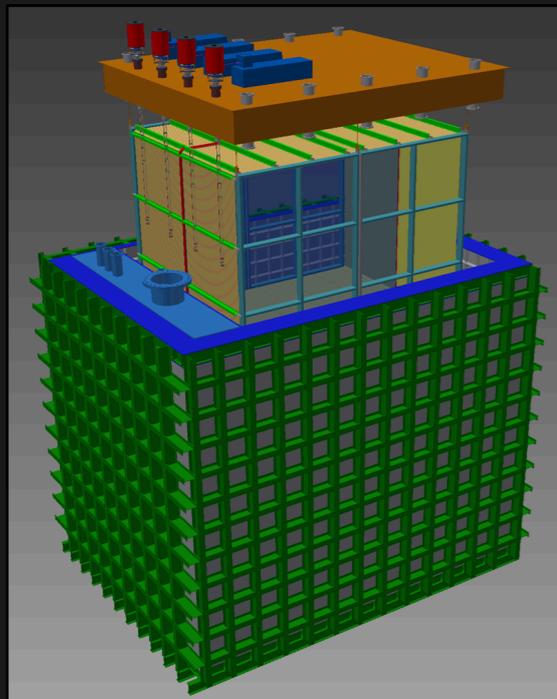
DUNE is a **HUGE** Liquid Argon Time Projection Chamber

The DUNE Far Detector

Detecting the Neutrinos

DUNE is a **HUGE** Liquid Argon Time Projection Chamber

We met a few of these last week, searching for sterile neutrinos:



