Title: The Era of Three Generations: Possible hints from neutrinos in elucidating the matter/antimatter asymmetry of the Universe

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Abstract: Despite being one of the most abundant constituents of the Universe and more than a half a century of study, some of the most fundamental properties of the neutrino have only been recently uncovered, and others still remain unresolved. I will discuss important developments in the phenomenon of neutrino oscillations, a transmutation process that allows neutrinos to change between three types as they propagate in time. In particular, recent discoveries have opened up the possibility of CP violation in neutrino oscillations, asymmetries in the behavior of neutrinos and their anti-matter counterparts. CP violation, along with other unresolved properties of the neutrino, may play a central role in how the universe came to a matter-dominated state. I will also discuss a new generation of experiments that may allow us to establish whether CP violation does indeed occur in neutrino oscillations.

INSTITUTE OF
PARTICLE
PHYSICS

The Era of Three Generations:

Hints from neutrinos on elucidating the matter/antimatter asymmetry of the Universe

H. A. Tanaka (UBC/IPP)

Perimeter Institute
Colloquium September 2013

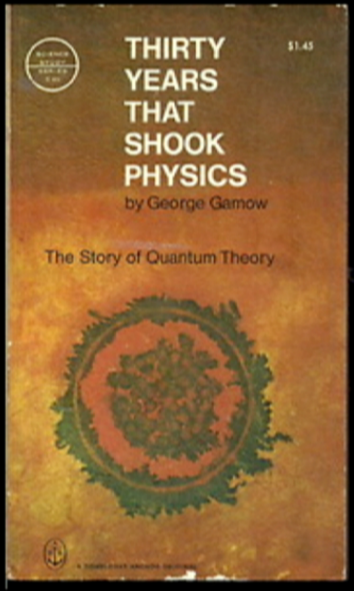
Japanese Neutrino Finding Could Explain Why There Is Matter in the Universe

A new kind of oscillation could be the key to life, the universe, and everything

By Clay Dillow Posted 06.15.2011 at 11:49 am 6 Comments

- In this talk, I will try to explain some of the claims that are being made about recent developments in neutrino physics

Particle Physics c. 1930



- In the tumultuous era that gave birth to:
  - special/general relativity
  - quantum mechanics

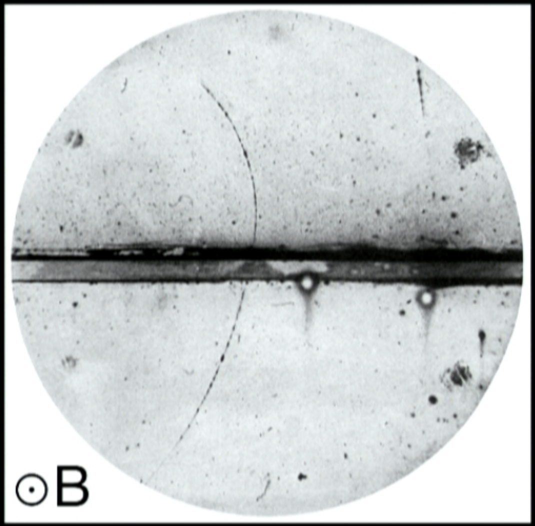
  an exceedingly simple picture emerged regarding "particle" physics:

p e$^-$ γ

- atoms are some number of protons bound together in the nucleus, with an equal number of electrons bound to them electromagnetically

A few developments then completely disrupted this simple picture

Antimatter:



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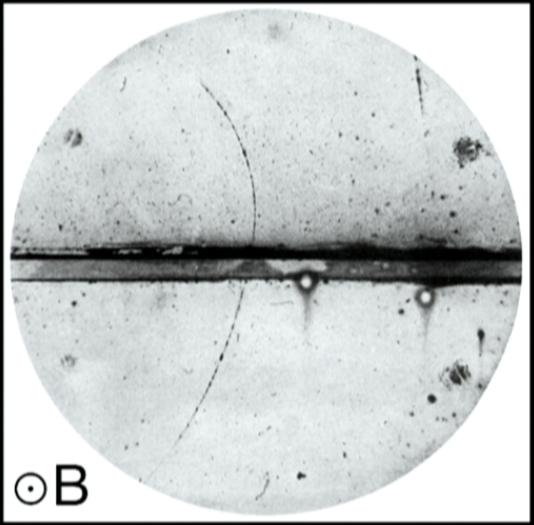
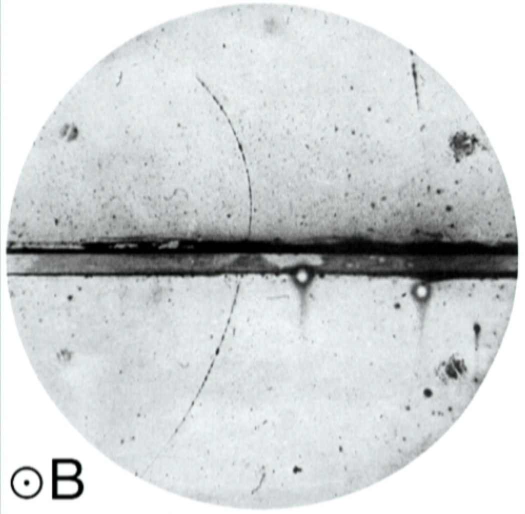


$$(i\gamma\cdot\partial - m)\psi = 0$$

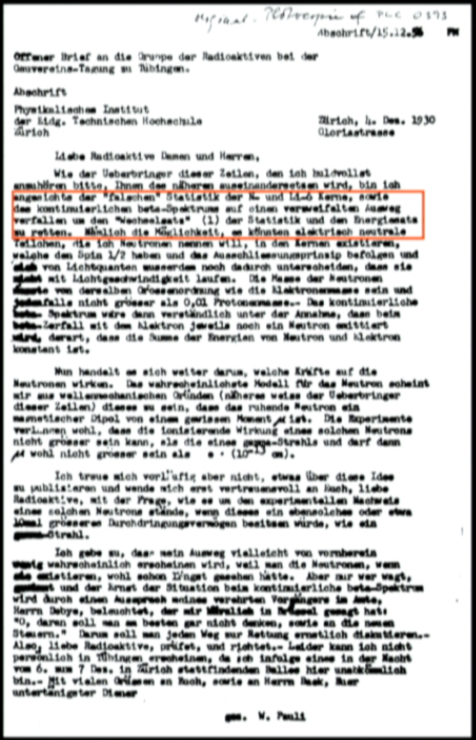
Antimatter:



$$(i\gamma\cdot\partial - m)\psi = 0$$

- Marriage of SR with QM leads to the prediction of antimatter
- A positively charged particle, which appears otherwise identical to electron, is observed in cosmic rays

The neutron and neutrino



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

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 angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

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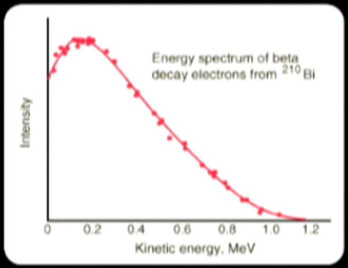
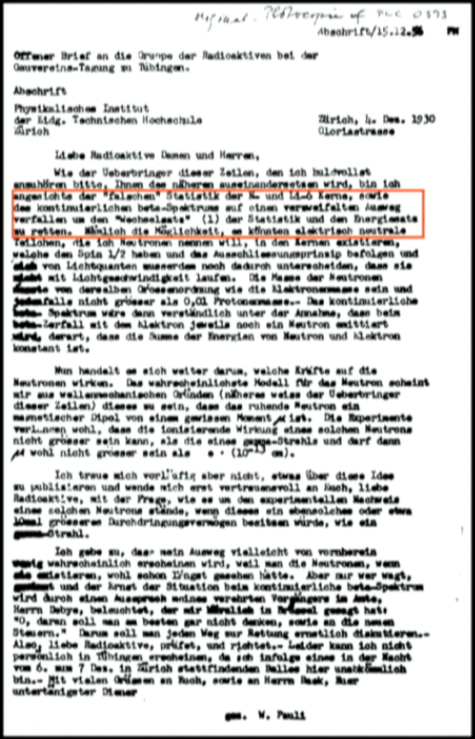
gez. W. Pauli



- Leftover issues:
  - nuclear spin-statistics issue:
    - some nuclei do not have the expected spin (i.e. ^{14}N has +1 spin)
  - continuous spectrum of β-decay
    - only two outgoing particles observed.
    - momentum should be fixed?
- A new neutral particle?
  - bound within the nucleus with protons
  - emitted in β-decay (3-body)

The neutron and neutrino



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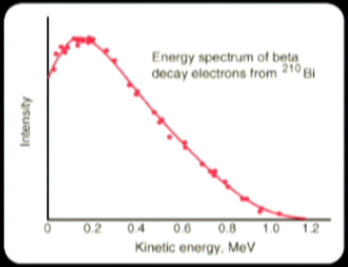

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Examine and Judge . . .

- new particle(s) disturb simple picture whose only purpose was to solve a few problems.
  - “a desperate remedy”
- Some, like Bohr, would prefer to consider that energy conservation didn’t hold in the nucleus

- The “neutron” sorted it self out quickly:
  - Already postulated by Rutherford
  - Discovered in 1932 by Chadwick

- Fermi: theory of “weak” neutrino interactions
  - related expected interaction rate with β decay lifetime
  - became clear that the cross section is **extremely small**
- Pauli: “I have done a terrible thing, I have postulated a particle that cannot be detected.”

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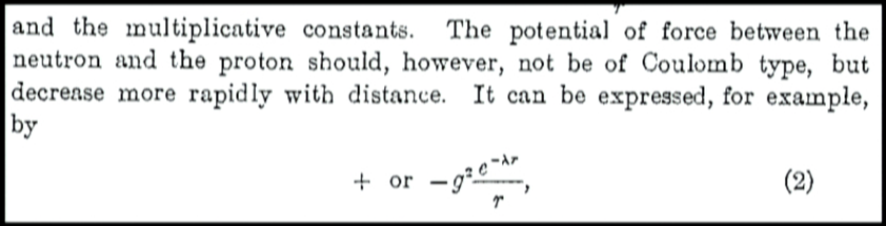
The pion and muon

- What holds the nucleus together?
    - a new force must bind the protons (and neutrons)
- Yukawa predicts a new particle: the "pion"
    - like the photon, it is responsible for a "force"
    - infer the mass of the particle from the size of the nucleus

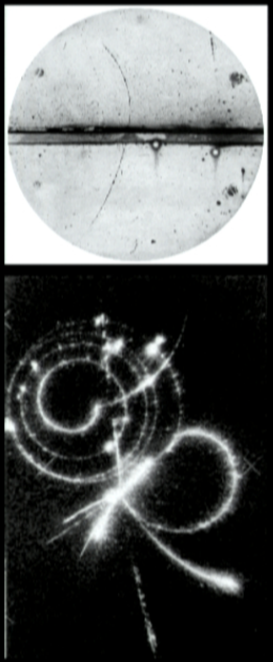


and the multiplicative constants. The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$+ \text{ or } -g^2 \frac{e^{-\lambda r}}{r}, \qquad (2)$$

Who ordered that?

