OVERVIEW: UDiG Workshop BNL

Stephen Parke
Fermilab
Oct 16, 2008

LBL Neutrino Oscillations
Proton Decay
Supernova Neutrinos
Other: Solar & Atm. Nus ...

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"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times 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

Detecting Neutrinos

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

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

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,

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Bajram Curri, in nc

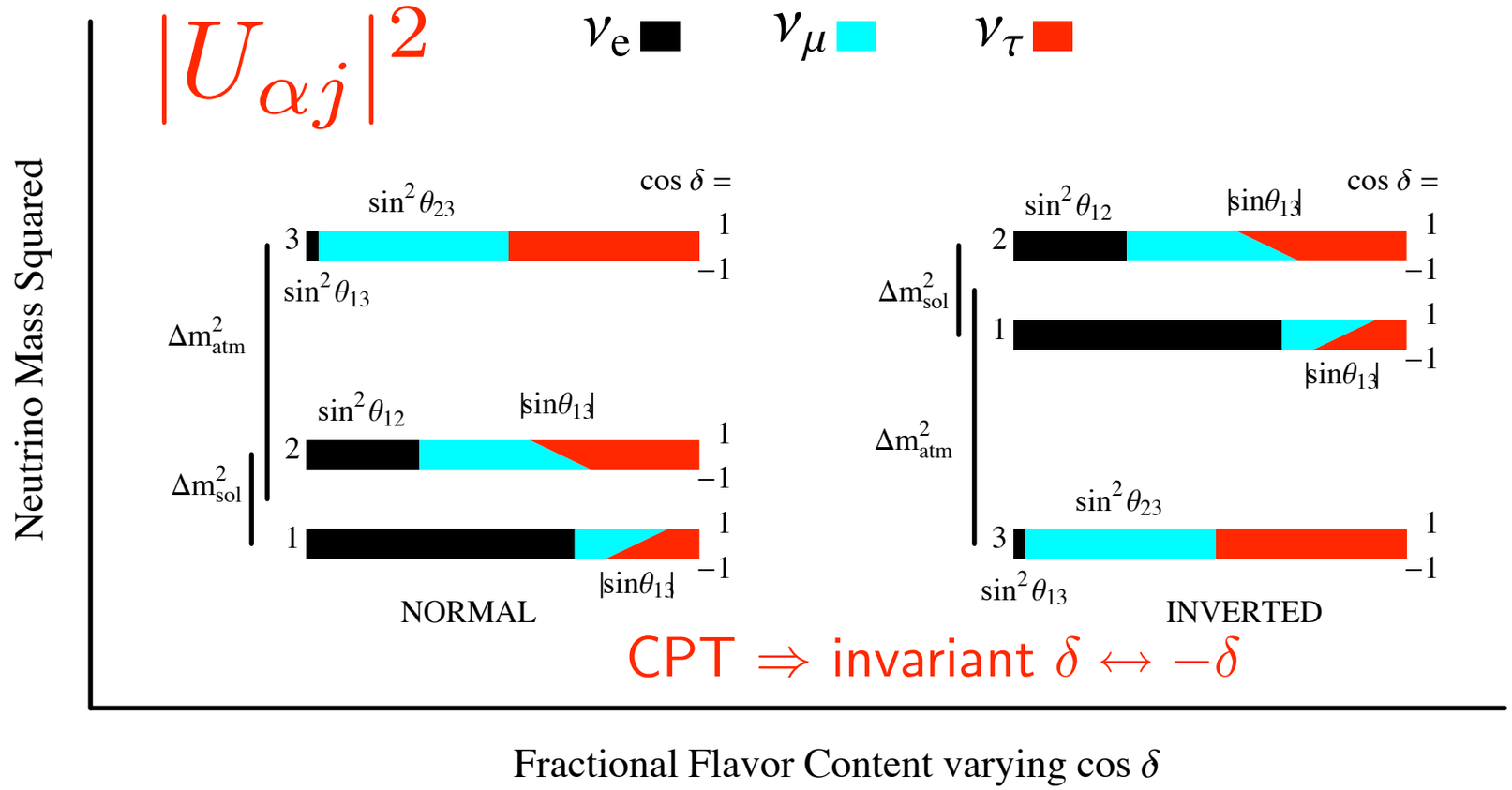
Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV 15km/MeV



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

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

$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

One Global Fit:

Dominated by

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND
MINOS
SNO
SuperK
Chooz

arXiv:0808.2016

Neutrino

Mass Spectrum:

- Quasi-Degenerate ?
- Hierarchical ?
- Normal or Inverted ?

Mixings:

- Deviations from $U_{Tri-Bi-Max}$

  $\boxed{\sin^2\theta_{13},}$ $(\sin^2\theta_{23} - 1/2)$, $(\sin^2\theta_{12} - 1/3)$
- Relationship between these deviations and

  $V_{CKM} - 1$

  if any ?
- Magnitude and sign of CPV:

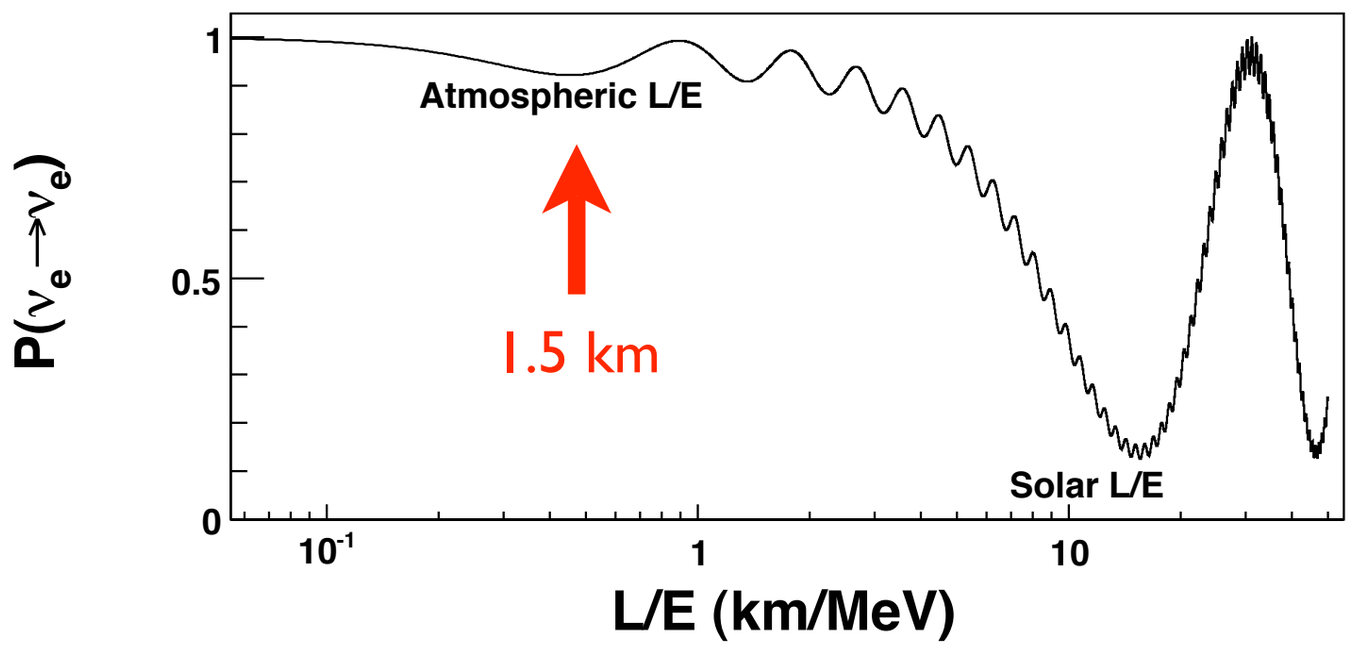
  $\propto \sin\theta_{13}\sin\delta$

$\sin^2\theta_{13}$ from Reactor Neutrinos:

kinematic phase:

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \end{aligned}$$



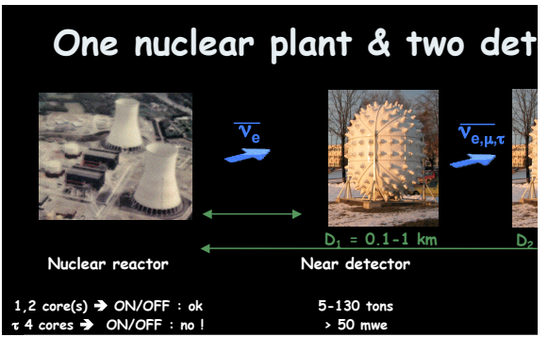
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

< 0.002

> 0.01

$$\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$$

Double Chooz:



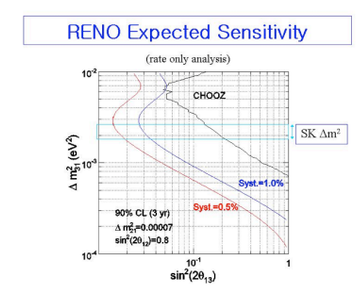
Daya Bay

RENO

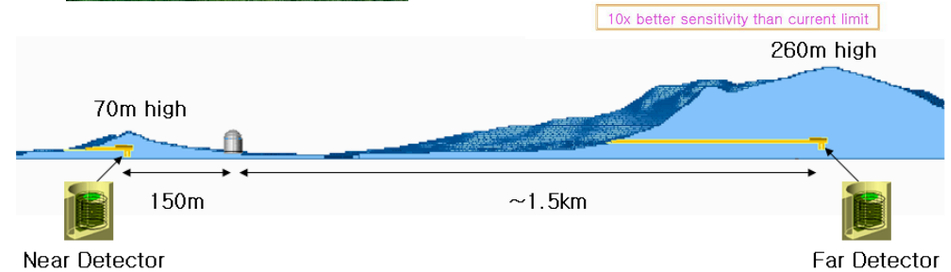
(Reactor Experiment for Neutrino Oscillation)

push the limi

$\sin^2 2\theta_{13} < 0$



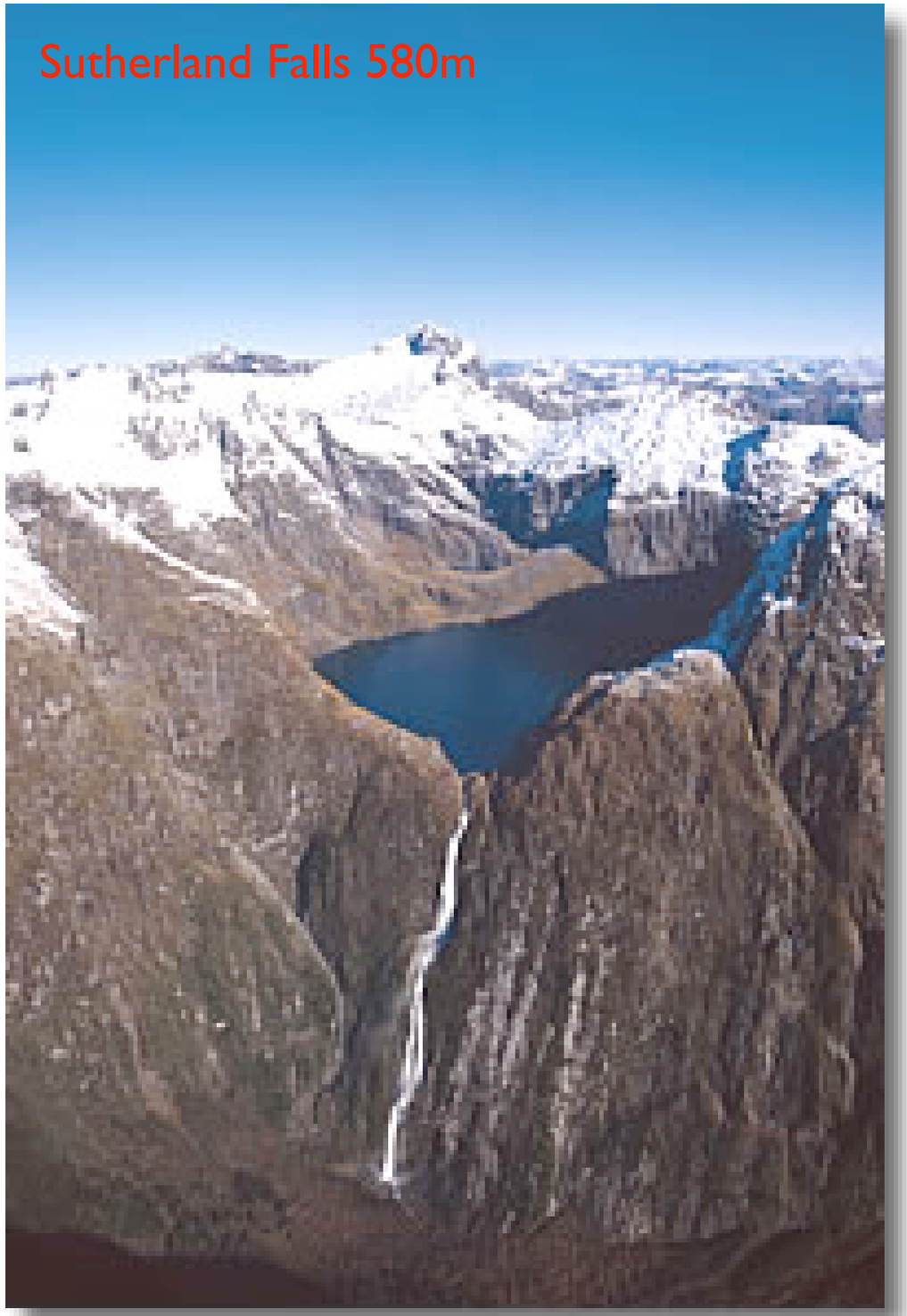
10x better sensitivity than current limit



$\sin^2\theta_{13}$ from LBL:

$$\nu_\mu \longrightarrow \nu_e$$

and related processes:



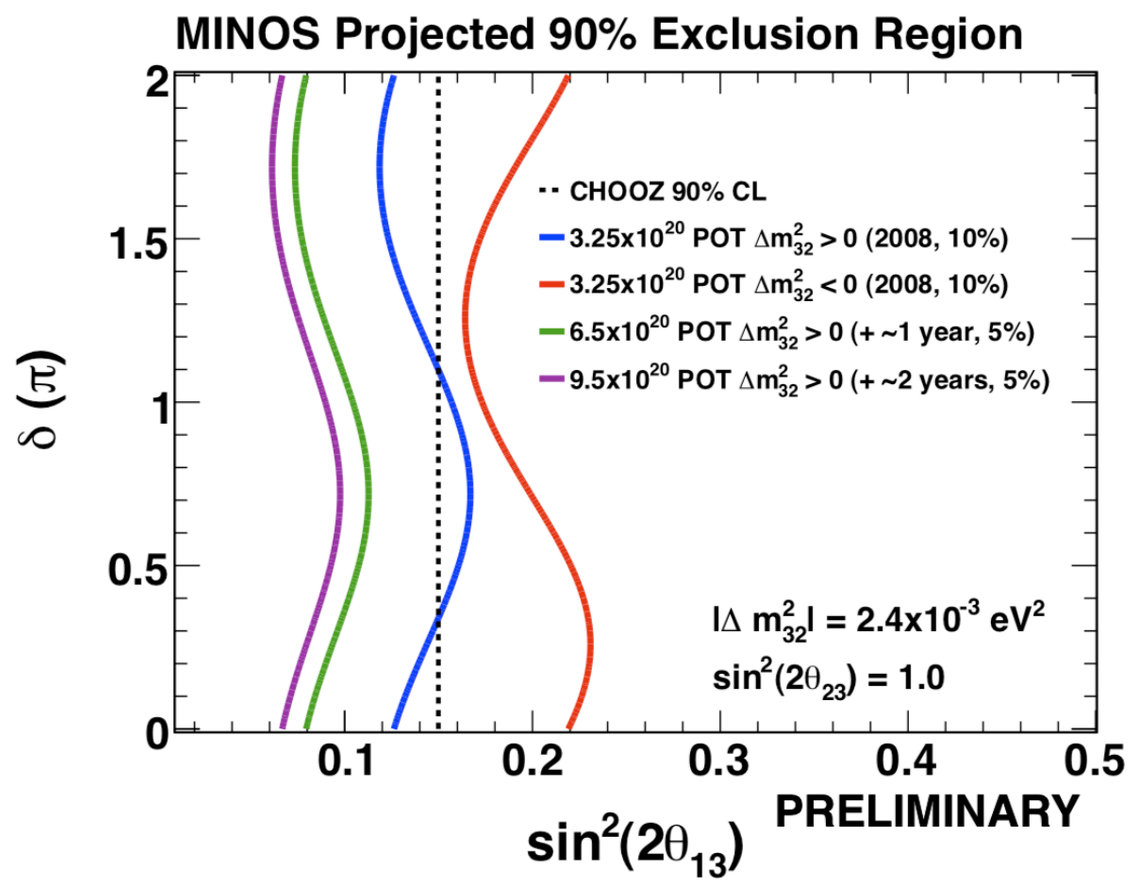
$$
\begin{array}{ccccc}
 & & \text{CP} & & \\
 & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\
\text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\
 & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e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

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

MINOS:

ν_e Sensitivity

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008



At CHOOZ limit expect 12 ν_e signal events and 42 background events with 3.25×10^{20} protons.

