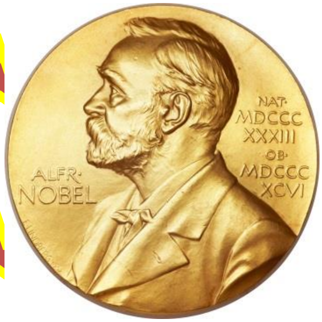
Neutrino Physics

today, tomorrow ... or later



1. Neutrinos have mass!

2. What are neutrinos and how do we know

3. Light neutrinos and heavy neutrinos

4. light neutrino physics ... mass hierarchy, CP violation

5. heavy neutrino physics
   -- neutrinoless double beta decay (Majorana mass term?)
   -- search for heavy neutrinos : SBN, SHIP, FCC

Who are the neutrinos ?

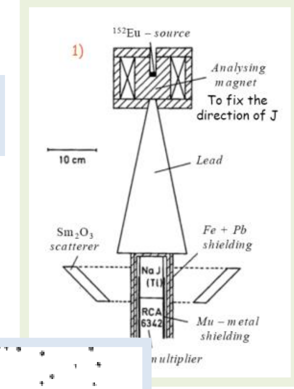
1930 W. Pauli introduces neutrinos to solve *both* the 'missing energy' and the 'missing angular momentum' problems in nuclear beta decay

1956-59 $\bar{\nu}_e$ are discovered at reactors (Reines/Cowan)

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

ν_e are *not* discovered at reactors (Davis)

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



1957 neutrinos have ***negative helicity***

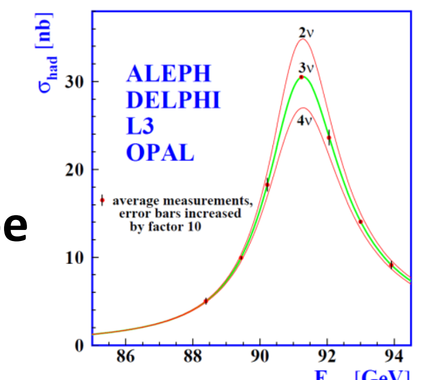
$$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu$$

1962 neutrinos from pion decays are $\boldsymbol{\nu_\mu}$ **, not** $\boldsymbol{\nu_e}$

1974 neutrino also interact by neutral currents
Experimental birth of the Standard Model

1975 τ lepton discovered, ν_s from $\tau \rightarrow \pi\nu$ are $\boldsymbol{\nu_\tau}$ **not** $\boldsymbol{\nu_\mu}$ **or** $\boldsymbol{\nu_e}$

1989 LEP : there are 3 types of active neutrinos only.
The Standard Model includes 3 massless neutrino type



The Standard Model:
3 families of spin ½ quark and leptons
interacting with spin 1 vector bosons (g, W&Z, gluons)

charged leptons	e	μ	τ
	mc^2=0.0005 GeV	0.106 GeV	1,77 GeV
neutral leptons = neutrinos	ν_e	ν_μ	ν_τ
	mc^2 ?=? <0.2 eV	<0.2 eV	<0.2 eV
quarks	d	strange	beauty
	mc^2=0.005 GeV	0.200 GeV	5 GeV
	u	charm	top
	mc^2=0.003 GeV	1.5 GeV	mc^2=175 GeV
	First family	Seconde family	Third family

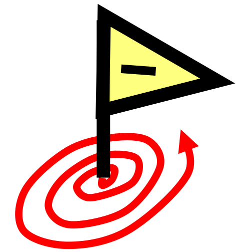
some remarkable symmetries:

each quark comes in 3 colors

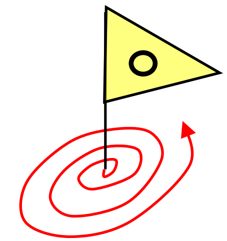
sum of charges is

$$-1 + 0 + 3 \times (\, 2/3 \;\; - 1/3) = \mathbf{0}$$

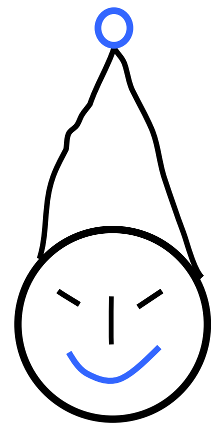
this turns out to be a necessary condition for the stability of univers because of higher order radiative corrections



Electron
charge -1

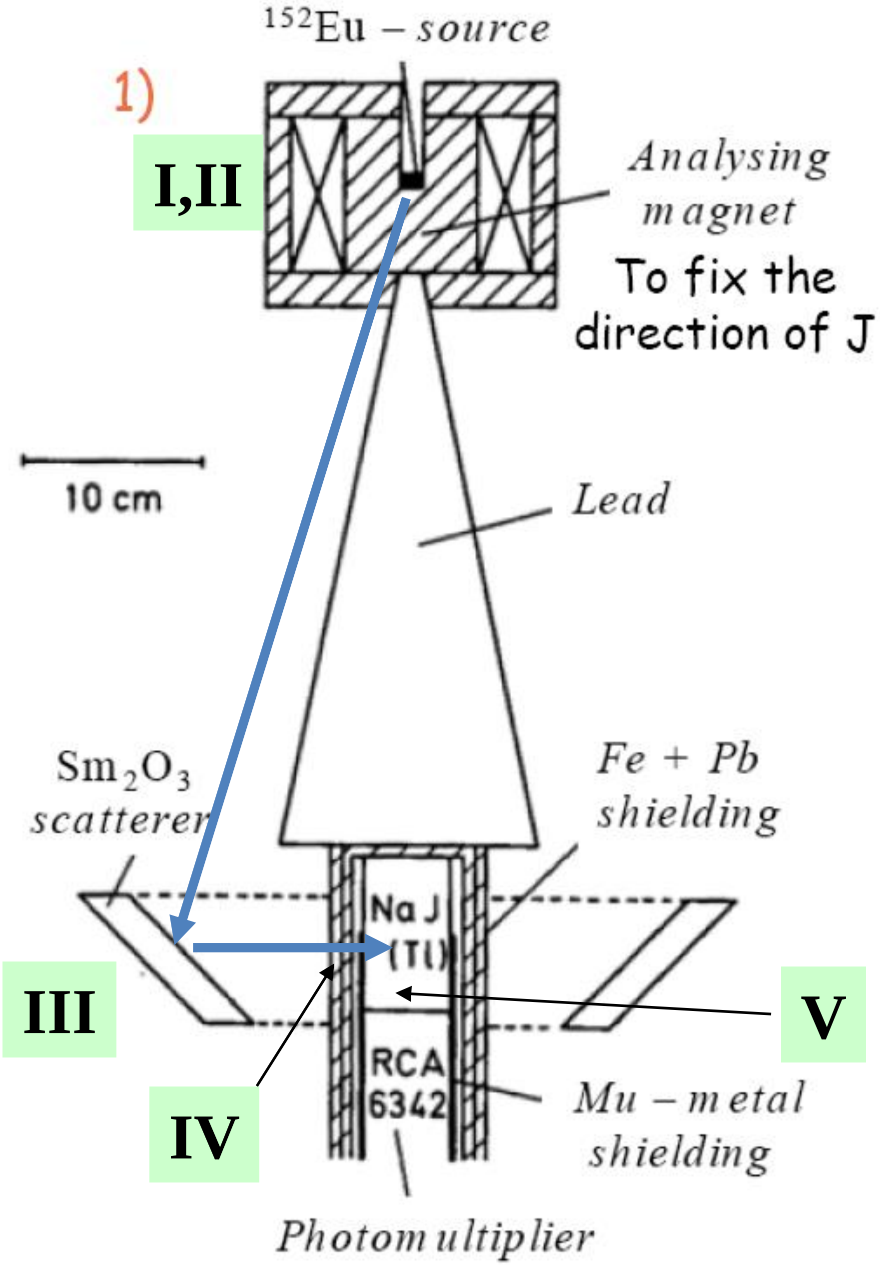


Neutrino
charge 0



Quark up
charge 2/3

Quark down
charge -1/3



Step I neutrino emission

$$^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu$$

Step II photon emission

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

E_γ = 961 keV/c (1 ± v (Sm*) /c)

Step III photon absorption/emission

$$\gamma + {}^{152}Sm \rightarrow {}^{152}Sm^*$$

E_γ > 961 keV/c

$$^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

Step IV photon filter through magnetic iron

Step V photon detection in NaI cristal

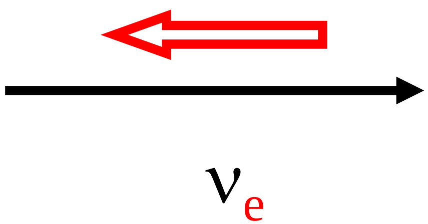
A stunning property

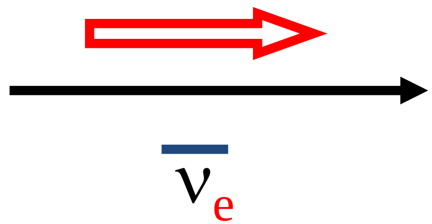
1957: Neutrino helicity is measured (M. Goldhaber et al):

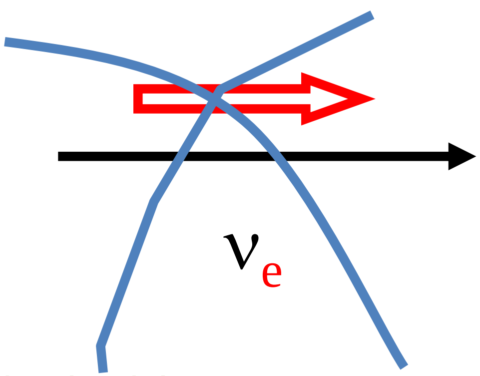
Neutrinos have negative helicity (spin clockwise) (left-handed)

since: Anti-neutrinos have positive helicity (spin earth-wise) (right-handed)

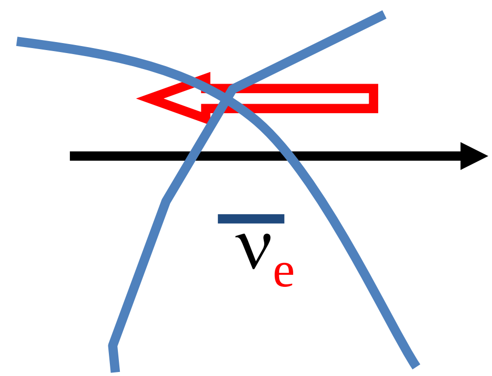
➔ **Parity violation**



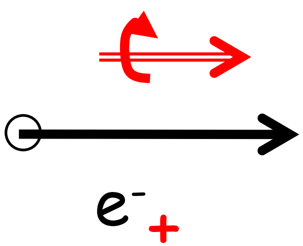


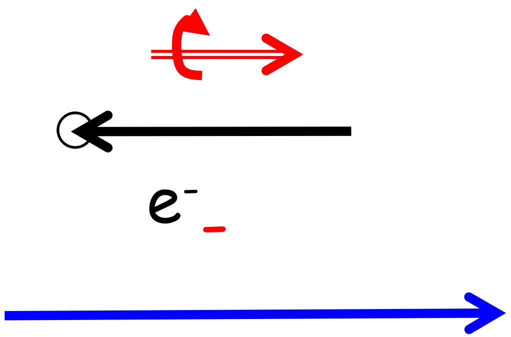


Never observed!



However, if neutrinos had mass it would be possible to do this:

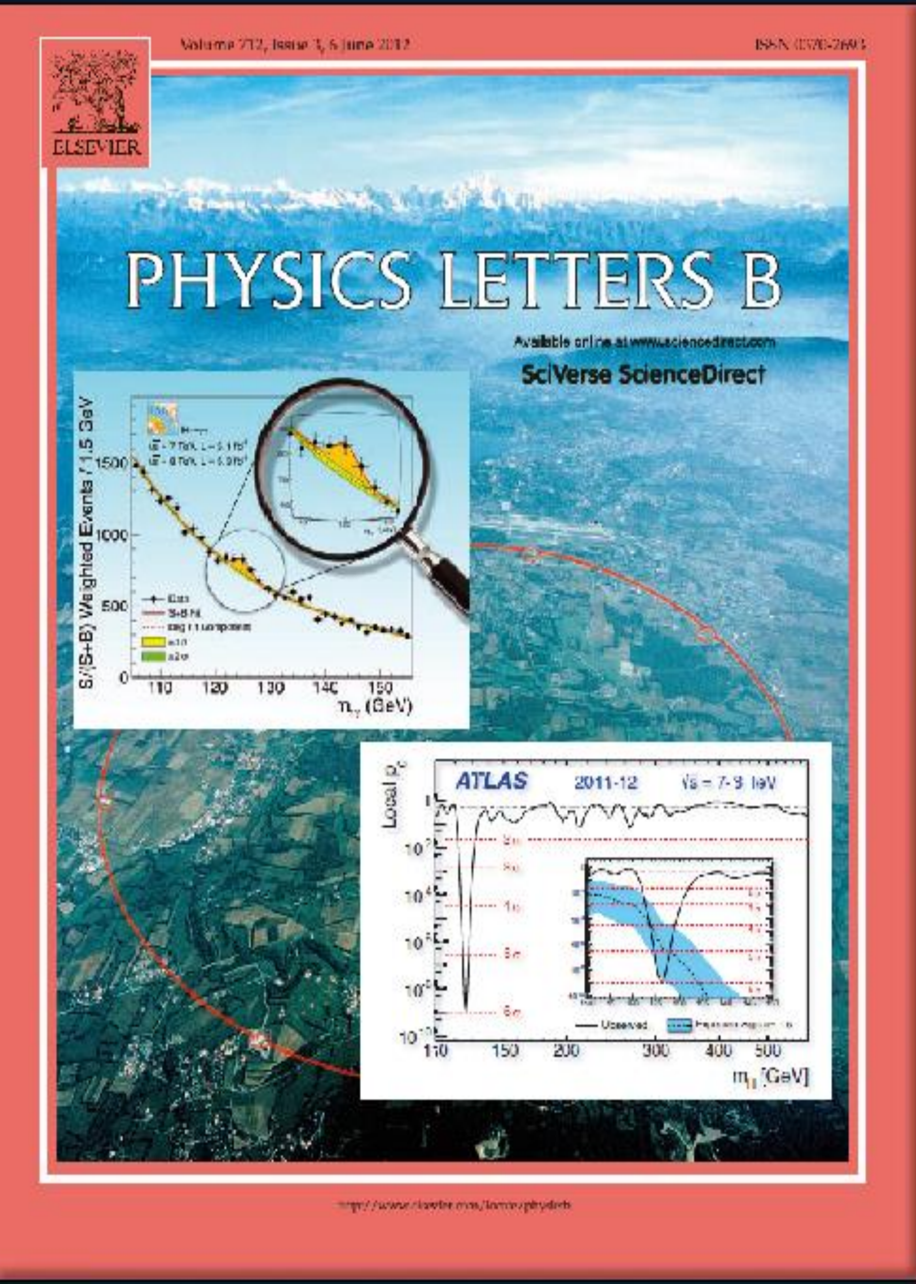




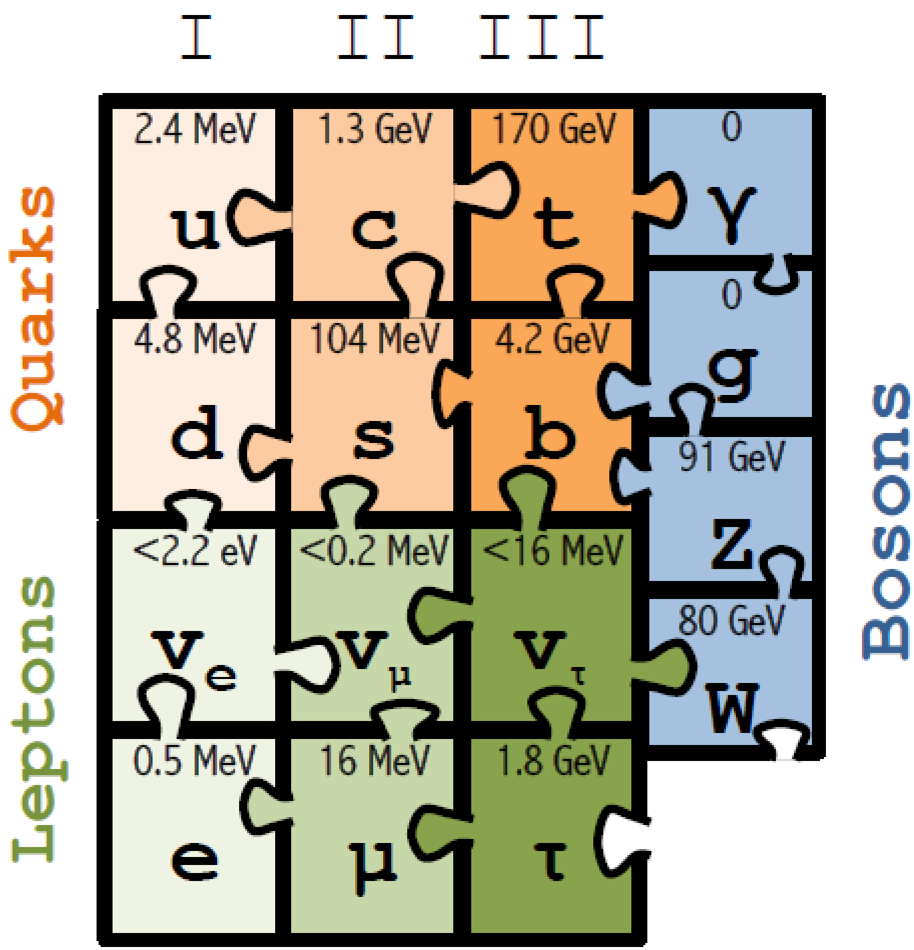
Lorentz boost

The Standard Model finesses the issue by assuming neutrinos have no mass.

FOUR YEARS AGO ALREADY



1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize

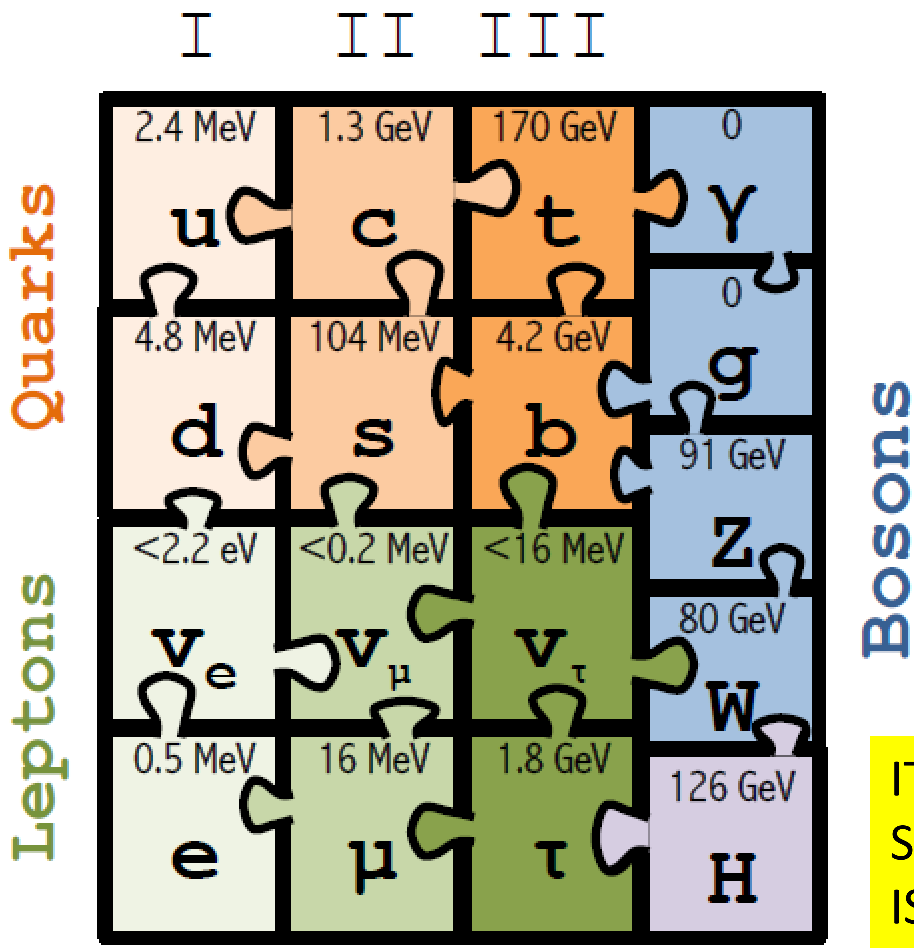


(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

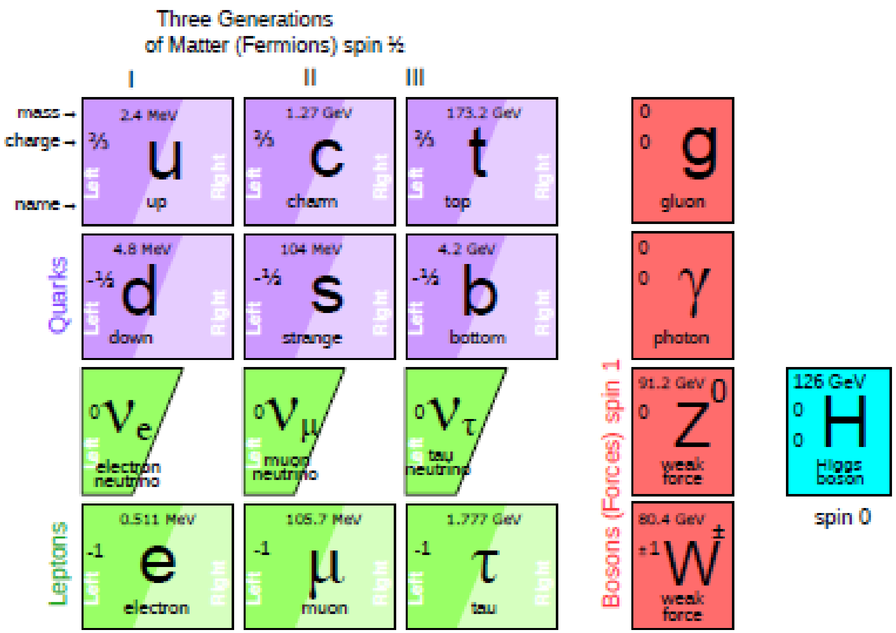
Englert and Higgs get Nobel Prize



IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

(c) Sfyrla

at least 3 pieces are still missing



The right handed neutrinos are missing!

Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Q | Terms

Breakthrough prize

LAUREATES

Breakthrough Prize   Special Breakthrough Prize   New Horizons Prize   Physics Frontiers Prize

2016   2015   2014   2013   2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration


Koichiro Nishikawa and the K2K and T2K Collaboration


Atsuto Suzuki and the KamLAND Collaboratio


Arthur B. McDonald and the SNO Collaboration


Takaaki Kajita and the Super K Collaboration


Yoichiro Suzuki and the Super K Collaboration

The prize, presented by the Breakthrough Prize Foundation, was awarded "for the fundamental discovery of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics".

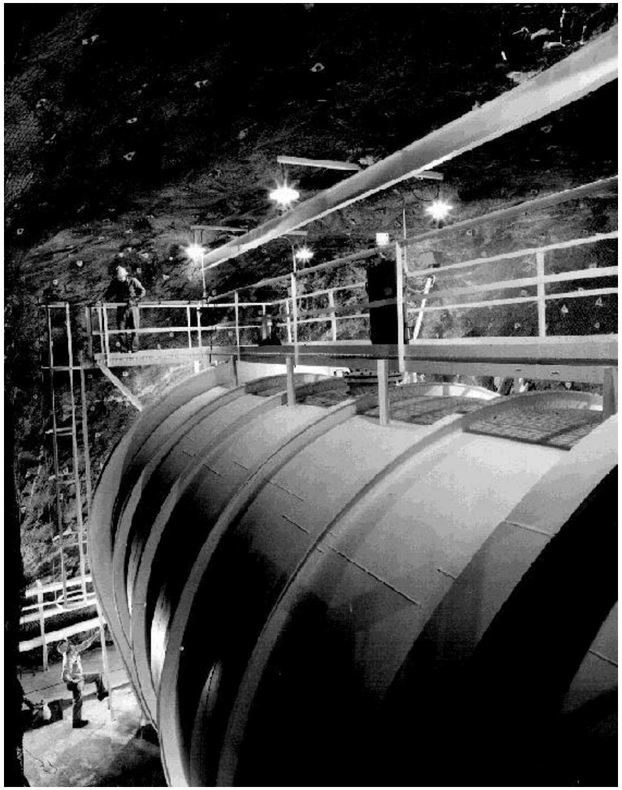
CP violation and the existence of heavy right-handed neutrinos are expected, and will provide an intense reseach program for many years to come. Neutrinos are leading candidates to explain the dominance of matter over anti-matter in the Universe, and constitute good dark matter candidates.

