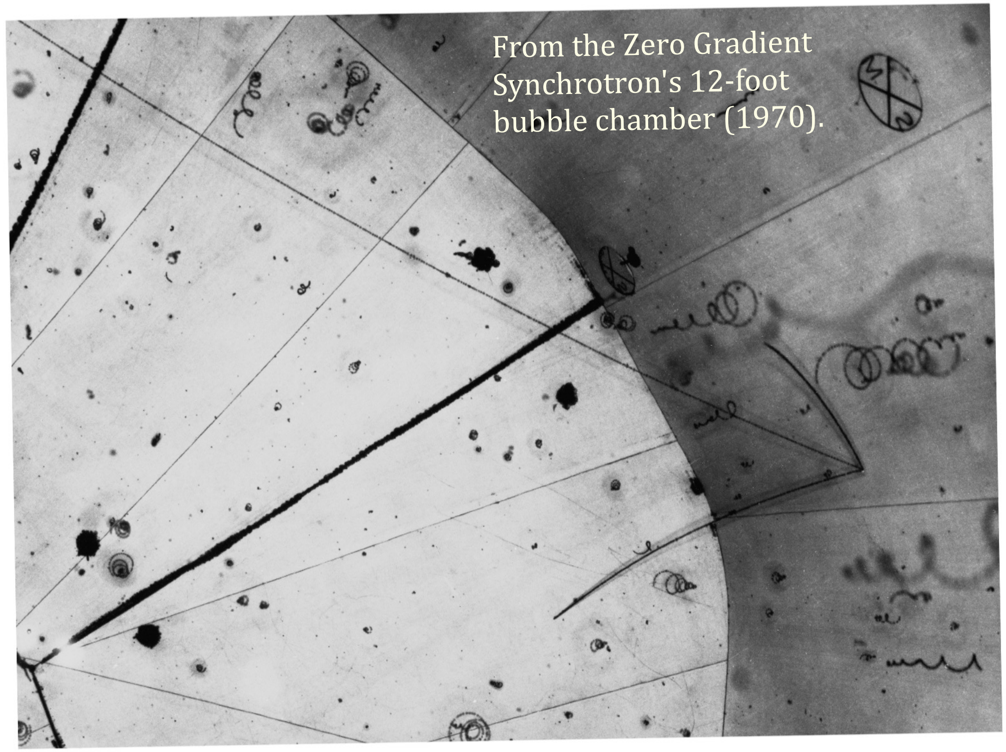


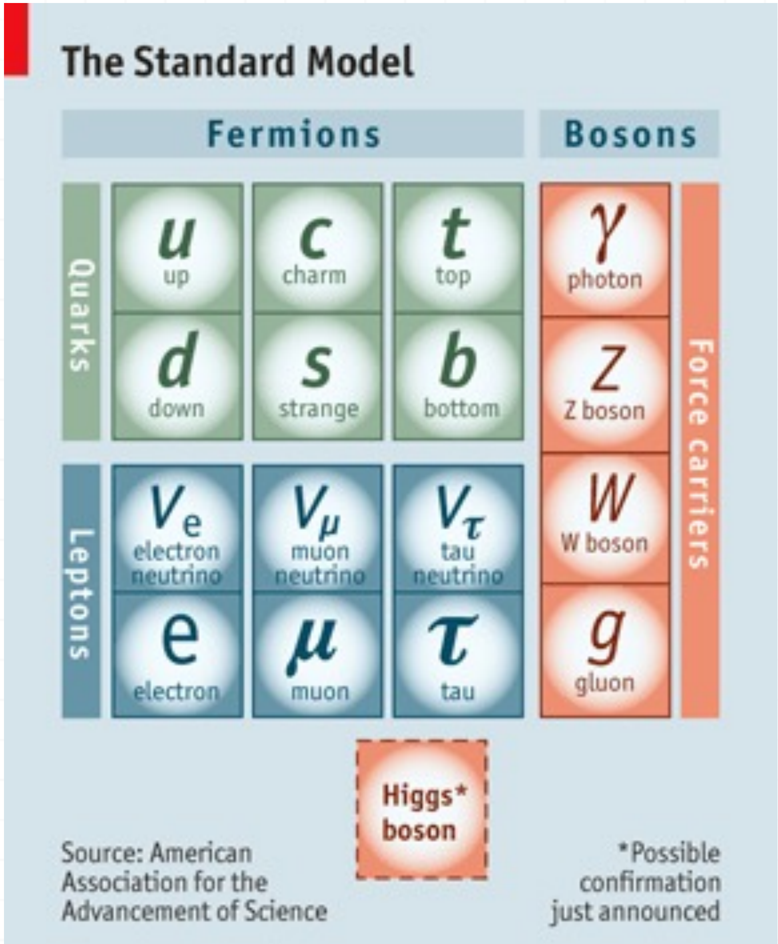
Probing an existential asymmetry: The quest to understand neutrino masses

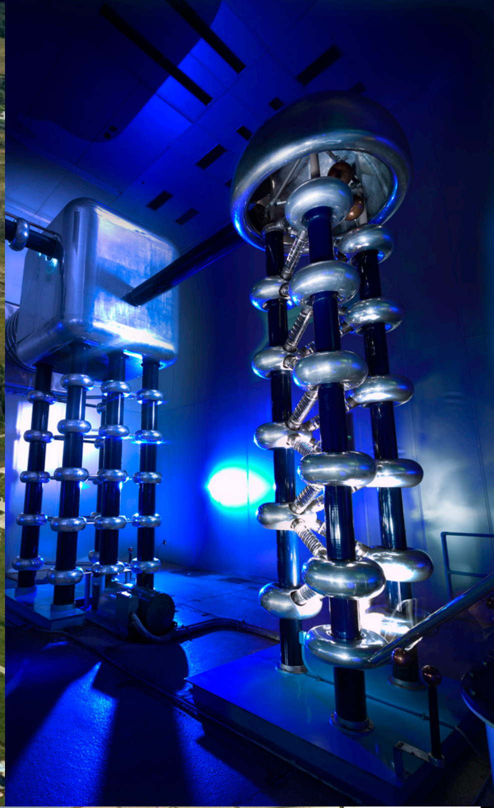
P. Vahle, William and Mary

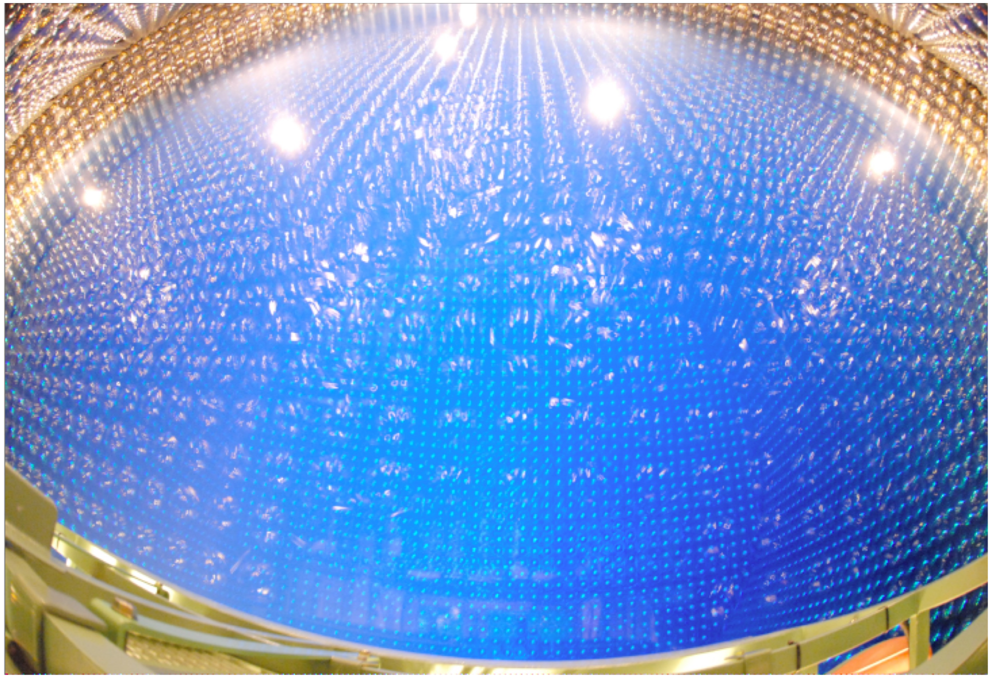
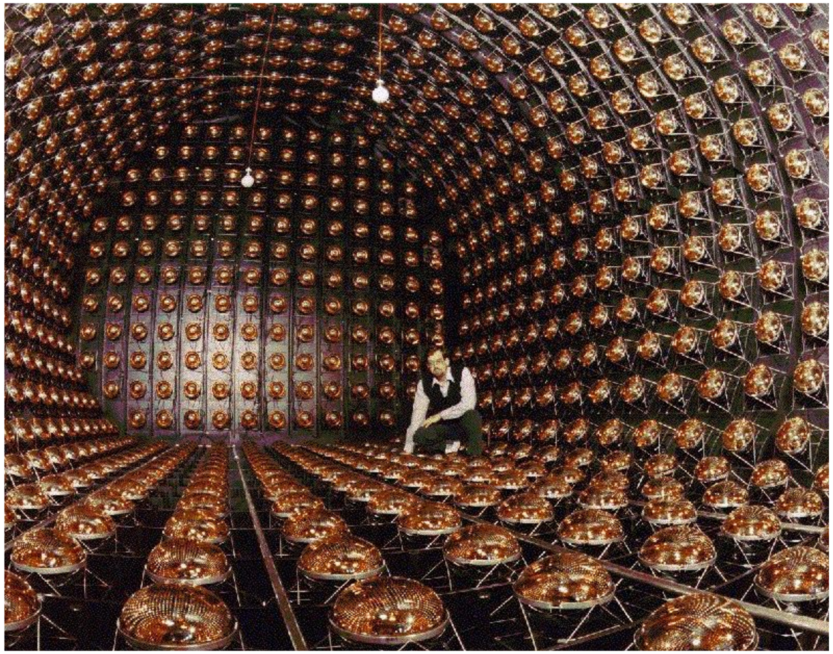
Nov. 11, 2020

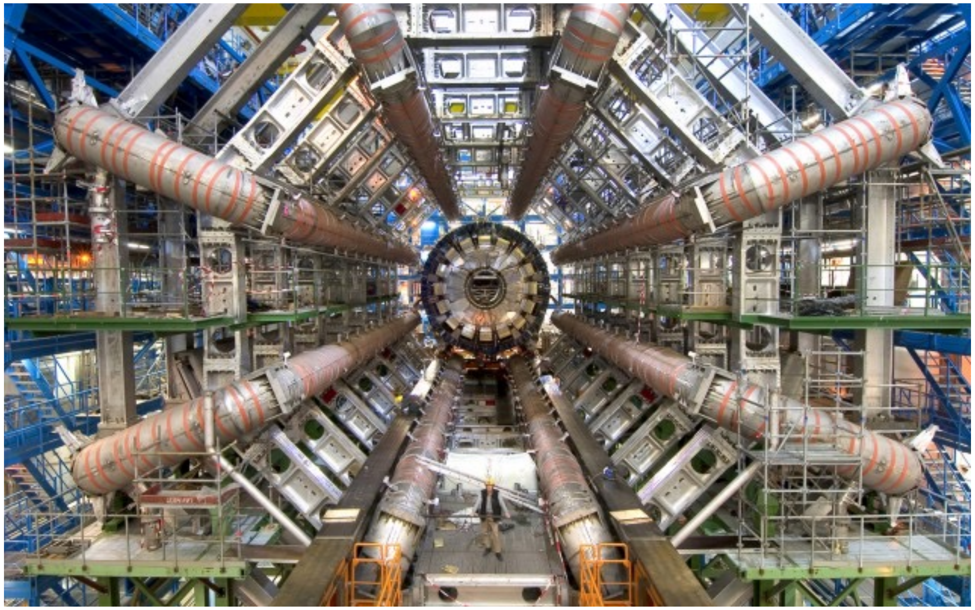
The Standard Model

- The Standard Model of particle interactions describes the interactions of all the particles that make up matter
  - Now complete with the discovery of the Higgs
  - A phenomenal success
    - SM has predicted the existence of every particle discovered since its inception
    - Properties of particles and their interactions can be computed to astounding precision

