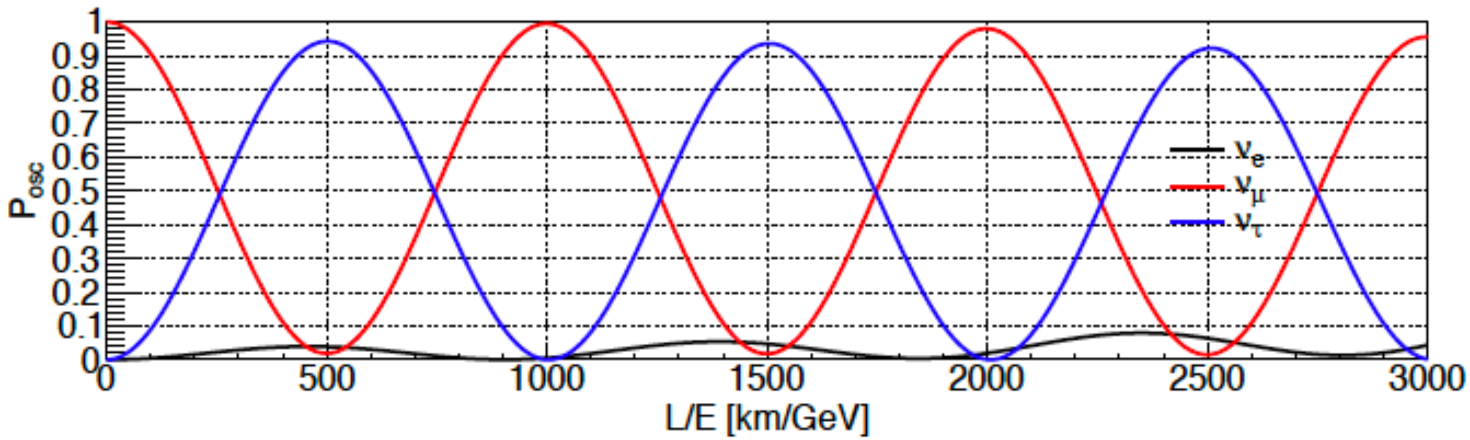
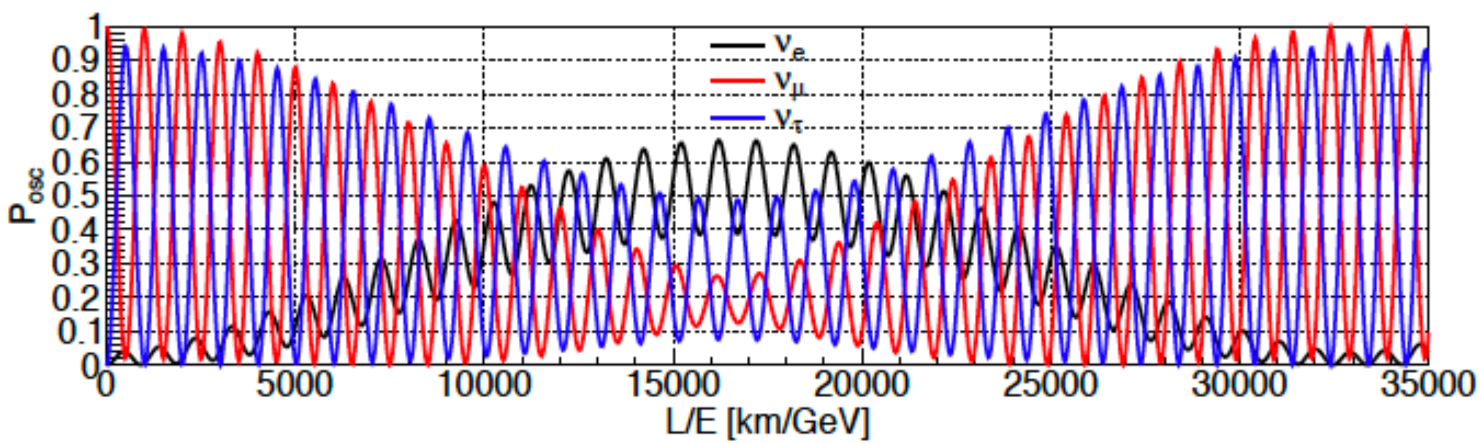
Oscillations in vacuum, starting with muon neutrino

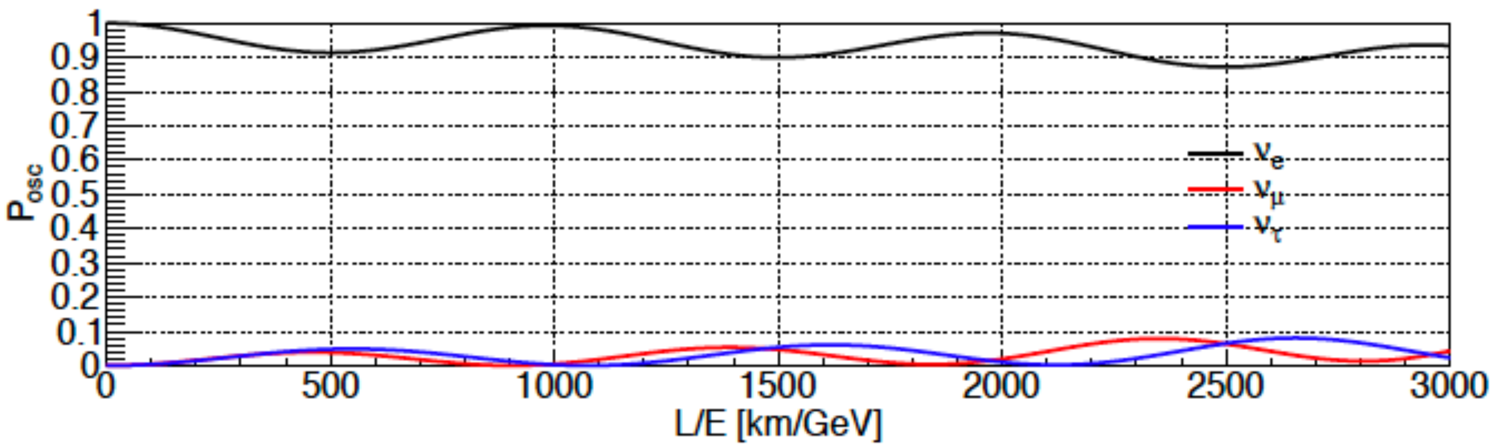


(c) ν_μ, short range

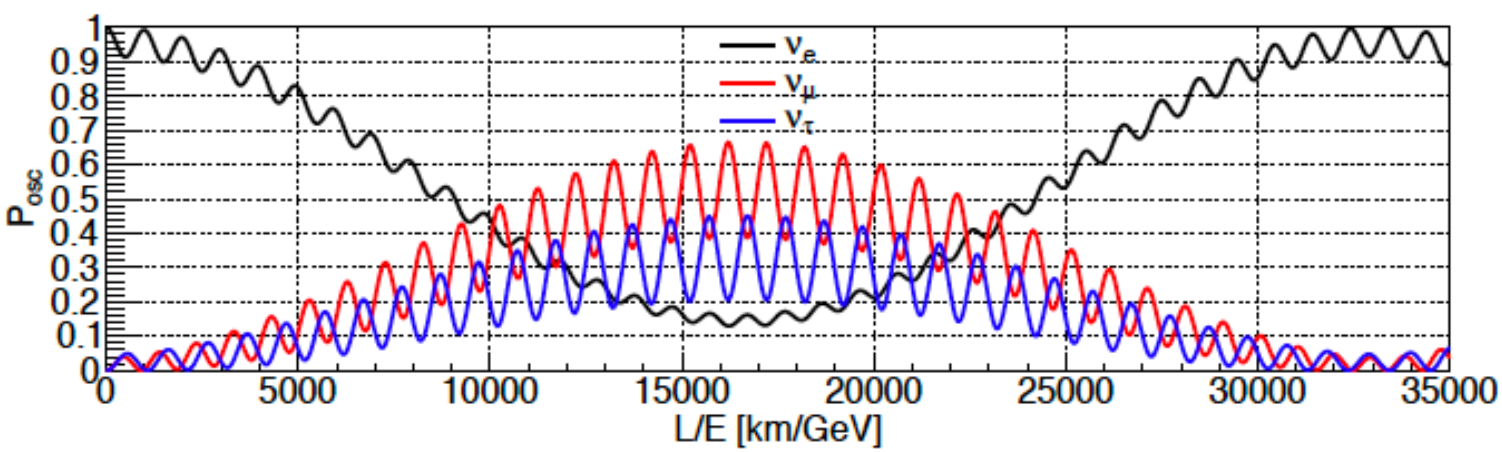


(d) ν_μ, long range

Oscillations in vacuum, starting with electron neutrino



(a) ν_e, short range

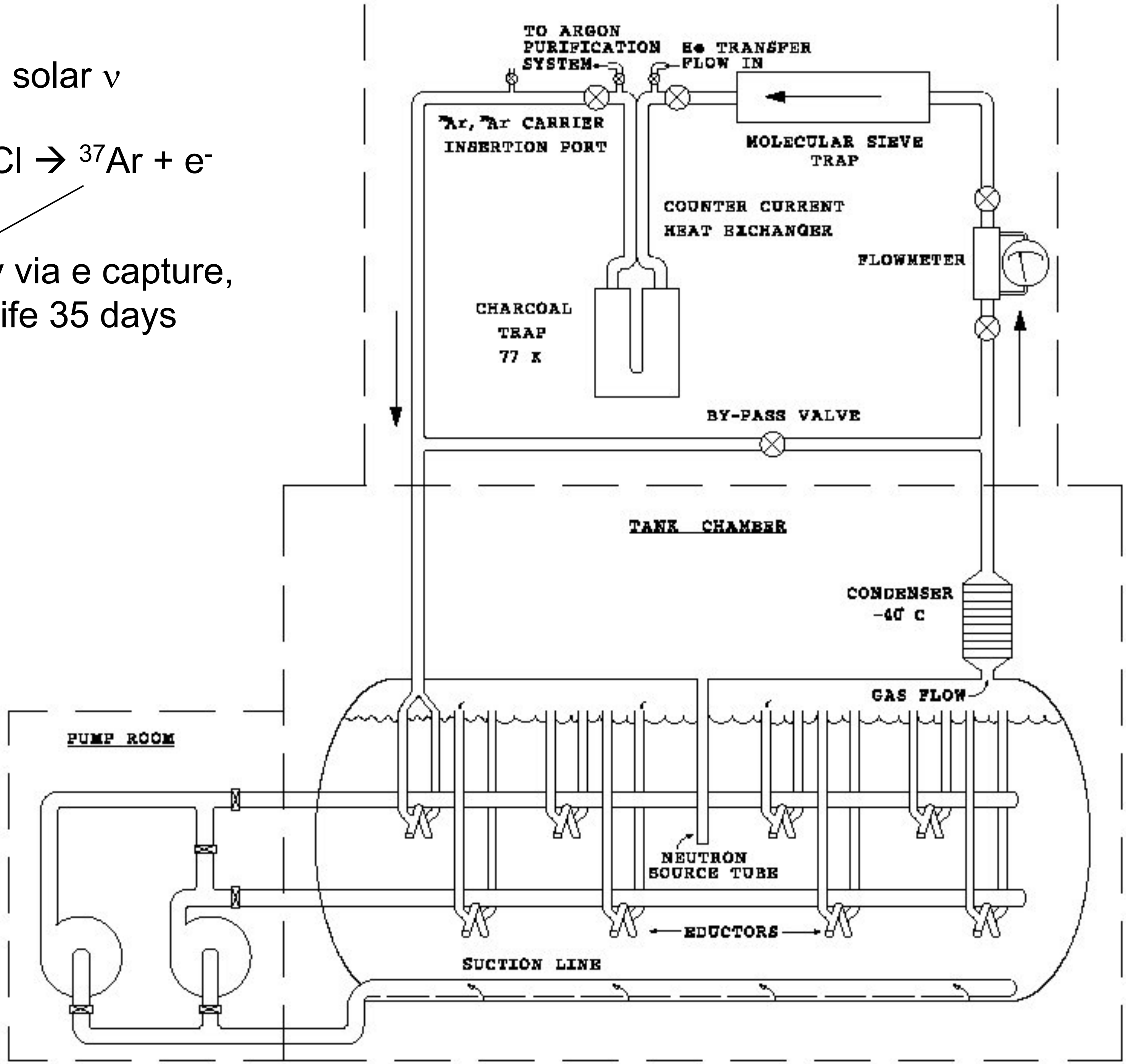


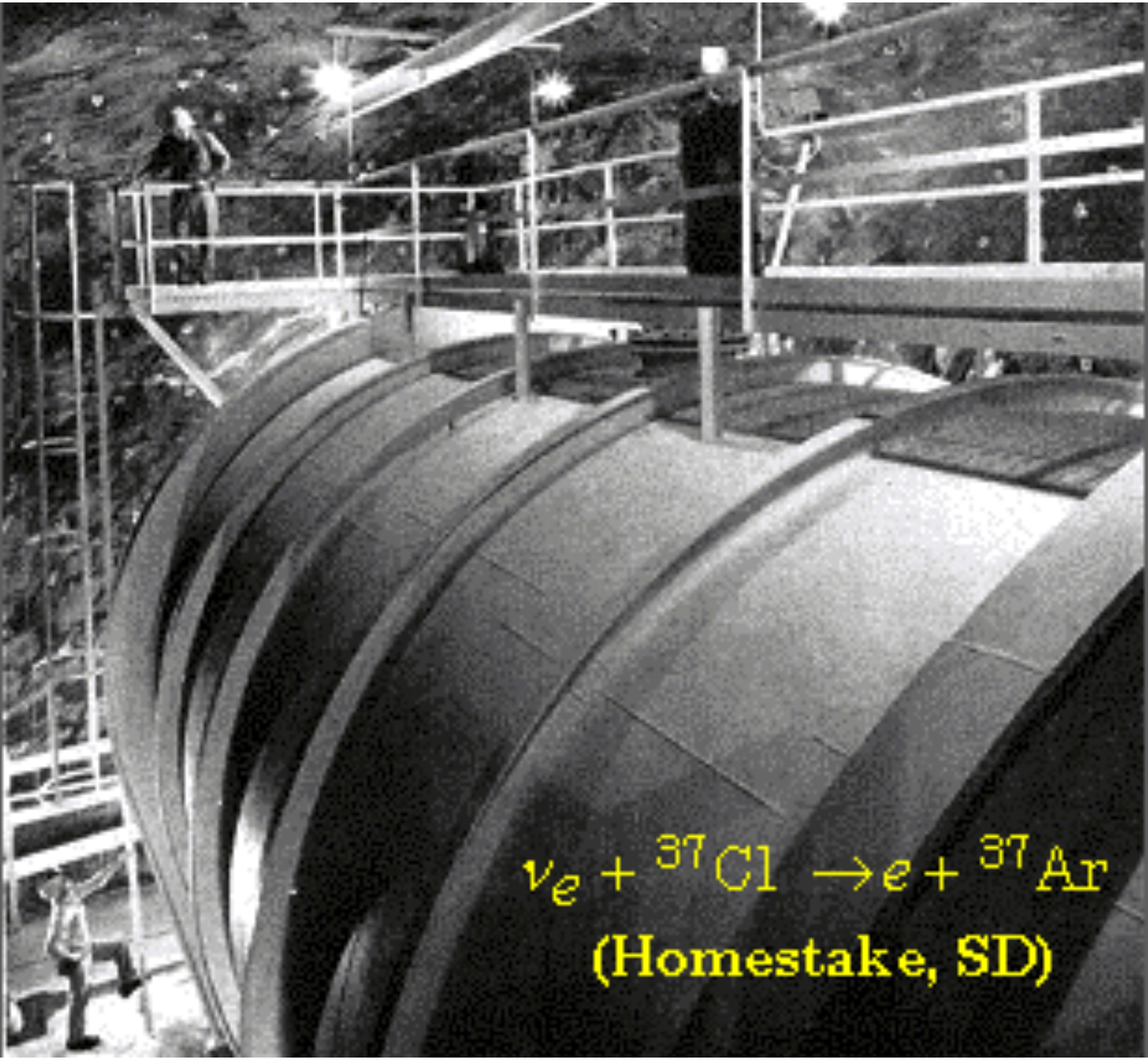
(b) ν_e, long range

Davis, solar ν

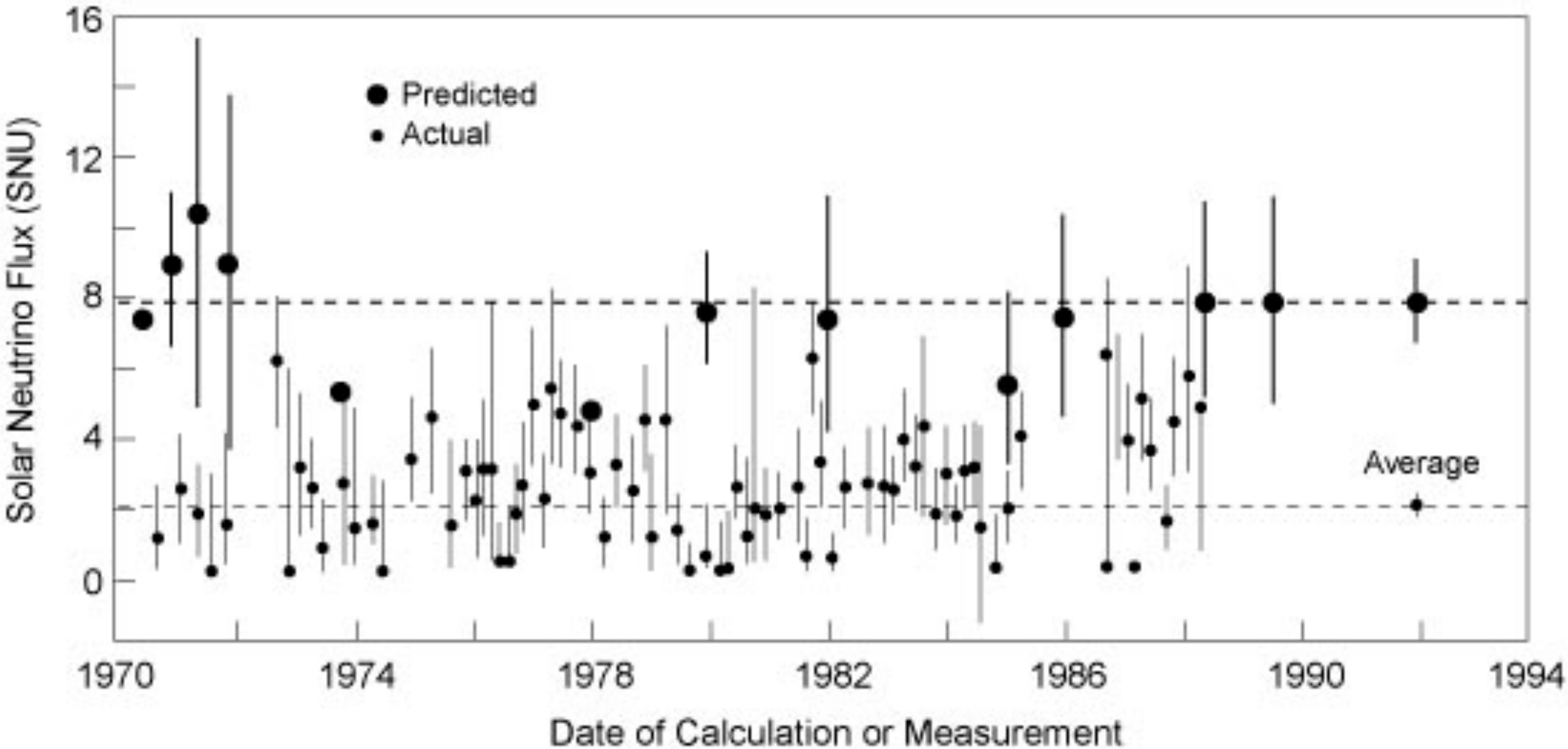
$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Decay via e capture,
half-life 35 days




$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e + {}^{37}\mathrm{Ar}$
(Homestake, SD)

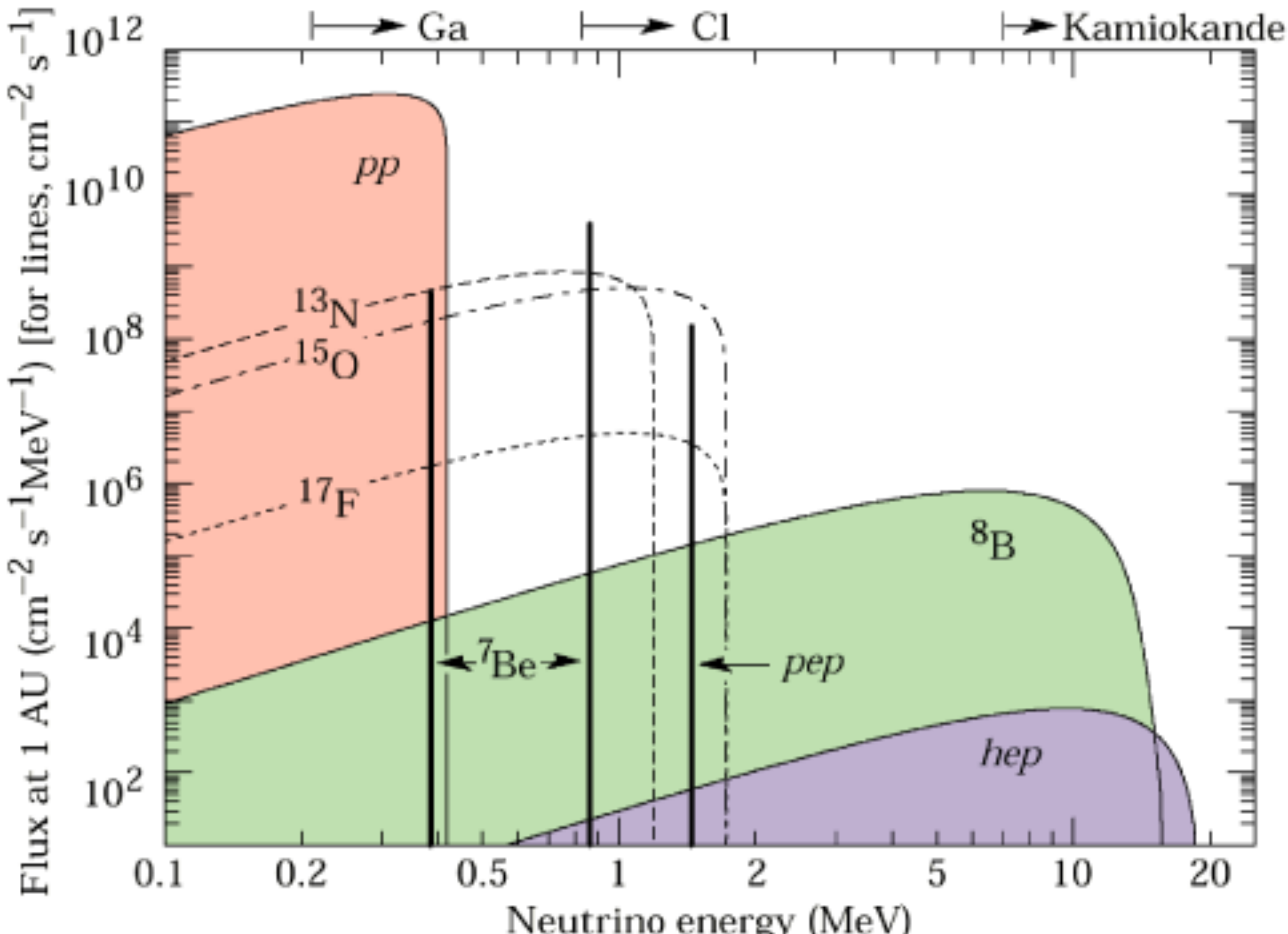
Davis' result:



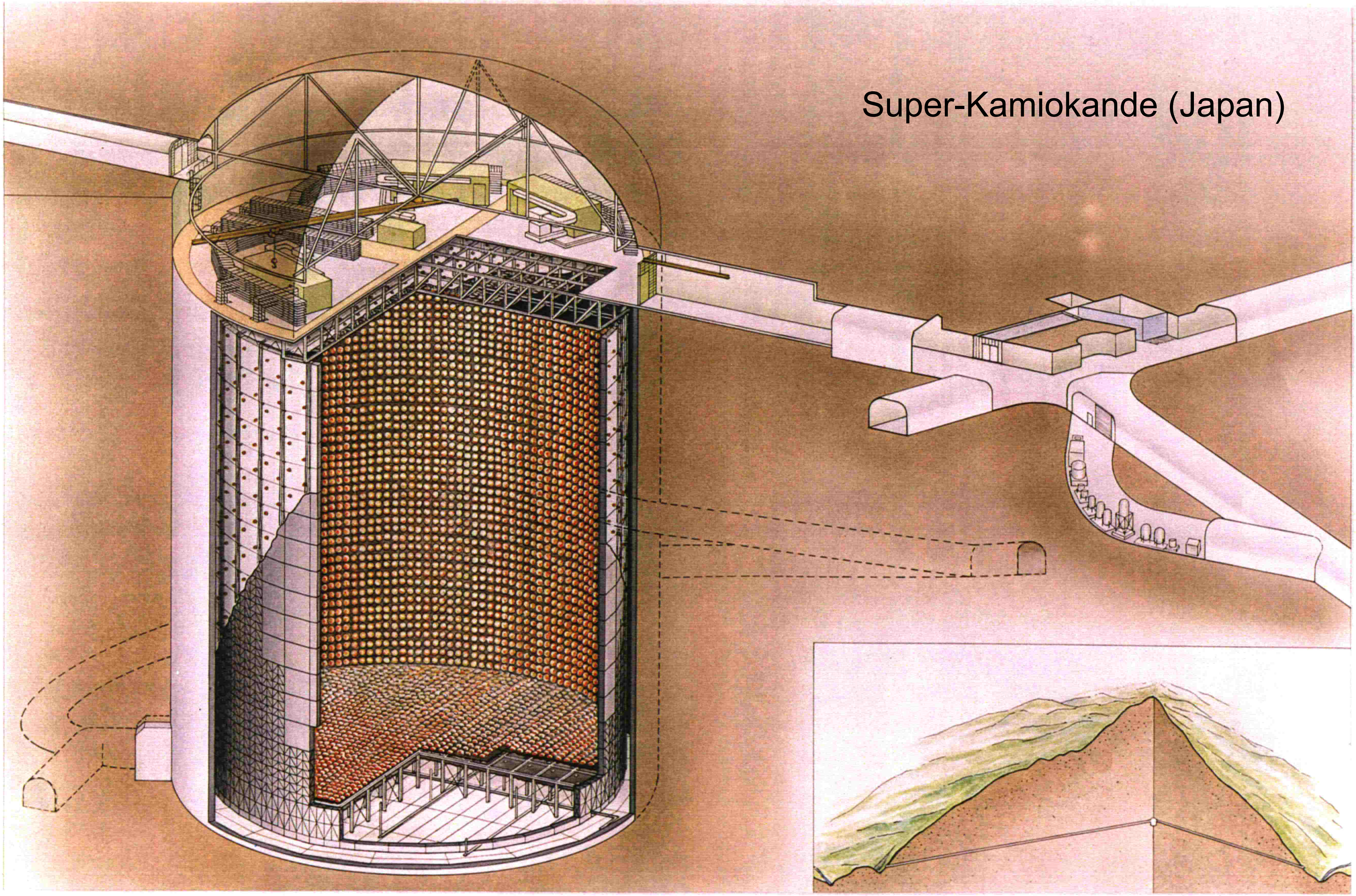
1 SNU = 1 interaction / (10^{36} Cl atoms • s)

→ The sun produces neutrinos, but not nearly enough!