Neutrinos
astrophysical neutrinos

Ray Davis

since ~1968

Homestake Detector



Solar Neutrino Detection
600 tons of chlorine.

- Detected neutrinos E> 1MeV
- fusion process in the sun

solar : pp $\rightarrow$ pn e^{+} ν_e (then D gives He etc…)

these ν_e do $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^{-}$

they are neutrinos

- The rate of neutrinos detected is **three** times less than predicted!

solar neutrino 'puzzle' since 1968-1975!

solution: 1) solar nuclear model is wrong or 2) neutrino oscillate

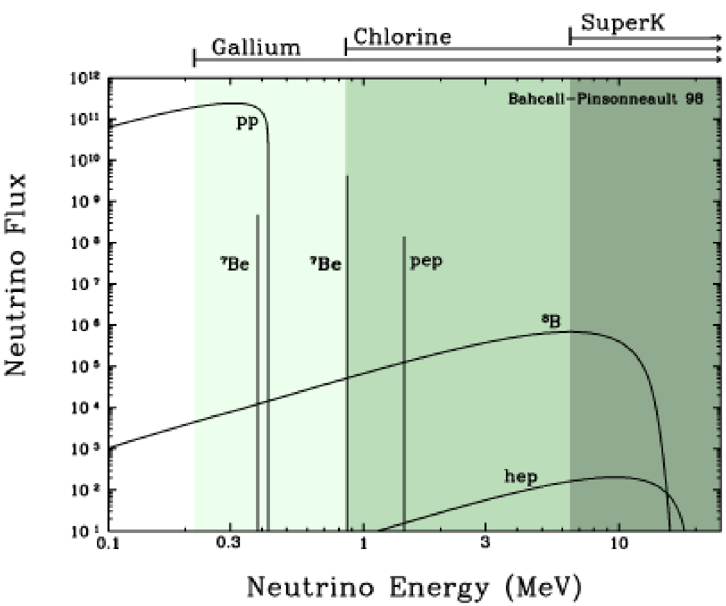
ν_e solar neutrinos

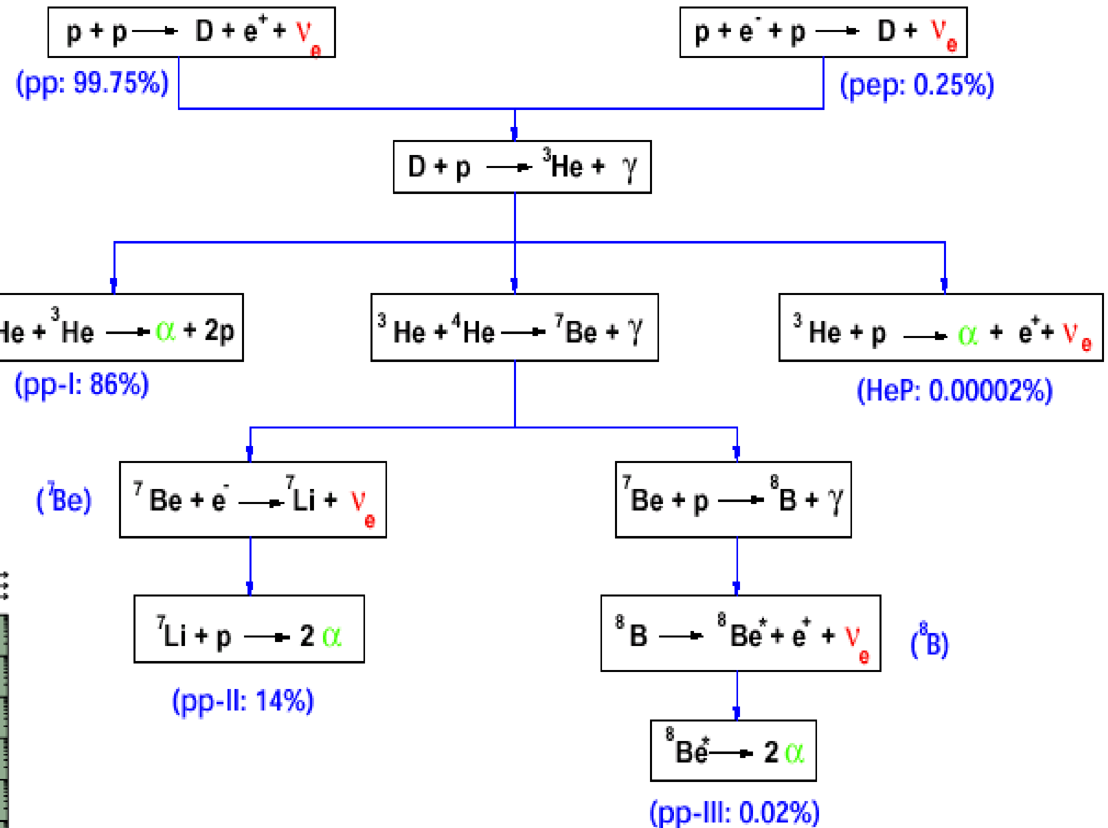
Sun = Fusion reactor

Only ν_e produced

Different reactions

Spectrum in energy



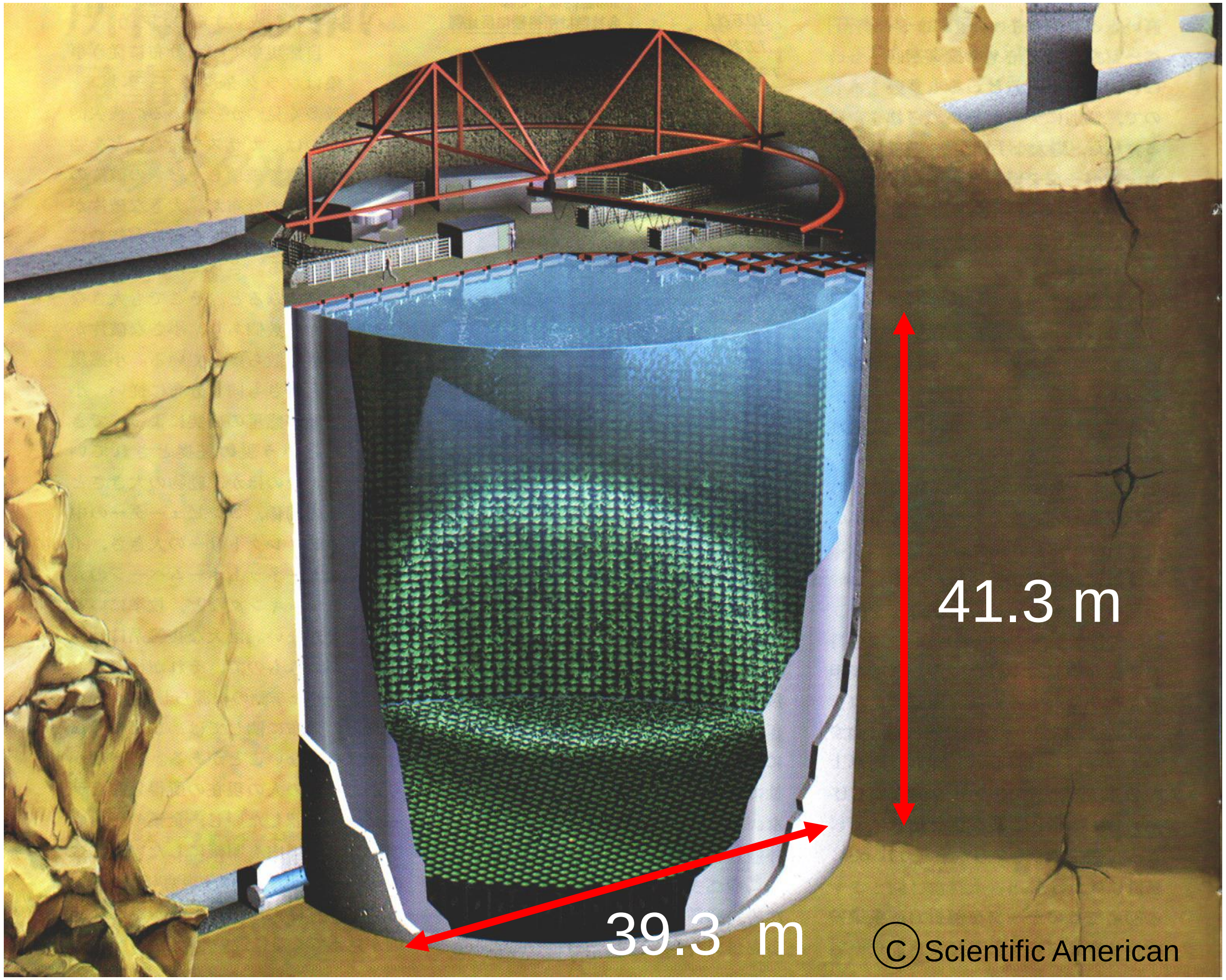


Counting experiments vs flux calculated by SSM

BUT ...

Super-K detector

Koshiba (Nobel 2002)



Masatoshi Koshiba

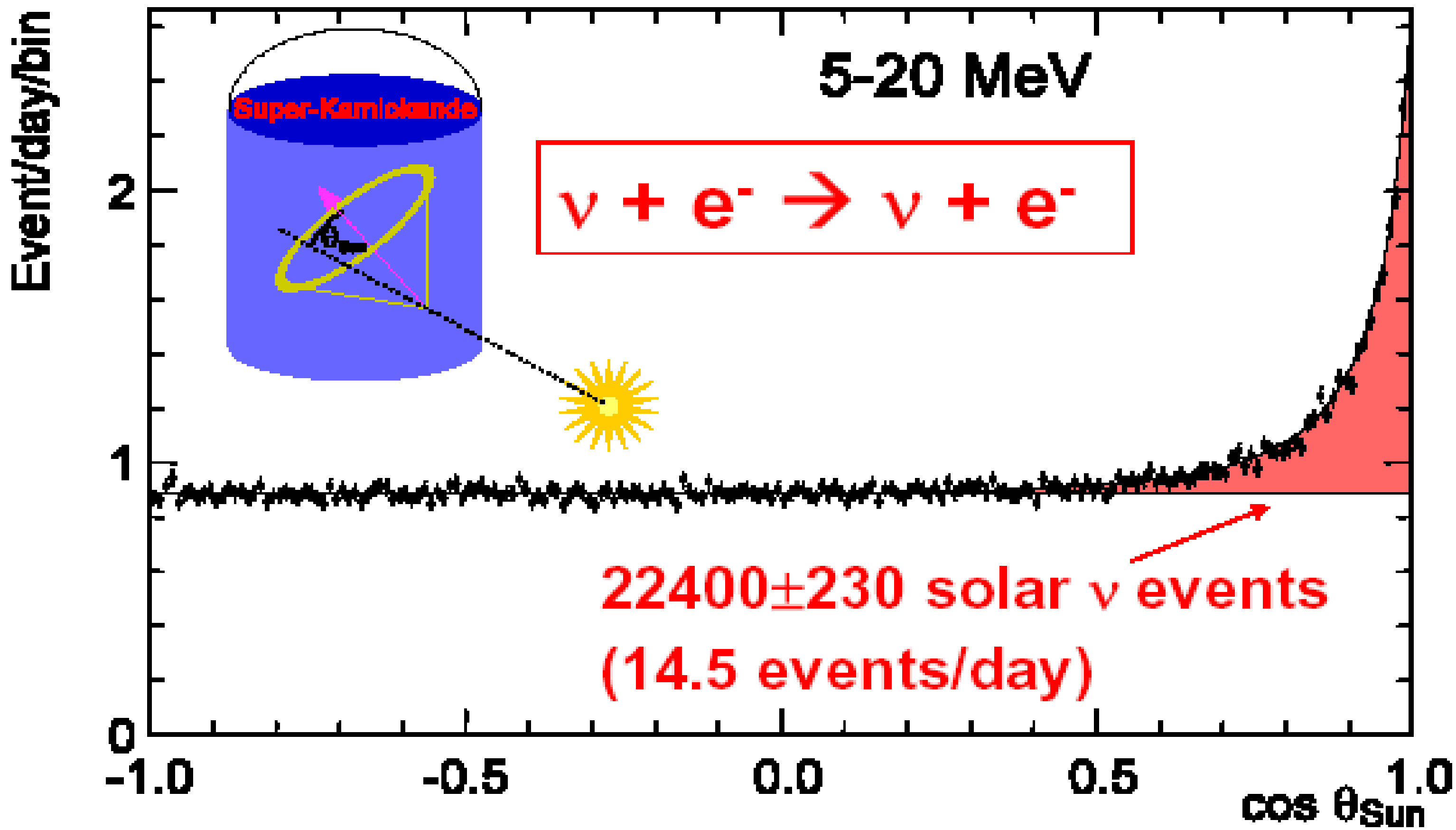
Cerenkov
à Eau

50000 tonnes d'eau
ultra-pure

≈10000 Photo
Multiplicateurs de
80 cm de diamètre à
10k$ pièce)

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, {}^{+0.014}_{-0.013}$$

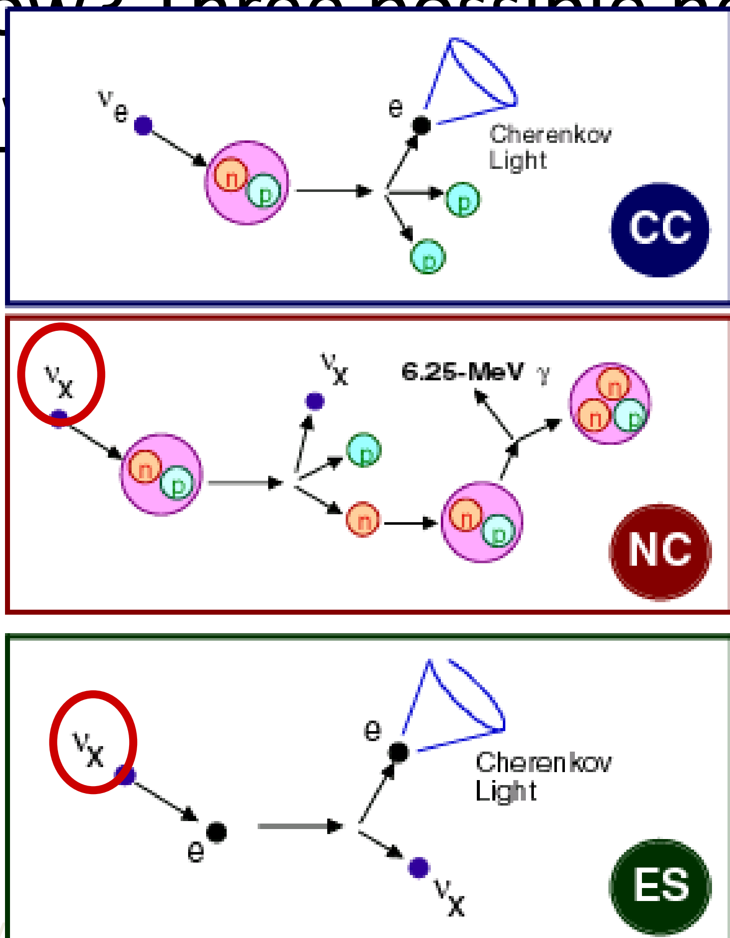
(Data/SSM(BP2000) = $0.465 \pm 0.005 \, +0.016/-0.015$)

Art Mc Donald:

SNO detector

are there non-ν_e neutrinos in pure solar ν_e bea

How? Three possible neutrino reaction in heavy



only ν_e

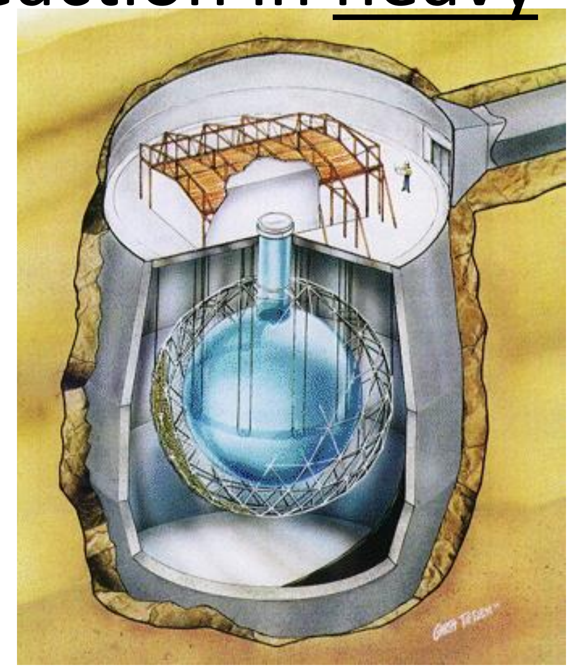
equally

$\nu_e + \nu_\mu + \nu_\tau$

in-equally

$\nu_e +$

$0.1\ (\nu_\mu + \nu_\tau)$



1000 ton of $D_2 0$

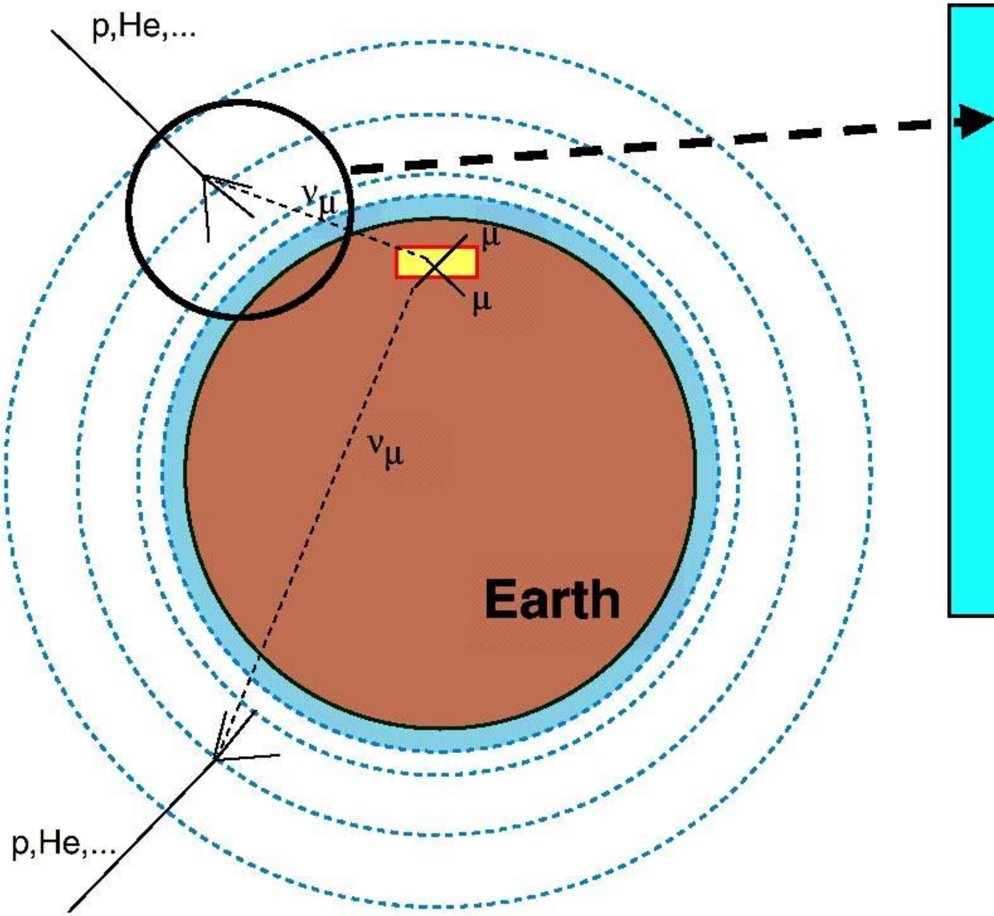
12 m diam.

9456 PMTs

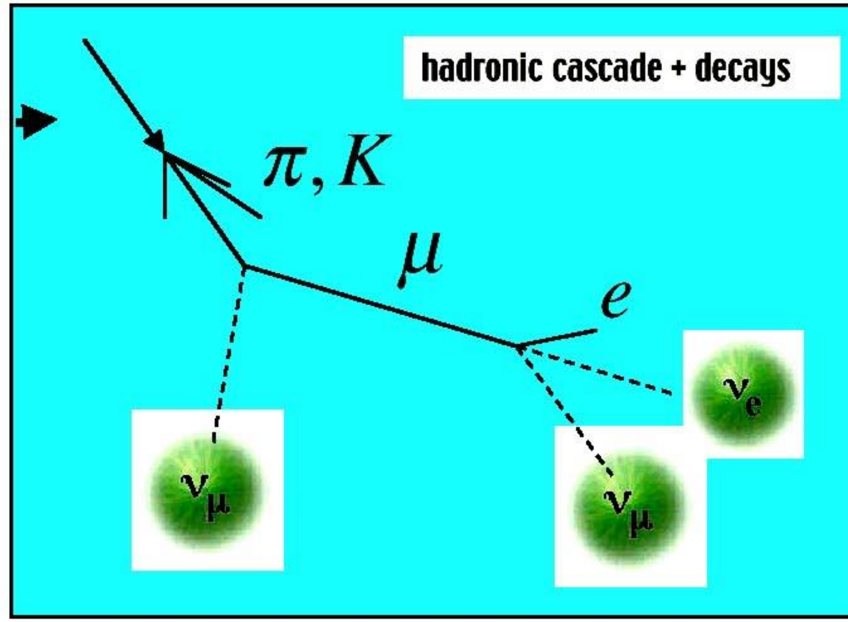
Neutrinos Atmosphériques


Photo © Takaaki Kajita
Takaaki Kajita

Distance entre production et détection de ~20km à 12700 km



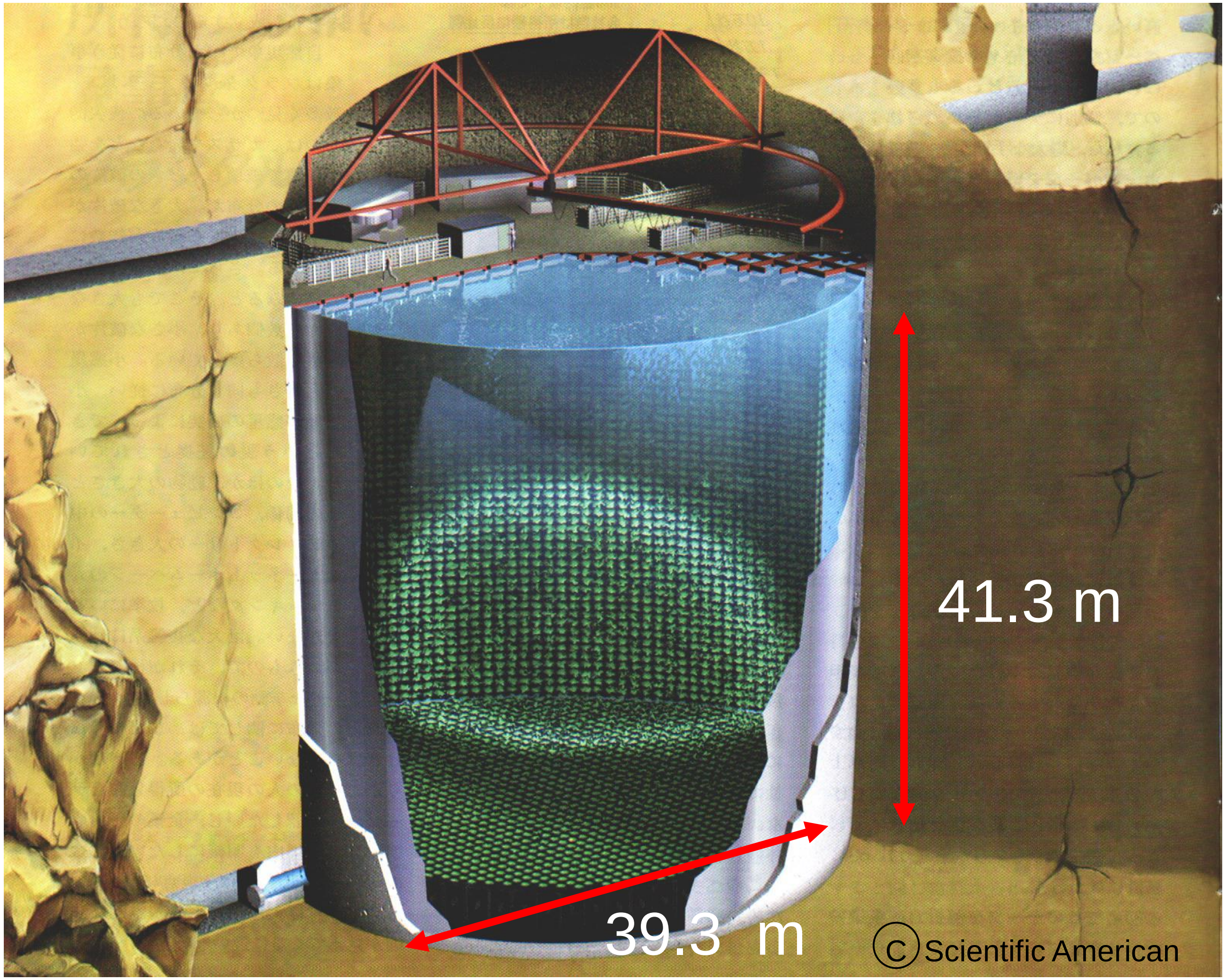
almost isotropic source
(geomagnetic effects)