$(i\gamma\cdot\partial-m)\psi=0$



- While the other particles came with some "early warning" the muon came out of nowhere.
  - why does such a particle exist?
- Anti-matter appears on equal footing to matter in theory and experiment
  - early idea: "anti-electron" is the proton
  - why is there a "mirror" family of particles?
  - why is there matter everywhere, but not anti-matter?

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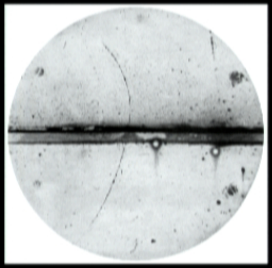

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Whence/wherefore anti-matter ?

- Once the boat was rocked, it didn't stop . . .
    - "Strange" particles: interact strongly, decay weakly
    - "Mesons": relatives of the pion family
    - "Hyperons": baryonic counterparts related to protons/neutrons
    - Corresponding anti-particles: anti-protons, anti-neutrons, etc.
    - The neutrino! in a few species (ν_e, ν_μ, . .)
- By the end of the 1960's, there were "too many" particles

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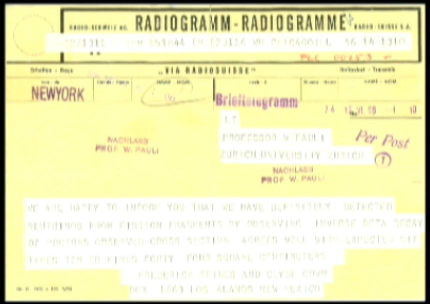
- Willis Lamb (1955): "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be **punished by a $10,000 fine.**"



RADIOGRAMM - RADIOGRAMME

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

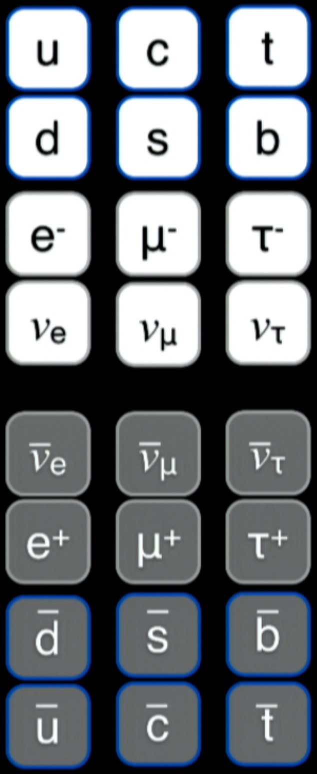
Per Post

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

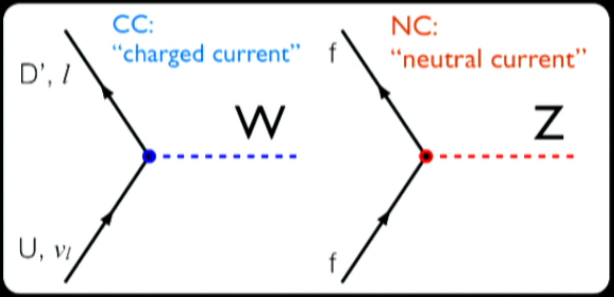
As we now it now:

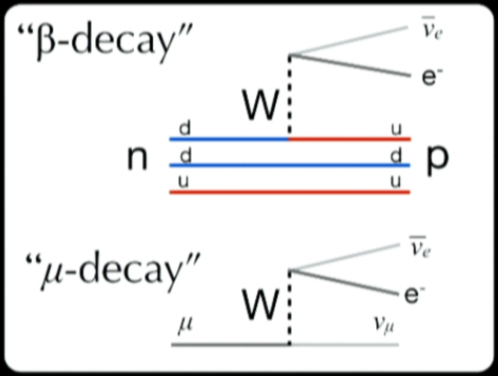


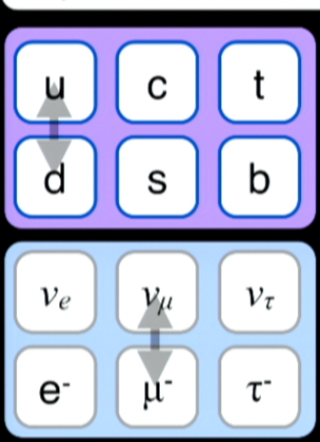
- 1970s: "Mendeleevian+Newtonian" synthesis:
  - all known "matter" composed of six quarks and six leptons in three "generations"
  - Add in gauge field theories + SSB:

  - and we ~have the "Standard Model"

Weak Interactions



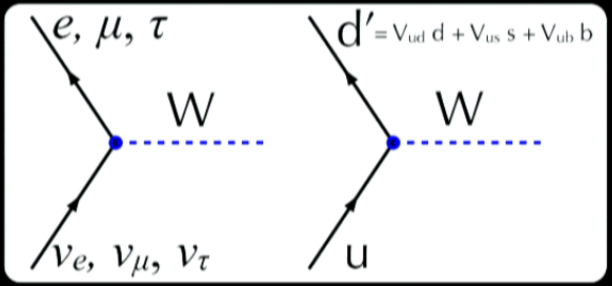


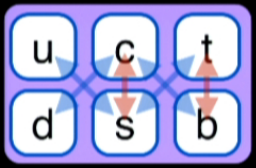


- Charged current (CC):
  - interaction between top/bottom rows
  - exchange of "W" boson
- Neutral current (CC)
  - interaction that maintains identity of particles
  - very much like EM interaction through photon
- N.B.: The quarks are labeled as mass eigenstates
  - historical artifact from era of massless neutrinos

Flavor eigenstates:

- Cross generational CC transitions also possible
  - quark “flavor” state are a linear combination of quark mass states
    - d′ is the quark associated with u, a combination of d, s, b quarks
  - Likewise ν_e is the neutrino associated with e in weak interaction, etc.





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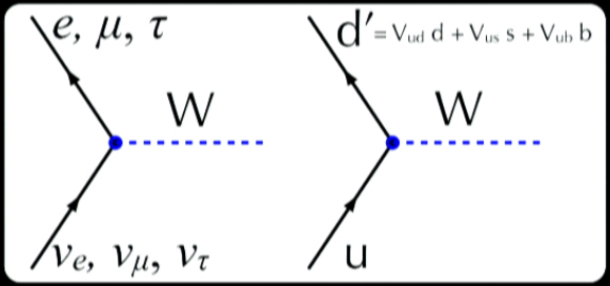
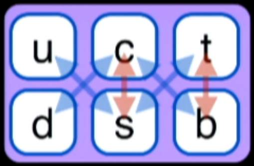


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$



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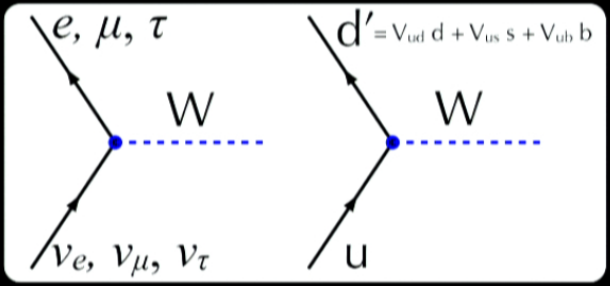

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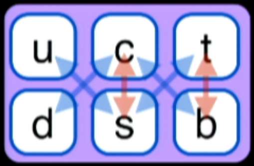
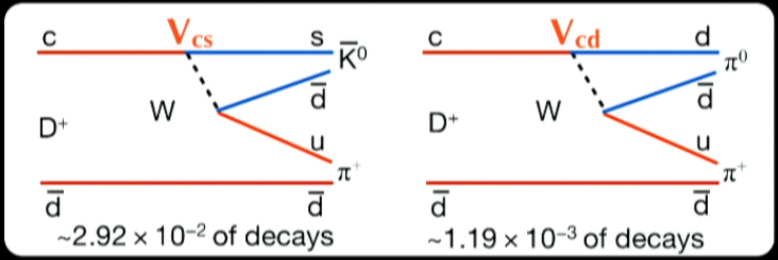




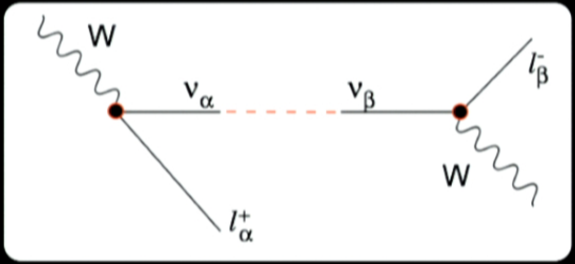
~2.92 × 10^{-2} of decays

~1.19 × 10^{-3} of decays

Neutrino Oscillations

- Neutrinos produced in weak decays are linear combinations of mass/energy eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

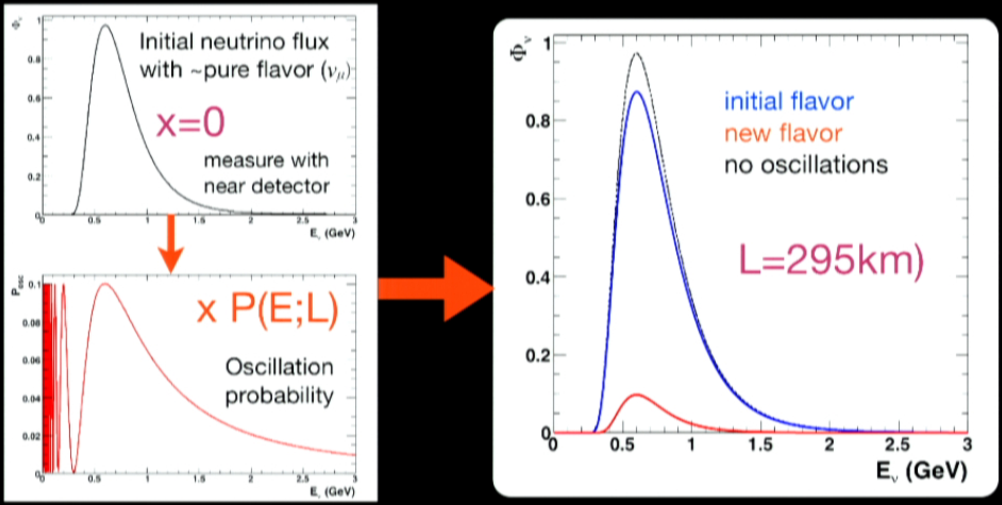


- Time evolution: component of another flavor may be acquired

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \; & \delta_{\alpha\beta} \\ & -4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] \\ & +2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\;[2.54\Delta m^2_{ij}(L/E)] \end{aligned}$$

