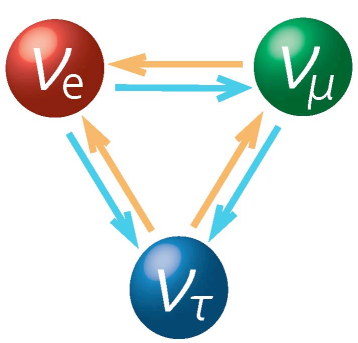
The 2015 Neutrino Nobel Prize:

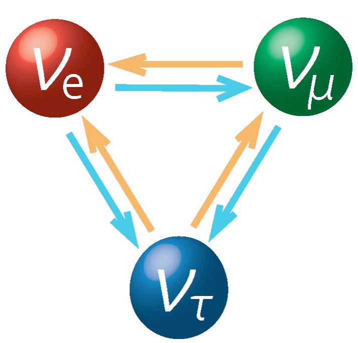
- a theoretical perspective



Stephen Parke
Fermilab

The 2015 Neutrino Nobel Prize:

- a theoretical perspective



Stephen Parke
Fermilab

Ernest Rutherford, master of simplicity

By Ashutosh Jogalekar | August 30, 2013 | 6

Ernest Rutherford, emperor of the atomic domain (Image: Wikipedia Commons)

Ernest Rutherford, master of simplicity

By Ashutosh Jogalekar | August 30, 2013 | 6

Ernest Rutherford, emperor of the atomic domain (Image: Wikipedia Commons)

"theorists play games with their symbols while we discover truths about the universe". And yet

Ernest Rutherford, master of simplicity

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Ernest Rutherford, emperor of the atomic domain (Image: Wikipedia Commons)

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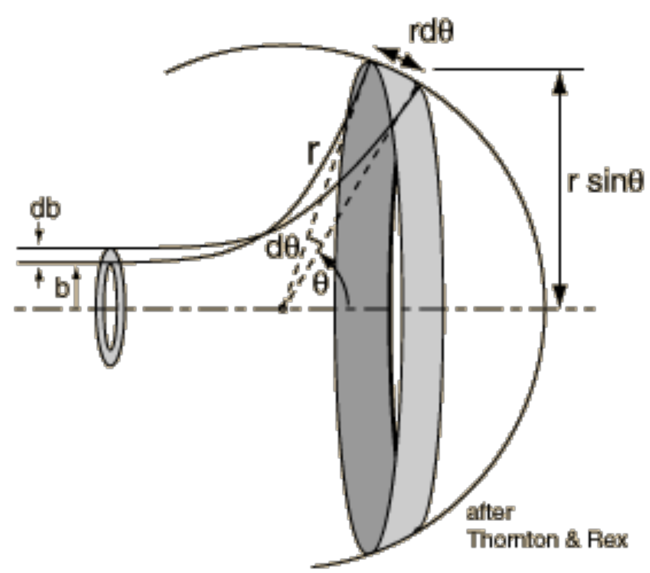


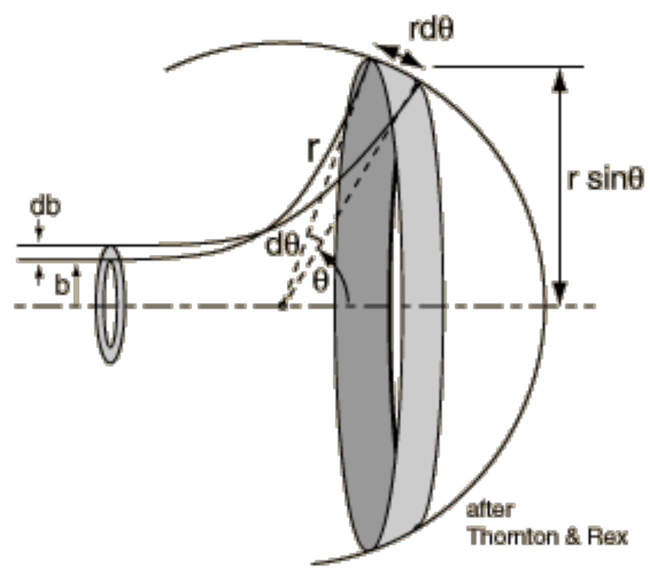
$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE} \right)^2 \left(\frac{1+\cos\theta}{1-\cos\theta} \right)$$

Ernest Rutherford, master of simplicity

By Ashutosh Jogalekar | August 30, 2013 | 6

Ernest Rutherford, emperor of the atomic domain (Image: Wikipedia Commons)

"theorists play games with their symbols while we discover truths about the universe". And yet

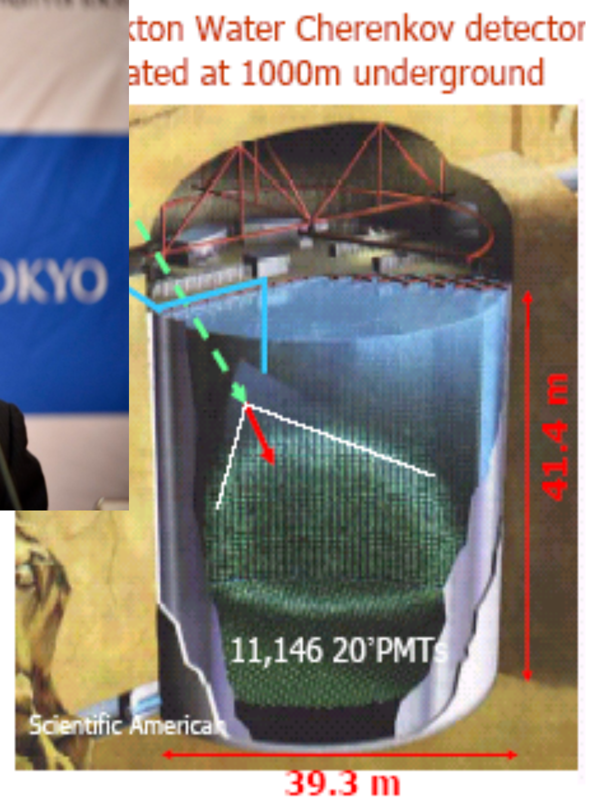


$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE}\right)^2 \left(\frac{1+\cos\theta}{1-\cos\theta}\right)$$

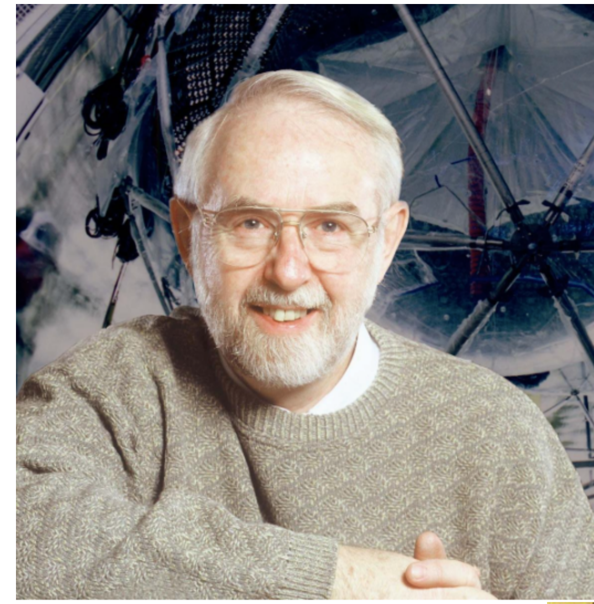
he had an eye for theoretical talent that allowed him to nurture Niels Bohr, as dyed-in-the-wool a theoretician and philosopher as you could find.

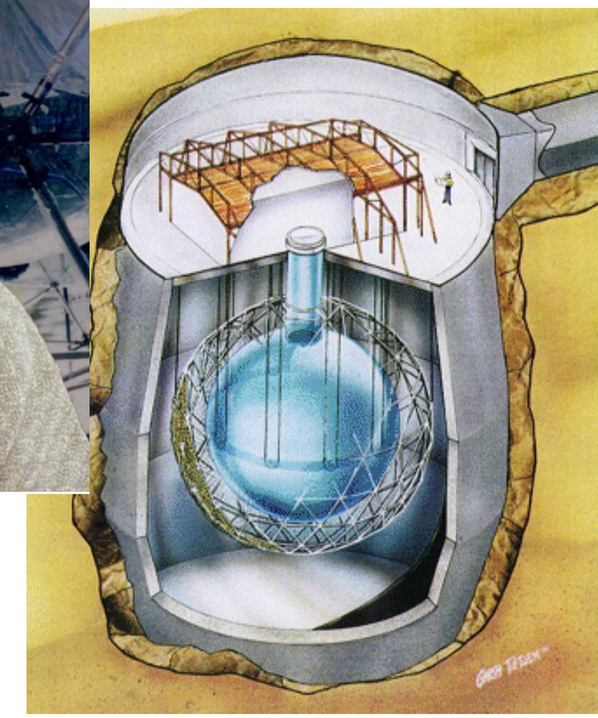
Neutrino Nobel Prizes:

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



Takaaki Kajita
SuperKamiokaNDE





Art McDonald
SNO

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

NOBEL 2015

Takaaki Kajita, ICRR Tokyo
SuperKamiokaNDE

NOBEL 2015

Takaaki Kajita, ICRR Tokyo
SuperKamiokaNDE

Yoji Totsuka, Tokyo
1942-2008

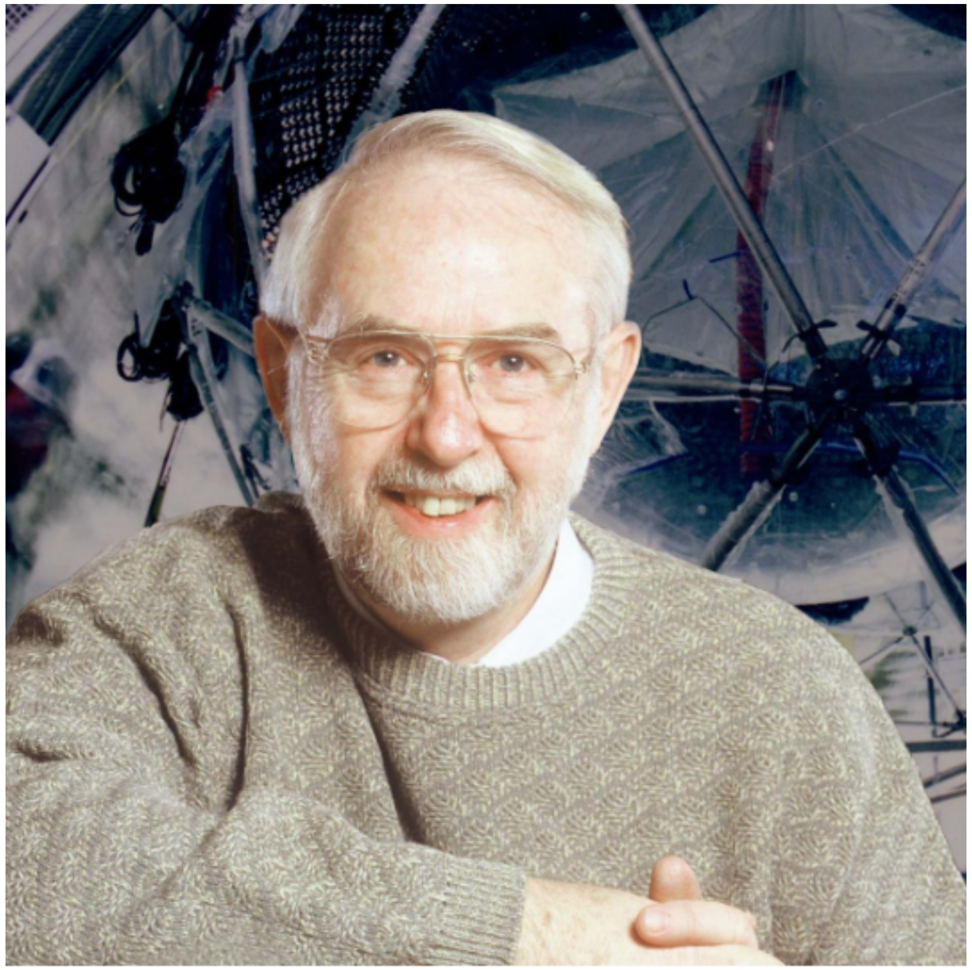
NOBEL 2015

Takaaki Kajita, ICRR Tokyo
SuperKamiokaNDE

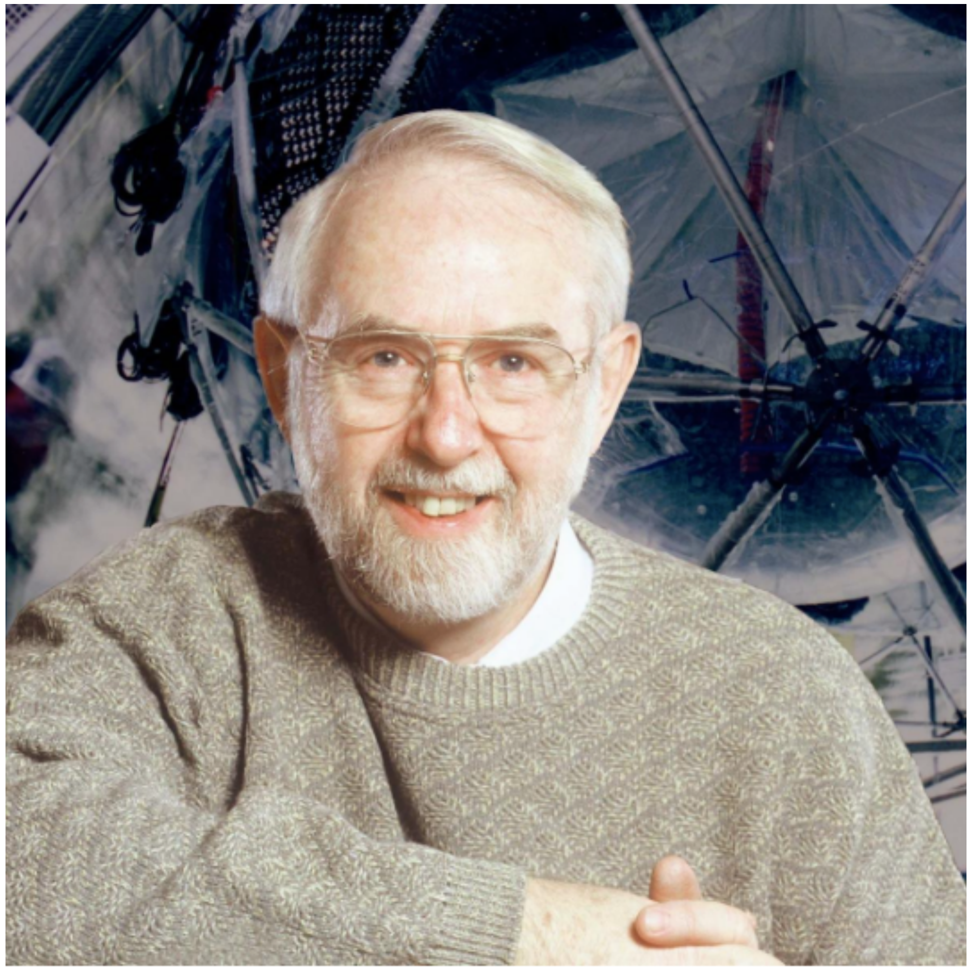
Yoji Totsuka, Tokyo
1942-2008

2002 Panofsky Prize: Koshiba*/Totsuka/Kajita

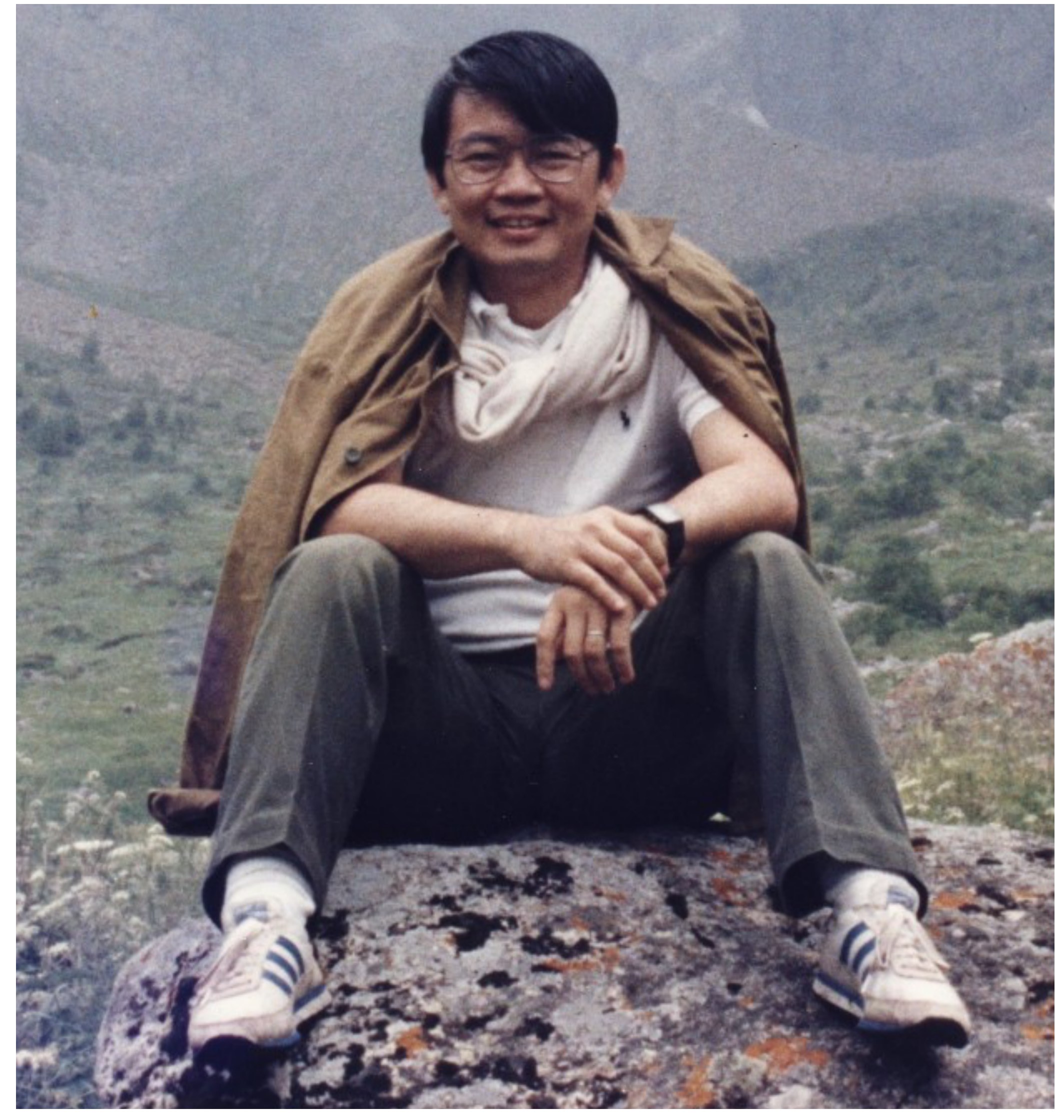
"For compelling experimental evidence for neutrino oscillations using atmospheric neutrinos."



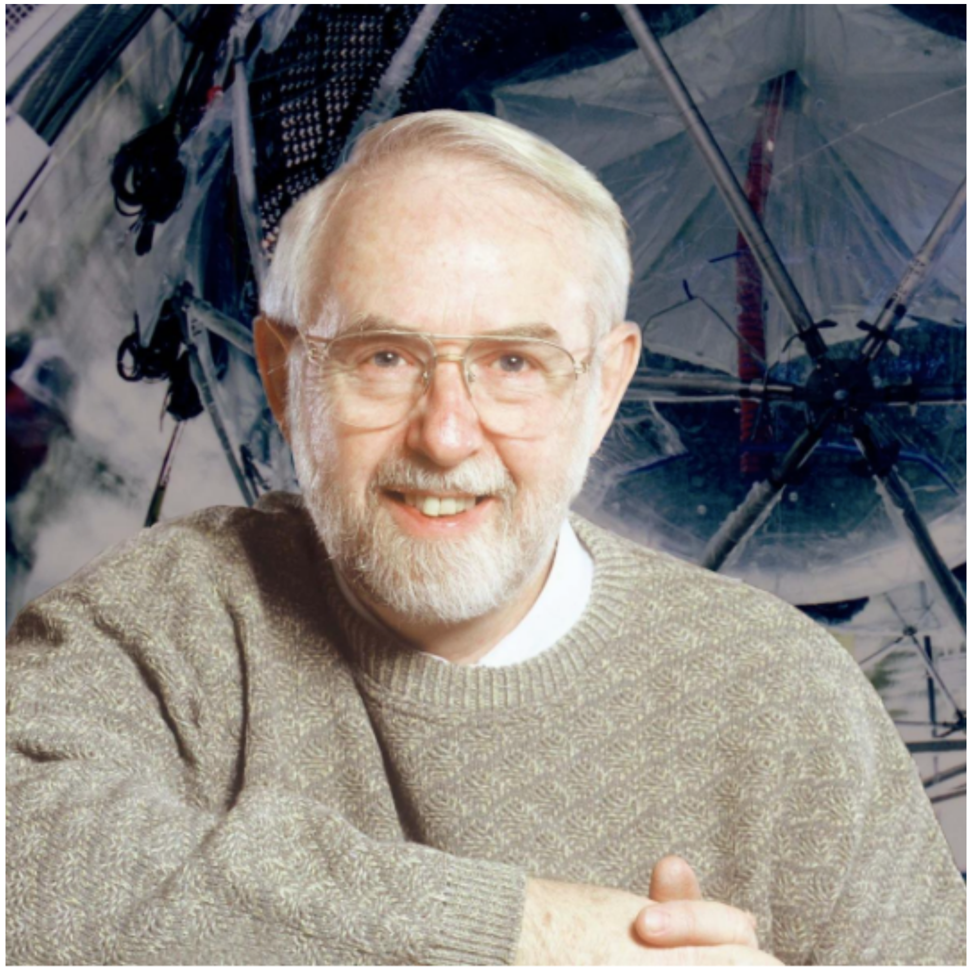
Art McDonald, Queens
SNO



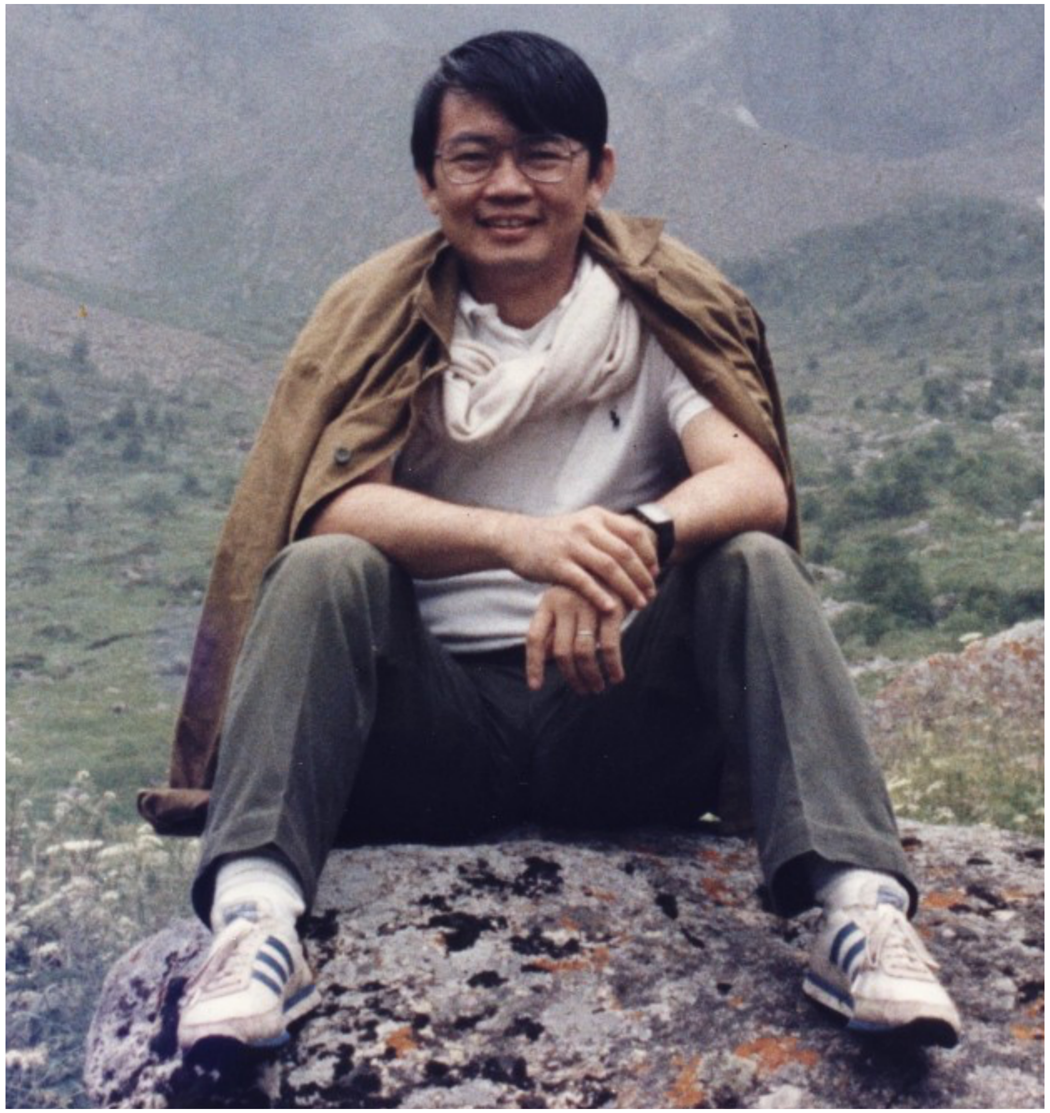
Art McDonald, Queens
SNO



Herbert Chen, Irvine
1942-1987



Art McDonald, Queens
SNO



Herbert Chen, Irvine
1942-1987

2007 B. Franklin Medal: McDonald/Totsuka

"for discovering that the three known types of elementary particles called neutrinos change into one another when traveling over sufficiently long distances, and that neutrinos have mass."

NOBEL 2015

SuperK

SNO

NOBEL 2015

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

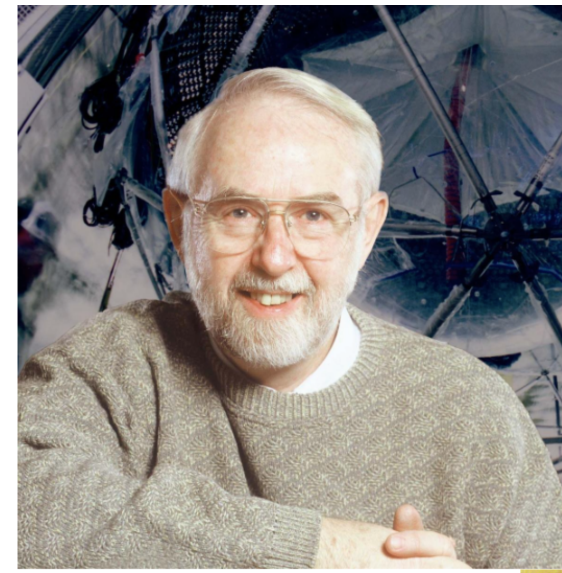
Takaaki Kajita
SuperKamiokaNDE

Art McDonald
SNO

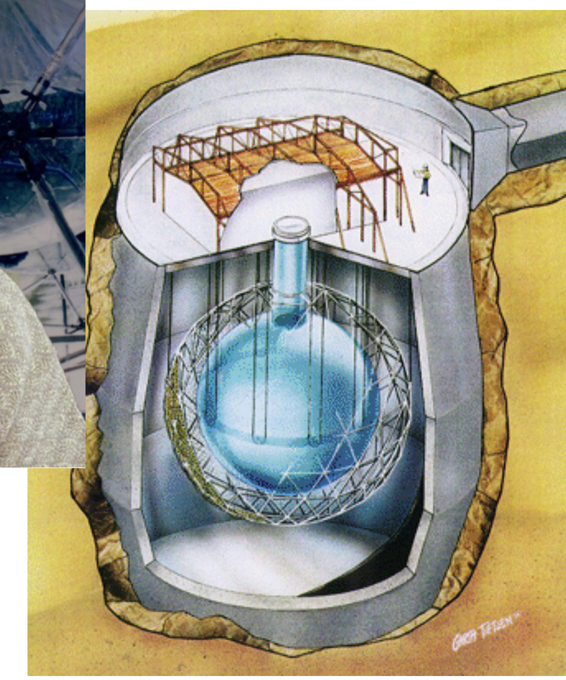
NOBEL 2015

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

Takaaki Kajita
SuperKamiokaNDE



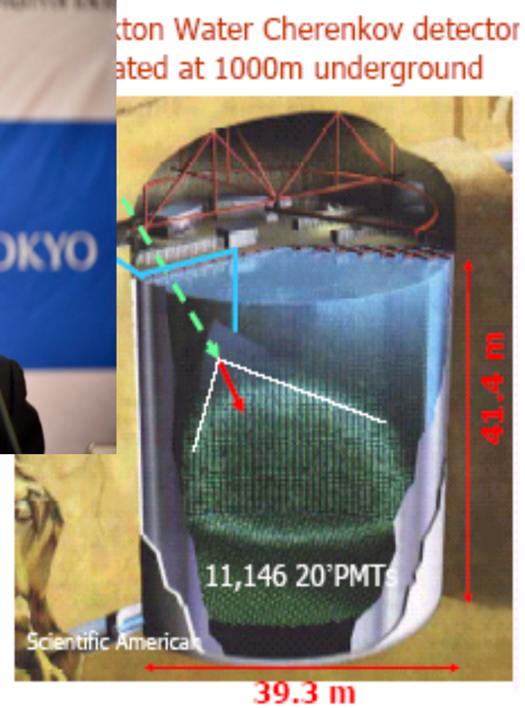
Art McDonald
SNO



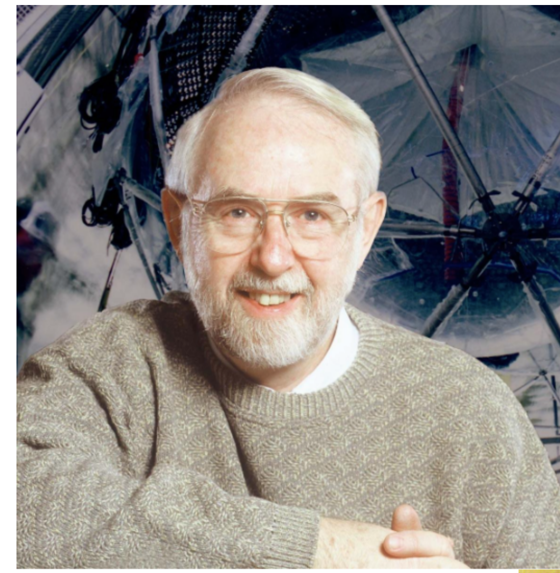
"for the discovery of neutrino flavor transformations, which shows that neutrinos have mass"

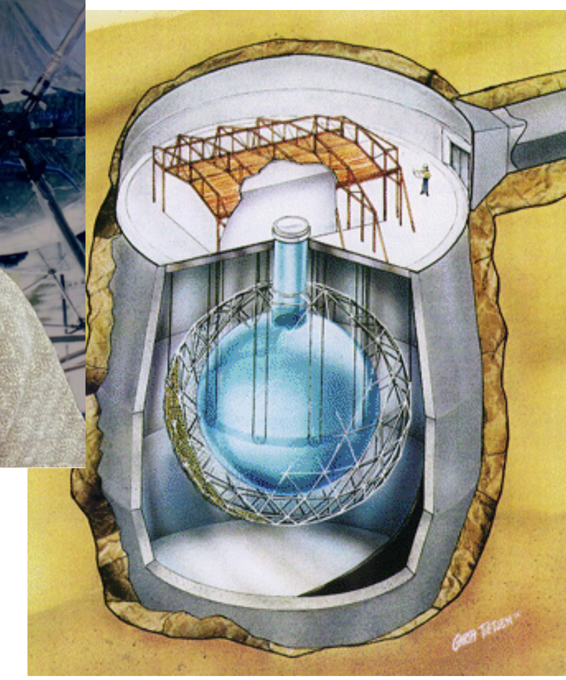
NOBEL 2015

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



Takaaki Kajita
SuperKamiokaNDE





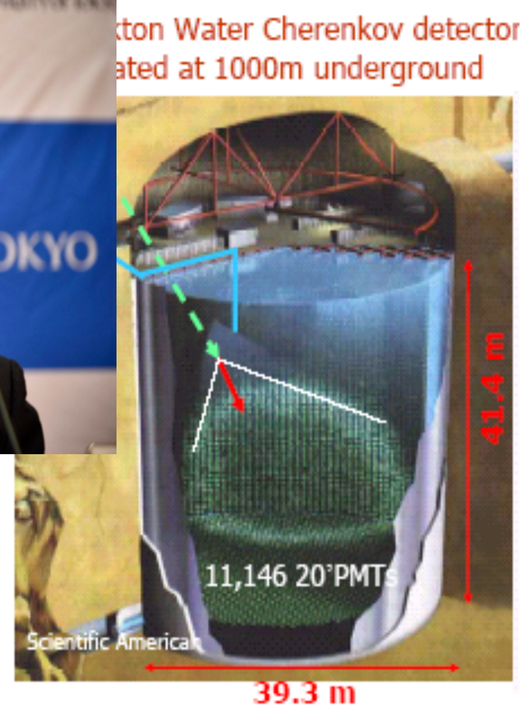
Art McDonald
SNO

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

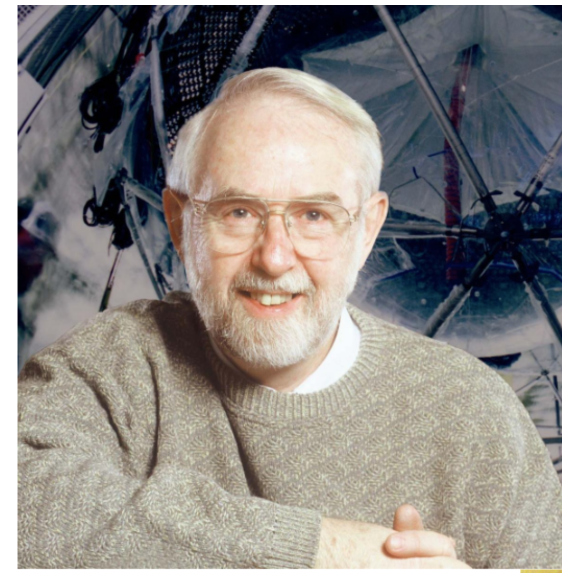
~ vacuum oscillations

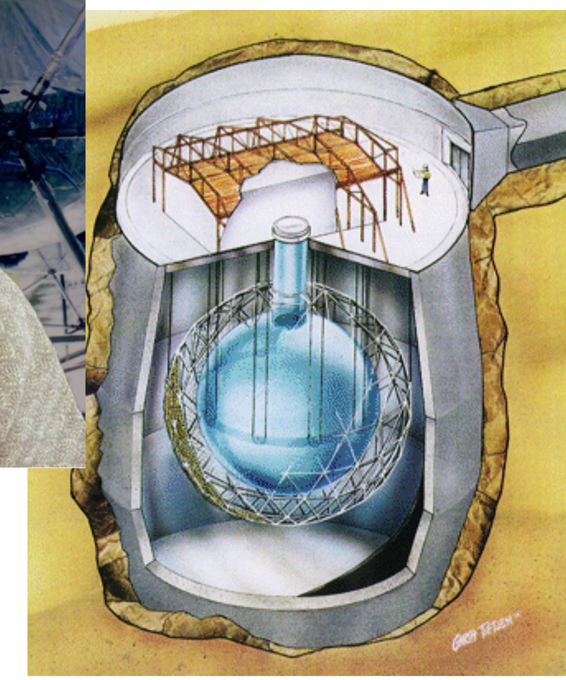
NOBEL 2015

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



Takaaki Kajita
SuperKamiokaNDE





Art McDonald
SNO

“for the discovery of neutrino flavor transformations, which shows that neutrinos have mass”

~ vacuum oscillations

Wolfenstein matter effects dominant

ATMOSPHERIC NEUTRINOS:

KamiokaNDE 1kton H2O 1994

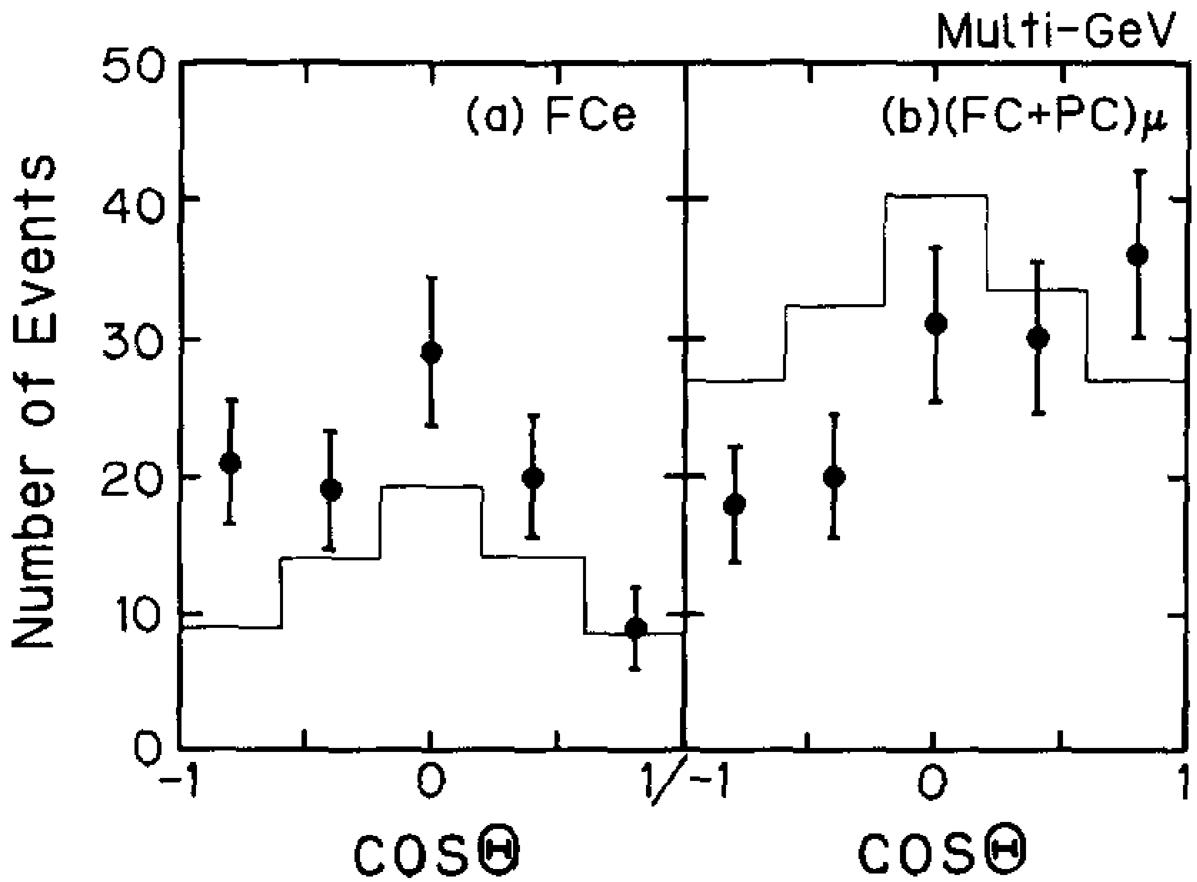


Fig. 3. Zenith-angle distributions for (a) the e-like events and (b) μ-like events (the fully-contained and partially-contained events are combined). The circles with error bars show the data and the histogram the MC (without neutrino oscillations). The downward direction is given by $\cos\Theta = 1$.

