## Neutrino Physics - a pragmatic introduction

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노눌

NOBEL 2015

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

## SuperK



SNO


NOBEL 2015


SNO


## Neutrino Nobel Prizes:

- 1988 Lederman, Schwartz and Steinberger
- 1995 Reines \& Perl
- 2002 Davies and Koshiba \& Giaconni
- 2015 Kajita and McDonald
- 20yx ???????

NOBEL 2015
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"


NOBEL 2015
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

"for the discovery of neutrino flavor transformations, which shows that neutrinos have mass"
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~ vacuum oscillations

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Wolfenstein matter effects dominant

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Wolfenstein matter effects dominant
See Smirnov arXiv:1609.02386

# Flavor Change implies <br> Mass \& Mixings 

## Key Experimental Neutrino Questions:

- Nature of Neutrino Mass:
- 2 comp \& L violation (Majorana)
- or 4 comp \& L conserved (Dirac)
- Neutrino Standard Model:
- Perform stringent tests 3 nu paradigm: check unitarity, ...
- Determine size and sign of CPV
- Determine atmospheric mass ordering
- Does nu_mu or nu_tau dominate nu_3 (theta_23 octant)
- Beyond 3 nus:
- Steriles, Non-Standard Interactions, Lorentz violation, nuBSM, ....


## Flavor Content of Mass Eigenstates:

- Labeling massive neutrinos: $\left|U_{e 1}\right|^{2}>\left|U_{e 2}\right|^{2}>\left|U_{e 3}\right|^{2}$


Fractional Flavor Content

$$
\begin{aligned}
& \delta m_{s o l}^{2}=+7.6 \times 10^{-5} \mathrm{eV}^{2} \\
& \left|\delta m_{a t m}^{2}\right|=2.4 \times 10^{-3} \mathrm{eV}^{2}
\end{aligned}
$$

$\sin ^{2} \theta_{12} \sim \frac{1}{3}$
$\sin ^{2} \theta_{23} \sim \frac{1}{2}$
$0 \leq \delta<2 \pi$
$\sqrt{\delta m_{\text {atm }}^{2}}=0.05 \mathrm{eV}<\sum m_{\nu_{i}}<0.5 \mathrm{eV}$.
$\sin ^{2} \theta_{13} \sim 0.02$

Neutrino Masses:


$$
\begin{gathered}
\left|\delta m_{a t m}^{2}\right|=2.4 \times 10^{-3} \mathrm{eV}^{2} \\
500 \mathrm{~km} / \mathrm{GeV} \\
\delta m_{\text {sol }}^{2}=+7.6 \times 10^{-5} \mathrm{eV}^{2}
\end{gathered}
$$

## $15 \mathrm{~km} / \mathrm{MeV}$



## Neutrino Standard Model:

$$
\left(\begin{array}{l}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{array}\right)
$$



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$$

$$
\left(\begin{array}{l}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{array}\right)
$$



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\left(\begin{array}{l}
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$$

$$
\left(\begin{array}{l}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{array}\right)
$$



$$
\overbrace{\delta_{i j} e^{-i m_{i}^{2} L / 2 E}}^{\nu_{i}}
$$

$v_{3}$

Neutrino Standard Model:

$$
\left(\begin{array}{c}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{array}\right)=\left(\begin{array}{ccc}
\mathbf{U}_{e 1} & \mathbf{U}_{\mathrm{e} 2} & \mathbf{U}_{e 3} \\
U_{\mu 1} & U_{\mu 2} & \mathbf{U}_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & \mathbf{U}_{\tau 3}
\end{array}\right) \quad\left(\begin{array}{c}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{array}\right)
$$



Mixing Matrix

$$
\overbrace{\delta_{i j} e^{-i m_{i}^{2} L / 2 E}}^{\nu_{j}}
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U_{\tau 1} & U_{\tau 2} & \mathbf{U}_{\tau 3}
\end{array}\right) \quad\left(\begin{array}{c}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{array}\right)
$$



## Mixing Matrix

$$
\overbrace{\delta_{i j} e^{-i m_{i}^{2} L / 2 E}}^{\nu_{j}}
$$

$$
\left|U_{e 1}\right|^{2}>\left|U_{e 2}\right|^{2}>\left|U_{e 3}\right|^{2}
$$

Neutrino Standard Model:

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\nu_{\tau}
\end{array}\right)=\left(\begin{array}{ccc}
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U_{\mu 1} & U_{\mu 2} & \mathbf{U}_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & \mathbf{U}_{\tau 3}
\end{array}\right) \quad\left(\begin{array}{c}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{array}\right)
$$

$$
\left.\left|U_{e l}\right|^{2}>\left|U_{e 2}\right|^{2}\right\rangle\left|U_{e s}\right|^{2}
$$