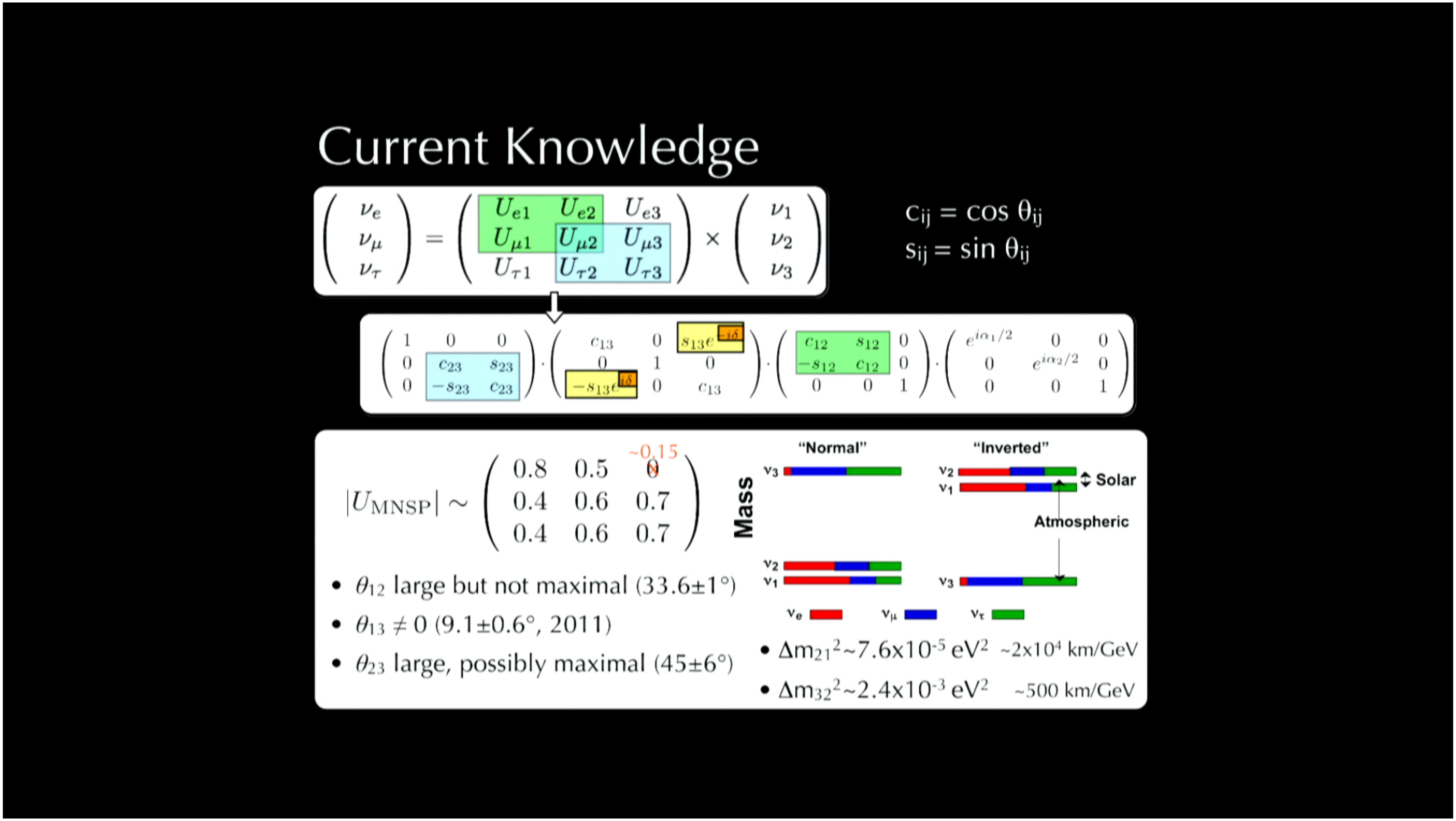
- Flavor composition varies sinusoidally as neutrino traverse space/time
  - "neutrino oscillations" with L/E as "phase"
- Amplitudes determined by mixing matrix U_{ij}
- Wavelengths determined by mass^2 differences Δm^2_{ij}

Measuring Oscillations



- Magnitude of disappearance/appearance
  - ➡ θ_{ij}: mixing angles governing amplitudes
- Energy of maximum oscillation probability
  - ➡ Δm^2_{ij}: measures the first maximum in L/E

Simple two
flavor model



Current Knowledge

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

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \cdot \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \cdot \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \cdot \begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

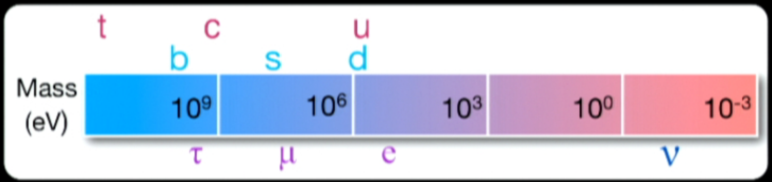
$$|U_{\mathrm{MNSP}}| \sim \begin{pmatrix}0.8 & 0.5 & \overset{\sim 0.15}{\cancel{0}}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}$$

- θ_{12} large but not maximal (33.6±1°)
- $\theta_{13} \neq 0$ (9.1±0.6°, 2011)
- θ_{23} large, possibly maximal (45±6°)

- $\Delta m_{21}^2 \sim 7.6\times10^{-5}$ eV^2 ~2x10^4 km/GeV
- $\Delta m_{32}^2 \sim 2.4\times10^{-3}$ eV^2 ~500 km/GeV

Scientific Opportunities

$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix} \quad |U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



- What determines the pattern of:
  - mixing in quarks and leptons?
  - masses in quarks and leptons?
- For neutrino oscillations:
  - precise measure of parameters
  - determine the mass hierarchy
  - search for CP violation . .

How to make a matter universe

- Baryon number violation
  - current universe reflects a state of baryon number asymmetry. Baryon number violation is needed to depart from B=0
- C-symmetry and CP-symmetry violation
  - process and its CP conjugate (anti-matter counterpart) differ in rate.

$$\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})$$

- Departure from thermal equilibrium.
  - prevent asymmetry from being washed out by reverse process (chemical equilibrium)

Andrei Sakharov
Physicist and Dissident
(Nobel Peace Prize 1975)

(Anti)-matter in the universe

Slate

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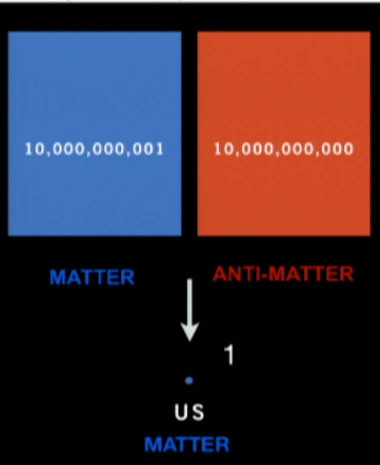
HOME / SCIENCE : THE STATE OF THE UNIVERSE

Four Reasons You Shouldn't Exist

Physics says you're an impurity in an otherwise beautiful universe.

By Dave Goldberg | Posted Thursday, Aug. 29, 2013, at 1:24 PM



"Amid perfect cosmic symmetry, there's us."

- We know more about the matter-antimatter asymmetry of the universe
  - matter/anti-matter were created and annihilated equally to 1 part in ~10^{10}
  - What remained from this tiny imbalance is the matter in the universe as we know it.
- The challenge is to quantitatively explain this imbalance

CP Violation

- Kobayashi/Maskawa: to support a CP-odd phase in the mixing, at least three generations are needed.
  - proposed to explain CP violation in the quarks.
  - Now fully verified in quark sector
- If there were only two generations, CPV is not possible in weak interactions.

- Is this the CP violation needed by Sakharov?
  - It appears that the quark sector CP violation is insufficient . . .
    - fails to produce the necessary asymmetry by many orders of magnitude
  - We do not know if there is CP violation in neutrino oscillations
    - however, “this” CPV cannot directly be responsible . . . .
    - the theory of leptogenesis connects neutrinos to heavy particles whose CPV decays may be responsible for the primordial asymmetry

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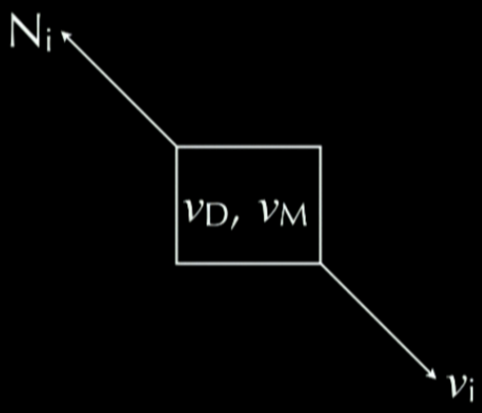
The See-Saw and Leptogenesis

$$\boxed{\nu_{\mathrm{D}},\ \nu_{\mathrm{M}}}$$

- Unlike quarks, neutrinos can have two forms of mass:
  - “Dirac”: neutrino/anti-neutrino are distinct particles
  - “Majorana”: neutrino is self-conjugate (neutrino is its own antiparticle)

The See-Saw and Leptogenesis



$m_N \sim m_M$ N_i

ν_D, ν_M

ν_i $m_\nu \sim m_D^2/m_M$

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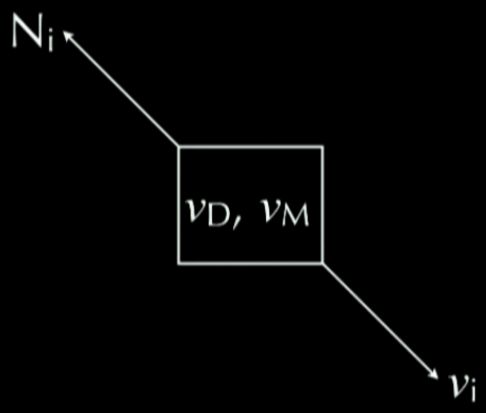

$m_N \sim m_M$ N_i

ν_D, ν_M

$m_\nu \sim 0.01$ eV
$m_D \sim m_{EW}$
$\Rightarrow m_M \sim 10^{15}$ GeV

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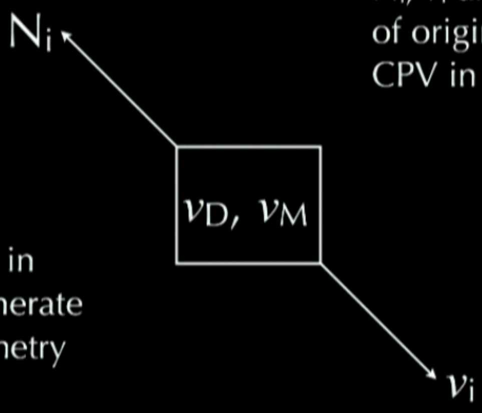
The See-Saw and Leptogenesis



$m_N \sim m_M$

$m_N \sim 10^{15}$ GeV
$\sim m_{GUT}$

CPV decays of N_i in
early universe generate
primordial asymmetry

N_i

$\nu_D,\ \nu_M$

ν_i

N_i, ν_i are Majorana eigenstates
of original mass matrix
CPV in ν_i is related to CPV in N_i

