H. A. TANAKA

NEUTRINOS (ν):

THE DESPERATE REMEDY

Colloquium, Queen's University
20 November, 2015

SUPPOSE I HAVE A CHAIR:

source unknown . . . .
possibly “Москва-петушки”
Moscow to the End of the Line
by Venedikt Yerofeyev

SUPPOSE I HAVE A CHAIR:

- it doesn’t have arms . . . .

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SUPPOSE I HAVE A CHAIR:

- it doesn’t have arms . . . .
- nor does it have a back . . . . .

source unknown . . . .
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SUPPOSE I HAVE A CHAIR:

- it doesn't have arms . . . .
- nor does it have a back . . . . .
- it also doesn't have legs . . . . .

source unknown . . . .
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SUPPOSE I HAVE A CHAIR:

- it doesn't have arms . . . .
- nor does it have a back . . . . .
- it also doesn't have legs . . . . .
- oh, and it doesn't have a seat . . . .

source unknown . . . .
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- it doesn't have arms . . . .
- nor does it have a back . . . . .
- it also doesn't have legs . . . . .
- oh, and it doesn't have a seat . . . .

"at some point you wonder
if I have anything at all . . . "

source unknown . . . .
possibly "Москва-петушки"
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SUPPOSE I HAVE A PARTICLE . . .

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- It doesn't have any electric charge . . . . . .

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- It doesn’t have any electric charge . . . . . .
- It doesn’t experience the strong interaction . . . .

SUPPOSE I HAVE A PARTICLE . . .

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- It doesn't experience the strong interaction . . . .
- It may have no mass . . . . . .

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- It interacts so feebly that it can pass through 10^{10} m lead

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- It interacts so feebly that it can pass through 10^{10} m lead
- and yet . . . . . .

SUPPOSE I HAVE A PARTICLE . . .

- It doesn't have any electric charge . . . . . .
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- It interacts so feebly that it can pass through 10^{10} m lead
- and yet . . . . . .
    - it is a fundamental constituent of the universe

SUPPOSE I HAVE A PARTICLE . . .

- It doesn't have any electric charge . . . . . .
- It doesn't experience the strong interaction . . . .
- It may have no mass . . . . . .
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- and yet . . . . . .
  - it is a fundamental constituent of the universe
  - it is produced copiously and omnipresent

SUPPOSE I HAVE A PARTICLE . . .

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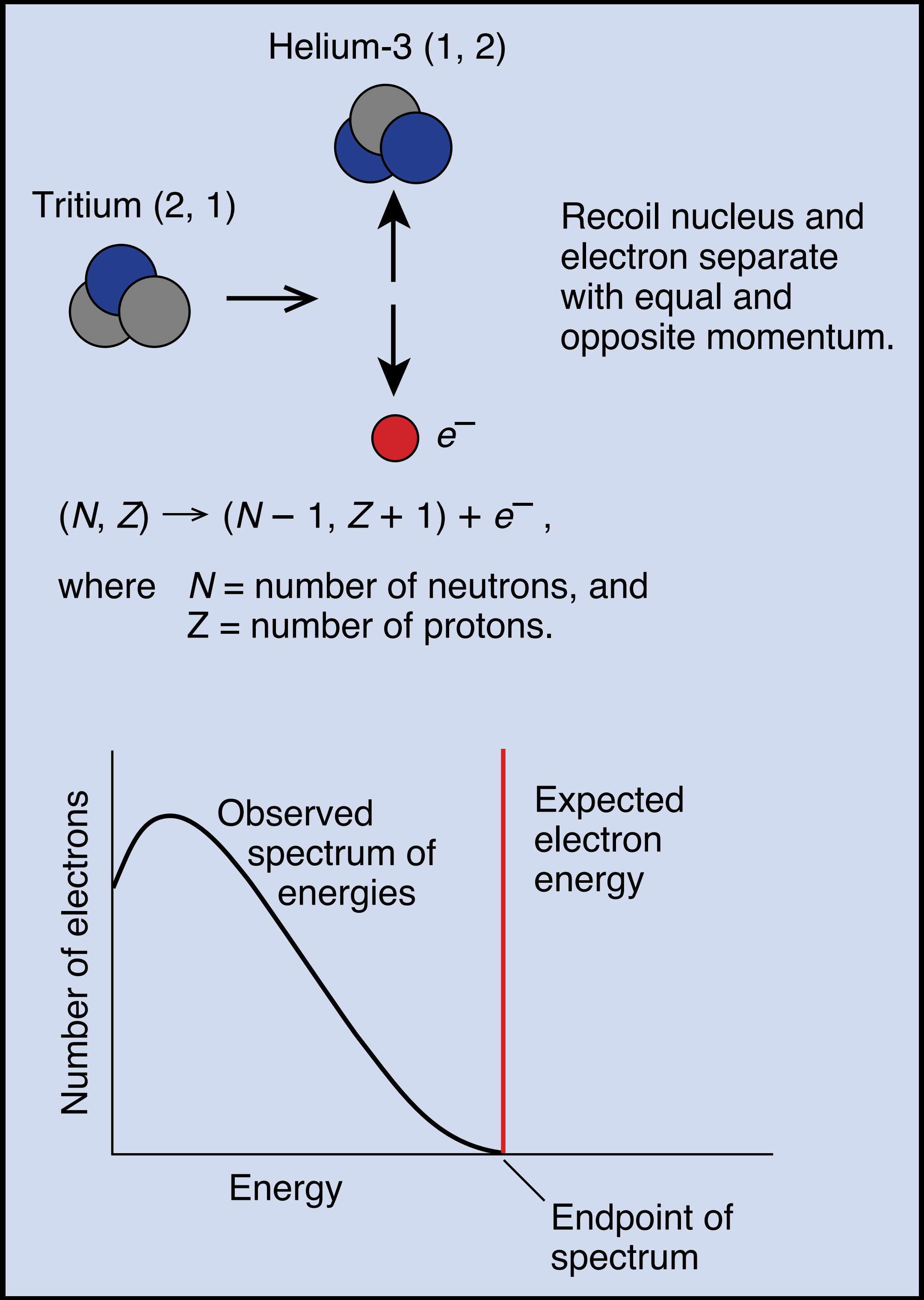
- It may have no mass . . . . . .
- It interacts so feebly that it can pass through 10^{10} m lead
- and yet . . . . . .
  - it is a fundamental constituent of the universe
  - it is produced copiously and omnipresent
  - it plays a critical role in the evolution of the universe, the burning of stars, the explosion of a supernovae, etc.

CONSERVATION CRISIS:



from Los Alamos Science

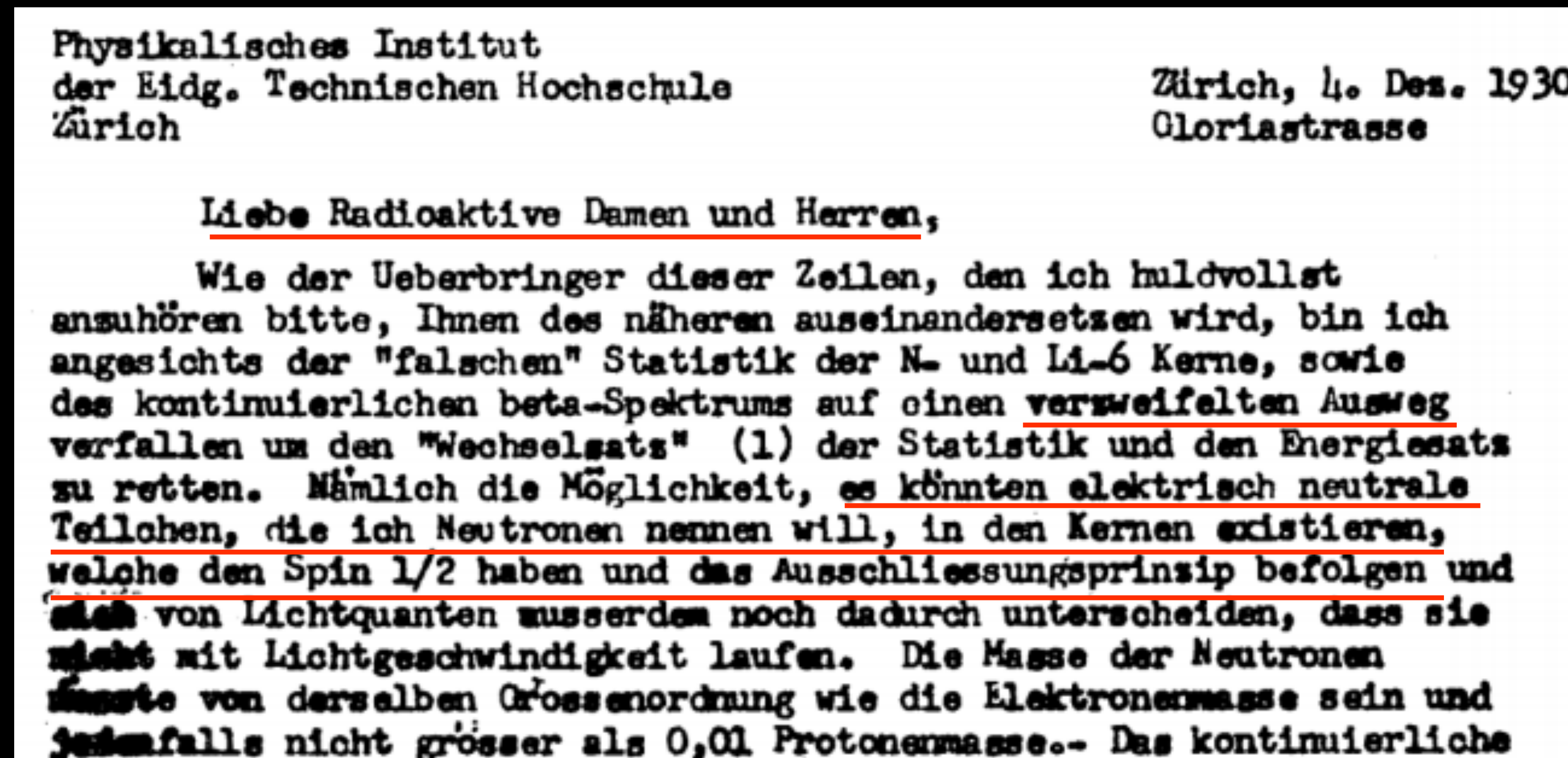
APS photo archive

- β decay: nucleus decays into an e + another nucleus
- energy spectrum of electron appears to be continuous (Hahn, Meitner)
- N. Bohr: "no evidence either empirical or theoretical" exists for energy conservation in the nucleus.

DEAR RADIOACTIVE LADIES AND GENTLEMEN:

APS photo archive

"Copenhagen spin crisis of 1930"



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören 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 "Wechselsats" (1) der Statistik und den Energiesats su 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 Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche

- "a desperate remedy":
  - a neutral, spin 1/2 particle exists within the nucleus
- As it turns out, there are two particles (E. Fermi)
  - spin-statistics → "neutron" bound in nucleus
  - energy conservation→ "neutrino" emitted in β decay

$$n \to p + e + \bar{\nu}_e$$

APS photo archive

PAULI'S PROBLEM CHILD

Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

APS photo archive

- "Thus, dear radioactives, **examine and judge . . . .**"
- The "neutron" is quickly found (Chadwick, 1932)
- Initial estimate for neutrino interaction cross section (Bethe, Peierls):
  - $\sigma \sim 10^{-44}$ cm^2
  - $P = n\,\sigma\,L \rightarrow L \sim 10^{20}$ cm = 10^{15} km ~ 100 light years
  - cf.: L(neutron), L(photon) ~ 10^2 cm
  - "**there is no practically possible way of observing the neutrino**"
- Pauli: "I have done a terrible thing.
  - I have postulated **a particle that cannot be detected.**"

THE NUCLEAR AGE

F. Reines, Nobel Lecture 1995

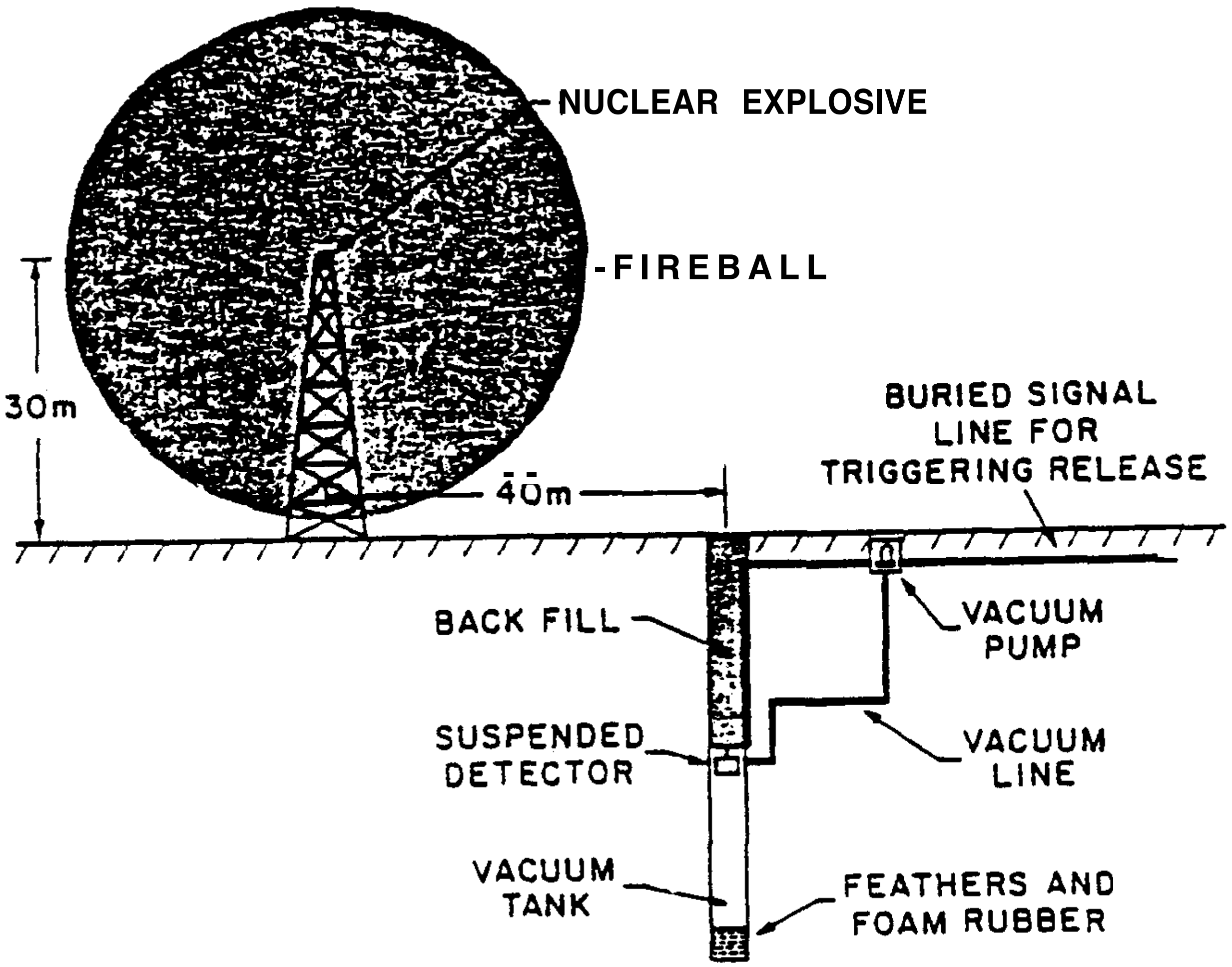
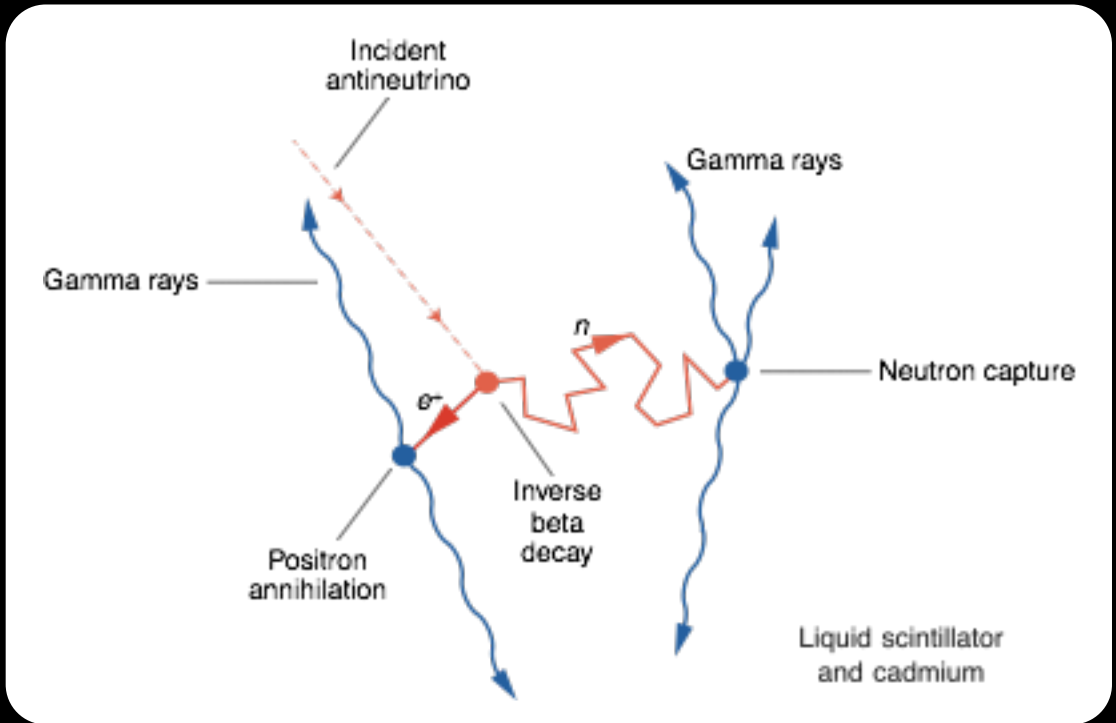


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

So why did we want to detect the free neutrino? Because everybody said, you couldn't do it. Not very sensible, but we were attracted by the challenge. After all, we had a bomb which constituted an excellent intense neutrino source. So, maybe we had an edge on others. Well, once again being brash,



$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$n + \mathrm{Cd} \rightarrow \mathrm{Cd}' + \gamma(9\mathrm{MeV})$$

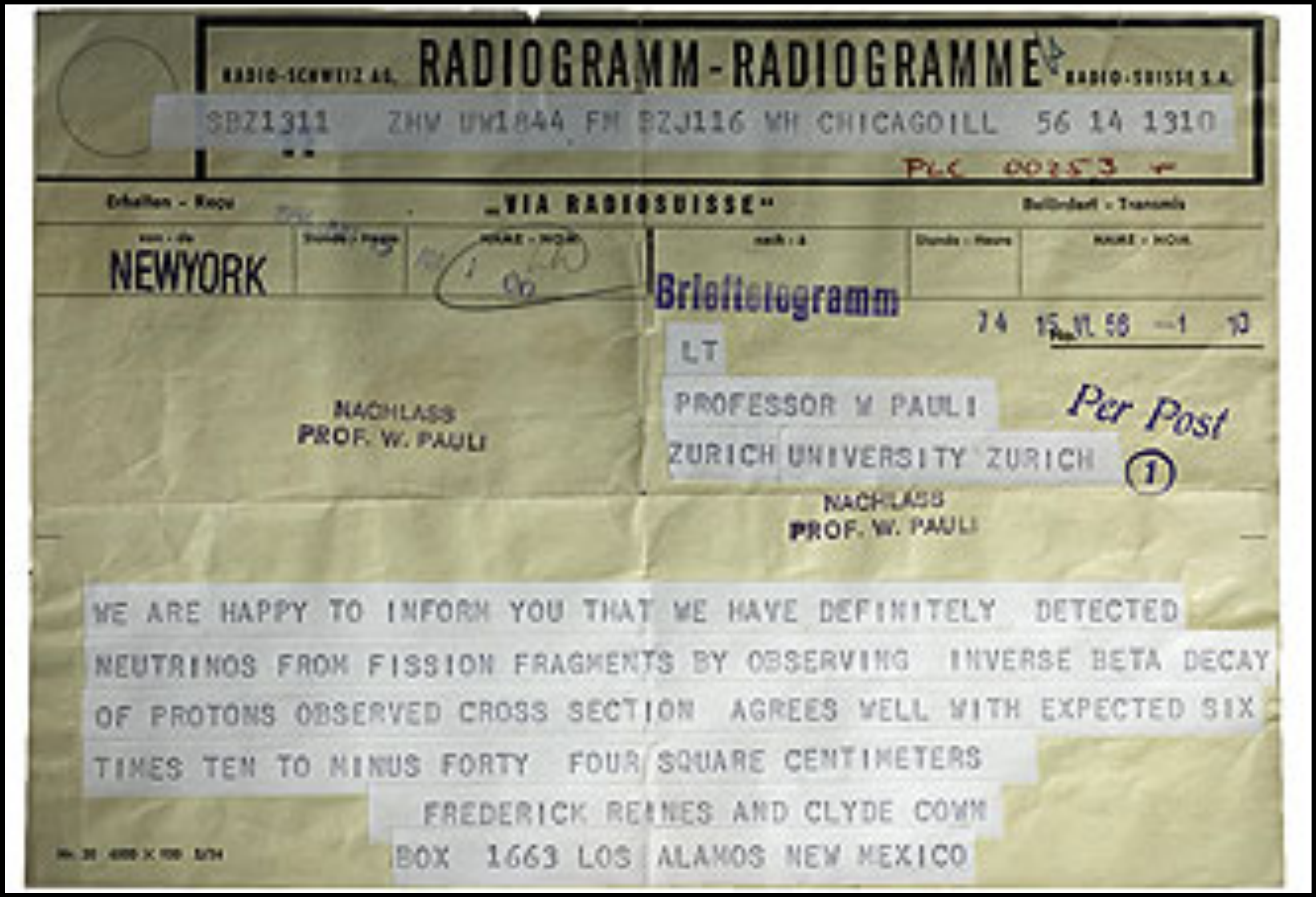
"inverse β decay"

double signature from e^+ and n

- Nuclear technology changes the picture:
  - ~10^{13} ν/cm/sec^2 from Hanford and Savannah River reactor facilities
  - ~ton scale detectors with high neutron detection efficiency

PAULI'S REDEMPTION

LANL, "Celebrating the Neutrino"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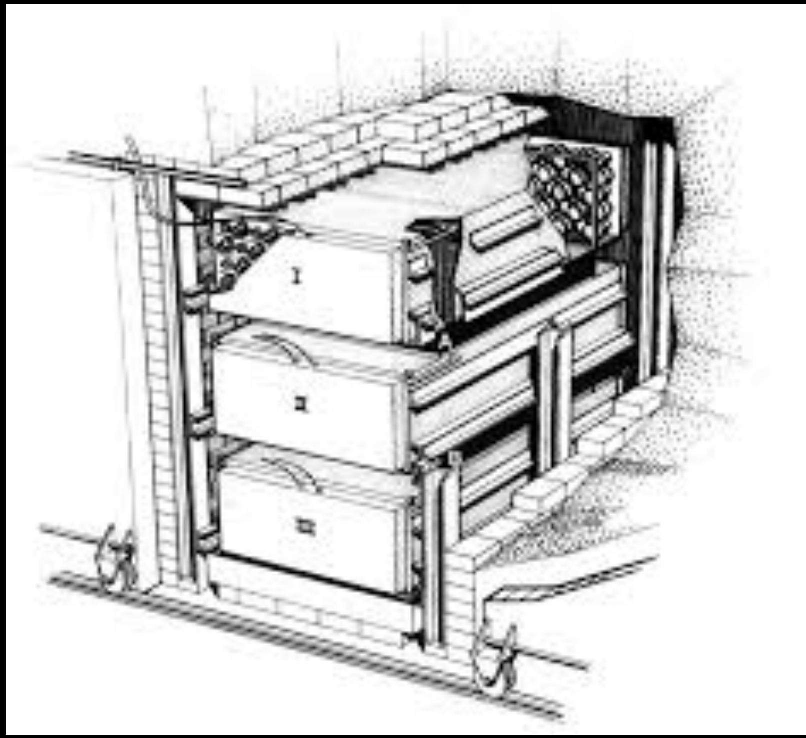
"VIA RADIOSUISSE"
NEWYORK
Brieftelegramm
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS
PROF. W. PAULI
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

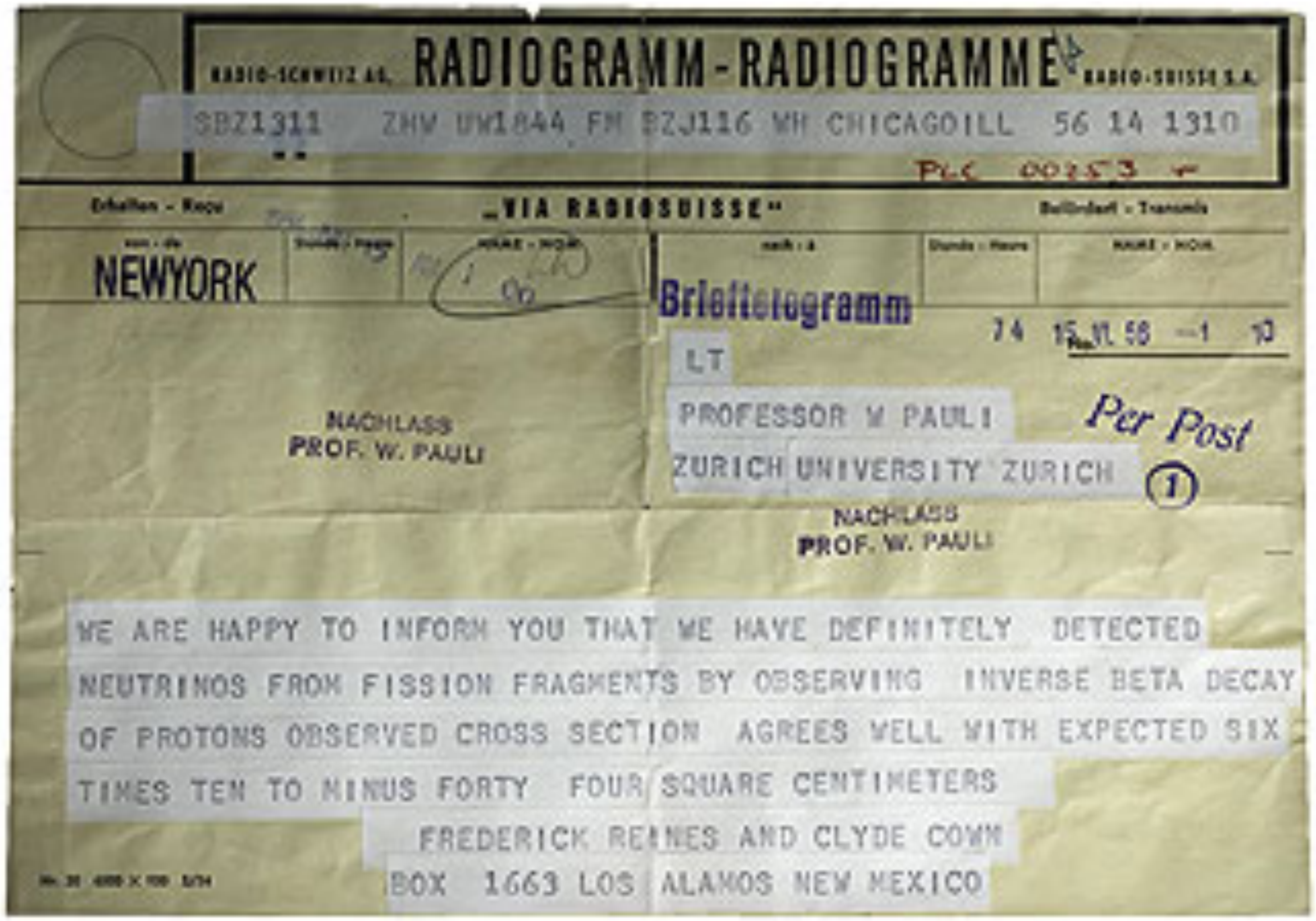


PAULI'S REDEMPTION

LANL, "Celebrating the Neutrino"

Fred Reines

1 day ago near Los Alamos



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Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

NEWYORK

Brieftelegramm

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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

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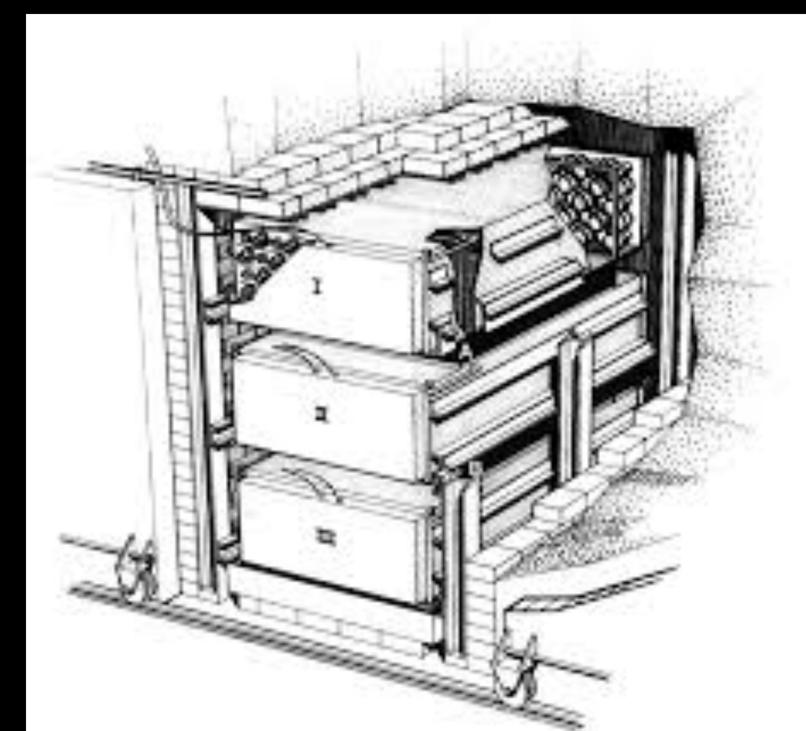
Like · Comment · Share

Wolfgang Pauli likes this

Write a comment . . .