Mixing Matrix

$$
\stackrel{\nu}{i} \delta_{i j} e^{-i m_{i}^{2} L / 2 E}
$$

## Unitary <br> 

$\square$


## M. Ross-Lonergan + SP arXiv:1508.05095



## Quarks:


M. Ross-Lonergan + SP arXiv:1508.05095


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M. Ross-Lonergan + SP arXiv:1508.05095

Unitarity Triangle Closures

Normalisations

M. Ross-Lonergan + SP arXiv:1508.05095

$$
\begin{array}{ccc}
1-\left(\left|U_{\alpha 1}\right|^{2}+\left|U_{\alpha 2}\right|^{2}+\left|U_{\alpha 3}\right|^{2}\right) & \text { or } & 1-\left(\left|U_{e i}\right|^{2}+\left|U_{\mu i}\right|^{2}+\left|U_{r i}\right|^{2}\right) \\
\text { Rows } & \text { Columns }
\end{array}
$$

## ARE THERE LIGHT STERILE

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$$
U_{\mathrm{PMNS}}^{\text {Extended }}=\left(\begin{array}{cccc}
(\overbrace{U_{e 1}}^{U_{e 1}} & U_{e 2} & U_{e 3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\text {PM M S }} & U_{\tau 2} & U_{\tau 3}
\end{array}\right)\left(\begin{array}{cc}
U_{e n} \\
\cdots & U_{\mu n} \\
\vdots & \vdots
\end{array}\right.
$$

## ARE THERE LIGHT STERILE

$$
\begin{aligned}
& \left|\sum_{i=1}^{3} U_{e i} U_{\mu i}\right|^{2} \leq\left(1-\sum_{i=1}^{3}\left|U_{e i}\right|^{2}\right)\left(1-\sum_{i=1}^{3}\left|U_{\mu i}\right|^{2}\right) \\
& \text { - } \nu_{\mu} \text { Disappearance } \\
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\end{aligned}
$$

MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

## ARE THERE LIGHT STERILE



MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

- $\nu_{e}$ Disappearance

Daya Bay, RENO, many $\sim 10 \mathrm{~m}$ Reactor experiments \& source experiments.

## ARE THERE LIGHT STERILE



- $\nu_{\mu}$ Disappearance

MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

- $\nu_{e}$ Disappearance

Daya Bay, RENO, many $\sim 10 \mathrm{~m}$ Reactor experiments \& source experiments.

- $\nu_{\mu} \rightarrow \nu_{e}$ Appearance

Fermilab SBN Program, T2K and NOvA: DUNE \& HyperK

## The Three-Detector SBN Program

Distance from Active

| Detector | BNB Target | LAr Mass |
| :--- | :---: | :---: |
| SBND | 110 m | 112 ton |
| MicroBooNE | 470 m | 87 ton |
| ICARUS | 600 m | 476 ton |




(collection plane view)


Assuming Unitary with 3 flavors:

$$
\left(\begin{array}{ccc}
\mathbf{U}_{e 1} & \mathbf{U}_{\mathbf{e} 2} & \mathbf{U}_{e 3} \\
U_{\mu 1} & U_{\mu 2} & \mathbf{U}_{\mu \mathbf{3}} \\
U_{\tau 1} & U_{\tau 2} & \mathbf{U}_{\tau 3}
\end{array}\right)
$$

$$
=\left(\begin{array}{ccc}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{array}\right)\left(\begin{array}{ccc}
c_{13} & 0 & s_{13} e^{i \delta_{\mathrm{cp}}} \\
0 & 1 & 0 \\
-s_{13} e^{-i \delta_{\mathrm{cp}}} & 0 & c_{13}
\end{array}\right)\left(\begin{array}{ccc}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{array}\right)\left(\begin{array}{ccc}
e^{i \eta_{1}} & 0 & 0 \\
0 & e^{i \eta_{2}} & 0 \\
0 & 0 & 1
\end{array}\right)
$$

## Disappearance:

$$
\begin{aligned}
& \nu_{\mu} \rightarrow \nu_{\mu} \\
& 500 \mathrm{~km} / \mathrm{GeV}
\end{aligned}
$$

$$
\begin{array}{ll}
\nu_{e} \rightarrow \nu_{e} & \nu_{e} \rightarrow \nu_{e} \\
500 \mathrm{~km} / \mathrm{GeV} & 15 \mathrm{~km} / \mathrm{MeV}
\end{array}
$$

Appearance:

$$
\nu_{\mu} \rightarrow \nu_{e}
$$

## 500 km/GeV

## Oscillation Probabilities in Vacuum:

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decompose flavor states into mass eigenstates
$\Rightarrow$ then propagator
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$$
P\left(\nu_{\alpha} \rightarrow \nu_{\beta}\right)=\left|\sum_{i} U_{\alpha i}^{*} e^{-i m_{i}^{2} L / 2 E} U_{\beta i}\right|^{2}
$$