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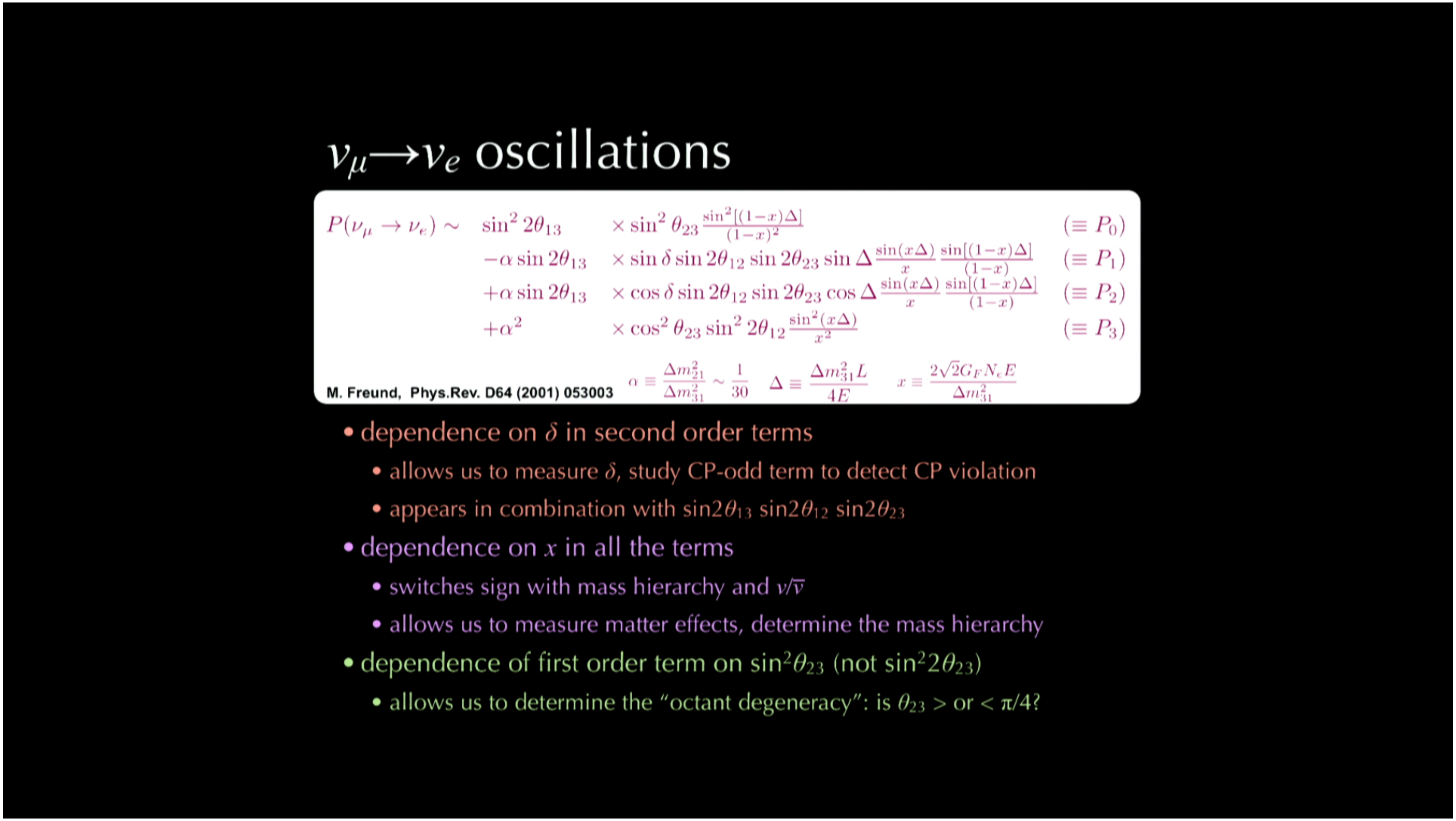
Neutrino oscillations in the three flavor era

Two-Flavors:

- In a past era (i.e. ~last year), we could work with the following:
- "ν_μ disappearance"
  - $P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \Delta m^2_{32}(L/4E)$
- "ν_e appearance"
  - $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta m^2_{32}(L/4E)$
- Now with:
  - with increasing precision in all oscillation parameters
  - knowledge of θ_{13} is not zero (and not very small)
- we need to work with more precise formulas
  - these formulas involve more oscillation parameters
    - including matter effects on neutrino oscillations
  - two-flavor model → three flavor model



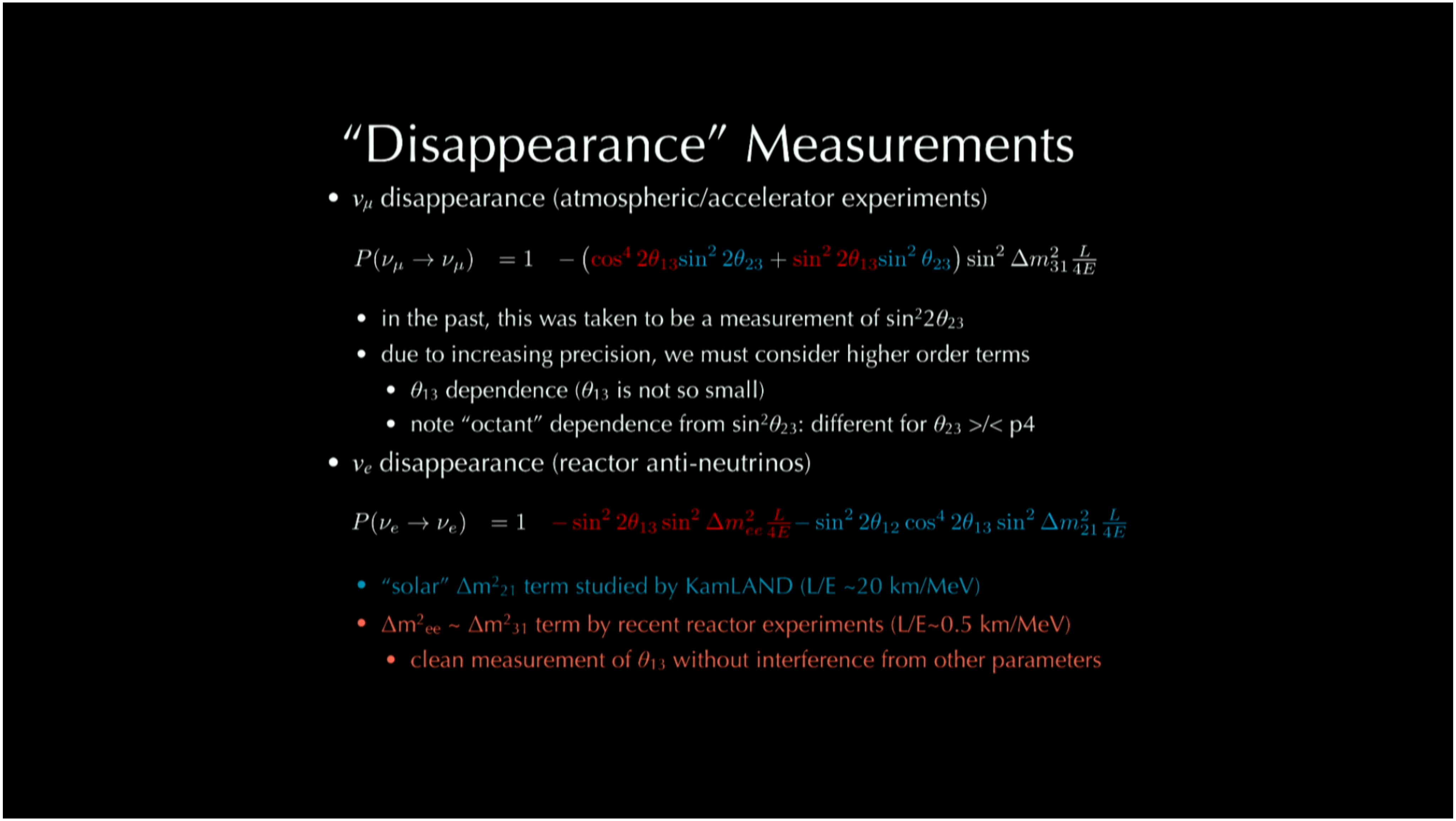
$\nu_\mu \longrightarrow \nu_e$ oscillations

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim \quad & \sin^2 2\theta_{13} && \times \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} && (\equiv P_0) \\
& -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_1) \\
& +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_2) \\
& +\alpha^2 && \times \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} && (\equiv P_3)
\end{aligned}
$$

M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \quad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

- dependence on δ in second order terms
  - allows us to measure δ, study CP-odd term to detect CP violation
  - appears in combination with $\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$
- dependence on x in all the terms
  - switches sign with mass hierarchy and $\nu/\overline{\nu}$
  - allows us to measure matter effects, determine the mass hierarchy
- dependence of first order term on $\sin^2\theta_{23}$ (not $\sin^2 2\theta_{23}$)
  - allows us to determine the "octant degeneracy": is $\theta_{23} >$ or $< \pi/4$?



"Disappearance" Measurements

- ν_μ disappearance (atmospheric/accelerator experiments)

$$P(\nu_\mu \to \nu_\mu) \quad = 1 \quad - \left(\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}\right) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

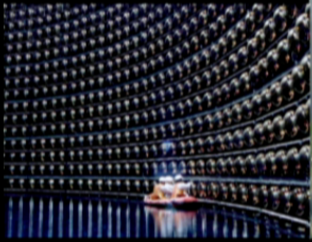
  - in the past, this was taken to be a measurement of $\sin^2 2\theta_{23}$
  - due to increasing precision, we must consider higher order terms
    - θ_{13} dependence (θ_{13} is not so small)
    - note "octant" dependence from $\sin^2\theta_{23}$: different for θ_{23} >/< p4
- ν_e disappearance (reactor anti-neutrinos)

$$P(\nu_e \to \nu_e) \quad = 1 \quad - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{ee} \frac{L}{4E} - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \Delta m^2_{21} \frac{L}{4E}$$

  - "solar" Δm^2_{21} term studied by KamLAND (L/E ~20 km/MeV)
  - Δm^2_{ee} ~ Δm^2_{31} term by recent reactor experiments (L/E~0.5 km/MeV)
    - clean measurement of θ_{13} without interference from other parameters

T2K

Super Kamiokande
“far” detector



ND280
“near” detector

J-PARC

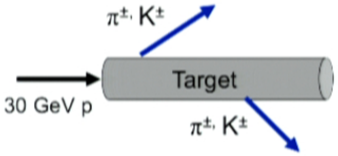
~500 collaborators from
58 institutions, 12 nations

Intense ~600 MeV ν_μ beam for neutrino oscillation studies

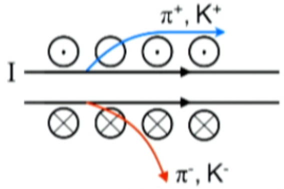
- $\nu_\mu \longrightarrow \nu_e$ oscillations to probe θ_{13}
- Precision measurement of θ_{23}, Δm^2_{32}

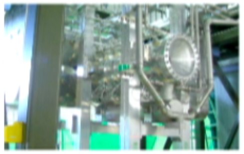
see “T2K Experiment”
arXiv:1106.1238 submitted to NIM A

Neutrino Beam



Proton-Carbon interactions produce secondary particles, in particular pions, kaons



