

Title: Beyond the Standard Model – Experiment: Other low energy experiments

Date: Jul 10, 2015 11:45 AM

URL: <http://pirsa.org/15070033>

Abstract:

## Neutrino Mixing Math

### PMNS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{aligned} c_{ij} &= \cos \theta_{ij} \\ s_{ij} &= \sin \theta_{ij} \end{aligned}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

Oscillation Probability  
 $\nu_\alpha \rightarrow \nu_\beta$  over distance  $L$

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

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# Neutrino Mixing Math

## PMNS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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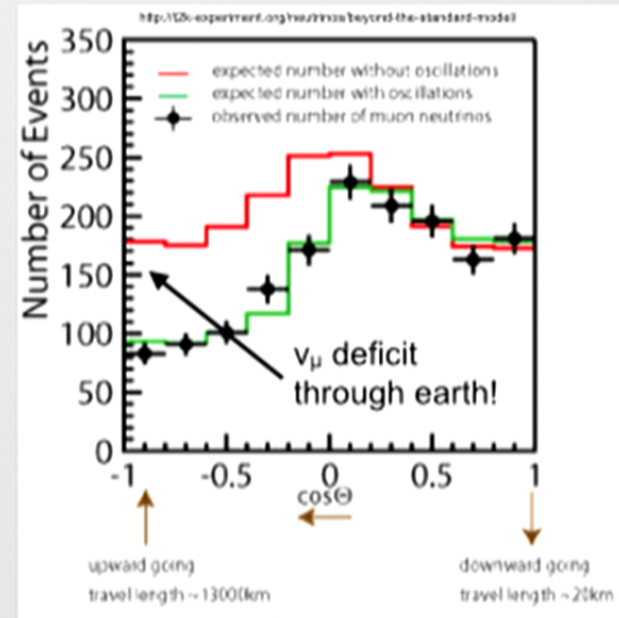
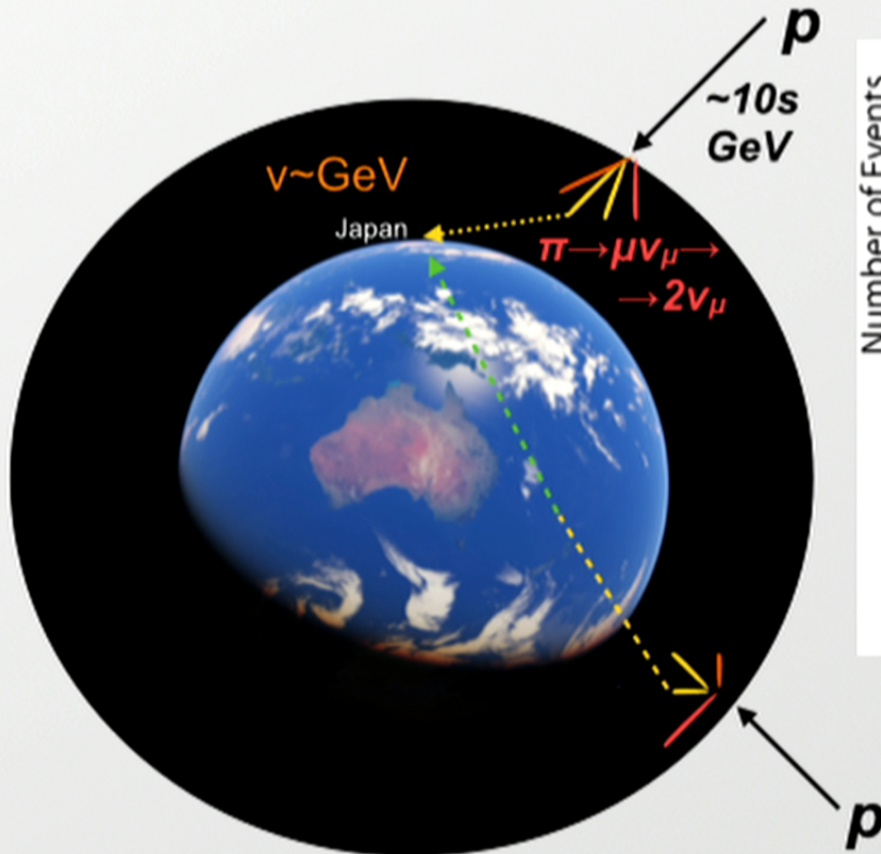
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2-flavor  
approximation

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

key experimental parameter:  $\frac{L}{E}$

# Neutrinos from the sky...



$$E(\nu_\mu) \sim \text{GeV}$$

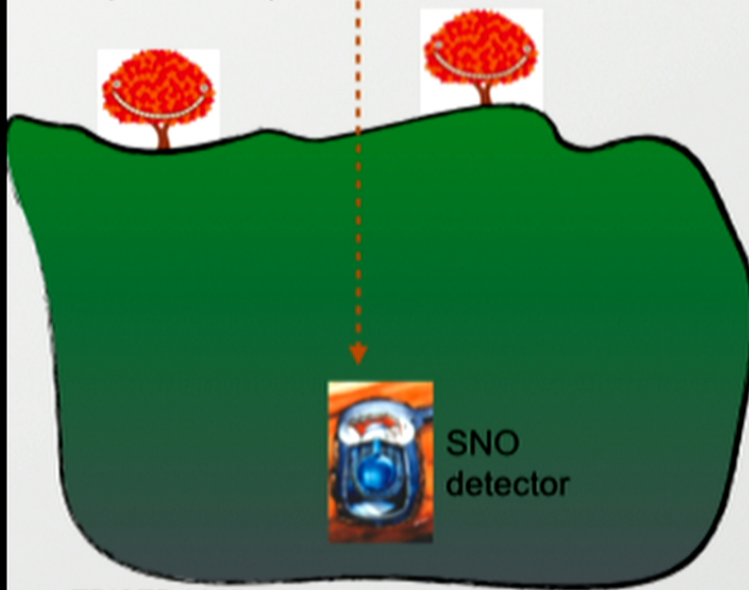
$$L \sim 20 - 1500 \text{ km}$$



# Neutrinos from the sun...



most change *inside* sun (MSW effect)