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decompose flavor states into mass eigenstates
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\begin{gathered}
P\left(\nu_{\alpha} \rightarrow \nu_{\beta}\right)=\left|\sum_{i} U_{\alpha i}^{*} e^{-i m_{i}^{2} L / 2 E} U_{\beta i}\right|^{2} \\
P\left(\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta}\right)=\left|\sum_{i} U_{\alpha i} e^{-i m_{i}^{2} L / 2 E} U_{\beta i}^{*}\right|^{2}
\end{gathered}
$$

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P\left(\nu_{\alpha} \rightarrow \nu_{\beta}\right) & =\left|\sum_{i} U_{\alpha i}^{*} e^{-i m_{i}^{2} L / 2 E} U_{\beta i}\right|^{2} \\
P\left(\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta}\right) & =\left|\sum_{i} U_{\alpha i} e^{-i m_{i}^{2} L / 2 E} U_{\beta i}^{*}\right|^{2} \\
& =P\left(\nu_{\beta} \rightarrow \nu_{\alpha}\right) \quad C P T
\end{aligned}
$$

Disappearance: $\nu_{e} \rightarrow \nu_{e}$ and $\bar{\nu}_{e} \rightarrow \bar{\nu}_{e}$
In vacuum the electron neutrino disappearance is

$$
\begin{aligned}
P= & 1-4\left|U_{e 2}\right|^{2}\left|U_{e 1}\right|^{2} \sin ^{2} \Delta_{21} \\
& -4\left|U_{e 3}\right|^{2}\left|U_{e 1}\right|^{2} \sin ^{2} \Delta_{31}-4\left|U_{e 3}\right|^{2}\left|U_{e 2}\right|^{2} \sin ^{2} \Delta_{32} \\
= & 1-\cos ^{4} \theta_{13} \sin ^{2} 2 \theta_{12} \sin ^{2} \Delta_{21} \\
& -\sin ^{2} 2 \theta_{13}\left(\cos ^{2} \theta_{12} \sin ^{2} \Delta_{31}+\sin ^{2} \theta_{12} \sin ^{2} \Delta_{32}\right)
\end{aligned}
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& -4\left|U_{e 3}\right|^{2}\left|U_{e 1}\right|^{2} \sin ^{2} \Delta_{31}-4\left|U_{e 3}\right|^{2}\left|U_{e 2}\right|^{2} \sin ^{2} \Delta_{32} \\
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& \approx \sin ^{2} \Delta_{e e} \quad \text { with } \Delta m_{e e}^{2}=c_{21}^{2} \Delta m_{31}^{2}+s_{21}^{2} \Delta m_{32}^{2} \\
& \approx \sin ^{2} 2 \theta_{13}
\end{aligned}
$$

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$$

$$
=1-\cos ^{4} \theta_{13} \sin ^{2} 2 \theta_{12} \sin ^{2} \Delta_{21}
$$

$$
-\sin ^{2} 2 \theta_{13}\left(\cos ^{2} \theta_{12} \sin ^{2} \Delta_{31}+\sin ^{2} \theta_{12} \sin ^{2} \Delta_{32}\right)
$$

$$
\approx \sin ^{2} \Delta_{e e} \quad \text { with } \Delta m_{e e}^{2}=c_{21}^{2} \Delta m_{31}^{2}+s_{21}^{2} \Delta m_{32}^{2}
$$

KamLAND

$$
\begin{aligned}
& \begin{array}{r}
\text { Daya Bay } \\
\text { RENO }
\end{array}
\end{aligned}
$$

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& \approx \sin ^{2} \Delta_{e e} \quad \text { with } \Delta m_{e e}^{2}=c_{21}^{2} \Delta m_{31}^{2}+s_{21}^{2} \Delta m_{32}^{2}
\end{aligned}
$$

> Daya Bay RENO
> D-Chooz
> RENO 50

KamLAND


# Solar Neutrinos 

## \&

Matter Effects

Coherent Forward Scattering:


Wolfenstein ‘78



## Identical Solar Twins:



## Identical Solar Twins:

~ fractions are energy dependent


## Identical Solar Twins:

~ fractions are energy dependent

\# of oscillation lengths in Solar radius is

## Identical Solar Twins:

~ fractions are energy dependent
(䇇
\# of oscillation lengths in Solar radius is $2 \times 10(4 \pm 1)$