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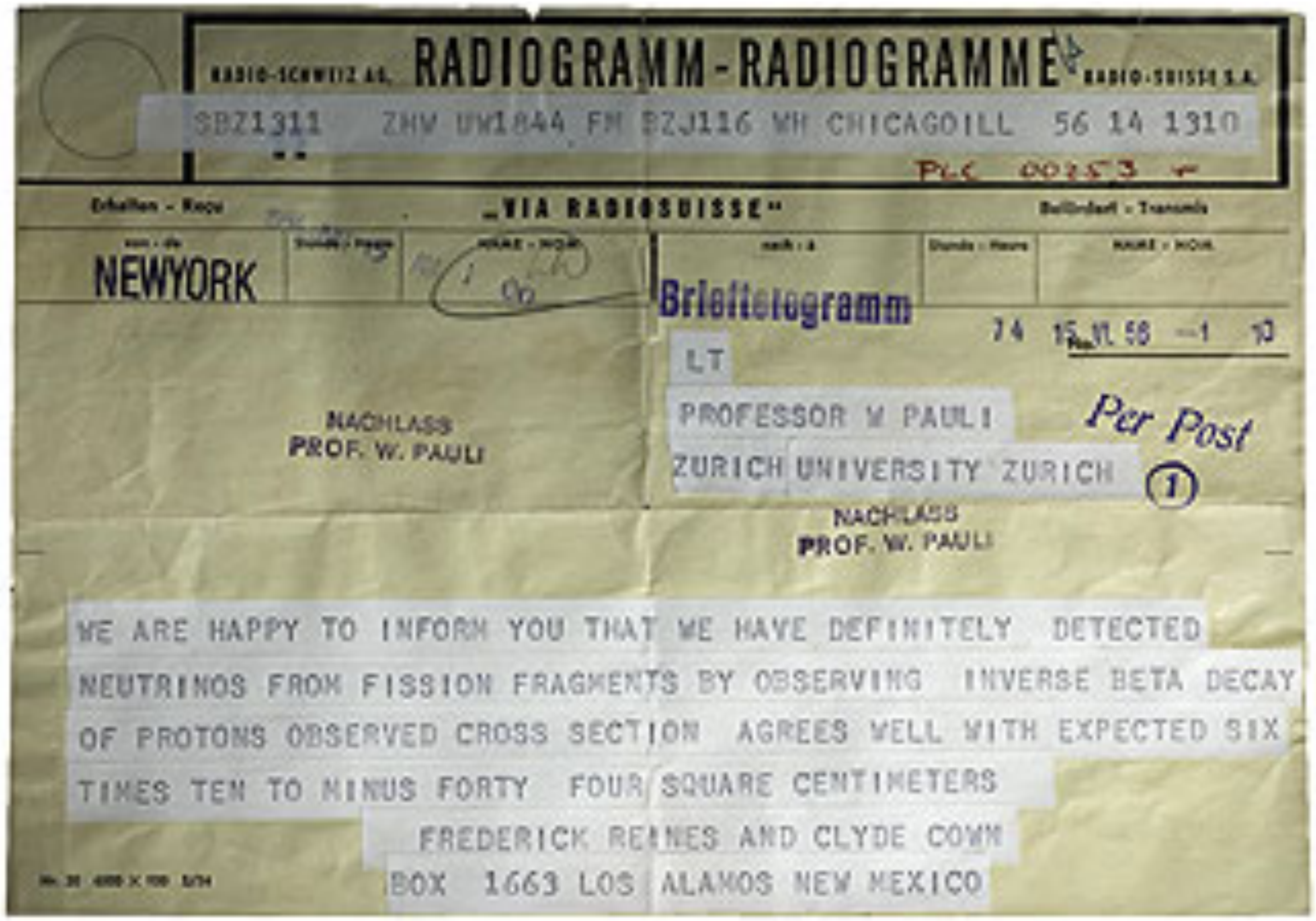
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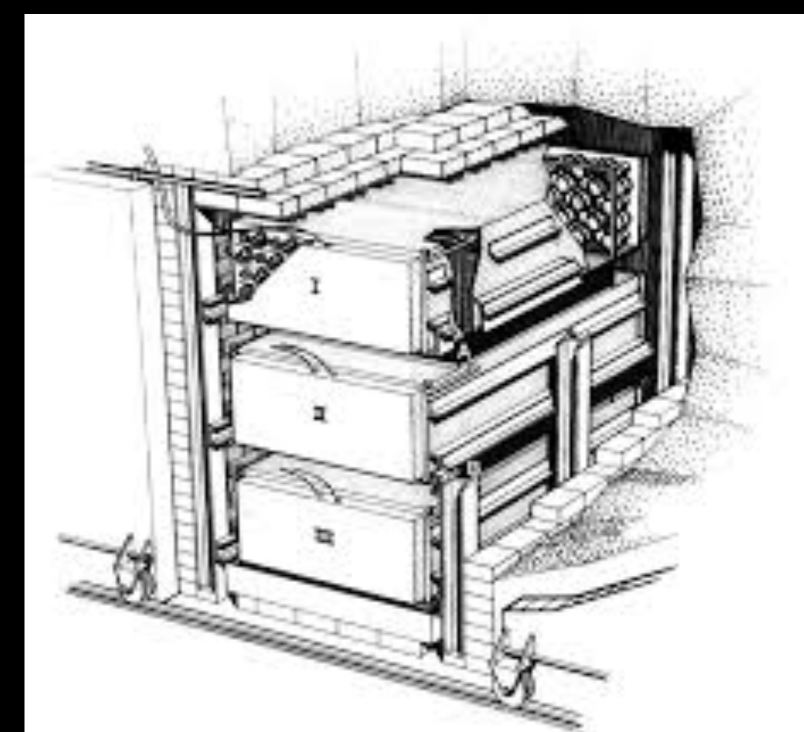
Wolfgang Pauli likes this

Fred Reines: "no practically possible way", eh?
30 min · Like

Write a comment . . .



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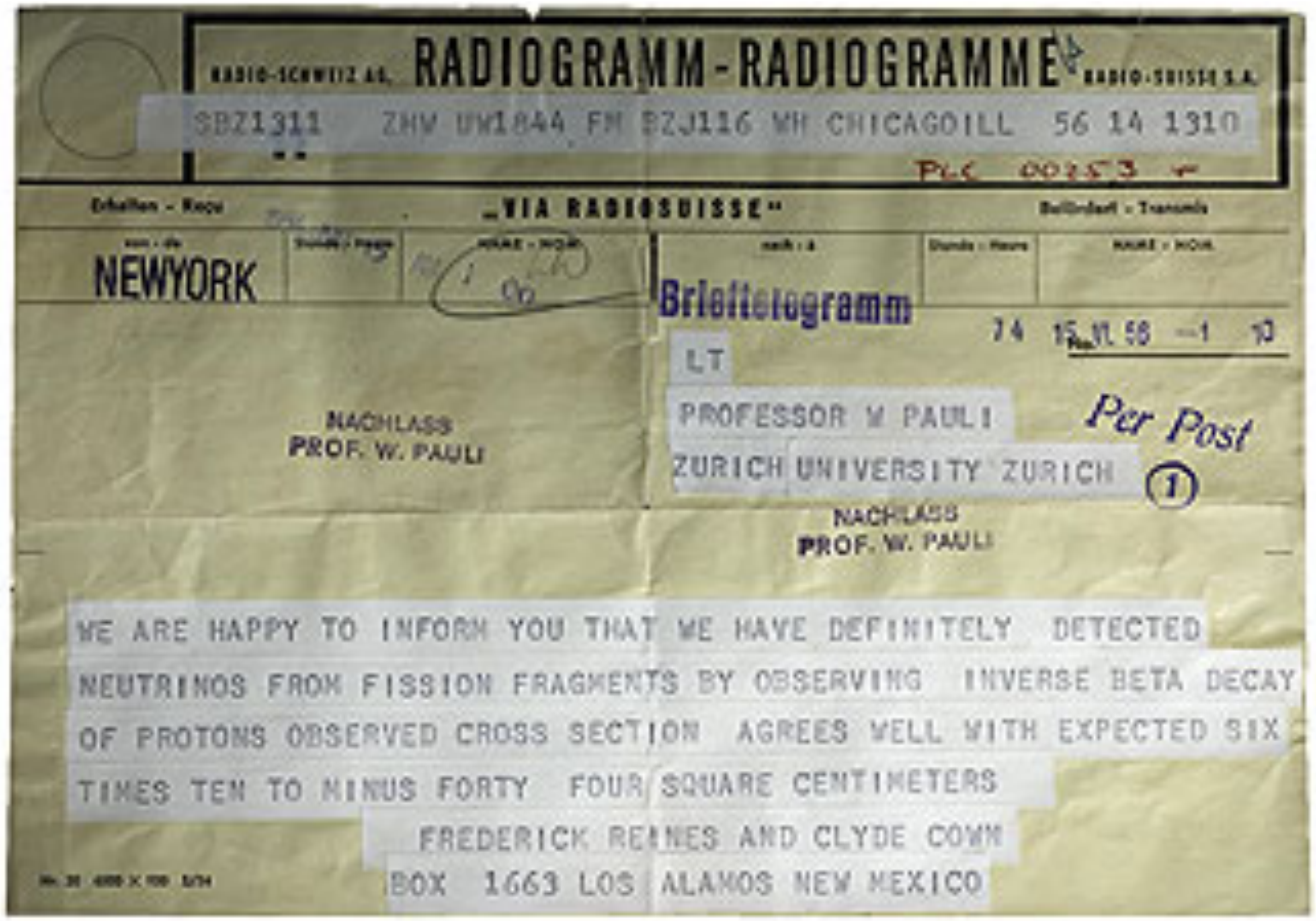

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Like · Comment · Share

Wolfgang Paoli likes this

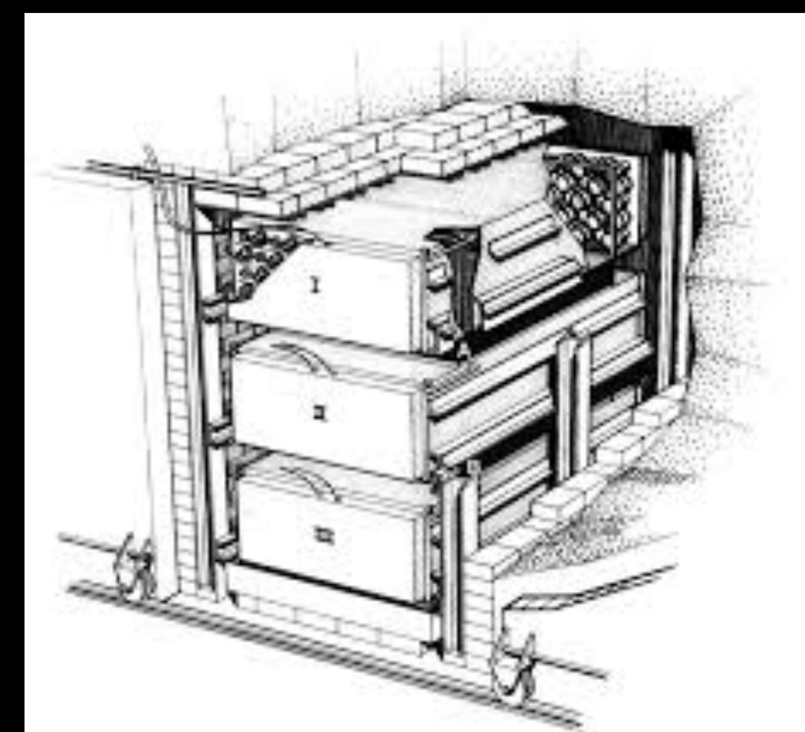
Fred Reines: "no practically possible way", eh?

30 min · Like

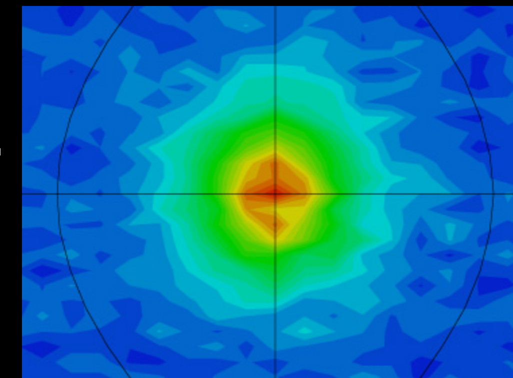
Hans Bethe: well, you shouldn't believe everything you read in papers

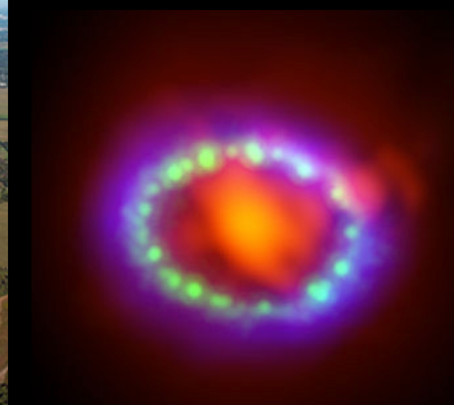
1 min · Like

Write a comment . . .



EXTREME SCIENCE

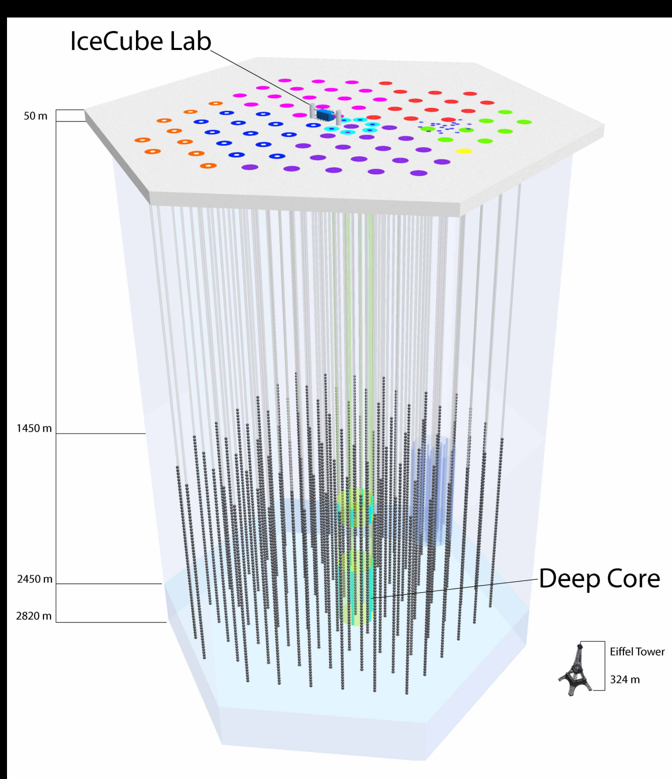


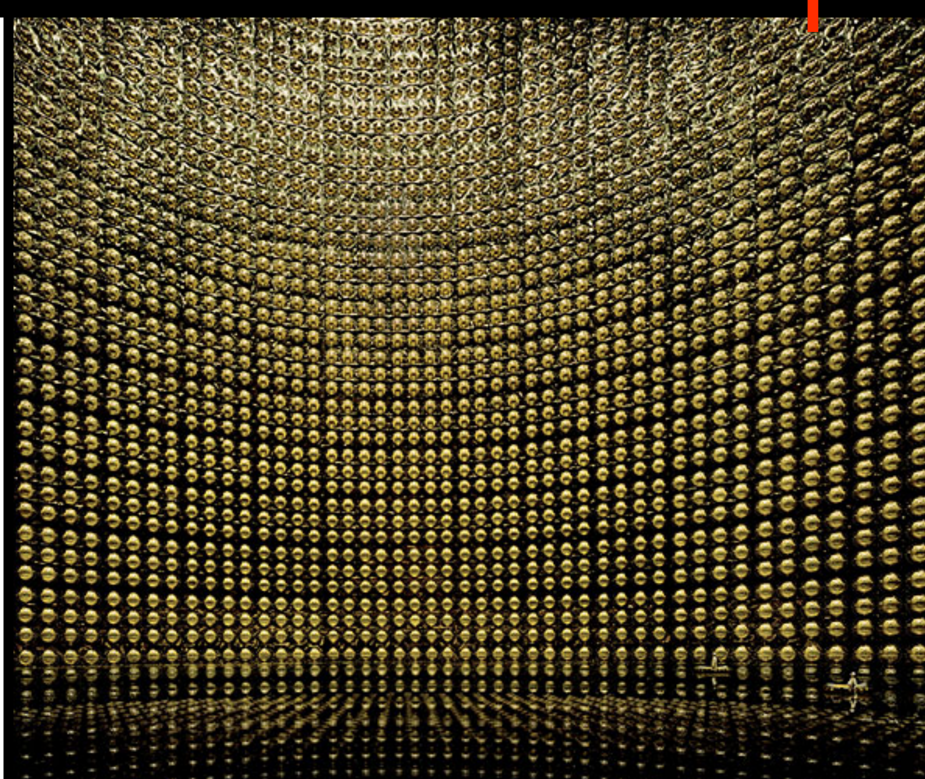


Intense sources:

- Nuclear reactors O(10 GW)
- Astrophysical sources:
    - supernovae, sun, etc.
- Accelerator beams with continuous output with O(MW) power

$$N \propto \boxed{\Phi_\nu} \times \boxed{V \times \rho \times \epsilon} \times \sigma_\nu$$

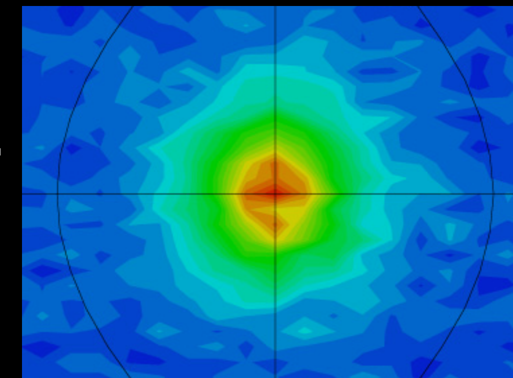


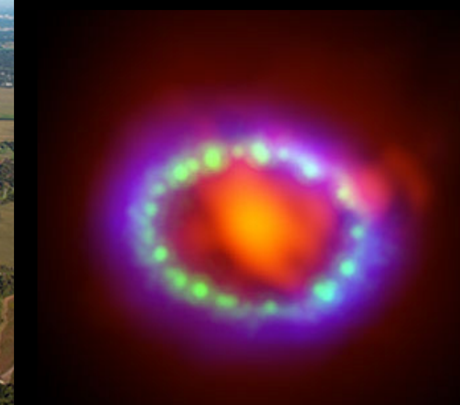


Enormous detectors:

- large volumes of water/ice
    - Antarctic ice (IceCube)
    - Mediterranean Sea (KM3NET)
    - Underground caverns
        - **SNO, SK**, IMB
- Iron plates from WWII battleships
- kiloton of liquid scintillator

EXTREME SCIENCE





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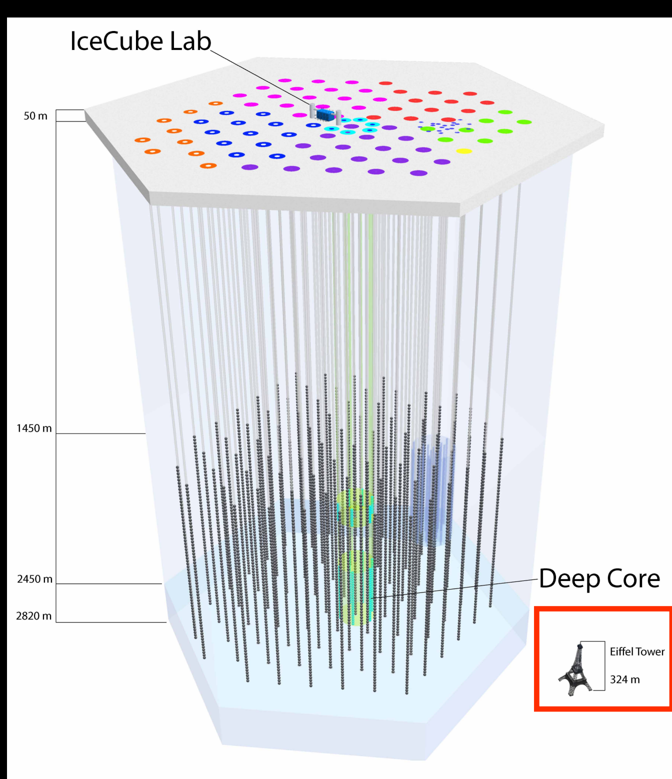

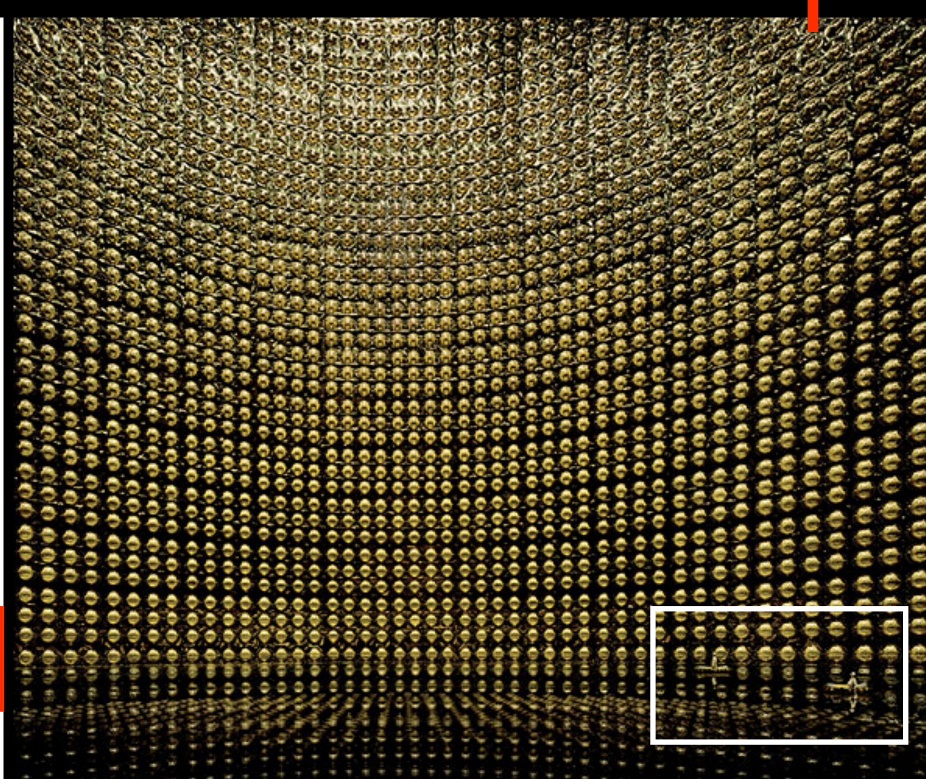

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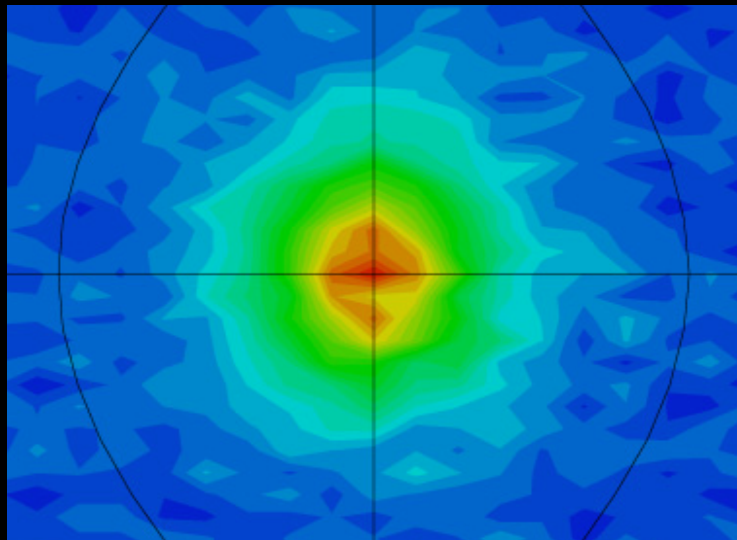
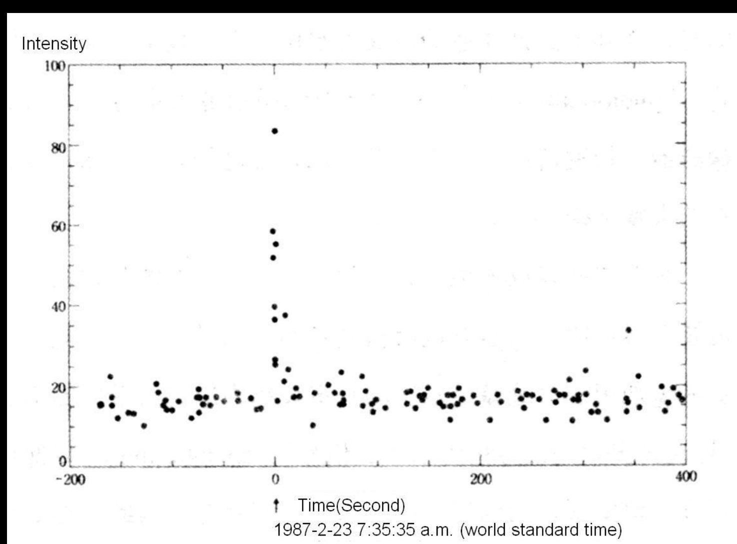
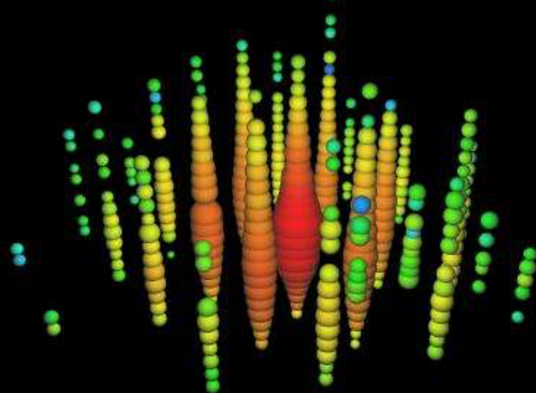


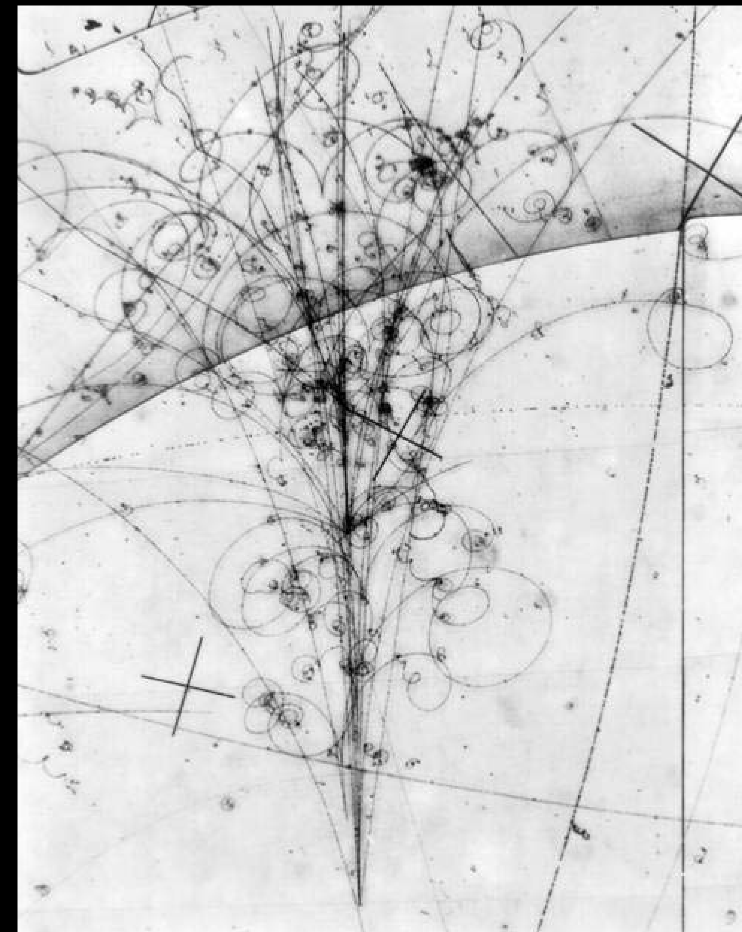
neutrinos produced in the solar fusion processes

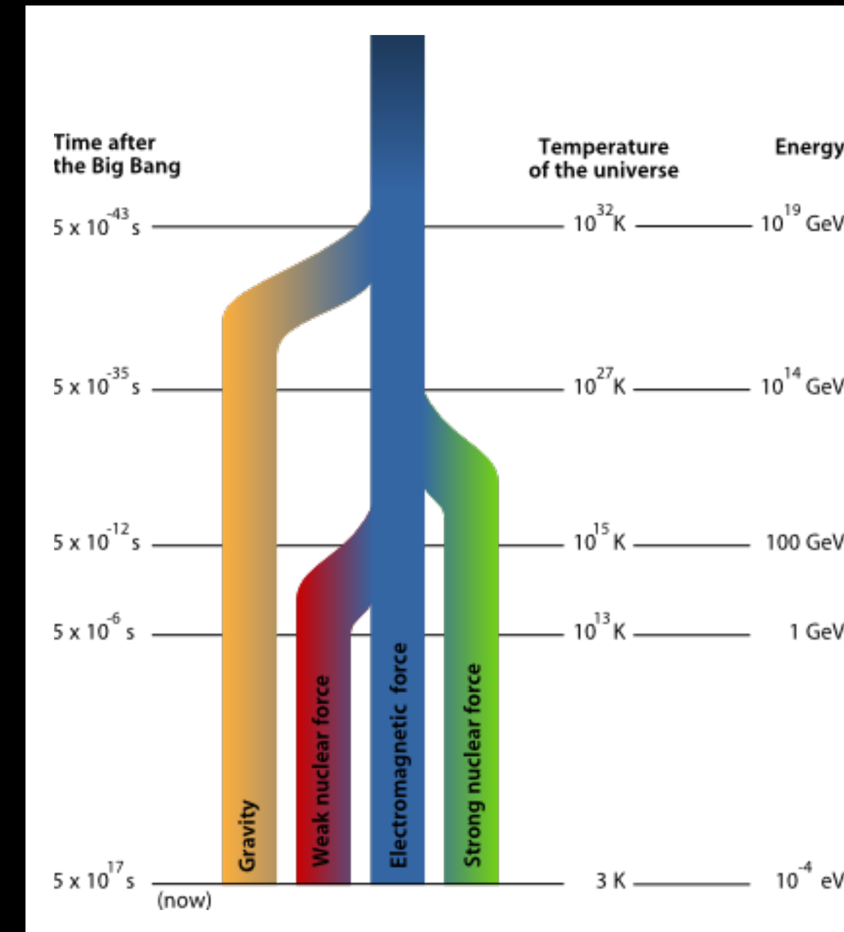


~99% of the energy of supernova in neutrinos



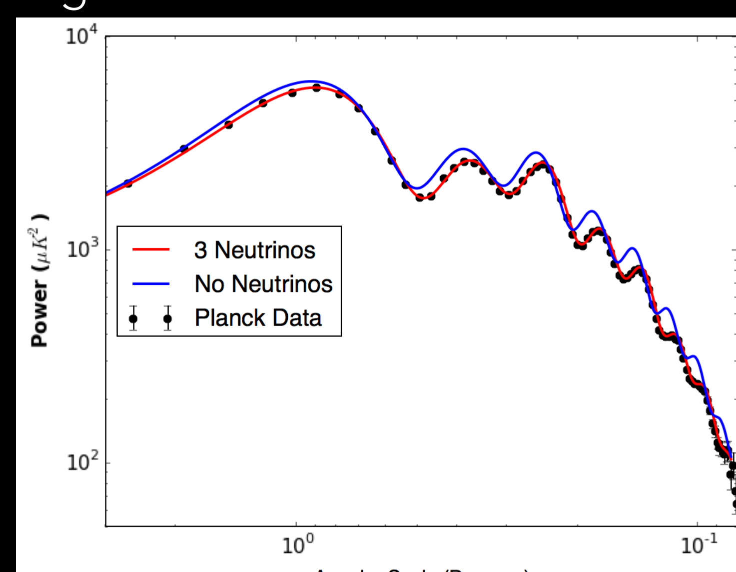
PeV (=10^{15} eV) neutrinos

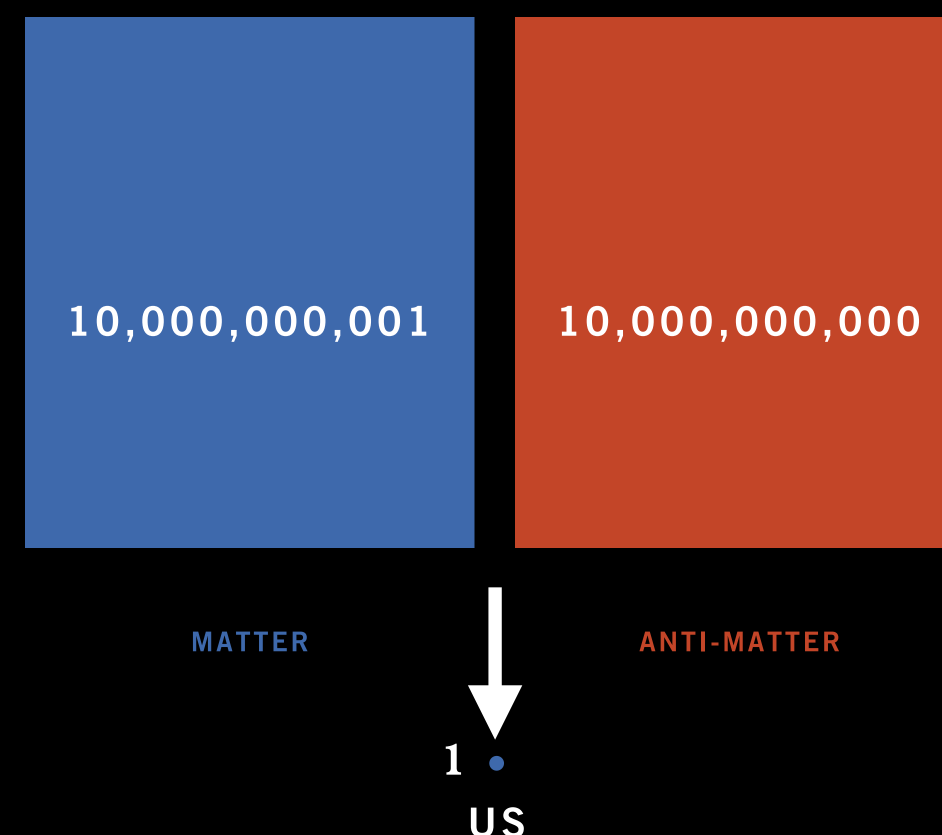




ν

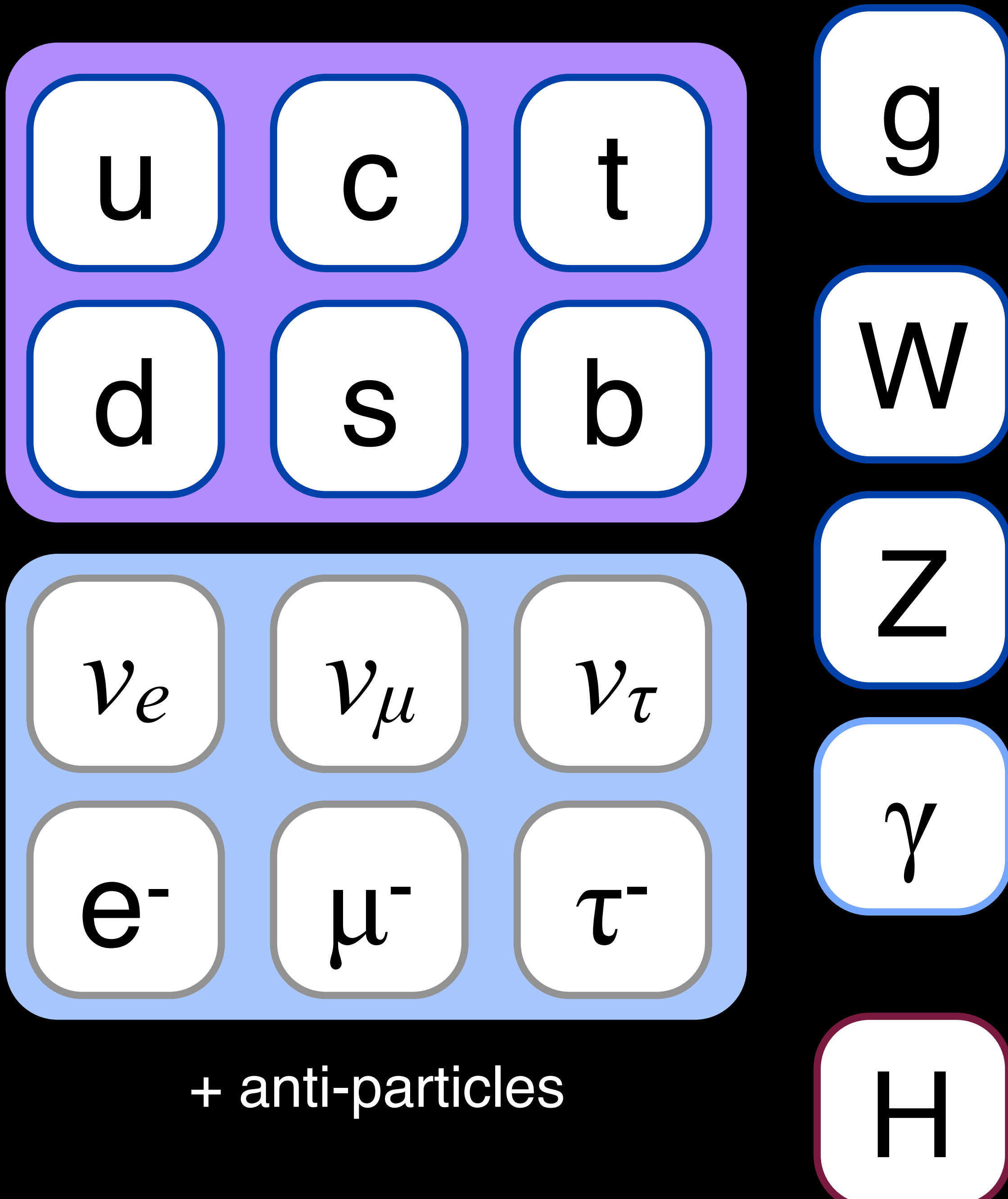
neutrinos shape CMB and large scale structure of the universe





Do neutrinos have a role in the primordial matter dominance of the universe?