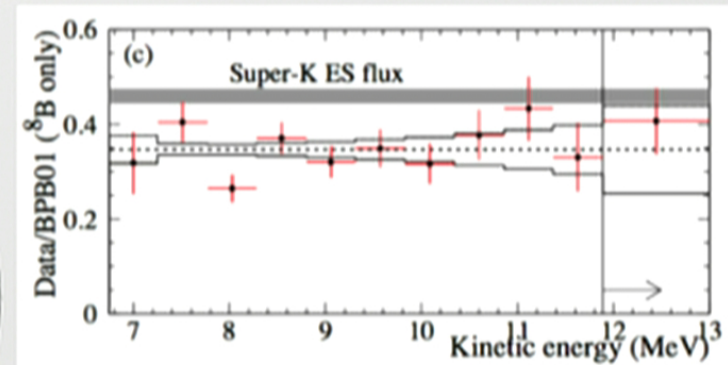
## $\nu_e$ elastic scattering

$$\nu + e^- \rightarrow \nu + e^- \quad (\text{flavor generic})$$

→ gives  $\nu$  normalization

## $\nu_e$ CC scattering

$$\nu_e + d \rightarrow e^- + p \quad (\text{only } \nu_e)$$



SNO Collaboration, PRL87, 071301 (2001)

$$E(\nu_e) \sim 10 \text{ MeV}$$

$$L \sim 10^8 \text{ km}$$



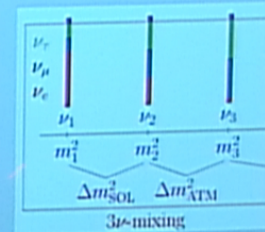
# Neutrino Mixing Math

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right) \rightarrow 0 \text{ if } \delta=0$$

2-flavor approximation

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

Atmospheric  $\sim \theta_{23}, \Delta m_{23}^2$   
 Solar  $\sim \theta_{12}, \Delta m_{12}^2$





## Neutrinos!

- Do they have mass?
  - YES!
- Ok...now what?
  - Is there CP-violation in lepton sector?
  - Are there right-handed neutrinos?
    - Are there "sterile" neutrinos?
  - Are there more than 3 flavors?
  - How much mass?
    - Not much...why so light?
  - What kind of mass?
  - How do they get mass?
  - Could neutrinos be the solution to the dark matter puzzle?

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## The PMNS Matrix Today

$$|U_{\text{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.5 & 0.6 & 0.6 \\ 0.2 & 0.6 & 0.8 \end{pmatrix}$$

Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
$\theta_{12}$	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
$\theta_{23}$	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
$\theta_{13}$	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
$\Delta m_{21}^2$	$+(7.54 \pm 0.22) \times 10^{-5} \text{ eV}^2$	$m_3 \gg m_2$
$ \Delta M^2 $	$(2.43^{+0.10}_{-0.06}) \times 10^{-3} \text{ eV}^2$	$67 \pm 5^\circ$
$\delta_{\text{CP}}$	$-170 \pm 54^\circ$	

These are very different

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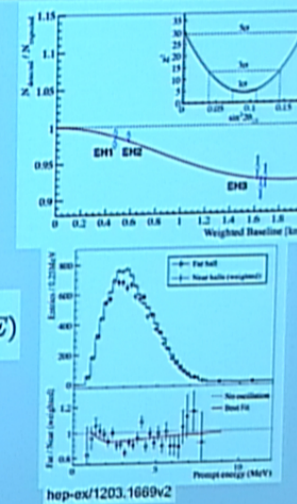
## The last angle...

Daya Bay reactor experiment

$E(\bar{\nu}_e) \sim 10 \text{ MeV}$   
 $L \sim 2\text{-}3 \text{ km}$

$$P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$

$$\sin^2 2\theta_{13} \sim 0.1$$



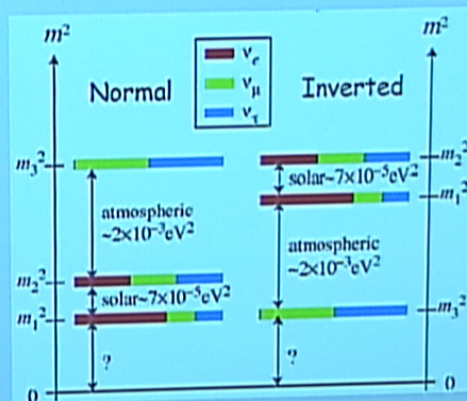
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## Mass Hierarchy

*we don't know  $\nu$  masses; we don't even know the order the masses are in ...*

