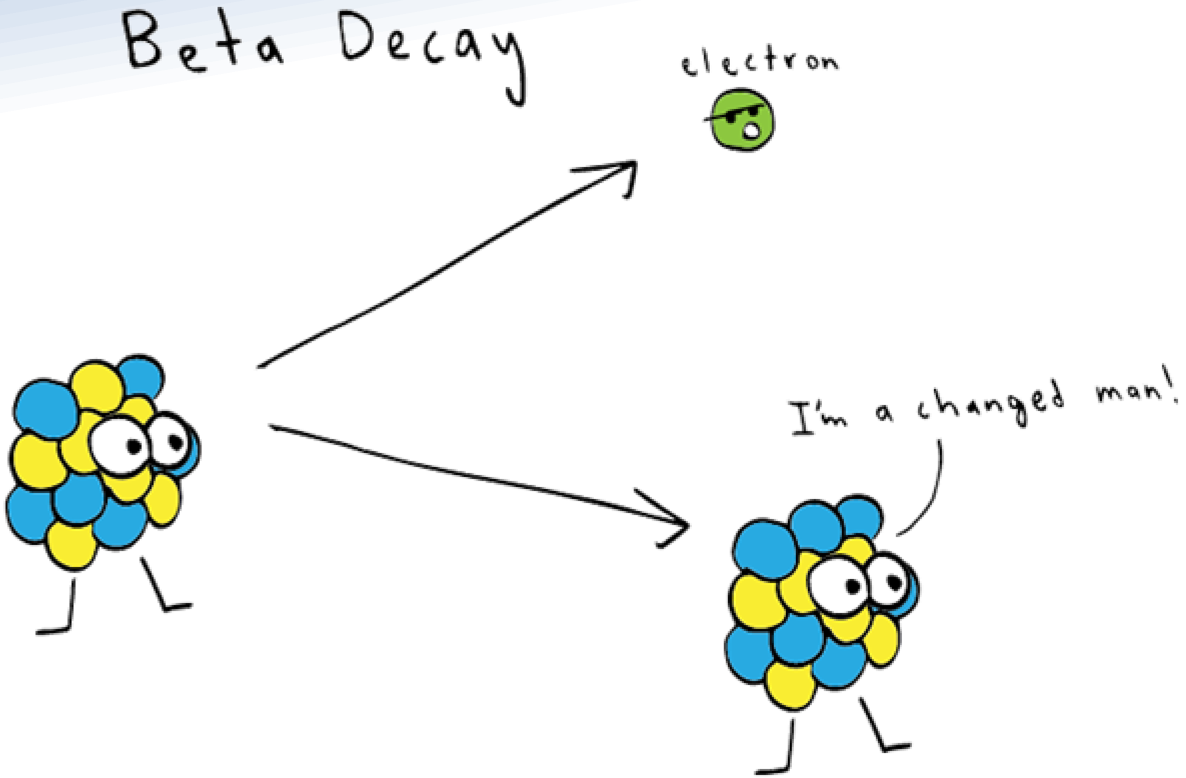
Introduction to Neutrinos and Neutrino Oscillations

Alex Himmel

Fermilab

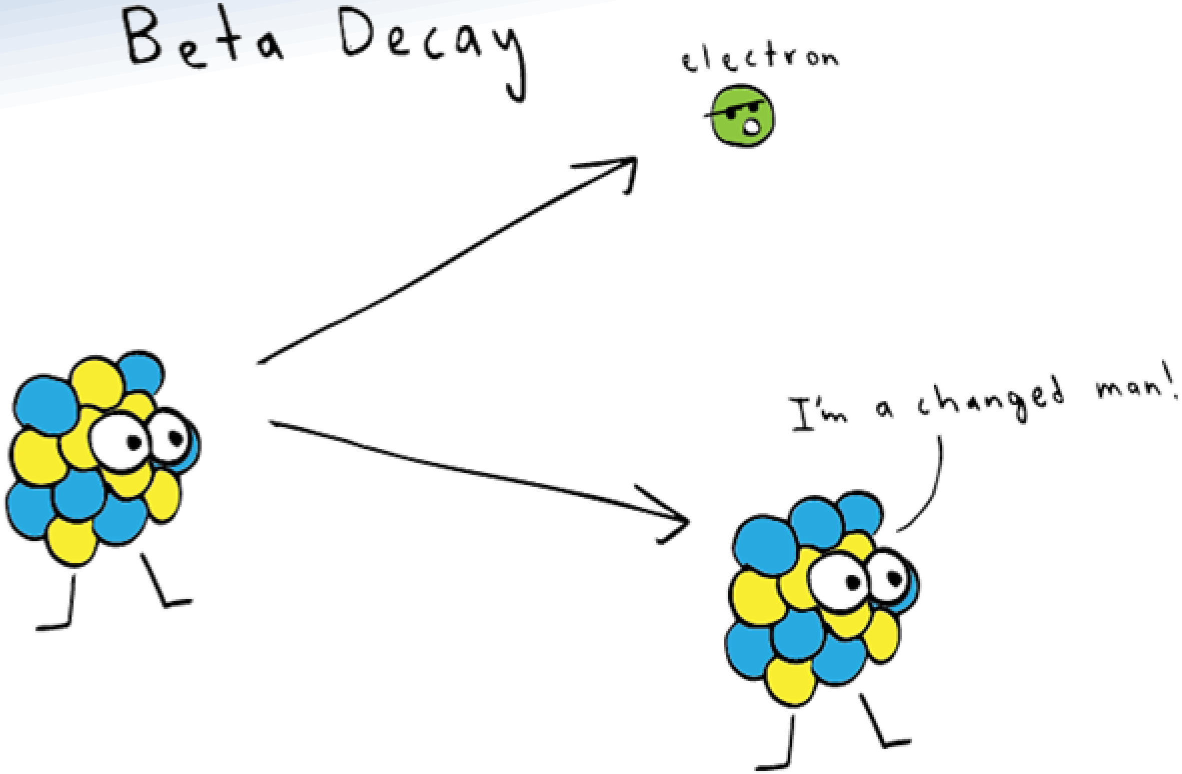
2025 Neutrino University

June 25th, 2025



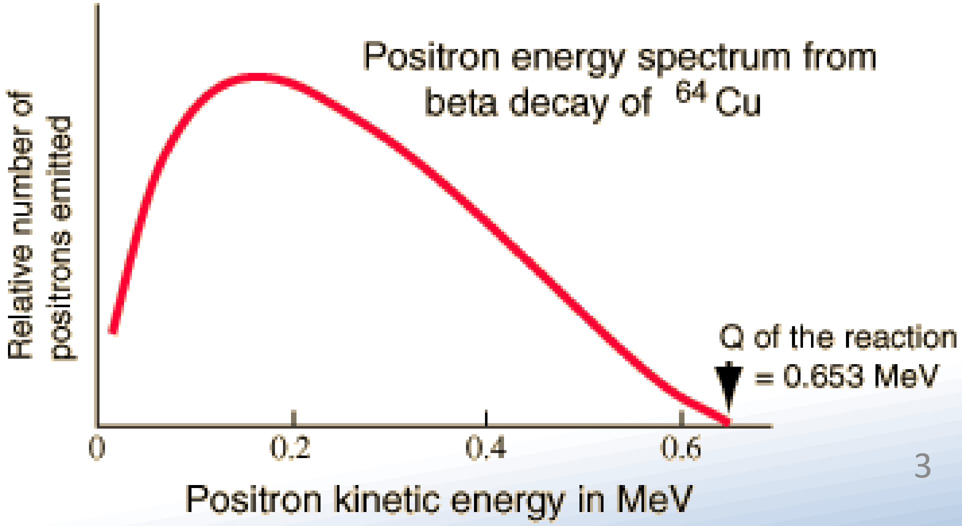
1913

$$^{60}Co \rightarrow {}^{60}Ni + e^{-}$$



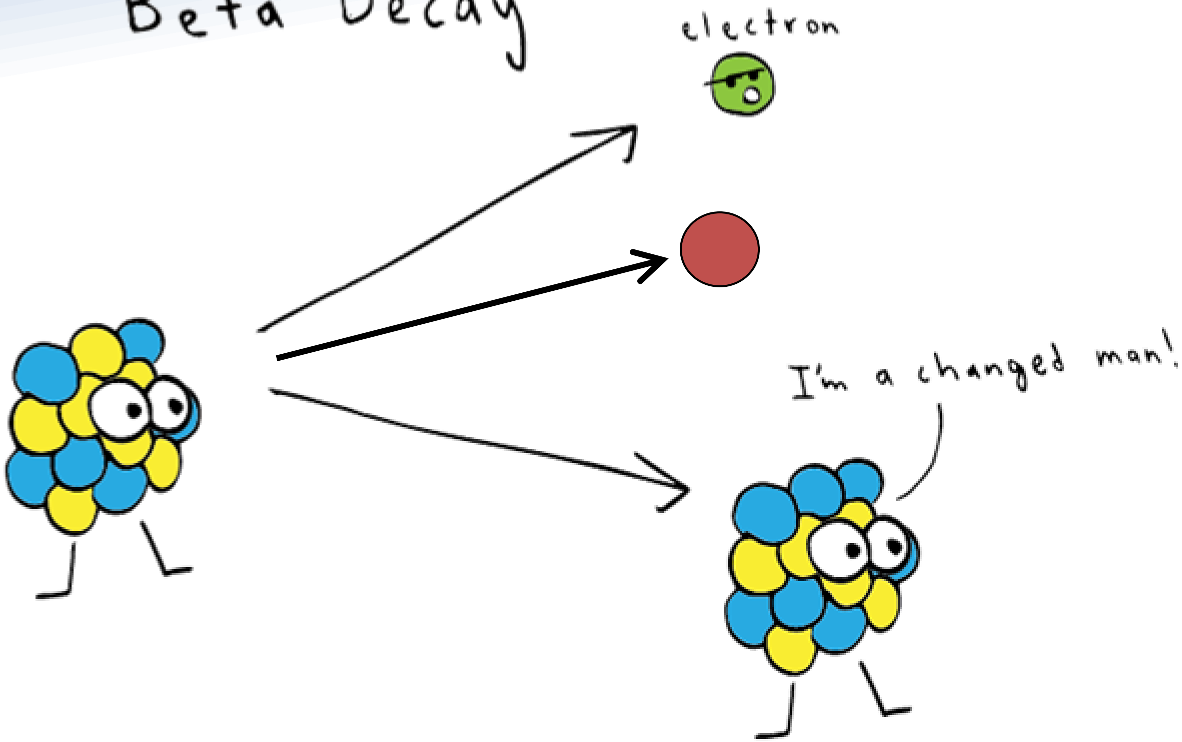
1913

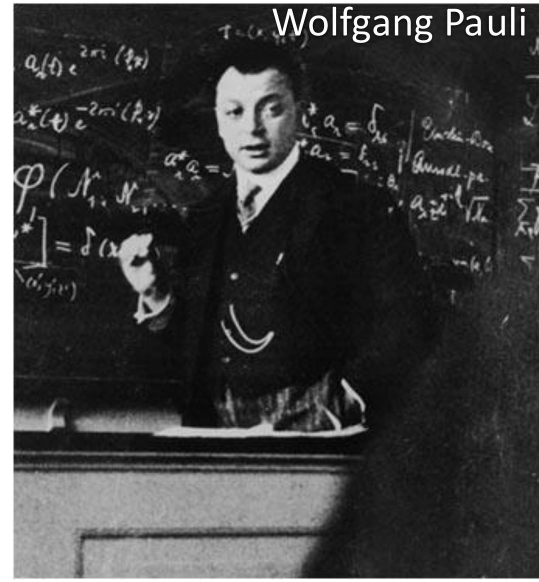
$$^{60}Co \rightarrow {}^{60}Ni + e^-$$



Beta Decay

1930





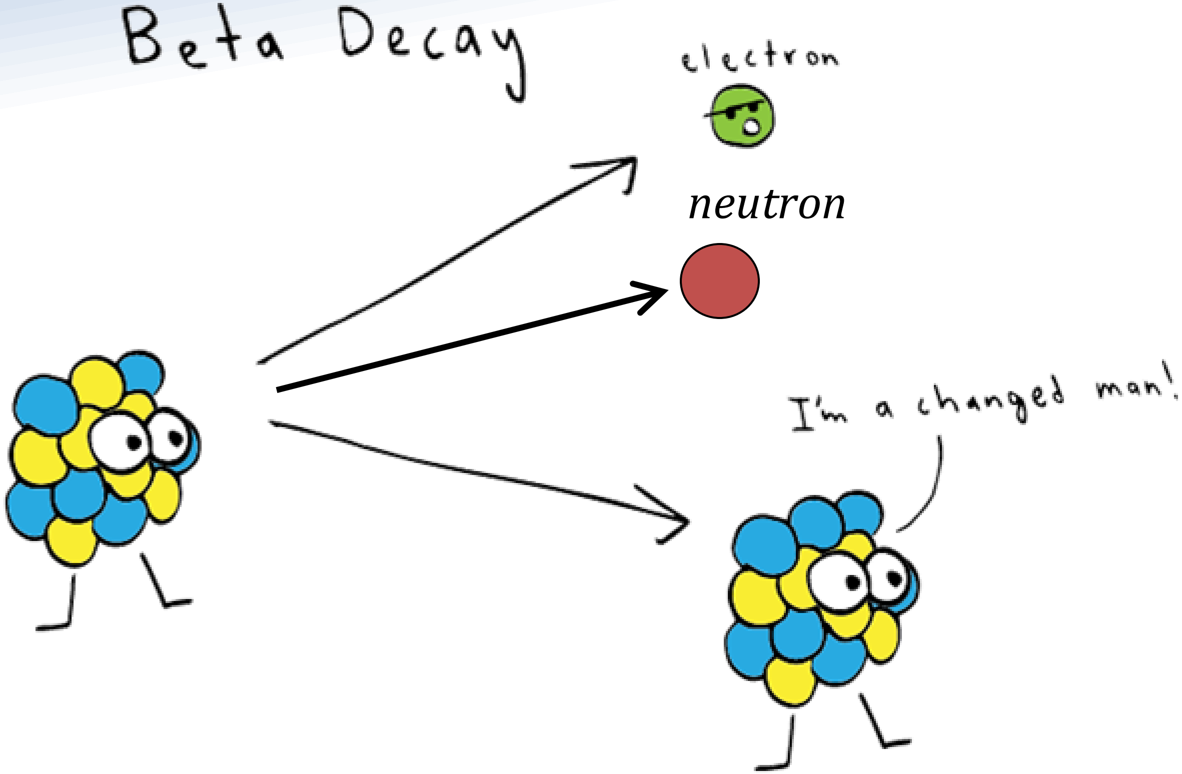
$$^{60}Co \rightarrow {}^{60}Ni + e^{-} + ?$$

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

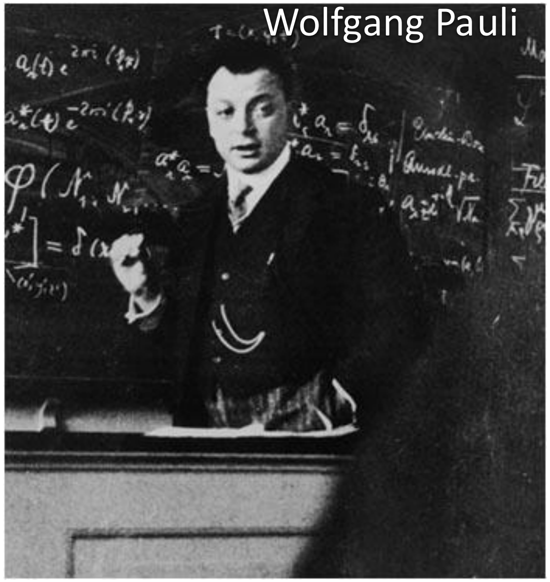
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich

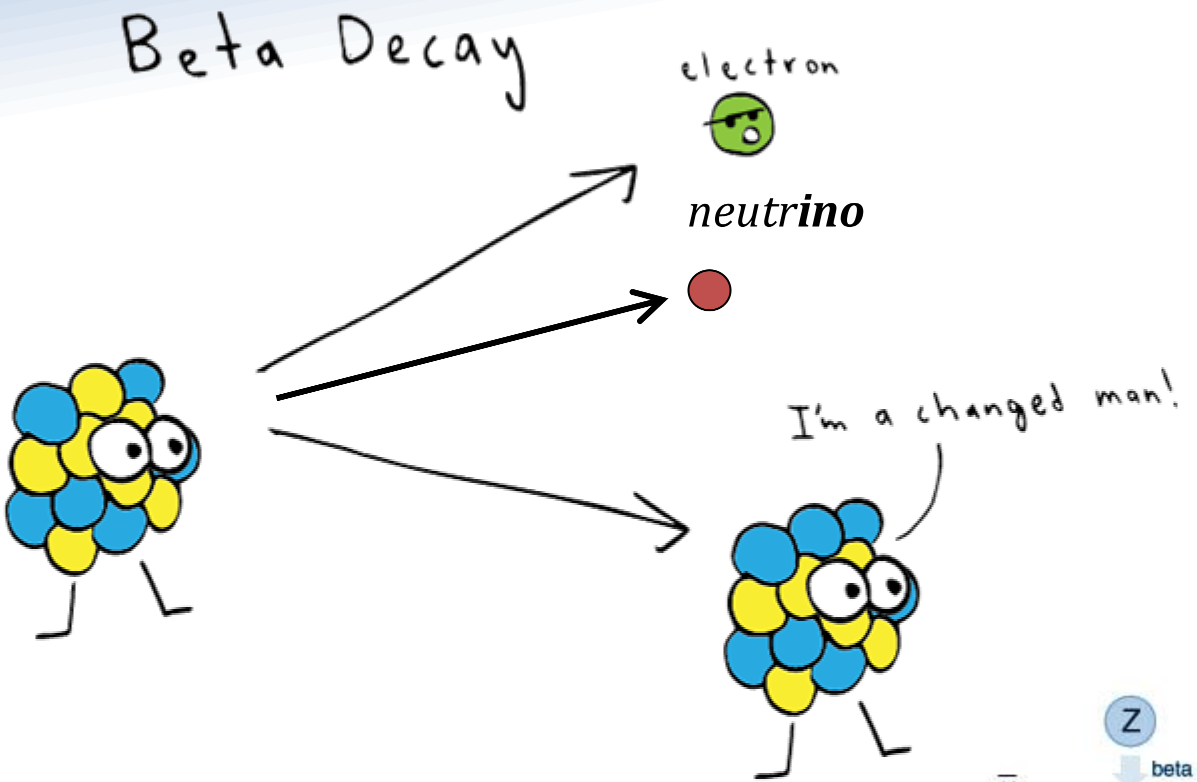


1930

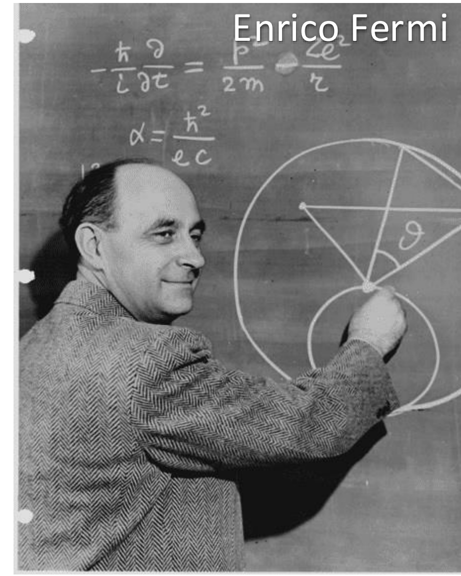


$$^{60}Co \rightarrow {}^{60}Ni + e^{-} + ?$$

beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

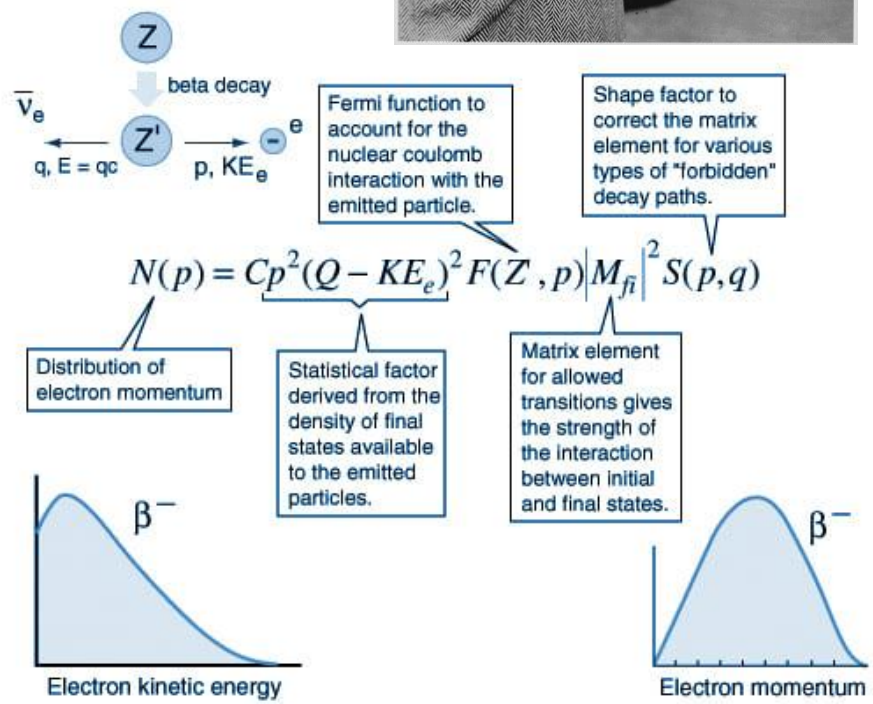


1933



$$^{60}Co \rightarrow {}^{60}Ni + e^{-} + \nu$$

Fermi's neutrino is massless and feels only the weak force



Only Weak Interactions

Strength ~ frequency of collisions

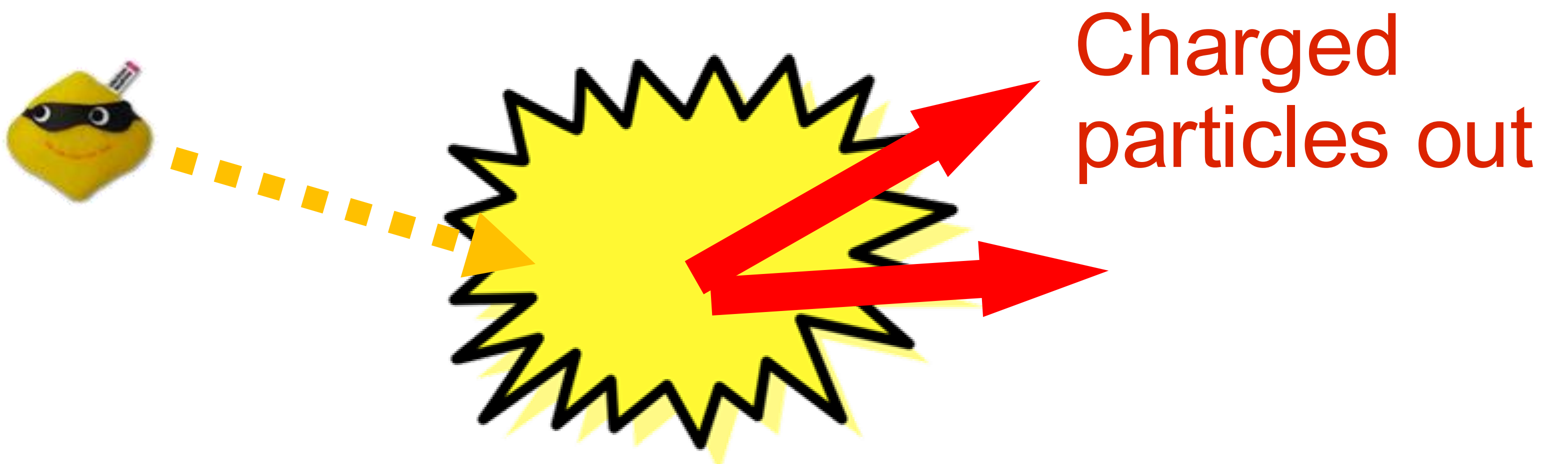
Interaction length for a high-energy photon in carbon is **~20 cm**.