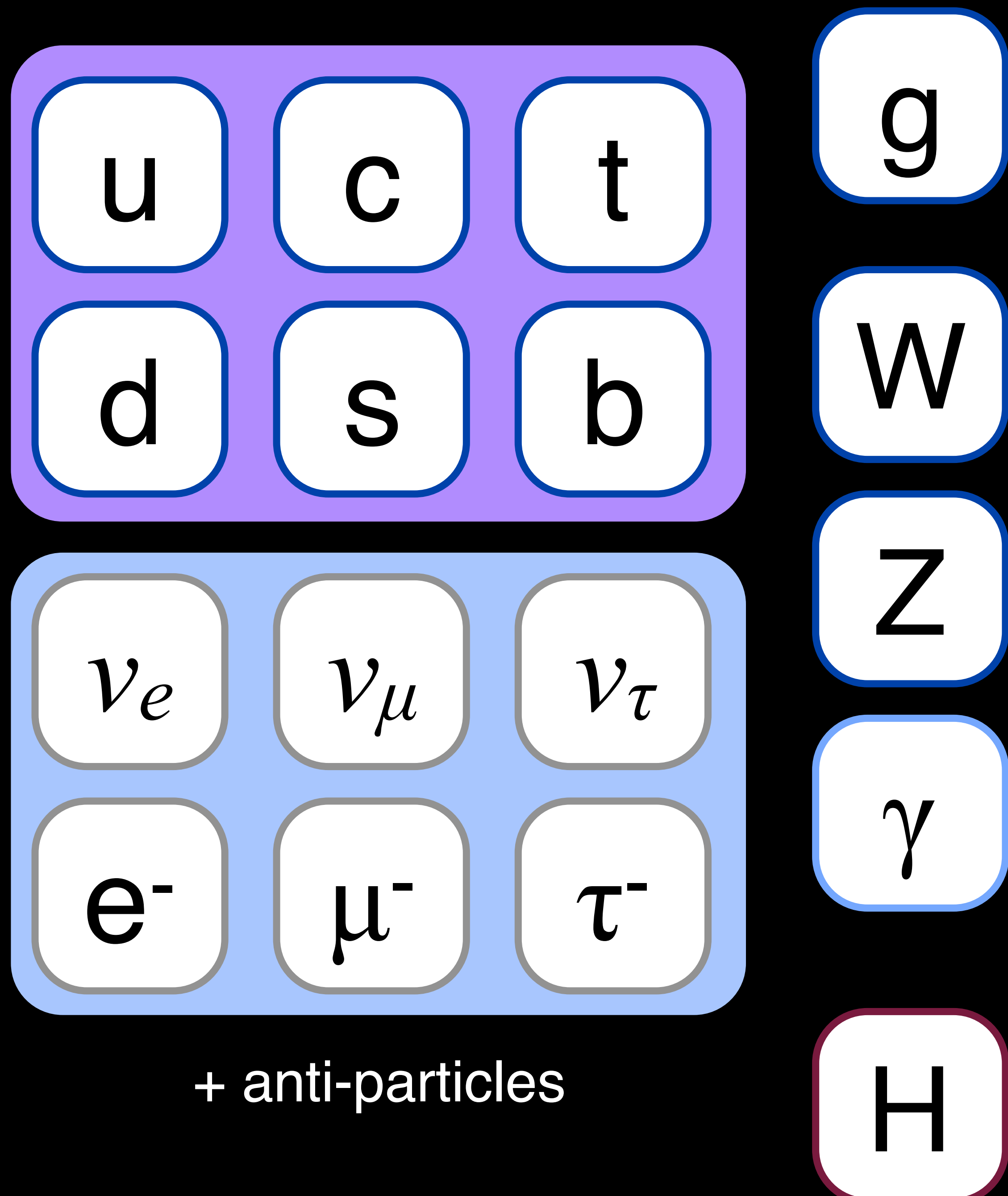
NEUTRINOS IN THE STANDARD MODEL



+ anti-particles

- Neutrinos are spin 1/2 “fermions”
  - cousins of the quarks
  - siblings of the charged leptons
- They come in three species
  - ν_e, ν_μ, ν_τ
  - corresponding antiparticles (“antineutrinos”)
- They are not assigned masses

NEUTRINOS IN THE STANDARD MODEL



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  - cousins of the quarks
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- They come in three species
  - ν_e, ν_μ, ν_τ
  - corresponding antiparticles ("antineutrinos")
- They are not assigned masses

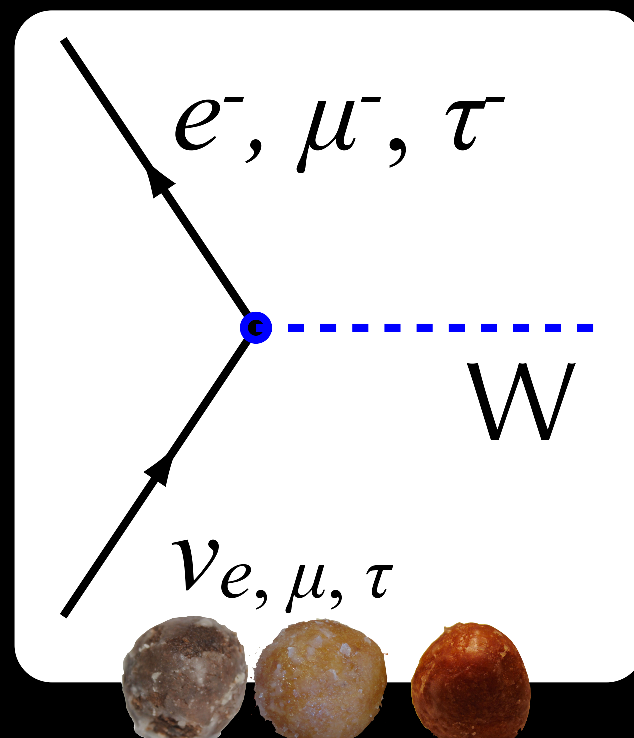
- Neutrinos undergo weak interactions via the W, Z

A CLOSER LOOK:

WHAT KIND OF TIMBIT ARE YOU?

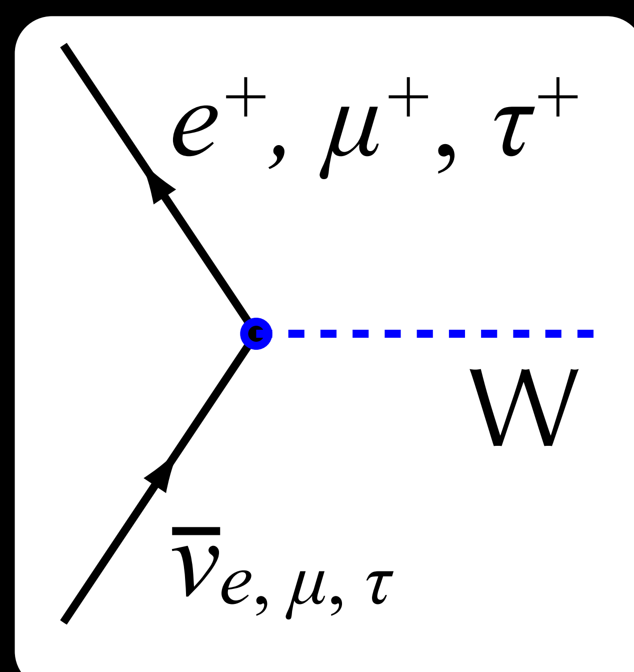
neutrinos and leptons

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-



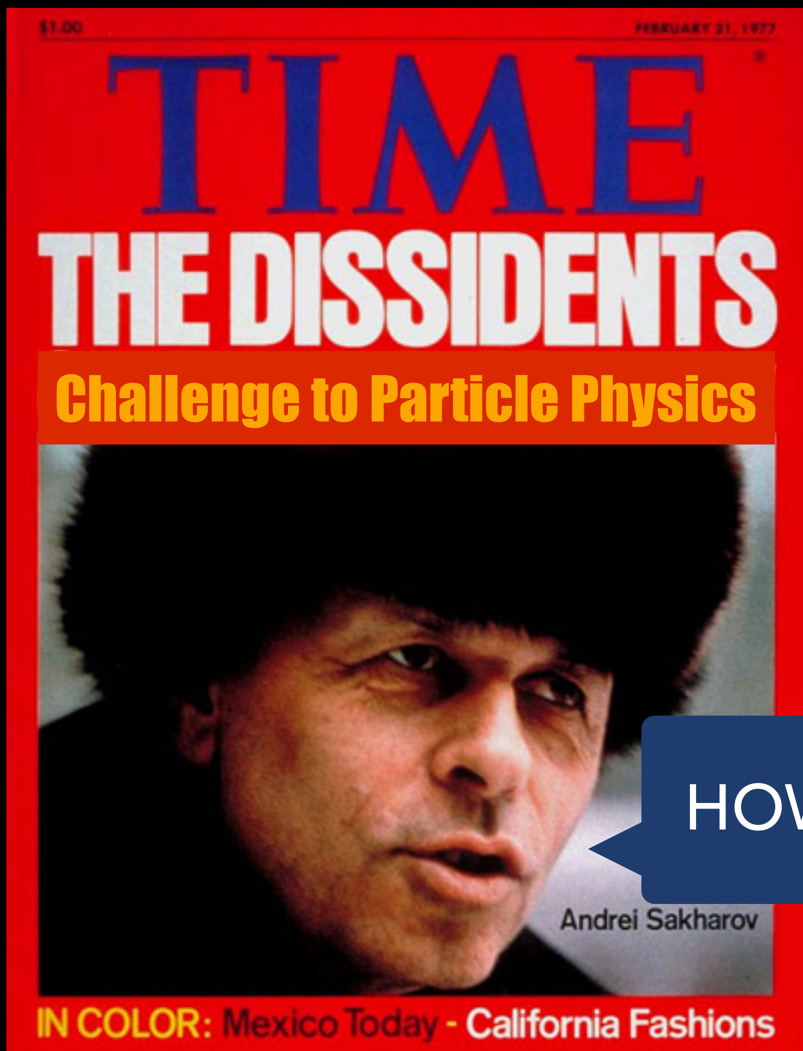
anti-neutrinos and anti-leptons

$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
e^+	μ^+	τ^+



- Three species or "flavors" defined by its association to a charged lepton ($e^\mp$, $\mu^\mp$, $\tau^\mp$):
  - neutrinos are created along with its corresponding charged anti-lepton
  - neutrinos produce its corresponding charged lepton upon interacting
- All flavours interact equally through the Z "neutral current"

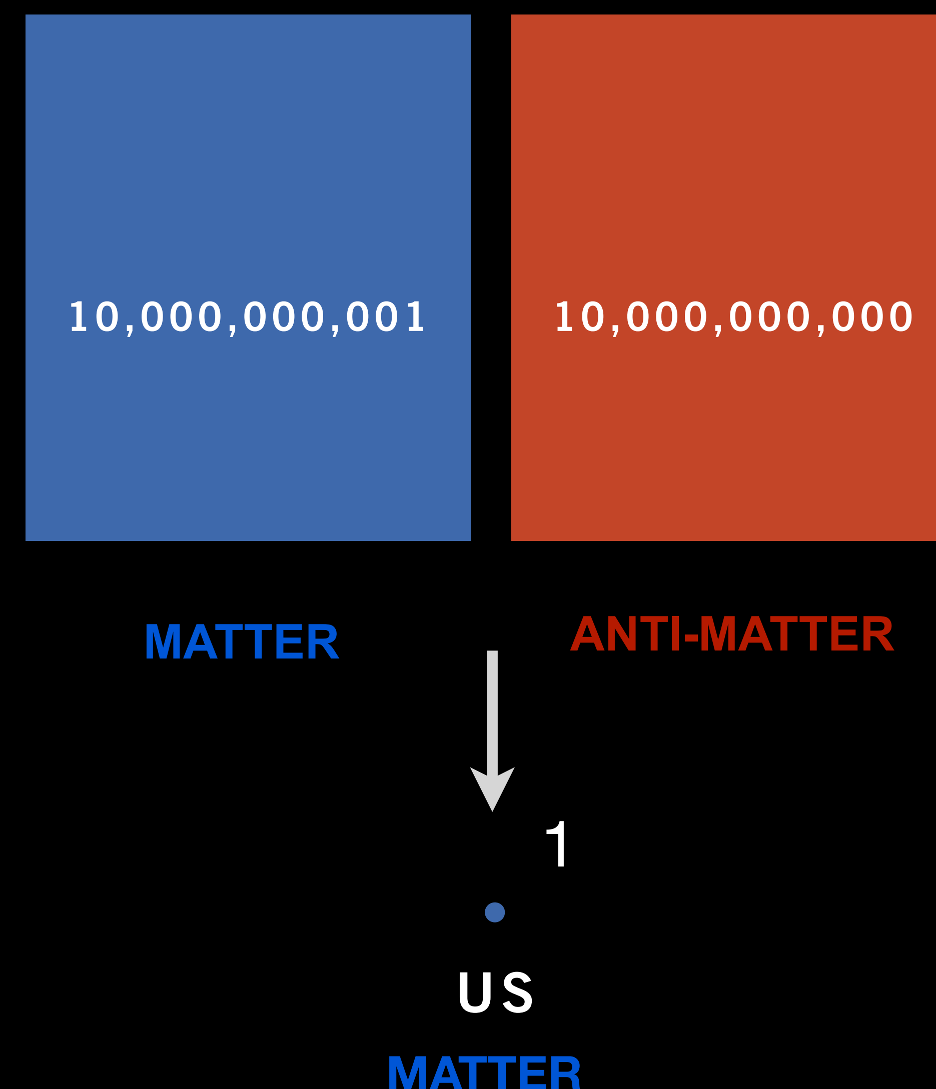
MATTER/ANTIMATTER ASYMMETRY



- Sakharov conditions
  - Baryon number (B) violation
  - C, CP violation
  - Departure from Thermal Equilibrium

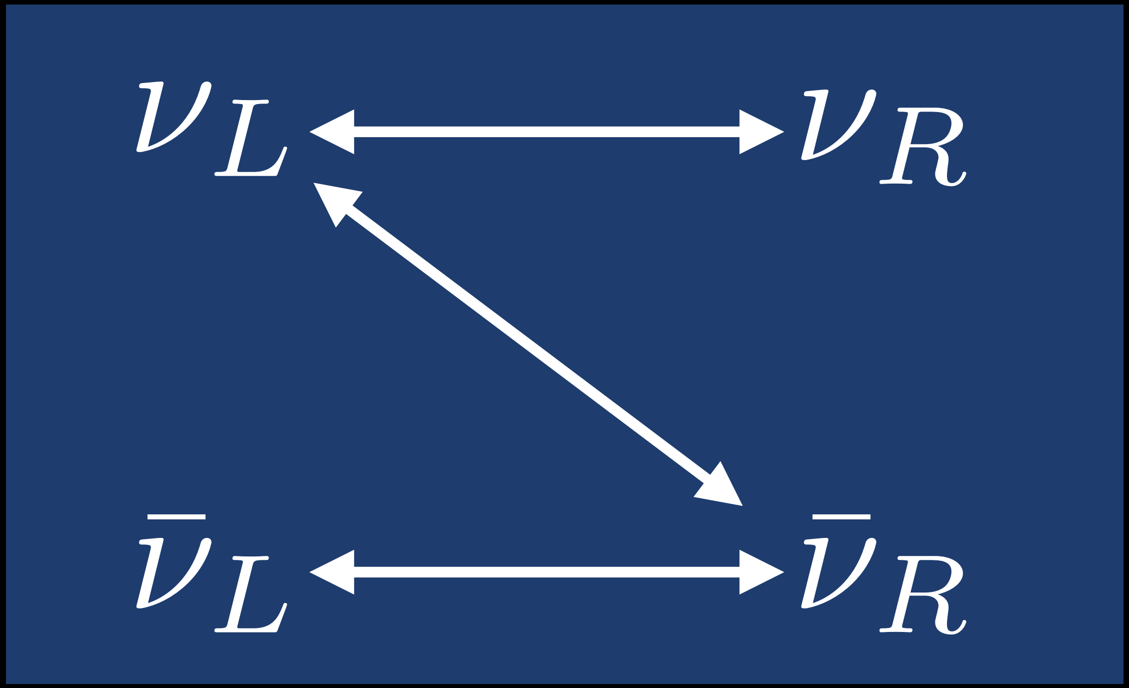
HOW DID THIS HAPPEN?

$$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$$



- Extremely small?
- Extremely large?
  - Known sources of CPV (quark CKM) cannot produce this asymmetry
  - are neutrinos the answer?

WHAT IS NEUTRINO MASS



Dirac

Majorana

- For a spin 1/2 particle, mass couples left- and right-handed states
- Quarks/charged leptons have "Dirac" masses
  - particle/antiparticle are distinct chiral pairs

- Neutrinos may have either/both "Dirac" and "Majorana" masses:
  - absence of electric charge or other conserved quantum numbers
  - "Majorana": mass from left-chiral particle to right-chiral "antiparticle"
  - neutrinos may be their own antiparticles

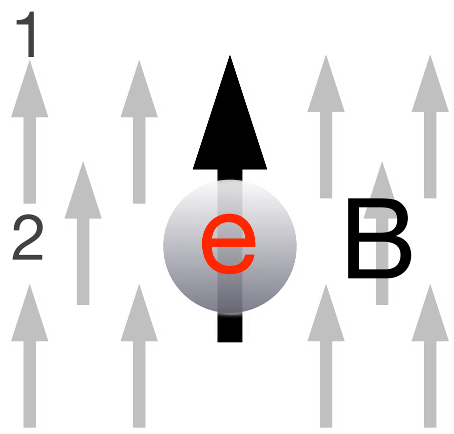
QUESTIONS:

- Is the flavour (species) of a neutrino immutable?
- Does it have mass? what "kind" of mass?
- What is the relation of the neutrino to the antineutrino?
  - do neutrinos exhibit "CP violation"?
- These questions are inextricably linked due to "mixing"
  - general QM concept when we have two observables
  - In this case:
    - mass/energy (i=1,2,3)
    - flavor (α = e, μ, τ)

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

Unitary matrix relates eigenstates of one observable with eigenstates of another

SPIN 1/2 ANALOGY:



$$H|\mathrm{up}\rangle = E_1|\mathrm{up}\rangle$$

$$|\mathrm{up}\rangle \xrightarrow{t} e^{-iE_1 t}|\mathrm{up}\rangle \qquad P(\mathrm{up} \xrightarrow{t} \mathrm{down}) = 0$$

- [H,S] = 0: Eigenvalues of S are eigenvalues of H
  - eigenstates of S are stationary

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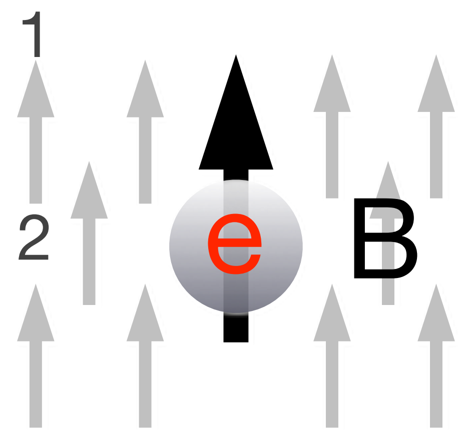

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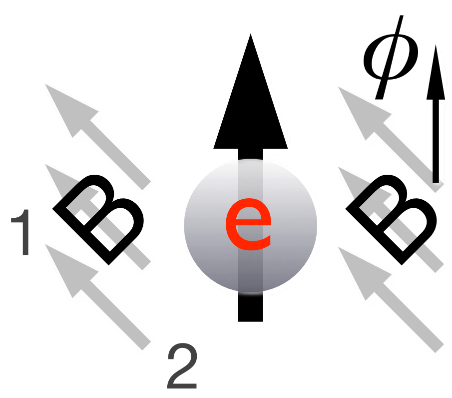
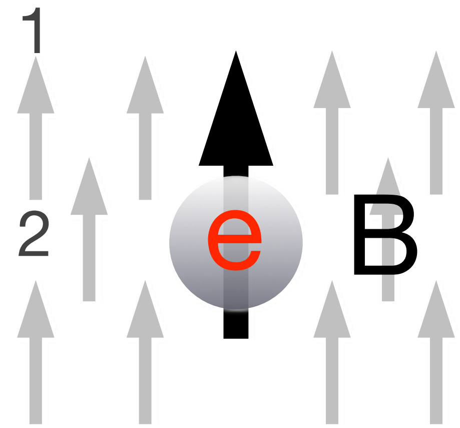


$$|\text{up}\rangle \xrightarrow{t} \cos\frac{\phi}{2}e^{-iE_1 t}|1\rangle - i\sin\frac{\phi}{2}e^{-iE_2 t}|2\rangle$$

$$P(\text{up} \xrightarrow{t} \text{down}) = \sin^2\phi\,\sin^2\frac{E_1 - E_2}{2}t$$

SPIN 1/2 ANALOGY:



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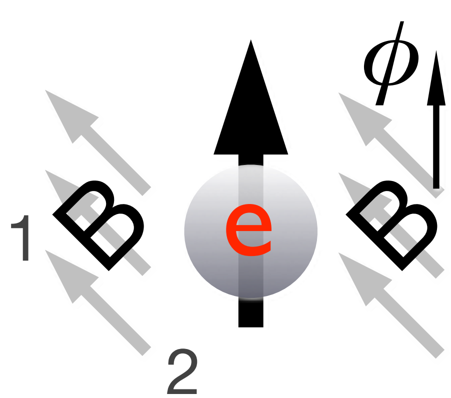

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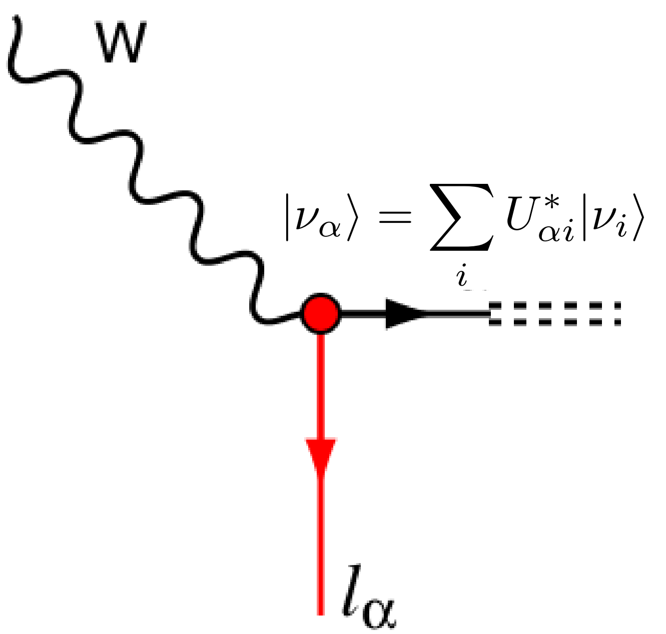
$$P(\text{up} \xrightarrow{t} \text{down}) = \sin^2\phi \sin^2\frac{E_1 - E_2}{2}t$$

- Eigenvectors of S are not energy eigenstates: [H, S] ≠ 0
  - eigenstates of S are no longer stationary
  - non-zero chance to observe different eigenvalue after time.

TWO NEUTRINOS



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

$$|\nu_\alpha\rangle \xrightarrow{t} \cos\theta \; e^{-iE_1 t}|\nu_1\rangle + \sin\theta \; e^{-iE_2 t}|\nu_2\rangle$$

$$P(\nu_\alpha \xrightarrow{t} \nu_\beta) = \sin^2 2\theta \sin^2 \frac{E_1 - E_2}{2} t$$

transformation properties

energy difference (special relativity)

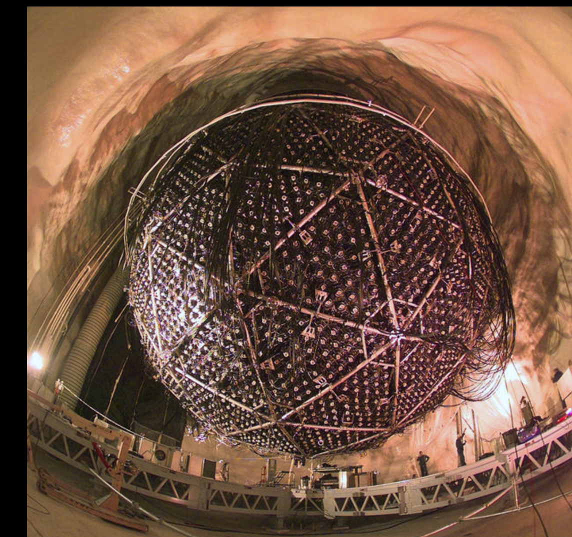
$$P(\nu_\alpha \xrightarrow{t} \nu_\beta) = \sin^2 2\theta \;\; \sin^2 1.27 \frac{\Delta m^2_{21}(\mathrm{eV}^2)}{E(\mathrm{GeV})} L(\mathrm{km})$$

unit conversion

"time"

- Angle (θ) describes "rotation" of flavor states relative to mass states
- mass difference^2 governs "wavelength" of oscillations in L/E
- Directly probe the mass differences, flavor/mass mixing of neutrinos.





