WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

WIPAC WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

Neutrino Physics

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Outline

- Neutrinos in the Standard Model
- Neutrino Oscillations
- Open Questions

Neutrinos in the Standard Model

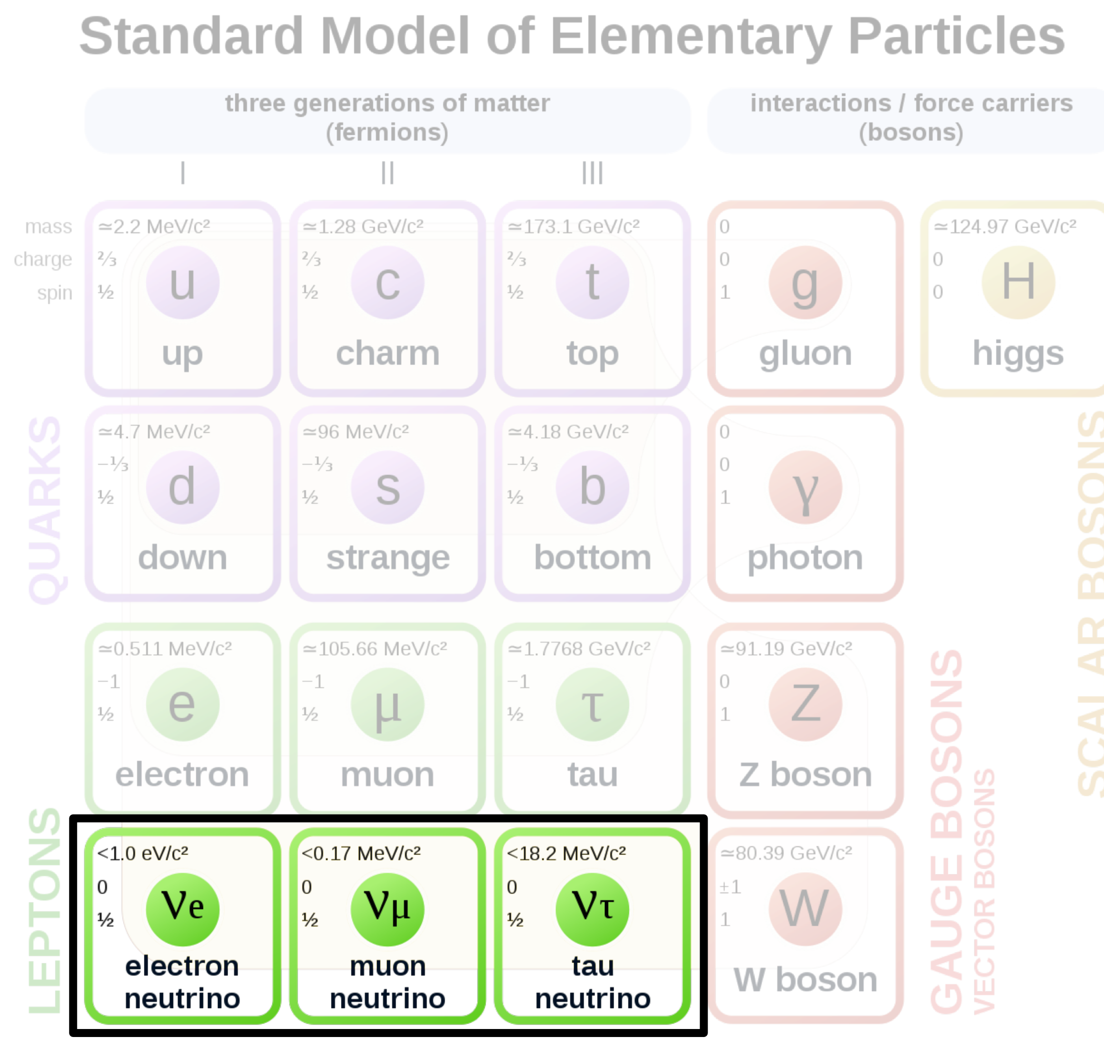
Why study neutrinos?

- One of the most abundant particles in the Universe
- Yet also one of the least well understood
- Properties that confirm the existence of physics Beyond the Standard Model (neutrino oscillations)

Neutrinos in the Standard Model

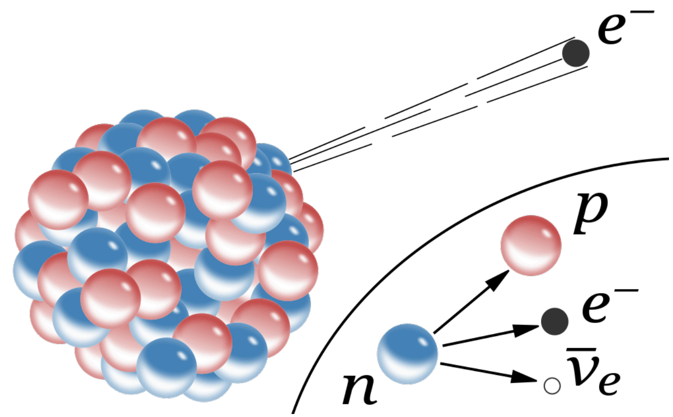
- Leptons
- no charge
- "no mass"

- 3 flavors
- Each flavor has a charged lepton as a sister particle

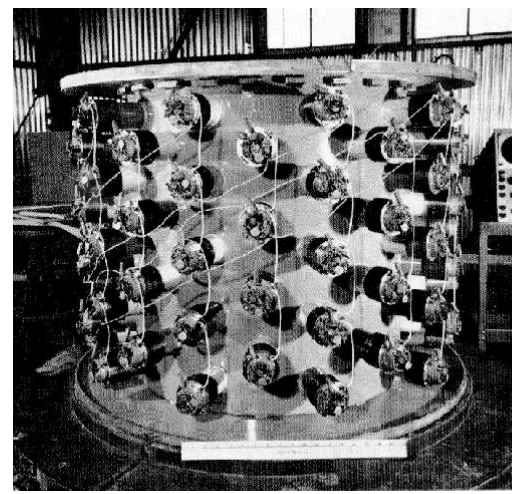


History

- 1931 – Wolfgang Pauli proposes electrically neutral, invisible particle called a "neutron" to explain missing energy in beta decays



- 1934 – Enrico Fermi proposes beta decay theory, including "neutrino"