SBND
Short-Baseline
Near Detector



MicroBooNE
Addressing the
MiniBooNE Anomaly

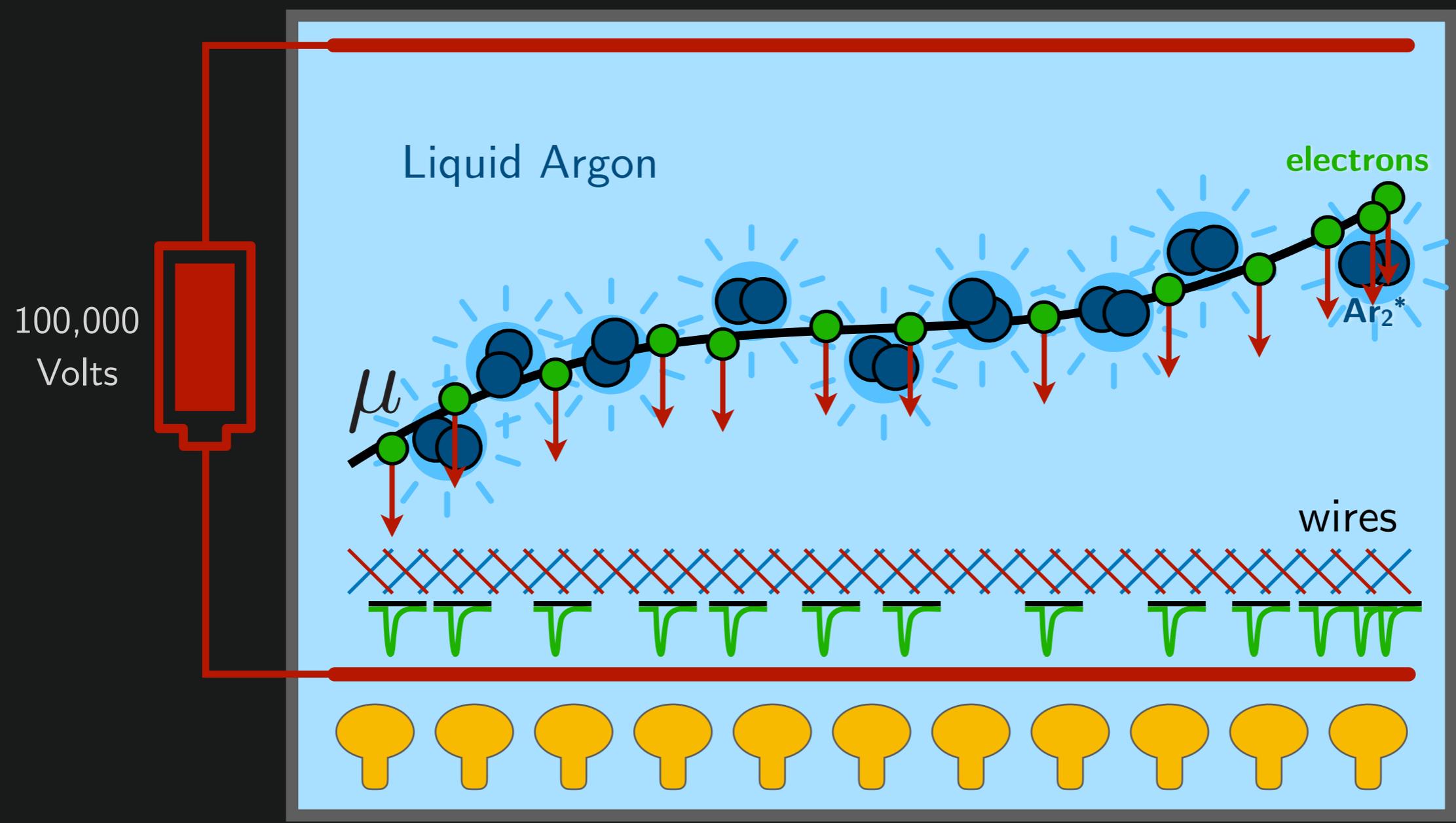


ICARUS
The Far Detector
from Far Away

LArTPCs

Liquid Argon Time Projection Chambers

Brr!
-300°F



LArTPCs

μ BooNE

Top-down
view

LArTPCs give us a detailed
view of each neutrino interaction

ν_μ

time
wire

30 cm

Run 3469 Event 28734, October 21st, 2015

The DUNE Detectors

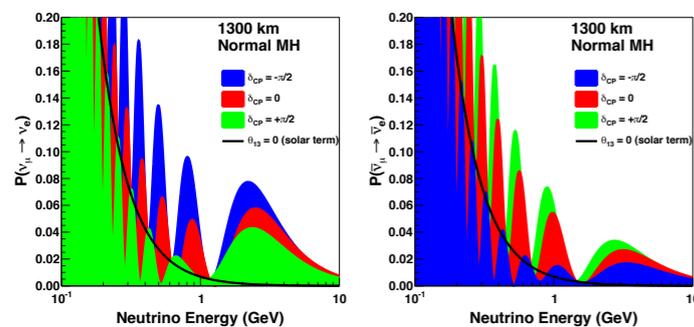


3.5 Olympic size swimming pools in each module

All together, DUNE uses 70,000 tons of liquid argon

40 feet tall
45 feet wide
170 feet long

TPC Module



The DUNE Detectors



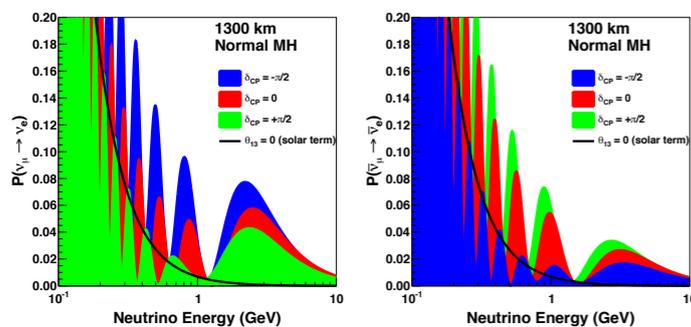
3.5 Olympic size swimming pools in each module