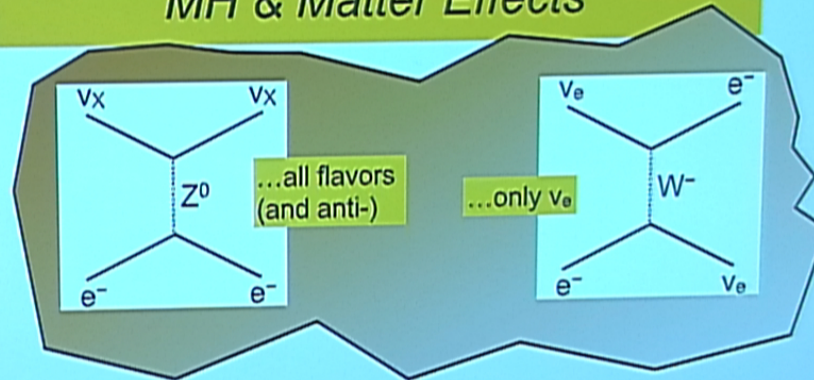


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## MH & Matter Effects



...there is a bunch of math...but the oscillation probability is either enhanced or suppressed depending on the sign of  $\Delta m^2_{31}$  (remember, that's a signed quantity)

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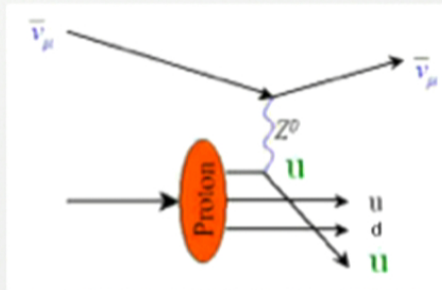


# Neutrino Sources

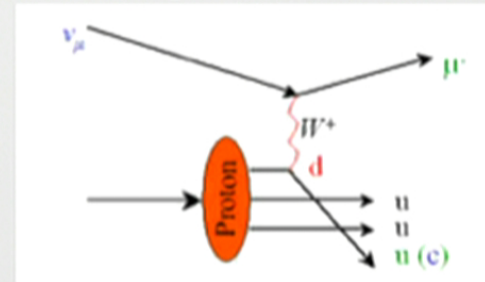
- Naturally occurring...
  - solar ~ up to ~30MeV; only electron neutrinos (produced)
  - atmospheric ~ 1-10GeV (though goes very high); all flavors
  - geo (rocks) ~ few MeV; mostly from U & Th decays
  - super-nova ~ 1-100 MeV (mostly <30MeV); always be vigilant!
  - cosmic ~ up to PeV (!)
- Man-made sources...
  - nuclear reactors ~ few MeV electron anti-neutrinos
  - beams ~ 10s of MeV to 100s of GeV; all flavors (but mostly  $\nu_\mu$ )
    - key to long- and short-baseline experiments
    - I'll go into some detail on this...

## Neutrino Detection & Types of Neutrino Interactions

neutral current



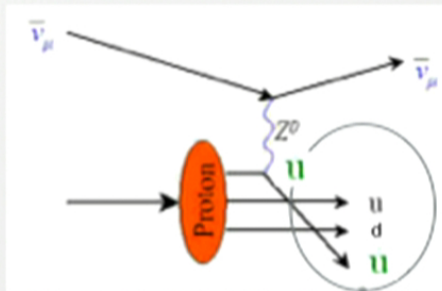
charged current



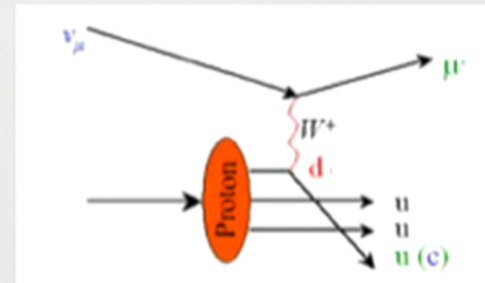


# Neutrino Detection & Types of Neutrino Interactions

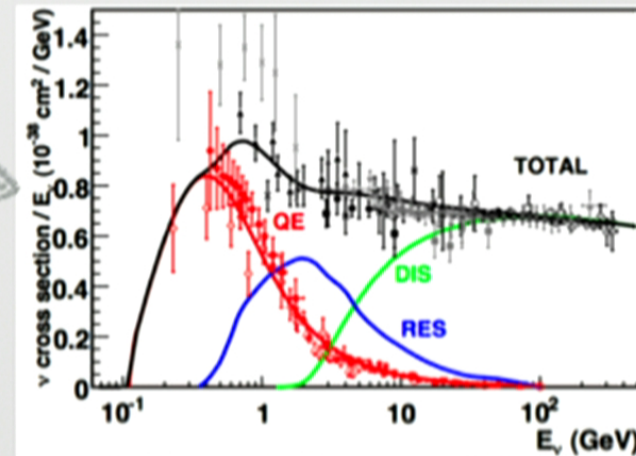
neutral current



charged current



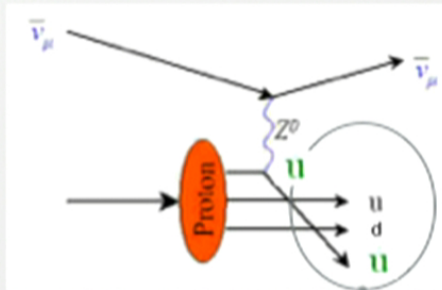
what happens to  
the nucleon (or nucleus)  
depends on energy ...