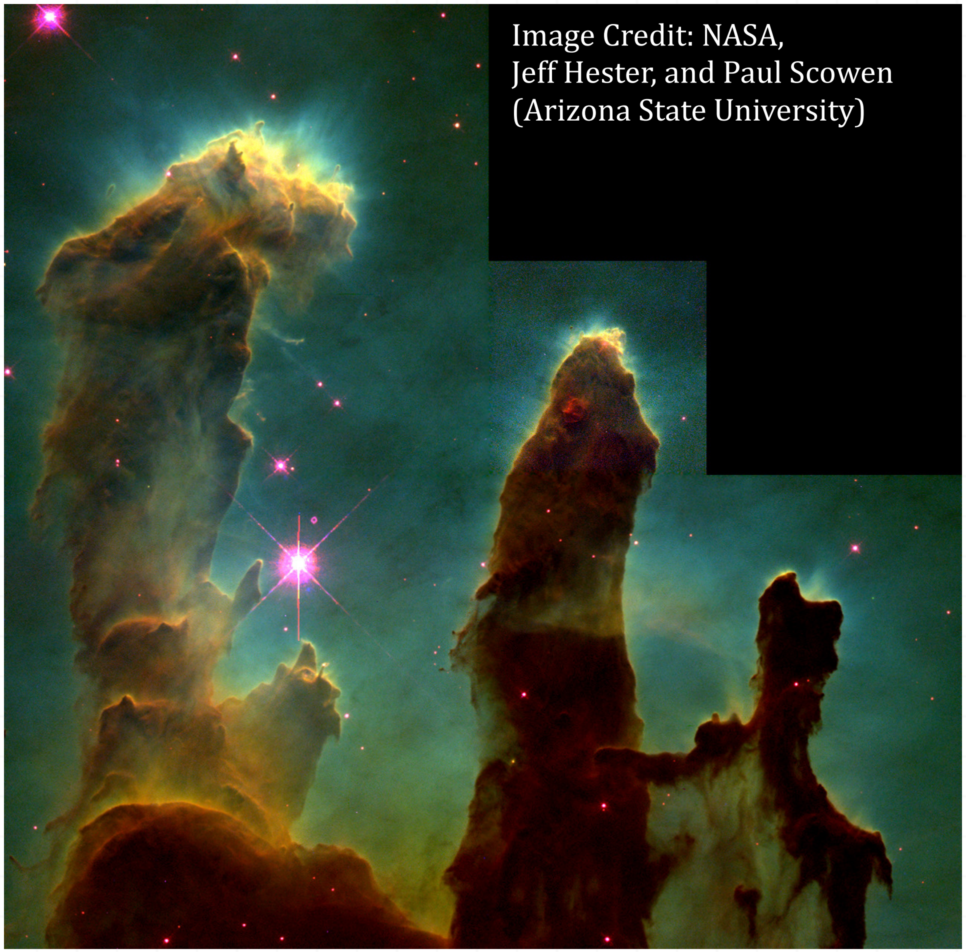






The Rest of the Story

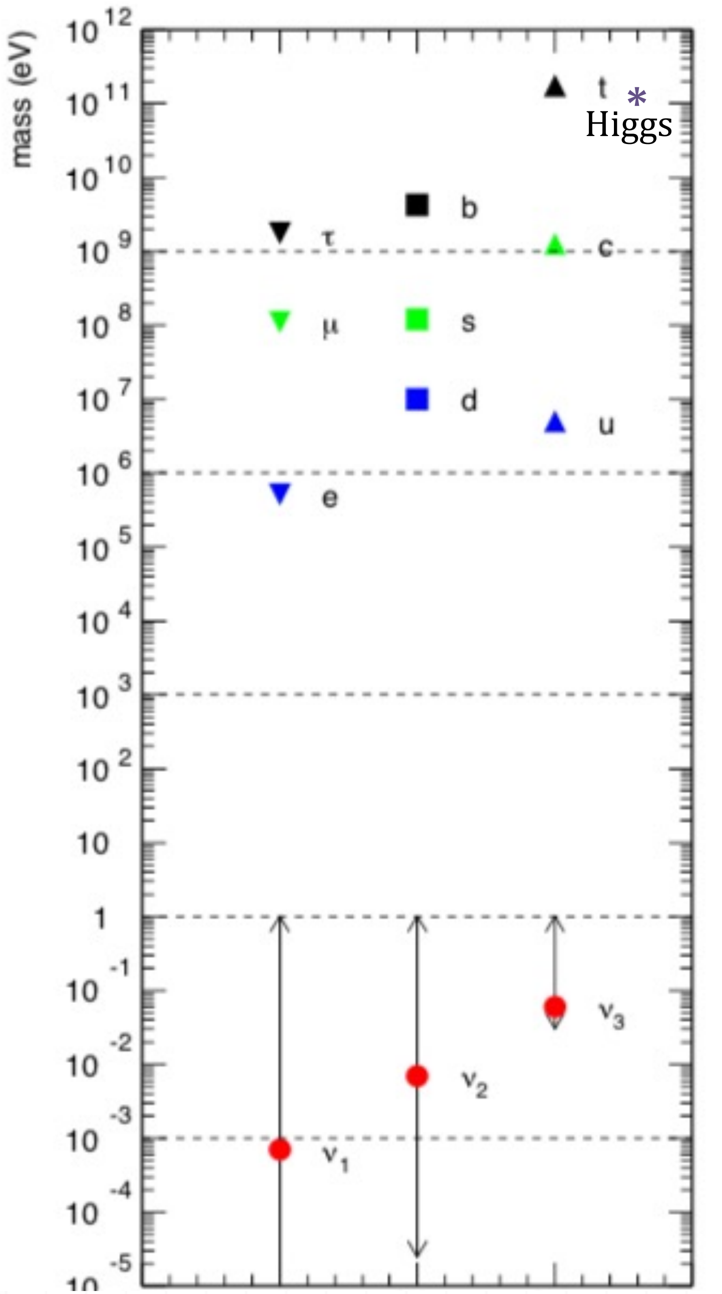


- The Standard Model predicts particles and their antiparticles should be produced in equal amounts
  - All the visible matter in the universe appears to be made up of particles
  - Where did all the antimatter go?
  - When matter and antimatter meet, they annihilate, leaving behind only energy
  - How did the matter survive to form our galaxies, solar system, and planets?
- The elusive neutrino may hold the answer!

The little neutral one

- No electrical charge
- Very small mass
- Doesn't feel the strong nuclear force
- Only interacts via Nature's Weak Interaction

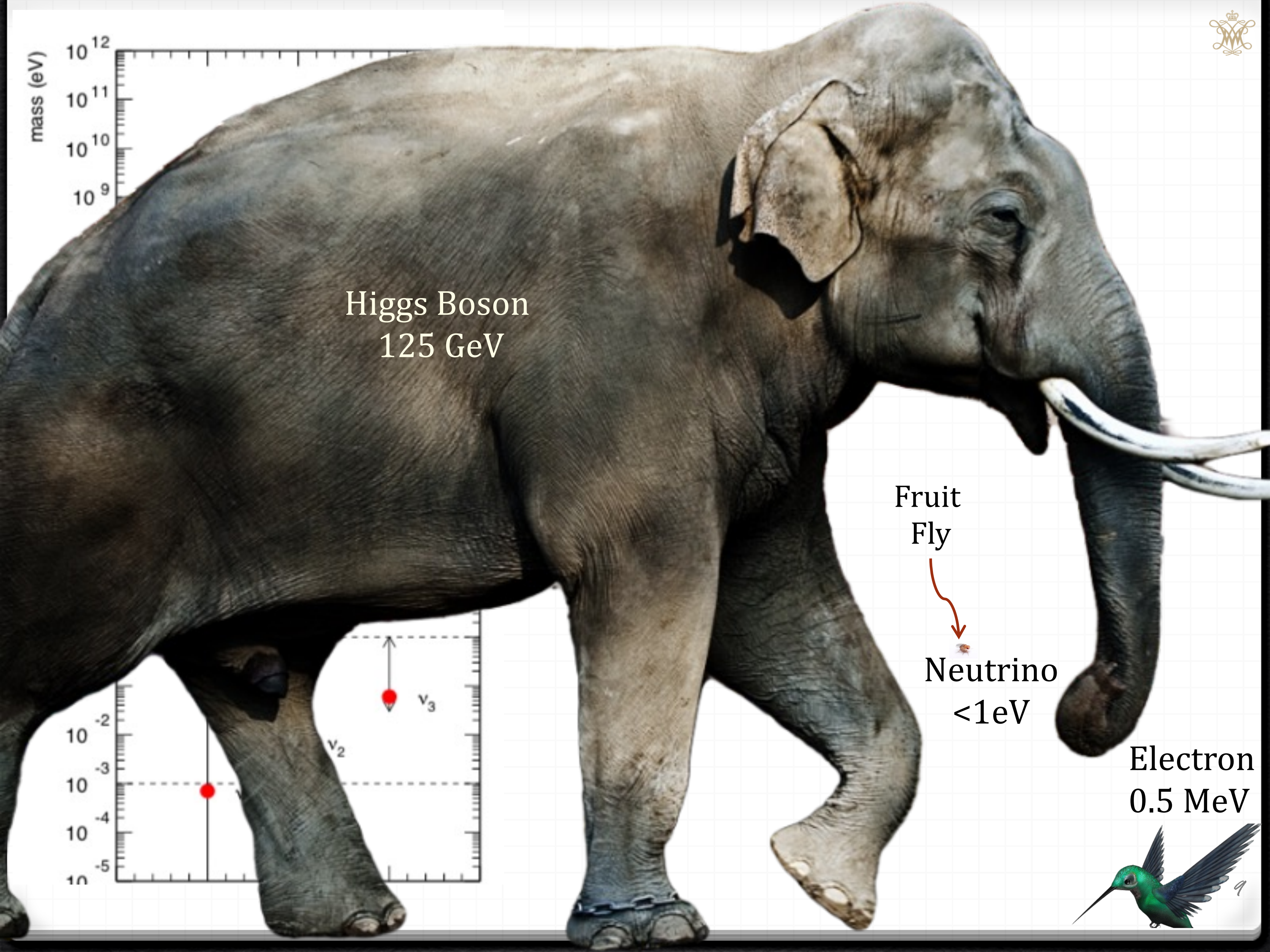
The neutrino can travel through
astronomical amounts of material without stopping,
and yet they are the most abundant matter particle in the universe

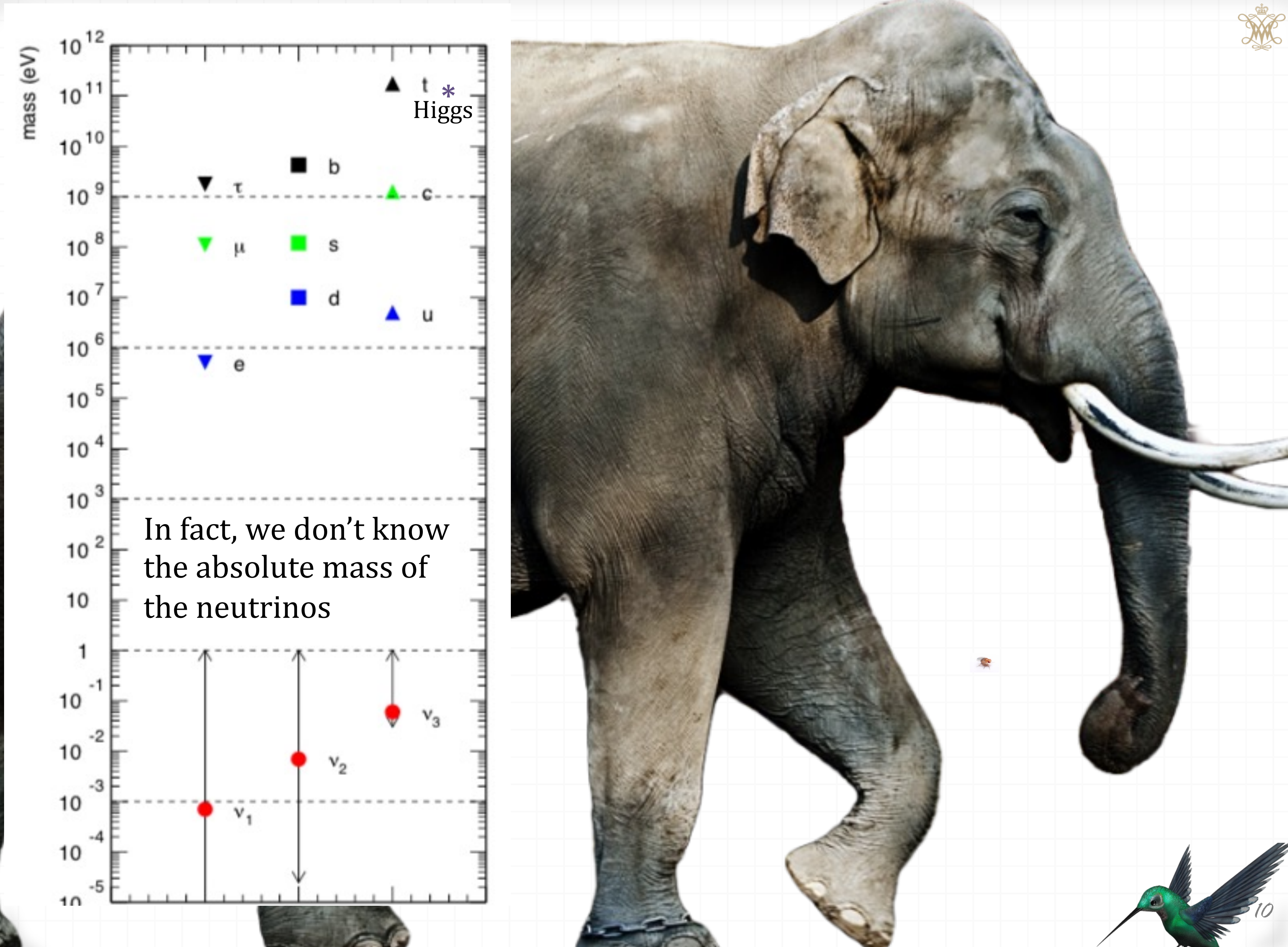


A. de Gouvea, arXiv:0902.4656

Masses of the Particles of the Standard Model

- The electron is the lightest of the charged fundamental particles
- The Higgs boson and the Top Quark weigh in 5 orders of magnitude heavier
- The neutrinos are at least 5 orders of magnitude lighter


mass (eV)
10^{12}
10^{11}
10^{10}
10^{9}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
ν_3
ν_2
Higgs Boson
125 GeV
Fruit
Fly
Neutrino
<1eV
Electron
0.5 MeV
9


mass (eV)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
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10^{4}
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10^{2}
10
1
10^{-1}
10^{-2}
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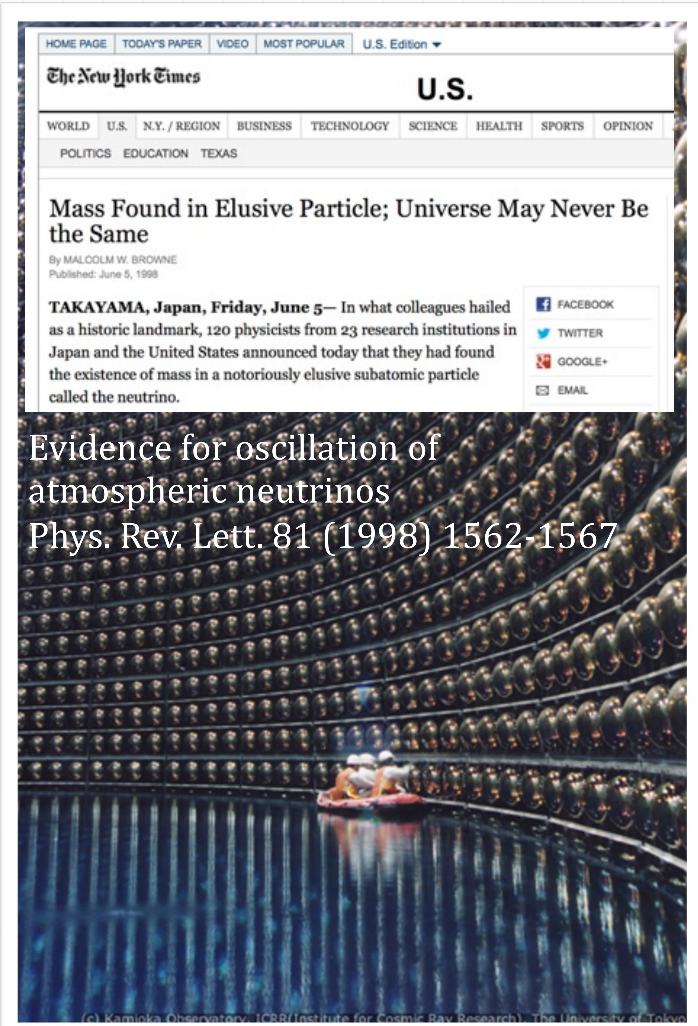
10^{-4}
10^{-5}
t
*
Higgs
τ
b
c
μ
s
d
u
e
ν_3
ν_2
ν_1
In fact, we don't know the absolute mass of the neutrinos

How do we know they have any mass at all?

How do we know they have mass?


HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | U.S. Edition

The New York Times — U.S.