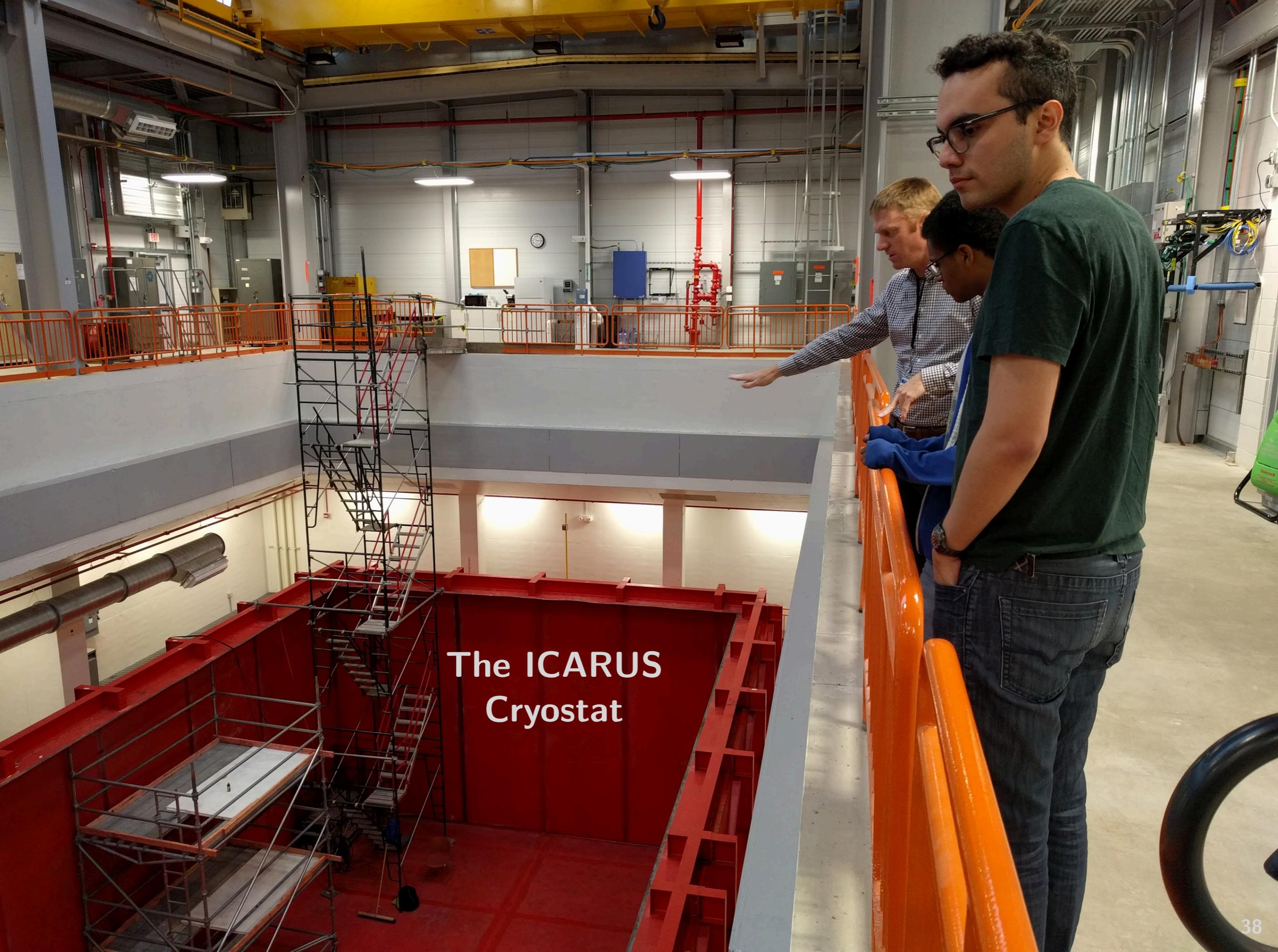
But rather brisk at -300°F ❄️

All together, DUNE uses 70,000 tons of liquid argon

40 feet tall
45 feet wide
170 feet long

TPC Module





The ICARUS
Cryostat

The DUNE Detector