Y. Fukuda et al. / Physics Letters B 335 (1994) 237–245

KamiokaNDE 1kton H2O
1994

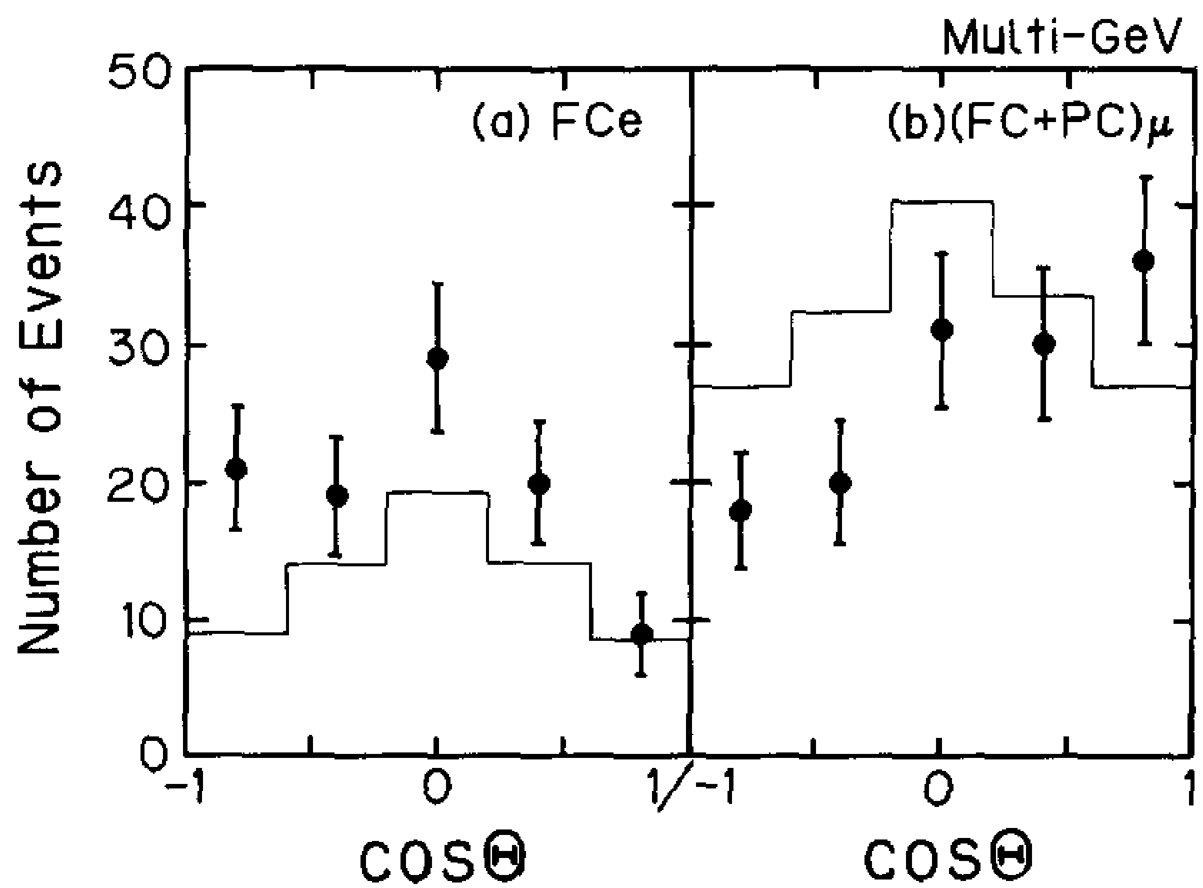
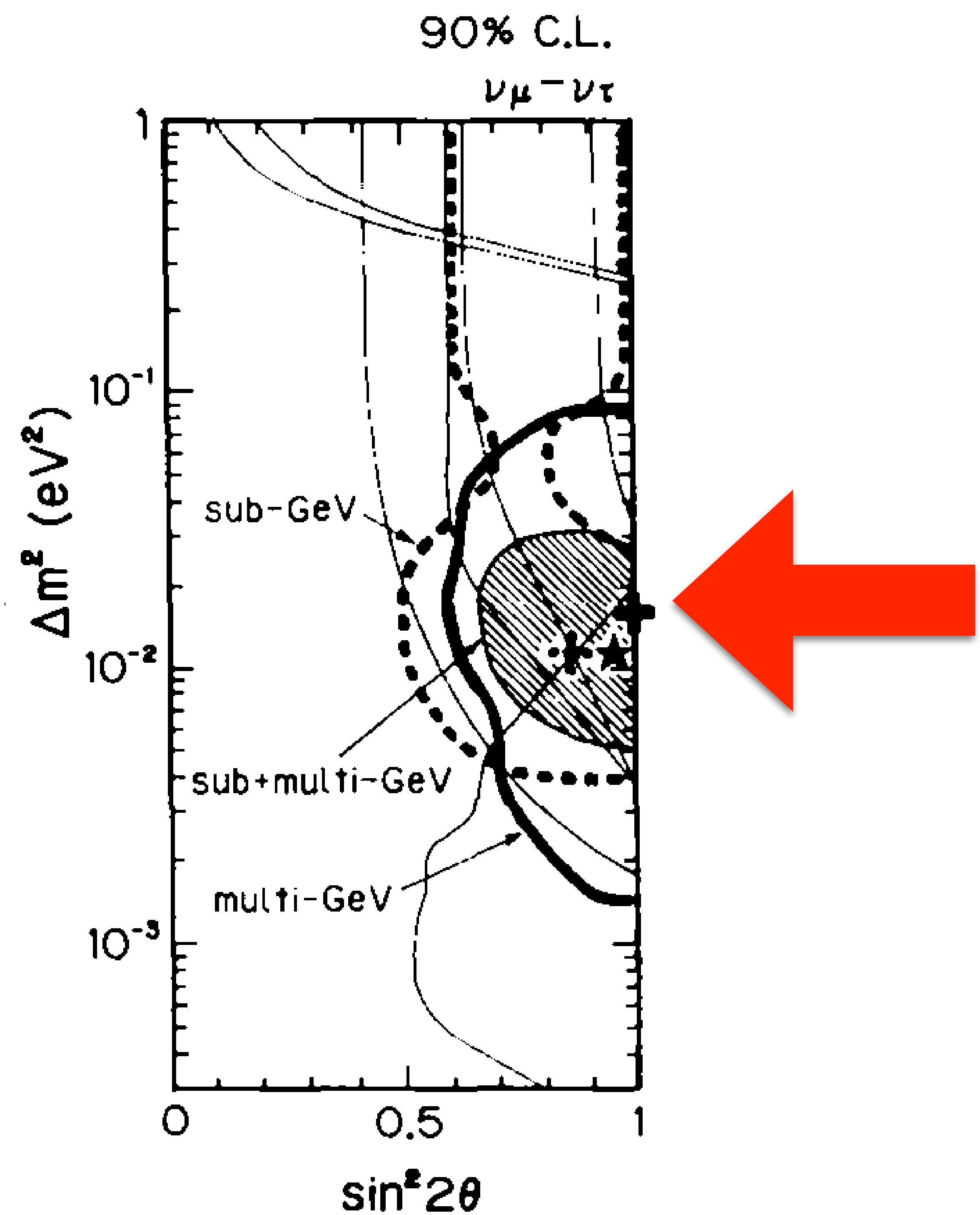
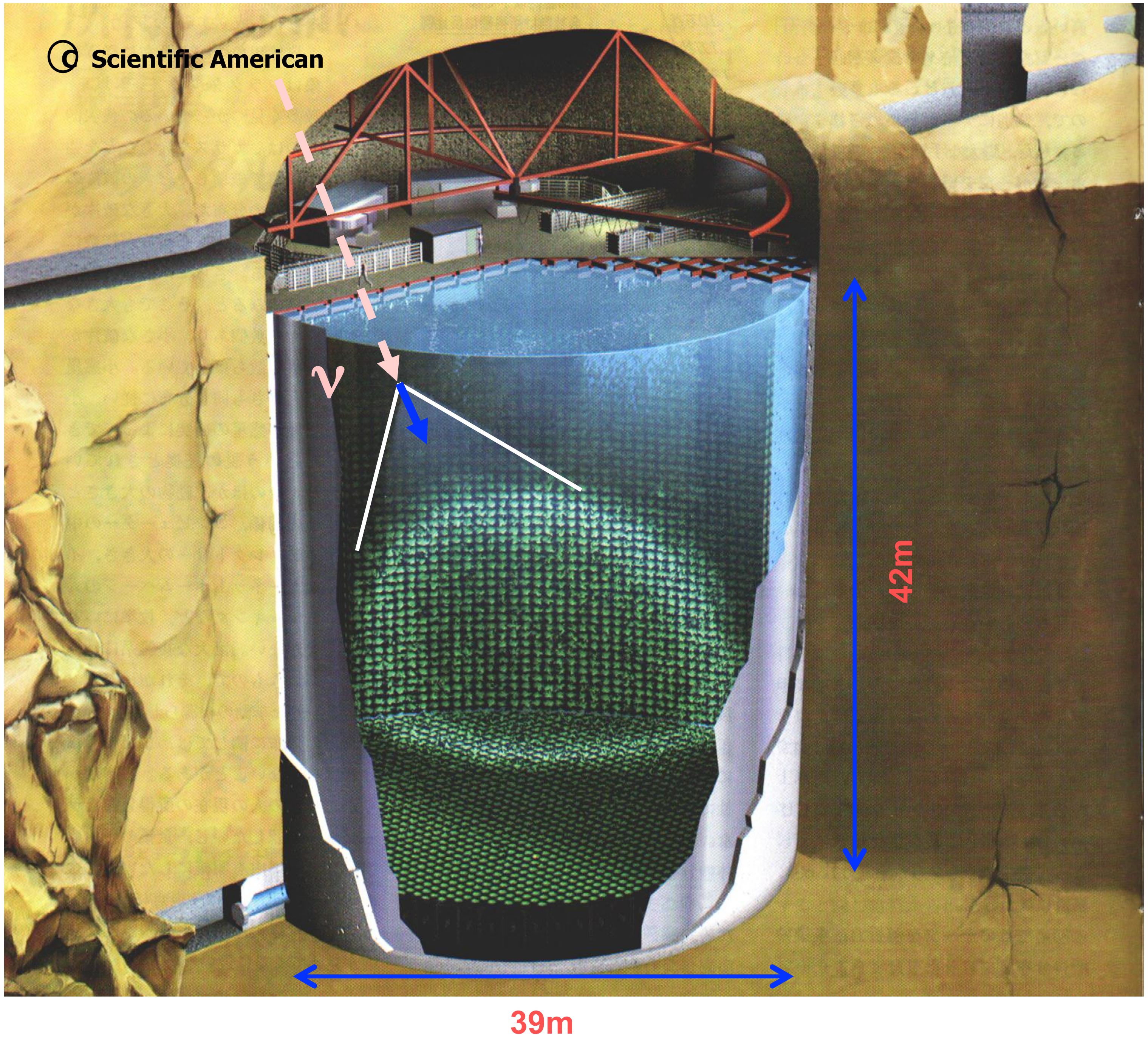


Fig. 3. Zenith-angle distributions for (a) the e-like events and (b) μ-like events (the fully-contained and partially-contained events are combined). The circles with error bars show the data and the histogram the MC (without neutrino oscillations). The downward direction is given by $\cos\Theta = 1$.



Y. Fukuda et al. / Physics Letters B 335 (1994) 237–245

SuperKamiokaNDE
(H_2O 50 ktons)



successor to KamiokaNDE 1 kton


NEUTRINO'98
XVIII INTERNATIONAL CONFERENCE
ON
NEUTRINO PHYSICS AND ASTROPHYSICS
Takayama, Japan - June 4-9, 1998
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B.Barish (Caltech)
J.Cronin (Chicago)
J.Ellis (CERN)
S.Glashow (Harvard)
T.Kirsten (Heidelberg)
L.Lederman (Fermilab)
A.McDonald (Queens)
A.Morales (Zaragoza)
F.Reines (Irvine)
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Attendance by Invitation
Further information:
URL: http://www-sk.icrr.u-tokyo.ac.jp/nu98/
E-mail: nu98@suketto.icrr.u-tokyo.ac.jp
Supported by
- International Union of Pure and Applied Physics (C4)
- Japan National Committee for Physics, Science Council of Japan
Organized by Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo
Higashi-mozumi, Kamioka-cho, Gifu 506-1205, Japan

17+ years ago

"All the News
That's Fit to Print"

The New York Times

VOL. CXLVII . . . . No. 51,179

FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

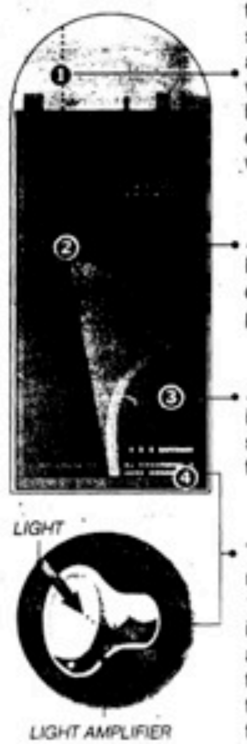
Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos



(1) Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

(2) . . . and collide with other particles . . .

(3) . . . producing a cone-shaped flash of light.

(4) The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

ν98, @Takayam[a]
June 1998

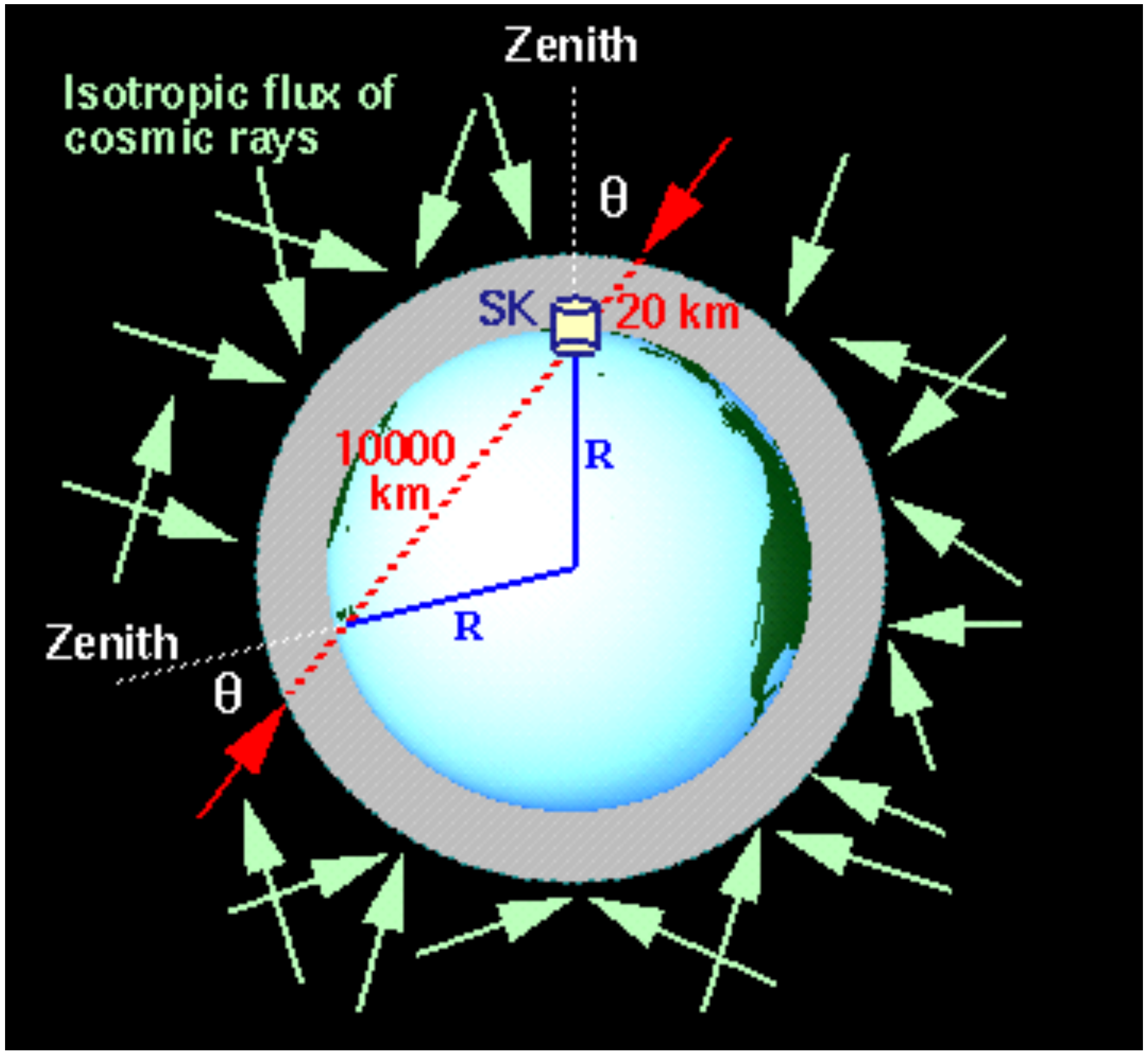
Atmospheric neutrino results
from Super-Kamiokande & Kamiokand[e]

— Evidence for ν_μ oscillations —

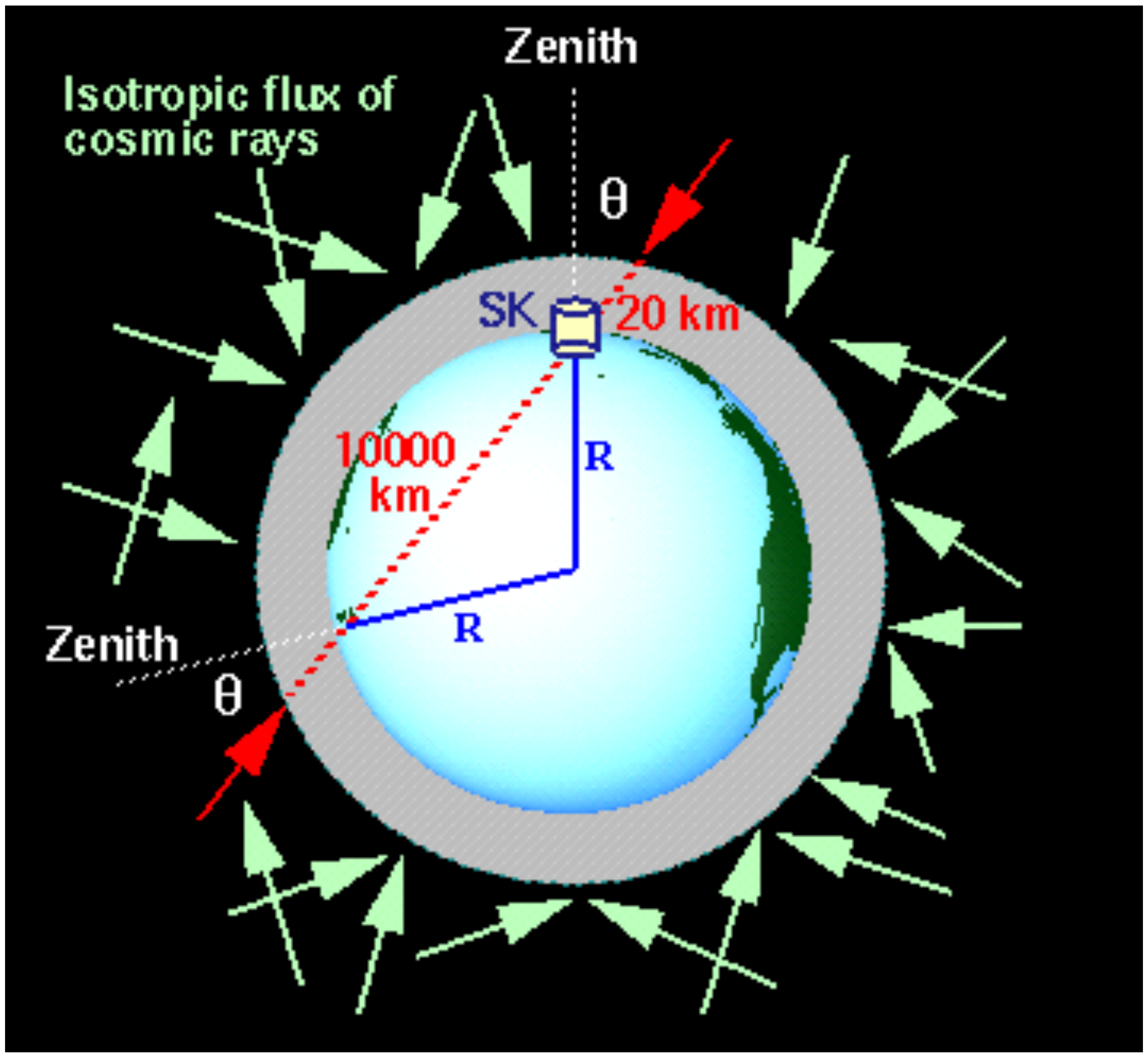
T. Kajita
Kamioka observatory, Univ. of Tokyo

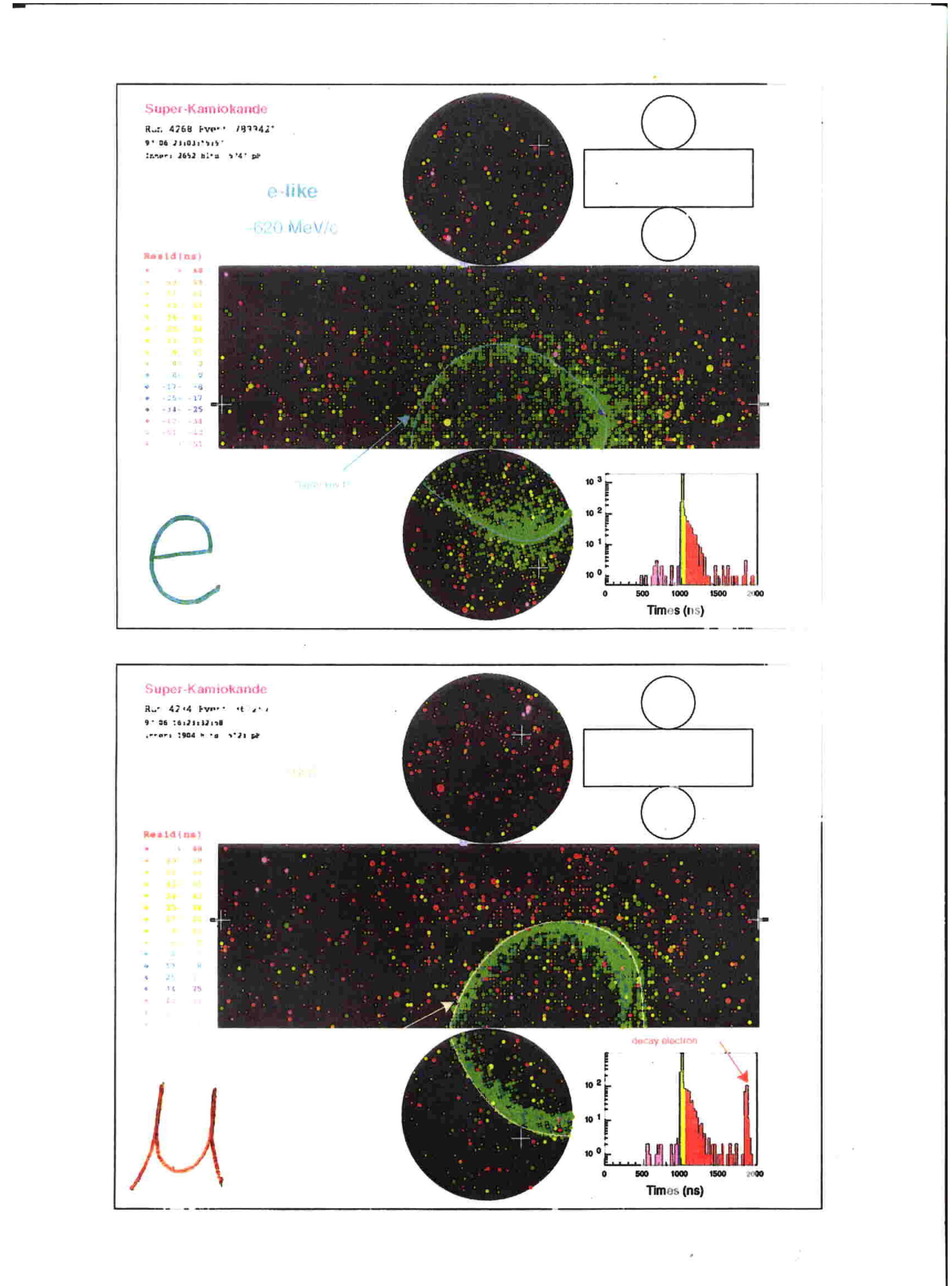
for the {Kamiokande / Super-Kamiokande} Collaborations

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

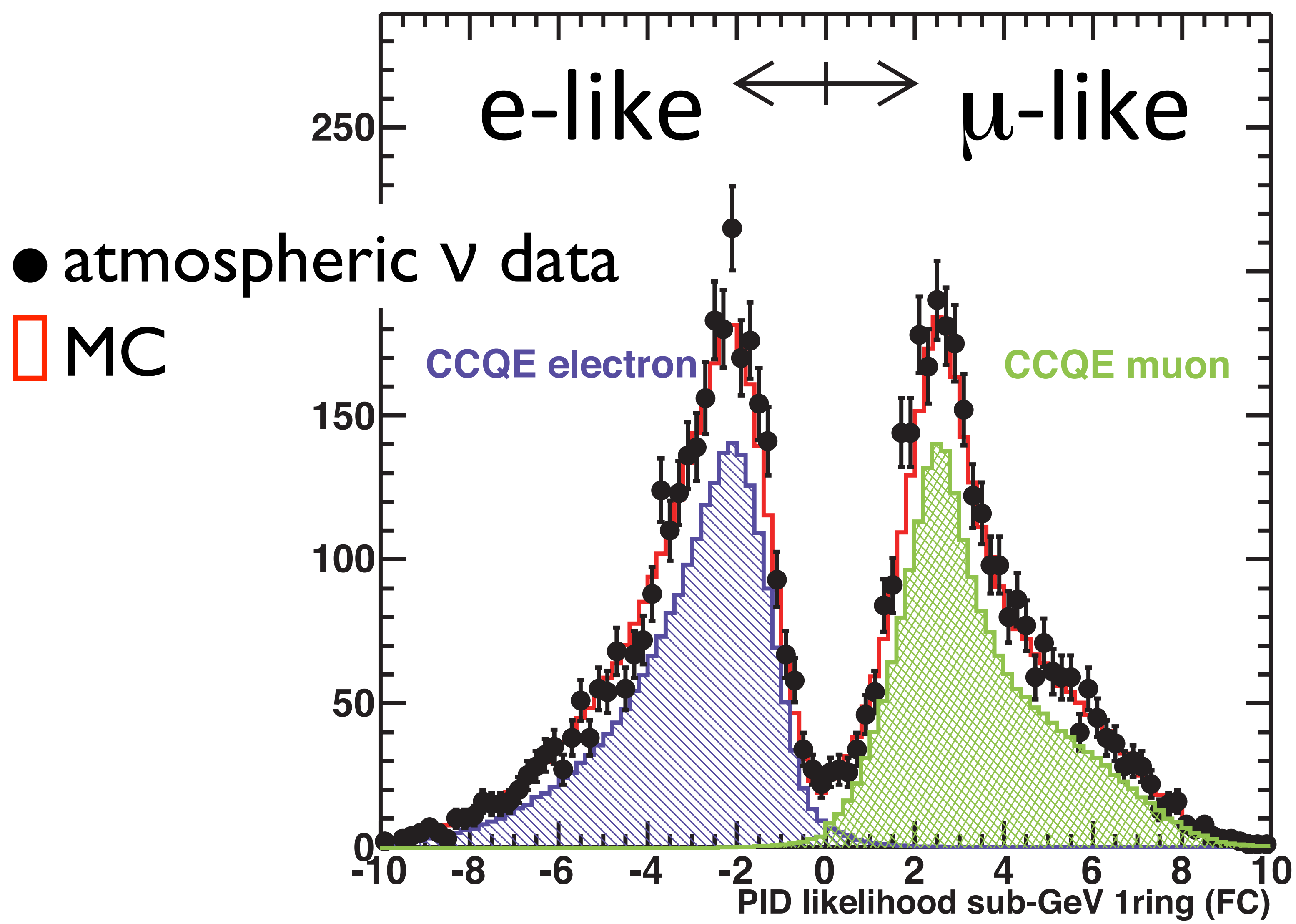


Zenith
Isotropic flux of
cosmic rays
θ
SK
20 km
10000
km
R
R
Zenith
θ

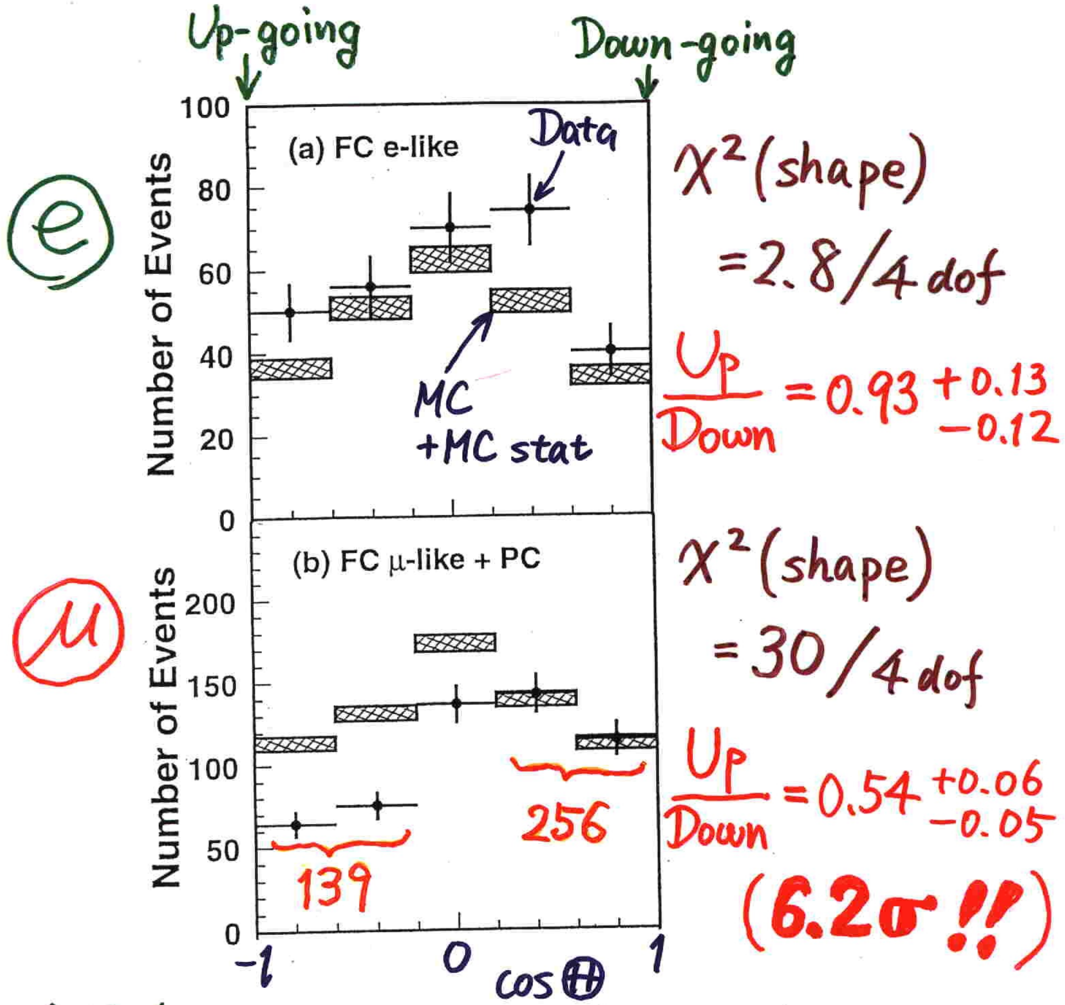

Zenith
Isotropic flux of cosmic rays
θ
SK
20 km
10000 km
R
R
Zenith
θ


Super-Kamiokande
e-like
~620 MeV/c
e
Times (ns)
Super-Kamiokande
decay electron
μ
Times (ns)

circa 2015


e-like
μ-like
● atmospheric ν data
MC
CCQE electron
CCQE muon
250
150
100
50
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
PID likelihood sub-GeV 1ring (FC)

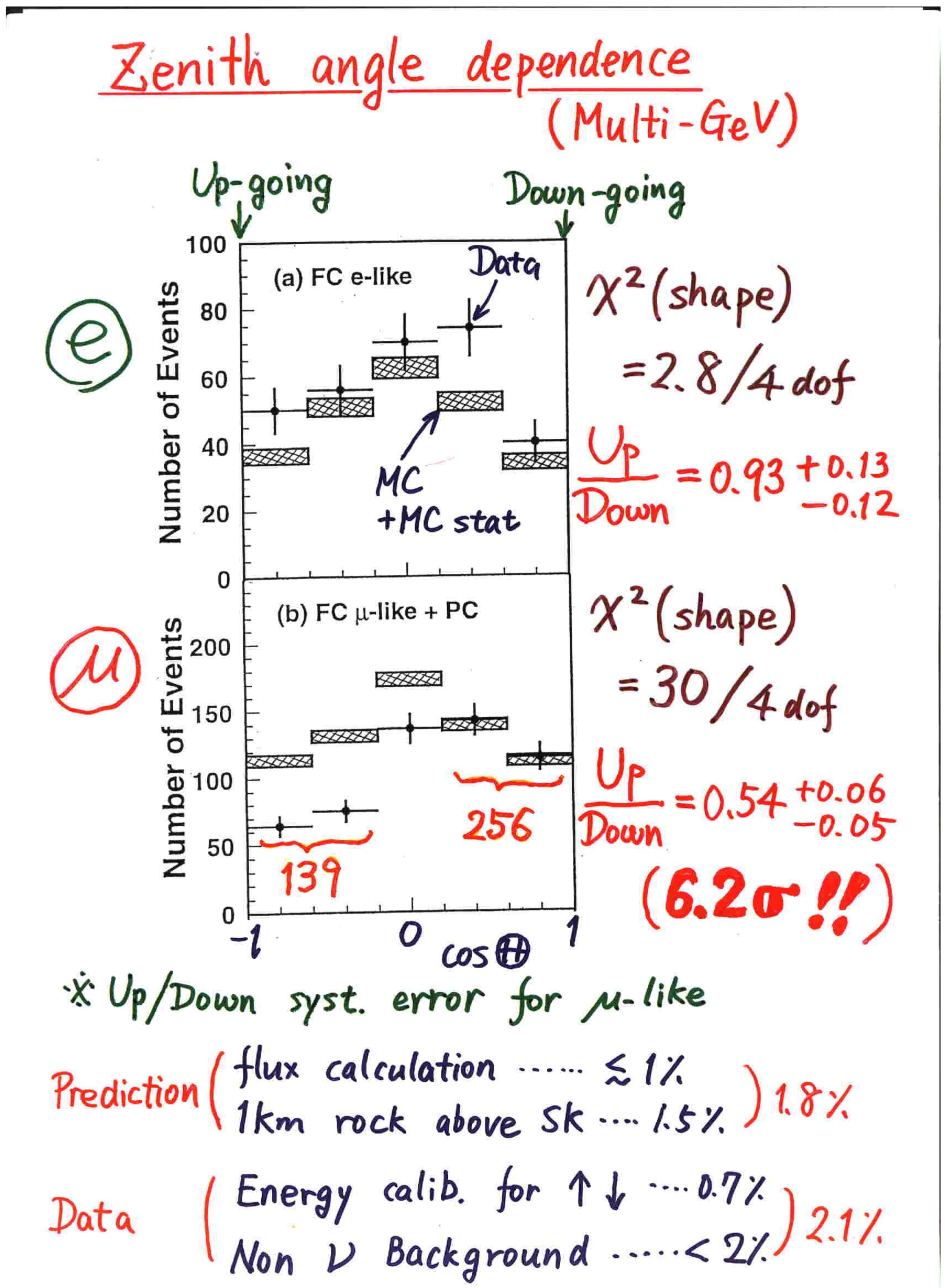
Zenith angle dependence (Multi-GeV)