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

Super-K detector

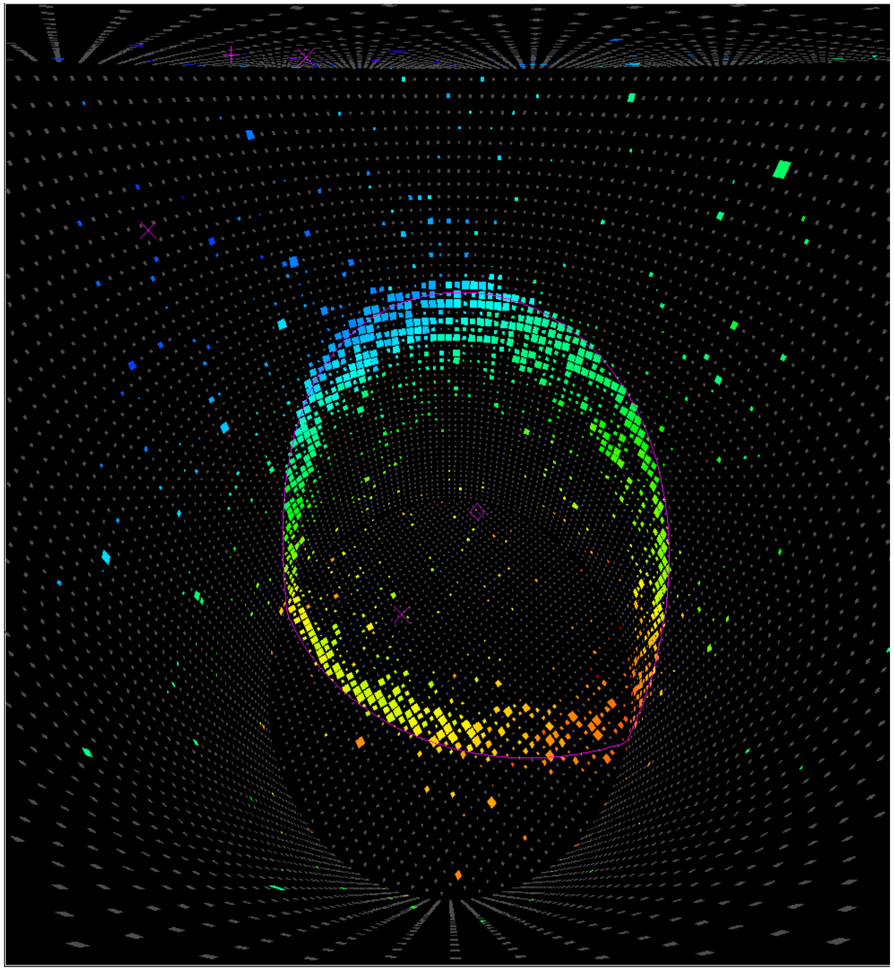


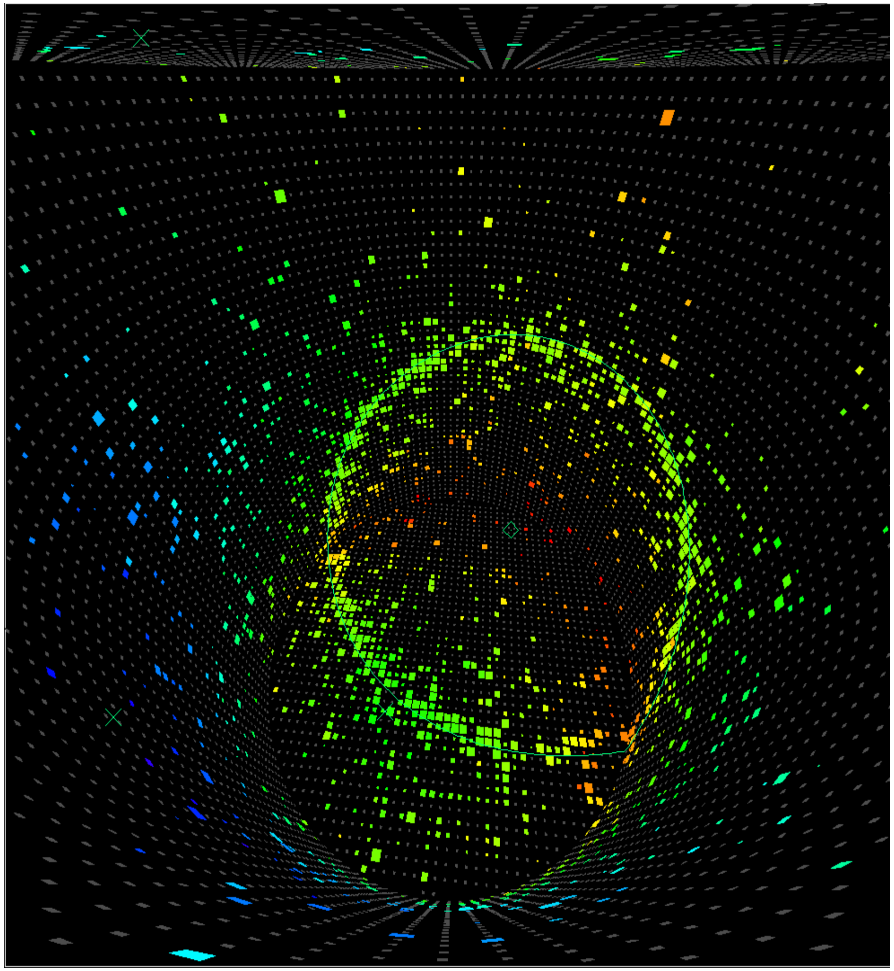
Water Cerenkov detector

50000 tons of pure light water

≈10000 PMTs

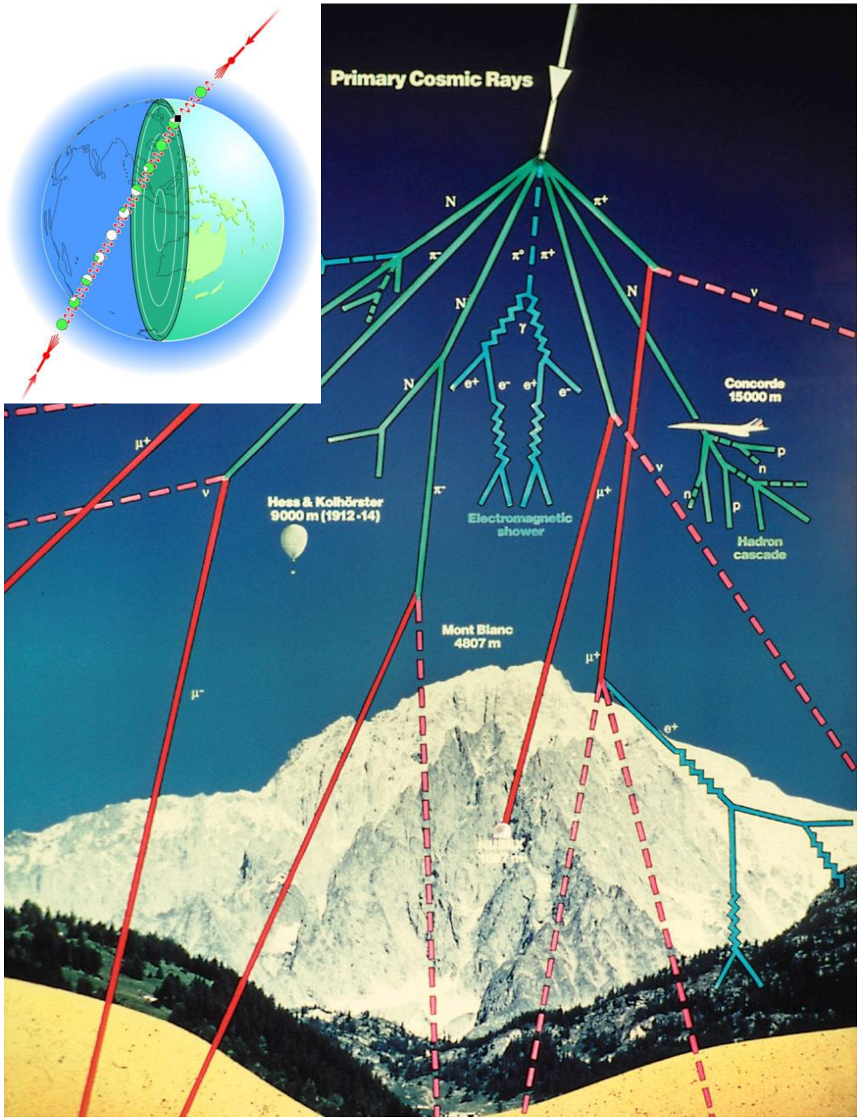
Séparer ν_μ et ν_e



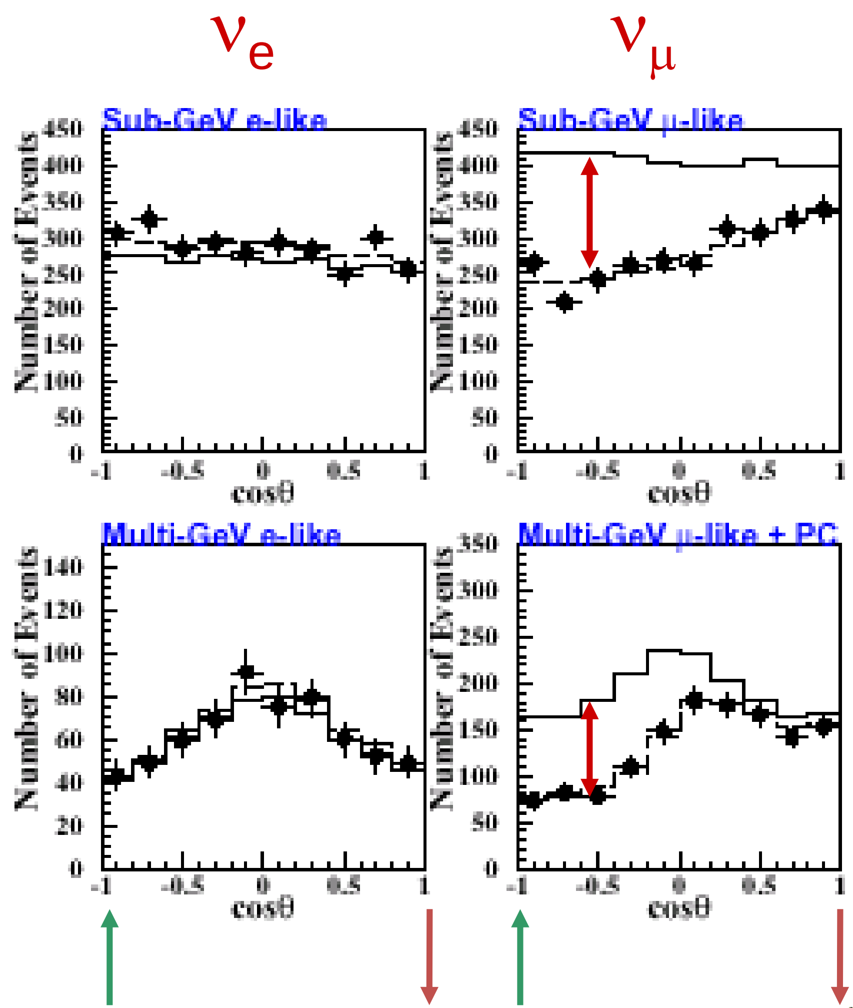


$\nu_\mu \; N \rightarrow \mu^- \; X$ $\qquad\qquad$ $\nu_e \; N \rightarrow e^- \; X$

Atmospheric ν : up-down asymmetry



Super-K results

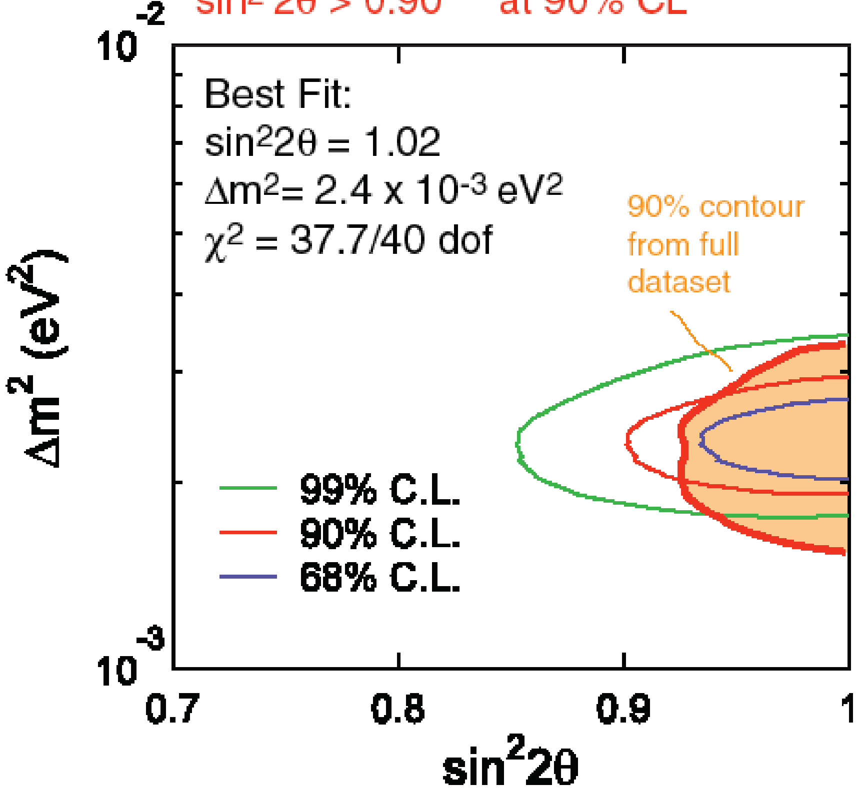


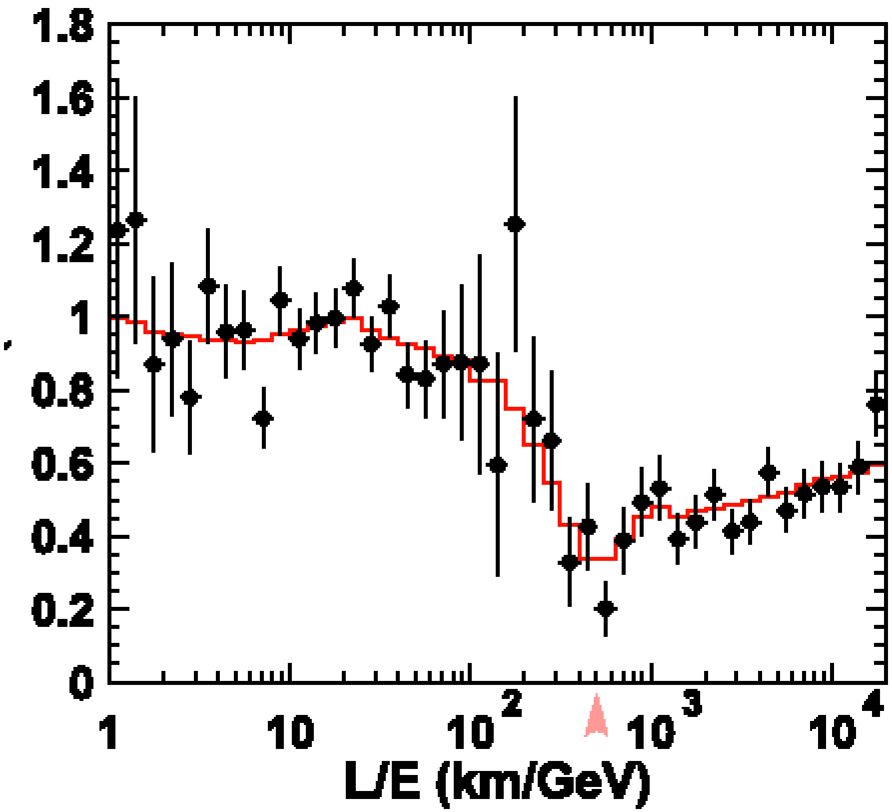
up down

Atmospheric Neutrinos

SuperKamiokande Atmospheric Result

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$
$\sin^2 2\theta > 0.90$ at 90% CL





~Oscillation

NEUTRINO TRANSFORMATIONS

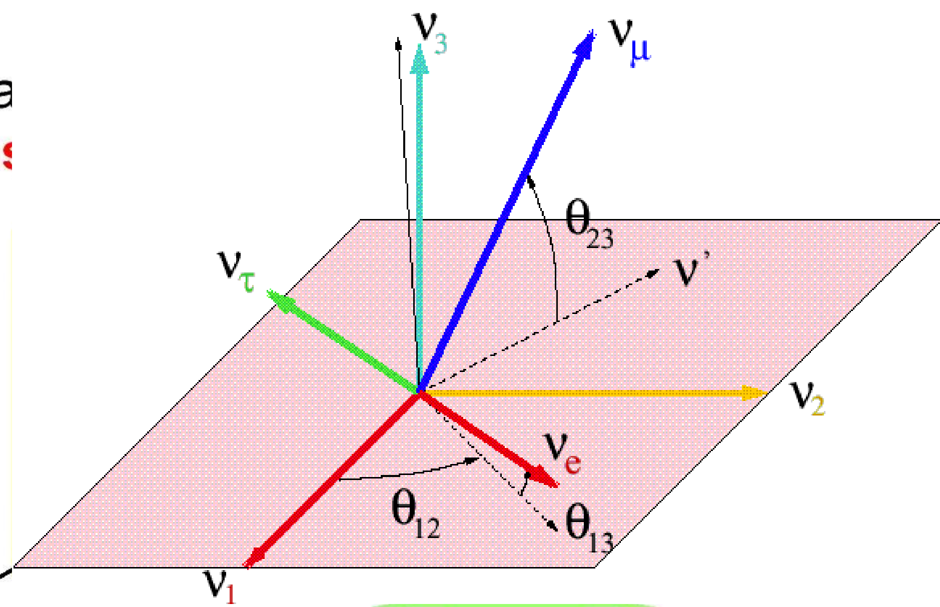
The fact that neutrinos seem to disappear in their travel
through the sun and space (while they are not inteacting or decaying)
is a clear sign that they have mass.
(a massless particle has infinite proper time τ = E/m and cannot transform)

It is expected that they undergo **oscillations.**

Oscillation is a coherent quantum interference which happens thanks to
1. the extreme smallness of neutrino masses and mass differences
2. the weakness of their interactions, which preserves coherence over long distances.

Lepton Sector Mixing

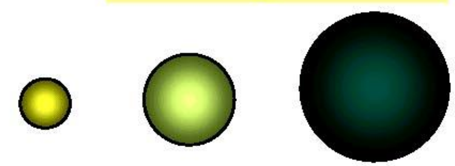
- If neutrinos a… …hat the **mass eigens…** …the same:



Weak eigenstates „flavor eigenstates"

3 independent parameters + 1 complex phase

Mass eigenstates

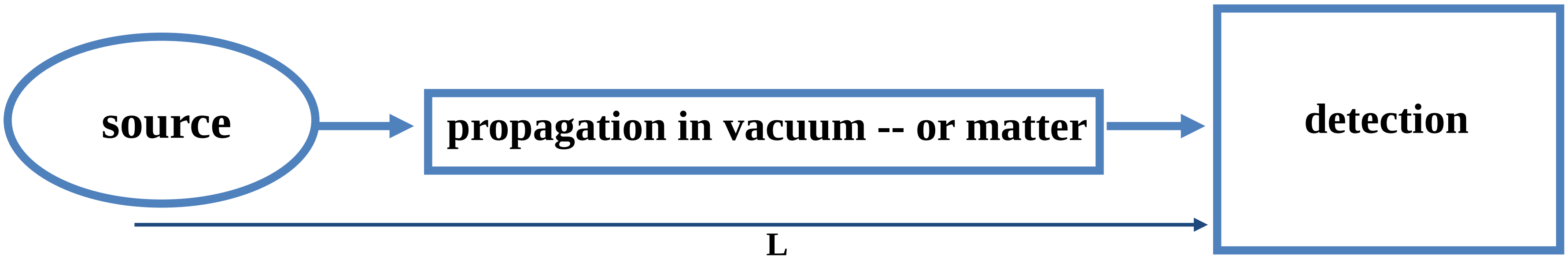


m_1 m_2 m_3

similar to CKM flavour mixing matrix

Pontecorvo 1957

Neutrino Oscillations (Quantum Mechanics lesson 5)



weak interaction
produces
'flavour' neutrinos

e.g. pion decay $\pi \rightarrow \mu\nu$

$|\nu_\mu\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$

Energy (i.e. mass) eigenstates
propagate

$$|\nu(t)\rangle = \alpha\,|\nu_1\rangle\ \exp(i\,E_1\,t) + \beta\,|\nu_2\rangle\ \exp(i\,E_2\,t) + \gamma\,|\nu_3\rangle\ \exp(i\,E_3\,t)$$

$t \propto L/E$

weak interaction: (CC)

$\nu_\mu\ N \rightarrow \mu^-\ X$

or $\nu_e\ N \rightarrow e^-\ X$

or $\nu_\tau\ N \rightarrow \tau^-\ X$

$$P(\mu \rightarrow e) = |\langle \nu_e | \nu(t)\rangle|^2$$

α is noted $U_{1\mu}$

β is noted $U_{2\mu}$

γ is noted $U_{3\mu}$ etc....