For a neutrino of the same energy its **~1 light year**!

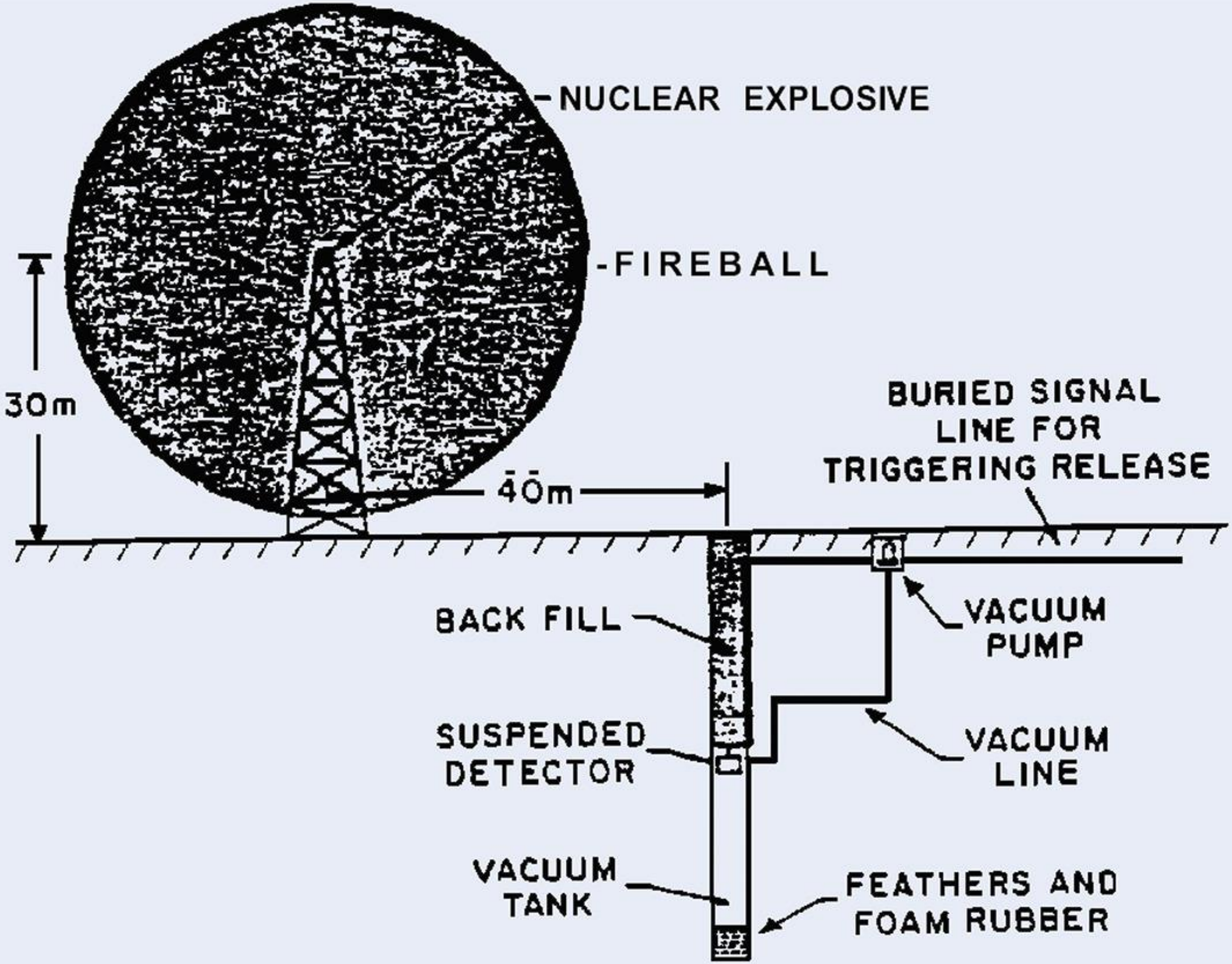
How to “See” a Neutrino

- Neutrinos, being neutral, do not interact with photons. They are *literally* invisible.

How to “See” a Neutrino



- Neutrinos, being neutral, do not interact with photons. They are *literally* invisible.
- When the neutrino collides with an atom, it produces charged particles.
- They *are* visible and seem to appear out of nowhere.



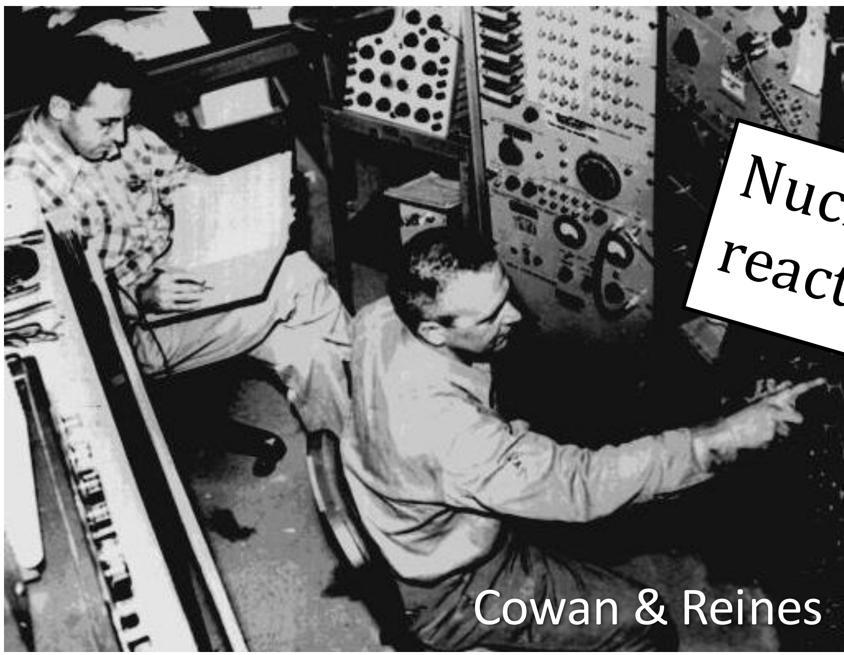
NUCLEAR EXPLOSIVE
FIREBALL
30m
40m
BURIED SIGNAL LINE FOR TRIGGERING RELEASE
BACK FILL
VACUUM PUMP
SUSPENDED DETECTOR
VACUUM LINE
VACUUM TANK
FEATHERS AND FOAM RUBBER

The First Detection

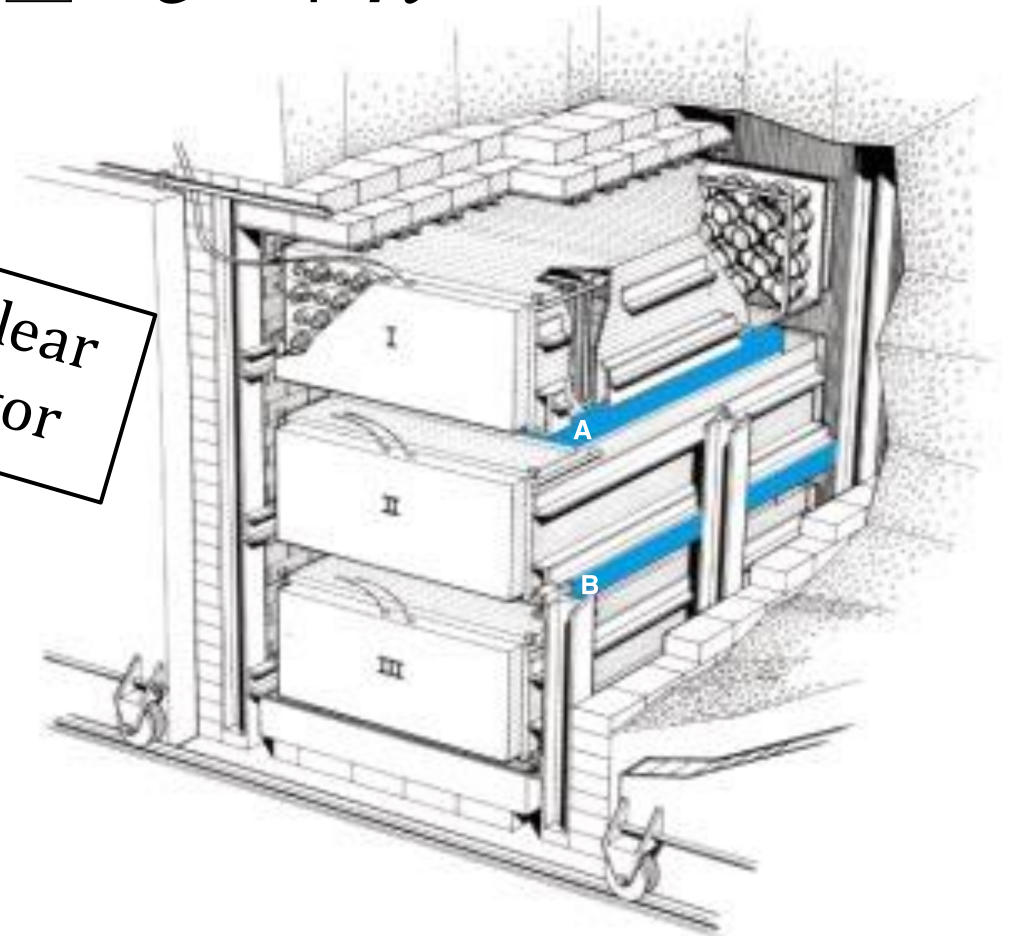
1956

Invisible

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



Nuclear reactor



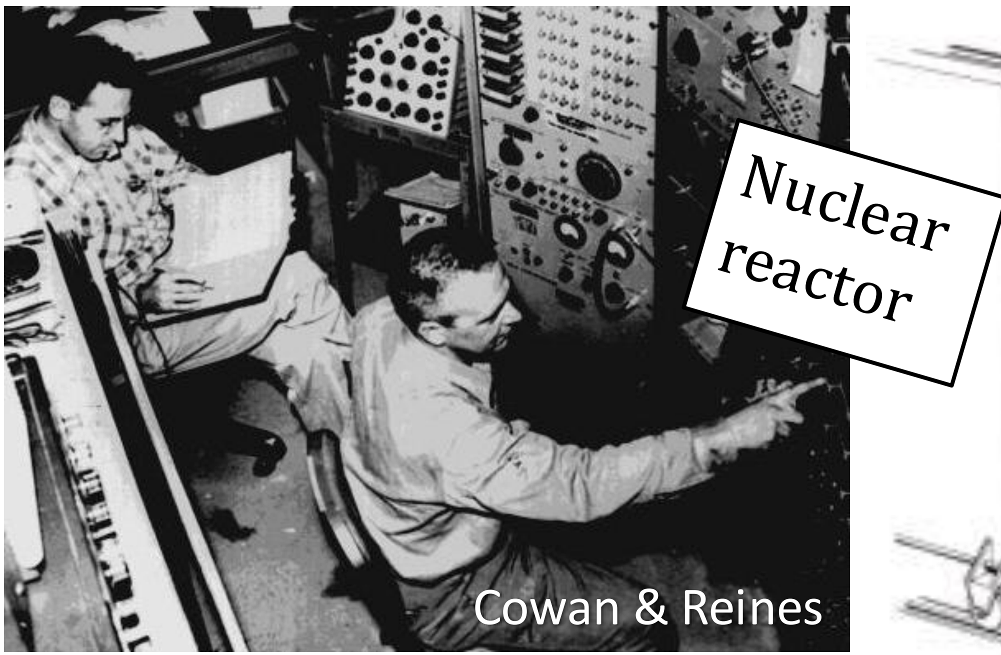
The First Detection

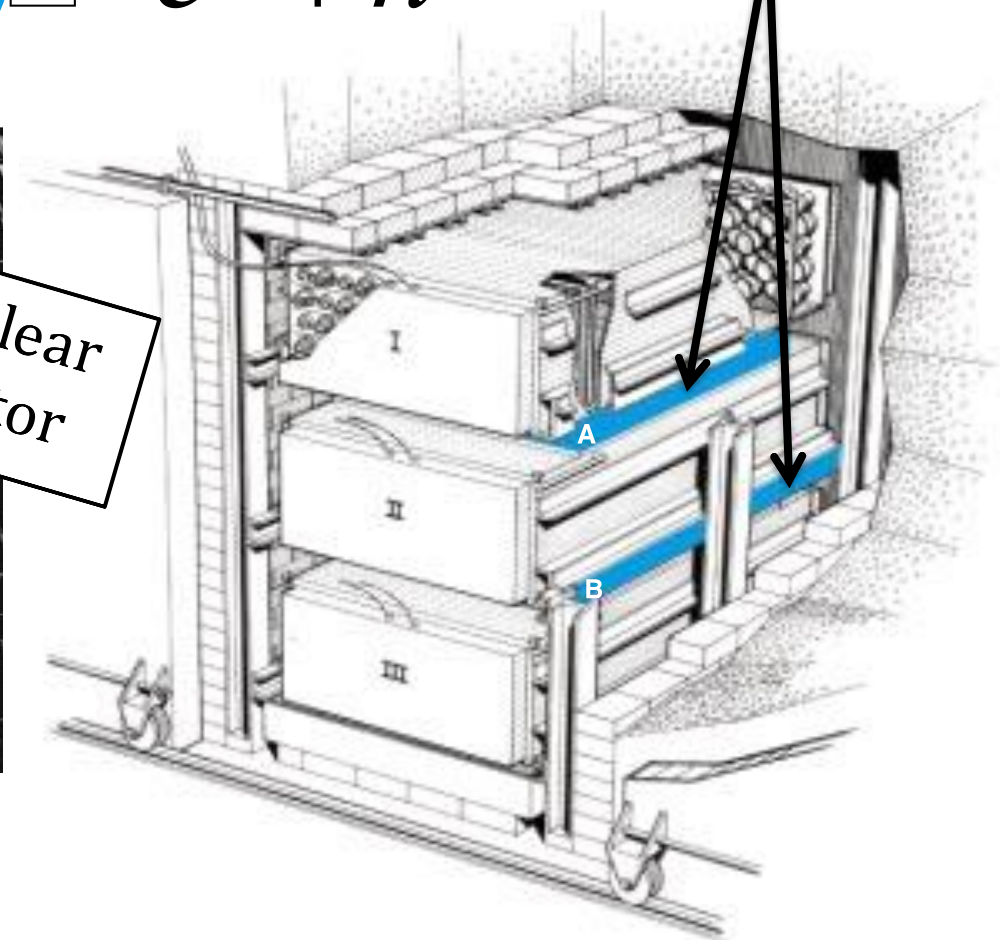
1956

Invisible Hydrogen

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

$H_2O + Cd$





The First Detection

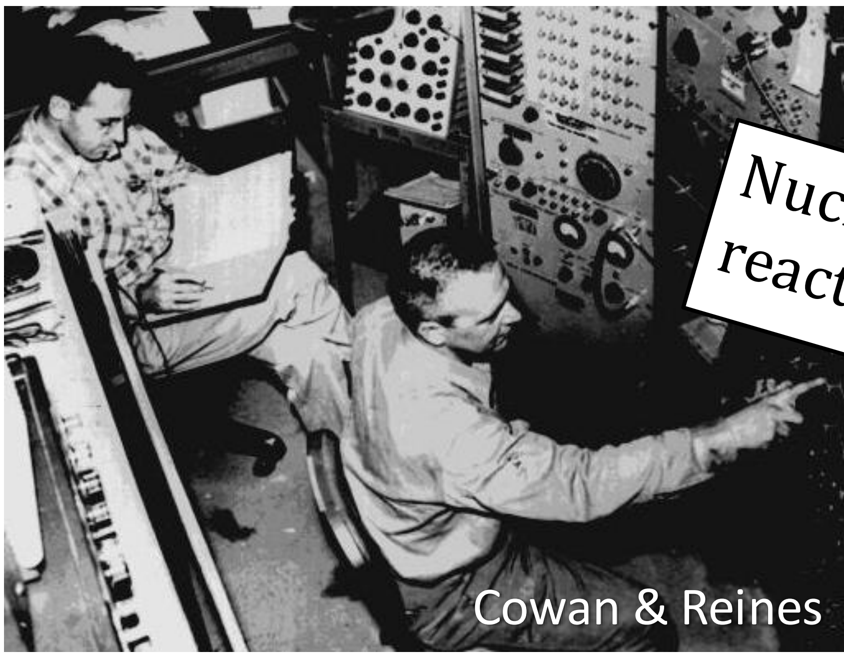
1956

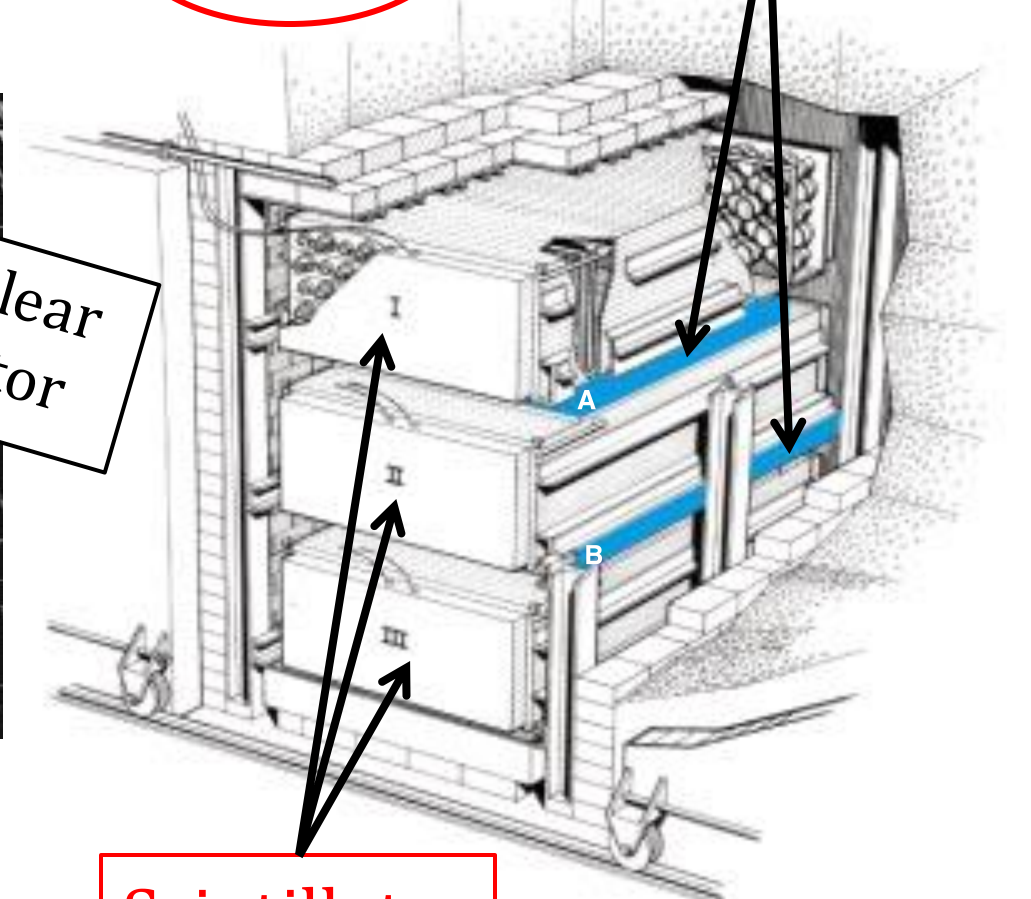
Invisible Hydrogen

Produce light in Scintillator

$H_2O + Cd$

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





Scintillator

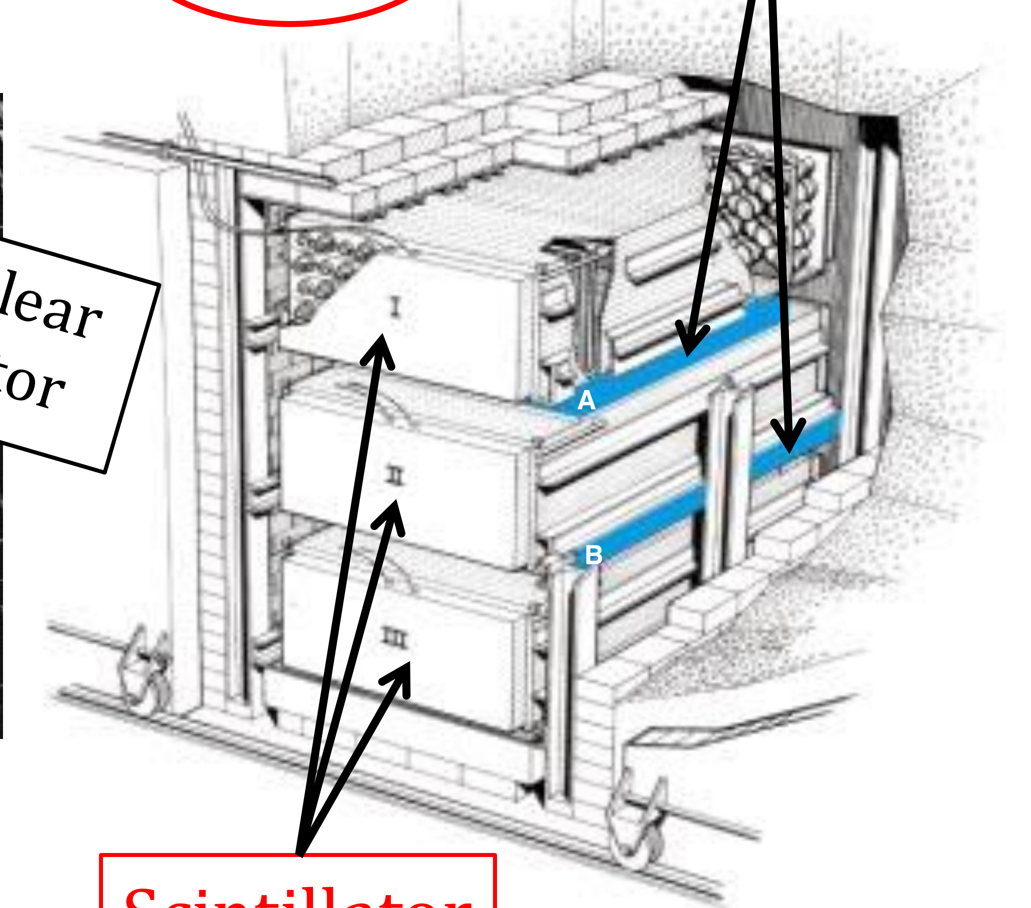
The First Detection

1956

Invisible Hydrogen

Produce light in Scintillator

$$\bar{\nu} + p \square e^{+} + n$$

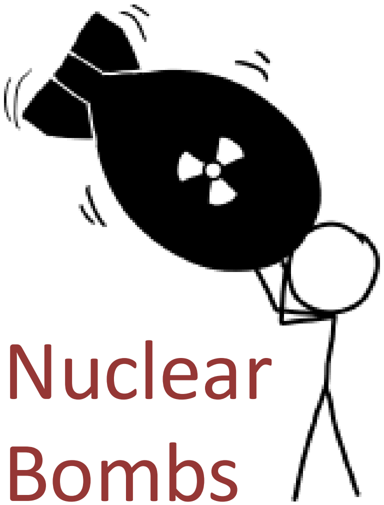


$H_2O + Cd$

Scintillator

Where do neutrinos come from?