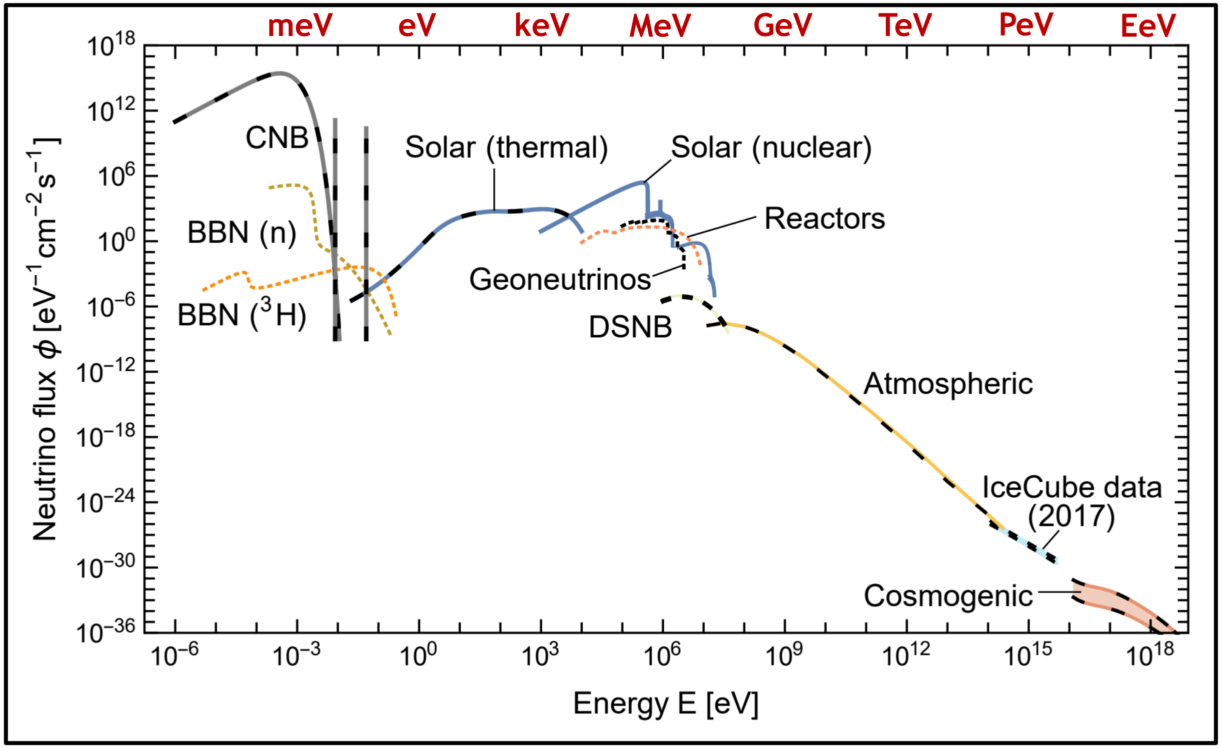


- 1956 – Frederick Reines & Clyde L. Cowan discover neutrino at Savannah River Site with underground reactor experiment

1995

Where do neutrinos come from?

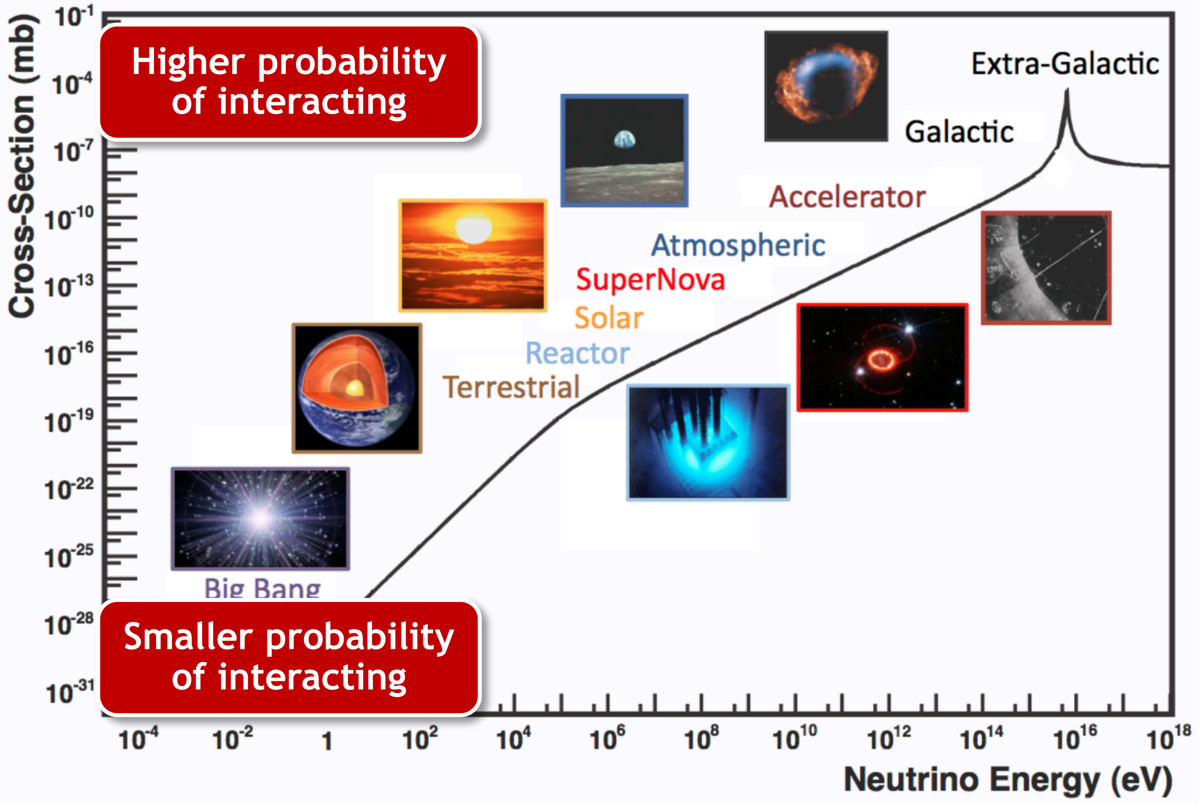
- Natural
  - Big Bang
  - Sun
  - Earth (Geo.)
  - Earth Atmosphere
  - Galactic
  - Extragalactic
- Man-made
  - Nuclear reactors
  - Accelerators