Use sidebands to study predicted far detector backgrounds.

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

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

CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

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

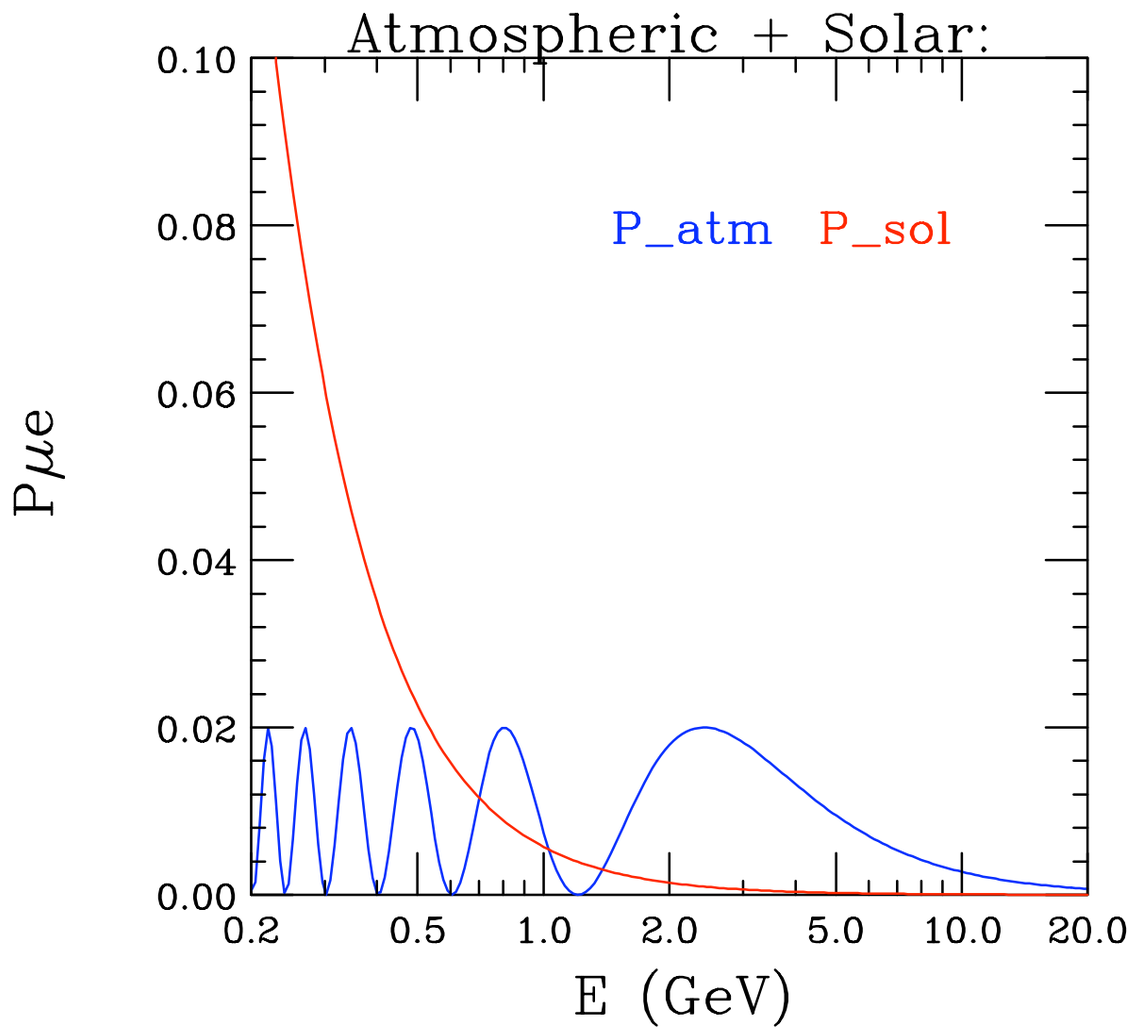
$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}}$$

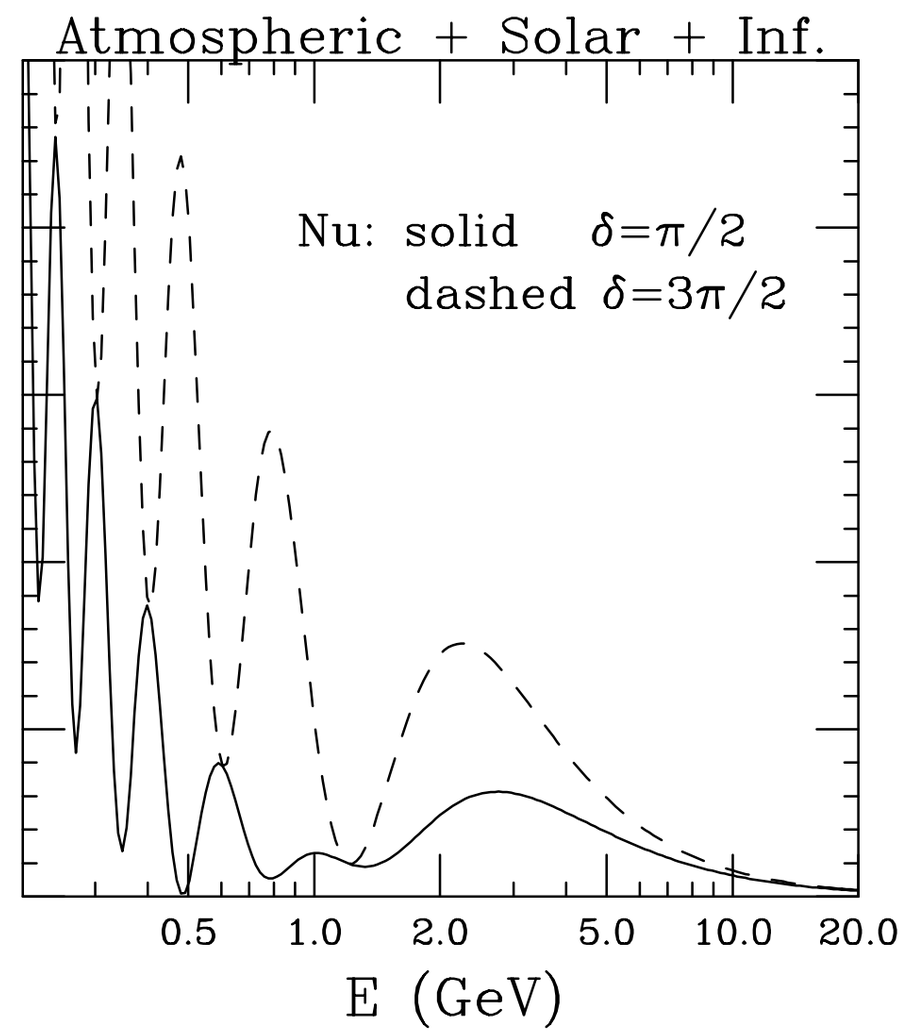
only CPV

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

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

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



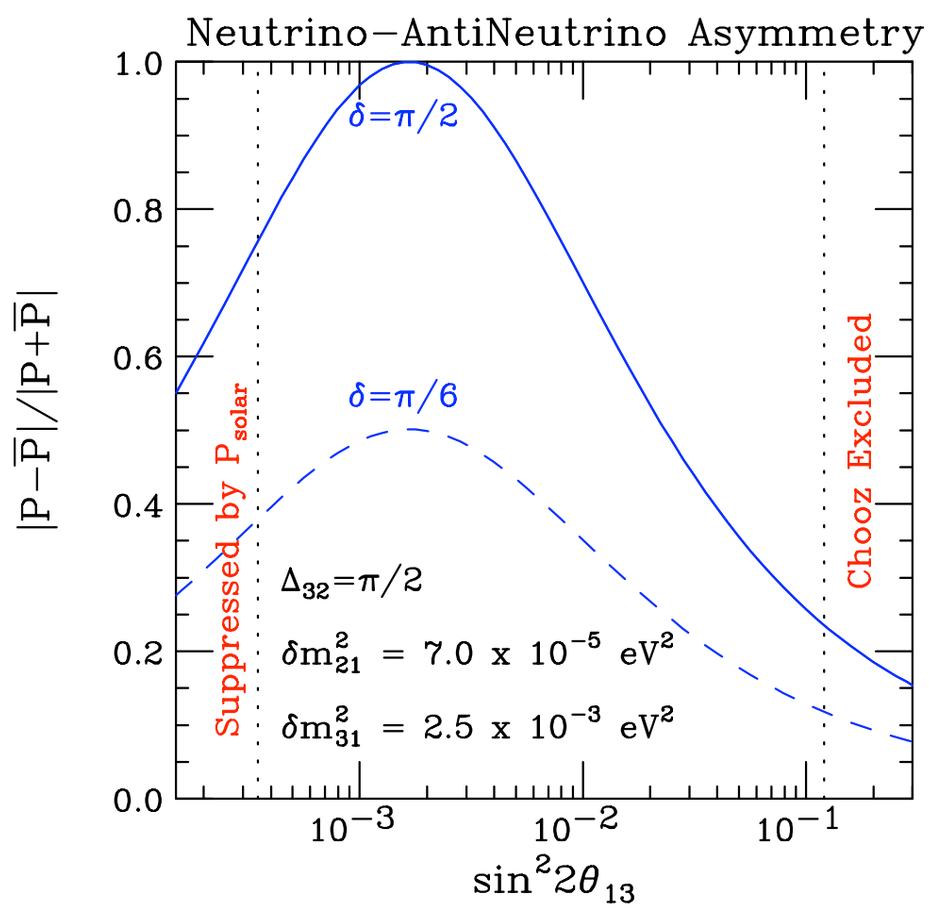


x 3

phase varies

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

Asymmetry Peaks:



$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}} \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

In Matter:

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

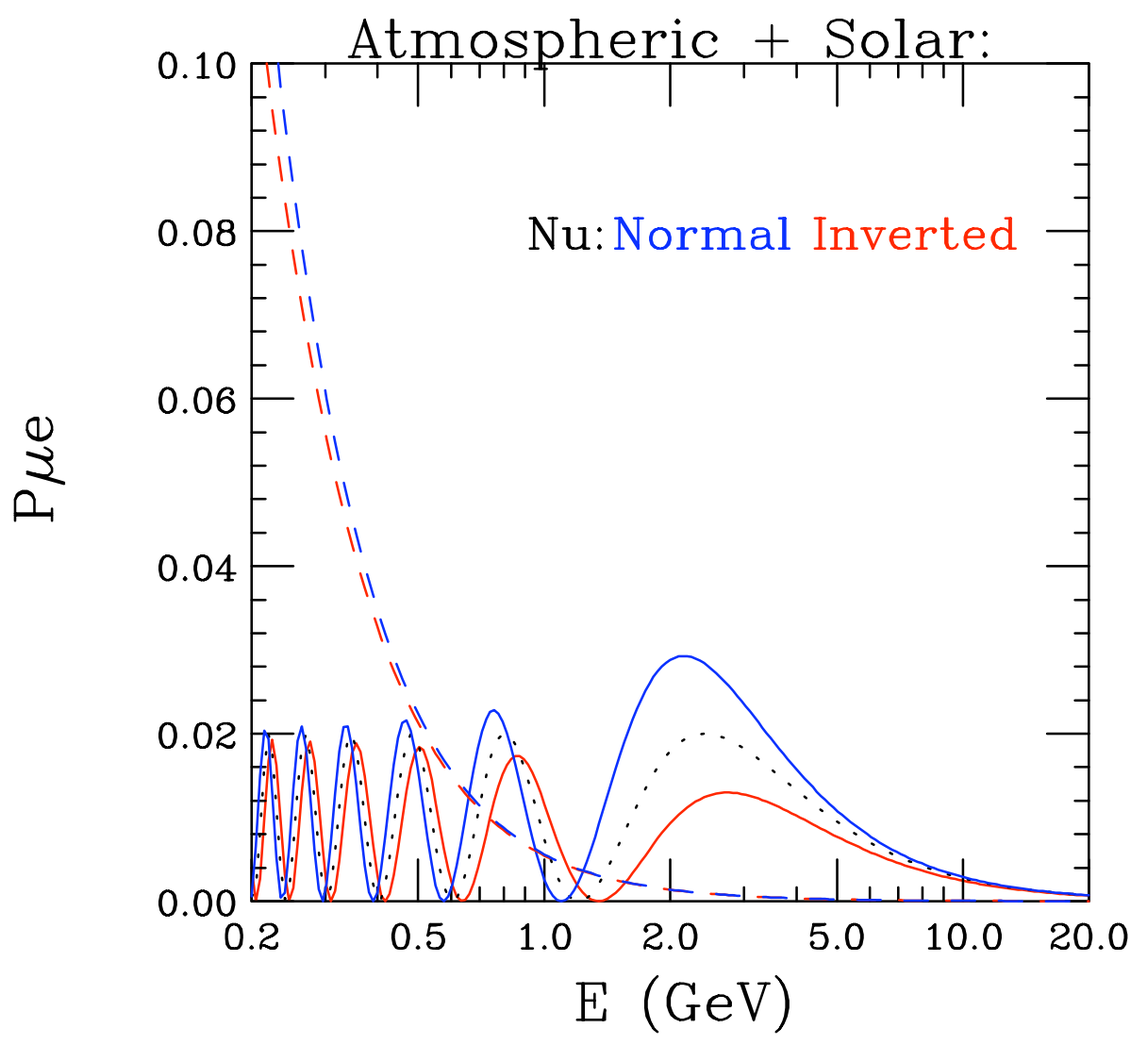
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