The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

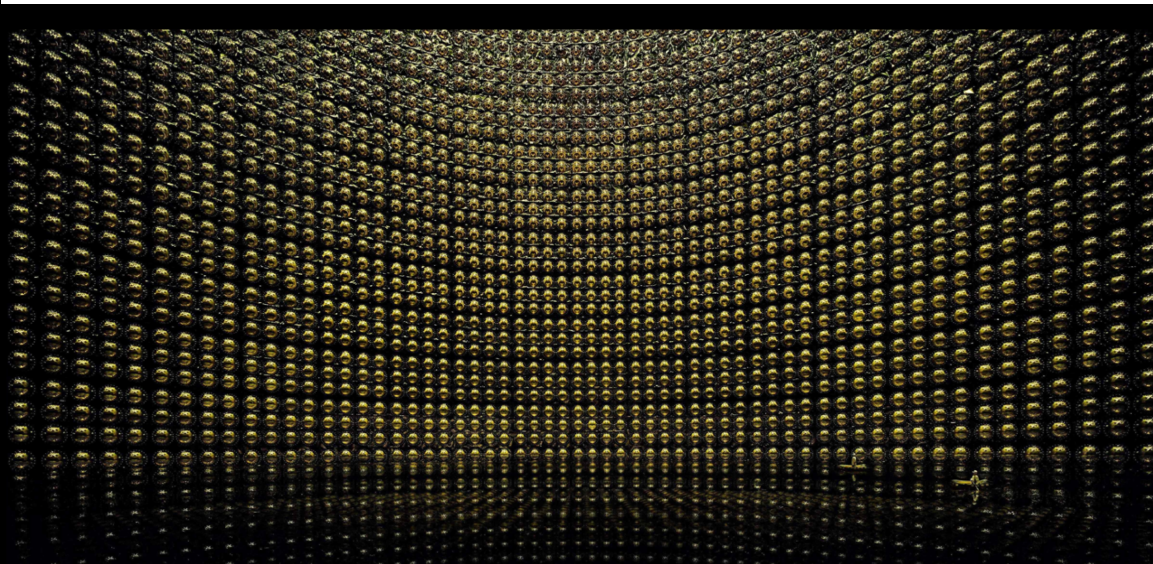
Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

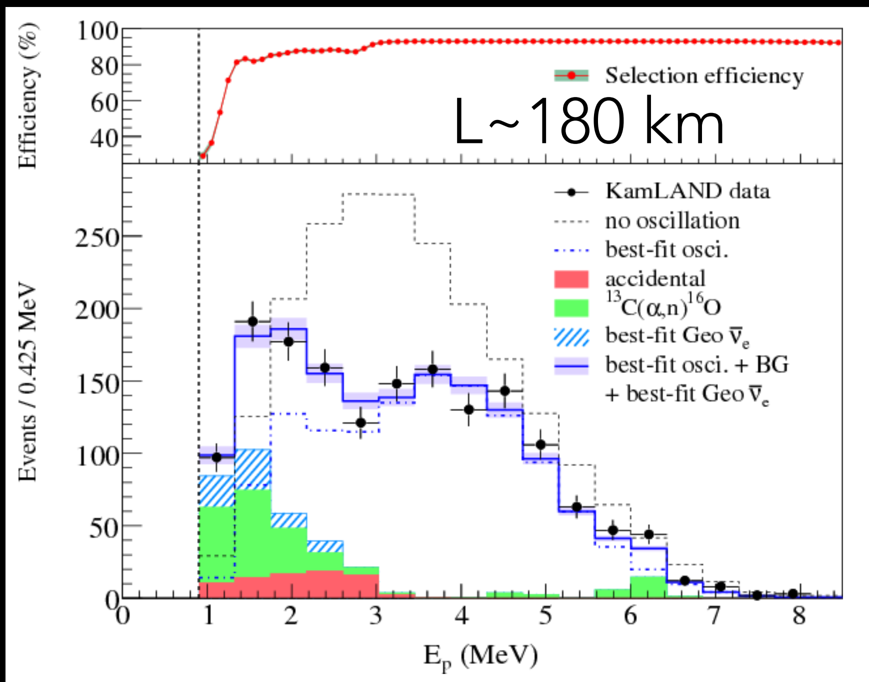
Arthur B. McDonald

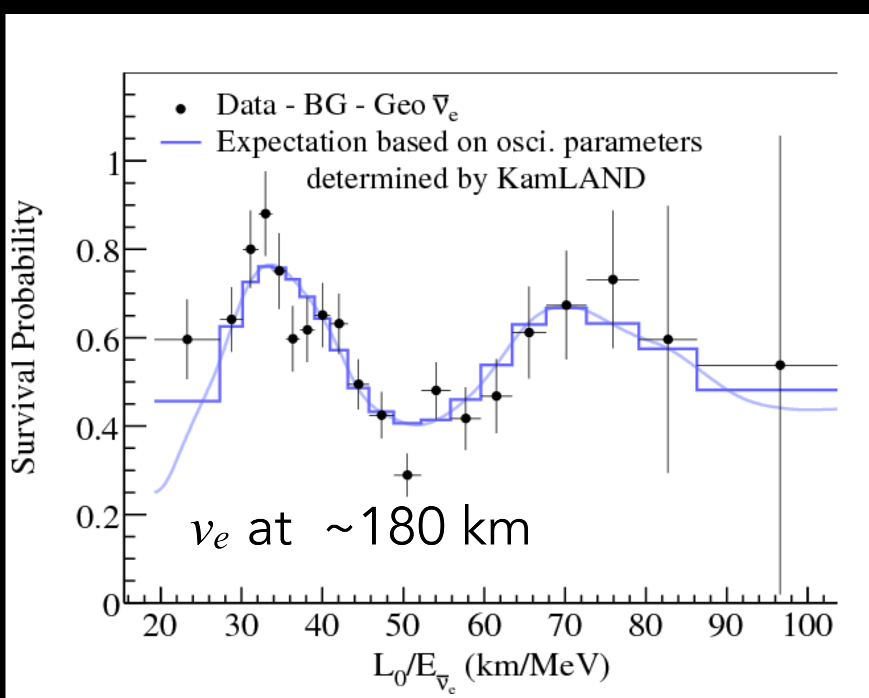
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

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

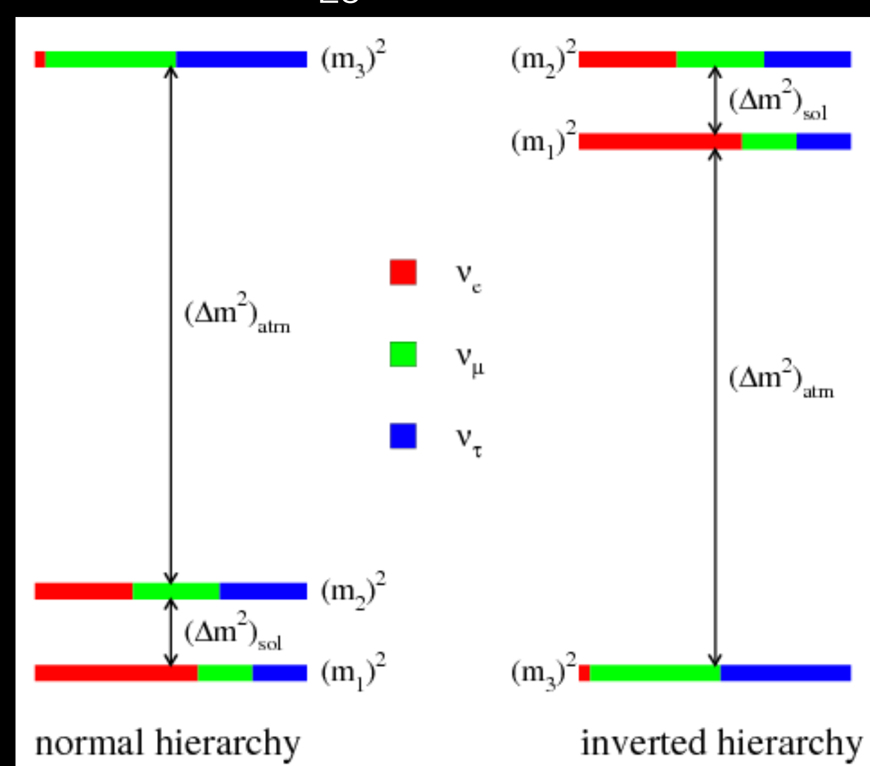


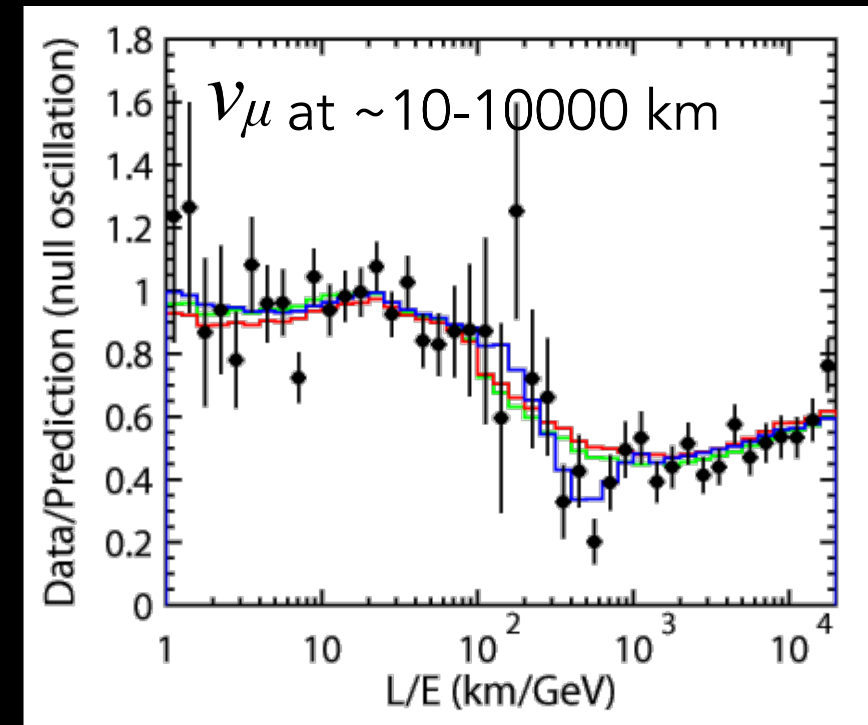
EXAMPLES:

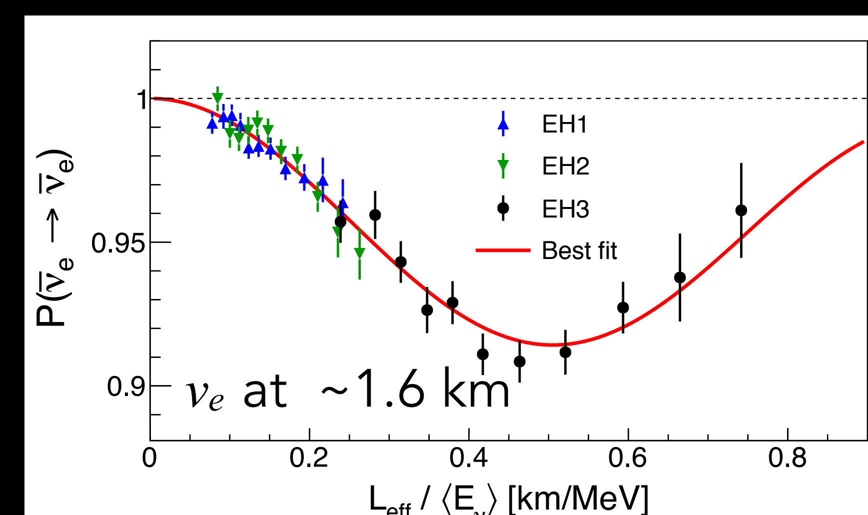




- "wavelength" in L/E ~ $1/\Delta m^2$
- "amplitude" ~ $\sin^2 2\theta$
- "Slow" (solar)
  - $\Delta m^2_{21} \sim 7.8 \times 10^{-5}$ eV^2
  - $\sin^2 2\theta_{12} \sim 0.846 \pm 0.021$
- "Fast" (atmospheric)
  - $\Delta m^2_{31} \sim 2.4 \times 10^{-3}$ eV^2
  - $\sin^2 2\theta_{13} \sim 0.084 \pm 0.005$
  - $\sin^2 2\theta_{23} \sim 1.0$

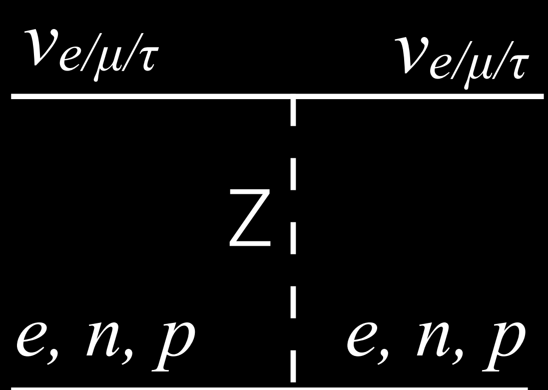






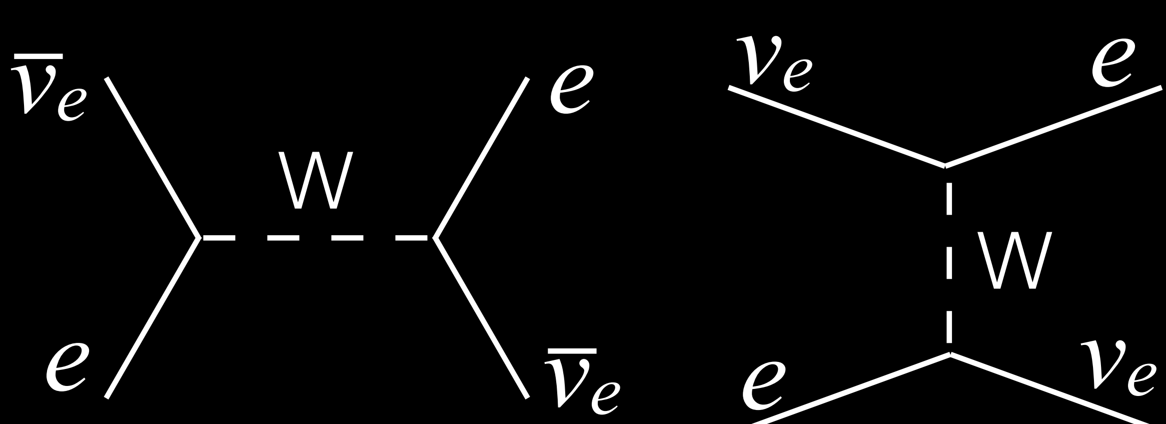
THE "MATTER EFFECT"

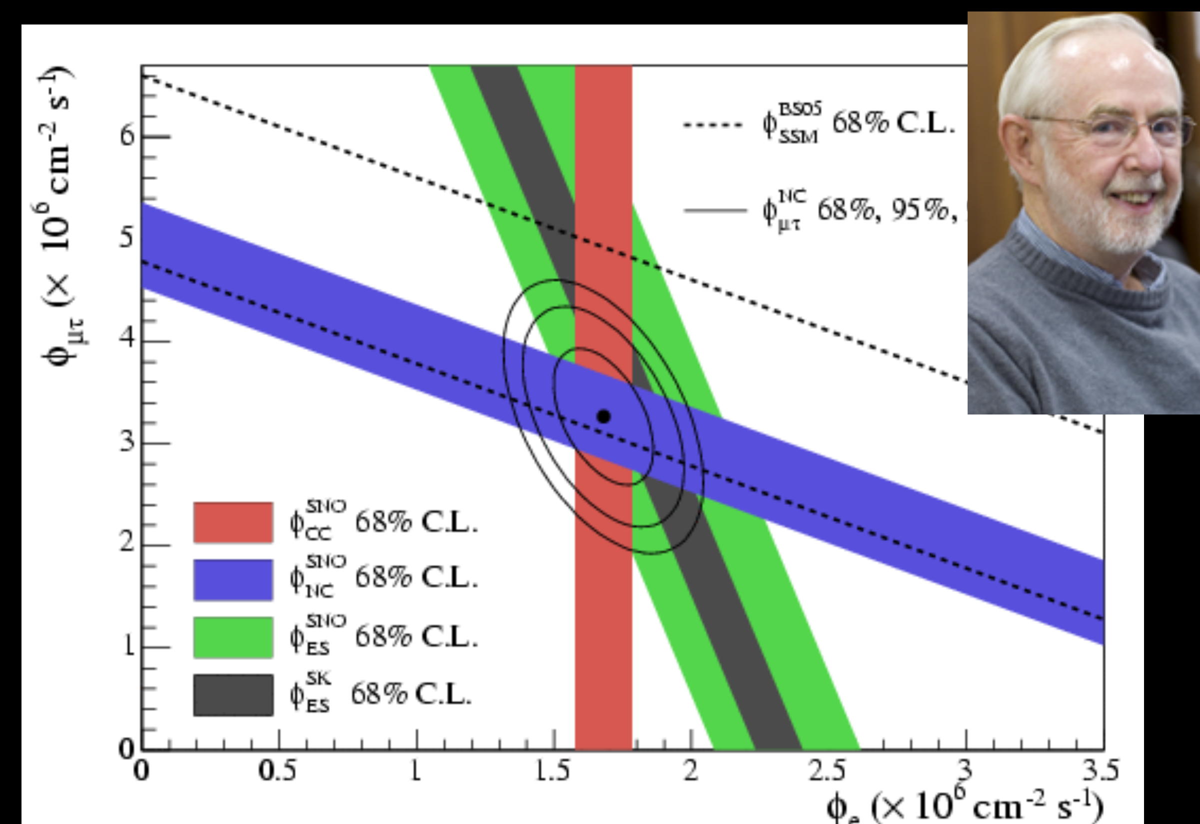
- Neutrinos experience coherent forward scattering in material:



$$H = H_{VAC} + H_M = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V & 0 \\ 0 & 0 \end{pmatrix}$$

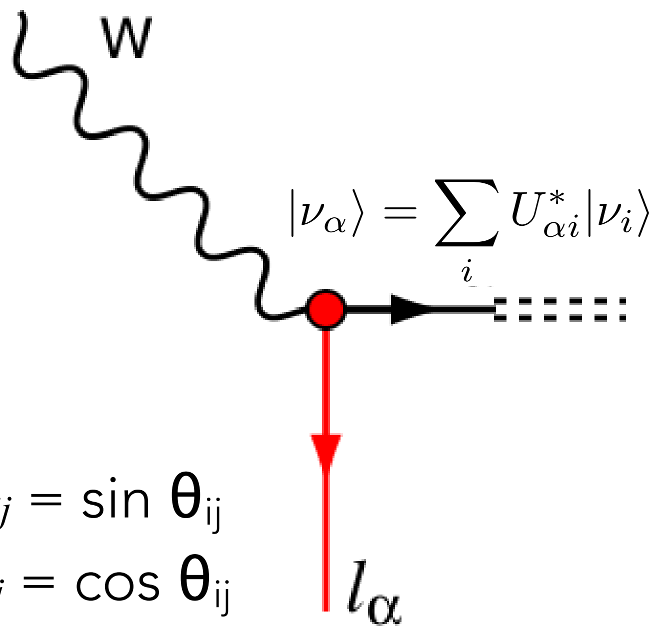
$$V = \sqrt{2} G_F N_e$$





- V (matter potential) changes sign for neutrino ↔ antineutrino
- Sign of Δm^2 relative to V "matters" → sensitivity to mass ordering ("hierarchy")
- Neutrinos emerging from the Sun are in ~a mass eigenstate (V dominates H)
  - measure ν_e content of the mass eigenstate when we detect ν_e from the sun

THREE'S COMPANY



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

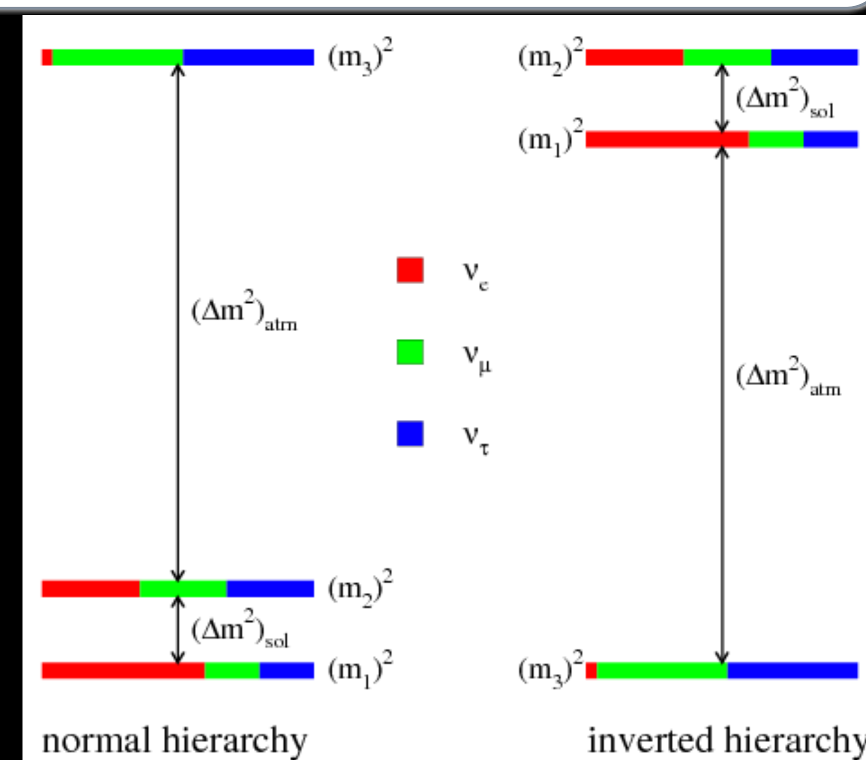
$s_{ij} = \sin \theta_{ij}$

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

"standard" parametrization

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

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- One complex phase δ_{CP}
  - additional phases possible if neutrinos are "Majorana" (more on this later)
  - **changes sign for antineutrino oscillations**



ND280
“near” detector

J-PARC

Super Kamiokande
“far” detector

~500 collaborators from
58 institutions, 12 nations

Intense $\nu_\mu / \bar{\nu}_\mu$ beam sent 295 km across Japan and detected with the Super-Kamiokande detector to study neutrino oscillations

ν_μ "DISAPPEARANCE"

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

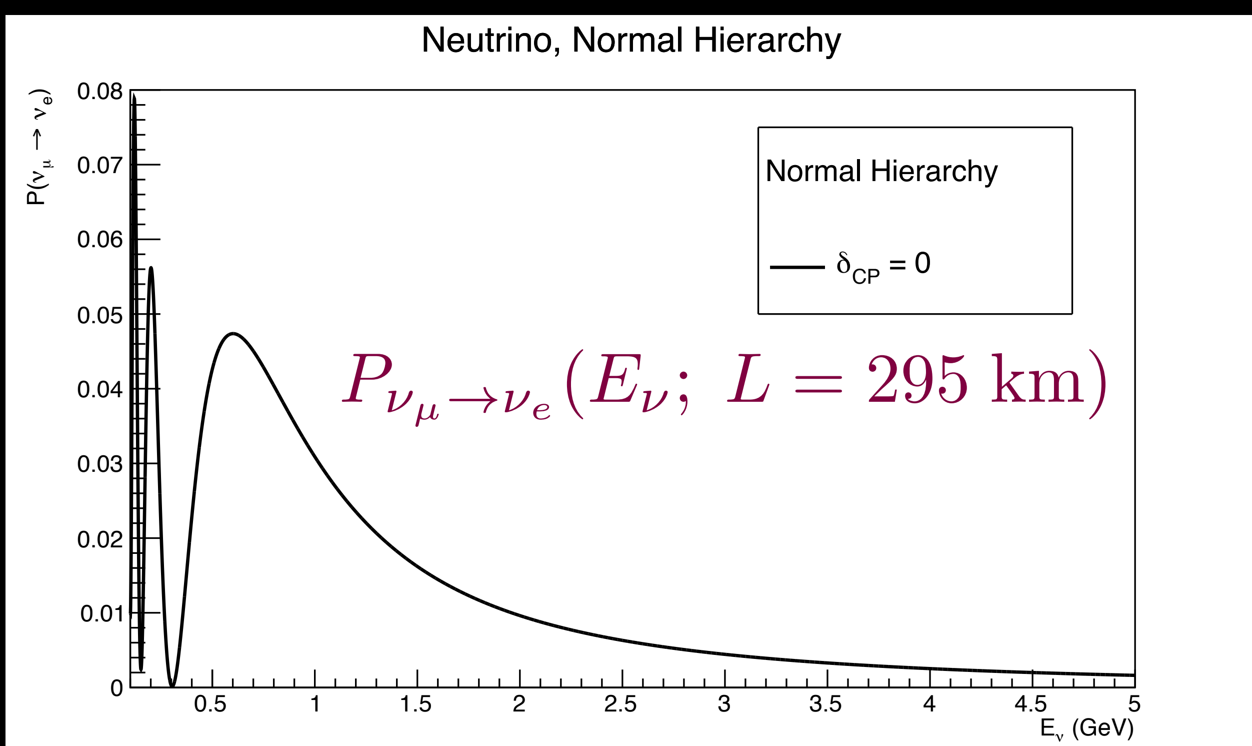
- "Survival" probability for initial ν_μ to be detected as ν_μ
  - the rest turns to ν_e, ν_τ
- θ_{13} determined by reactor experiment
- No CP asymmetry
  - ν_μ disappearance and $\bar{\nu}_\mu$ disappearance should be the same.

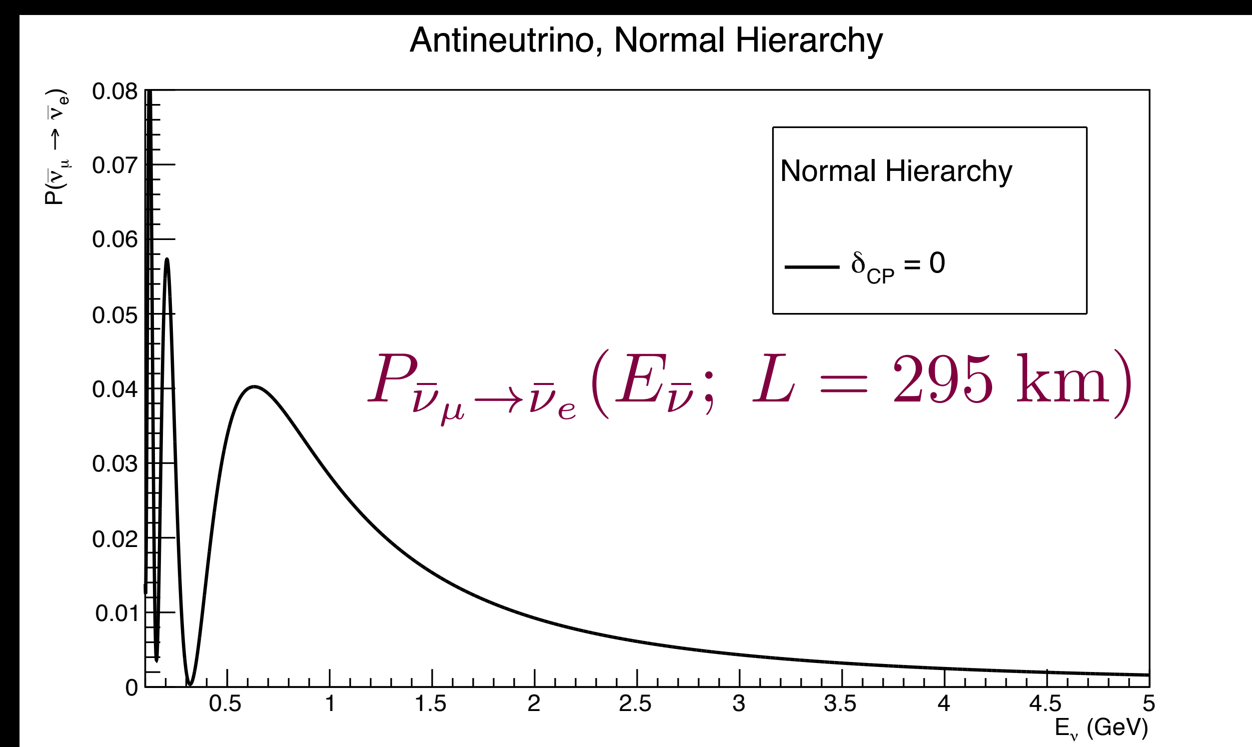
$\nu_\mu \rightarrow \nu_e$ oscillation

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

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

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





- Asymmetries from both δ_{CP} and matter effects
  - both switch sign in considering neutrino vs. antineutrino oscillations

$\nu_\mu \rightarrow \nu_e$ oscillation

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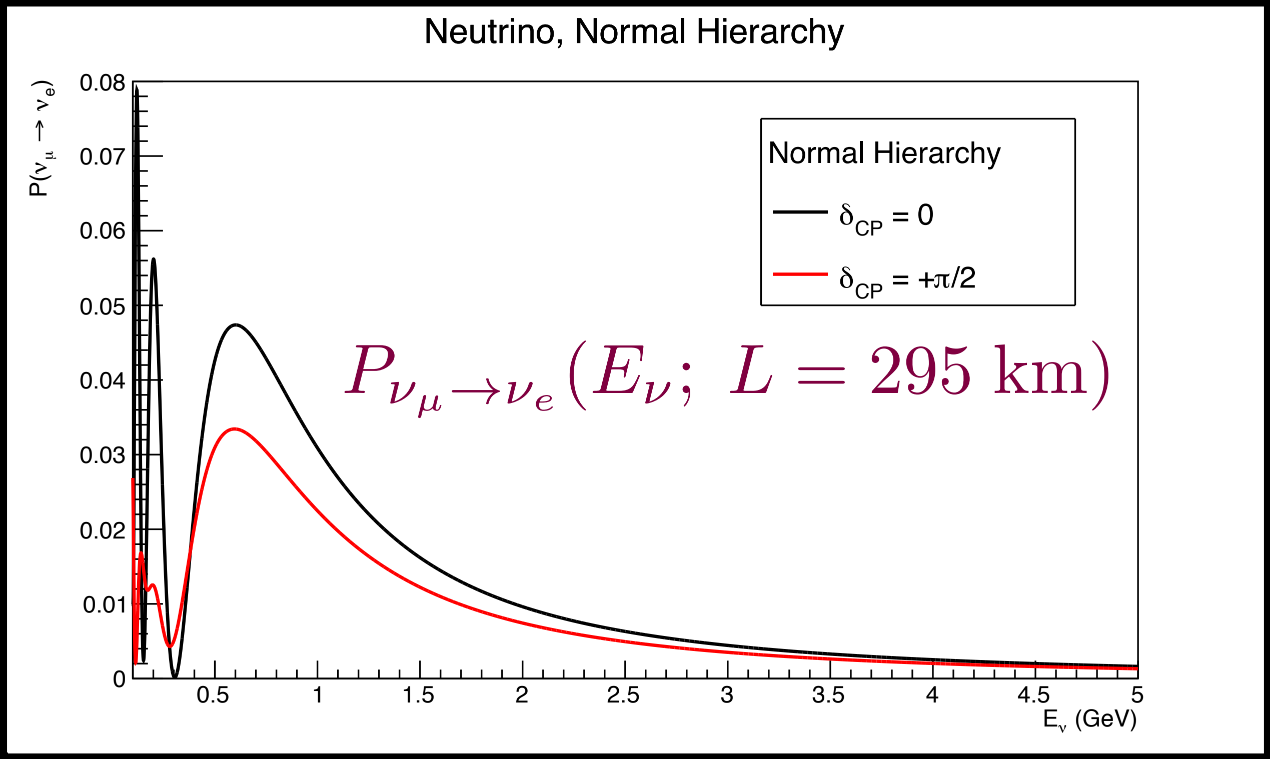

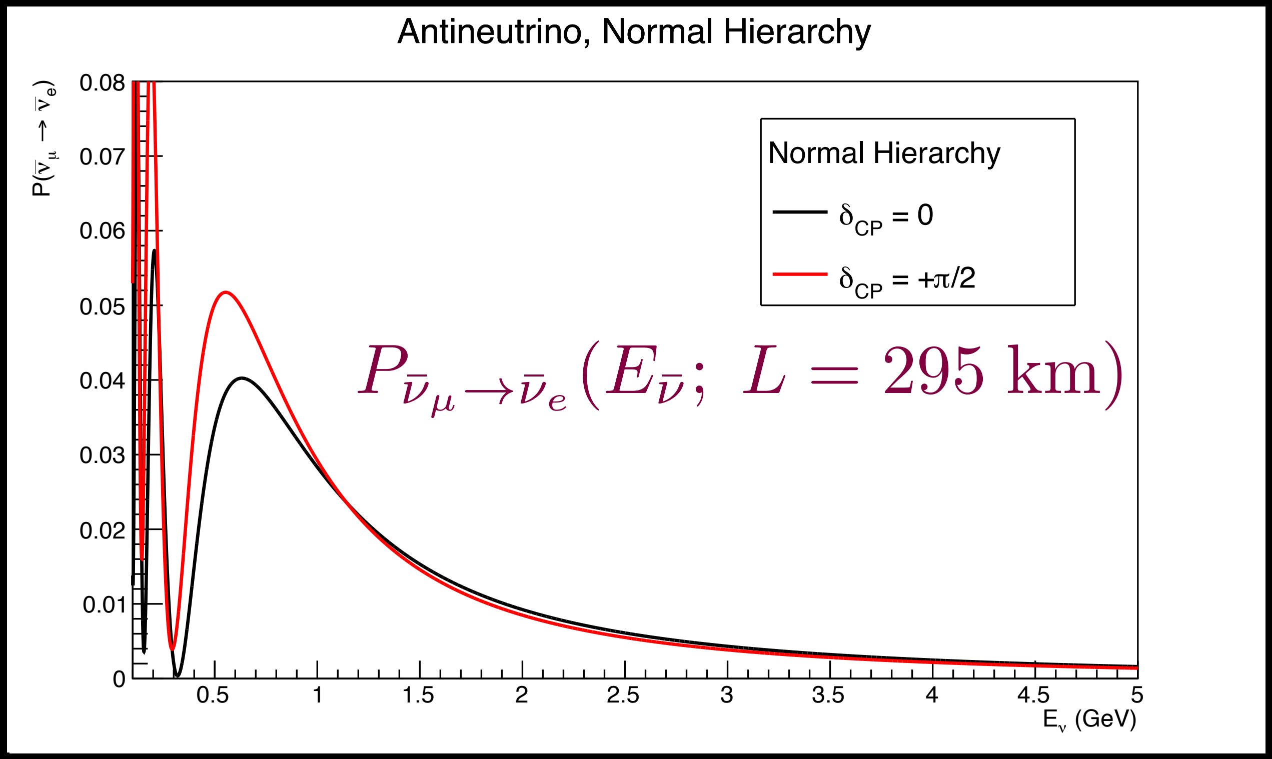

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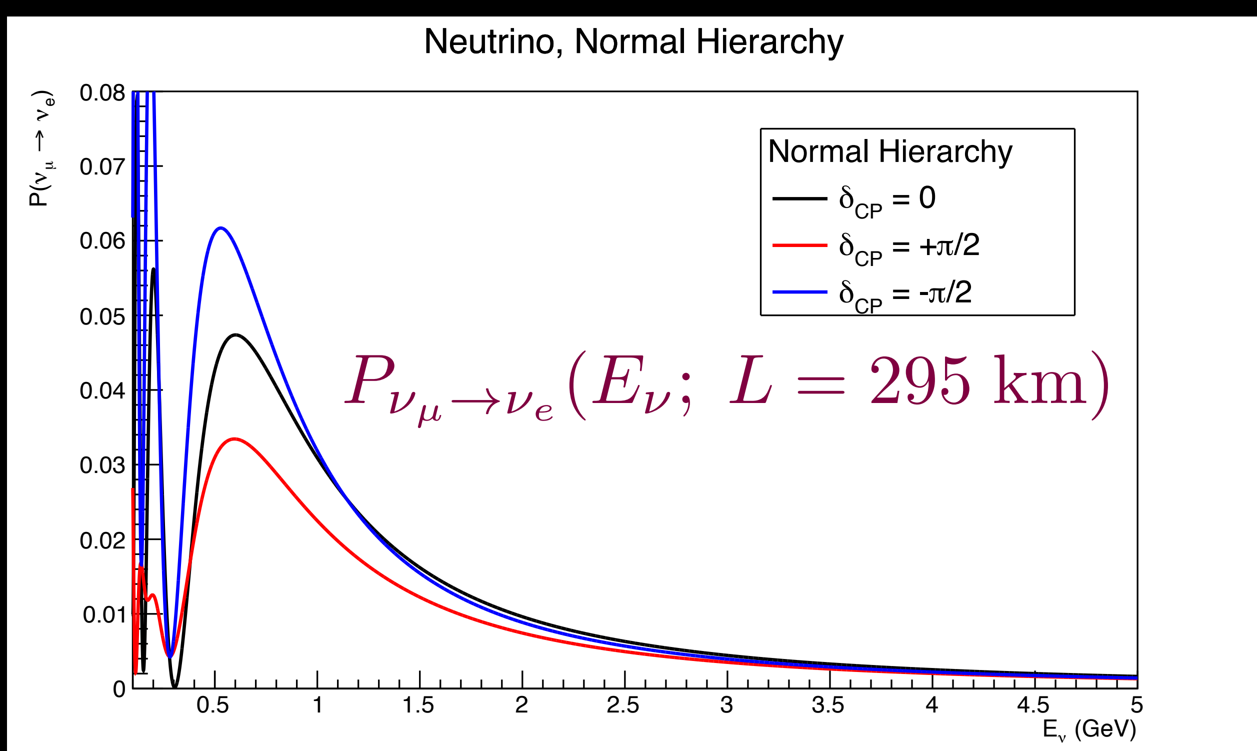