Solar neutrino spectrum



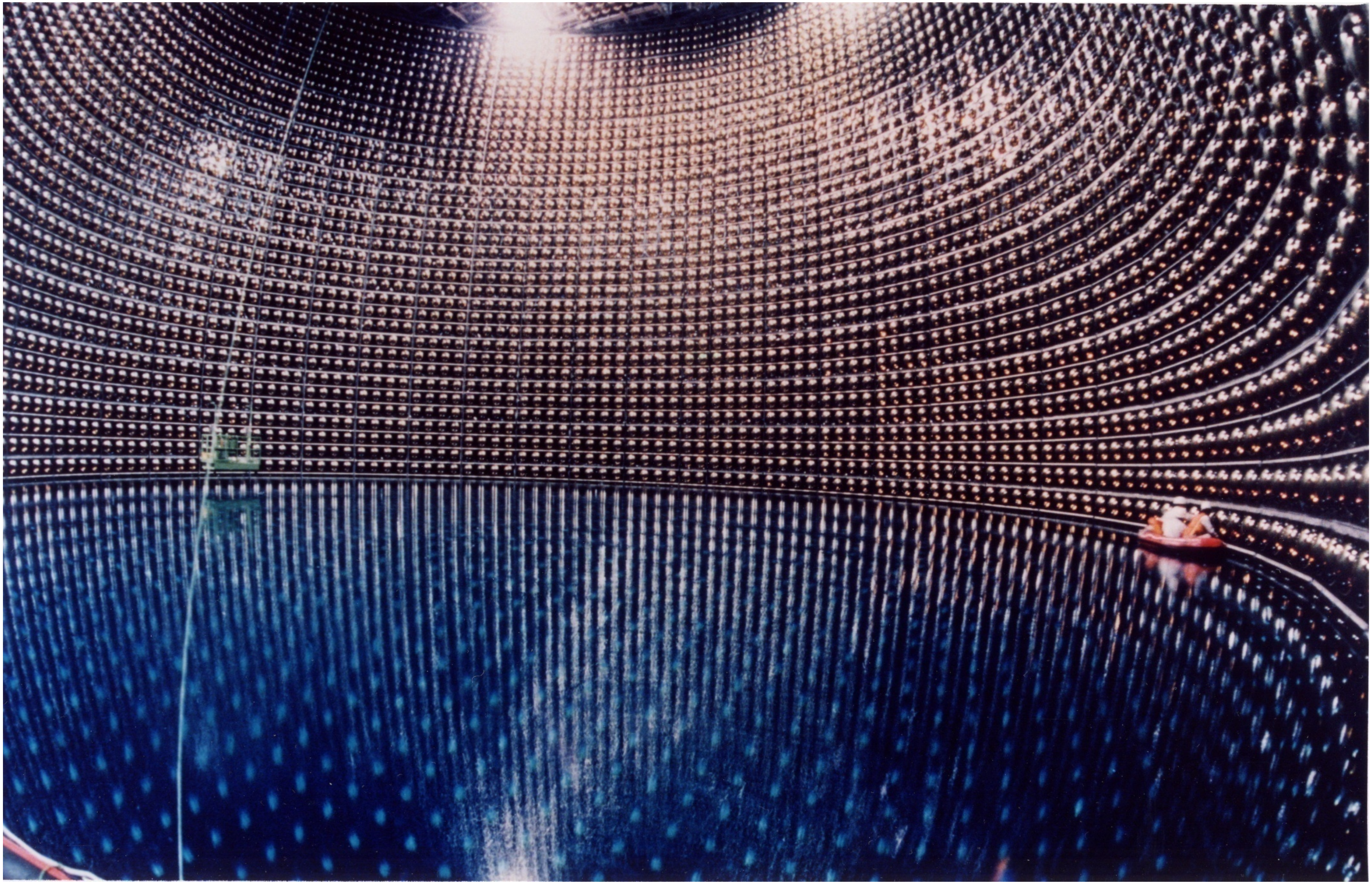
Super-Kamiokande (Japan)



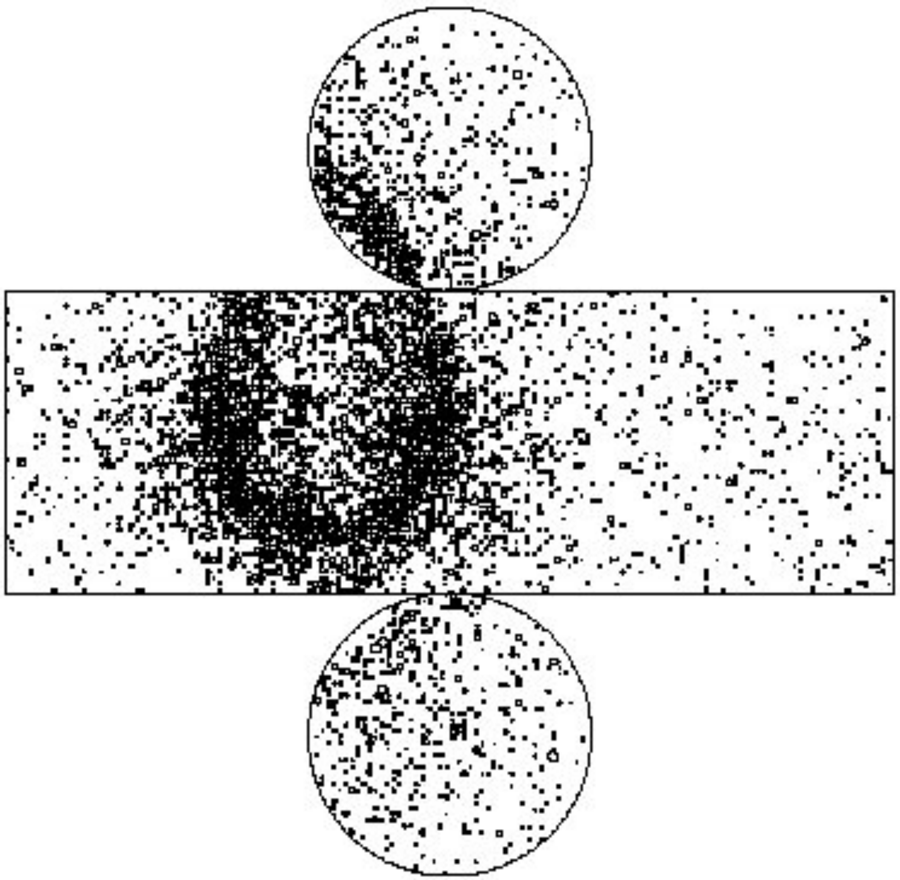
SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKEI
planners | architects | engineers

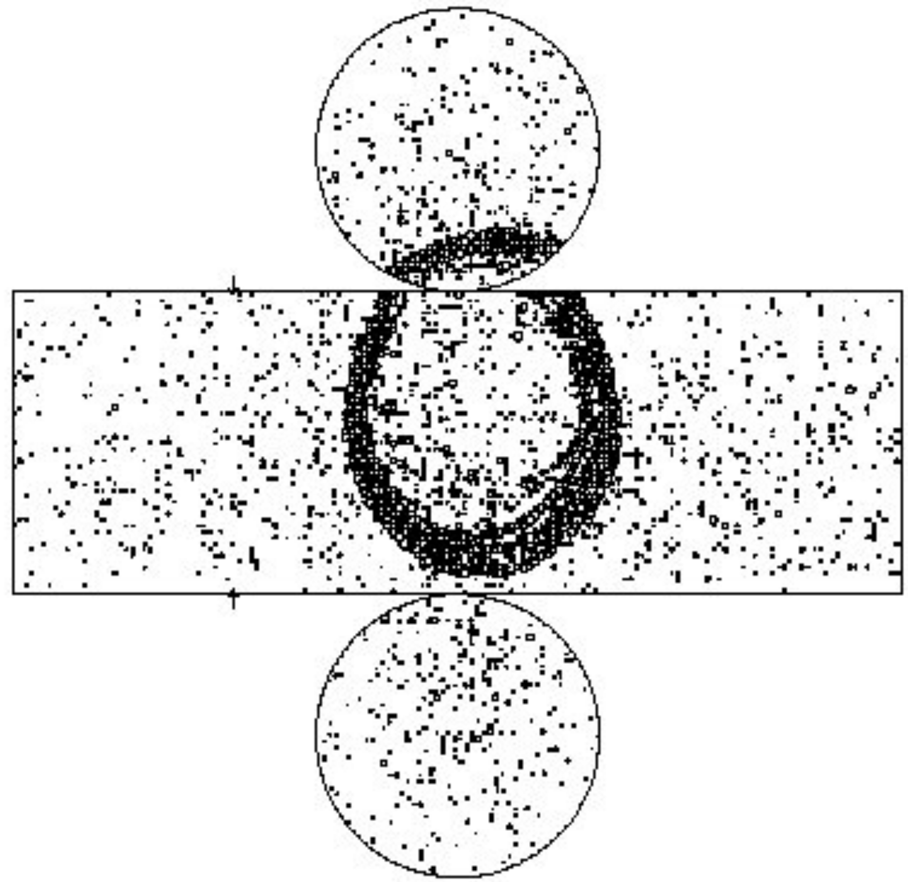
Super-Kamiokande: water Cerenkov detector

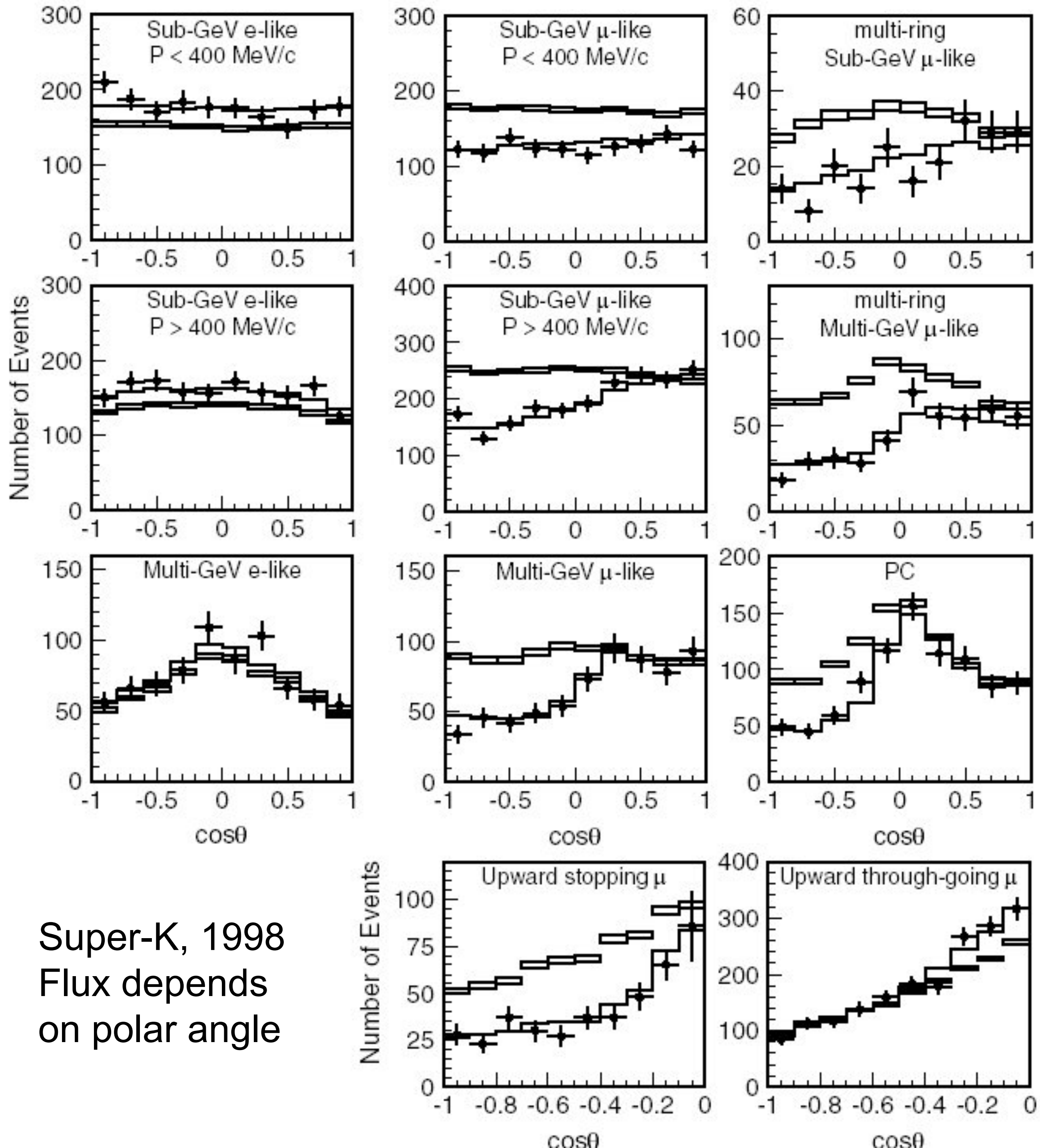


electron



muon



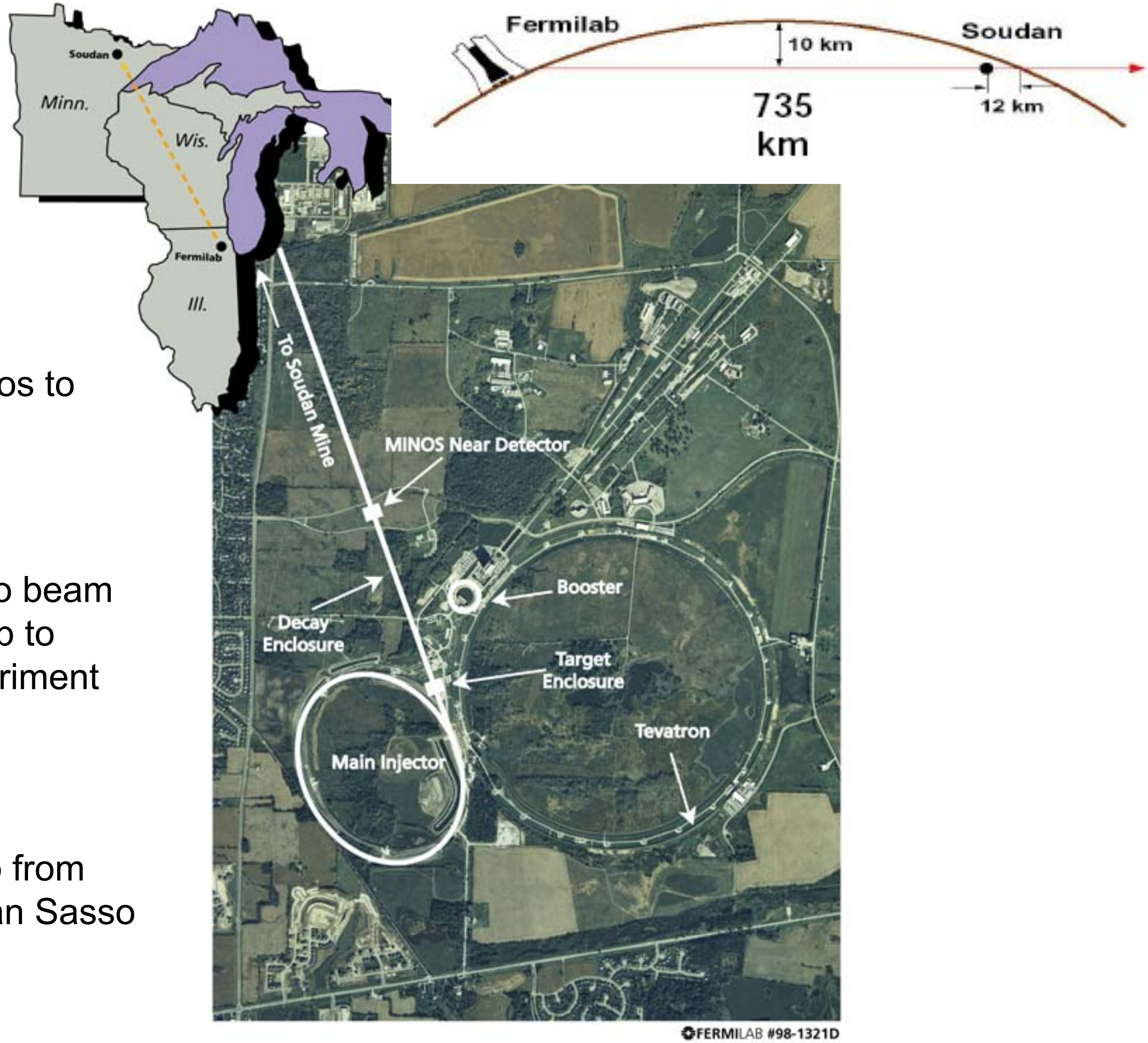


Super-K, 1998
Flux depends
on polar angle

NuMi: neutrinos to Minnesota

Muon neutrino beam from Fermilab to MINOS experiment

Similar set-up from CERN to Gran Sasso

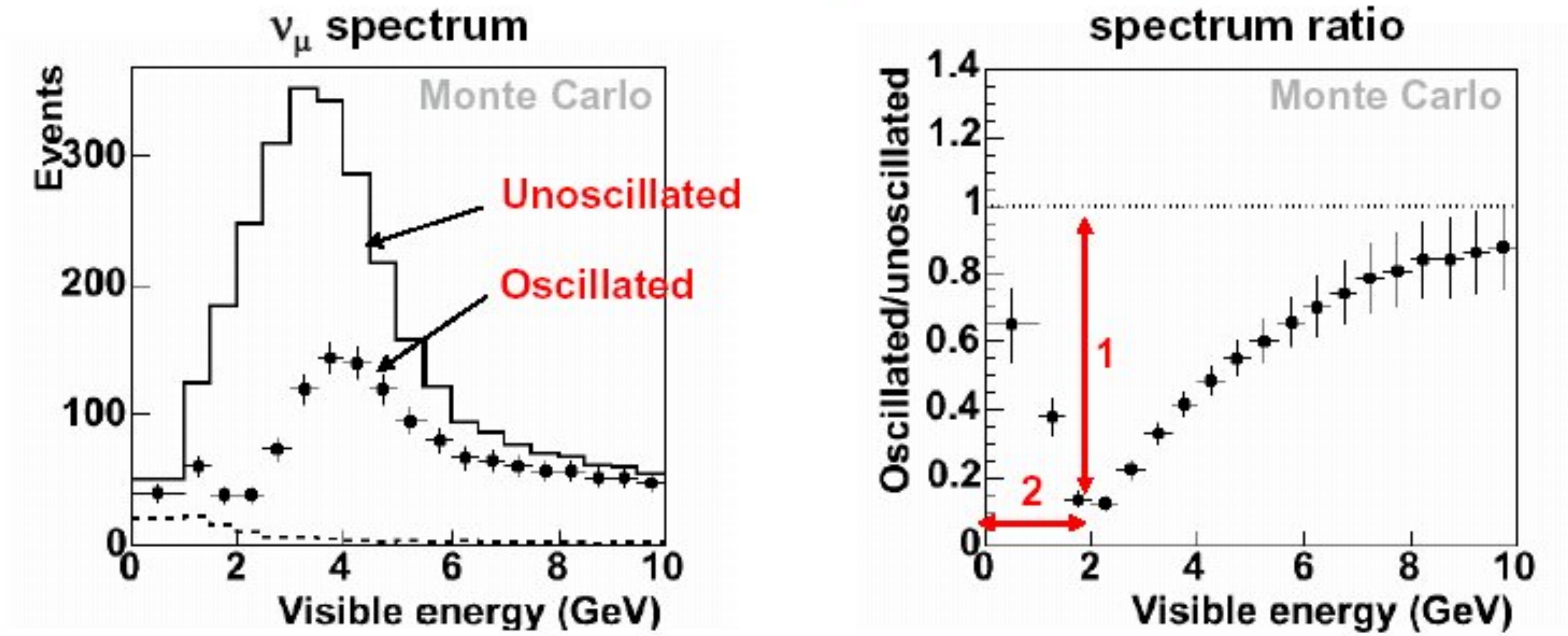


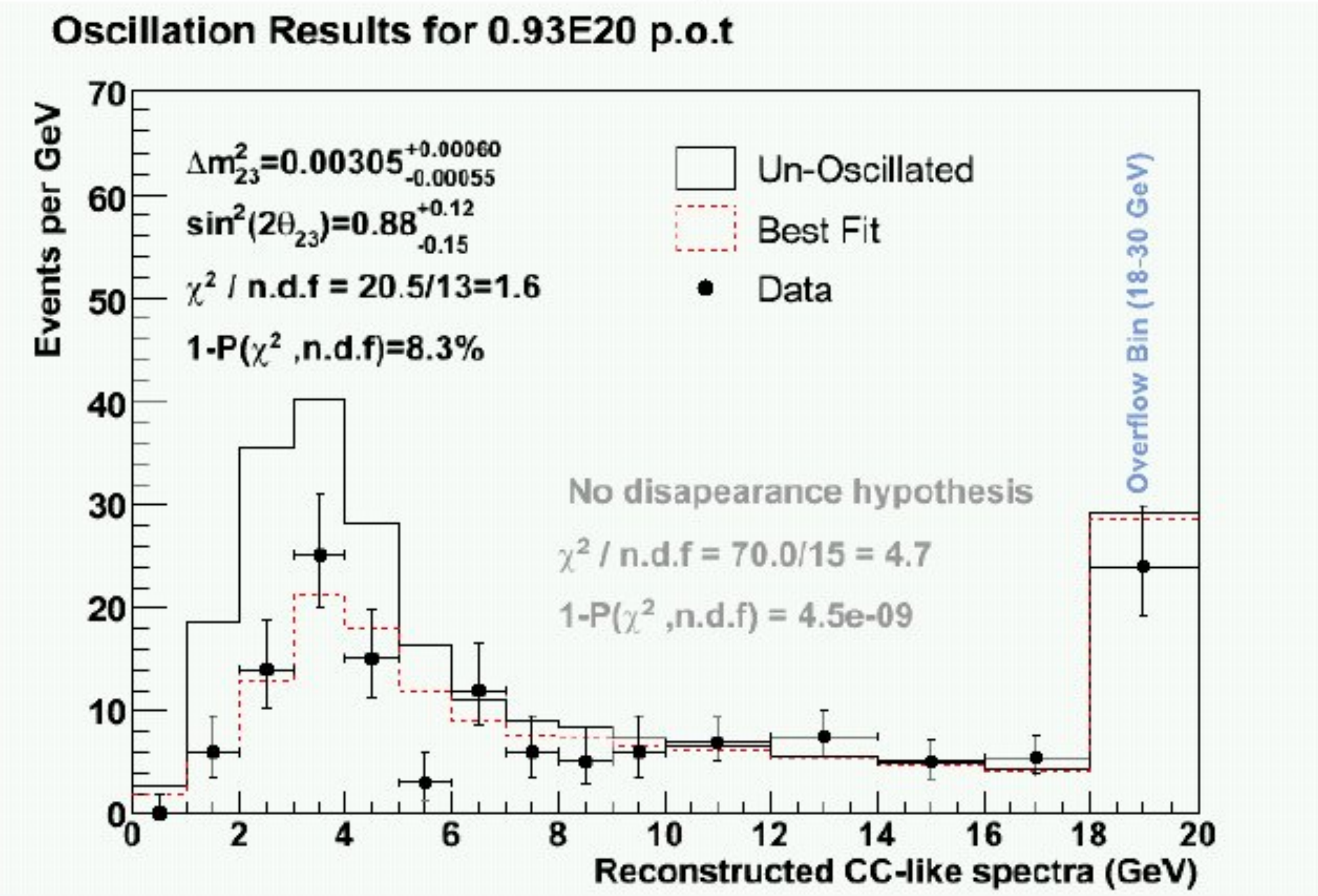
MINOS detector

Example of a ν_μ disappearance measurement

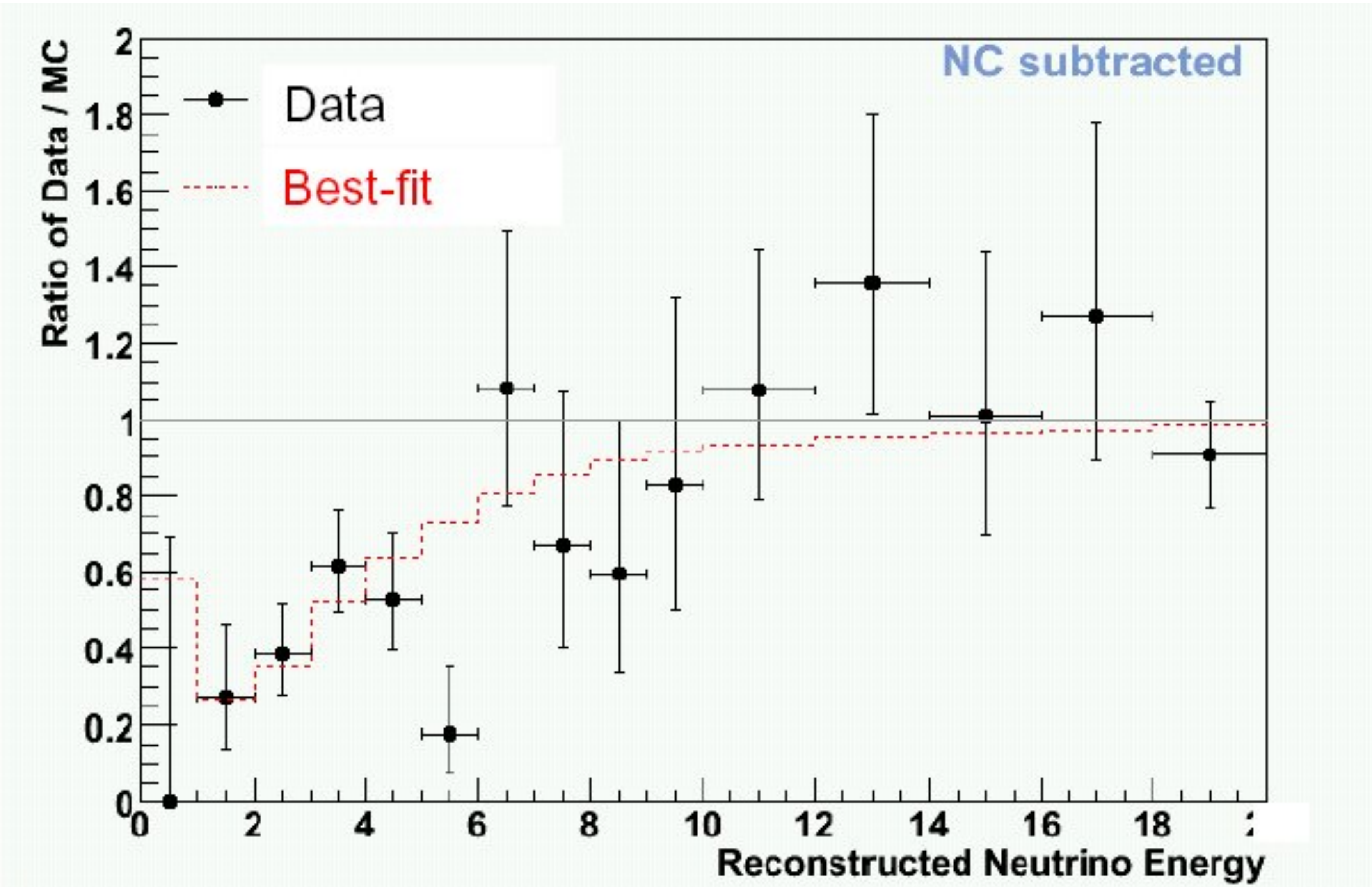
- Look for a deficit of ν_μ events at Soudan…