3.5 Olympic size swimming pools in each module

But rather brisk at -300°F ❄️

All together, DUNE uses 70,000 tons of liquid argon

40 feet tall
45 feet wide
170 feet long

TPC Module

ICARUS ■

Less than 1/20th of a single DUNE module

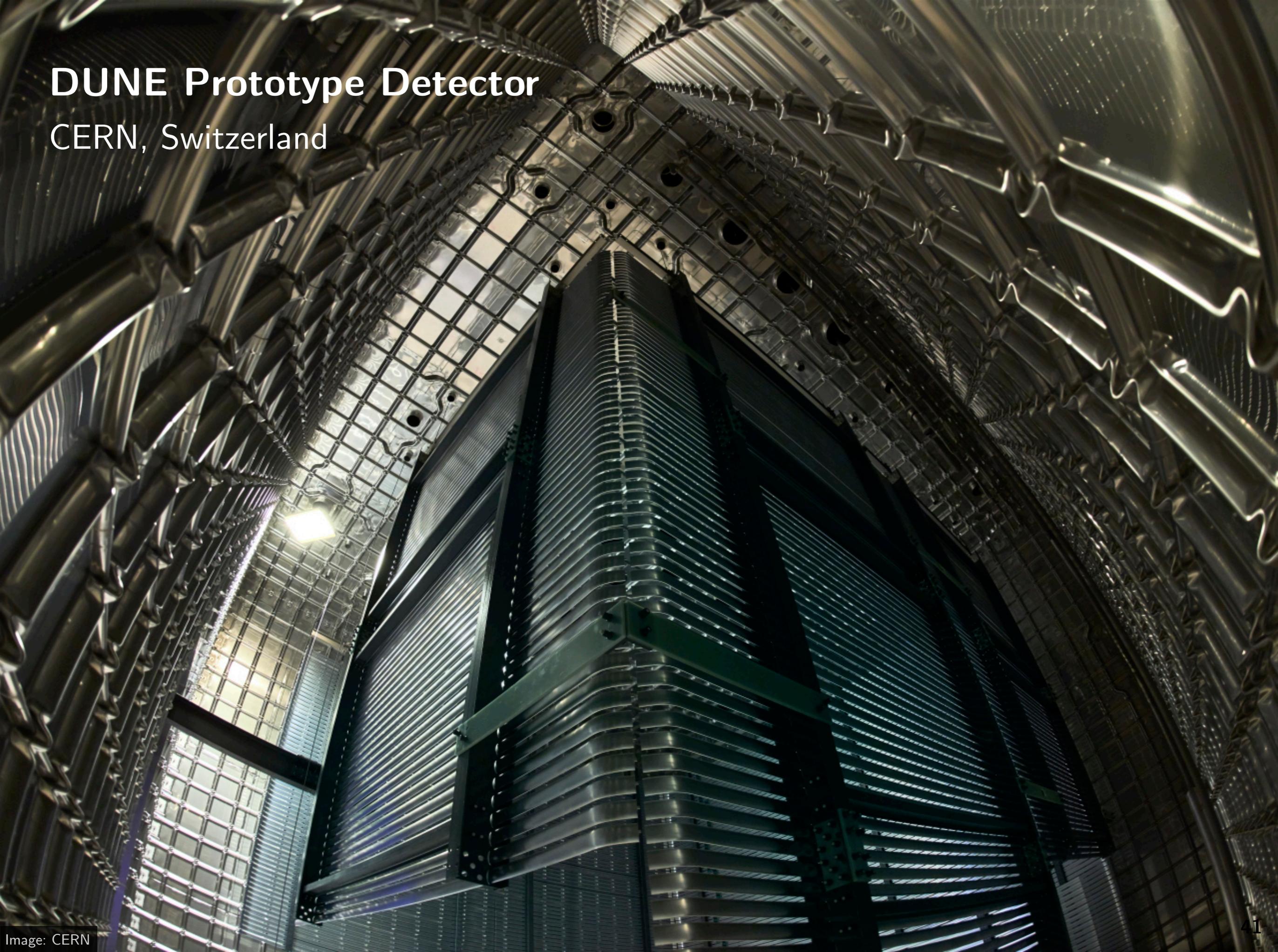
DUNE Prototypes

"Small" Prototypes Built at CERN



DUNE Prototype Detector

CERN, Switzerland

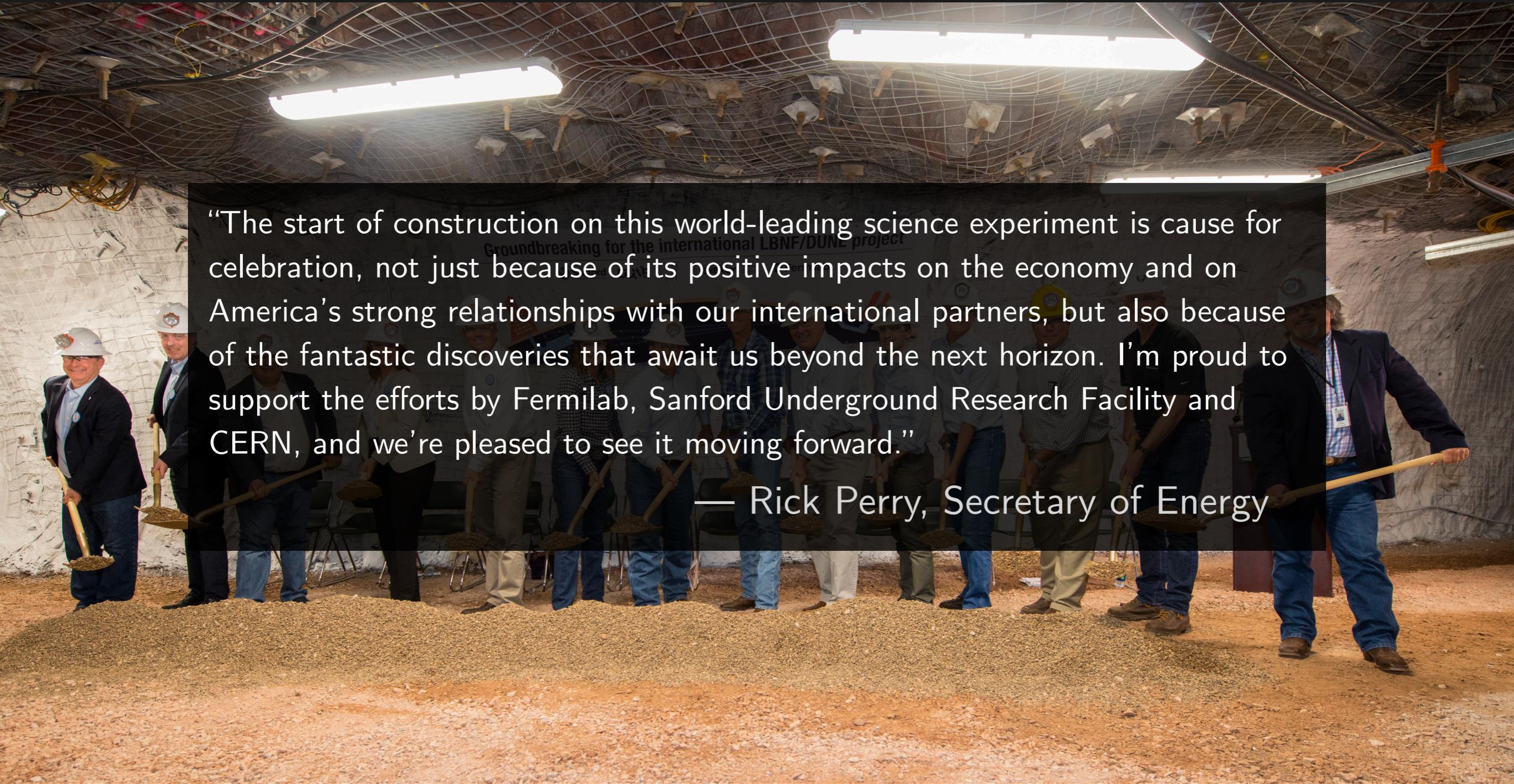


Groundbreaking Science!