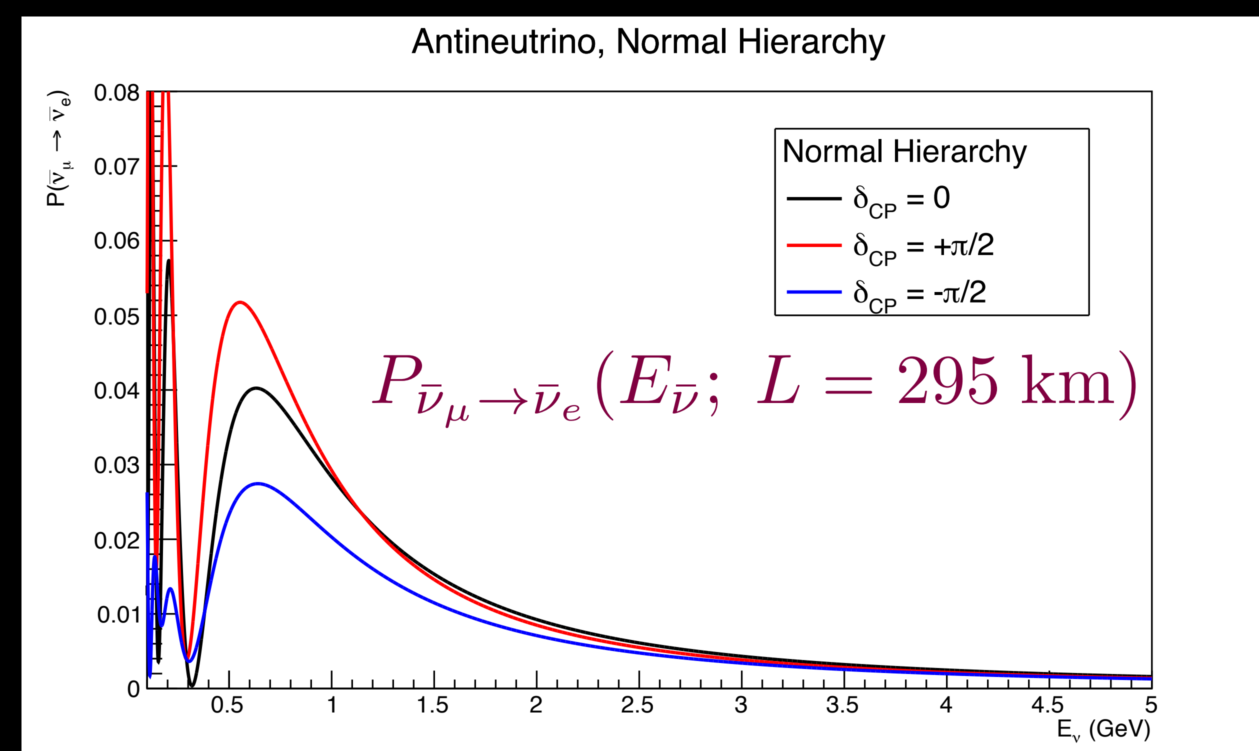

- Asymmetries from both δ_{CP} and matter effects
  - both switch sign in considering neutrino vs. antineutrino oscillations

$\nu_\mu \rightarrow \nu_e$ oscillation

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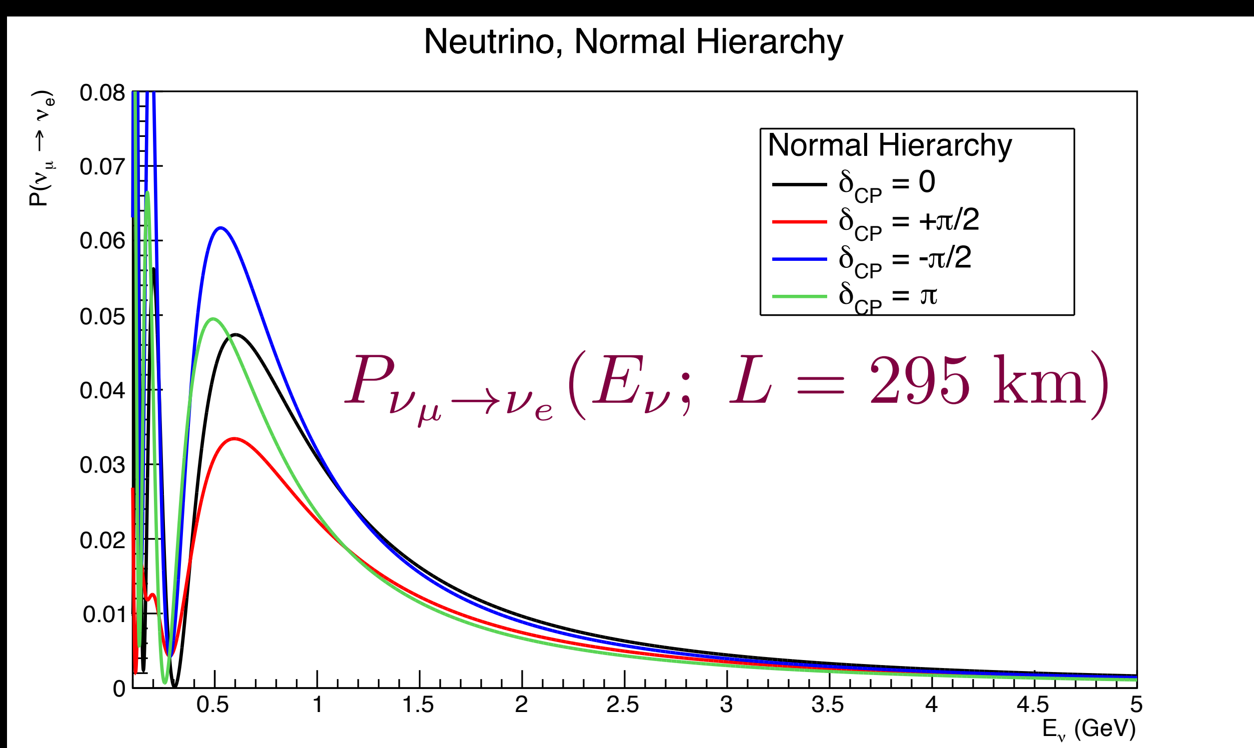
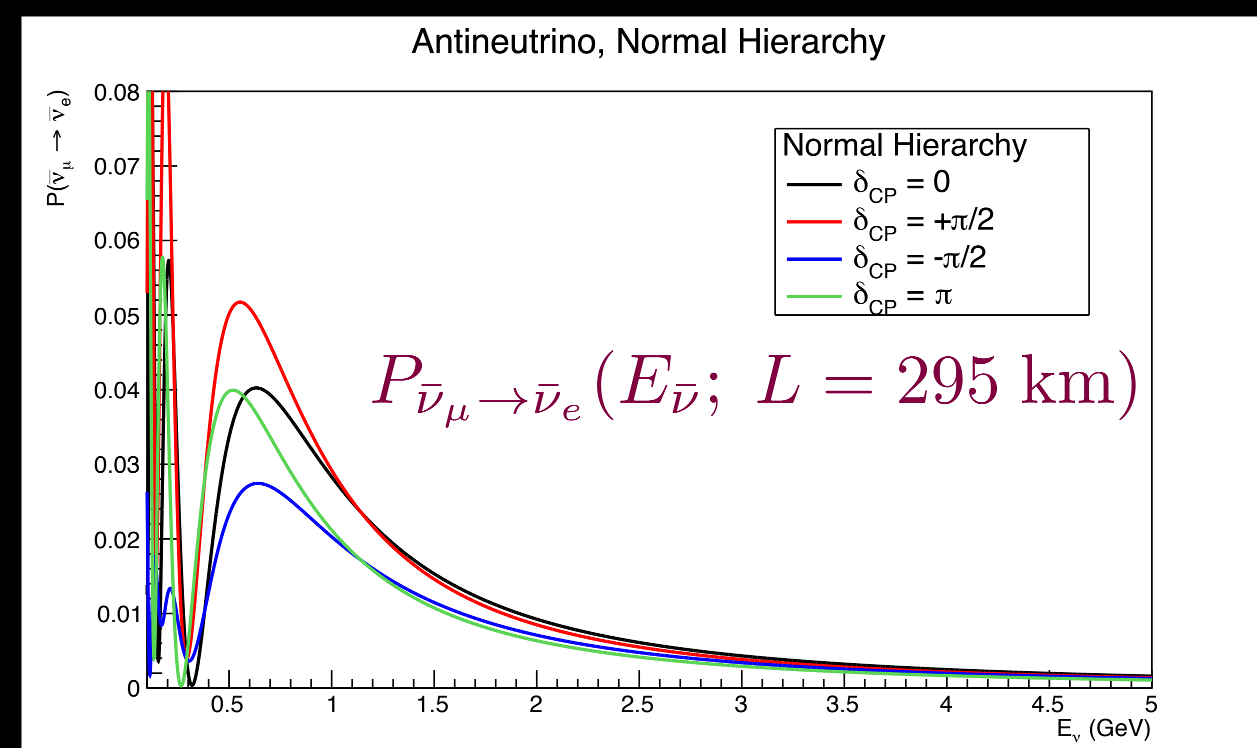
$$





- Asymmetries from both δ_{CP} and matter effects
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$\nu_\mu \longrightarrow \nu_e$ oscillation

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
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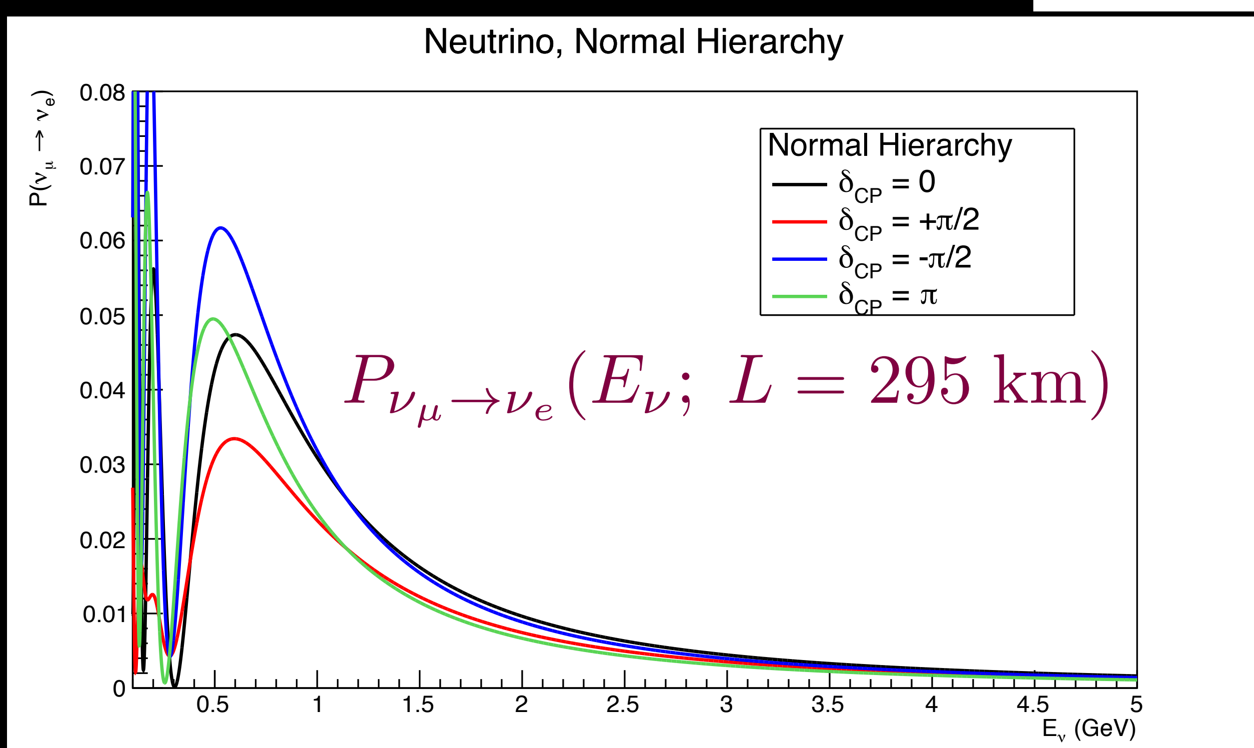
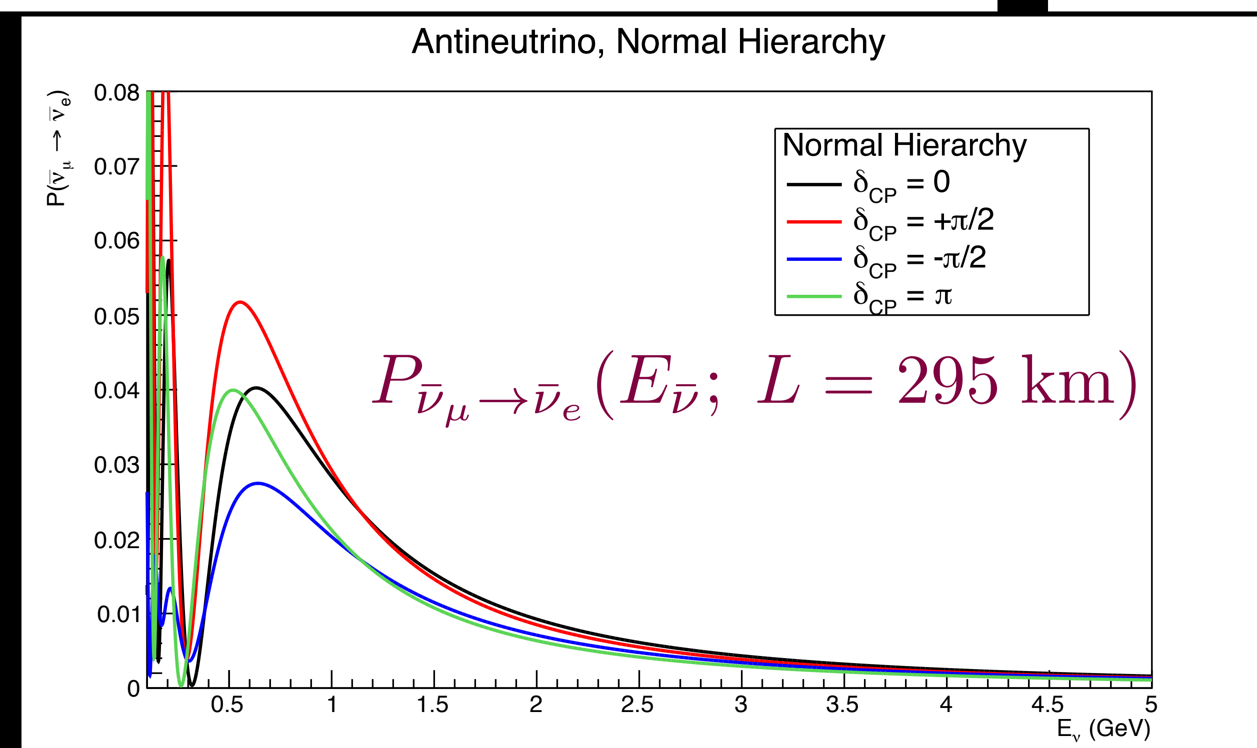
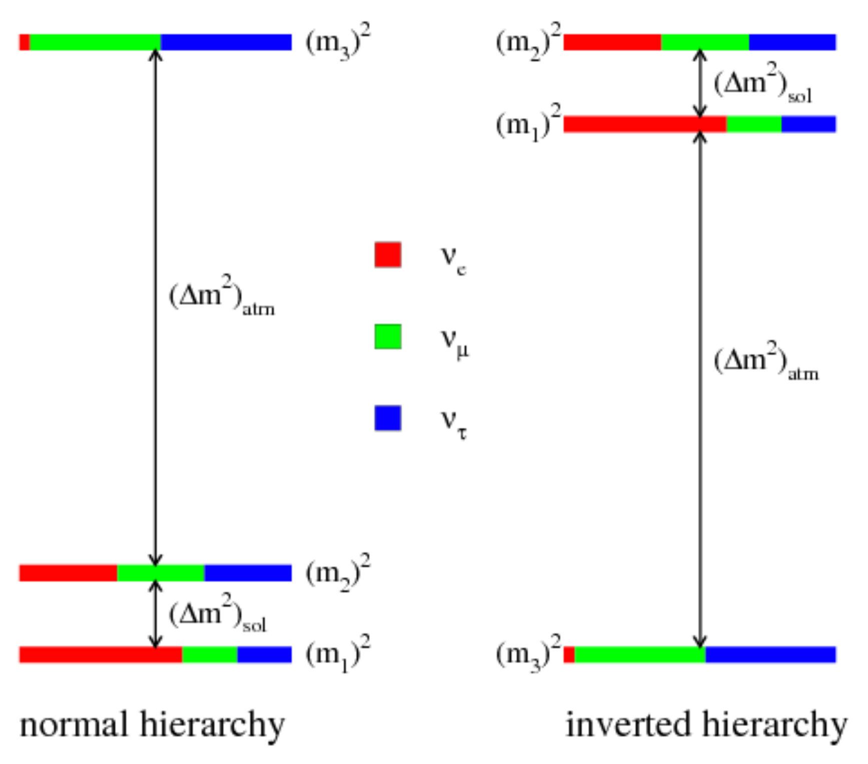




- Asymmetries from both δ_{CP} and matter effects
  - both switch sign in considering neutrino vs. antineutrino oscillations

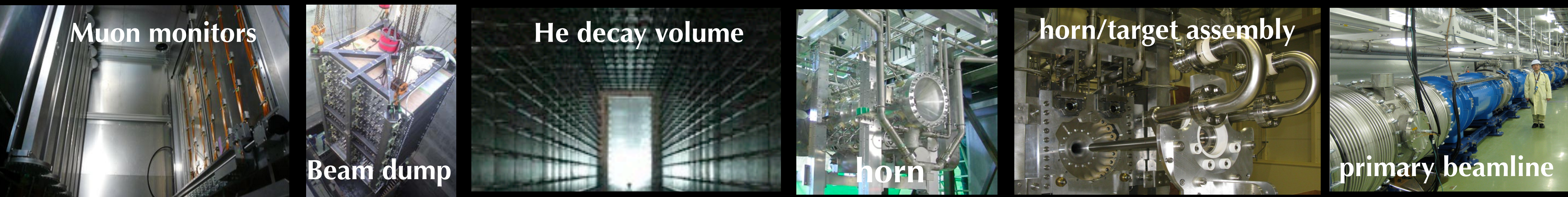
QUICK SUMMARY

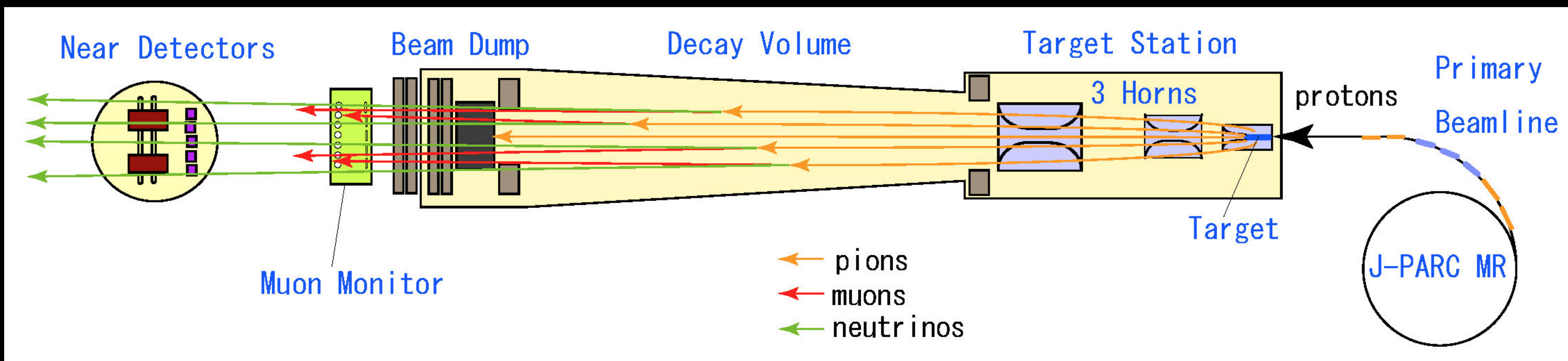
- CP violating parameter δ
  - δ =0,π: no CP violation: vacuum oscillation probabilities equal
  - δ ~-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - δ ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
  - enhance both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- "normal" hierarchy:
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



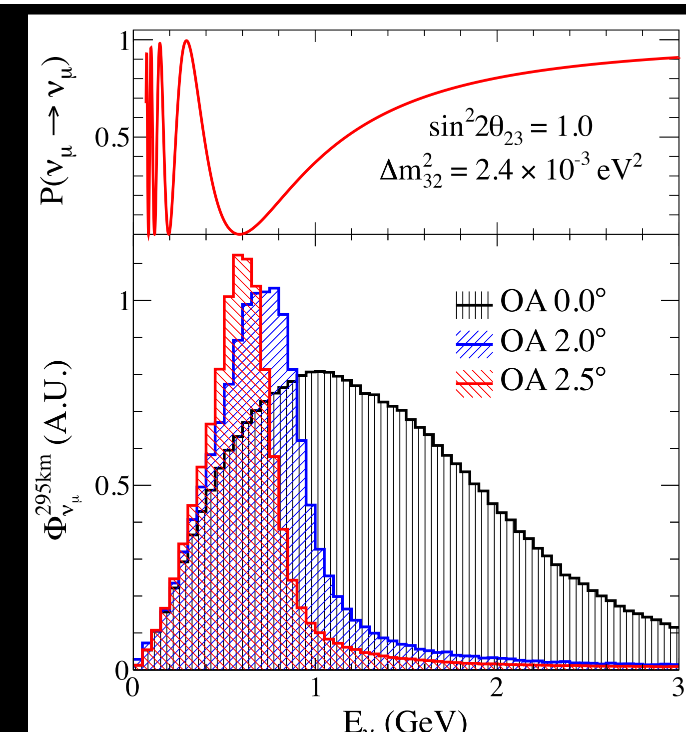
- "inverted" hierarchy:
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

PRODUCING THE BEAM

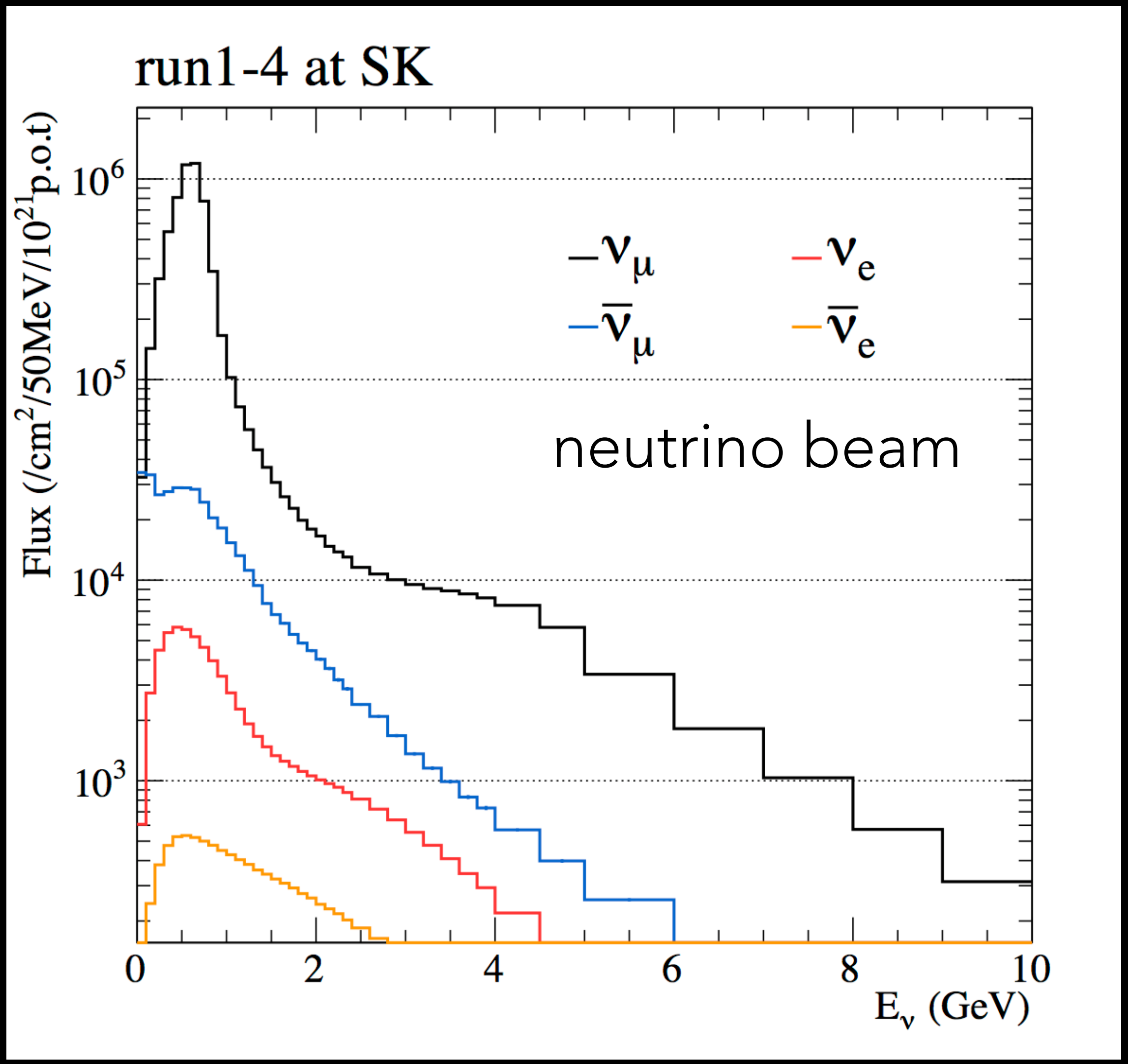




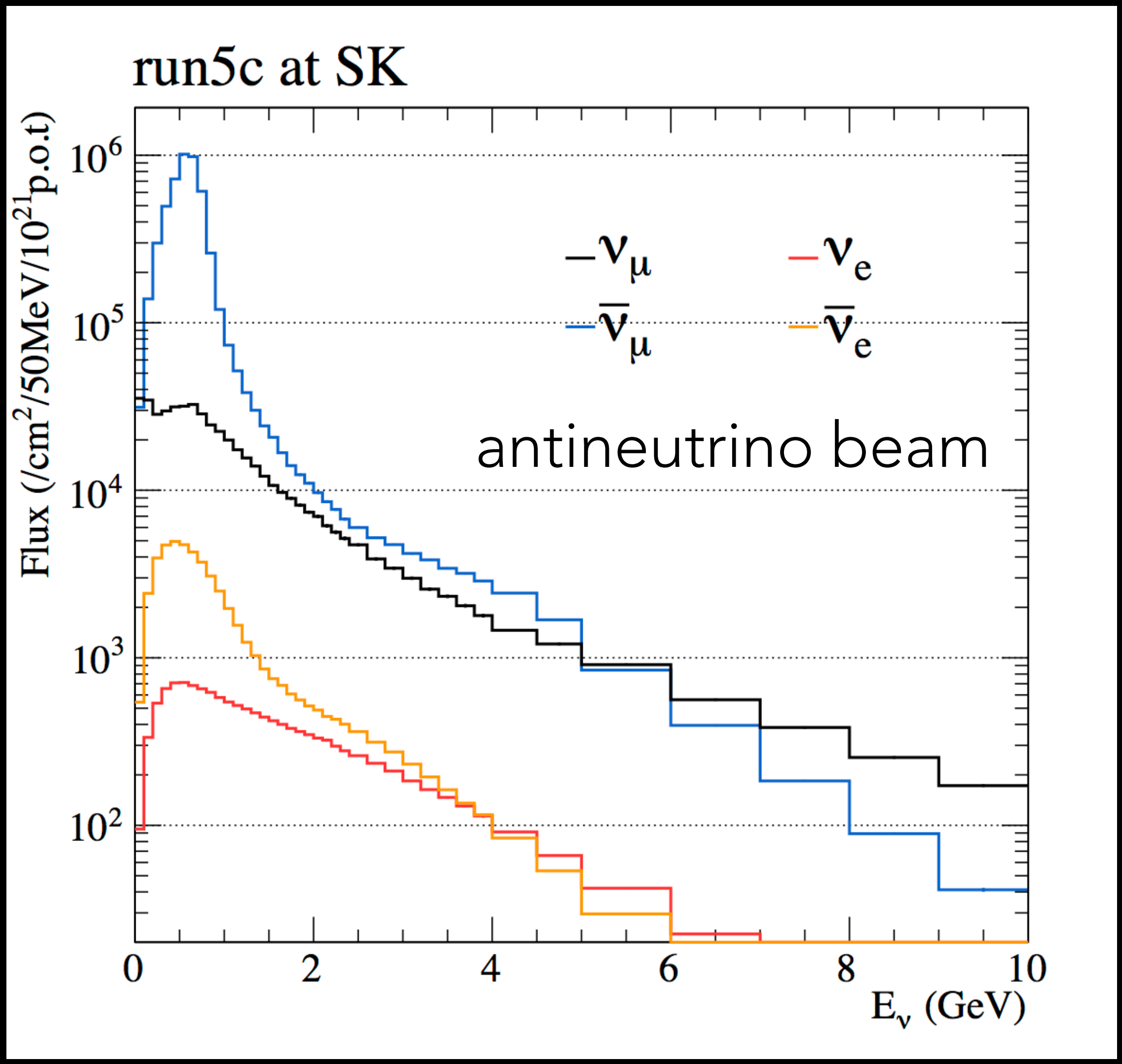
- 30 GeV protons extracted from J-PARC MR a target
  - secondary π^+ focussed by three EM "horns"
  - primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - reverse polarity for antineutrino beam: $\pi^- \rightarrow \mu^+ + \nu_\mu$
  - spectrum peaked at 600 MeV "off axis"
    - expected oscillation "maximum" for L=295 km