arXiv:1910.11878

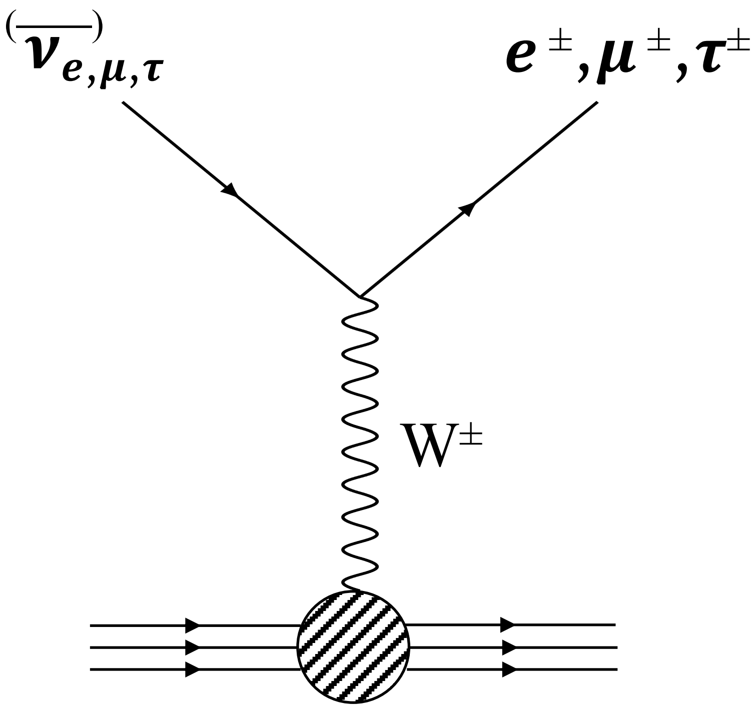
Cross Section

- Neutrinos rarely interact with matter because of their small cross section
- Cross section scales with energy