Reactors



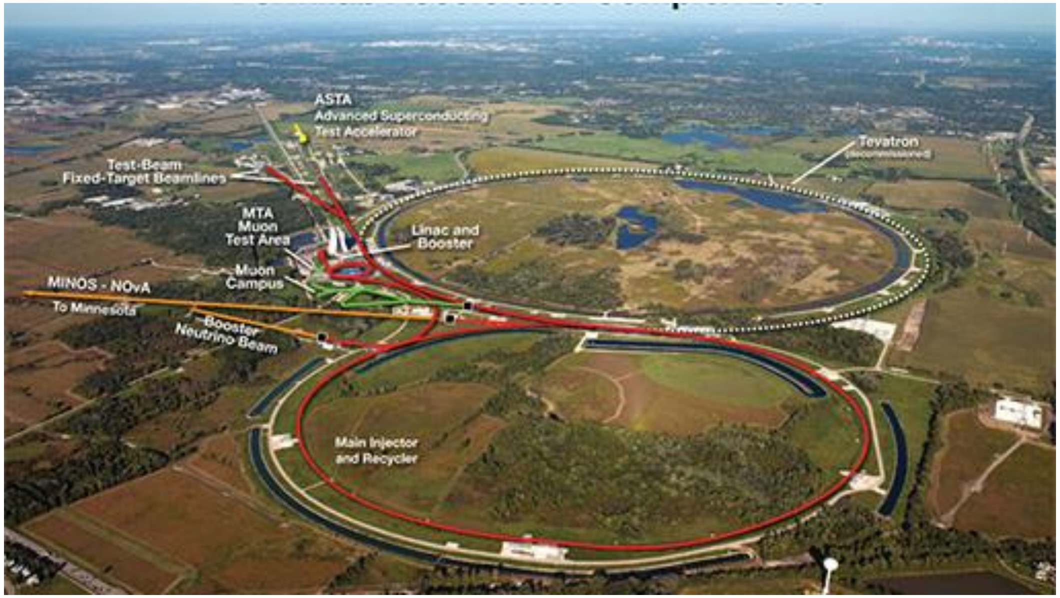
Nuclear Bombs

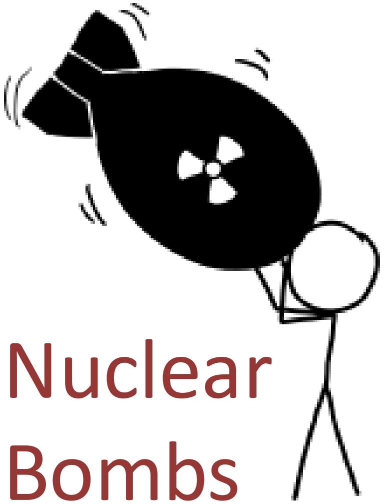
https://what-if.xkcd.com/73/

Where do neutrinos come from?

Reactors

Accelerators





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Discovery of Neutrino Flavor

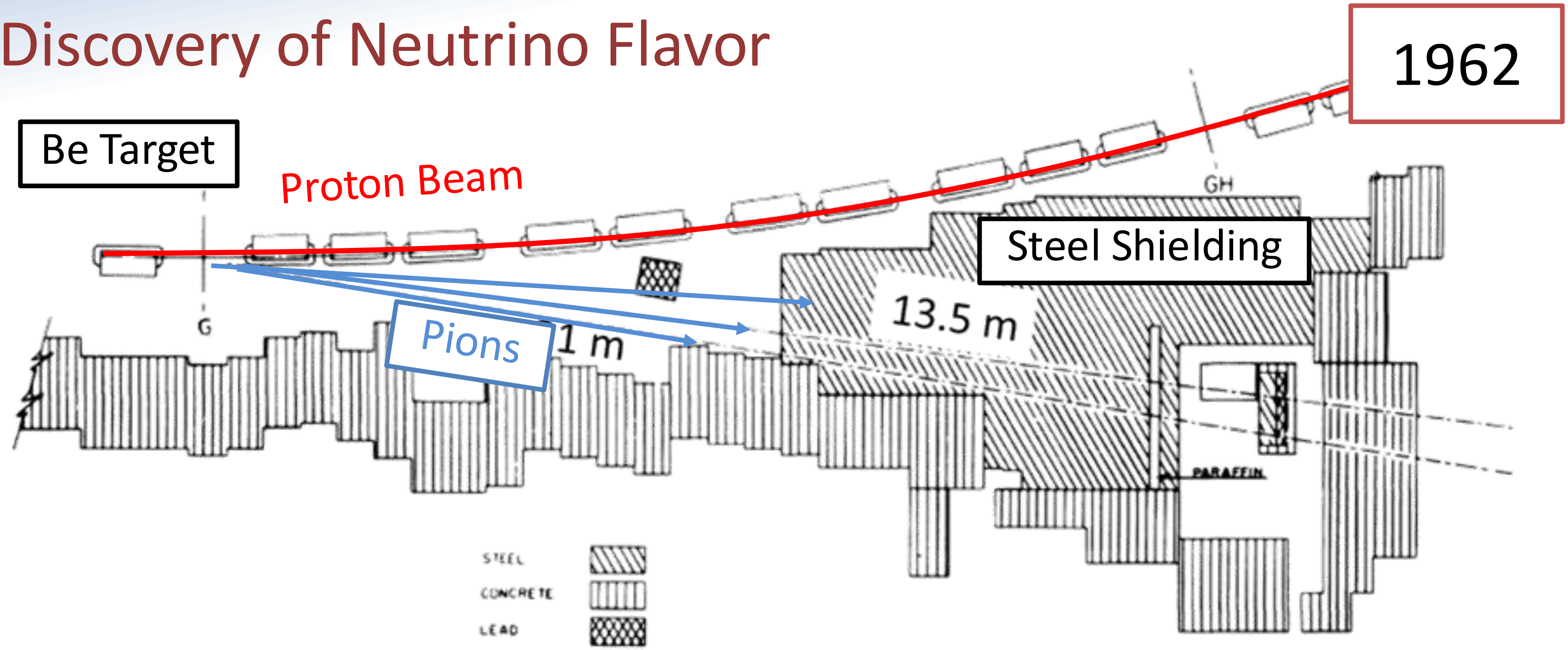


FIG. 1. Plan view of AGS neutrino experiment.

$$p + \text{Be} \rightarrow \pi^{+} + \ldots$$

Discovery of Neutrino Flavor

1962

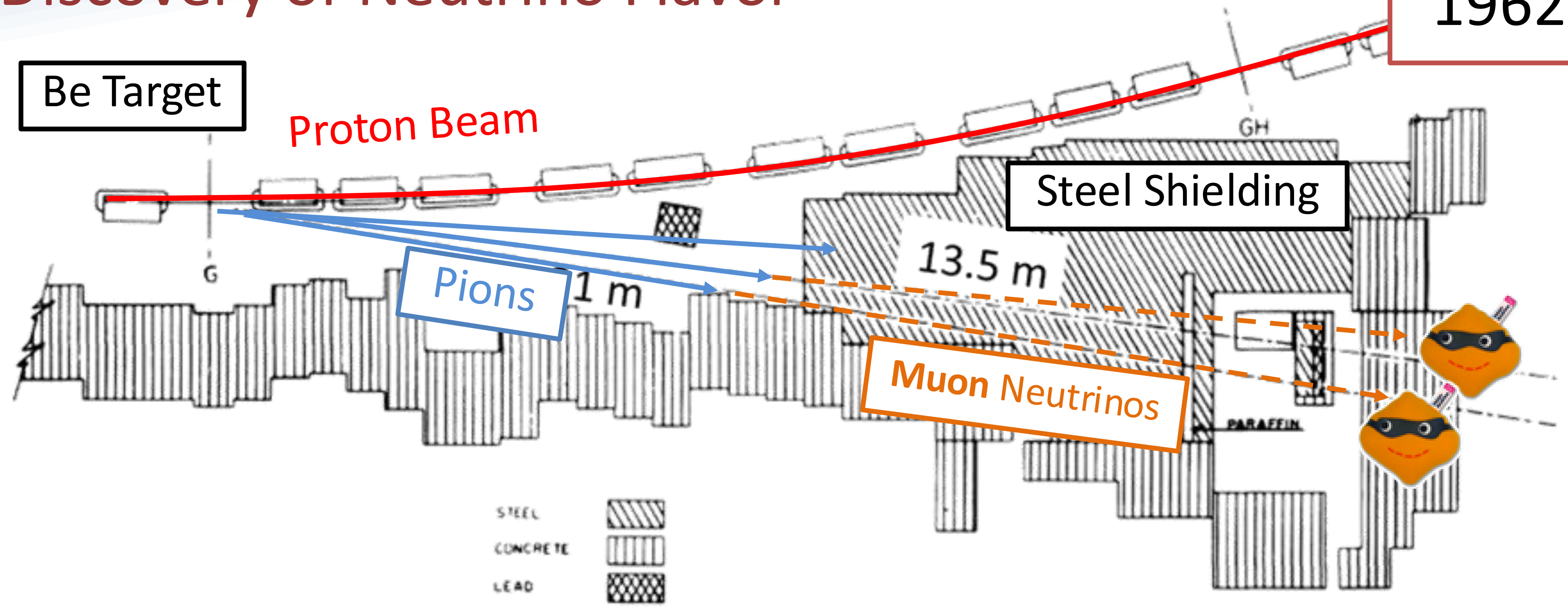


FIG. 1. Plan view of AGS neutrino experiment.

$$p + \text{Be} \rightarrow \overbrace{\pi^+ + \ldots}^{\text{Stopped by steel shielding}}$$

$$\pi^+ \rightarrow \mu^+ + \boxed{\nu_\mu}$$

Discovery of Neutrino Flavor

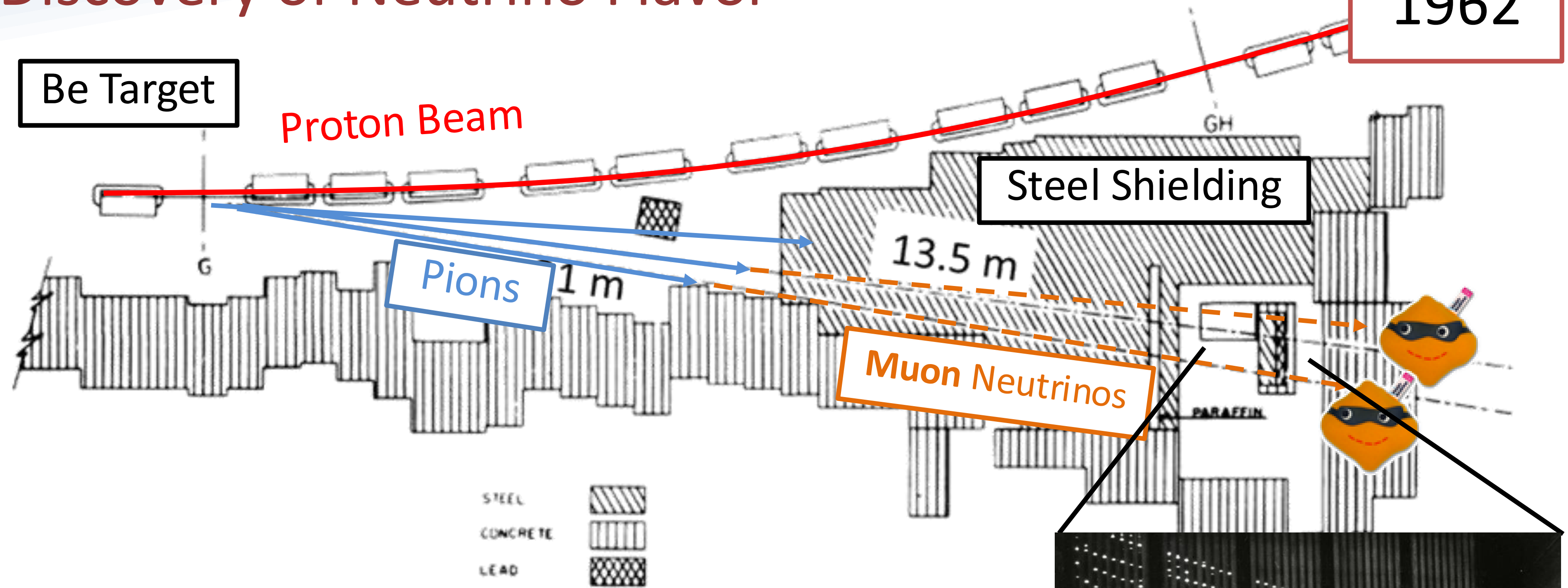
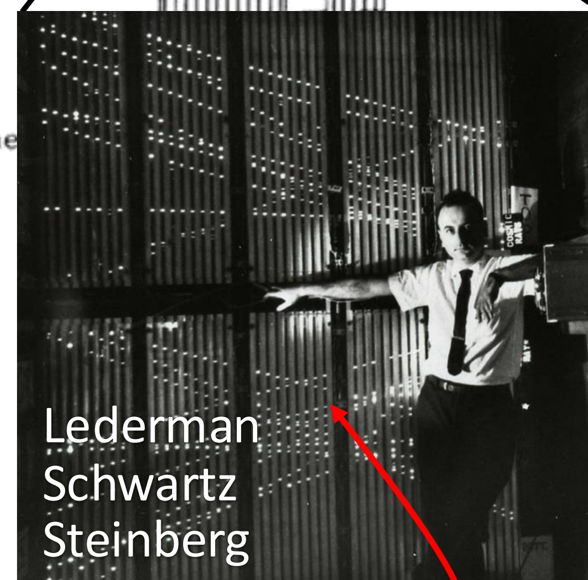


FIG. 1. Plan view of AGS neutrino experime

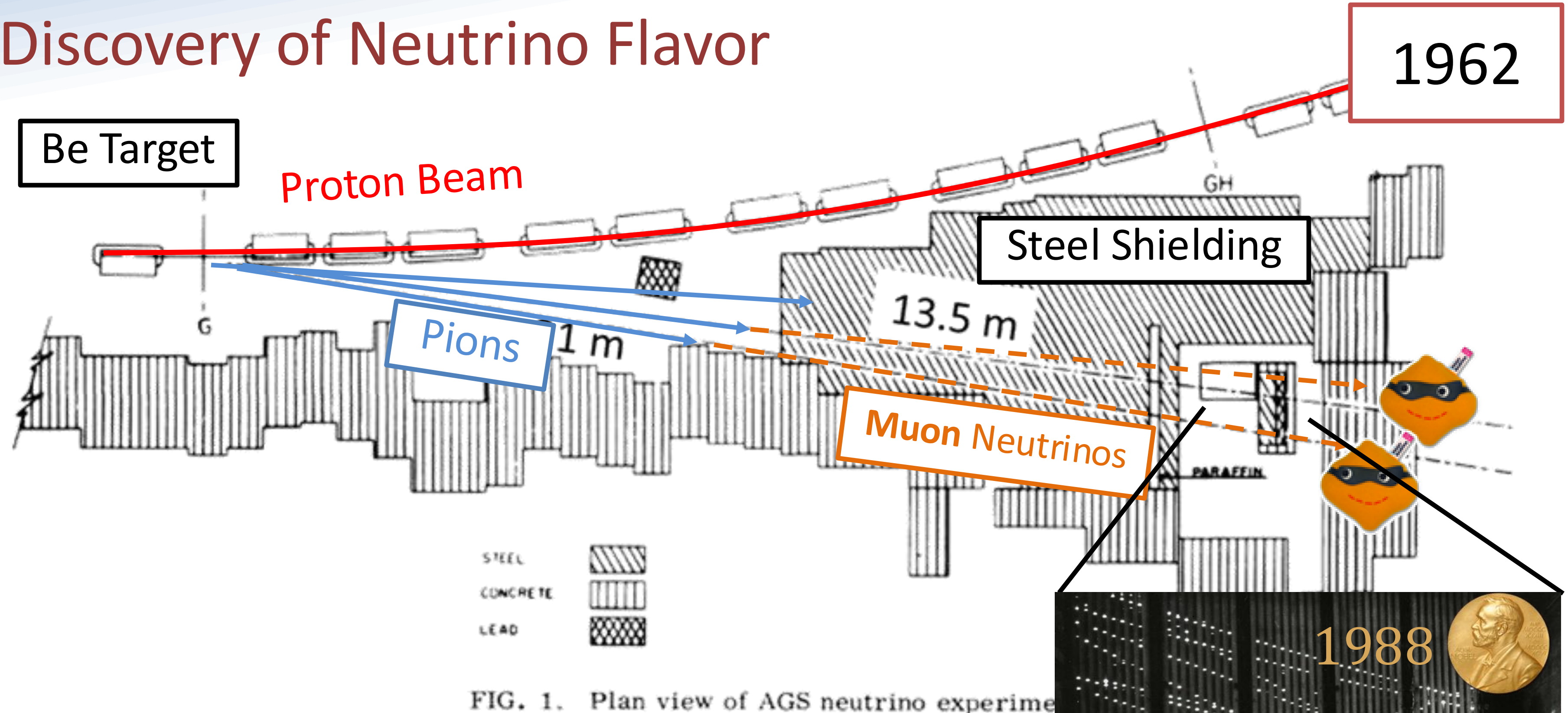


$$p + \text{Be} \rightarrow \overbrace{\pi^+ + \ldots}^{\text{Stopped by steel shielding}}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\nu_\mu + n \rightarrow p + \mu^-$$

Discovery of Neutrino Flavor



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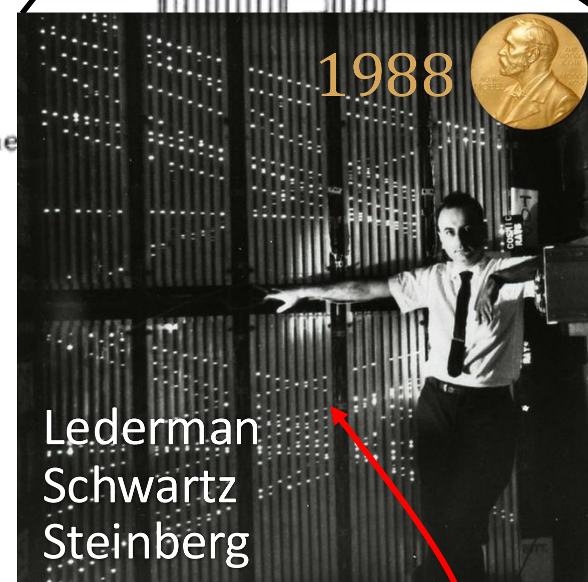

$$p + \mathrm{Be} \rightarrow \overbrace{\pi^+ + \ldots}^{\text{Stopped by steel shielding}}$$

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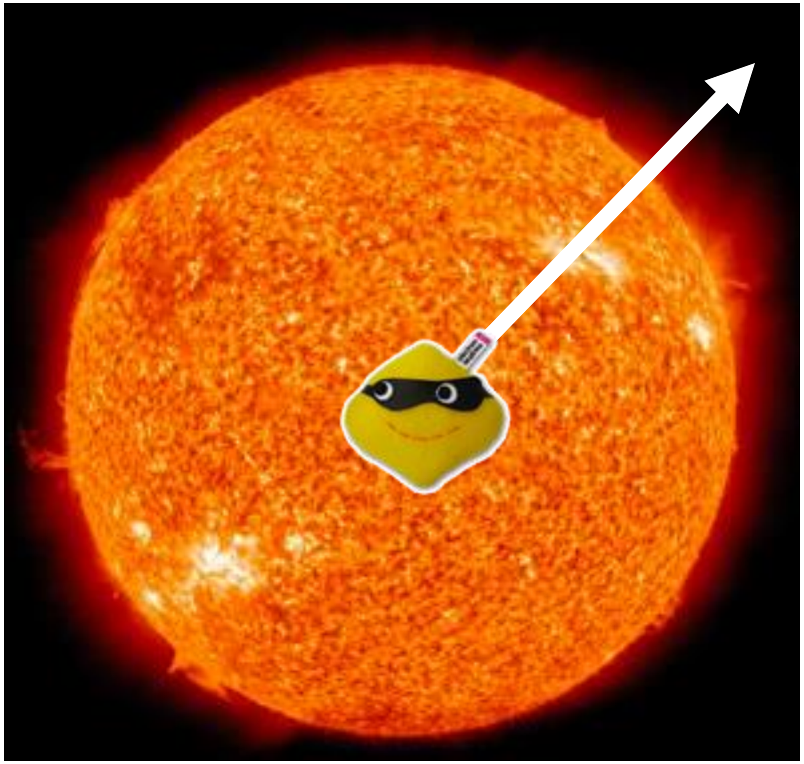
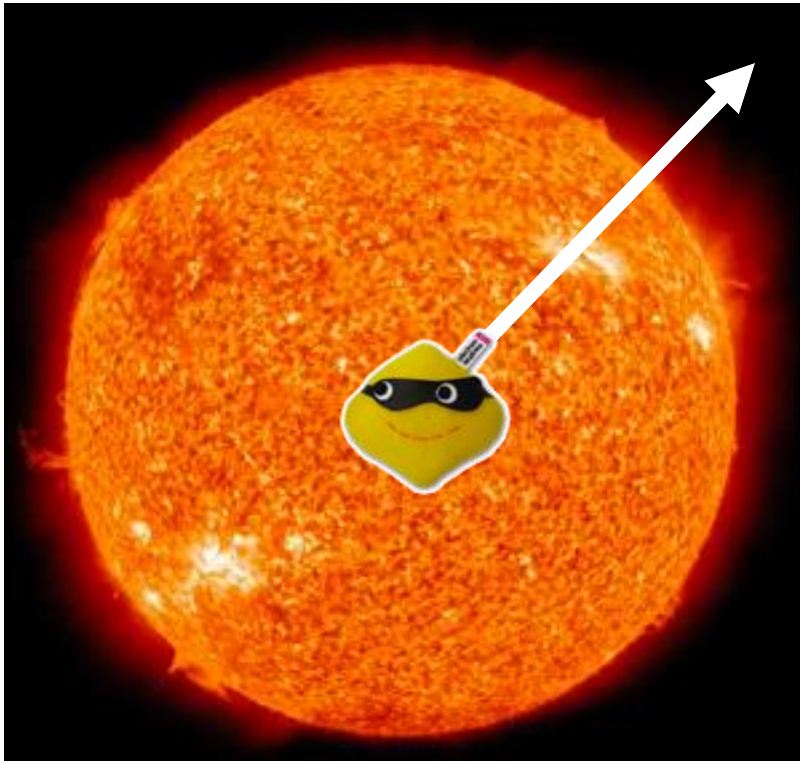
Solar Neutrinos

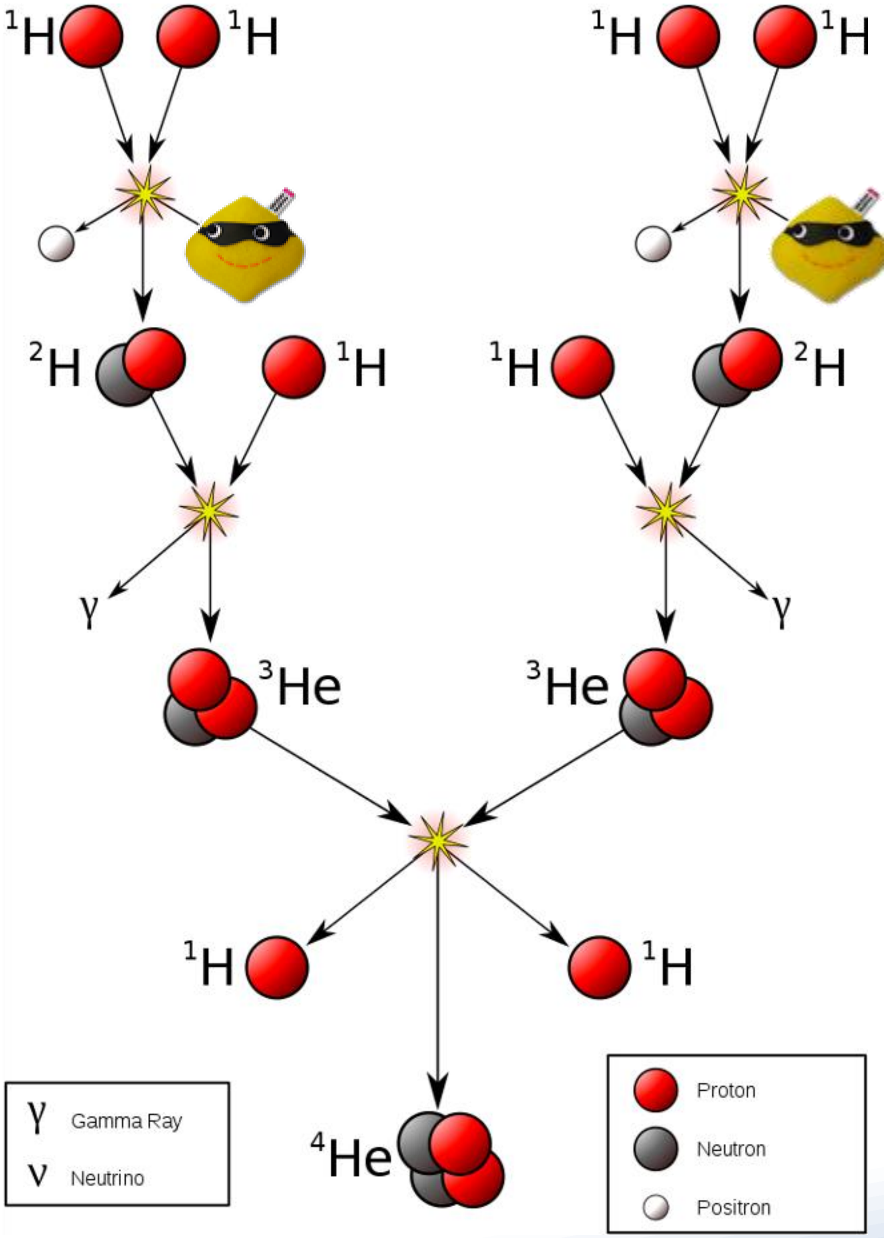


- Blessing of weak interactions – carry information from deep inside heavy objects.