## ~vacuum

pp and ${ }^{7} \mathrm{Be}$


$$
\begin{aligned}
& f_{1} \sim 69 \% \\
& f_{2} \sim 31 \%
\end{aligned}
$$

## ~vacuum

pp and ${ }^{7} \mathrm{Be}$


$$
\begin{aligned}
& f_{1} \sim 69 \% \\
& f_{2} \sim 31 \%
\end{aligned}
$$


$f_{2} \sim 90 \%$
matter dominated

## Life of a Boron-8 Solar Neutrino:

$\nu_{e} \approx \nu_{2}$ for ${ }^{8} B$

## at birth

Solar Center



## Life of a Boron-8 Solar Neutrino:

Once a $\nu_{2}$ always a $\nu_{2}$ !
at birth toddler

Solar Center

$$
v_{\mathrm{e}} \square \quad v_{\mu} \square \quad v_{\tau} \square
$$

## Life of a Boron-8 Solar Neutrino:



## at birth toddler teenager

Solar Center

Exit Core

$$
v_{\mathrm{e}} \square \quad v_{\mu} \square \quad v_{\tau} \square
$$

## Life of a Boron-8 Solar Neutrino:



## Life of a Boron-8 Solar Neutrino:



$$
\begin{array}{lll}
v_{\mathrm{e}} ■ \quad v_{\mu} & v_{\tau} \square
\end{array}
$$

$$
\nu ?+e \rightarrow \nu+e \quad \mathrm{CC}+\mathrm{NC}
$$

$$
\begin{aligned}
& \nu_{?}+e \rightarrow \nu+e \quad \mathrm{CC}+\mathrm{NC} \\
& \nu_{e}, \nu_{\mu}, \nu_{\tau}
\end{aligned}
$$

$$
\begin{aligned}
\nu ?+e & \rightarrow \nu+e \quad \mathrm{CC}+\mathrm{NC} \\
\nu_{e}, \nu_{\mu}, \nu_{\tau} & +\nu_{1}, \nu_{2}, \nu_{3}
\end{aligned}
$$

## $\nu_{2}$

$$
\begin{aligned}
\nu ?+e & \rightarrow \nu+e \quad \mathrm{CC}+\mathrm{NC} \\
\nu_{e}, \nu_{\mu}, \nu_{\tau} & +\nu_{1}, \nu_{2}, \nu_{3}
\end{aligned}
$$

## Tension between KamLAND \& Solar Data

NuFIT 2.1 (2016)



## Tension between KamLAND \& Solar Data



SNOs CC/NC measurement

## $\sin ^{2} \theta_{13}$

## Reactor $\theta_{13}$ Experiments

## Daya Bay



## RENO

## Double Chooz



## 曼 from Daya Bay: arXiv:1505.03456






$$
\Delta m_{e e}^{2} \equiv c_{12}^{2} \Delta m_{31}^{2}+s_{12}^{2} \Delta m_{32}^{2} \quad \text { Double Chooz? }
$$

## $\sin ^{2} \theta_{13}$



## neutrino SM Physics Channels for LBL:

Disappearance: $\nu_{\mu} \rightarrow \nu_{\mu} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}$

Appearance: $\quad \nu_{\mu} \rightarrow \nu_{e} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$

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Disappearance: $\boldsymbol{\nu}_{\mu} \rightarrow \nu_{\mu} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}$

Appearance: $\quad \nu_{\mu} \rightarrow \nu_{e} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$

- Perform Stringent tests of the 3 neutrino paradigm

\author{

- Is there CP Violation
}
- Atm Mass Ordering
(SNO solar ordering)
Dominant Flavor Content of $v \_3$


## Three nuSM Questions for LBL:



Is there CP Violation

O. Mena \& SP
hep-ph/0312131

- Atm Mass Ordering
(SNO solar ordering)
Dominant Flavor Content of $v \_3$


## Three nuSM Questions for LBL:



- Is there CP Violation

O. Mena \& SP
hep-ph/0312131
$\mathrm{CPT} \Rightarrow$ invariant $\delta \leftrightarrow-\delta$
- Atm Mass Ordering
(SNO solar ordering)


Dominant Flavor Content of $v \_3$

## Three nuSM Questions for LBL:



- Is there CP Violation

O. Mena \& SP
hep-ph/0312131
CPT $\Rightarrow$ invariant $\delta \leftrightarrow-\delta$
- Atm Mass Ordering
(SNO solar ordering)
- Dominant Flavor Content of $v \_3$

$\sin ^{2} \theta_{23}=$
$\theta_{23}$ octant?

- Disappearance:

$$
\nu_{\mu} \rightarrow \nu_{\mu} \quad \Leftrightarrow \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}
$$

$\Delta m_{\mu \mu}^{2}$ and $\left|U_{\mu 3}\right|^{2}=c_{13}^{2} s_{23}^{2}\left(\right.$ but degenerate with $\left.\left(1-\left|U_{\mu 3}\right|^{2}\right)\right)$

$$
\nu_{\mu} \rightarrow \nu_{\mu} \quad \Leftrightarrow \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}
$$

$\Delta m_{\mu \mu}^{2}$ and $\left|U_{\mu 3}\right|^{2}=c_{13}^{2} s_{23}^{2}$ ( but degenerate with $\left(1-\left|U_{\mu 3}\right|^{2}\right)$ )


$$
\nu_{\mu} \rightarrow \nu_{\mu} \quad \Leftrightarrow \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}
$$