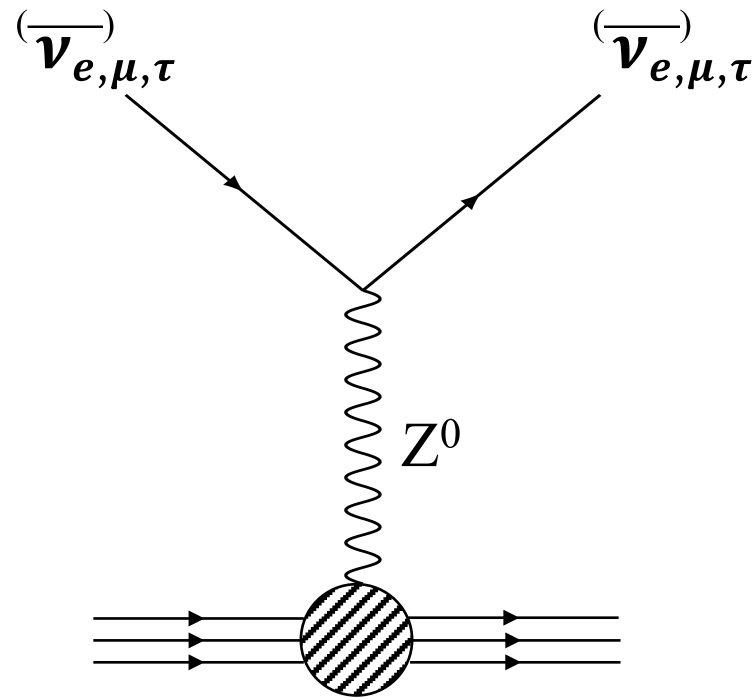
Neutrino Interactions

Charged Current



Neutrino in,
Charged particle out

Neutral Current



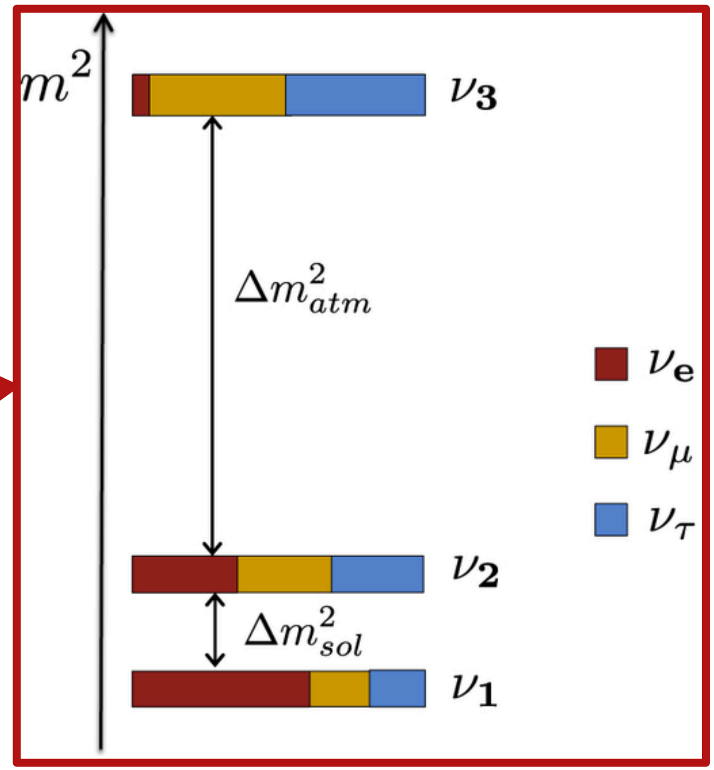
Neutrino in,
Neutrino out

Neutrino Oscillations

Neutrino Masses

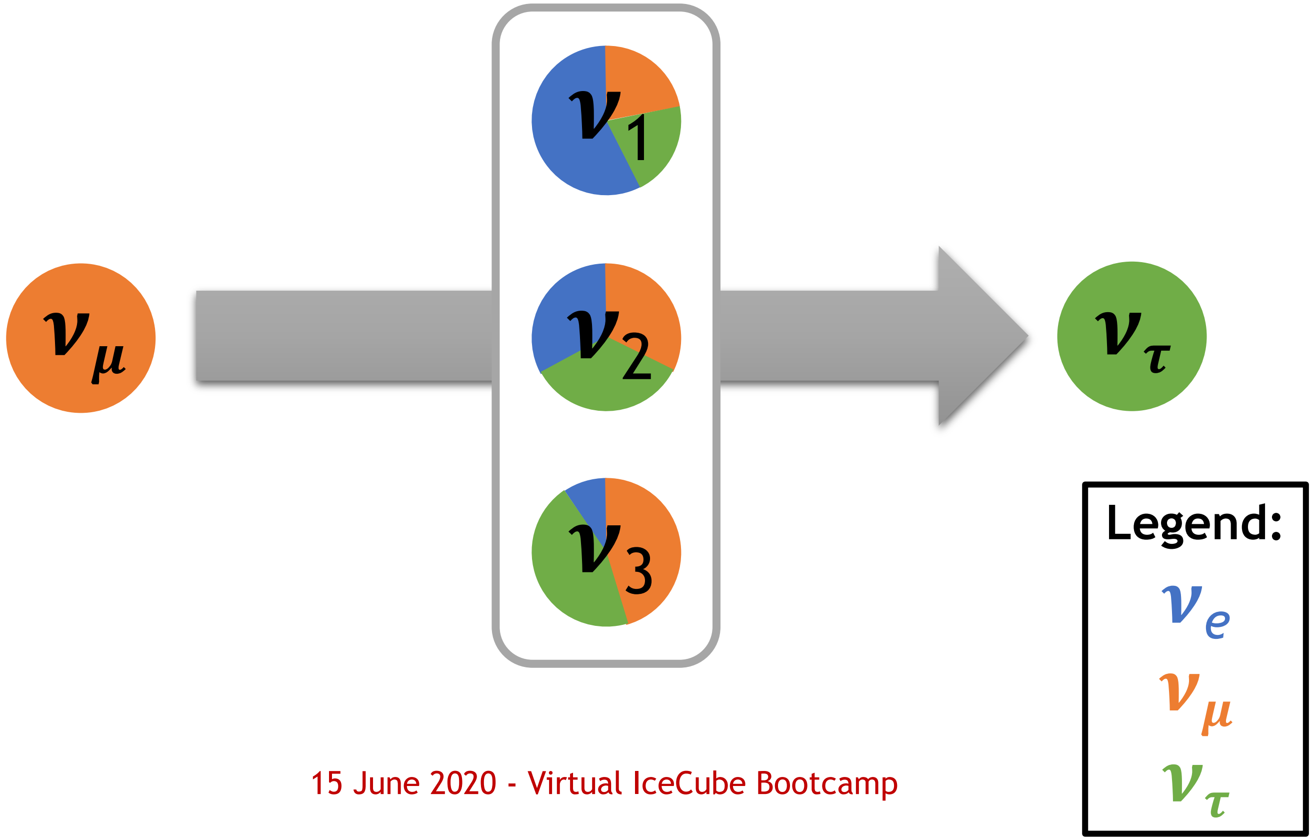
- There are 3 “orthogonal” neutrinos.
- But there are different bases to describe them.
- The bases do not have the same eigenstates.
  - Mass Basis: ν_1 , ν_2 , ν_3
  - Flavor Basis: ν_e , ν_μ , ν_τ

Mass states can be expressed as linear combination of flavor states.



Neutrino Oscillations

- Neutrinos are created in their flavor state
- Neutrinos travel in their mass states
- Neutrinos are detected in their flavor state



Describing Neutrino Oscillations