Oscillation Probability

- The case with two neutrinos:
  - A mixing angle: θ
  - A mass difference:

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

$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

Dm2 en ev2
L en km
E en GeV

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector
E = neutrino energy

Hamiltonian= E = sqrt($p^2 + m^2$) = p + $m^2 / 2p$
for a given momentum, eigenstate of propagation in free space are the mass eigenstates!

neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \rightarrow \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

Oscillation maximum $1.27\ \Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}$ eV^2 L = 500 km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}$ eV^2 L = 18000km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ oscillation at L_{atm}
(discovered by T2K)

$$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \tfrac{1}{2} \sin^2 2\theta_{13} + \ldots \text{(small)}$$

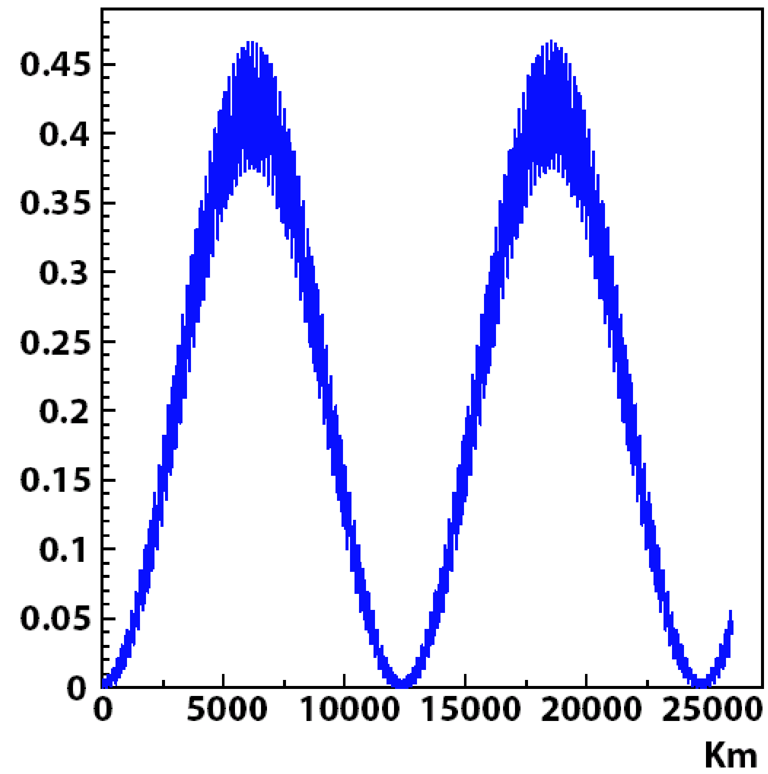
II There will be CP violation

CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

III we do not know if the neutrino ν_1 which contains more ν_e is
the lightest one (natural?)
or not (inverted)

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



$$P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \ \sin\delta$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \ \sin\delta$$

$$\frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} = A_{CP}\ \alpha\ \frac{\sin\delta\ \ \sin(\Delta m^2_{12}\, L/4E)\ \ \sin\theta_{12}\,\sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

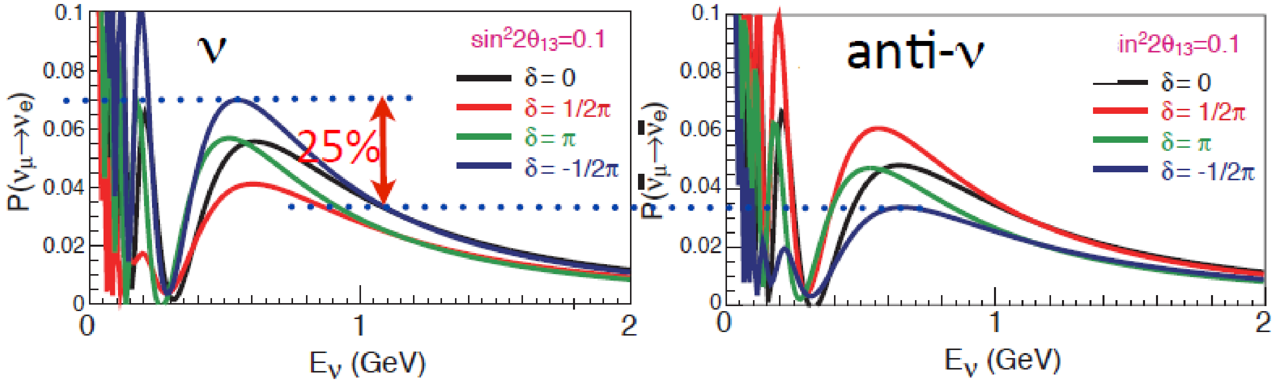
… need APPEARANCE … $P(\nu_e \rightarrow \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \rightarrow \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$

ν_e appearance



for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$
- $\delta \to -\delta$
- $a \to -a$

$P(\nu_\mu \to \nu_e) =$

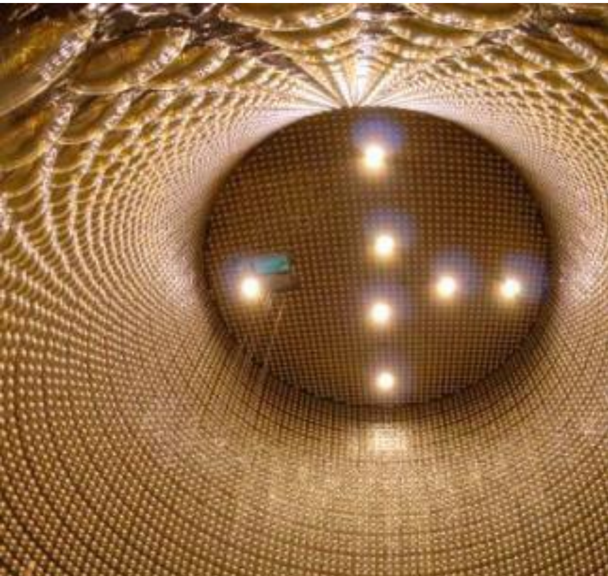
$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1 + \frac{2a}{\Delta m_{13}^2}\left(1 - 2s_{13}^2\right)\right)$$ **θ_{13}(Leading term)**

$$+8c_{13}^2 s_{12} s_{13} s_{23}\left(c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}\right)\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$ **CPC**

$$-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$ **CPV**

$$+4s_{12}^2 c_{13}^2\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13}\cos\delta\right)\sin\frac{\Delta m_{21}^2 L}{4E}$$ **Solar**

$$-8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}\left(1 - 2s_{13}^2\right)$$ **Matter effect**



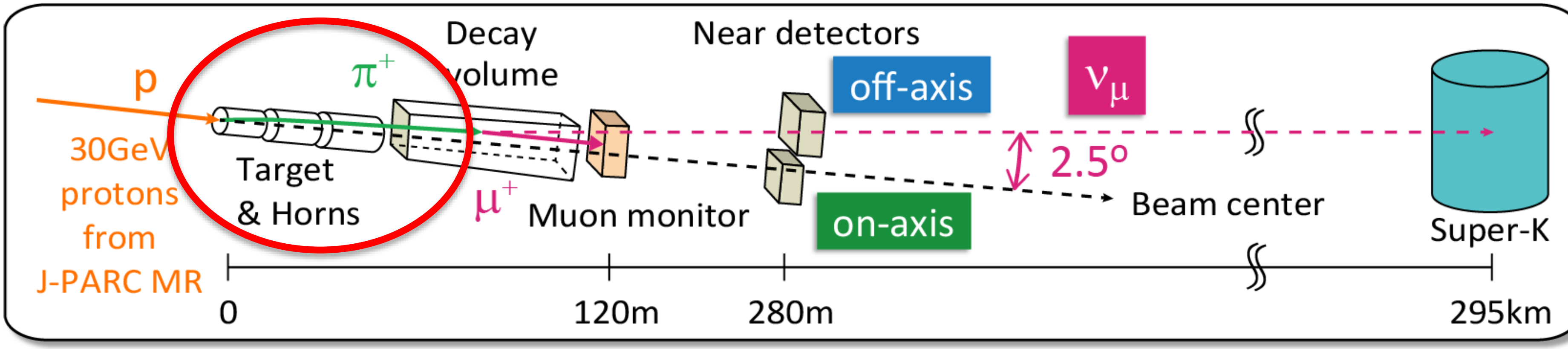
Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

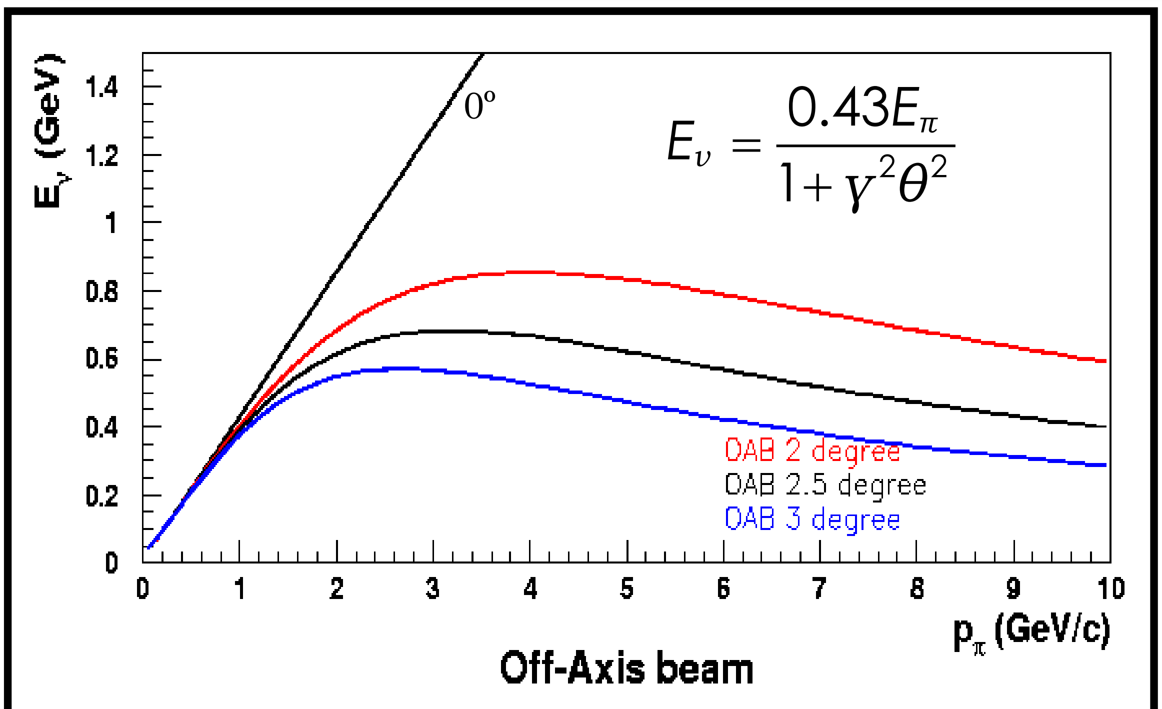
-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

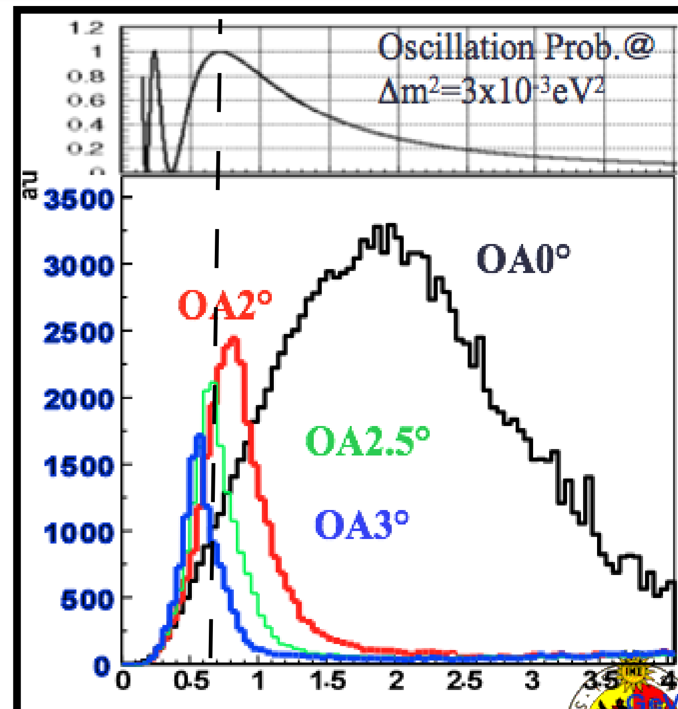
-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

-- baseline 295 km ➔ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis

Design Principle

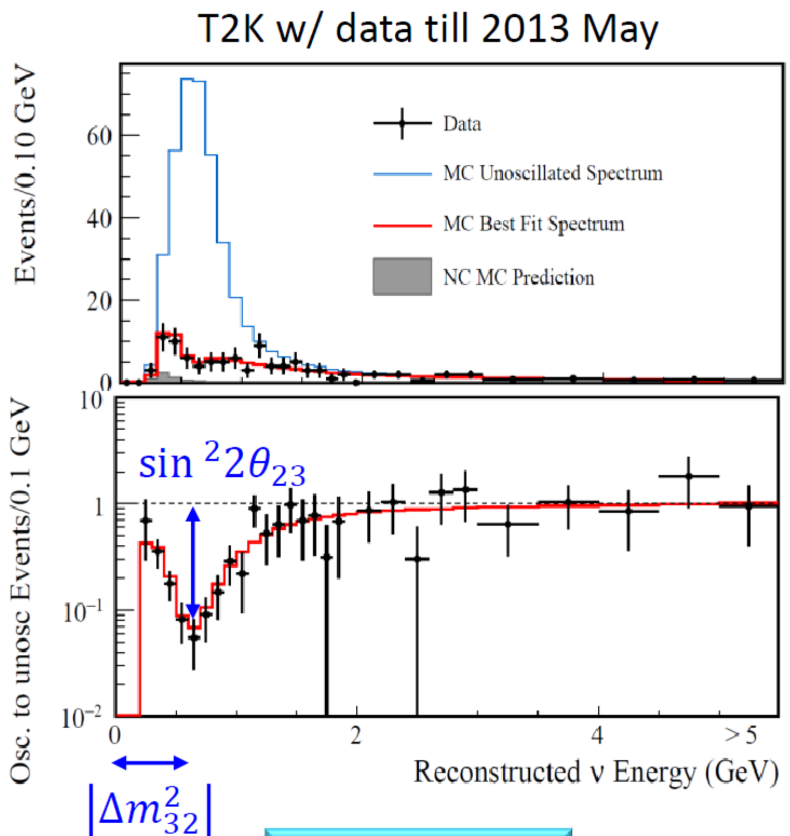






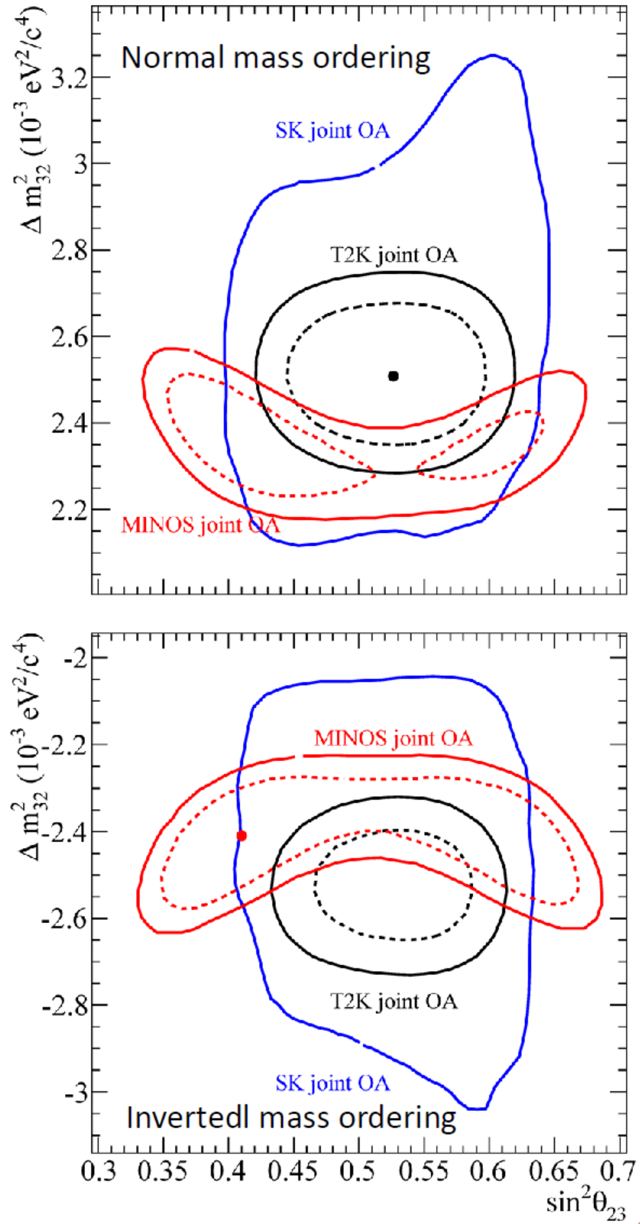
The neutrino energy spectrum is mainly defined by the off-axis angle

ν_μ DISAPPEARANCE



$46° \pm 3°$

T2K

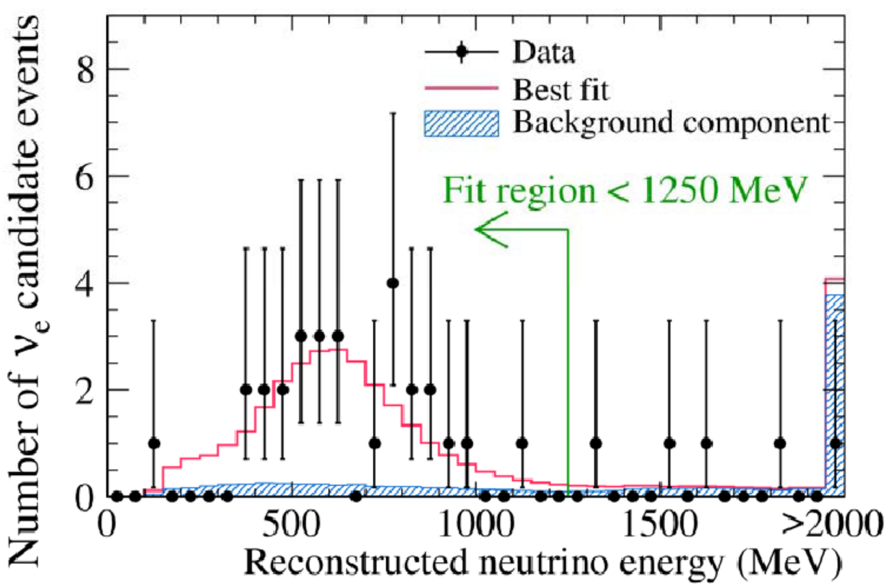


Phys. Rev. D 91, 072010 (2015)

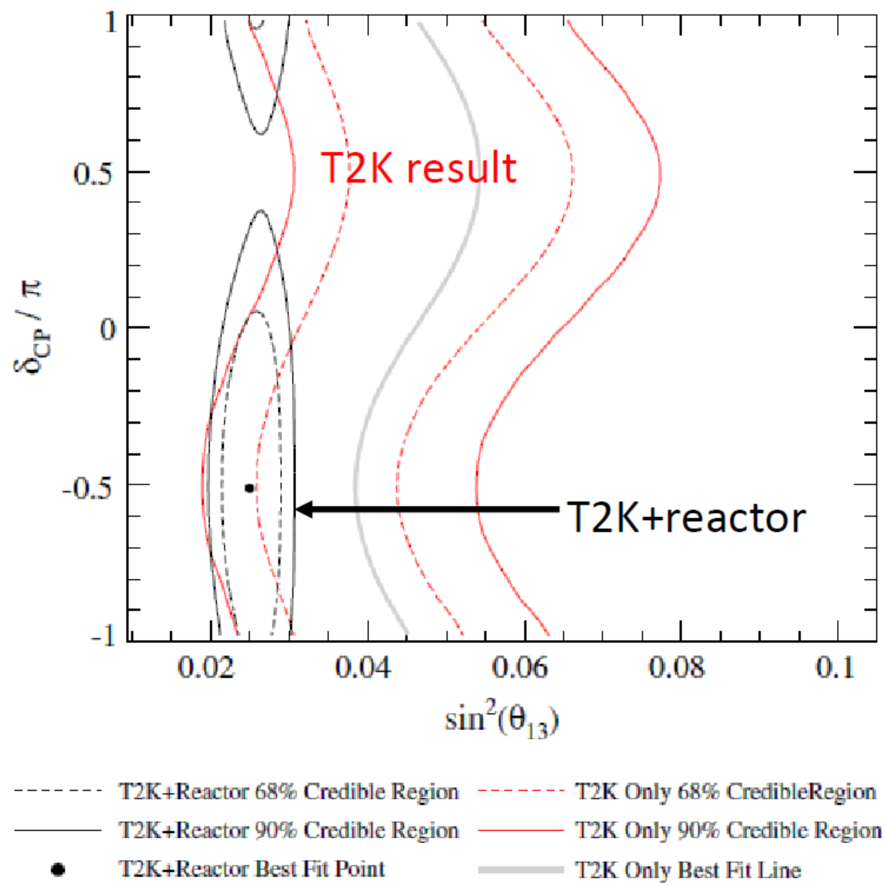
discovery of ν_e appearance

released in August 2013 w/ data till May 2013

Phys. Rev D.91, 072010(2015)

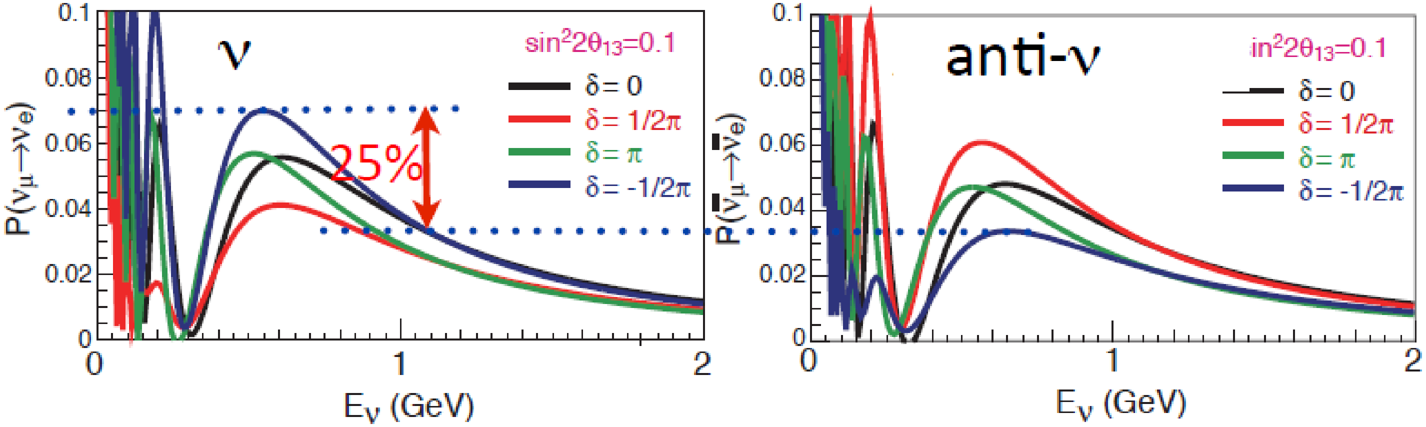


PhysRevLett.112.061802 (2014)



28 events observed over 4.92±0.55 bkgs → 7.3σ excess
First Confirmation of 'Appearance phenomenon' w/ > 5σ significance.