$\Delta m_{\mu \mu}^{2}$ and $\left|U_{\mu 3}\right|^{2}=c_{13}^{2} s_{23}^{2}$ ( but degenerate with $\left(1-\left|U_{\mu 3}\right|^{2}\right)$ )


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$\Delta m_{\mu \mu}^{2}$ and $\left|U_{\mu 3}\right|^{2}=c_{13}^{2} s_{23}^{2}$ ( but degenerate with $\left(1-\left|U_{\mu 3}\right|^{2}\right)$ ) difference


$$
\begin{aligned}
\left|U_{\mu 3}\right|^{2}\left(1-\left|U_{\mu 3}\right|^{2}\right)=s_{23}^{2} c_{23}^{2}-s_{13}^{2} s_{23}^{2} & \cos 2 \theta_{23}-s_{13}^{4} s_{23}^{4} \\
& \approx 0
\end{aligned}
$$

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

T2K

## NOvA



$$
\sin ^{2}\left(\theta_{23}\right)=0.40_{-0.02}^{+0.03}\left(0.63_{-0.03}^{+0.02}\right)
$$

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


|  | NH | IH | $\sin ^{2}\left(\theta_{23}\right)=0.40_{-0.02}^{+0.03}\left(0.63_{-0.03}^{+0.02}\right)$ |
| :---: | :---: | :---: | :---: |
| $\sin ^{2} \theta_{23}$ | $0.532_{-0.068}^{+0.046}$ | $0.534_{-0.066}^{+0.043}$ | $\sin ^{+0.02}$ |

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


| NH | IH | $\sin ^{2}\left(\theta_{23}\right)=0.534_{-0.066}^{+0.043}$ |
| :---: | :---: | :---: |
| $\sin ^{2} \theta_{23}$ | $0.532_{-0.068}^{+0.046}$ | $\sin _{-0.03}^{+0.03}\left(0.63_{-0.0}^{+0.02}\right.$ |

- $\Delta \chi^{2}$ flat


## $\sin ^{2} \theta_{23}$

NuFIT 2.2 (2016)


## Ve Appearance Channel:

$$
\begin{aligned}
& \\
& \nu_{\mu} \rightarrow \nu_{e}
\end{aligned} \stackrel{\mathrm{CP}}{\Longleftrightarrow} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}
$$

## Ve Appearance Channel:


$\nu_{e}$ Appearance Channel:

$$
\bar{\nu}_{\mu} \longrightarrow \bar{\nu}_{e}
$$

$$
V_{\mu} \longrightarrow V_{e}
$$



$$
\nu_{e} \rightarrow \nu_{\mu}
$$



$$
\begin{gathered}
\Uparrow \\
\bar{\nu}_{e} \rightarrow \bar{\nu}_{\mu}
\end{gathered}
$$

T
$\nu_{e}$ Appearance Channel:


Ve Appearance Channel:


> T2K (295km) and NOvA (810km)
$\nu$ Appearance Channel:


- Running experiments:

> T2K (295km) and NOvA (810km)

- Future experiments:

> DUNE ( 40 ktons LAr, 1300 km )
> HyperKamiokaNDE $\left(0.5 \mathrm{kMtons} \mathrm{H}_{2} \mathrm{O}, 295 \mathrm{~km}\right)$
$\nu$ Appearance Channel:


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- Future experiments:

DUNE (40 ktons LAr, 1300km)
HyperKamiokaNDE ( $0.5 \mathrm{kMtons} \mathrm{H}_{2} \mathrm{O}, 295 \mathrm{~km}$ )

$$
\nu_{\mu} \rightarrow \nu_{e} \quad \Leftrightarrow \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}
$$

$\mathrm{CPV} / \delta$, mass ordering and dominant flavor of $\nu_{3}$


$$
\begin{aligned}
A_{\mu e}=A_{31}+e^{i\left(\delta+\Delta_{32}\right)} A_{21} & \Delta_{i j}=\Delta m_{i j}^{2} L / 4 E \\
P\left(\nu_{\mu} \rightarrow \nu_{e}\right)=A_{\mu e} A_{\mu e}^{*} &
\end{aligned}
$$

$$
\begin{gathered}
A_{\mu e}=A_{31}+\underbrace{e^{i\left(\delta+\Delta_{32}\right)}} A_{21} \quad \Delta_{i j}=\Delta m_{i j}^{2} L / 4 E \\
P\left(\nu_{\mu} \rightarrow \nu_{e}\right)=A_{\mu e} A_{\mu e}^{*}
\end{gathered}
$$