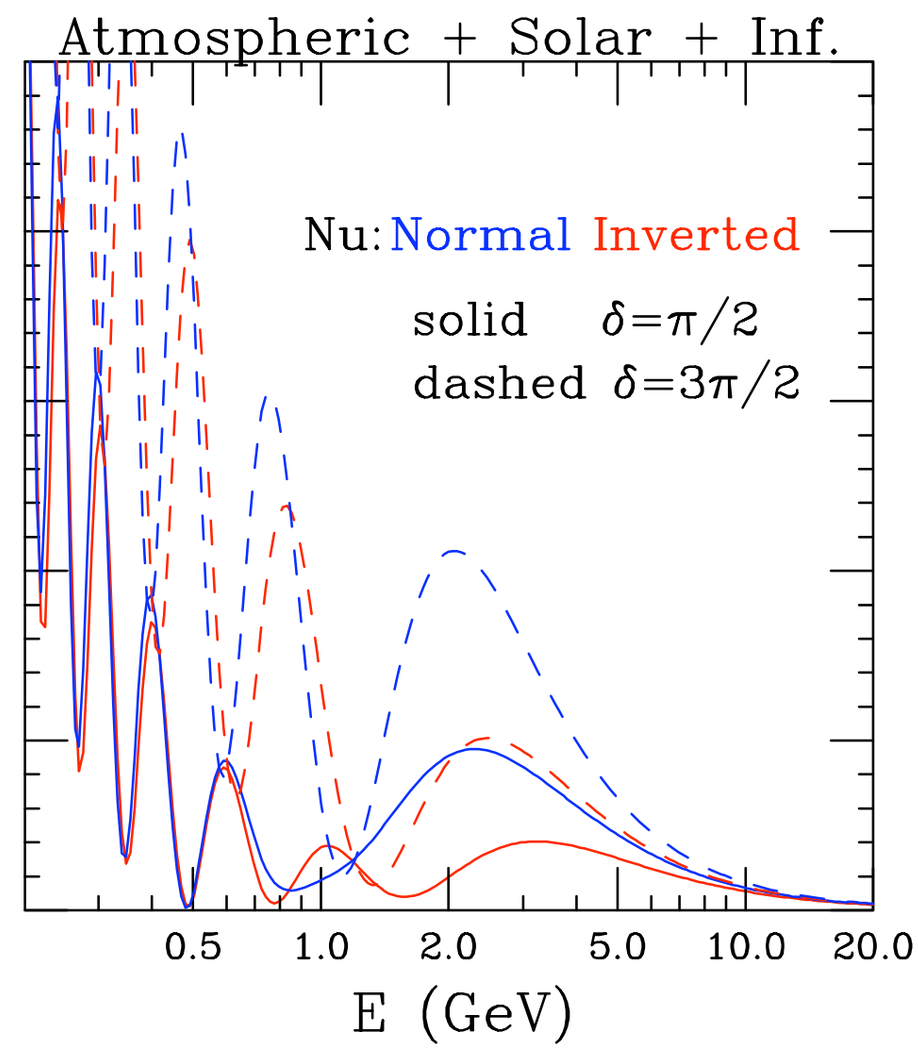
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

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

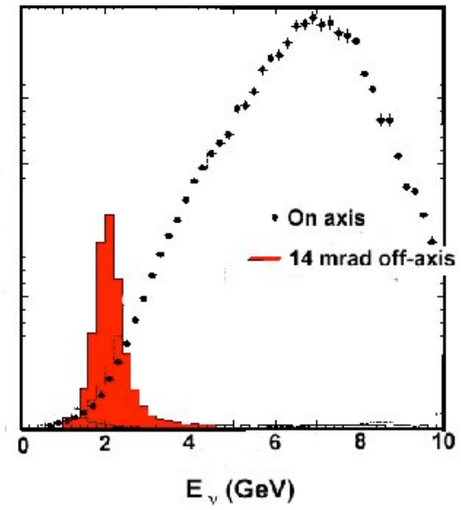
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





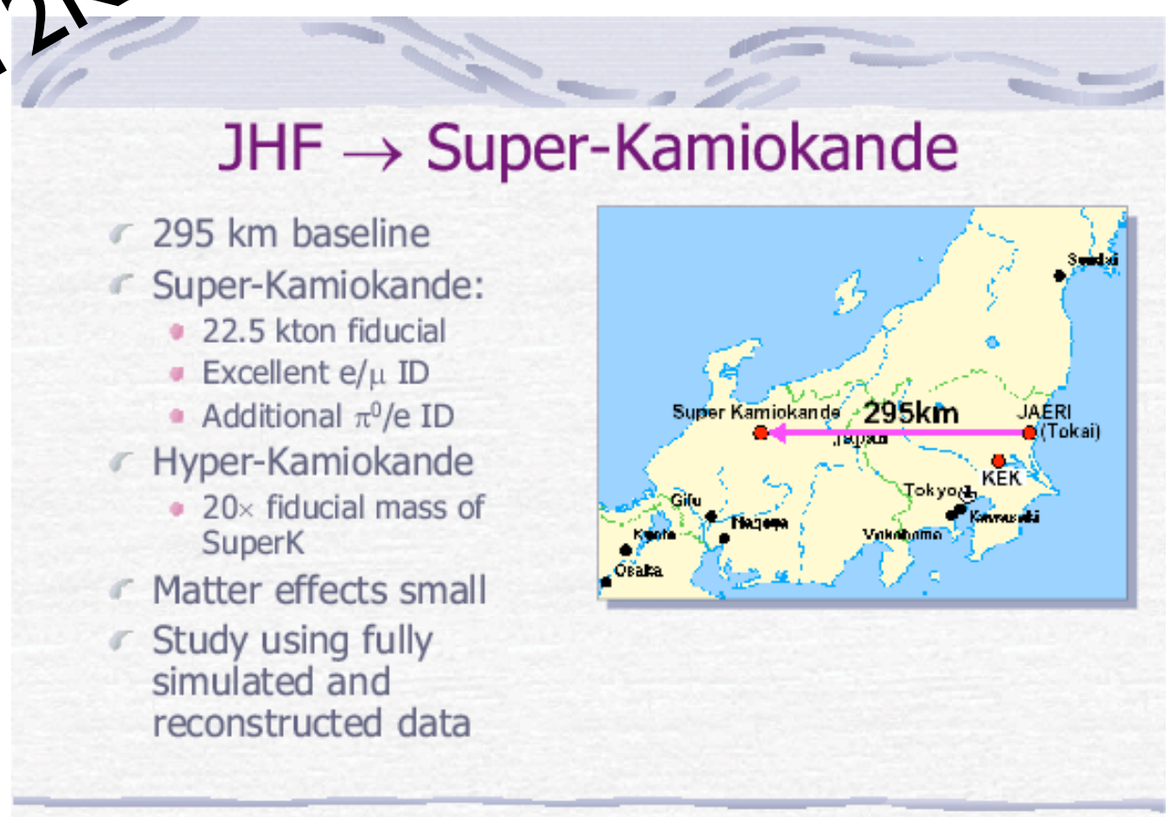
Off-Axis Beams

BNL 1994



π^0 suppression

T2K



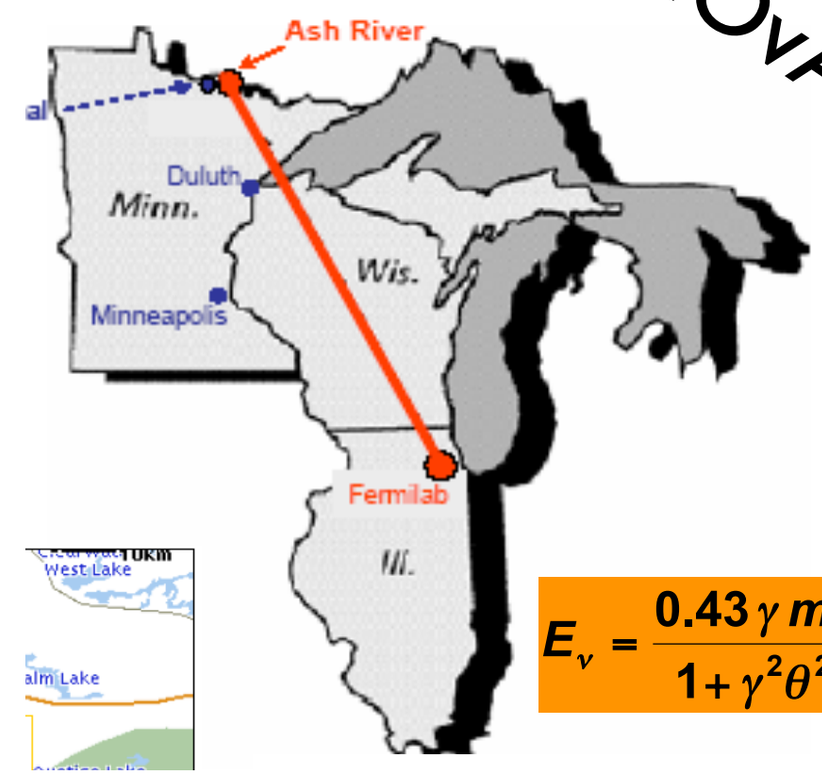
L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

NOvA



$$E_\nu = \frac{0.43\,\gamma\, m_\pi}{1+\gamma^2\theta^2}$$

L=700 - 1000 km and

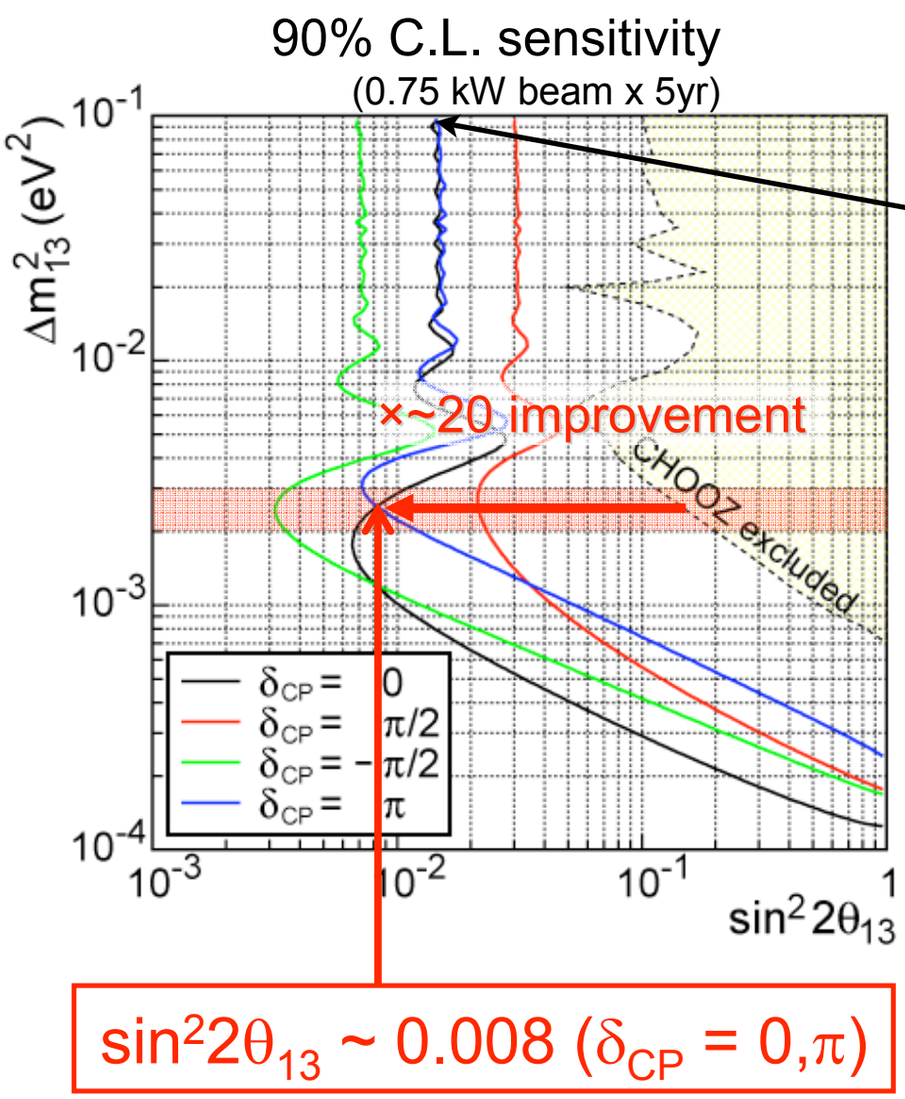
Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

T2K

Search for ν_e appearance



$\sin^2 2\theta_{13} \sim 0.008$ (δ_{CP} = 0,π)

For LARGE δm^2_{31}

$$\langle P(\nu_\mu \to \nu_e)\rangle = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13} - \frac{1}{2}J.\Delta_{21} + \cos^2\theta_{23}\sin^2 2\theta_{12}\Delta^2_{12}$$

$$J = \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta$$

$$\Delta_{21} = \delta m^2_{21} L/4E$$

At $\delta = 0$ *or* π

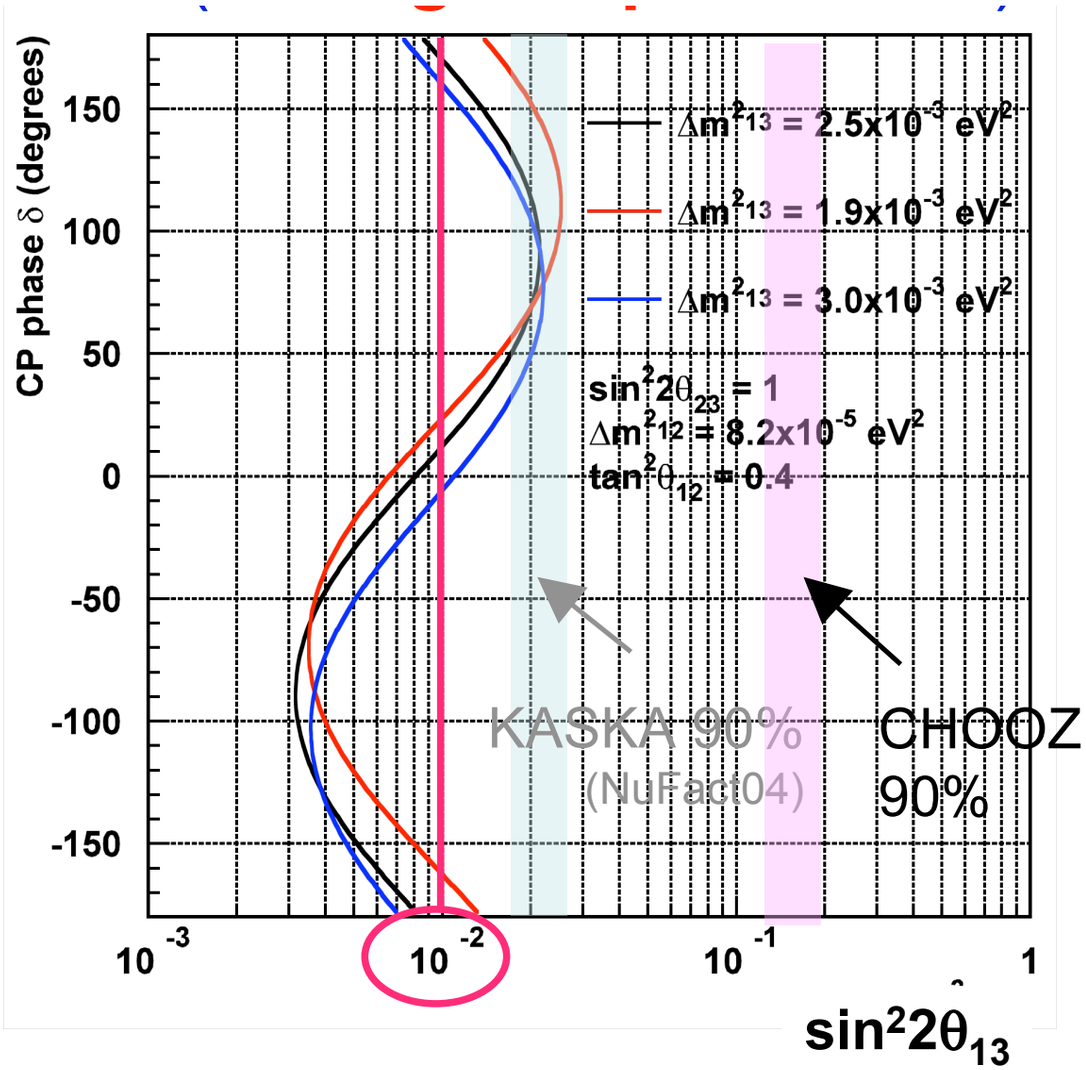
$$\langle P(\nu_\mu \to \nu_e)\rangle = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13} + \cos^2\theta_{23}\sin^2 2\theta_{12}\Delta^2_{12}$$
$$\approx 0.5\%$$

$$\langle P(\nu_\mu \to \nu_e)\rangle_{T2K} \approx 0.5\%$$

0.5% ν_e in beam

T2K:

Aihara for T2K, P5 talk

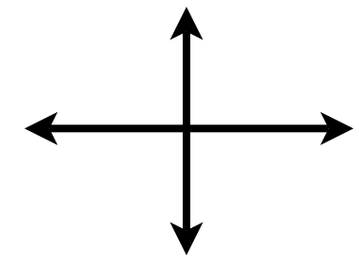


Phase I

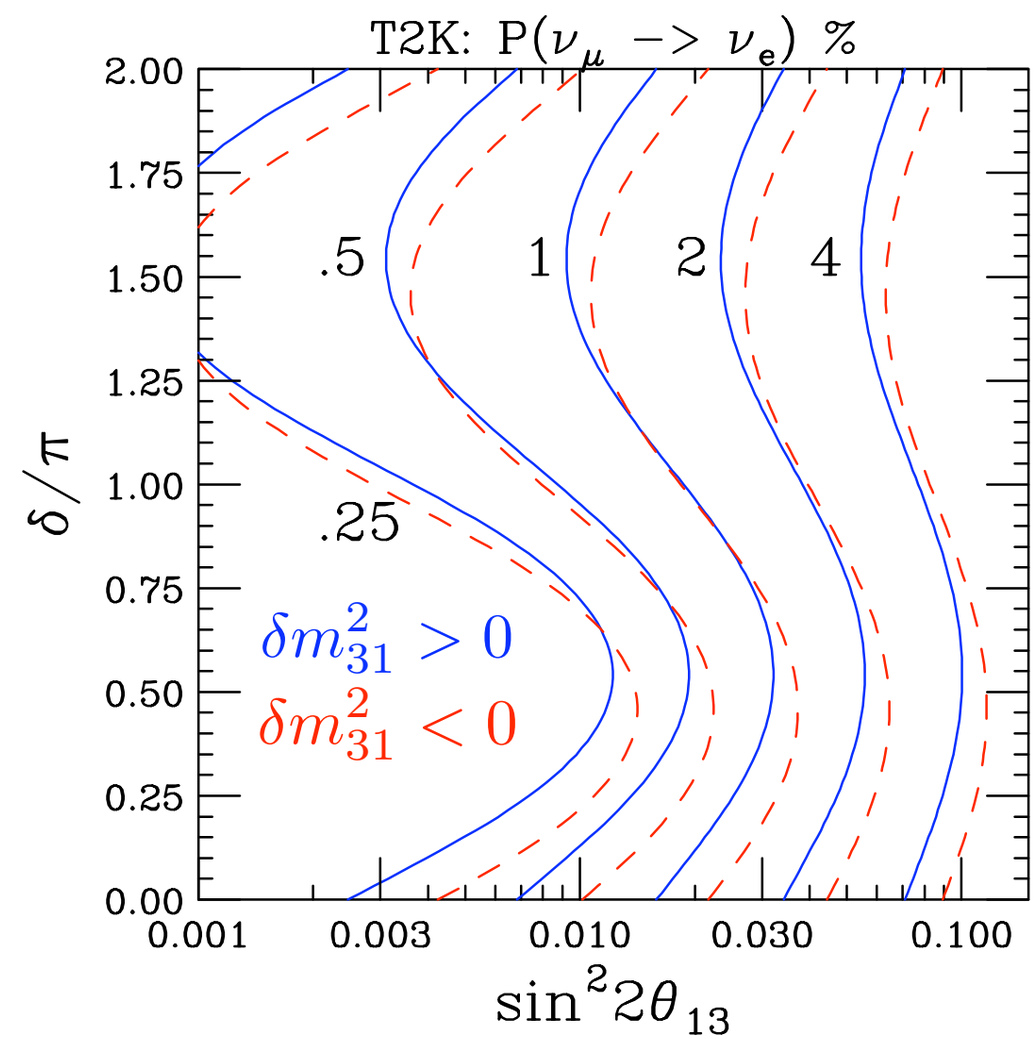
Sensitivity approx 0.5%

Beam 0.5%

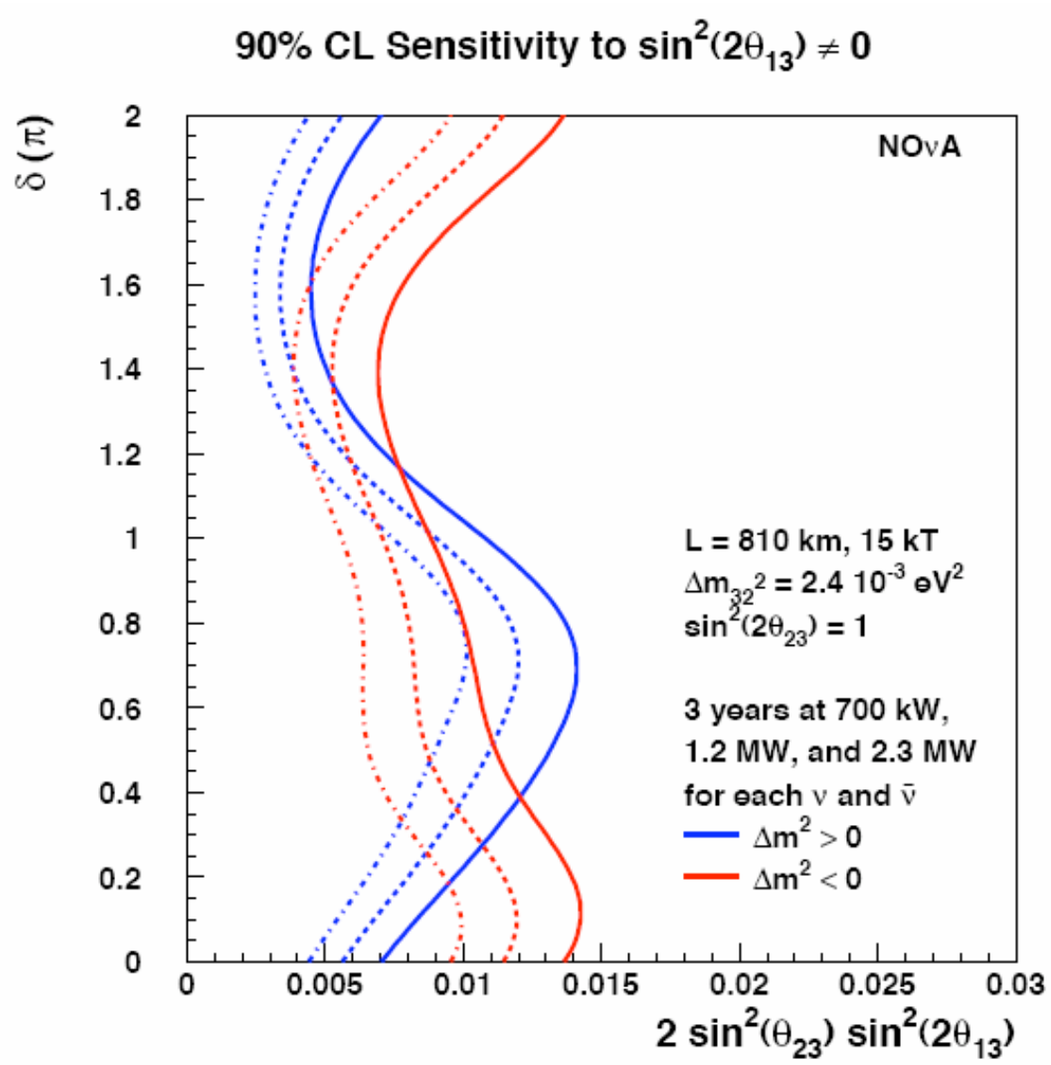
VOM: $\Delta_{31} \neq \pi/2$



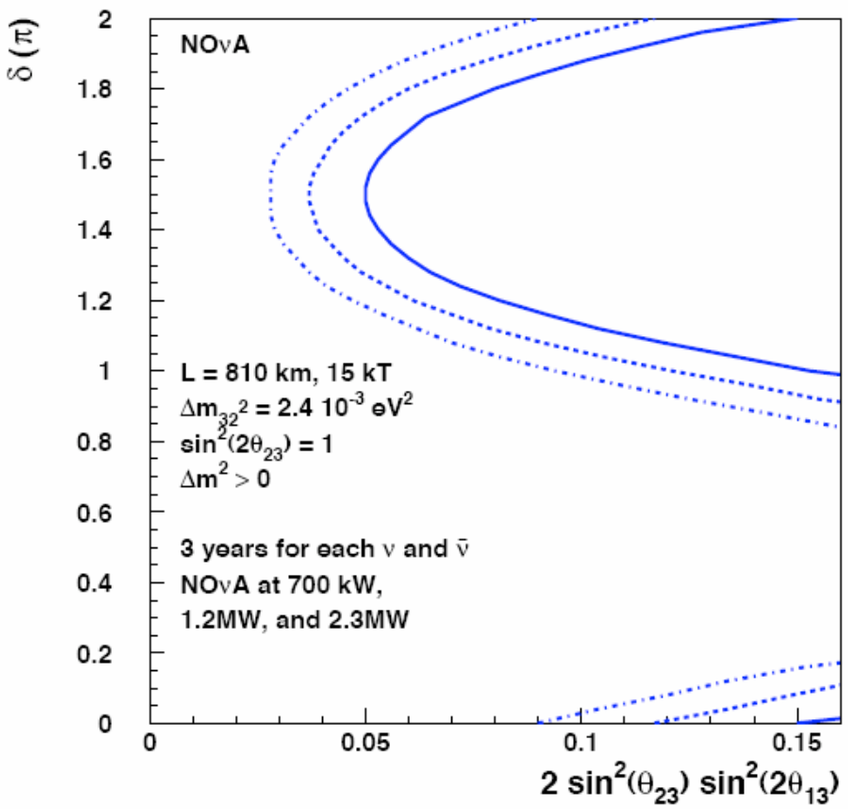
Matter Effect:



Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

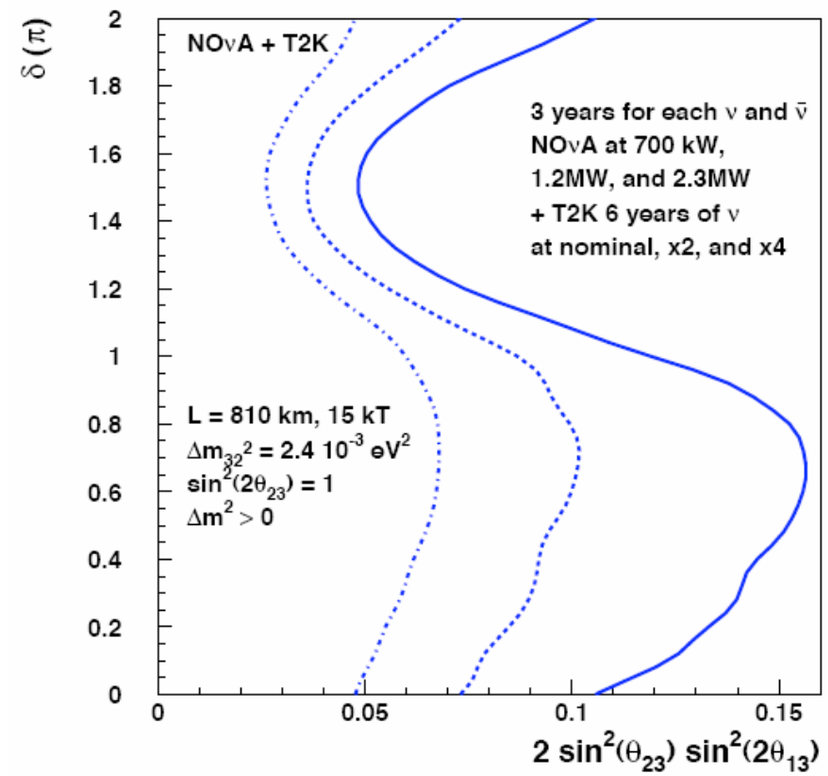


95% CL Resolution of the Mass Ordering
NOνA Alone



Normal Ordering

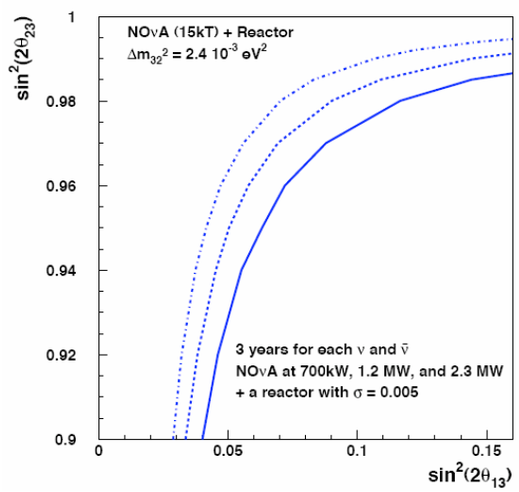
95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