ν_e appearance



for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

- $\delta \to -\delta$
- $a \to -a$

$$P(\nu_\mu \to \nu_e) =$$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1+\frac{2a}{\Delta m_{13}^2}\left(1-2s_{13}^2\right)\right)$$ **θ_{13}(Leading term)**

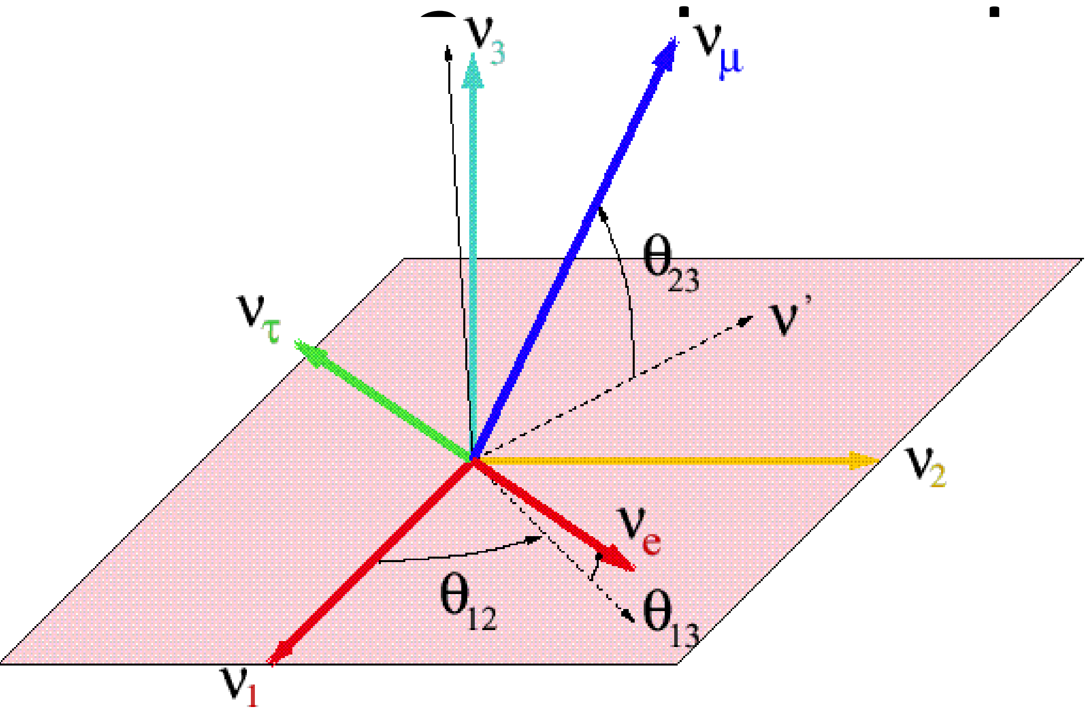
$$+8c_{13}^2 s_{12} s_{13} s_{23}\left(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}\right)\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$ **CPC**

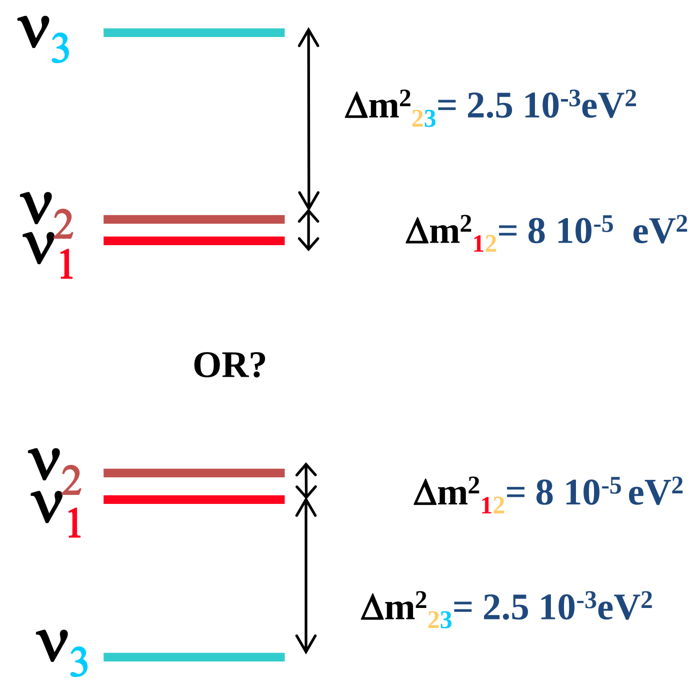
$$-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$ **CPV**

$$+4s_{12}^2 c_{13}^2\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right)\sin\frac{\Delta m_{21}^2 L}{4E}$$ **Solar**

$$-8c_{13}^2 s_{13}^2 s_{23}^2\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}\left(1-2s_{13}^2\right)$$ **Matter effect**

The neutrino mixing matrix: phase δ





θ_{23} (atmospheric) = 45^0,
θ_{12} (solar) = 32^0,
θ_{13} (reactor/T2K) =8.5^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

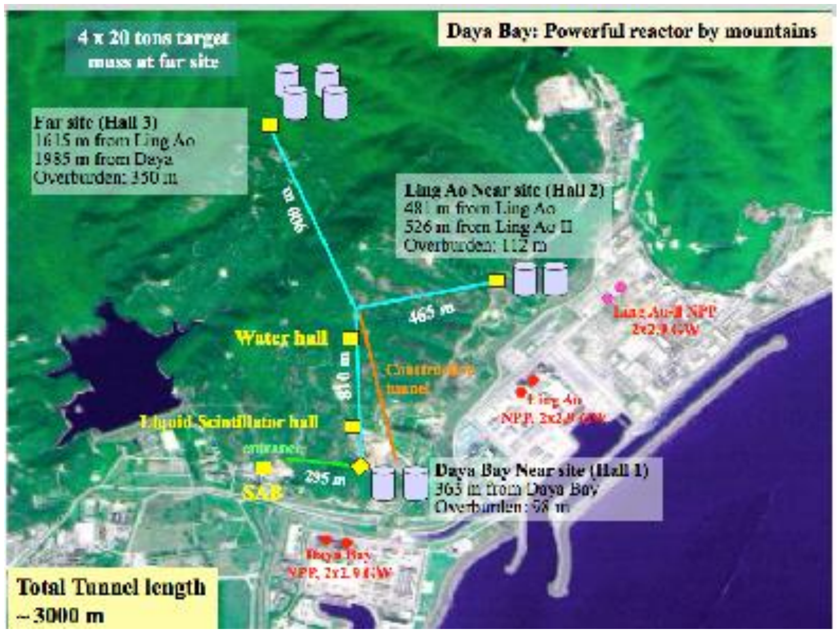
Unknown or poorly known in 2015:
CP phase δ, sign of $\Delta m_{13}{}_2$

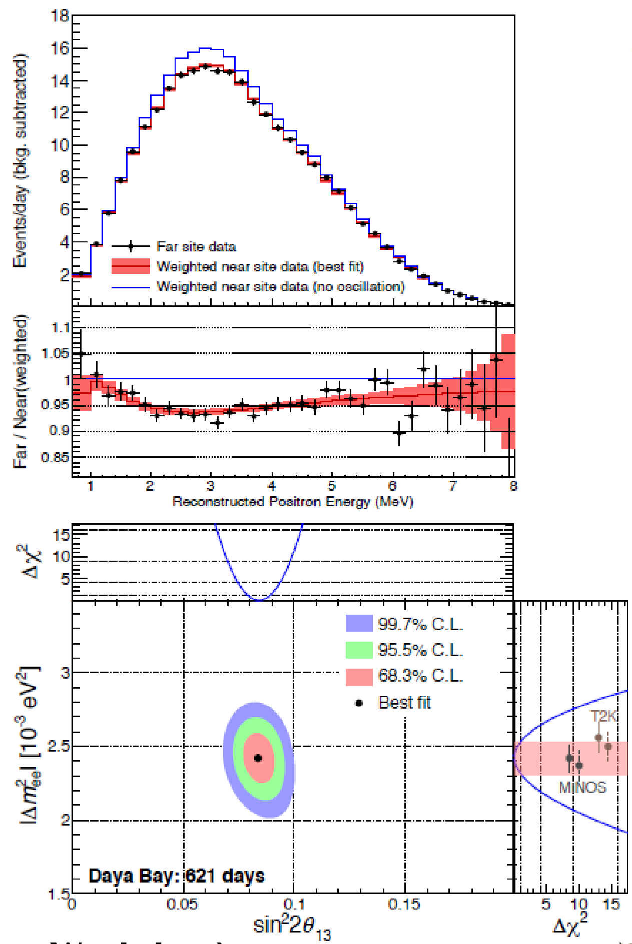
Towards CP Violation

Double-Chooz (France), Daya-Bay (China) & Reno (Korea) have observed precisely the $\bar{\nu}_e$ appearance.

T2K experiment has observed $\nu_\mu \rightarrow \nu_e$ appearance. (28 events)

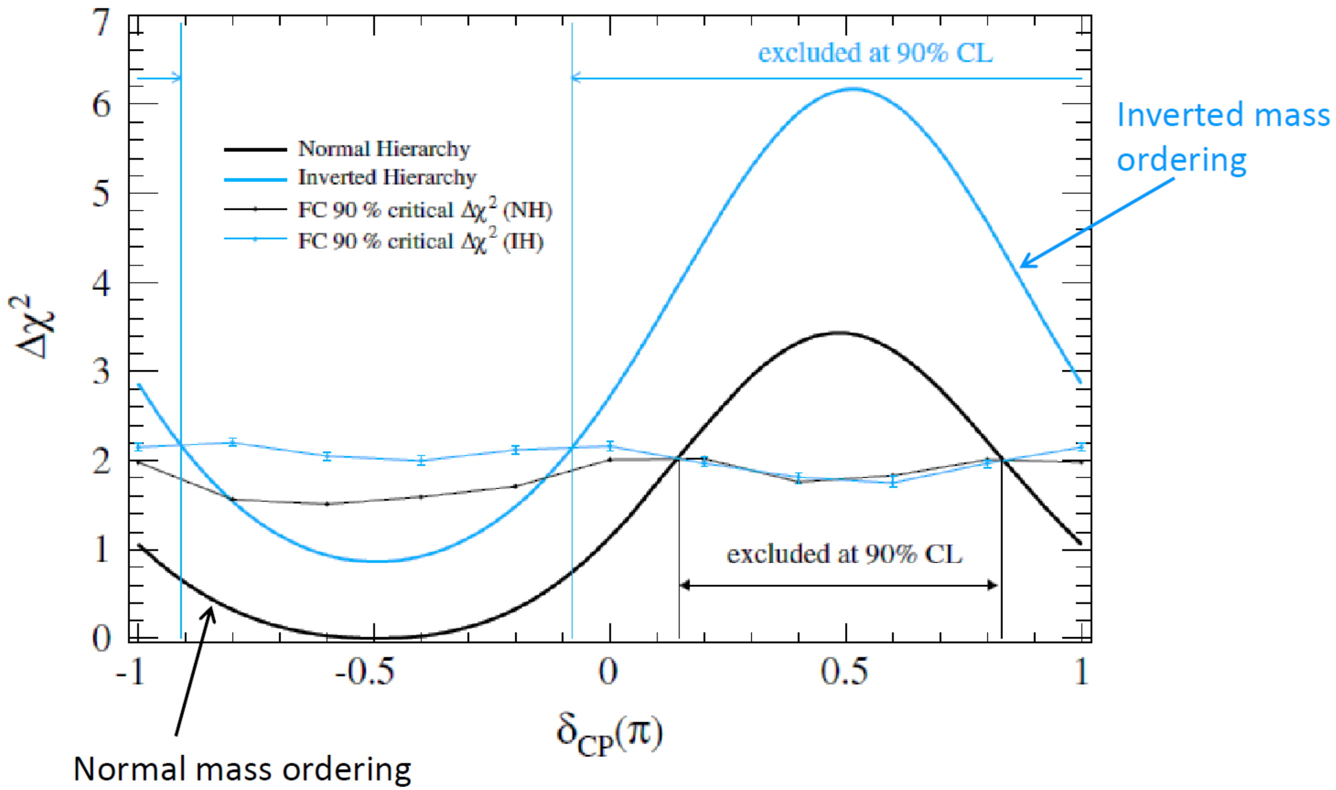
The comparison of the two points to hint of CP violation





$$\begin{cases} \sin^2 2\theta_{13} = 0.084 \pm 0.005 \\ |\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} eV^2 \end{cases}$$

First constraint on δ_{CP} by T2K

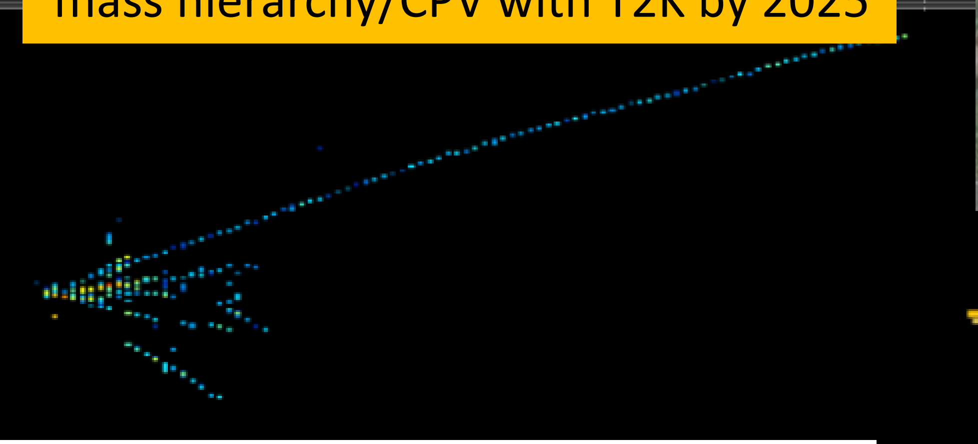


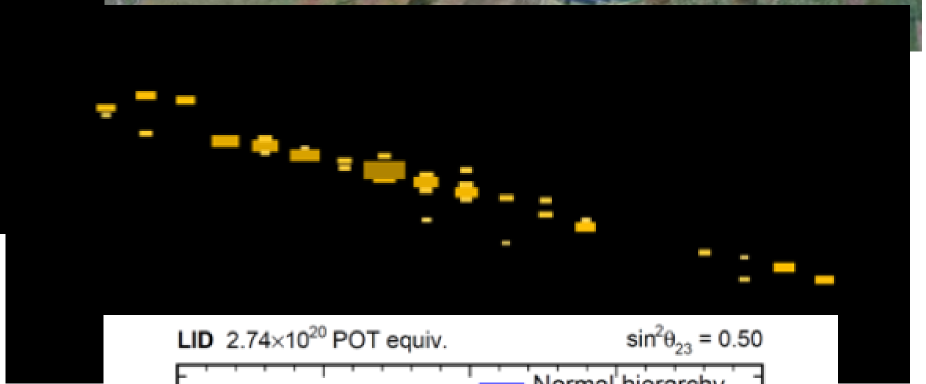
Phys. Rev D.91, 072010(2015)

comparison of T2K appearance with reactor disapearance gives constraint in $\{\theta_{13}$, δ_{CP} , mass hierarchy (±)$\}$ parameter space.
With NOvA, PINGU and JUNO, can solve the problem!

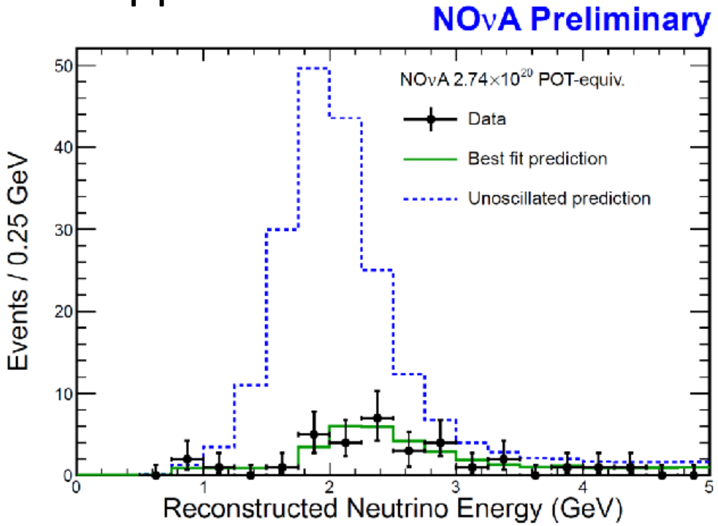
NOνA experiment

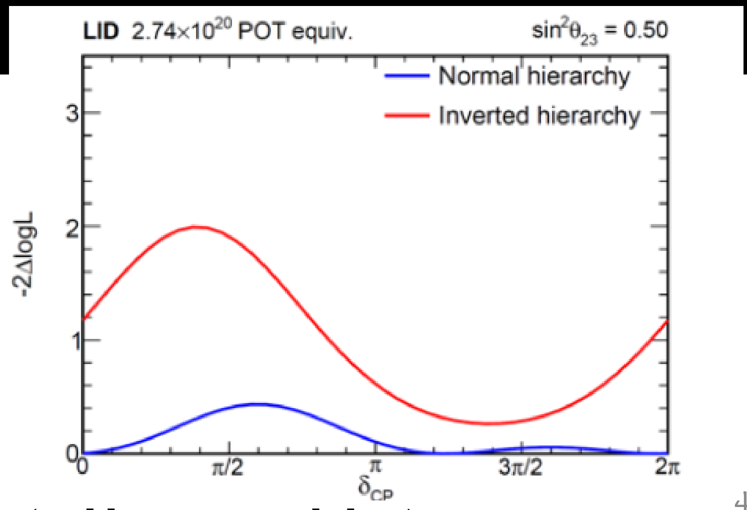
preliminary results shown summer15
Same preference as T2K for $\delta_{CP}=-\pi/2$
Longer baseline should allow
mass hierarchy/CPV with T2K by 2025



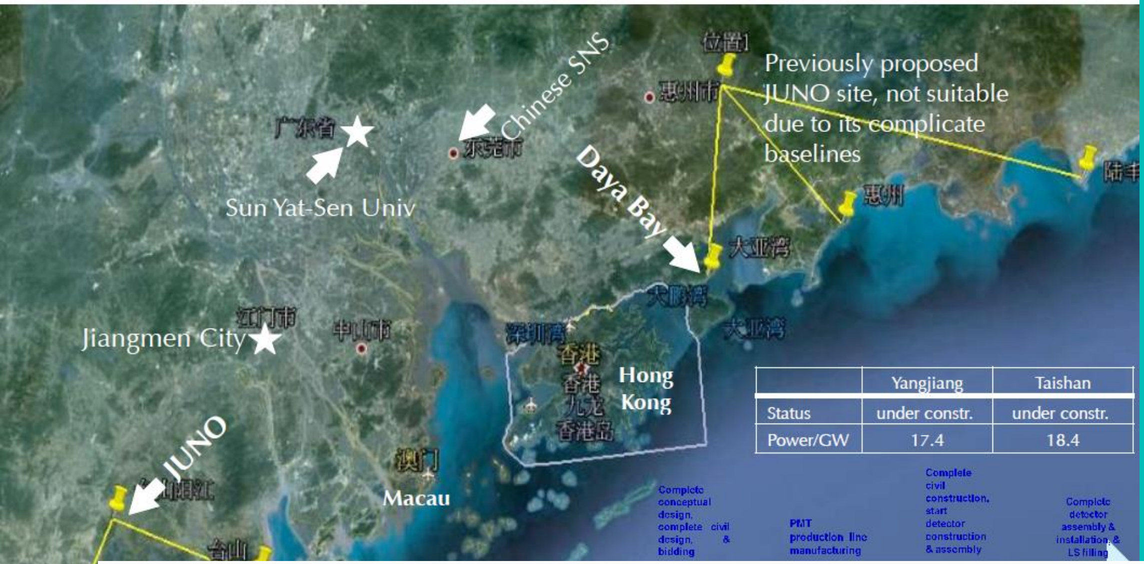


disappearance

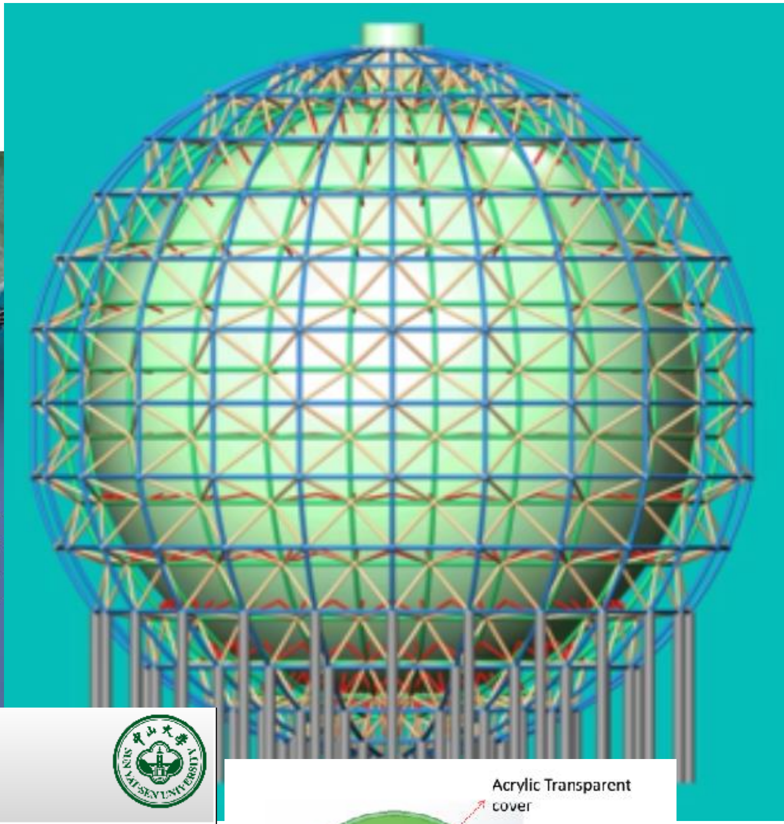




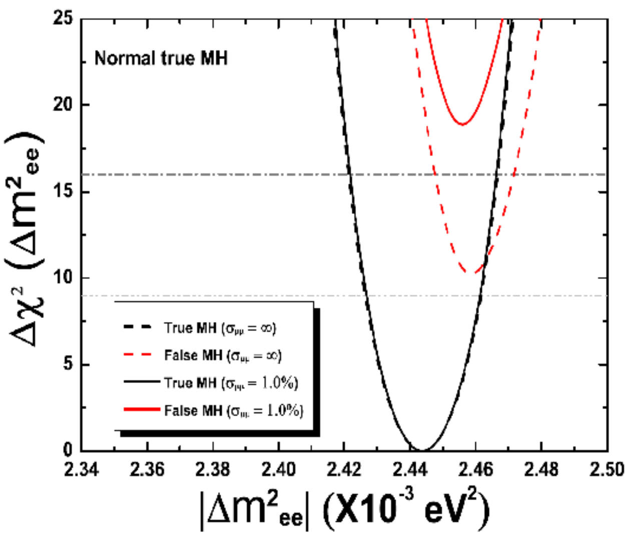
JUNO 20kton Liquid Scintillator



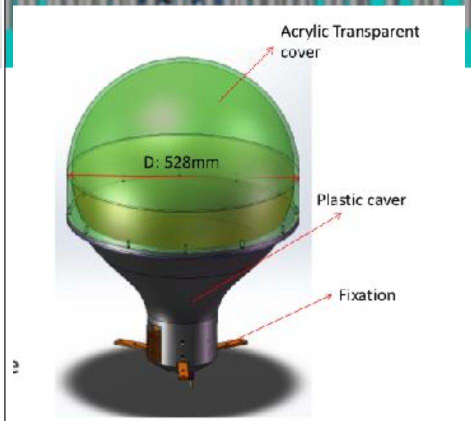
	Yangjiang	Taishan
Status	under constr.	under constr.
Power/GW	17.4	18.4



Expected Significance to Mass Hierarchy



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external Δm^2 measured to ~1% level in ν_μ beam oscillation experiments
  - ~1% in Δm^2 is reachable based on the combined T2K+NOvA analysis by S.K. Agarwalla, S. Prakash, WW, arXiv: 1312.1477
- *(Side remark: What is the global picture considering the inputs from PINGU and ORCA? NuFACT'16?)*



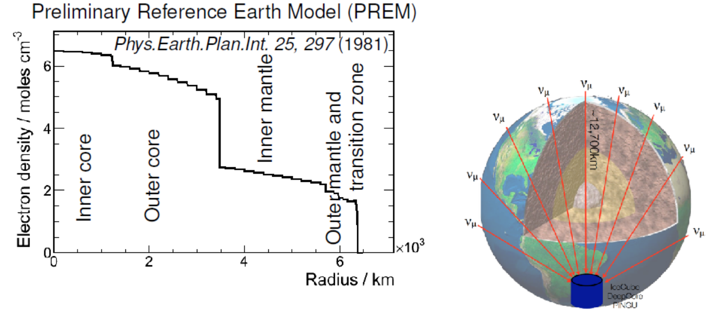
Conceptual explosion proof Structure of PMT