$$
A_{\mu e}=A_{31}+e^{i\left(\delta+\Delta_{32}\right)} A_{21}
$$

$$
\Delta_{i j}=\Delta m_{i j}^{2} L / 4 E
$$



$$
A_{\mu e}=A_{31}+e^{i\left(\delta+\Delta_{32}\right)} A_{21}
$$

$$
\Delta_{i j}=\Delta m_{i j}^{2} L / 4 E
$$



## $A_{31}=2 s_{23} s_{13} c_{13} \sin \Delta_{31}$

$$
A_{21}=2 c_{13} c_{23} s_{12} c_{12} \sin \Delta_{21}
$$

$$
A_{\mu e}=A_{31}+e^{i\left(\delta+\Delta_{32}\right)} A_{21}
$$

$$
\Delta_{i j}=\Delta m_{i j}^{2} L / 4 E
$$


$\delta=0.0 \pi$
$\Delta_{32}=0.40 \pi$

Denton \& Parke

## $A_{31}=2 s_{23} s_{13} c_{13} \sin \Delta_{31}$

$$
A_{21}=2 c_{13} c_{23} s_{12} c_{12} \sin \Delta_{21}
$$

$$
A_{\mu e}=A_{31}+e^{i\left(\delta+\Delta_{32}\right)} A_{21}
$$

$$
\Delta_{i j}=\Delta m_{i j}^{2} L / 4 E
$$



$$
\begin{align*}
& \delta=0.0 \pi \\
& \Delta_{32}=0.40 \pi \\
& \begin{array}{ll}
-A_{31} \\
- & A_{21} \\
- & A_{\mu e} \\
- & \bar{A}_{\mu e}^{*}
\end{array} \quad \begin{array}{l}
P\left(\nu_{\mu} \rightarrow \nu_{e}\right)=A_{\mu e} A_{\mu e}^{*} \\
P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right)=\bar{A}_{\mu e}^{*} \bar{A}_{\mu e}
\end{array}
\end{align*}
$$

CPV:
$\nu_{\mu} \rightarrow \nu_{e}$

$$
\begin{aligned}
\Delta P & \equiv P\left(\nu_{\mu} \rightarrow \nu_{e}\right)-P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \\
& =\left|A_{31}+e^{i\left(\Delta_{32}+\delta\right)} A_{21}\right|^{2}-\left|A_{31}+e^{i\left(\Delta_{32}-\delta\right)} A_{21}\right|^{2} \\
& \uparrow \begin{array}{c}
\text { only difference }
\end{array}{ }^{2}
\end{aligned}
$$

CPV:

$$
\begin{aligned}
\Delta P & \equiv P\left(\nu_{\mu} \rightarrow \nu_{e}\right)-P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \\
& =\left|A_{31}+e^{i\left(\Delta_{32}+\delta\right)} A_{21}\right|^{2}-\left|A_{31}+e^{i\left(\Delta_{32}-\delta\right)} A_{21}\right|^{2}
\end{aligned}
$$

$$
=2 A_{31} A_{21}\left\{\cos \left(\Delta_{32}+\delta\right)-\cos \left(\Delta_{32}-\delta\right)\right\}
$$

$$
=-2 \cos \theta_{13} \sin 2 \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin \delta \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}
$$

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=-2 \cos \theta_{13} \sin 2 \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin \delta \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}
$$

J=Jarlskog Invariant

CPV:
$\nu_{\mu} \rightarrow \nu_{e}$

$=2 A_{31} A_{21}\left\{\cos \left(\Delta_{32}+\delta\right)-\cos \left(\Delta_{32}-\delta\right)\right\}$
$=-2 \cos \theta_{13} \sin 2 \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin \delta \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$

J=Jarlskog Invariant
$4 \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$ $=\sin \left(2 \Delta_{31}\right)-\sin \left(2 \Delta_{32}\right)-\sin \left(2 \Delta_{21}\right)$

CPV:
$\nu_{\mu} \rightarrow \nu_{e}$

$$
A_{21}=2 c_{13} c_{23} s_{12} c_{12} \sin \Delta_{21}
$$

$$
\begin{aligned}
\Delta P & \equiv P\left(\nu_{\mu} \rightarrow \nu_{e}\right)-P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \\
& =\left|A_{31}+e^{i\left(\Delta_{32}+\delta\right)} A_{21}\right|^{2}-\left|A_{31}+e^{i\left(\Delta_{32}-\delta\right)} A_{21}\right|^{2}
\end{aligned}
$$

$$
=2 A_{31} A_{21}\left\{\cos \left(\Delta_{32}+\delta\right)-\cos \left(\Delta_{32}-\delta\right)\right\}
$$

$$
=-2 \cos \theta_{13} \sin 2 \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin \delta \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}
$$

## J=Jarlskog Invariant

$$
\underset{\frac{L}{E} \rightarrow 0}{\sim} 2^{2}\left(\Pi \Delta m_{i j}^{2}\right)\left(\frac{L}{4 E}\right)^{3}
$$

## $4 \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$

$$
=\sin \left(2 \Delta_{31}\right)-\sin \left(2 \Delta_{32}\right)-\sin \left(2 \Delta_{21}\right)
$$

CPV:
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& \Delta P \equiv P\left(\nu_{\mu} \rightarrow \nu_{e}\right)-P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \\
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& \uparrow
\end{aligned}
$$