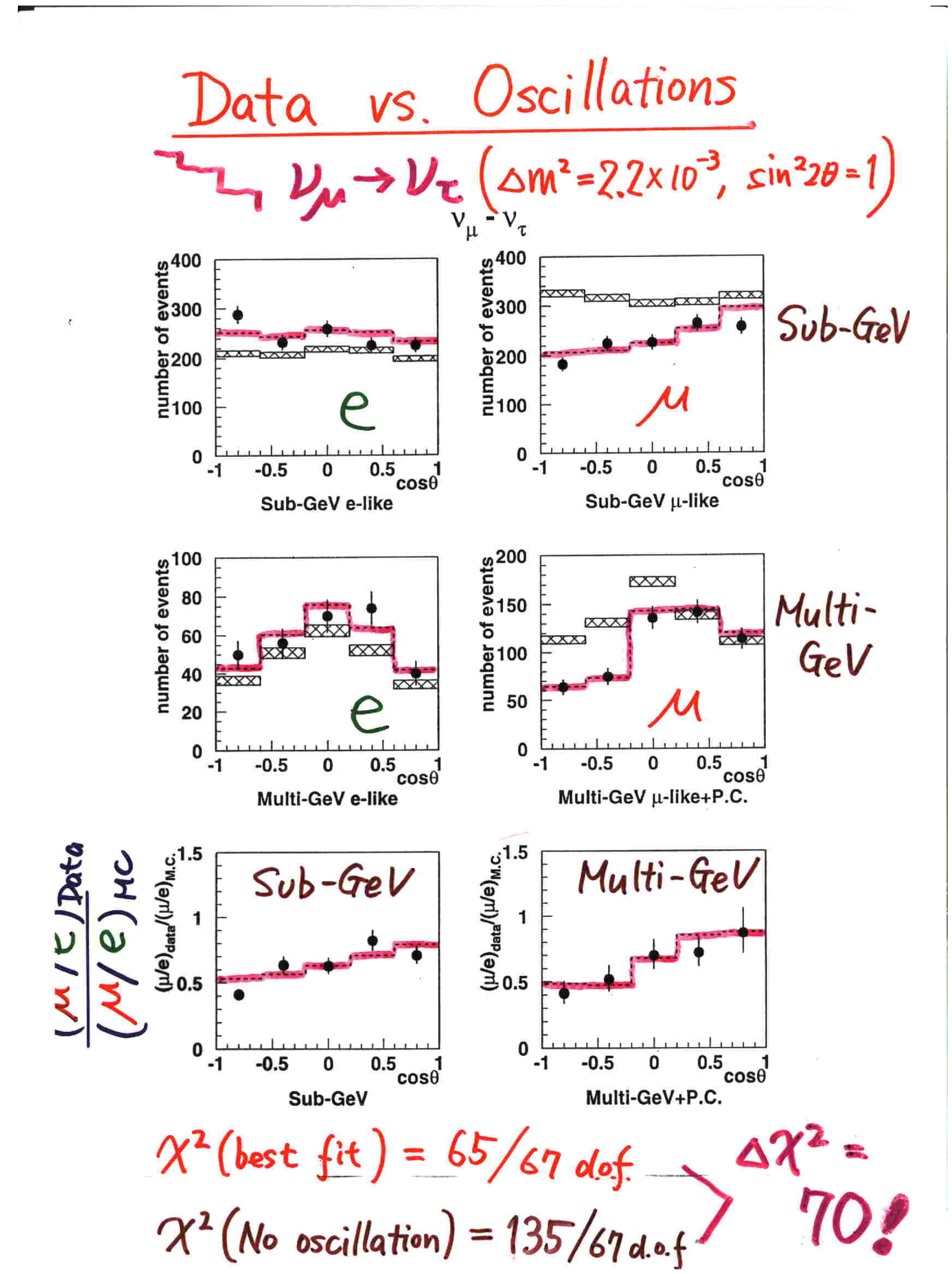


※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

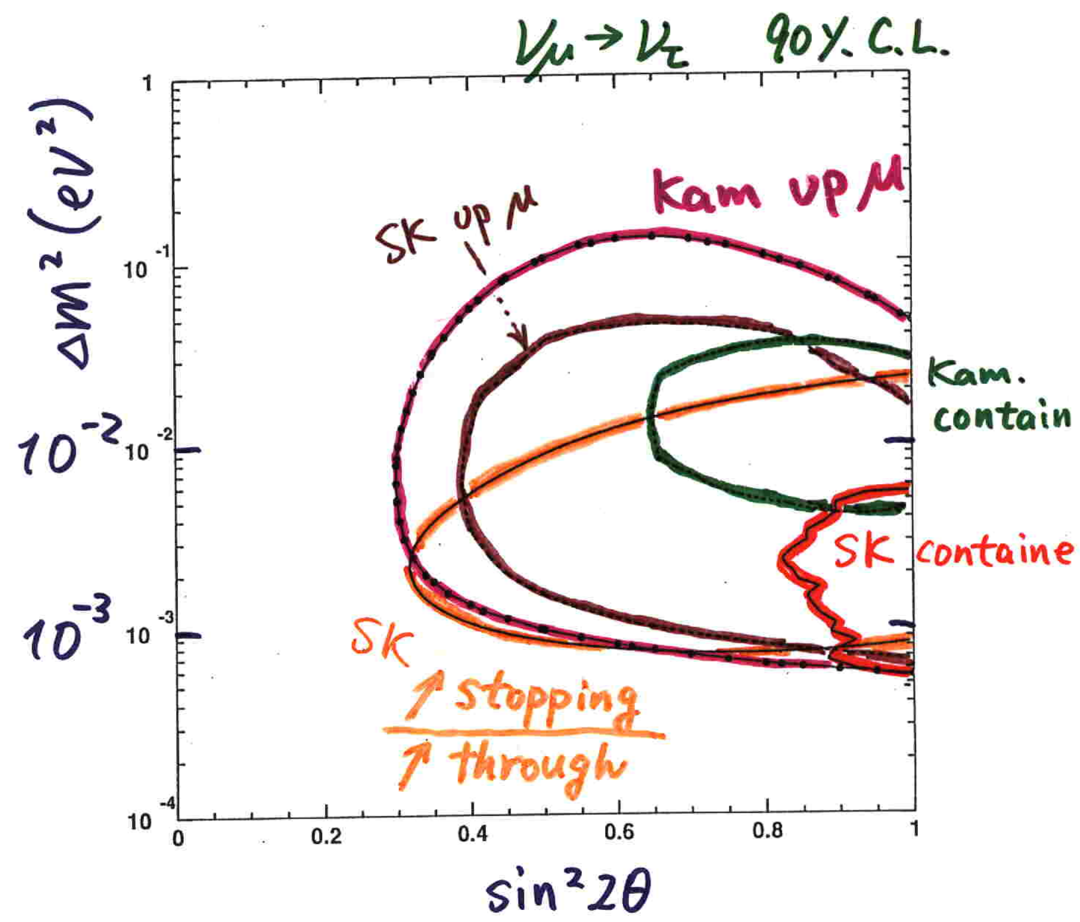
Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background …..< 2%) 2.1%


Zenith angle dependence
(Multi-GeV)
Up-going
Down-going
(a) FC e-like
Data
MC
+MC stat
Number of Events
(b) FC μ-like + PC
139
256
cos Θ
χ²(shape)
=2.8/4 dof
Up/Down = 0.93 +0.13 −0.12
χ²(shape)
=30/4 dof
Up/Down = 0.54 +0.06 −0.05
(6.2σ!!)
※ Up/Down syst. error for μ-like
Prediction (flux calculation …… ≲1%
1km rock above SK …. 1.5%) 1.8%
Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background …..< 2%) 2.1%


Data vs. Oscillations
νμ → ντ (Δm² = 2.2×10⁻³, sin²2θ = 1)
νμ - ντ
number of events
Sub-GeV e-like
Sub-GeV μ-like
Sub-GeV
Multi-GeV e-like
Multi-GeV μ-like+P.C.
Multi-GeV
cosθ
(μ/e)data/(μ/e)M.C.
(μ/e)Data / (μ/e)MC
Sub-GeV
Multi-GeV+P.C.
χ²(best fit) = 65/67 d.o.f.
χ²(No oscillation) = 135/67 d.o.f
Δχ² = 70!

Summary

Evidence for ν_μ oscillations

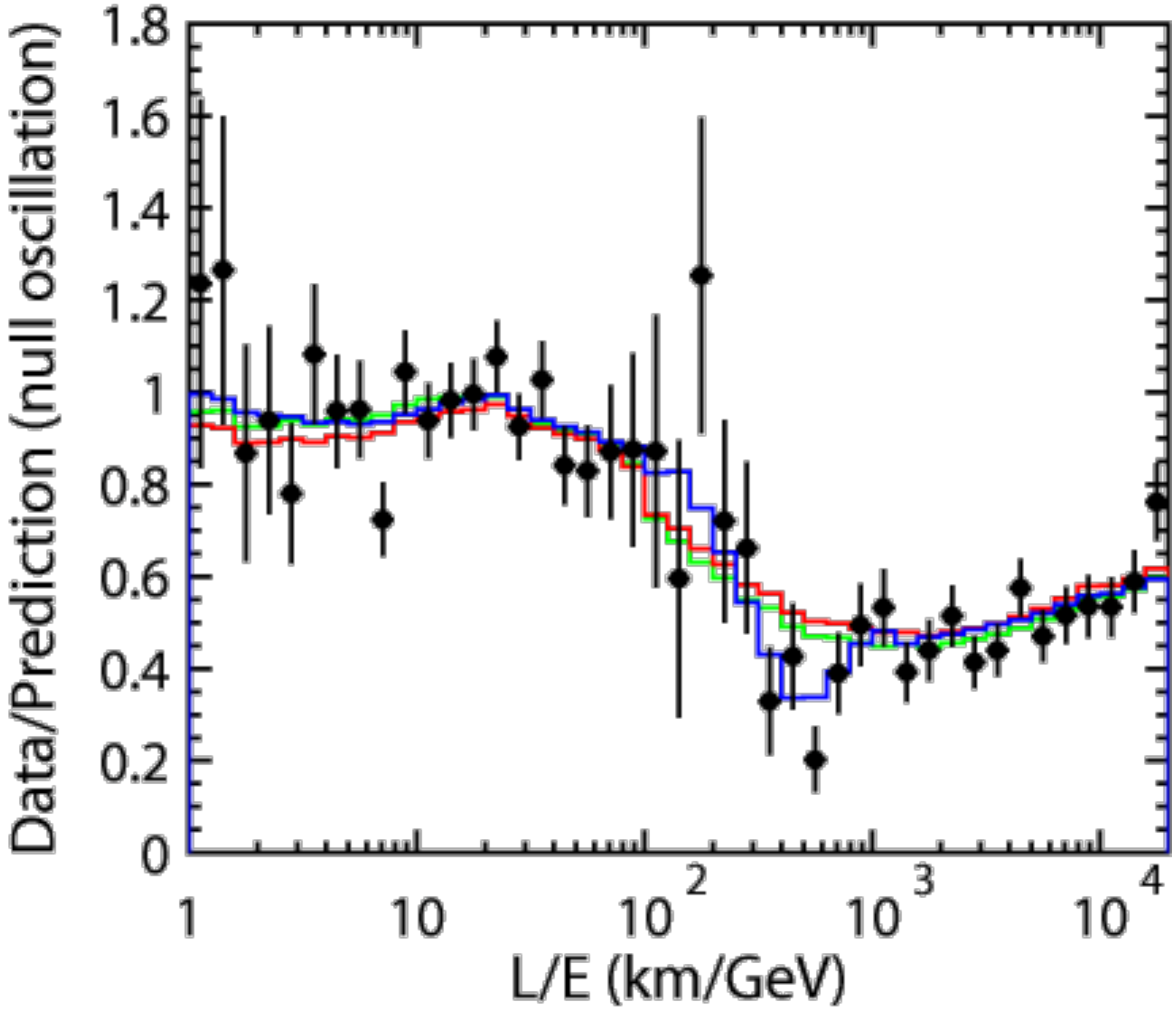


- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

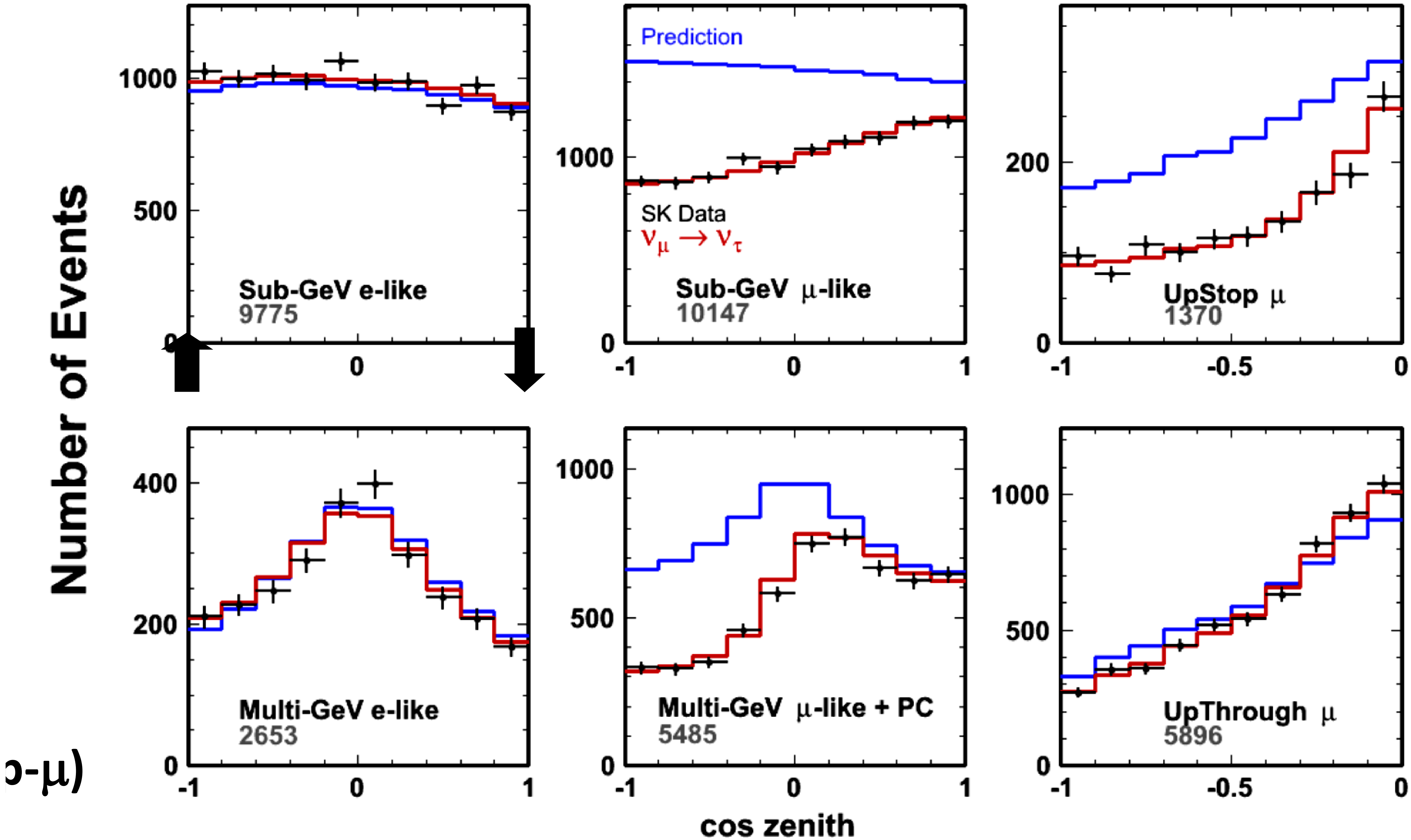
$\nu_\mu \to \nu_\tau$ ($\Delta m^2 = 2.2 \times 10^{-3}$, $\sin^2 2\theta = 1$)

$\nu_\mu - \nu_\tau$



Data/Prediction (null oscillation)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
10^3
10^4
L/E (km/GeV)

Zenith angle distribution of each sample



MINOS / T2K / NOvA

T2K: 1502.01550

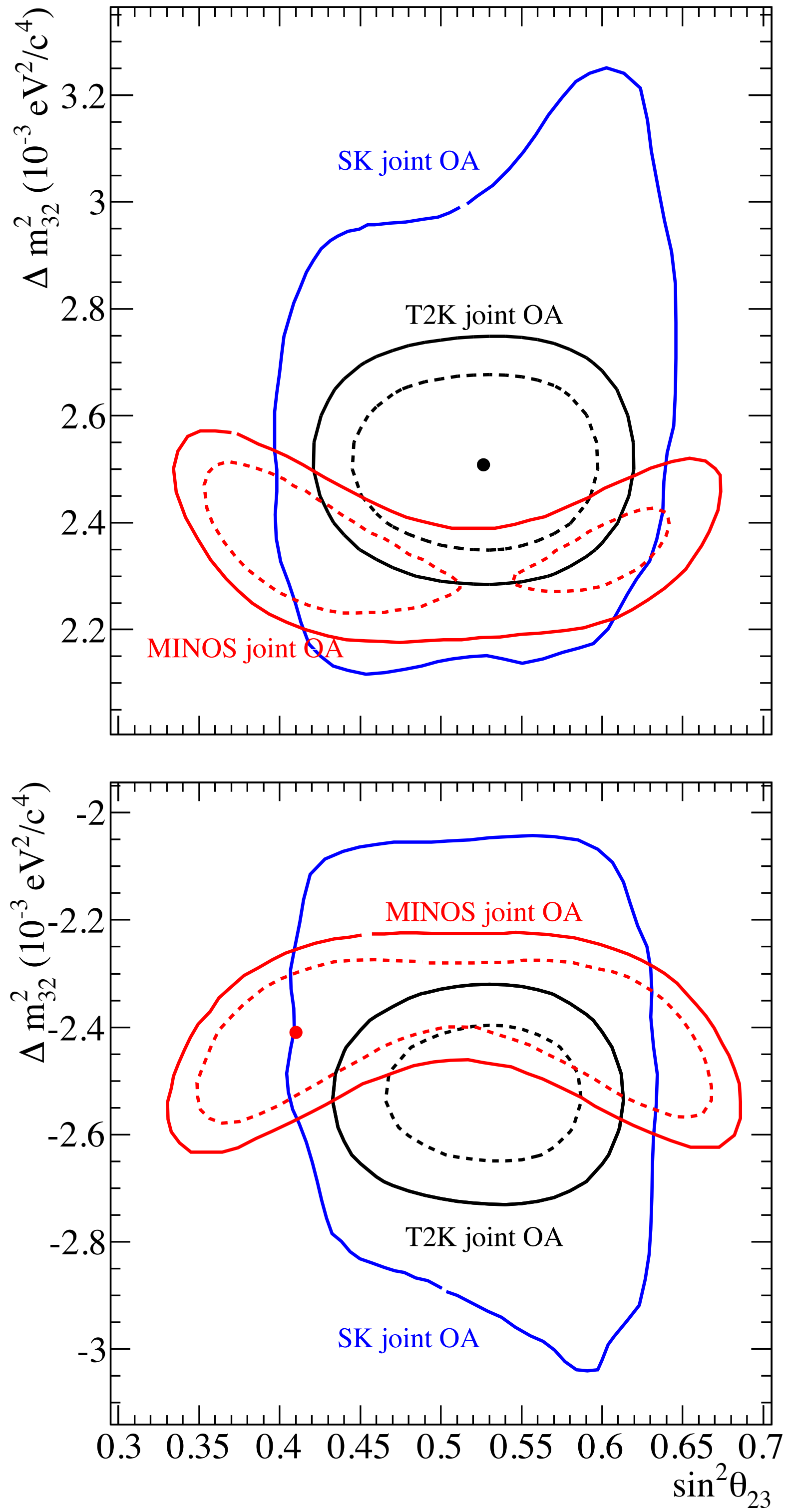
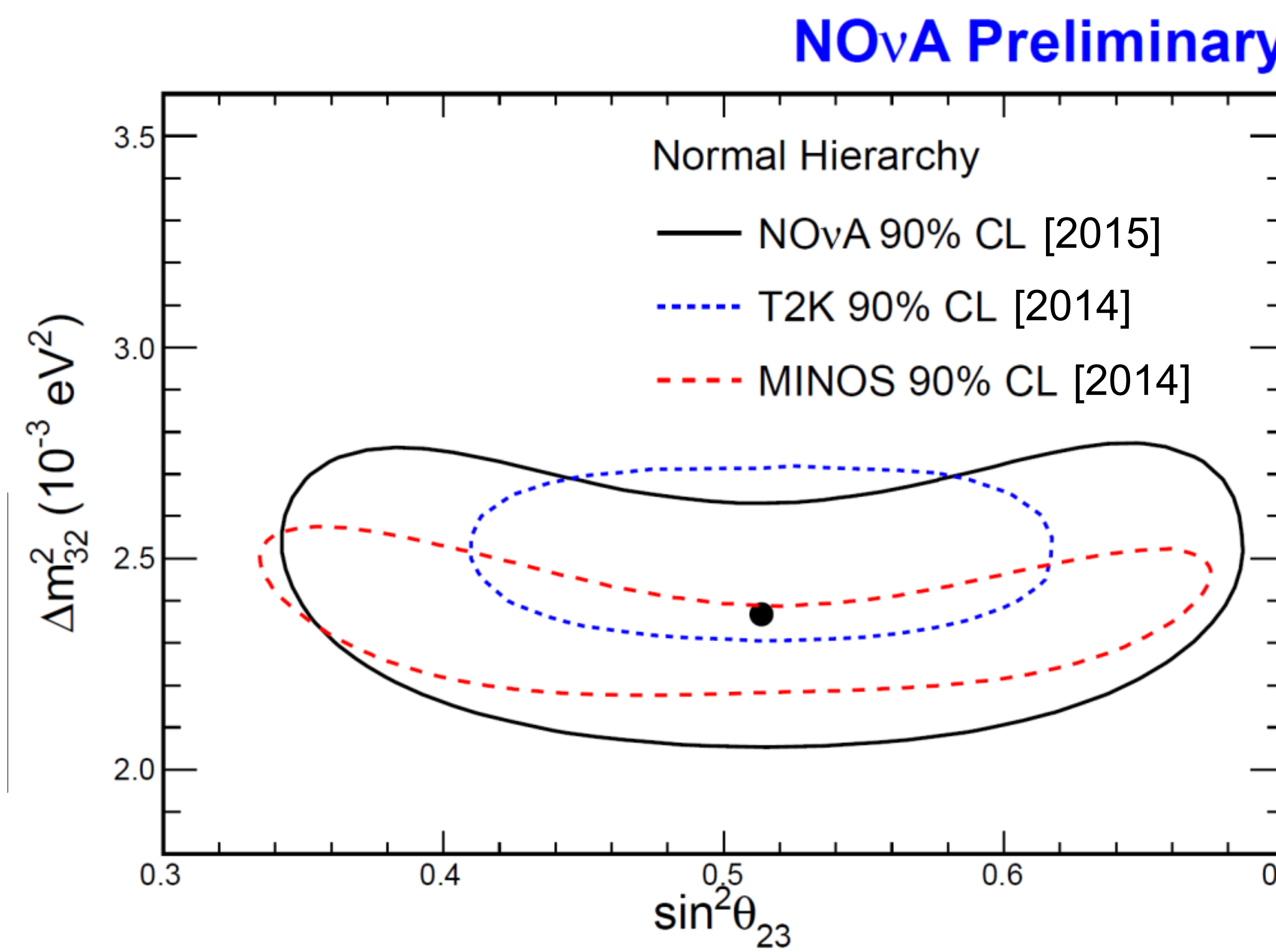
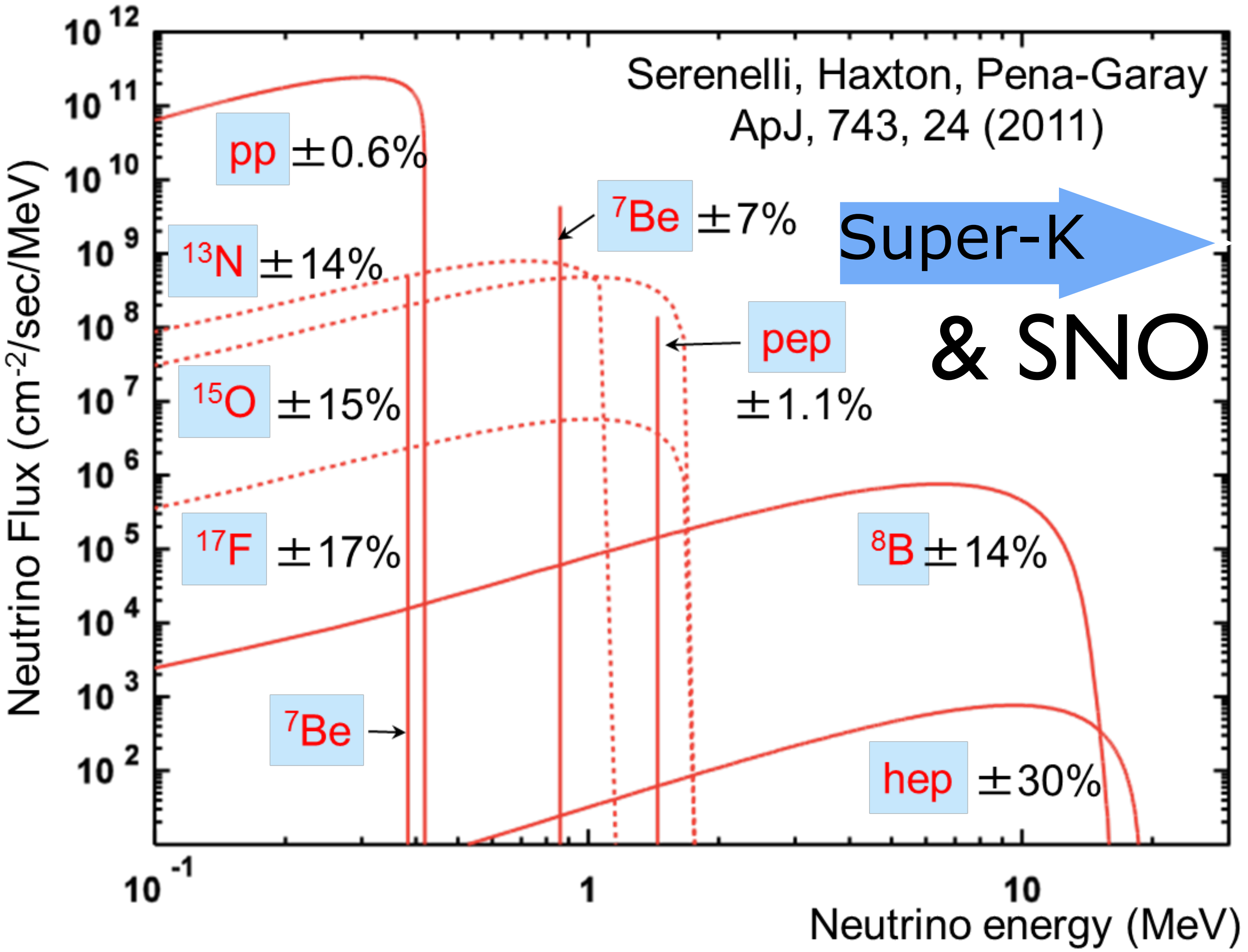
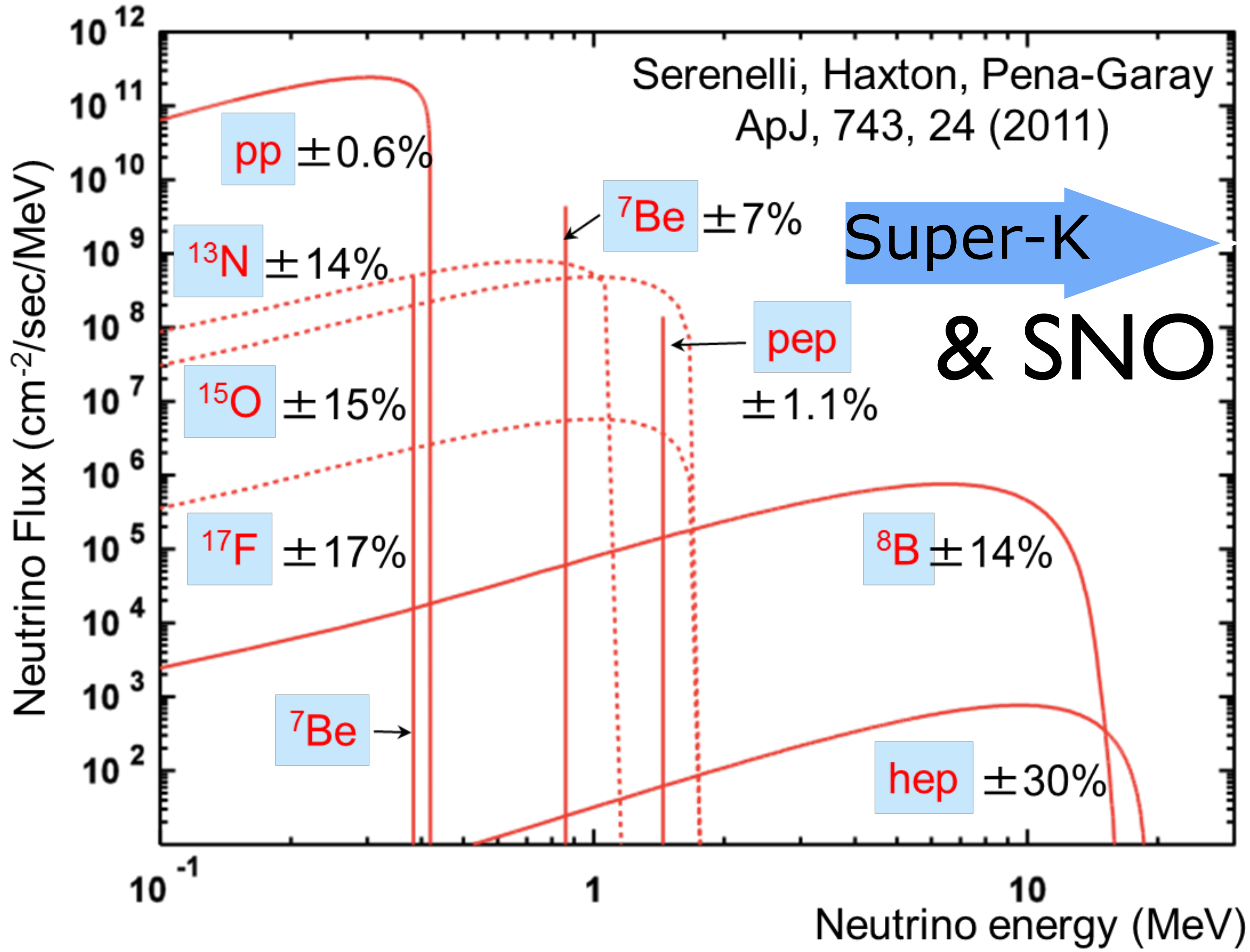


FIG. 36: 68% (dashed) and 90% (solid) CL regions for normal (top) and inverted (bottom) mass hierarchy combined with the results from reactor experiments in the ($\sin^2\theta_{23}$, Δm^2_{32}) space compared to the results from the Super-Kamiokande [131] and MINOS [132] experiments.