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

POLITICS | EDUCATION | TEXAS

Mass Found in Elusive Particle; Universe May Never Be the Same

By MALCOLM W. BROWNE
Published: June 5, 1998

TAKAYAMA, Japan, Friday, June 5— In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

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GOOGLE+
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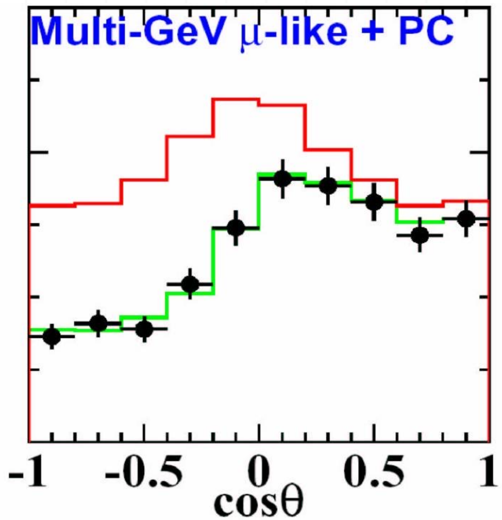
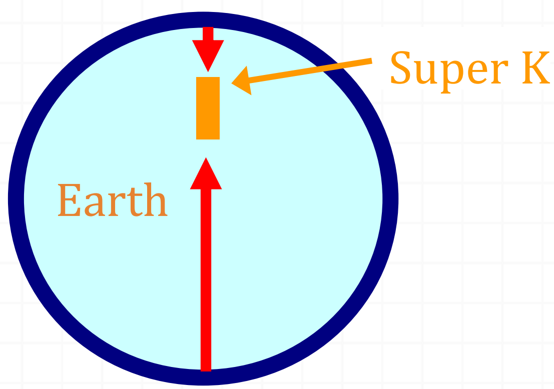




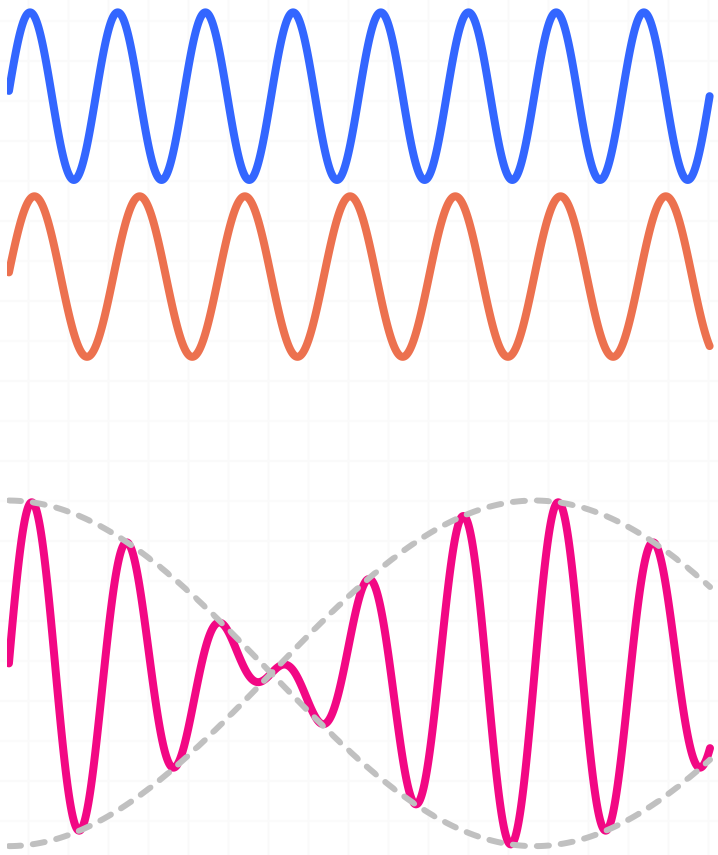
Super K measures flux of neutrinos from interactions in atmosphere vs. zenith angle

Expected number of muon neutrinos come from overhead, but too few from below

Neutrinos oscillate, or change flavor, as they travel, which only happens if neutrinos have mass

Particle or Wave?

- Neutrinos (and in fact all subatomic particles) act like waves
- If neutrinos have mass, each flavor is a combination of different waves, oscillating at different frequencies
- These different waves interfere
- the flavor of the neutrino changes back and forth as the waves constructively and destructively interfere



Animation courtesy D. Schmidt

Neutrino Mass

- Neutrinos from the sun, the atmosphere, nuclear reactors, and accelerators all oscillate
- Oscillations only reveal the differences in masses of neutrinos (squared)
- Three neutrinos means two mass differences

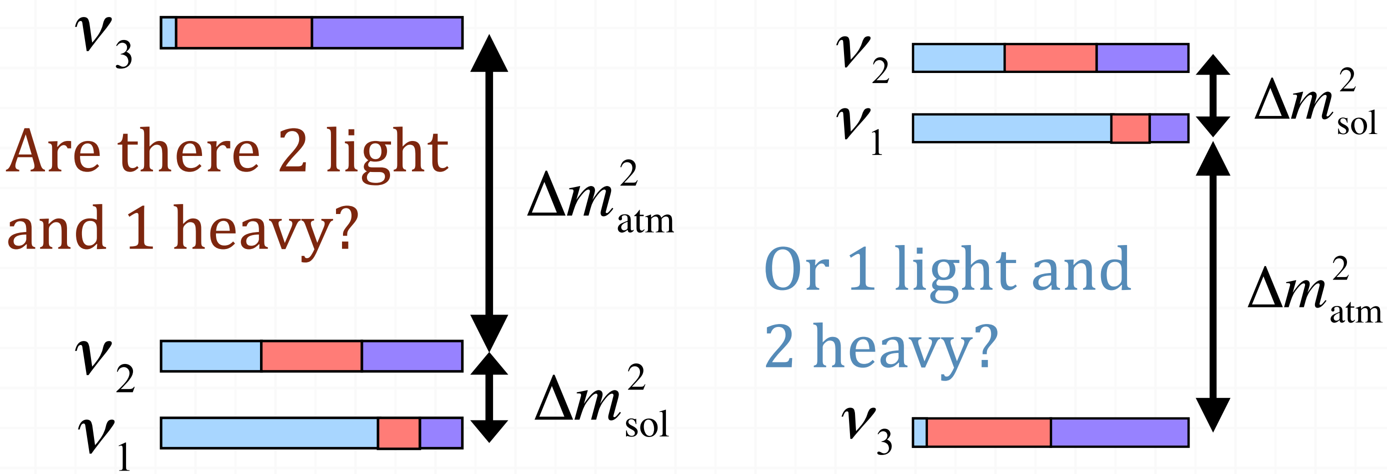
Neutrino mass limit ~1 eV

Big mass difference ~0.05 eV

Small mass difference ~0.009 eV

Mass Ordering

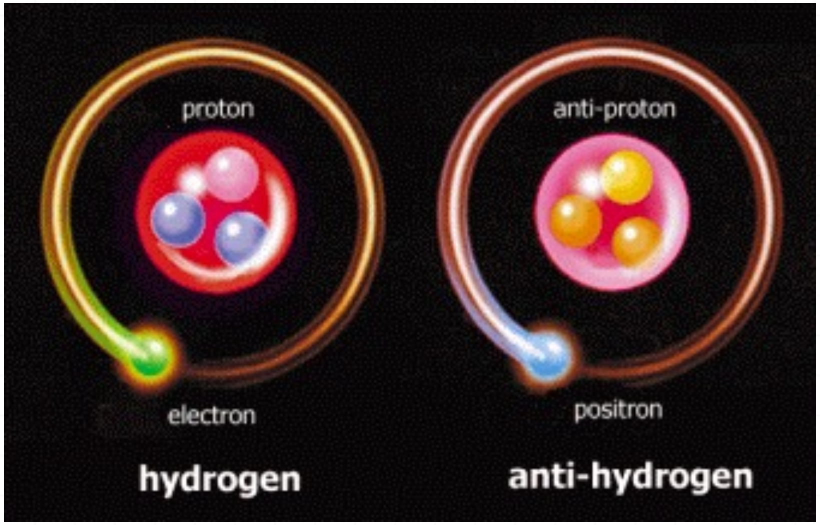
- But how are they ordered?



Normal Hierarchy Inverted Hierarchy

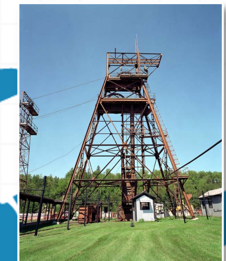
- When neutrinos travel through matter, there are a lot of electrons in the way, but no muons or taus. Oscillations into electron type neutrinos are enhanced or suppressed depending on this ordering.

CP Violation?



- What would happen if we turn all the matter into antimatter?
- Do we measure the same oscillations?
- We can't turn detectors into anti-detectors, nor can we change the Earth into anti-Earth, but we can make a beam of anti-neutrinos and compare their oscillations to what we measure with neutrinos
- If they are not the same, it might give us a clue to what caused our matter/anti-matter assymmetry problem!

NOvA



- Long-baseline neutrino oscillation experiment
- Study neutrinos and antineutrinos from NuMI beam at Fermilab
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD (a control)

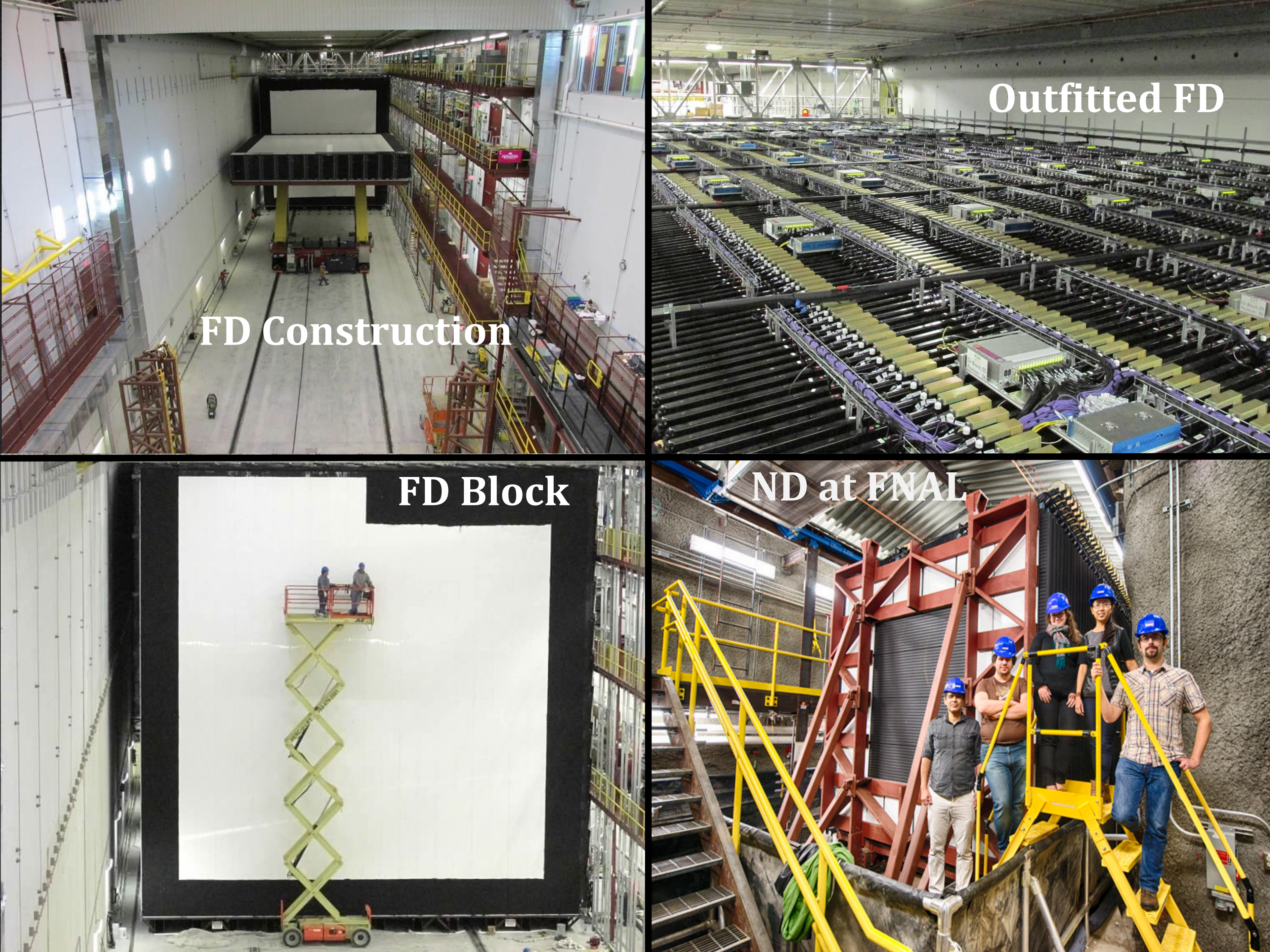
NOvA

268 collaborators at 50 institutions across 7 countries

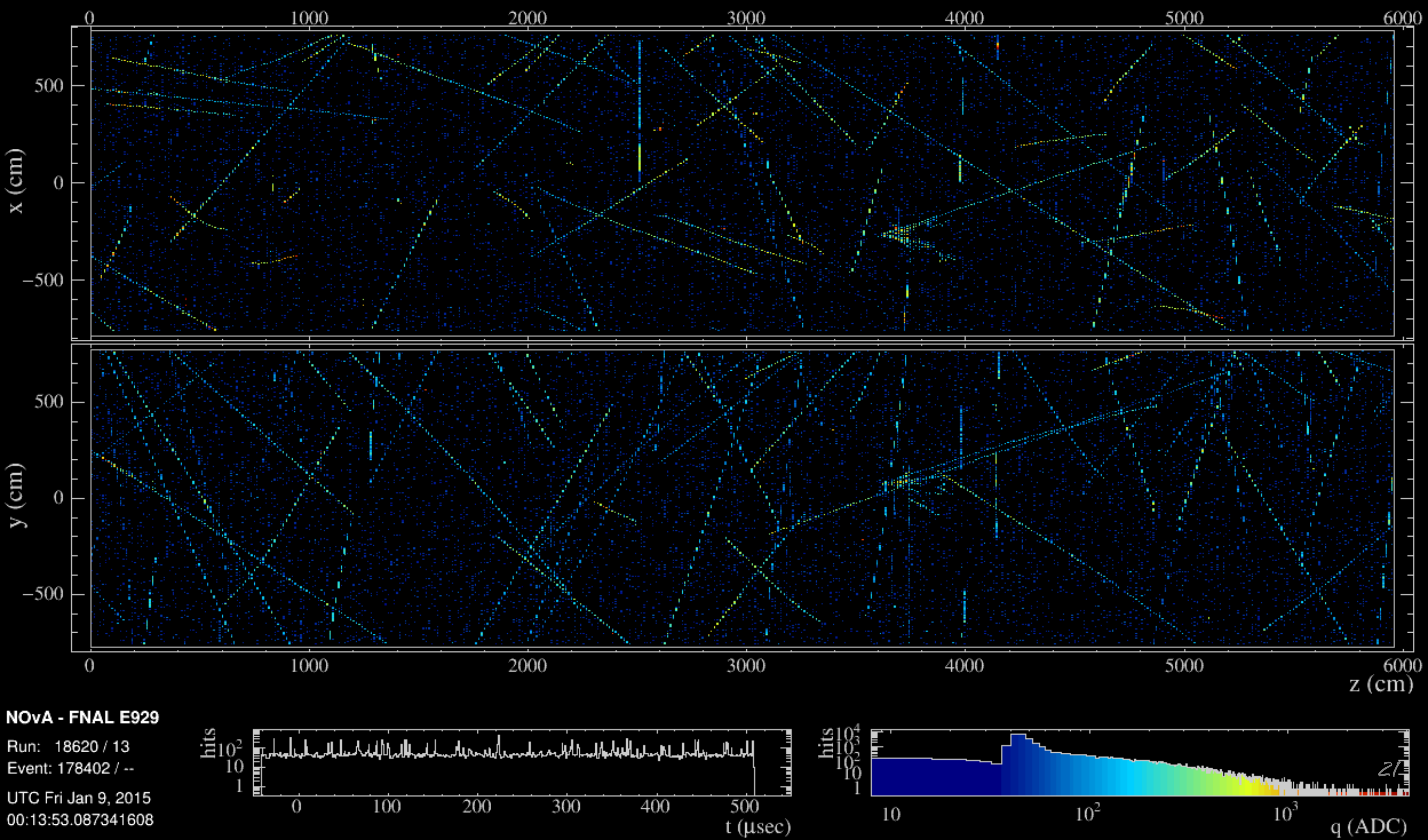
Seeing Neutrinos

Make enough neutrinos, put enough mass in their way, sometimes we get lucky and detect a few.