Solar Neutrinos



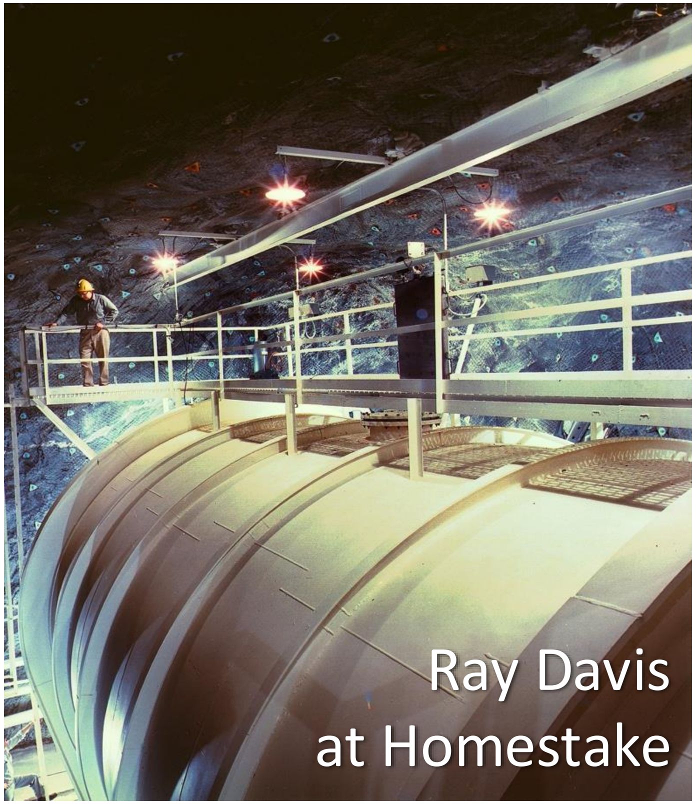
- Blessing of weak interactions – carry information from deep inside heavy objects.
- Rate of neutrinos from fusion is extremely sensitive to the temperature of the sun.

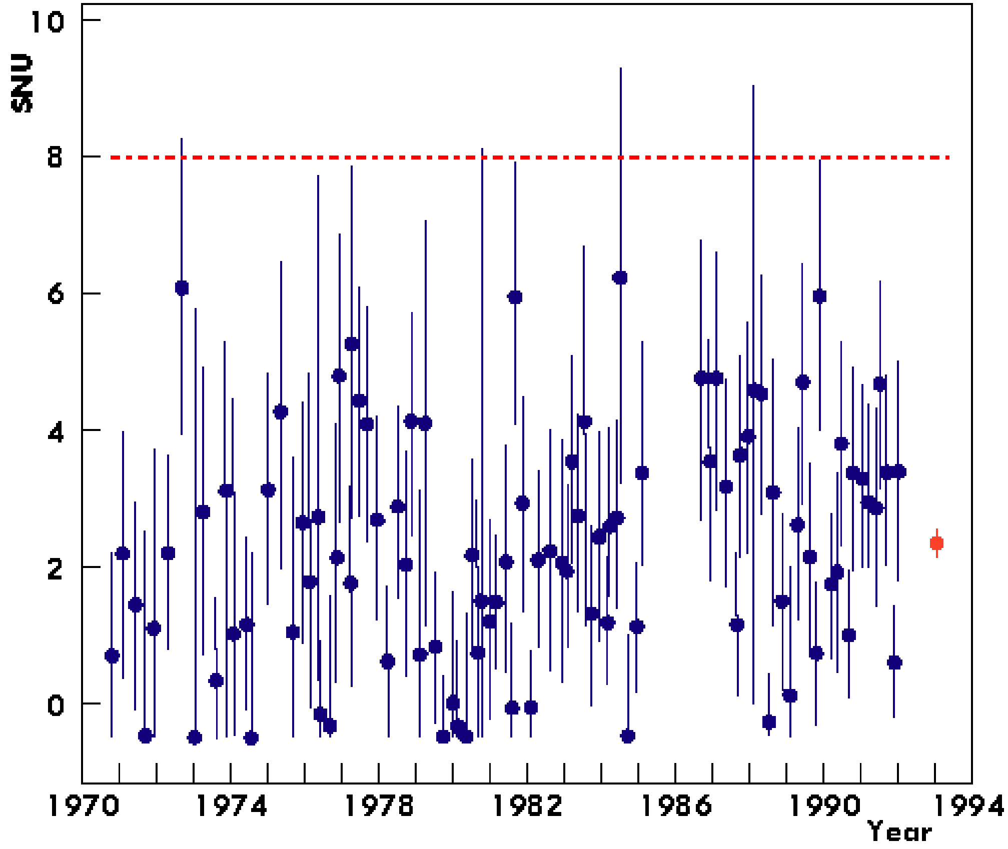


Solar Neutrinos become a Problem

1969

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

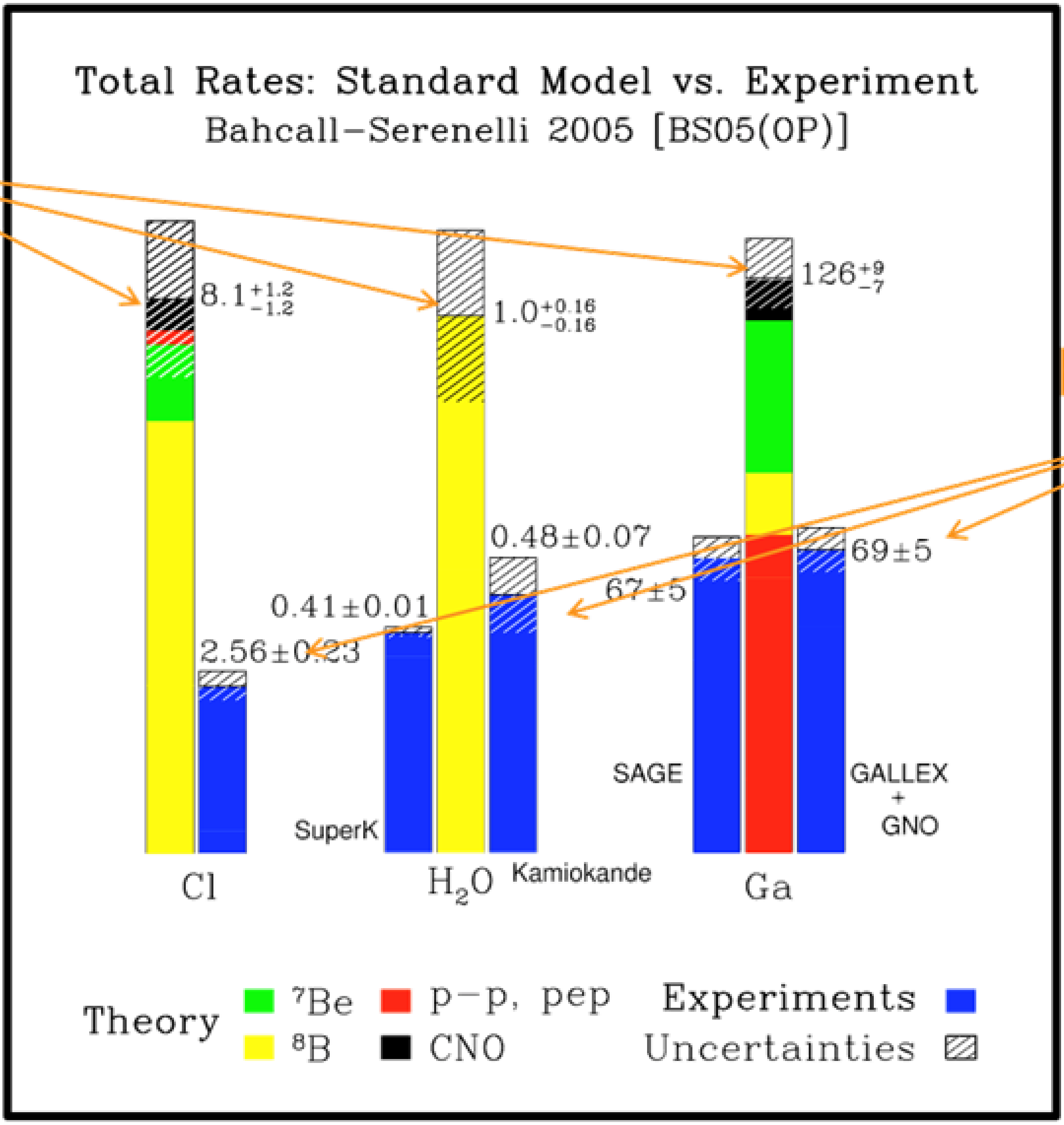




1969-1991

Theory

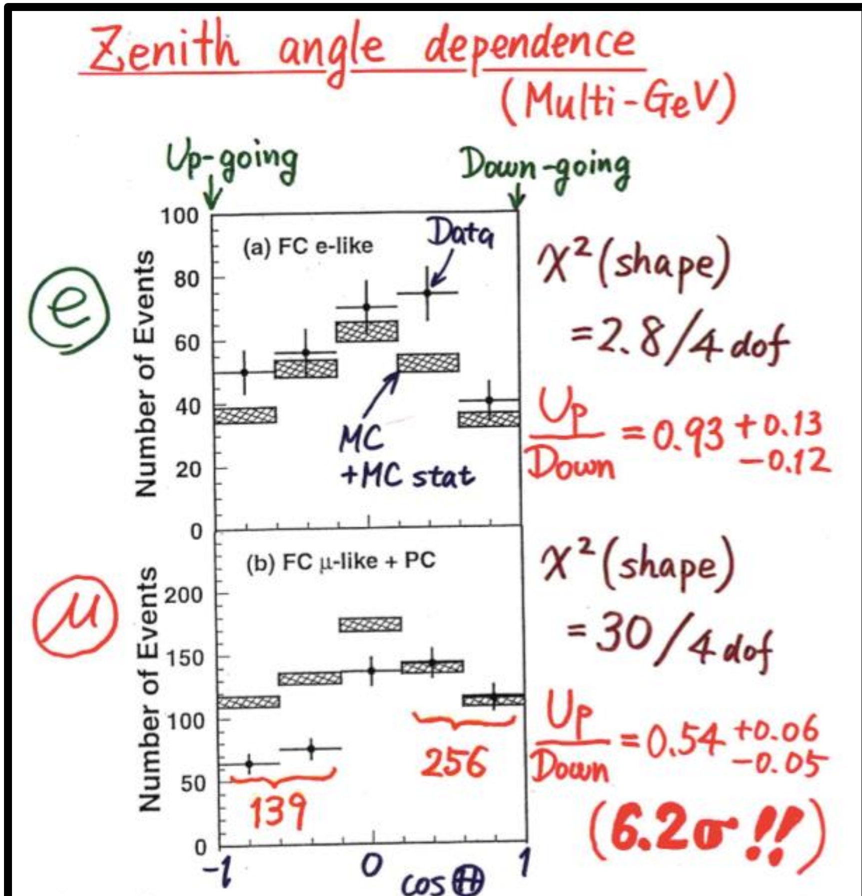
Experiments

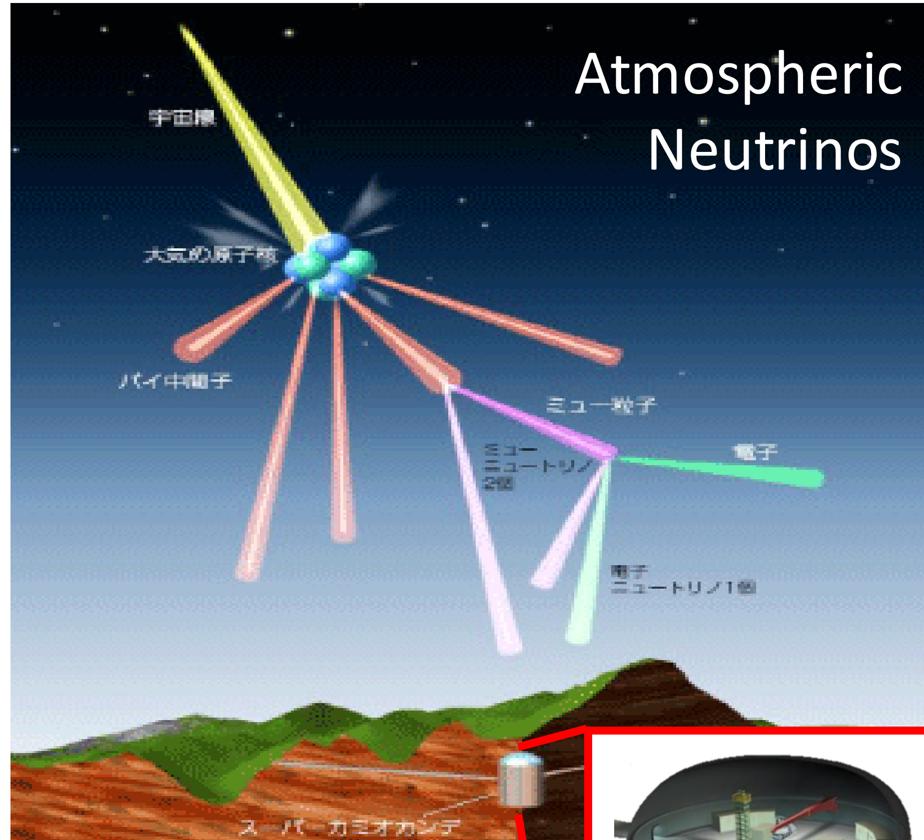


The Solution: Neutrino Oscillations

1998

Discovered in 1998 by
Super-Kamiokande





T. Kajita
Neutrino 1998

The Solution: Neutrino Oscillations

1998

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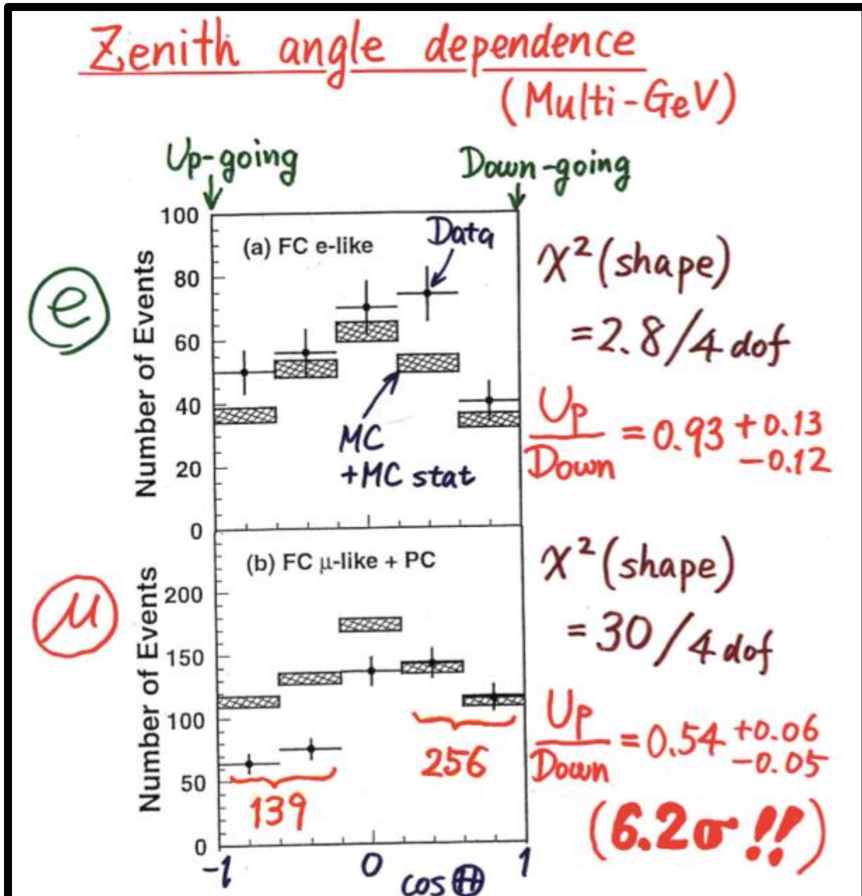
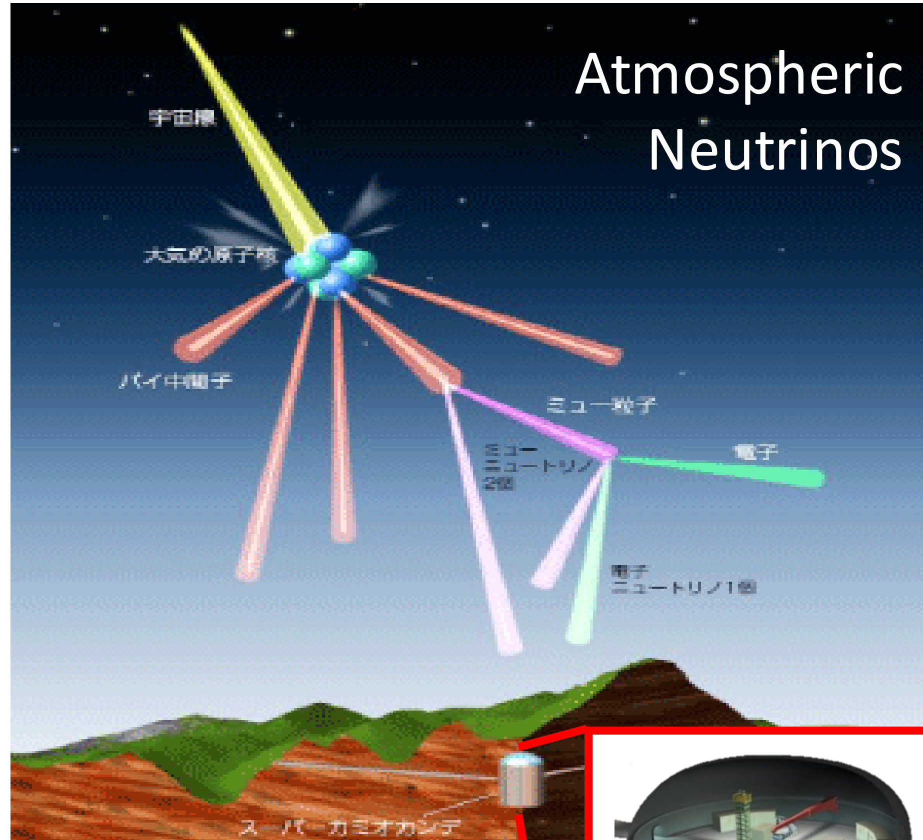




T. Kajita
Neutrino 1998

Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

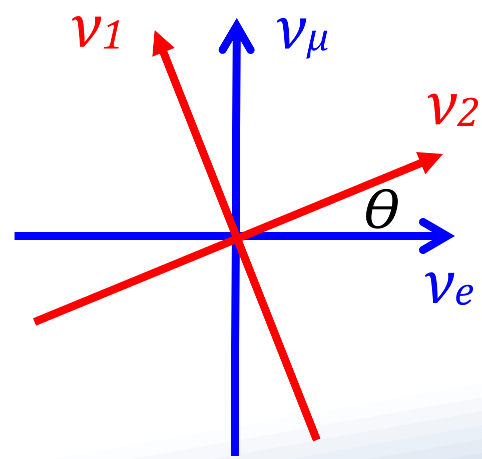
Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

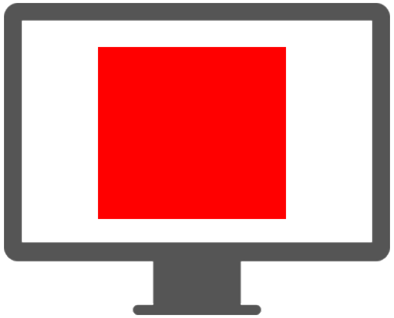
- Each flavor (e, μ) is a superposition of different masses (1, 2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

"Mixing Matrix"

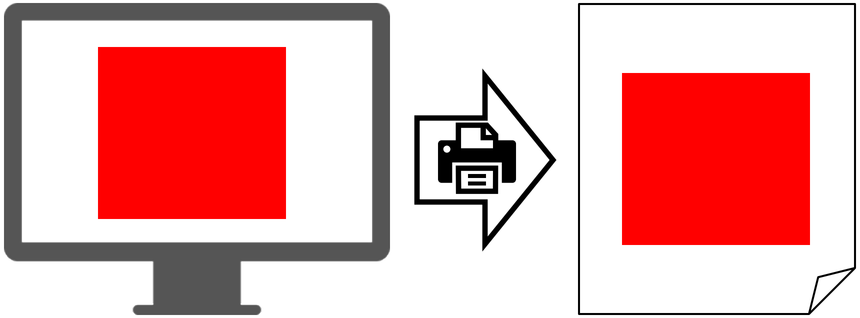


A Colorful Analogy



Red	**100%**
Green	0%
Blue	0%

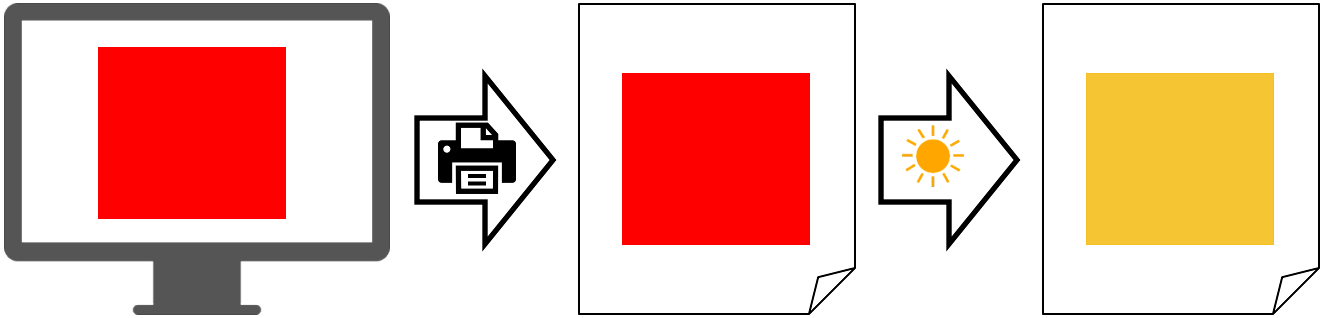
A Colorful Analogy



Red	**100%**
Green	0%
Blue	0%

Cyan	0%
Magenta	**84%**
Yellow	**94%**
Black	1%

A Colorful Analogy



Red	**100%**
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Cyan	0%
Magenta	20%
Yellow	**94%**
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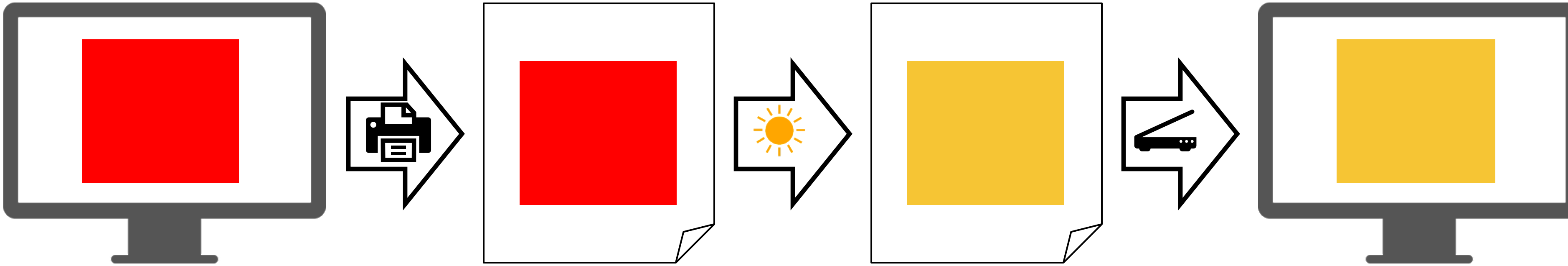
A Colorful Analogy