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta}_{1} \sin^2(1.267 \underbrace{\Delta m^2}_{2} L/E)$$

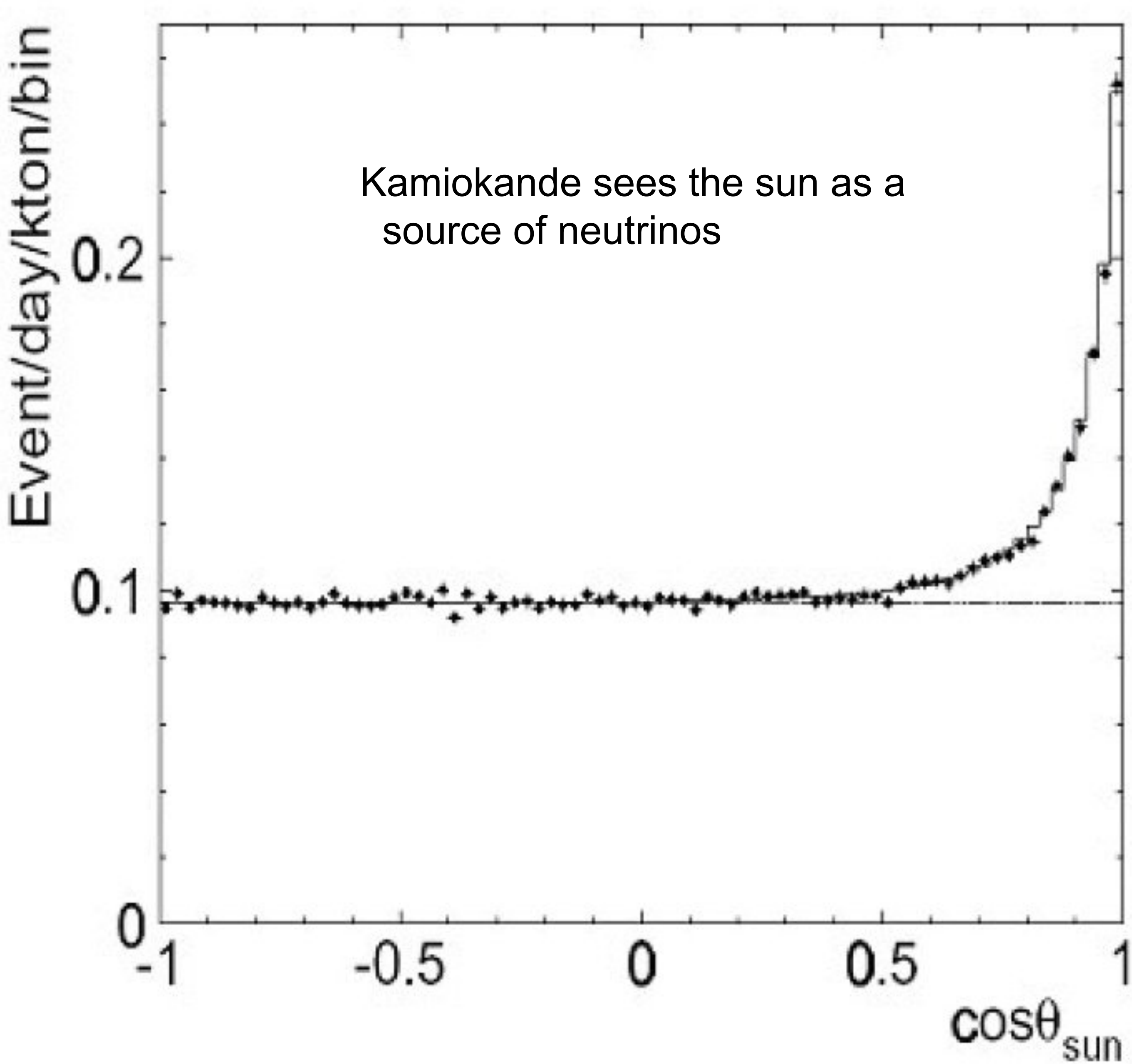


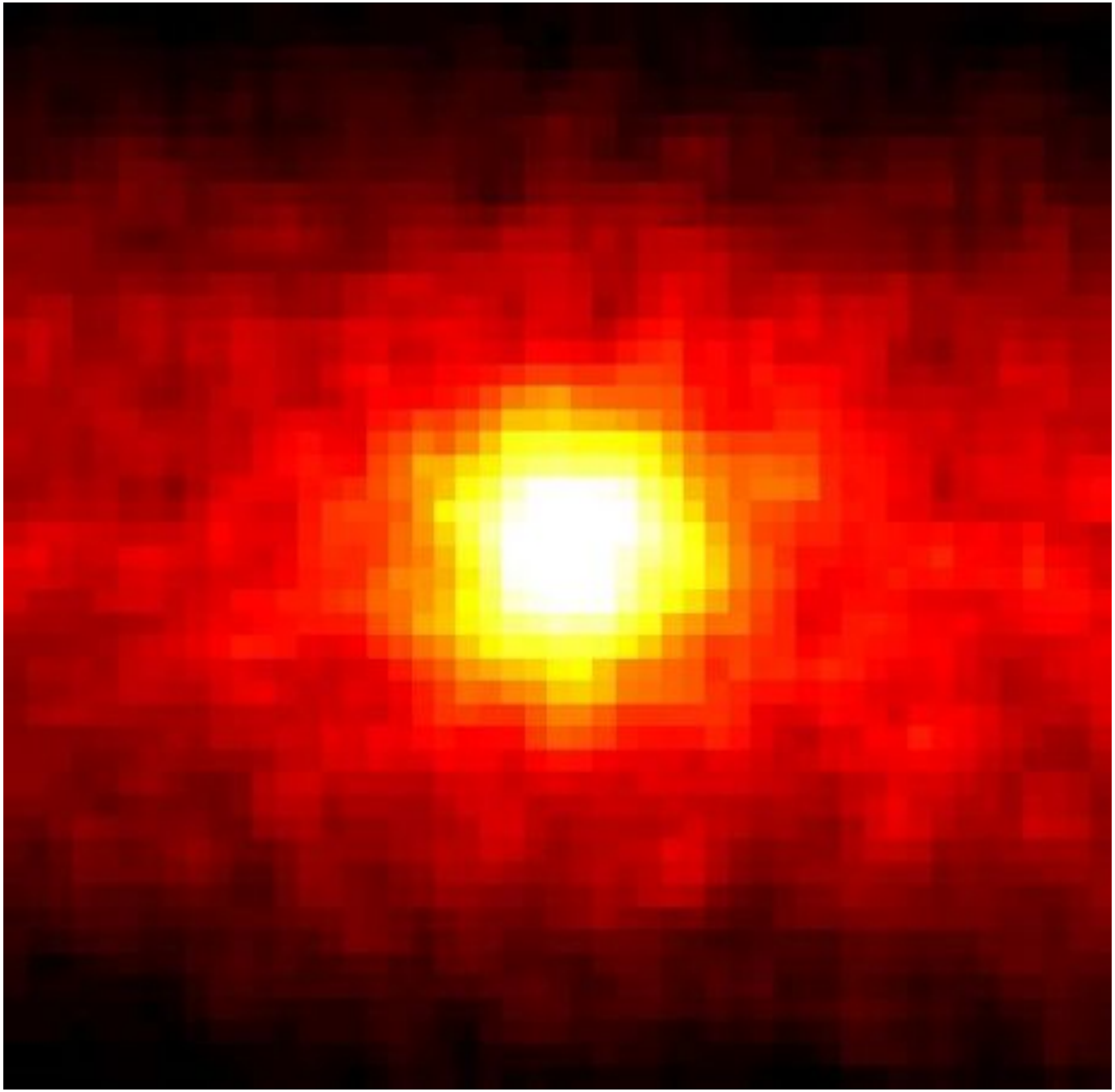


Oscillation Results for 0.93E20 p.o.t
$\Delta m^2_{23}=0.00305^{+0.00060}_{-0.00055}$
$\sin^2(2\theta_{23})=0.88^{+0.12}_{-0.15}$
χ^2 / n.d.f = 20.5/13=1.6
1-P(χ^2 ,n.d.f)=8.3%
Un-Oscillated
Best Fit
Data
Overflow Bin (18-30 GeV)
No disapearance hypothesis
χ^2 / n.d.f = 70.0/15 = 4.7
1-P(χ^2 ,n.d.f) = 4.5e-09
Events per GeV
Reconstructed CC-like spectra (GeV)
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20



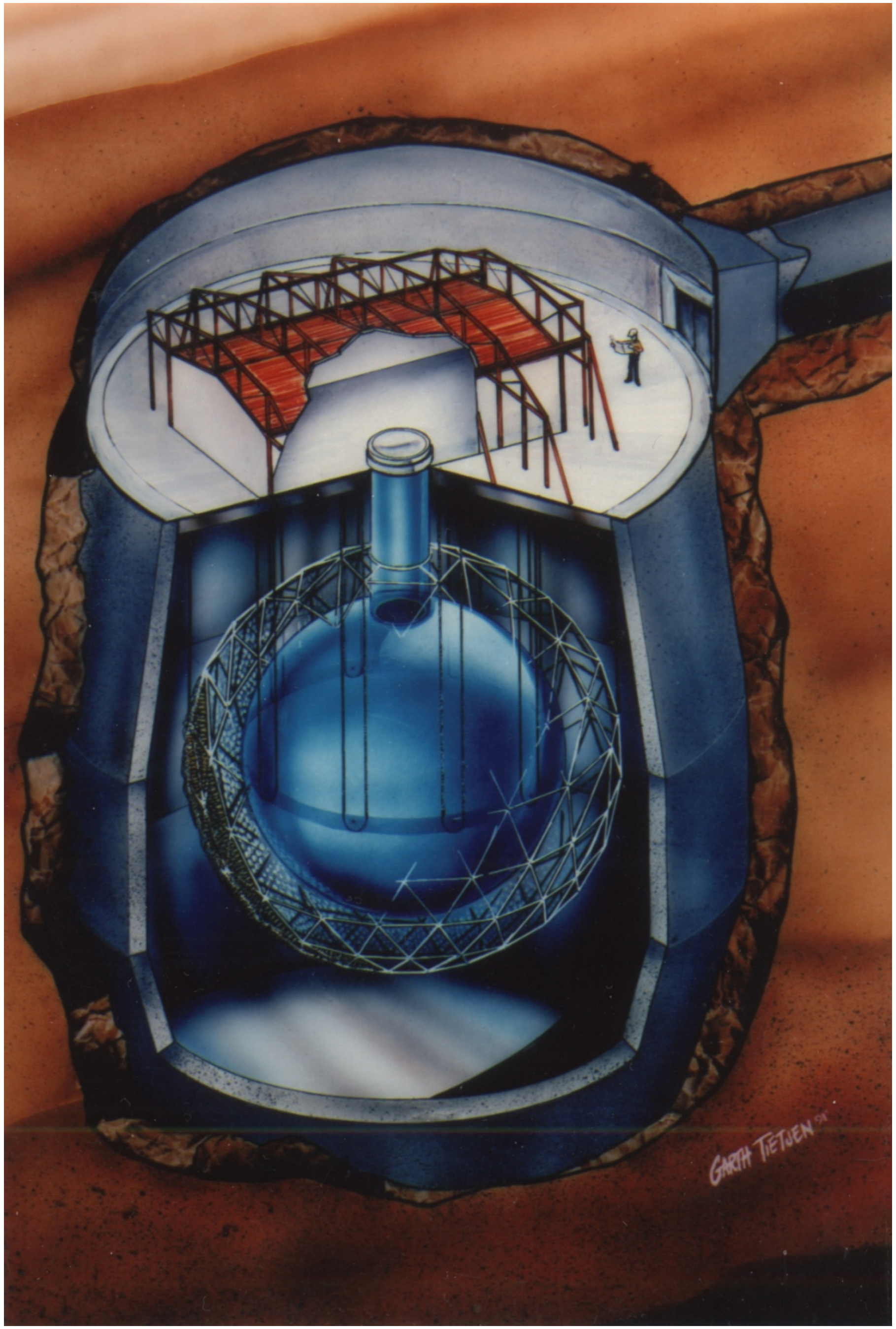
NC subtracted
Data
Best-fit
Ratio of Data / MC
Reconstructed Neutrino Energy
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18


Kamiokande sees the sun as a
source of neutrinos
Event/day/kton/bin
0.2
0.1
0
-1
-0.5
0
0.5
1
cosθsun



SNO

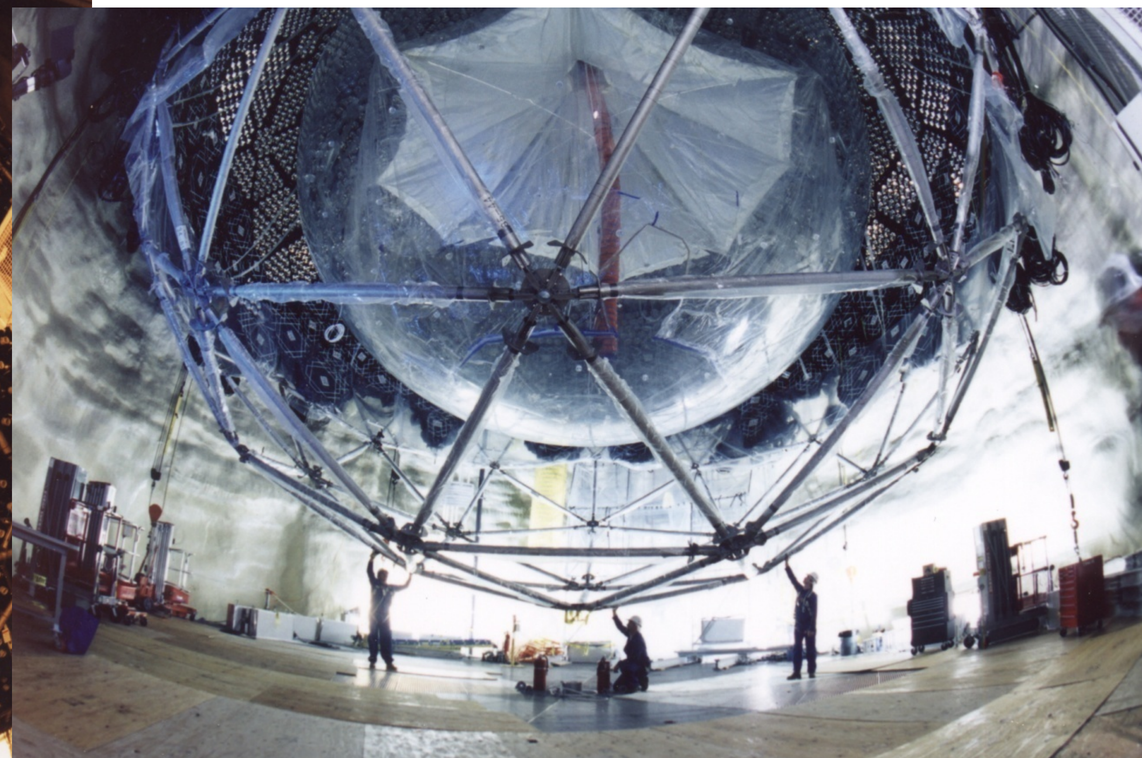
Sudbury
Neutrino
Observatory



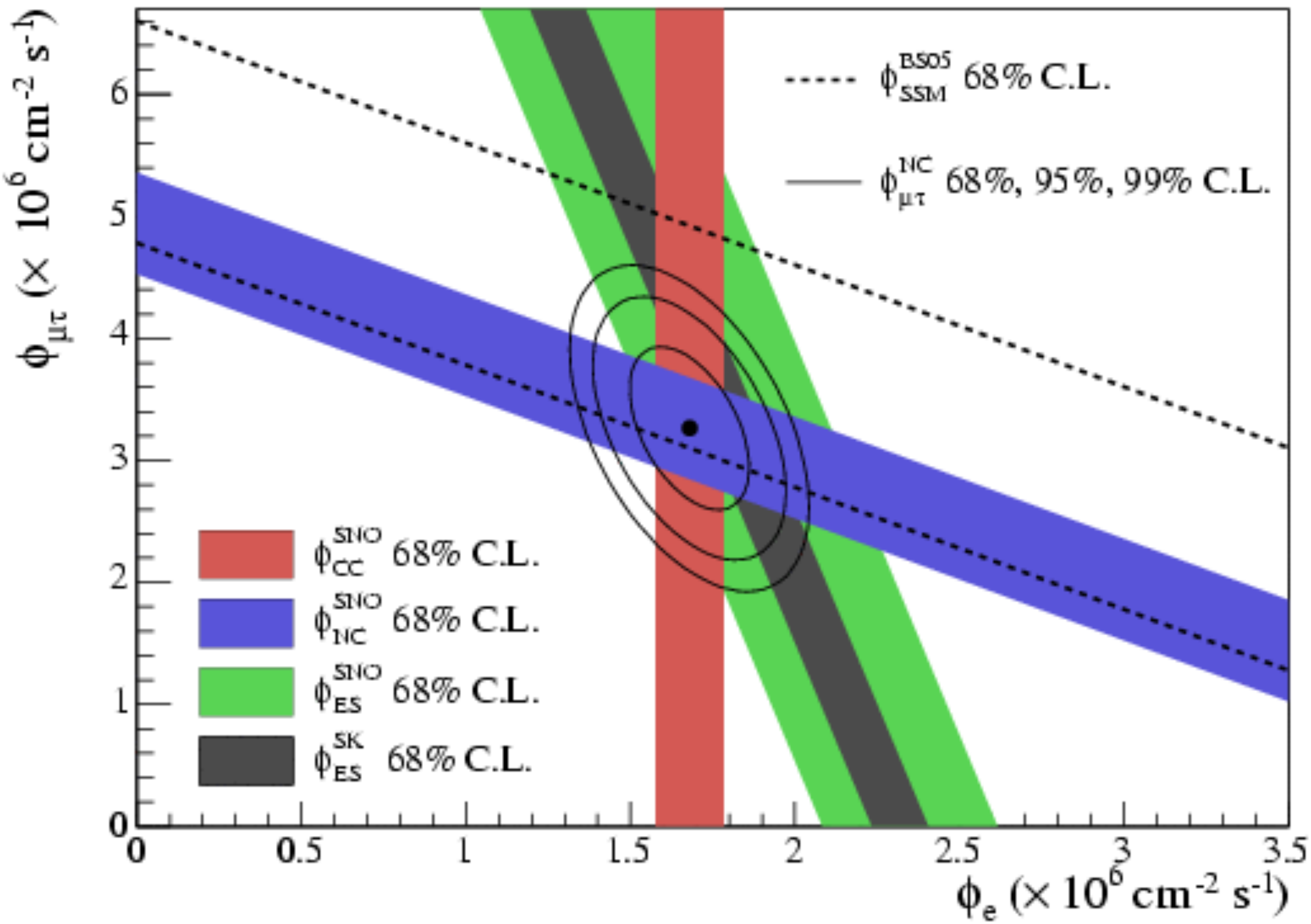
Measures CC as well as NC scattering

CC: only electron neutrinos

NC: all neutrino flavours

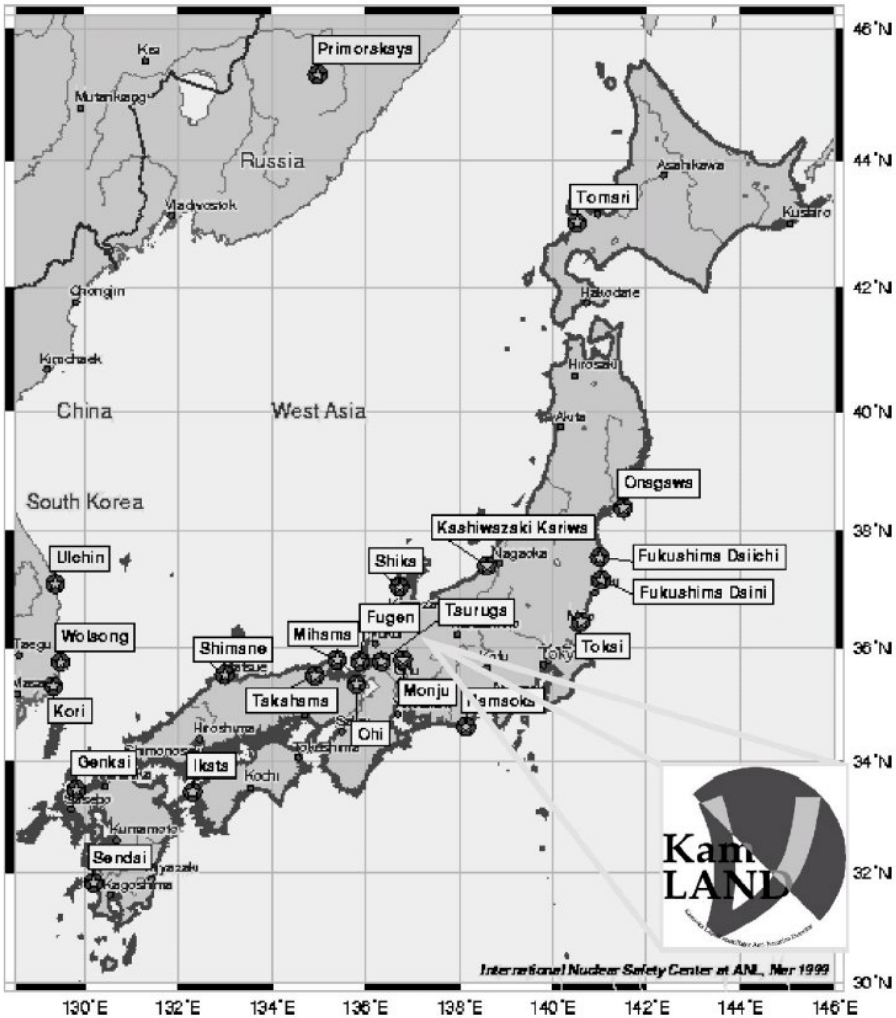


Result: neutrino flux agrees with solar models
but only 1/3 are electron neutrinos