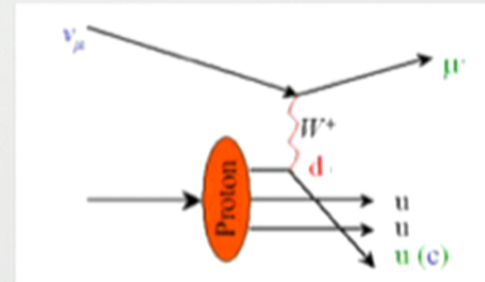


# Neutrino Detection & Types of Neutrino Interactions

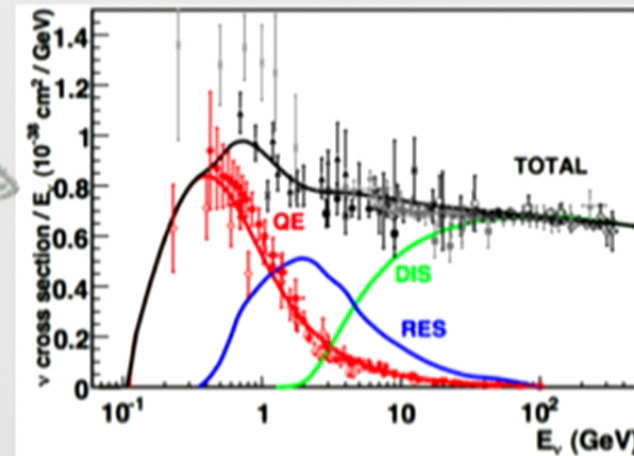
neutral current



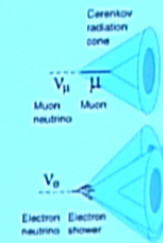
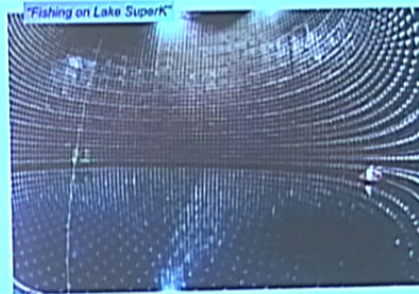
charged current



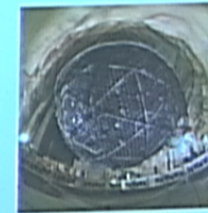
what happens to  
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# Cherenkov Detectors



H2O: SuperK (50kT)  
D2O: SNO  
Mineral Oil: MiniBoone



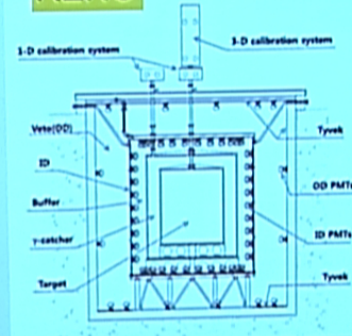
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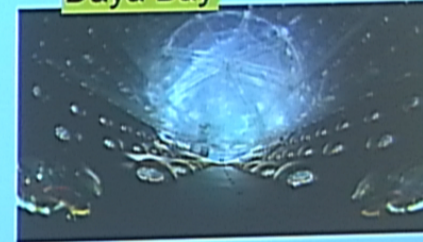


# Scintillator Bags

## RENO



## Daya Bay



Inverse beta decay ( $\text{anti-}\nu_e + p \rightarrow n + e^+$ )  
...lots of protons in organic scintillator (hydrocarbons)  
Gd doping to get neutron

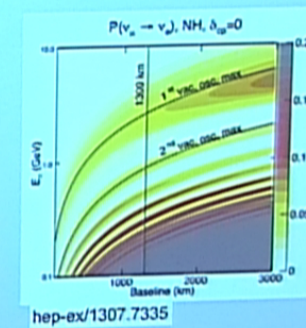
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## X-Baseline X-periments

- The key parameter for neutrino oscillation is  $L/E$
- Plot of oscillations vs  $L/E$
- Long Baseline: MINOS, NOvA, OPERA, T2K
- Short Baseline: LSND, MiniBoone, microBoone

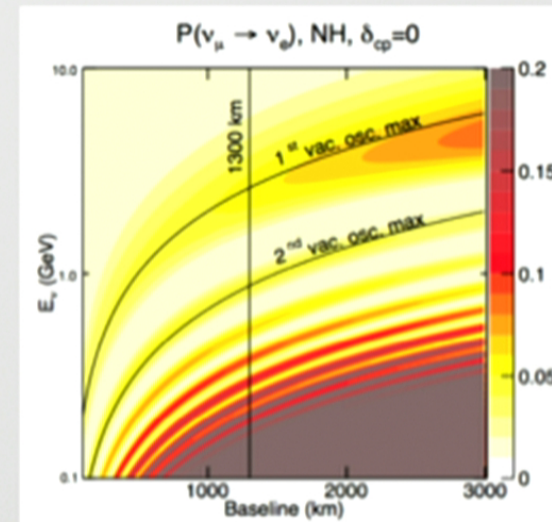


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# X-Baseline X-periments

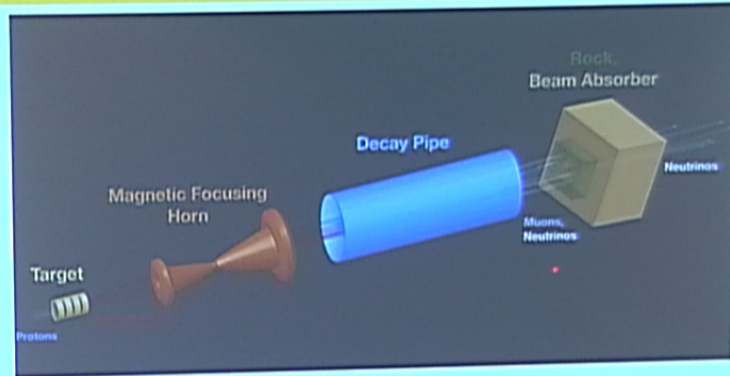
- The key parameter for neutrino oscillation is L/E
- Plot of oscillations vs L/E
- Long Baseline: MINOS, NOvA, OPERA, T2K
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hep-ex/1307.7335