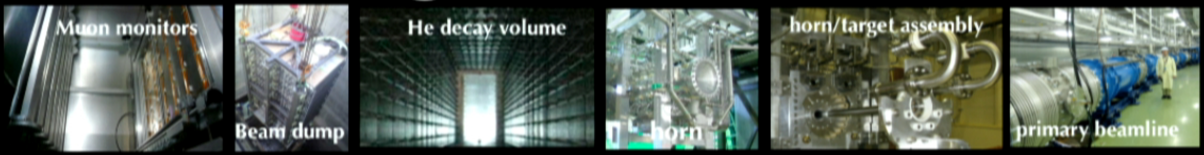


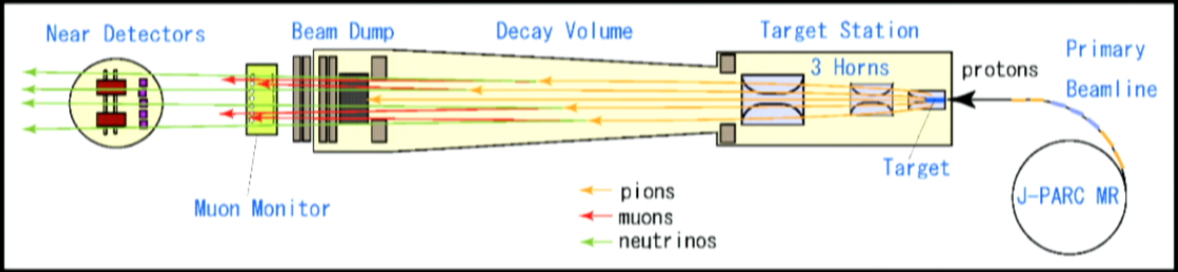
250 kA pulse in 3 “horns” produces toroidal magnetic field to focus positive particles

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \nu_\mu + e^+ + \nu_e$$
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

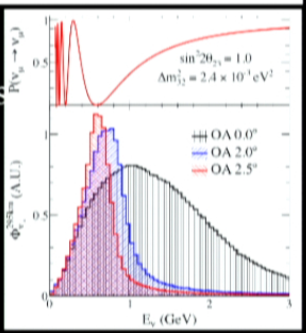
Particles enter a 100 m decay region where they produce neutrinos. Absorber terminates particles other than neutrinos

Producing ν_μ beam





- 30 GeV protons extracted from J-PARC MR a target
  - secondary π^+ focussed by three electromagnetic horns
  - primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - **Also:** ν_e from μ decay, high energy ν_μ/ν_e from K decay
  - spectrum peaked at 600 MeV
    - expected oscillation "maximum" for L=295 km



Analysis Strategy

Far (θ_{ij}, Δm^2_{ij})
$\nu_\mu \rightarrow \nu_e$ (θ_{23}, θ_{13})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ (θ_{23}, Δm^2_{32})
ν_μ, ν_e backgrounds

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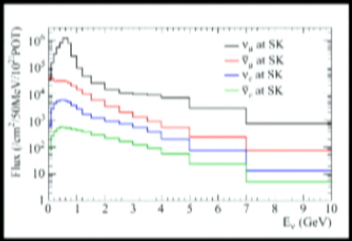
ν_μ, ν_e backgrounds

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

φ_ν



MC simulation of neutrino
beamline tuned with external
data + operational parameters

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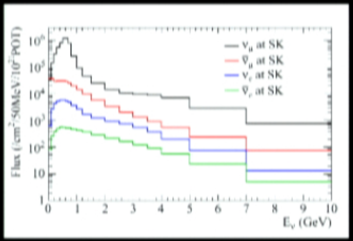
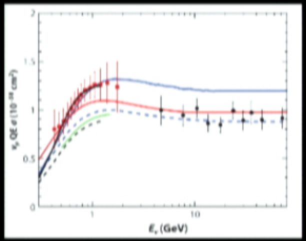


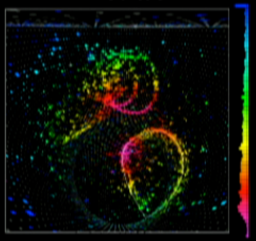
MC simulation of neutrino beamline tuned with external data + operational parameters

σ_ν



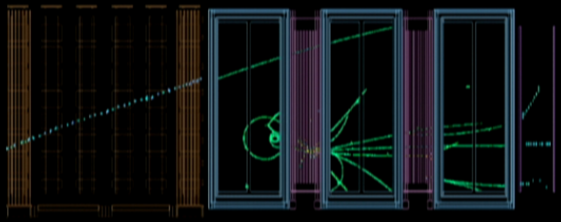
Neutrino cross section and interaction model tuned to external measurements

ε_{FAR}



Detector simulation to determine efficiencies/ backgrounds

Analysis Strategy



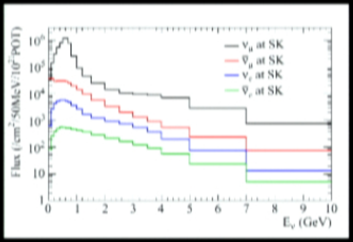
Near detector observes the same neutrinos prior to neutrino oscillations

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{\mathrm{NEAR}}$

Far $(\theta_{ij}, \Delta m^2_{ij})$
$\nu_\mu \rightarrow \nu_e$ $(\theta_{23}, \theta_{13})$
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ $(\theta_{23}, \Delta m^2_{32})$
ν_μ, ν_e backgrounds

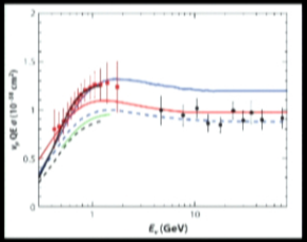
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{\mathrm{FAR}} \cdot P_{\mathrm{osc}}$

φ_ν



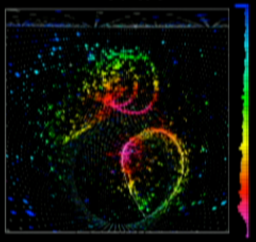
MC simulation of neutrino beamline tuned with external data + operational parameters

σ_ν



Neutrino cross section and interaction model tuned to external measurements

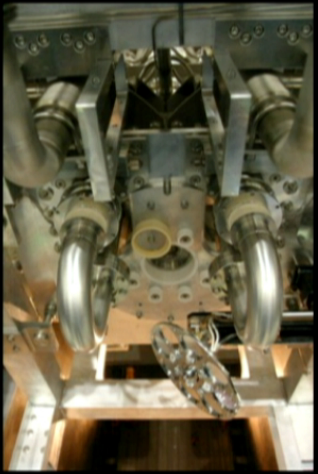
$\varepsilon_{\mathrm{FAR}}$

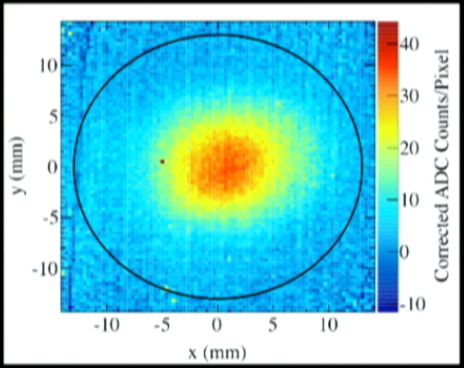


Detector simulation to determine efficiencies/ backgrounds

Extreme Science:

- Neutrino cross section at 1 GeV ~10^{-38} cm^2
  - Interaction length in Pb = $1/n\sigma$ ~1 light year
    - 1 GeV photon: conversion length ~1 cm
- Number of events = N(targets) σ(cm^2) ϕ(ν/cm^2)
  - σ is more or less immutable
  - N: bigger detector O(kilo-megaton)
  - **ϕ: intense beam: O(megawatt) proton beam**





- At design intensity, 2×10^{14} 30 GeV protons strike the target every 2-3 seconds
  - 1MJ in 5 μsec (1/4 kg of TNT)
- Optical Transition Radiation (OTR) monitor developed/built at York to monitor protons in its "final approach" to the target

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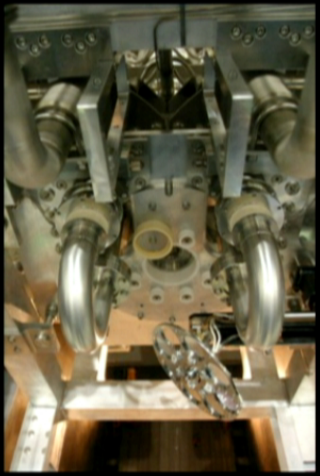

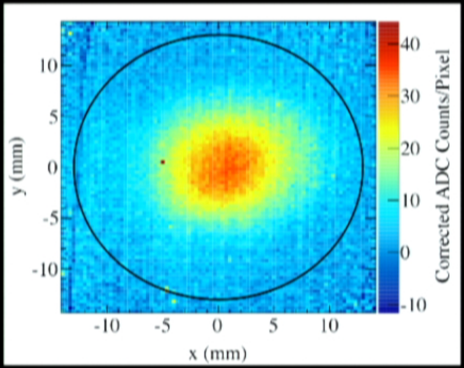

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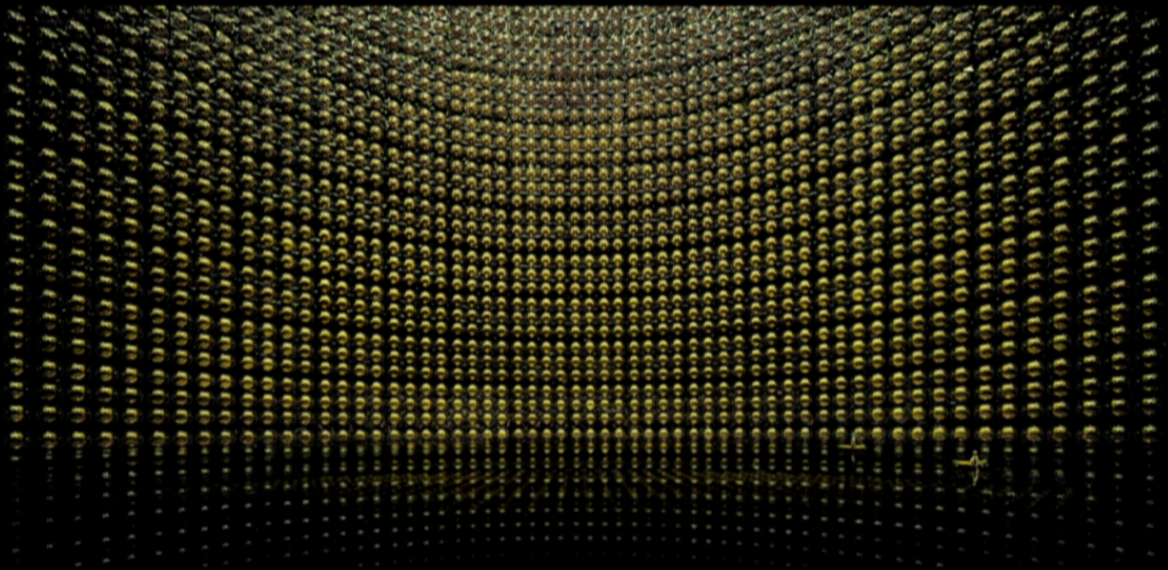