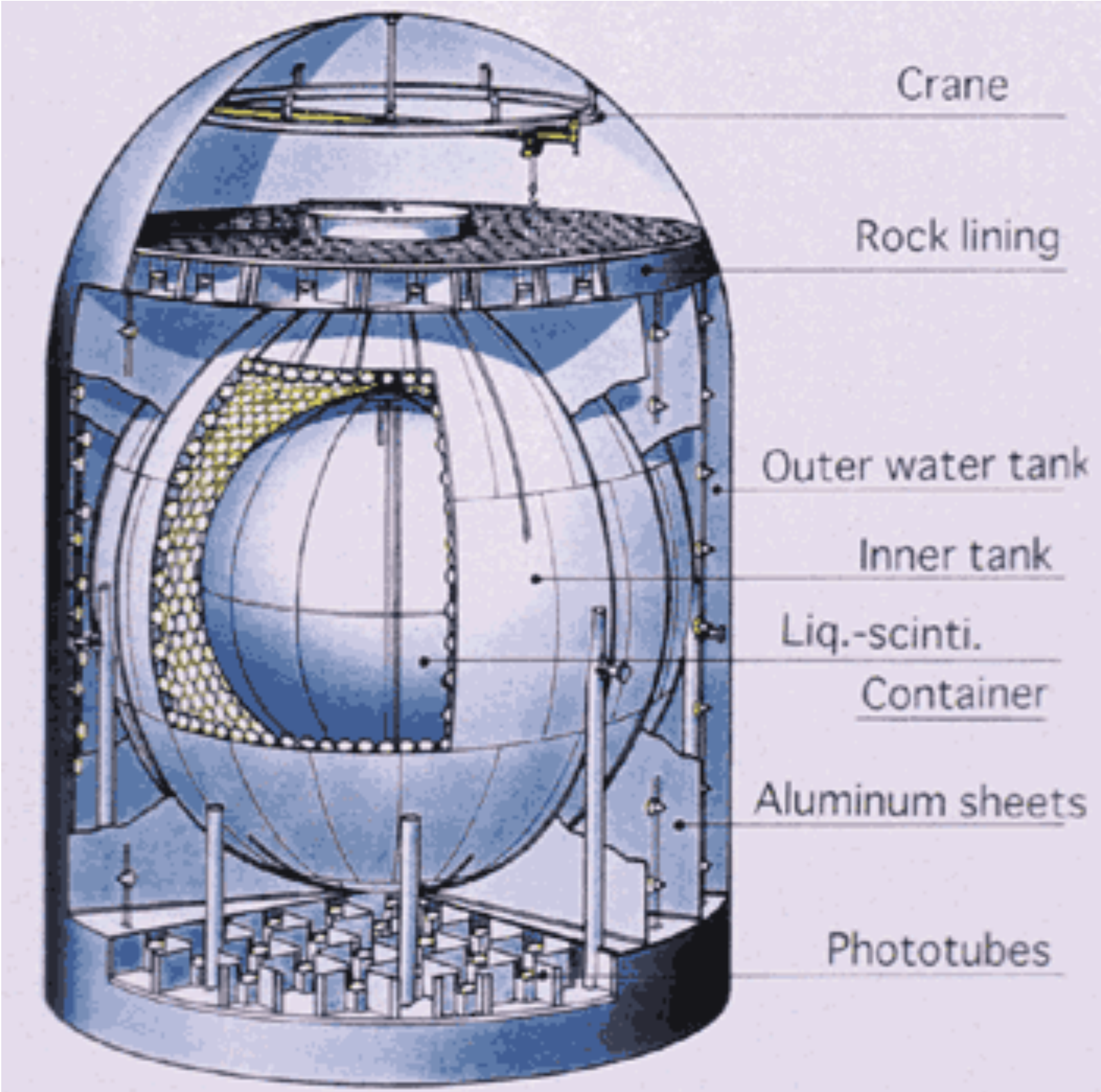


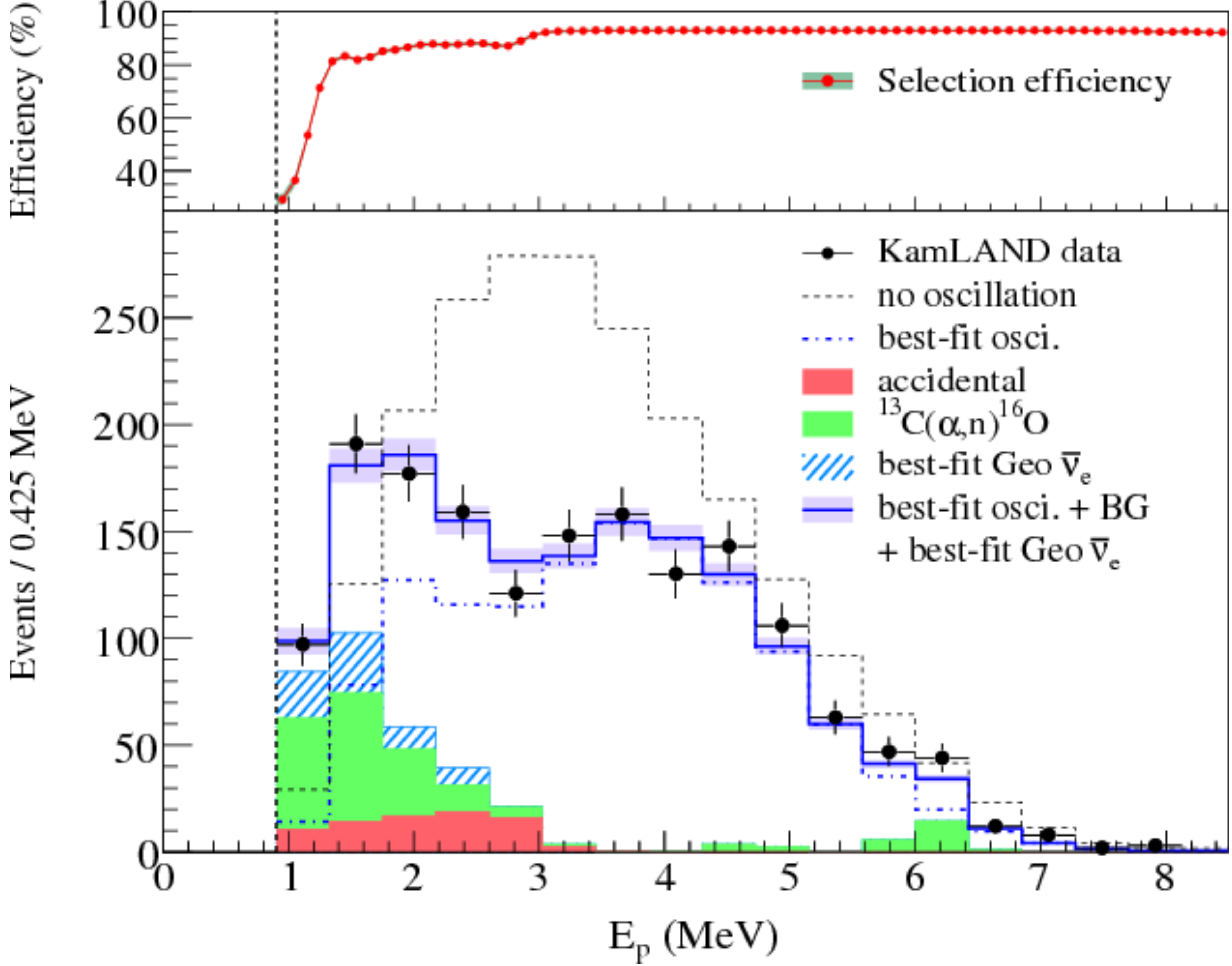
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
0.5
1.5
2.5
3.5

KamLAND



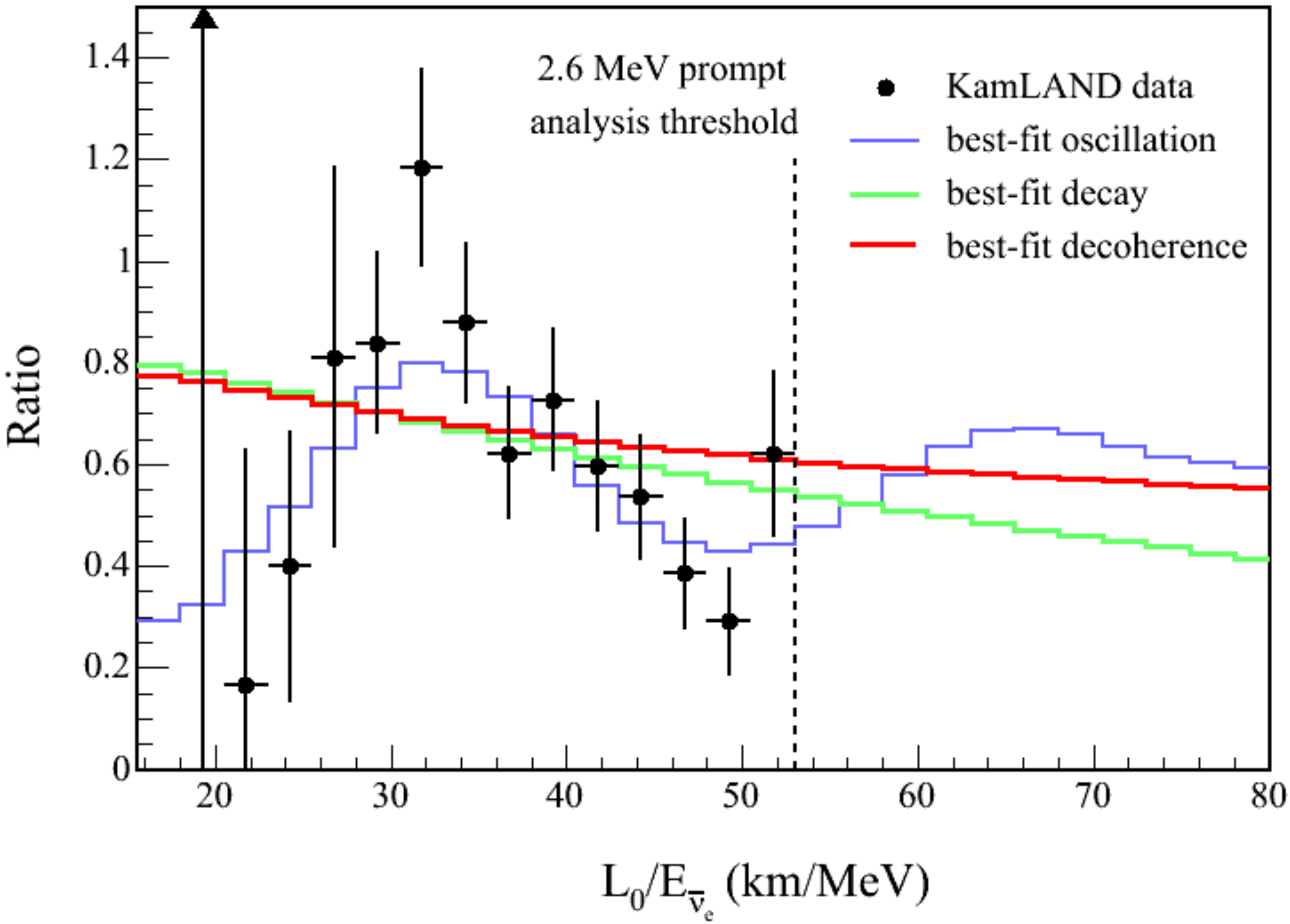
Site	Distance (km)	of cores	P_{th} (GW)	Flux ($\bar{\nu}_e$ cm^{-2} s^{-1})	Signal ($\bar{\nu}_e$/yr)
Japan					
Kashiwazaki	160.0	7	24.6	4.25×10^5	348.1
Ohi	179.5	4	13.7	1.88×10^5	154.0
Takahama	190.6	4	10.2	1.24×10^5	101.8
Hamaoka	214.0	4	10.6	1.03×10^5	84.1
Tsuruga	138.6	2	4.5	1.03×10^5	84.7
Shiga	80.6	1	1.6	1.08×10^5	88.8
Mihama	145.4	3	4.9	1.03×10^5	84.5
Fukushima-1	344.0	6	14.2	5.3×10^4	43.5
Fukushima-2	344.0	4	13.2	4.9×10^4	40.3
Tokai-II	294.6	1	3.3	1.7×10^4	13.7
Shimane	414.0	2	3.8	9.9×10^3	8.1
Onagawa	430.2	2	4.8	9.8×10^3	8.1
Ikata	561.2	3	6.0	8.4×10^3	6.9
Genkai	755.4	4	6.7	5.3×10^3	4.3
Sendai	824.1	2	3.3	3.5×10^3	2.8
Tomari	783.5	2	5.3	2.4×10^3	2.0
South Korea					
Ulchim	~750	4	11.2	8.8×10^3	7.2
Wolsong	~690	4	8.1	7.5×10^3	5.2
Yonggwang	~940	6	16.8	8.4×10^3	6.9
Kori	~700	4	8.9	8.0×10^3	6.6
Total		69	175.7	1.34×10^6	1101.6


Crane
Rock lining
Outer water tank
Inner tank
Liq.-scinti.
Container
Aluminum sheets
Phototubes

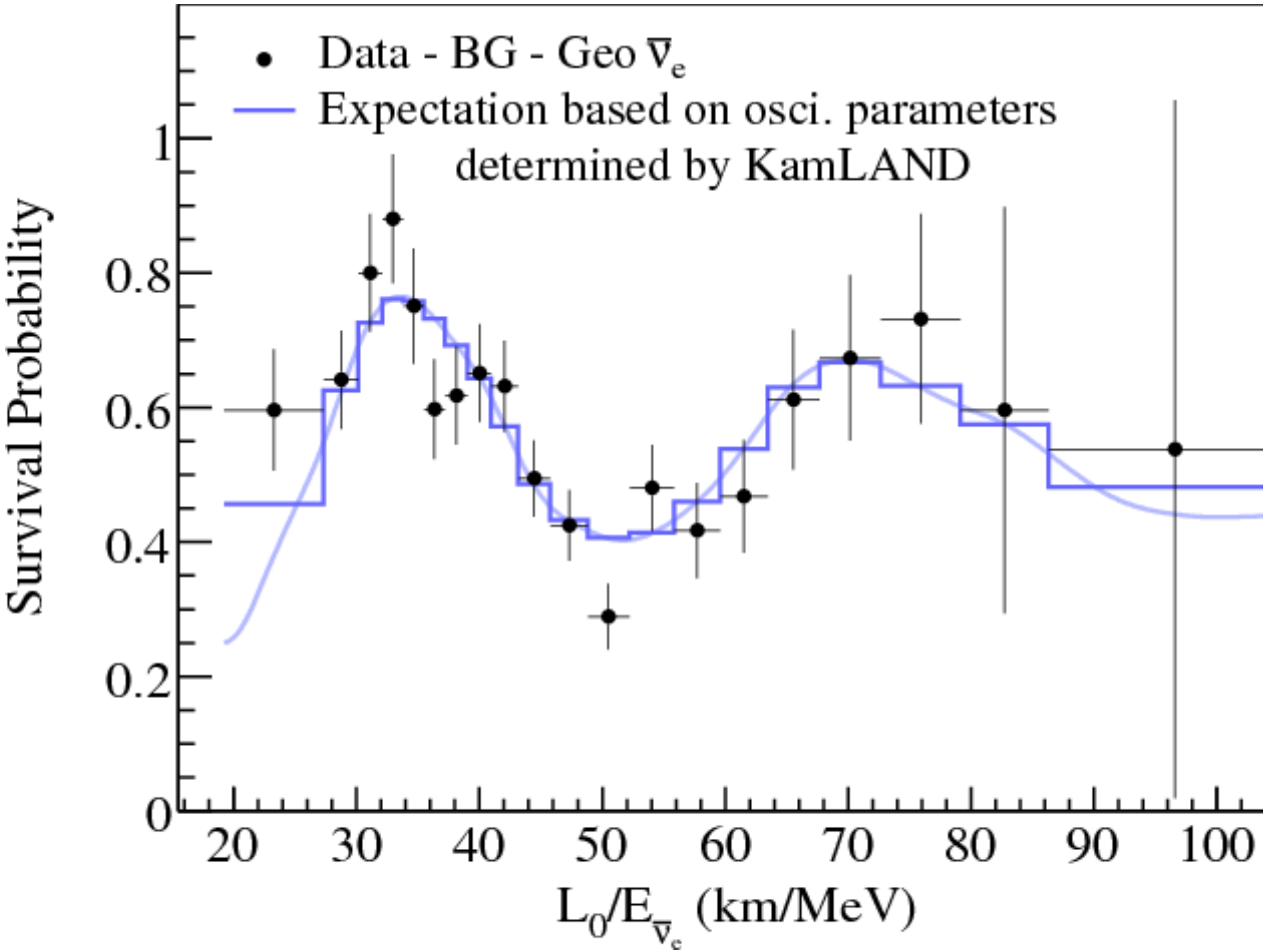


Efficiency (%)
100
80
60
40
Selection efficiency
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
Events / 0.425 MeV
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
E_p (MeV)

Older results

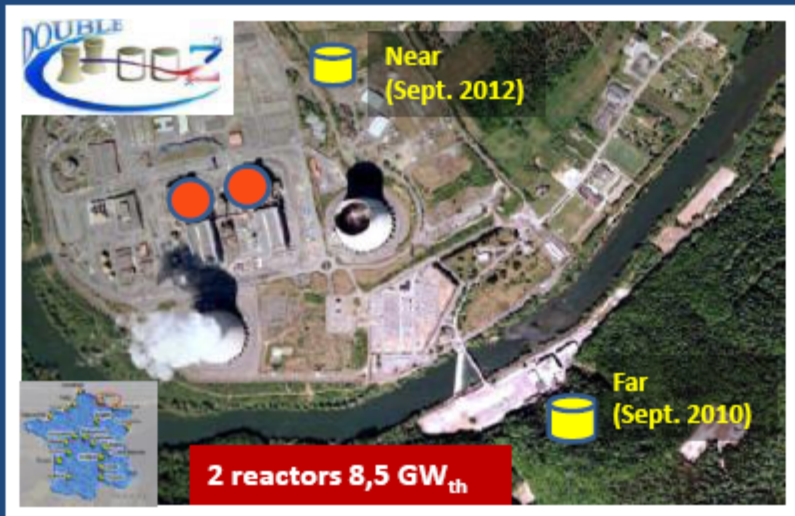


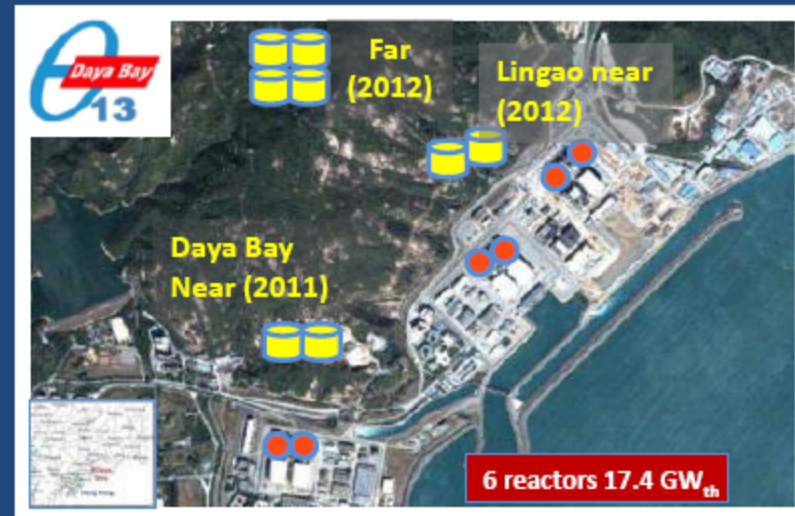
New results



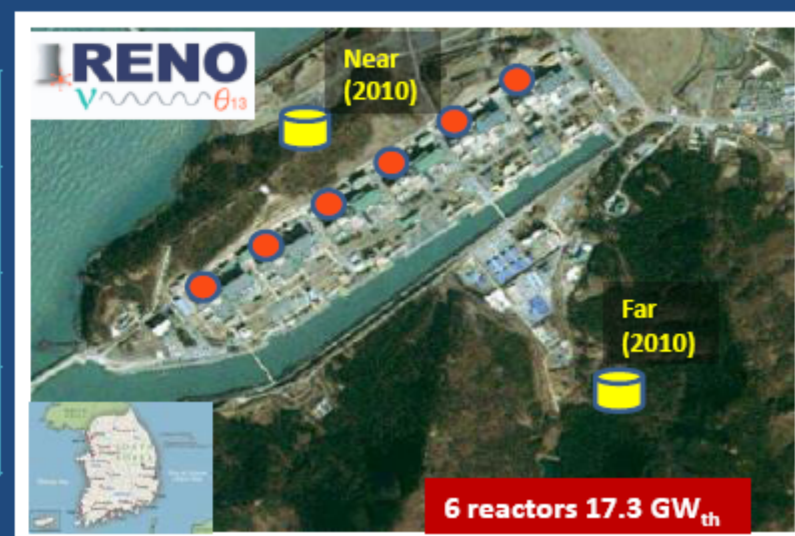
Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters determined by KamLAND
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

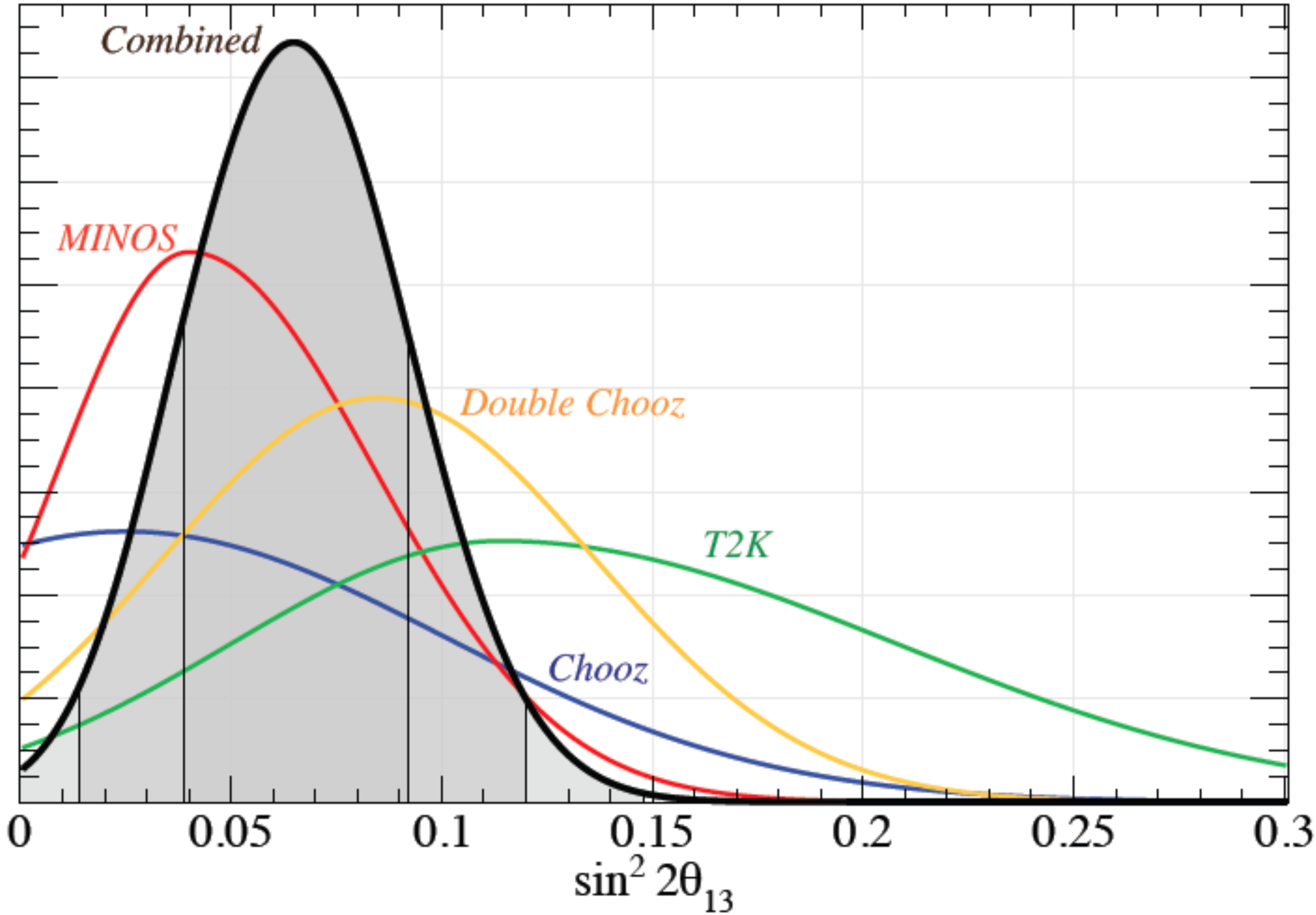
Reactor neutrinos



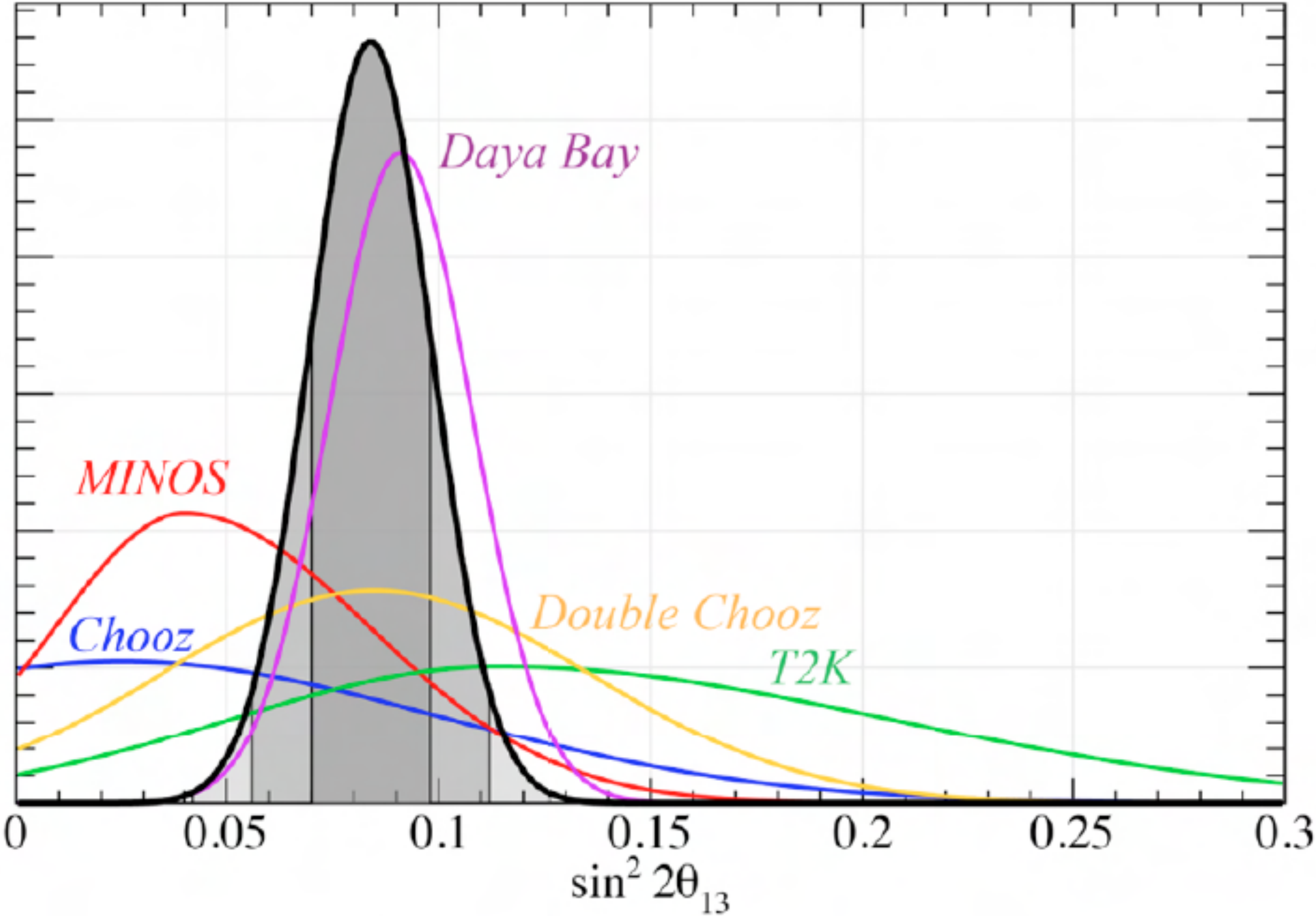


	Location	Thermal Power	Distance Near/far	Depth Near/far
Double Chooz	France	8.5	410/1050	120/300
RENO	South Korea	17.3	290/1380	120/450
DAYA BAY	China	17.4	360/1985 500/1613	260/910