## Making a Neutrino Beam



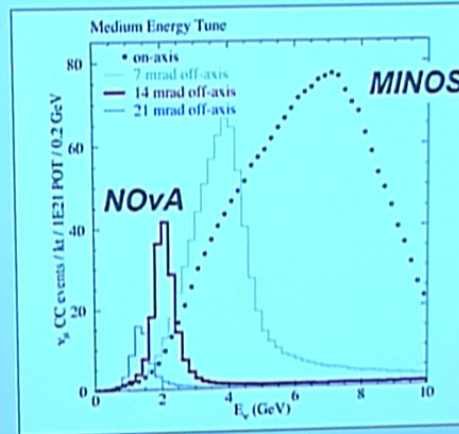
proton beam on target  $\rightarrow$  lots of pions which are focused  
(& charge selected) and decay to  $\mu\nu_\mu \rightarrow$  muons are  
absorbed in the rock giving more  $\nu_\mu$   
(with some small  $\nu_e$  contamination)

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## For example: the NuMI Beam



NuMI beam uses 120 GeV protons from main injector supplies both MINOS & NOvA

...by being off-axis, NOvA receives electrons at a well defined energy → makes oscillations easier to discern from uncertainties in the spectrum

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## ~~LBNE @ SURF~~ DUNE @ LBNF @ SURF

- There are a couple of pieces to the neutrino SM puzzle we're completely missing:
  - mass hierarchy
  - CPV phase in neutrino sector
  - We could also need to take the next step in precision for the other parameters
- The international community has come together for DUNE:
  - DUNE — the detector, 4x10kT LAr TPCs
    - "Detector of Underground Neutrinos Experiment"?
    - refers to the collaboration including near & far detectors
  - LBNF — the cavern holding the detector @ 4850 ft mwe & the beam at FNAL
    - "Long Baseline Neutrino Facility"
  - SURF — the lab where the cavern is
    - "Sanford Underground Research Facility"

*All references to "LBNE" are typos*

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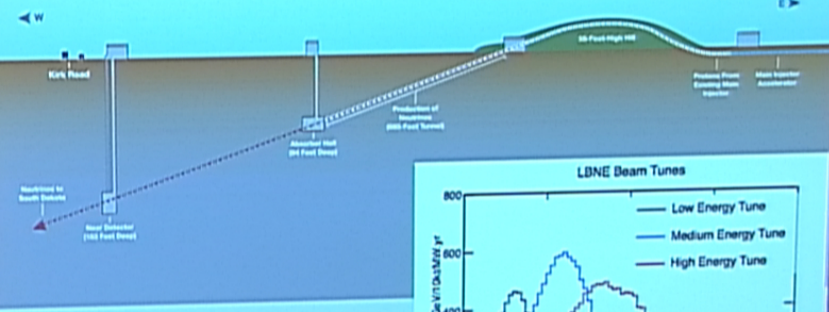
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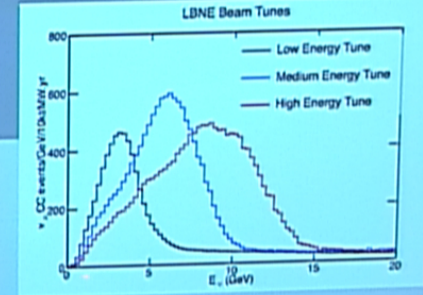




# Beam & Near Detector



new beam line:  
1.2(-2.3MW)  
60-120GeV protons

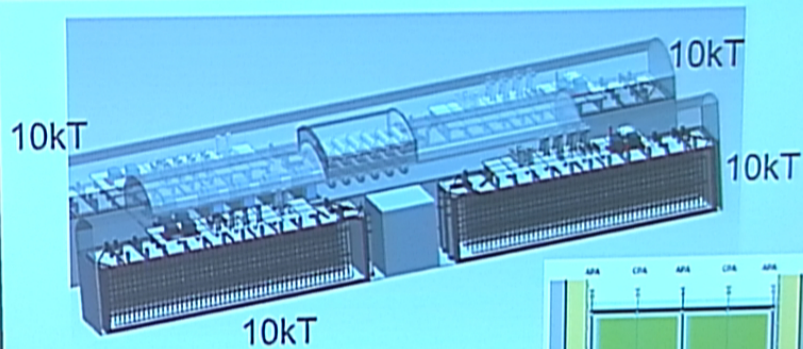


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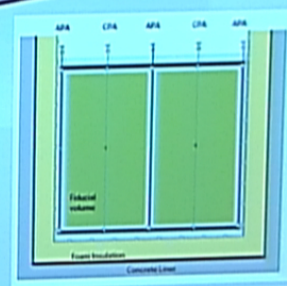
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## The DUNE Detector (v1)