- Plan A: 20″ MCP-PMT
- Plan B: 10″ Photonis China
- Plan C: 20″ SBA Hamamatsu

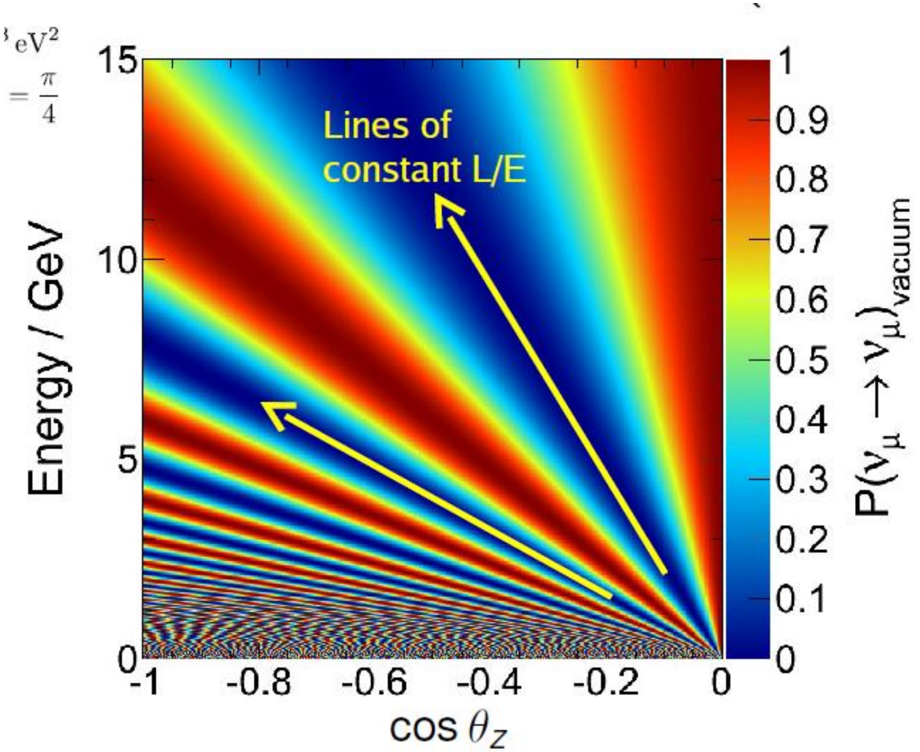
PINGU, ORCA

Atmospheric neutrino oscillations
can be seen in large Water Cherenkovs
at ~GeV energy.
Energy vs distance analysis could lead to
detection of matter effect
in PINGU (fine grain @south pole
and ORCA (fine gran in mediteranean)
and thus determination of mass hierarchy

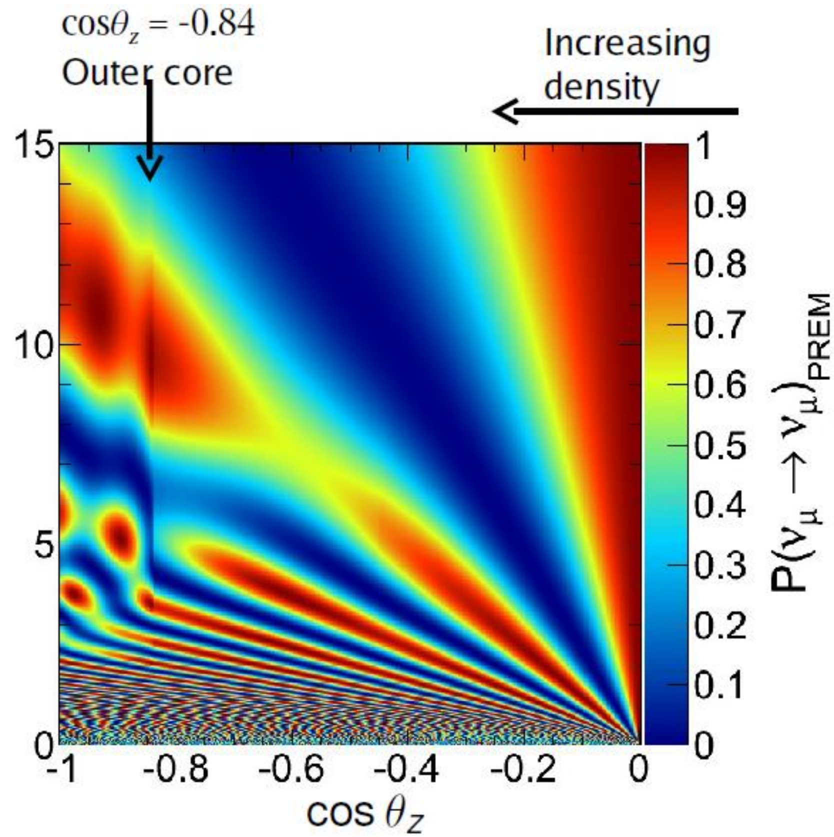
Matter Effects



- MSW effect alter oscillation probabilities of ν (NH) or $\overline{\nu}$ (IH)
  - Sharp changes in density between zones produce visible effects in oscillation probabilities
- Different paths "see" different mass patterns $\Rightarrow$ can be probed by measuring the zenith of the neutrino

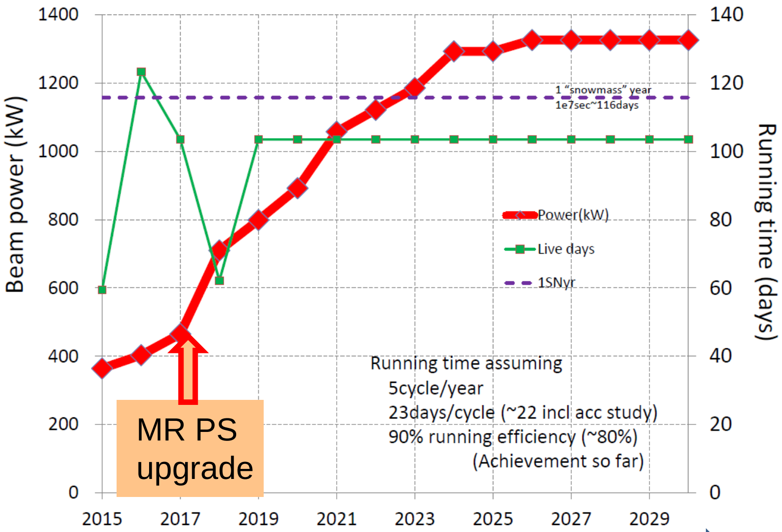


s (Isolc

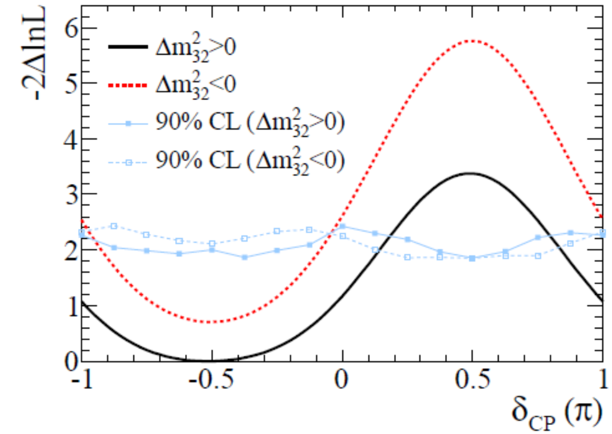


Workshop for Neutrino Programs with facilities in Japan (4-8 Aug-2015)

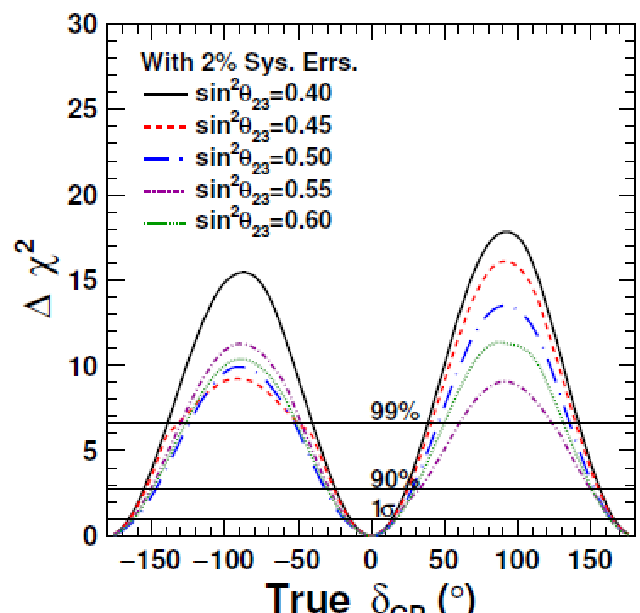
https://kds.kek.jp/indico/event/19079/



T2K **T2HK (proposed)**



T2K, PRL 112 (2014) 061802



T2K is proposing to run until 2025 with beam power progressively increasing up to 1.3 MW

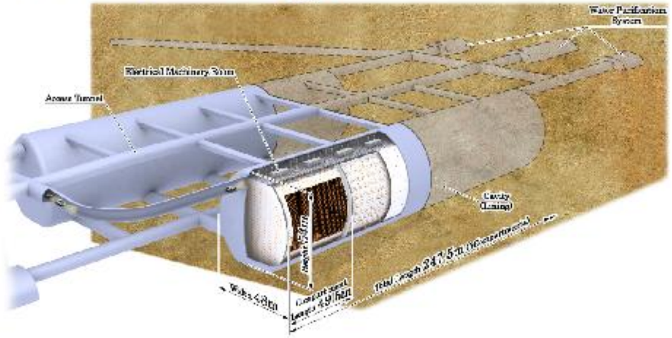
➔ 3-4 s.d. evidence for CP violation is possible
if the presently preferred point is correct.
This requires systematic errors at 3% level.

HYPERK -- from 22kton to 200-500 kton

Rock in Kamioka is of excellent cavity, gneiss and migmatite
large span vertical cylinder caverns offer better cost/volume ratio

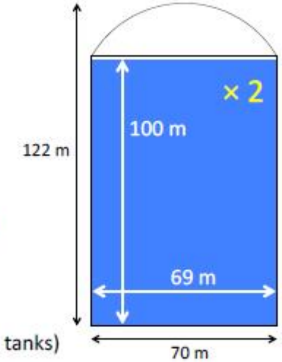
Proposed to study 4 cases

baseline design



Case 1

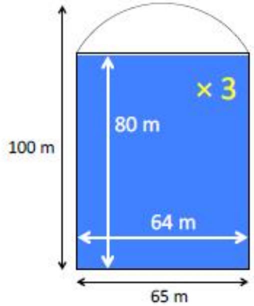
- Water tank size
  - Depth : 100 m, Diameter : 69 m
- Water volume (2 tanks)
  - Total : 747.9 kt
  - Fiducial : 568.7 kt
- Excavation volume (2 caverns)
  - 868000 m³ 72% of current one
- ID surface area (2 tanks)
  - 52800 m² 53% of current one
- Number of ID photodetectors (2 tanks)



NB :
this is the cost driver for the project!

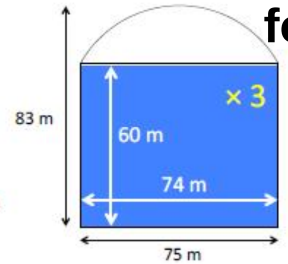
Case 2

- Water tank size
  - Depth : 80 m, Diameter : 64 m
- Water volume (3 tanks)
  - Total : 772.1 kt
  - Fiducial : 565.2 kt
- Excavation volume (3 caverns)
  - 915000 m³ 76% of current one
- ID surface area (3 tanks)
  - 60300 m² 61% of current one
- Number of ID photodetectors (3 tanks)
  - 38.0 k 38% of current one



Case 3

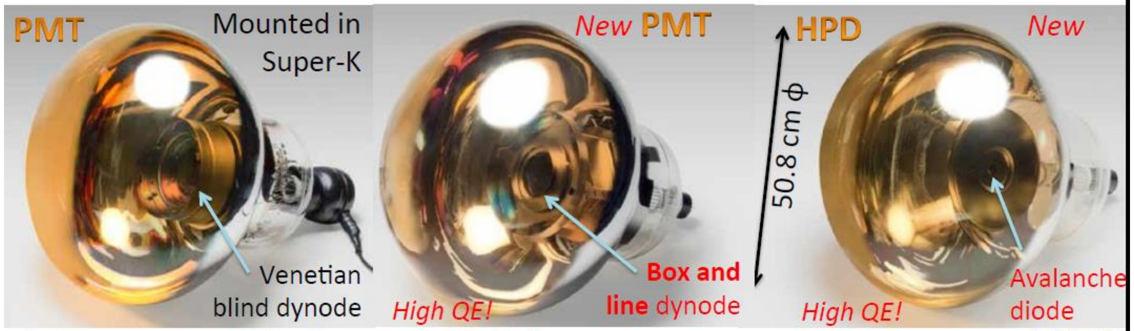
- Water tank size
  - Depth : 60 m, Diameter : 74 m
- Water volume (3 tanks)
  - Total : 774.2 kt
  - Fiducial : 561.0 kt
- Excavation volume (3 caverns)
  - 968000 m³ 81% of current one
- ID surface area (3 tanks)
  - 60200 m² 61% of current one
- Number of ID photodetectors (3 tanks)
  - 38.0 k 38% of current one



2. Producing 40’000 high Q.E. 20’ PMTs

By Hamamatsu Photonics K.K.

- New 50 cm Φ photodetectors developed for HK.



Model R3600 (Used for 2-30 yrs) R12860 R12850 † still in R&D

New detectors offer higher Q.E. by typically 50-100%.
Presently investigating noise and time resolution of various options and calculating consequences for physics.
Box and line offers x2 photons and 1 ns time resolution/photon
➔ **baseline**

TF Optimizing PMT coverage for physics; possibly staging.

Hamamatsu new plant for mass production

- To realize mass production for HK, Hamamatsu built a new large plant and PMT division is moving in it.
  - Automated transportation, test facility, earthquake-resistant, …
- We have to determine PD for HK 2 years before mass production.
  - Design for 0.5 year, equipment for 0.5-1 year, startup for 0.5-1 year
- Around 6 years for mass production.

Alai

Some physics

HYPERK , δ_{CP}=0, and NH

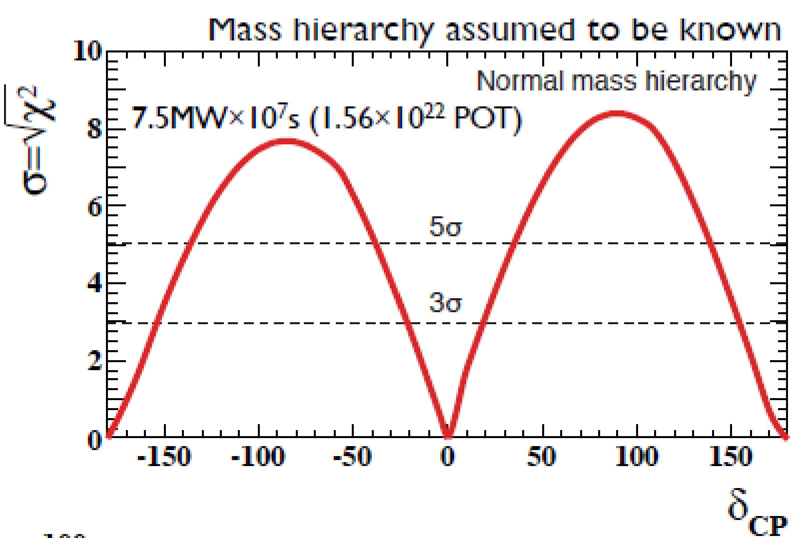
	Signal ($\nu\mu\to\nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

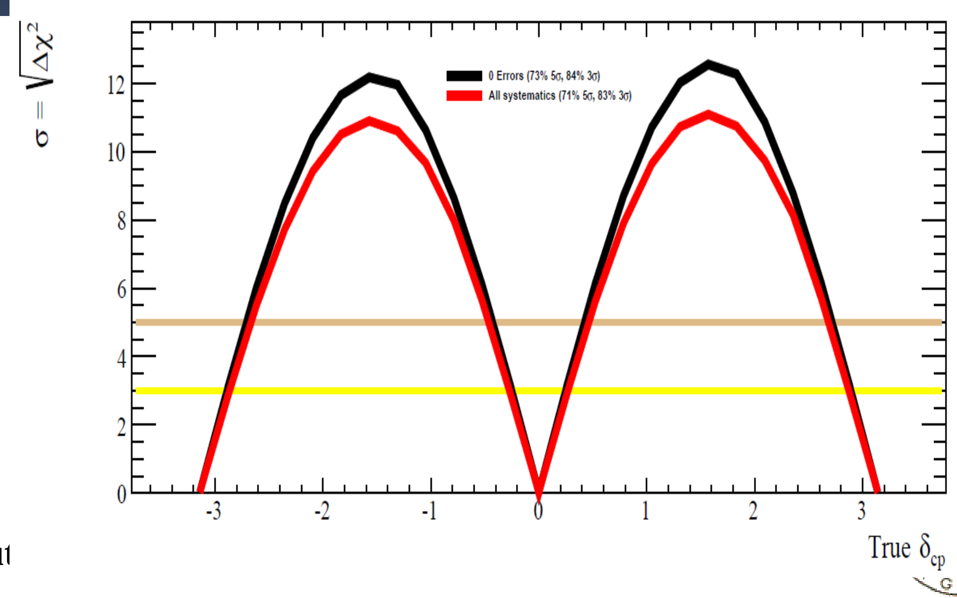
750 kW x10yrs x500kton

ELBNF 40KT

Run Mode	Signal Events δ_{CP} $-\pi/2$	0	$\pi/2$	Background Events ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33

Dominant error:
(anti) ν_e/ν_μ x-sections
as measureable:
56% 5σ ,76% 3σ
If use th. calculations
(71% 5σ, 83% 3σ)



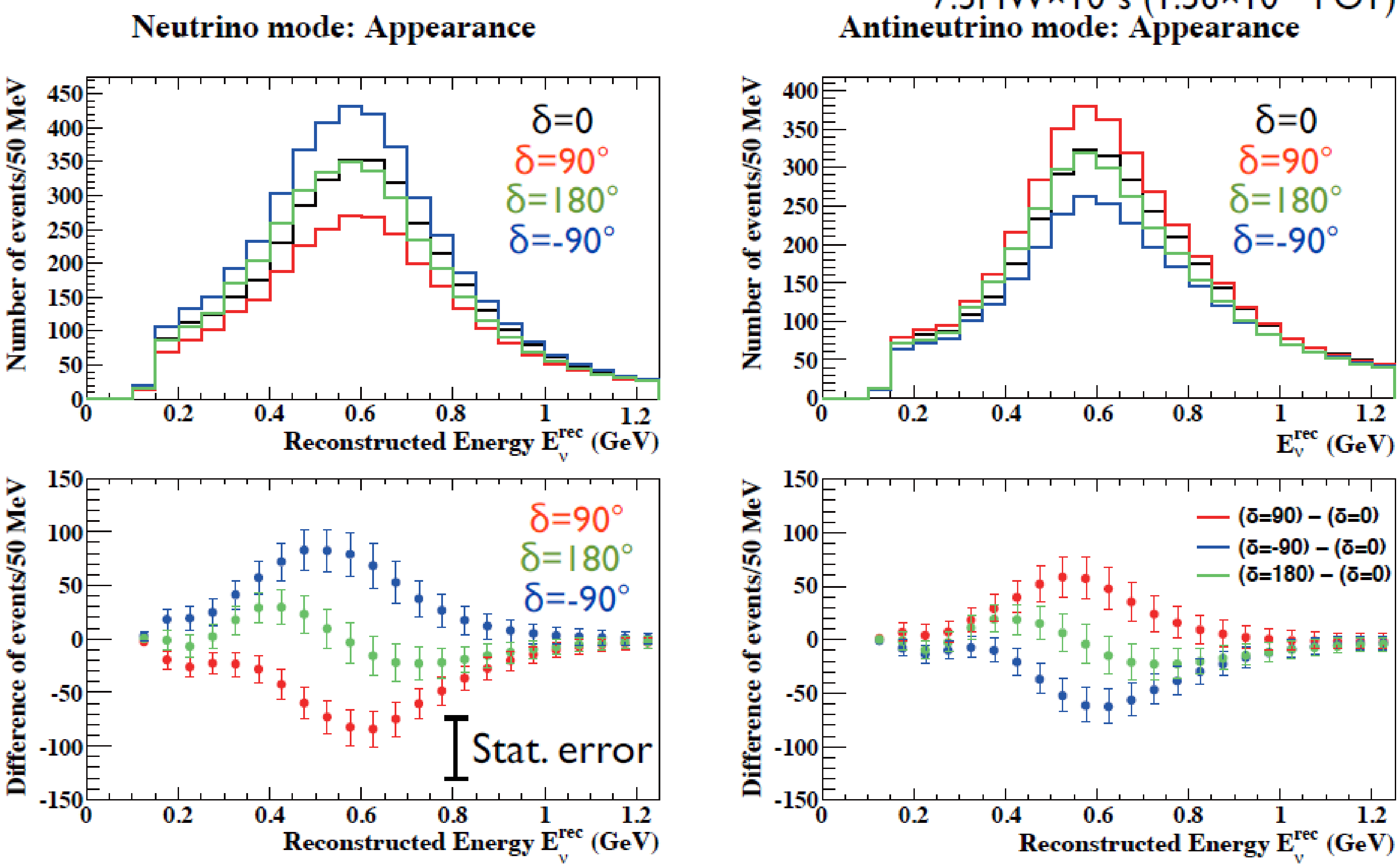


δ_{CP} dependence of observables

7.5MW×10^7s (1.56×10^{22} POT)

Ve candidates

Difference from δ=0



Sensitive to all values of δ with numbers + shape

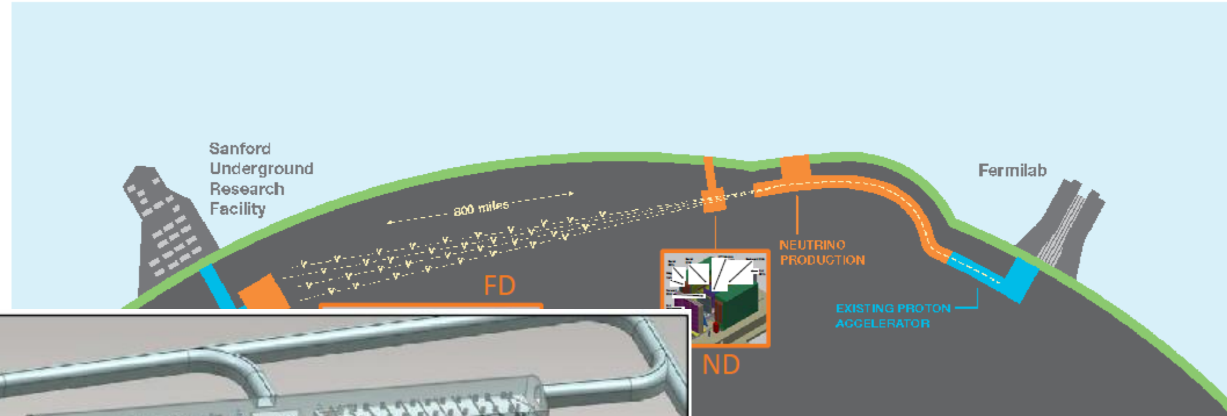
LBNF/DUNE

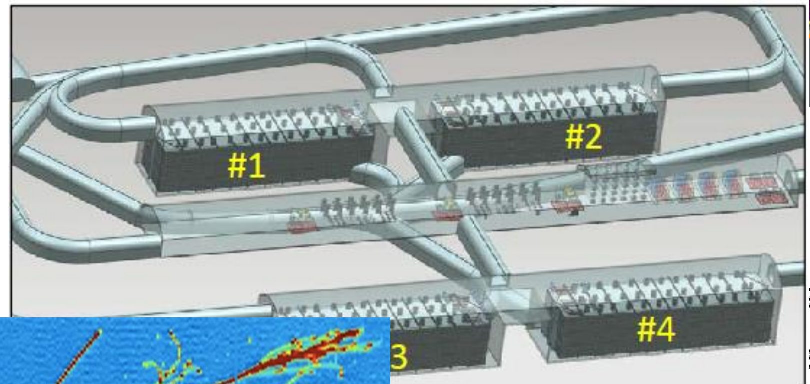
new beam line
allowing to reach 2MW POT
raised target station
baseline 1300km
to S. Dakota

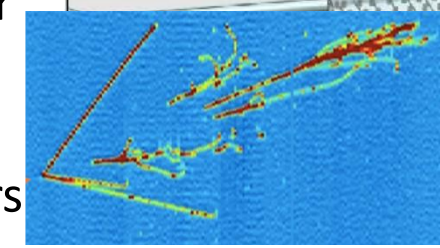
WB beam; use energy
resolution of detector