- We want to perform a change of basis.
  - Mass Basis: ν_1 , ν_2 , ν_3
  - Flavor Basis: ν_e , ν_μ , ν_τ
- The matrix that performs this transformation is known as the PMNS Matrix (Pontecorvo-Maki-Nakagawa-Sakata).

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- We can use PMNS matrix to calculate the probability of starting of starting in one flavor state, and ending in a different flavor state:

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

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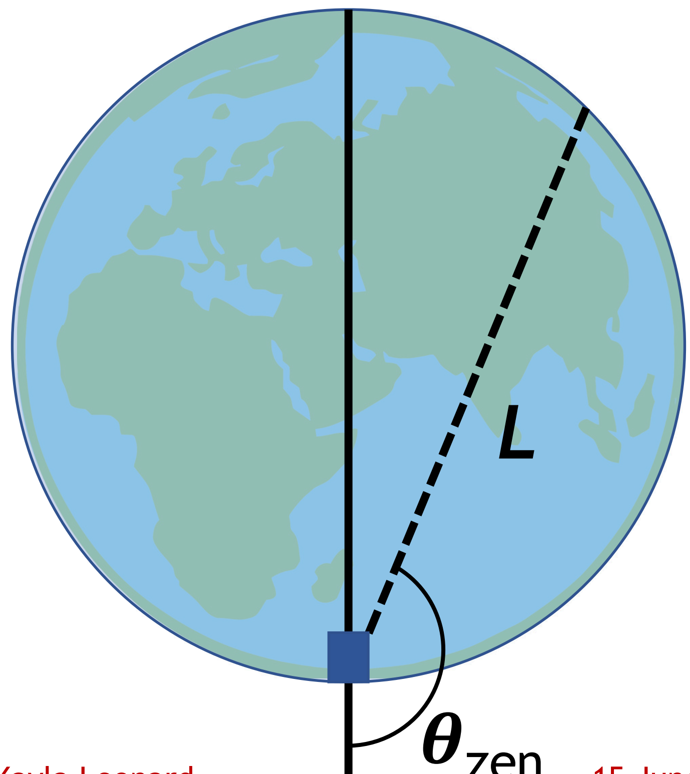
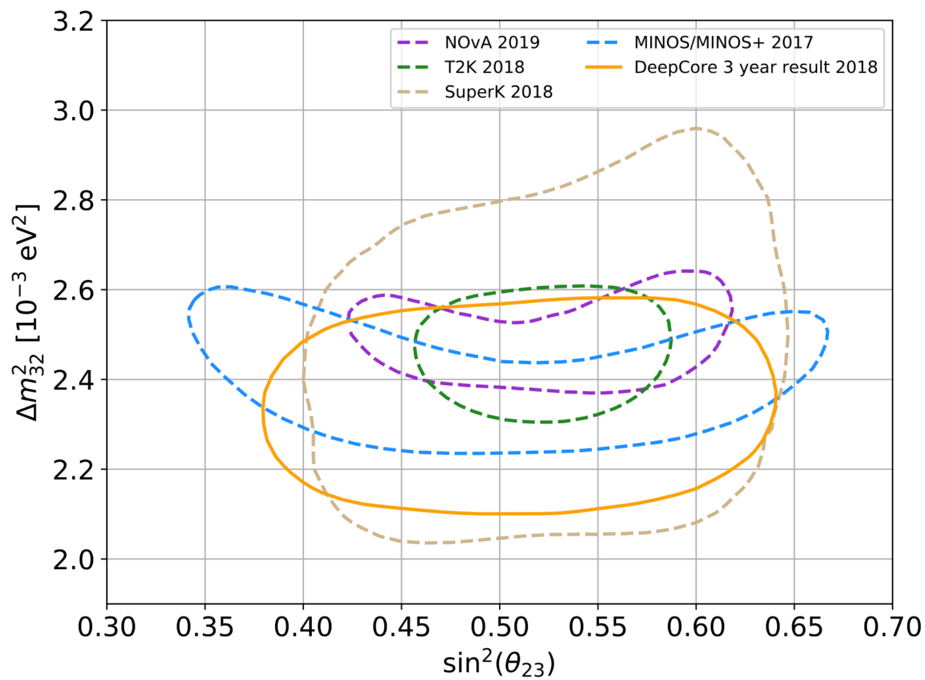
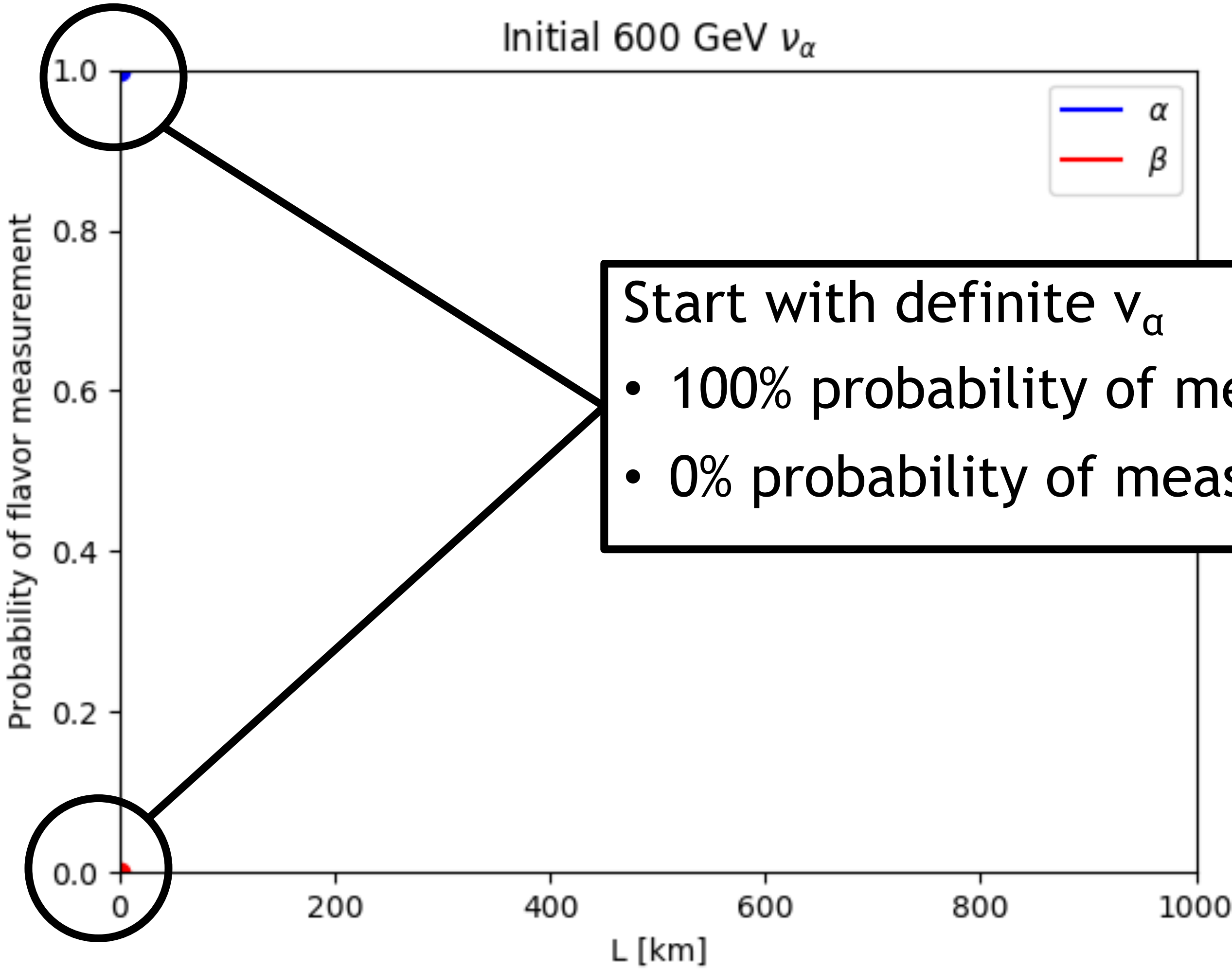
- We can estimate the ***Energy*** and the ***Length*** travelled
- We want to measure ***$sin^2(\theta)$*** and ***Δm^2*** (physics parameters)