each 10kT cryostat contains  
150 sets of wire planes; ~1.5M  
wires total

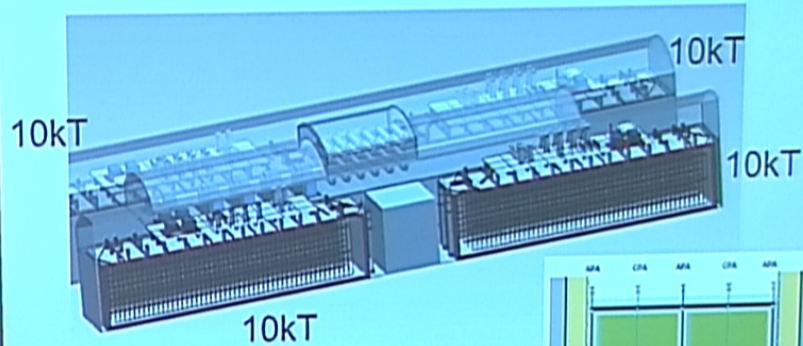


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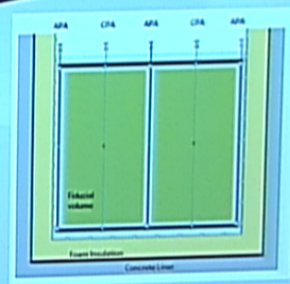
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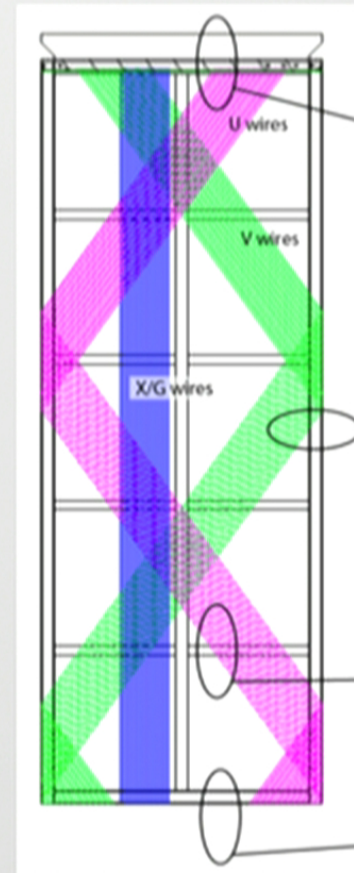
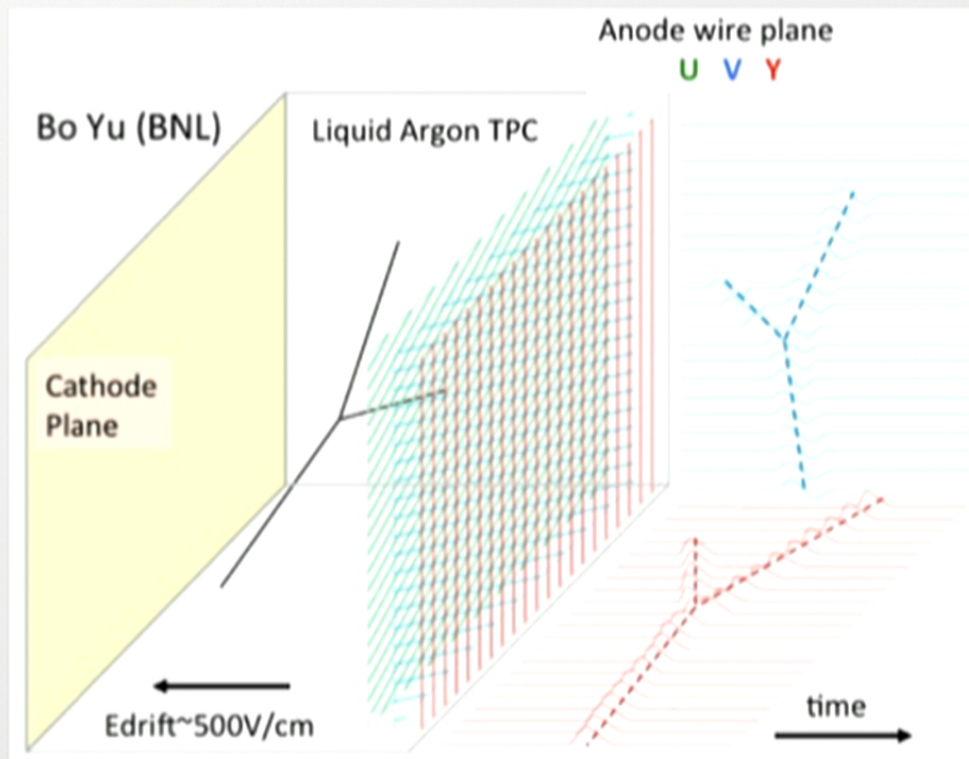