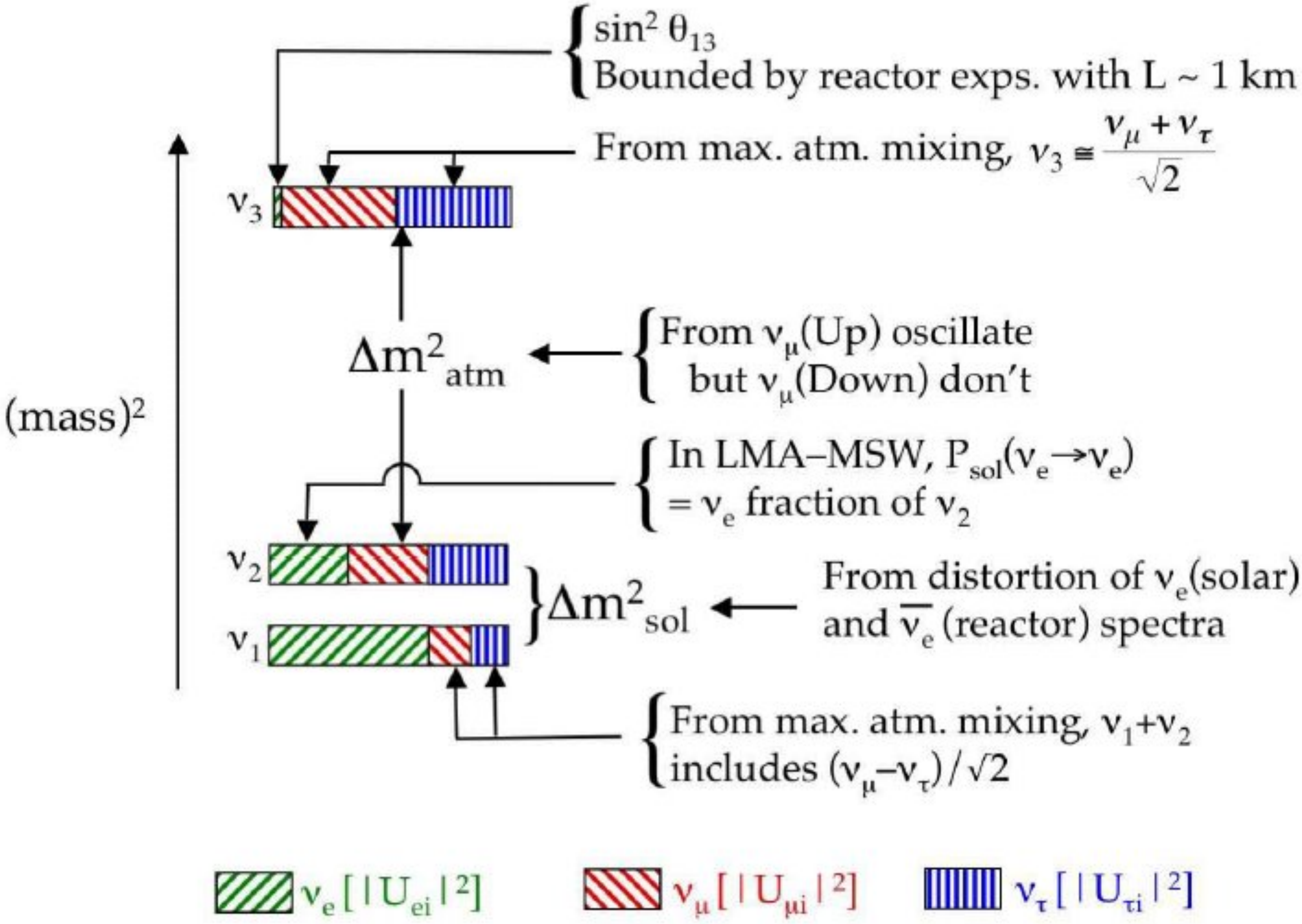




Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}

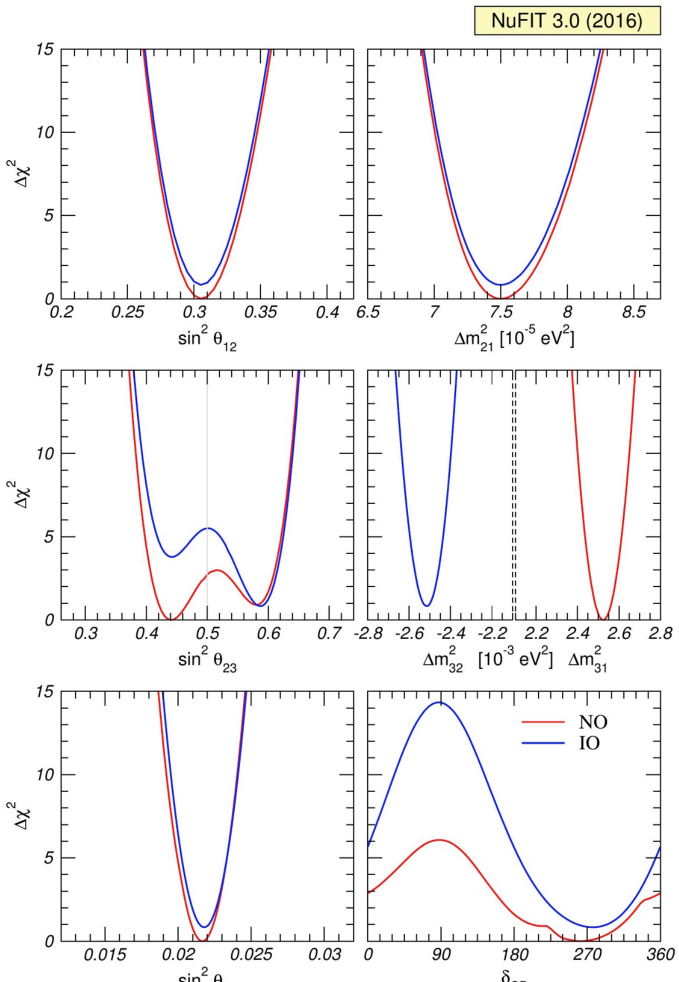


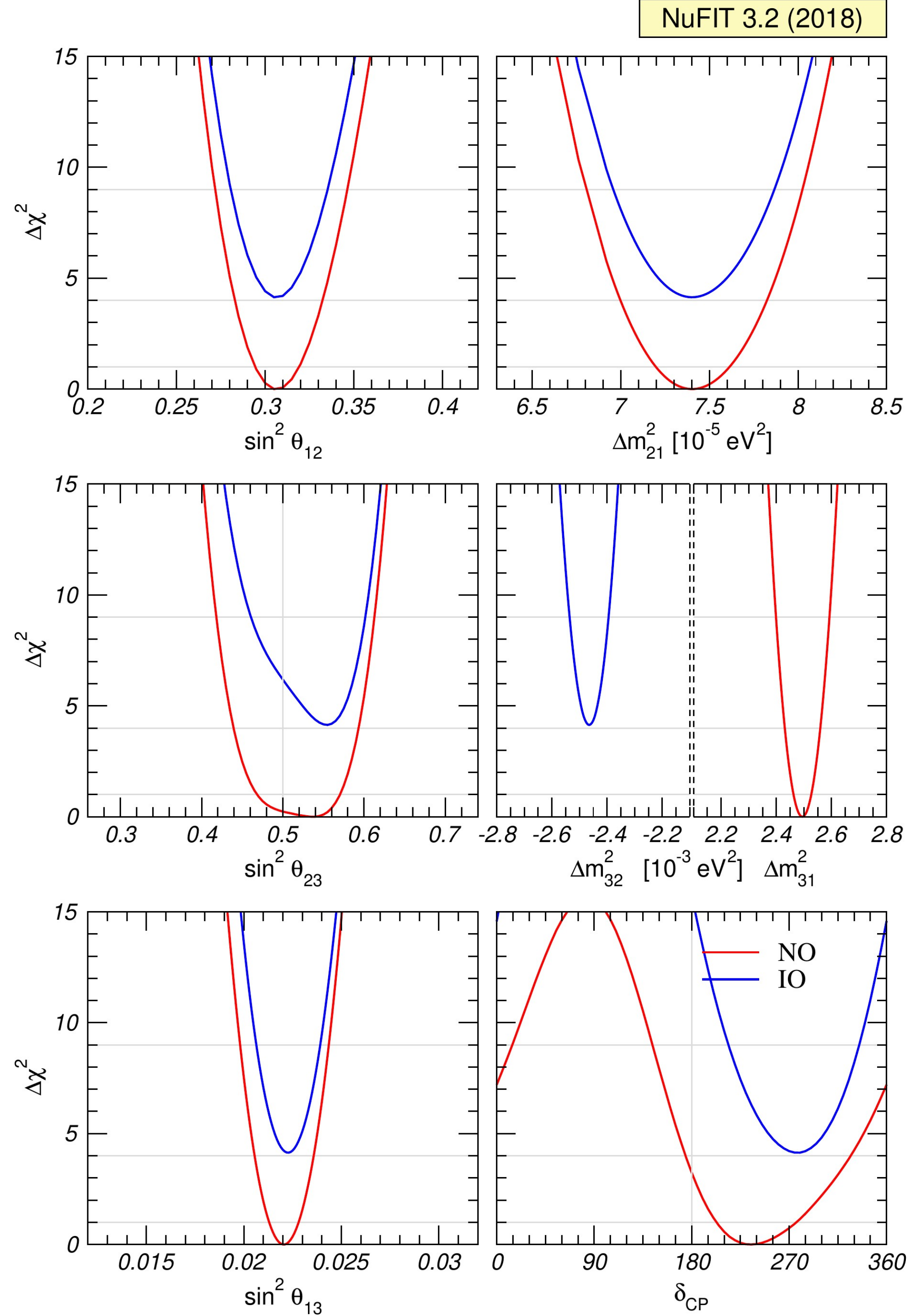
Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}

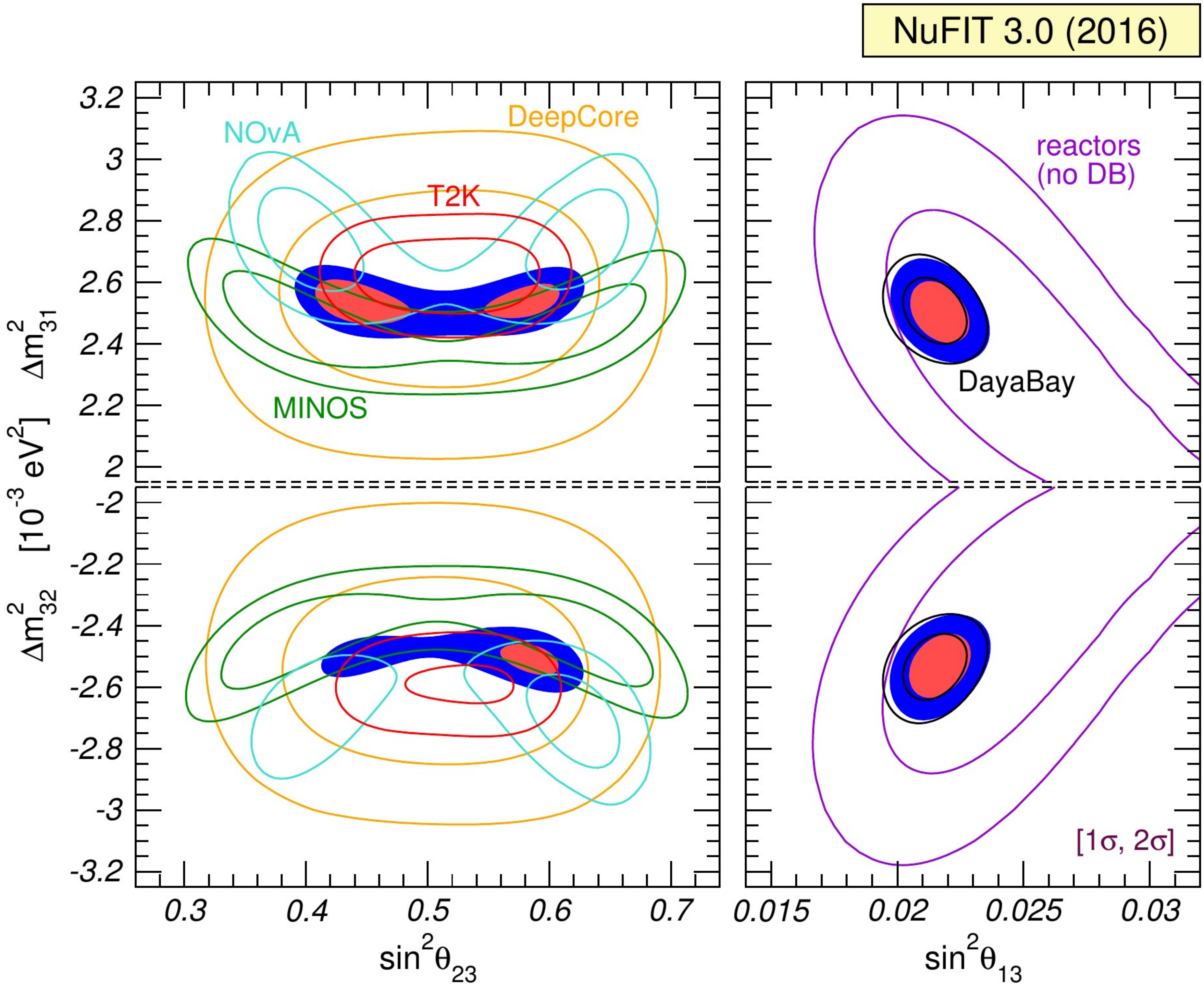


sin² θ13
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, ν3 ≅ (νμ + ντ)/√2
ν3
Δm²atm
From νμ(Up) oscillate
but νμ(Down) don't
(mass)²
In LMA–MSW, Psol(νe→νe)
= νe fraction of ν2
ν2
ν1
Δm²sol
From distortion of νe(solar)
and ν̄e (reactor) spectra
From max. atm. mixing, ν1+ν2
includes (νμ–ντ)/√2
νe [|Uei|²]
νμ [|Uμi|²]
ντ [|Uτi|²]

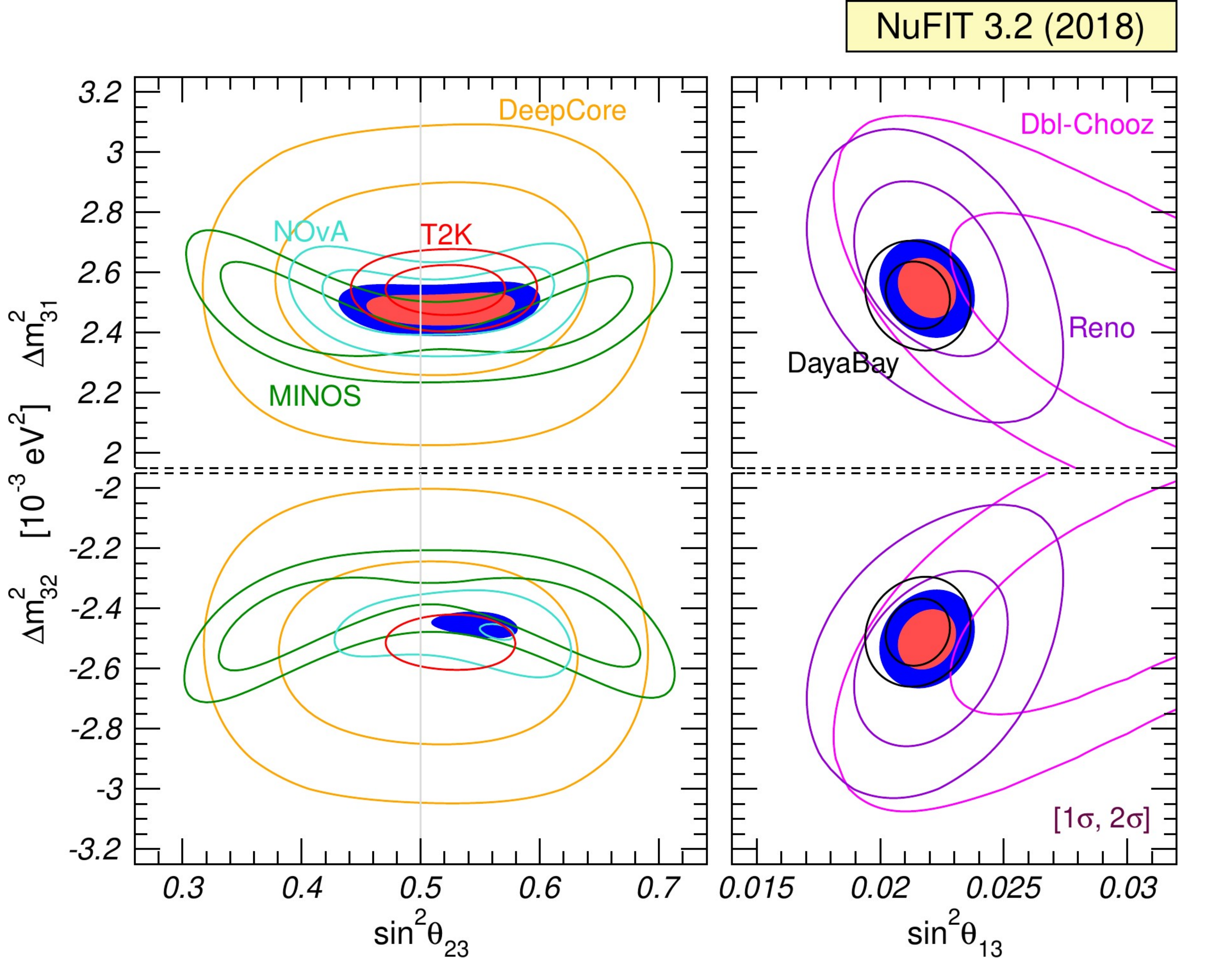
Current status of parameter fits







NuFIT 3.0 (2016)
NOvA
DeepCore
T2K
MINOS
reactors
(no DB)
DayaBay
[1σ, 2σ]
3.2
3
2.8
2.6
2.4
2.2
2
-2
-2.2
-2.4
-2.6
-2.8
-3
-3.2
0.3
0.4
0.5
0.6
0.7
0.015
0.02
0.025
0.03
Δm^2_{31} [10^{-3} eV^2] Δm^2_{32}
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$



NuFIT 3.2 (2018)
DeepCore
NOvA
T2K
MINOS
Dbl-Chooz
Reno
DayaBay
[1σ, 2σ]
Δm^2_{31}
Δm^2_{32}
[10^{-3} eV^2]
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$\theta_{12} \sim 32^0$ — Big mixing

$\theta_{23} \sim 45^0$ — (Almost?) Maximal mixing!

$\theta_{13} \sim 8^0$ — Small but nonzero mixing!

PMNS:

$$\begin{bmatrix} 0.83 & 0.54 & 0.15 \\ 0.49 & 0.57 & 0.66 \\ 0.28 & 0.62 & 0.73 \end{bmatrix}$$

CKM:

$$\begin{bmatrix} 0.98 & 0.22 & 0.004 \\ 0.22 & 0.98 & 0.04 \\ 0.004 & 0.04 & 1 \end{bmatrix}$$

This is very different from CKM matrix! Why? Nobody knows!

Open questions: Hierarchy ν_1, ν_2, ν_3 (mass ordering) ?

δ ?

Is the 3-neutrino picture correct?

Explain the form of the PMNS matrix?

What are the neutrino masses exactly?
Why are they so small?

Neutrinos: Dirac or Majorana?

TB Mixing

TB mixing is close to the data; less now, but still: θ_{12}, θ_{23} agree at $< \sim 2\sigma$ and θ_{13} is the smallest angle

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

At 1σ: Fogli et al '13

$\sin^2\theta_{12} = 1/3$: 0.291- 0.325

$\sin^2\theta_{23} = 1/2$: 0.40 - 0.45

$\sin\theta_{13} = 0$: 0.15 - 0.16

A coincidence or a hint?

Called:
Tri-Bimaximal mixing

Harrison, Perkins, Scott '02

$$\nu_3 = \frac{1}{\sqrt{2}}(-\nu_\mu + \nu_\tau)$$

$$\nu_2 = \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$$

θ_{13} largish and θ_{23} non maximal move away from exact TB (still remains a good first approximation)

TB Mixing naturally leads to discrete flavour groups (similarly for GR, BM....)

TB Mixing:

$$U = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

This is a particular rotation matrix with specified fixed angles

TB: Group A4, S4, T'.....

A vast literature (Ma, Rajasekaran '01.....)

Some recent works: A4 Ferreira et al '13; Morisi et al '13; Gonzalez-Felipe et al '13 Holthausen et al '12; Ben Tov et al '12; King et al '12 ...

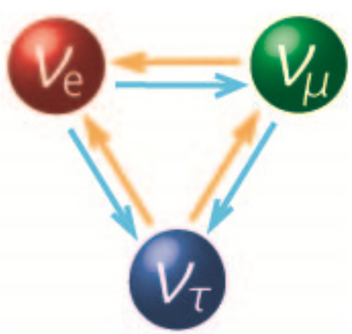
S4 Bazzocchi et al '12; Hagedorn et al '12; Zhao '11.....

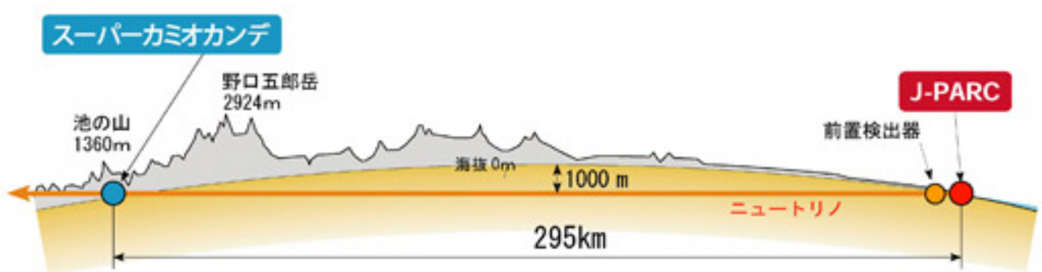
T' Chen et al '13; Meroni et al '12; Merlo et al '11.....

Future experiments

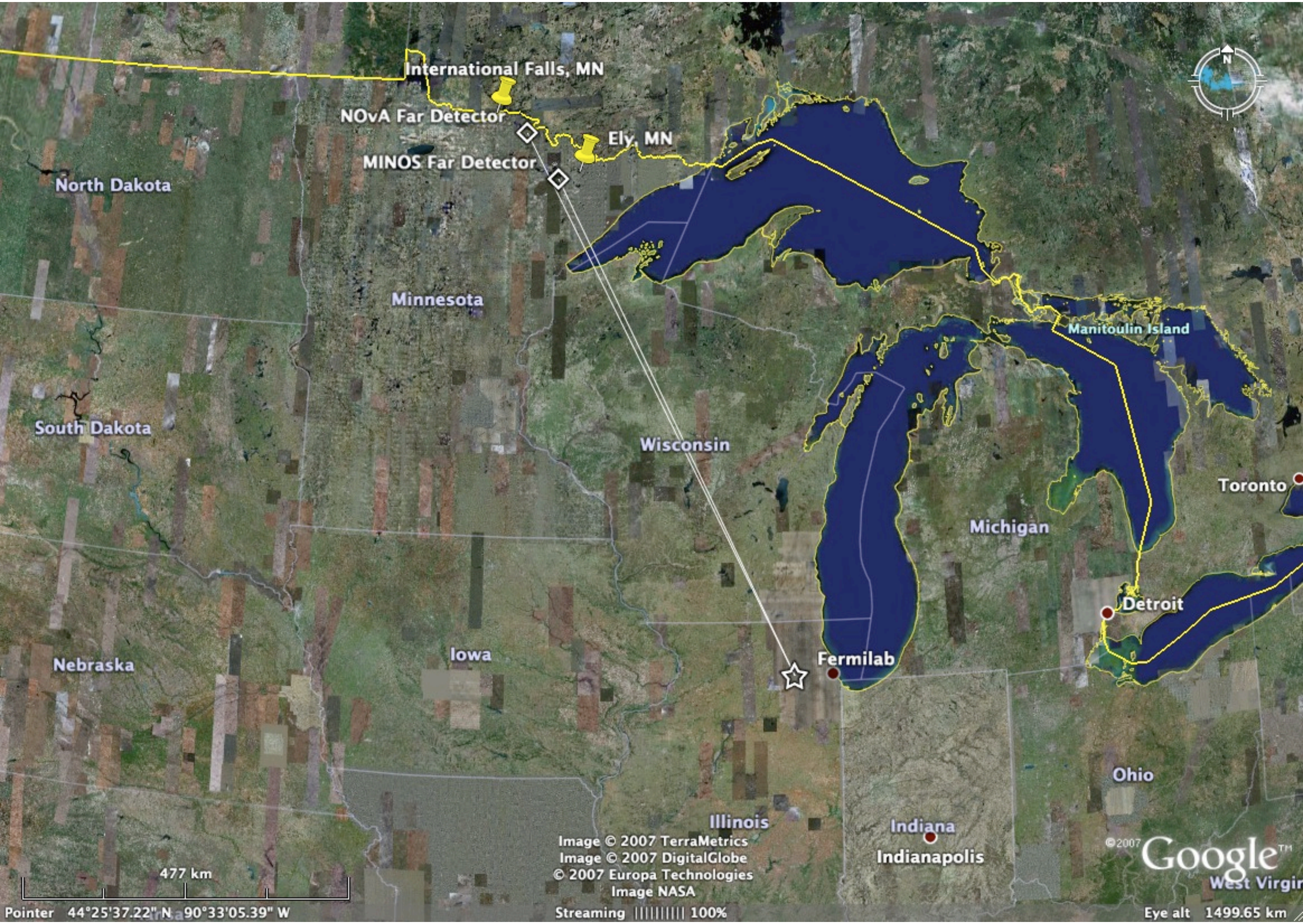
T2K

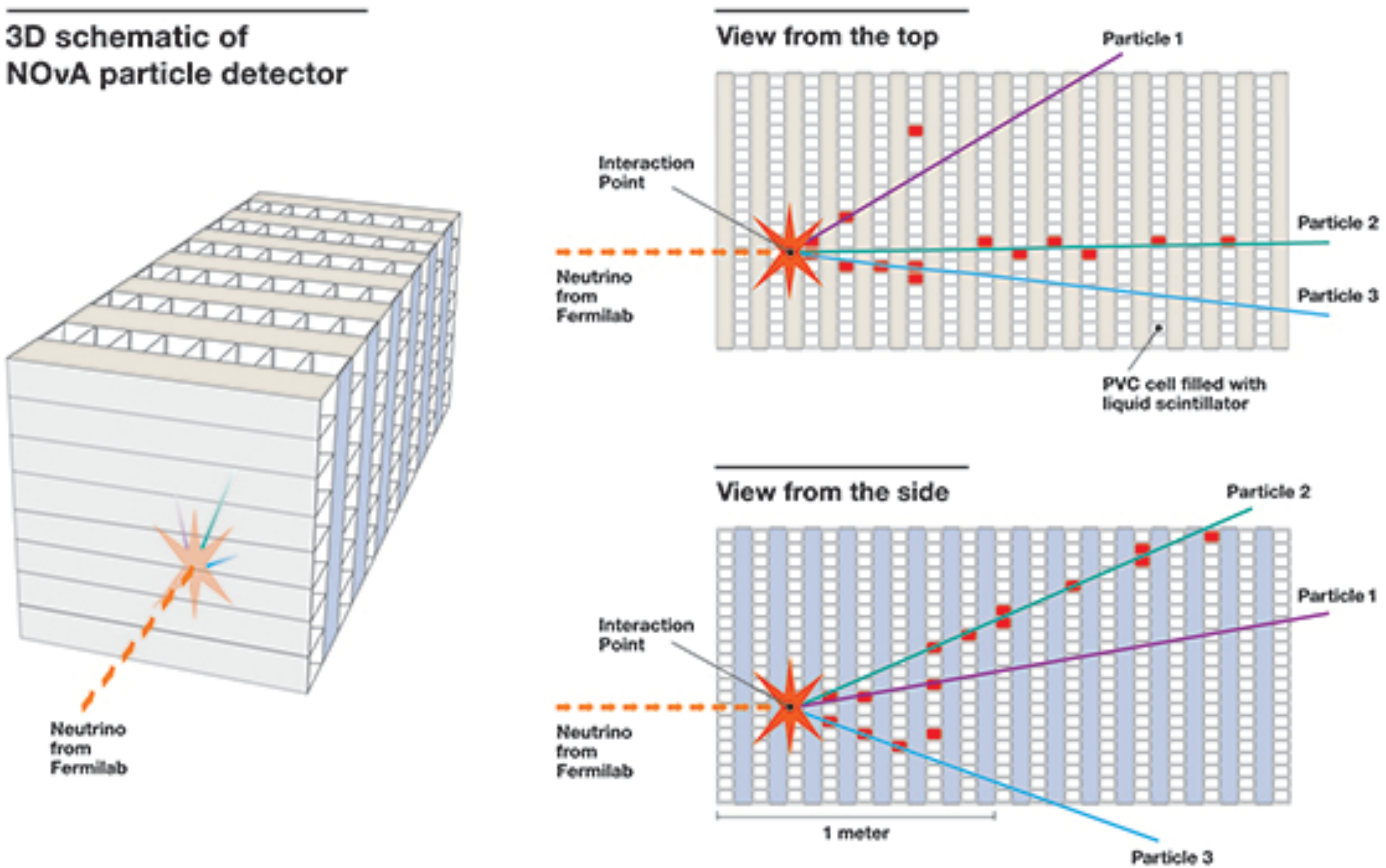
Super-Kamiokande
(ICRR, Univ. Tokyo)
295km
Neutrino Facility
at J-PARC
(KEK-JAEA, Tokai)
Shimonikawa
Nagano
Tochigi
Gunma
KEK
Japan
Saitama
Yamanashi
Tokyo
Chiba
Kanagawa
Mt.Fuji
Gifu
Aichi
Shiga
Shizuoka
Mie
Asahi
Fukushima
Iwaki
E137° 30'
E138° 30'
E139° 30'
E140° 30'
N35° 30'
N37° 30'
N38° 30'
N34° 30'