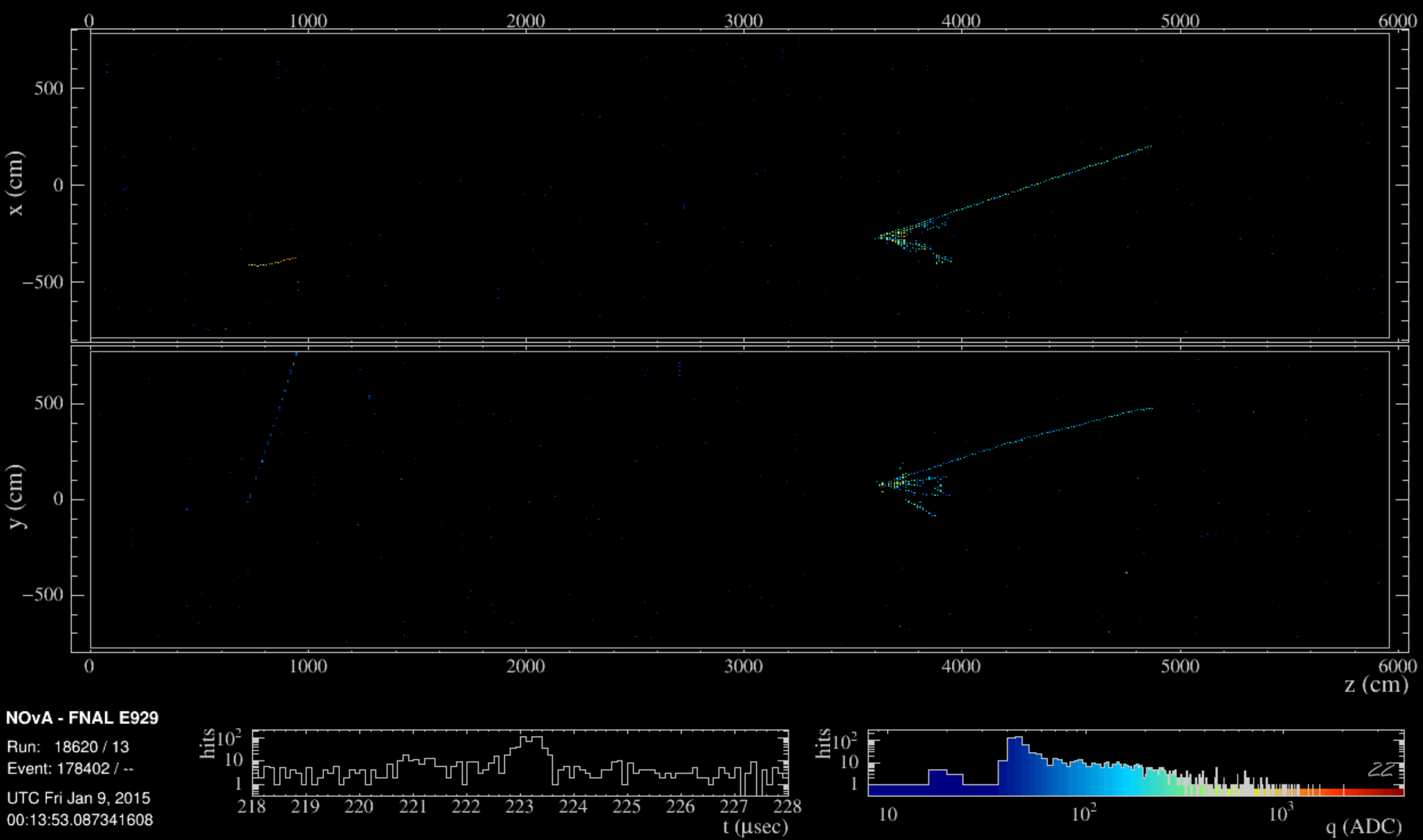
- ND: Underground at Fermilab
- FD: In Northern Minnesota


FD Construction
Outfitted FD
FD Block
ND at FNAL

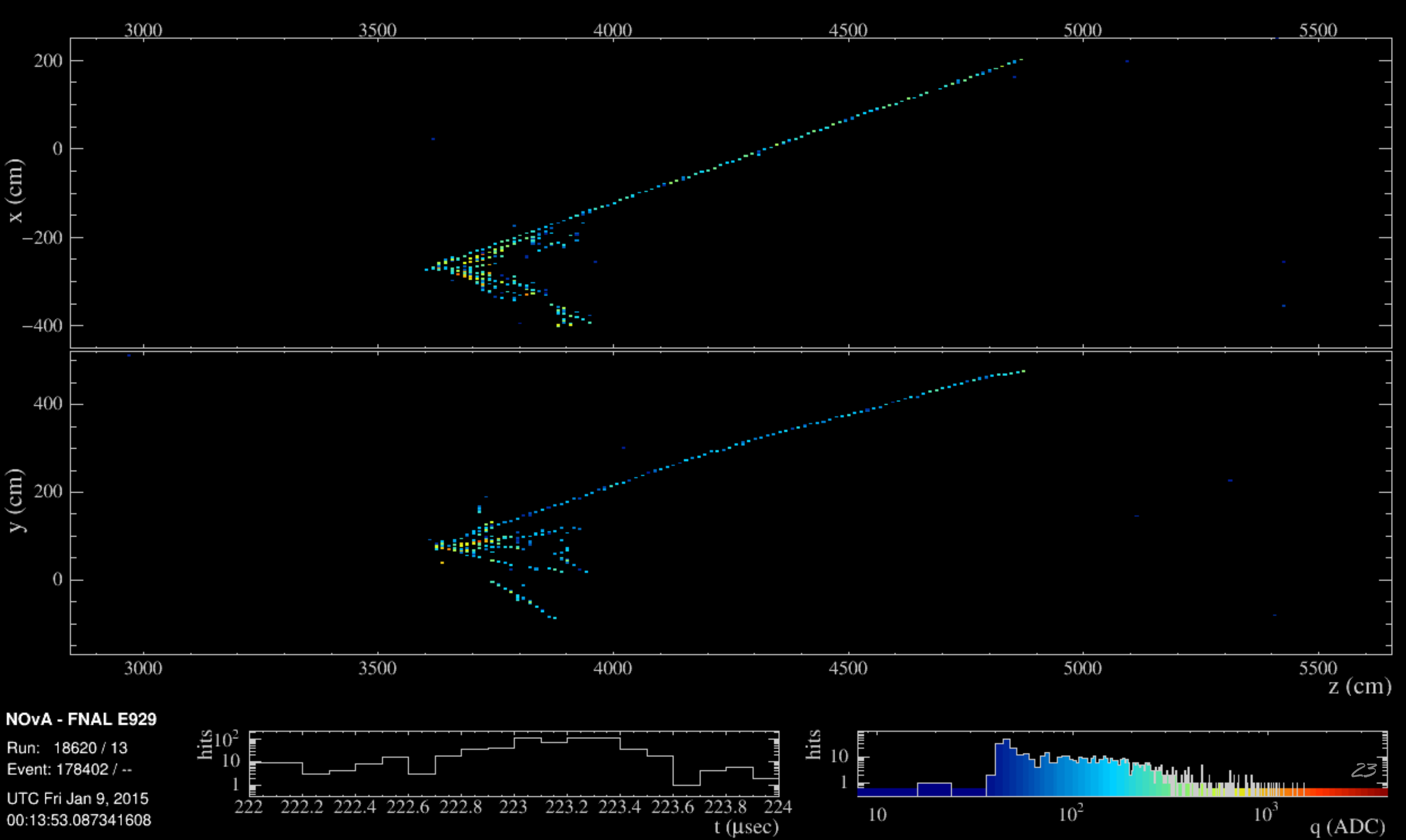
Searching for Neutrinos



Searching for Neutrinos

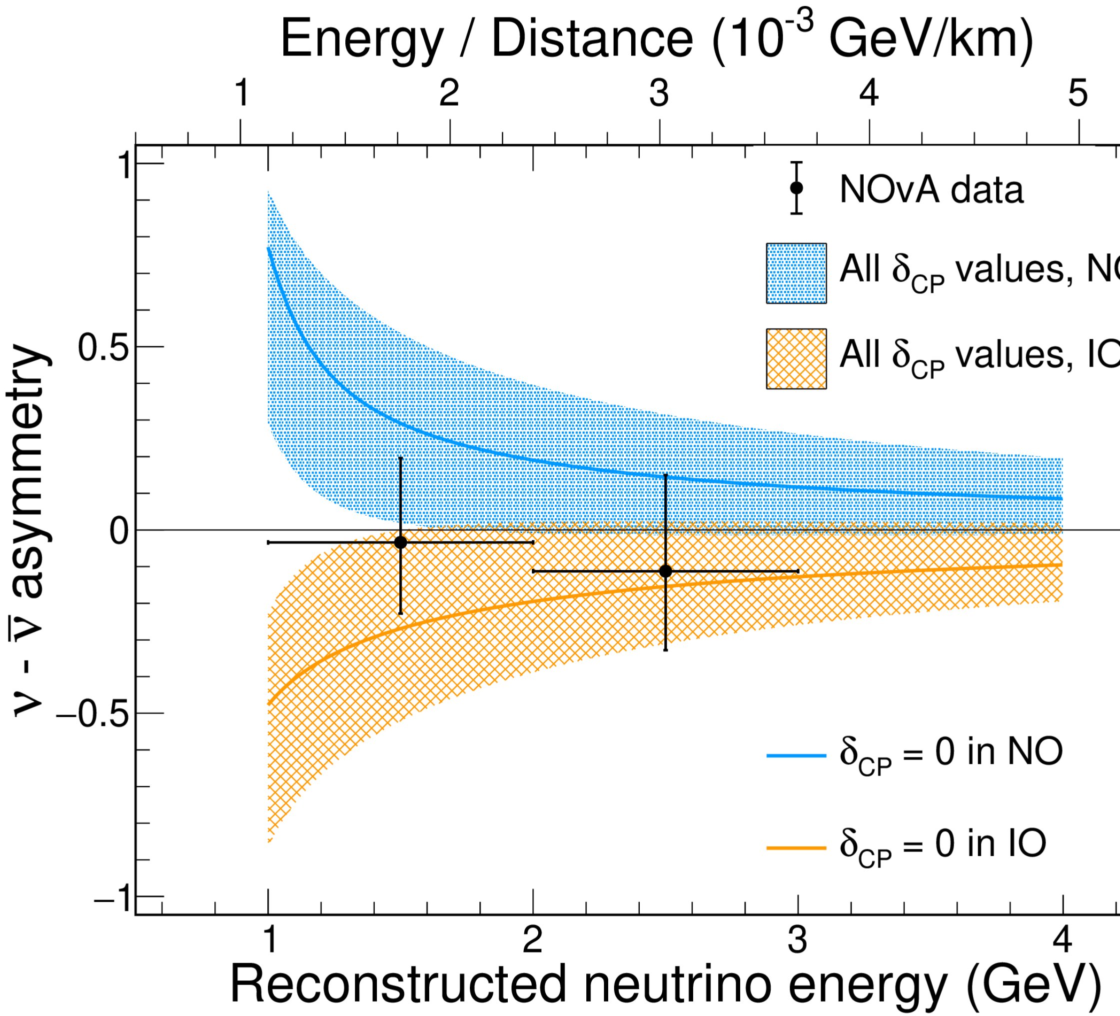


Searching for Neutrinos

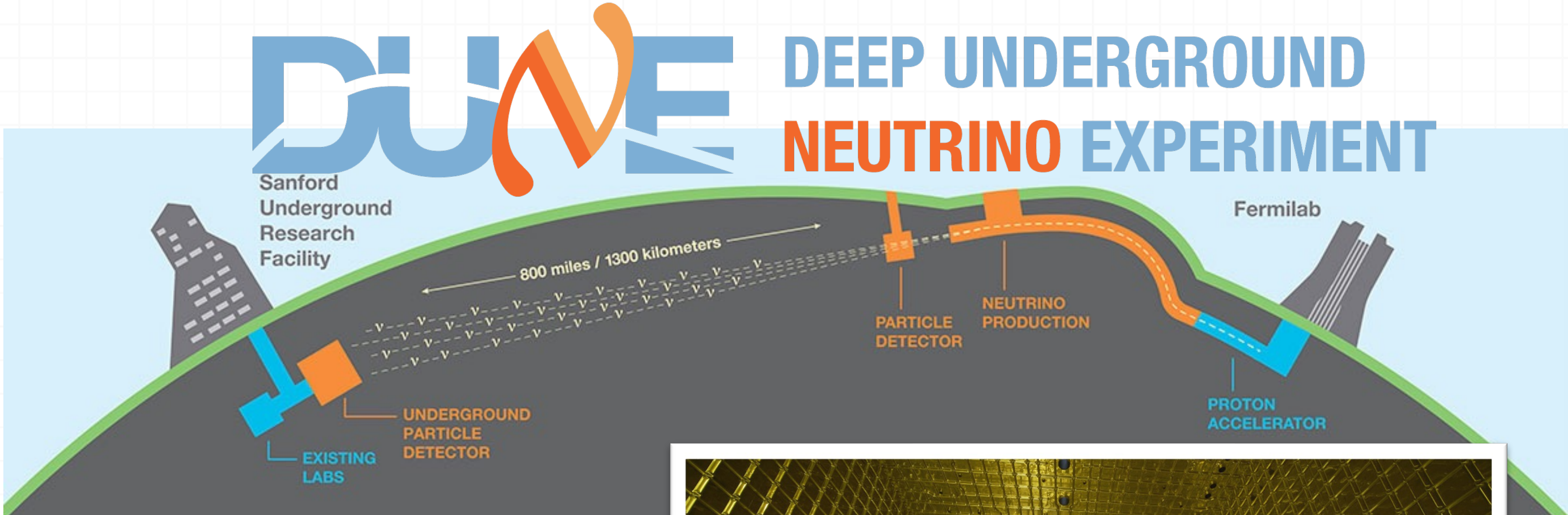


NOvA's Latest Results

Current data does not show a strong asymmetry between neutrino and antineutrino oscillations. Expect to run until 2027 and collect double the data.