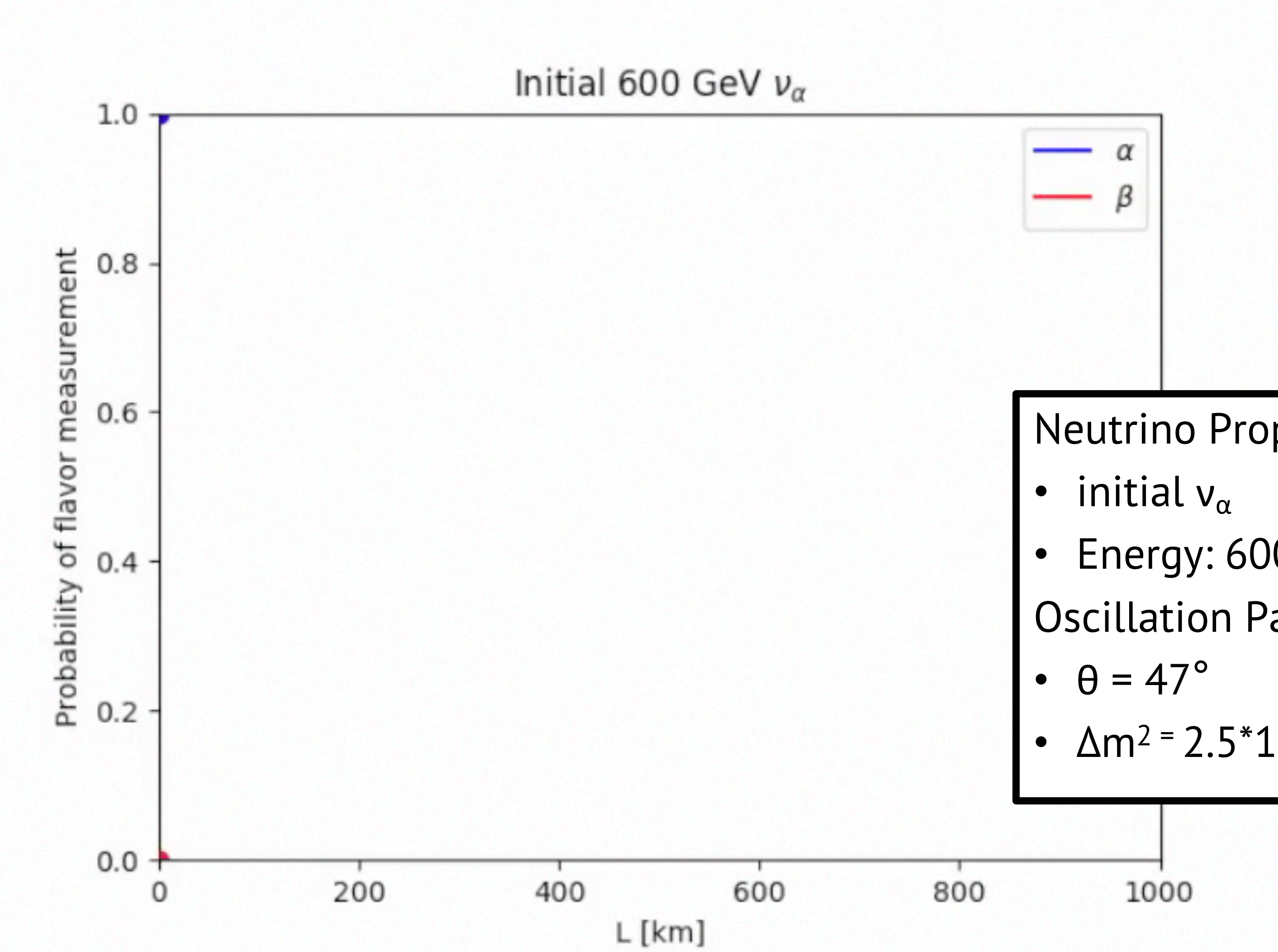
Toy Model



Start with definite ν_α

- 100% probability of measuring ν_α
- 0% probability of measuring ν_β

Toy Model



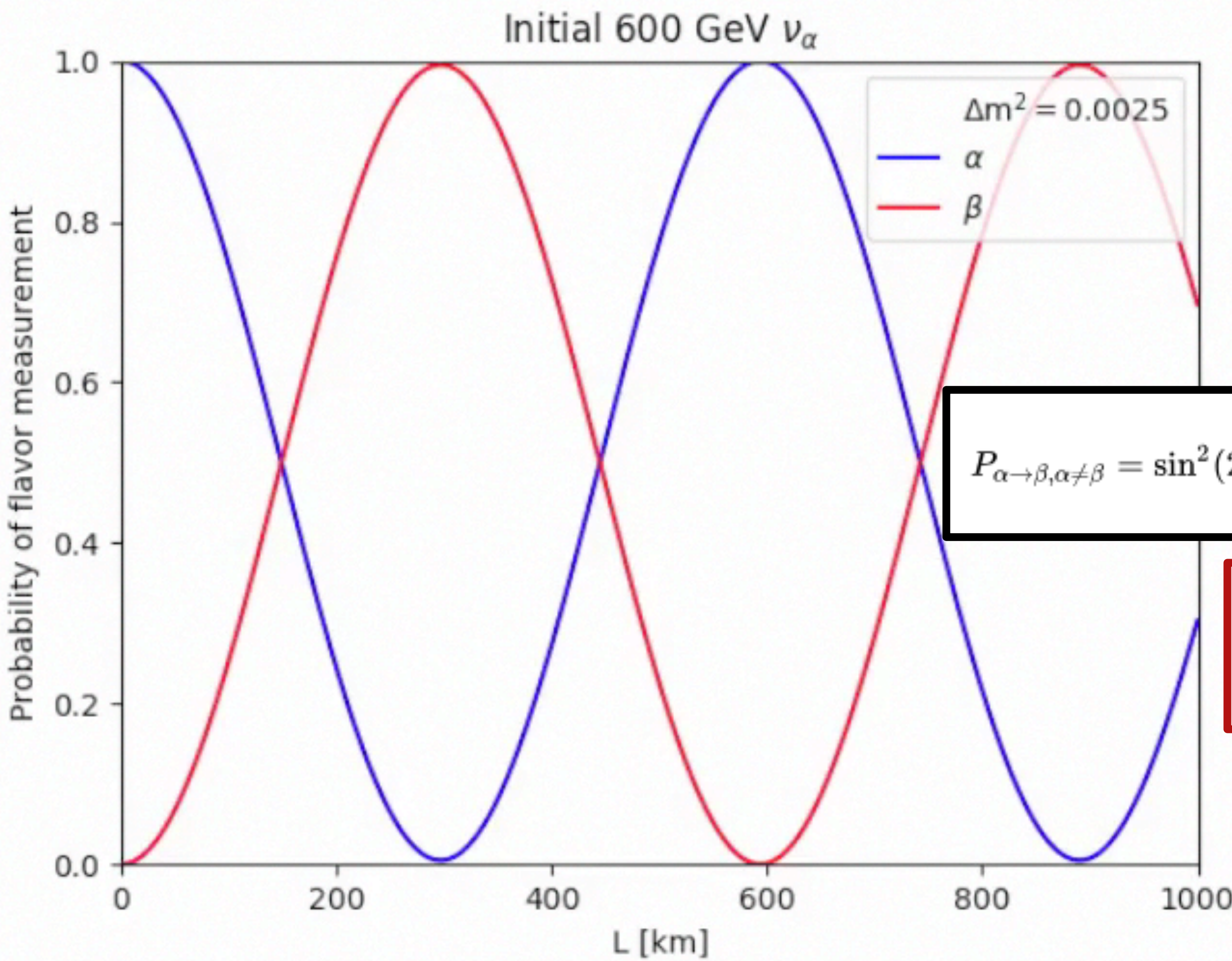
Neutrino Properties:

- initial ν_α
- Energy: 600 GeV

Oscillation Parameters:

- $\theta = 47°$
- $\Delta m^2 = 2.5 * 10^{-3}$ eV^2

Toy Model

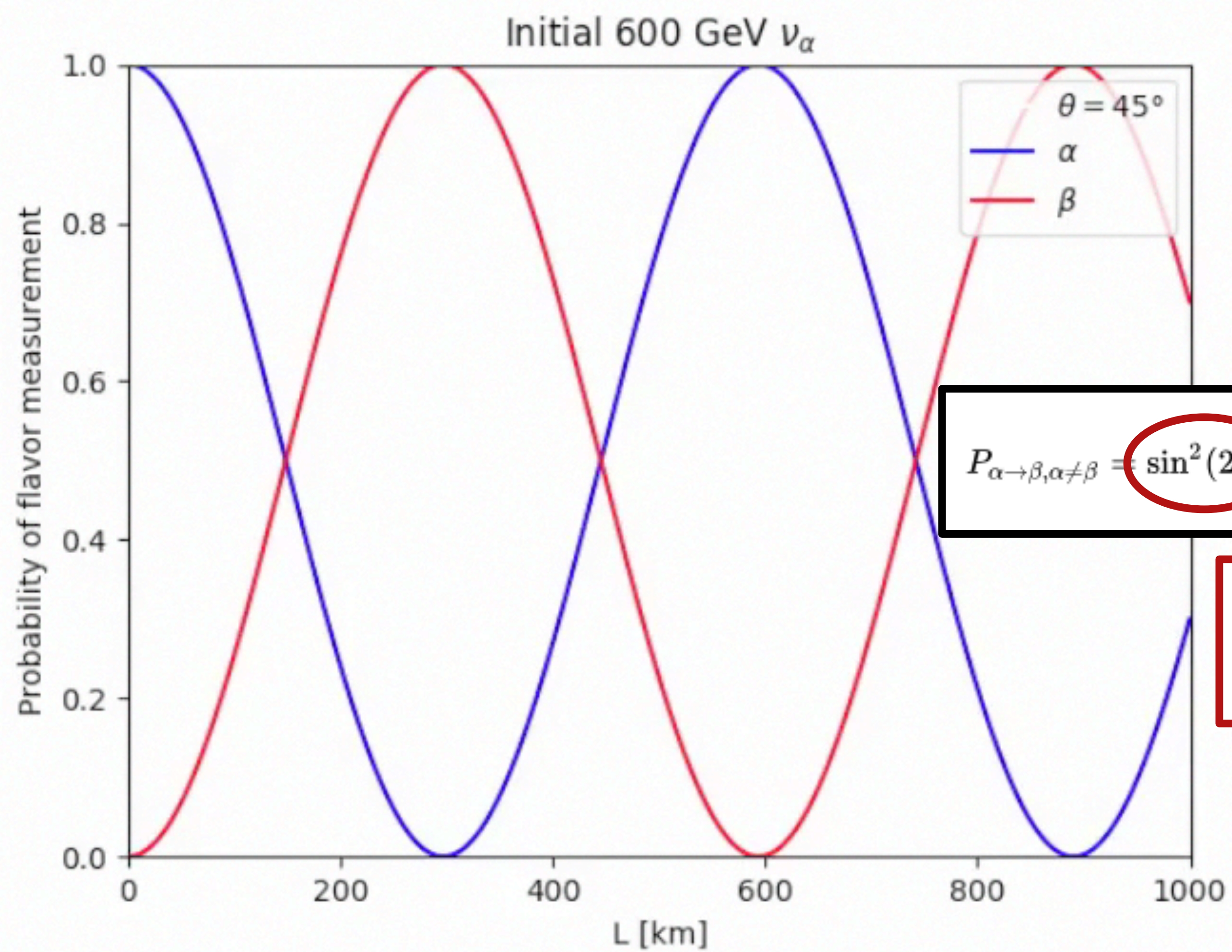


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

Δm² **controls period**

θ controls amplitude

Toy Model



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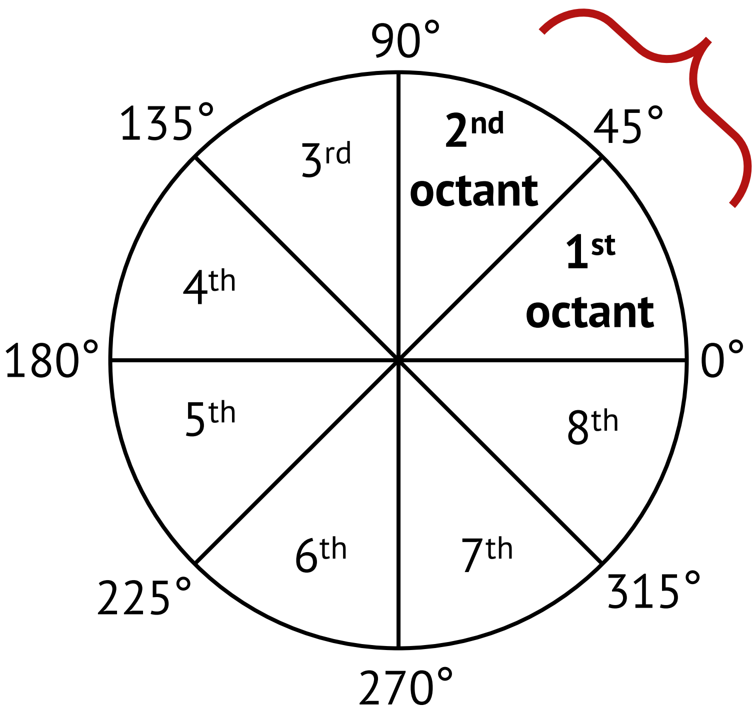
Δm^2 controls period

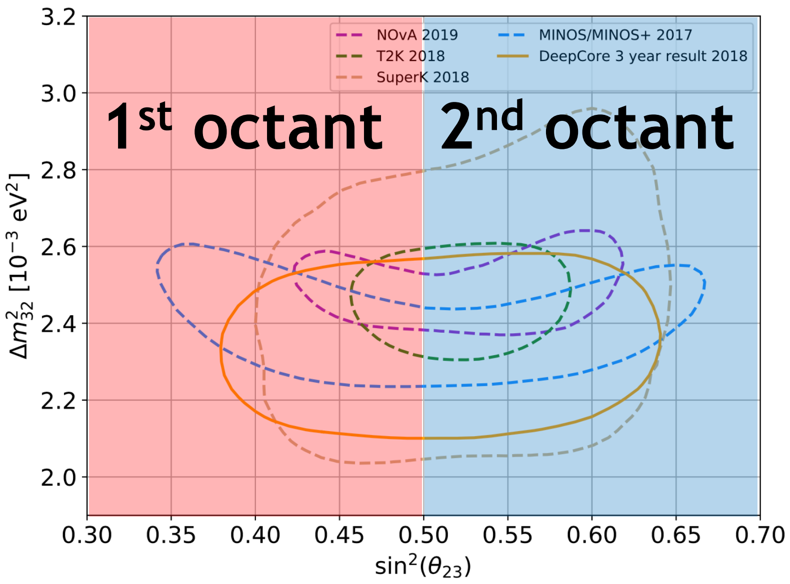
θ controls amplitude

Open Questions

Octant?

- Oscillation probabilities have terms with *sin²(**2***θ_{23}*)* so there is a degeneracy near 45° if non-maximal.
  - ex. $\sin^2(2*44°) = \sin^2(2*46°)$
- So if we measure a certain amount of oscillation, how do know if θ_{23} is a little above 45 or a little below 45?