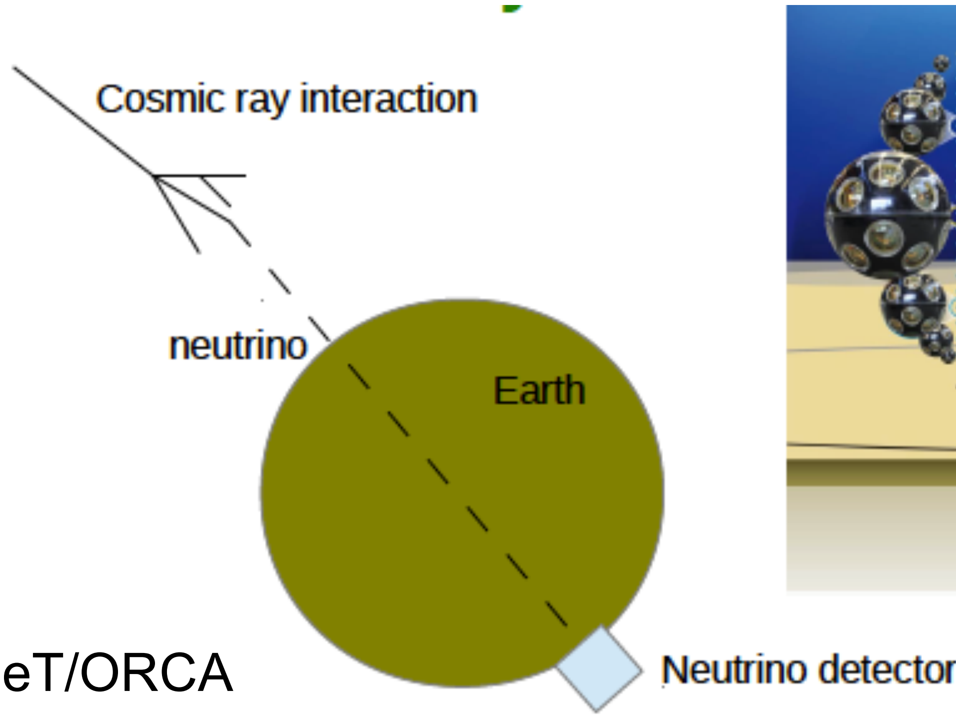


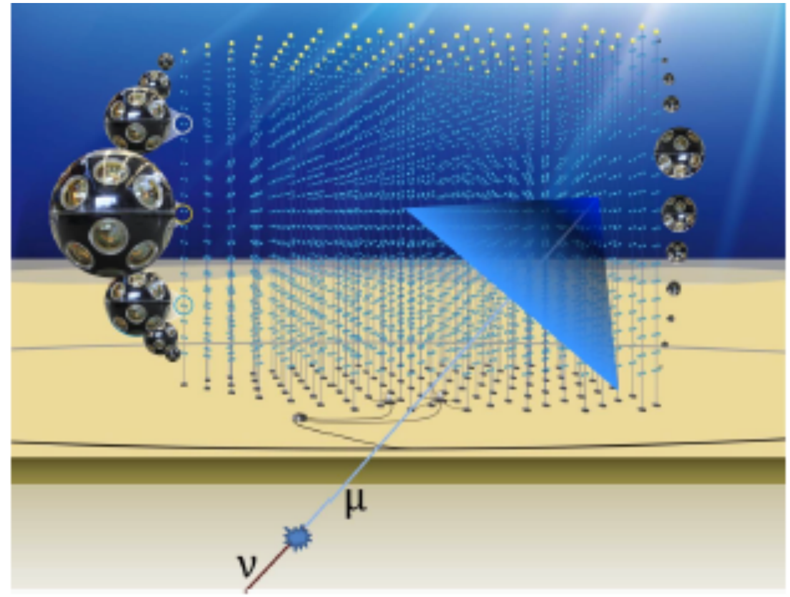
スーパーカミオカンデ
野口五郎岳
2924m
池の山
1360m
海抜 0m
1000 m
J-PARC
前置検出器
ニュートリノ
295km


International Falls, MN
NOvA Far Detector
Ely, MN
MINOS Far Detector
North Dakota
South Dakota
Minnesota
Wisconsin
Manitoulin Island
Michigan
Toronto
Detroit
Nebraska
Iowa
Fermilab
Illinois
Indiana
Indianapolis
Ohio
Image © 2007 TerraMetrics
Image © 2007 DigitalGlobe
© 2007 Europa Technologies
Image NASA
477 km
©2007 Google™
West Virgi
Pointer 44°25'37.22" N 90°33'05.39" W
Streaming 100%
Eye alt 1499.65 km

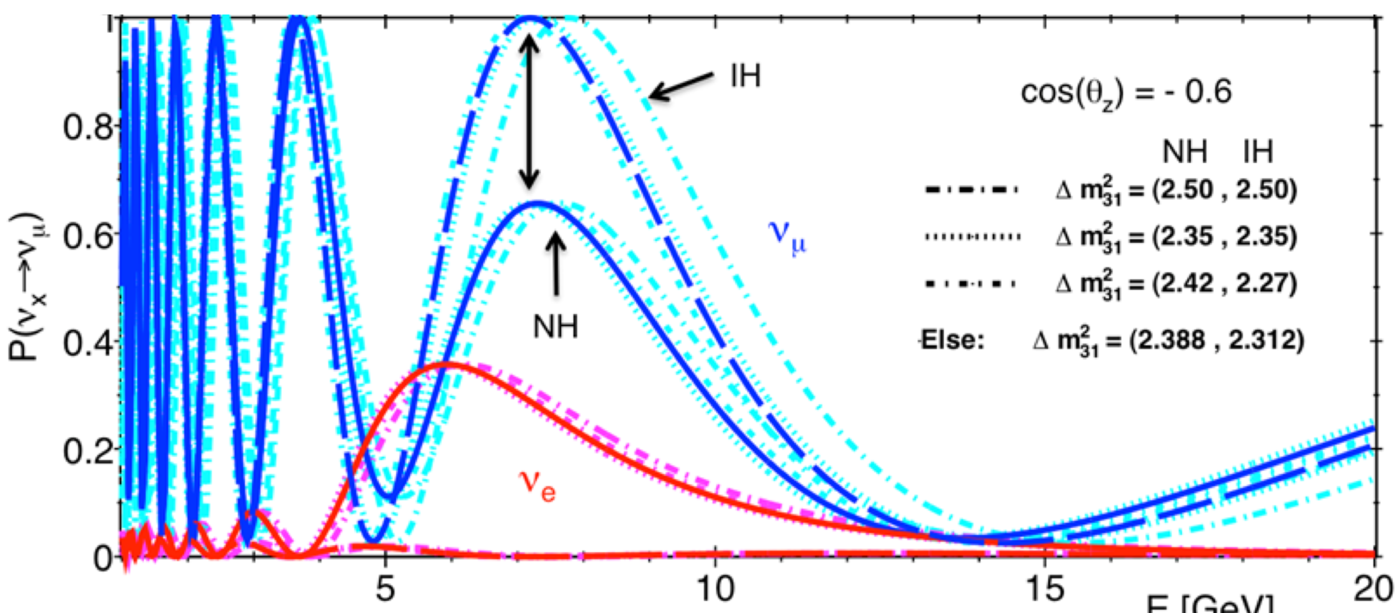

3D schematic of
NOvA particle detector
Neutrino
from
Fermilab
View from the top
Particle 1
Interaction
Point
Particle 2
Neutrino
from
Fermilab
Particle 3
PVC cell filled with
liquid scintillator
View from the side
Particle 2
Particle 1
Interaction
Point
Neutrino
from
Fermilab
1 meter
Particle 3

NOvA

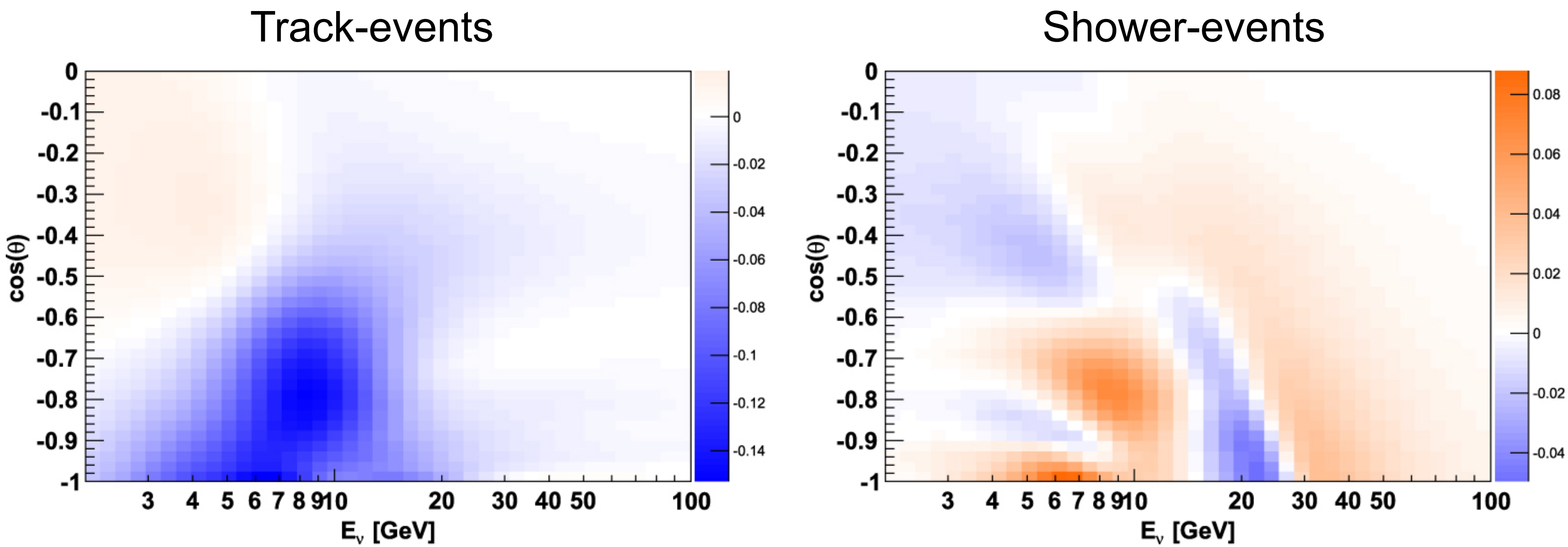

Cosmic ray interaction
neutrino
Earth
Neutrino detector


μ
ν

KM3NeT/ORCA

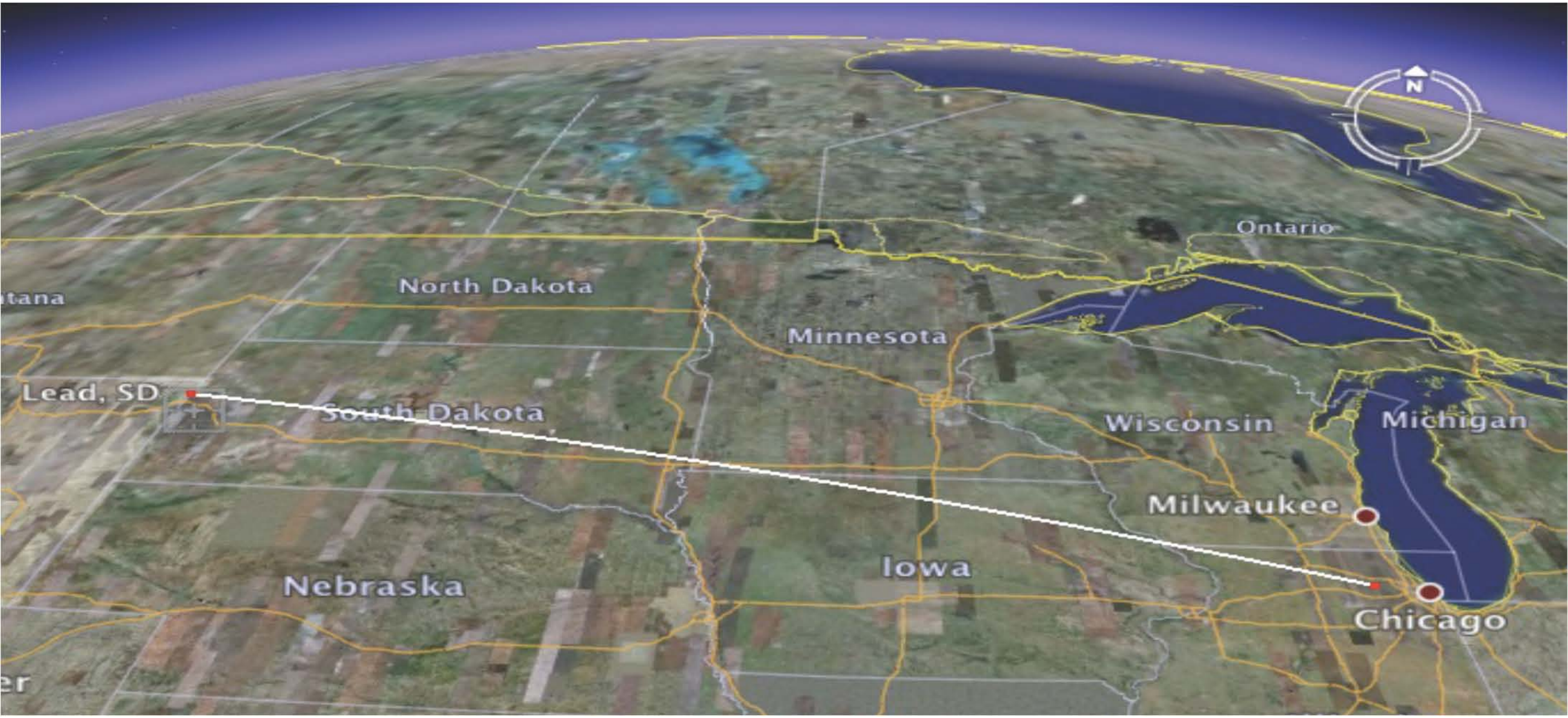

IH
NH
cos(θz) = - 0.6
NH IH
Δ m²31 = (2.50 , 2.50)
Δ m²31 = (2.35 , 2.35)
Δ m²31 = (2.42 , 2.27)
Else: Δ m²31 = (2.388 , 2.312)
νμ
νe
P(νx→νμ)
E [GeV]
0
0.2
0.4
0.6
0.8
5
10
15
20

Asymmetry = NH / IH

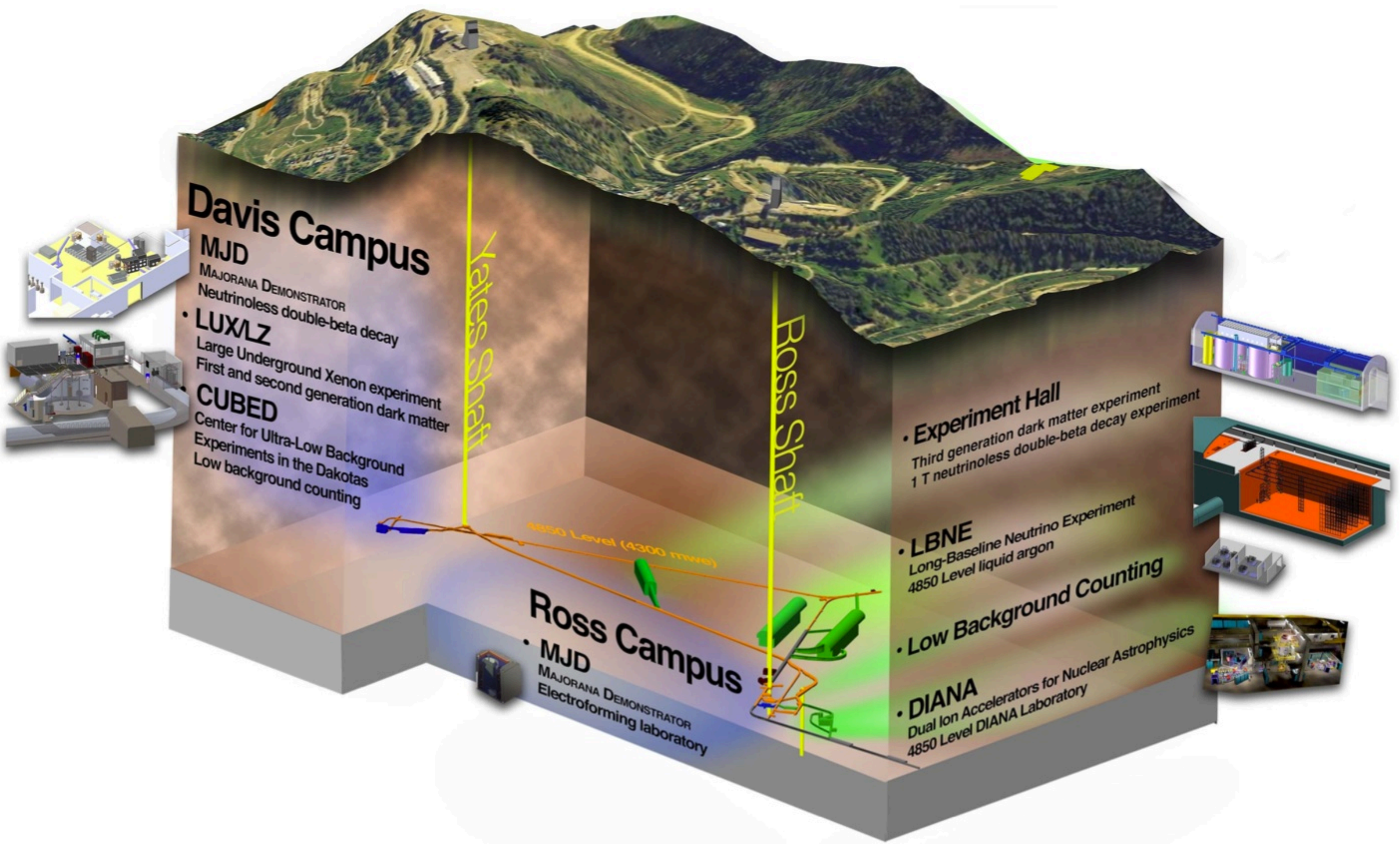


Long Baseline Neutrino Facility (Chicago-South Dakota)

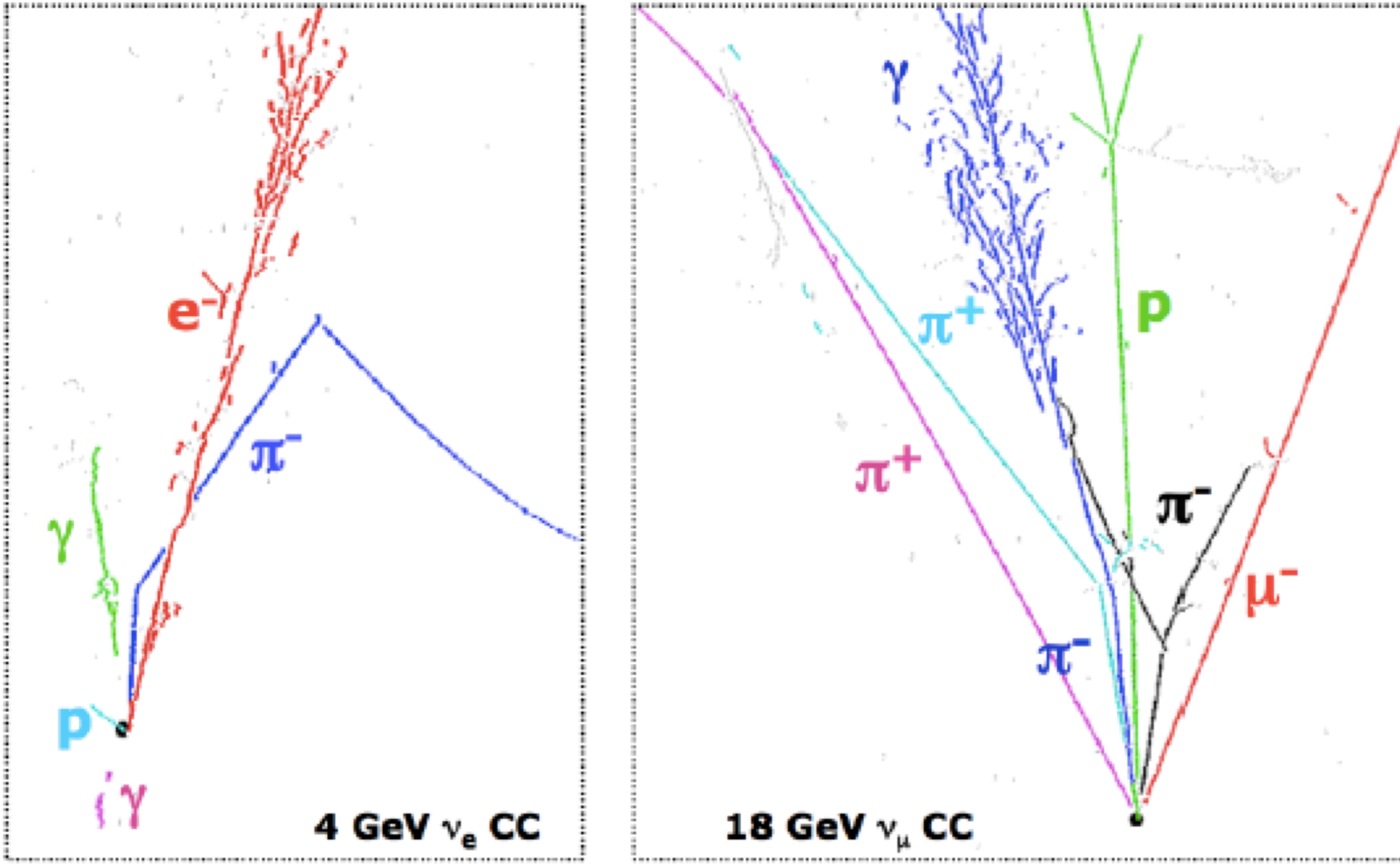
1300 km, muon (anti)neutrino beam, start 2026