Future Prospects




W&M grad students and undergrads at CERN (Switzerland)

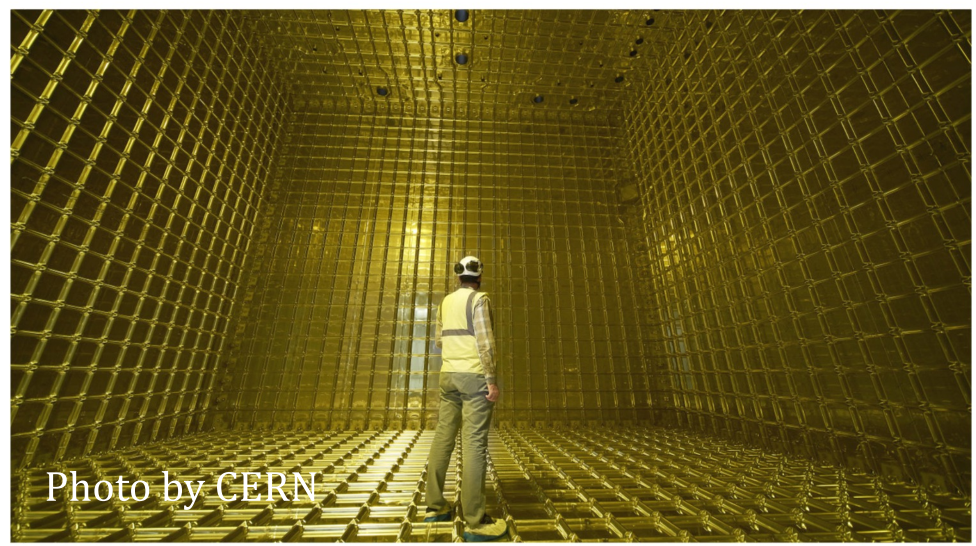


Photo by CERN

Summary

- The quest to understand neutrino mass is well underway
- Neutrinos could hold the answers to multiple unsolved puzzles in physics and cosmology
- Neutrinos may yet have more surprises in store for us

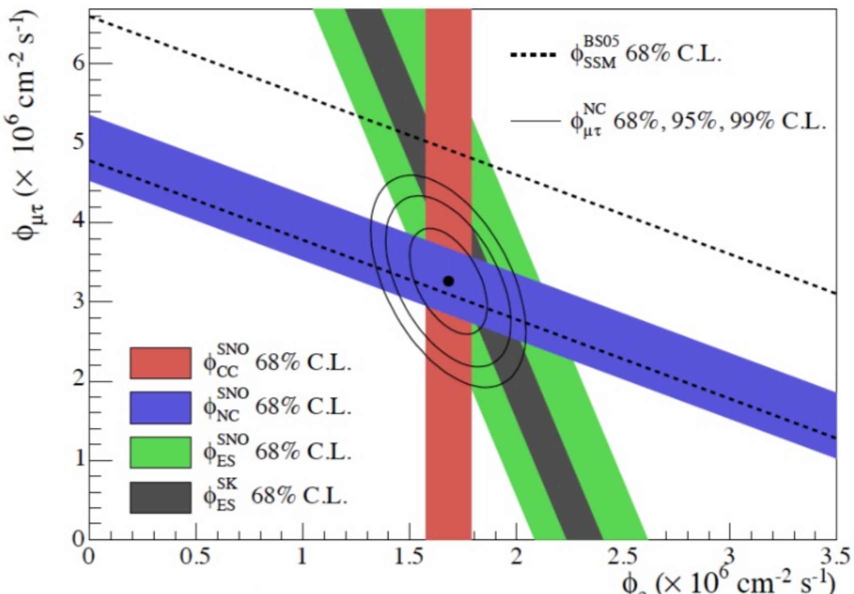
My work funded by the
National Science Foundation

The NOvA experiment is supported by the
Department of Energy, Office of Science

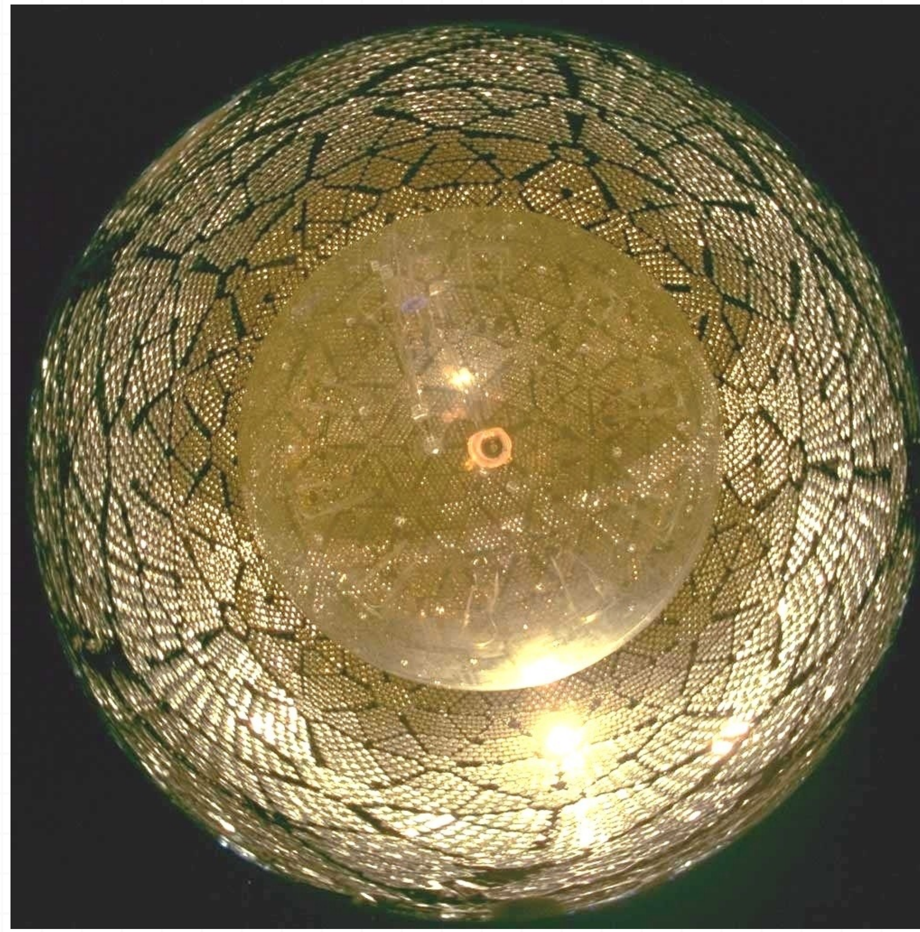
Backup Slides

…and change their flavor

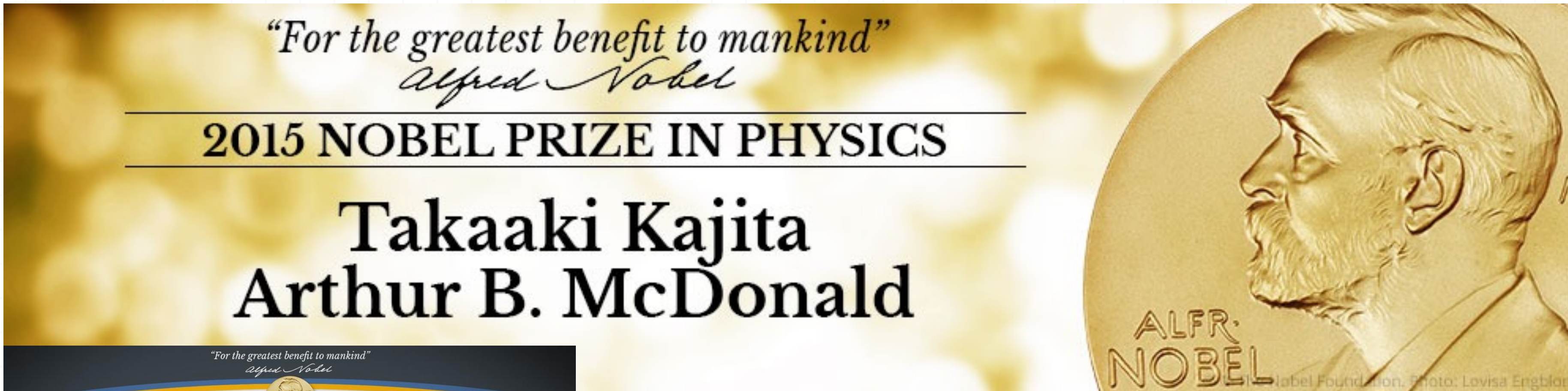
SNO Solar Neutrino Data

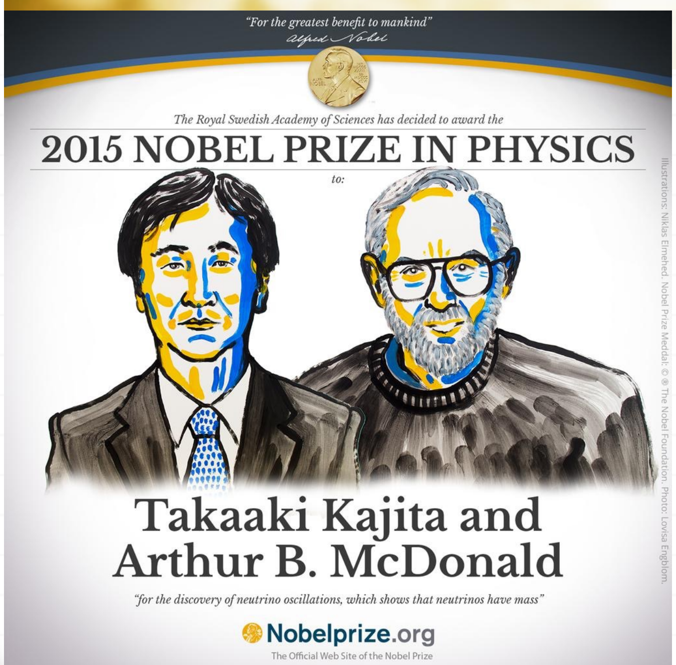


Phys. Rev. Lett. **89**, 011302 (2002)



Neutrinos Have Mass!





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

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

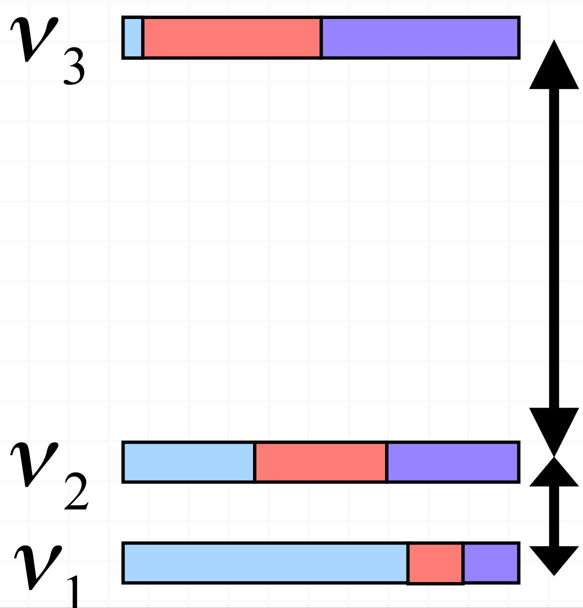
- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij}=m^2_i-m^2_j$)
  - The mixing amplitudes ($U_{\alpha j}$)

The PMNS Mixing Matrix

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 9^\circ$ $\theta_{12} \approx 34^\circ$

What we know



$$\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3}\text{eV}^2$$

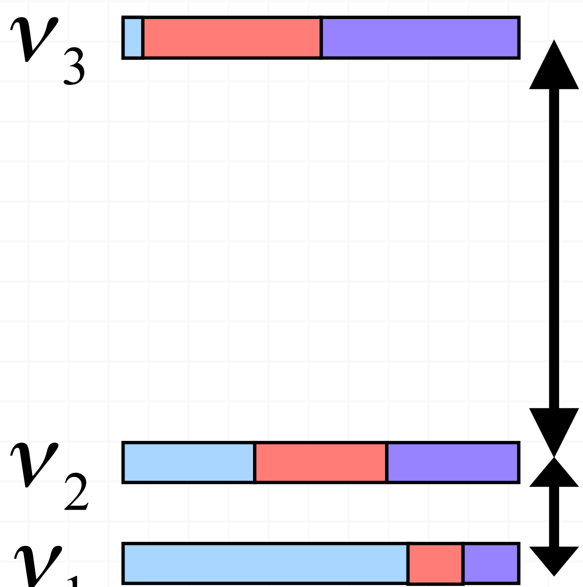
$$\Delta m^2_{\text{sol}} \approx 8 \times 10^{-5}\text{eV}^2$$

The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2(\theta_{23}) : 5\%$ $\sin^2(\theta_{13}) : 3.5\%$ $\sin^2(\theta_{12}) : 5.5\%$

How well we know it



$\Delta m^2_{atm} : 1.5\%$

$\Delta m^2_{sol} : 2.5\%$

From M. Tortola, Neutrino2018 and deSalas et al, 1708.01186 (May 2018)

What we don't know

The PMNS Mixing Matrix

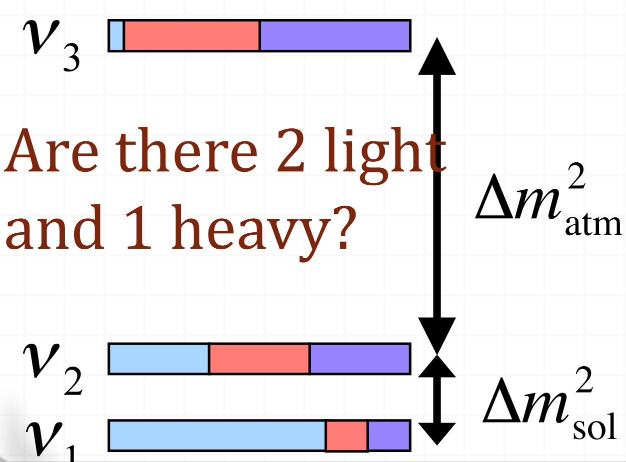
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Is it really 45°?