NEUTRINO AND ANTINEUTRINO



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



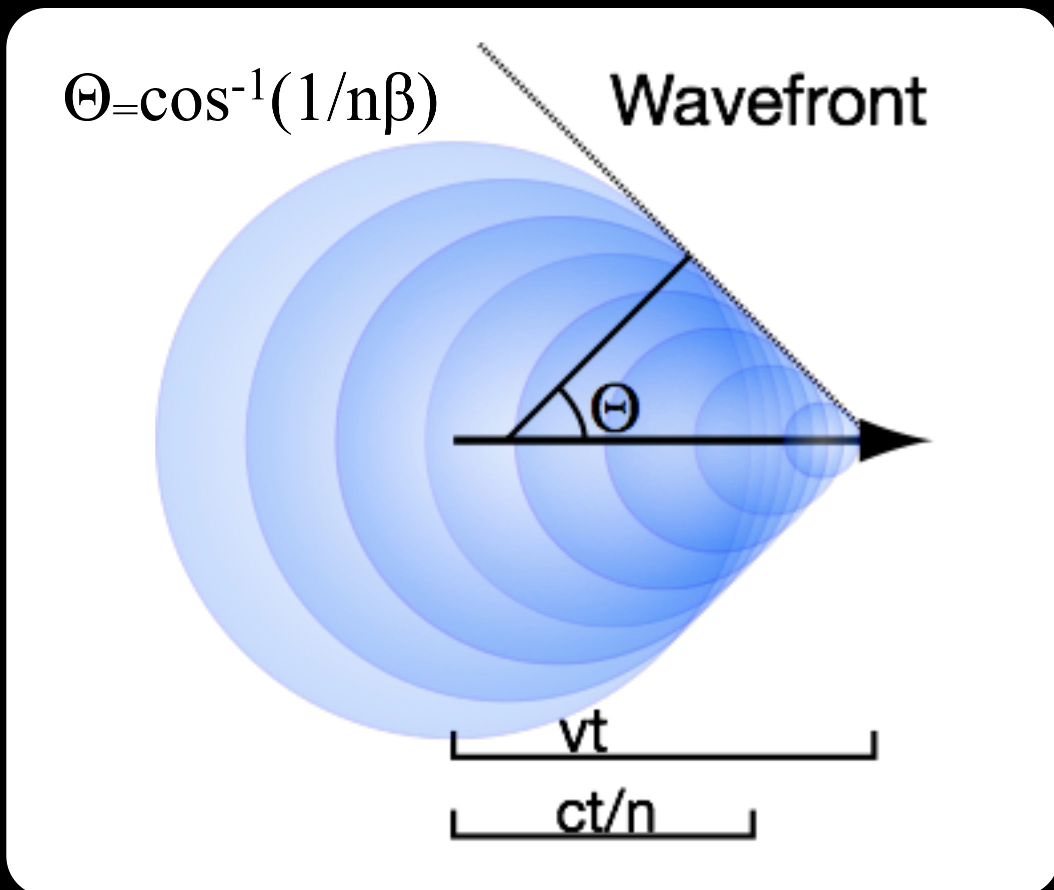
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

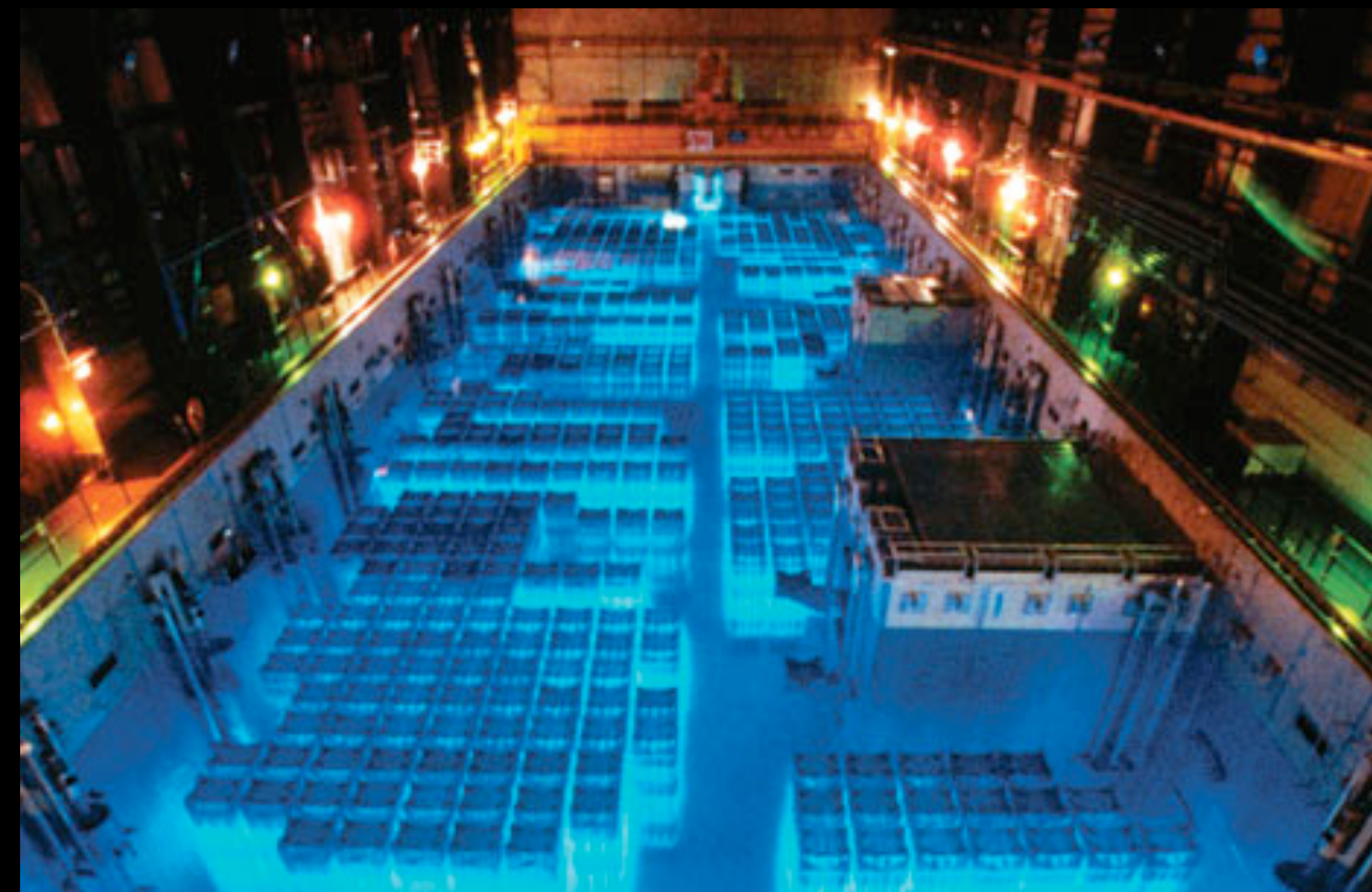
- <1% impurity from $\nu_e/\bar{\nu}_e$ at energy peak; important for backgrounds
- Magnetic focussing allows T2K to switch between a neutrino/anti-neutrino beam
- We can study neutrino and antineutrino oscillations.

SUPER-KAMIOKANDE

- 50 kiloton water Cherenkov detector
- 40 m diameter x 40 m height
- 11146 50 cm photomultiplier tubes

CHERENKOV RADIATION



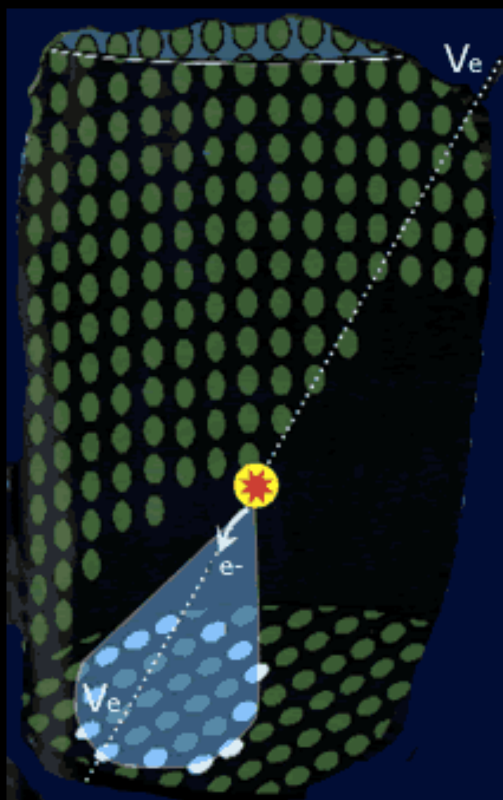


findagrave.com

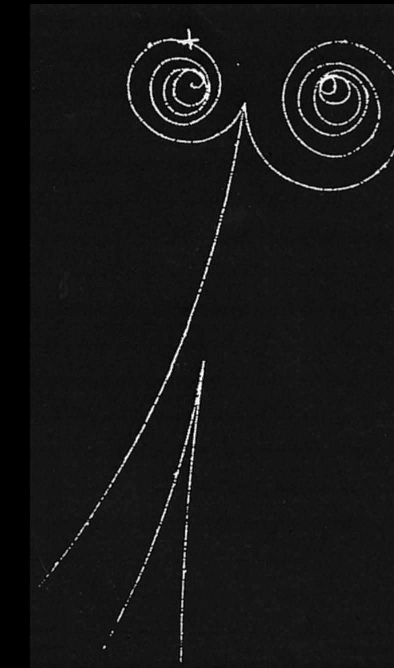
EM radiation emitted when a charged particle exceeds velocity of light in a dielectric medium

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

DETECTION PRINCIPLE:

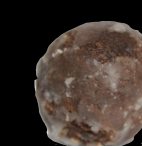


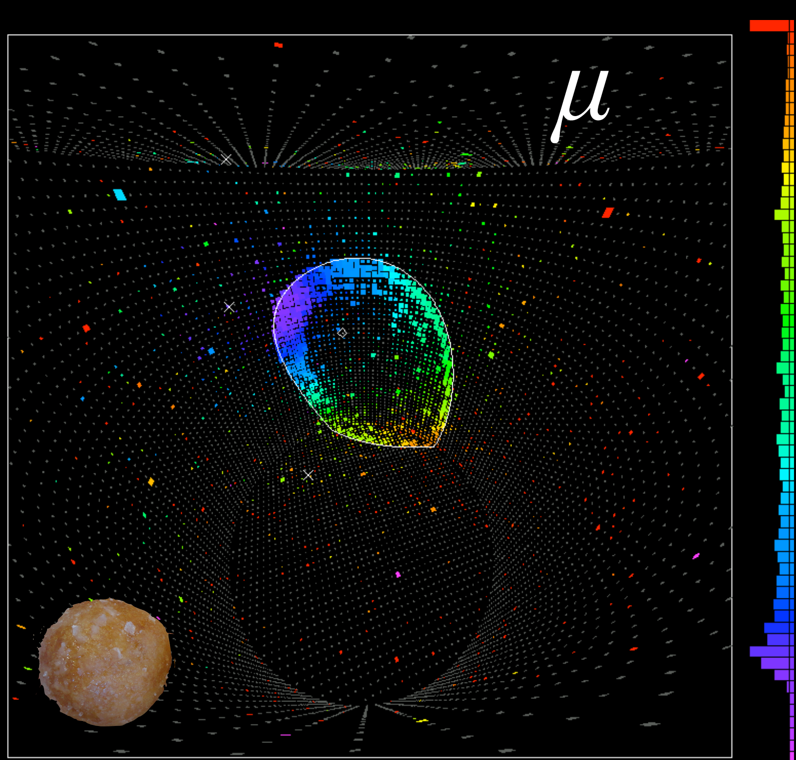
- Minimum-ionizing particles (e.g. μ) travel along a ~straight line, emitting a cone of Č light
- e/γ: shower produces e^+/e^- producing Č light.
- Identify single Č rings from

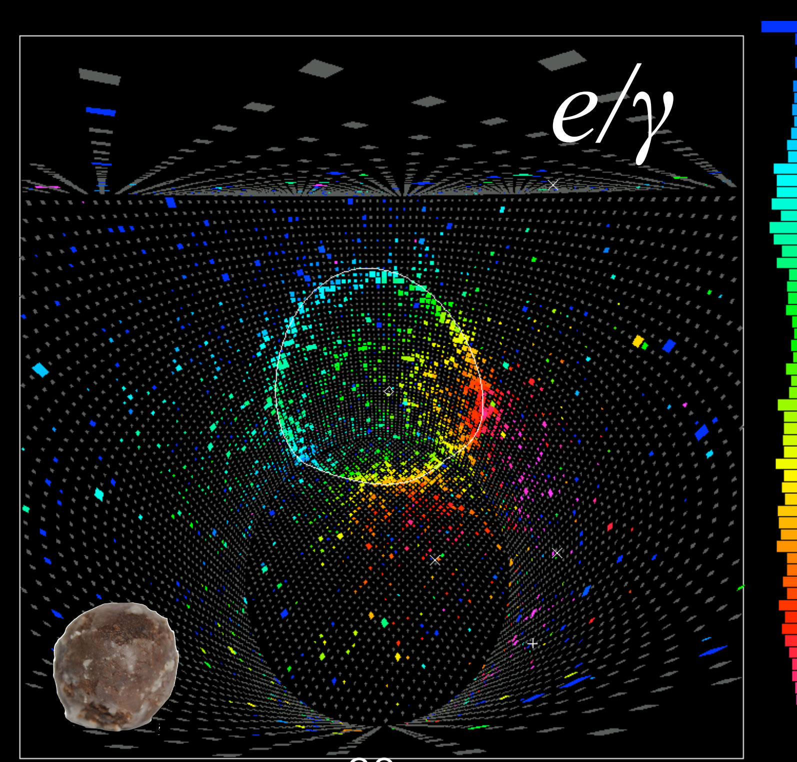


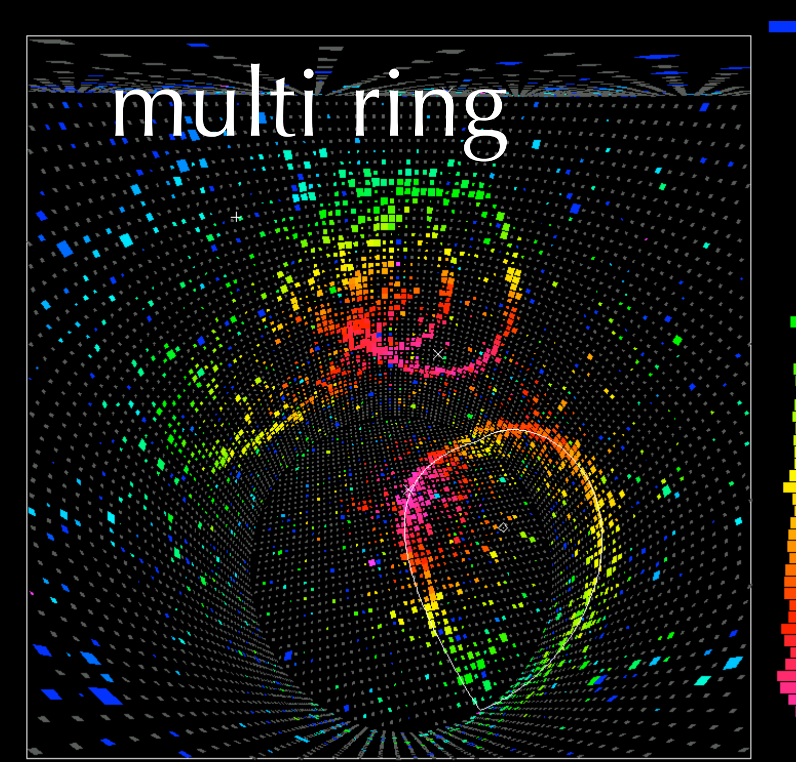
$$\nu_\mu + n \rightarrow \mu^- + p \qquad \bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

$$\nu_e + n \rightarrow e^- + p \qquad \bar{\nu}_e + p \rightarrow e^+ + n$$

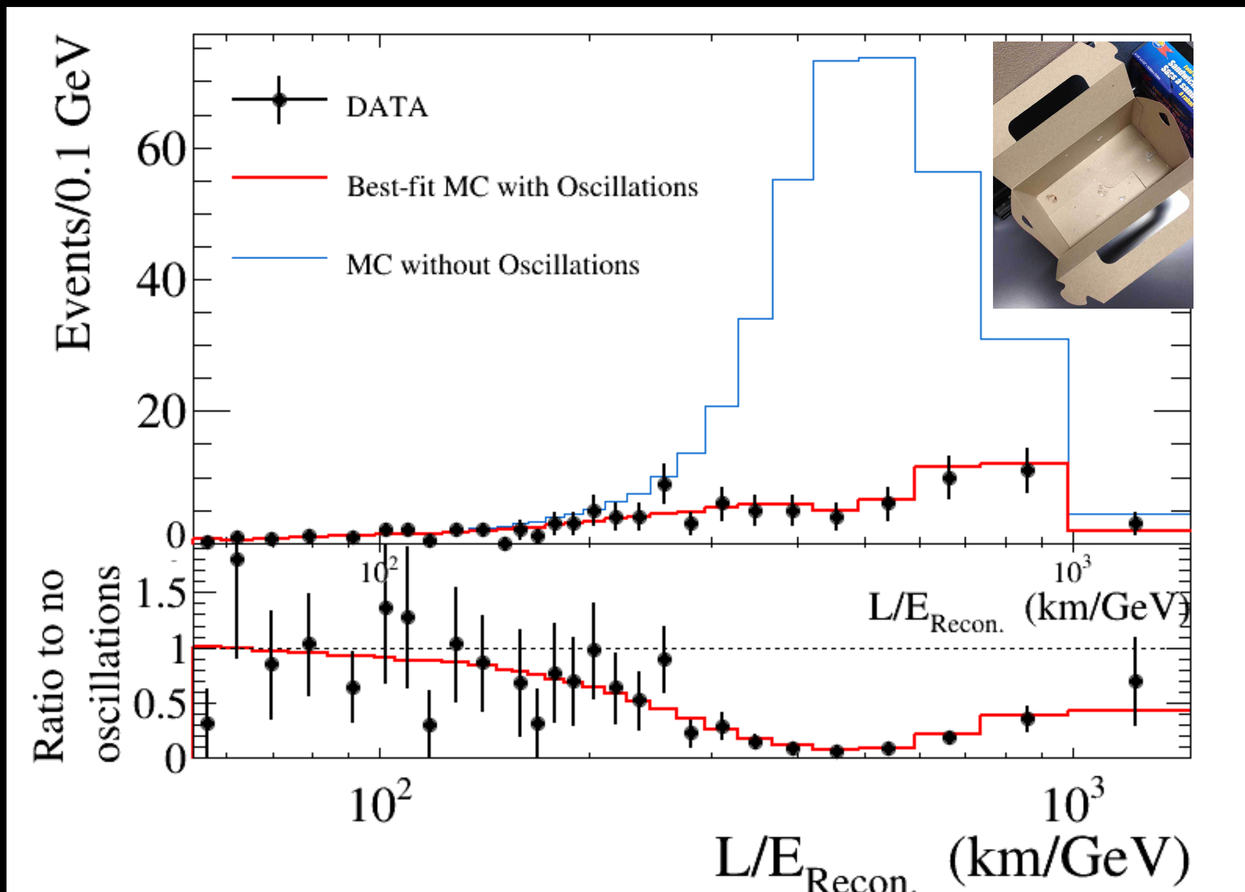


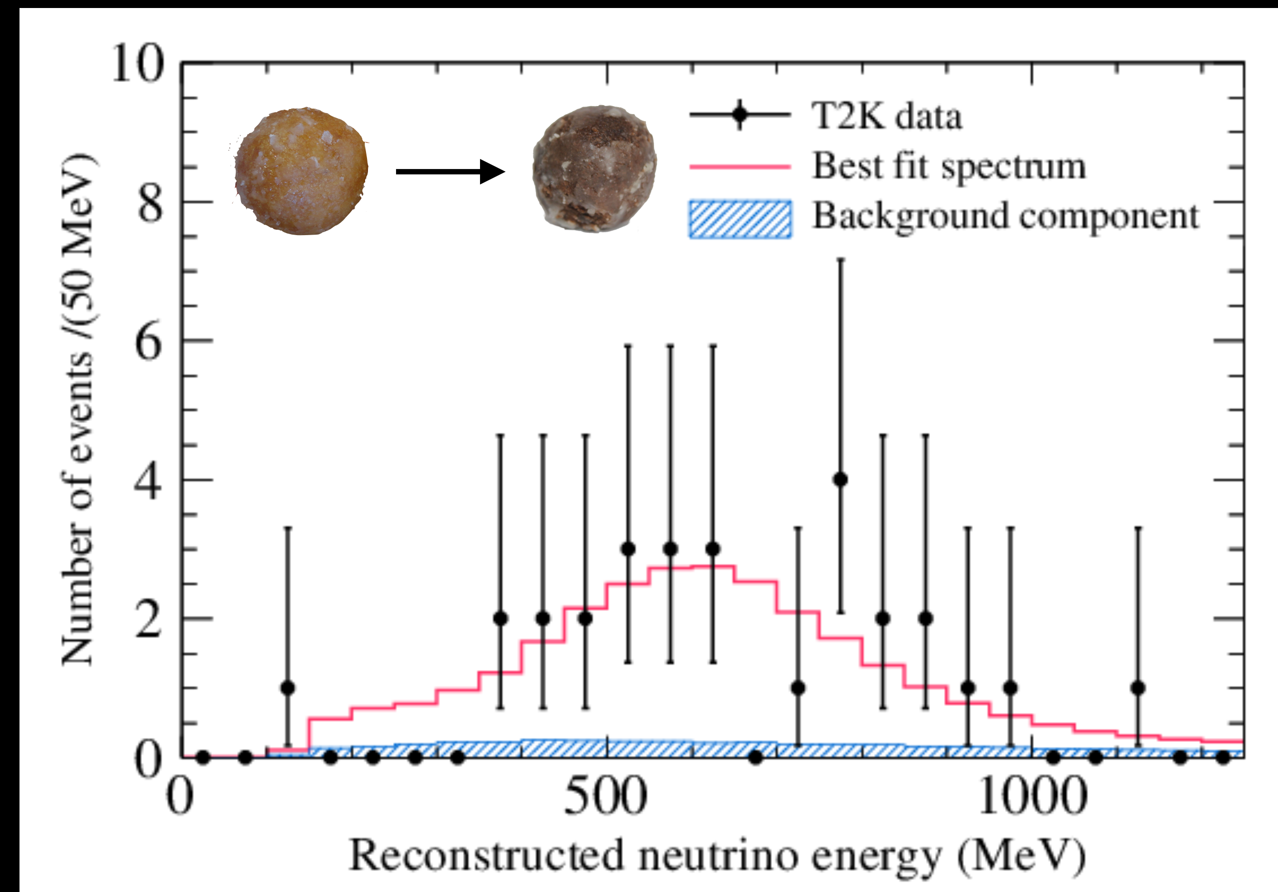






NEUTRINO MODE DATA





- 28 ν_e candidates observed
  - 5.0 expected in absence of osc. effects
- 120 ν_μ candidates observed
  - 446 expected in absence of osc. effects
- Most precise determination of ν_μ disappearance
  - $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$
  - $\Delta m^2_{32} = (2.51 \pm 0.51) \times 10^{-3}\ \mathrm{eV}^2/c^4$

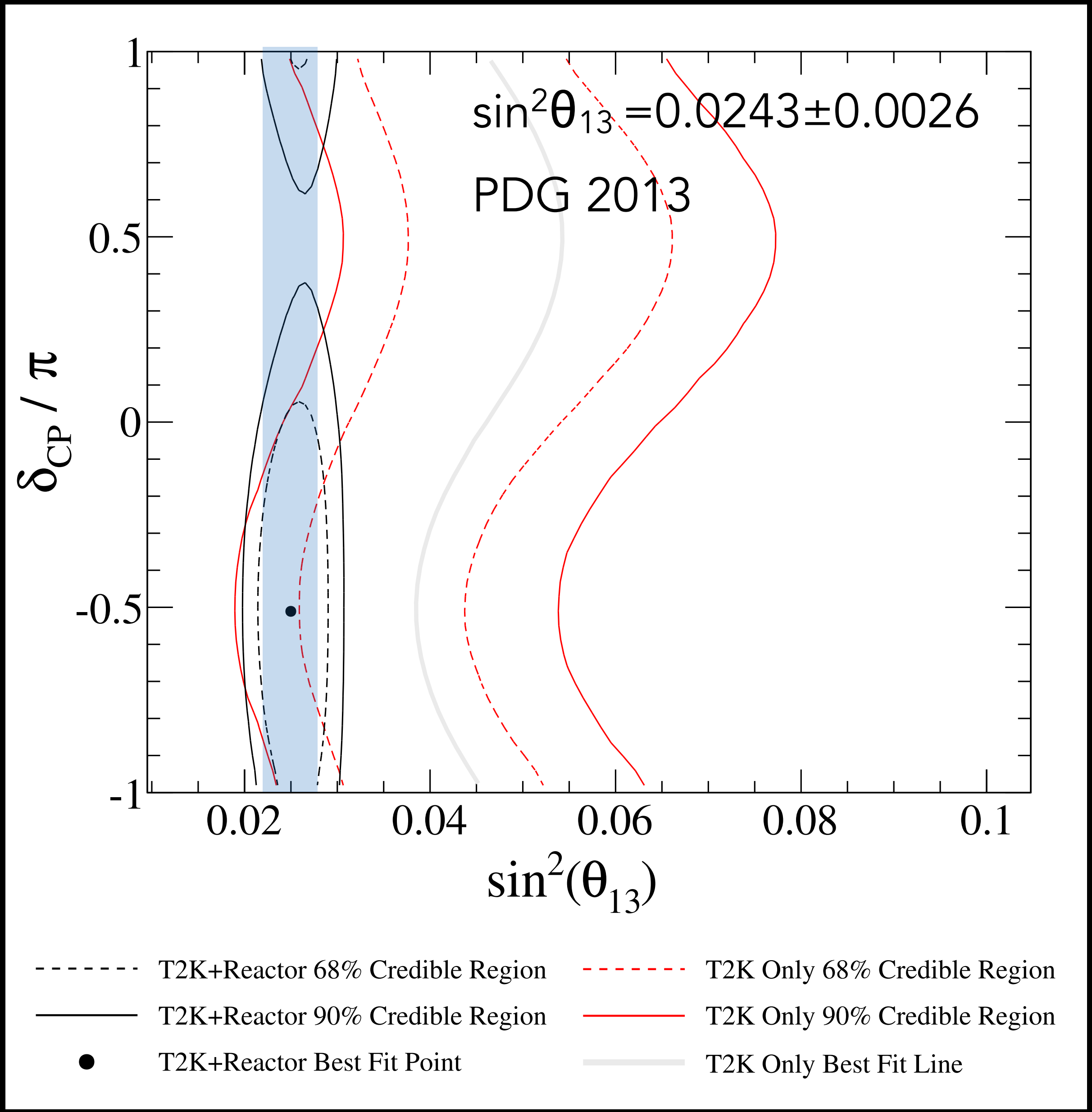
	Osc.	No osc.
ν_μ	0.9	1.4
$\bar{\nu}_\mu$	0.1	0.1
$\nu_e/\bar{\nu}_e$	3.3	3.5
$\nu_\mu\to\nu_e$	16.6	0.0
$\bar{\nu}_\mu\to\bar{\nu}_e$	0.2	0.0
Total	21.1	5.0

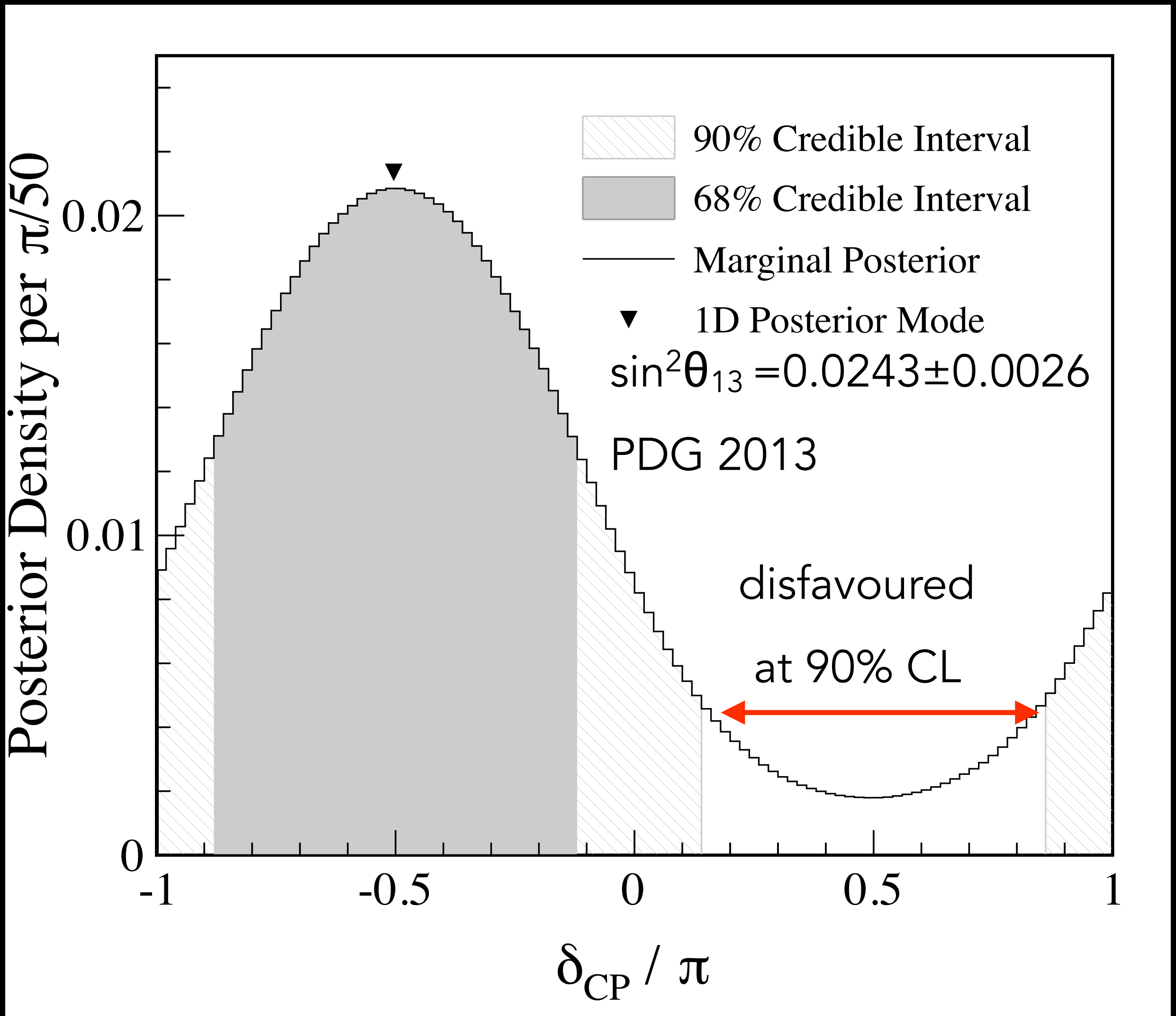
expected number of ν_e candidates

"Oscillation":
$\sin^2\theta_{23}=0.5$
$\sin^2\theta_{13} = 0.0243$
$\delta_{CP} = 0$
Norm. Hier.