for Inverted Hierarchy $\delta \rightarrow \pi - \delta$

95% CL Resolution of the θ_{23} Ambiguity

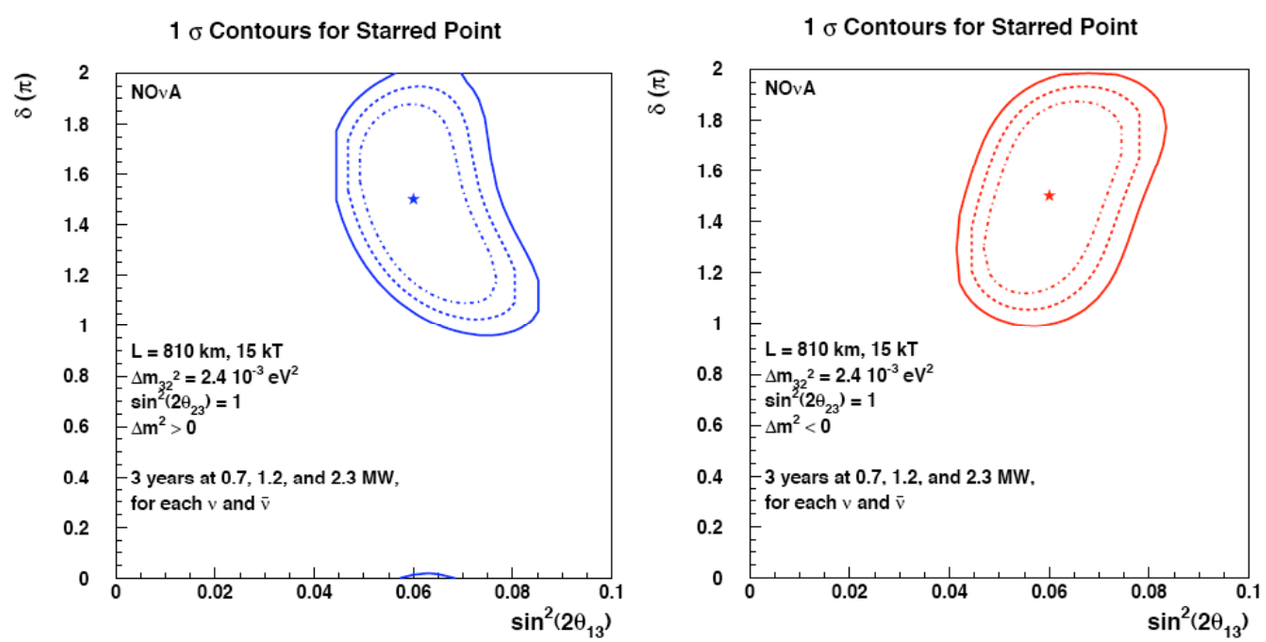


at Vac. Osc. Max.

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} + 2P_\odot$$

in $P + \bar{P}$ the matter effects approx. cancel
and CP effects approx. cancel.

CP Violation: δ vs. θ_{13} Contours



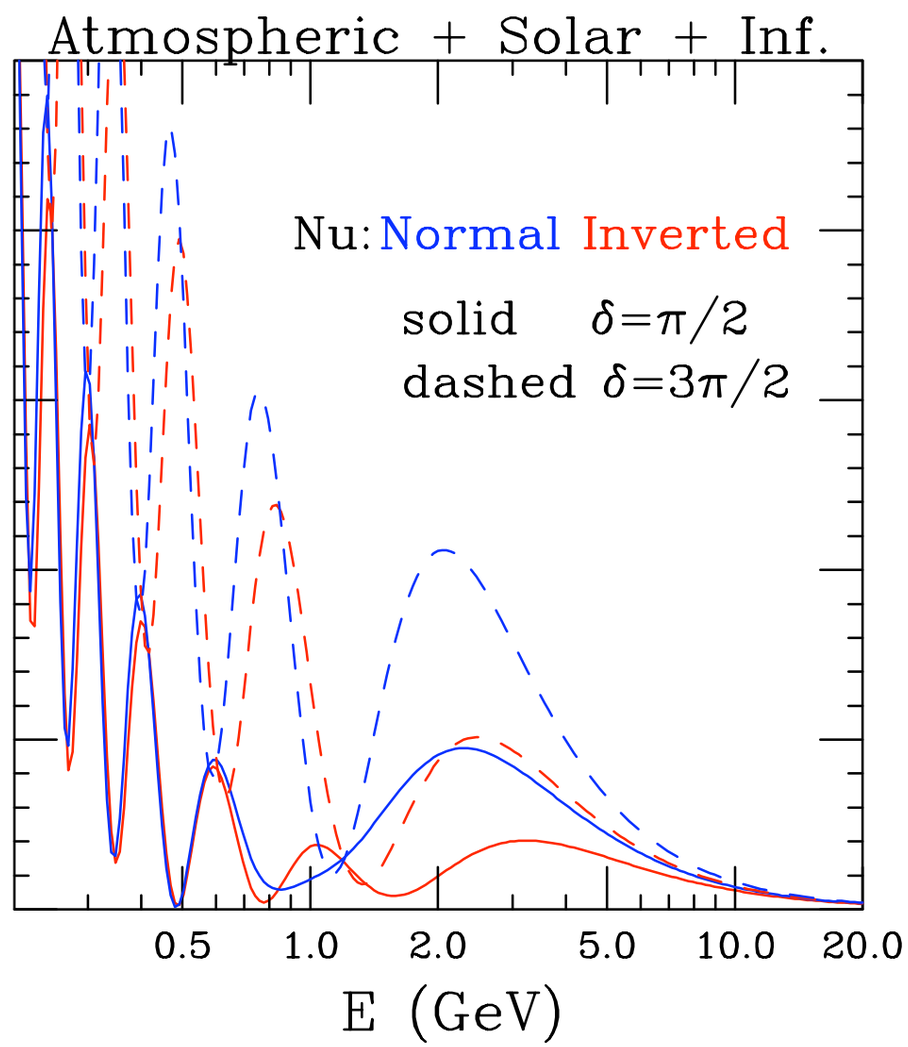
Way Forward:

Signal Events =
Fid. Mass
* P.O.T. (beam power*time)
* Efficiency

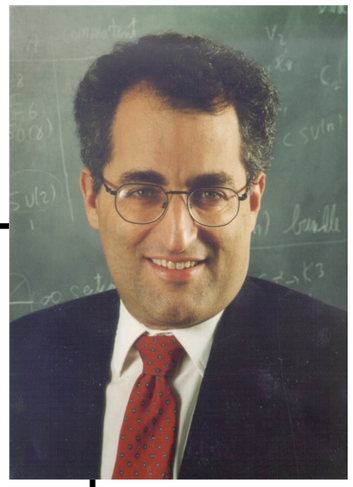
2nd Oscillation Maximum

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

Anti-Nu: Normal Inverted
dashes $\boldsymbol{\delta = \pi/2}$
solid $\boldsymbol{\delta = 3\pi/2}$

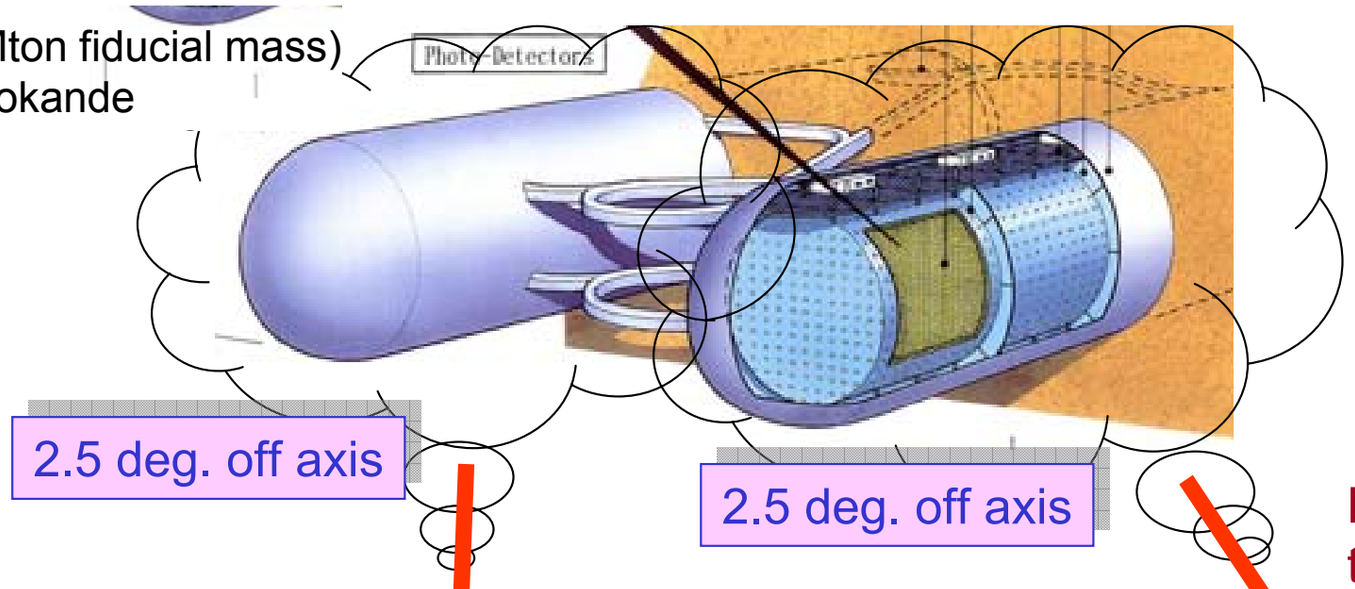


Off Axis:



Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

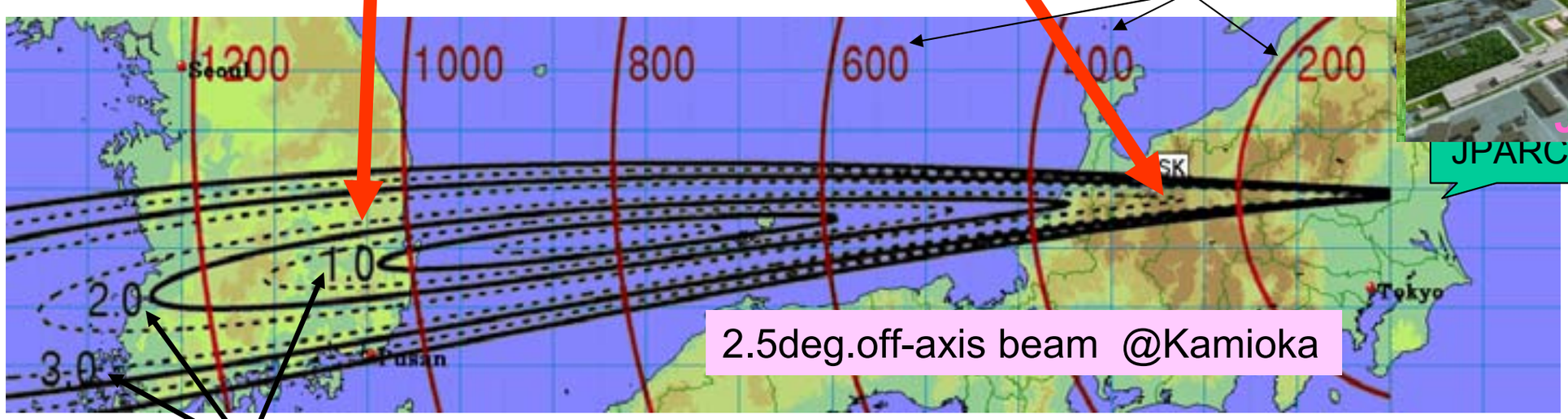


2.5 deg. off axis

2.5 deg. off axis

Total cost must be similar to the baseline design.

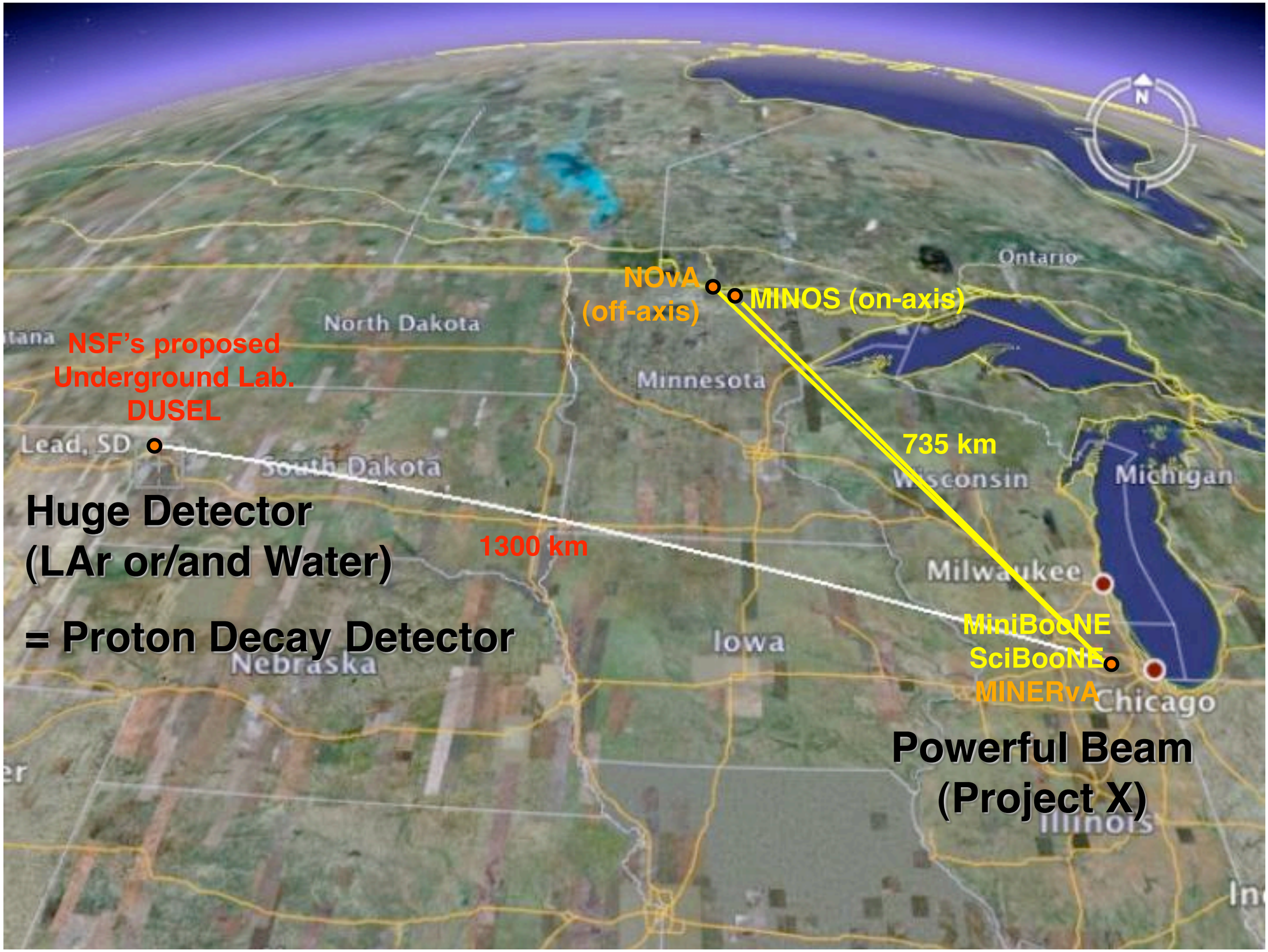
Distance from the target (km)