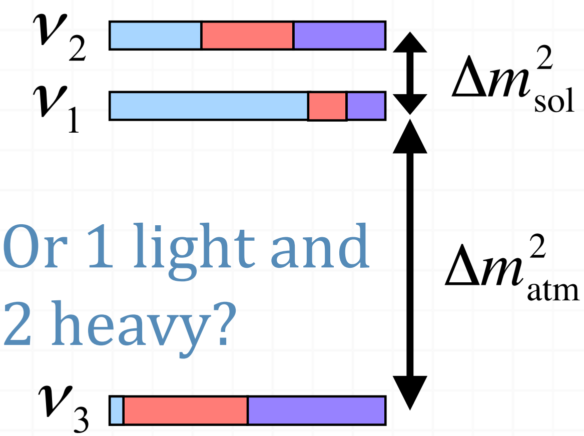
Is there CP violation?

Why is the mixing bigger than in quarks?

The Mass Hierarchy



Are there 2 light and 1 heavy?



Or 1 light and 2 heavy?

Are there more than 3?

What is the absolute mass?

Are neutrinos their own antiparticles?

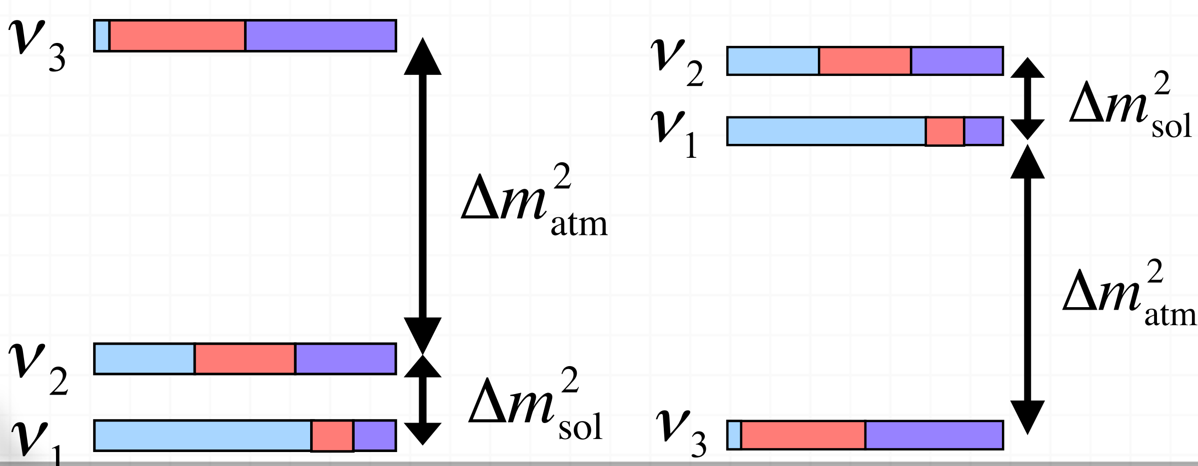
The PMNS Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation in neutrinos may help us understand the matter-antimatter asymmetry of the universe.

Why do we care?

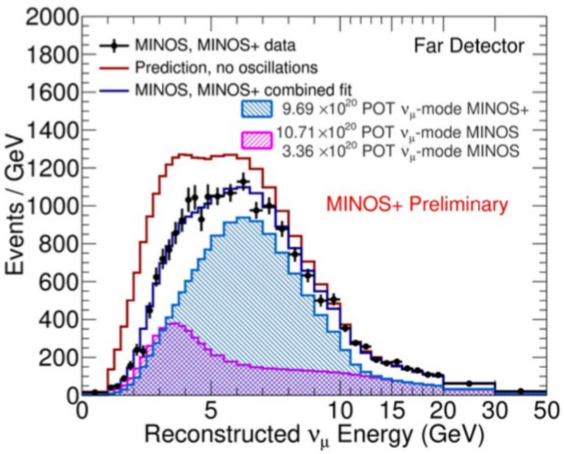
The Mass Hierarchy

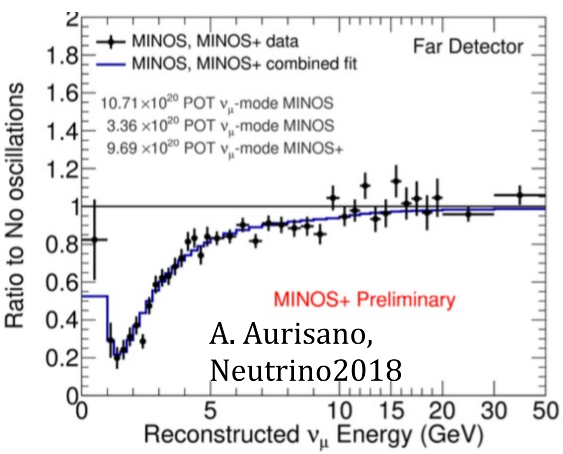


20 years on, we are still exploring how massive neutrinos fit into the Standard Model. Discrimination among models hinges on precision measurements and answers to these questions.

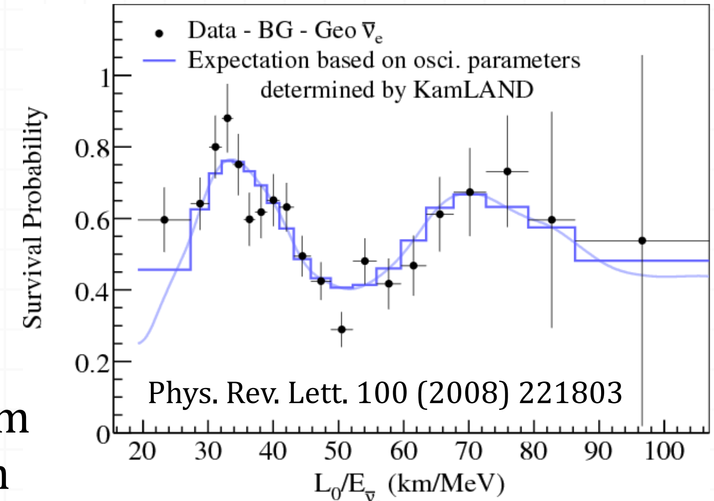
Oscillations

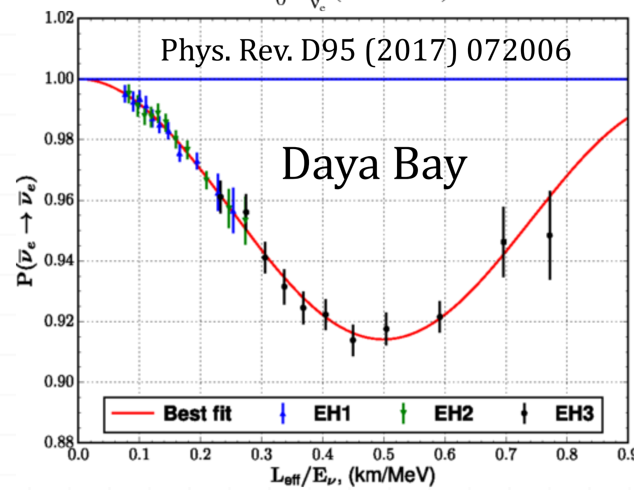
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$





Experiments measuring neutrinos from the sun, from the atmosphere, from nuclear reactors and from accelerators all observe neutrino oscillations

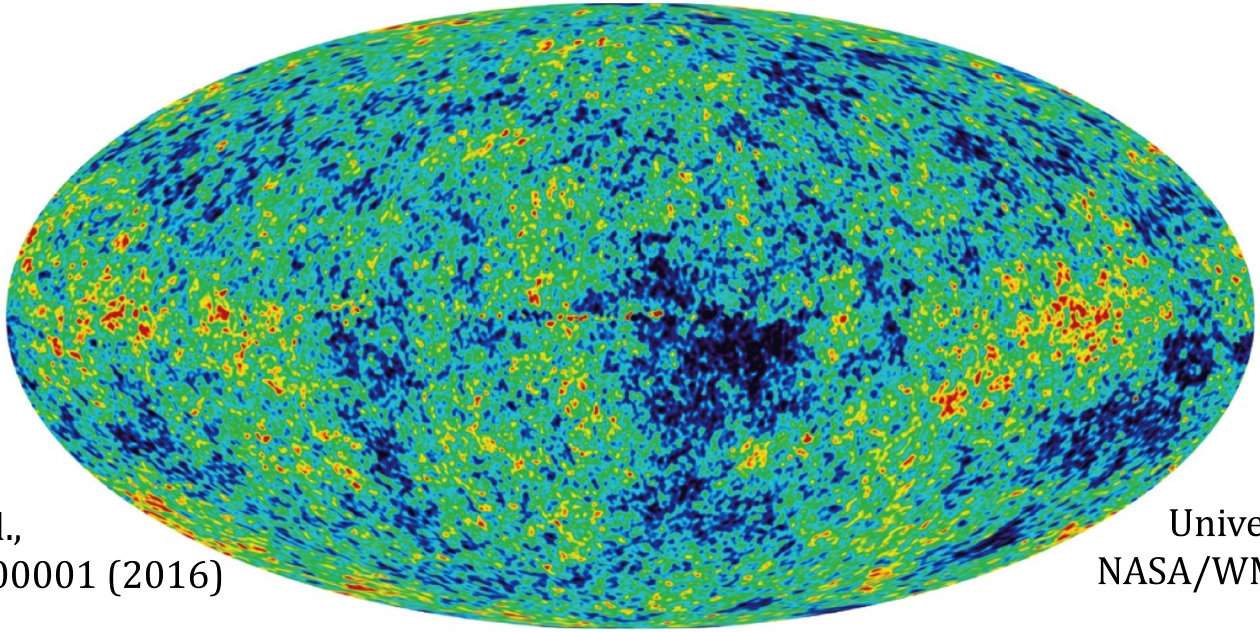




How do we measure the absolute neutrino mass?

Cosmological Bounds

Measuring the lightest particles with the Cosmos?



See PDG Review,
C. Patrignani et. al.,
Chin. Phys. C40 100001 (2016)

Figure from
Universe, Tenth Edition
NASA/WMAP Science Team

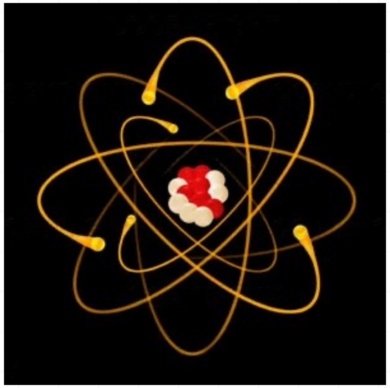
- Neutrinos are the second most abundant particle in the Universe
- Cosmological data limit sum of neutrino masses <0.1-0.7eV
- Model dependent and degenerate with other quantities

The little neutral one

- No electrical charge
- Very small mass
- Doesn't feel the strong nuclear force
- Only interacts via Nature's Weak Interaction

Pauli's particle should travel through astronomical amounts of material without stopping

Dear Radioactive Ladies and Gentlemen,



$n^0 \rightarrow p^+ + e^-$

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

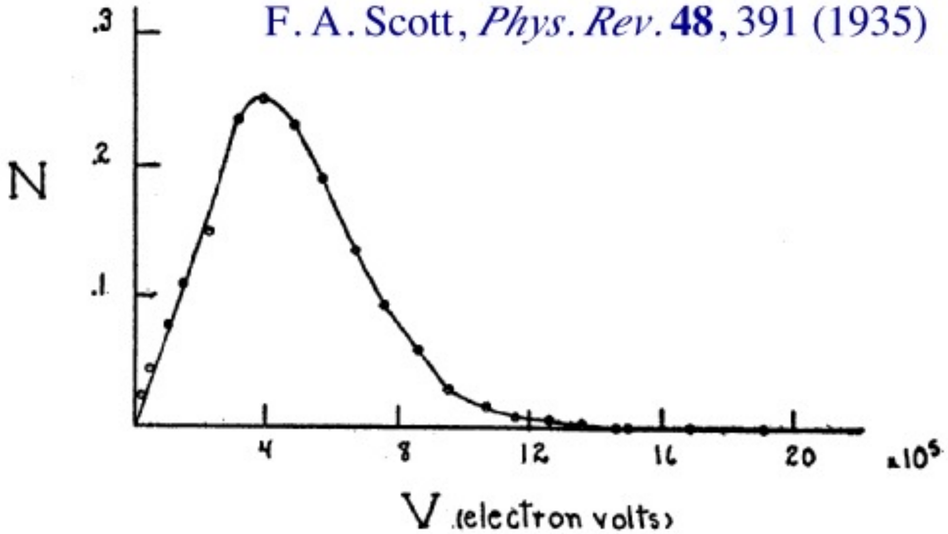
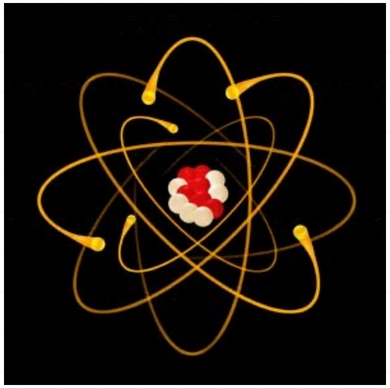


FIG. 5. Energy distribution curve of the beta-rays.

Dear Radioactive Ladies and Gentlemen,



$$n^0 \rightarrow p^+ + e^- + \bar{\nu}$$

...I have hit upon a desperate remedy...

...so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such [a particle]...