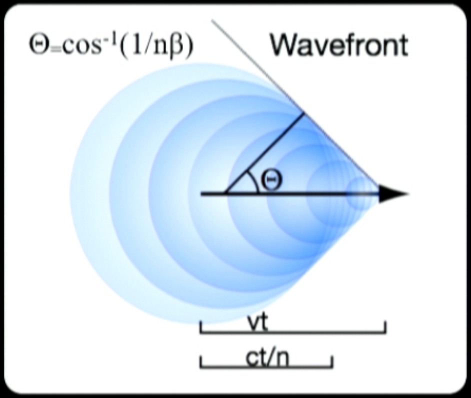
Events = N(targets) $\sigma(\mathrm{cm}^2)$ $\phi(\nu/\mathrm{cm}^2)$

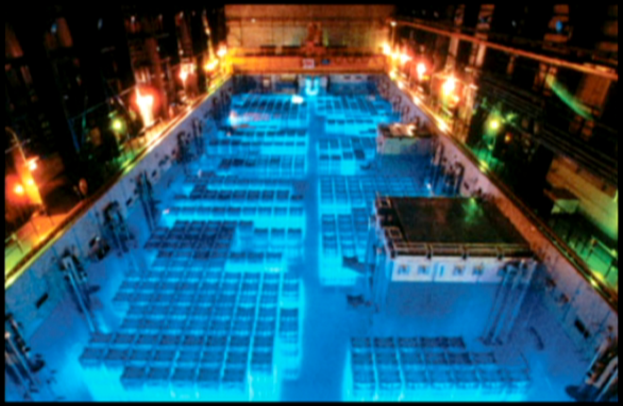
- σ is more or less immutable
- **N: bigger detector O(kilo-megaton)**
- ϕ:intense beam:

Super-Kamiokande:

- 50 (22.5 FV) kT water C detector
- 40 m diameter x 40 m height
- 11146 20″ photomultiplier tubes

Cherenkov Radiation

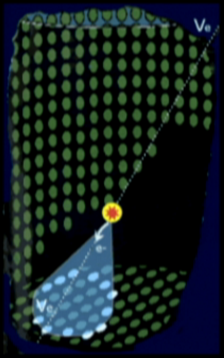




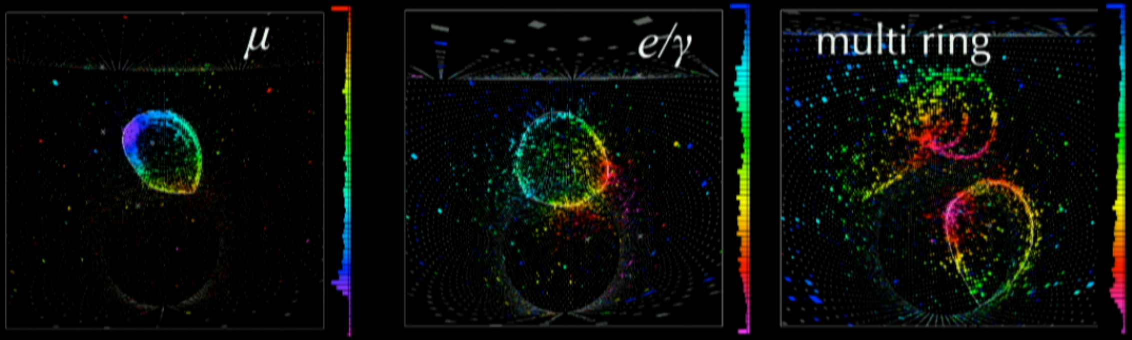
EM radiation emitted in when a charged particle exceeds velocity of light in a dielectric medium

- optical analog of "sonic boom"
    - blue-shifted optical light $(1/\lambda^2)$
- For water, $n \sim 1.33$
    - "threshold" for Č radiation is $0.75\,c$
    - $\Theta \sim 42°$ for $v \sim c$

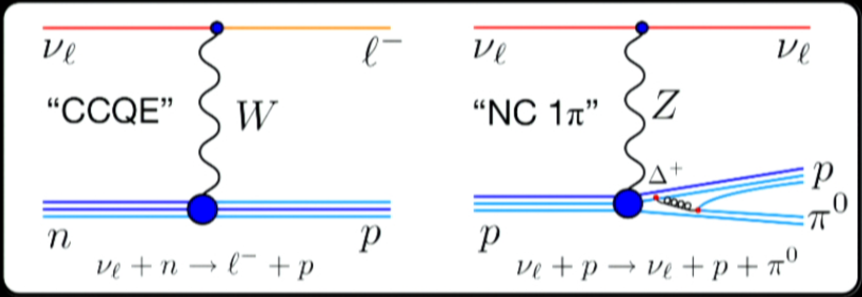
Detection Principle:

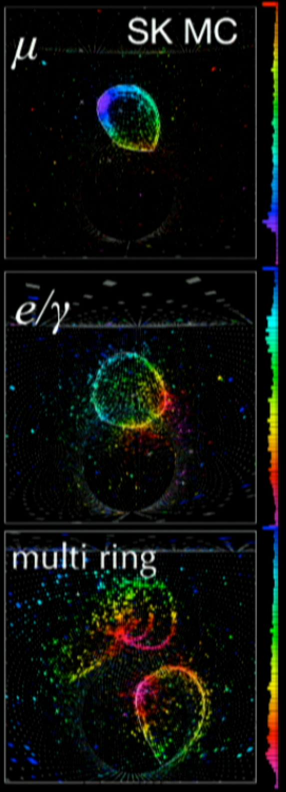


- Minimum-ionizing particles (e.g. μ) travel along a ~straight line, emitting a cone of Č light
- e/γ: shower produces e^+/e^- producing Č light.
  - e/γ are effectively indistinguishable
- Multiple particles detected by finding their rings



Neutrino Interactions





$\nu_\ell + n \rightarrow \ell^- + p$ **Signal**

- Appears as single μ/e-like ring
- E_ν by energy/direction of ring relative to beam
  - assumes CCQE kinematics

$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$ **Backgrounds**

$\nu_\ell + (n/p) \rightarrow \ell^- + (n/p) + \pi$

- $\pi^0 \rightarrow \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
- μ/π^+: ring counting, decay electron cut

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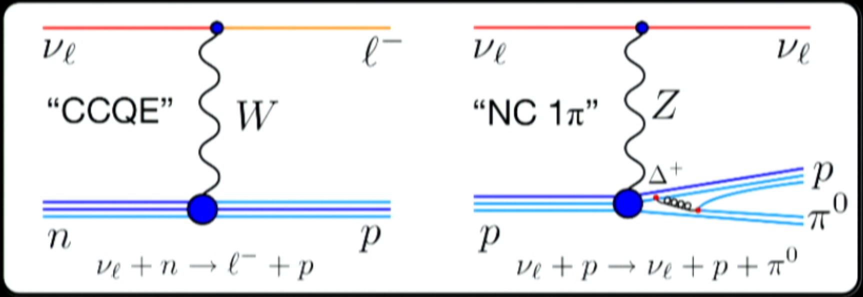
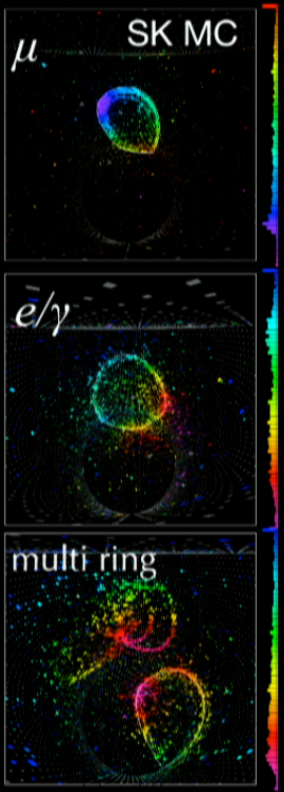


$\nu_\ell + n \to \ell^- + p$

$\nu_\ell + p \to \nu_\ell + p + \pi^0$



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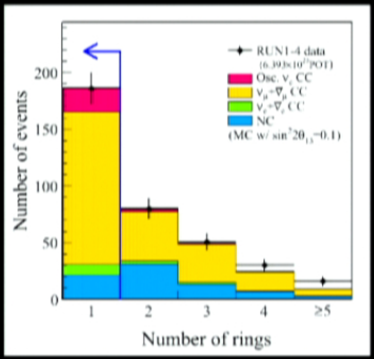
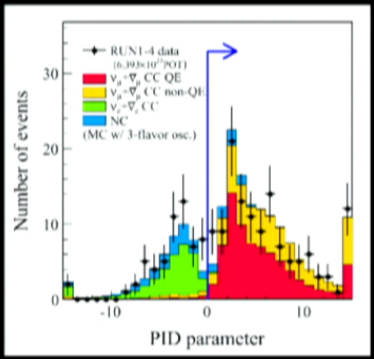
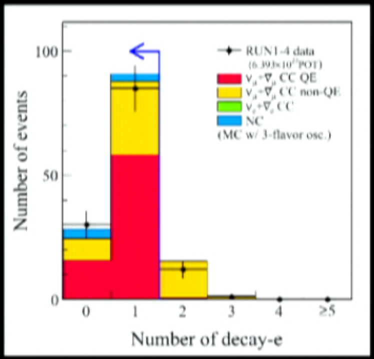
ν_μ events:



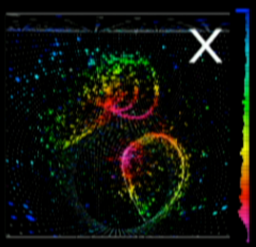
Count rings and select single ring events (1R)

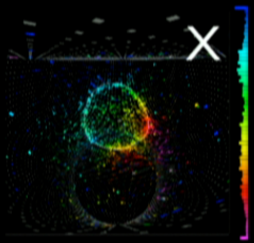


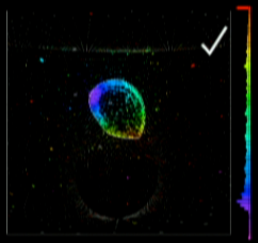
Use ring sharpness to select μ-like rings



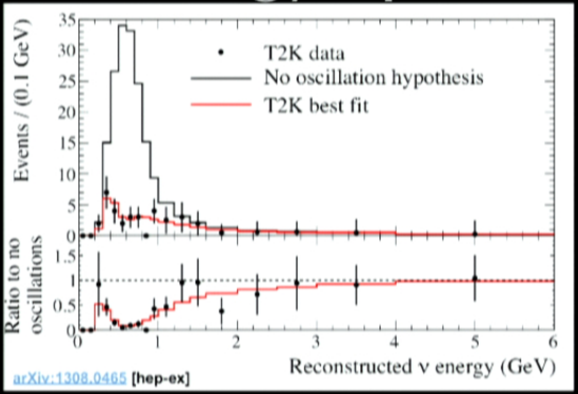
No more than one decay electron from $(\pi) \rightarrow \mu \rightarrow e$