6.6×10^{20} POT

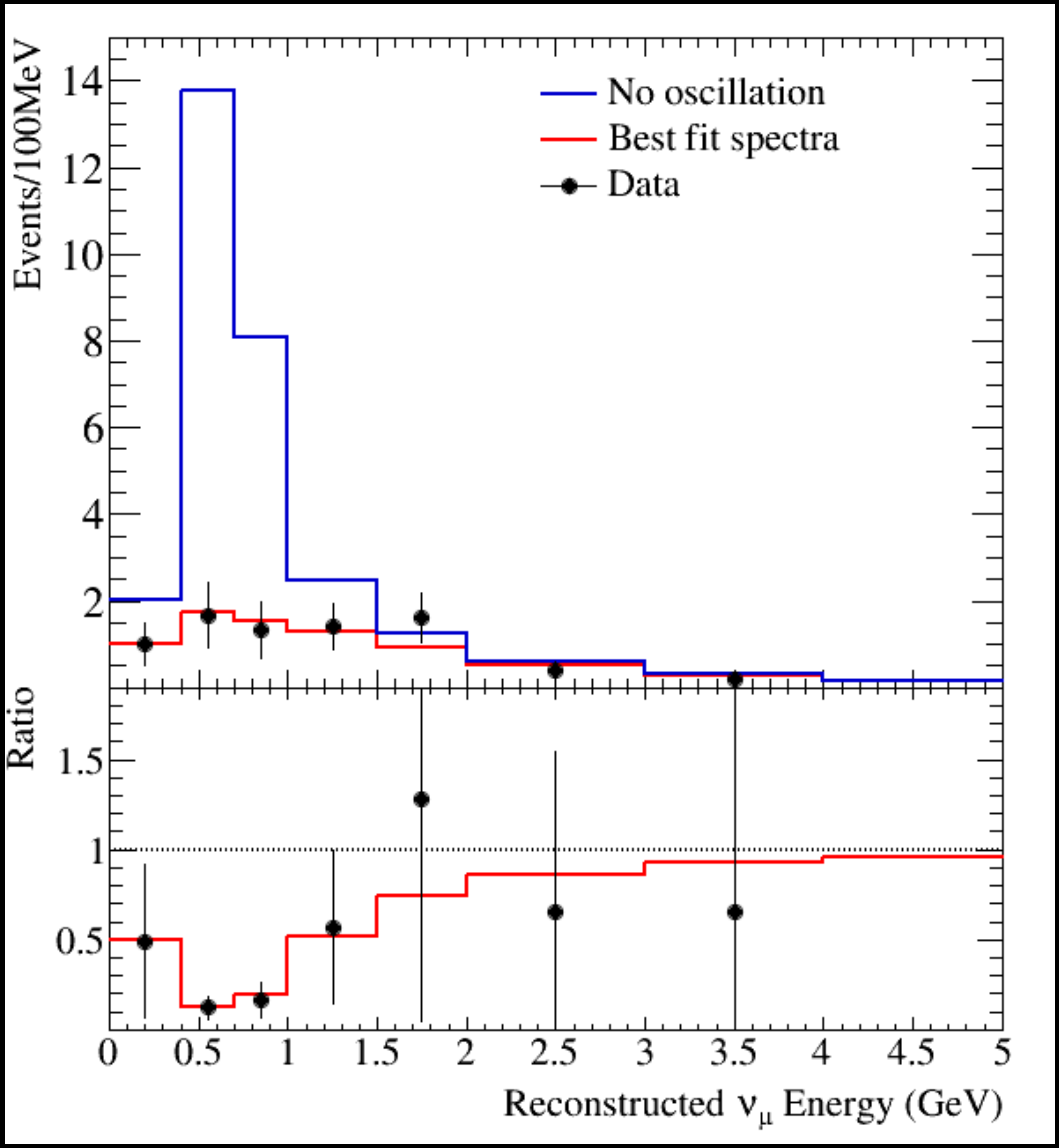
JOINT $\nu_\mu + \nu_e$ ANALYSIS

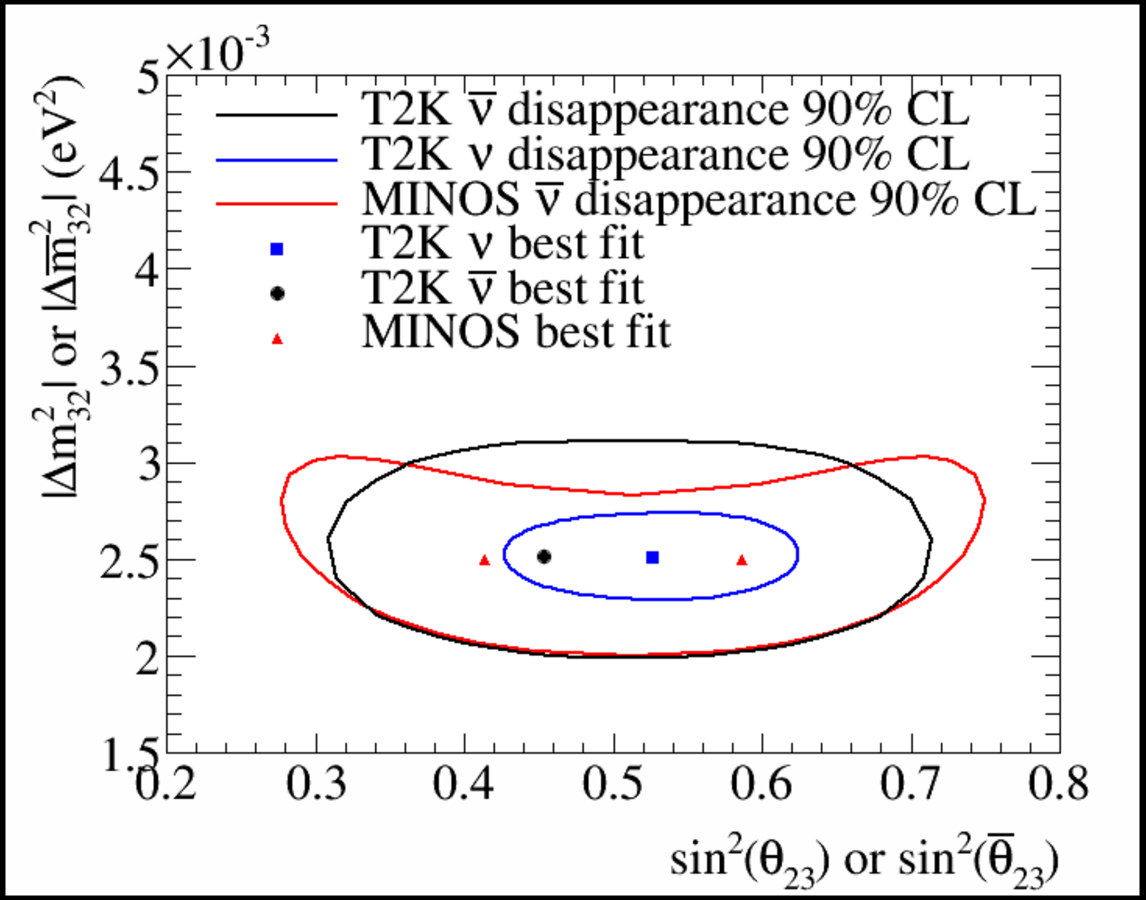




- With θ_{13} from reactor experiment, large ν_e appearance slightly prefers:
  - Normal Hierarchy, $\theta_{23} > \pi/4$
  - $\delta_{CP} \sim -\pi/2$,

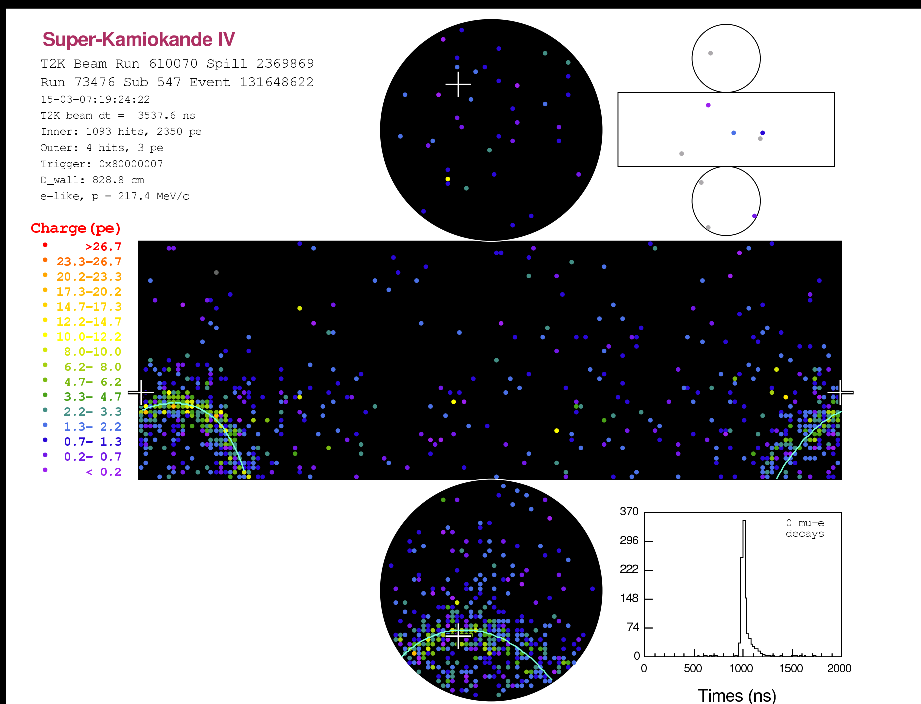
$\bar{\nu}_\mu$ CANDIDATES

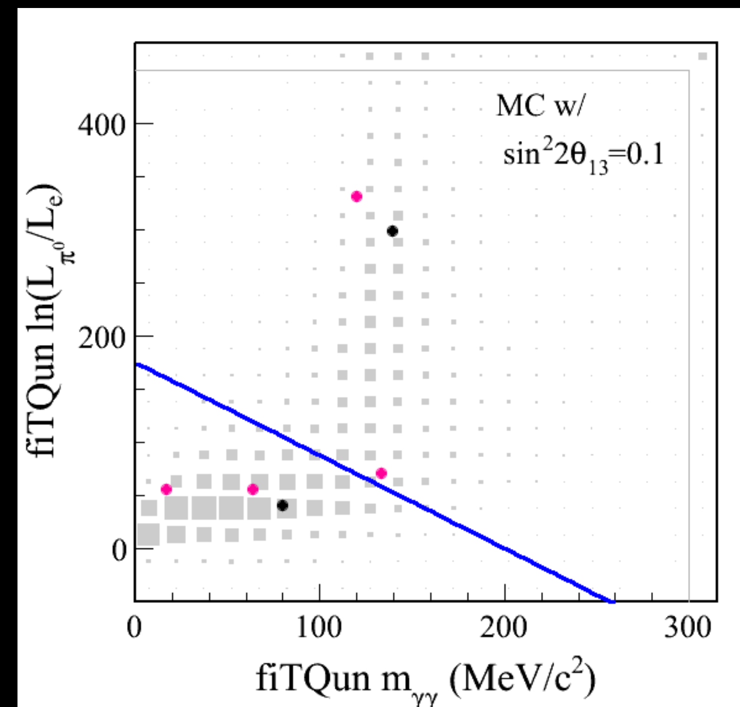




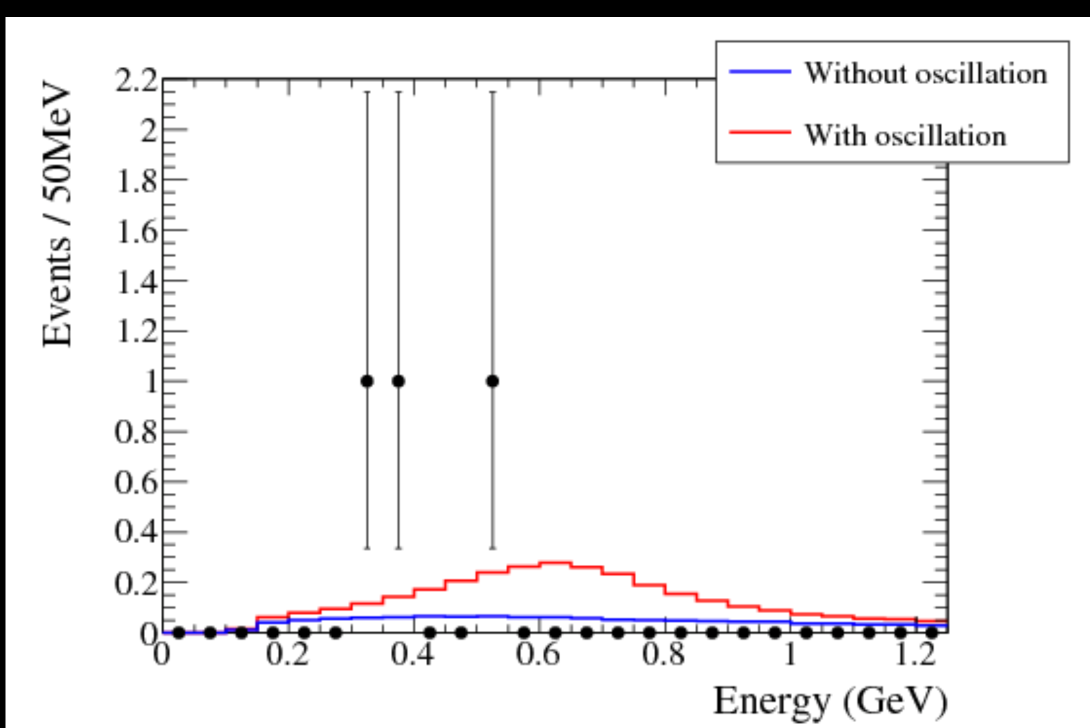
- 4.01×10^{20} POT in antineutrino mode
- 34 $\bar{\nu}_\mu$ candidates observed
  - 103.6 events expected in absence of oscillations
- Consistent parameters ($\bar{\theta}_{23}$, $\Delta\bar{m}^2_{32}$) with neutrino mode obtained

$\bar{\nu}_e$ CANDIDATES





	δ_{CP}		
	-π/2	0	+π/2
NC	0.4	0.4	0.4
Other	0.8	0.8	0.8
$\nu_\mu \to \nu_e$	0.6	0.5	0.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	**2.0**	**2.6**	**3.3**
Total	3.7	4.3	4.9



- 3 $\bar{\nu}_e$ candidates observed
  - 1.1 expected in the absence of $\nu_\mu \to \nu_e$
- More data needed to establish
  - observation of $\nu_\mu \to \nu_e$
  - consistency with $\bar{\nu}_\mu \to \bar{\nu}_e$ mode in PMNS model
- **First steps towards probing CPV in ν oscillations**
- Joint fit of all 4 modes in progress . . . .

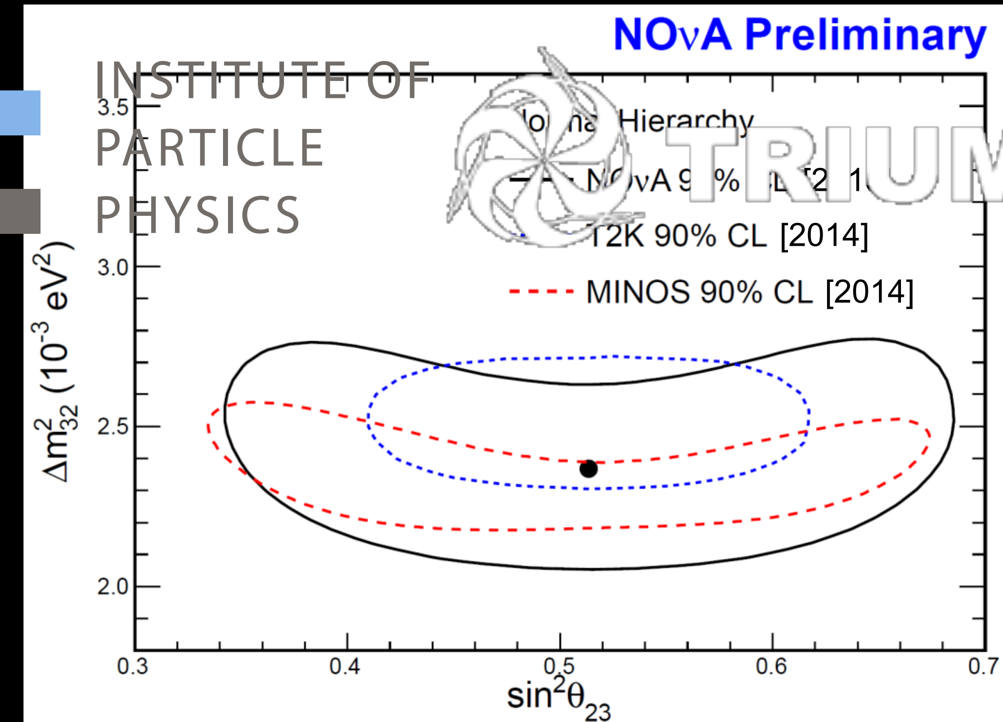
NOVA

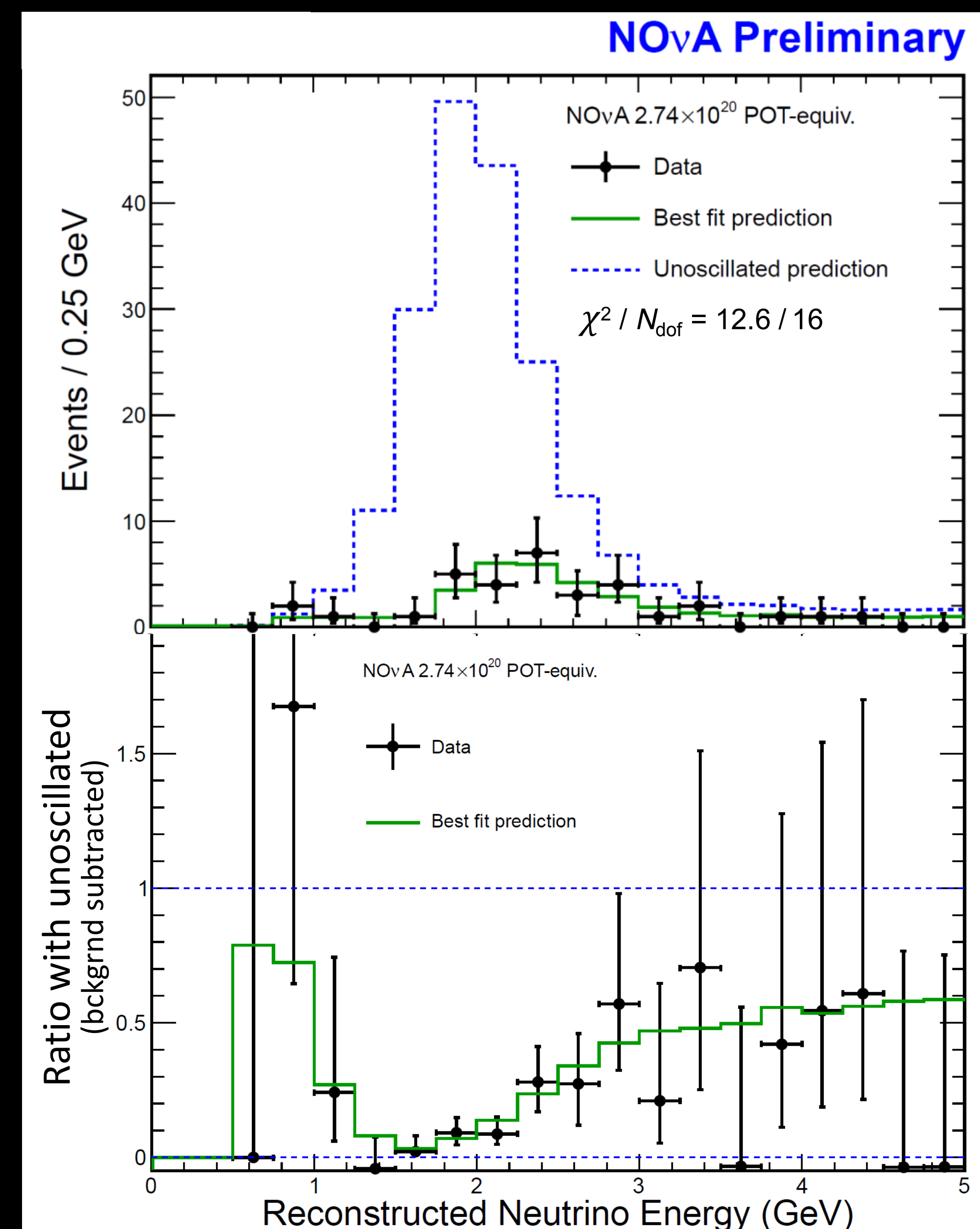
KYOTO UNIVERSITY FOUNDED 1897

UNIVERSITY OF TORONTO

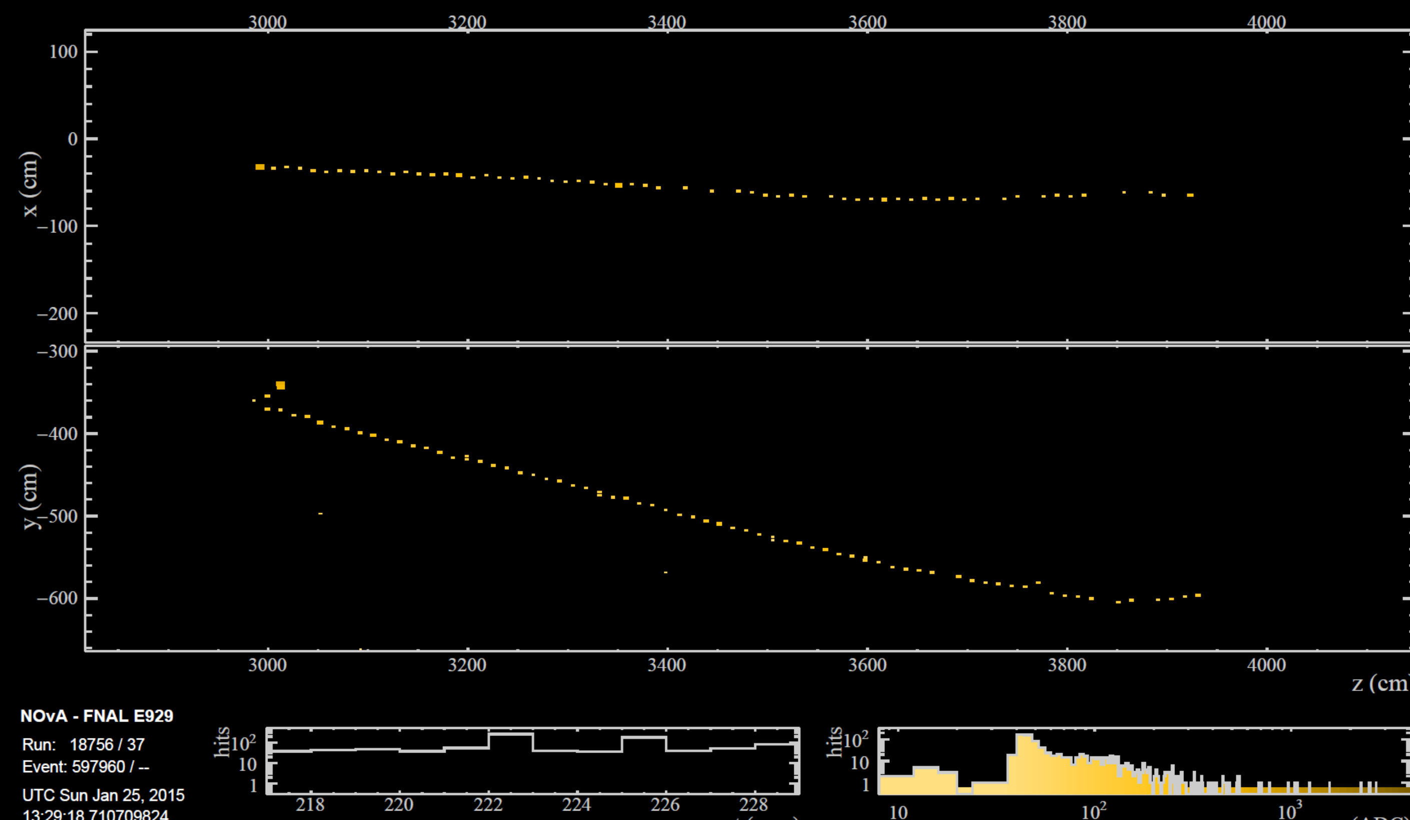
INSTITUTE OF PARTICLE PHYSICS

TRIUMF

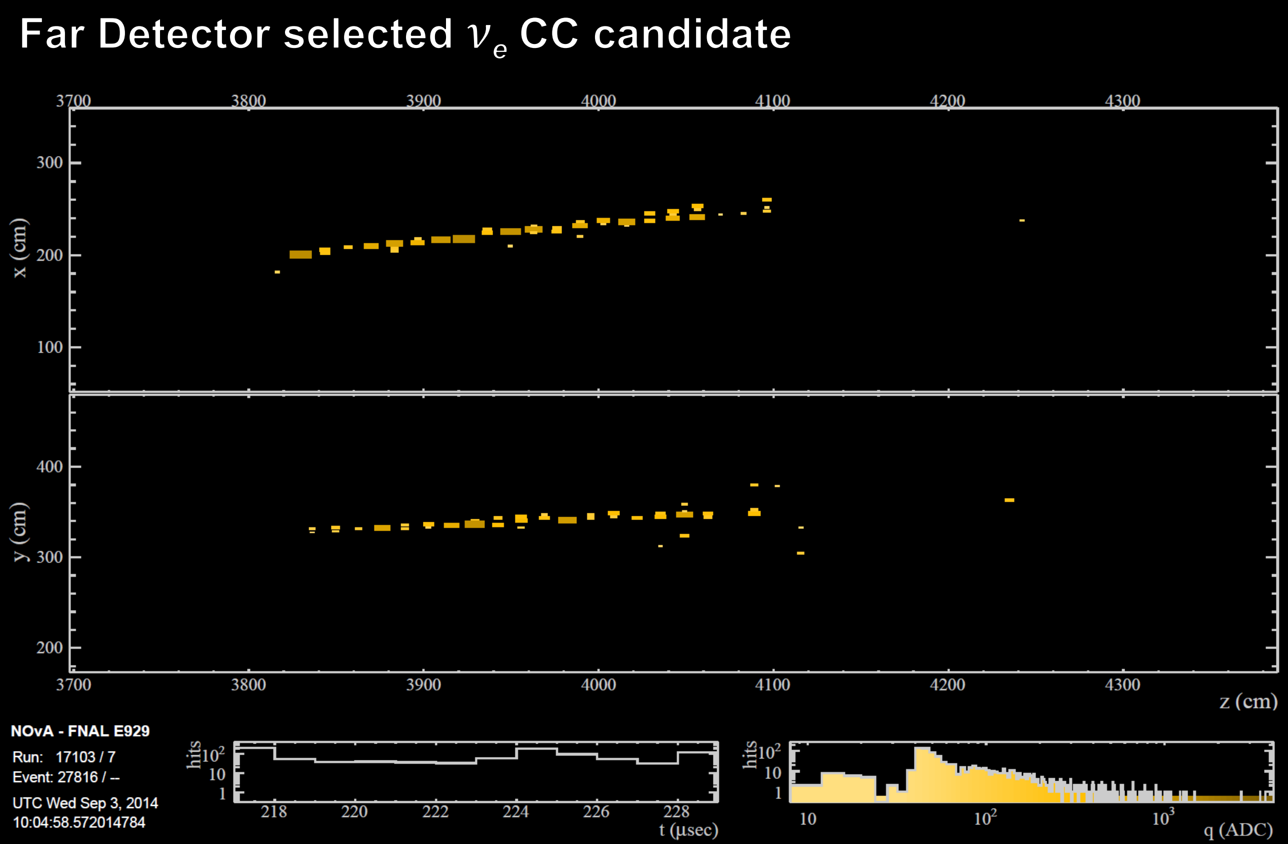




Far Detector selected ν_μ CC candidate

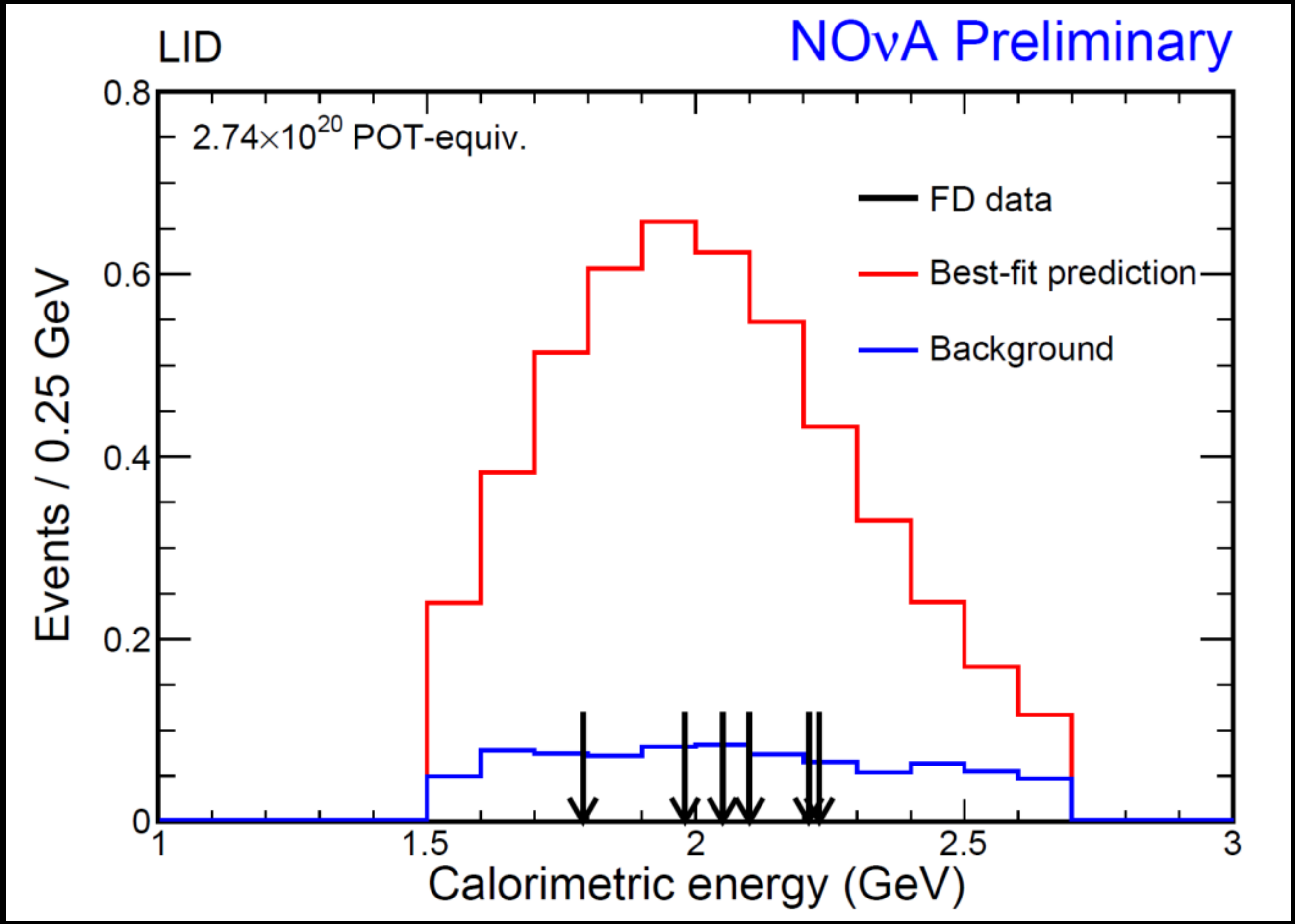


NOVA ν_e EVENTS:



- Background:
  - 0.9±0.1 events
- Expected signal:
  - 5.6±0.7 events (NH, δ_{CP}= -π/2)
  - 2.2±0.3 events (IH, δ_{CP} = +π/2)

- 6 events observed
  - "prefer normal hierarchy"
  - "prefer δ_{CP} ~ -π/2"



NEUTRINO ECONOMICS

	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	145.8	**106.0**	1.2	20.6	0.7	17.2
	$-\pi/2$	170.9	**131.4**	0.8			
$\bar{\nu}$ MODE	0	47.5	5.6	**24.4**	8.6	0.2	8.6
	$-\pi/2$	41.5	6.5	**17.5**			