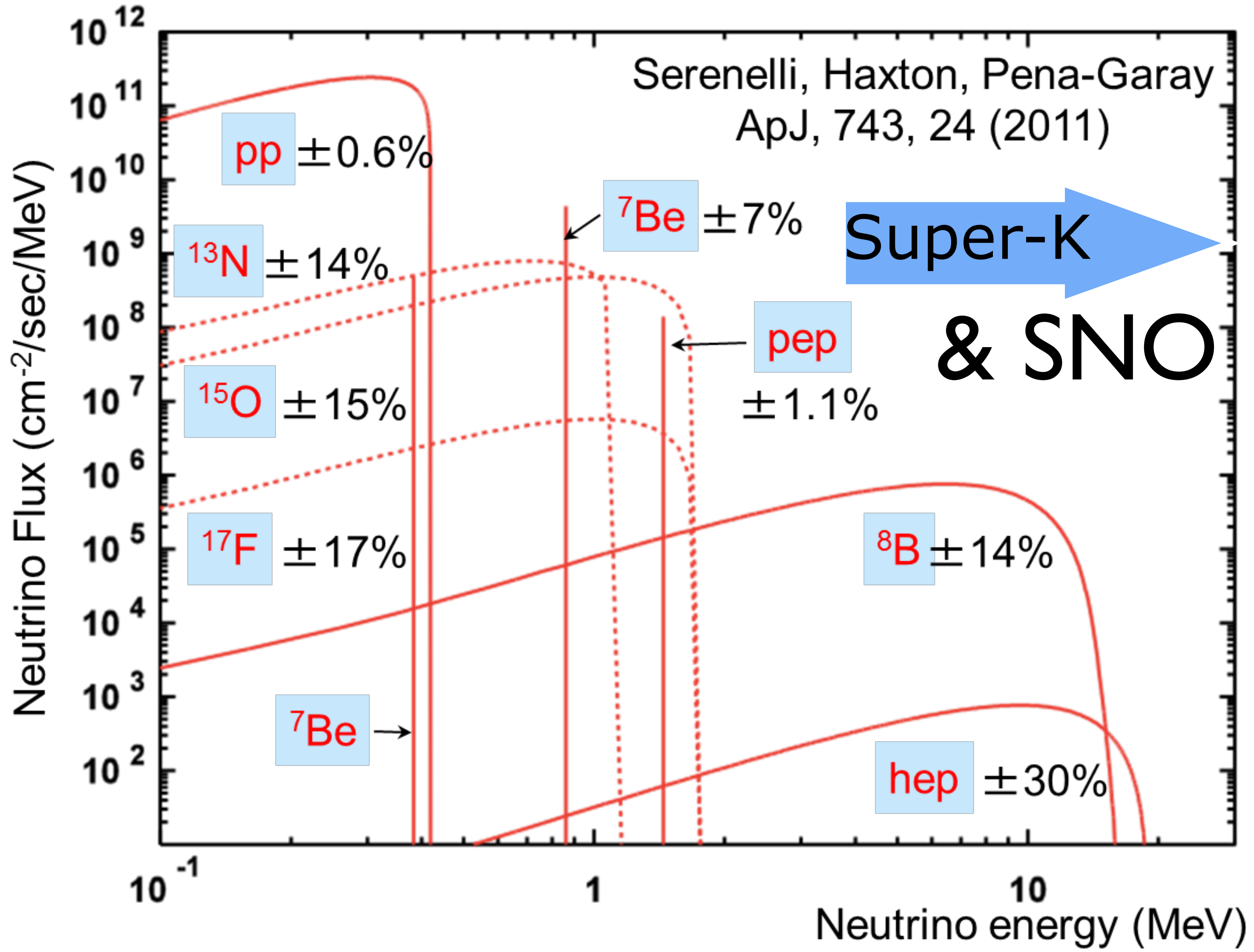


SOLAR NEUTRINOS:


Serenelli, Haxton, Pena-Garay
ApJ, 743, 24 (2011)
pp ±0.6%
^{7}Be ±7%
Super-K
& SNO
^{13}N ±14%
pep
±1.1%
^{15}O ±15%
^{17}F ±17%
^{8}B ±14%
^{7}Be
hep ±30%
Neutrino Flux (cm^{-2}/sec/MeV)
Neutrino energy (MeV)



Center of the Sun produces $\mathbf{1.7 \times 10^{38}}\ \boldsymbol{\nu_e}/\mathrm{sec}$



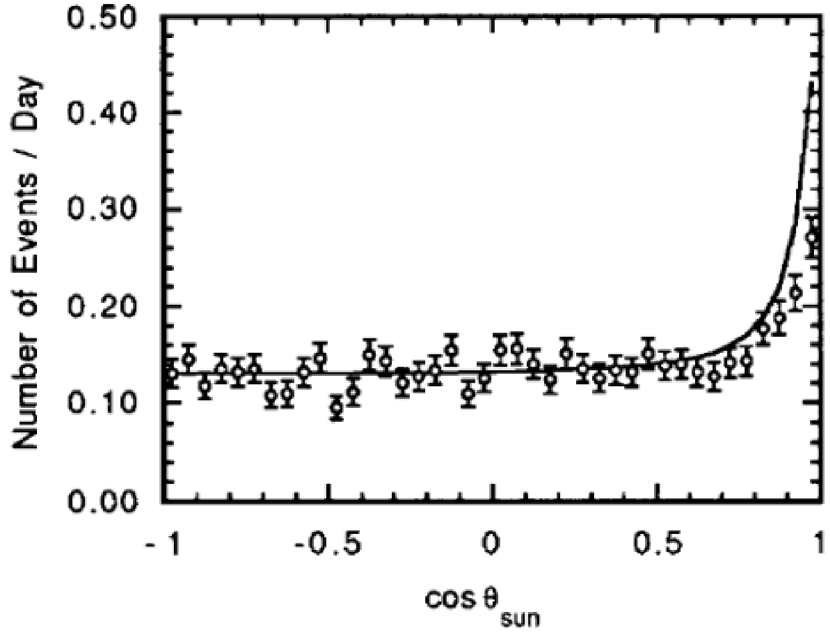
Center of the Sun produces $1.7 \times 10^{38}\ \nu_e/\text{sec}$

At Earth this is $6.0 \times 10^{10}\ \nu/\text{cm}^2/\text{sec}$

OR

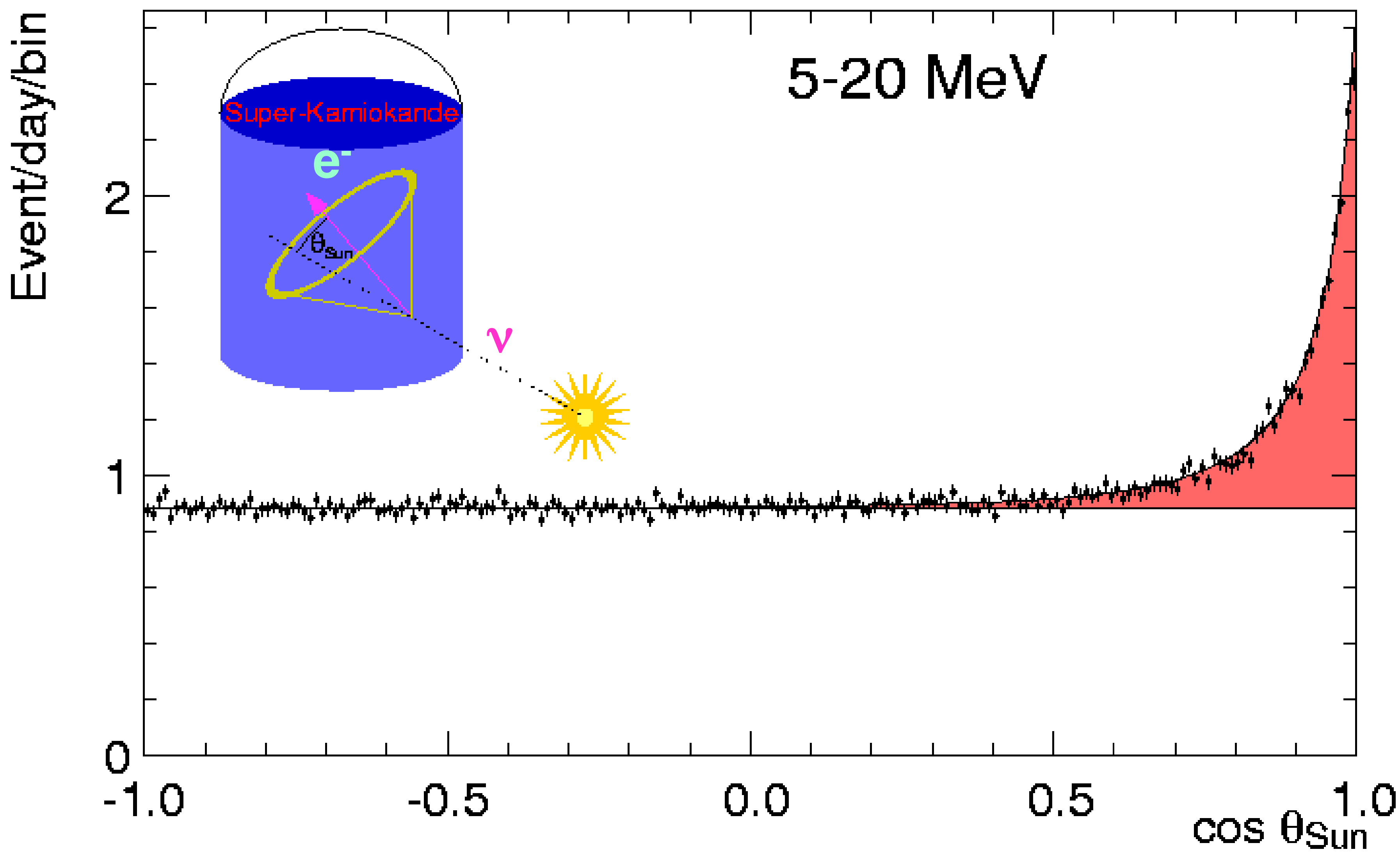
2 every 1 cm^3

Kamiokande (1989)



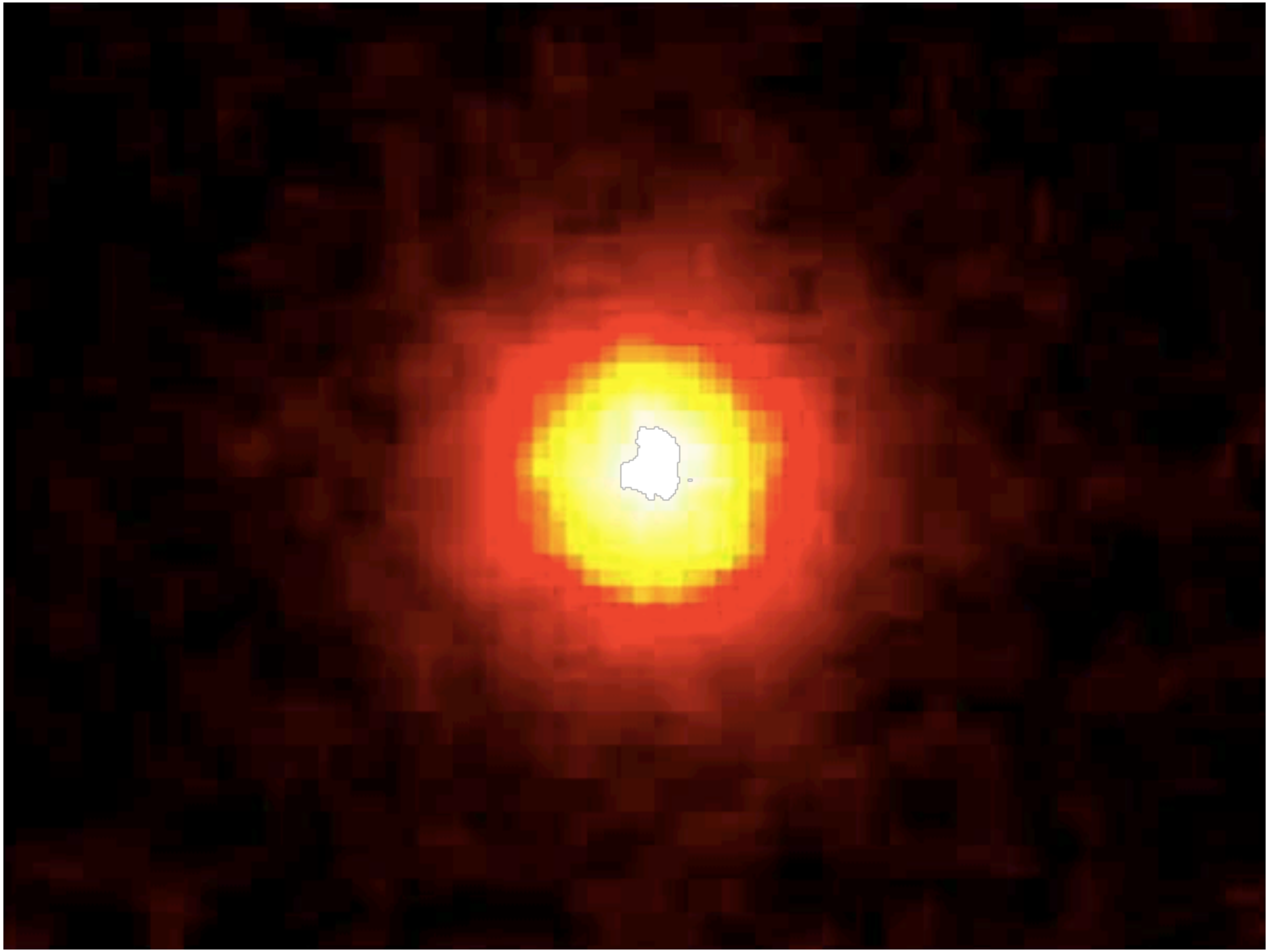
$$\nu + e^- \rightarrow \nu + e^-$$

SuperKamiokande



SuperK neutrino picture of the Sun

$$\nu + e^- \to \nu + e^-$$



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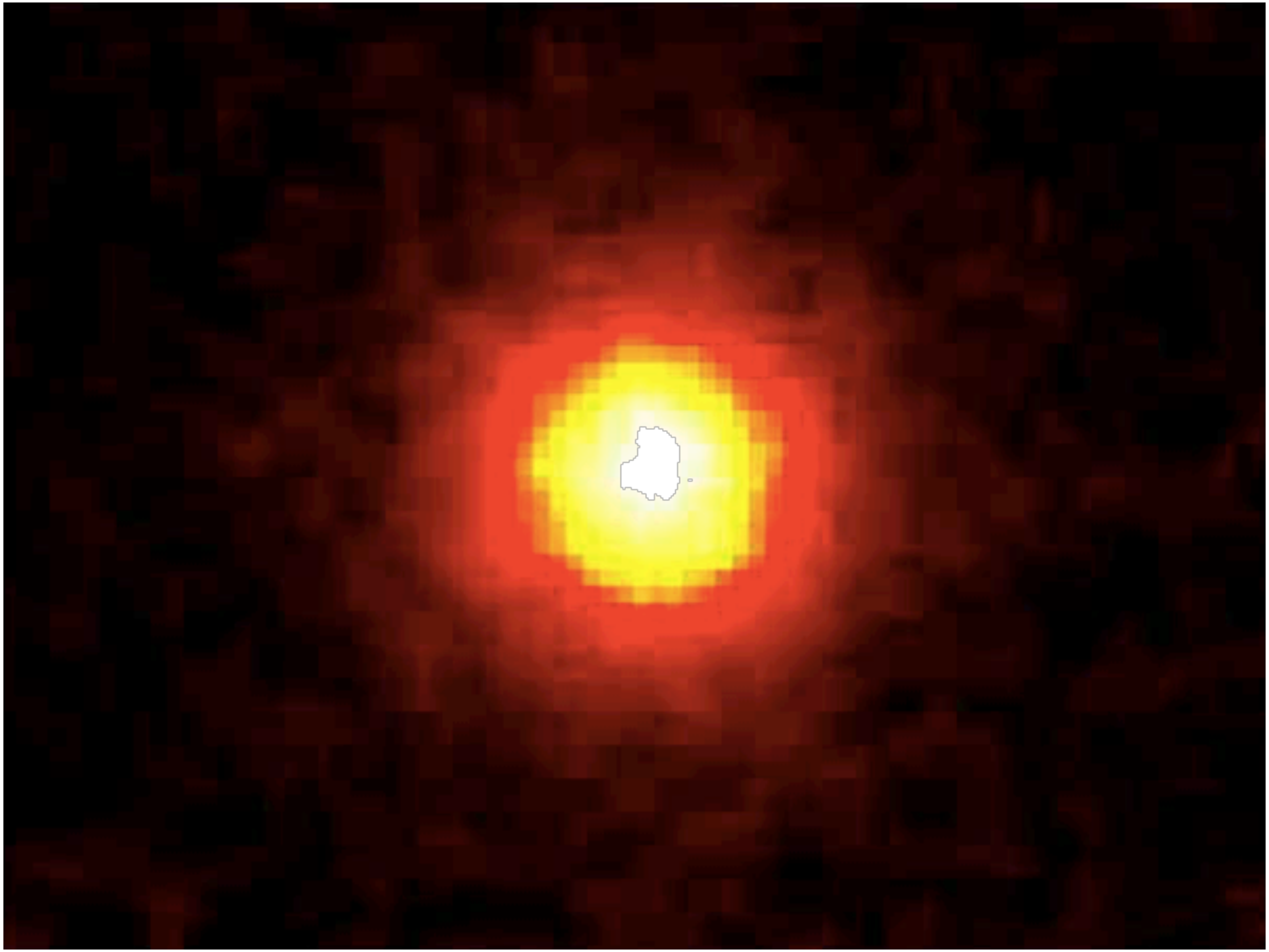
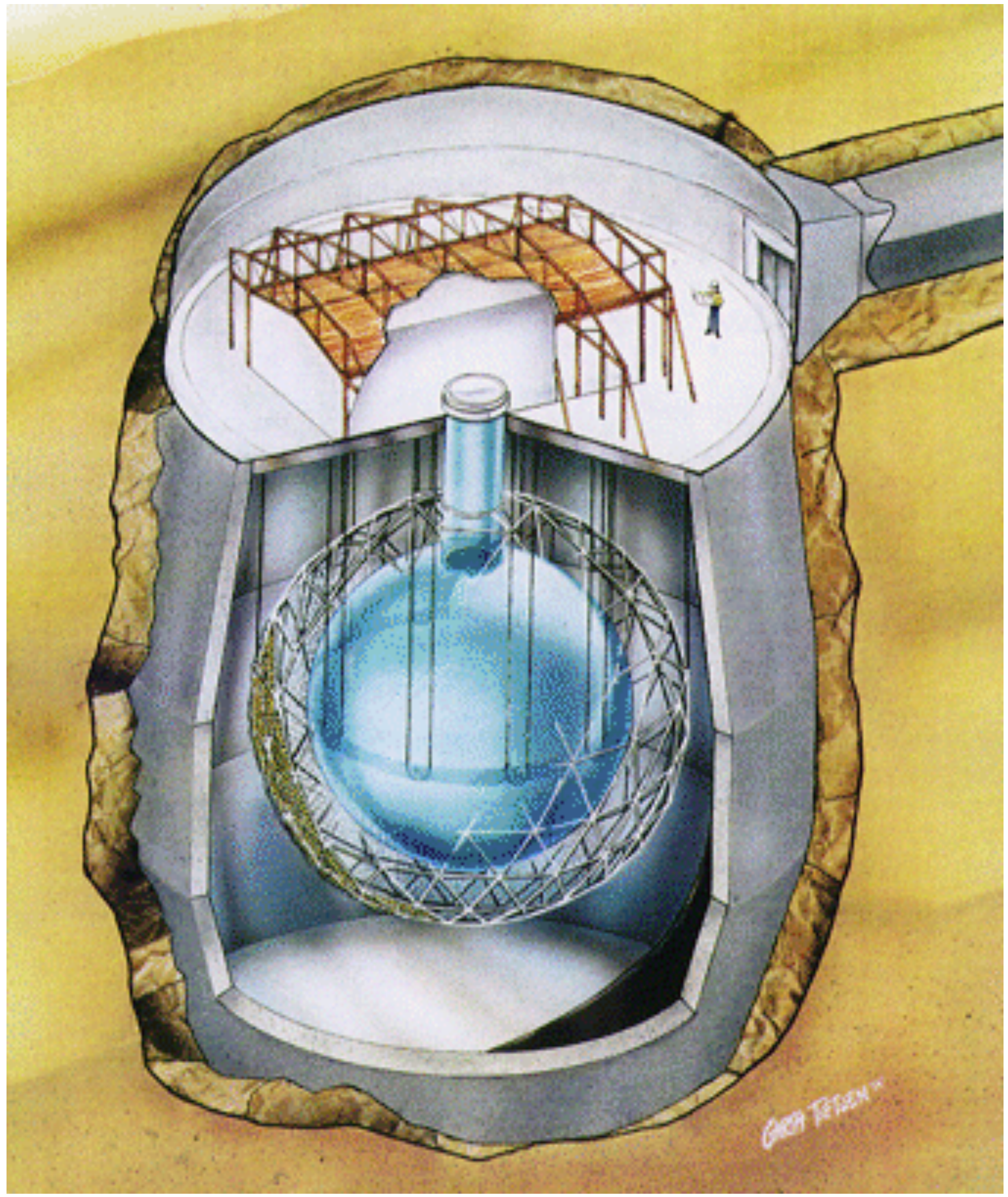


Which Neutrinos ?

SNO (D2O 1 kton)



Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Phys. Rev. Lett. **55**, 1534 – Published 30 September 1985

ABSTRACT

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from $^8\mathrm{B}$ decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

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Received 27 June 1985

Article

Il Nuovo Cimento C

March 1986, Volume 9, Issue 2, pp 308-317

First online:

Proposal to build a neutrino observatory in Sudbury, Canada

D. Sinclair, A. L. Carter, D. Kessler, E. D. Earle, P. Jagam, J. J. Simpson, R. C. Allen, H. H. Chen, P. J. Doe, E. D. Hallman, W. F. Davidson, R. S. Storey, A. B. McDonald, G. T. Ewan, H. -B. Mak, B. C. Robertson Show less

SNO Results: 2001

CC: $\nu_e + D \rightarrow p + p + e^-$

NC: $\nu_x + D \rightarrow p + n + \nu_x$

ES: $\nu_e + e^- \rightarrow \nu_e + e^-$
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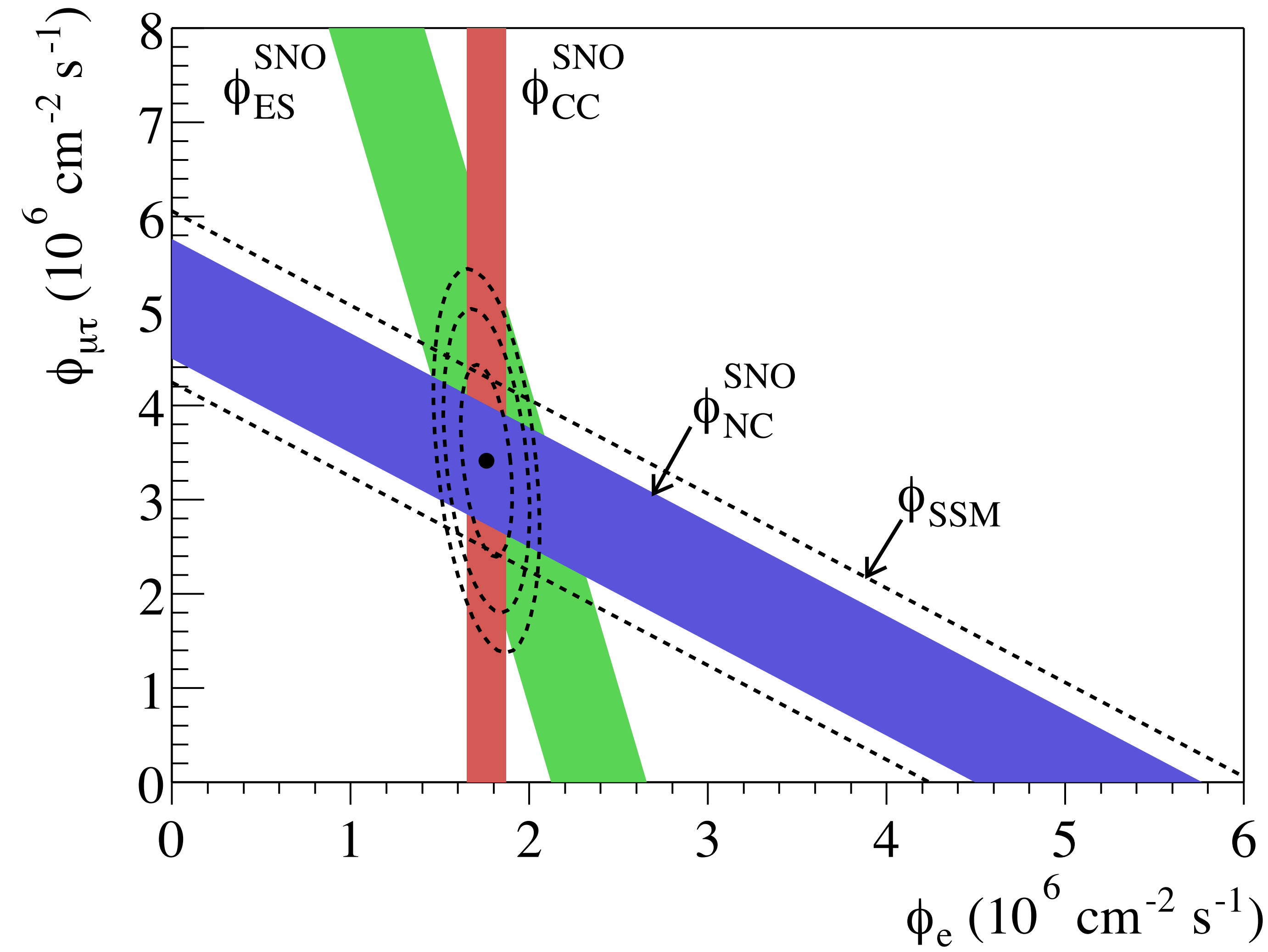

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Beacom and SP: hep-ph/0106128

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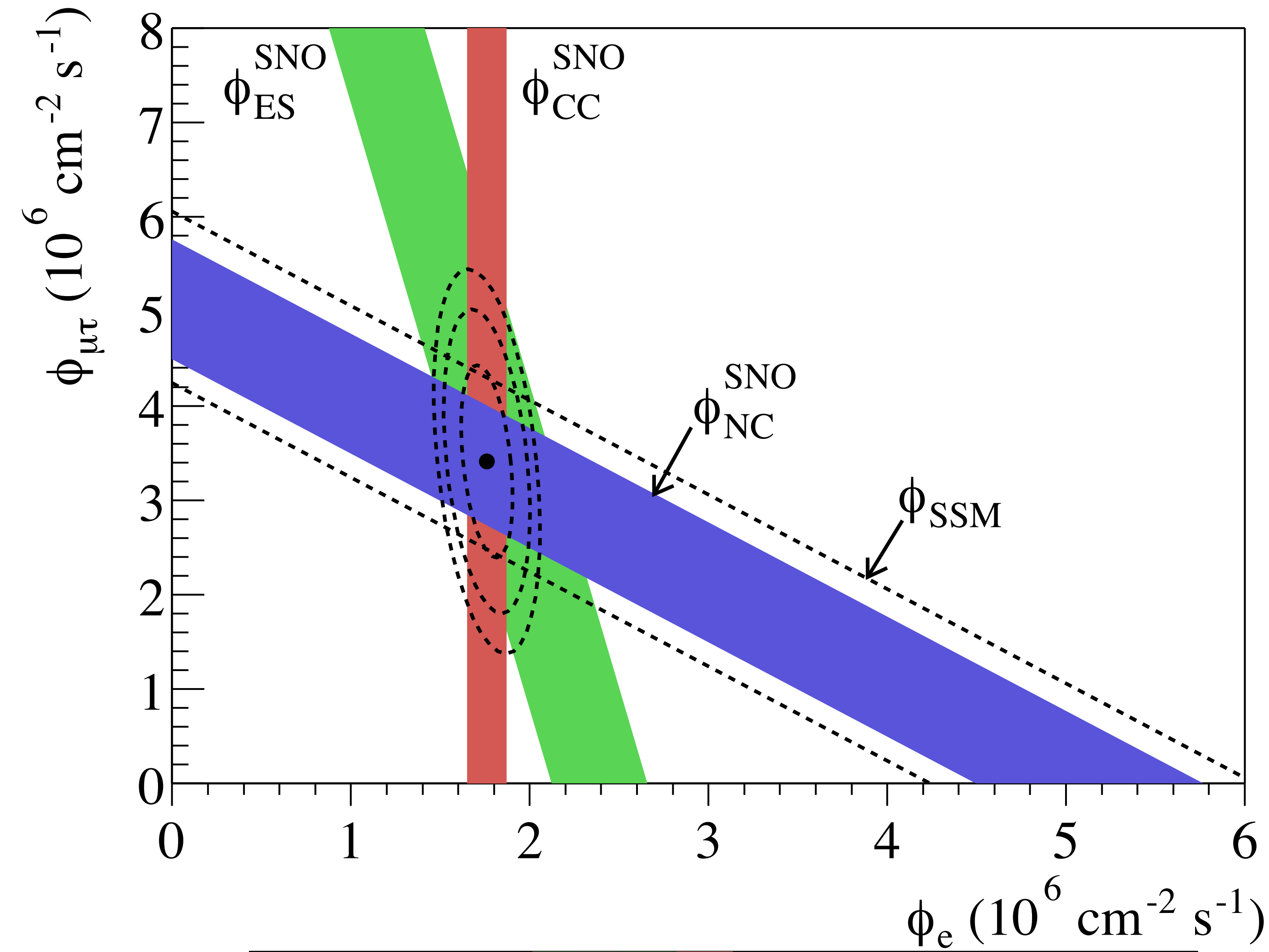
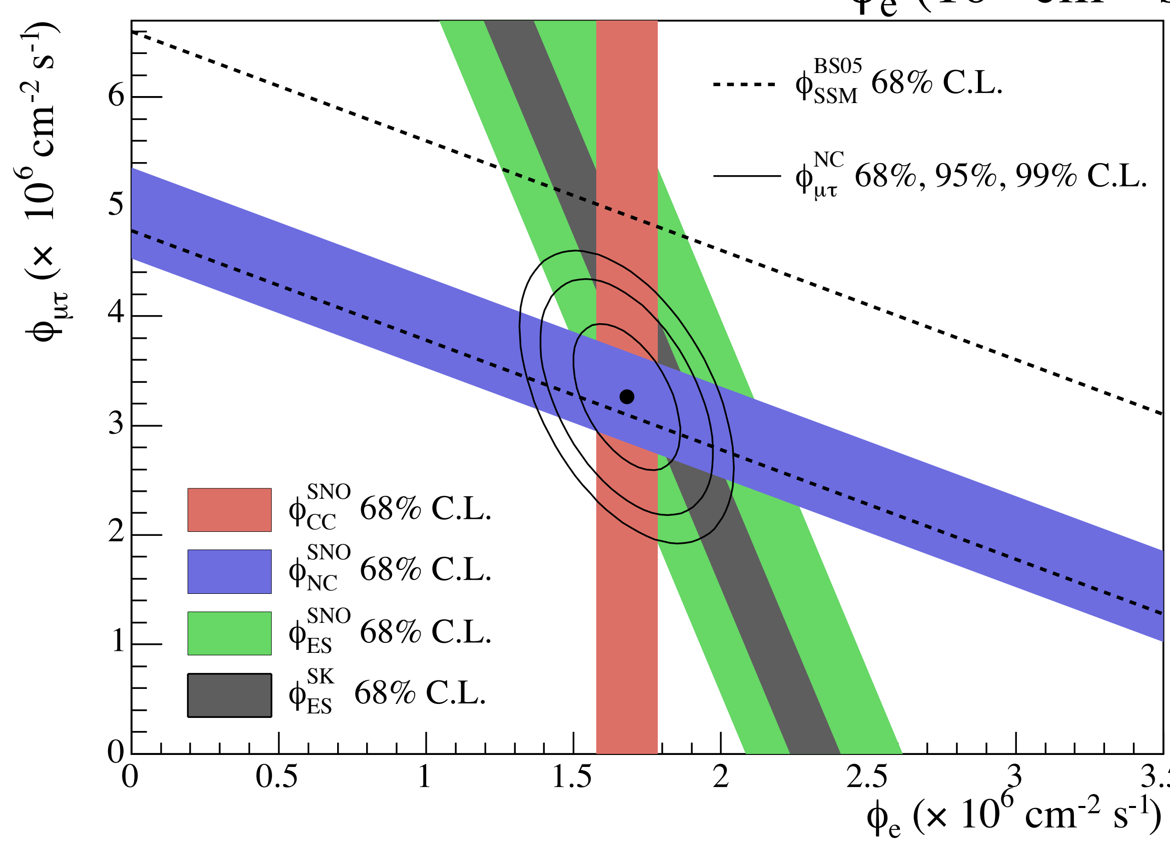
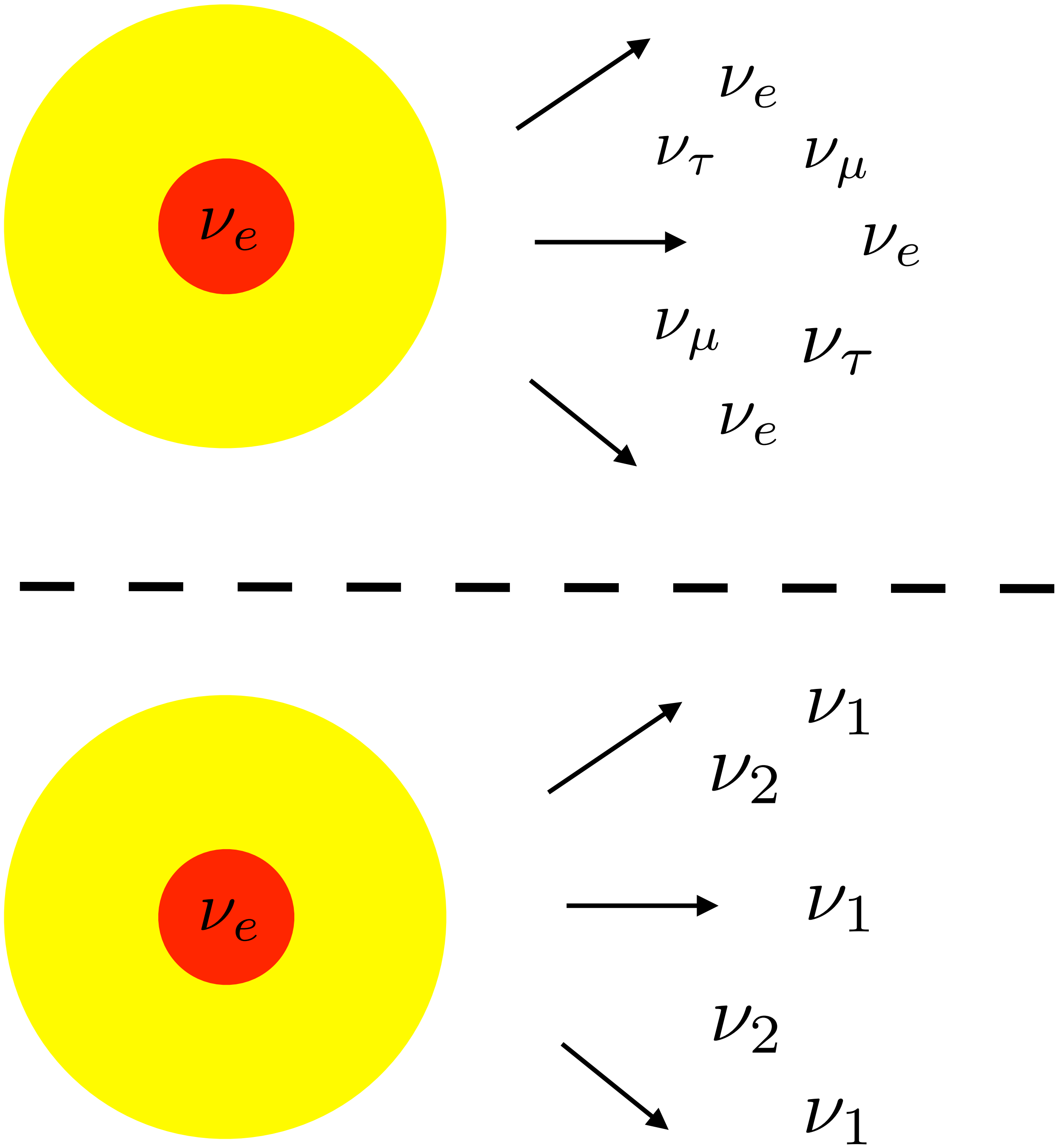




Beacom and SP: hep-ph/0106128

Identical Solar Twins:



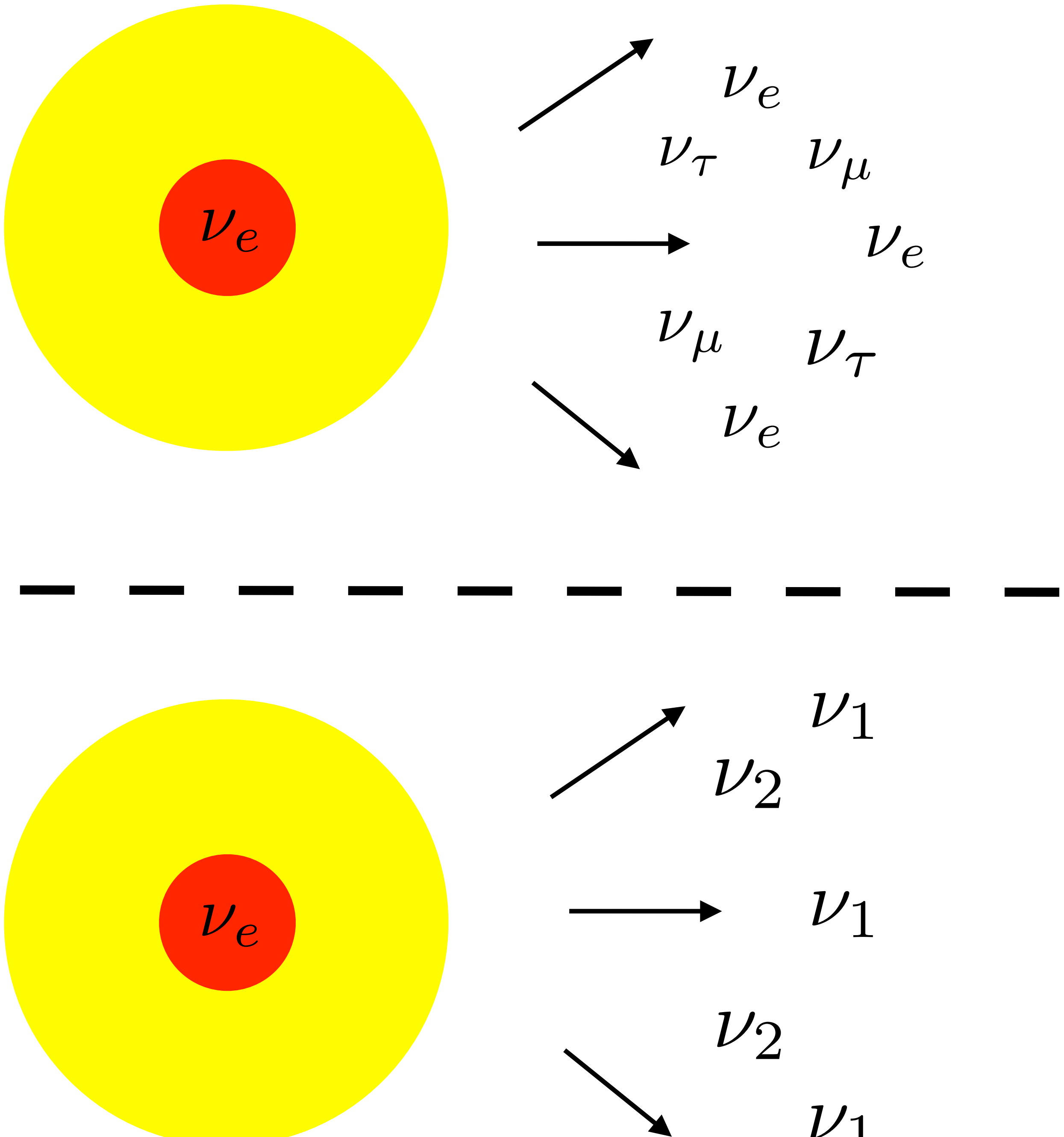
flavor eigenstates

?????

mass eigenstates

Identical Solar Twins:

~ fractions are energy dependent



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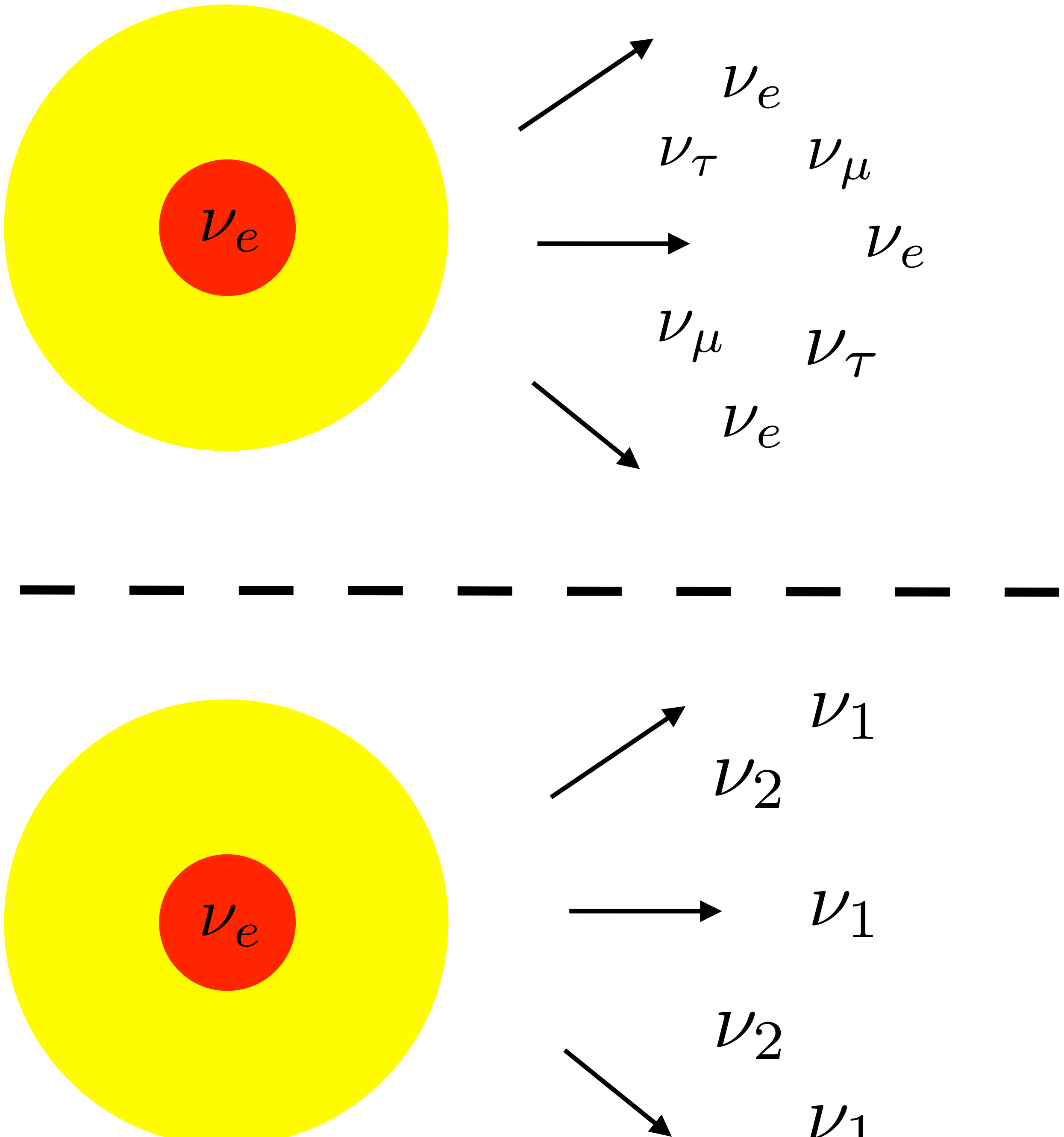

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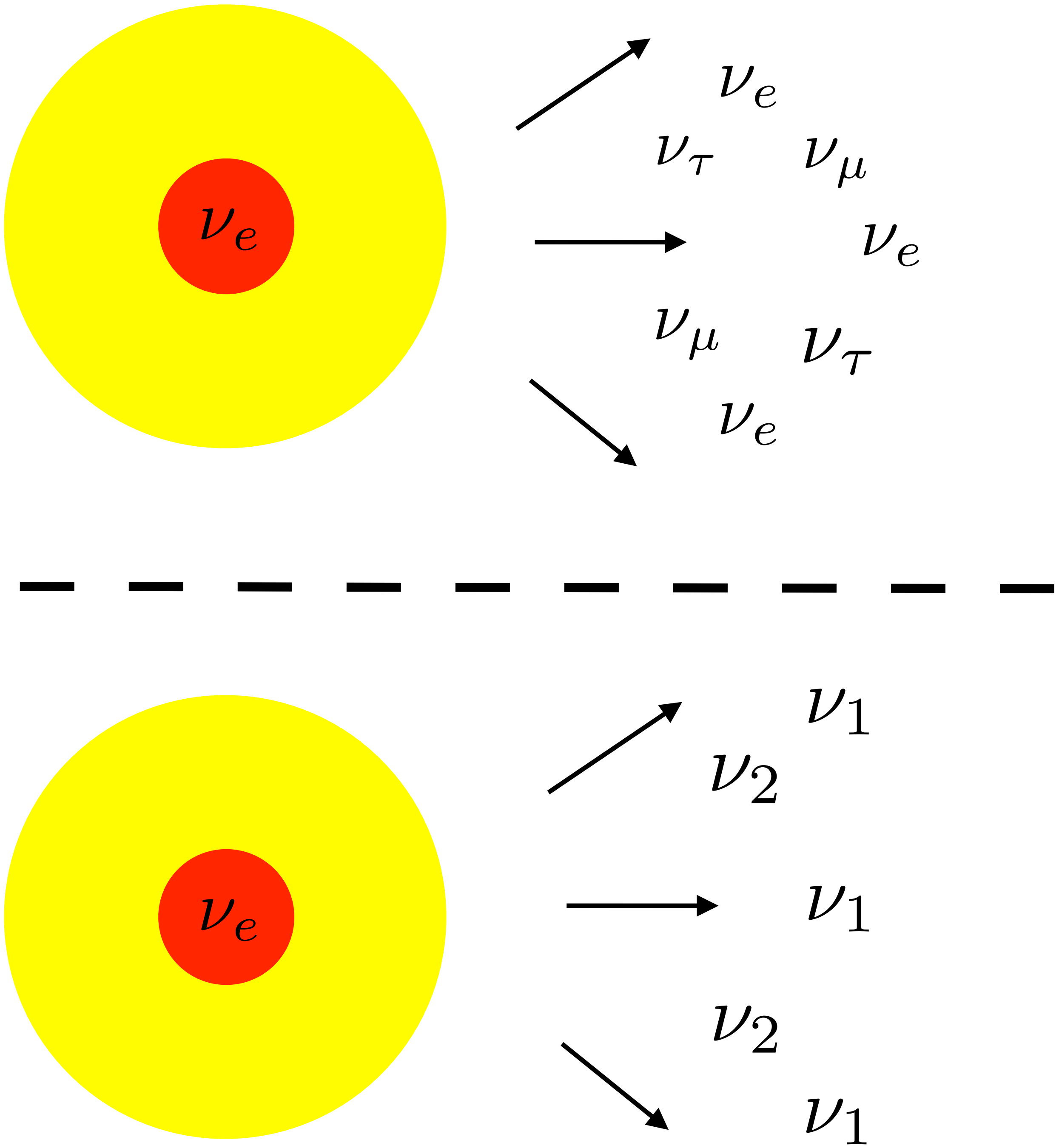


flavor eigenstates

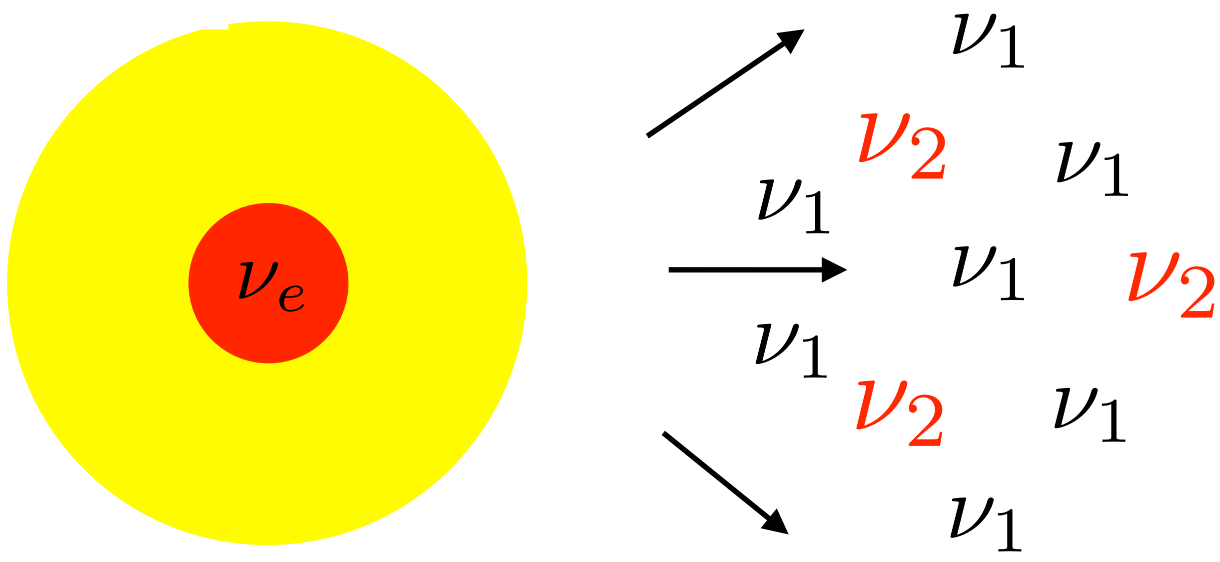
?????

mass eigenstates

$\#$ of oscillation lengths in Solar radius is $2 \times 10^{(4\pm1)}$

~vacuum

pp and ^{7}Be

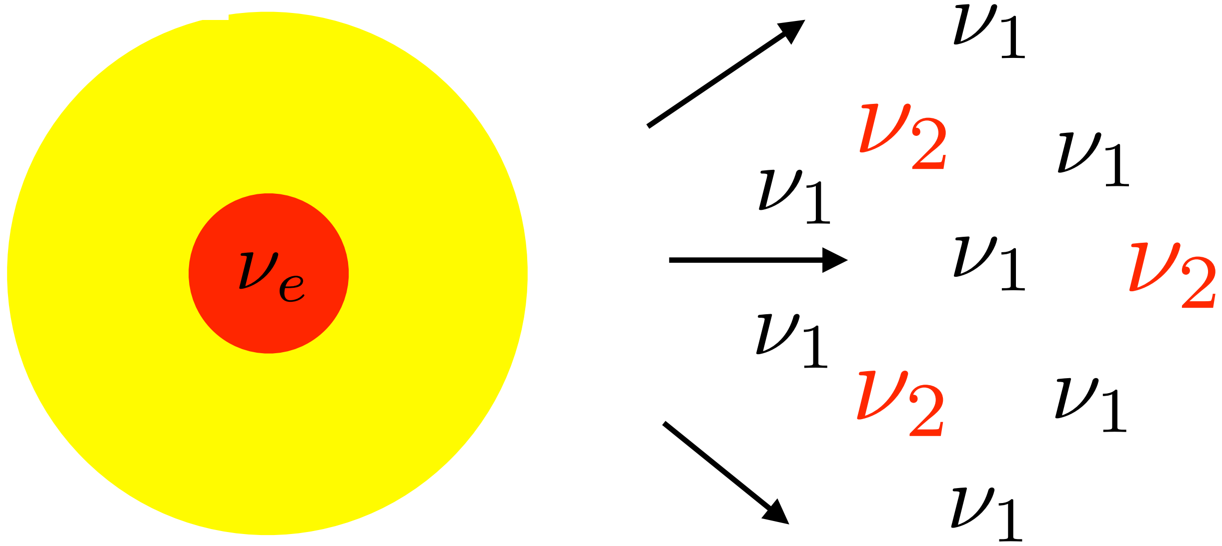


$f_1 \sim 69\%$

$f_2 \sim 31\%$

~vacuum

pp and ^{7}Be



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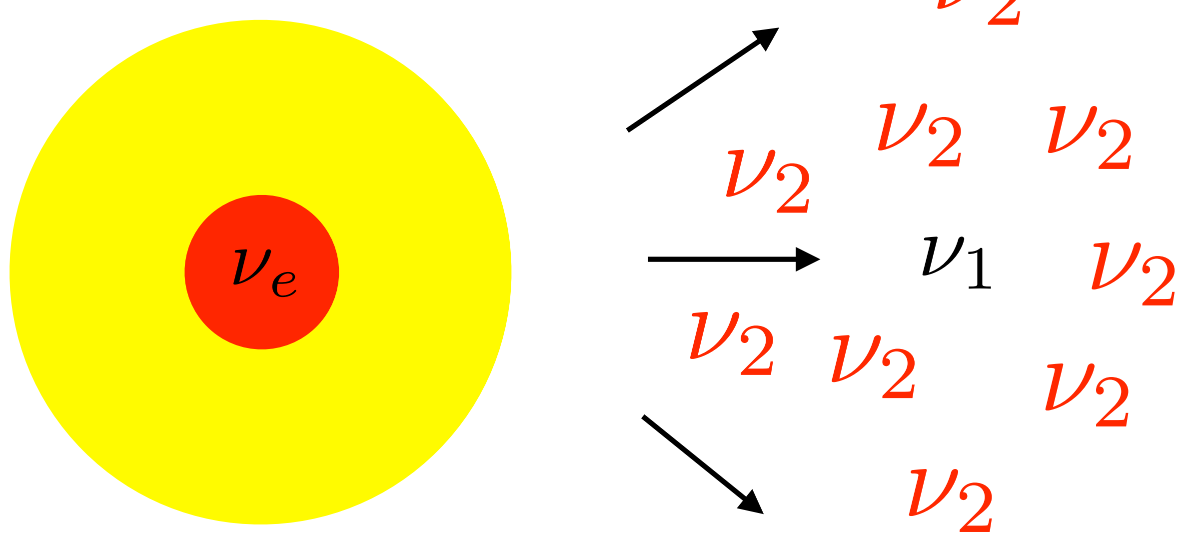


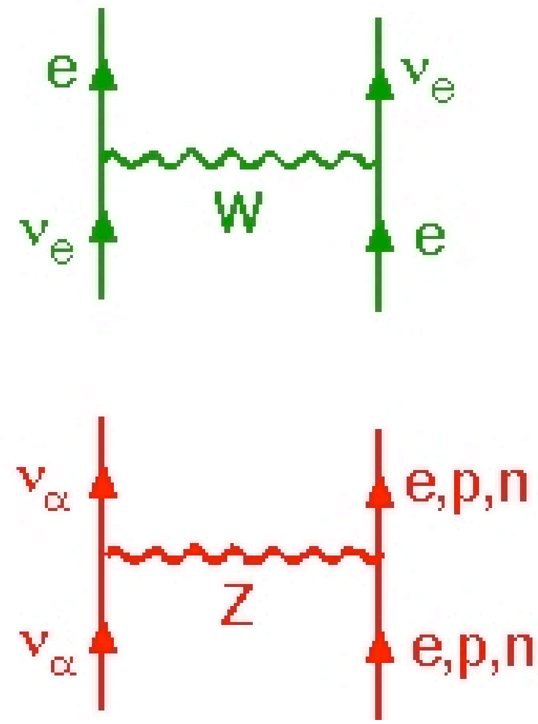
$f_2 \sim 90\%$

$f_1 \sim 10\%$

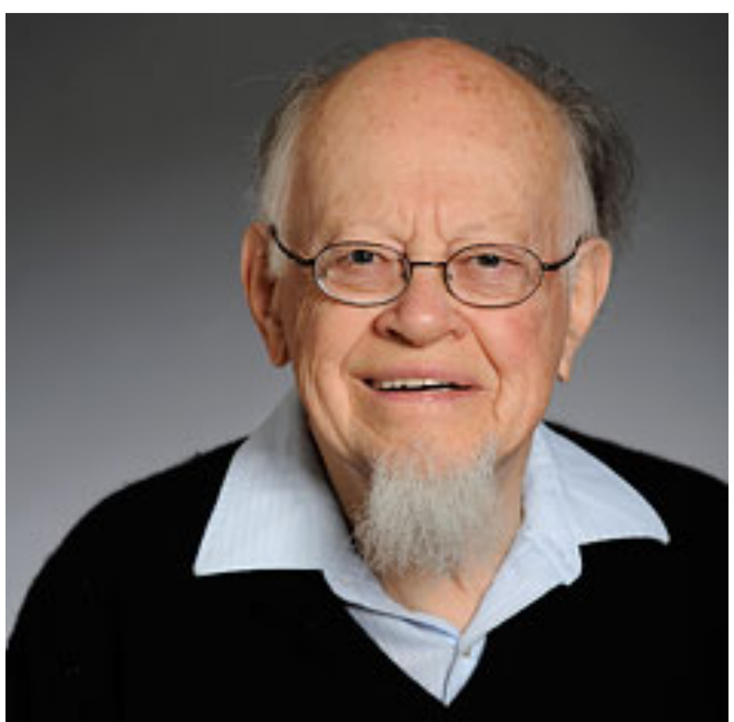
matter dominated

Coherent Forward Scattering:

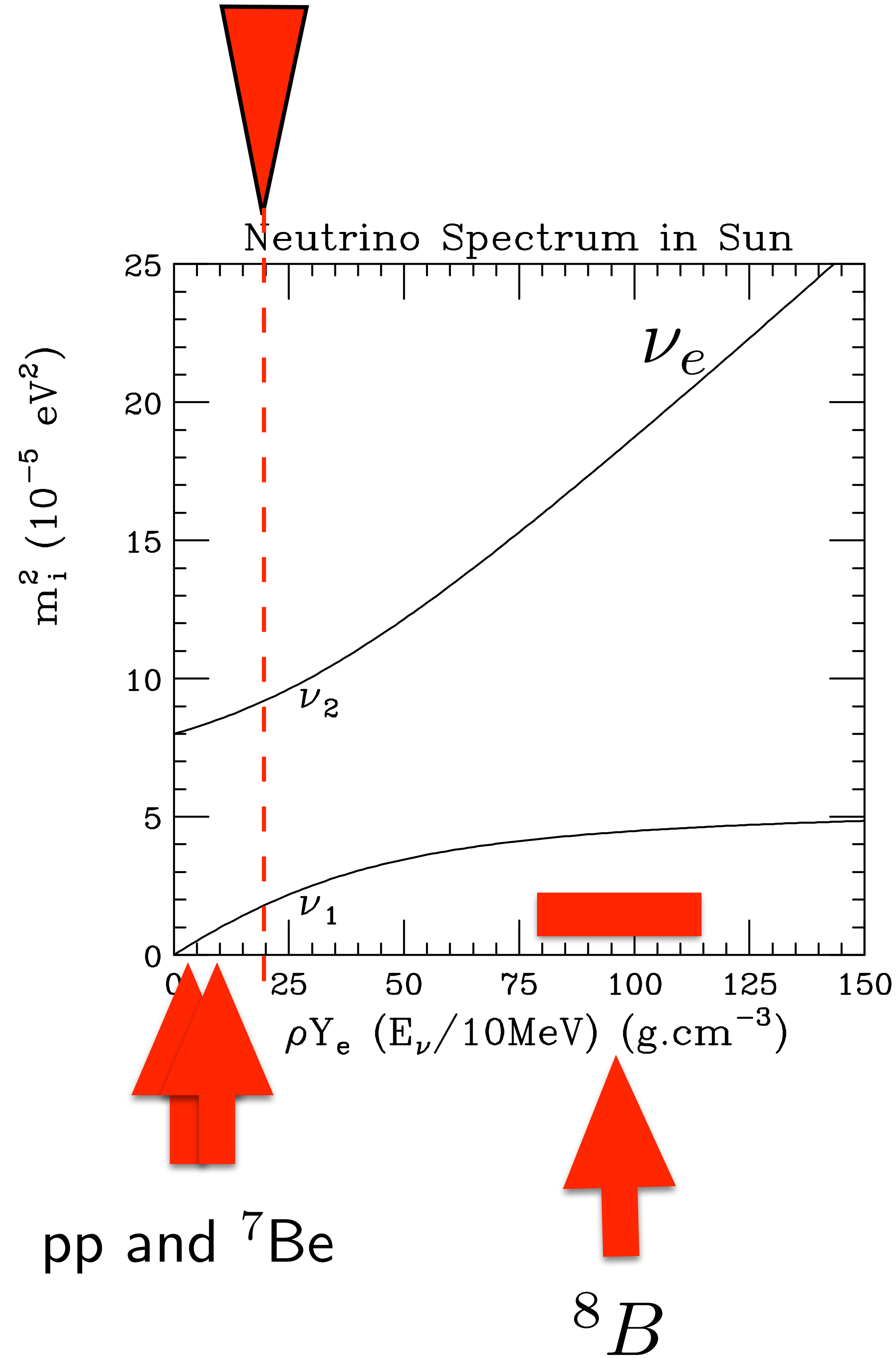
Mikheyev + Smirnov Resonance WIN '85



Wolfenstein '78

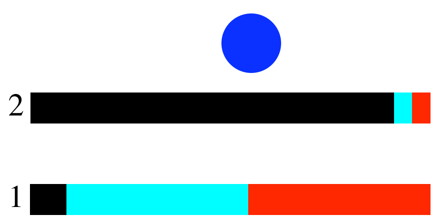


1923-2015



Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B



at birth

Solar Center

ν_e ■ ν_μ ■ ν_τ ■

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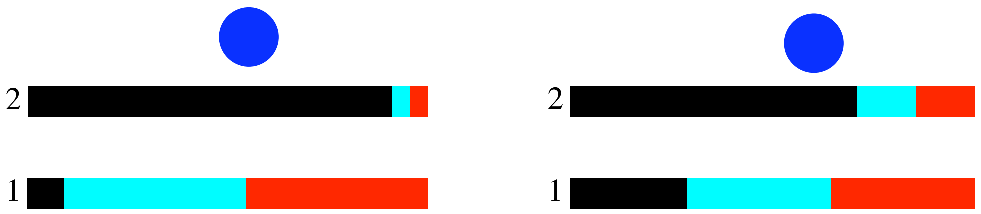
Once a ν_2 always a ν_2!



at birth

toddler

Solar Center

ν_e ν_μ ν_τ

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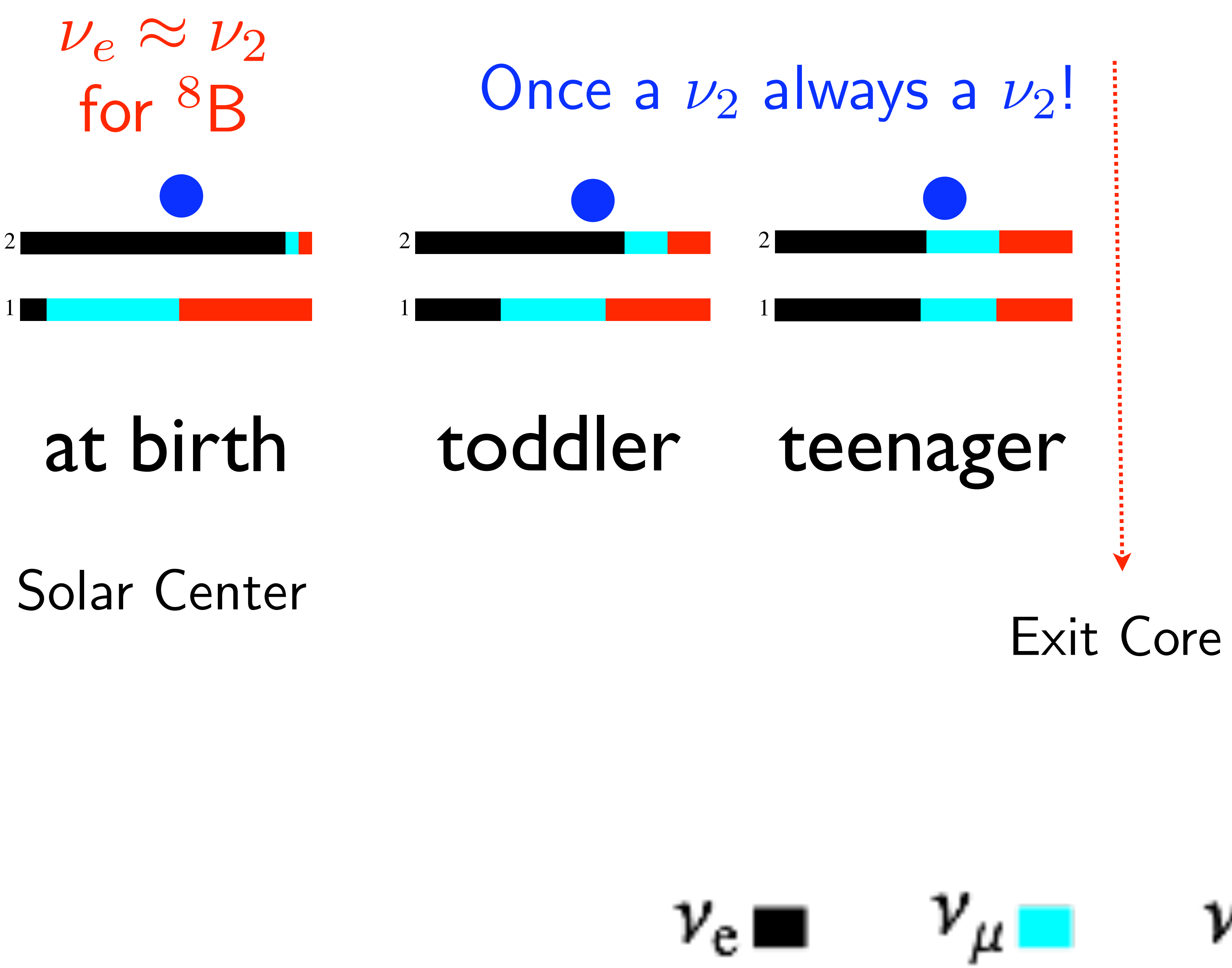

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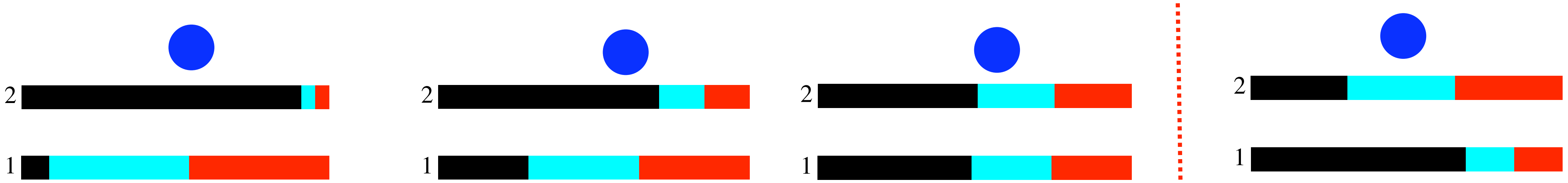


at birth

toddler

teenager

adult

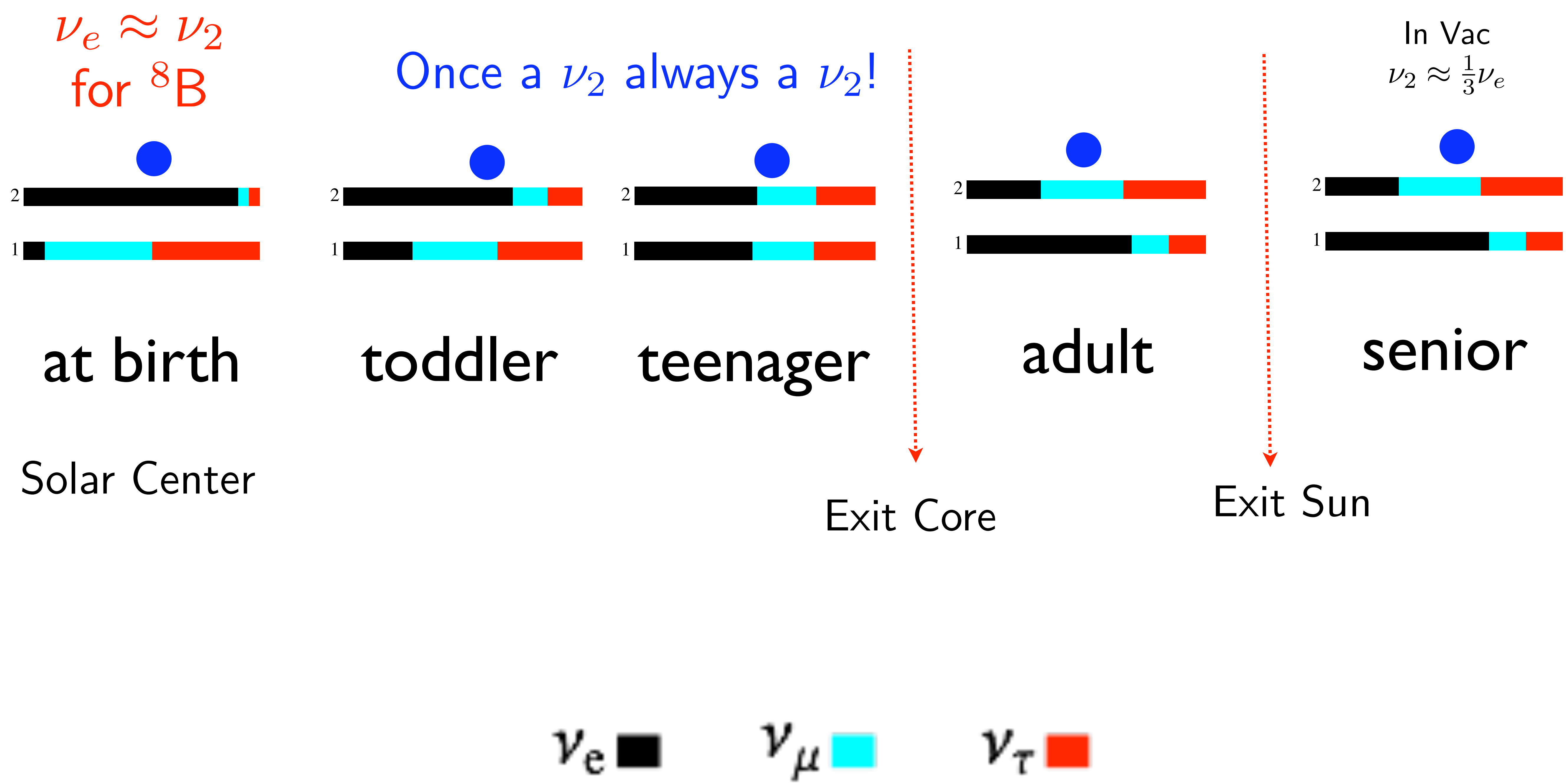
Solar Center

Exit Core

Exit Sun

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:



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- ^8B neutrinos exit the Sun as nearly pure ν_2 ($> 90\%$), so that $\frac{CC}{NC} \approx \sin^2\theta_{12}$

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why use $\tan^2\theta$?

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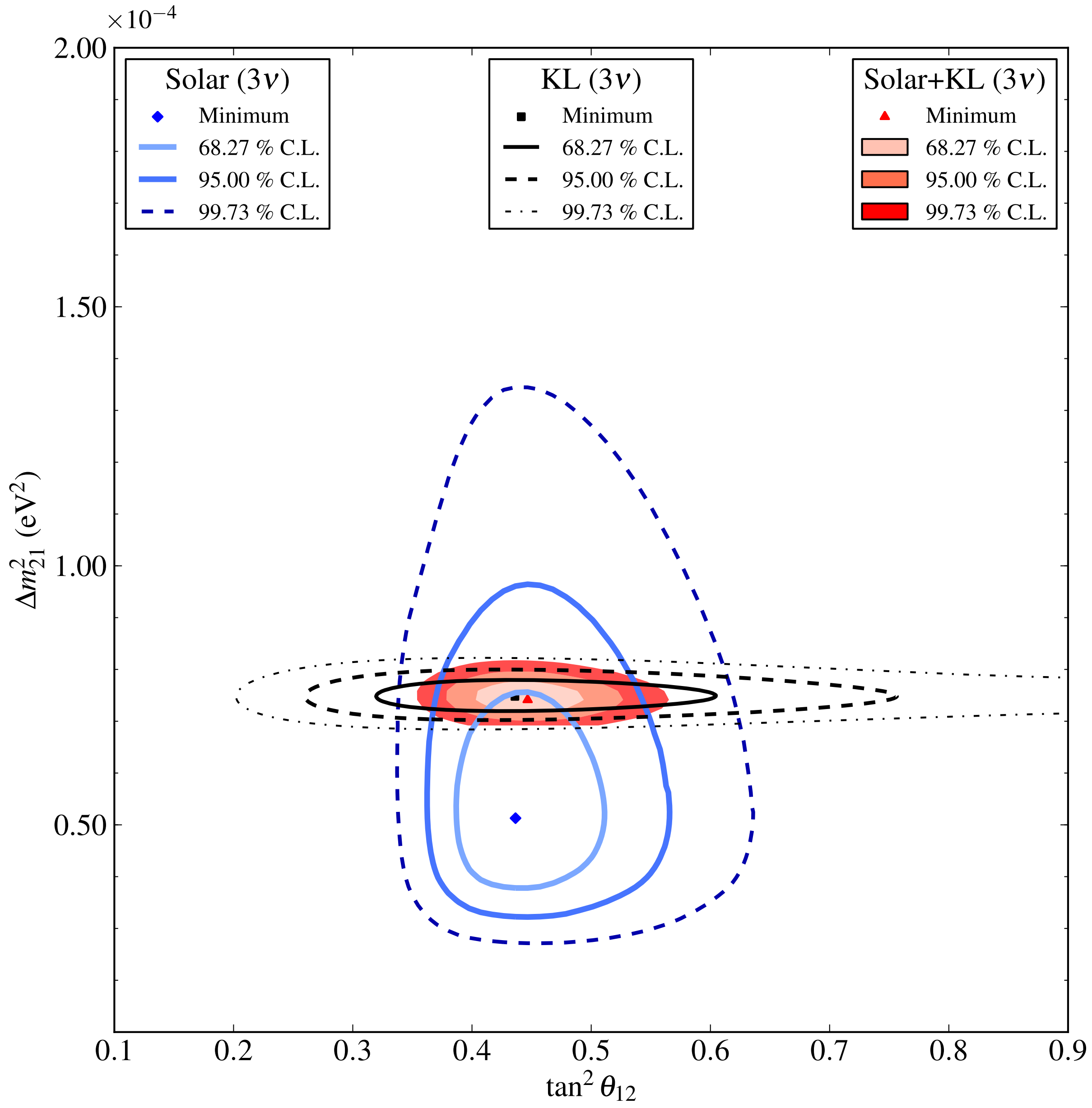
why use $\tan^2\theta$?