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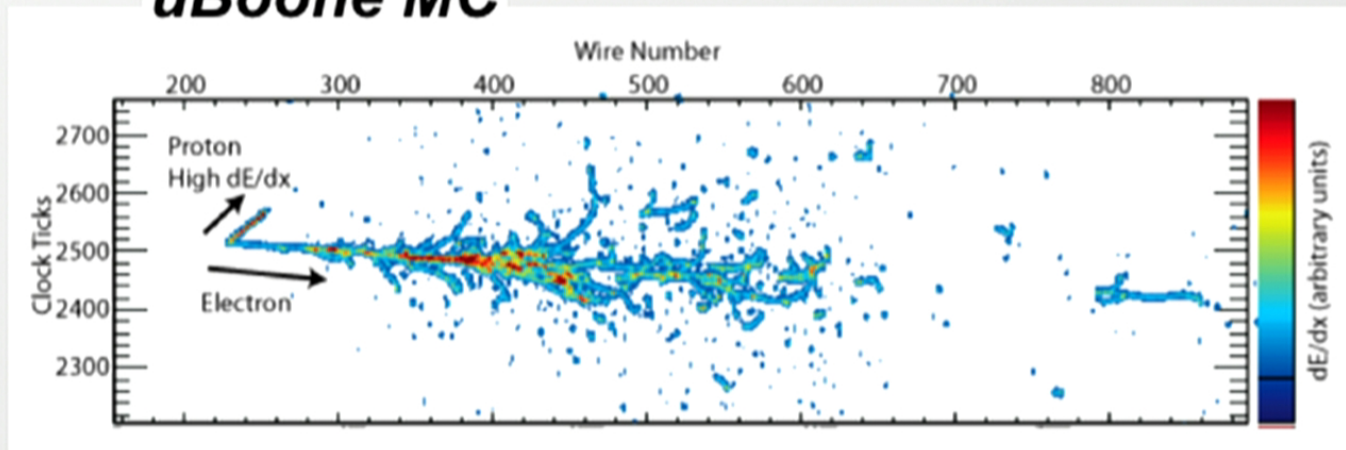


# (DUNE) Liquid Argon TPC



# A Fake Neutrino Event in LAr TPC

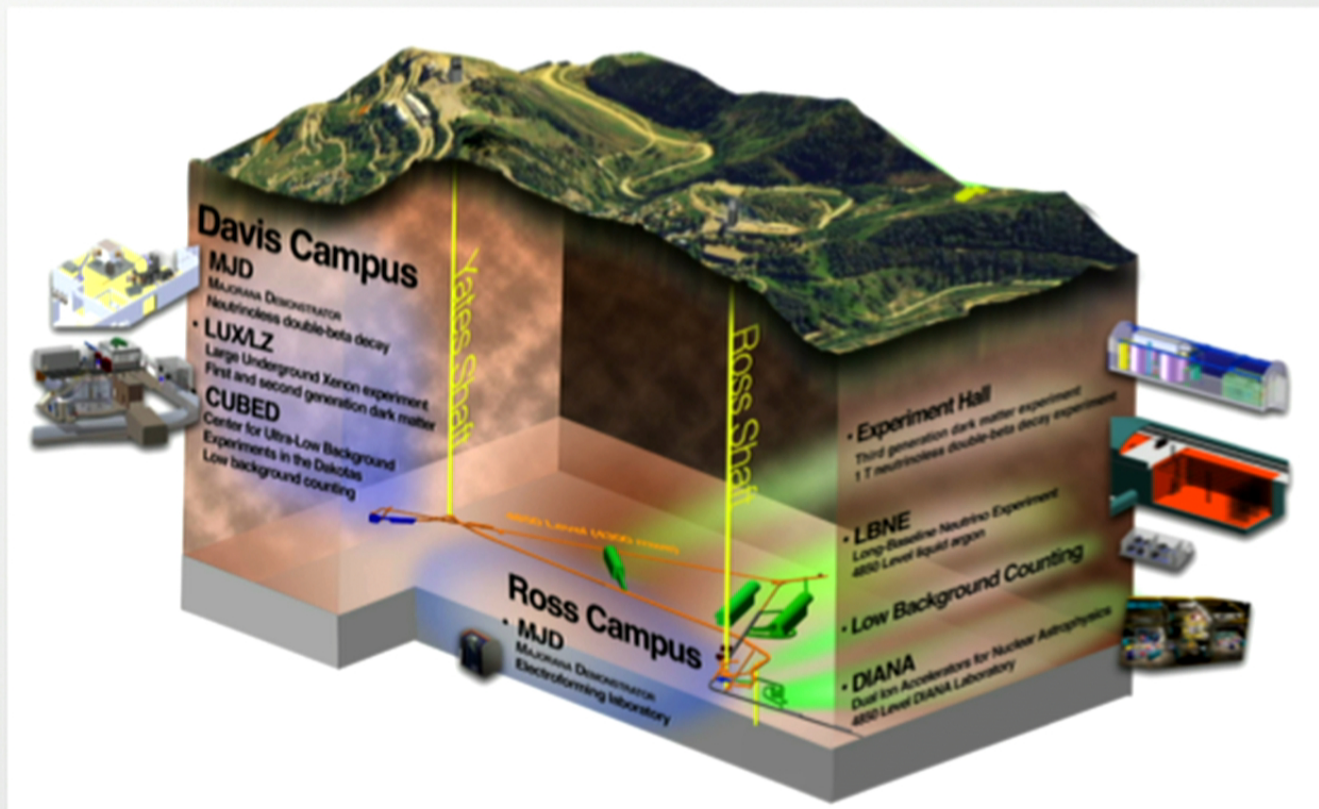
**uBoone MC**



There's a lot going on in this graph...