$=2 A_{31} A_{21}\left\{\cos \left(\Delta_{32}+\delta\right)-\cos \left(\Delta_{32}-\delta\right)\right\}$
$=-2 \cos \theta_{13} \sin 2 \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sin \delta \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$

J=Jarlskog Invariant
$4 \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$

$$
=\sin \left(2 \Delta_{31}\right)-\sin \left(2 \Delta_{32}\right)-\sin \left(2 \Delta_{21}\right)
$$

$$
\underset{\frac{L}{E} \rightarrow 0}{\sim} 2_{J\left(\Pi \Delta m_{i j}^{2}\right)\left(\frac{L}{4 E}\right)^{3}}
$$

Depends on ALL $\theta$ 's, $\delta$ and $\Delta m^{2}$ s !
This includes $\Delta m_{21}^{2}$ !!!

## Matter Effects:

$$
\begin{gathered}
A_{31}+e^{i\left(\Delta_{32} \pm \delta\right)} A_{21} \\
A_{31}=2 s_{23} s_{13} c_{13} \frac{\sin \left(\Delta_{31 \mp a L)}\right.}{\left(\Delta_{31 \mp a L)}\right.} \Delta_{31} \\
A_{21}=2 c_{13} c_{23} s_{12} c_{12} \frac{\sin (a L)}{(a L)} \Delta_{21} \\
\quad a=G_{F} N_{e} / \sqrt{2}=(4000 \mathrm{~km})^{-1},
\end{gathered}
$$

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Denton \& Parke


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A_{21}=2 c_{13} c_{23} s_{12} c_{12} \frac{\sin (a L)}{(a L)} \Delta_{21} \\
\quad a=G_{F} N_{e} / \sqrt{2}=(4000 \mathrm{~km})^{-1},
\end{gathered}
$$

$$
\delta=0.0 \pi
$$



$$
a=\frac{G_{F} N_{e}}{\sqrt{2}}
$$

$$
\approx(4000 \mathrm{~km})^{-1}
$$

$$
\begin{aligned}
& P_{\mu \rightarrow e} \approx\left|A_{31}+e^{i\left(\Delta_{32} \pm \delta\right)} A_{21}\right|^{2} \\
& \text { where } A_{31}=\sqrt{P_{a t m}}=2 s_{23} s_{13} c_{13} \frac{\sin \left(\Delta_{31} \mp a L\right)}{\left(\Delta_{31} \mp a L\right)} \Delta_{31} \\
& \text { and } \quad A_{21}=\sqrt{P_{\text {sol }}}=2 c_{13} c_{23} s_{12} c_{12} \frac{\sin (a L)}{(a L)} \Delta_{21}
\end{aligned}
$$

$$
P_{\mu \rightarrow e} \approx\left|A_{31}+e^{i\left(\Delta_{32} \pm \delta\right)} A_{21}\right|^{2}
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$$
a=\frac{G_{F} N_{e}}{\sqrt{2}}
$$

$$
\approx(4000 \mathrm{~km})^{-1}
$$

$$
P_{\mu \rightarrow e} \approx\left|A_{31}+e^{i\left(\Delta_{32} \pm \delta\right)} A_{21}\right|^{2}
$$



$$
P_{\mu \rightarrow e} \approx P_{a t m}+2 \sqrt{P_{a t m} P_{s o l}} \cos \left(\Delta_{32} \pm \delta\right)+P_{\text {sol }}
$$

$$
\cos \left(\Delta_{32} \pm \delta\right)=\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta
$$

## Correlations between $\nu_{\mu} \rightarrow \nu_{e} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$

## Normal Ordering - Inverted Ordering

$$
\boldsymbol{\nu}_{\boldsymbol{\mu}} \rightarrow \boldsymbol{\nu}_{\boldsymbol{\mu}} \text { gives: } \quad \sin ^{2} 2 \theta_{\mu \mu} \equiv 4\left|U_{\mu 3}\right|^{2}\left(1-\left|U_{\mu 3}\right|^{2}\right)=0.96-1.00
$$

T2K/HK


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\left|U_{\mu 3}\right|^{2} \leftrightarrow\left(1-\left|U_{\mu 3}\right|^{2}\right) \text { degeneracy ! }
\end{gathered}
$$

T2K/HK


NOvA


## Correlations between

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\nu_{\mu} \rightarrow \nu_{e} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}
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\end{gathered}
$$



## NOvA



DUNE
Same L/E as NO $/ \mathrm{A}$


## Correlations between

$$
\nu_{\mu} \rightarrow \nu_{e} \quad \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}
$$

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\boldsymbol{\nu}_{\boldsymbol{\mu}} \rightarrow \boldsymbol{\nu}_{\boldsymbol{\mu}} \text { gives: }
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\begin{gathered}
\sin ^{2} 2 \theta_{\mu \mu} \equiv 4\left|U_{\mu 3}\right|^{2}\left(1-\left|U_{\mu 3}\right|^{2}\right)=0.96-1.00 \\
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\end{gathered}
$$