- Mass Ordering of ν_1 & ν_2:

$$m_2 > m_1$$

(using defn $|U_{e2}|^2 < |U_{e1}|^2$)

Solar + Kamland 2011



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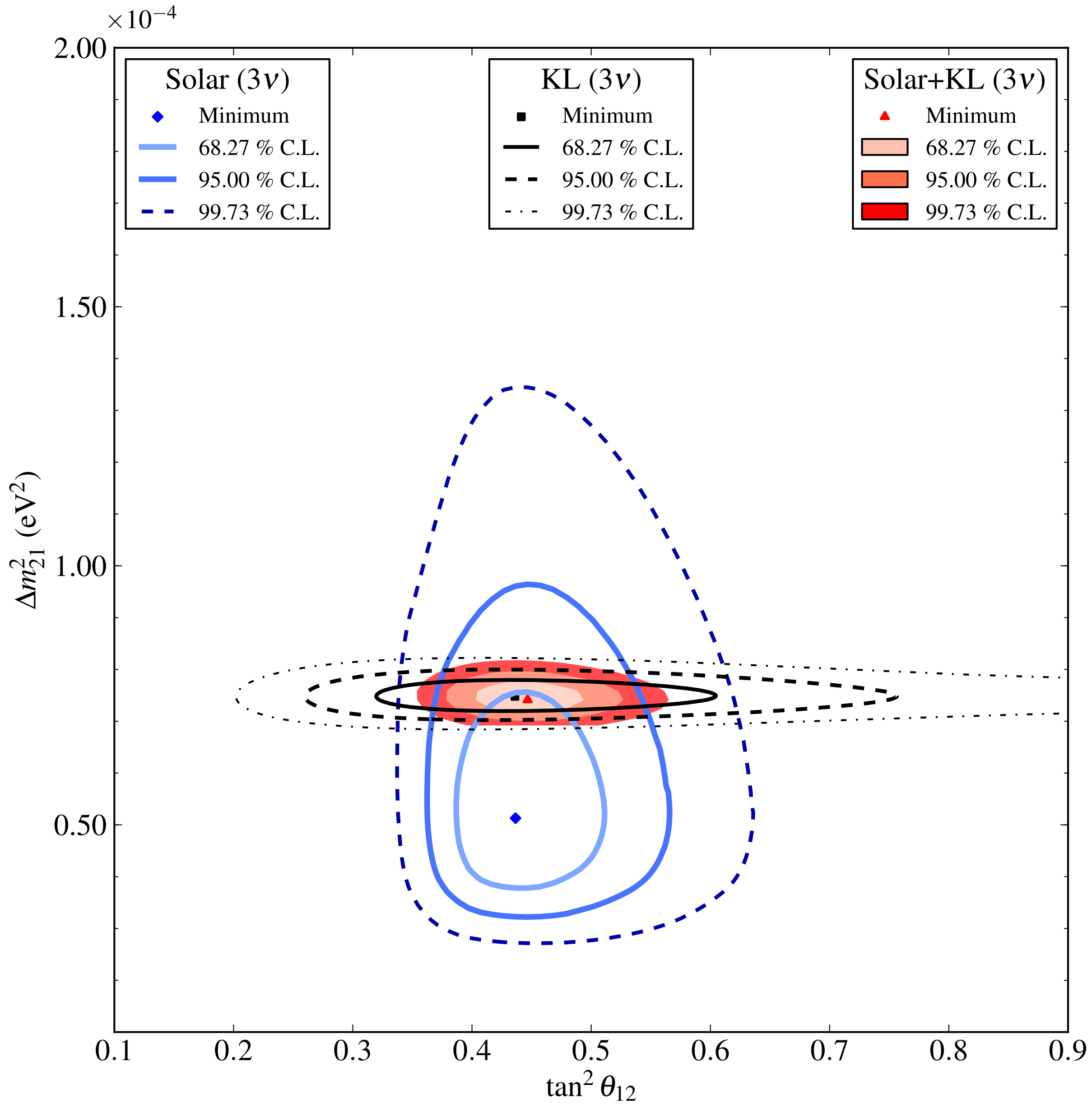

if $\frac{CC}{NC} = 0.30 \approx \sin^2\theta_{12}$ **then** $\tan^2\theta_{12} \approx \frac{CC/NC}{1-CC/NC} = 0.43$

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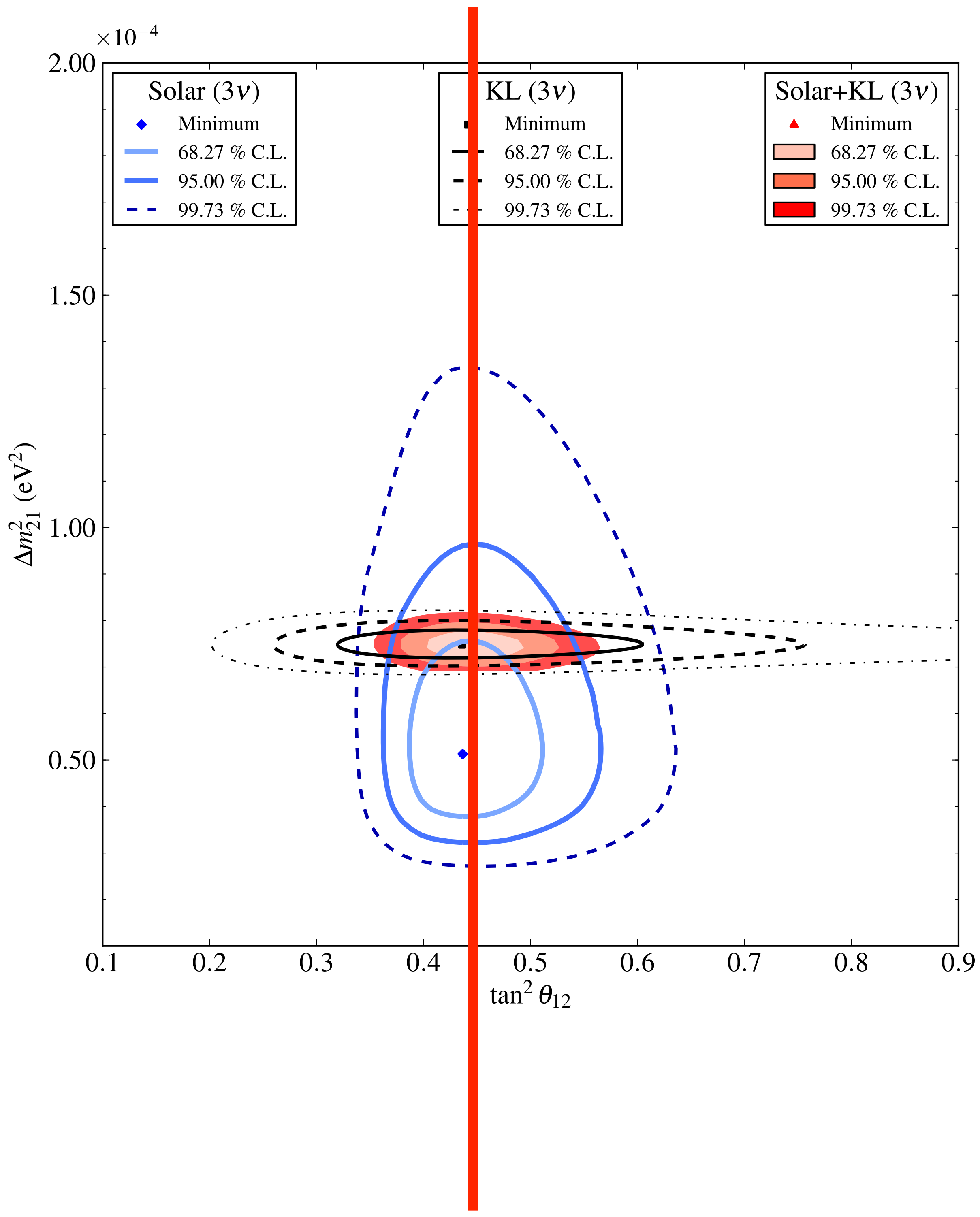

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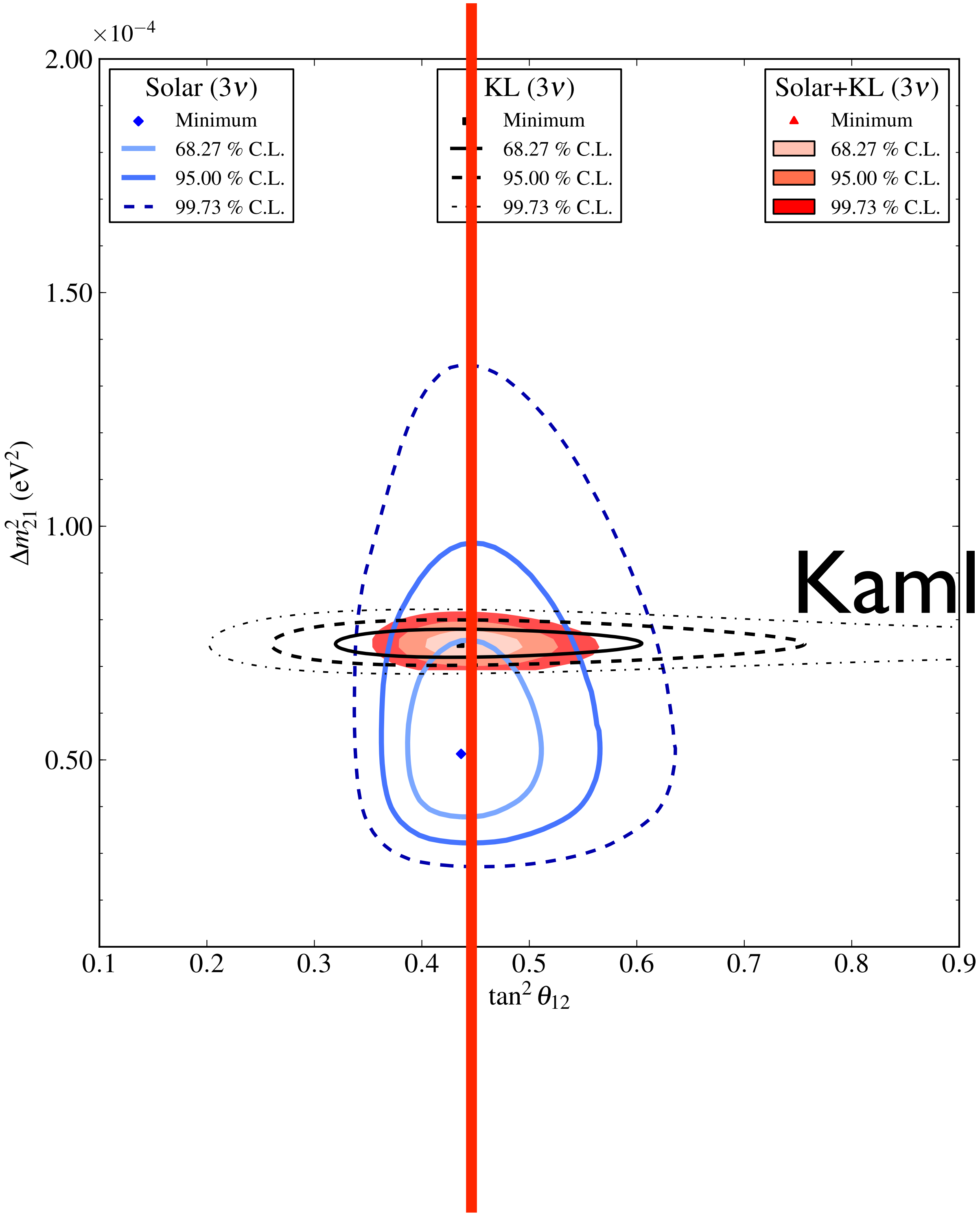
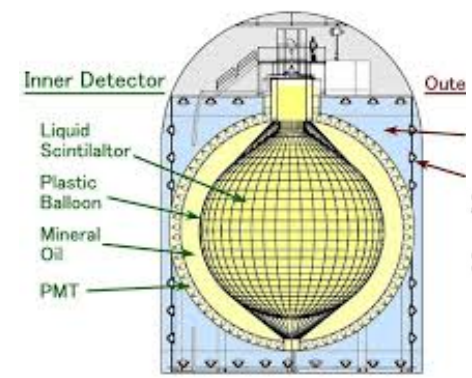
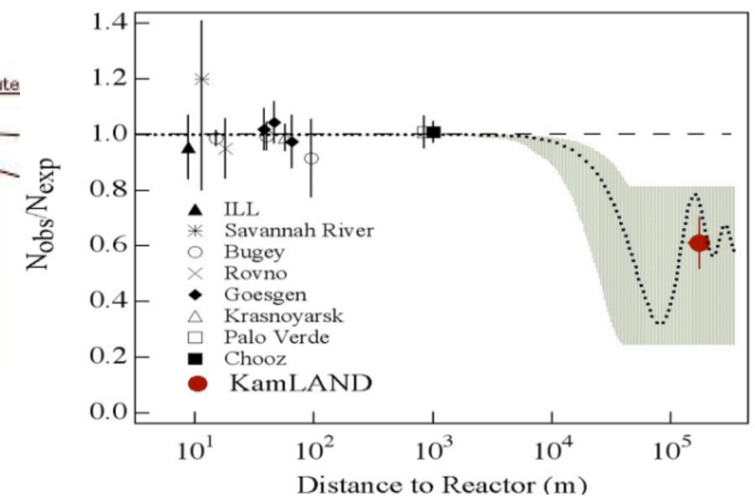
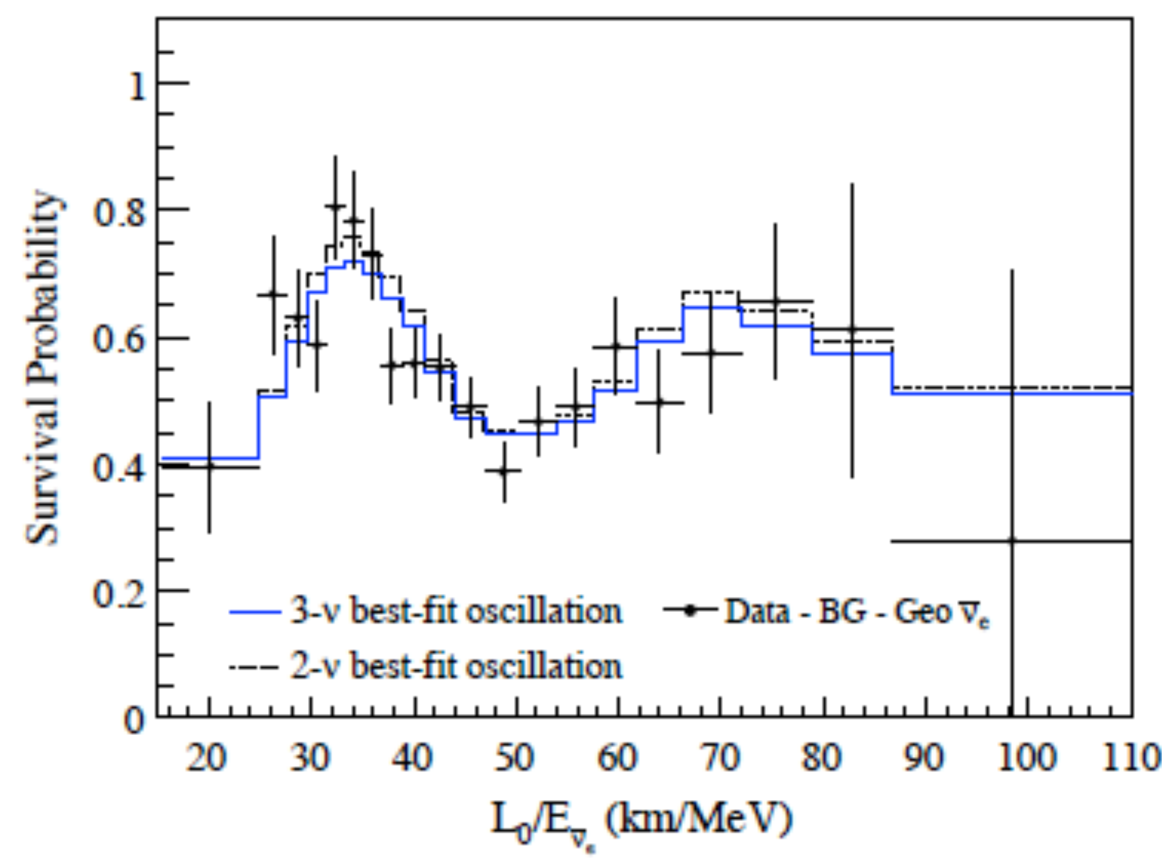


Kamland







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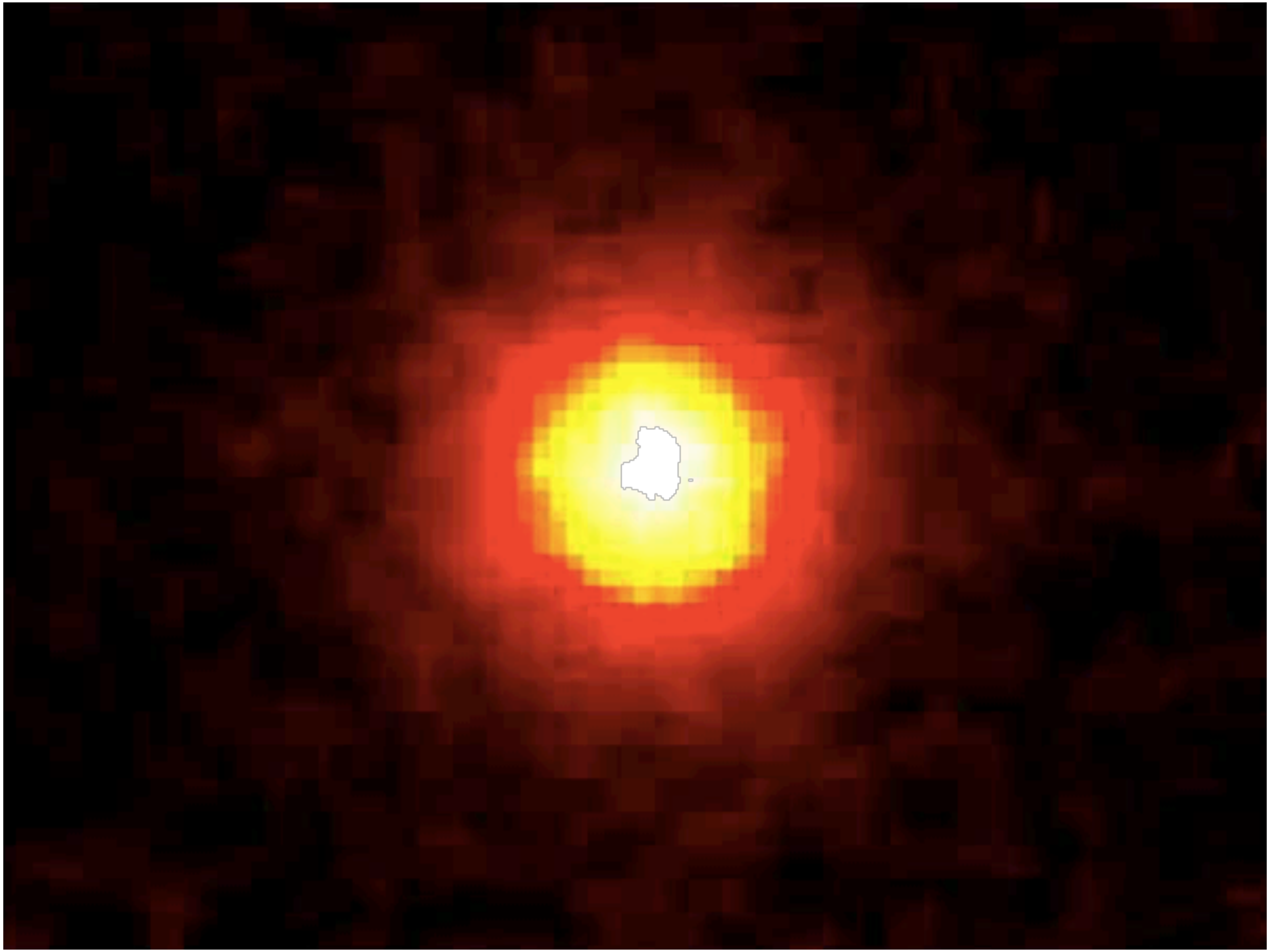
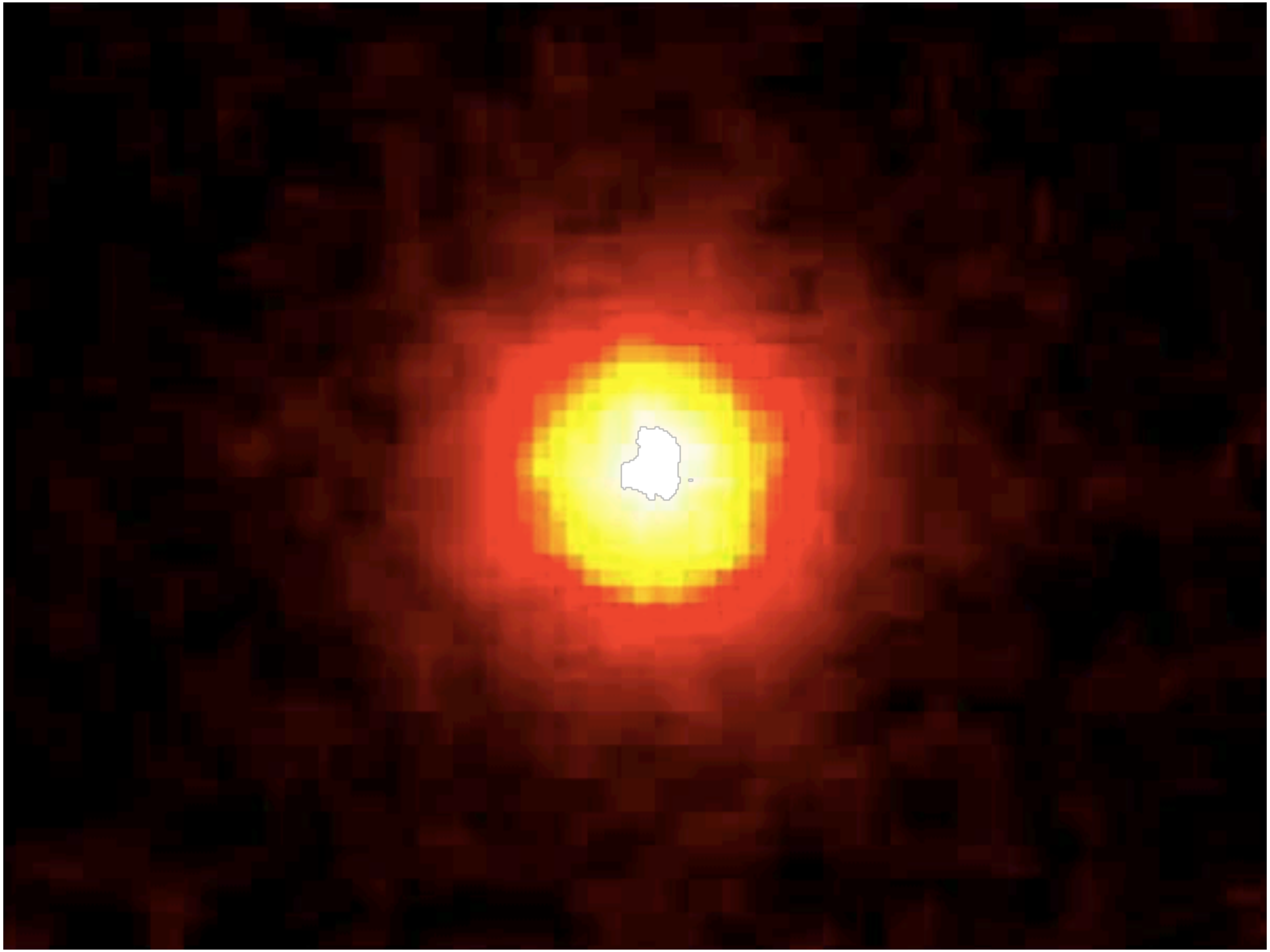


Which Neutrinos ? not ν_e



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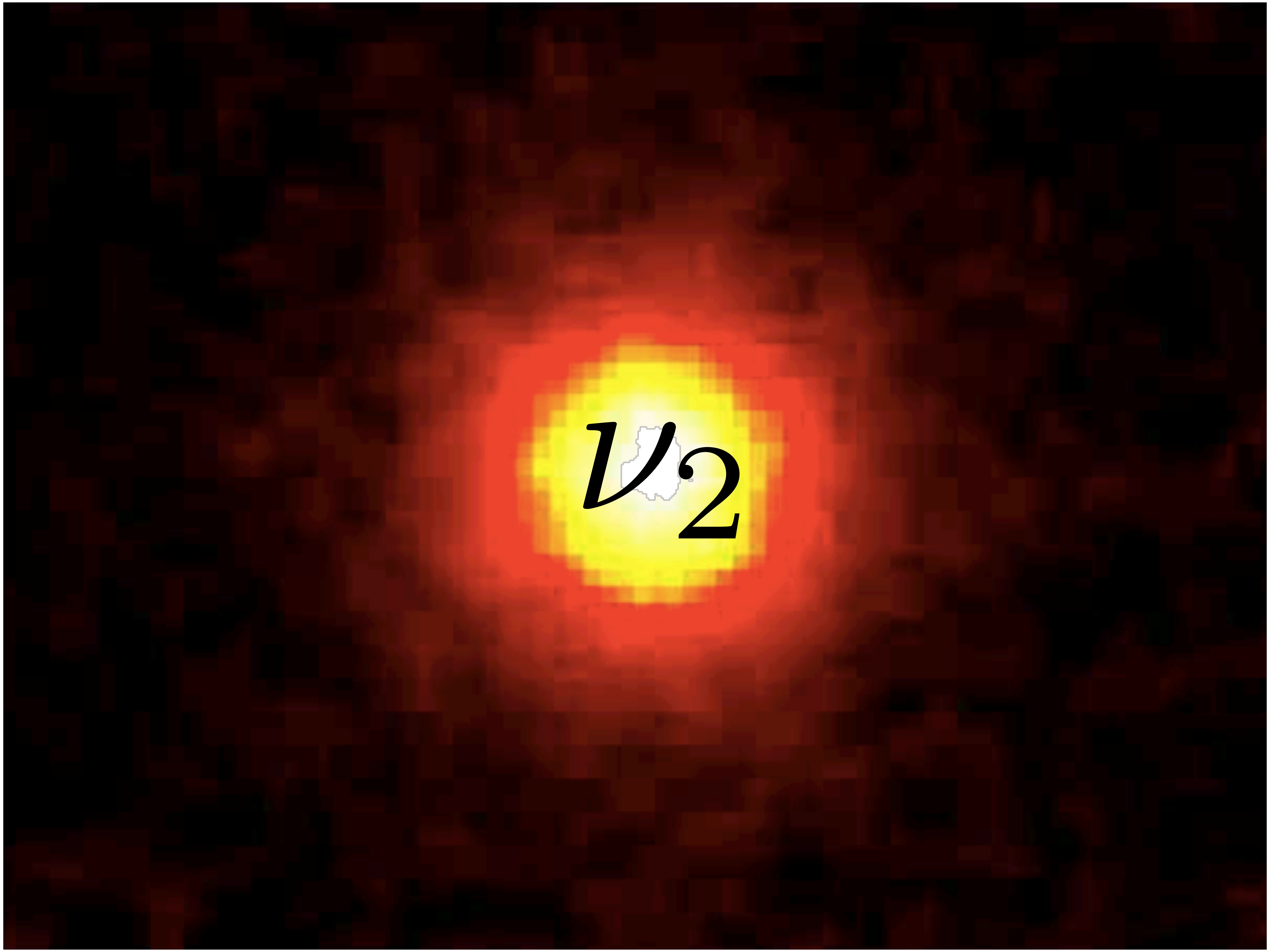

Circa 2015

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- Labeling massive neutrinos:

$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$

Except: LSND, miniBooNE, reactor anomaly, gallium anomaly.

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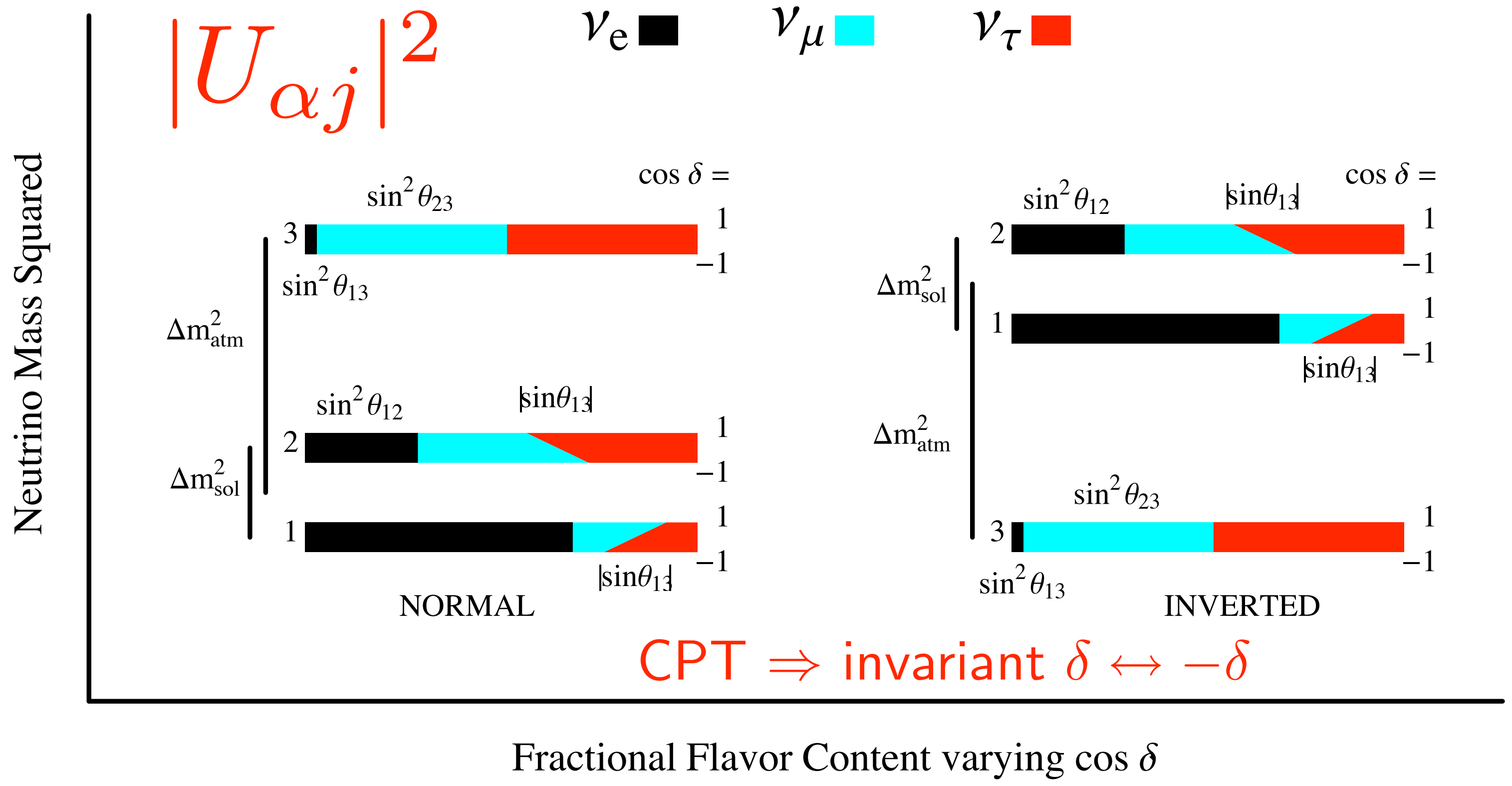

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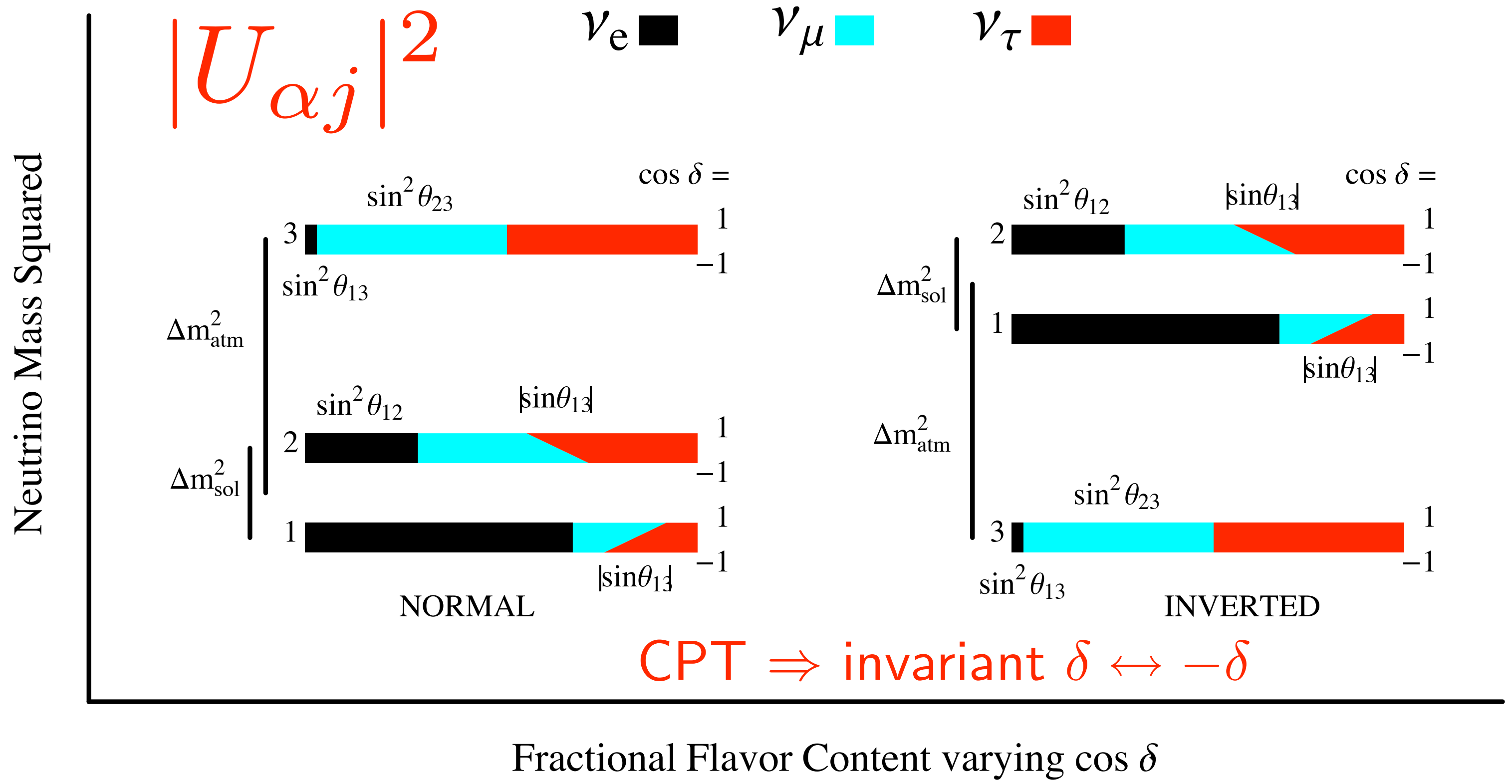

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \qquad \sin^2\theta_{12} \sim \frac{1}{3}$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \qquad 0 \leq \delta < 2\pi \qquad \sin^2\theta_{23} \sim \frac{1}{2}$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03 \qquad \sin^2\theta_{13} \sim 0.02$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

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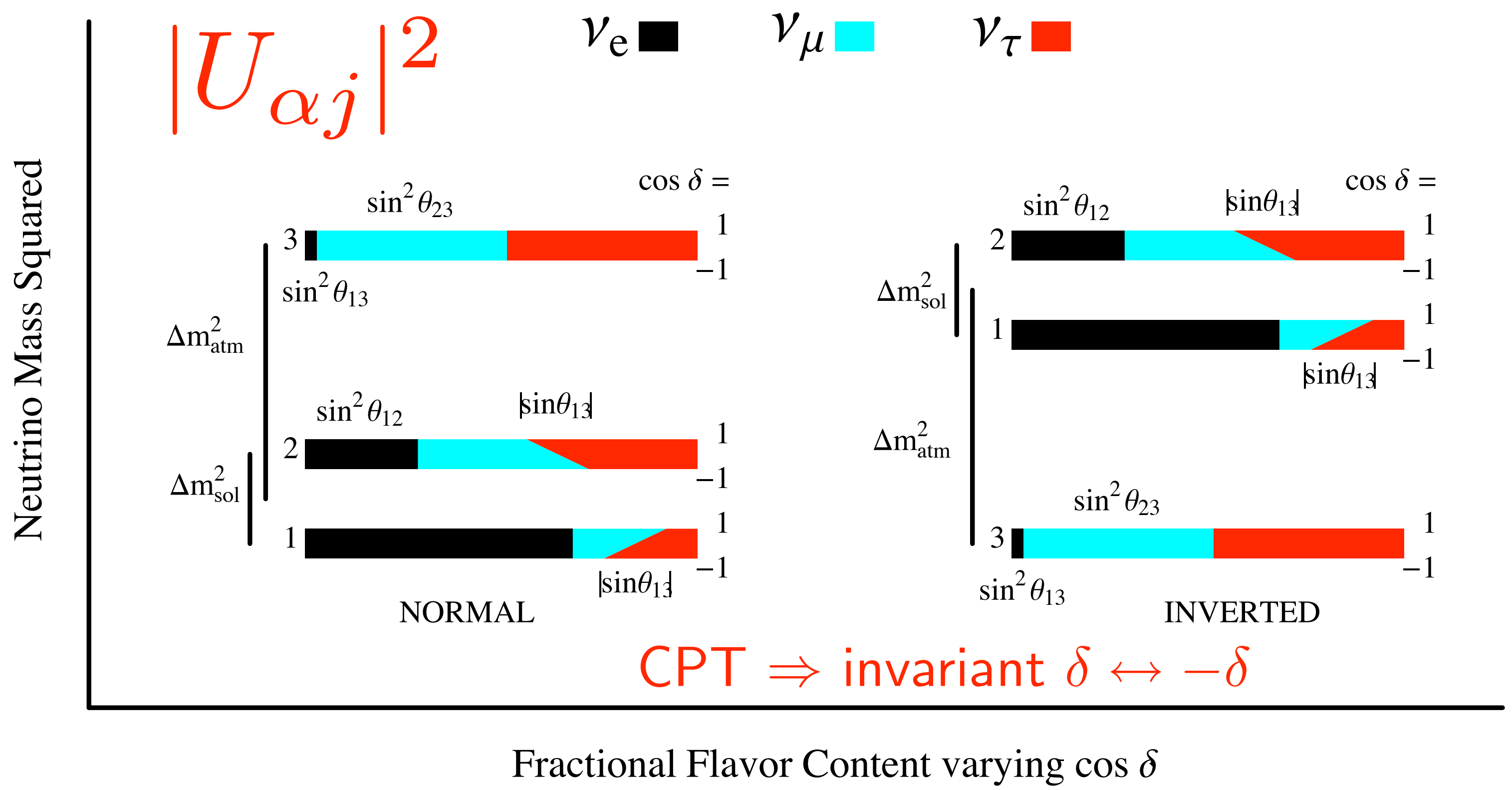