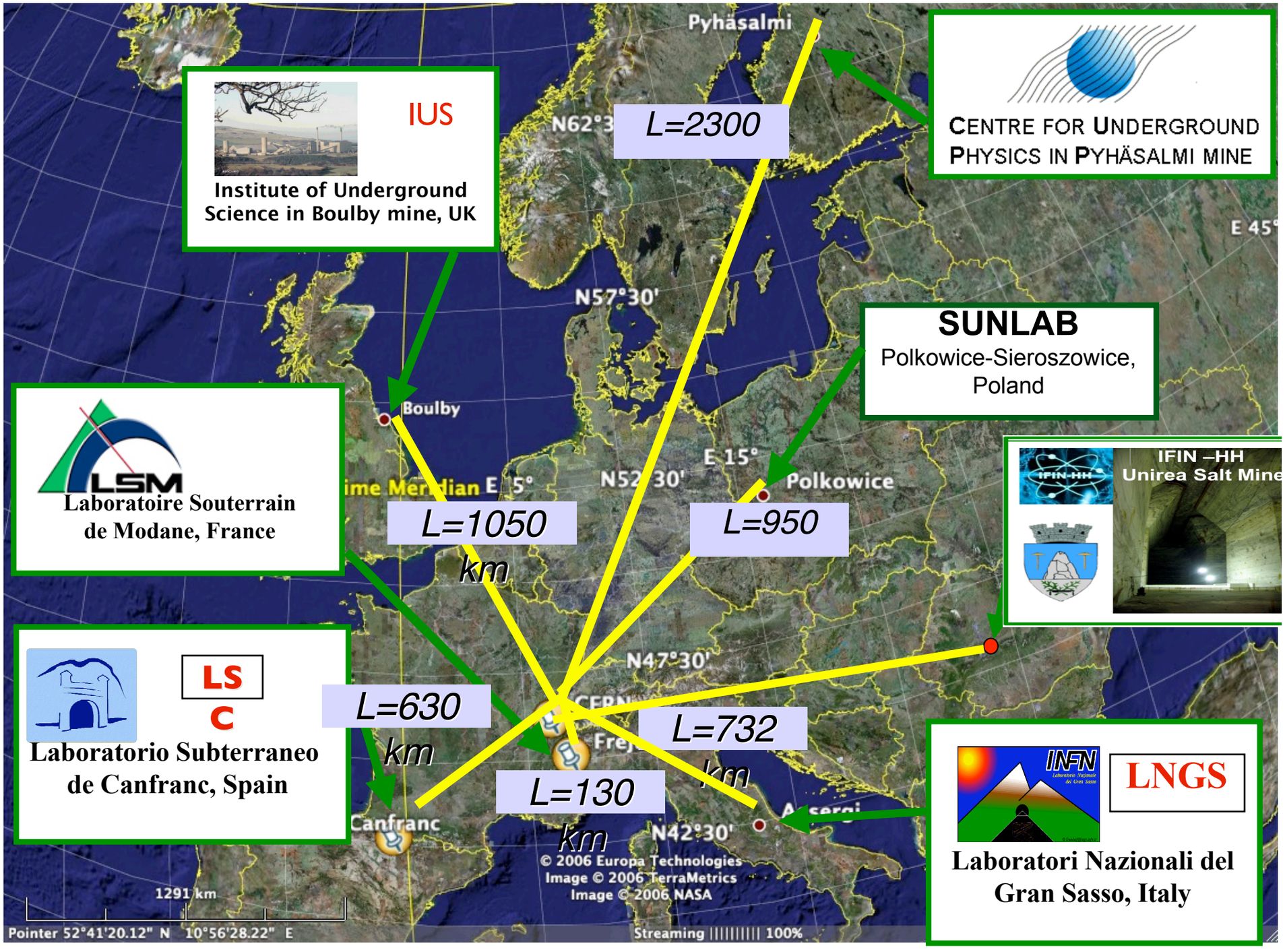


JPARC

Off-axis angle

see Kajita talk:


NOvA
(off-axis)
MINOS (on-axis)
NSF's proposed
Underground Lab.
DUSEL
Lead, SD
735 km
1300 km
Huge Detector
(LAr or/and Water)
= Proton Decay Detector
MiniBooNE
SciBooNE
MINERvA
Powerful Beam
(Project X)
North Dakota
Minnesota
South Dakota
Ontario
Wisconsin
Michigan
Milwaukee
Chicago
Iowa
Nebraska
Illinois


IUS
Institute of Underground Science in Boulby mine, UK
L=2300
CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE
Pyhäsalmi
SUNLAB
Polkowice-Sieroszowice, Poland
Boulby
Polkowice
L=1050 km
L=950
LSM
Laboratoire Souterrain de Modane, France
IFIN –HH
Unirea Salt Mine
LS C
Laboratorio Subterraneo de Canfranc, Spain
L=630 km
L=732 km
L=130 km
Canfranc
LNGS
Laboratori Nazionali del Gran Sasso, Italy
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1291 km
Pointer 52°41'20.12" N 10°56'28.22" E
Streaming 100%

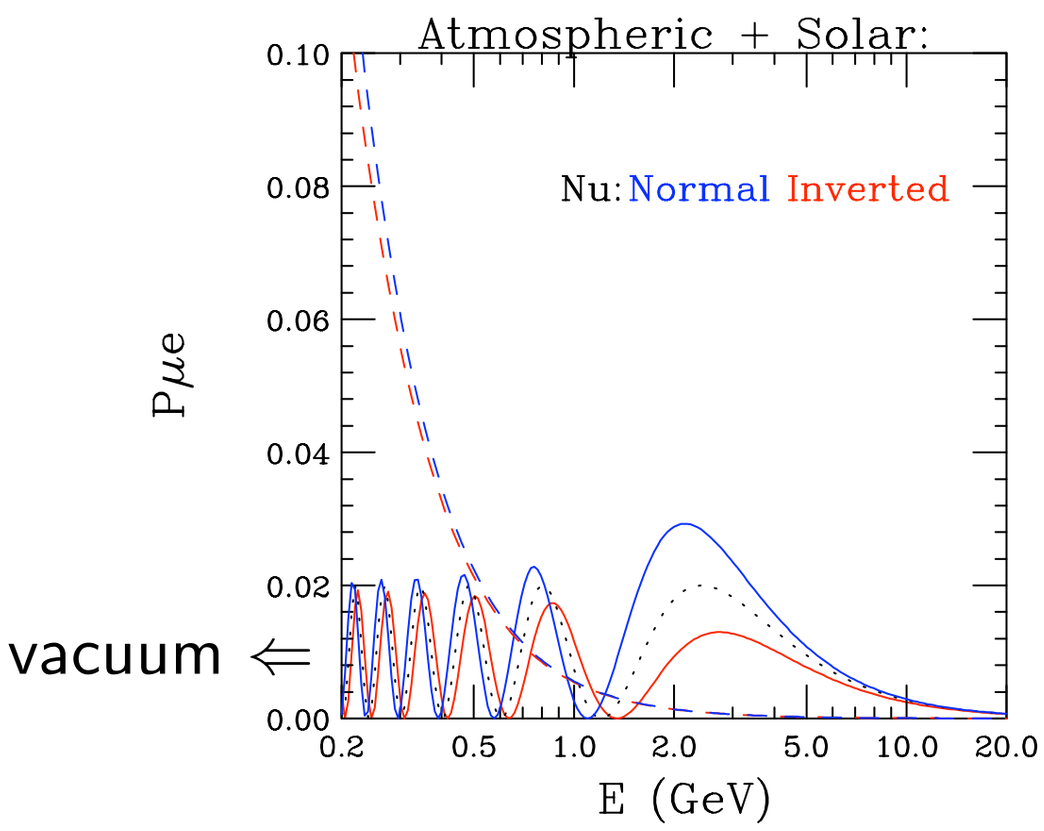
Narrow Band Beam: Same E, Longer L T2KK

Broadband Beam: Same L, Lower E Fermilab to DUSEL

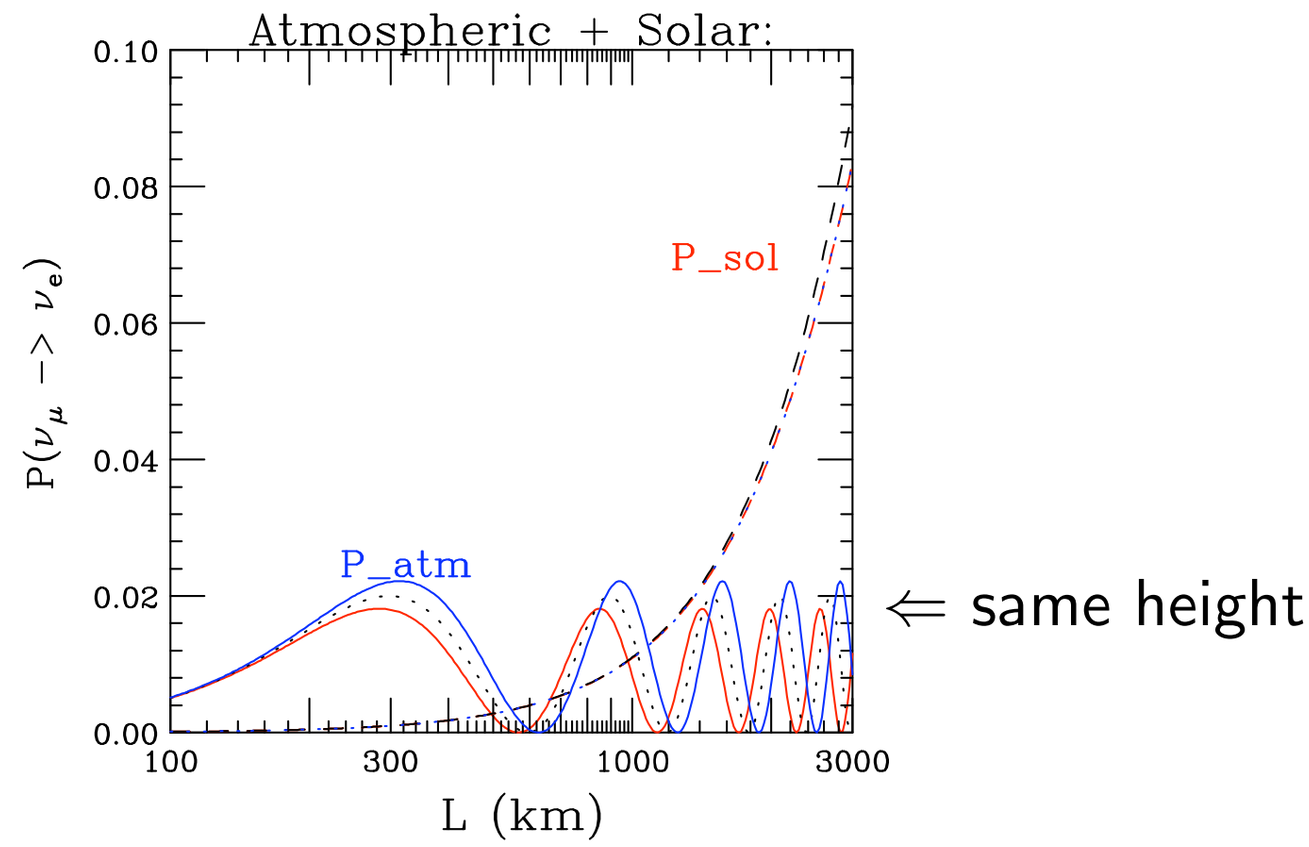
In VACUUM the SAME but NOT in MATTER

$$\sin^2 2\theta_{13} = 0.04$$

L=1200km



E=0.6 GeV

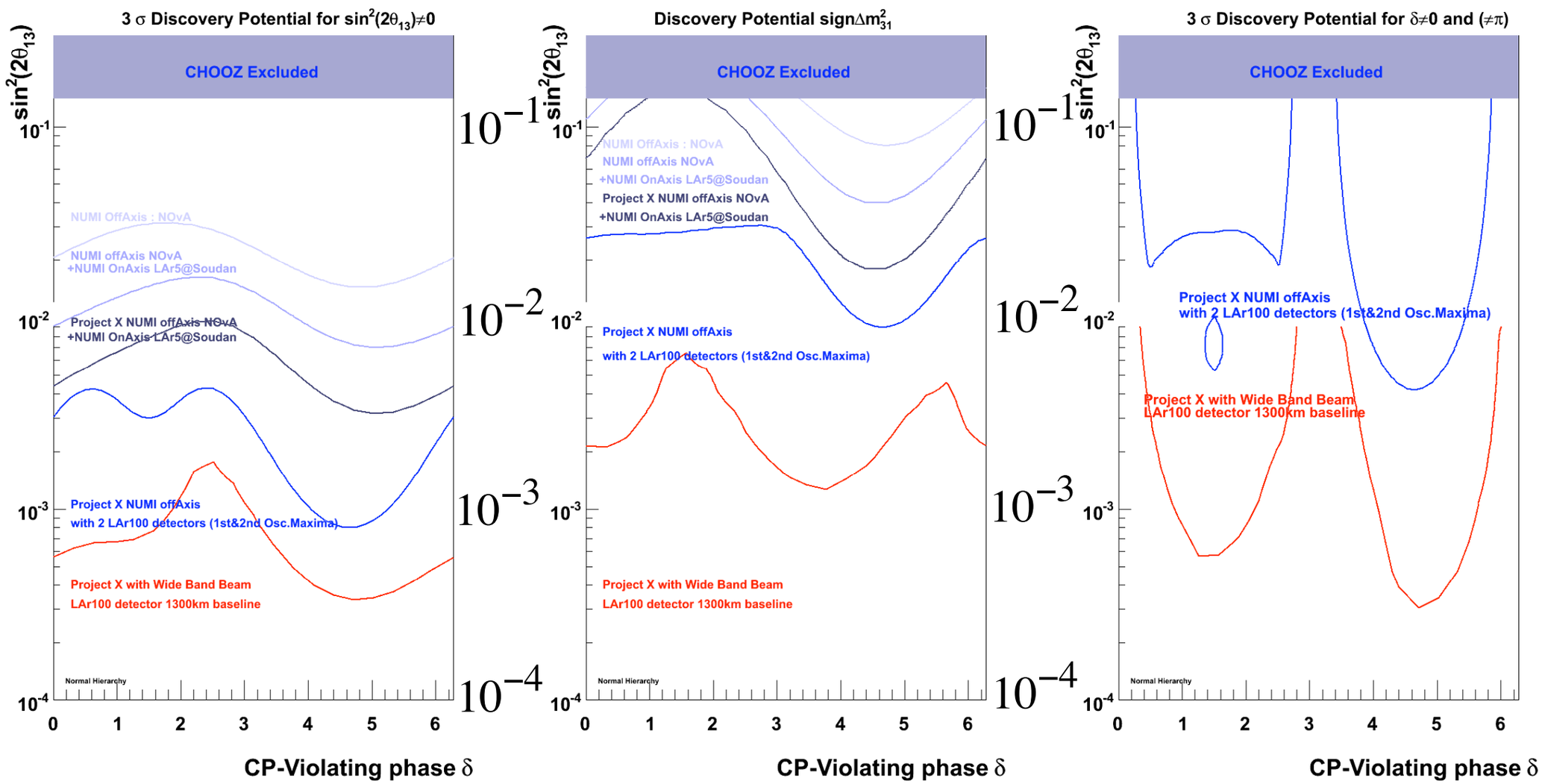


$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

Fermilab to DUSEL (T2KK similar)