--Signed, W. Pauli

Measuring the Neutrino Mass

- Look at the endpoint of the electron energy distribution
- The heavier the neutrino, the less energy there is for the electron

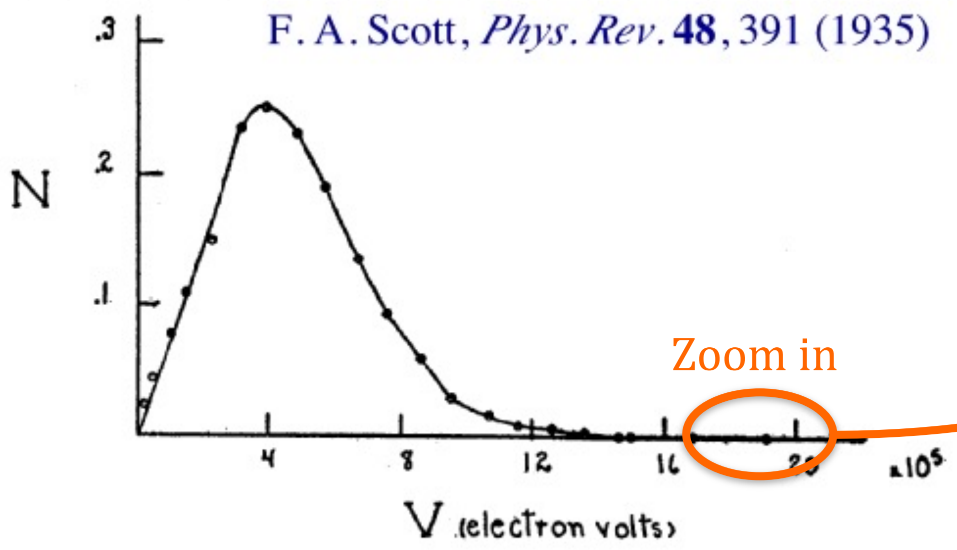
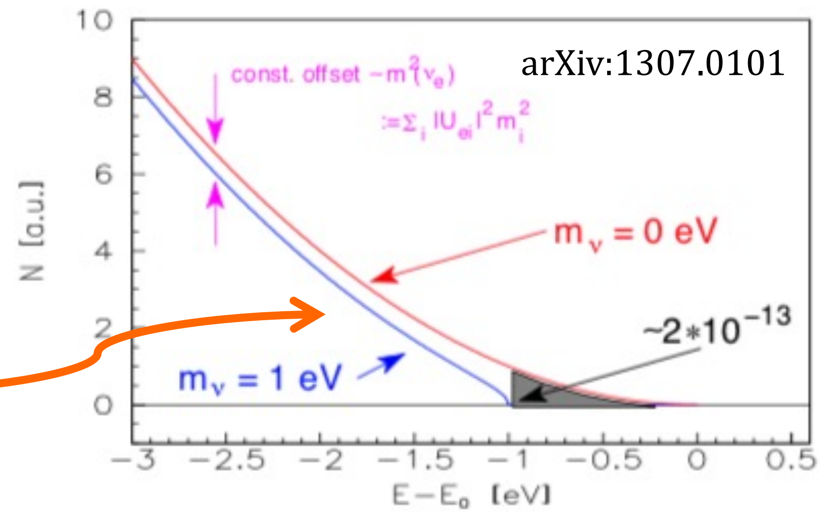


FIG. 5. Energy distribution curve of the beta-rays.

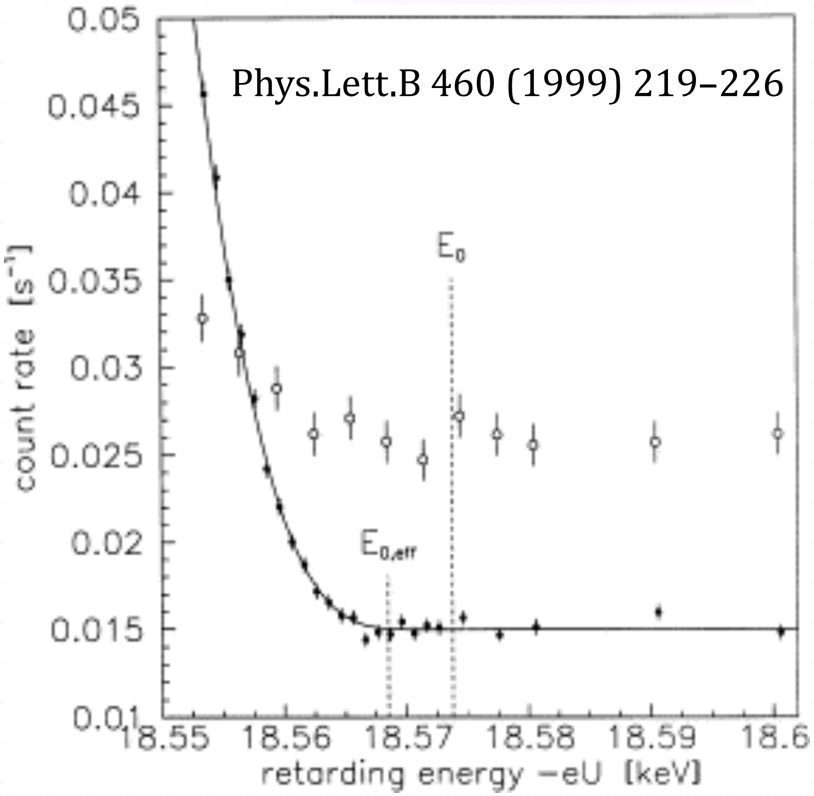


Current Direct Limit

- Look at Tritium decays:

$$^3H \rightarrow \ ^3He^+ + e^- + \bar{\nu}_e$$

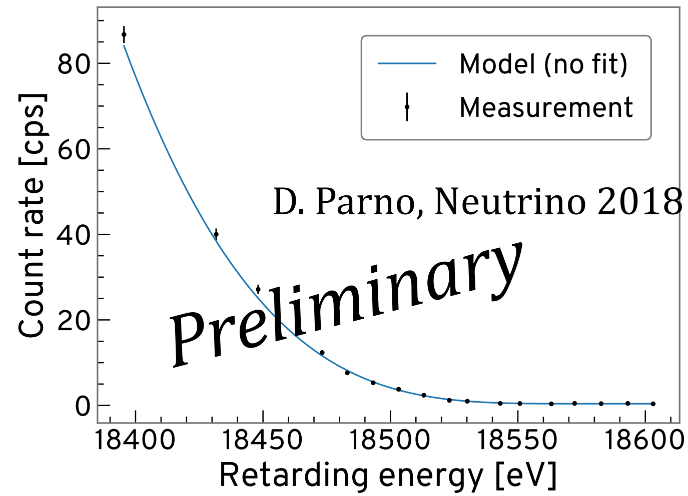
- Maximum electron energy with no neutrino mass is 18.6 keV
- Mainz neutrino mass experiment limits neutrino mass to < 2.8 eV

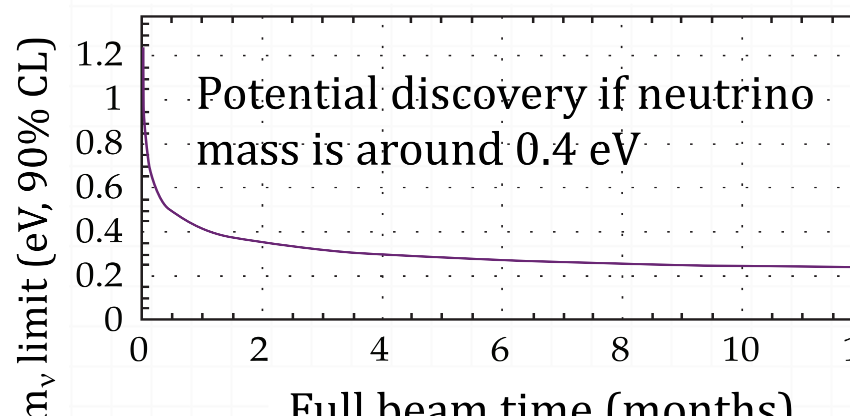


KATRIN

The Karlsruhe Tritium Neutrino Experiment

Taking Tritium Data as of 2018!

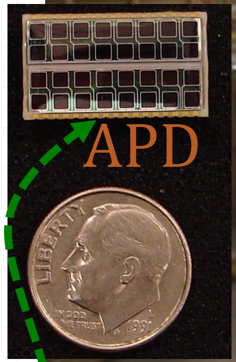


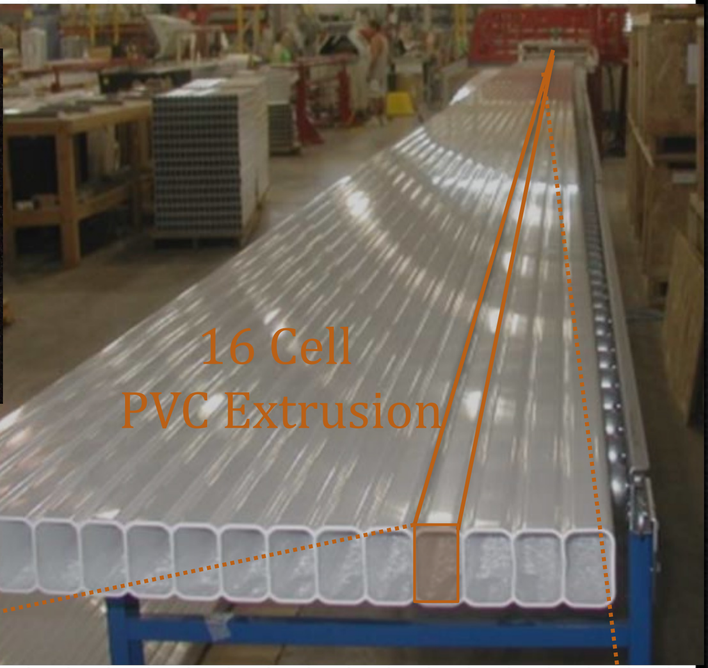


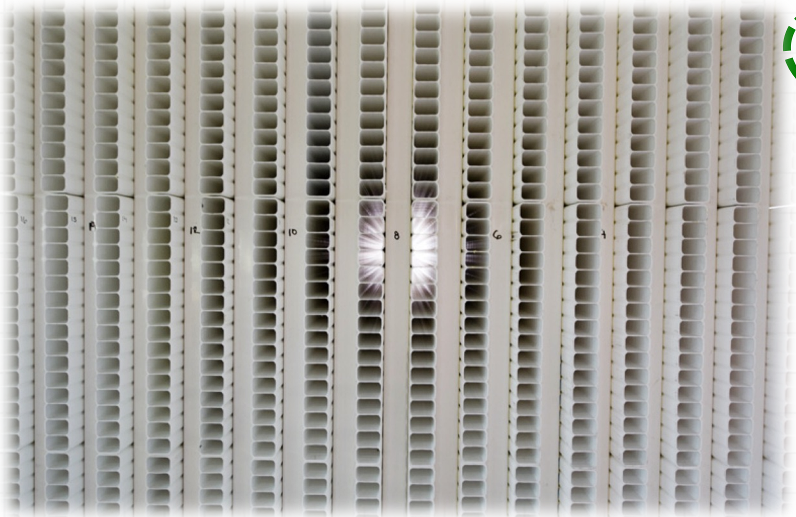
NOvA

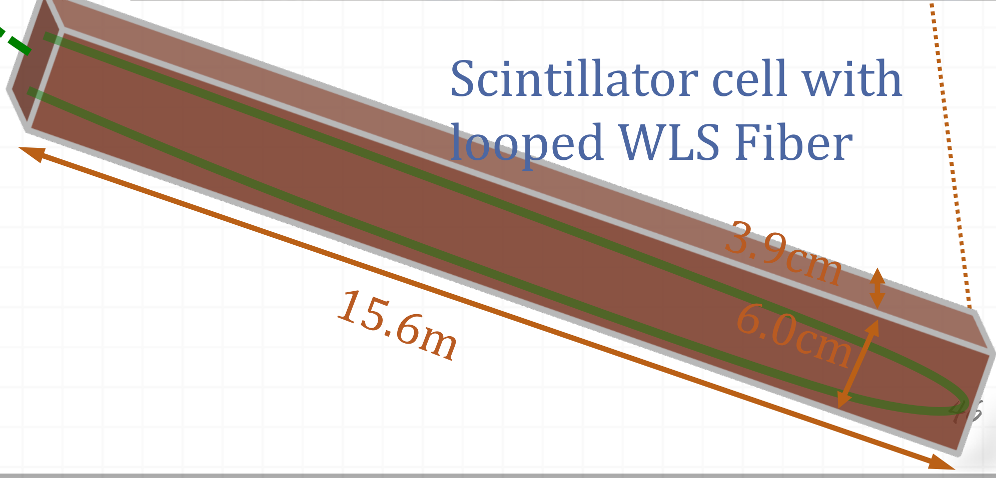
Detector Technology

- PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views

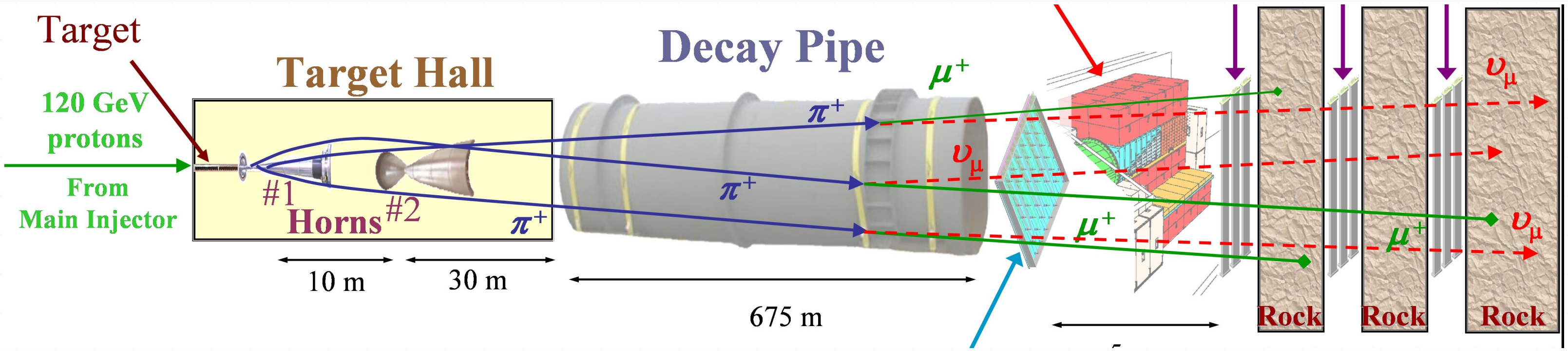


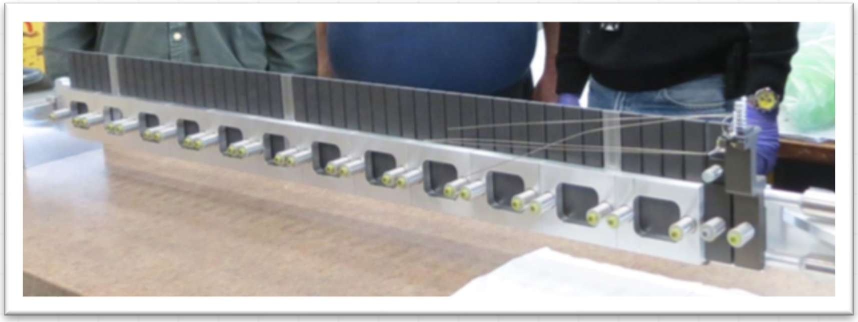


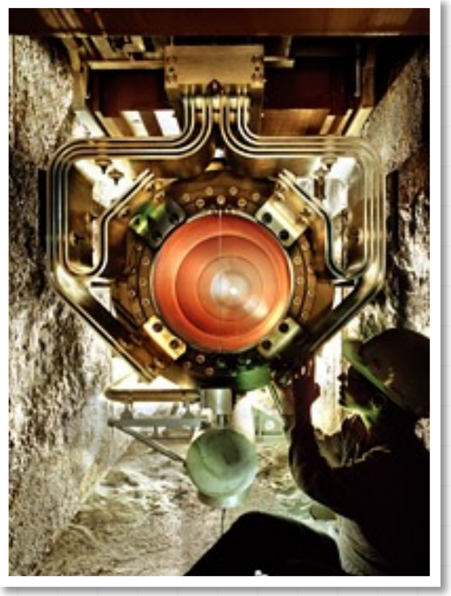




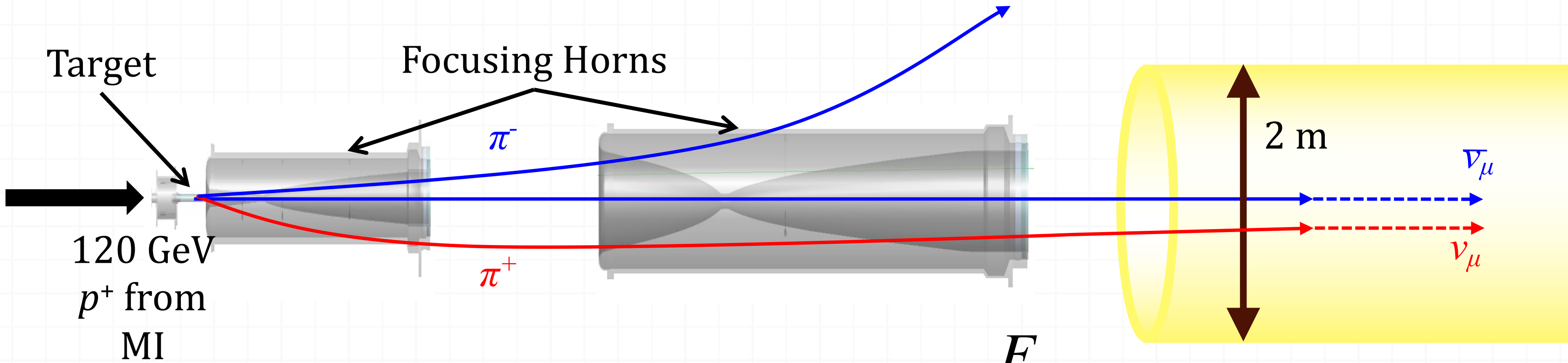
How do you make a neutrino beam?