Start of construction at DUNE, July 2017

Groundbreaking Science!



“The start of construction on this world-leading science experiment is cause for celebration, not just because of its positive impacts on the economy and on America’s strong relationships with our international partners, but also because of the fantastic discoveries that await us beyond the next horizon. I’m proud to support the efforts by Fermilab, Sanford Underground Research Facility and CERN, and we’re pleased to see it moving forward.”

— Rick Perry, Secretary of Energy

Start of construction at DUNE, July 2017

DUNE Timeline



DUNE Collaboration



DUNE Collaboration



32
Nations



175
Institutions



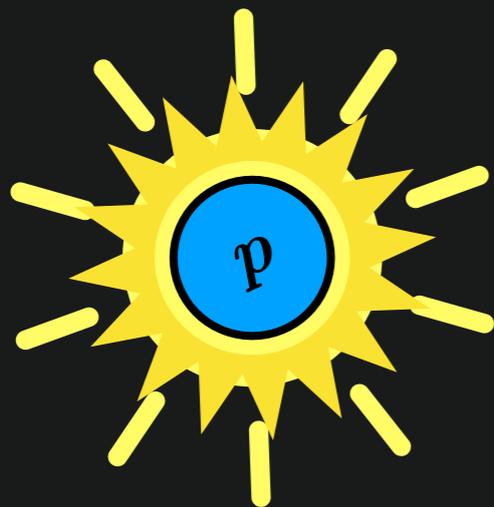
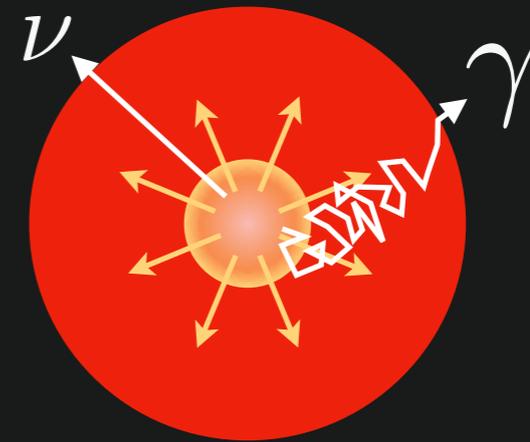
1083
Collaborators

Discovery at DUNE



Searching for CP violation in neutrino interactions helps us explain the matter/antimatter asymmetry that leads to the observable universe

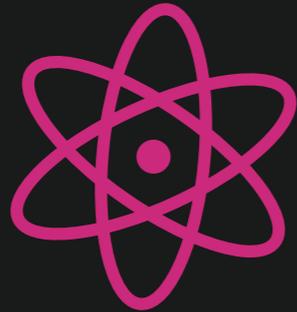
DUNE will be a world-class detector for studying supernova neutrinos (fingers crossed for a supernova!)



It will also conduct sensitive searches for the decay of protons, a very rare process predicted in many theories beyond the Standard Model

Discovery at DUNE

Discovery at DUNE



Pushing the boundaries of science and addressing some of our grandest questions



Pushing the boundaries of technology and engineering, with many potential applications



A huge, international undertaking building connections around the world, with many benefits here at home

The background of the slide is a deep field image from the Hubble Space Telescope, showing a vast field of galaxies in various colors and shapes, including blue, yellow, and red, set against a dark cosmic background.

V
Thank You!