Red	**100%**
Green	0%
Blue	0%

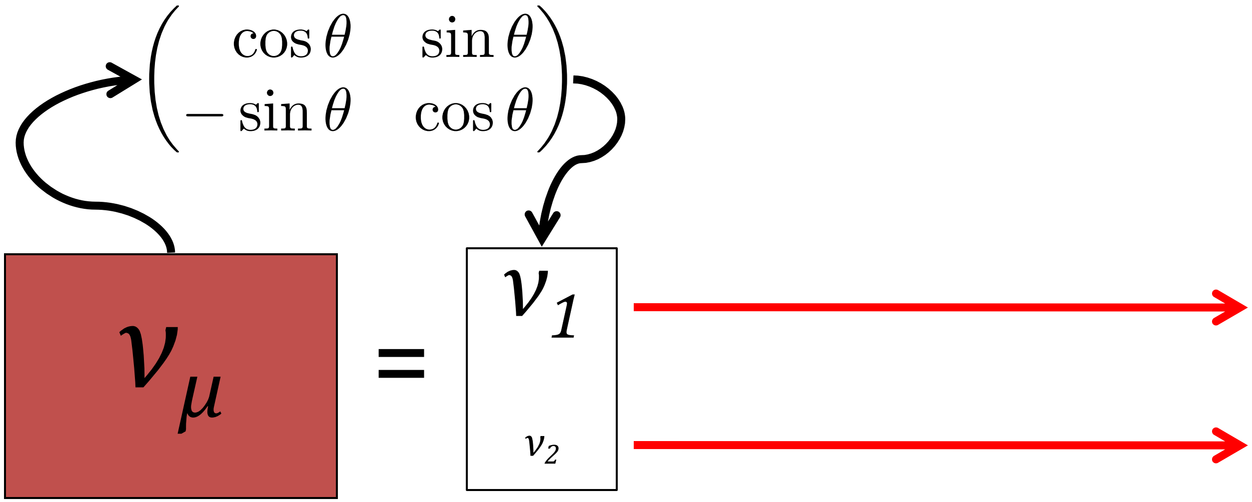
Cyan	0%
Magenta	**84%**
Yellow	**94%**
Black	1%

Cyan	0%
Magenta	20%
Yellow	**94%**
Black	1%

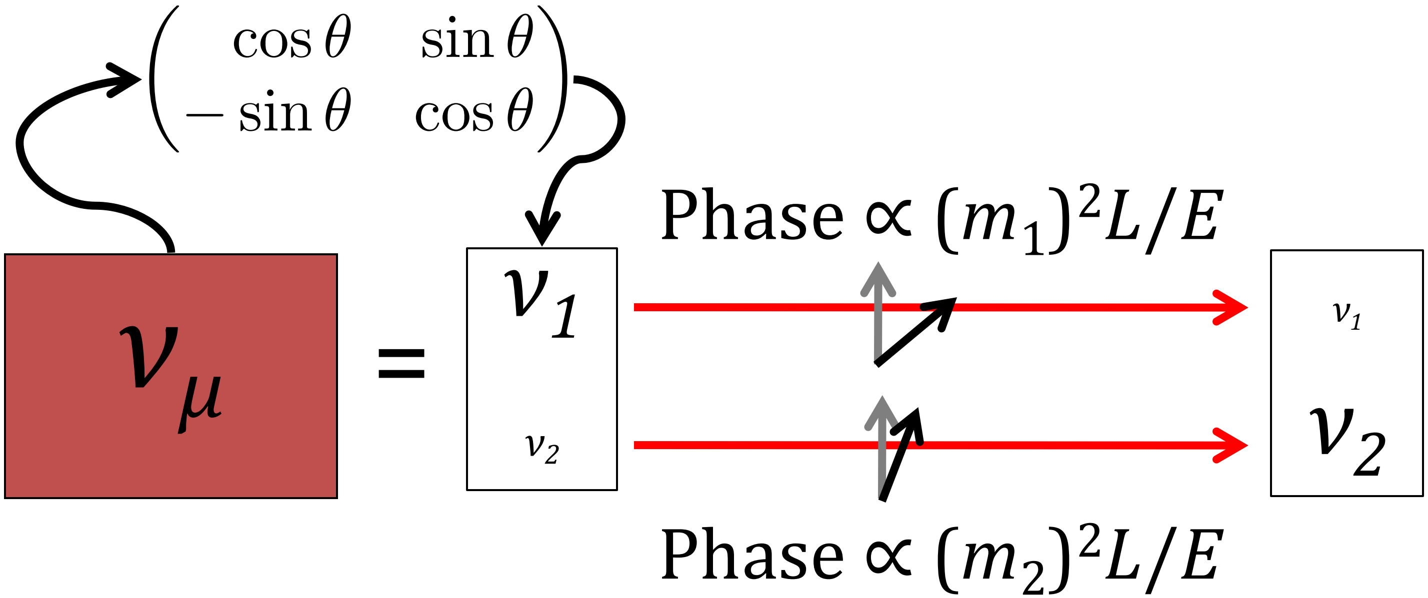
Red	**50%**
Green	**40%**
Blue	10%

Neutrino Oscillations

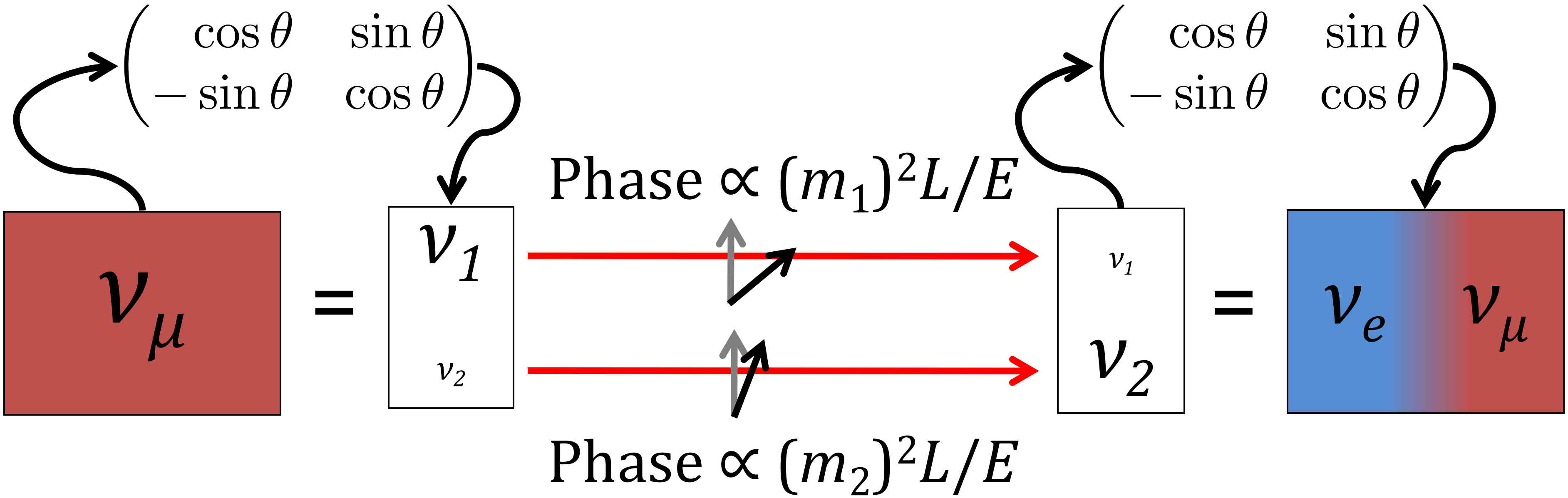
Neutrino Oscillations



Neutrino Oscillations

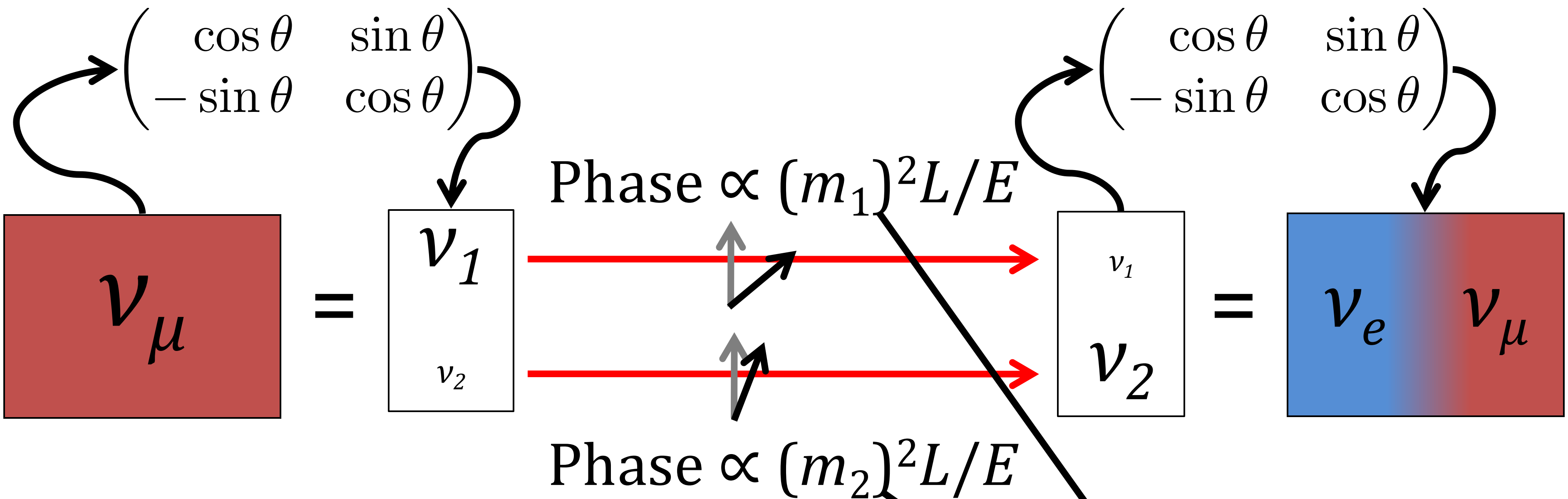


Neutrino Oscillations



Neutrino oscillations require that neutrinos have mass!

Neutrino Oscillations



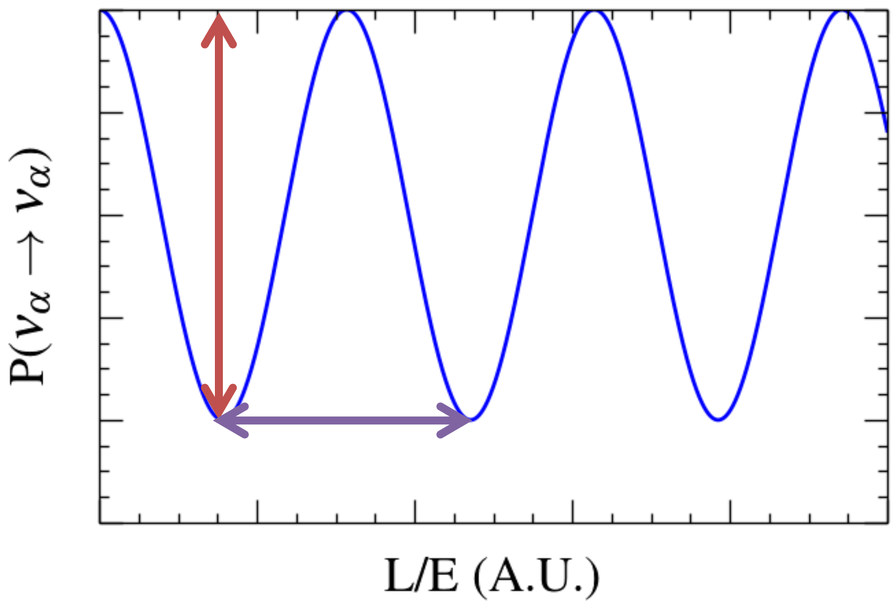
Muon Neutrino Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

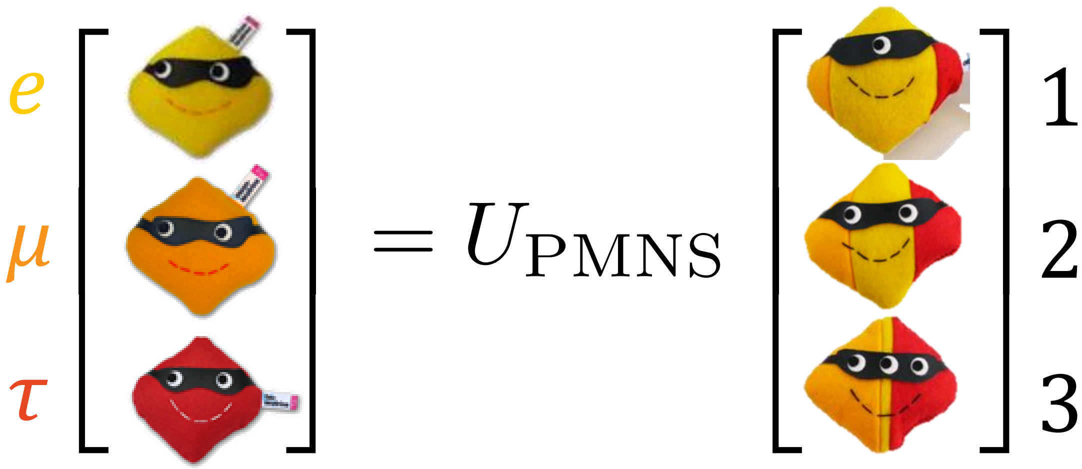
Neutrino Oscillations

- With only 2 neutrinos, the oscillation formula is simple:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Three-flavor Neutrino Oscillations



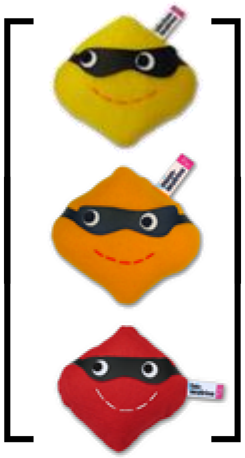
- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix

Three-flavor Neutrino Oscillations

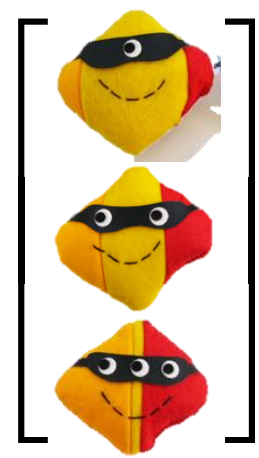
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}

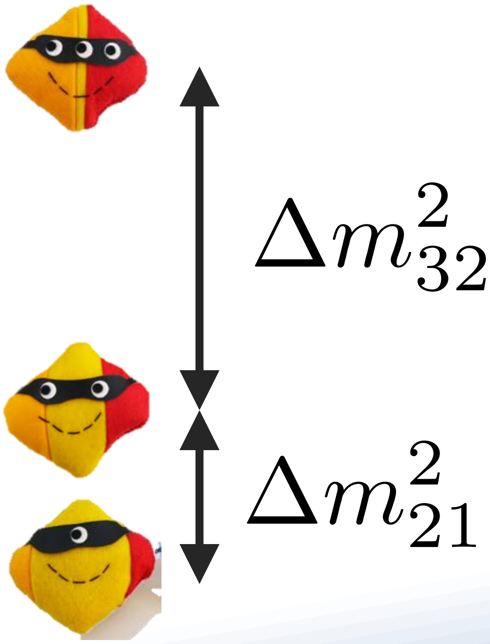
Three-flavor Neutrino Oscillations



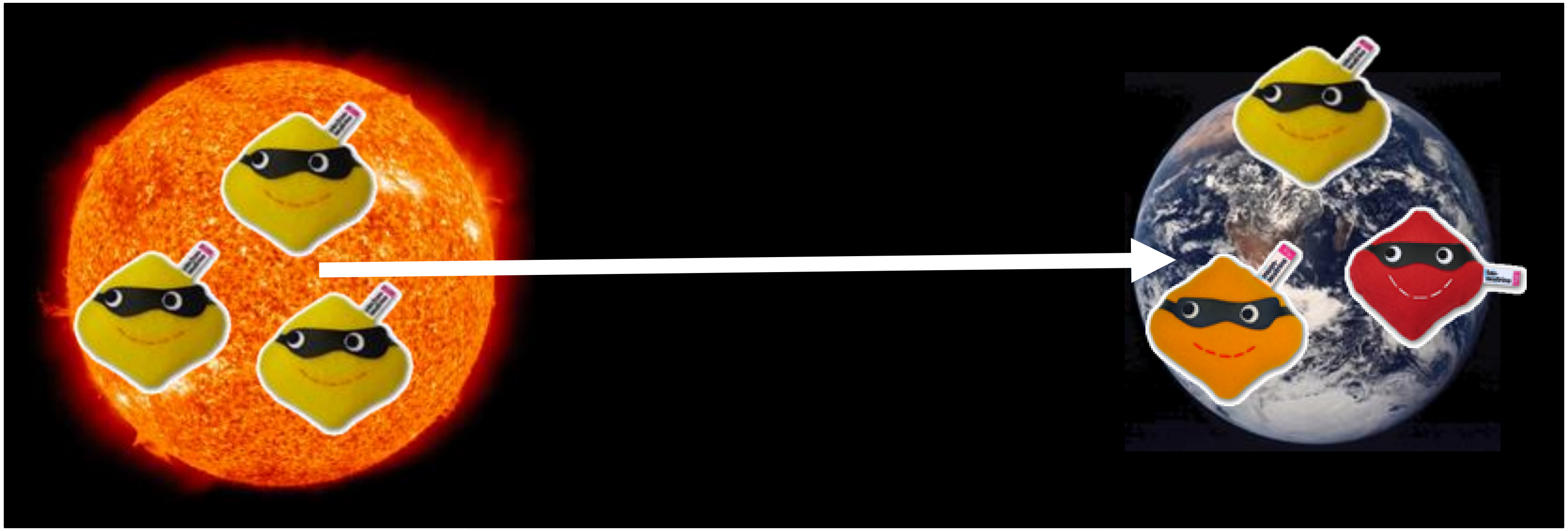
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

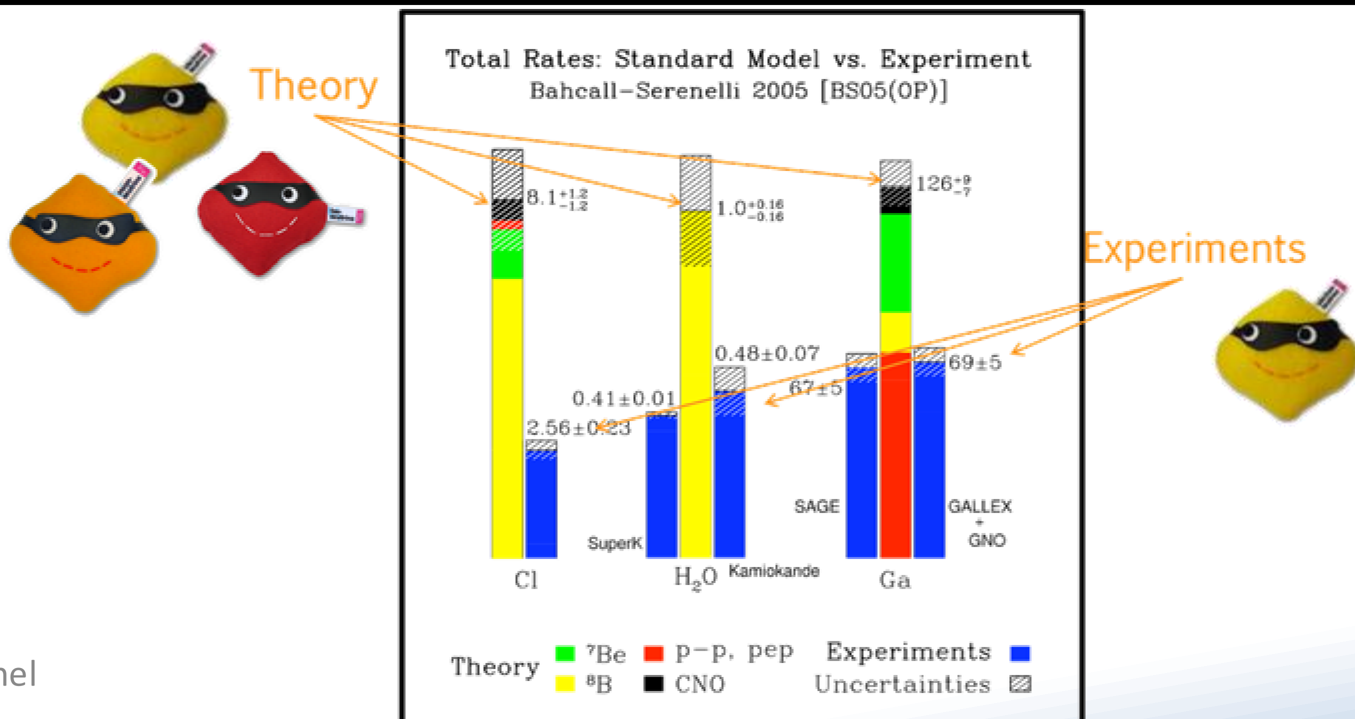


- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
  - The mass differences
    - Δm^2_{32}, Δm^2_{21}



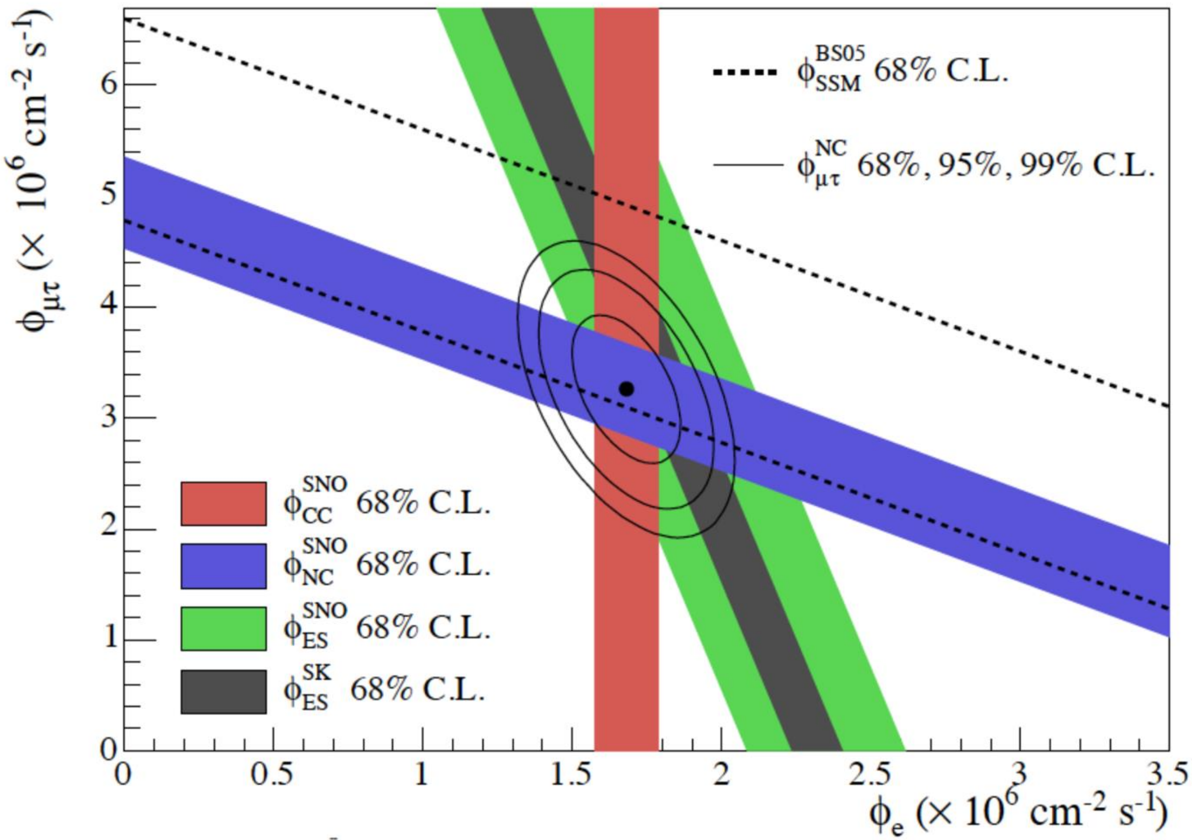
Solar Neutrinos

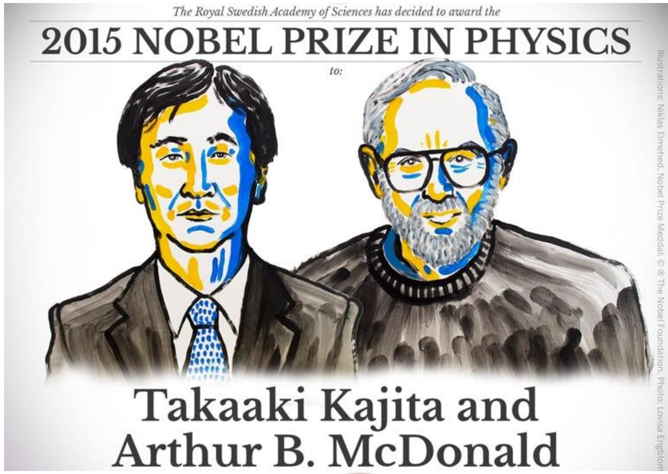




SNO

1998

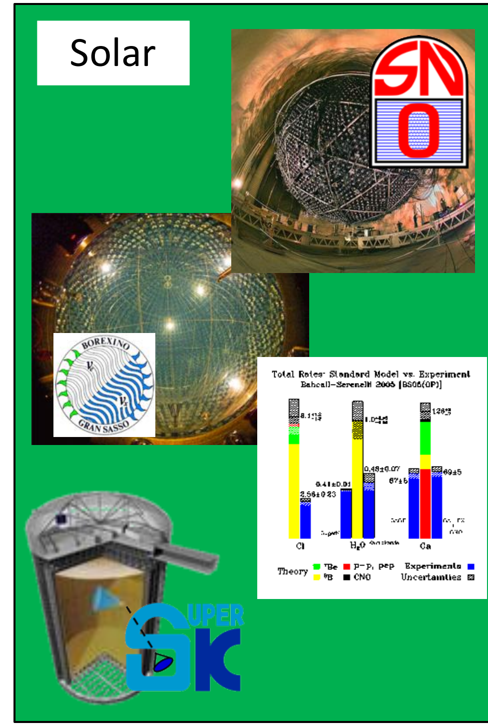


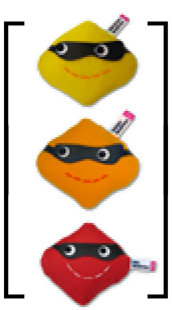


- The definitive solution came from the SNO experiment, which measured both the νe and all-ν fluxes together.