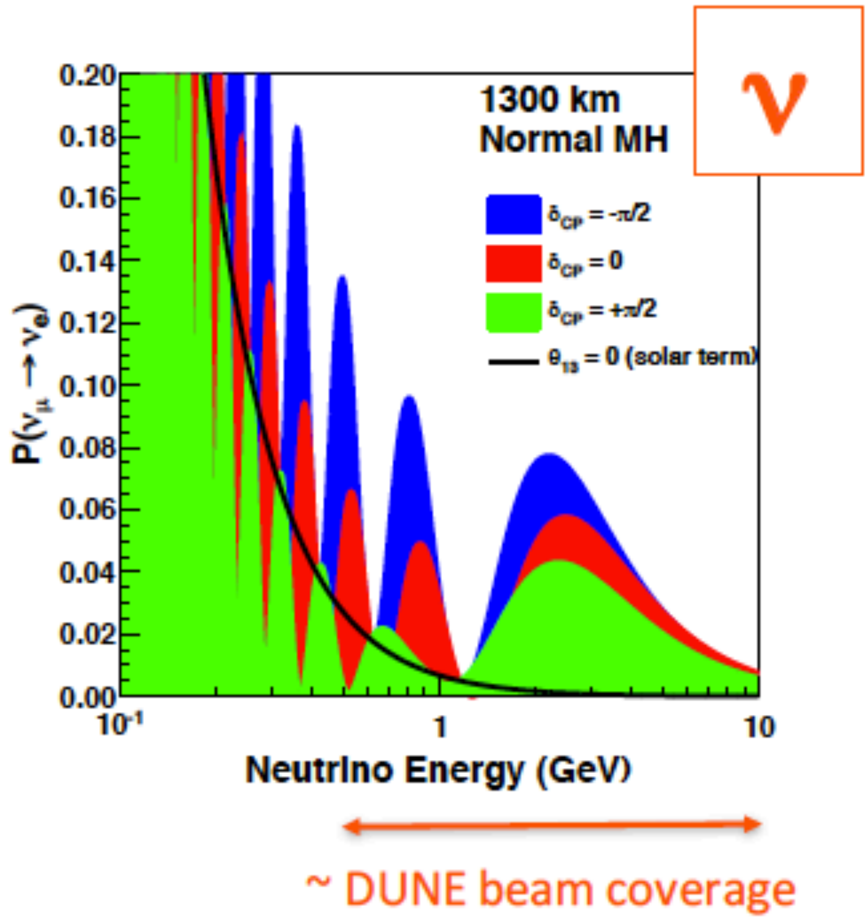
DUNE experiment in the Homestake mine.   40 kton liquid argon TPC

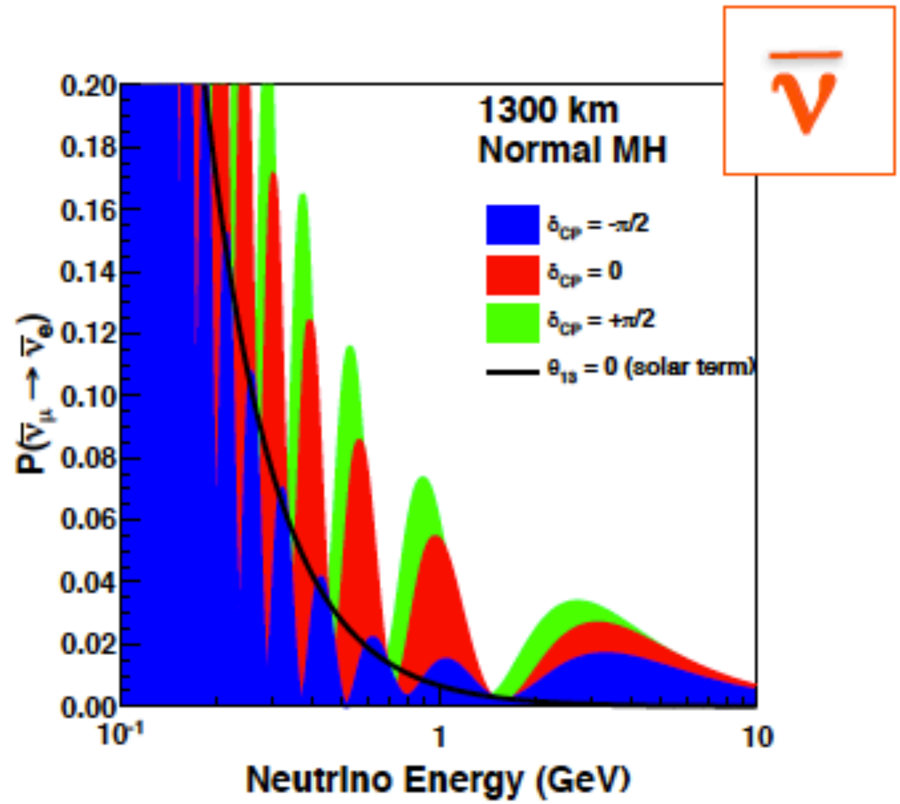


DUNE: Liquid argon TPC   (Time Projection Chamber)



Measure asymmetry between muon neutrinos and muon antineutrinos





ν oscillations measure Δm^2. What is m^2?

$\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2$; $\Delta m^2_{sun} \sim 8\ 10^{-5}\ eV^2$

- Direct limits

$m_{"\nu e"} < 2.2\ eV$
$m_{"\nu\mu"} < 170\ KeV$
$m_{"\nu\tau"} < 18.2\ MeV$

End-point tritium β decay (Mainz, Troitsk, future: Katrin)

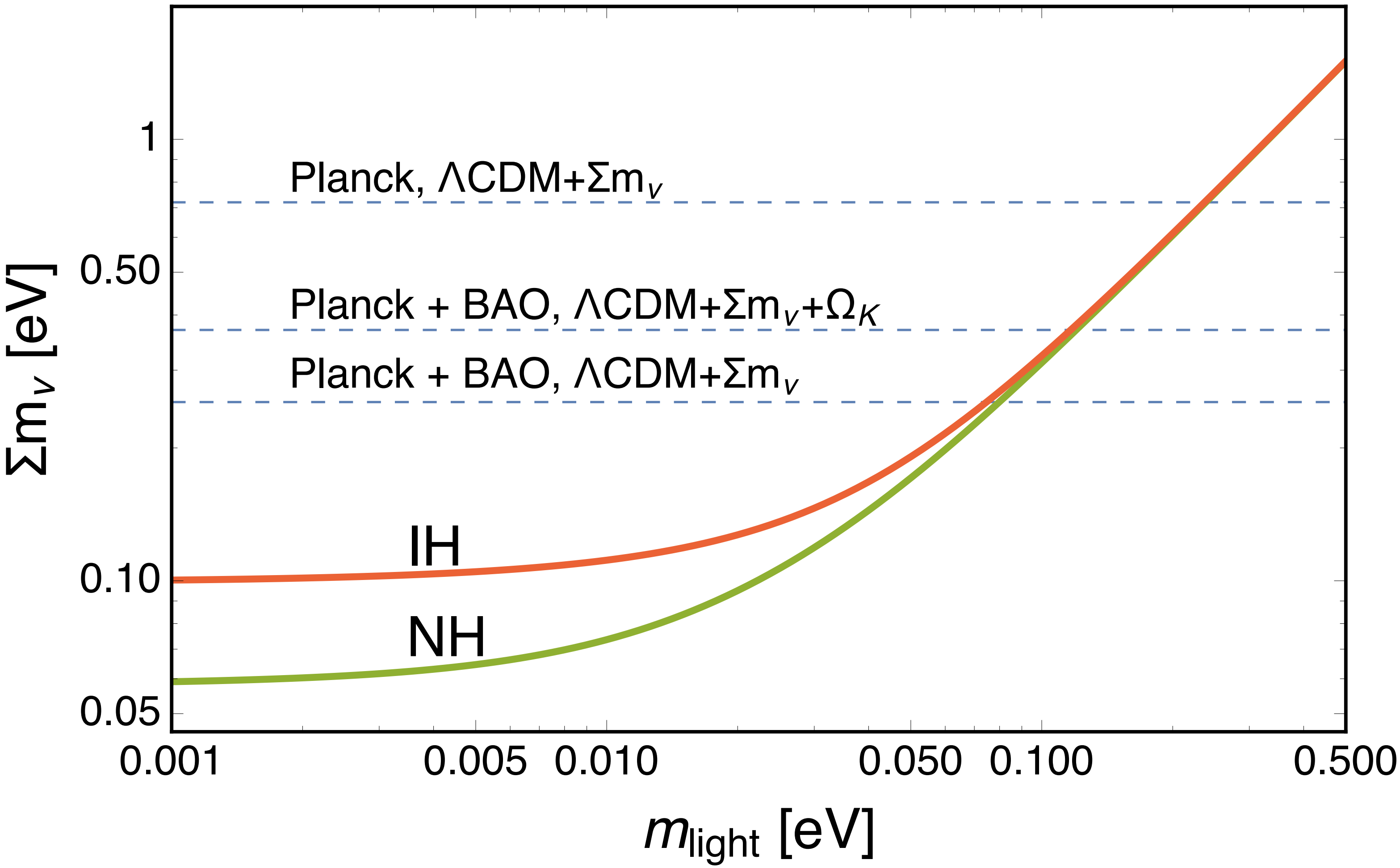
- $0\nu\beta\beta$ $m_{ee} < 0.2 - 0.7 - ?\ eV$ (nucl. matrix elements)

$m_{ee} = |\Sigma\, U_{ei}^2\, m_i|$

- Cosmology $\Omega_\nu\, h^2 \sim \Sigma_i m_i\ /94eV$ $(h^2 \sim 1/2)$

$\Sigma_i m_i < 0.23 - 0.8\ eV$ 95% Planck +BAO+WMAPPol+HighL

Any ν mass $< 0.08 - 0.27\ eV$ depends on cosmology priors



Planck, ΛCDM+Σm$_\nu$
Planck + BAO, ΛCDM+Σm$_\nu$+Ω$_K$
Planck + BAO, ΛCDM+Σm$_\nu$
IH
NH
Σm$_\nu$ [eV]
1
0.50
0.10
0.05
0.001
0.005
0.010
0.050
0.100
0.500
$m_{\rm light}$ [eV]

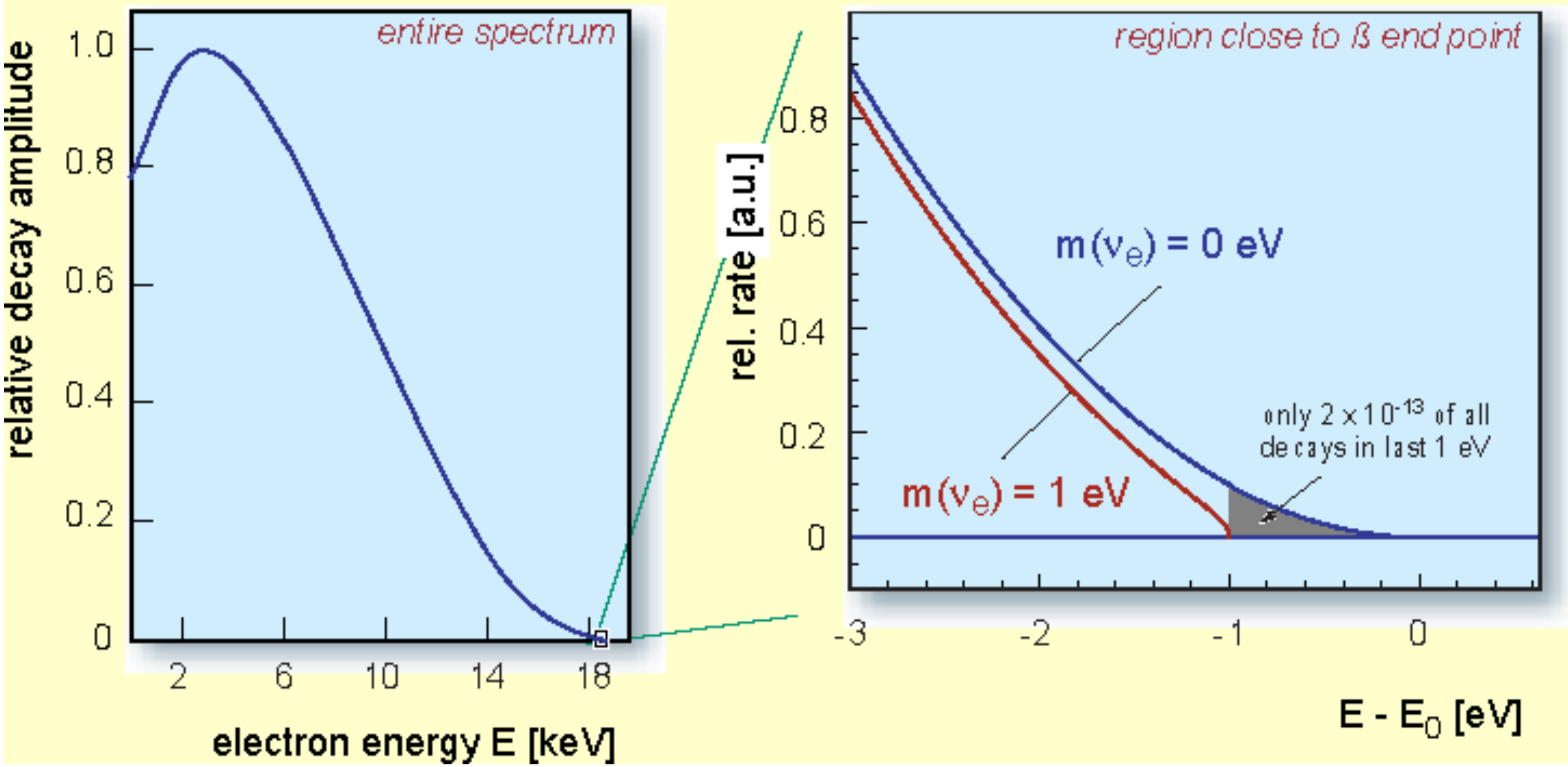
tritium ß-decay and the neutrino rest mass

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

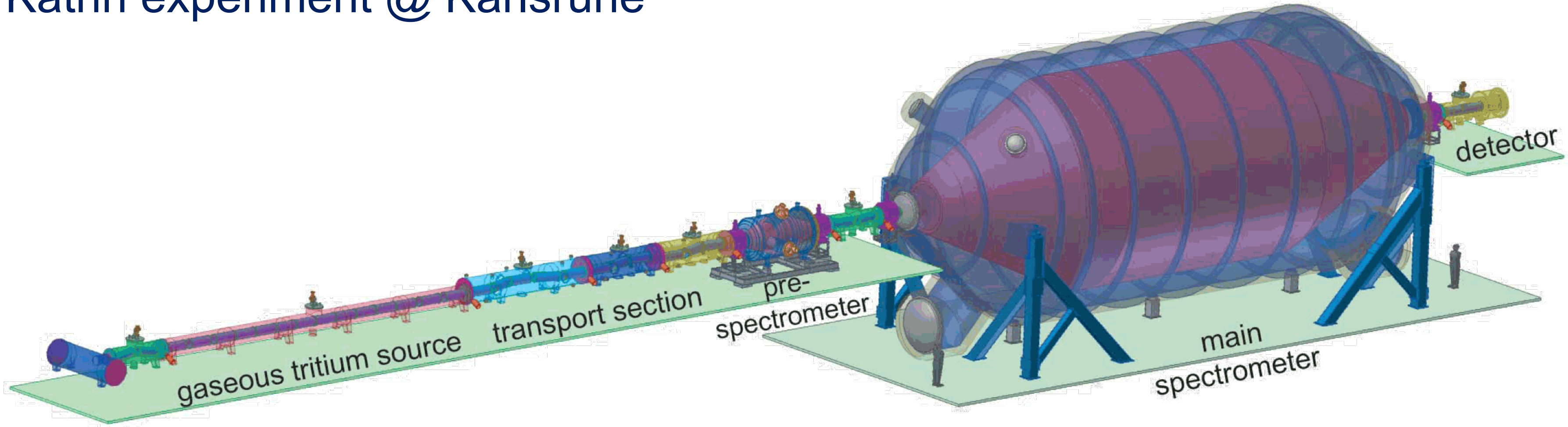
superallowed

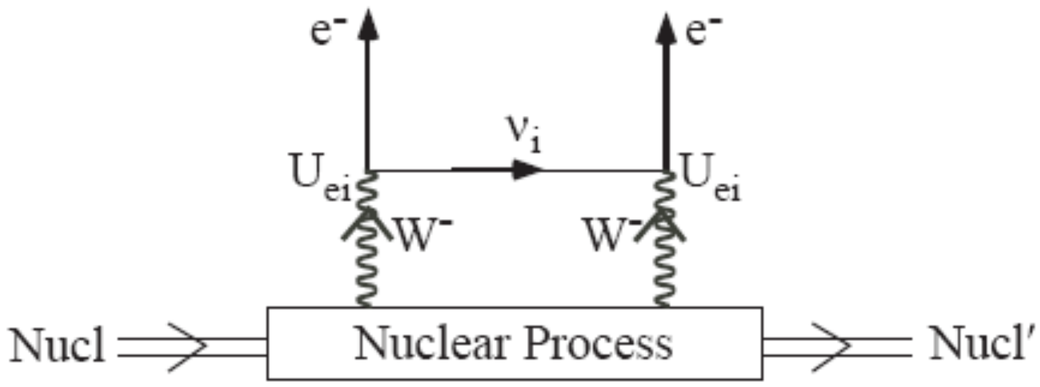
half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



Katrin experiment @ Karlsruhe



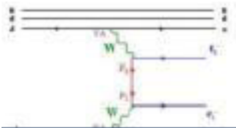


Neutrinoless double beta decay (0νββ)

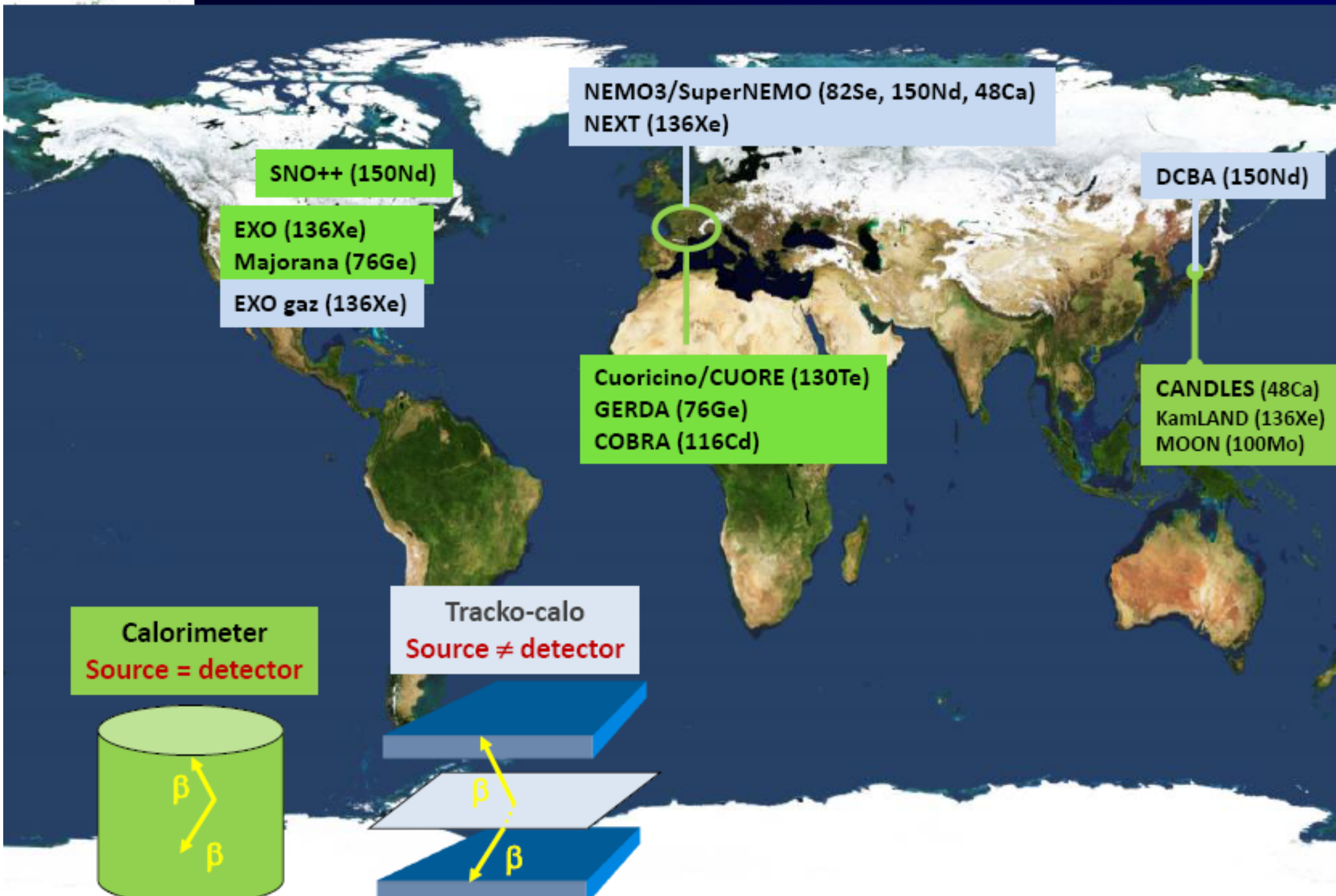
Not possible if neutrino is Dirac particle: $\bar{\nu} \neq \nu$

But possible if neutrino is Majorana particle: $\bar{\nu} = \nu$
(Violation of lepton number!)

Experimental sign: double beta decay, no energy lost by neutrinos
Rare! Need low noise detectors, excellent energy resolution!



ββ(0ν) : experiments and projects

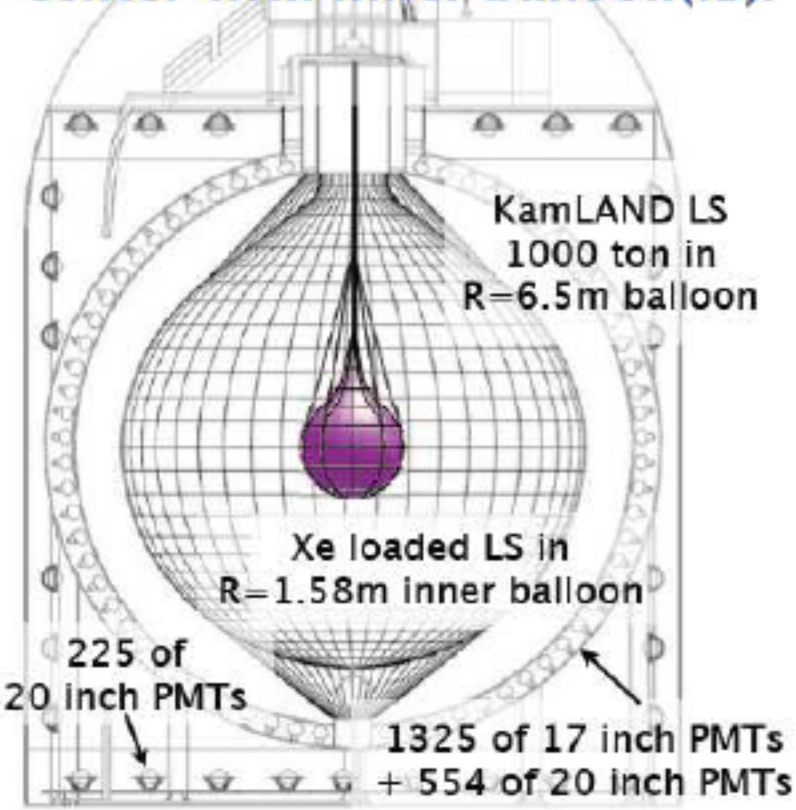


KamLAND-Zen(Zero neutrino double beta decay)

KamLAND-Zen :
Modification of KamLAND.
1,000 tons of
highly purified liquid scintillator.

BIG & Low BG

^{136}Xe loaded LS → into KamLAND
center with inner balloon(IB).



Double beta decay isotope
~300 kg of ^{136}Xe (91% enriched)
Largest amount for DBD experiment.
Already have another 200kg for next phase.
Q-value : 2.476MeV

Target for 1st phase
Search for KKDC claim and
Degenerated hierarchy.

Why Xe?
- Soluble to LS ~3% by weight.
- easily extracted.
- Isotopic enrichment, purification established.

Schedule
2011 Aug. Modification
Sep. 24th, 2011 data taking start
Oct. 12th, 2011 -Jan 2nd, 2012.
77.6 days data for 1st result.