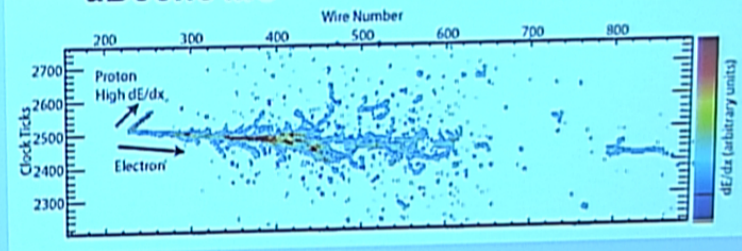


# SURF & LBNF @ Homestake, SD



## A Fake Neutrino Event in LAr TPC

**uBoone MC**



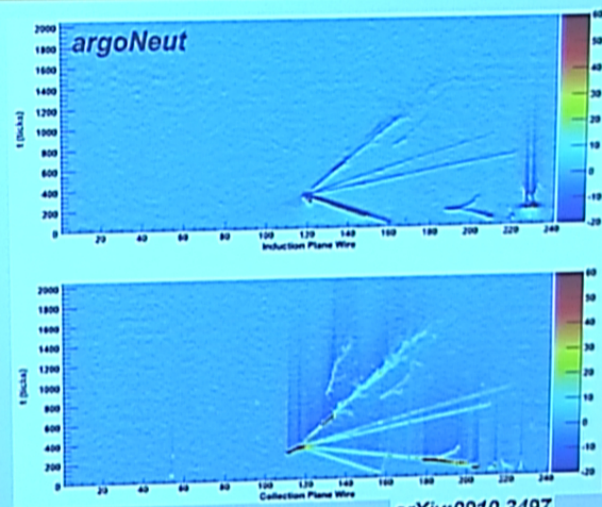
There's a lot going on in this graph...

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## A Real Neutrino Event in LAr TPC



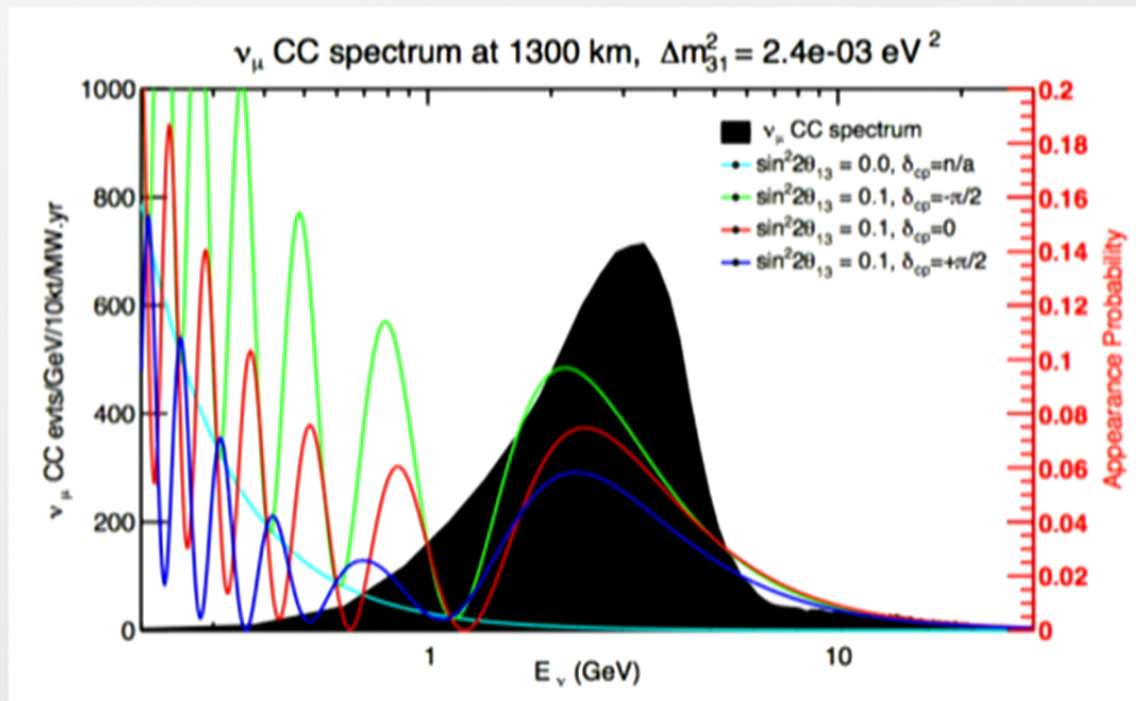
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arXiv:0910.3497

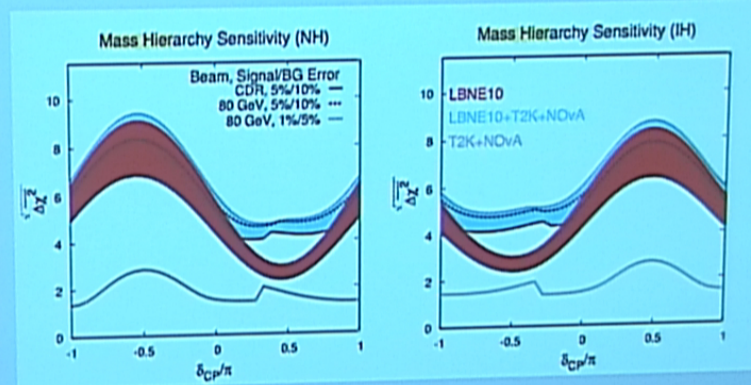
# Neutrino Spectrum @ LBNF

the “golden mode” for DUNE is  $\nu_e$  appearance





## DUNE Mass Hierarchy Reach



T2K only runs in "v-mode"

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## The Plan for DUNE

- There has been a ton of reconfiguration on the LBNE/ DUNE project/collaboration in the past ~3 years
- Things are looking up!
  - The international community is rallying around DUNE/LBNF
  - currently doing a CD-1 "refresh" @ DOE for the detector
  - the facility (LBNF) is doing the CD3 later this year
  - you probably don't know what these mean, and that's good.
- Hope to start excavation ~2018
- Hope to start 1st 10kT cryostat installation ~2020
- Hope to start 1st data taking ~ 2023

...we have a lot of hope...

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