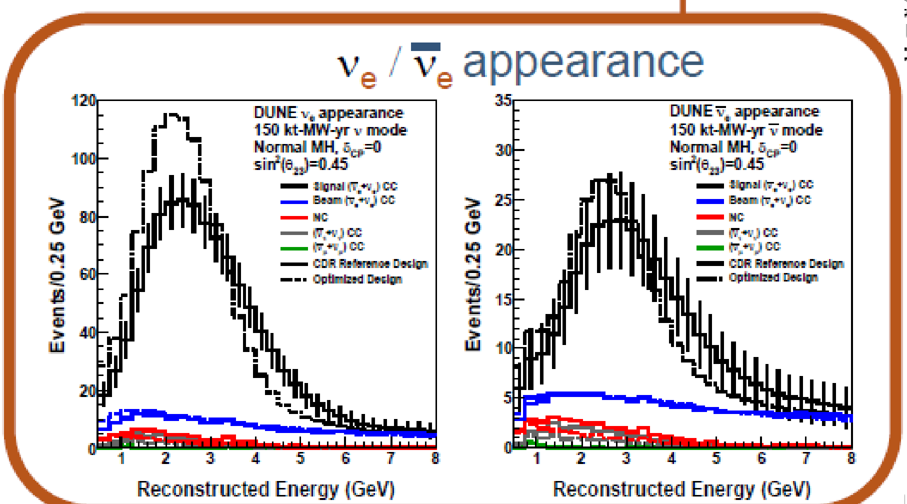
detector 4 x 10kton
Liquid argon detectors
Beautiful ➔

energy spectrum
of appearance:

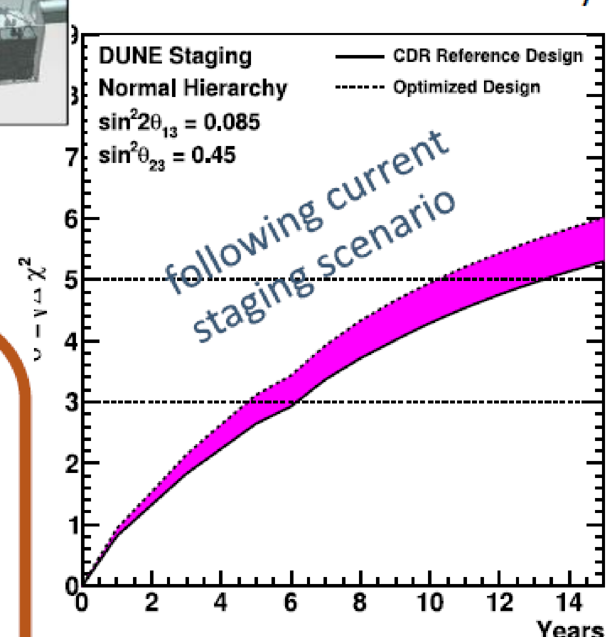




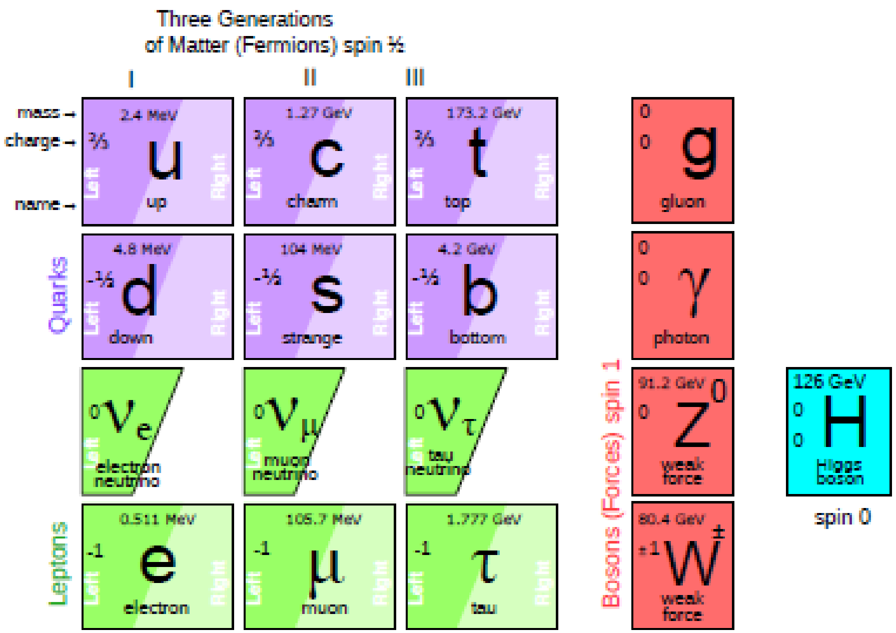


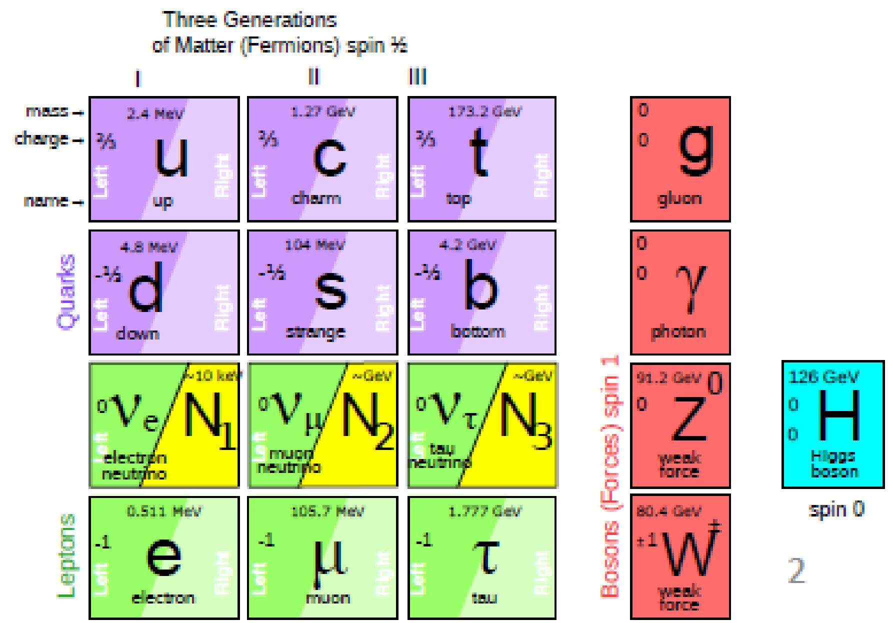


50 % CP Violation Sensitivity



But at least 3 pieces are still missing





neutrinos have mass...

and this very probably implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

.... but could perhaps explain all: DM, BAU,ν-masses

some REFERENCES

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

Department of Physics, Syracuse University, Syracuse, New York 132

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a)], A. Iba

theories of the el

and mixings with

JHEP

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RECEIVED: *September 23, 2013*
ACCEPTED: *December 25, 2013*
PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

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Search for Heavy Right Handed Neutrinos at the FCC-ee

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CERN–PPE/96–195

18 December 1996

Neutral Heavy Leptons
uced in Z Decays

DELPHI Collaboration

The Role of Sterile Ne... Astrophysics

Alexey Boyarsky*†, Oleg Ruchayskiy‡ and Mikhail Shaposhni

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, ... Lausanne, Switzerland

Phys.Lett.B631:151-156,2005
arXiv:hep-ph/0503065

FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshops*
http://indico.cern.ch/category/5684/

Preprint typeset in JHEP style - HYPER VERSION

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The Search for Heavy Majorana Neutrinos

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

Electroweak eigenstates

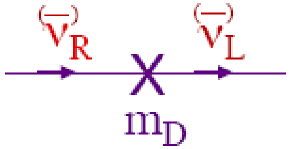
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$	$(\mu)_R$	$(\tau)_R$	Q= -1
	$(\nu_e)_R$	$(\nu_\mu)_R$	$(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0			

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? --

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

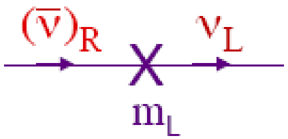
$$m_D \nu_L \overline{\nu}_R \qquad m_D \overline{\nu}_L \nu_R$$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> prevents adding then a term like

$$m_M \overline{\nu_R{}^c}\, \nu_R$$



and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

It is perfectly conceivable ('natural'?) that both terms are present ➔ 'see-saw'

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw in a general way :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}^c_R)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu^c_L \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_R$	$\bar{\nu}_L$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m ↑

dominantly:

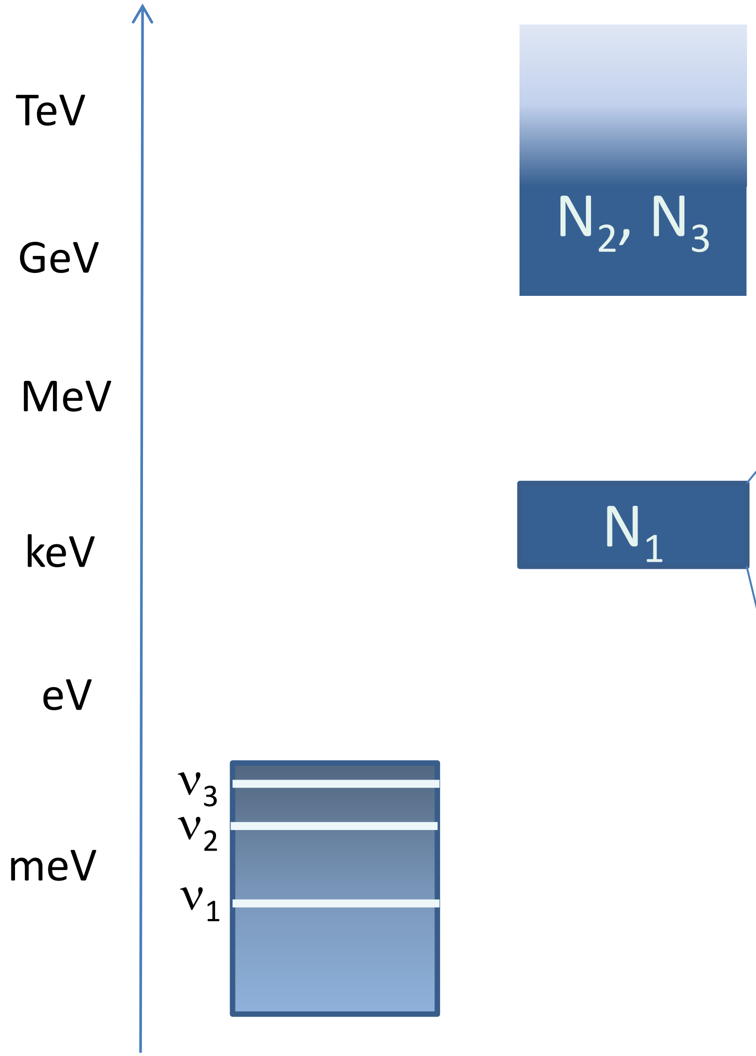
	ν_L	N_R	$\bar{\nu}_R$	$\bar{N}_L$
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

There even exists a scenario that claims to explain everything: the νMSM

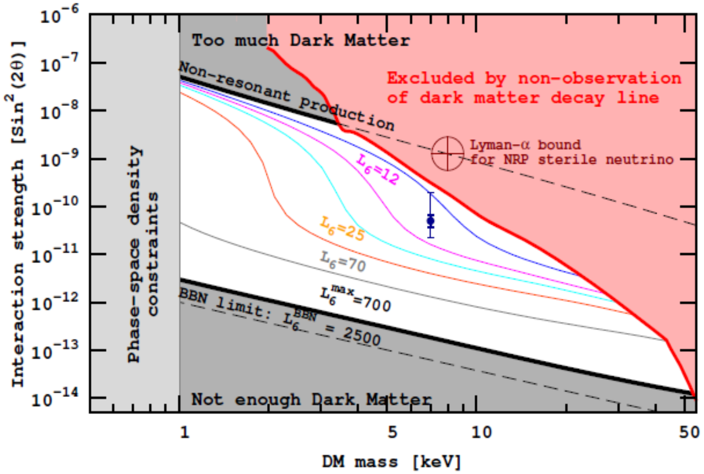
Shaposhnikov et al



can generate Baryon Asymmetry of Universe
if $m_{N2,N3} > 140$ MeV

constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$

$N_1 \rightarrow \nu\,\gamma$



soon excluded?

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^{\ 2}}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu L \cos\theta - N^c{}_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino which couples to weak inter.
and $\neq N_R$, which does'nt.

what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

-- mixing with active neutrinos leads to various observable consequences
- -- if very light (eV) , possible effect on neutrino oscillations (short baseline)
- -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- possibly measurable effects at High Energy

If N is heavy it will decay in the detector (not invisible)

- ➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
- ➔ Higgs, W, Z exotic decays $H \rightarrow \nu_i \ \bar{N}_i$ and $Z \rightarrow \nu_i \ \bar{N}_i$, $W \rightarrow l_i \ \bar{N}_i$
- ➔ also in charm and b decays via $W^* \rightarrow l_i \ \bar{N}_i$
- ➔ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

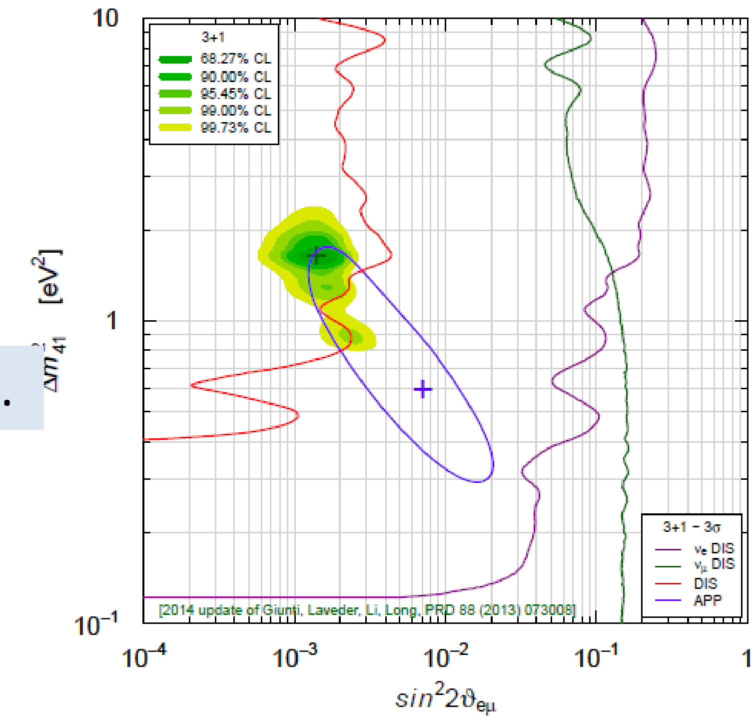
-- Couplings are small (m_ν / m_N) *(but who knows?)* and generally out of reach of hadron colliders *(but this deserves to be revisited for detached vertices @LHC, HL-LHC, FCC-hh)*

Sterile neutrino searches

Some ‘signal’ observed in LSND experiment at Los Alamos since 1993
(neutrinos from pion decas at rest) -- 3.8sigma.
Since then, «interesting effects» (1-2 sigma)
Observed in reactor neutrinos,
miniBoone,
Ga source calibration ....
None very significant or compelling.

Important to clean situation with definitive expt.

Our Fit



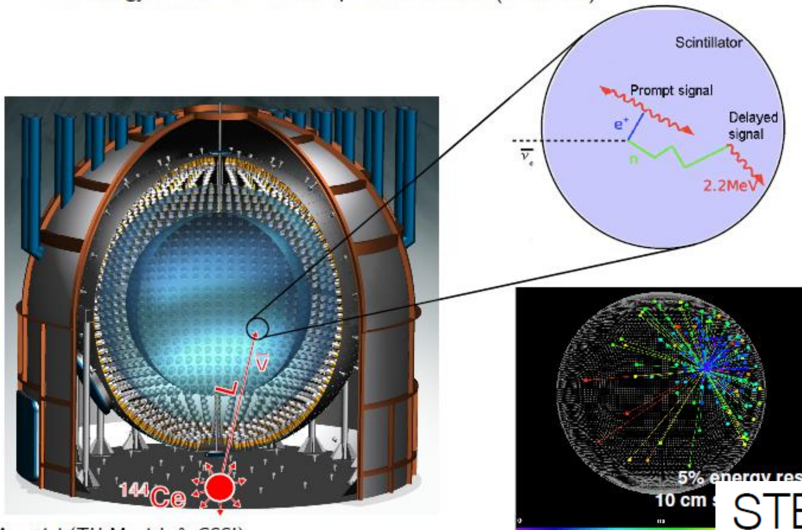
$\mathrm{GoF} = 5\%$

$\mathrm{PGoF} = 0.1\%$

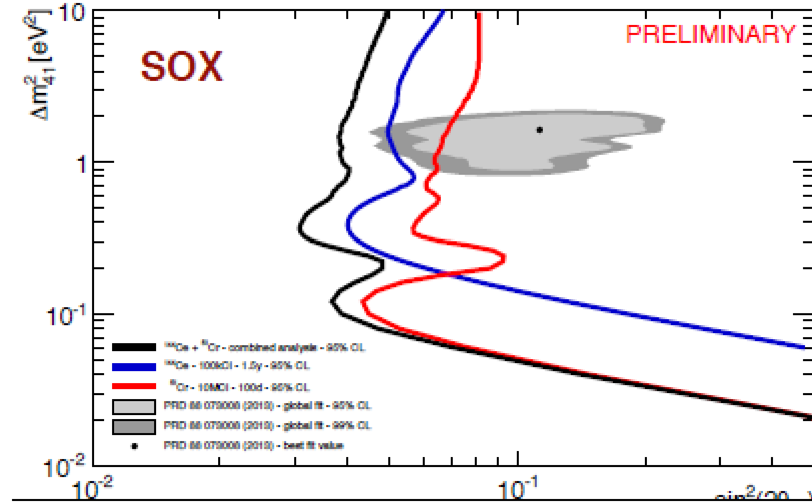
SOX

Detection concept

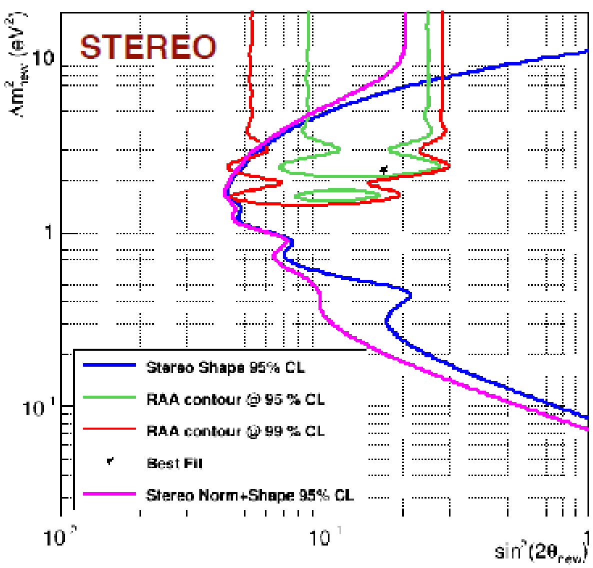
1) $\bar{\nu}_e$ interact via inverse beta decay:
   prompt e^+/e^- annihilation + delayed neutron absorption (2.2 MeV)
2) scintillation photons detected by PMTs (energy and time-of-flight)
   5% energy resolution – 10 cm spatial resolution (at 1 MeV)



Matteo Agostini (TU Munich & GSSI)

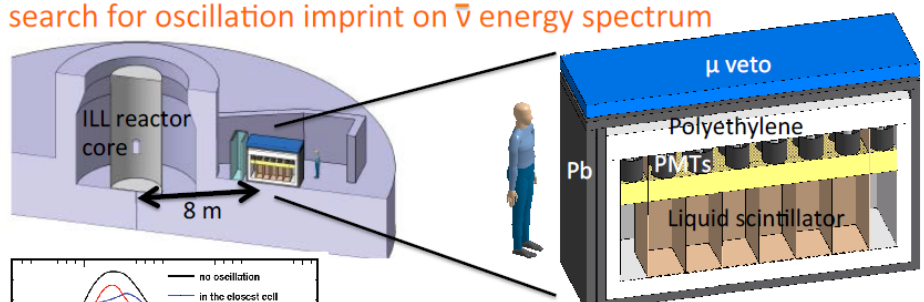


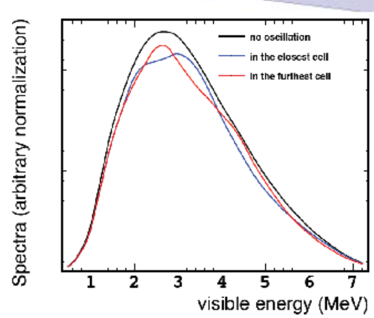
STEREO and SOLID

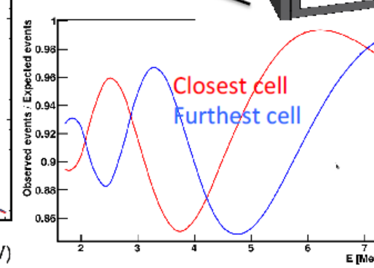


...lain Blondel

- Not just another flux measurement: in very short baselines, search for oscillation imprint on $\bar{\nu}$ energy spectrum