NOvA


DUNE
Same L/E as NO $\nu \mathrm{A}$

$\propto \rho L \sin ^{2} \theta_{23}$

## Normal Ordering - Inverted Ordering

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\boldsymbol{\nu}_{\boldsymbol{\mu}} \rightarrow \boldsymbol{\nu}_{\boldsymbol{\mu}} \text { gives: }
$$

$$
\begin{gathered}
\sin ^{2} 2 \theta_{\mu \mu} \equiv 4\left|U_{\mu 3}\right|^{2}\left(1-\left|U_{\mu 3}\right|^{2}\right)=0.96-1.00 \\
\left|U_{\mu 3}\right|^{2} \leftrightarrow\left(1-\left|U_{\mu 3}\right|^{2}\right) \text { degeneracy ! }
\end{gathered}
$$



DUNE bi-Probability Diagrams:
Normal Ordering - Inverted Ordering

DUNE bi-Probability Diagrams:
Normal Ordering - Inverted Ordering

## VOM





near Osc Min

## 2nd Osc Max: (vacuum)



DUNE 2 osc max , ESSnuSB

草

## Where are we Today!

T2K \& NOvA:


1 sigma:
NO
IO
Appearance data

T2K \& NOvA:


1 sigma:

10

Appearance data

T2K \& NOvA:


1 sigma:

Appearance data

T2K \& NOvA:


1 sigma:
NO
IO
Appearance data

T2K \& NOvA:


1 sigma:
NO
IO

Appearance data

T2K \& NOvA:


1 sigma:

IO

Appearance data

Close-up of neutrino interaction in the Far Detector


NOvA

T2K \& NOvA:


1 sigma:

IO

Appearance data

T2K \& NOvA:


1 sigma:


IO

Appearance data

T2K \& NOvA:


1 sigma:


IO

Appearance data

Disappearance v Appearance for:
$\theta_{23}$


Minakata, Parke 1303.6178; Coloma, Minakata, Parke 1406.2551

## Surprises: Non-Standard Interactions

$$
i \frac{d}{d t}\left(\begin{array}{c}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{array}\right)=\left[U\left(\begin{array}{ccc}
0 & 0 & 0 \\
0 & \Delta_{21} & 0 \\
0 & 0 & \Delta_{31}
\end{array}\right) U^{\dagger}+A\left(\begin{array}{ccc}
1+\varepsilon_{e e} & \varepsilon_{e \mu} & \varepsilon_{e \tau} \\
\varepsilon_{e \mu}^{*} & \varepsilon_{\mu \mu} & \varepsilon_{\mu \tau} \\
\varepsilon_{e \tau}^{*} & \varepsilon_{\mu \tau}^{*} & \varepsilon_{\tau \tau}
\end{array}\right)\right] \quad\left(\begin{array}{c}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{array}\right)
$$



NSI




P.Coloma
arXiv:1511.06357

What is DUNE/LBNF?

- DUNE/LBNF will consist of
- An intense (1-2 MW) neutrino beam from Fermilab
- A massive (70 kton) deep underground LAr Detector South Dakota
- A large Near Detector at Fermilab
- A large International Collaboration (~1000 scientist)

1300 km

South Dakota


DUNE is a large (70 kton) LAr underground ( 1.5 km ) detector exposed to an intense (1-2 MW) Neutrino beam from Fermilab (1300km)

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- Perform Stringent tests of the 3 neutrino paradigm

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- Complete the Mass Ordering ( $m \_1<m \_2<m \_3$ or $m \_3<m \_1<m \_2$ )

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- Perform Stringent tests of the 3 neutrino paradigm
- Determine the size and sign of CP Violation in Nu Sector
- Complete the Mass Ordering $\left(m_{-} 1<m \_2<m \_3\right.$ or $\left.m \_3<m \_1<m \_2\right)$
- Determine which flavor Dominates nu_3 (least nu_e neutrino mass state)

DUNE
DUNE is a large (70 kton) LAr underground ( 1.5 km ) detector exposed to an intense (1-2 MW) Neutrino beam from Fermilab (1300km)

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- Perform Stringent tests of the 3 neutrino paradigm
- Determine the size and sign of CP Violation in Nu Sector
- Complete the Mass Ordering ( $m \_1<m \_2<m \_3$ or $m \_3<m \_1<m \_2$ )
- Determine which flavor Dominates nu_3 (least nu_e neutrino mass state)
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- Surprises: NSI, sterile neutrinos, Nu Decay, Decoherence, Lorentz Violatión,......


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- A convincing Model of Neutrino Masses and Mixing with confirmed predictions.


## Thank You!

## extras

$\nu_{\boldsymbol{\tau}}$ appearance
$\nu_{\mu} \rightarrow \nu_{\tau}$

$\boldsymbol{T}$ threshold