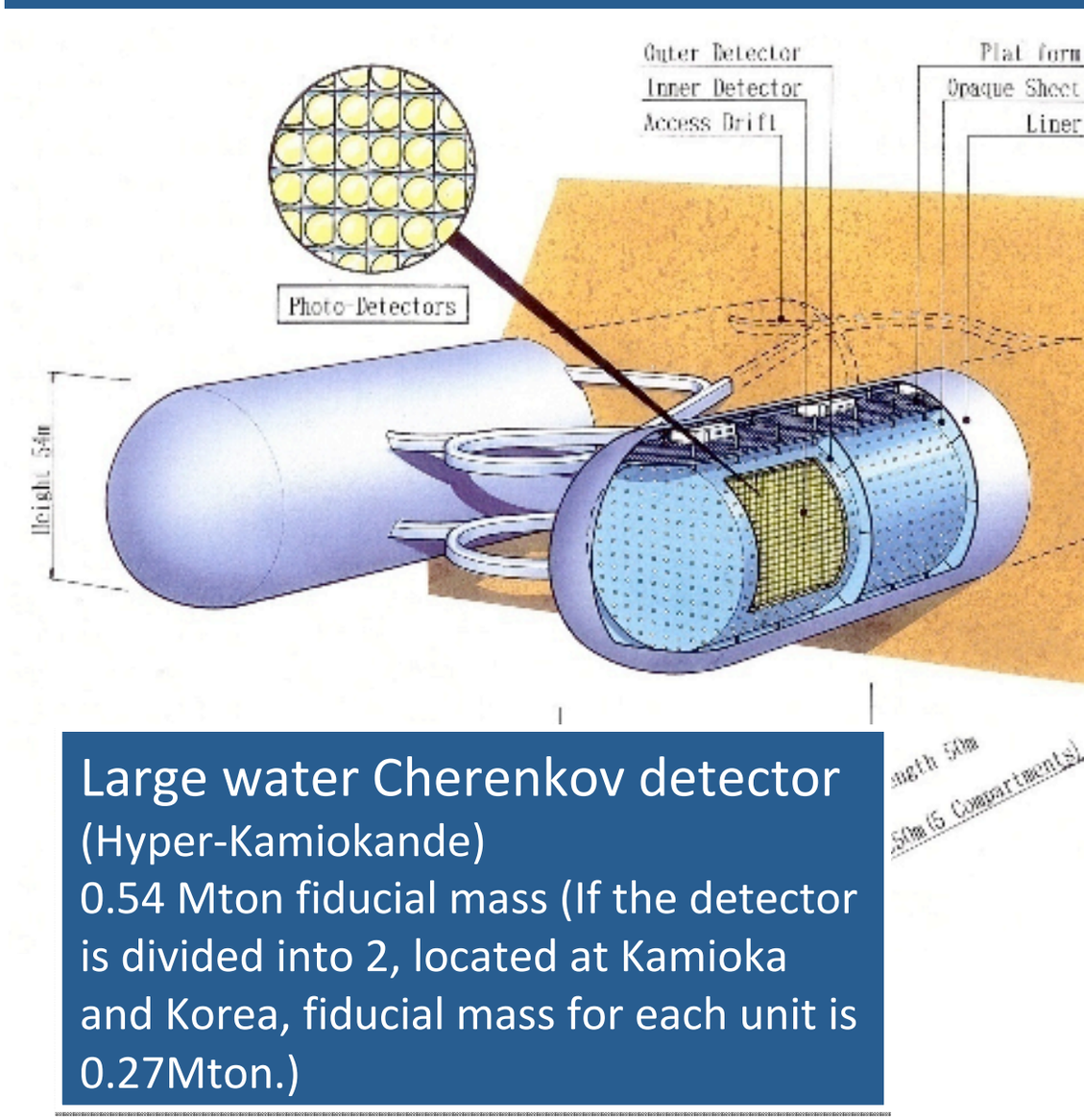
The 3σ Reach of the Successive Phases

$\sin^2 2\theta_{13}$ | Mass Ordering | CP Violation

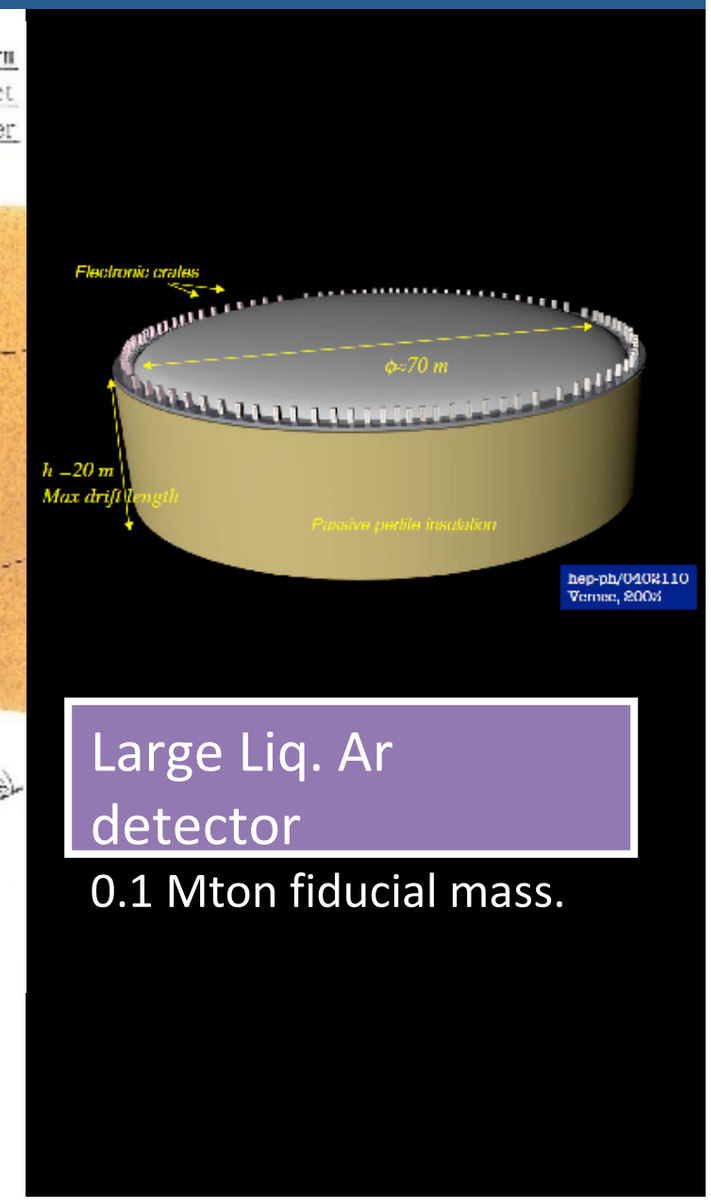


N. Saoulidou

Possible detector options…

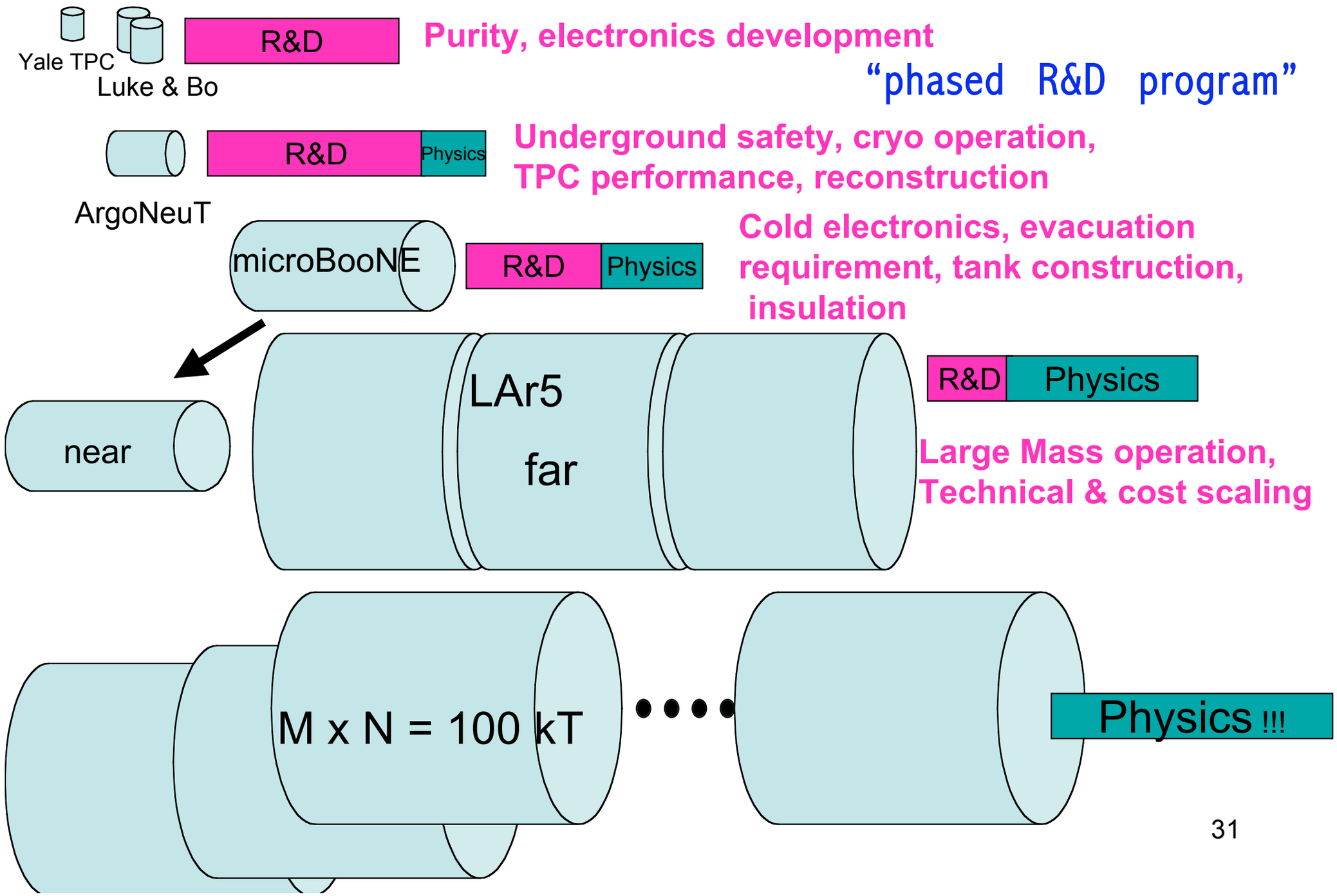


Large water Cherenkov detector
(Hyper-Kamiokande)
0.54 Mton fiducial mass (If the detector is divided into 2, located at Kamioka and Korea, fiducial mass for each unit is 0.27Mton.)



Large Liq. Ar detector
0.1 Mton fiducial mass.

Evolution of the Liquid Argon Physics Program



Proton Decay:

$p \rightarrow \pi^0 e^+$

Water Cherenkov (500 kt) ~ 10^{35} y (5000 kt y exposure)

Limit SK-I and II: t > 8.4×10^{33} y

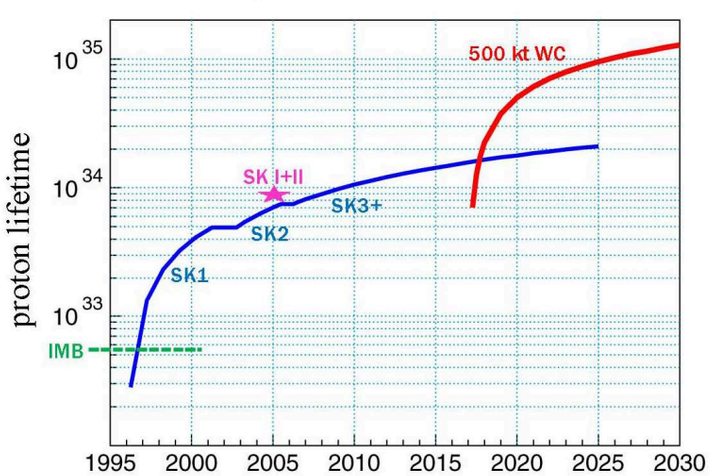
$p \rightarrow K^+ \bar{\nu}$

Liquid Argon (100kt) ~ 10^{35} y (1000 kt y exposure)

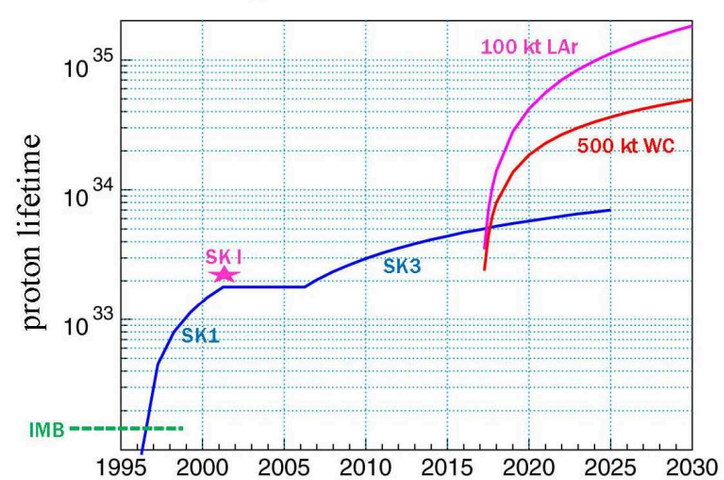
Liquid Scintillator (50kt) 5 x 10^{34} y (500 kt y exposure)