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Reactor θ_{13} Experiments

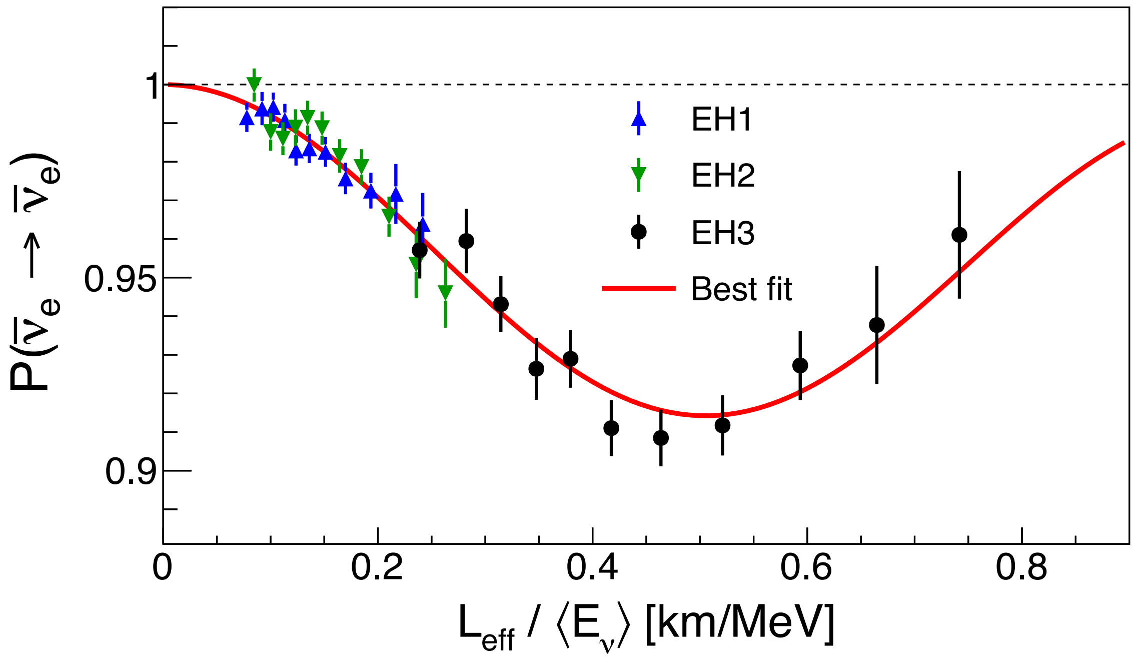
Daya Bay

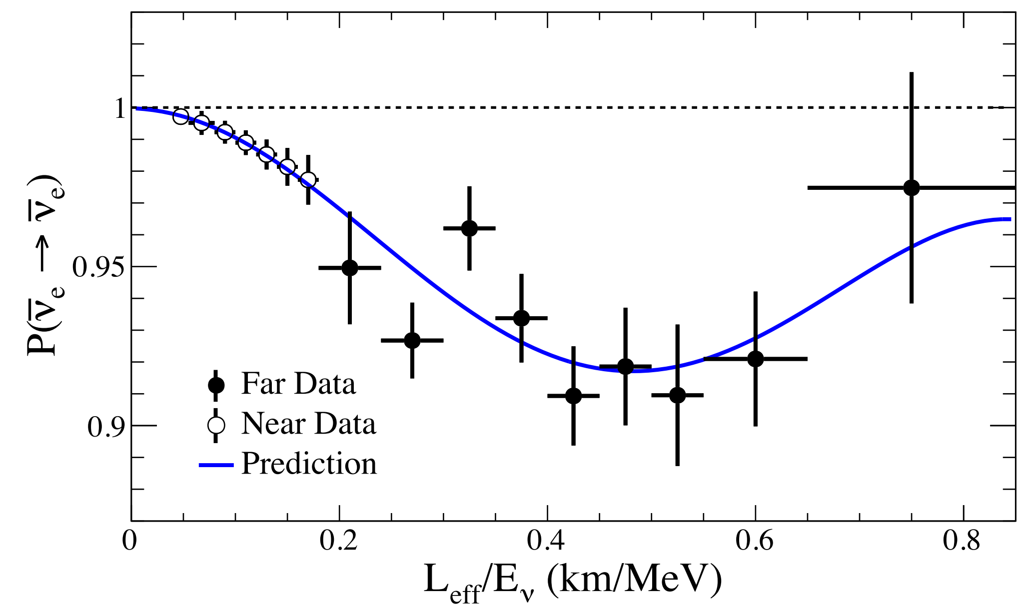
RENO

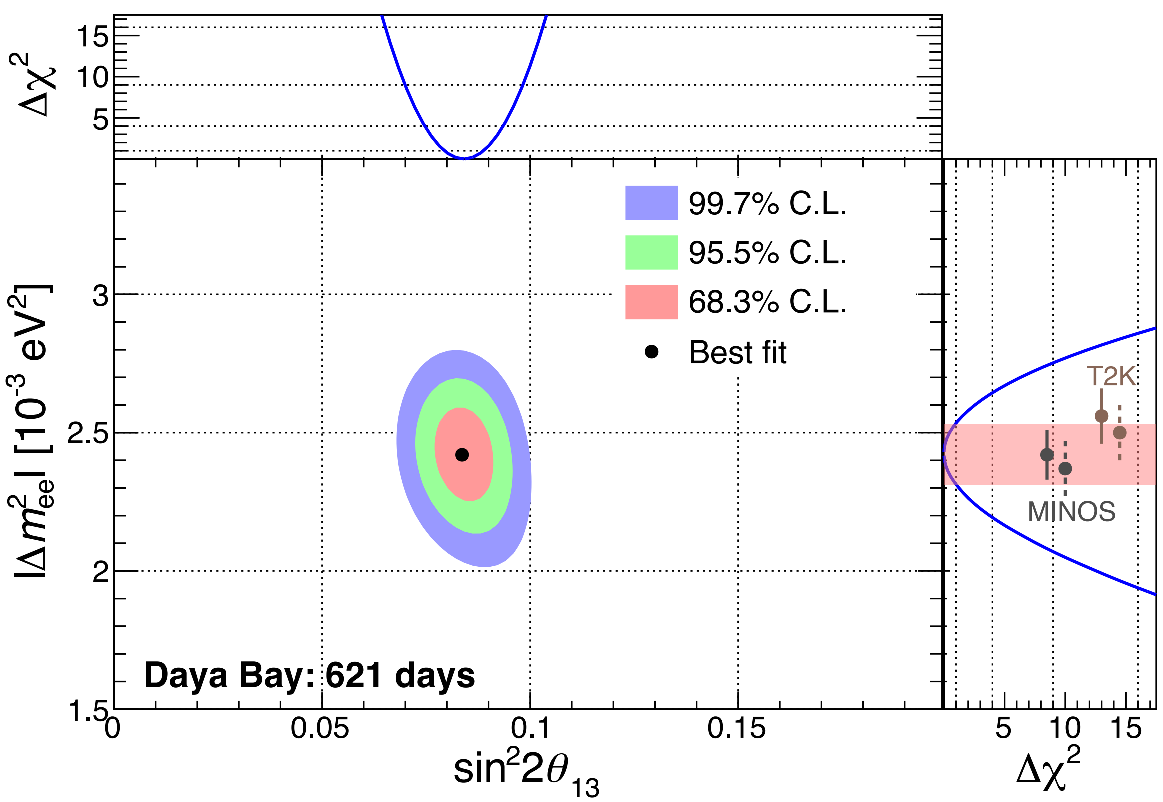
Double Chooz

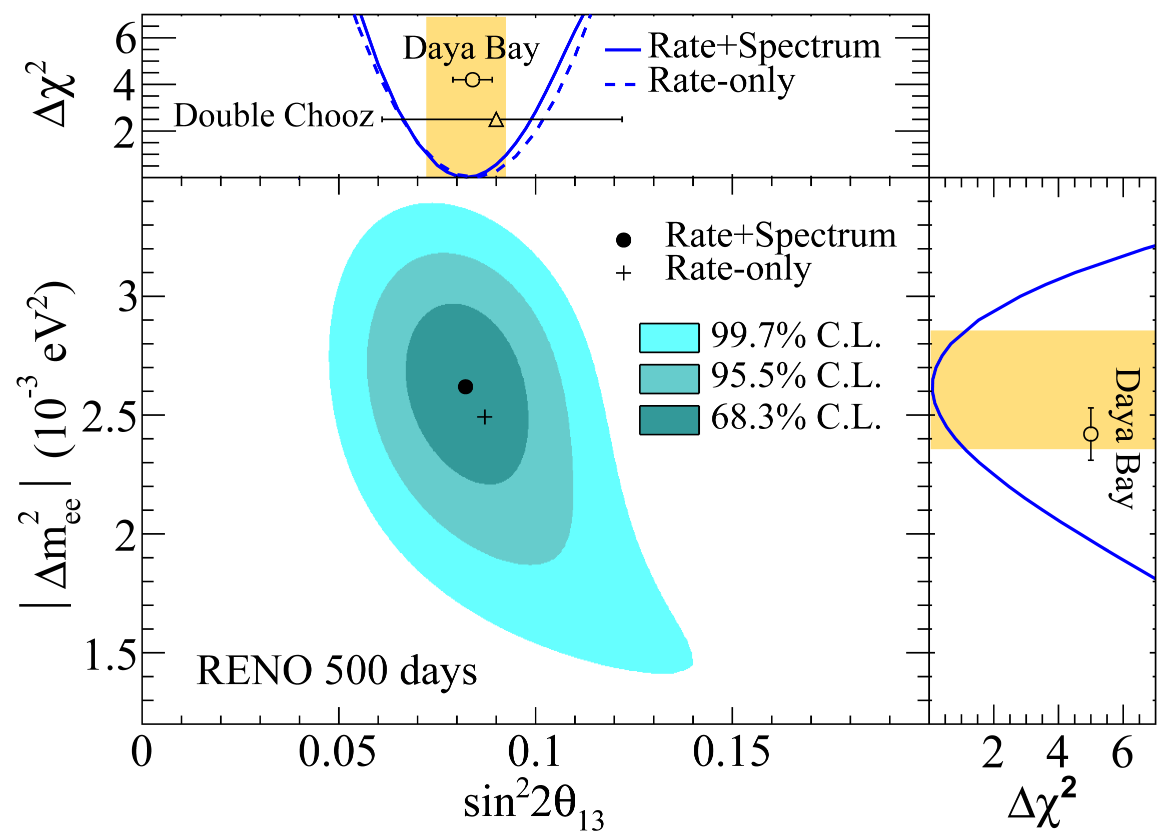
from Daya Bay: arXiv:1505.03456

from RENO arXiv:1511.05849









$$\Delta m^2_{ee} \equiv c^2_{12}\ \Delta m^2_{31} + s^2_{12}\ \Delta m^2_{32}$$

Double Chooz ?

Appearance Experiments:

$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \rightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \rightarrow \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \rightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \rightarrow \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

Appearance Experiments:

CP

$$\nu_\mu \to \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \to \bar{\nu}_e$$

T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$$\nu_e \to \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \to \bar{\nu}_\mu$$

CP

- Running experiments:

T2K (295km) and NOvA (810km)

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CP

- Running experiments:

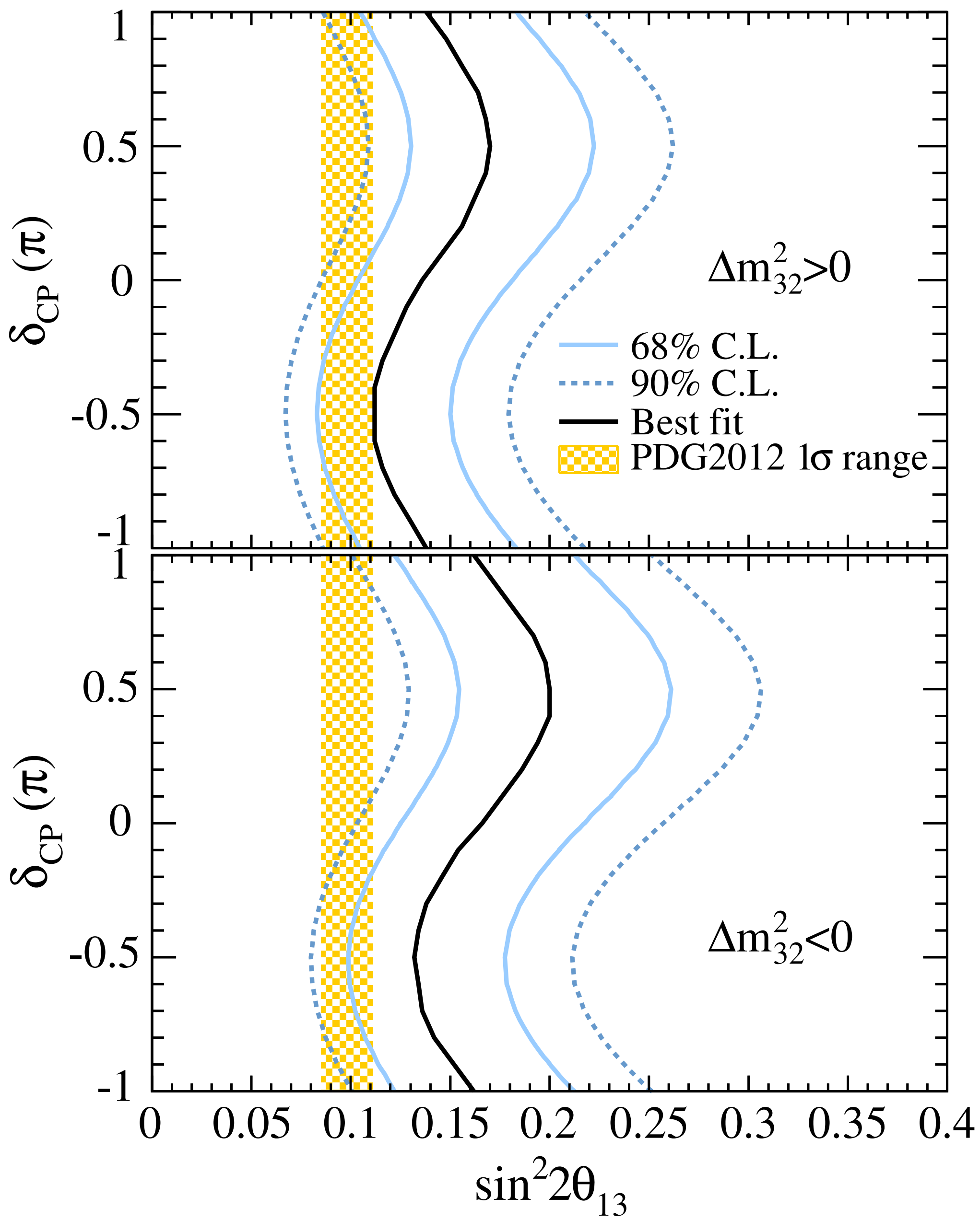
  T2K (295km) and NOvA (810km)

- Future experiments:

  DUNE (40 ktons LAr, 1300km)

  HyperKamiokaNDE (0.5kMtons H_2O, 295km)

T2K and Reactors:



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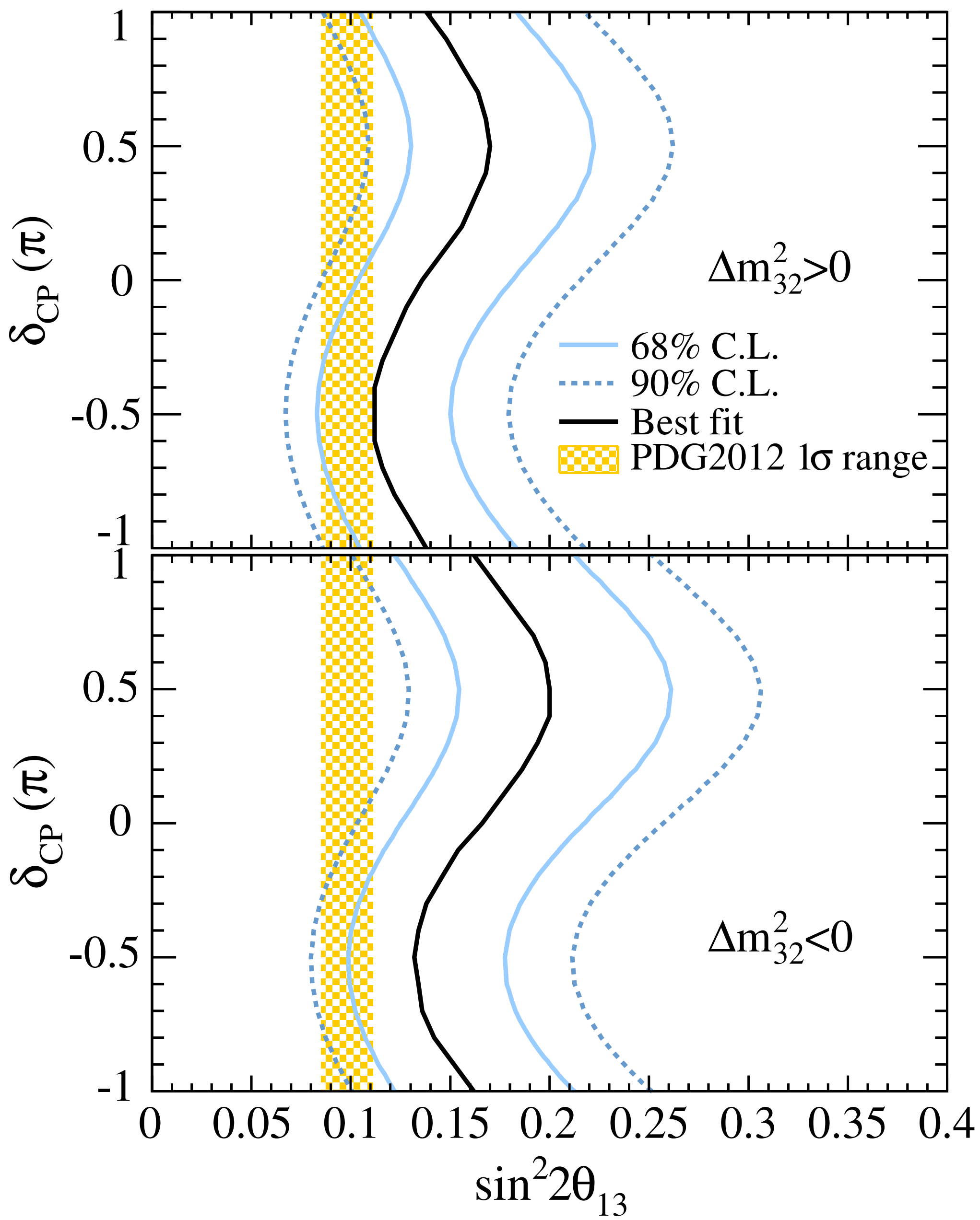
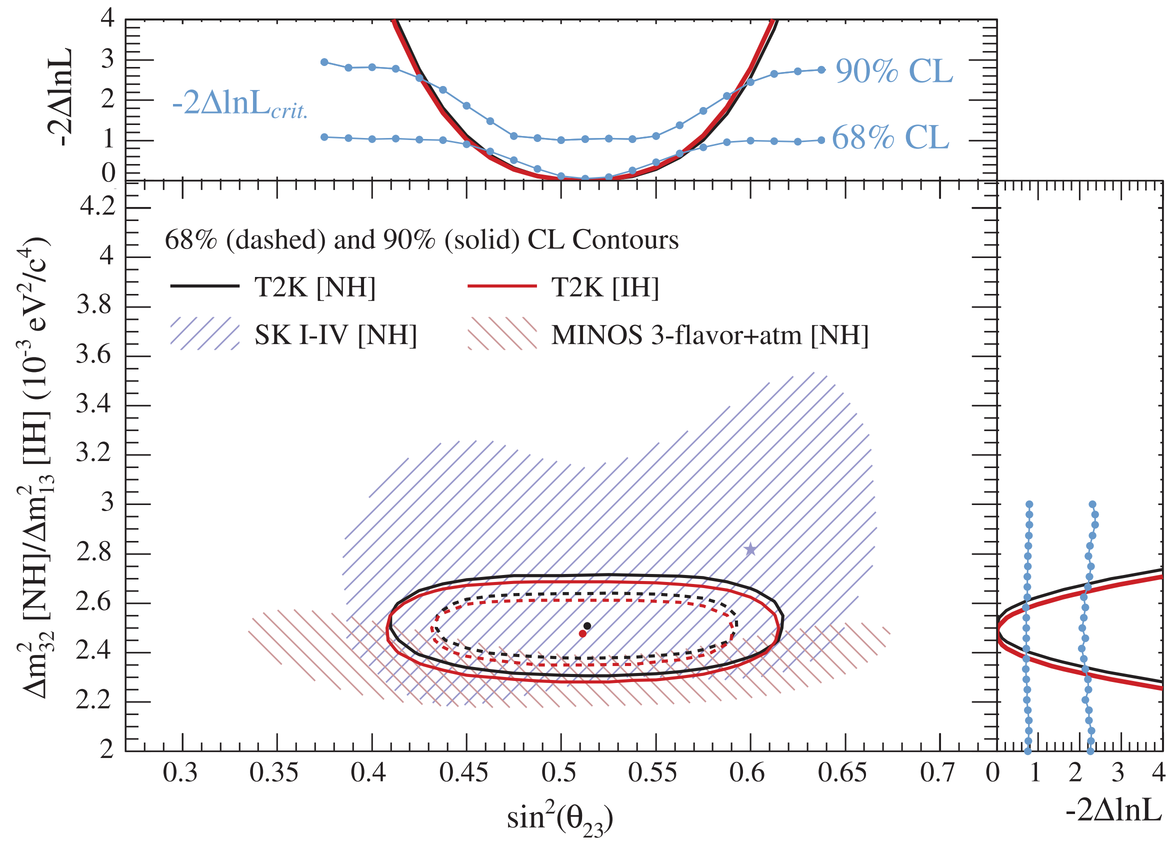


θ_{23} ?



$\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

"sum of two flavor amplitudes, with phase between them" !

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"sum of two flavor amplitudes, with phase between them" !

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

$\nu_\mu \rightarrow \nu_e$

$$P_{\mu\rightarrow e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

"sum of two flavor amplitudes, with phase between them" !

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}$

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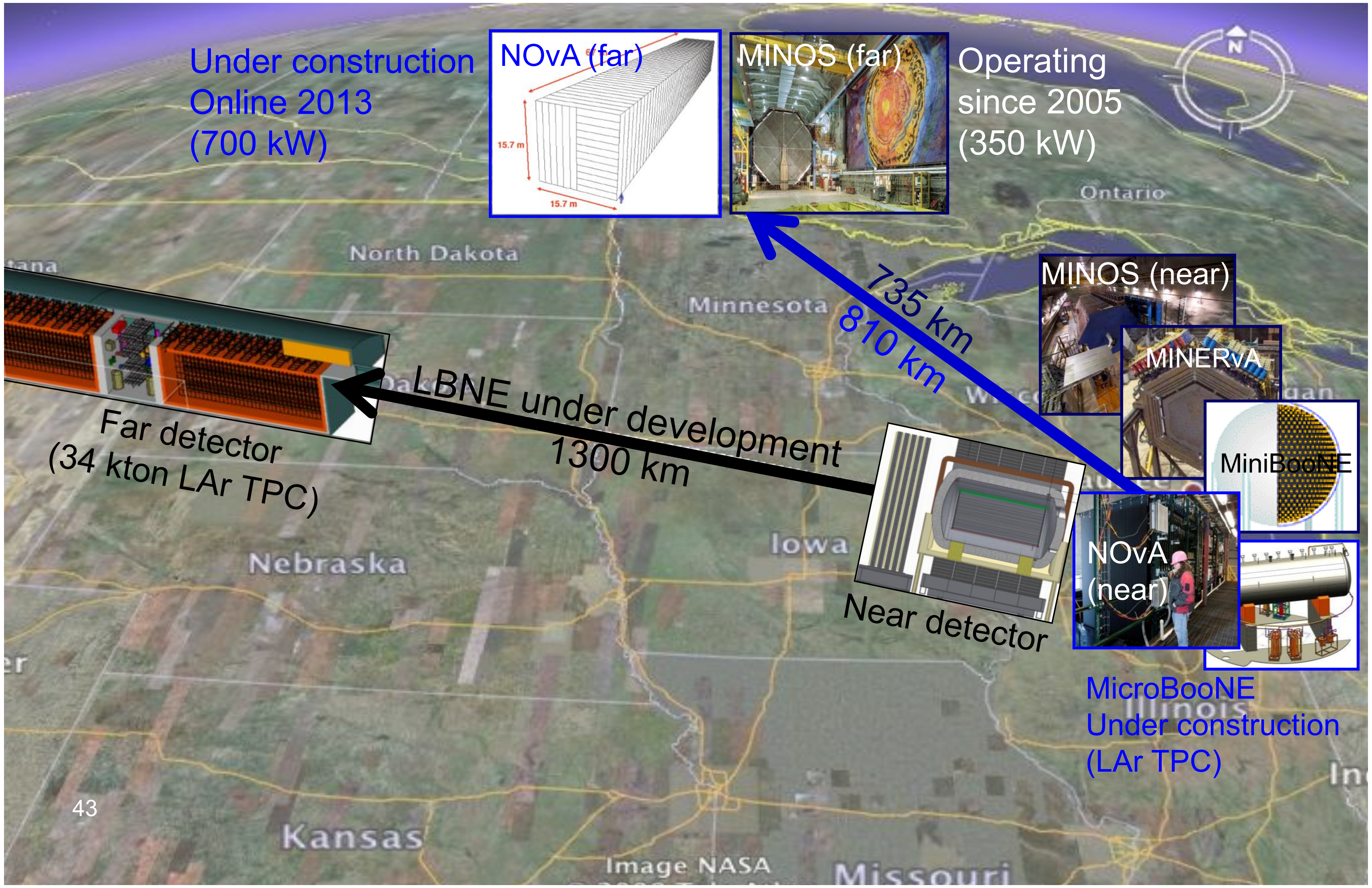
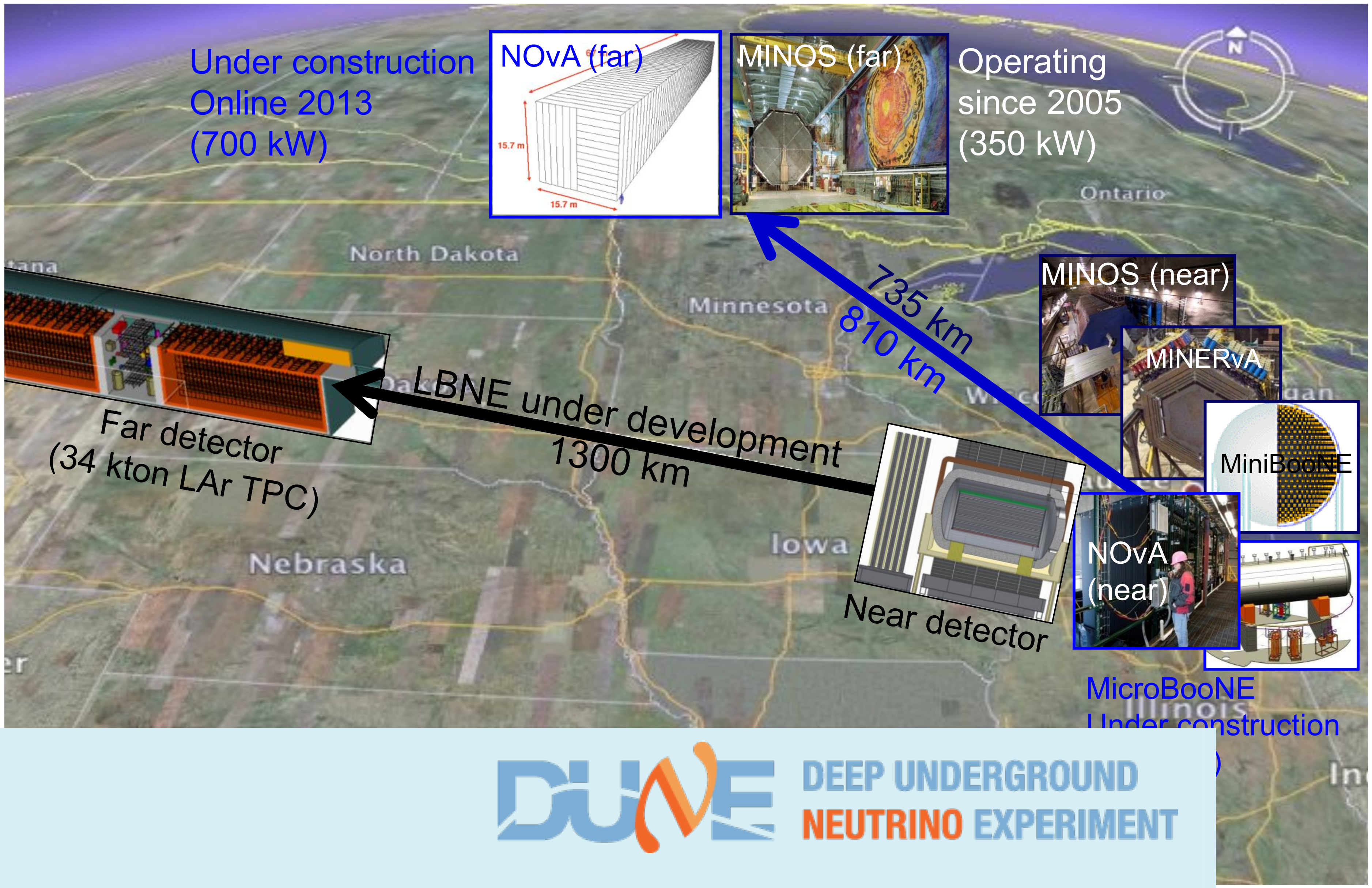
New ! and leads to CPV

LBNF + DUNE


Under construction
Online 2013
(700 kW)
NOvA (far)
MINOS (far)
Operating
since 2005
(350 kW)
North Dakota
Minnesota
Ontario
MINOS (near)
MINERvA
MiniBooNE
735 km
810 km
LBNE under development
1300 km
Far detector
(34 kton LAr TPC)
Near detector
NOvA
(near)
Nebraska
Iowa
MicroBooNE
Under construction
(LAr TPC)
Illinois
43
Kansas
Image NASA
Missouri

LBNF + DUNE



Under construction
Online 2013
(700 kW)
NOvA (far)
15.7 m
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Ontario
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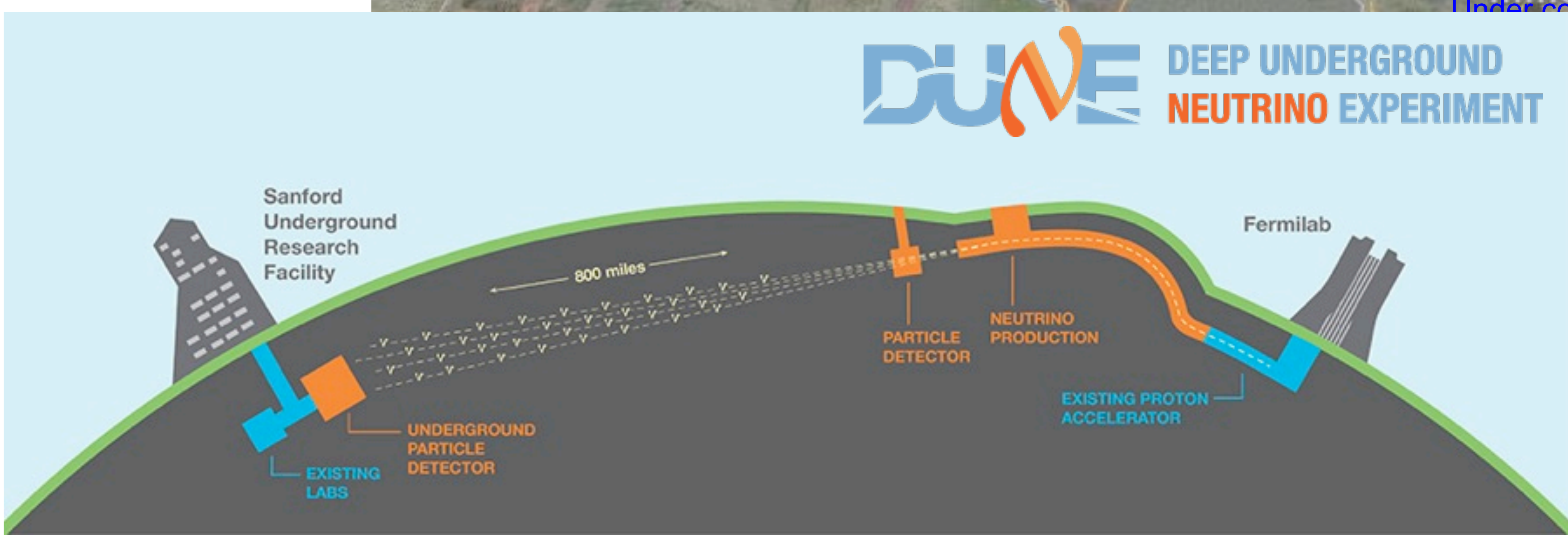
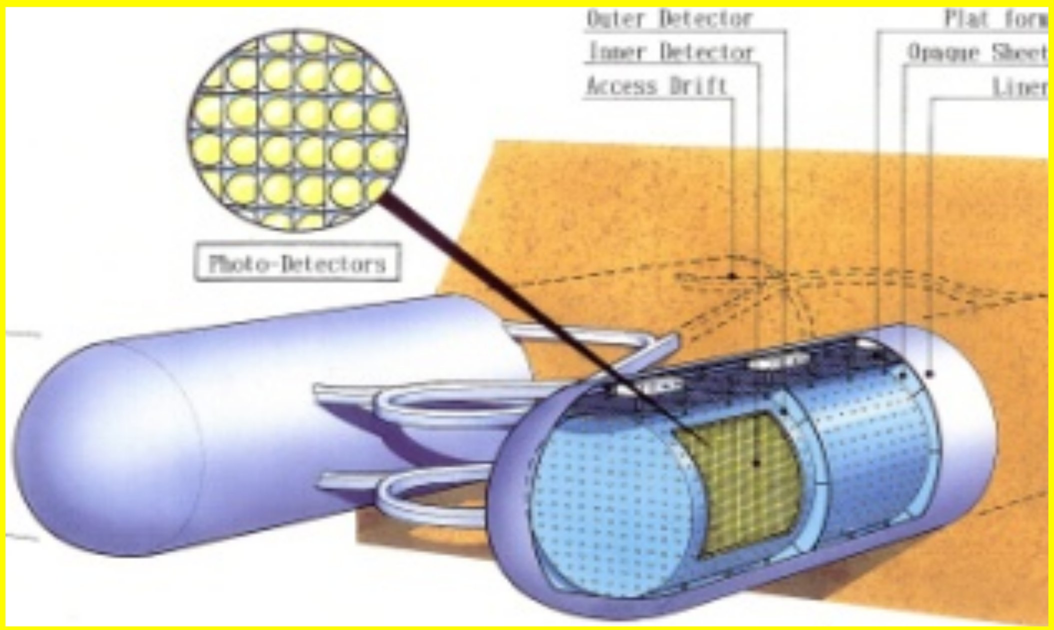


DEEP UNDERGROUND
NEUTRINO EXPERIMENT
Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
EXISTING PROTON
ACCELERATOR
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS

Future LBL plans using J-PARC

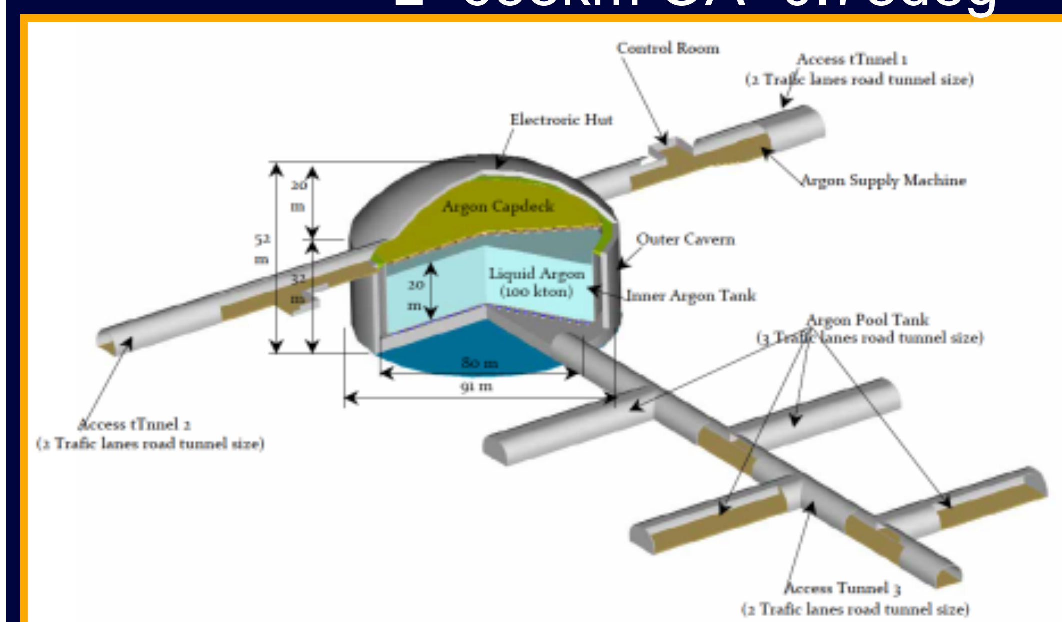
Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

J-PARC+HK @ Kamioka
L=295km OA=2.5deg

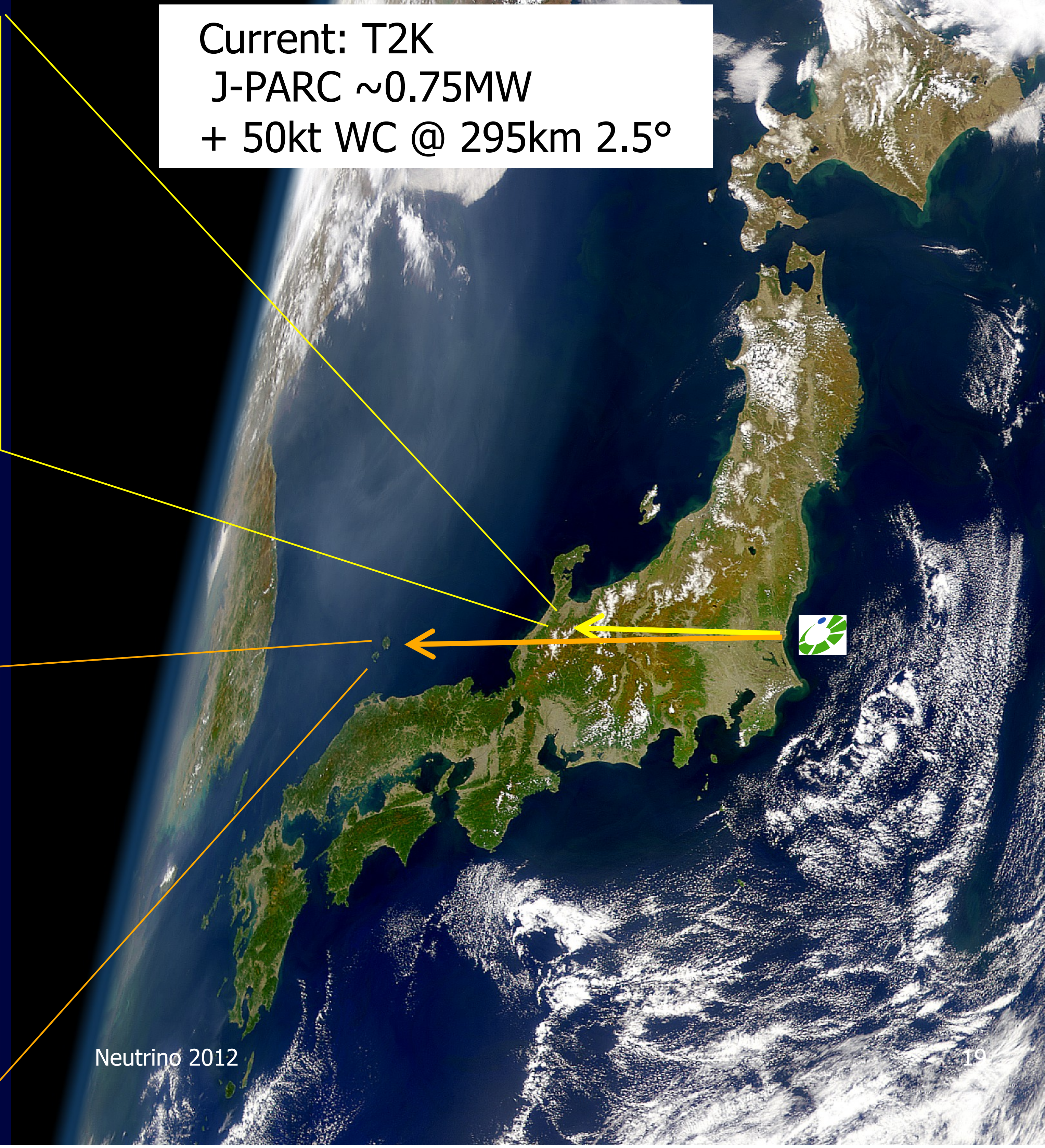


LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima
L=658km OA=0.78deg



J-PARC P32 (LAr TPC R&D), arXiv:0804.2111



The Physics:

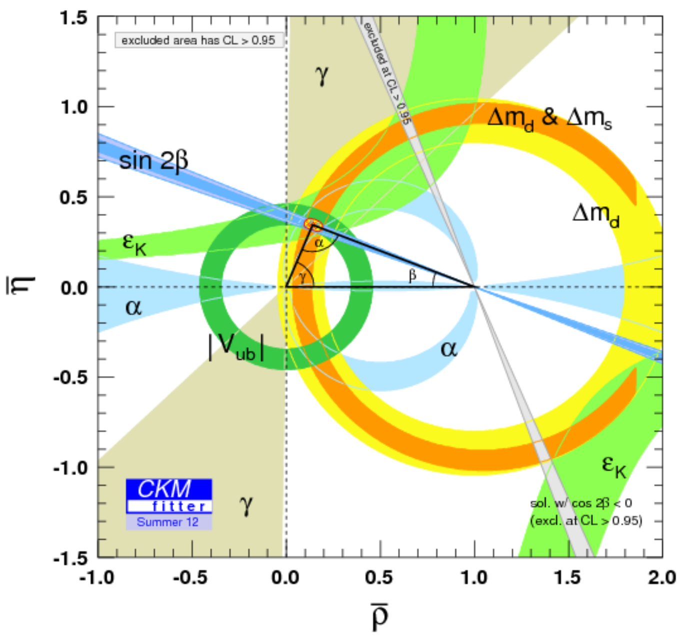
- Stringent tests of the 3 ν paradigm !
  (Surprises?)