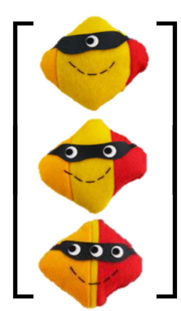
2015

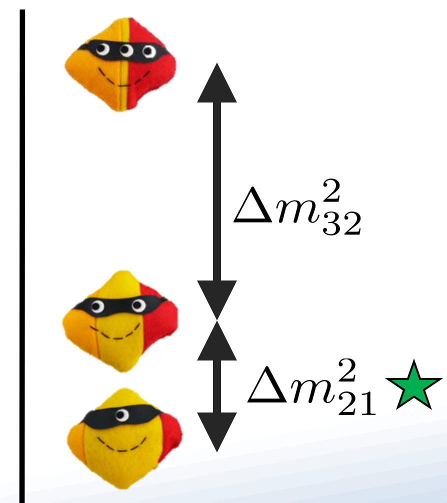
Understanding oscillations: a world-wide effort





$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \bigstar$$





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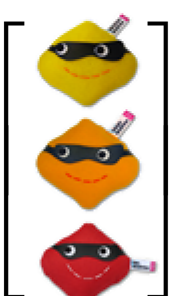

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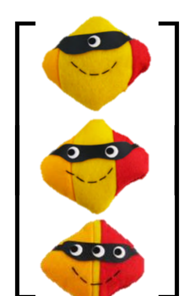

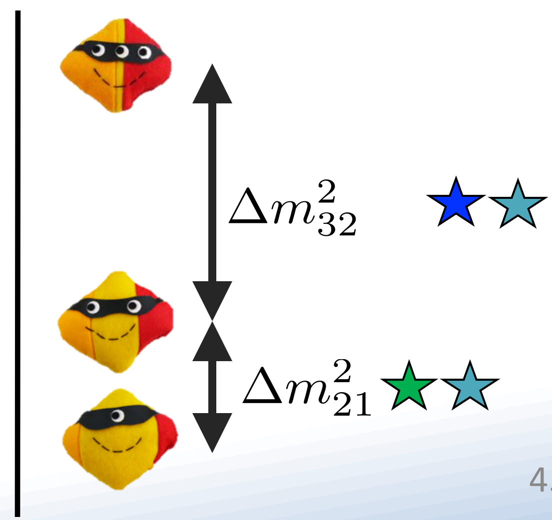

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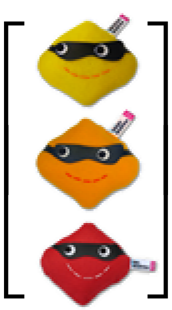

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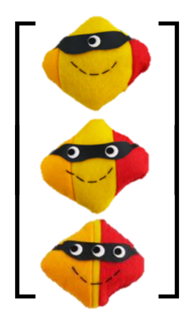
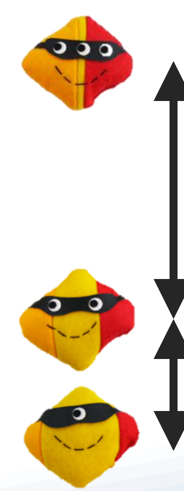
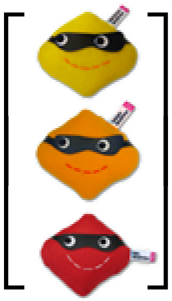




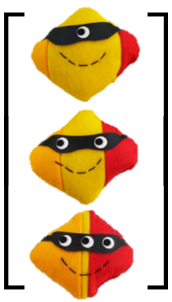
Δm^2_{32}

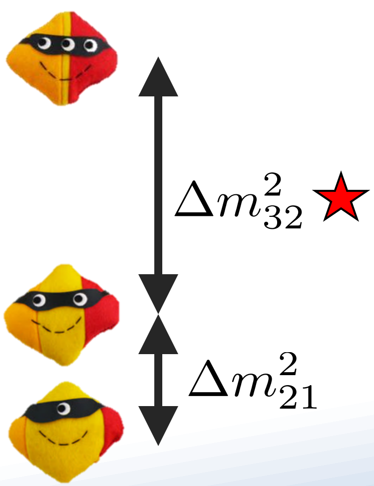
Δm^2_{21}

Understanding oscillations: a world-wide effort



$$= \overset{\star}{R}(\theta_{23}) \cdot R(\overset{\star}{\theta}_{13}, \overset{\star}{\delta}_{CP}) \cdot R(\theta_{12})$$

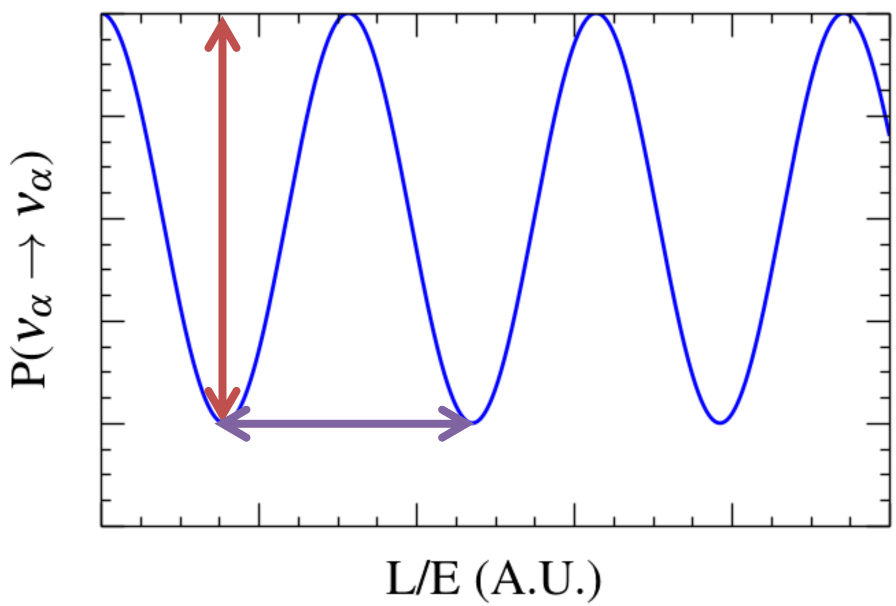


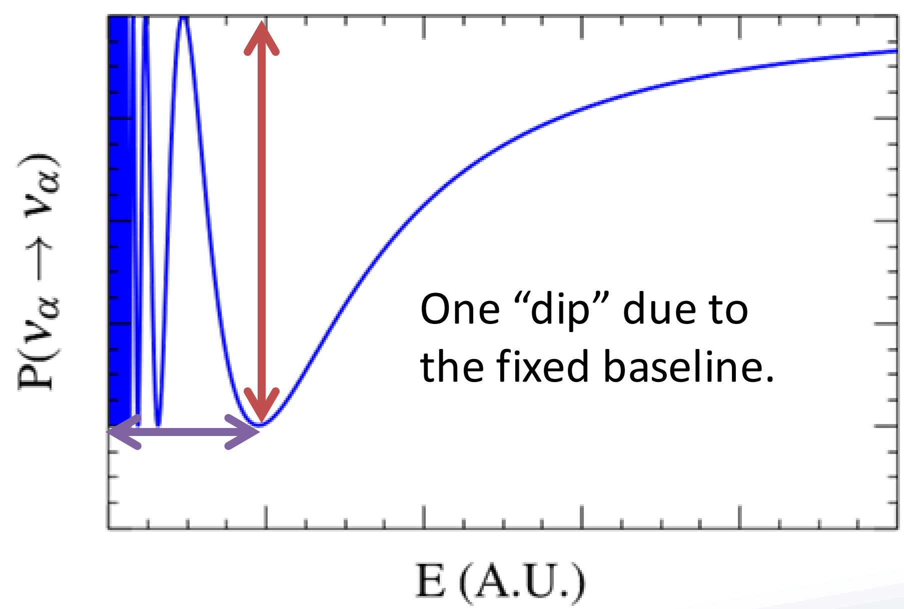


How to study oscillations: Disappearance

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

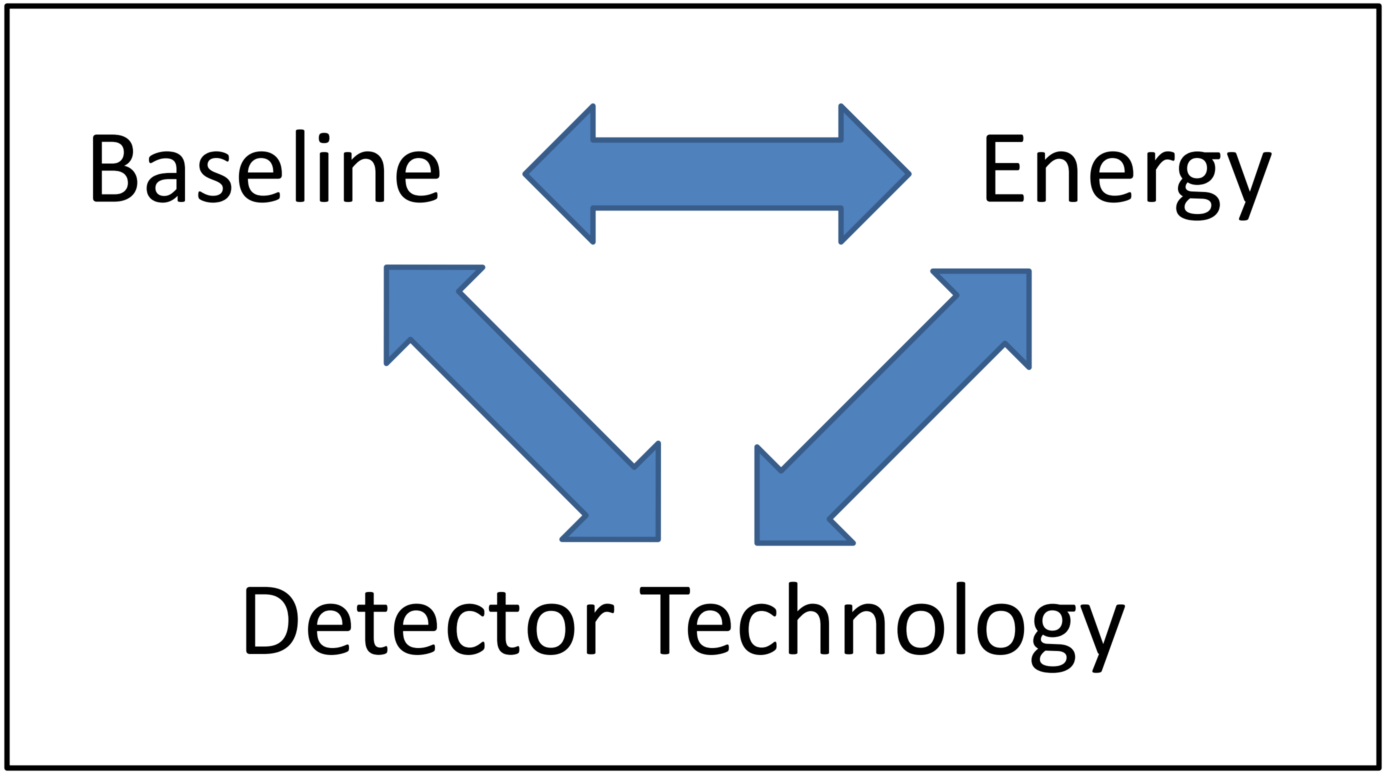




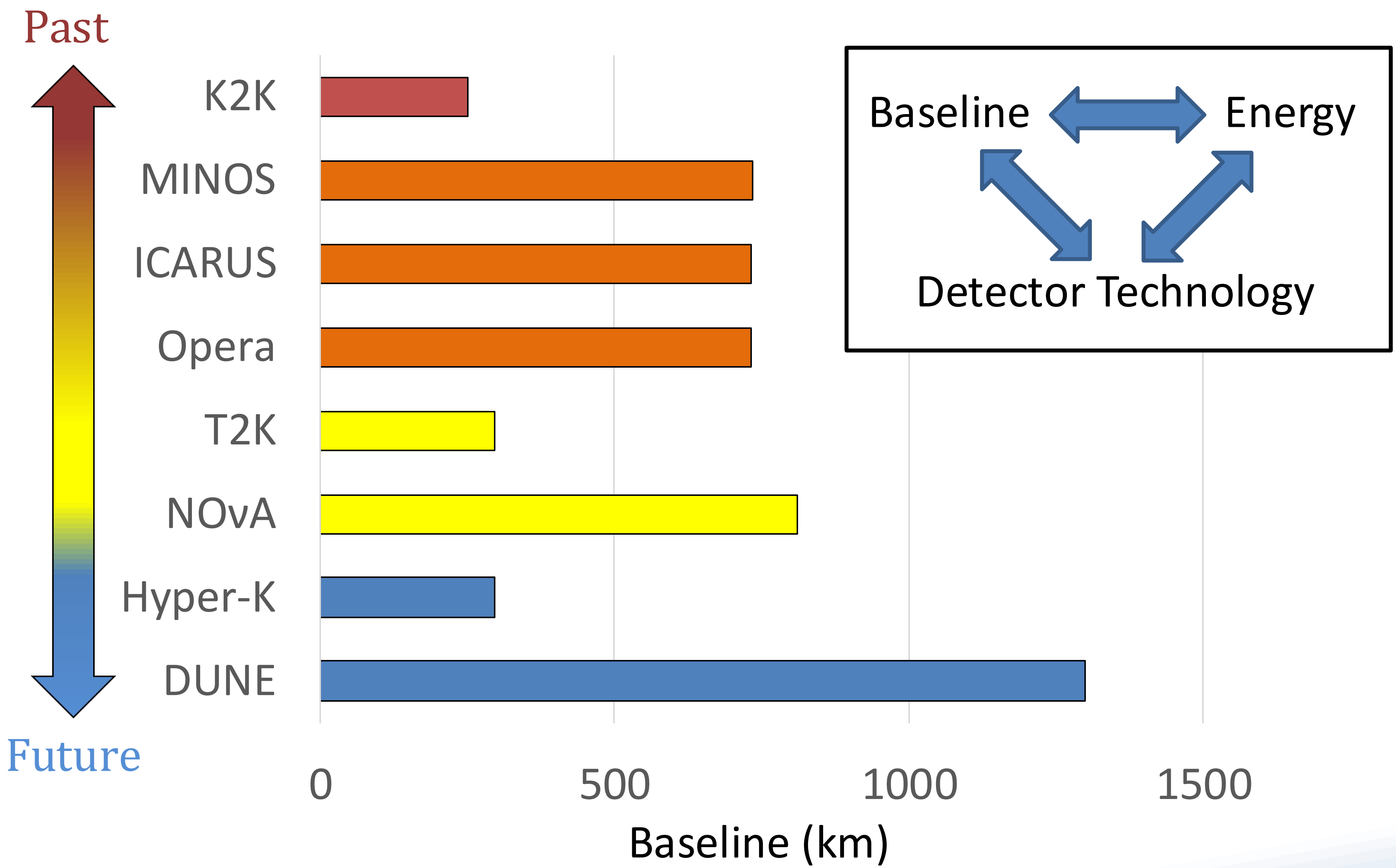
One "dip" due to the fixed baseline.

Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Designing an Accelerator ν Experiment



Designing an Accelerator ν Experiment



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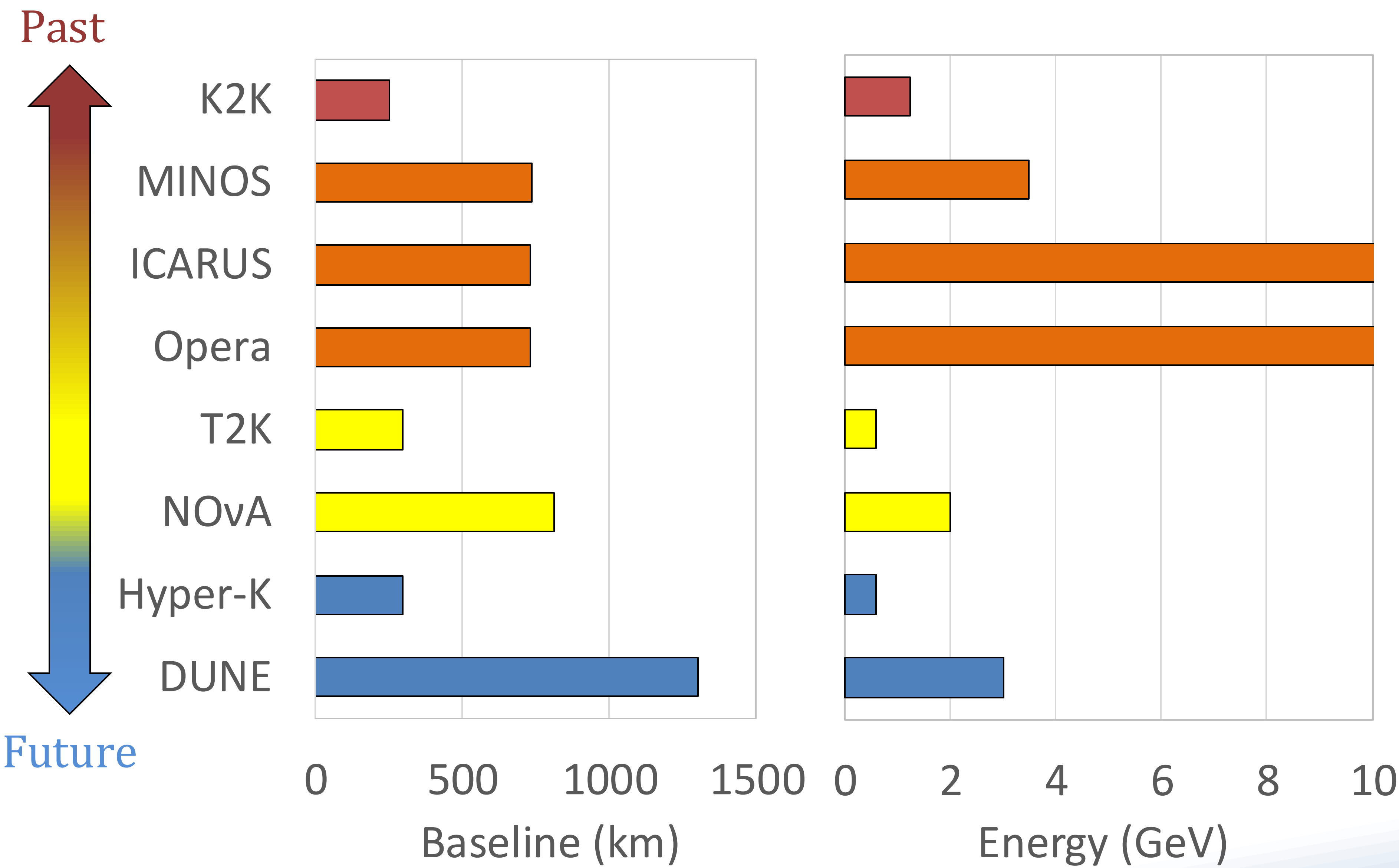
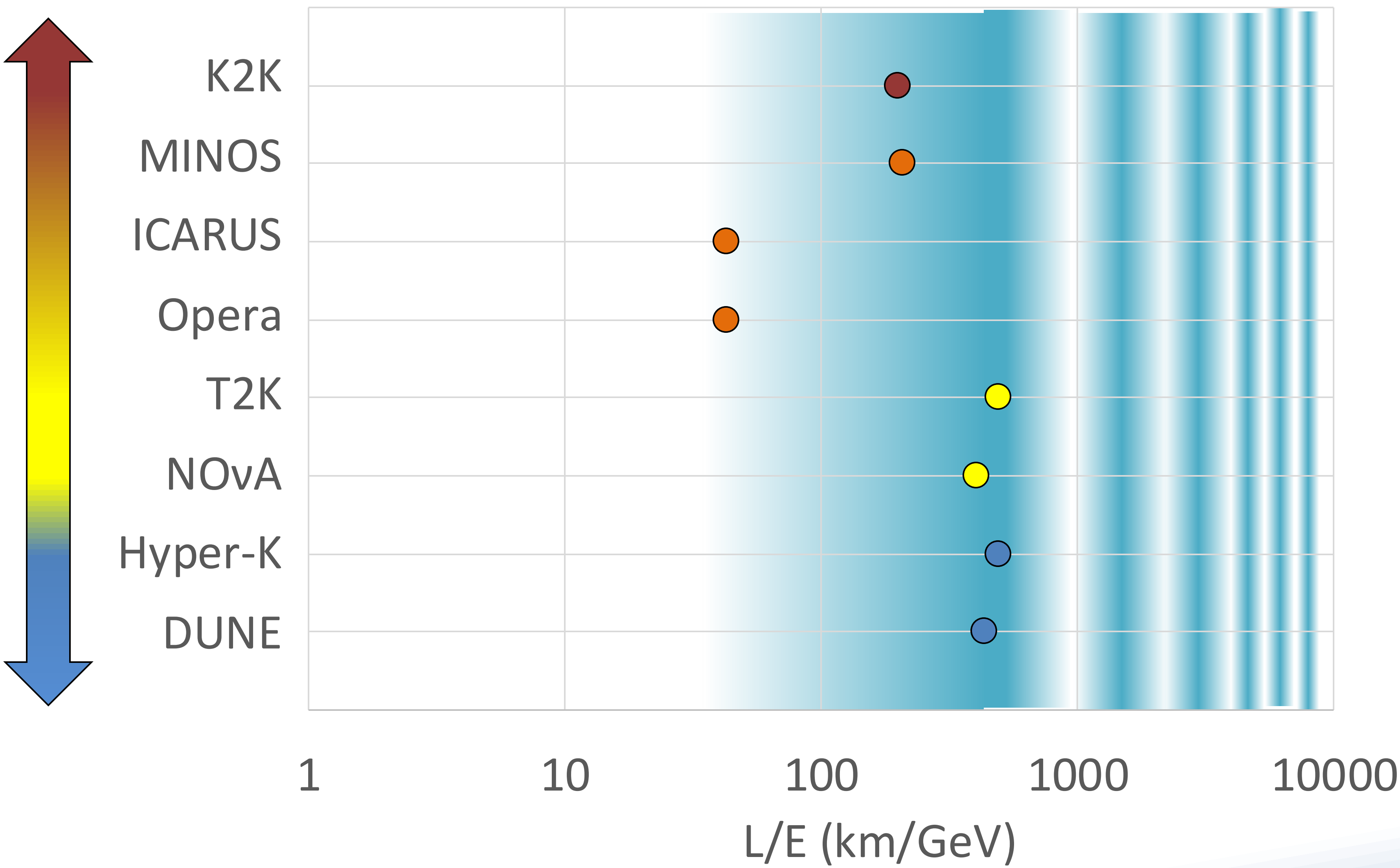
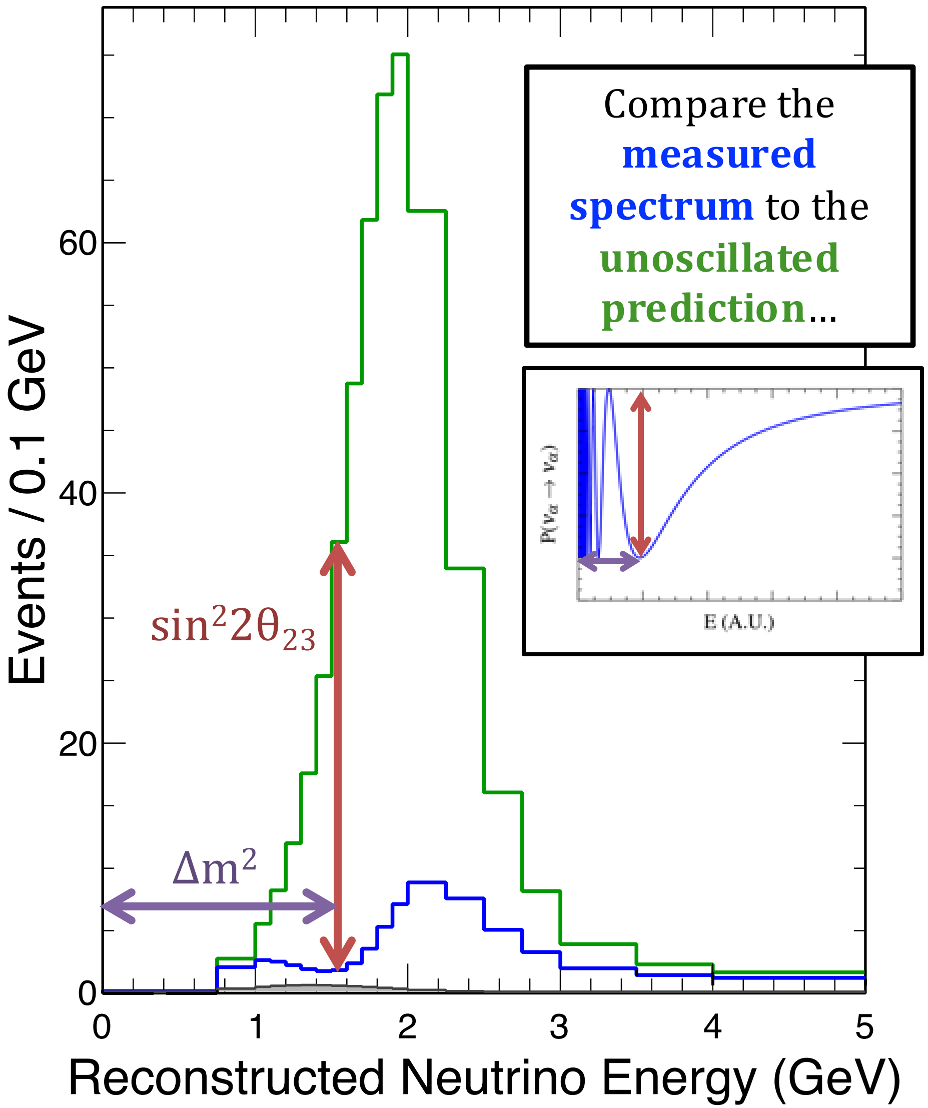