- Expected event rate for 50% ν/ 50% $\bar{\nu}$ running at T2K ~2021

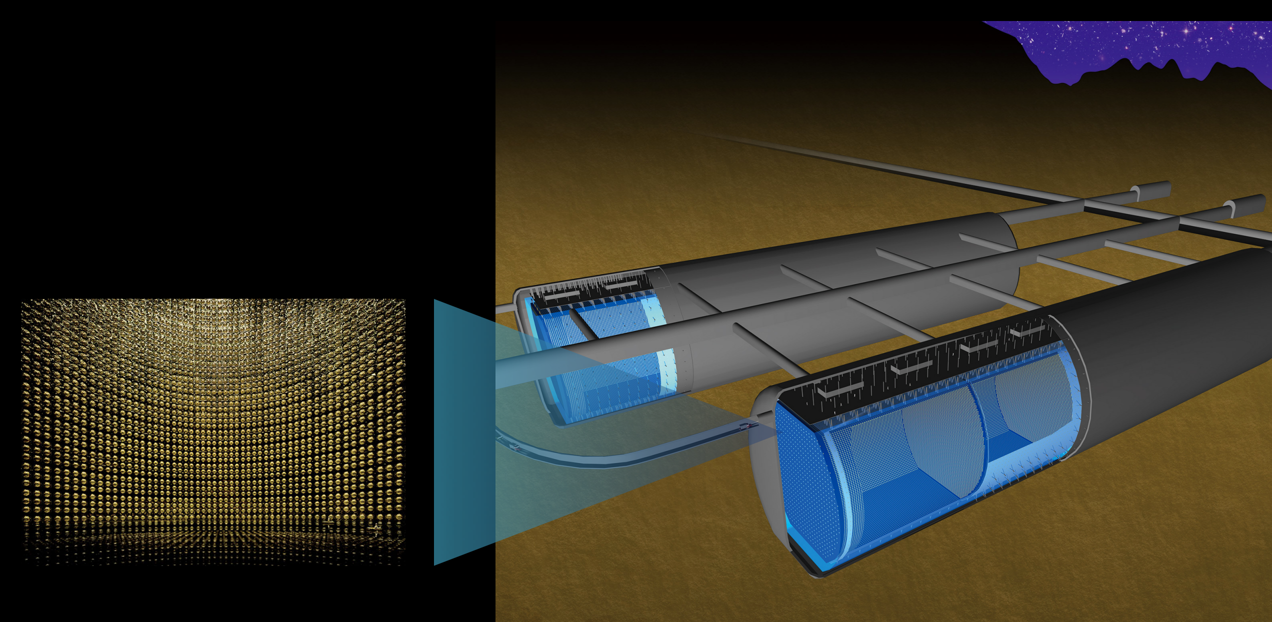
Neutrino source upgrades

- 400 kW → 750 kW →1.3 MW

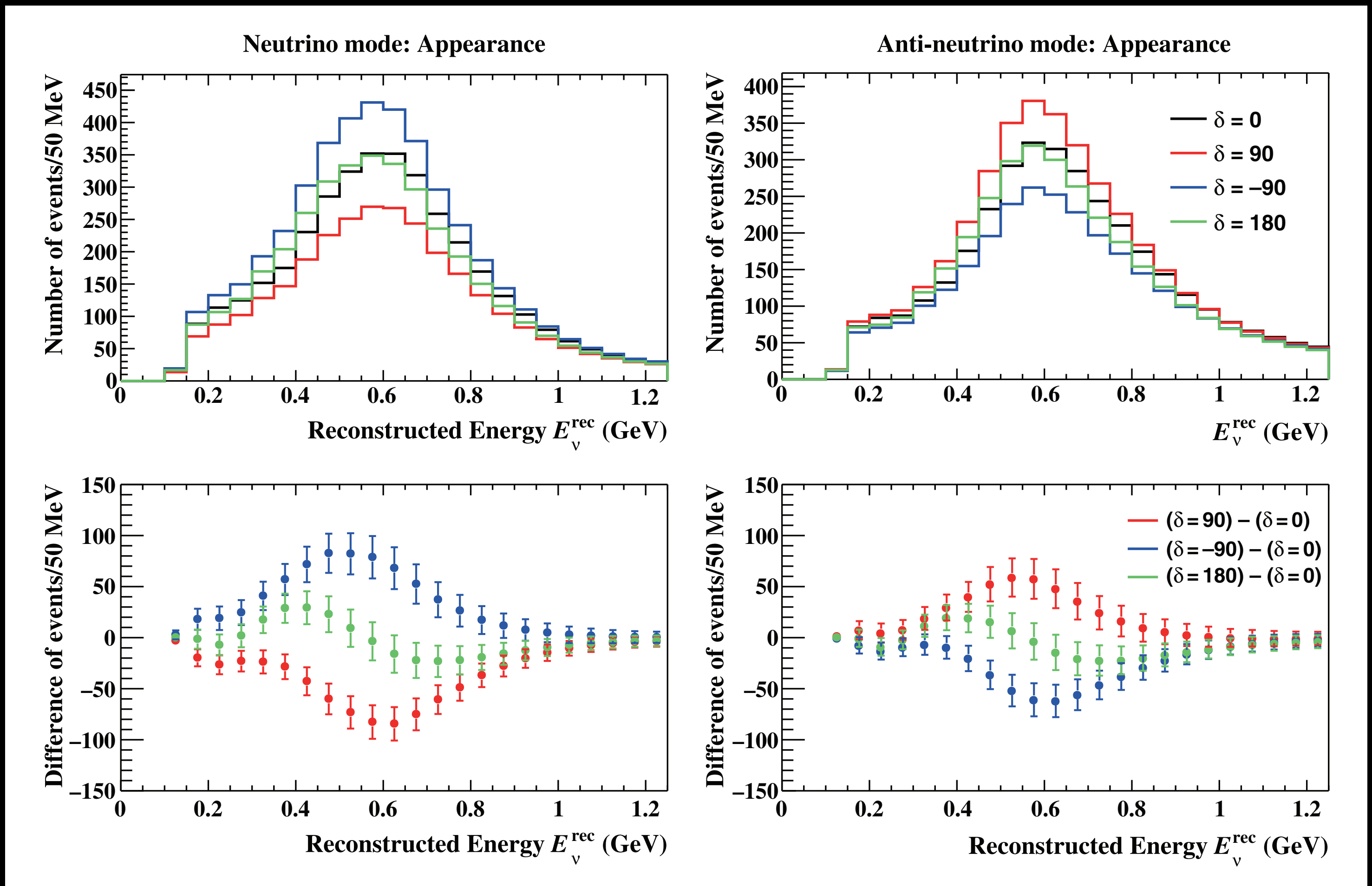
$$N \propto \boxed{\Phi_\nu} \times \boxed{V \times \rho \times \epsilon} \times \sigma_\nu$$

Detector upgrades

- Super-Kamiokande →Hyper-Kamiokande
  - 50 kT → ~1 MT

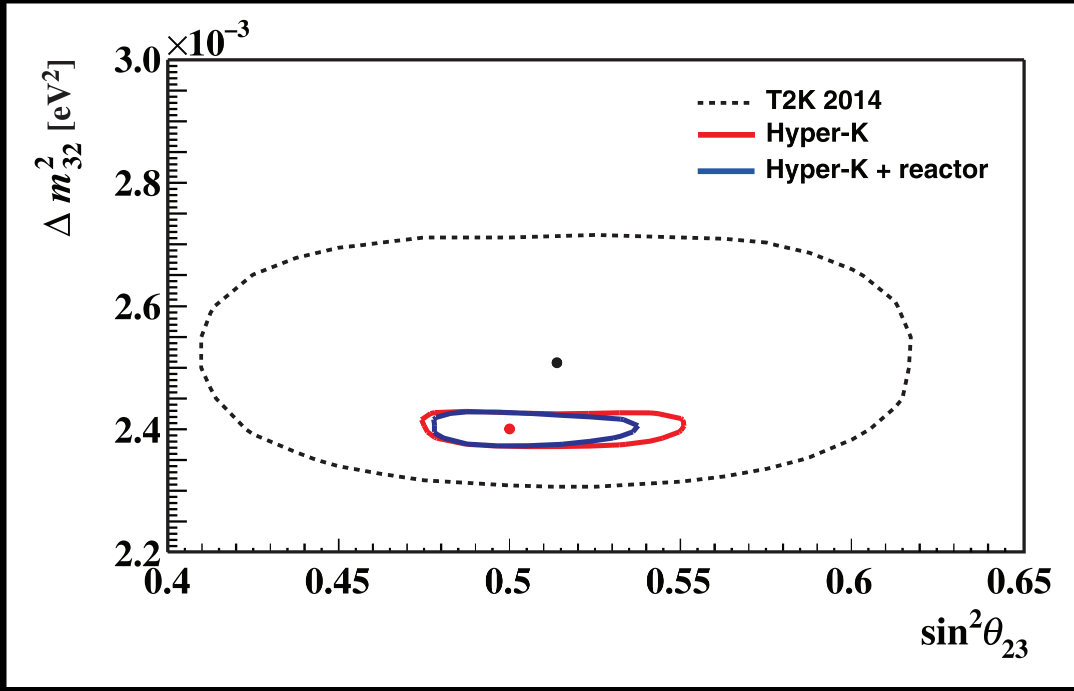


THE NEXT GENERATION



- x10-100 sensitivity in CPV searches at Hyper-Kamiokande and DUNE
- Probe rate and spectral asymmetry induced by CP violation
- Precision on δ_{CP} to ~7°
- $\sin^2\theta_{23}$ to ~0.01 precision

- Part of a very broad program:
  - proton decay
  - neutrino astrophysics
    - indirect dark matter
    - supernova bursts from as far as M31
    - relic supernovae neutrinos
  - + . . .



QUESTIONS AND ANSWERS:

- Is the flavour (species) of a neutrino immutable?
  - is neutrino flavour conserved? **NO**
- Does it have mass? **YES**
- Do mass/flavor states mix? **YES**
  - mass/energy (i=1,2,3)
  - flavor (α = e, μ, τ)

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

Unitary matrix relates eigenstates of one observable with eigenstates of another

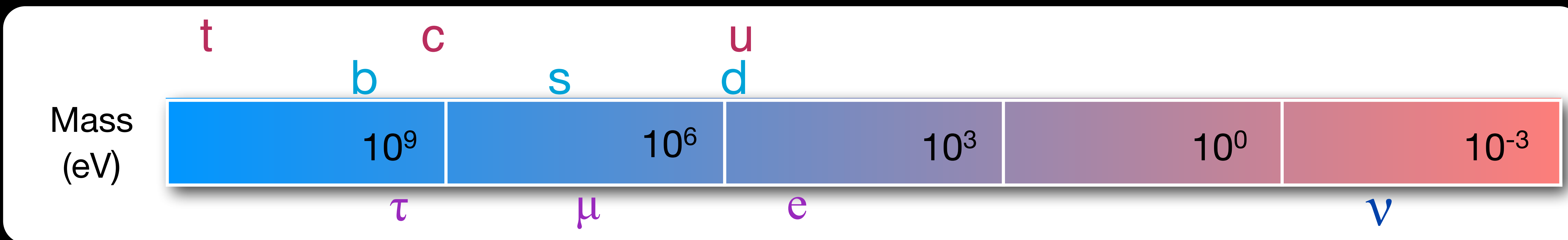
ANSWERS?

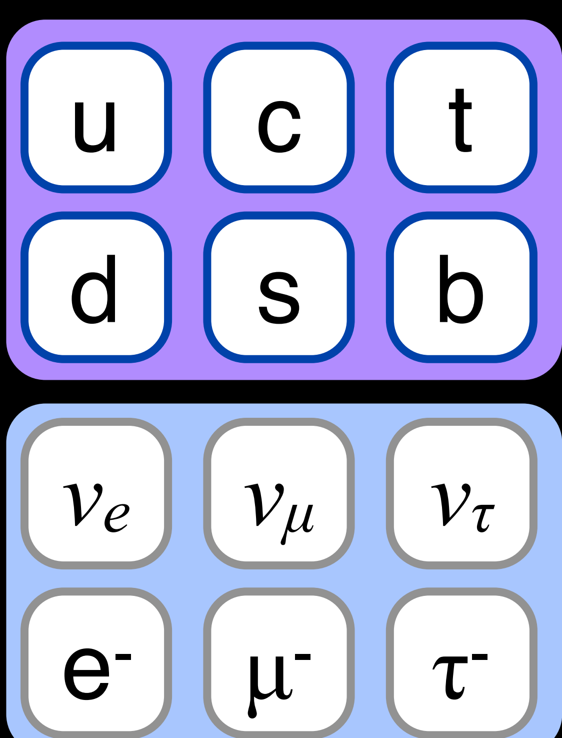
$$|U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

Quark

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

Lepton





- Why is quark and lepton mixing so different?
  - is neutrino mixing “maximal”?
- Why are neutrino masses so tiny?
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  - do neutrinos get mass some other way?

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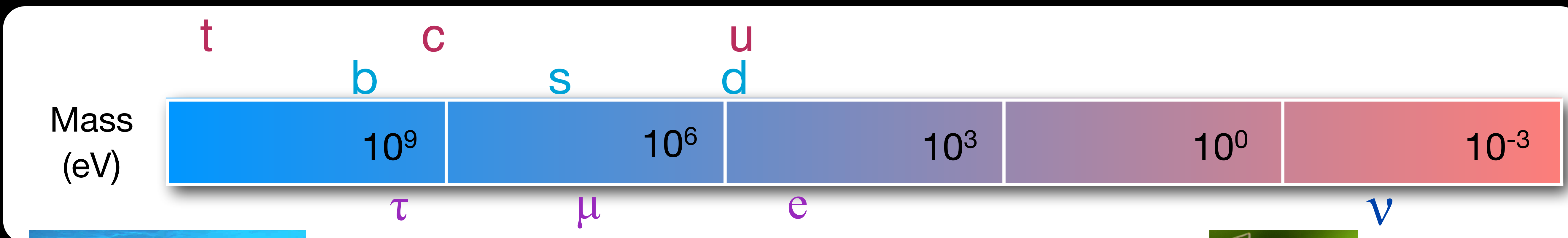

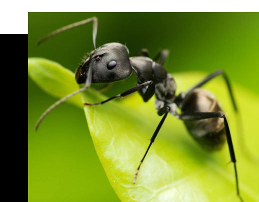

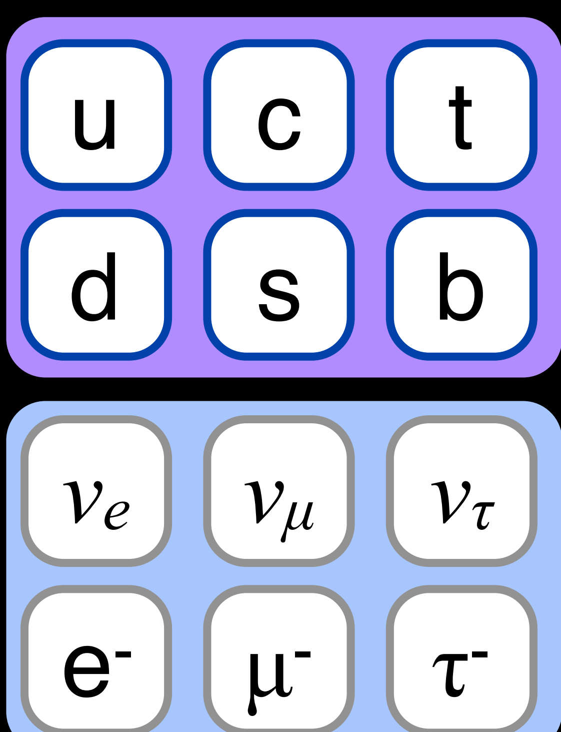

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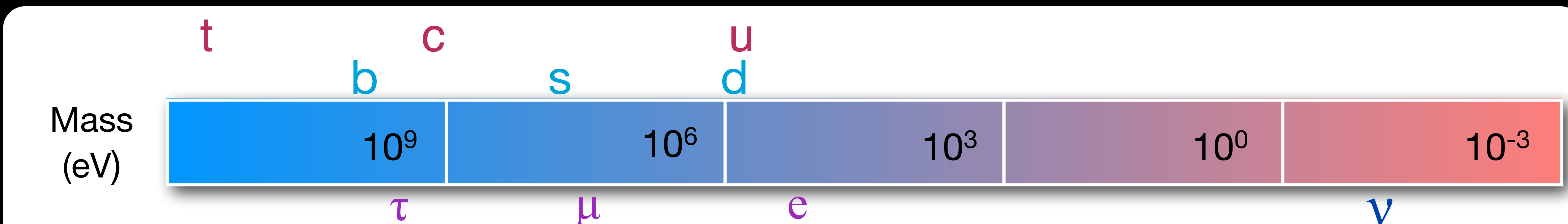




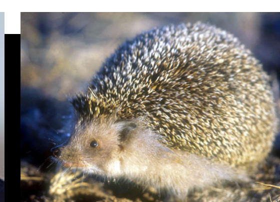
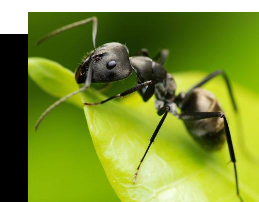

u c t
d s b

ν_e ν_μ ν_τ
e^- μ^- τ^-

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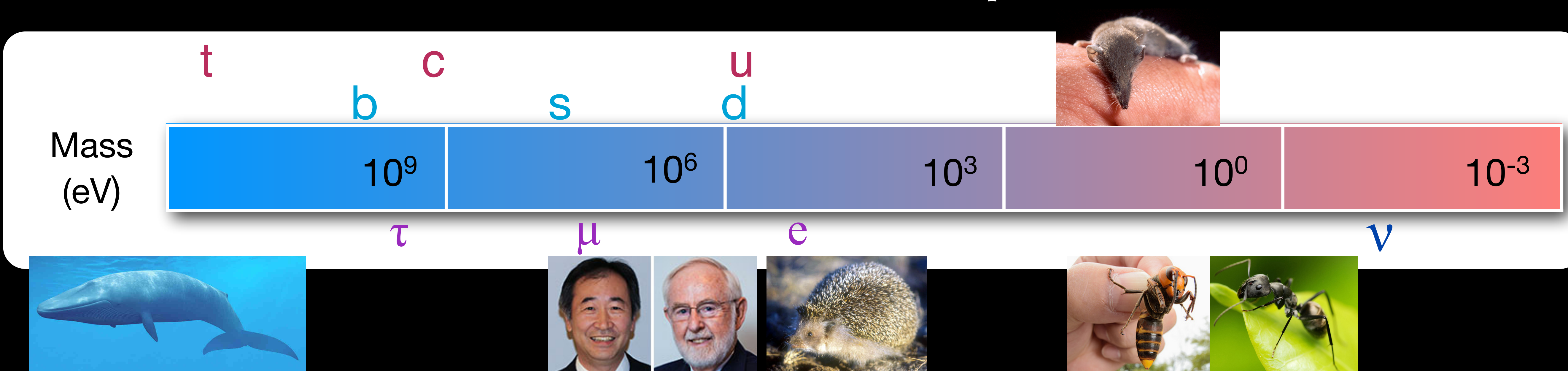

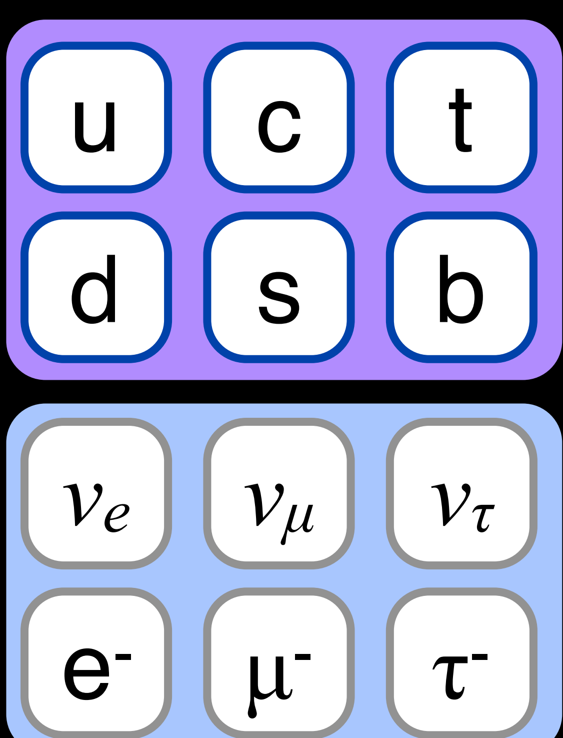

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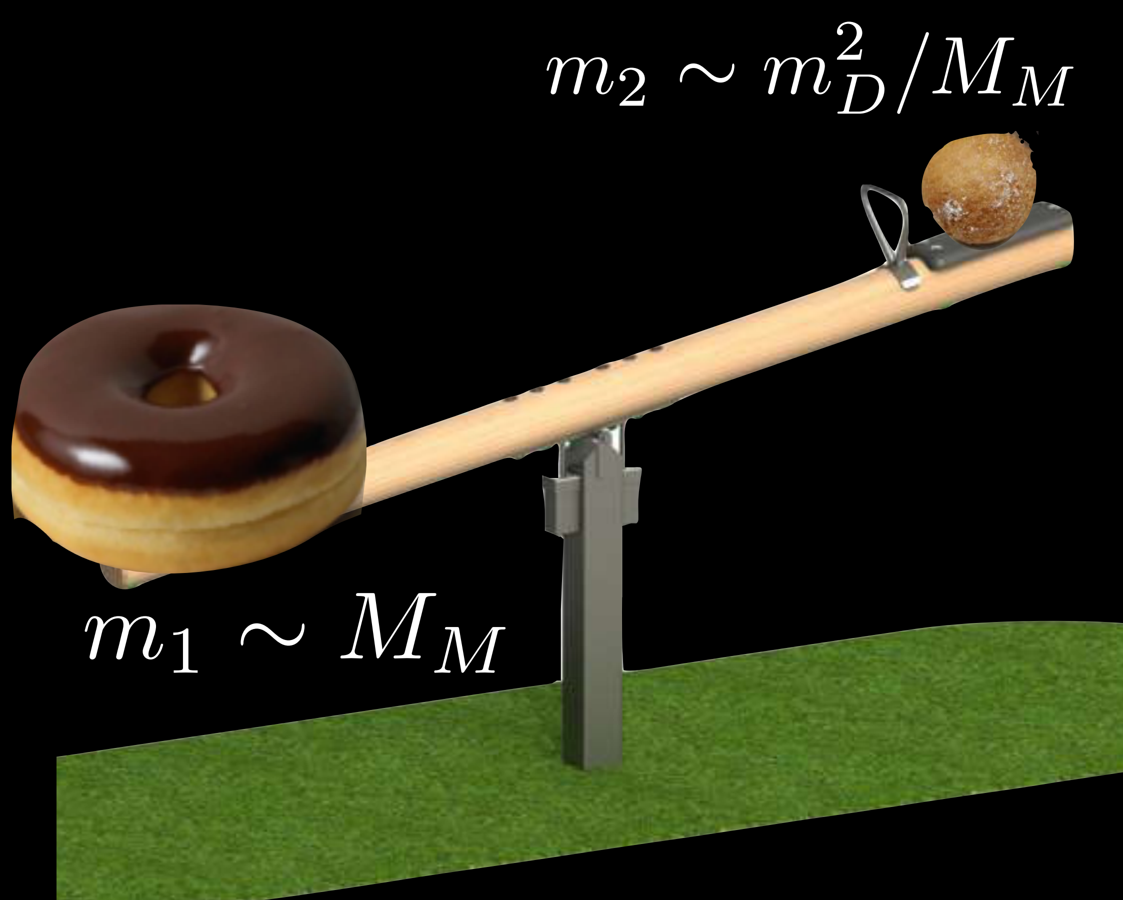
SEE-SAW MECHANISM



- Several people (Minkowski, Gell-Mann, etc.) observed the following:
- If the neutrino mass matrix contains both Dirac (m_D) and Majorana (M_M) terms

$$M = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}$$

  - "see-saw" in masses result:
    - if $m_D \ll M_M$, then $m_1 \ll m_2$
    - "lightness" of m_1 is due to "heaviness" of m_2 and M_M
  - Heavy partners of "light" neutrinos (i.e. neutrinos we know and love) should exist

- With
  - m_D ~ electroweak ~100 GeV
  - M_M ~ grand unification ~$10^{15\text{-}16}$ GeV
- $\Longrightarrow$ $m_2 \sim 10^{-(2\text{-}3)}$ eV

Are neutrino masses related to physics at very high energies?

21ST CENTURY DESPERATE REMEDY

10,000,000,001

10,000,000,000

MATTER

ANTI-MATTER

↓

1

US

MATTER

Give me:

- Baryon number violation
- C, CP violation
- Departure from Thermal Equilibrium

- Leptogenesis: Primordial matter/antimatter asymmetry was fuelled by CPV in
  - "heavy" neutrino decays?  Fukugita, Yanagida PLB174 45
  - "light" neutrinos?  Pascoli, Petcov, Riotto NPB774 1-52, PRD75 0835111

- With both possibilities and heavy neutrinos far out reach,
  - how can we know what happened?
  - Can we assemble enough clues to convince ourselves?

SUMMARY

- Neutrinos have mass and mix resulting in oscillations
- Neutrinos and antineutrinos may oscillate differently
  - a critical clue into how the universe became matter dominated
    - neutrinos may be part of a "desperate remedy" to explain this
  - First searches for CPV in neutrinos underway at T2K: first faint hints?
- Measurements of neutrino mass/mixing parameters reveal a paradoxical pattern
  - masses are much lighter than other particles
  - mixing is very large compared to quarks
  - suggests neutrino mass/mixing is of a different nature from any other particle
- Continued measurements and new experiments:
  - may definitively observe CP violation in neutrinos
  - significantly improve precision on mixing parameters.

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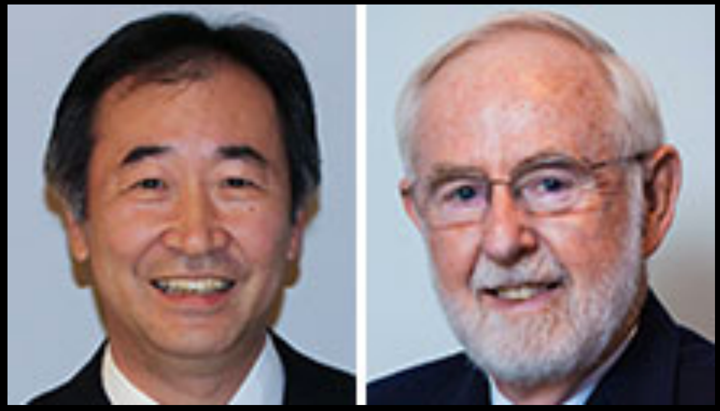

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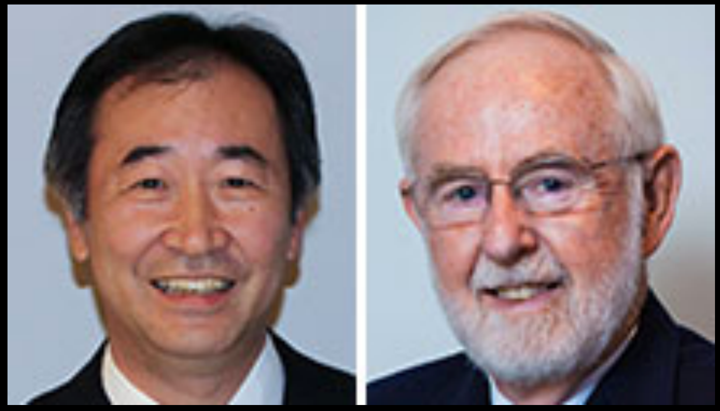
Building on the shoulders of giants . . .

Many exciting developments to come



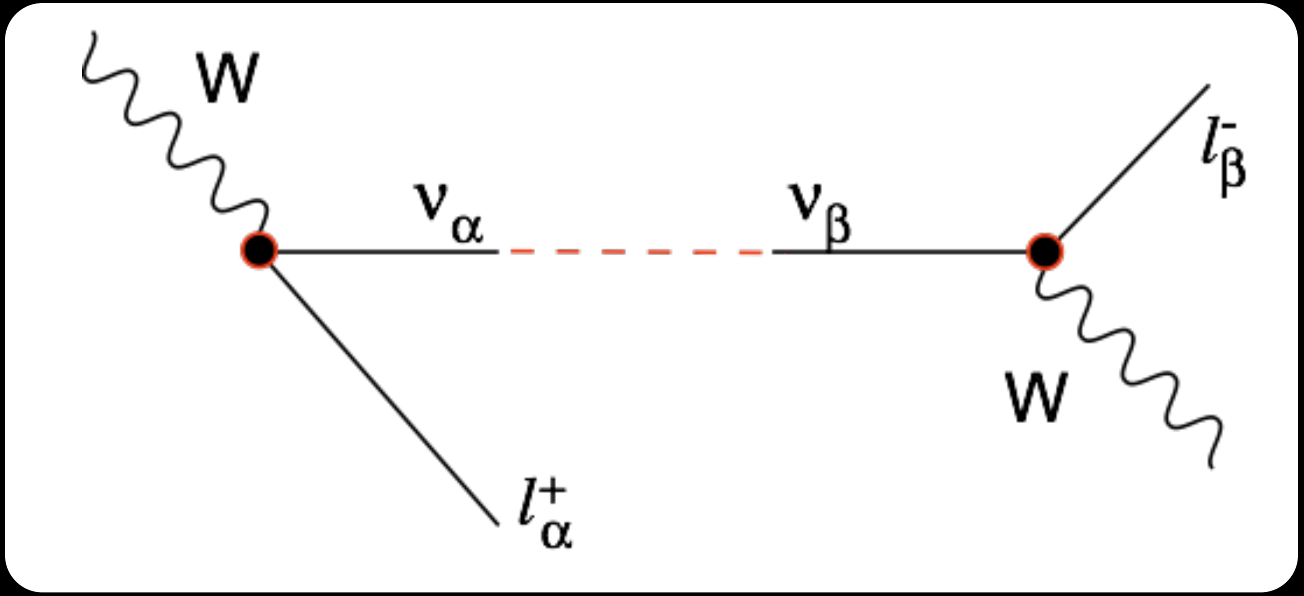
Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

—John Updike

GENERAL FRAMEWORK (IN VACUUM)

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

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

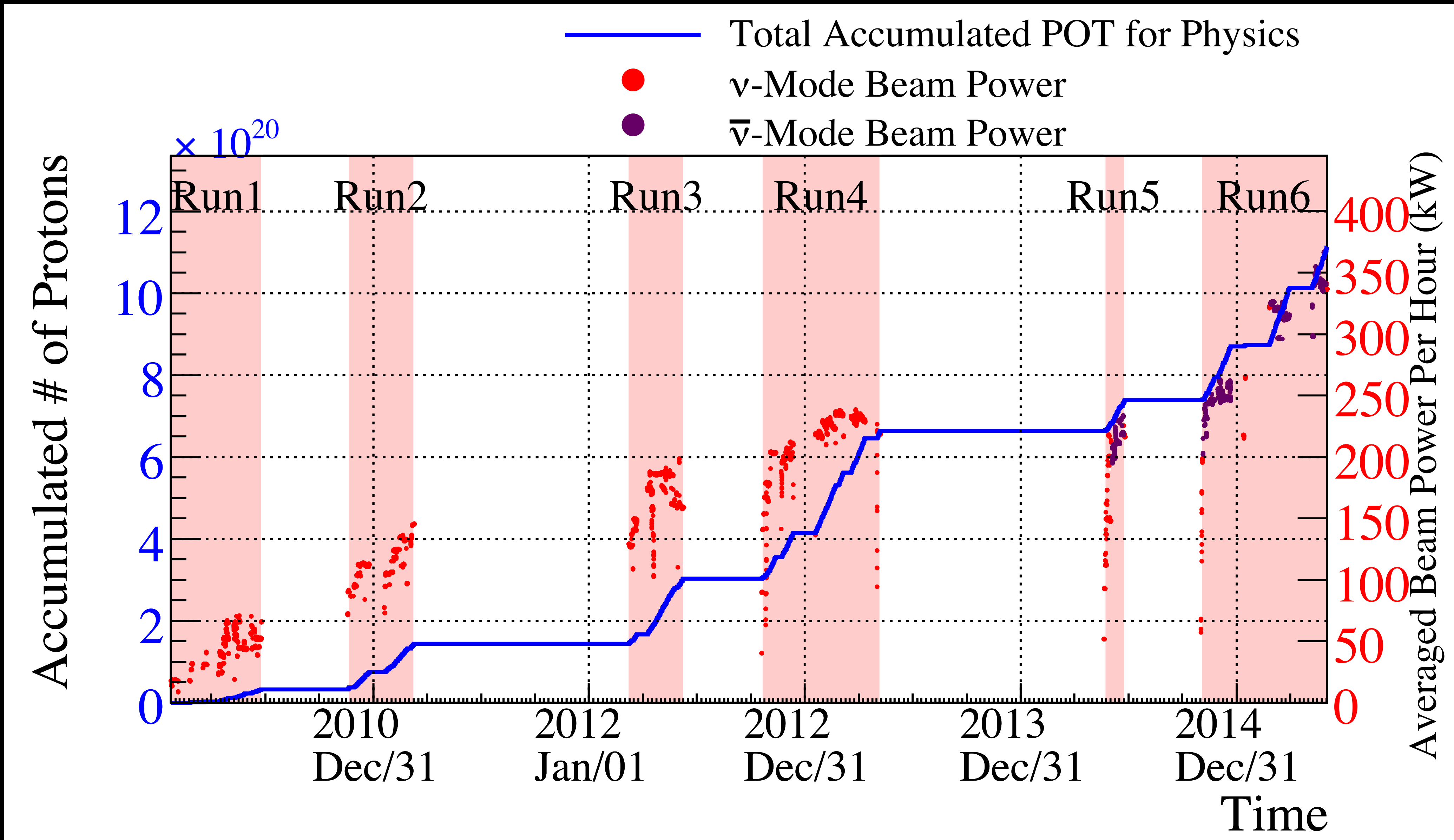


- Time evolution: component of another flavor may be acquired

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

- 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}

additional effects in the presence of matter



	Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2	2.48	132	0.42	measurement
2	8	2.48	529	1.7	estimation
3	8	1.3	1009	3.2	estimation

The MR has capability to reach 1MW with the high repetition rate operation.

JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS New magnet PS	2.48 s R&D	Large scale 1st PS		Mass production installation/test	1.3 s	1.3 s	1.2 s
High gradient rf system	Manufacture, installation/test						
2nd harmonic rf system		R&D, manufacture, installation/test					
VHF cavity	R&D						
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system	Kicker PS improvement, Septa manufacture /test						
FX system	Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields			Local shields				
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					