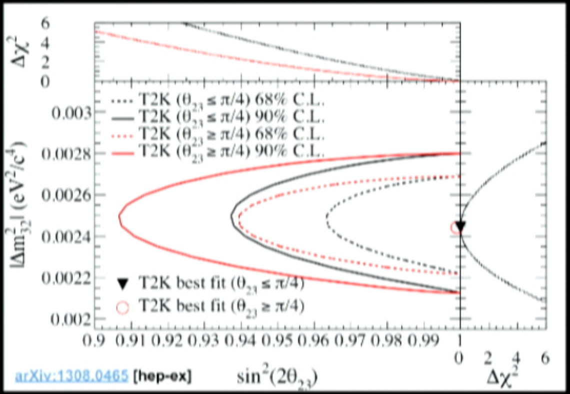




ν_μ Energy Spectrum and fit



arXiv:1308.0465 [hep-ex]

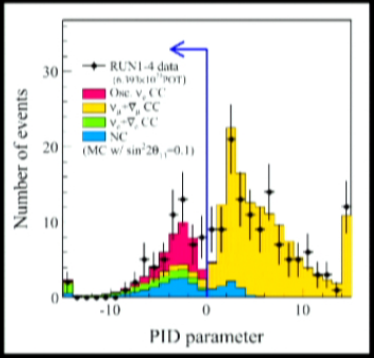


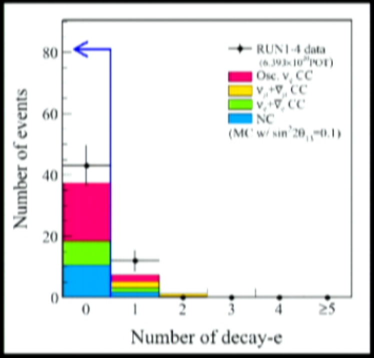
arXiv:1308.0465 [hep-ex]

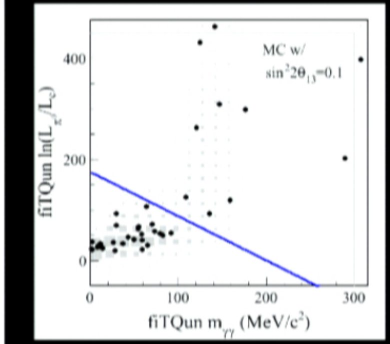
$$P(\nu_\mu \to \nu_\mu) = 1 - \left(\cos^4 2\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2 \theta_{23}\right) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

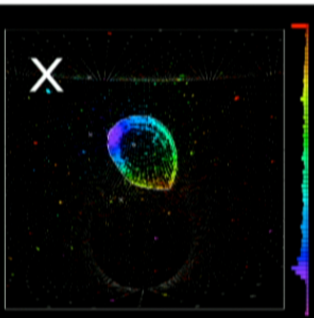
- Higher precision means we must consider higher order terms
  - θ_{13}: now known to be not so small! $\sin^2\theta_{13} \sim 0.03$
  - θ_{23}: sensitive to “octant”: is θ_{23} less/greater than 45°
    - maximal ν_μ disappearance is not at θ_{23} =45°
- One of the strongest experimental constraints on θ_{23} to date
  - will continue to significantly improve with more T2K data

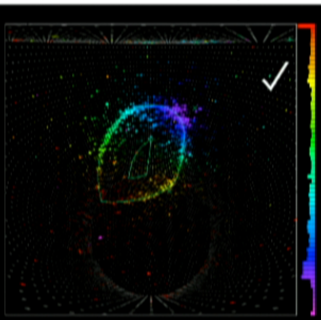
ν_e events

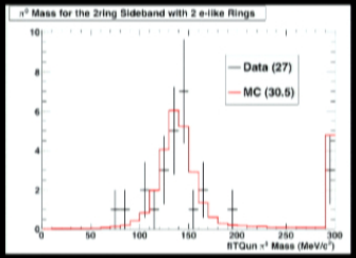










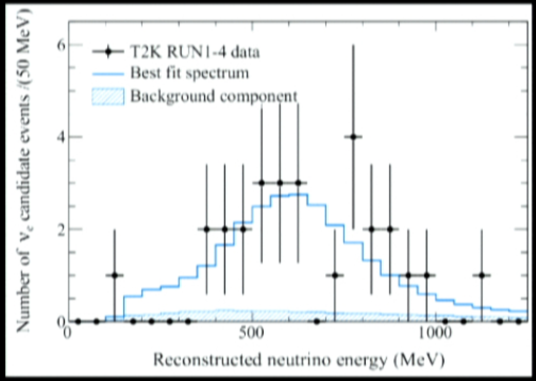


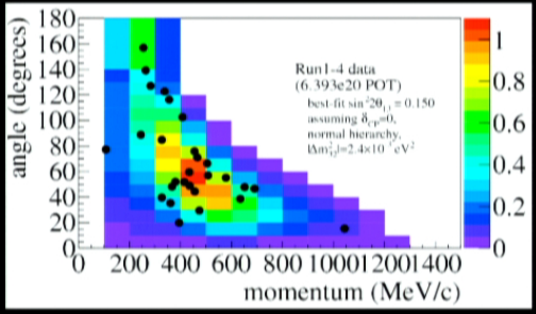
select single e-like rings with no decay electrons

additional π^0 rejection with
2 ring reconstruction

Refining ν_e selection

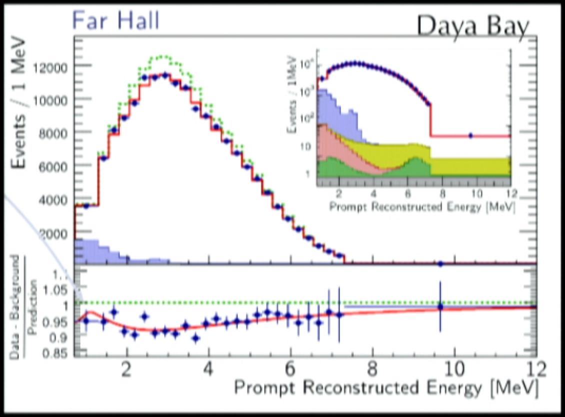
	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
$\nu_\mu \rightarrow \nu_e$	0.38	16.42
ν_e bkg.	3.17	2.93
ν_μ bkg	0.89	0.89
$\bar{\nu}_\mu$, $\bar{\nu}_e$ bkg	0.20	0.19
Total (%err)	4.6 (11.1%)	20.4 (8.8%)

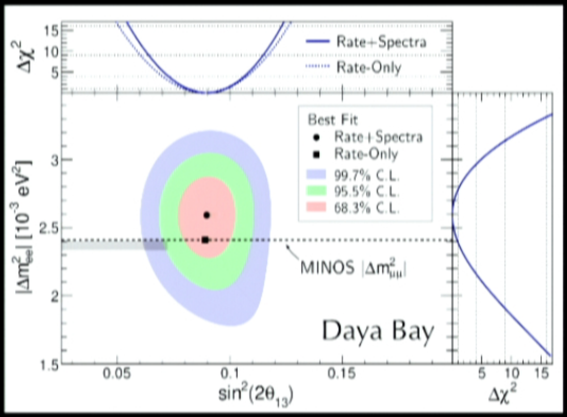




- 28 ν_e candidates observed
  - 7.4 σ excess of ν_e candidates consistent with $\nu_\mu \rightarrow \nu_e$ oscillations
  - **first definitive observation of new neutrino flavor explicitly detected in a beam initially of a different flavor**

Reactor θ_{13} measurements





$$P(\nu_e \to \nu_e) \;\; = 1 \;\; - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{ee} \frac{L}{4E}$$

$$- \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \Delta m^2_{21} \frac{L}{4E}$$

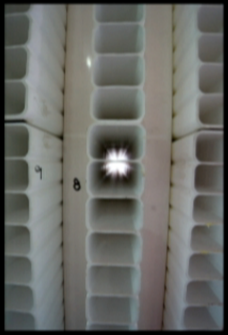
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009} \qquad \Delta m^2_{ee} = (2.59^{+0.19}_{-0.20}) \times 10^{-3}\mathrm{eV}^2/c^4$$

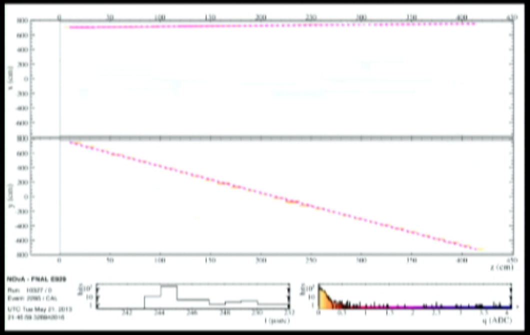
$$= 0.113 \pm 0.013(\mathrm{stat.}) \pm 0.019(\mathrm{sys.}) \quad \text{RENO}$$

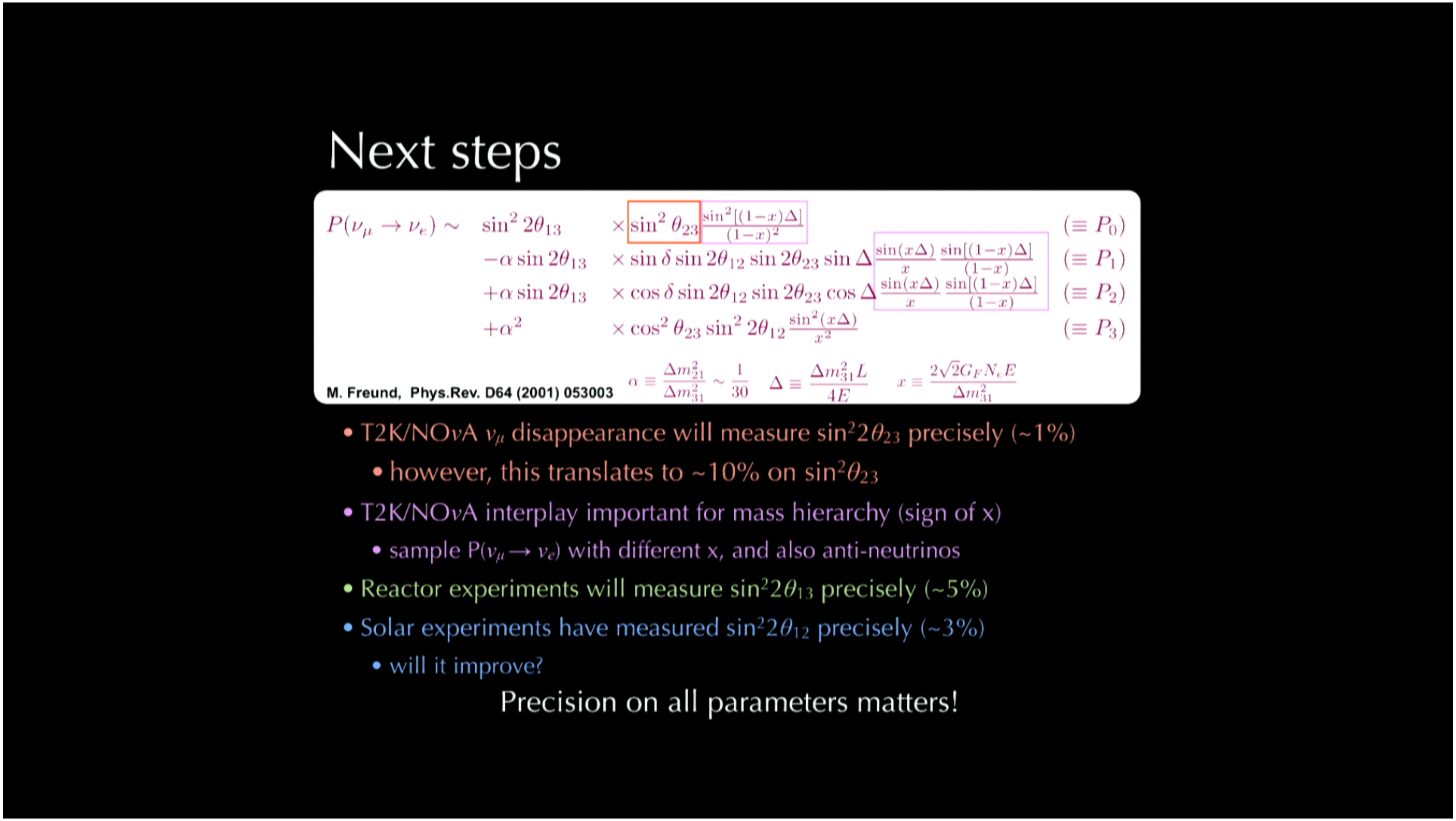
$$= 0.109 \pm 0.030(\mathrm{stat.}) \pm 0.025(\mathrm{sys.}) \quad \text{Double Chooz}$$