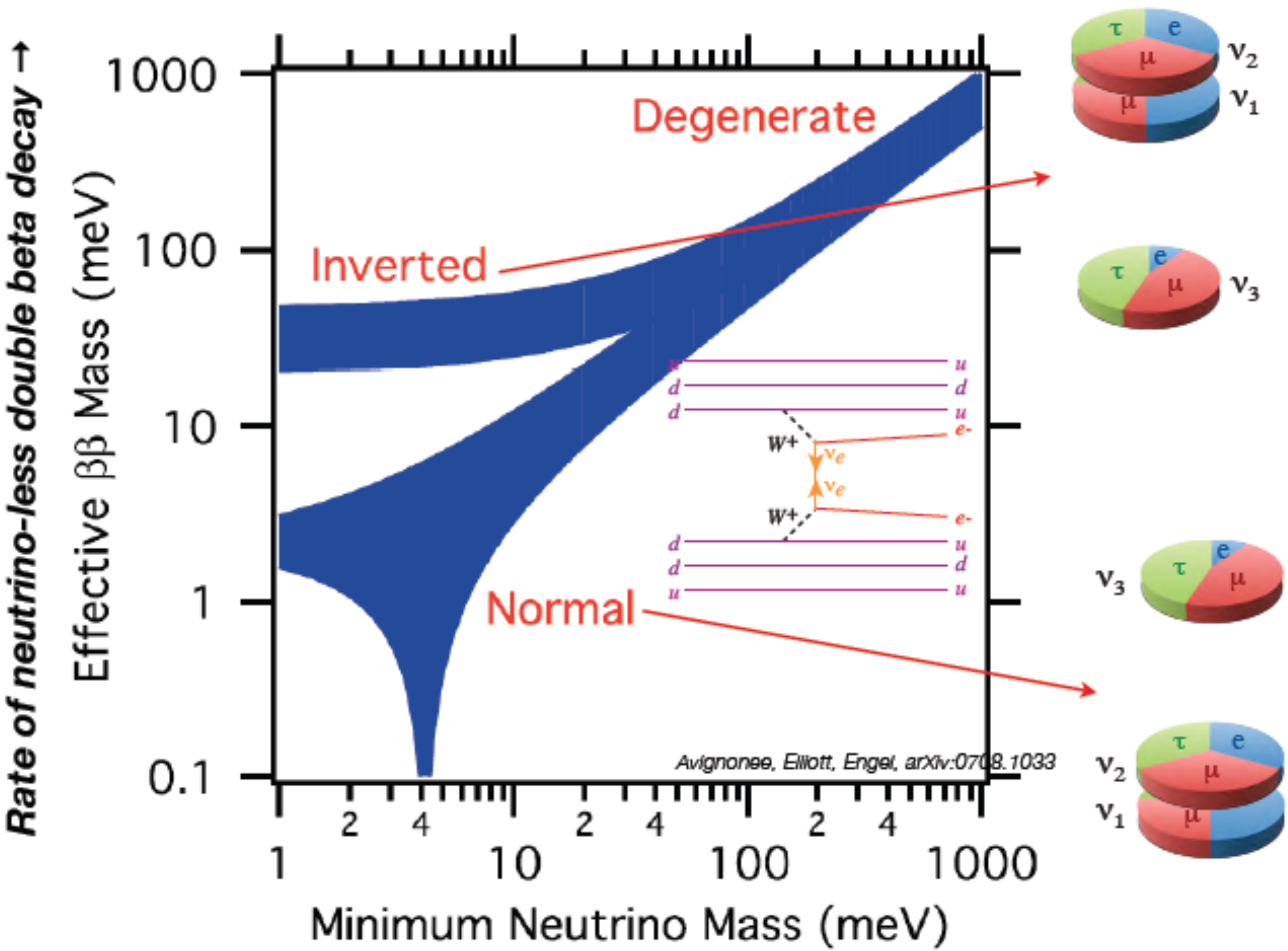
Present results on neutrinoless DBD

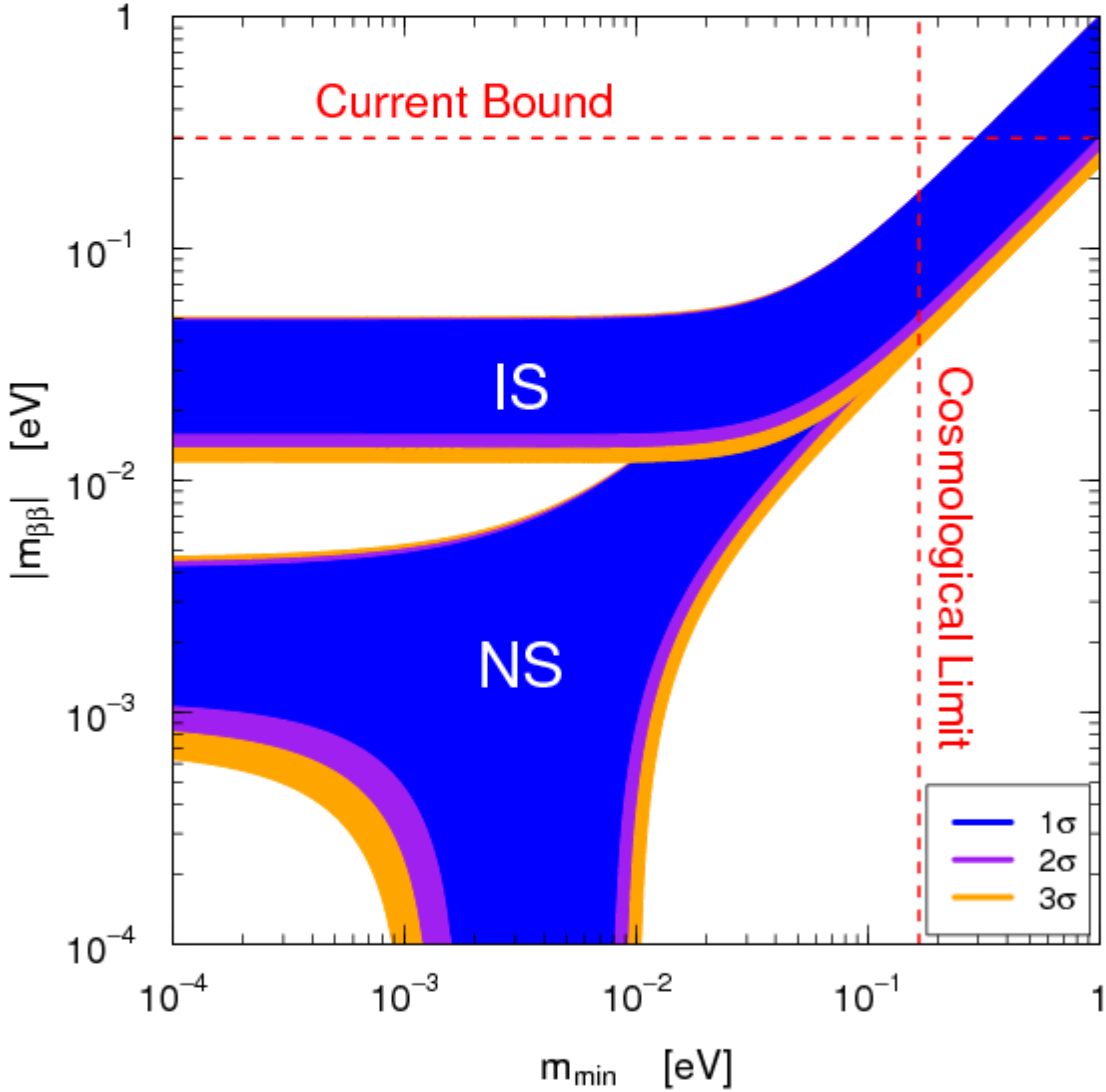
Fiorini

Isotope	Technique	$\tau^{0v}_{1/2\,(y)}$	$<m_{\beta\beta}>$ eV
^{48}Ca	CaF_2 scint	>1.4x10^{22}	<7-45
^{76}Ge (HM)	Ge diode	>1.9x10^{25}	<(0.3-1.27)
^{76}Ge (IGEX)	Ge diode	>1.6x10^{25}	<(0.33-1.35)
^{76}Ge (Klapdor 2004)	Ge diode	1.2x10^{25}	.38
^{76}Ge (Klapdor 2006)	Ge diode	2.2x10^{25}	.28
^{76}Ge (GERDA I)	Ge diode	>2.1x10^{25}	<(.29-1.1)
^{76}Ge (GERDA+HM+IGEX)	Ge diode	>3x10^{25}	<(.25-.98)
^{82}Se	Foil&track	>.6x10^{23}	<(0.89-2.)
^{96}Zr	Foil&track	>9.2x10^{21}	<(7.2-19.5)
^{100}Mo	Foil&track	>1.1x10^{24}	<(0.31-.79)
^{116}Cd	Scintillator	>1.7x10^{23}	<1.7
^{128}Te	Geochem	>7.7x10^{24}	<(1.1-1.35)
^{130}Te	Bolometer	>2.8x10^{24}	<(0.3-.7)
^{136}Xe	EXO	>1.6x10^{25}	<140-380
^{136}Xe	Kamland Zen	>1.9x10^{25}	**<128-349**
^{136}Xe	EXO+Kamzen		<120-250
^{150}Nd	Foil TPC	>1.8x10^{22}	

here Ettore forgot the dot: 0.140 etc

Mass hierarchy and the nature of the neutrino





Current Bound
Cosmological Limit
IS
NS
1σ
2σ
3σ
$|m_{\beta\beta}|$ [eV]
m_{min} [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Why CP Violation (~~CP~~) In Neutrino Oscillation Would Be Very Interesting

It would establish that ~~CP~~ is not special to quarks.

A major motivation to look for it:

Its observation would make it more plausible that —

— the baryon-antibaryon asymmetry of the universe —

— arose, at least in part, through **Leptogenesis**.

Leptogenesis

Explains the baryon-antibaryon asymmetry of the universe by CP-violating heavy neutrino decays.

Heavy ($m_N > 10^9$ GeV) Majorana neutrino

SM lepton

SM BEH scalar boson

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

This $\not{CP}$ creates a ***lepton-antilepton*** asymmetry.

The SM Sphaleron process converts part of this asymmetry into the observed ***baryon-antibaryon*** asymmetry.

Generically, leptogenesis and light-neutrino $\not{CP}$ imply each other.

(B.K. 1012.4469)

Baryogenesis I: Electroweak Baryogenesis

Sakharov's Conditions

1. Baryon number violation → satisfied by **sphaleron transitions** ✓ *(see next slide)*
2. Violation of C and CP → satisfied by **weak force** ✓
3. Conditions in which processes take place out of thermal equilibrium → satisfied **if Electroweak Phase Transition was first-order** ✓ *(see below)*

Electroweak Phase Transition

- The transition to a phase with massive gauge bosons
- Whether it is first- or second-order depends on the mass of the Higgs boson

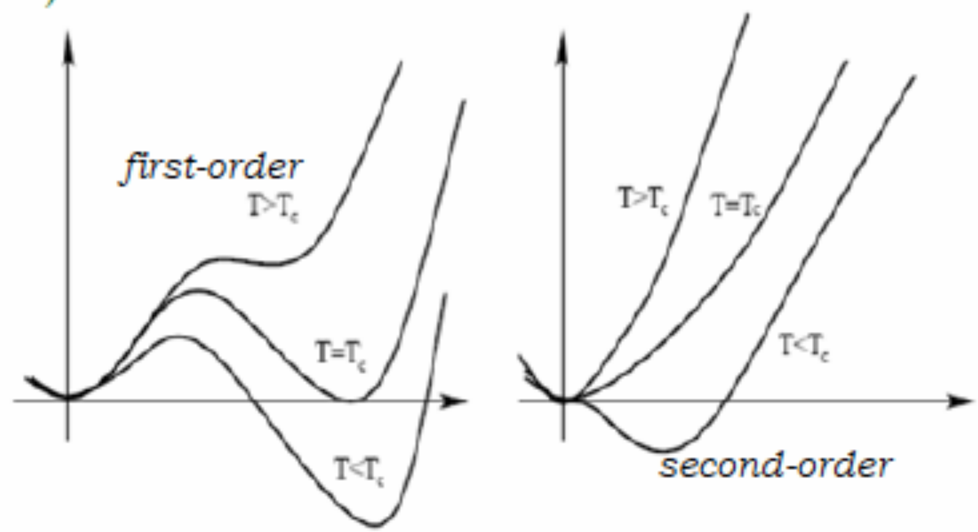


Image from Dine et al. (Ref. 2)

Sphaleron Transitions

Yang-Mills vacuum structure (non-Abelian gauge theory):

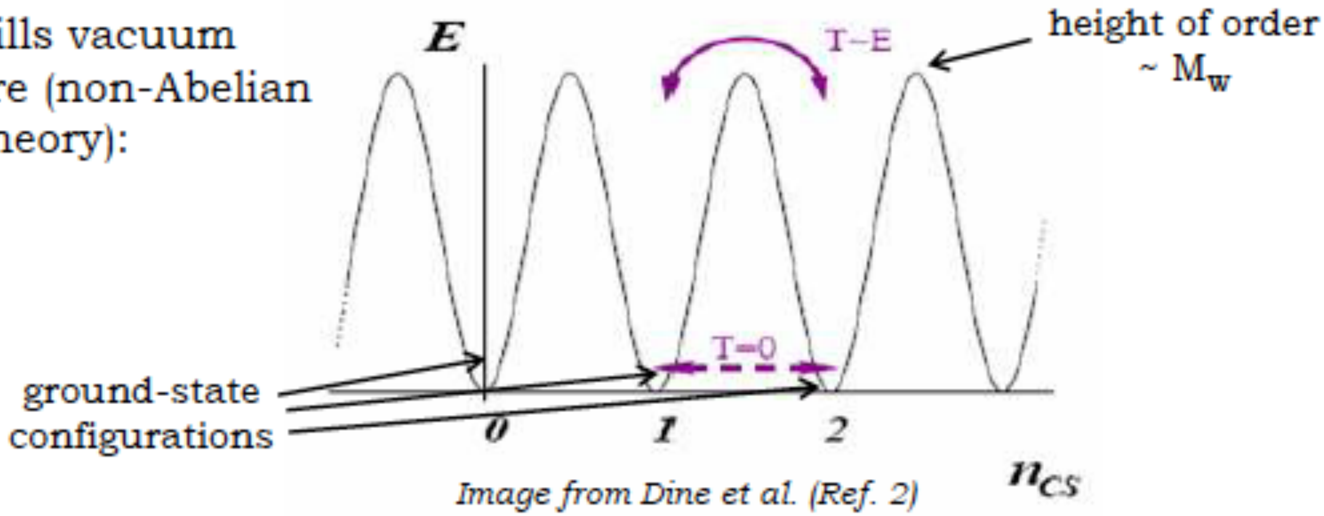


Image from Dine et al. (Ref. 2)

- Transitions among the different ground-state configurations conserve (B-L), but not B and L separately
- The probability of tunneling decreases as the universe cools, and within a given minimum (e.g. the universe today) B and L are conserved separately
- These processes also play an important role in the mechanism of leptogenesis (to be covered later in the talk)

Leptogenesis: Starting from Seesaw

A Dirac mass term couples a right-handed field to a left-handed field or vice versa.

A Majorana mass term couples a right-handed field to another right-handed field or vice versa.

Type I Seesaw introduces heavy right-handed singlet neutrinos as counterparts to the familiar light neutrinos in order to provide a 'natural' explanation for the small mass of the neutrino:

Mass matrix for (ν_L, ν_R) system

$$\begin{pmatrix} 0 & h_\nu v \\ h_\nu^T v & M_R \end{pmatrix} \Rightarrow m_\nu \approx -h_\nu^2 v^2 / M_R$$

Dirac terms: similar scale to quark, charged lepton sectors

Majorana term: much heavier, $M_R >> h_\nu v$

* Majorana neutrinos explicitly violate L

* L can be converted to B by sphaleron processes

The 3-ν paradigm successfully describes many experimental results,

but not all.

Are There

More Than 3

Mass Eigenstates?

Are There

Sterile Neutrinos?

Sterile Neutrino

One that does not couple to the SM W or Z boson

A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

Sterile ν's? A number of "hints" with some "tensions"

(they do not make an evidence but pose an important experimental problem that needs clarification)

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

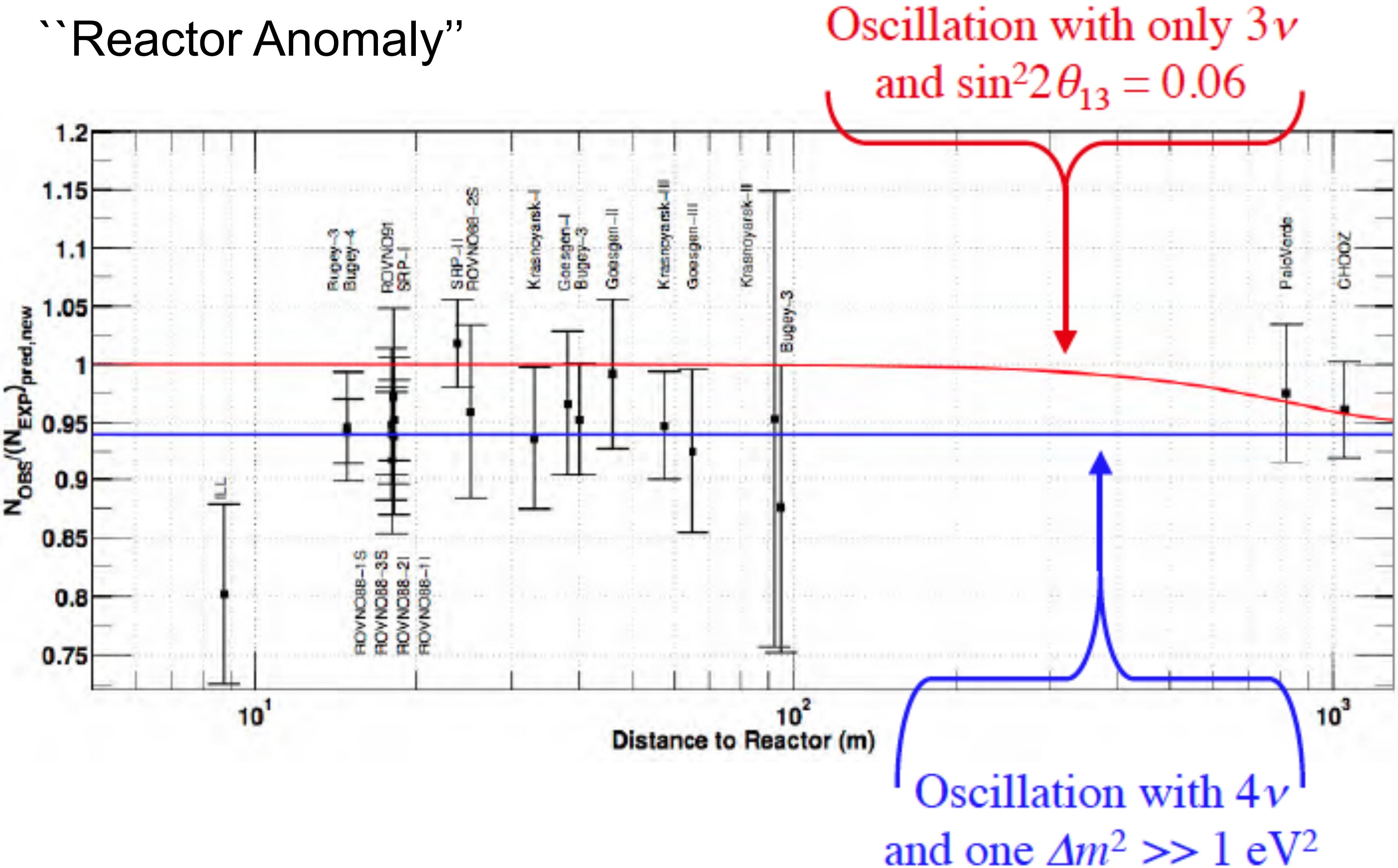
- LSND and MiniBoone (appearance)
- Reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium (ν_e disappearance)

These data hint at sterile neutrinos at ~ 1 eV which would represent a major discovery in particle physics

Important information also from

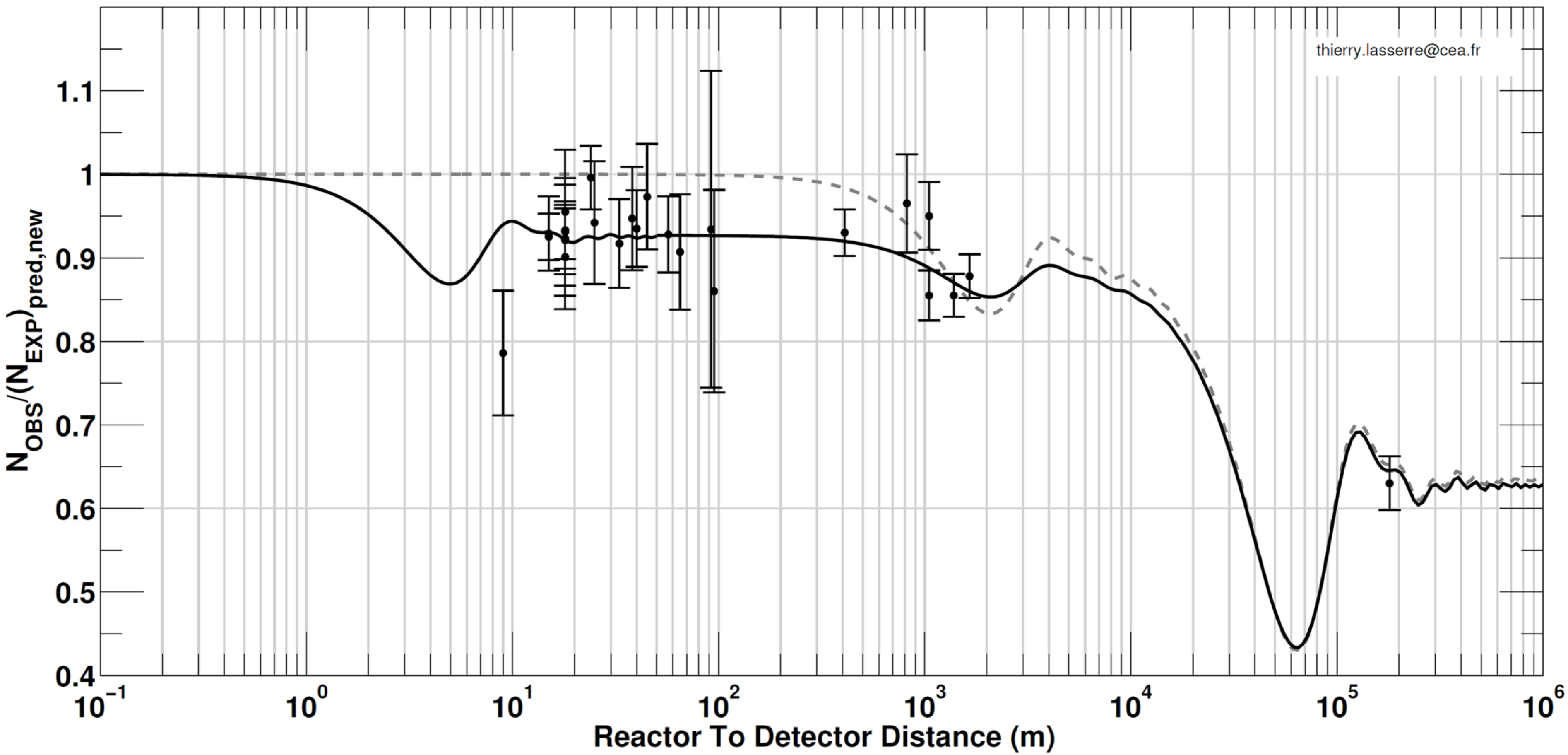
- ν_μ / ν^{bar}_μ disappearence expts (MINOS, CDHSW, CCFR...)
- Neutrino counting from cosmology

``Reactor Anomaly''



Disappearance at $L(\text{m})/E(\text{MeV}) \gtrsim 1$ suggests oscillation with $\Delta m^2 \gtrsim 1$ eV^2, like LSND and MiniBooNE.

dashed: 3 neutrino flavours + oscillations
full: 3 + 1 flavours



Latest news, april 2017:

https://phys.org/news/2017-04-antineutrino-anomaly-fueled-error.html

The Hint From ^{51}Cr and ^{37}Ar Sources

These radioactive sources were used to test gallium solar ν_e detectors.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05$$

(Giunti, Laveder)

Rapid disappearance of ν_e flux due to oscillation with a large Δm^2??

The Hint From Cosmology

Big Bang Nucleosysthesis (BBN) and CMB anisotropies count the effective number of relativistic degrees of freedom, N_{eff}, at early times.

Light sterile neutrinos mixed with the active ones as required by the terrestrial anomalies would very likely have thermalized in the early universe.

Then N_{eff} grows by 1 for each sterile species.

The evidence suggests that perhaps $N_{\mathrm{eff}} > 3$.

N_{eff} From BBN

Model	Data	N_{eff}	Ref.
$\eta+N_{\mathrm{eff}}$	$\eta_{\mathrm{CMB}}+Y_{\mathrm{p}}$+D/H	$3.8^{(+0.8)}_{(-0.7)}$	[10]
	$\eta_{\mathrm{CMB}}+Y_{\mathrm{p}}$+D/H	$<(4.05)$	[11]
		3.85 ± 0.26	[13]
	Y_{p}+D/H	3.82 ± 0.35	[13]
		3.13 ± 0.21	[13]
$\eta+N_{\mathrm{eff}}, (\Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - 3.046 \geq 0)$	η_{CMB}+D/H	3.8 ± 0.6	[12]
	$\eta_{\mathrm{CMB}}+Y_{\mathrm{p}}$	$3.90^{+0.21}_{-0.58}$	[12]
	Y_{p}+D/H	$3.91^{+0.22}_{-0.55}$	[12]

Cosmology is fully compatible with N_{eff} ~3 but could accept one sterile neutrino

The bound from nucleosynthesis is the most stringent (assuming thermal properties at decoupling)

- BBN:
  - $N_s = 0.22 \pm 0.59$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]
  - $N_s = 0.64^{+0.40}_{-0.35}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

ΔN_s

- BBN: $N_s < 1.2$ (95% CL) Mangano, Serpico, 1103.1261

- BBN: $N_s < 1.54$ (95% CL) [M. Pettini, et al, arXiv:0805.0594]

A "simple" cosmology emerges from Planck

No evidence for sterile neutrinos

N_{eff}=3.36±0.34

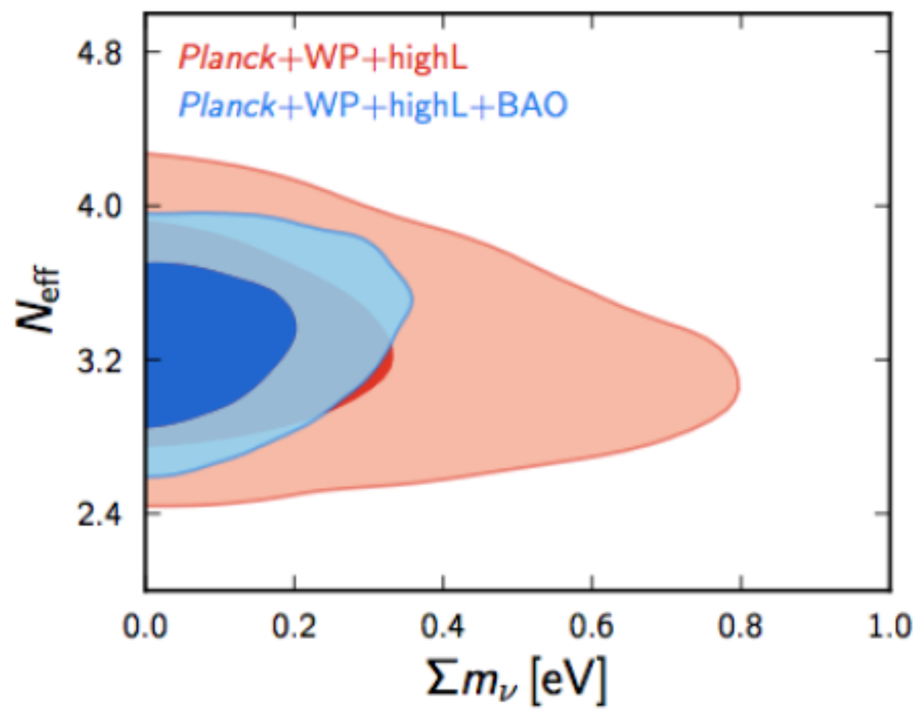
More precise values of cosmological parameters

$\Omega_\Lambda=0.686\pm0.020$

$\Omega_m=0.314\pm0.020$

$\Omega_b h^2=0.02207\pm0.00033$

$h=0.674\pm0.014$



Σm_ν< 0.23 - 0.80 eV

Neutrinos the next steps

In fact there are several directions to study the neutrino paradigm

1. Neutrino oscillations: determine mass hirarchy and search *CP* violation. Measure precisely the mixing parameters

2. Search for neutrino less double beta decay
Present level 0.5 eV. Next level 200 meV. Need more than one isotope!

3. Search for sterile neutrinos (a..k.a. right handed neutrinos)
- if there is a Dirac mass term they should exist!

4. Determine the mass of neutrinos by direct measurement.