Designing an Accelerator ν Experiment

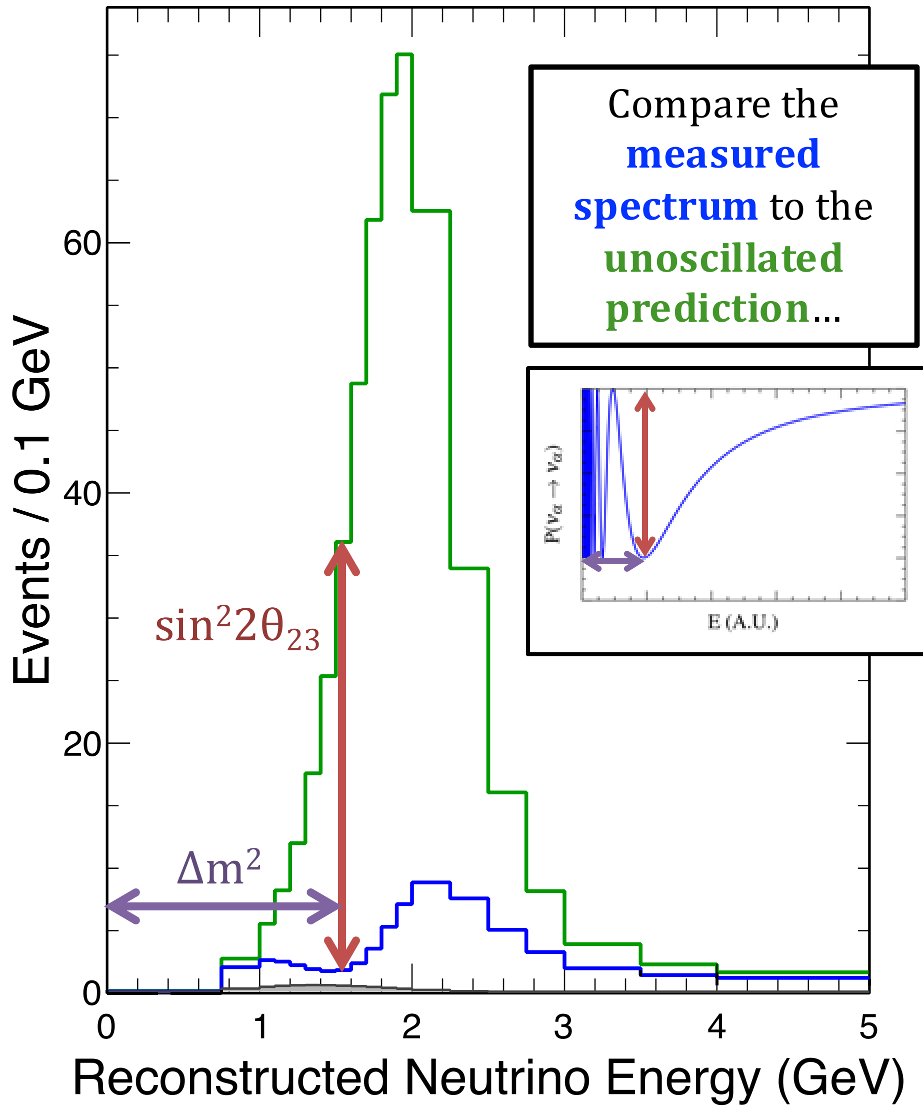


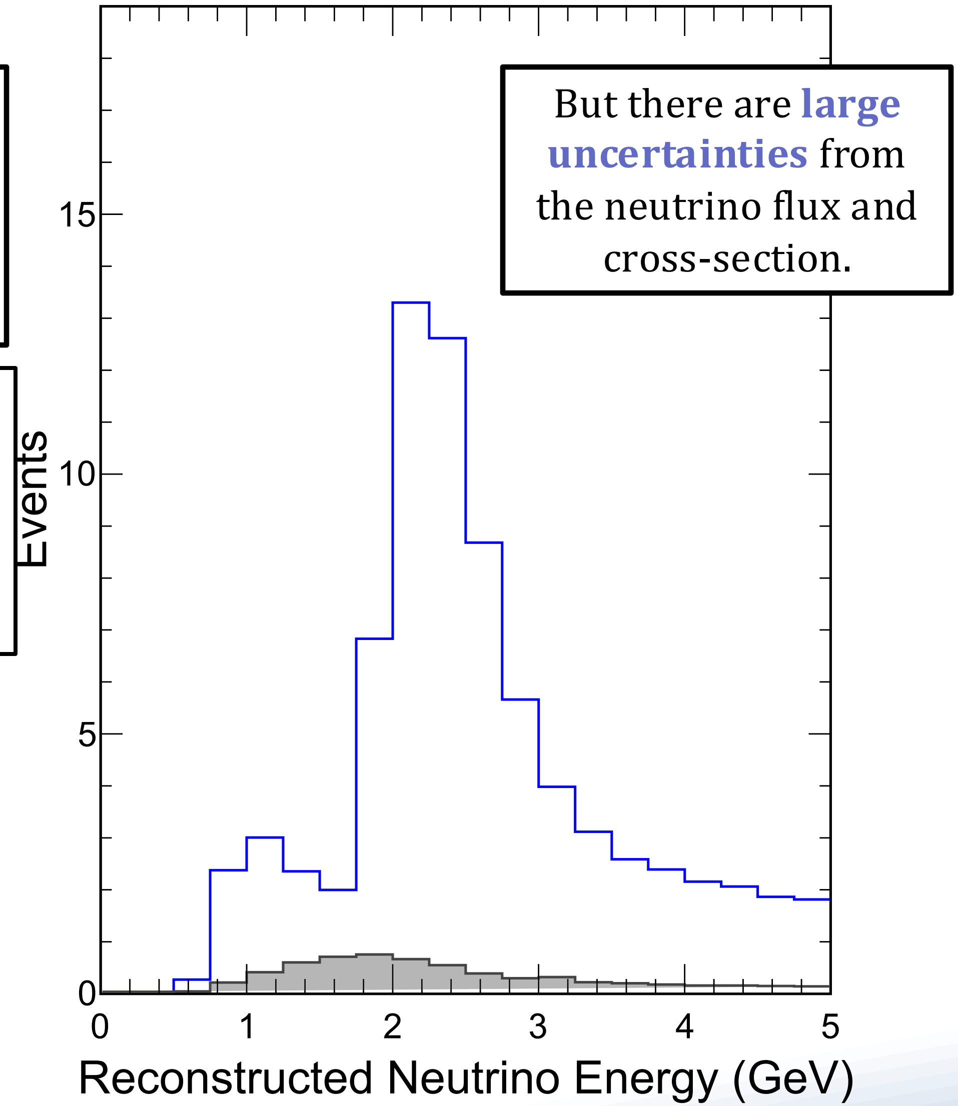
How to study oscillations: Disappearance



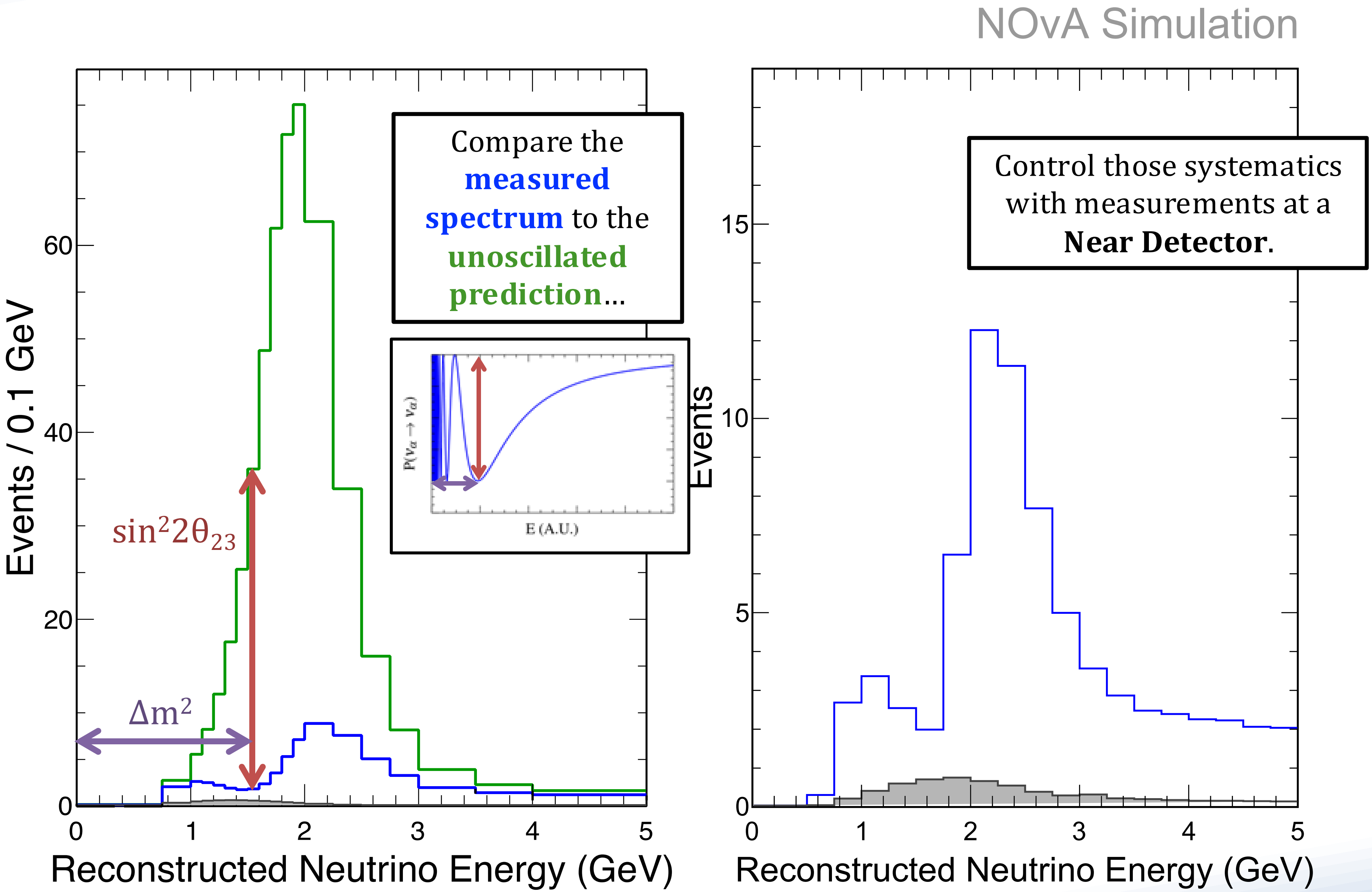
How to study oscillations: Disappearance

NOvA Simulation

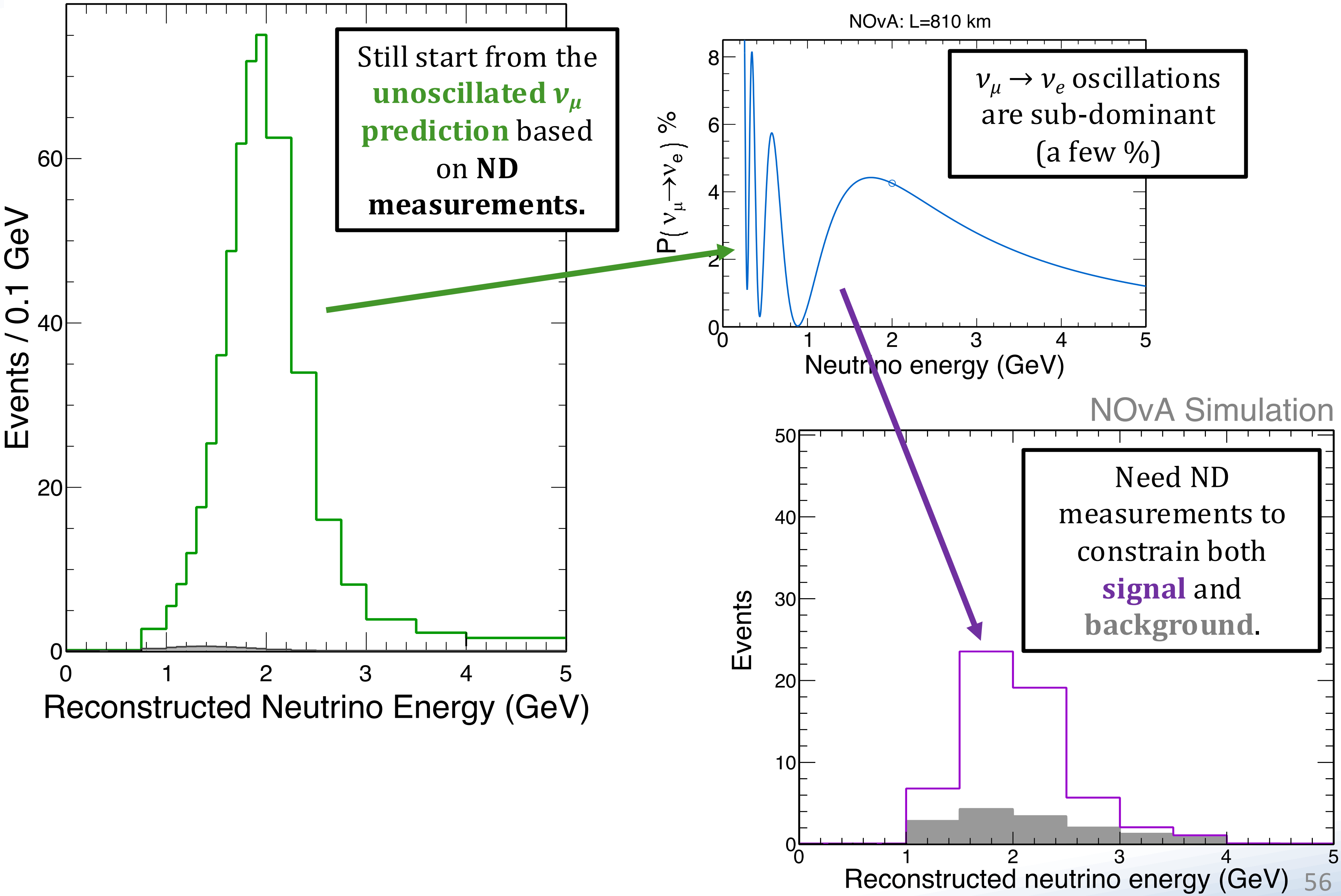




How to study oscillations: Disappearance

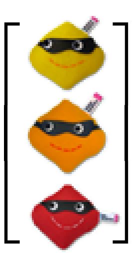


How to study oscillations: Appearance

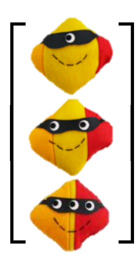


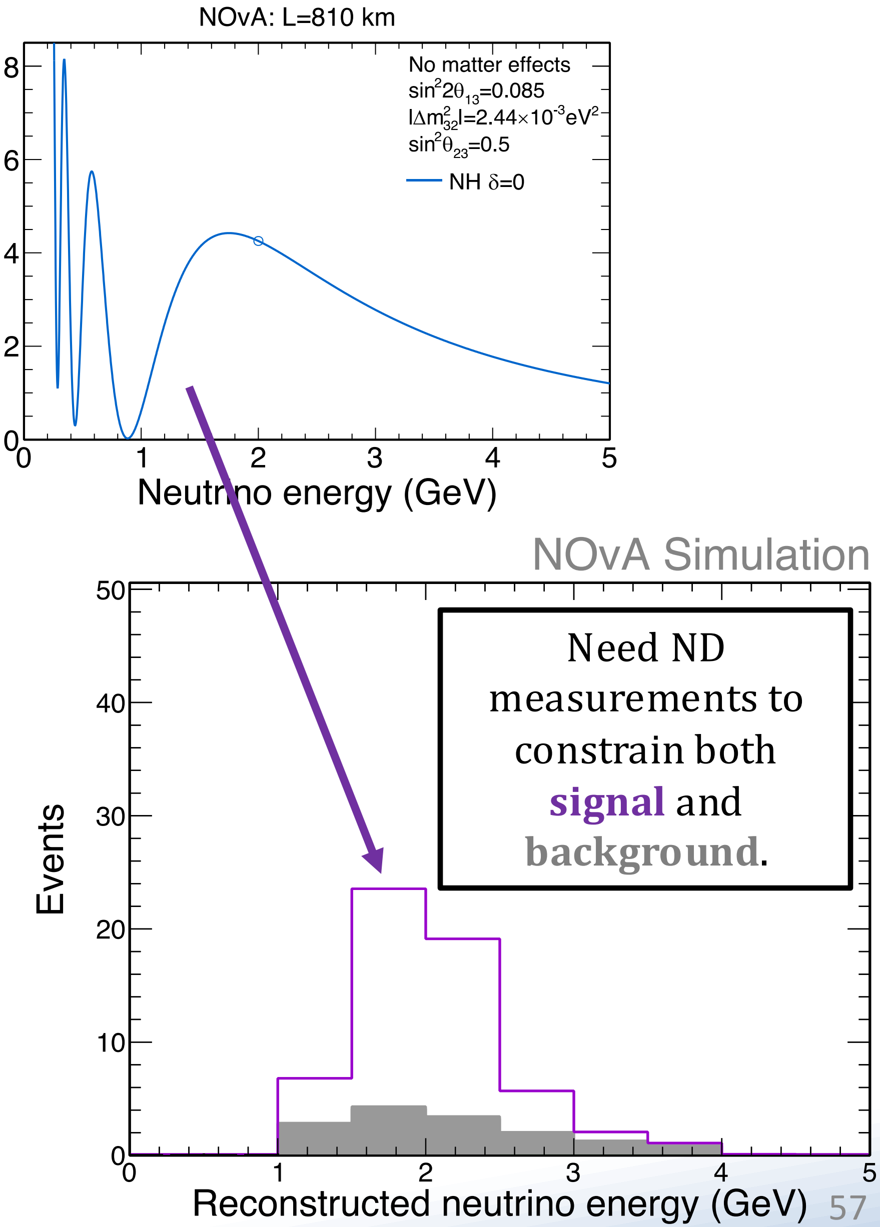
How to study oscillations: Appearance

- Depends on *every* oscillation parameter.
  - All angles must be non-0.
  - We didn't know we could do this until 2012!
- All the unanswered (oscillation) questions depend on ν_e appearance.
- ...but they're unanswered because it's really hard!