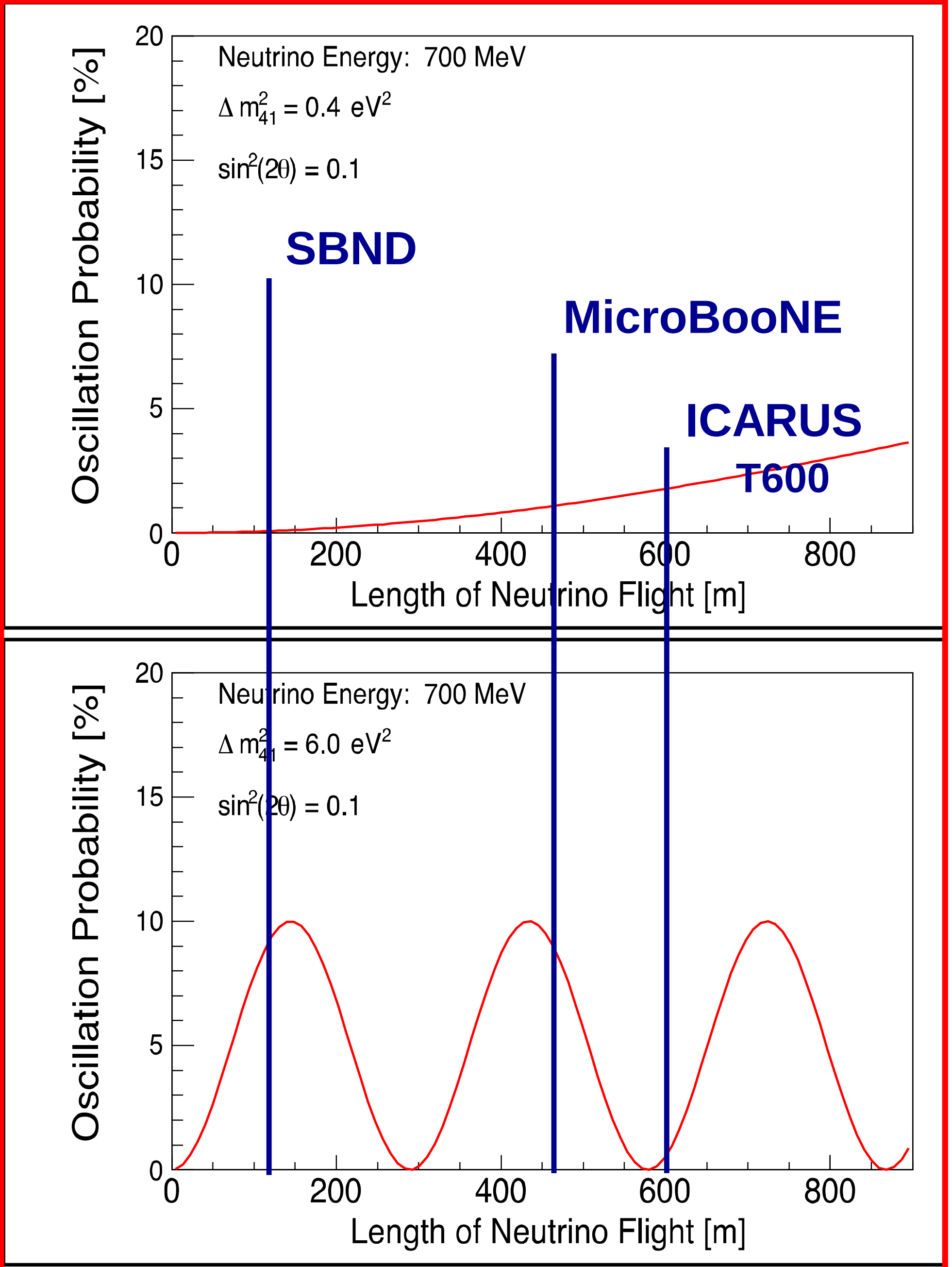




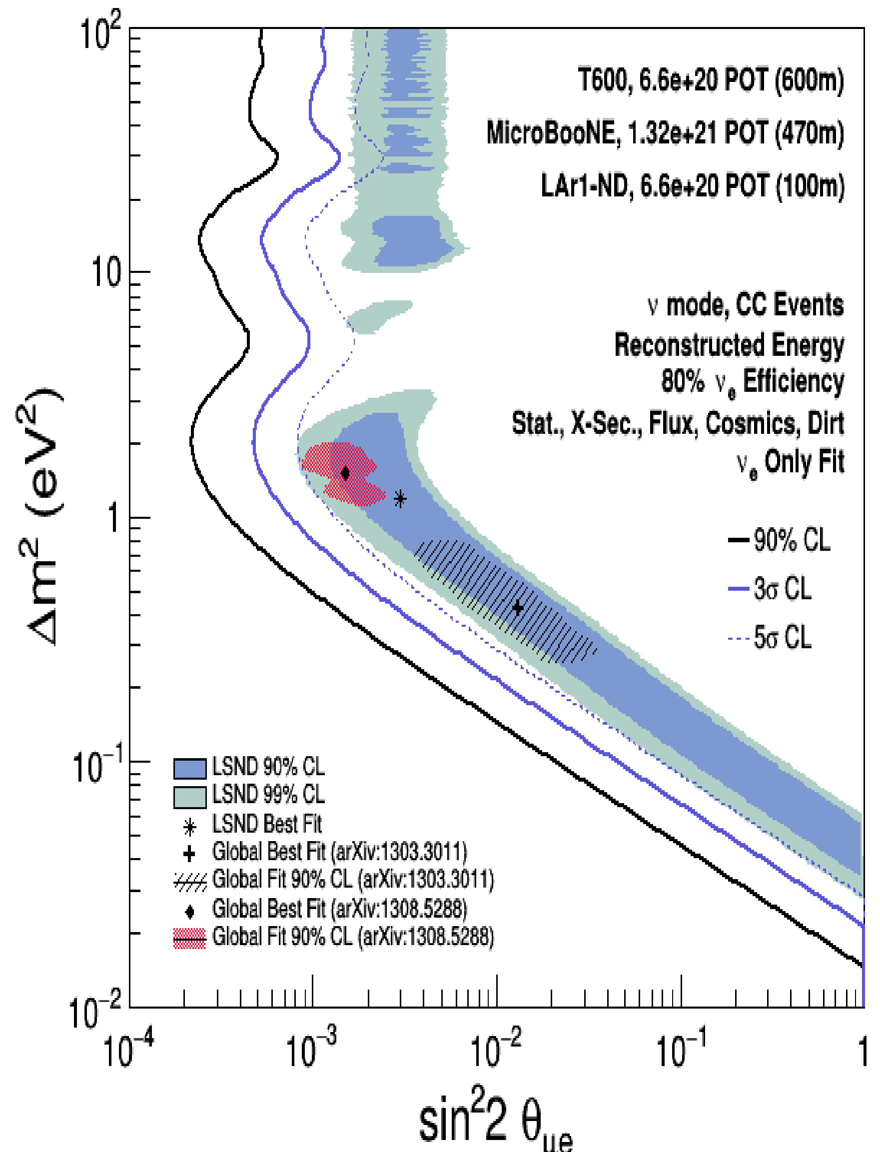


Short Baseline Neutrino programme

- **Definitive search for $\Delta m^2 \sim 1\text{eV}^2$ sterile neutrinos:**
  - **Exploit *L*, *E* and *L*/*E* modulation; detectors at three baselines**
    - **Appearance, $\nu_\mu \rightarrow \nu_e$, *and*, disappearance, $\nu_e \rightarrow \nu_X$**
  - **Exploit 3 LAr detectors; minimise inter-detector systematics**
- **Robustly address backgrounds and uncertainties:**
  - **ν_e contamination in FNAL Booster Neutrino Beam**
  - **Photons produced by NC and CC νN and cosmic rays**
  - **External ν interactions in earth or experimental hall**



Oscillation Probability [%]
Neutrino Energy: 700 MeV
Δ m²41 = 0.4 eV²
sin²(2θ) = 0.1
SBND
MicroBooNE
ICARUS
T600
Length of Neutrino Flight [m]
Oscillation Probability [%]
Neutrino Energy: 700 MeV
Δ m²41 = 6.0 eV²
sin²(2θ) = 0.1
Length of Neutrino Flight [m]



T600, 6.6e+20 POT (600m)
MicroBooNE, 1.32e+21 POT (470m)
LAr1-ND, 6.6e+20 POT (100m)
ν mode, CC Events
Reconstructed Energy
80% νe Efficiency
Stat., X-Sec., Flux, Cosmics, Dirt
νe Only Fit
90% CL
3σ CL
5σ CL
LSND 90% CL
LSND 99% CL
LSND Best Fit
Global Best Fit (arXiv:1303.3011)
Global Fit 90% CL (arXiv:1303.3011)
Global Best Fit (arXiv:1308.5288)
Global Fit 90% CL (arXiv:1308.5288)
Δm² (eV²)
sin²2 θμe

by 2020

Indirect effects

-- neutrino Majorana mass term can lead to lepton number violating processes by virtual neutrino exchange and to flavour violation

-- neutrinoless double beta decay (the most powerful one)

-- FCNC ($\mu \rightarrow e\gamma$) etc...

-- at a Z factory : $Z \rightarrow \tau\mu$ $Z \rightarrow \tau e$ $Z \rightarrow \tau\tau$, $\tau \rightarrow \mu\gamma$ $\tau \rightarrow e\gamma$ etc...

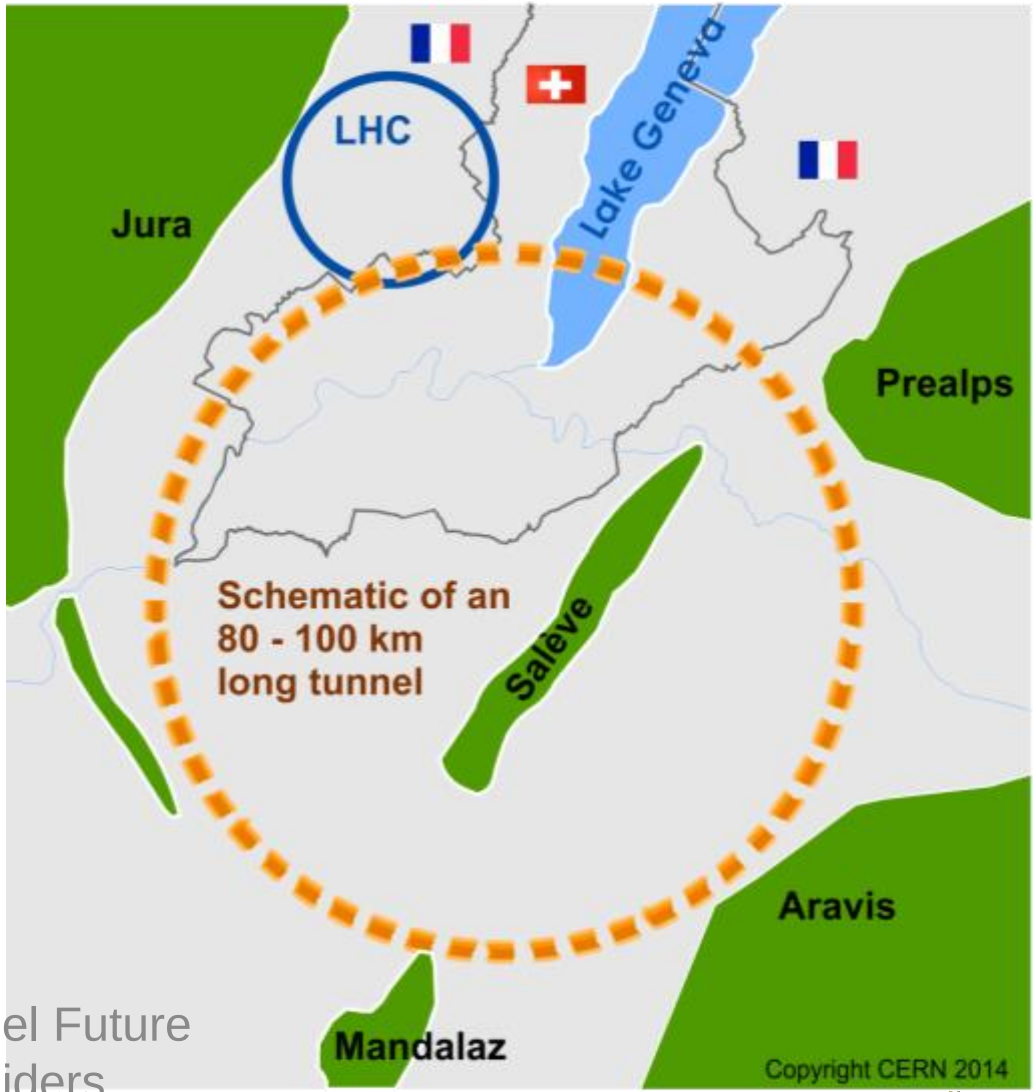
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km	
~20 T ⇒ 100 TeV *pp* in 80 km	

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step ECM=90-400 GeV
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



RHASnu's production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\bar{\nu}\right) |U|^2 \left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for anti neutrino and add contributions of 3 neutrino species (with differe

Decay

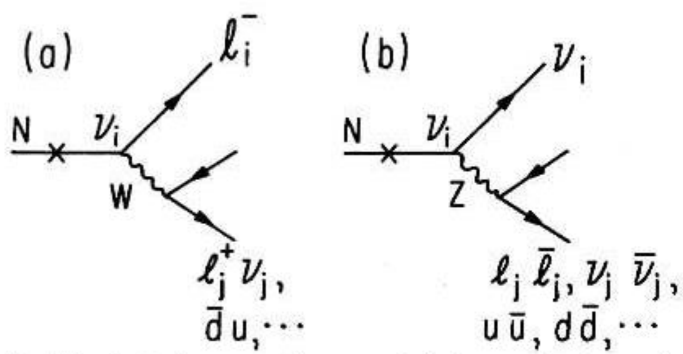


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

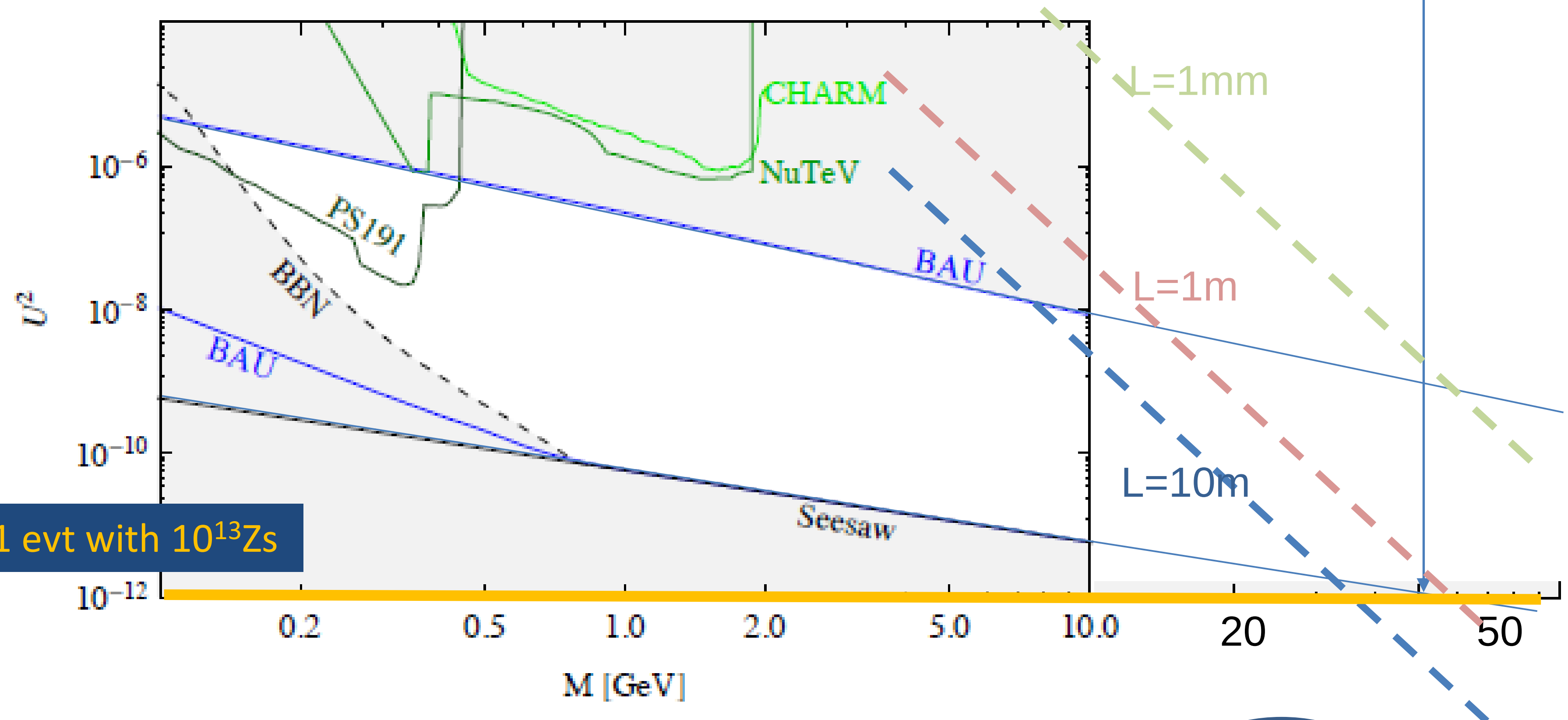
$$L \approx \frac{3\ \text{cm}}{|U|^2\left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → W^{*+} W^{*-} e+e- → Z*(νν) + (Z/γ)*

Decay length

Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



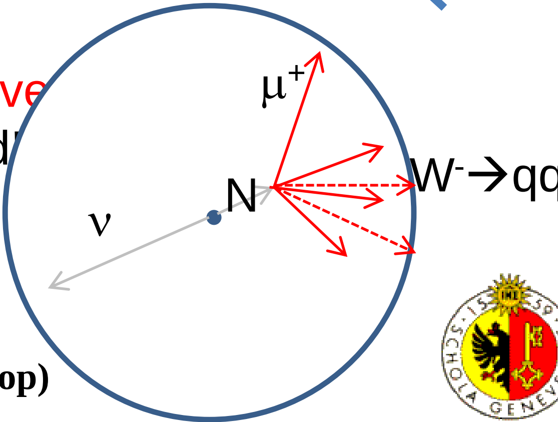
~1 evt with 10^{13}Zs

heavy neutrino mass ~ M

a large part of the interesting region will lead to detached ve

... ➔very strong reduction of background!

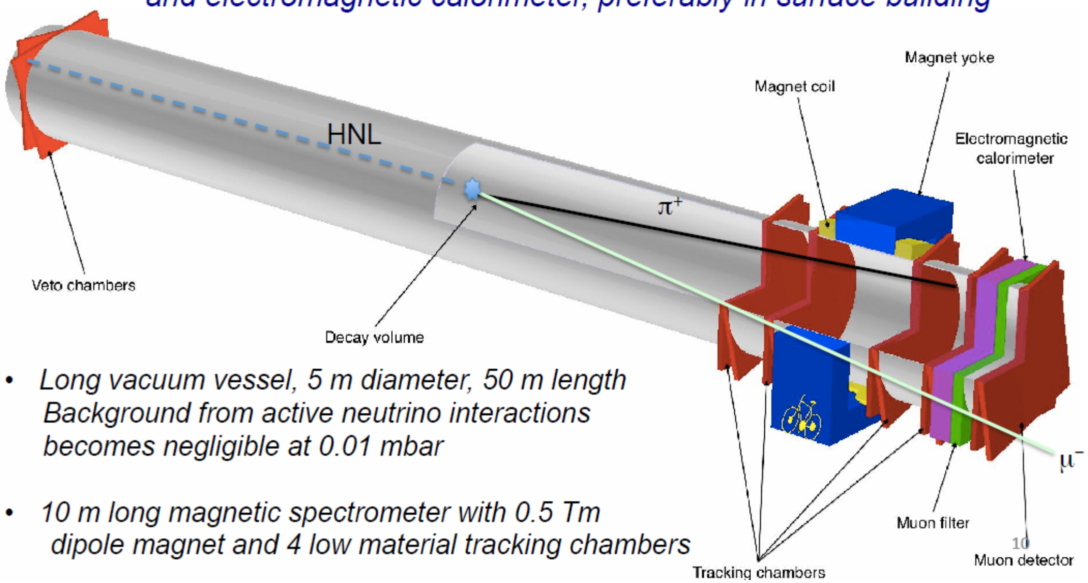
Exact reach domain will depend on detector size
and details of displaced vertex efficiency & background



Detector concept
(based on existing technologies)

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$*

Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building



- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Proposal to search for Heavy Neutral Leptons at the SPS

(CERN-SPSC-2013-024 / SPSC-EOI-010)

Disclaimer: It is not a classical neutrino physics experiment

On behalf of:

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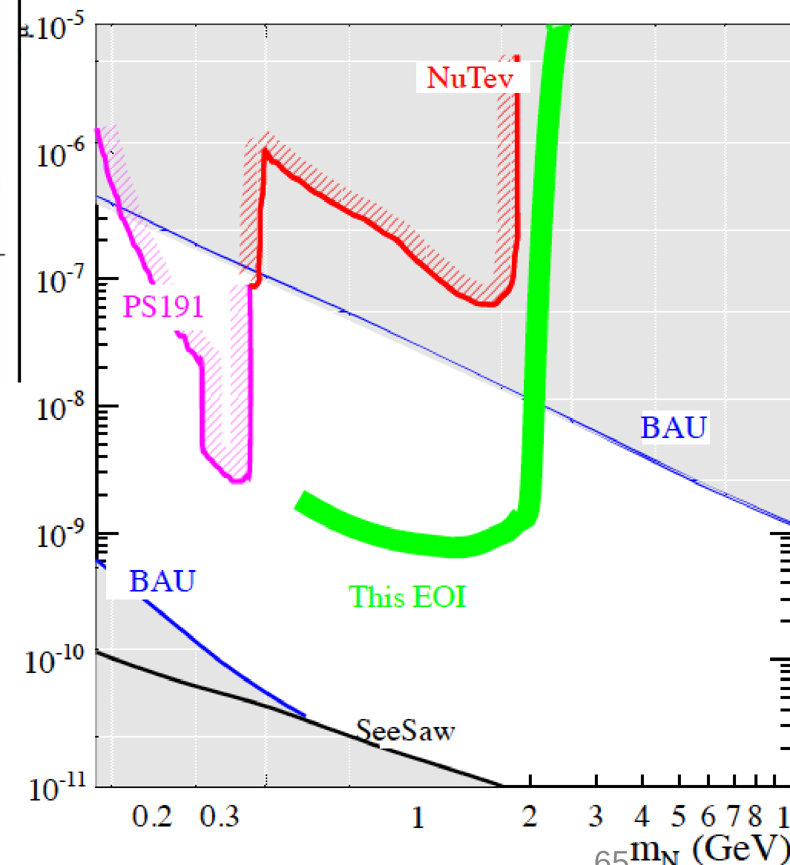

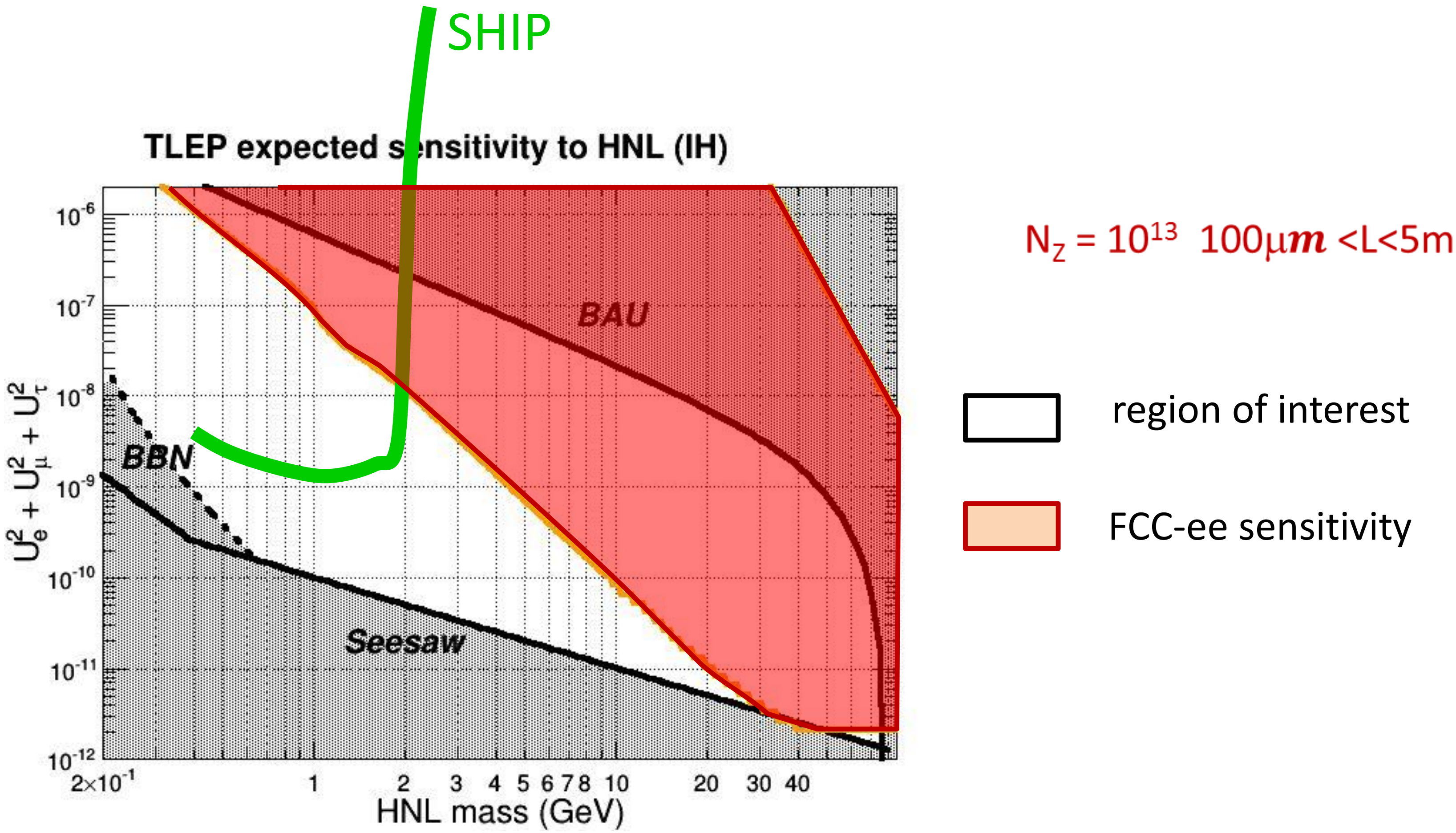

NB very large detector caverns for FCC-hh may allow very large FCC-ee detector (R=15m?) leading to improved reach at lower masses.

CONCLUSIONS

Neutrinos have mass!
This is the only known particle physics fact beyond the Standard Model

Opens possibility of
-- CP violation in leptons
-- heavy right handed neutrinos
-- fermion-antifermion transitions

all leading the possible explanations for the Baryon dominance in the Universe and perhaps even dark matter.

An important and growing experimental program is happening and planned in the many aspects of interest:
nuclear physics, neutrino beams natural, from reactors, from accelerators
all the way to high energy colliders.

We will work on neutrinos for many years to come!