NOνA

- "Similar" long baseline experiment to T2K
  - 832 km baseline, 2 GeV neutrino energy
  - enhanced matter effects relative to T2K
    - x ~ 0.2 compared to 0.05 for T2K
  - Long extruded scintillator cells provide 3D tracking. Detector partially operational
  - FNAL beam operations starting after major upgrade







Next steps

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} && \times \boxed{\sin^2\theta_{23}}\,\boxed{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} && (\equiv P_0) \\ & -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_1) \\ & +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} && (\equiv P_2) \\ & +\alpha^2 && \times \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} && (\equiv P_3) \end{aligned}$$

M. Freund, Phys.Rev. D64 (2001) 053003 $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30}$ $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$ $x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$

- T2K/NOνA ν_μ disappearance will measure $\sin^2 2\theta_{23}$ precisely (~1%)
  - however, this translates to ~10% on $\sin^2\theta_{23}$
- T2K/NOνA interplay important for mass hierarchy (sign of x)
  - sample P($\nu_\mu \to \nu_e$) with different x, and also anti-neutrinos
- Reactor experiments will measure $\sin^2 2\theta_{13}$ precisely (~5%)
- Solar experiments have measured $\sin^2 2\theta_{12}$ precisely (~3%)
  - will it improve?

Precision on all parameters matters!

Next steps

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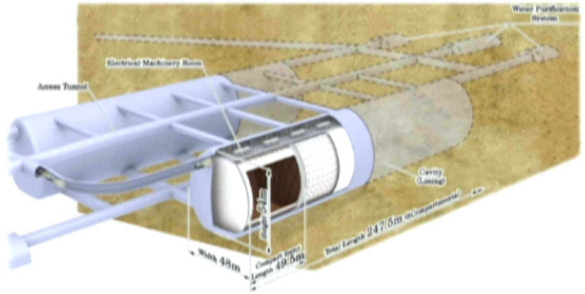
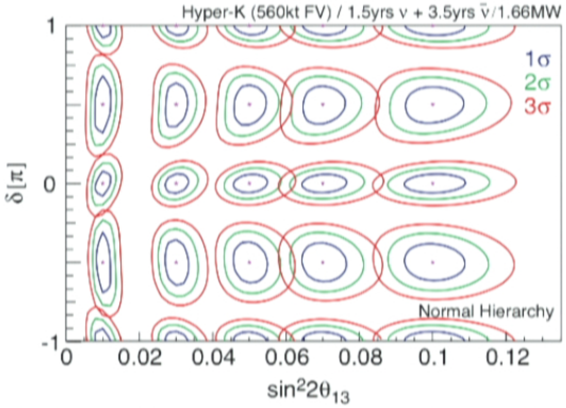
Towards CPV





- Hyper-Kamiokande
  - 1 Megaton of water with ~100k photosensors
    - ~20x upgrade of SK
  - upgrade to J-PARC neutrino beam also proposed
    - 700 kW → 1.66 MW
  - situated near the current SK site in the T2K beam
- Preparing major contribution in Canada as a continuation of T2K

Beyond Neutrino Oscillations:

$m_N \sim m_M$

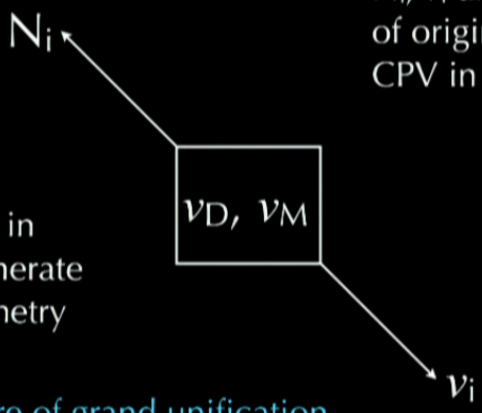
$m_N \sim 10^{15}$ GeV

$\sim m_{GUT}$

CPV decays of N_i in early universe generate primordial asymmetry

proton decay:

definitive signature of grand unification



N_i, ν_i are Majorana eigenstates of original mass matrix

CPV in ν_i is related to CPV in N_i

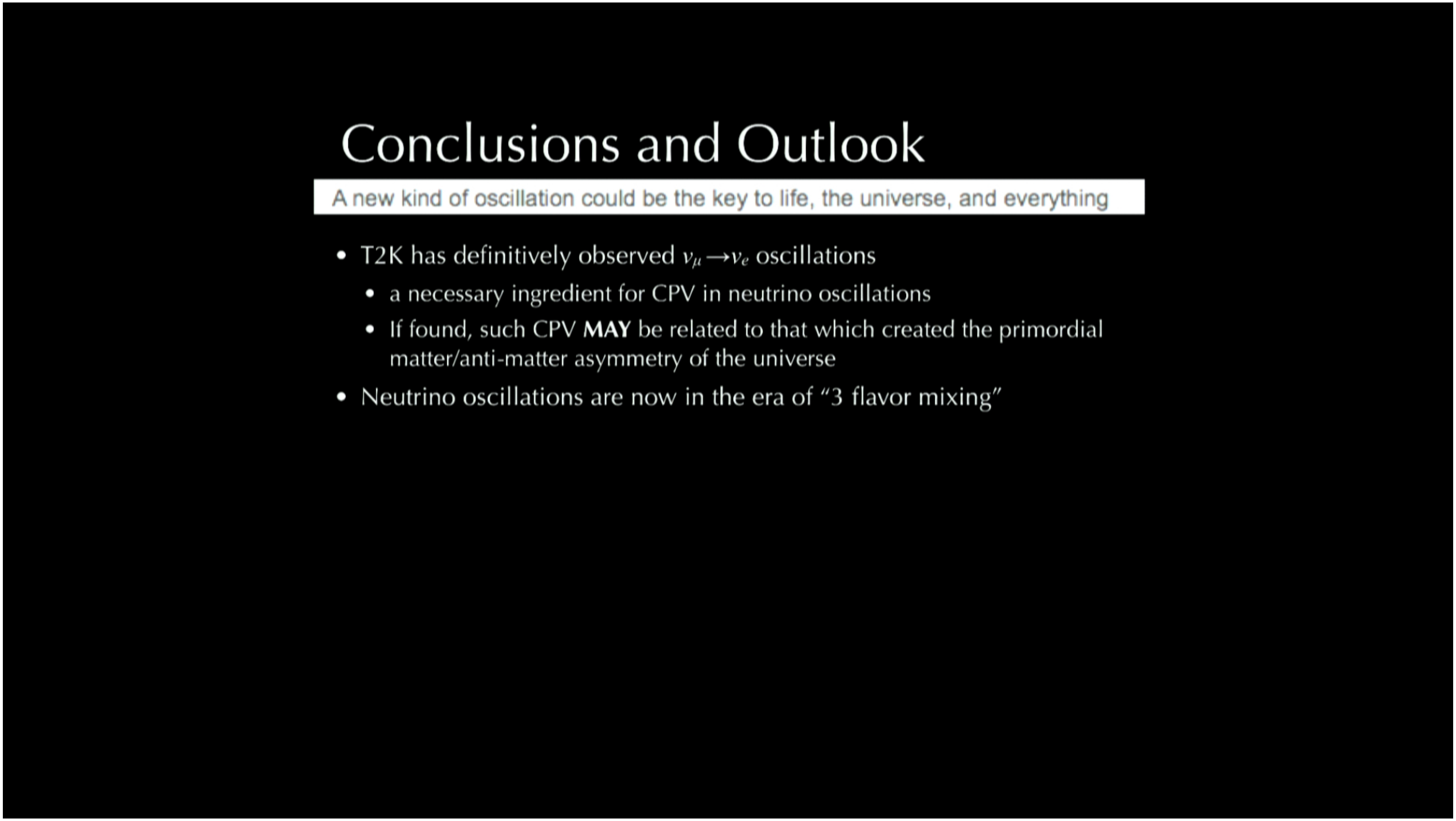
$m_\nu \sim 0.01$ eV

$m_D \sim m_{EW}$

$\Rightarrow m_M \sim 10^{15}$ GeV

$m_\nu \sim m_D^2/m_M$

- In addition to a leap in CPV sensitivity and precision in neutrino oscillation mixing parameters
  - an order of magnitude in gain sensitivity for proton decay
  - can detect neutrinos from supernovae as far away as M31

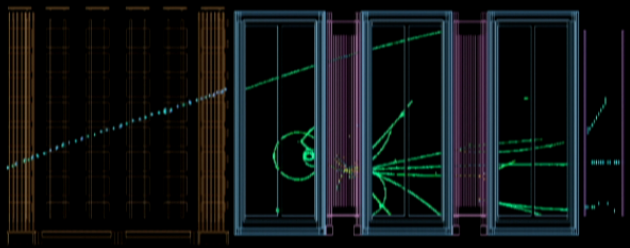


Conclusions and Outlook

A new kind of oscillation could be the key to life, the universe, and everything

- T2K has definitively observed $\nu_\mu \rightarrow \nu_e$ oscillations
  - a necessary ingredient for CPV in neutrino oscillations
  - If found, such CPV **MAY** be related to that which created the primordial matter/anti-matter asymmetry of the universe
- Neutrino oscillations are now in the era of “3 flavor mixing”

Near Detector ν_μ



- ν_μ CC selected in ND280 tracker with
  - negative μ track in downstream TPC
  - vertex in FGD1, no upstream TPC track
- CC0π/CC1π/CCNπ categories
  - additional track(s) in TPC
  - decay electron in FGD1 ($\pi \rightarrow \mu \rightarrow e$)
- Yields in p/θ bins input into fit to constrain flux/neutrino interaction systematic error
  - error on extrapolated far detector rate reduced from 28.1% to 8.8%