- Which flavor dominates ν_3 ?
  (θ_{23} octant) $[\nu_\mu \to \nu_\mu]$

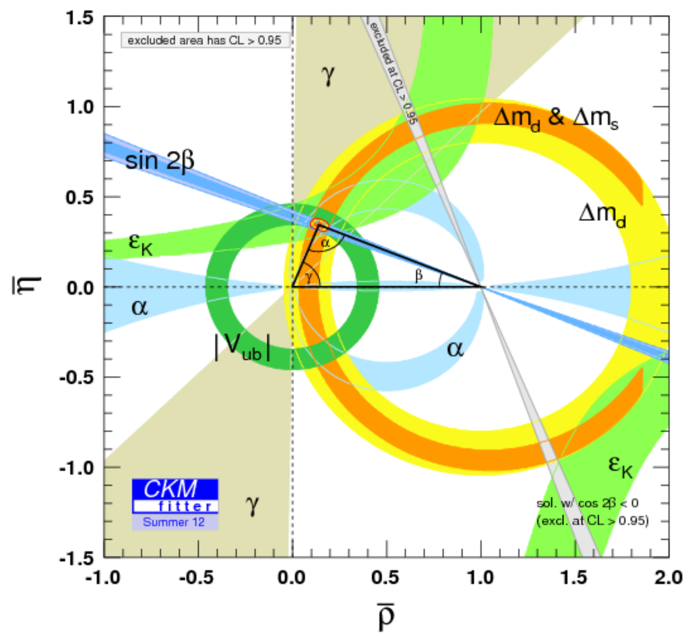
- Is ν_3 lighter or heavier than ν_2, ν_1 ?
  (atmospheric mass ordering)

- What is the size of CPV ?
  (δ)

LEPTOGENESIS?



3X3 UNITARITY



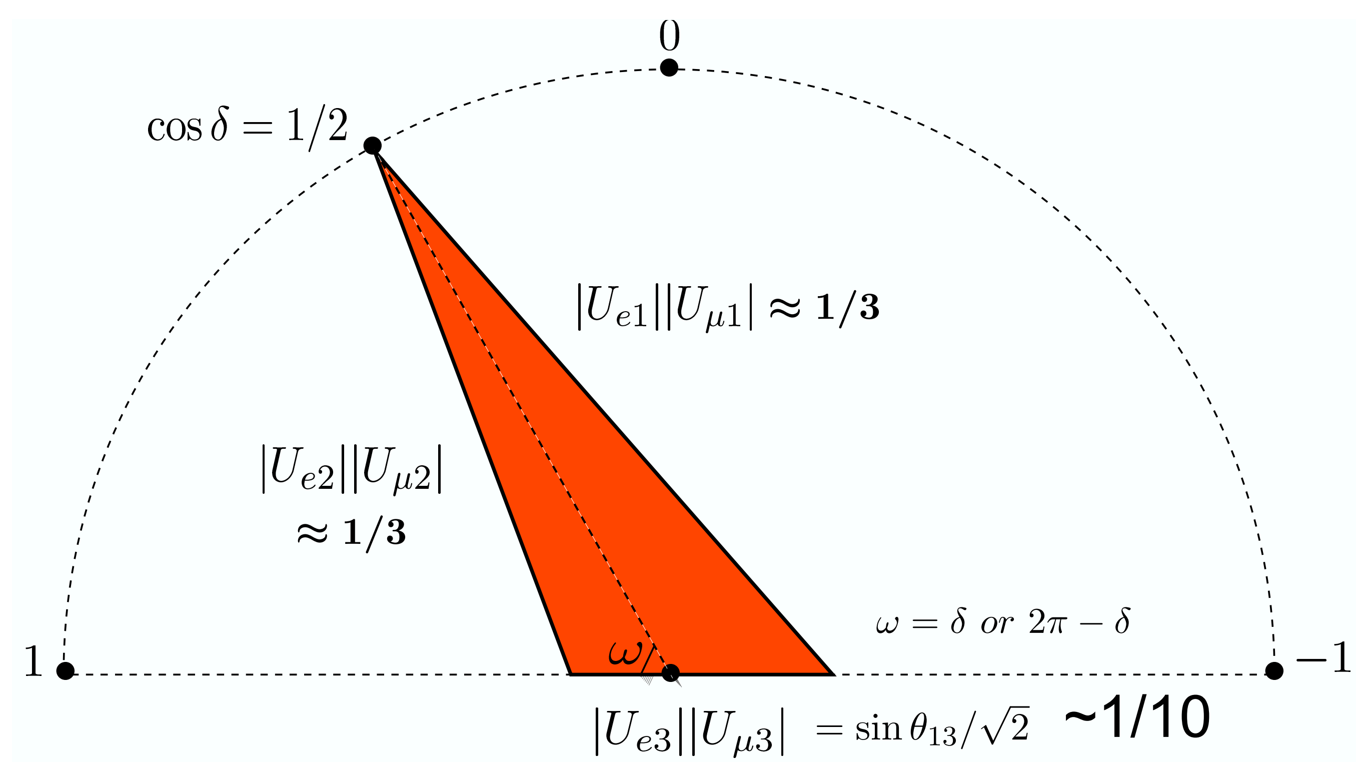
3X3 UNITARITY

Neutrino Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$

only Unitarity triangle that doesn't involve ν_τ !

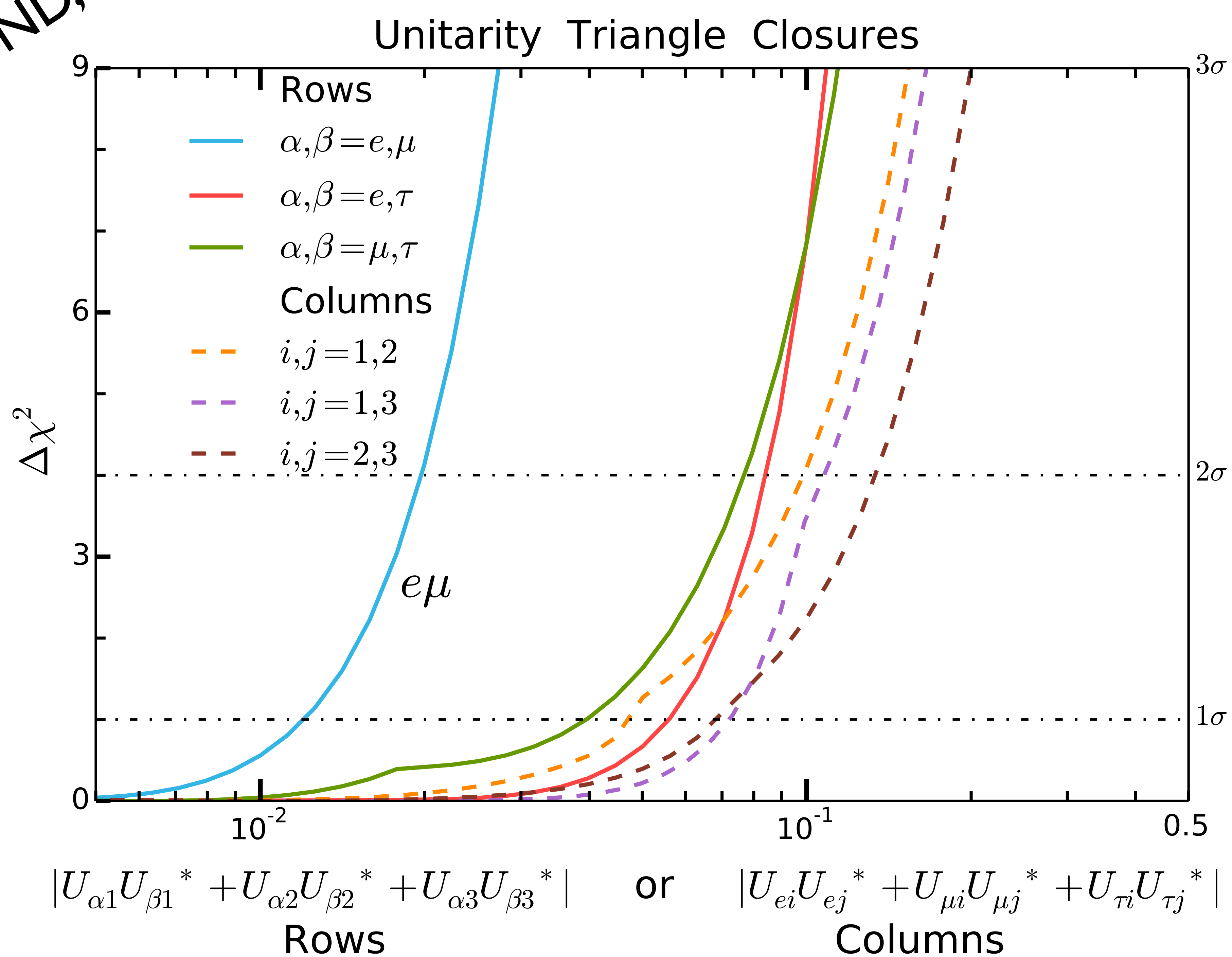
$$|J| = 2 \times \mathcal{A}rea$$



$$|U_{e1}||U_{\mu 1}| = \mathbf{0.0 - 0.5}; \;\; |U_{e2}||U_{\mu 2}| = \mathbf{0.2 - 0.4}; \;\; |U_{e3}||U_{\mu 3}| = \mathbf{0.1(1 \pm 0.2)}$$

Row and Column Triangles:

without LSND, miniBooNE

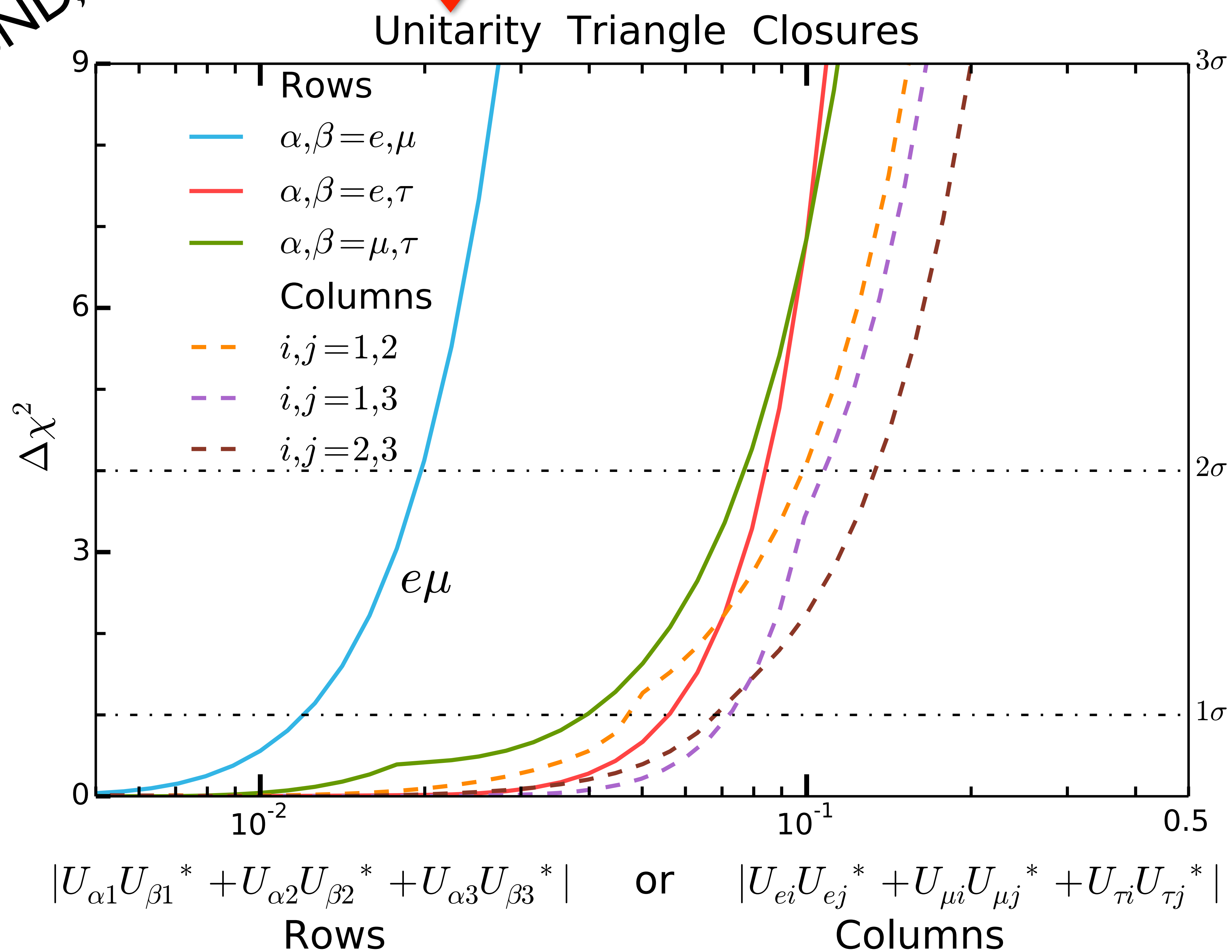


Ross-Lonergan +SP 1508.05095

Row and Column Triangles:

without LSND, miniBooNE

LSND, MINIBOONE



Ross-Lonergan +SP 1508.05095

ARE THERE LIGHT STERILE NEUTRINOS ?

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\rm PMNS}^{\rm 3x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

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Cauchy-Schwartz

$$\left| \sum_{i=1}^{3} U_{ei} U_{\mu i}{}^{*} \right|^2 \leq \left(1 - \sum_{i=1}^{3} |U_{ei}|^2\right) \left(1 - \sum_{i=1}^{3} |U_{\mu i}|^2\right)$$

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- ν_μ Disappearance

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

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Daya Bay, RENO, many ~10m Reactor experiments & source experiments.

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

- ν_e Disappearance

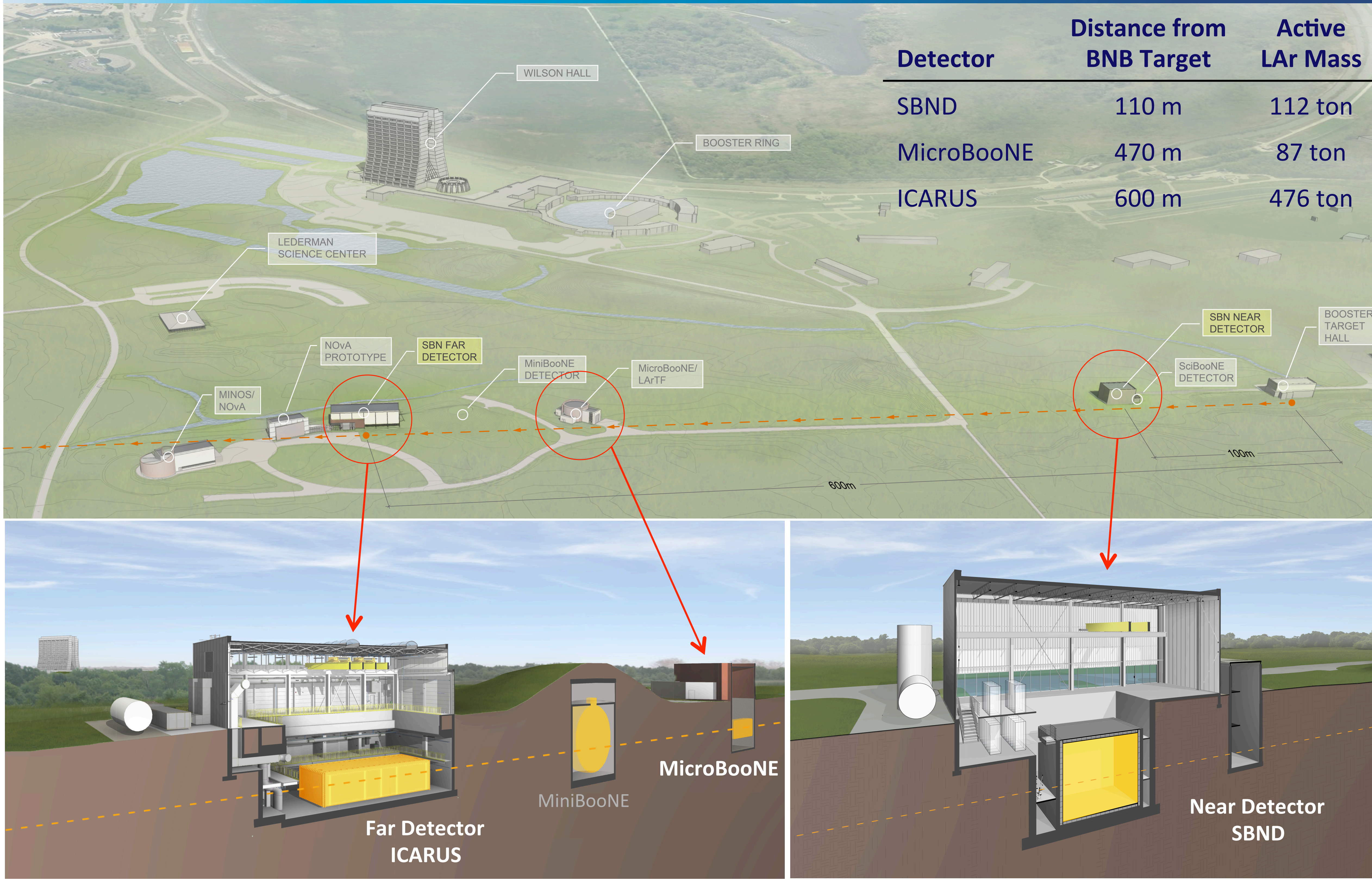
Daya Bay, RENO, many ~10m Reactor experiments & source experiments.

- $\nu_\mu \to \nu_e$ Appearance

Fermilab SBN Program, T2K and NOvA: DUNE & HyperK

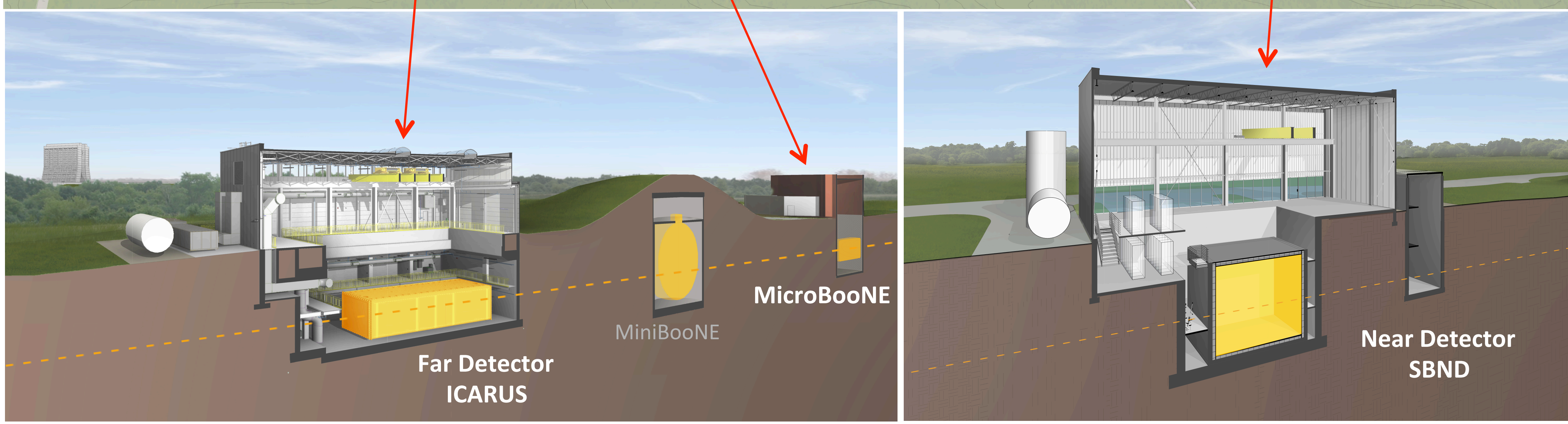
The Three-Detector SBN Program

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



The T… rogram

Distance from BNB Target
Active LAr Mass
110 m
112 ton
NE
470 m
87 ton
600 m
476 ton
LEDERM
SCIENC
MINOS/ NOvA
MiniBooNE DETECTOR
MicroBooNE/ LArTF
SBN NEAR DETECTOR
SciBooNE DETECTOR
BOOSTER TARGET HALL
100m
600m



MicroBooNE
MiniBooNE
Far Detector ICARUS
Near Detector SBND

The …rogram

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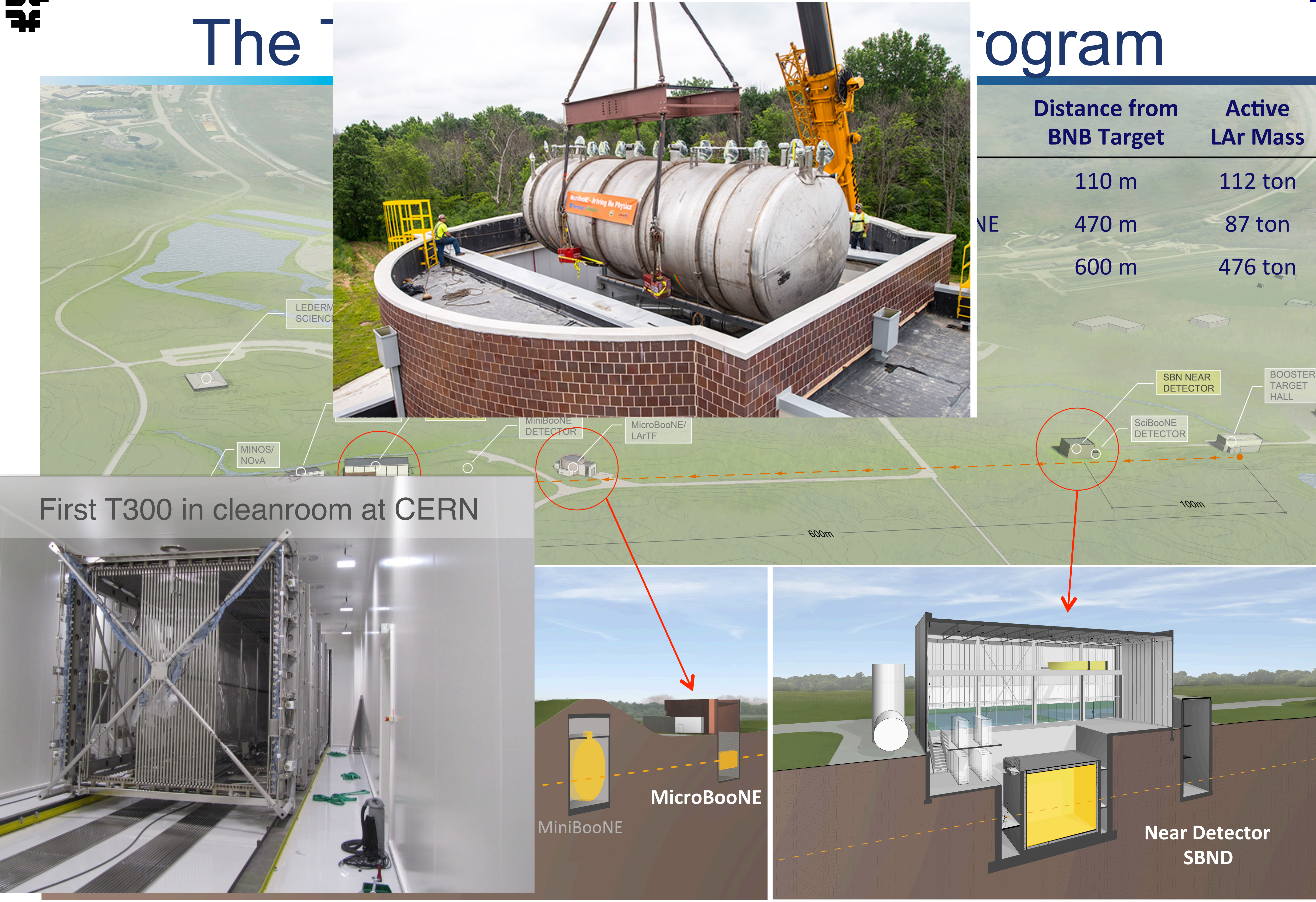

The T … rogram

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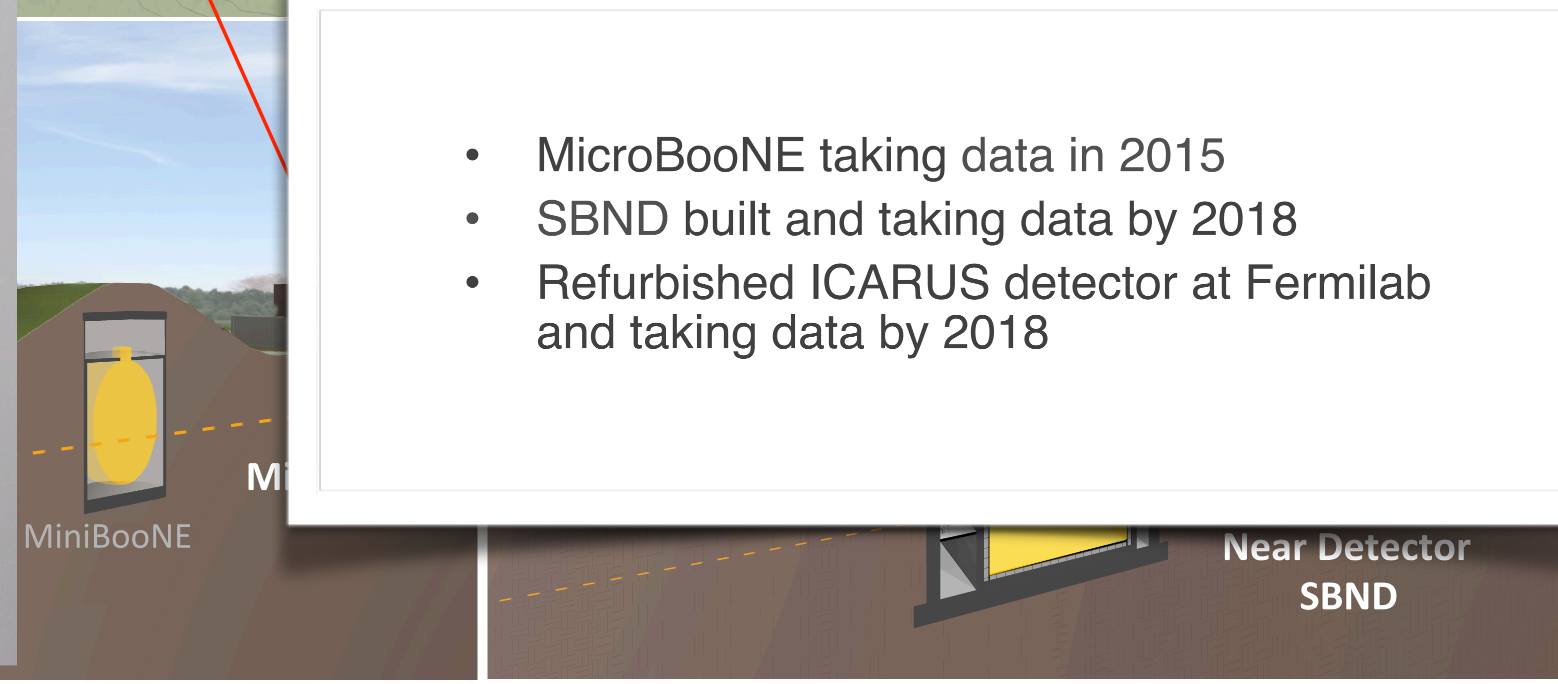
First T300 in cleanroom at CERN



- MicroBooNE taking data in 2015
- SBND built and taking data by 2018
- Refurbished ICARUS detector at Fermilab and taking data by 2018

Holiday Reading:
by

Holiday Reading:
by

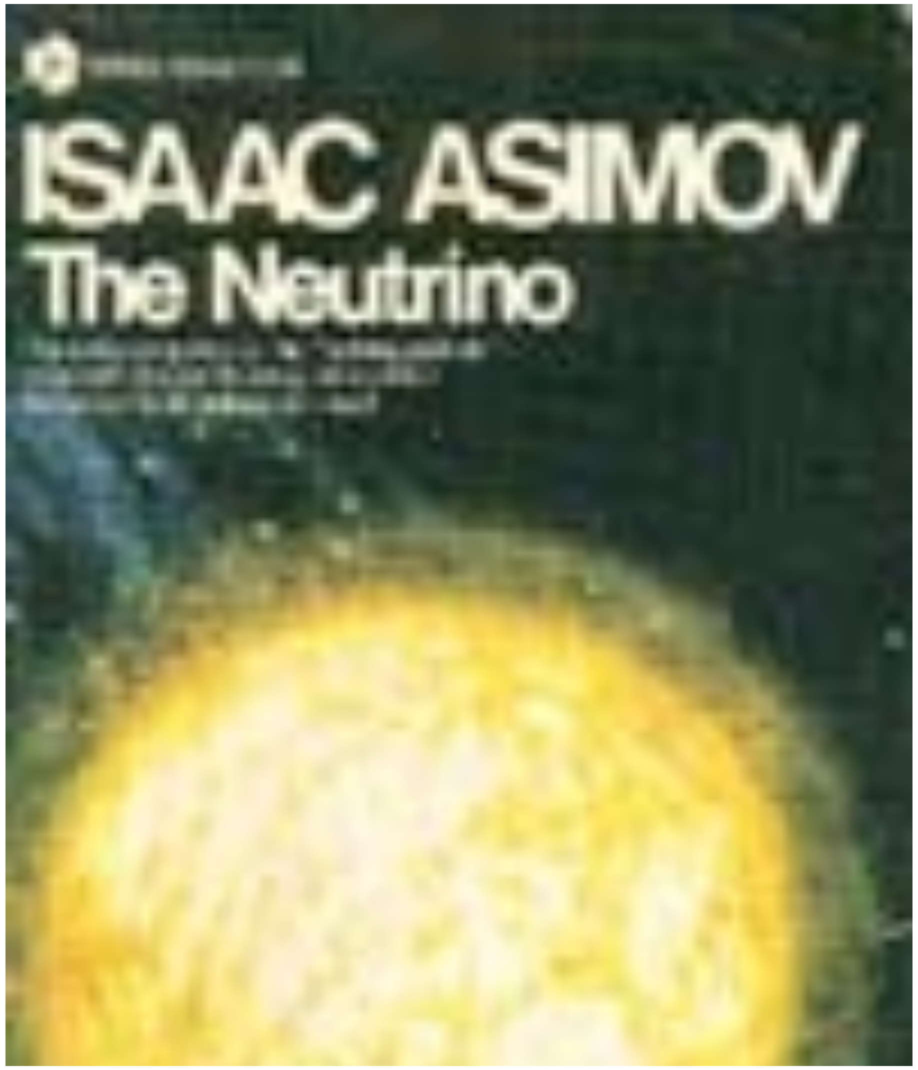
Isaac Asimov

1966

1966

“ And yet the nothing-particle is not a nothing at all ”

1966



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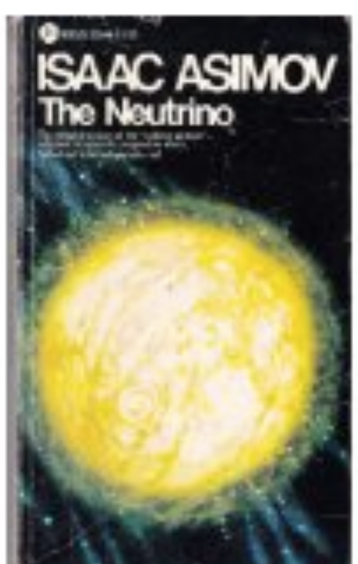

The Neutrino: Ghost Particle of the Atom Aug 1980
by Isaac Asimov

Mass Market Paperback
$0.48 used & new (36 offers)

★★★★★ 1

Possible Future Neutrino Nobel Prizes:

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- Nature of the Neutrino
  (Majorana (2) v Dirac (4))

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- Observing CPV in Neutrino Sector ($\sin\delta \neq 0$)

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

- Your Neutrino Surprise !