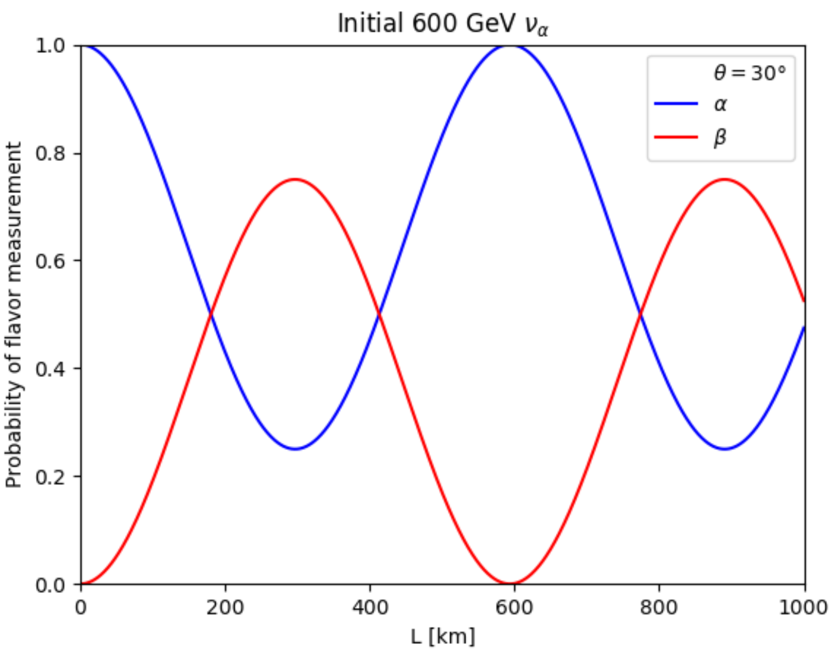




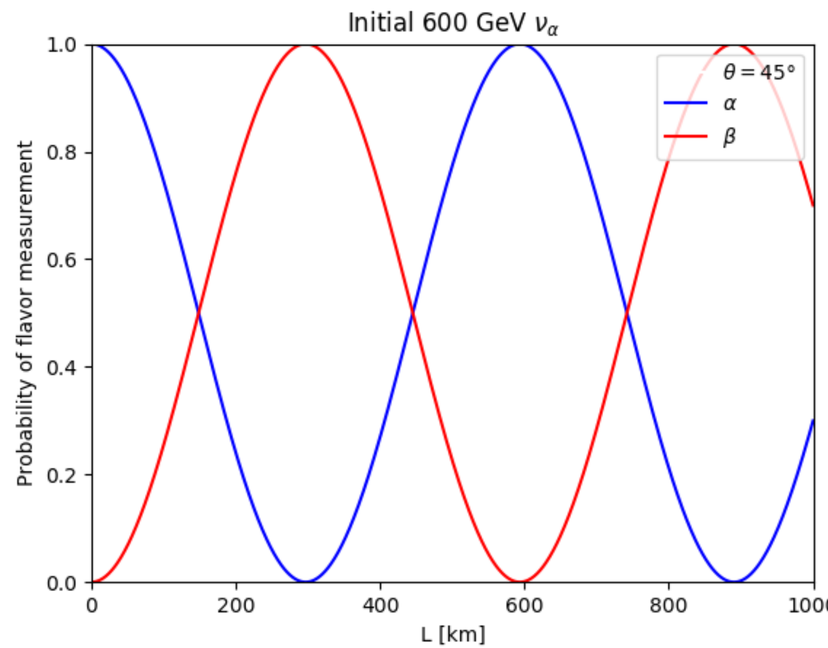
Maximal Mixing

- Experiments tell us the true value of θ_{23} is near 45°.
- There is still tension about whether or not it is *exactly* maximal.

$\theta_{23} \neq 45°$
"non-maximal mixing"



$\theta_{23} = 45°$
"maximal mixing"



Maximal Mixing

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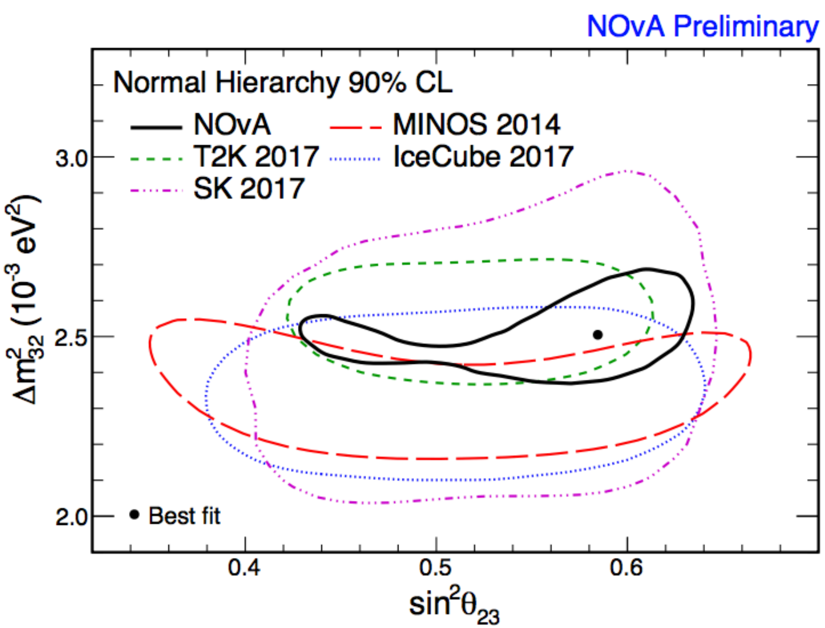
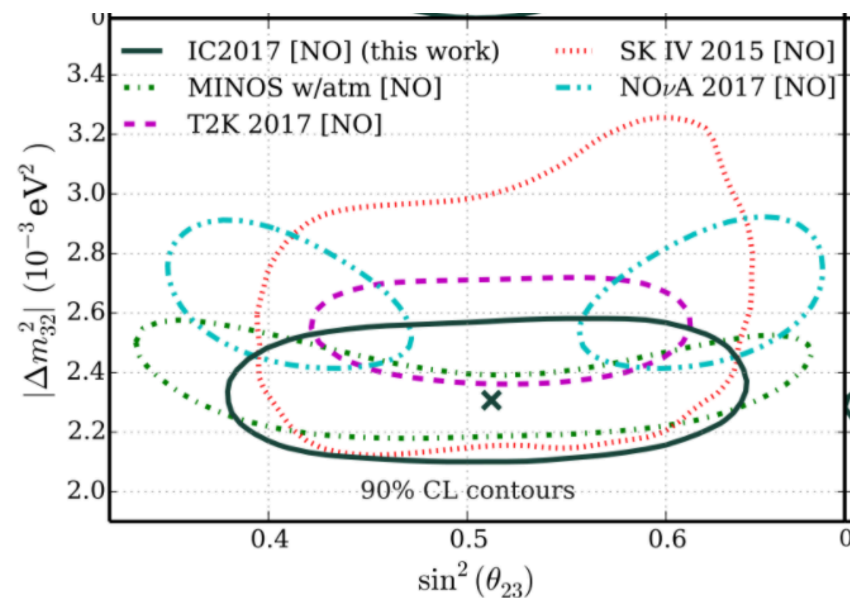
- There is still tension about whether or not it is *exactly* maximal.

NOvA prefers non-maximal [3]



Others centered closer to maximal



Beyond the Standard Model

- Are there additional neutrino flavors called "Sterile Neutrinos"? These proposed particles don't interact with regular matter, but the other flavors could oscillate to and from the sterile state.
- Could Sterile Neutrinos be Dark Matter?
- Much more!

Thanks for listening!

Questions?