$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



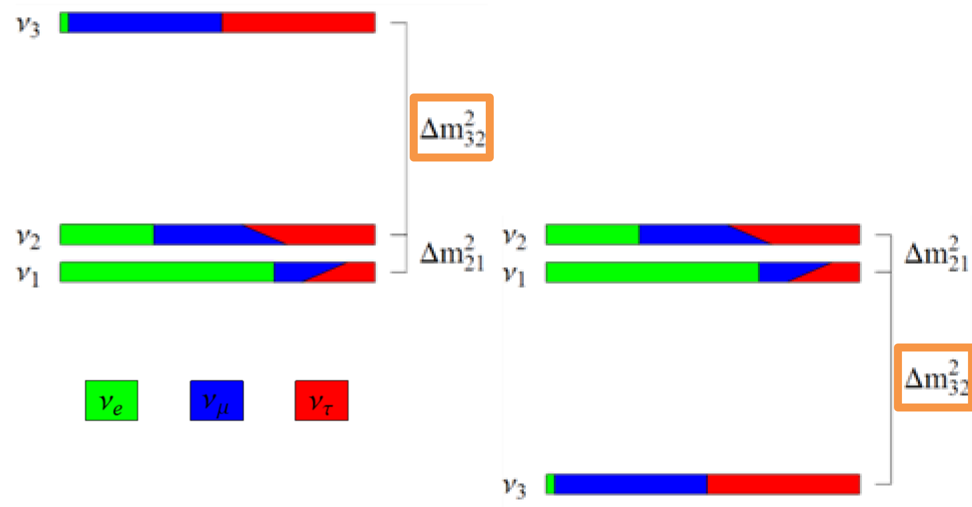


Open questions in neutrino oscillations

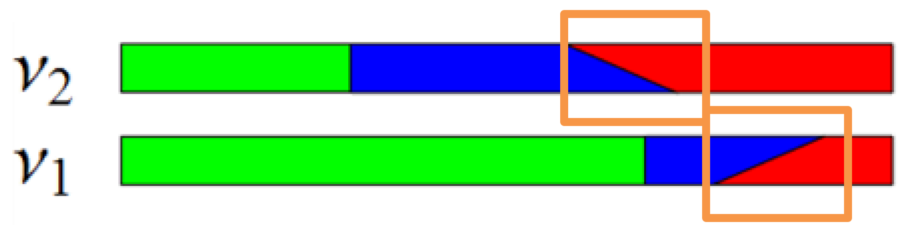
1. Do neutrino oscillations violate *CP* symmetry directly via δ_{CP}?

$$R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

2. Is the mass hierarchy "normal" or "inverted?



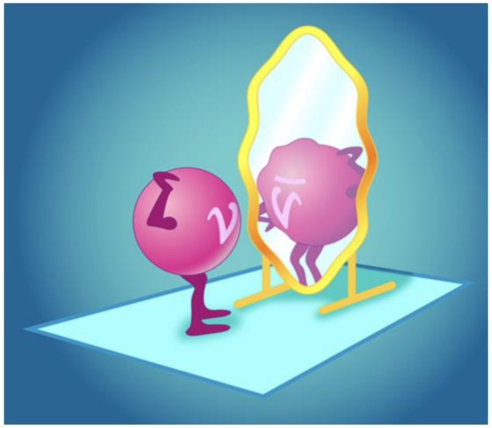
3. What is the "octant" of θ_{23}?
   - Or is the mixing "maximal" (e.g. θ_{23} = 45°)?



Aside – what is *CP* symmetry?

- We are very interested in symmetries and broken symmetries since they are deeply related to fundamental laws.
- ***C* = charge**, which means particle-antiparticle symmetry
- ***P* = parity**, which means symmetry under mirror reflections
- Large violations of *C* and *P* symmetry are common, but violations of *C* & *P* together are very rare.
- Important: more *CP* violation is needed to explain why the universe is made of matter!

Emmy Noether



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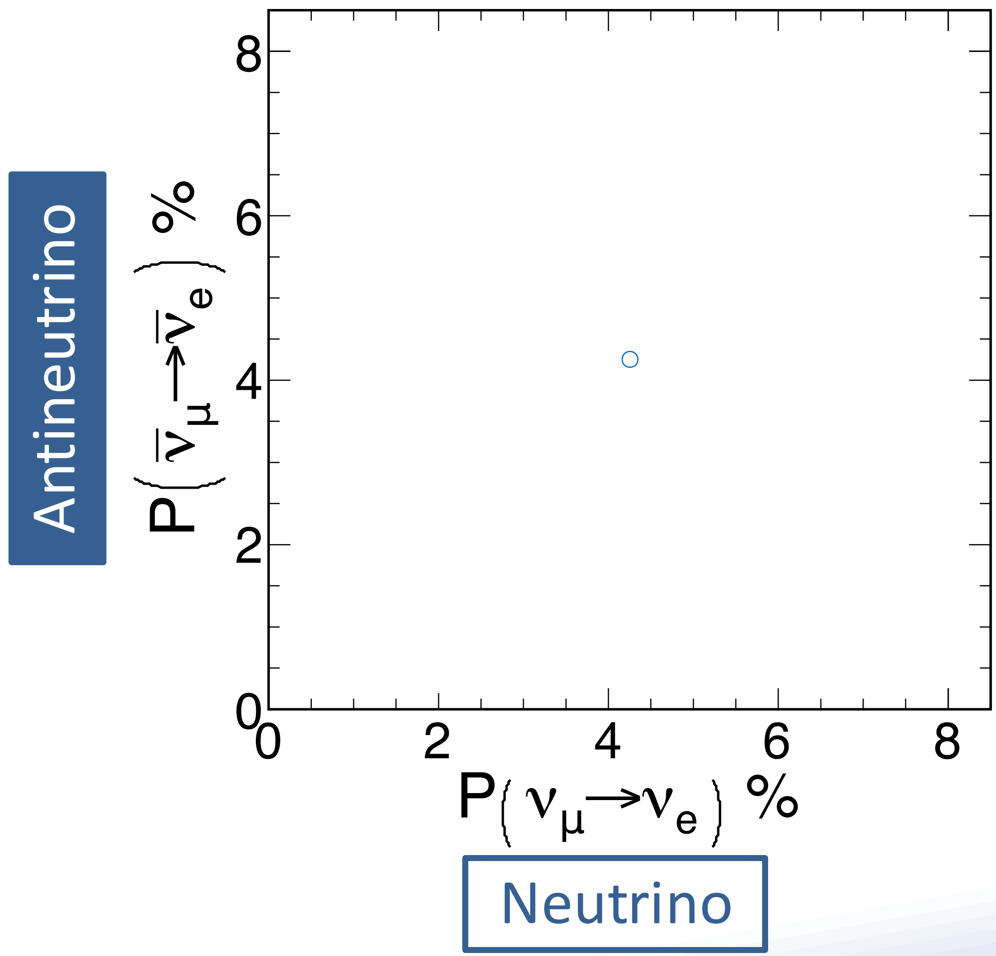
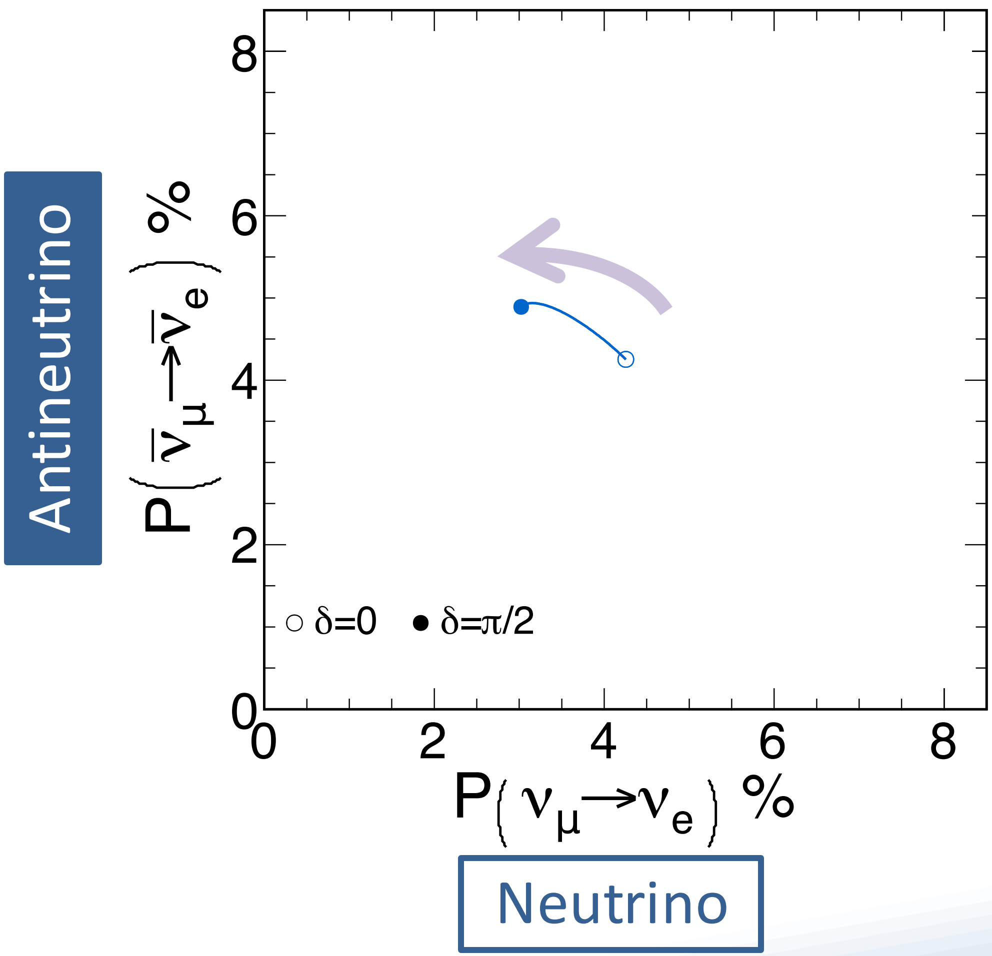
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the “octant” of θ_{23}?



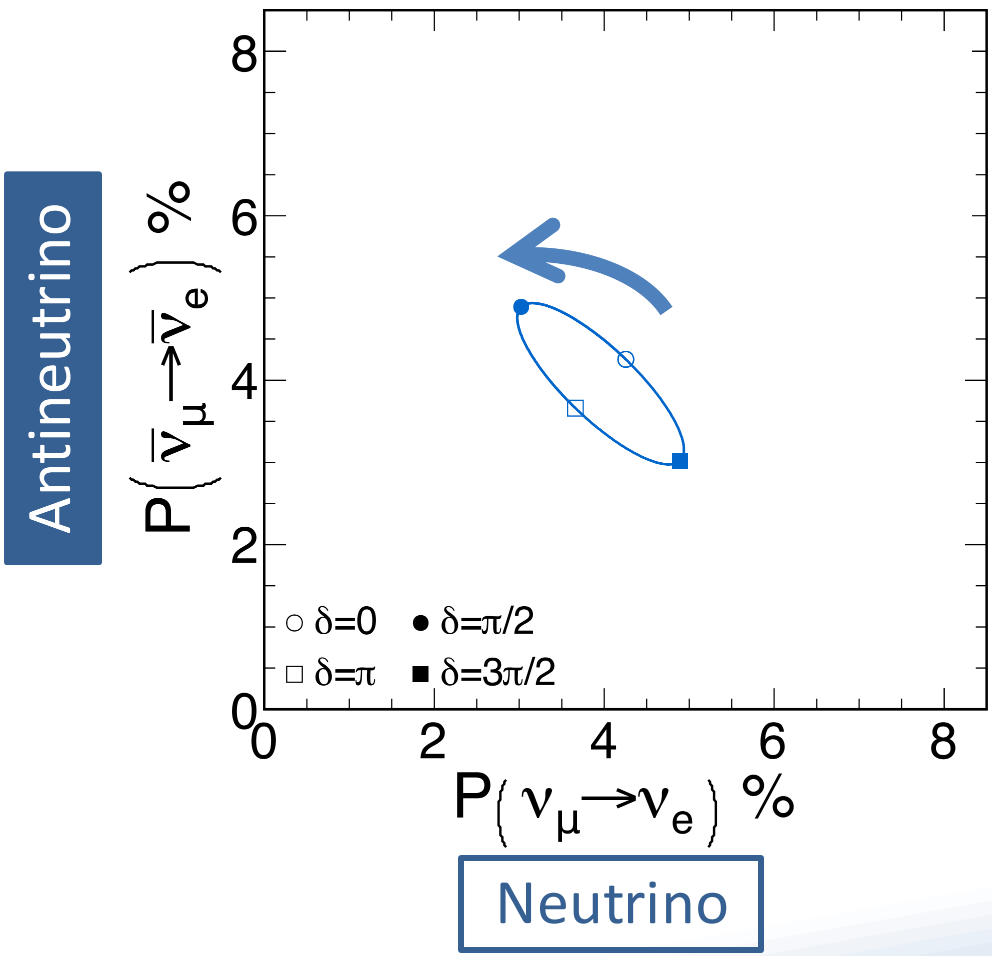
Vacuum and no CP violation: neutrinos and antineutrinos are the same

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



CP-violation through δ creates opposite effects in neutrinos and antineutrinos

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



CP-violation through δ creates opposite effects in neutrinos and antineutrinos

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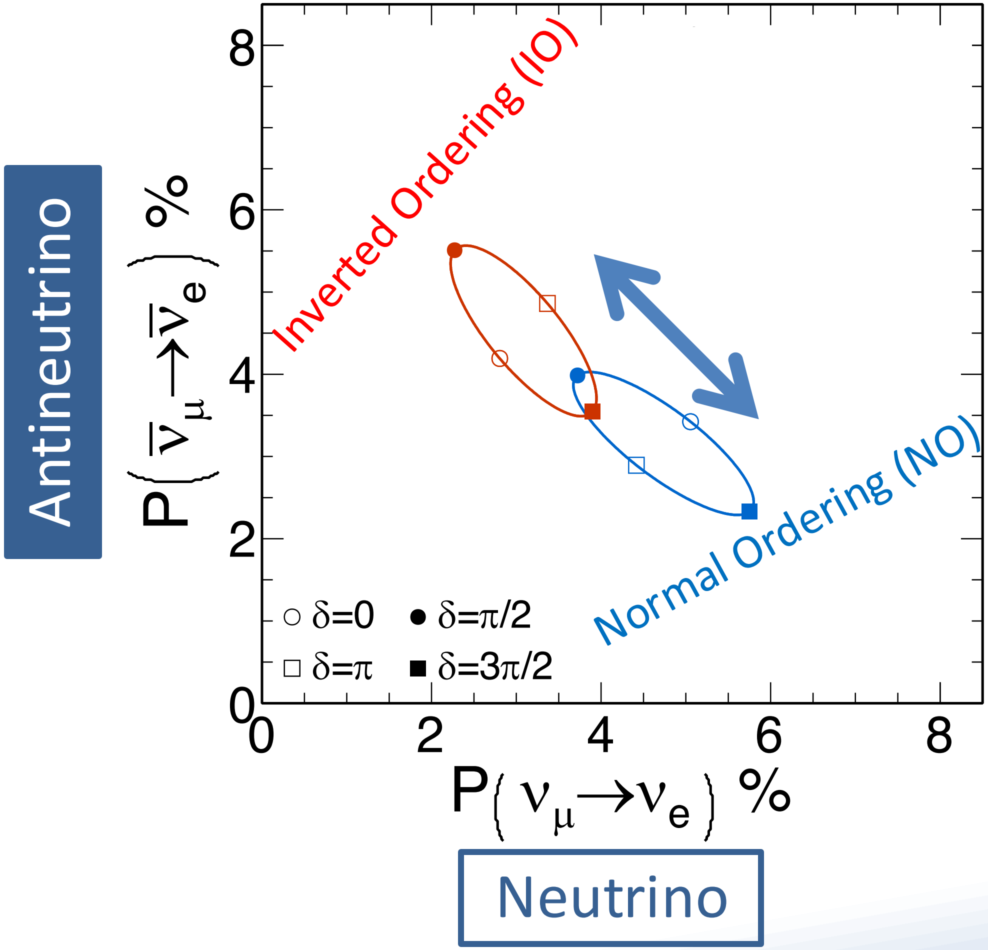
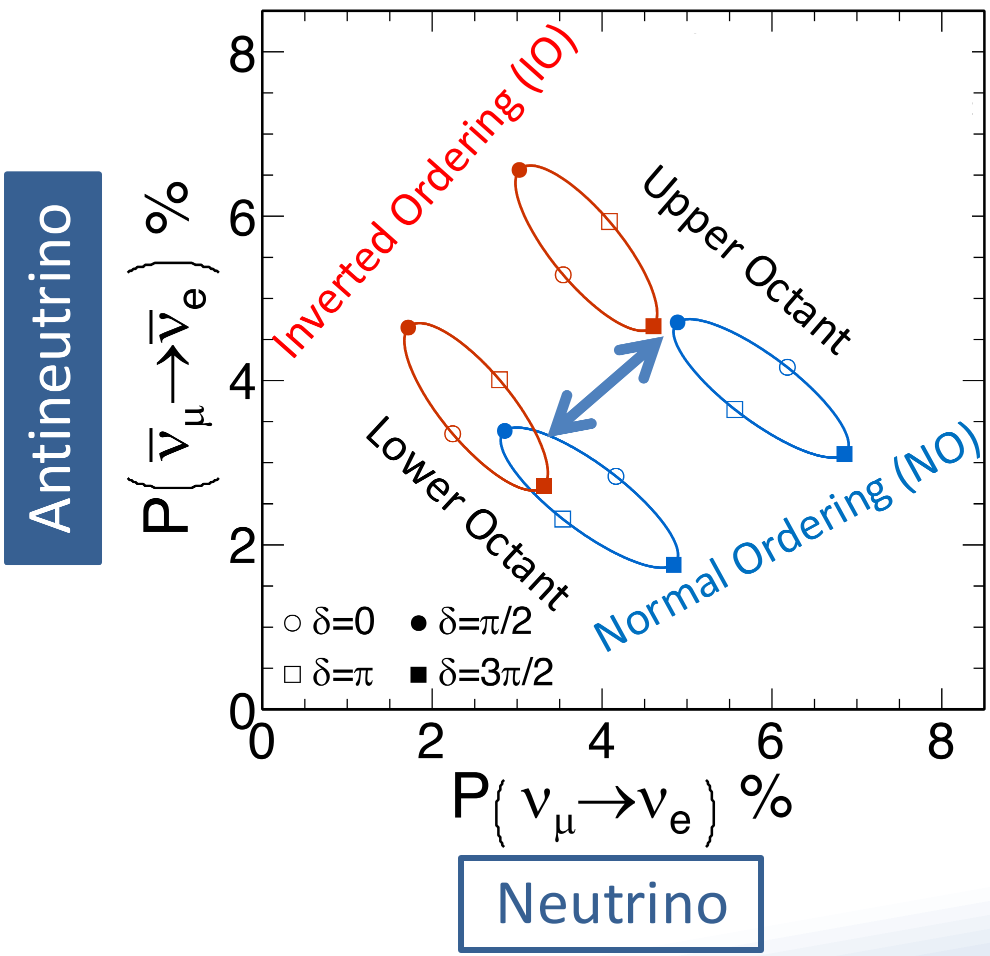


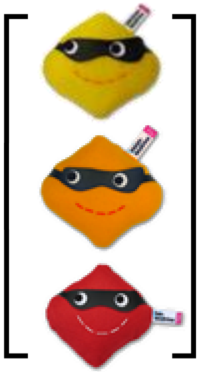
Matter effects also introduce opposite neutrino-antineutrino effects.

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



The octant creates the *same* effect in neutrinos and antineutrinos.

So, what do we know?



So, what do we know?

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

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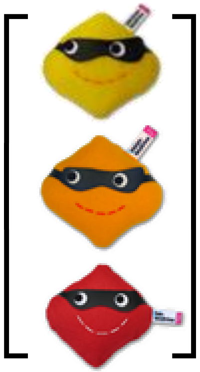

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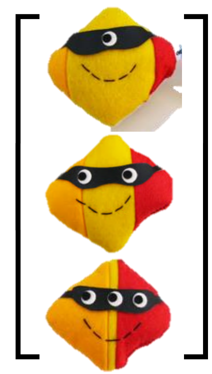

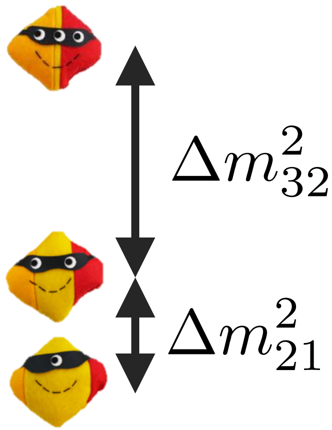

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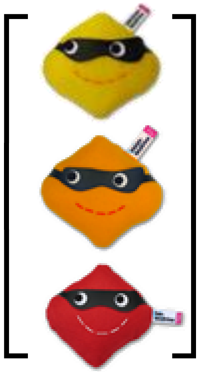

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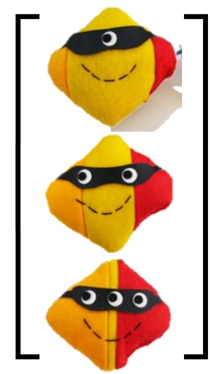
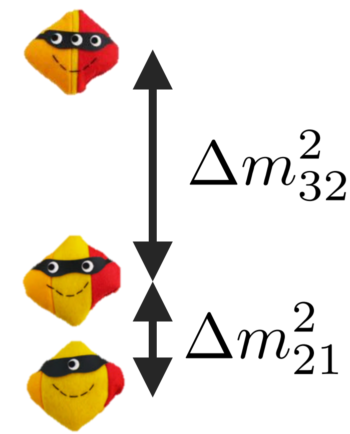


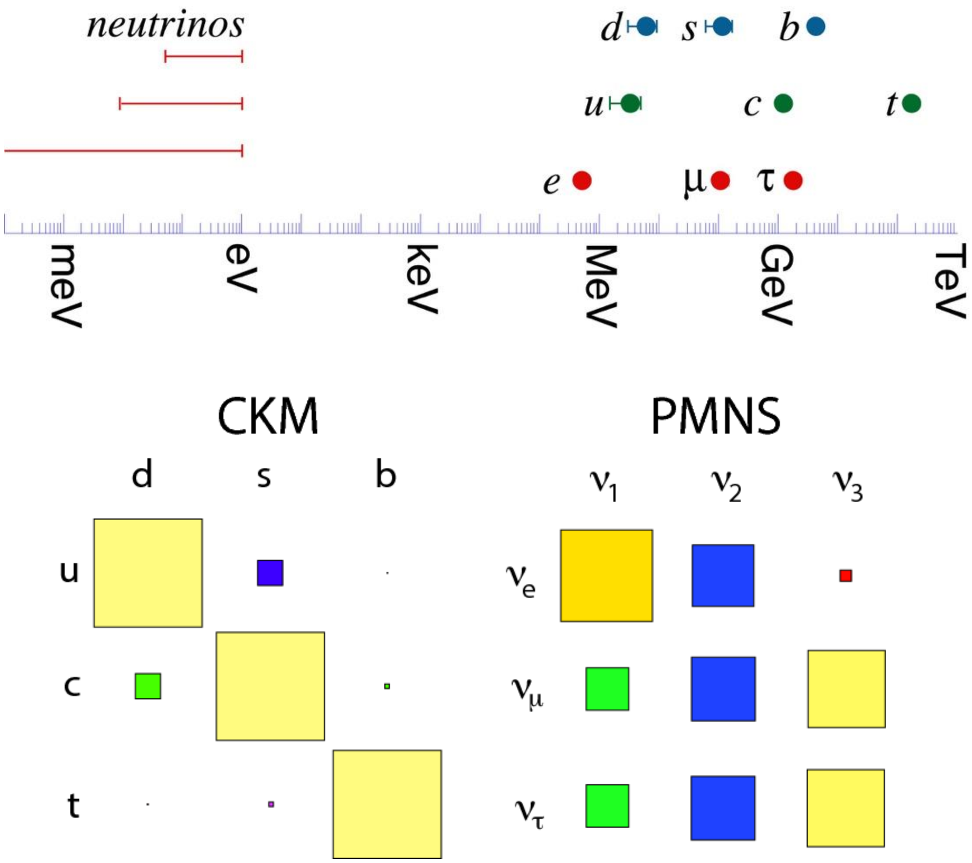


parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncert
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0 %
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49	
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	5.4%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38	

From M. Tórotola at NEUTRINO2024

What are we still trying to learn?

- The neutrino mass
  - ...and why it's so small
  - But oscillations can't answer those questions.
- The ordering of the neutrino masses.
  - Are they like the rest of the particles or not?
- Whether neutrinos violate *CP* symmetry.
- Why neutrino mixing is so different from quark mixing.



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