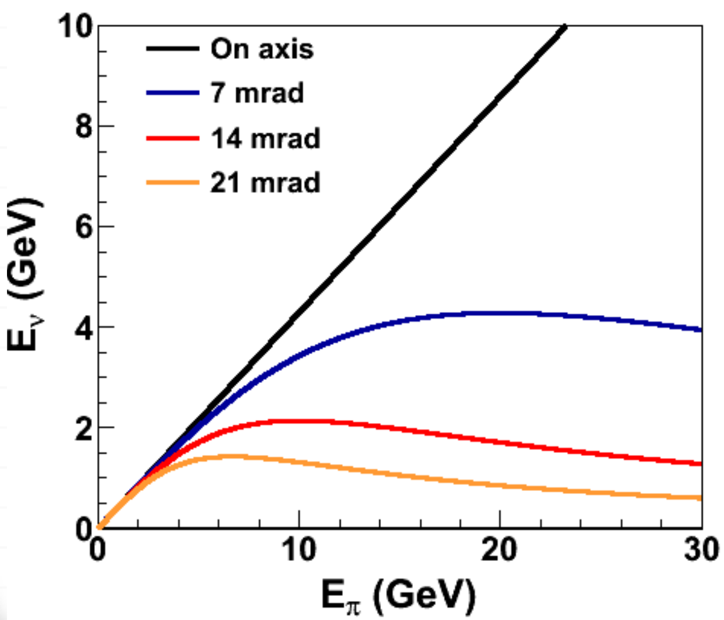






Making a Neutrino Beam

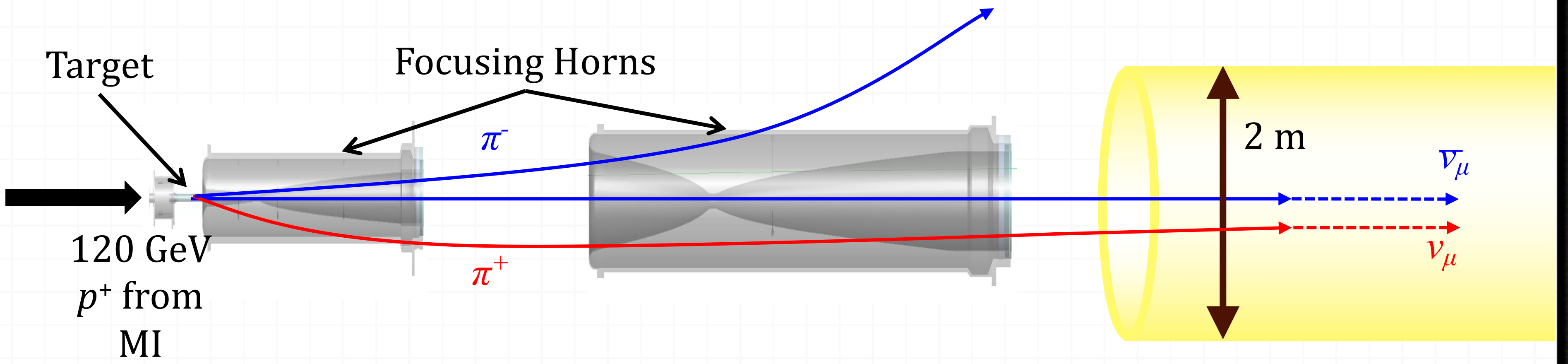


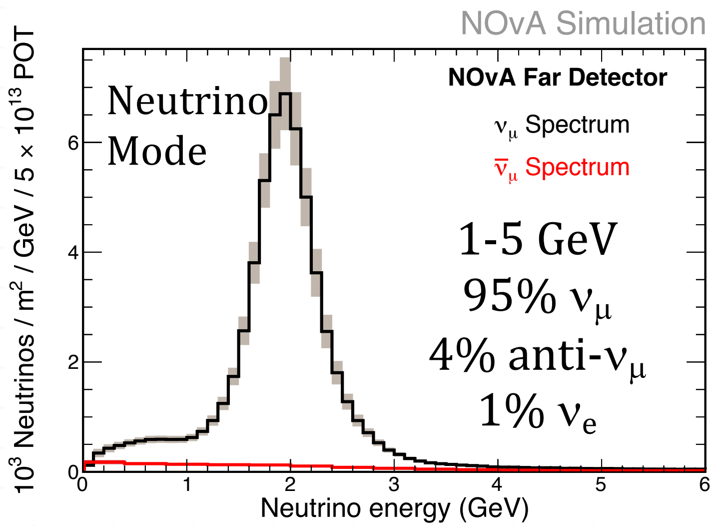


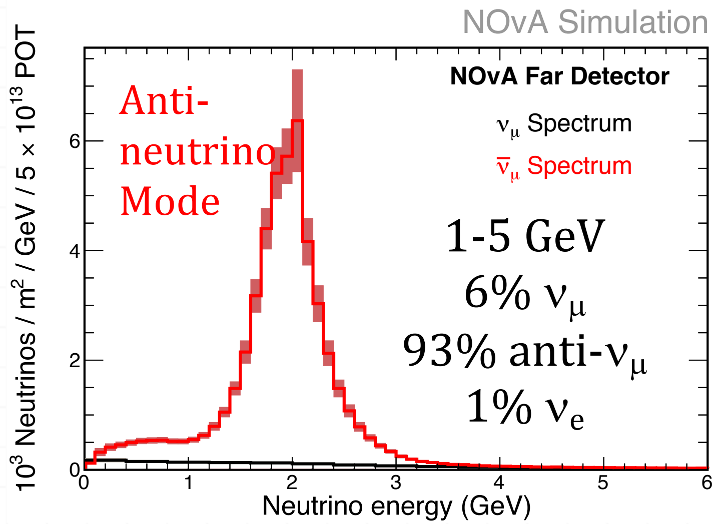
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- NOvA is 14 mrad off-axis, sees a narrow band beam peaked at 2 GeV
  - Near (but slightly above) oscillation maximum
  - Few high energy NC background events

Making a Neutrino Beam





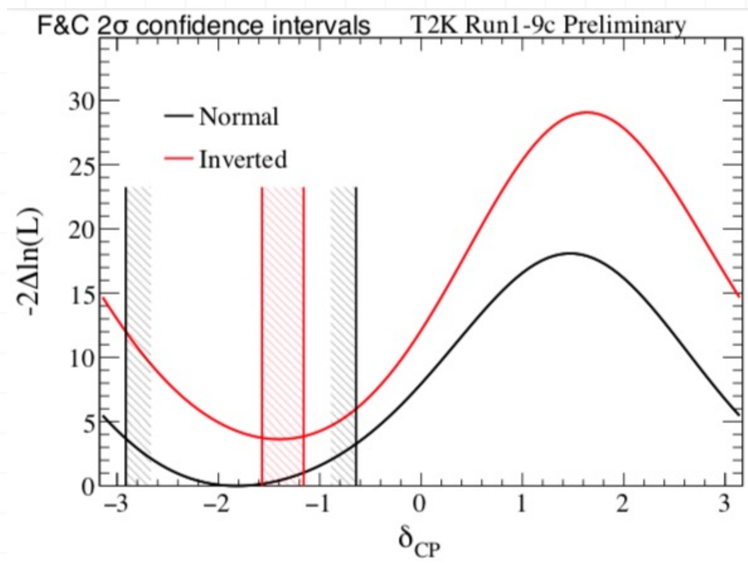


T2K Event Counts

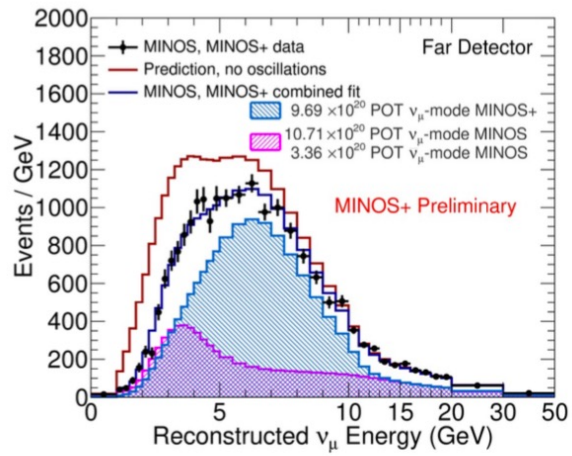
SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

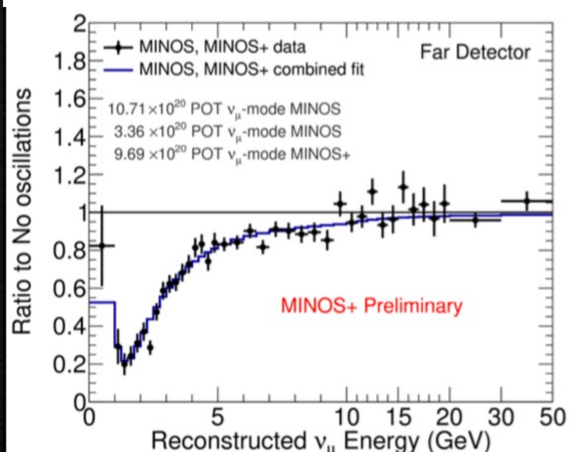
M. Wascko, Neutrino2018

- T2K observe fewer appeared electron antineutrinos than expected for any value of delta CP
  - Expect 6.5 events with no disappearance
  - Distribution of angle and momentum also more consistent with background spectra than appearance spectra
- CP Conserving values outside the 2 sigma region for both hierarchies
- Bayes factor of NH/IH is 7.9



MINOS+ and OPERA



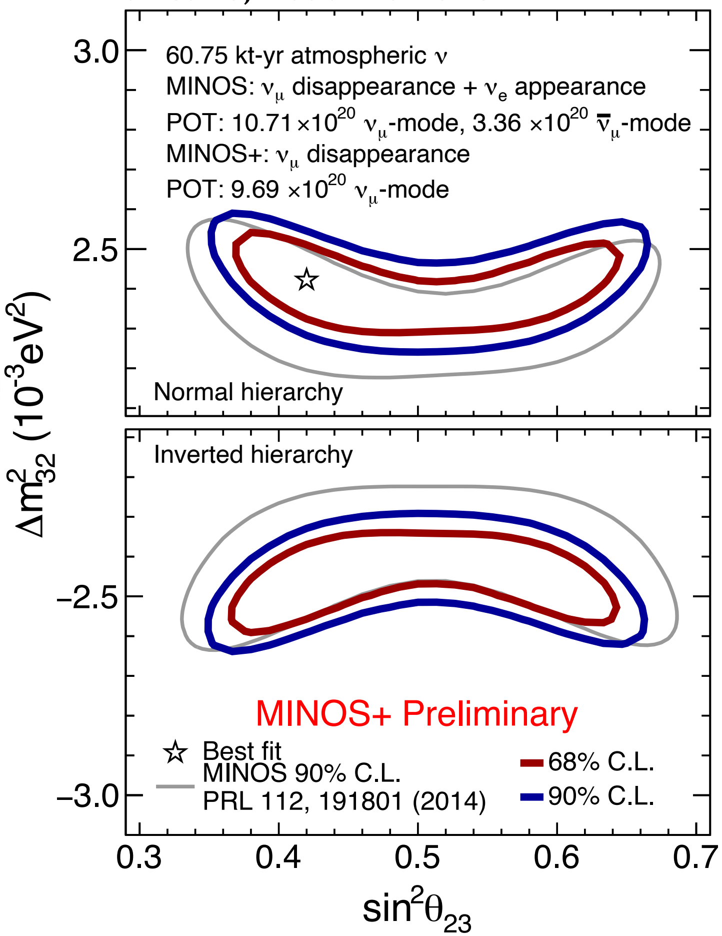


Best fit

$\Delta m^2_{32} = 2.42 \times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.42$

A. Aurisano, Neutrino 2018



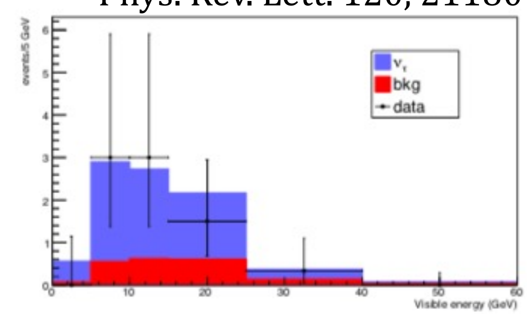
Exclusion of maximal mixing: 1.1σ

Preference for lower octant: 0.8σ

Preference for normal hierarchy: 0.2σ

- Opera final results:
  - 10 tau neutrino candidates
  - 6.1sigma evidence of appearance
  - 20% measurement of mass splitting agrees with disappearance measurements

Phys. Rev. Lett. 120, 211801



KATRIN

- KATRIN promises a direct limit an order of magnitude better than current limit
- Discovery if neutrino mass is around 0.4 eV