Limit SK-I: t > 2.3×10^{32} y

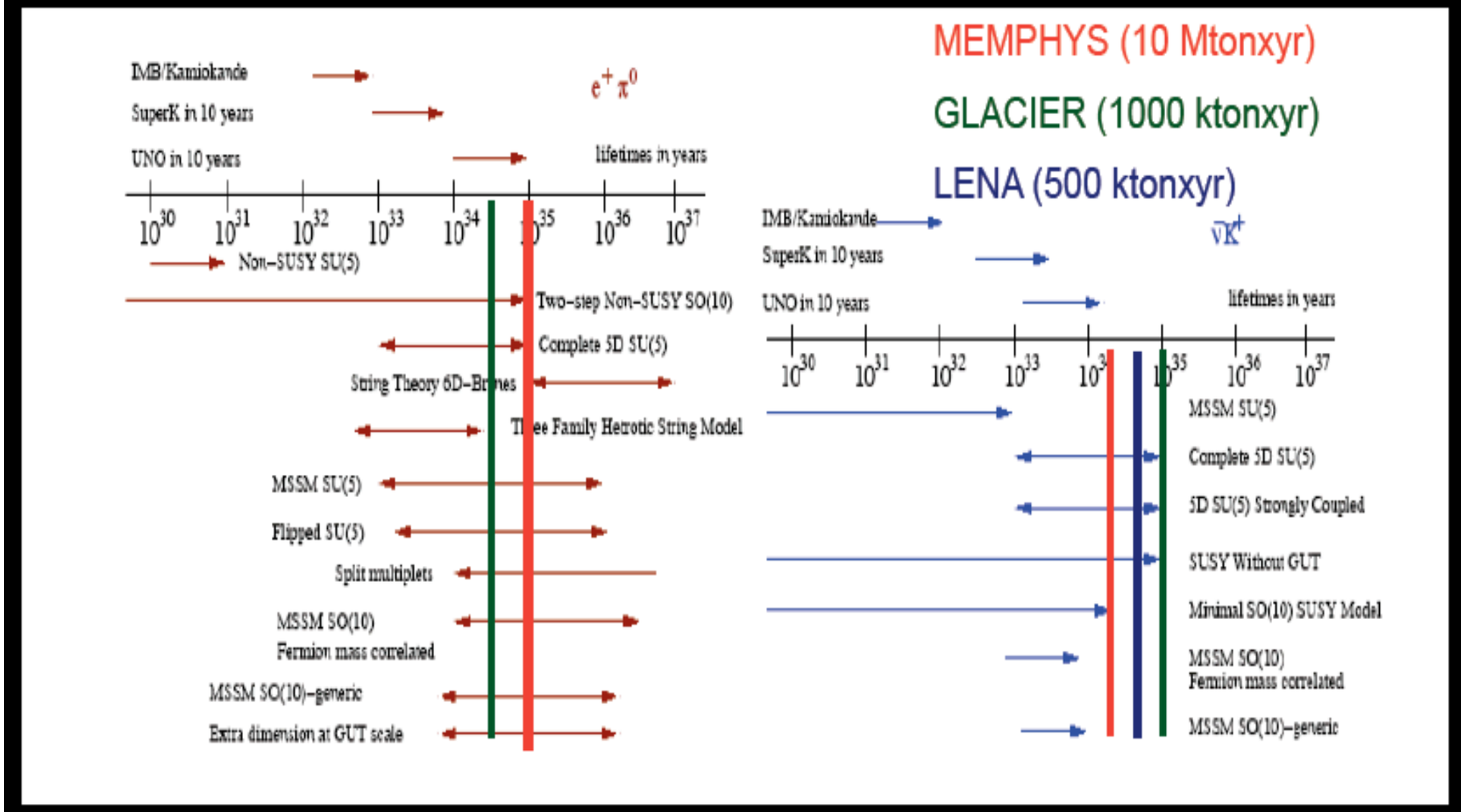
$p \rightarrow e^+ \pi^0$



$p \rightarrow K^+ \nu$



Sensitivity to proton decay: comparison with theory



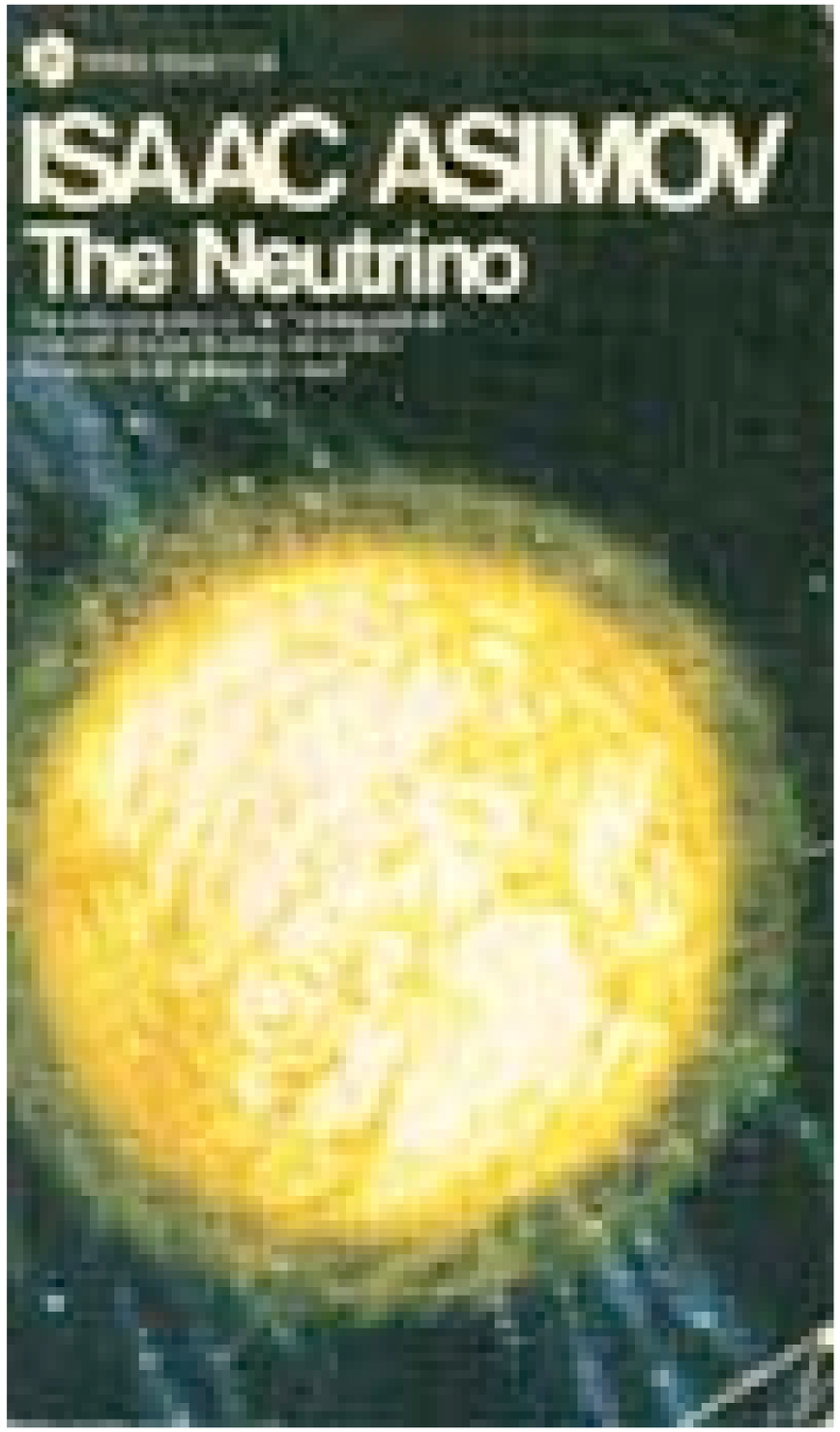
Higher dimension models (eg. 6D SO(10)) not included

LAGUNA

SUPERNOVA:

1987a Feb 24

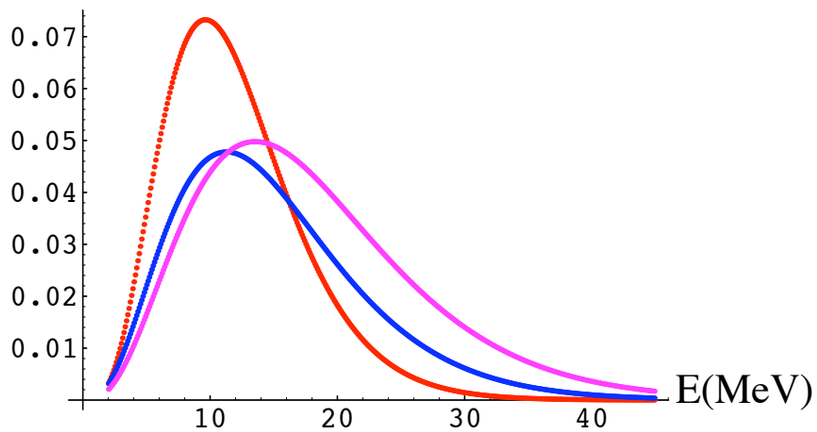
1966



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

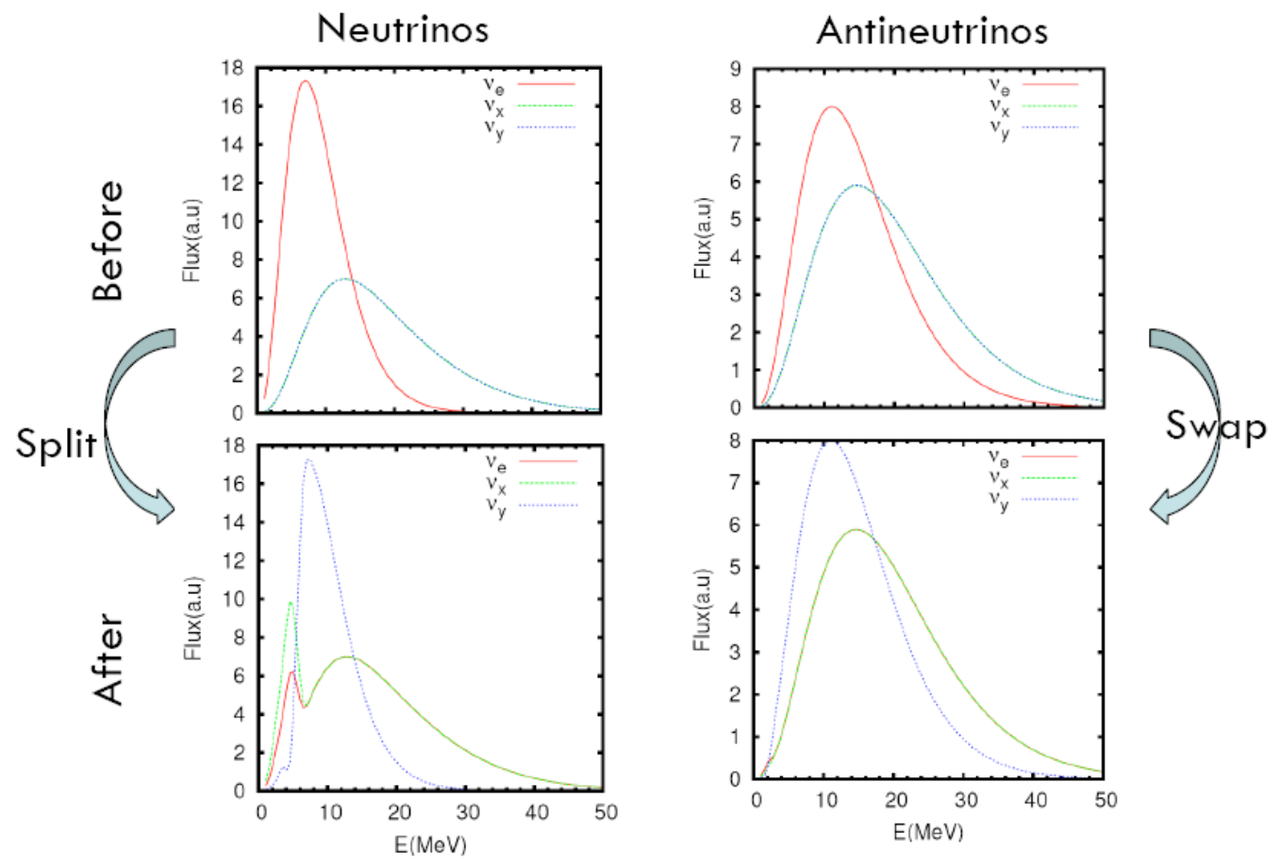
We are "due" for a supernova anytime now we can only hope that it will hold off until the science of neutrino astronomy is further advanced.

Neutrino fluxes:



$E_0(\nu_e) \approx$ 10–12 MeV
$E_0(\bar{\nu}_e) \approx$ 13–16 MeV
$E_0(\nu_x) \approx$ 15–25 MeV

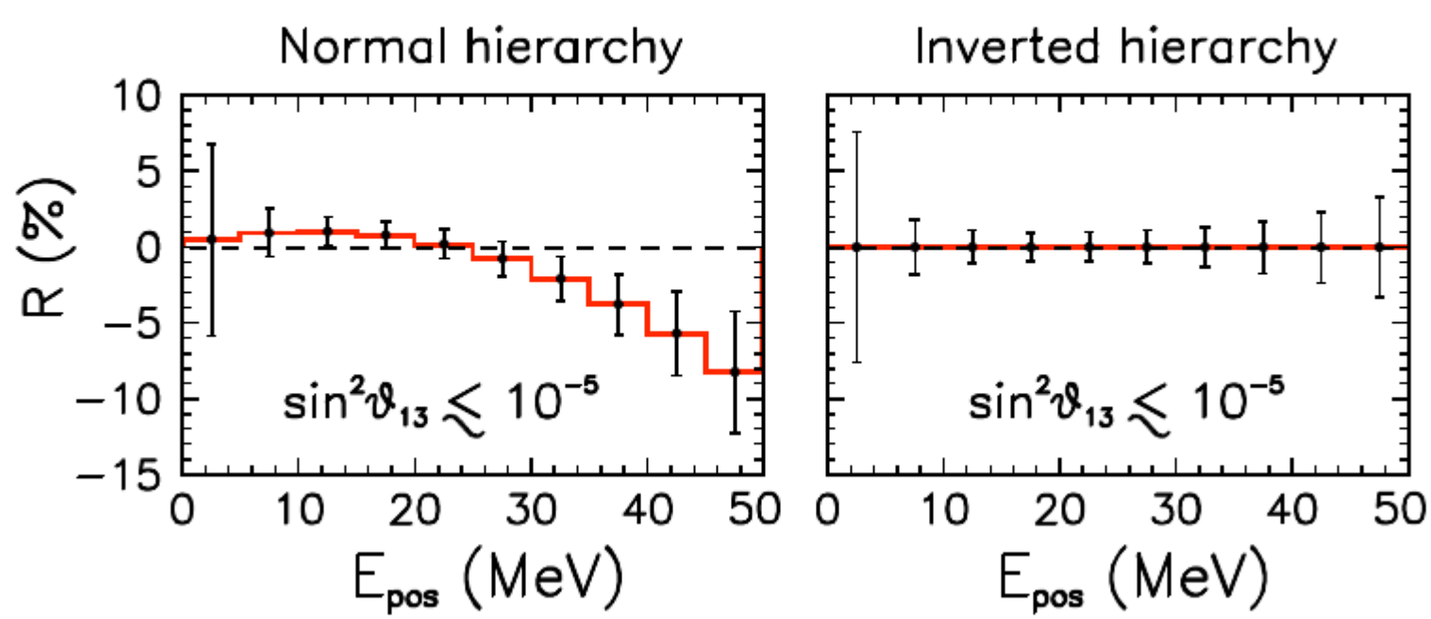
SN spectra reaching Earth



For Inverted Hierarchy

Mass hierarchy at very small θ_{13}

- $R = (N_{Shadowed} - N_{Not\ Shadowed}) / N_{Not\ Shadowed}$.



Conclusions

- A Large Underground Detector is the way forward for:
  - Neutrino Properties
    ($\sin^2\theta_{13}$, sign$\{\delta m^2_{31}\}$, $\sin\delta$, $\sin^2\theta_{23}$, surprises)
  - Proton Decay
    (beyond 10^{35} years in both $p \to \pi^0 e^+$ and $p \to K^+\bar{\nu}$)
  - Supernova Neutrinos
    ($> 10^5$ events for galactic event)
  - Other - solar, atmospheric neutrinos ...
- Both Japan (T2HK, T2KK ...) and Europe (LAGUNA) are exploring similar options.